Cosmic-Ray and Gamma-Ray Studies with Fermi LAT and LHAASO

คณะวิทยาศาสตร์ มหาวิทยาลัยมหิดล
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ThaisCube Meeting
Chiang Mai, Thailand
Aug 11, 2023

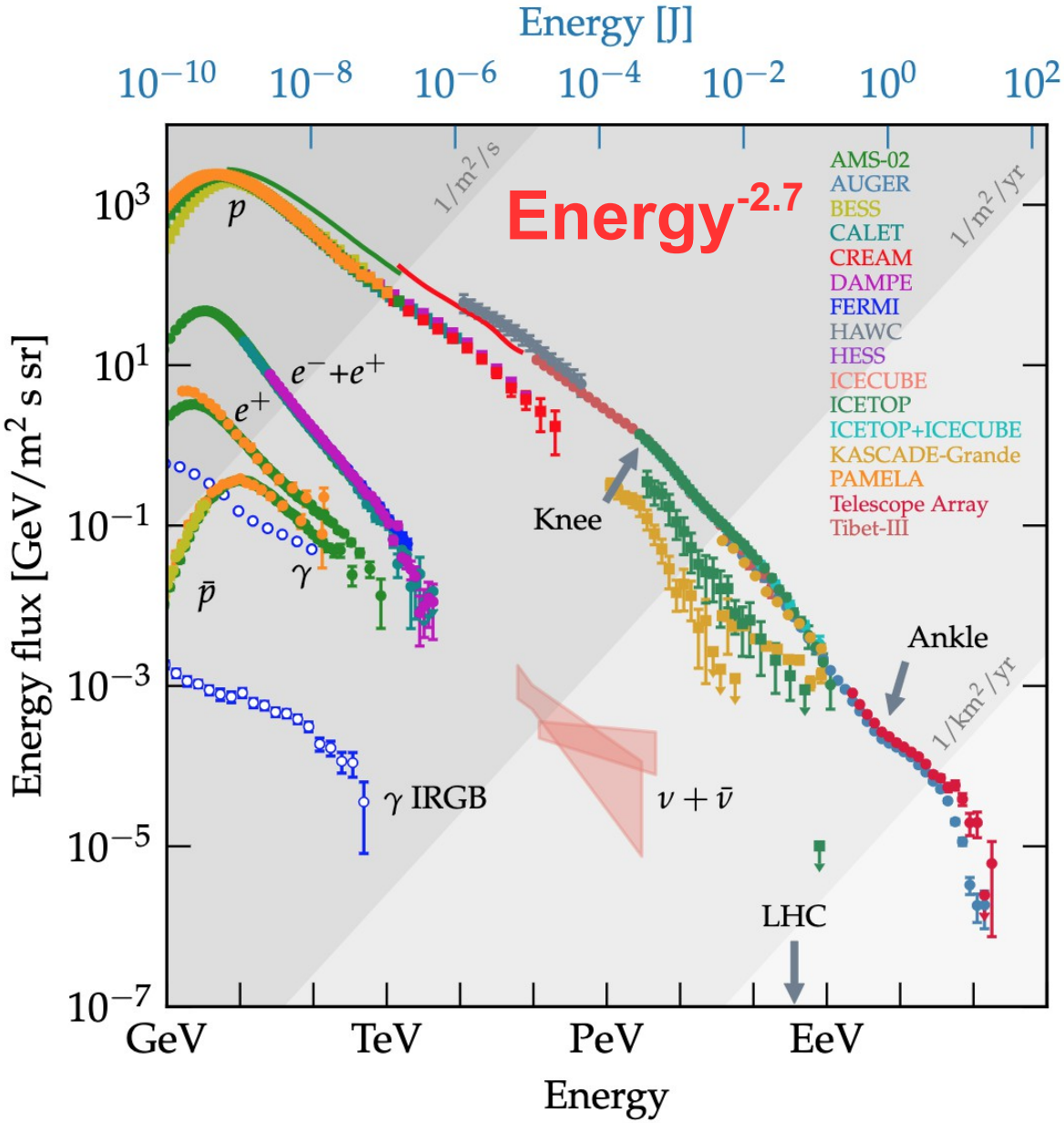
Fermi Gamma-ray Space Telescope

NARIT

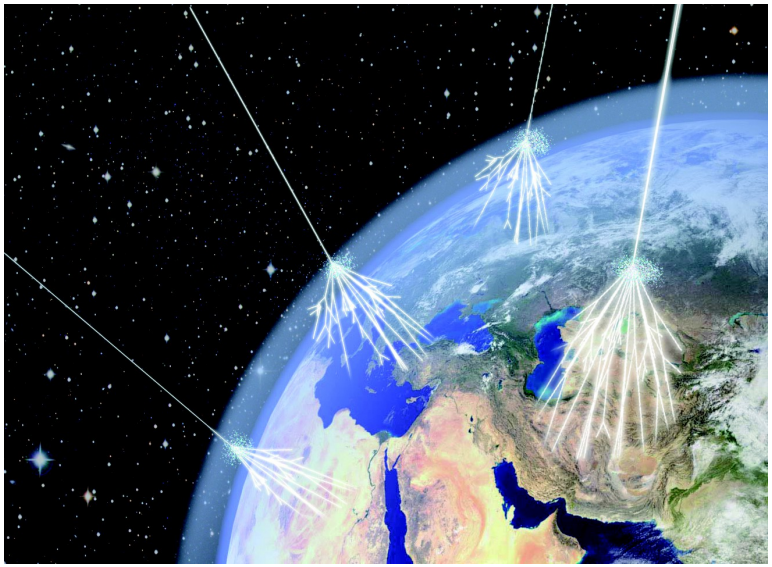
Institute of High Energy Physics
Chinese Academy of Sciences

SLAC NATIONAL ACCELERATOR LABORATORY

Cosmic Rays (CRs) and Gamma Rays (γ)

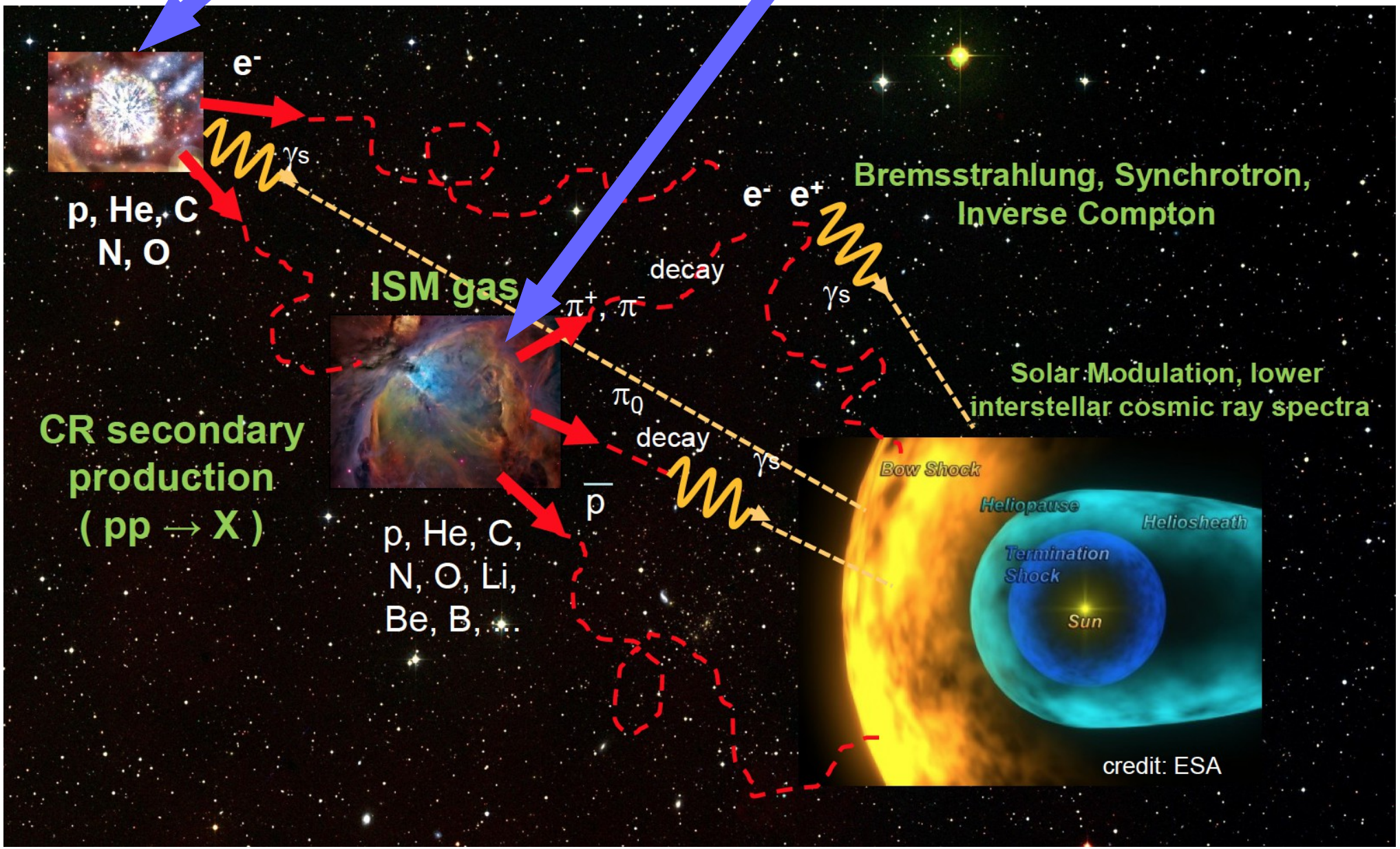


Evoli, Carmelo. (2018). The Cosmic-Ray Energy Spectrum. Zenodo. https://doi.org/10.5281/zenodo.4309926

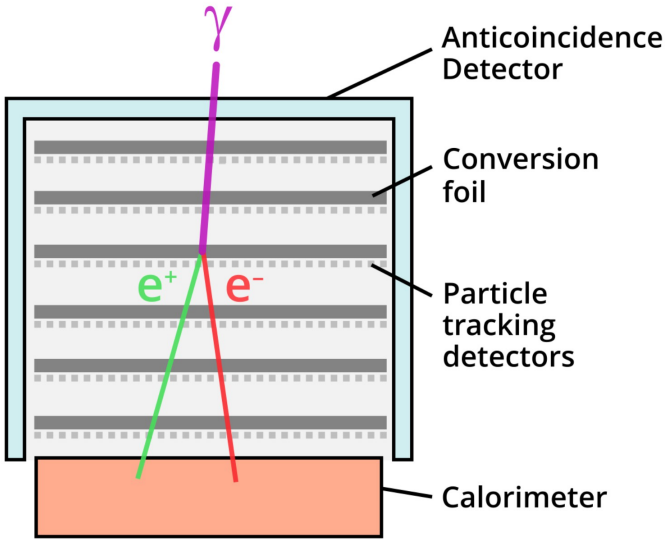


- CRs = high-energy particles and in space
- ~89% protons, ~9% He, small fraction of heavy nuclei, e^-, e^+, γ, etc
- Sources: Supernovae, pulsars, AGNs, stellar winds, Sun, etc

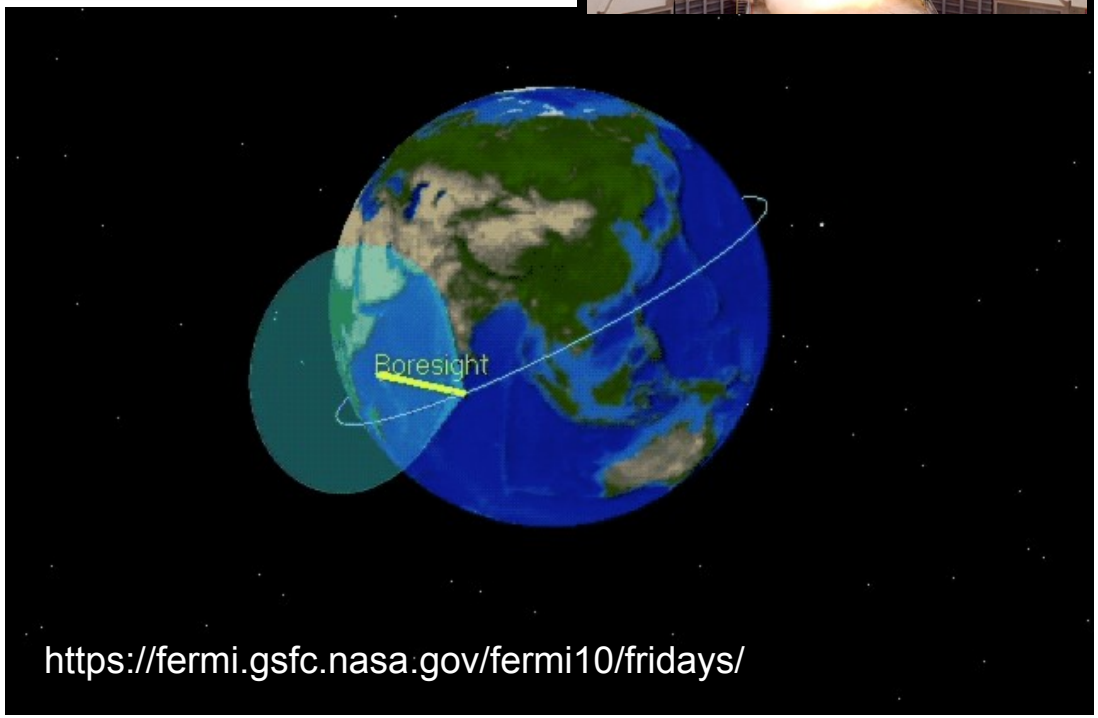
Primary and secondary CRs



Fermi LAT

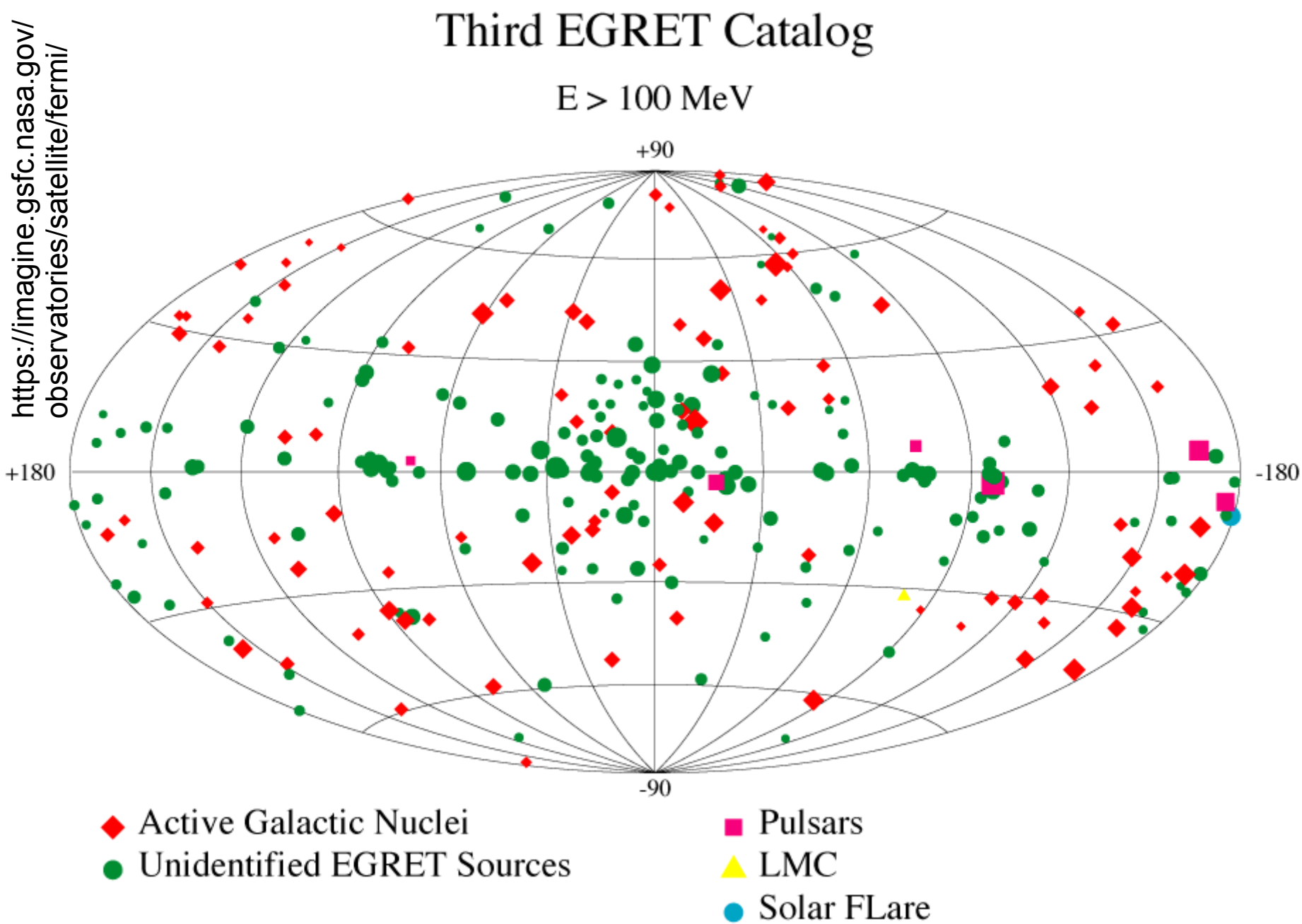

γ
Anticoincidence Detector
Conversion foil
e+
e−
Particle tracking detectors
Calorimeter


