Gamma-ray astronomy

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Program

★ Introduction

✦ Gamma-ray production and detection

✦ Scientific objectives

★ Selected relevant and/or recent results*

Big overlap
Folders → Labels

✦ Cosmic-ray acceleration and propagation → cosmic rays

✦ Multi-wavelength/Multi-messenger astronomy → MW/MM

✦ Particle acceleration in extreme environments → accelerators

✦ Propagation effects → propagation

✦ Physics beyond the Standard Model → BSM

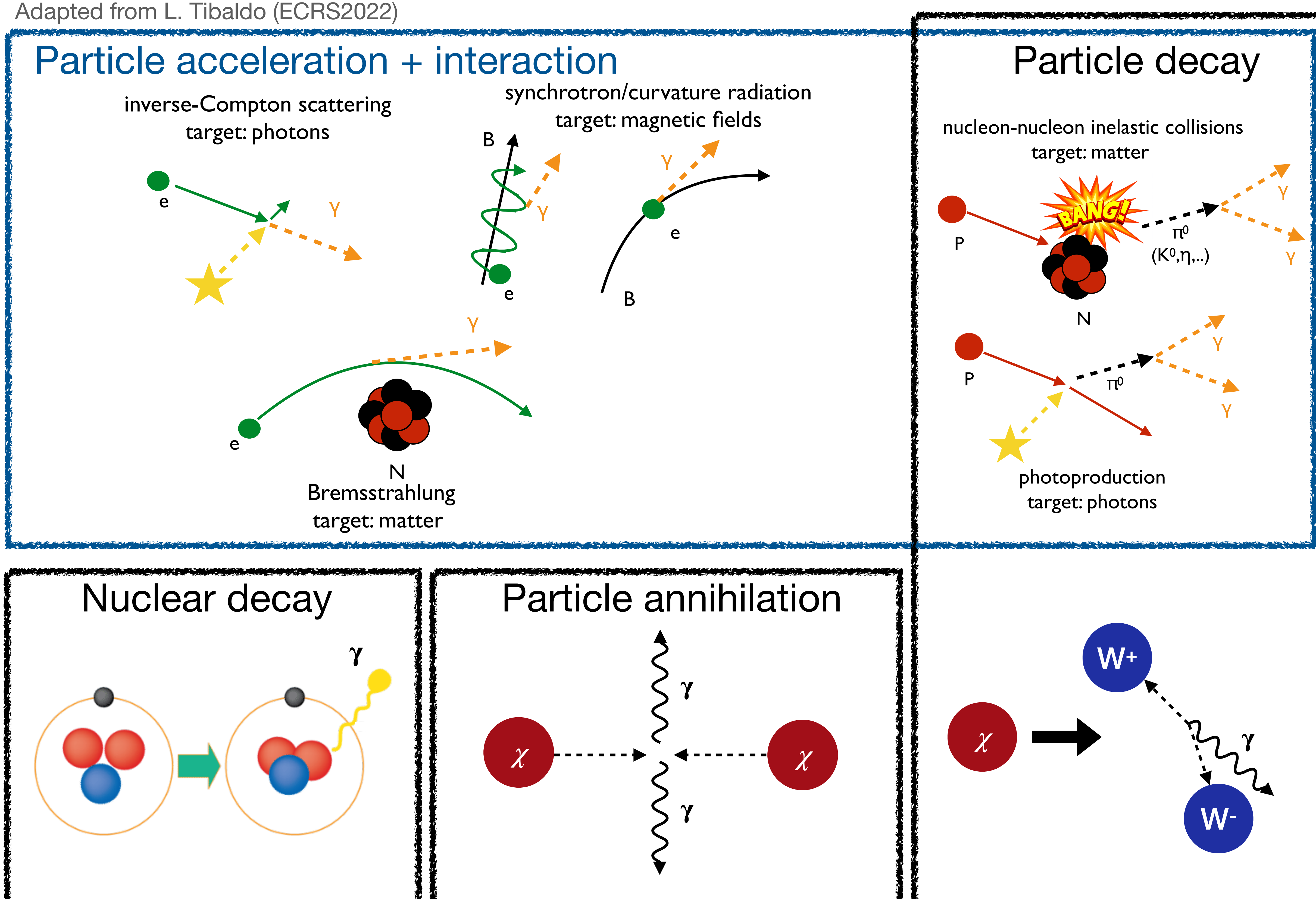
★ The future

* of course, with a personal bias…

Introduction

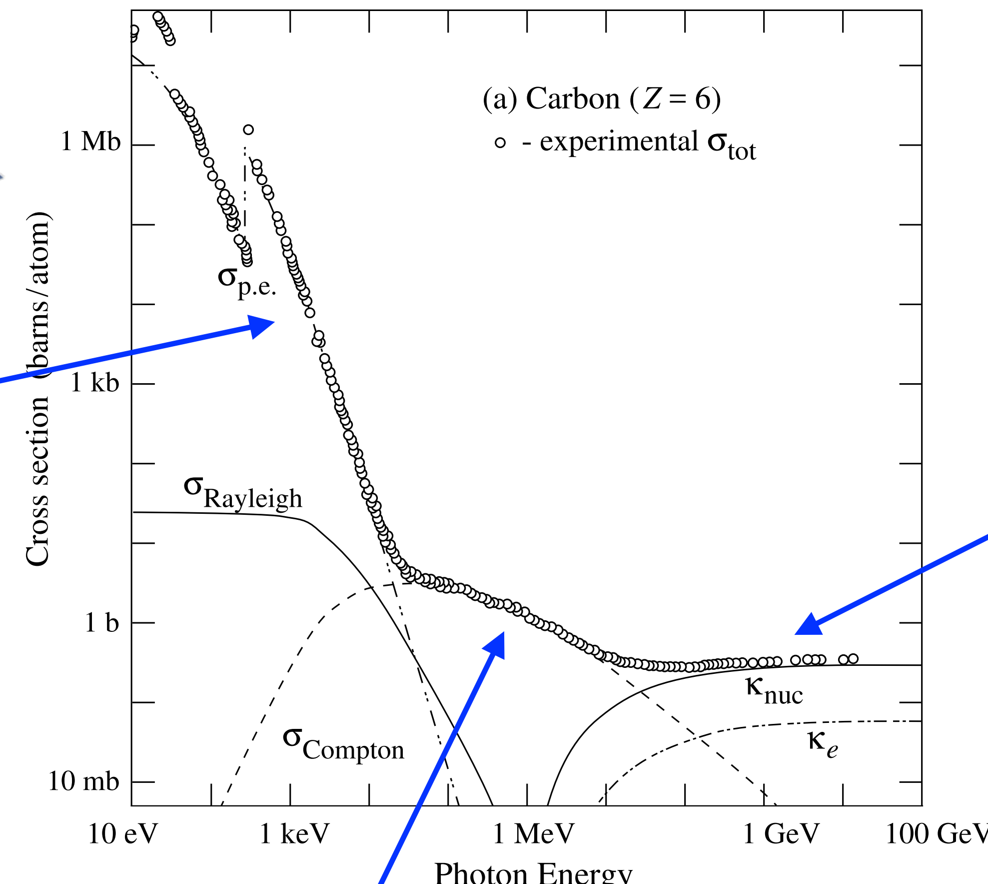
Gamma-ray production

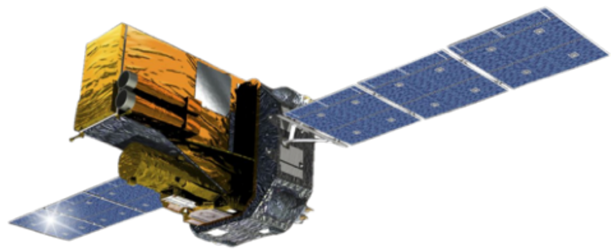
Adapted from L. Tibaldo (ECRS2022)



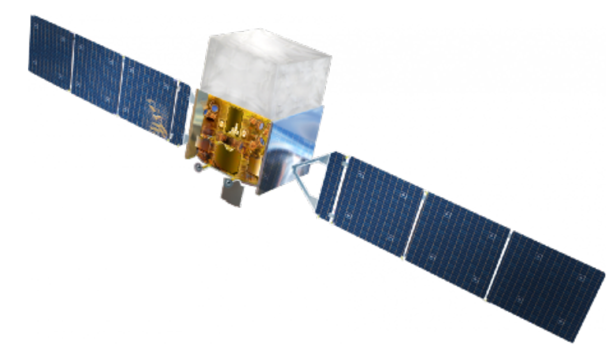
Direct gamma-ray detection

Workman et al. (PDG) PTEP 2022 (2022) 083C01





- ★ Low energy (LE)
  - 15 keV - 10 MeV
  - Coded masks
  - INTEGRAL (2002)



- ★ High Energy (HE)
  - 100 MeV - 300 GeV
  - Pair conversion tracker + calorimeter
  - Fermi-LAT (2008), Agile (2007), CALET (2015), DAMPE (2015)

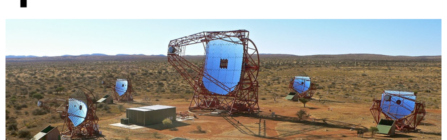
- ★ Medium energy (ME)
  - 1-30 MeV
  - Compton camera
  - COMPTEL (1991-2000)

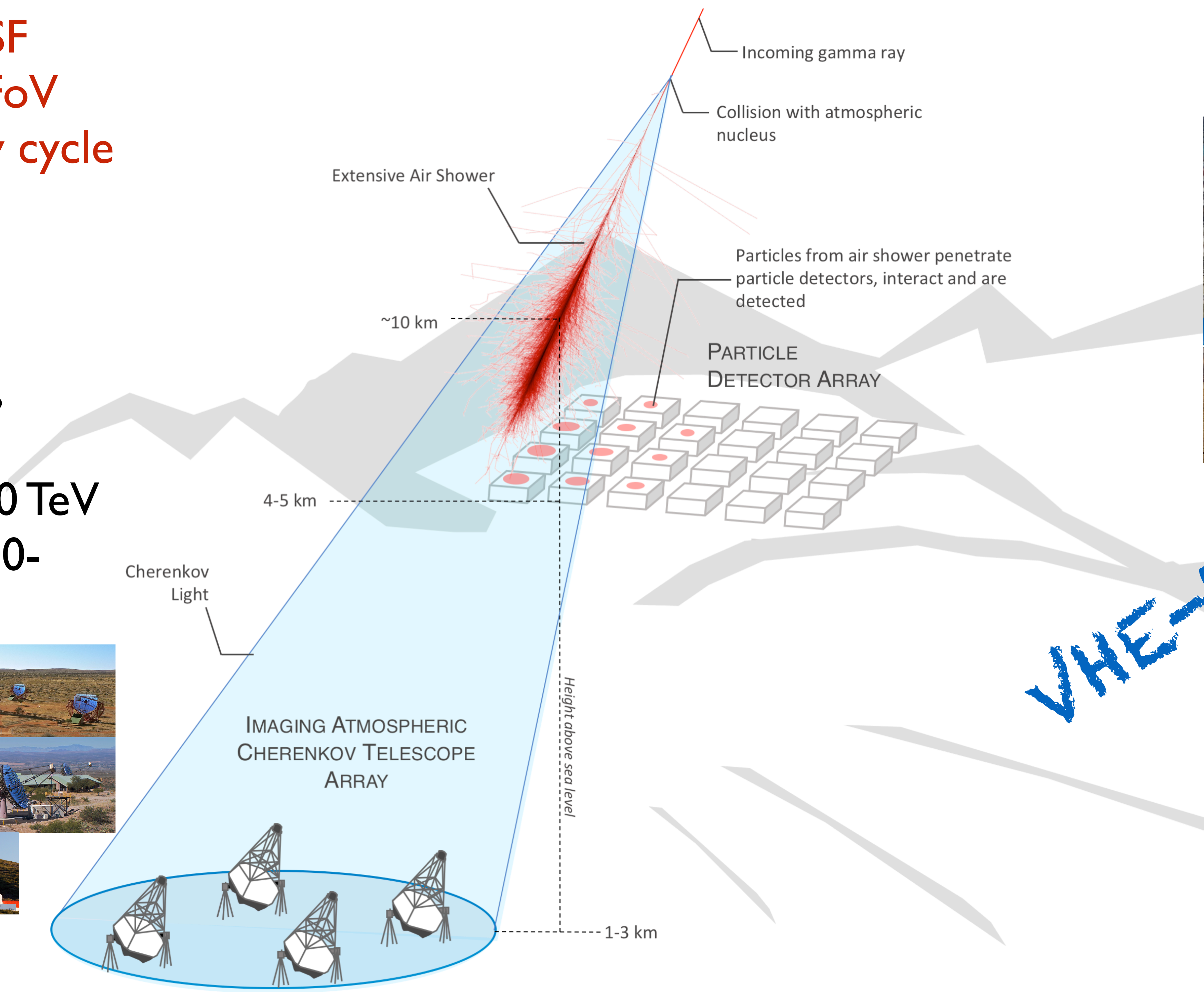
Indirect gamma-ray detection

Better PSF
Modest FoV
Low duty cycle

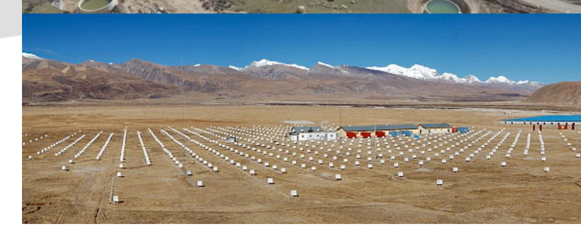
VHE

H.E.S.S.,
VERITAS,
MAGIC
0.03 - 100 TeV
Early 2000-present









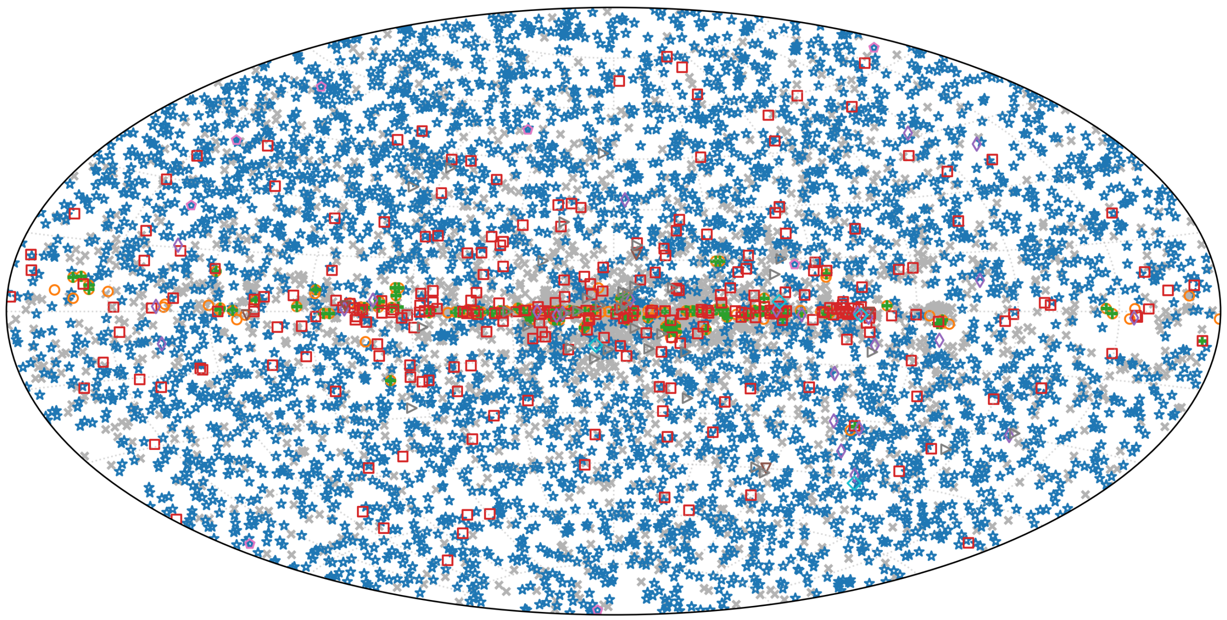
VHE-UHE

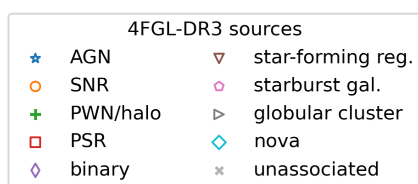
HAWC,
LHAASO,
Tibet AS Gamma
1 TeV - 2 PeV
~2010's - present
Modest PSF
Large FoV
High duty cycle

Credit: R. White

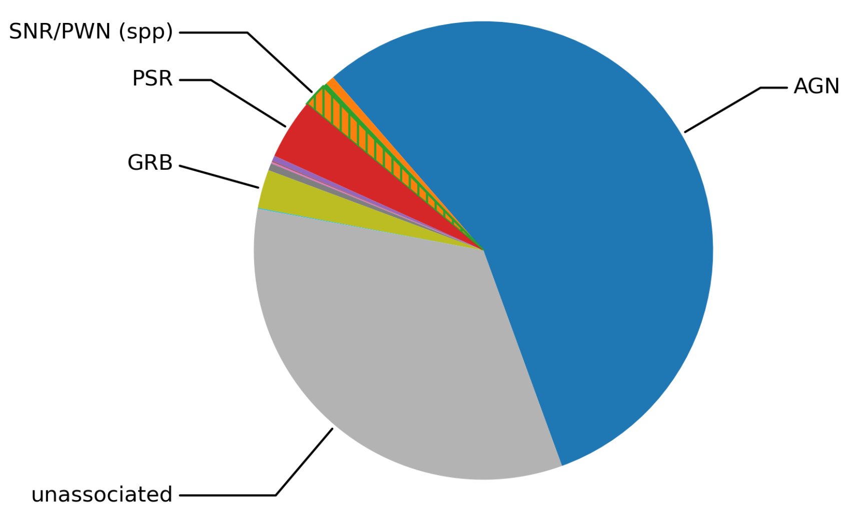
HE sources

HE

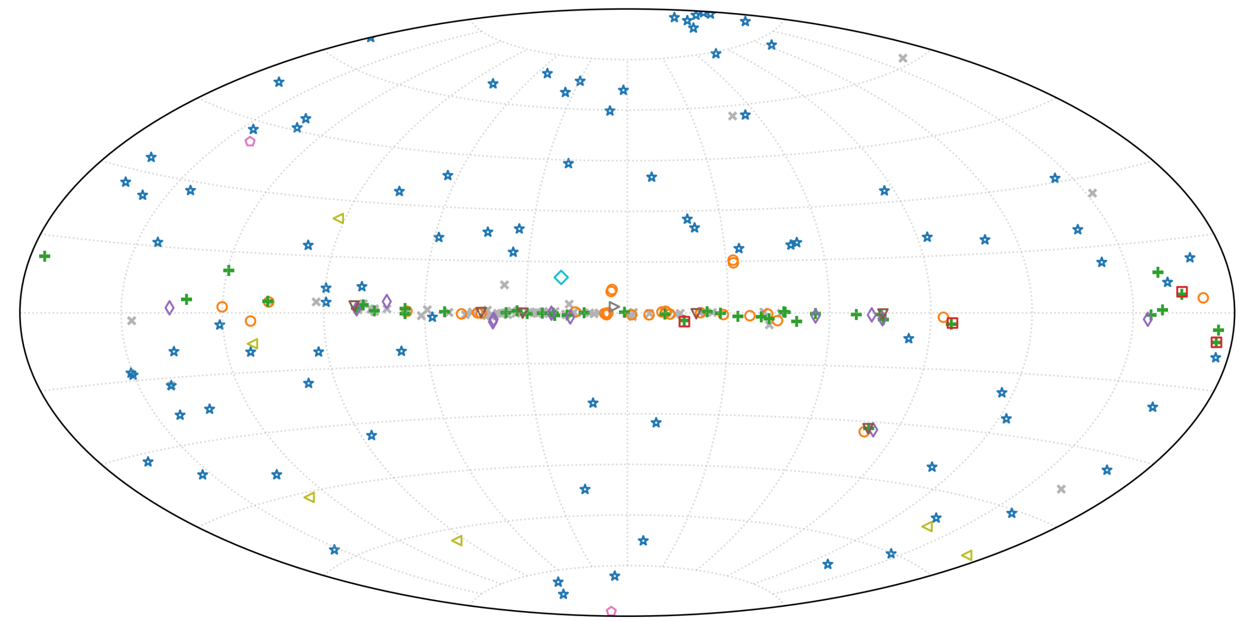


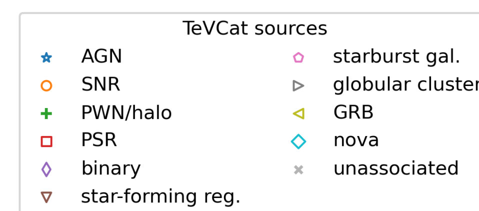


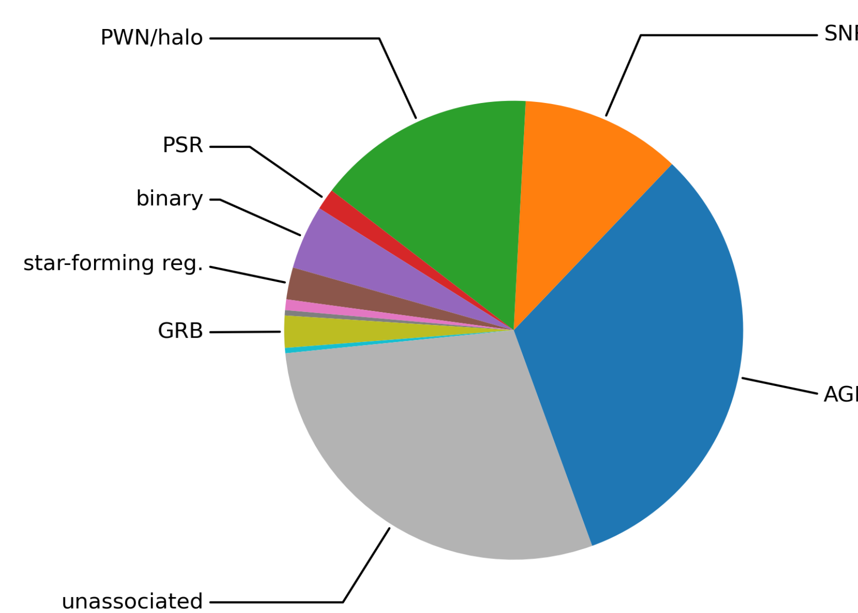
⚠ General LAT catalogs based on long-term significance: transients not included. The second LAT GRB catalog contains 186 GRBs not shown on this map.



VHE

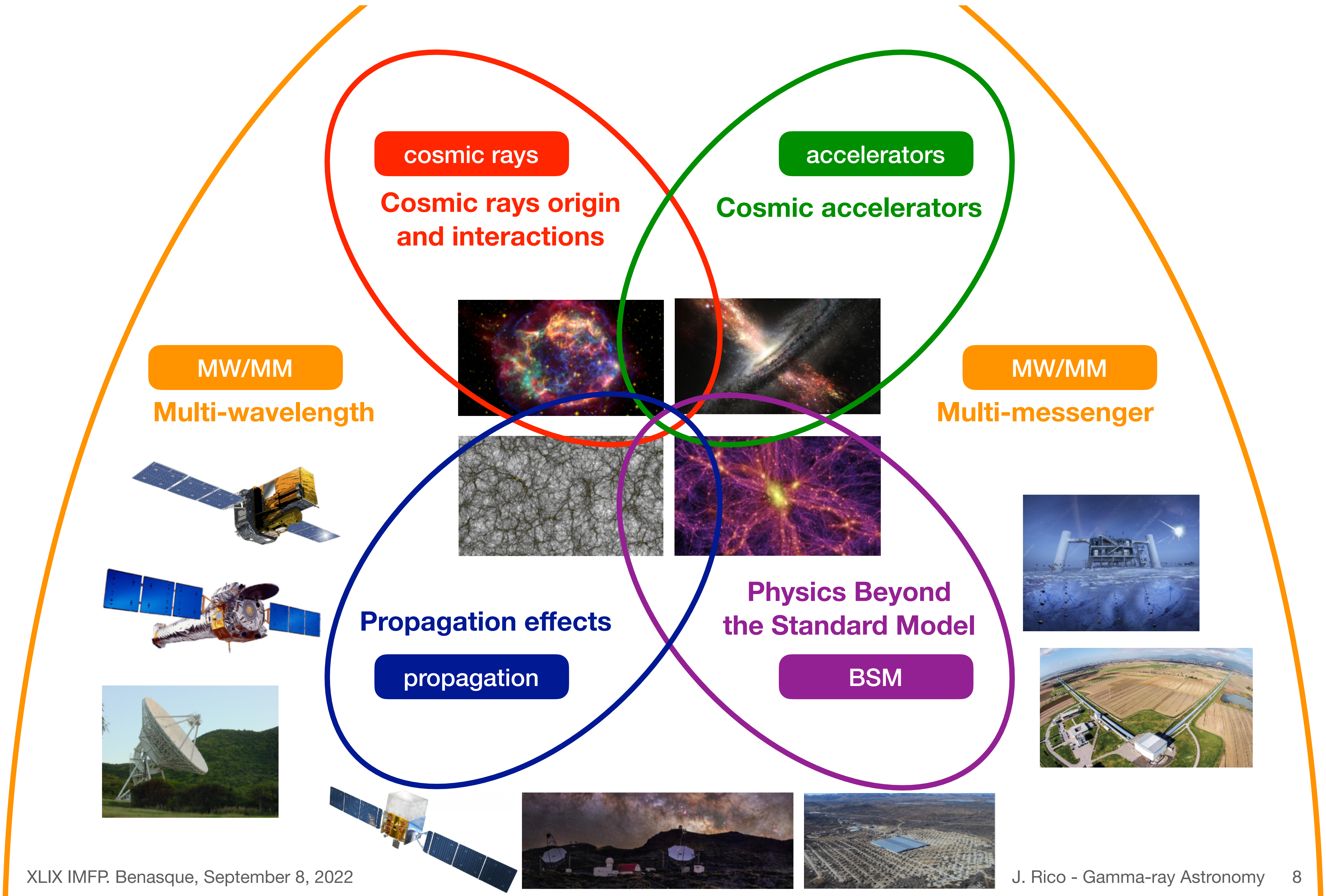






Credit: L. Tibaldo (ECRS2022)

Science with HE and VHE gamma rays

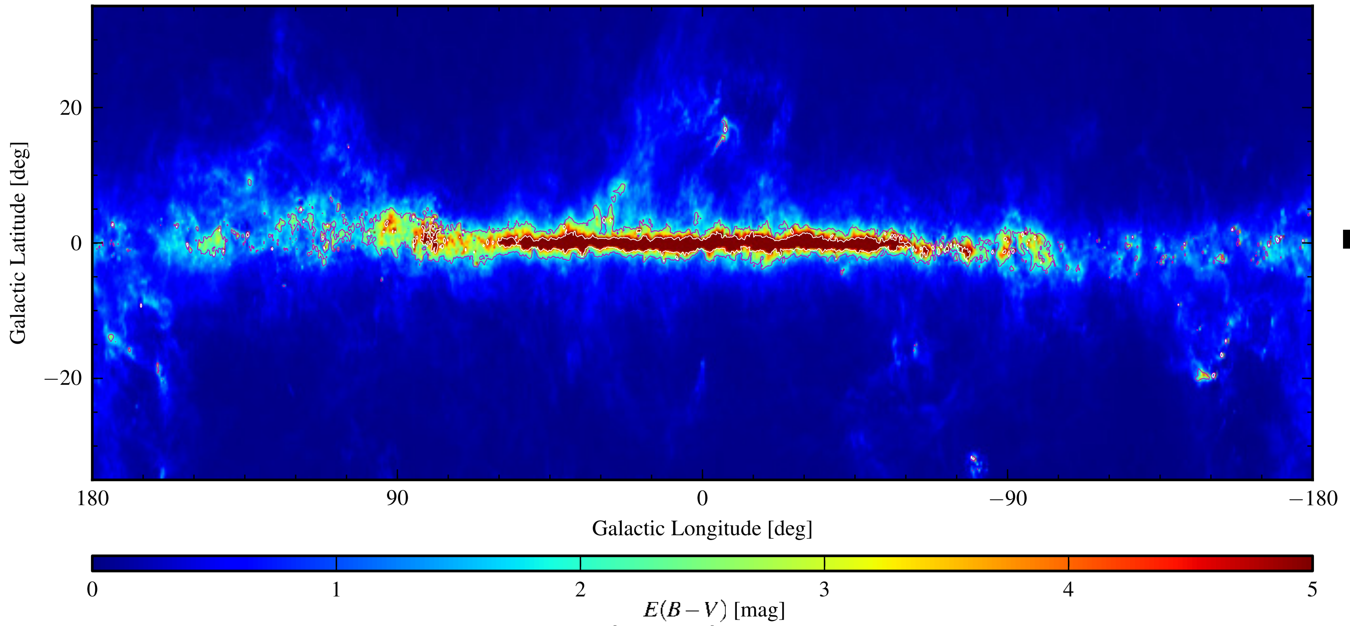


Cosmic rays origin and interactions

Galactic diffuse emission

cosmic rays

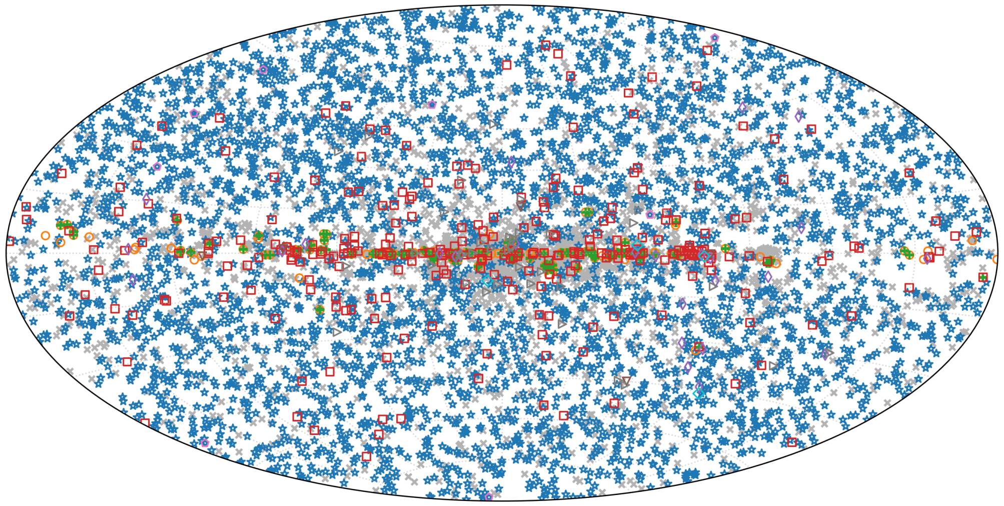
Interstellar matter tracers (H_2, H_I,, H_{II}, dust, ...)



Ackermann et al. ApJ 750 (2012) 3

+

Point-like sources



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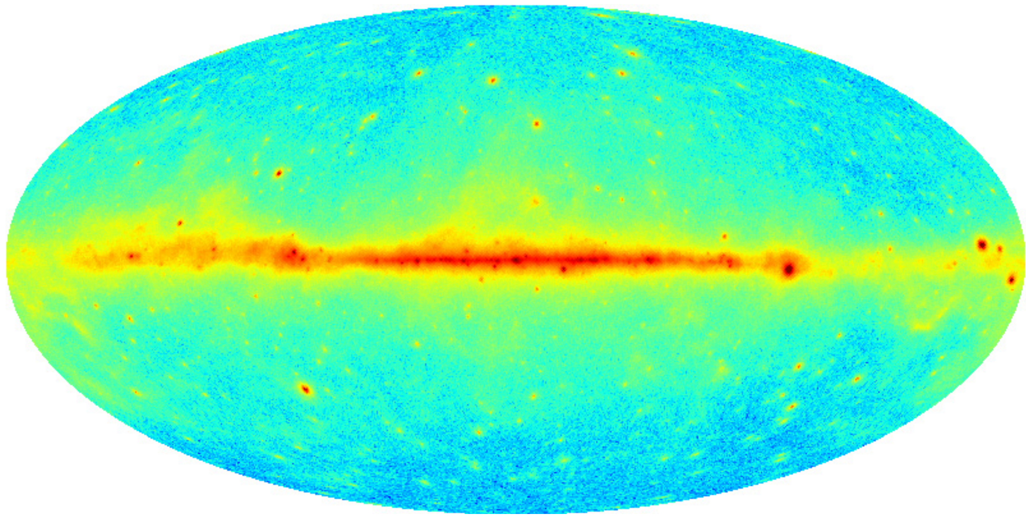
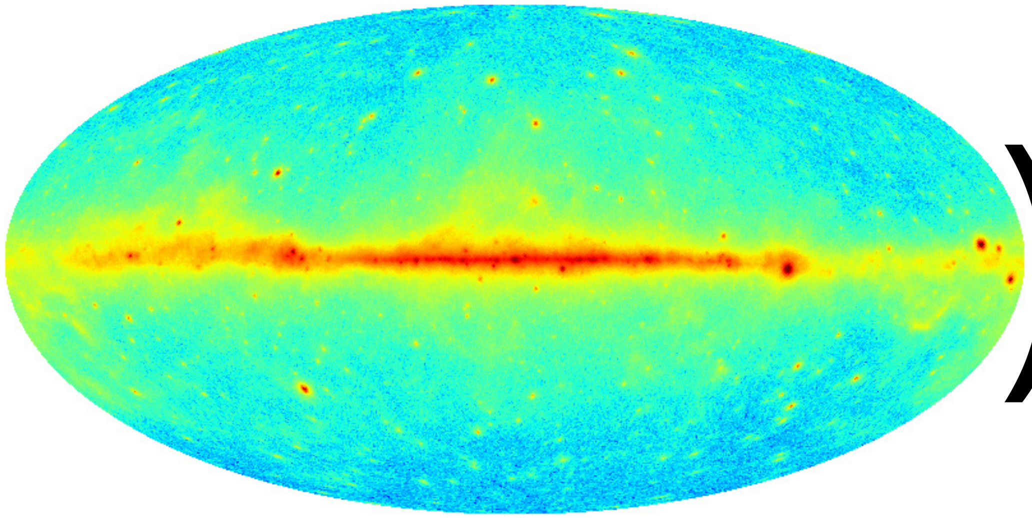


Predicted counts

(vs



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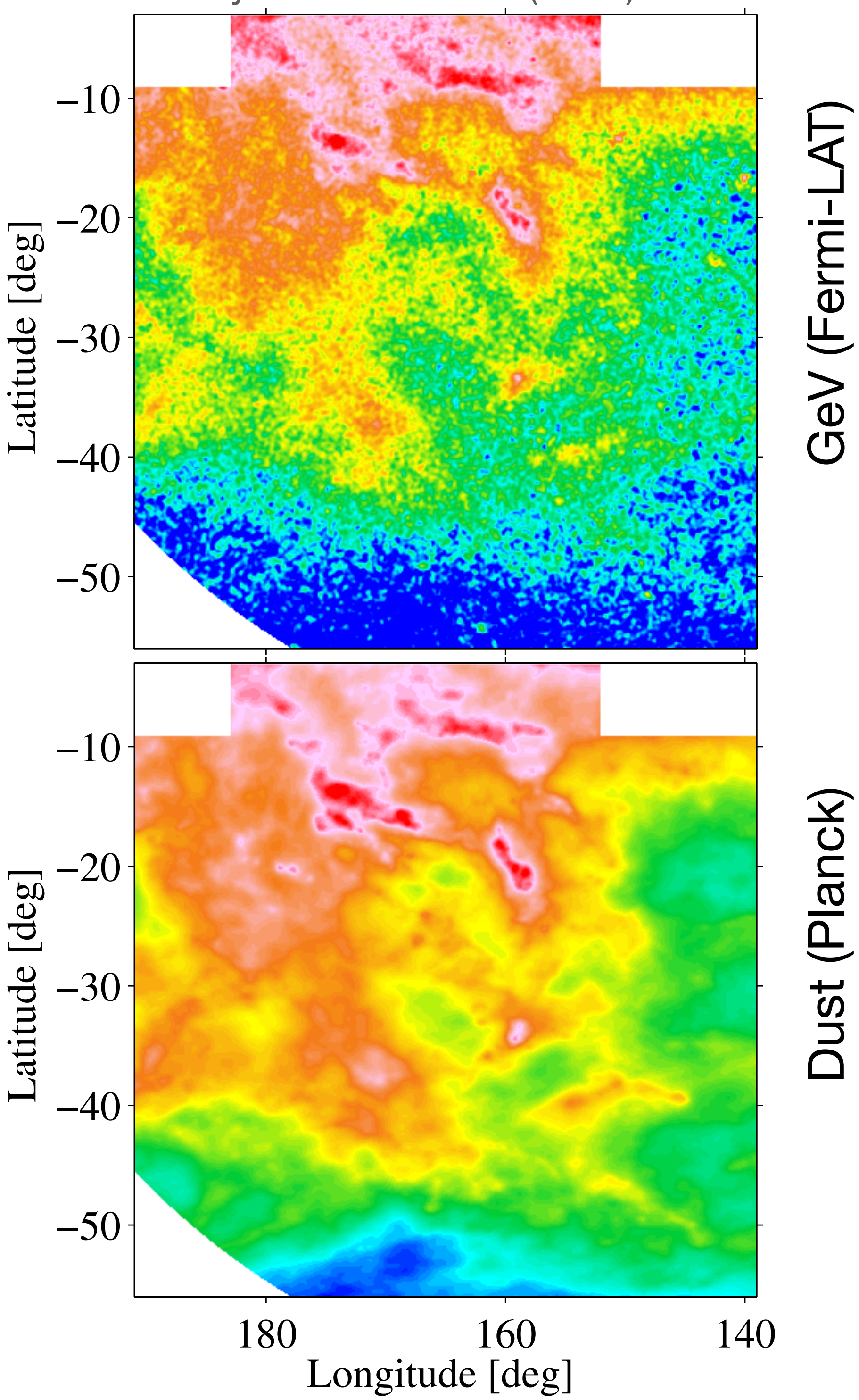
Observed counts

Diffuse emission

cosmic rays

Remy et al. A&A 601 (2017) A78

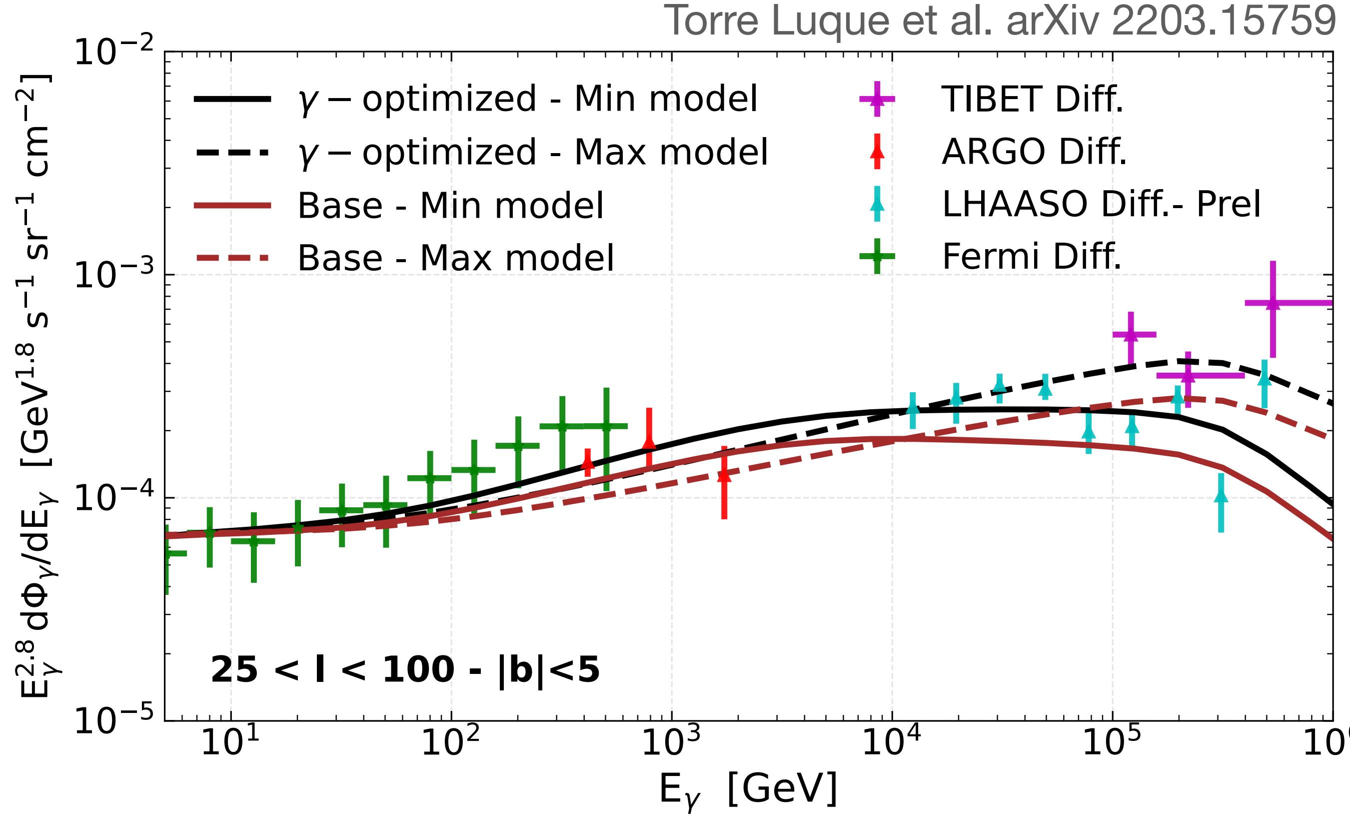


★ GeV/interstellar matter correlation at all scales → CR interactions

★ Diffuse emission measured up to PeV (with TeV gap)

★ Some excesses over predictions (unresolved sources? exotic origin?)

