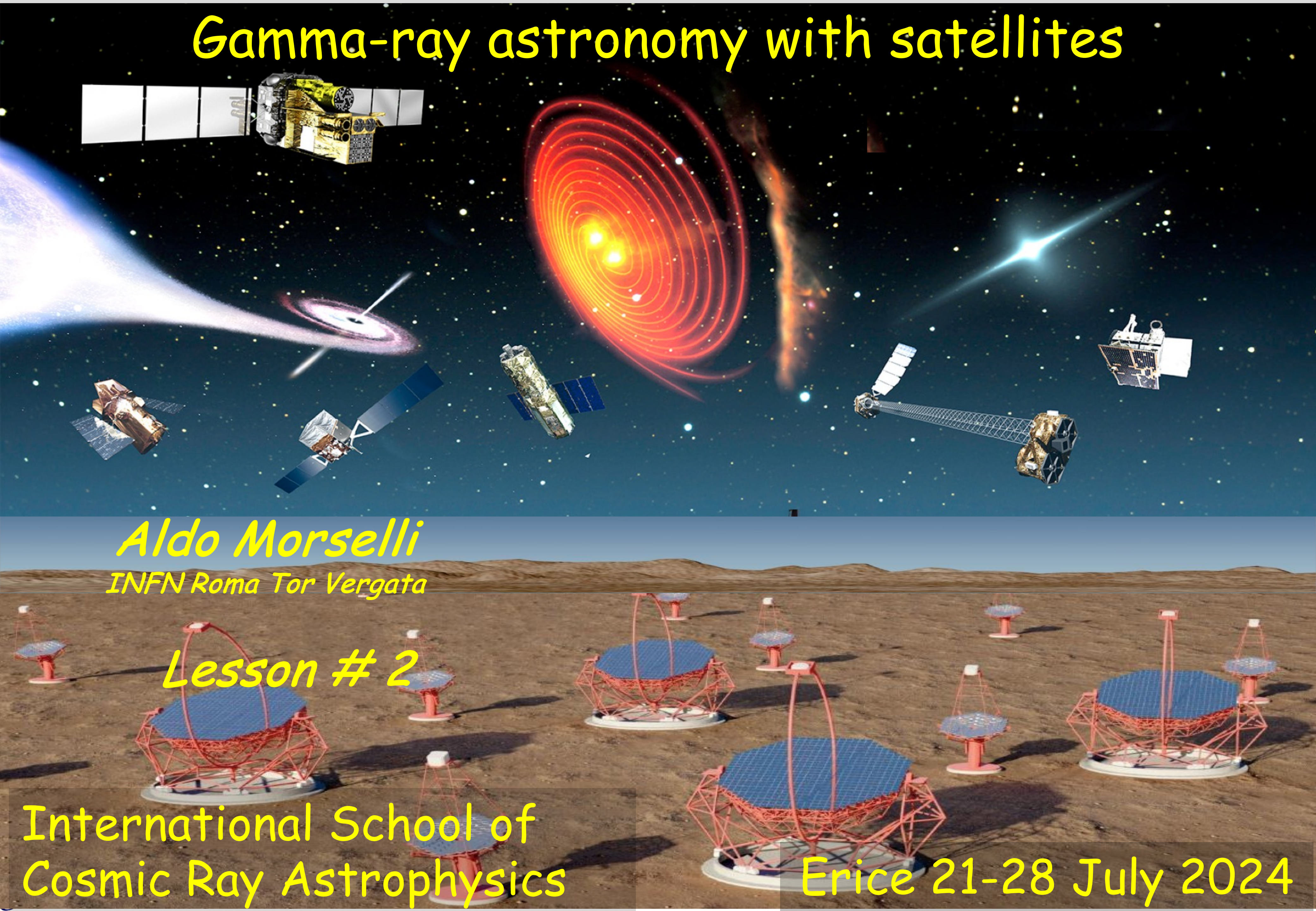
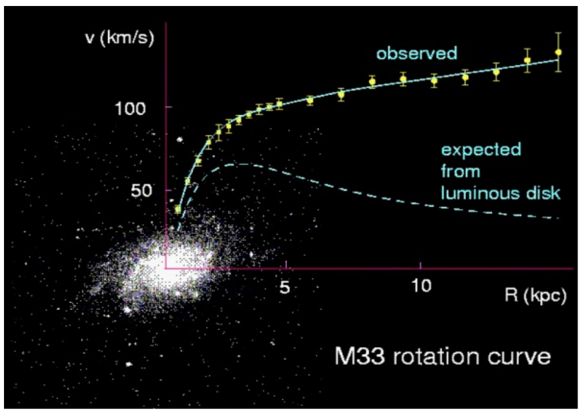

Gamma-ray astronomy with satellites
Aldo Morselli
INFN Roma Tor Vergata
Lesson # 2
International School of
Cosmic Ray Astrophysics
Erice 21-28 July 2024

Dark Matter EVIDENCE

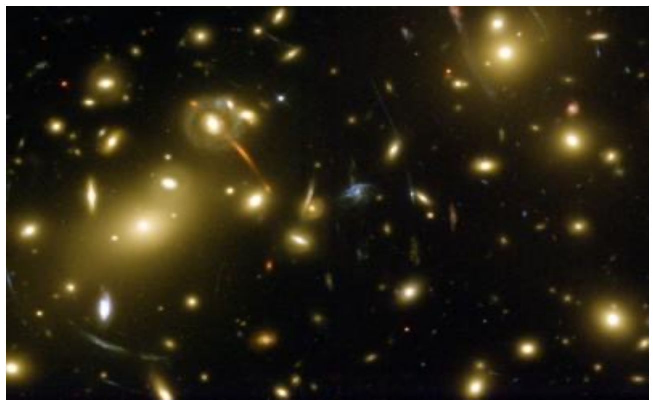
In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies.

Since then, even more evidence:

Rotation curves of galaxies

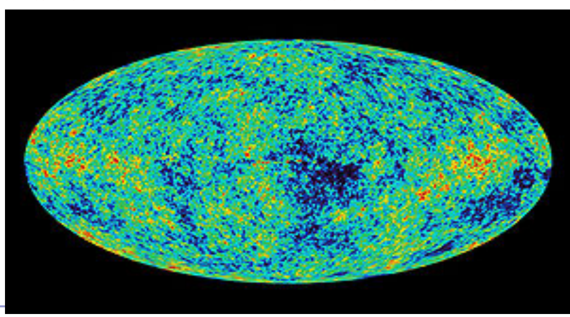


Gravitational lensing

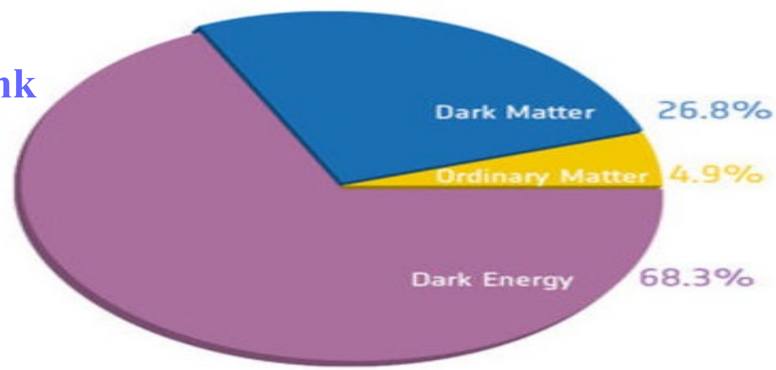


Bullet cluster

Structure formation as deduced from CMB



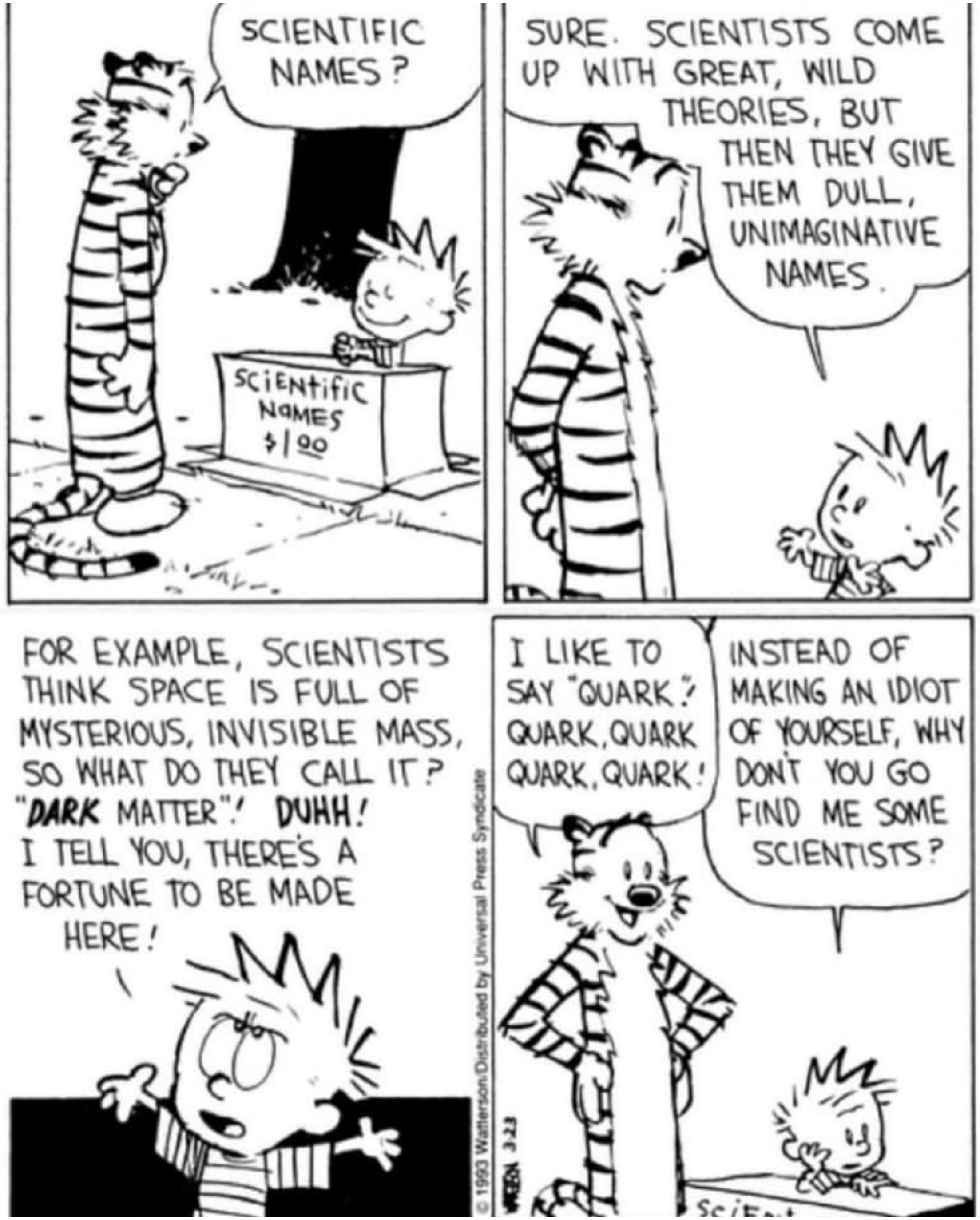
Data by Plank imply:



$\Omega_{DM} \approx 26.8\%$

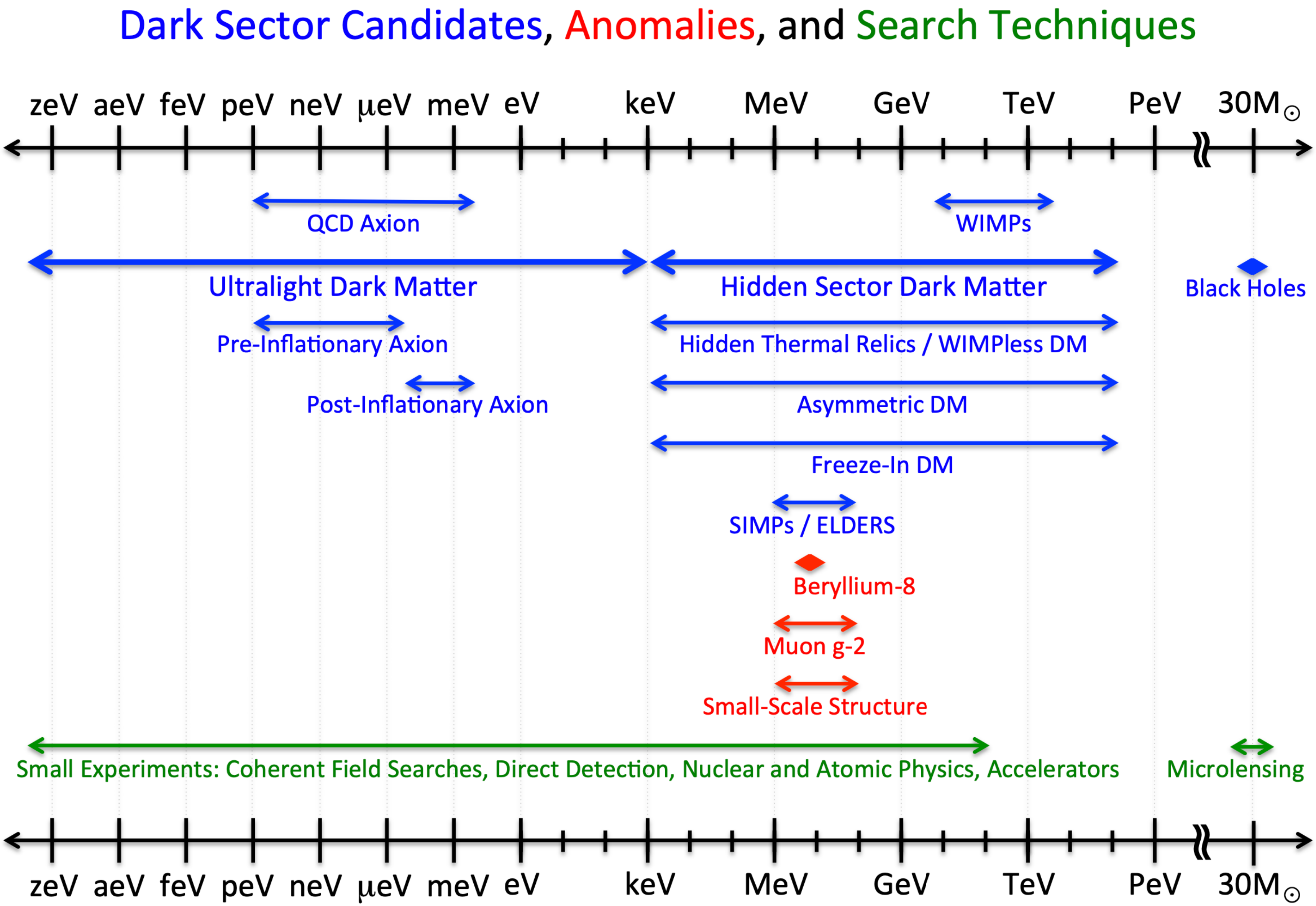
$\Omega_M \approx 4.9\%$

Dark Matter


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1 00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
© 1993 Watterson/Distributed by Universal Press Syndicate
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

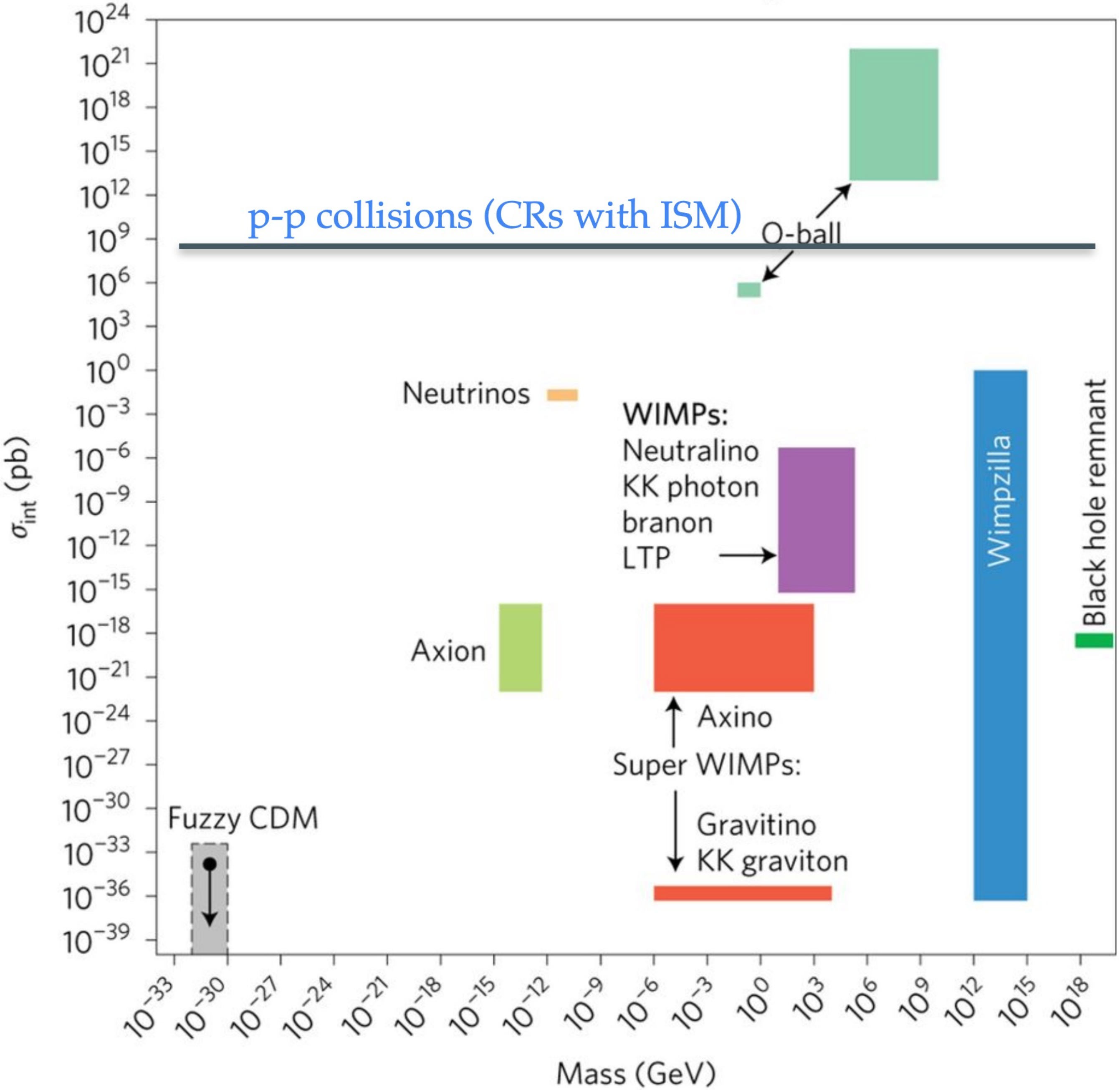
What is dark matter made of ?

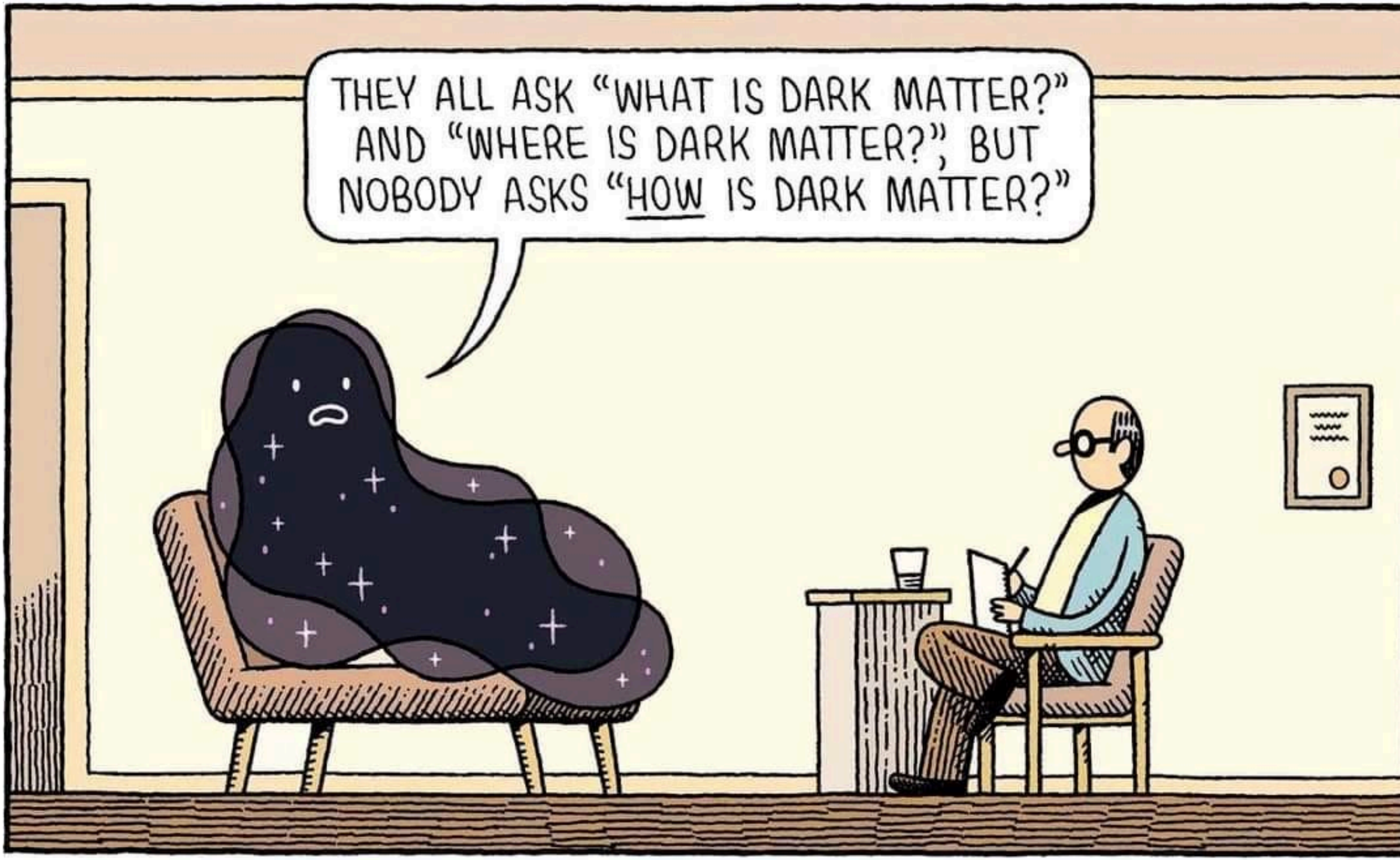
Dark Sector Candidates, Anomalies, and Search Techniques



New Ideas in Dark Matter 2017 : Community Report arXiv:1707.04591

Some particle dark matter candidates

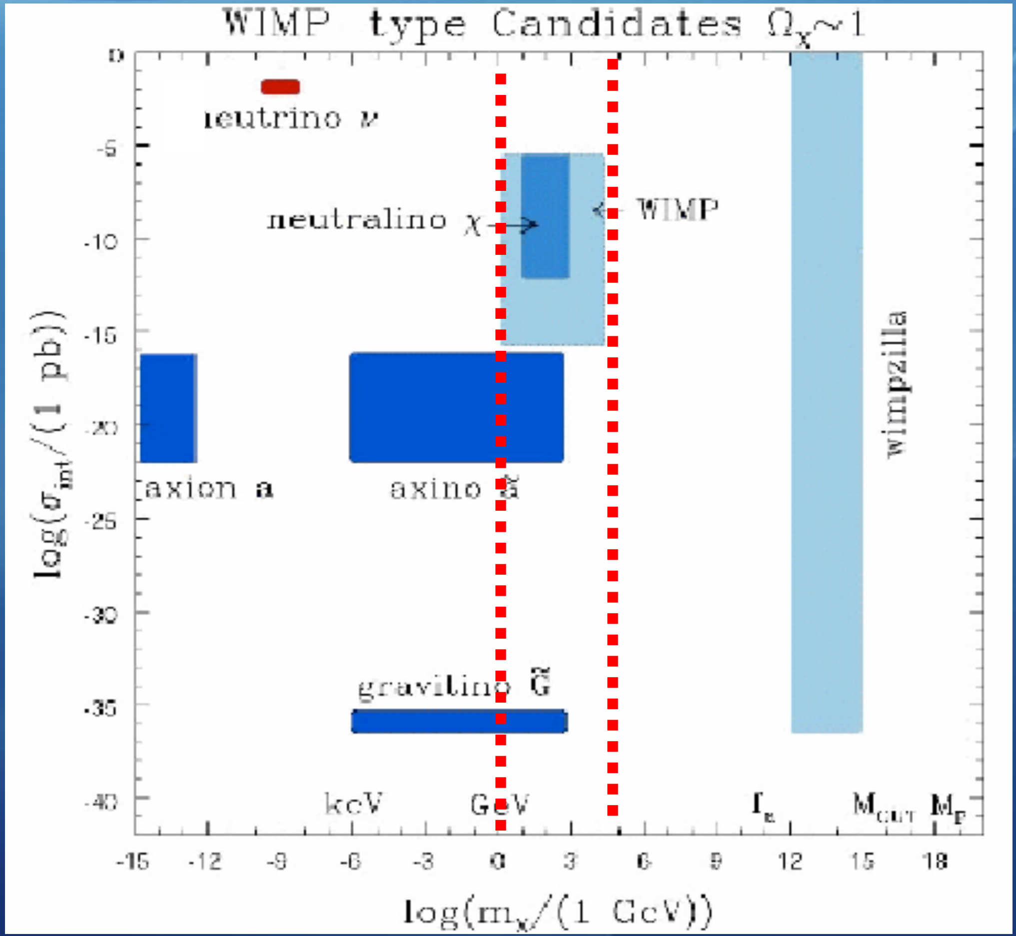




TOM GAULD for NEW SCIENTIST

Dark Matter Candidates

- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



Dark Matter Candidates

- Kaluza-Klein DM inUED
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- **NEUTRALINO**
- Messenger States in GMSB
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- Chaplygin Gas
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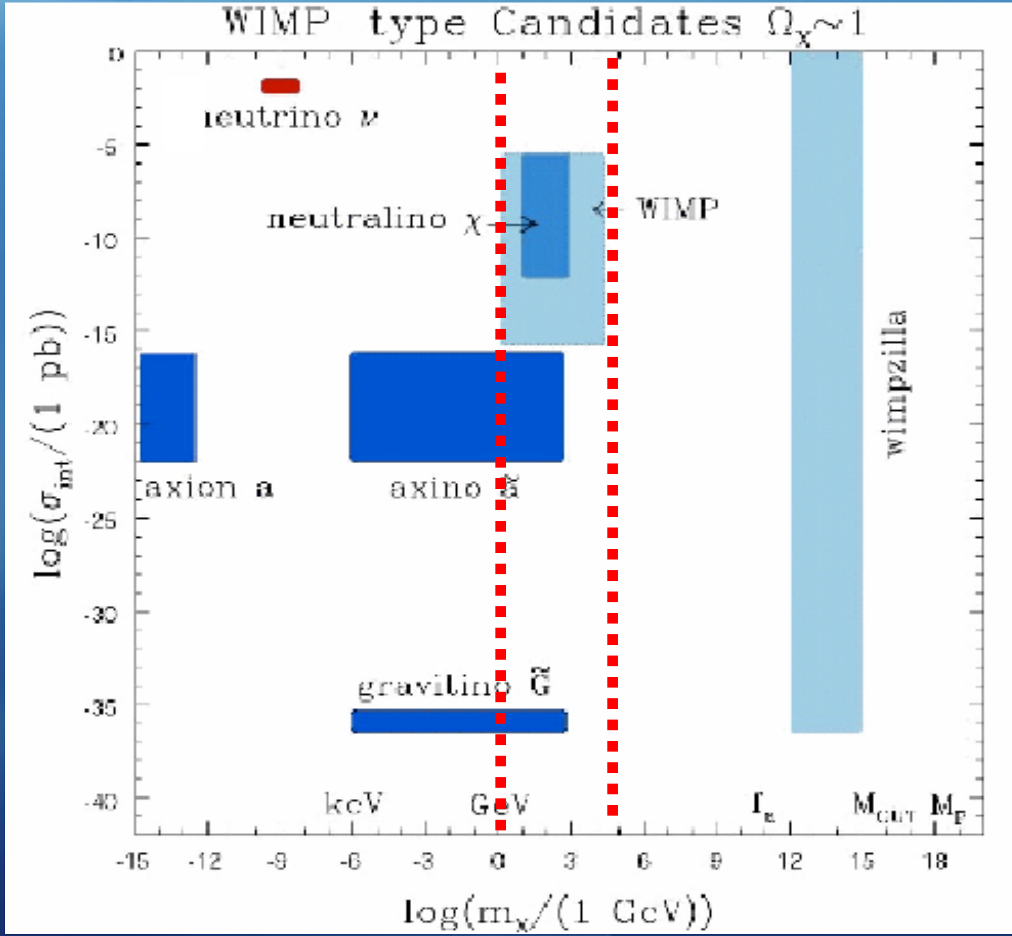



THIS IS WHERE YOU LOST YOUR WALLET?
NO, I LOST IT IN THE PARK. BUT THIS IS WHERE THE LIGHT IS.

Dark Matter really exist ?

astro:ph/0608407

color image from the Magellan images
of the merging cluster 1E0657−558

Chandra image of the cluster

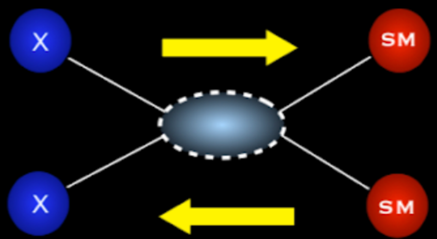
200 kpc

Due to the collision of two clusters, the dissipationless stellar component and the fluid-likeX-ray emitting plasma are spatially segregated

WIMPs

By far the most studied class of dark matter candidates.

The WIMP paradigm is based on a simple yet powerful idea:



$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

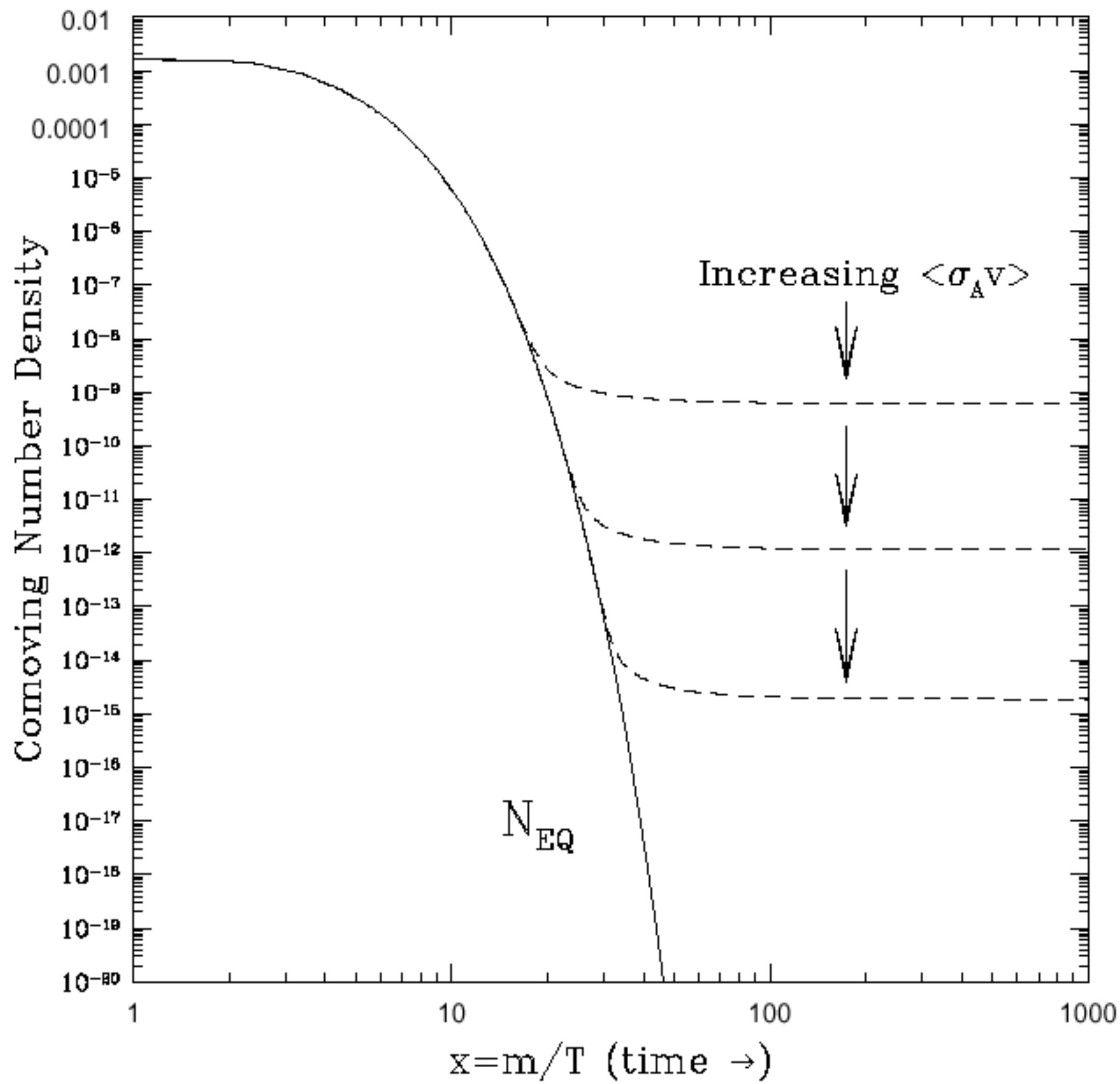
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

'WIMP miracle': new physics at ~1TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

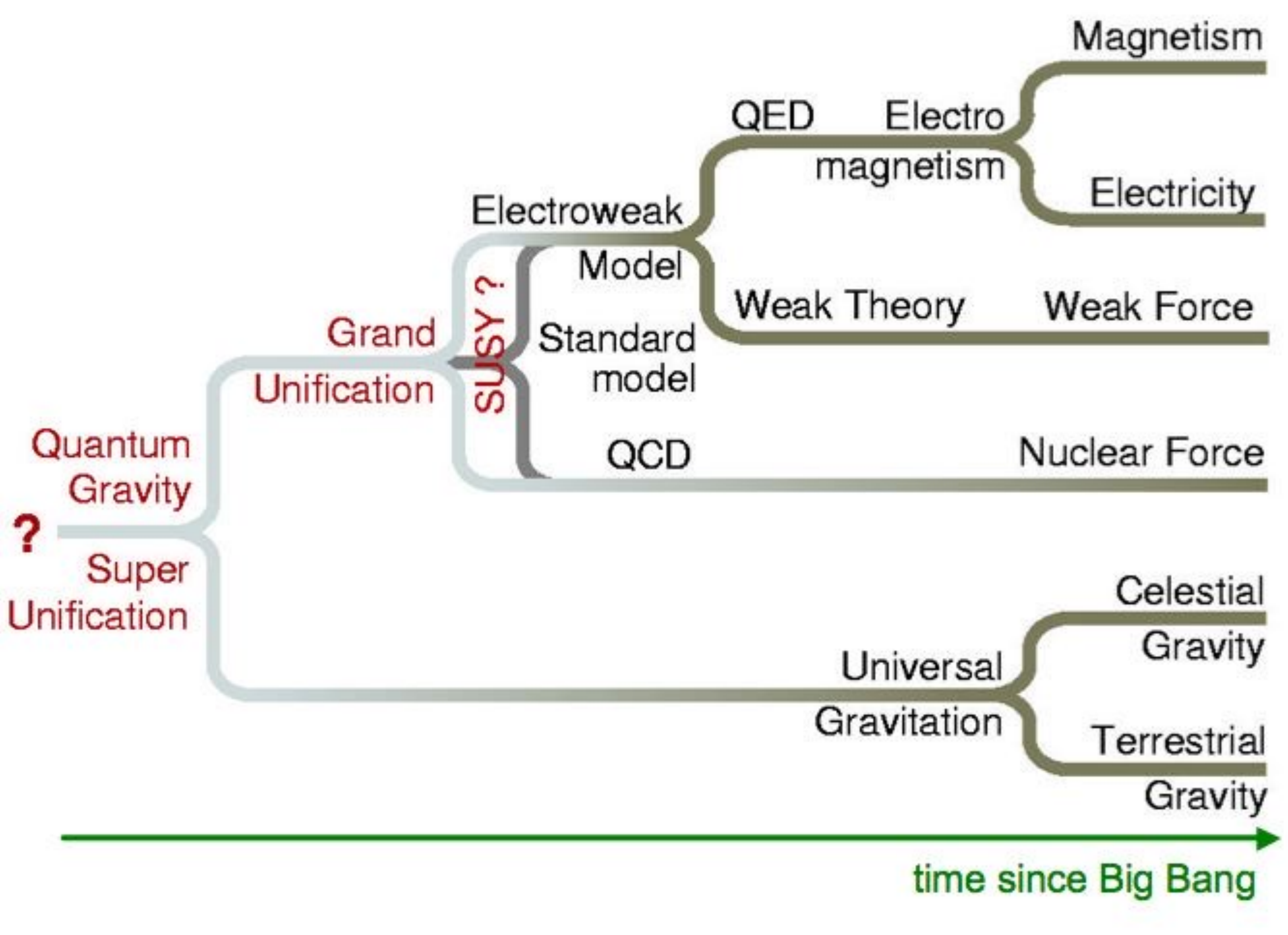
Termal relics

Freeze out at $\Omega_\chi h^2 = \dfrac{m_\chi n_\chi}{\rho_c}$

$$\approx \frac{3\ 10^{-27}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}}{\sigma_a v}$$



Particle Physics after Big Bang



Supersymmetry

Particle ⟷ Sparticle

For unbroken supersymmetry they shoul be degenerate in mass

Sparticle have not be found at accelerators so far

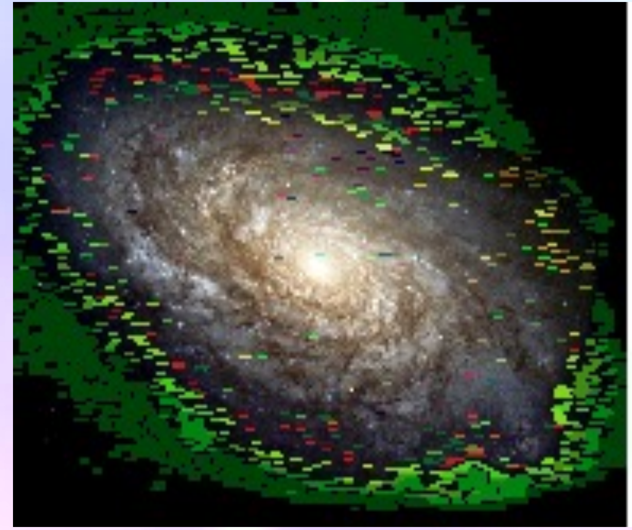
⇓

Supersymmetry is broken

Supersymmetry breaking schemes:

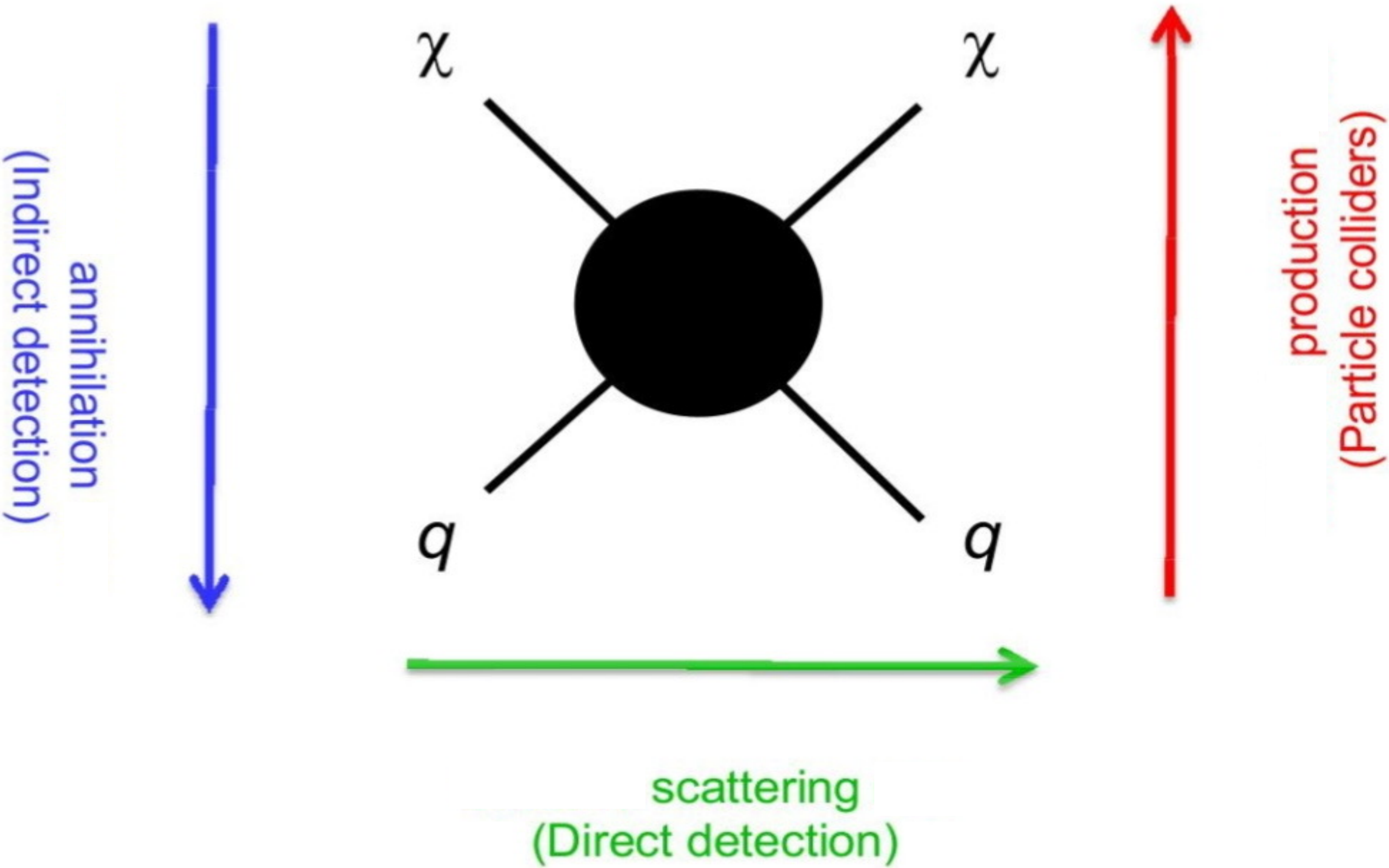
1) gravity-mediated scenarios
2) Gauge mediated scenarios
3) Anomaly mediated scenarios

Neutralino WIMPs

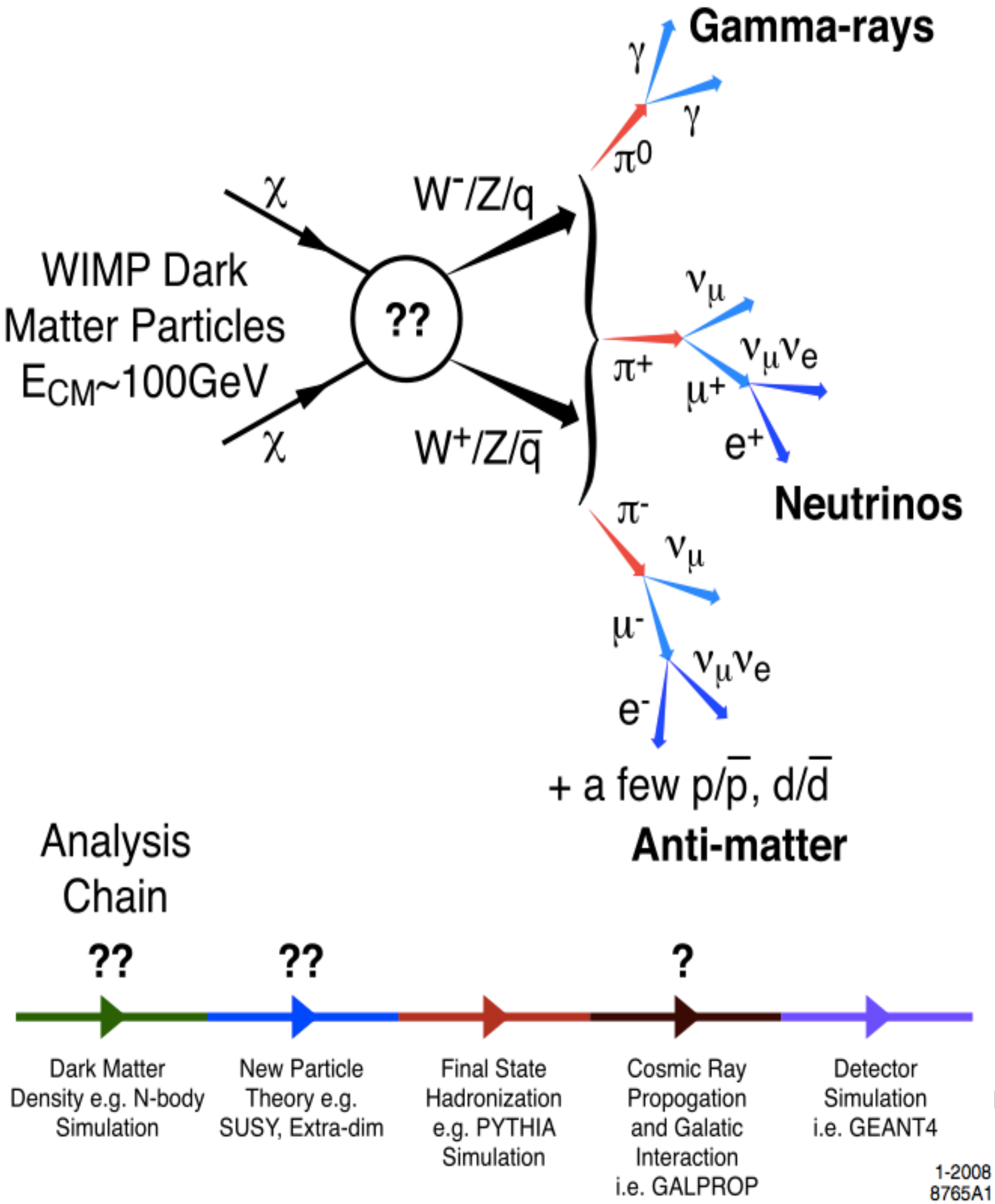


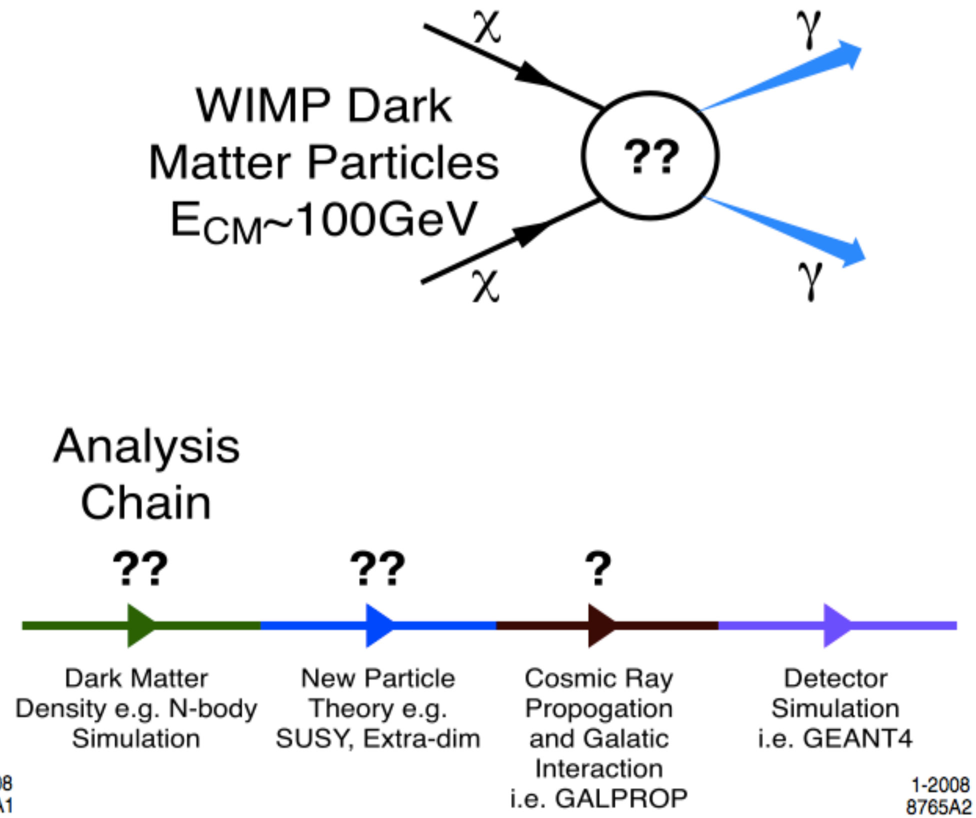
Assume χ present in the galactic halo

- χ is its own antiparticle => can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p --> p + X)
- So, any extra contribution from exotic sources (χ χ annihilation) is an interesting signature
- ie: χ χ --> p + X
- Produced from (e. g.) χ χ --> q / g / gauge boson / Higgs boson and subsequent decay and/ or hadronisation.