Launched in 2008

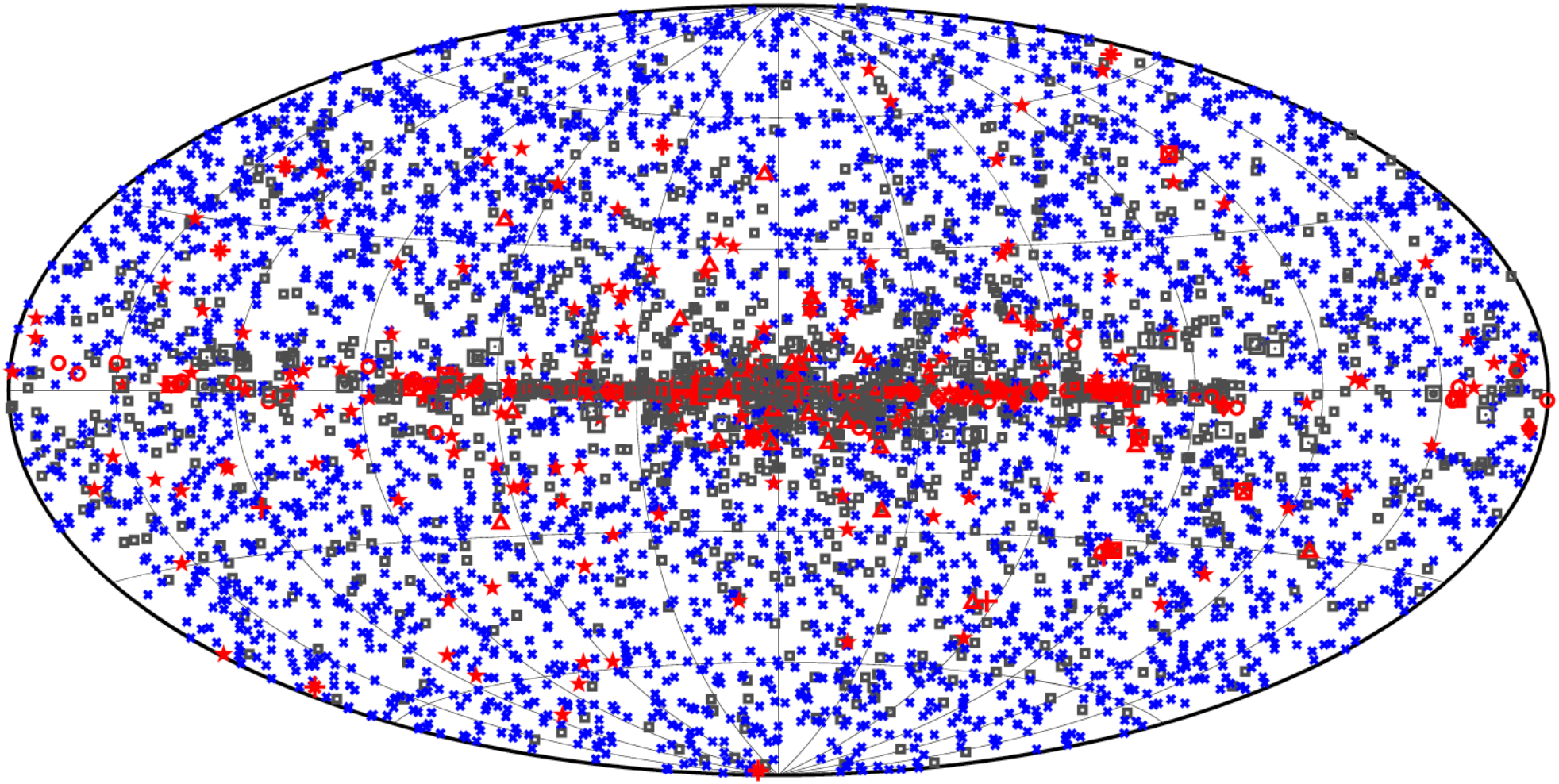

Boresight
https://fermi.gsfc.nasa.gov/fermi10/fridays/

GeV Gamma-Ray Sky before Fermi LAT

https://imagine.gsfc.nasa.gov/observatories/satellite/fermi/



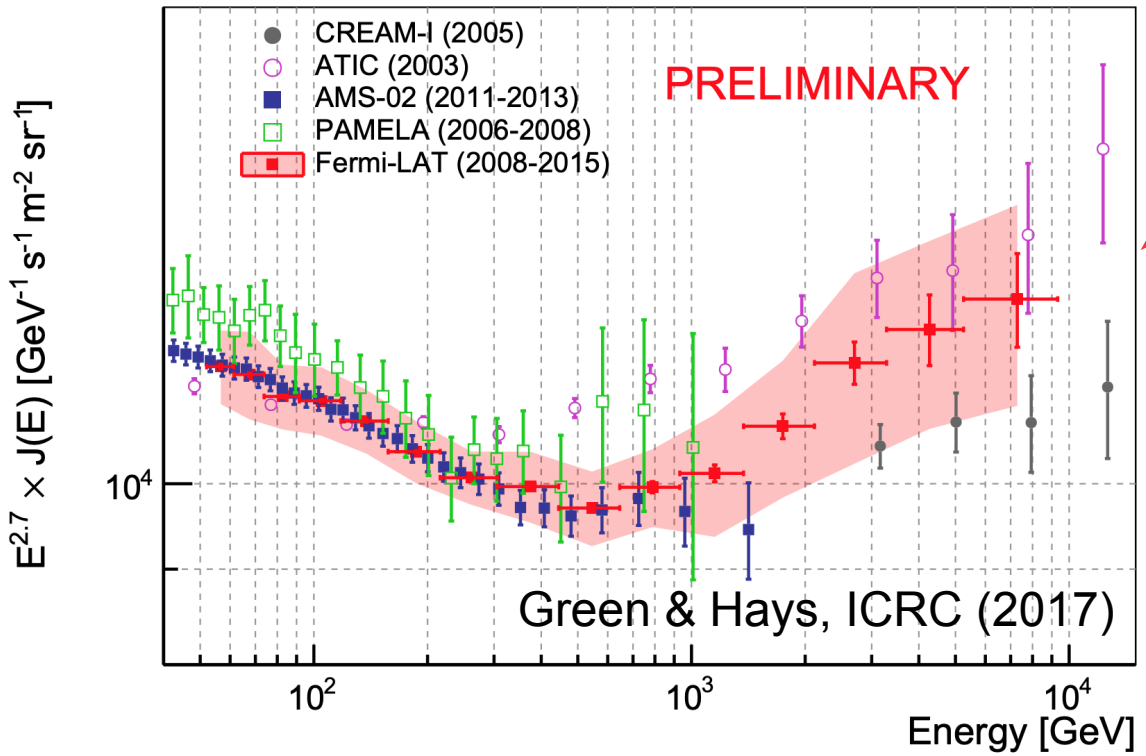
GeV Gamma-Ray Sky after Fermi LAT

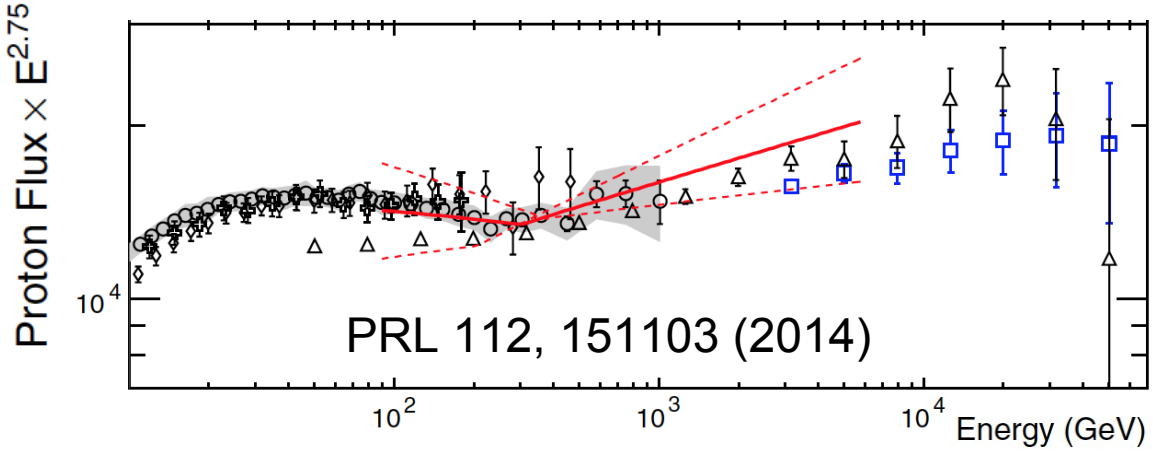


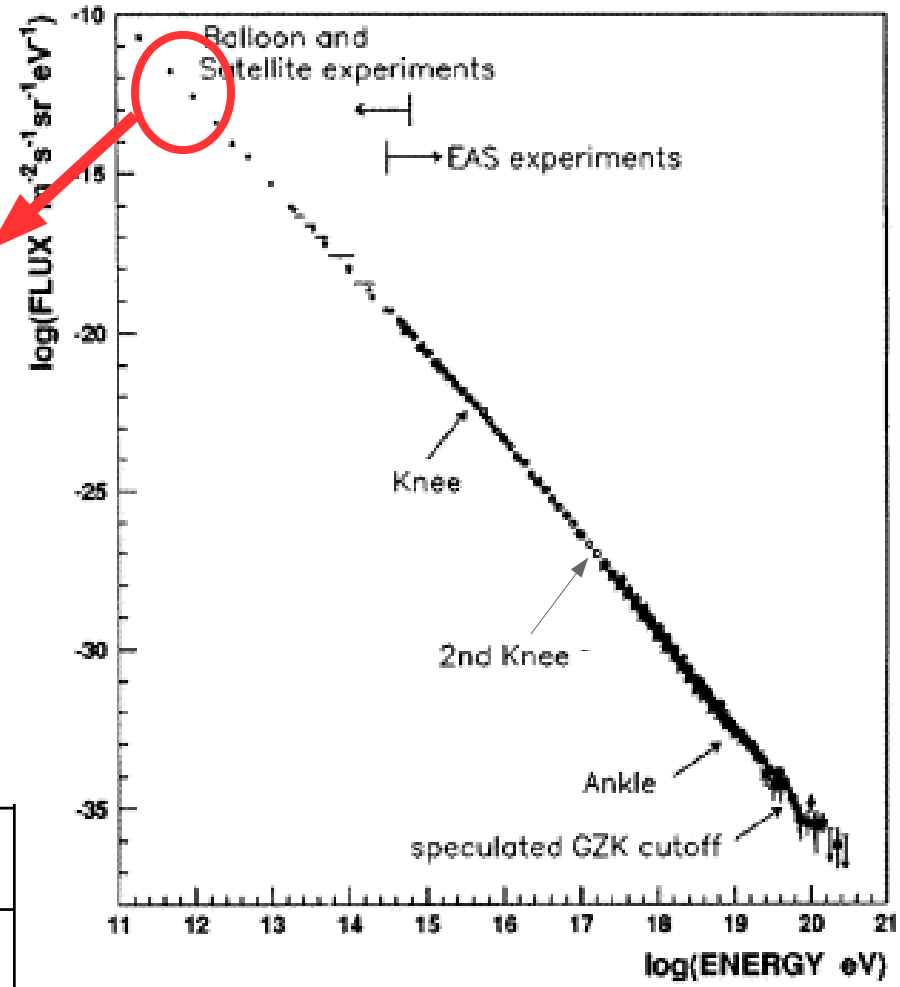
No association	Possible association with SNR or PWN		AGN
Pulsar	Globular cluster	Starburst Galaxy	PWN
Binary	Galaxy	SNR	Nova
Star-forming region	Unclassified source		

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 247:33 (37pp), 2020 March

CR proton spectrum

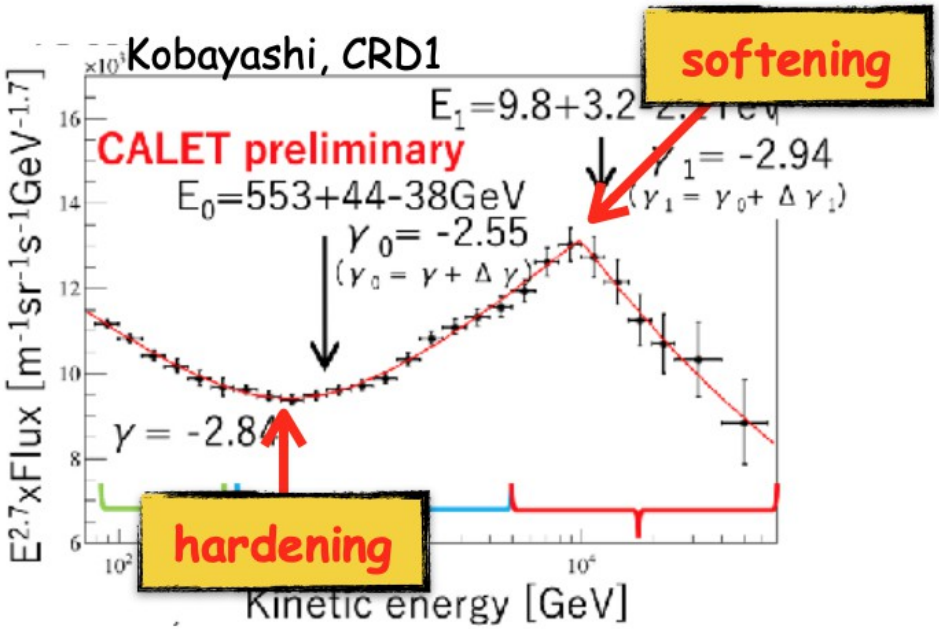


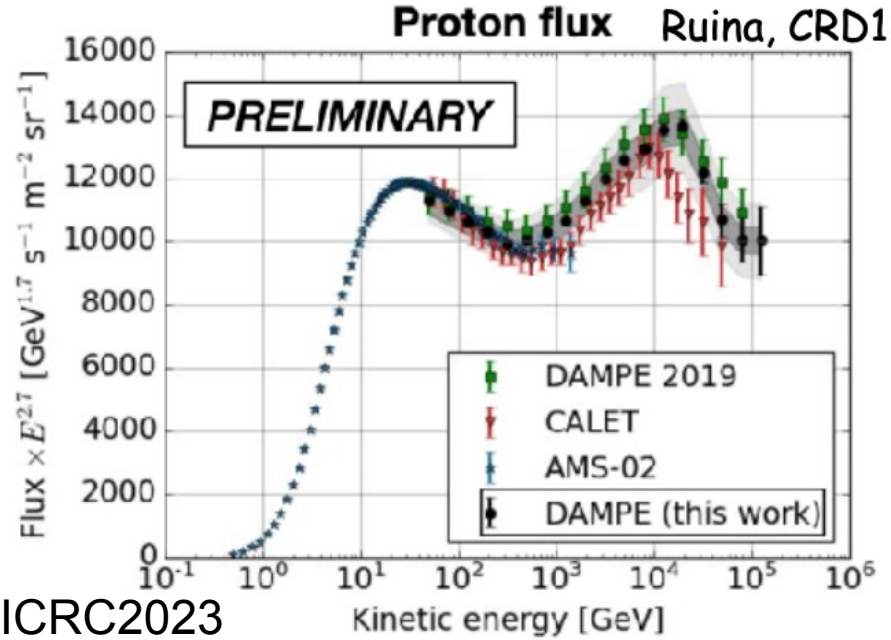




Confirm new spectral features for proton at ~500 GeV

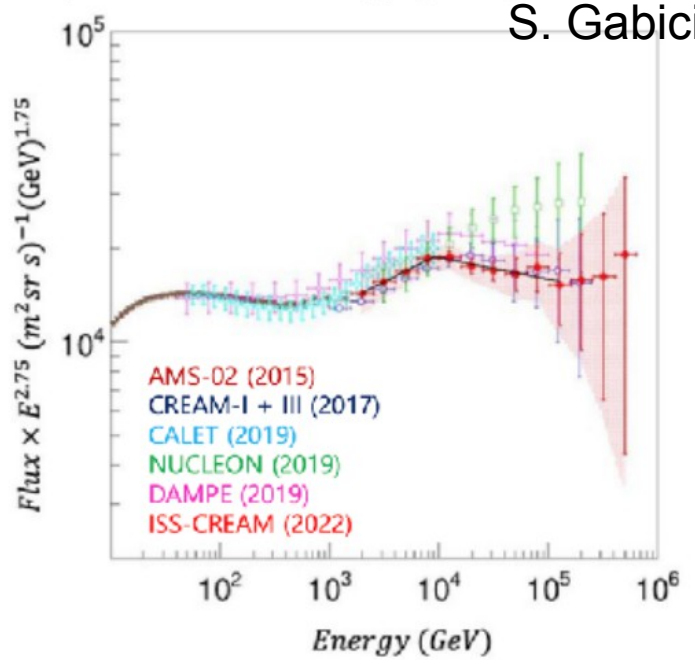
Give me a break! (CR protons)

