Ground-Based Gamma-Ray Astronomy

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H.E.S.S.

CTAO
Cherenkov Telescope Array Observatory

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DFG Deutsche Forschungsgemeinschaft

GEFÖRDERT VOM
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Universität Potsdam

Outline

0. Introduction

I. Detection Principles and Instruments

Lecture I

II. Ground-Based Galactic
Gamma-Ray Astronomy

Lecture II

III. Ground-Based Extragalactic
Gamma-Ray Astronomy,
Non-Gamma Science

IV. Outlook/Future

Lecture III

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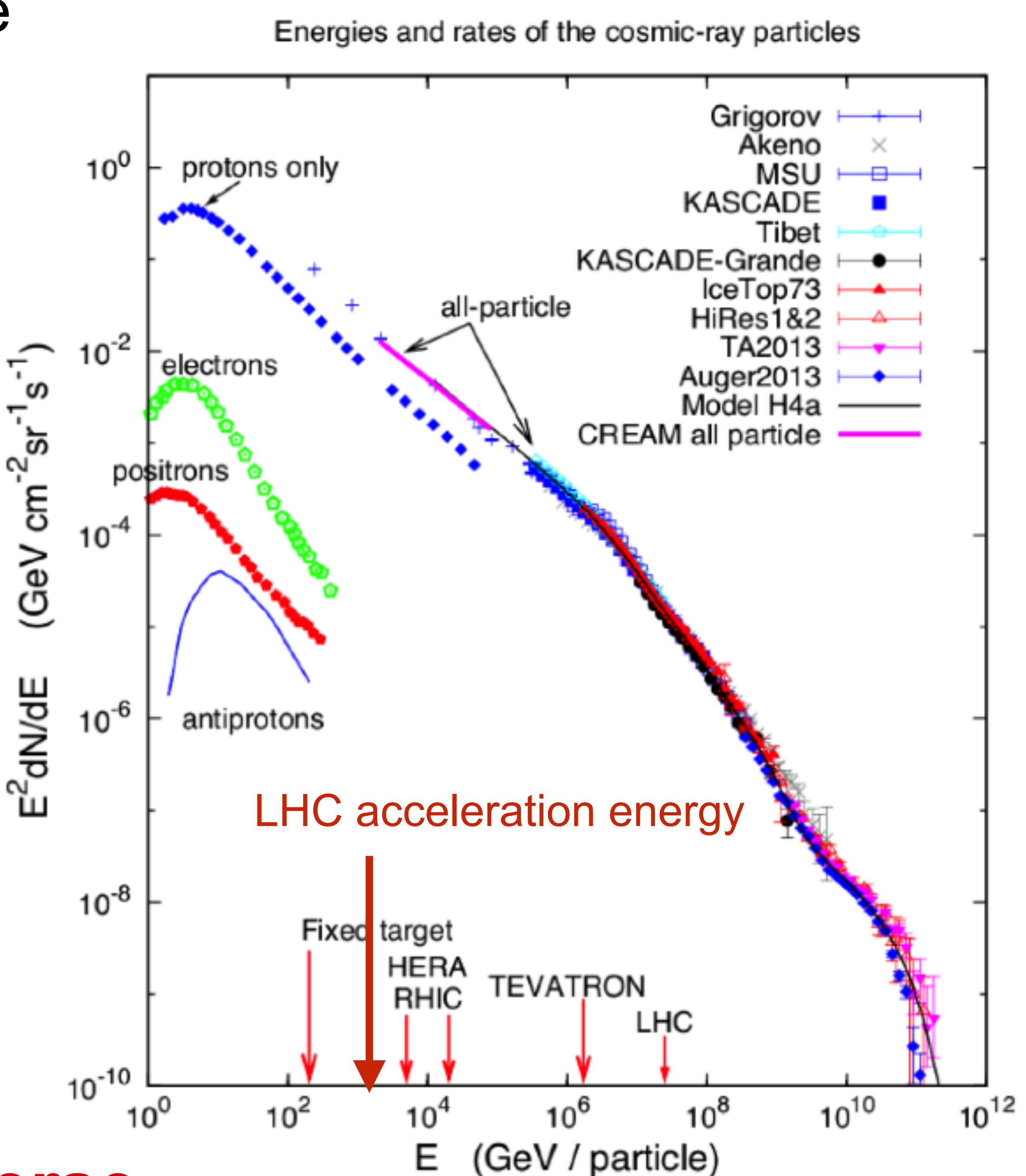
0. Introduction to TeV Astronomy

- TeV photons probe the non-thermal universe
- Produced by energetic particles:
  cosmic rays *(& dark matter?)*
- Up to the knee in the CR spectrum (~PeV energies):
  sources assumed to be Galactic
- Standard paradigm: diffusive shock acceleration in supernova remnants
- Presumed extragalactic sources:
  Active Galactic Nuclei, gamma-ray bursts…



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→ Observations of the Extreme Universe

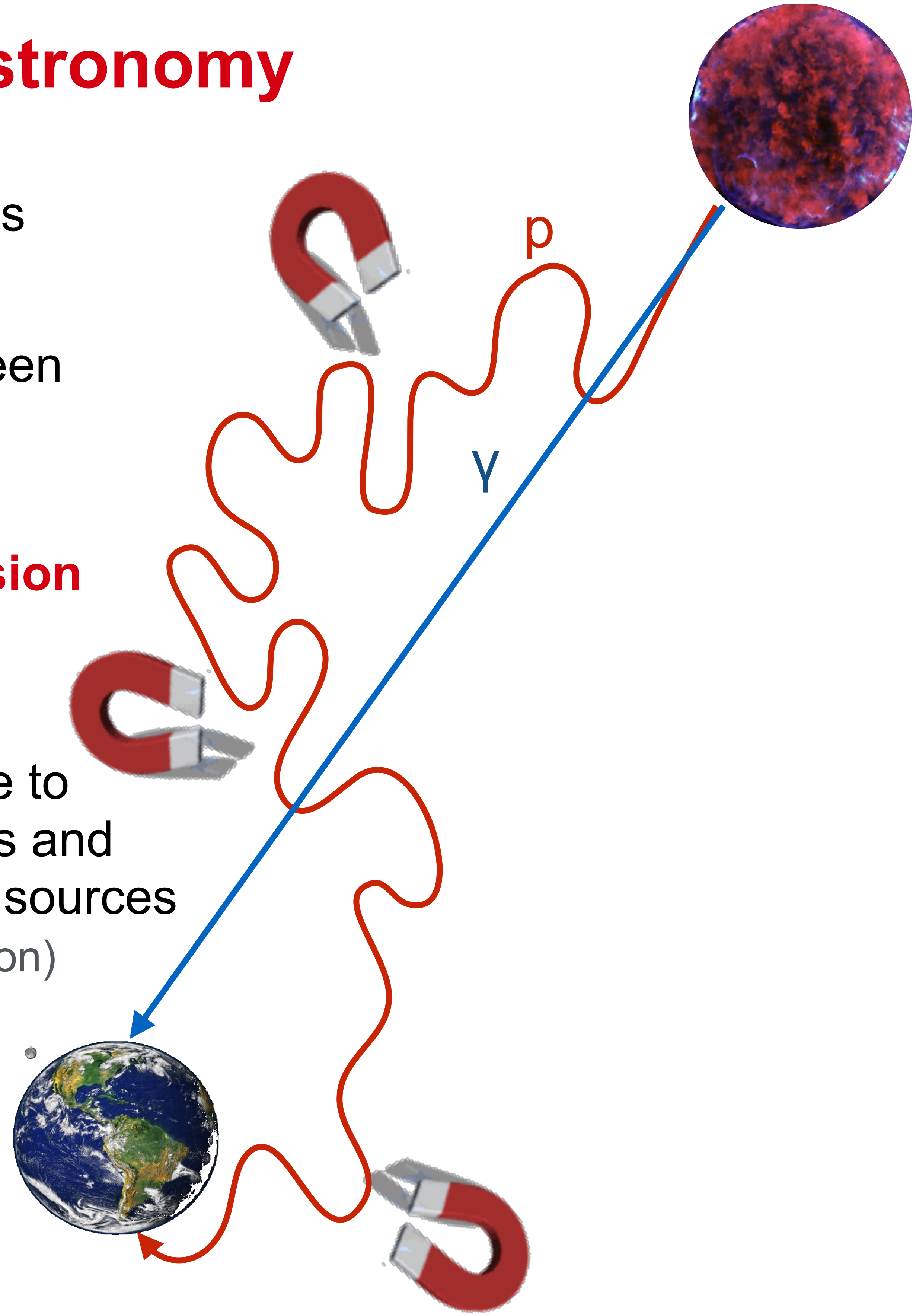
0. Introduction to TeV Astronomy

Observations of cosmic rays
via neutral messengers

Cosmic-ray accelerators seen
as **gamma-ray sources**

cosmic-ray propagation
as **diffuse gamma-ray emission**

At TeV energies, we are close to
the limit of Galactic accelerators and
the observational limit of extragal. sources
(due to gamma-gamma absorption)

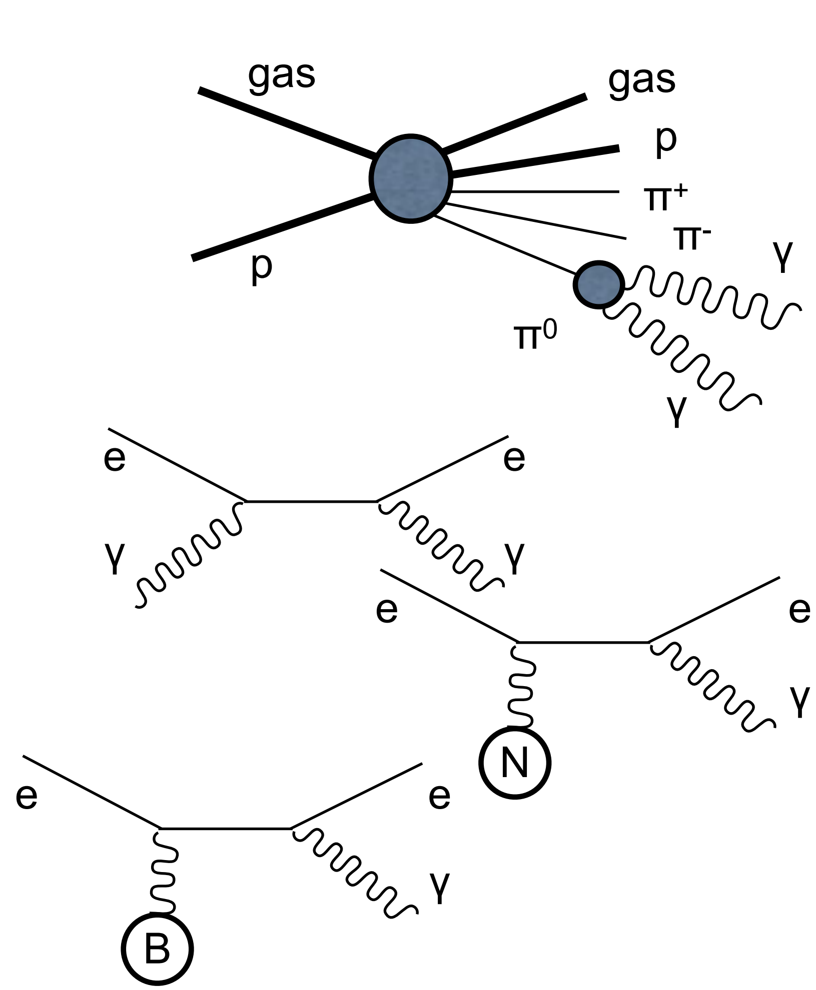


From Particles To Radiation

- **Pion production and decay**
  $p + N_{gas} \rightarrow \pi^o + \ldots \rightarrow \gamma\ \gamma$
- **Inverse Compton scattering**
  $e^{\pm} + \gamma_{LE} \rightarrow e^{\pm} + \gamma_{HE}$
- Bremsstrahlung
  $e^{\pm} + N_{gas} \rightarrow e^{\pm} + \gamma$
- Synchrotron radiation
  $e^{\pm} + B \rightarrow e^{\pm} + \gamma$

hadronic mechanism

leptonic mechanisms



- Need for target "material": interstellar medium, radiation fields, B fields
- γ-rays are the line-of-sight integral of CR density and target material:

$$F_\gamma(E_\gamma) = \int dl_d \int d\sigma_{CR+t\rightarrow\gamma}/dE_{CR} \cdot n_t(l,b,l_d) \cdot n_{CR}(l,b,l_{d,}E_{CR})\ \ dE_{CR}$$

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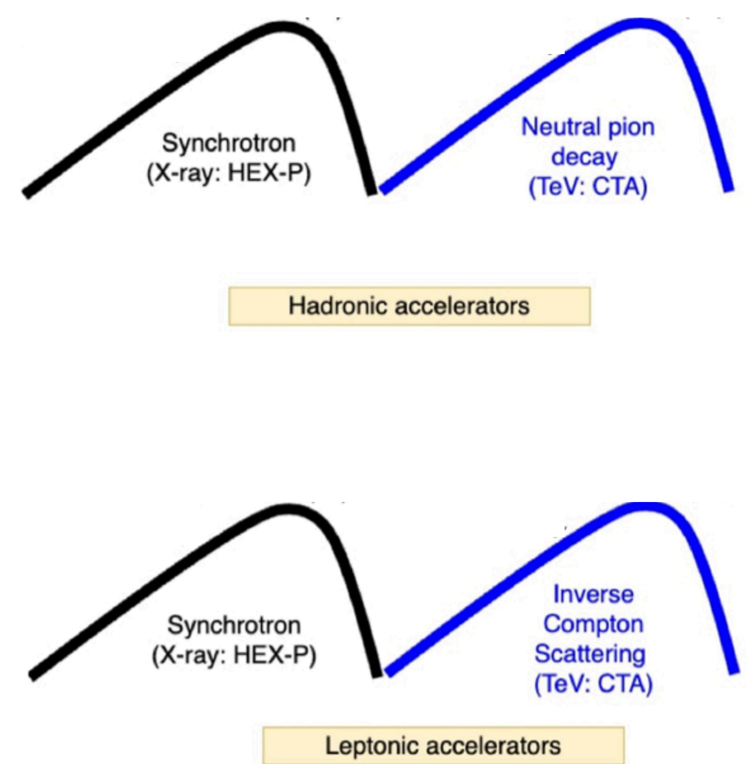
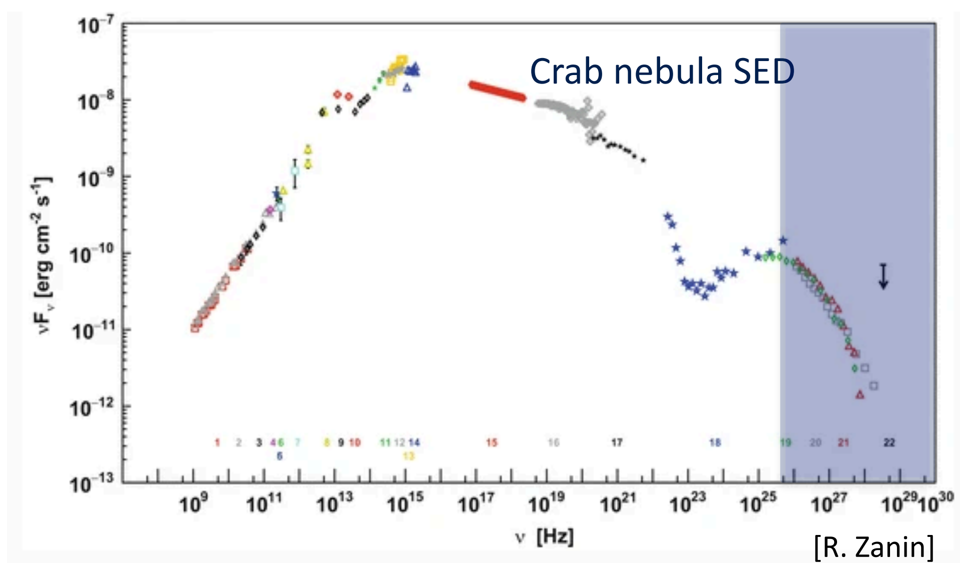
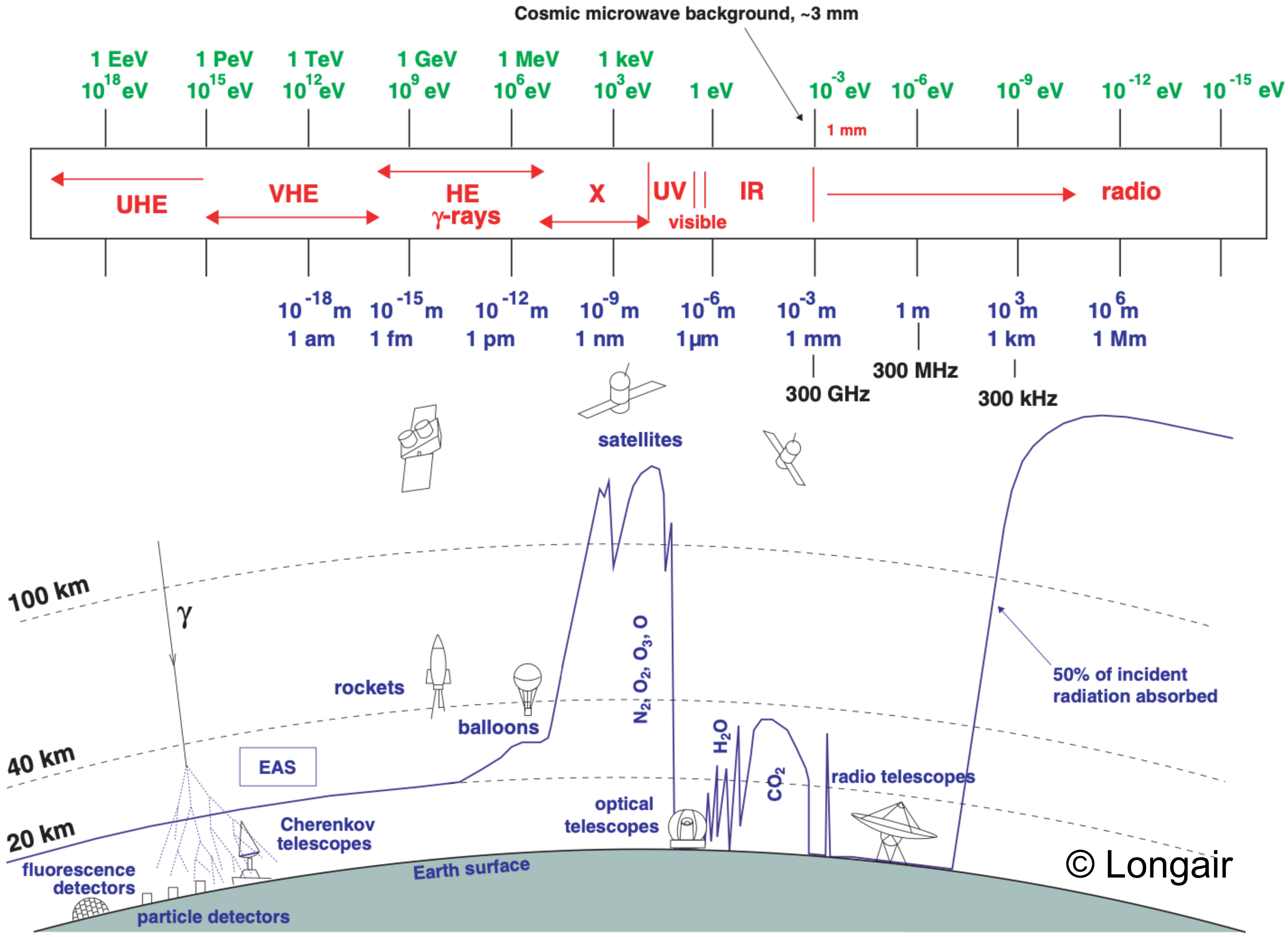


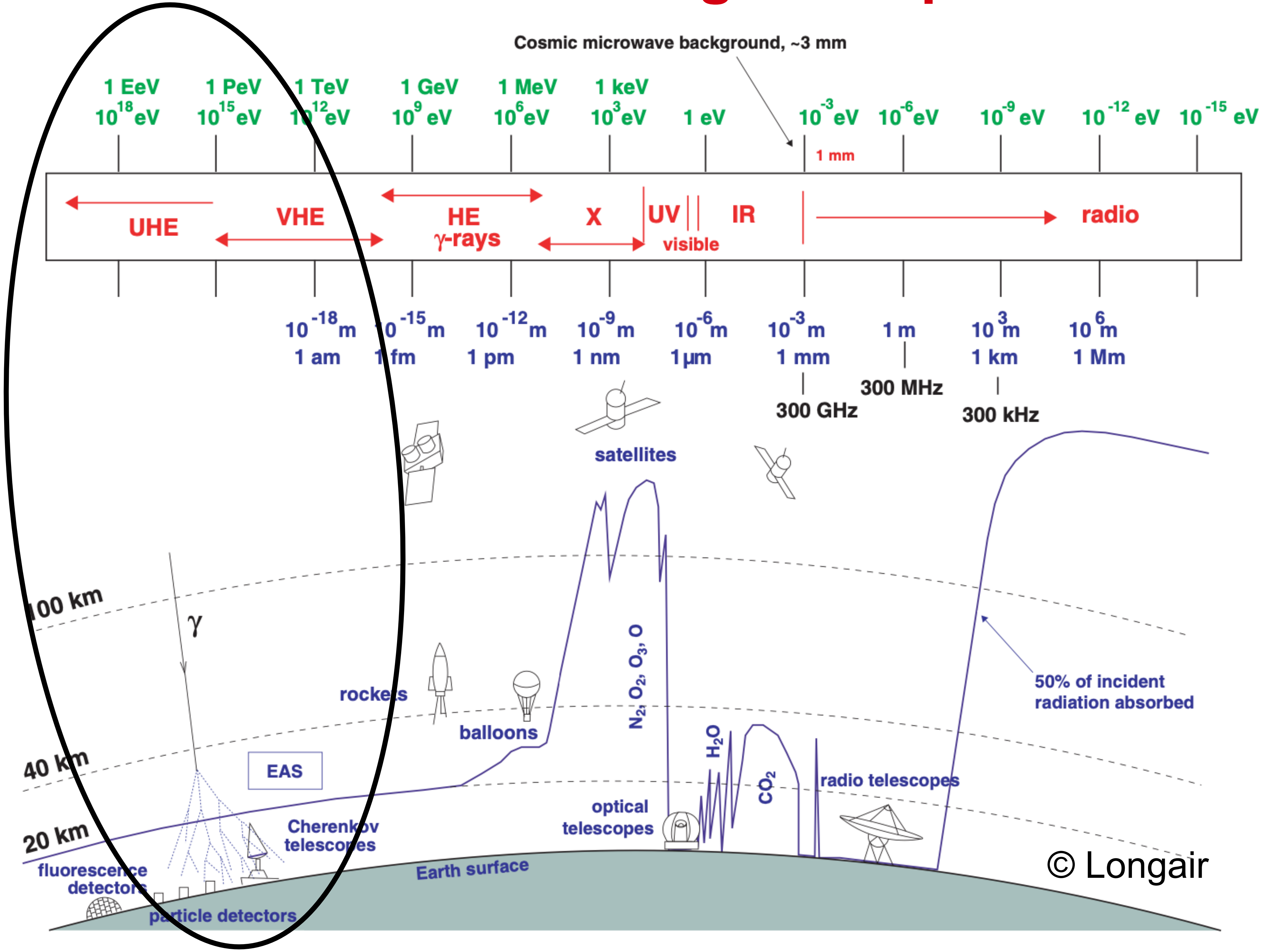
Mori et al.



Observations in the electromagnetic spectrum



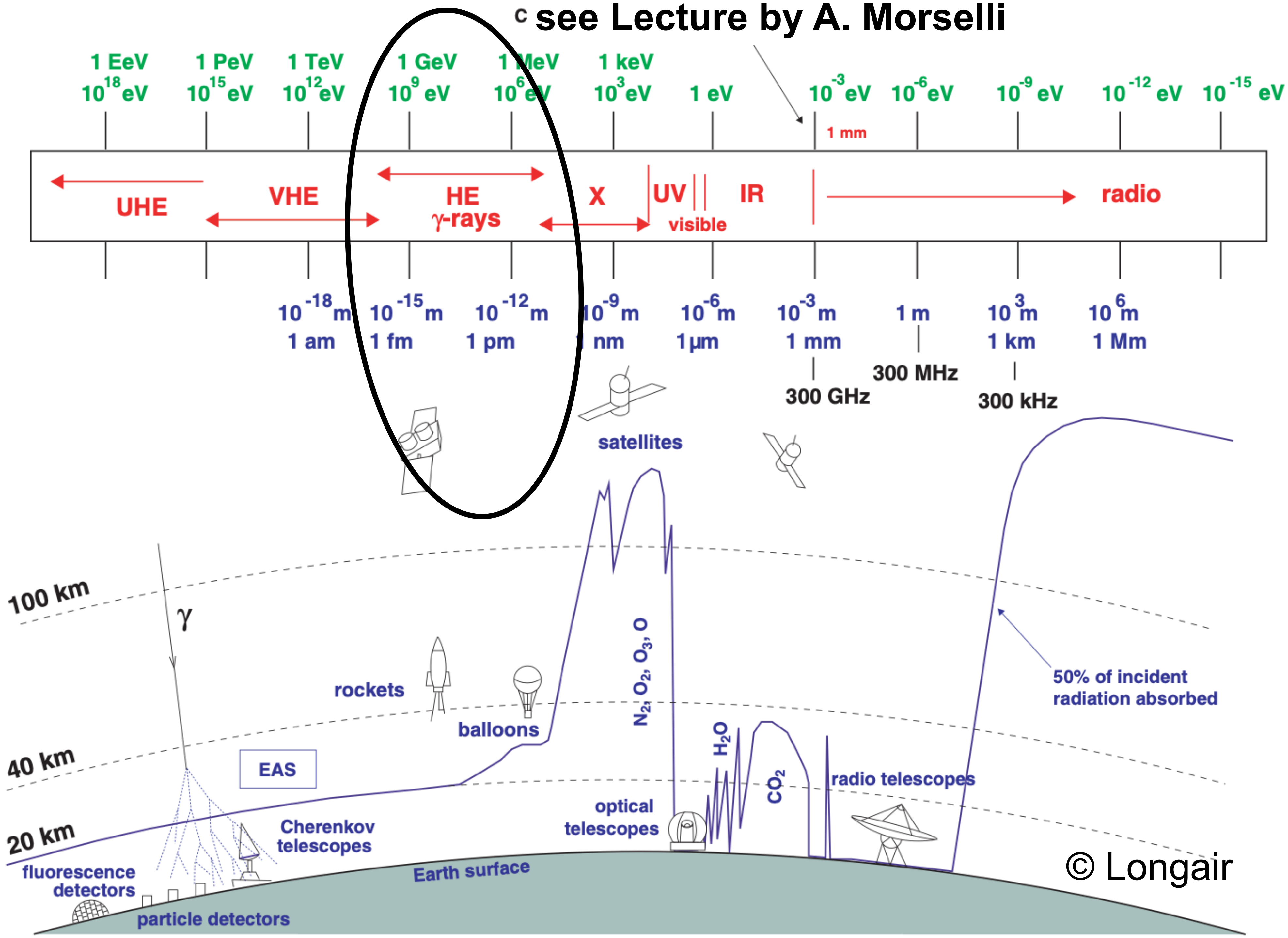
Observations in the electromagnetic spectrum



Ground-based detection at VHE energies via extensive air showers

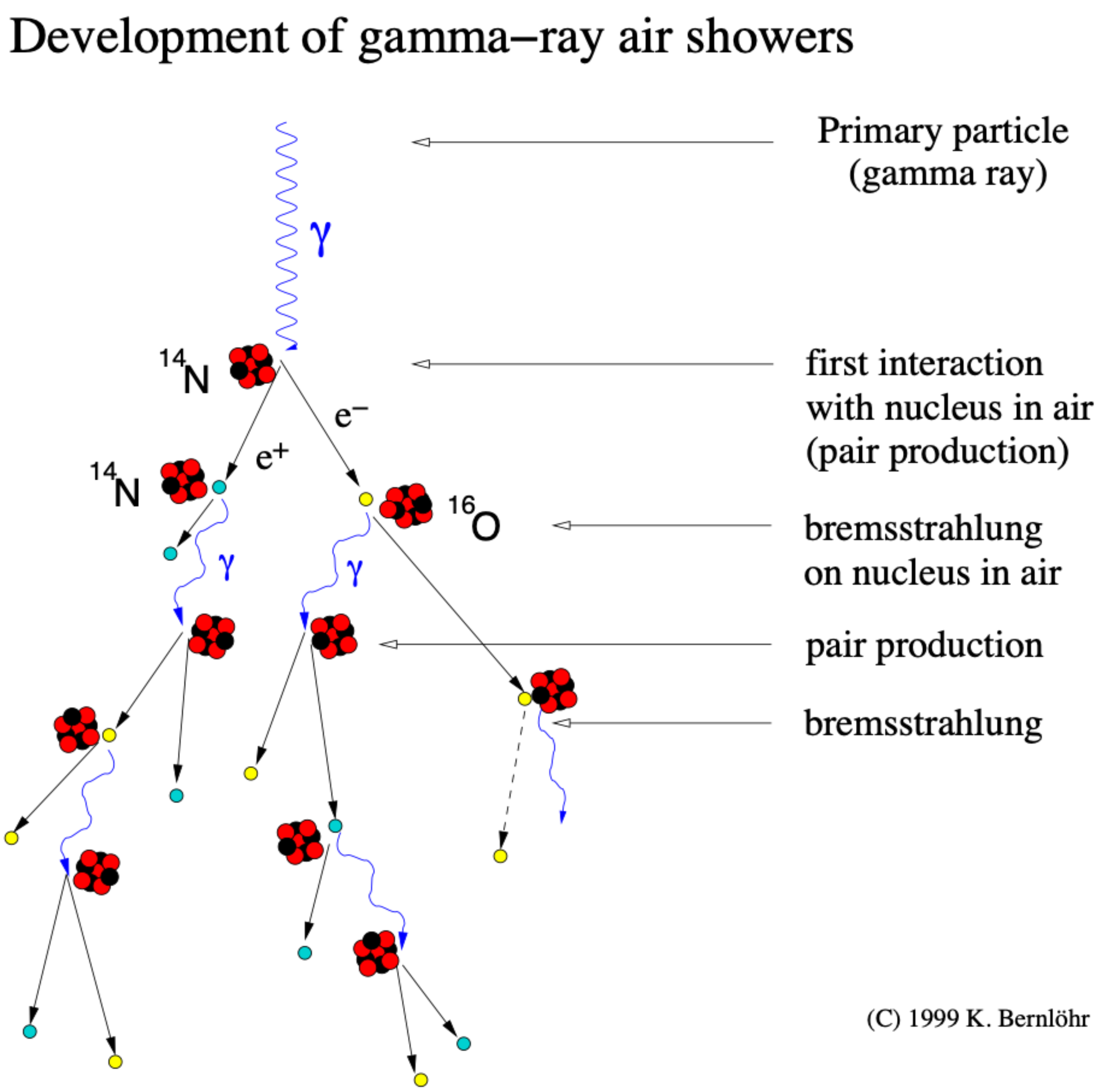
Observations in the electromagnetic spectrum

c see Lecture by A. Morselli



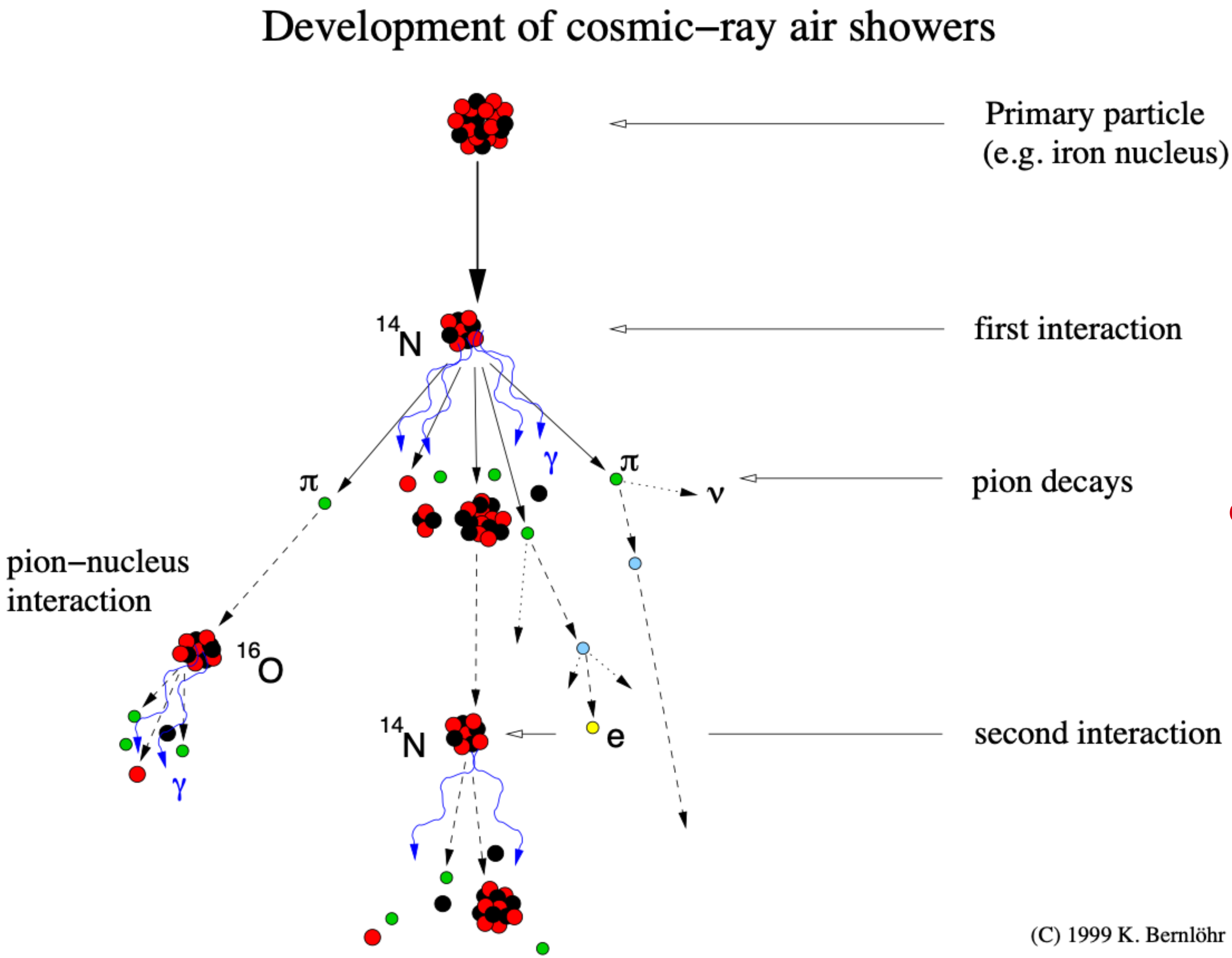
Ground-based detection at VHE energies via extensive air showers

Air Showers



pair production
and
bremsstrahlung

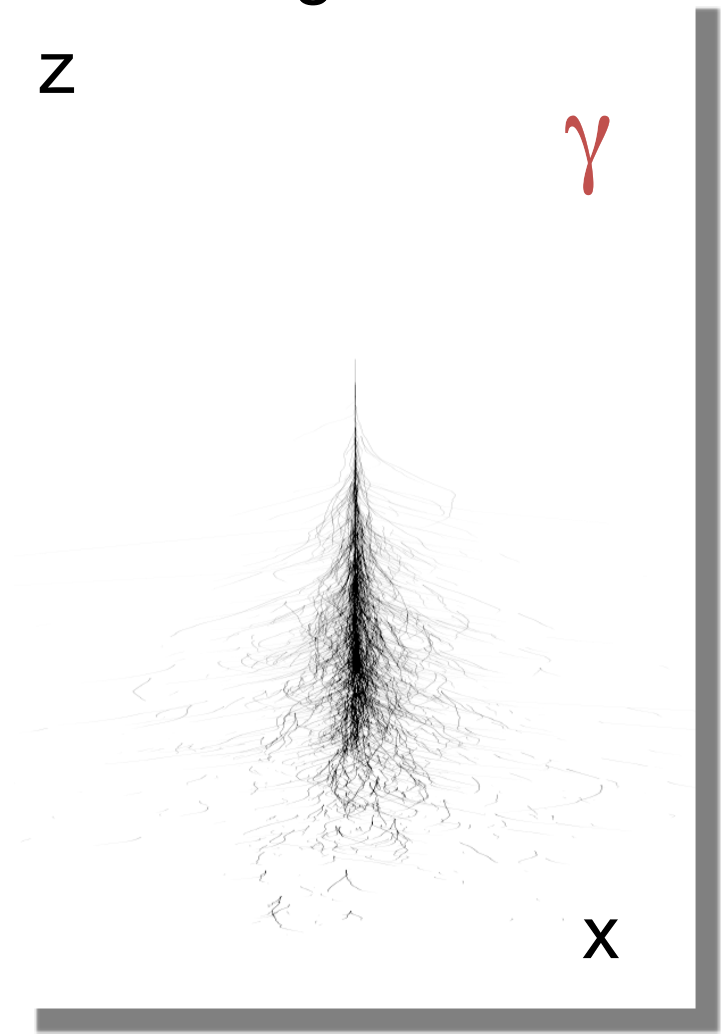
Air Showers



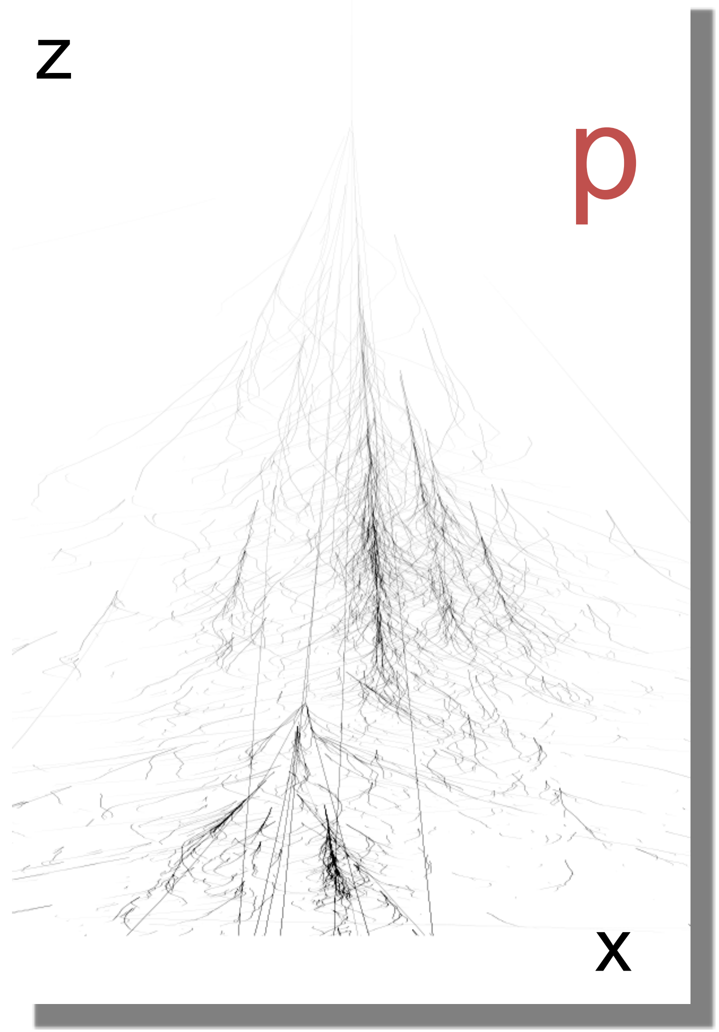
fragmentation, strong interactions producing hadrons, decays, el.-mag. subcascades

Air Showers

Electromagnetic shower

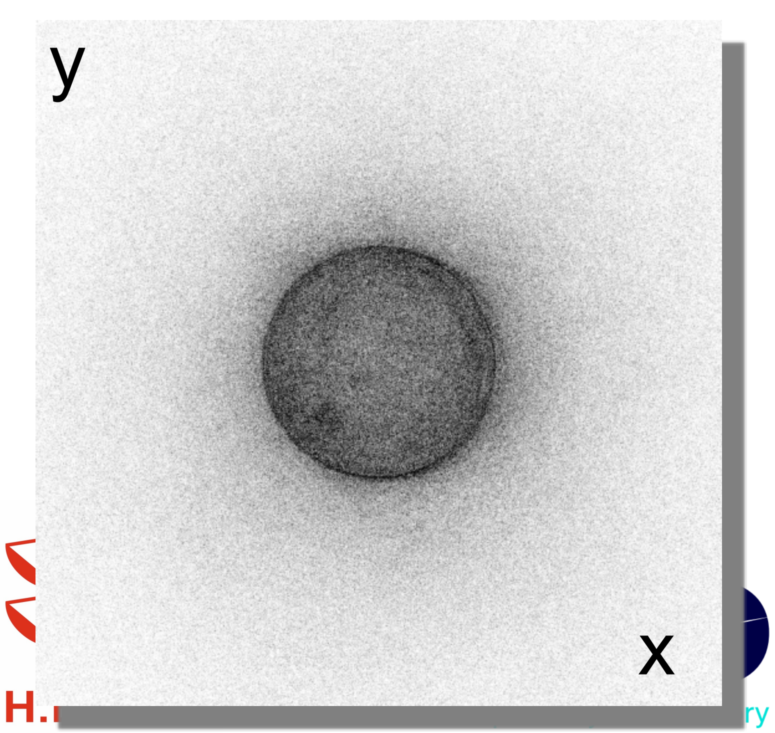


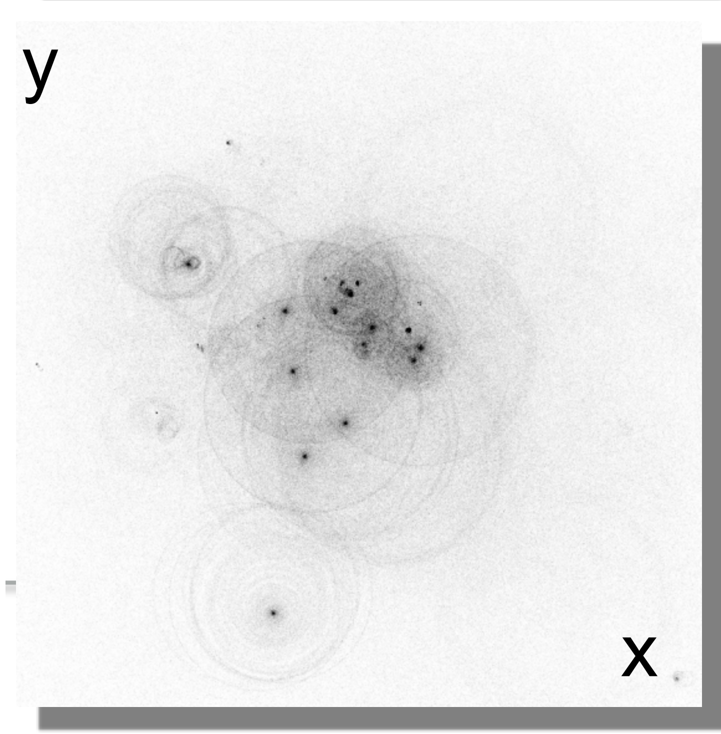
Hadronic shower



Detailed air-shower simulations contain
atmospheric information,
possible interactions and decays

x axis exaggerated
for visualisation purpose





Clear differences seen between
electromag. and hadronic showers

Cherenkov Radiation

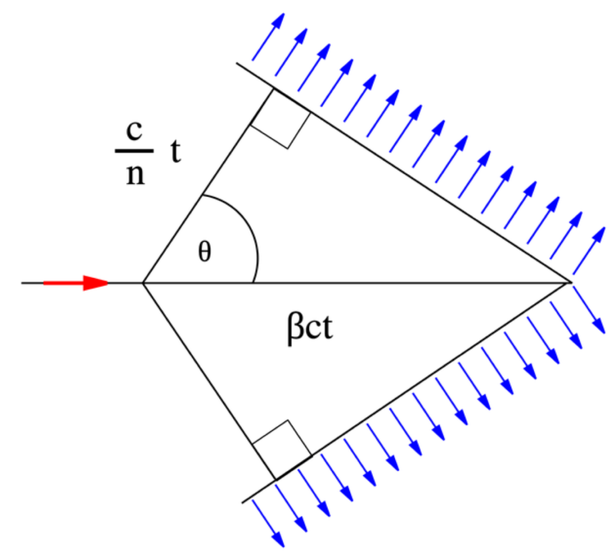
one of the favourite techniques for detecting relativistic air-shower particles

