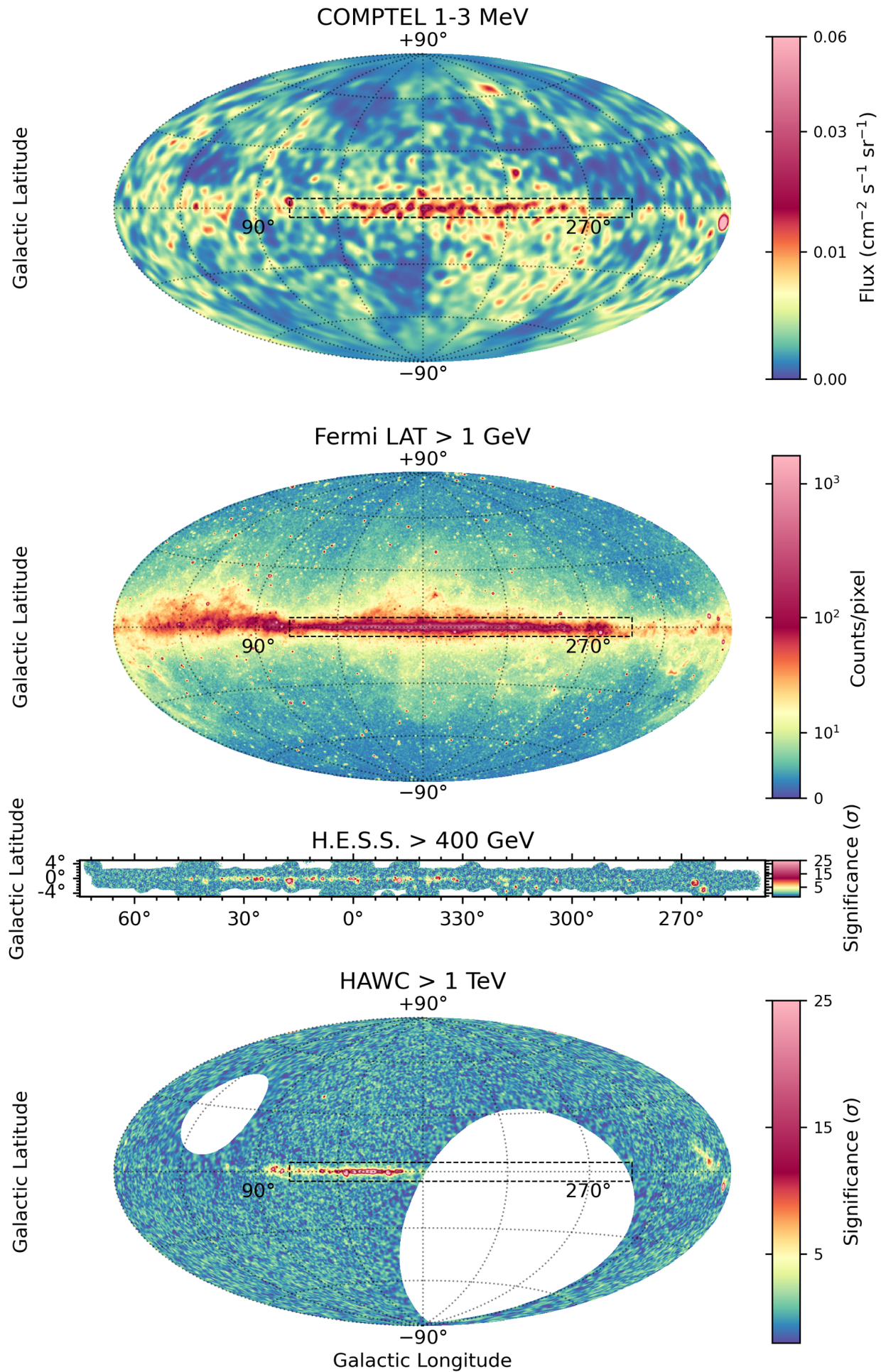

Gamma-ray astronomy: coming of age and revolutions

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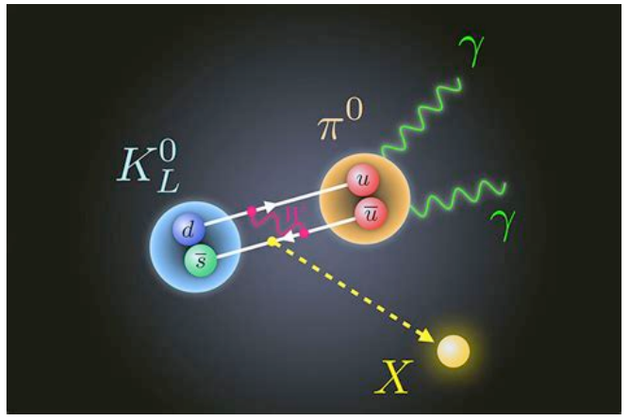
IRAP, Université de Toulouse, CNRS, UPS, CNES

ECRS, Nijmegen
July 28 2022

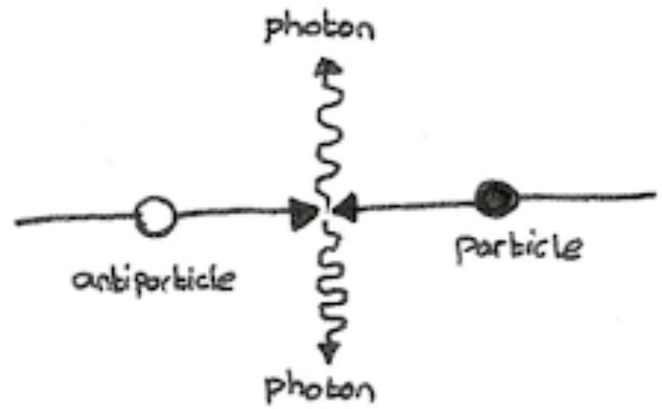
- Introduction
- The coming of age of gamma-ray astronomy
  - Sources
  - Diffuse emission
  - Highlights on recent advances
    - Pulsar halos
    - Star-forming regions
    - VHE emission from gamma-ray bursts
- Revolutions
  - Multimessenger astronomy with gamma rays
  - The PeV frontier
- Future prospects

Gamma-ray production

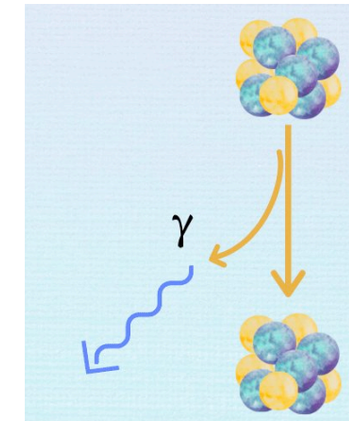
Particle decays



Particle annihilation

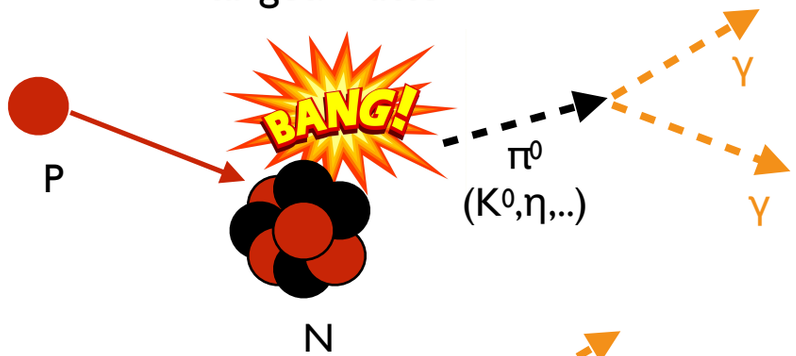


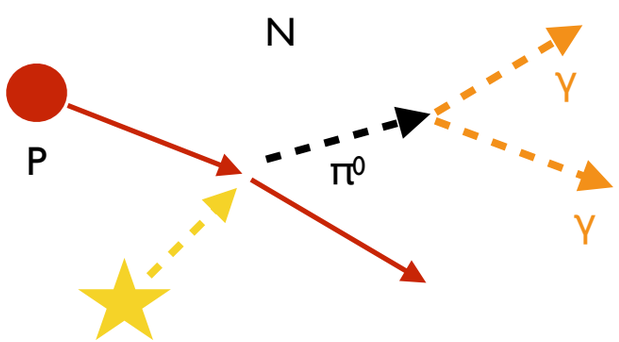
Nuclear decays



Particle acceleration + interactions

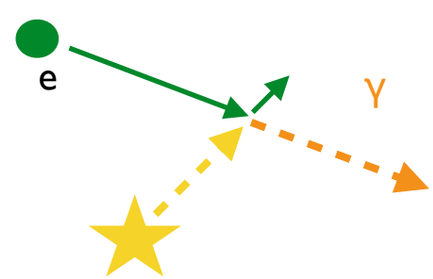
nucleon-nucleon inelastic collisions
target: matter