χ
χ
q
q
annihilation
(Indirect detection)
production
(Particle colliders)
scattering
(Direct detection)

Annihilation channels





Signal rate from WIMP annihilation

gamma-ray flux from WIMP annihilation

$$\phi(E,\Delta\Omega) \propto \left(\frac{\sigma v}{m_\chi^2}\right) \int_{l.o.s} \int_{\Delta\Omega} \rho^2(l)\,dl\,d\Omega)$$

governed by particle physics (supersymmetric parameters .. etc)

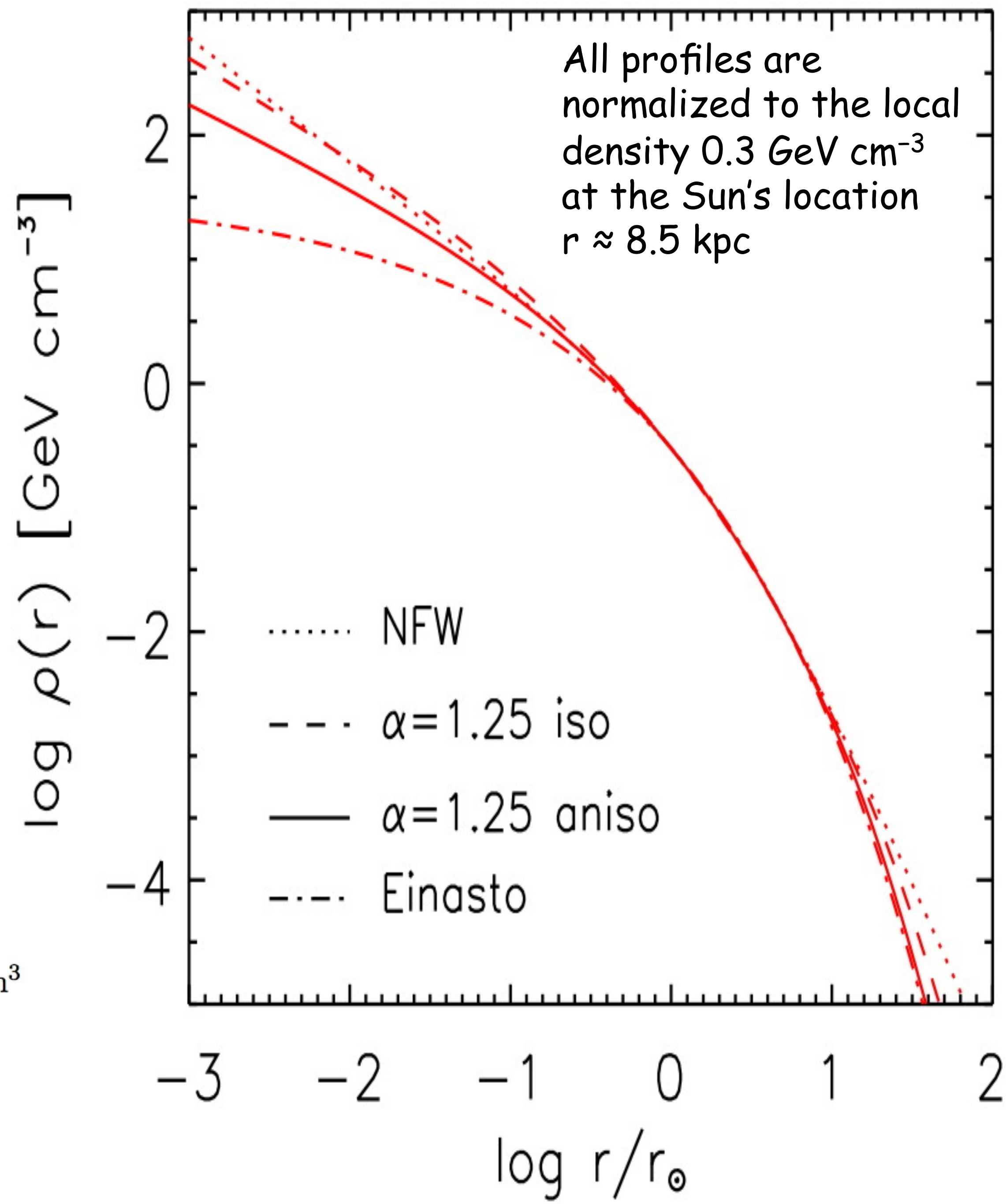
J(φ): governed by halo distribution

Milky Way Dark Matter Profiles

$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

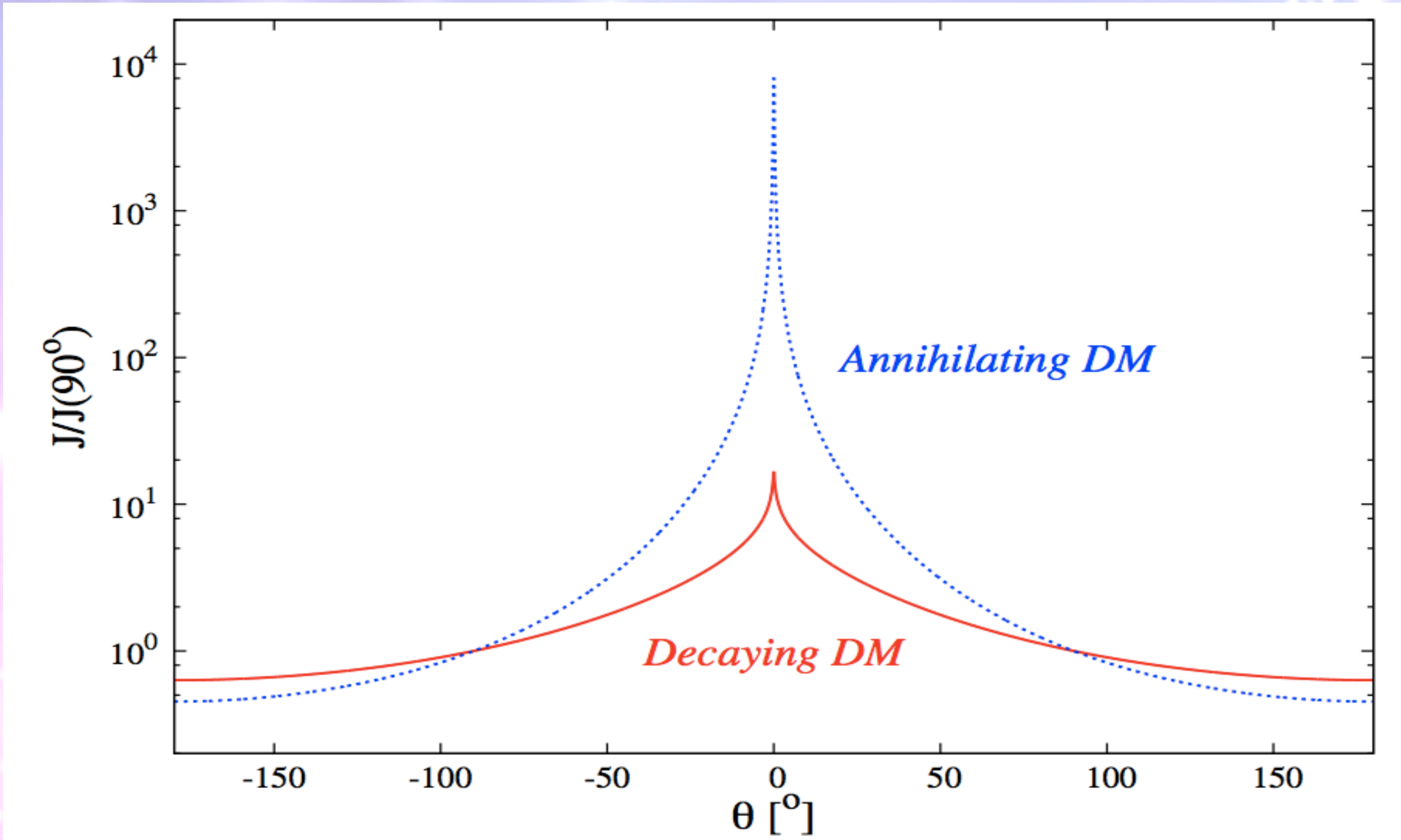
Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

Einasto | $\alpha = 0.17$ $r_s = 20\,\text{kpc}$ $\rho_s = 0.06\,\text{GeV/cm}^3$



A.Lapi et al. arXiv:0912.1766

Different spatial behaviour for decaying or annihilating dark matter



The angular profile of the gamma-ray signal is shown, as function of the angle θ to the centre of the galaxy for a Navarro-Frenk-White (NFW) halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line

In the minimal supersymmetric extension of the Standard Model four neutral spin-1/2 Majorana particles are introduced:

- the partners of the neutral gauge bosons **B**, **W**
- the neutral CP-even higgsinos $\mathbf{H^0{}_1}$, $\mathbf{H^0{}_2}$.

Diagonalizing the corresponding mass matrix, four mass eigenstates are obtained.

The lightest of these, **χ** , is commonly referred as the neutralino.

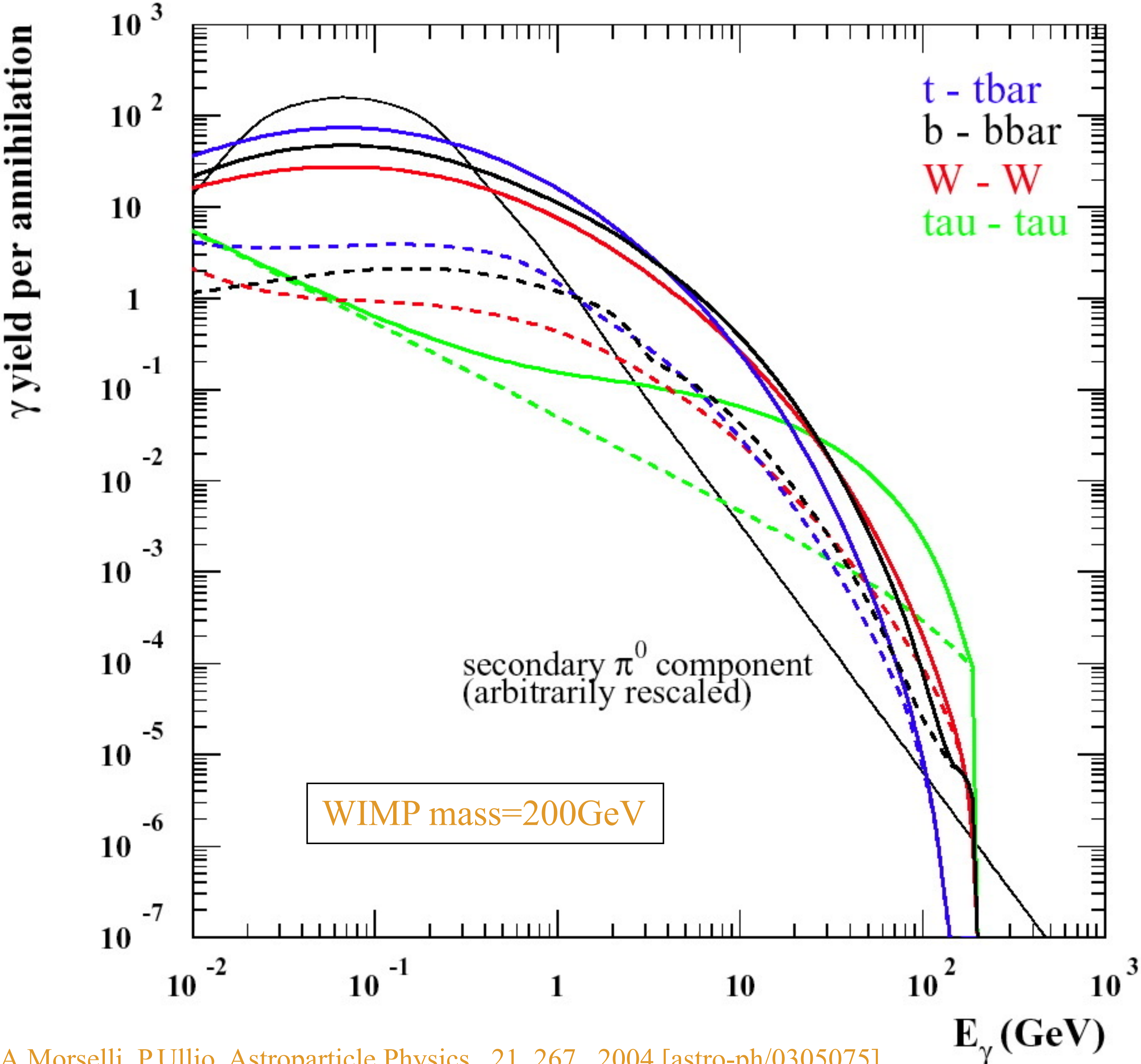
$$\tilde{\chi}^0 = N_1\tilde{B} + N_2\tilde{W}^3 + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0$$

It is useful to introduce the gaugino fraction Z_g defined as:

$$Z_g = |N_1|^2 + |N_2|^2$$

and classify the neutralino as higgsino-like when $Z_g < 0.01$, mixed when $0.01 < Z_g < 0.99$ and gaugino like if $Z_g > 0.99$.

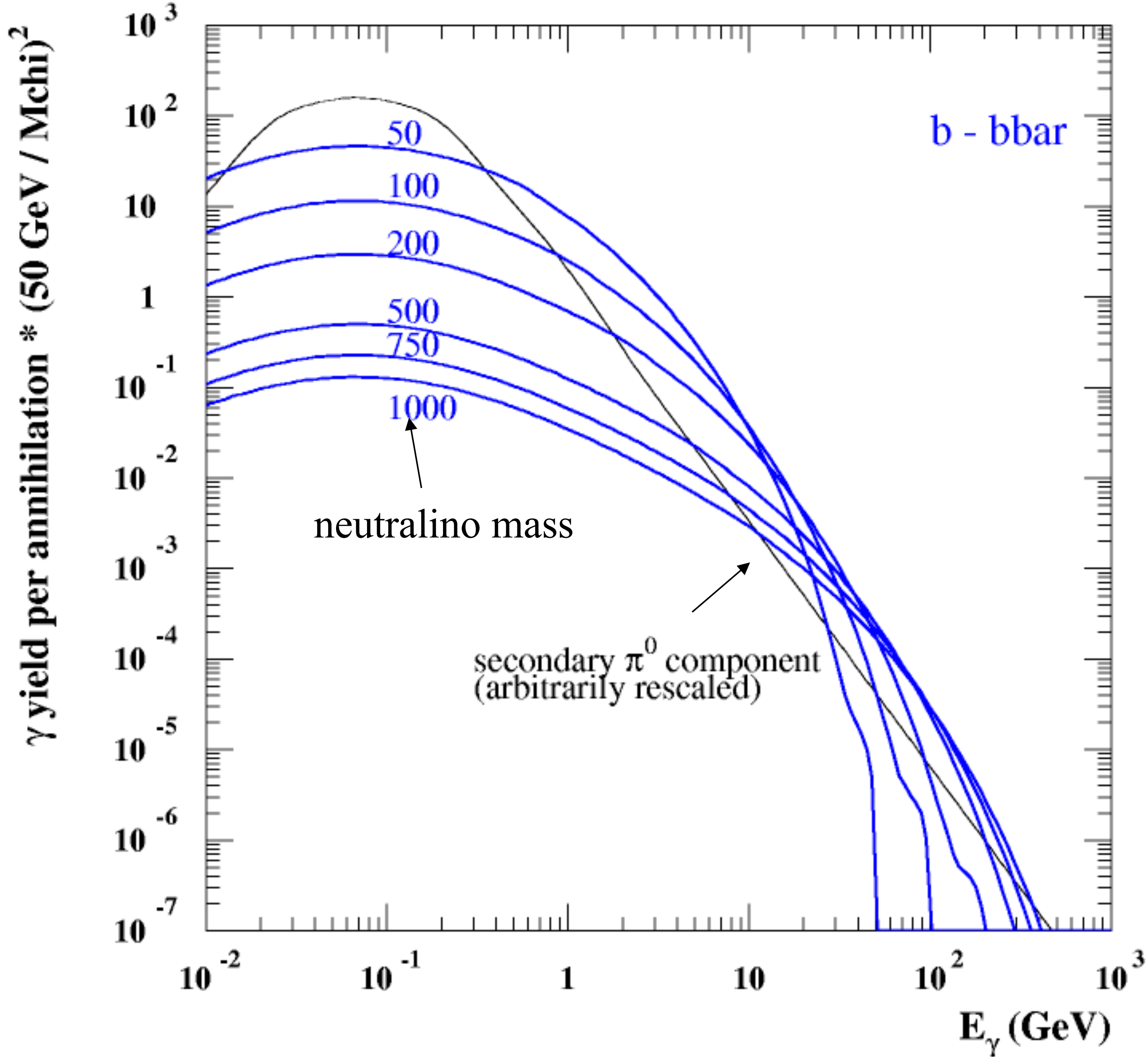
Differential yield for each annihilation channel



dashed lines are components not due to π^0 decay.

A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

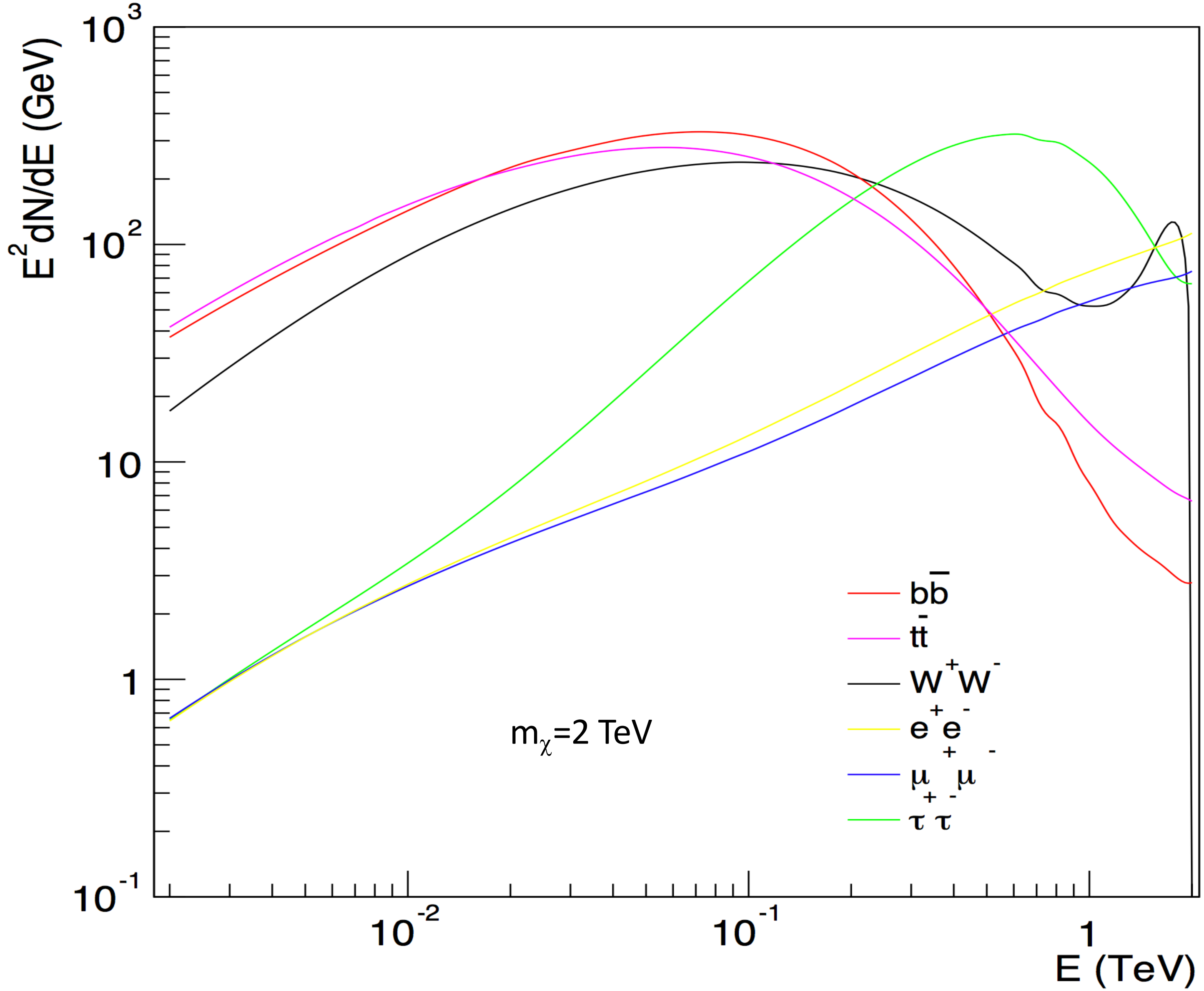
Differential yield
for b bar



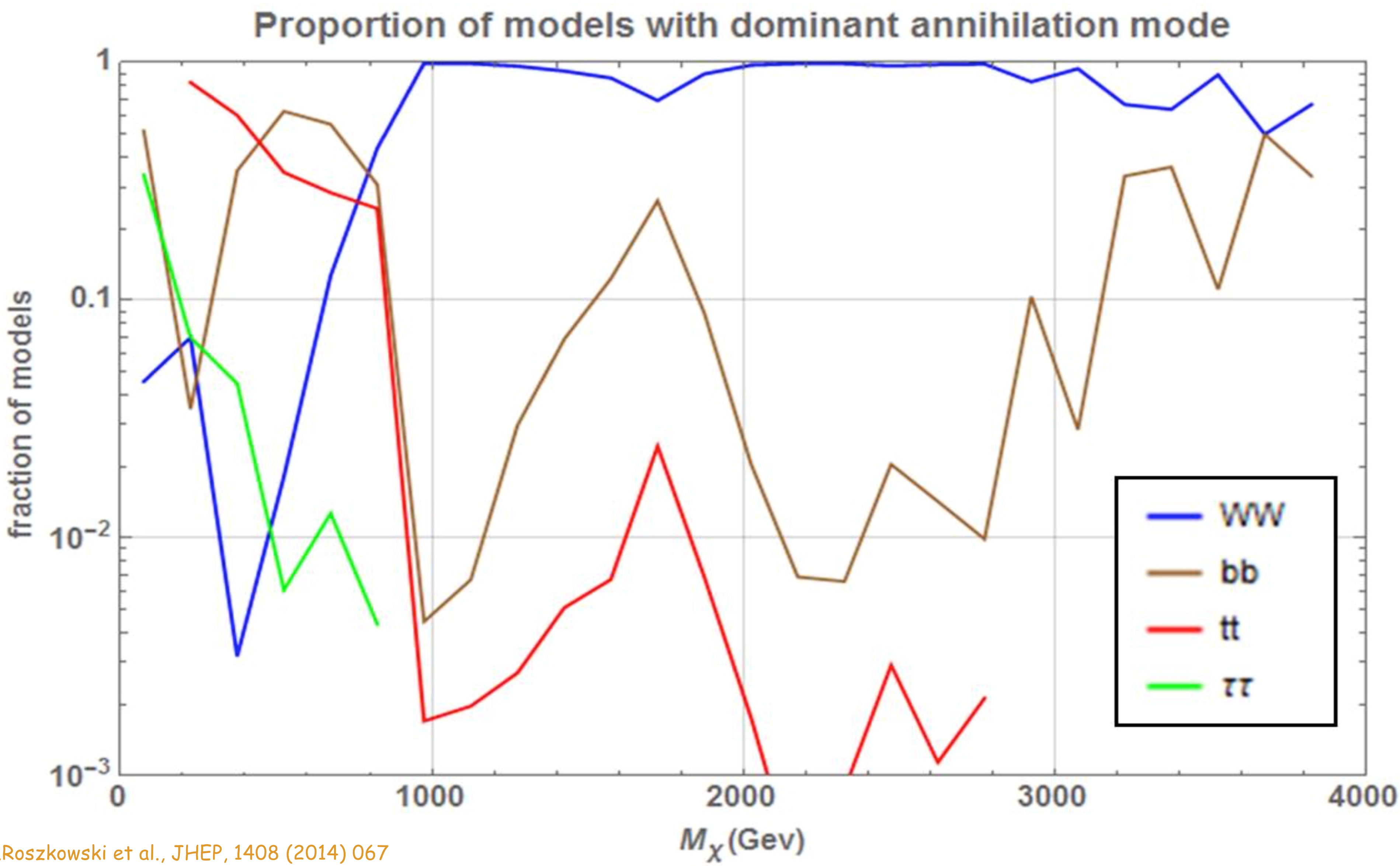
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267-285, 2004 [astro-ph/0305075]

Annihilation spectra for the continuum signal from the quark, lepton and gauge boson primary channels

The line-like feature expected from the virtual internal Bremsstrahlung process contribution is particularly prominent for the W^+W^- channel

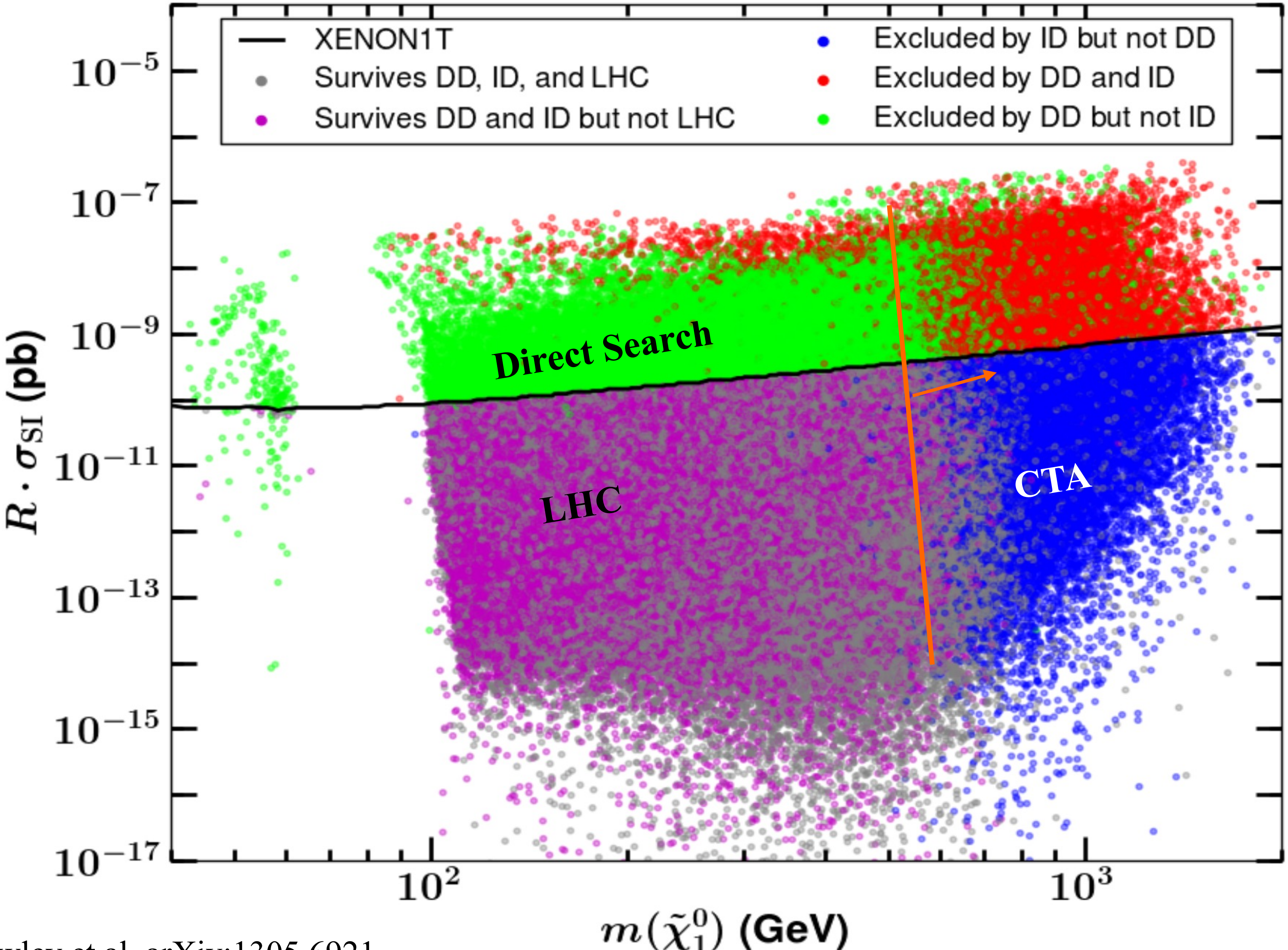


Which channel to choose?
Example: The dominant annihilation modes in the pMSSM scan



L.Roszkowski et al., JHEP, 1408 (2014) 067
[arXiv:1405.4289]

Complementarity and Searches for Dark Matter in the pMSSM



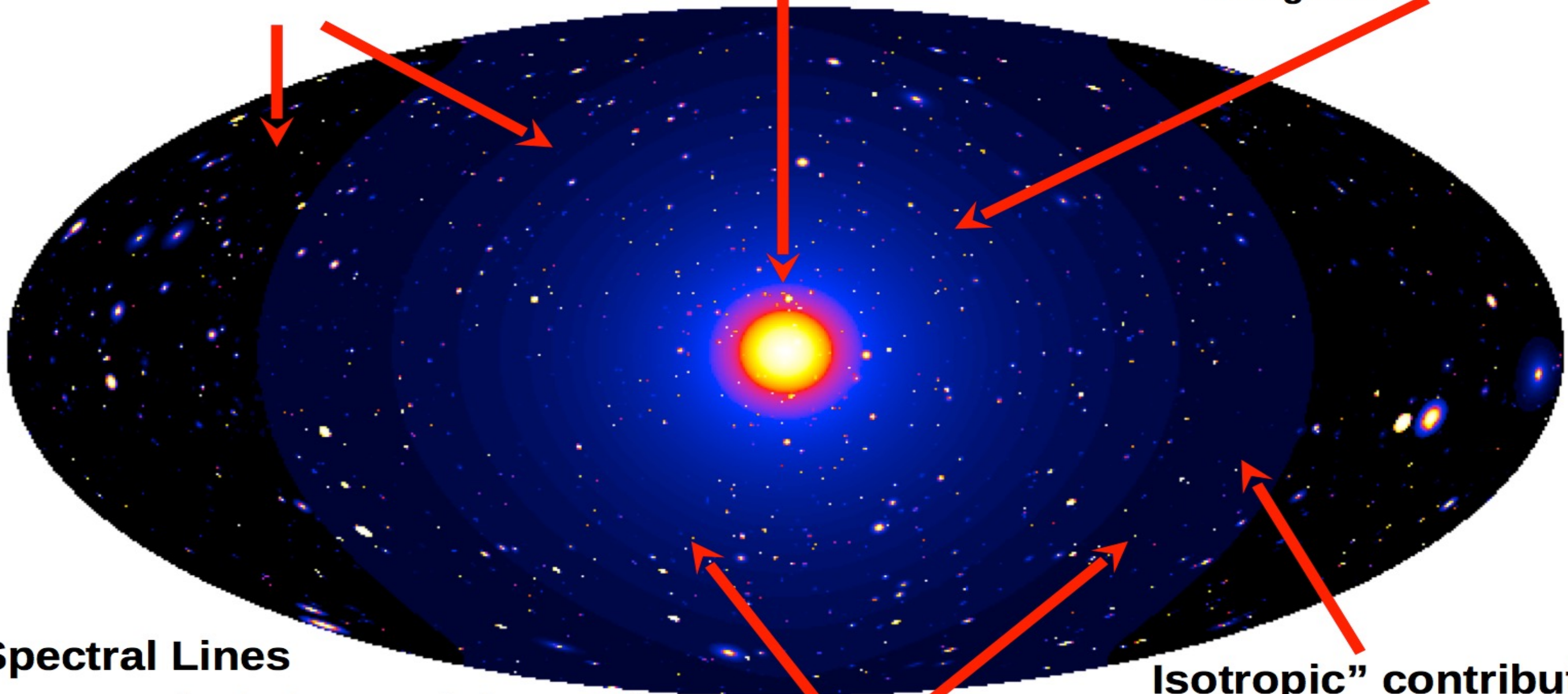
Cahill-Rowley et al. arXiv:1305.6921

Dark Matter Search: Targets and Strategies

Satellites
Low background and good source id, but low statistics

Galactic Center
Good Statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background



Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

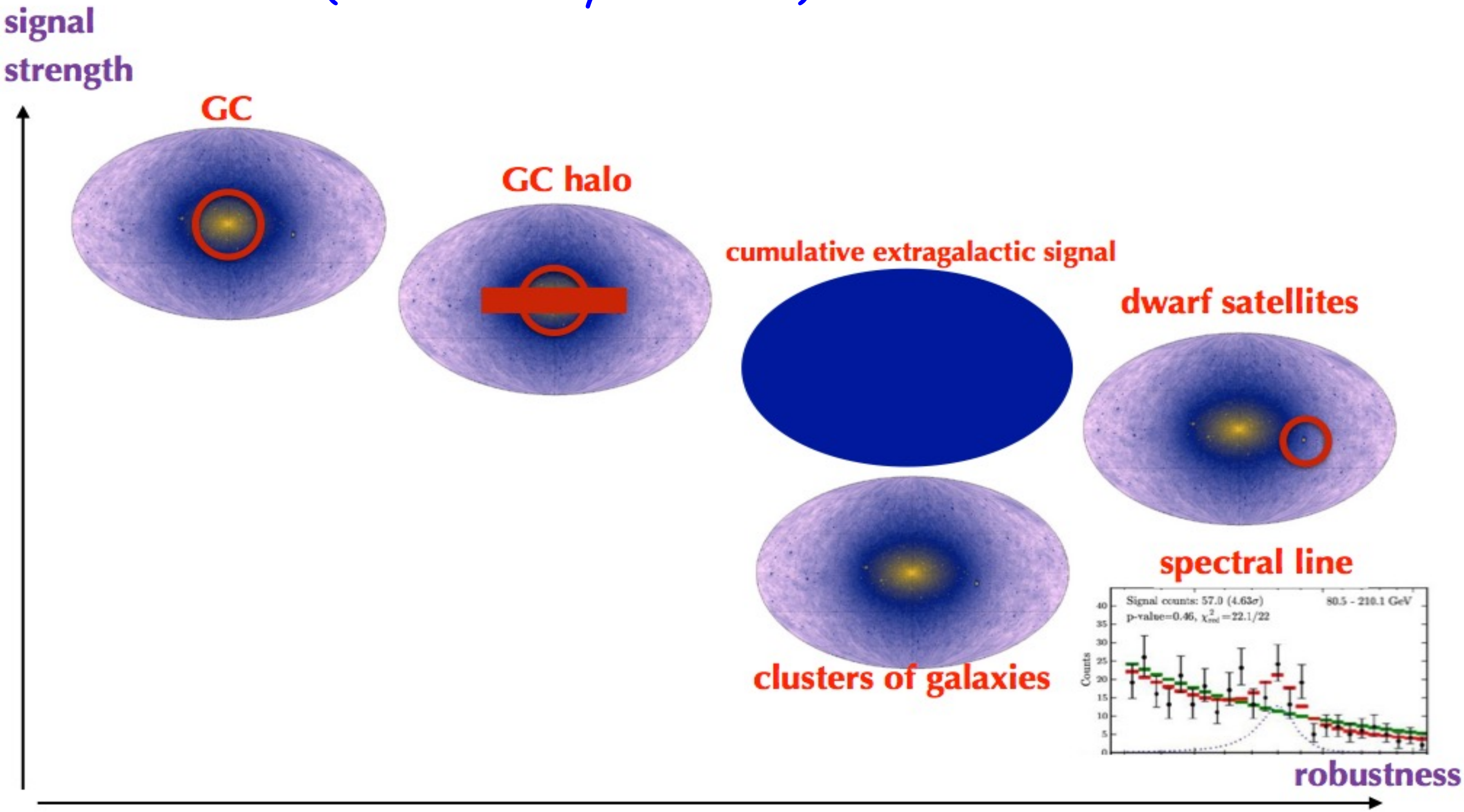
Galaxy Clusters
Low background, but low statistics

Isotropic" contributions
Large statistics, but astrophysics, galactic diffuse background

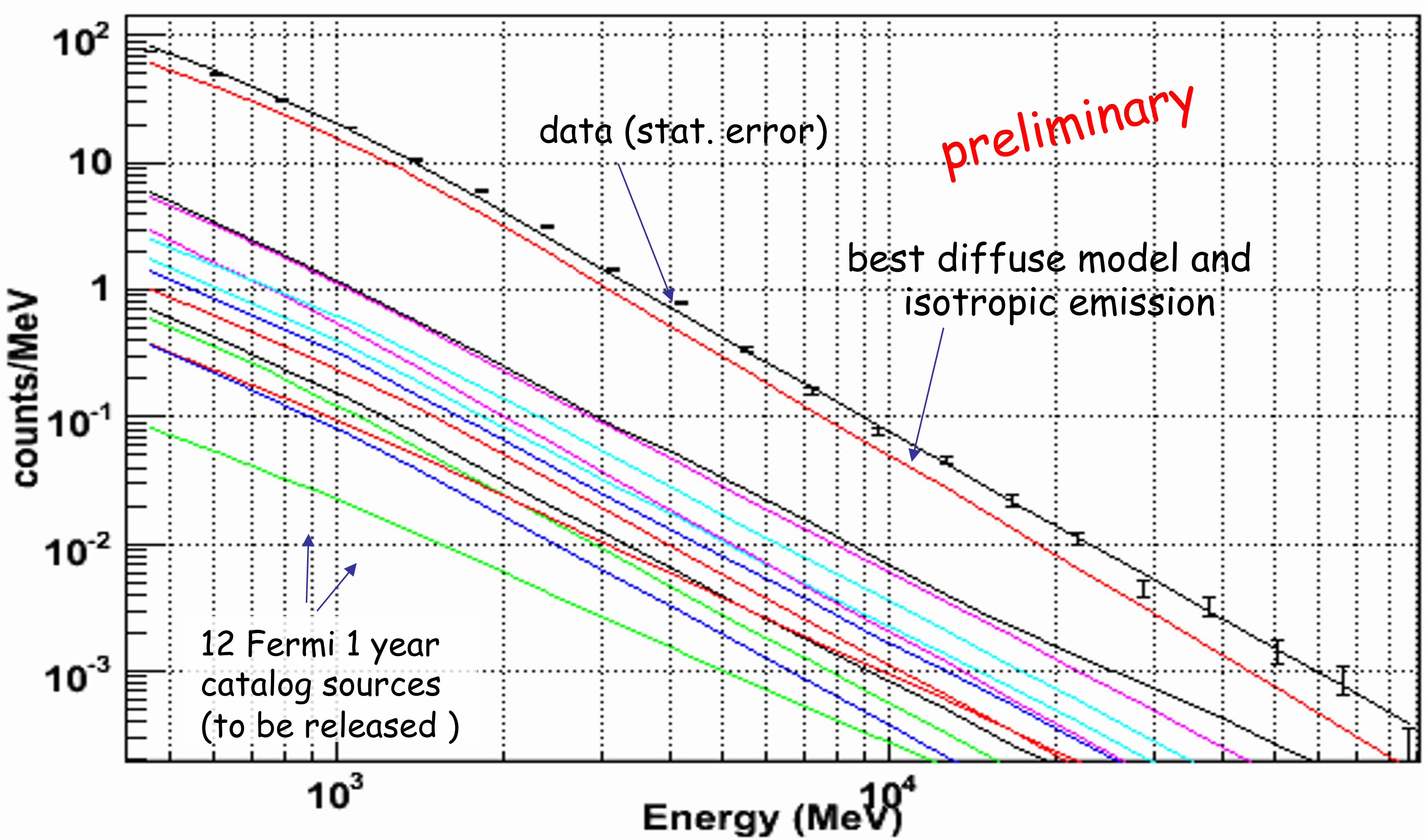
Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