- In a medium with refractive index n:
- Speed of light: c/n
- Charged particle moving with v>c/n emits Cherenkov light
- Emission angle:

$$\cos\theta_c = \frac{1}{n\beta}$$

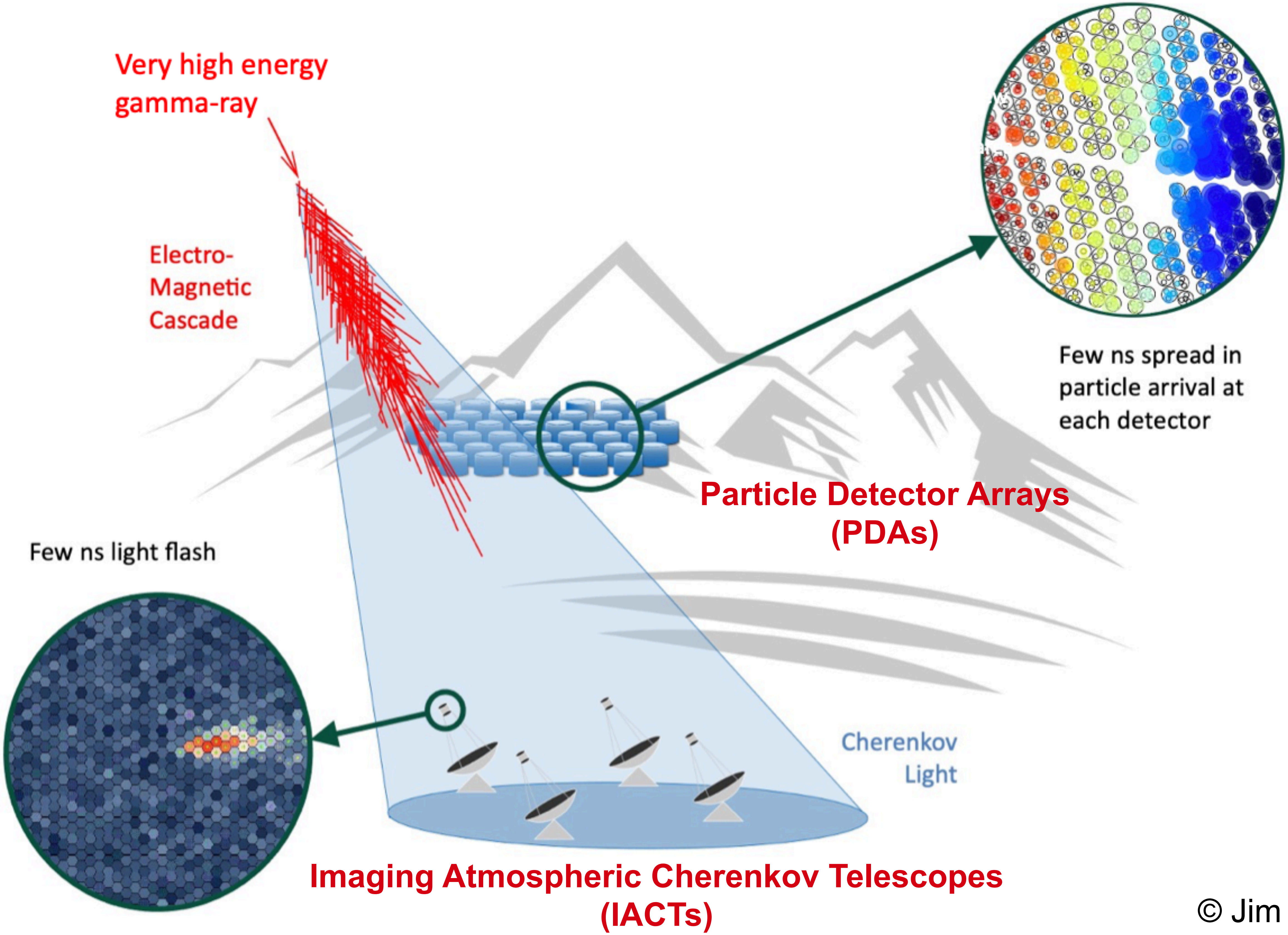
- ~1° in air, ~40° in water

Foto: Katerina_S / shutterstock.com



Charged air-shower particles can emit Cherenkov light either in the **air** or in a suitable medium like **water**

Two Techniques for Ground-Based Observations



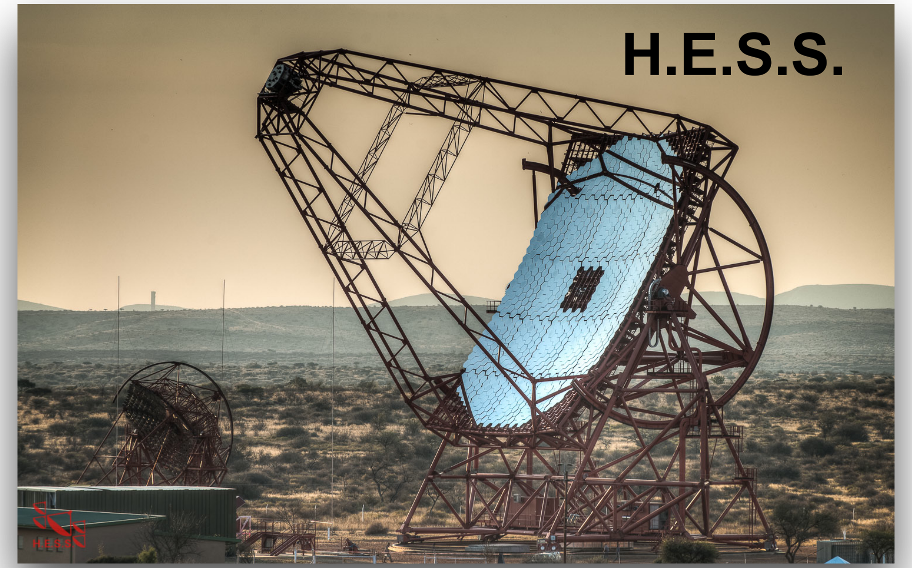
Two Techniques for Ground-Based Observations

Particle Detector Arrays

Cherenkov light in water

24/7 observations

observation of full sky above detector



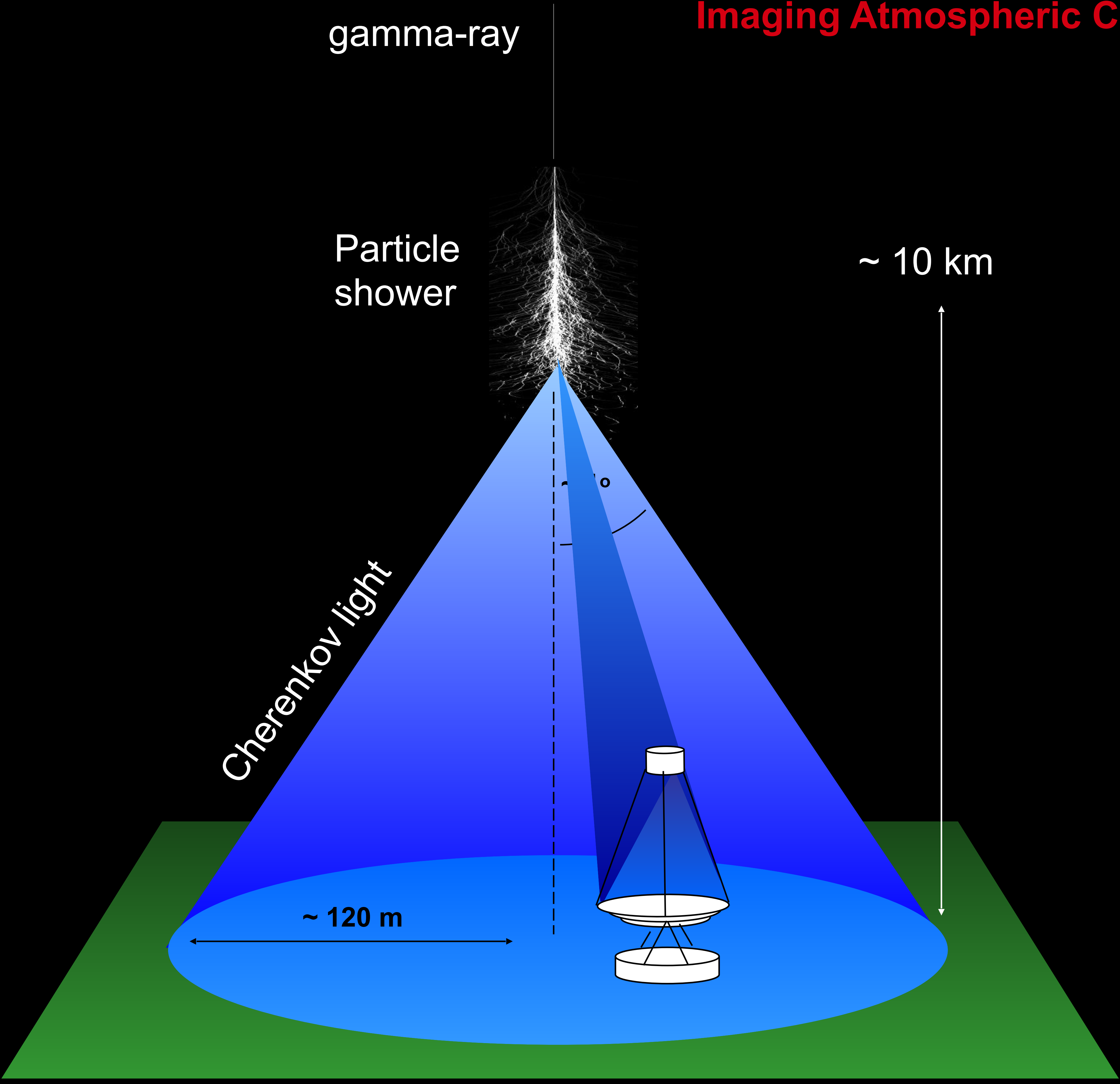
Imaging Atm. Cherenkov Telescopes

Cherenkov light in atmosphere

(moon-less) night observations

small field of view/
pointed observations

Imaging Atmospheric Cherenkov Telescopes



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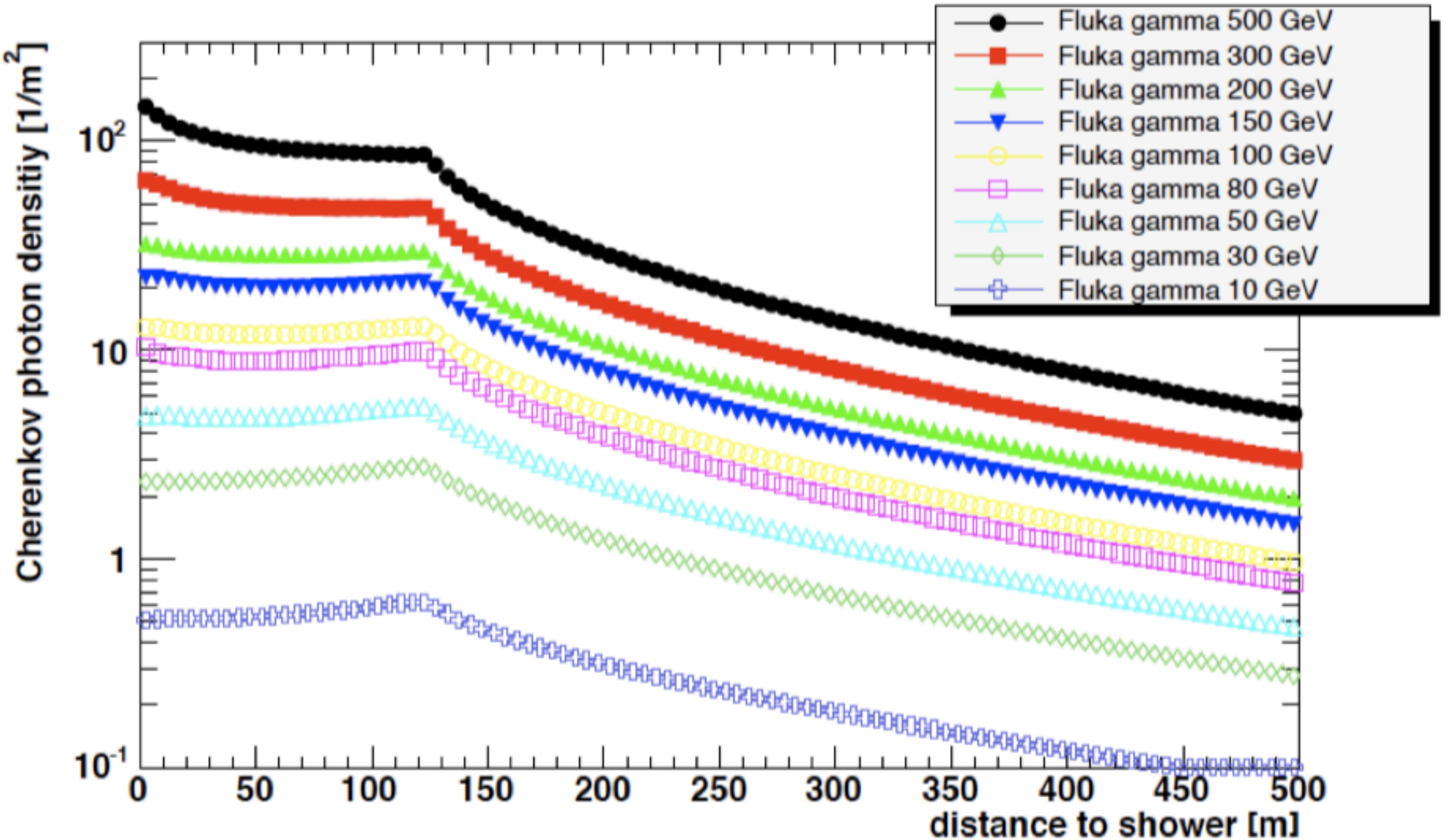
Cherenkov light on the ground

Gamma

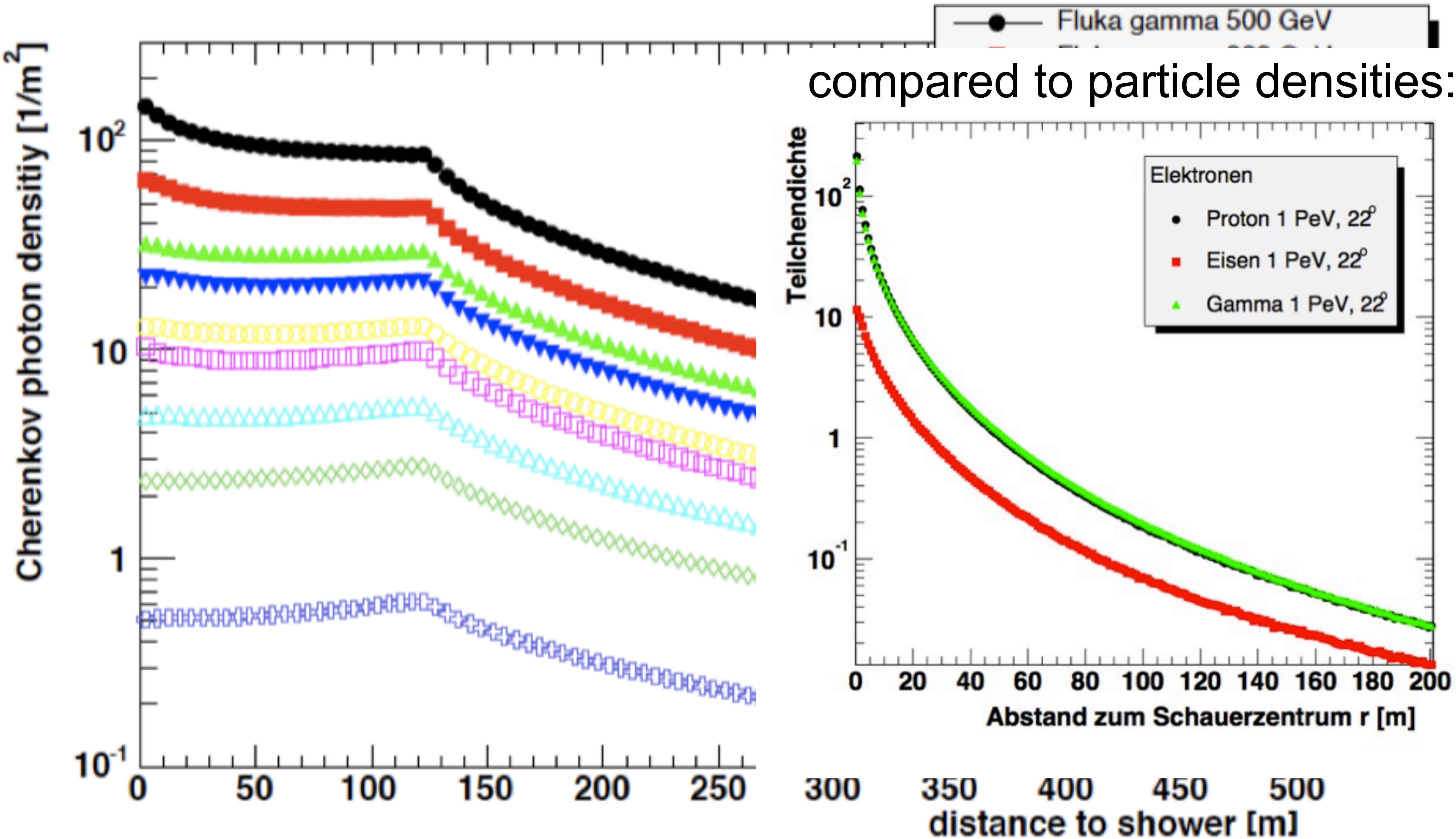
~ 100 Photons per TeV and m^2

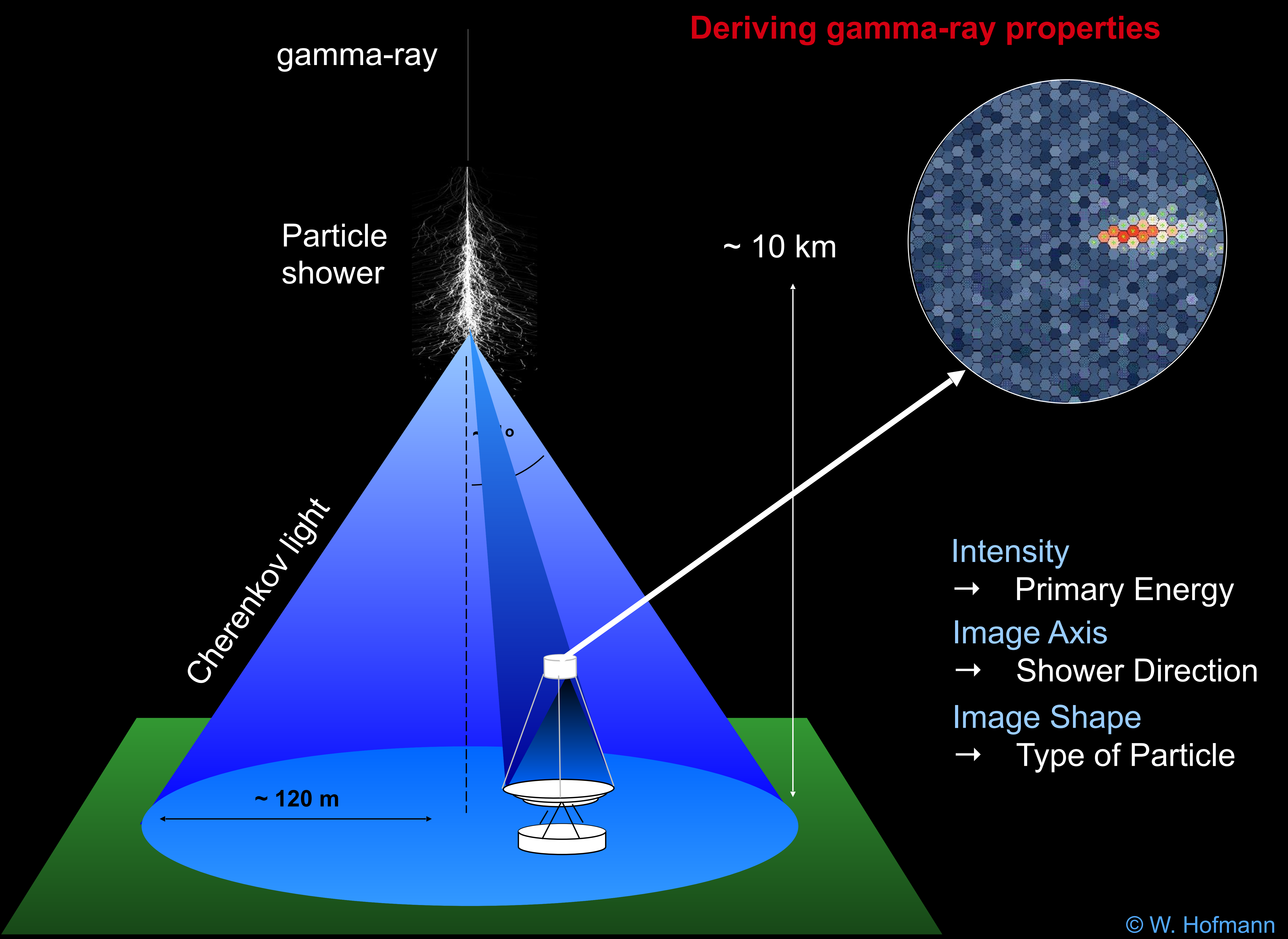
- large mirrors
- dark skies
- short exposures (~ 10 ns)

Cherenkov light on the ground



Cherenkov light on the ground




Deriving gamma-ray properties
gamma-ray
Particle shower
~ 10 km
Cherenkov light
~ 120 m
Intensity
→ Primary Energy
Image Axis
→ Shower Direction
Image Shape
→ Type of Particle
© W. Hofmann

Stereoscopy for better direction reconstruction

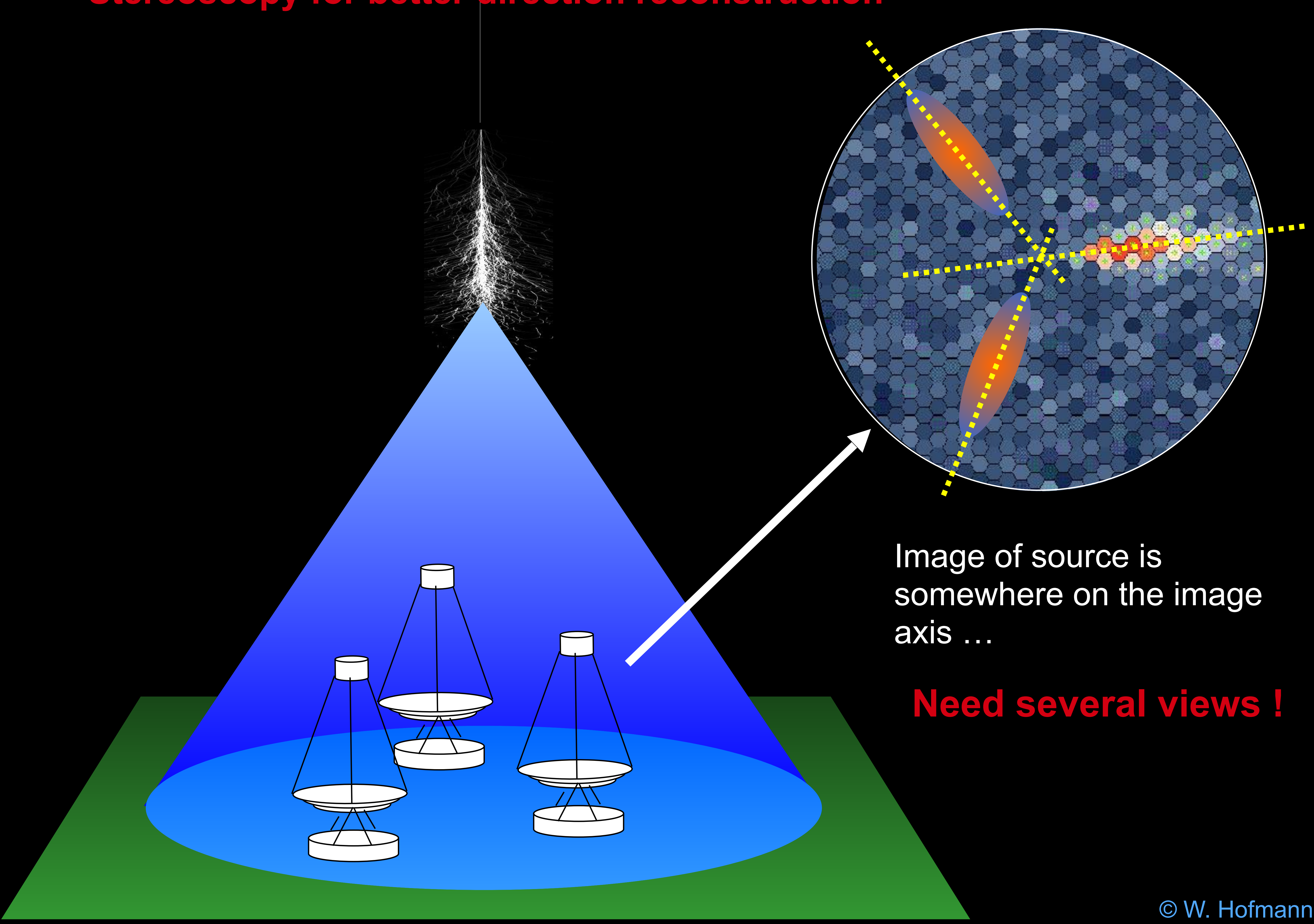
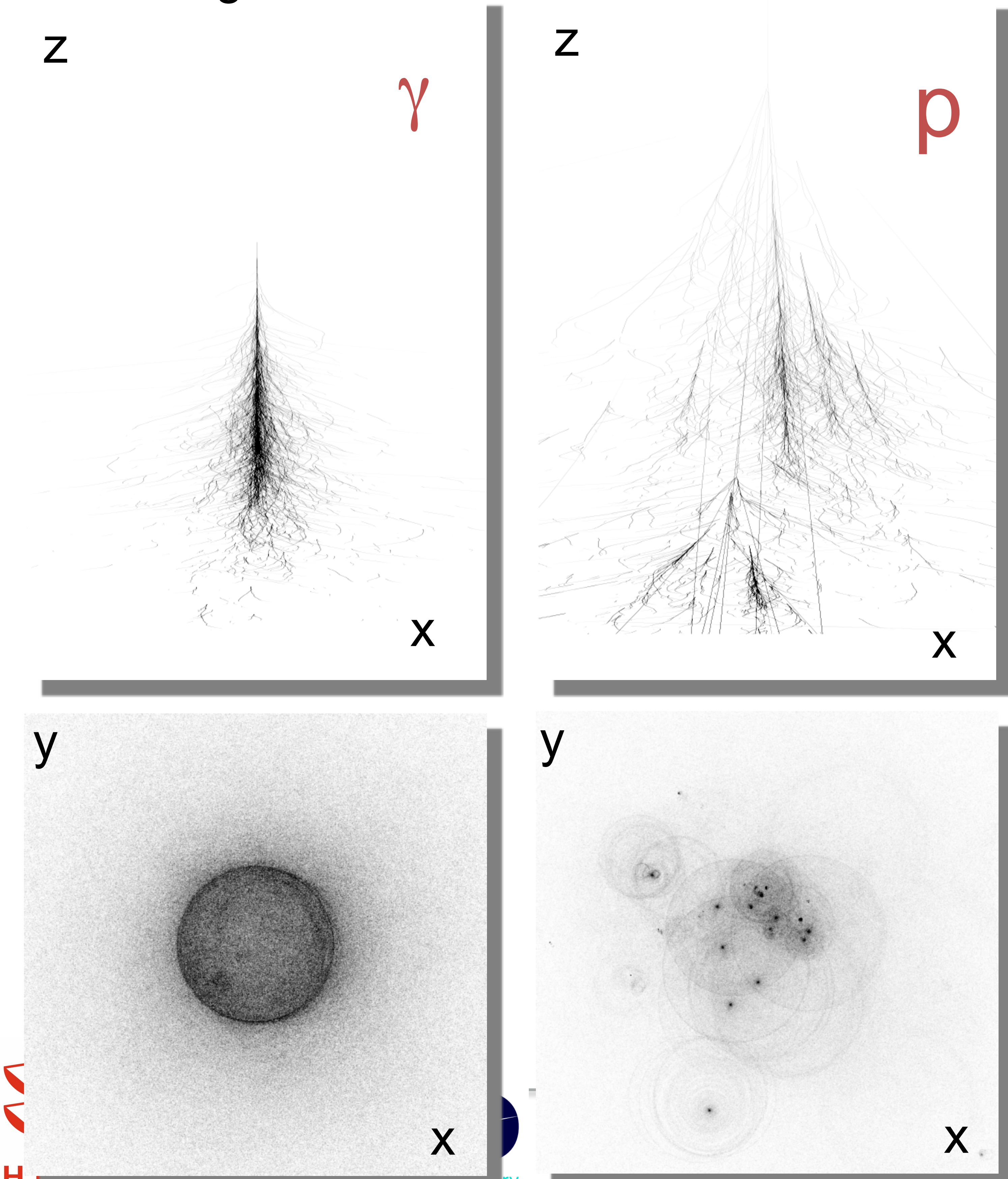


Image of source is somewhere on the image axis …

Need several views !

Background discrimination / γ-hadron separation

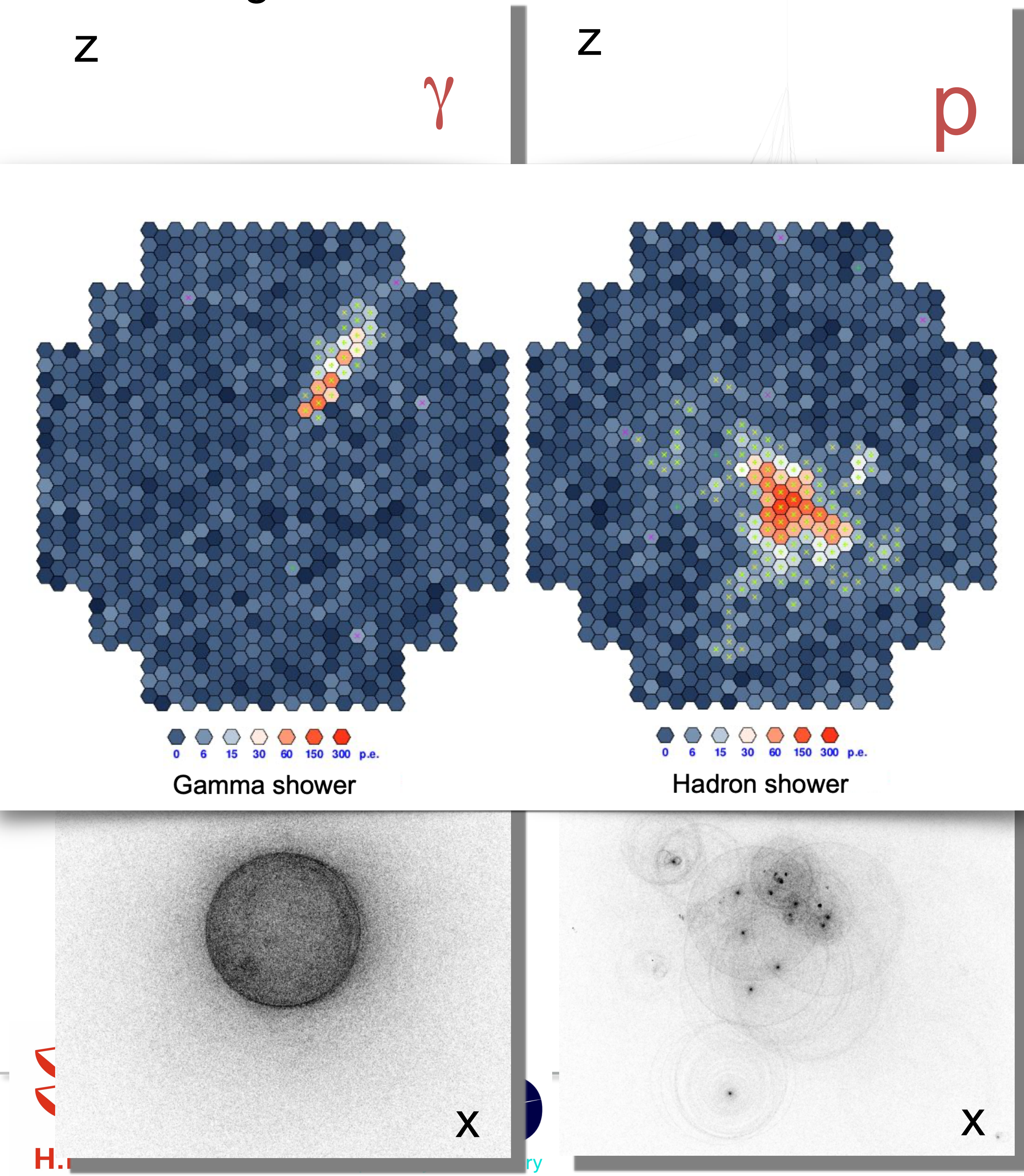
Electromagnetic shower | Hadronic shower



Difference between elmag. and hadronic showers used for classification

Background discrimination / γ-hadron separation

Electromagnetic shower Hadronic shower



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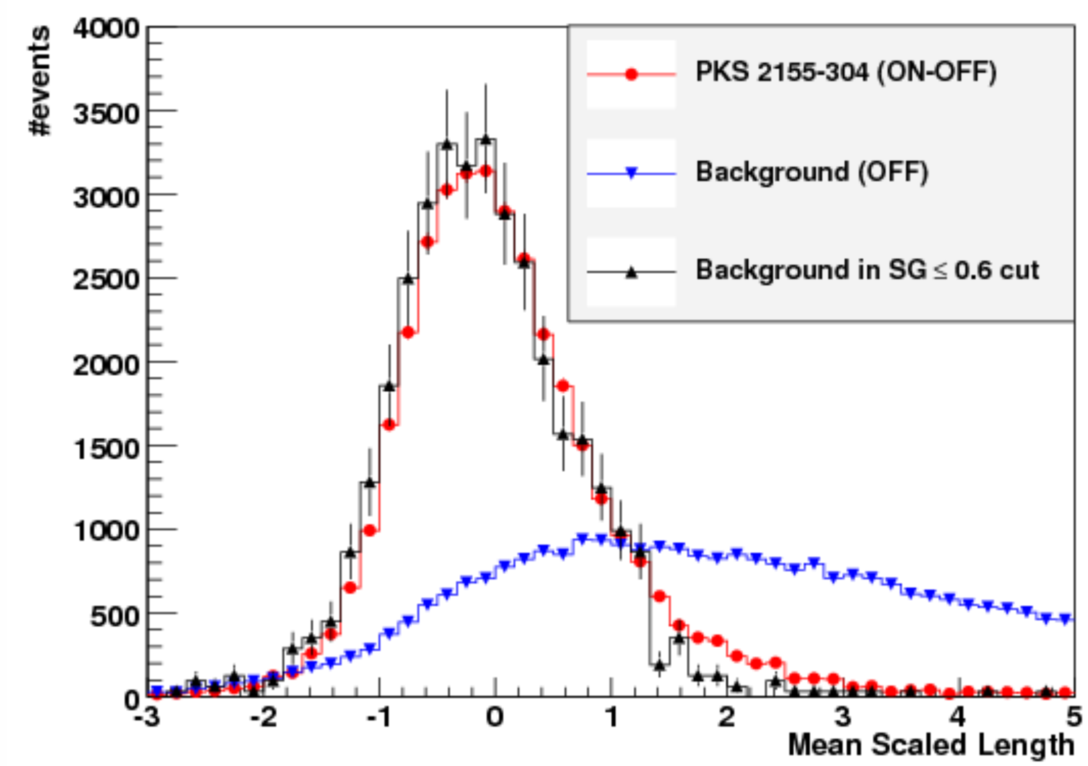
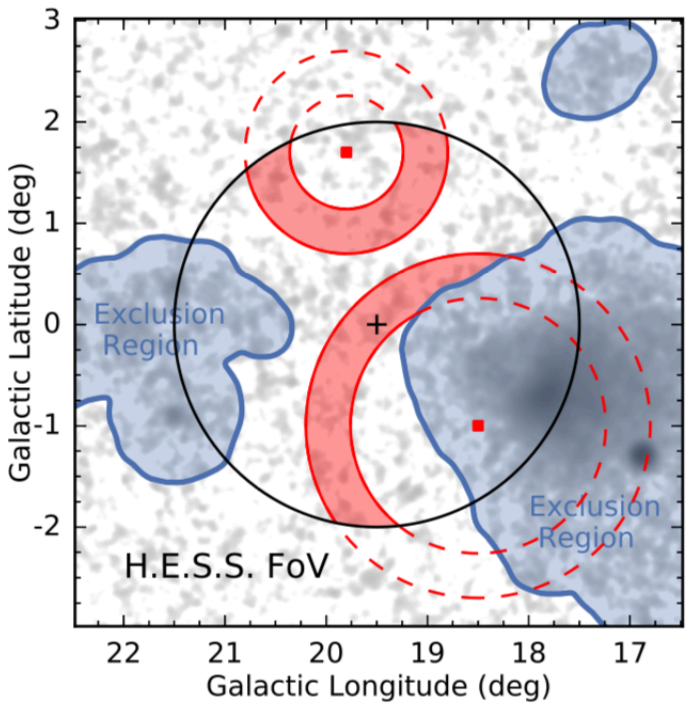


Width of the camera image normalised to width of γ-distribution

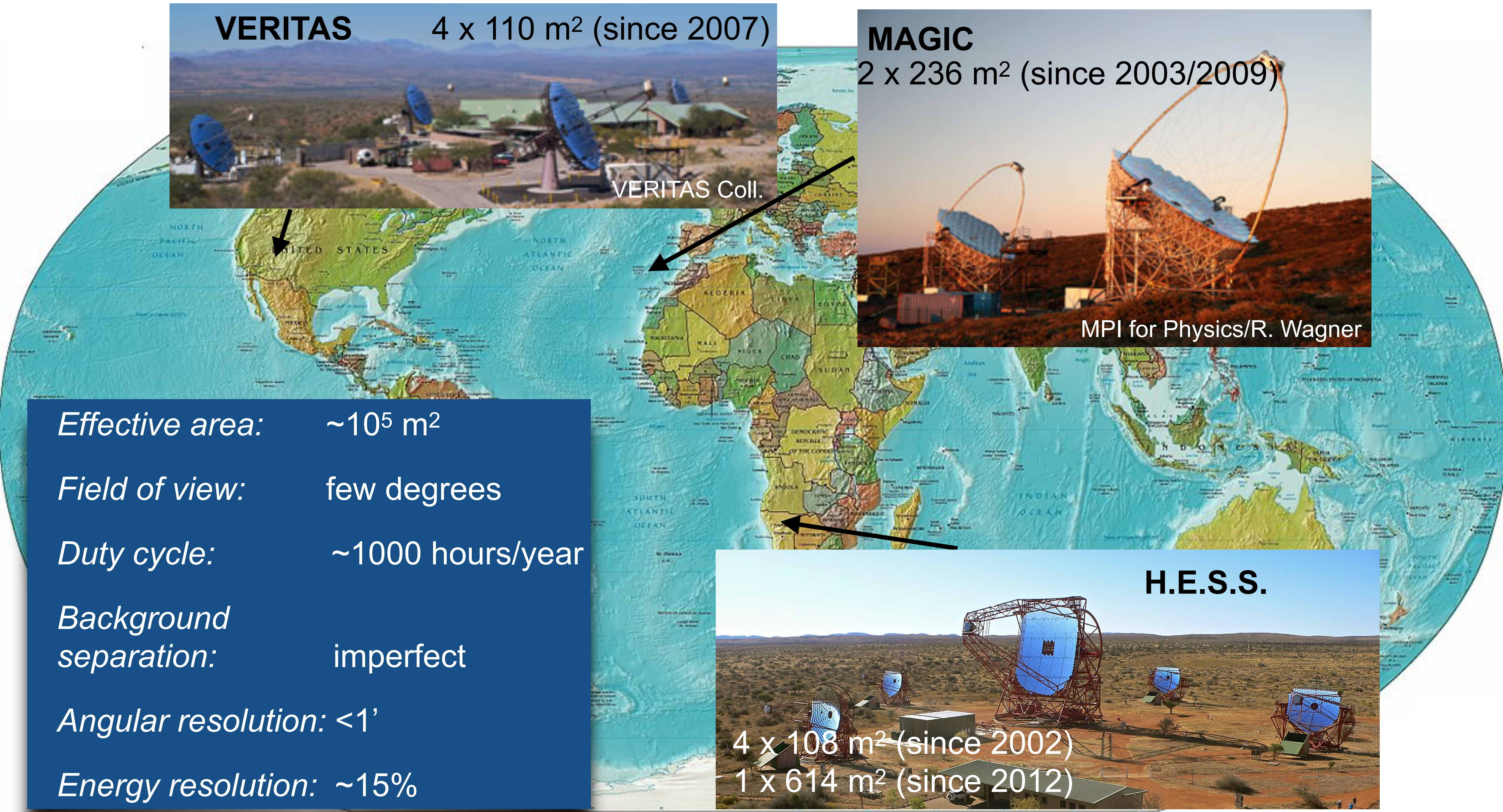
Background Subtraction

- Necessary because of imperfect gamma/ hadron separation
- Performed in background measurements in the FoV (+ assumption on system response)
- Iterative exclusion of regions with gamma-ray emission
- *Advantage*: 1st order cancelation of systematics related to condition of instrument and atmosphere
- *Disadvantage*: Results in subtraction of any large-scale gamma-ray emission together with the background



