

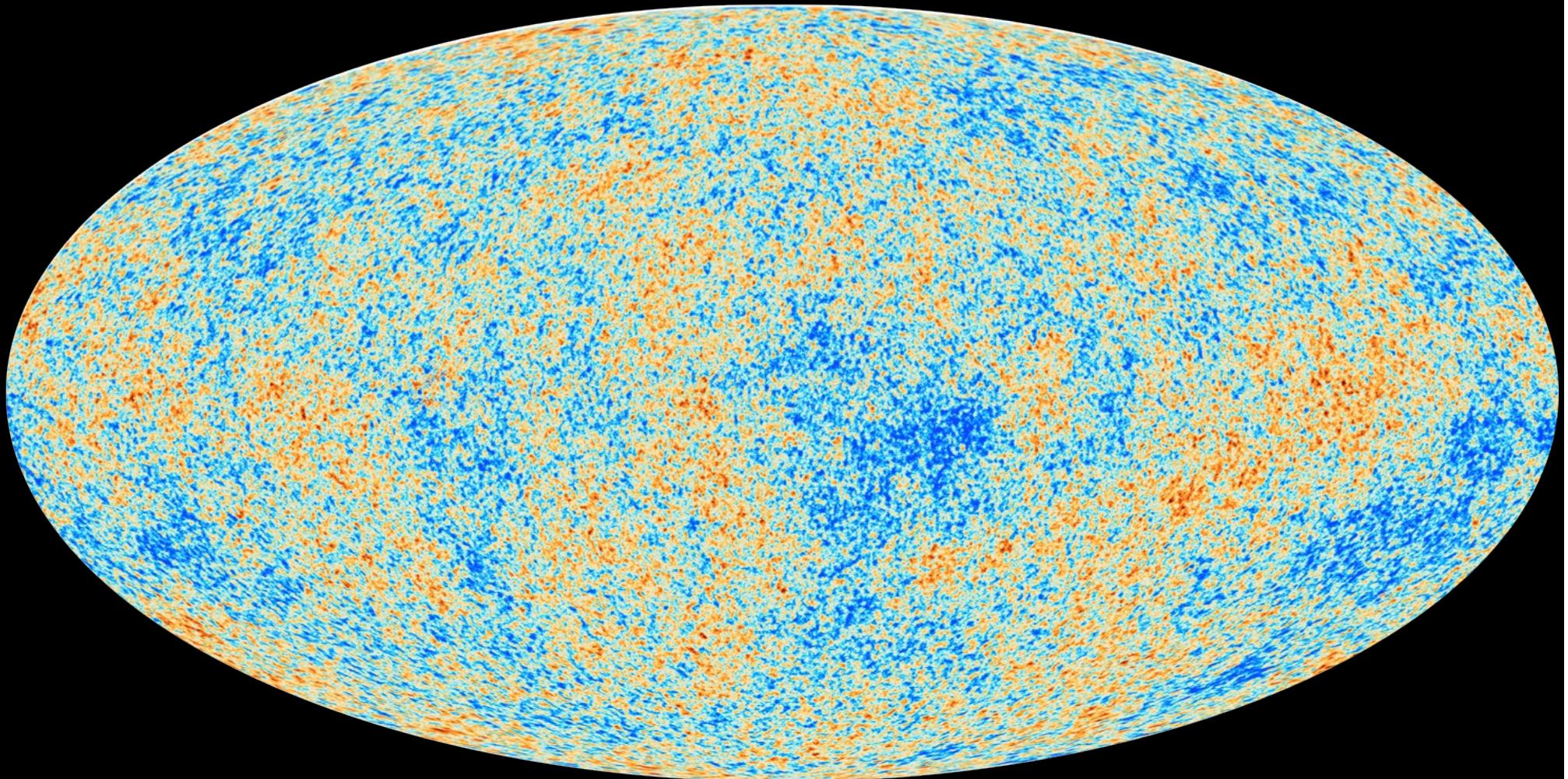


IceCube: the discovery of cosmic neutrinos francis halzen

- some history, cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

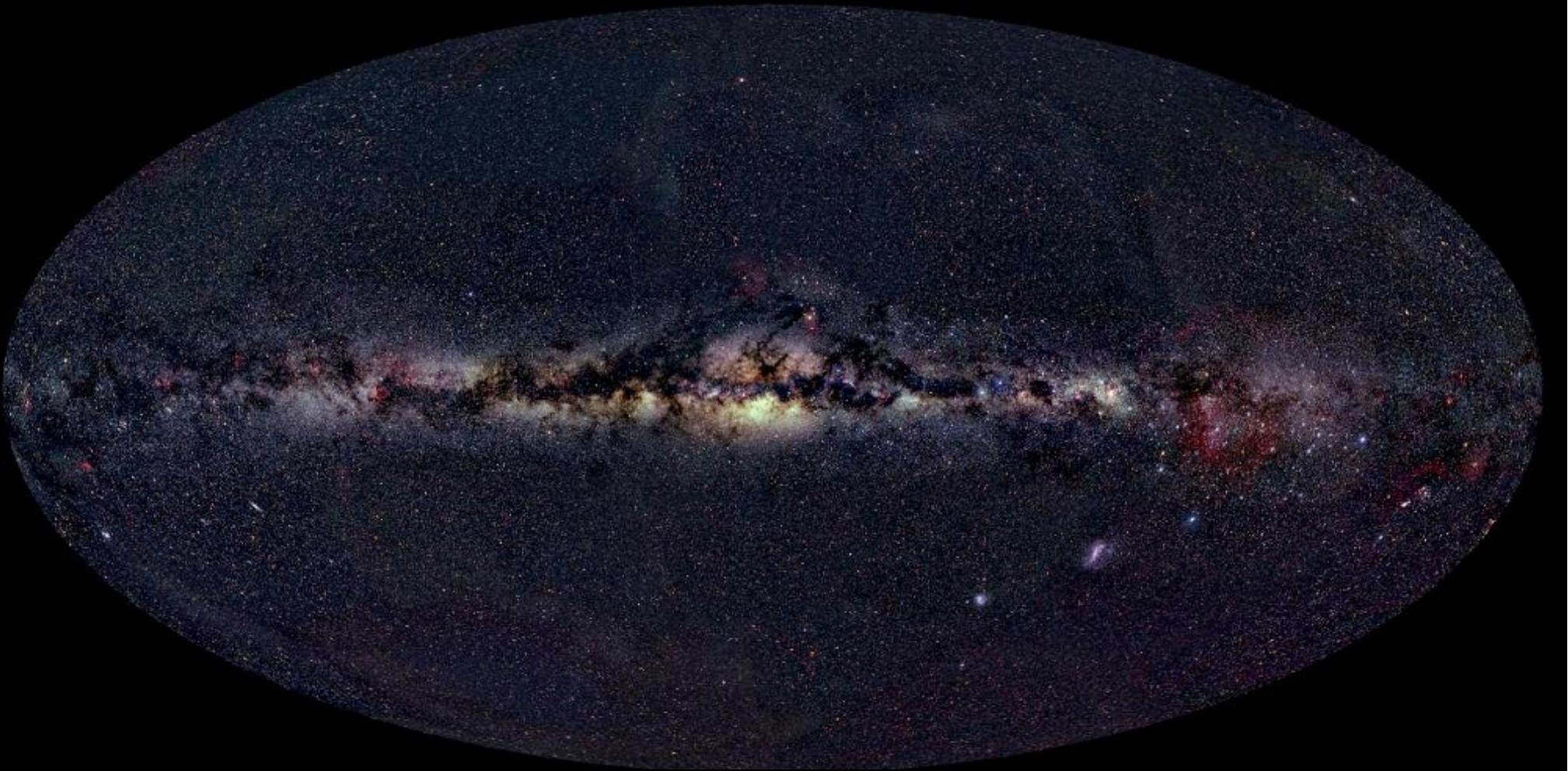
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



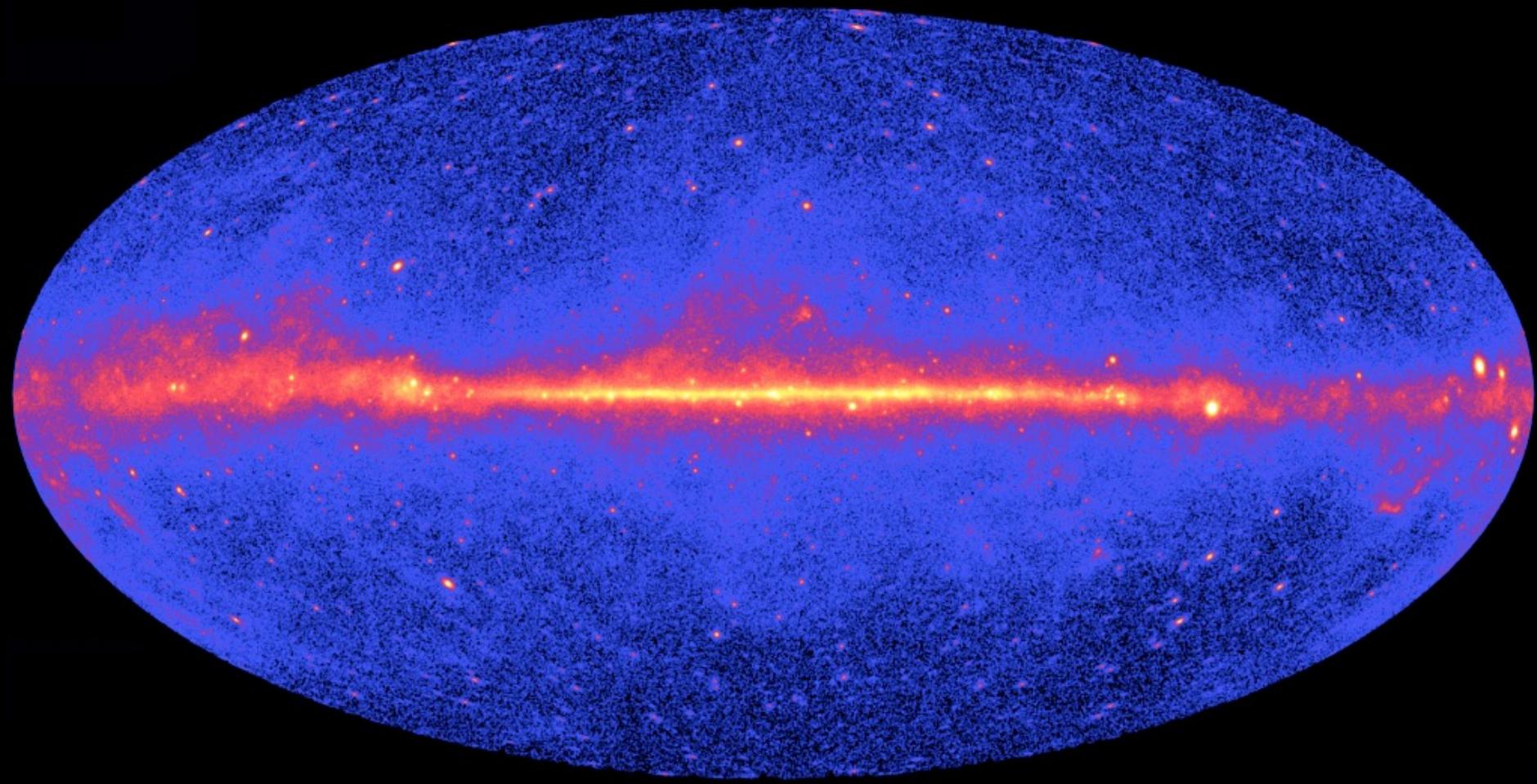
wavelength = 1 mm \Leftrightarrow energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m \Leftrightarrow energy = 1 eV

Cosmic Horizons – Gamma Radiation

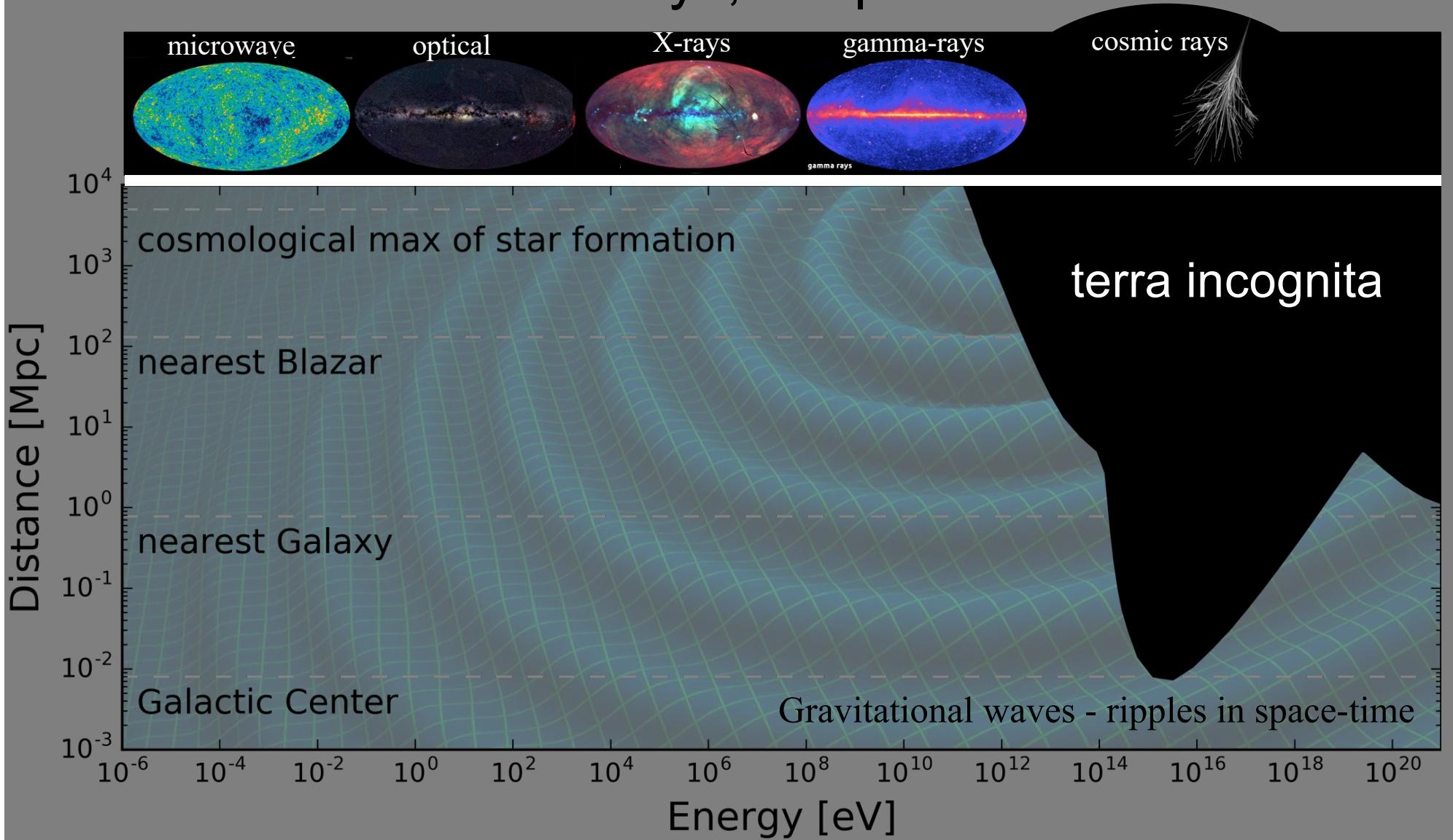


wavelength = 10^{-15} m \Leftrightarrow energy = 10^9 eV

Cosmic Horizons – Highest Energies

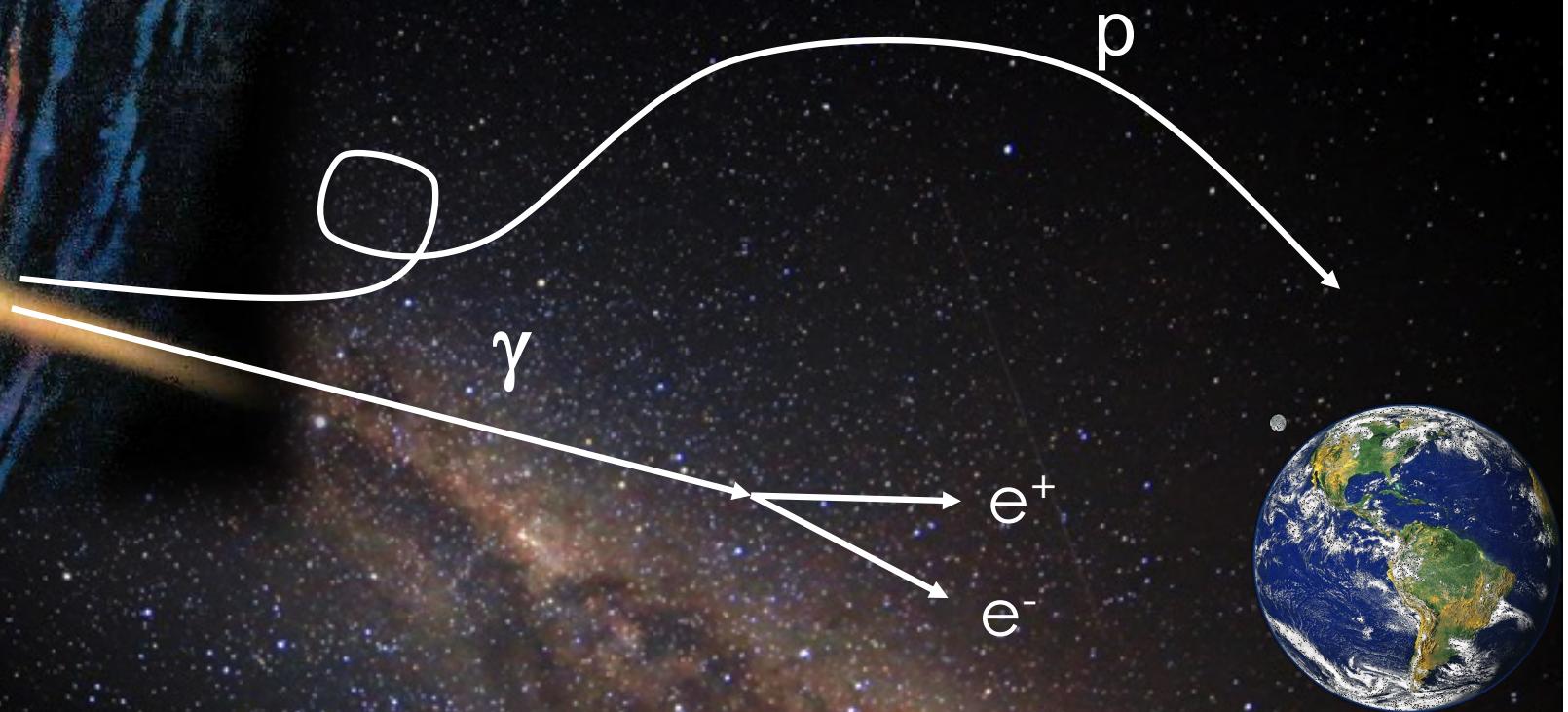
wavelength = 10^{-21} m \Leftrightarrow energy = 10^3 TeV

highest energy “radiation” from the Universe: cosmic rays, not photons



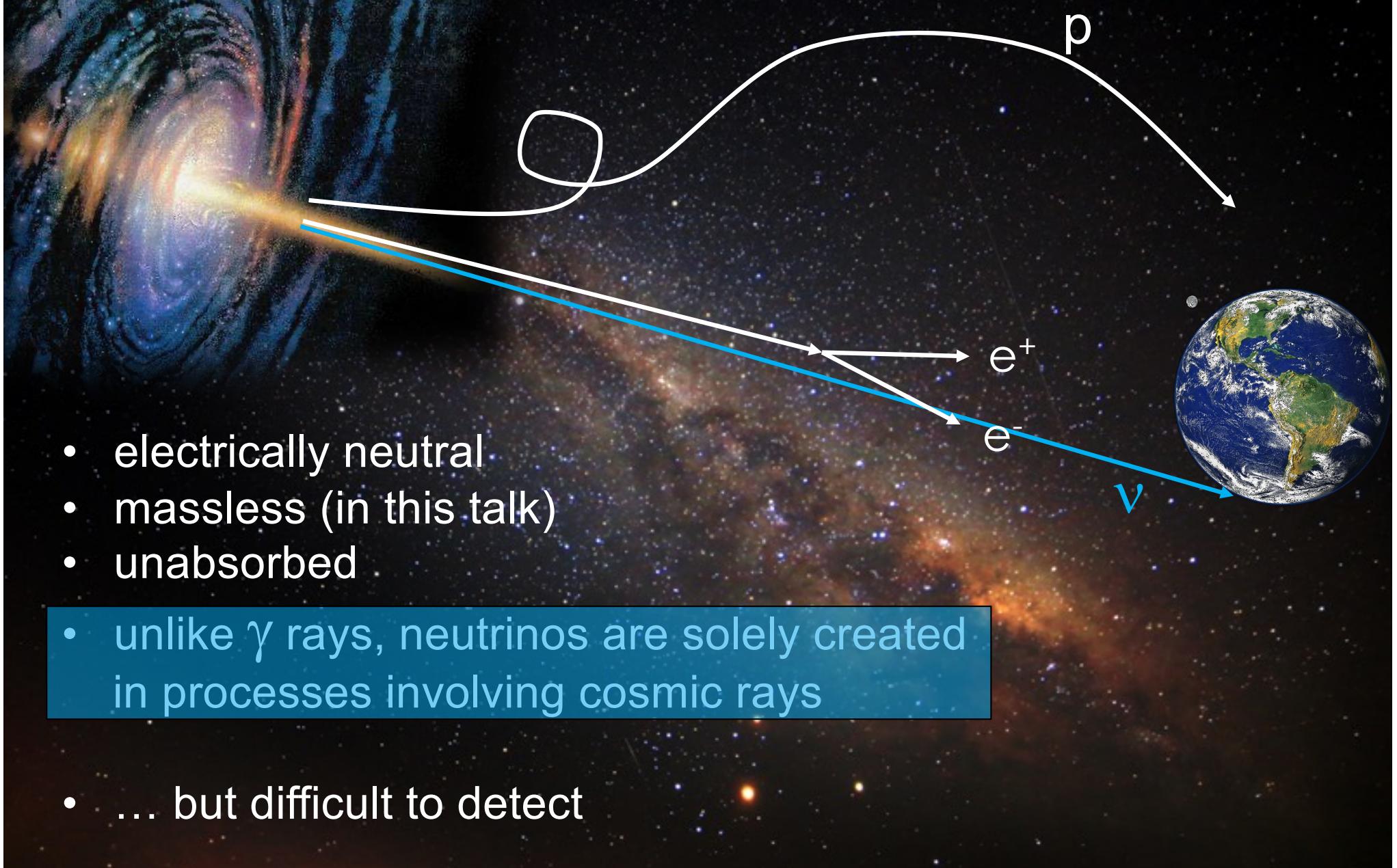
Universe beyond our Galaxy is eventually opaque to gamma rays

The opaque Universe

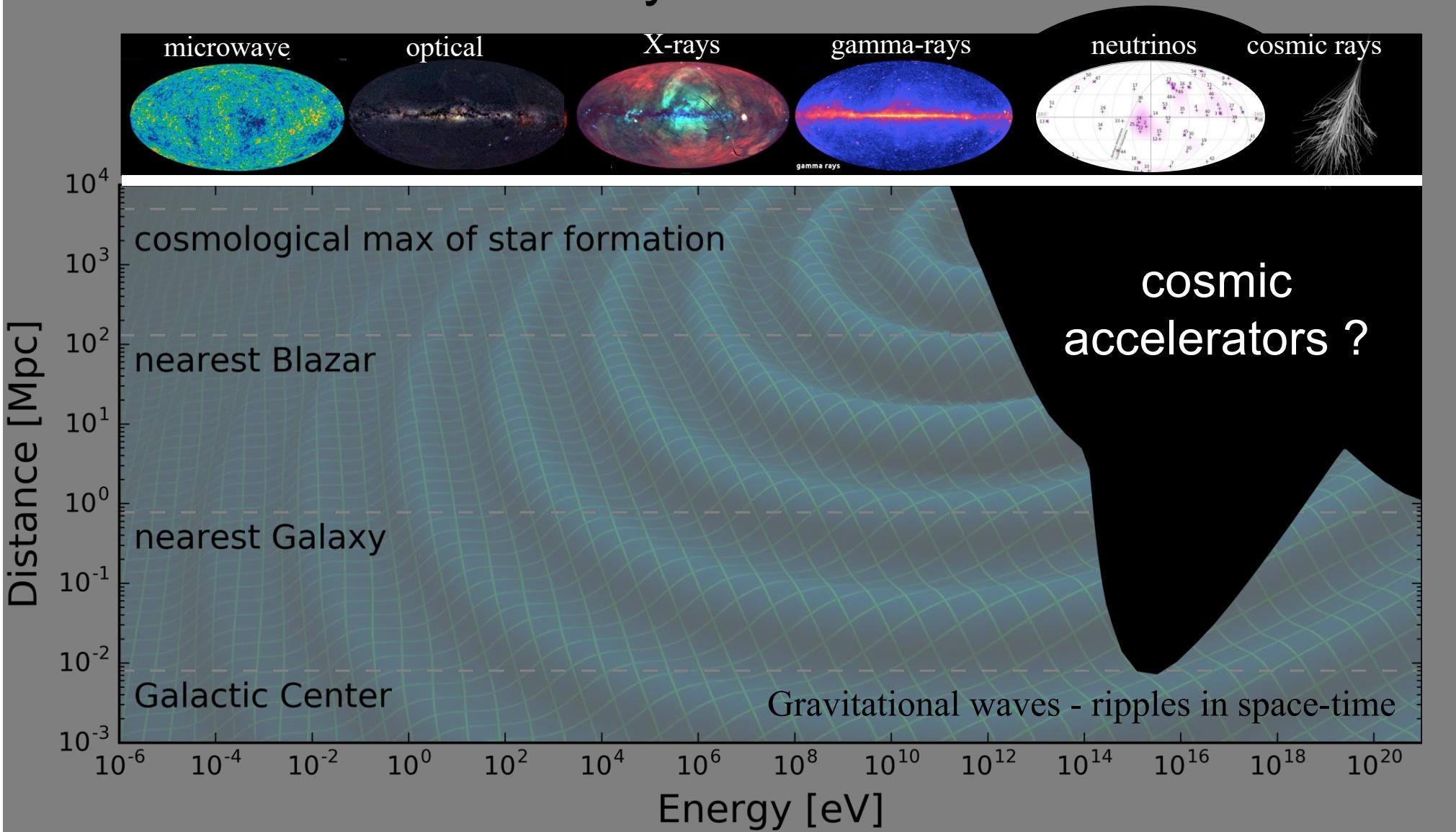


PeV photons interact with microwave photons ($411/\text{cm}^3$) before reaching our telescopes
enter: neutrinos

Neutrinos? Perfect Messengers



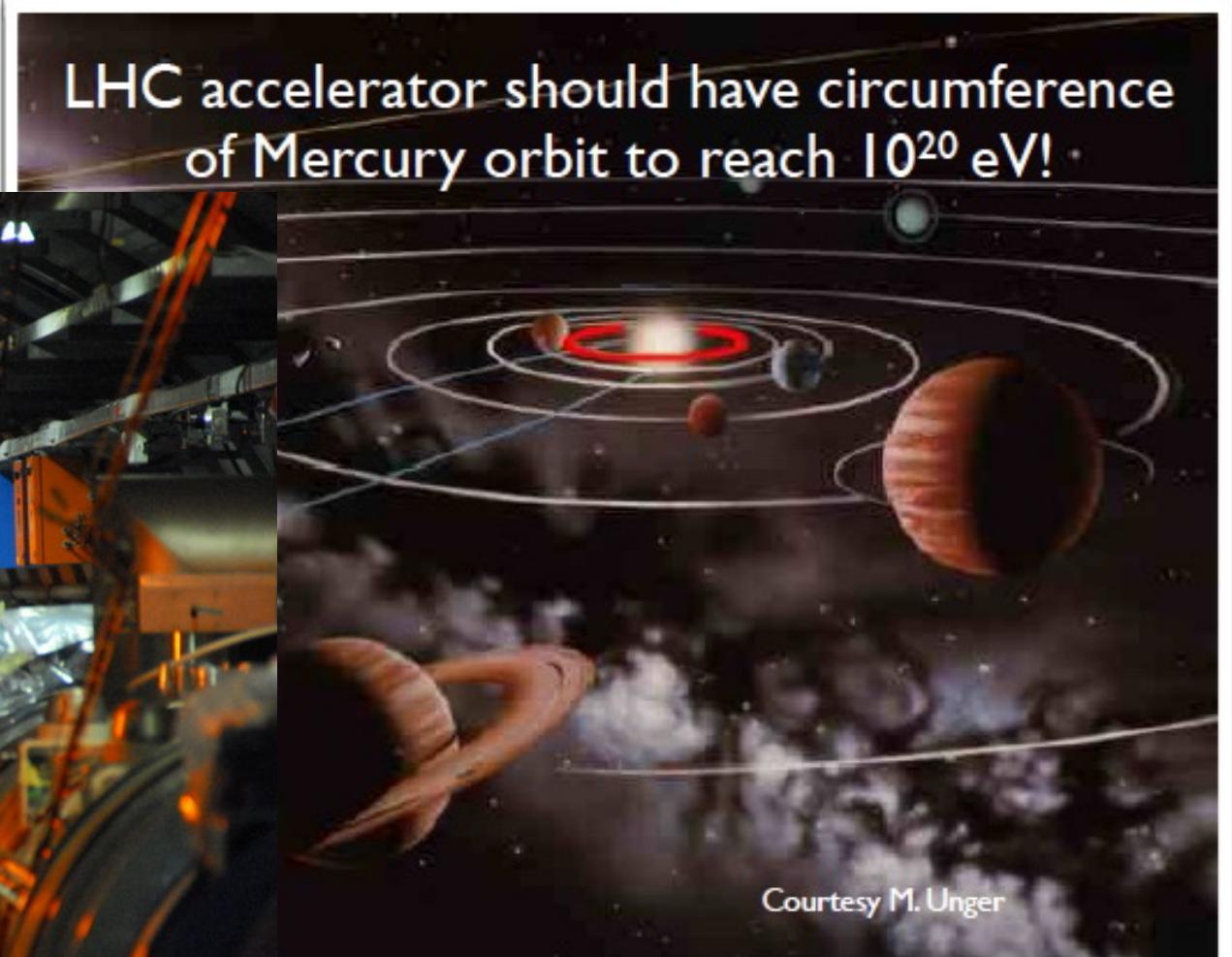
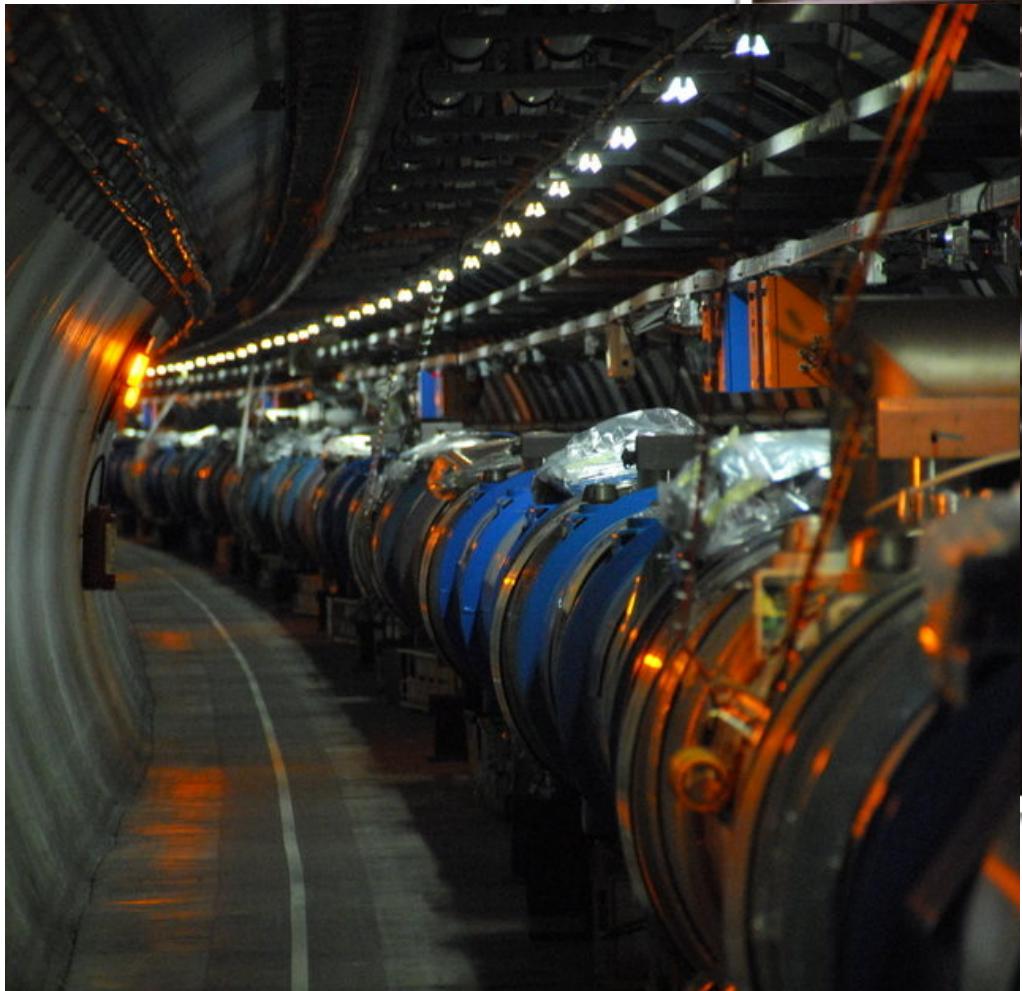
highest energy “radiation” from the Universe: cosmic rays and neutrinos



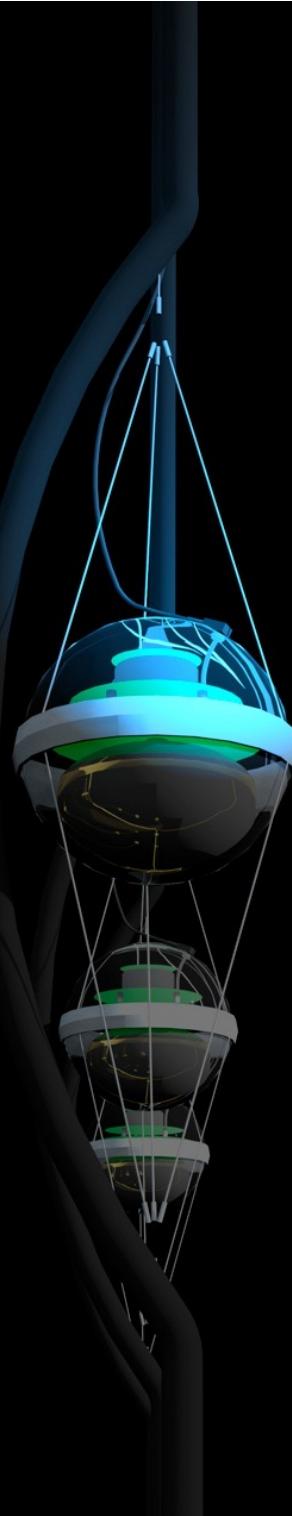
Universe beyond our Galaxy is eventually opaque to gamma rays

highest energy radiation from the Universe: not γ -rays !

high energy
high luminosity



Fly's Eye 1991
300,000,000 TeV

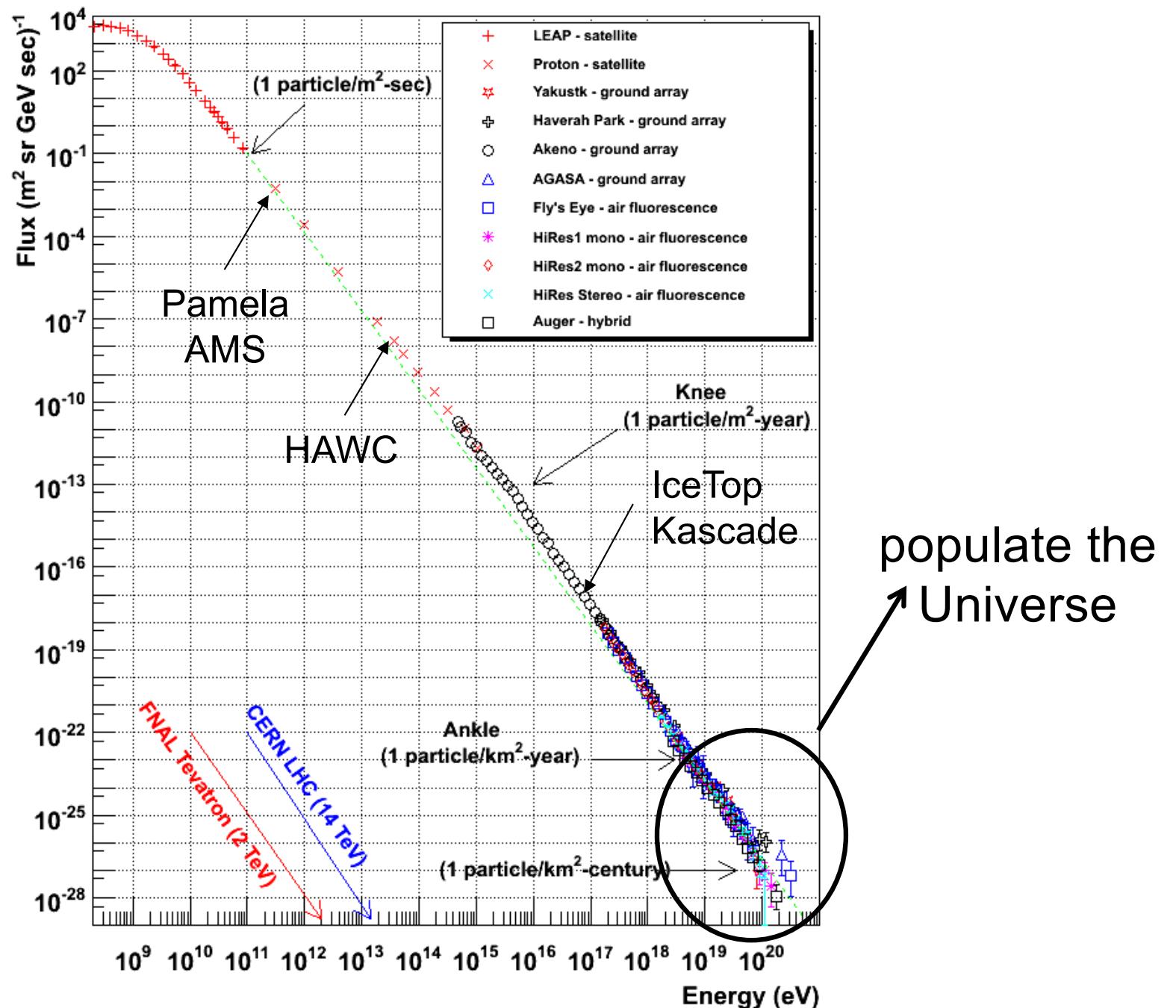


IceCube: the discovery of cosmic neutrinos

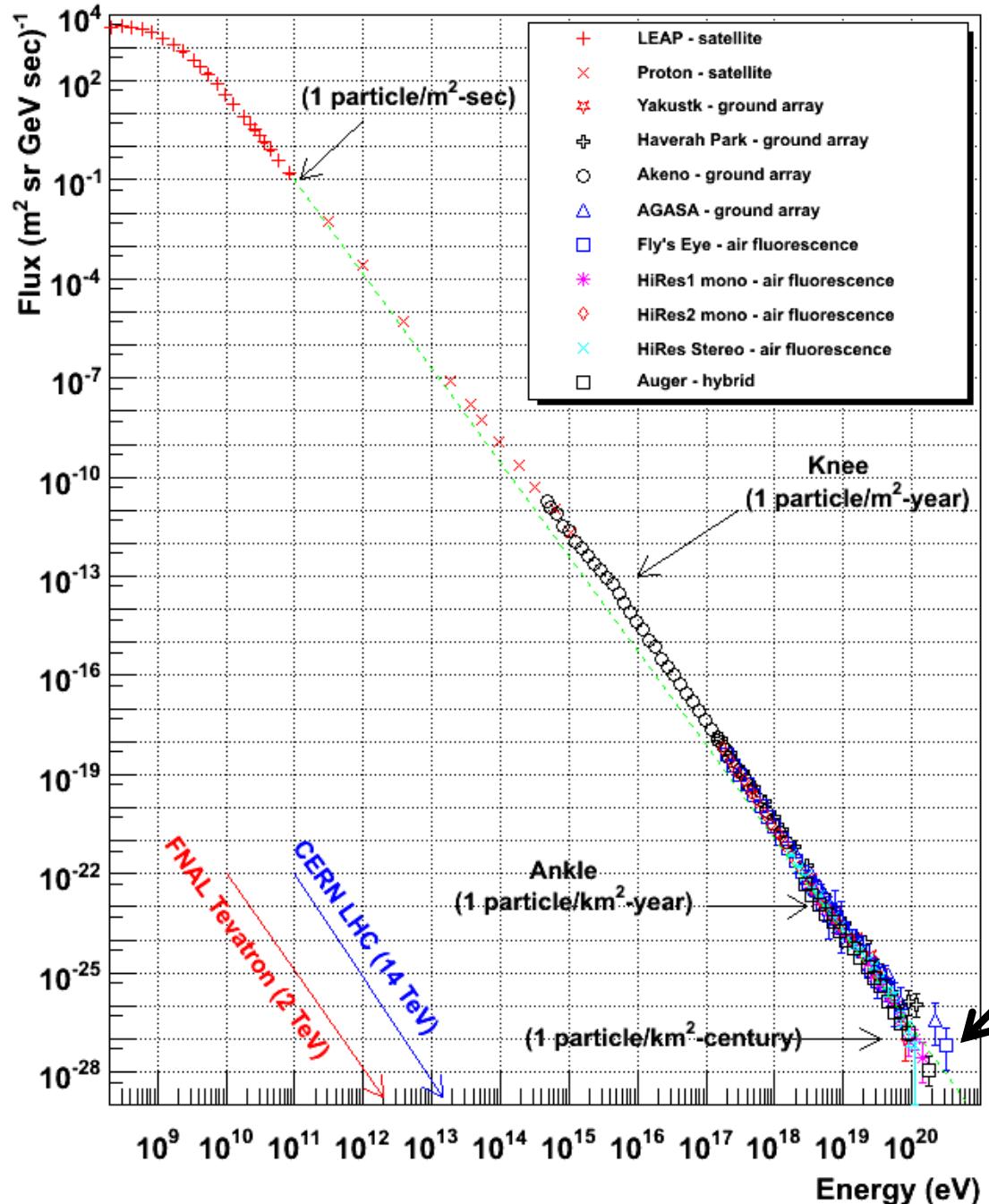
francis halzen

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Cosmic Ray Spectra of Various Experiments



origin of cosmic rays: oldest problem in astronomy

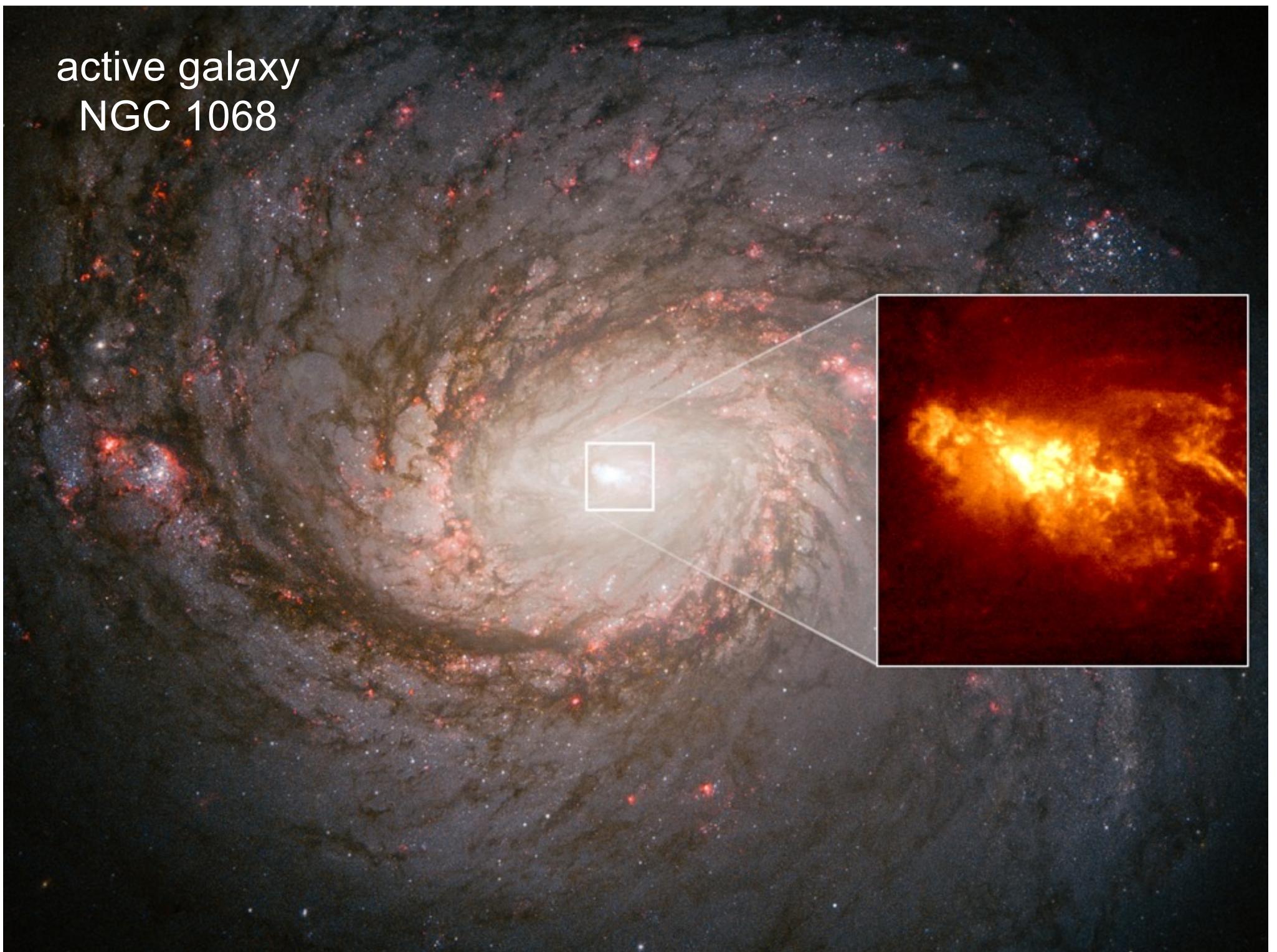


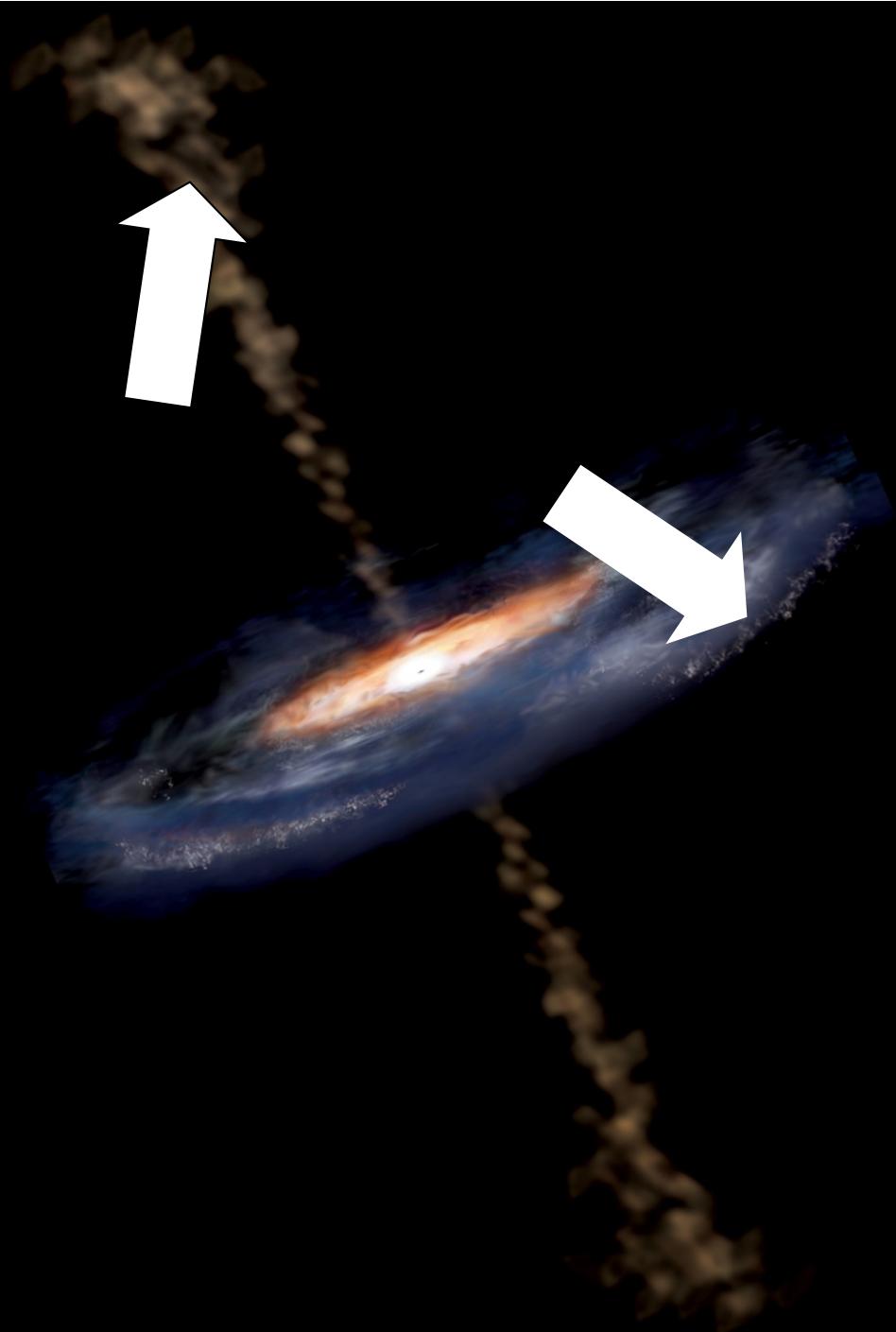
cosmic ray challenge

both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

active galaxy
NGC 1068





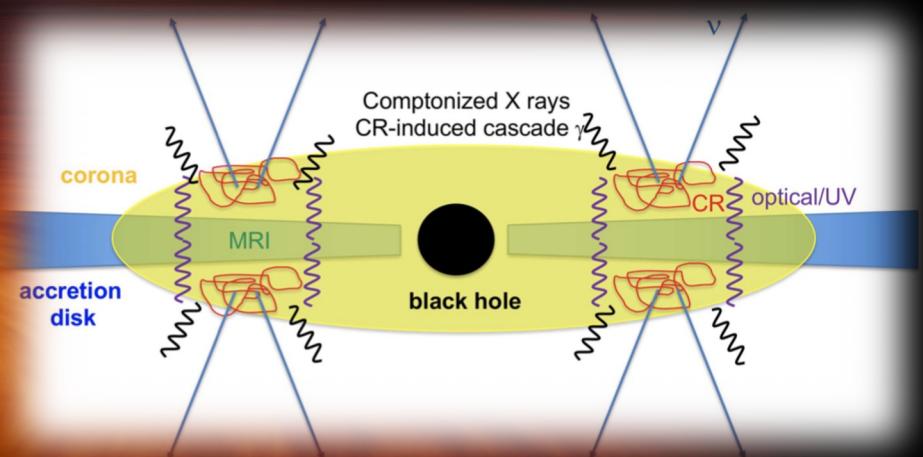
active galaxy

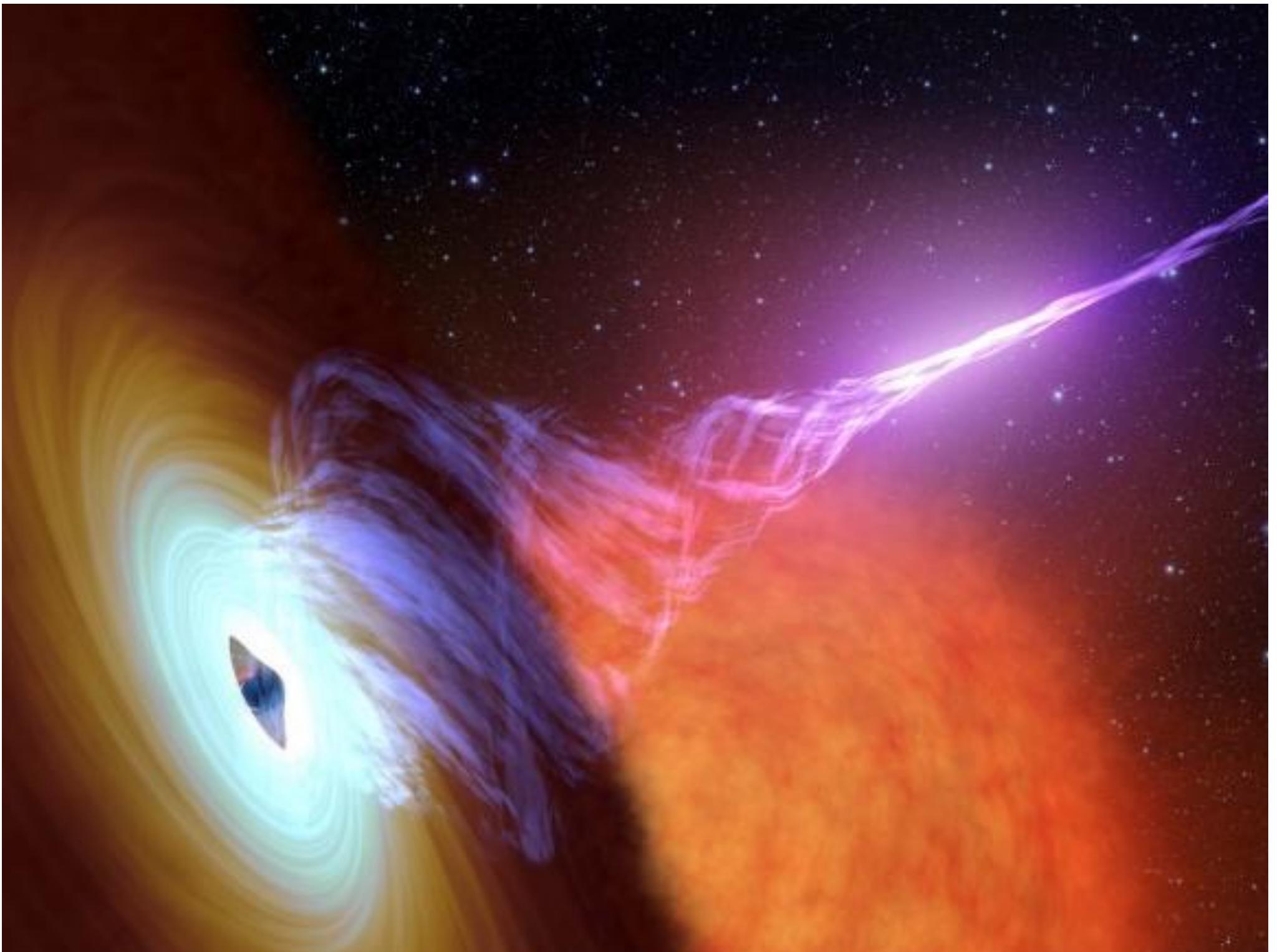
particle flows near
supermassive
black hole

cores of active galaxies as cosmic accelerators

acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona (0.1 pc) emitting most of the X-rays

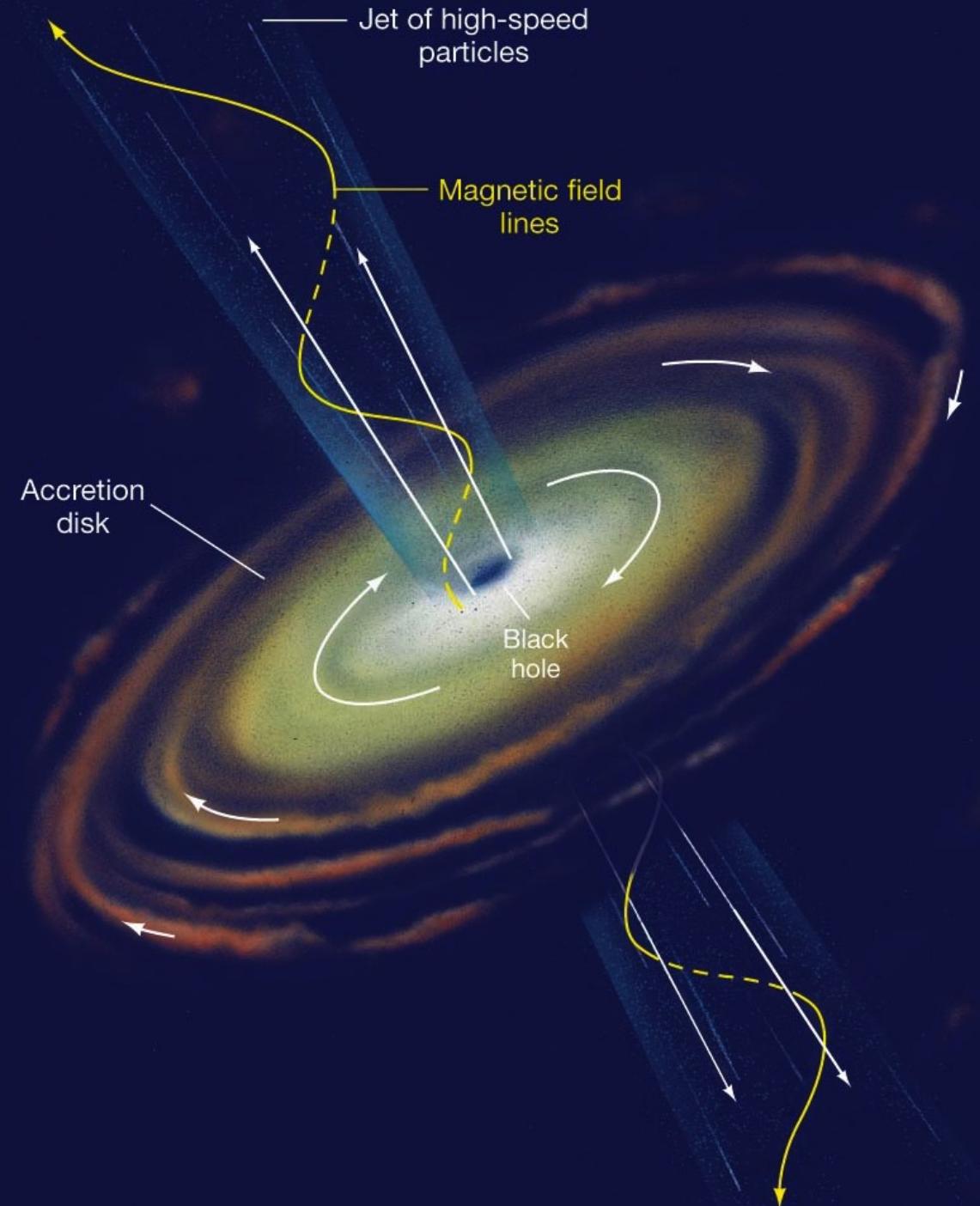
the core is the target for neutrino production
and gamma-ray obscured

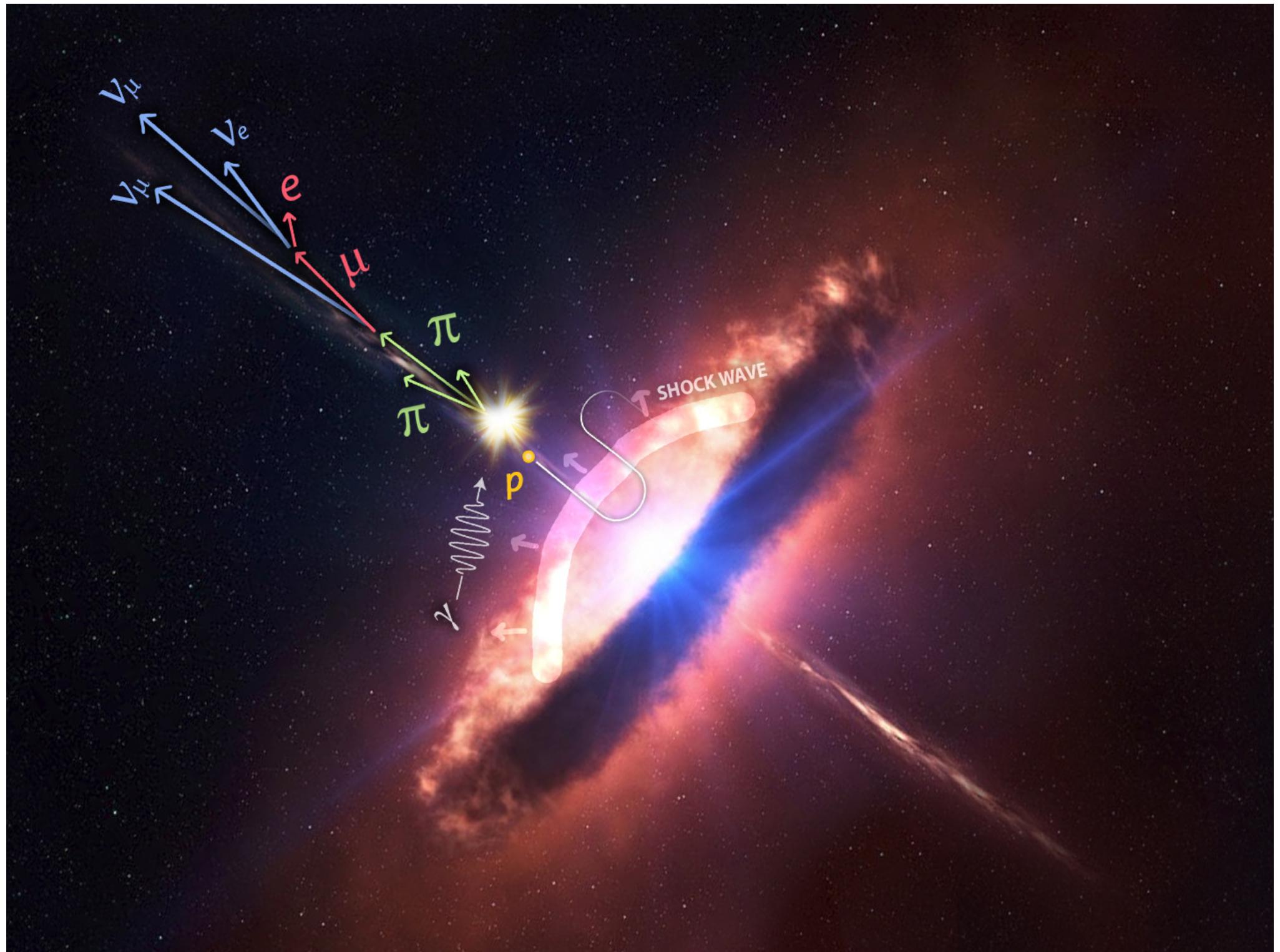




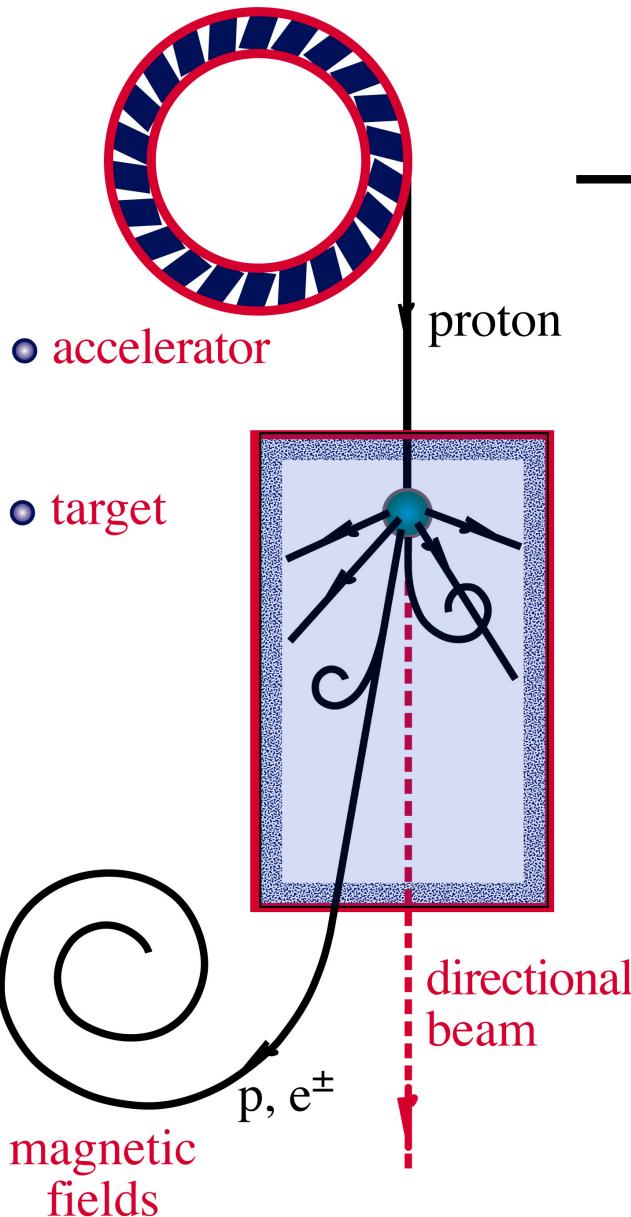
cores of active galaxies and jets

- some of the matter falling into a supermassive black hole is accelerated in a jet along its rotation axis
- fast spinning infalling matter comes in contact with the rotating black hole
- spacetime around spinning black hole drags on the field winding it into a tight cone around the rotation axes
- plasma from the accretion disk is then flung out along these field lines





ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy



**black hole
neutron star**

**radiation
and dust**

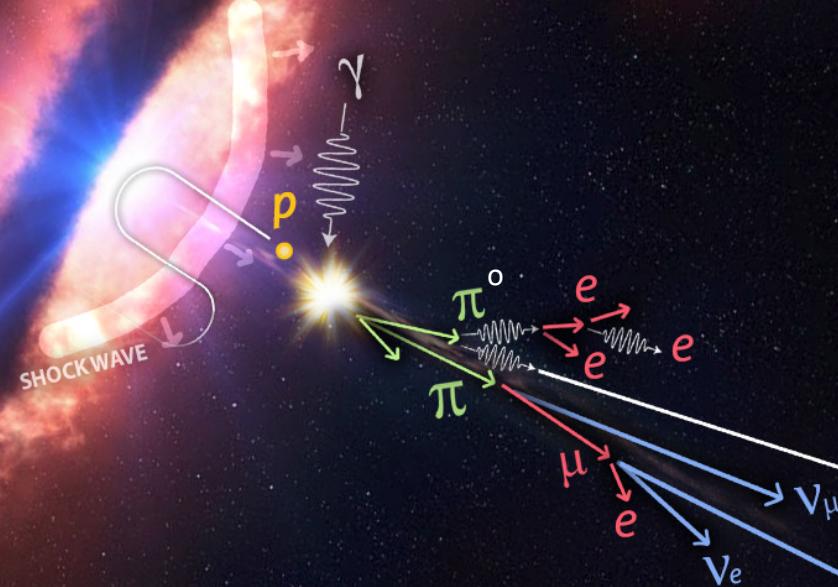
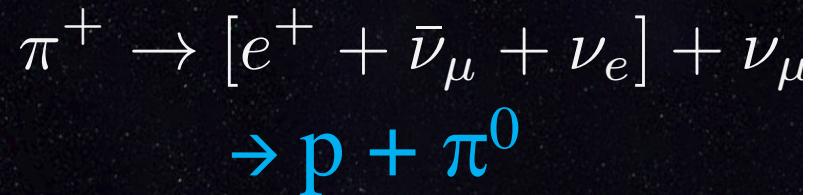
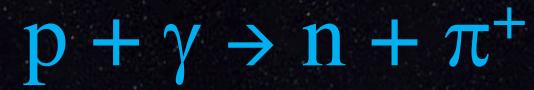


\sim cosmic ray + neutrino

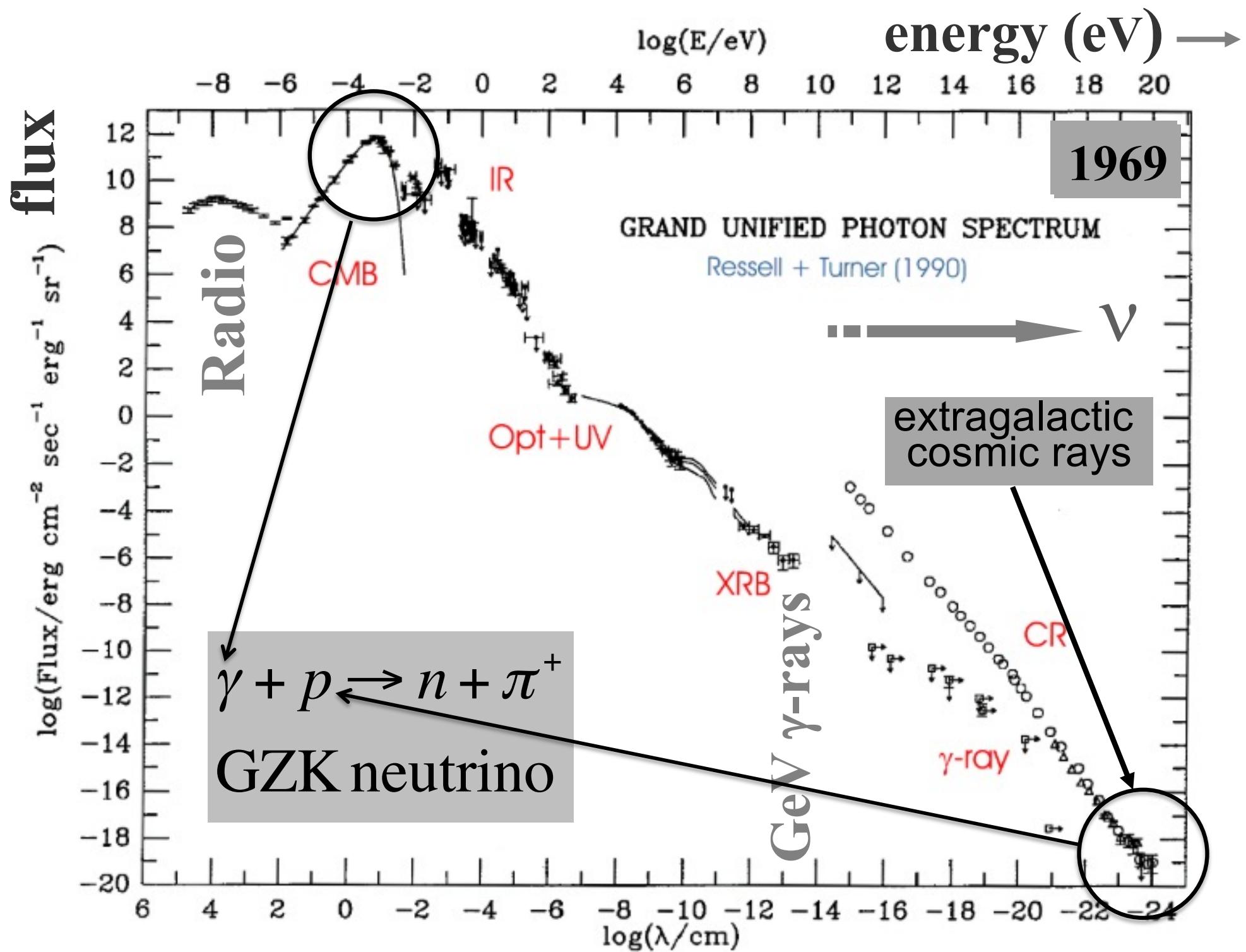


\sim cosmic ray + gamma

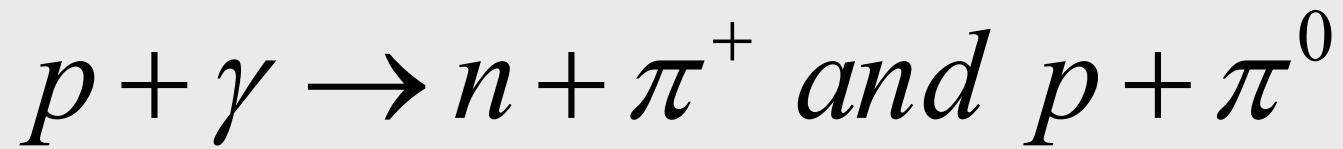
multimessenger astronomy



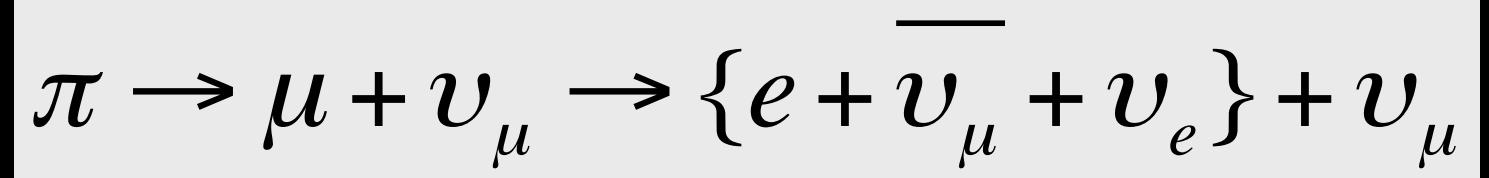
- gamma rays accompany neutrinos, but, unlike neutrinos,
- gamma rays lose energy in interactions with the extragalactic background light, and likely in the dense target that produces the neutrinos.



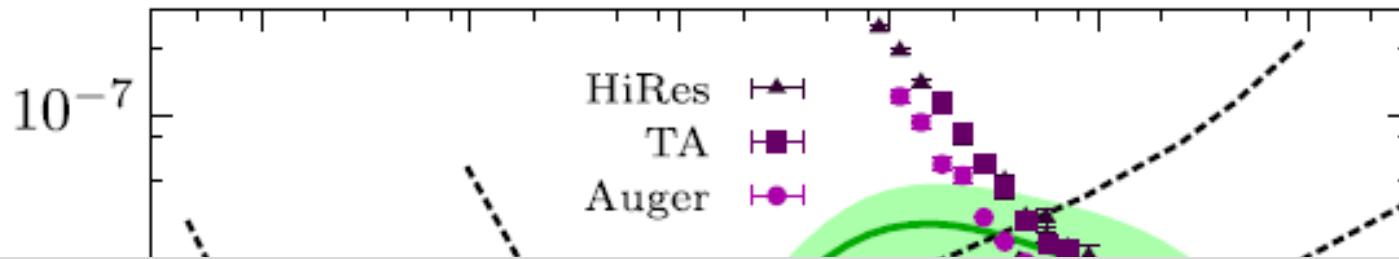
cosmic rays interact with the microwave background



cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

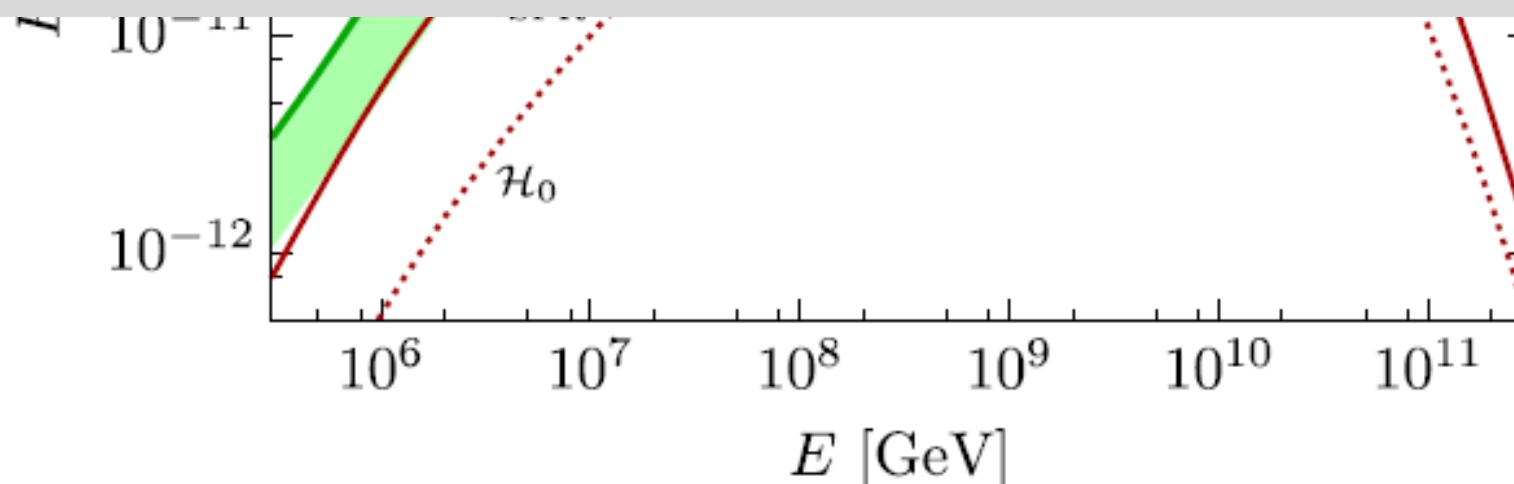


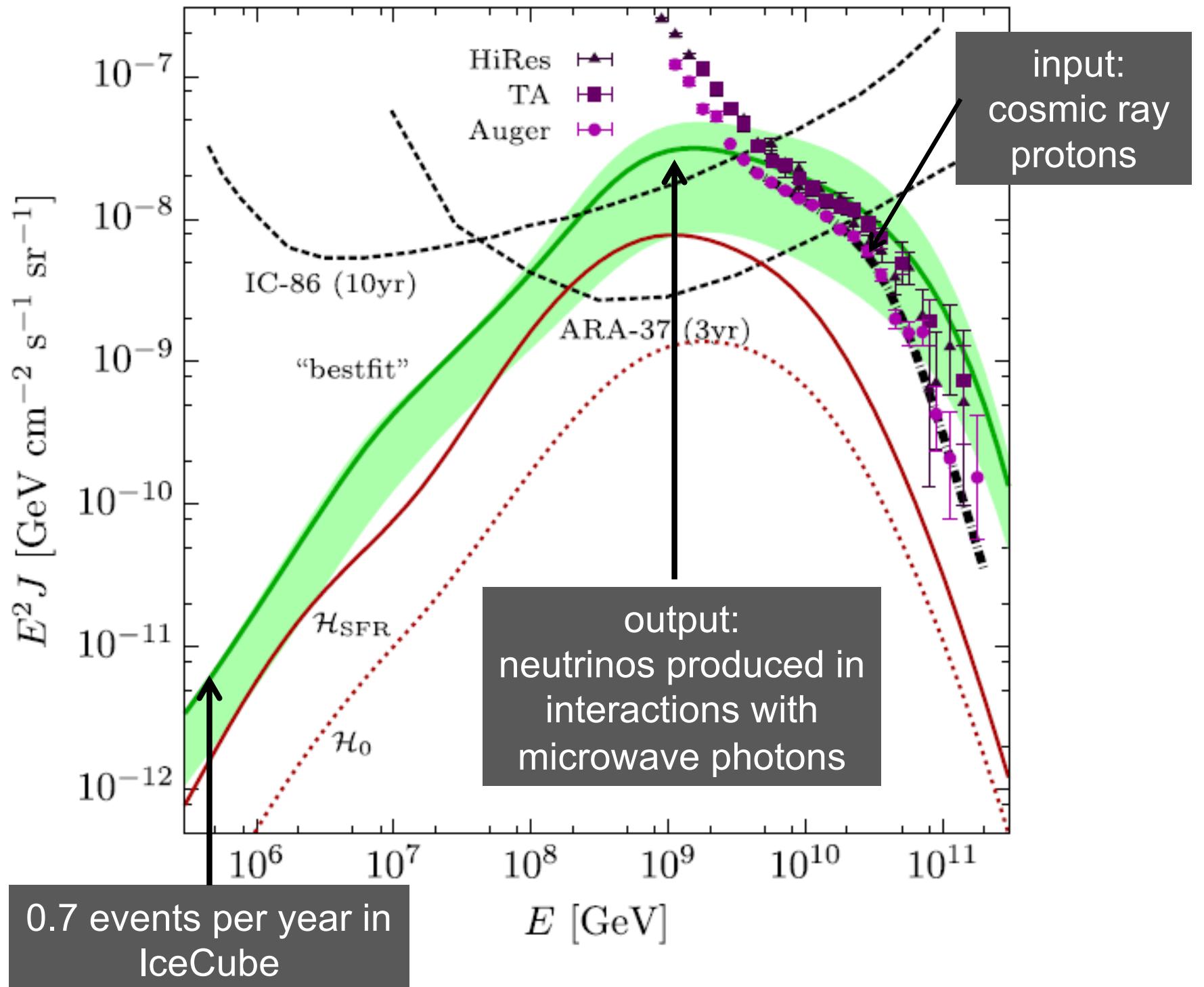
1 event per cubic kilometer per year
...but it points at its source!

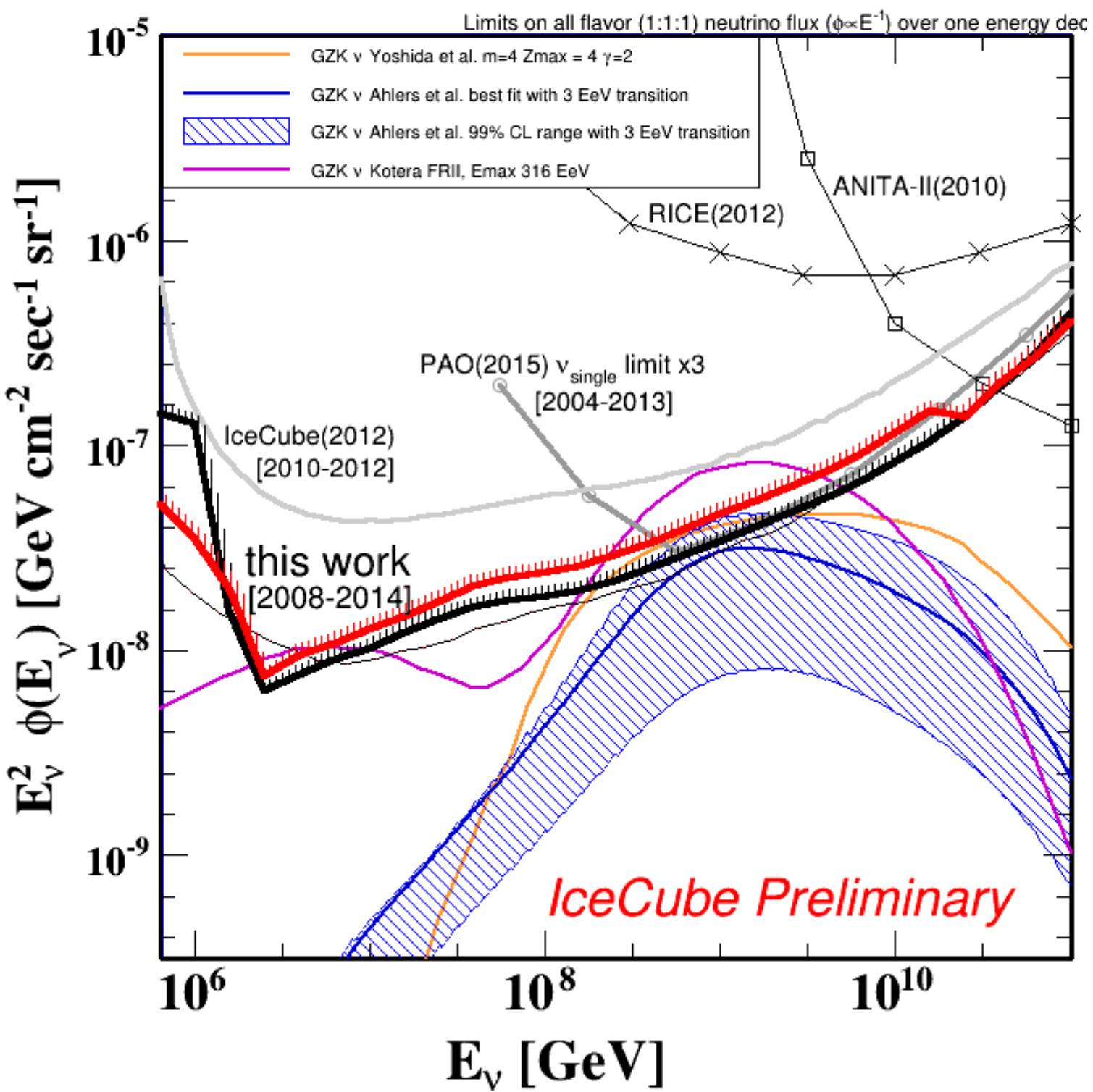


the extragalactic accelerators: knobs to turn

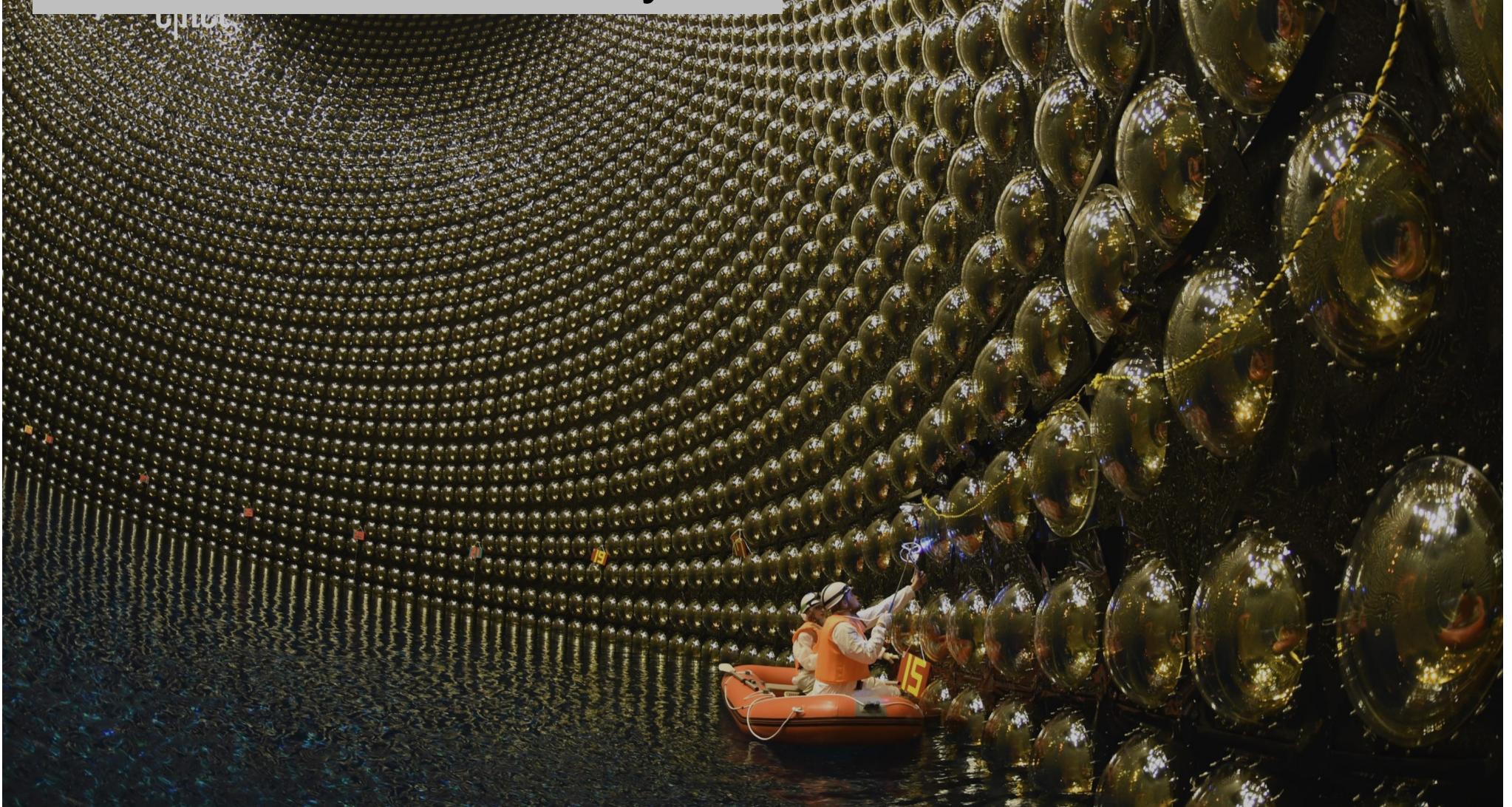
- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution

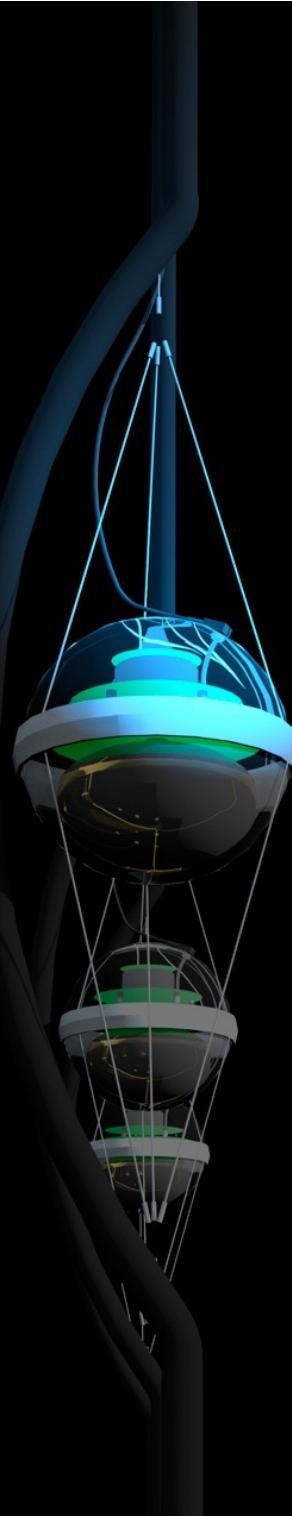






10,000 times too small to
do neutrino astronomy...