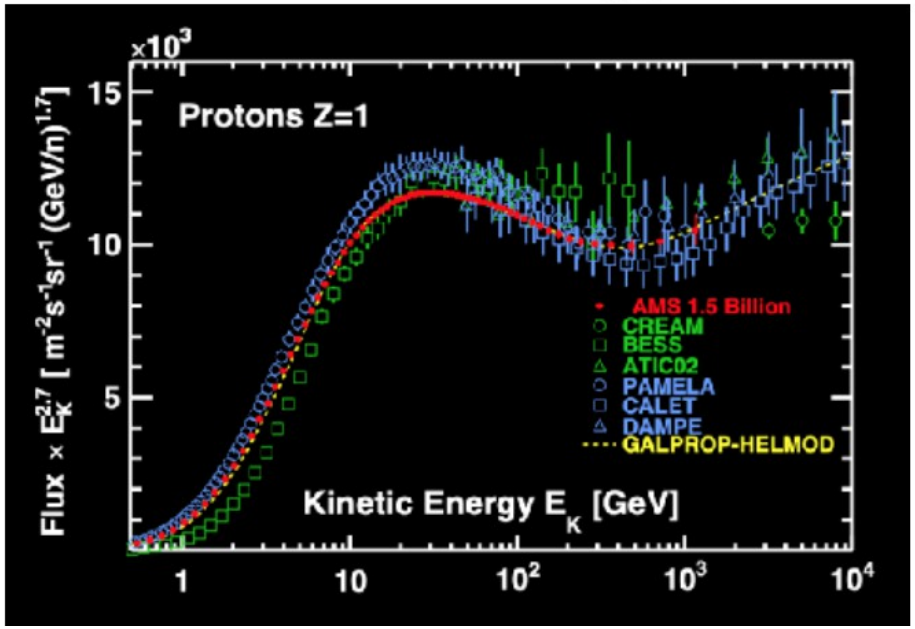




S. Gabici, APC, ICRC2023

Choi, CRD1

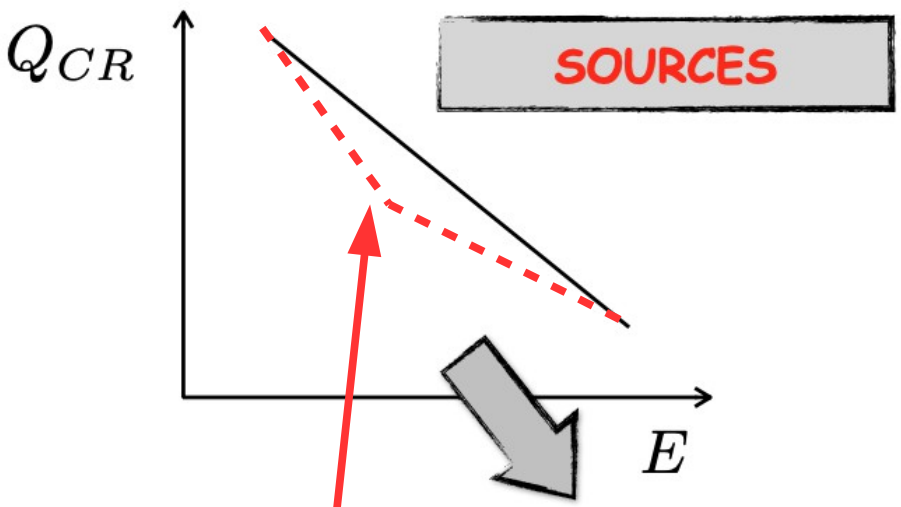




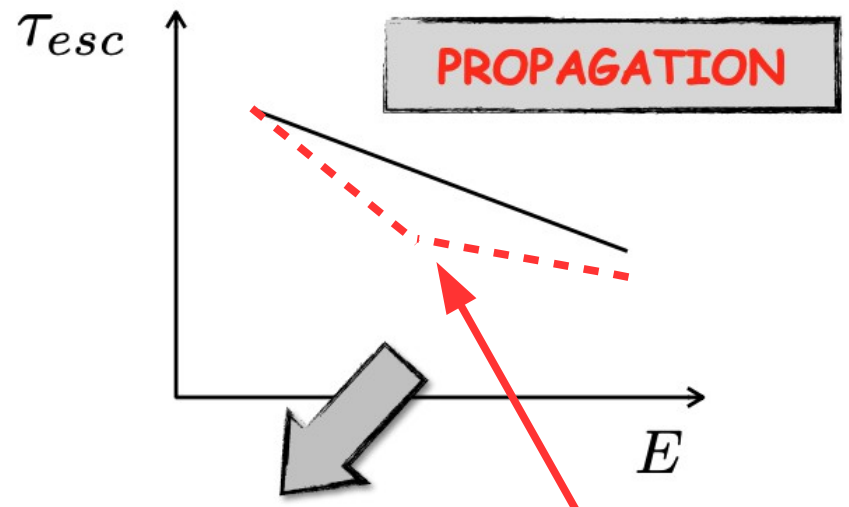
Oliva, CRD2

How to Explain the Break

$$Q_{CR}(E) \propto E^{-\delta}$$

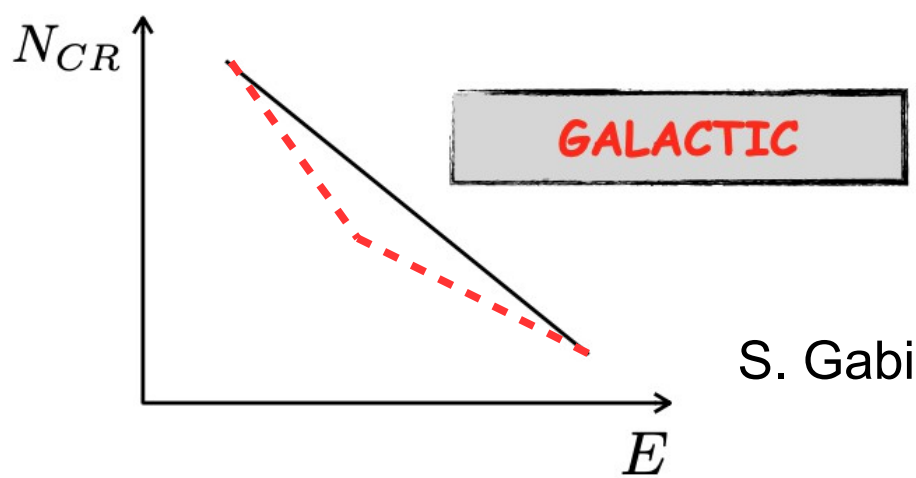


$$\tau_{esc}(E) \propto E^{-\alpha}$$



Either put the break at here

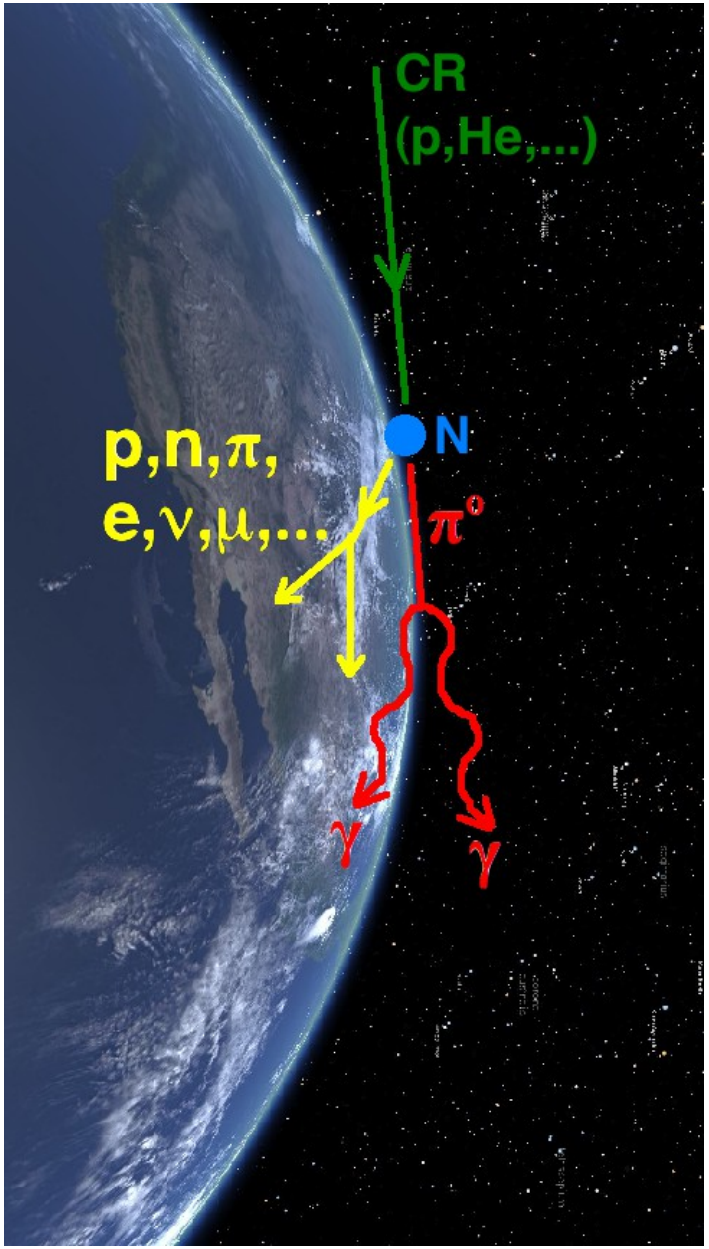
or here

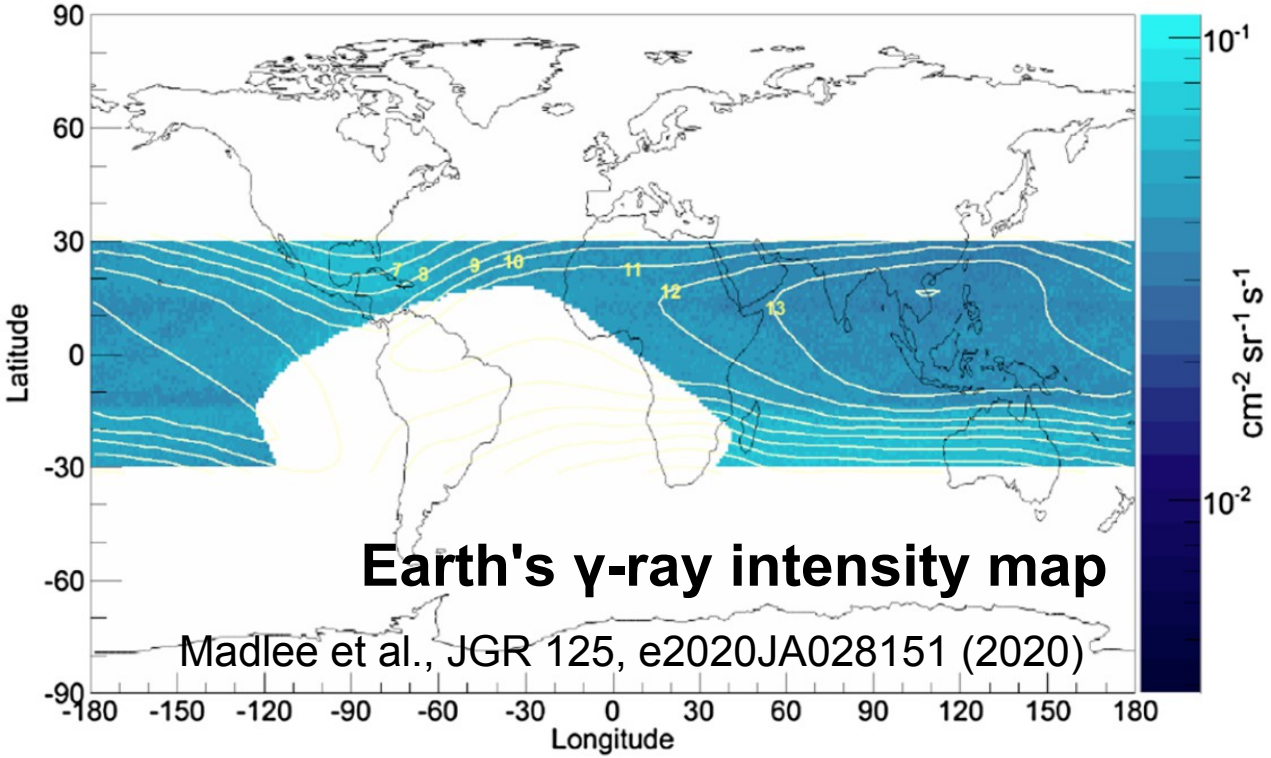


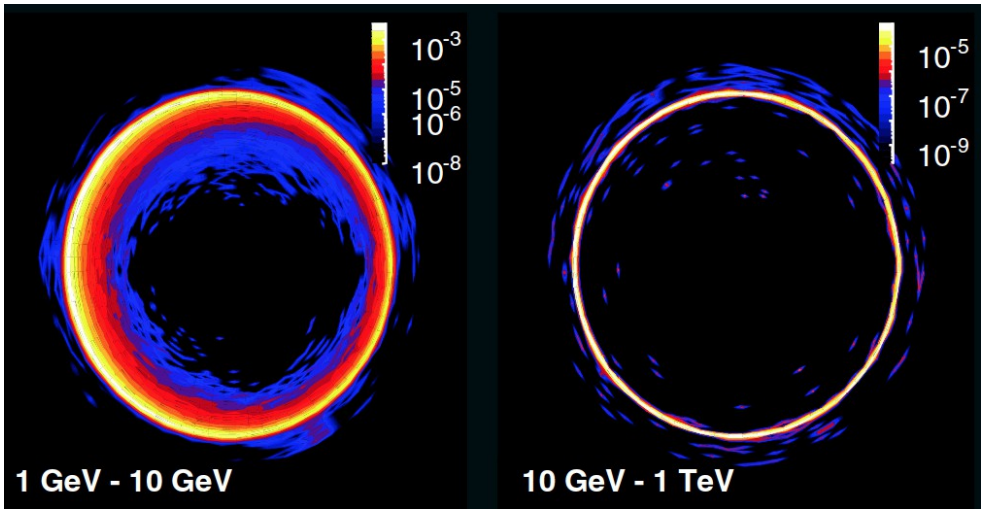
S. Gabici, APC, ICRC2023

$$N_{CR}(E) = Q_{CR}(E) \times \tau(E) \propto E^{-\delta-\alpha}$$

CR-induced γ-ray emission of Earth



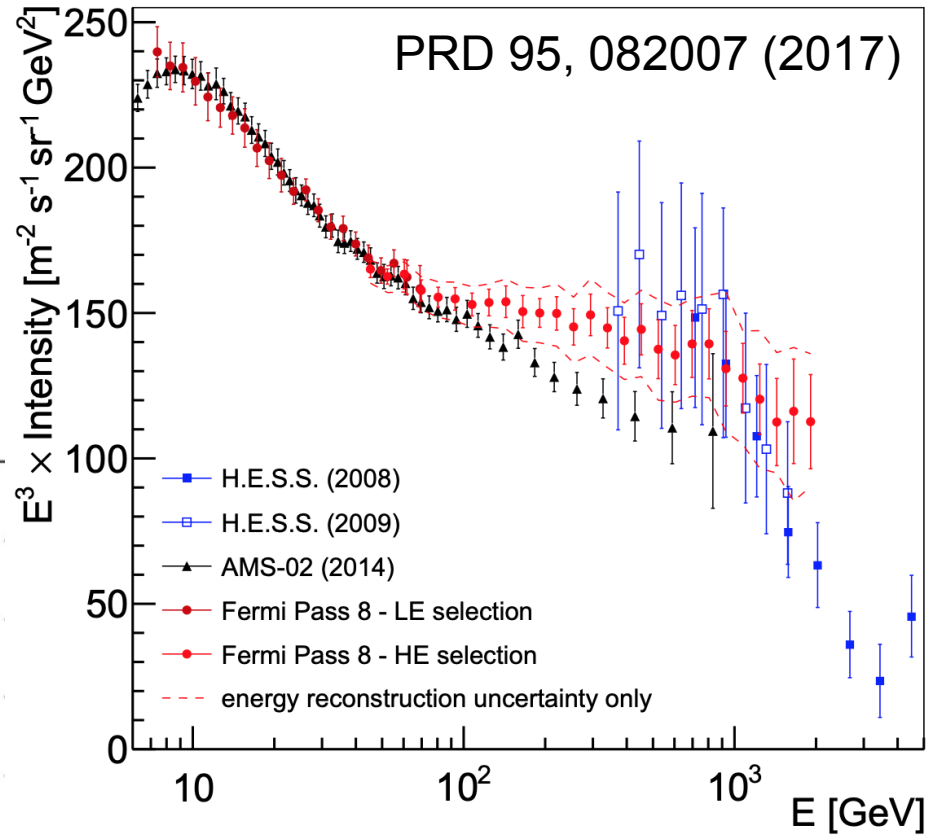




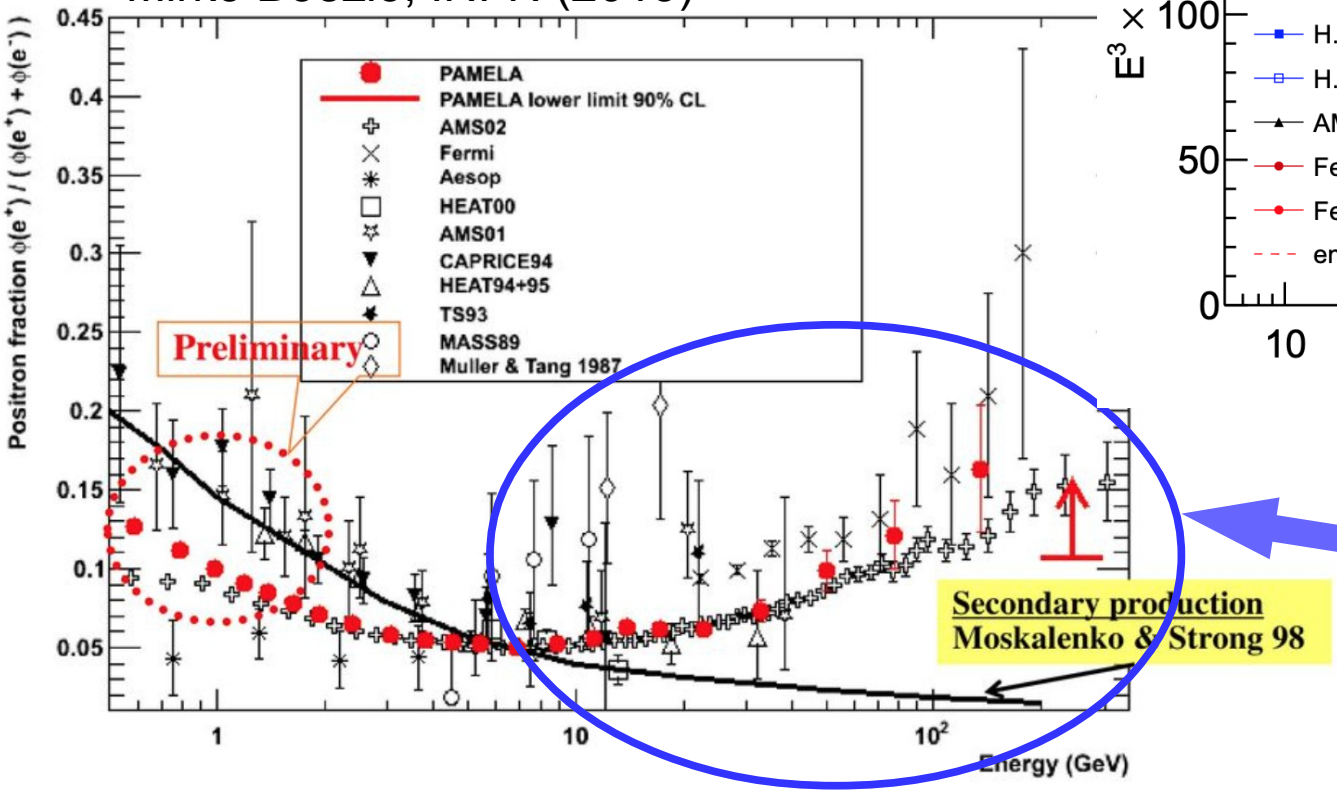
PRD 80, 12004 (2009)

Excess e^+/e^- at high energy

Above ~10 GeV, measurements indicate excess e^+ and e^- above secondary background model



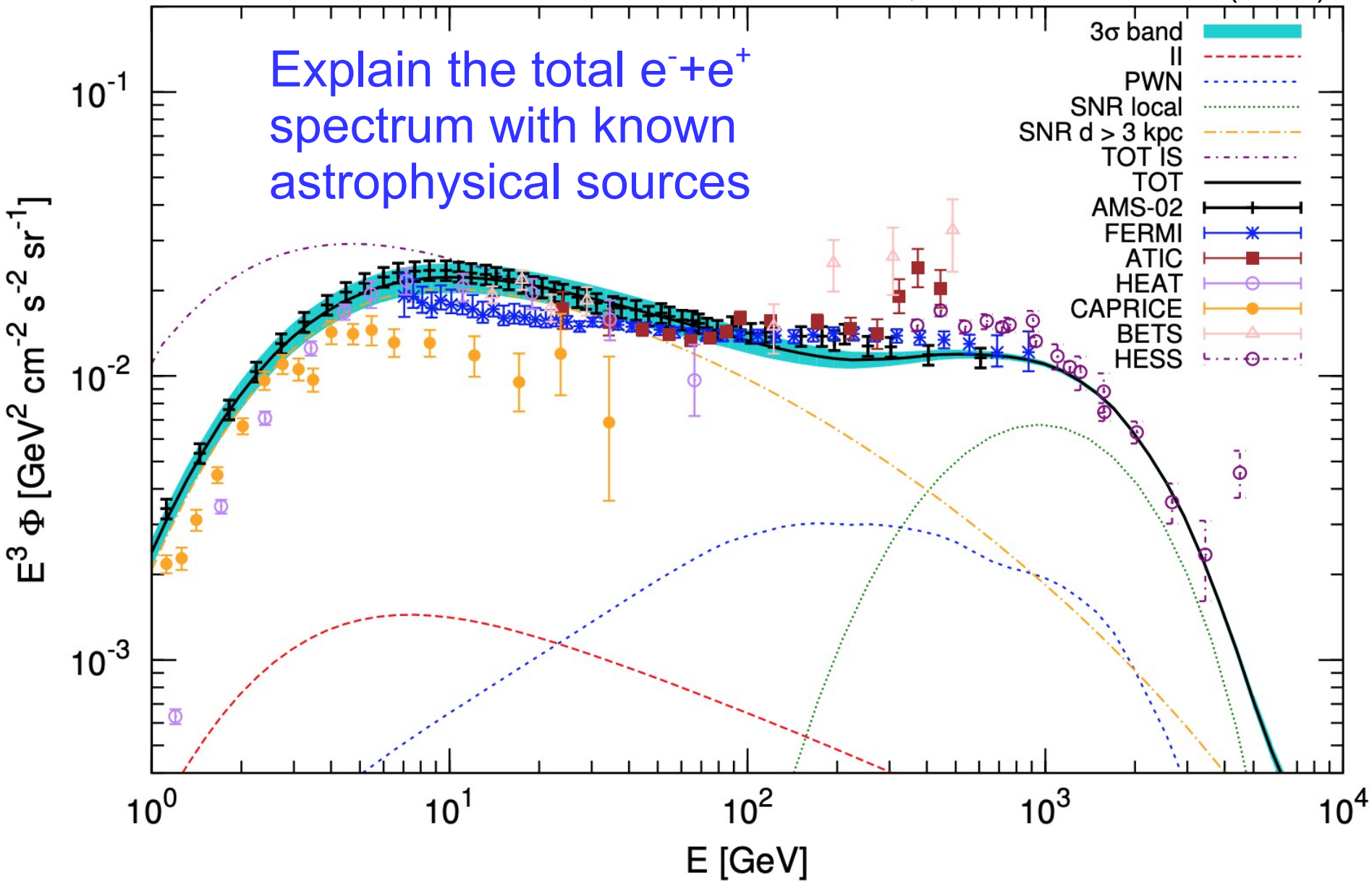
Mirko Boezio, INFN (2013)



Contradicts secondary e^+ model at high energy

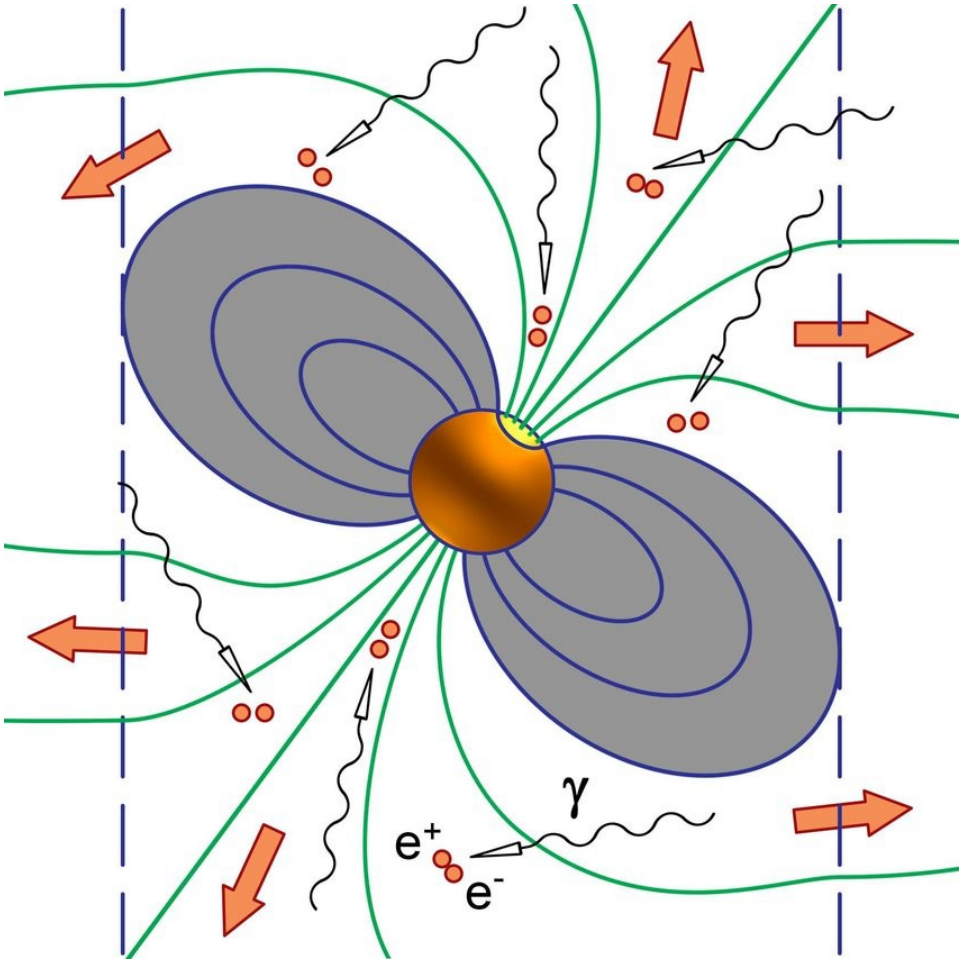
Combined e^-+e^+ spectrum

Di Mauro et al., arXiv:1402.0321v2 (2014)