→ method optimised for sources much smaller than the field of view

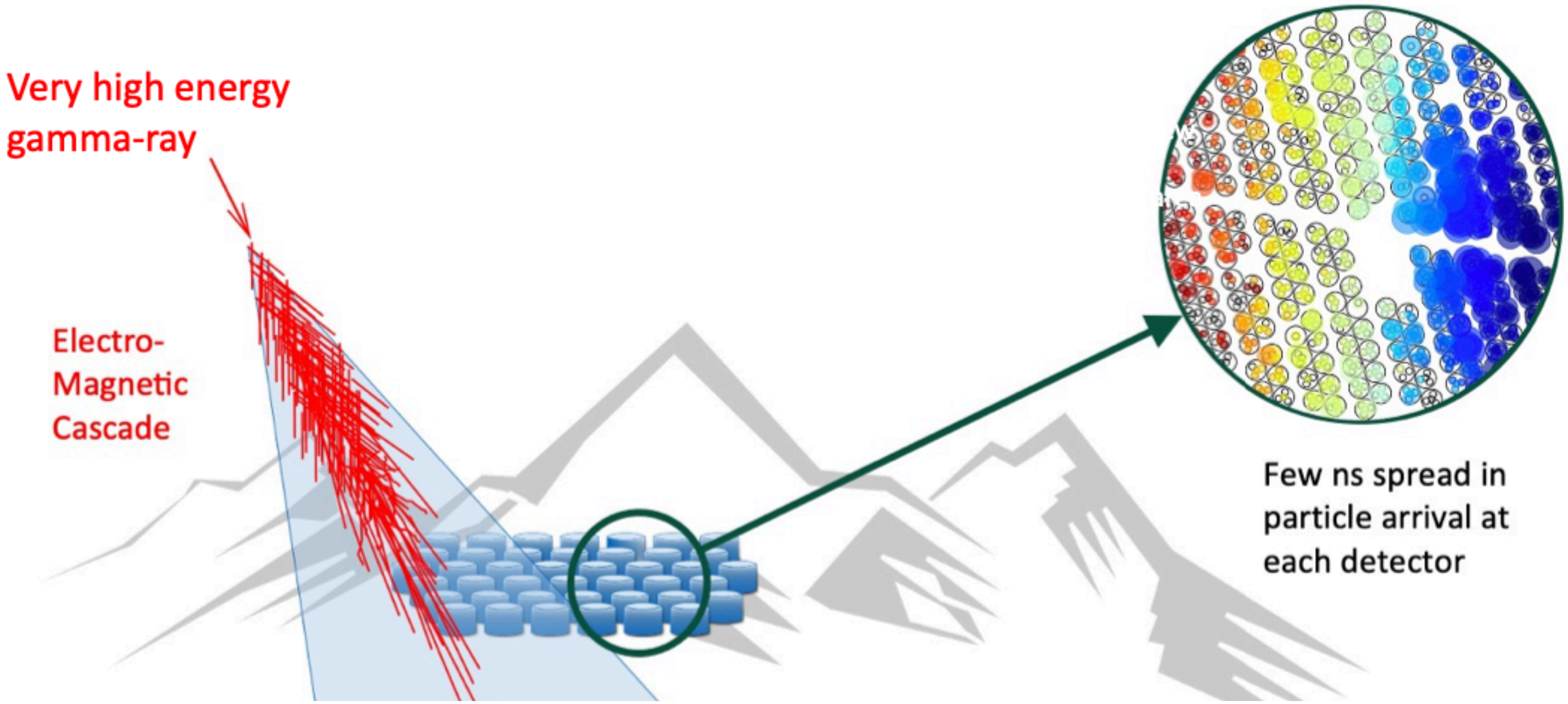
Current IACT Instruments



Effective area:	~10^5 m^2
Field of view:	few degrees
Duty cycle:	~1000 hours/year
Background separation:	imperfect
Angular resolution:	<1’
Energy resolution:	~15%

Particle Detector Arrays

- Particle detectors can be *scintillators* or *water tanks*
- Detection of the tail of the air shower reaching the ground
  → preferably in *high locations* / higher energy threshold
- Observables: *Particle density* and *time of arrival* at each detector position



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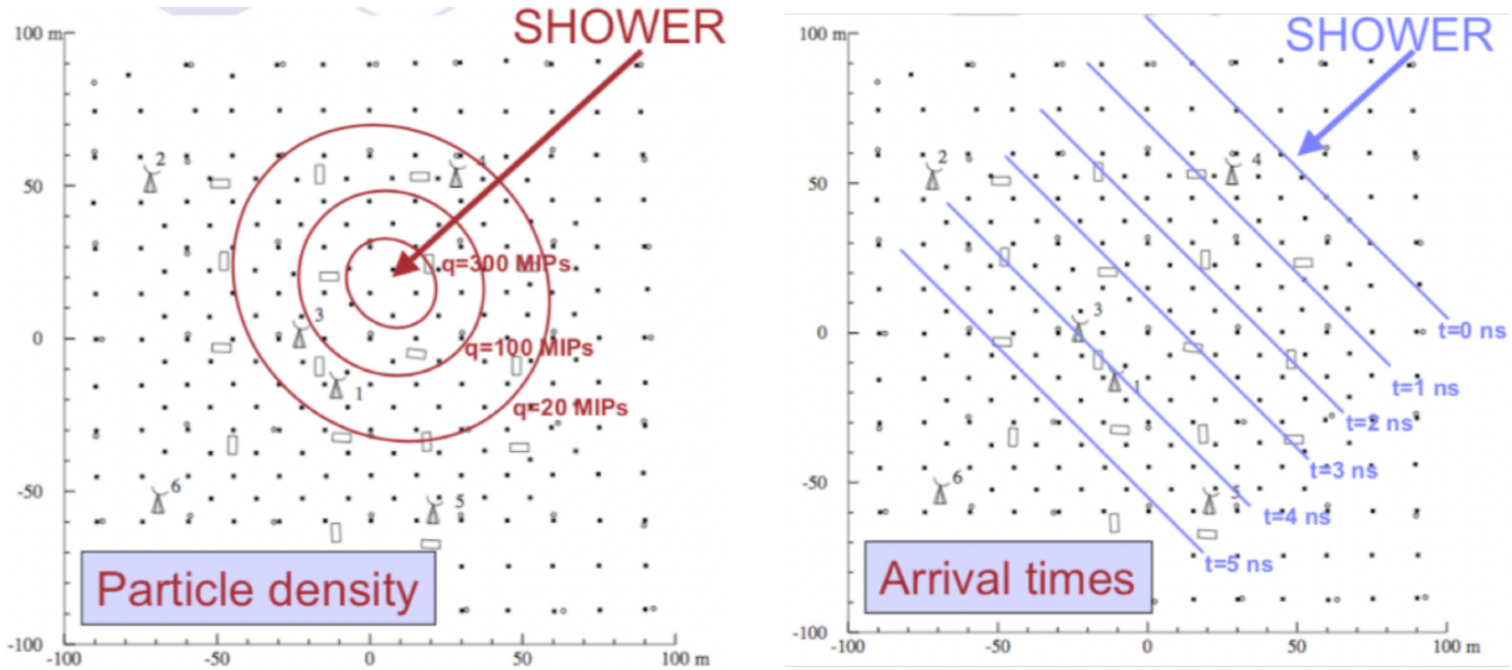
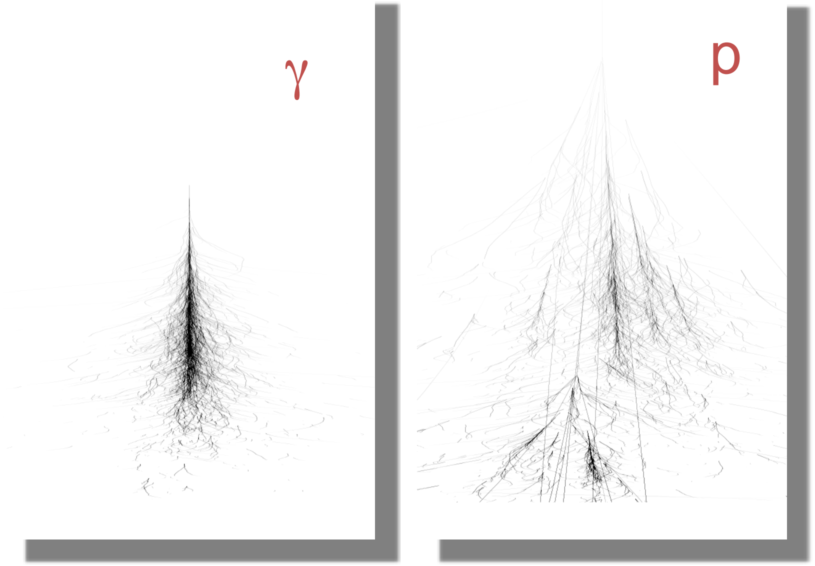
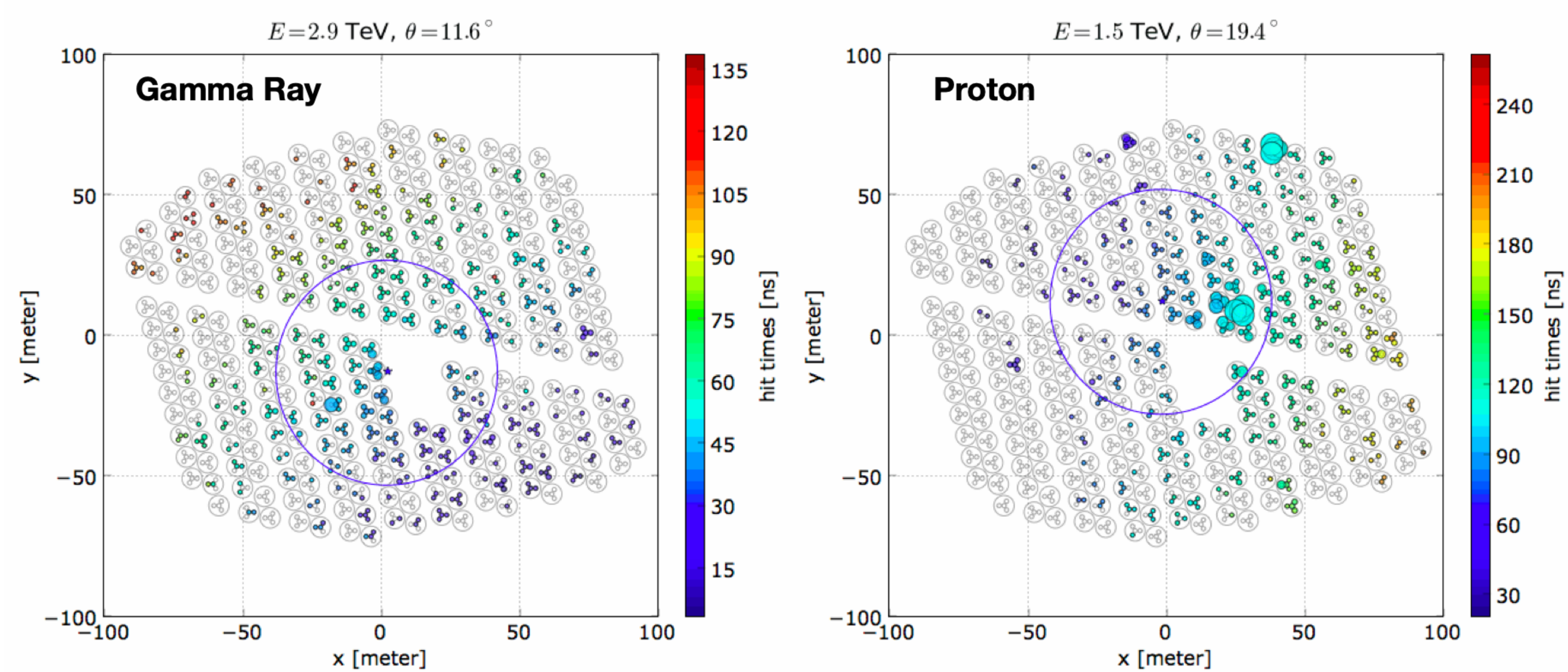


- Time gradient and center of gravity used for direction
- Energy from total signal
- Uniformity for gamma/ hadron separation

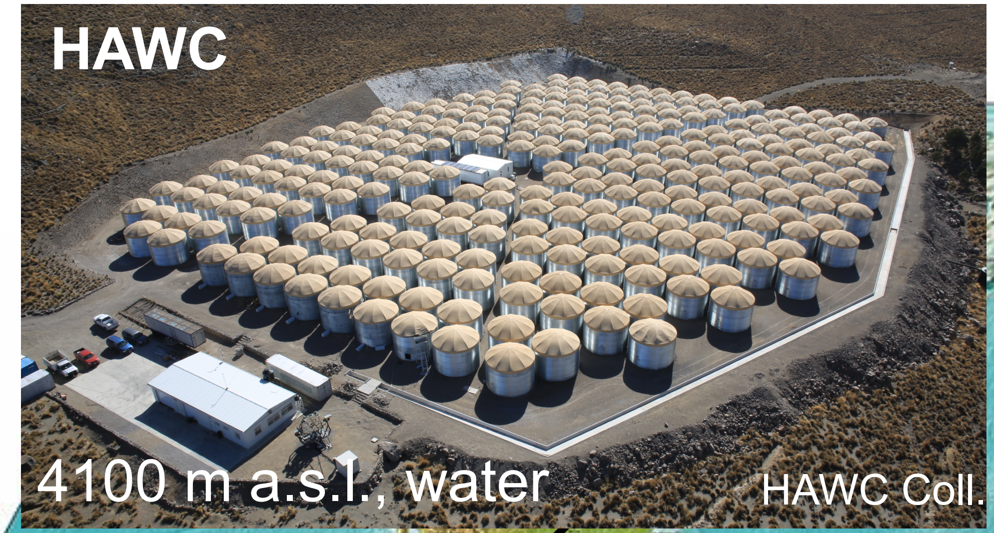
Hadron Background

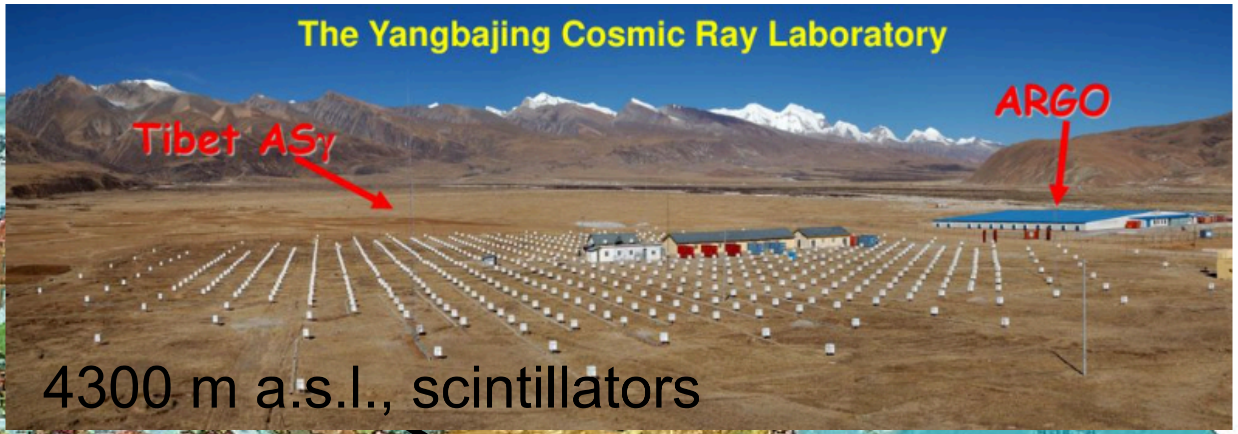


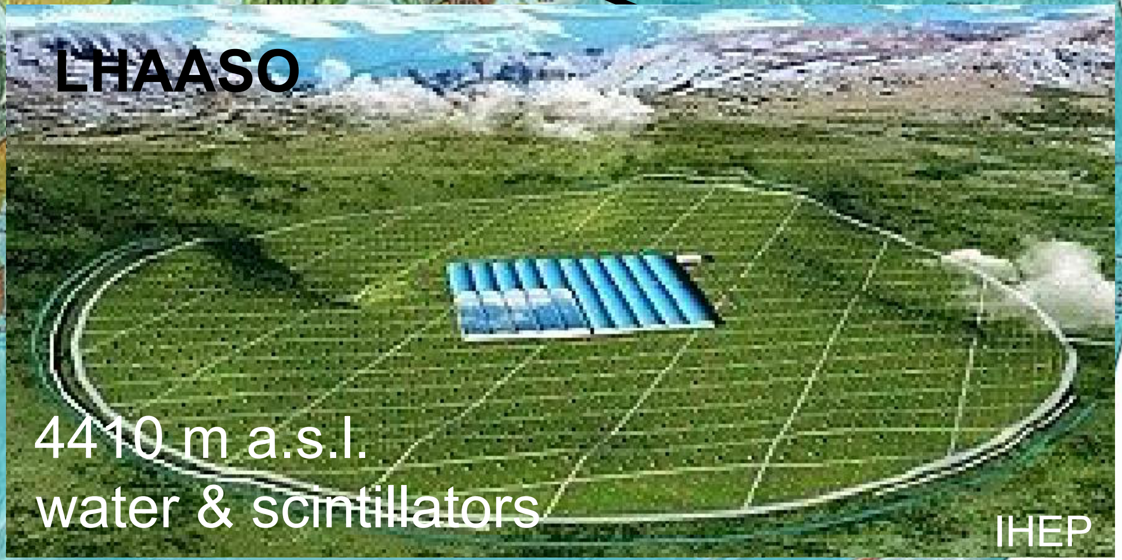
- Patchiness of the signal → compactness parameter
- Subtraction of remaining background: Direct integration from the data collected prior to and after the source transited in local coordinates (θ,φ)



Current Particle Detector Array Instruments



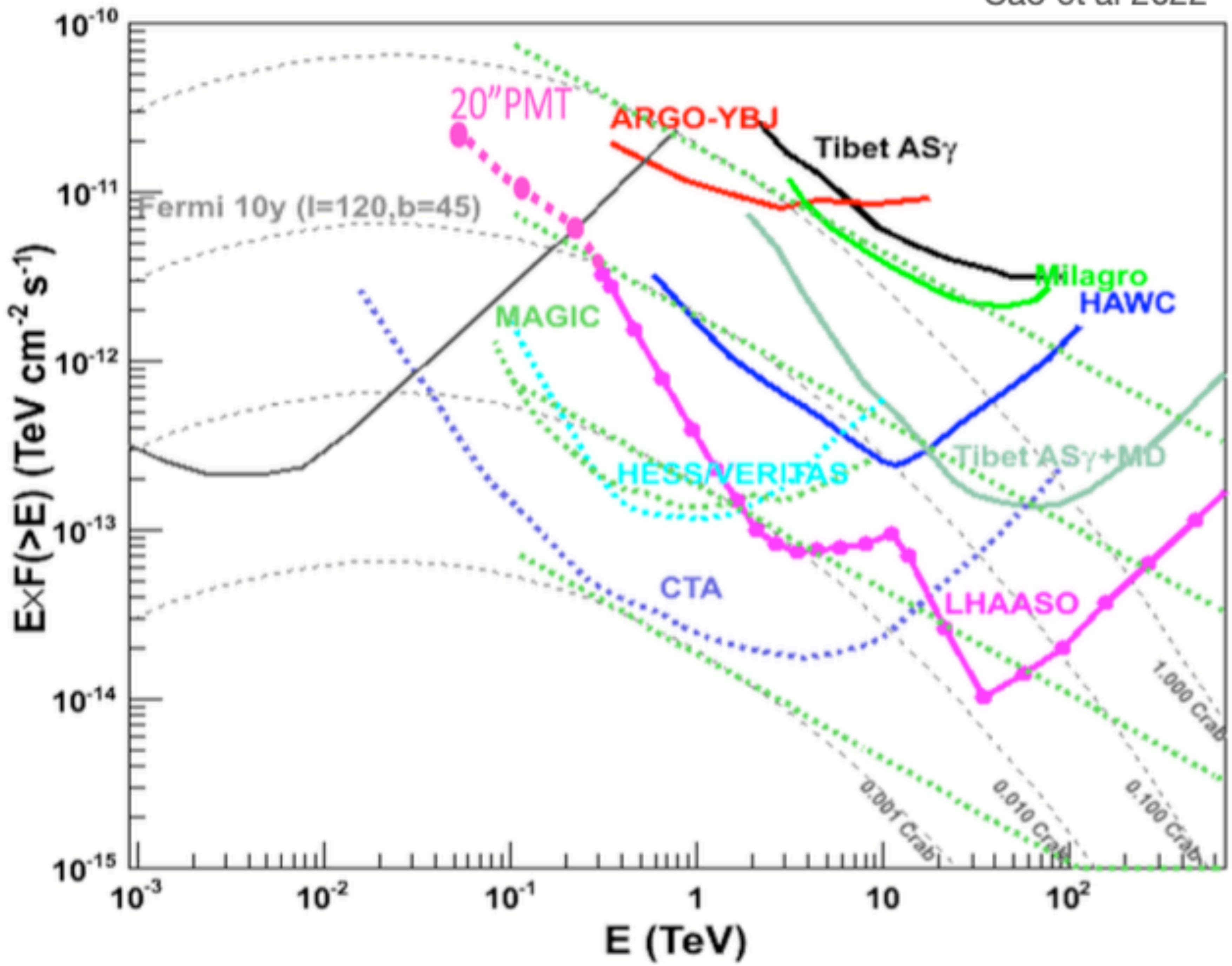




Field of view:	sky above detector
Duty cycle:	24/7
Background separation:	modest
Angular resolution:	~0.5°
Energy resolution:	~50%

Sensitivities

Cao et al 2022



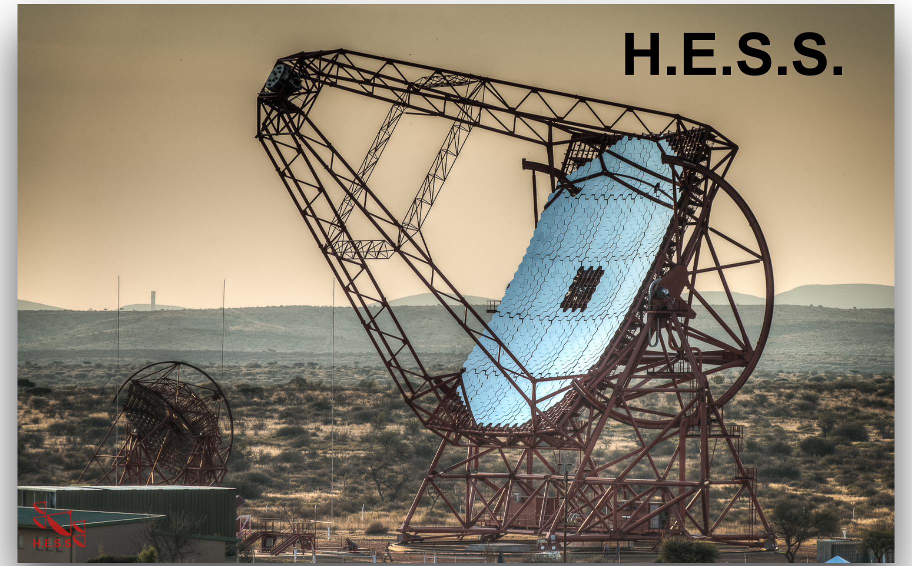
Two Techniques for Ground-Based Observations

Particle Detector Arrays

Angular resolution of ~0.5 deg

Wide fields of view

Large duty cycle



Imaging Atm. Cherenkov Telescopes

Angular resolution of $\lesssim$0.1 deg

Small fields of view

Larger instantaneous sensitivity
(put into perspective by small FoV and low duty cycle)

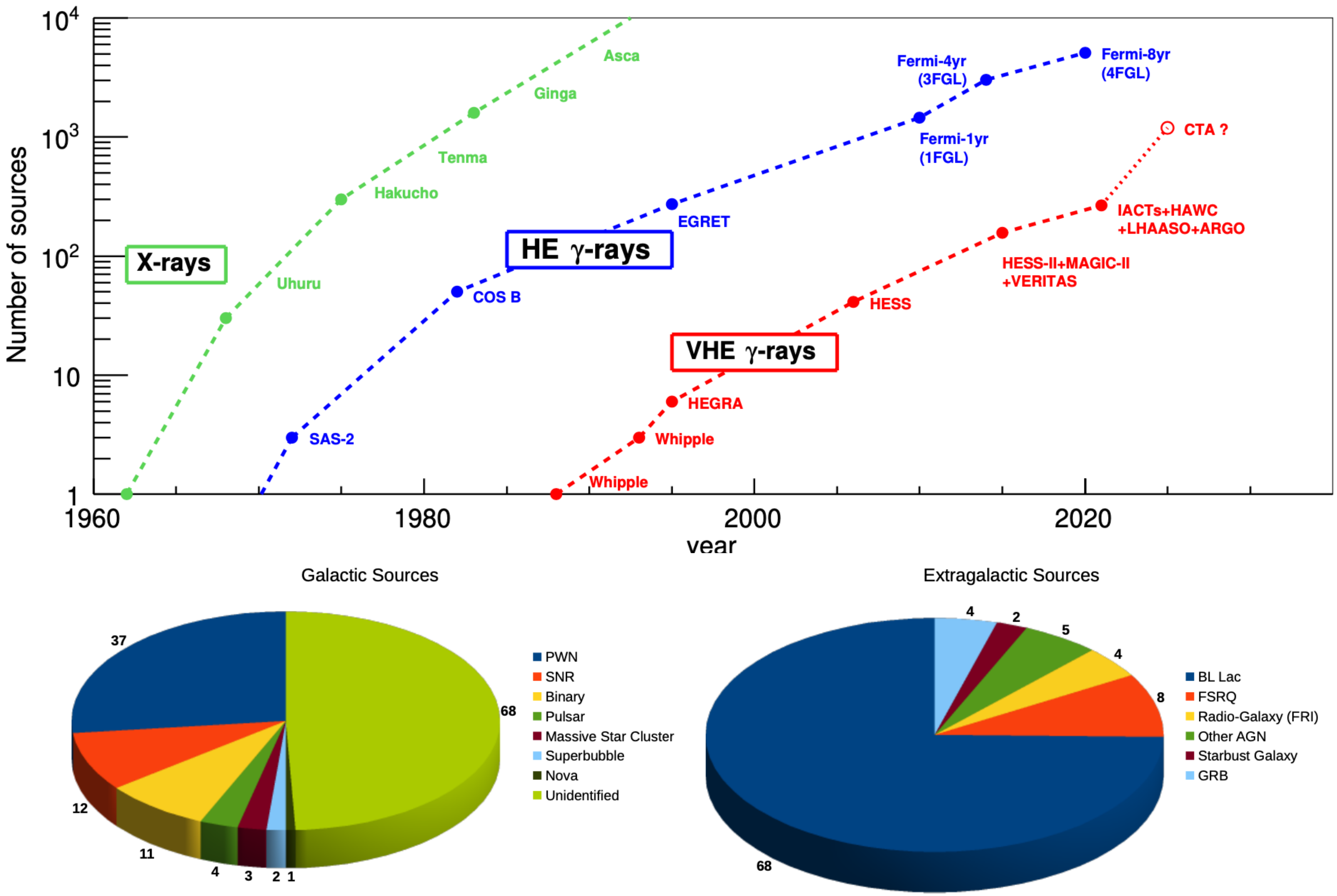
Survey instruments at somewhat higher energies

Very strong complementarity!

Pointed precision instruments with somewhat lower energy threshold

TeV Observations

A rapidly developing field



with a large variety in sources!

Mathieu de Naurois (2021)

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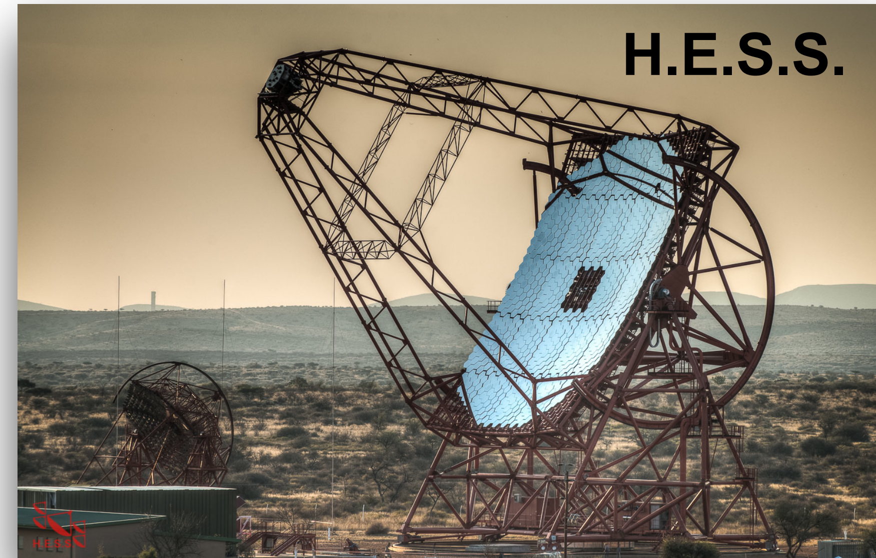

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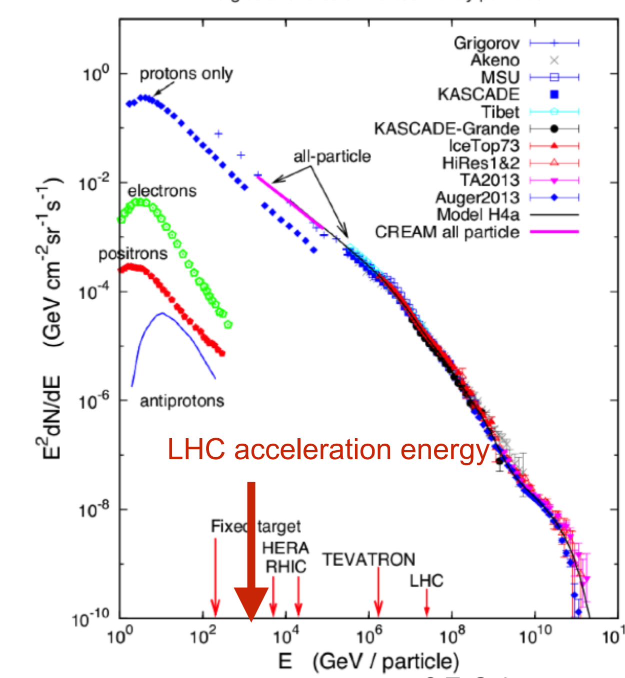
Galactic Gamma-Ray Astronomy



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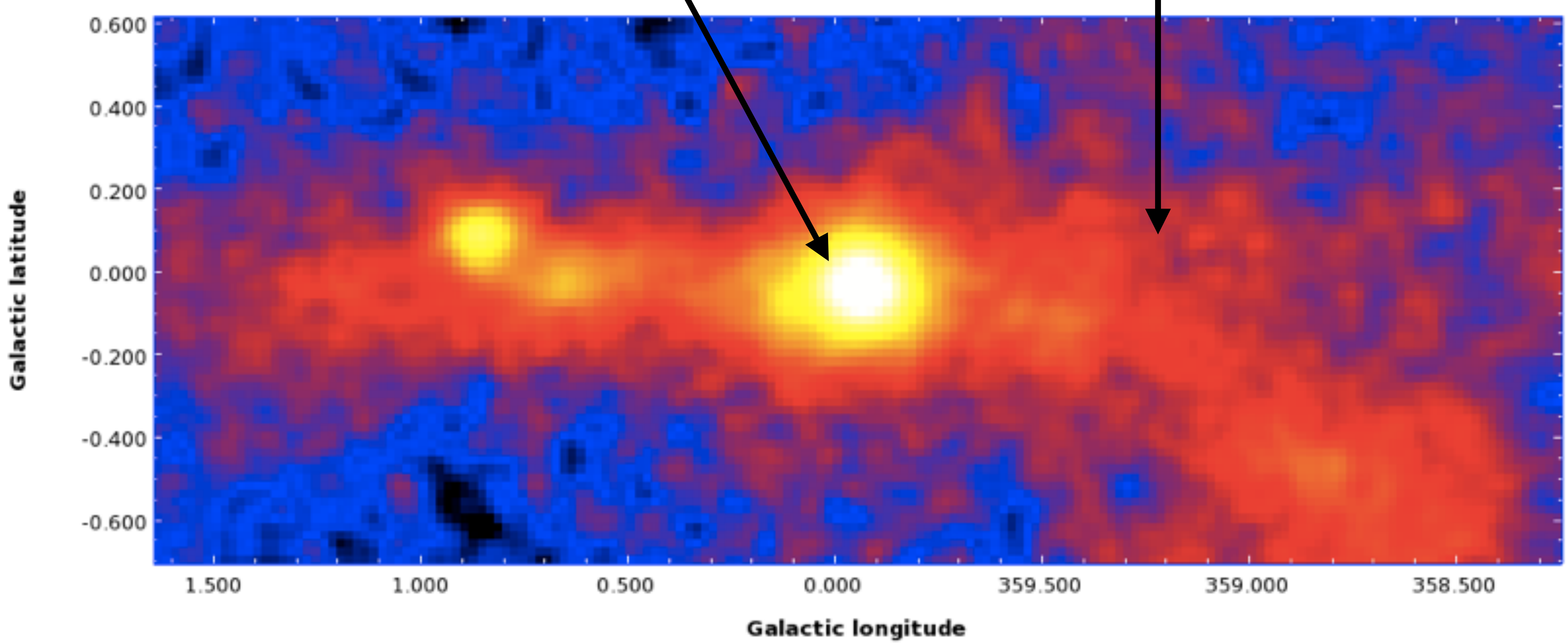
Cosmic-ray accelerators:
gamma-ray sources

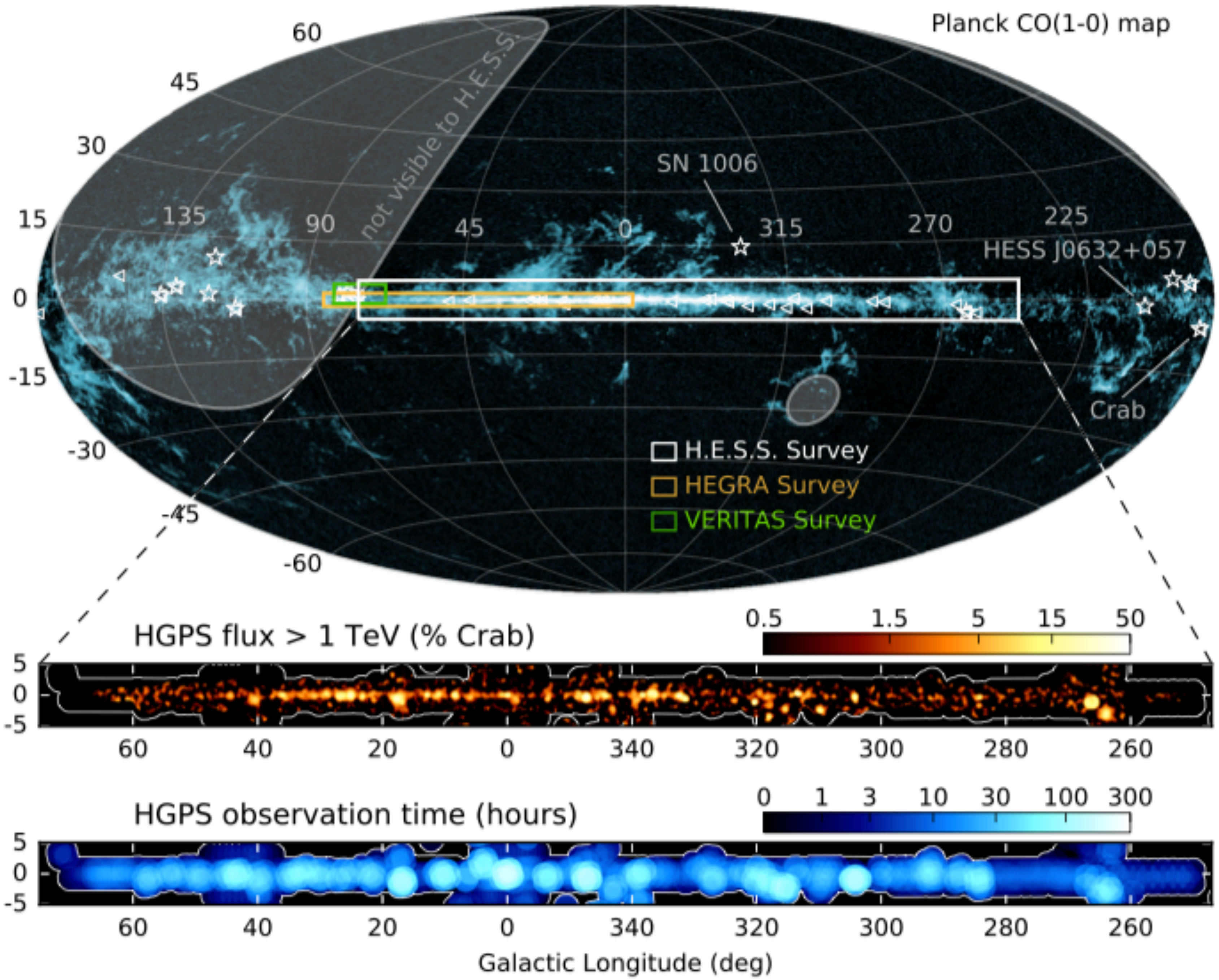
with ≥30 TeV gamma-rays probing CRs up to the knee

Propagating cosmic rays:
diffuse gamma-ray emission



The View on our Milky Way

The H.E.S.S. Galactic Plane Survey

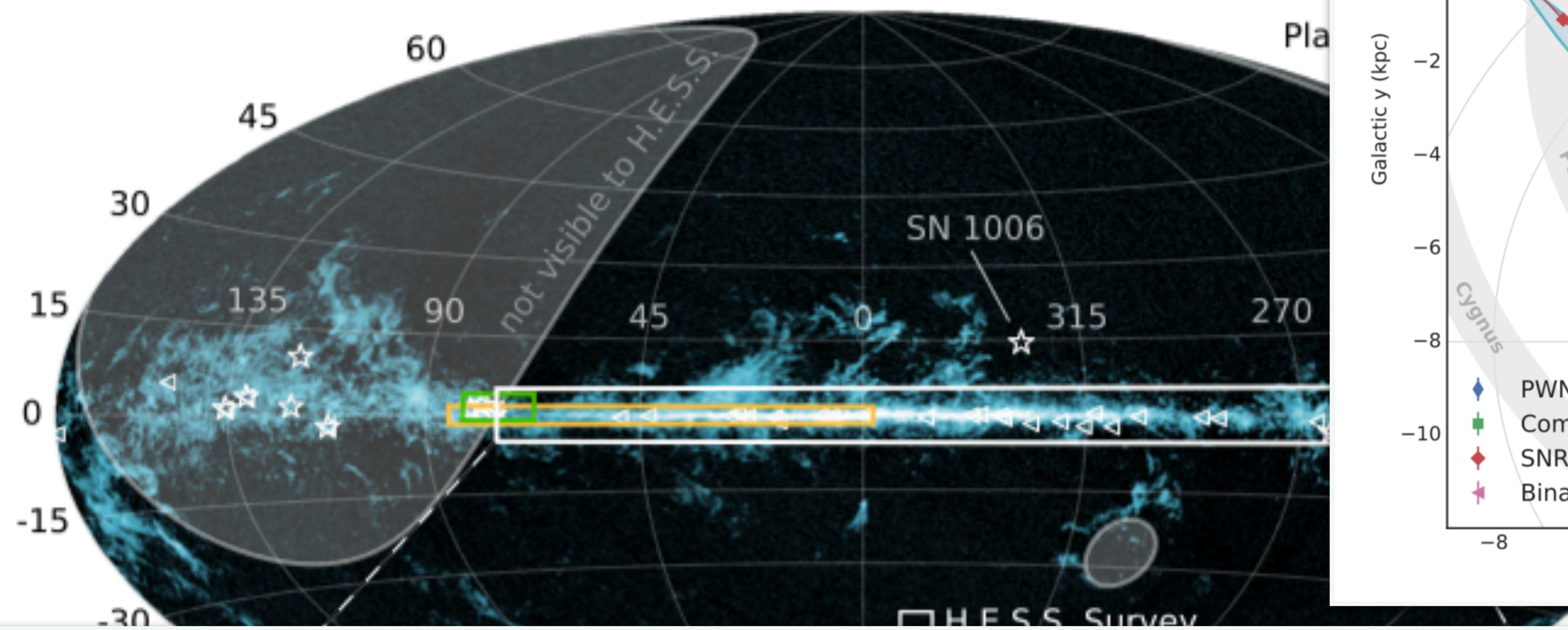


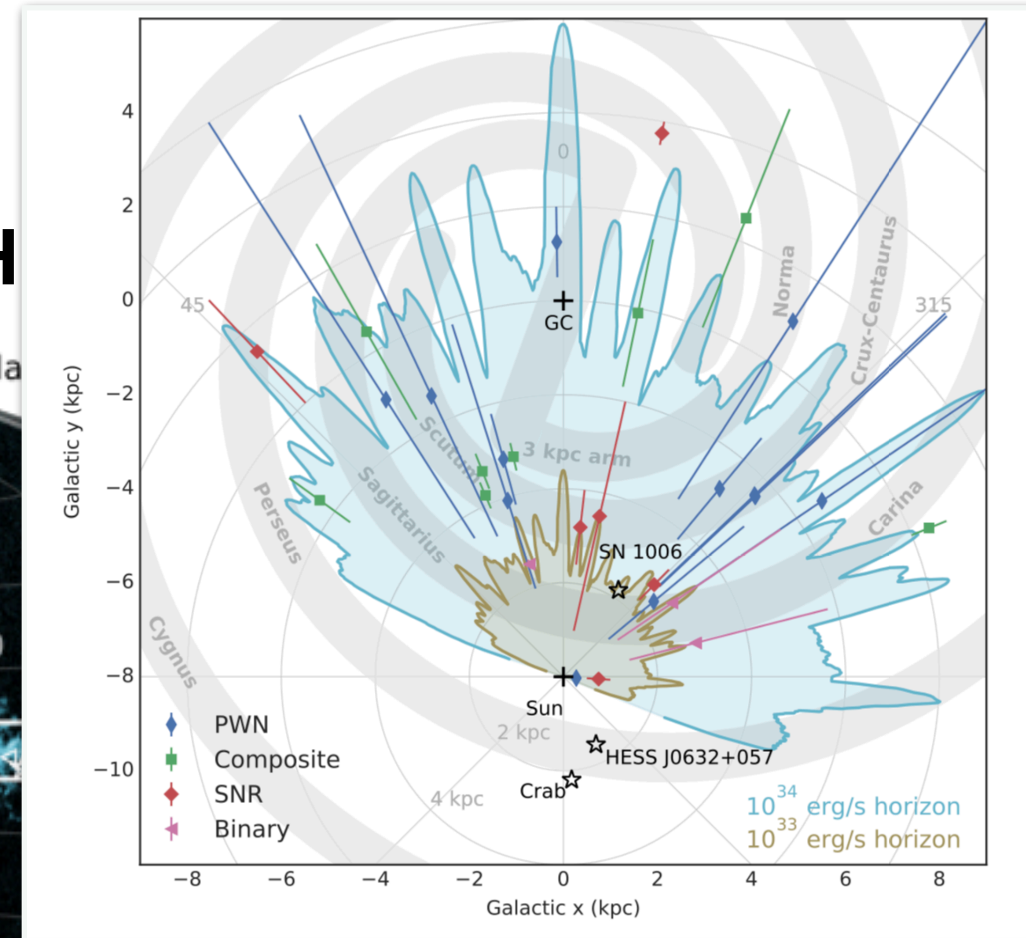
- Major effort of almost 10 years of pointed observations 2004 - 2013
- 2673 hours of high-quality data
- Covered area: l = 250° to 65°, |b| < 3°
- Inhomogeneous exposure

H.E.S.S. Collaboration, A&A 2018

The View on our Milky Way

The H y





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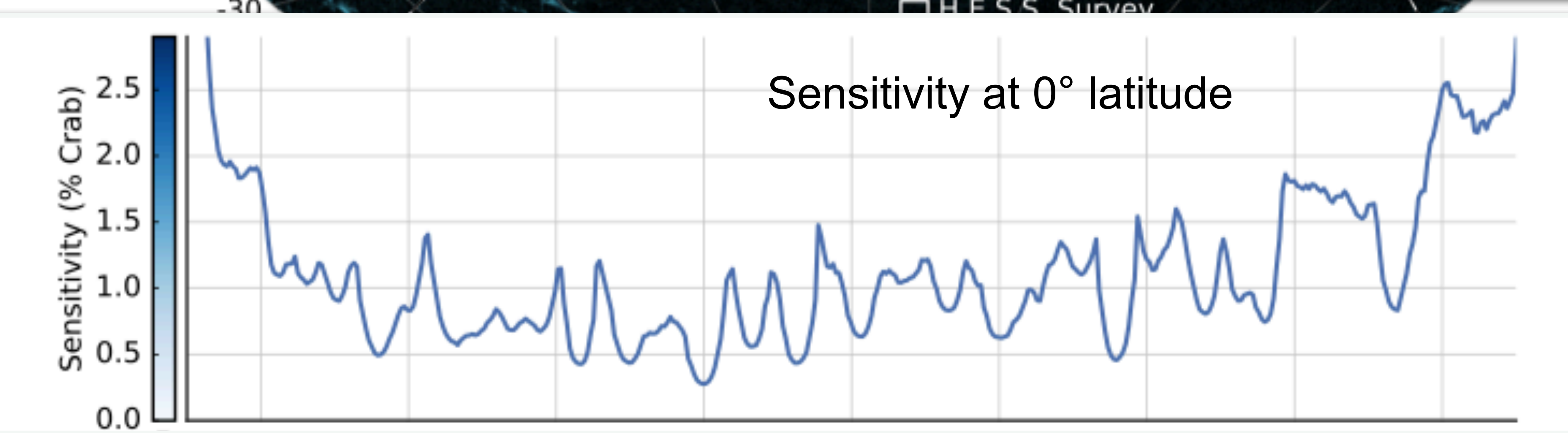