IceCube: the discovery of cosmic neutrinos

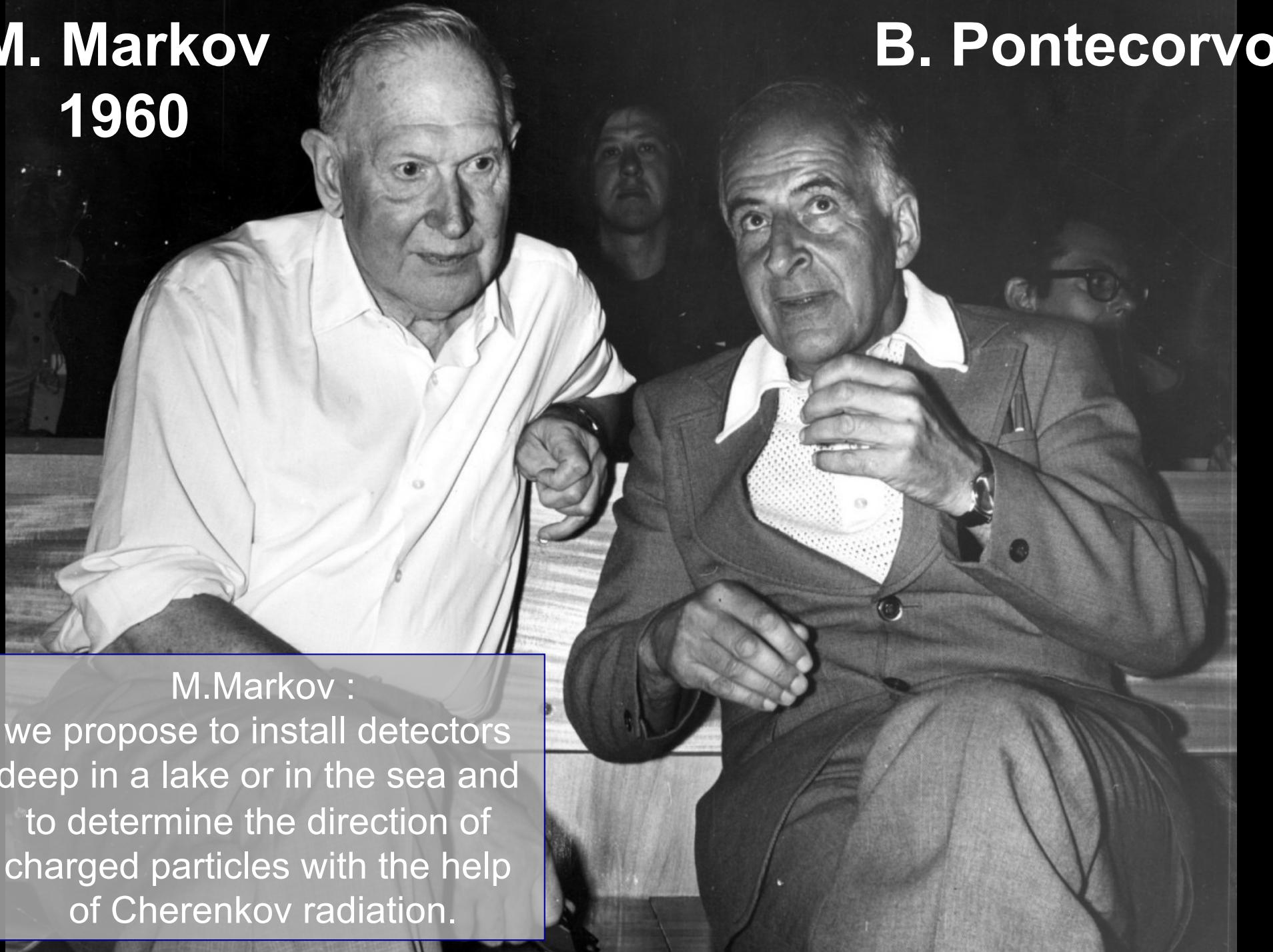
francis halzen

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M. Markov

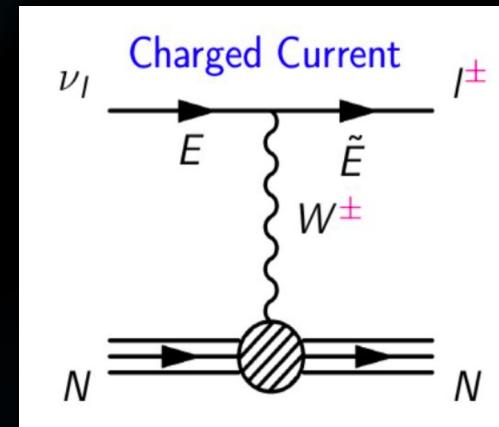
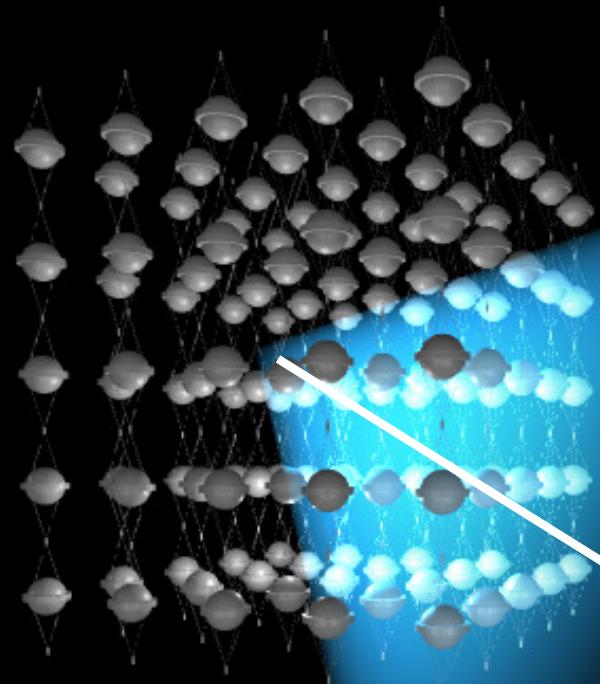
1960

B. Pontecorvo



M. Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

charged secondary
particles produced
as the neutrino
disappears

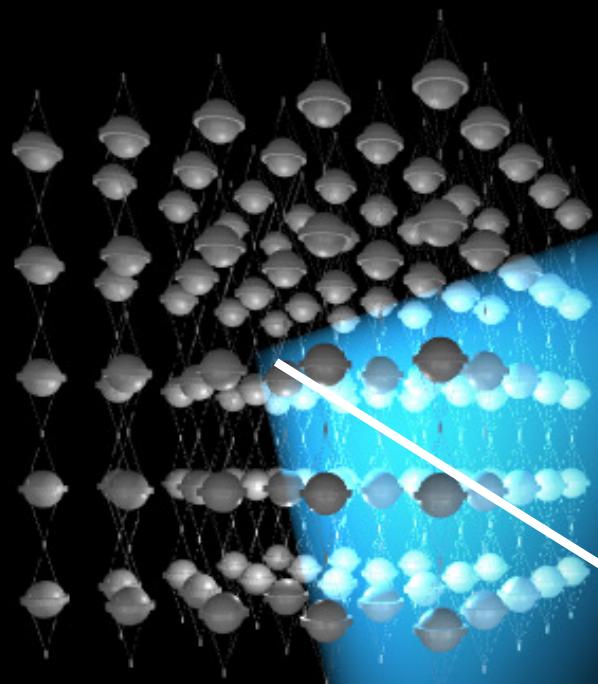


nuclear
interaction

neutrino

- lattice of photomultipliers

- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
- speed of light in water $\sim 3/4 c \rightarrow$ shockwave



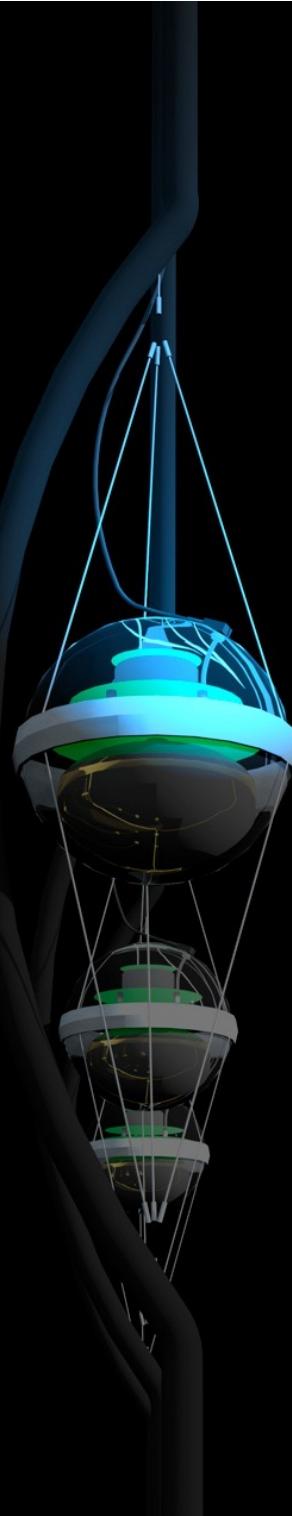
muon

interaction



- lattice of photomultipliers

neutrino

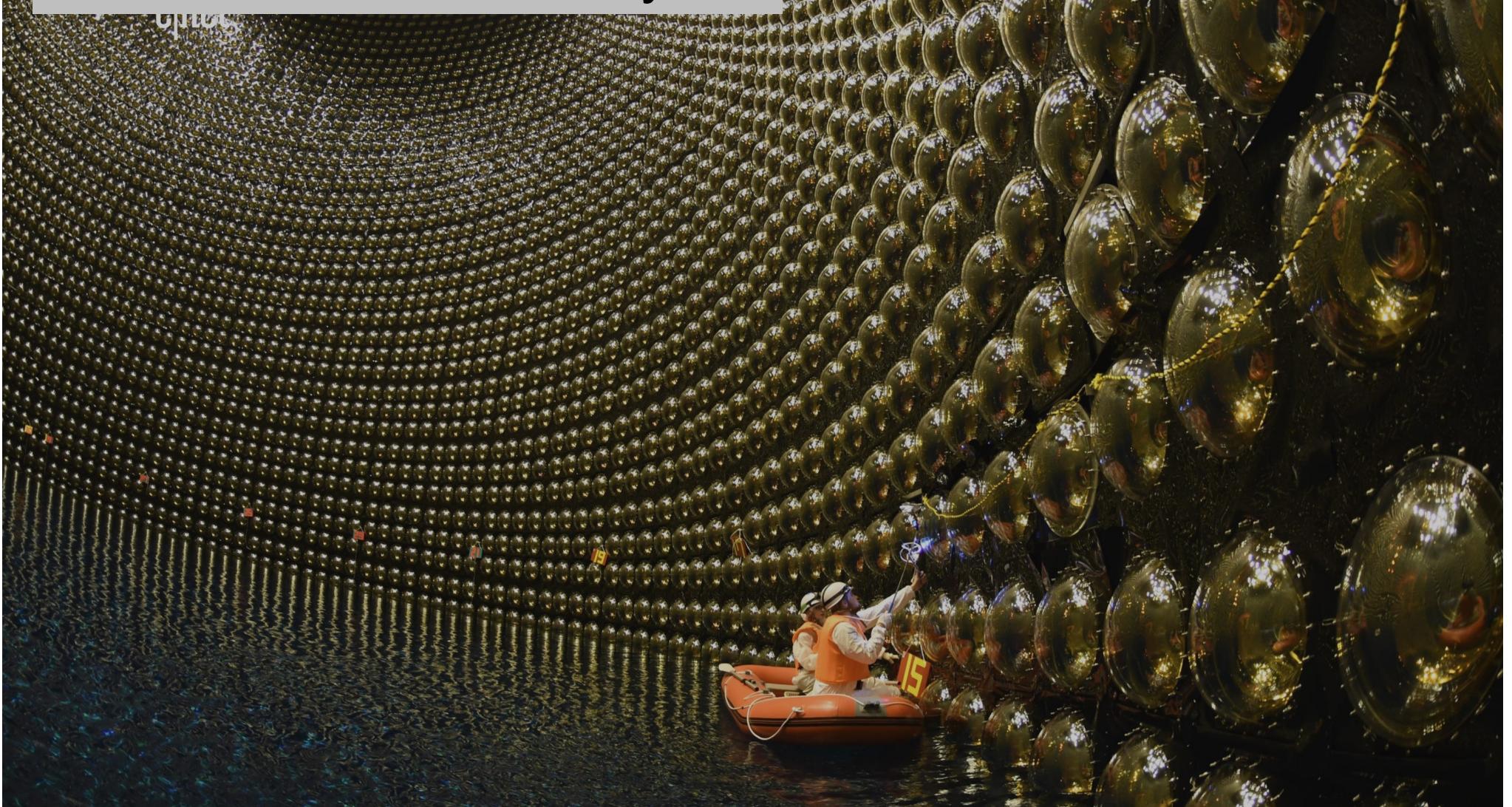


IceCube: the discovery of cosmic neutrinos

francis halzen

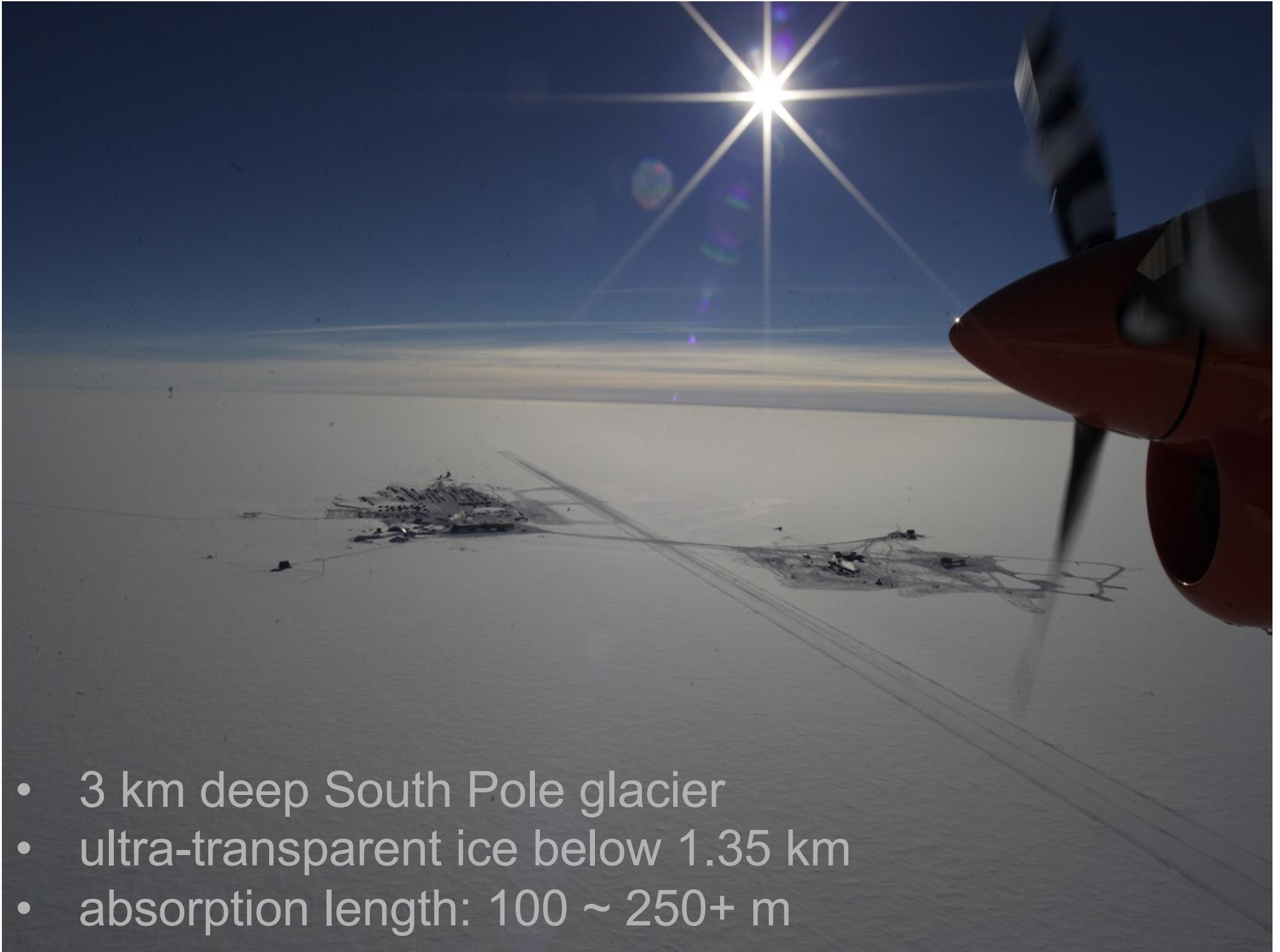
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10,000 times too small to
do neutrino astronomy...

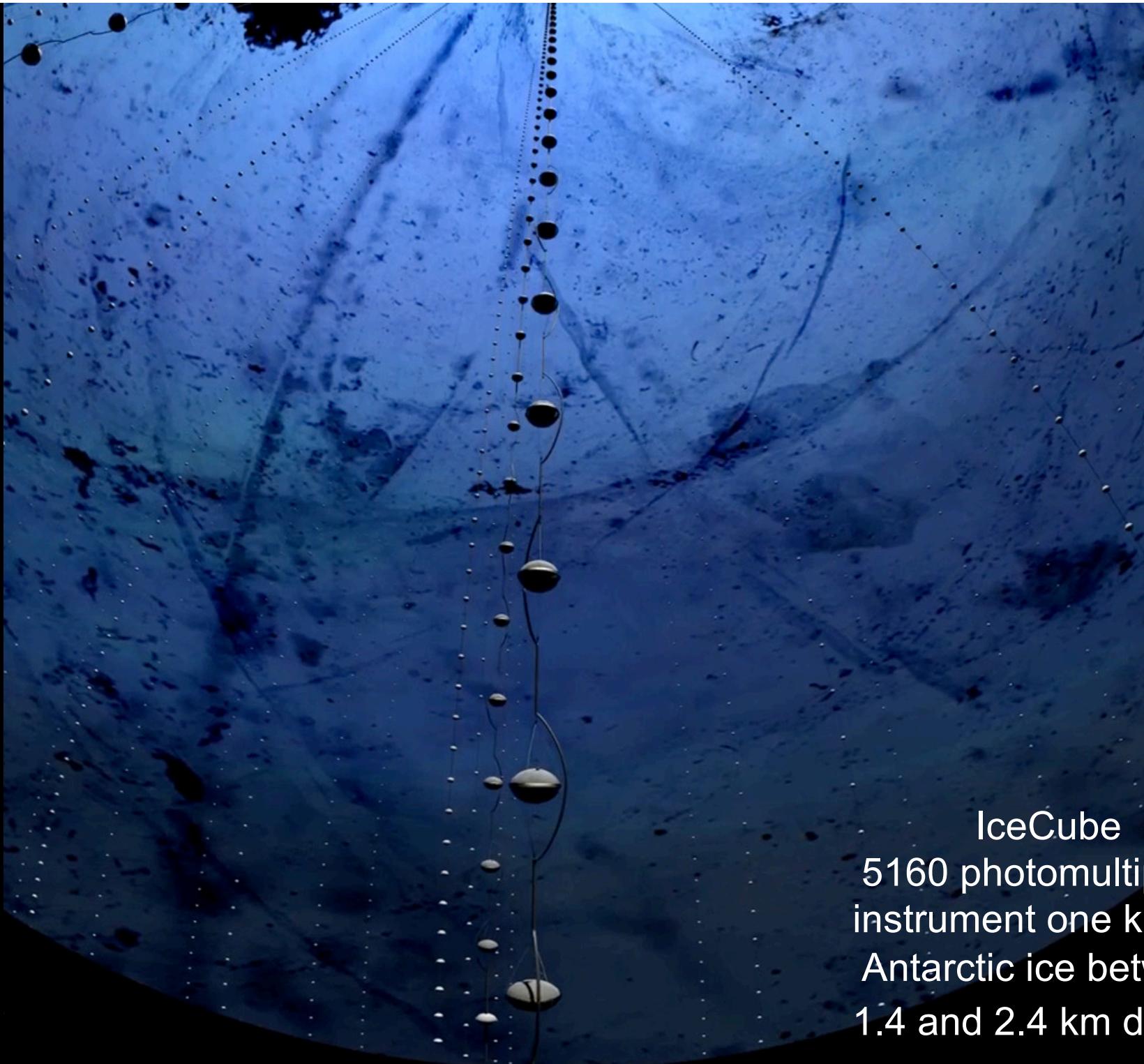


ice 1.4 kilometers below geographic South Pole

- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings \sim absorption length
- add data acquisition and computers

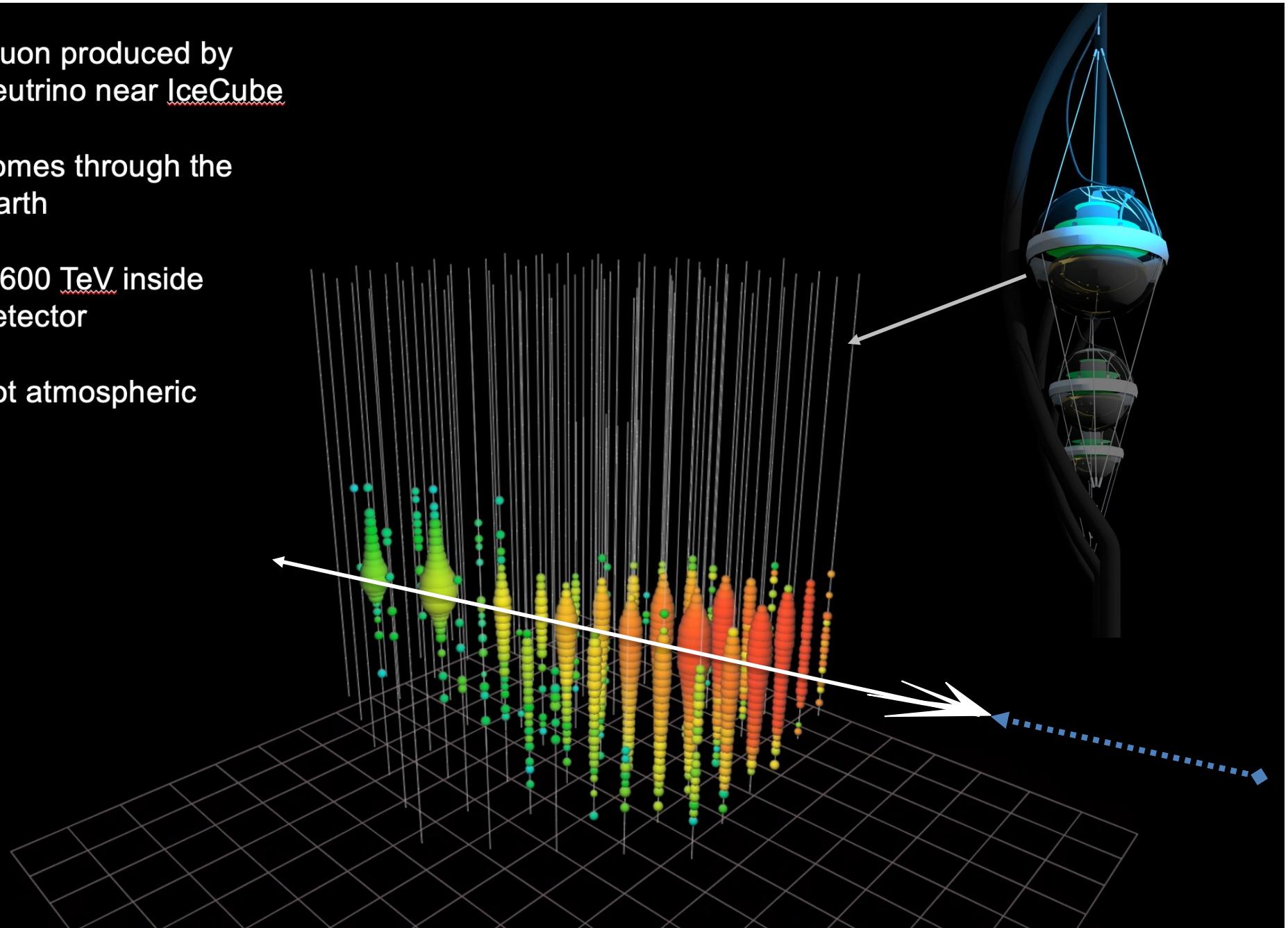


- 3 km deep South Pole glacier
- ultra-transparent ice below 1.35 km
- absorption length: $100 \sim 250+$ m

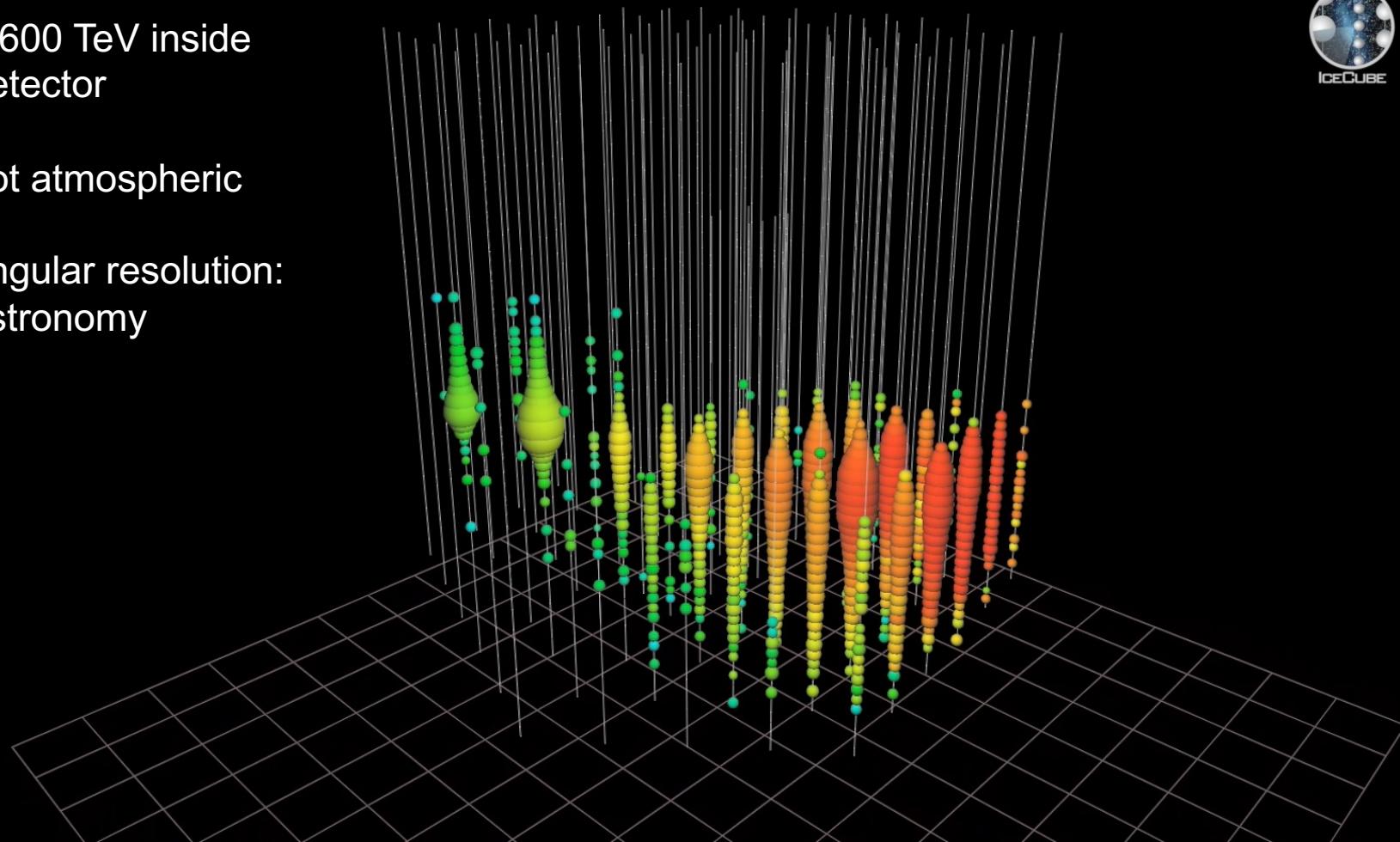


IceCube
5160 photomultipliers
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth

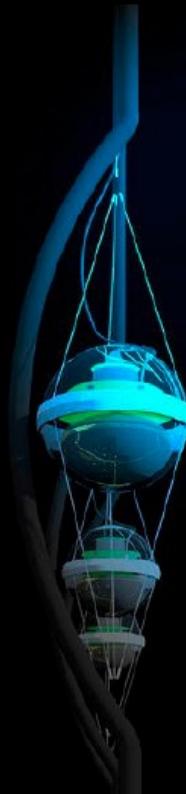
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



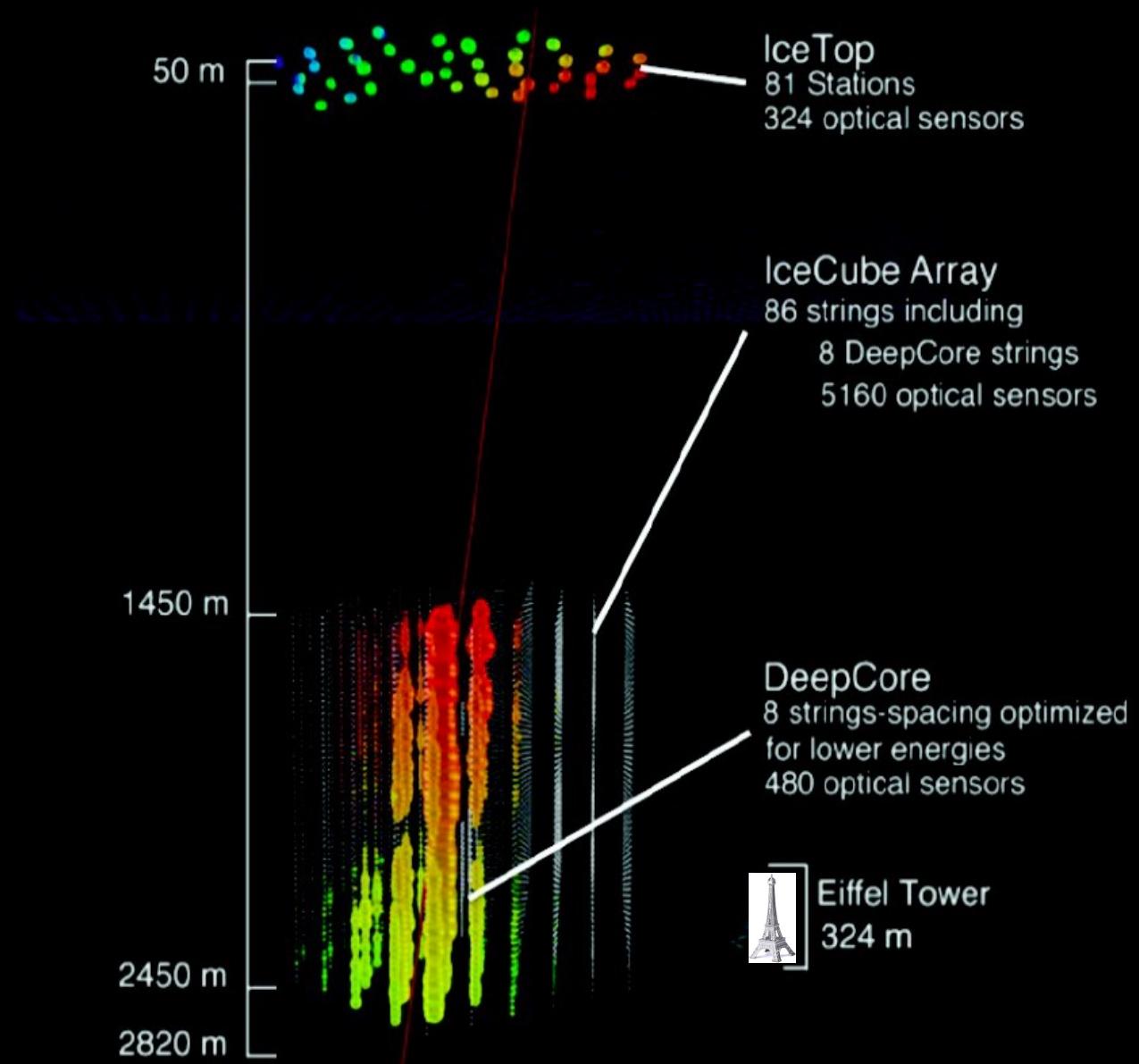
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution: astronomy



the IceCube Neutrino Observatory



5160 DOMs
instrumenting 1 km³
(1 GT) of clear ice
2 ns time resolution



photomultiplier
tube -10 inch

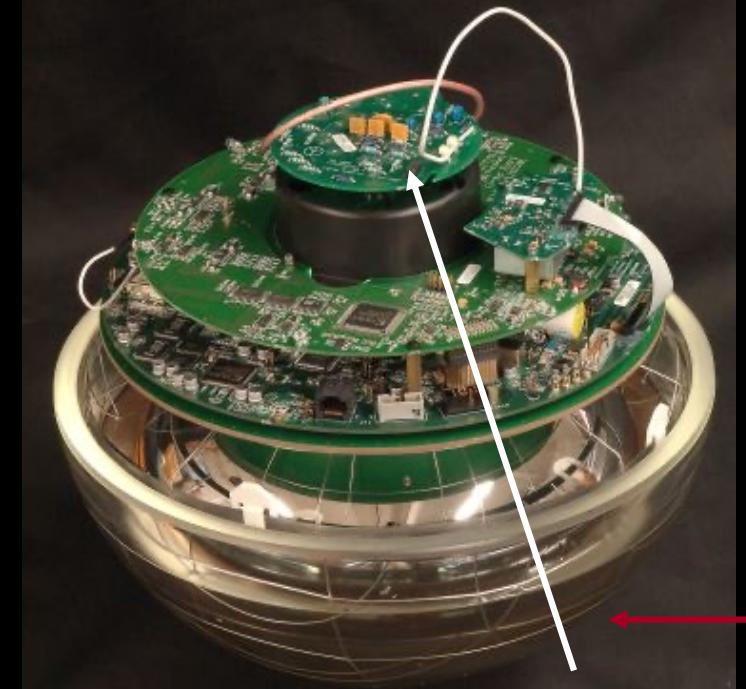
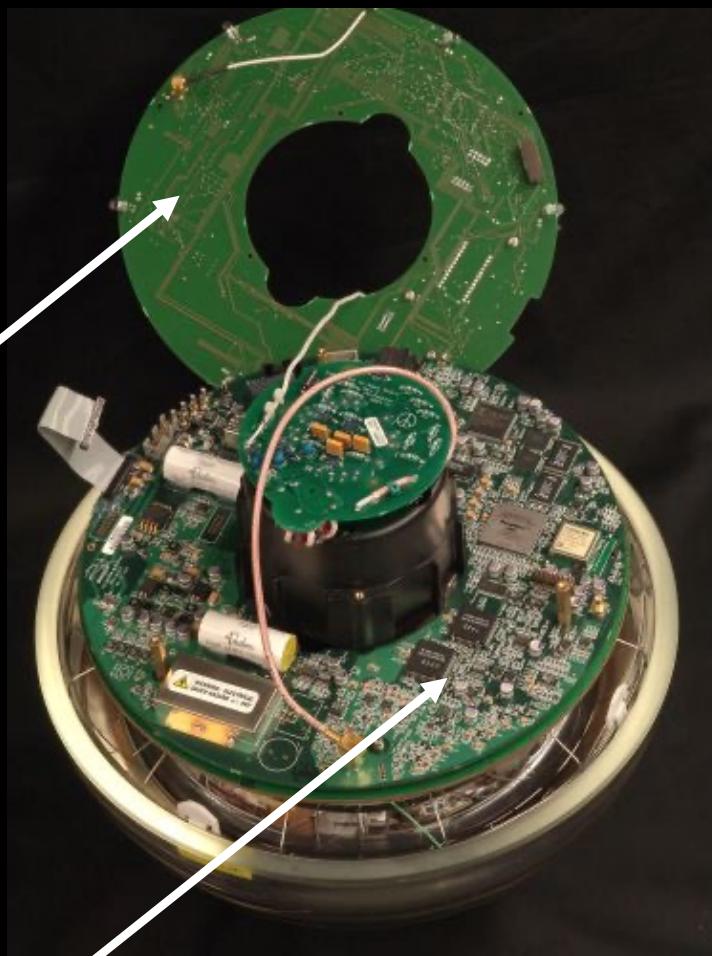


architecture of independent DOMs

LED
flasher
board

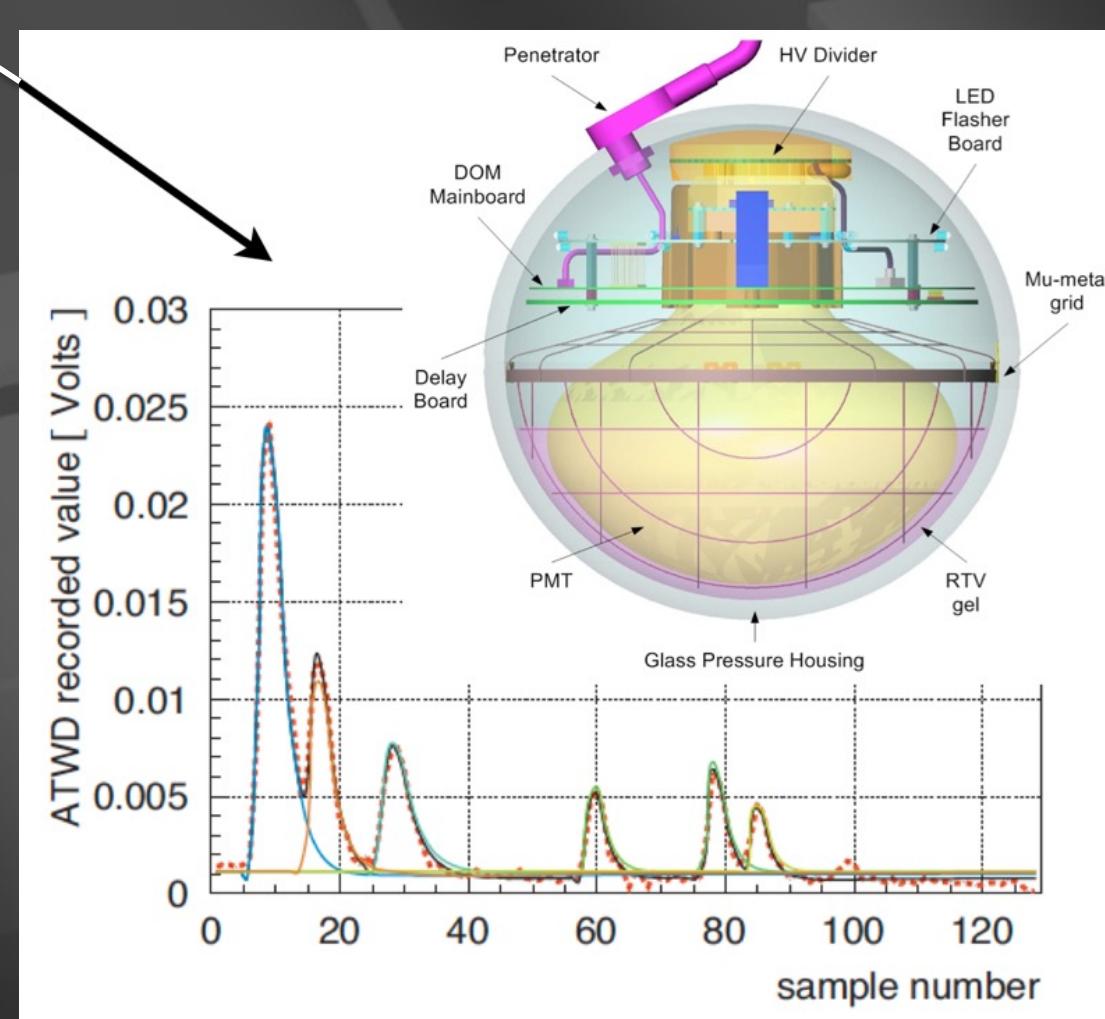
main
board

10 inch pmt →

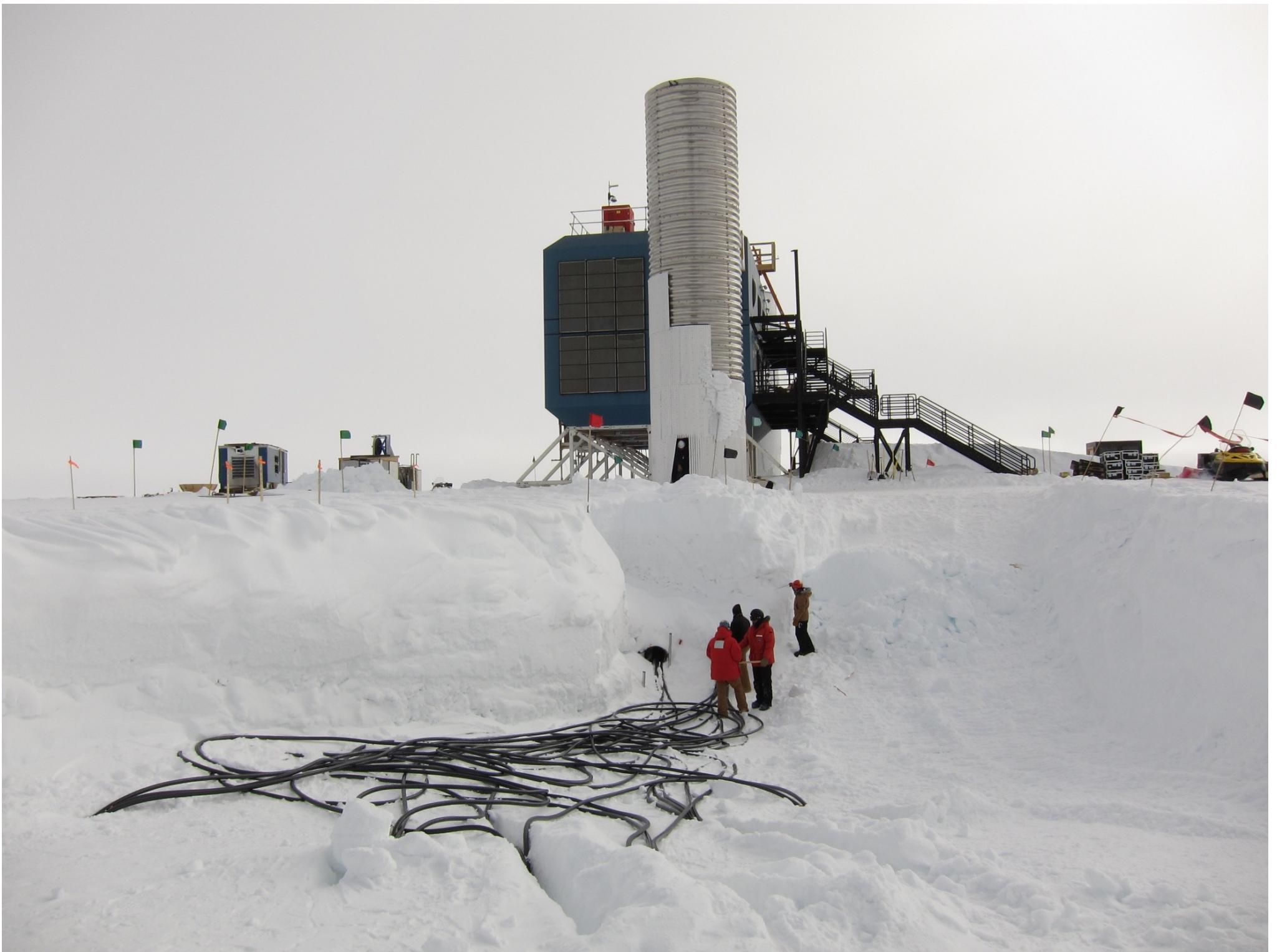


HV board

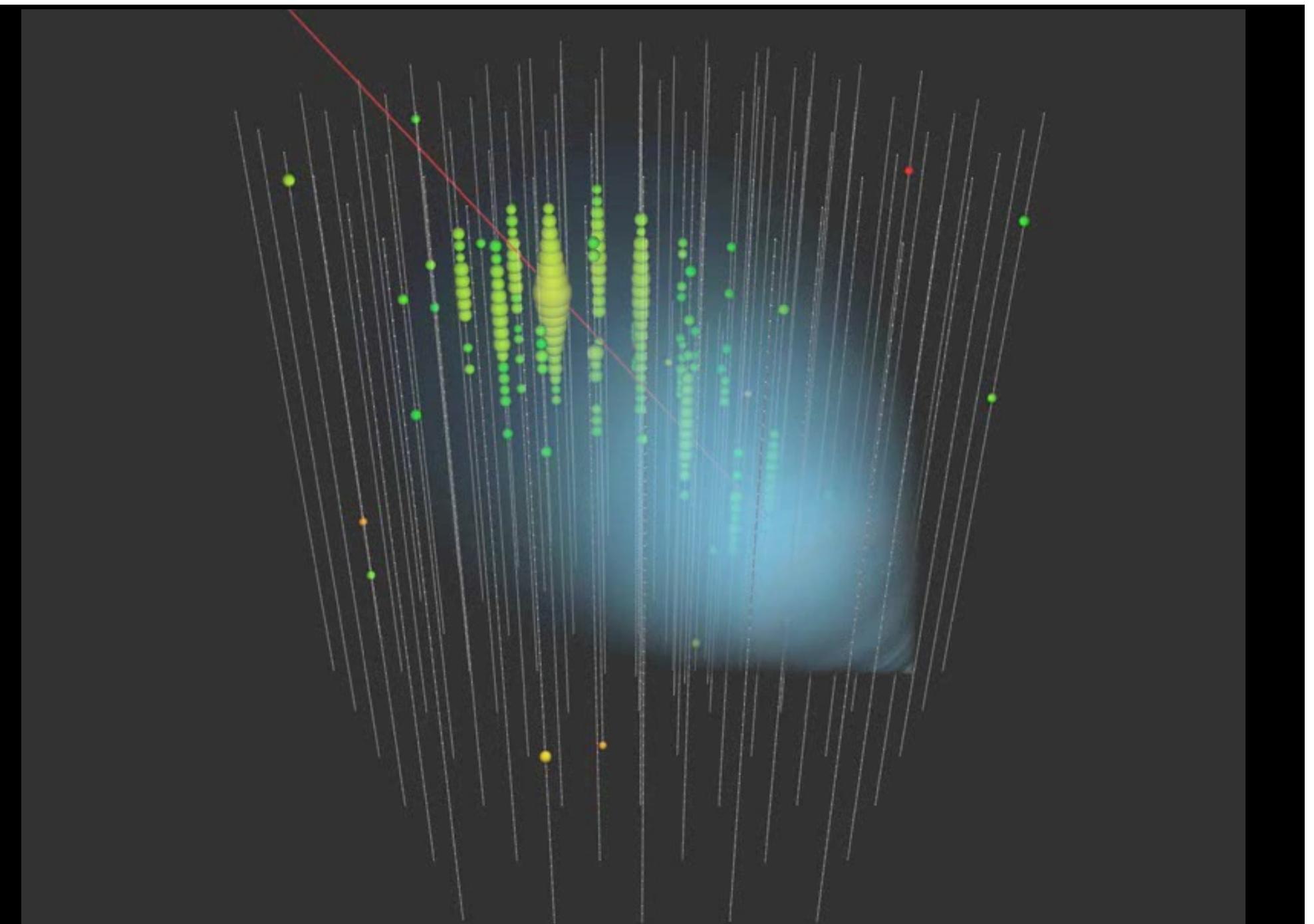
... each Digital Optical Module independently collects light signals like this, digitizes them,



...time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events...





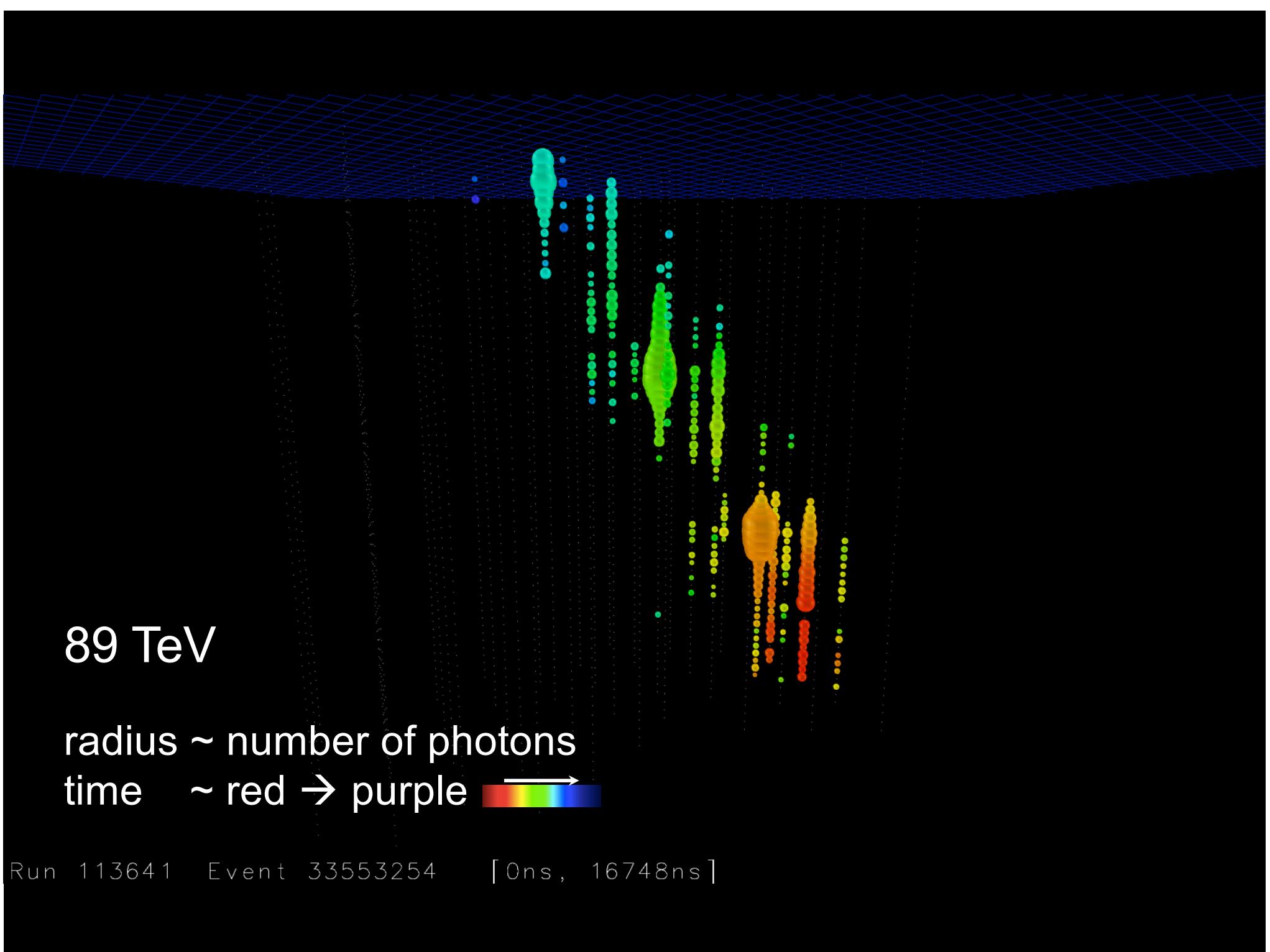


muon track: color is time; number of photons is energy

89 TeV

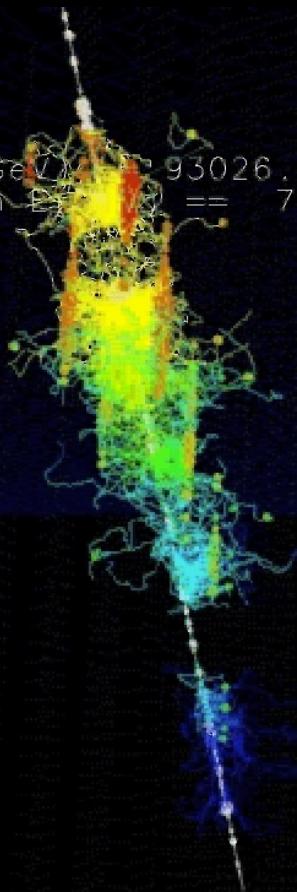
radius ~ number of photons
time ~ red → purple

[0ns , 16748ns]

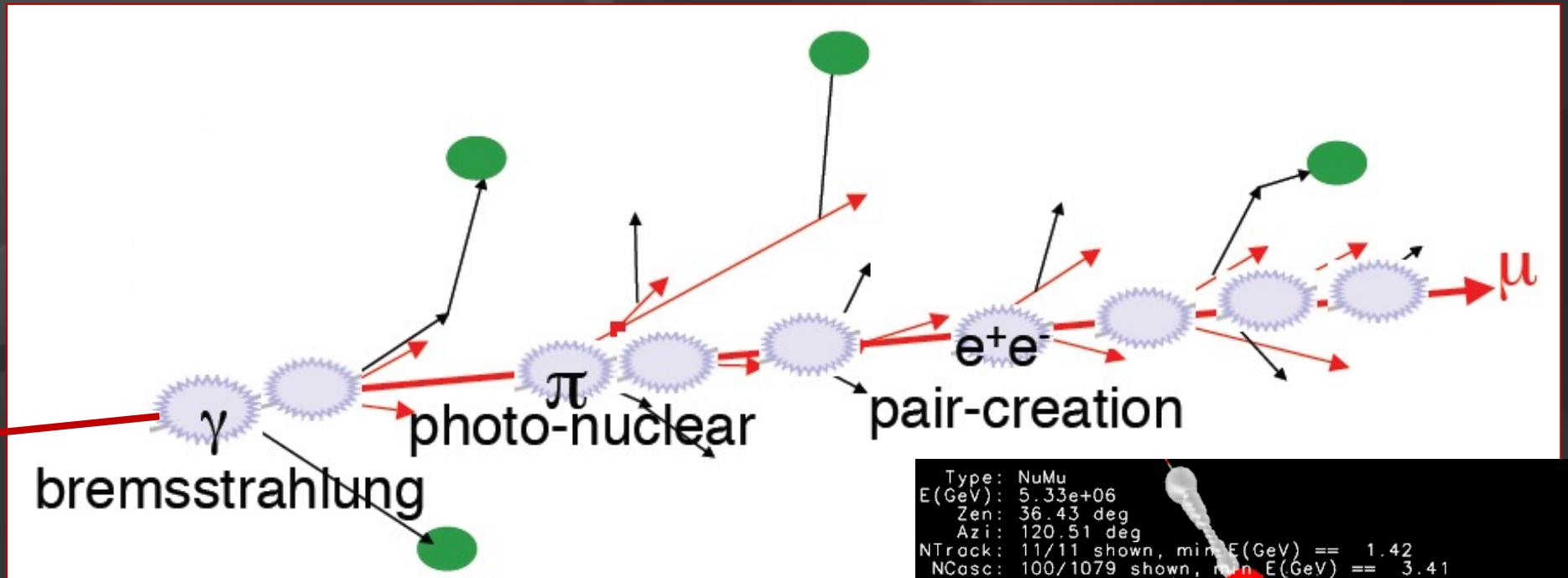


93 TeV muon: light ~ energy

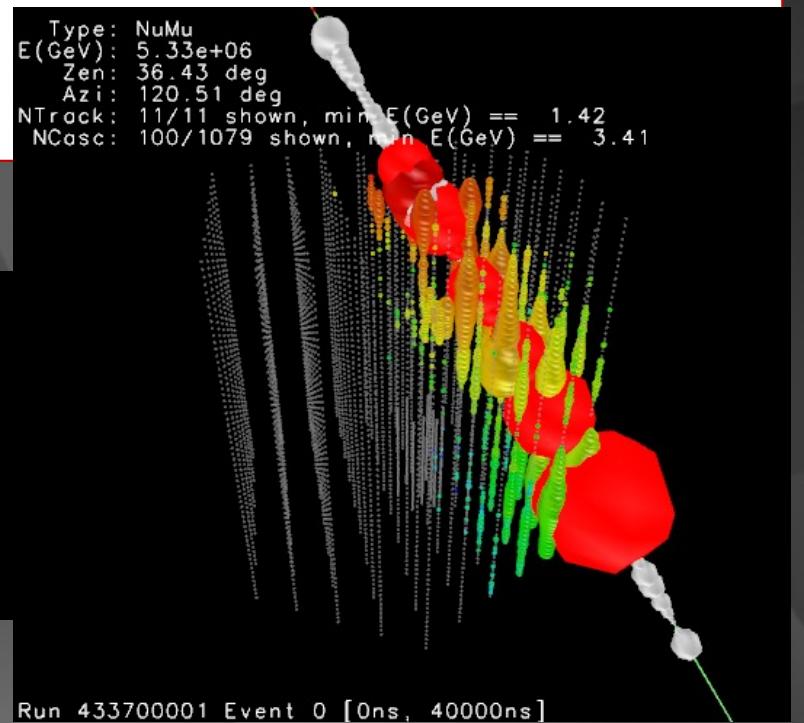
Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) = 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99



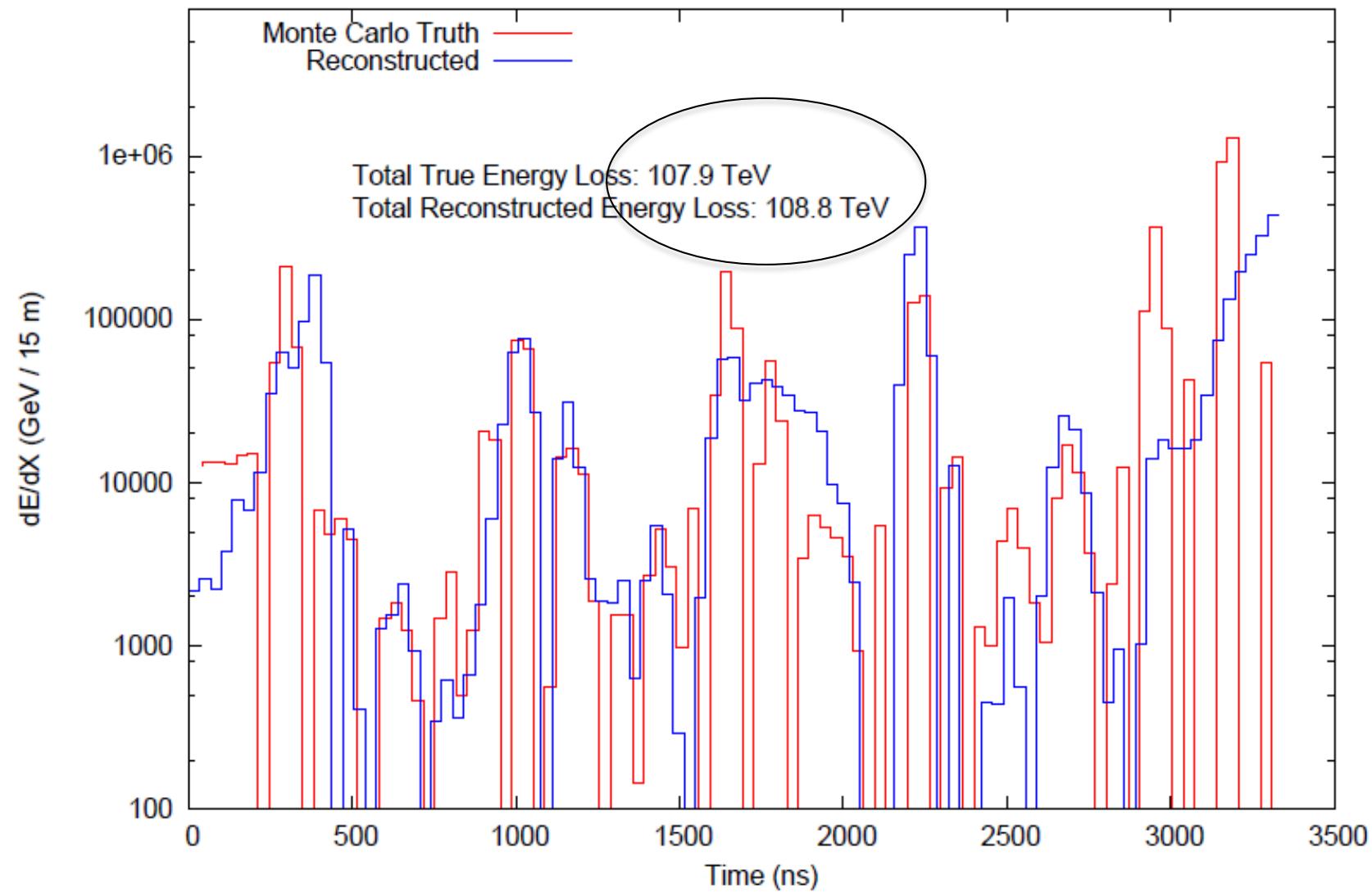
energy measurement (> 100 TeV)



convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx , ...)

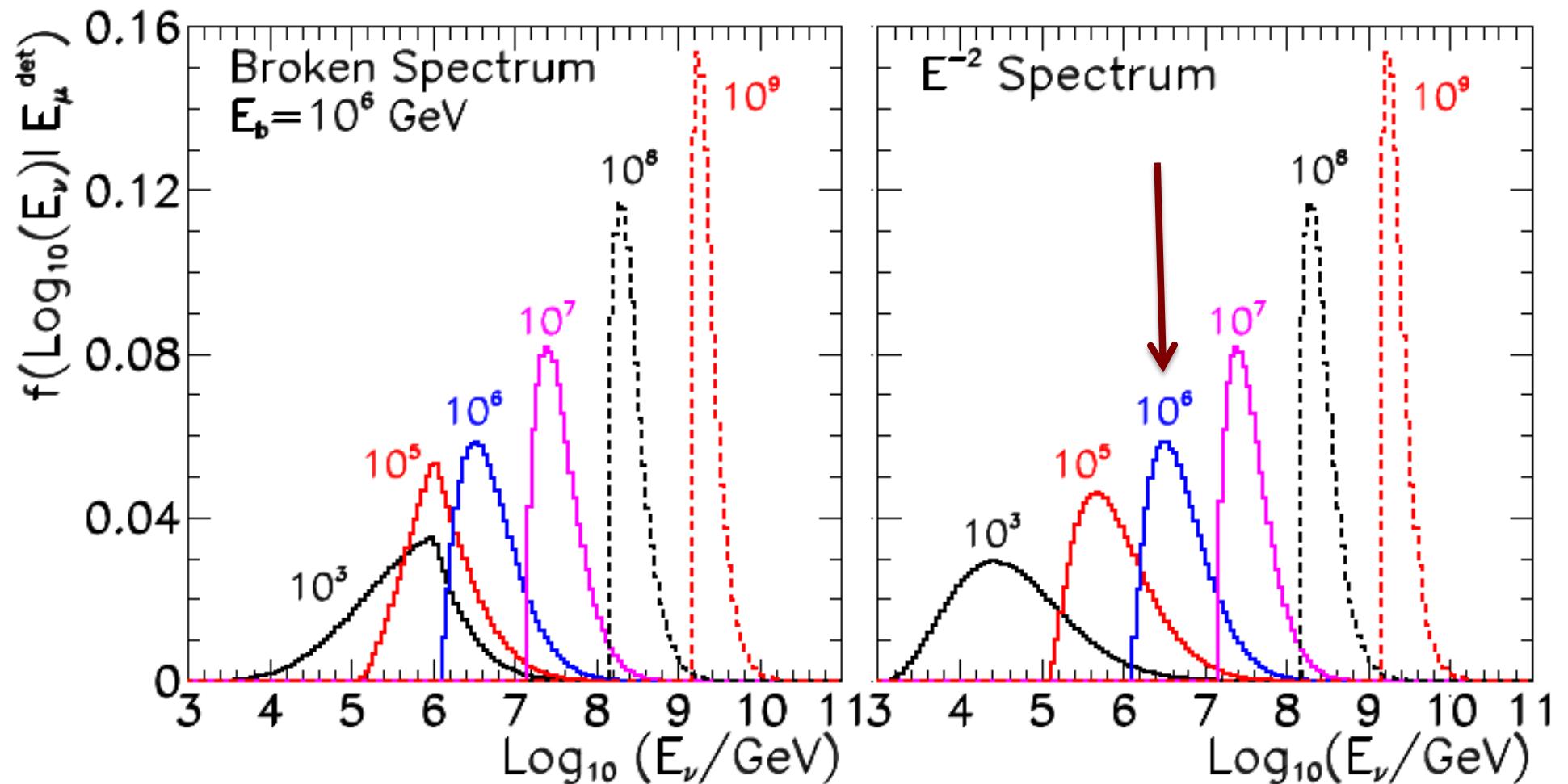


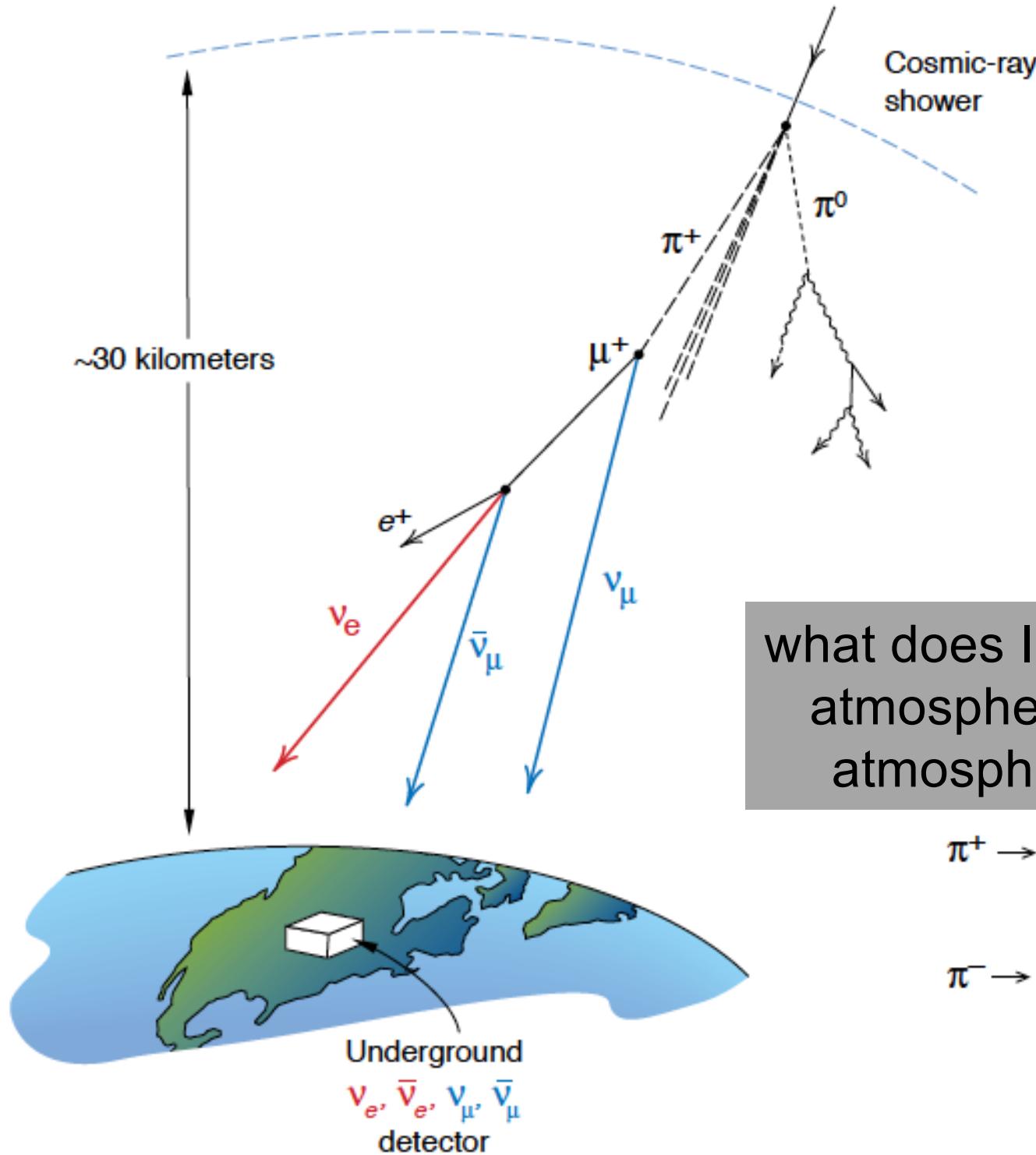
Differential Energy Reconstruction of 5 PeV Muon in IC-86



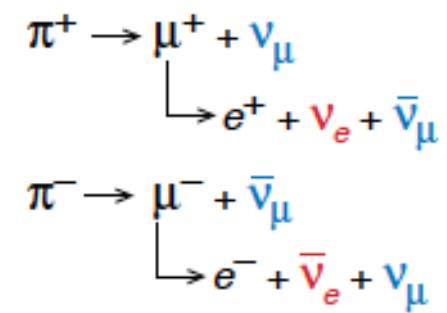
← 1.1 km →
improving energy and angular resolution

distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube

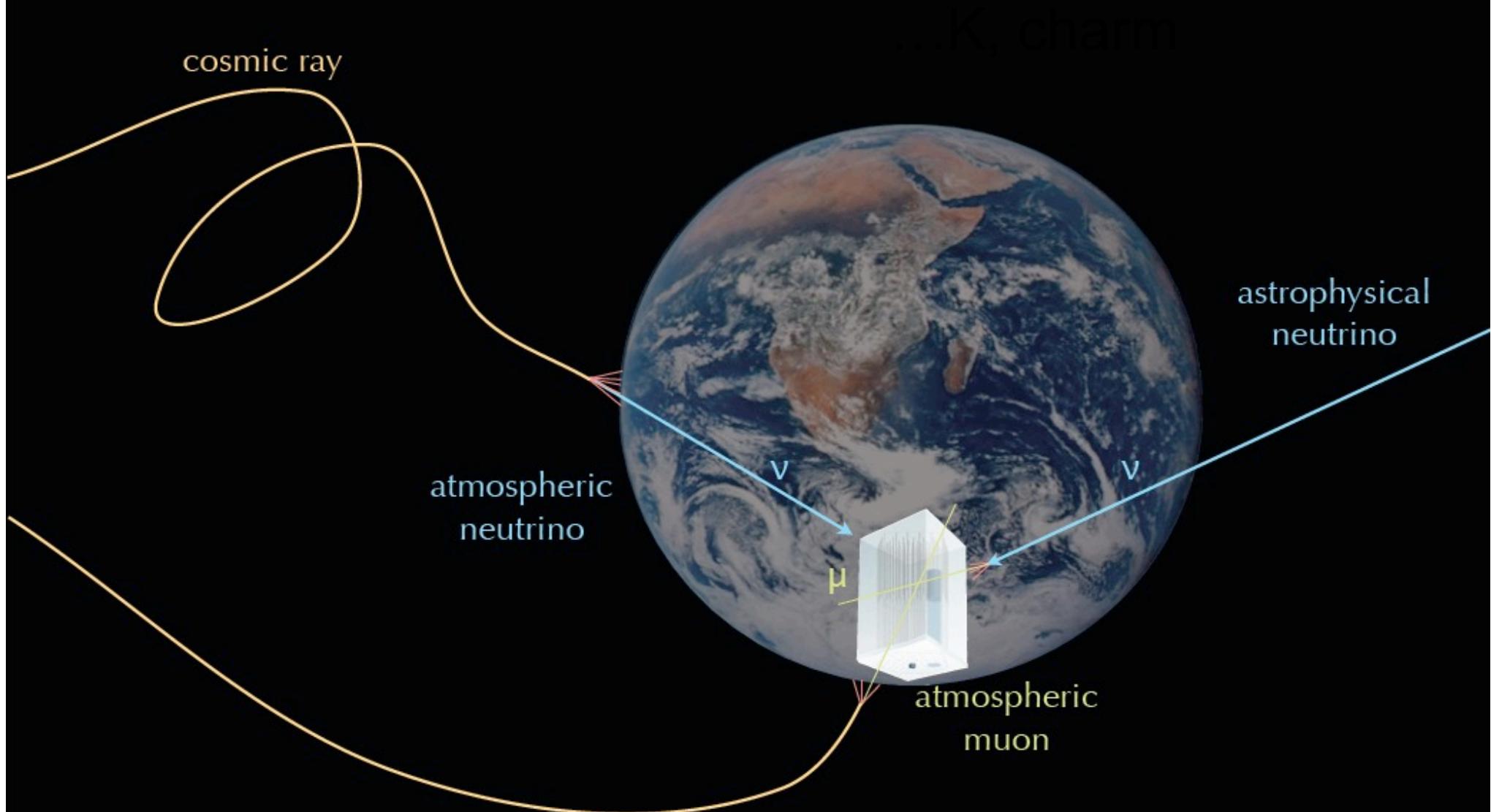


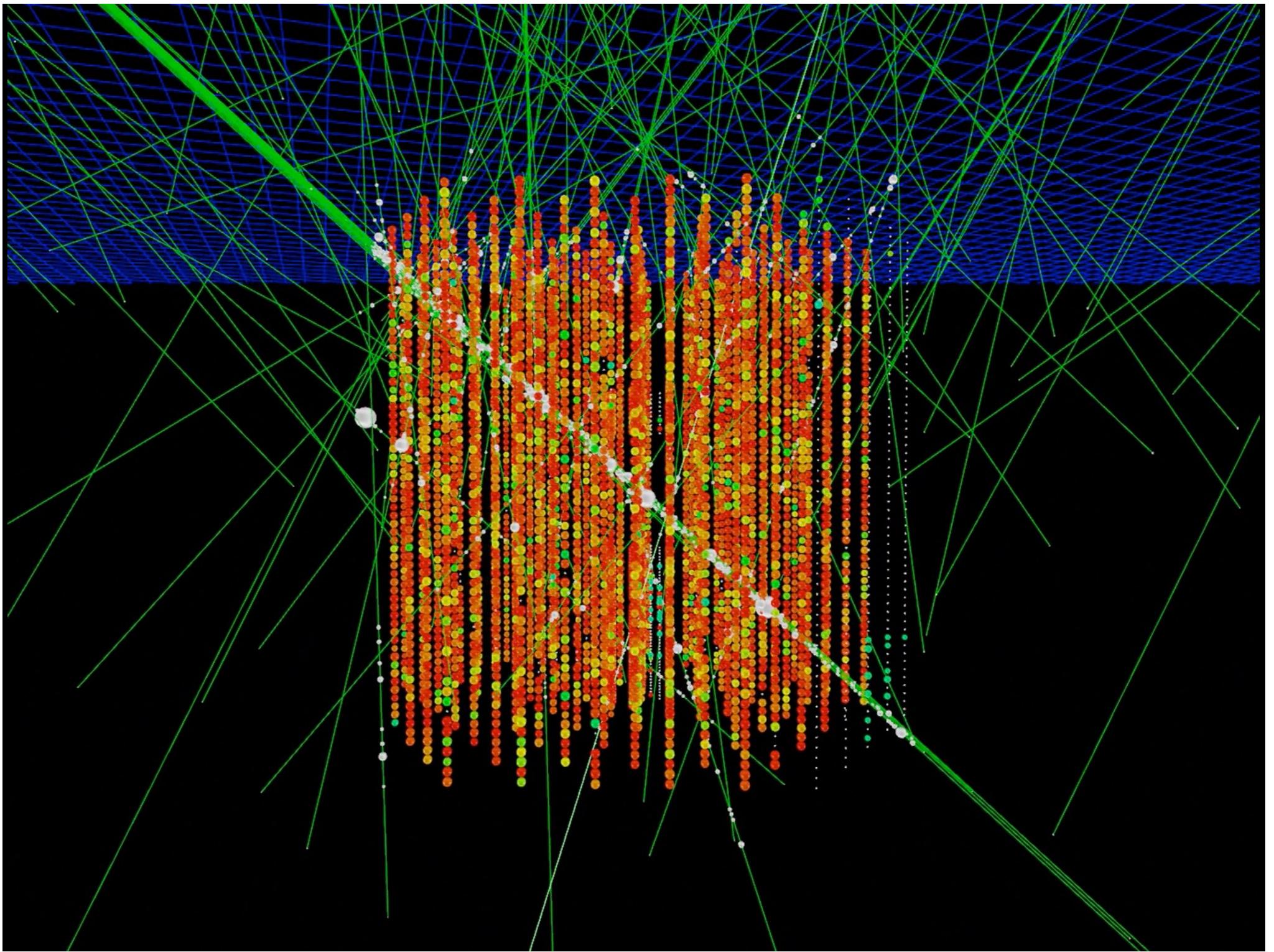


what does IceCube reveal ?
atmospheric muons and
atmospheric neutrinos



Signals and Backgrounds





... you looked at 10msec of data !