Dark Matter Search: Targets and Strategies

(Another way to see it)



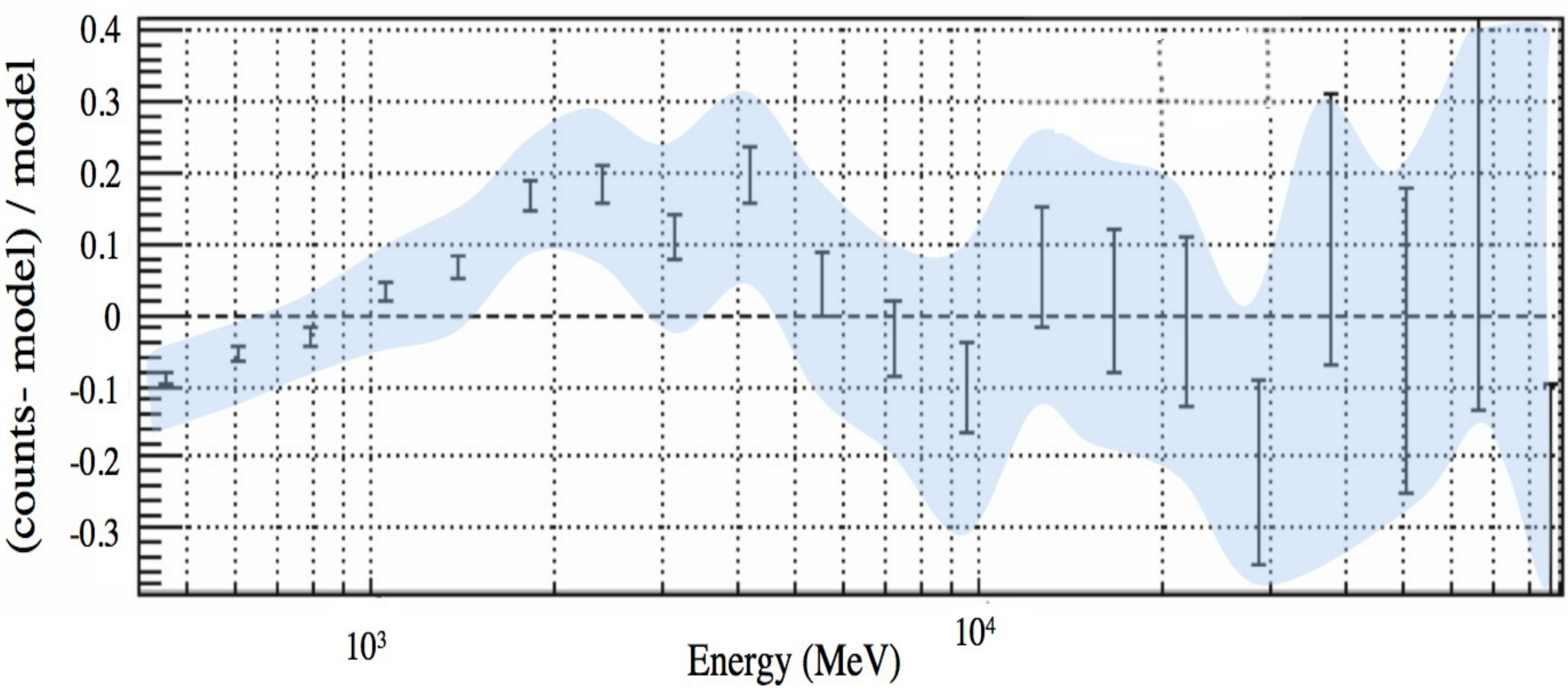
Spetrum (E> 400 MeV, 7° x7° region centered on the Galactic Center analyzed with binned likelihood analysis)



The GeV excess 7° x7° region centered on the Galactic Center

11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



V.Vitale, A.Morselli, Fermi Coll. 2009 arXiv:0912.3828 Fermi Symposium eConf Proceedings C091122

the GALACTIC CENTER : any hints of Dark Matter?

the beginning of the history :

The Galactic Center as a Dark Matter Gamma-Ray Source
A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nuclear Physics B 113B (2002) 213-220 [astro-ph/0211327]
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio Astroparticle Physics 21, 267-285, 2004 [astro-ph/0305075]

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope
Lisa Goodenough, Dan Hooper arXiv:0910.2998

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope
Vincenzo Vitale, Aldo Morselli, the Fermi/LAT Collaboration
Proceedings of the 2009 Fermi Symposium, 2-5 November 2009, eConf Proceedings C091122 **arXiv:0912.3828 21 Dec 2009**

Search for Dark Matter with Fermi Large Area Telescope: the Galactic Center
V.Vitale, A.Morselli, the Fermi-LAT Collaboration NIM A 630 (2011) 147–150 (Available online 23 June 2010)

Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope
Dan Hooper, Lisa Goodenough. (21 March 2011). 21 pp. **Phys.Lett. B697 (2011) 412-428**
....

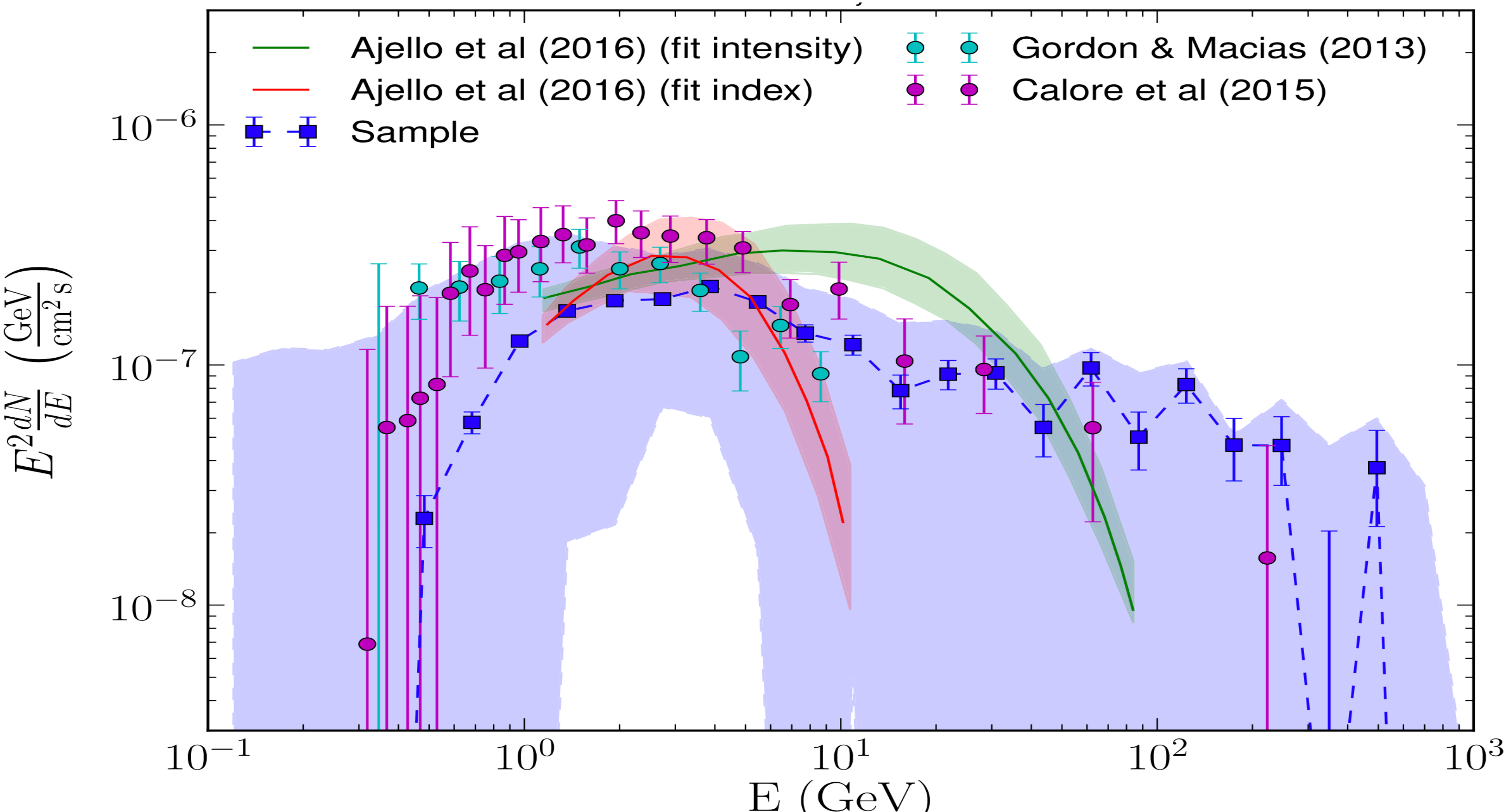
Background model systematics for the Fermi GeV excess
F.Calore, I. Cholis, C. Weniger JCAP03(2015)038 **arXiv:1409.0042v1**

Fermi–LAT observations of high-energy γ-ray emission toward the galactic centre
M. Ajello et al.[Fermi-LAT Coll.] **Apj 819:44 2016 arXiv:1511.02938**

The Fermi galactic center GeV excess and implications for dark matter
M. Ajello et al.[Fermi-LAT Coll.] **Apj 819:44 2016 arXiv:1511.02938**

Revisiting the Gamma-Ray Galactic Center Excess with Multi-Messenger Observations
IC, Zhong, McDermott, Surdutovich, PRD 105, 103023 (2022)

The GeV excess (Pass8 analysis)



following uncertainties have relatively small effect on the excess spectrum

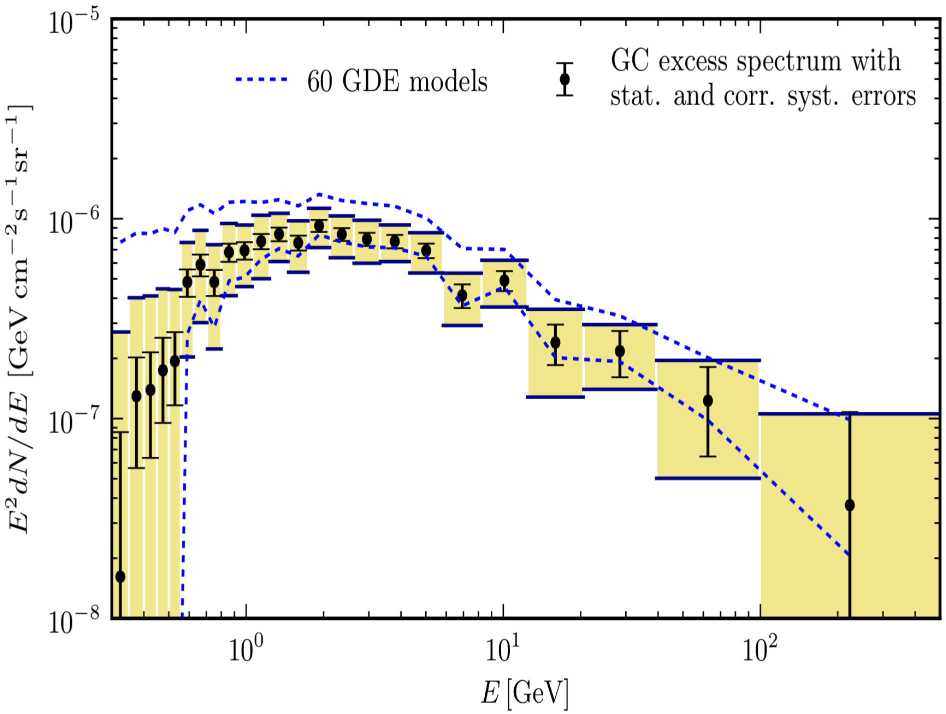
– Variation of GALPROP models – Distribution of gas along the line of sight

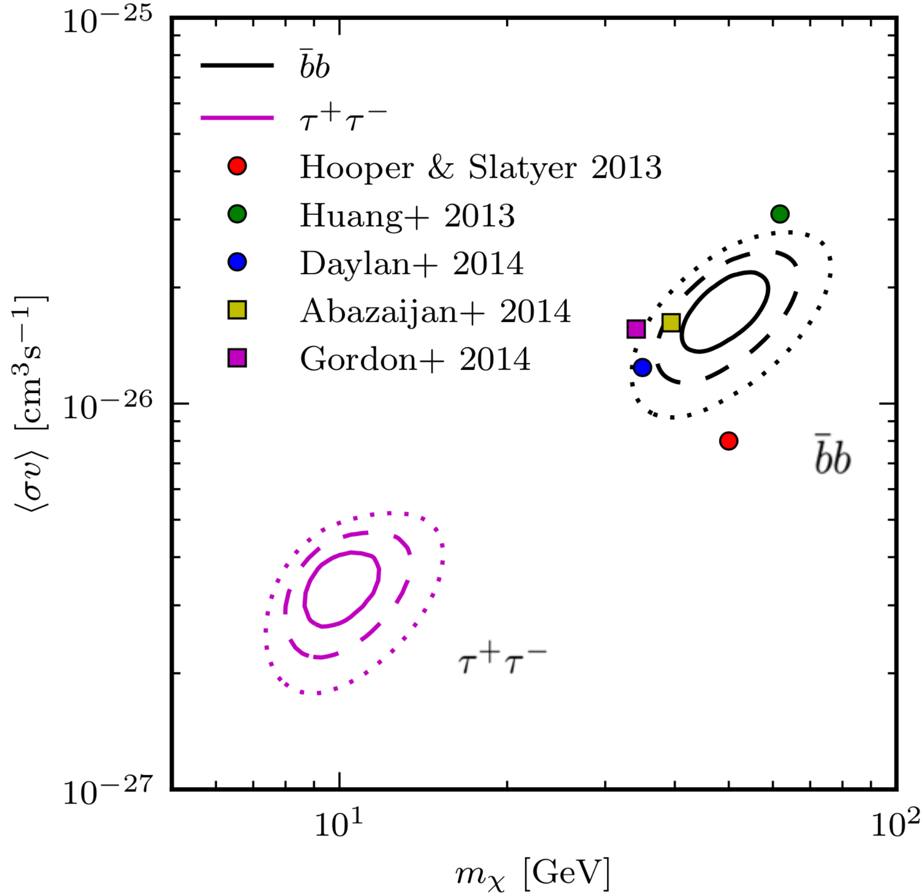
- **Most significant sources of uncertainty are:**

– Fermi bubbles morphology at low latitude – Sources of CR electrons near the GC

Fermi-LAT Collaboration Apj 840:43 2017 May 1 arXiv:1704.03910

The GeV excess





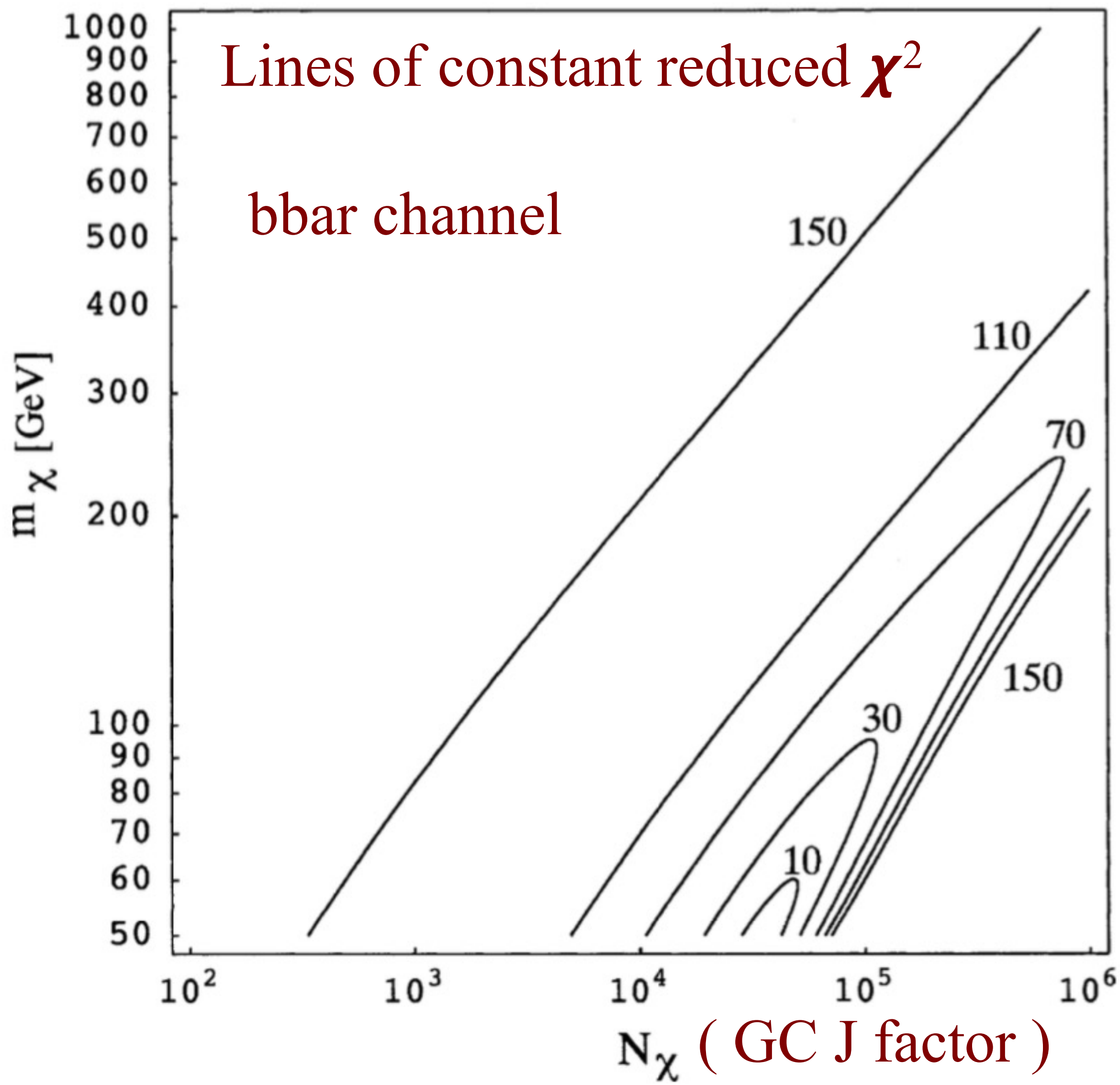
A lot of activity outside the Fermi collaboration with claims of evidence for dark matter in the Galactic Center

Calore et al., arXiv:1409.0042
Cholis et al., Phys. Rev. D 105, 103023 (2022) arXiv:2112.09706

Lines of constant reduced χ^2 corresponding to best fits of the EGRET GC excess

Very similar to the mass range found with the EGRET data in 2004 !

mass ~ 50- 80 GeV

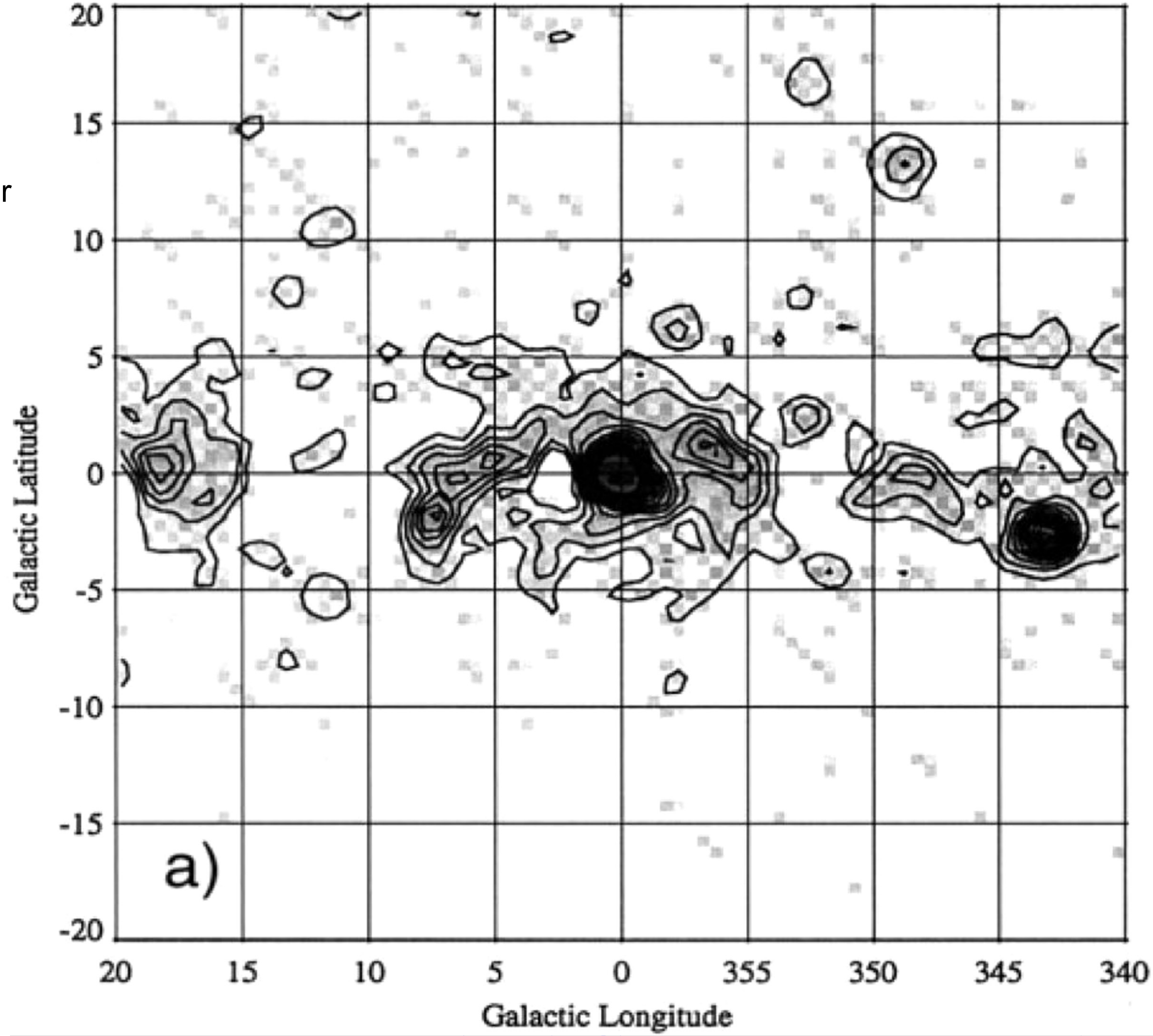


A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

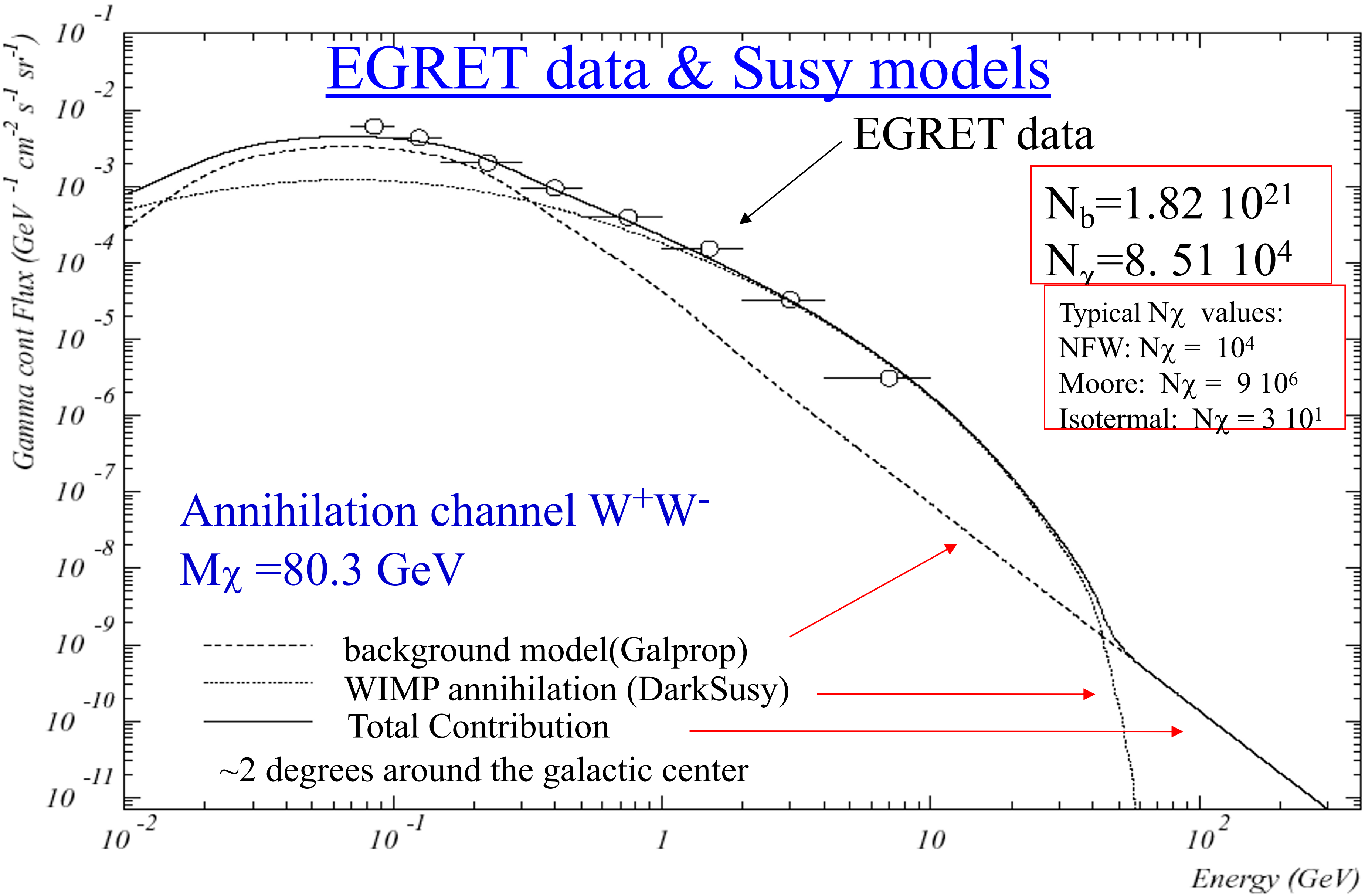
EGRET,

E > 1GeV

Mayer-Hasselwander et al, 1998



EGRET data & Susy models



A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, Nucl. Phys. B 113B (2002) 213-220 [astro-ph/0211327]

The GeV excess : Other explanations exist

• past activity of the Galactic center

(e.g. Petrovic et al., arXiv:1405.7928, Carlson & Profumo arXiv:1405.7685)

• Series of Leptonic Cosmic-Ray Outbursts

Cholis et al. arXiv:1506.05119

• Stellar population of the X-bulge and the nuclear bulge

Macias et al. arXiv:1611.06644

• Molecular Clouds in the disk

De Boer et al. arXiv:1610.08926, arXiv:1707.08653

• Population of pulsars in the Galactic bulge

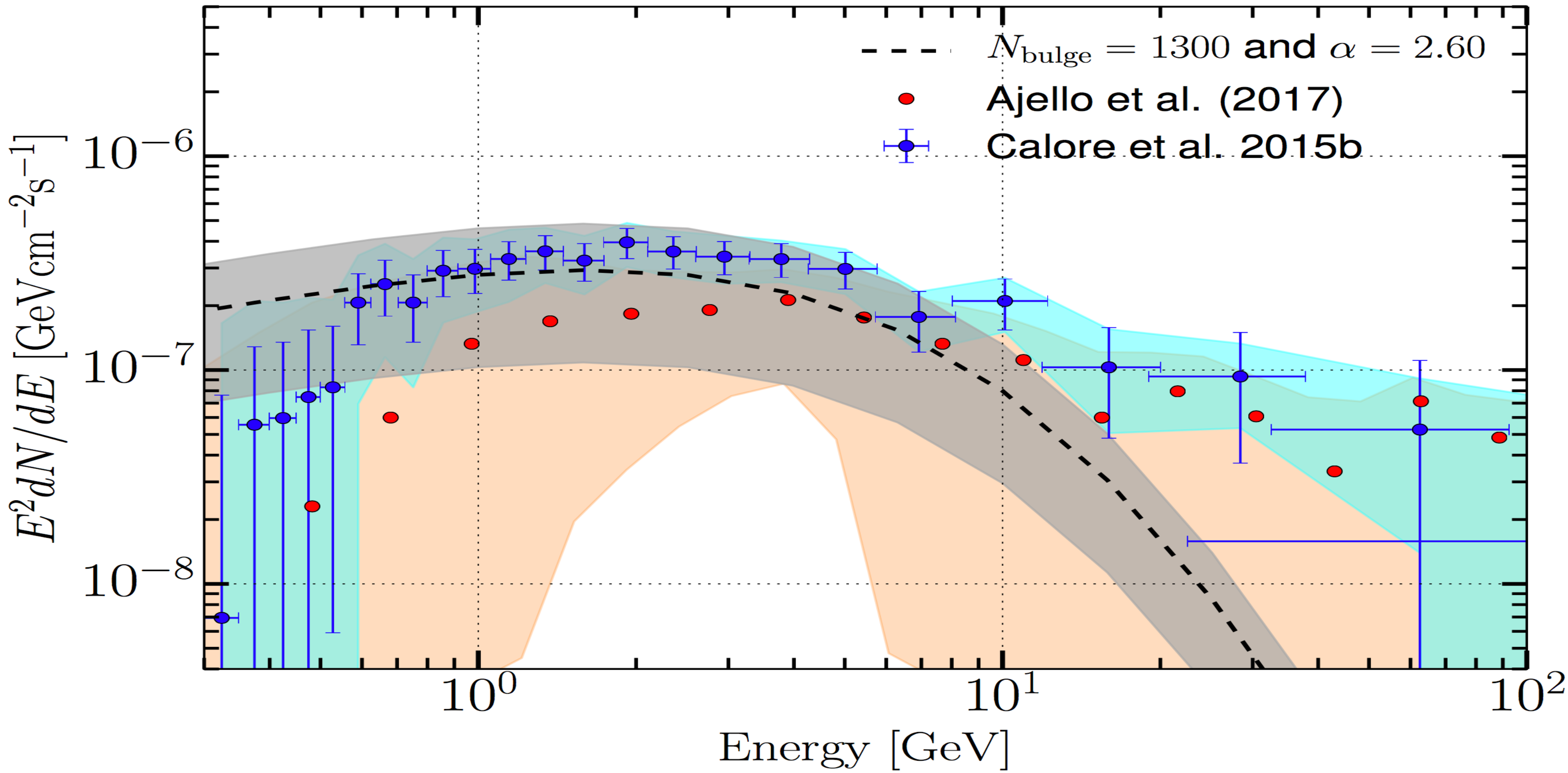
e.g. , Yuan and Zhang arXiv:1404.2318v1, Lee et al. arXiv:1506.05124, Bartels et.al. 1506.05104

M.Ajello et al. [Fermi-LAT Coll.] Phys. Rev. D 95, 082007 (2017)   [arXiv:1704.07195]

....

How to discriminate between different hypothesis ?

Population of pulsars in the Galactic bulge and the GeV excess



a population with about 2.7 γ-ray pulsars in the Galactic disk for each pulsar in the Galactic bulge is consistent with the population of known γ-ray pulsars as well as with the spatial profile and energy spectrum of the GC excess

M.Ajello et al. [Fermi-LAT Coll.] Apj sub. [arXiv:1705.00009]

How to discriminate between different hypothesis ?

eROSITA
- Modeling of the Fermi bubbles
- Look for correlated features near the Galactic center

HESS, MAGIC, CTA
- Fermi bubbles near the GC are much brighter
- Possible to see with Cherenkov telescopes?

Radio observations, MeerKAT, SKA
- Search for individual pulsars in the halo around the GC

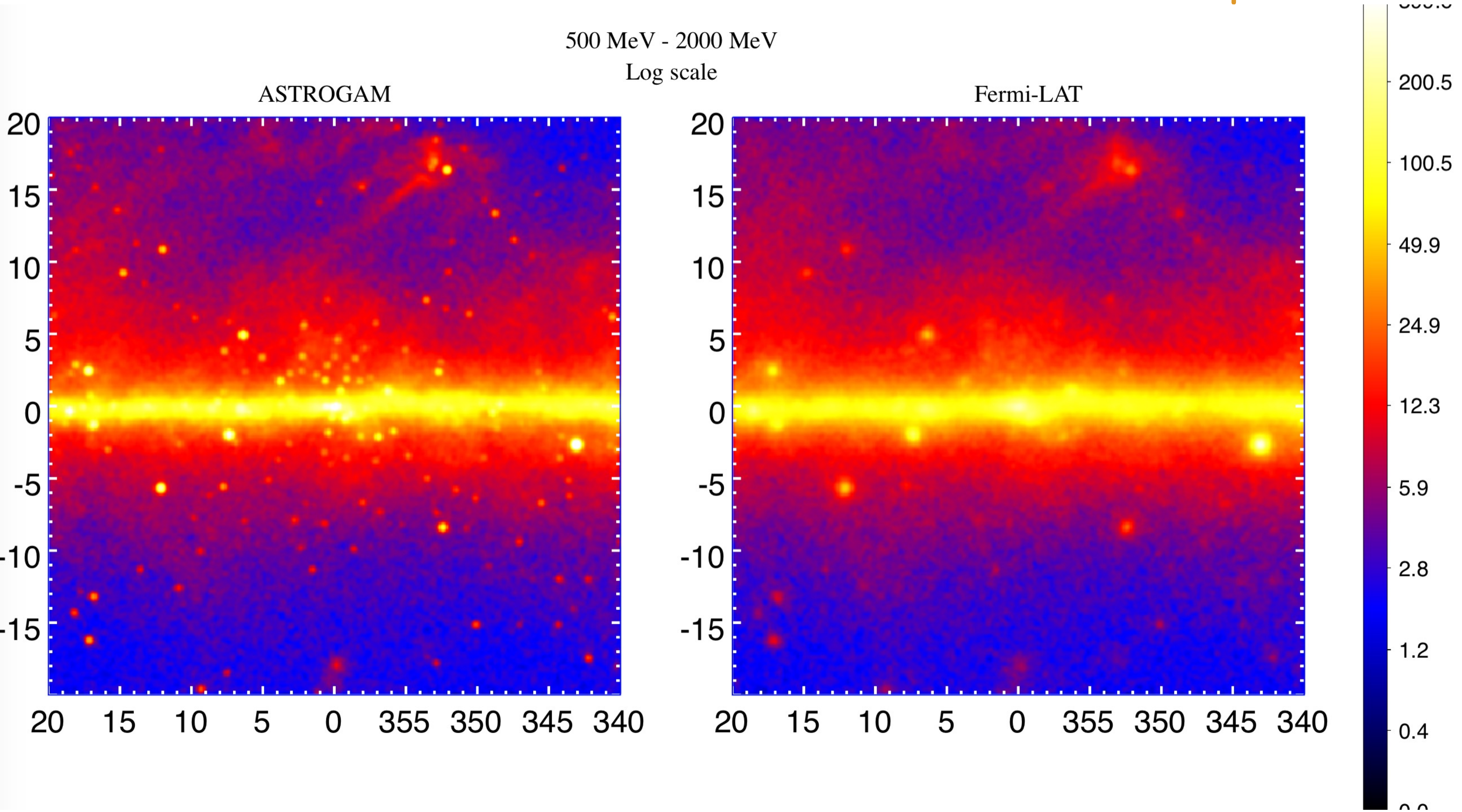
Radio surveys, Planck
- Look for correlated synchrotron emission near the GC

More Fermi LAT analysis
- Diffuse emission modeling
- Analysis of point sources near the GC

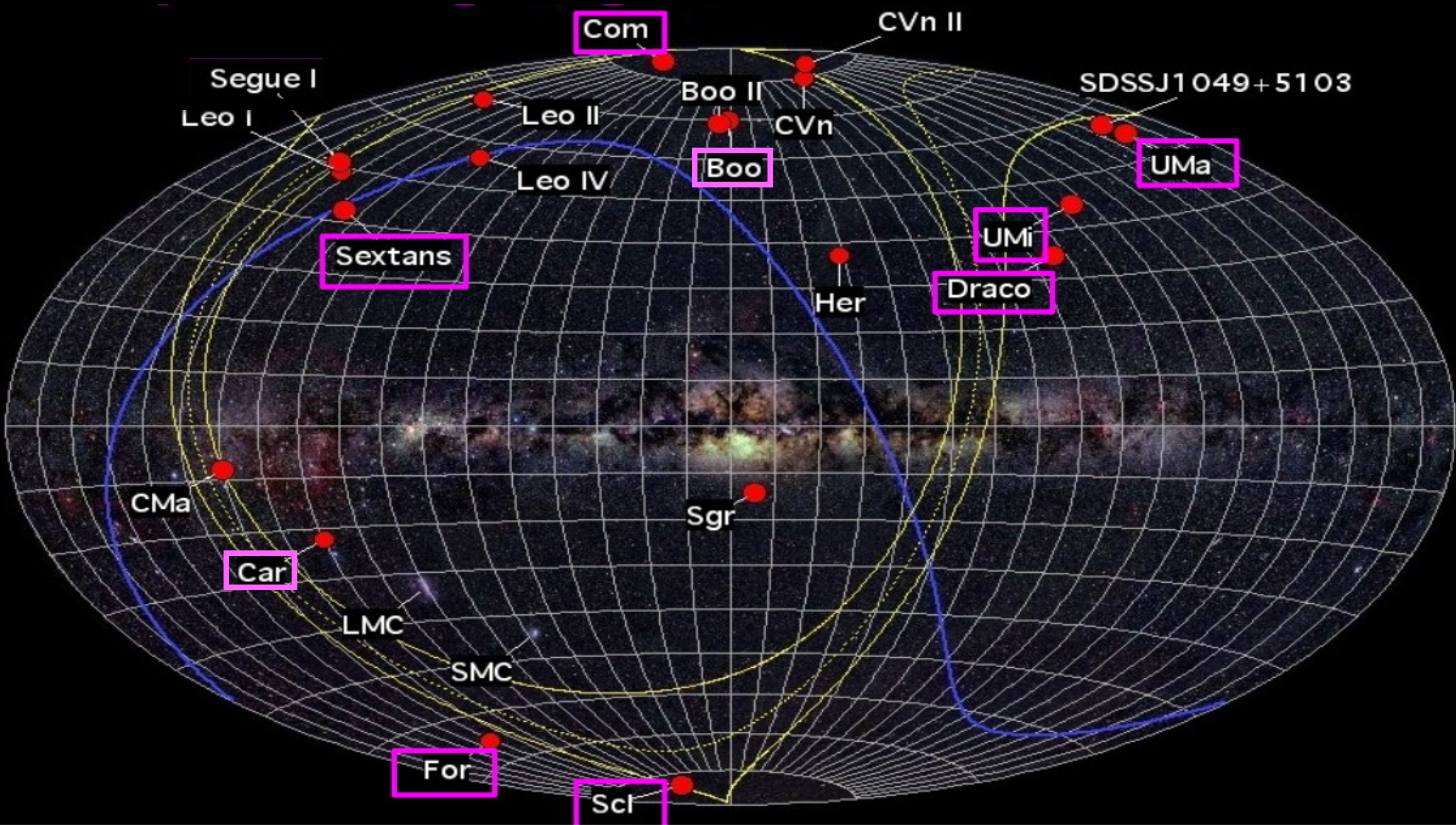
But ultimately We need a new experiment with better angular resolution below 100 MeV