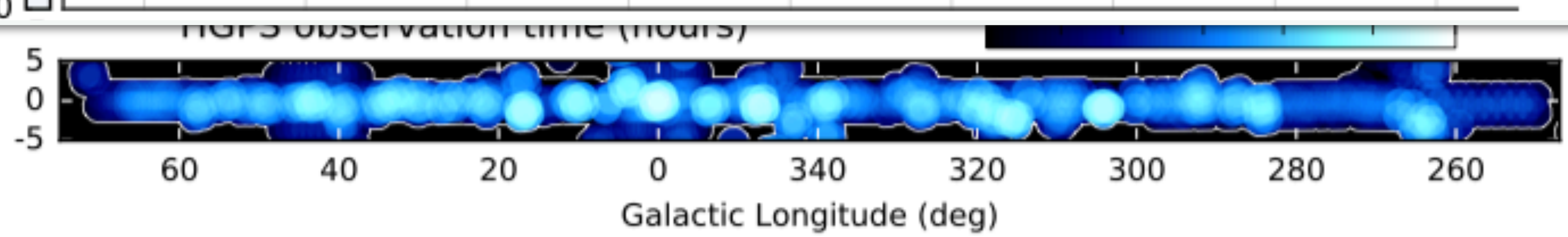

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H.E.S.S. Collaboration, A&A 2018

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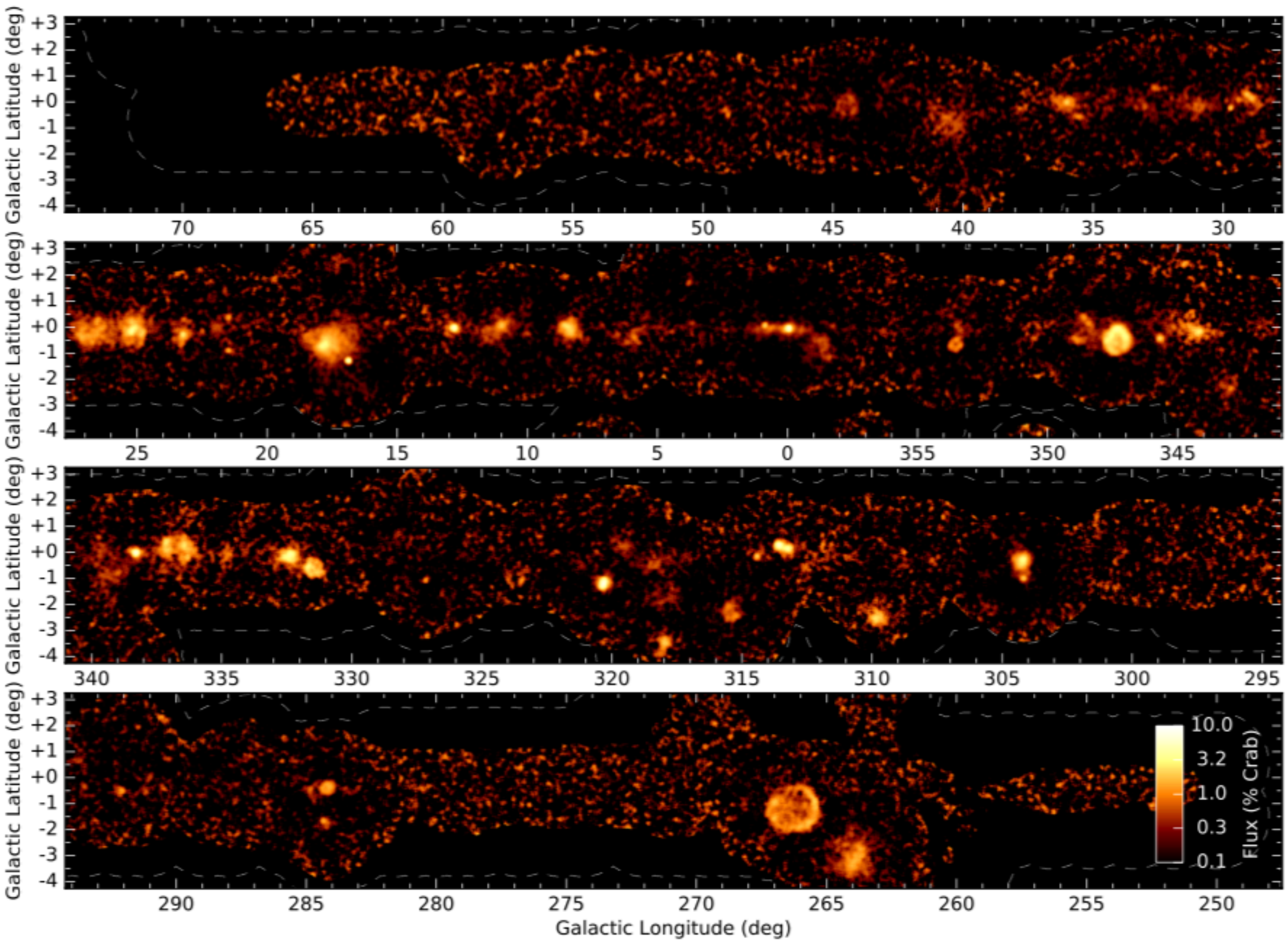
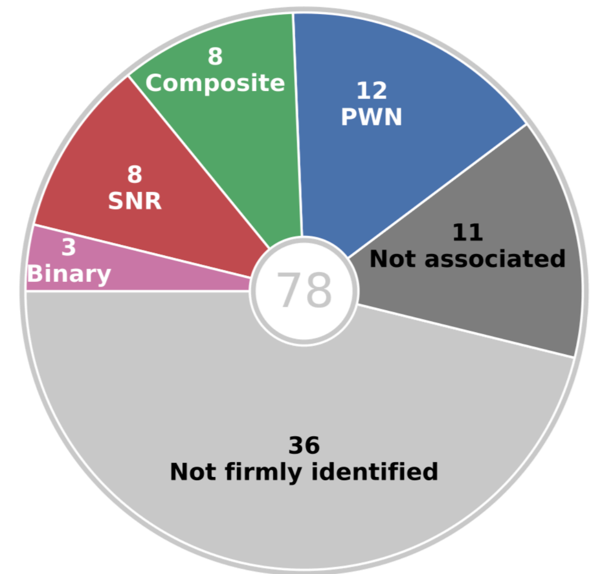


H.E.S.S. Collaboration, A&A 2018

- Detection of 78 VHE sources along the plane,



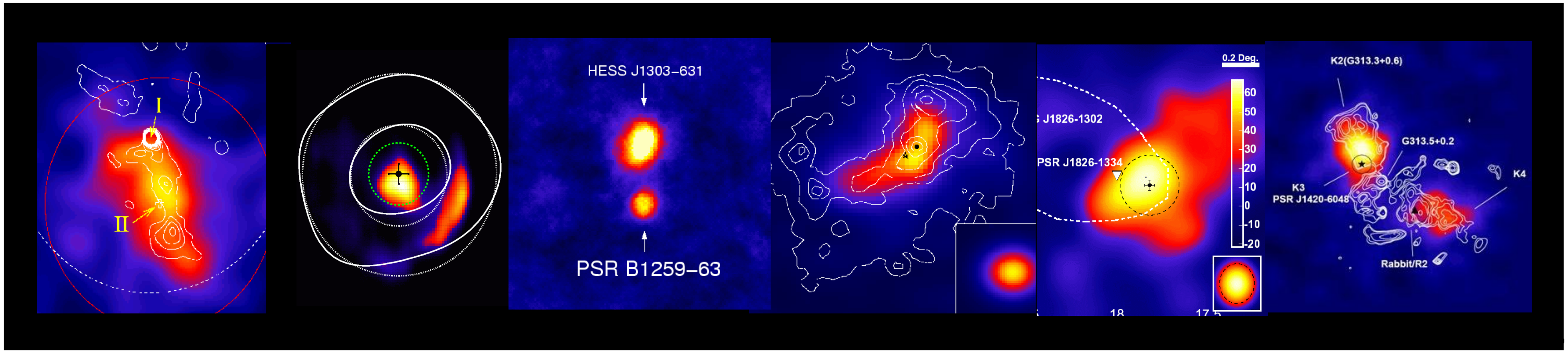
- A PeVatron in the Galactic Center,
- And a component of large-scale diffuse emission

Pulsar Wind Nebulae

Powerful winds driven by pulsars

Consisting of electromagnetic energy and highly relativistic particles

Wind interaction with ambient medium gives rise to a complex structure



Many known X-ray PWN identified as TeV emitters and almost all of the highest spin-down power radio pulsars have associated TeV emission

Efficient particle accelerators (leptonic emission)

Exist in many sizes, shapes, morphologies, distances to PSR

Many of our unidentified sources may be PWN

Supernova Remnants

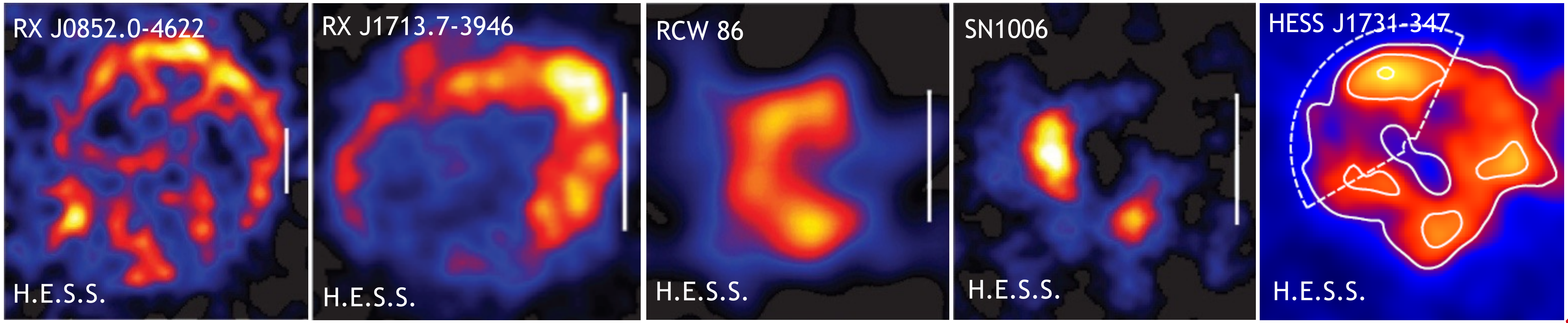
Shells created by a supernova explosion (E~10^{51} erg)

Consist of a mixture of supernova ejecta and shocked circumstellar medium

Initial velocities >~10,000 km/s, young SNRs (~500 yr) ~2000-5000 km/s

Site of particle acceleration by 1st order Fermi mechanism

~250 Galactic SNRs identified as extended radio sources (Green's catalog)



Morphology

What are the accelerated particles?
Is emission leptonic or hadronic?

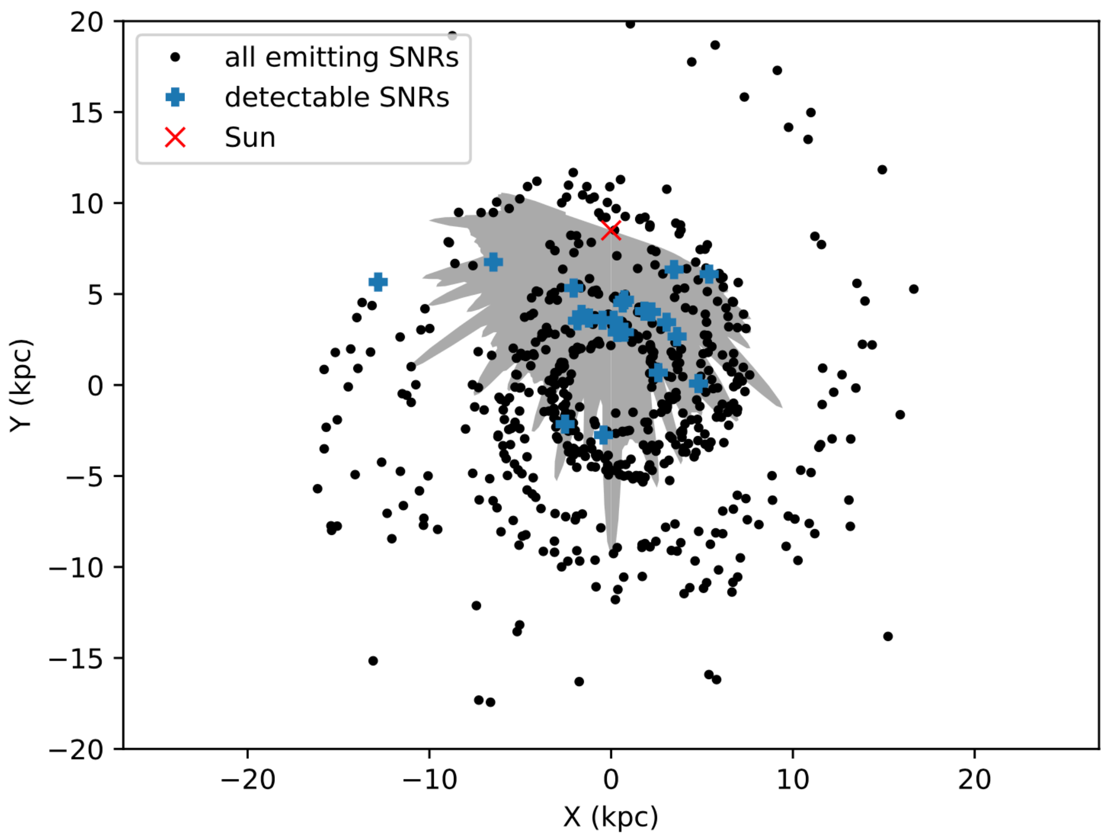
correlation with gas? → hadronic origin
correlation with radio? → leptonic origin

→ angular resolution crucial!

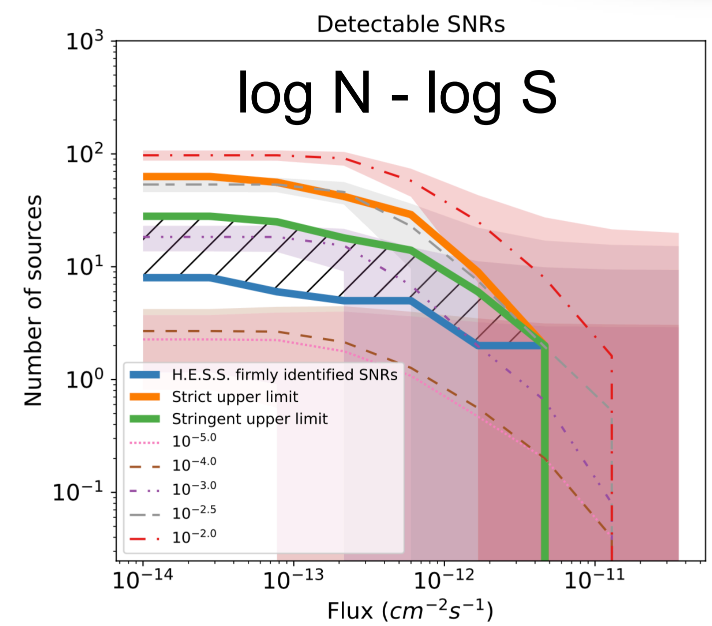
Going from single sources to source populations

Only a small and based subsample of sources visible

Requires population synthesis to derive population properties



1. Simulation of population
2. Determination of detectable subsample (detection threshold)
3. Comparison with data



example:
variation of the e/p ratio:
10^{-2} - 10^{-5}

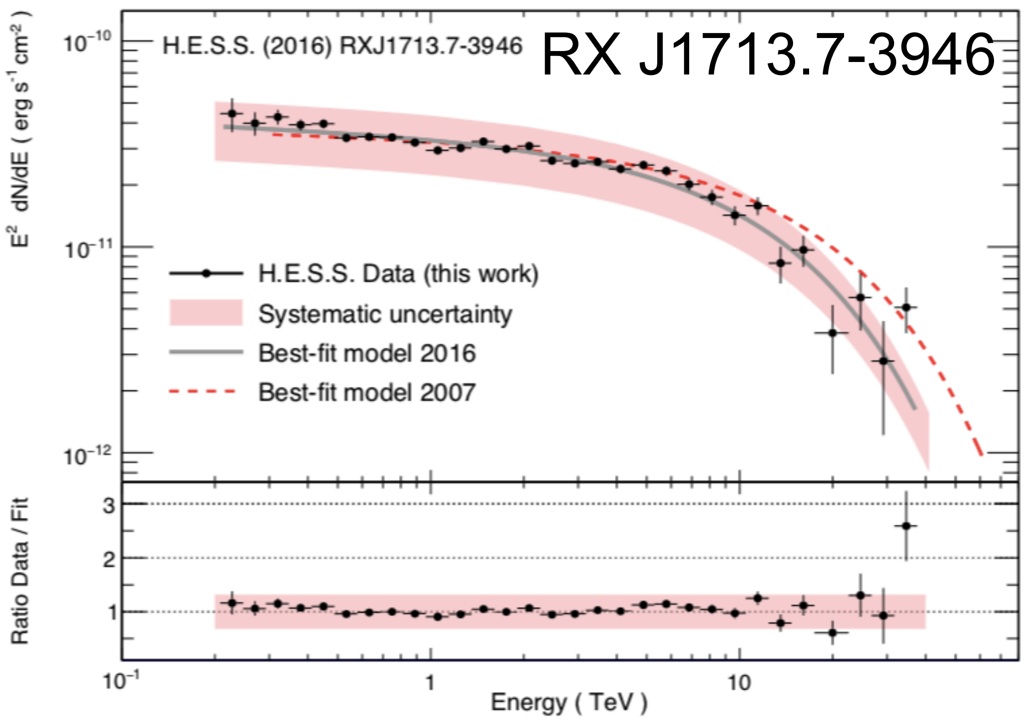
Batzofin et al. 2024

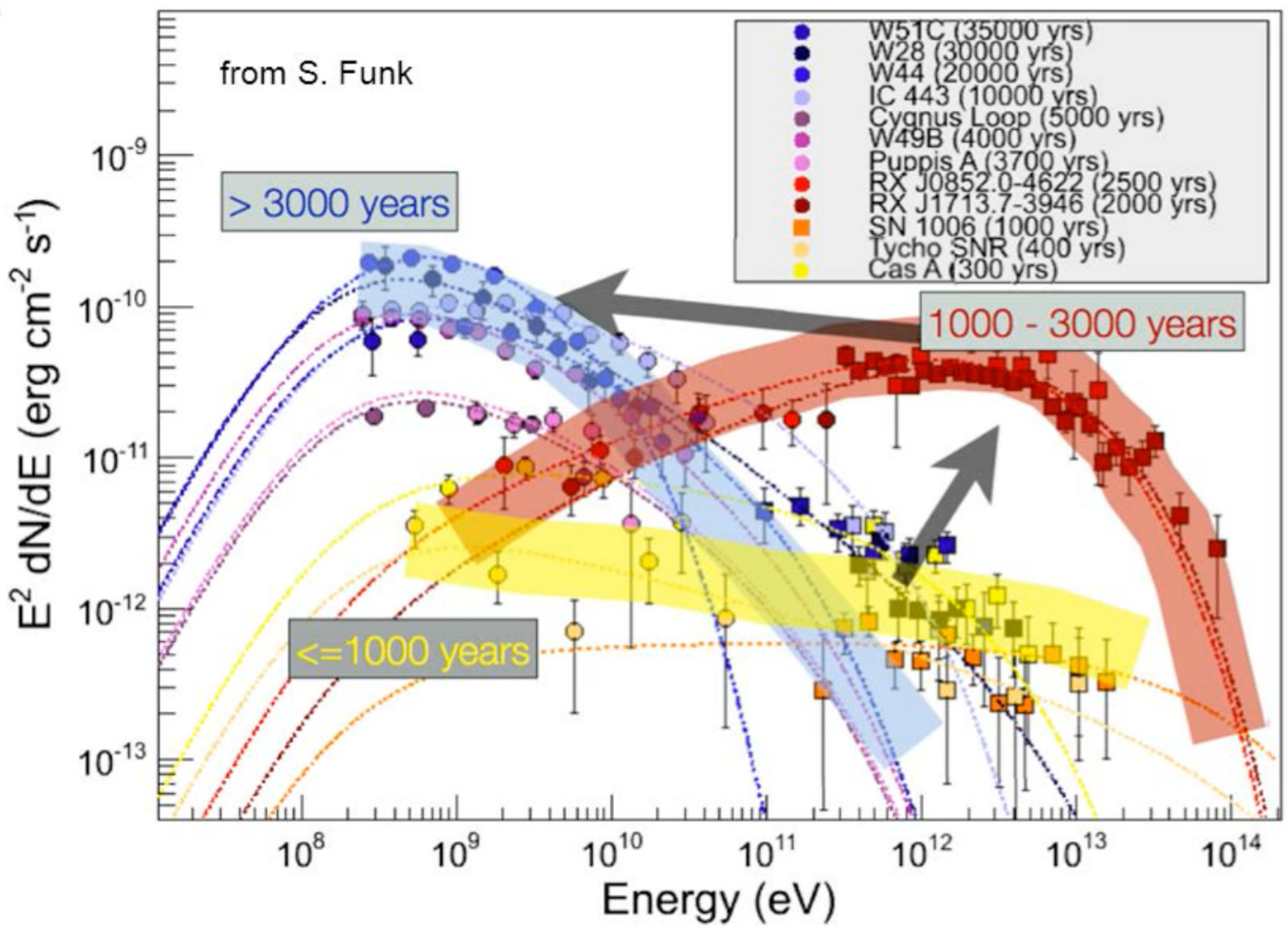
→ preference for small fraction of electrons while having decent number of leptonic-dominated SNRs detected

see poster by Rowan Batzofin

Do SNRs accelerate cosmic rays up to the knee?

- Besides differentiation of leptonic vs hadronic, need spectral information!
- Most SNRs (and other sources as well) feature cutoffs at few TeV

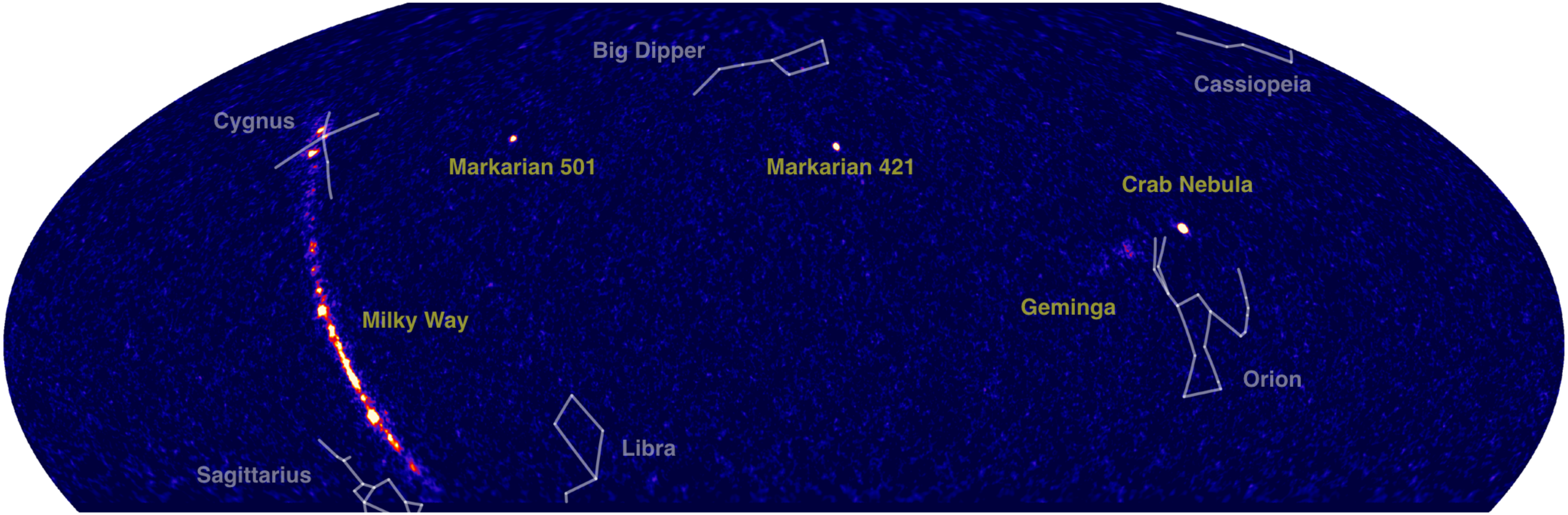




Could be timing problem…

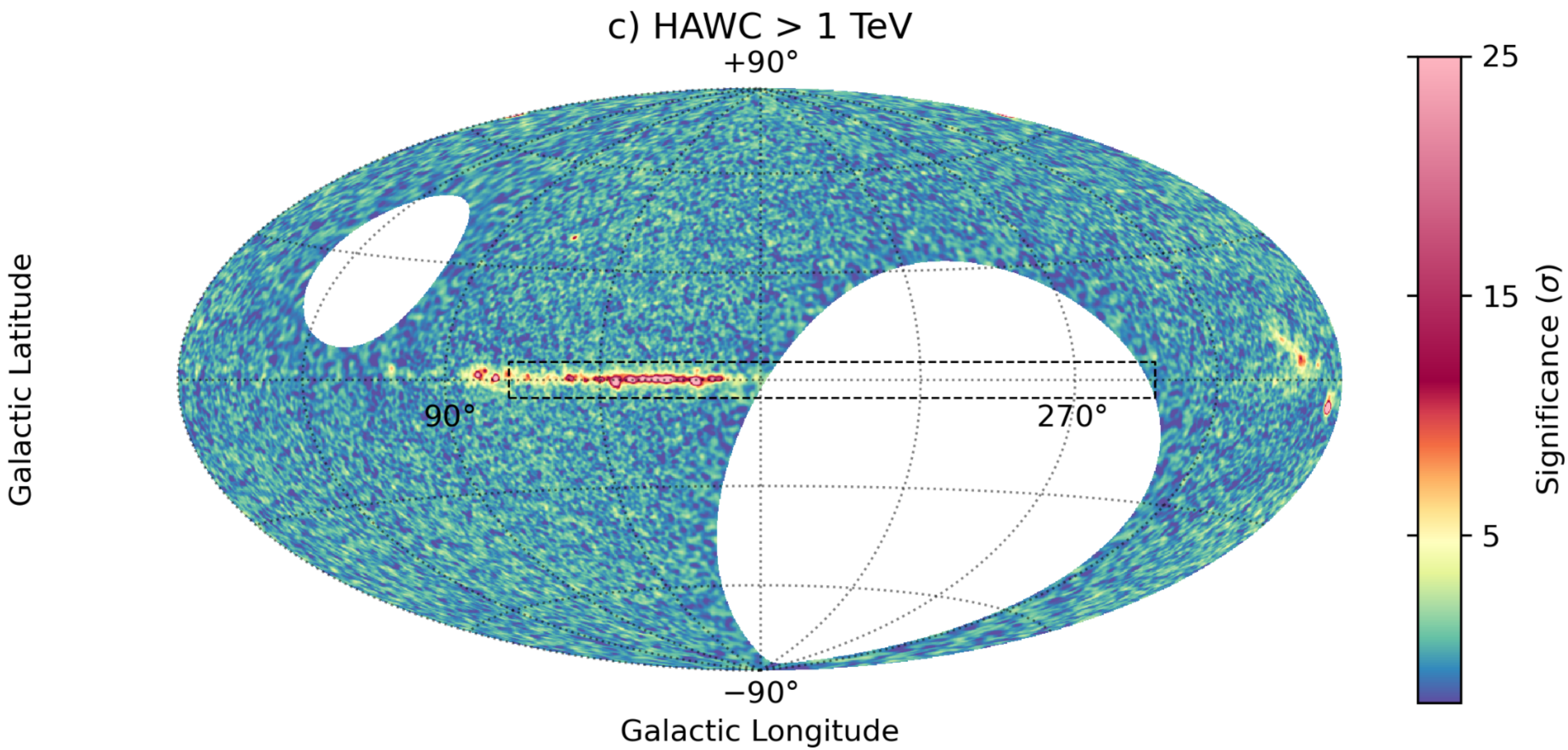
What About Other Experiments?

HAWC sky

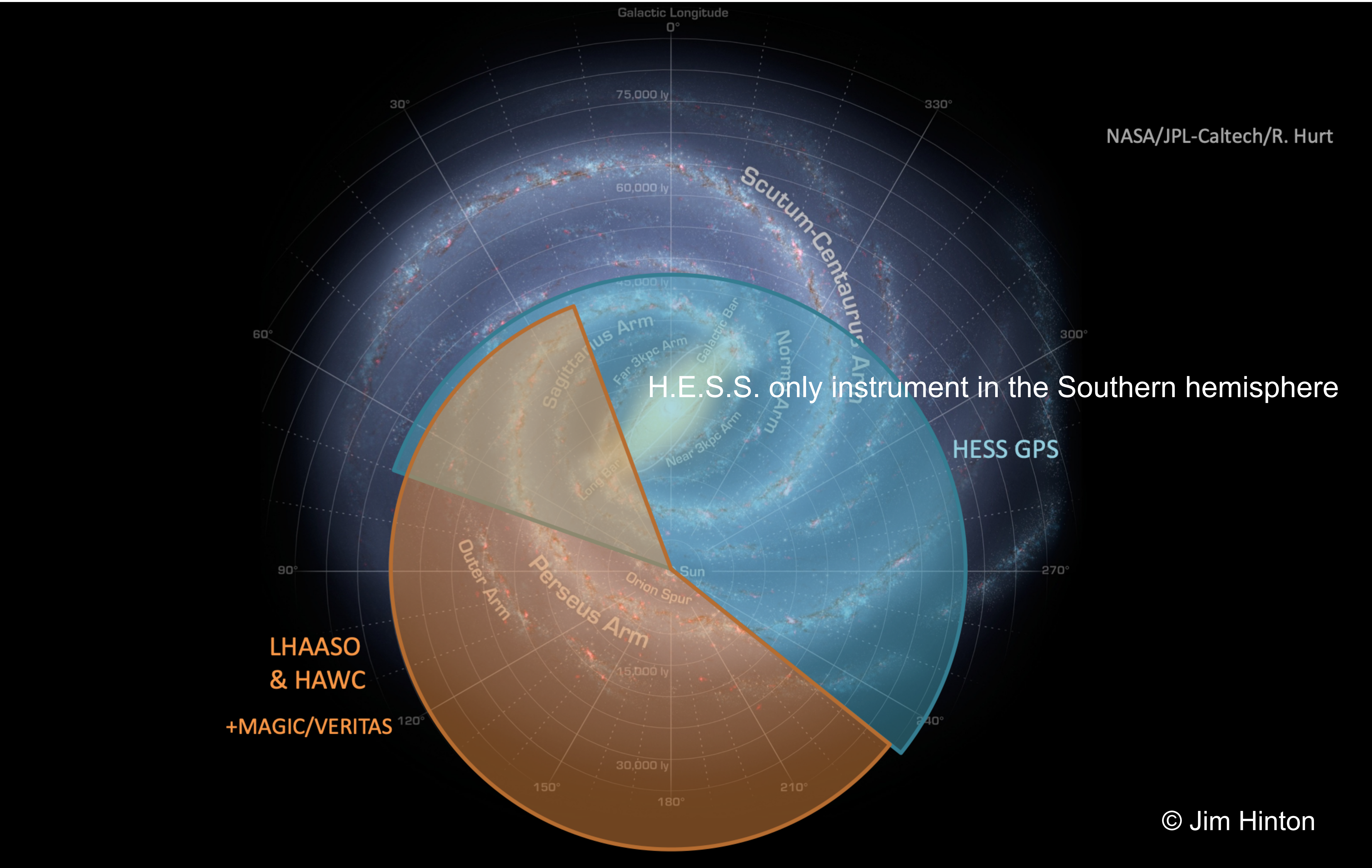


Beautiful view on the Northern Hemisphere

What About Other Experiments?

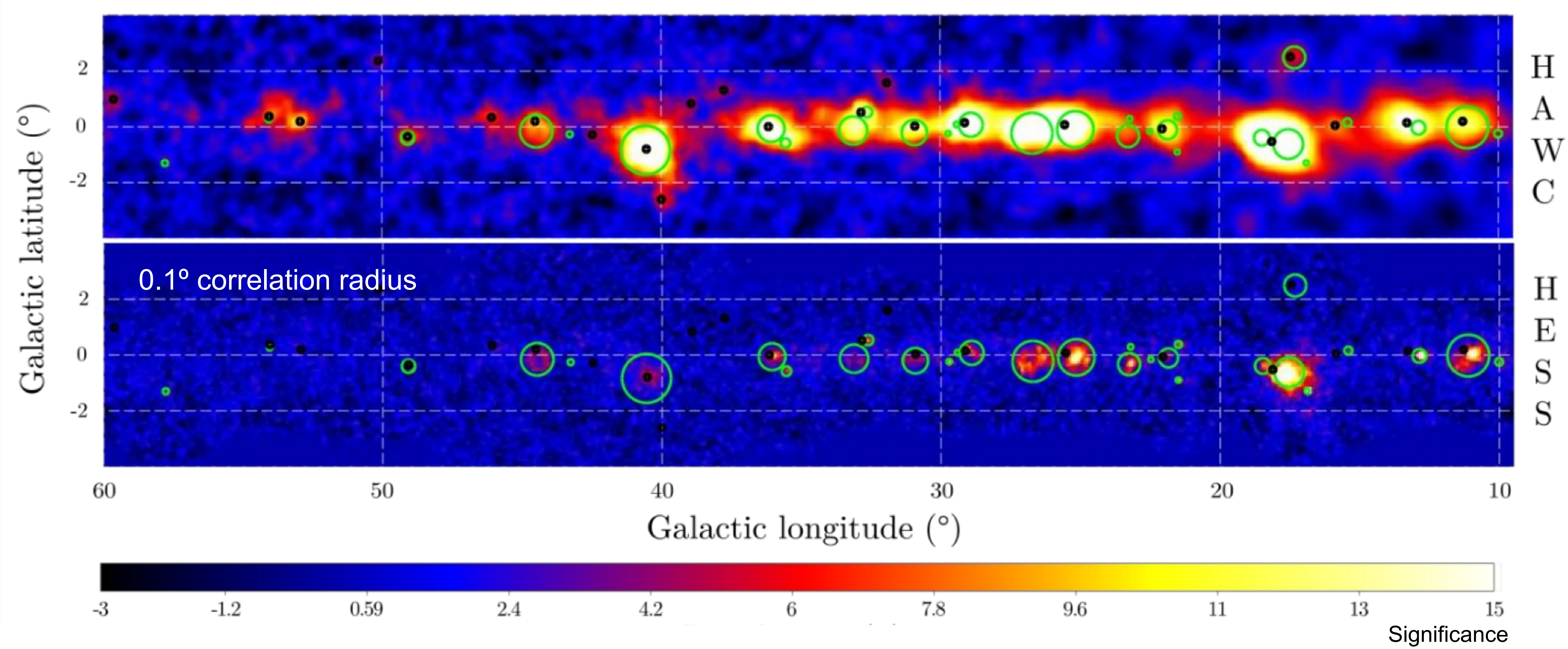


What About Other Experiments?



HAWC - H.E.S.S. Comparison

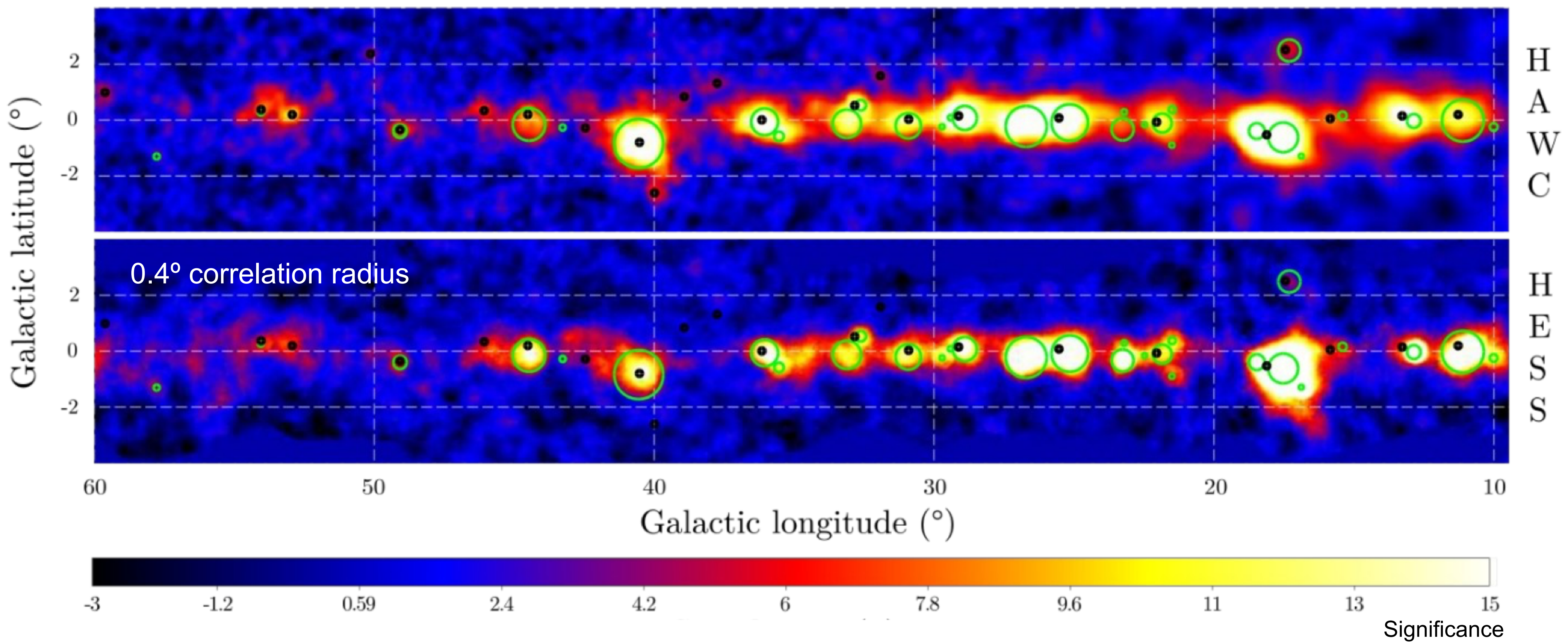
In the region of overlap



Completely different pictures of the same sky

HAWC - H.E.S.S. Comparison

In the region of overlap



Consequence of the different point spread functions!

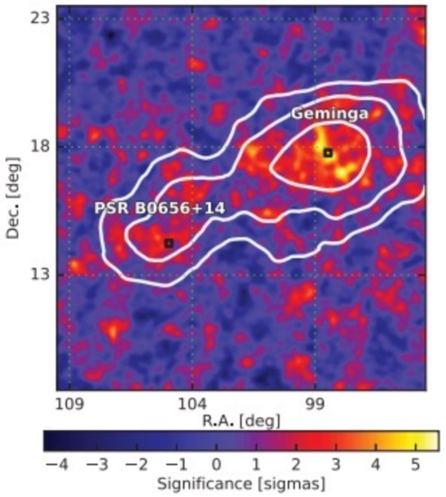
Example of a Very Extended Source

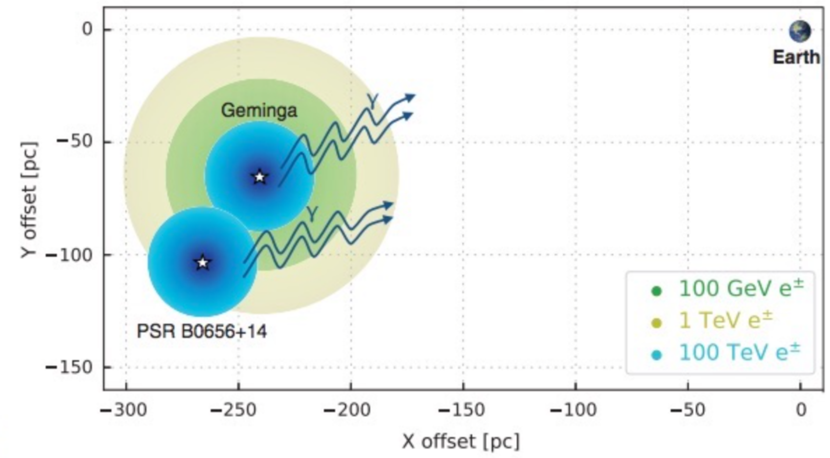
Geminga and **Monogem** pulsars surrounded by a spatially extended region (~20 pc) emitting multi-TeV gamma-rays

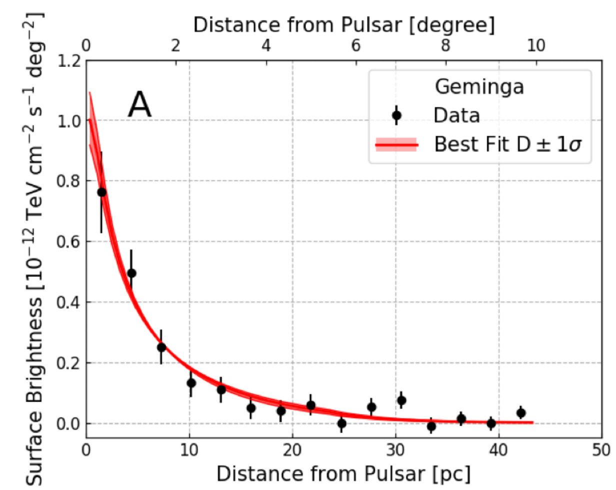
TeV halos as new source class

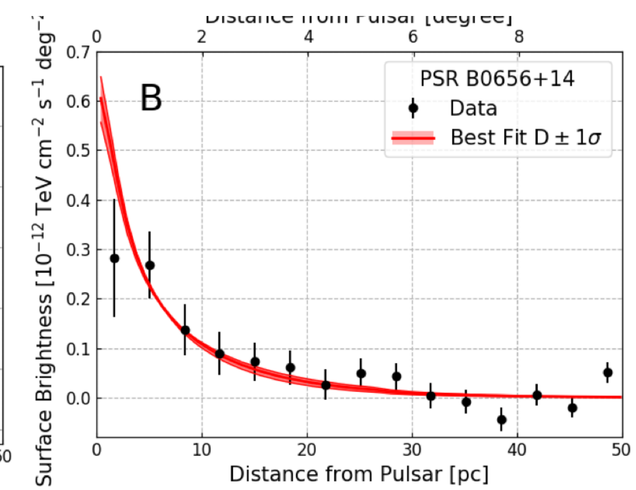
- Diffusion coefficient two orders of magnitude lower?
- H.E.S.S. results dependent on the applied background subtraction technique

HAWC





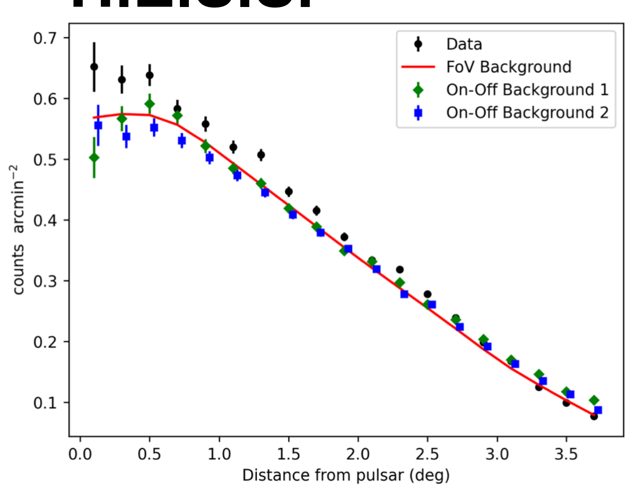


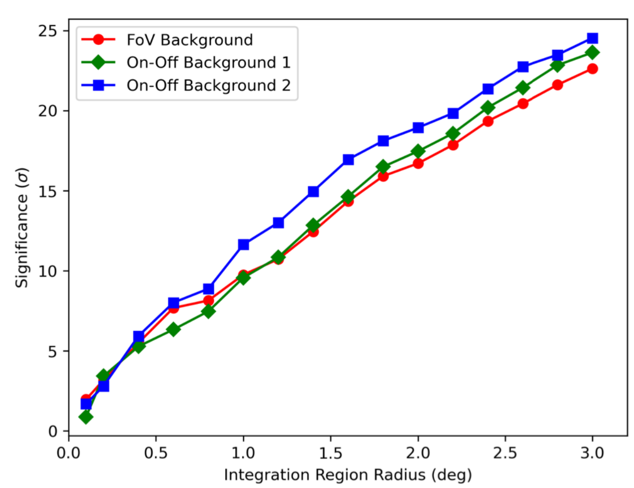


HAWC Collaboration 2017

Crucial for IACTs: subtraction of the background of charged cosmic rays!