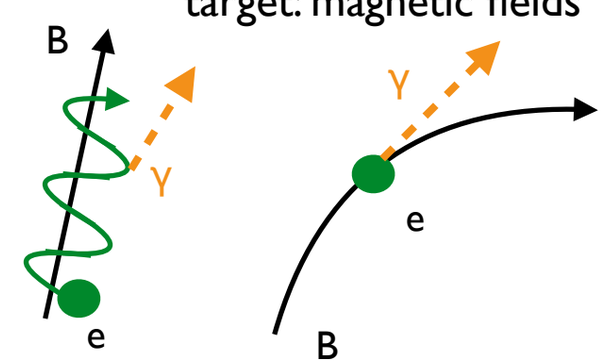


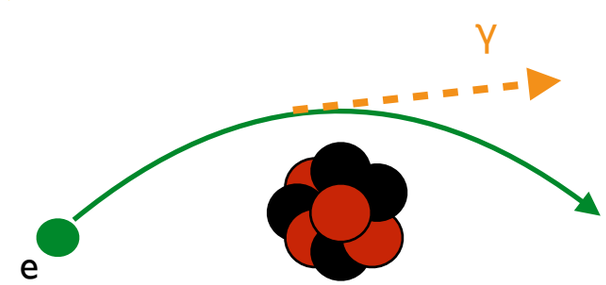
photoproduction
target: photons

inverse-Compton scattering
target: photons



synchrotron/curvature radiation
target: magnetic fields

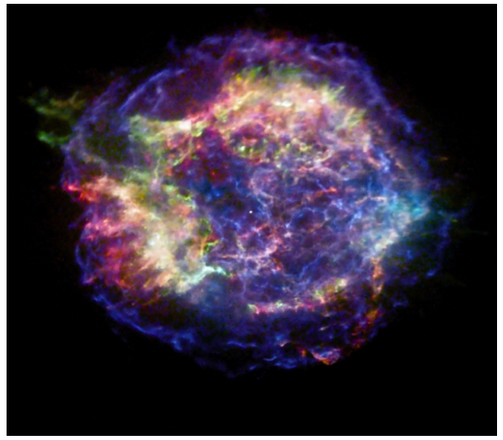




Bremsstrahlung
target: matter

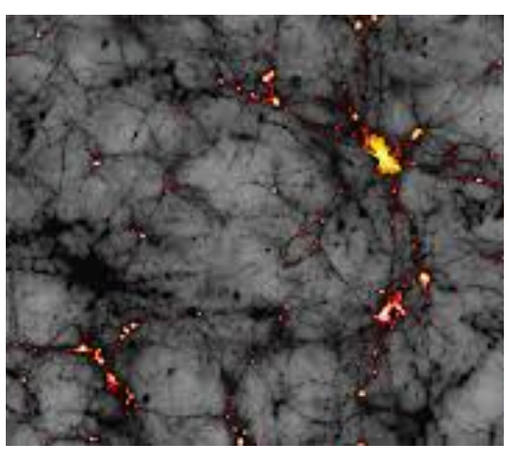
Science with gamma rays

Origin and interactions of cosmic rays



Physical processes in extreme environments

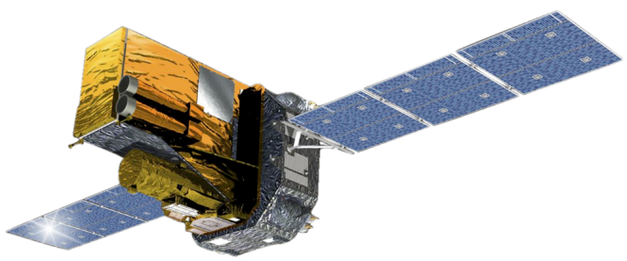
Physics beyond the standard model*



*Review by G. Zaharijas on dark-matter searches

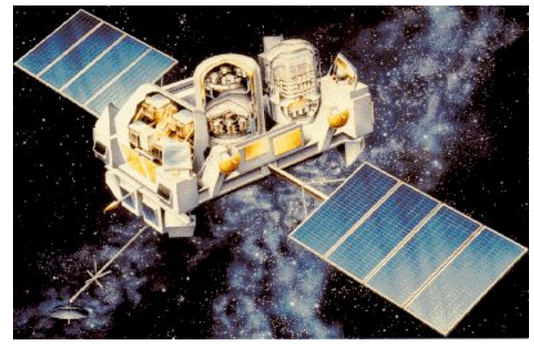
Formation of heavy elements

Space telescopes



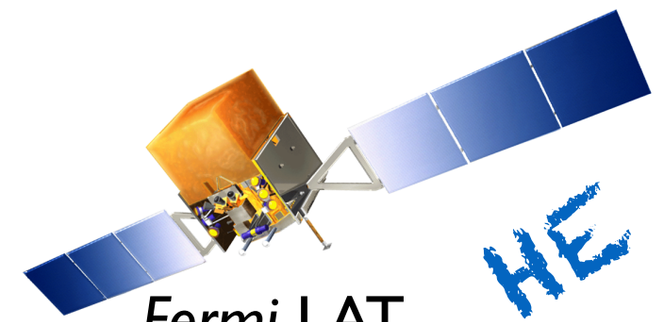
INTEGRAL IBIS&SPI
2002-present
15 keV-10 MeV
coded mask +
scintillating crystals/
semiconductor
detectors

LE



COMPTEL
1991-2000
800 keV-30 MeV
liquid+crystal scintillator
& ballons (COSI, SMILE)

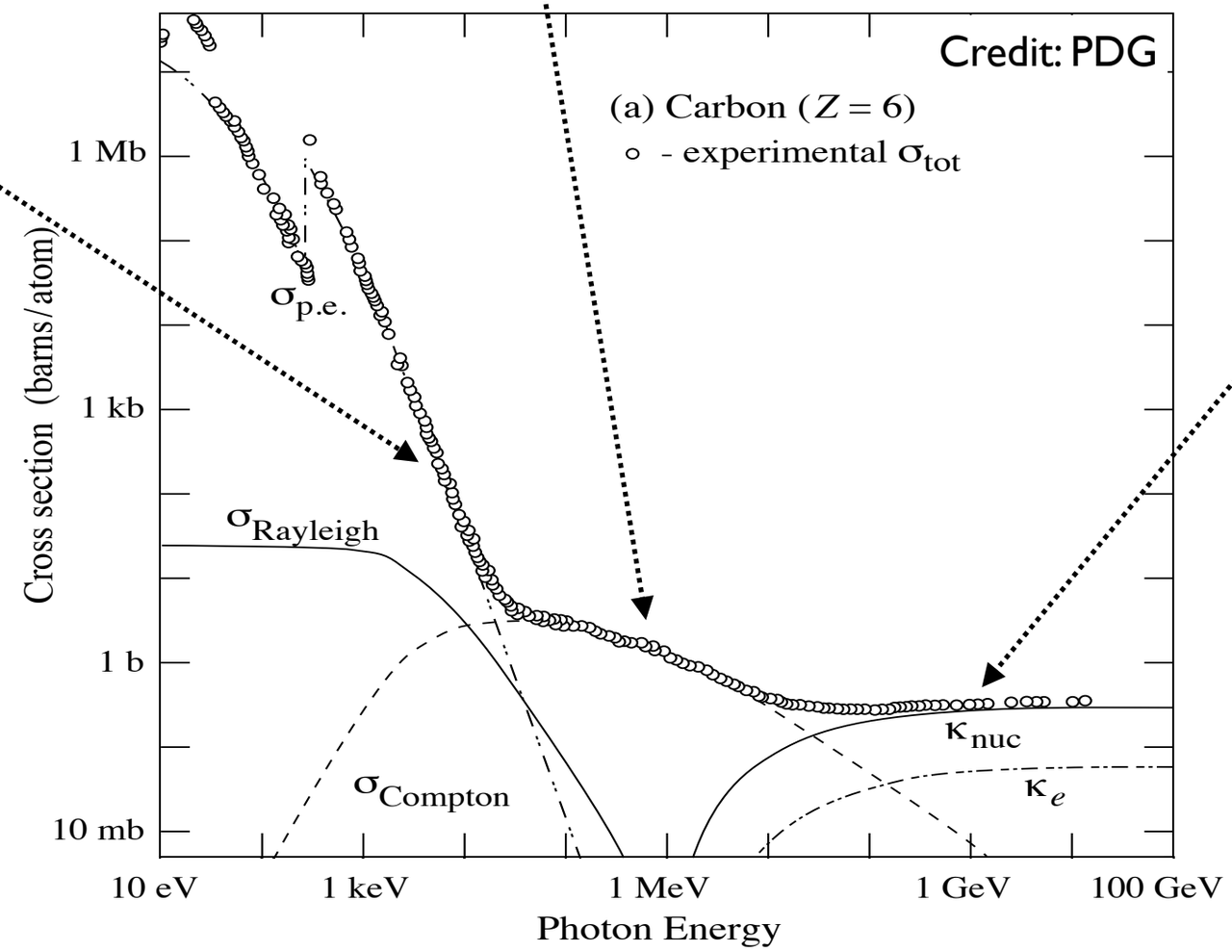
ME



HE

Fermi LAT
2008-present
30 MeV-1 TeV
Si-W tracker-
converter +
electromagnetic
calorimeter