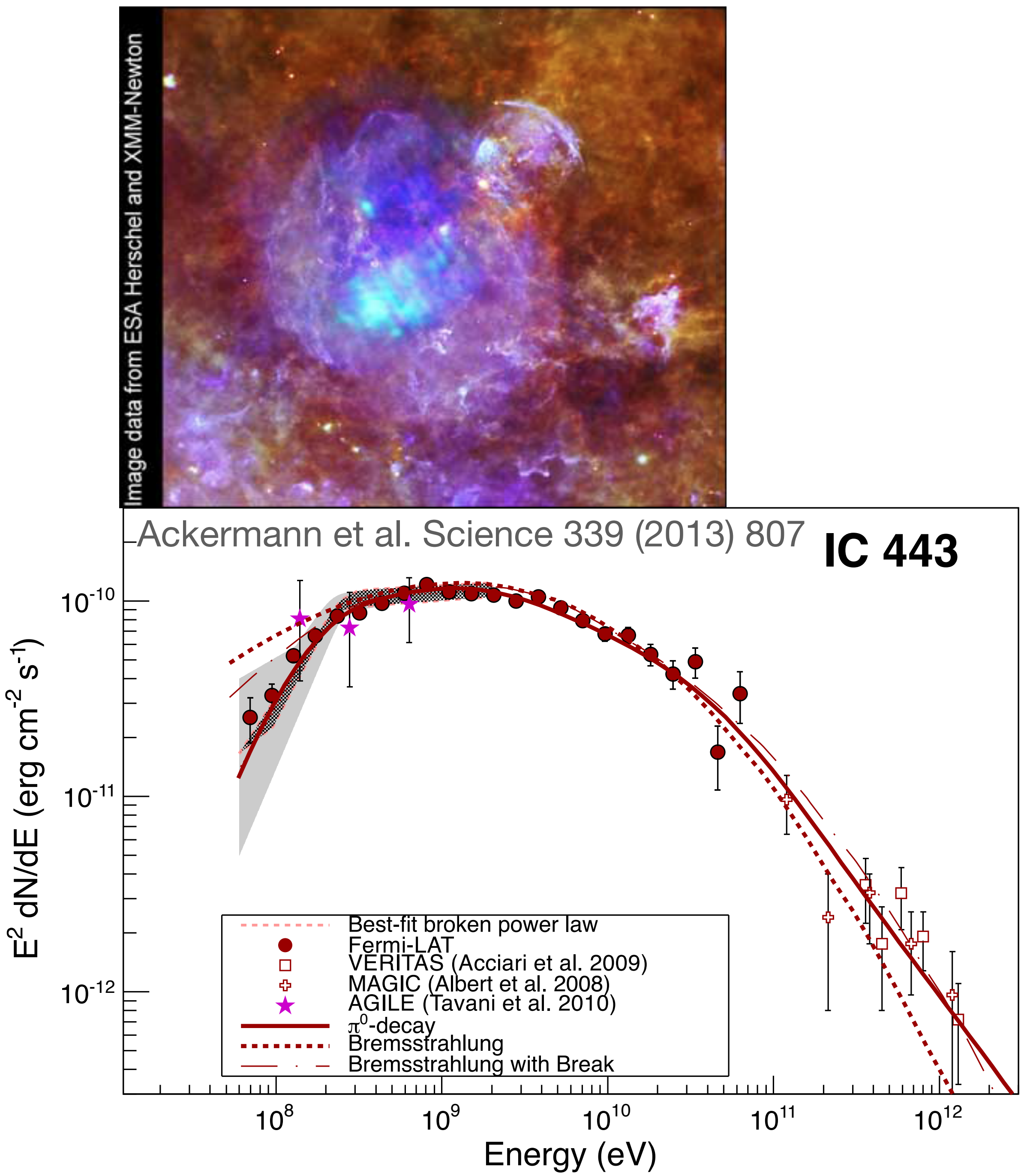
Torre Luque et al. arXiv 2203.15759

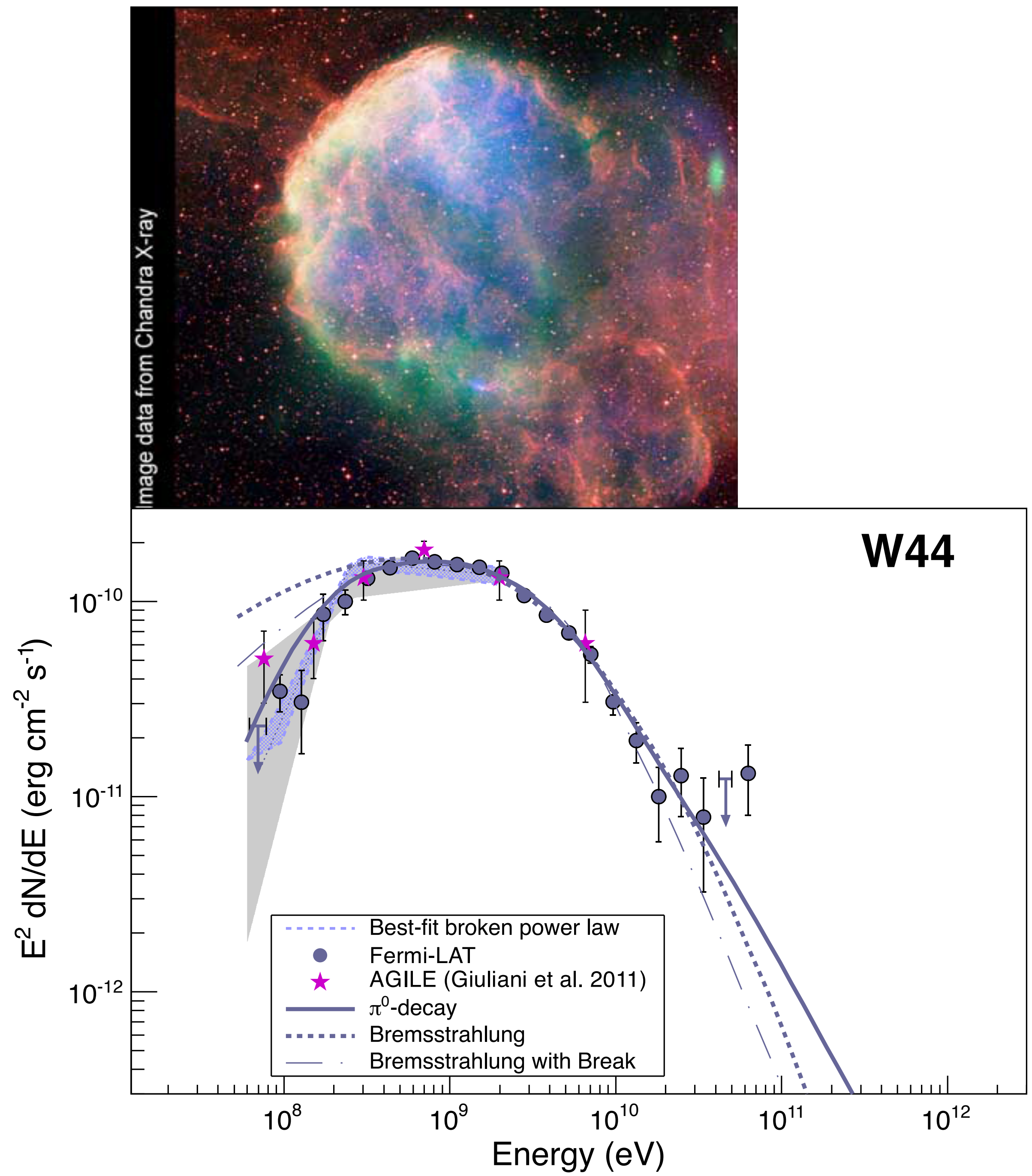


CR acceleration in SNRs

cosmic rays accelerators

★ First direct evidence of CR acceleration in SNR by observing the characteristic "pion bump"



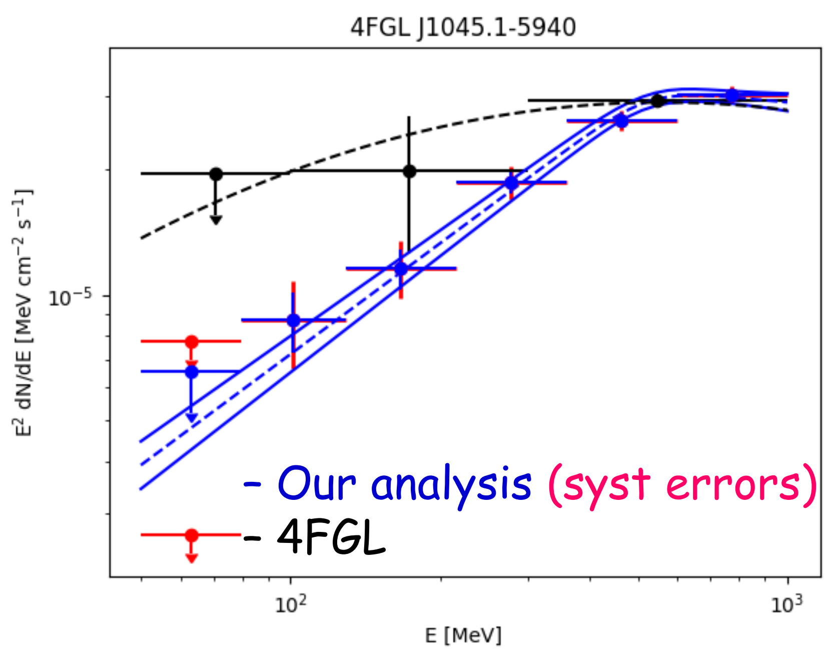


New CR accelerator candidates

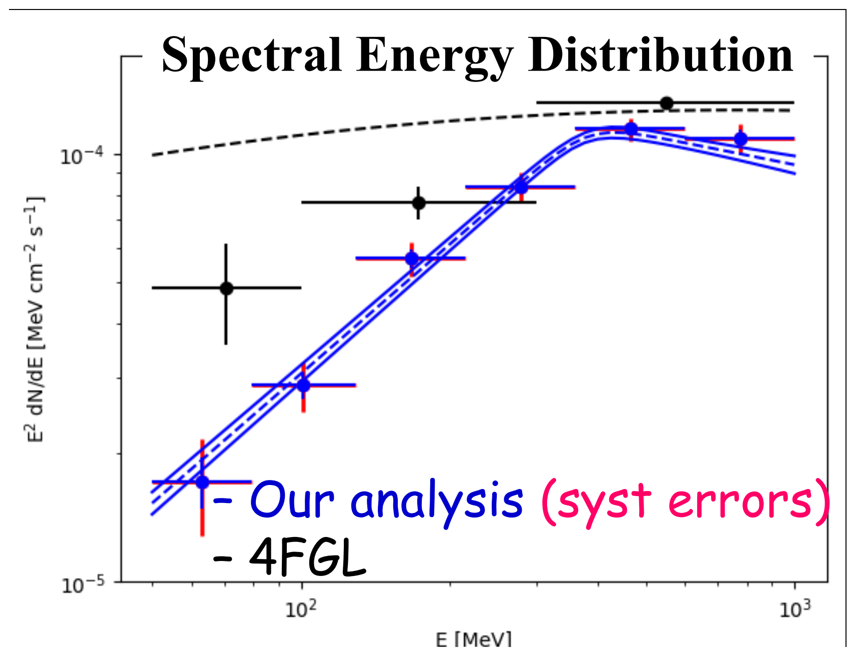
cosmic rays | accelerators

★ 8 years Fermi-LAT, better control on systematics → 56 out of 311 candidates are confirmed to have characteristic spectral break

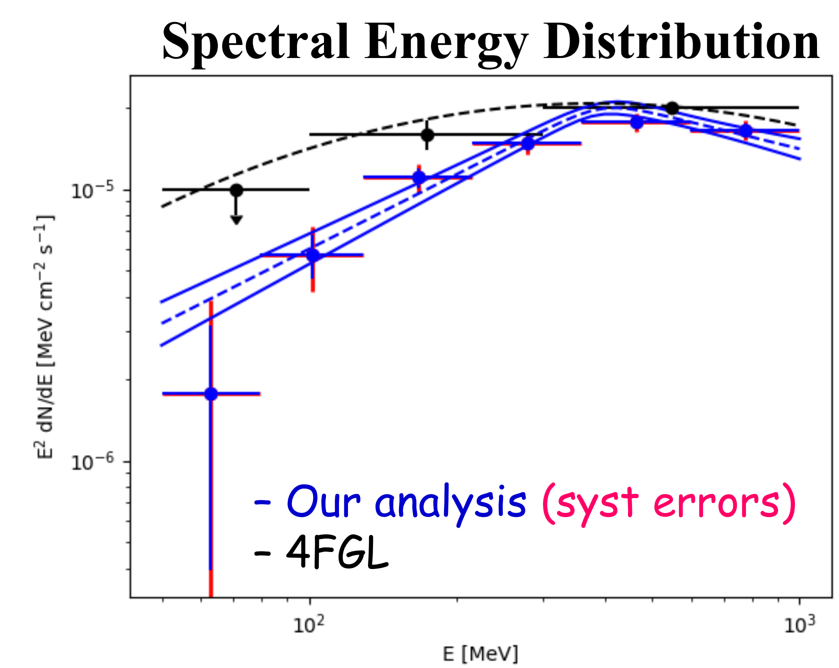
Binary system η-Carinae



Cygnus star-forming region



SNR HB21



Abdollahi et al. arXiv:2205.03111

★ SNRs dominate

★ Binaries could also contribute significantly

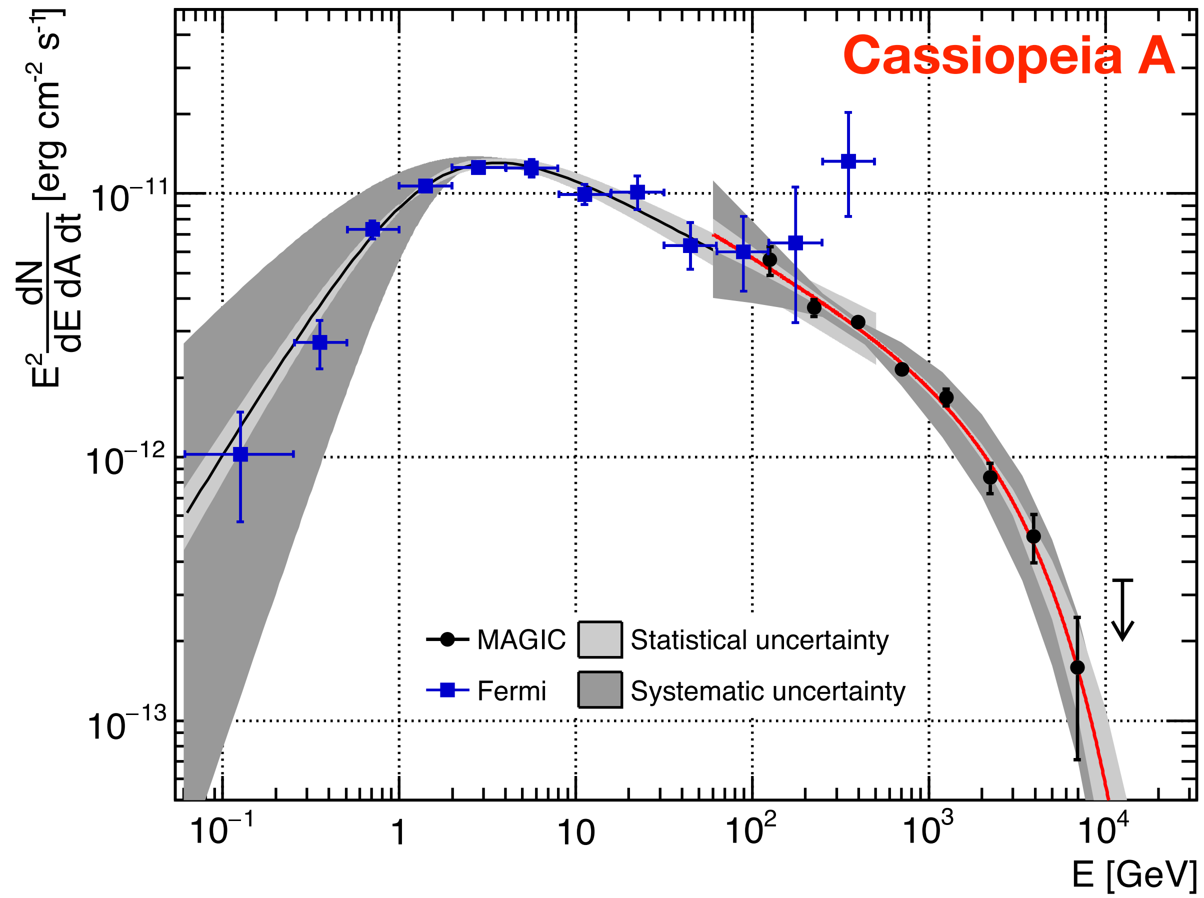
Source class	Analyzed	Confirmed
Supernova remnant (SNR)	23	13
Pulsar wind nebulae (PWN)	4	2
Supernova remnant / Pulsar wind nebula (SPP)	37	6
Star-forming region (SFR)	1	1
Unknown (UNK)	31	4
Binary/High-mass binary (BIN/HMB)	5	4
Unidentified (UNID)	210	26

PeVatrons

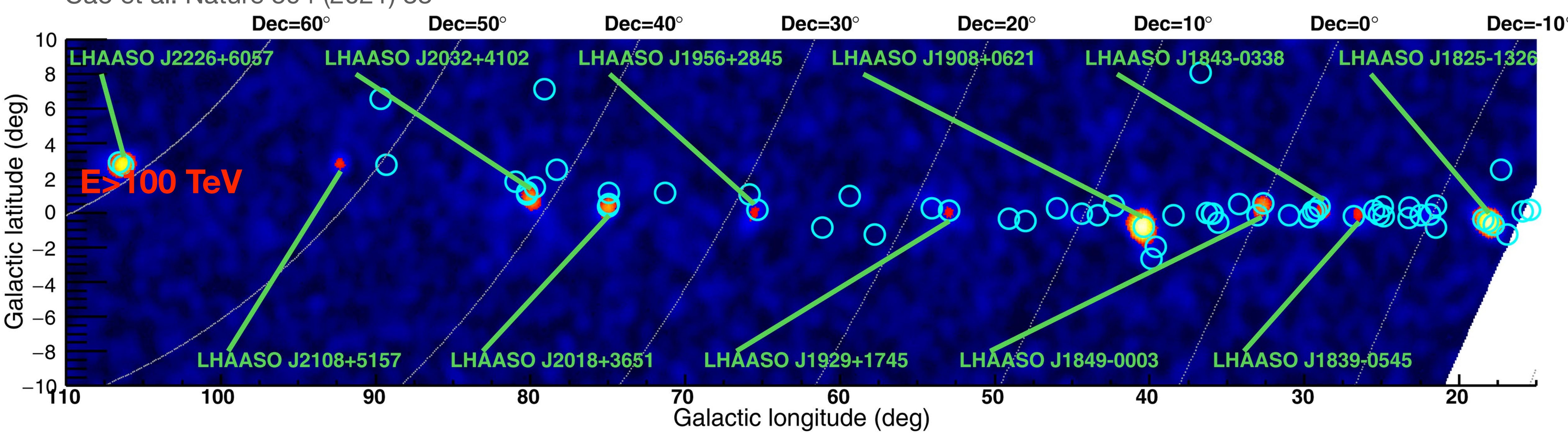
cosmic rays | accelerators

- ★ Galactic CR accelerators must reach 10^{15} eV
- ★ Not all SNRs are PeVatrons!
- ★ 12 PeVatrons recently discovered by LHAASO

Ahnen et al. MNRAS 472 (2017) 2956



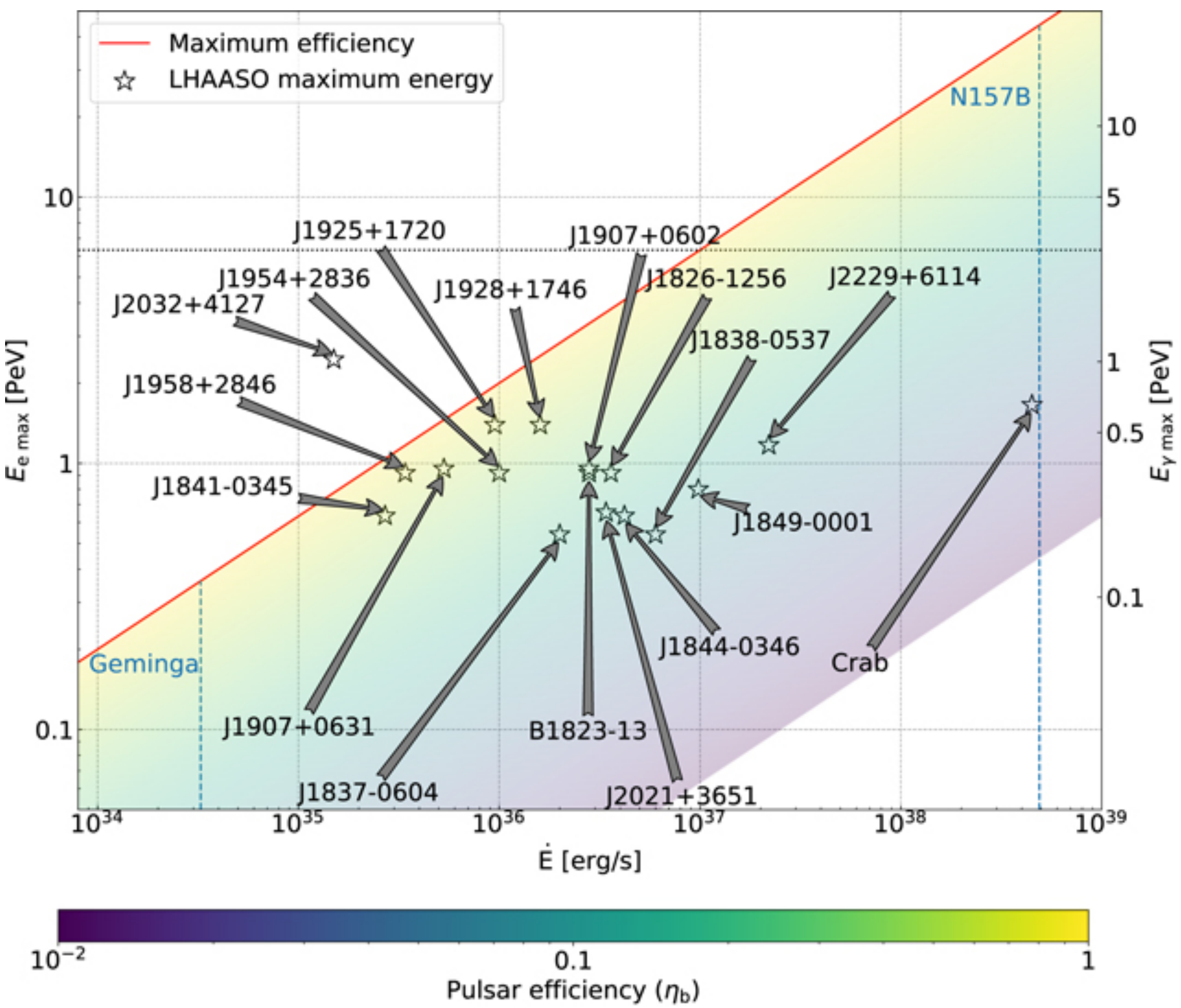
Cao et al. Nature 594 (2021) 33



Leptonic PeVatrons?

cosmic rays | accelerators

Oña Wilhelmi et al. ApJL 930 2022 L2

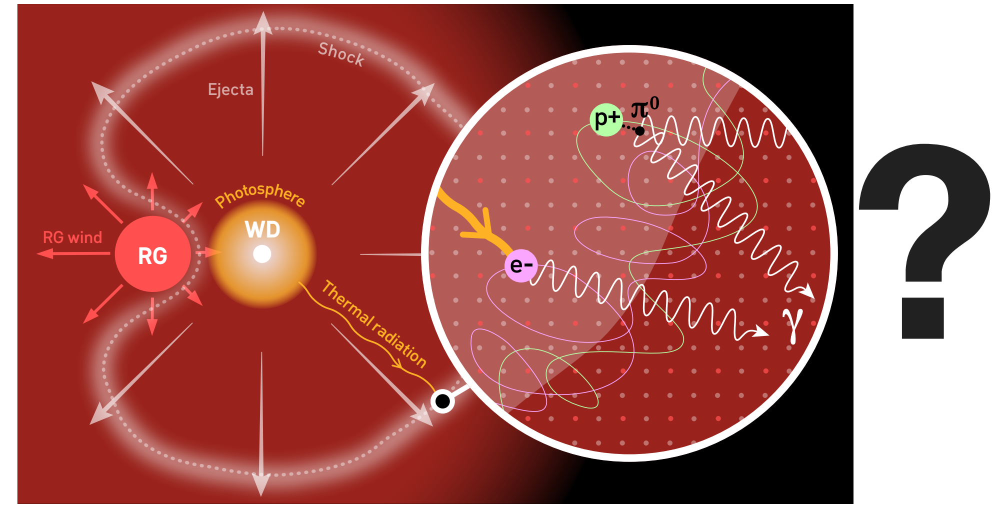


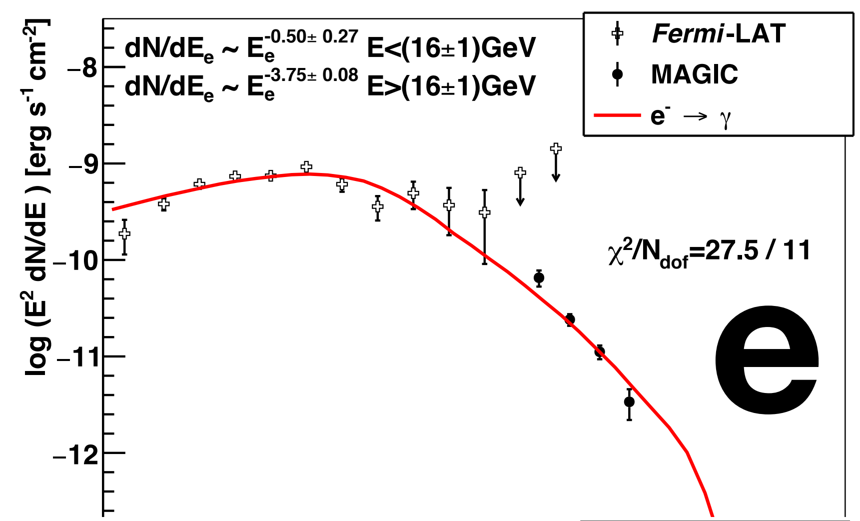
- ★ Many possible associations of LHAASO sources (except for the Crab Nebula)
- ★ Maximum energy detected photons compatible spin-down power from possible associated PWNe
- ★ Other associations are possible (PWN, SNR, SFR…)

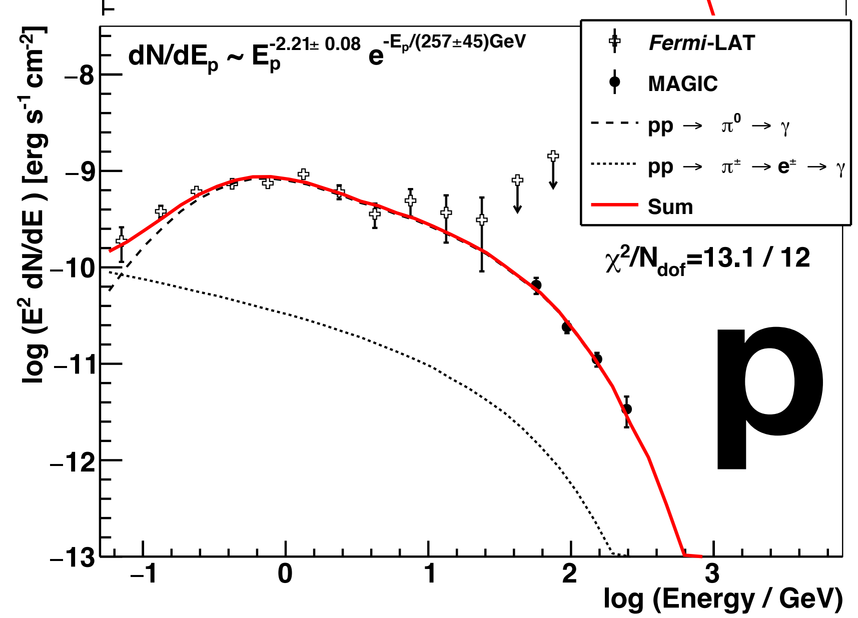
Recurrent nova RS Oph

cosmic rays | accelerators

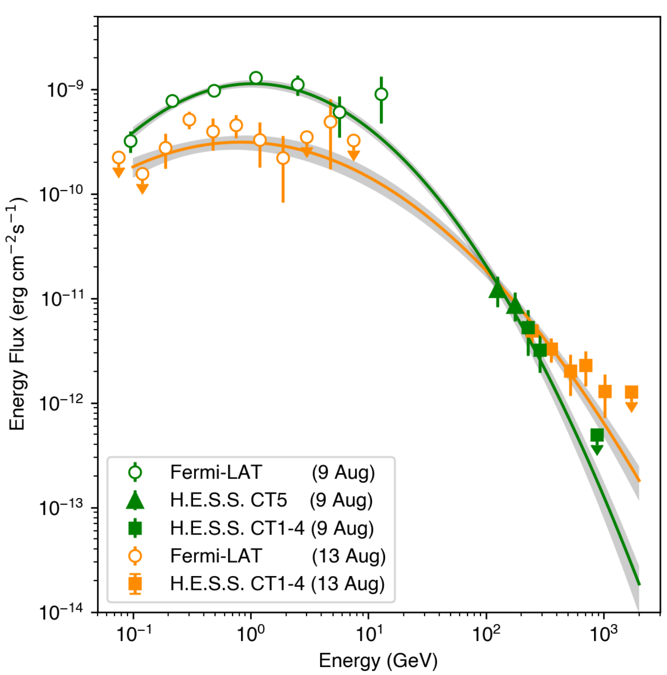
- ★ RS Ophiuchi recurrent symbiotic nova August 2021 outburst detected (among many others) by Fermi-LAT, MAGIC, HESS
- ★ New type of VHE gamma-ray emitter
- ★ Proton acceleration strongly favored by spectrum and cutoff energy increasing with time
- ★ Minor contribution to Galactic cosmic rays & indirect support to bulk CRs from SNRs



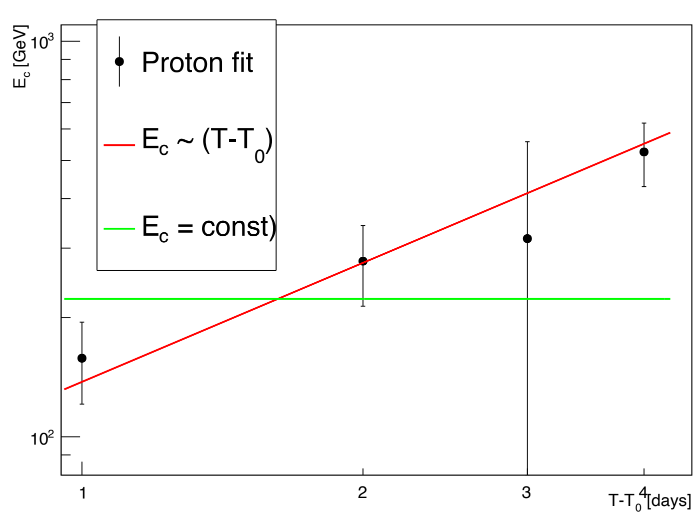




HESS Coll. Science 376 (2022) 77



MAGIC Coll. Nat. Astron. 6 (2022) 689



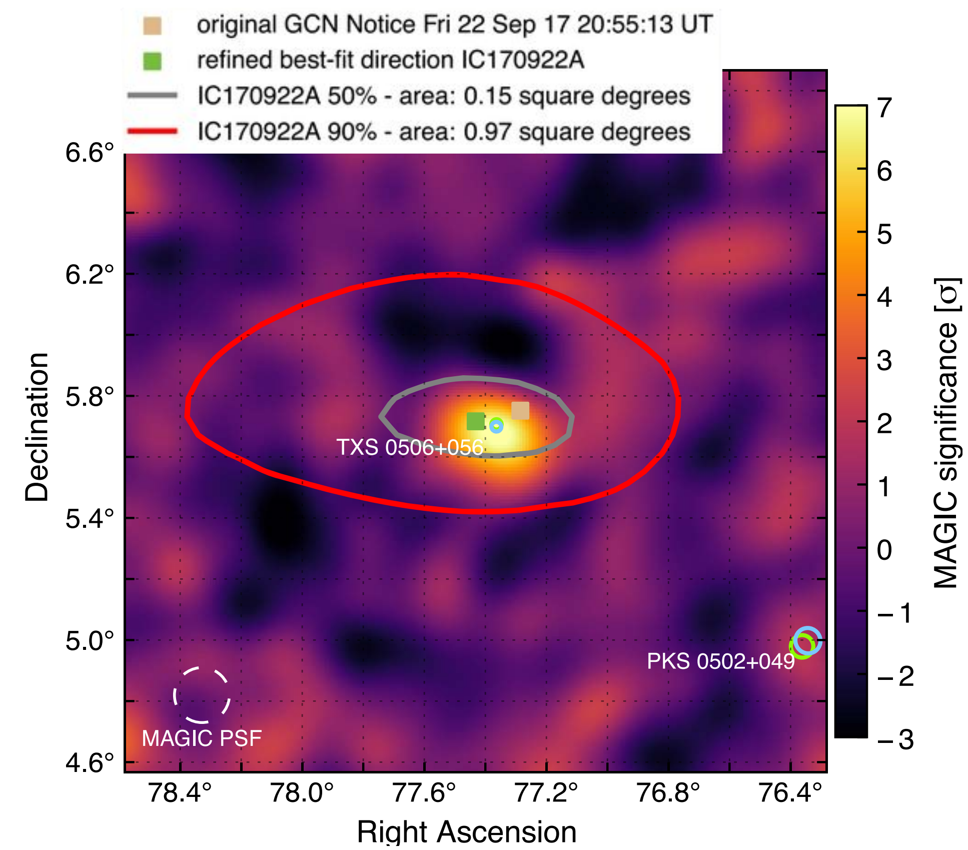
Multi-wavelength/Multi-messenger astronomy

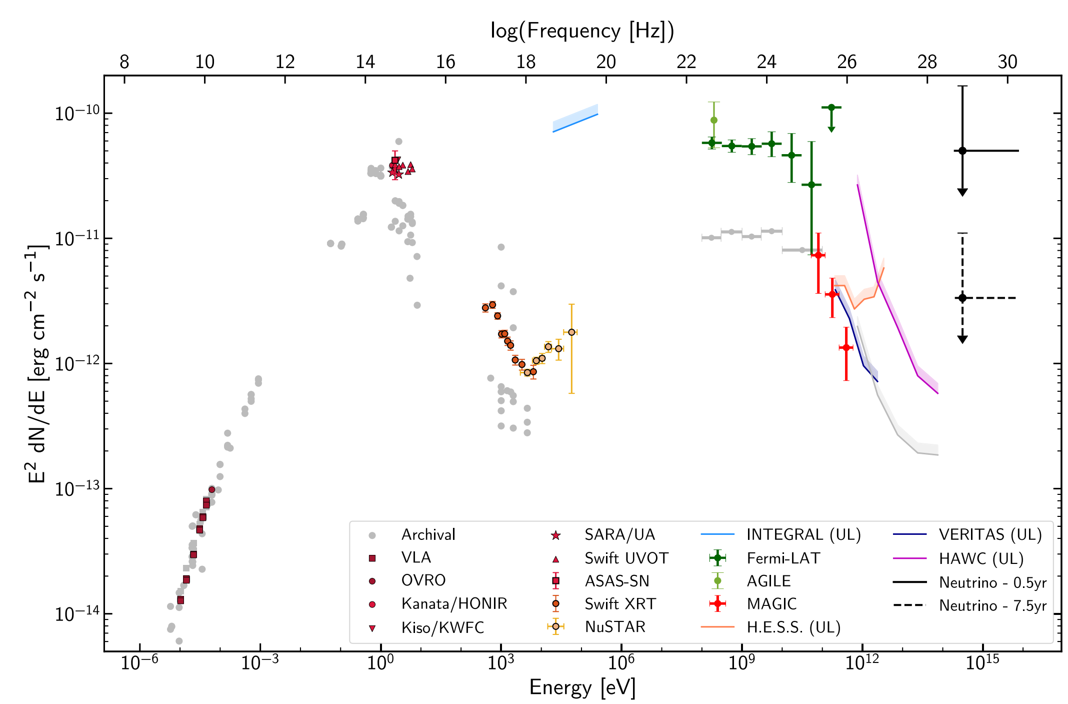
TXS 0506+056

MW/MM | accelerators | cosmic rays

- ★ 3σ association of a high-energy (290 TeV) neutrino with gamma-ray source (Fermi-LAT+MAGIC)
- ★ First evidence for an electromagnetic counterpart (flaring blazar, z=0.34) of a neutrino source
- ★ Multi-messenger SED
- ★ Deep monitoring (120h, 2017-2021) with MAGIC reveals several flares compatible with no further neutrino detection [Acciari et al. Astroph. J. 927 (2022) 197]