H.E.S.S.





H.E.S.S. Collaboration 2023

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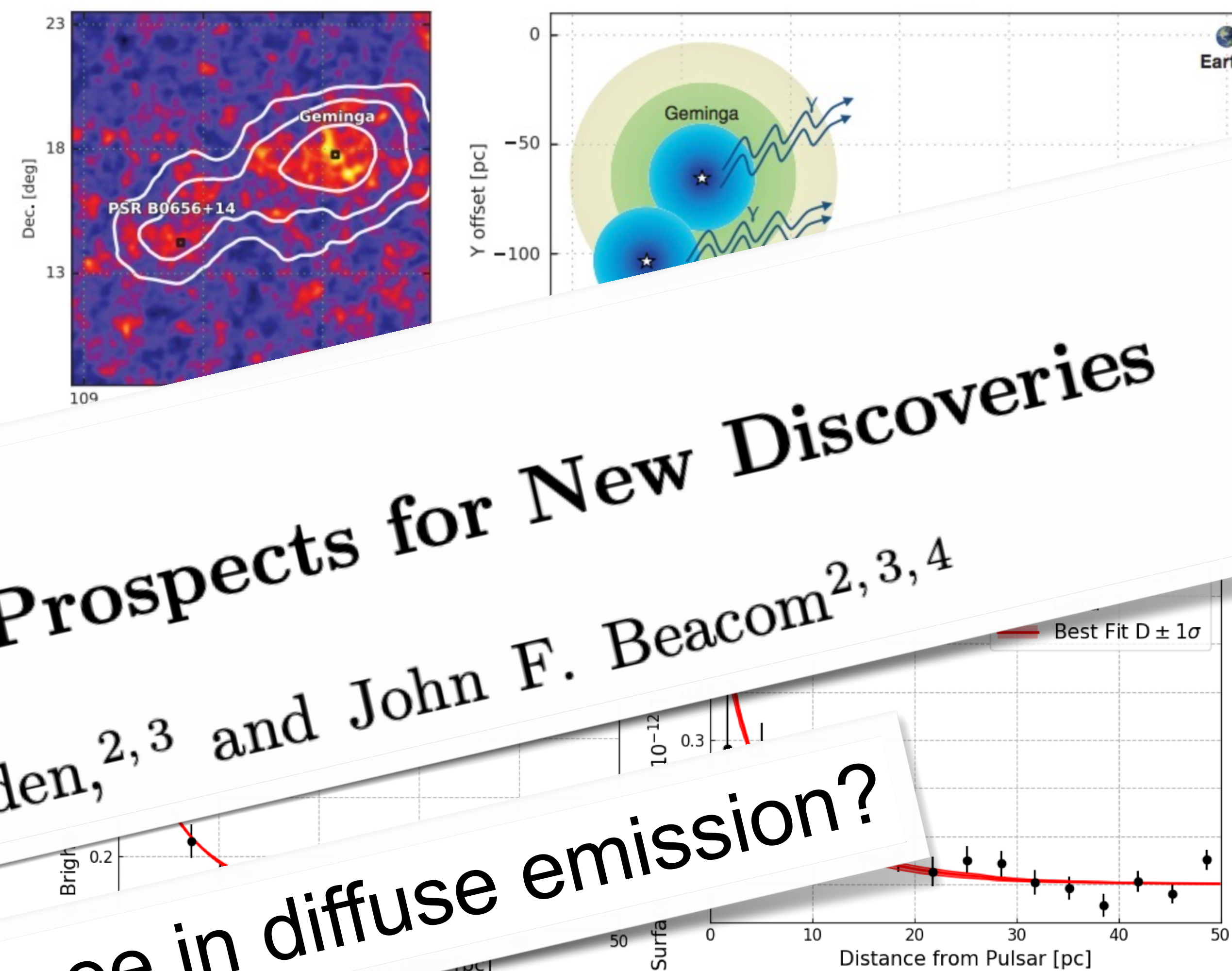
TeV halos as new source class

- Diffusion coefficient two ord… magnitude lowe…

HAWC

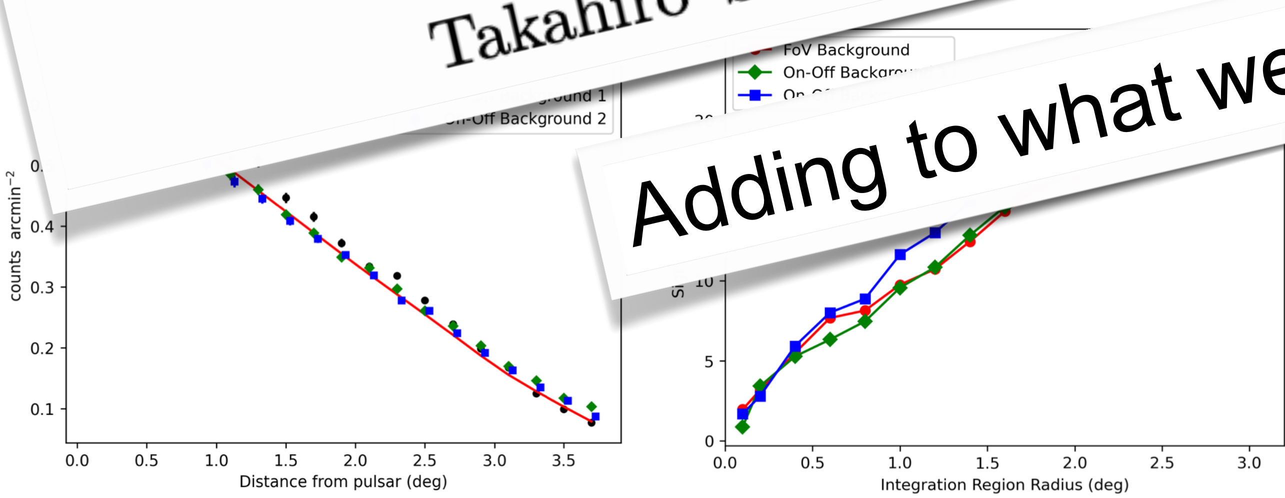


HAWC Collaboration 2017

TeV Halos are Everywhere: Prospects for New Discoveries

Takahiro Sudoh,[1,2] Tim Linden,[2,3] and John F. Beacom[2,3,4]

Adding to what we see in diffuse emission?

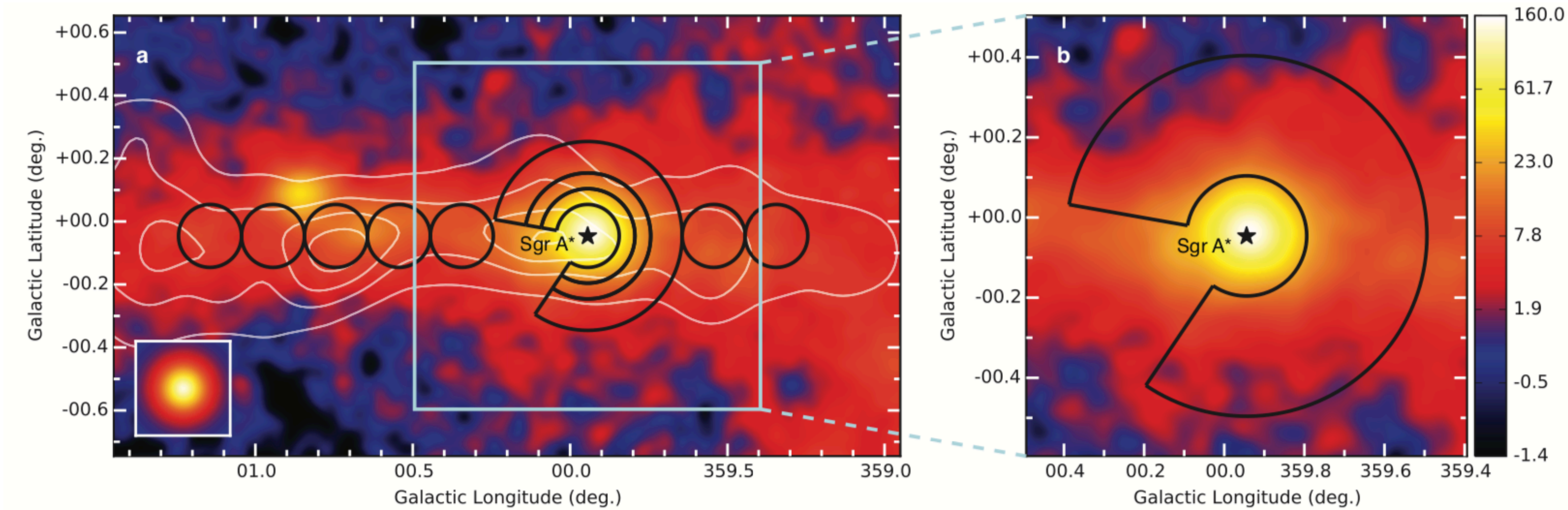


H.E.S.S. Collaboration 2023

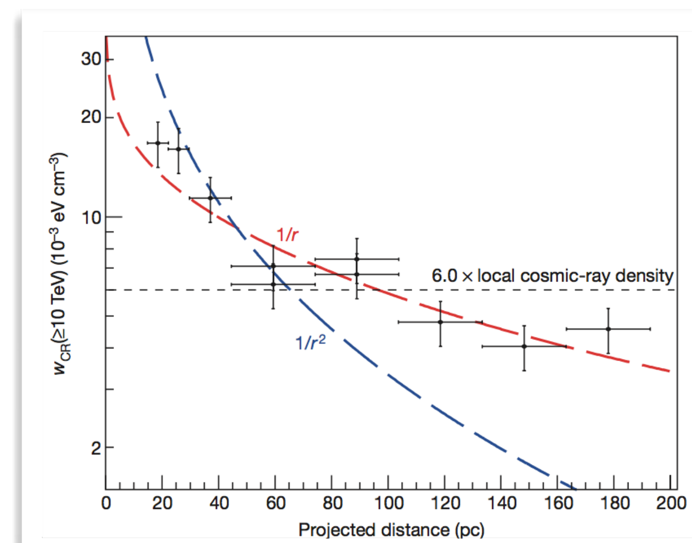
Crucial for IACTs: subtraction of the background of charged cosmic rays!

Where are the PeVatrons?

Diffuse Emission in the Galactic Centre ridge



H.E.S.S. Collaboration, Nature 2016



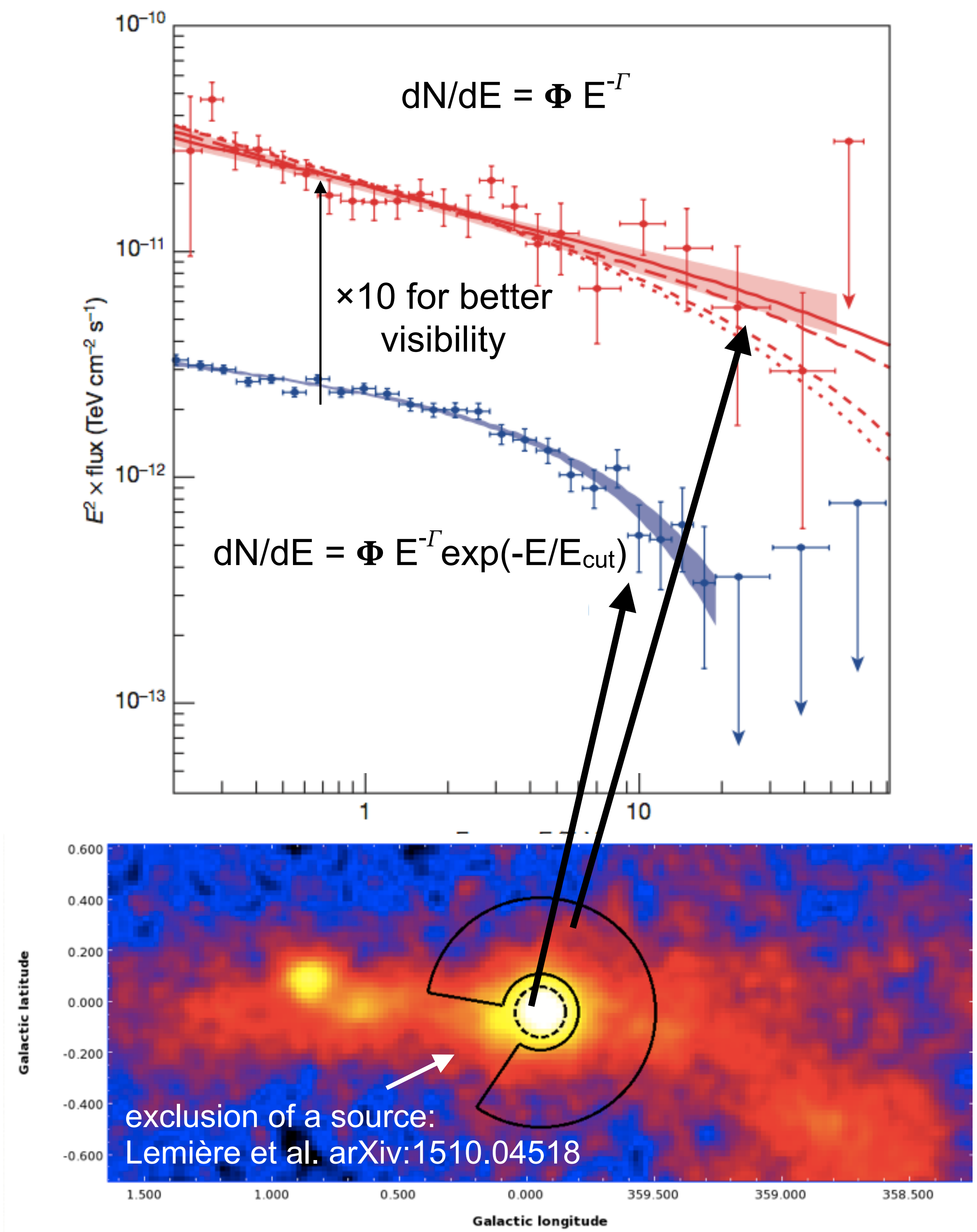
Cosmic-ray density from
ratio of gamma-ray luminosity and gas density

→ Central accelerator located within 10 pc from GC,
injecting CRs continuously over more than 1000 years

Where are the PeVatrons?

- Gamma-ray spectrum up to 50 TeV with no (statistically significant) energy cut-off
- From transport equation for p injected at GC and fitted to H.E.S.S. data: a pure power-law primary proton spectrum with index ~2.4
  - 68% CL with cut-off 2.9 PeV
  - 90% CL with cut-off 0.6 PeV
  - 95% CL with cut-off 0.4 PeV

→ Indirect evidence for the first PeVatron!



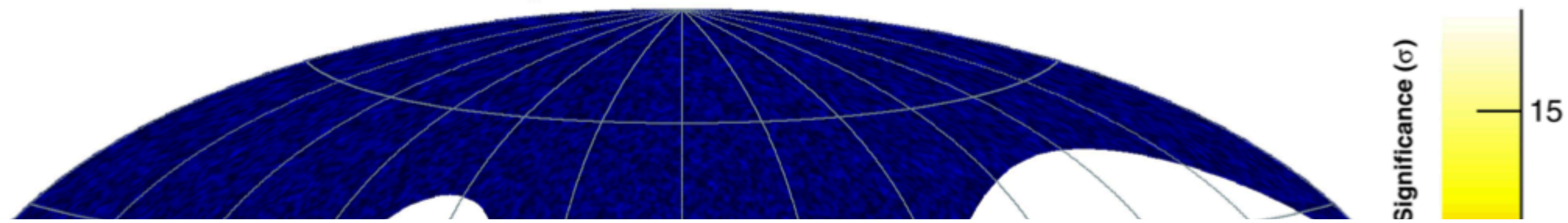
H.E.S.S. Collaboration, Nature 2016

PeVatrons everywhere!

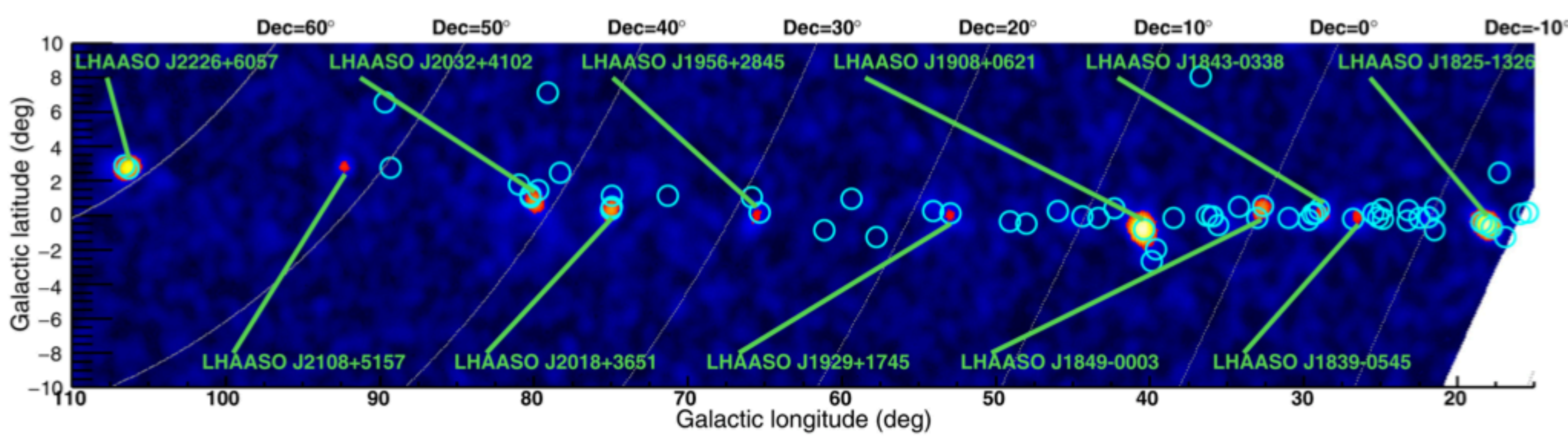
12 sources with energies between 100 TeV and 1.4 PeV!

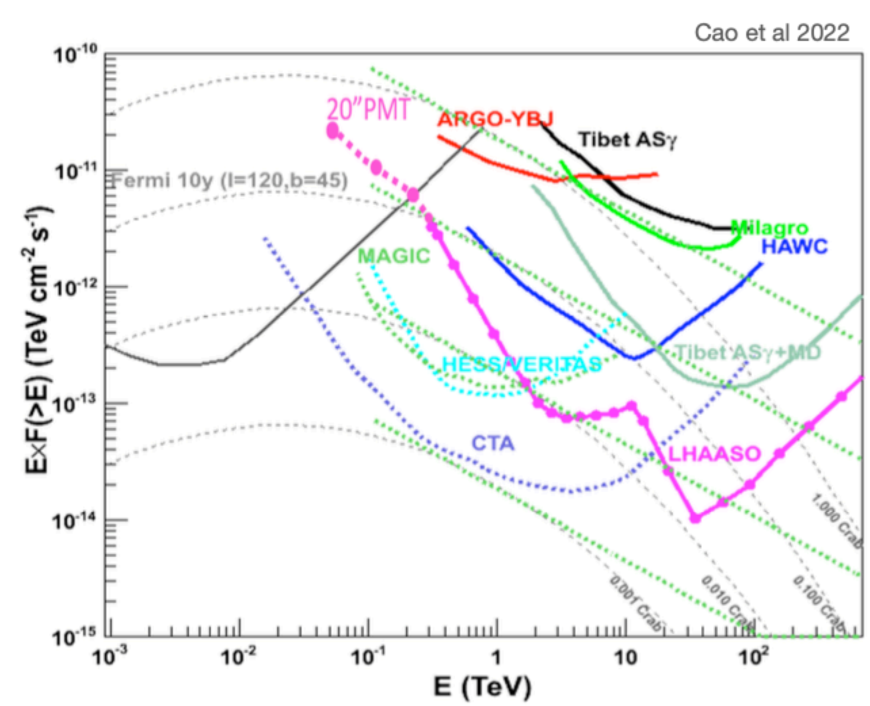
→ consequence of the LHAASO sensitivity at E~100 TeV

LHAASO Sky @ >100 TeV



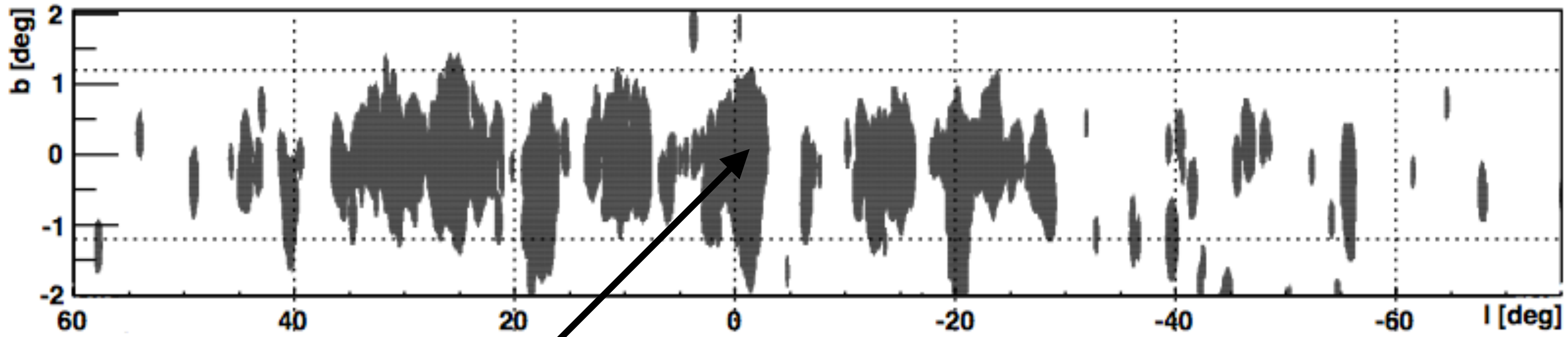
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)





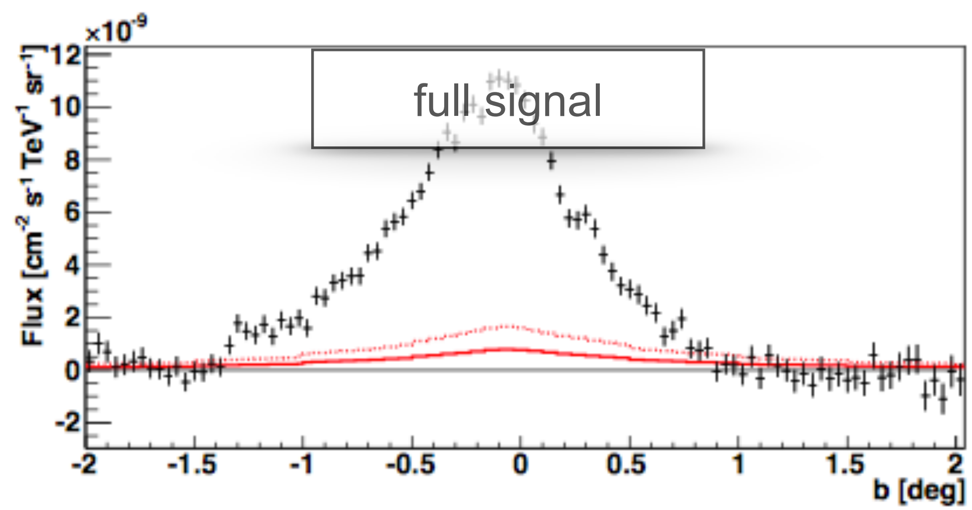
Diffuse Emission at TeV energies (IACTs)

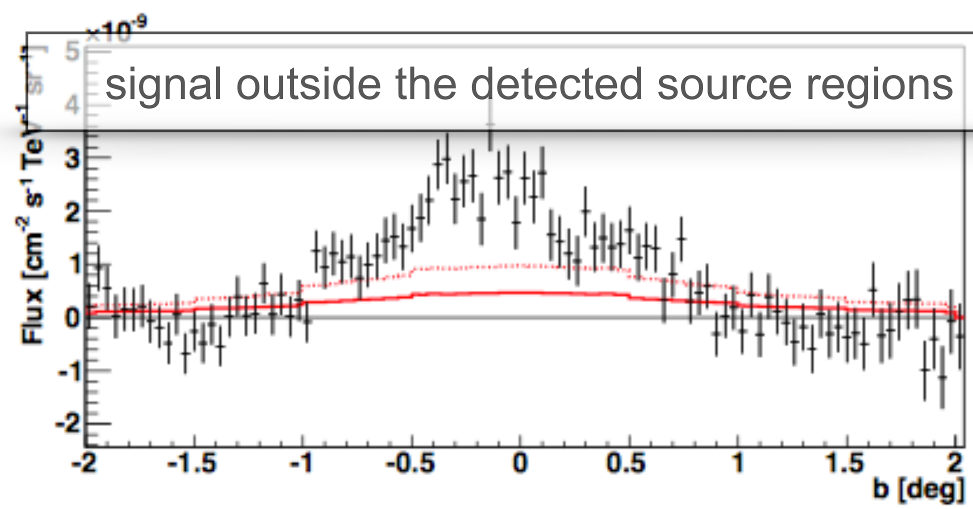
- Complicated due to the bright sources everywhere



significantly detected γ-ray sources

- Accumulated large-scale signal outside source regions
- Affected by background subtraction → measurable only a relative excess
- Signal is mixture of
  - hadronic component from π^0 decay
  - inverse Compton component
  - unresolved gamma-ray sources





H.E.S.S. Collaboration, PRD 2014

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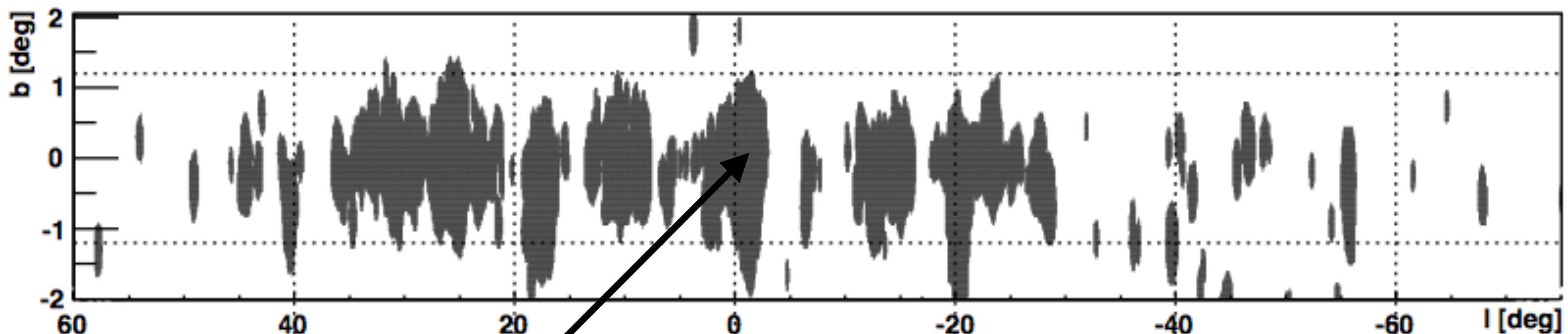
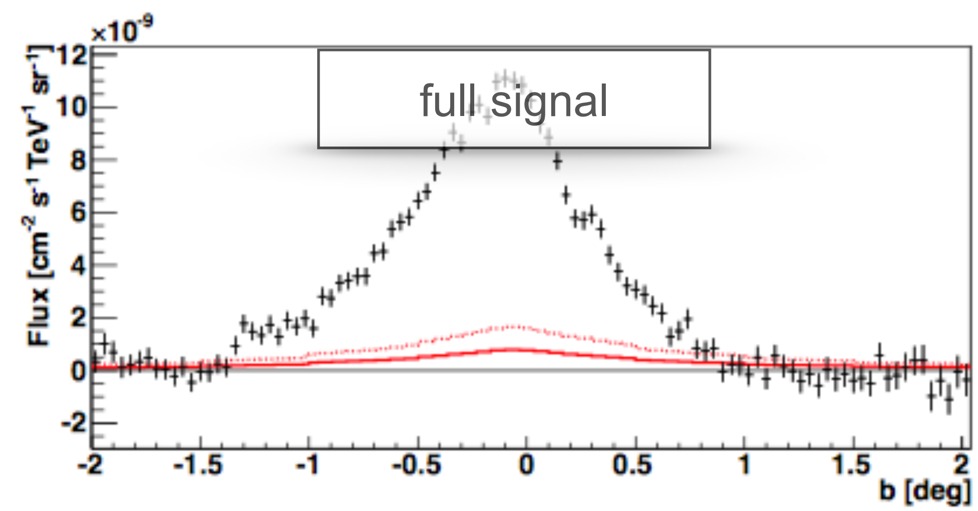


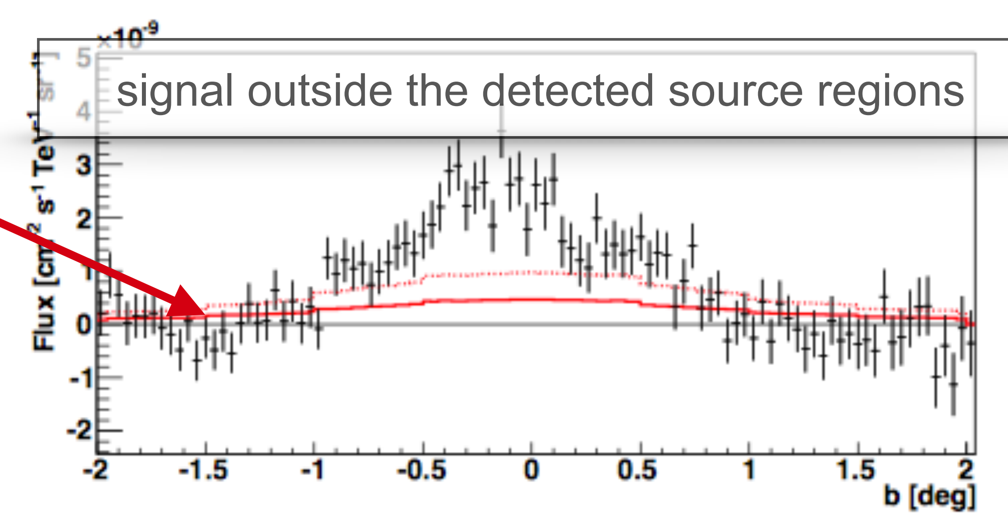
significantly detected γ-ray sources

Minimum contribution of hadronic emission with protons only/inclusion of heavier nuclei:

$F_\gamma(E_\gamma) = \int dl_d \int d\sigma_{p\rightarrow\gamma}/dE_p \cdot n(l,b,l_d) \cdot J(E_p) \;\; dE_p$

- Target material $n(l,b,l_d)$:
  - HI (Leiden-Argentine-Bonn survey)
  - H_2 traced by CO (NANTEN) with conversion factor $X_{CO} = 2 \cdot 10^{20}$ cm^{-2} K^{-1} km s^{-1}
- Cosmic-ray spectrum $J(E_p)$: measured at Earth

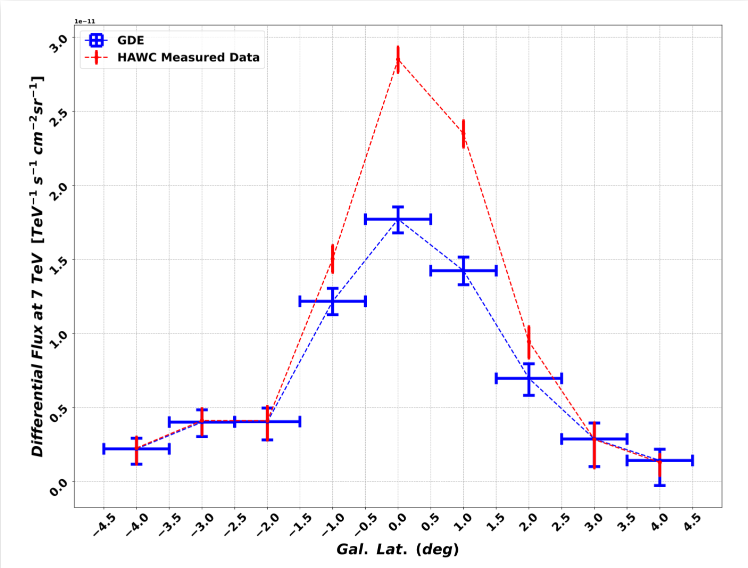




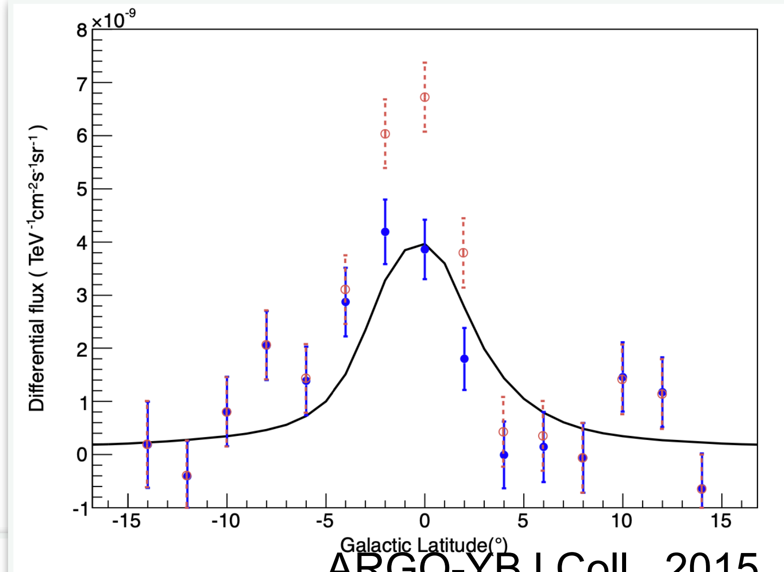
H.E.S.S. Collaboration, PRD 2014

Diffuse Emission (Particle Detector Arrays)

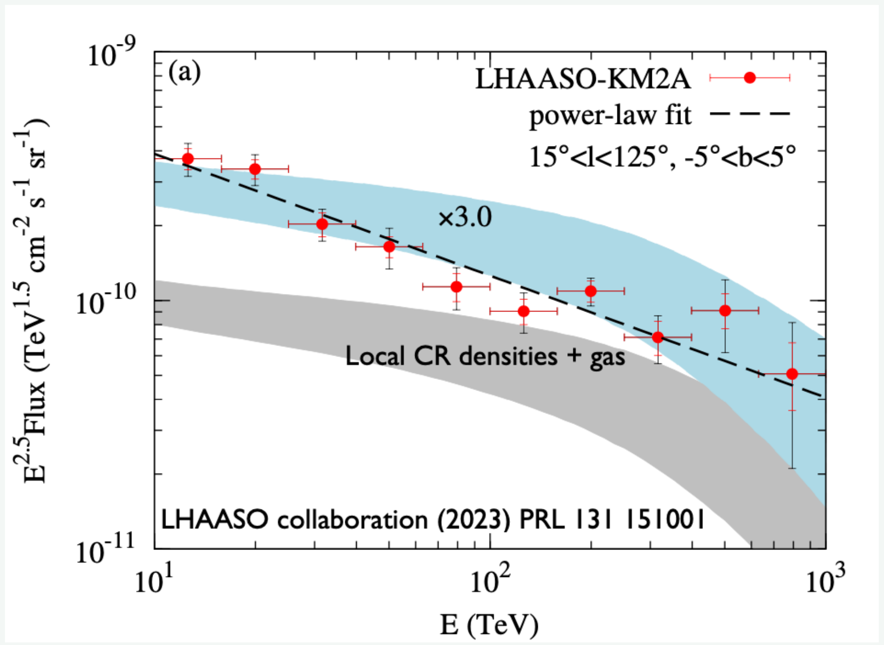
- Many recent measurements
- Careful in detail comparisons
  → different regions, different signal!
- Large contribution of diffuse emission to total emission

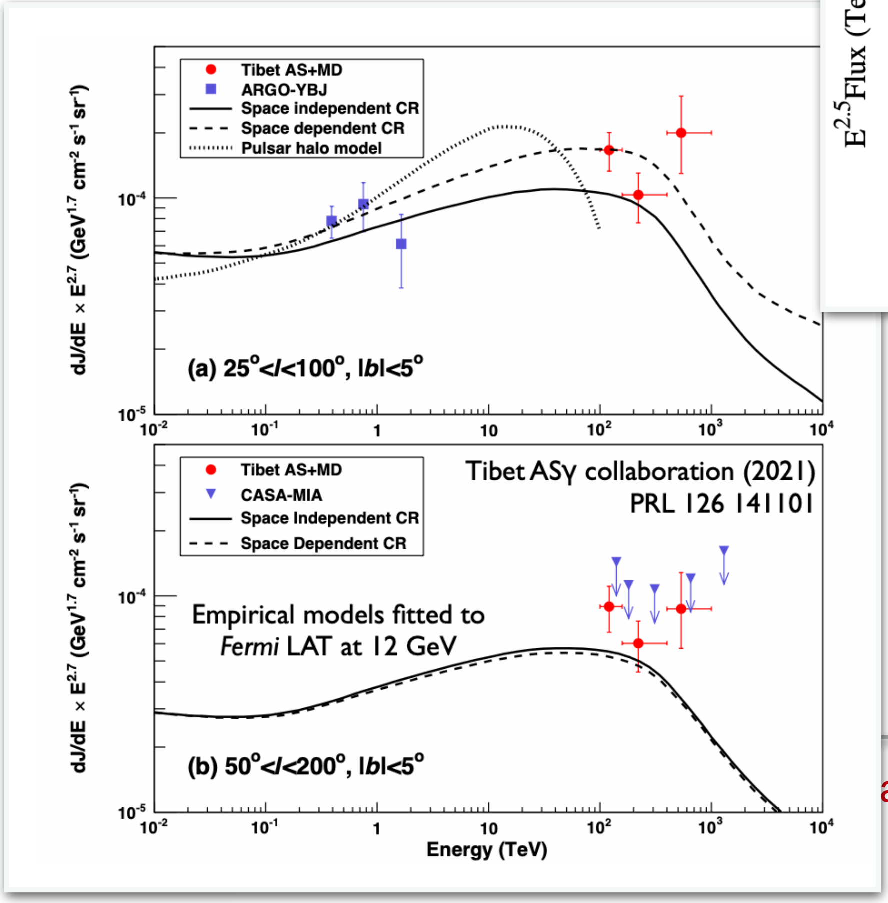


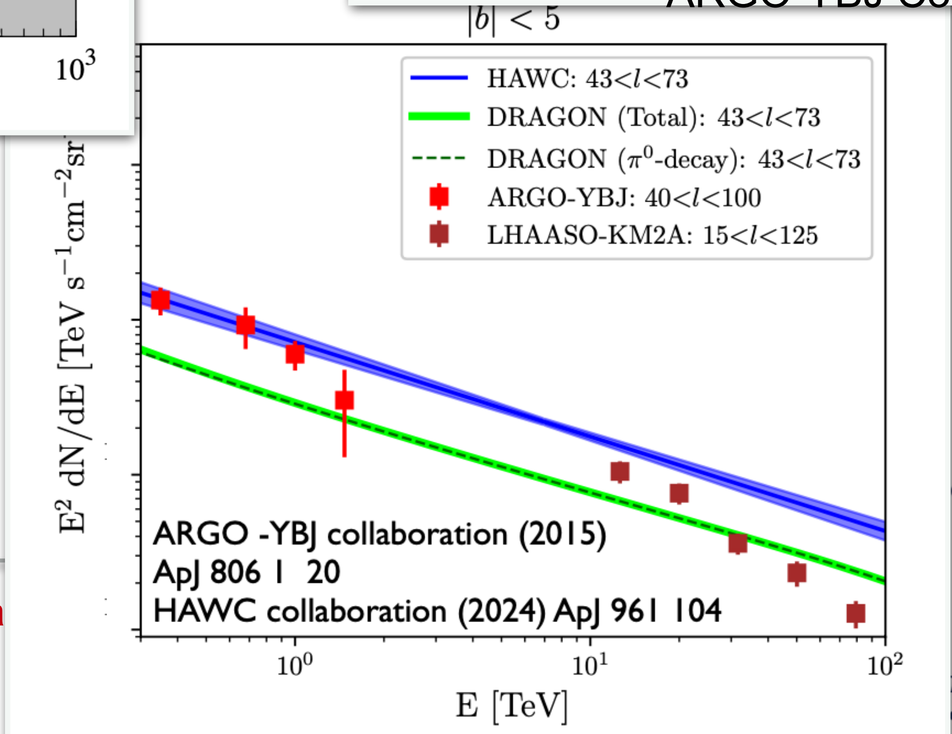
7 TeV diff. flux, 43° < l < 73°
(HAWC 2023)



ARGO-YBJ Coll., 2015







TeV sky dominated by sources or diffuse emission?

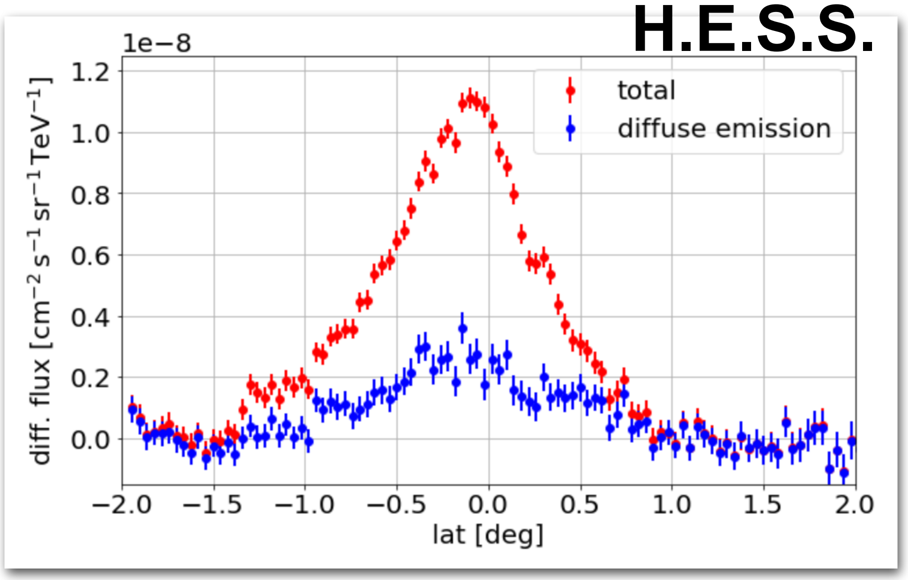
Imaging Atm. Cherenkov Telescopes

Small fields of view

Angular resolution of $\lesssim$0.1 deg

Larger instantaneous sensitivity
(put into perspective by small FoV
and low duty cycle)

H.E.S.S.