Galactic Center Region 0.5-2 GeV

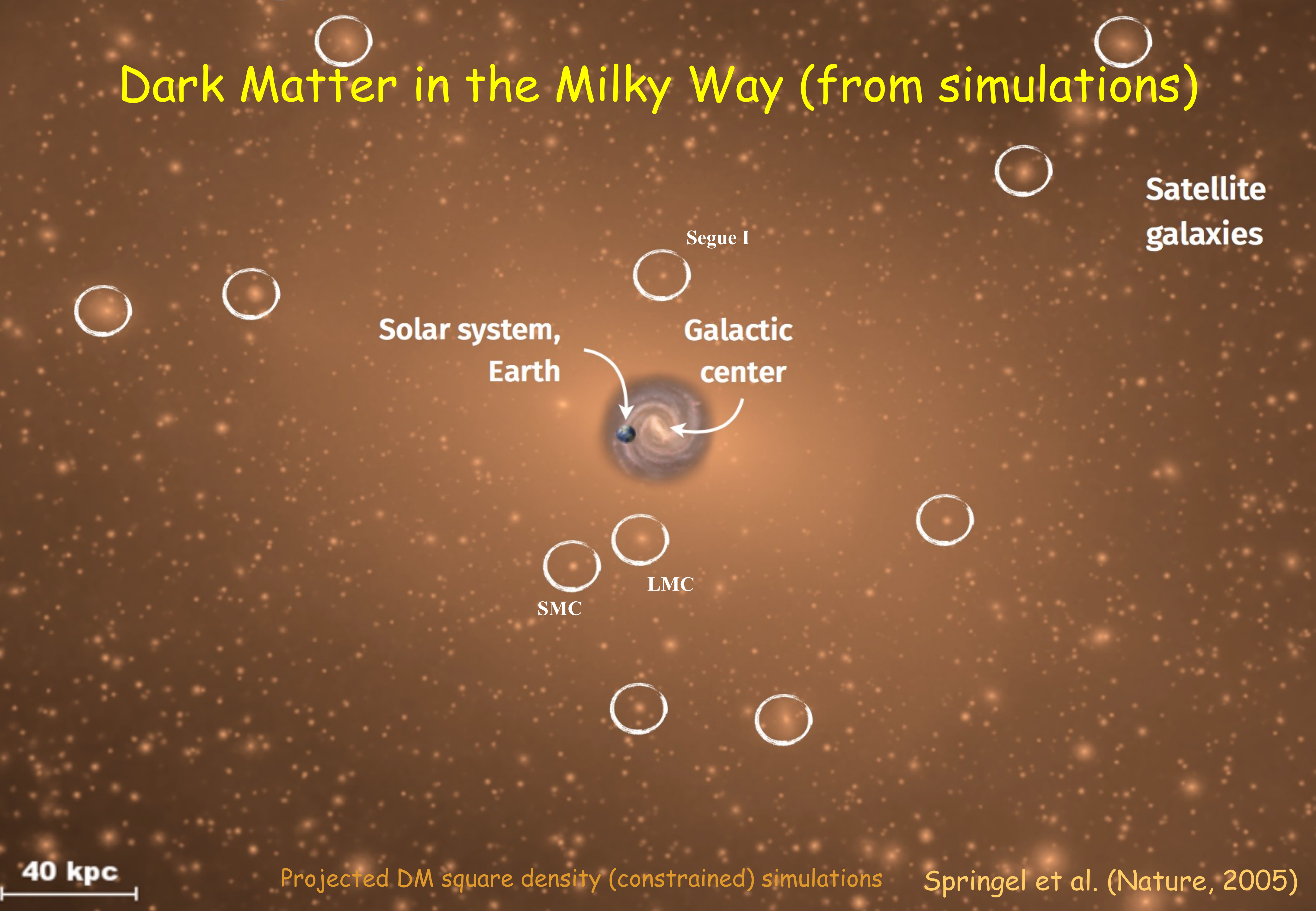
Fermi PSF Pass7 rep v15 source



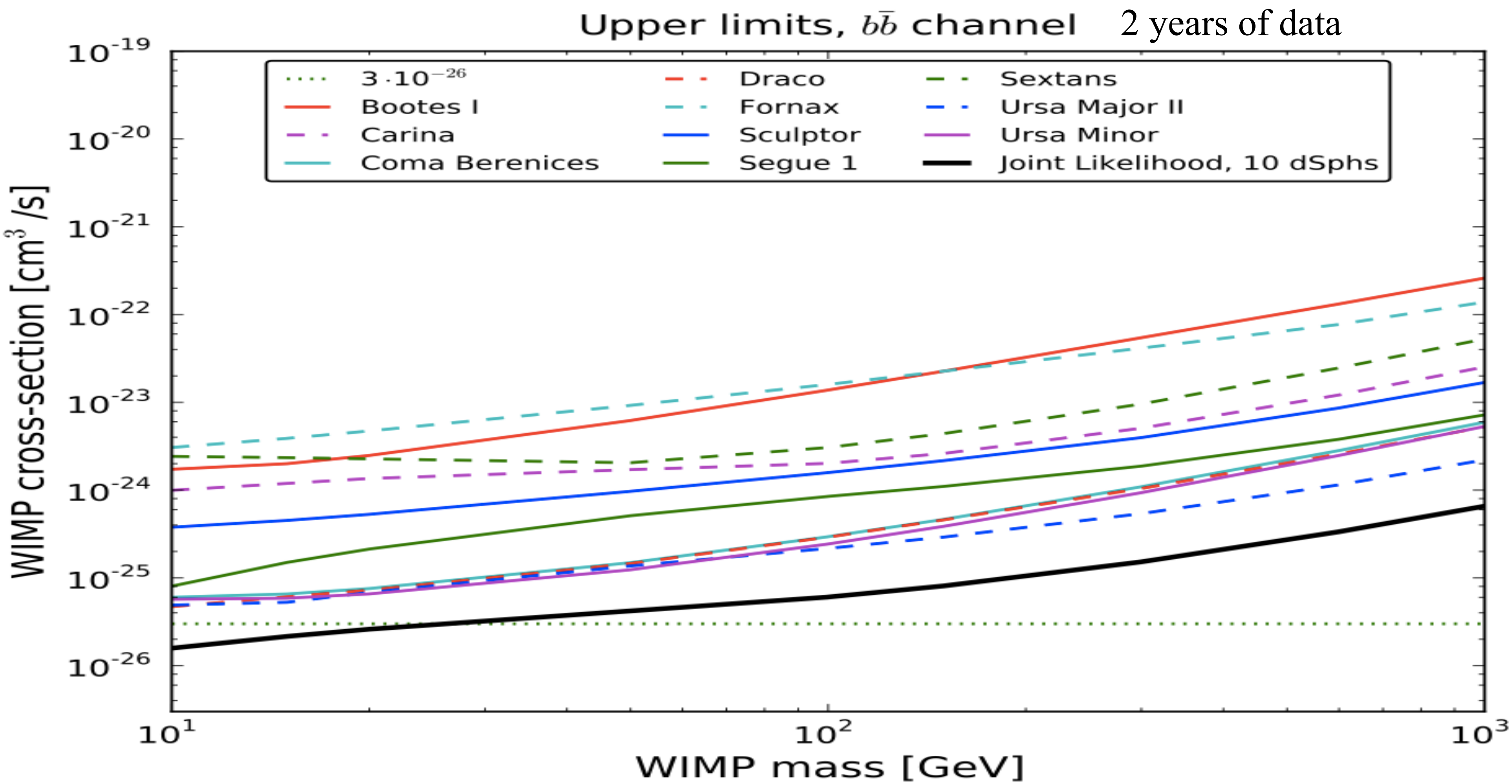
Classical Dwarf spheroidal galaxies: promising targets for DM detection



Dark Matter in the Milky Way (from simulations)



Dwarf Spheroidal Galaxies combined analysis

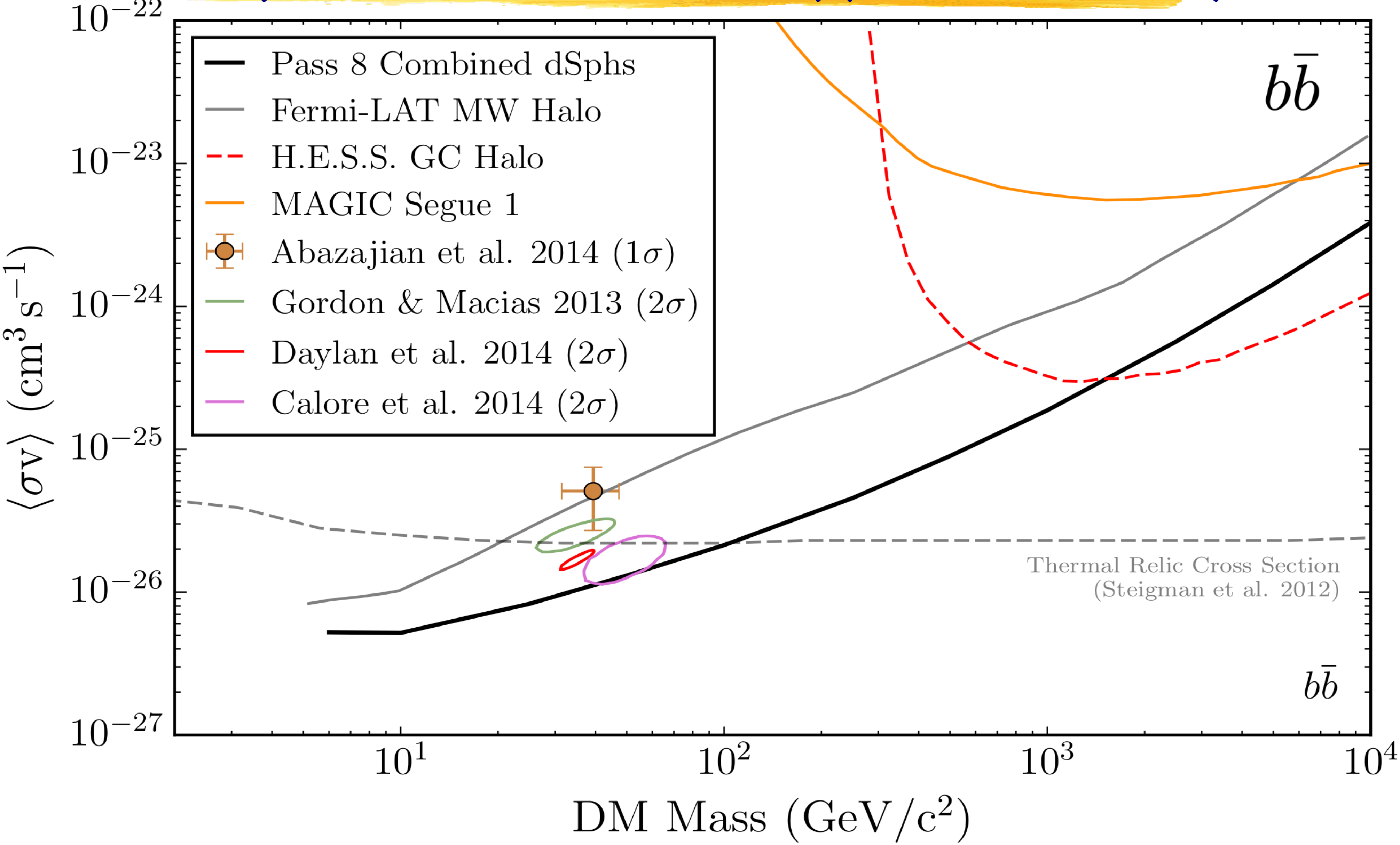


robust constraints including J-factor uncertainties from the stellar data statistical analysis

NFW. For cored dark matter profile, the J-factors for most of the dSphs would either increase or not change much

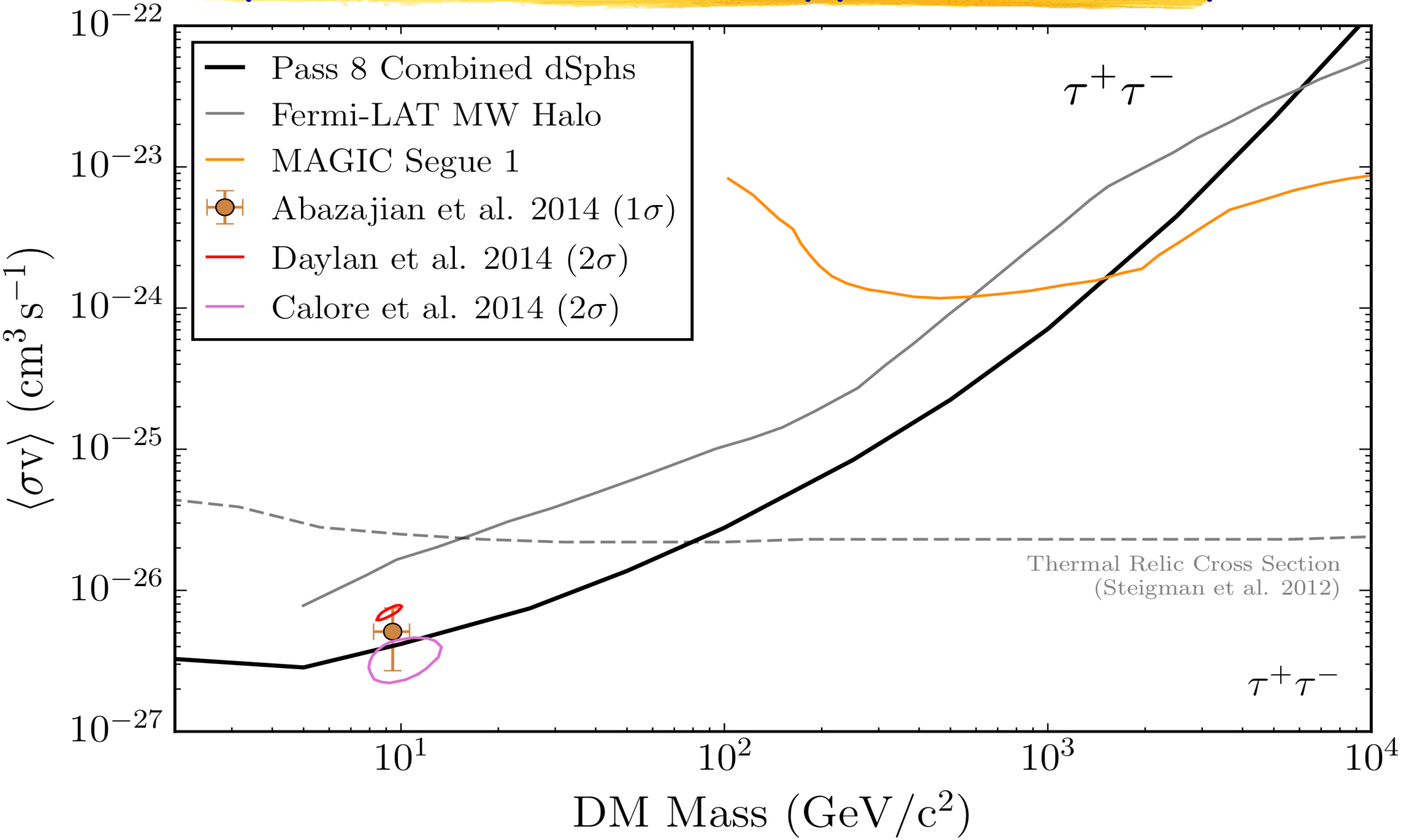
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies upper-limits (6 years)



M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

Dwarf Spheroidal Galaxies upper-limits (6 years)

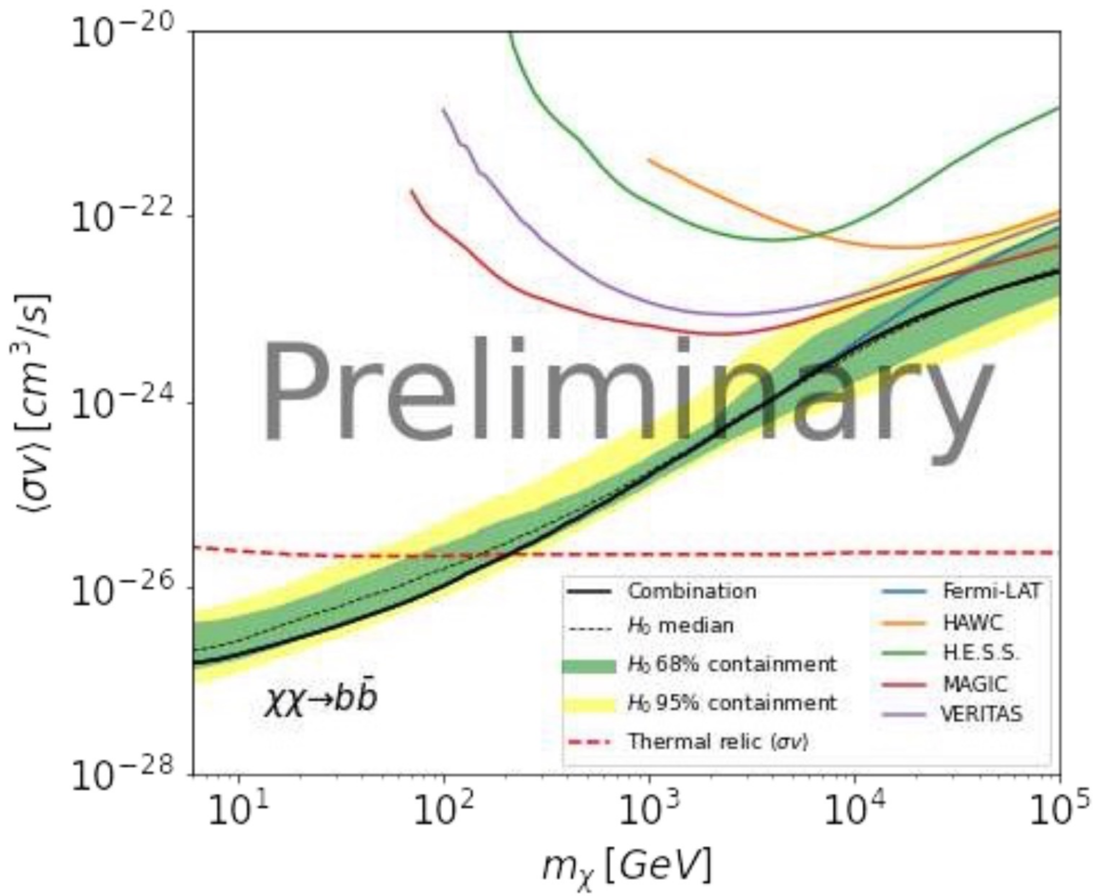


M.Ackermann et al., [Fermi Coll.] PRL 115, 231301 (2015) [arXiv:1503.02641]

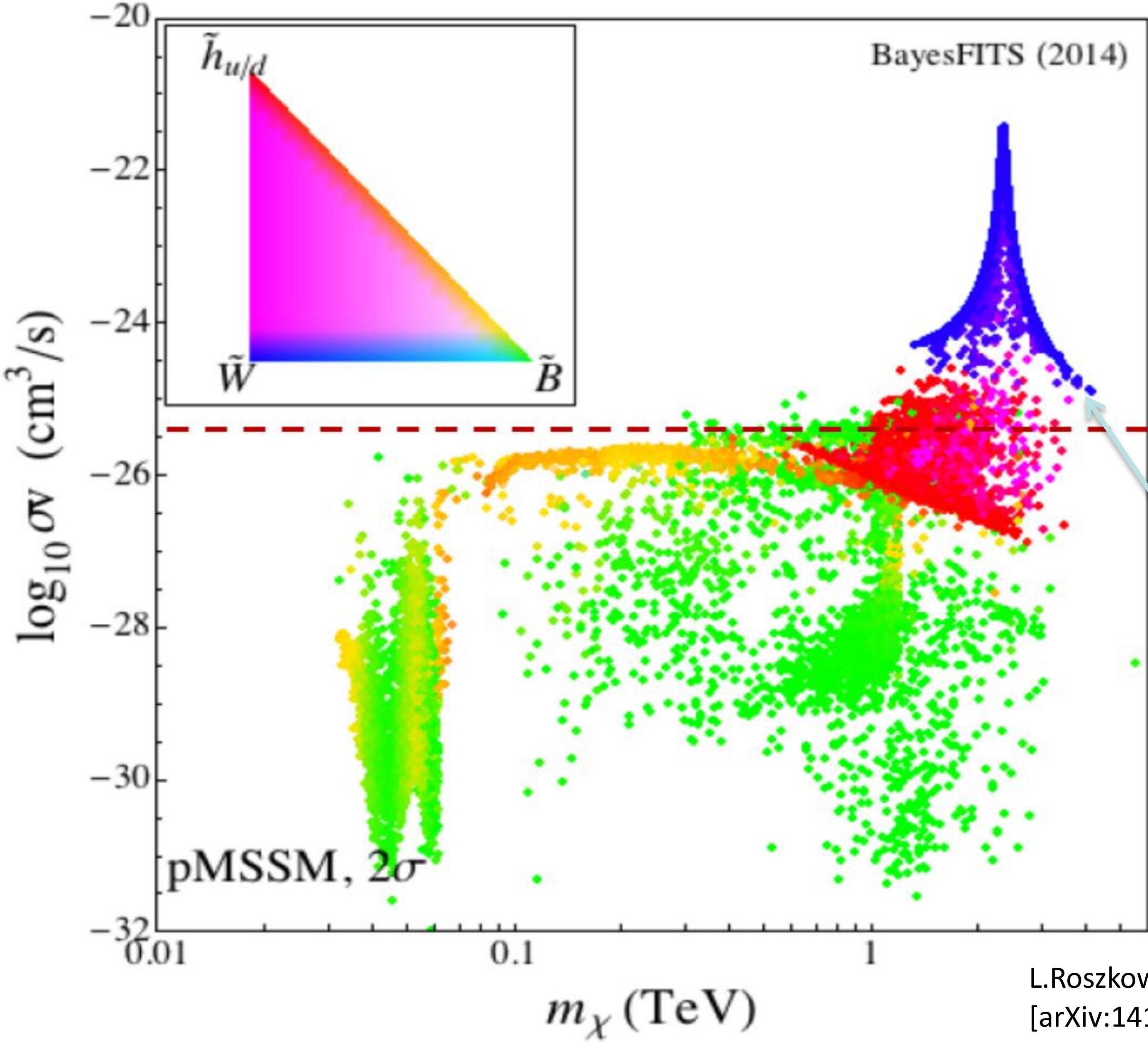
Combining all dSph observations

• Combination of the observation results towards 20 dwarf spheroidal galaxies (dSphs)
- Significant increase of the statistics
-> Increase the sensitivity to potential dark matter signals
- Cover the widest energy range ever investigated : 20 MeV – 80 TeV

• Common elements :
- Agreed model parameters
- Sharable likelihood table formats
- Joint likelihood test statistic



note:the “thermal” cross section is only a reference value. The real cross section can be higher or lower



Example: Annihilation cross-section points from a 19 dimensional pMSSM fit

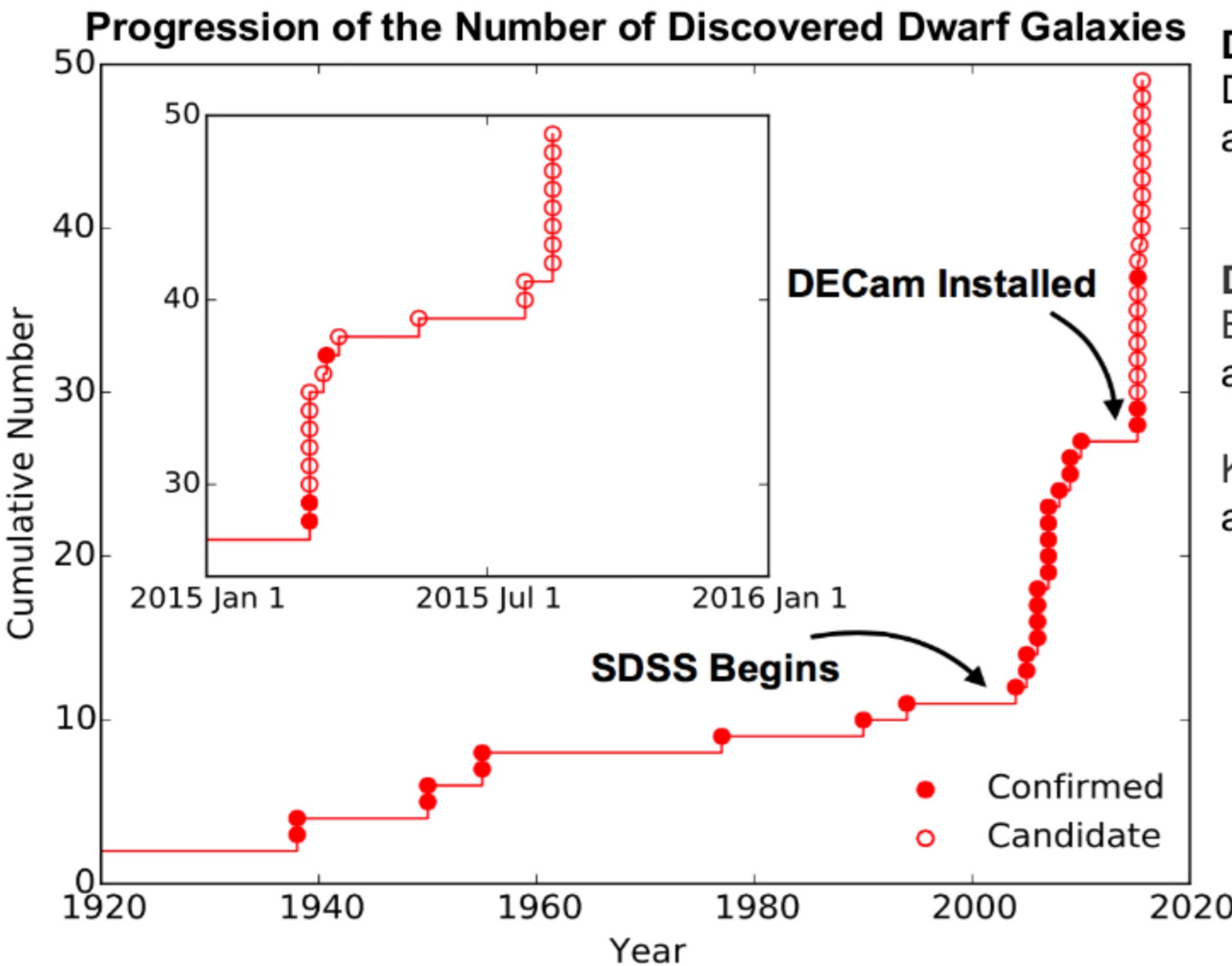
“thermal” cross-section

3×10^{-26} cm^3 s^{-1}

Note that a strong enhancement of the annihilation cross section occurs for winos around 2-3 TeV due to Sommerfeld enhancement.

L.Roszkowski et al., JHEP 1502 (2015) 014 [arXiv:1411.5214]

Dwarf Spheroidal Galaxies: Growing number of known targets



DES Year 2 Data:
Drlica-Wagner+,
arXiv:1508.03622

DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

Koposov+:
arXiv:1503.02079

Measuring DM densities in dSph halos

Optimal dSphs selected according to:
1. Distance(d<100pc)
2. Culmination zenith angle (ZAmin < 30°)

Targets with no/poor brightness and/ or kinematic data excluded from the MCMC Jeans analysis.

Surviving sample:

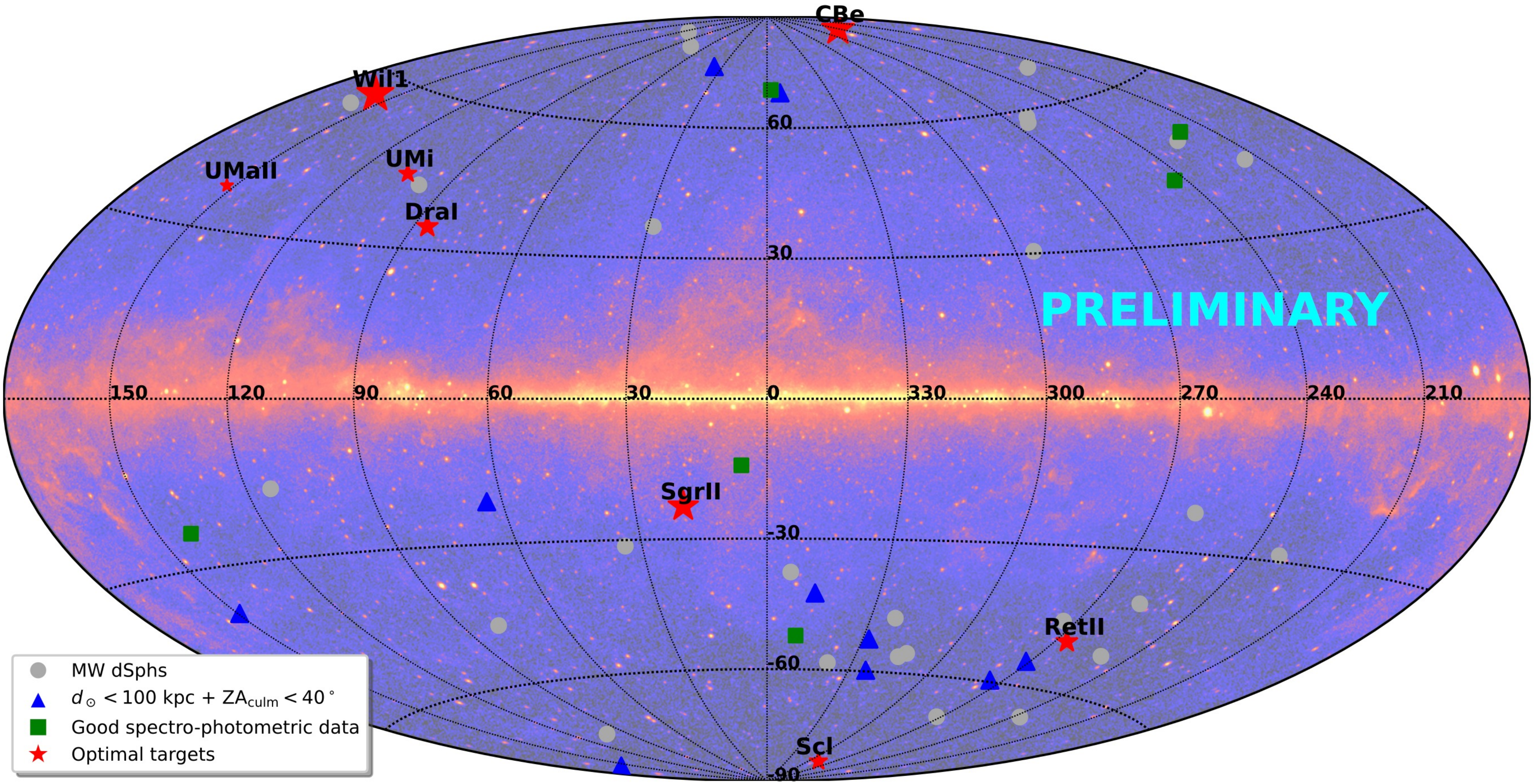
— 6 Northern dSphs (1 classical + 5 ultra-faint)

— 6 Southern dSphs (3 classical + 3 ultra-faint)

Name	Abbr.	Type	R.A. (hh mm ss)	dec. (dd mm ss)	Distance (kpc)	ZA_{culm} N (deg)	ZA_{culm} S (deg)	Month
Andromeda XVIII	AndXVIII	uft	00 02 14.5	+45 05 20	1330 ± 104	16.3	69.7	Sep
Aquarius	Aqr	uft	20 46 51.8	−12 50 53	1030 ± 57	41.6	11.8	Aug
Boötes I	BoöI	uft	14 00 06.0	+14 30 00	65 ± 3	14.3	39.1	Apr
Boötes II	BoöII	uft	13 58 00.0	+12 51 00	39 ± 2	15.9	37.5	Apr
Boötes III	BoöIII	uft	13 57 12.0	+26 48 00	46 ± 2	2.0	51.4	Apr
Canes Venatici I	CVnI	uft	13 28 03.5	+33 33 21	216 ± 8	4.8	58.2	Apr
Canes Venatici II	CVnII	uft	12 57 10.0	+34 19 15	159 ± 8	5.6	58.9	Apr
Carina	Car	cls	06 41 36.7	−50 57 58	106 ± 1	79.7	26.3	Dec
Cetus I	CetI	uft	00 26 11.0	−11 02 40	748 ± 31	39.8	13.6	Sep
Cetus II	CetII	uft	01 17 52.8	−17 25 12	30 ± 3	46.2	7.2	Oct
Columba I	ColI	uft	05 31 26.4	−28 01 48	182 ± 18	56.8	3.4	Dec
Coma Berenices	CBe	uft	12 26 59.0	+23 54 15	42 ± 2	4.9	48.5	Mar
Draco I	DraI	cls	17 20 12.4	+57 54 55	75 ± 4	29.2	82.5	Jun
Draco II	DraII	uft	15 52 47.6	+64 33 55	20 ± 3	35.8	89.2	May
Eridanus II	EriII	uft	03 44 21.5	−43 31 48	330 ± 16	72.3	18.9	Nov
Eridanus III	EriIII	uft	02 22 45.5	−52 16 48	95 ± 27	81.0	27.7	Oct
Fornax	For	cls	02 39 59.3	−34 26 57	146 ± 1	63.2	9.8	Oct
Grus I	GruI	uft	22 56 42.4	−50 09 48	120 ± 17	78.9	25.5	Sep
Grus II	GruII	uft	22 04 04.8	−46 26 24	53 ± 5	75.2	21.8	Aug
Hercules	Her	uft	16 31 02.0	+12 47 30	137 ± 11	16.0	37.4	May
Horologium I	HorI	uft	02 55 28.9	−54 06 36	87 ± 13	82.9	29.5	Oct
Hydra II	HyaII	uft	12 21 42.1	−31 59 07	134 ± 10	60.7	7.4	Mar
Indus I	IndI	uft	21 08 48.1	−51 09 36	69 ± 16	79.9	26.5	Aug
Indus II	IndII	uft	20 38 52.8	−46 09 36	214 ± 16	74.9	21.5	Aug
Laevens 3	Lae3	uft	21 06 54.3	+14 58 48	67 ± 3	13.8	39.6	Aug
Leo I	LeoI	cls	10 08 28.1	+12 18 23	272 ± 10	16.5	36.9	Feb
Leo II	LeoII	cls	11 13 28.8	+22 09 06	240 ± 9	6.6	46.8	Mar
Leo IV	LeoIV	uft	11 32 57.0	−00 32 00	151 ± 4	29.3	24.1	Mar
Leo V	LeoV	uft	11 31 09.6	+02 13 12	169 ± 5	26.5	26.9	Mar
Leo T	LeoT	uft	09 34 53.4	+17 03 05	377 ± 28	11.7	41.7	Feb
Phoenix I	PheI	uft	01 51 06.3	−44 26 41	427 ± 31	73.2	19.8	Oct
Phoenix II	PheII	uft	23 39 57.6	−54 24 36	95 ± 18	83.2	29.8	Sep
Pictor I	PicI	uft	04 43 48.0	−50 16 48	126 ± 24	79.0	25.7	Nov
Pisces II	PscII	uft	22 58 31.0	+05 57 09	182 ± 13	22.8	30.6	Sep
Reticulum II	RetII	uft	03 35 40.9	−54 03 00	32 ± 2	82.8	29.4	Nov
Reticulum III	RetIII	uft	03 45 26.3	−60 27 00	92 ± 13	89.2	35.8	Nov
Sagittarius I	SgrI	dis	18 55 19.5	−30 32 43	31 ± 1	59.3	5.9	Jul
Sagittarius II	SgrII	uft	19 52 40.5	−22 04 05	67 ± 5	50.8	2.6	Jul
Sculptor	Scl	cls	01 00 09.4	−33 42 33	84 ± 2	62.5	9.1	Oct
Segue 1	Seg1	uft	10 07 04.0	+16 04 55	23 ± 2	12.7	40.7	Feb
Segue 2	Seg2	uft	02 19 16.0	+20 10 31	36 ± 2	8.6	44.8	Oct
Sextans	Sex	cls	10 13 03.0	−01 36 53	84 ± 3	30.4	23.0	Feb
Triangulum II	TriII	uft	02 13 17.4	+36 10 42	30 ± 2	7.4	60.8	Oct
Tucana I	TucI	uft	22 41 49.6	−64 25 10	855 ± 35	—	39.8	Sep
Tucana II	TucII	uft	22 52 16.7	−58 33 36	58 ± 6	87.3	33.9	Sep
Tucana III	TucIII	uft	23 56 35.9	−59 36 00	25 ± 2	88.4	35.0	Sep
Tucana IV	TucIV	uft	00 02 55.3	−60 51 00	48 ± 4	89.6	36.2	Sep
Ursa Major I	UMaI	uft	10 34 52.8	+51 55 12	105 ± 2	23.2	76.6	Mar
Ursa Major II	UMaII	uft	08 51 30.0	+63 07 48	35 ± 2	34.4	87.8	Feb
Ursa Minor	UMi	cls	15 09 08.5	+67 13 21	68 ± 2	38.5	—	May
Willman 1	Wil1	uft	10 49 21.0	+51 03 00	38 ± 7	22.3	75.7	Mar

preliminary, in prep. 2024

Dwarf Spheroidal Galaxies: Selection of optimal candidates for CTA



Optimal dSphs selected according to:

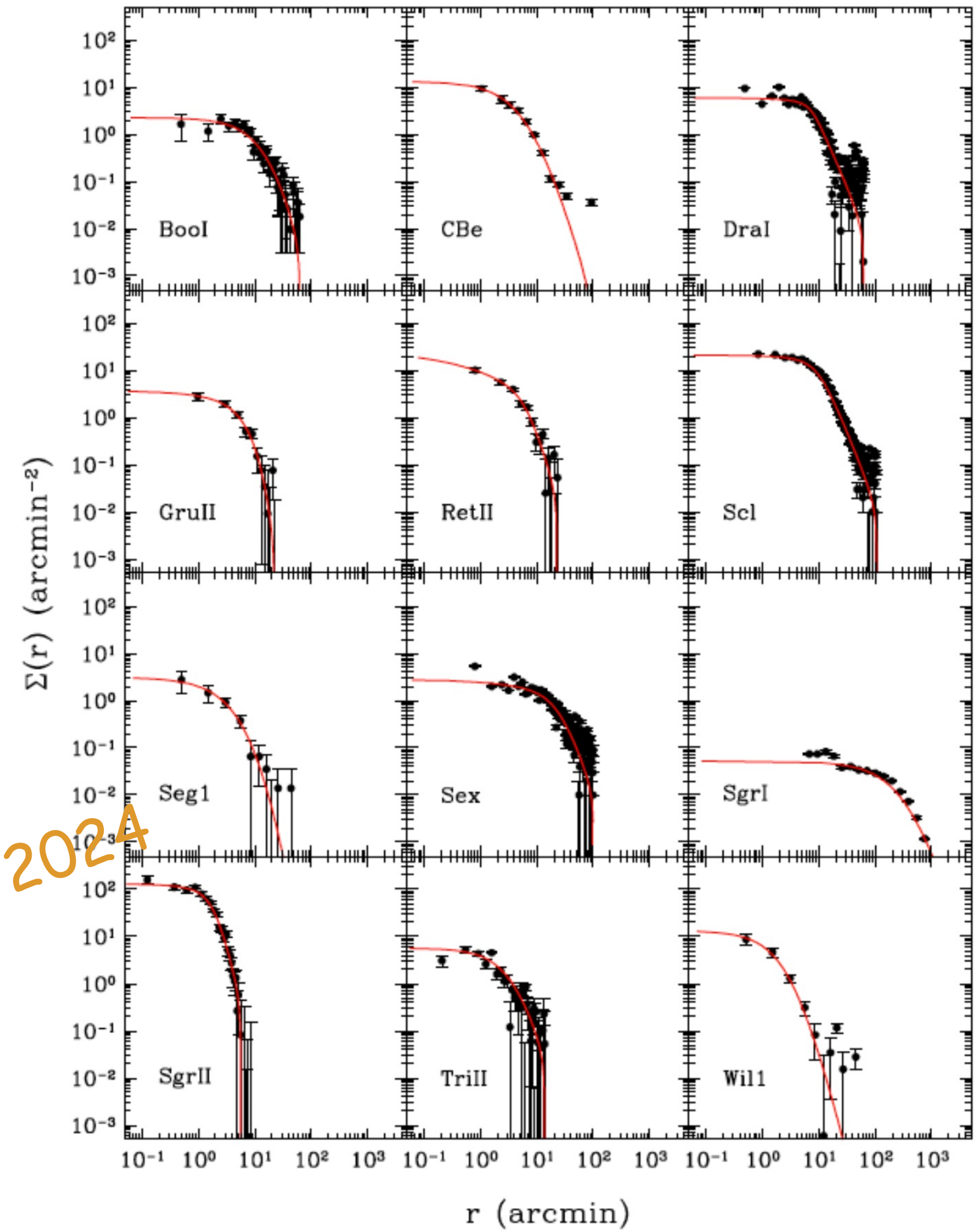
1.distance (d < 100 pc) 2. culmination zenith angle (ZA < 40°) 3. availability of good spectro-photometric data.