Aartssen et al. Science 361 (2018) eaat1378

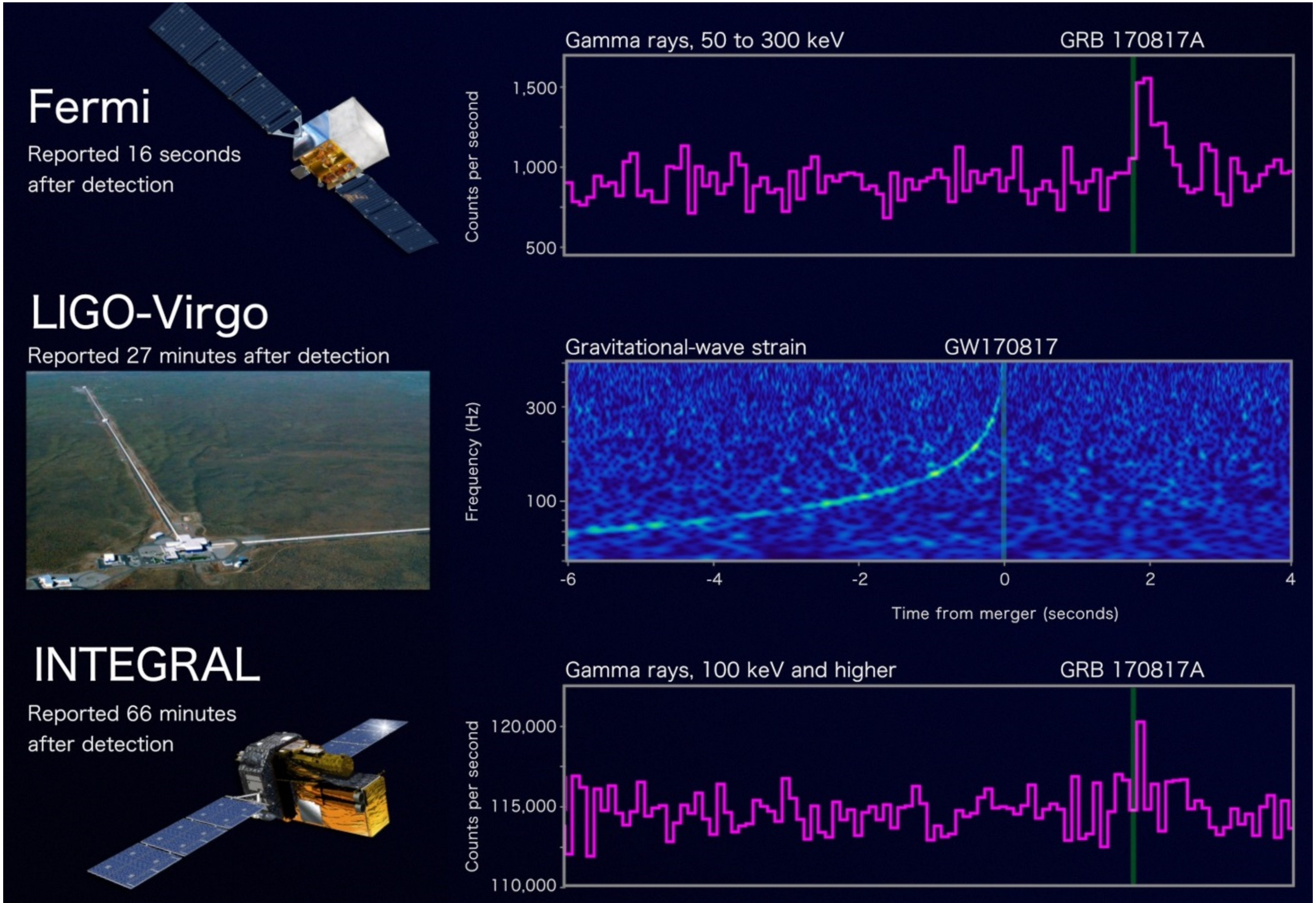




GW170817

MW/MM | accelerators

https://francis.naukas.com/2017/10/20/la-alerta-de-las-senales-gw170817-y-sgrb170817/

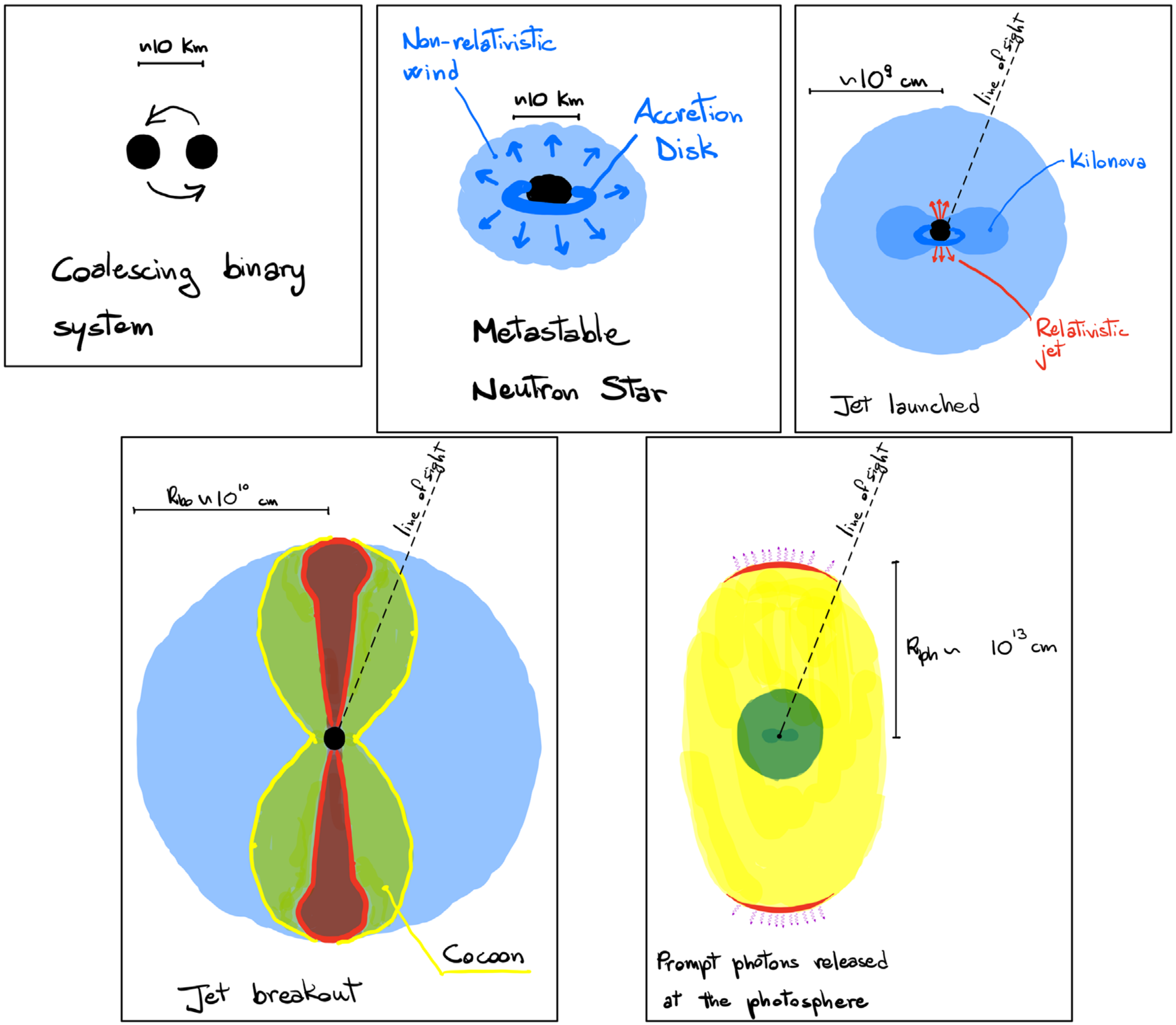


NSBS/kilonova/short GRB connection

MW/MM

accelerators

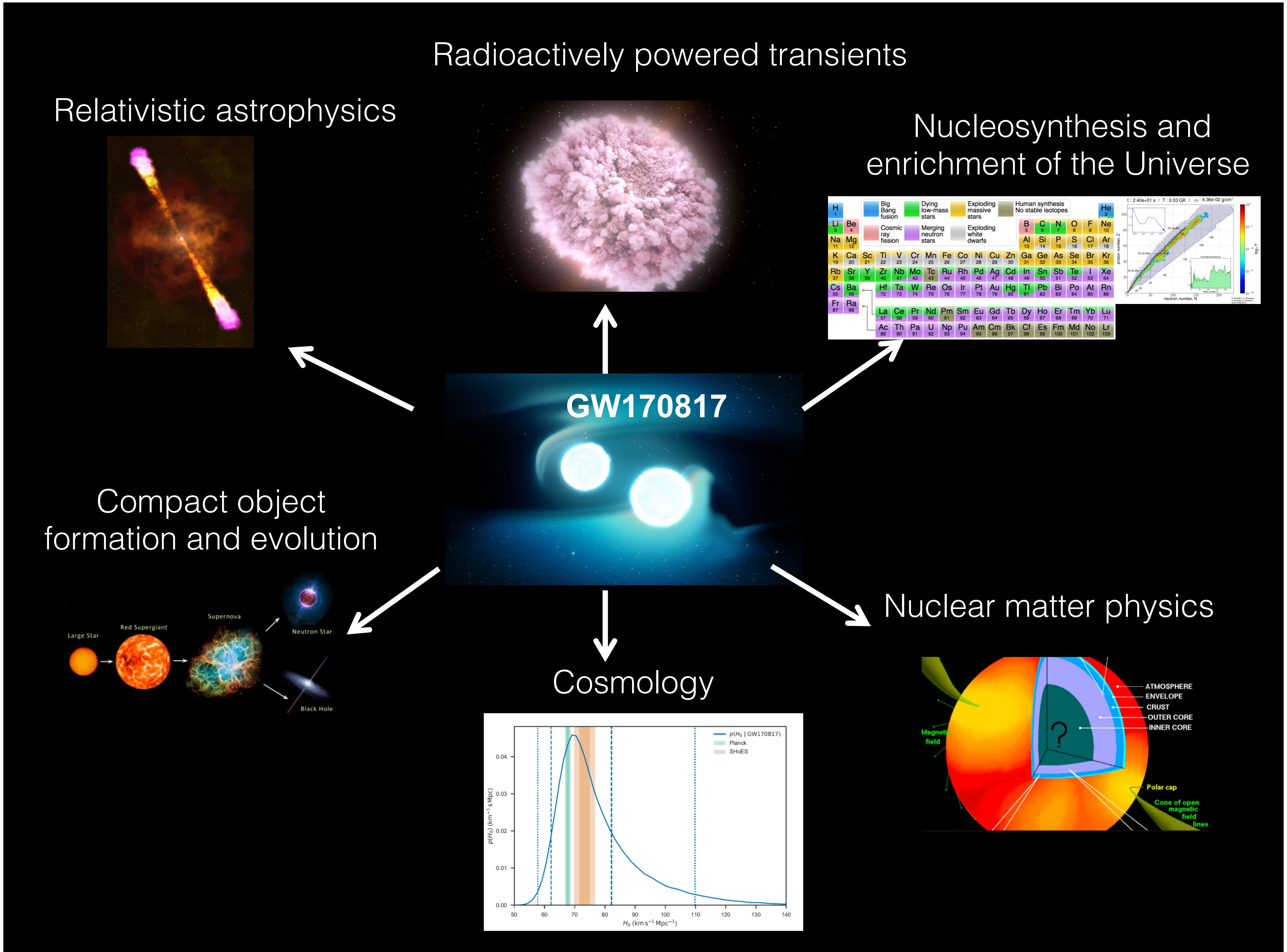
Lazzati et al. ApJ 898 (2020) 59



GW170817: an enlightening event

MW/MM | accelerators

Branchesi @ Gamma2022



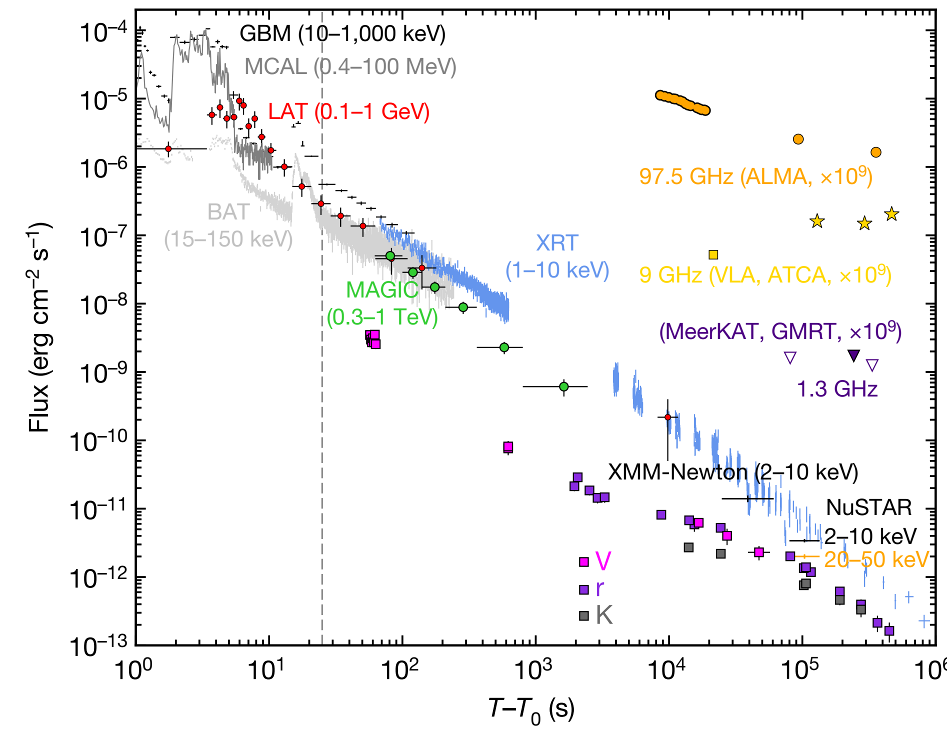
Particle acceleration in extreme environments

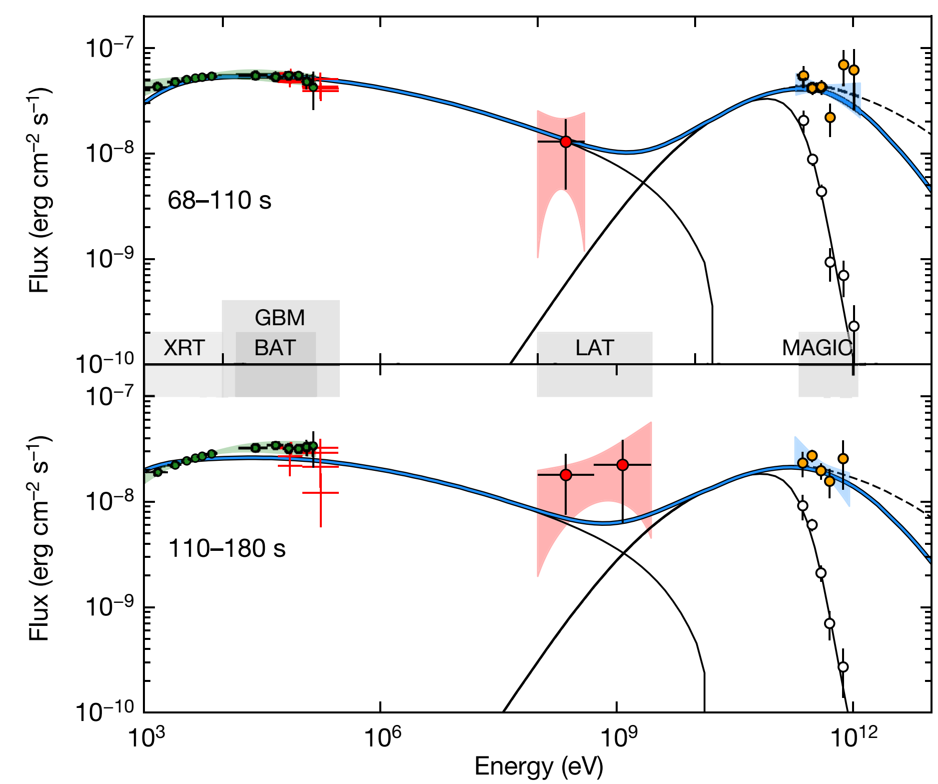
GRB 190114C

accelerators MW/MM

- ★ Long gamma-ray burst (T_{90} = 361s)
- ★ First detection of VHE emission from GRB (>50σ)
  - ✦ MAGIC observation started at T_0+50s
  - ✦ Brightest VHE source ever → 100×Crab
  - ✦ Emission above 100 GeV strongly absorbed by interaction with extragalactic background light
- ★ Exhaustive MWL coverage
  - ✦ Afterglow emission produced by jet interaction with surrounding medium
  - ✦ Synchrotron emission excluded, SSC favored

MAGIC Coll. Nature 575 (2019) 455
MAGIC Coll. et al. Nature 575 (2019) 459



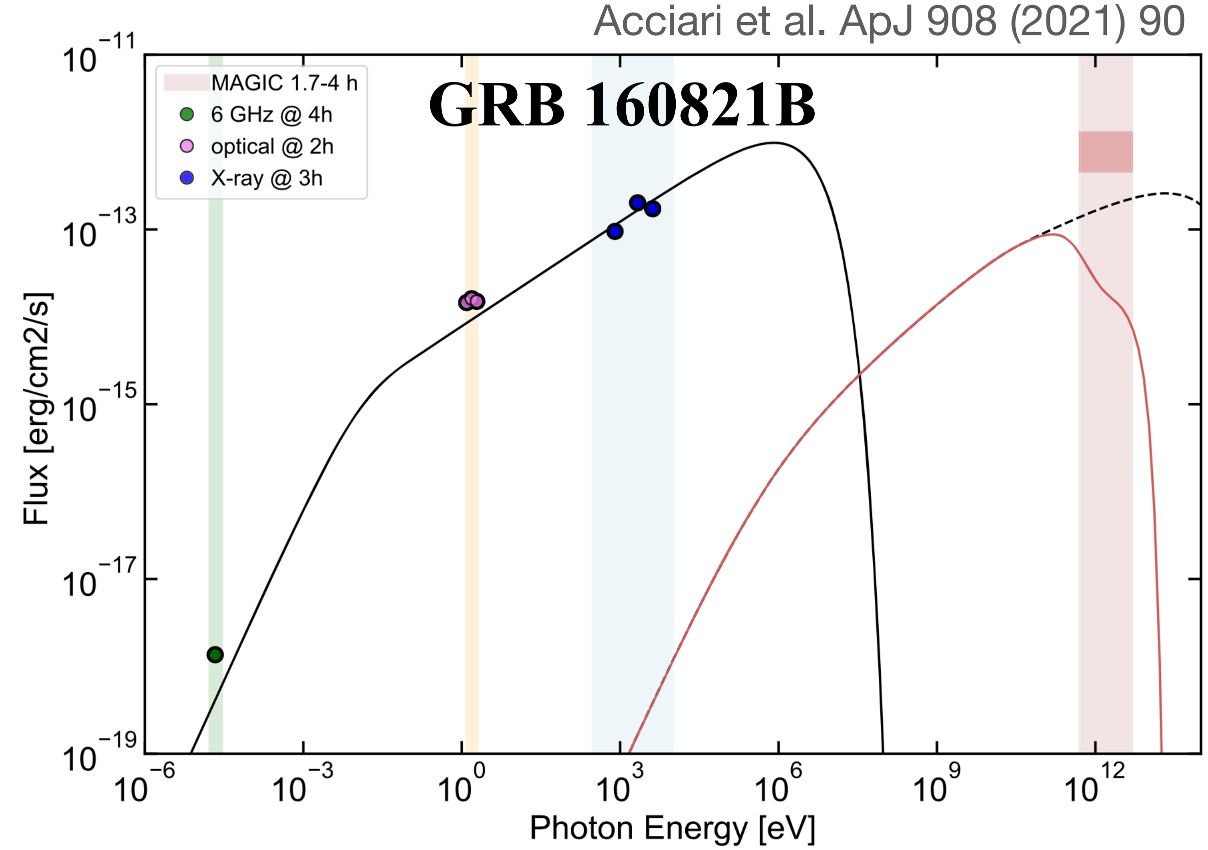


Other GRB detections

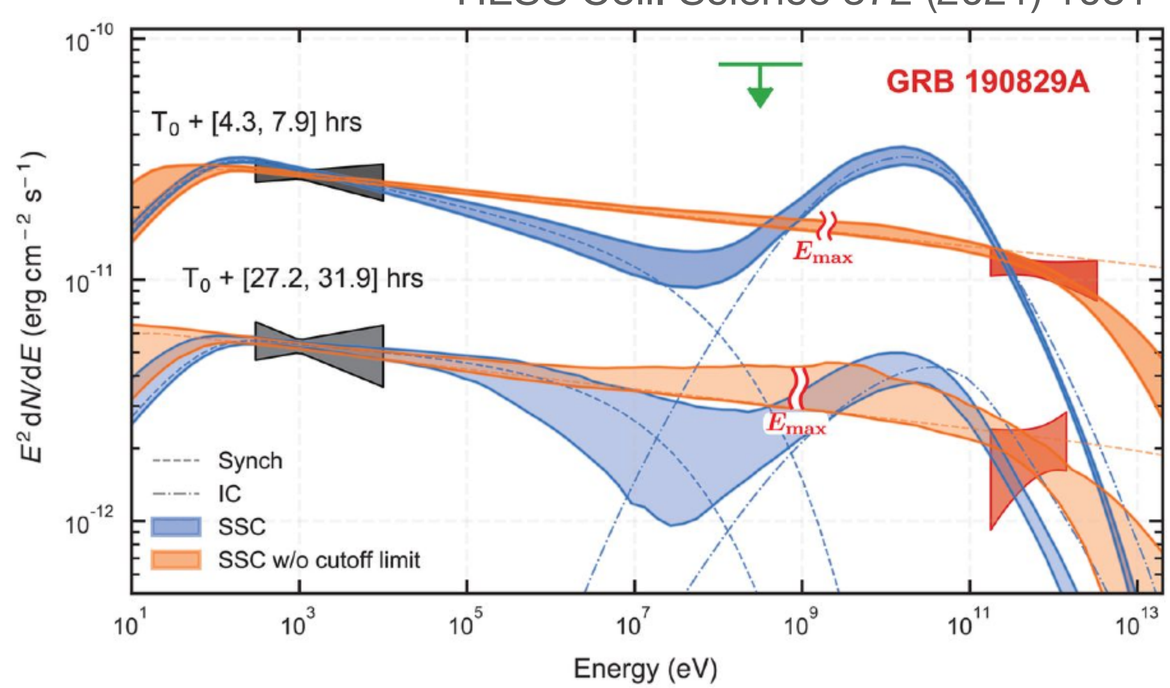
accelerators MW/MM

- ★ The detection of GRB190114 have opened the can for almost routine GRB detections (4.5 detections so far by MAGIC and HESS)
- ★ Spectra difficult to explain by SSC process
  - ✦ No evidence of two components
  - ✦ No evidence of Klein-Nishina cut-off
  - ✦ Extended synchrotron above the expected maximum energy?

Acciari et al. ApJ 908 (2021) 90



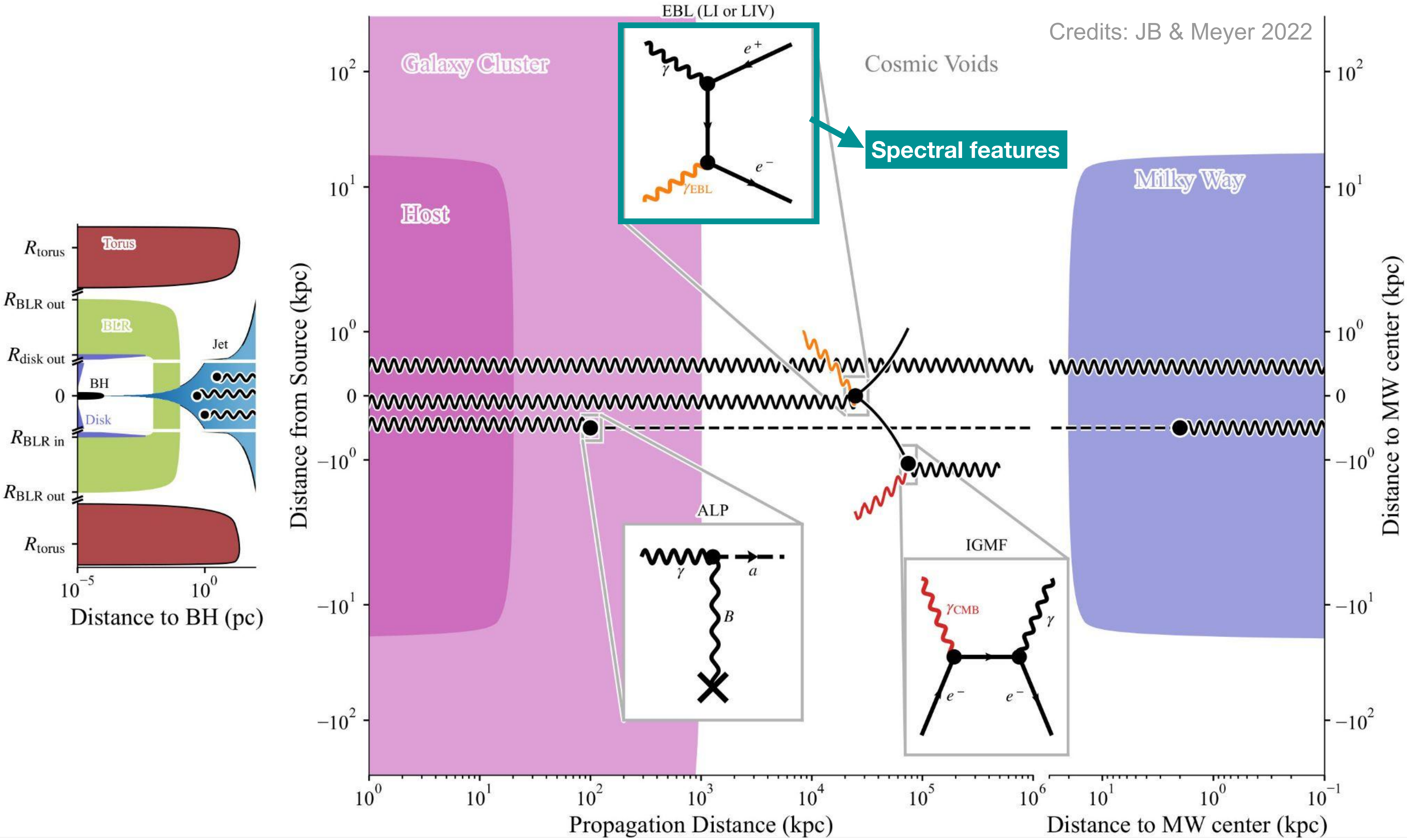
HESS Coll. Science 372 (2021) 1081



Propagation effects

Gamma-ray propagation: EBL

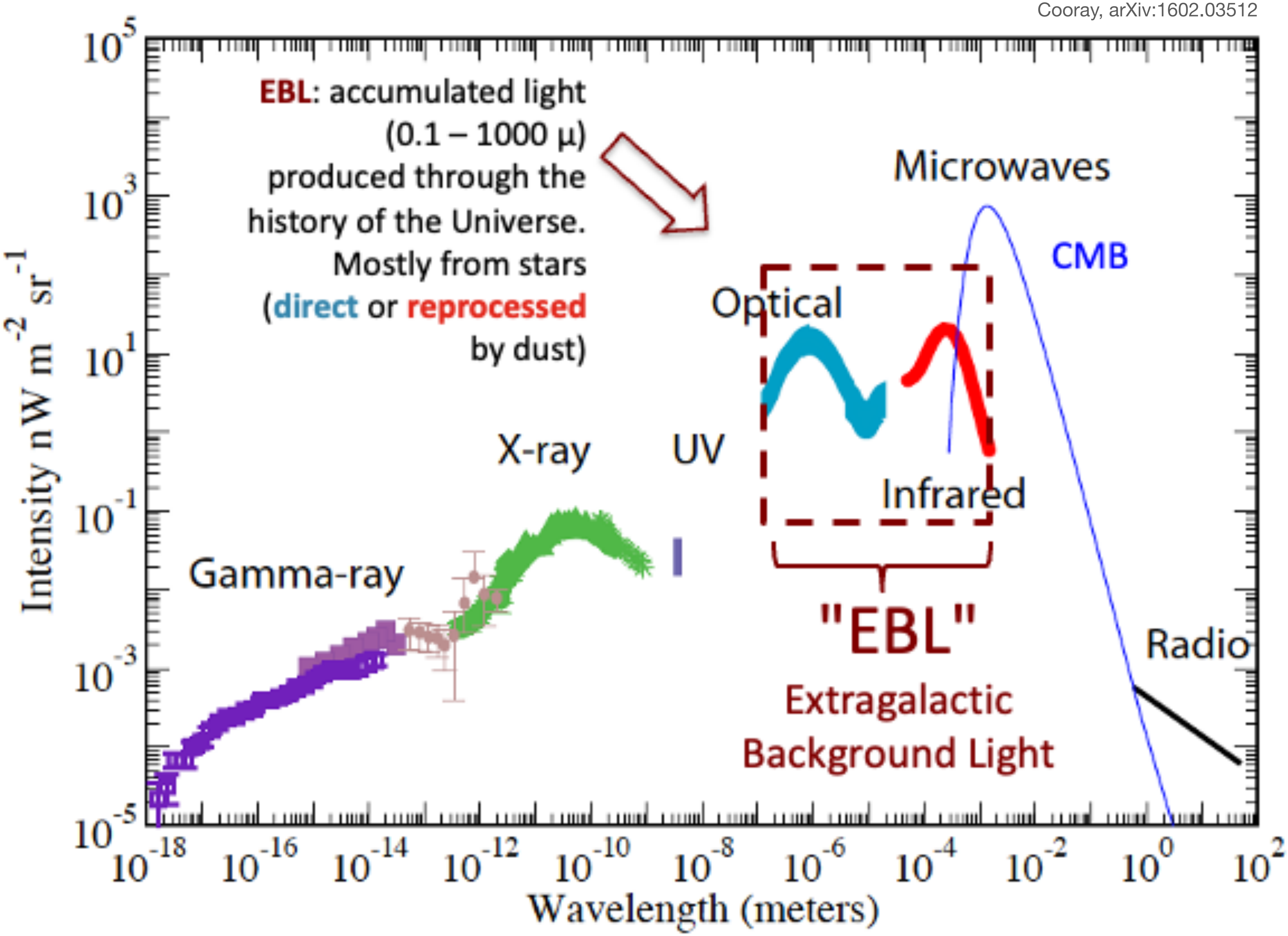
propagation



Extragalactic background radiation

propagation

Cooray, arXiv:1602.03512

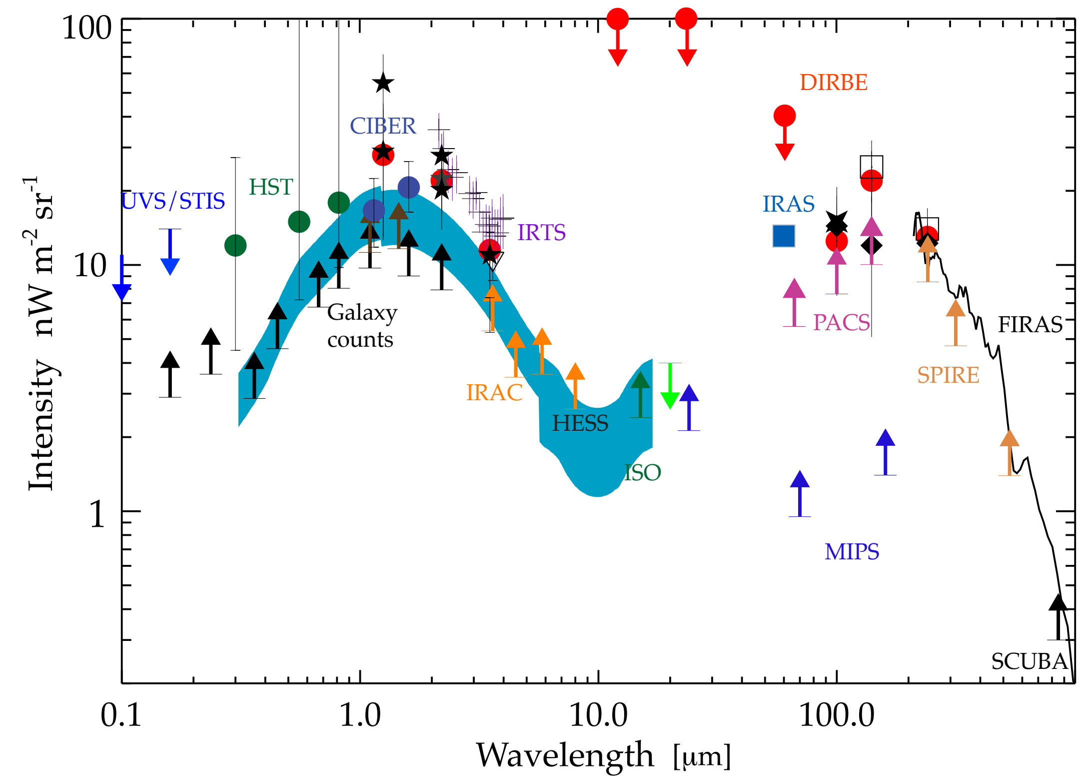


Measuring EBL

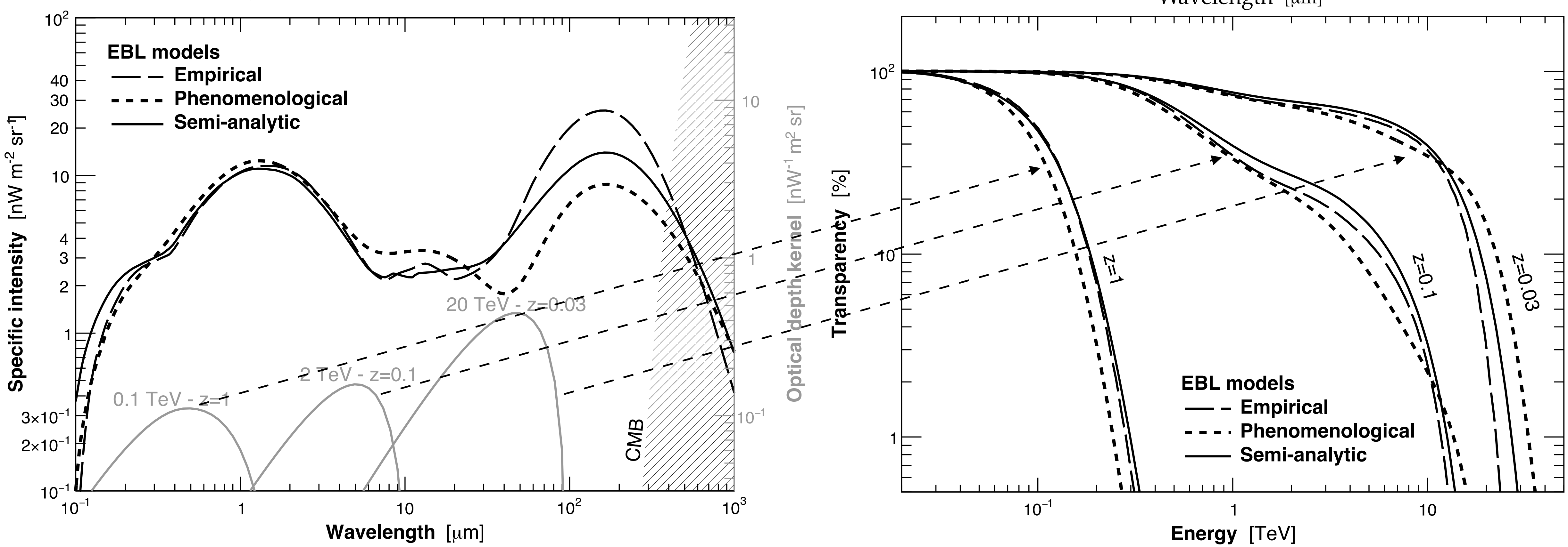
propagation

- ★ Directly:
  - ✦ Direct measurements (lots of foregrounds)
  - ✦ Galaxy counts (lower limit)
- ★ Indirectly
  - ✦ Attenuation of gamma rays traveling cosmological distances