1 TeV diff. flux, $-75^{\circ} < l < 60^{\circ}$ (H.E.S.S. 2014)

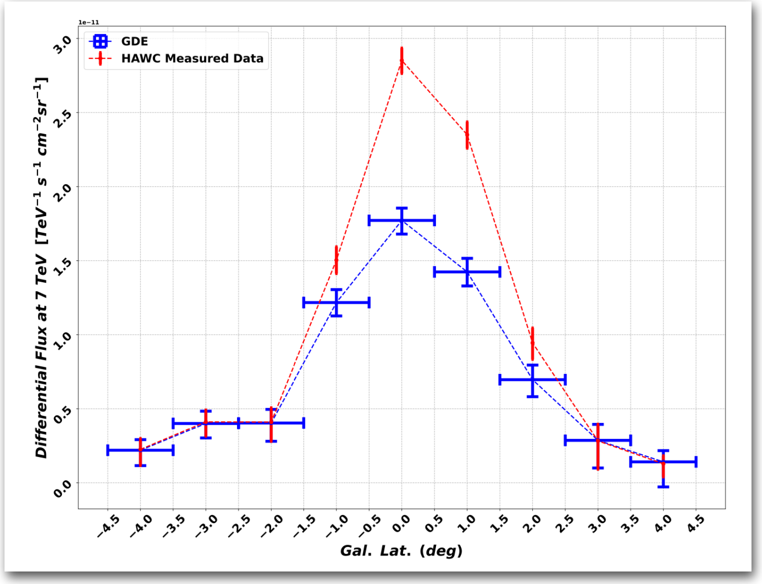
Particle Detector Arrays

Wide fields of view

Angular resolution of ~0.5 deg

Large duty cycle

HAWC



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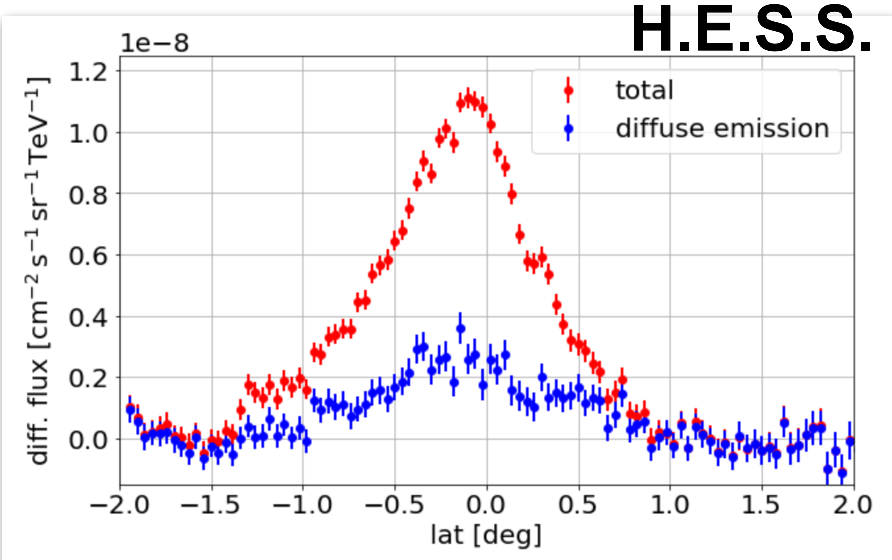

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Angular resolution of ~0.5 deg

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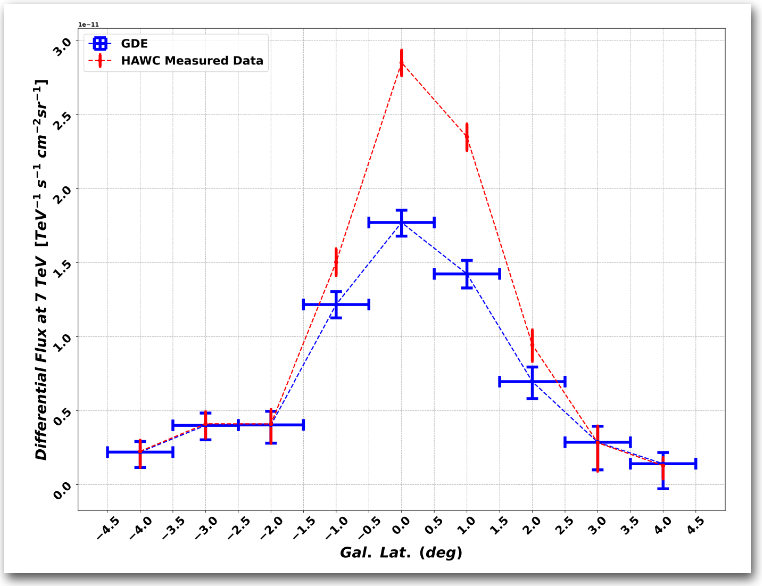

7 TeV diff. flux, $43^\circ < l < 73^\circ$
(HAWC 2023)

Causes double drawback for IACTs:

1. limits the data set and the region to be probed
2. renders background estimation from within FoV challenging

→ underestimation of diffuse signal in IACTs

TeV sky dominated by sources or diffuse emission?

Imaging Atm. Cherenkov Telescopes

Small fields of view

Angular resolution of $\lesssim$0.1 deg

Larger instantaneous sensitivity

(put into perspective by small FoV
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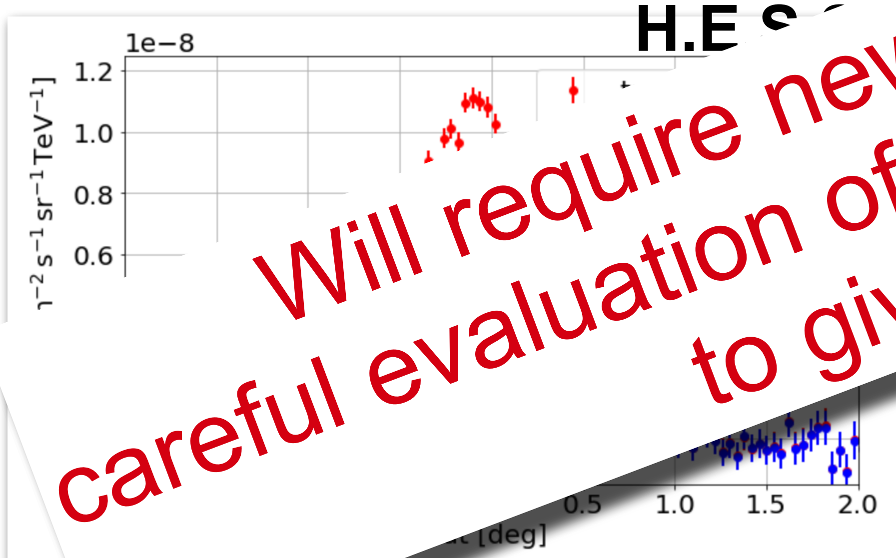
H.E.S.

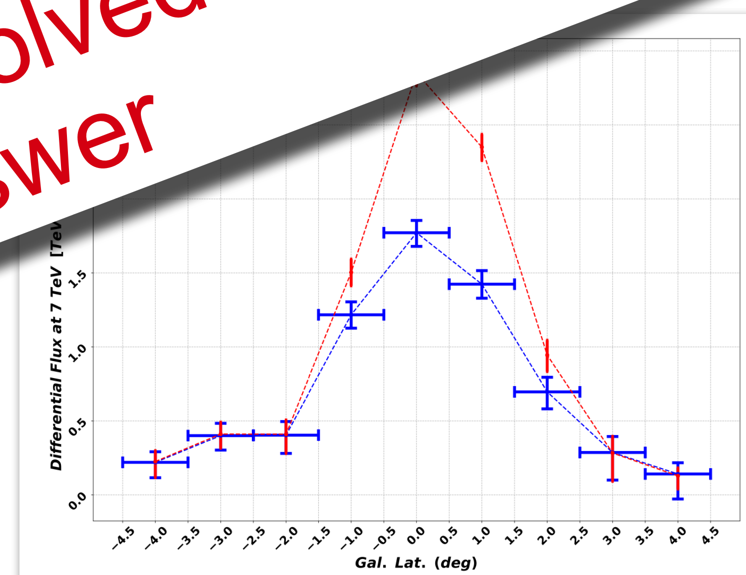


...n. flux, $-75^\circ < l < 60^\circ$ (H.E.S.S. 2014)

Particle Detector Arrays

Wide fields of view

Angular resol... 5 deg



7 TeV diff. flux, $43^\circ < l < 73^\circ$
(HAWC 2023)

Will require new measurements and
careful evaluation of the unresolved contribution
to give final answer

Helps not only in resolving structures
but also in the discrimination of γ-ray sources

measurable diffuse = truly diffuse + unresolved sources

→ **overestimation of diffuse signal in air shower particle detectors**

H.E.S.S. Cherenkov Telescope Array Observatory

Outline

0. Introduction

I. Detection Principles and Instruments

Lecture I

II. Ground-Based Galactic
Gamma-Ray Astronomy

Lecture II

III. Ground-Based Extragalactic
Gamma-Ray Astronomy,
Non-Gamma Science

Lecture III

IV. Outlook/Future

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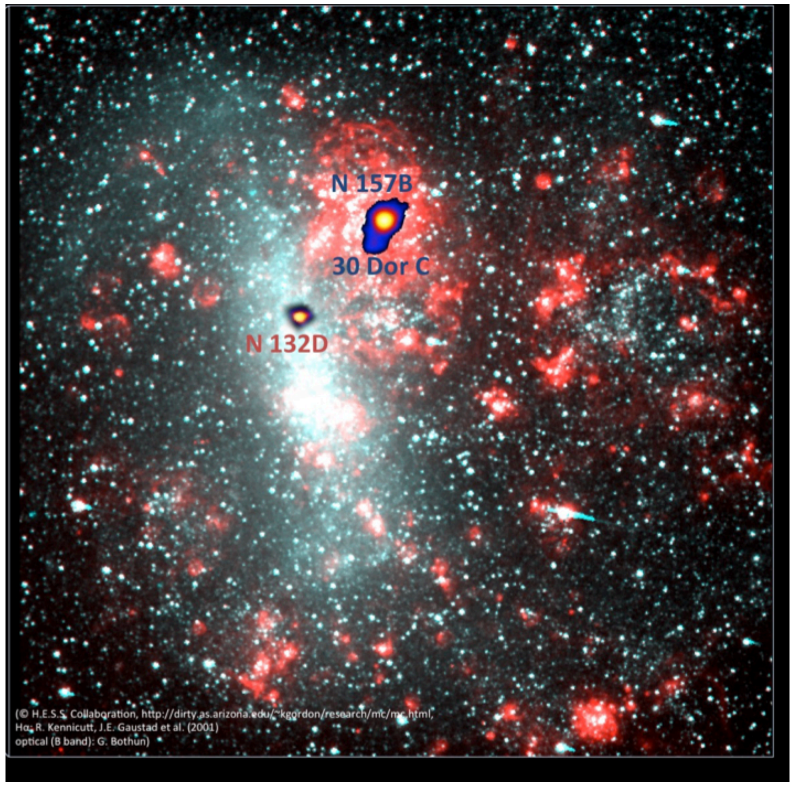
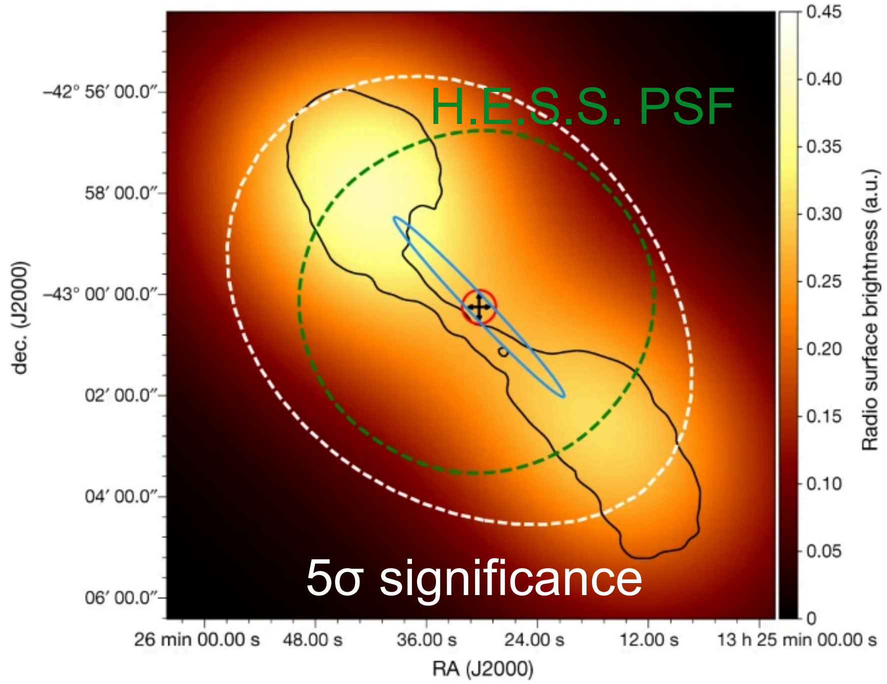
Extragalactic Gamma-Ray Astronomy

Distances get larger, angular scales smaller

LMC

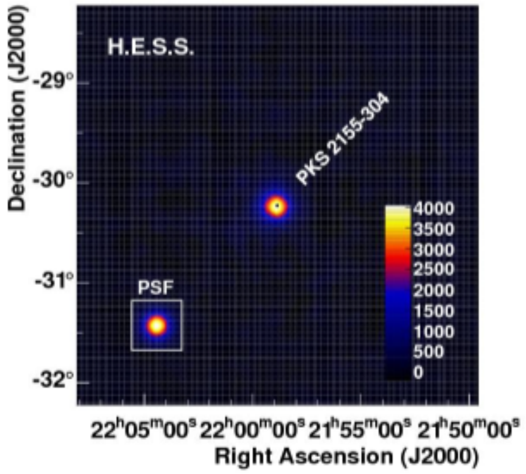


Cen A

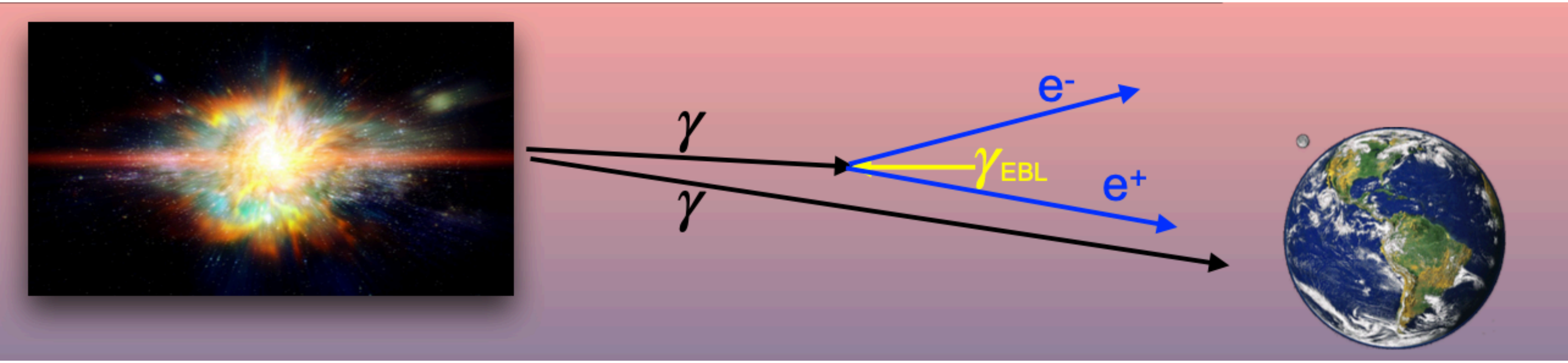


VLA radio surface brightness (smoothed and as contours)

PKS 2155-304

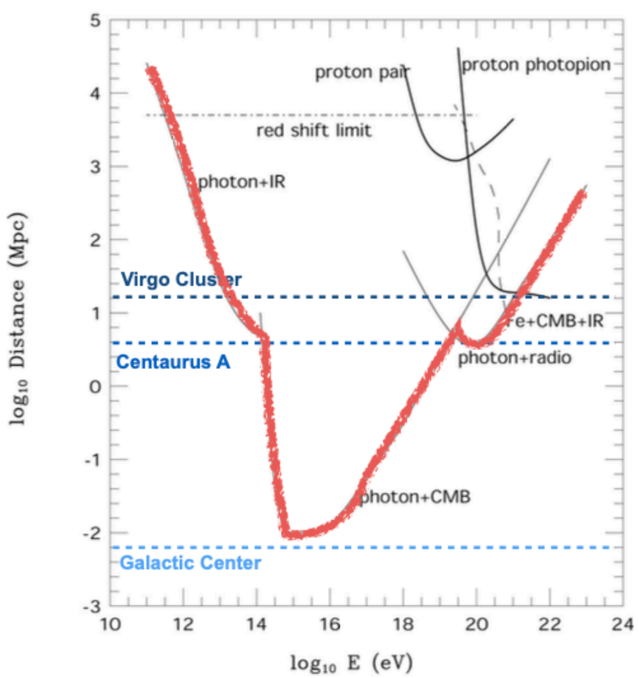


Observable energies are smaller as well



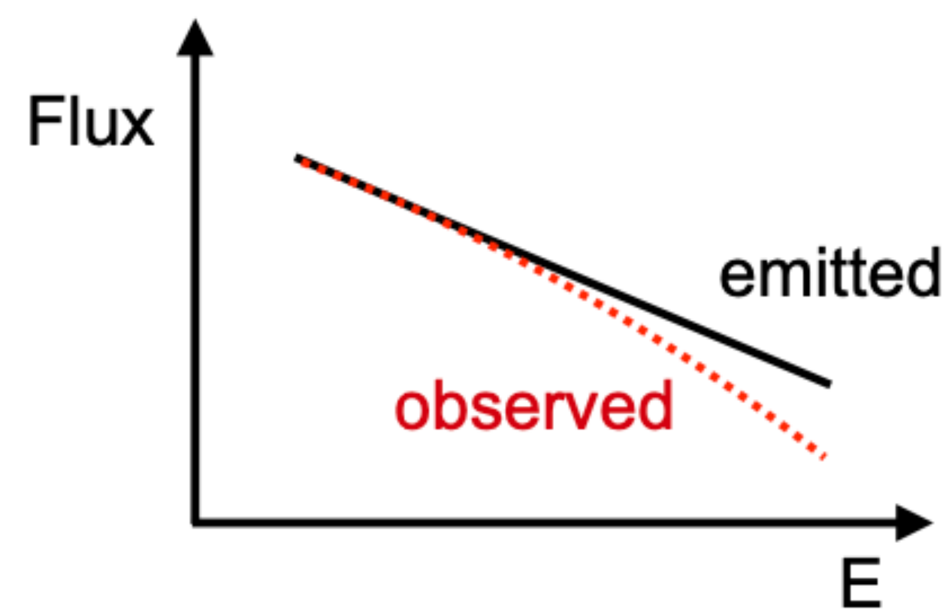
Absorption in extragalactic background light (EBL)

exponential flux decay, depending on gamma energy and EBL opacity (redshift)

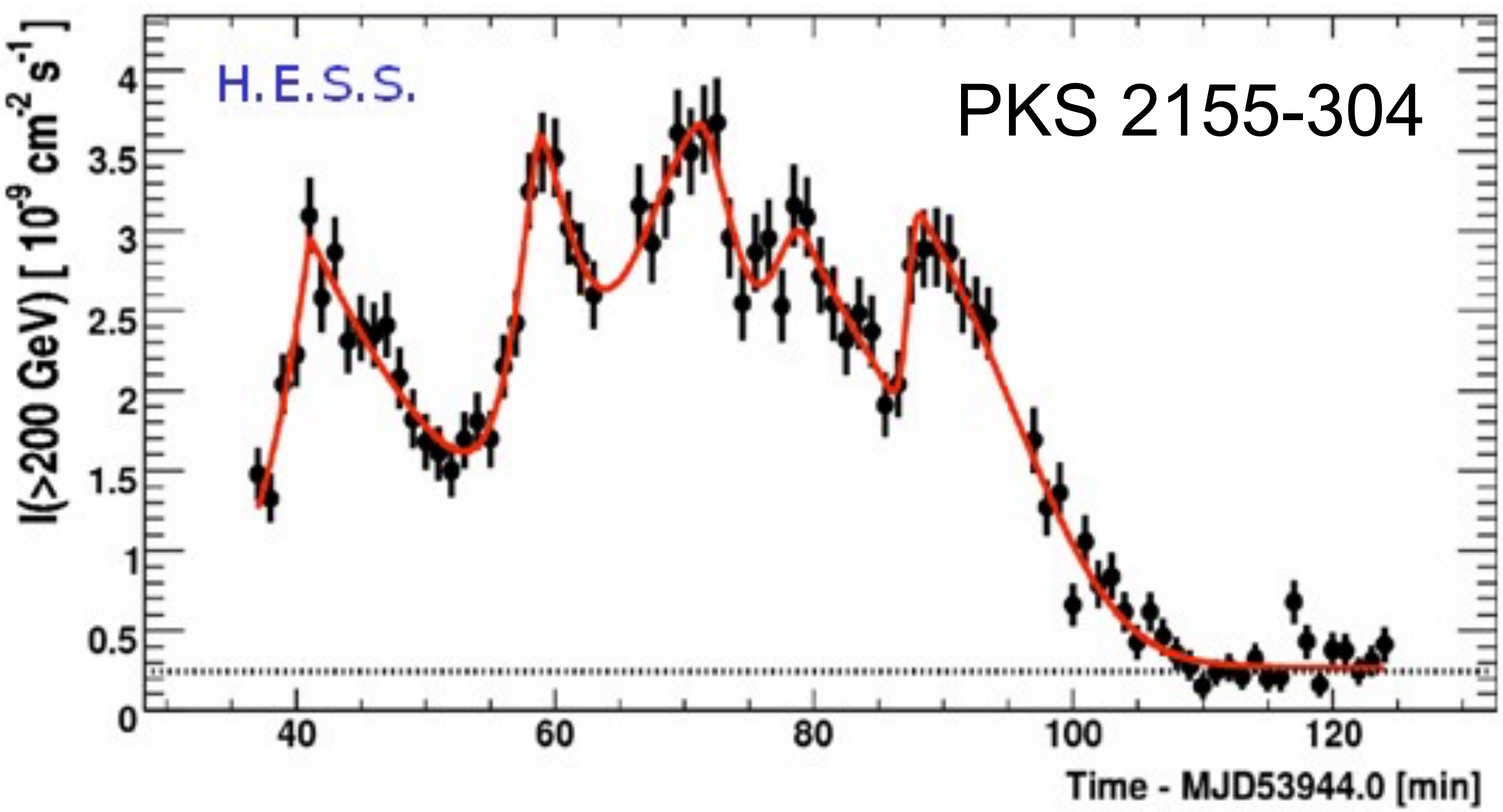


We see CR "PeVatrons" only in Galactic sources!

Gamma energies do not reflect maximum energy reached by the system



Time-Variability!



Emission increases by factor of 100

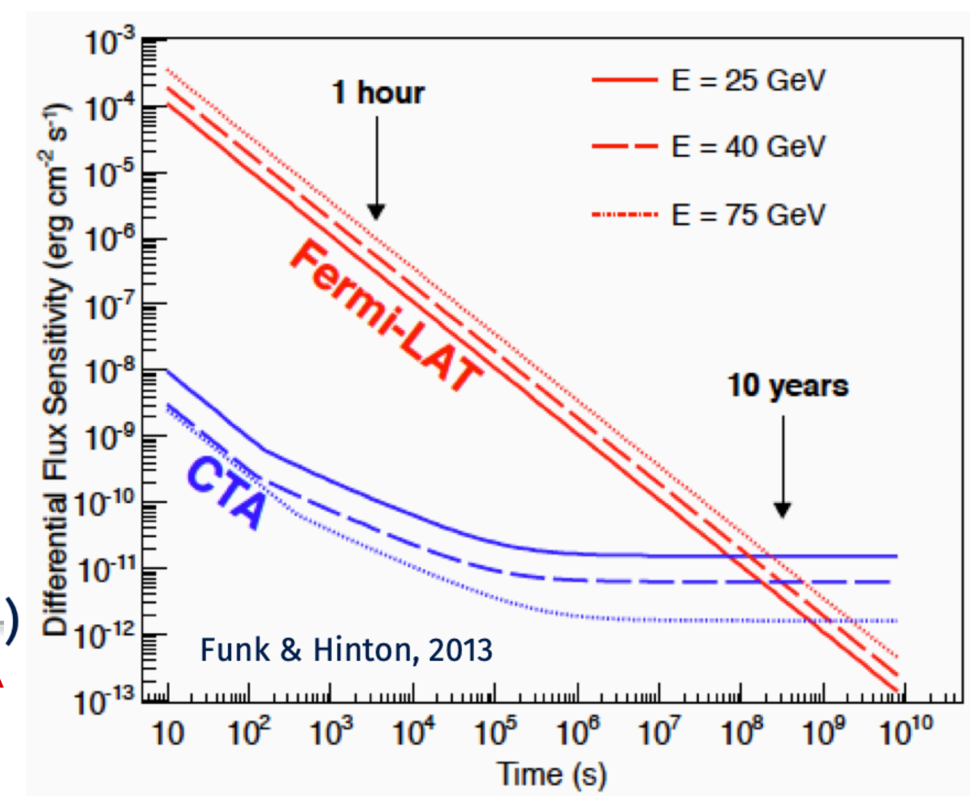
12 orders of magnitude higher energy output than the Crab nebula

Variability on time scales of few minutes

→ Possibility to probe size of emission region

→ Timing as crucial observable

→ Requires large instantaneous sensitivity



Sensitivity and Timing

Strong time variability, sometimes on very short scales
(e.g. short GRBs ~few seconds)
and unpredictable

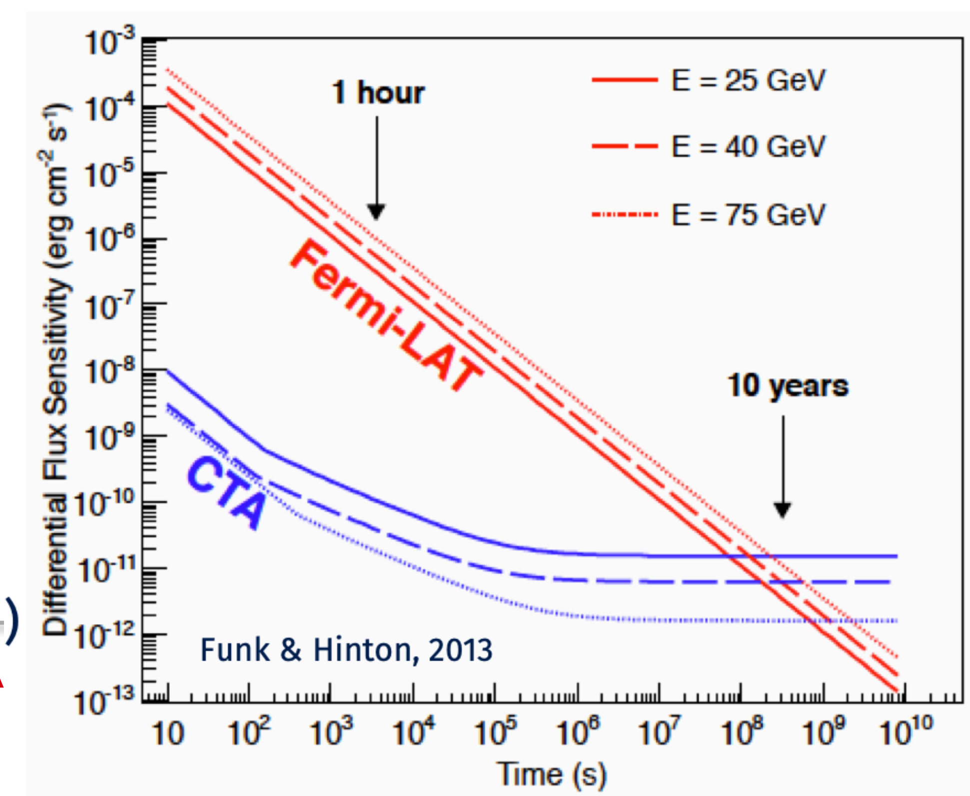
Catching the event on short time scales
→ **survey instruments**

Trade off

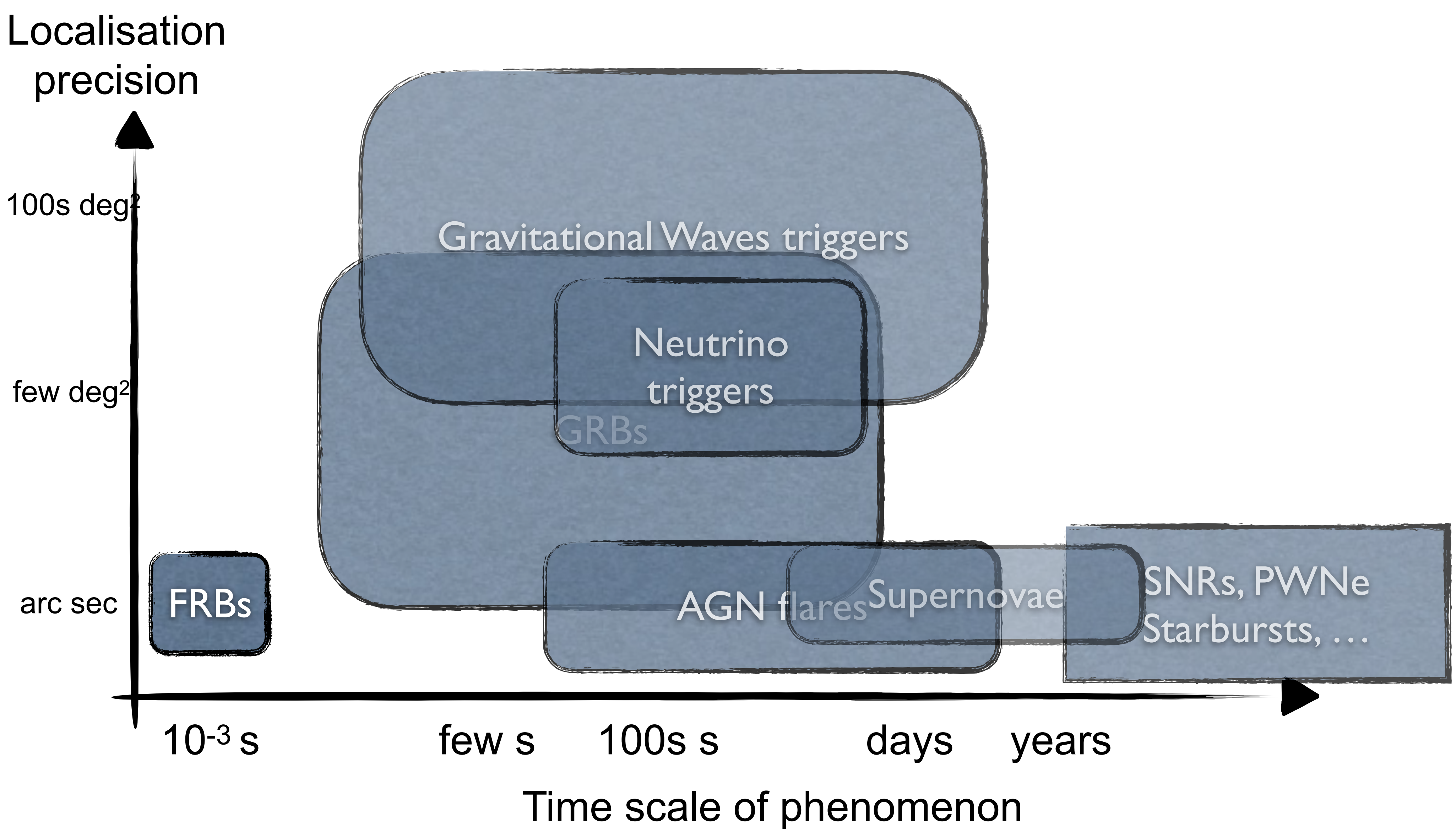
Short signal
→ large instantaneous sensitivity of **pointed instruments**

IACTs can typically repoint in < 1 min if observations are possible

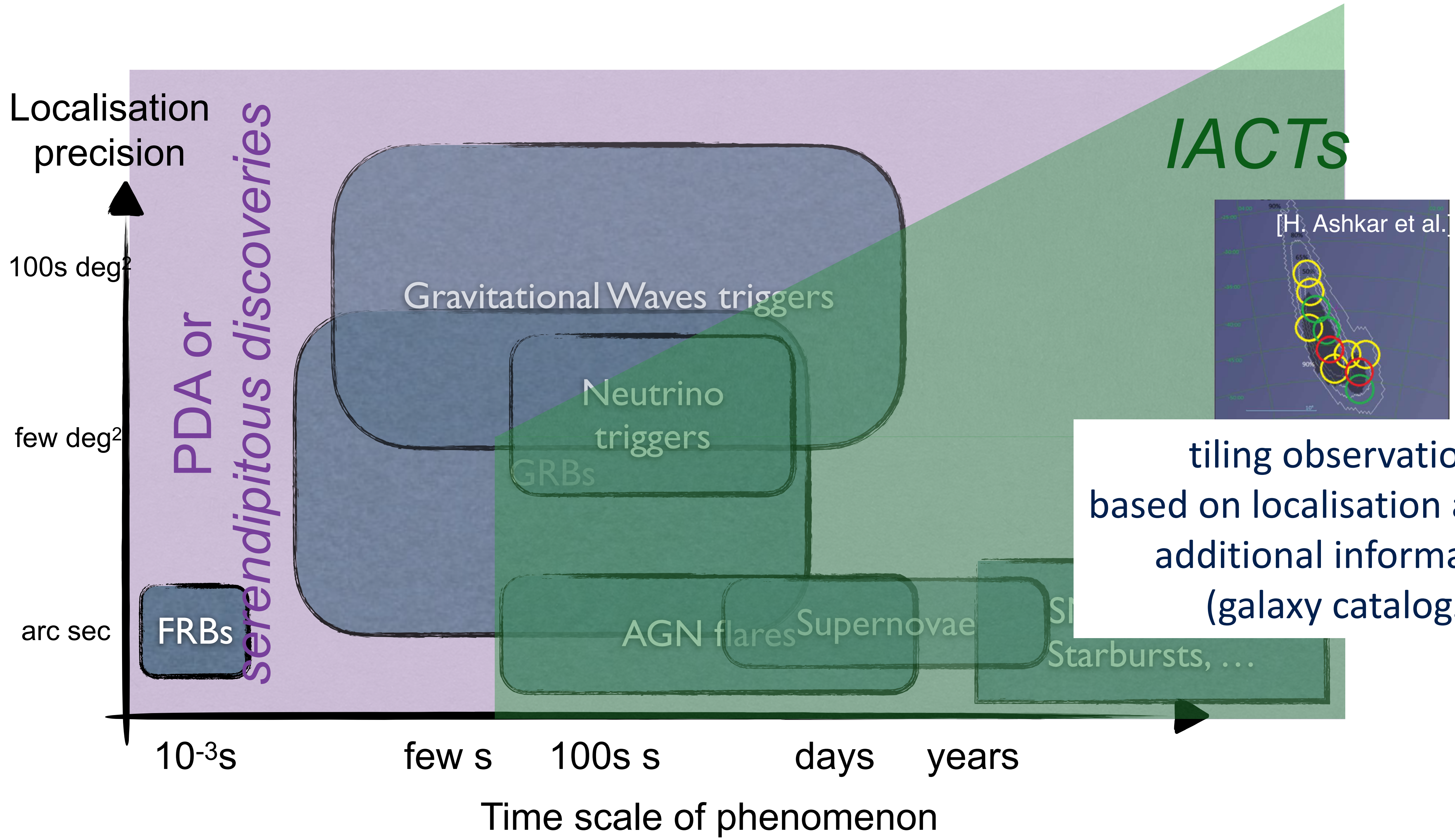
Crucial:
Coordination with other instruments for triggering of observations



Challenge for the Extragalactic Sky: Timing

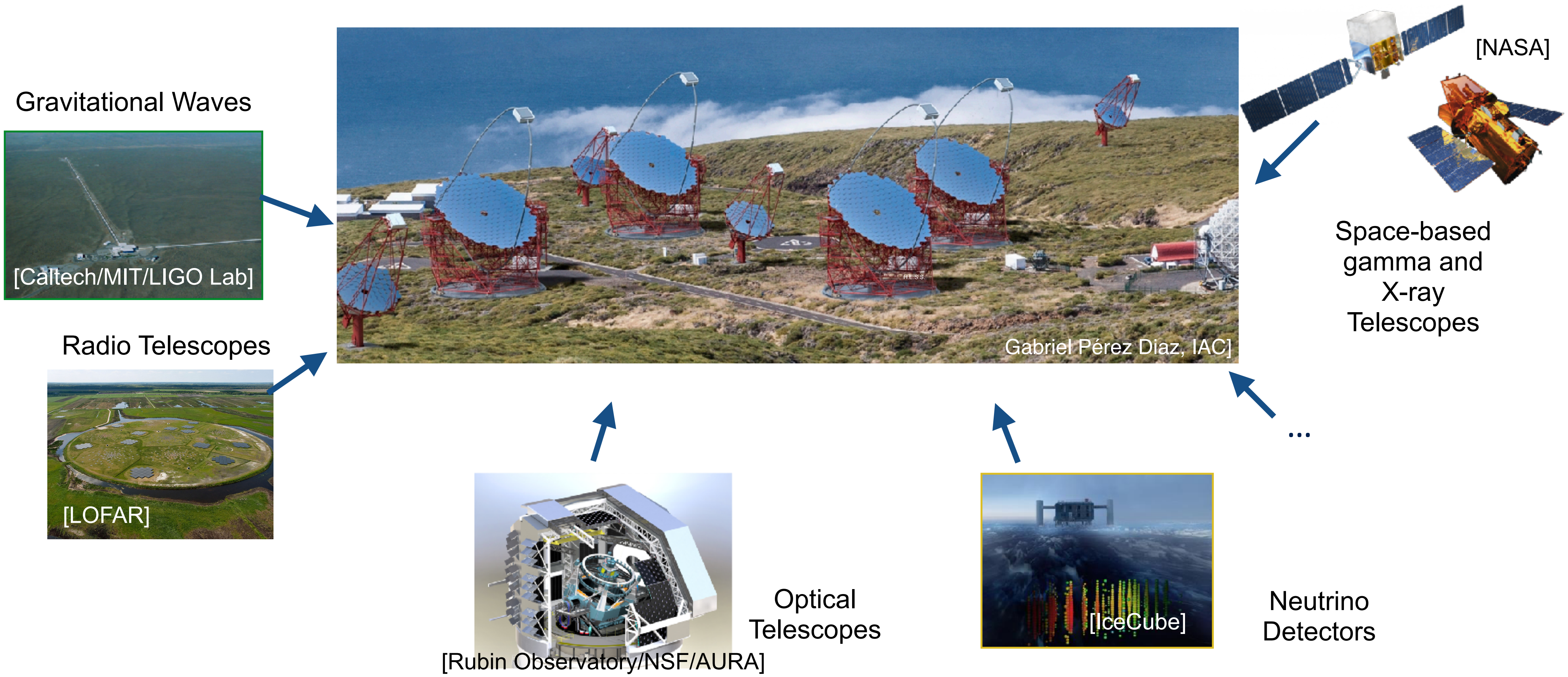


Challenge for the Extragalactic Sky: Timing



tiling observations based on localisation area and additional information (galaxy catalogs)

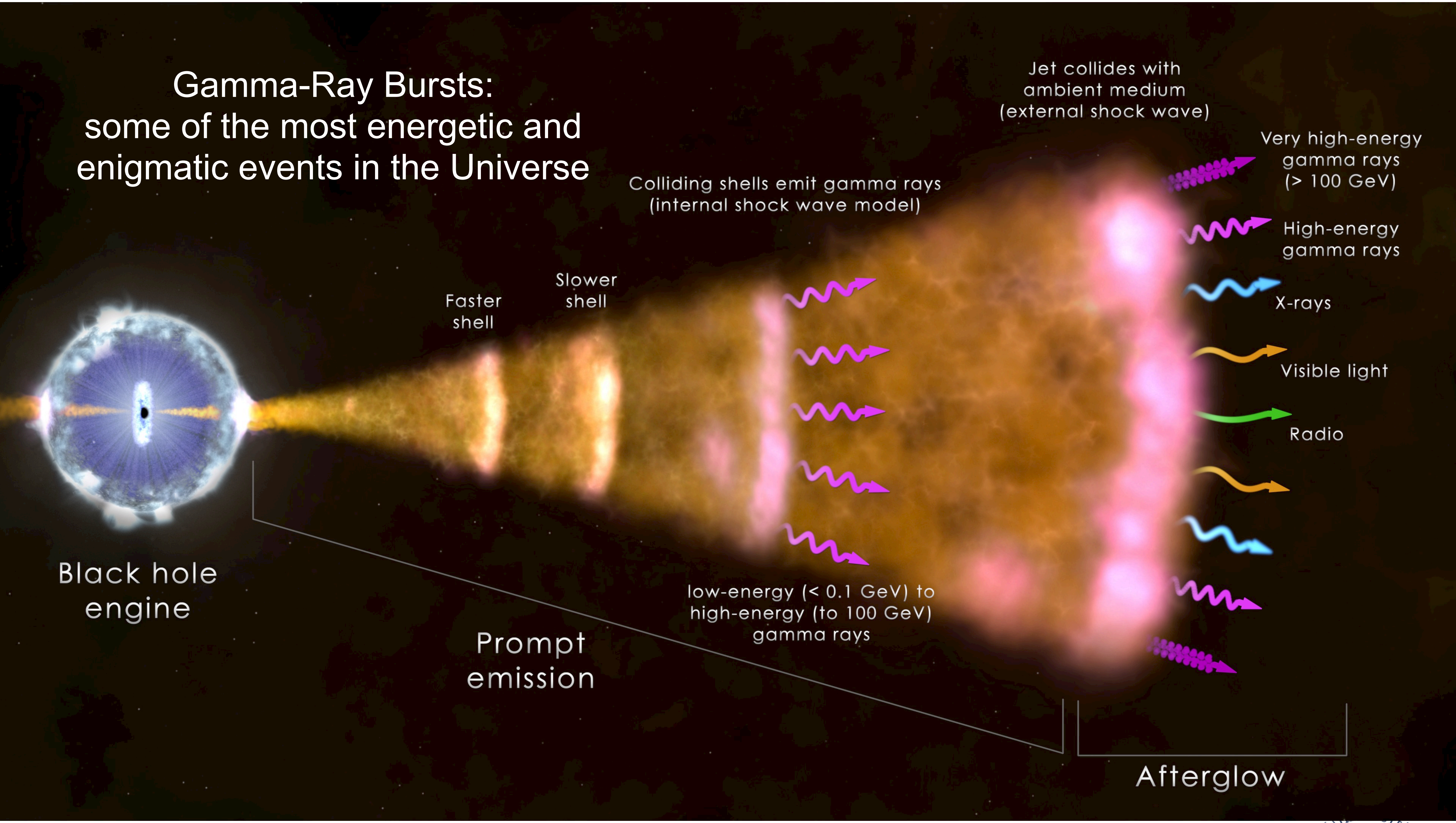
Challenge for the Extragalactic Sky: Timing



see Poster by Tiffany Collins

→ Requires automated systems that filter information with very short turn-around times and initiates follow-up observations

Transient Phenomena



Ground-Based GRB Detections

All ground-based gamma-ray instruments
have been hunting GRBs for more than a decade

Then, in 2019…

Article

Teraelectronvolt emission from the γ-ray burst GRB 190114C

https://doi.org/10.1038/s41586-019-1750-x
Received: 10 May 2019
Accepted: 2 September 2019
Published online: 20 November 2019

MAGIC Collaboration*

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies (from radio waves to gigaelectronvolt γ-rays), which originates from synchrotron radiation generated by energetic electrons in the accompanying shock waves[3,4]. Although emission of γ-rays at even higher (teraelectronvolt) energies by other radiation mechanisms has been theoretically predicted[5–8], it has not been previously detected[7,8]. Here we report observations of teraelectronvolt emission from the γ-ray burst GRB 190114C. γ-rays were observed in the energy range 0.2–1 teraelectronvolt from about one minute after the burst (at more than 50 standard deviations in the first 20 minutes), revealing a distinct emission component of the afterglow with power comparable to that of the synchrotron component. The observed similarity in the radiated power and temporal behaviour of the teraelectronvolt and X-ray bands points to processes such as inverse Compton upscattering as the mechanism of the teraelectronvolt emission[9–11]. By contrast, processes such as synchrotron emission by ultrahigh-energy protons[10,12,13] are not favoured because of their low radiative efficiency. These results are anticipated to be a step towards a deeper understanding of the physics of GRBs and relativistic shock waves.