and AGILE
2007-present
DAMPE
2015-present
CALET
2015-present

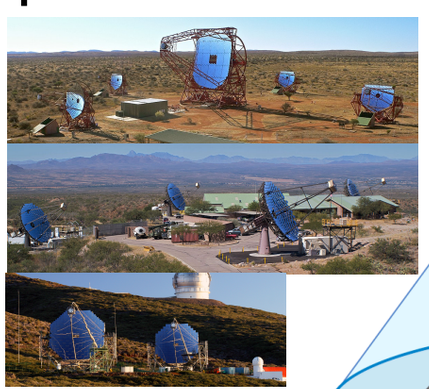


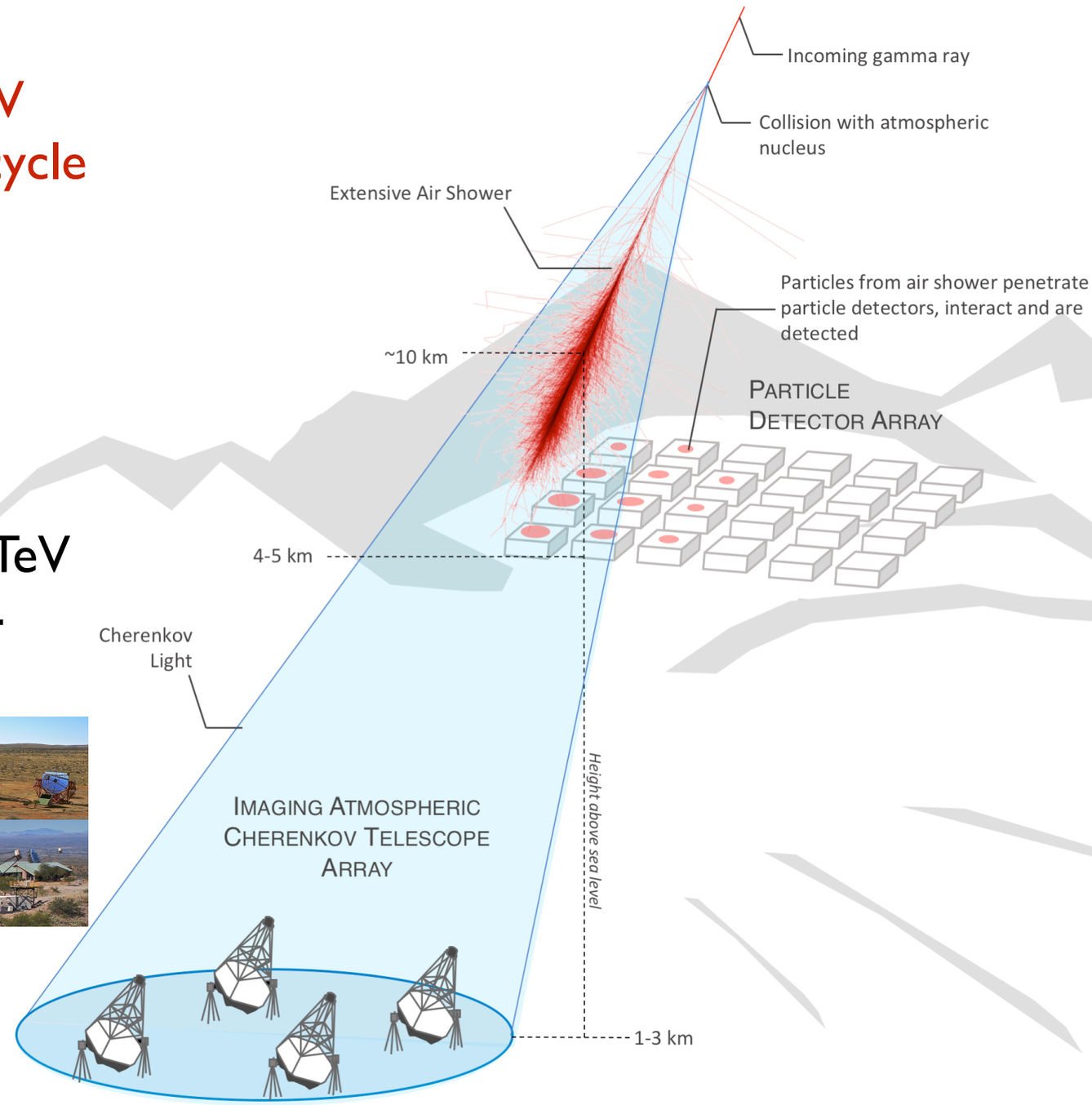
Ground-based detectors

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

Modest PSF
Large FoV
High duty cycle

Credit: Richard White

See highlights by
P. Hüntemeyer and A. Mitchell

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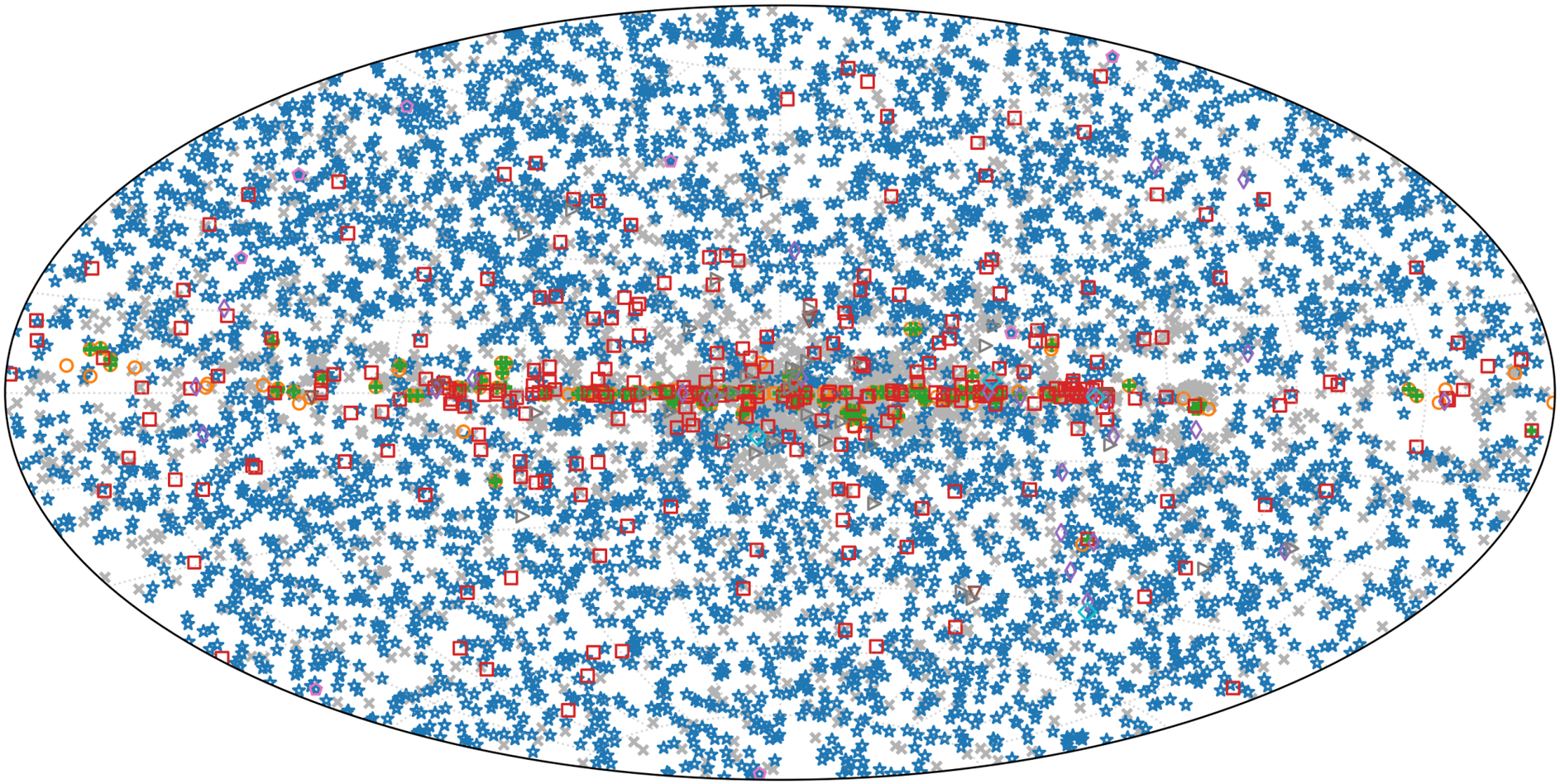
HE sources