Cooray, arXiv:1602.03512



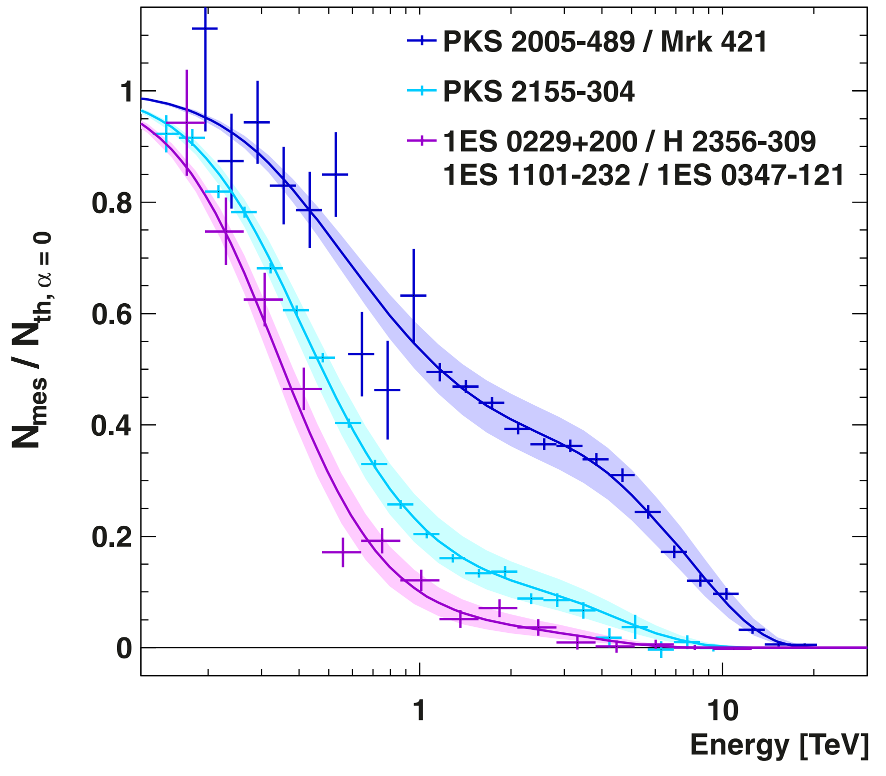
Pueschel & Biteau, arXiv:2112.05952



Measuring the EBL imprint

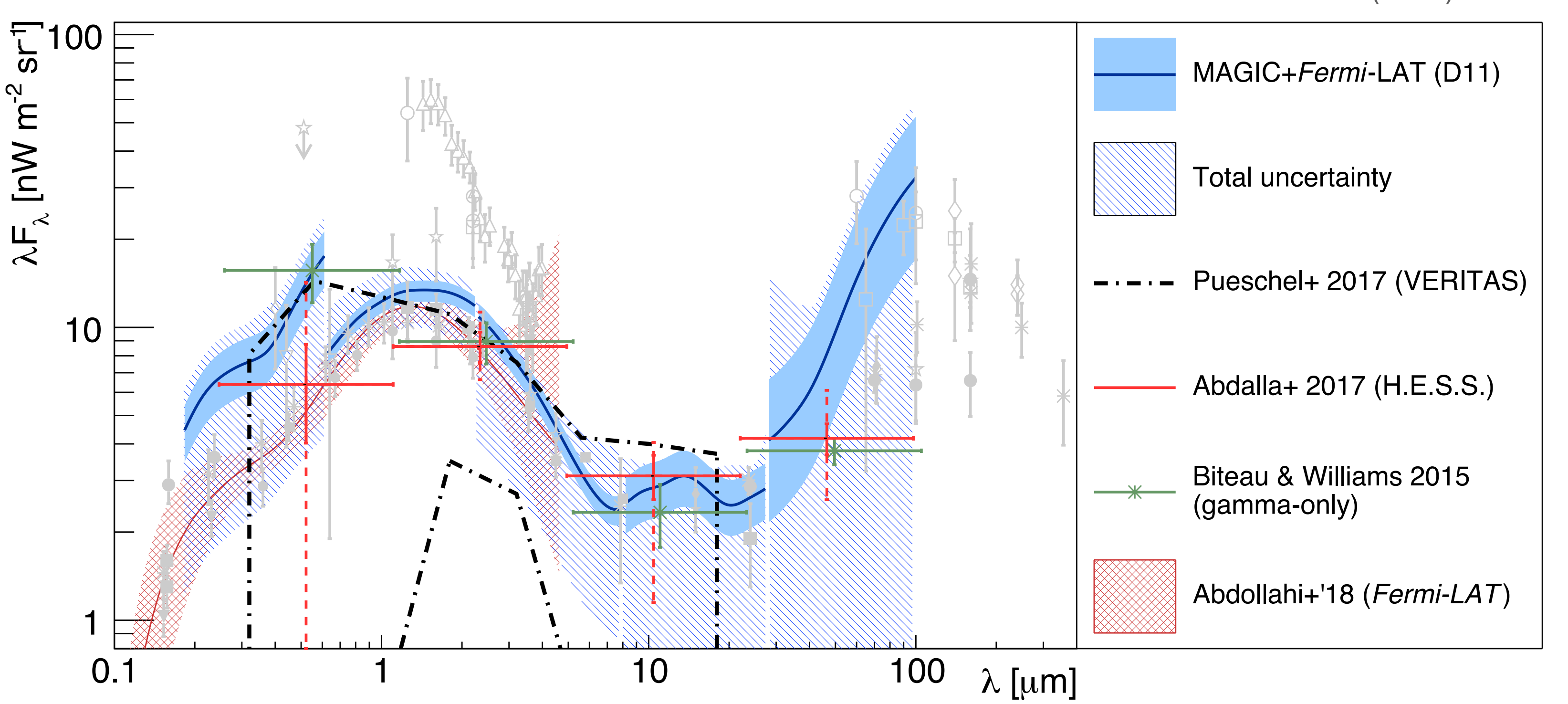
propagation accelerators

HESS Coll. A&A 550 (2013) A4



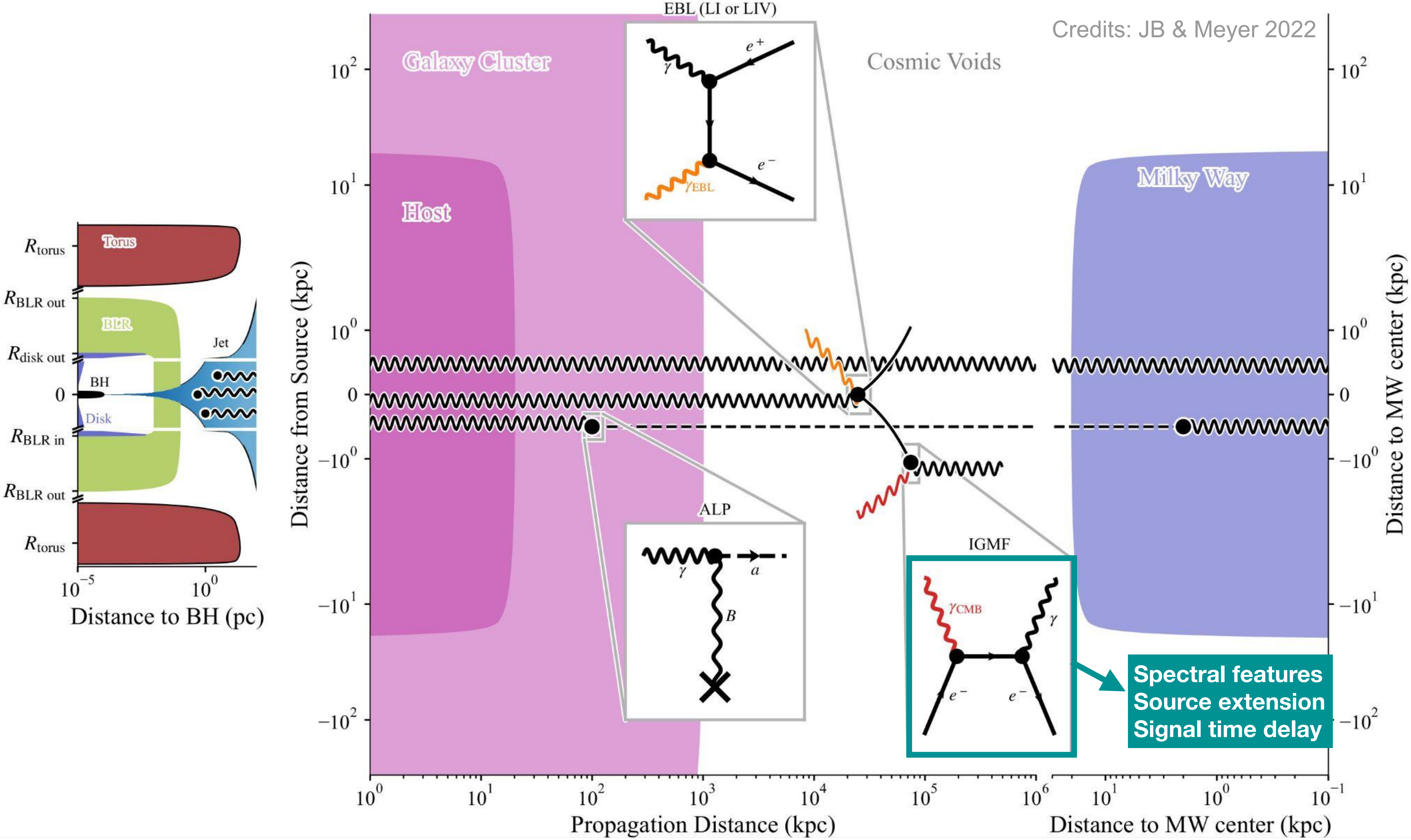
- ★ The measurement is dominated by systematics
  - ✦ Energy scale
  - ✦ Intrinsic spectra
- ★ Still, useful & constraining upper limits

MAGIC Coll. MNRAS 486 (2019) 4233



Gamma-ray propagation: IGMF

propagation

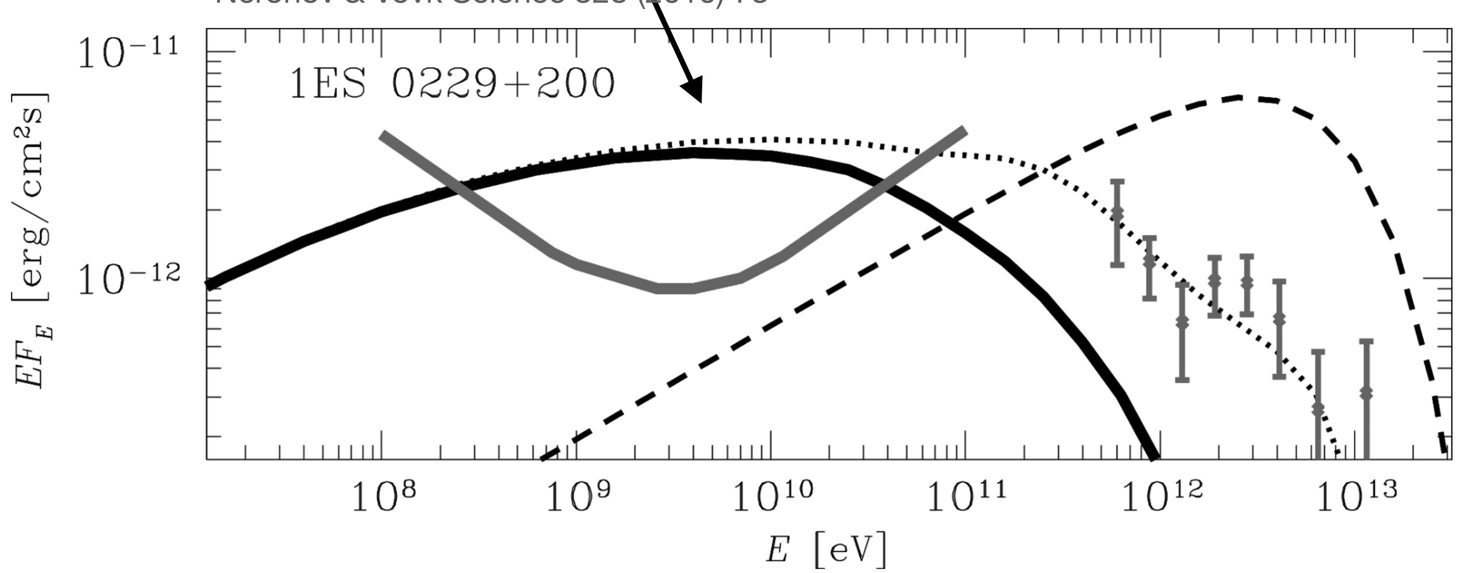


Intergalactic magnetic fields

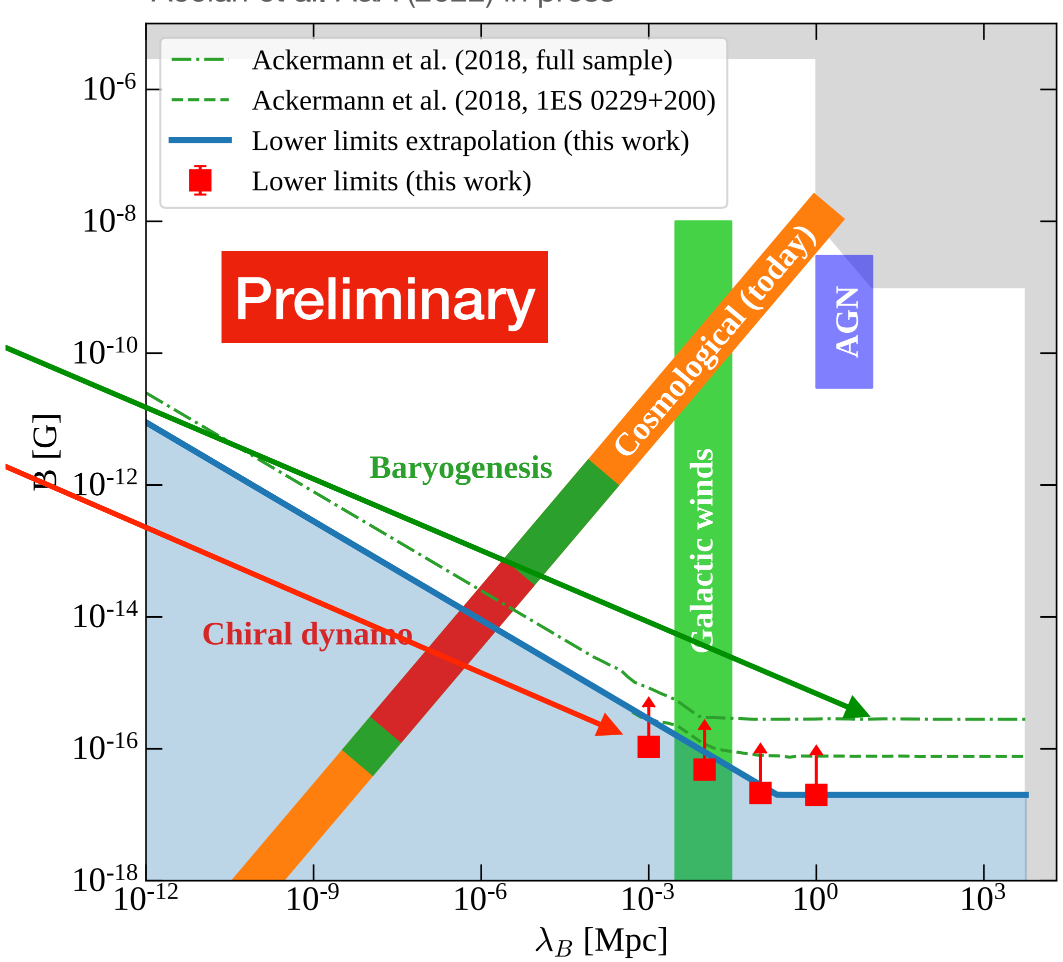
propagation

- ★ TeV + EBL produce e+e- pairs, which lose energy through IC with CMB, producing GeV secondaries
- ★ Depending on IGMF intensity, GeV secondary emission should be:
  - ✦ extended
  - ✦ delayed
  - ✦ inexistent

Neronov & Vovk Science 328 (2010) 73



Acciari et al. A&A (2022) in press

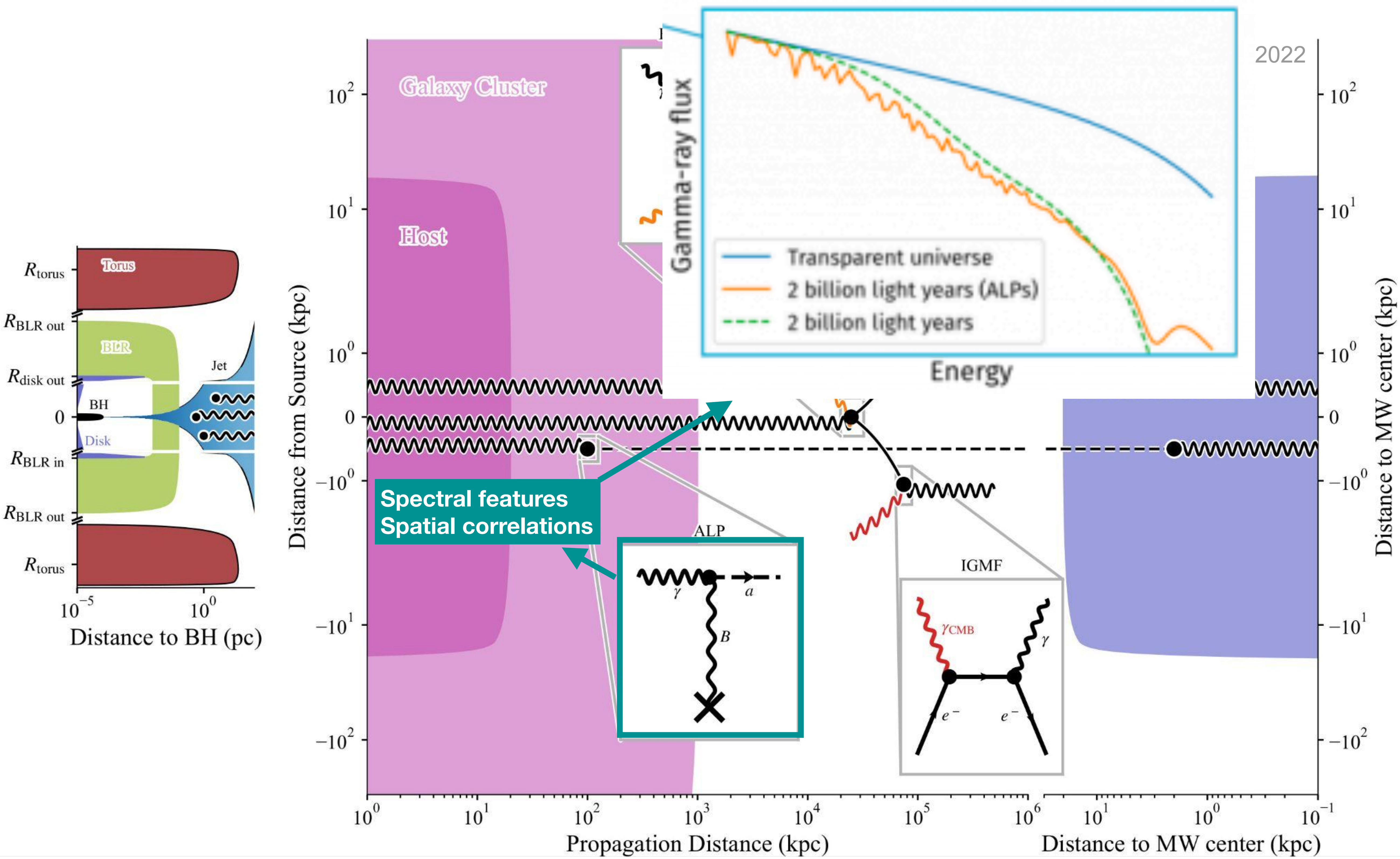


$$B \geq 3 \times 10^{-16}\ \text{G}$$

Physics beyond the Standard Model

Gamma-ray propagation: ALPs

propagation

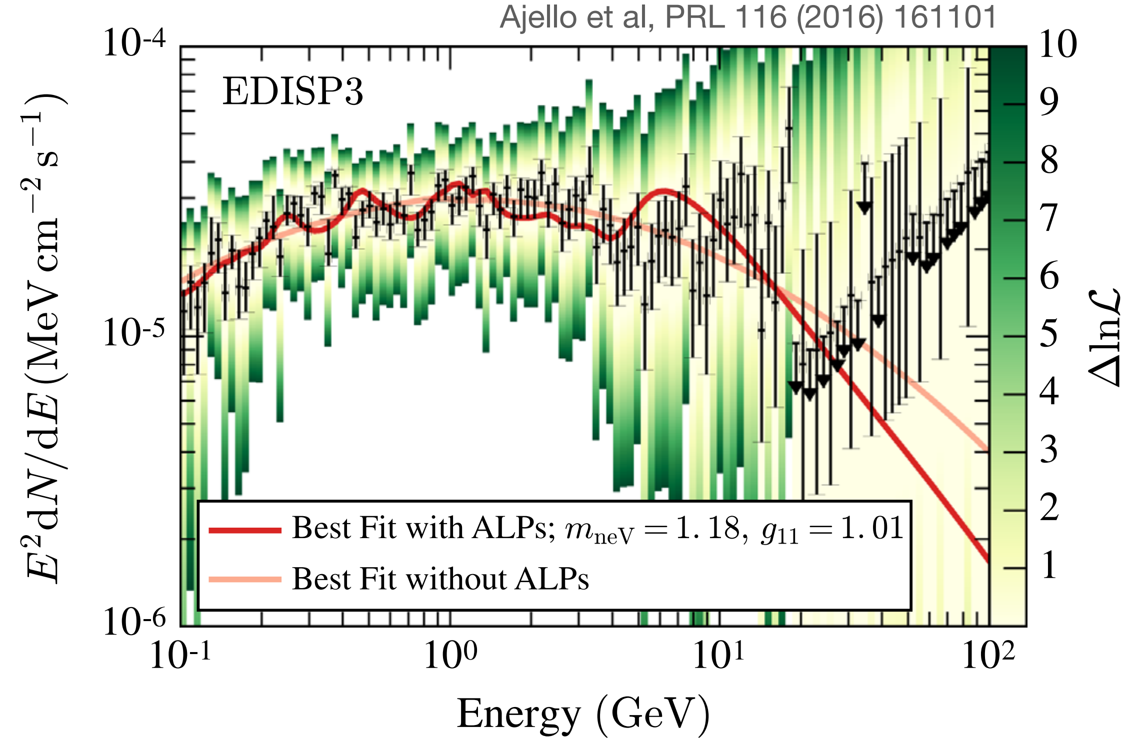


Search for spectral irregularities

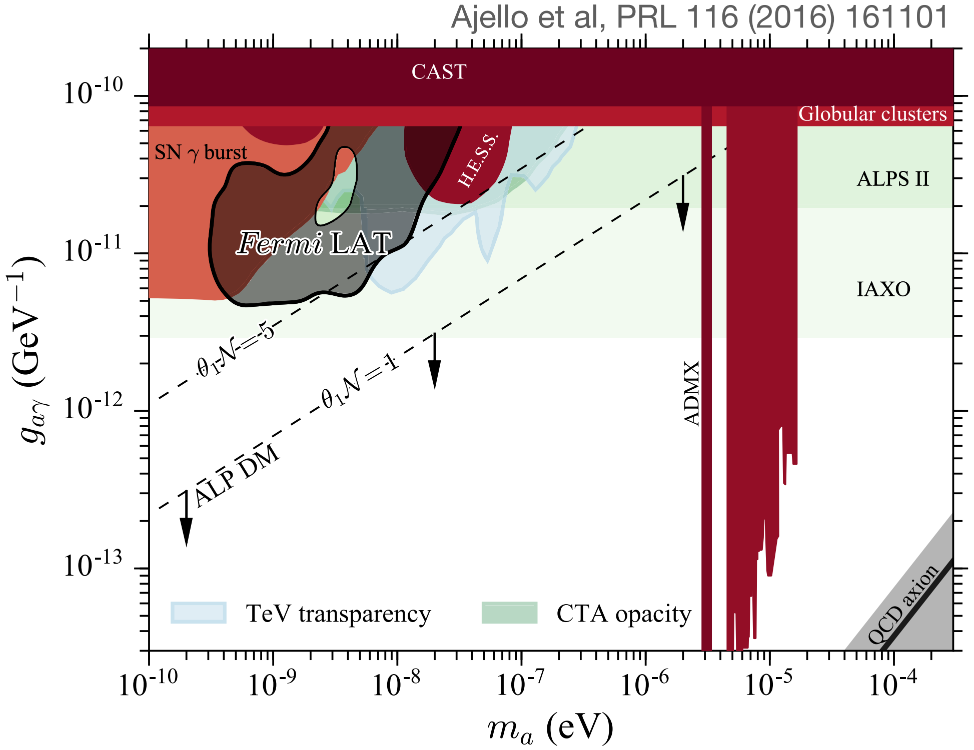
BSM propagation

- ★ Cause: magnetic field in the source
- ★ Observations:
  - ✦ NGC1275 (6 years with Fermi-LAT)
  - ✦ PKS2155-304 (13 h super flare with HESS)
- ★ No preference for ALP hypothesis found in the data

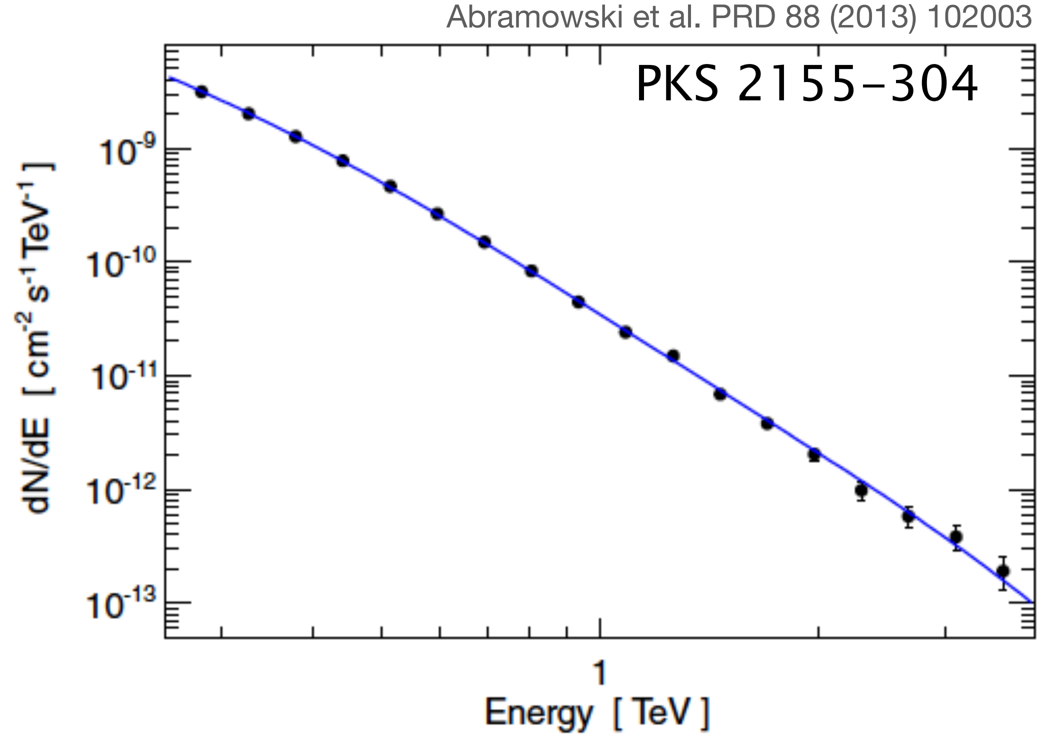
Ajello et al, PRL 116 (2016) 161101



Ajello et al, PRL 116 (2016) 161101



Abramowski et al. PRD 88 (2013) 102003



Search for high energy boost in flux

BSM | propagation

★ Cause: escape EBL while being ALP

★ No evidence for ALP-induced high-E flux boost in a large compilation of HE+VHE spectra (106 blazars)

Biteau & Williams ApJ 812 (2015) 60

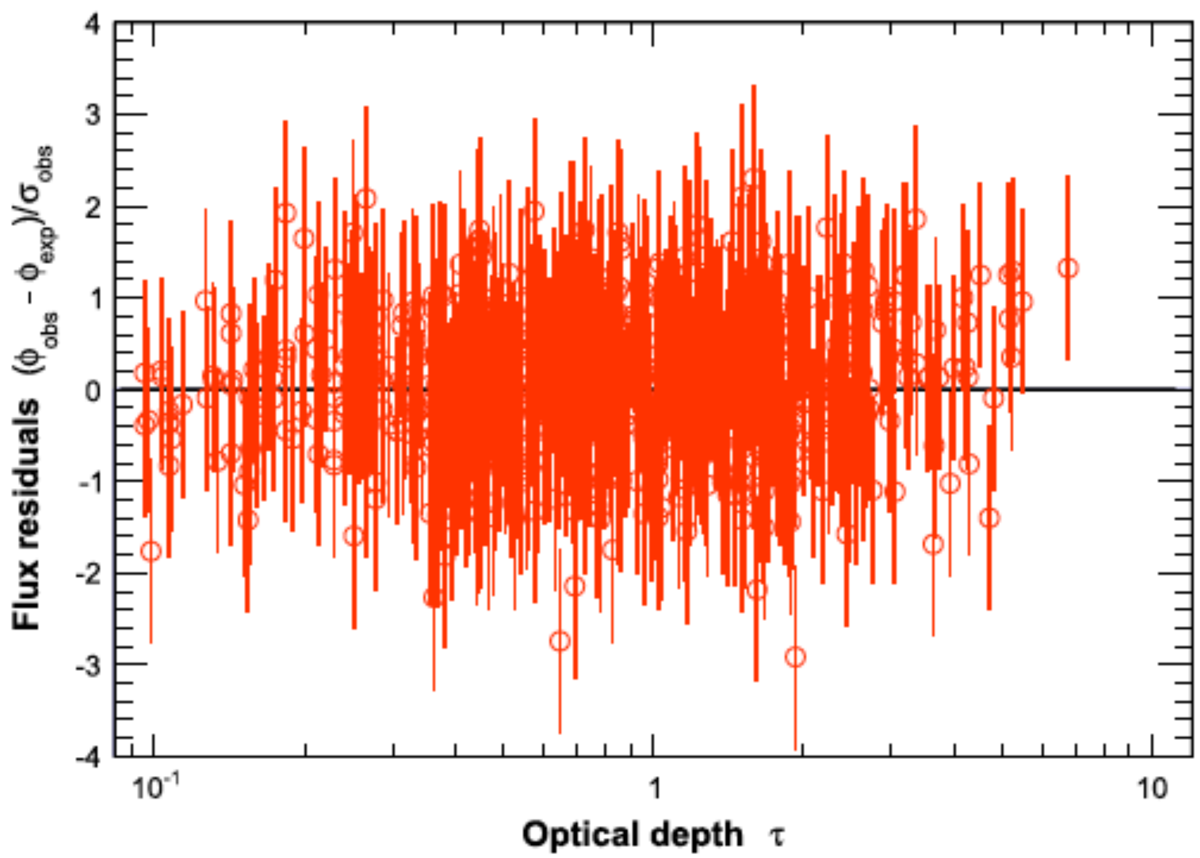


Figure 7. Residuals to the best-fit models for the 106 spectra (737 points) studied in this paper, as a function of optical depth.

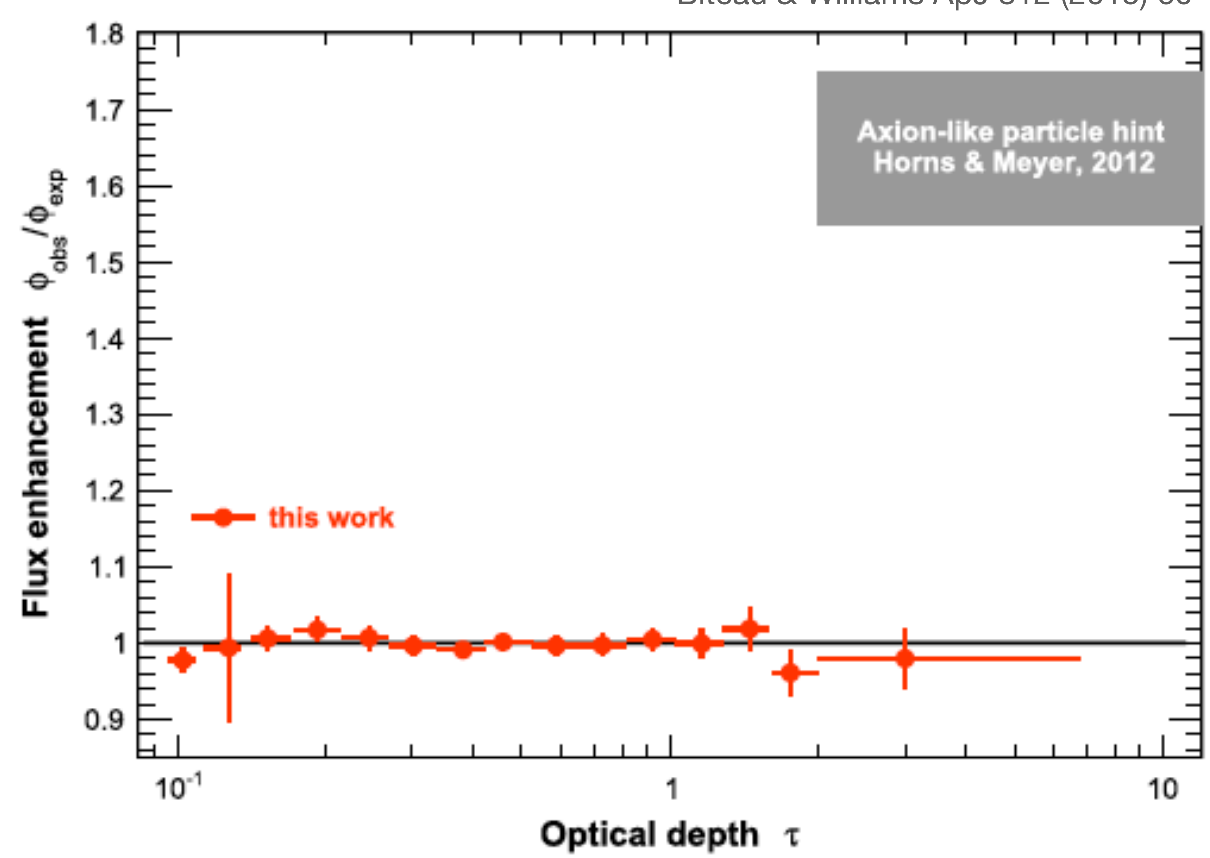
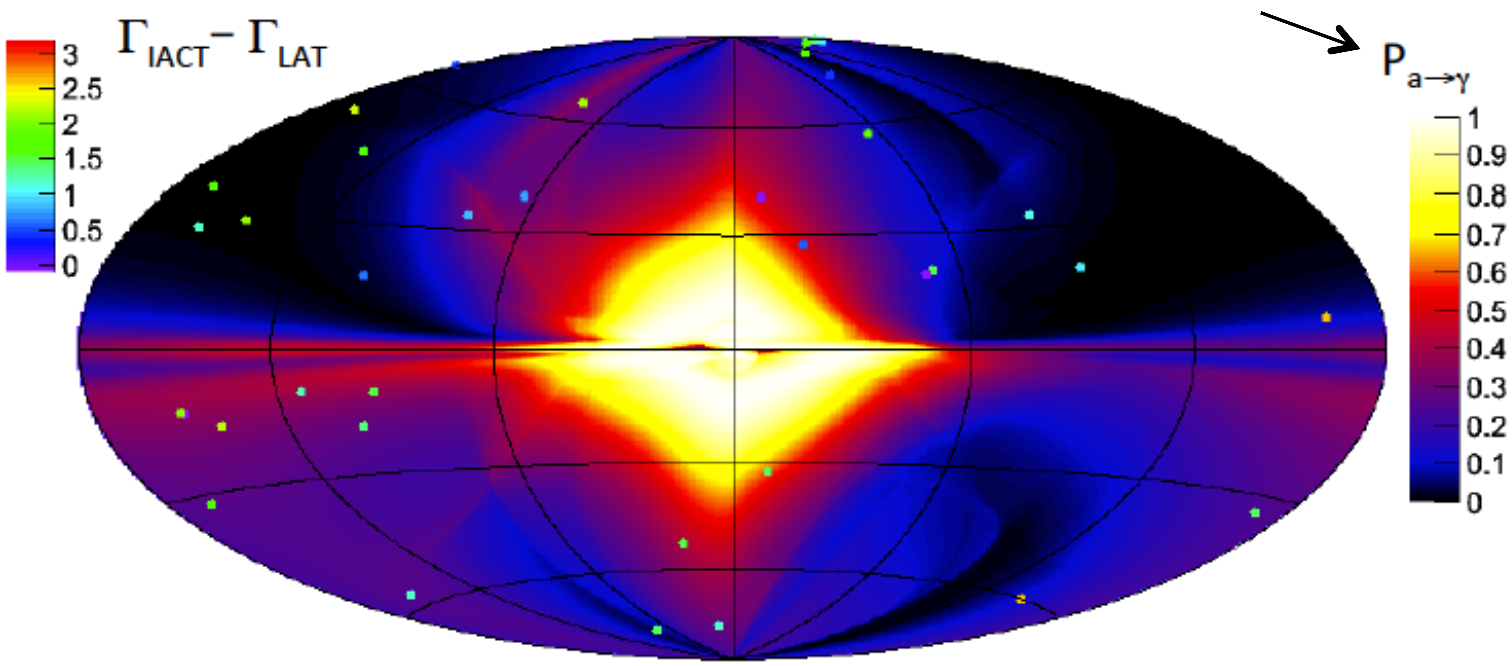


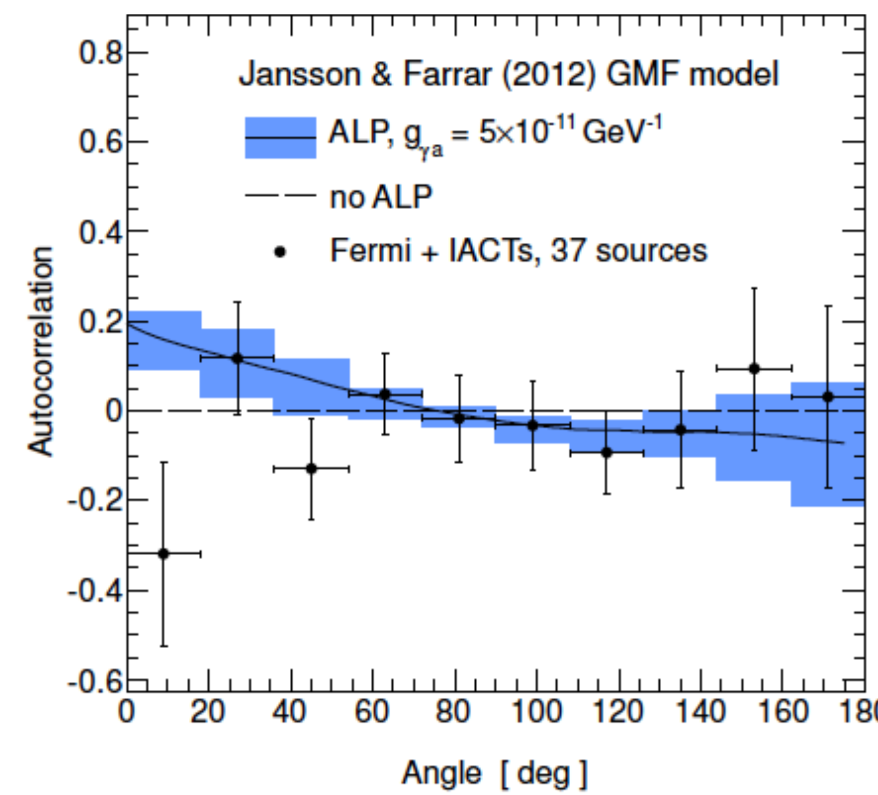
Figure 8. Flux enhancement, defined by the ratio of observed and expected fluxes, as a function optical depth. The shaded gray region is the flux enhancement implied by the results of Horns & Meyer (2012).