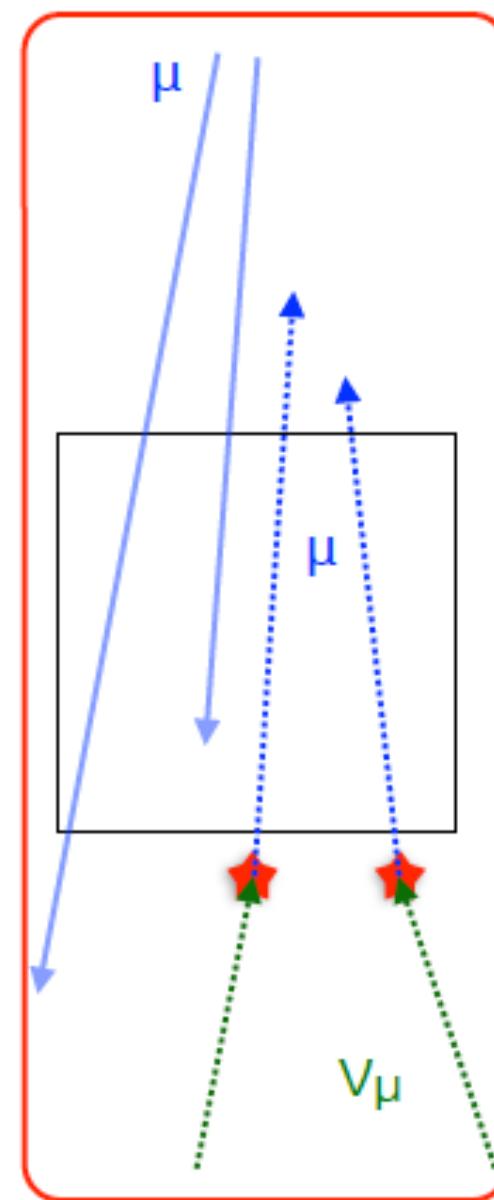
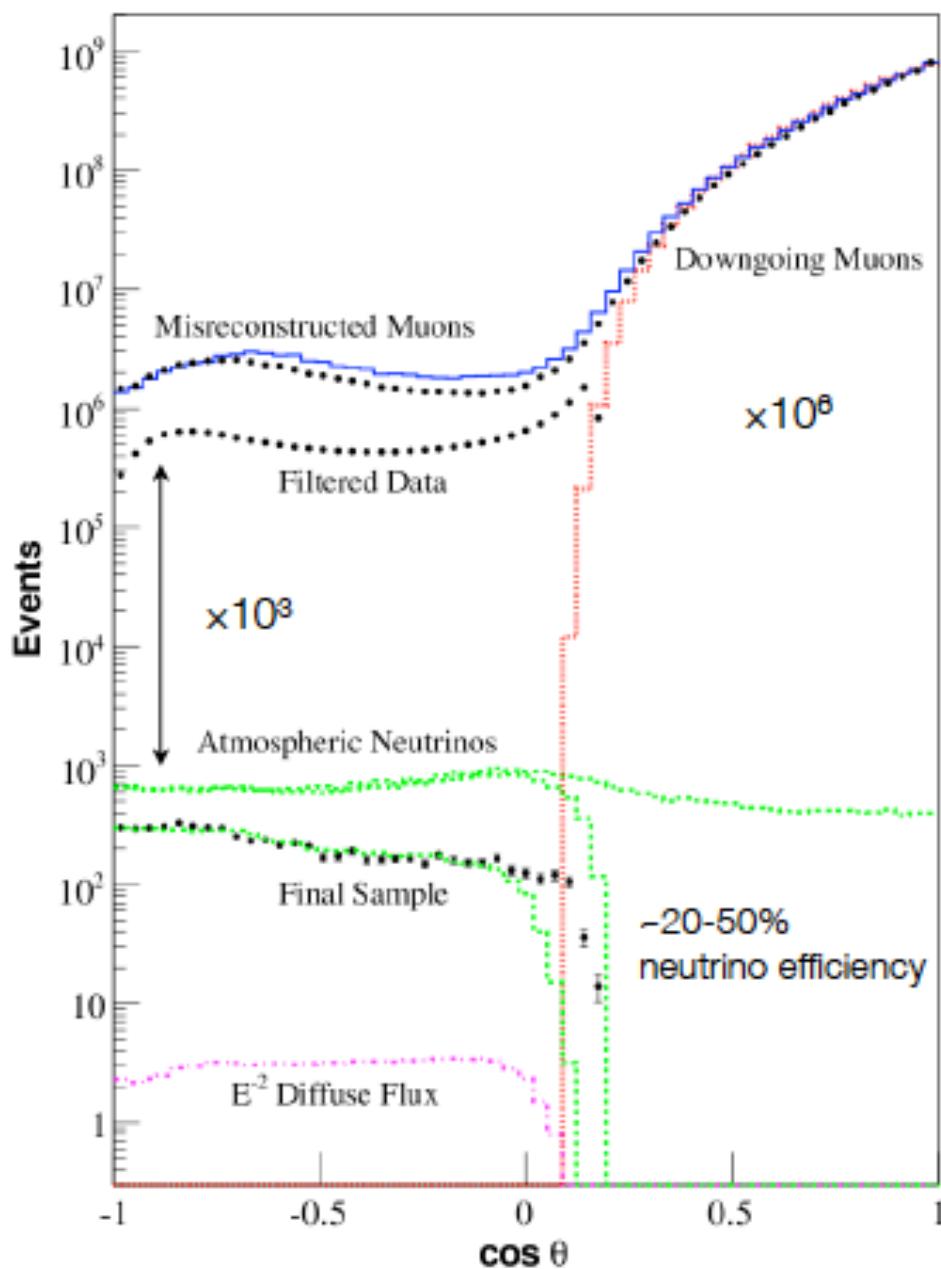
muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 200

* 3000 per second

** 1 every 4 minutes

through-going (tracks)



selection cuts for on-line numu extraction

Cut Level	Selection criterion	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	$\cos \theta_{\text{MPE}} < 0$	1010.5	1523.81	7.166	6.23
1	$S\text{LogL}(3.5) \leq 8$	282.49	504.44	5.826	5.62
2	$N_{\text{Dir}} \geq 9$	8.839	22.01	3.076	4.06
3	(($\cos \theta_{\text{MPE}} > -0.2$) AND ($L_{\text{Dir}} \geq 300$ m)) OR ($\cos \theta_{\text{MPE}} \leq -0.2$) AND ($L_{\text{Dir}} \geq 200$ m))	1.124	4.30	2.313	3.69
4	$\Delta_{\text{Split/MPE}} < 0.5$	0.100	2.15	1.899	3.26
5	(($\cos \theta_{\text{MPE}} \leq -0.07$) OR (($\cos \theta_{\text{MPE}} > -0.07$) AND ($\Delta_{\text{SPE/Bayesian}} \geq 35$)))	0.080	2.08	1.880	3.25
6	(($\cos \theta_{\text{MPE}} \leq -0.04$) OR (($\cos \theta_{\text{MPE}} > -0.04$) AND ($\Delta_{\text{SPE/Bayesian}} \geq 40$)))	0.075	2.06	1.875	3.24

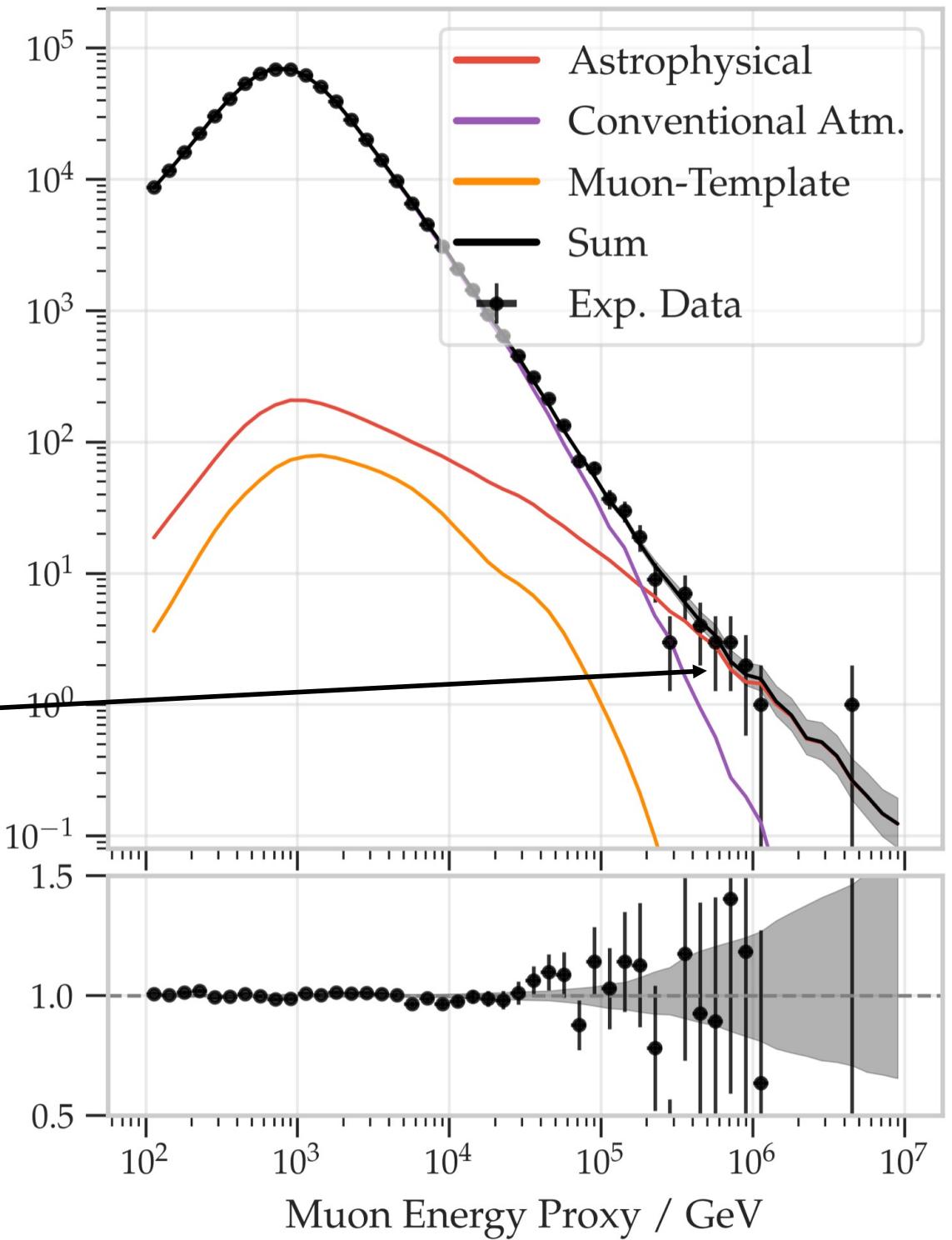
Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction by Honda [71], but atmospheric-muon rate is calculated from CORSIKA simulations. The event rate for IceCube data stream corresponds to the total livetime of 332.36 days. The astrophysical neutrino flux is estimated assuming $dN/dE = 1 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} (\frac{E}{\text{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)

...as opposed to 35 in original AMANDA publication

Name	Precut	Summary
<i>CoG_rhoIC</i>	—	center of gravity, radial distance
<i>CoG_zIC</i>	< 500 m	center of gravity, z-component
<i>LSepIC</i>	> 50 m	track hits separation length
<i>BayesLlhDiff</i>	> 20	$\log \mathcal{L}_{\text{Bayesian}} - \log \mathcal{L}_{\text{SPE2it}}$
<i>cosZen</i>	≥ 82 deg	$\cos(\text{SplineMPE zenith})$
<i>Plogl3p5</i>	< 10	$\log \mathcal{L}_{\text{SplineMPE}} / (N_{Ch} - 3.5)$
<i>LDirCIC</i>	> 75 m	direct track length
<i>NDirEIC</i>	≥ 6	number of direct hits
<i>sigma_CramerRao_deg</i>	< 25 deg	Cramér-Rao error estimate (in degrees)
<i>AbsSmoothnessEIC</i>	—	$ \text{smoothness} $ of direct hits
<i>AvgDistQtotDomNoCutIC</i>	< 250 m	average charge-weighted track-to-DOM distance
<i>LEmptyIC</i>	< 600 m	empty track length
<i>cos_SplineMPE_LF</i>	< 60 deg	angle between SplineMPE and LineFit
<i>Linefit_Speed</i>	< 3	LineFit speed
<i>logNChIC</i>	≥ 6 DOMs	number of hit DOMs
<i>DiffCosMinSplitZenith</i>	—	$\cos \min(\theta_{\text{Split}}) - \cos \theta_{\text{SplineMPE}}$

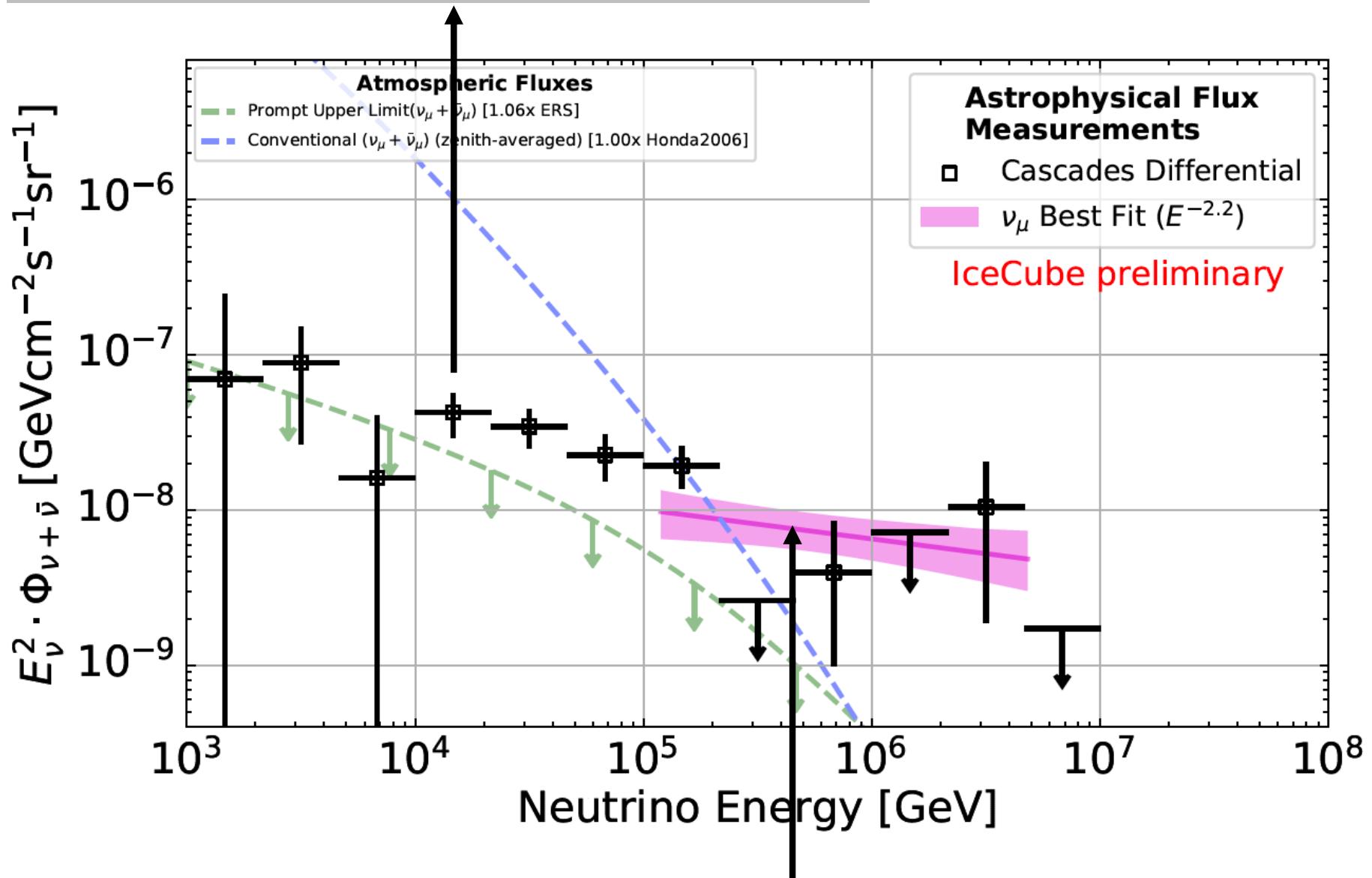
muon neutrino flux
filtered by the Earth:
atmospheric vs
cosmic

Number of Events per Bin



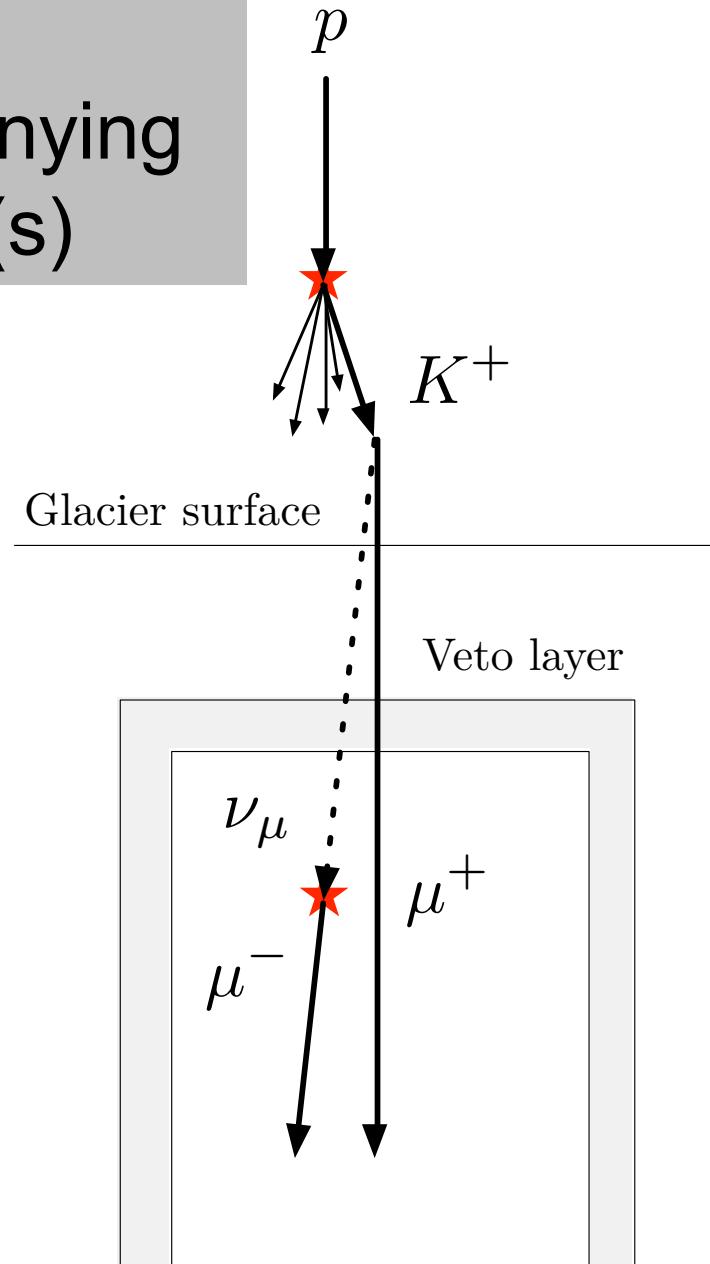
electron and tau neutrinos (showers)

flux $\Phi = dN/dE \sim E^{-2.5}$

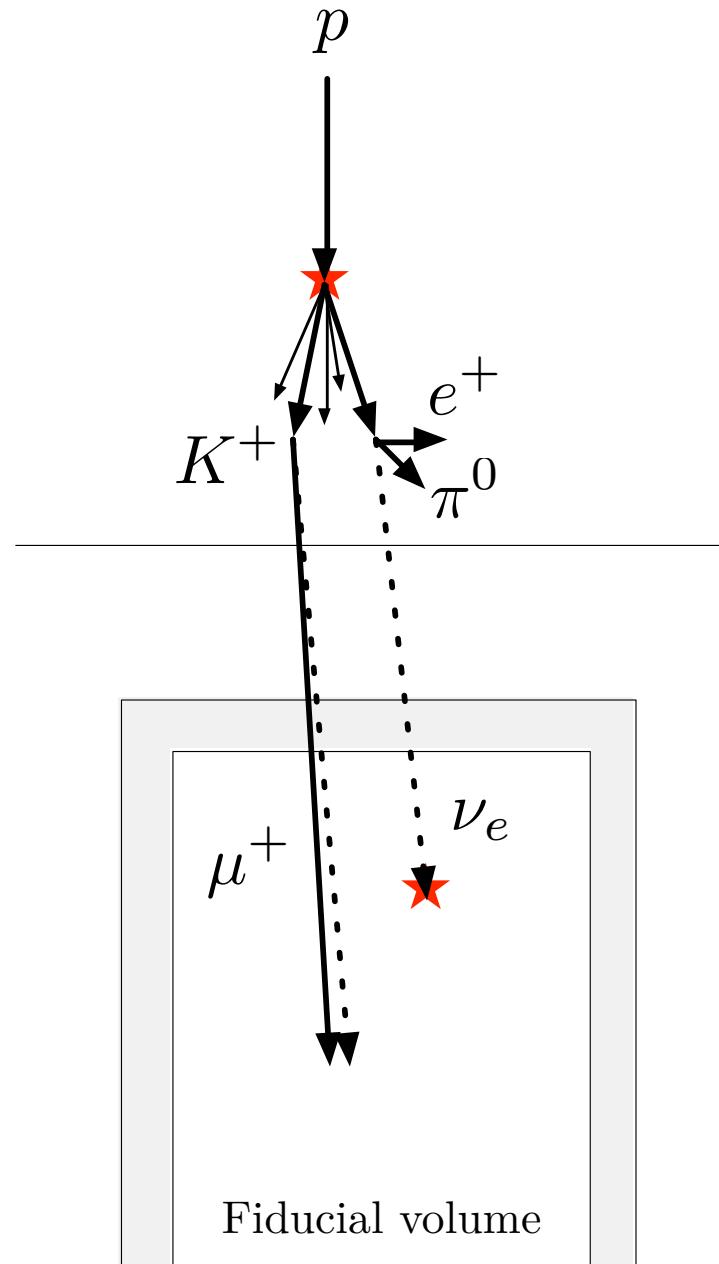


muon neutrinos through Earth (tracks)

no
accompanying
muon(s)

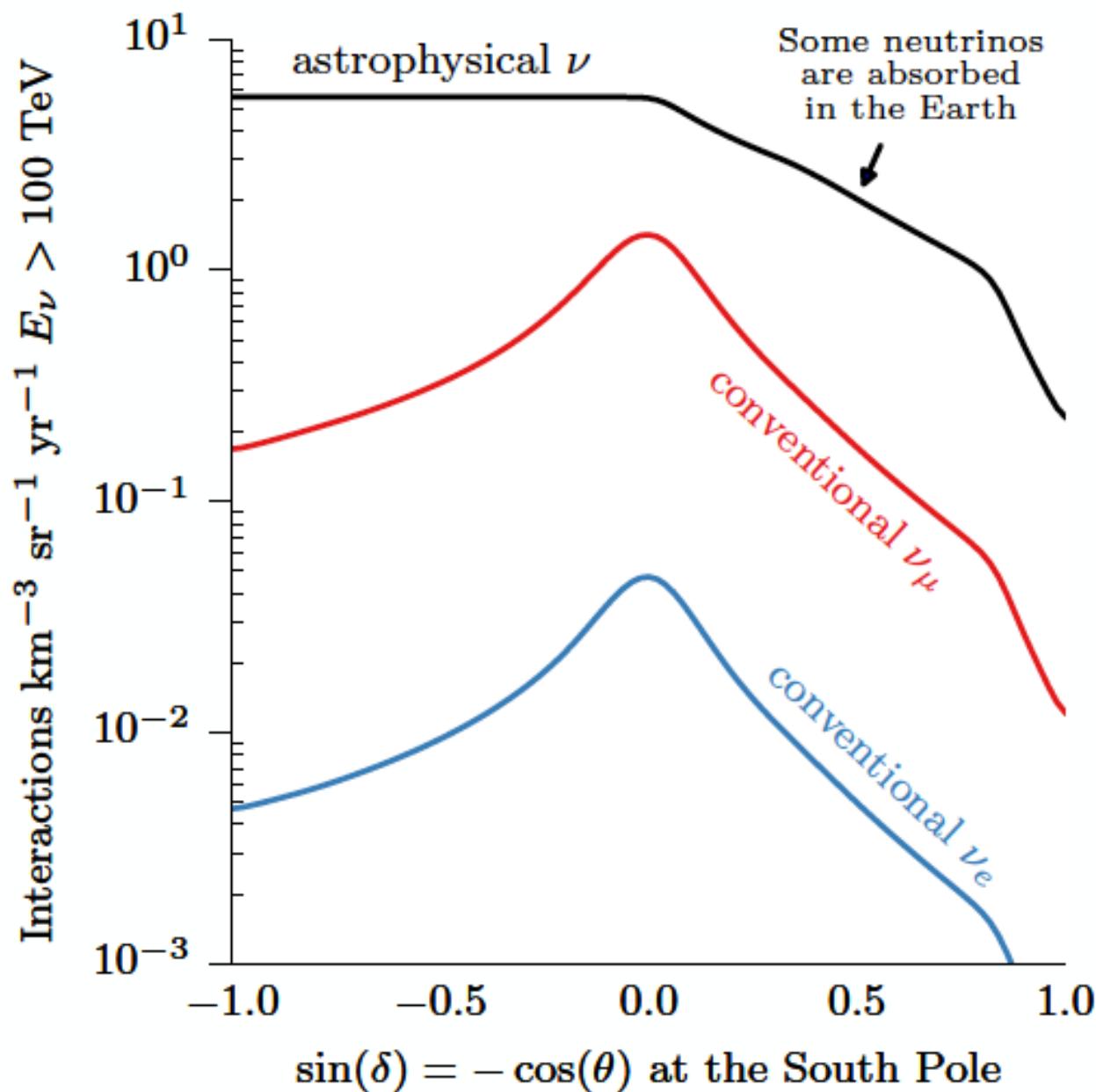


Veto by correlated muon

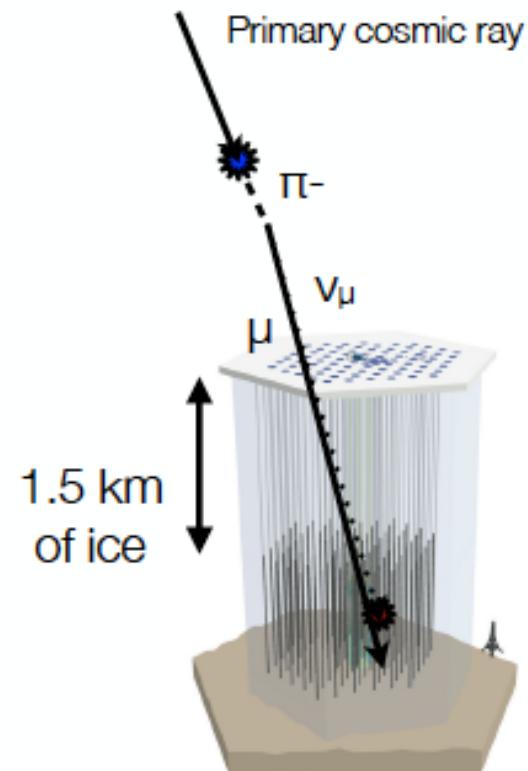


Veto by uncorrelated muon

Atmospheric neutrino self-veto



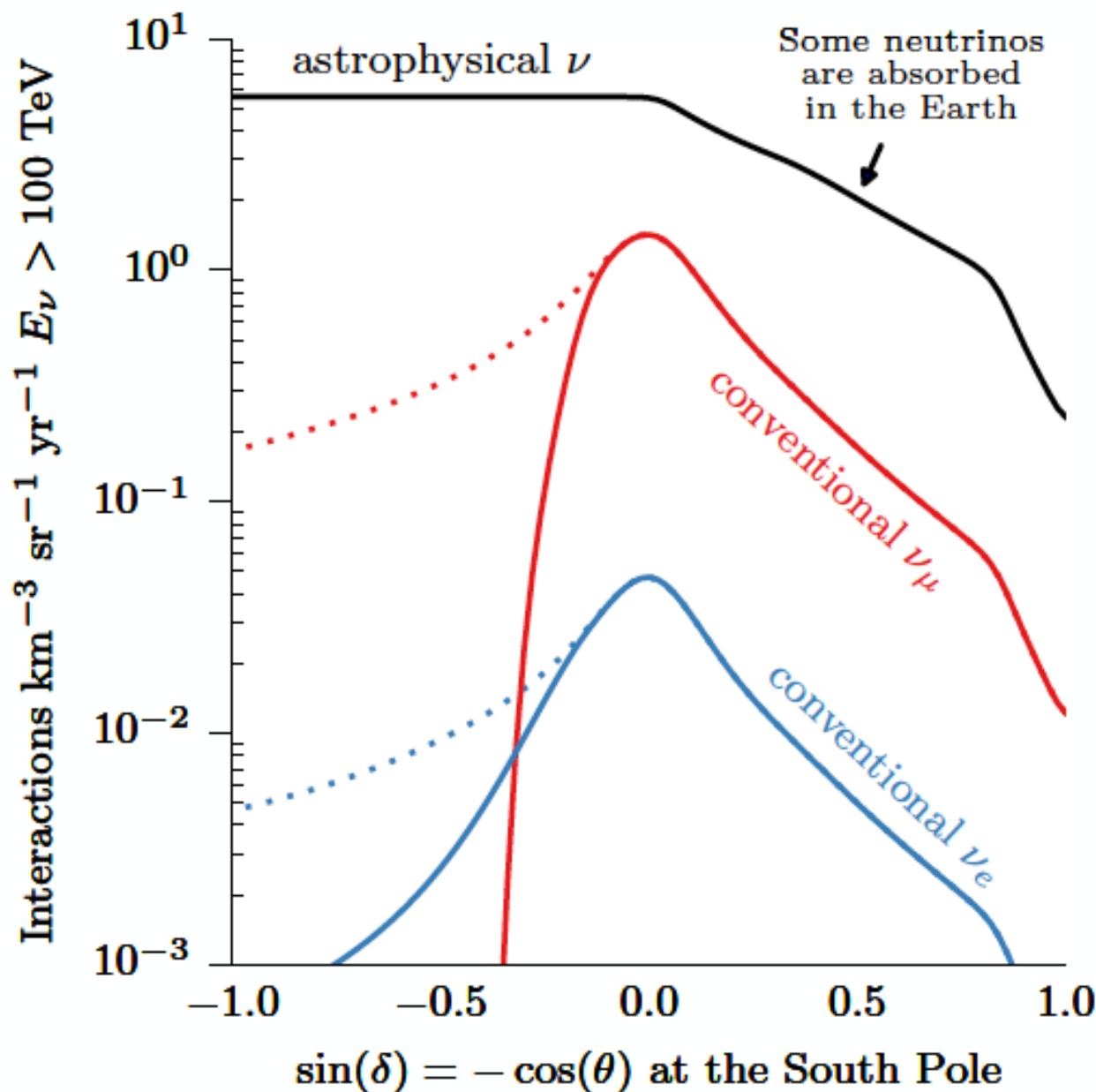
An active muon veto removes down-going atmospheric neutrinos.



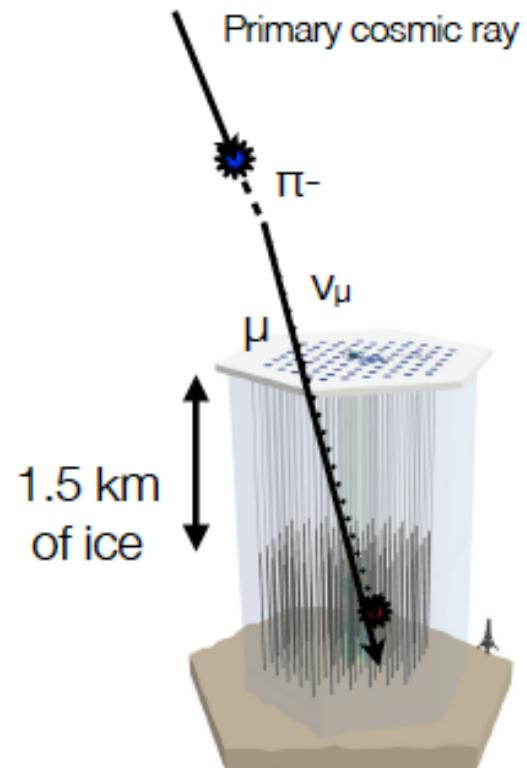
Schönert, Resconi, Schulz,
Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen,
Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



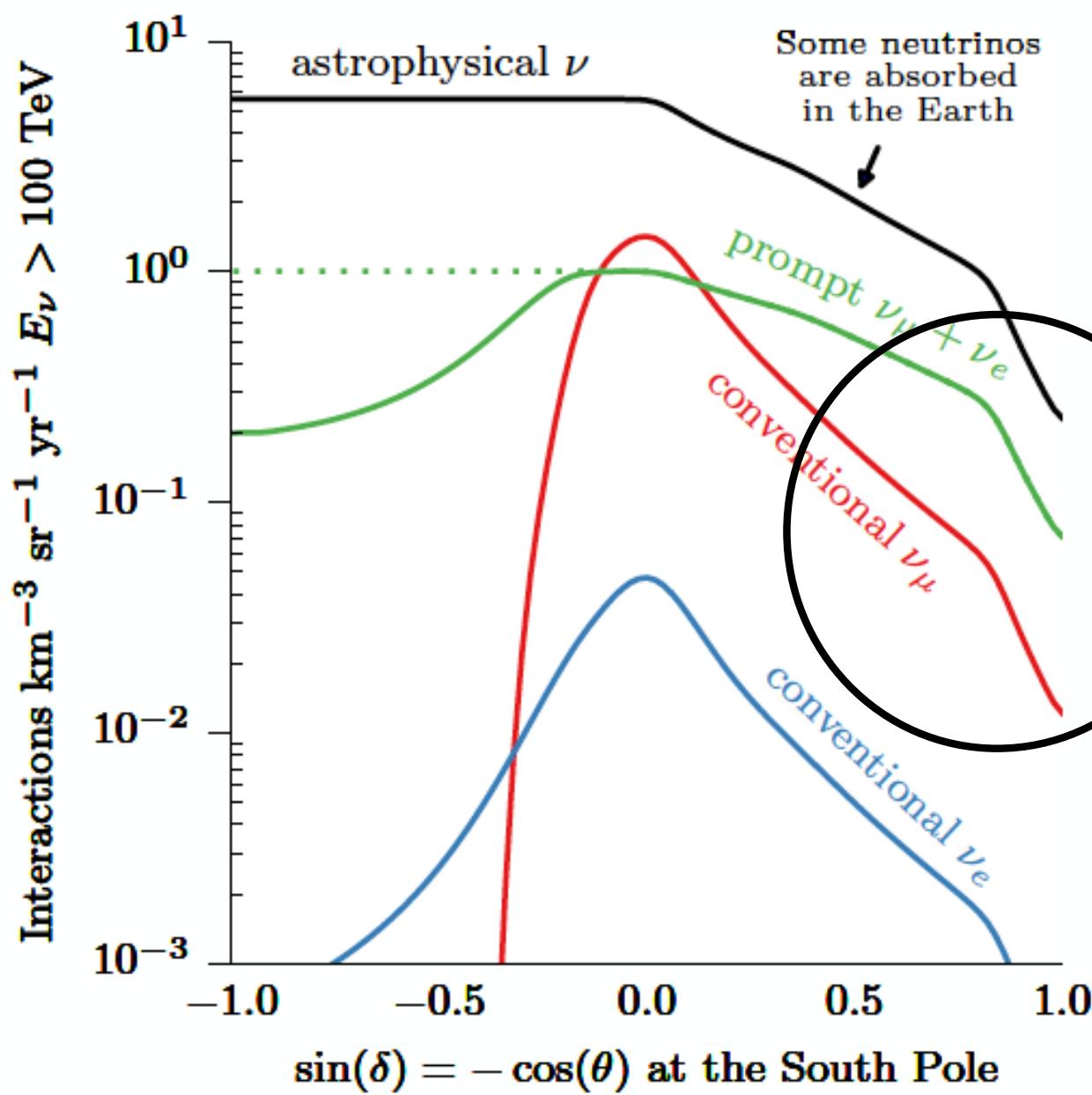
An active muon veto removes down-going atmospheric neutrinos.



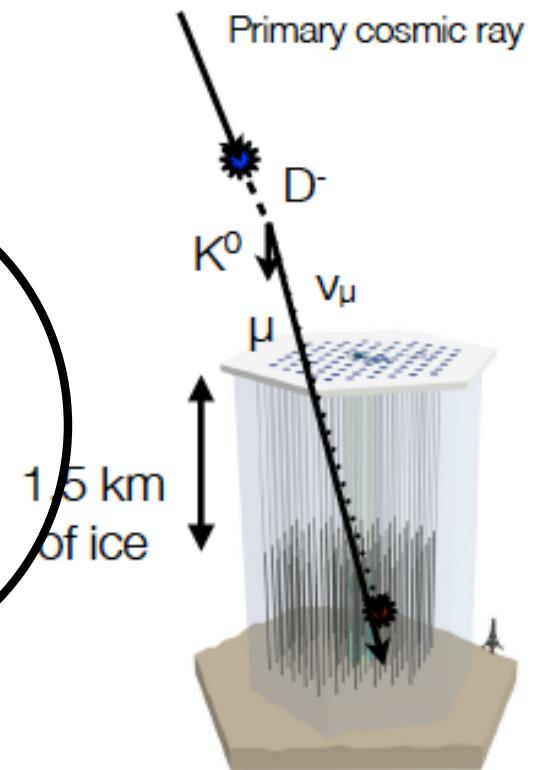
Schönert, Resconi, Schulz,
Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen,
Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto

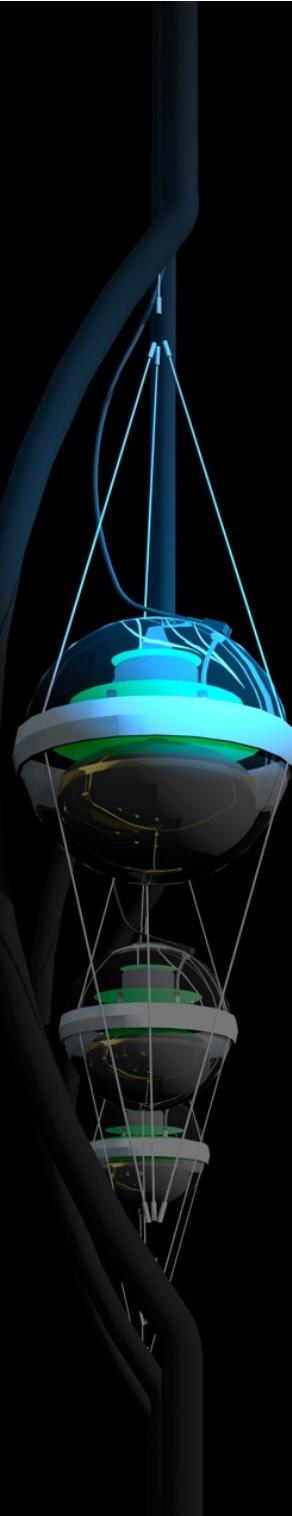


Prompt atmospheric neutrinos are vetoed, too.



Schönert, Resconi, Schulz,
Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen,
Phys. Rev. D, 90:023009 (2014)

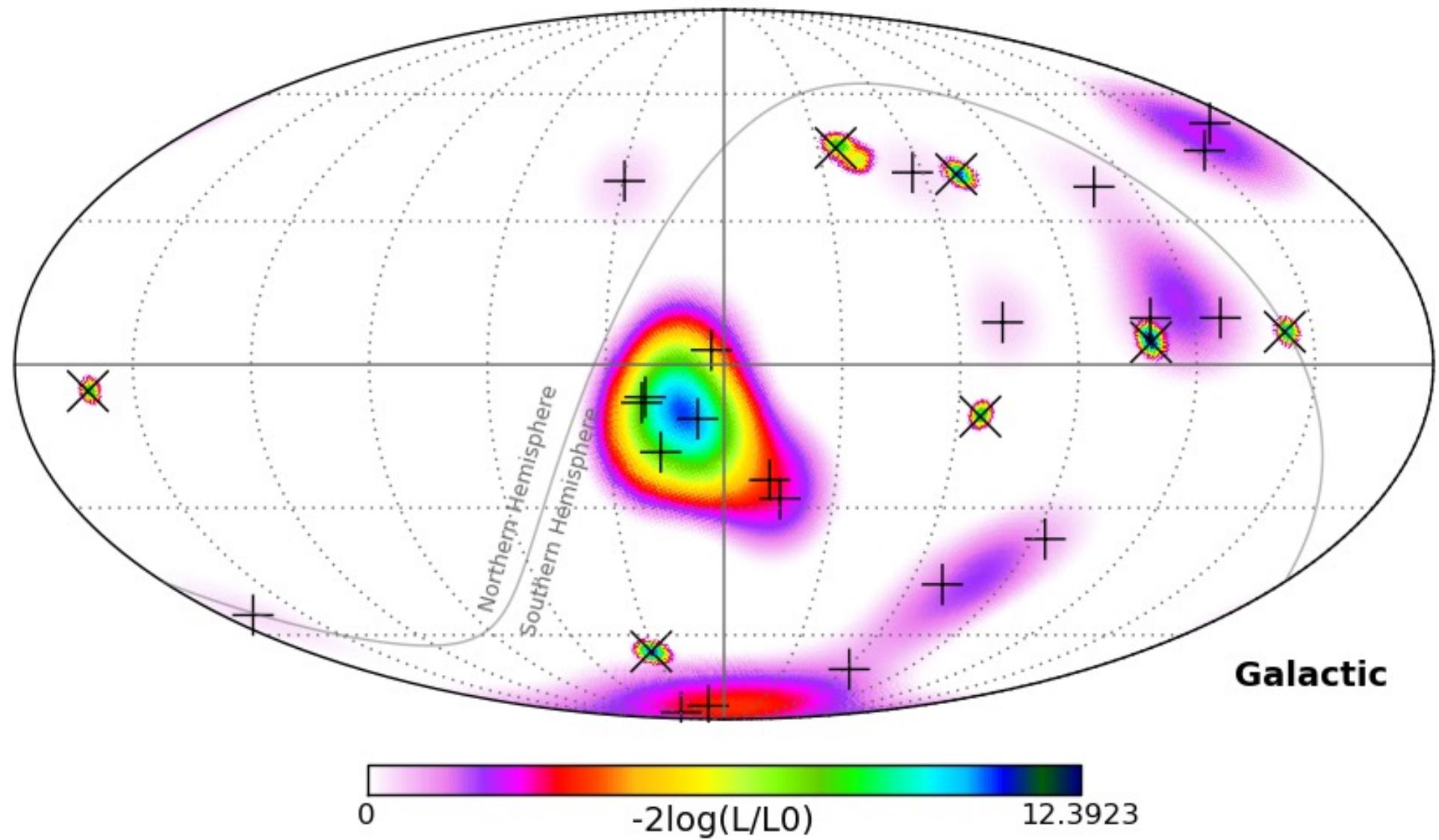


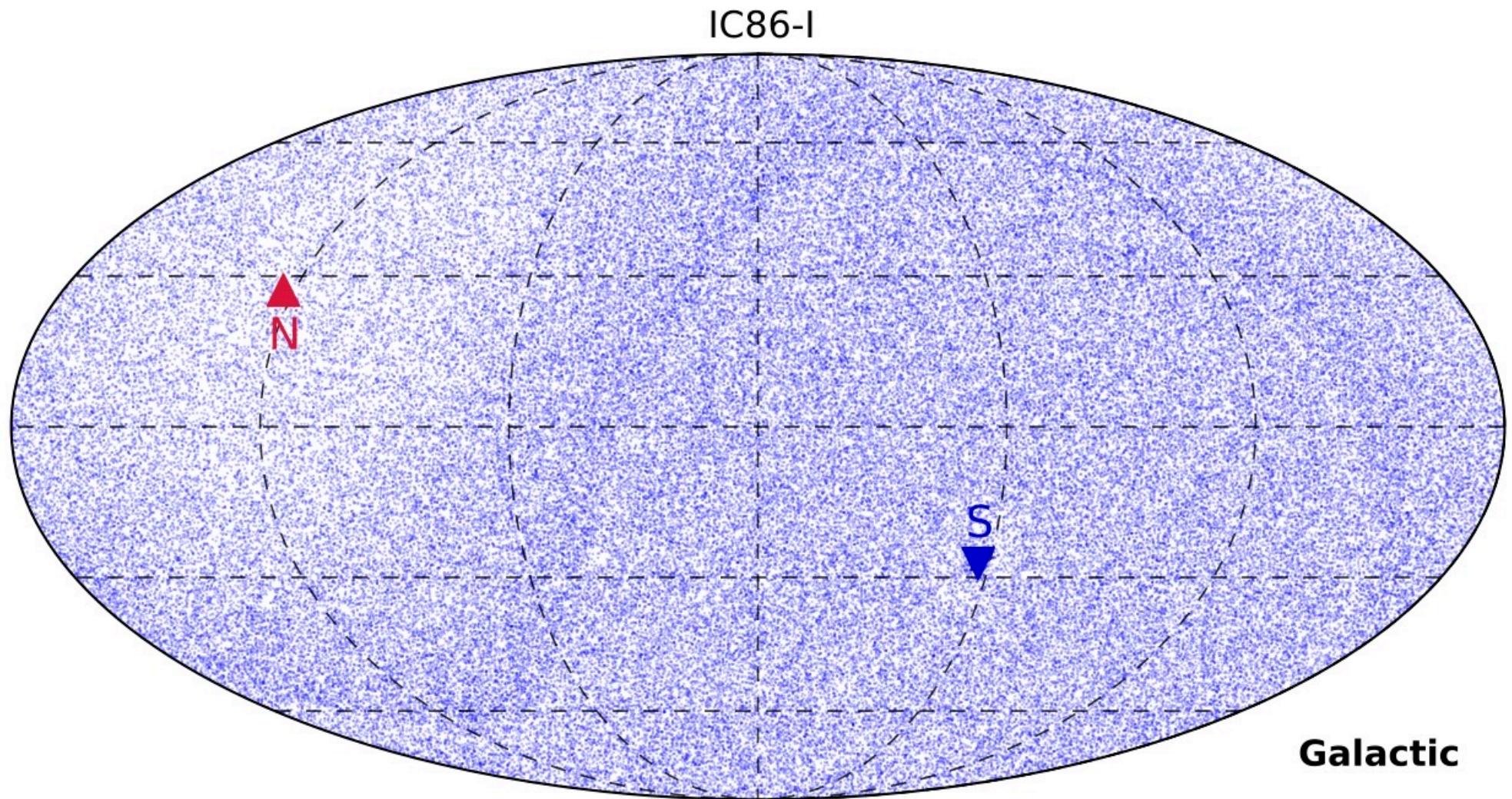
IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

2 year HESE

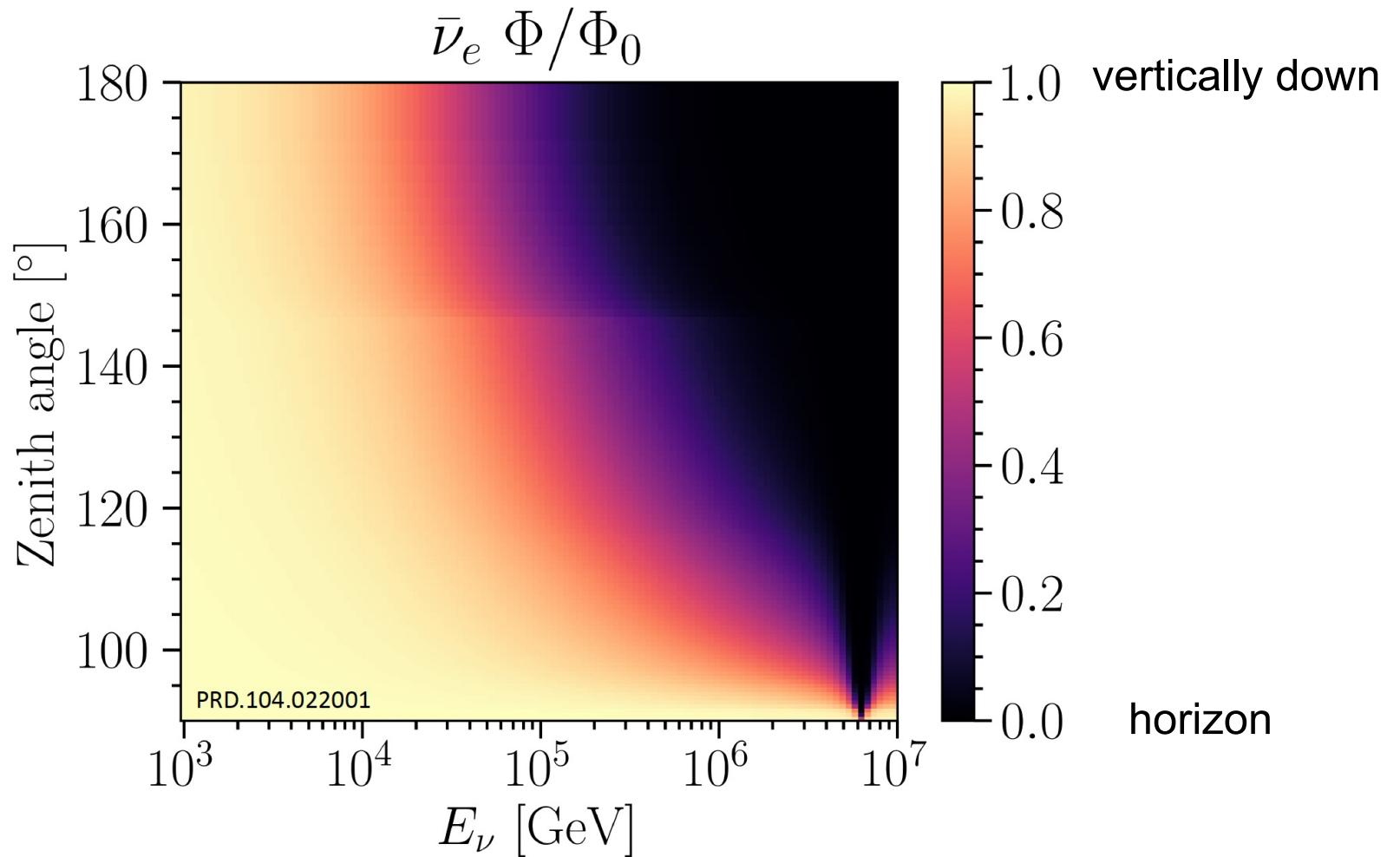
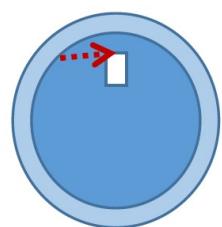
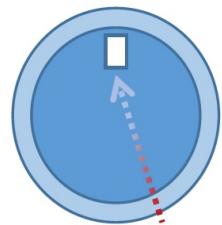


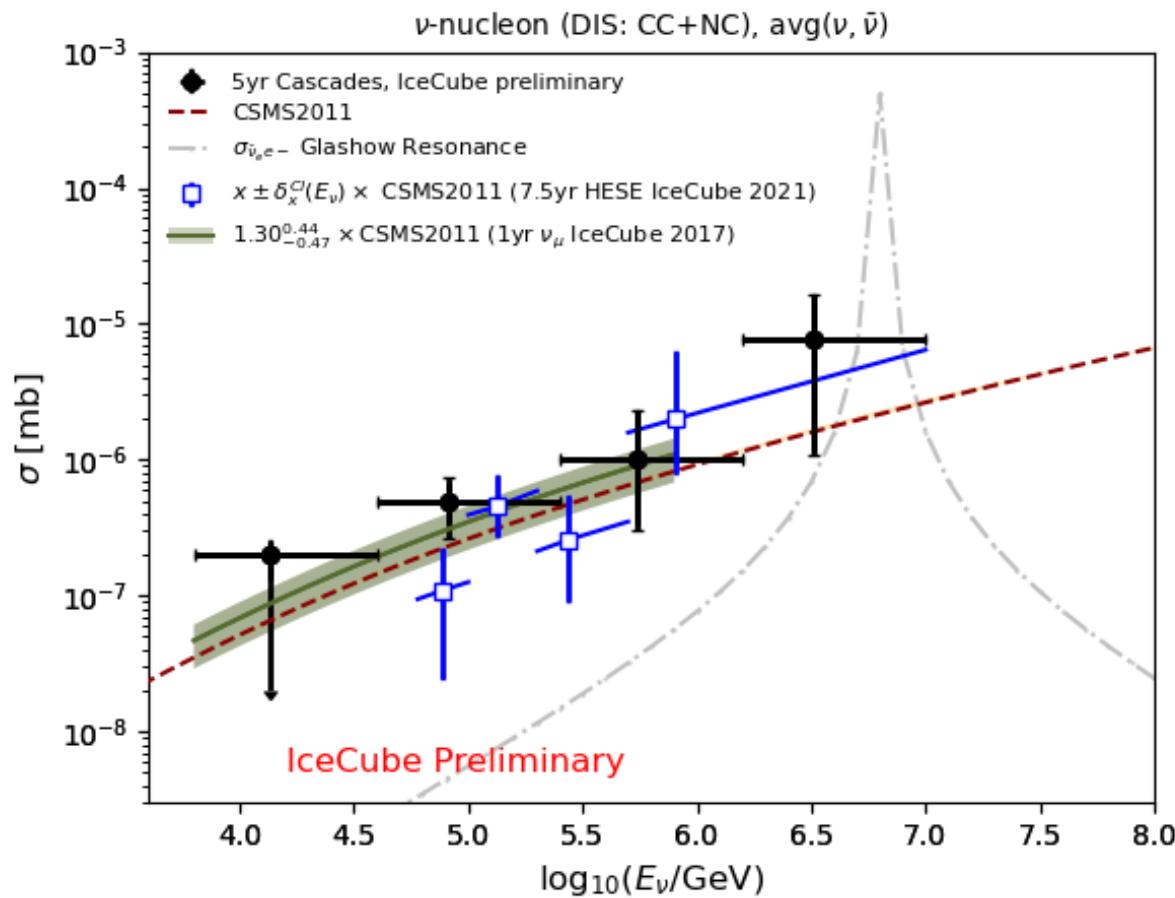


138322 neutrino candidates in one year

120 cosmic neutrinos

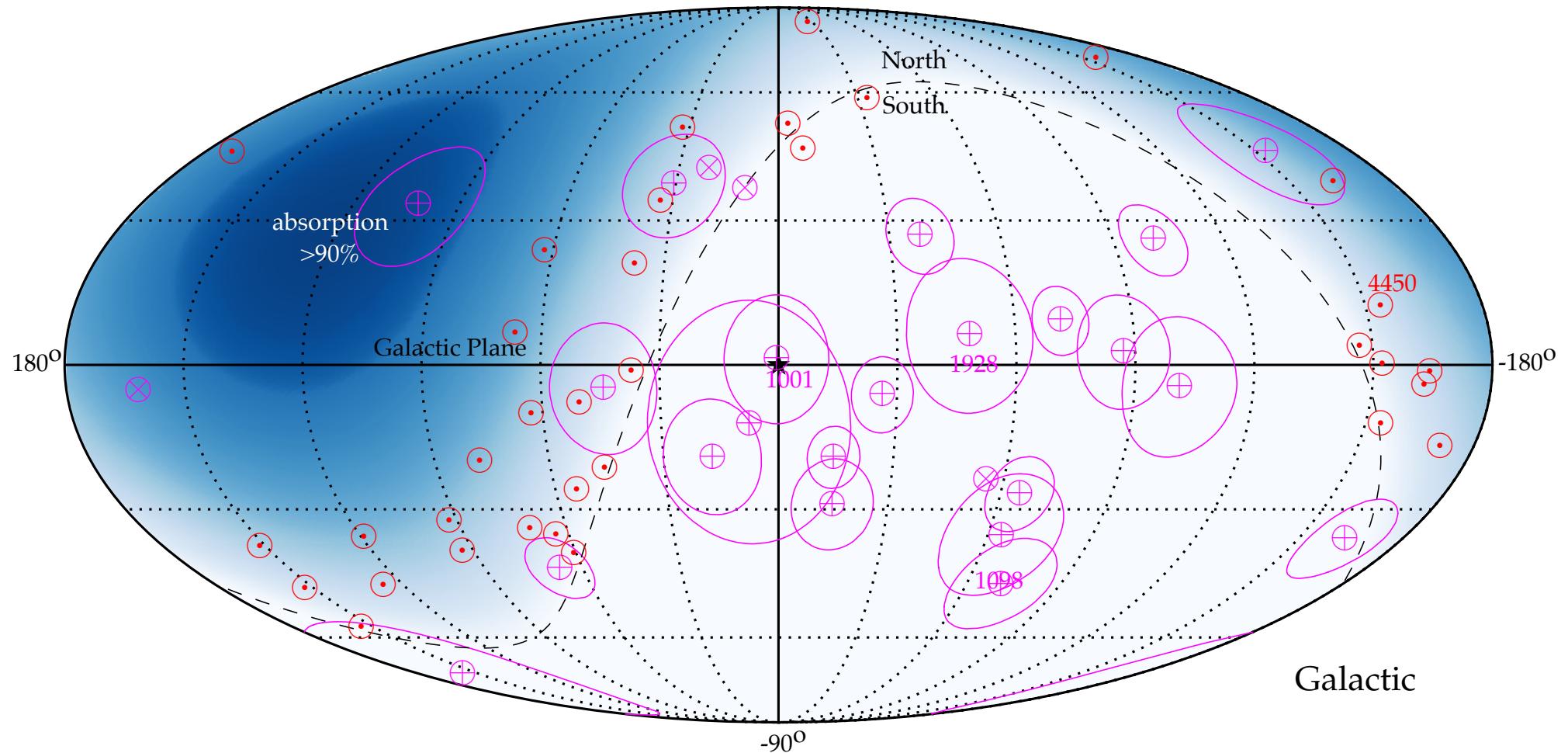
~12 separated from atmospheric background with $E > 60$ TeV
structure in the map results from neutrino absorption by the Earth

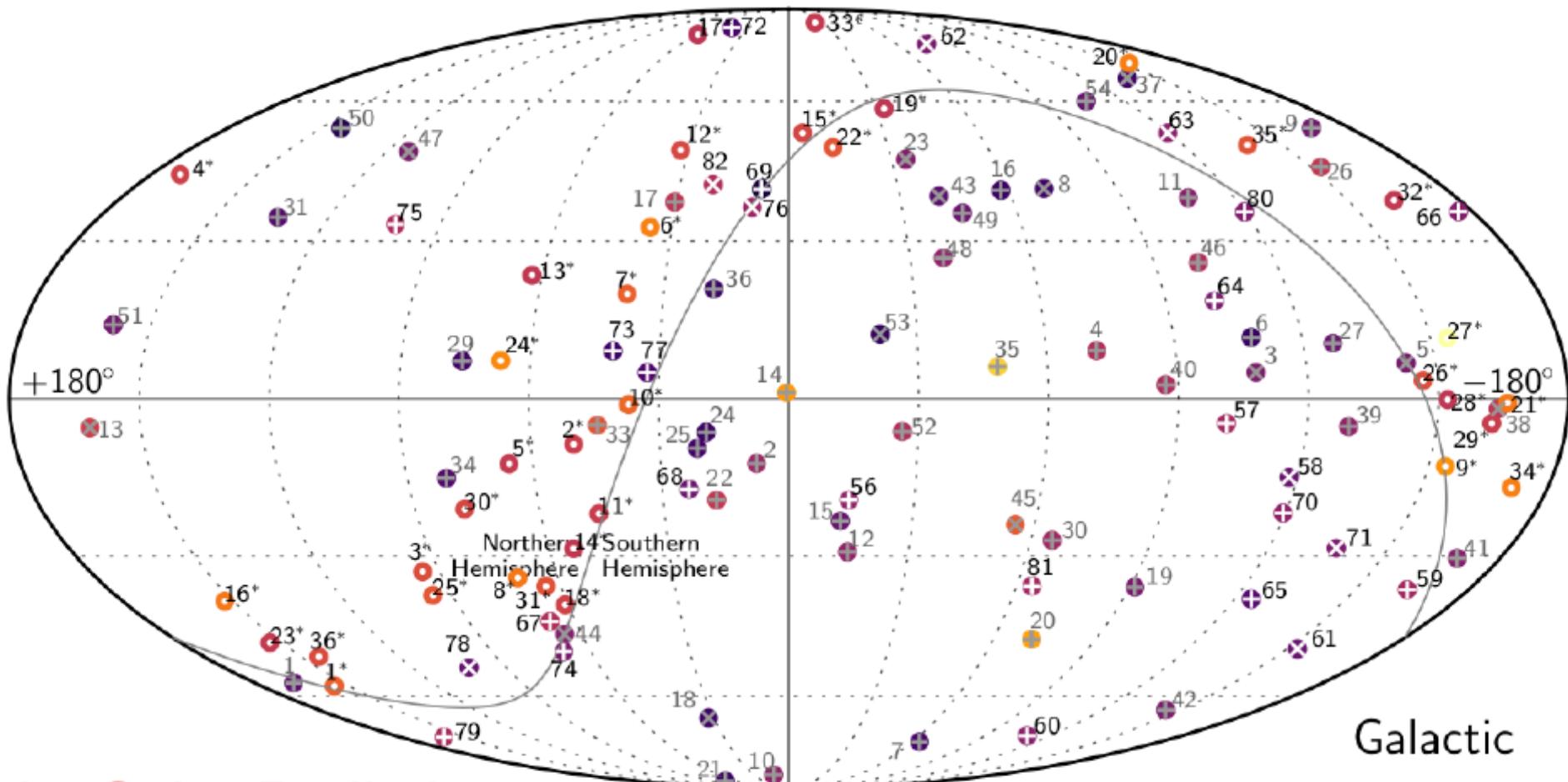




neutrinos with probable cosmic origin: are they correlated to astronomical sources?

Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red))





IceCube Preliminary



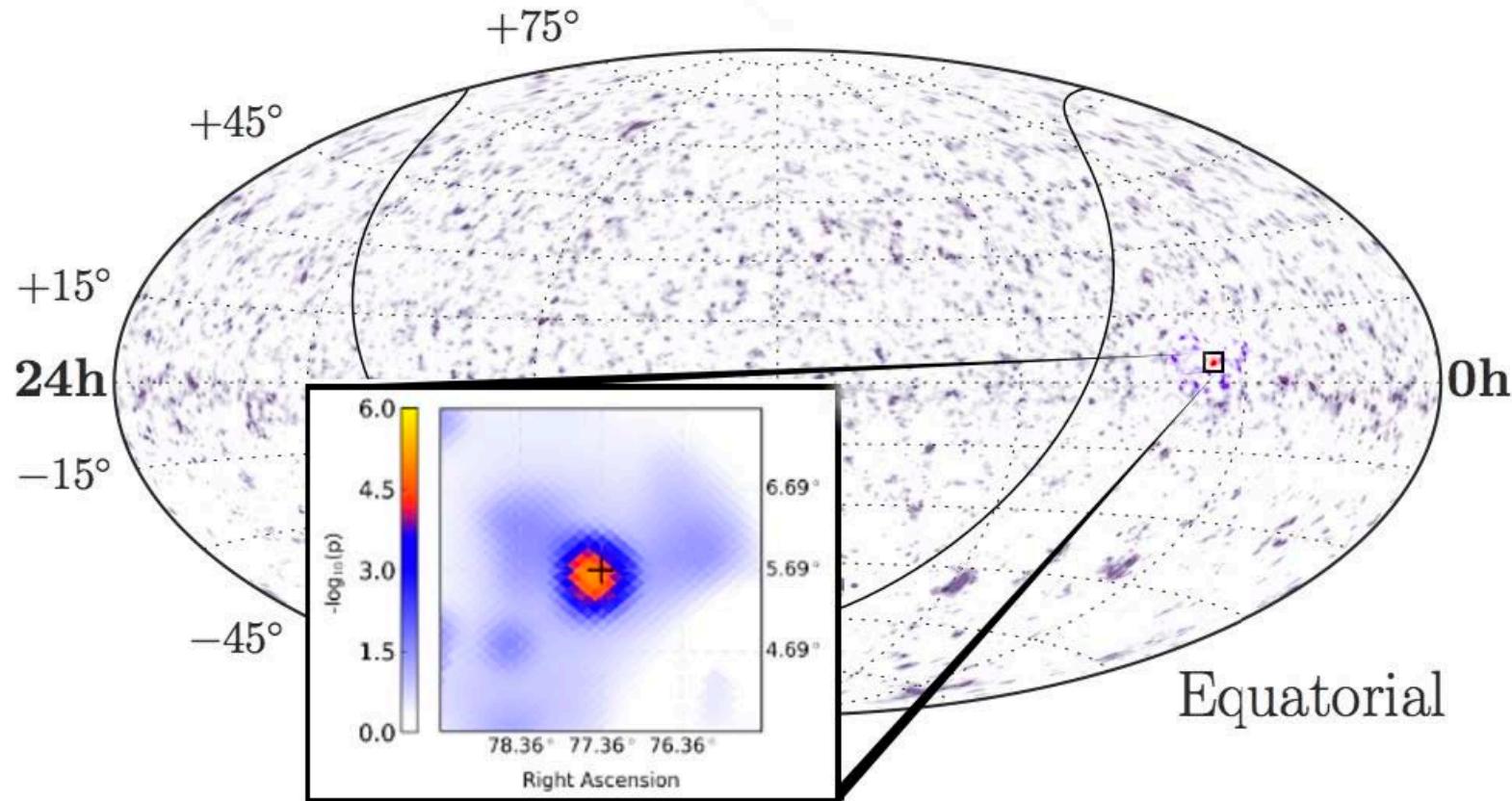
Deposited Energy or Muon Energy Proxy [TeV]

- ✖ N New Starting Tracks
- ✖ N New Starting Cascades

- ✖ N Earlier Starting Tracks
- ✖ N Earlier Starting Cascades

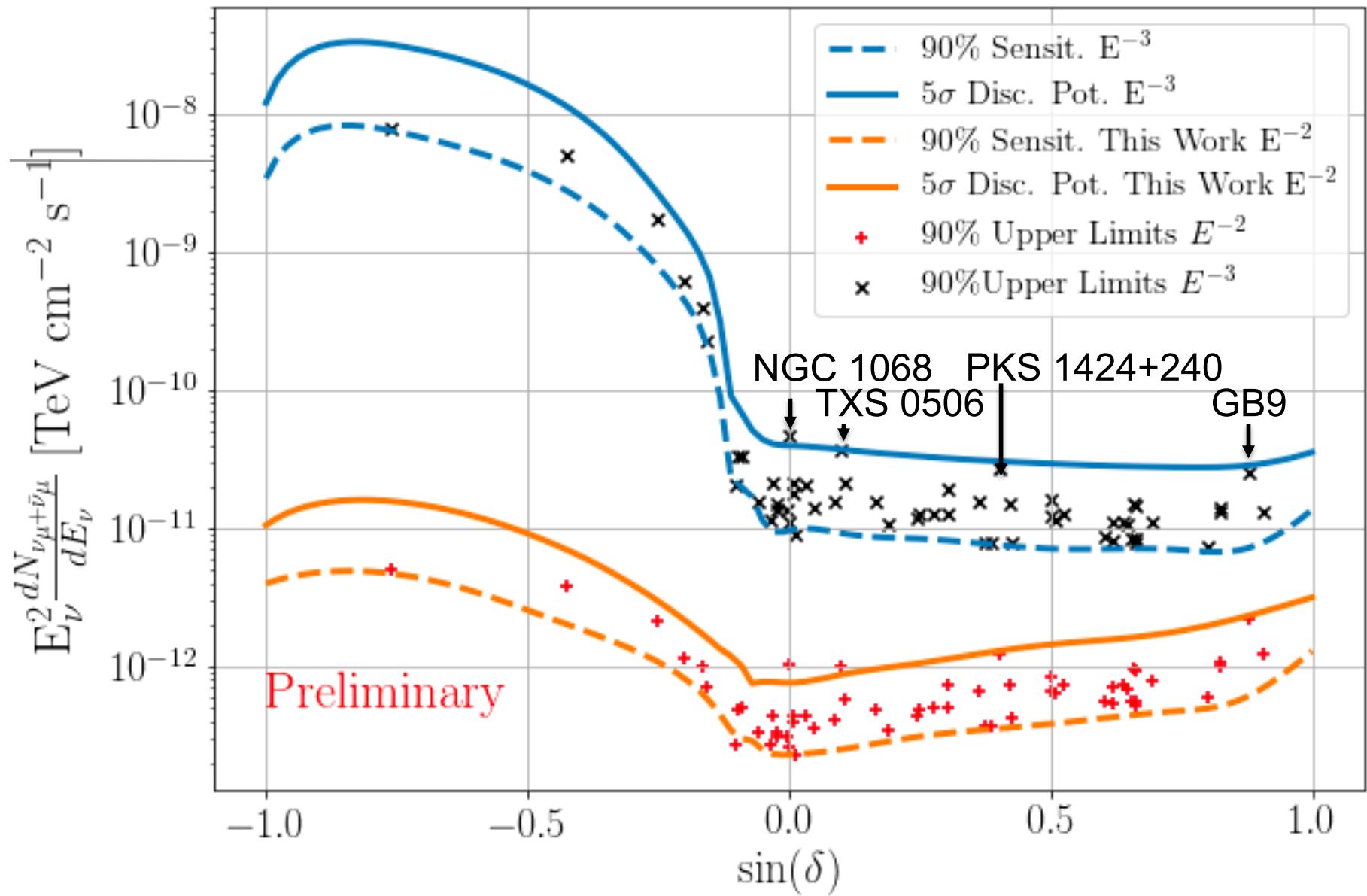
- N^* Throughgoing Tracks

pre-trial p-value for clustering of high energy neutrinos



hottest spot coincident with
NGC 1068 (M77)

evidence for non-uniform sky map in 10 years of IceCube data :
mostly resulting from 4 extragalactic source candidates



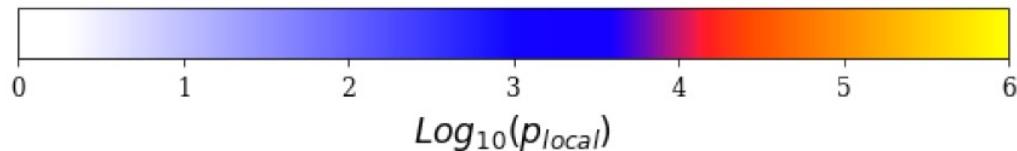
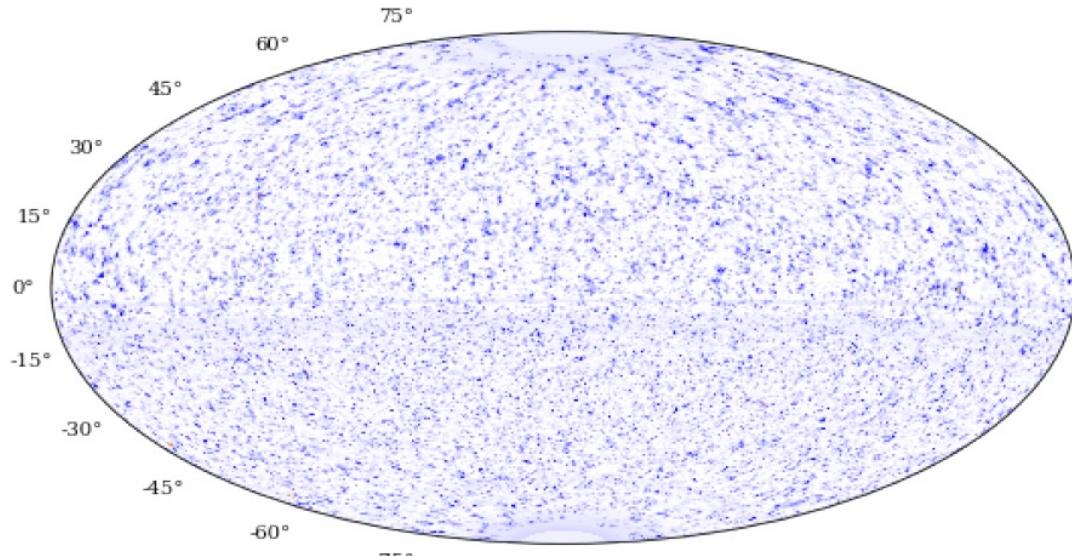
limits and interesting fluctuations (?)

Source List Results							
Name	Class	α [deg]	δ [deg]	\hat{n}_s	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	4.9
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	?	267.87	-9.61	2.2	3.2	1.72	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	BLL	235.75	61.50	29.7	3.0	2.74	22.0
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	BLL	216.76	23.80	41.5	3.9	2.80	12.3
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.39	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
Ton 599	FSRQ	179.88	29.24	0.0	2.2	0.29	4.5

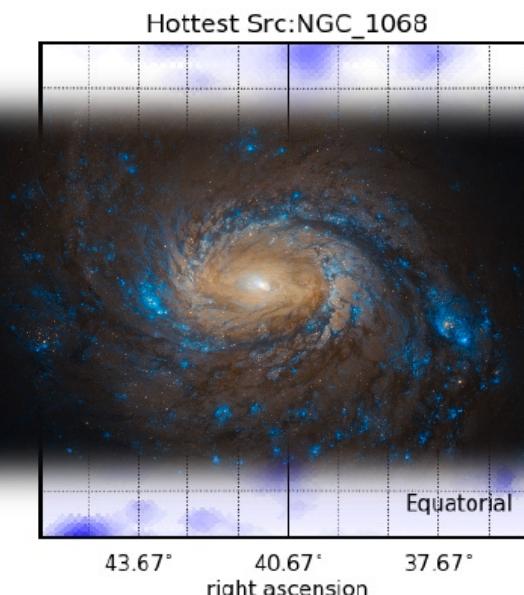
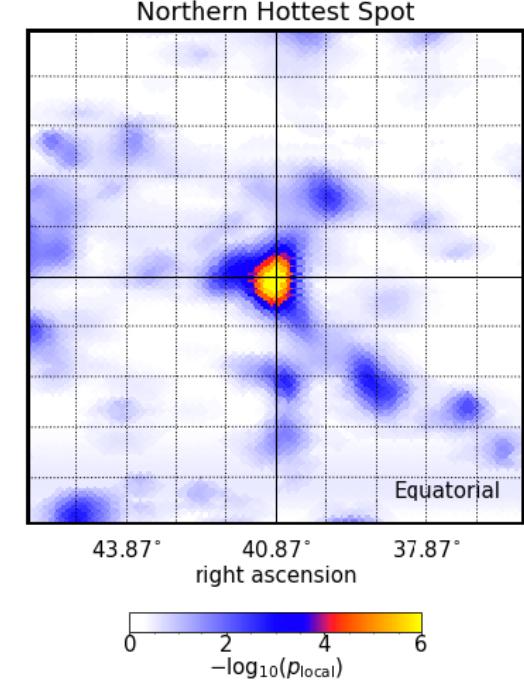
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	2.6	0.29	4.5
4C +55.17	FSRQ	149.42	55.38	11.9	3.3	1.02	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	BLL	77.35	5.70	12.3	2.1	3.72	10.1
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0421+01	FSRQ	65.82	-1.41	0.32	4.0	0.52	3.4
TXS 0534+01	FSRQ	54.98	1.47	0.35	4.0	0.99	4.4
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5
NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.74	10.5
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1
4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	3.6
3C 66A	BLL	35.67	43.04	0.0	2.8	0.30	3.9
B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.33	4.3
PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.27	2.3
MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.43	3.5
TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.31	3.5
B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.28	4.1
NGC 598	SBG	23.52	30.62	11.4	4.0	0.63	6.3
S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.30	3.7
4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4
M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6
PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4
PKS 2233-148	BLL	339.14	-14.56	5.3	2.8	1.26	21.4
HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8
HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0
PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1
PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1
NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.31	50.2
3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.20	2.7
PKS 0805-07	FSRQ	122.07	-7.86	0.0	2.7	0.31	4.7
PKS 0727-11	FSRQ	112.58	-11.69	1.9	3.5	0.59	11.4
LMC	SBG	80.00	-68.75	0.0	3.1	0.36	41.1
SMC	SBG	14.50	-72.75	0.0	2.4	0.37	44.1
PKS 0048-09	BLL	12.68	-9.49	3.9	3.3	0.87	10.0
NGC 253	SBG	11.90	-25.29	3.0	4.0	0.75	37.7

avoid $>10^5$ trials \rightarrow search 110 preselected source candidates

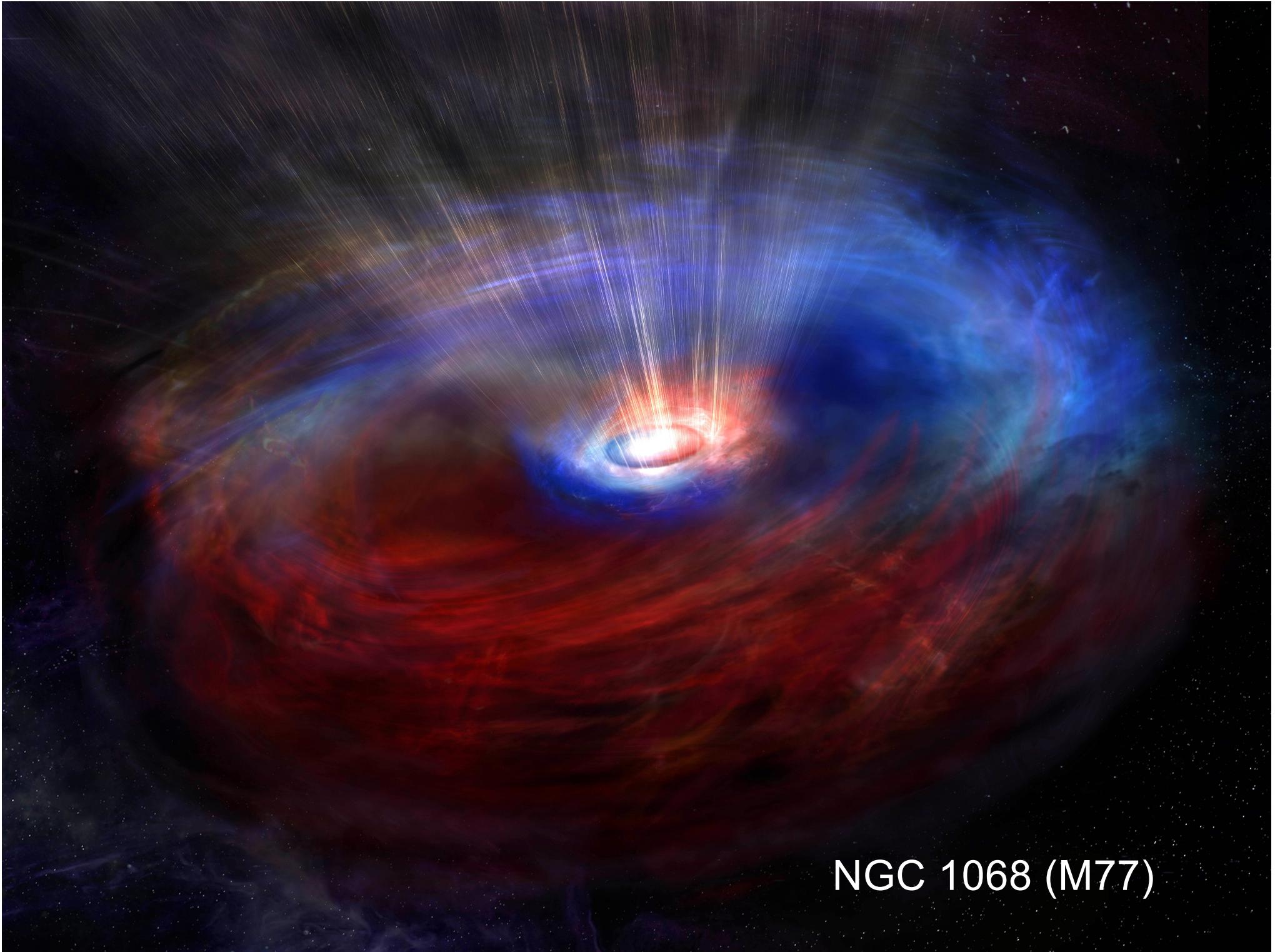
10 years of muon neutrinos



Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	$10^{**}-6.45$	0.09
	South	$10^{**}-5.37$	0.476
Source List	North	$10^{**}-4.7$ (4.1σ)	0.002 (2.875 σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3 σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496



Tessa Carver

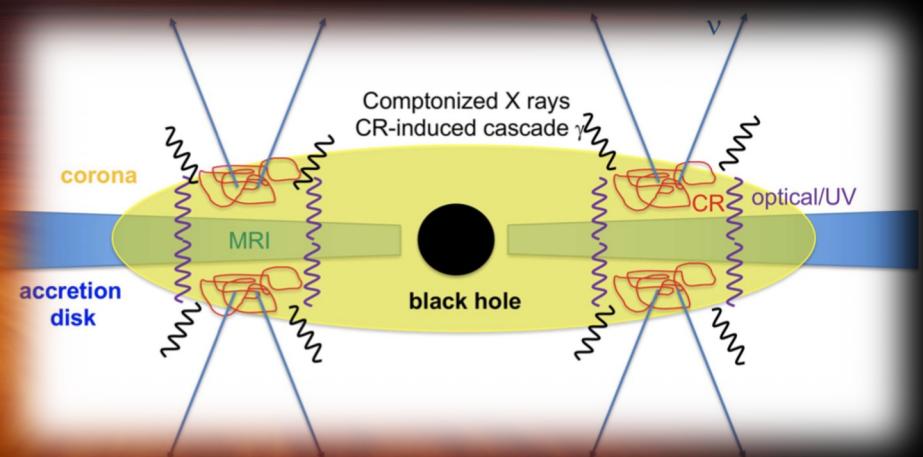


NGC 1068 (M77)

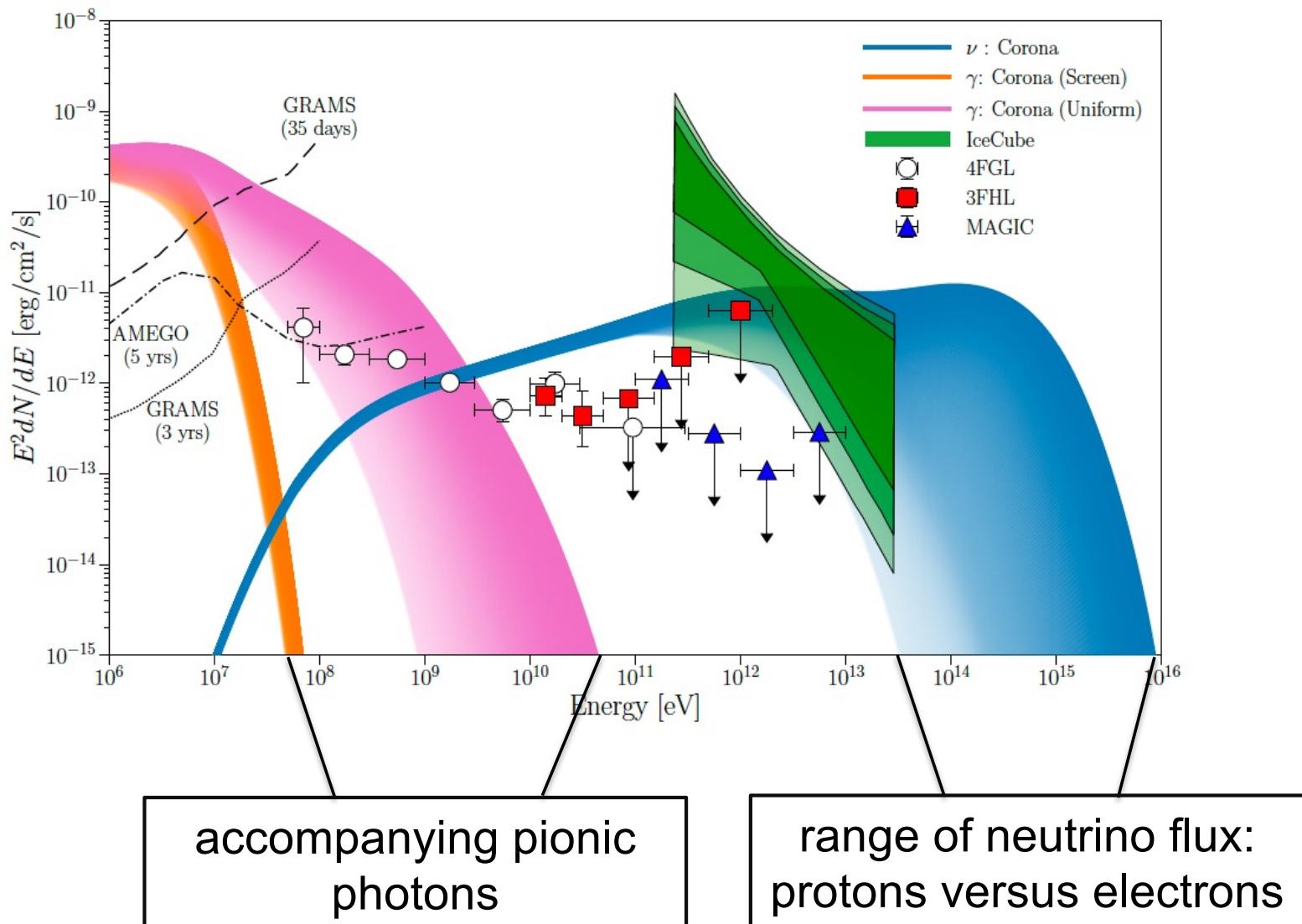
cores of active galaxies as cosmic accelerators

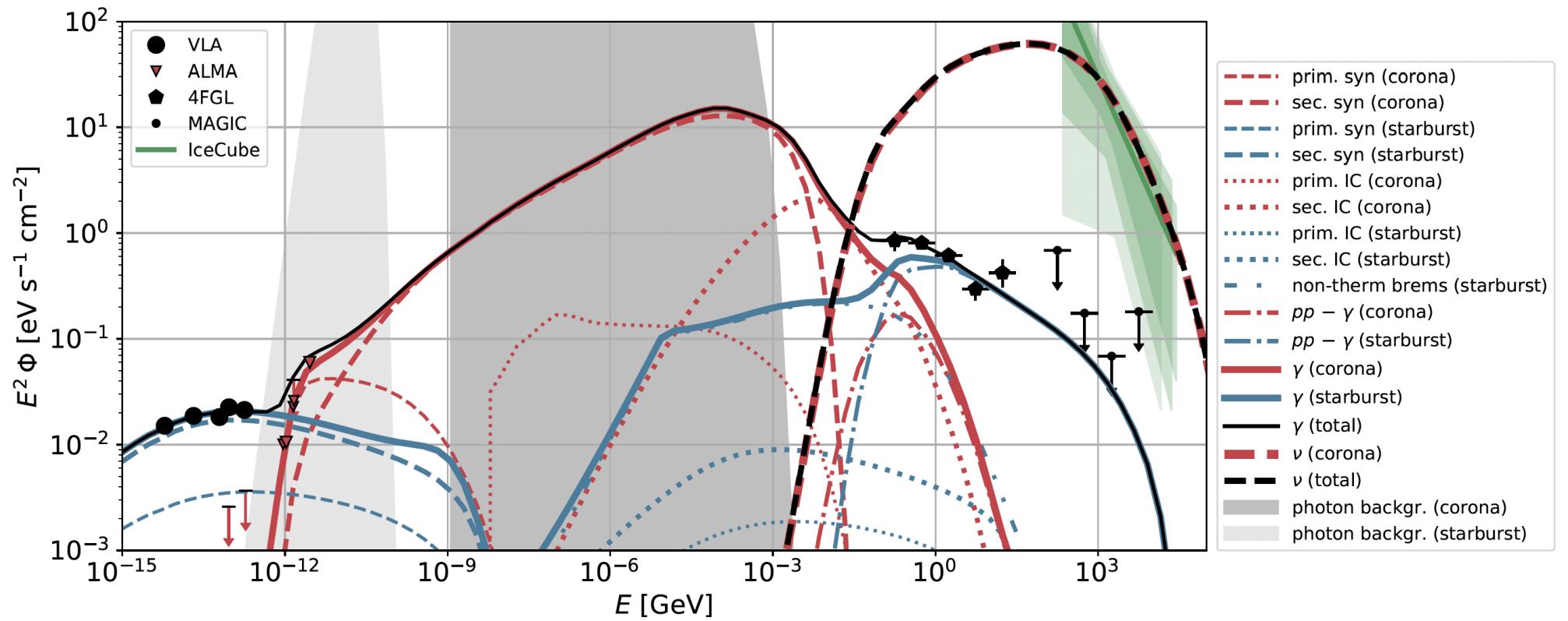
acceleration of electrons and protons
in the high field regions associated
with the accretion disk and the optically
thick corona (0.1 pc) emitting most of the X-rays

the core is the target for neutrino production
and gamma-ray obscured



neutrinos produced in the gamma-ray obscured core of NGC 1068





interesting fluctuations or neutrino sources?

→ ongoing program to upgrade the performance of IceCube

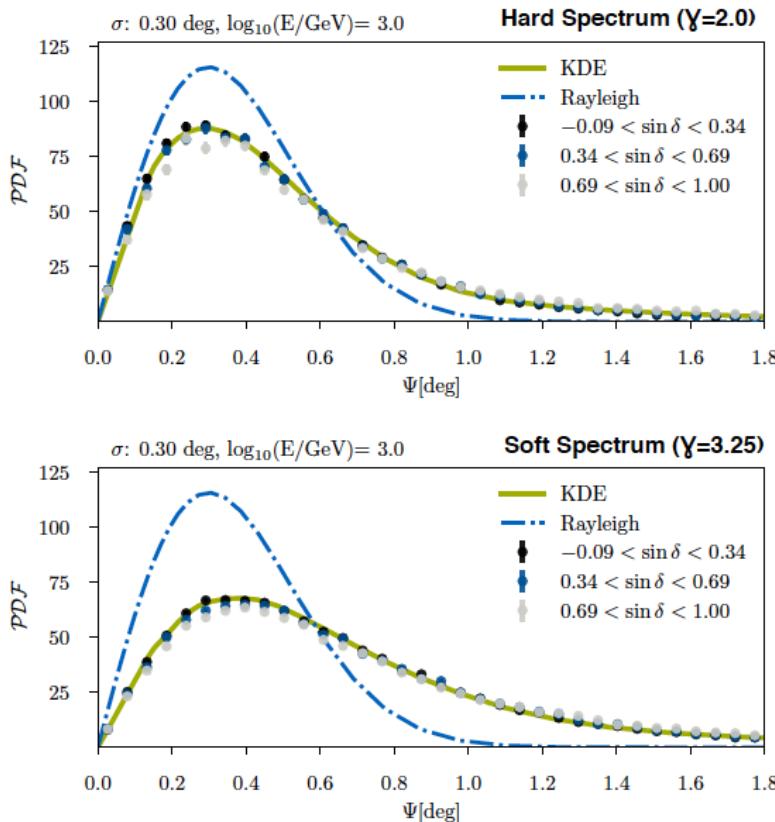
- improved detector calibration and ice model (pass 2)

→ improved muon track reconstruction

- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics
- improved modeling of the optics of the ice

answer soon...