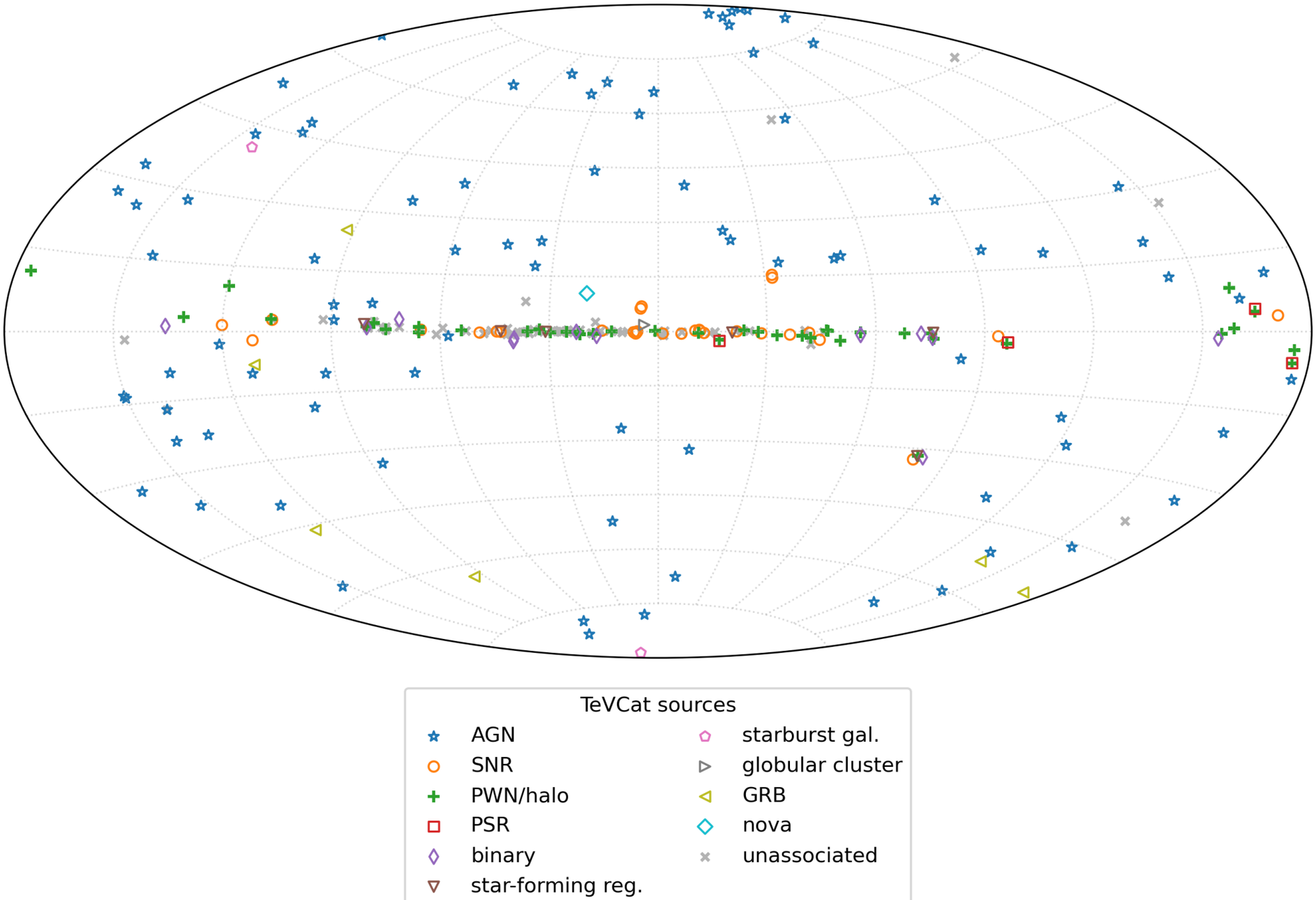
4FGL-DR3 sources

AGN	star-forming reg.
SNR	starburst gal.
PWN/halo	globular cluster
PSR	nova
binary	unassociated

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

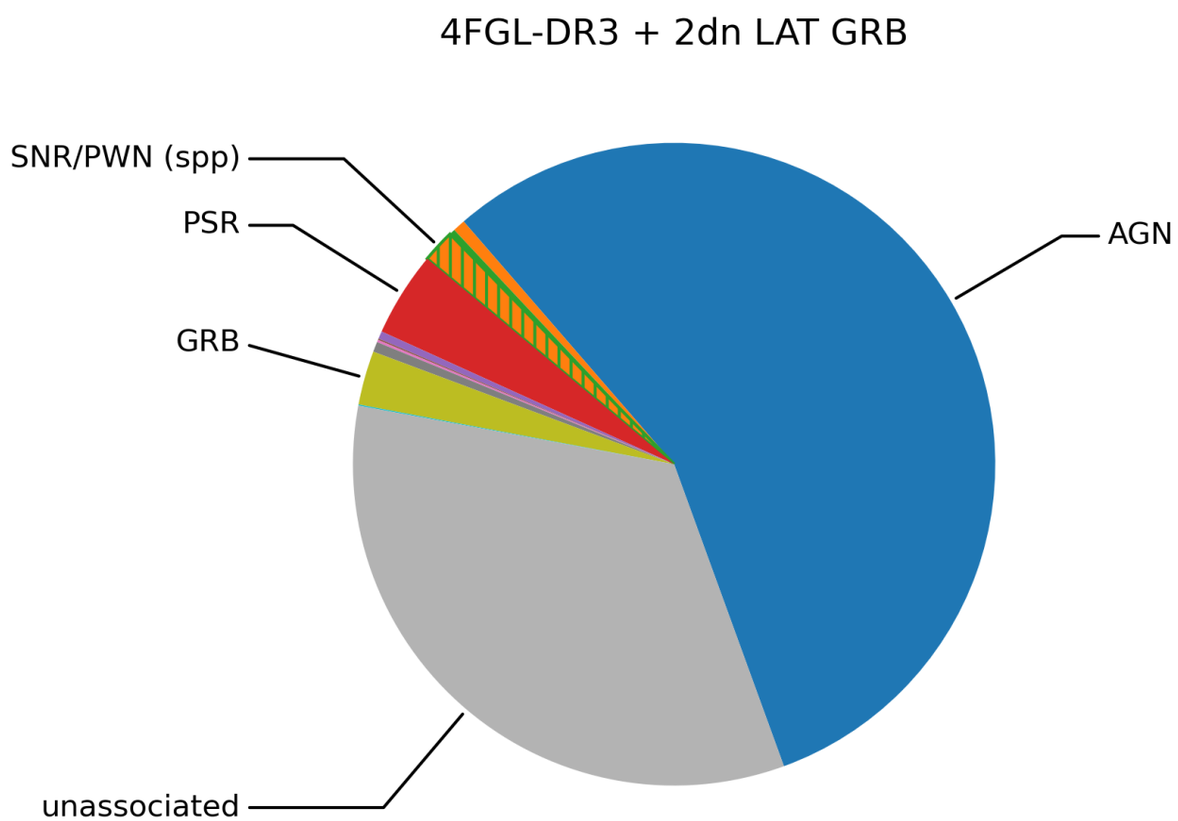
VHE sources

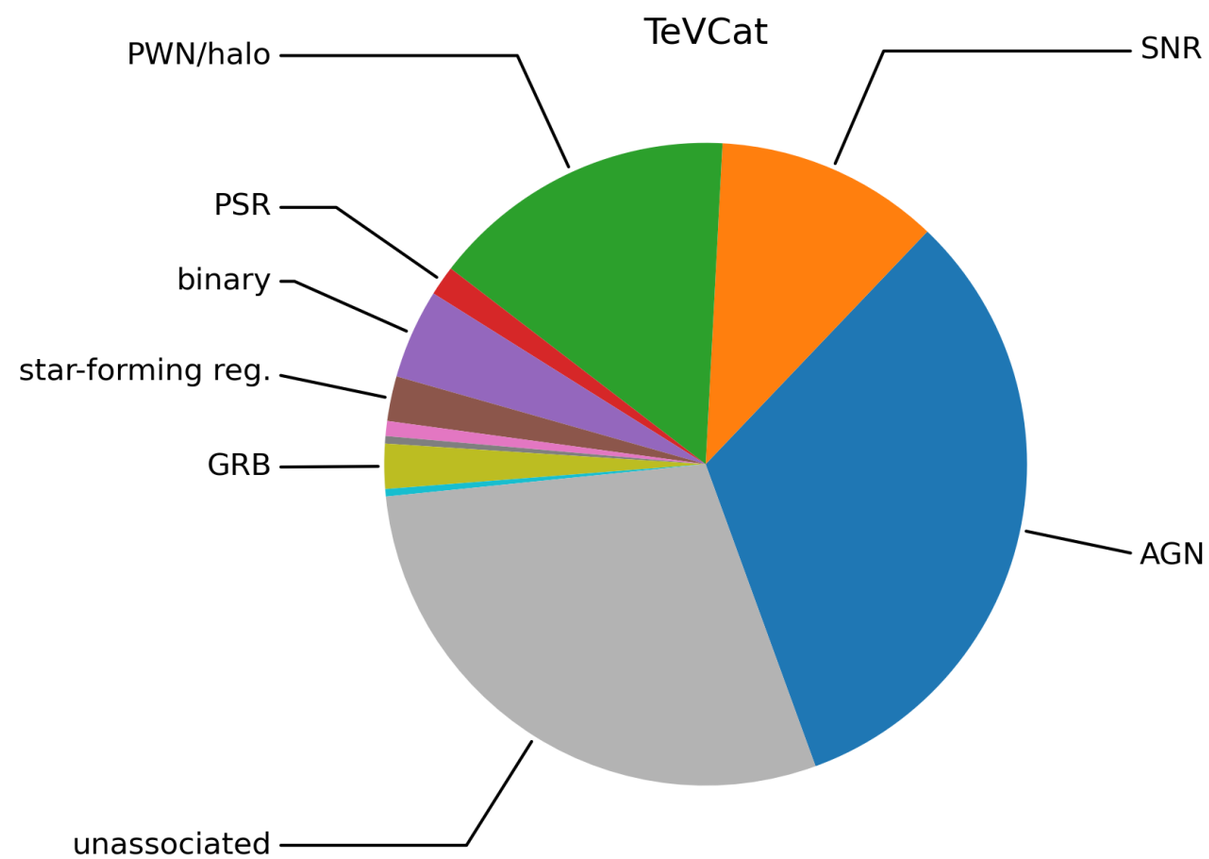
Thanks to D. Horan and S. Wakely for sharing TeVCat data