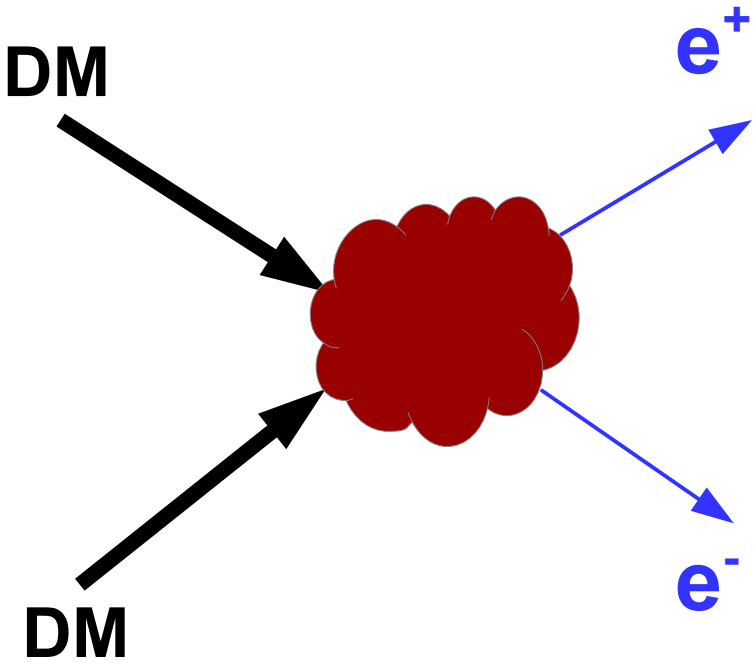
Possible nearby primary e^+ sources

Pulsars



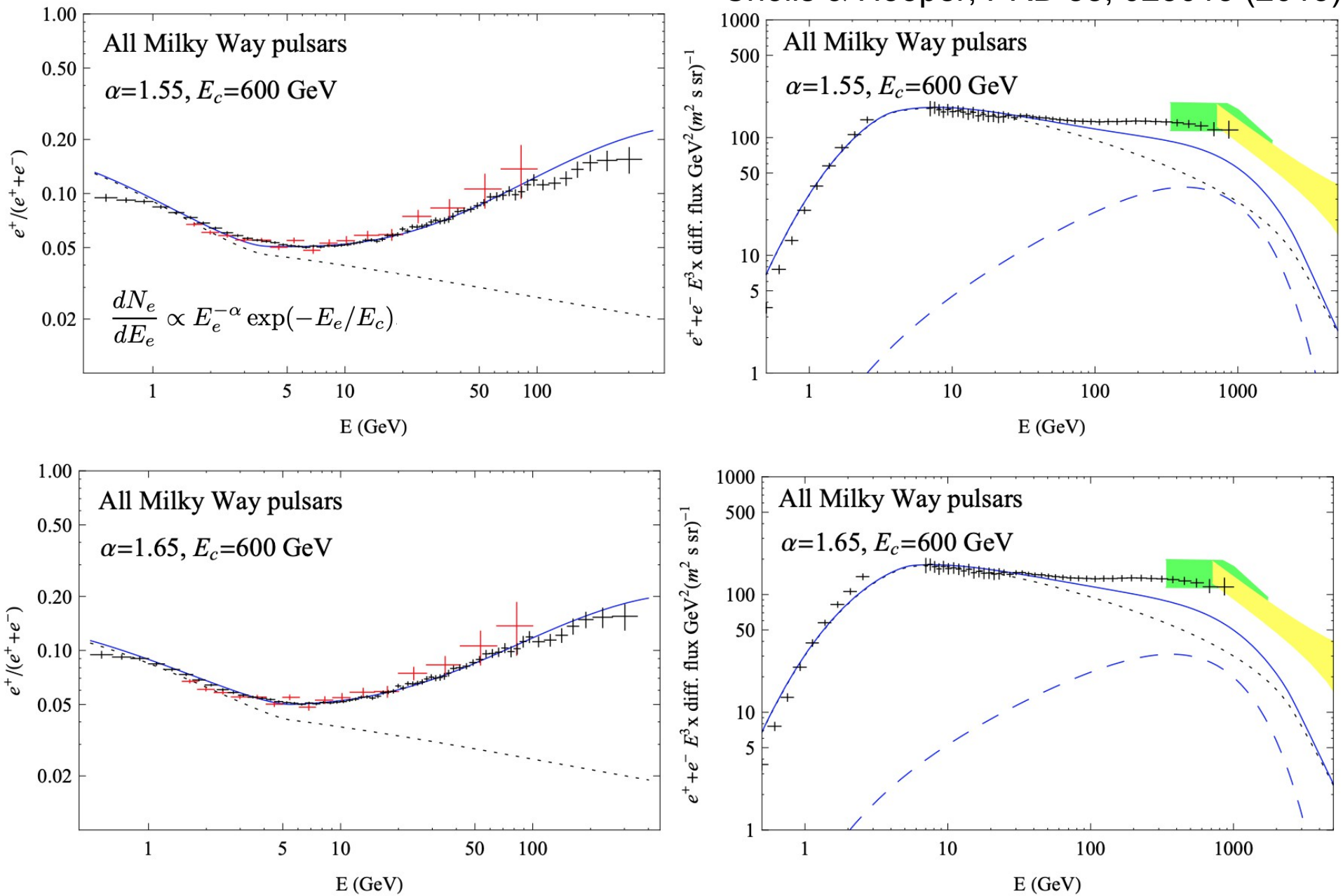
Istomin et al. (2020) arXiv:2007.08287v1

Dark Matter

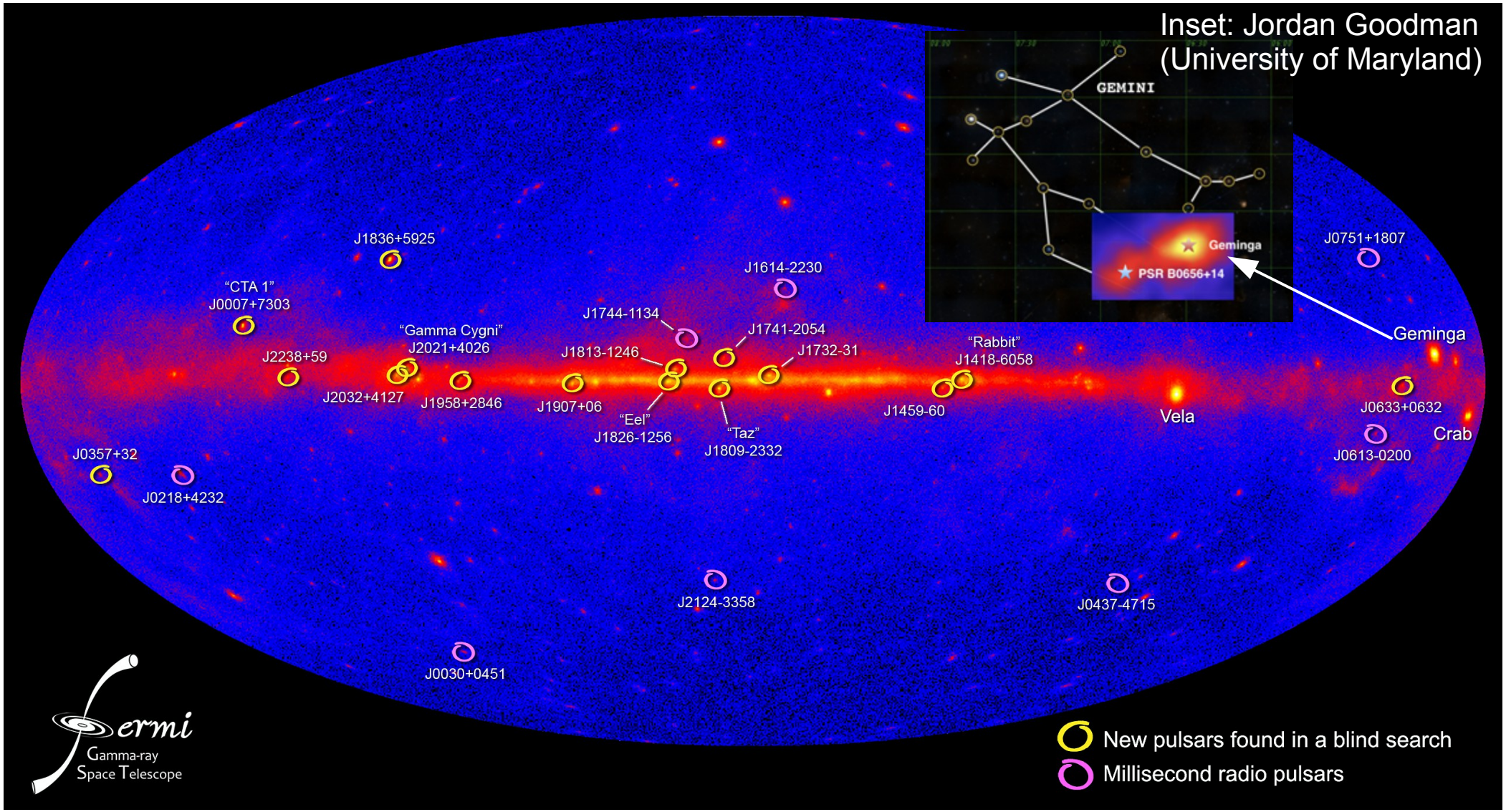


Constrain some parameters of pulsars

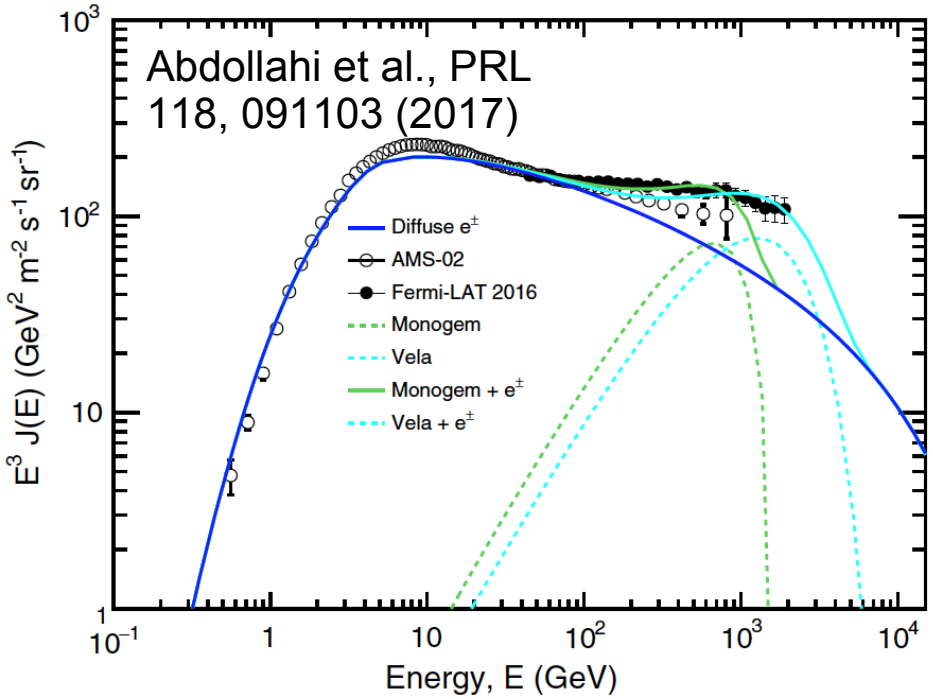
Cholis & Hooper, PRD 88, 023013 (2013)

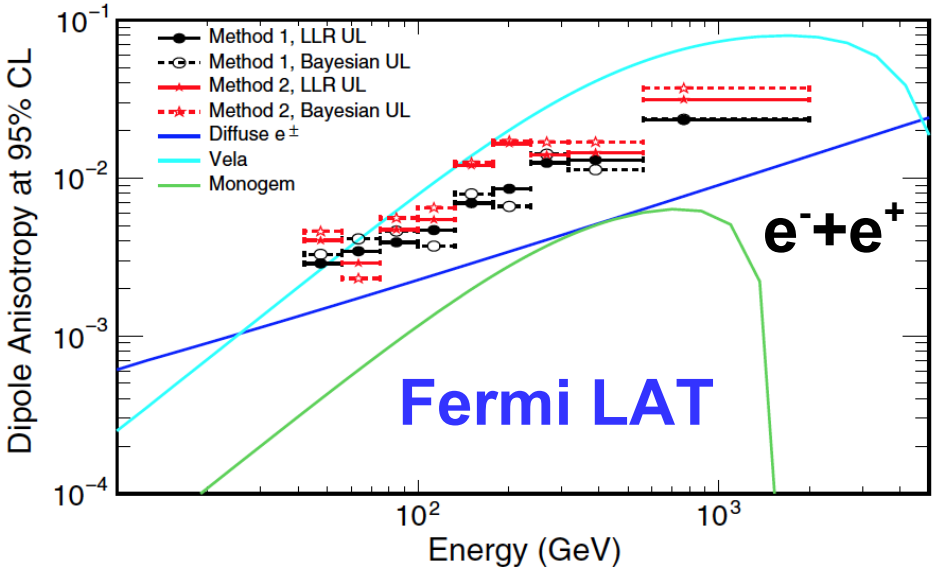


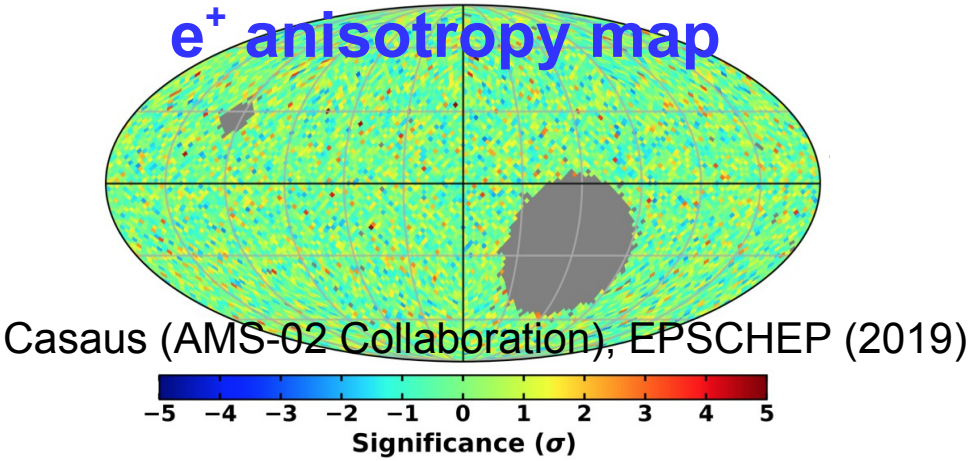
Bright γ-ray pulsars



Anisotropy Measurements



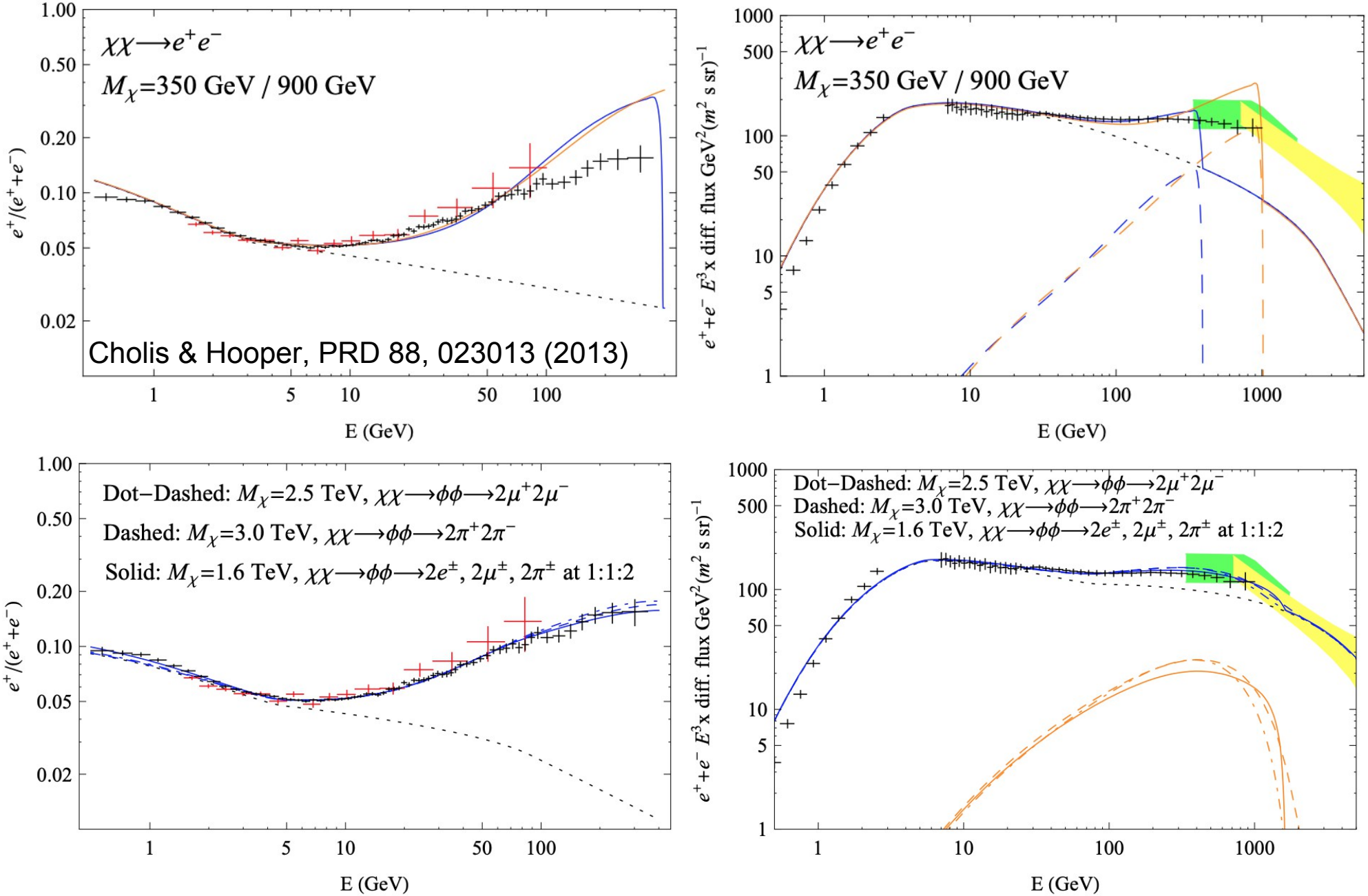




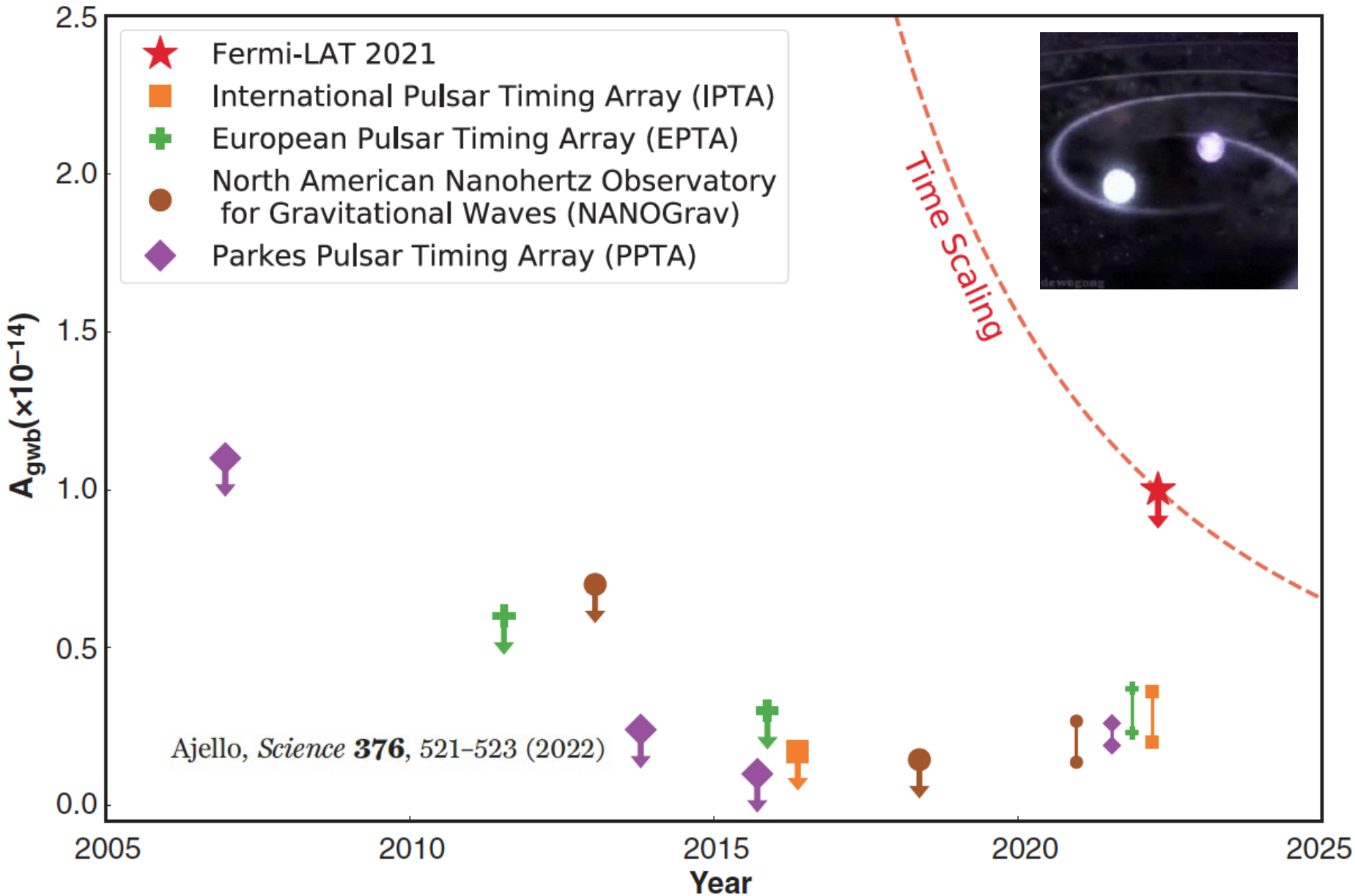
Casaus (AMS-02 Collaboration), EPSCHEP (2019)