- point spread function consistent with simulation
- insensitive to systematics



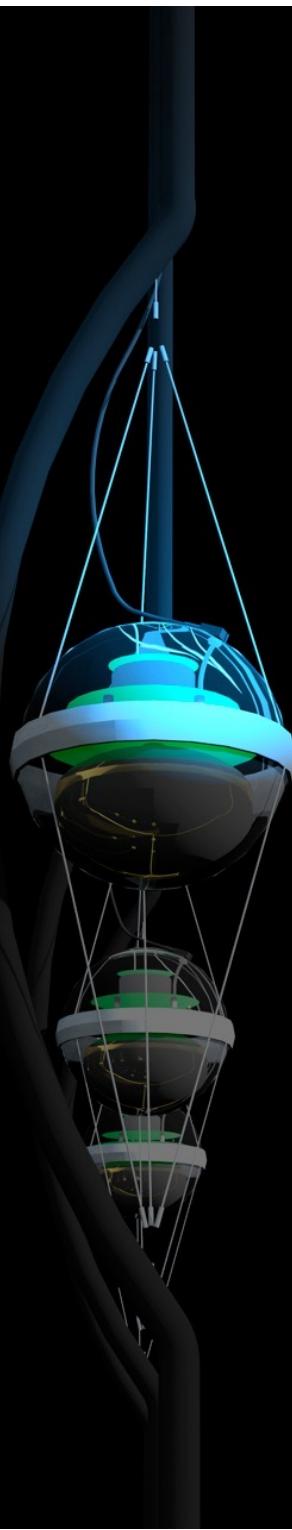
- ▶ Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- ▶ The distribution depends on the spectral index!
- ▶ Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- ▶ **Solution:** Obtain a numerical representation of the γ -dependent spatial term from MC simulation (for example using KDEs)

$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}(\psi | \sigma, E_\mu, \gamma)$$

Virtual Collaboration Meeting, 2020-09-22

very soon!

- we observe a diffuse flux of neutrinos from extragalactic sources
- skymap reveals structure at the 3σ level associated with 4 sources
- a subdominant Galactic component is emerging but does not reach 3σ level
- where are the PeV gamma rays that accompany PeV neutrinos?

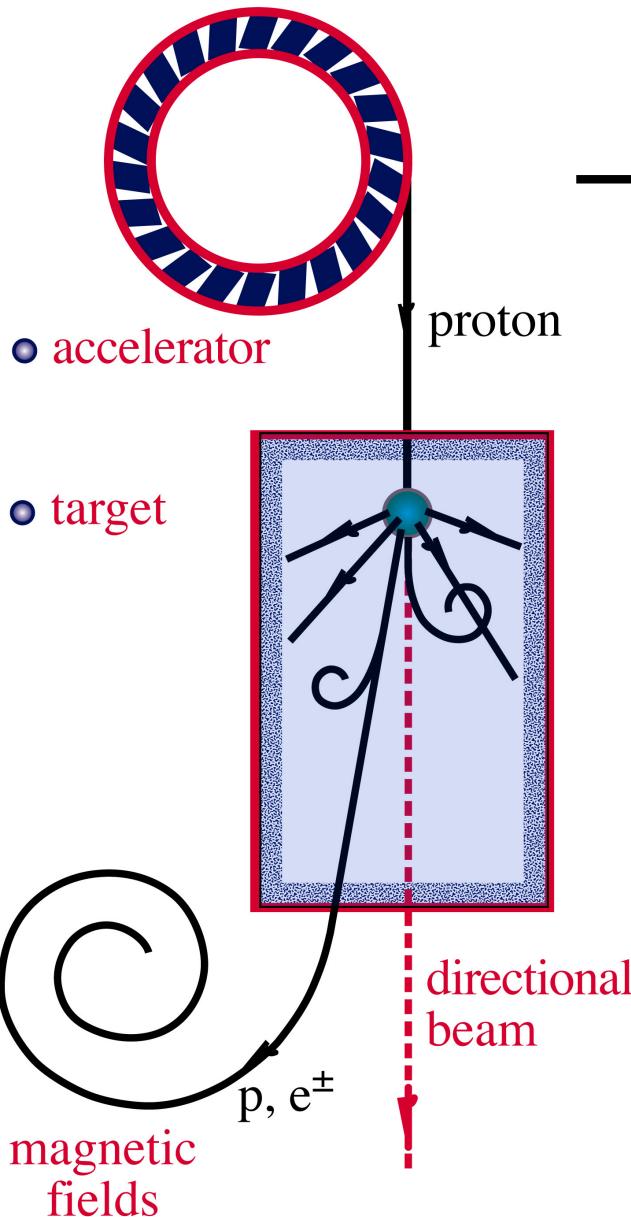


IceCube

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- cosmic neutrinos below 100 TeV?

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy



**black hole
neutron star**

**radiation
and dust**

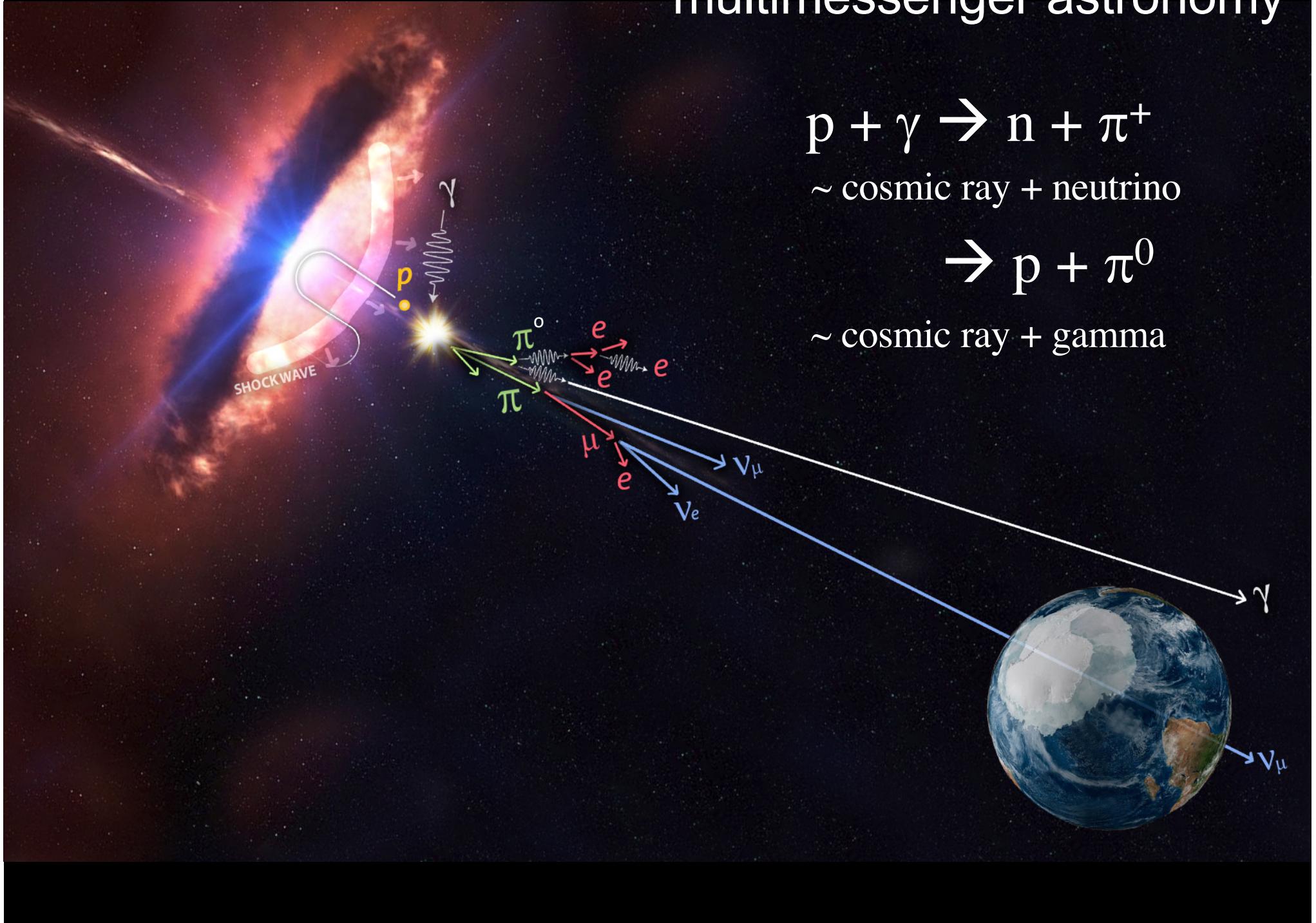


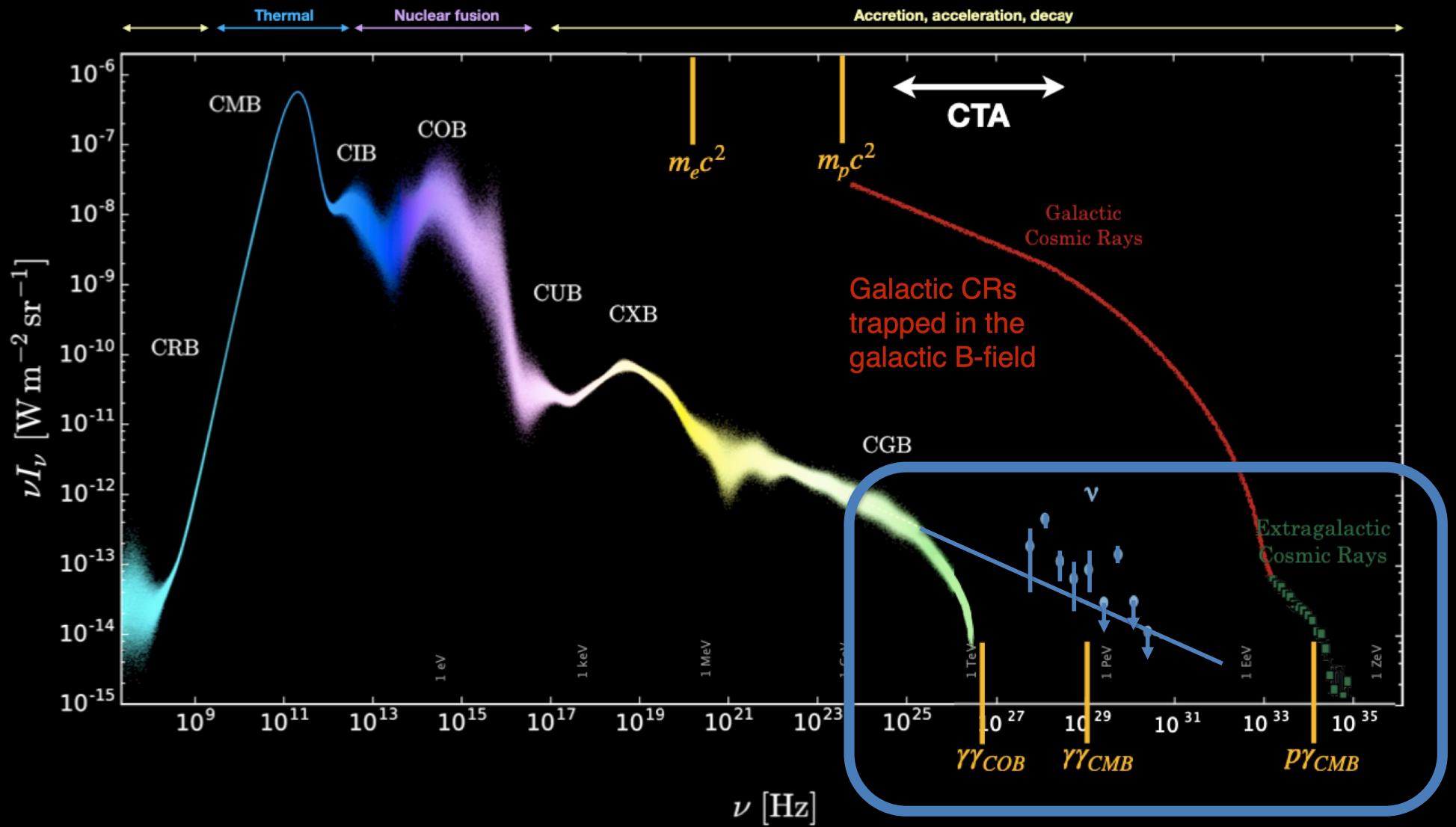
\sim cosmic ray + neutrino



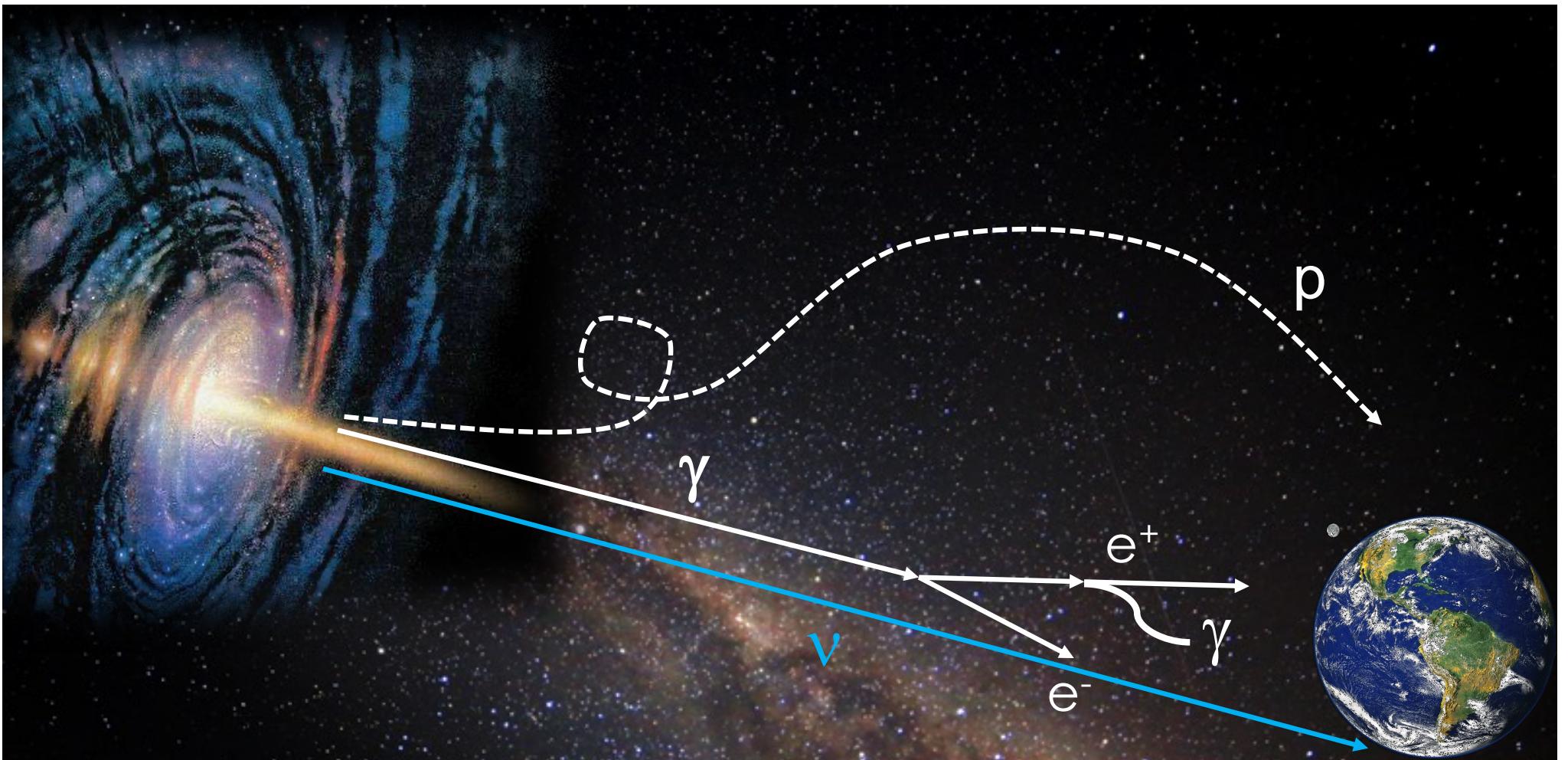
\sim cosmic ray + gamma

multimessenger astronomy

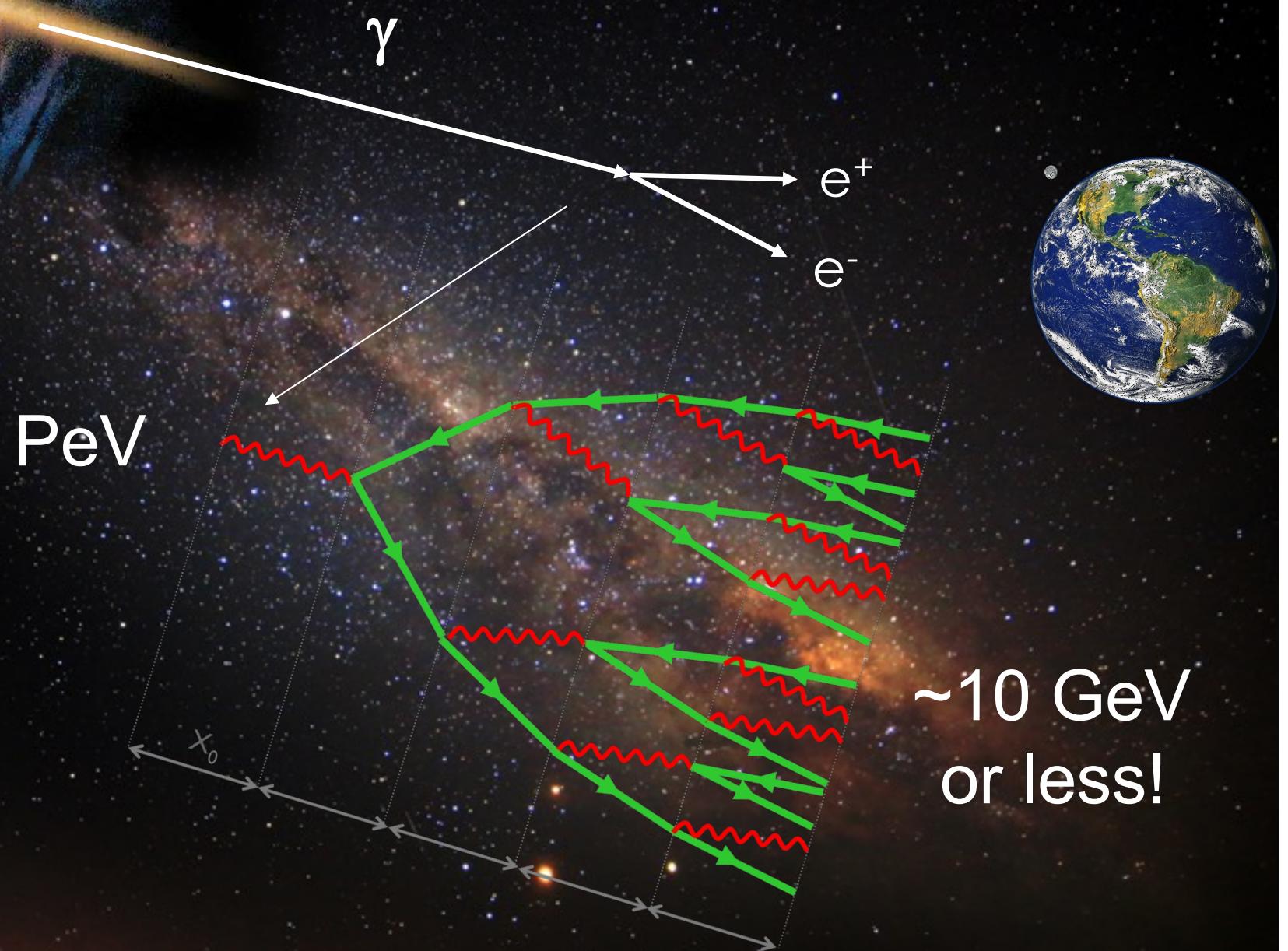


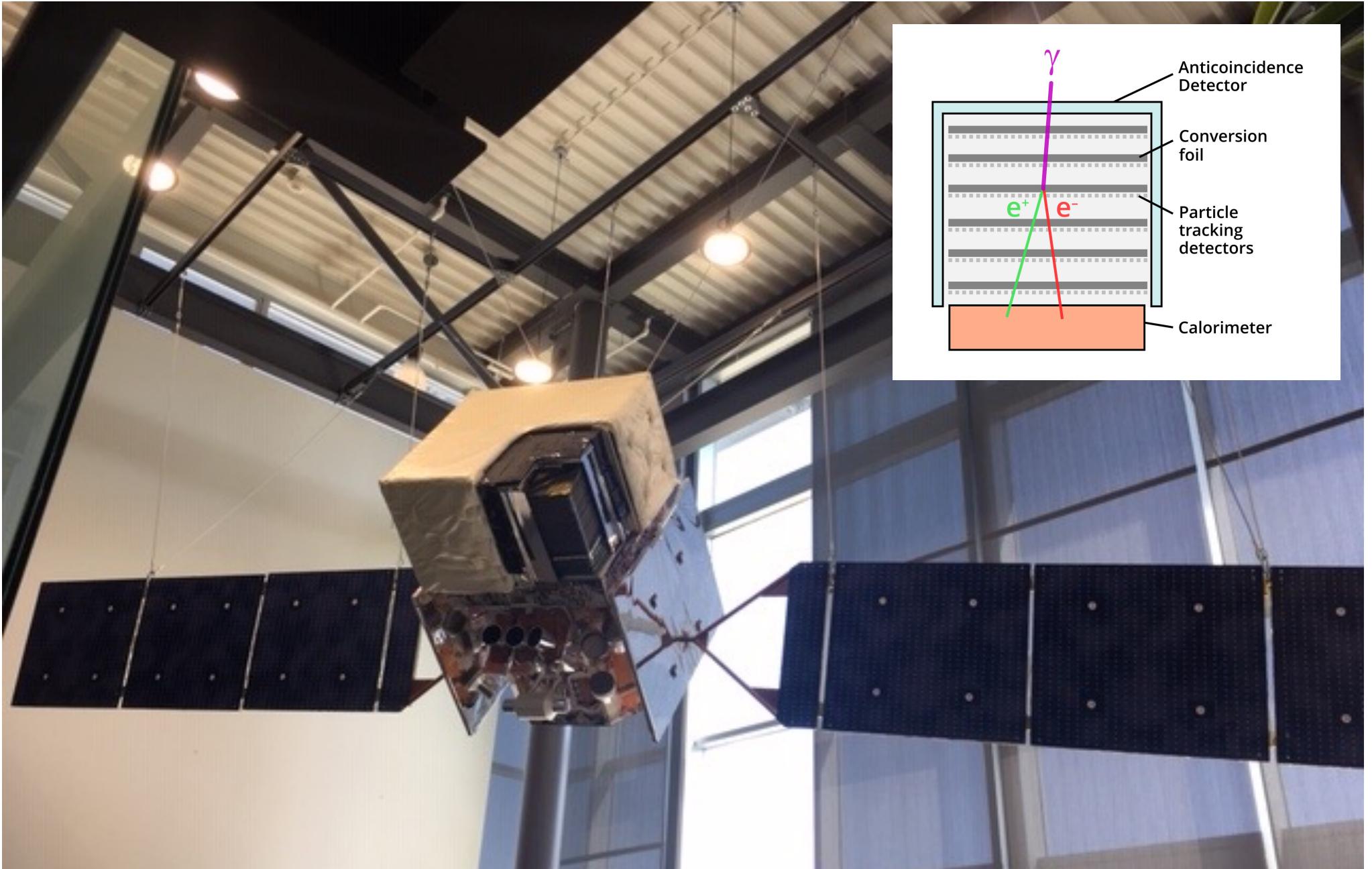


energy in neutrinos similar to the energy in gamma rays and cosmic rays

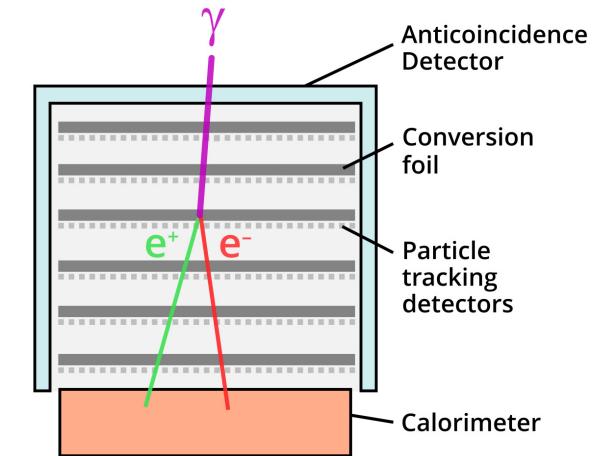


- gamma rays accompanying IceCube neutrinos interact with *the target producing the neutrinos* and with interstellar photons on their way to earth
- the gamma rays fragment into multiple lower energy gamma rays that reach Earth

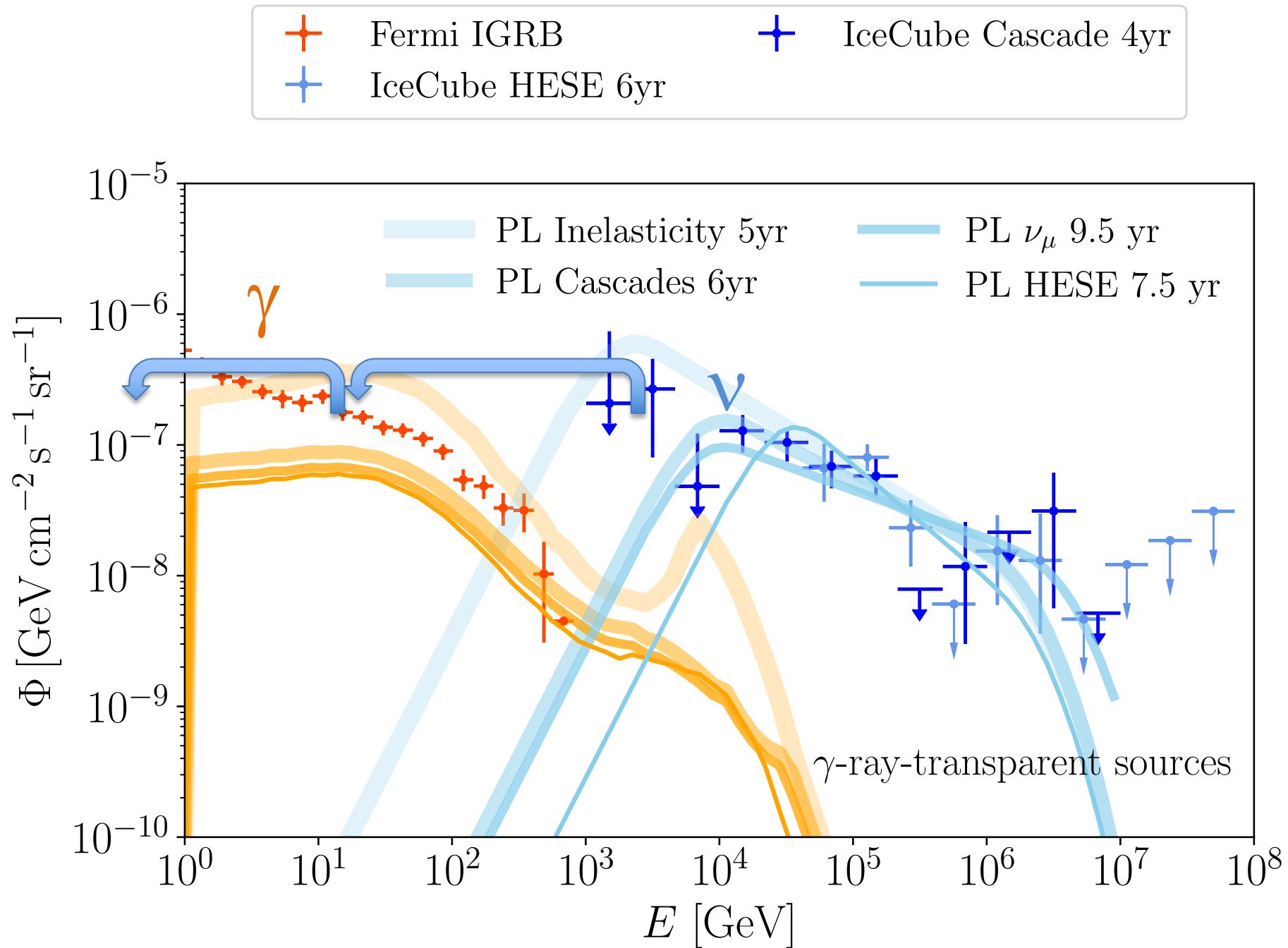




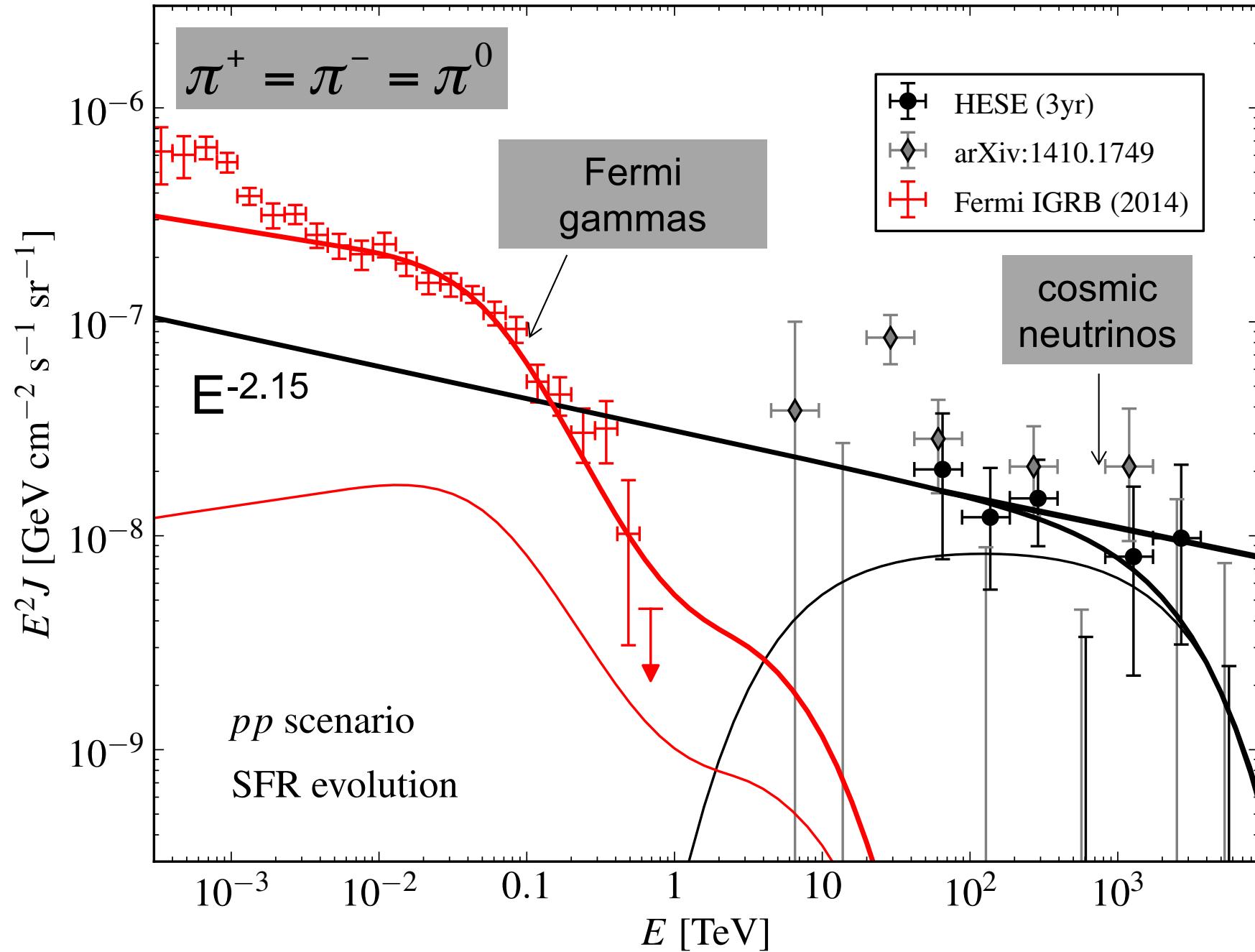
GeV photons: Fermi pair spectrometer $\gamma \rightarrow e^+ + e^-$

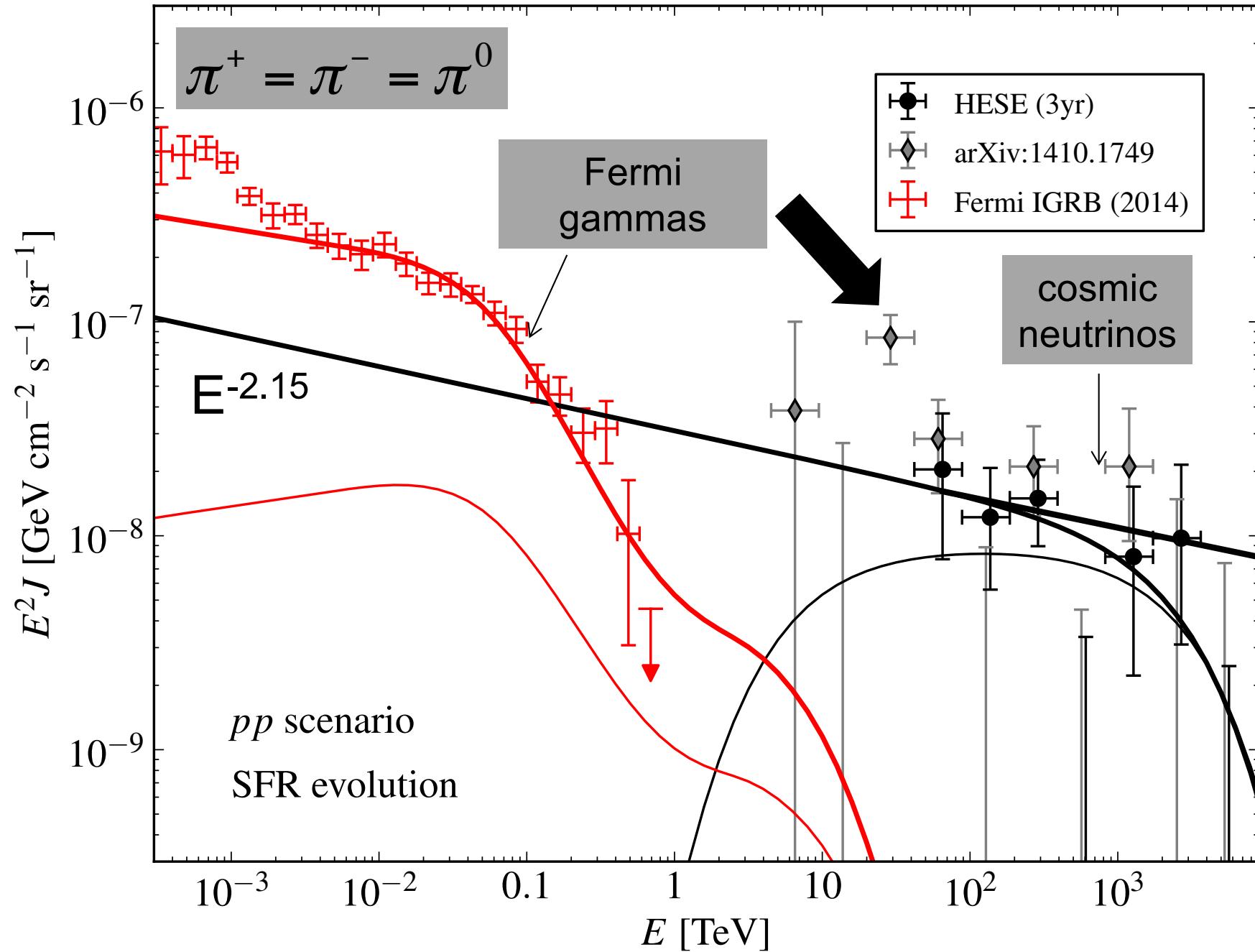


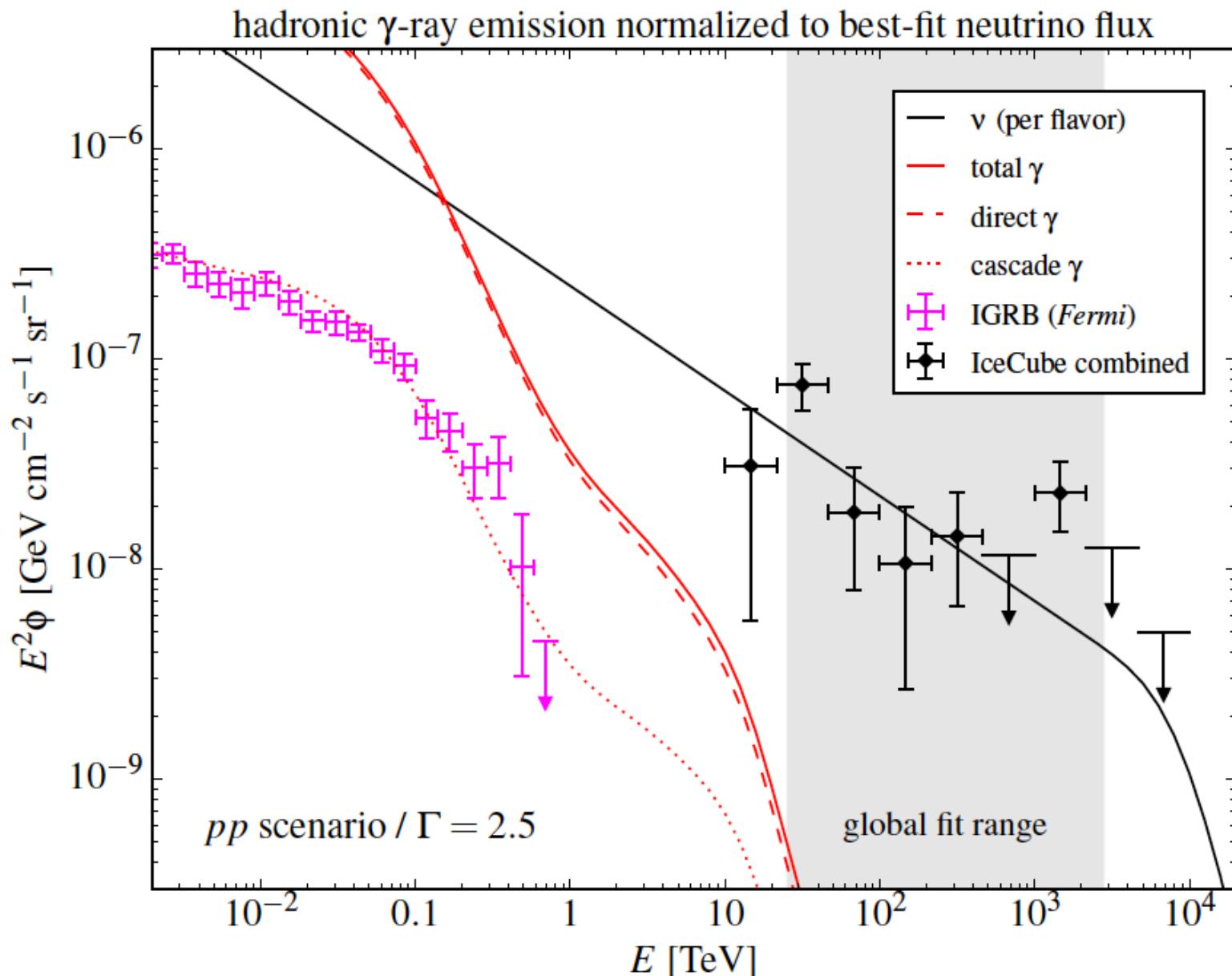
- we observe a diffuse flux of neutrinos from extragalactic sources
- energy flux of neutrinos in the non-thermal Universe is similar to that in gamma-rays
- extragalactic cosmic accelerators outshine nearby neutrino sources in our own Galaxy



the neutrino sources are opaque to gamma rays





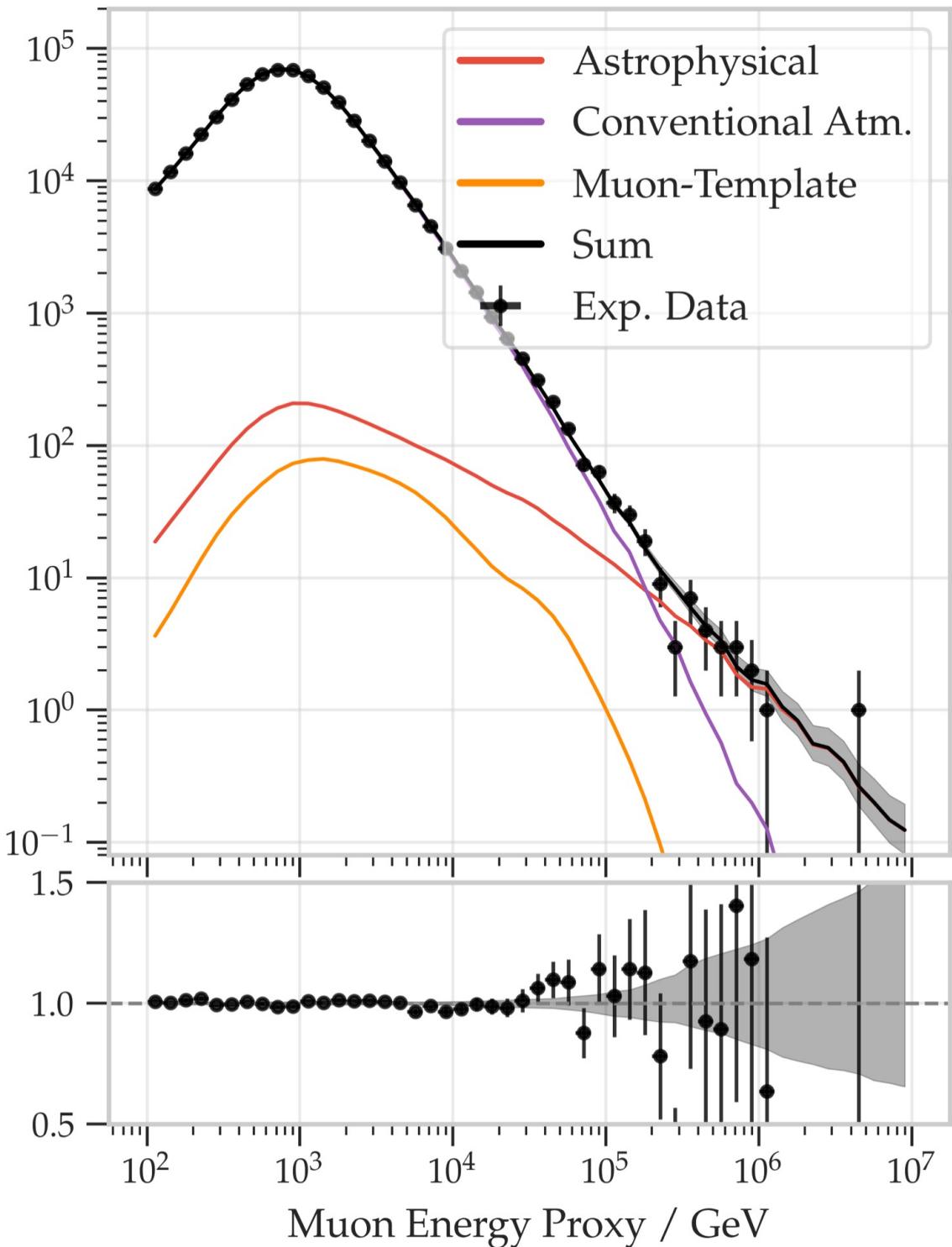


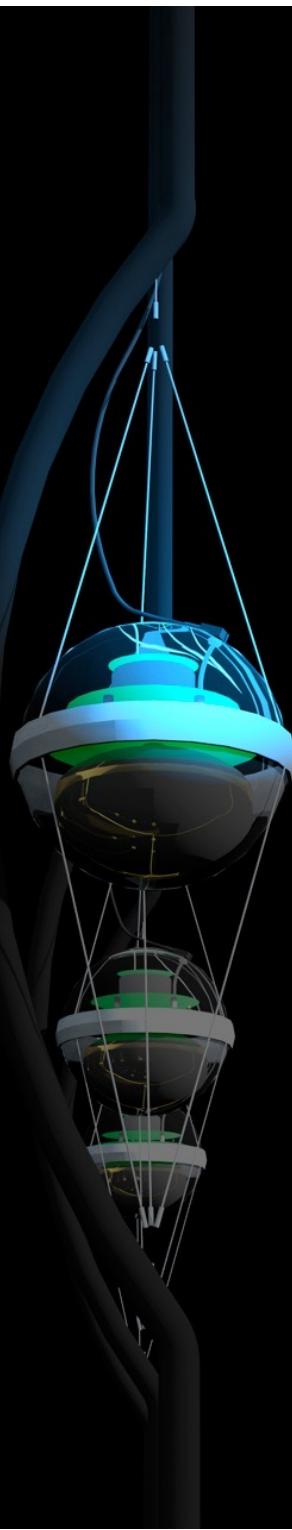
dark sources below 100 TeV not seen in γ 's ?
gamma rays cascade in the source to lower energy

Number of Events per Bin

Nuisance parameter	Prior	Fit-Result
Optical Efficiency	-	0.99
Bulk Ice Absorption	-	0.97
Bulk Ice Scattering	-	1.03
Hole-Ice p_0	-	-0.25
Conventional Flux Normalization	-	1.21
Muon Template Normalization	1.0 ± 0.5	1.01
Cosmic-Ray Flux: Shape $\lambda_{\text{CRModel.}}$	0 ± 1.0	1.41
Cosmic-Ray Flux: Spectral Index γ_{CR}	-	-0.01
Barr H^\pm	$0. \pm 0.15$	-0.08
Barr W^\pm	$0. \pm 0.40$	0.02
Barr Y^\pm	$0. \pm 0.30$	-0.08
Barr Z^\pm	$0. \pm 0.12$	-0.01

Table 5.4: Best-fit values for all nuisance parameters. The nuisance parameters for the IC59-season are kept separate in the analysis, see Sec. B.1 in the Appendix.



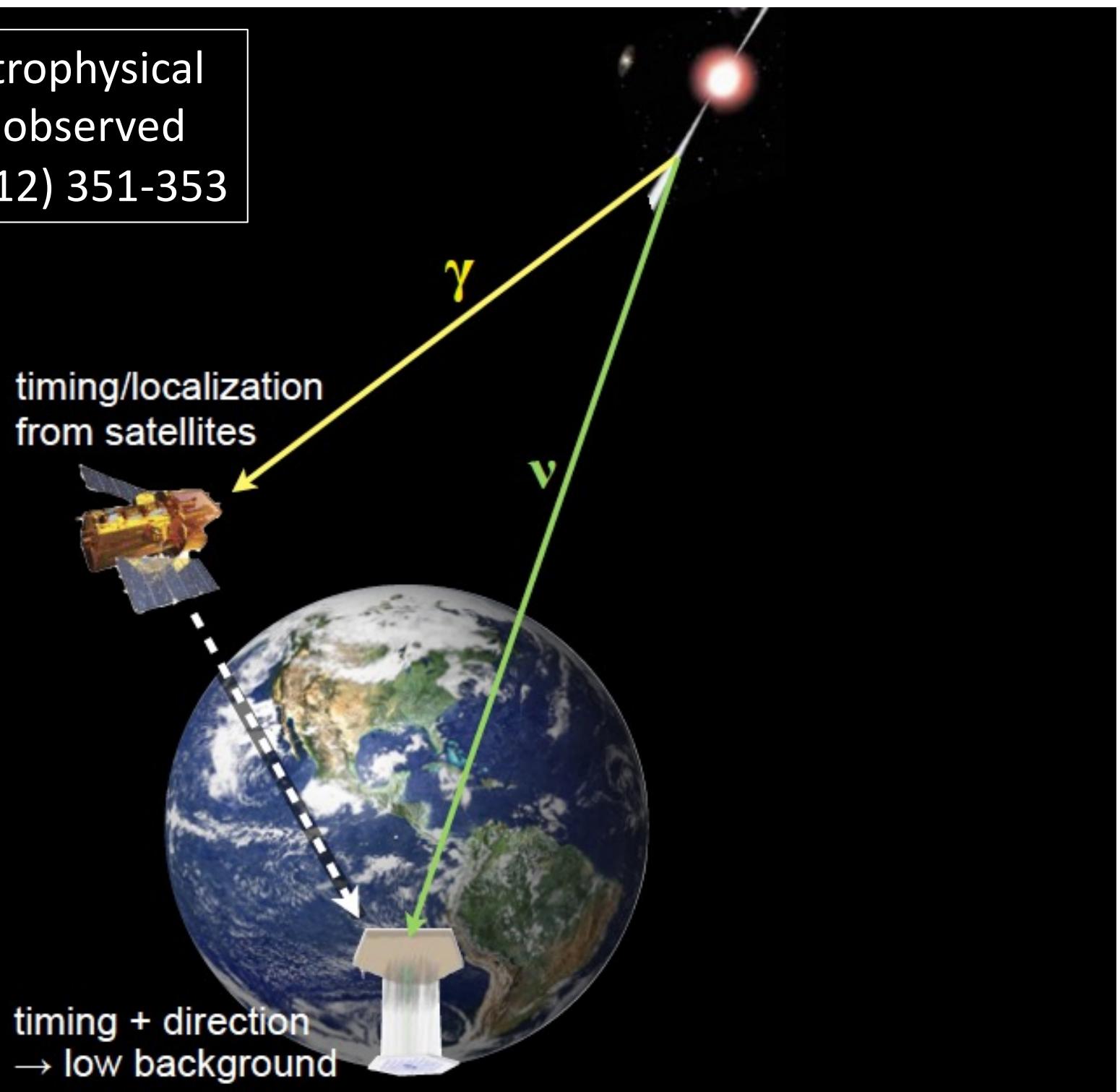


IceCube

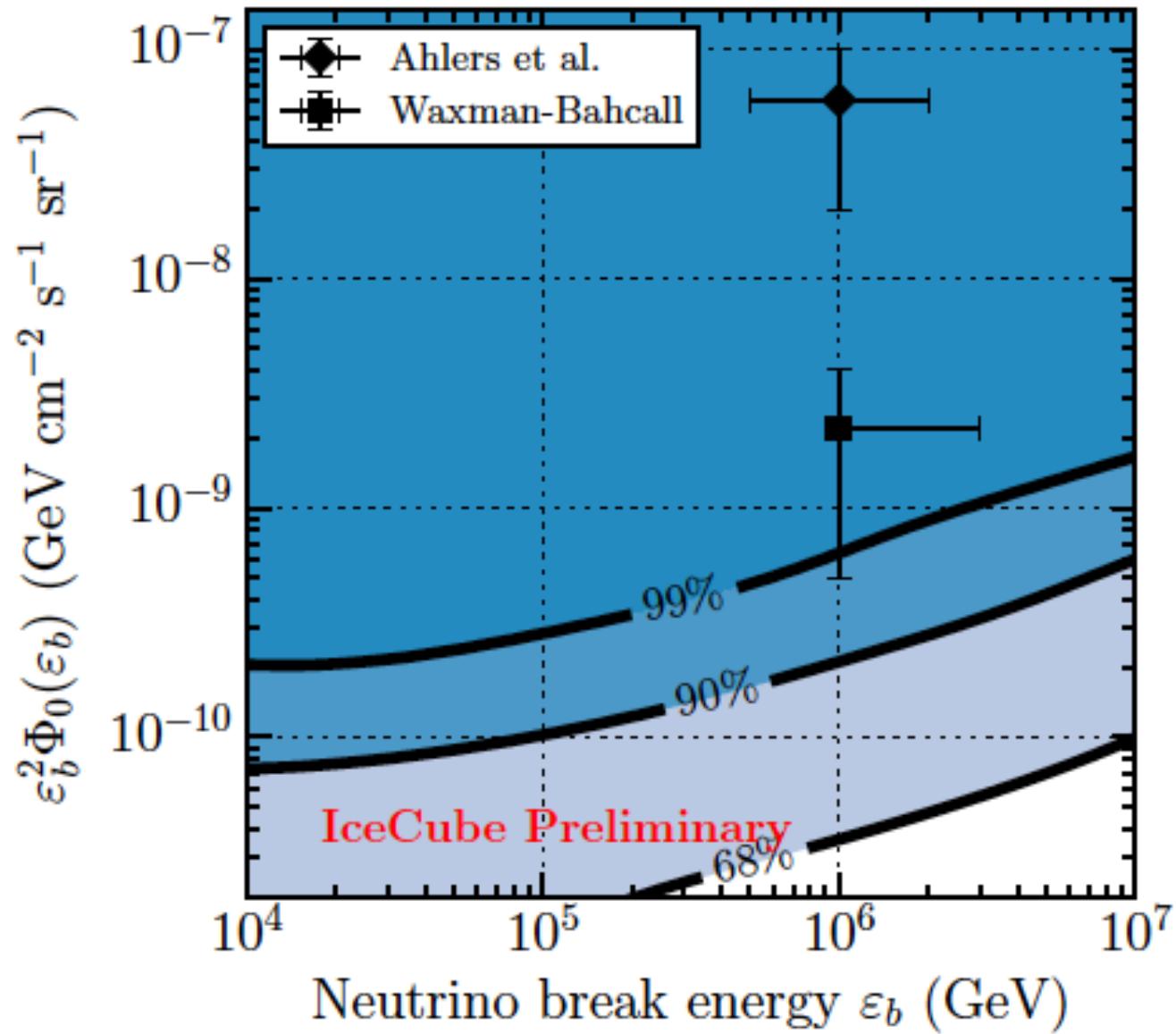
francis halzen

- IceCube
- cosmic neutrinos: two independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

flux < 1% of astrophysical
neutrino flux observed
Nature 484 (2012) 351-353



multimessenger astronomy: wrong alerts?





HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

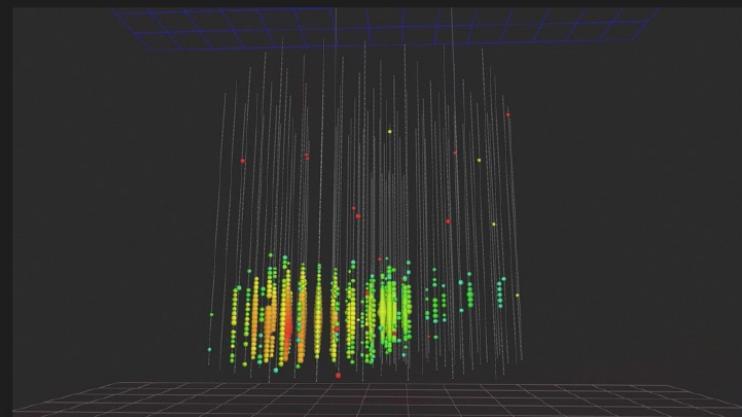
We send our high-energy events in real-time as public GCN alerts now!

47

TITLE: GCN/AMON NOTICE
 NOTICE_DATE: Wed 27 Apr 16 23:24:24 UT
 NOTICE_TYPE: AMON ICECUBE HESE
 RUN_NUM: 127853
 EVENT_NUM: 67093193
 SRC_RA: 240.5683d {+16h 02m 16s} (J2000),
 240.7644d {+16h 03m 03s} (current),
 239.9678d {+15h 59m 52s} (1950)
 SRC_DEC: +9.3417d {+09d 20' 30"} (J2000),
 +9.2972d {+09d 17' 50"} (current),
 +9.4798d {+09d 28' 47"} (1950)
 SRC_ERROR: 35.99 [arcmin radius, stat+sys, 90% containment]
 SRC_ERROR50: 0.00 [arcmin radius, stat+sys, 50% containment]
 DISCOVERY_DATE: 17505 TJD; 118 DOY; 16/04/27 (yy/mm/dd)
 DISCOVERY_TIME: 21152 SOD {05:52:32.00} UT
 REVISION: 2
 N_EVENTS: 1 [number of neutrinos]
 STREAM: 1
 DELTA_T: 0.0000 [sec]
 SIGMA_T: 0.0000 [sec]
 FALSE_POS: 0.0000e+00 [s^-1 sr^-1]
 PVALUE: 0.0000e+00 [dn]
 CHARGE: 18883.62 [pe]
 SIGNAL_TRACKNESS: 0.92 [dn]
 SUN_POSTN: 35.75d {+02h 23m 00s} +14.21d {+14d 12' 45"}

GCN notice for starting track sent Apr 27

We send **rough reconstructions** first and then **update them**.



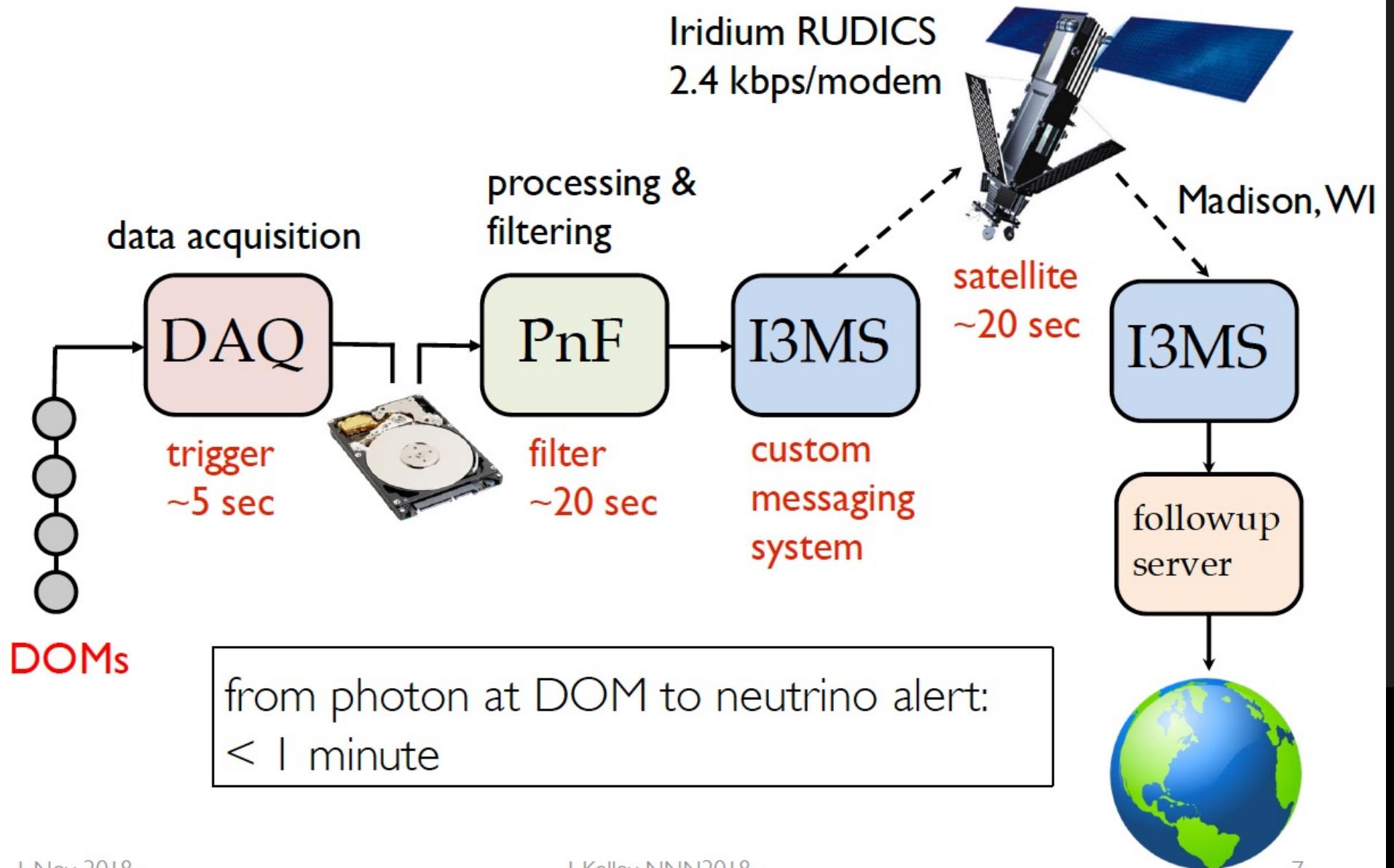
from light in the ice to astronomer in less than one minute