Correlation with Galactic magnetic fields

BSM propagation

Wouters & Brun JCAP 01 (2014)

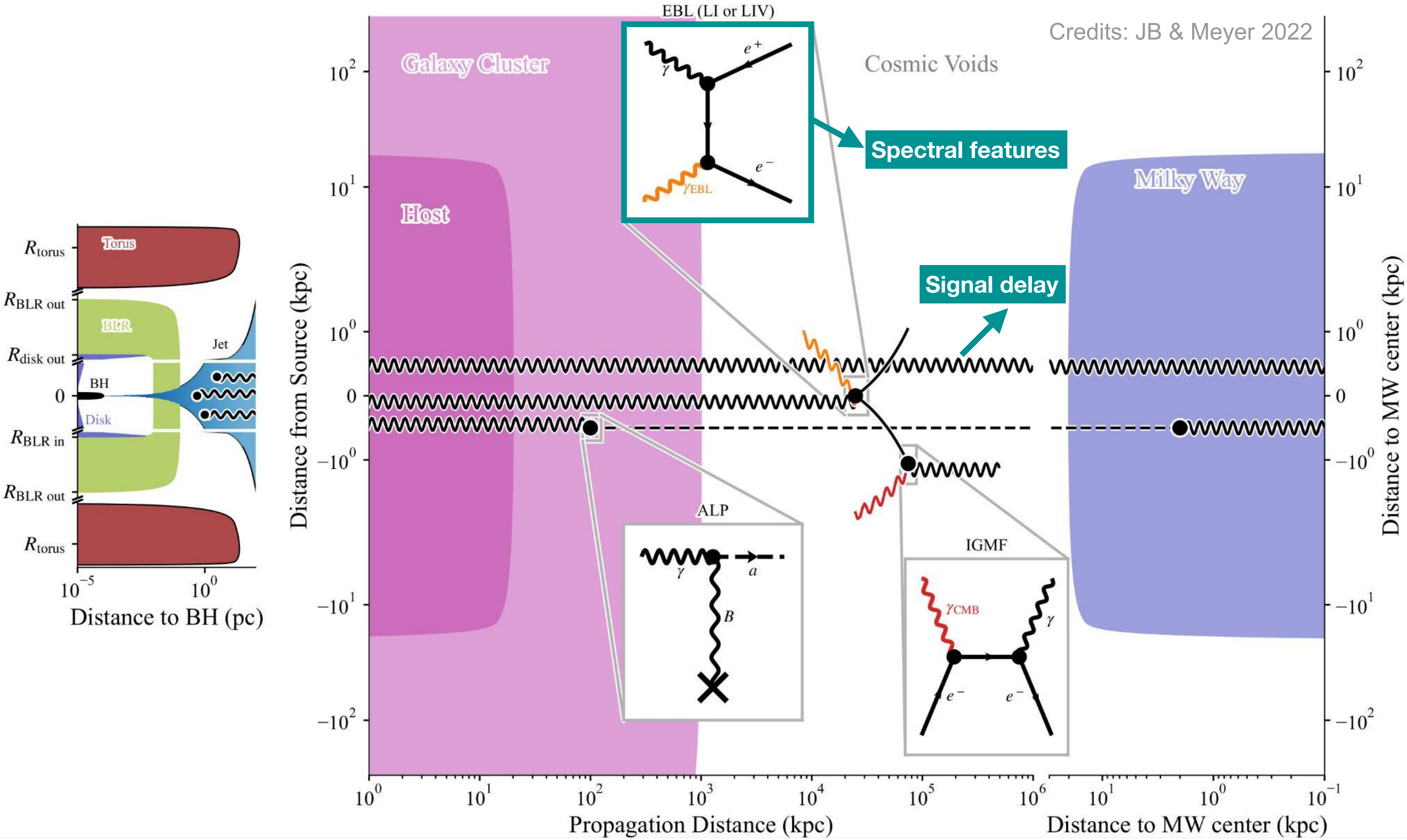




- ★ Assuming ALP-γ conversions only at source and Galaxy
- ★ Simple approach: compare HE and VHE photon indices, look for autocorrelations among sources.
- ★ No correlation observed even compared to expected for $g_{a\gamma}$ close to CAST limit

Gamma-ray propagation: LIV

propagation



Lorentz Invariance Violation

BSM | propagation

- ★ Lorentz Invariance violation (LIV) expressed by Taylor expansion of the dispersion relation:

$$E^2 = p^2c^2 + m^2c^4 \pm E^2\left(\frac{E}{E_{QG}}\right)^n$$

+ → "superluminal"
- → "subluminal"

- ★ $E_{QG} \approx E_{Pl} \approx 10^{28}$ eV, vs:

  $E_{max,CR} \approx 10^{20}$ eV

  $E_{max,\gamma} \approx 10^{15}$ eV

- ★ LIV Manifestations include:
  - ✦ **Energy dependent speed of light in vacuum**
  - ✦ **Modification of energy threshold of reactions** (e.g. UHECR with CMB or γ **with EBL**)
  - ✦ **Photon decay** **(**γ **→ e^+e^-** and/or γ **→ 3** γ**)**
  - ✦ Vacuum birefringence
  - ✦ Vacuum Cherenkov radiation (by superluminal electrons in vacuum)
  - ✦ Suppression of particle interactions/decays
  - ✦ …

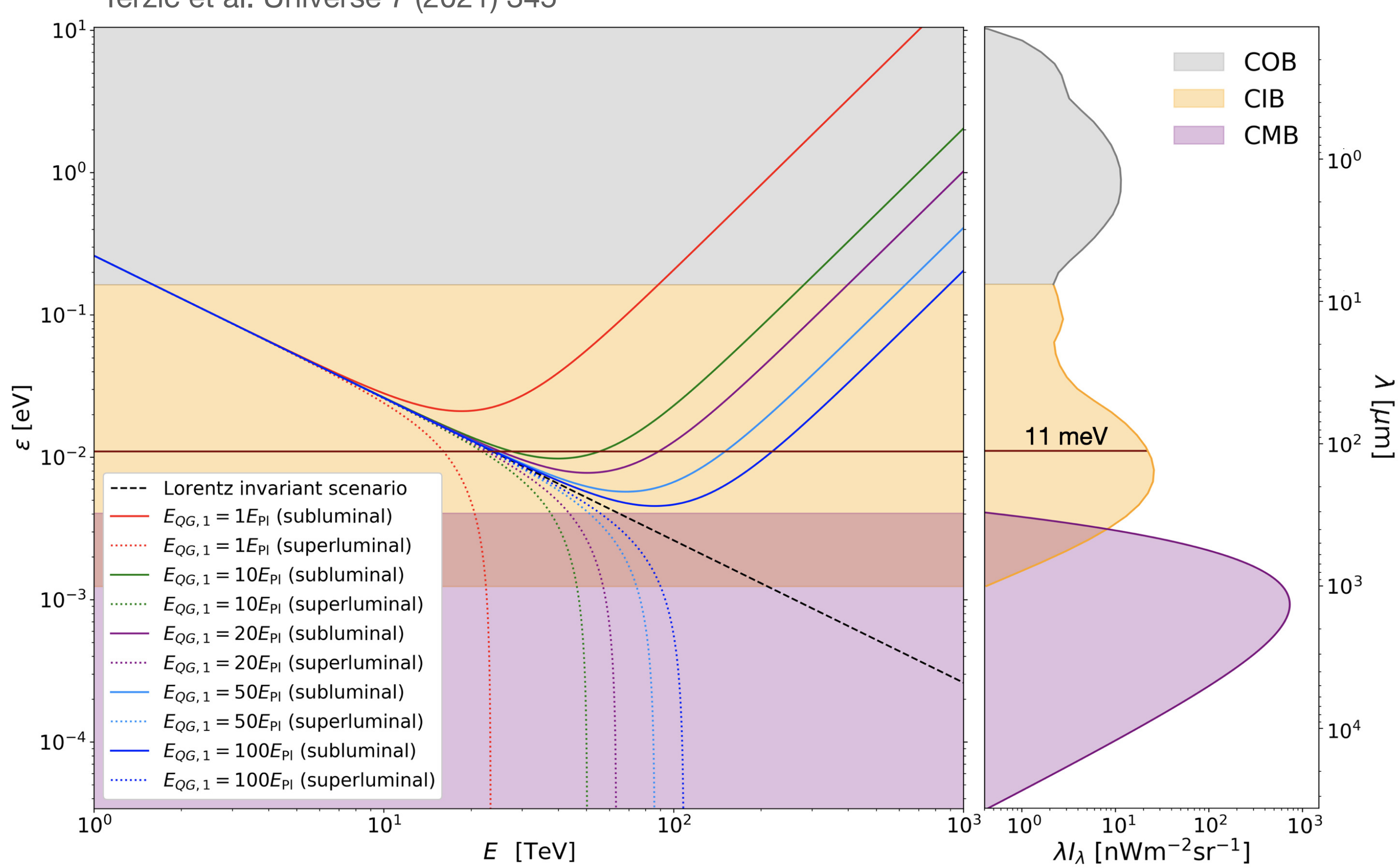
Subluminal LIV anomalous transparency

BSM | propagation

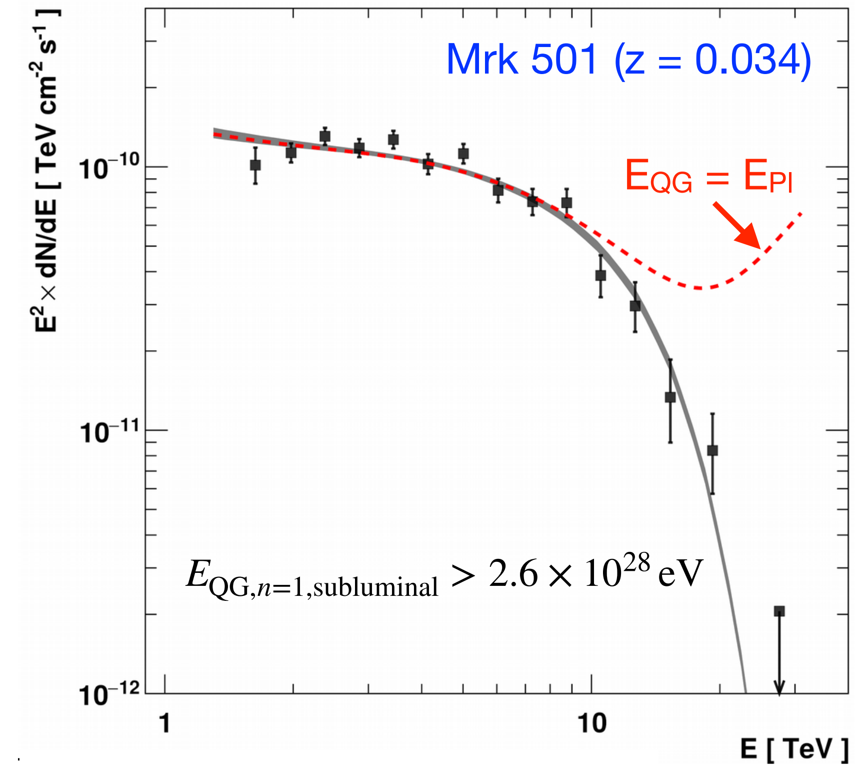
★ Change in the threshold for EBL absorption:

$$\epsilon_{\rm th} = \frac{m_e^2}{E_\gamma} \quad \rightarrow \quad \frac{m_e^2}{E_\gamma} \mp \frac{1}{4}\left(\frac{E_\gamma}{E_{{\rm QG},n}}\right)^n E_\gamma$$

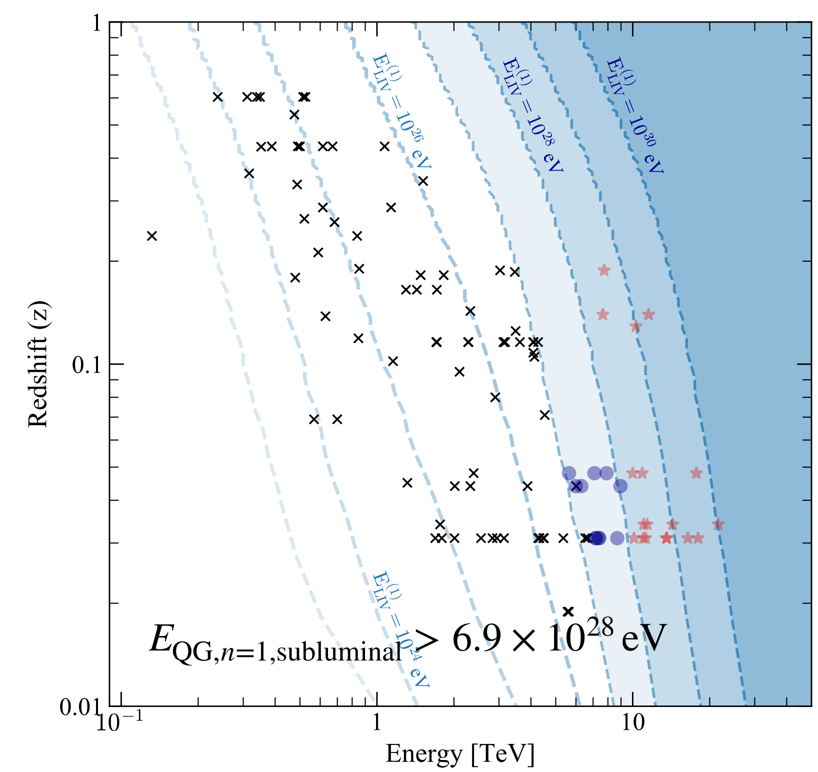
Terzić et al. Universe 7 (2021) 345



HESS Coll. ApJ 870 (2019) 93



Lang et al. PRD 99 (2019) 043015



Time-of-flight LIV searches

BSM propagation

★ Energy dependent photon group velocity:

$$v_\gamma = \frac{dE}{dp} \simeq c \left[1 \pm \sum_{n=1}^{\infty} \frac{n+1}{2} \left(\frac{E}{E_{\rm QG}} \right)^2 \right]$$

★ Difference in time of flight of two photons with energies $E_h > E_l$

$$\Delta t \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{H_0 E_{\rm QG}^n} \kappa_n(z)$$

Effect accumulates over cosmological distances

LIV with GRB090510 at HE

BSM propagation

★ GRB090510 detected by Fermi GBM and LAT

★ $z = 0.903$

★ GBM provides T_0

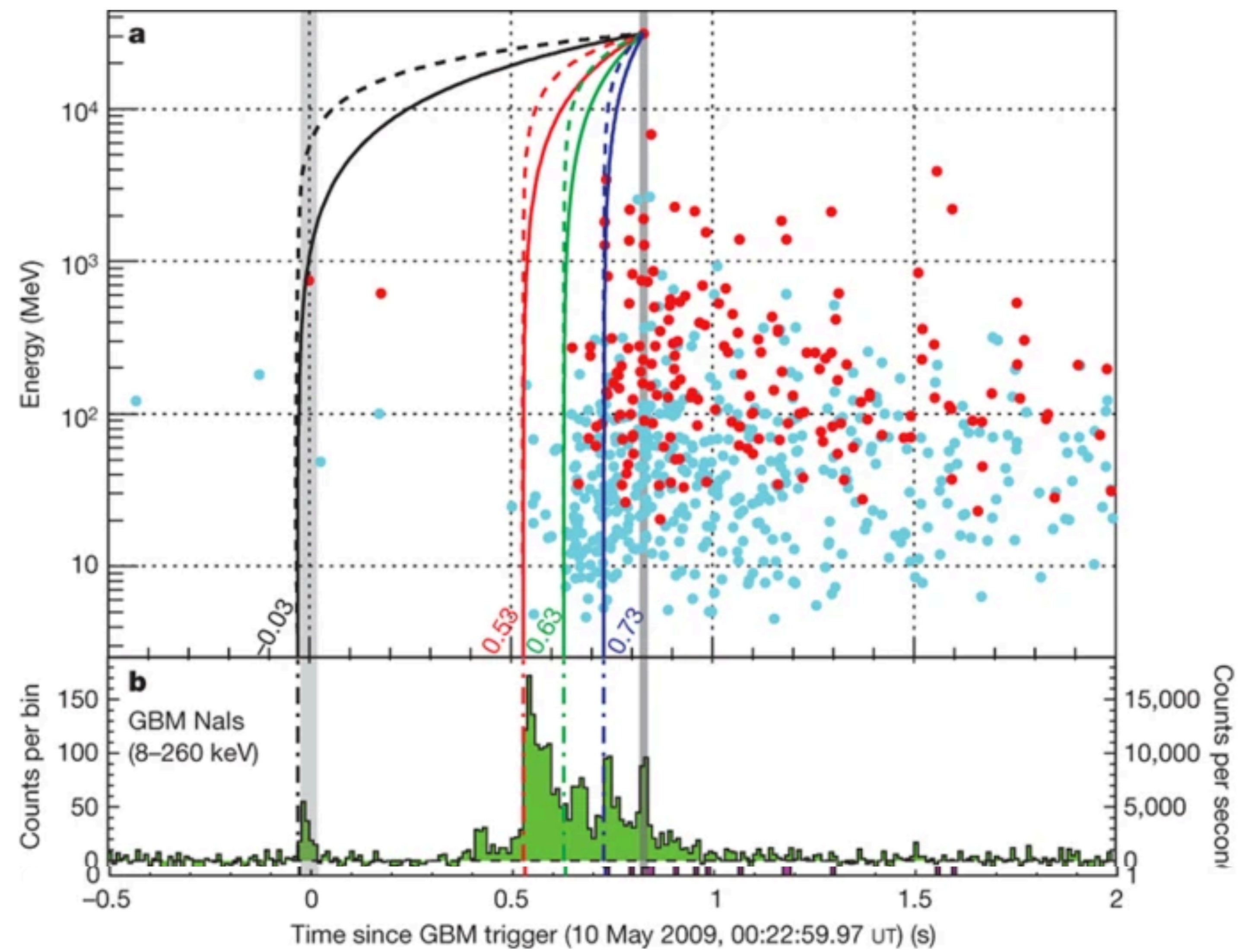
★ Largest energy photon E = 31 GeV detected 0.8 s after T_0:

  ✦ Conservative maximum delay $\tau \lesssim 26$ s/TeV

★ Limits (95% CL):
$E_{QG,n=1} > 1.5\times10^{28}$ eV
$E_{QG,n=2} > 3.0\times10^{19}$ eV

★ Most constraining limits on time-of-flight LIV up to date

Abdo et al. Nature 462, (2009) 331

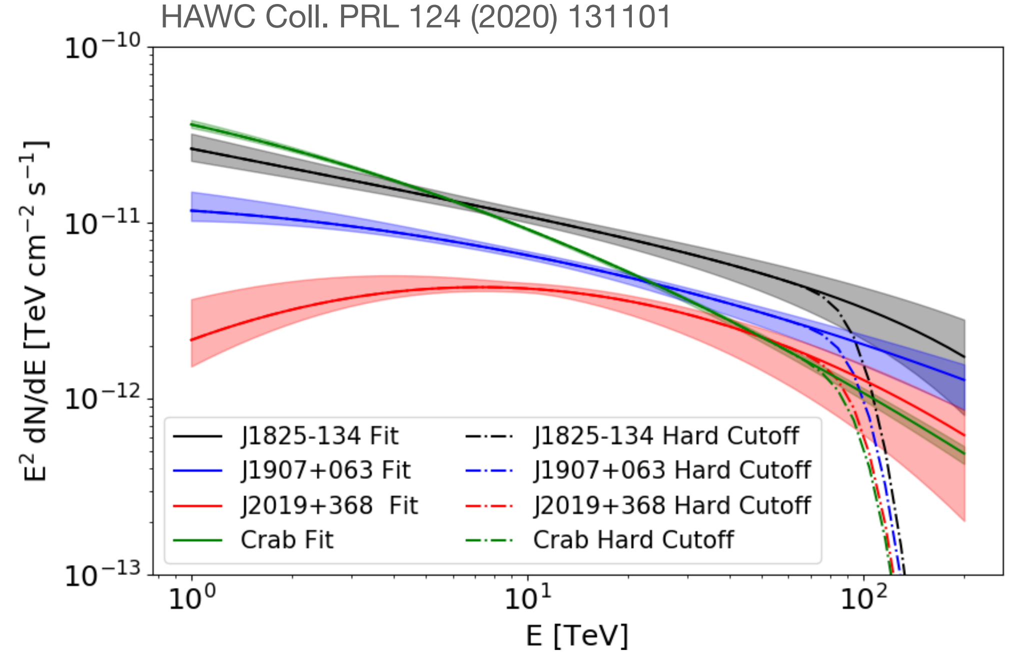


Superluminal LIV gamma decay

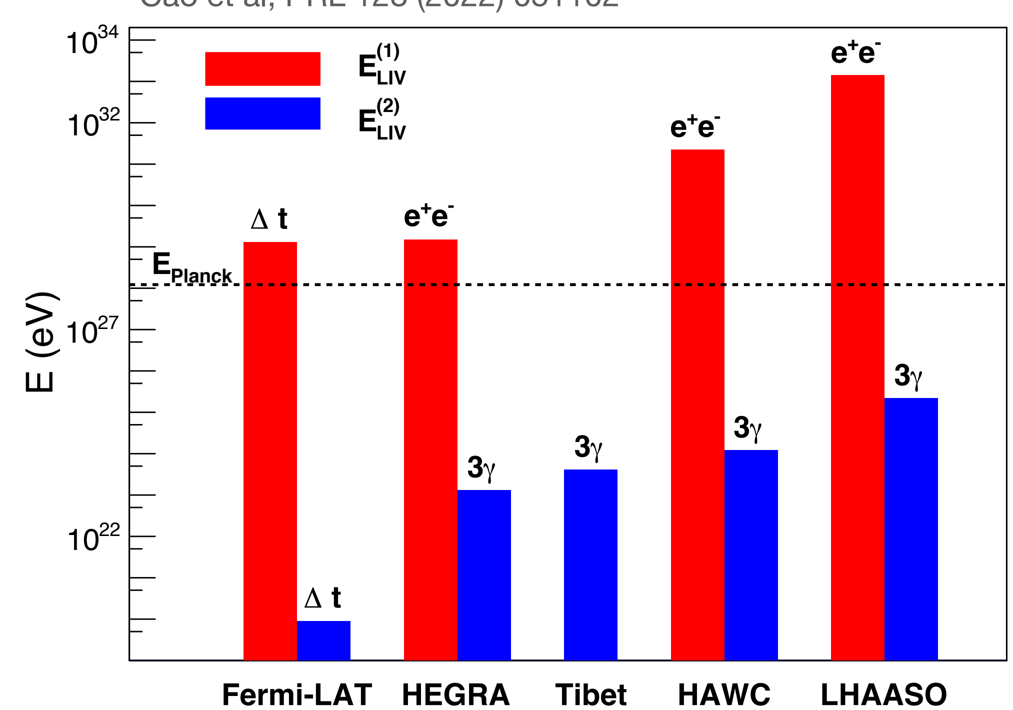
BSM

- ★ Modified dispersion relation (superluminal case) allows the decays $\gamma \rightarrow e^+e^-$ (n=1) and $\gamma \rightarrow 3\,\gamma$ (n=2)
- ★ Both reactions lead to hard spectral cutoff at high energies
- ★ No dependence on distance: use Galactic sources, not affected by increase of threshold for interaction with EBL
- ★ HAWC and LHAASO observations of ~PeV photons set strong limits to cutoff and hence to LIV effects

HAWC Coll. PRL 124 (2020) 131101

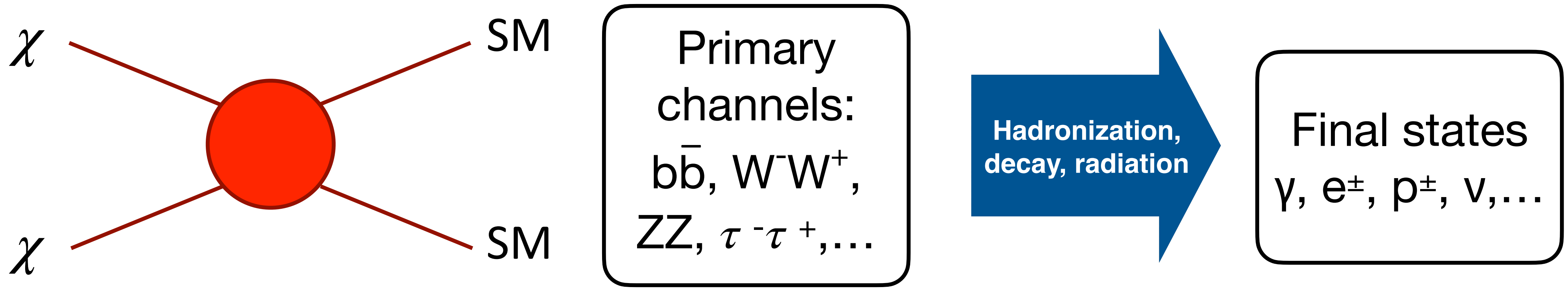


Cao et al, PRL 128 (2022) 051102



WIMP searches

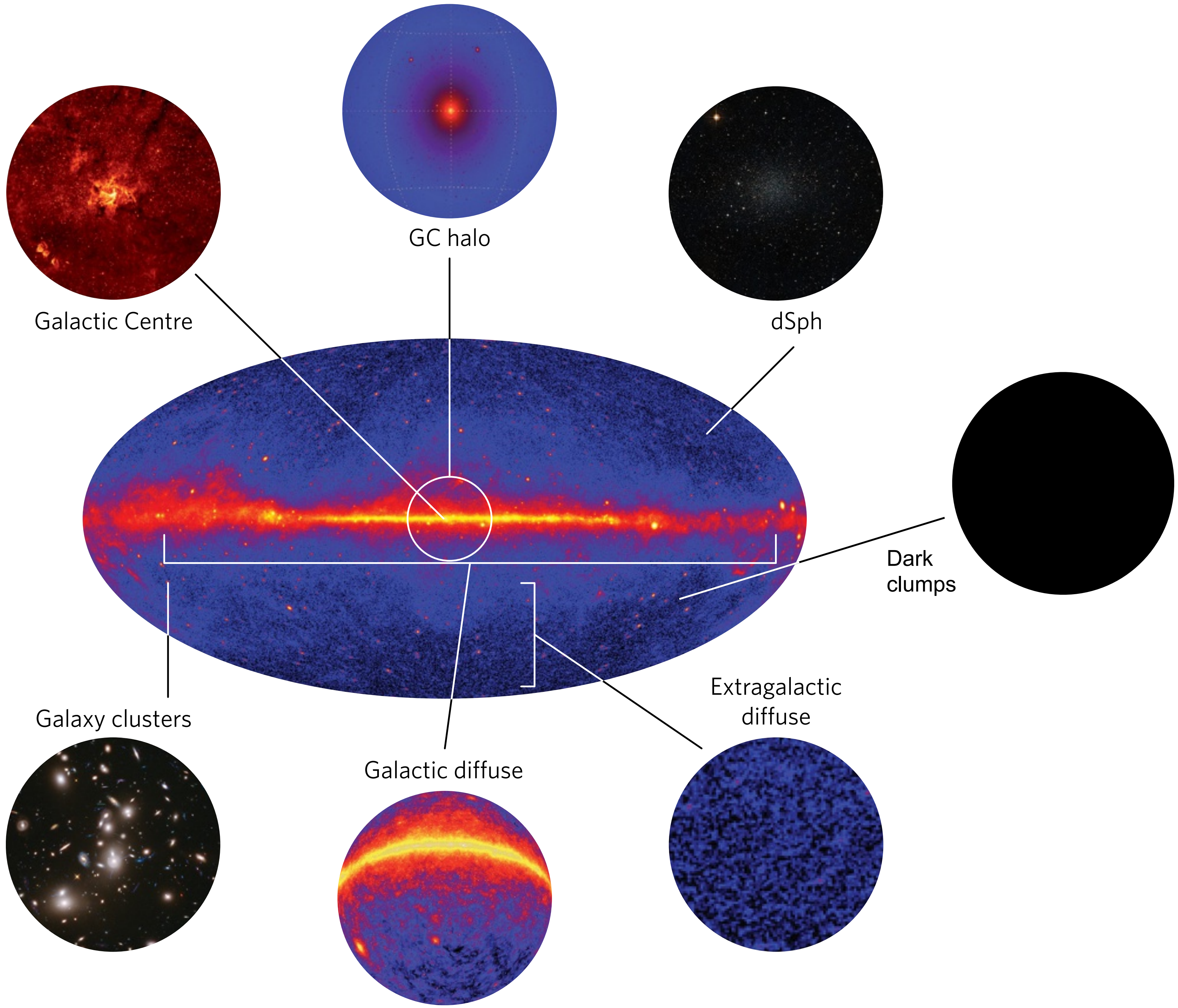
BSM



- **Indirect searches**: looking for spectral and spatial signatures of dark matter in the extra-terrestrial fluxes of stable SM particles
- **HE Messangers:**
  - Gamma-rays
  - Neutrinos
  - Electron/positrons
  - Antiprotons, Antideuterium, Anti-nuclei
- **Characteristic spectral features**:
  - Separation from background
  - Can measure basic physical properties: mass, cross-section / lifetime
- **Gamma-rays or neutrinos do not suffer from propagation effects**:
  - Exploit spatial features known from simulations
  - Can determine DM abundance and distribution in the Universe

Posible DM gamma-ray sources

BSM



Adapted from Conrad & Reimer, Nat. Phys. 13 (2017) 224

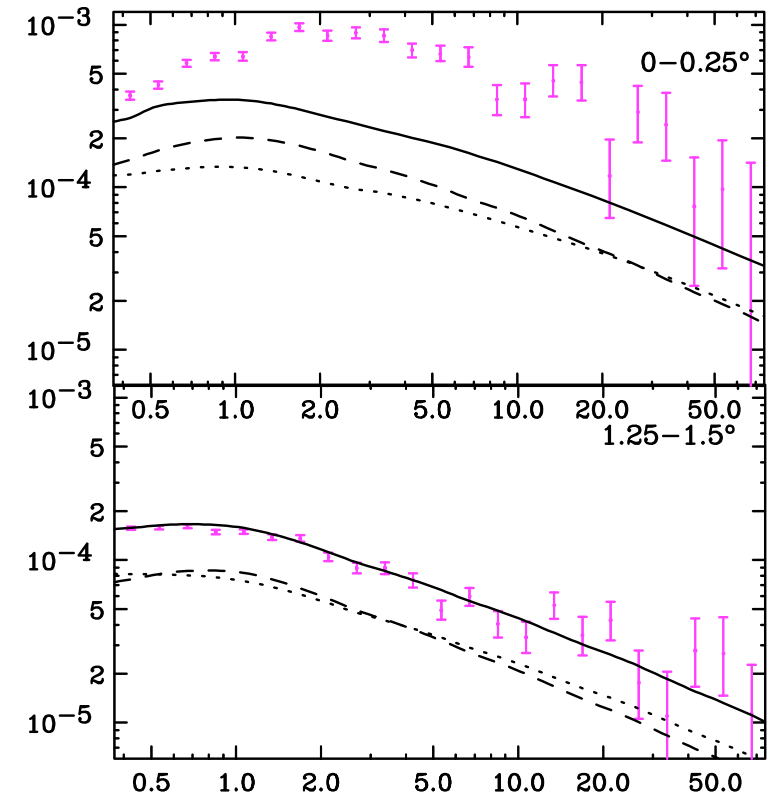
GeV Galactic Center excess

BSM

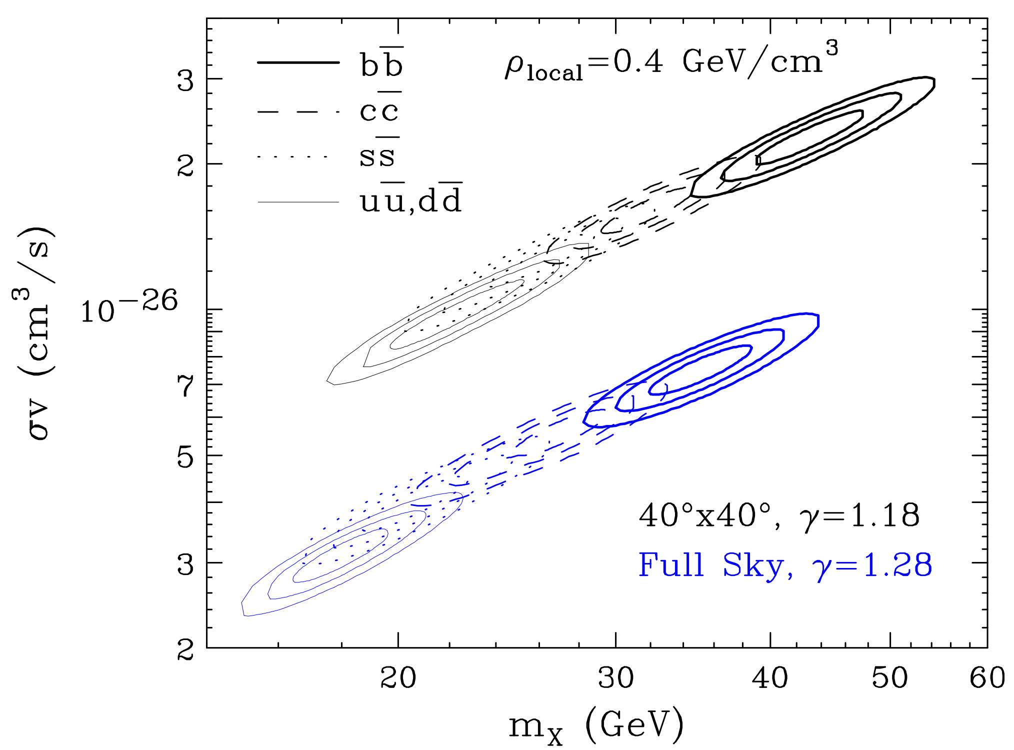
★ In Fermi-LAT: removing contributions from known sources and diffuse emission, residuals between 0.3 and 30 GeV have some of the DM properties (radial profile, spectrum)

★ Interpretation as annihilation of DM particles with m_{DM} ~ few 10 GeV with close to relic cross-section

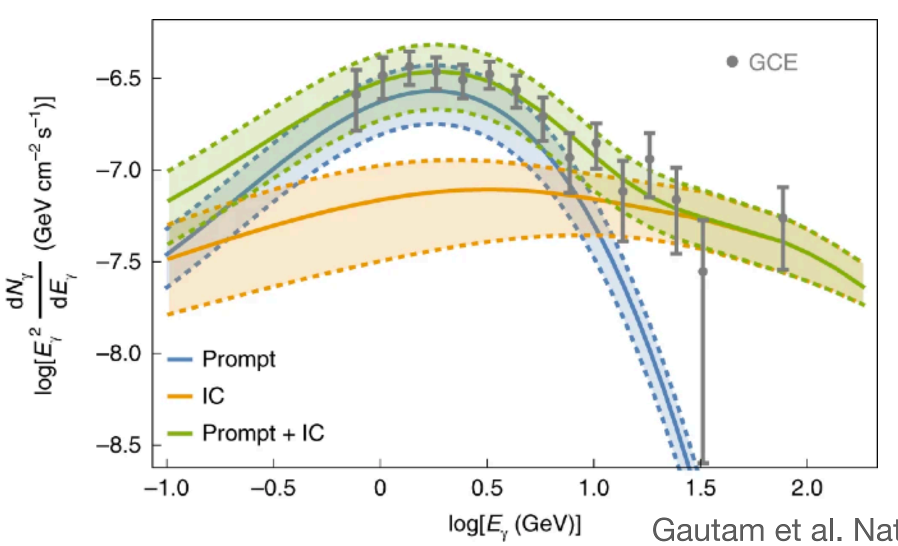
Hooper et al. PLB 697 (2011) 412



Daylan et al. Phys. Dark. Univ. 12 (2016) 1



★ Favored astrophysical interpretation: unresolved population of millisecond pulsars:

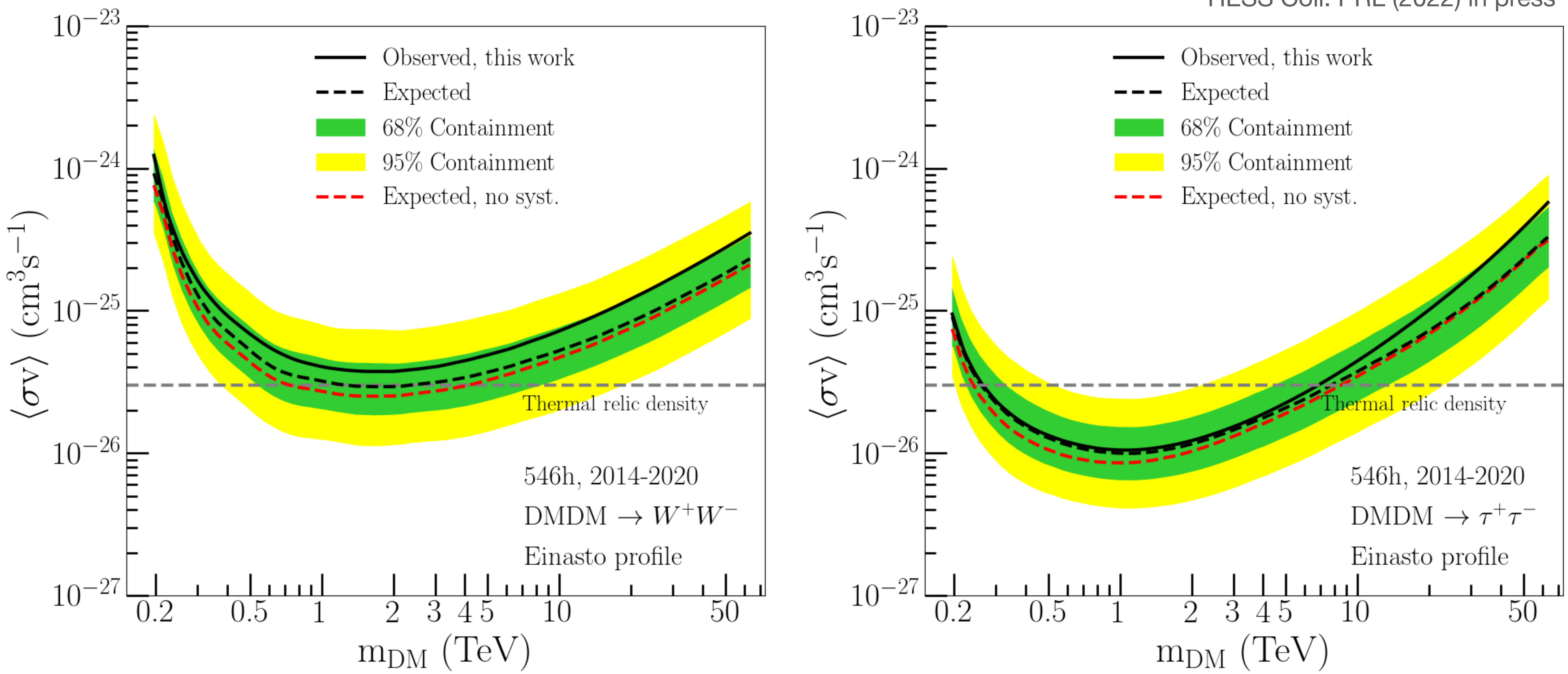


Gautam et al. Nat. Astron. 6 (2022) 703

Galactic Center at Very High Energy

BSM

HESS Coll. PRL (2022) in press



★ Galactic Center (halo) observed by HESS for 546h!