Surviving sample: 8 Northern dSphs (2 classical + 6 ultra-faint) 6 Southern dSphs (3 classical + 3 ultra-faint)

CTA Consortium in prep. 2023

Measuring Dark Matter densities in dSph halos

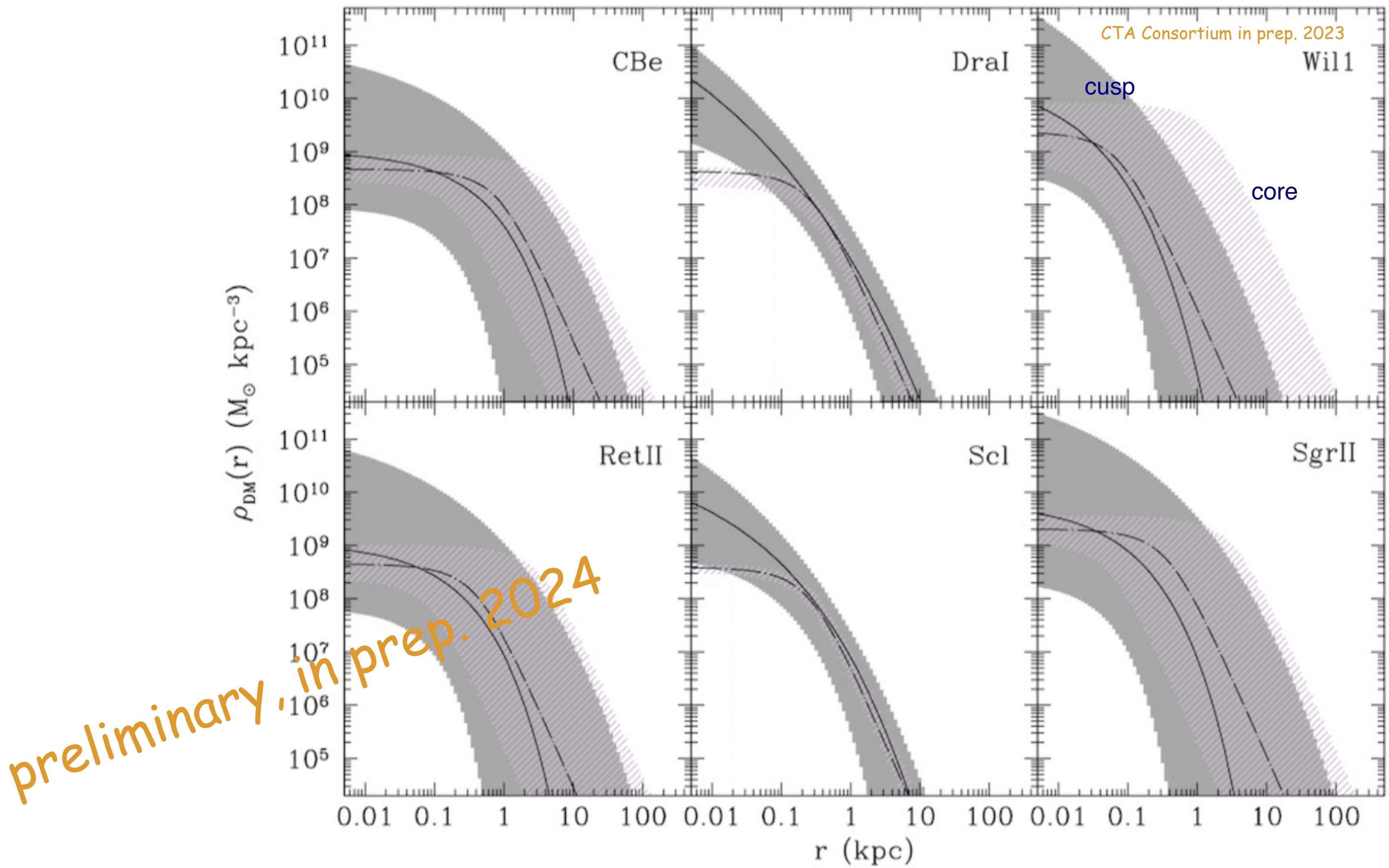
Best-fit brightness profiles Σ(r) of the analyzed dSphs as a function of the object's projected (2D) radial coordinate r from the dSph centroid



preliminary, in prep. 2024

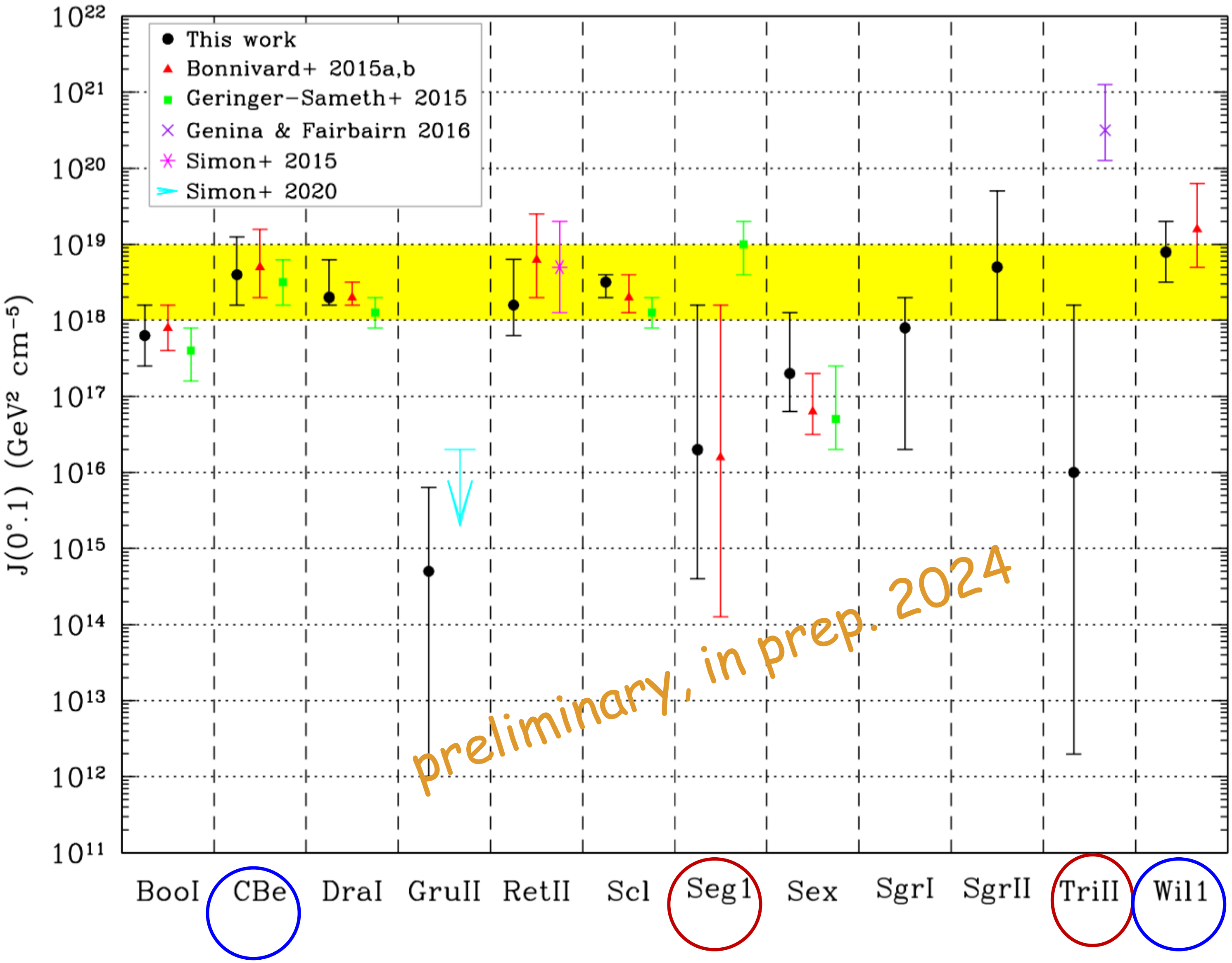
Measuring Dark Matter densities in dSph halos

Core and cusp DM density profiles for 6 dSphs targets



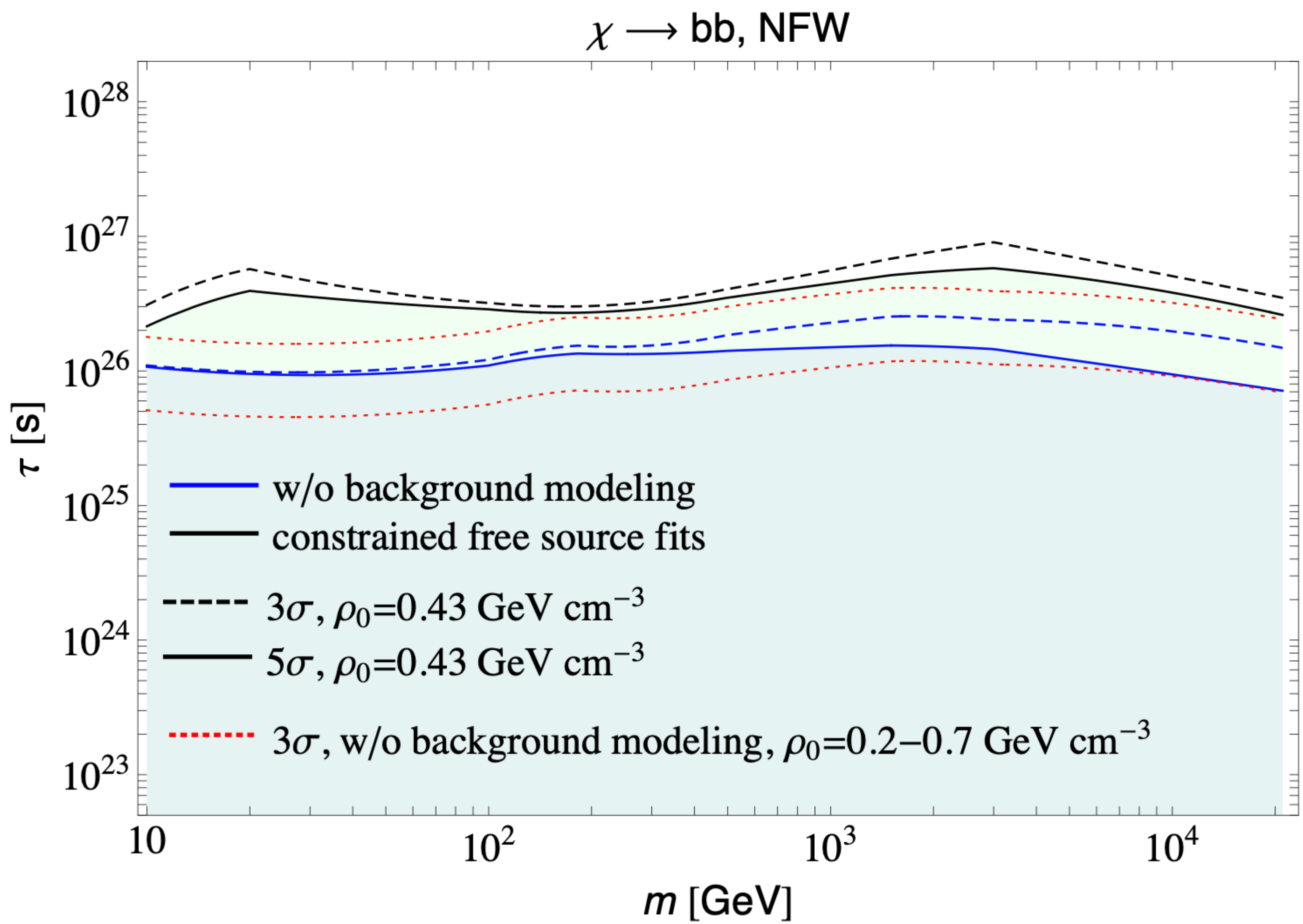
Measuring Dark Matter densities in dSph halos

Comparison of astrophysical factor for DM annihilation within 0.1 deg of integration



Limit on DM lifetime

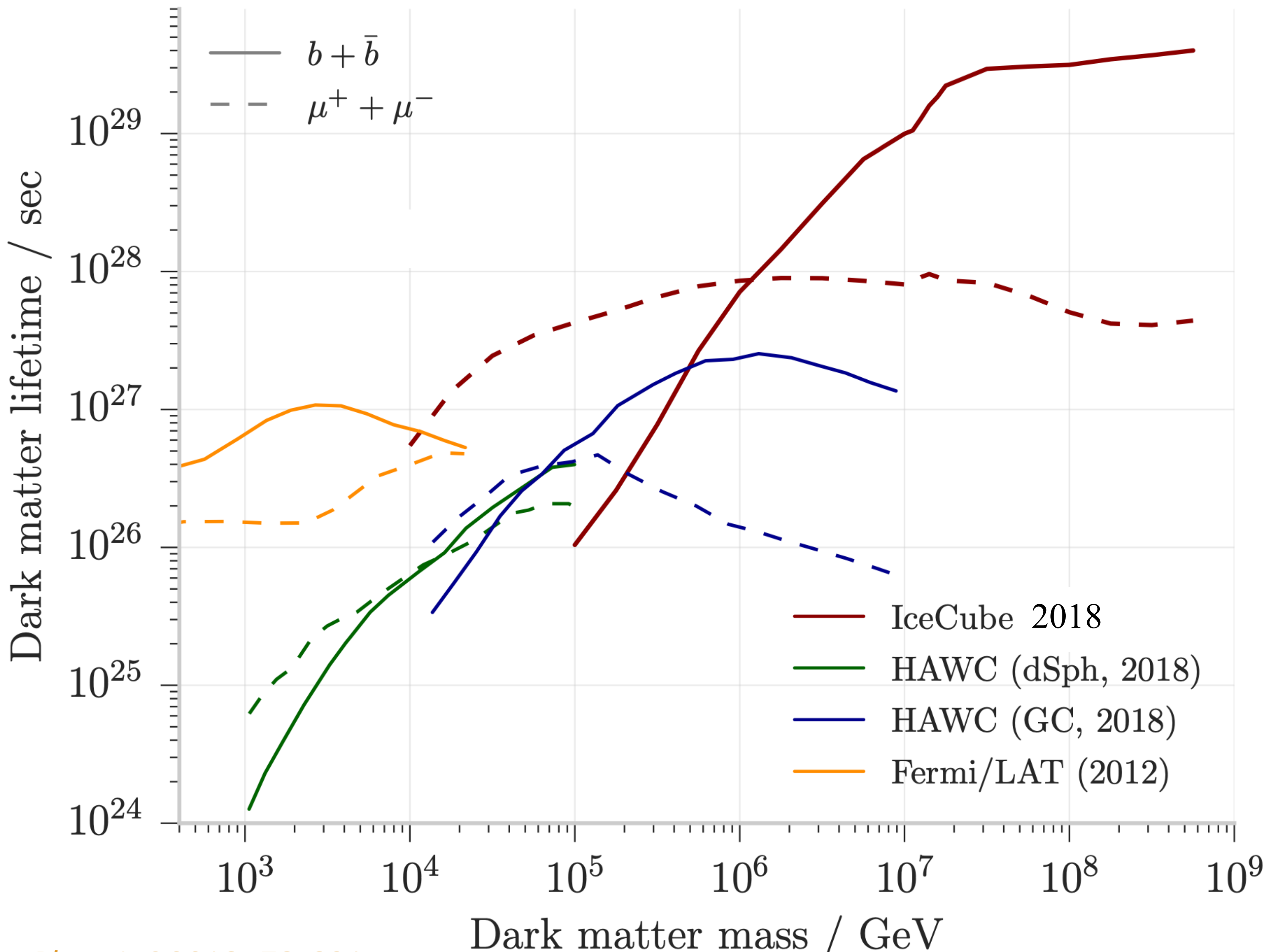
Lower limits on the lifetime of decaying DM



Fermi Coll. ApJ 761 (2012) 91 [arXiv:1205.6474]

Limit on Dark Matter lifetime

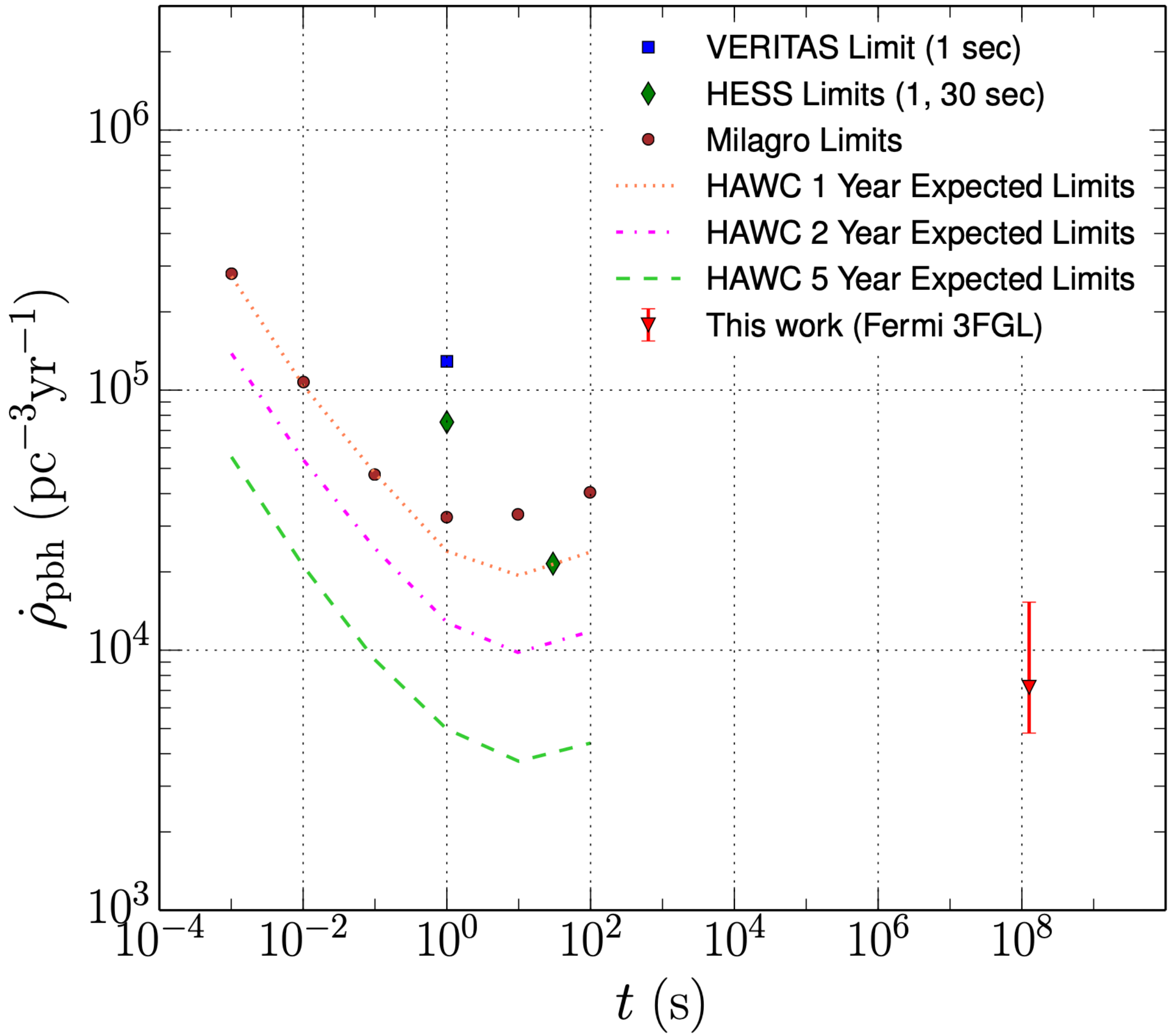
Lower limits on the lifetime of decaying DM Fermi/LAT, HAWC, and IceCube



Aartsen et al. *Eur. Phys. J. C* 2018, *78*, 831

Limit on PBH evaporation rate in the vicinity of the Earth

searching for proper motion of gamma-ray point sources, and applying it to 318 unassociated point sources at high galactic latitude in the third Fermi-LAT source catalog (3FGL)



Ferm Coll. ApJ 2018, ApJ, 857, 49 [arXiv:1802.00100]

Search for Dark Matter beyond WIMP

Axion Like Particle (ALP) search prospects

γ + B -> a + B -> γ' + ...

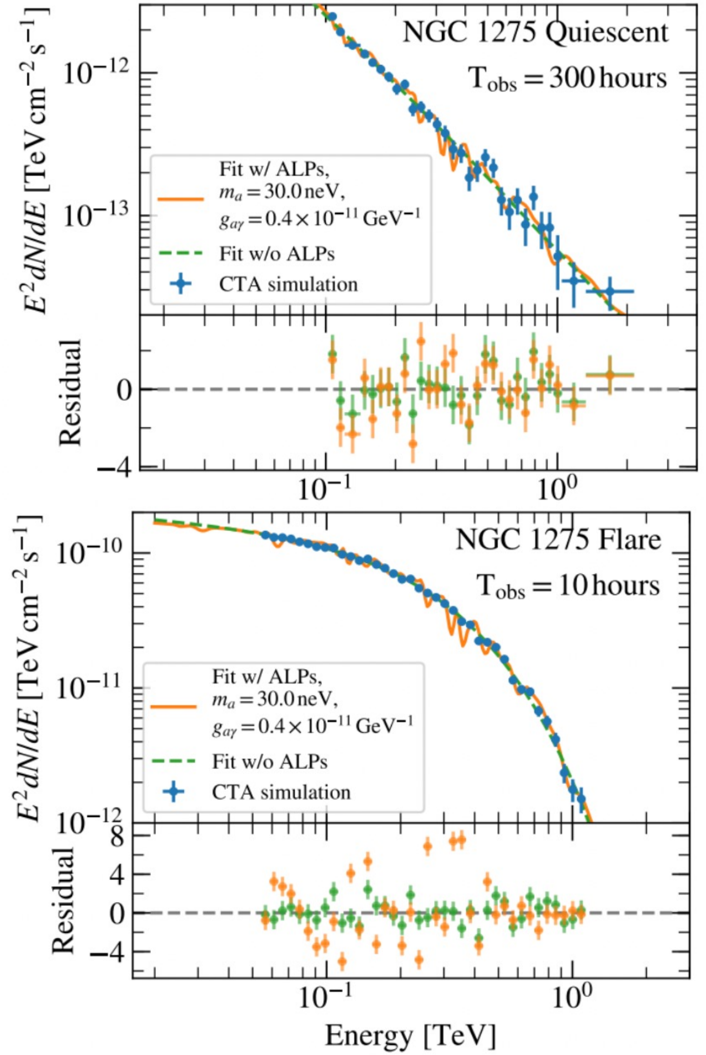
conversion probability ($E > E_{crit}$)

$$P_{a\gamma} \sim \sin^2\left(\frac{g_{a\gamma}Bl}{2}\right),$$

$$E_{\rm crit} \sim 2.5\ \text{GeV} \times \left(\frac{|m_a - \omega_{\rm pl}|}{1\text{neV}}\right)^2 \left(\frac{B}{1\mu\text{G}}\right)^{-1} \left(\frac{g_{a\gamma}}{10^{-11}\text{GeV}^{-1}}\right)^{-1}$$

the observation is simulated without an ALP effect and is modeled both without ALPs and with a fixed set of magnetic-field realization and ALP parameters that are excluded at 95 % confidence level by the flaring state simulation

Simulated spectra of the radio galaxy NGC 1275

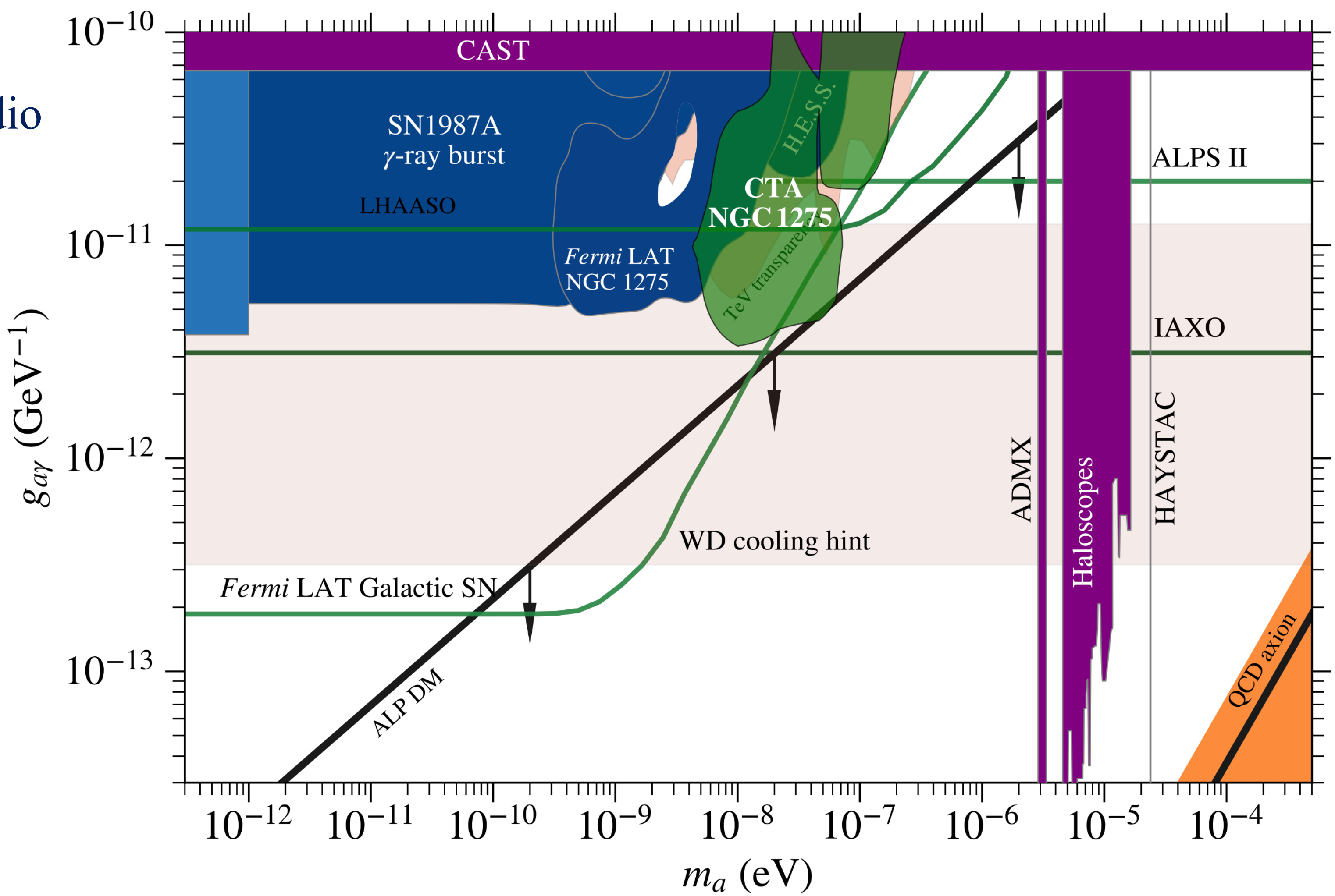


The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]

Search for Dark Matter beyond WIMP

Axion Like Particle search prospects

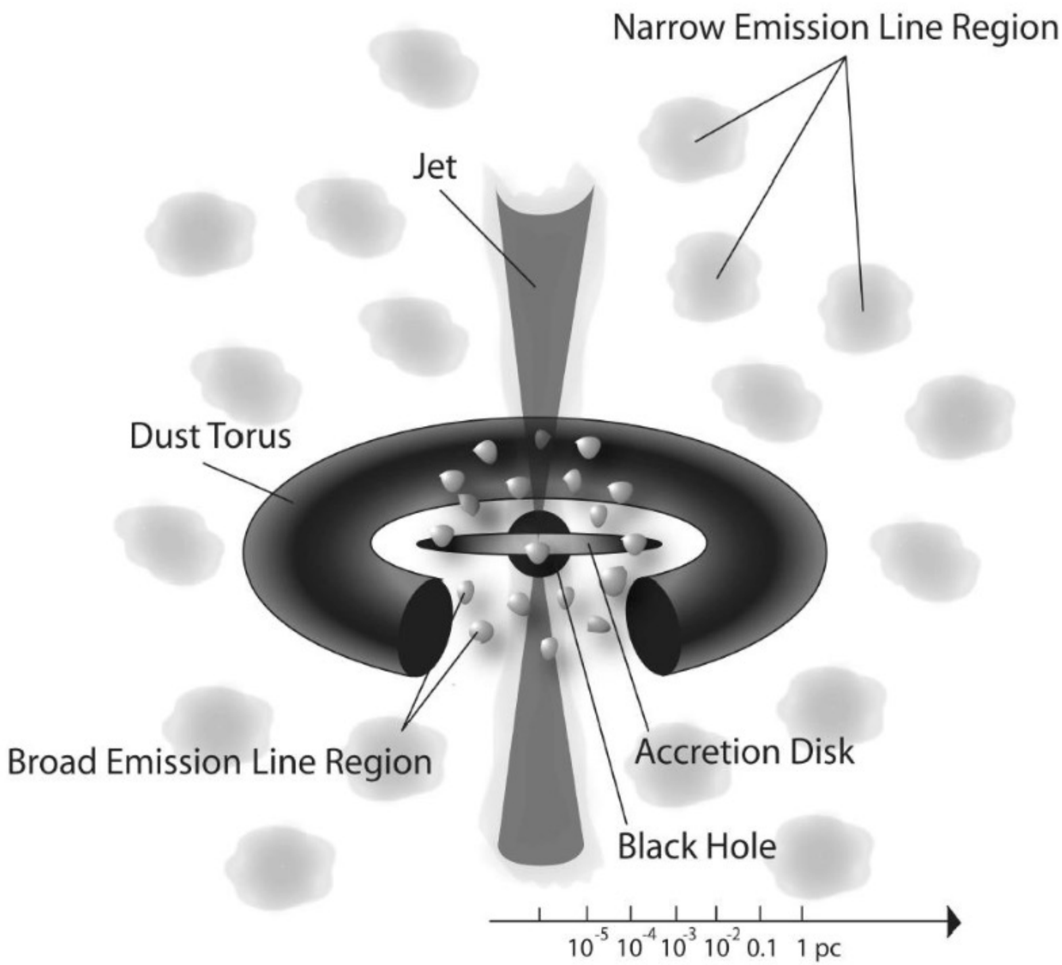
- Observation of a flaring state of the radio galaxy NGC 1275 inside the Perseus cluster



The CTA Consortium, JCAP 02 (2021) 048, 2021 [arXiv:2010.01349]


Come to
the dark side.
We have cookies...
Come to
the dark side.
We have cookies...
-V

ACTIVE GALACTIC NUCLEI



- At the center of (probably) all galaxies there is a large mass concentration (millions or even billions of solar masses).
- Mass is very compact essentially certainly a Super Massive Black Hole
- Accretion on the central object generates radiation in a very broad spectrum

ACTIVE GALACTIC NUCLEI

- The most luminous persistent sources in whole electromagnetic spectrum —> Galaxies with a super-massive black hole located in their center

- The great power in the AGN (blazars are subfamilies) is driven by accreting matter into a Super Massive Black Hole (SMBH).

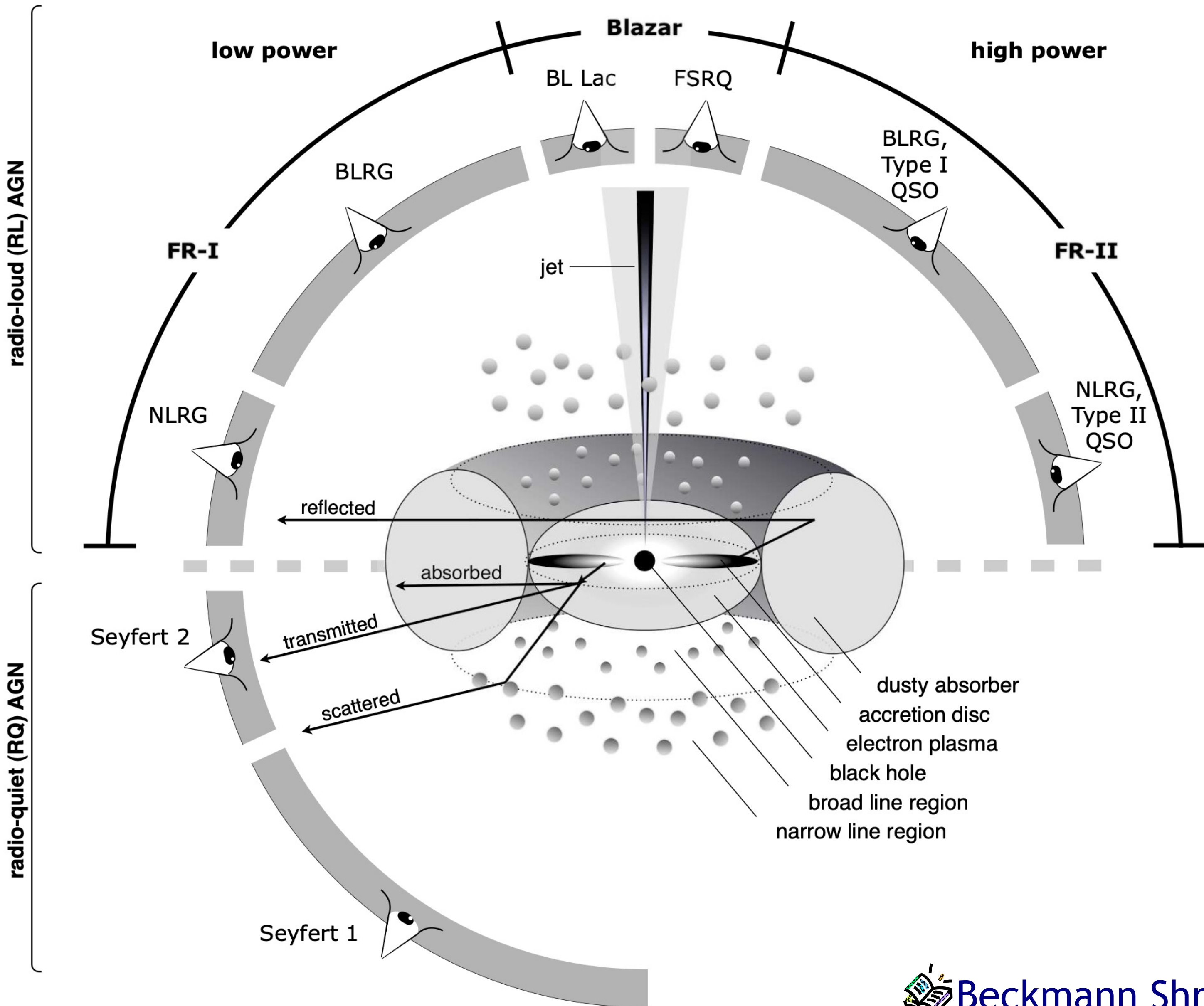
- Emission across entire electromagnetic spectrum from radio, microwaves to X-ray and gamma-ray

  - Not thermal emission

- Strong variability

- AGN as multi-messenger astroparticle sources: cosmic PeV- energy neutrinos, UHE cosmic rays, axion-like supersymmetric particles (ALPs), intense very-low frequency gravitational waves.

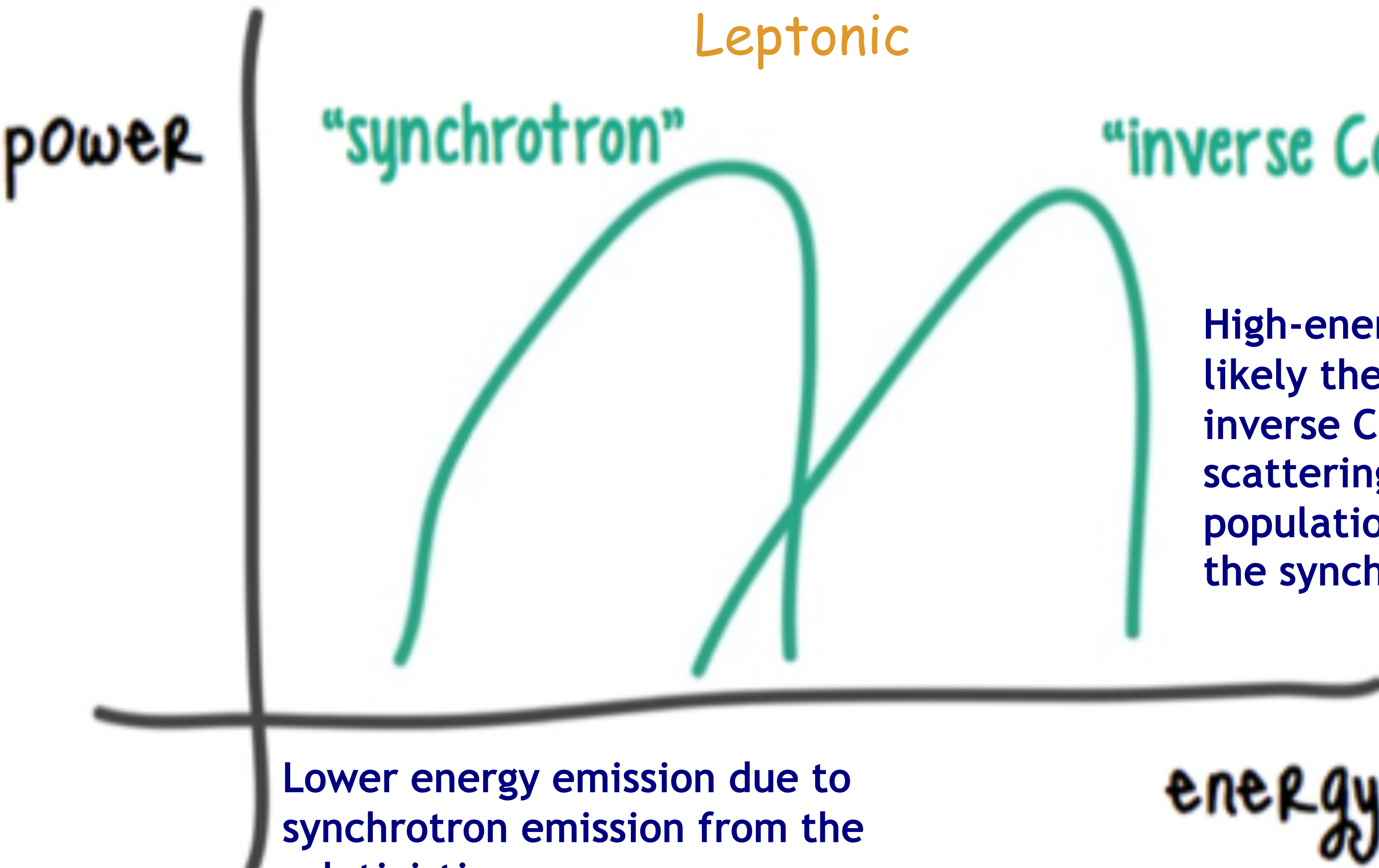
AGN Classes (it all depends on the point of view)



Blazars:
- FSRQ
- BL Lacertae Objects

Beckmann Shrader arXiv:1302.1397

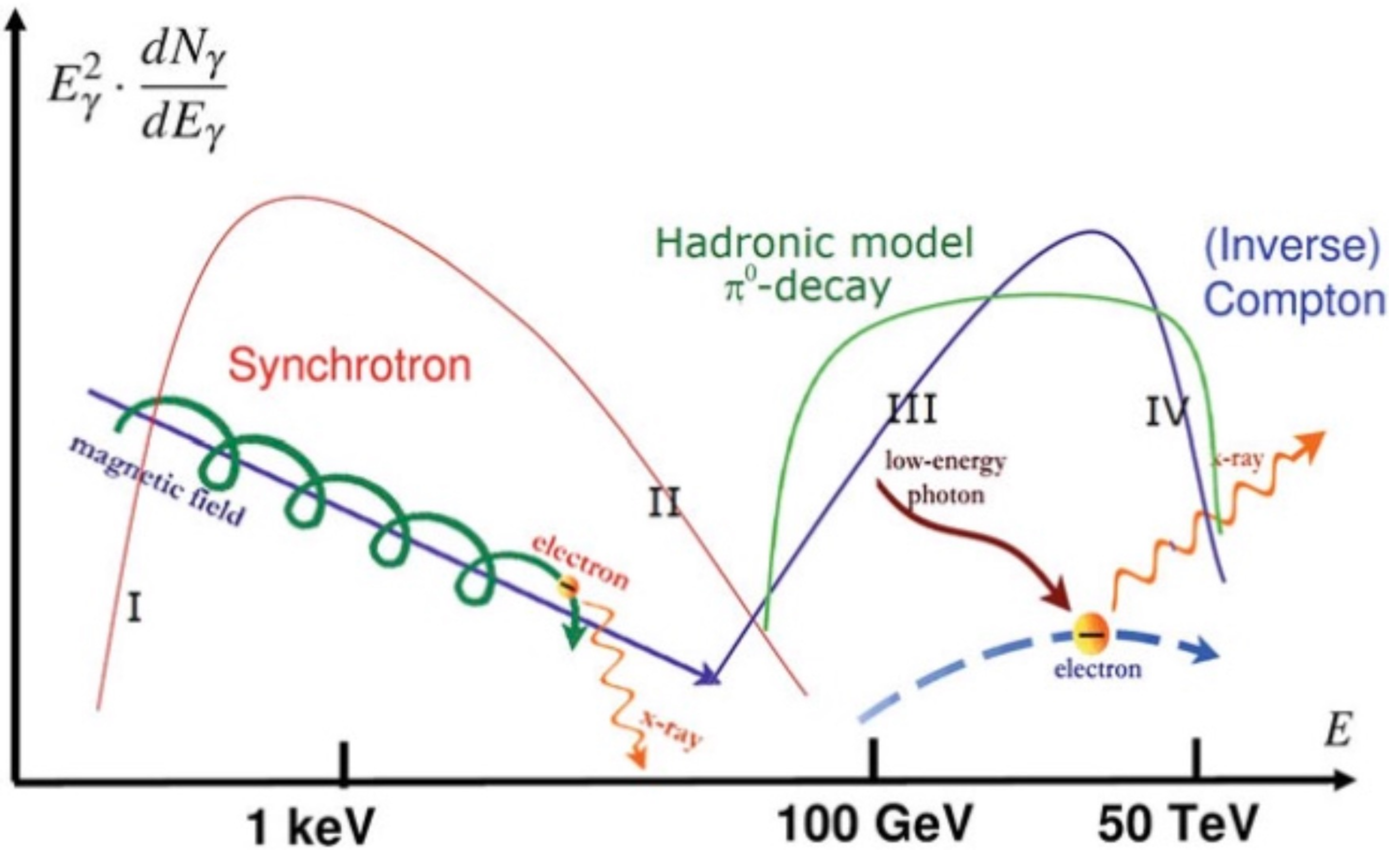
Model of blazar emission



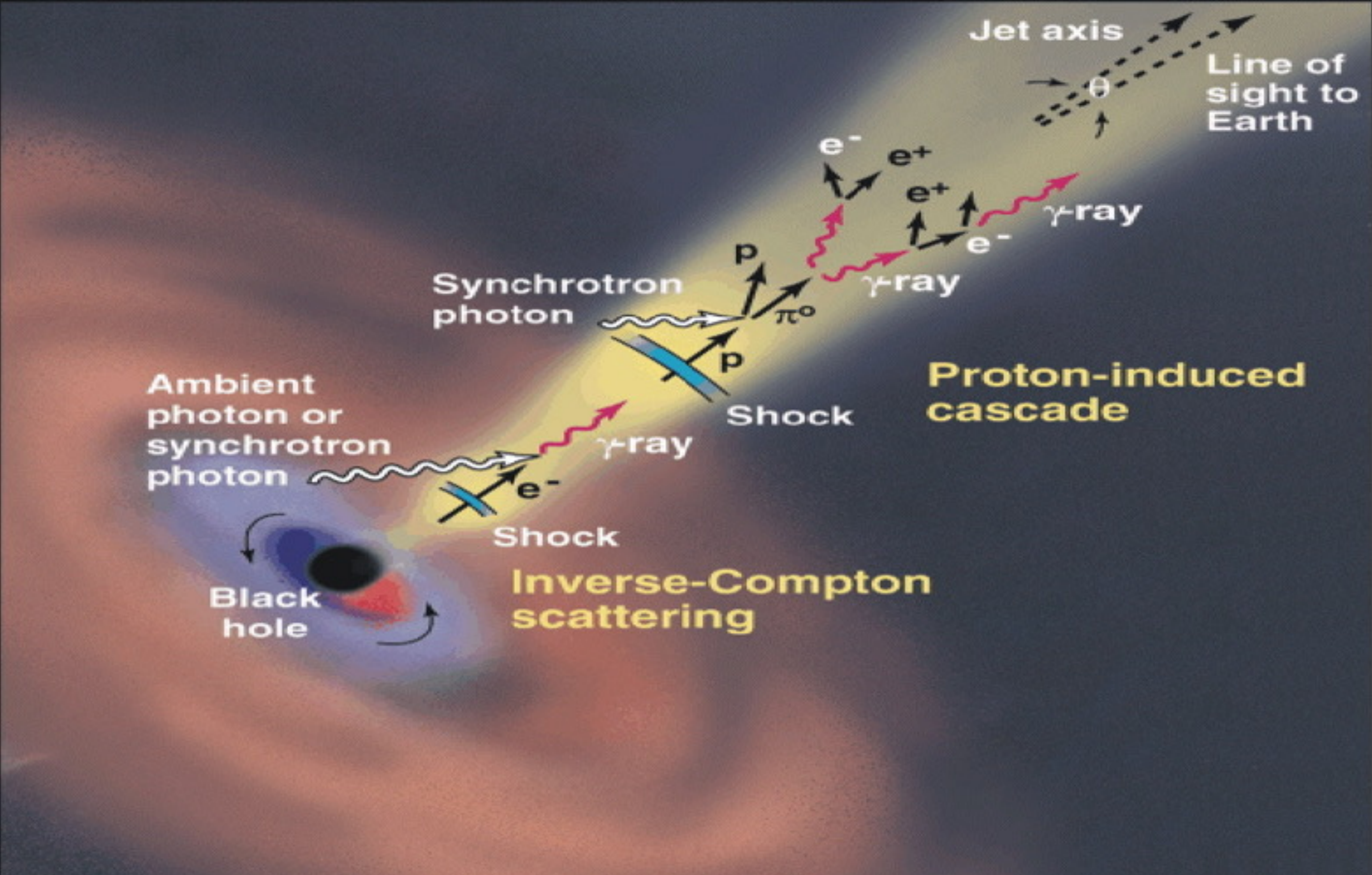
High-energy photons most likely the result of inverse Compton scattering by the same population that produced the synchrotron

Lower energy emission due to synchrotron emission from the relativistic e-s in the jet