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

M. Richman

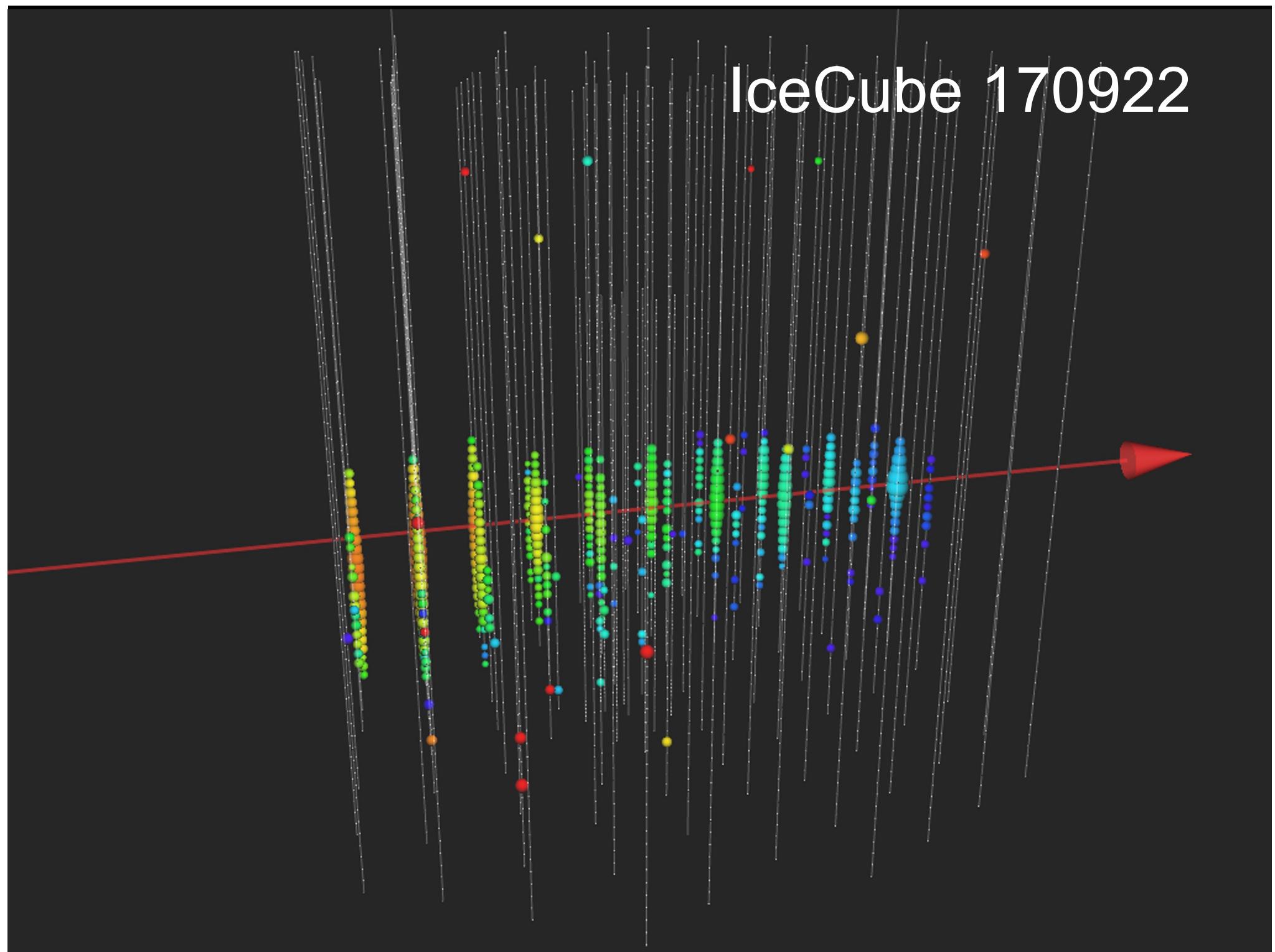


IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////GCN/AMON NOTICE
TITLE:          GCN/AMON NOTICE
NOTICE_DATE:    Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:    AMON ICECUBE EHE
RUN_NUM:        130033
EVENT_NUM:      50579430
SRC_RA:         77.2853d {+05h 09m 08s} (J2000),
                77.5221d {+05h 10m 05s} (current),
                76.6176d {+05h 06m 28s} (1950)
SRC_DEC:        +5.7517d {+05d 45' 06"} (J2000),
                +5.7732d {+05d 46' 24"} (current),
                +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:      14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE: 18018 TJD;    265 DOY;    17/09/22 (yy/mm/dd)
DISCOVERY_TIME: 75270 SOD {20:54:30.43} UT
REVISION:       0
N_EVENTS:       1 [number of neutrinos]
STREAM:         2
DELTA_T:         0.0000 [sec]
SIGMA_T:         0.0000e+00 [dn]
ENERGY :        1.1998e+02 [TeV]
SIGNALNESS:     5.6507e-01 [dn]
CHARGE:         5784.9552 [pe]
```

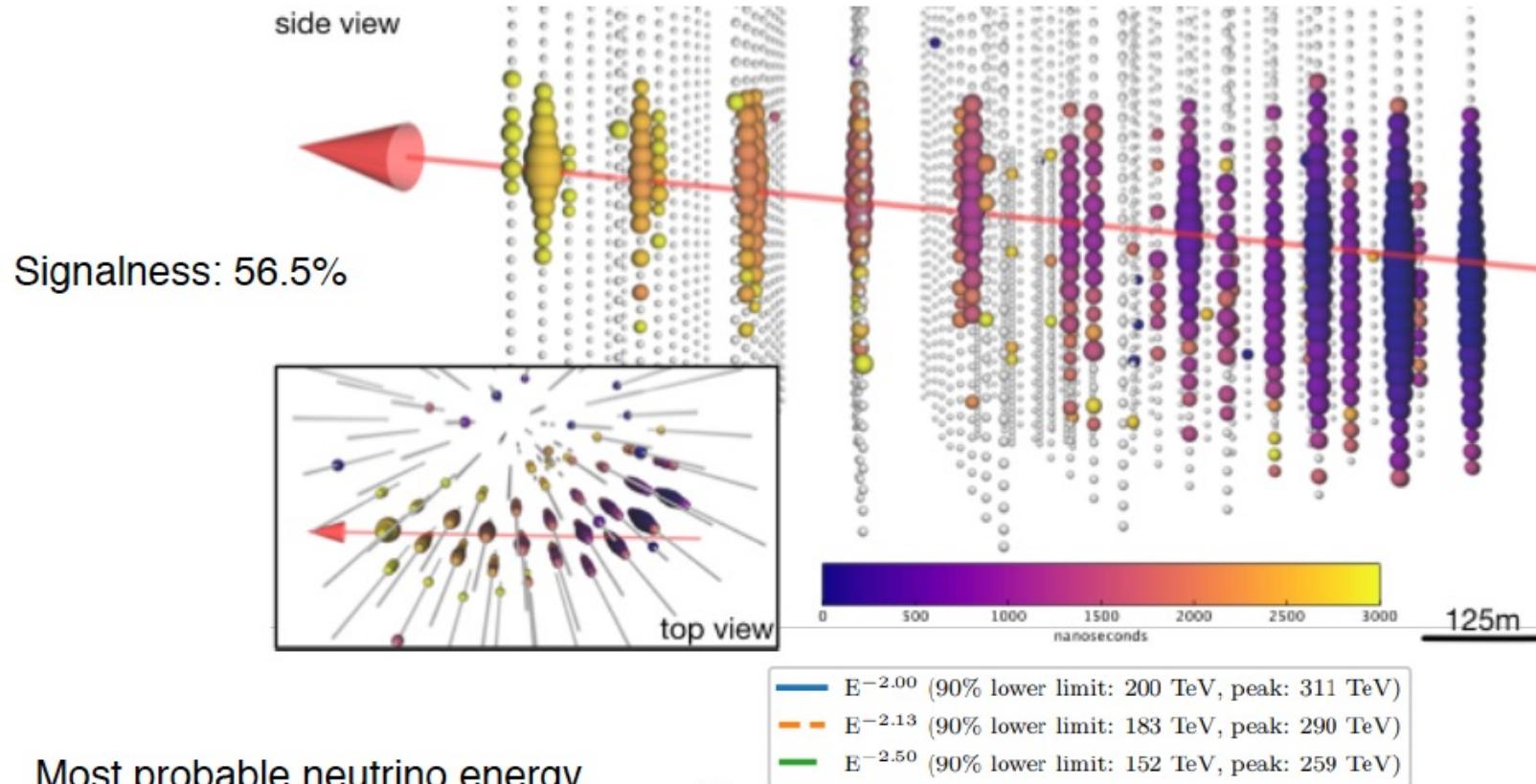
IceCube 170922



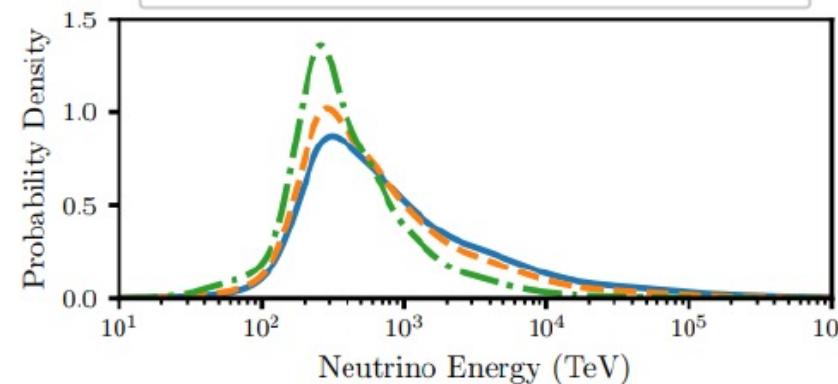
IC-170922A



23.7 ± 2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

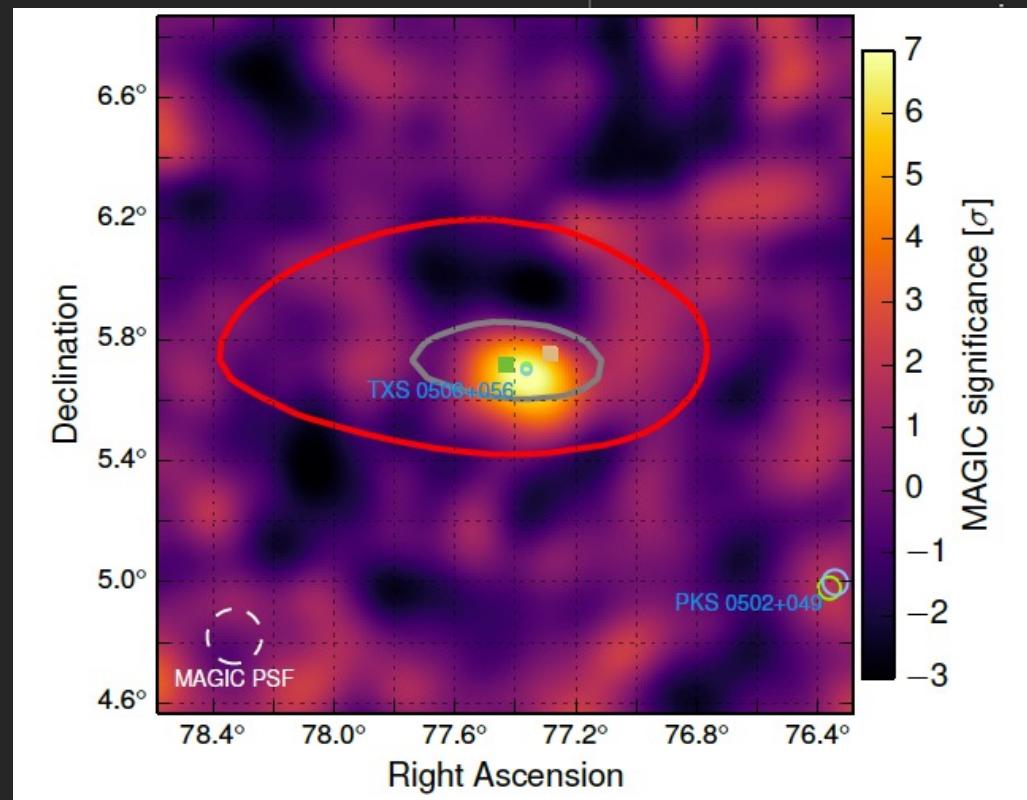


Most probable neutrino energy
 ~ 290 TeV. Upper limit at 90%
 CL is 4.5 PeV (7.5) PeV for a
 spectral index of -2.13 (-2).

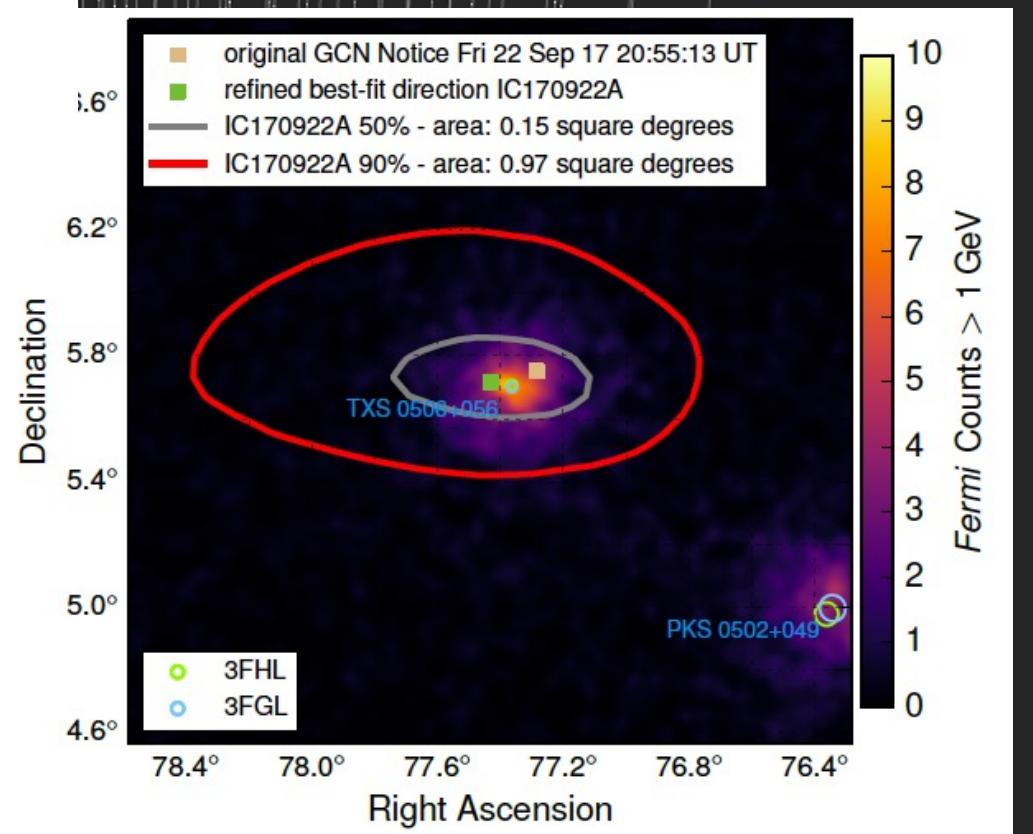


IceCube, Fermi-LAT,
 MAGIC, AGILE, ASAS-SN,
 HAWC, H.E.S.S.,
 INTEGRAL, Kapteyn,
 Kanata, Kiso, Liverpool,
 Subaru, Swift, VERITAS,
 VLA, Science 2018

[https://gcn.gsfc.nasa.gov/notices_amon/
 50579430_I30033.amon](https://gcn.gsfc.nasa.gov/notices_amon/50579430_I30033.amon)



MAGIC
detects emission of
 > 100 GeV gammas





gamma ray

TeV
atmospheric Cherenkov
telescopes

HESS, MAGIC, VERITAS



MAGIC atmospheric Cherenkov telescope

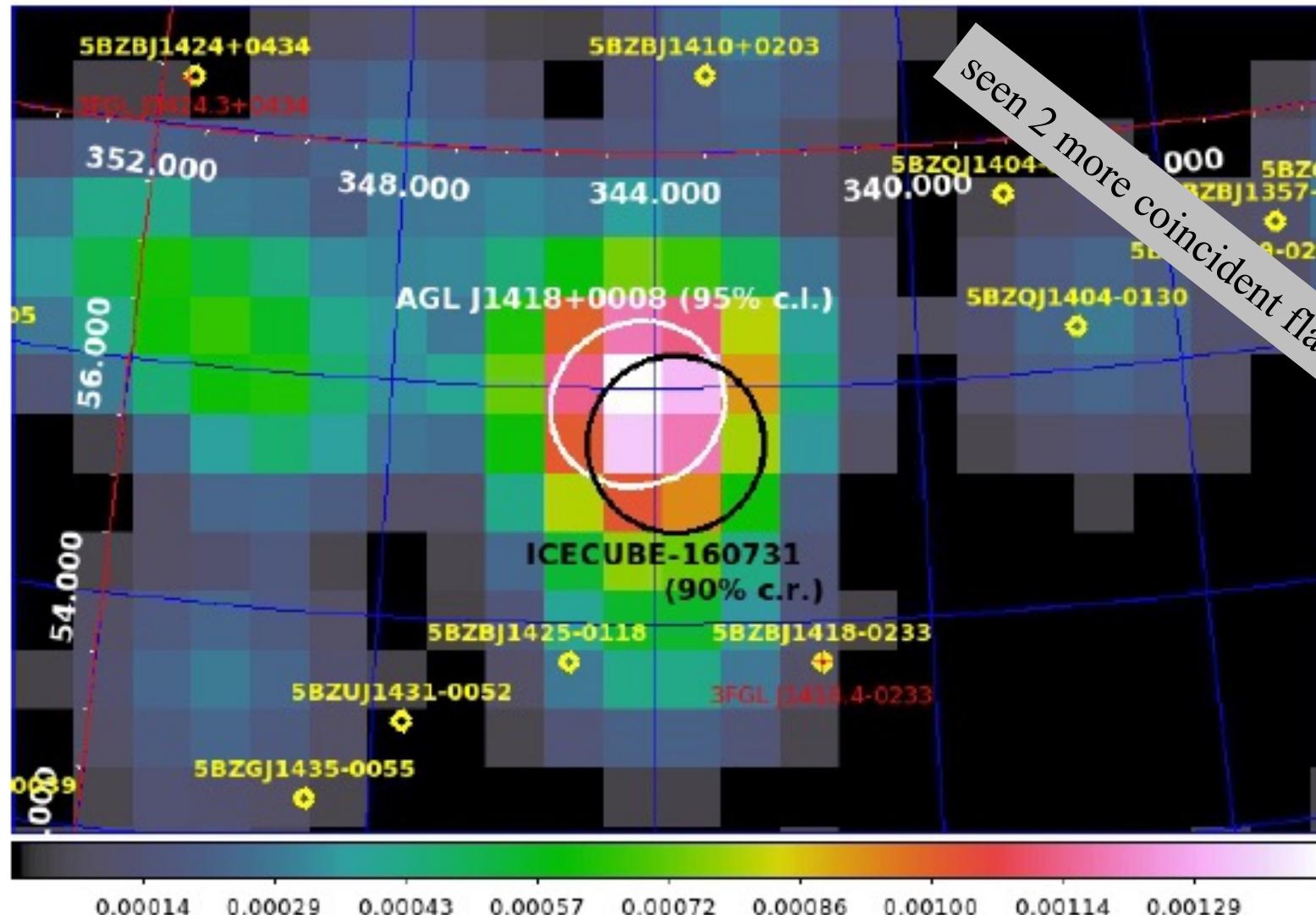


AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

F. LUCARELLI,^{1,2} C. PITTORI,^{1,2} F. VERRECCHIA,^{1,2} I. DONNARUMMA,³ M. TAVANI,^{4,5,6} A. BULGARELLI,⁷ A. GIULIANI,⁸

L. A. ANTONELLI,^{1,2} P. CARAVEO,⁸ P. W. CATTANEO,⁹ S. COLAFRANCESCO,^{10,2} F. LONGO,¹¹ S. MEREGHETTI,⁸

A. MORSSELLI,¹² L. PACCIANI,⁴ G. PIANO,⁴ A. PELLIZZONI,¹³ M. PILIA,¹³ A. RAPPOLDI,⁹ A. TROIS,¹³ AND S. VERCCELLONE¹⁴



Corresponding author: Fabrizio Lucarelli
fabrizio.lucarelli@asdc.asi.it

MASTER robotic optical telescope network: after 73 seconds

Follow-up detections of IC170922 based on public telegrams



IceCube
September 22



Swift
September 26



Fermi, ASAS-SN
September 28



SALT, Kapteyn
October 7



MAGIC
October 4



Liverpool, AGILE
September 29



Kanata, NuSTAR
October 12



VLA
October 17



Subaru
October 25



THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

SIMONA PAIANO,^{1,2} RENATO FALOMO,¹ ALDO TREVES,^{3,4} AND RICCARDO SCARPA^{5,6}¹*INAF, Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5 I-35122 Padova - ITALY*²*INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*³*Università degli Studi dell’Insubria, Via Valleggio 11 I-22100 Como - ITALY*⁴*INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY*⁵*Instituto de Astrofísica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*⁶*Universidad de La Laguna, Dpto. Astrofísica, s/n E-38206 La Laguna (Tenerife) - SPAIN*

(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak ($\text{EW} \sim 0.1$ Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift $z = 0.3365 \pm 0.0010$.

Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

- we do not see our own Galaxy
- we do not see the nearest extragalactic sources
- we find a “blazar” at 4 billion lightyears!

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

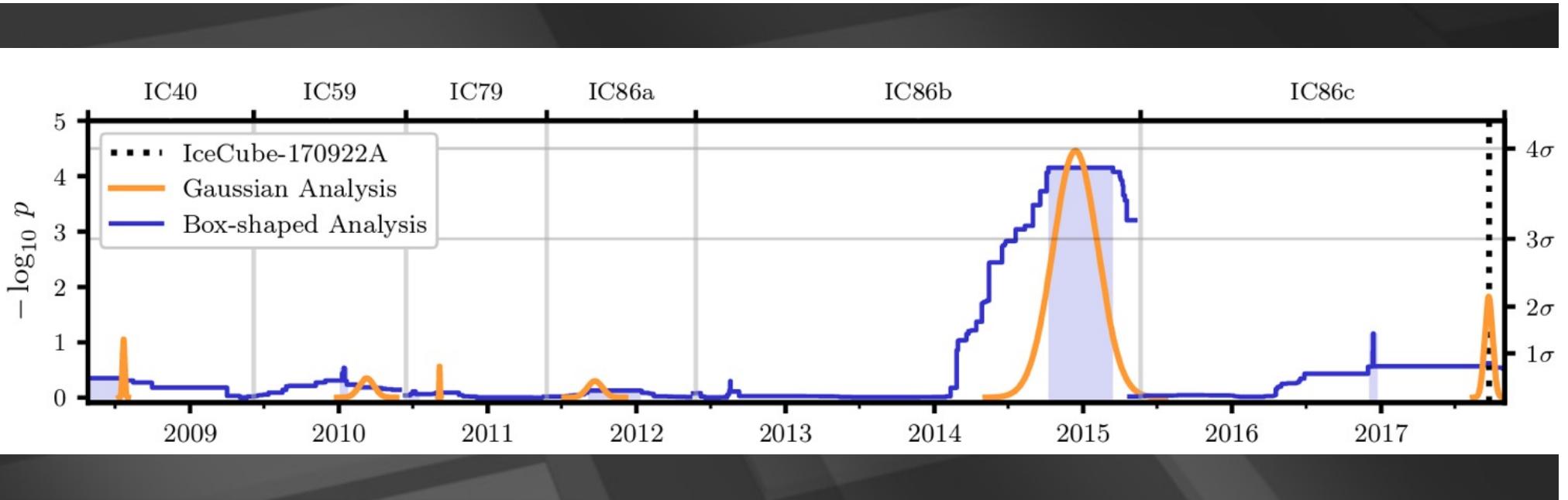
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

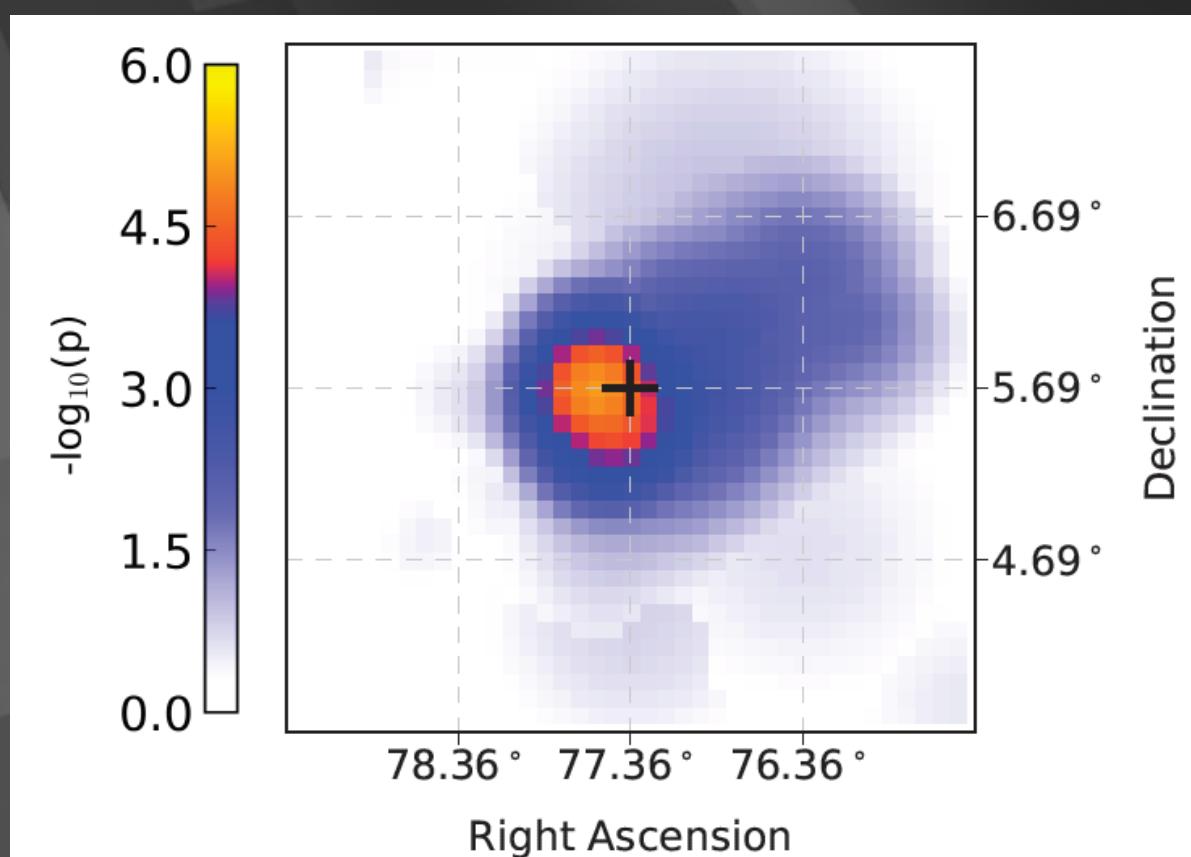
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*†



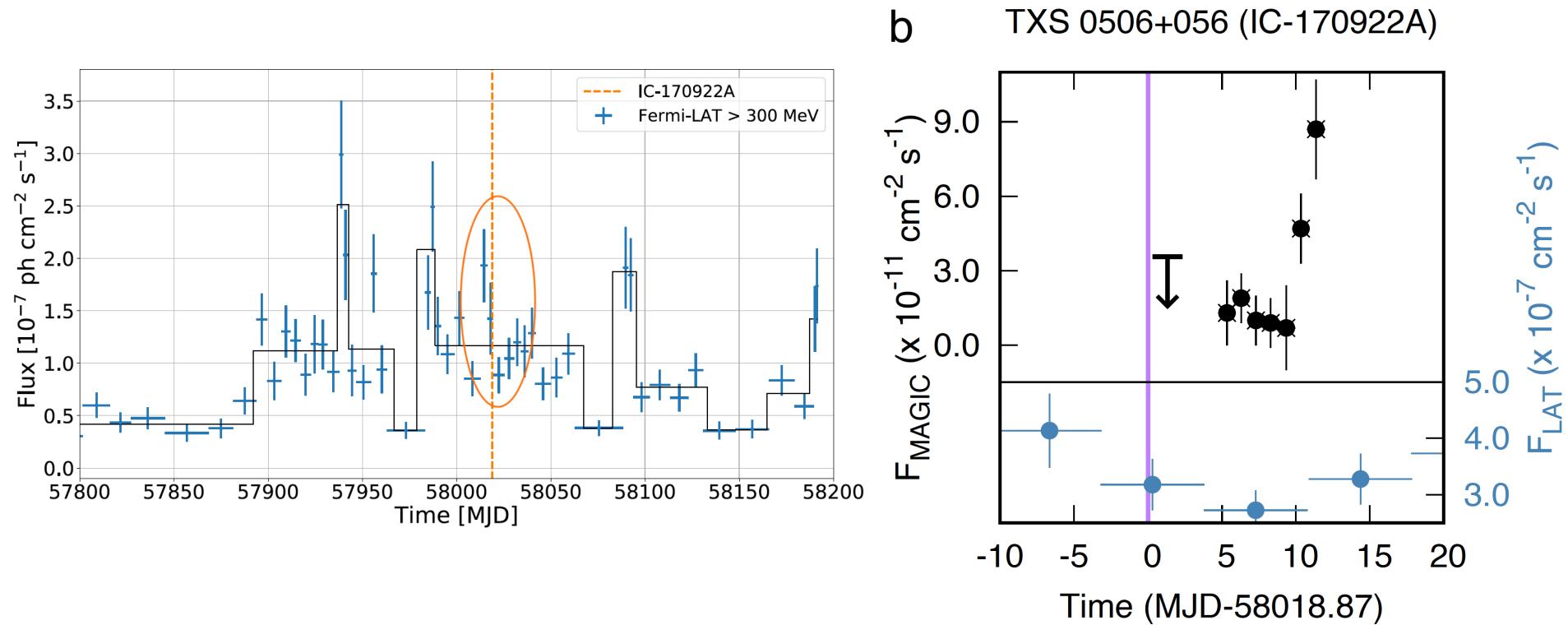
search in archival IceCube data:

- 100-day flare in 2014
- spectrum $E^{-2.2}$
- 19 ν (bkg < 6)
- no gamma ray flare!



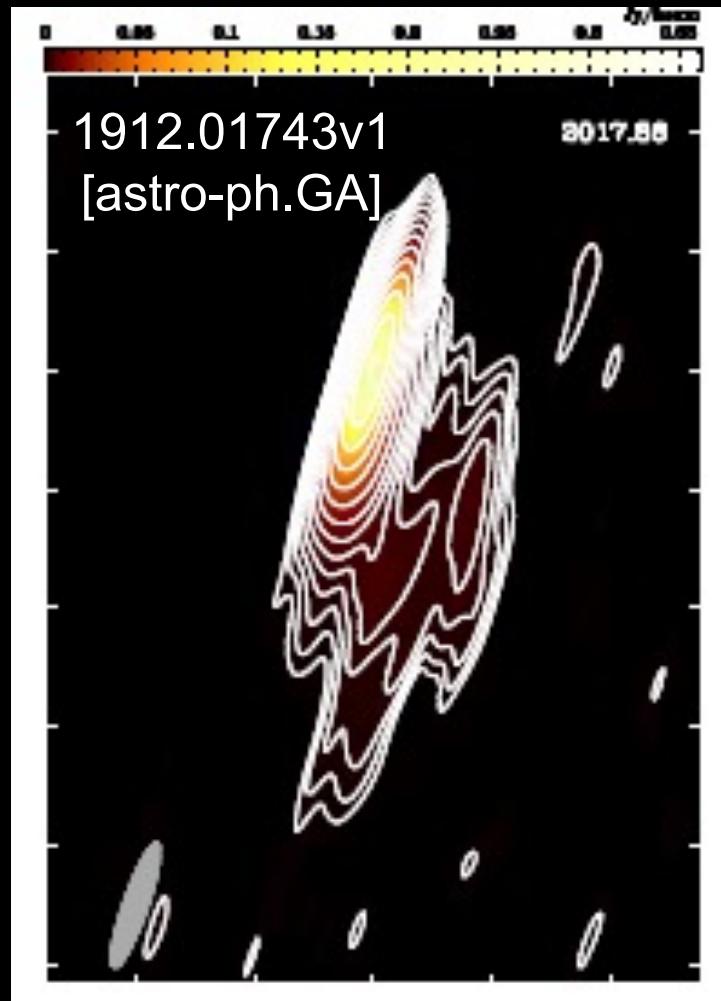
gamma rays in 2017 at the time the neutrino is produced ?

consistent with an obscured source, not a blazar

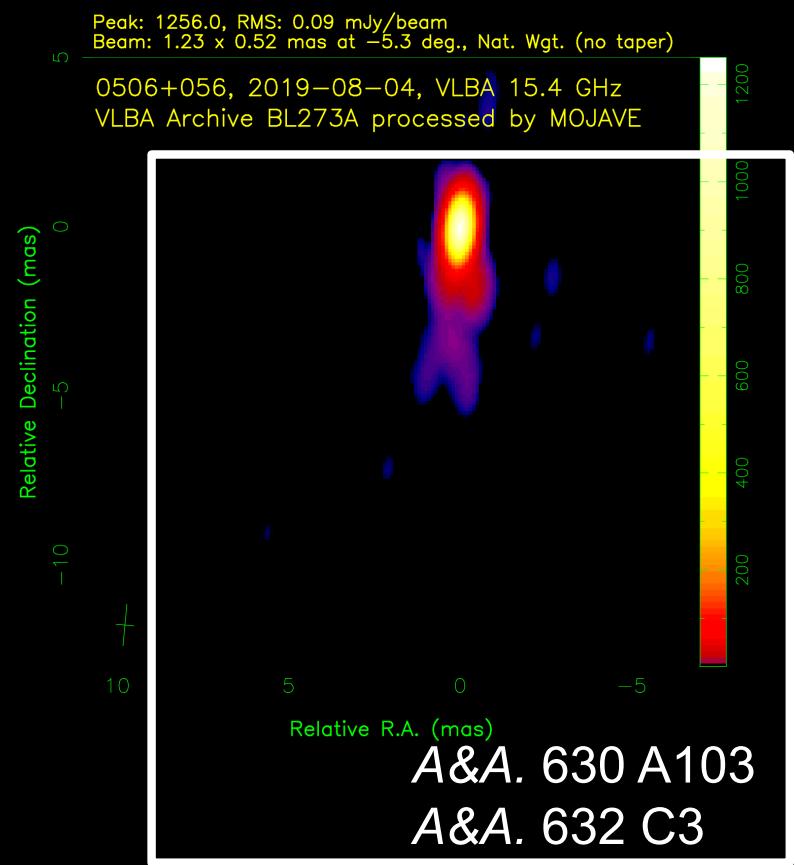


- MAGIC, HESS and VERITAS: TeV flux is highly variable and there is no TeV gamma ray emission at the time the neutrino is produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- confirmed by MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

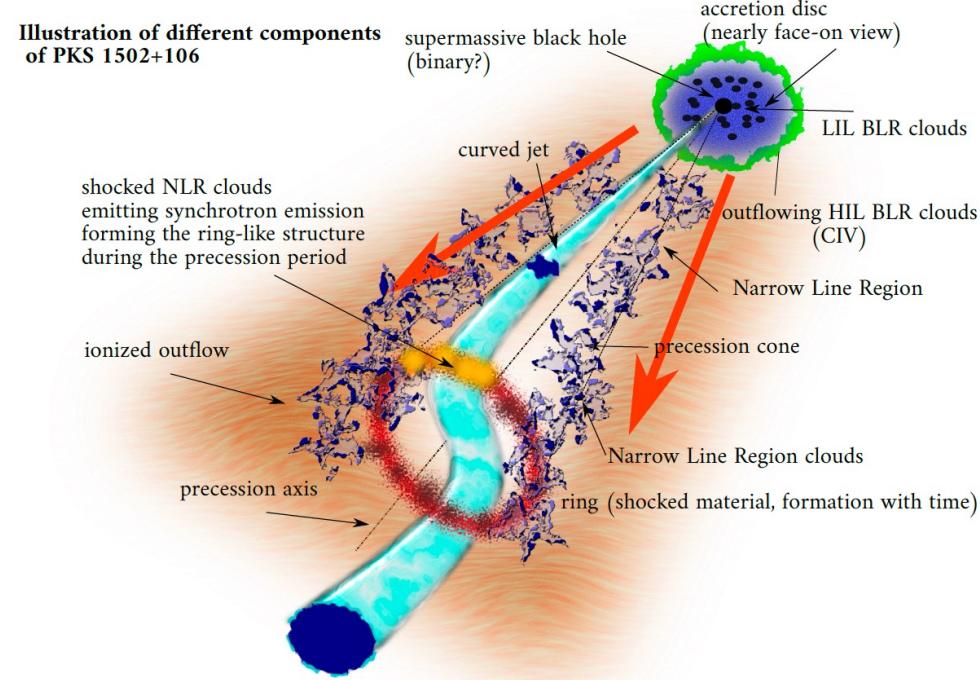
RADIO INTERFEROMETRY

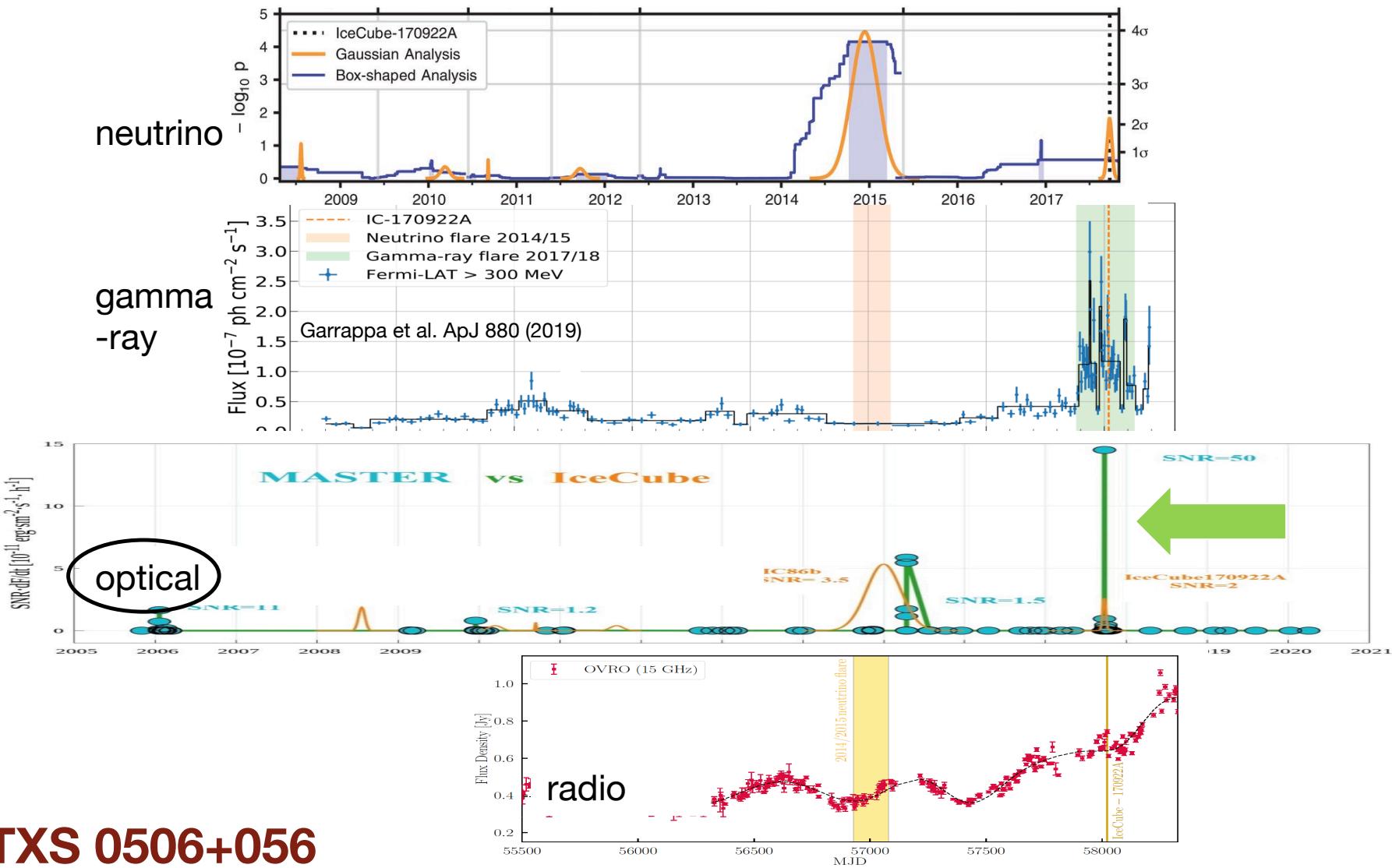


- core brightening observed in a radio burst that started 5 years ago
- beyond 5 milliarcseconds the jet loses its tight collimation



- PARSEC-SCALE JET STRUCTURE
- jet found a target after tens of pc to produce neutrinos
- obscures the gamma rays





- multimessenger observations in the time domain
- change of flux 2 hours after 170922 neutrino
- source is quiet 10 previous and 3 following years

global robotic network of
optical telescopes
connects TXS 0506+056
to IC170922A in the time
domain



“MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level”

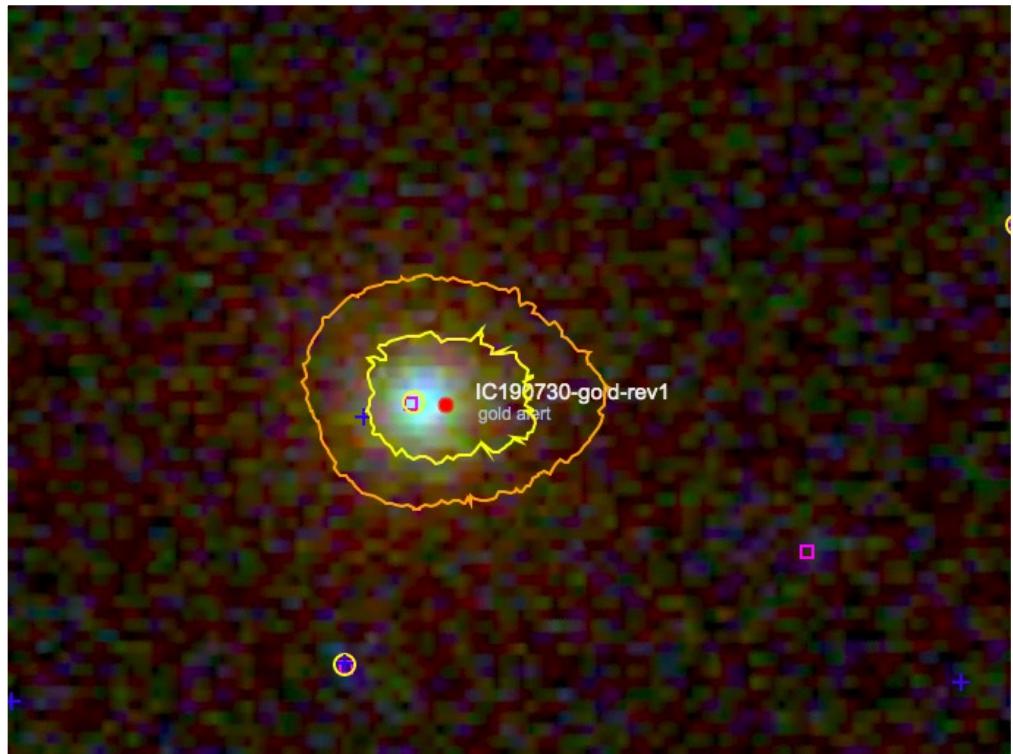
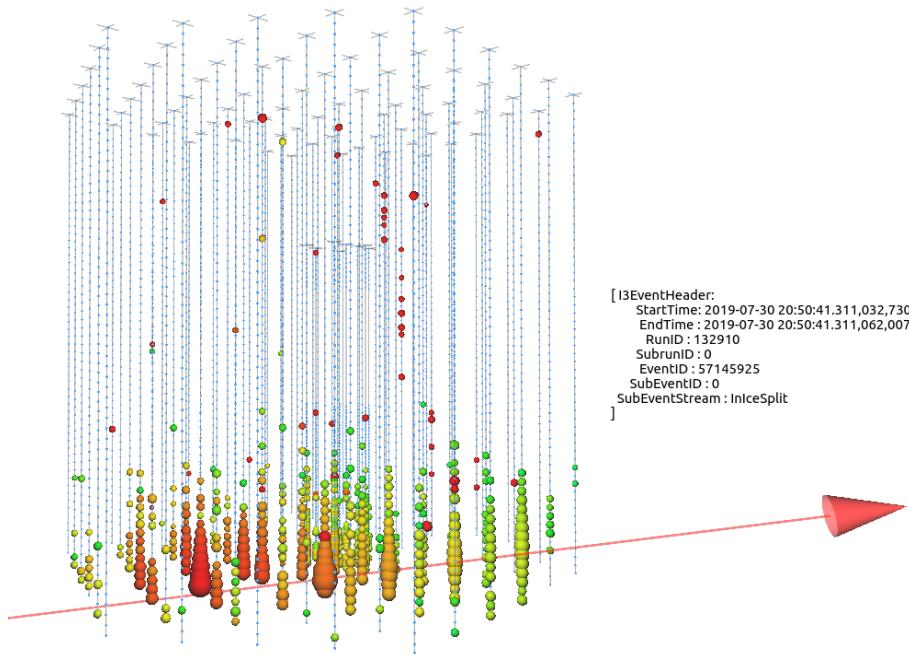
Optical Observations Reveal Strong Evidence for High Energy Neutrino Progenitor

V.M. Lipunov^{1,2}, V.G. Kornilov^{1,2}, K.Zhirkov¹, E. Gorbovskoy², N.M. Budnev⁴, D.A.H.Buckley³, R. Rebolo⁵, M. Serra-Ricart⁵, R. Podesta^{9,10}, N.Tyurina², O. Gress^{4,2}, Yu.Sergienko⁸, V. Yurkov⁸, A. Gabovich⁸, P.Balanutsa², I.Gorbunov², D.Vlasenko^{1,2}, F.Balakin^{1,2}, V.Topolev¹, A.Pozdnyakov¹, A.Kuznetsov², V.Vladimirov², A. Chasovnikov¹, D. Kuvshinov^{1,2}, V.Grinshteyn^{1,2}, E.Minkina^{1,2}, V.B.Petkov⁷, S.I.Svertilov^{2,6}, C. Lopez⁹, F.Podesta⁹, H.Levato¹⁰, A. Tlatov¹¹, B. Van Soelen¹², S. Razzaque¹³, M. Böttcher¹⁴

TXS 0506+056

- two statistically independent observations above the $> 3\sigma$ level
- it is also the second source in the all-sky search
- supported by TeV gamma ray, optical observations and by radio imaging of the core
- high-statistic association of IC170922 with optical variation in time domain
- we observe gamma-ray obscured neutrino flares, also from TXS 0506+056
- radio interferometry images show that the jet loses its tight collimation after 5 millarcseconds

highest energy alert so far



[Previous | Next]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; **S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. Würzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)**
on 7 Aug 2019; 12:31 UT

Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar



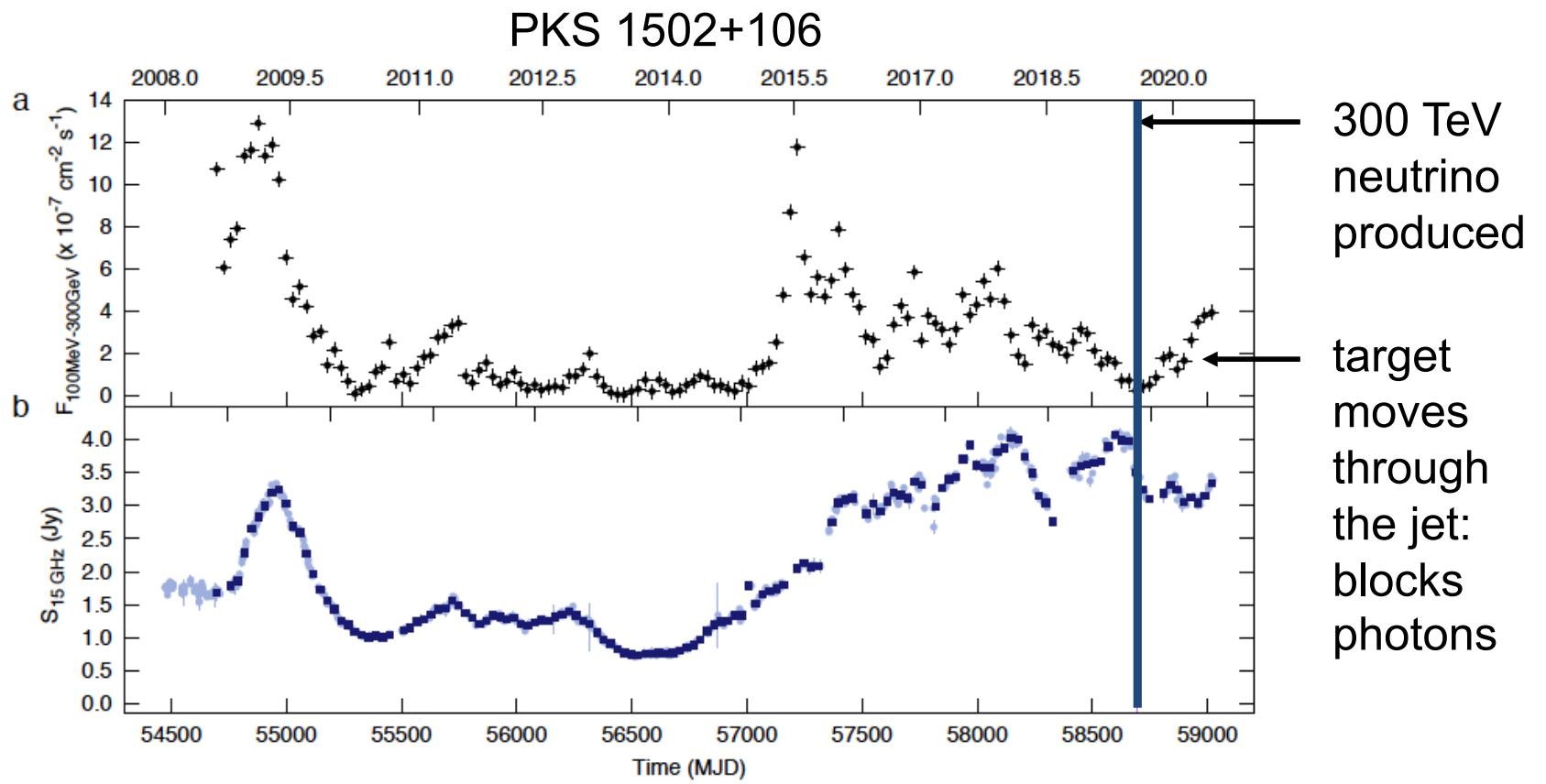
On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event [IceCube-170922A](#).

Related

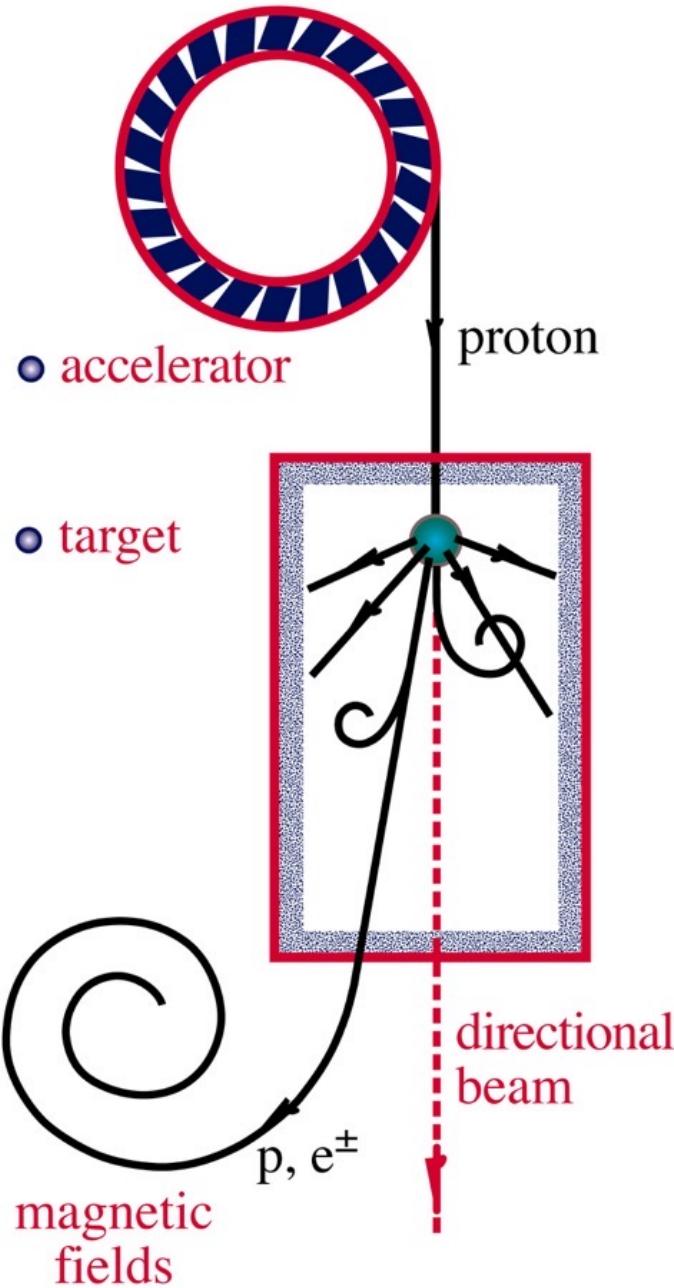