HE and VHE source classes

Thanks to D. Horan and S. Wakely for sharing TeVCat data

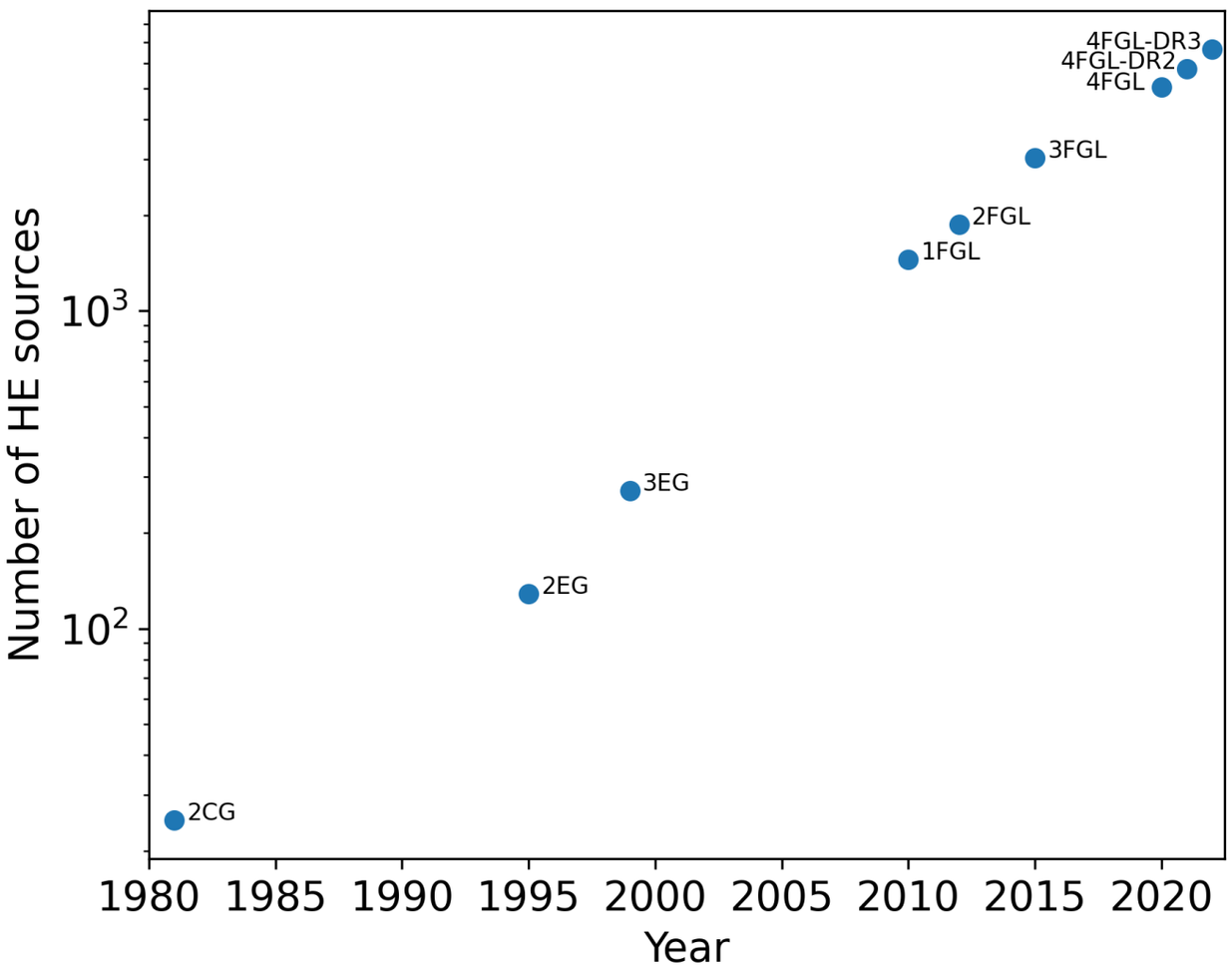


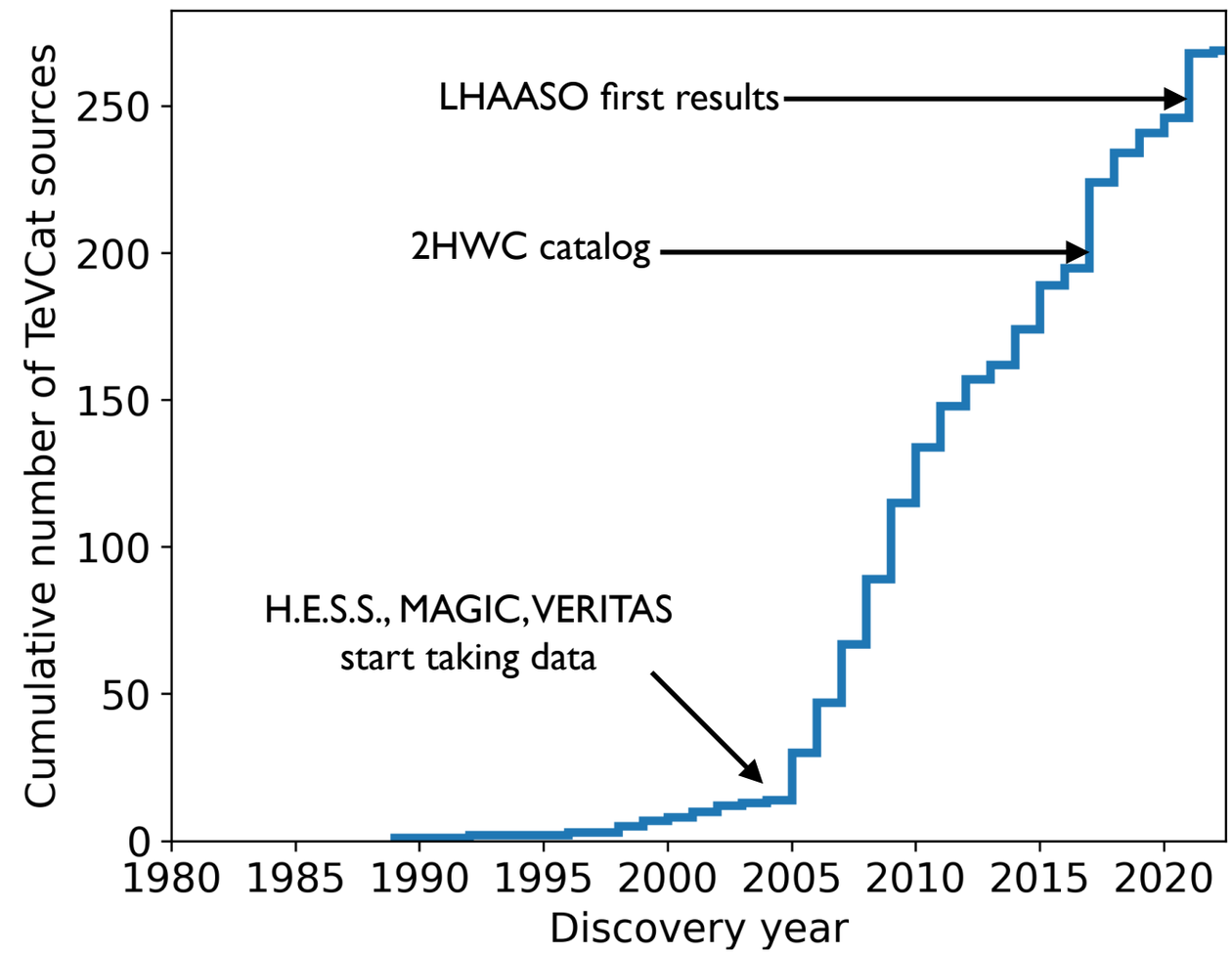


Source diversity → particle acceleration and transport in a variety of astrophysical conditions and environments.