Model of blazar emission



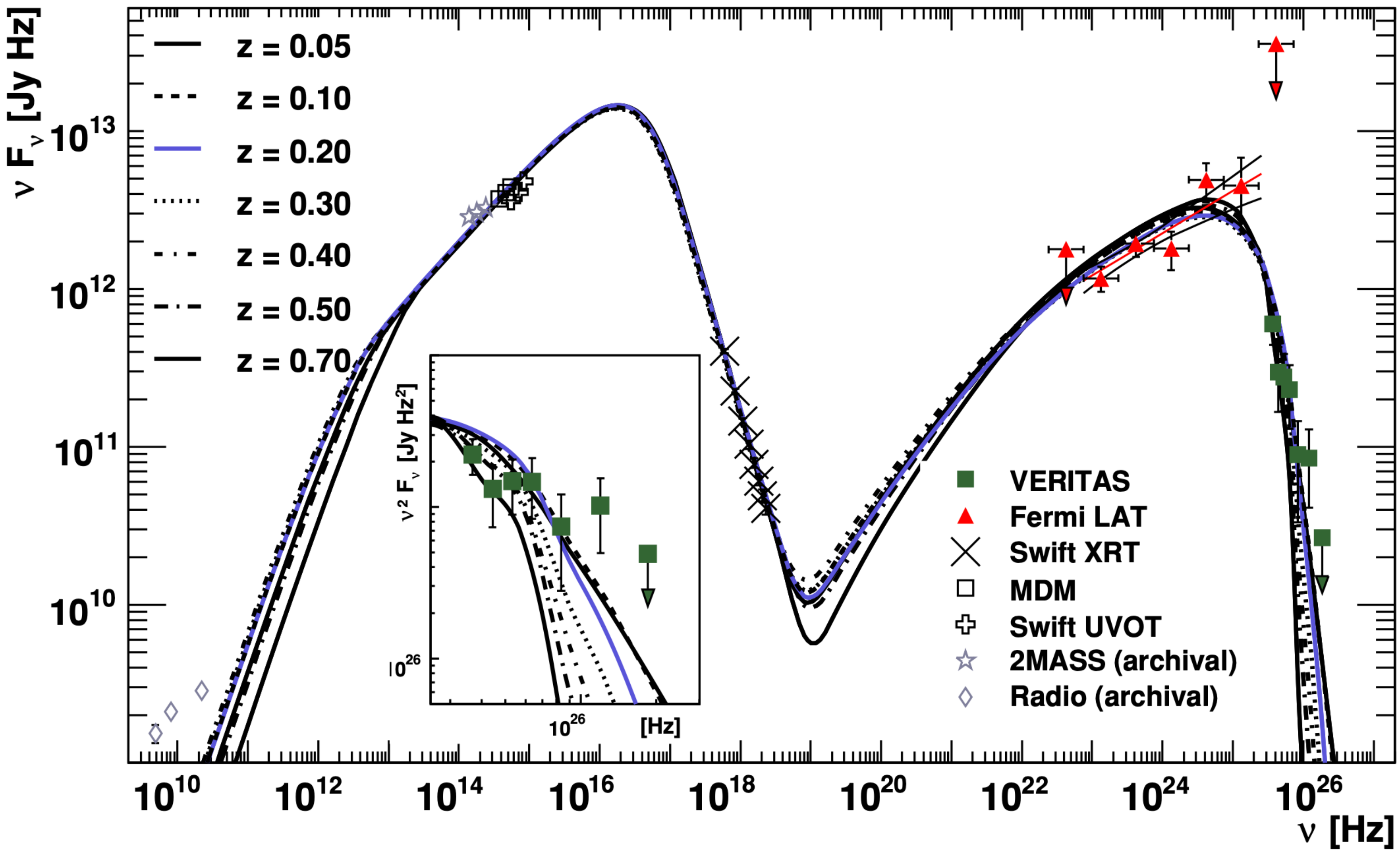
Spectral energy distribution of photons produced in leptonic/hadronic models. Synchrotron radiation is caused by relativistic electrons accelerated in a magnetic field. Photons from synchrotron emission represent also the target for inverse Compton scattering of the parent electrons. When hadrons interact with matter or ambient photons, a distribution of γ-rays from π^0 decays as indicated by the *green* curve could be obtained. Superimposition of γ-rays from both leptonic and hadronic mechanisms is assumed in case of mixed models



Models for High Energy Emission: A cartoon

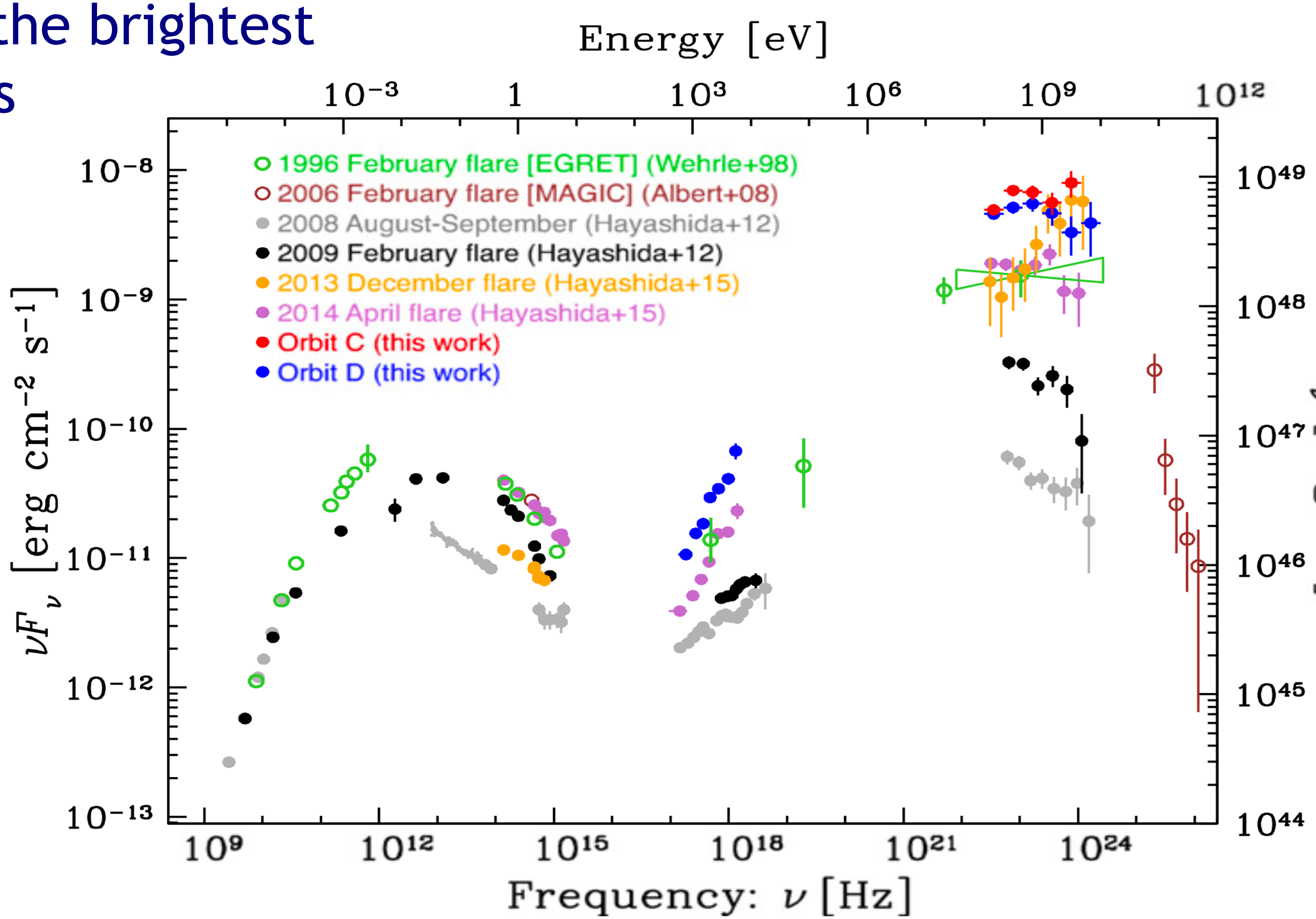
Blazars - BL Lac

Leptonic model provide a good fits to many blazars



Discovery of Very High Energy Gamma Rays from PKS 1424+240 and Multiwavelength Constraints on Its Redshift, Fermi Coll. Astrophysical Journal Letters, 708(2010) L100–L106

3C 279: One of the brightest powerful blazars



the observed variability timescale constrains the characteristic size of the emitting region radius

$$R_\gamma < \mathcal{D} c t_{\rm var,obs}/(1+z) \simeq 10^{-4}(\mathcal{D}/50)\,{\rm pc}$$

Minute-Timescale >100 MeV gamma-ray variability during the giant outburst of quasar 3C 279 observed by Fermi-LAT in 2015 June
Fermi Lat Coll. The Astrophysical Journal Letter 824 L20 2016 June 20 [arxiv:1605.05324]

in the future: Multimessenger observation of blazars with neutrinos

IC 170922A and TXS 0506+056

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
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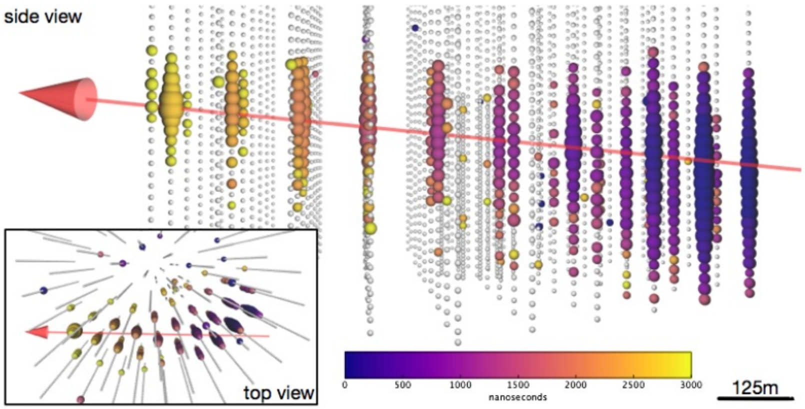
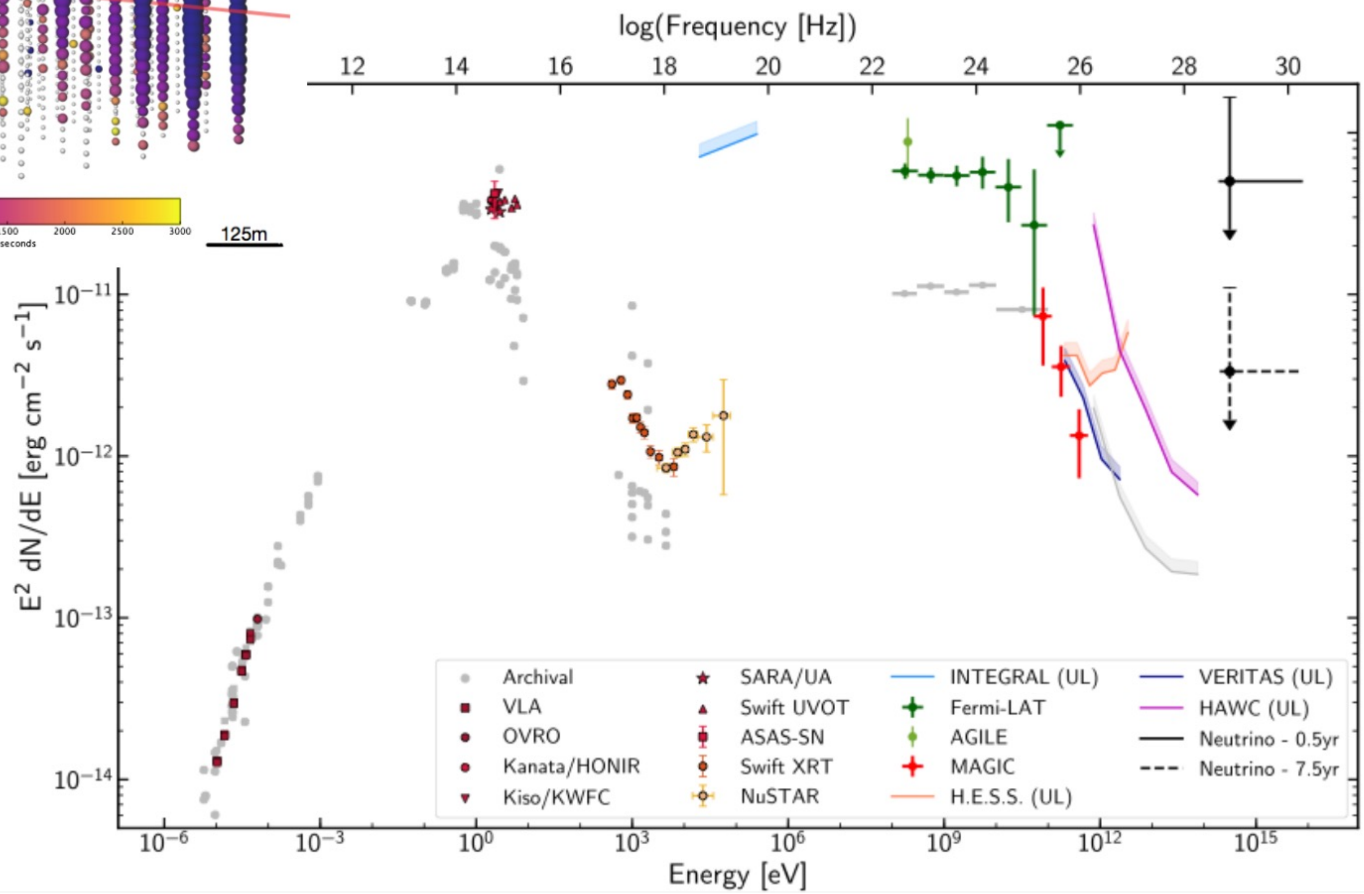
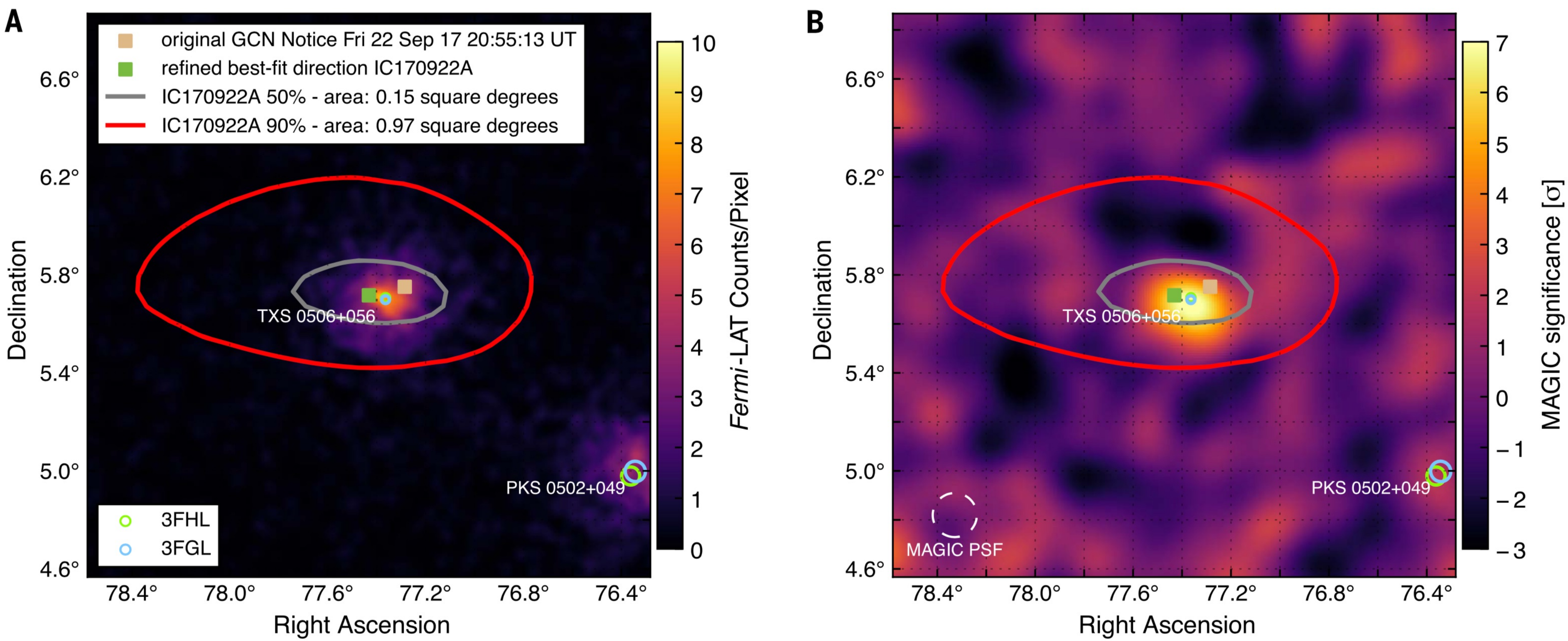




IceCube et al. 18

Multimessenger Astronomy: Neutrinos

- Are AGN sources of VHE neutrinos and thus of UHECR?
- The case of EHE 170922 (TXS 0506 +056)

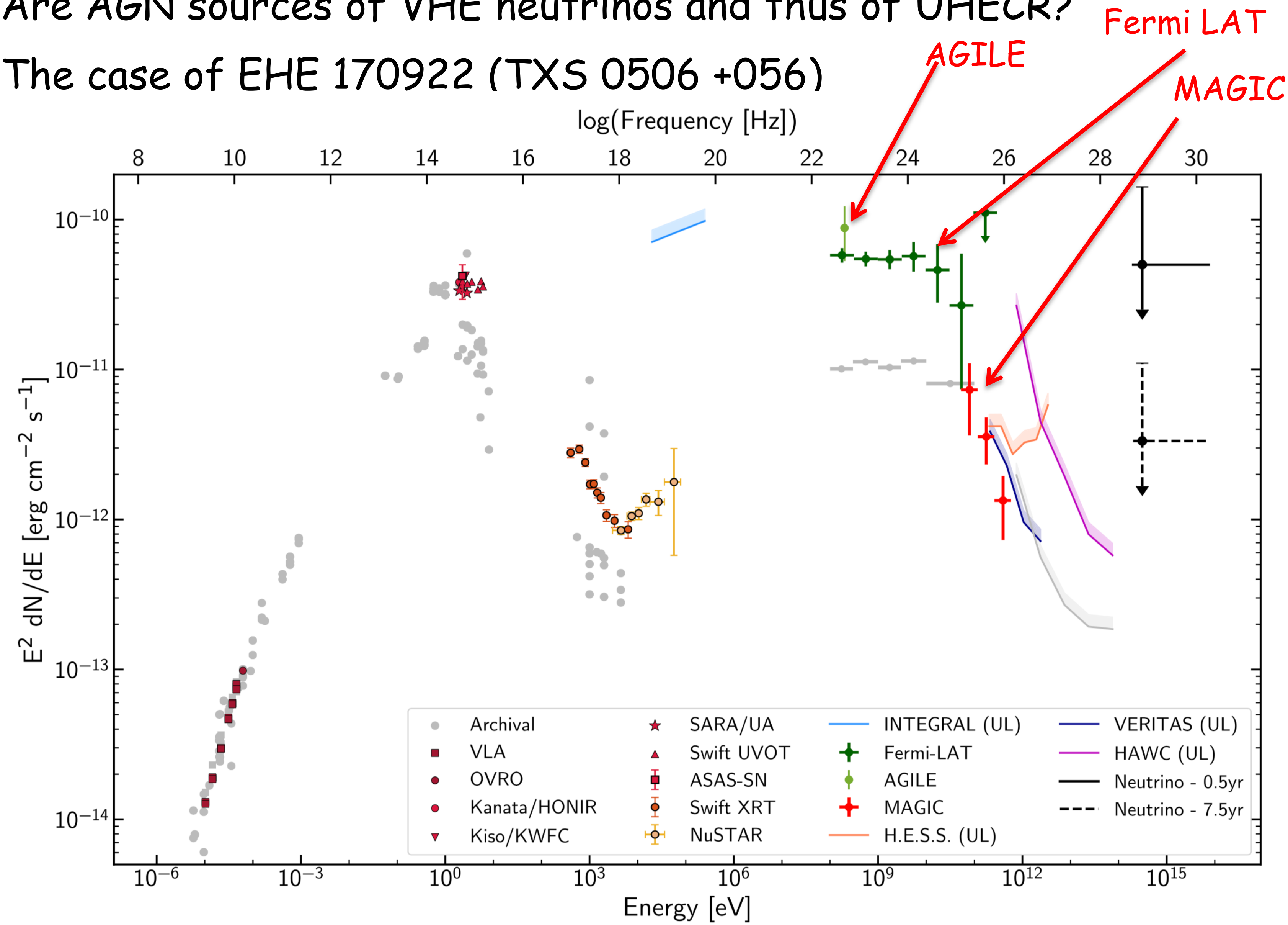


Fermi-LAT and MAGIC observations of IceCube-170922A's location.

Science 361, eaat1378 (2018) 12July

Broadband spectral energy distribution for the blazar TXS 0506+056

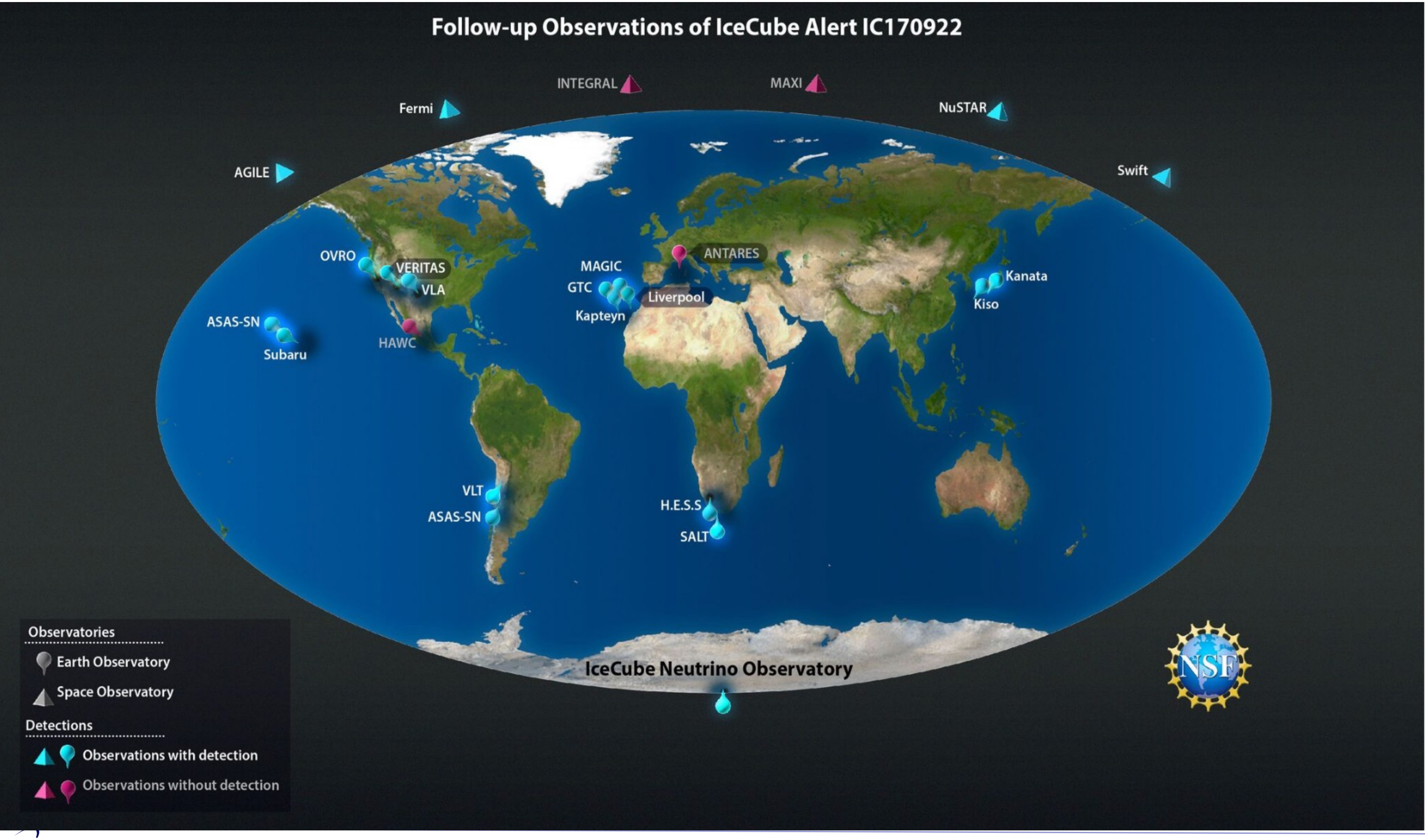
- Are AGN sources of VHE neutrinos and thus of UHECR?
- The case of EHE 170922 (TXS 0506 +056)



Science 361, eaat1378 (2018) 12July

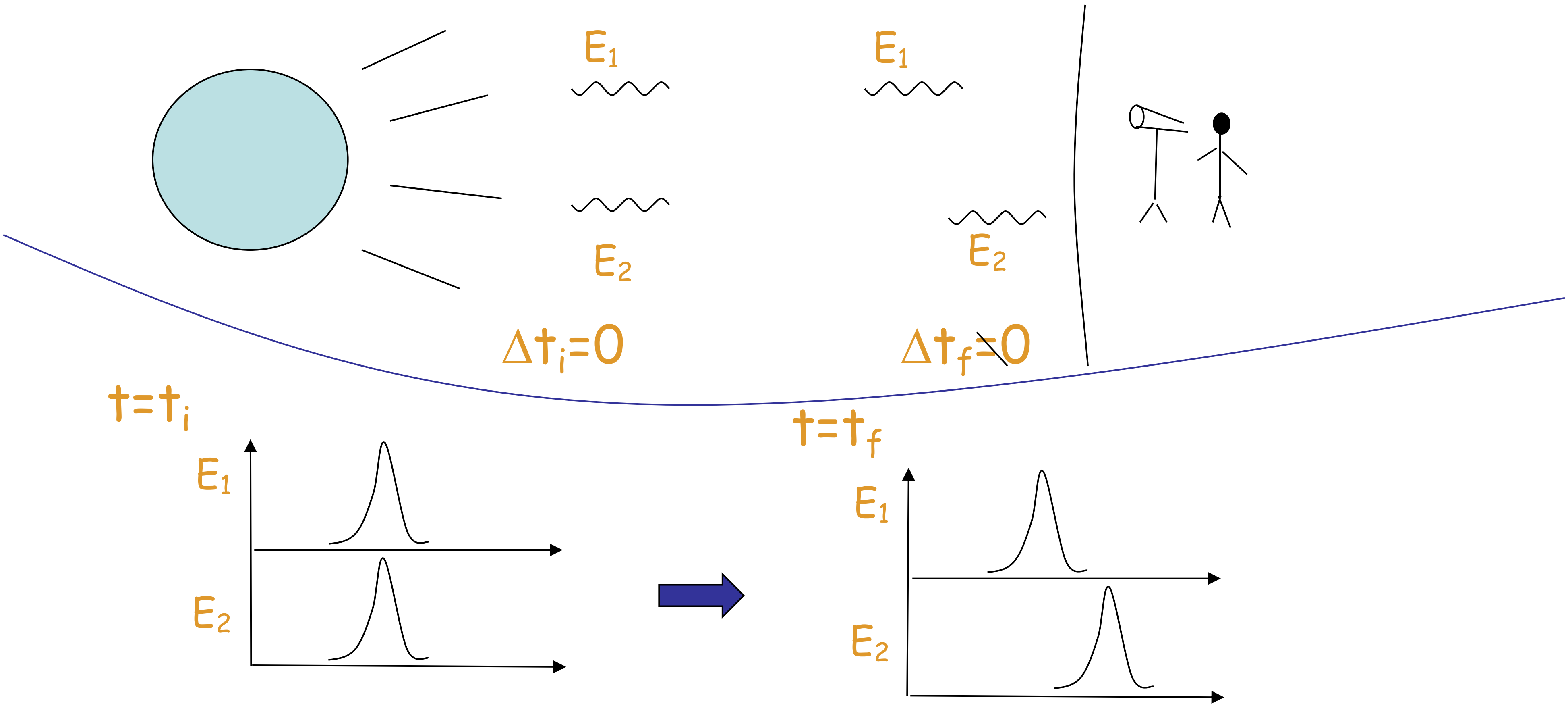
in the future: Multimessenger observation of blazars with neutrinos

IC 170922A and TXS 0506+056



Test of Quantum Gravity (2)

$\Delta t = \sim \alpha \, E/E_{QG} \, D/c$



$D \sim 2\ 10^{28}$ cm $\ E_{QG} \sim 10^{19}$ GeV $\ c \sim 3\ 10^{10}$ cm ➡ $\Delta t(\text{ms}) \sim 60\ \Delta E(\text{GeV})$

even at pulsars distance: • $D \sim 6\ 10^{21}$ cm $\Delta t(\mu s) \sim 100$ ➡ $E_{QG} \sim 10^{14}$ GeV

Test of Quantum Gravity

Candidate effect:

$$c^2 P^2 = E^2 (1+ f(E/E_{QG}))$$

E=photon energy E_{QG} =effective quantum gravity energy scale

Deformed dispersion relation with function f model dependent function of E/E_{QG}

if $E<< E_{QG}$ series expansion is applicable

$$c^2 P^2 = E^2 (1+ \alpha(E/E_{QG})+ O(E/E_{QG})^2)$$

$$\Rightarrow \quad v = \delta E/\delta P \sim c (1+ \alpha(E/E_{QG}))$$

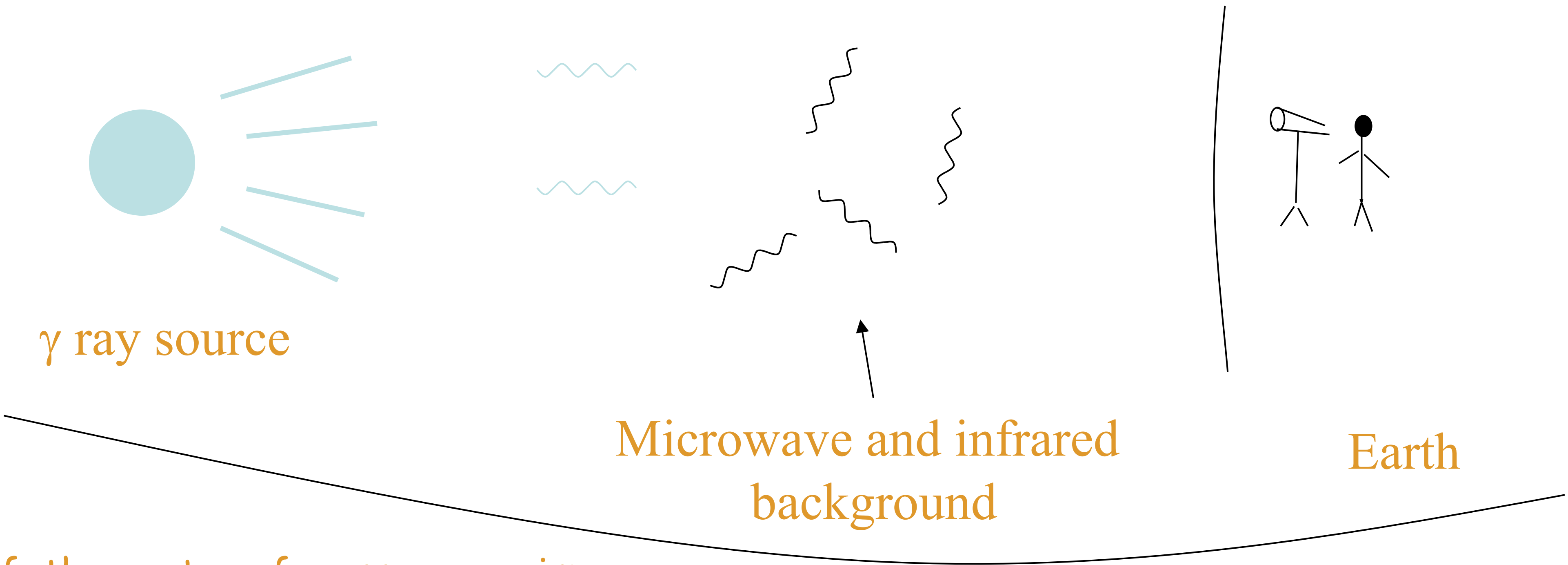
vacuum as quantum-gravitational medium which respond differently to the propagation of particle of different energies.

(analogous to propagation through an electromagnetic plasma)

Medium fluctuation at a scale of the order of $L_p \sim 10^{-33}$ *cm*

$$\Rightarrow \quad \Delta t = \sim \alpha\, E/E_{QG}\, D/c$$

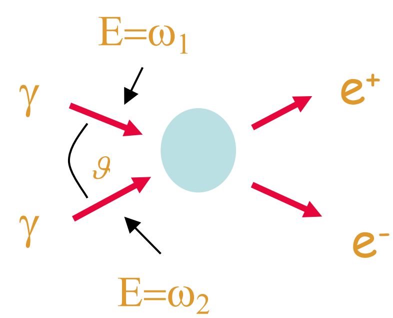
Flux absorption due to the interaction with the infrared and microwave background



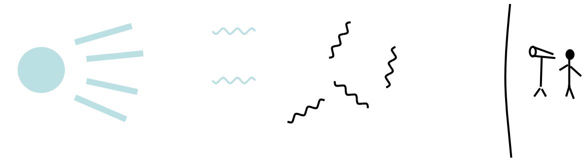
if the center of mass energy is:

$$\sqrt{2\omega_1\omega_2(1-\cos\vartheta)} \geq 2m_e$$

photons interactions produce electron positron pairs



Flux absorption due to the interaction with the infrared and microwave background



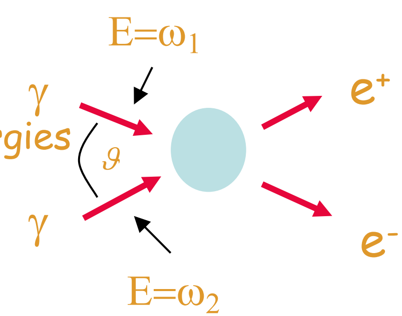
The cross section of the process $\gamma\gamma \to e^+e^-$ is:

$$\sigma_{\gamma\gamma} = \frac{\pi r_e^2}{2}(1-v^2)\left\{(3-v^4)\ln\left(\frac{1+v}{1-v}\right) - 2v(2-v^2)\right\}$$

where r_e is the classical radius of the electron and:

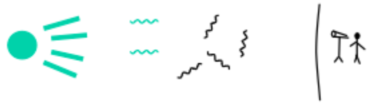
$$v = \sqrt{1 - \frac{4m_e^2}{2\omega_1\omega_2(1-\cos\vartheta)}}$$

ω_1 and ω_1 are respectively the energies of the low and the high energies gamma ray and ϑ is their angle of incidence.



Flux absorption due to the interaction with the infrared and microwave background

the ratio between the flux I(L) at a distance L from the source and the initial flux I can be written as:



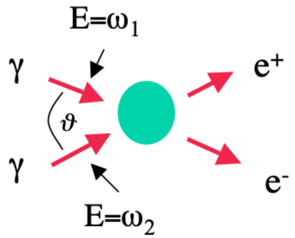
$$I(L)/I_o = \exp(-k_\gamma L)$$

where k_γ is the absorption coefficient:

$$k_\gamma = \frac{1}{2}\int_0^\infty \int_{\vartheta*}^{\pi} \frac{dn_\gamma}{d\omega_1} \sigma_{\gamma\gamma} \sin\vartheta \, d\vartheta \, d\omega_1$$

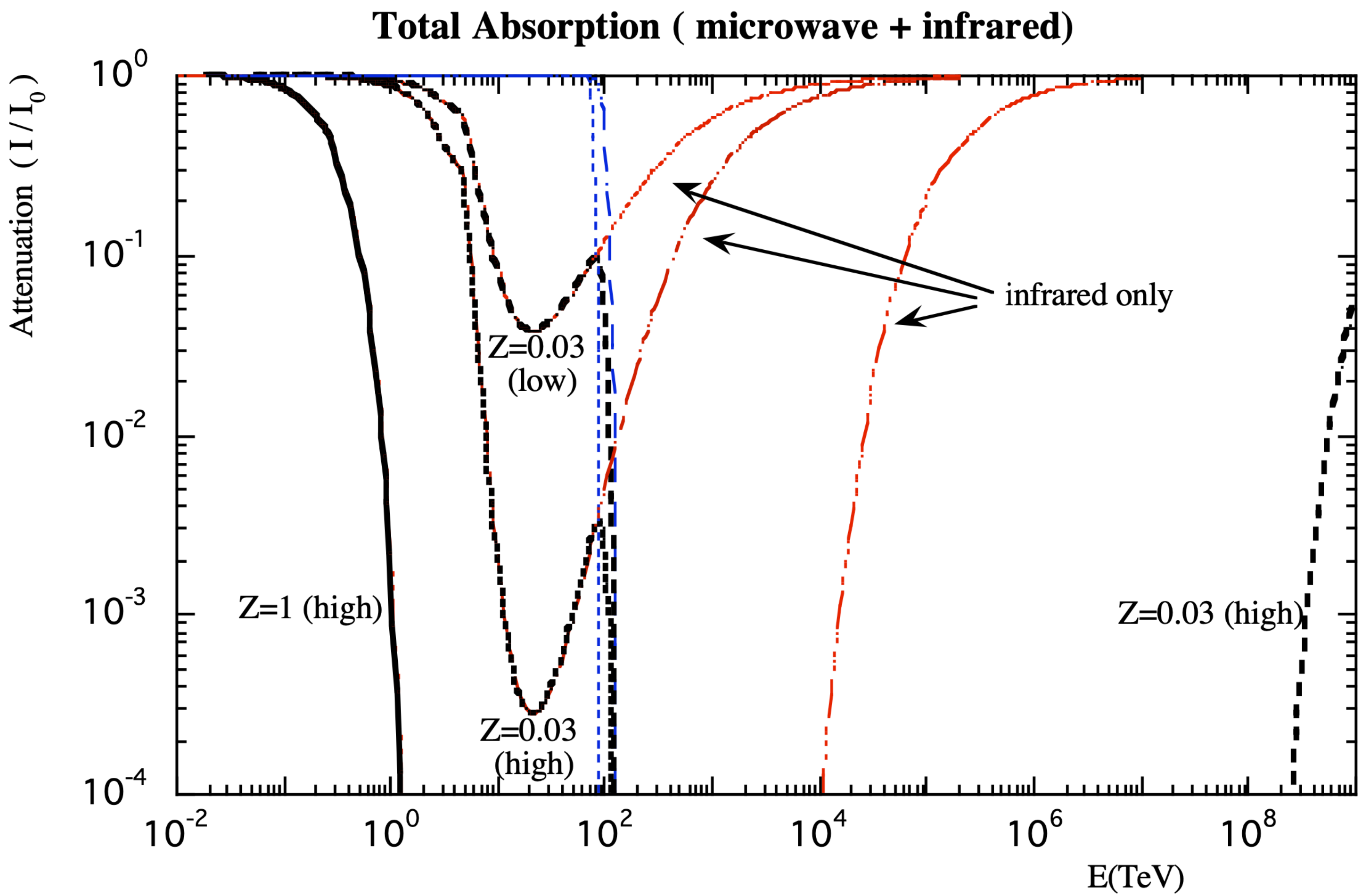
that contains the cross section and the low energy photon distribution.
For the microwave spectrum:

$$dn_\gamma/d\omega_1 = \frac{1}{\hbar^3 \; c^3 \; \pi^2} \frac{\omega_1^2}{\exp(\omega_1/kT) - 1}$$

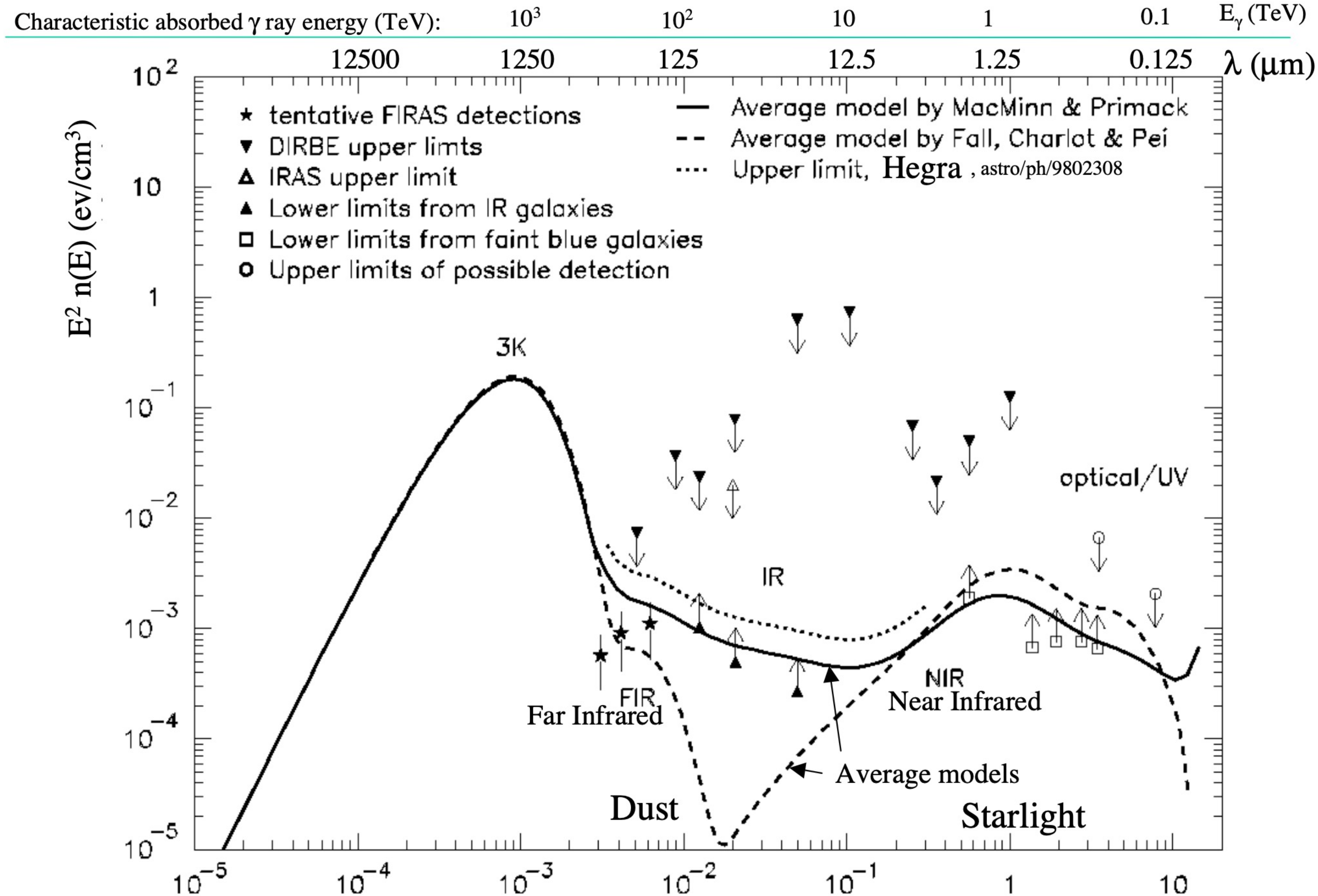


Ratio between surviving flux and initial flux versus photon energies for two different distances due to the sum of the infrared and black-body background

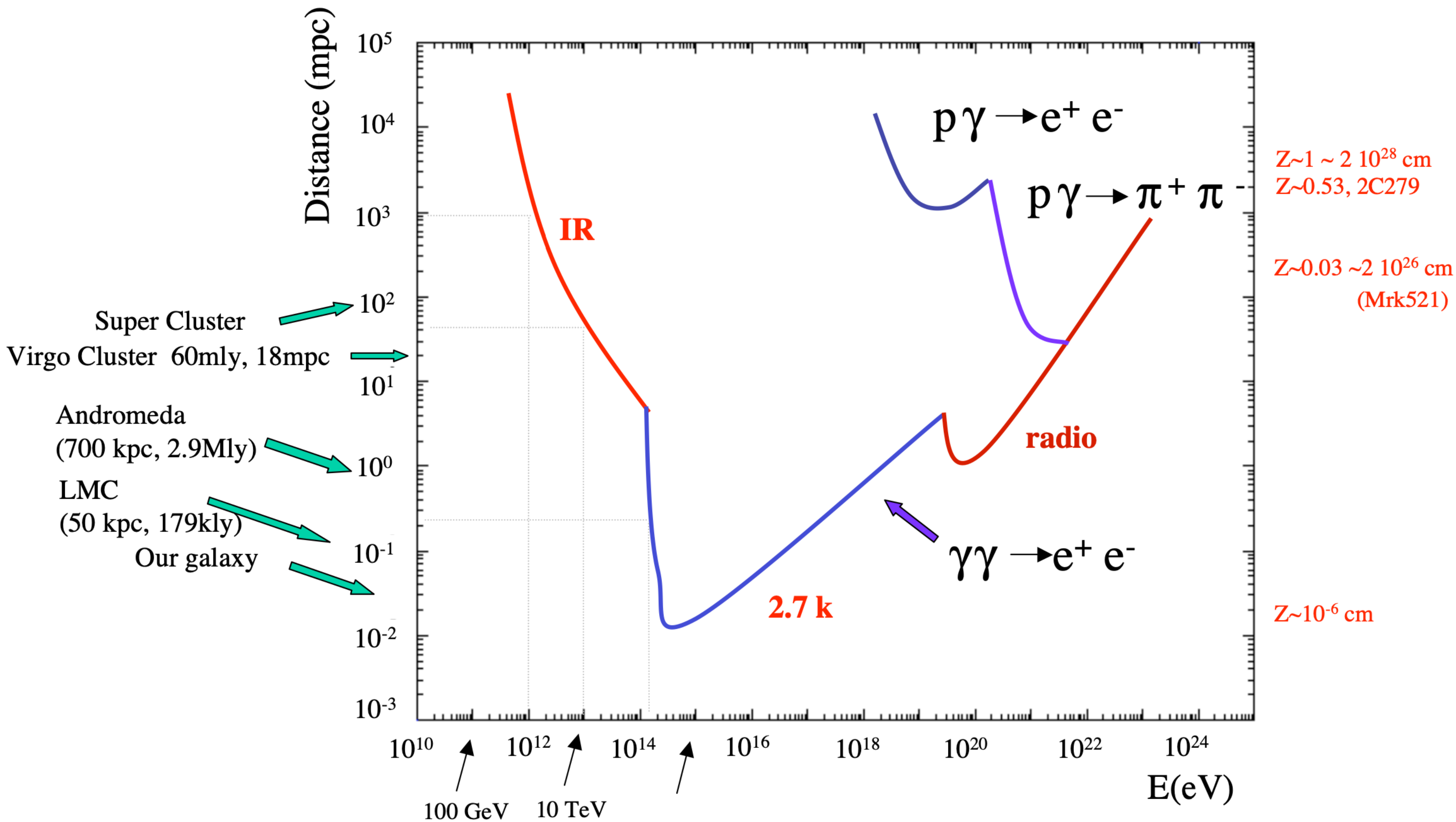
(4)