- 12996 Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
- 12985 IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
- 12983 Optical fluxes of candidate neutrino blazar PKS 1502+106
- 12981 ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
- 12974 Optical follow-up of IceCube-190730A with ZTF
- 12971 IceCube-190730A: MASTER alert observations and analysis
- 12967 IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
- 12926 VLA observations reveal increasing brightness of 1WHSP J104516.2+75133, a potential source of IC190704A

γ -ray

radio



NEUTRINO BEAMS



the pγ efficiency dilemma

- efficiency for producing the neutrinos in the photon target:

$$\tau_{p\gamma} = R_{\text{escape}} \eta_{p\gamma} \sigma_{p\gamma} n_{\text{photons}}$$

- likelihood of the multimessenger photons to be absorbed in target

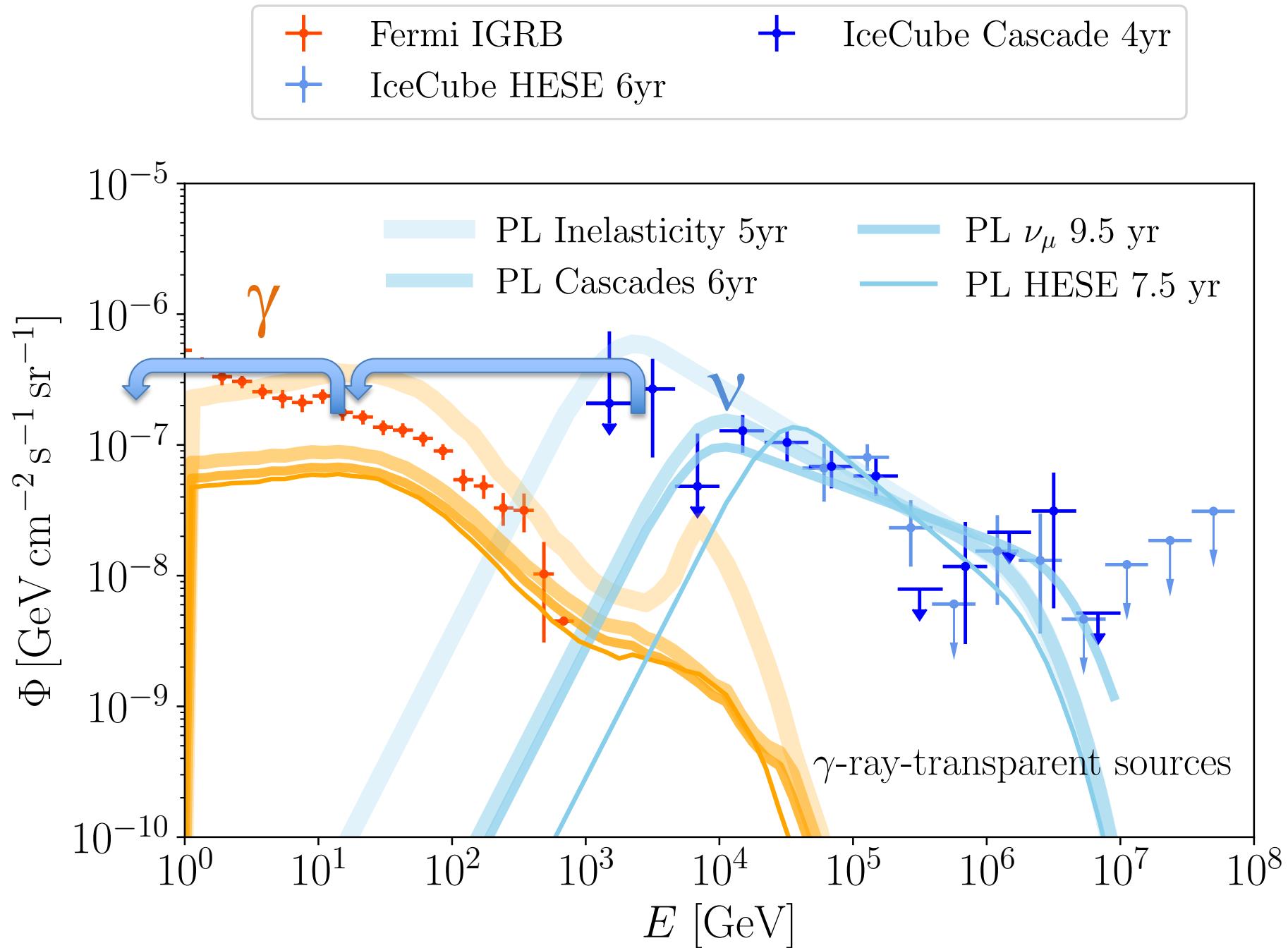
$$\tau_{\gamma\gamma} = R_{\text{target}} \eta_{\gamma\gamma} \sigma_{\gamma\gamma} n_{\text{photons}}$$

→ therefore, with $R_{\text{escape}} \sim R_{\text{target}}$

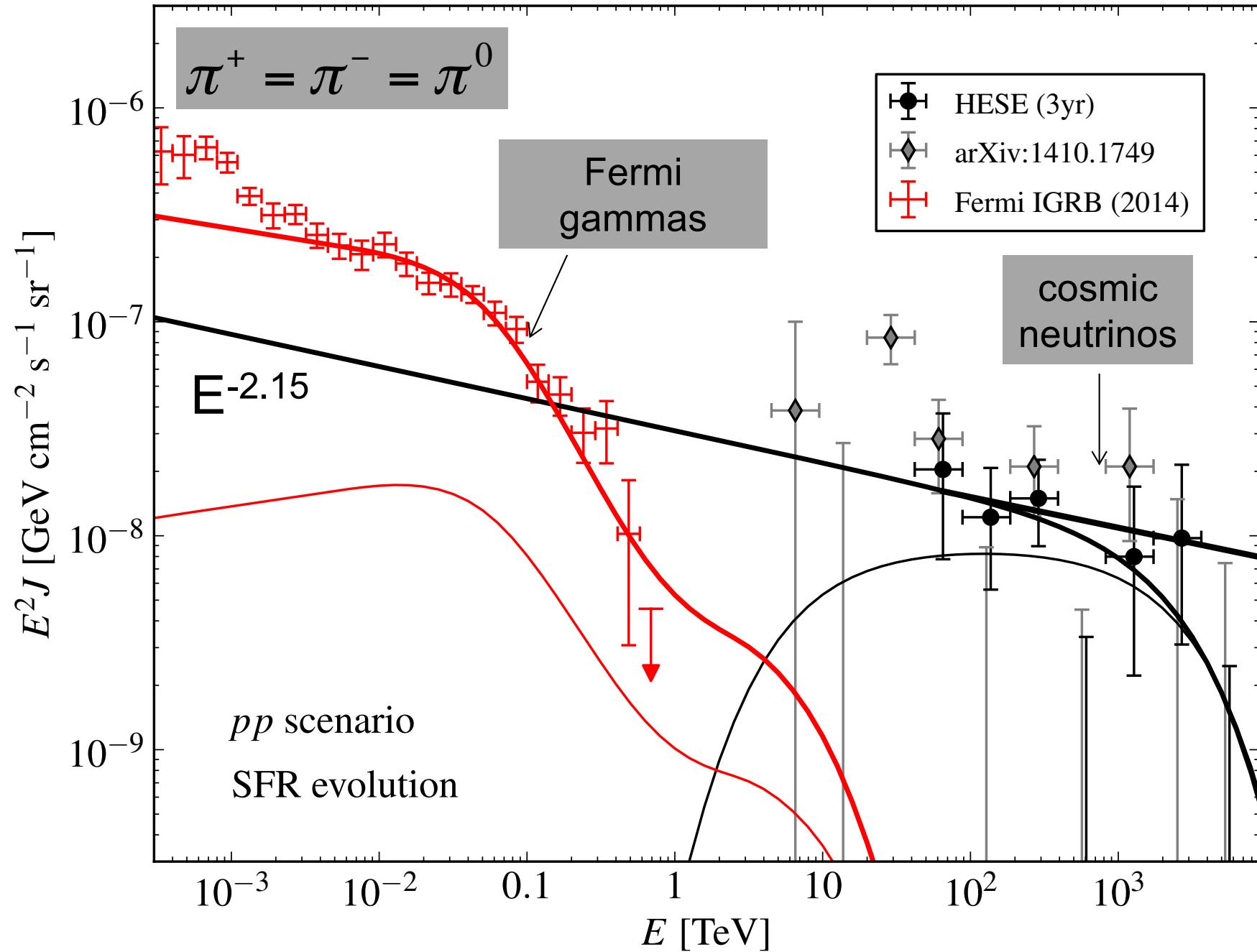
$$\tau_{\gamma\gamma} = \frac{\eta_{\gamma\gamma} \sigma_{\gamma\gamma}}{\eta_{p\gamma} \sigma_{p\gamma}} \frac{R_{\text{target}}}{R_{\text{escape}}} \tau_{p\gamma}$$

→ do not expect high energy gamma rays to accompany cosmic neutrinos

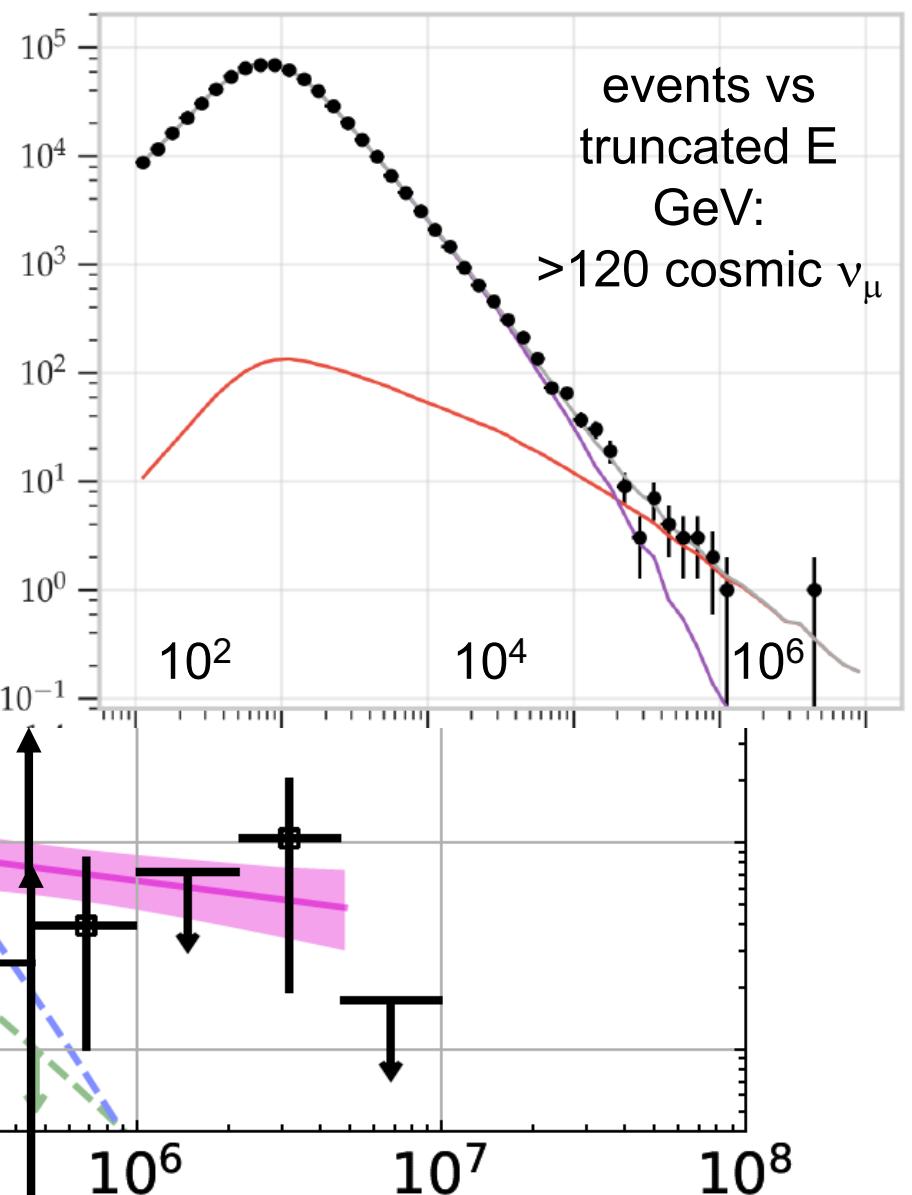
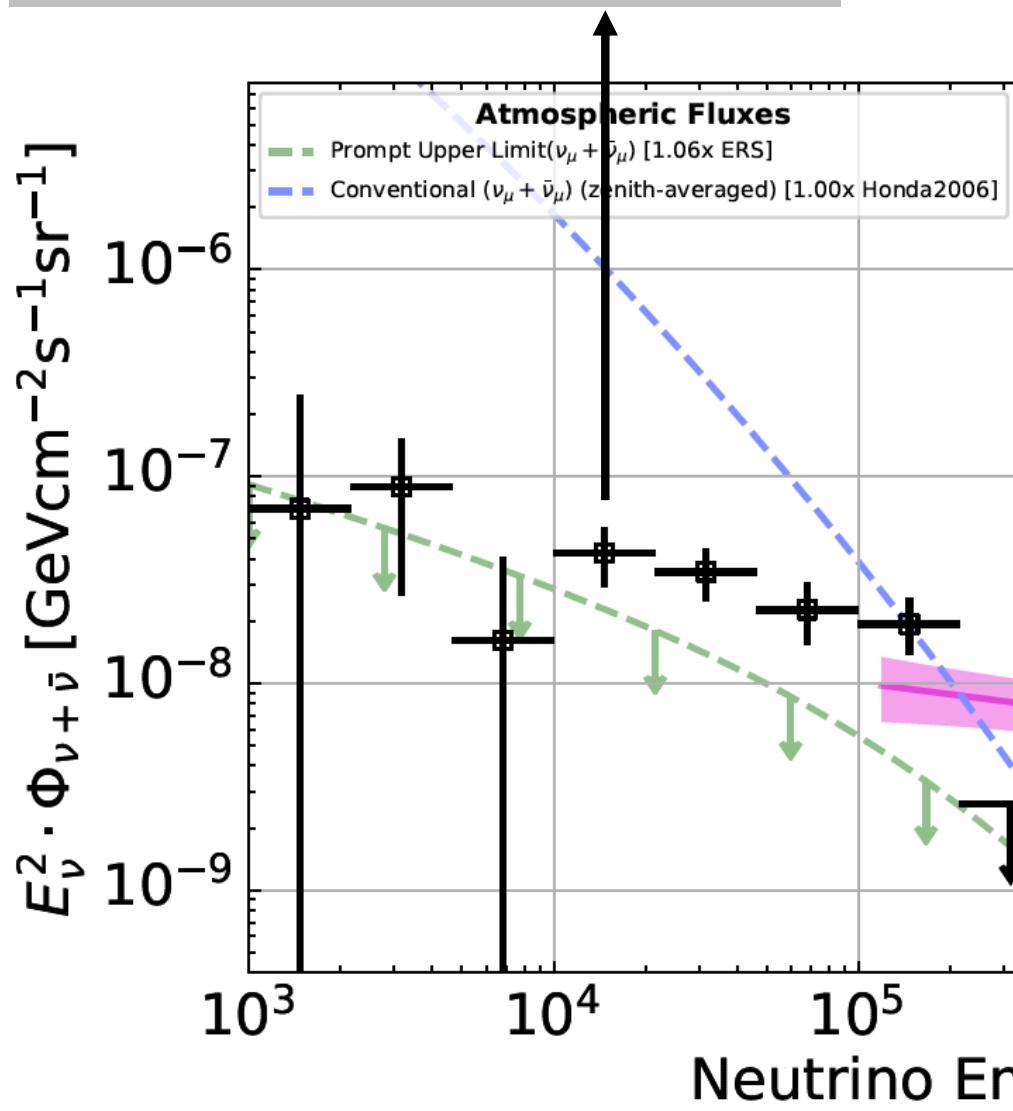
→ blazar jets are out



the neutrino sources are opaque to gamma rays

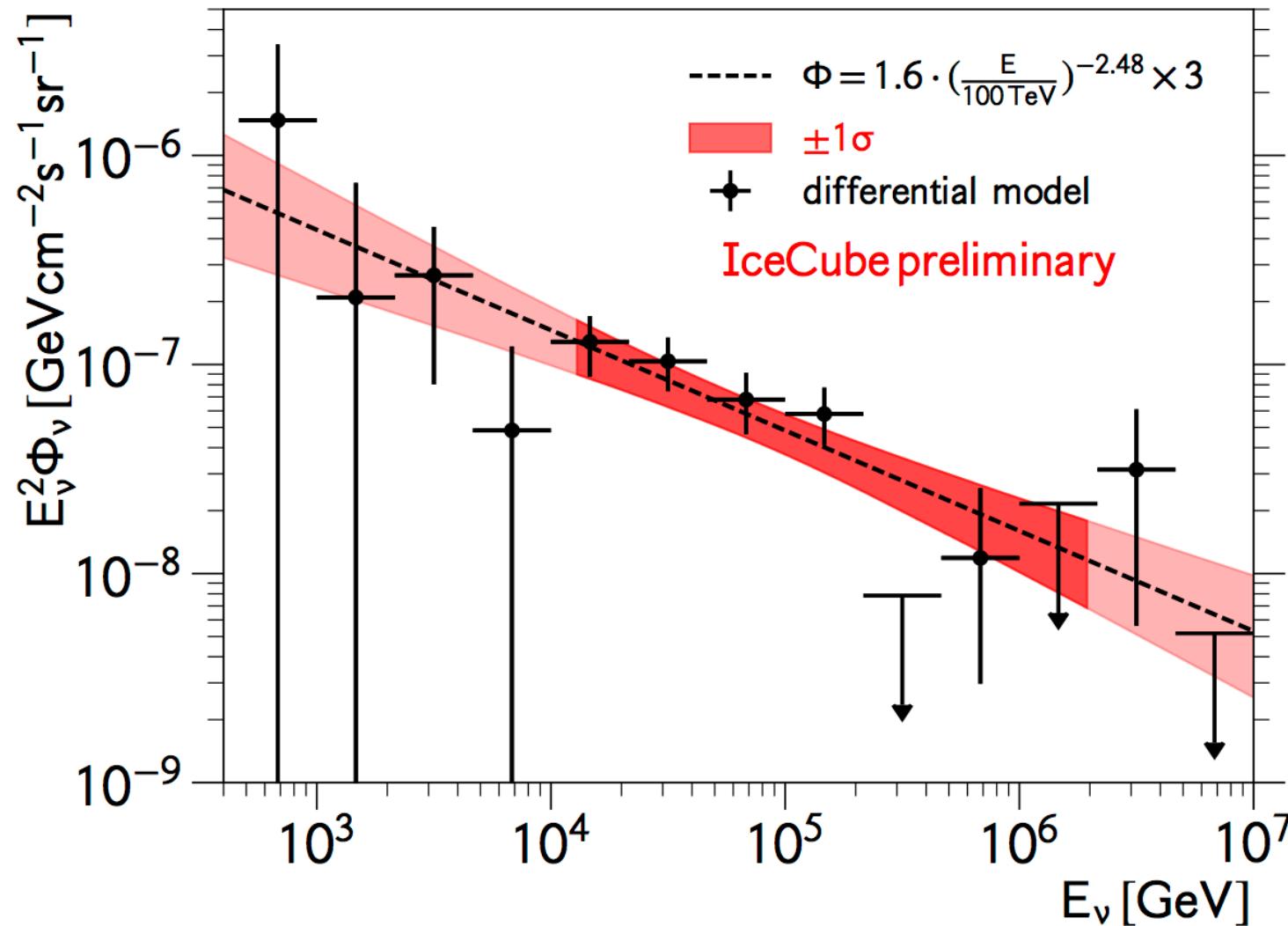


electron and tau neutrinos

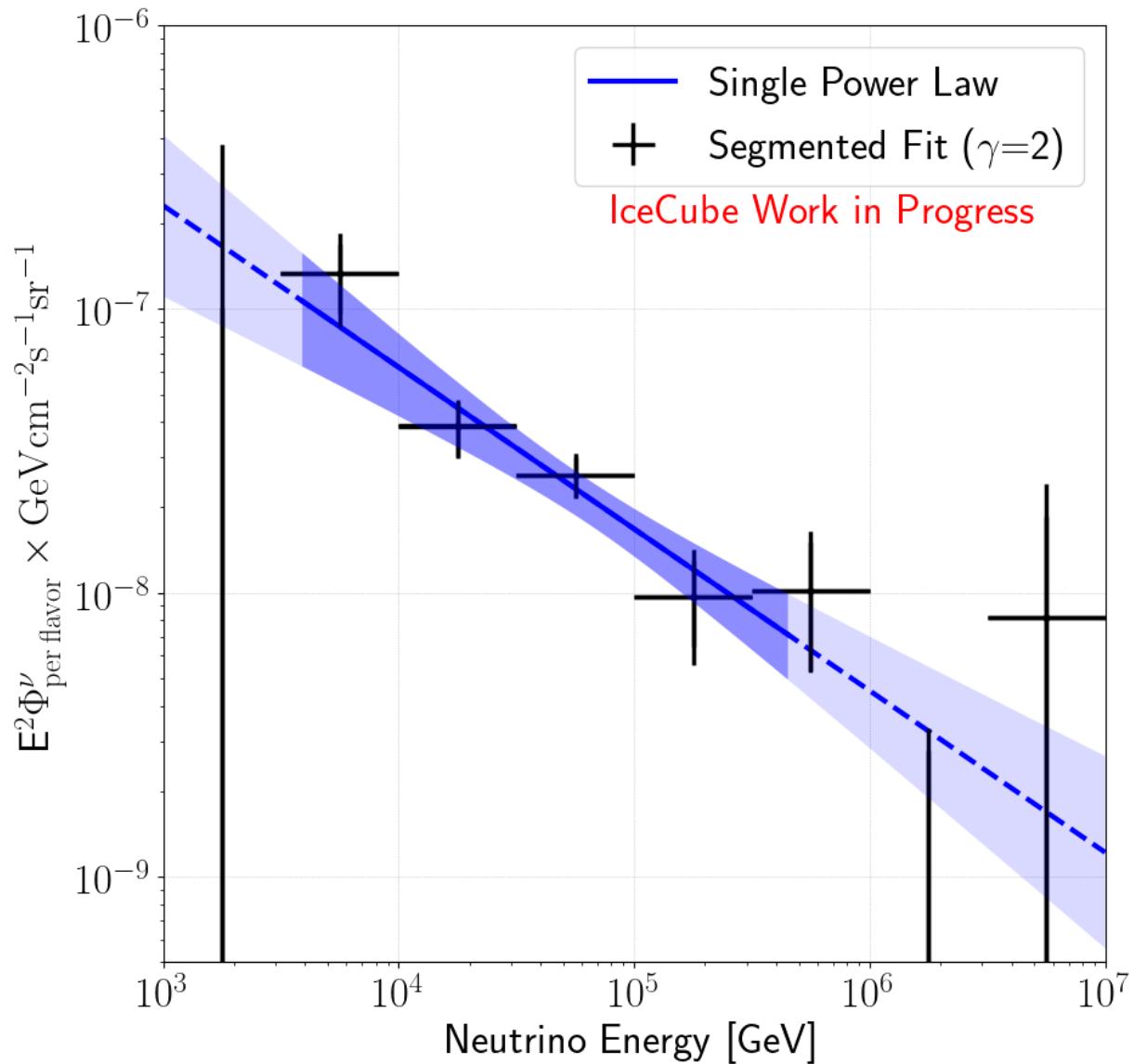


muon neutrinos

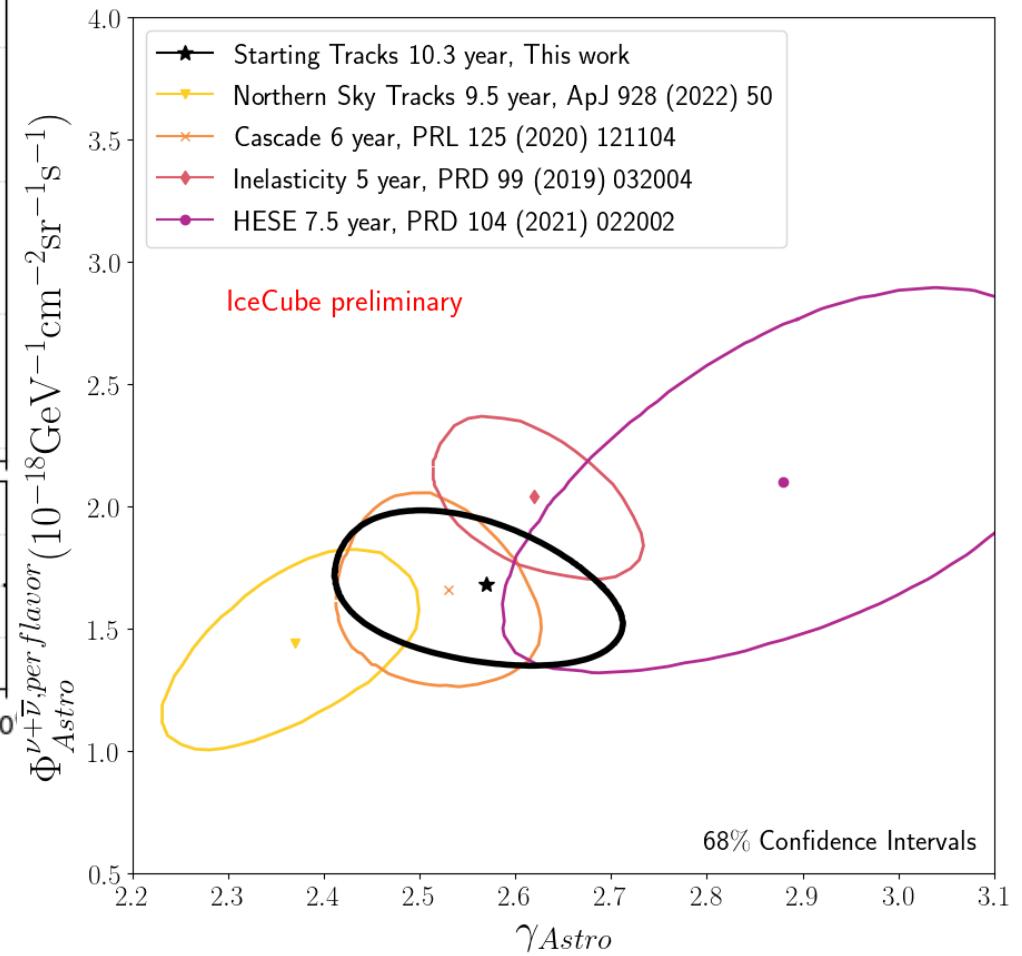
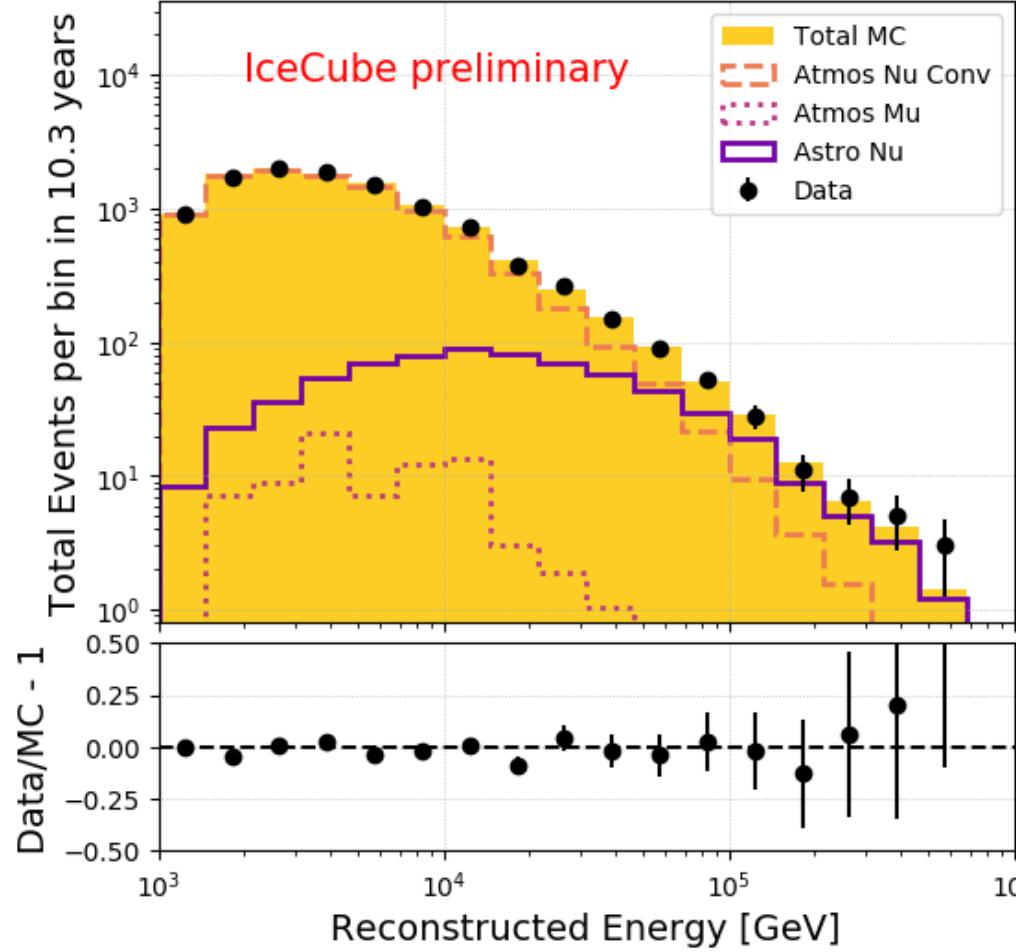
Multi-year cascade ($\nu e + \nu \tau$) analysis



multi-year starting ν_μ track analysis

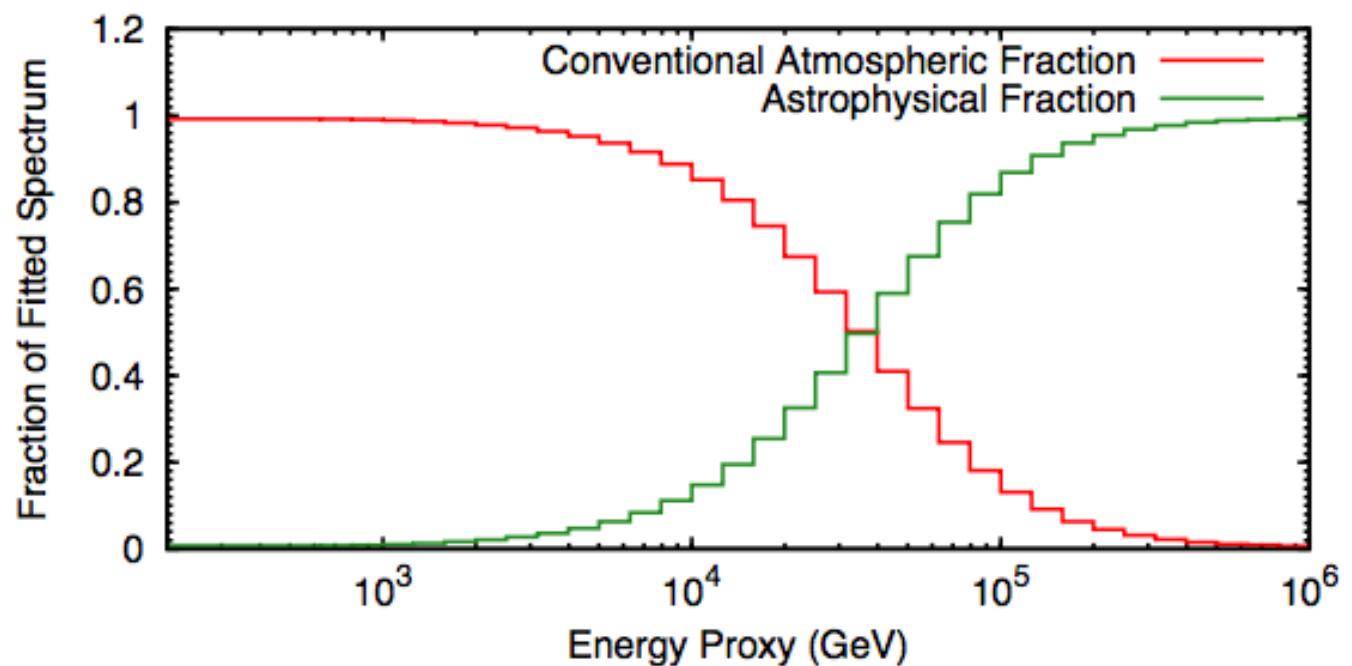


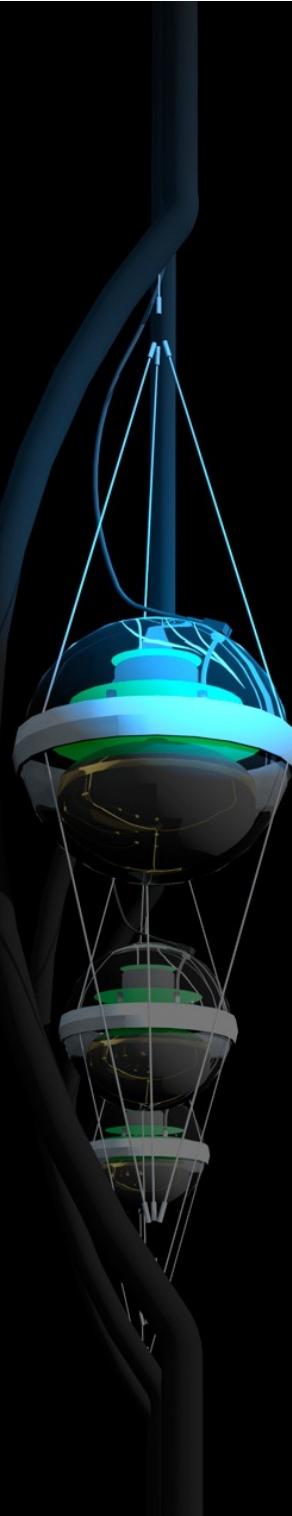
multi-year starting ν_μ track analysis (ctd)



fraction of atmospheric versus cosmic neutrinos in the data sample

Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5



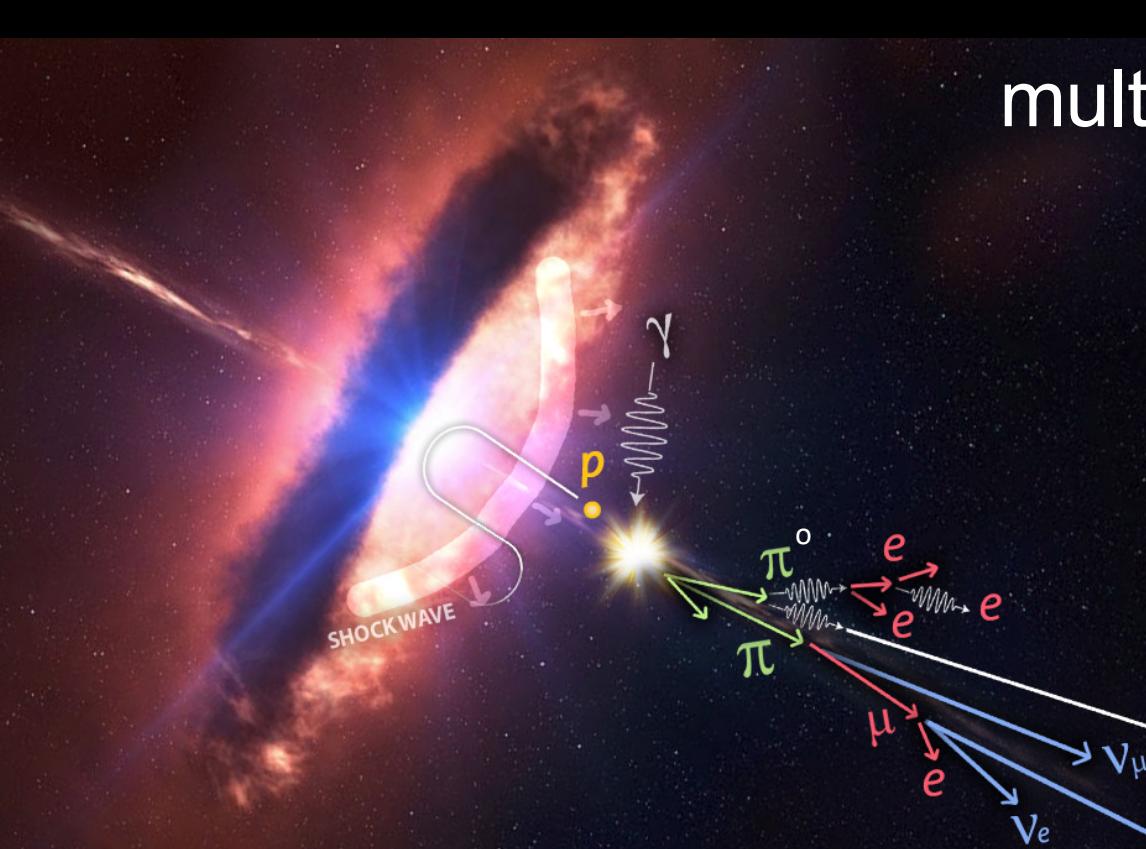
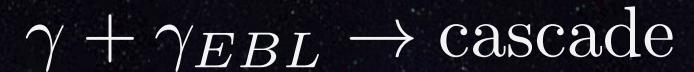
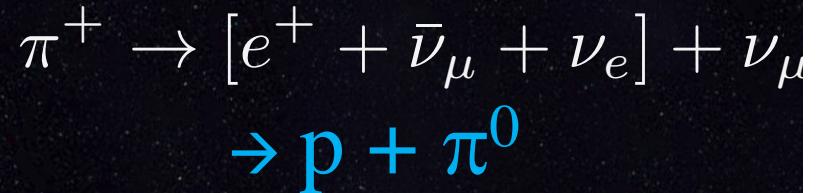
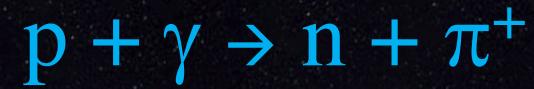


IceCube: the discovery of cosmic neutrinos

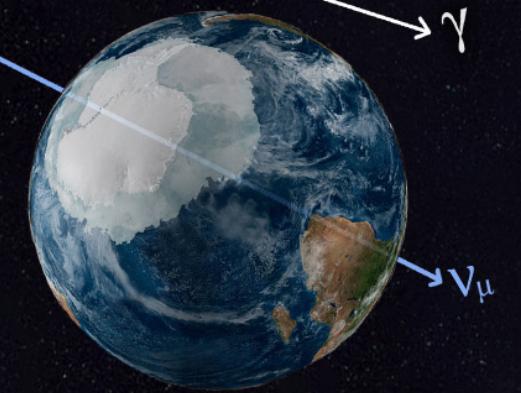
francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- the discovery of cosmic neutrinos
- where do they come from?
- intermezzo on obscured cores or agn
- beyond IceCube

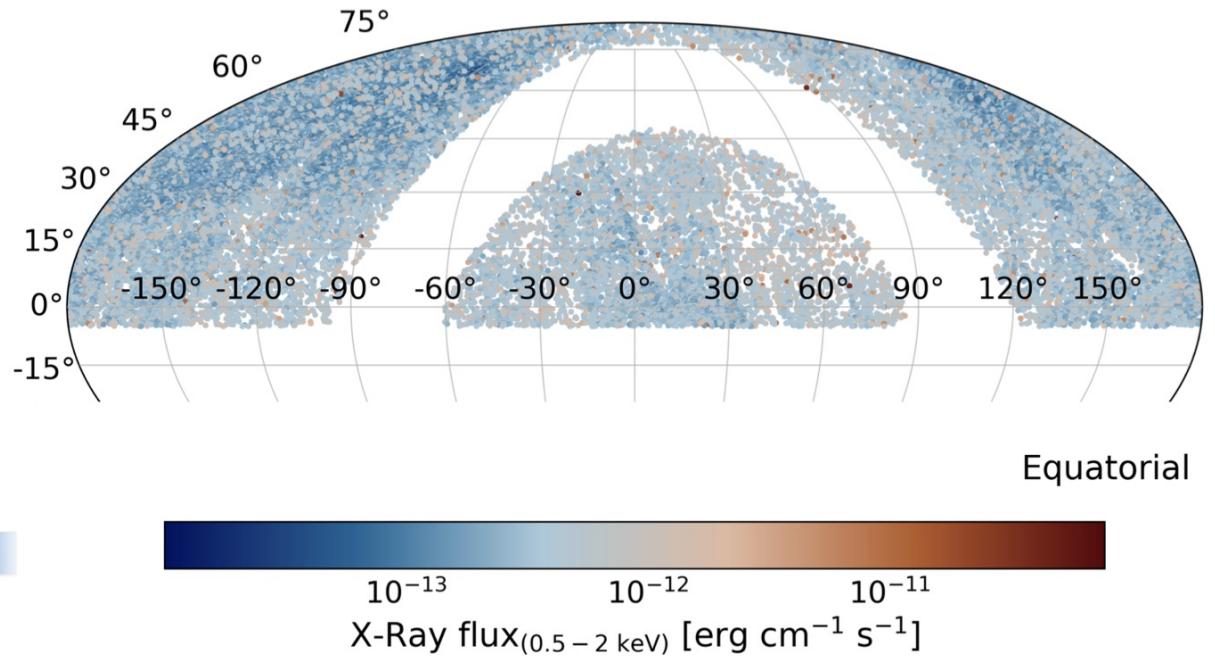
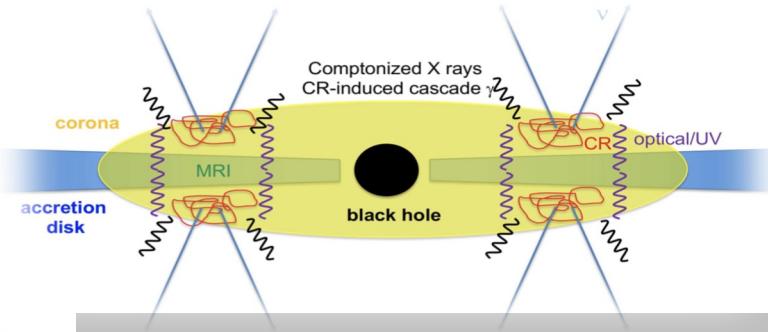
multimessenger astronomy



- efficient neutrino production sites are likely to be optically thick to gamma rays
- expect no correlation between gamma-ray and neutrino activity
- gamma rays lose energy on the target that produces neutrinos even before reaching the EBL



correlation between cores of active galaxies and cosmic neutrinos ($\gamma = -2.03$; 2.6σ post trial)



selection:

- X-ray catalogues 2RXS + XMMSL2
- IR WISE catalogue: X-rays associated with the core produce infrared light on dust at the center of the galaxy

TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5–2 keV energy range from the selected sources and the completeness (fraction of total X-ray flux from all AGN in the universe contained in the sample) are listed.

	Radio-selected AGN	IR-selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	ALLWISE + 2RXS + XMMSL2	ALLWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [$\text{erg cm}^{-2} \text{s}^{-1}$]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

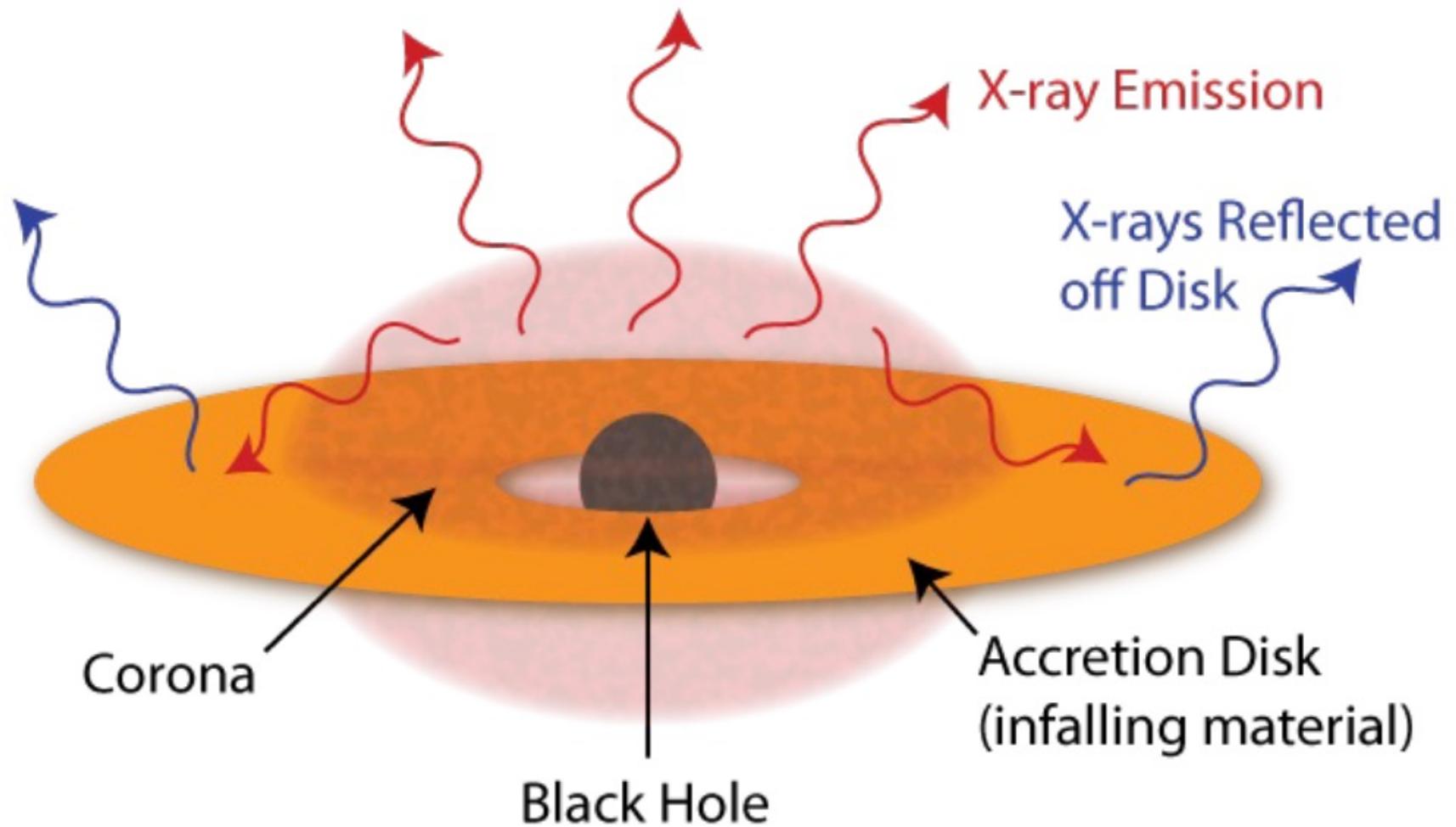
neutrino → gamma independent of the beam !

$$\langle E_\nu \rangle = \frac{1}{2} \langle E_\gamma \rangle = \frac{1}{4} \langle E_\pi \rangle = \frac{1}{4} \kappa E_p \simeq \frac{1}{20} E_p$$

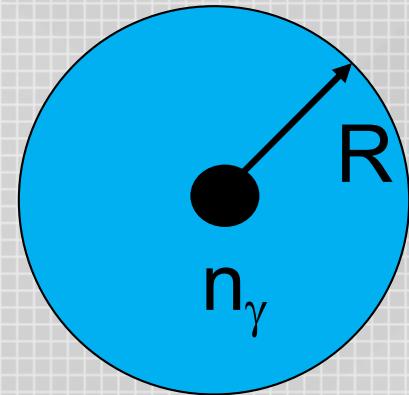
inelasticity $\kappa \simeq 0.2$ for both γp and $p p$

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} = \frac{4}{3} E_\nu^2 \frac{dN_\nu}{dE_\nu} \left(E_\nu = \frac{E_\gamma}{2} \right)$$

for $p p : 4/3 \rightarrow 2/3$



generic obscured core of active galaxy



target density n_γ centered on black hole

$n_\gamma \rightarrow u_\gamma$ [energy density]

$$u_\gamma = \frac{L_\gamma \Delta t}{\frac{4}{3} \pi R^3}$$

$$\Delta t = \frac{R}{c}$$

$$\begin{aligned}\tau_{p\gamma} &= \kappa \frac{R}{\lambda_{p\gamma}} \\ &= \kappa R n_\gamma \sigma_{p\gamma} \\ &= \kappa R \frac{u_\gamma}{E_\gamma} \sigma_{p\gamma} \\ &= \frac{3\kappa \sigma_{p\gamma}}{4\pi c} \frac{1}{R} \frac{L_\gamma}{E_\gamma}\end{aligned}$$

the source also absorbs the protons

→ essential to produce neutrinos

$$\tau_{p\gamma} = 1.4 \times 10^2 \left[\frac{R_s}{R} \right] \left[\frac{1 \text{ KeV}}{E_\gamma} \right] \left[\frac{L_\gamma}{L_{edd}} \right] \geq 1$$

for $E_\gamma = 10 \text{ KeV}$; $M = 10^7 M_{\text{sun}}$ and $L_\gamma \sim 10^{43} \text{ erg s}^{-1}$

$$R_s = [2GM]/c^2 = 3 \times 10^5 \text{ cm} \left[\frac{M}{M_{\text{sun}}} \right] \simeq 0.1 R$$

$$L_{edd} = \frac{4\pi GMm_p c}{\sigma_T} = 1.2 \times 10^{38} \frac{\text{erg}}{\text{s}} \left[\frac{M}{M_{\text{sun}}} \right] \simeq 10^2 L_\gamma$$

note the small value of $R \sim 10^{-4} \text{ pc}$

energy density injected by cosmic rays in the Universe

$$\rho_0 L_p = \frac{dE_{\text{tot}}}{dt} = E_p^2 \dot{Q}_p = 10^{43} \sim 10^{44} \text{ erg Mpc}^{-3} \text{ year}^{-1}$$

$\times c$

conversion of energy density to flux

$\times t_H \times \zeta_z$

Hubble time and redshift evolution factor [order unity]

$\times \tau_{p\gamma}$

fraction of energy into pions

$\times 1/2$

fraction into muon neutrinos in $\pi \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

$\times \frac{1}{4\pi}$

definition per steradian

$$[E^2 \Phi = E^2 \frac{dN}{dE dt} = v \times \rho_E]$$

equal energy in cosmic rays and neutrinos

$$E_p^2 \dot{Q}_p c t_H \zeta_z \tau_{p\gamma} \frac{1}{2} \frac{1}{4\pi} = E_p^2 \frac{dN_p}{dE_p} t_H \zeta_z \frac{c}{4\pi} \frac{1}{2} \tau_{p\gamma} = E_\nu^2 \frac{dN_\nu}{dE_\nu}$$

$$\simeq 10^{-11} \text{TeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

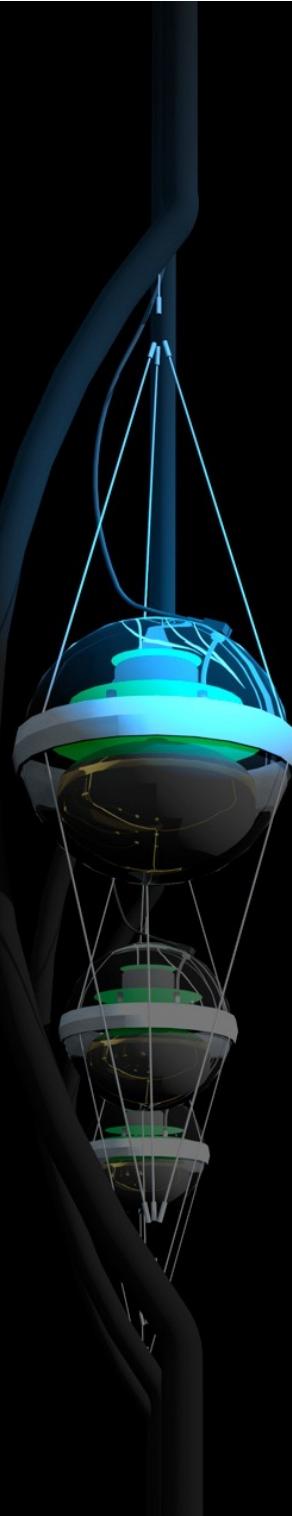
for $\tau_{p\gamma} \sim 1$ and $t_H \sim 13.7$ billion years

proton target : $\frac{1}{2} \tau_{p\gamma} \rightarrow \frac{2}{3} \tau_{pp}$

alternatively,

$$L_\nu = \frac{3}{8} \tau_{p\gamma} L_p = \frac{3}{8} \tau_{p\gamma} \frac{1}{\rho_0} dE/dt$$

- with $\rho_0 = 800 \text{ Gpc}^{-3}$ for active galaxies with $L_\gamma \leq 10^{43} \text{ ergs}^{-1}$
- dimensional analysis suggest somewhat smaller number with $\rho_0 \simeq 100 \text{ Gpc}^{-3}$
- 100 sources with the TXS flux saturate the diffuse flux



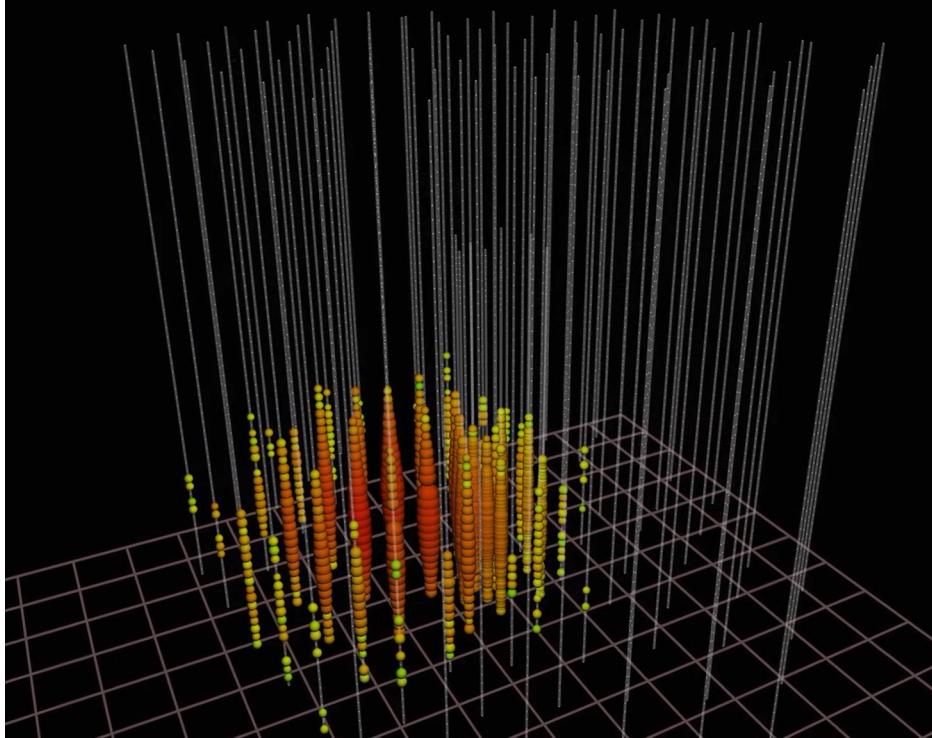
IceCube: the discovery of cosmic neutrinos

francis halzen

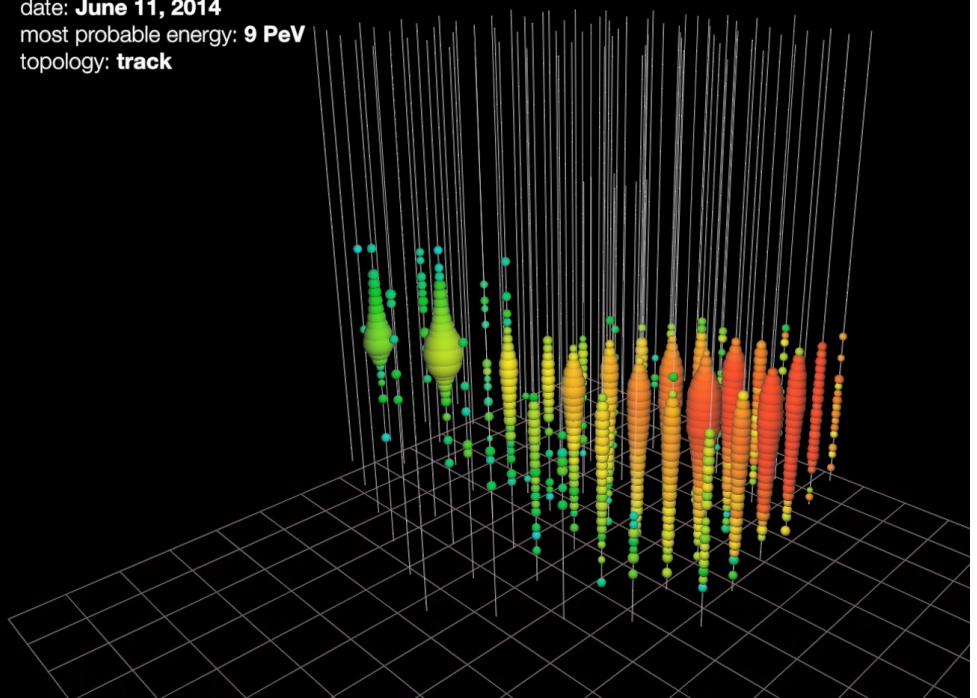
- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth

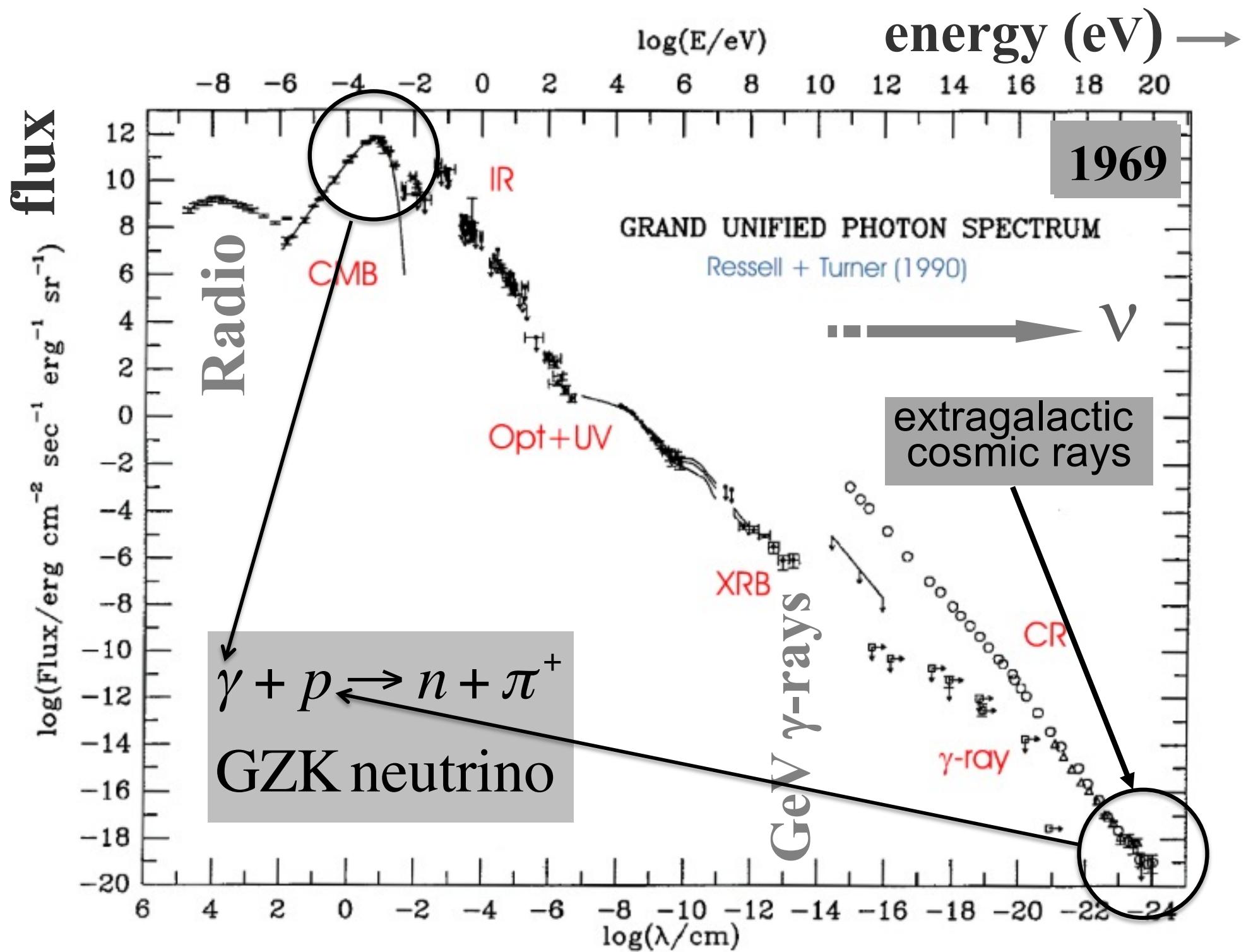