★ Most intense DM annihilation expected signal as seen from Earth

★ Most constraining limits of cross sections, below thermal relic cross section for leptonic channels

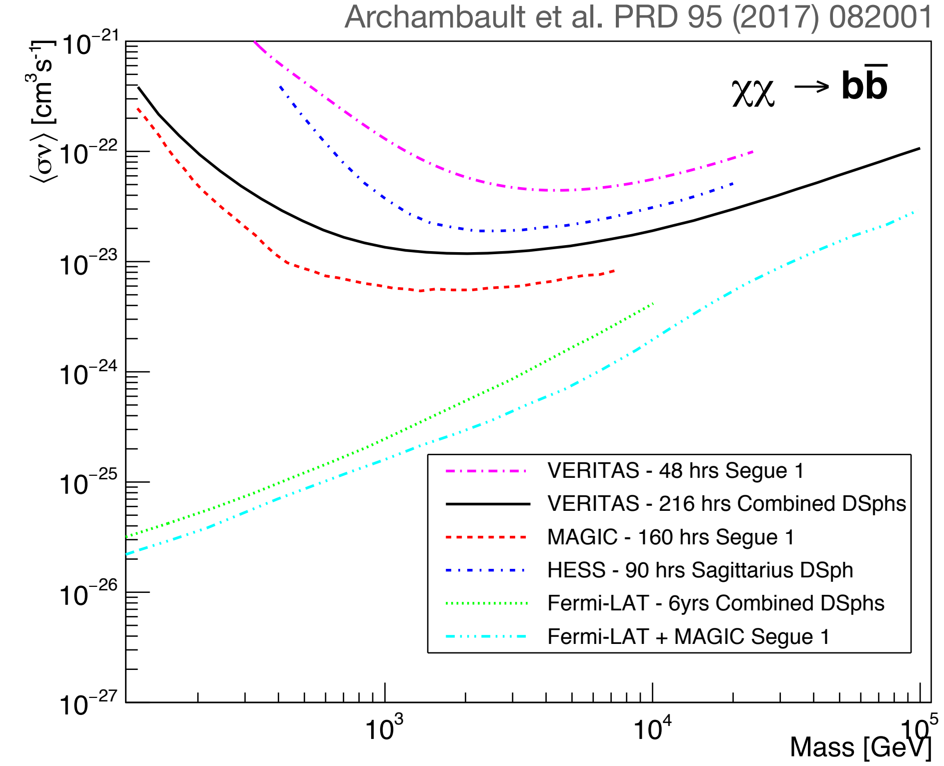
★ Caveat: assuming a cored density profile limit is O(2-3) times worse

Observations of dSphs

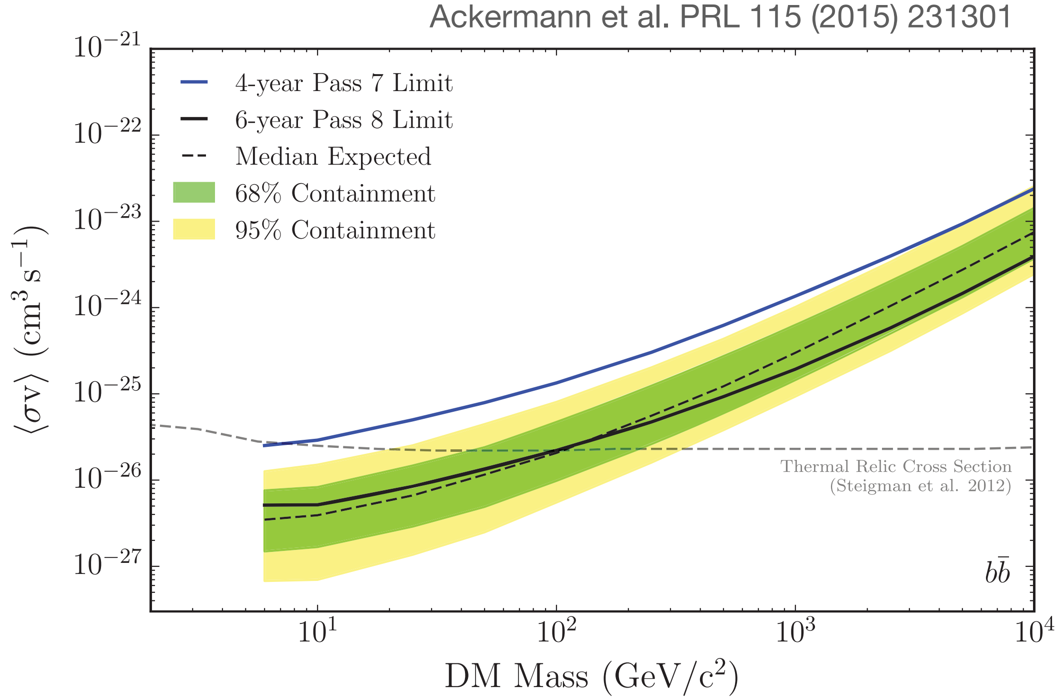
BSM

- ★ Low luminosity galaxies orbiting the Milky Way
- ★ Kinematics dominated by DM: M/L ~ *O*(1000) $M_\odot/L_\odot$
- ★ Moderate expected intensities, with relatively low uncertainties

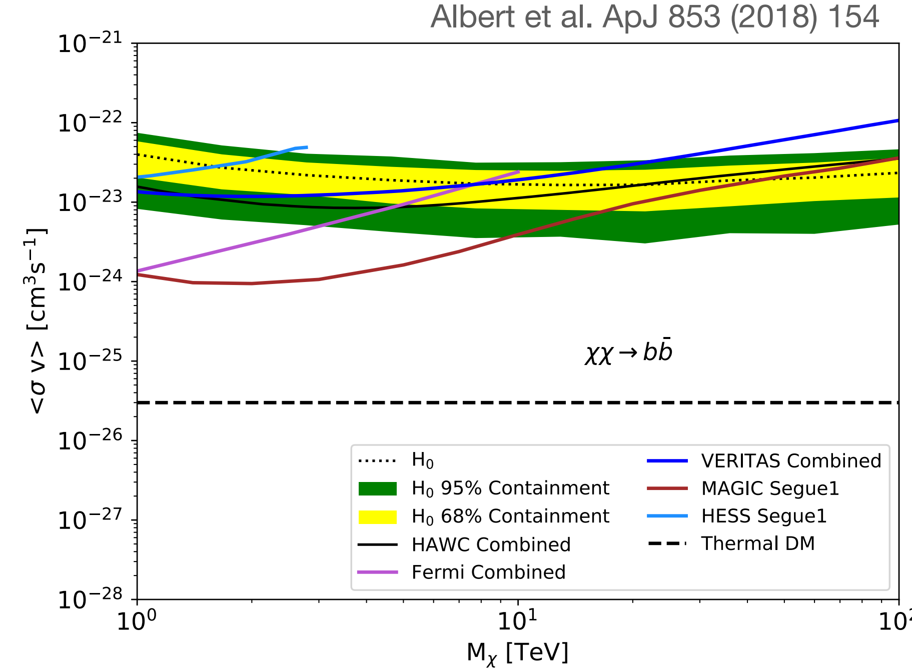
Archambault et al. PRD 95 (2017) 082001



Ackermann et al. PRL 115 (2015) 231301



Albert et al. ApJ 853 (2018) 154



Combining dSph results

BSM

★ Stack the likelihoods (not the data!), of different dSphs:

- with different uncertainties in J-factor

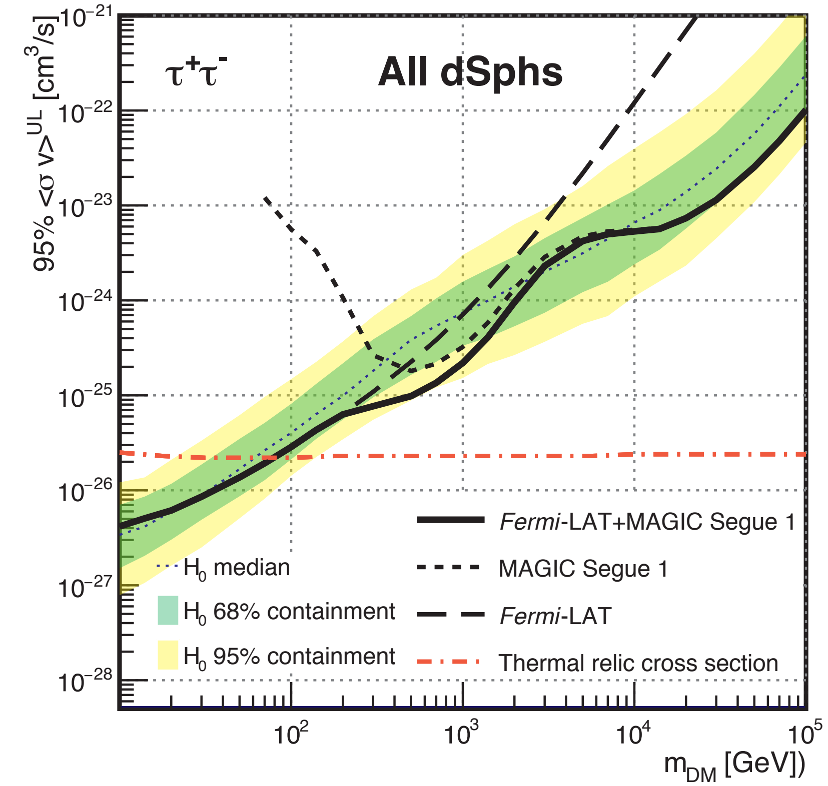
$$\mathcal{L}(\alpha;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{l=1}^{N_{\text{dSph}}} \mathcal{L}_\gamma(\alpha \bar{J}_l;\boldsymbol{\mu}_l|\boldsymbol{\mathcal{D}}_{\gamma_l}) \cdot \mathcal{L}_J(\bar{J}_l|\boldsymbol{\mathcal{D}}_{J_l})$$

$$\mathcal{L}_J(\bar{J}\,|\,\bar{J}_{\text{obs}},\sigma_J) = \frac{1}{\ln(10)\bar{J}_{\text{obs}}\sqrt{2\pi}\sigma_J} e^{-\left(\log_{10}(\bar{J})-\log_{10}(\bar{J}_{\text{obs}})\right)^2/2\sigma_J^2}$$

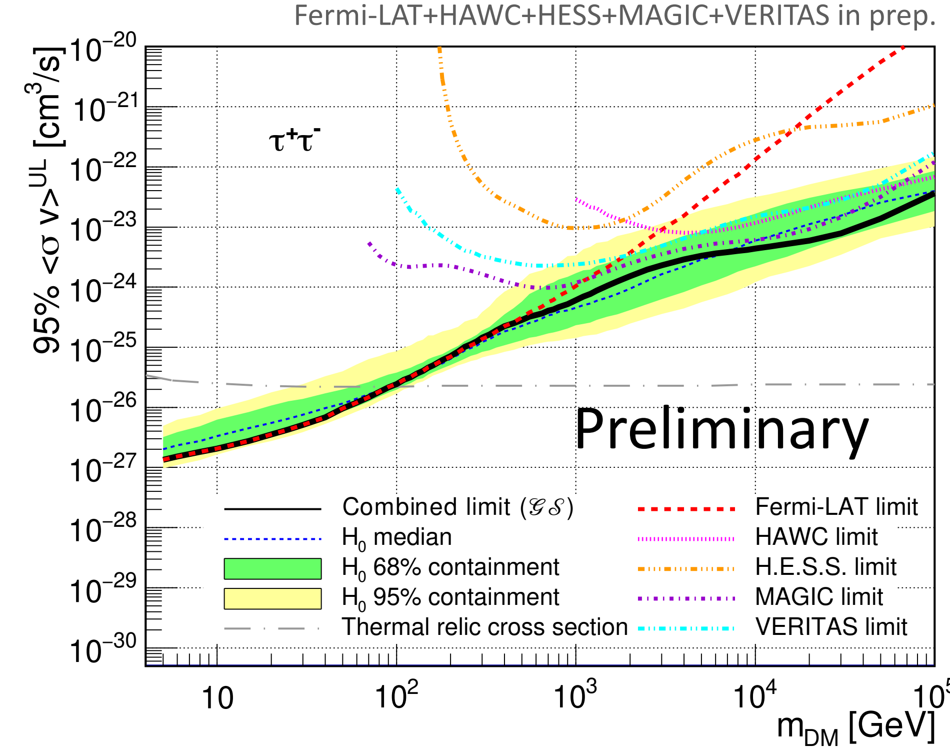
- observed by different instruments

$$\mathcal{L}_\gamma(\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\gamma) = \prod_{k=1}^{N_{\text{meas}}} \mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}_k|\boldsymbol{\mathcal{D}}_{\gamma,k})$$

Fermi-LAT+MAGIC: Ahnen et al. JCAP 1602 (2016) 39

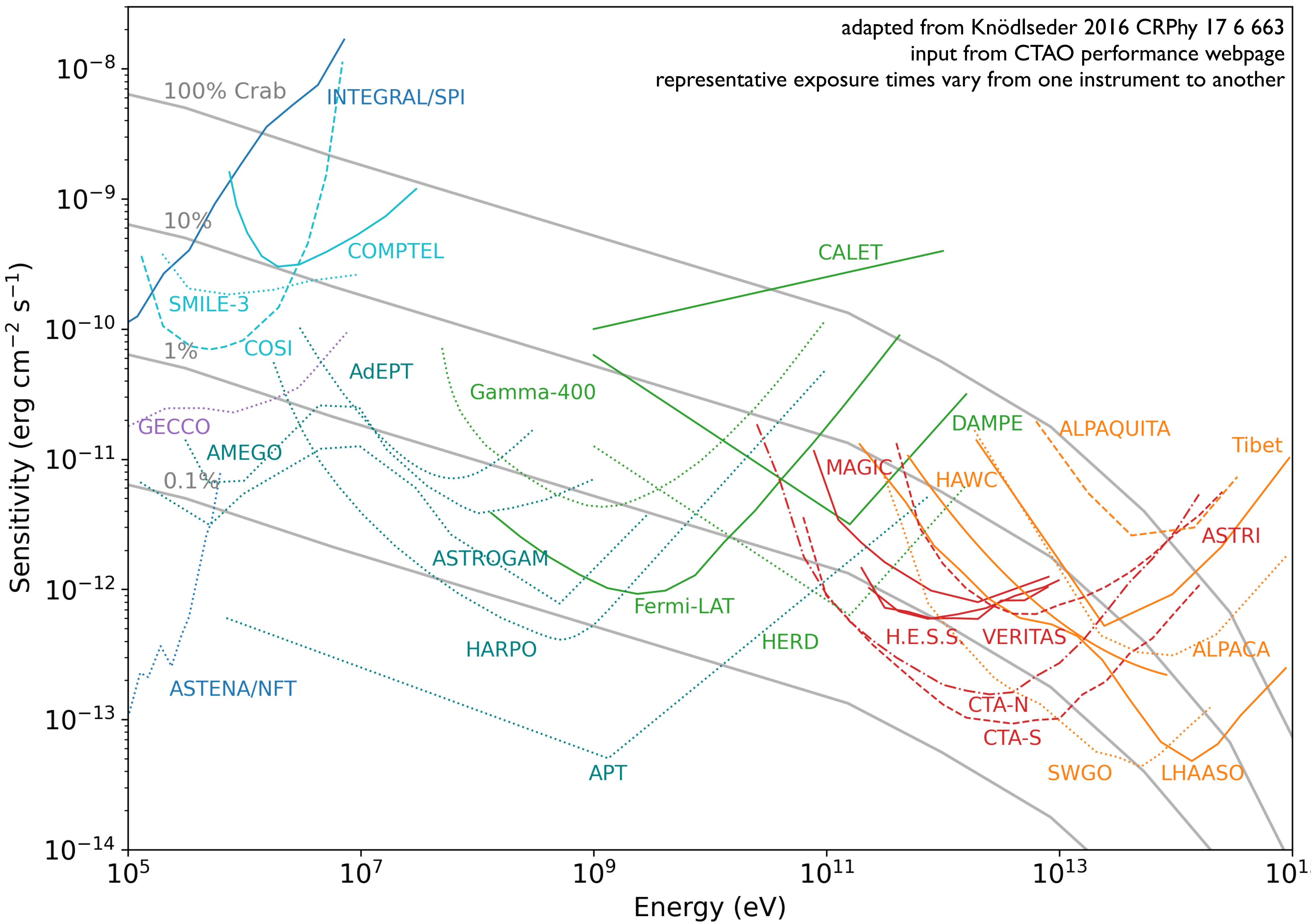


Fermi-LAT+HAWC+HESS+MAGIC+VERITAS in prep.



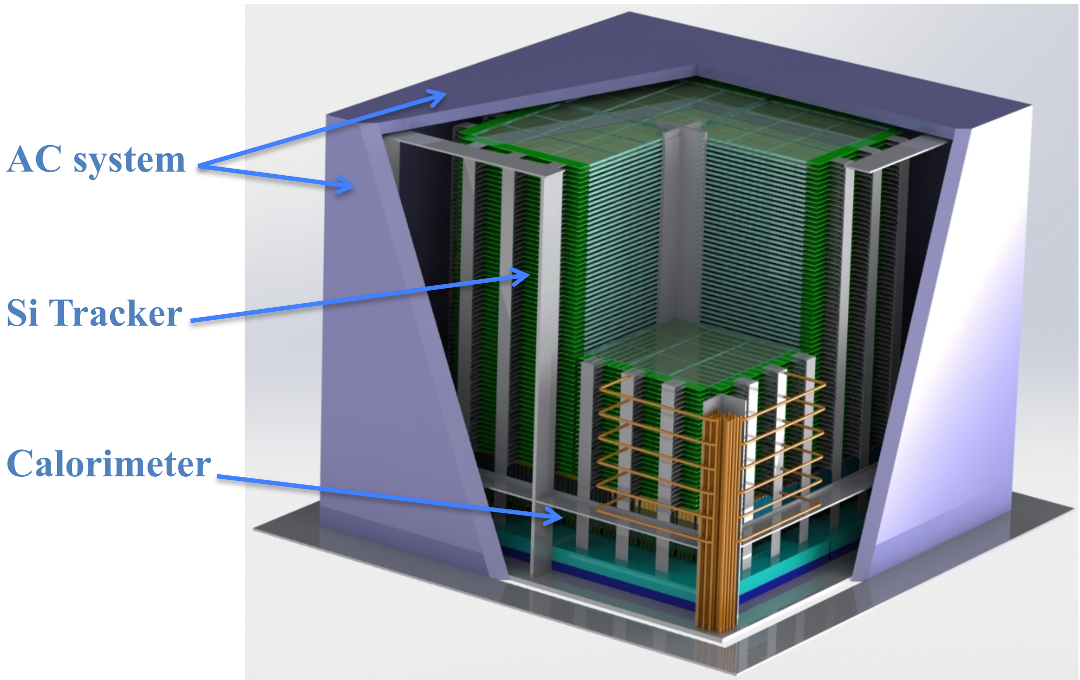
The future

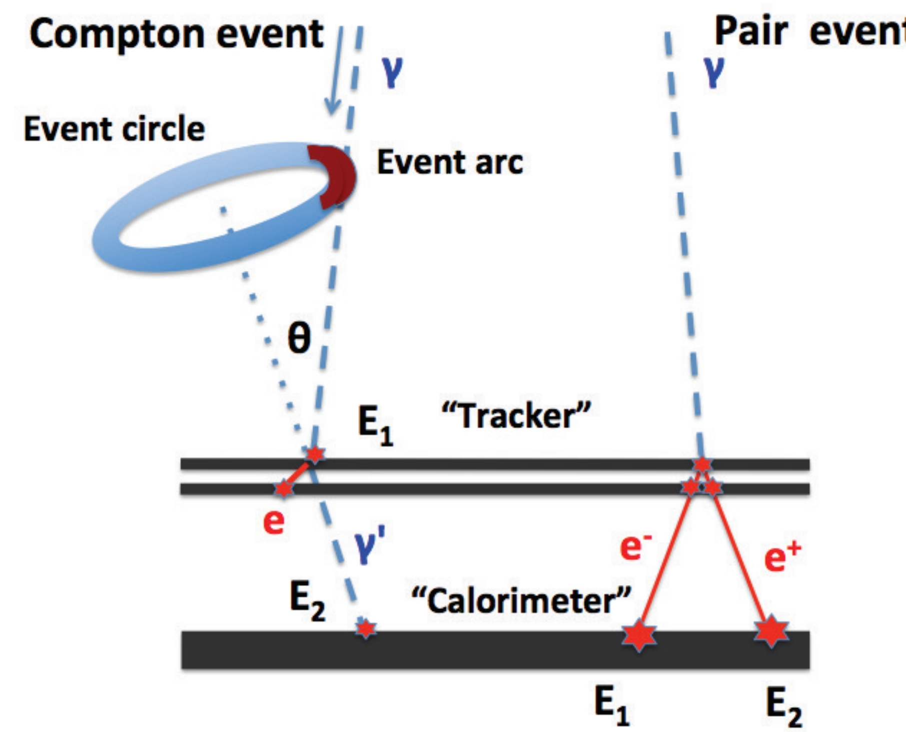
Present and future sensitivity



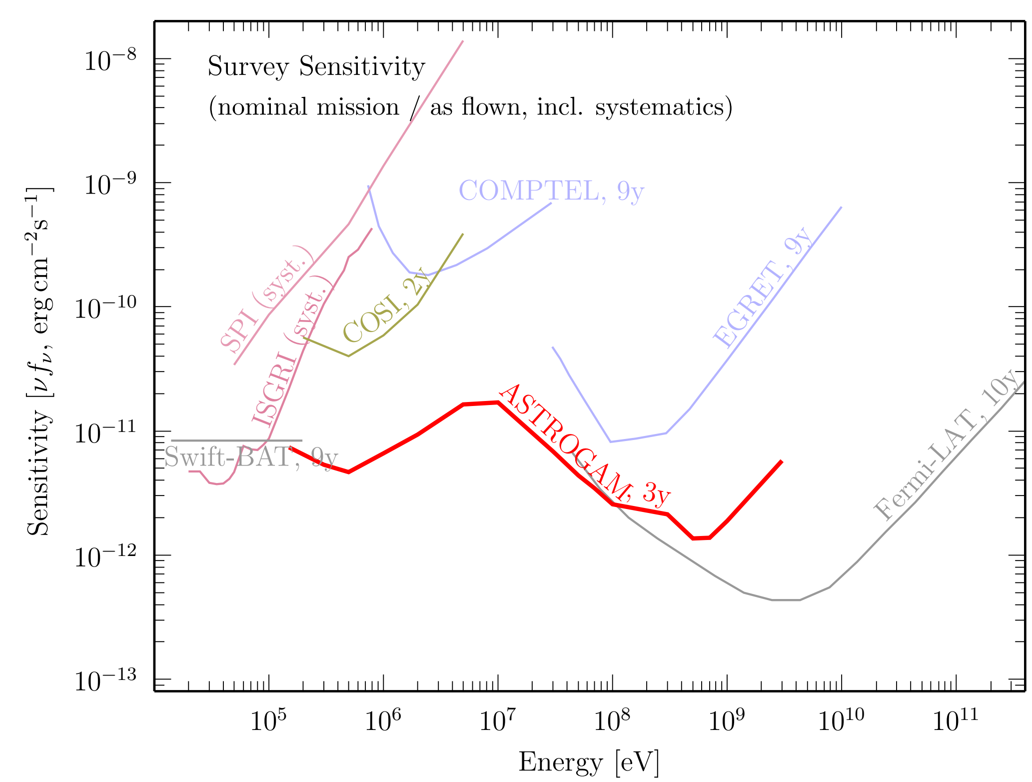
Credit: L. Tibaldo (ECRS2022)

ASTROGAM



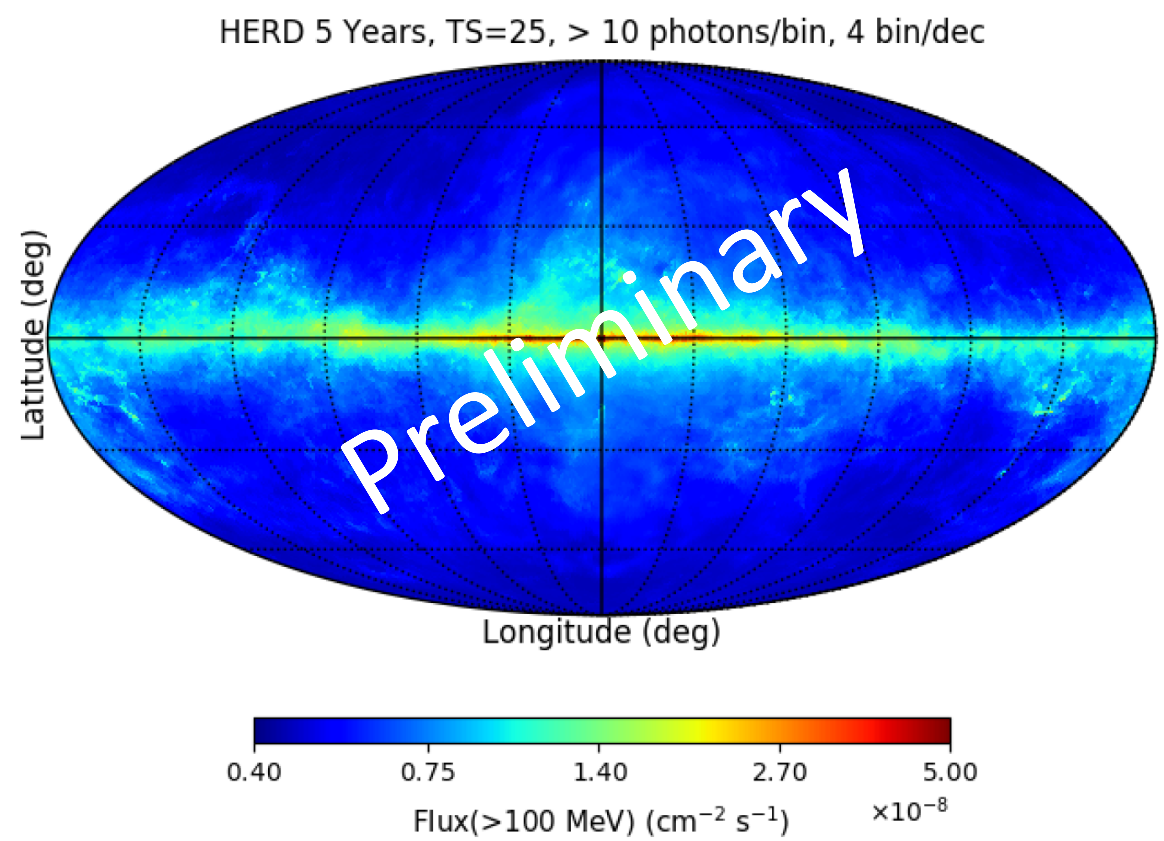


- ★ Proposed to M7 ESA call (launch 2037)
- ★ Cover the "MeV gap"
- ★ Improved angular resolution thanks to measurement of Compton electron track



HERD

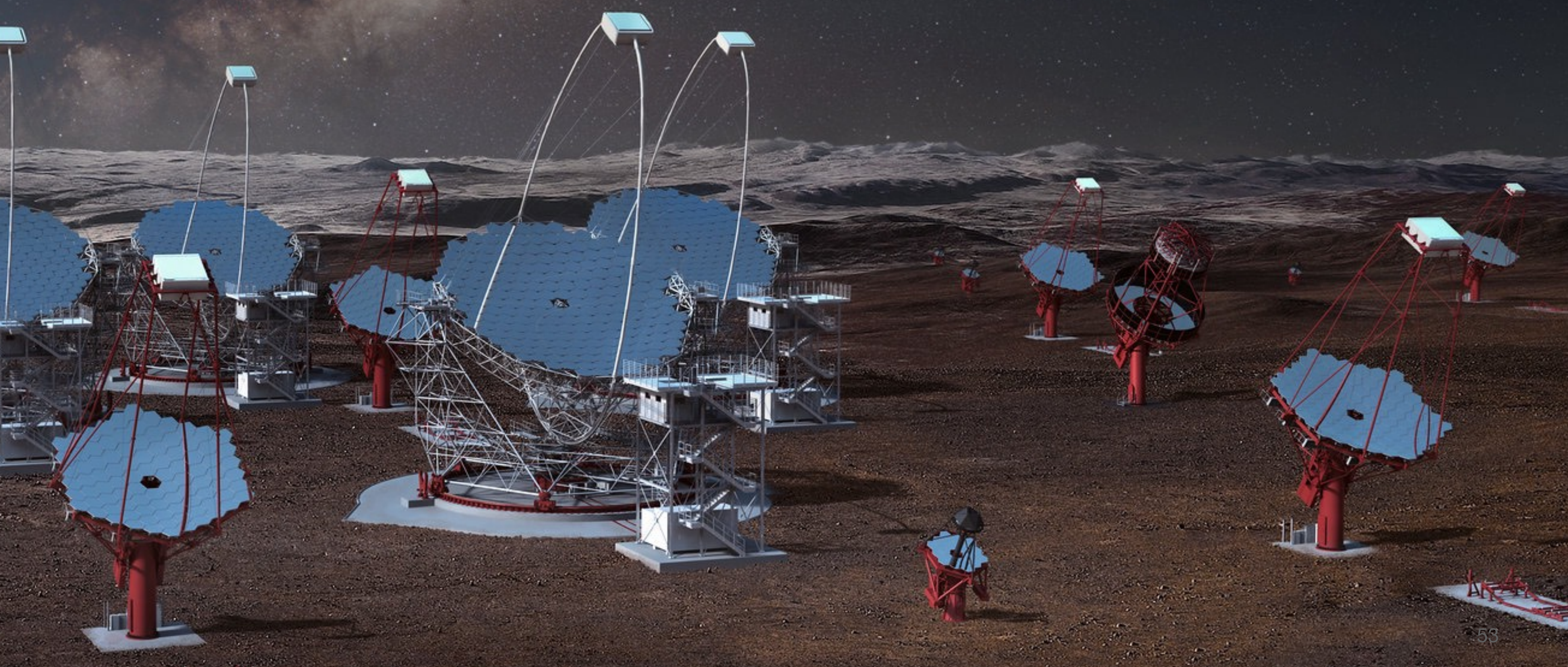
- ★ Cosmic-ray/Gamma-ray detector in the Chinese Space Station
- ★ Installation expected in 2027
- ★ 3D, homogeneous, isotropic, finely segmented calorimeter
- ★ Gamma energy coverage: 100 MeV - 1 TeV with superb angular and energy resolutions



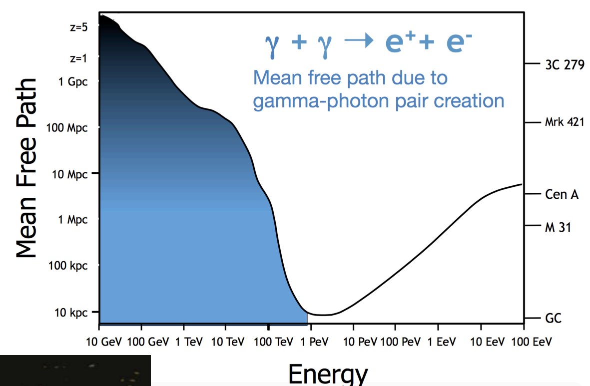
CTA

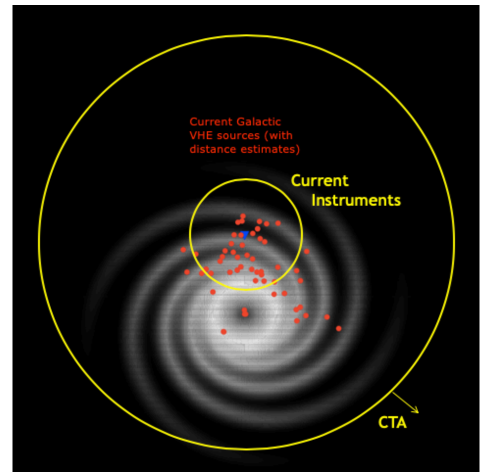
- Two sites: La Palma (N) and Paranal, Chile (S)
- 64 (13+51) telescopes of three different sizes
- ERIC should be operative beginning of 2023 when official construction phase will start

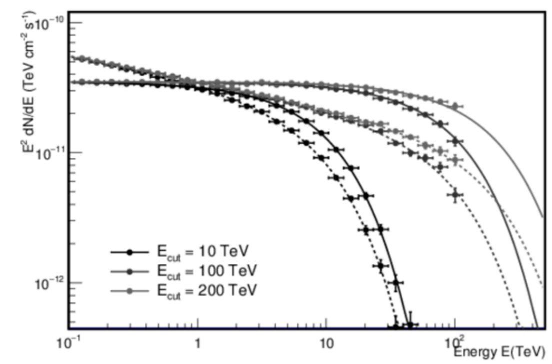
Pre-Construction	Pre-Production	Production
Current Phase	2022-2023	2023-2027

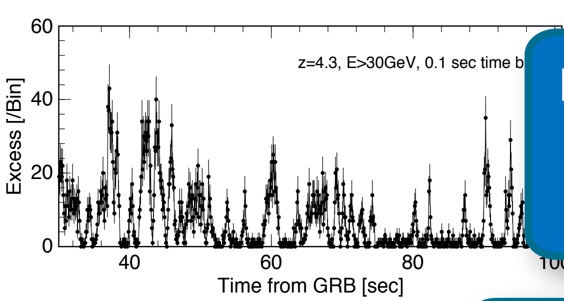


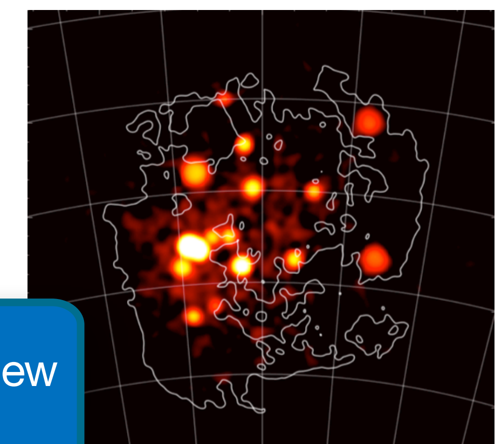
CTA capabilities

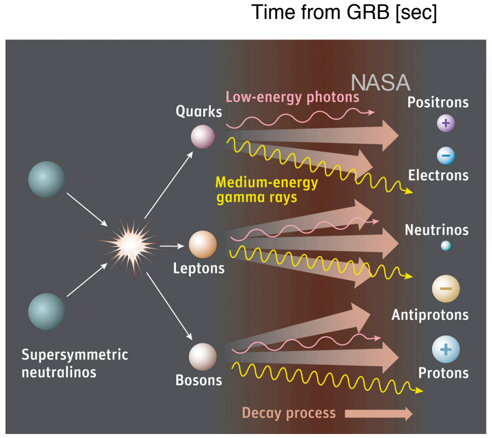


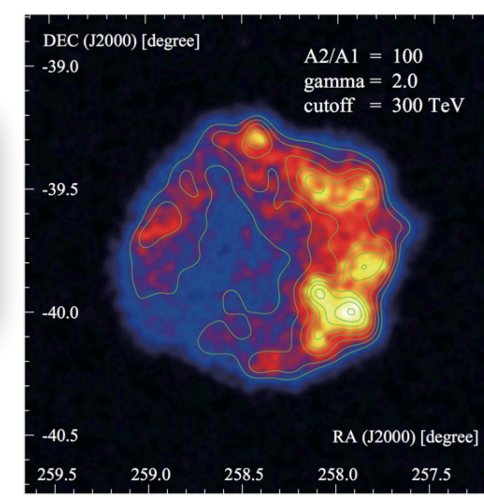












Energies down to 20 GeV
→ Cosmology++

10 x Sensitivity, Large Collection Area
→ all topics

Energies up to 300 TeV
→ Pevatrons

Rapid Slewing in 20 seconds
→ transients

8° Field of View
→ surveys, extended objects

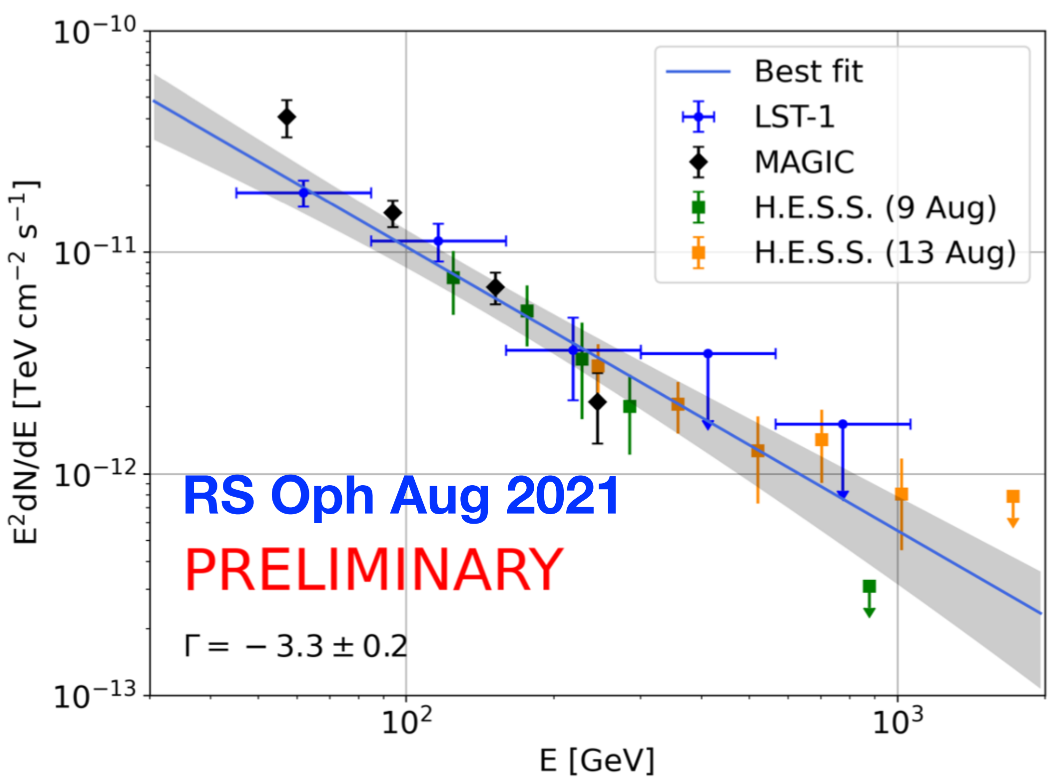
10% Energy Resolution
→ lines, features

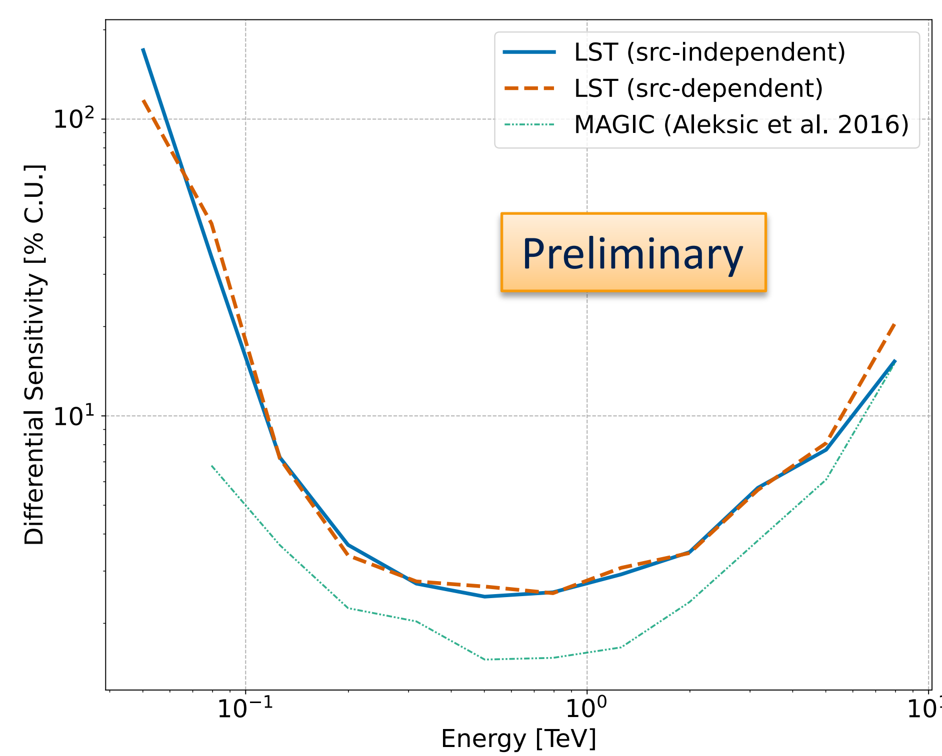
Few ' Angular Resolution
→ morphology

LST

- ★ LST1 installed @ La Palma in 2019
- ★ Finishing commissioning
- ★ LST2-4 under production
- ★ LST for South partially funded
- ★ LST1 producing science and preparing first papers

Cortina, Gamma2022
Cortina, Gamma2022





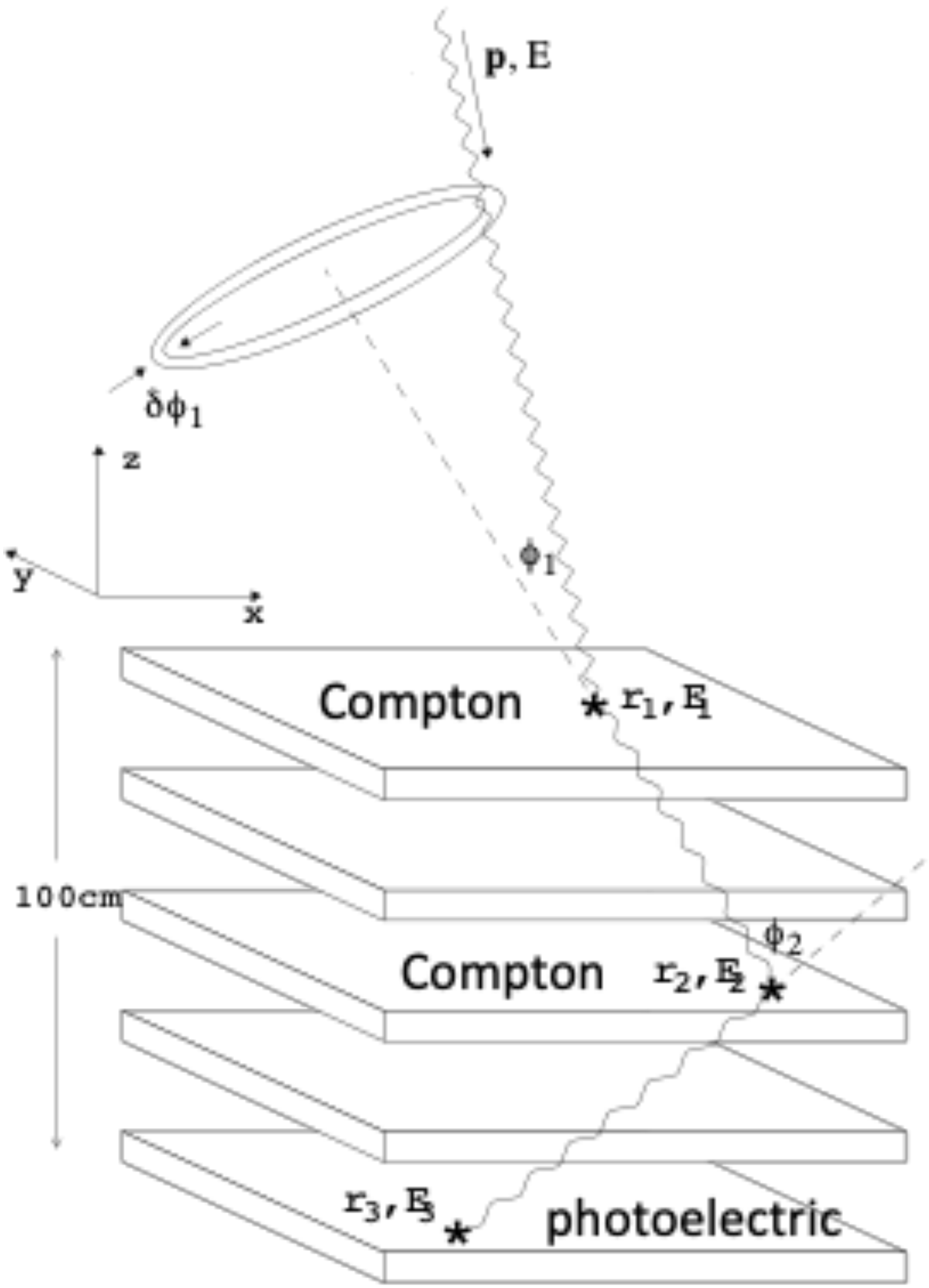
Summary

- ★ Gamma-ray Astronomy is a consolidated branch of astronomy
- ★ The current generation of instruments have produced/are producing significant advances in our understanding of:
  - ✦ The origin of Galactic cosmic rays
  - ✦ The origin of cosmic neutrinos and extragalactic cosmic rays
  - ✦ NS-NS mergers
  - ✦ Particle acceleration in known and new source classes
  - ✦ Radiation and magnetic fields in cosmic voids
  - ✦ Physics BSM (DM searches, LIV tests)
- ★ Future observatories such as CTA, HERD and ASTROGAM will improve further our understanding about these and other topics in a fully multi-wavelenth/multi-messenger approach to the study of our Universe

Thank you for your attention!