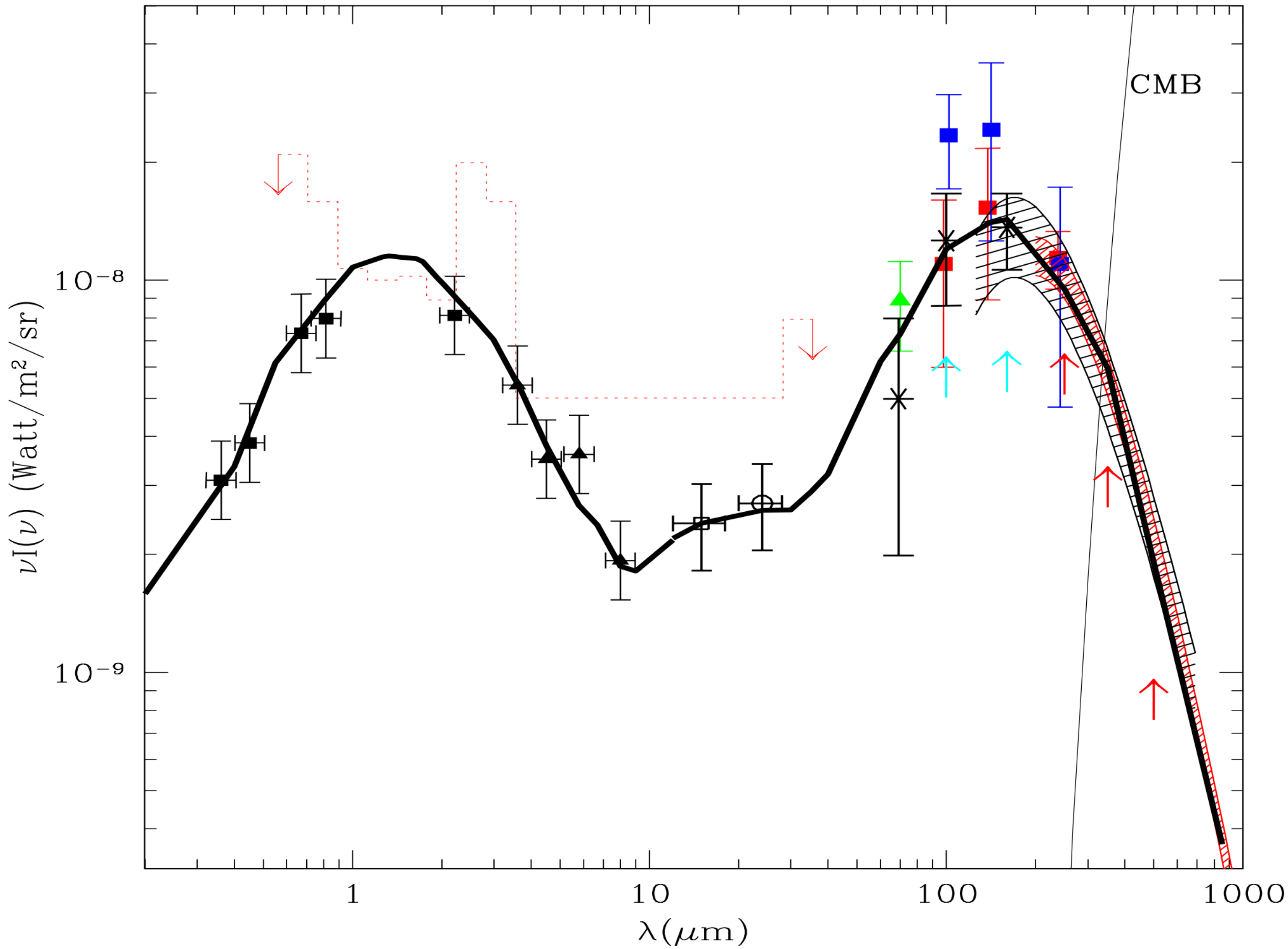
Energy density of the extragalactic diffuse background radiation



Transparency of the Universe

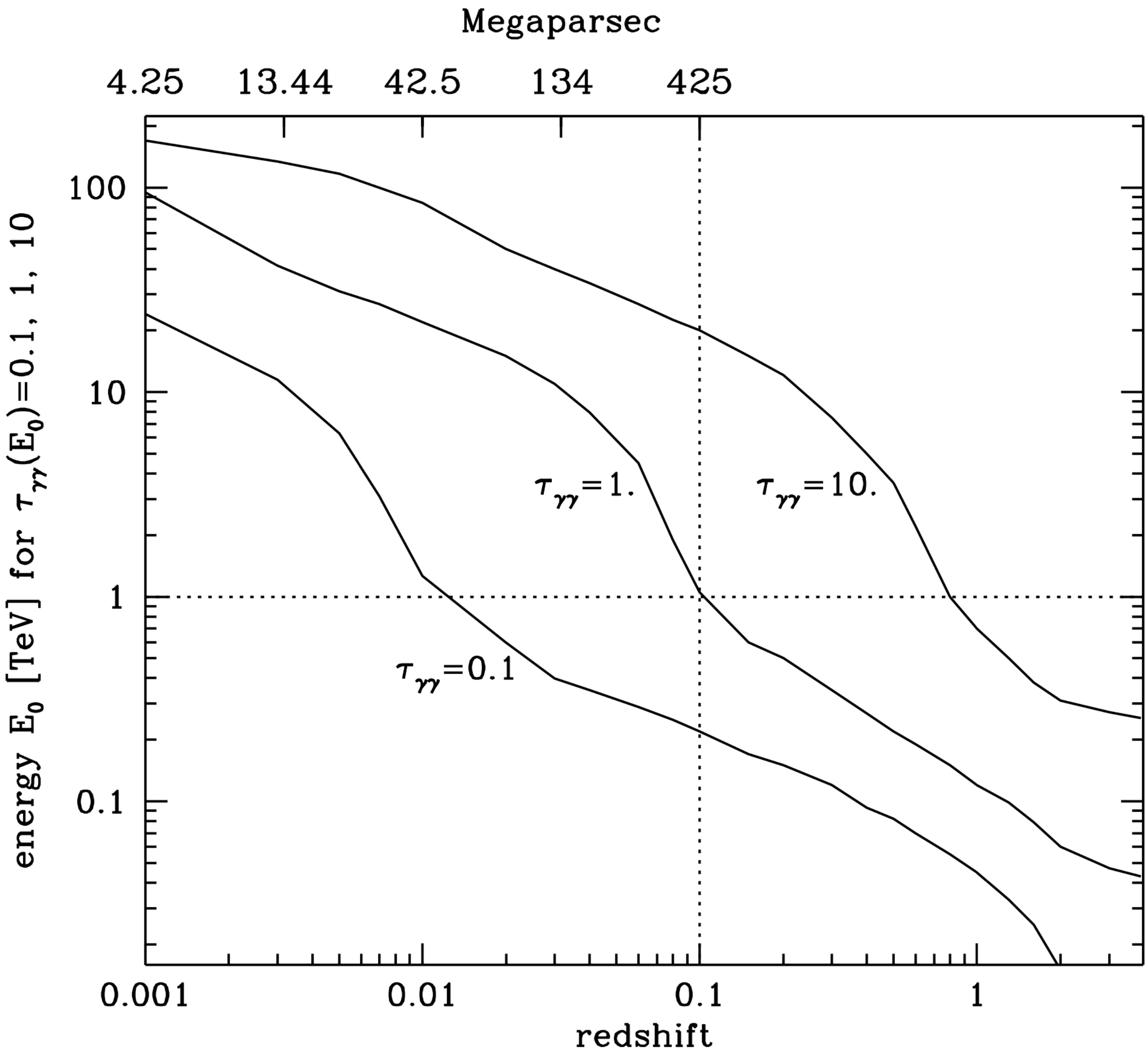


Energy density of the extragalactic diffuse background radiation



extragalactic background light revisited, Franceschini Rodighiero 1705.10256

The energies corresponding to optical depth values of different for photon-photon collisions, as a function of the redshift distance of the source



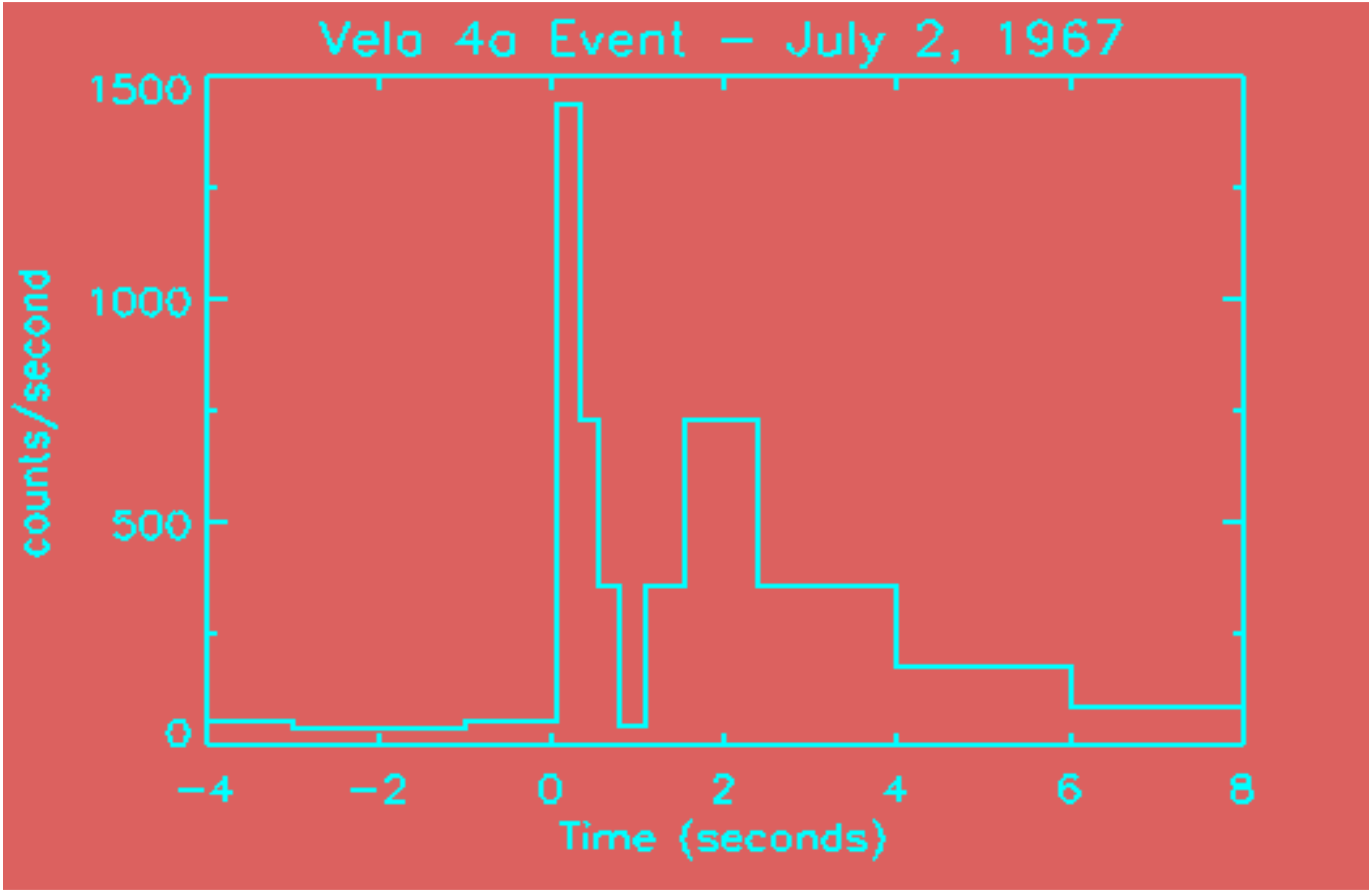
$P(\gamma\gamma) = e^{-\tau}$

extragalactic background light revisited Franceschini Rodighiero 1705.10256

Gamma ray burst GRBs

GRBs - Discovery (1967-1973)

- US Vela Nuclear test detection satellites



GRBs remained a complete mystery for almost 30 years !

- More than 150 different theories:
  - Magnetic flares
  - Black Hole evaporation
  - Anti-matter accretion
  - Deflected AGN jet
  - Magnetars, Soft Gamma-Ray Repeaters (SGRs)
  - Mini BH devouring NS
  - message from the Aliens
  - …..

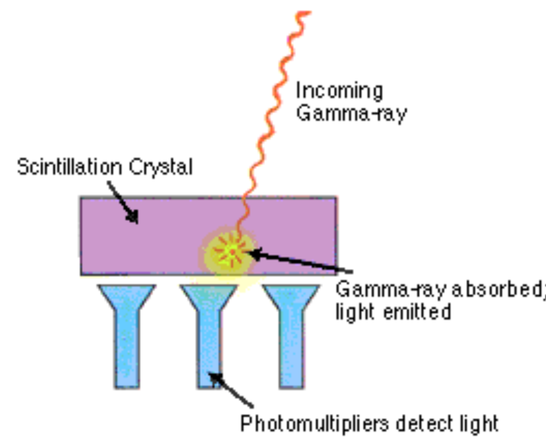
Compton Gamma-Ray Observatory (CGRO)

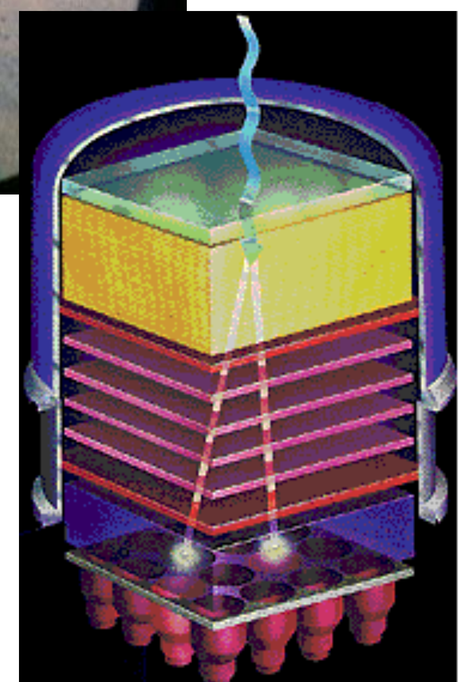
- CGRO launched in 1991(orbit above atmospheric absorption)

- **BATSE** (20 keV-1 MeV):

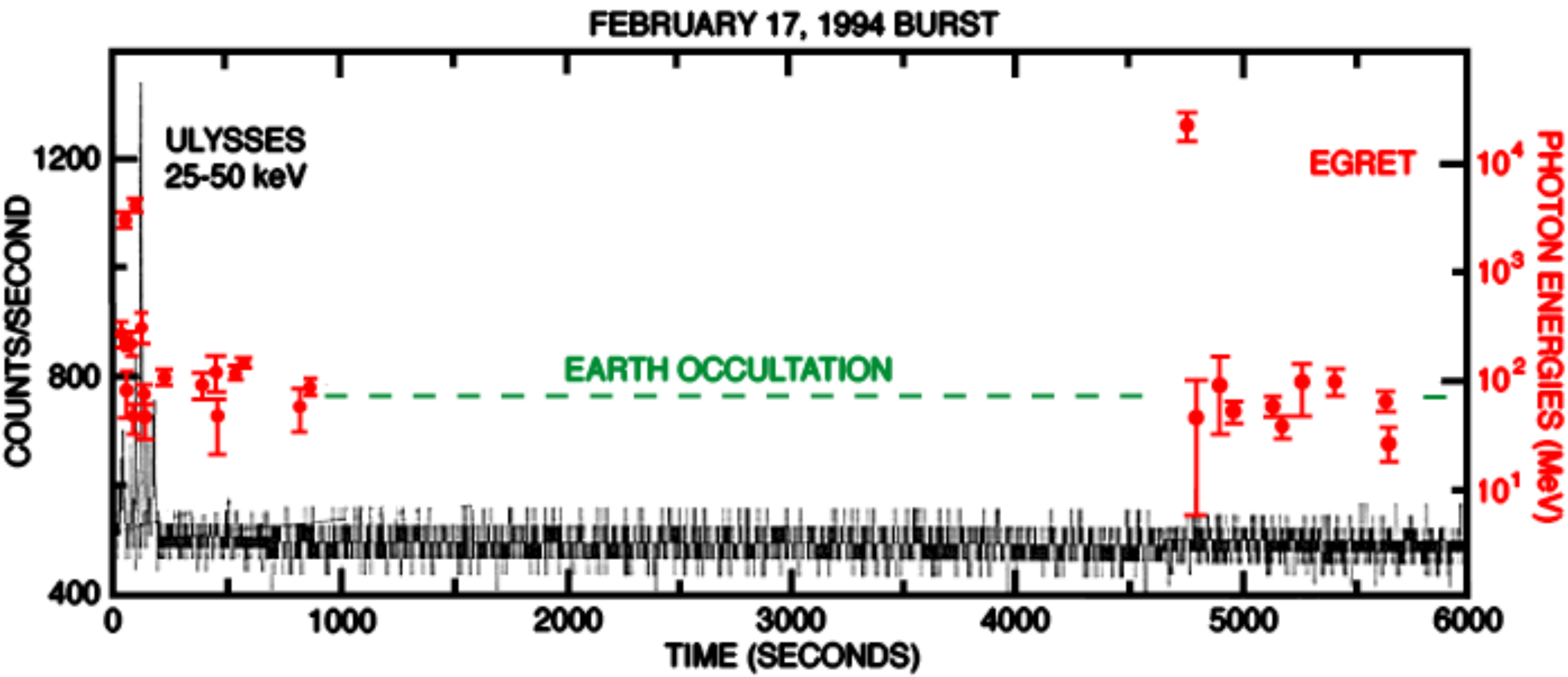
sensitive gamma-ray detector (scintillator)

- **EGRET** (20 MeV-30 GeV):
- Pair production detector
- looked at the whole sky
- GRB detection rate ~ 1 GRB/day
- thousands of GRBs detected over the whole mission





GRB studies with EGRET

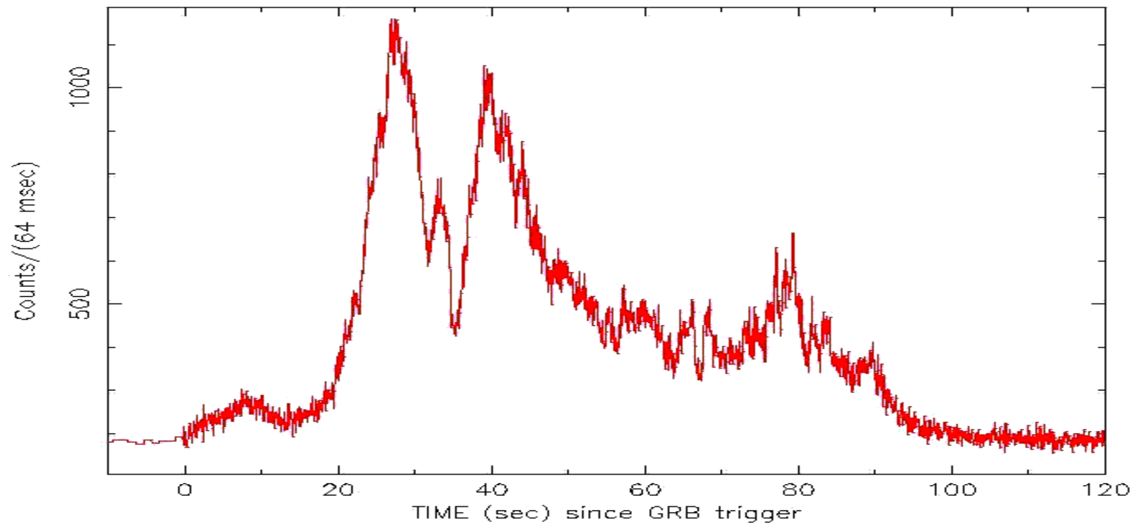


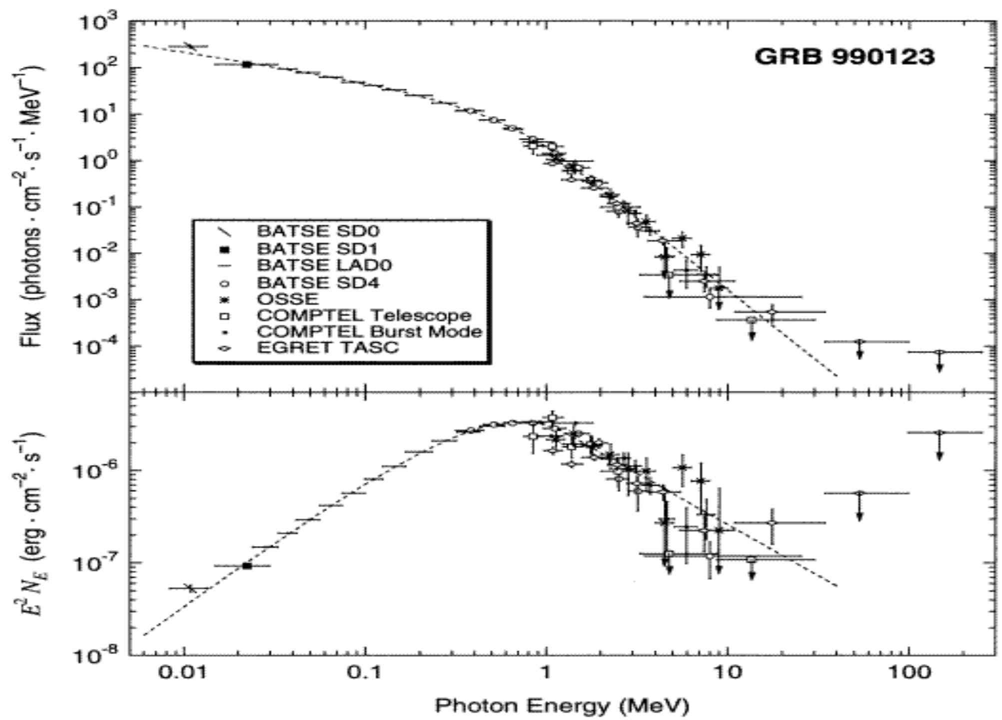
EGRET observed delayed GeV emission from the GRB of February 17, 1994, including a 20 GeV photon that arrived 80 minutes after the burst began. GLAST will make the definitive measurements of the high-energy behaviour of GRBs and GRB afterglows.

GRB lightcurve / spectrum

- Non thermal prompt emission
- Best spectral fit: smoothly joining broken power law

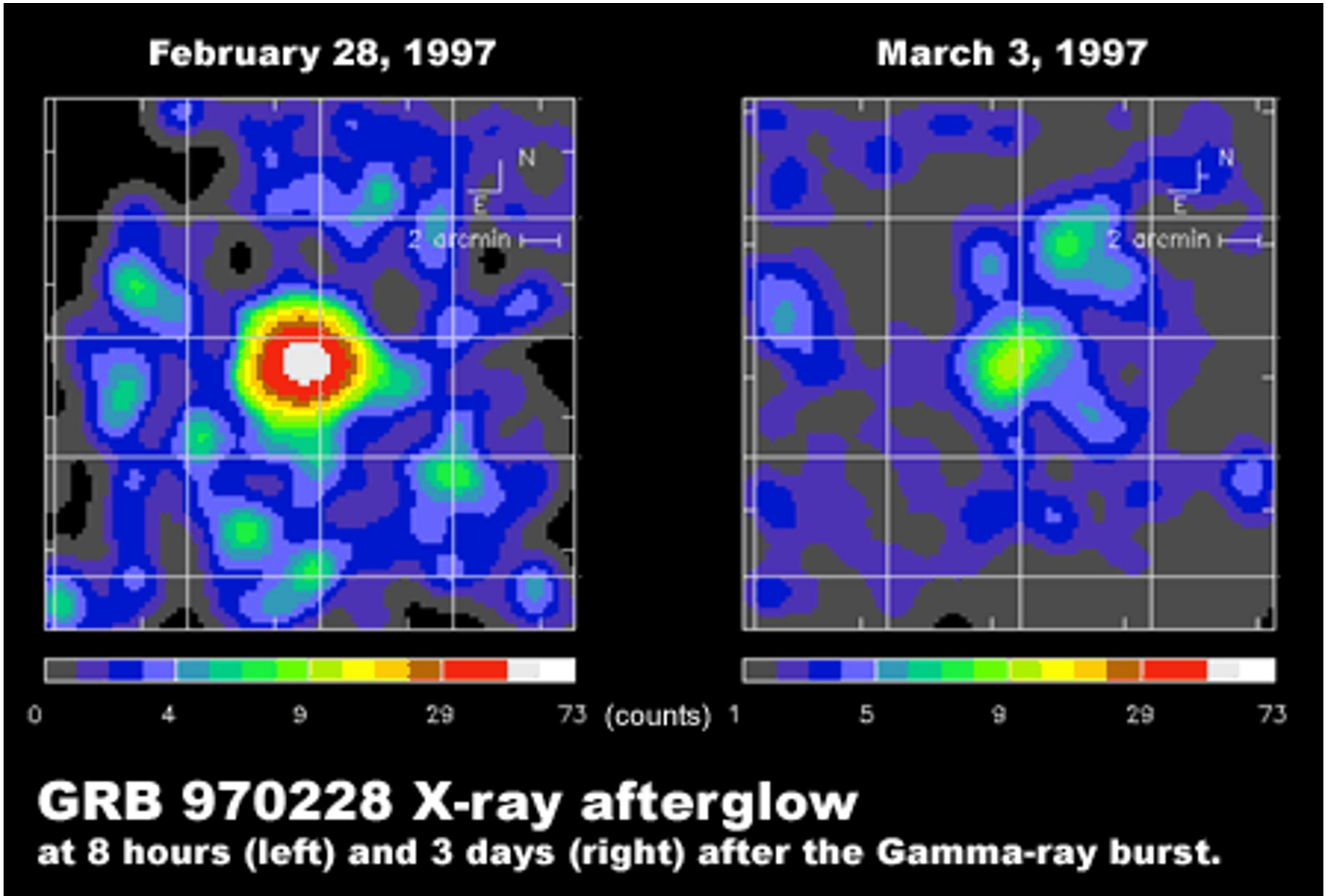
- <u>Compactness problem:</u>
  - Emitting region optically thin if emitting material has Lorentz factor > 100
  - -> Ultrarelativistic outflow (fastest bulk flow in the universe)





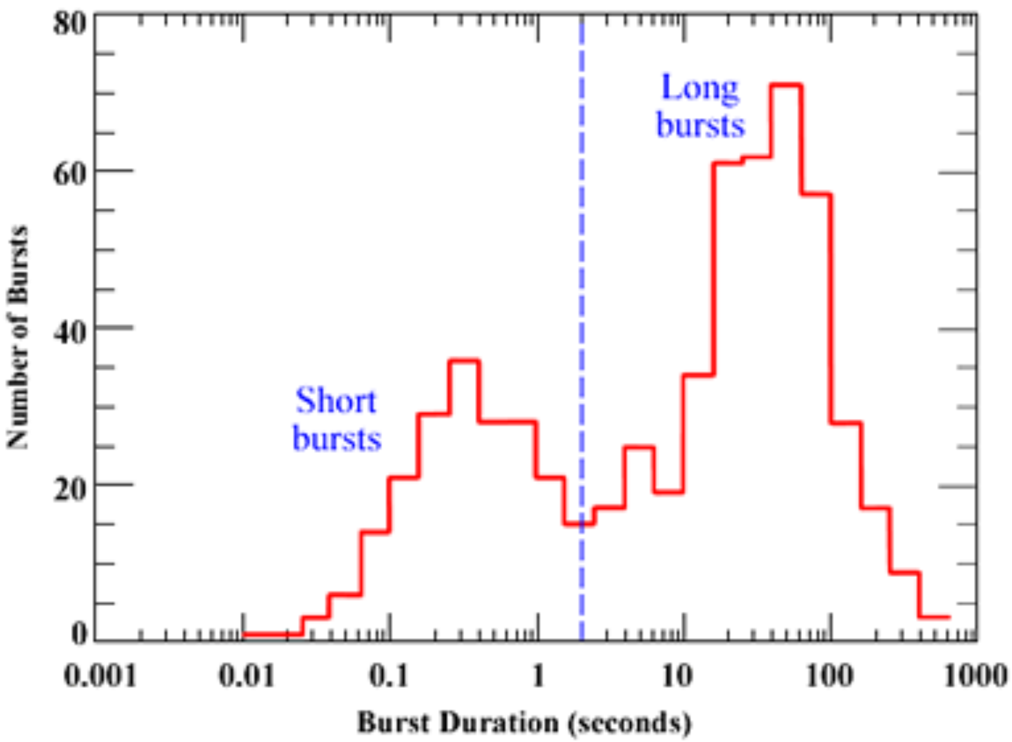
Galactic vs Cosmological origin

BeppoSAX: GRB 970228
1st X-ray/Optical afterglows detected
Host galaxy was identified at z ~ 0.7 !