- Latest measurements by Fermi LAT and AMS-02 show that CR e^-/e^+ are consistent with being isotropic
- Dipole upper limit by AMS-02 for E > 16 GeV:
  - e^-: $\delta < 0.005$
    PRL 122, 101101 (2019)
  - e^+: $\delta < 0.019$
    PRL 122, 041102 (2019)

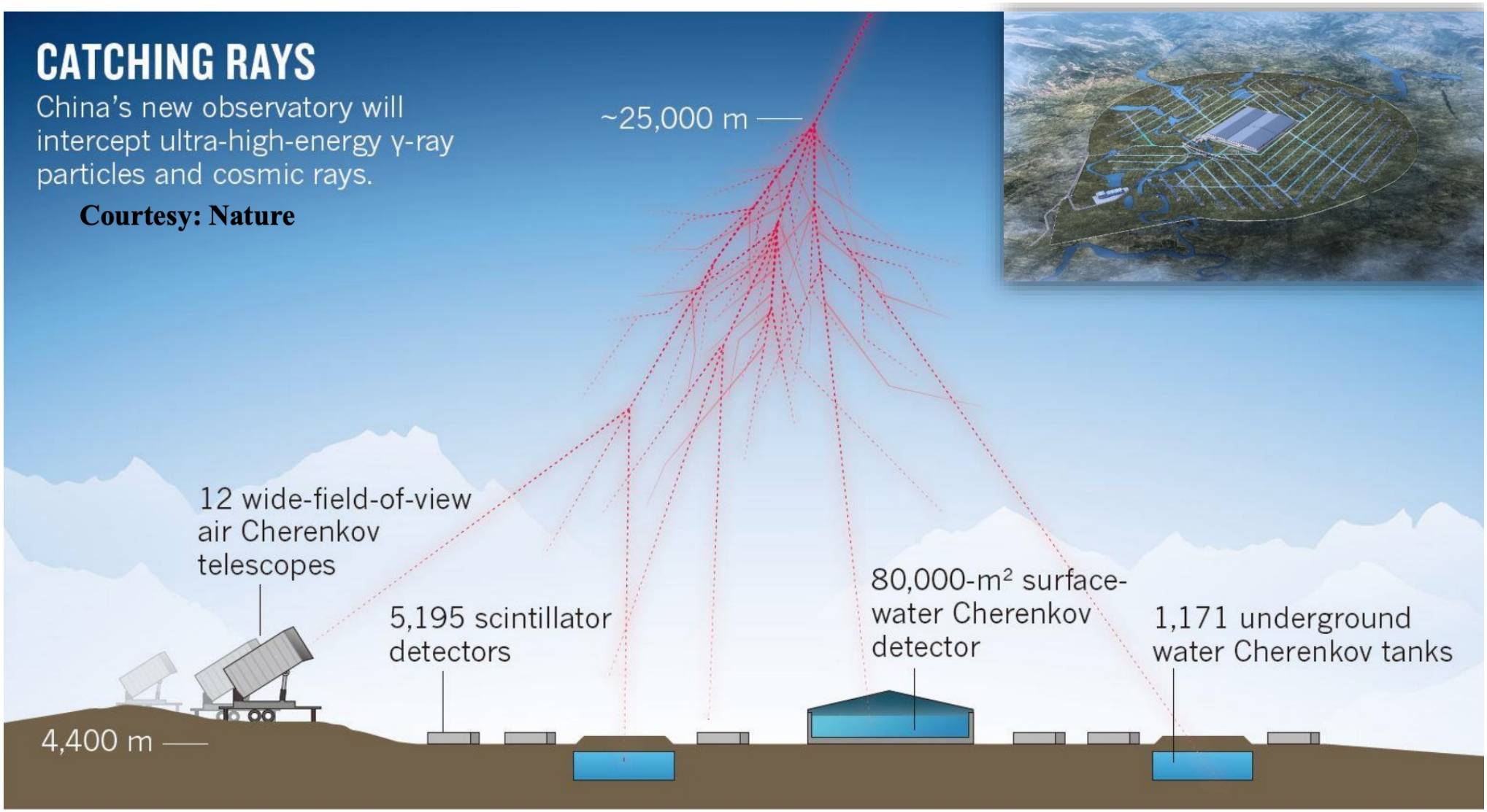
Constrain some parameters of DM



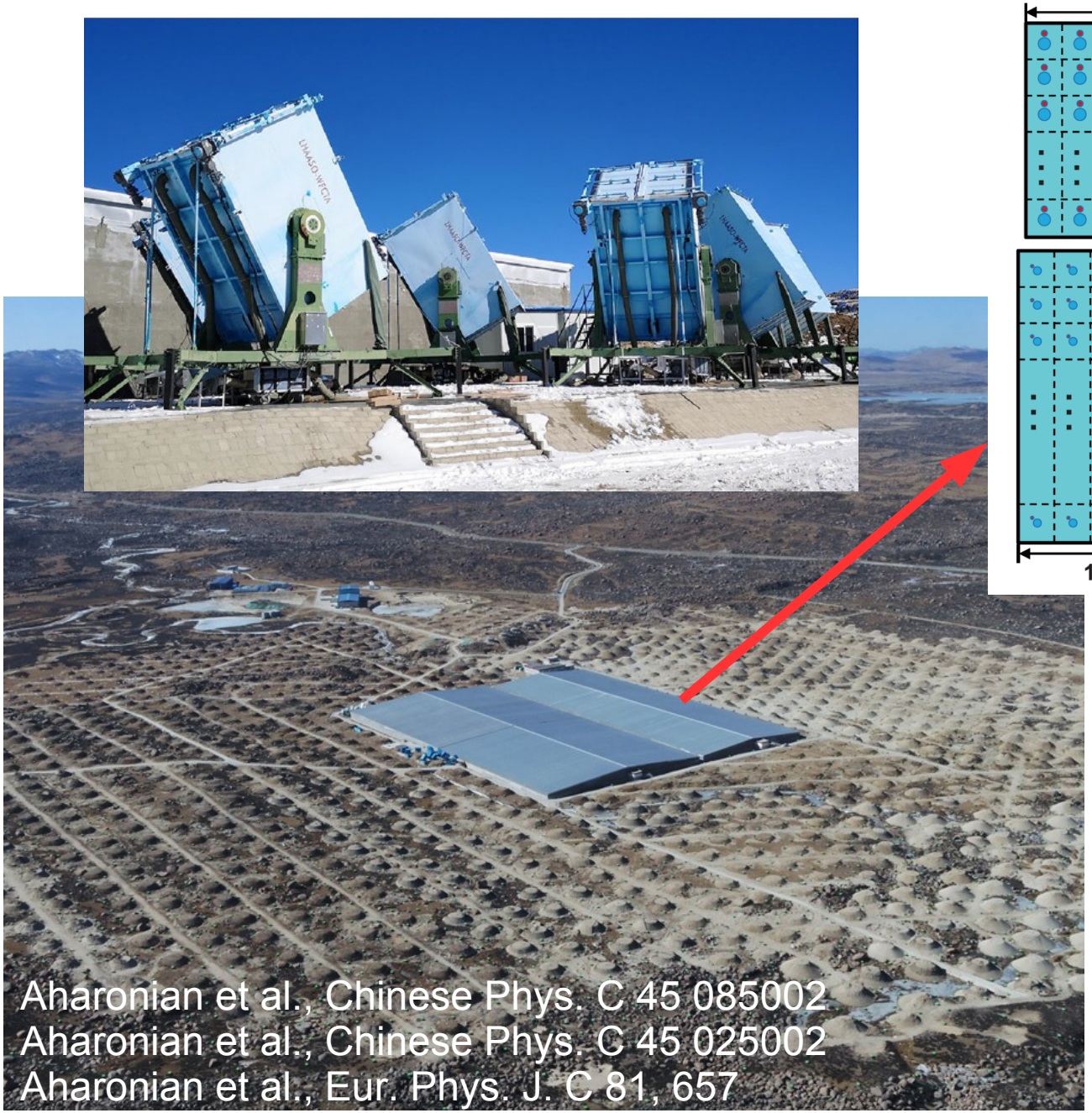
Pulsars and Gravitational Wave Background

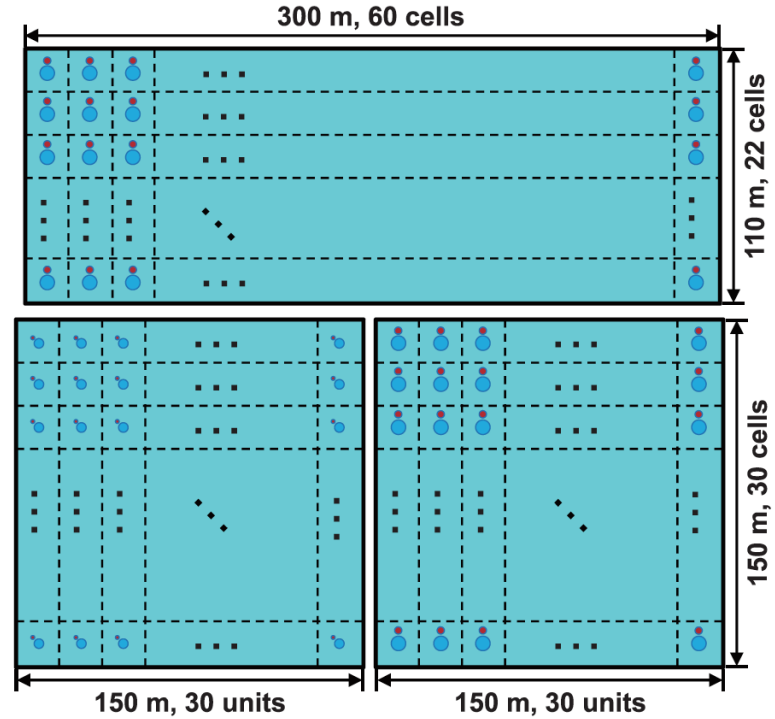


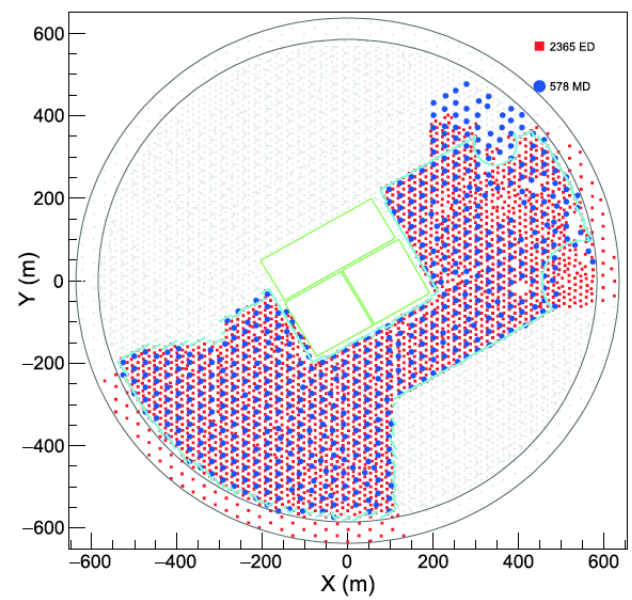
Large High Altitude Air Shower Observatory (LHAASO)



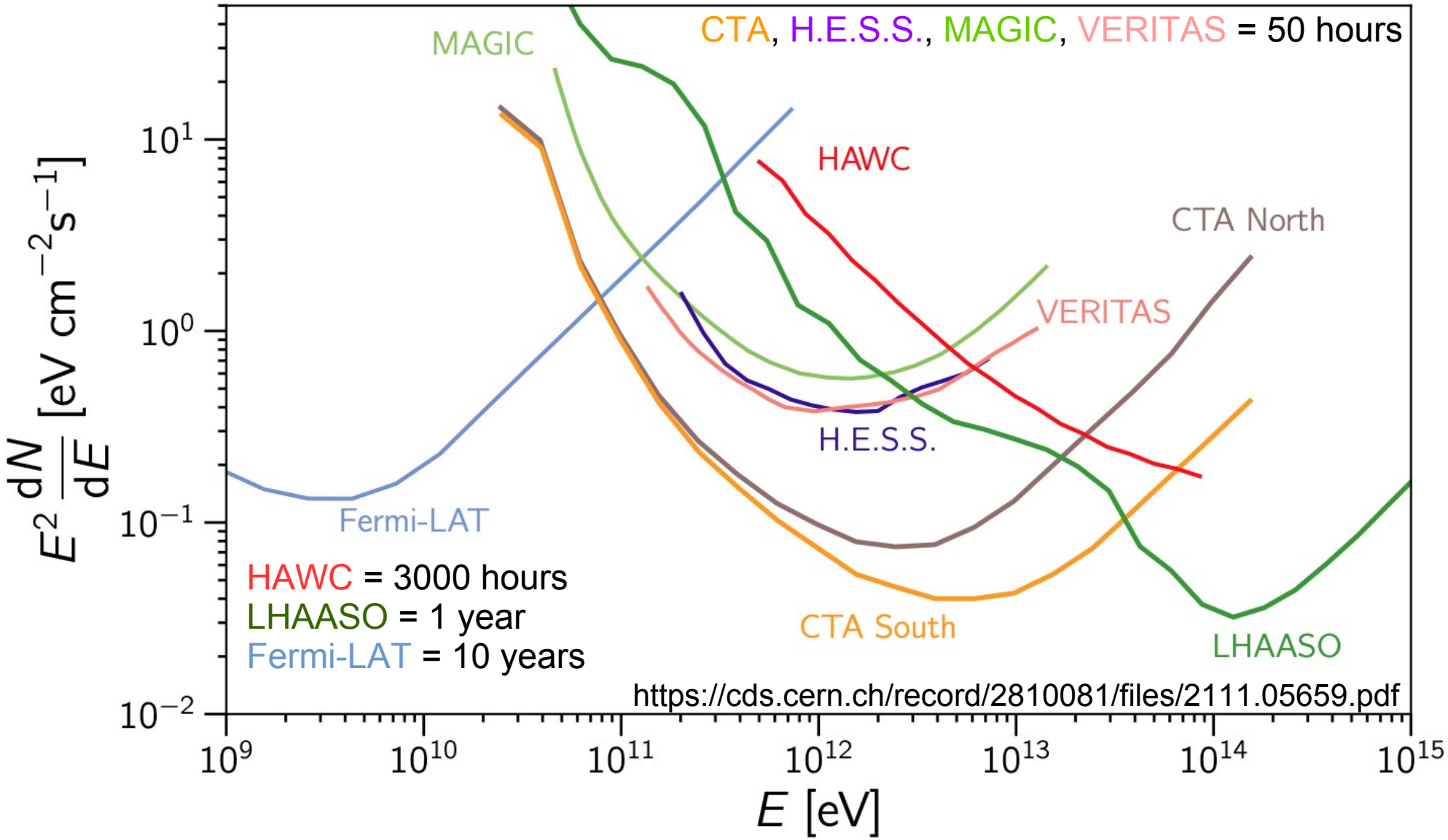
LHAASO


Aharonian et al., Chinese Phys. C 45 085002
Aharonian et al., Chinese Phys. C 45 025002
Aharonian et al., Eur. Phys. J. C 81, 657