Backup

LE: Compton camera



Boggs & Jean (2000)

E' = outgoing photon energy

$E = \Sigma E_i$

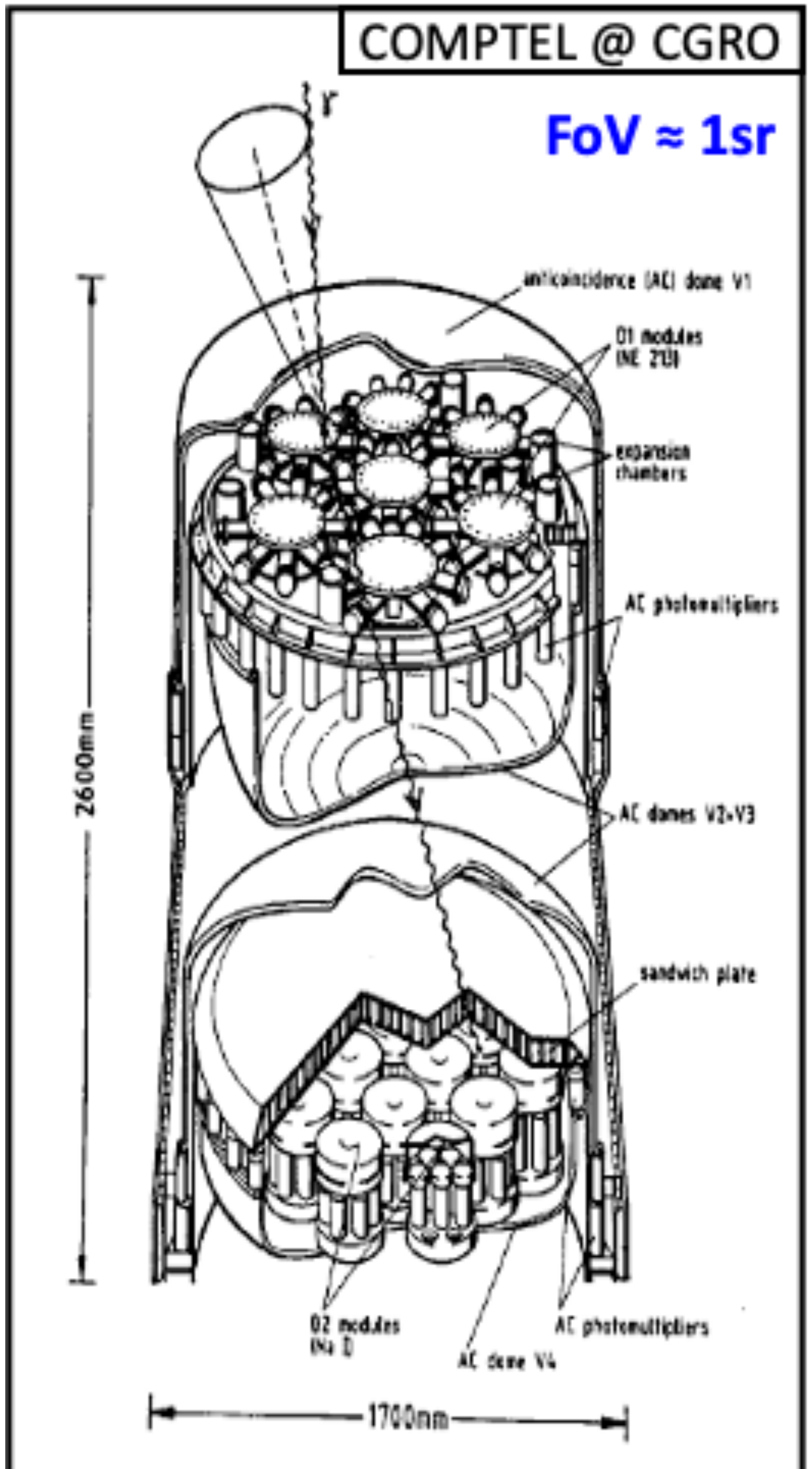
(original photon energy is the sum of all energy deposits)

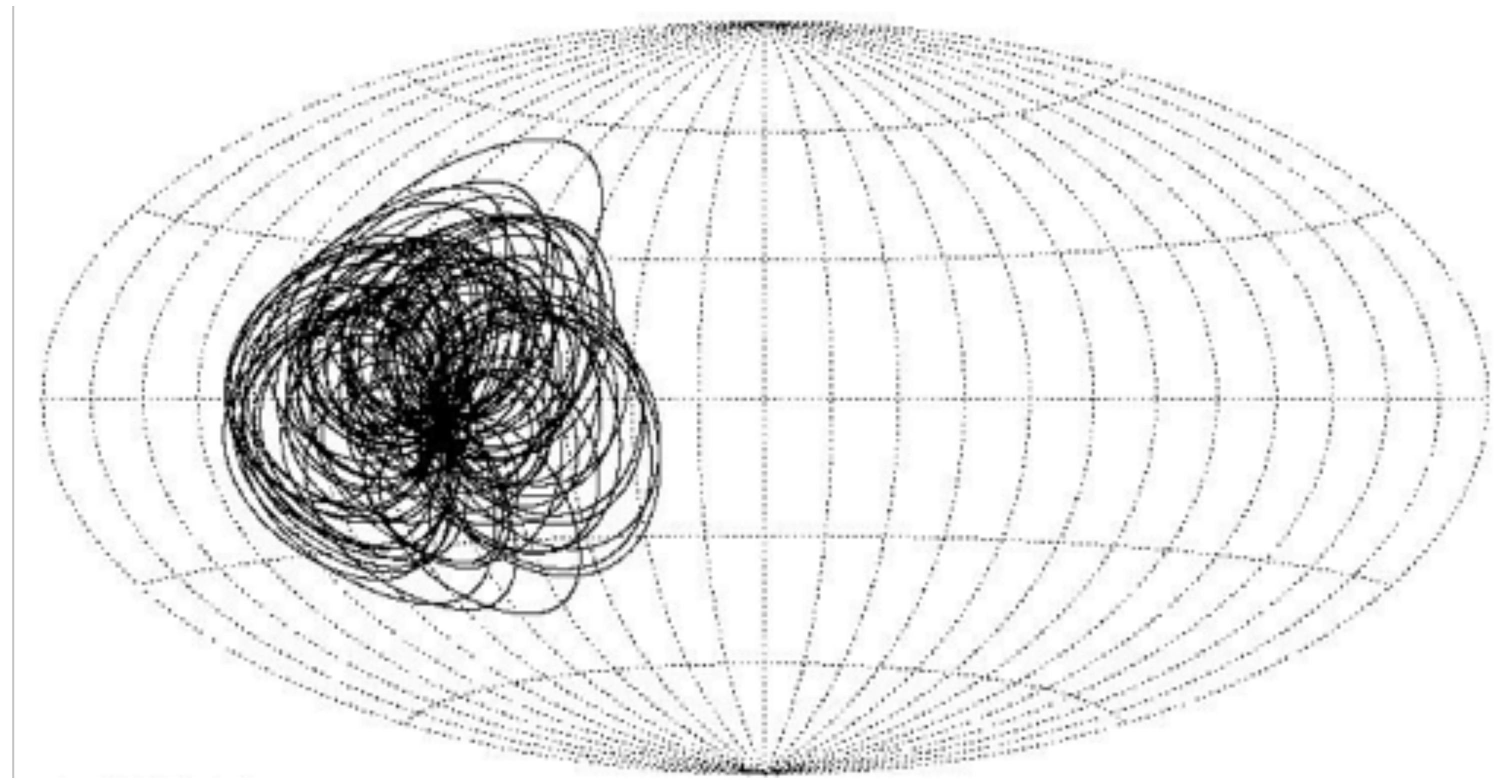
$E' = E - E_1$

$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_e c^2}(1 - \cos\phi)$$

⟹ we can obtain the primary photon E and a CONE of possible directions

COMPTEL

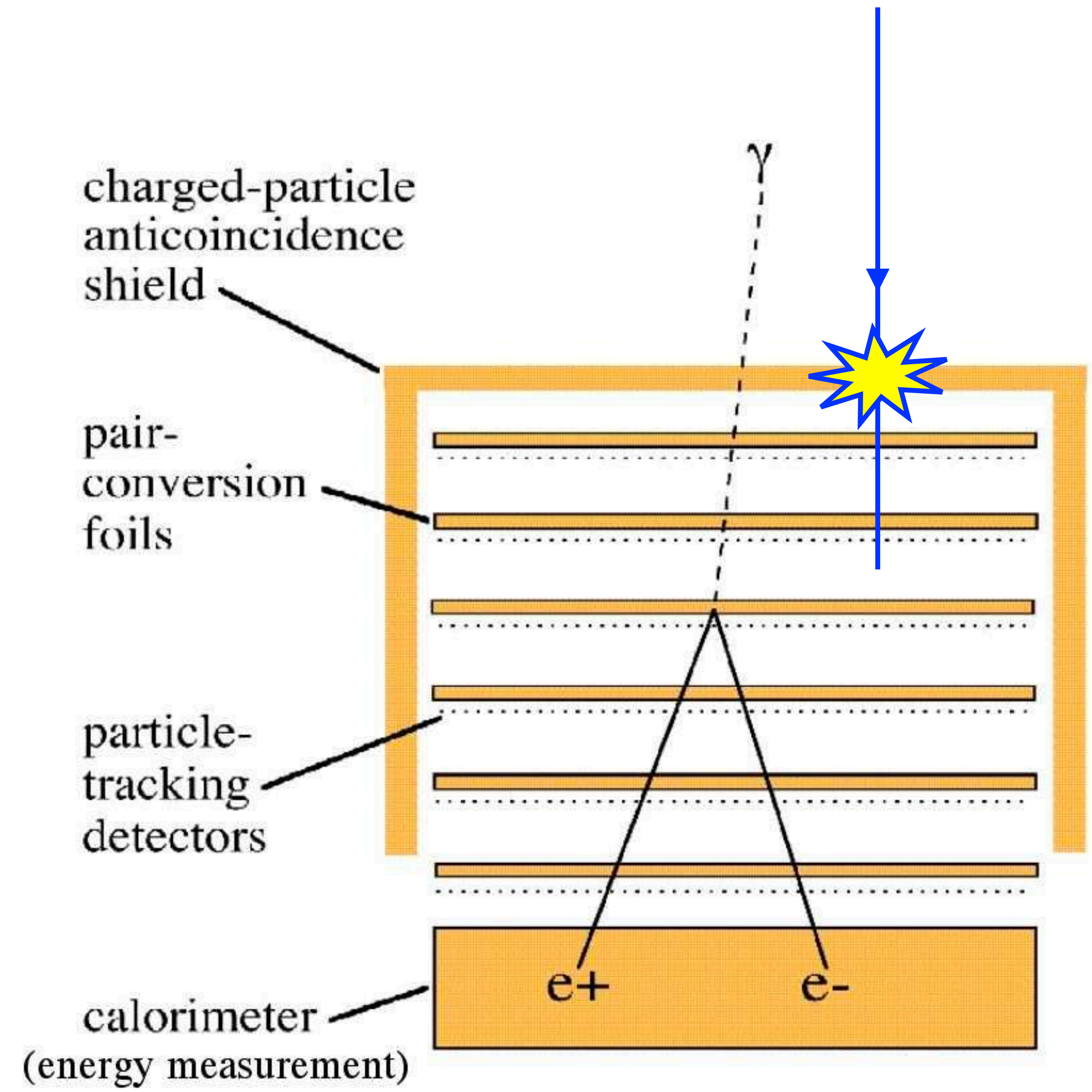




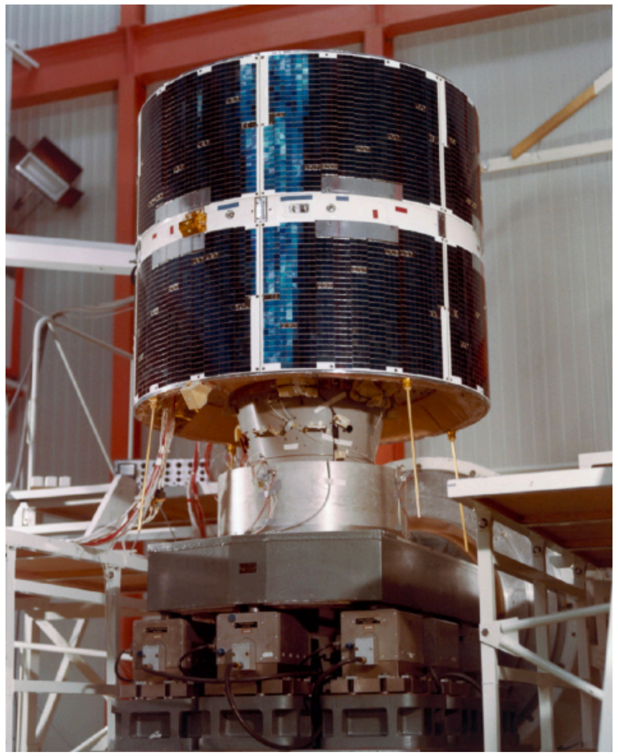
- ★ GRB May 3 1991
- ★ Method works for large S/N data
- ★ COMPTEL onboard CGRO (1991-2000)

HE: pair conversion camera

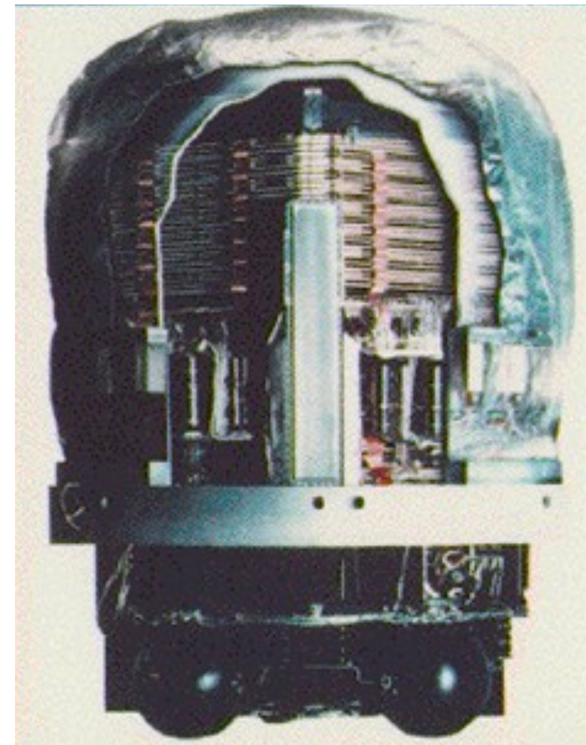
- ★ Pair production dominant above a few MeV
- ★ Anti-coincidence to veto dominant charged CaRs
- ★ High-Z foils before each tracking plane to maximize conversion probability
- ★ Tracker to measure direction
- ★ Calorimeter to measure energy



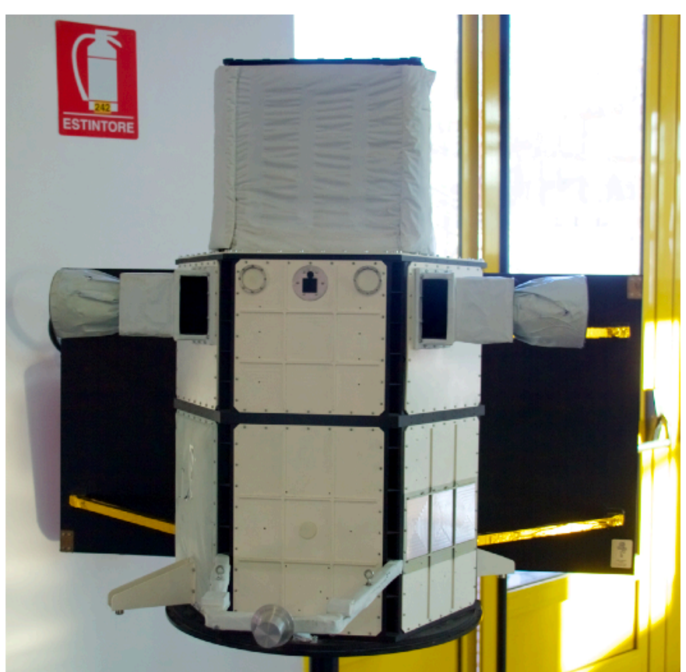
Pair conversion telescopes



- ★ COS-B (1975-1982)
- ★ ESA (first satellite)
- ★ 25 sources; first galactic map



- CGRO-EGRET (1991-2000)
- NASA
- 271 sources; (LMC, pulsars, blazars, UID)



- AGILE (2007)
- ASI
- Crab Nebular variability; Cyg X-3; pion bump in SNR W44;…

- Fermi-LAT (2008)
- NASA
- 5065 sources; GRBs Fermi bubbles; high resolution map; Galactic center excess; DM searches; constrain QG…

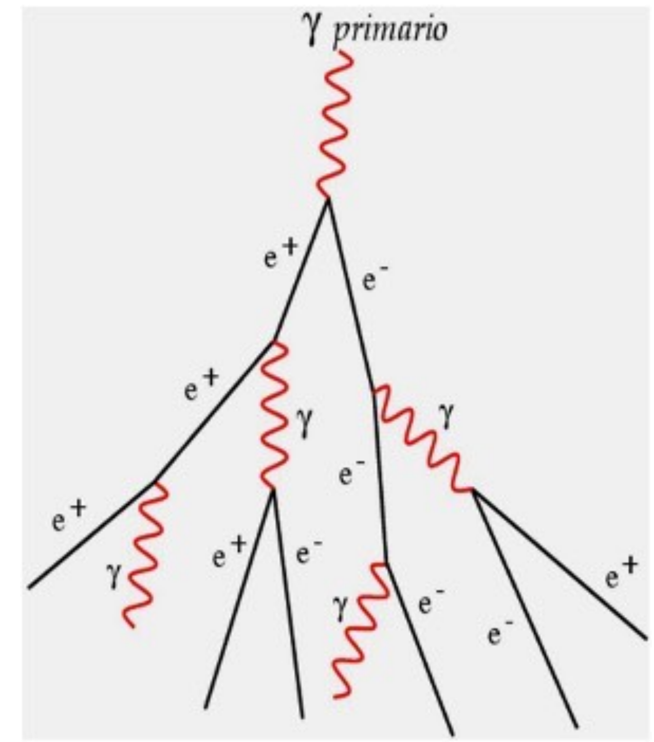
VHE and UHE: atmospheric showers

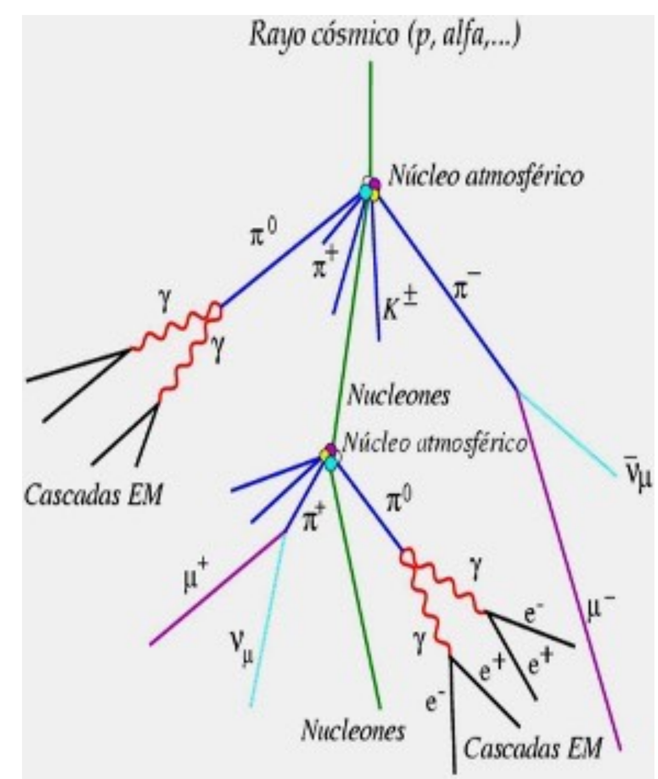
★ Small effective area results in extremely low detection rates at E > 100 GeV, even for strong sources:
$\Phi_{Crab,E>100GeV} \approx 100$ photons/m^2/year

★ Calorimeter depth ≤ 10 radiation lengths, which corresponds to ≈ 1 ton/m^2 (hard to put into orbit)
⇒ VHE showers leak out of the calorimeter

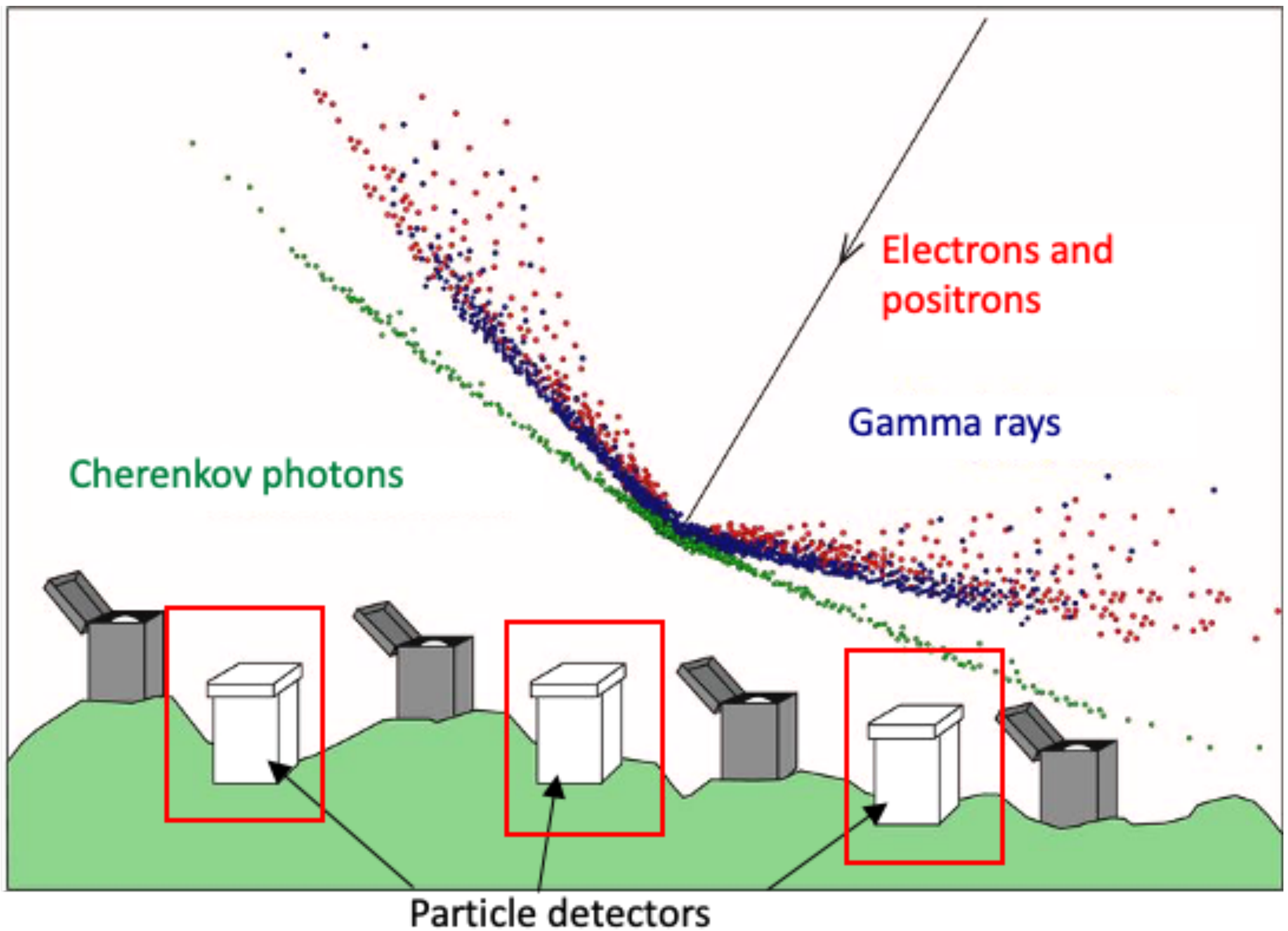
★ Solution: a "pair conversion telescope" in which the atmosphere is part of the detector

★ Ground-based detectors → geographical location relevant



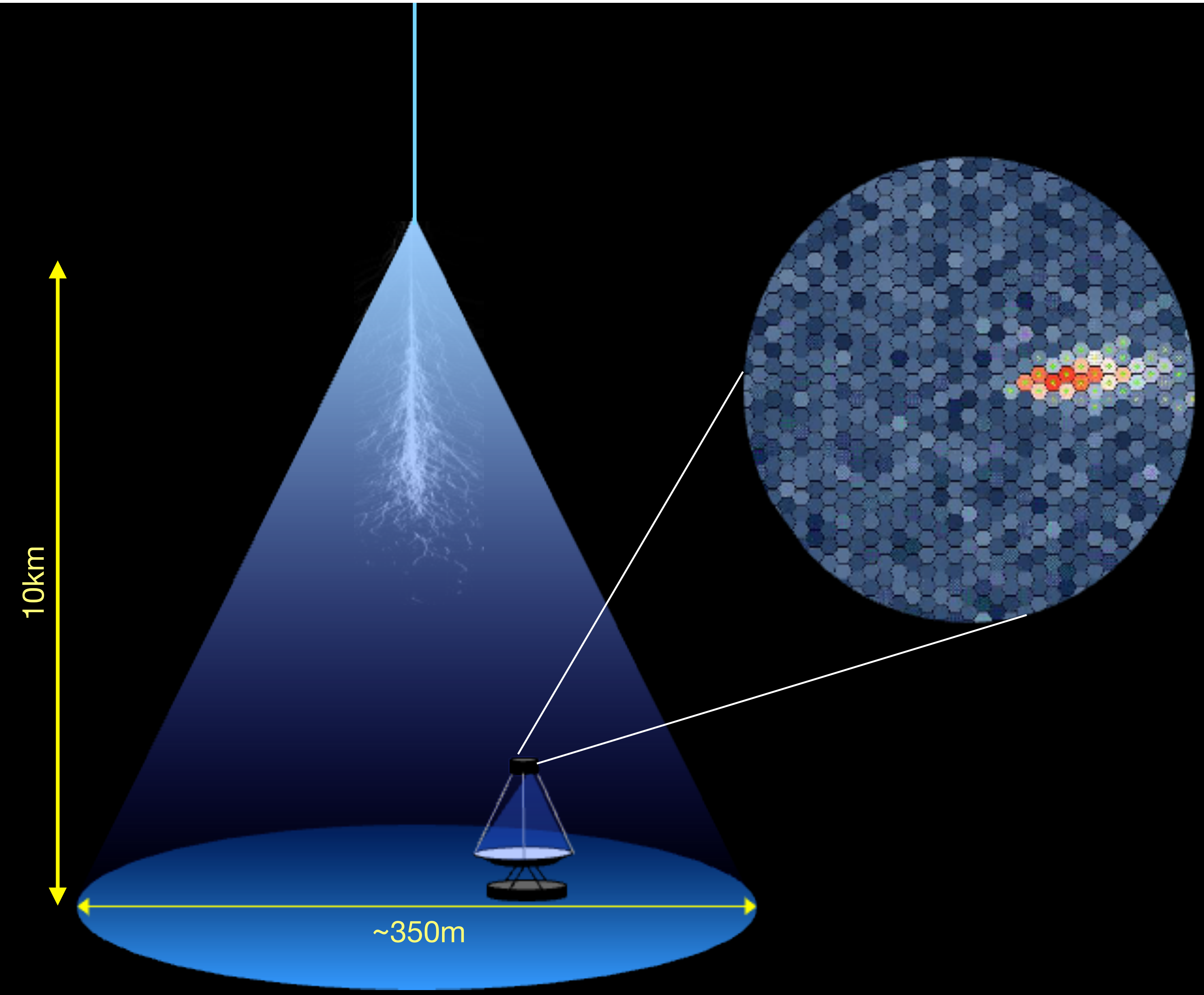


Air shower detectors



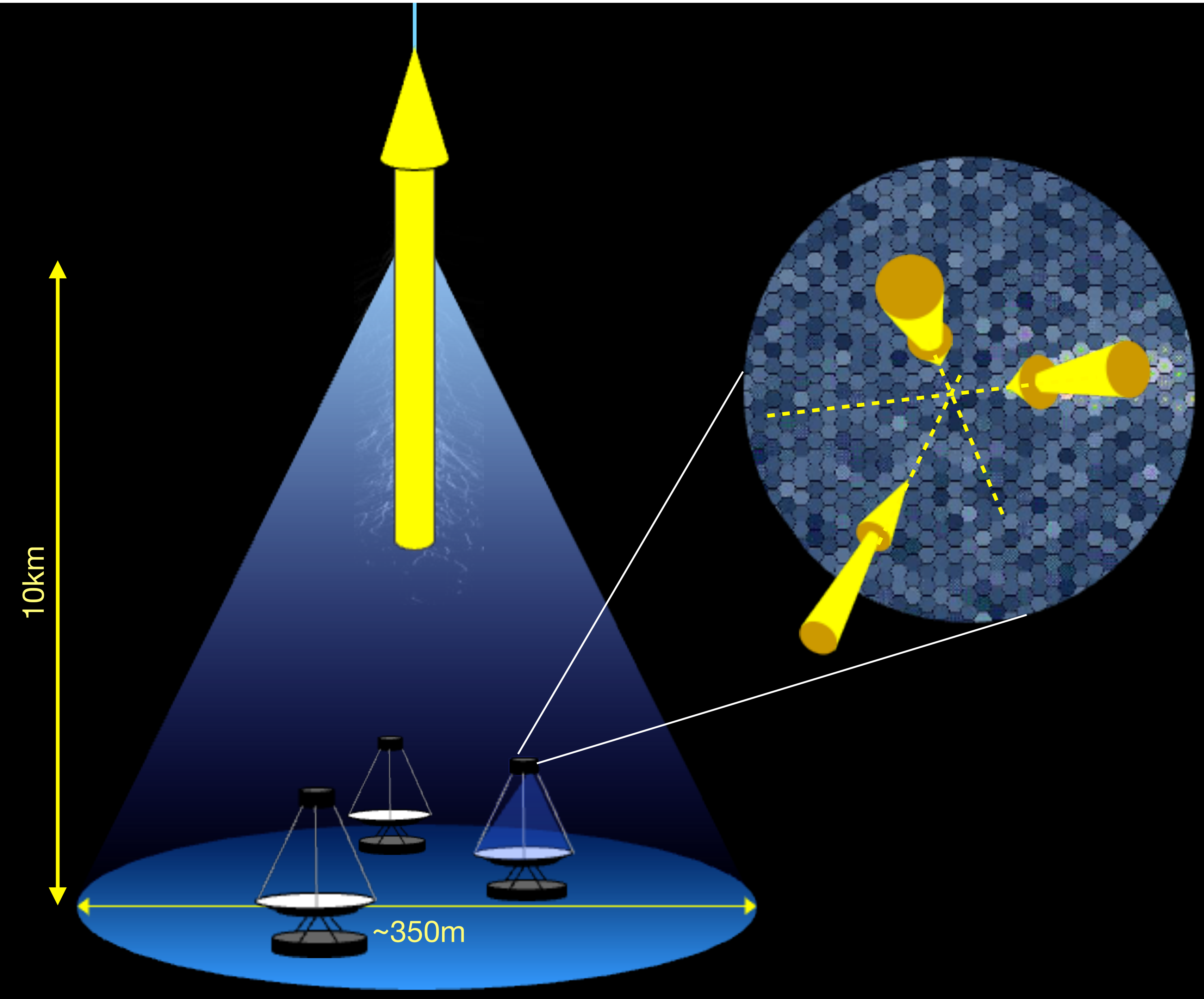
- ★ Detect particles of the shower
- ★ Thin particle fronts
- ★ Particle density proportional to primary energy
- ★ Particle arrival times correlated with primary direction
- ★ Particle spatial distribution related to primary ID

Cherenkov telescopes



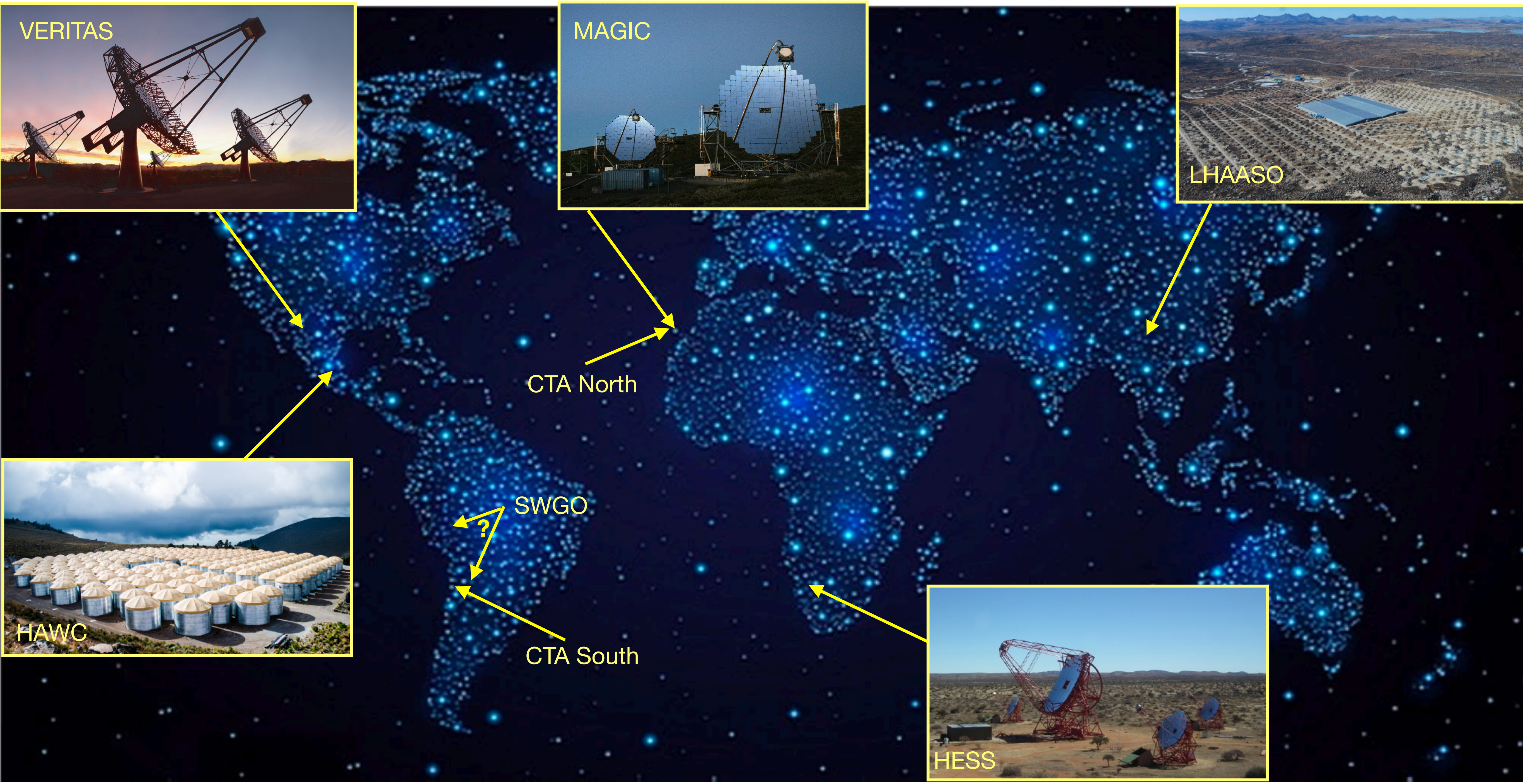
- ★ Huge collection area
- ★ Image intensity → γ energy
- ★ Image orientation → γ direction
- ★ Image shape → particle ID
- ★ Better determined by redundancy

Cherenkov telescopes



- ★ Huge collection area
- ★ Image intensity → γ energy
- ★ Image orientation → γ direction
- ★ Image shape → particle ID
- ★ Better determined by redundancy