MAGIC Coll., Nature 2019

Very high energy particle acceleration deep in the gamma-ray burst afterglow phase

H. Abdalla[1], R. Adam[27], F. Aharonian[3,4,5], F. Ait Benkhali[3], E.O. Angüner[19], M. Arakawa[38], C. Arcaro[1], C. Armand[22], H. Ashkar[17], M. Backes[8,1], V. Barbosa Martins[34], M. Barnard[1], Y. Becherini[10], D. Berge[34], K. Bernlöhr[3], E. Bissaldi[45,44], R. Blackwell[13], M. Böttcher[1], C. Boisson[14], J. Bolmont[15], S. Bonnefoy[34], J. Bregeon[16], M. Breuhaus[3], F. Brun[17], P. Brun[17], M. Bryan[9], M. Büchele[33], T. Bulik[18], T. Bylund[10], M. Capasso[26], S. Caroff[15], A. Carosi[22], S. Casanova[20,3], M. Cerruti[15,43], T. Chand[1], S. Chandra[1], A. Chen[21], S. Colafrancesco[21] †, M. Curyło[18], I.D. Davids[8], C. Deil[3], J. Devin[24], P. deWilt[13], L. Dirson[2], A. Djannati-Ataï[28], A. Dmytriiev[14], A. Donath[3], V. Doroshenko[26], J. Dyks[31], K. Egberts[32], G. Emery[15], J.-P. Ernenwein[19], S. Eschbach[33], K. Feijen[13], S. Fegan[27], A. Fiasson[22], G. Fontaine[27], S. Funk[33], M. Füßling[34], S. Gabici[28], Y.A. Gallant[16], F. Gaté[22], G. Giavitto[34], L. Giunti[28], D. Glawion[23], J.F. Glicenstein[17], D. Gottschall[26], M.-H. Grondin[24], J. Hahn[3], M. Haupt[34], G. Heinzelmann[2], G. Henri[29], G. Hermann[3], J.A. Hinton[3], W. Hofmann[3], C. Hoischen[32], T. L. Holch[7], M. Holler[12], D. Horns[2], D. Huber[12], H. Iwasaki[38], M. Jamrozy[35], D. Jankowsky[33], F. Jankowsky[23], A. Jardin-Blicq[3], I. Jung-Richardt[33], M.A. Kastendieck[2], K. Katarzyński[36], M. Katsuragawa[39], U. Katz[33], D. Khangulyan[38], B. Khélifi[28], J. King[23], S. Klepser[34], W. Kluźniak[31], Nu. Komin[21], K. Kosack[17], D. Kostunin[34], M. Kreter[1], G. Lamanna[22], A. Lemière[28], M. Lemoine-Goumard[24], J.-P. Lenain[15], E. Leser[32,34], C. Levy[15], T. Lohse[7], I. Lypova[34], J. Mackey[4], J. Majumdar[34], D. Malyshev[26], V. Marandon[3], A. Marcowith[16], A. Mares[24], C. Mariaud[27], G. Martí-Devesa[12], R. Marx[3], G. Maurin[22], P.J. Meintjes[37], A.M.W. Mitchell[3,42], R. Moderski[31], M. Mohamed[23],

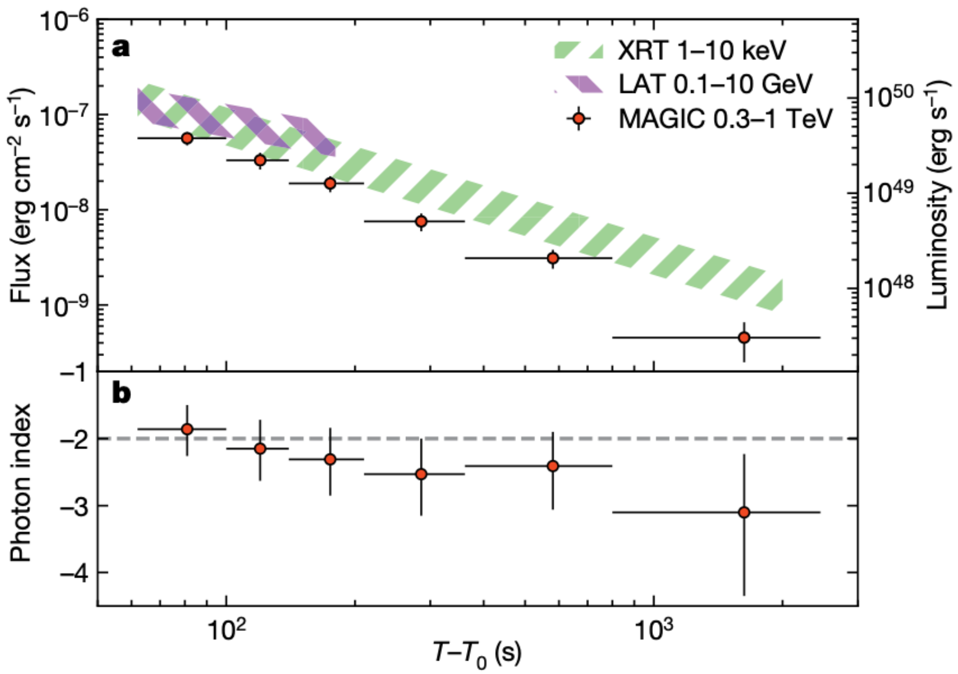
H.E.S.S. Coll., Nature 2019

Two Completely Different Cases

GRB190114C (MAGIC)

- Observations after 50 seconds
- >300 GeV
  (zenith of 60deg & partial moon)
- >20 sigma in first 20 min of observations

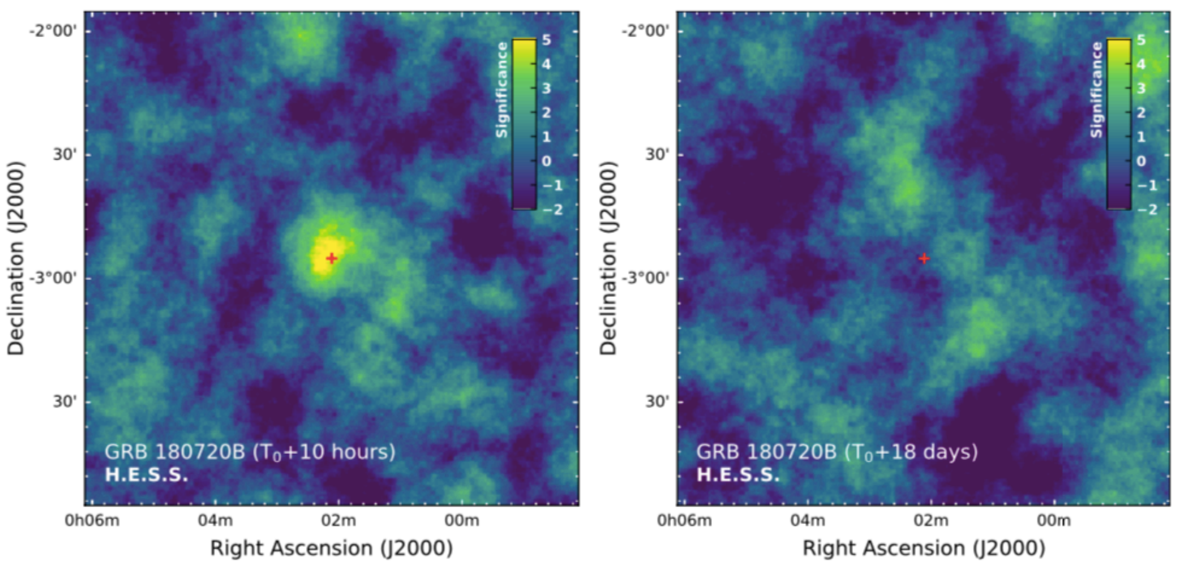
MAGIC Coll., Nature 2019



GRB180720B (H.E.S.S.)

- Observations after 10 hours
- 100 - 440 GeV
- 5 sigma accumulated over 2 hours

after 10 hours
after 18 days



H.E.S.S. Coll., Nature 2019

→ Probing GRBs as extreme accelerators over a diverse range of timescales becomes possible!

Two Completely Different Cases

GRB190114C (MAGIC)

- Observations after 50 seconds
- >300 GeV
  (zenith of 60deg & partial moon)
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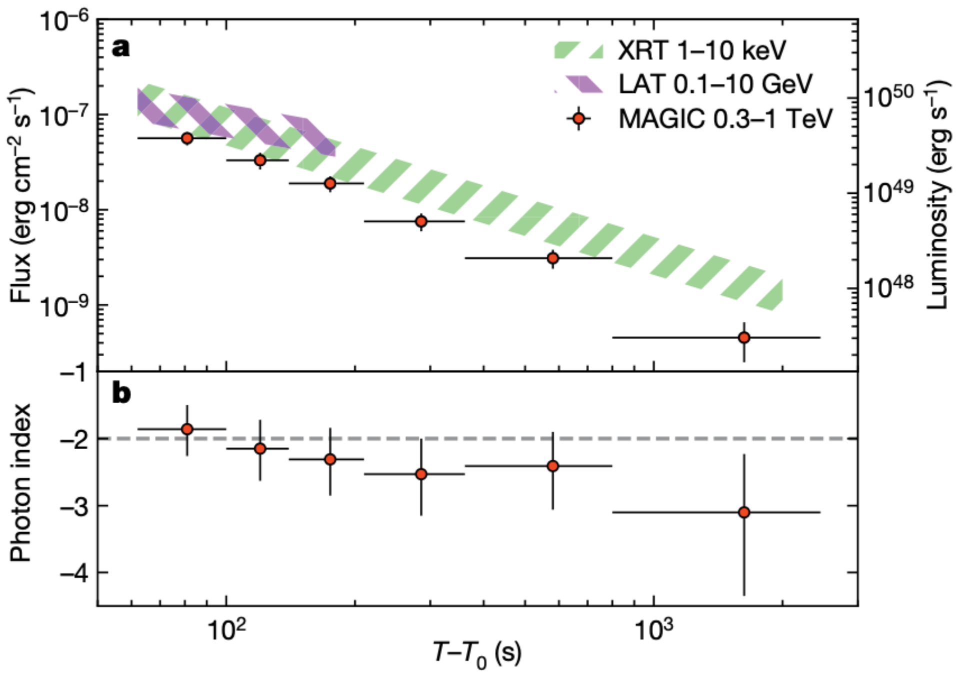
MAGIC Coll., Nature 2019



GRB180720B (H.E.S.S.)

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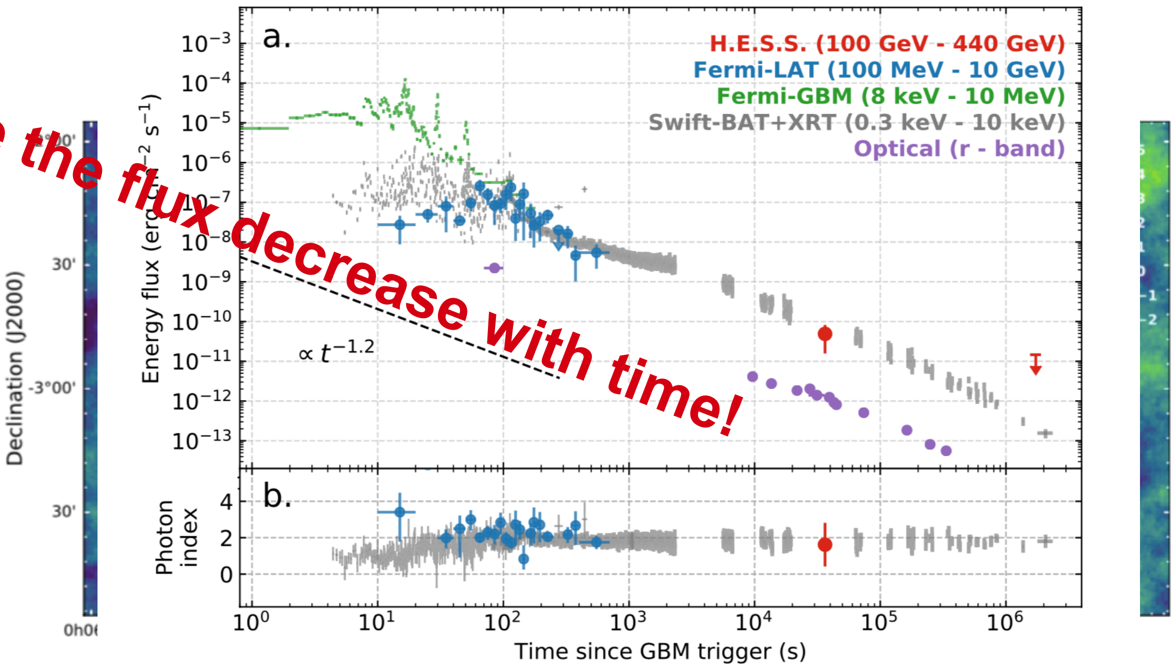


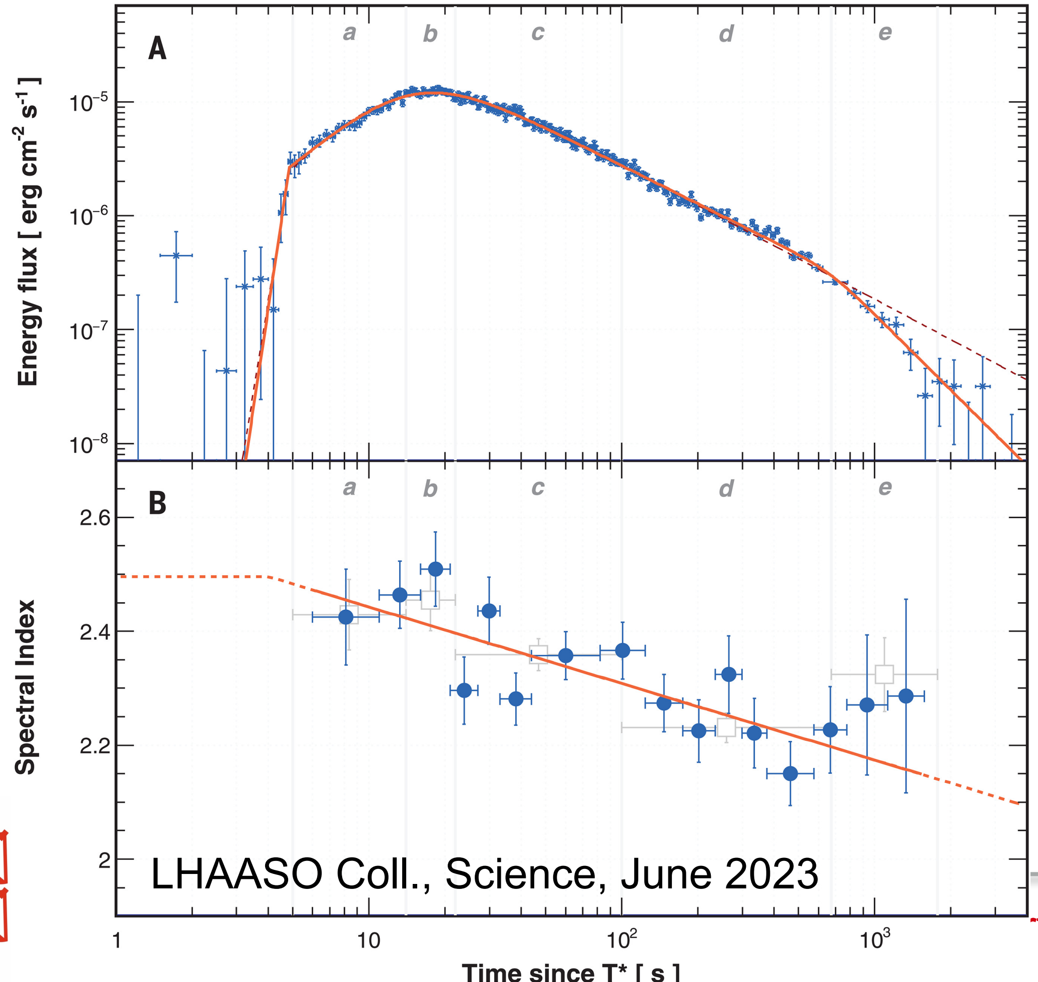
note the flux decrease with time!

H.E.S.S. Coll., Nature 2019

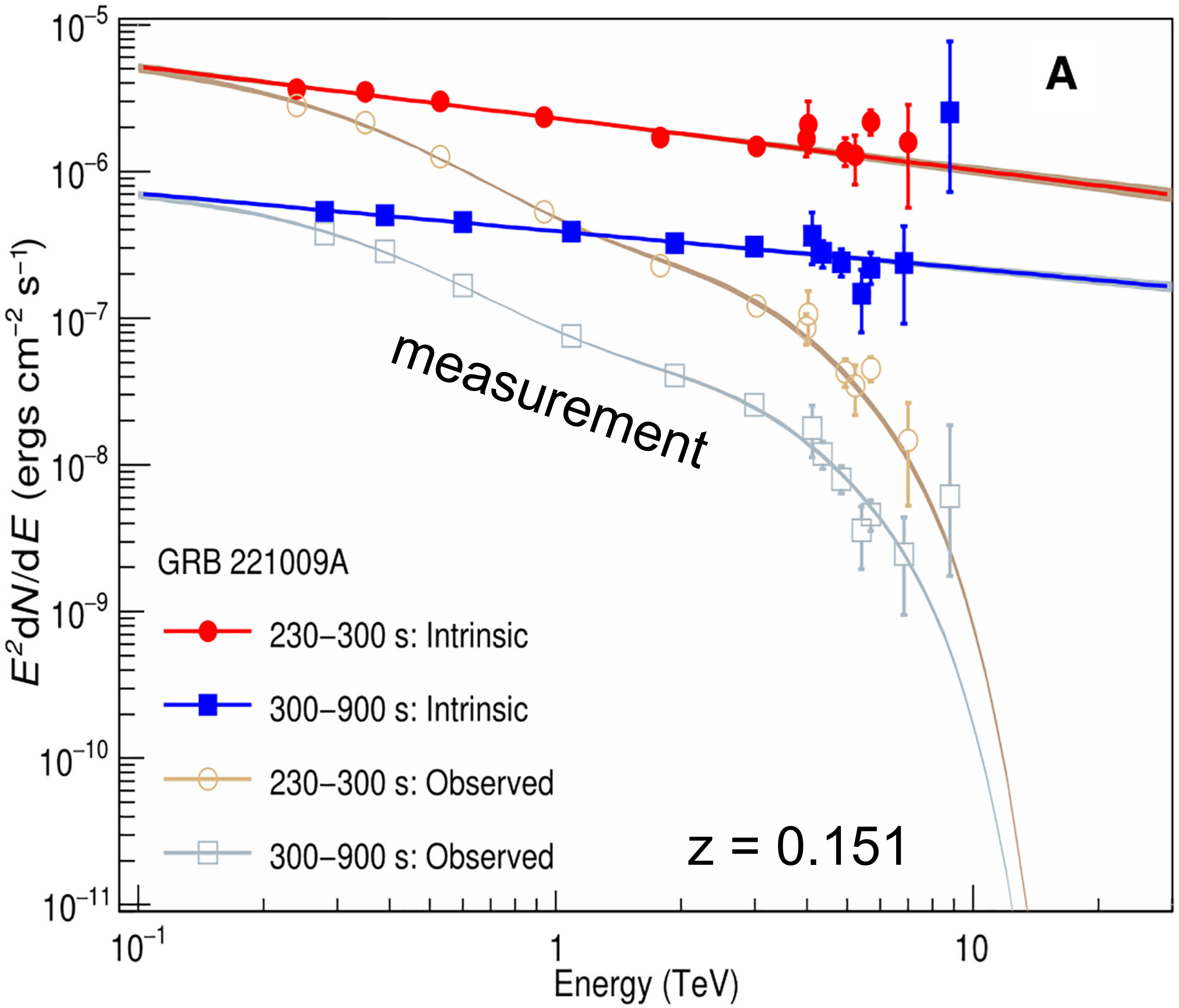
→ Probing GRBs as extreme accelerators over a diverse range of timescales becomes possible!

GRB 221009A - The Brightest Of All Times

- LHAASO detection >10 TeV
- ~3000 s after the trigger, >64,000 photons with energies between ~200 GeV and ~7 TeV
- EBL absorption by >2 orders of magnitude



LHAASO Coll., Science, June 2023



LHAASO Coll., Science, Nov 2023

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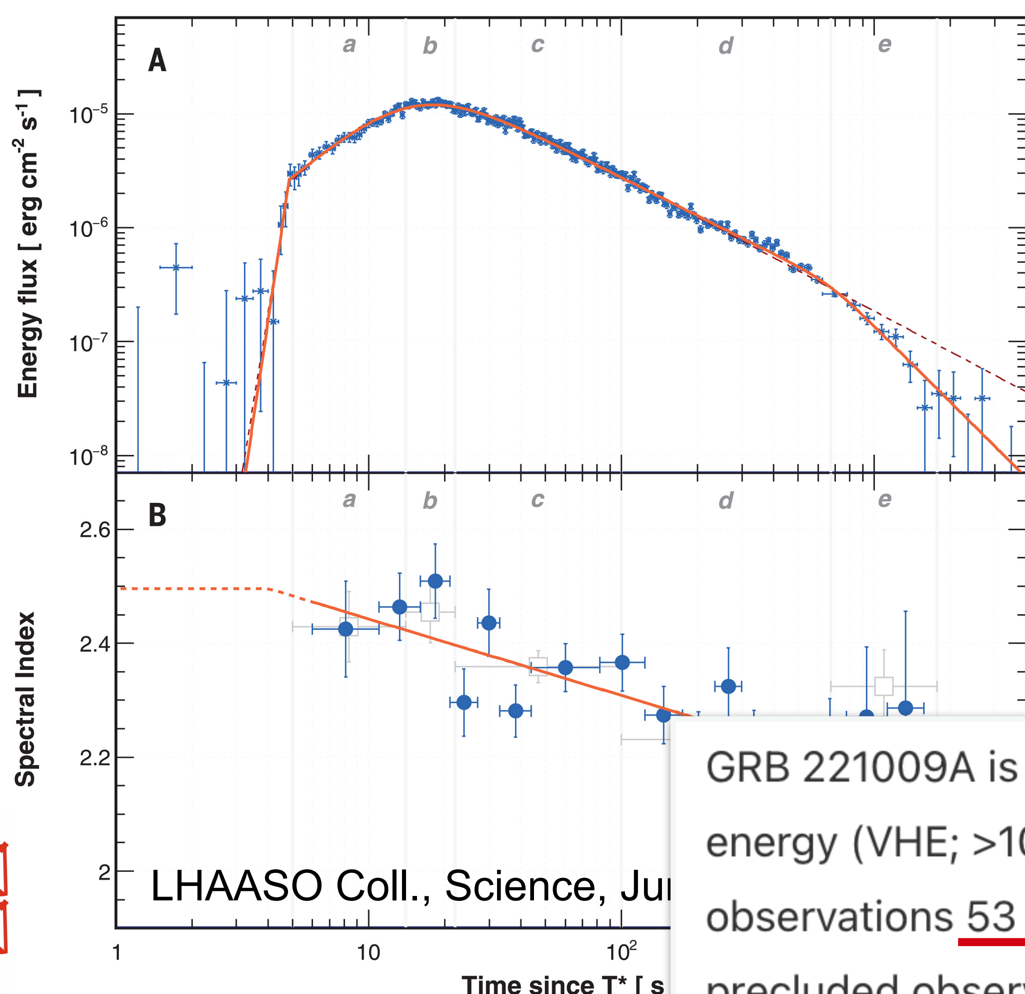
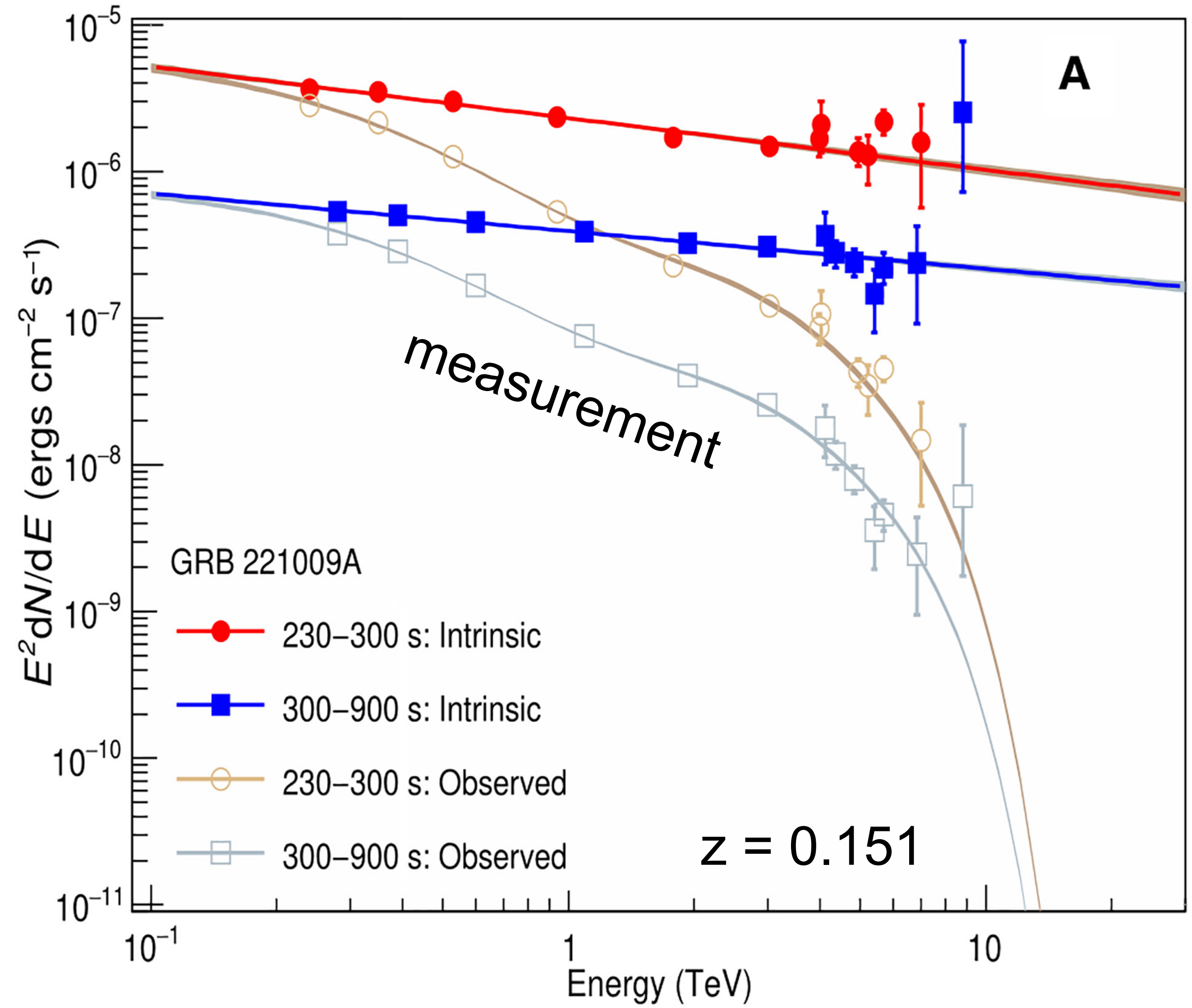




LHAASO Coll., Science, Nov 2023

IACTs:

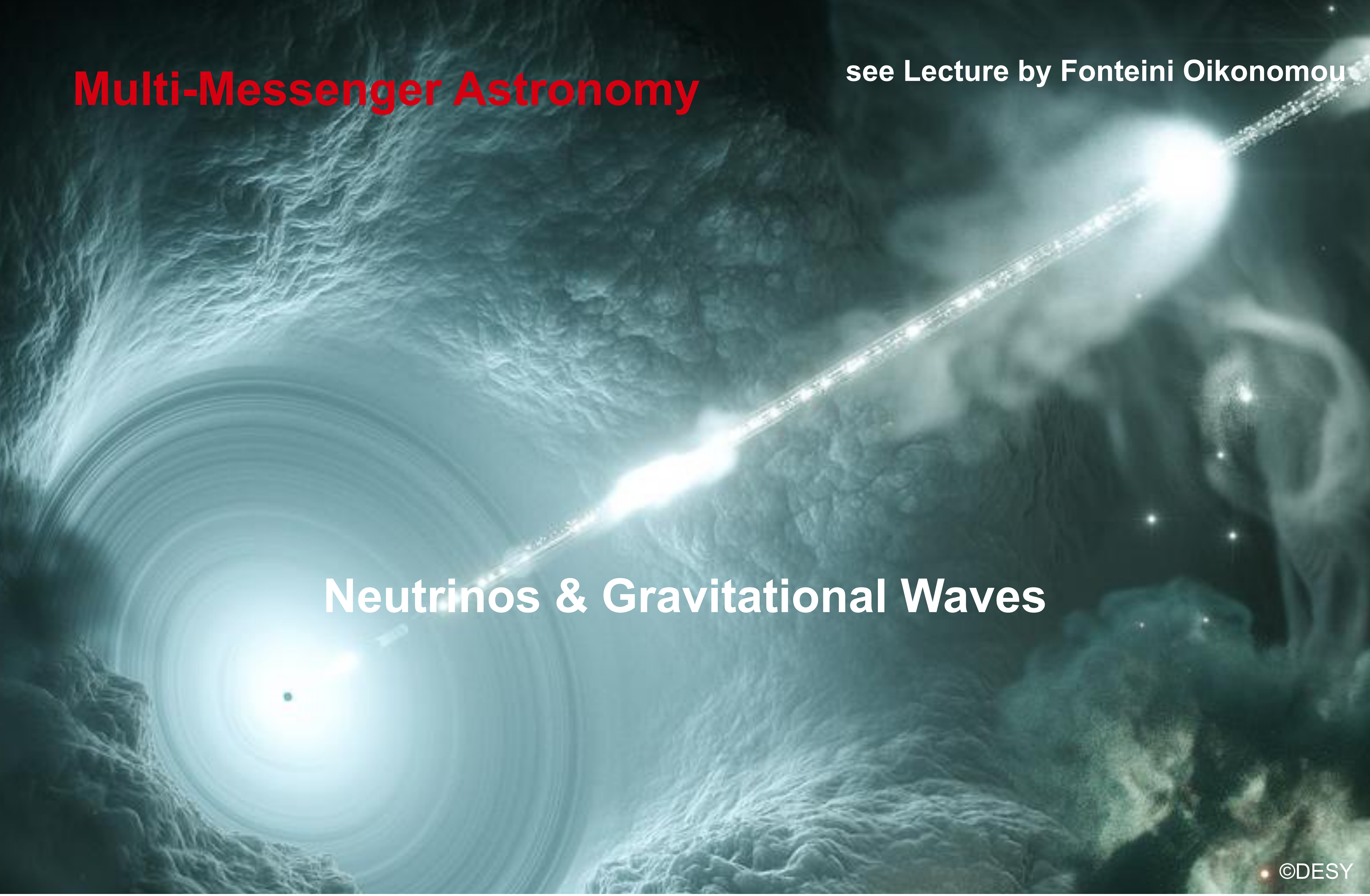
GRB 221009A is the brightest gamma-ray burst (GRB) ever detected. To probe the very-high-energy (VHE; >100 GeV) emission, the High Energy Stereoscopic System (H.E.S.S.) began observations 53 hr after the triggering event, when the brightness of the moonlight no longer precluded observations. We derive differential and integral upper limits using H.E.S.S. data from

H.E.S.S. Cherenkov Telescope Array Observat

Multi-Messenger Astronomy

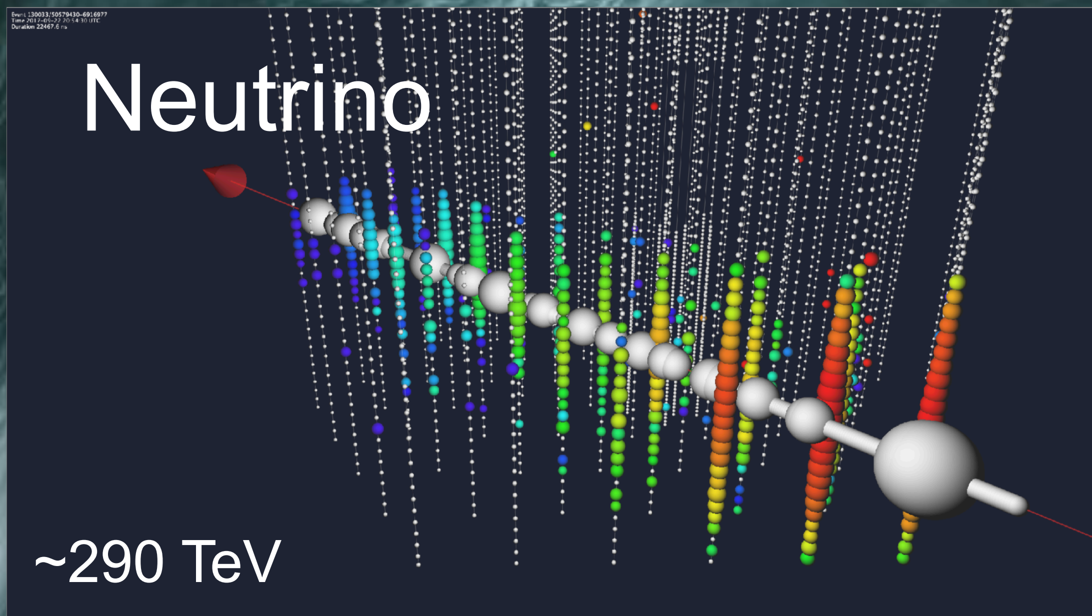
see Lecture by Fonteini Oikonomou

Neutrinos & Gravitational Waves



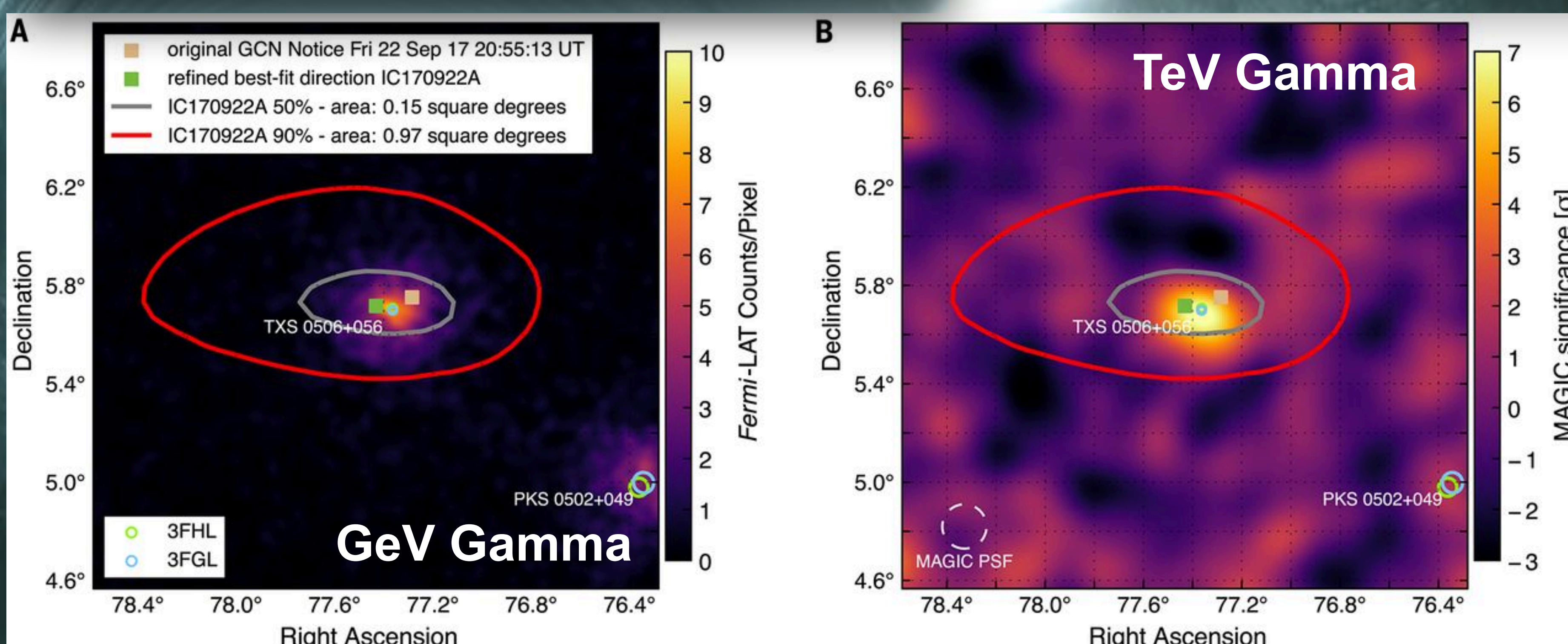
The Case of TXS 0506+056

see Lecture by Francis Halzen



A high-energy astrophysical neutrino in conjunction with a flaring blazar

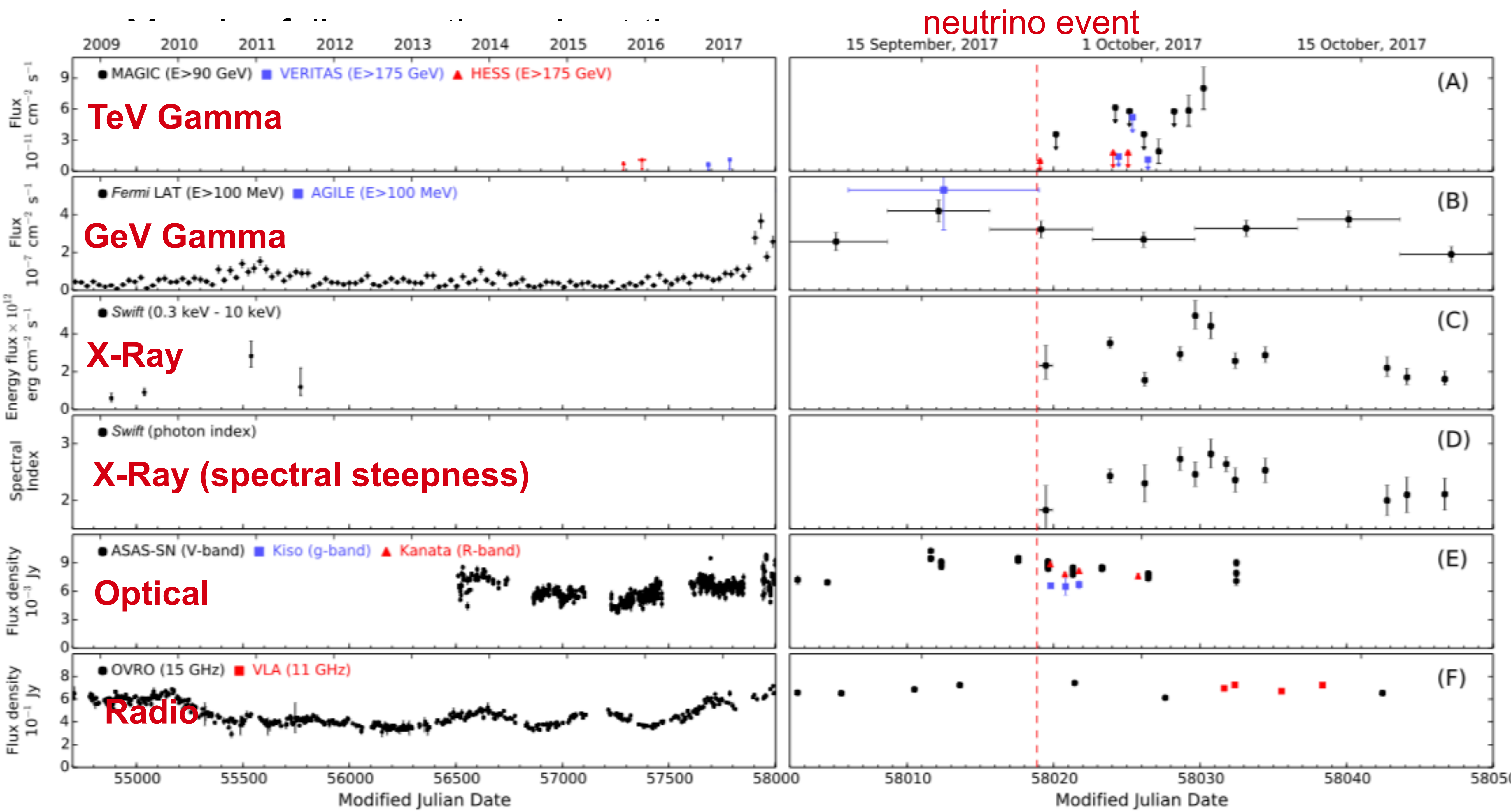
- 4.1 σ (3 σ after trials) correlation
- First known source of HE neutrinos (& first extragalactic source of cosmic rays)



Beginning of neutrino multi-messenger astronomy

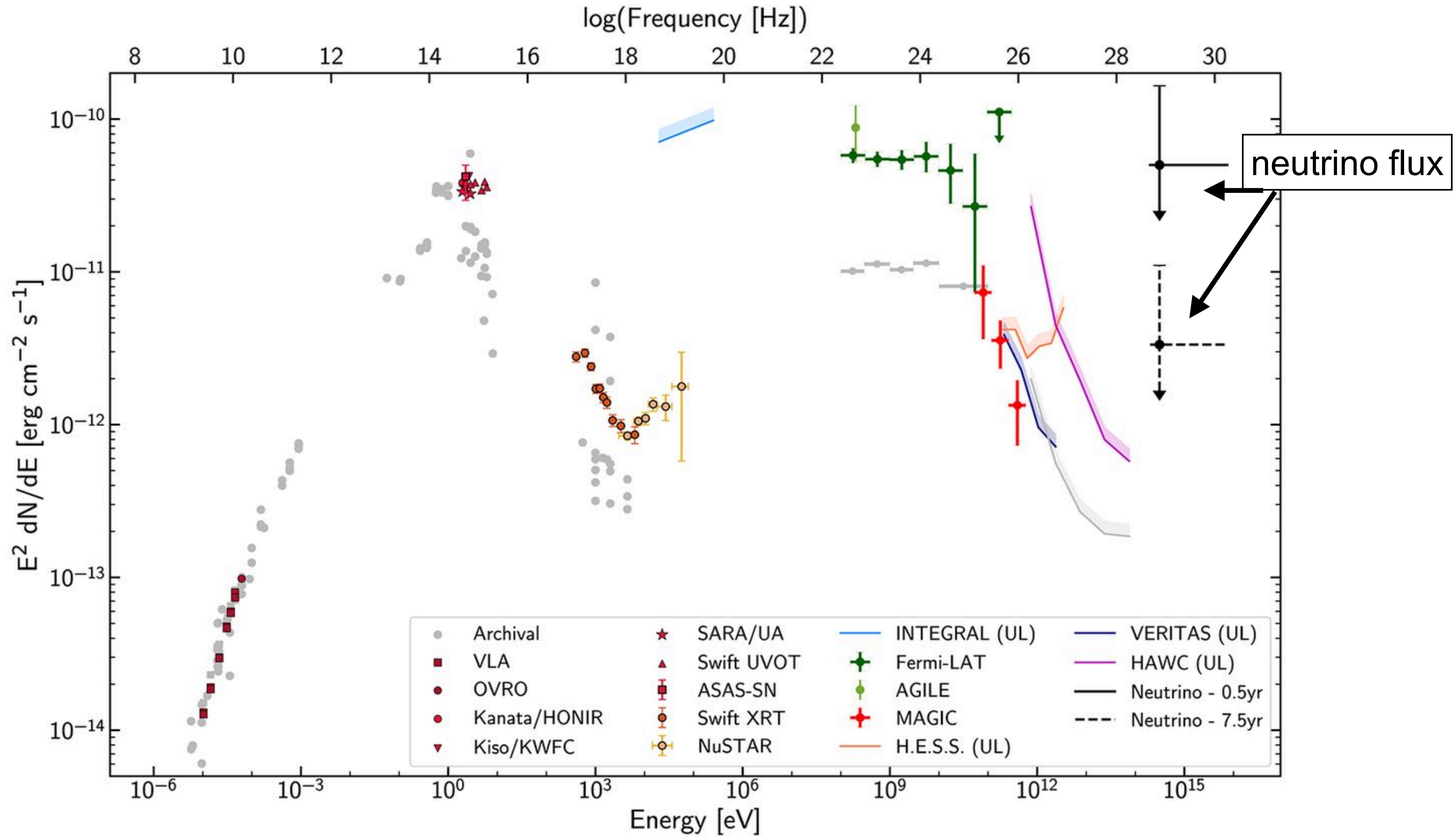
… together with a TeV detection!