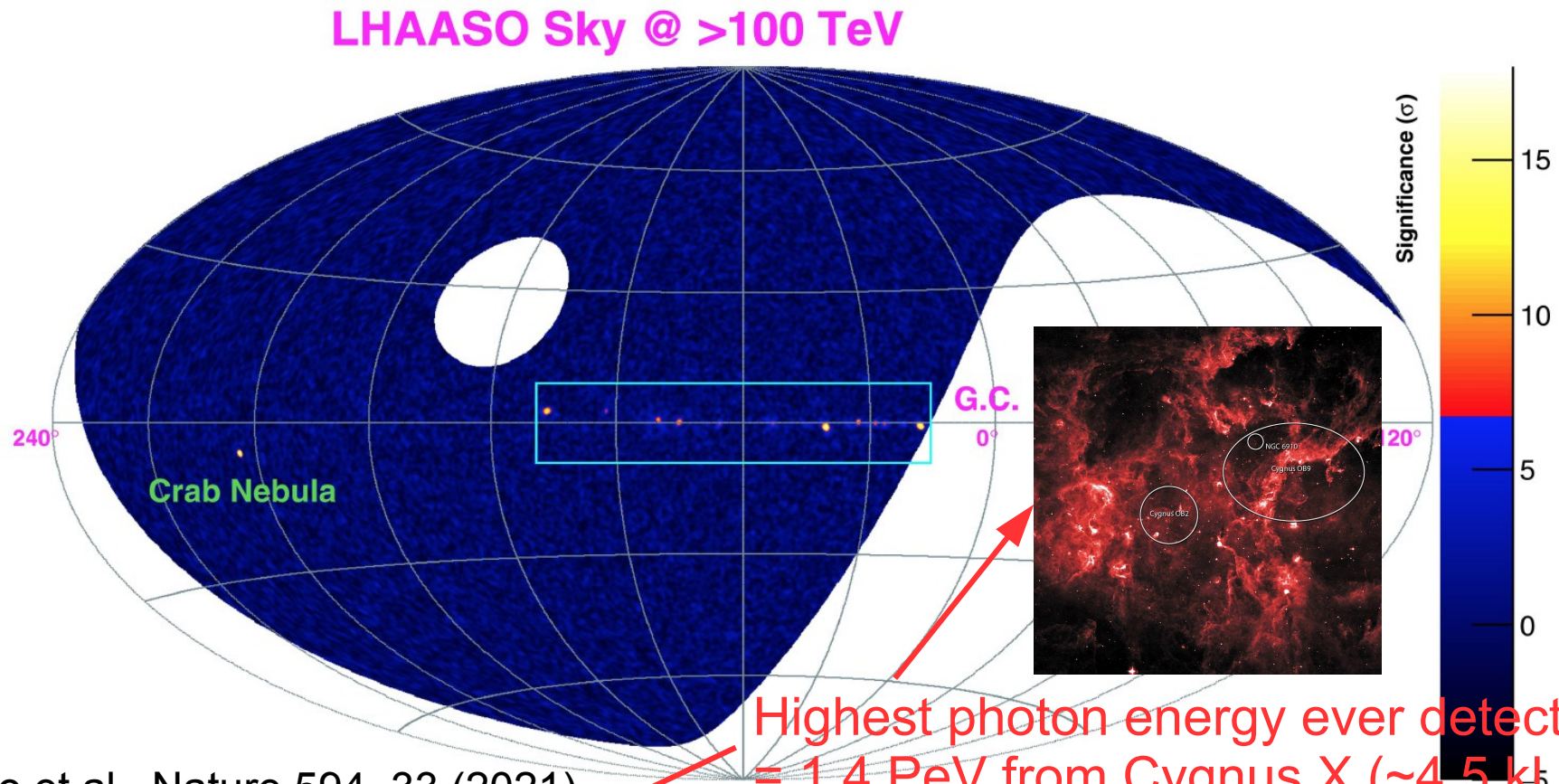

300 m, 60 cells
110 m, 22 cells
150 m, 30 cells
150 m, 30 units
150 m, 30 units


2365 ED
578 MD
Y (m)
X (m)
600
400
200
0
−200
−400
−600

LHAASO and Fermi LAT Energy

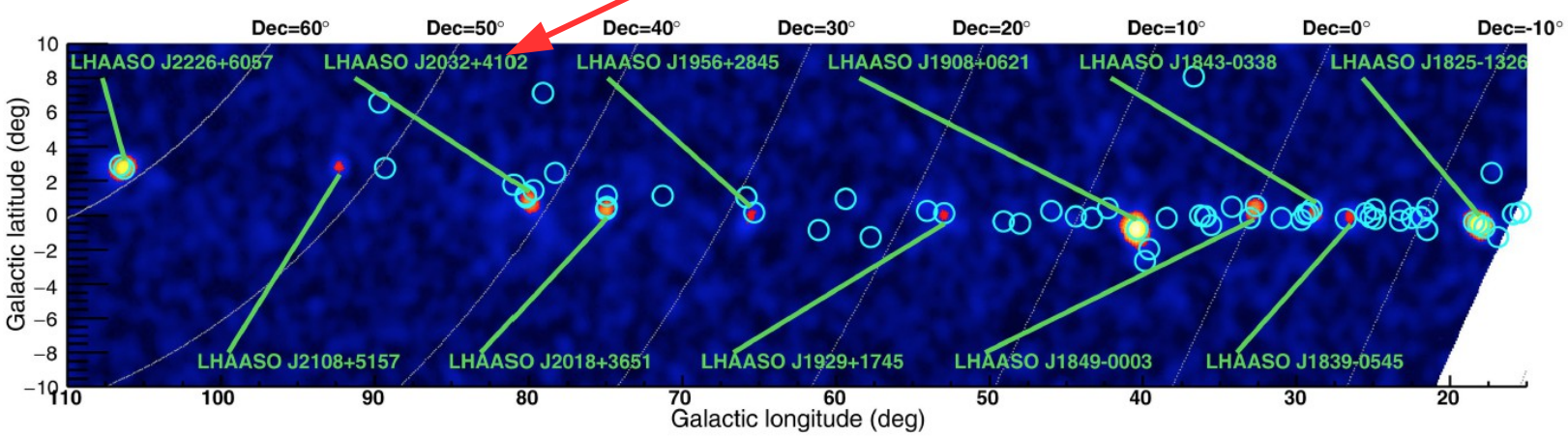


Cosmic "Pevatrons"



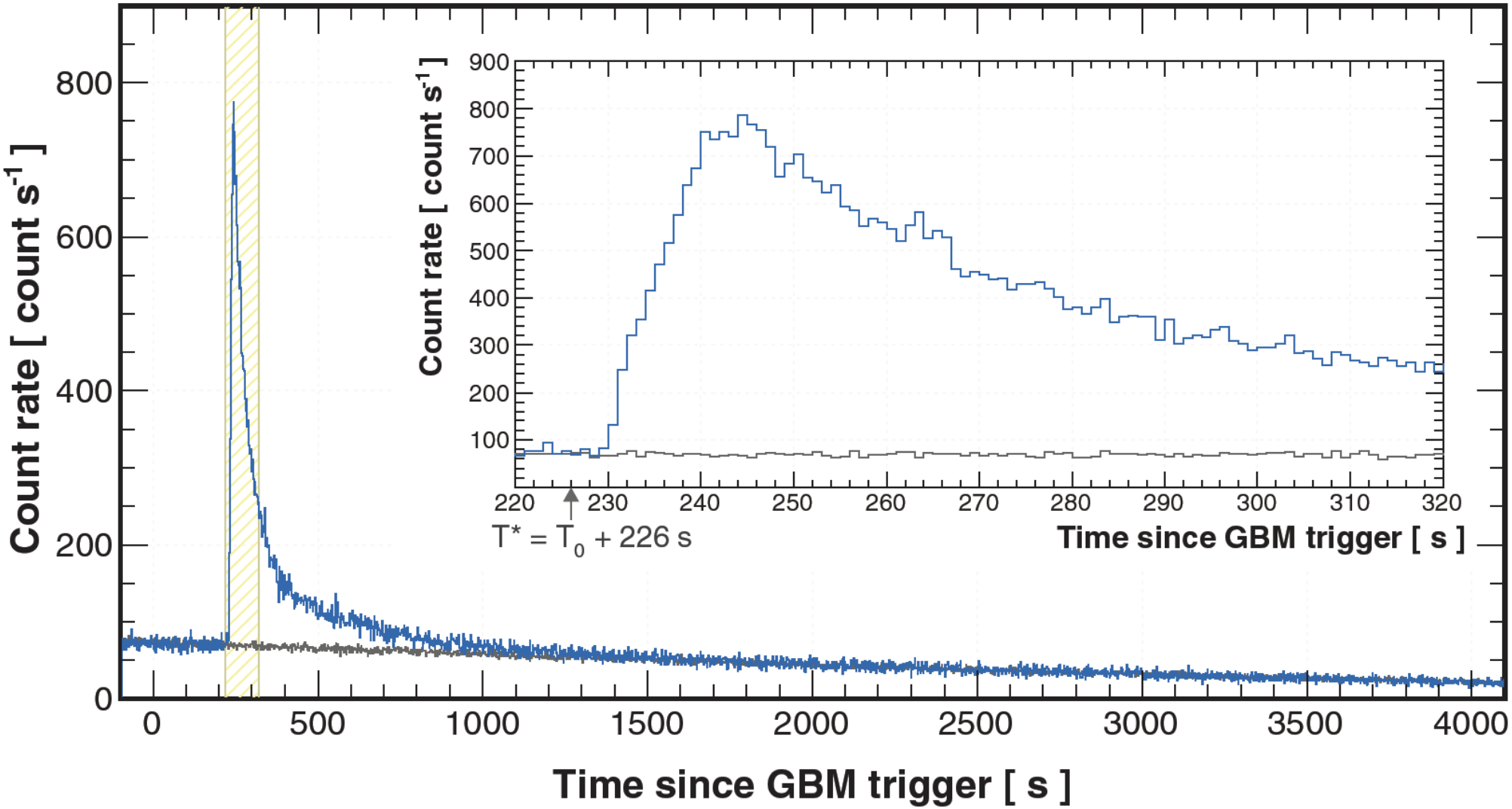
Highest photon energy ever detected
~ 1.4 PeV from Cygnus X (~4.5 kLY)

Cao et al., Nature 594, 33 (2021)



Gamma-Ray Burst GRB221009A

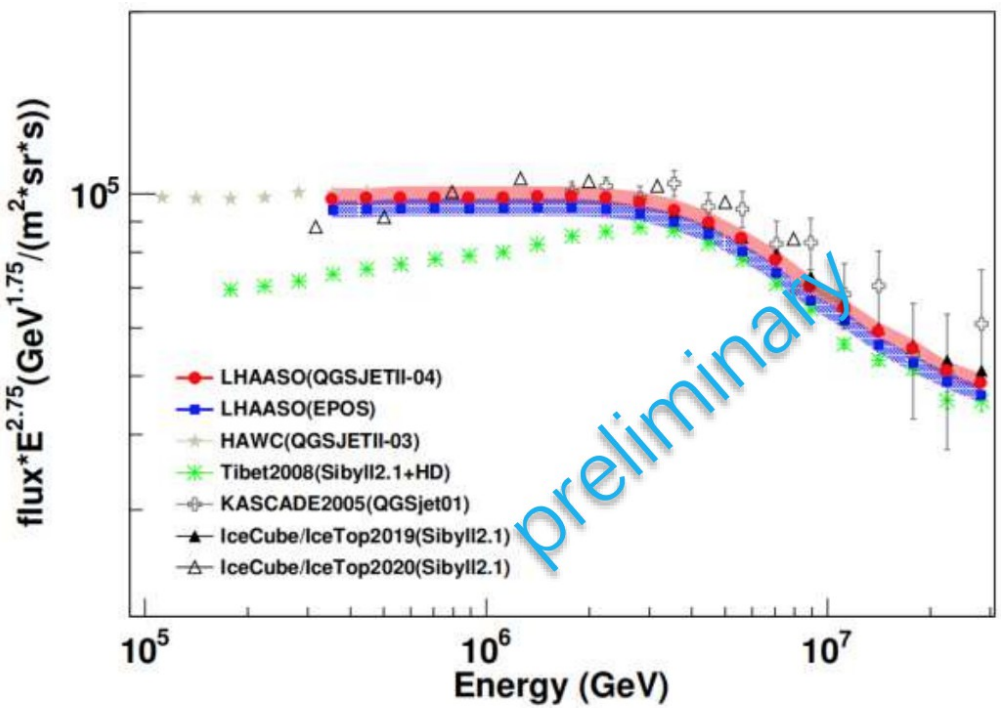
LHAASO Collaboration, *Science* **380**, 1390–1396 (2023)



CR Spectral Measurement (by KM2A)

All-particle energy spectrum of cosmic ray

H. Zhang, et al. (2023), ICRC2023



$$\frac{dJ(E)}{dE} = p_0 \cdot E^{p_2}\left(1+\left(\frac{E}{p_1}\right)^{p_4}\right)^{(p_3-p_2)/p_4}$$

T. Antoni et al., Astropart. Phys. 24, 1 (2005).

$$flux = \frac{\Delta N}{\Delta E * aperture * T}$$

$$\text{stat. err} = \frac{\sqrt{\Delta N}}{\Delta E * aperture * T}$$

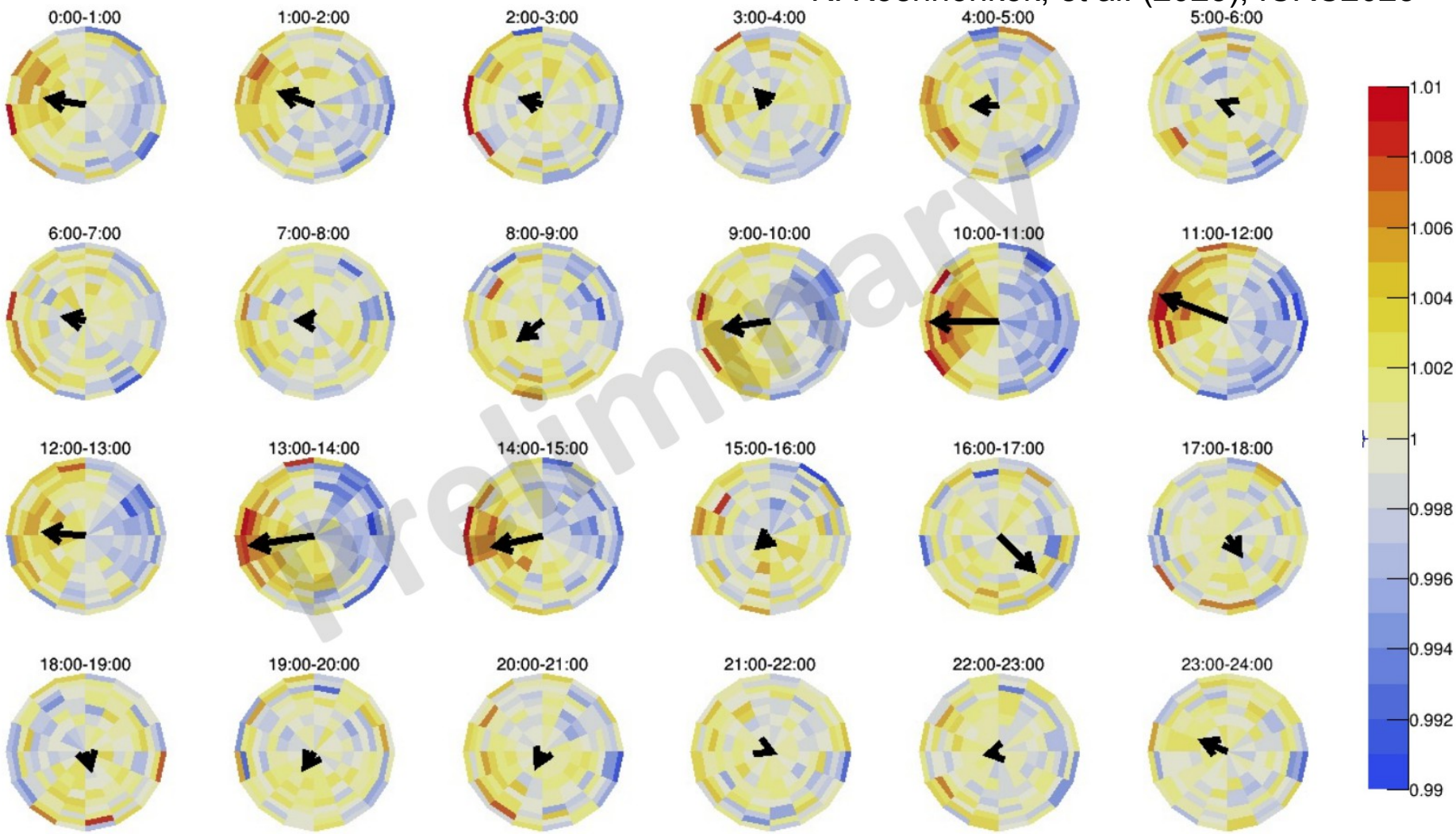
Red dot: 2021.09-2022.12 data measured all-particle energy spectrum of cosmic ray

QGSJETII-04	EPOS-LHC
Knee: 3.72±0.05 PeV	Knee: 3.62±0.05 PeV
γ_1=−2.743 ± 0.0004	γ_1=−2.743 ± 0.0004
γ_2=- −3.131 ± 0.005	γ_2=- −3.130 ± 0.005
Sharpness=4.1 ± 0.1	Sharpness=4.2 ± 0.1

Shadow band: systematic uncertainty

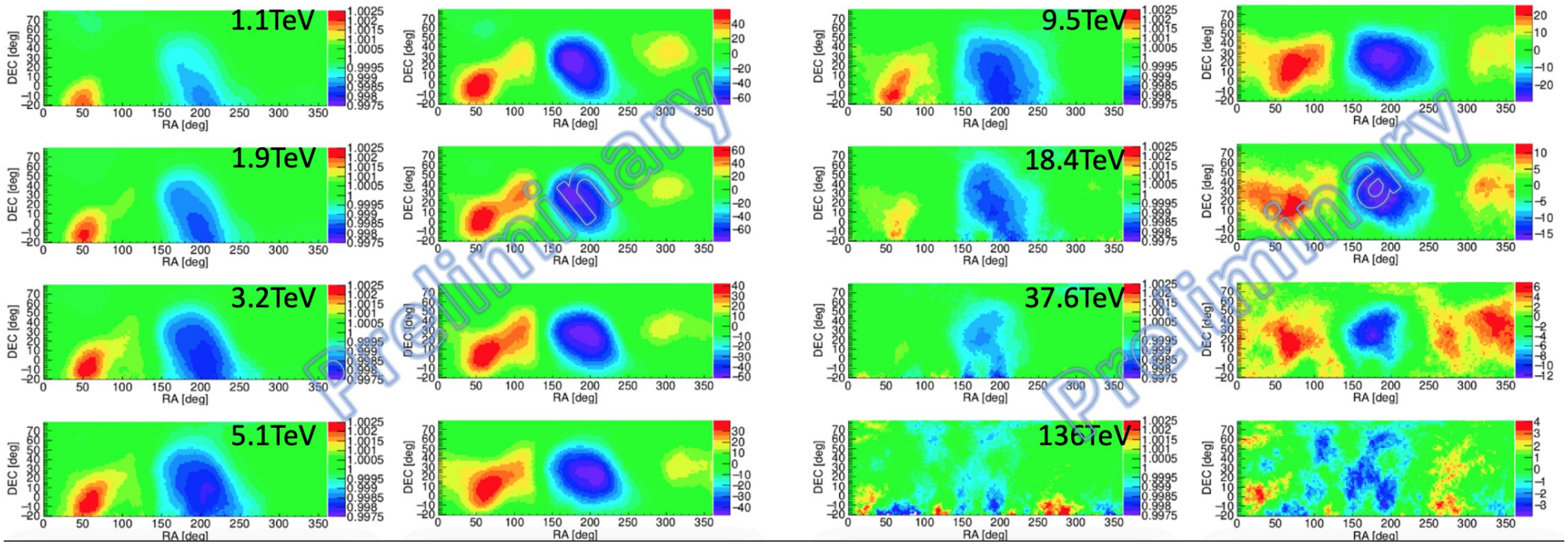
CR Anisotropy from Solar Storm

K. Koennonkok, et al. (2023), ICRC2023



Preliminary hourly WCDA skymaps centered at the zenith direction, out to a zenith angle of 45 degrees (outer circle), for $30 < N_{hit} < 100$ for each hour UT of 2021 Nov 4