VHE/UHE gamma-ray detectors



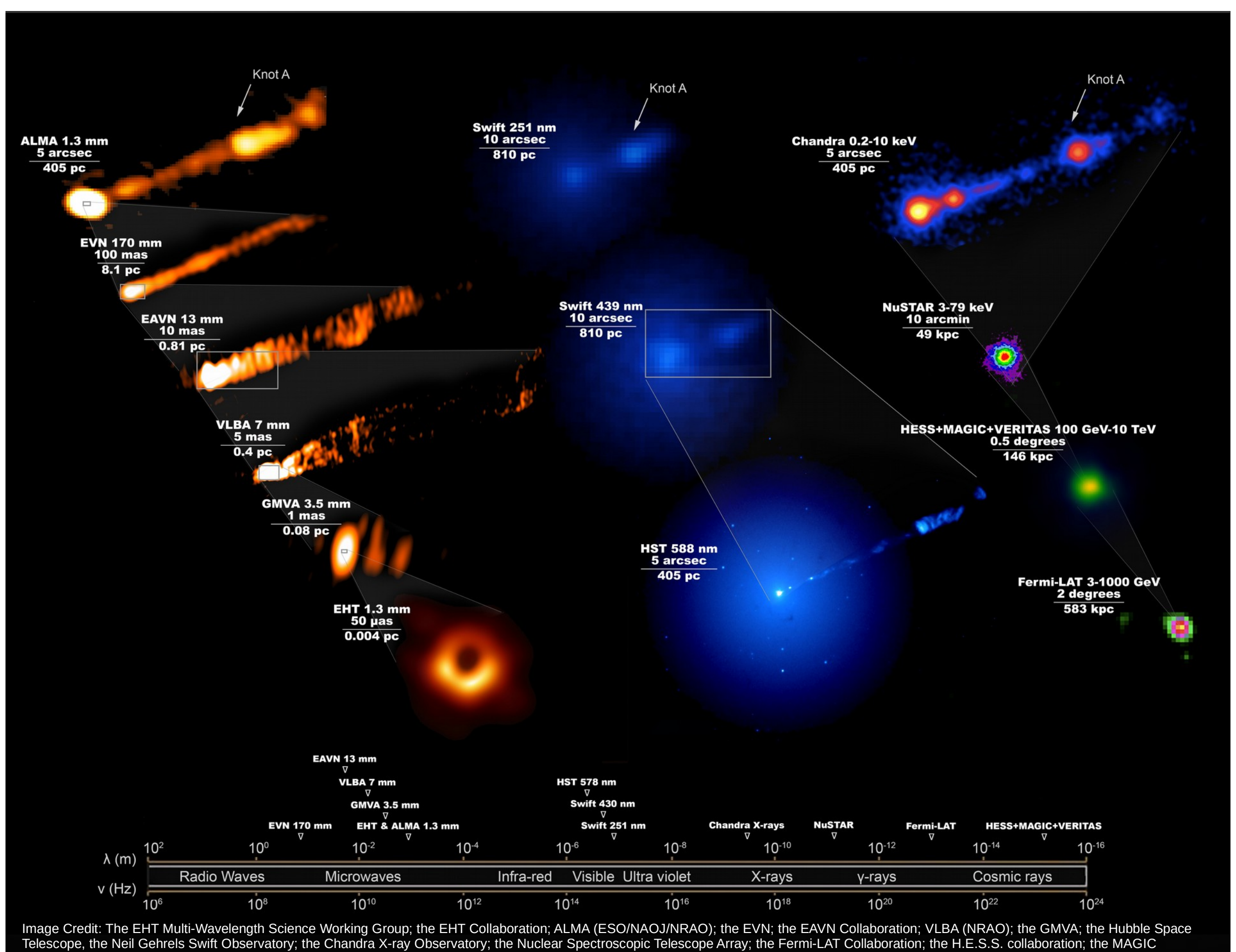
M87: a broad MWL view

accelerators MW/MM

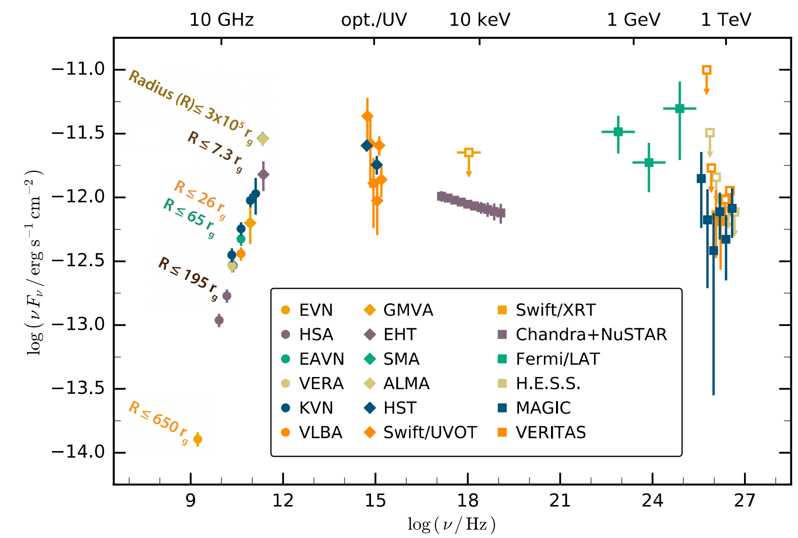
★ Broadband coordinated observations in 2017 during quiescent state (19 facilities in 15 decades of energy)

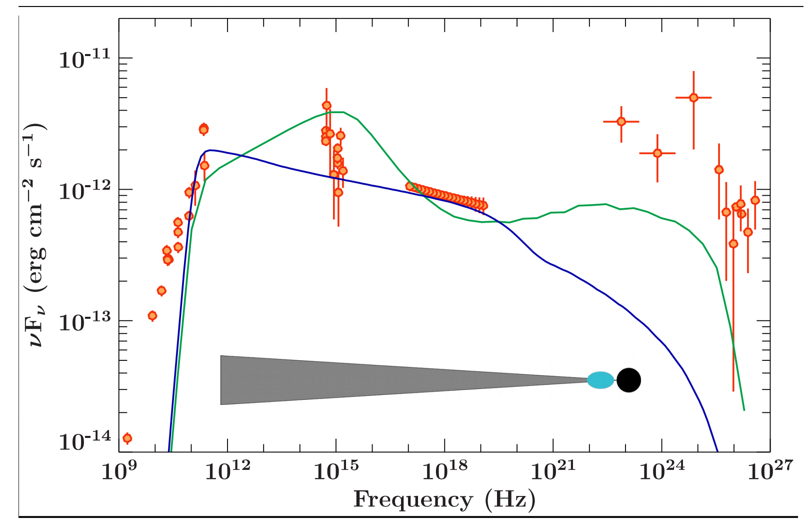
★ Cannot be modeled by single zone

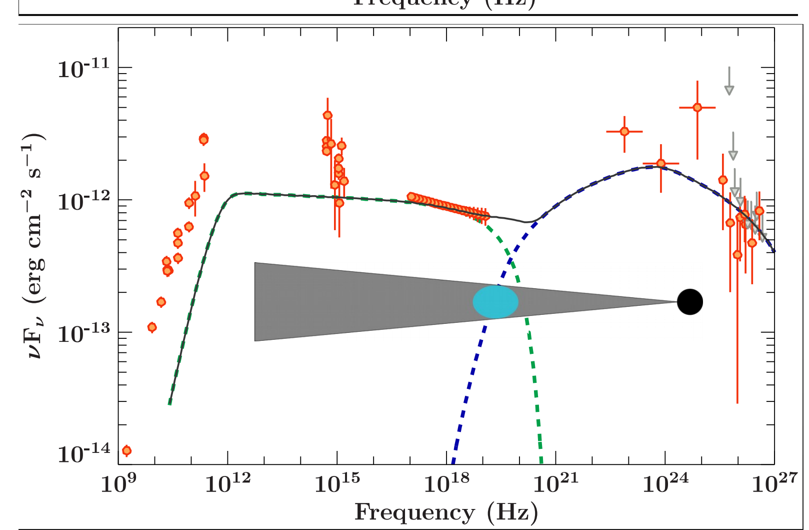
★ Structured jet and time dependence are key



Alagaba et al. ApJ Lett. 911 (2021) L11







Searches in gamma rays

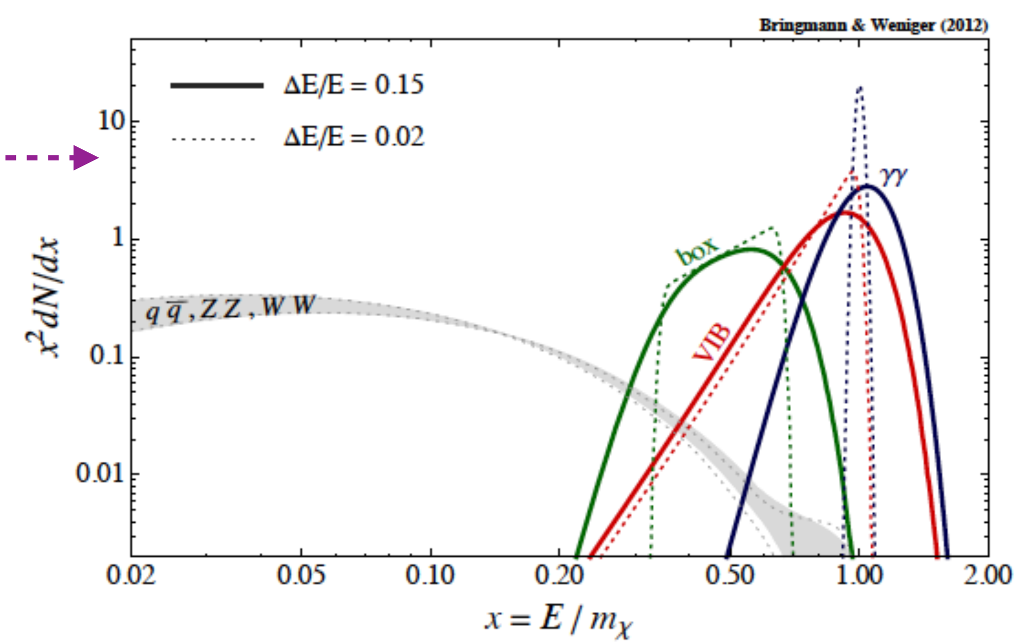
★ Gammas do not interact from nearby production sites to Earth:

- ✦ Keep direction information: allow measure DM distribution
- ✦ No need to use complicate transport equations

★ Expected fluxes:

Pythia

$$\frac{d^2\Phi}{dEd\Omega}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{dN_\gamma}{dE}(E)\int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl\, n_\chi(\hat{\boldsymbol{p}},l)\,\Gamma_\chi$$



Annihilation:

$$\Gamma_\chi = \frac{1}{k} n_\chi \langle\sigma v\rangle$$

Decay:

$$\Gamma_\chi = \frac{1}{\tau_\chi}$$

$$\frac{d^2\Phi_{\mathrm{ann}}}{d\Omega\, dE}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{k\, m_\chi^2}\frac{dJ_{\mathrm{ann}}}{d\Omega}(\hat{\boldsymbol{p}})\frac{dN_\gamma}{dE}(E)$$

$$\frac{d^2\Phi_{\mathrm{dec}}}{d\Omega\, dE}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\frac{dJ_{\mathrm{dec}}}{d\Omega}(\hat{\boldsymbol{p}})\frac{dN_\gamma}{dE}(E)$$

$$\frac{dJ_{\mathrm{ann}}}{d\Omega}(\hat{\boldsymbol{p}}) = \int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl \rho^2(\hat{\boldsymbol{p}},l)$$ ∝ mass & concentration

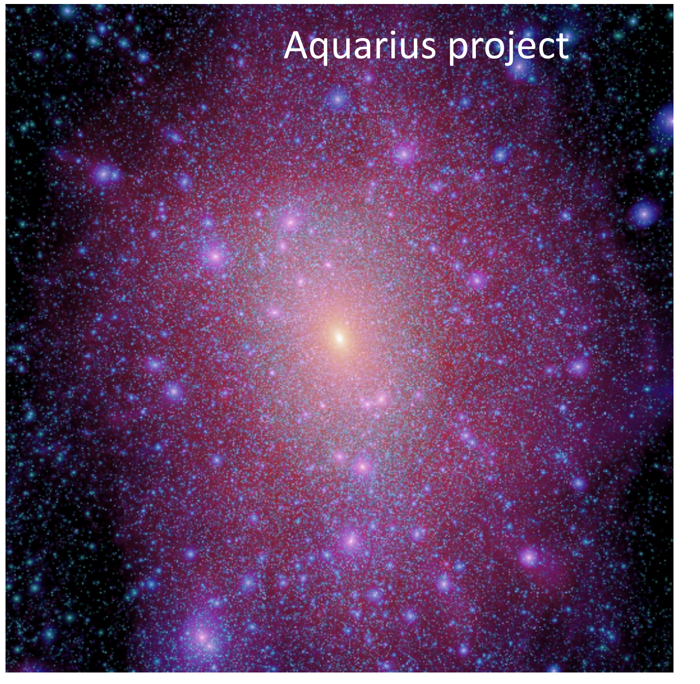
$$\frac{dJ_{\mathrm{dec}}}{d\Omega}(\hat{\boldsymbol{p}}) = \int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl \rho(\hat{\boldsymbol{p}},l)$$ ∝ mass

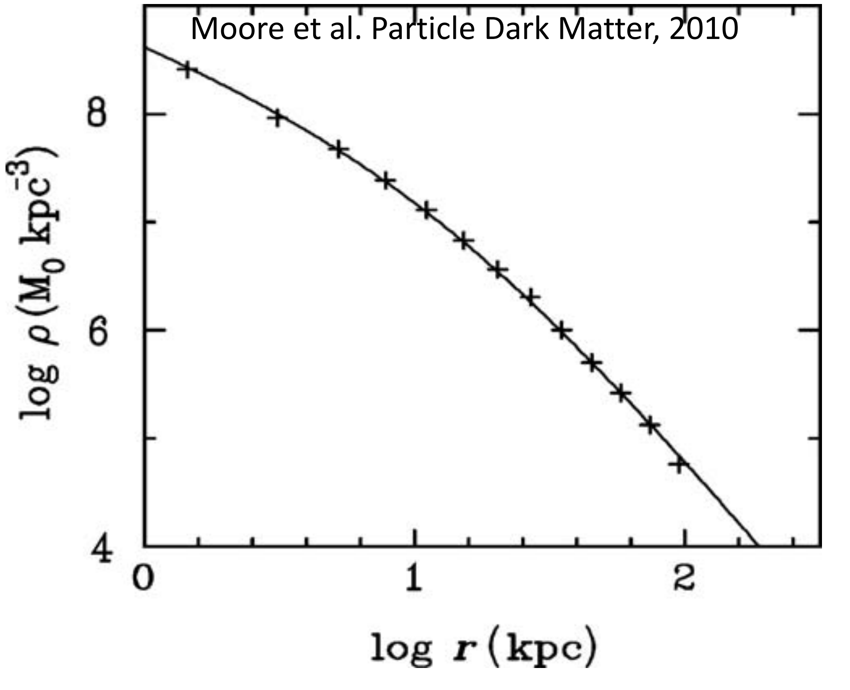
Density profiles

- DM distributes in quasi-spherical halos of gravitationally bound matter
- From N-body simulations we know:
  - Hierarchical: DM halos contain sub-halos
  - Density profile for all halo size described by:

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})^{\gamma}(1+r/r_{\rm s})^{3-\gamma}}$$

    (Navarro-Frenck-White profile)
  - Free parameters determined by fitting to measured kinematics of visible mass probes (stars and galaxies) - Jeans equation
- This does not include baryon-DM interplay, relevant at the centre of halos, normally baryon dominated
  - Disagreements at the smaller scales





Estimating measured DM fluxes

- Gamma-ray instruments measure number of counts coming from promising DM targets, as a function of measured energy and direction, and compare with background expectations, with a likelihood function:

$$\mathcal{L}_\gamma \; (\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\gamma) = \prod_{i=1}^{N_{E'}} \prod_{j=1}^{N_{\hat{\boldsymbol{p}}'}} P\left(s_{ij}(\alpha\bar{J};\boldsymbol{\mu}) + b_{ij}(\boldsymbol{\mu})|N_{ij}\right) \cdot \mathcal{L}_\mu(\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\mu)$$

α = <σv> or τ^{-1}

$\boldsymbol{D}_\gamma$ = data

$\boldsymbol{\mu}$ = nuisance parameters

s_{ij} = expected # of gamma events

b_{ij} = expected # of background events

N_{ij} = observed counts

$$\bar{J} = J(\Delta\Omega_{\text{tot}})$$

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \, \frac{dJ}{d\Omega}$$

- The number of expected measured gamma-ray counts is:

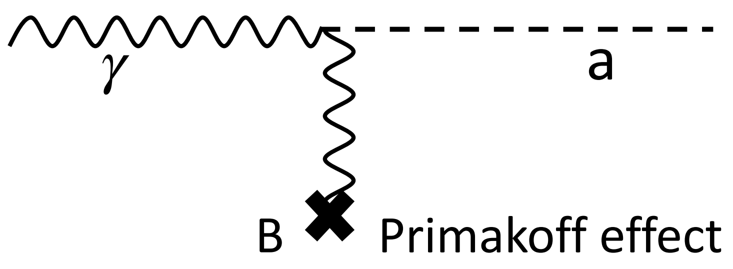
$$s_{ij}(\alpha\bar{J}) = \int_{\Delta E'_i} dE' \int_{\Delta\hat{\boldsymbol{p}}'_j} d\Omega' \int_0^\infty dE \int_{\Delta\Omega_{\text{tot}}} d\Omega \int_0^{T_{\text{obs}}} dt \, \frac{d^2\Phi(\alpha\bar{J})}{dE\, d\Omega} \, \text{IRF}(E',\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t)$$

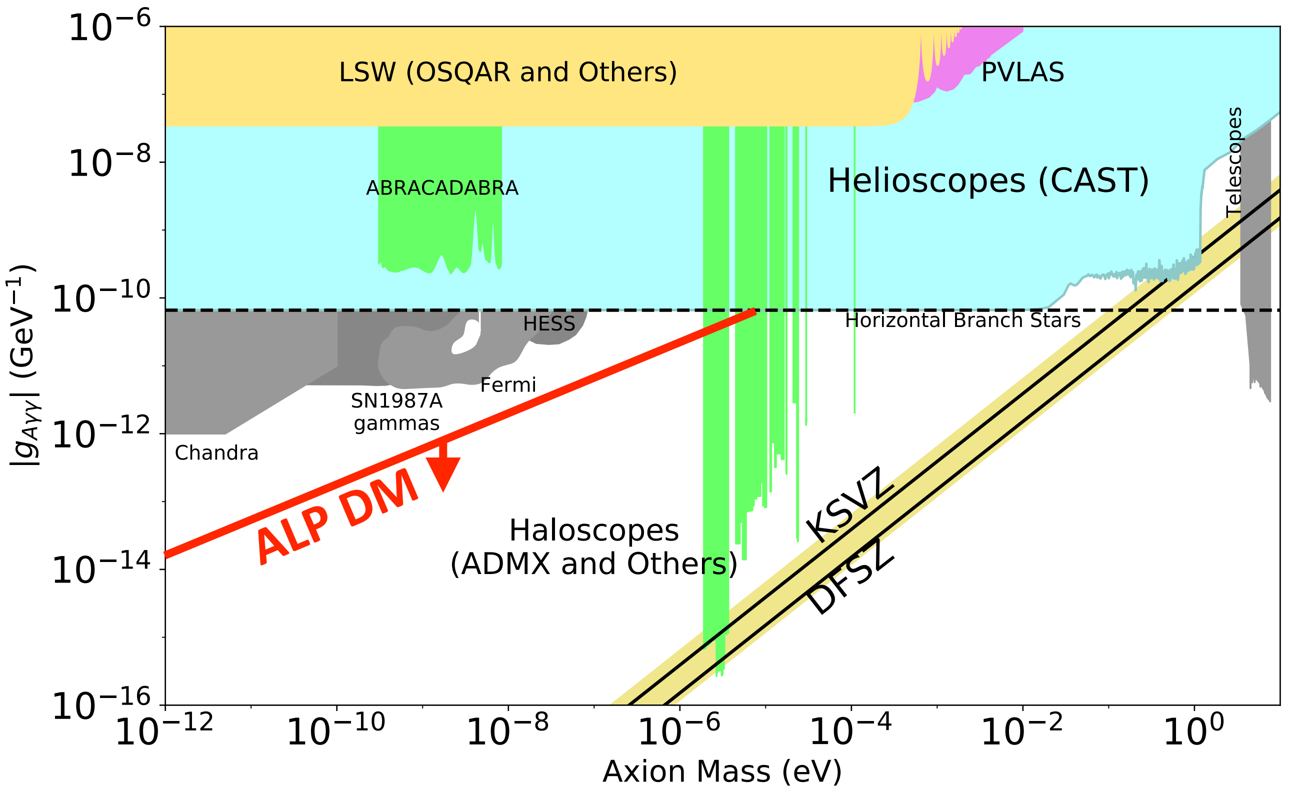
with IRF the Instrument Response Function, which can be factored in effective area times PDFs for energy and direction estimators

$$\text{IRF}(E',\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t) = A_{\text{eff}}(E,\hat{\boldsymbol{p}},t) \cdot f_E(E'|E,t) \cdot f_{\hat{\boldsymbol{p}}}(\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t)$$

Axion and axion-like particles

- **Axion**: Hypothetical spin-0 boson produced by spontaneous breaking of new symmetry introduced in the QCD Lagrangian to solve the "strong CP problem"
    - 2-photon vertex with weak coupling, proportional to their mass
- Generalized to **Axion-like particles** (**ALPs**): hypothetical spin-0 particles with 2-photon vertex
    - ALPs are very light and are not viable as thermal relic
    - Produced as a zero-momentum Bose-Einstein condensate when the temperature falls below the QCD scale → **Cold** dark matter!

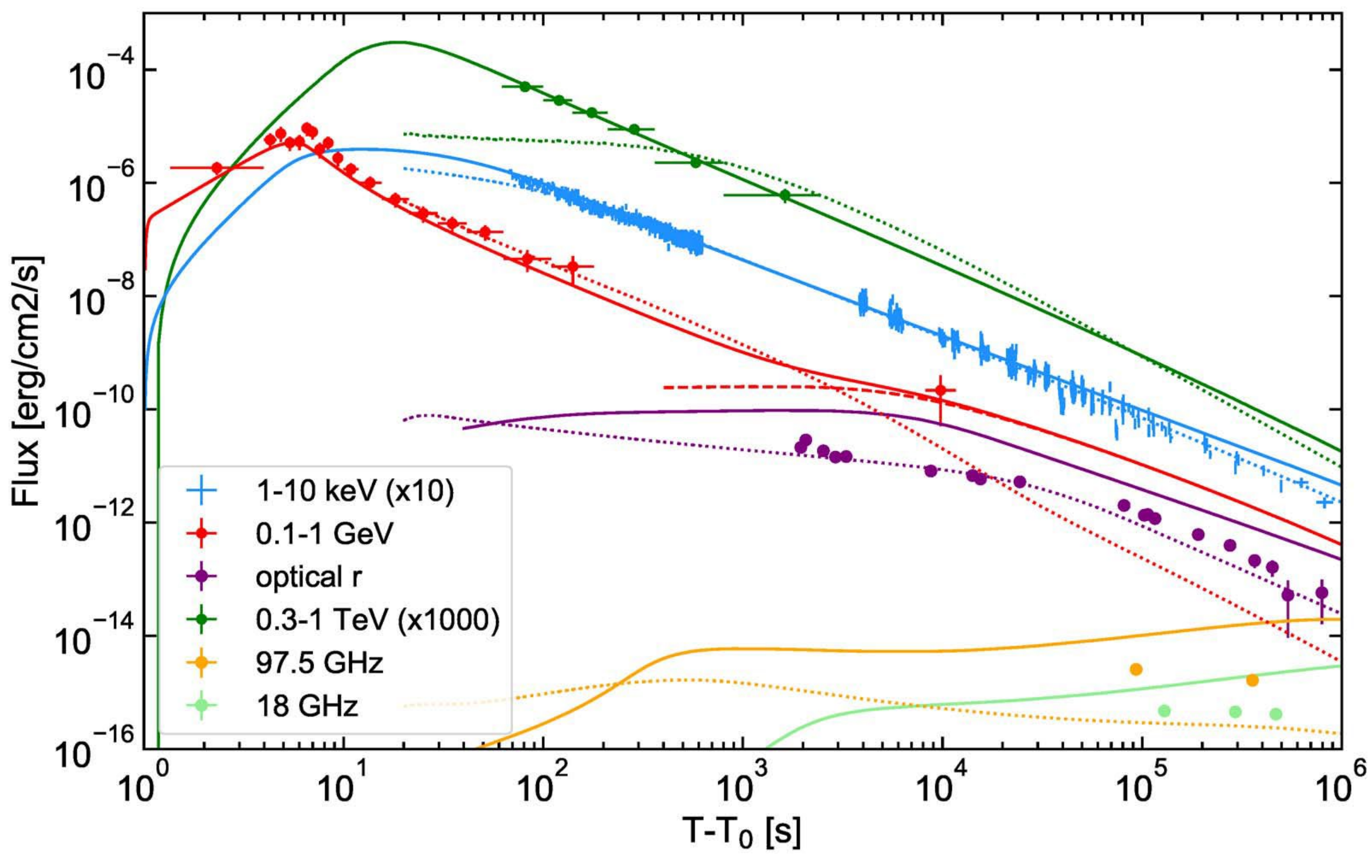




LIV with GRB190114C at VHE

BSM propagation

MAGIC Coll. Nature 575 (2019) 459



Acciari et al. Phys. Rev. Lett. 125 (2020) 021301

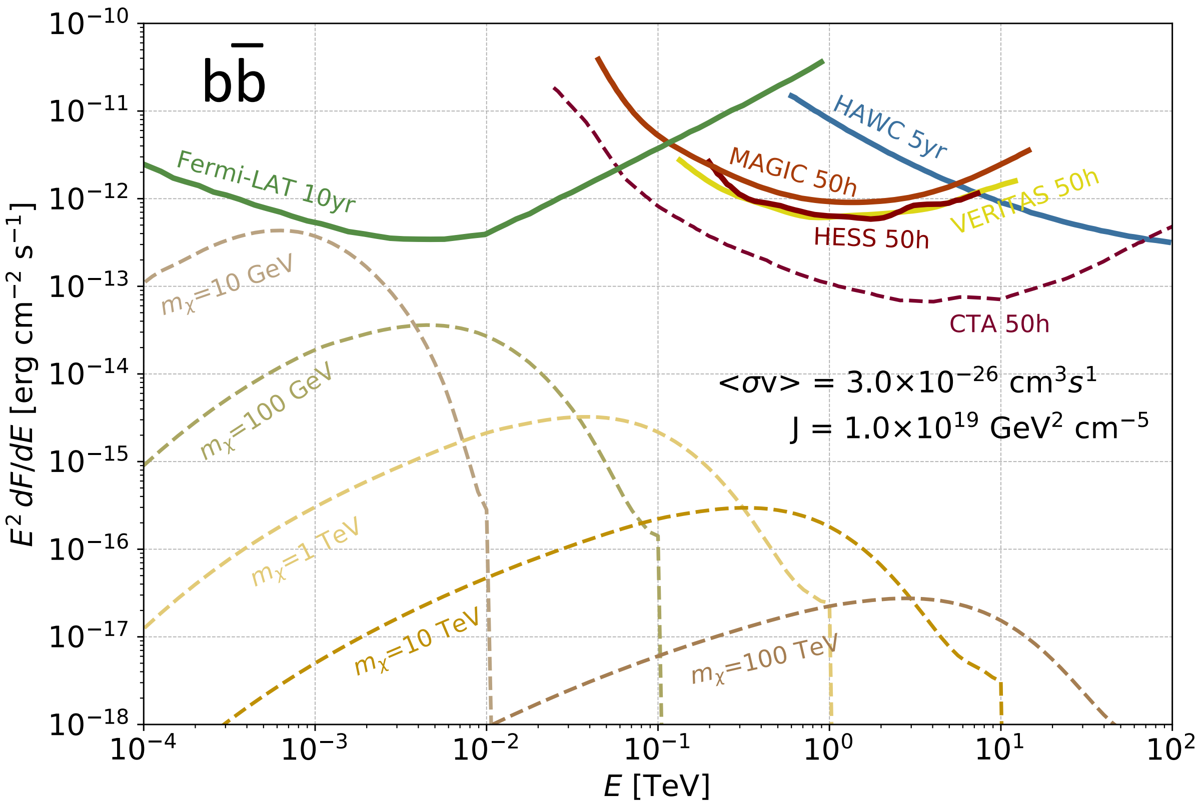
LC model	Minimal (step function)	Theoretical ([19])		
	η^{UL}	η^{LL}	η^{BF}	η^{UL}
η_1	4.4	-2.2	0.3	2.1
η_2	2.8	-4.8	1.3	3.7
	subl.	superl.		subl.
$E_{QG,1}$ [10^{19} GeV]	0.28	0.55		0.58
$E_{QG,2}$ [10^{10} GeV]	7.3	5.6		6.3

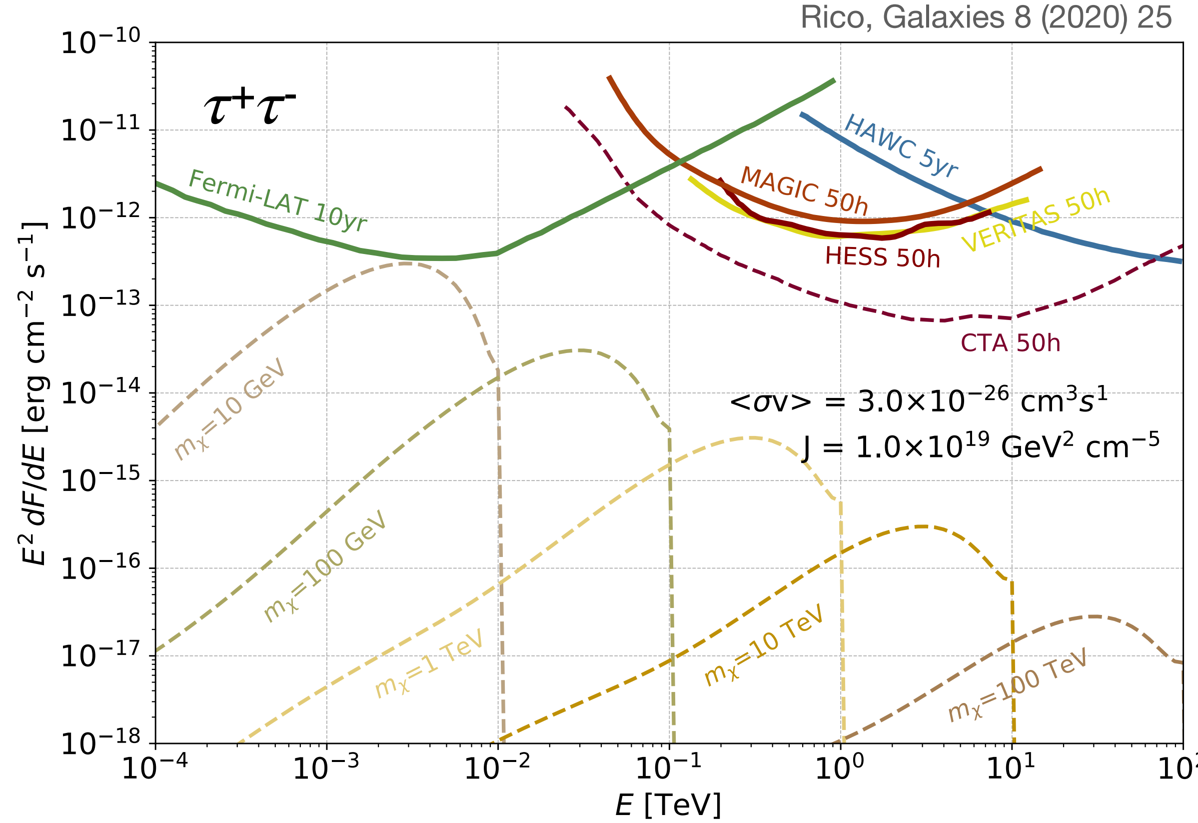
- ★ No dependence of observed light curve on energy for VHE gamma rays
- ★ No correlation of photon arrival time with gamma-ray energy
- ★ Derive limits to quantum gravity scale
  - ✦ Competitive for the quadratic leading order even for a featureless light curve

Fluxes vs sensitivity

BSM

Rico, Galaxies 8 (2020) 25





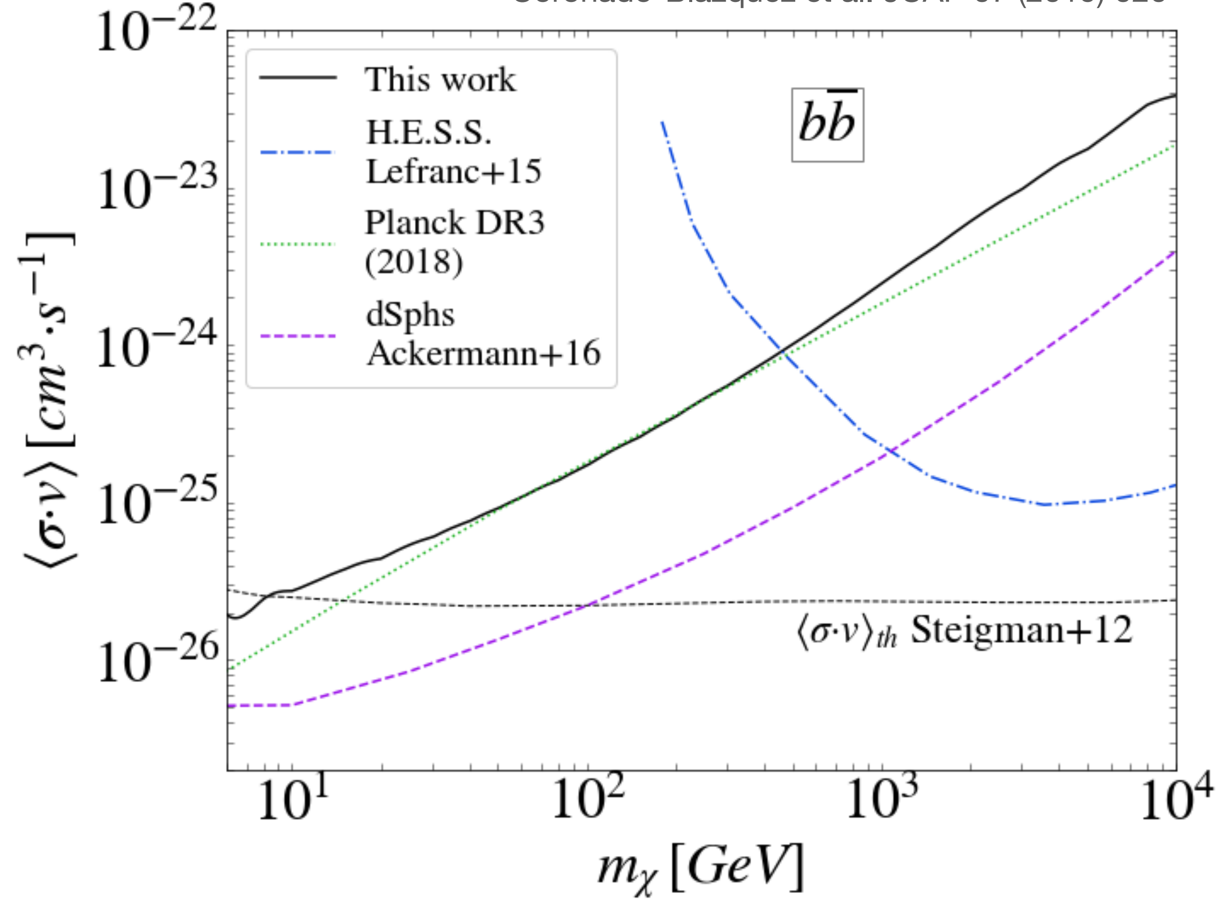
- ★ Fermi-LAT dominates searches up to m_{DM} ~1 TeV (100 GeV) for bb ($\tau^+\tau^-$) channel
- ★ Fermi-LAT is sensitive to the thermal relic density for m_{DM} ~10 GeV and the typical DM-dominated dSph (see later)
- ★ For higher masses sensitivity of Cherenkov telescopes and HAWC still not enough

Dark matter clumps

BSM

- DM galactic satellites (sub-halos) that have not triggered any stellar activity (they shine only in DM-related signals)
- Can only be found serendipitously or in unbiased surveys (Fermi-LAT, HAWC)
- DM clump selection criteria generally based on:
  - No association with astrophysical source/ no emission in other wavelengths
  - Steady sources
  - Spectrum compatible with DM emission
- Selection:
  - 1235 unidentified sources in Fermi-LAT catalogue
  - 44 survive criteria but no preference of DM spectrum over other astrophysical explanations

Coronado-Blázquez et al. JCAP 07 (2019) 020



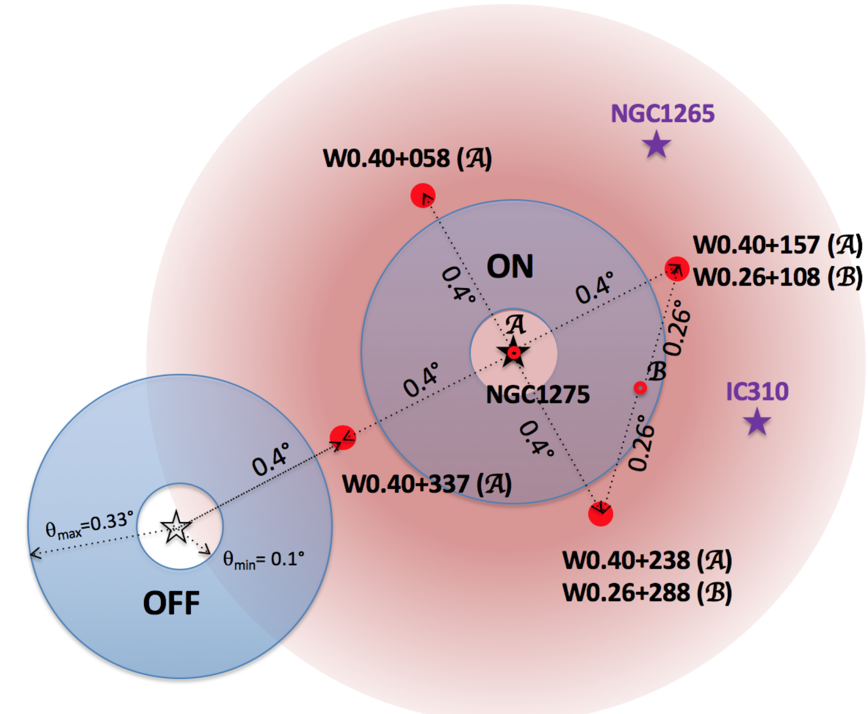
- Limits obtained assuming survivors are actually DM clumps and comparing with clumps from N-body simulations

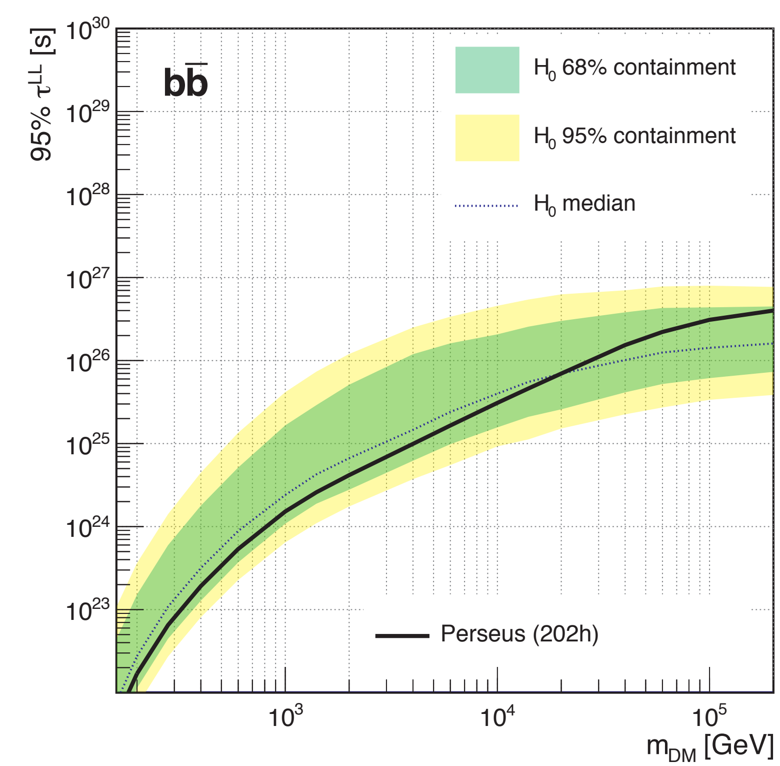
Galaxy clusters

BSM

- ★ Group of gravitationally bound galaxies
- ★ Largest and youngest (i.e. closest) structures in the Universe
- ★ Huge amounts of dark matter (M ~ 10^{15} $M_{\odot}$), but not highly concentrated (except for sub-halos)
  - ✦ good candidates to look for DM decay
  - ✦ (only hard constraint: DM lifetime should be larger than Hubble time: 10^{17}s)
- ★ Complex fields of view with possible foregrounds
- ★ Limits from Perseus cluster (MAGIC, 220h): $\tau_{DM} > 10^{26} - 10^{27}$ s
- ★ Other investigated clusters: Fornax (HESS), Coma (VERITAS+Fermi-LAT), Virgo (Fermi-LAT)

Acciari et al. Phys. Dark. Univ. 22 (2018) 38





Isotropic gamma-ray background

BSM

- All-sky diffuse gamma-ray emission measured by EGRET, Fermi-LAT
- Sources:
  - Unresolved members of extragalactic/high-latitude galactic sources:
    - AGNs
    - Star-forming galaxies
    - Millisecond pulsars
  - Dark matter?
- DM signal searched for in the auto-correlation power spectrum or cross-correlation with catalogues of astronomical objects
  - DM leaves imprints at different angular scales than other sources
  - Degeneracies broken by investigating in different energy windows and different catalogues

Ando et al. PRD 90 (2014) 023514