A growing number of sources

Thanks to D. Horan and S. Wakely for sharing TeVCat data





- 63 sources in COMPTEL catalog
- 939 sources in the 17-100 keV energy range in *INTEGRAL/* IBIS 1000-orbit catalog

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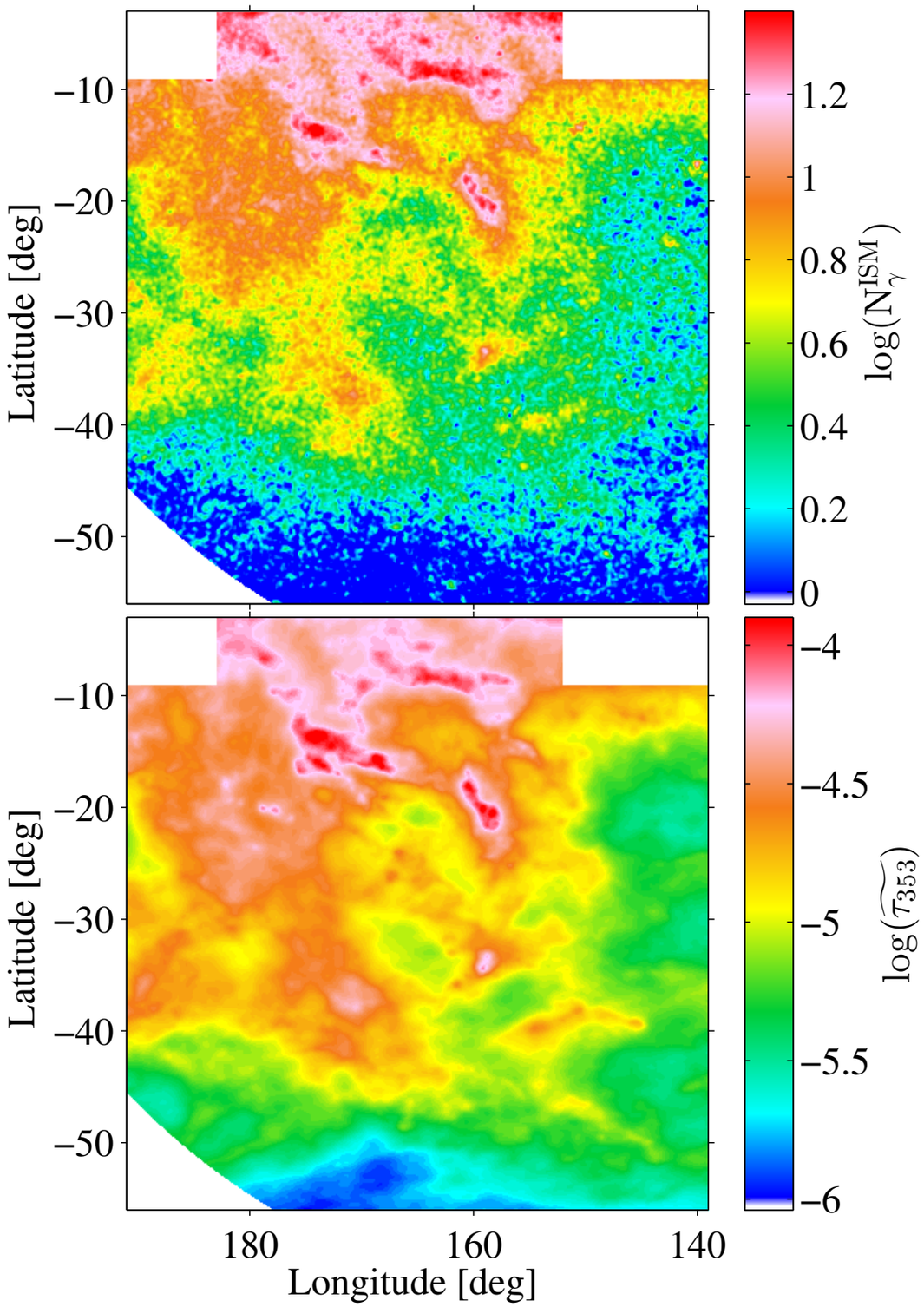
Diffuse emission

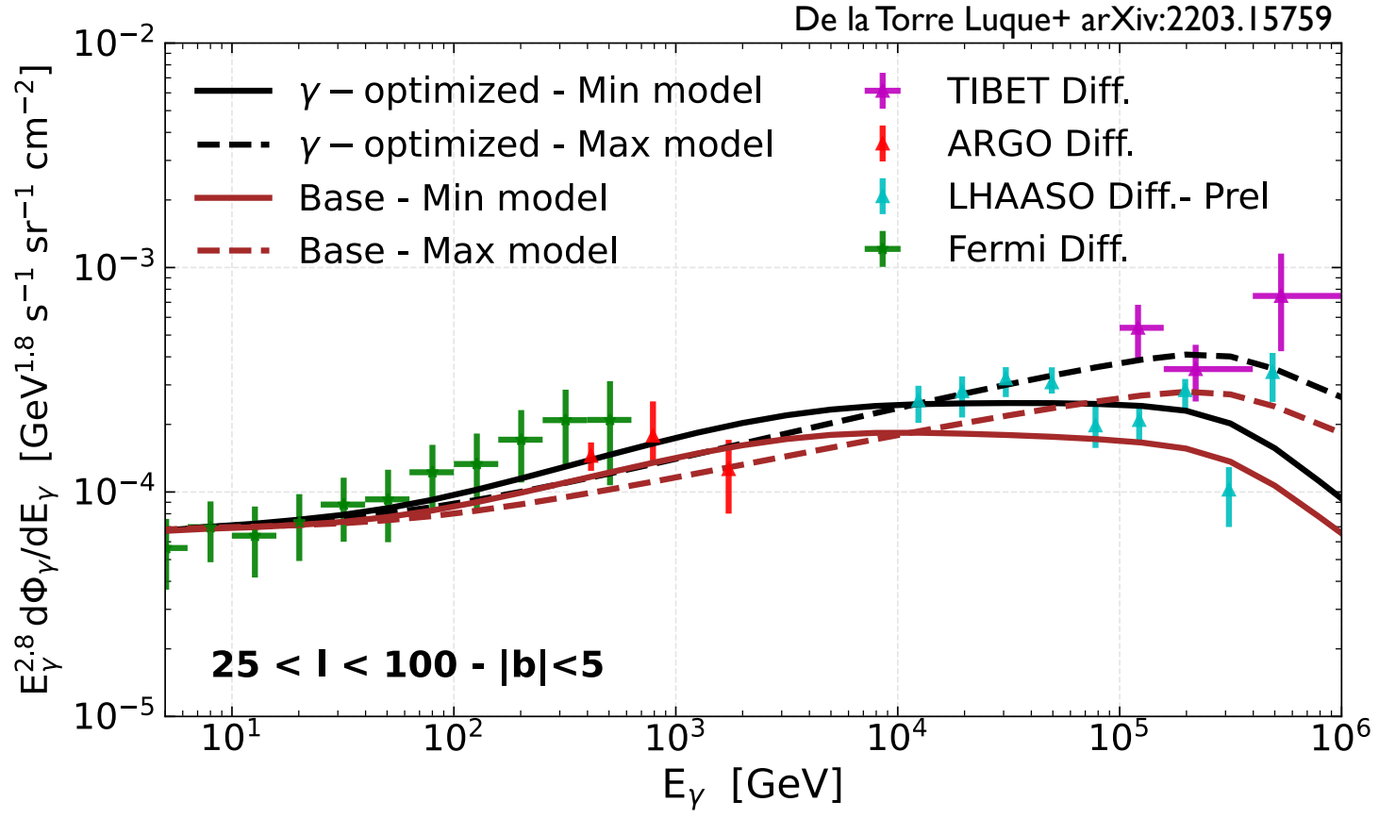
Anticenter clouds: *Fermi* vs *Planck*

Remy+ 2017 A&A 601 A78



- GeV: good correlation of gamma rays and interstellar matter → CR interactions
- Diffuse emission (not related to individual sources) detected from sub-MeV to sub-PeV energies