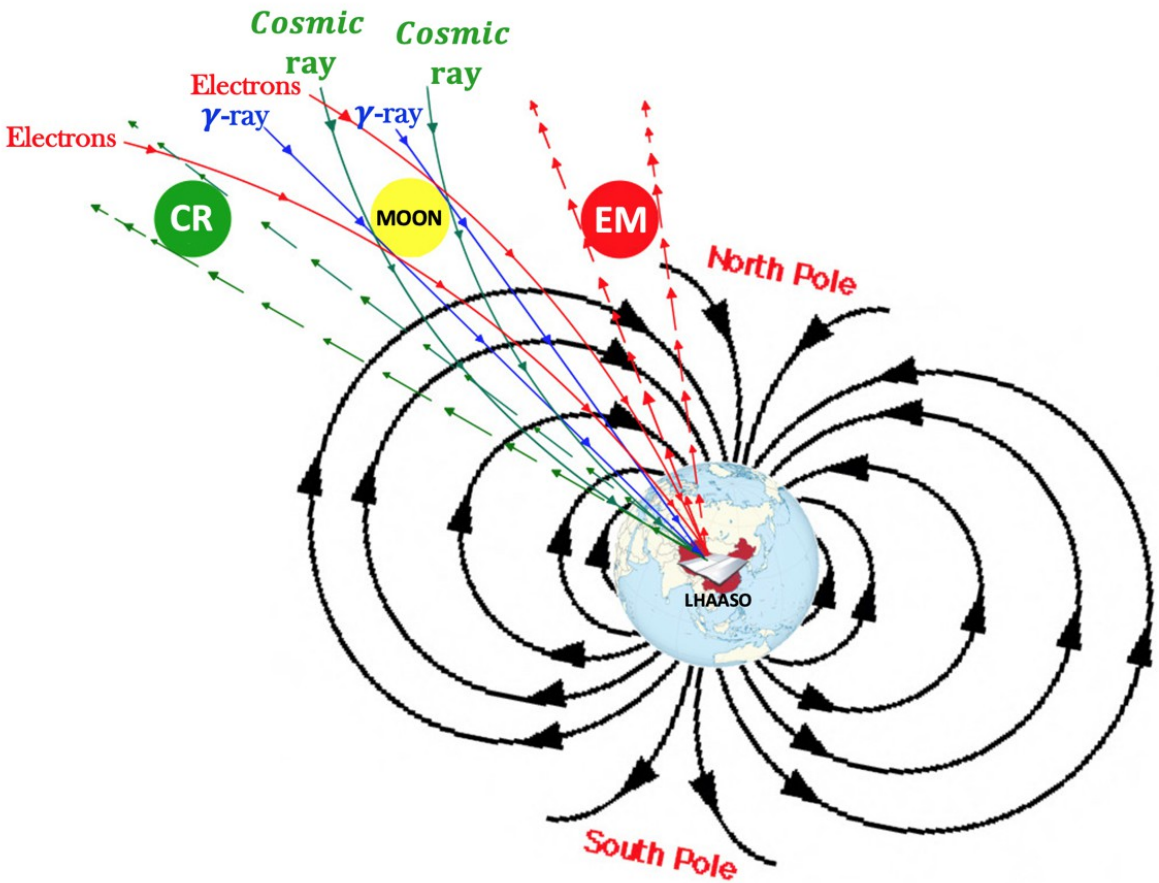
Sidereal Anisotropy from LHAASO-WCDA

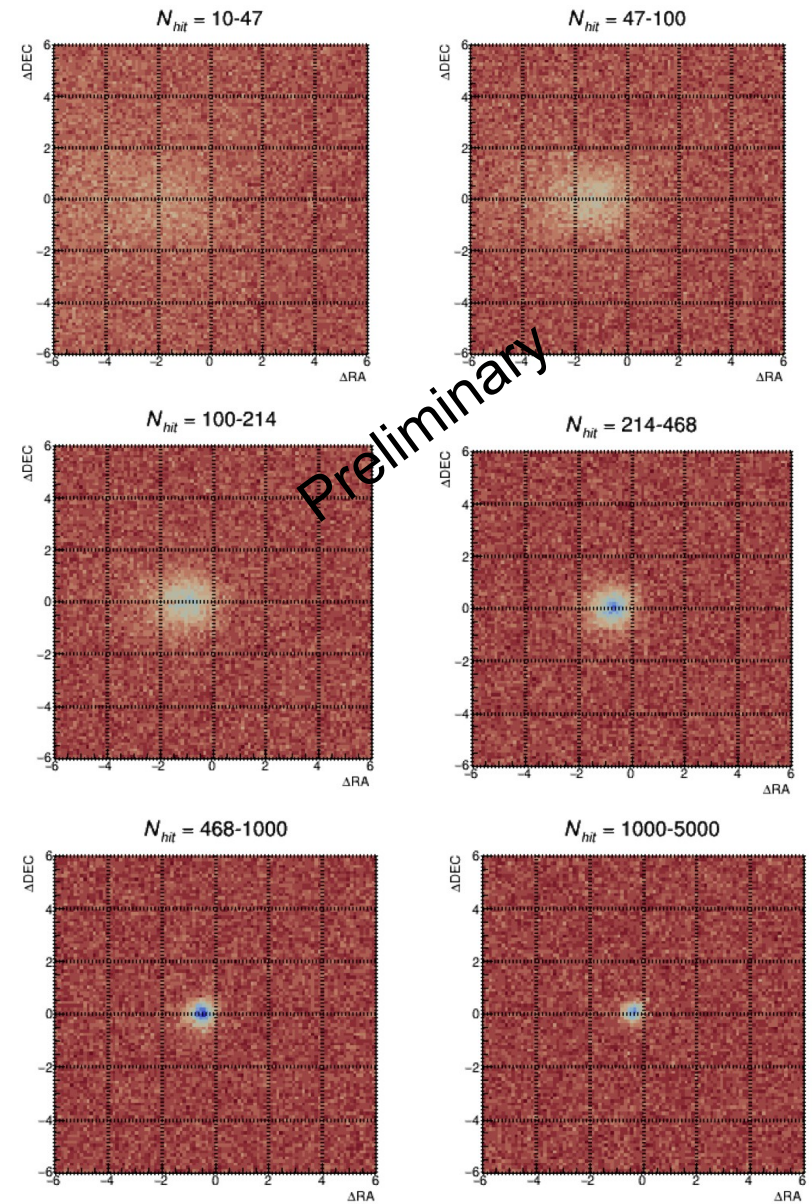


W. Liu, et al. (2023), ICRC2023

- Challenging to model
- Patterns do not vary much with energy
- May need to use KM2A data for E > 100 TeV

CR Moon shadow

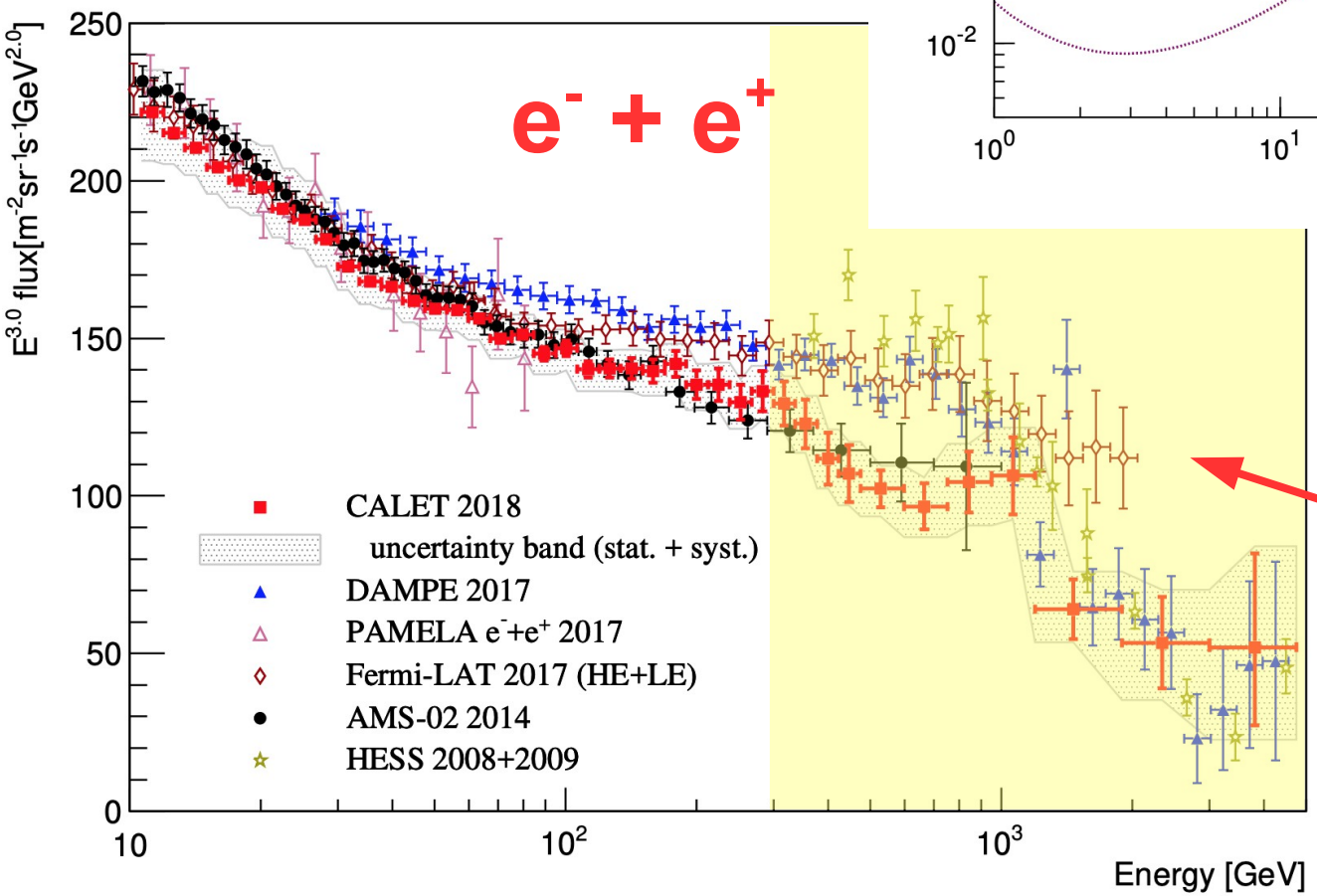


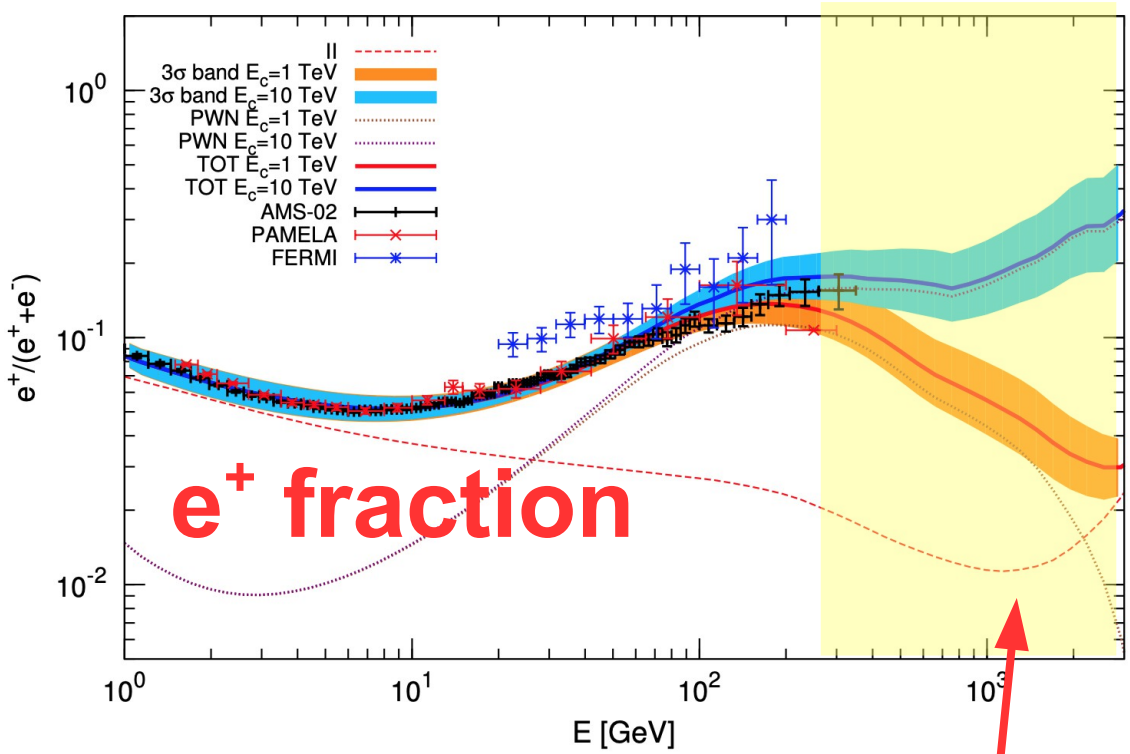


J. Maburee, et al. (2023), submitted to SPC2023

Latest Results on e^+/e^-

Adriani et al. (CALET Collaboration), PRL 120, 261102 (2018)

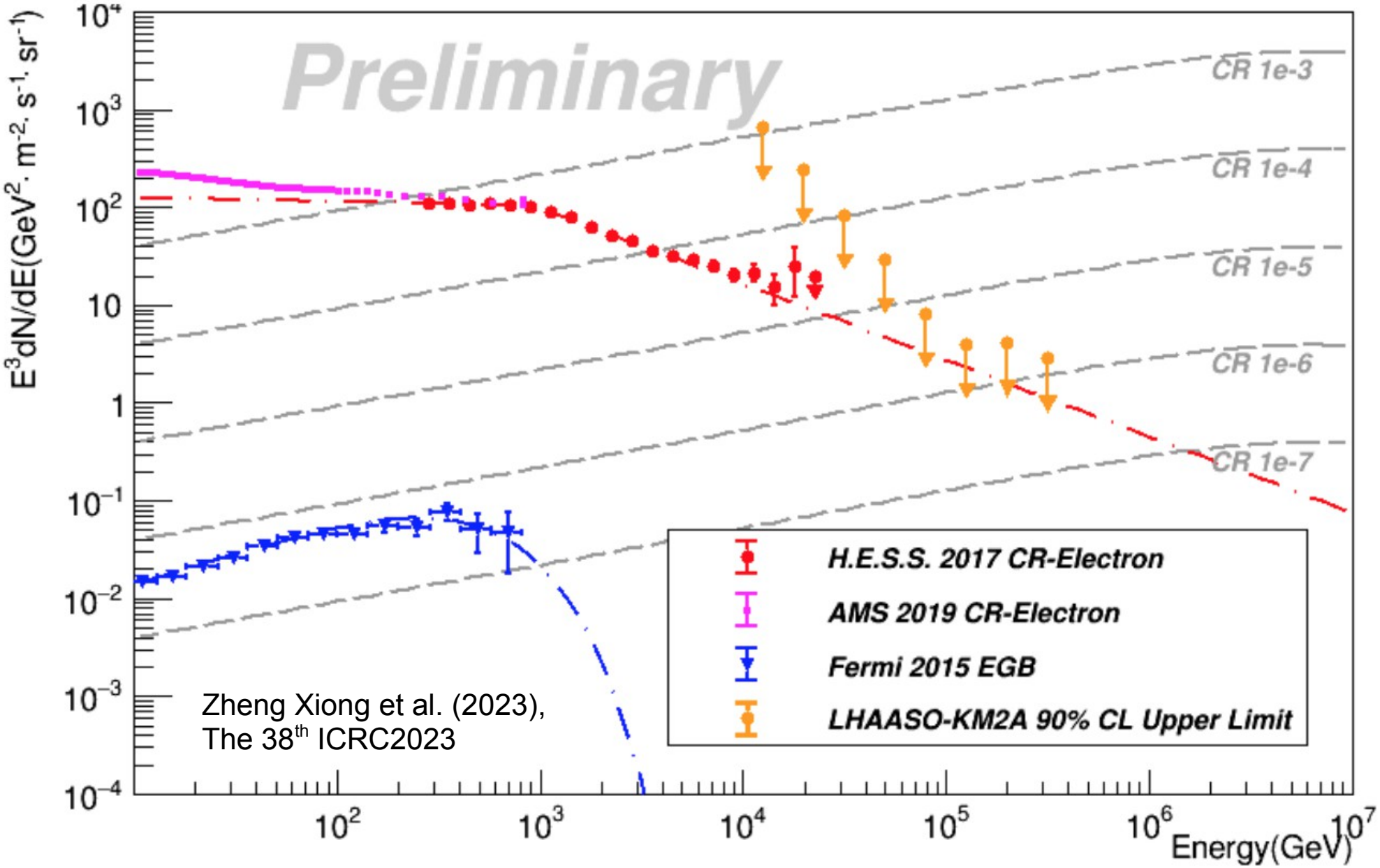




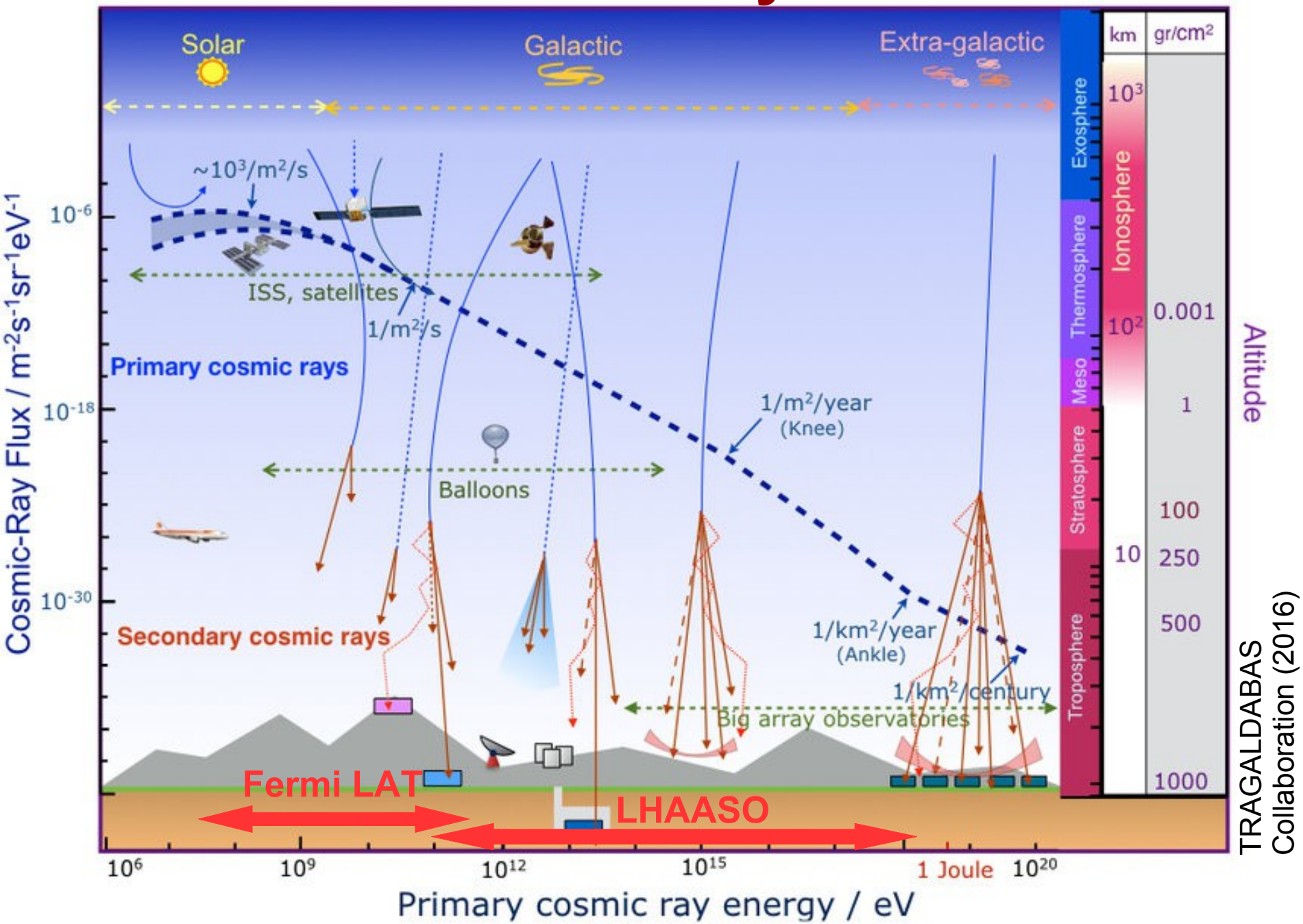
Di Mauro et al., arXiv:1402.0321v2 (2014)

Can LHAASO measure the e^+/e^- around 0.3 – 3 TeV?

Not yet...