date: June 11, 2014
most probable energy: 9 PeV
topology: track

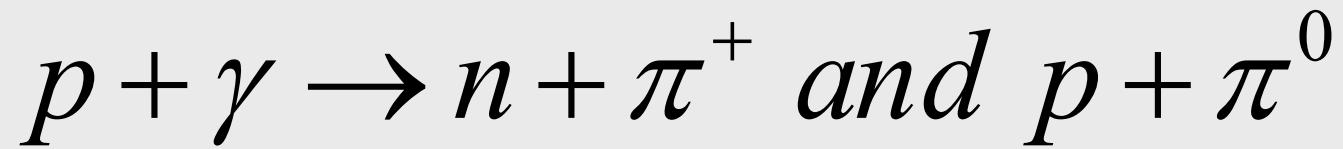


superior total energy
measurement
to 10%, all flavors, all sky

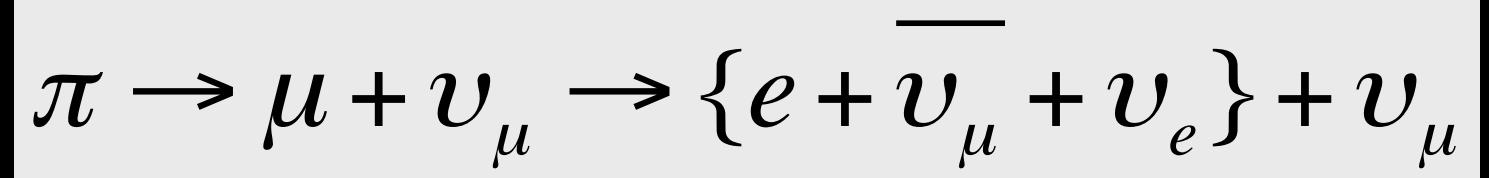
astronomy: superior
angular resolution
superior ($0.2\text{--}0.4^\circ$)



cosmic rays interact with the microwave background



cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear



1 event per cubic kilometer per year
...but it points at its source!

GZK neutrino search: two neutrinos with > 1,000 TeV

date: **August 9, 2011**

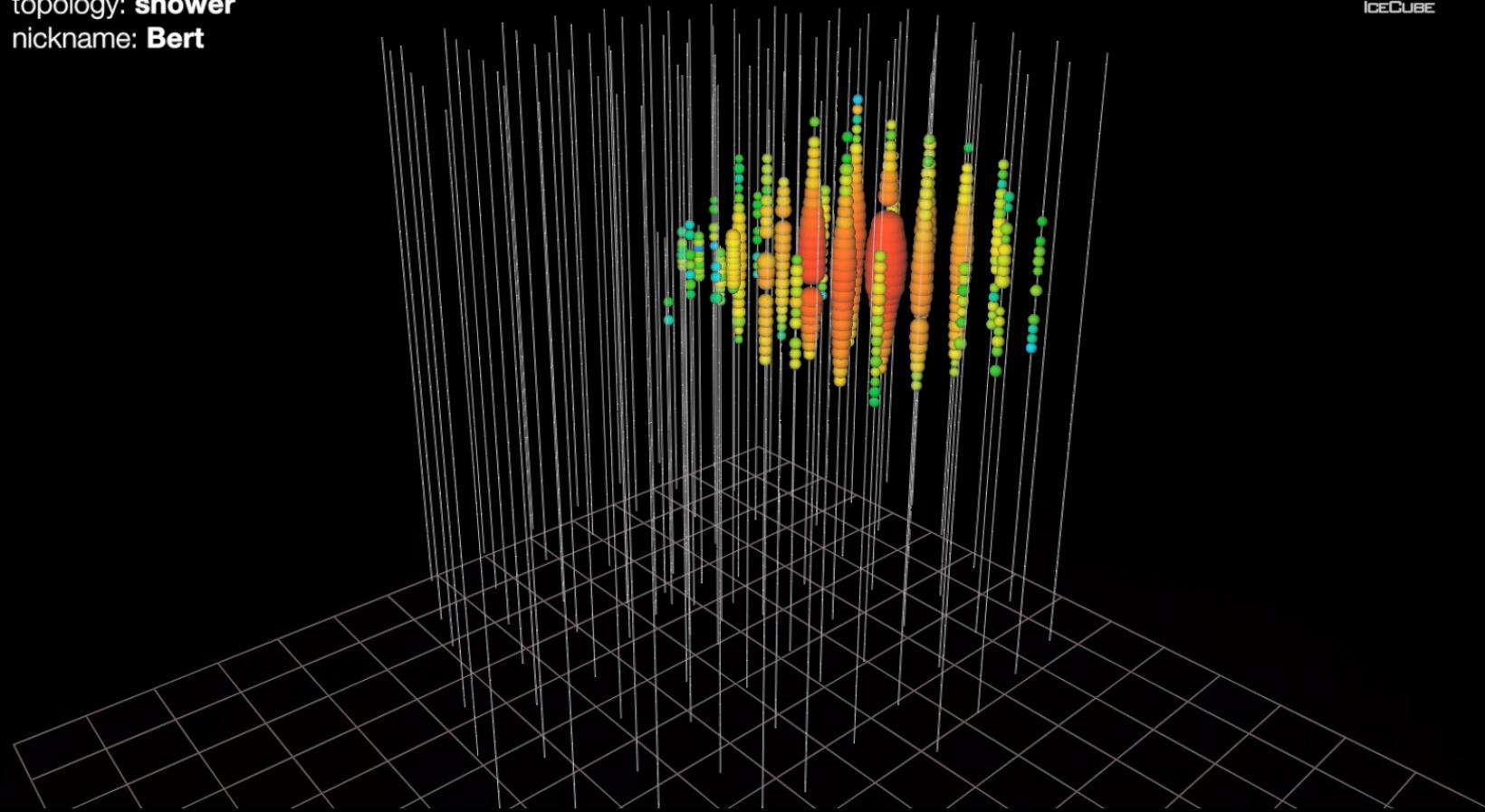
energy: **1.04 PeV**

topology: **shower**

nickname: **Bert**



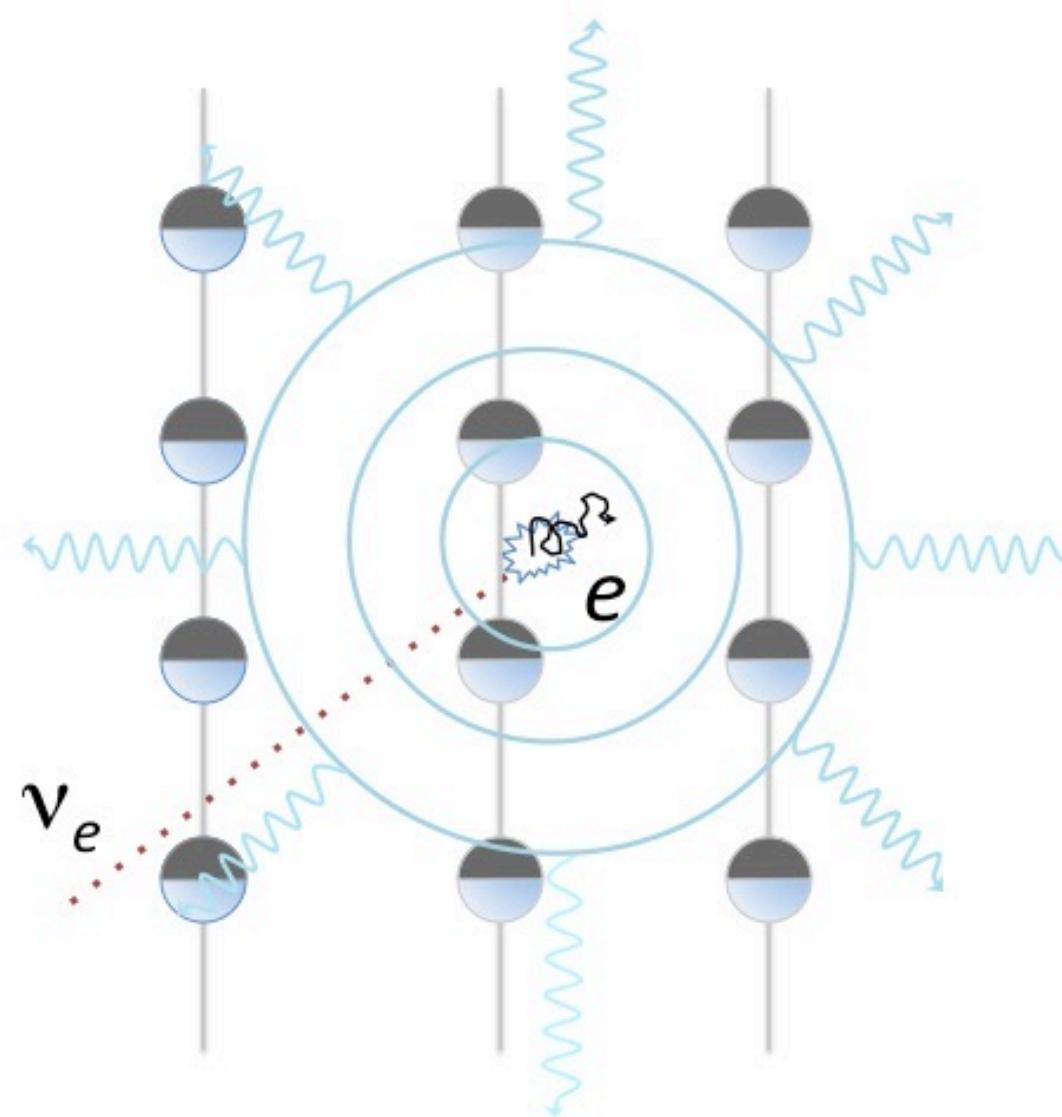
ICECUBE



electron showers versus muon tracks

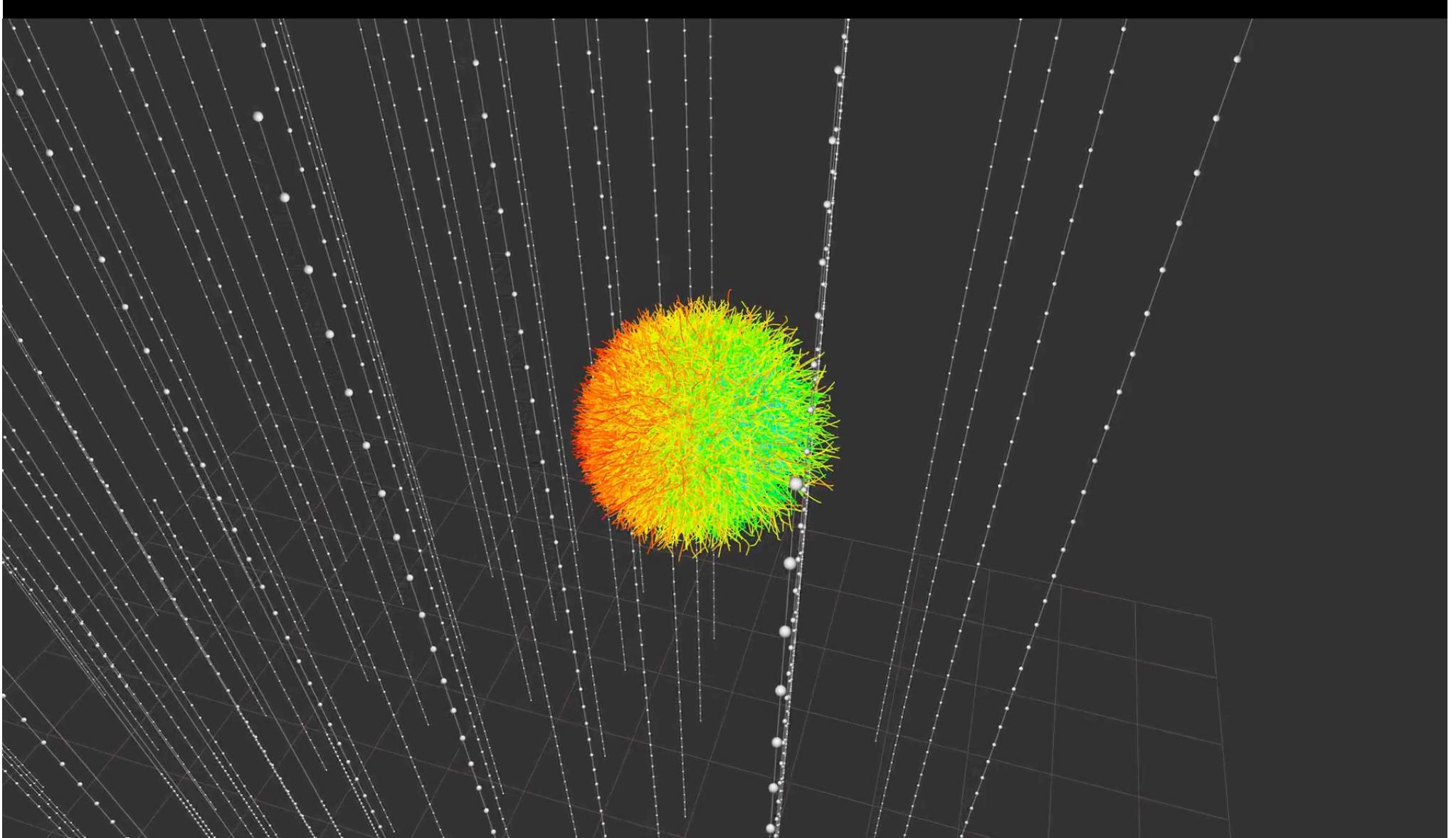
PeV ν_e and ν_τ showers:

- 10 m long
- volume $\sim 5 \text{ m}^3$
- isotropic after 25~50 m



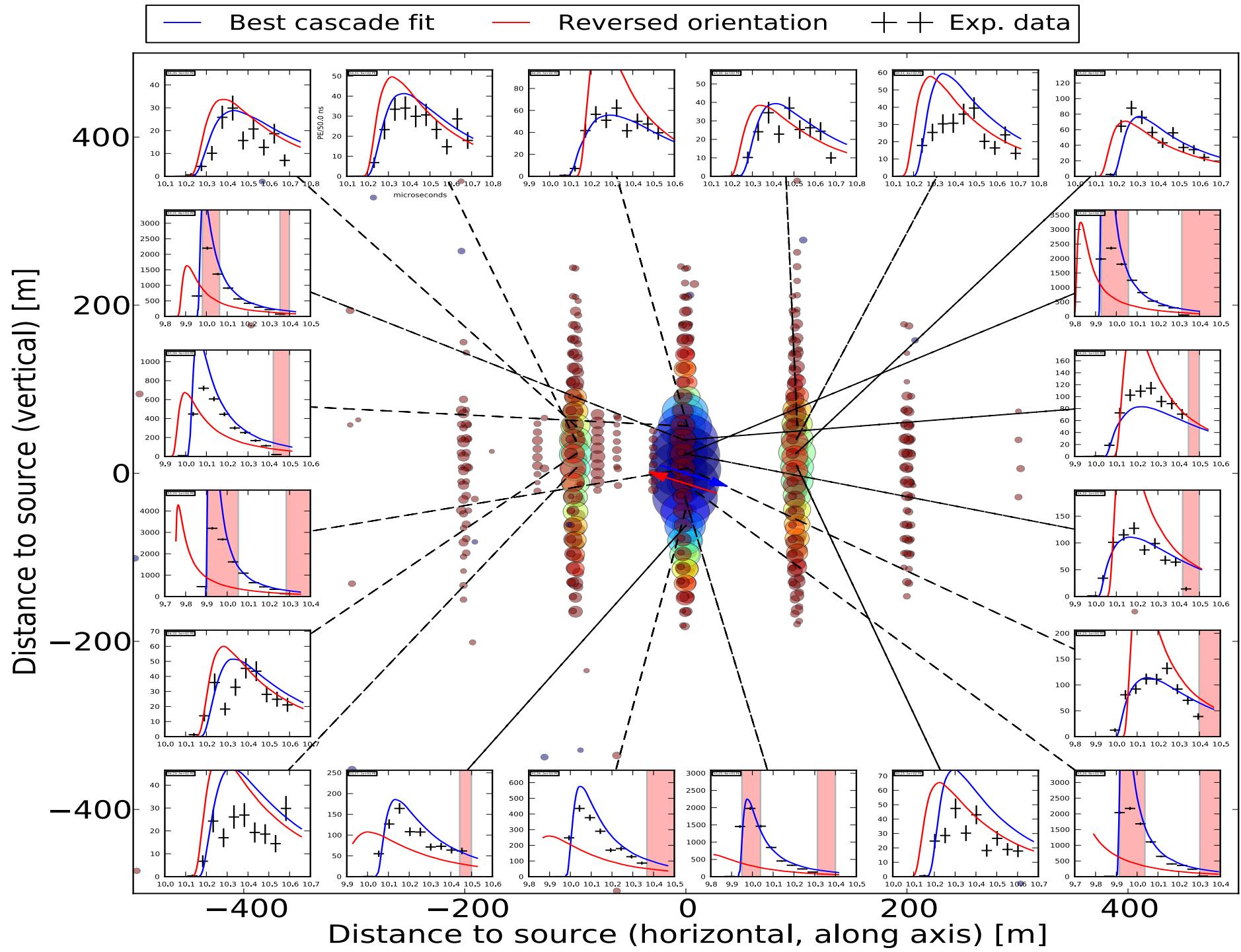


Cherenkov radiation from PeV electron (tau) shower
> 300 sensors > 100,000 pe reconstructed to 2 nsec

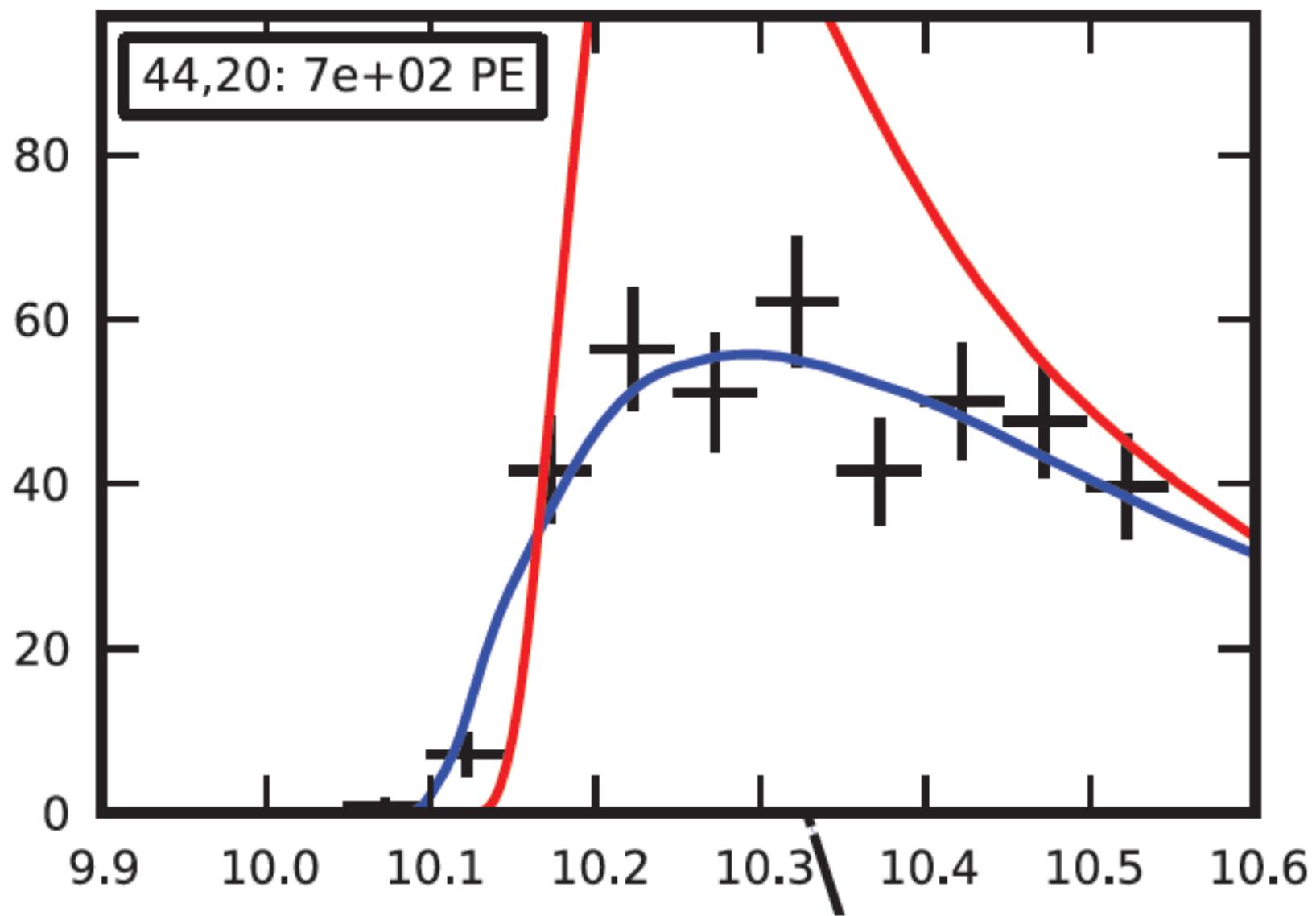


size = energy

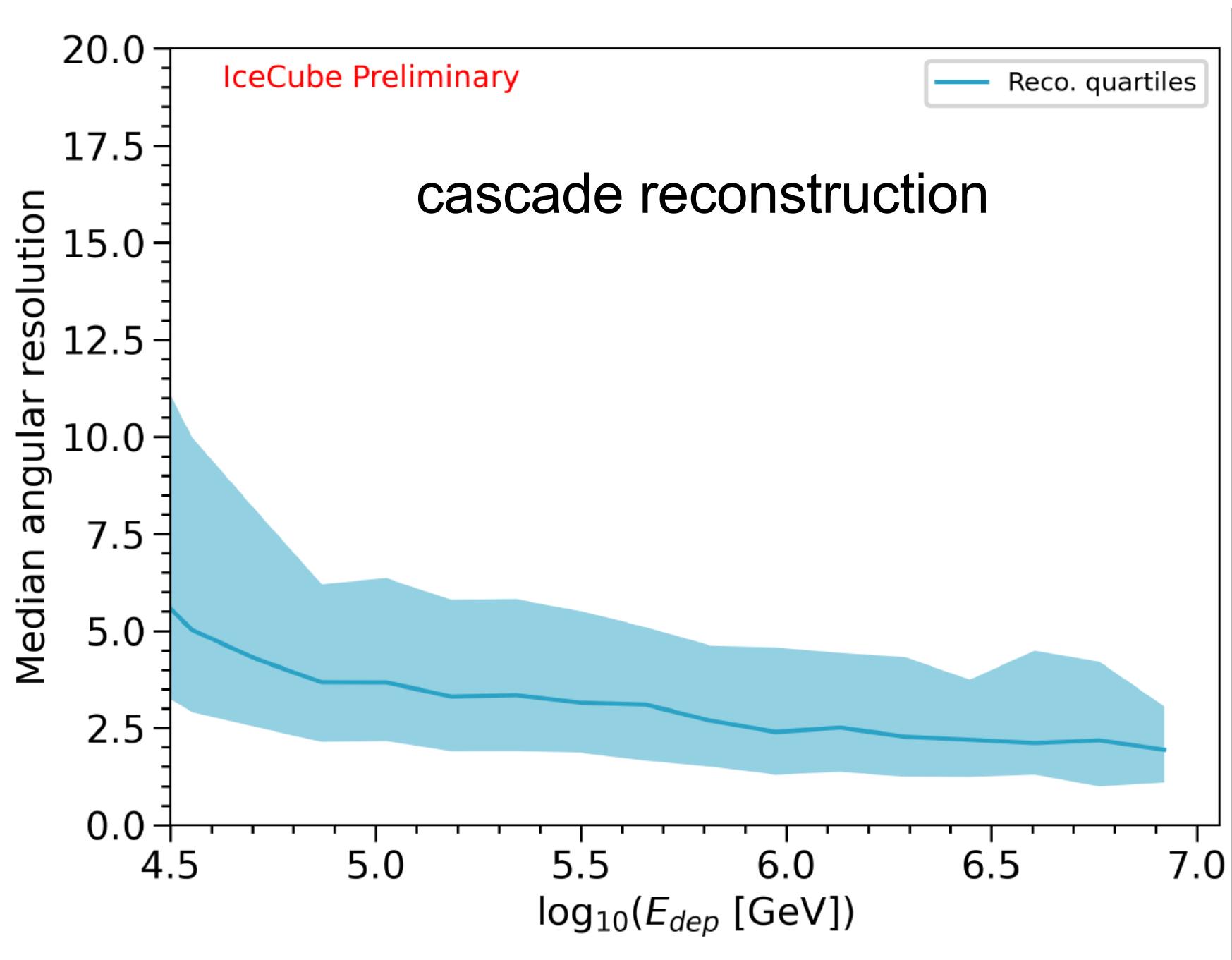
color = time = direction

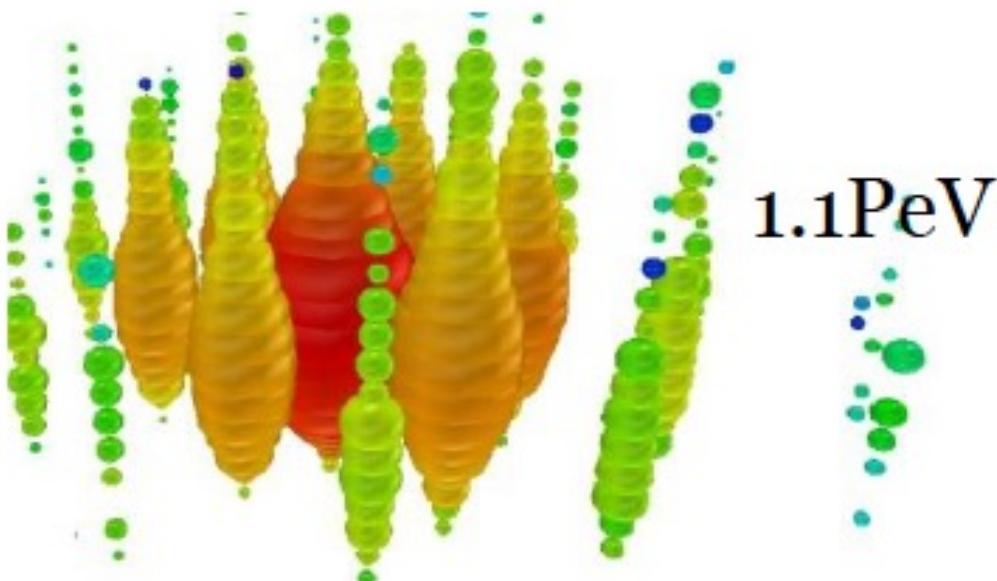
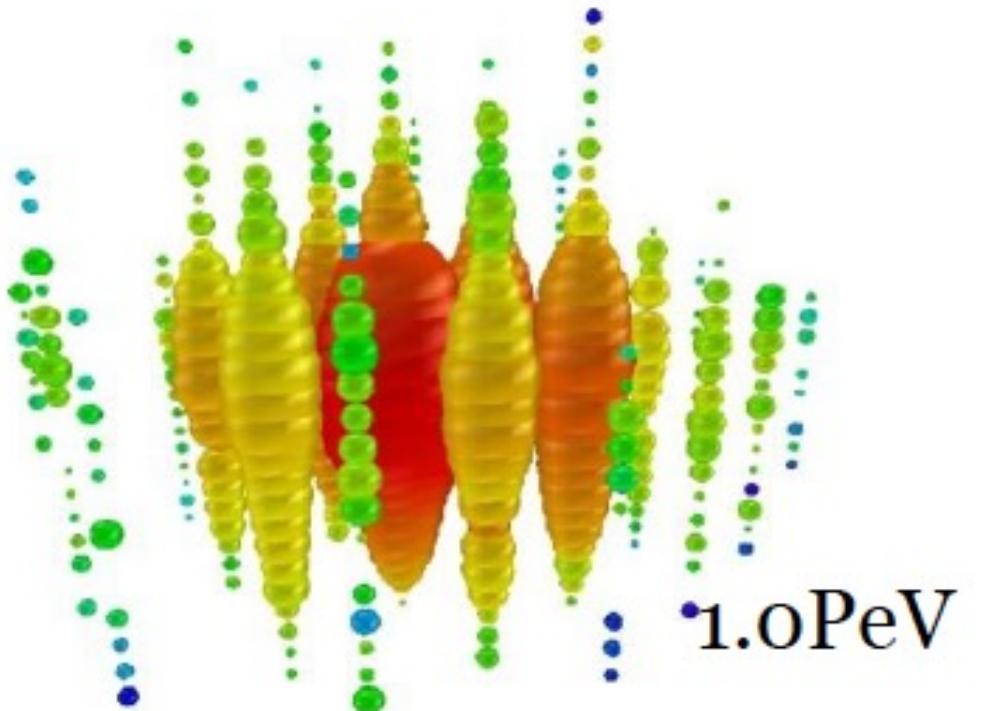


reconstruction limited by computing, not ice !



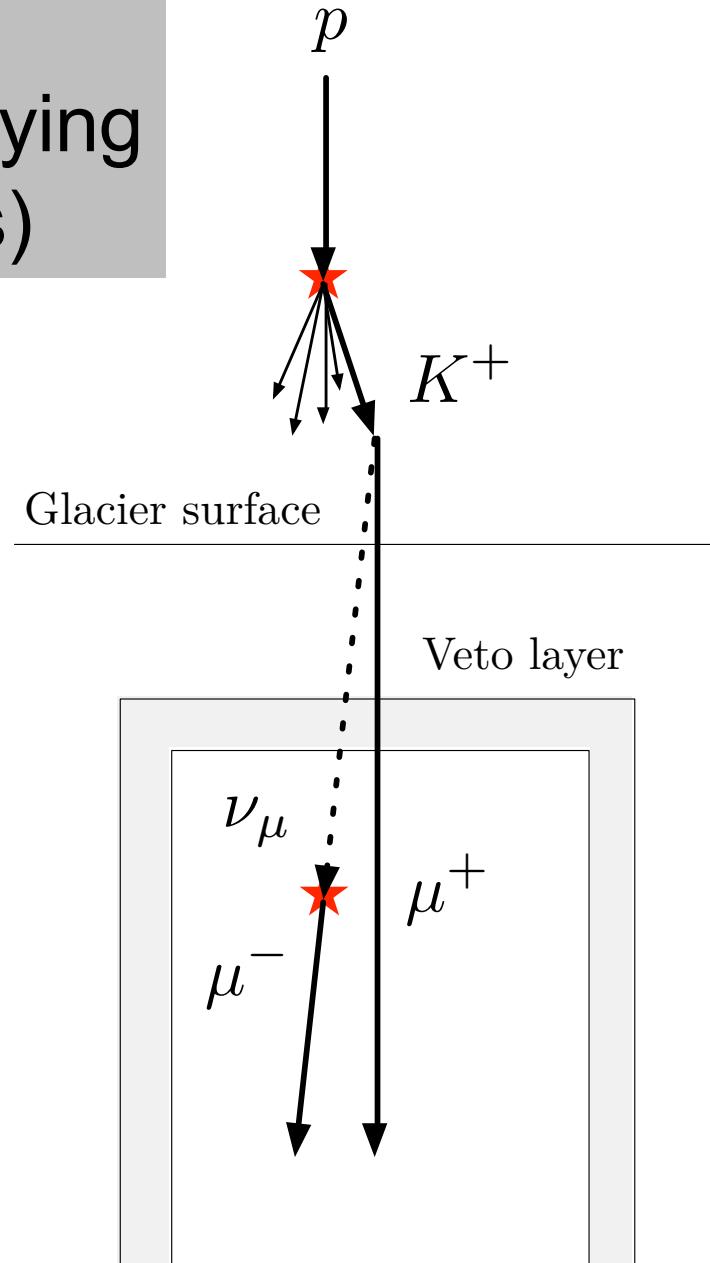
Blue: best-fit direction, red: reversed direction



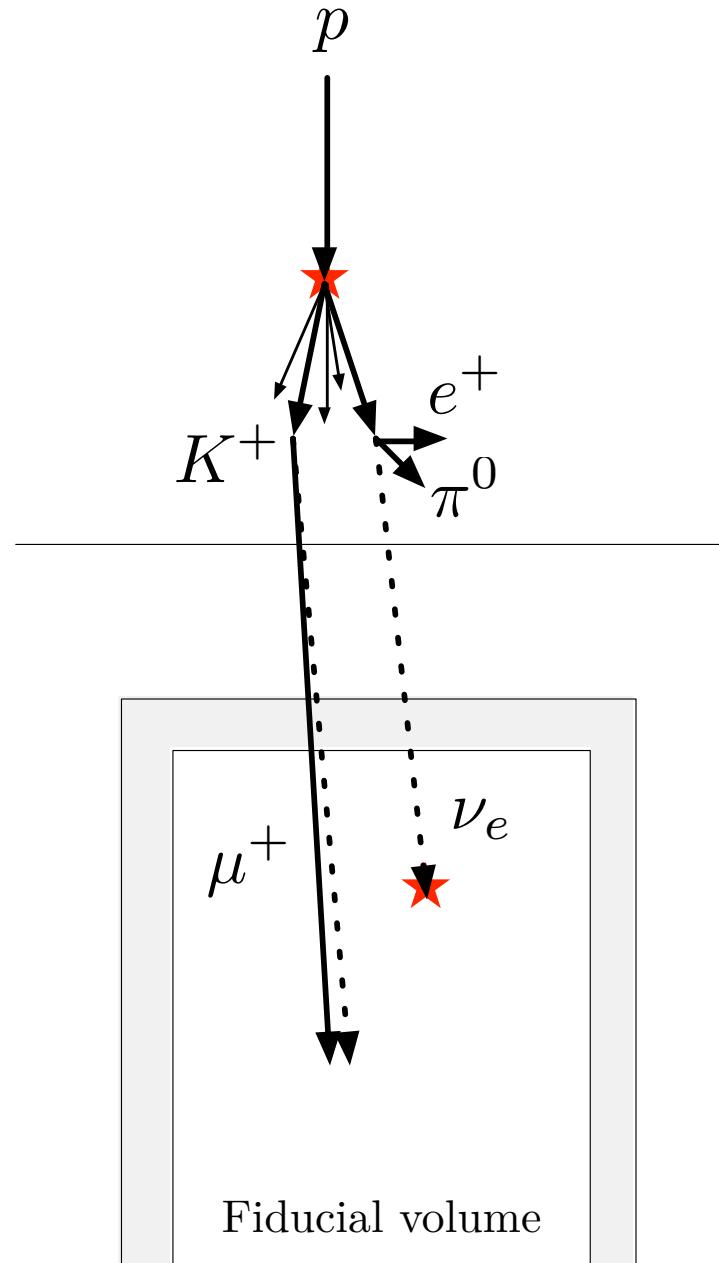


- energy
1,041 TeV
1,141 TeV
(15% resolution)
 - not atmospheric:
probability of
no accompanying
muon is 10^{-3} per
event
- flux at present
level of diffuse
limit

no
accompanying
muon(s)



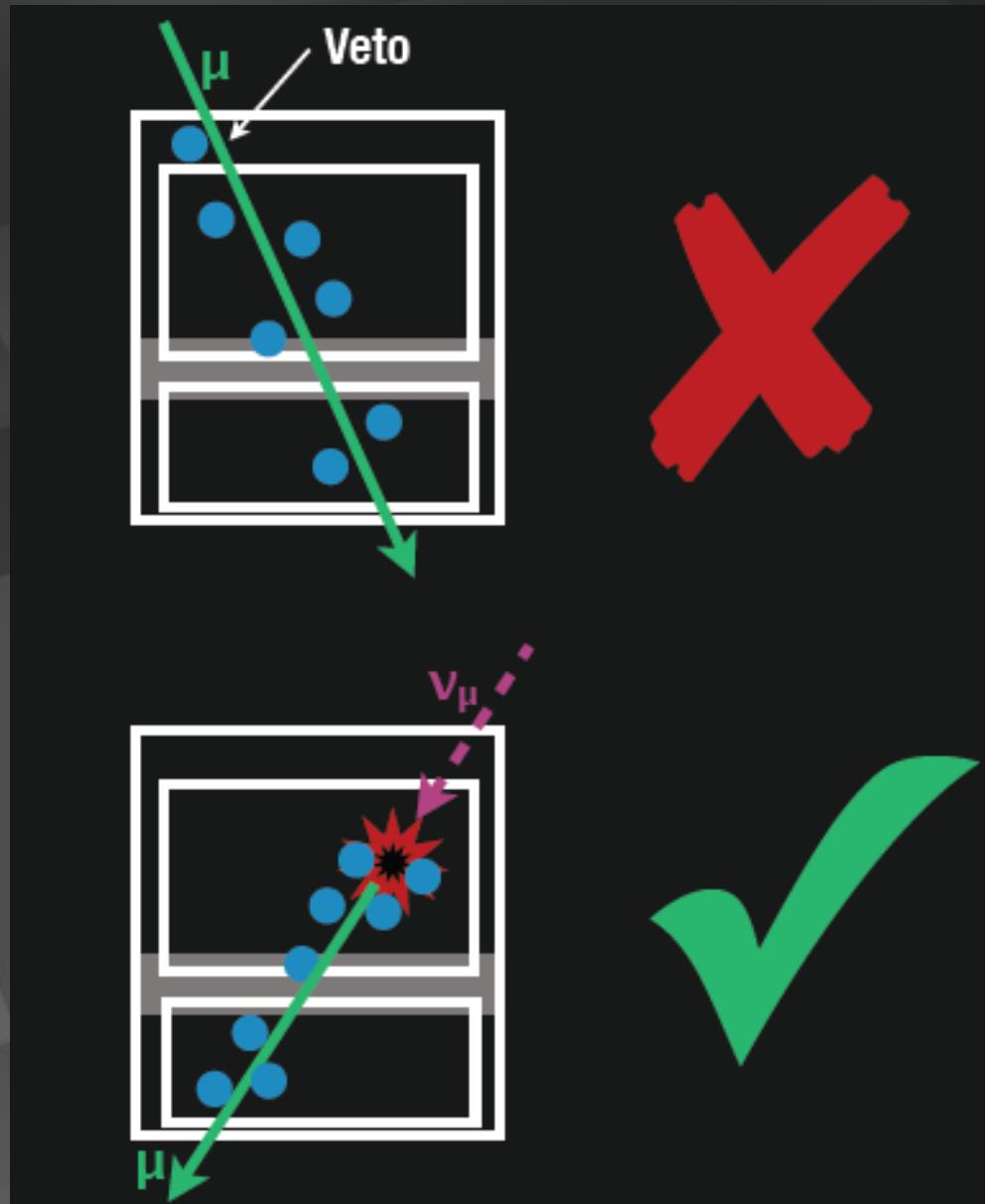
Veto by correlated muon



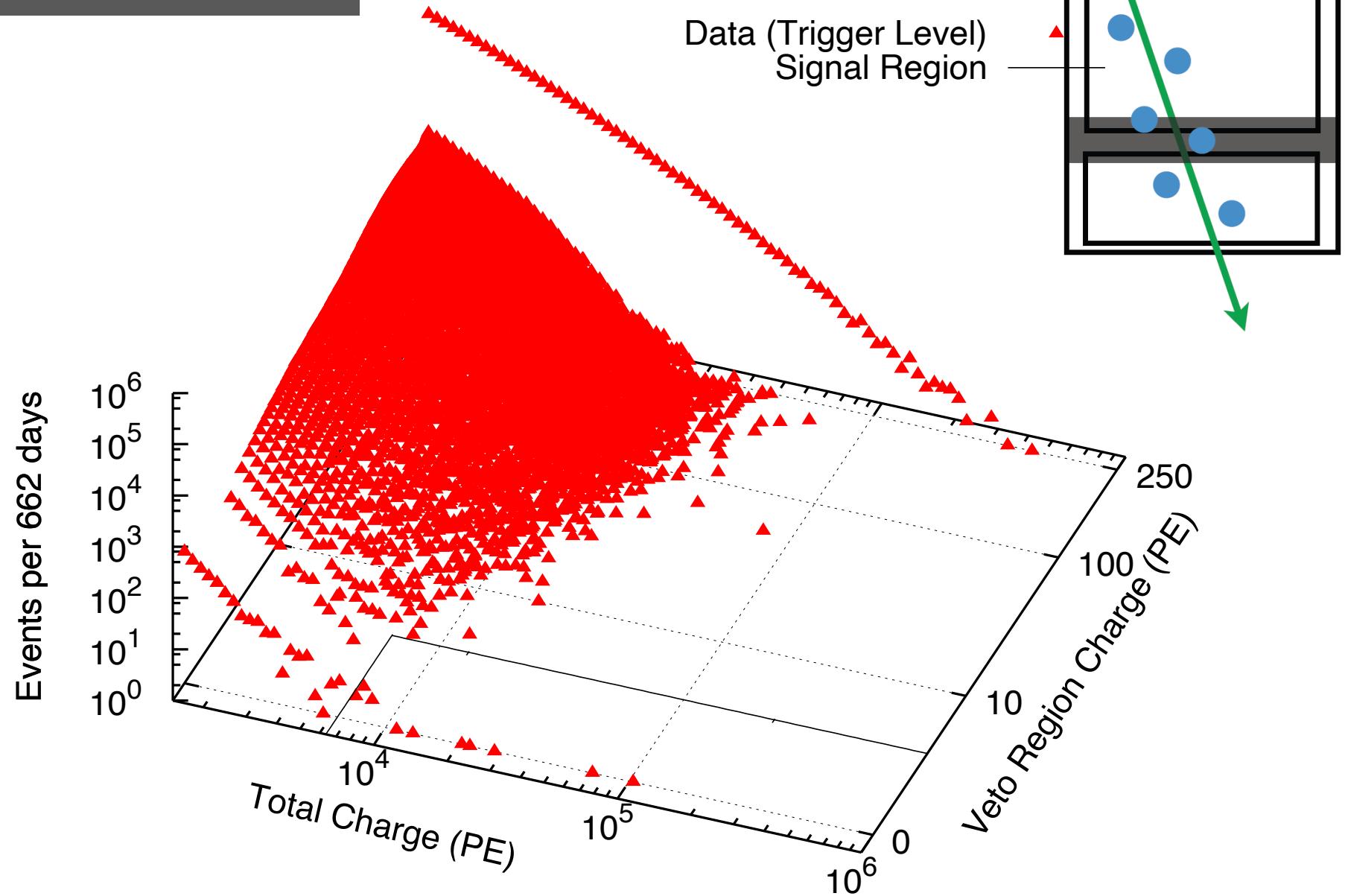
Veto by uncorrelated muon

events starting inside the detector

- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for *atmospheric* neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry

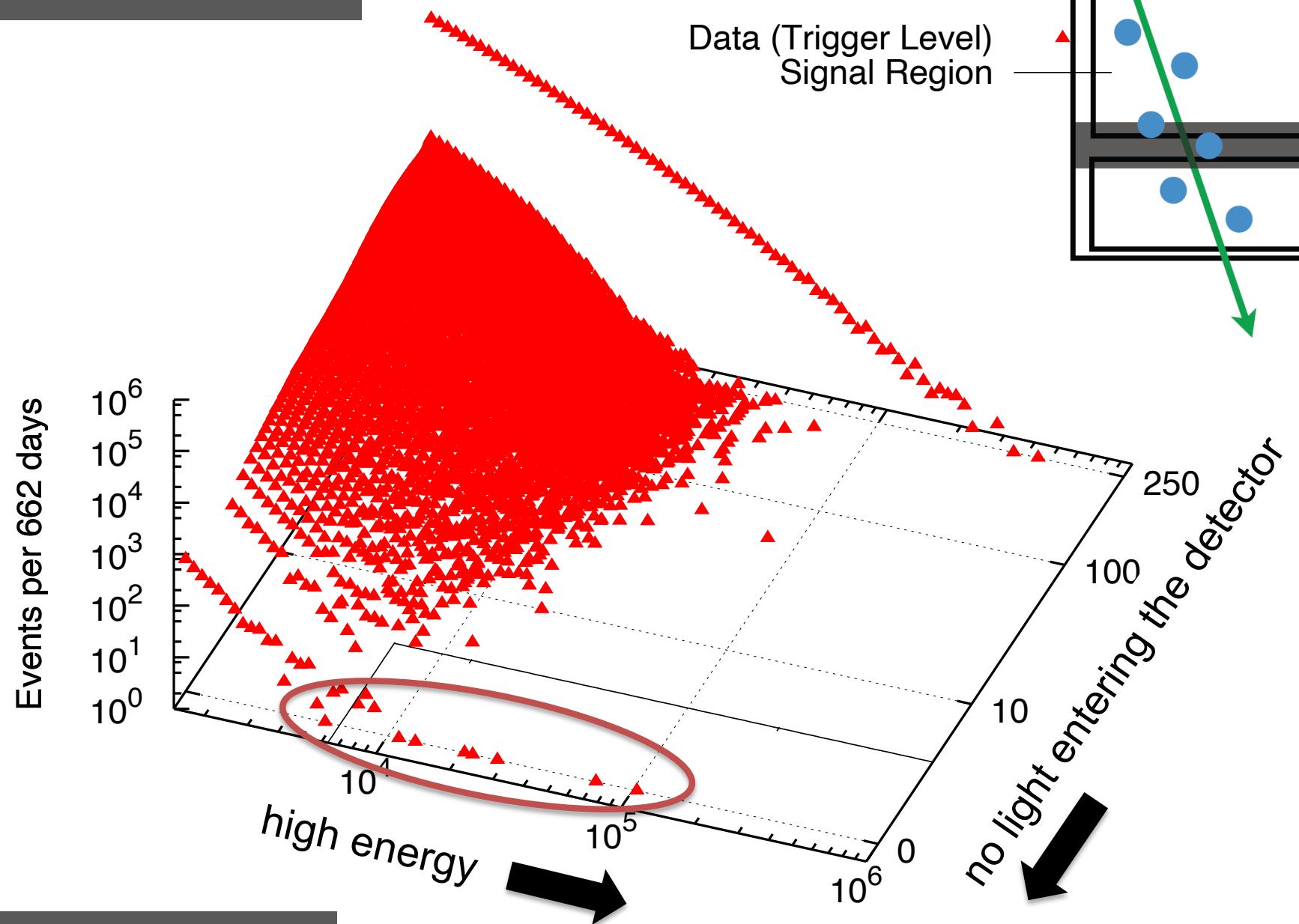


...and then there
were 26 more...

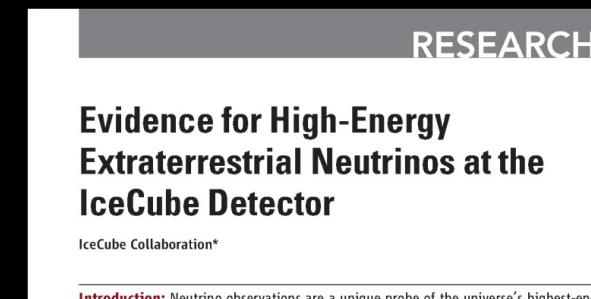


data: 86 strings one year

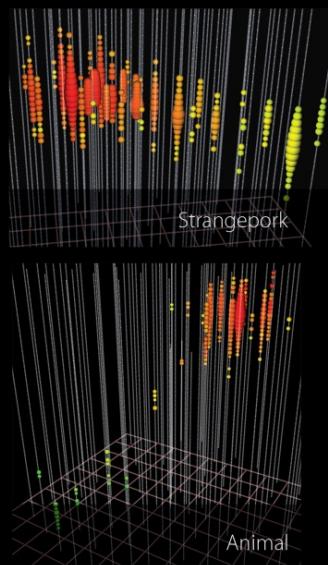
...and then there
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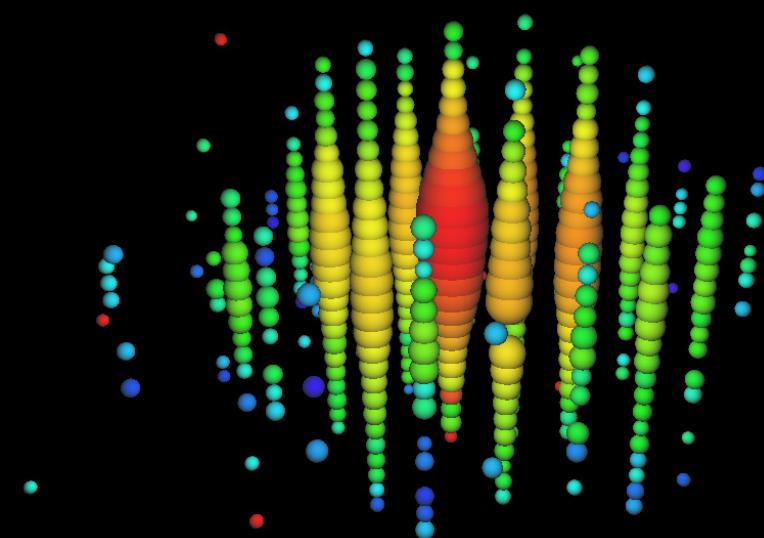
28 High Energy Events



Identified high-energy galactic or accelerators.

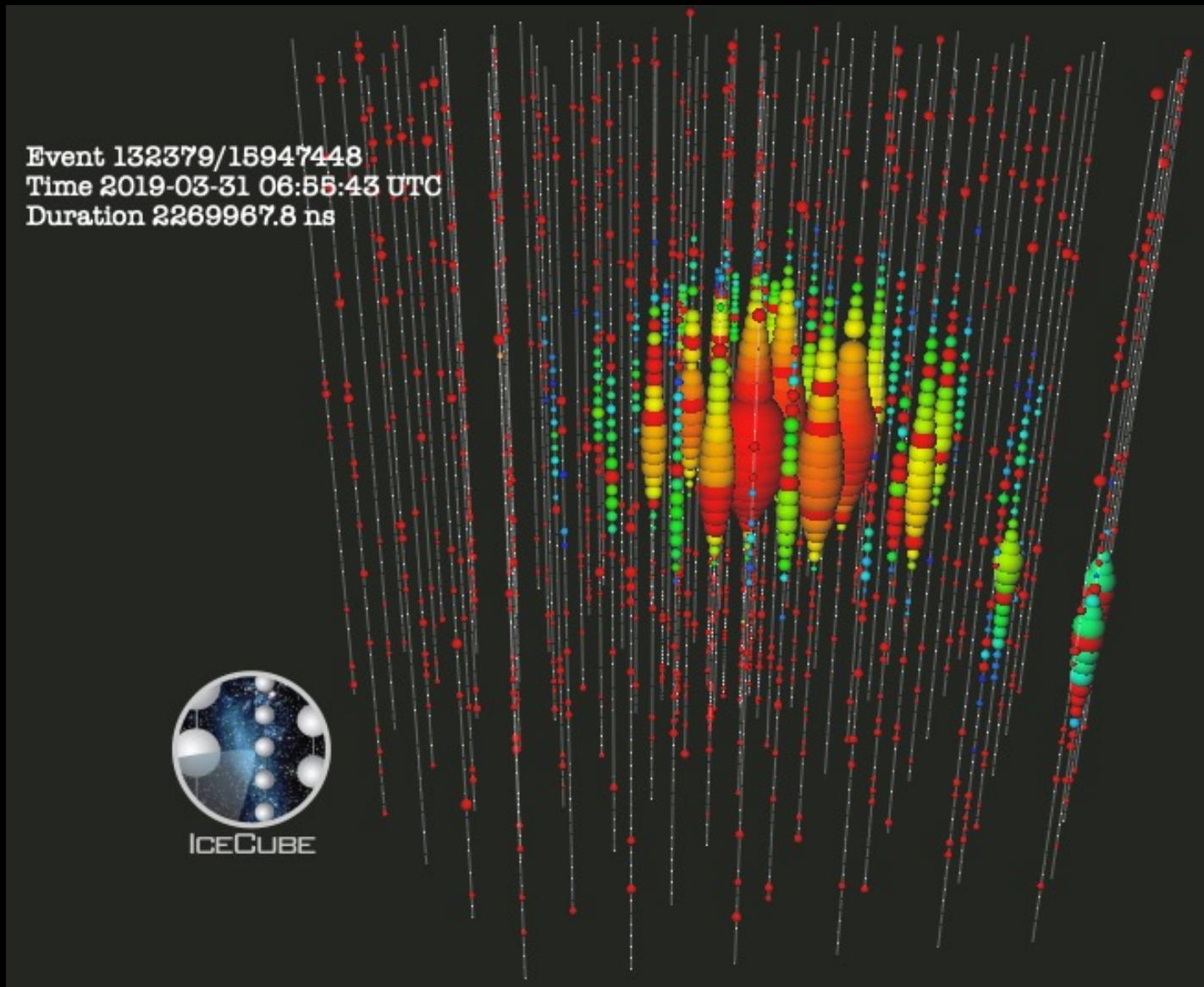
A 250 TeV neutrino interaction in interaction point (bottom), a large with a muon produced in the interaction left. The direction of the muon indicates original neutrino.

*The list of author affiliations is available online. Corresponding authors: C. Kopp (ckopp@mpip-mainz.mpg.de)

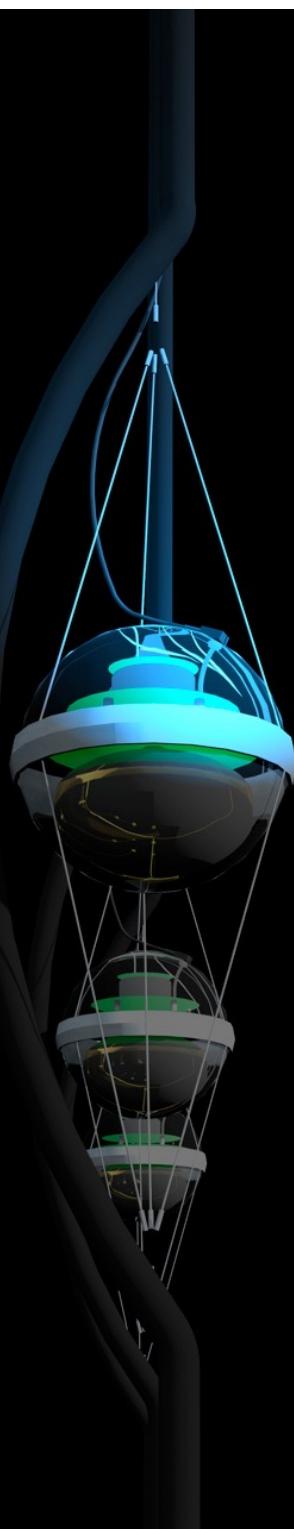


2004 TeV event in year 3

IC190331: 5300 TeV deposited inside the detector



initial neutrino energy > 10 PeV



neutrino astronomy

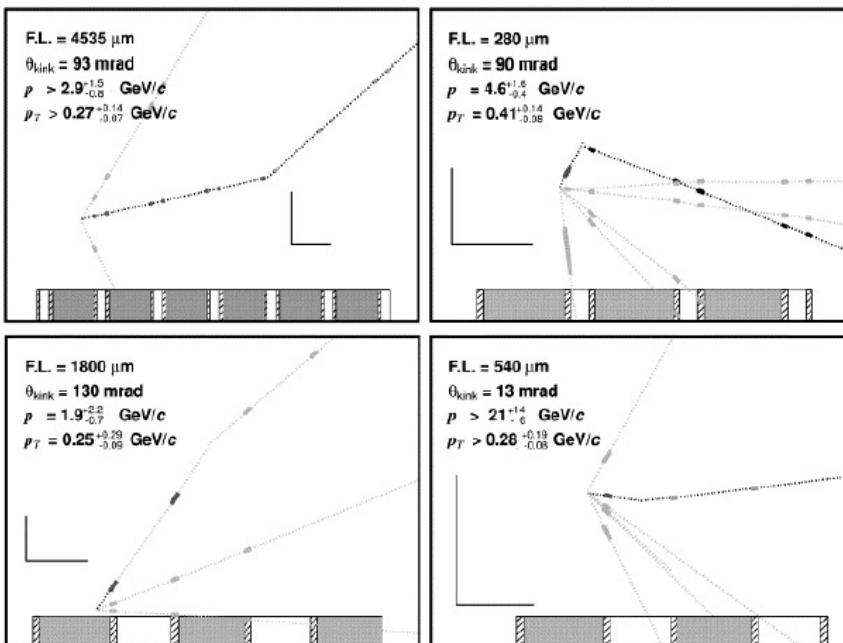
- cosmic neutrinos: four independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
 - tau neutrinos
 - Glashow event

multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

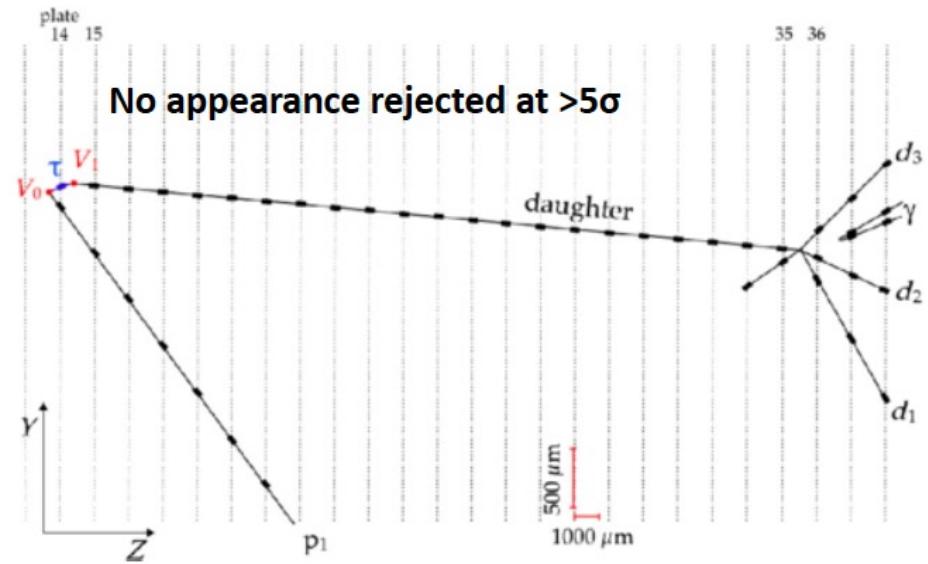
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion



DONUT Phys. Lett. B, [Volume 504, Issue 3, 12 April 2001, Pages 218-224](#)

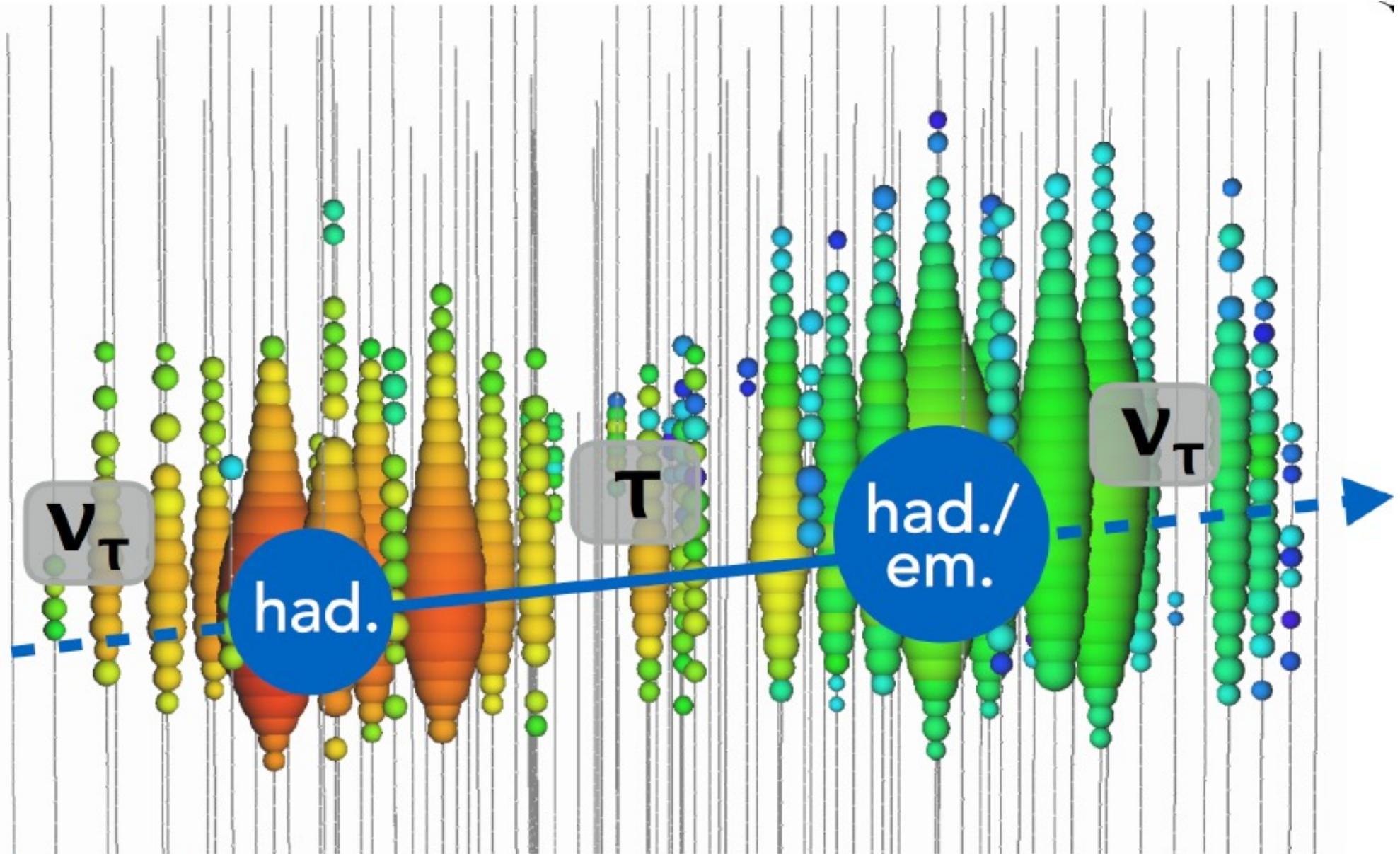
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



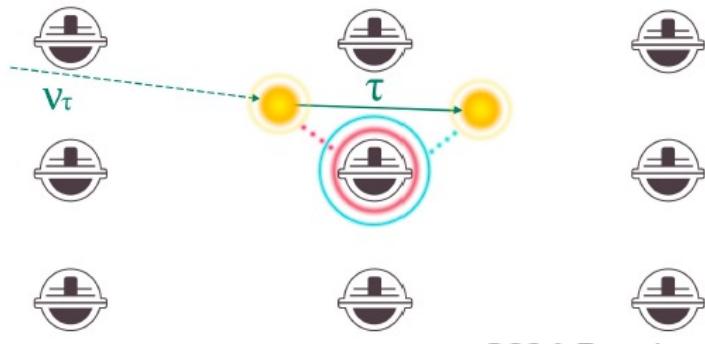
OPERA Phys. Rev. Lett. 115, 121802 (2015)

tau neutrino production and decay

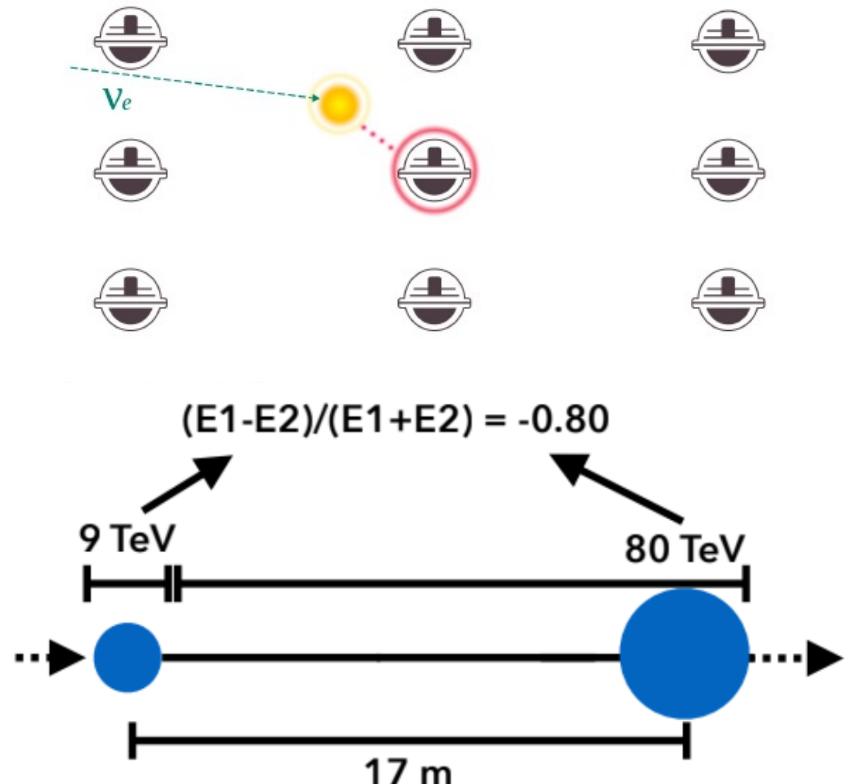
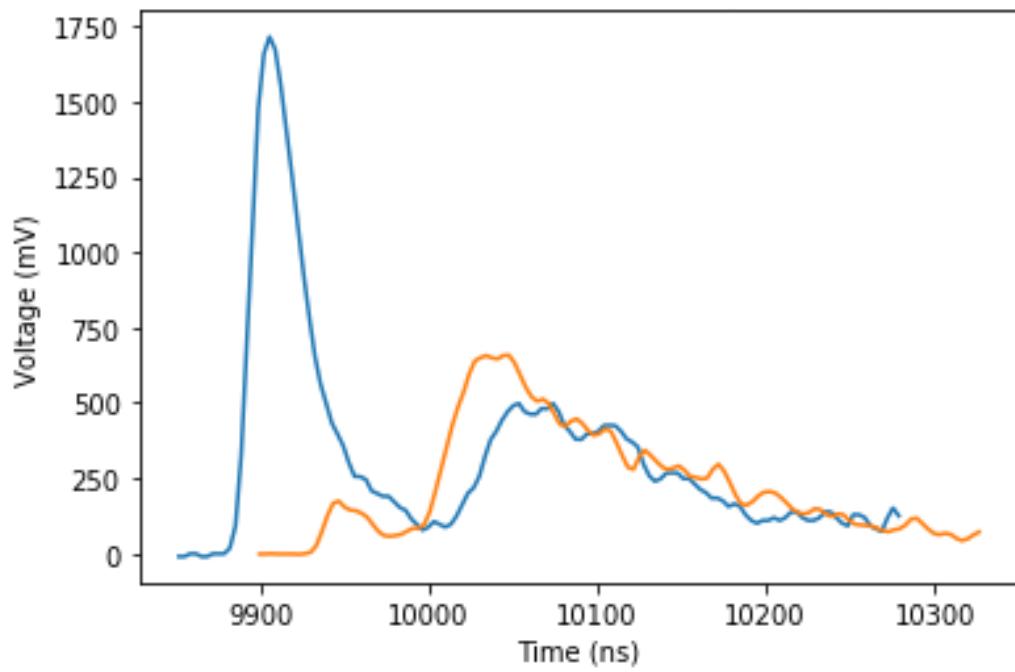
tau decay length:
 $\gamma c\tau = 50\text{m per PeV}$



tau decay length:
50m per PeV



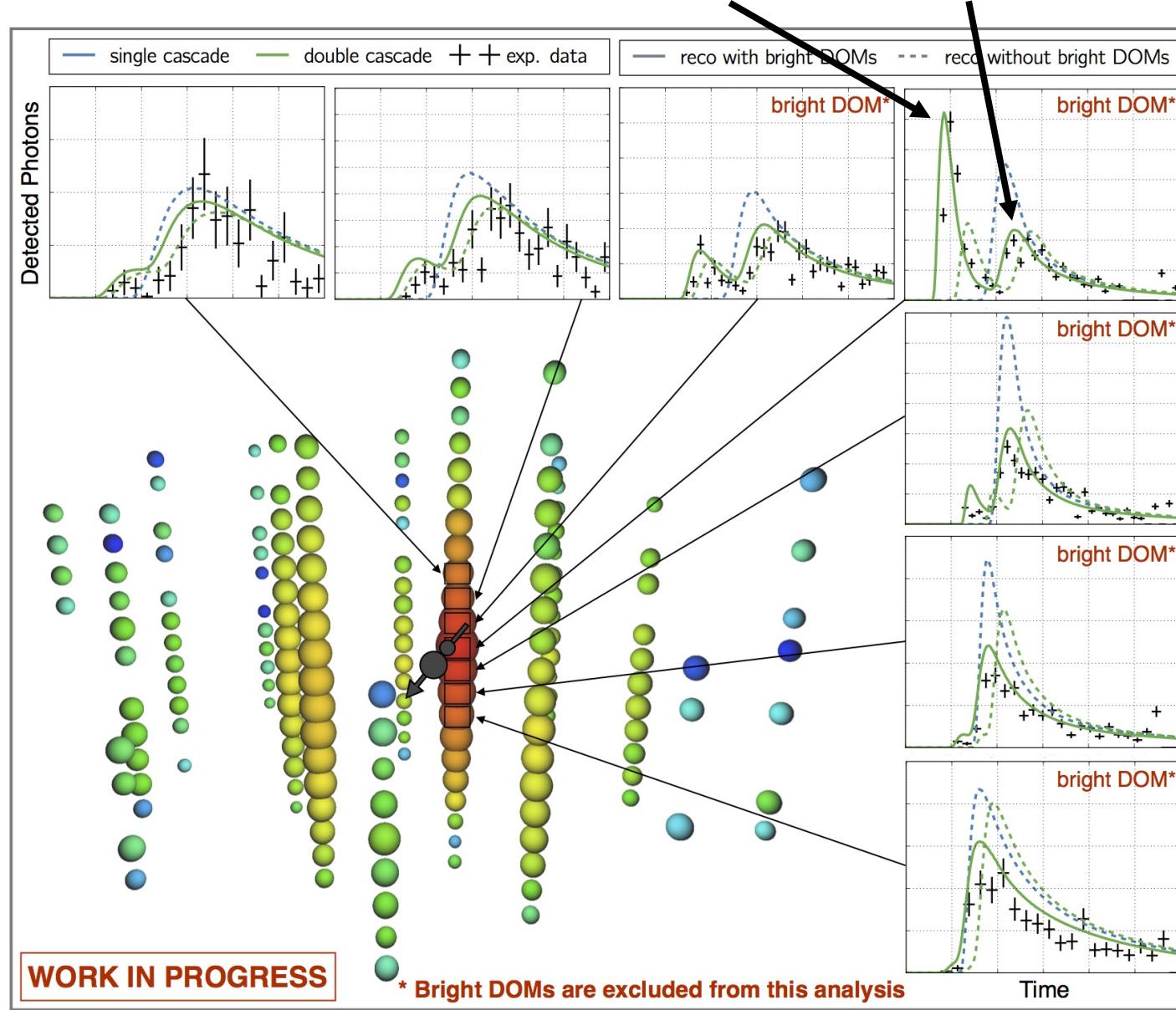
2014 Event



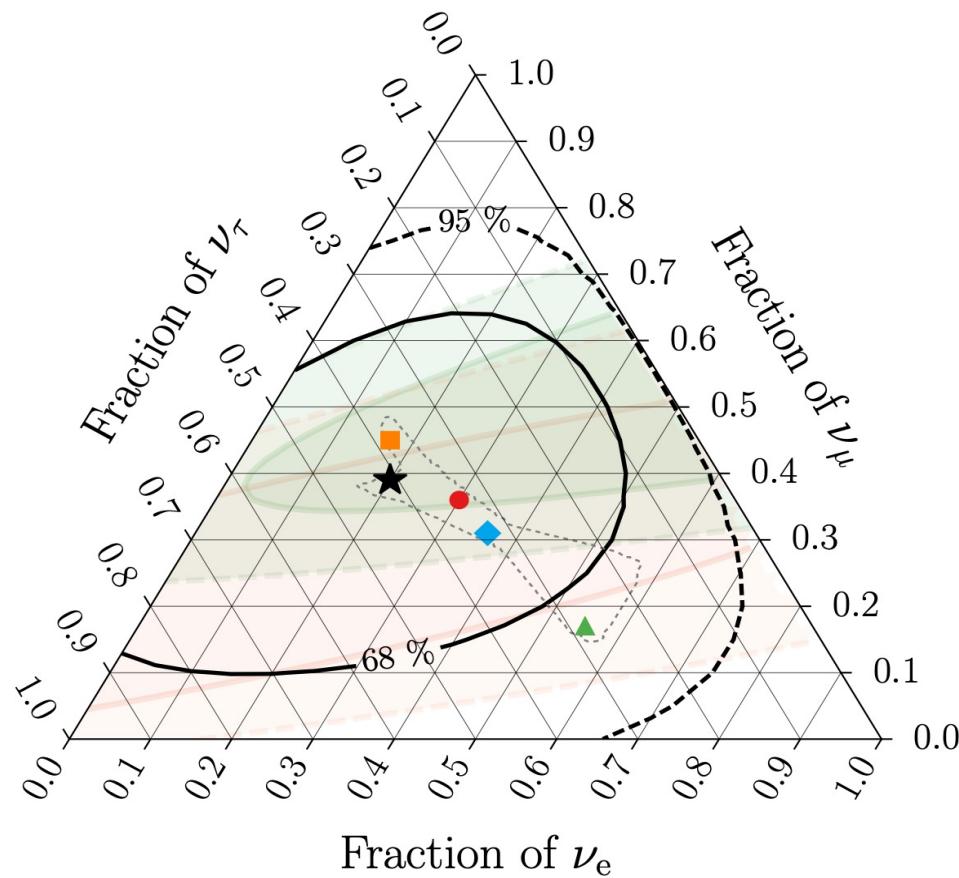
event found in 3 different analyses

a cosmic tau neutrino with 17m lifetime

light from nutau interaction and tau decay

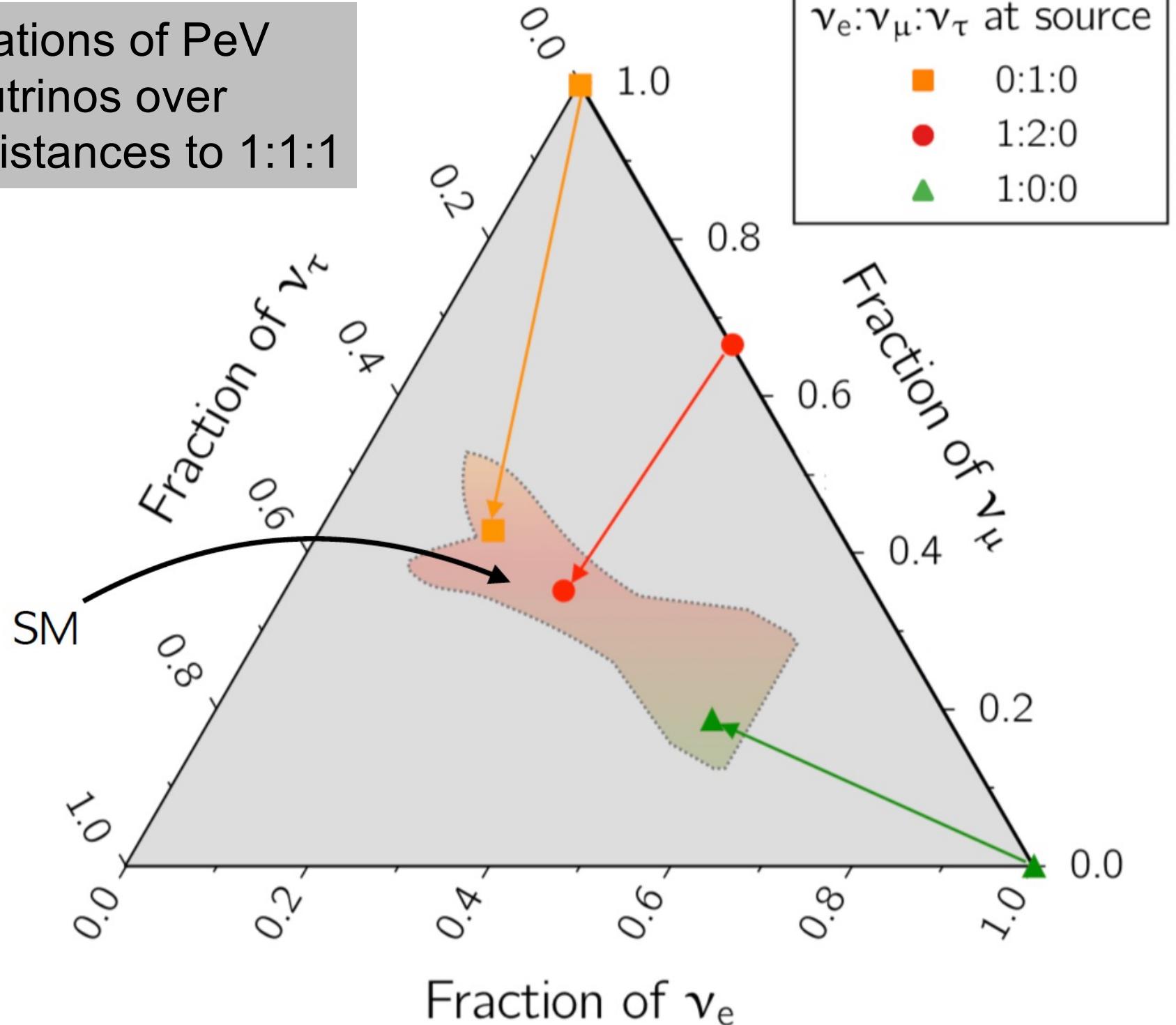


oscillations of PeV neutrinos over cosmic distances to 1:1:1

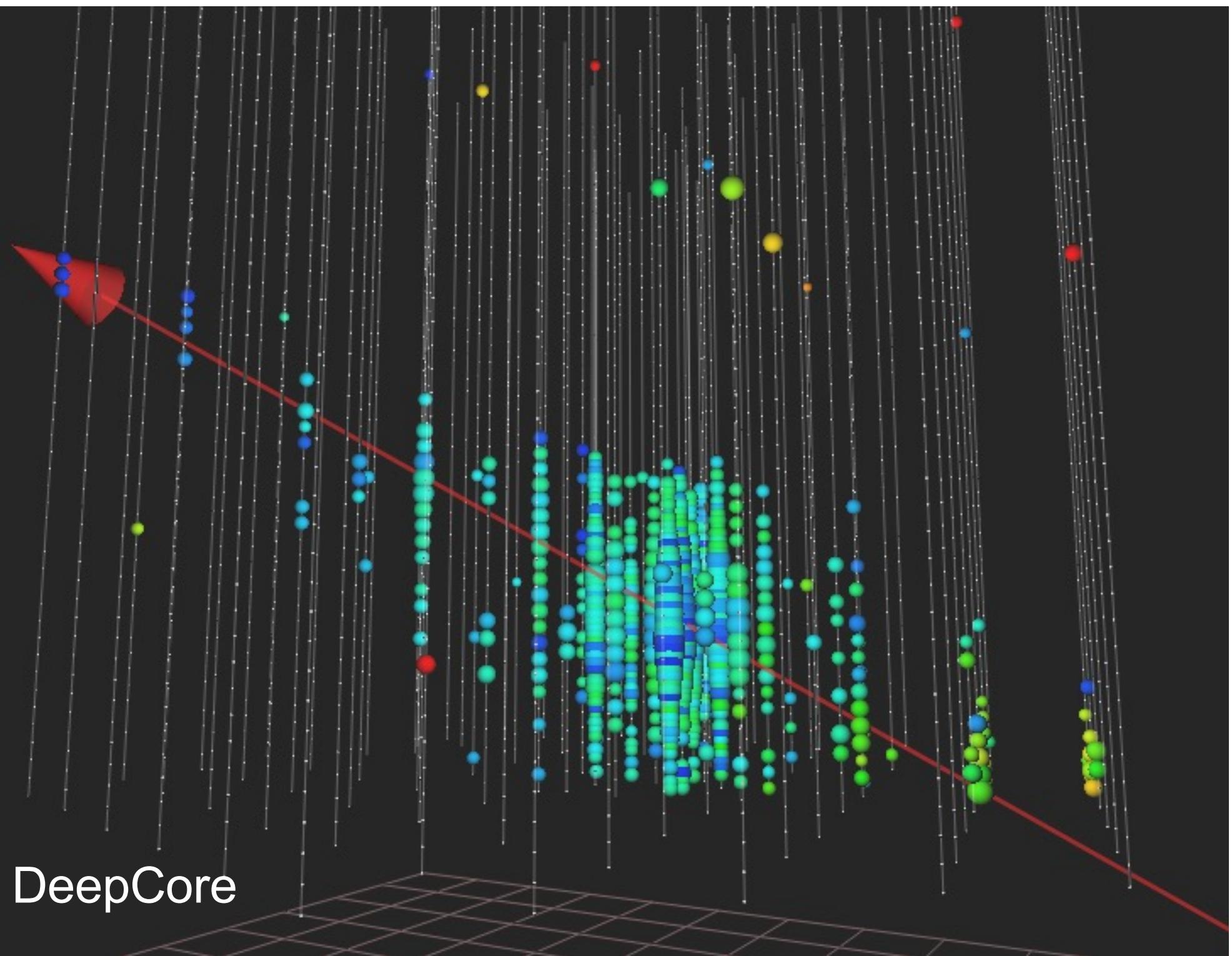


oscillating PeV neutrinos (7.5 years starting events)

oscillations of PeV
neutrinos over
cosmic distances to 1:1:1



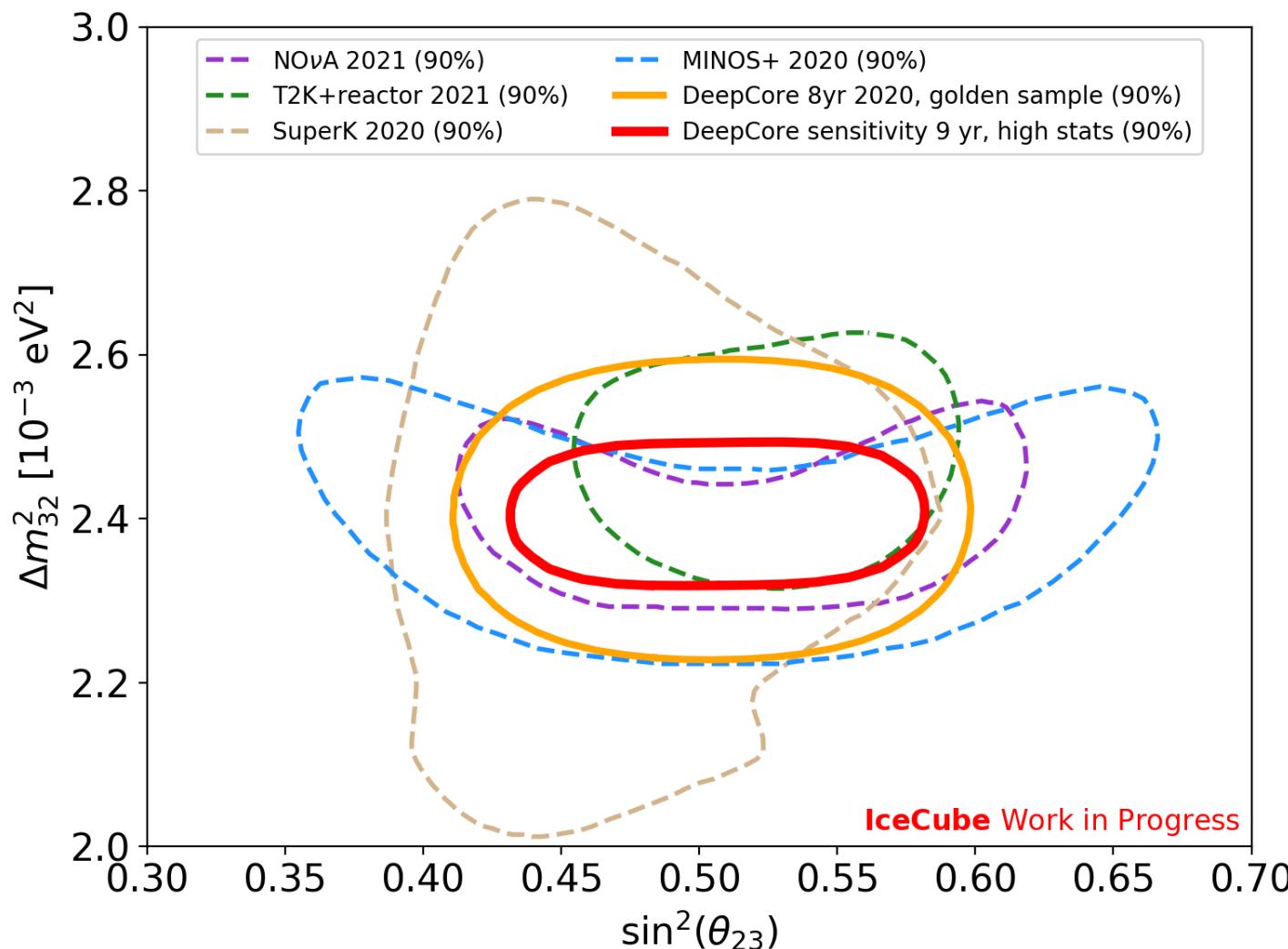
DeepCore



imminent unblinding:

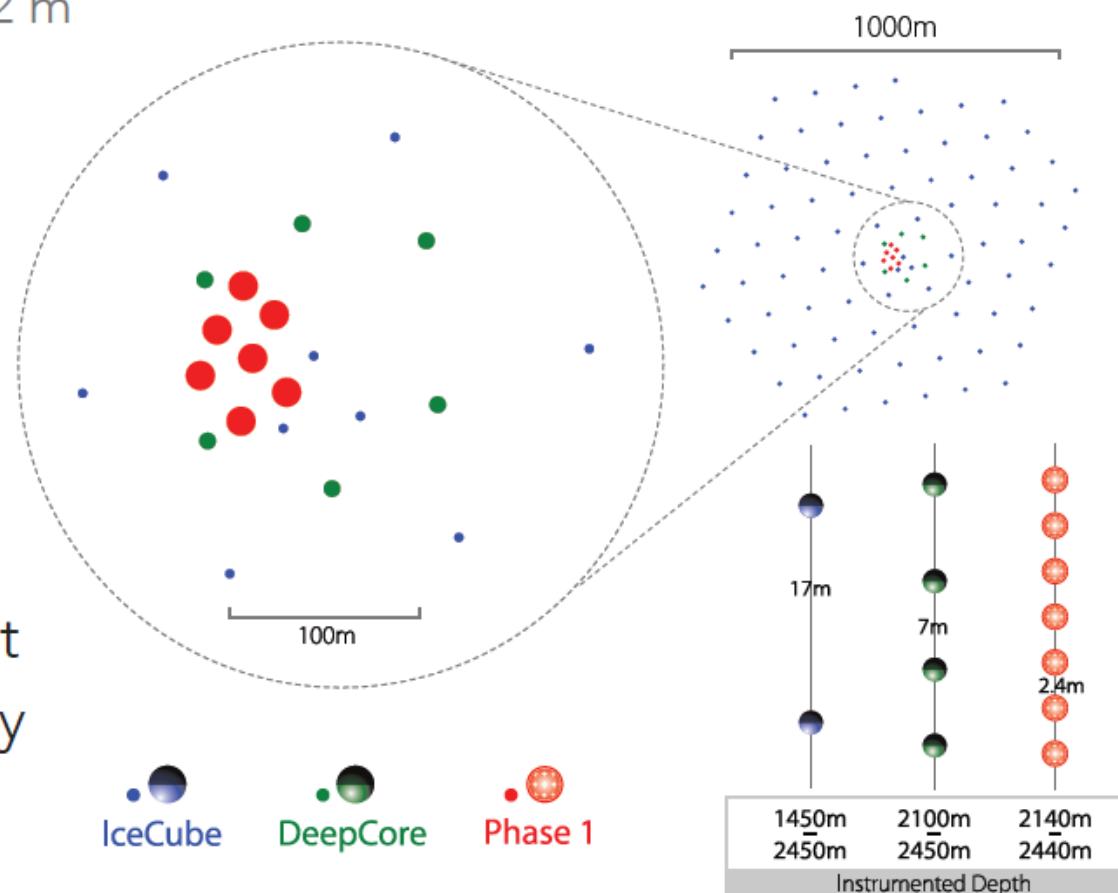
- analysis with a sample of 210,000 atmospheric neutrinos
- 9,600 tau neutrinos

(9.3 years and 97.3% purity with energies of 5~55 GeV)



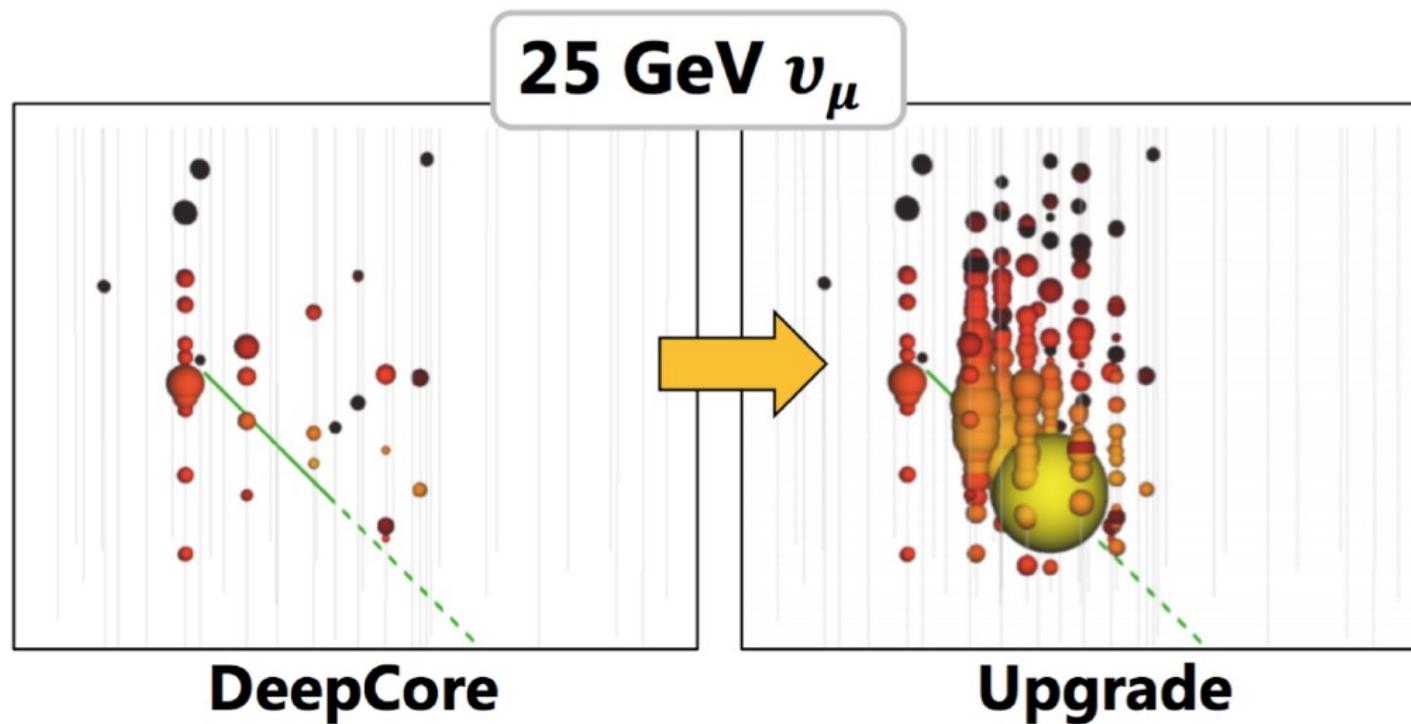
Next Step: the IceCube Upgrade (2022)

- Seven new strings of multi-PMT mDOMs in the DeepCore region
 - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



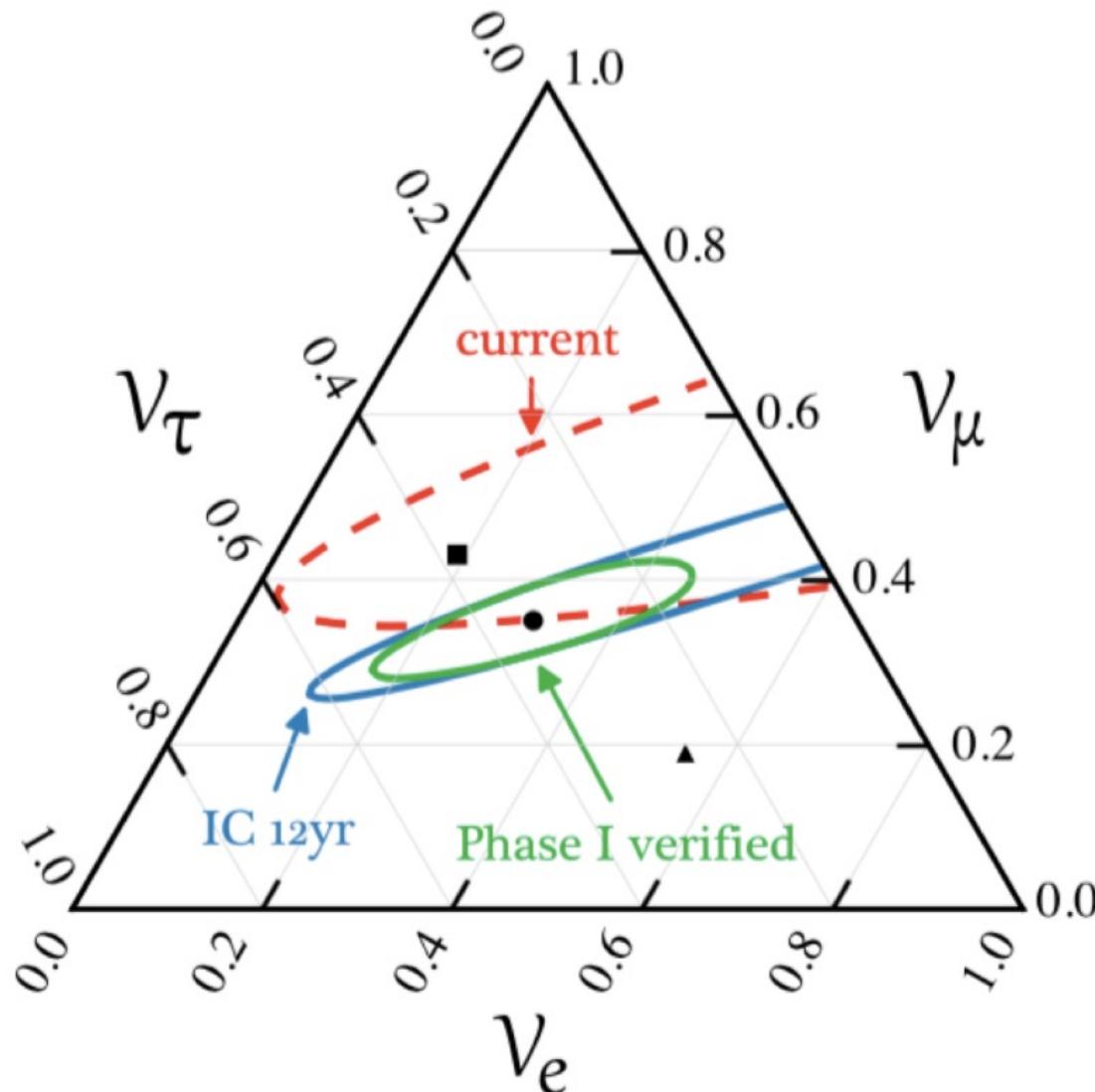
→ recalibration IceCube to reach 0.1° degree ang.res.

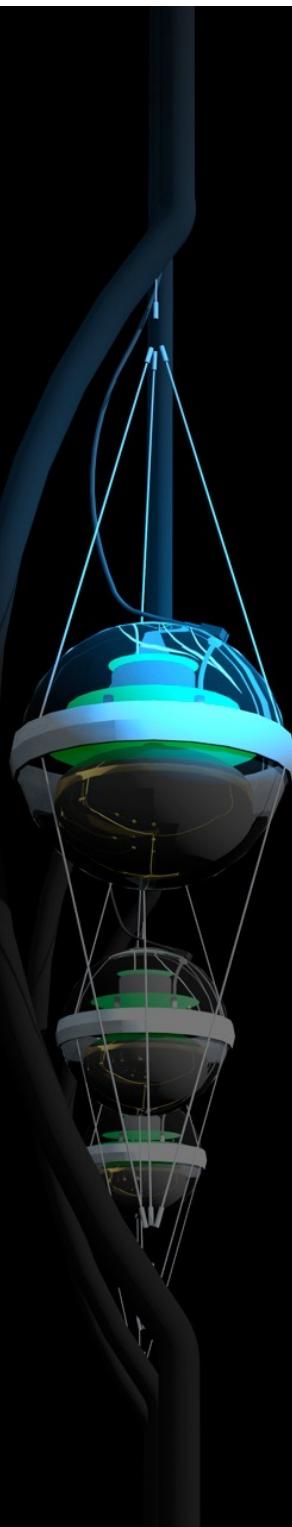
Low energy neutrinos in the Upgrade



ongoing upgrade: 2022 deployment

- neutrino oscillation at PeV energy
- nutau: test of the 3-neutrino scenario
- neutrino physics BSM
- IceCube Gen2 pathfinder





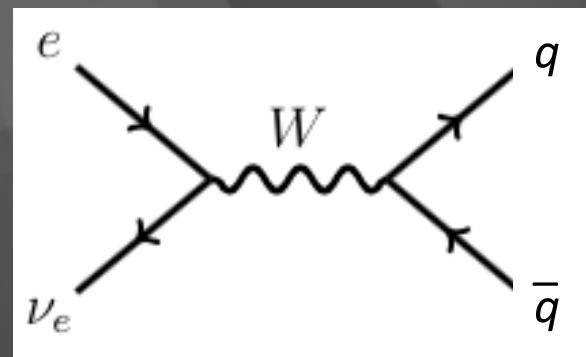
neutrino astronomy

- cosmic neutrinos: four independent observations
 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
 - tau neutrinos
 - Glashow event

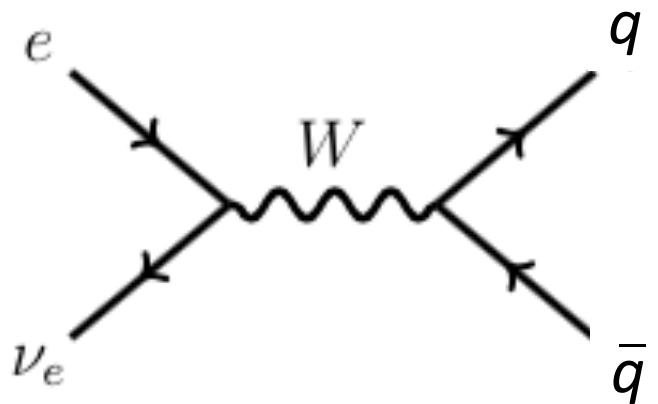
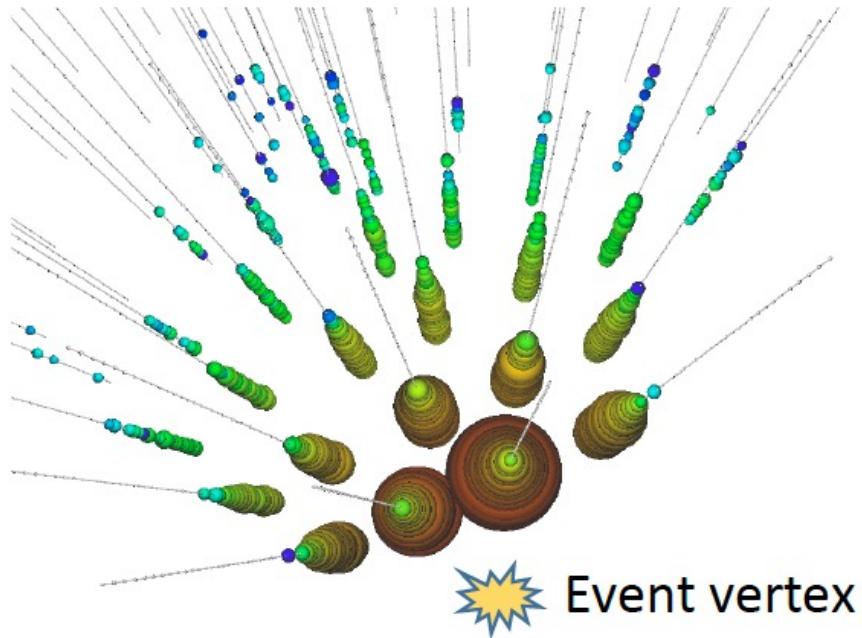
multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

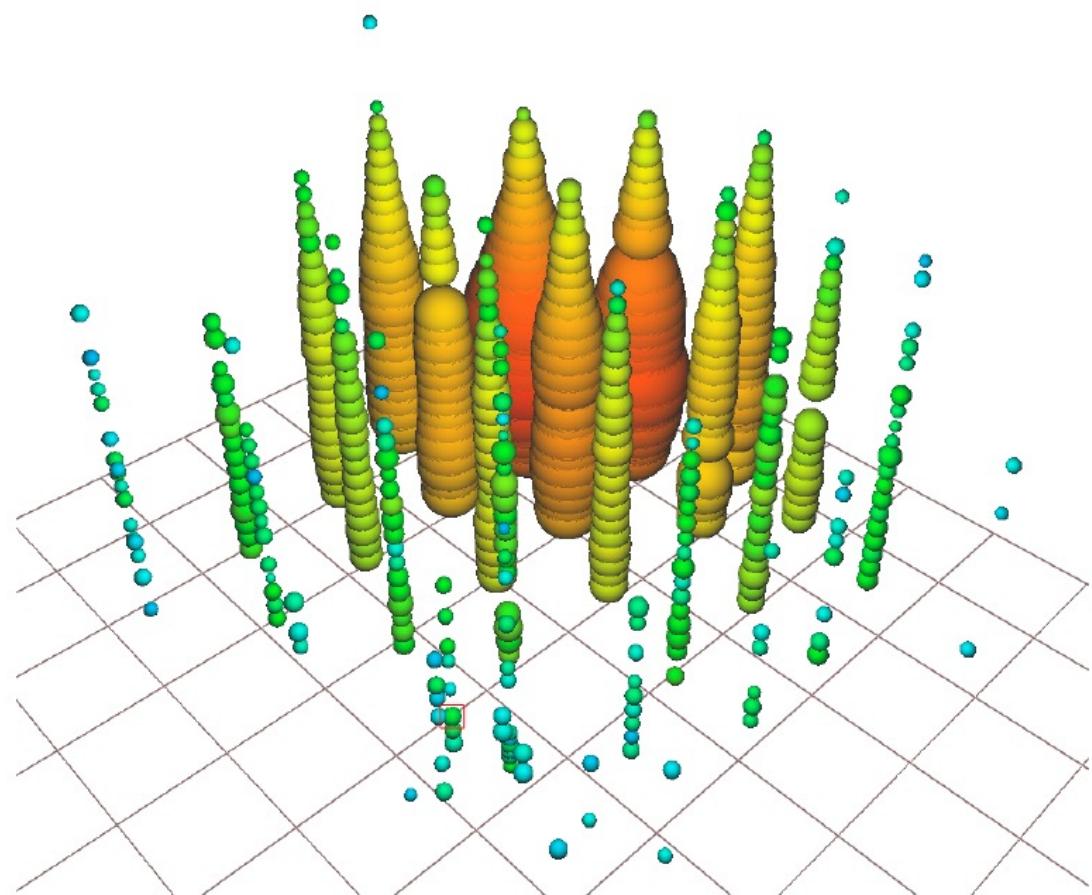
the first Glashow resonance event:
anti- ν_e + atomic electron \rightarrow real W at 6.3 PeV



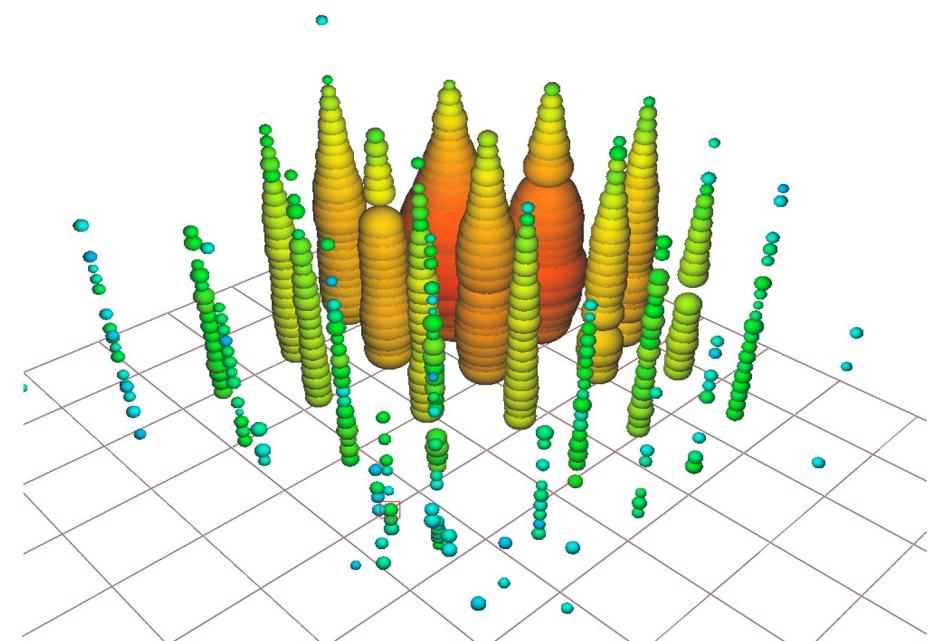
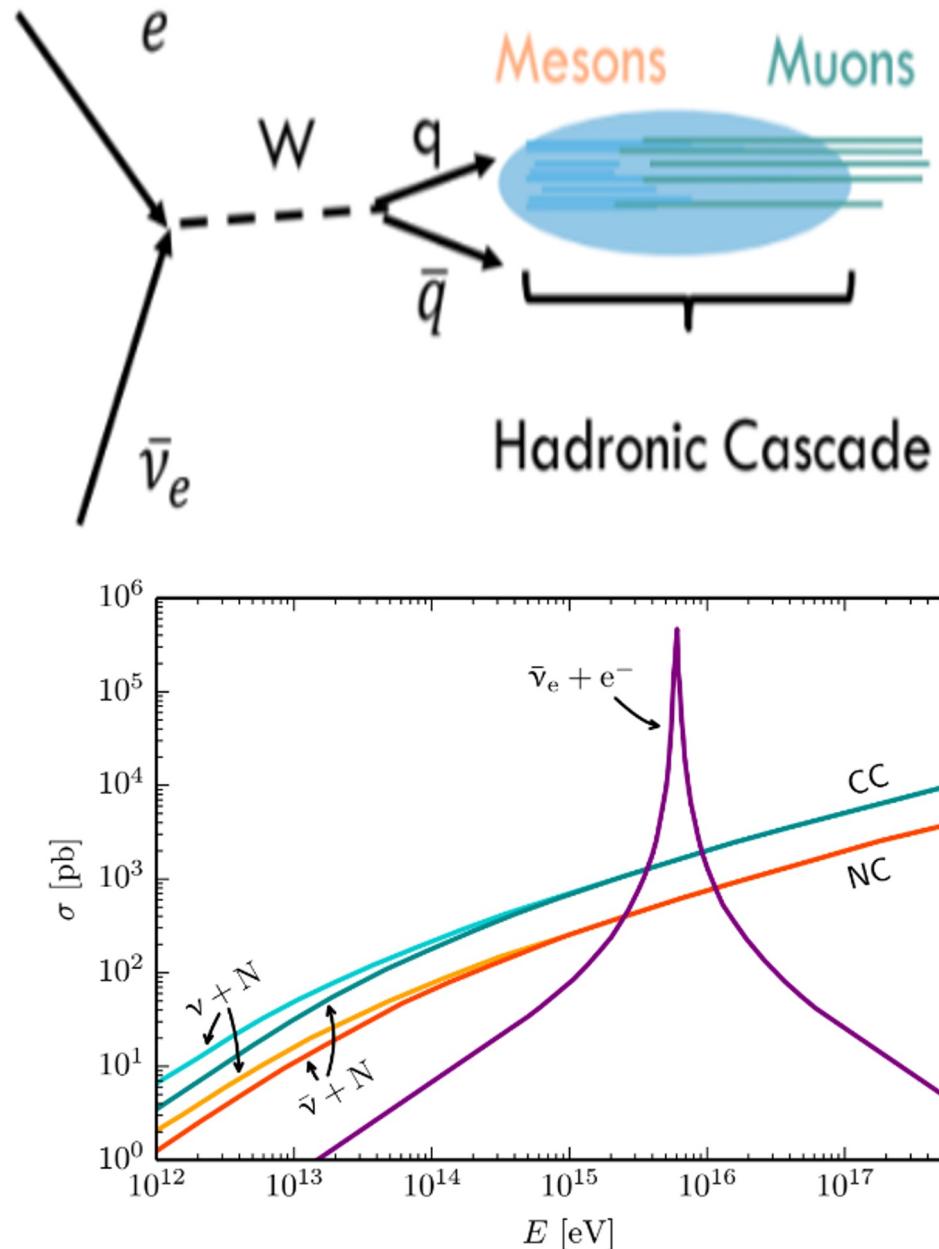
partially contained event with energy 6.3 PeV



resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron



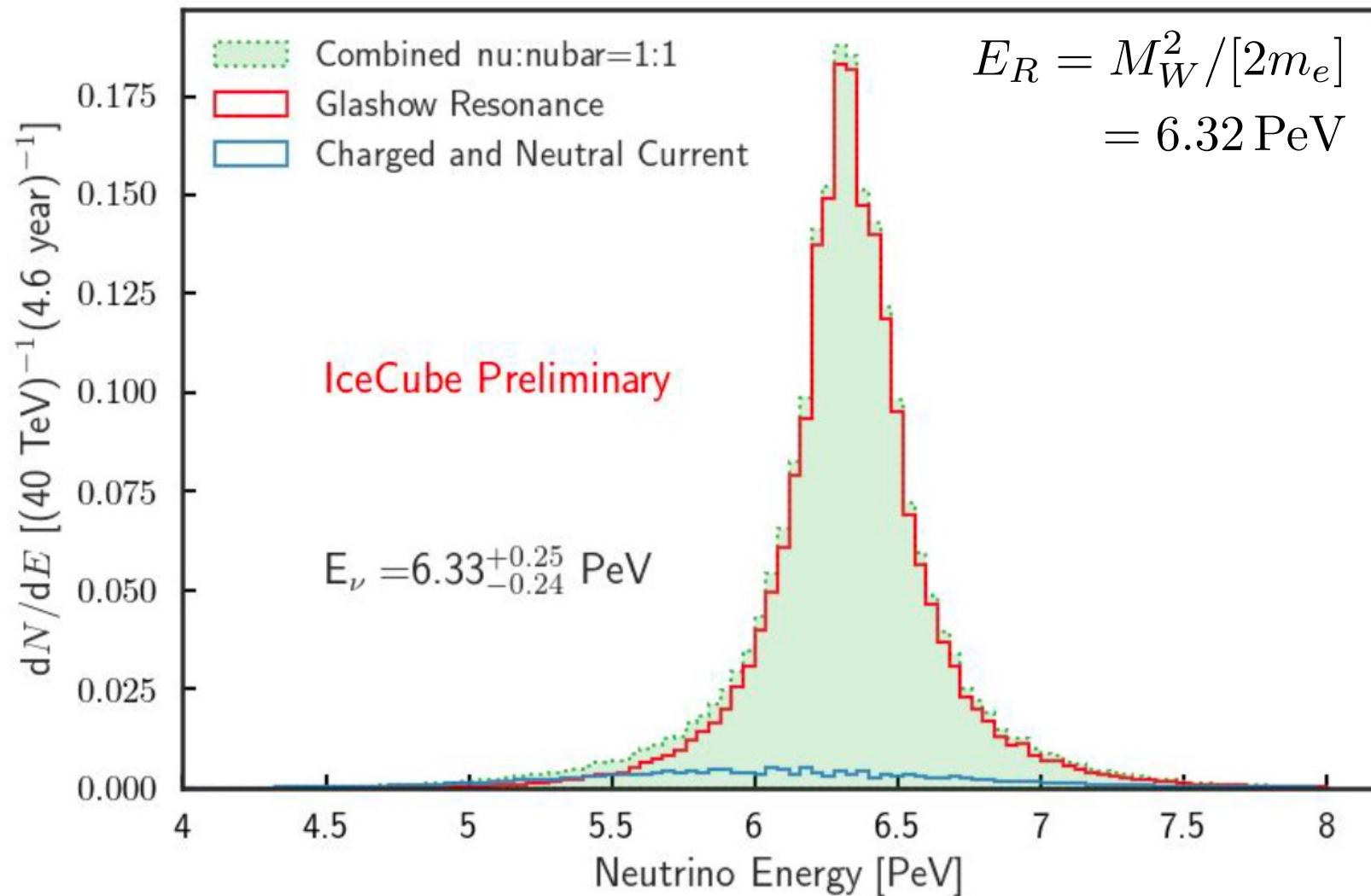
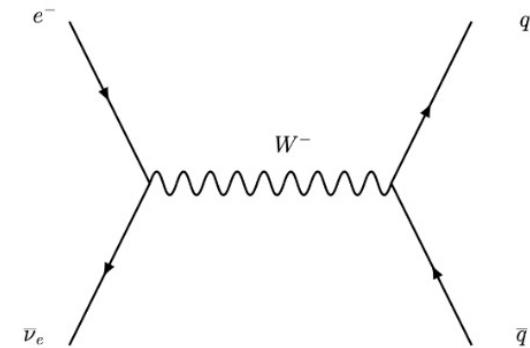
Glashow resonance: anti- ν_e + atomic electron \rightarrow real W



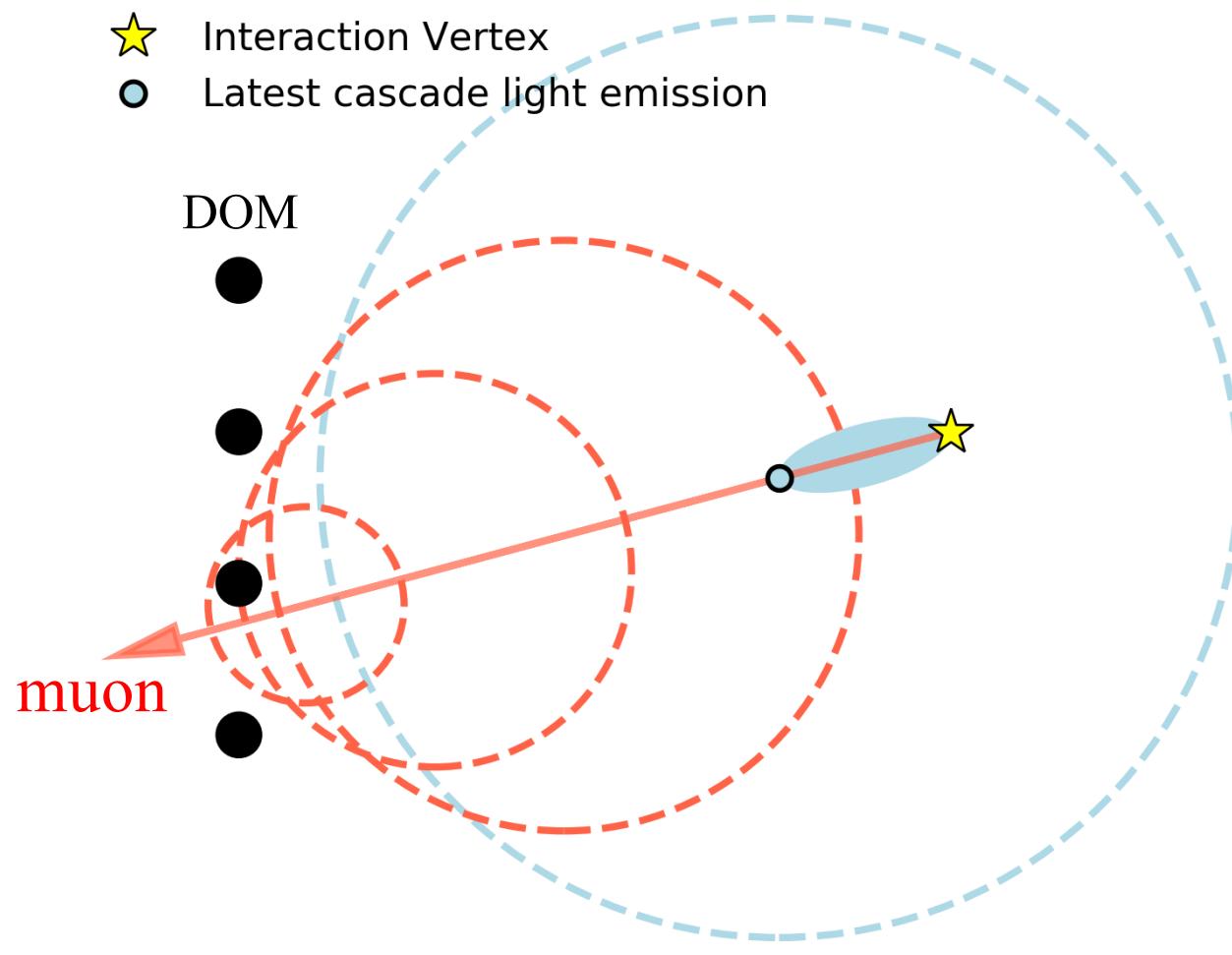
- partially-contained PeV search
- deposited energy: 5.9 ± 0.18 PeV
- visible energy is 93%
- \rightarrow resonance: $E_\nu = 6.3$ PeV

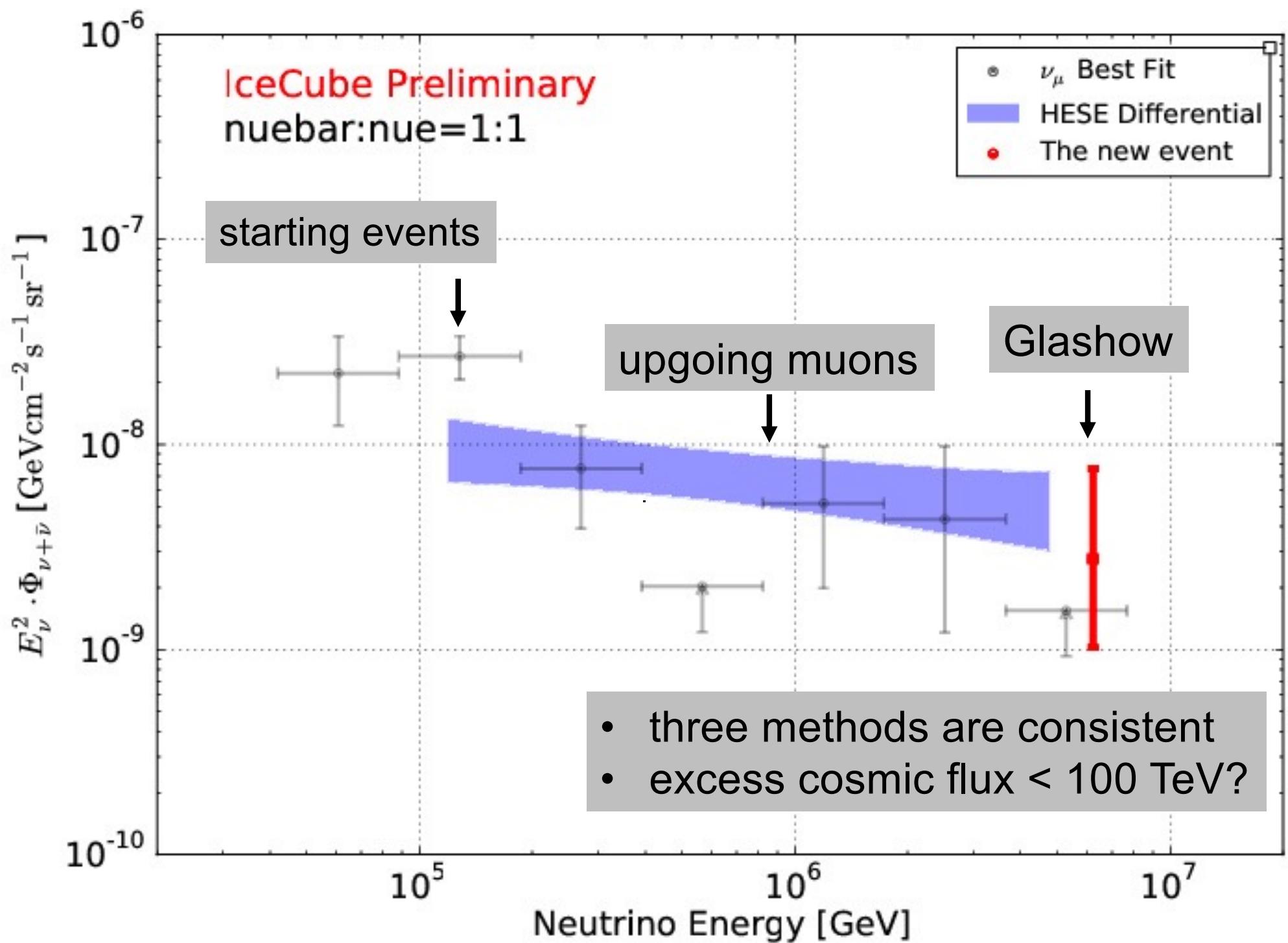
work on-going

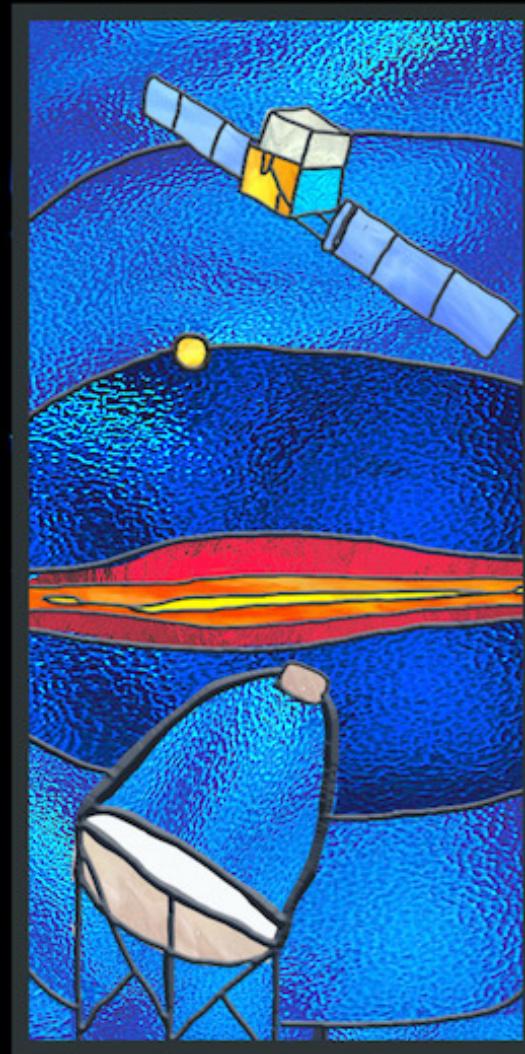
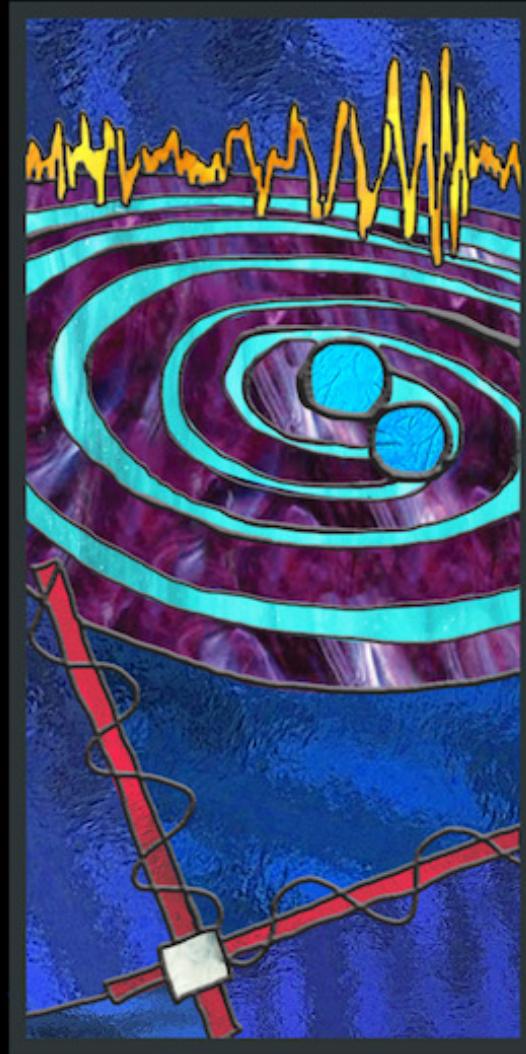
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino



- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?
- muons from pions ($v=c$) outrace the light propagating in ice that is produced by the electromagnetic component ($v < c$)







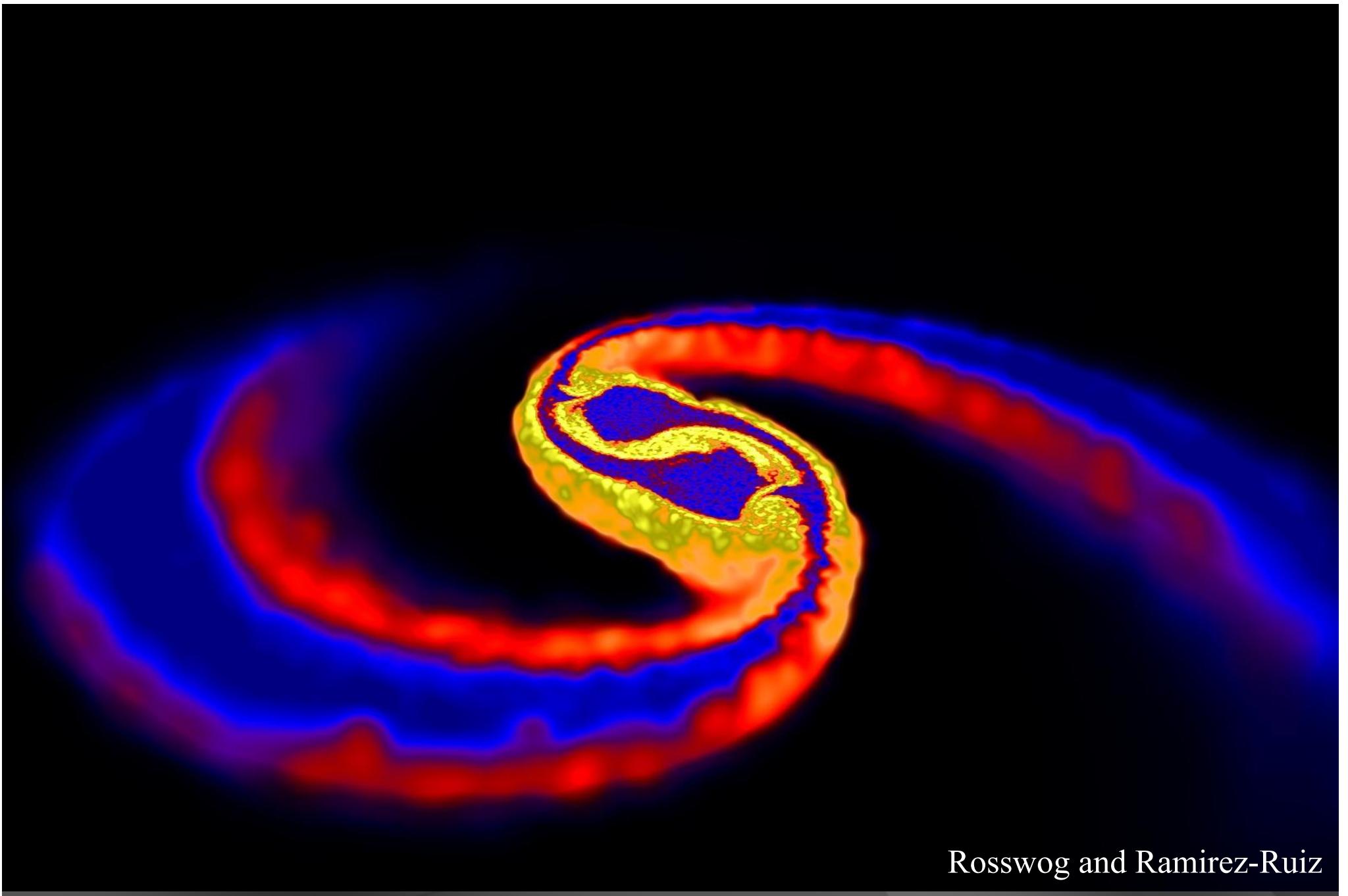
next attraction: gravitational waves + neutrinos?

(August 17, 2017 neutron star merger: jet not aligned ☹)

neutron star-neutron star merger

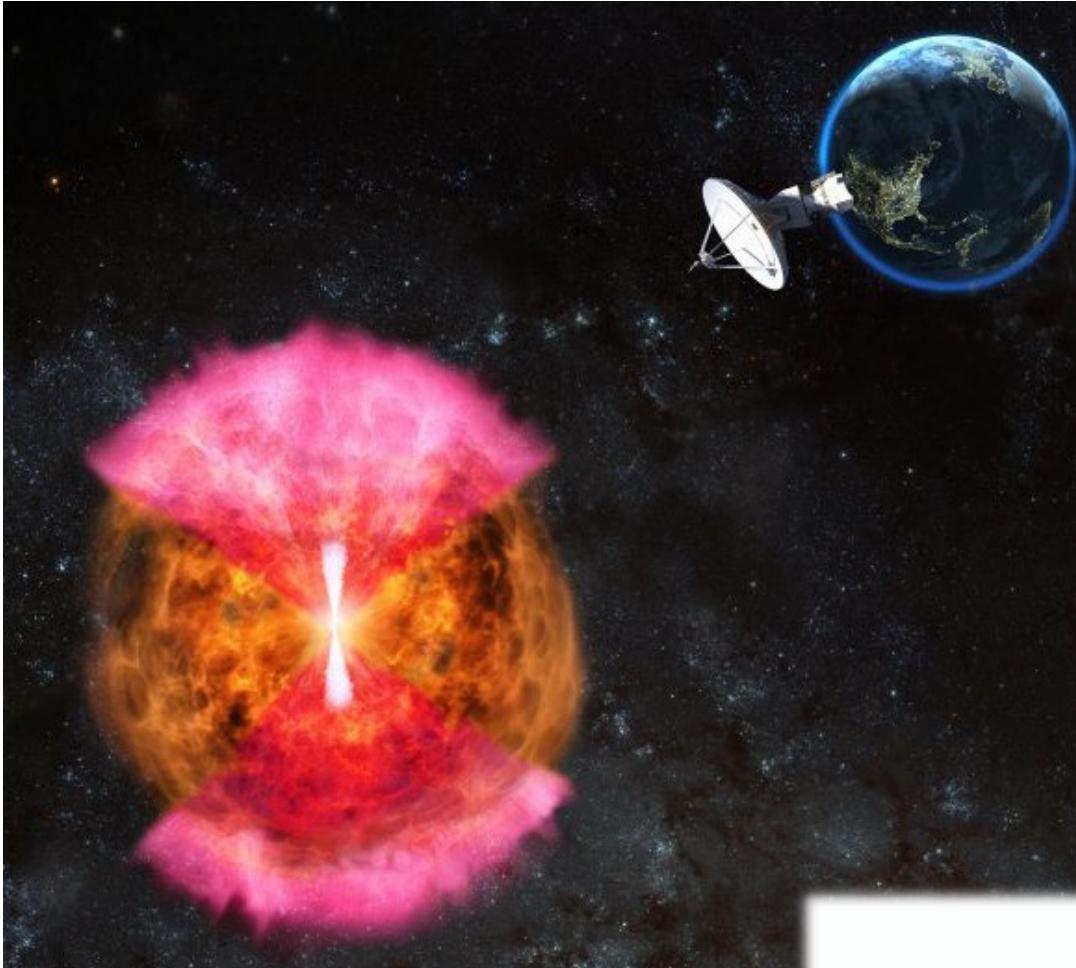


LIGO-VIRGO



Rosswog and Ramirez-Ruiz

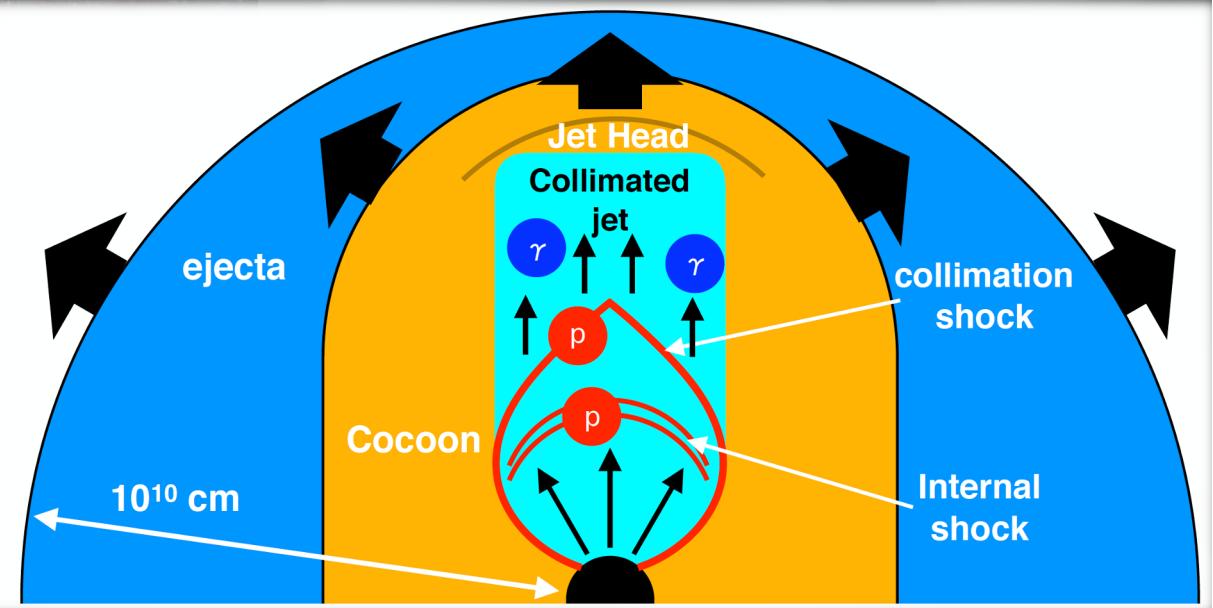
merger of neutron stars about to launch a jet

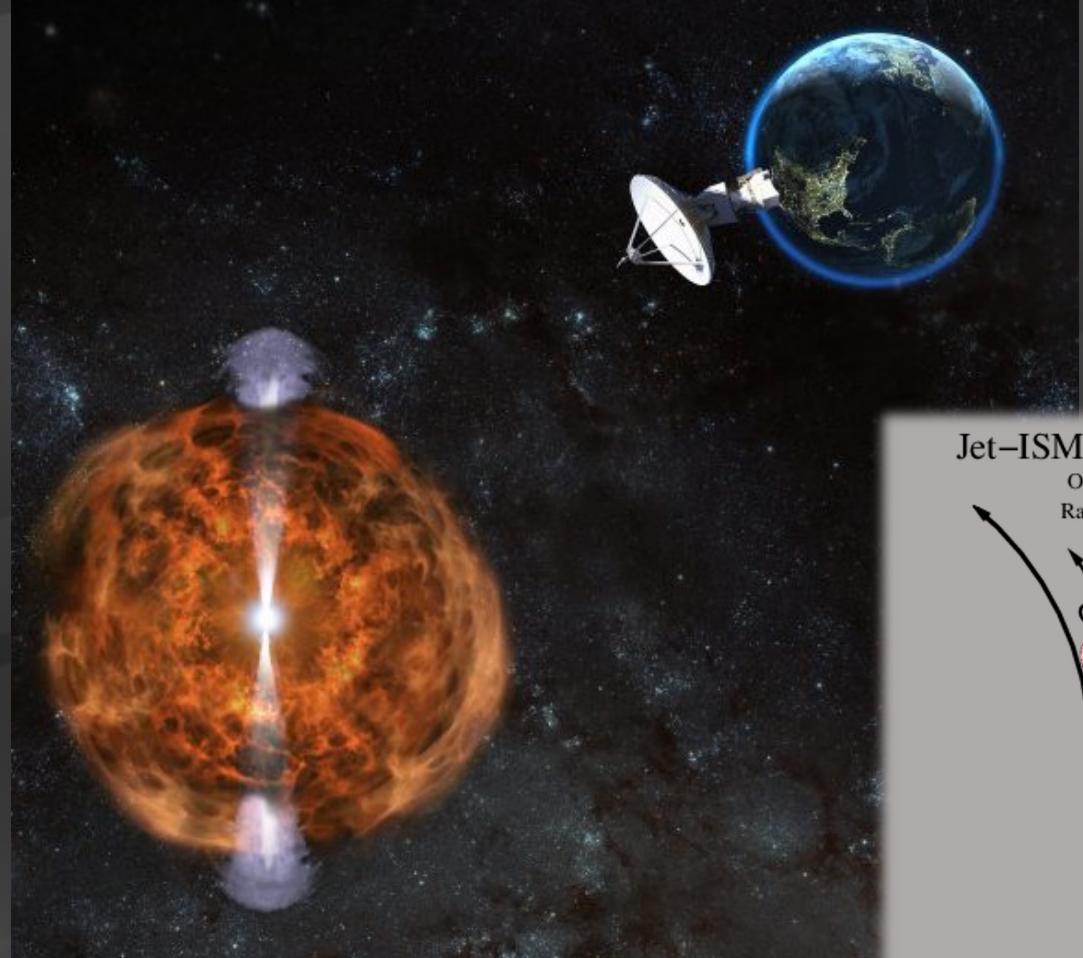


high-energy neutrinos:
from collimation (TeV) and
internal shocks (PeV):

protons photoproduce neutrinos

- on photons from leakage of the collimated jet
- on synchrotron photons from electrons (internal shock)





neutron star mergers