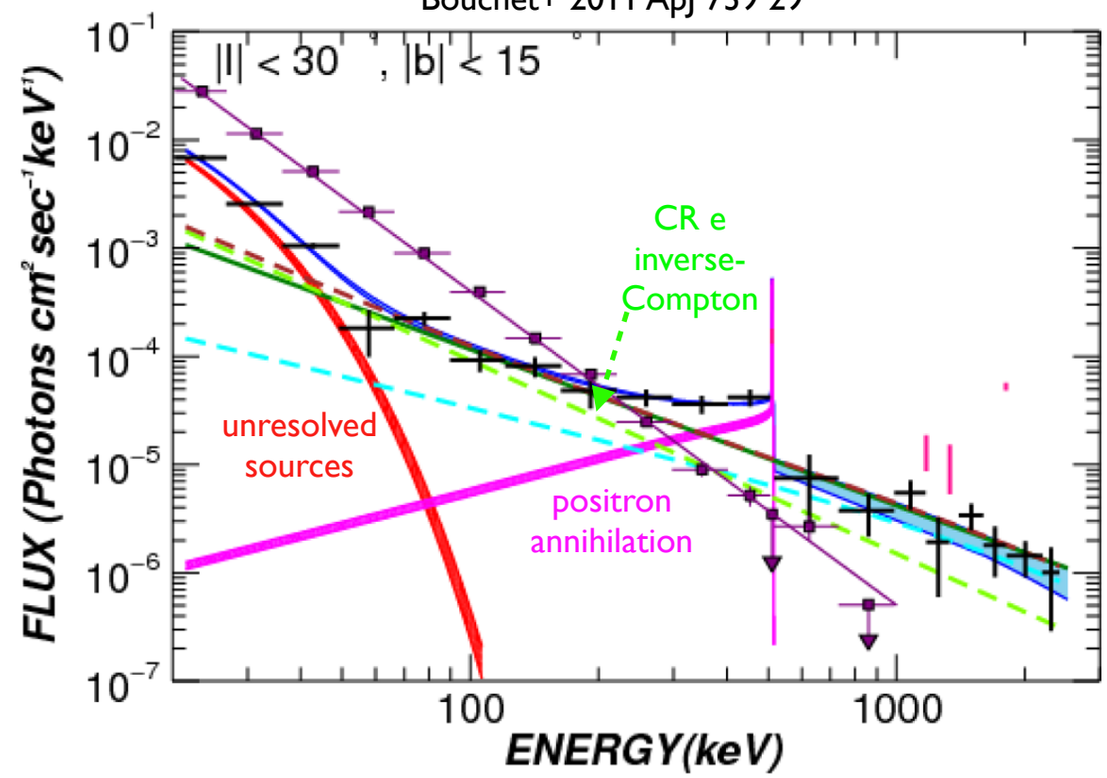
De la Torre Luque+ arXiv:2203.15759



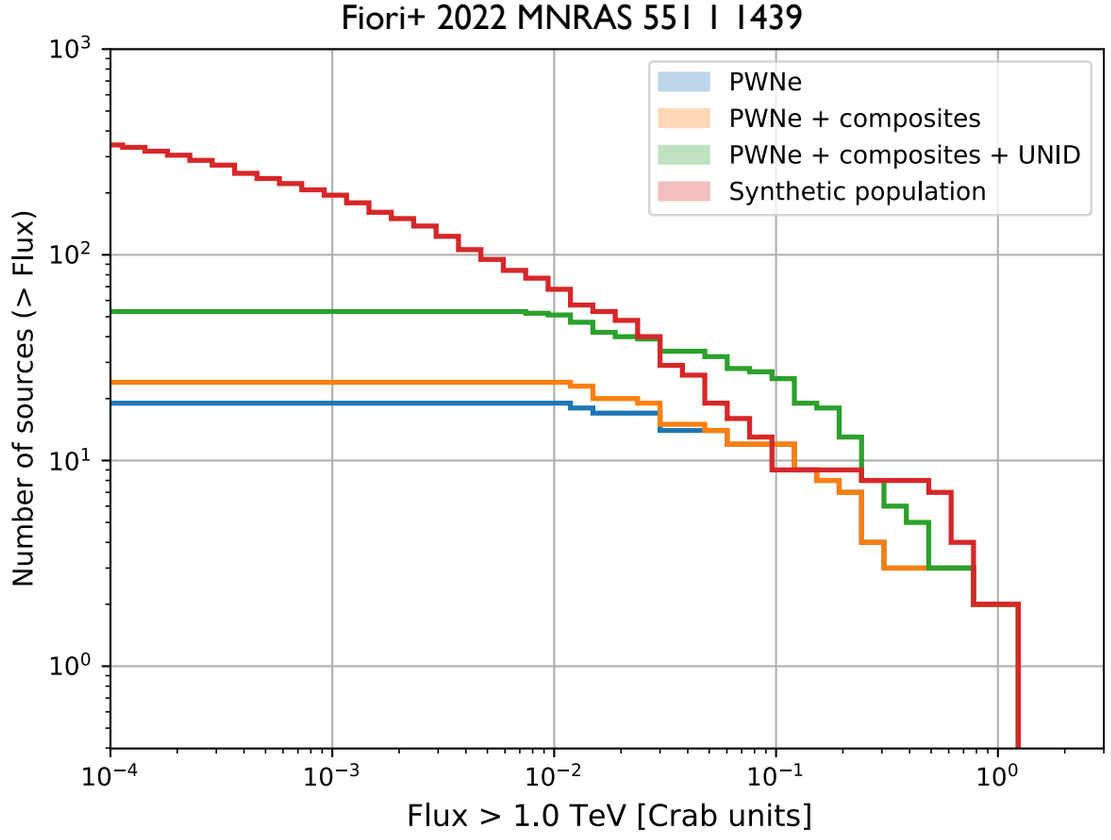
CR interactions or unresolved sources?

- GeV: dominated by CR hadronic emission
- < MeV: 3 times higher than expected from AMS-02+local synchrotron and gamma rays
  - significant contribution from secondary positrons and electrons?
  - unresolved sources
- TeV-PeV → relevant to address hardening of CR nuclei spectrum in the inner Galaxy, unresolved sources under scrutiny