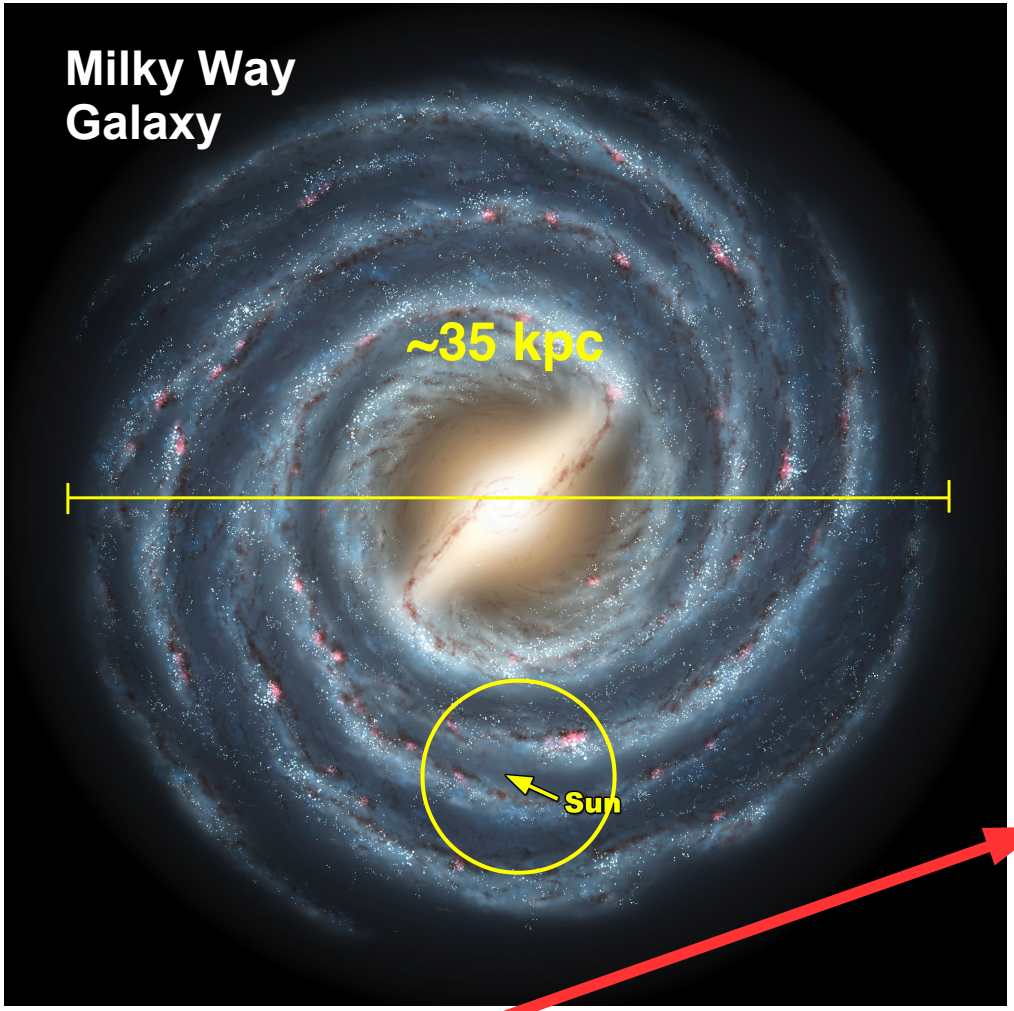

Preliminary
CR 1e-3
CR 1e-4
CR 1e-5
CR 1e-6
CR 1e-7
H.E.S.S. 2017 CR-Electron
AMS 2019 CR-Electron
Fermi 2015 EGB
LHAASO-KM2A 90% CL Upper Limit
Zheng Xiong et al. (2023),
The 38th ICRC2023
E3dN/dE(GeV2. m-2. s-1. sr-1)
Energy(GeV)

Summary


Solar
Galactic
Extra-galactic
~10³/m²/s
ISS, satellites
1/m²/s
Primary cosmic rays
1/m²/year
(Knee)
Balloons
Secondary cosmic rays
1/km²/year
(Ankle)
1/km²/century
Big array observatories
Fermi LAT
LHAASO
Cosmic-Ray Flux / m⁻²s⁻¹sr⁻¹eV⁻¹
10⁻⁶
10⁻¹⁸
10⁻³⁰
10⁶
10⁹
10¹²
10¹⁵
1 Joule
10²⁰
Primary cosmic ray energy / eV
Exosphere
Thermosphere
Meso
Stratosphere
Troposphere
Ionosphere
km
gr/cm²
10³
10²
10
0.001
1
100
250
500
1000
Altitude
TRAGALDABAS
Collaboration (2016)

Back Up

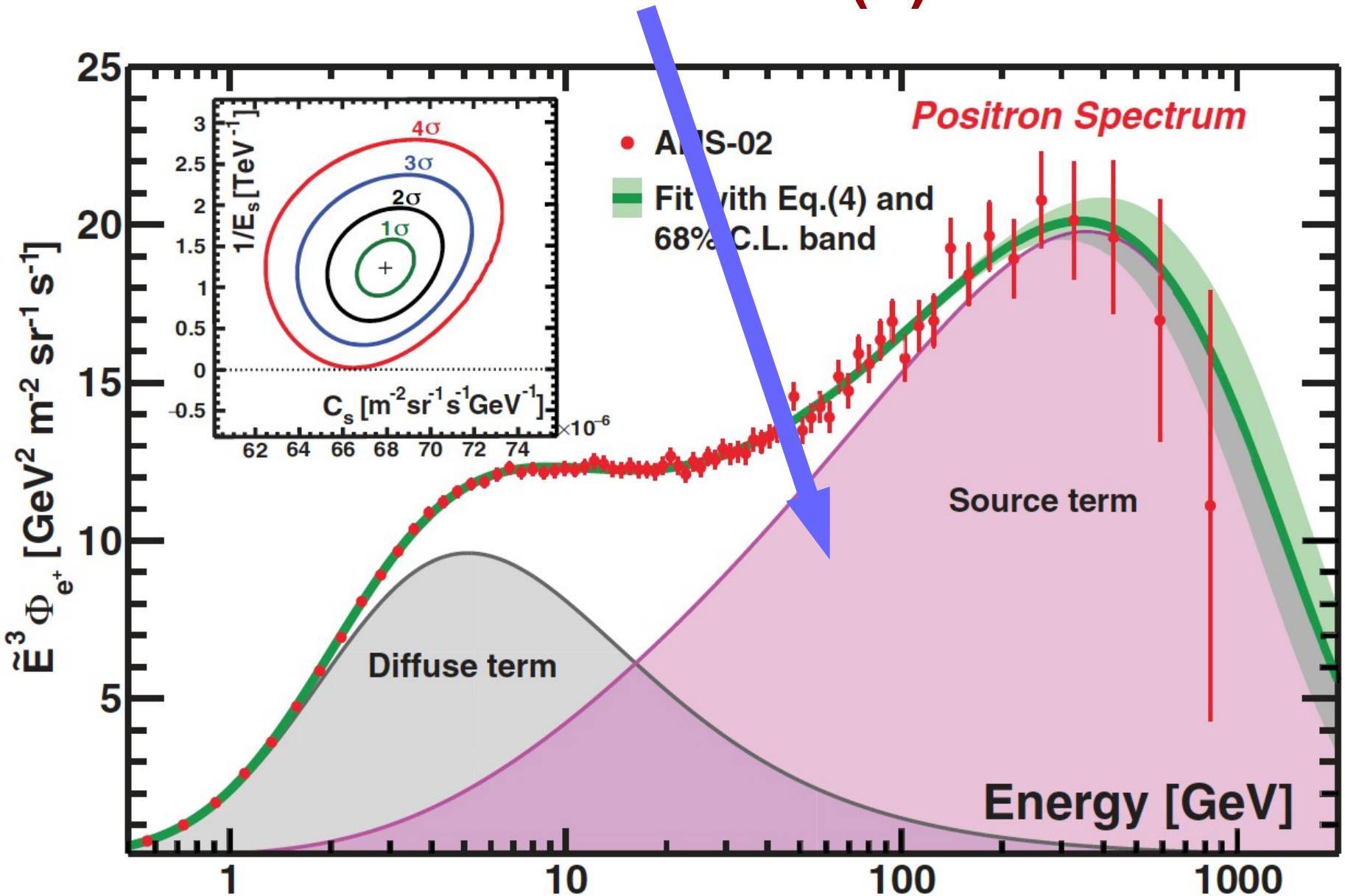
CR electrons (e^-) and positrons (e^+)



- CR = ~1% e^-, ~0.1% e^+
- High-energy e^-/e^+ lose energy rapidly → great probe of local (a few kpc) universe
- Spectral index (~3.1) much softer than proton (~2.7)
- e^+ created through e^-/e^+ pair, so if e^-/e^+ have the same origin, we expect positron fraction $e^+/(e^-+e^+)$ ~ 0.5
- Measured $e^+/(e^-+e^+)$ ~ 0.05 at 10 GeV, implying that e^+ are mostly secondary while e^- are mostly primary

This model predicts decreasing $e^+/(e^-+e^+)$ with energy

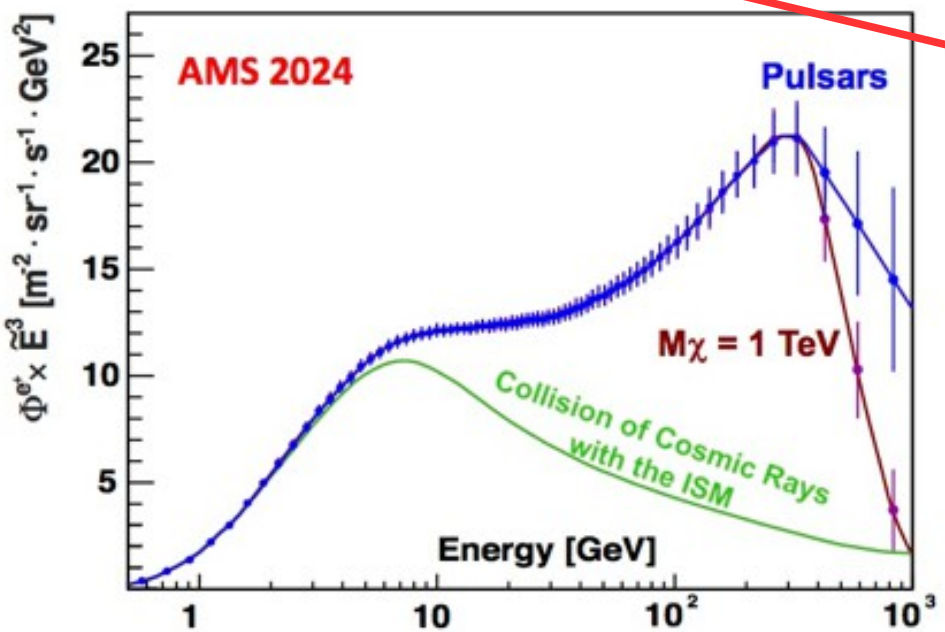
Additional source(s) of e^+



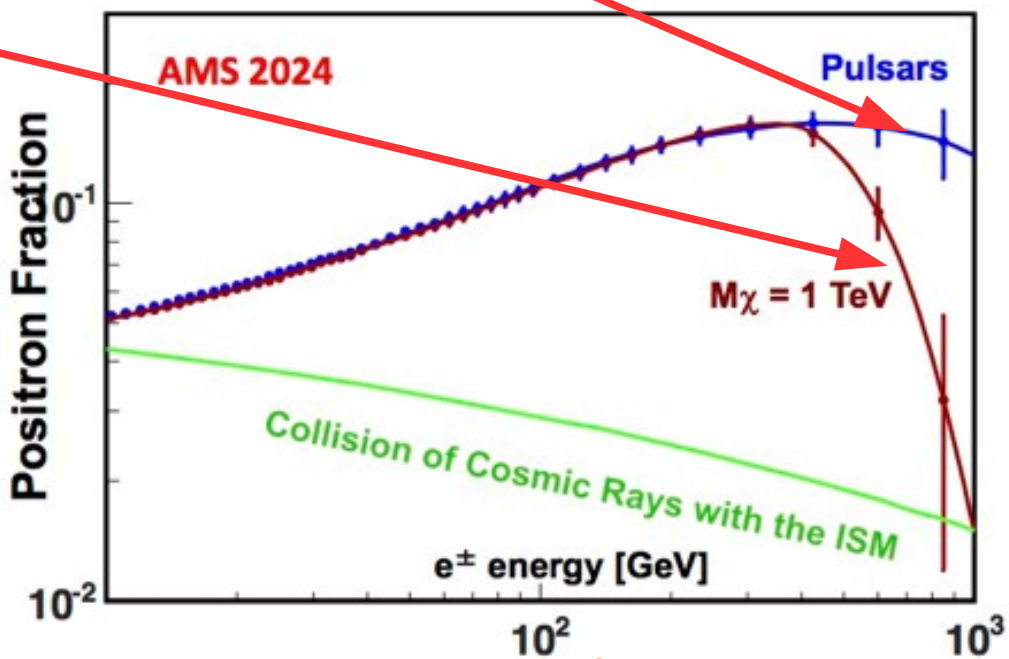
Aguilar et al. (AMS-02 Collaboration), PRL 122, 041102 (2019)

Known (pulsars) vs new (DM) physics

Some models suggest that $e^+/(e^-+e^+)$ at high energy exhibits sharp cutoff for dark matter and gradual decline for pulsars



Positron spectrum

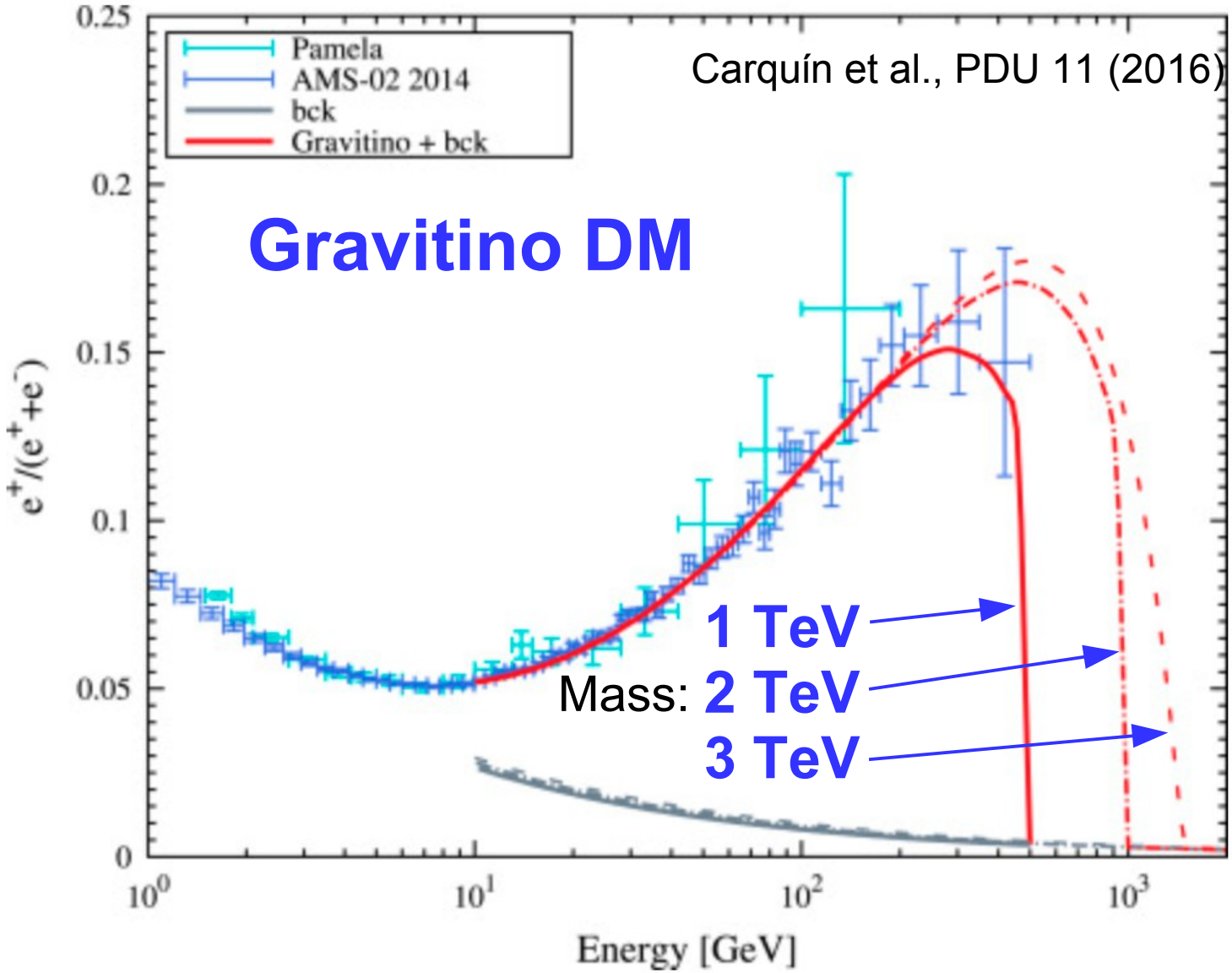


Positron fraction

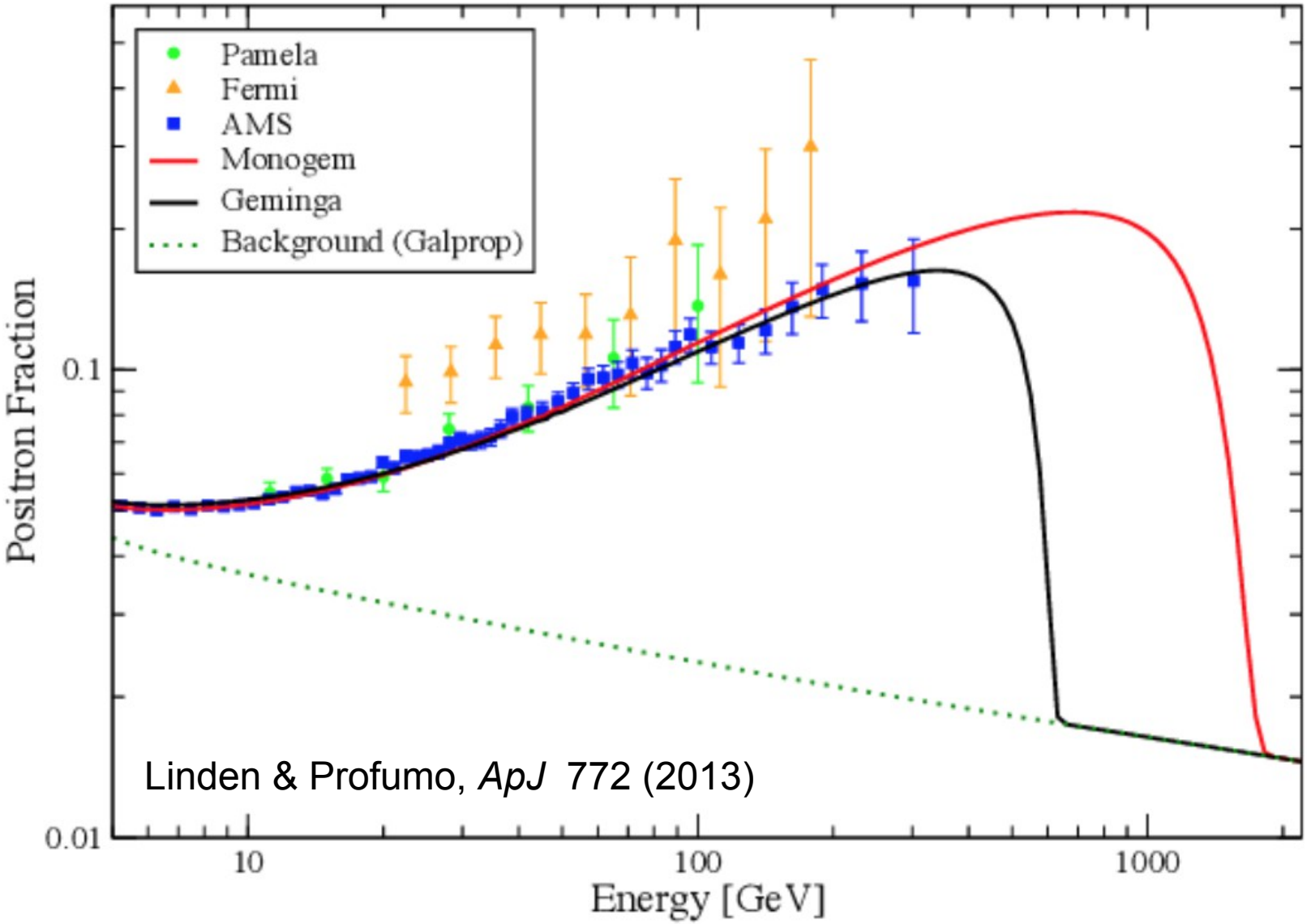
AMS-02 Collaboration (https://www.quantumdiaries.org/tag/ams/)

We expect larger anisotropy for e^+ from pulsars than from DM

$e^+/(e^-+e^+)$ cutoff explained with DM



$e^+/(e^-+e^+)$ cutoff explained with pulsars

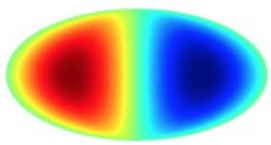


Anisotropy

$$r_e(\theta,\phi)/<r_e> = 1 + \sum_{\ell>0}\sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

Spherical harmonic expansion

Dipole components

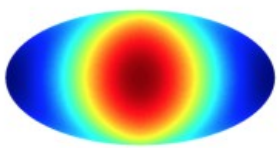


East-West

$$\rho_{EW} = \sqrt{\frac{3}{4\pi}} a_{1-1}$$

North-South

$$\rho_{NS} = \sqrt{\frac{3}{4\pi}} a_{1+0}$$



Forward-Backward

$$\rho_{FB} = \sqrt{\frac{3}{4\pi}} a_{1+1}$$

Dipole amplitude

$$\delta = \frac{\Phi_{\max} - \Phi_{\min}}{\Phi_{\max} + \Phi_{\min}} = \sqrt{\rho_{NS}^2 + \rho_{FB}^2 + \rho_{EW}^2}$$