The Case of TXS 0506+056



IceCube et al., Science 2018

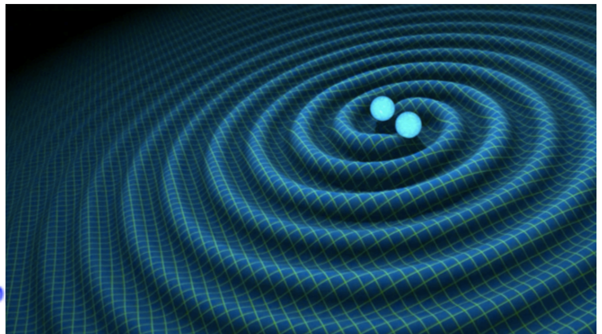
The Case of TXS 0506+056



IceCube et al., Science 2018

The Era of Gravitational Wave Astronomy
The Case of GW 170817

see Lecture by Patricia Schmidt



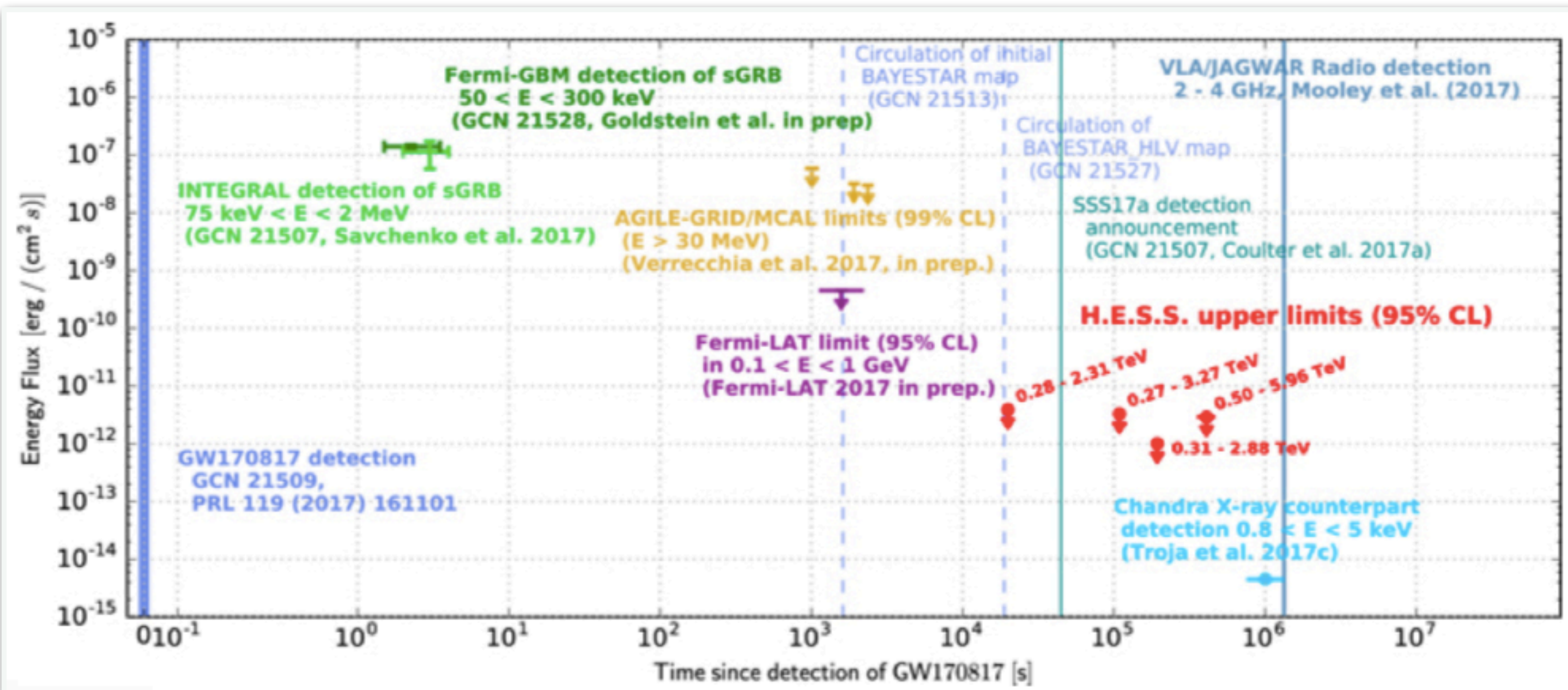
http

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger*



ollaboration, AstroSat Cadmium Zinc
laboration, The Swift Collaboration,
ollaboration, The DLT40 Collaboration,
ATCA: Australia Telescope Compact
eeper, Wider, Faster Program), AST3,
EM, GROWTH, JAGWAR, Caltech-
onsortium, KU Collaboration, Nordic
ent Robotic Observatory of the South
Collaboration, IKI-GW Follow-up
AWC Collaboration, The Pierre Auger
dra Team at McGill University, DFN:
R, and SKA South Africa/MeerKAT

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

>3500 authors
>70 observatories

A remarkable example of international collaboration!

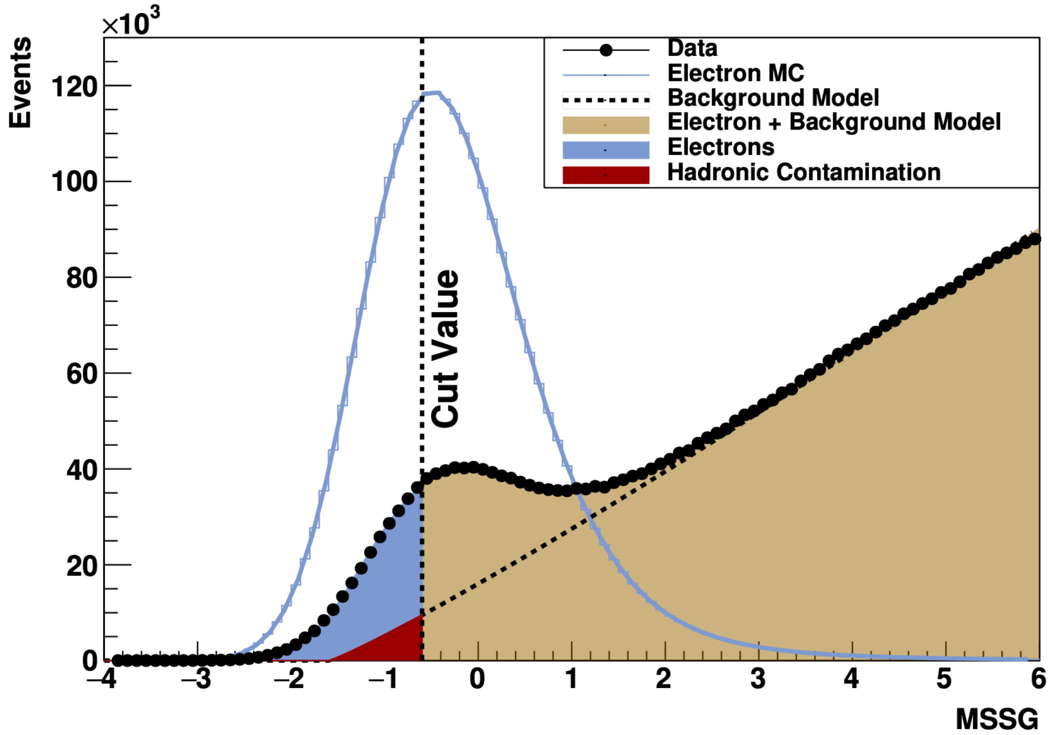
H.E.S.S.

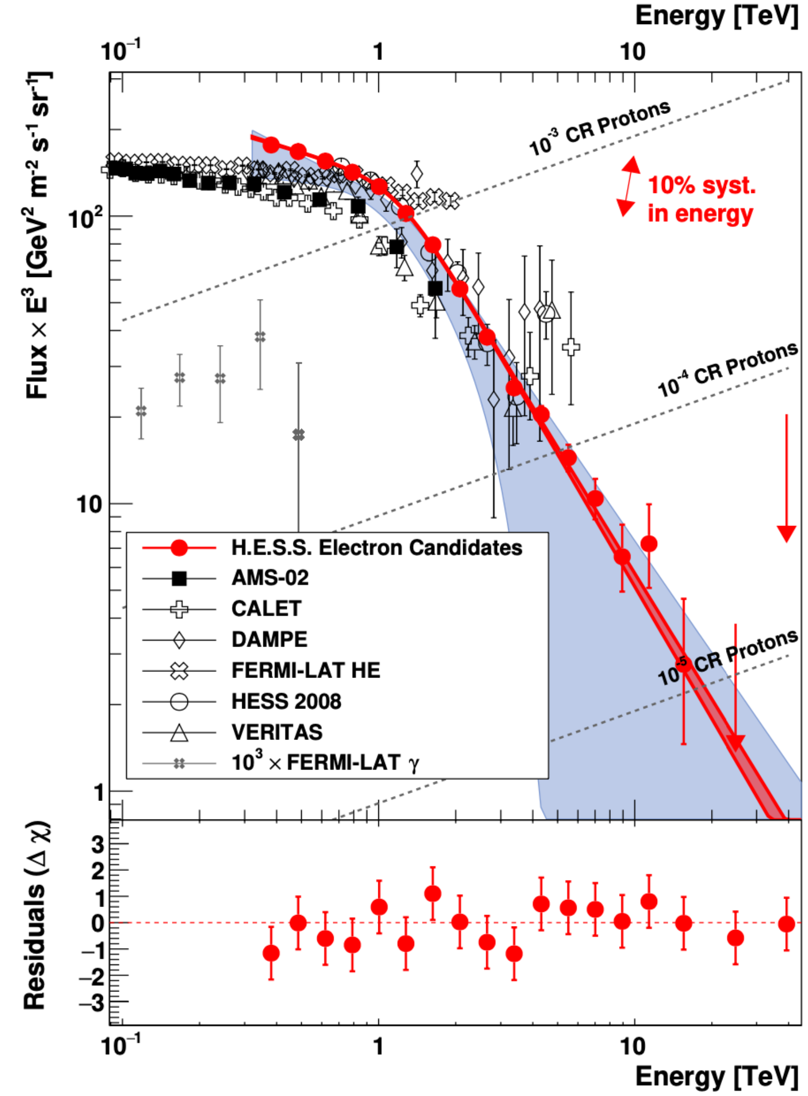
Universität Potsdam

Non-Gamma Science

Use the TeV instruments for other types of measurements

- Example: **cosmic-ray electrons**
- Due to their isotropy, very good separation power between hadrons and electrons required
- Can expand the measurable spectrum significantly beyond satellite capabilities



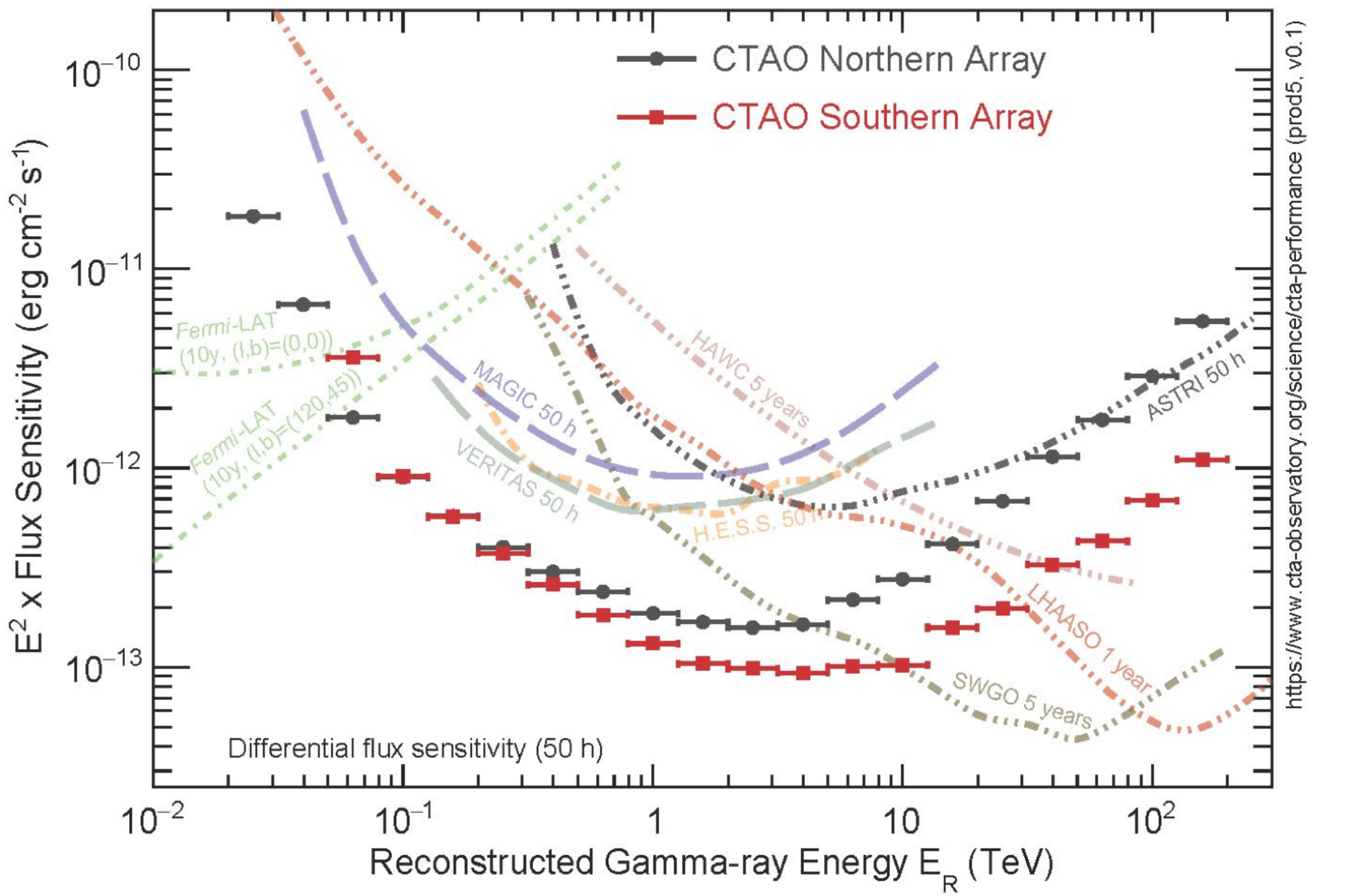


H.E.S.S. Coll., submitted to PRL

- Also other cosmic-ray measurements (e.g. proton, iron)
- Measurements of EBL in blazar absorption
- Stellar interferometry…

IV. Outlook

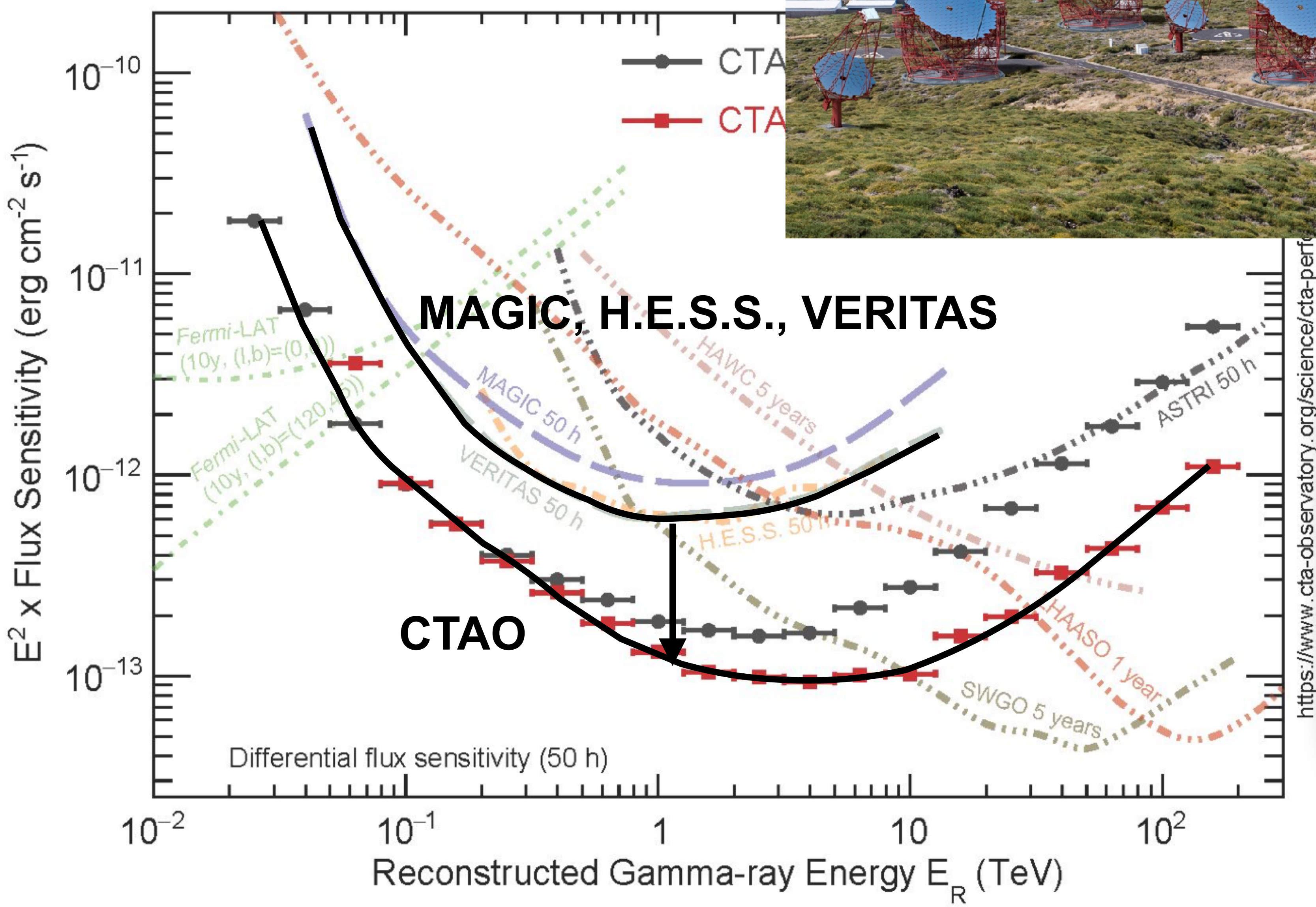
New experiments are around the corner: planning or construction phase



The next generation: CTAO & SWGO

IACTs

H.E.S.S., MAGIC, VERITAS → CTAO



note the different telescope sizes!

Two sites in La Palma and Chile for full sky coverage

Proposal-driven observatory

Wider energy coverage, better angular resolution, larger field of view

Order of magnitude increase in sensitivity!

H.E.S.S.

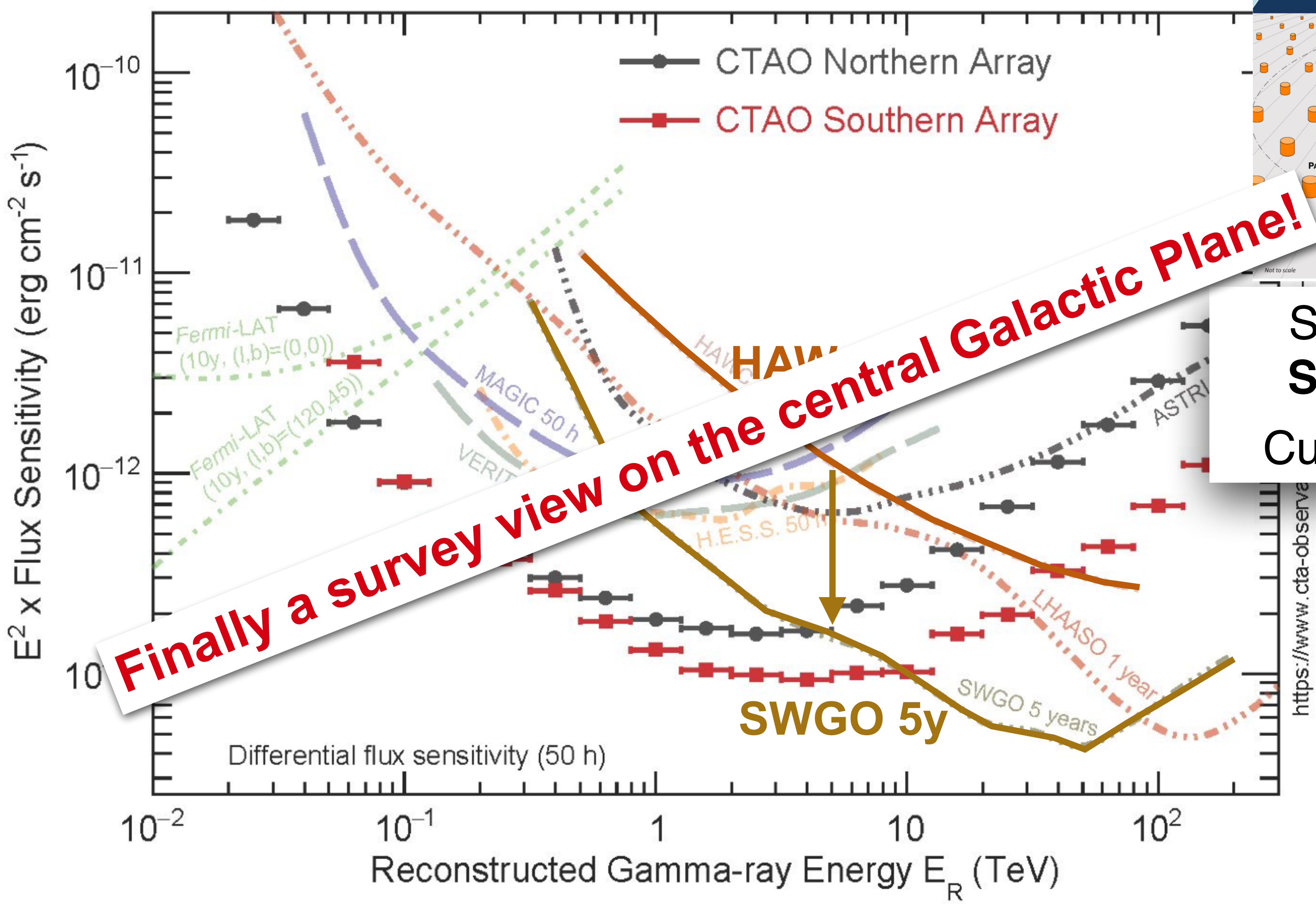
CTAO Cherenkov Telescope Array Observatory

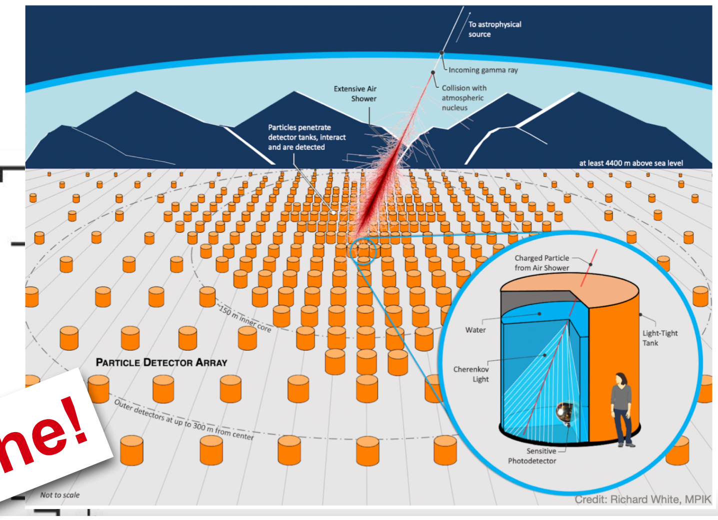
Universität Potsdam

The next generation: CTAO & SWGO

PDAs

HAWC → SWGO





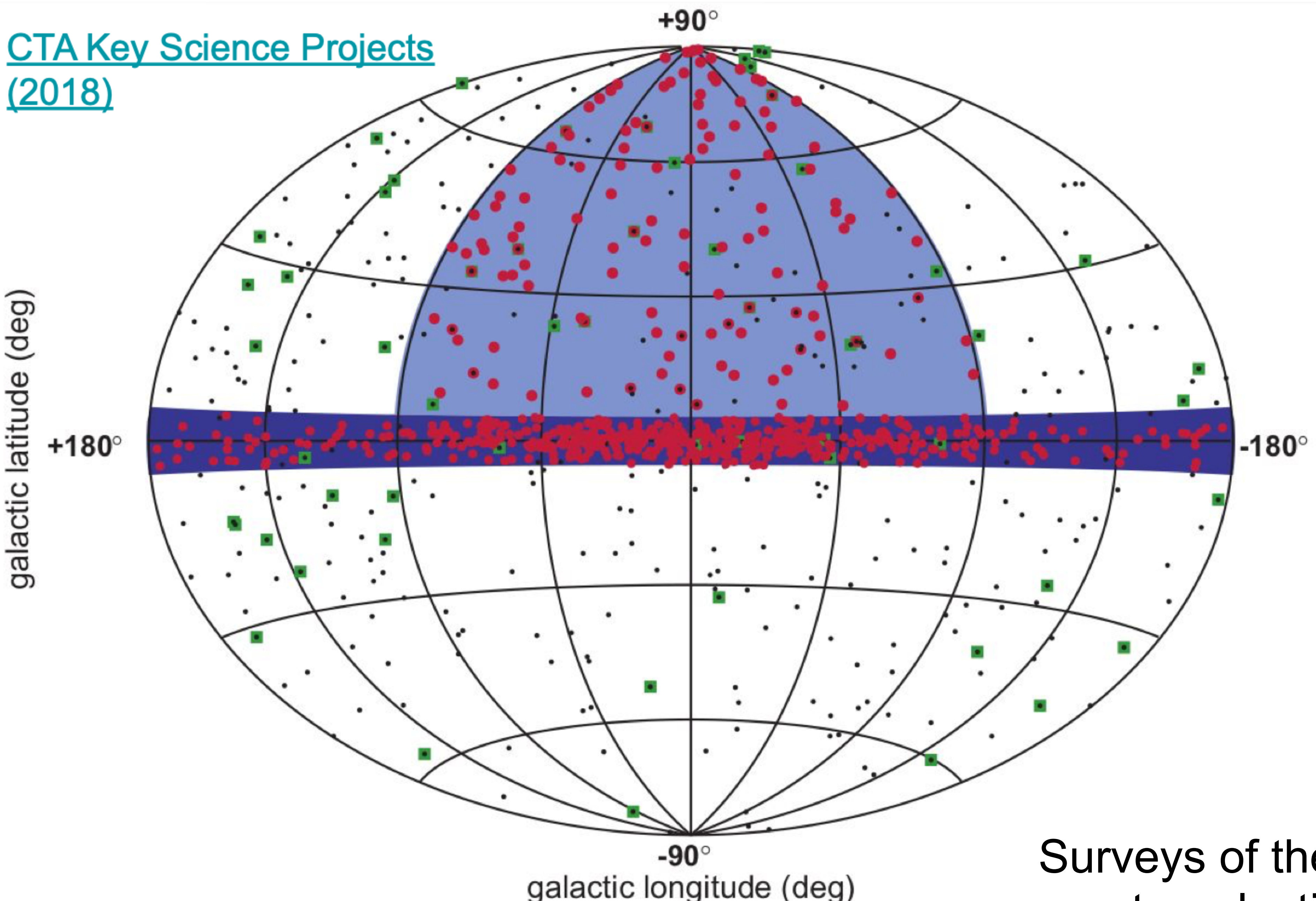
Site in the Andes in the **Southern hemisphere**

Currently in design phase

Order of magnitude increase in sensitivity!

CTAO: the Key-Science-Project Surveys

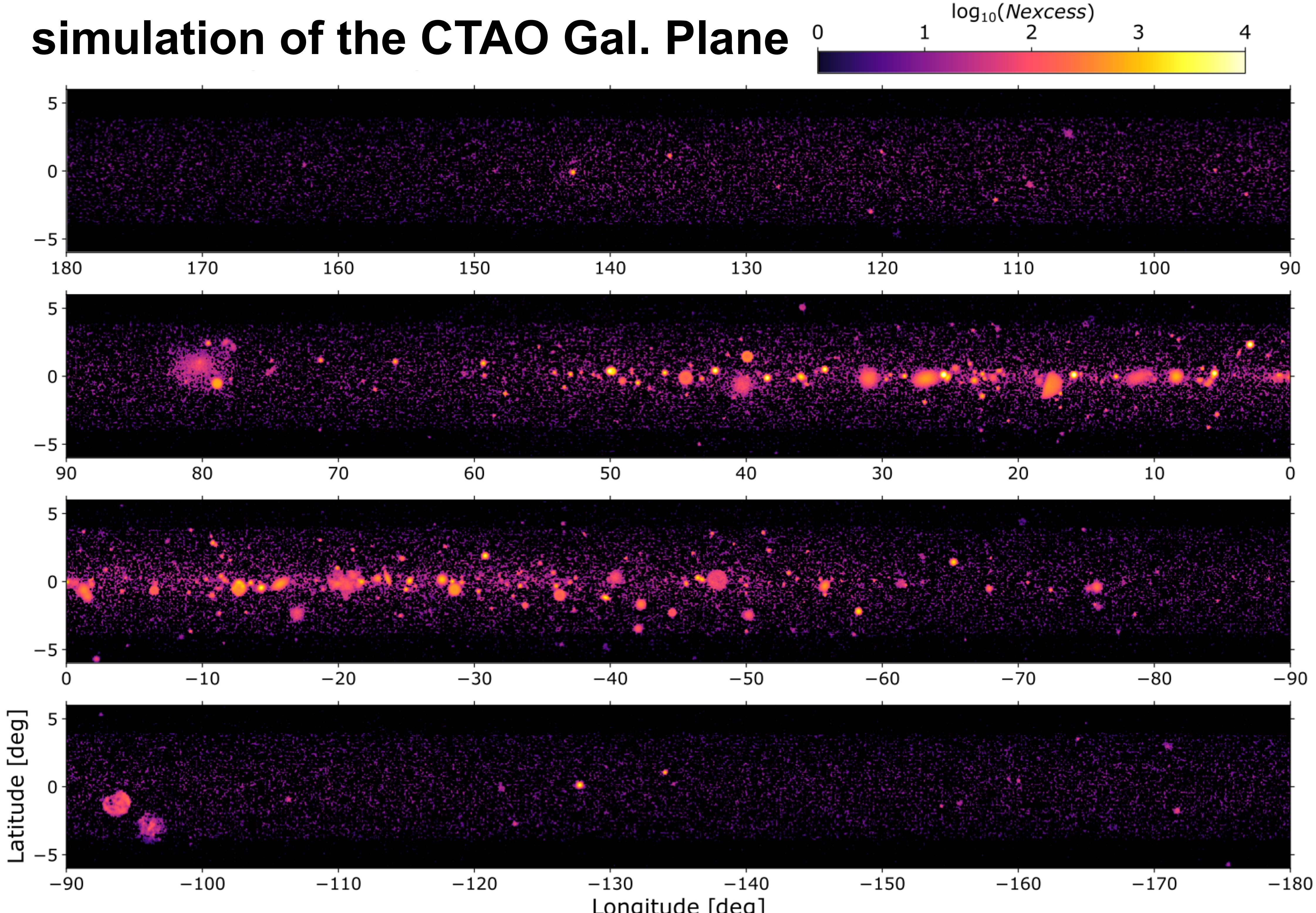
CTA Key Science Projects (2018)



Surveys of the Galactic and extragalactic (25%) sky

CTA Galactic Plane Survey: Performance Study

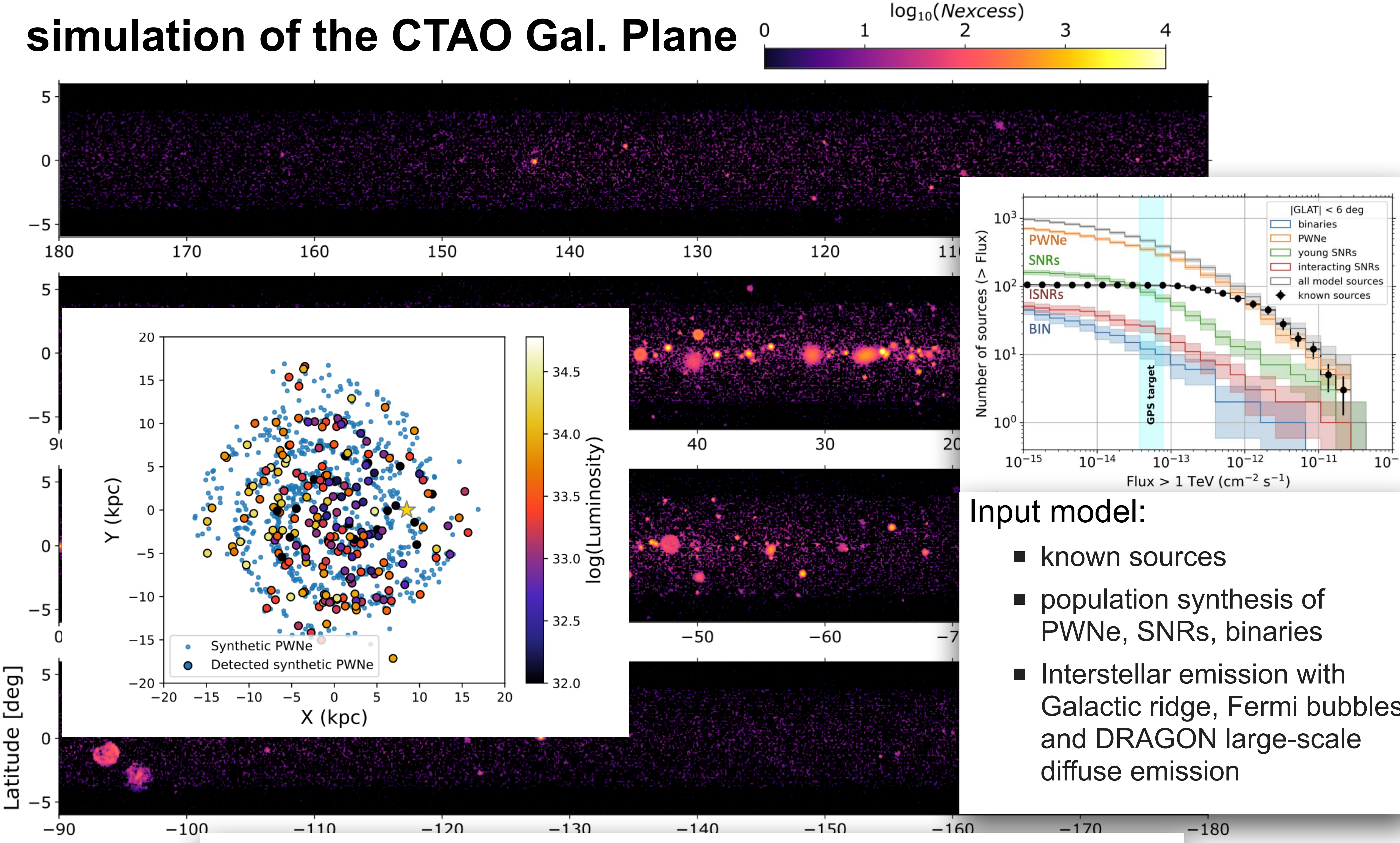
simulation of the CTAO Gal. Plane



CTA Consortium 2024

CTA Galactic Plane Survey: Performance Study

simulation of the CTAO Gal. Plane

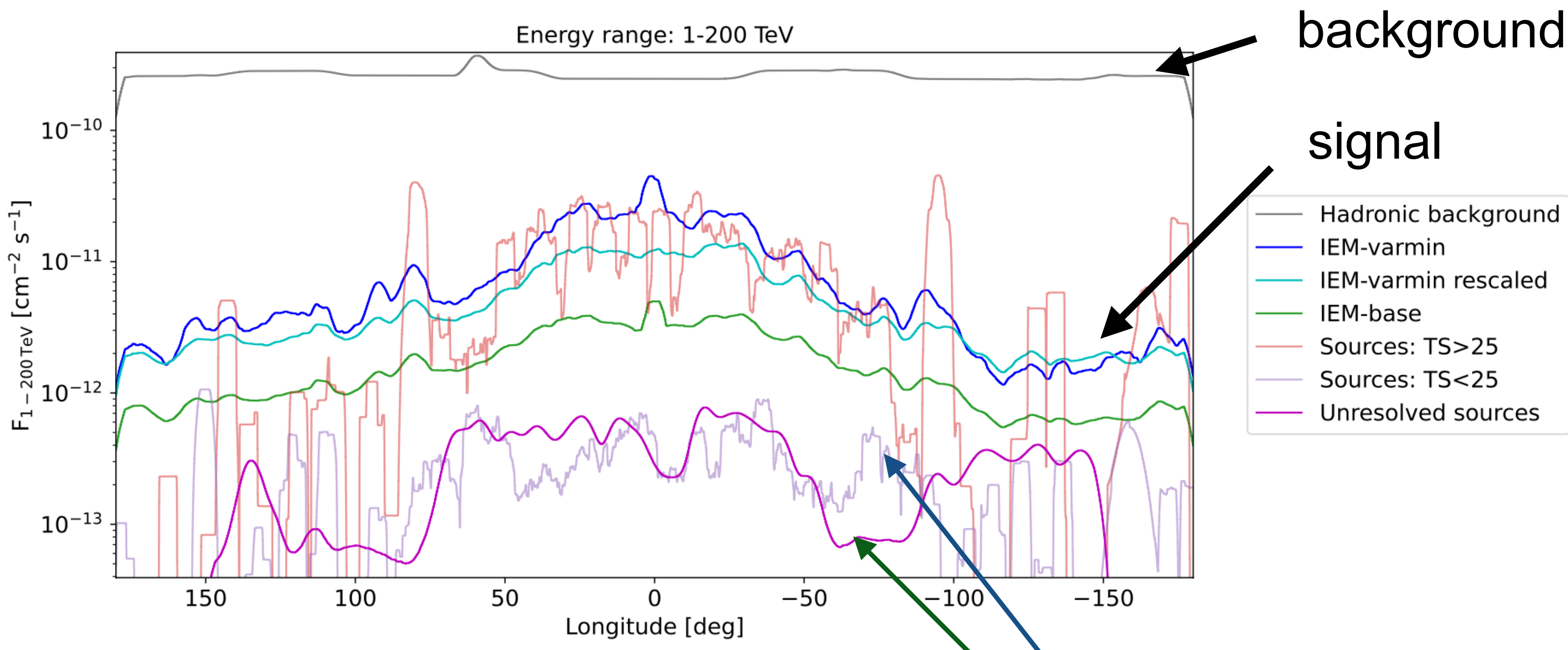


Input model:

- known sources
- population synthesis of PWNe, SNRs, binaries
- Interstellar emission with Galactic ridge, Fermi bubbles and DRAGON large-scale diffuse emission

Source count increase by factor of 5-7, probing the entire Milky Way

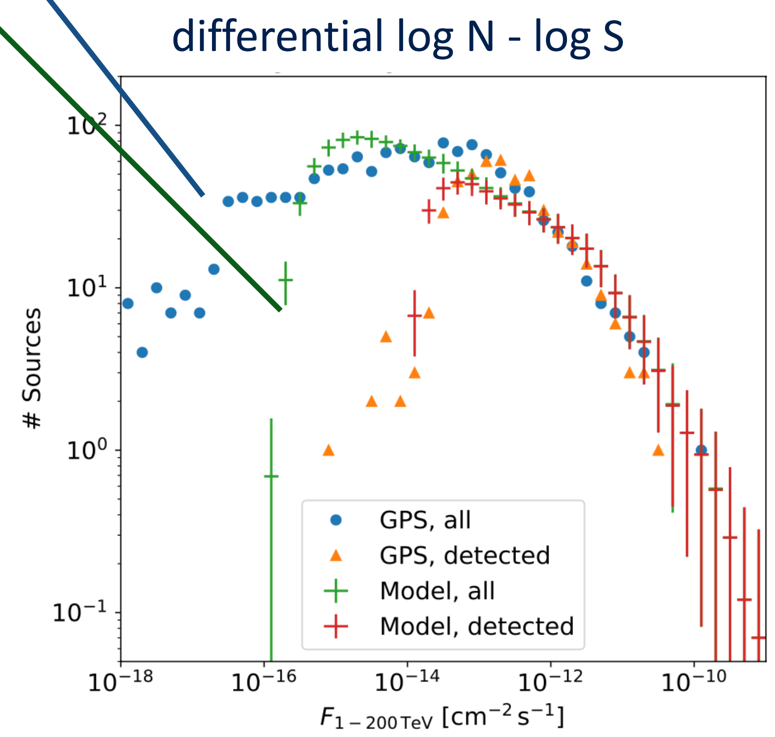
Large-Scale Diffuse Emission in the CTAO Era



Possibility to significantly detect large-scale diffuse emission

Background estimation facilitated by larger fields of view

Contribution of unresolved sources can be estimated by deriving population properties



Conclusion

- Gamma-rays at VHE and UHE are a crucial probe to study cosmic-ray accelerators to highest energies
- Current generation of ground-based detectors have shown that there is an **incredible diverseness and richness in the gamma-ray sky**
- Discovery space at the sensitivity limit, new detections, population studies, in-depth understanding of our Milky Way - with the **tenfold sensitivity of next-generation instruments** in reach
- **Coverage of both hemispheres** guarantees extragalactic as well as Galactic science to be ideally explored
- **Strong complementarity** between particle detector arrays and imaging atmospheric Cherenkov telescopes

Thank you!