*very weak short GRB
seen by Fermi
(off axis)*

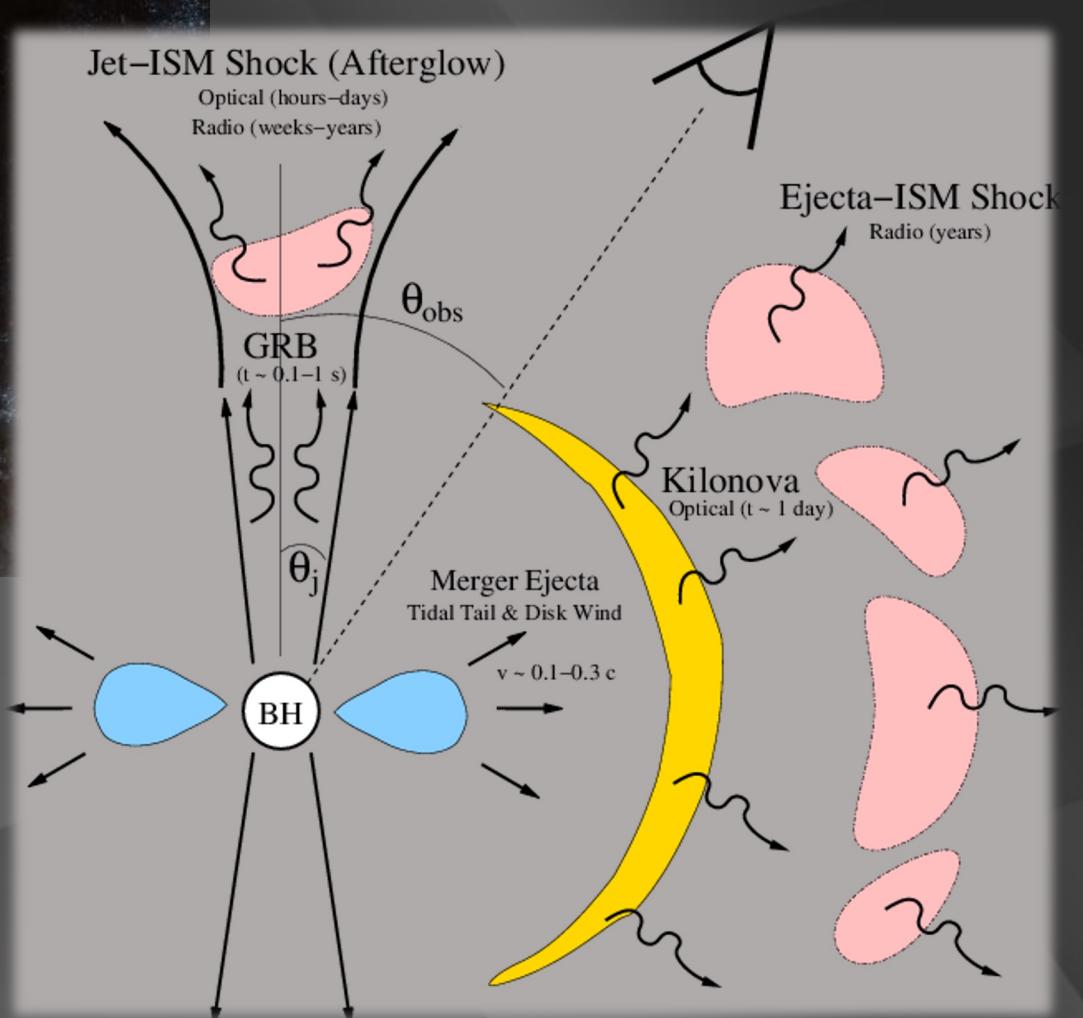
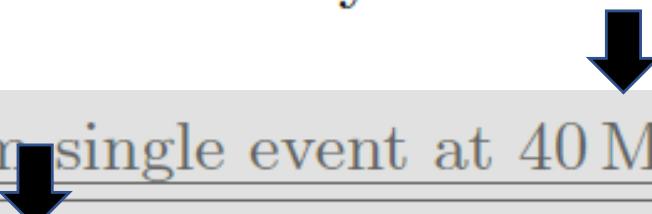


TABLE II. Detection probability of neutrinos by IceCube and
IceCube-Gen2



Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

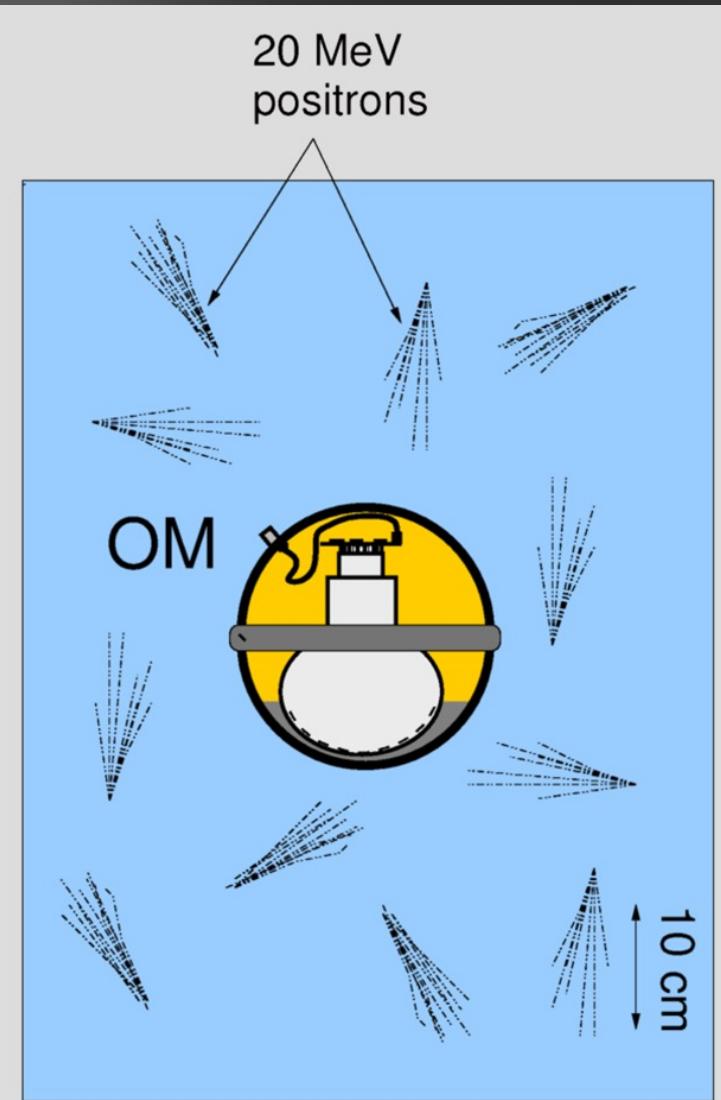
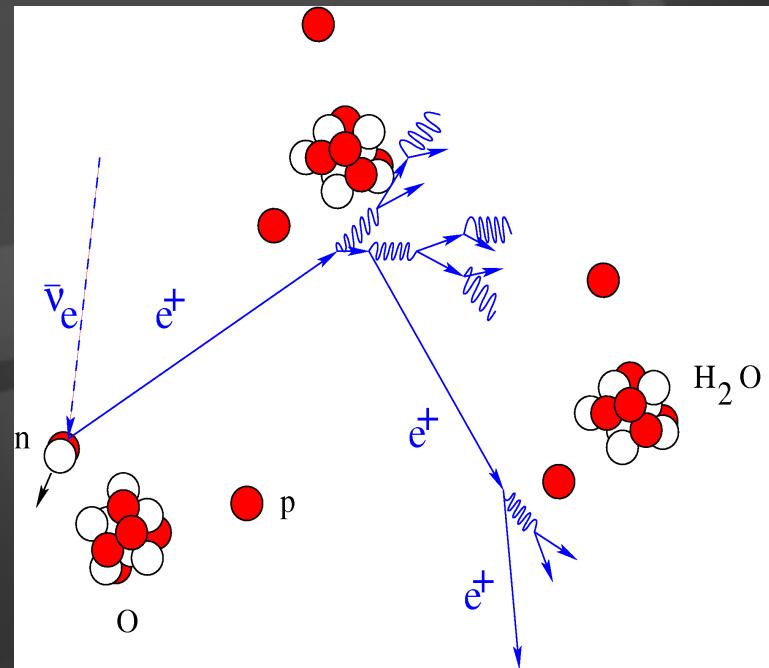
Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28

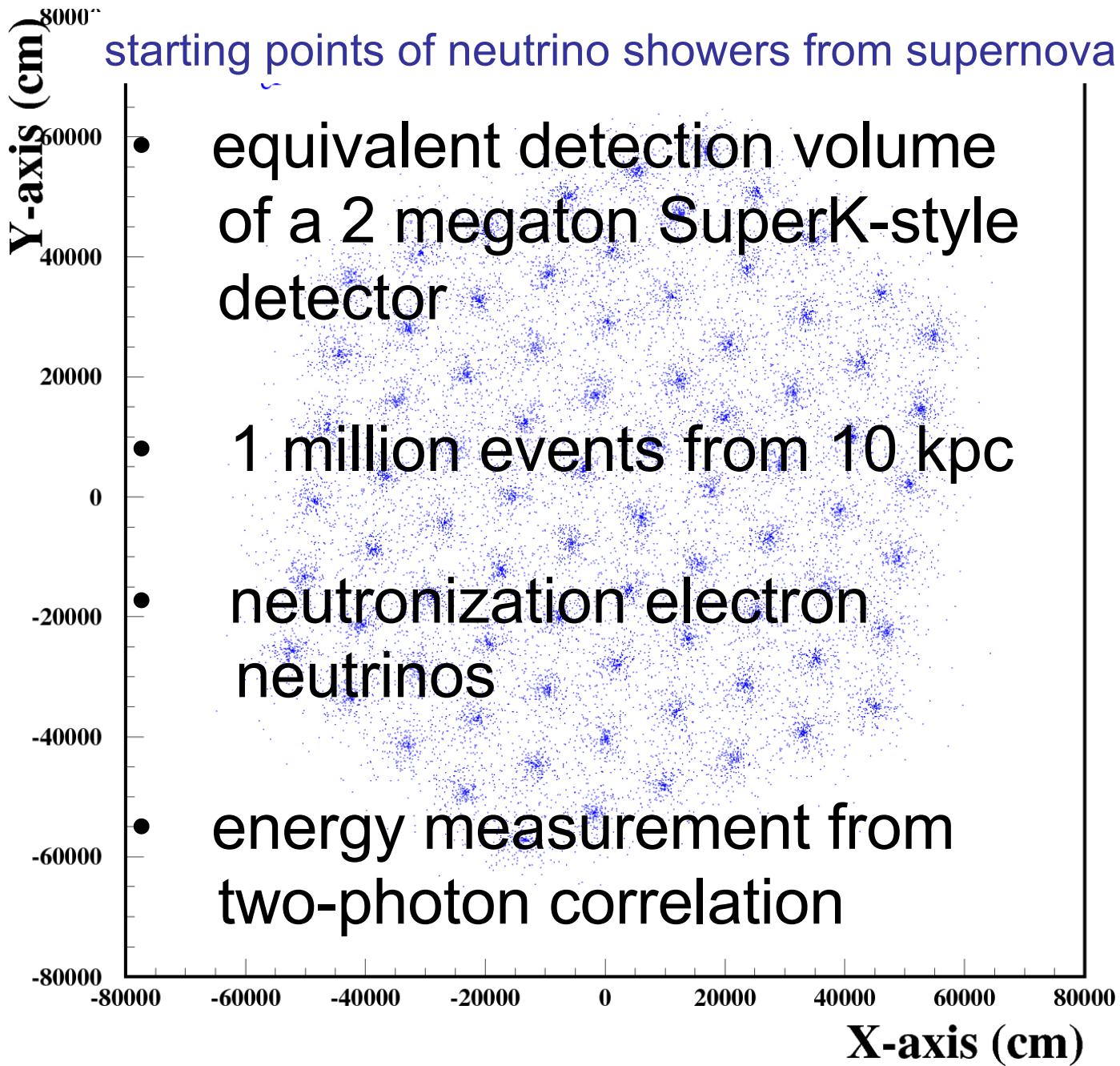
supernova 1987a: 24 neutrinos, thousands of papers



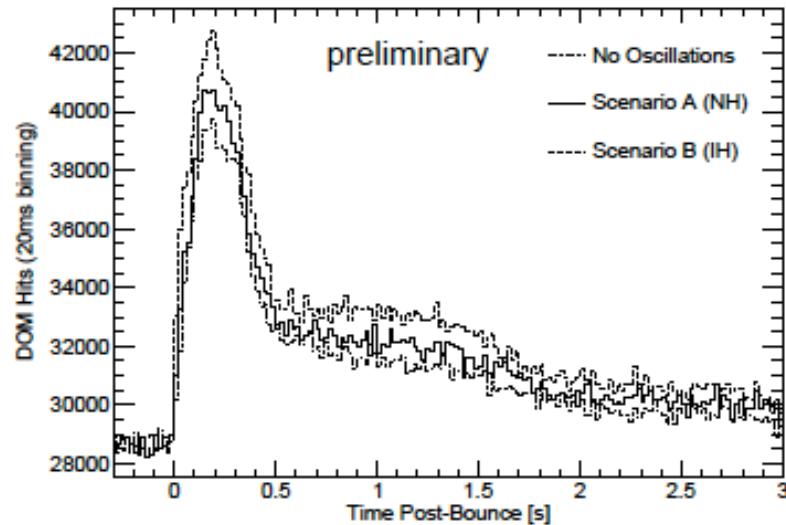
supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$



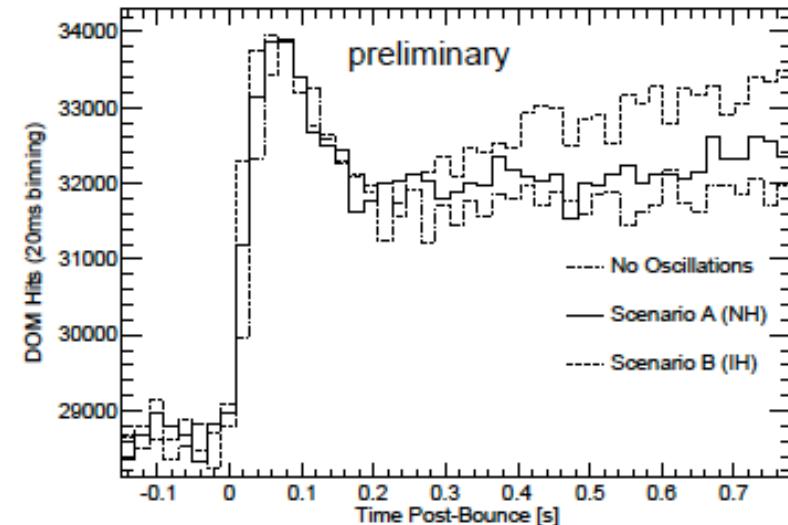
- 👉 PMT noise low (280 Hz)
- 👉 detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector



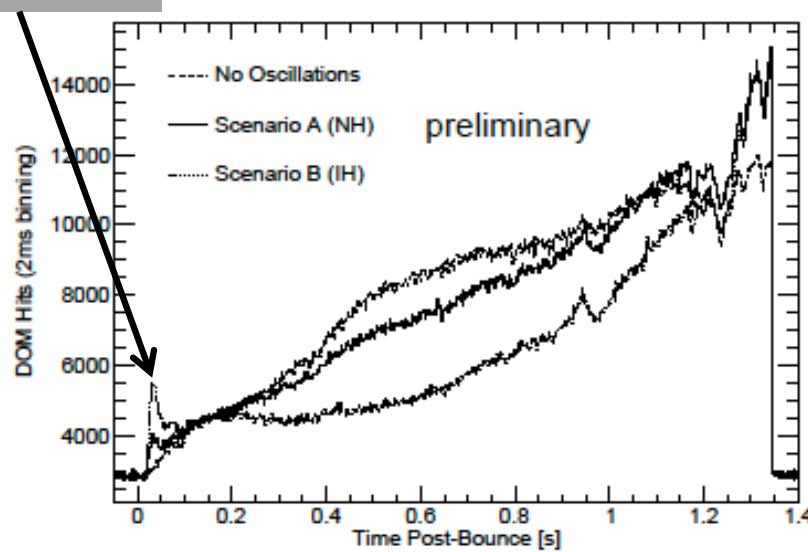
Livermore



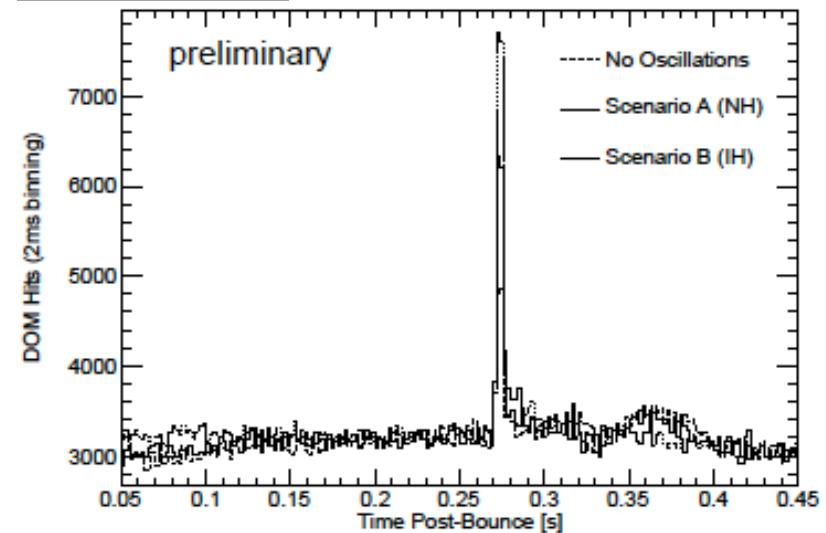
Garching



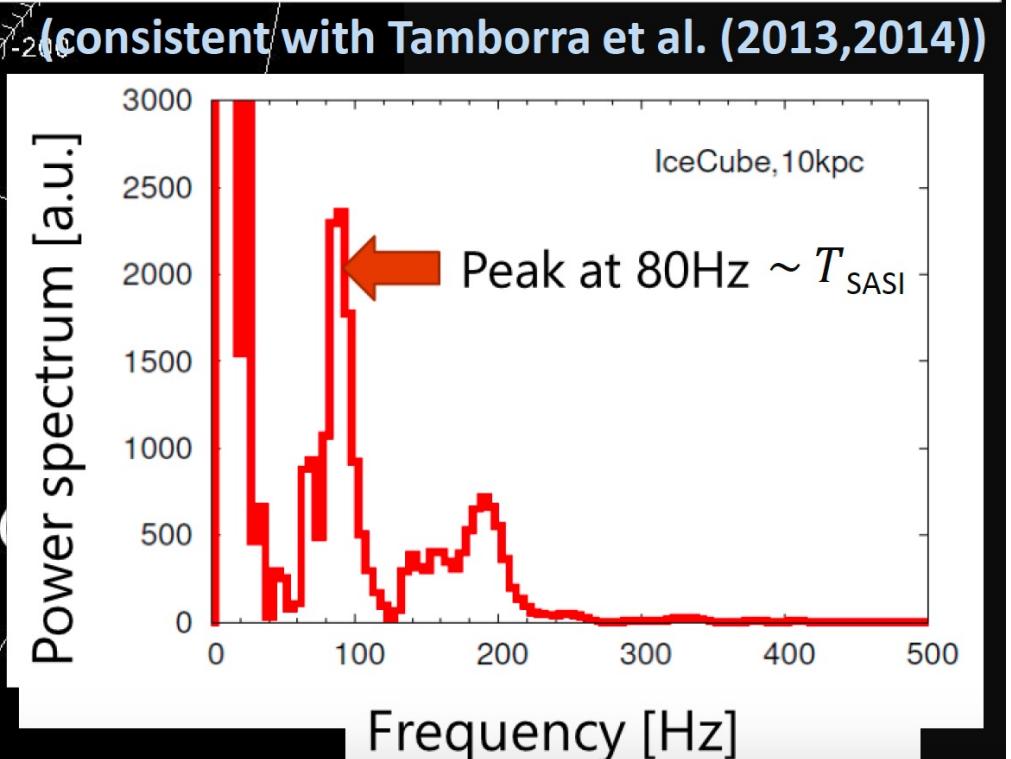
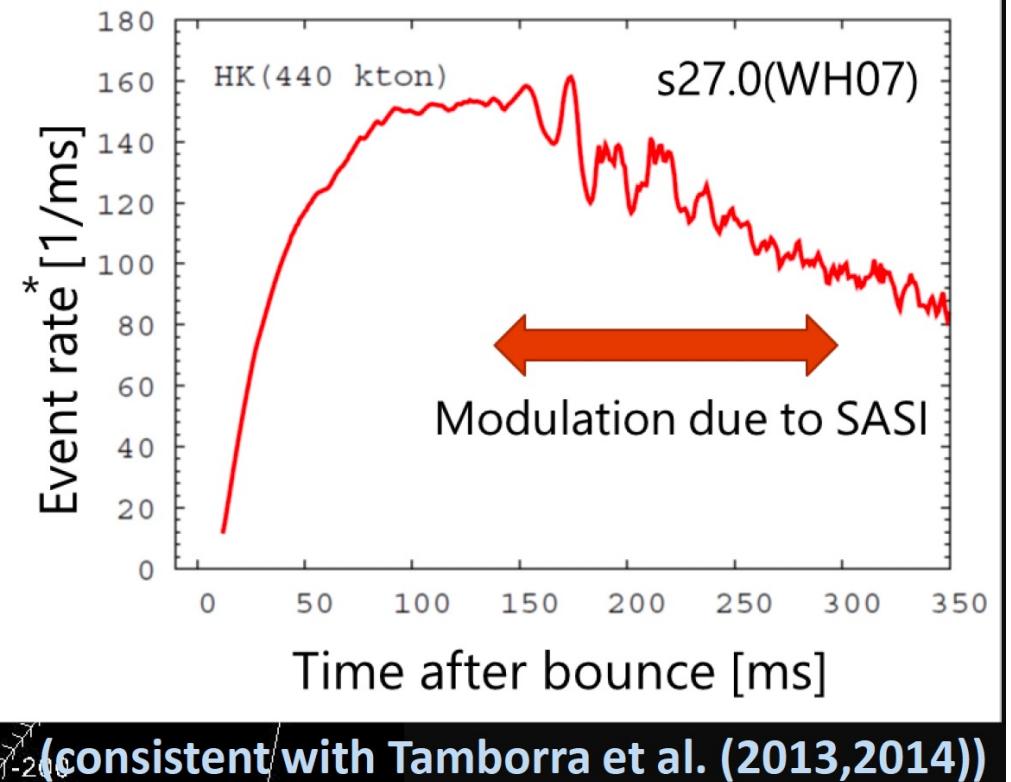
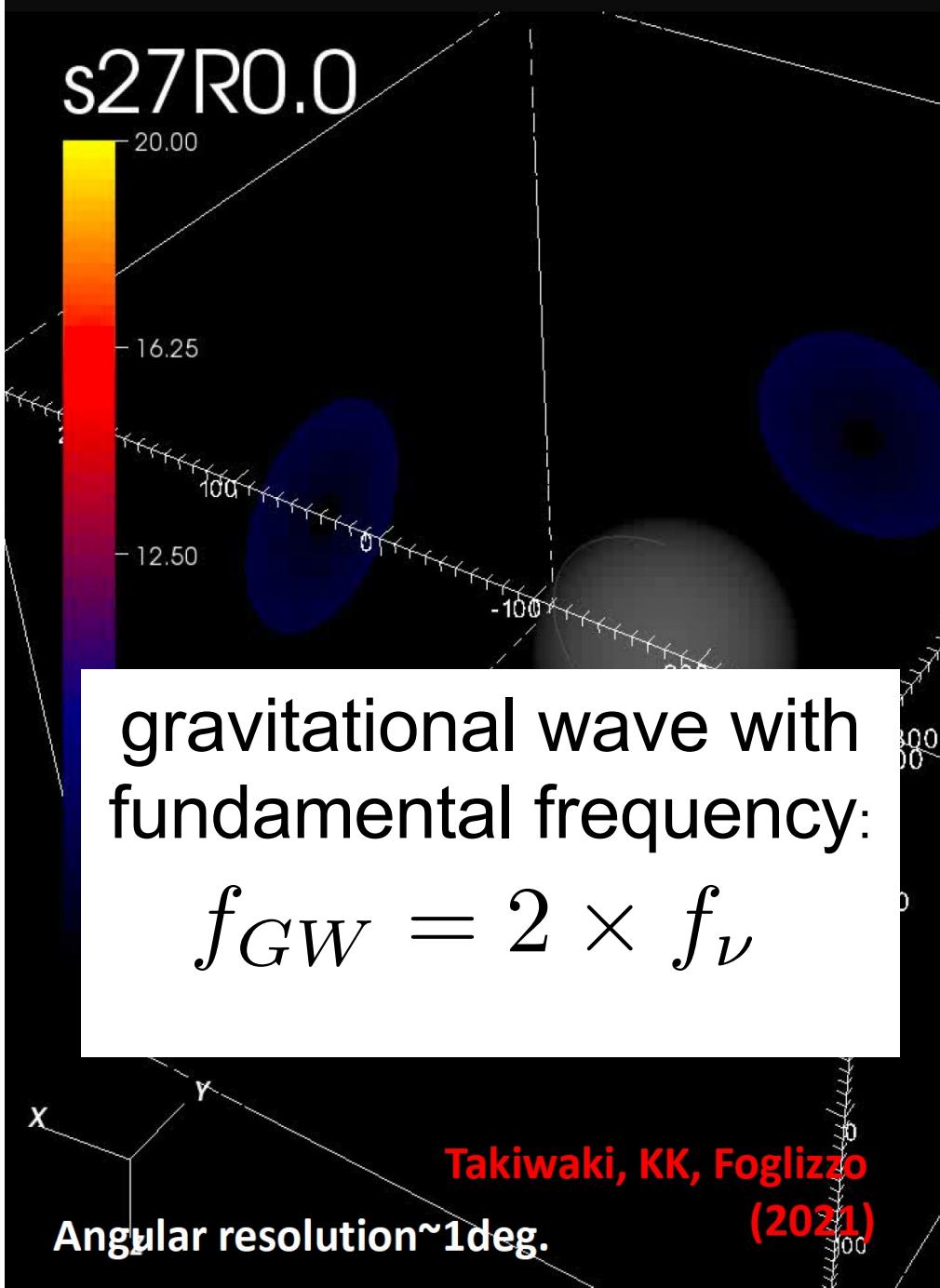
quark star

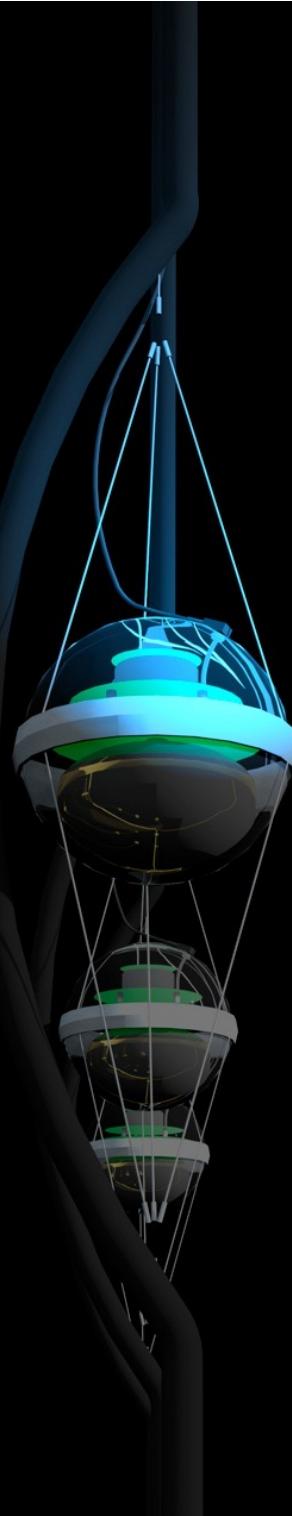


black hole



$27 M_{\text{sun}}$ progenitor (WH07)





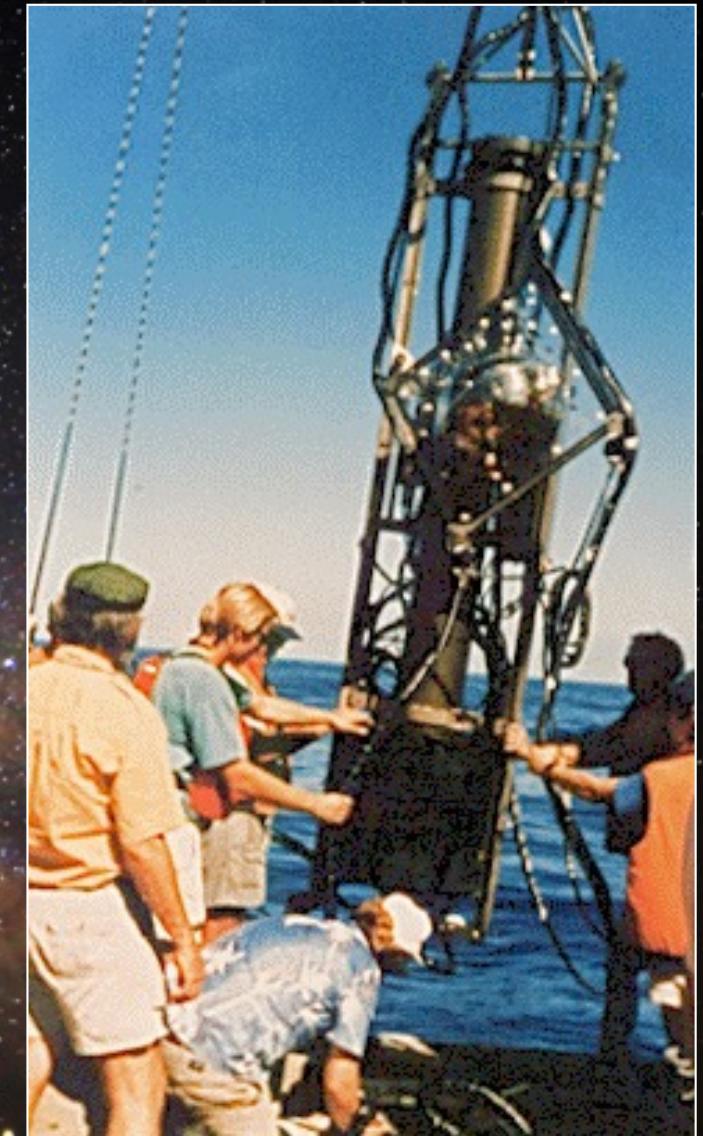
IceCube: the discovery of cosmic neutrinos

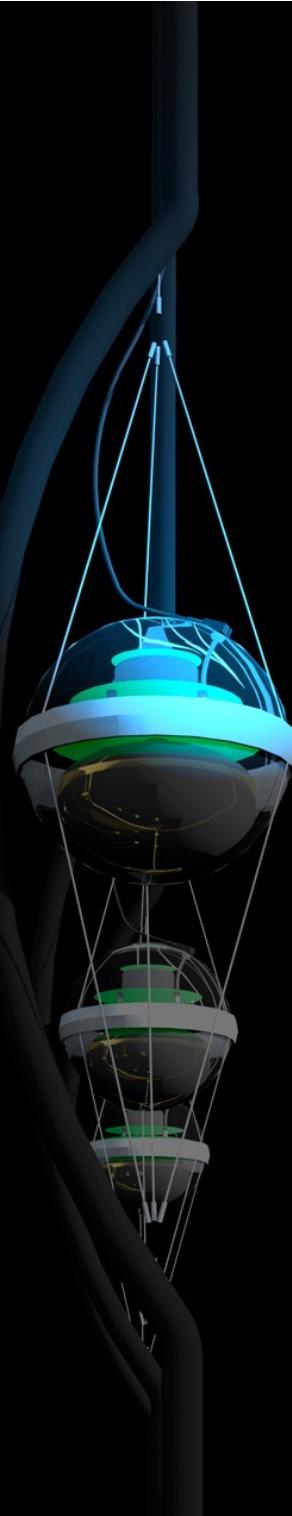
francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

standing on the shoulder of giants

1987: DUMAND test string





IceCube: the discovery of cosmic neutrinos

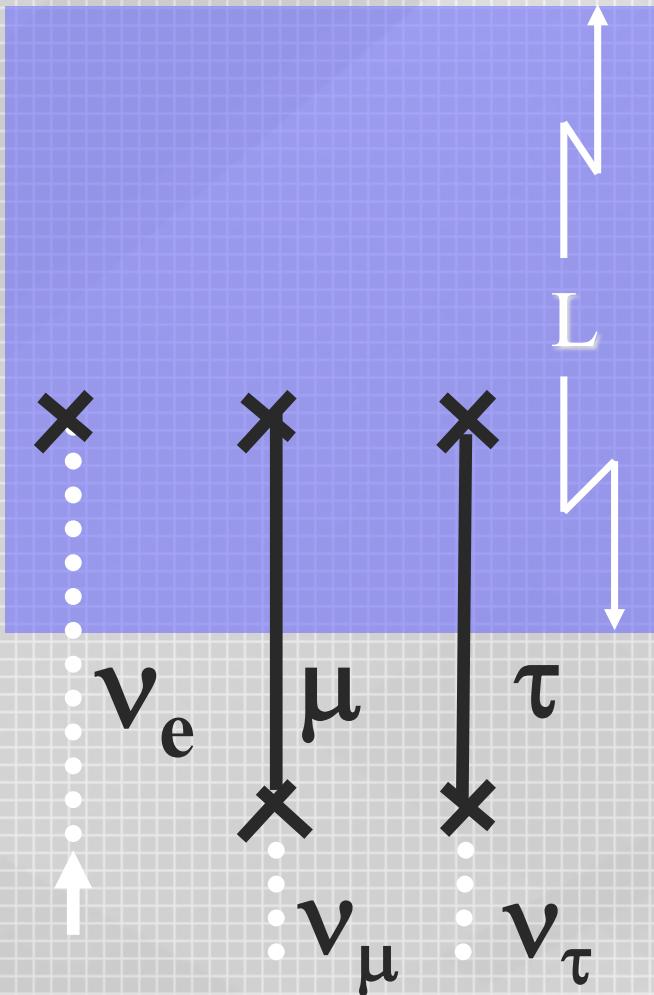
francis halzen

- cosmogenic neutrinos
- cosmic ray accelerators
- intermezzo on effective area
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

neutrino detection probability

neutrino
survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino
detected

$$1 - e^{-\frac{L}{\lambda_\nu}} \approx \frac{L}{\lambda_\nu}$$

$$\text{for } \nu_\mu \quad L \rightarrow R_\mu [E_\mu = (1 - y) E_\nu]$$

$$\text{for } \nu_\tau \quad L \rightarrow (E_\tau / m_\tau) c \tau_\tau$$

$$P_{\text{det}} = n \sigma_\nu L$$

neutrino and muon area

$$\begin{aligned} \text{events} &= A_\nu \times \Phi_\nu \\ &= A_\mu \times P_{\nu \rightarrow \mu} \times \Phi_\nu \end{aligned}$$

$$P_{\nu \rightarrow \mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \simeq 10^{-6} E_{TeV}$$

$$A_\nu = P_{\nu \rightarrow \mu} A_\mu$$

neutrino and muon area

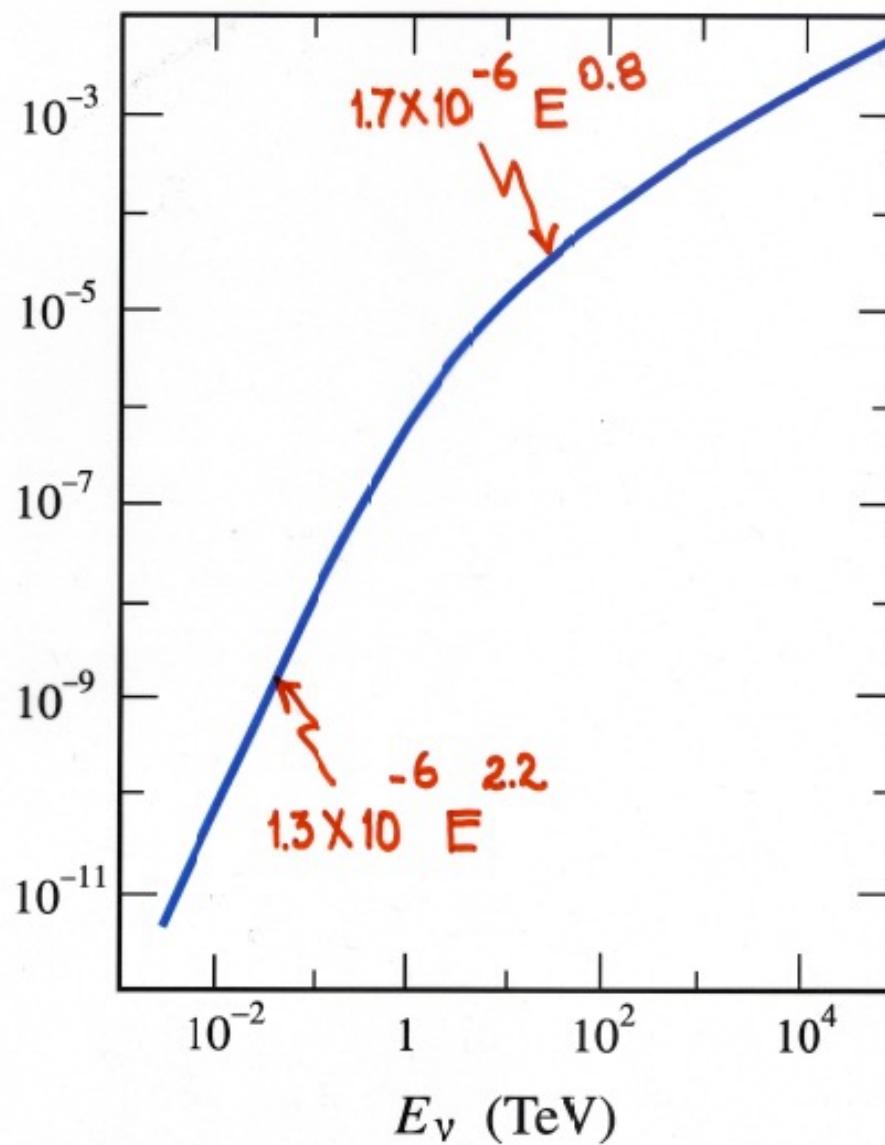
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu \rightarrow \mu} \times \Phi_\nu$$

$$P_{\nu \rightarrow \mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu \rightarrow A_\nu = P_{\nu \rightarrow \mu} \ P_{survival} \ A_\mu$$

- $P_{\nu \rightarrow \mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$

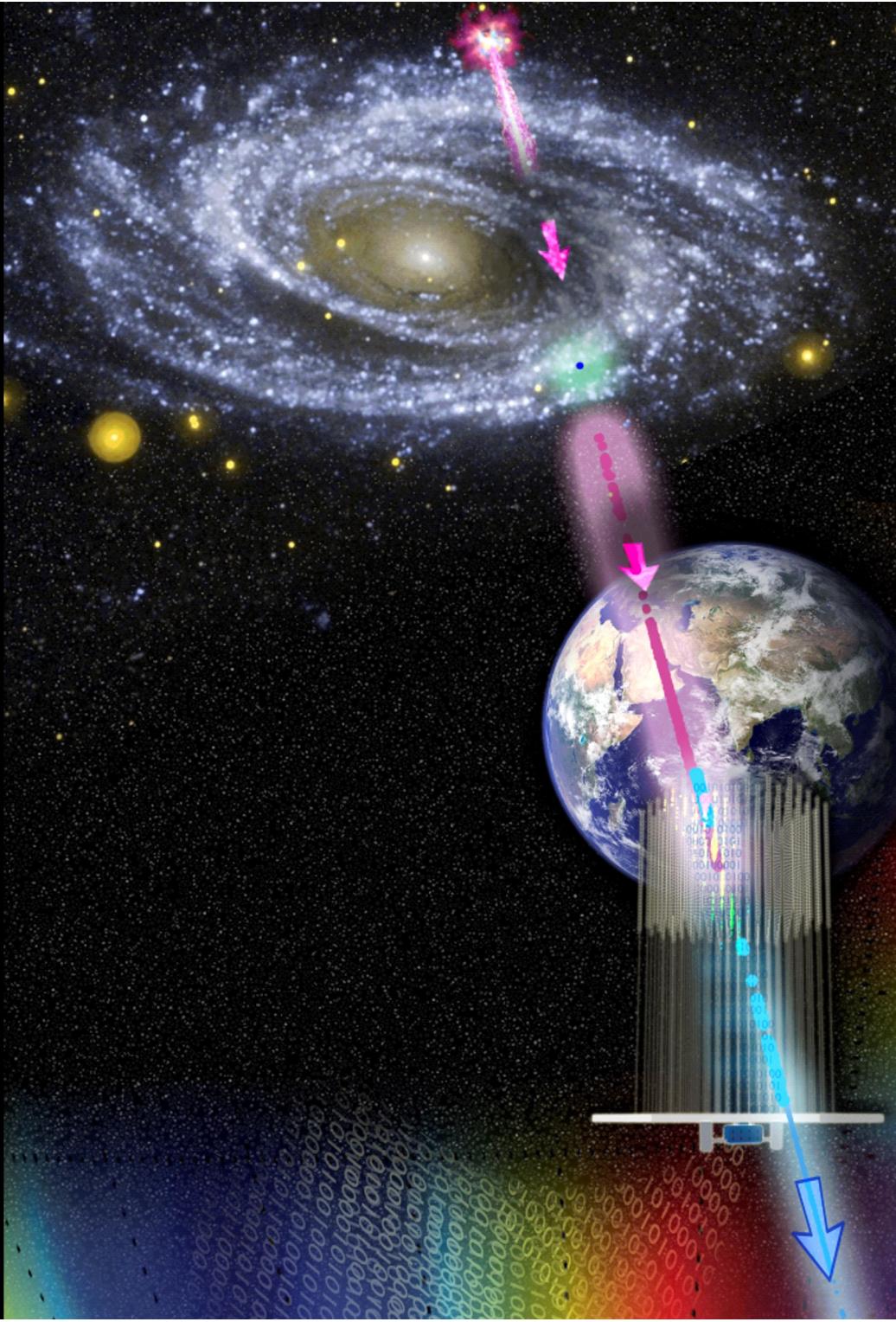


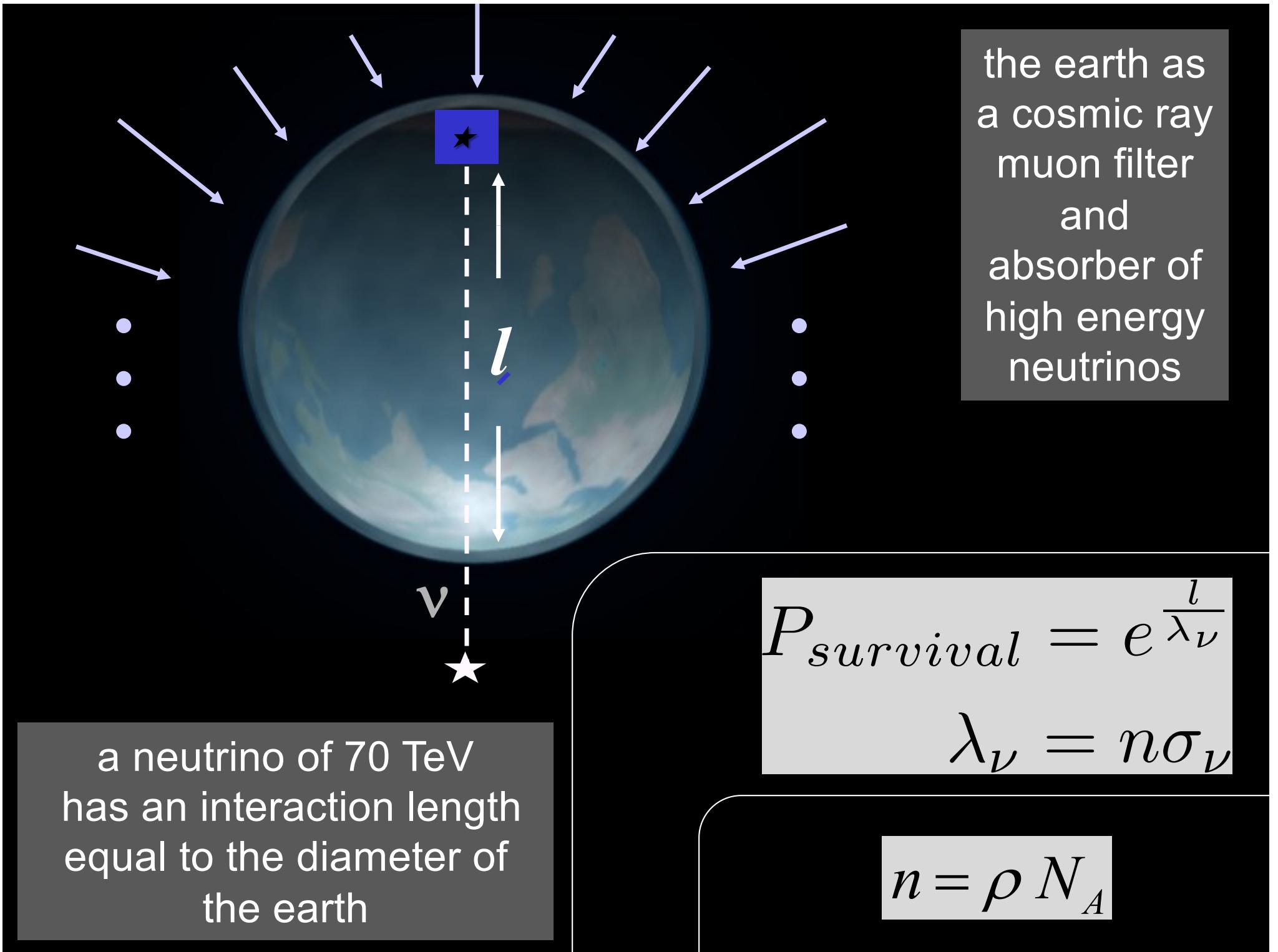
- $N_{\text{events}} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu \rightarrow \mu} dE$

effective telescope area at 100 TeV

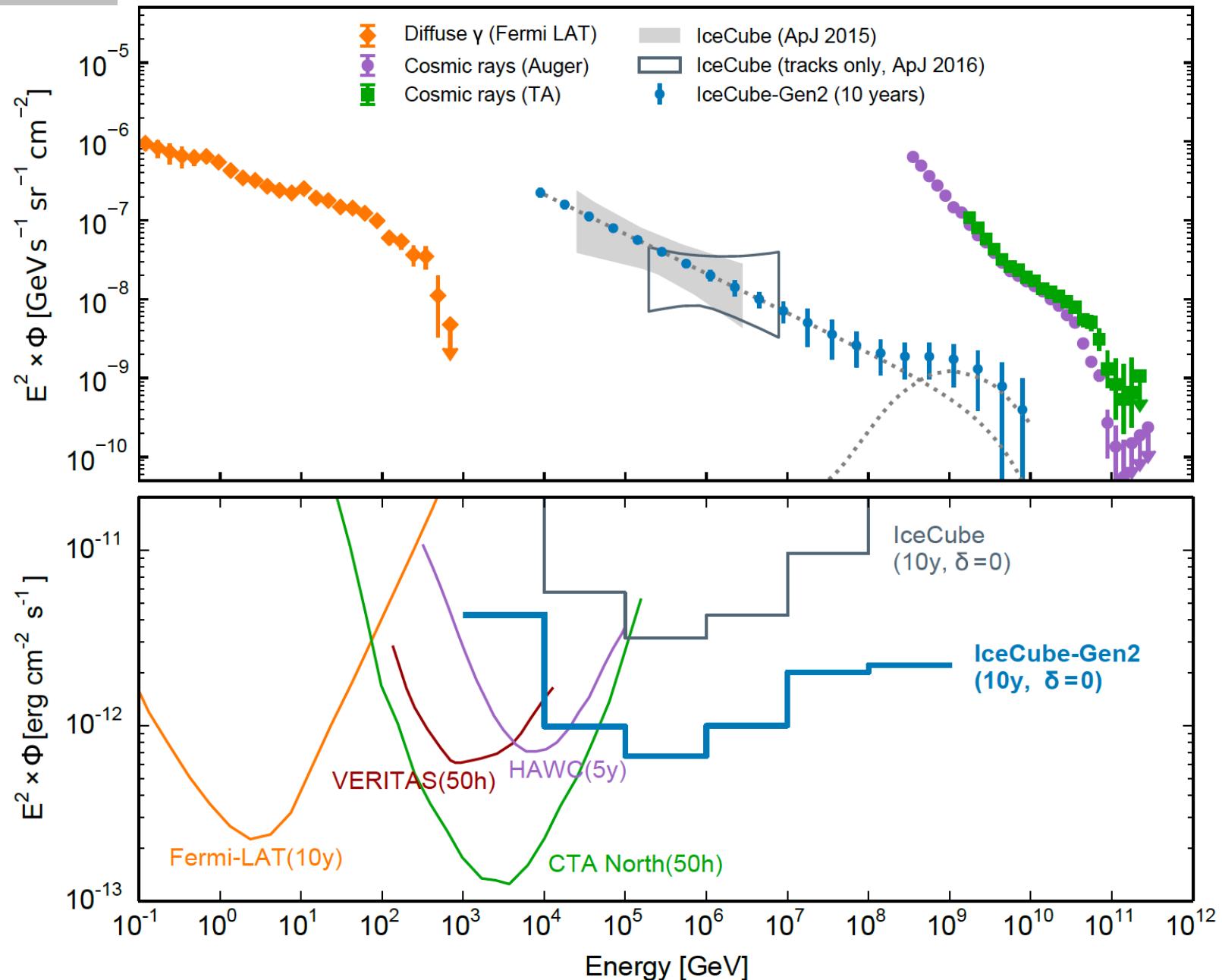
$$area \times P_{\mu \rightarrow \nu} \left(= \frac{\lambda_\mu}{\lambda_\nu} = n R_\mu \sigma_\nu \cong 10^{-6} E_{TeV} \right)$$

- AMANDA ~ ANTARES ~ $(1- 5) \text{ m}^2$
- IceCube 86 strings $\sim 100 \text{ m}^2$ at 100 TeV





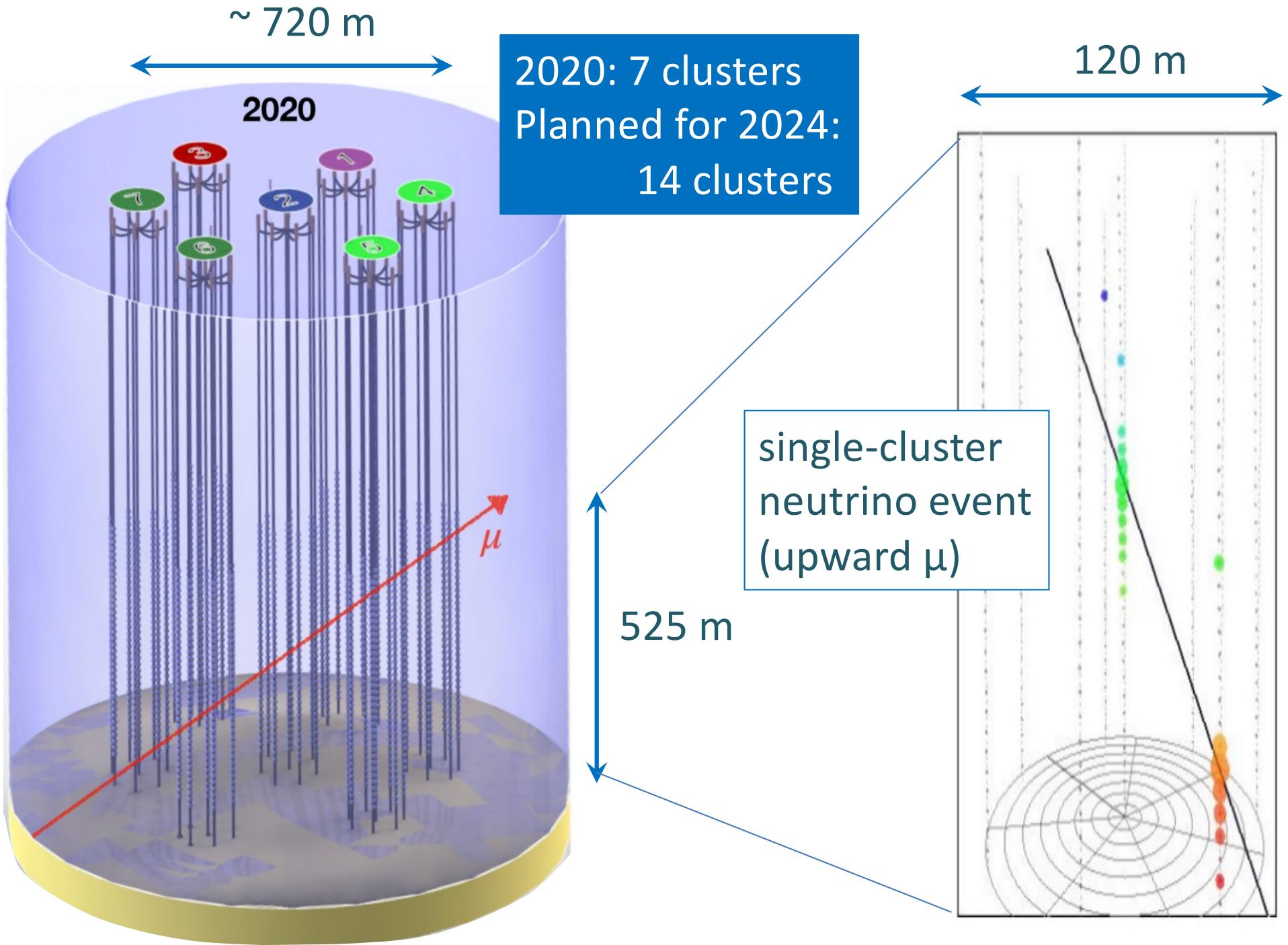
IceCube-Gen2

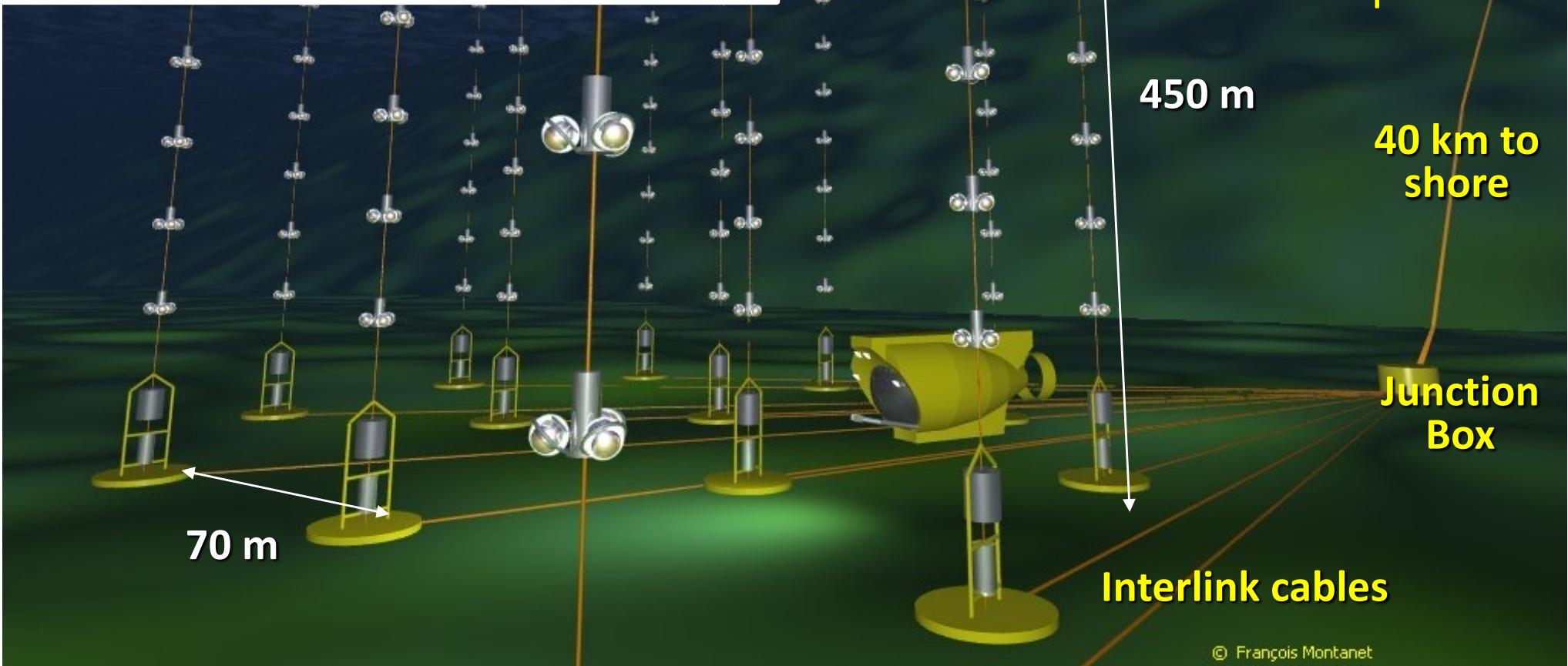
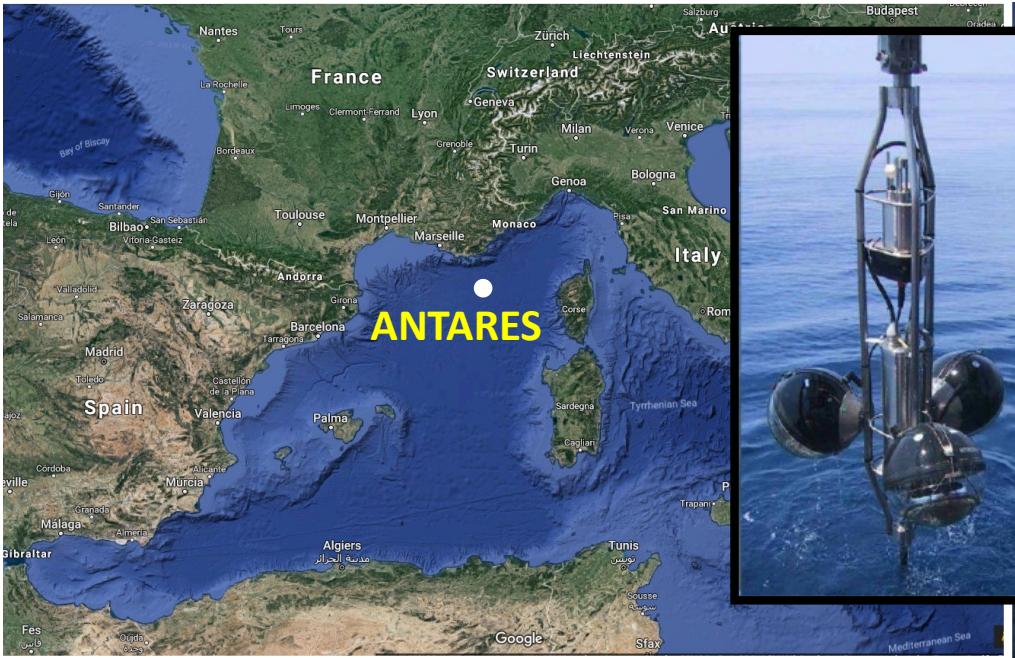


Lake Baikal experiment observes atmospheric neutrinos



Boris Shcheglov





ANTARES

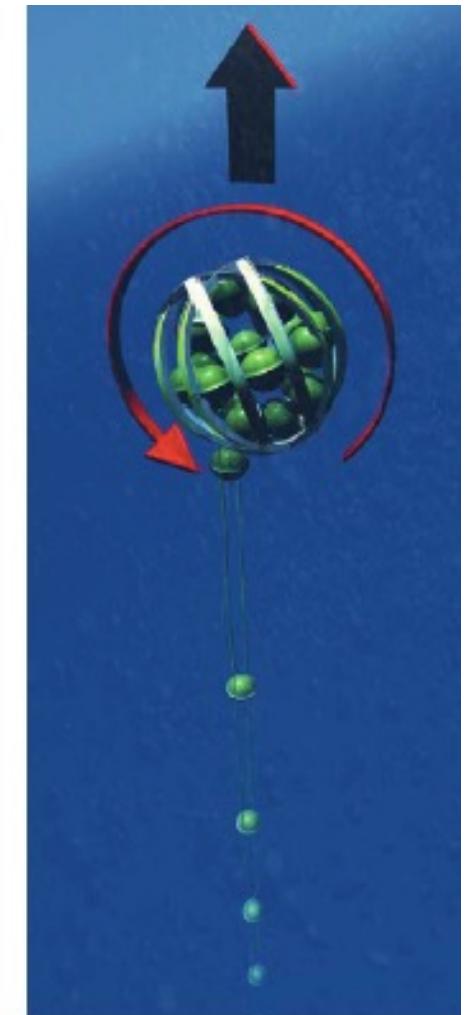
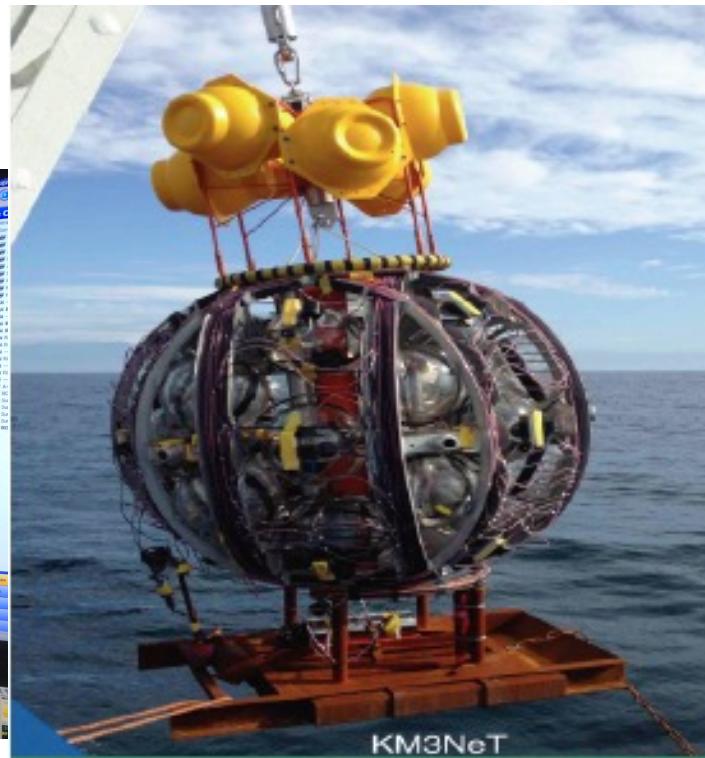
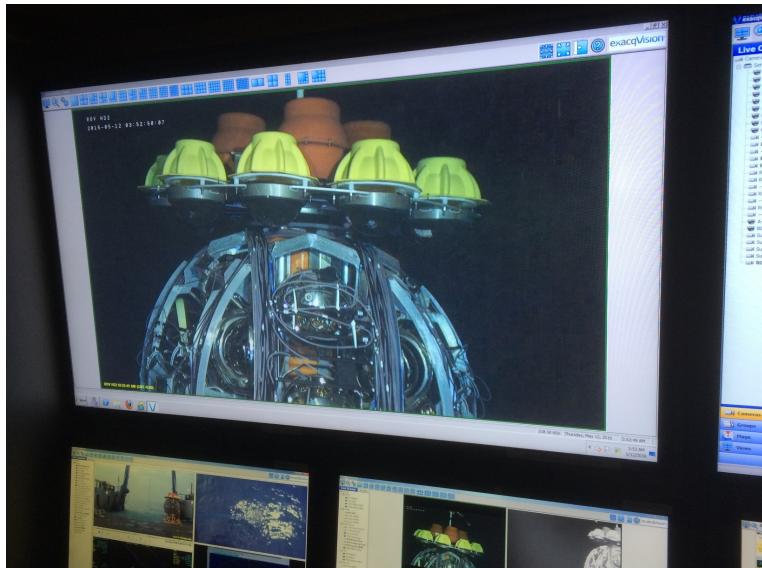
Running since 2007
885 10" PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep

450 m

40 km to
shore

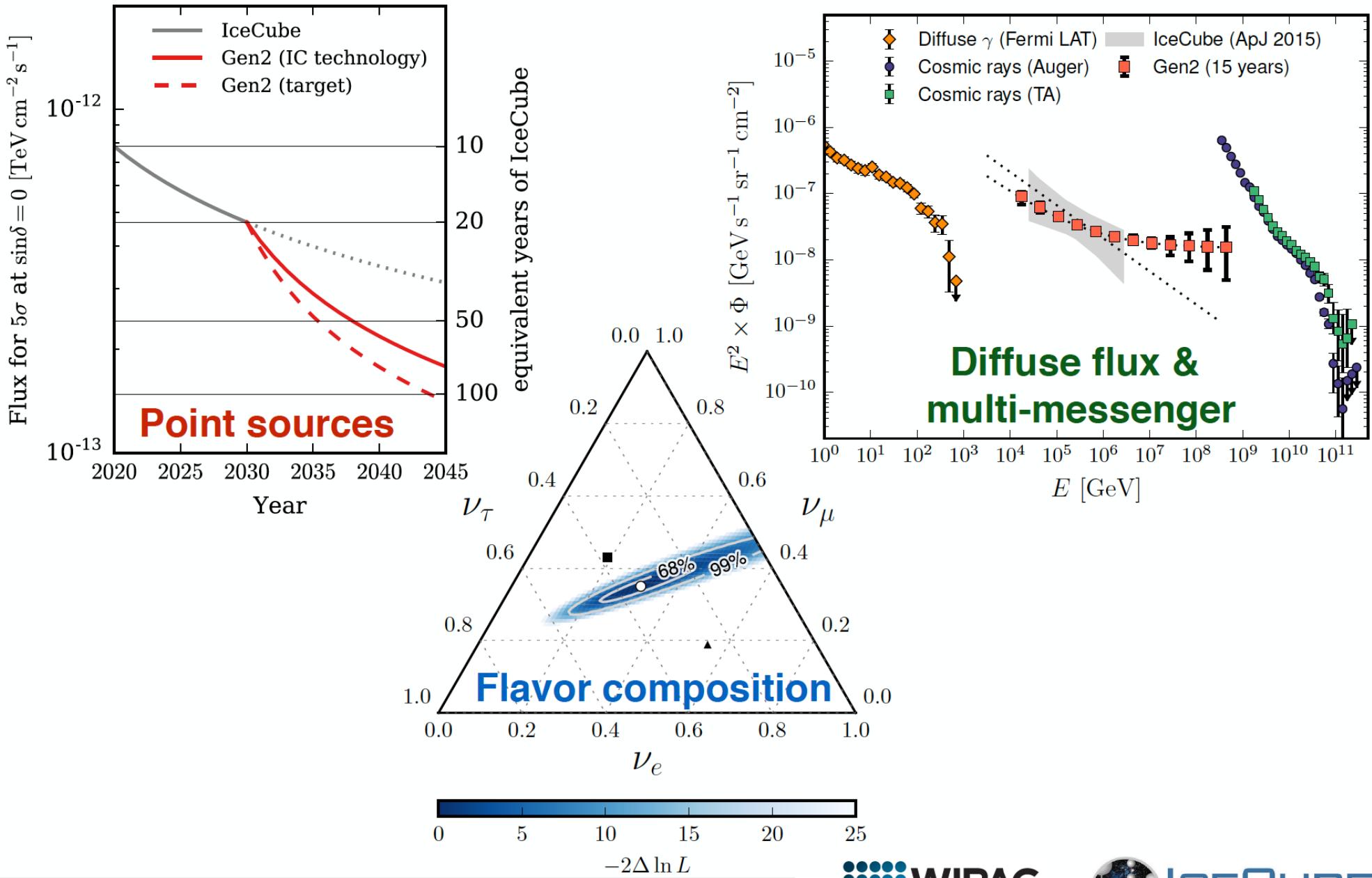
Junction
Box

Interlink cables



KM3NeT LoI <http://arxiv.org/pdf/1601.07459v2.pdf>

- a next-generation IceCube with a volume of more than 8 km^3 and an angular resolution of < 0.1 degrees will detect multiple neutrinos and identify the sources in the “diffuse” extragalactic flux
- need 1,000 events versus 100 now in a few years
- discovery instrument → astronomical telescope

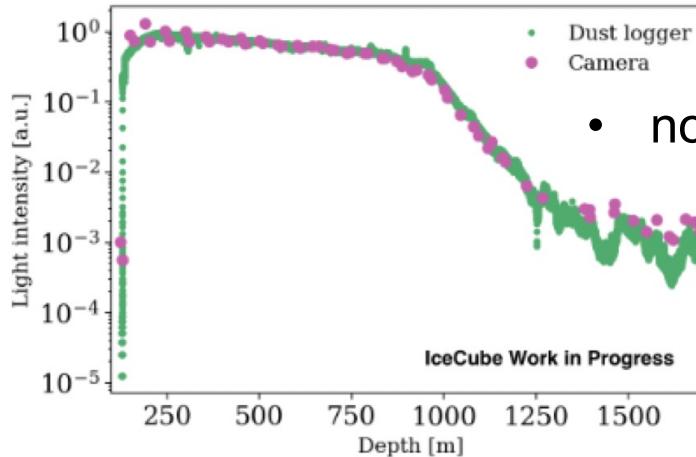
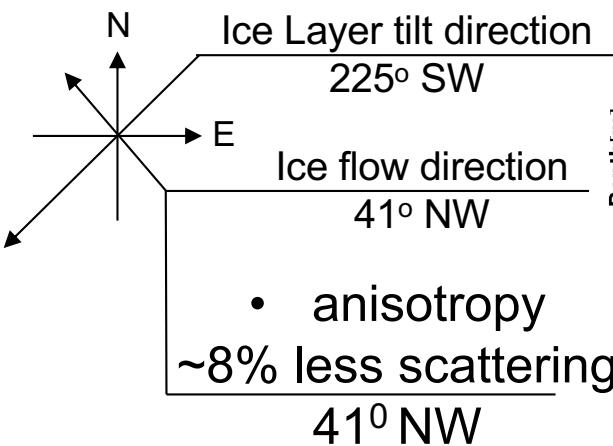


ice: step by step

- hole ice ?



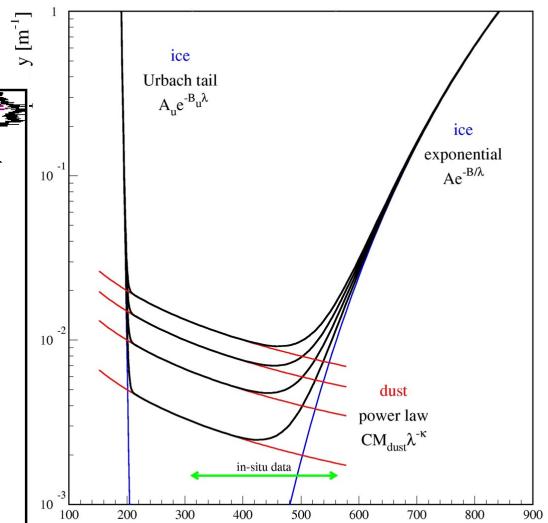
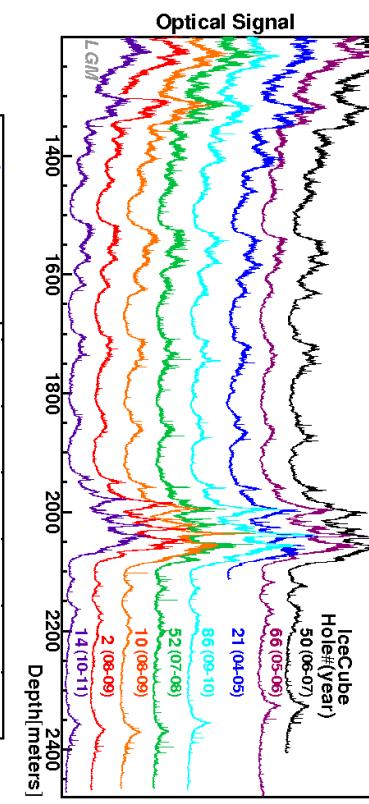
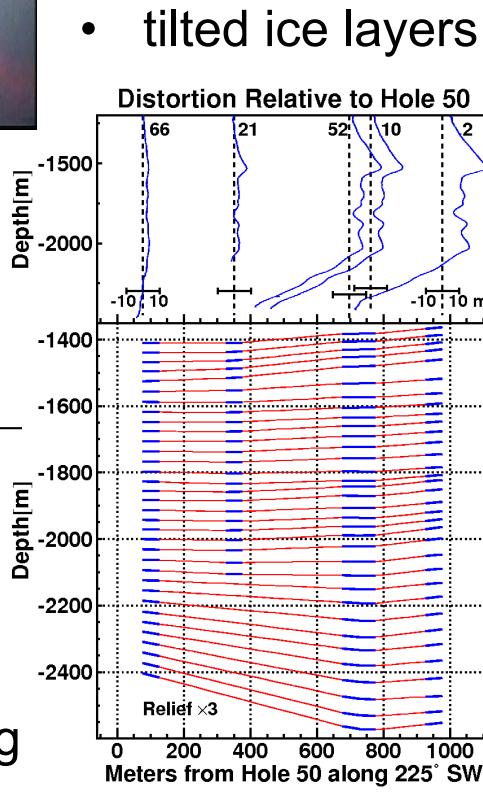
- some birefringence ?



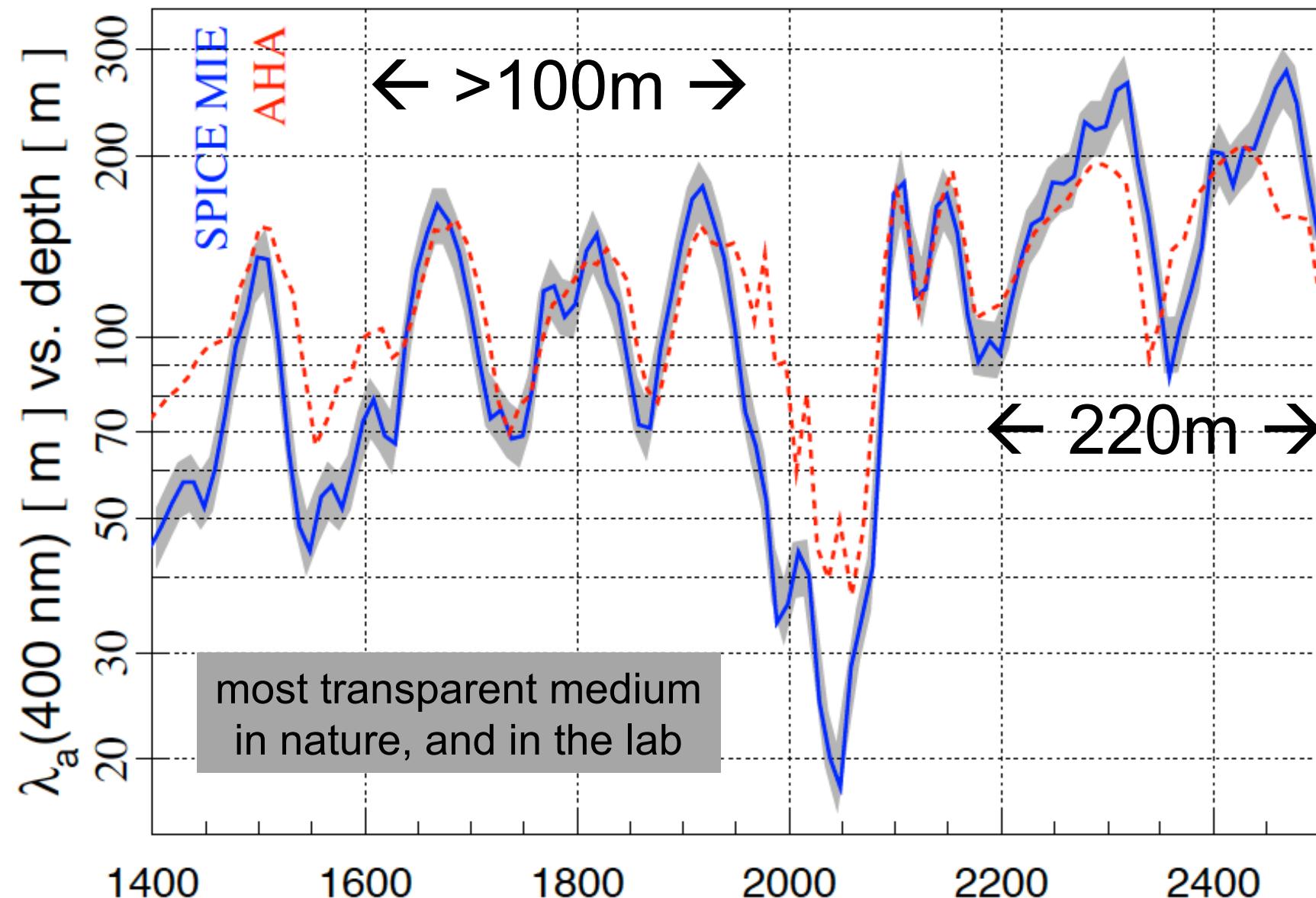
- no air bubbles/hydrates below 1350 m

- > 100 m absorption length limited by dust

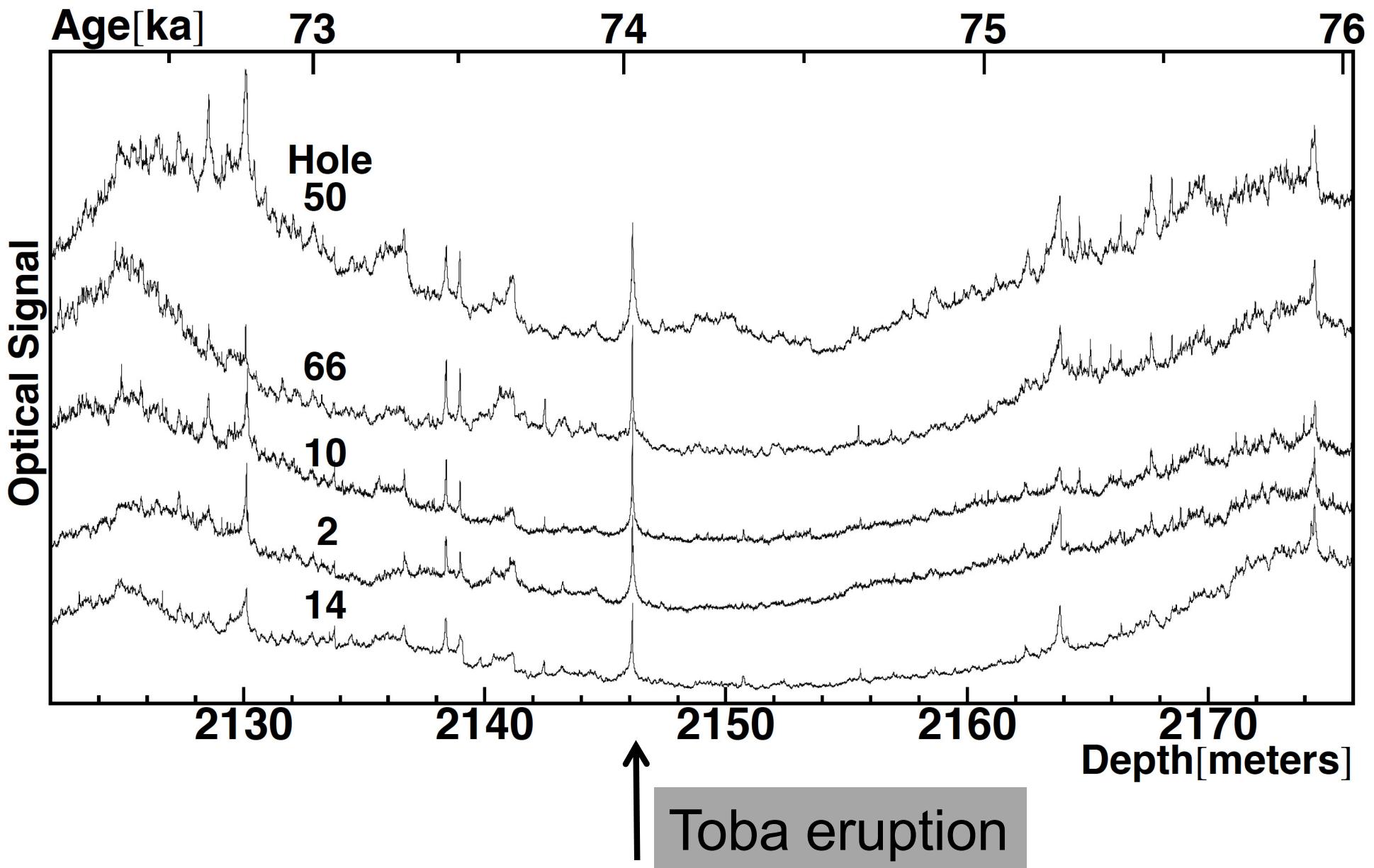
- ice layers



absorption length of Cherenkov light

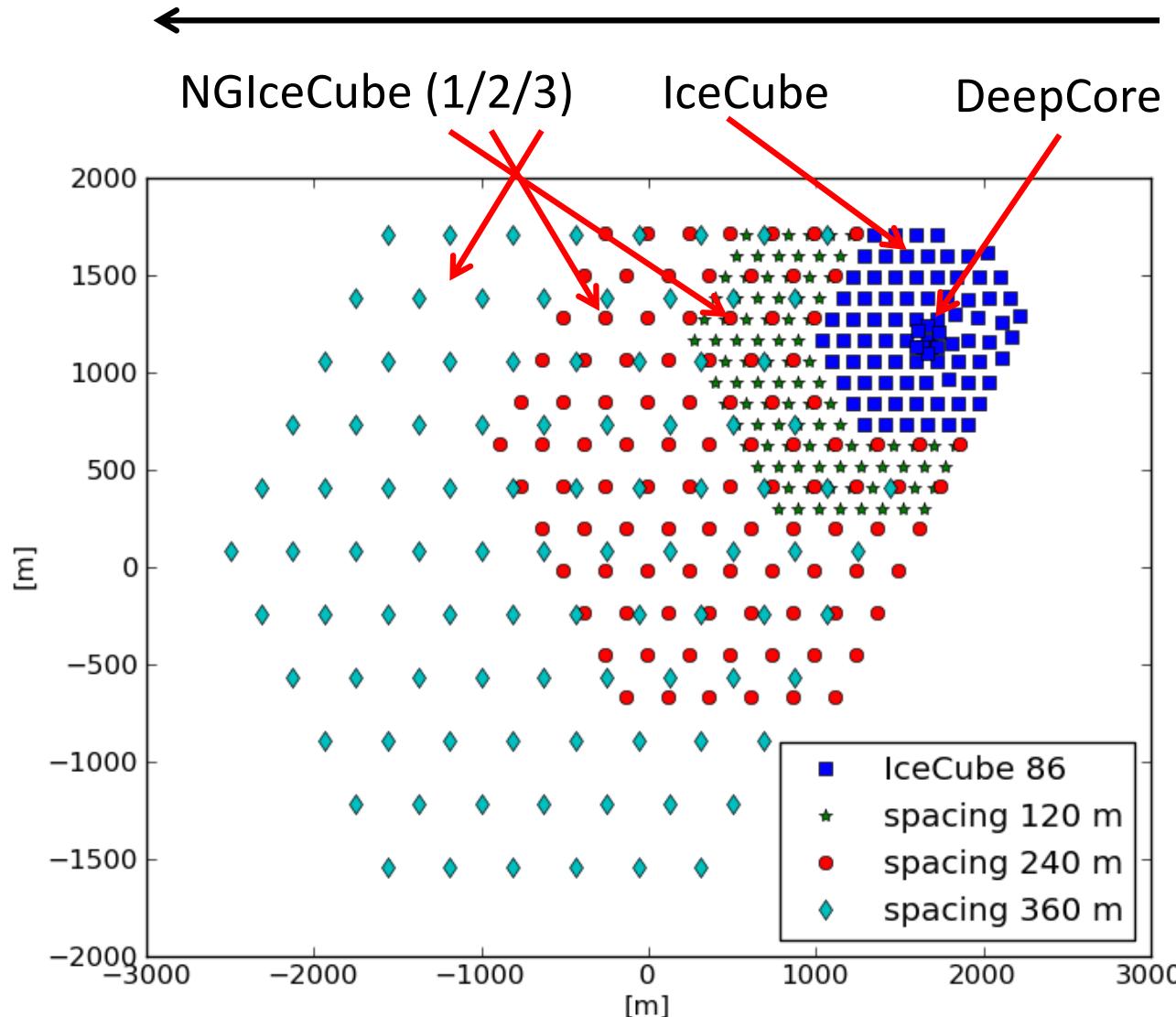


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

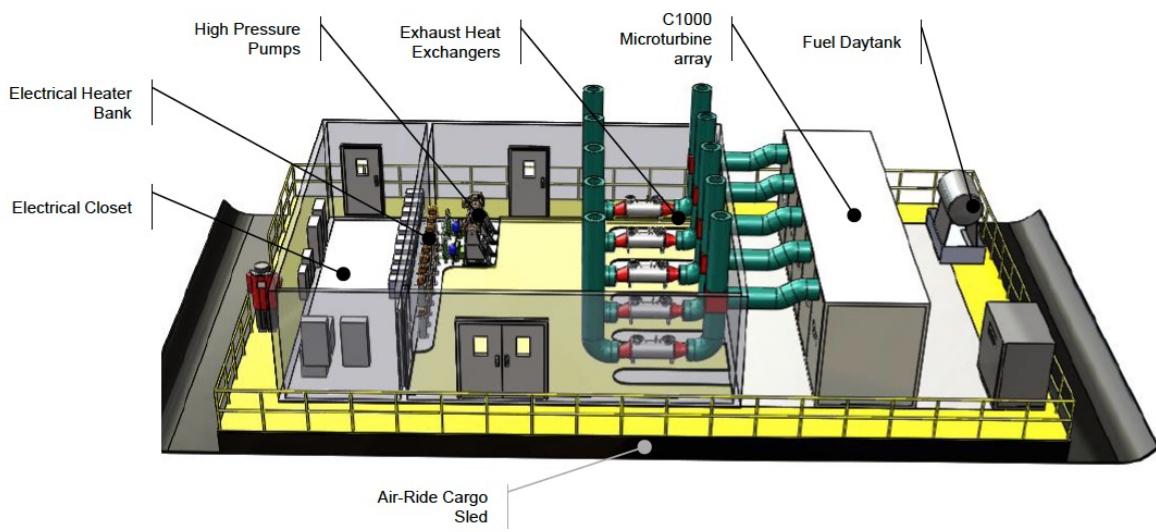
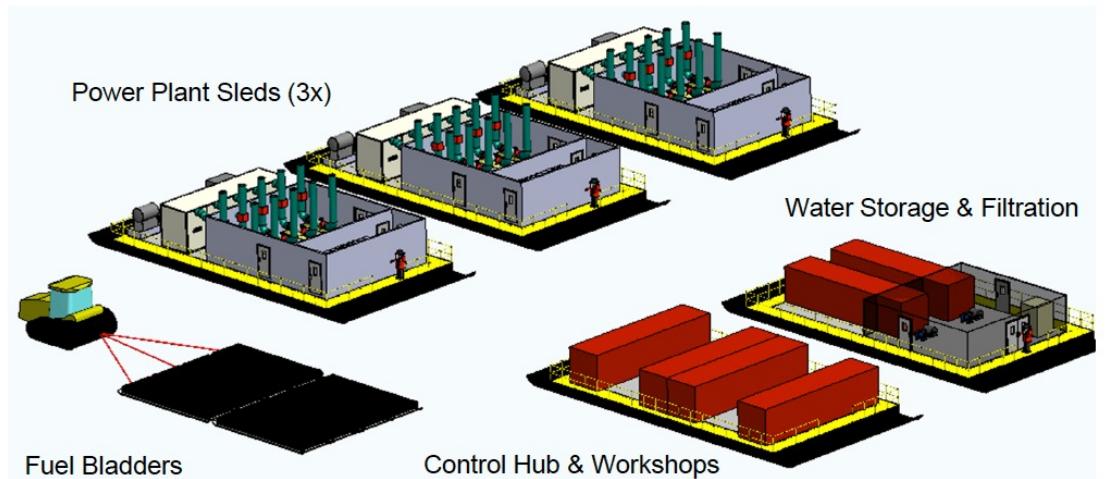
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

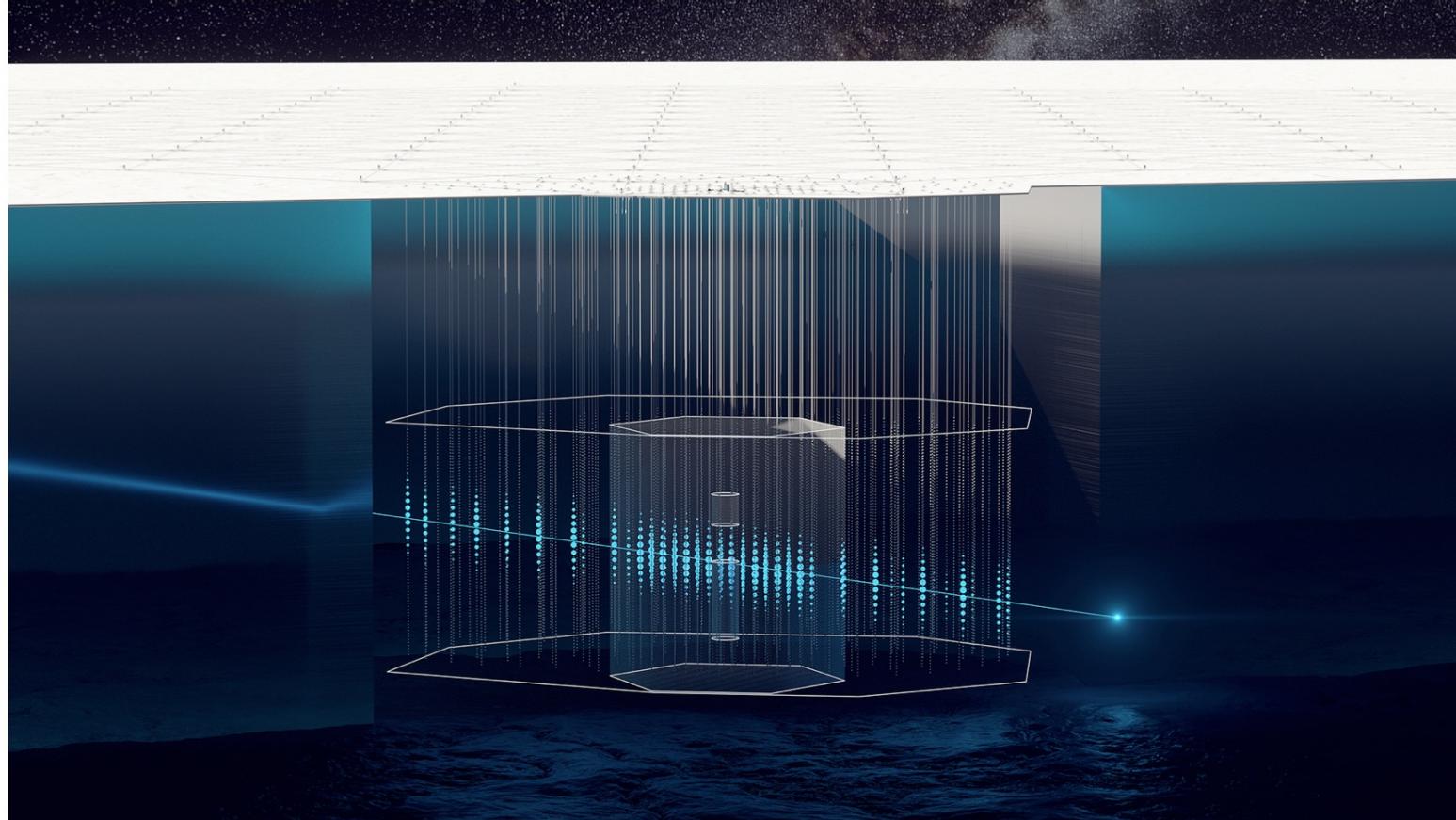
Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³



- Next-generation Enhanced Hot Water Drill
 - reduced footprint
 - smaller crew
- Transport equipment and fuel using South Pole Traverse
 - fewer flights needed
- May also reduce hole diameter
 - reduced fuel usage

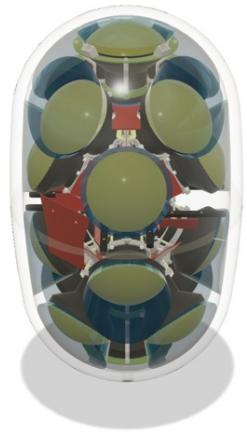
IceCube-Gen2



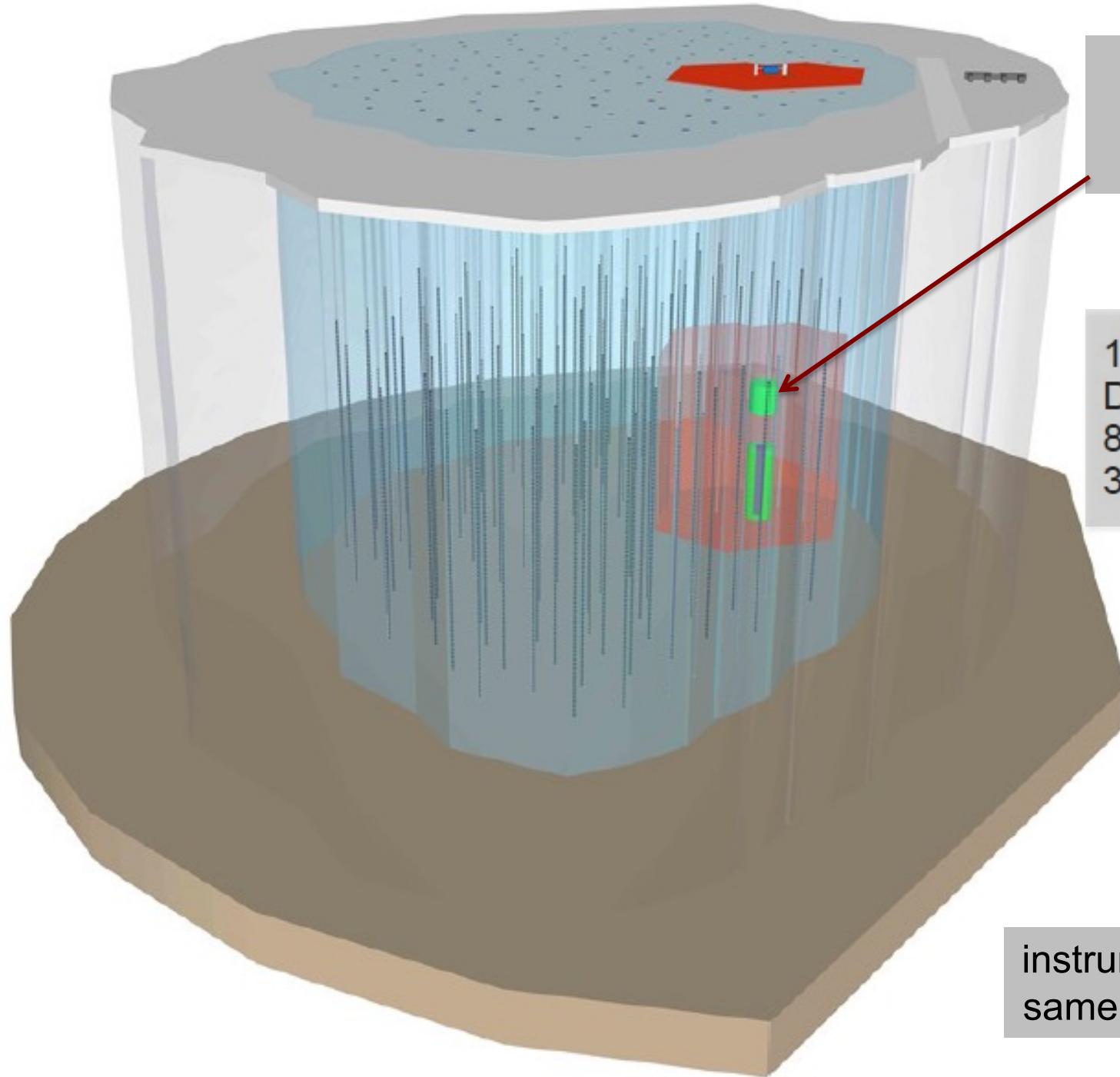
(a) IceCube-Gen2 schematic



(b) 16 PMTs



(c) 18 PMTs



Upgrade infill
40 strings
GeV threshold

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 8
same budget as IceCube

10 PeV

10 TeV
120 strings
1350-1600m
80 modules

100 GeV

1 GeV

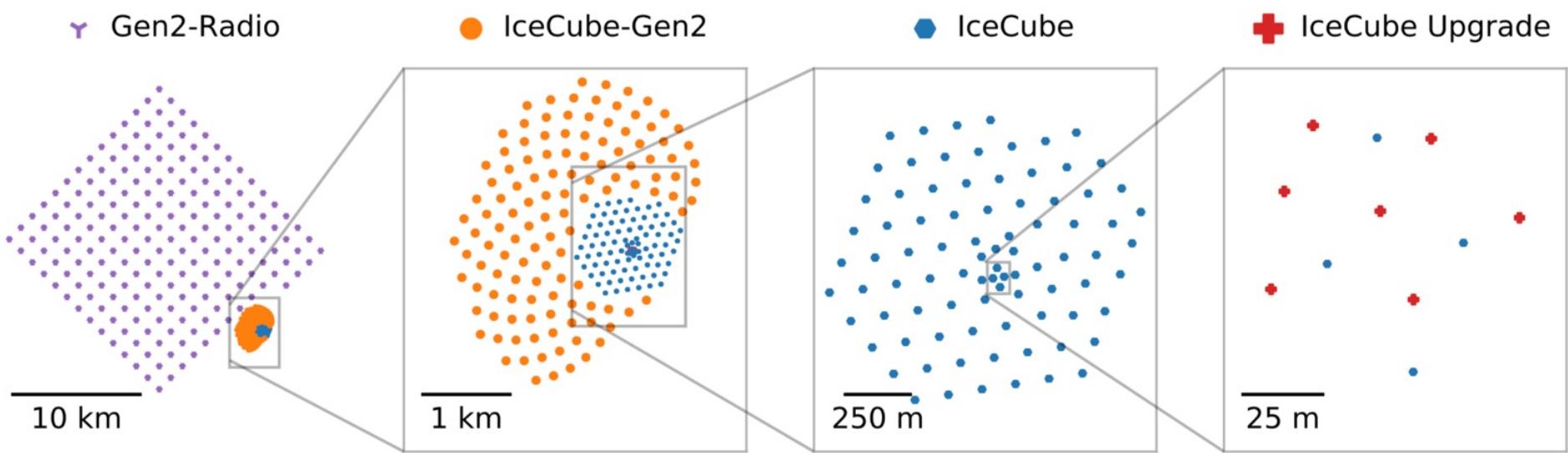
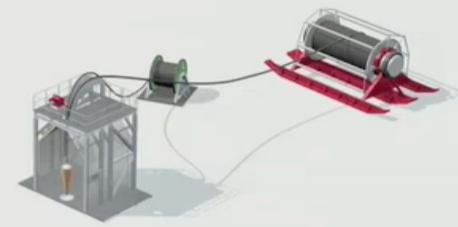


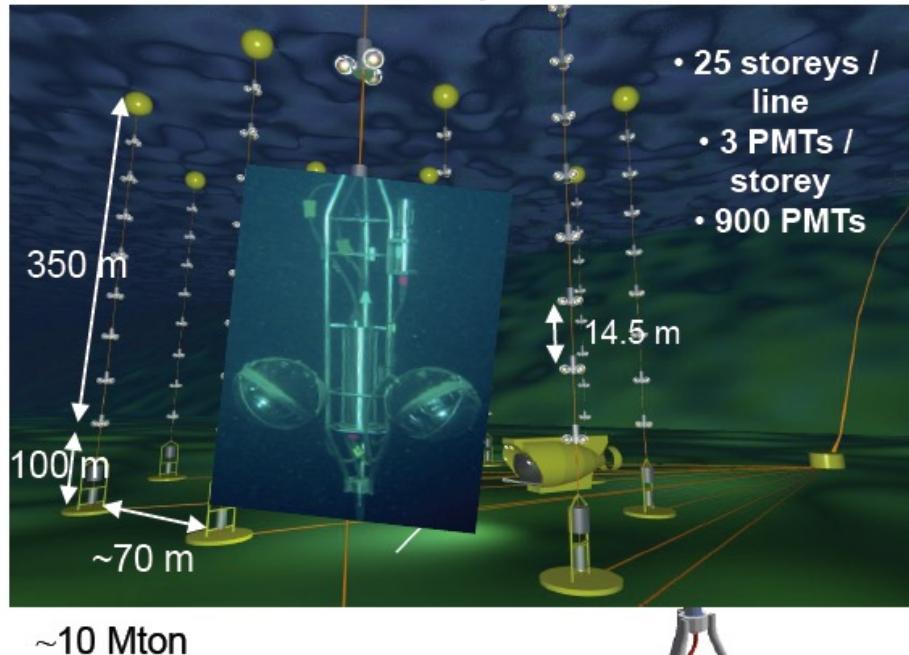
Figure 10: Exploded top-view of the full IceCube-Gen2 observatory. Far left shows the radio array, composed of individual stations resulting in a more than 500 km^2 instrumented area, relative to the Gen2 optical deep ice array and the existing IceCube detector.





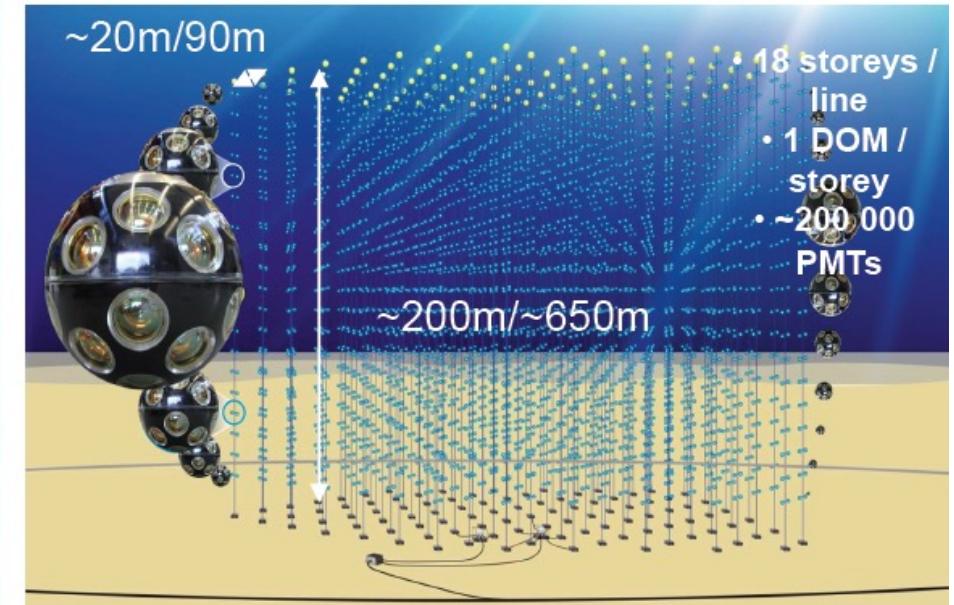
Mediterranean Detectors

ANTARES Complete since 2008

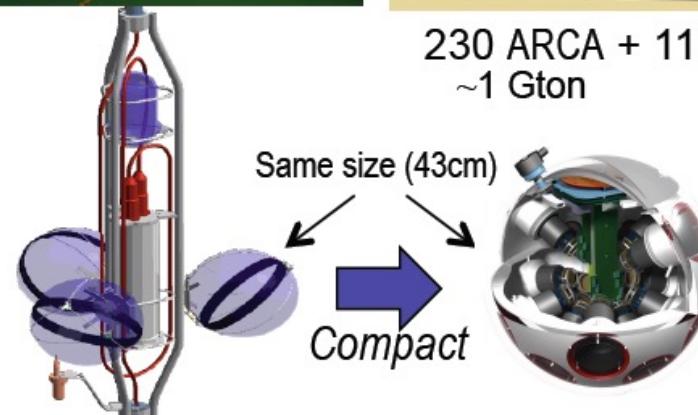


12 lines
First Generation
First line since 10 years

KM3NeT Under Construction

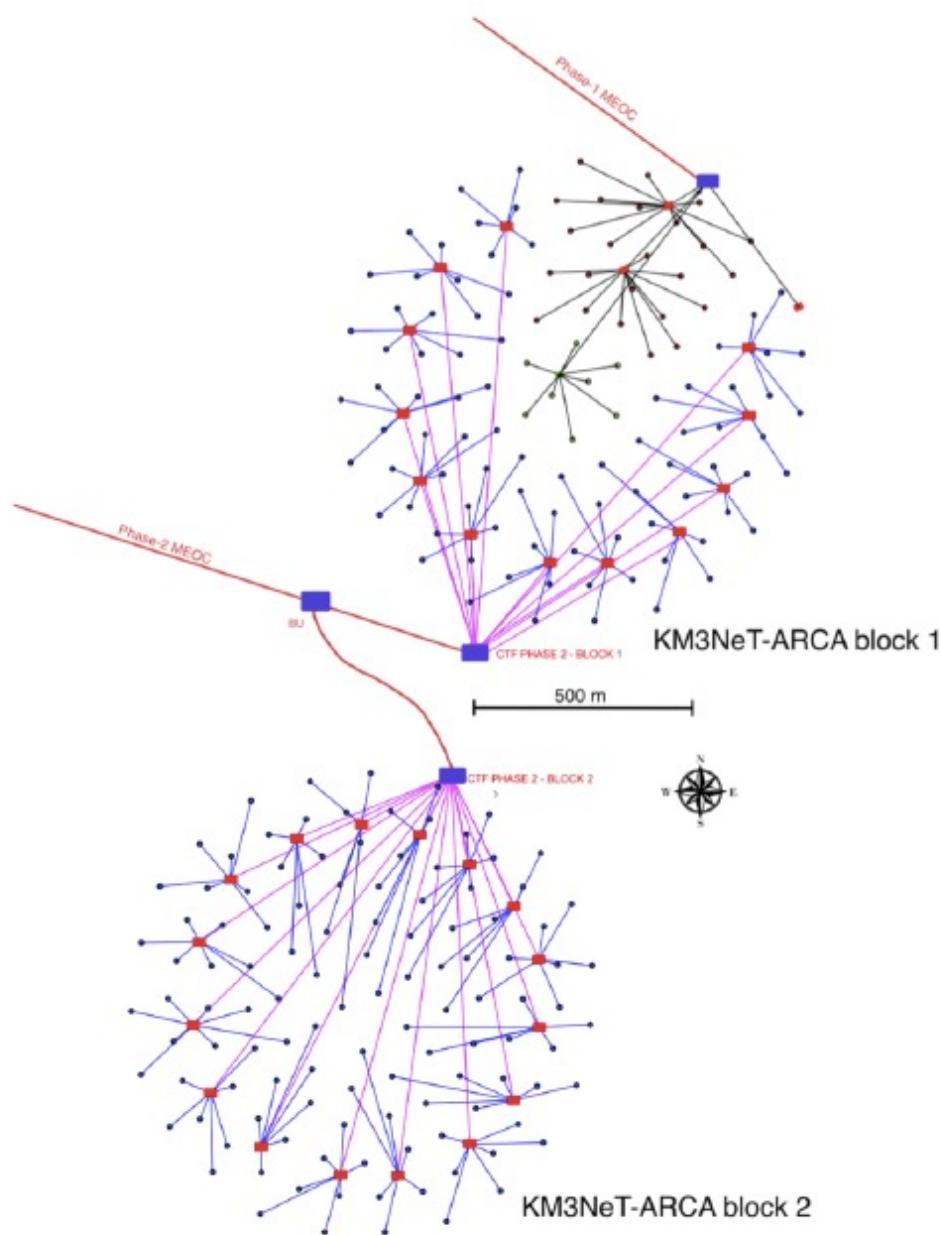


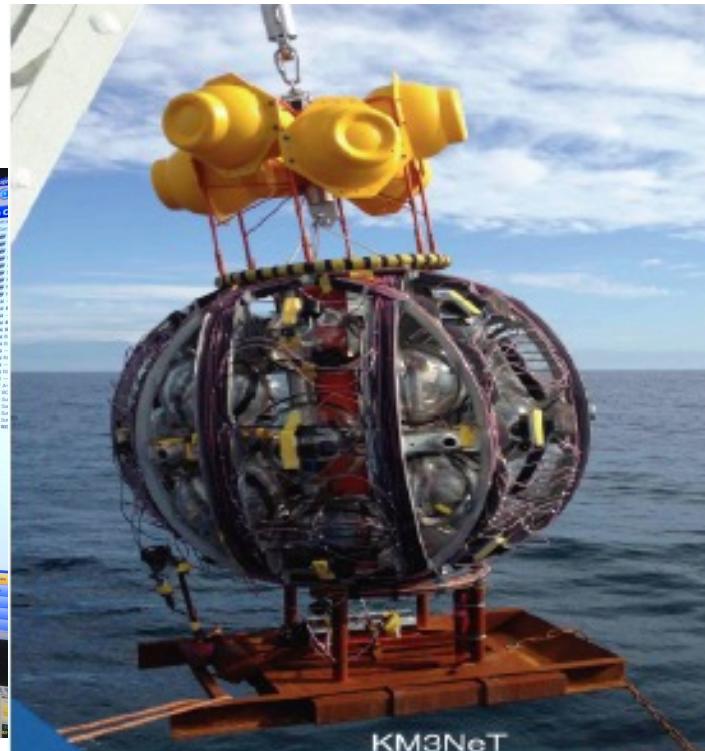
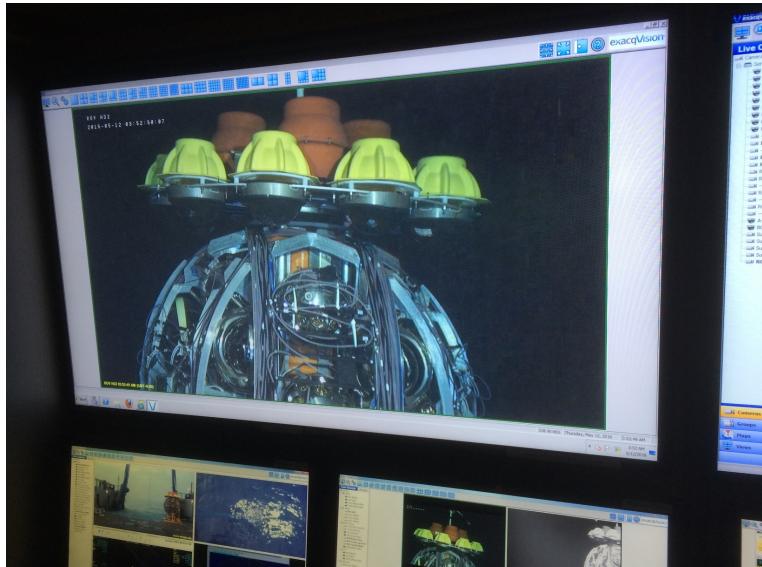
230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton



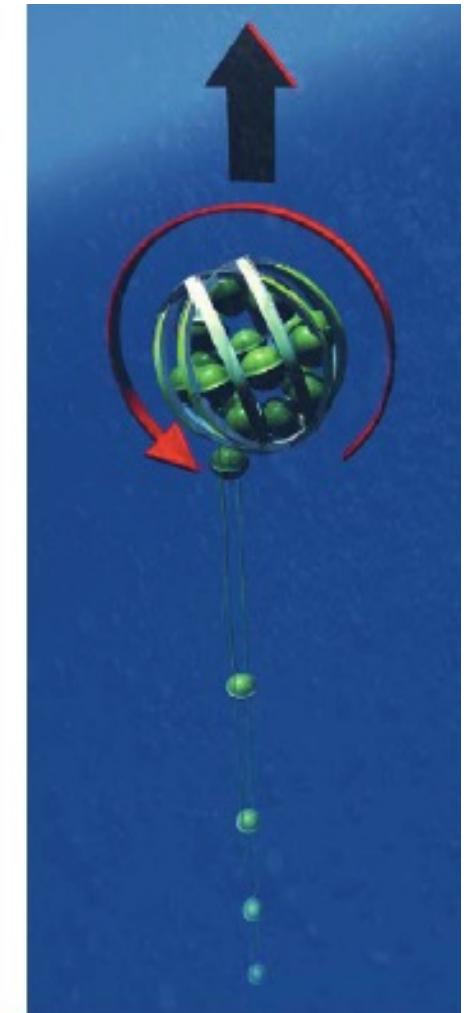
- DOM: 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

High energies ARCA





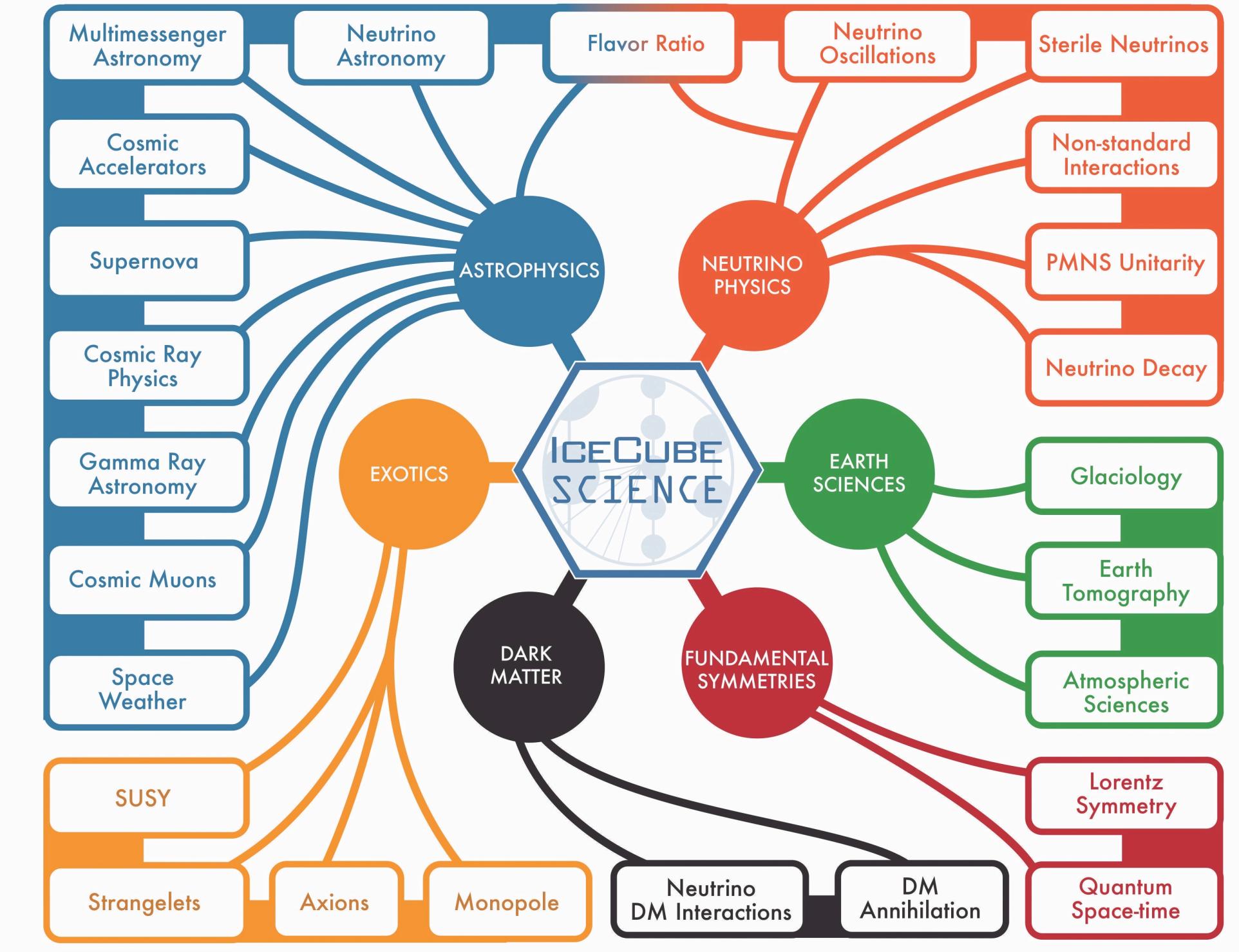
rapid deployment
autonomous unfurling
recoverable

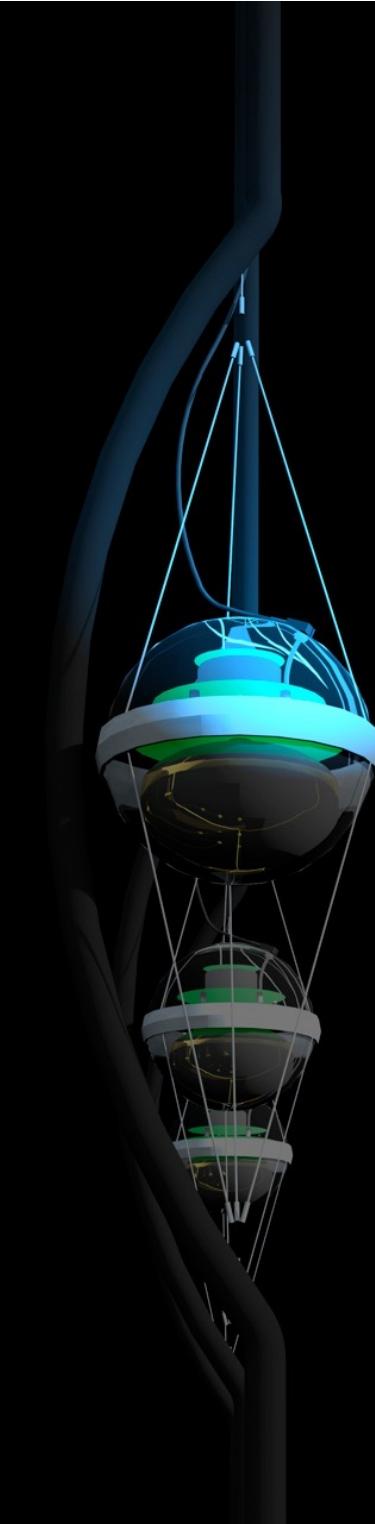


KM3NeT LoI <http://arxiv.org/pdf/1601.07459v2.pdf>

did not talk about:

- Galactic sources
- searches for dark matter, monopoles,...
- search for eV-mass sterile neutrinos
- cosmic ray physics, muon asymmetry,...
- PINGU/ORCA
-





neutrino astronomy 2022

- it exists
- more neutrinos, better neutrinos, more telescopes
- closing in on cosmic ray sources
- [are active galaxies with obscured cores the sources of cosmic rays?]
- two beams for neutrino physics