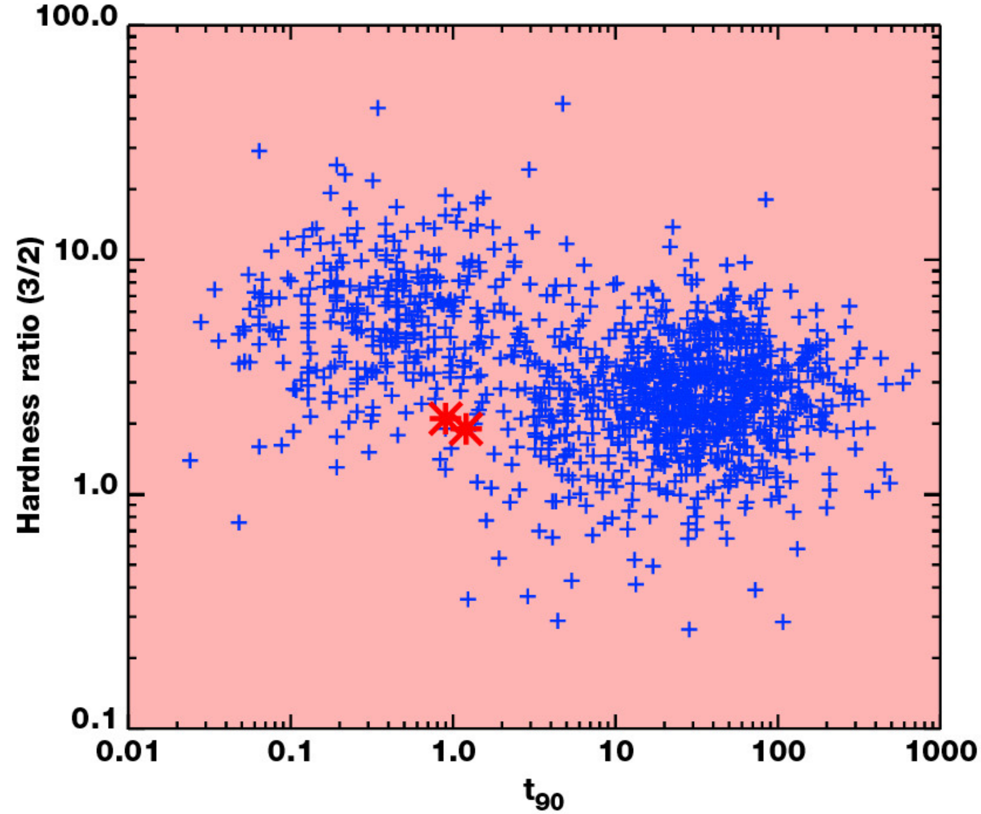


BATSE results

- 2 populations of GRBs:
  - Short-Hard / Long-Soft Bursts

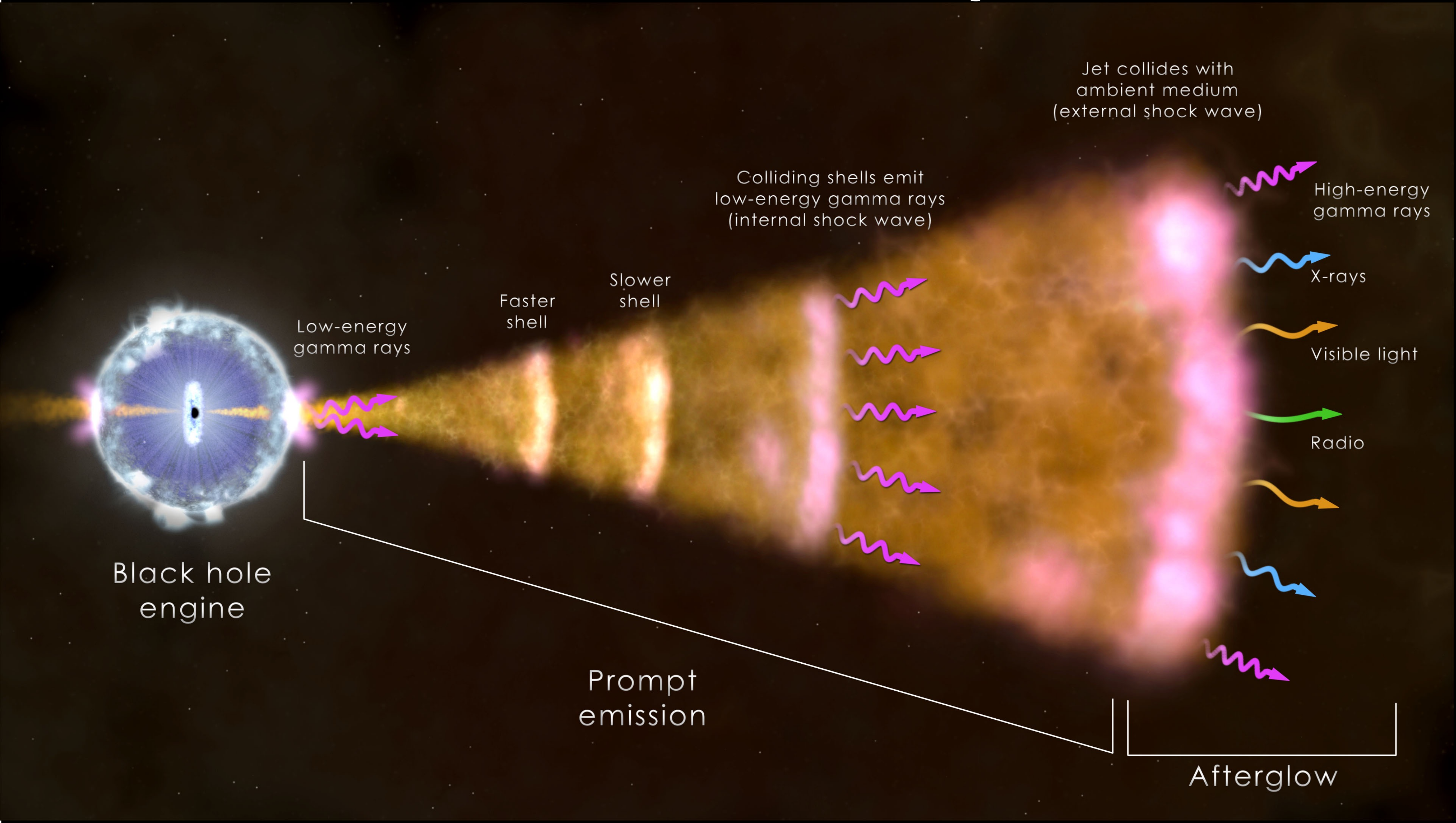


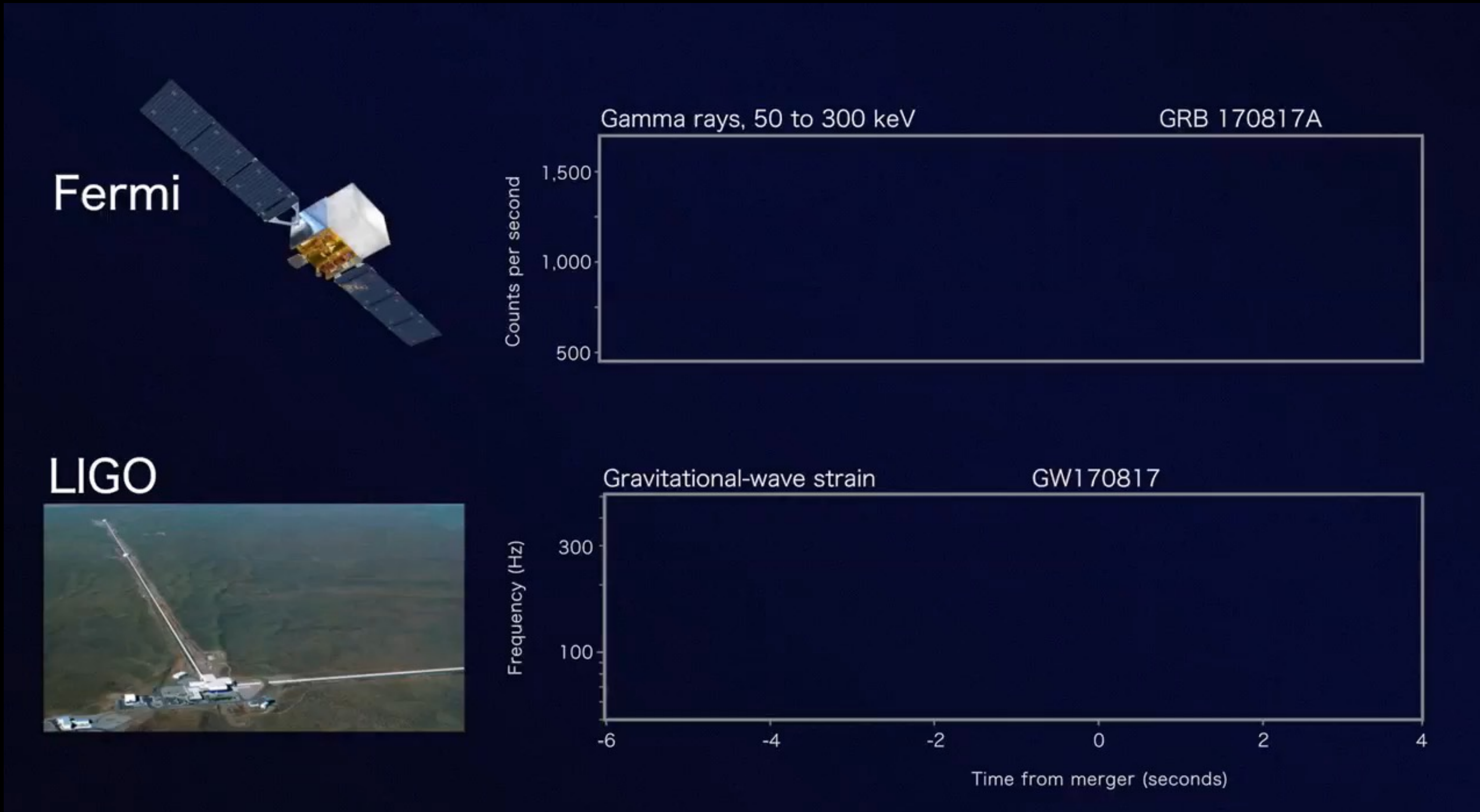
Burst duration



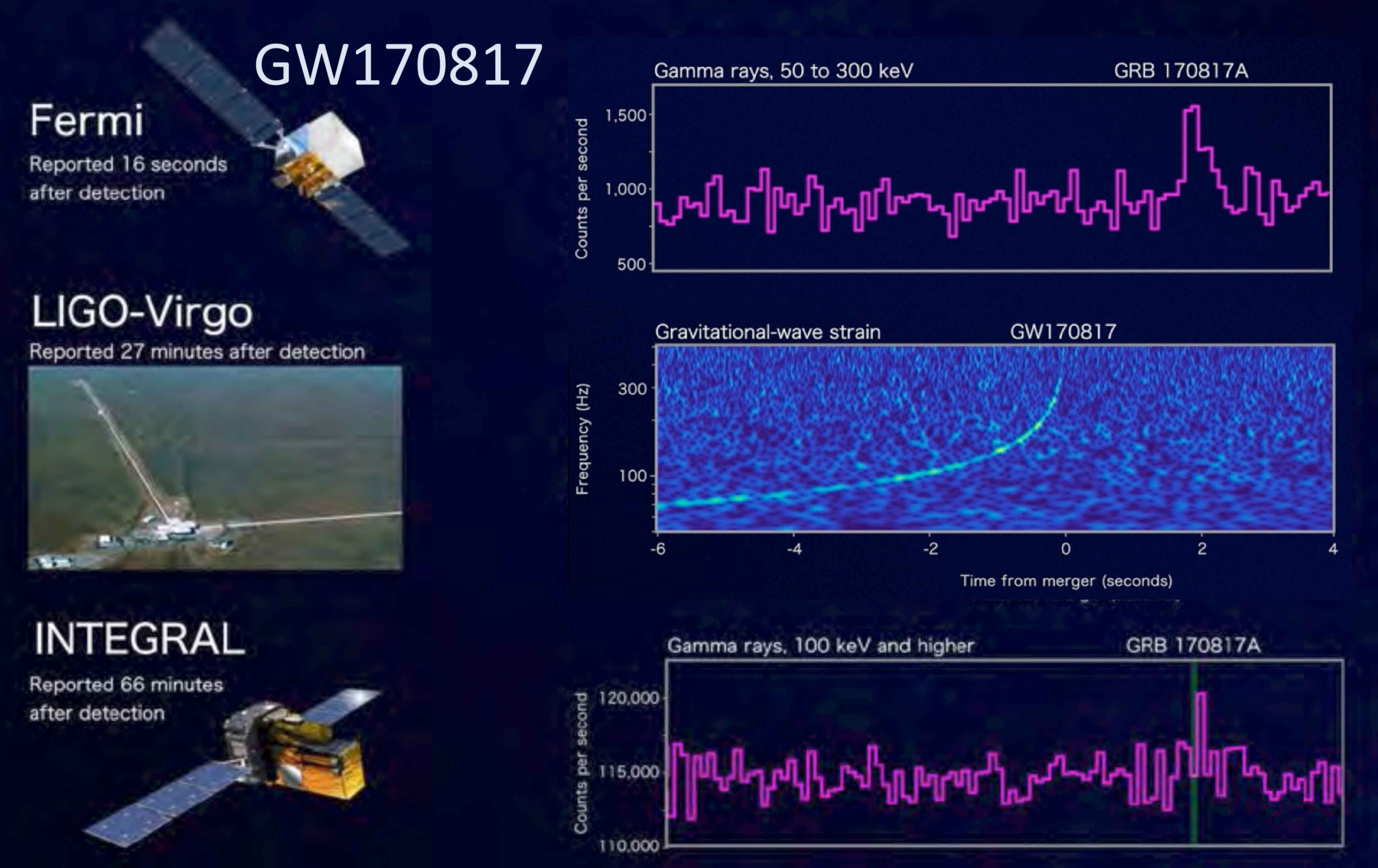
Hardness-duration diagram

Short Gamma Ray Burst



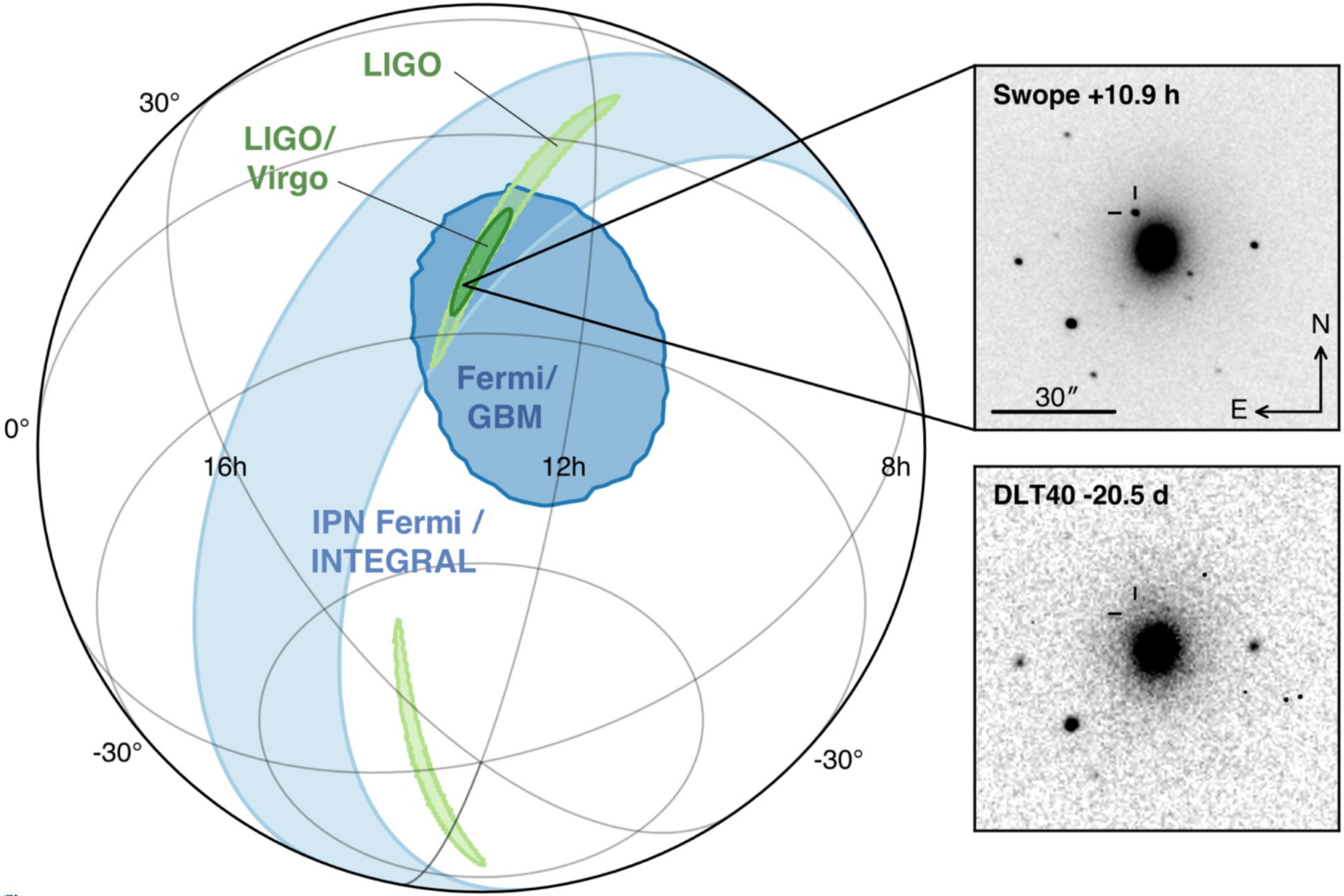


Credit: NASA‘ Goddard/Fermi Collaboration/LIGO Collaboration

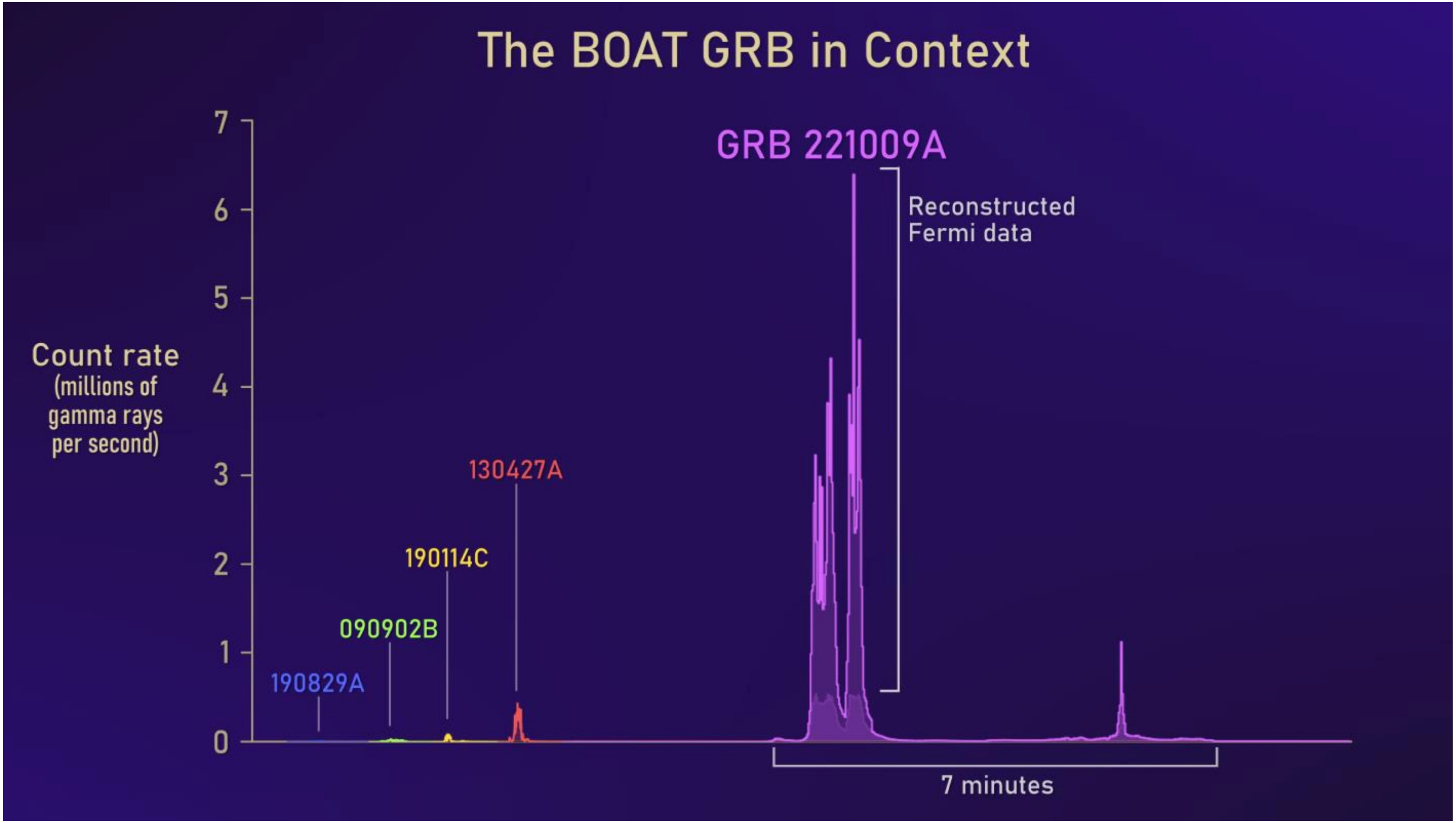


Multi-messenger Observations of a Binary Neutron Star Merger ApjL 848 L12 2017 [arXiv:1710.05833] 3656 authors !

THE MULTI-MESSENGER EVENT GRB170817A, GW170817



THE BOAT (BRIGHTEST OF ALL TIMES)

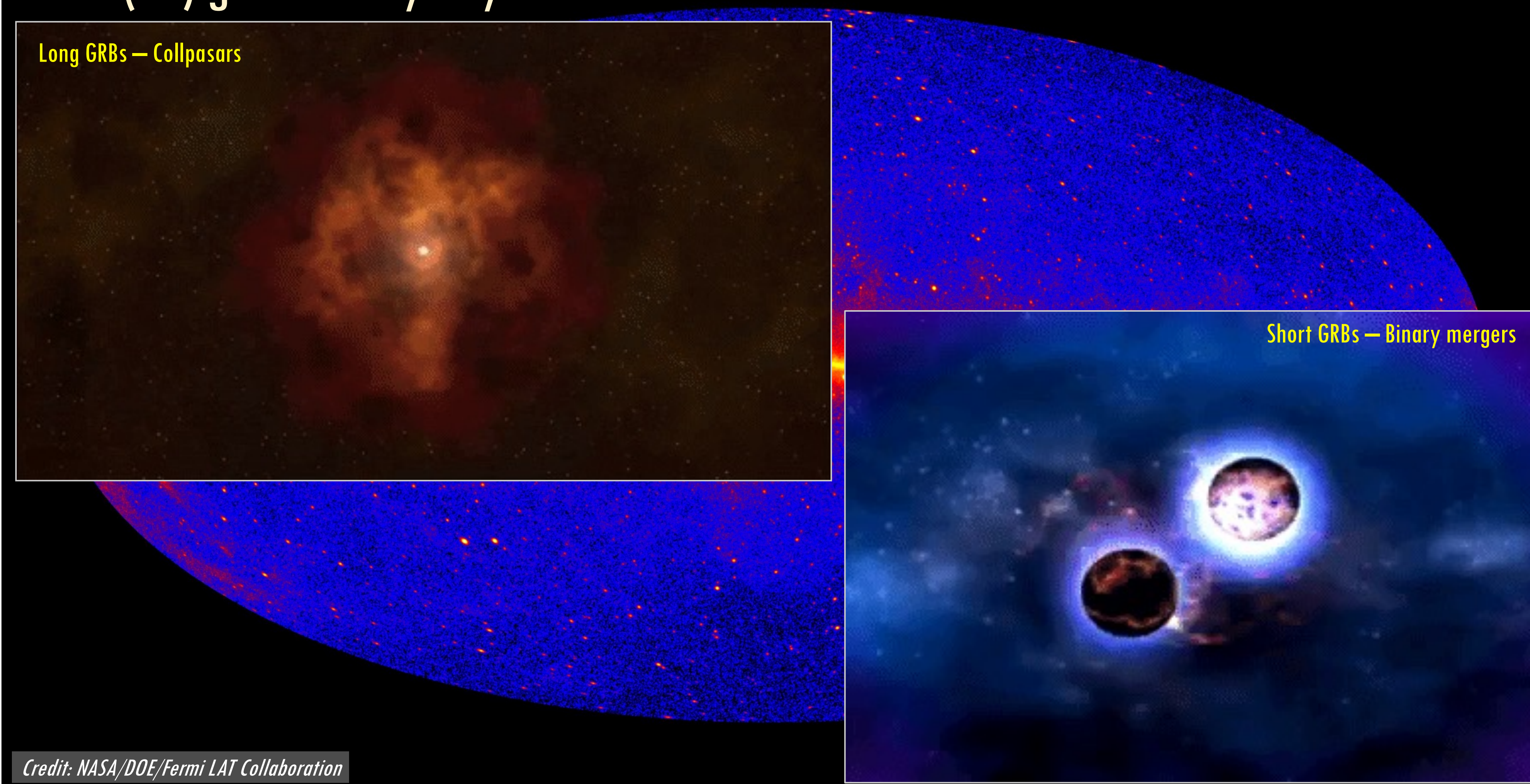


1-in-10000 year event ➤ Detected by Fermi GBM

➤ Severe saturation in GBM and LAT in main phase (Region IV)

➤ Detected by LHAASO and HAWC (IACTs: full moon)

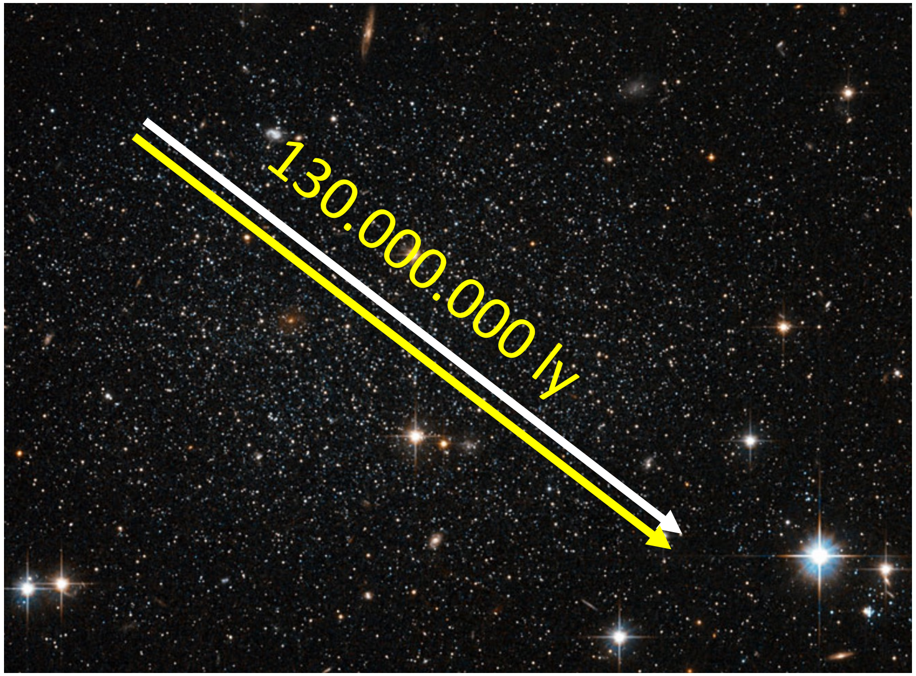
The (HE) gamma-ray sky



Credit: NASA/DOE/Fermi LAT Collaboration

August 17, 2017: coalescence between two neutron stars

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



GRB/GW delay

$$\Delta t = (1.74 \pm 0.05)\, s$$

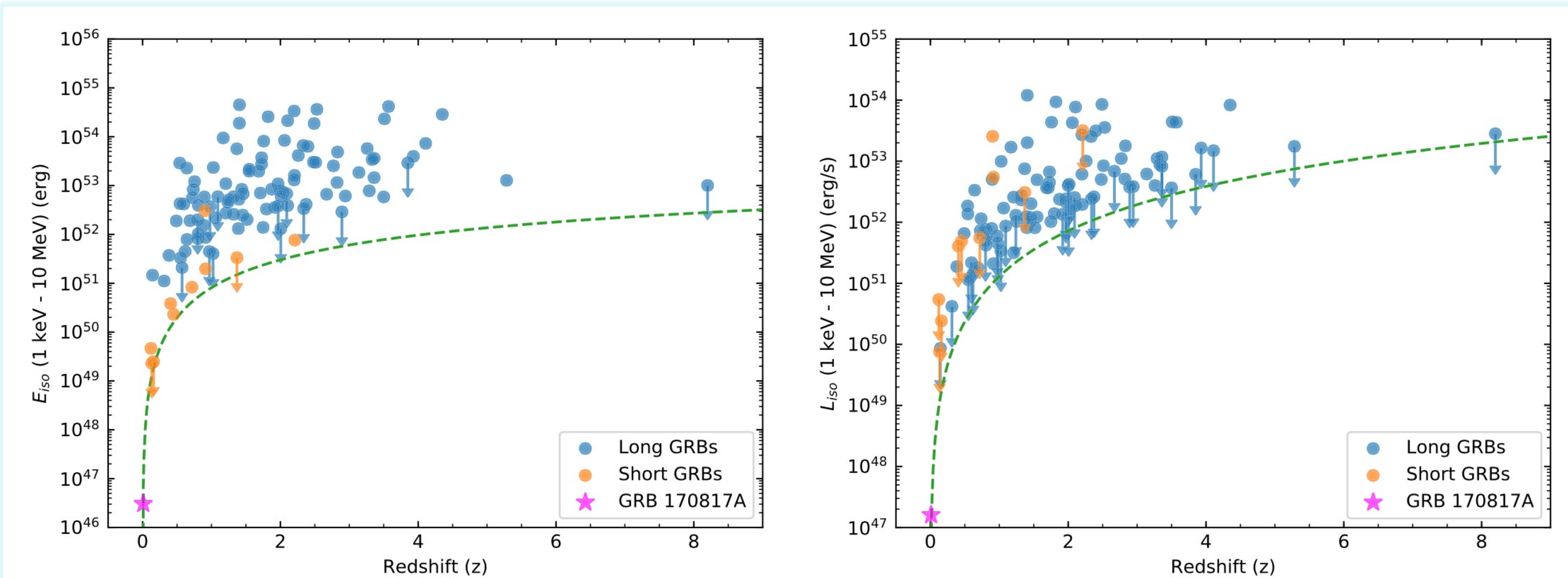
and 40 Mpc distance
→ difference speed of gravity and speed of light between

$$-3 \times 10^{-15} \leq \frac{\Delta c}{c} \leq 7 \times 10^{-16}$$

GWs propagate at the speed of light to within $1{:}10^{15}$!

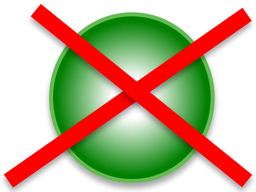
Consequences of multi-messenger detection of GW170817 for cosmology →
Constraint on the speed of GWs ruled out many classes of modified gravity models
(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. '17, Creminelli & Vernizzi '17)

GW 170817A

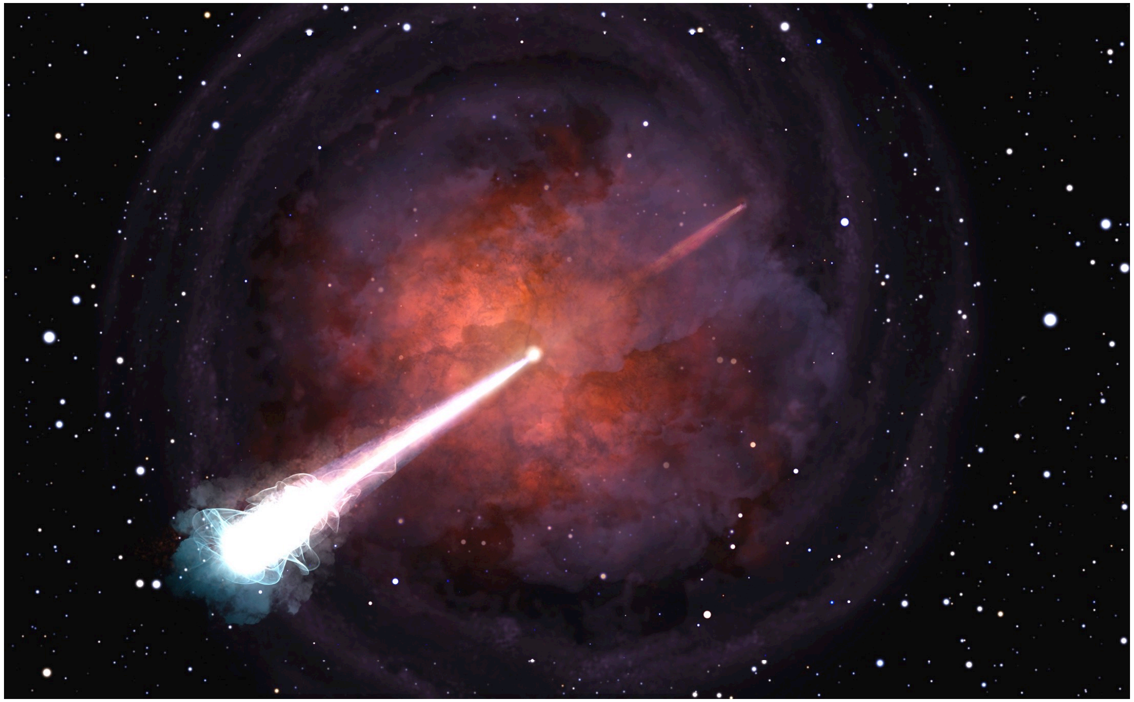


isotropic energy release isotropic peak luminosity

Intrinsically sub-luminous event
or a classical short GRB viewed off-axis?



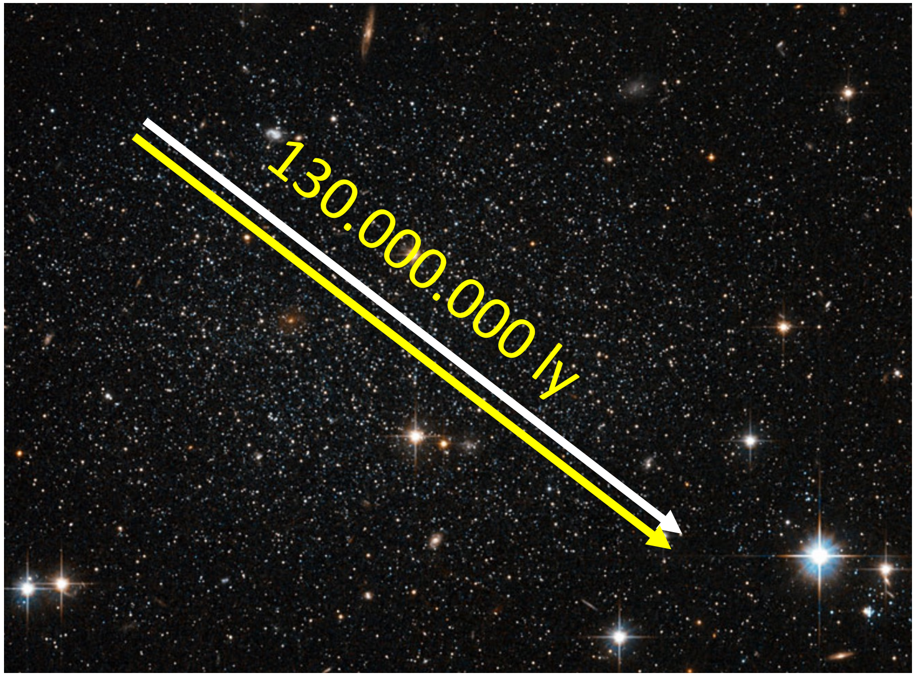
Ruled **out nearly isotropic, mildly relativistic outflow ,**
which predicts proper motion close to zero and
size > 3 mas after 6 months of expansion



A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!

based on Observations 207.4 days after BNS merger by global VLBI network of 33 radio telescopes over five continents constrain SOURCE SIZE < 2 mas

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



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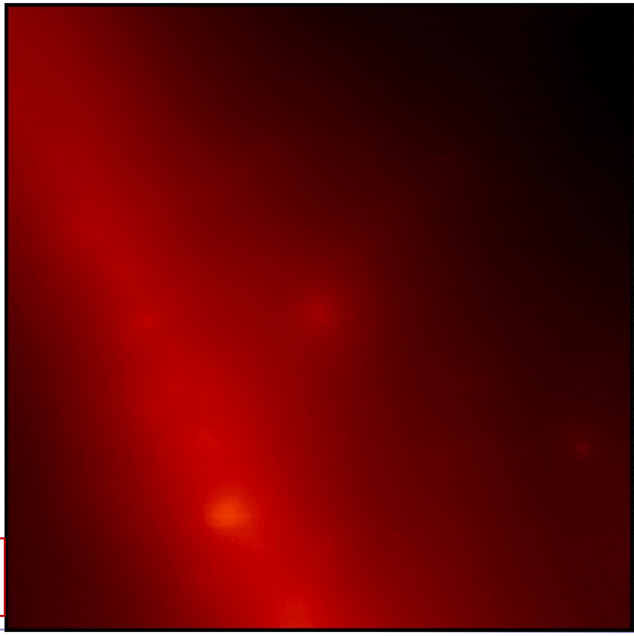
Oct 9, 2022 **Swift and Fermi Missions Detect Exceptional Cosmic Blast**

GRB 221009A

Sequence constructed from Fermi Large Area Telescope data reveals the sky in gamma rays centered on the location of GRB 221009A. Each frame shows gamma rays with energies greater than 100 MeV, ~ 10 hours of observations. The glow from the midplane of our Milky Way galaxy appears as a wide diagonal band. The image is about 20 degrees across.

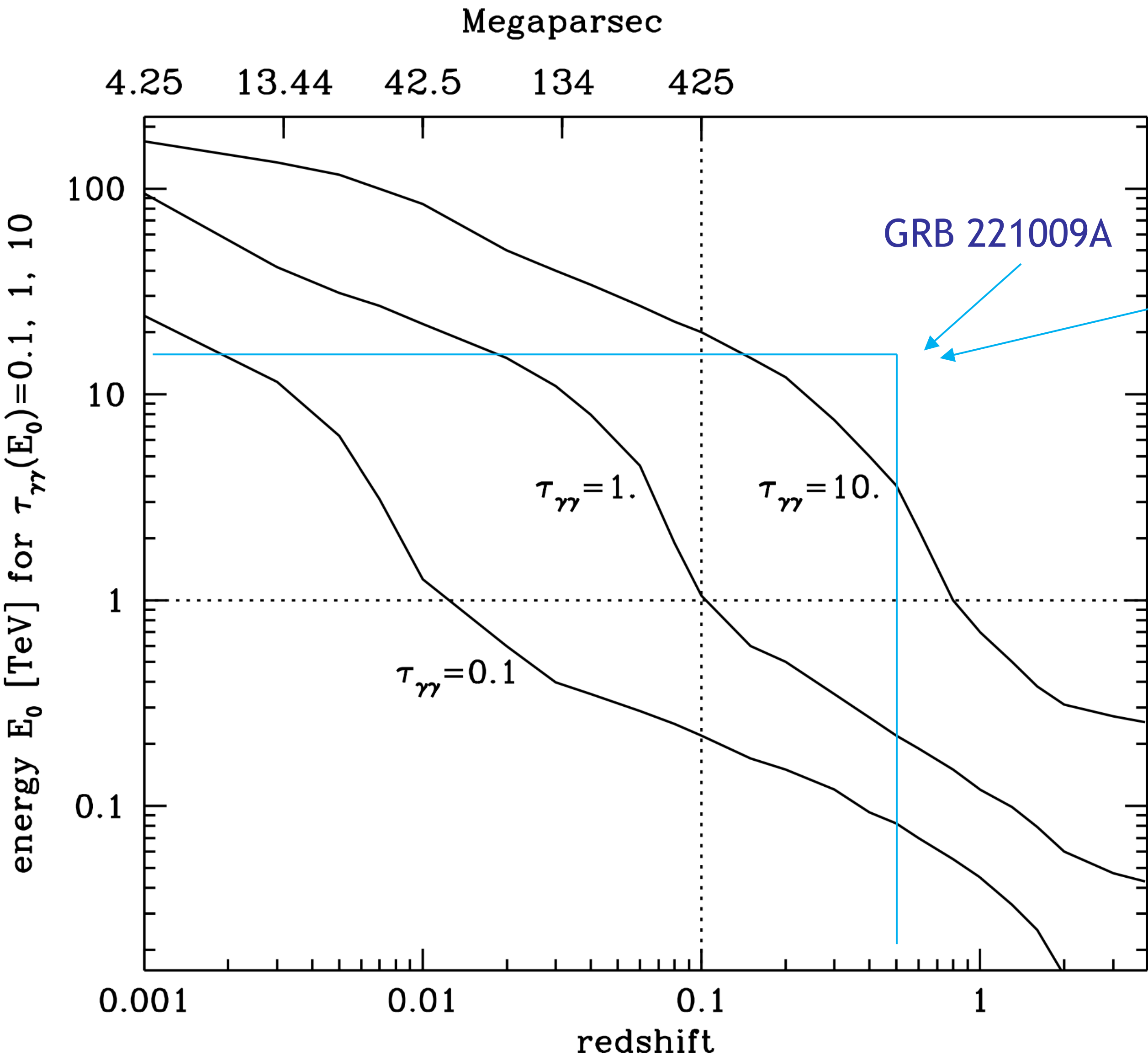
Gemini South telescope observation on 14 of October

Z=0,51



and Lhaaso in 2000 s detected ~5000 gammas with E > TeV up to 18 TeV

The energies corresponding to optical depth values of different for photon-photon collisions, as a function of the redshift distance of the source



$$\tau_{\mathrm{CP}} \simeq 14$$

photon survival probability

$$P(\gamma \to \gamma; E)_{\mathrm{CP}} = e^{-\tau_{\mathrm{CP}}} \simeq 8.5 \cdot 10^{-7}$$

New Physics?
LIV or Axion-like conversion

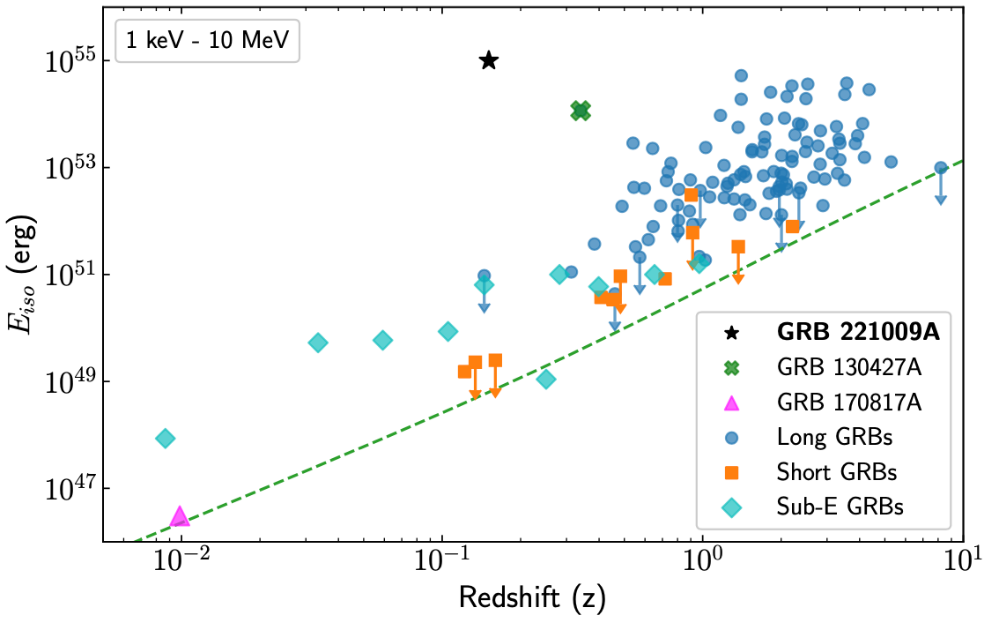
or some instrumental effect:
•cosmic rays identified as gammas)
* energy lower than 18 TeV

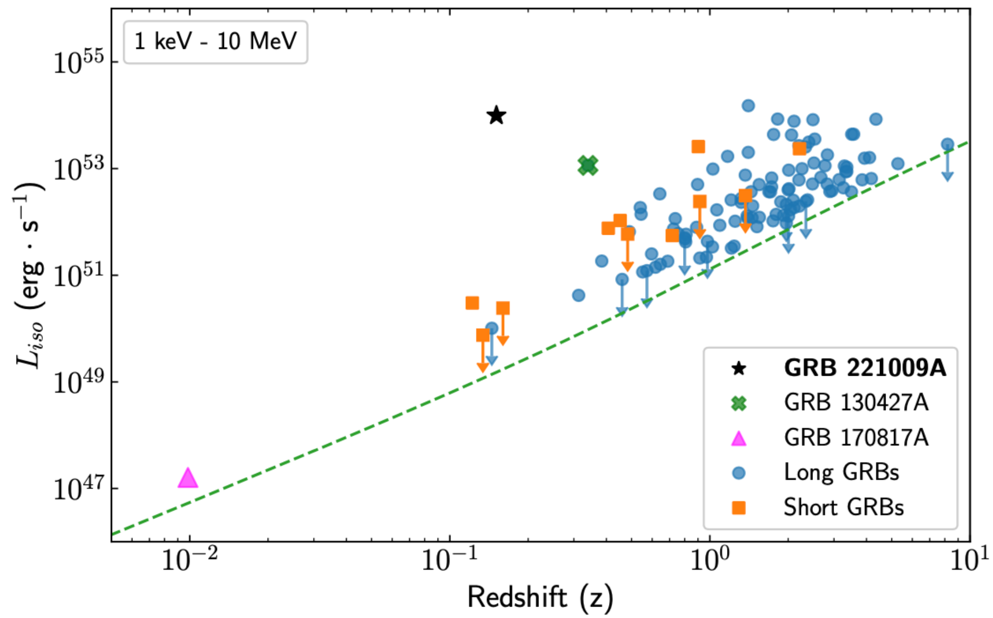
extragalactic background light revisited, Franceschini Rodighiero 1705.10256

GW170817

- in summary :
- gravitational wave measurements determined the mass of the merging neutron stars and an initial sky localization
- electromagnetic observations determined the host galaxy of the merger and the mass, speed, energy, and composition of matter ejected from the system during the merger'
- Optical/infrared light powered by nuclear decays involved in the production of many of the heaviest elements in nature.
- Indeed, the optical-infrared light provided strong evidence that neutron-star mergers are a significant astrophysical site for the production of rapid neutron capture elements (including the rare Earth metals, platinum, and gold), a long-standing mystery in our understanding of the origin of the elements traced in the spectra of stars.
- The combination of a gravitational wave distance to the merger and a redshift in the spectrum of the host galaxy also allowed a fully independent measurement of the Hubble constant.
- Although the single measurement with GW170817 is not as precise as other techniques, multi-messenger cosmology will increase in importance in the coming decade as we detect ever more binary neutron star and black hole mergers.

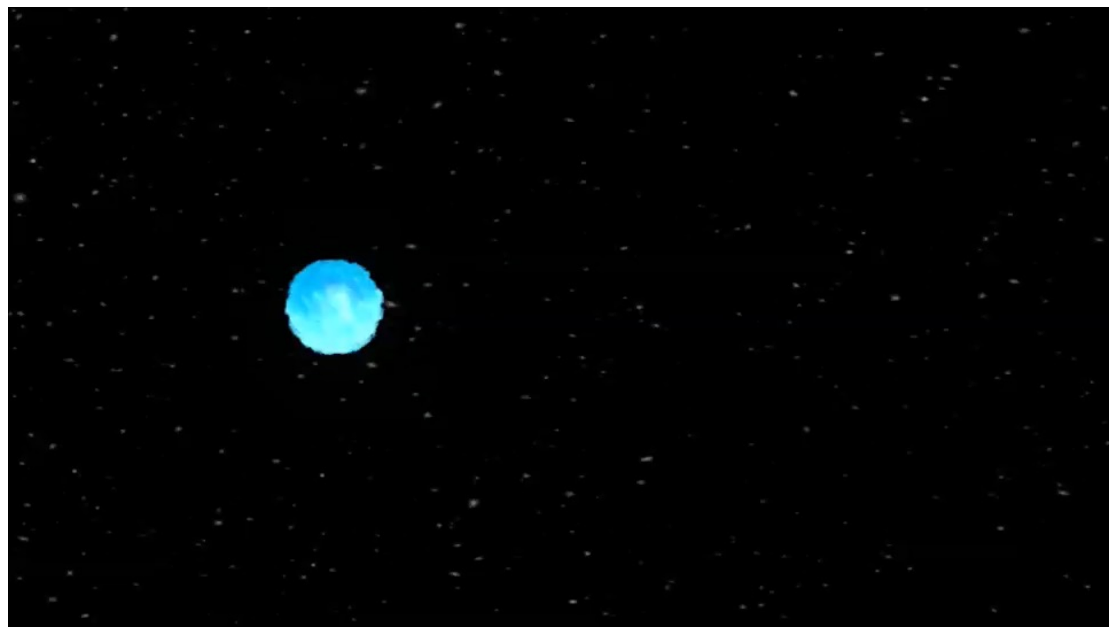
Oct 9, 2022 **Swift and Fermi Missions Detect Exceptional Cosmic Blast** GRB 221009A





Fermi Coll. arXiv:2303.14172

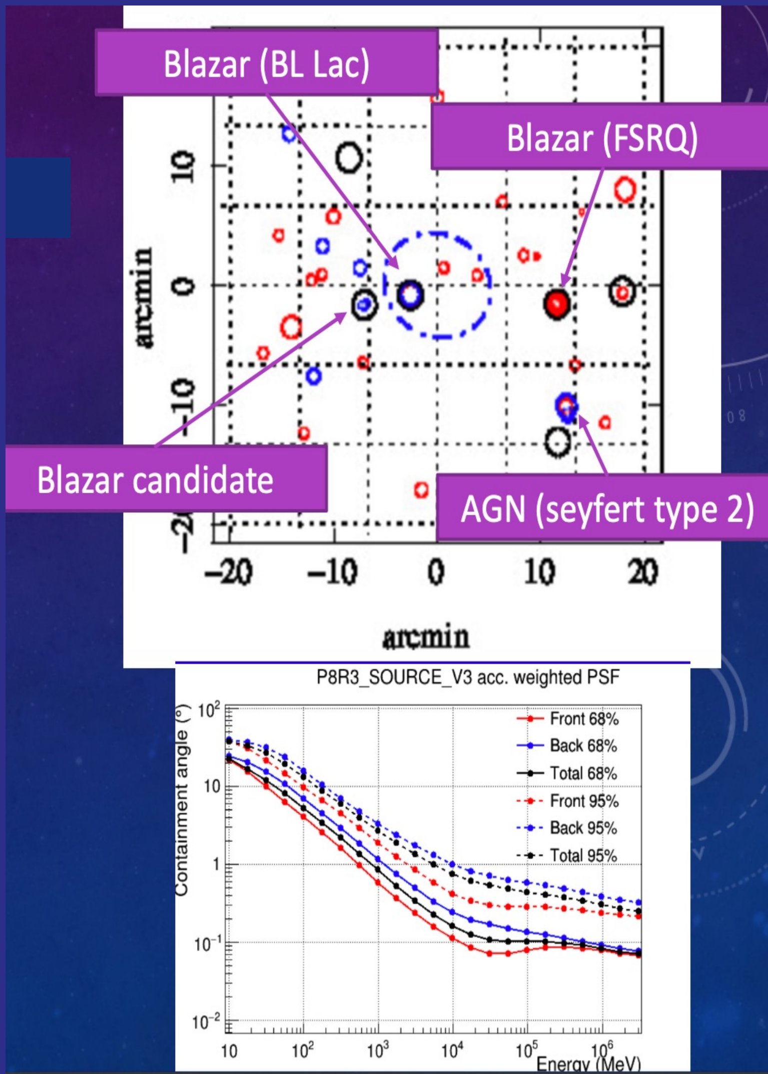
probably GRB 221009A represents the birth of a new black hole formed within the heart of a collapsing star.



First observation of a Gamma Ray Burst ?

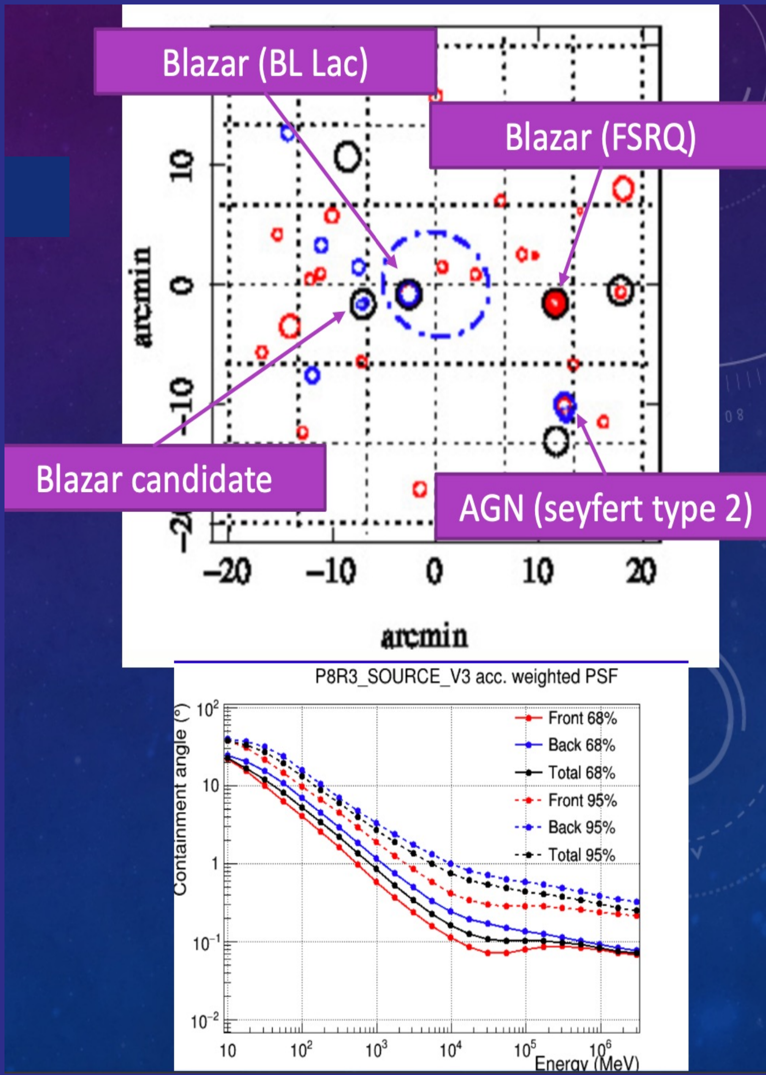
ASSOCIATION: BLAZAR AND OTHER AGN's

For AGNs we have a problem in some crowned fields. Many sources could be responsible for the gamma-ray emission detected by Fermi -LAT
Example: 4FGL J0114.8+1326
In a field of 40’X40’ we have at least 4 AGNs that “energetically” could emit gamma ray
The containment angle is 2 degrees at 1 GeV
A photon detected in the image above can come from any
source
What we can do?
We have to use a probabilistic approach



PROBABILISTIC ASSOCIATION METHOD: BAYESIAN METHOD

We are using two methods in AGN association, similar in idea but different in application: The Bayesian method and likelihood ratio association
The Bayesian method is based on spatial coincidence between the gamma-ray sources and their potential counterparts belonging to other catalogs:
It computes the probability of real association using the counterpart density in the case of a false (random) association. In addition, the posterior probability depends on a prior. This prior is calibrated via Monte Carlo simulations.
The sum of the association probabilities over all pairs (gamma-ray source, potential counterpart) gives the total number of real associations for a particular catalog, allowing the number of subthreshold associations to be estimated



PROBABILISTIC ASSOCIATION METHOD: LIKELIHOOD RATIO METHOD

While the Bayesian method works on catalogs, the Likelihood Ratio (LR) method provides supplementary associations with blazar candidates based on large radio and X-ray surveys: NVSS, SUMSS, ROSAT, and AT20G. With this method, we can estimate the chance to have a source bright in the survey of reference assessed from the survey log N–log S distribution. The false-association rate is derived from the density of objects brighter than the considered candidate.

LR method has a bigger discovery space since doesn't use catalogs but surveys that are complete in the sky.

While the LR method can handle large surveys, its fraction of false associations is notably larger than for the Bayesian method (typically 10% versus 2%).

After the associations (probability >0.8), we perform a search of redshift and optical spectra with a comparison of light curves in other bands to establish a class.