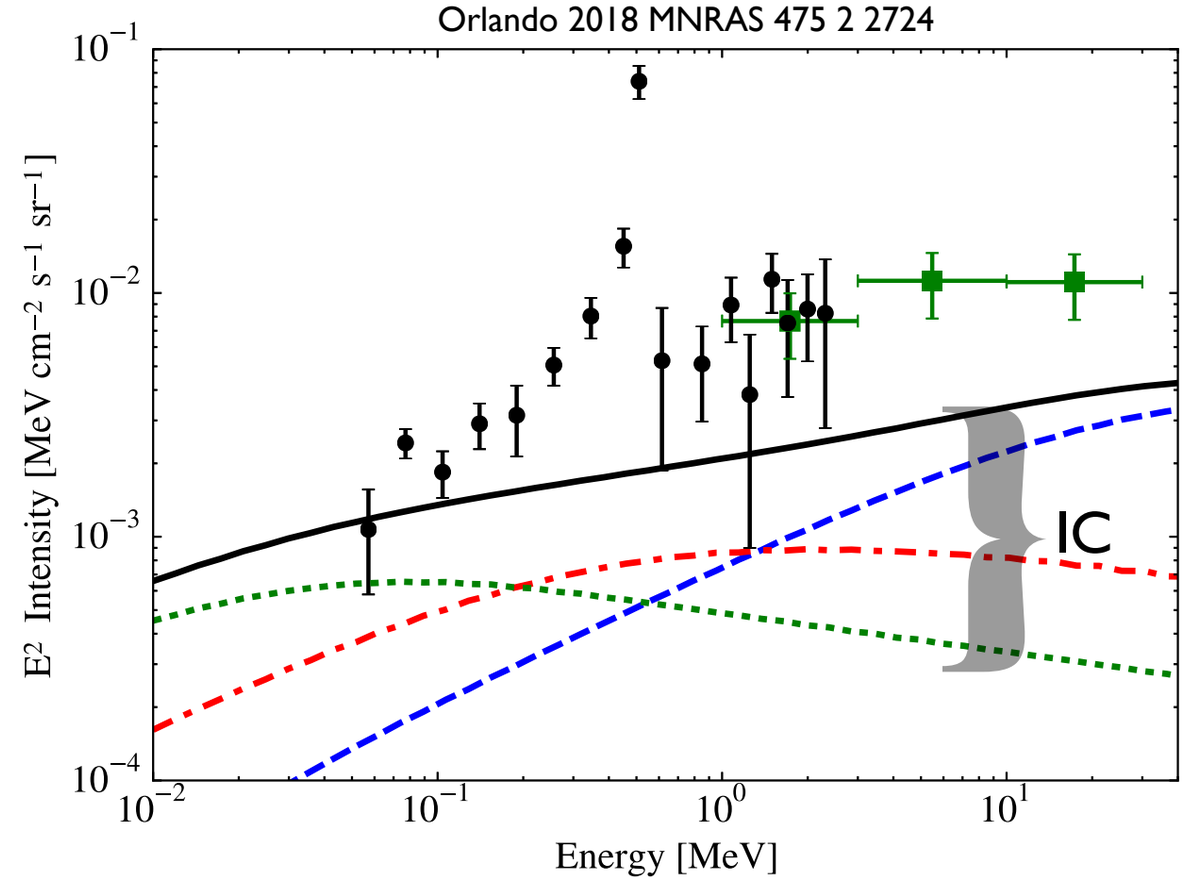
Bouchet+ 2011 ApJ 739 29



Fiori+ 2022 MNRAS 551 1 1439



Orlando 2018 MNRAS 475 2 2724



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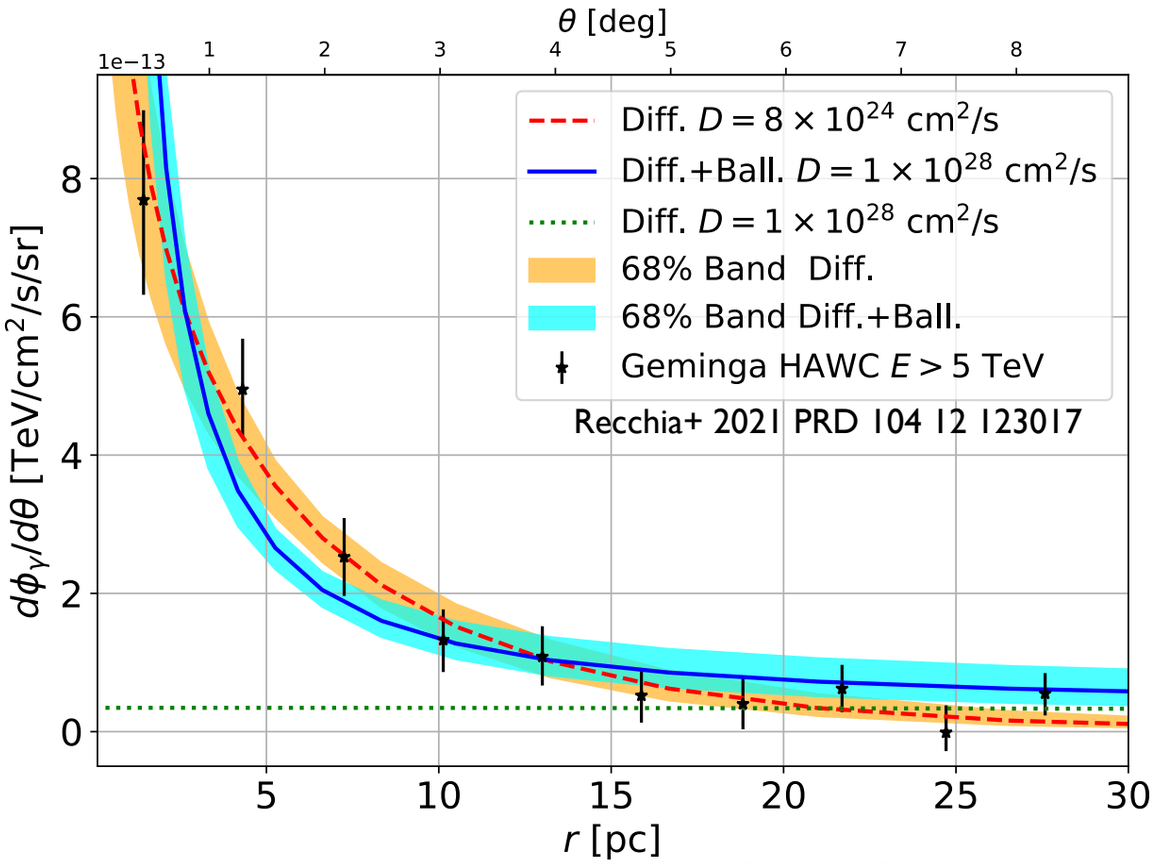
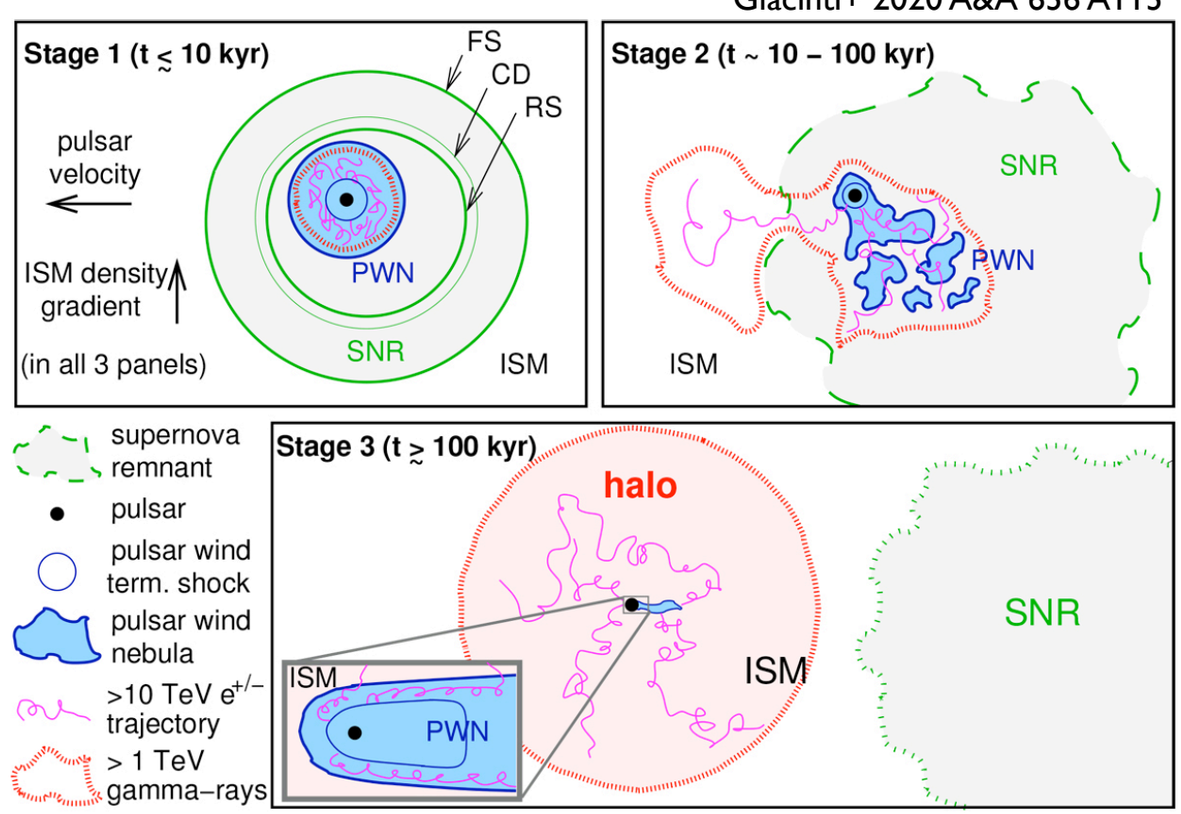
Pulsar halos

- HAWC: Geminga and PSR B0656+14 (> 100 kyr)
- Particles free from PWN
  - diffusion suppressed by ~100 w.r.t. Galactic "average"
  - or combination of ballistic + "average" diffusion?
- Few more candidates at TeV (transitional objects?) and tentative detection of Geminga halo with Fermi



Giacinti+ 2020 A&A 636 A113



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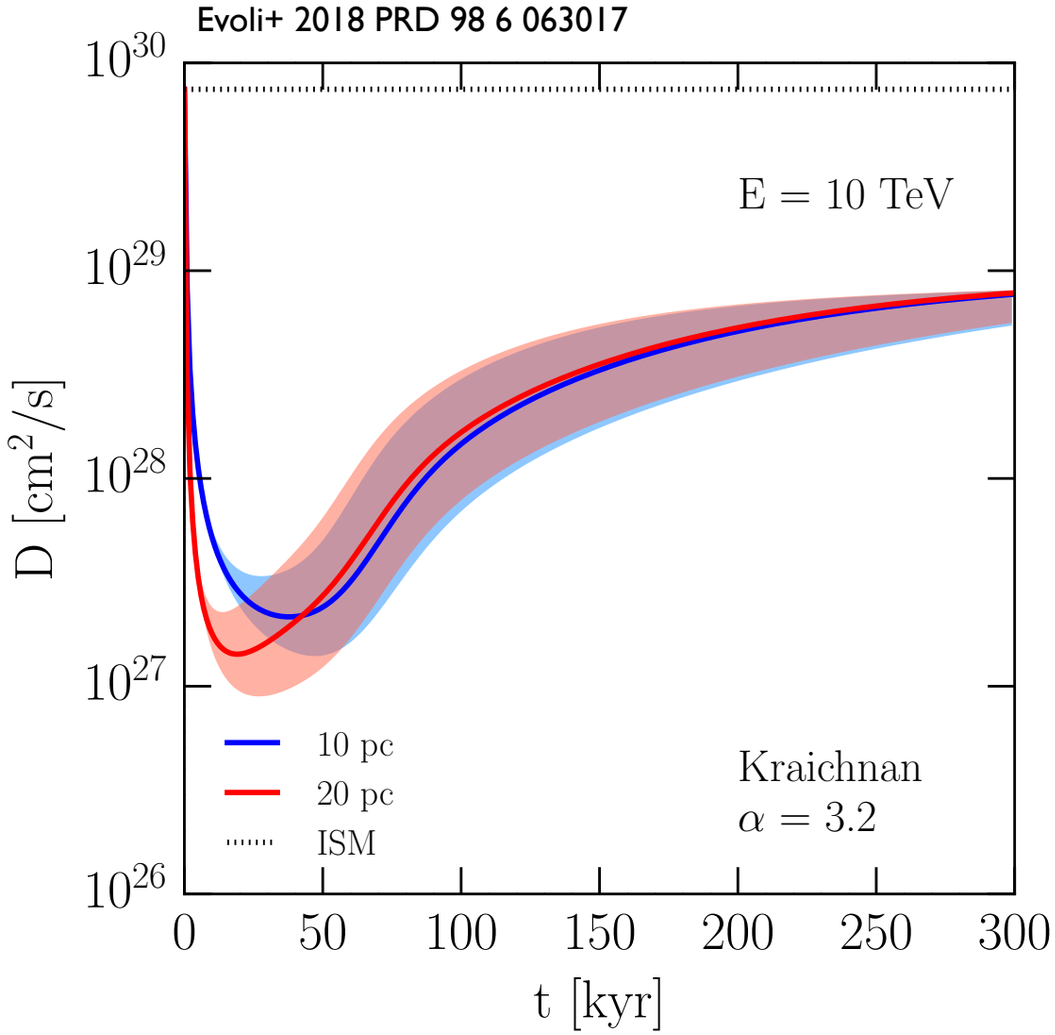
Pulsar halos: how and how many?

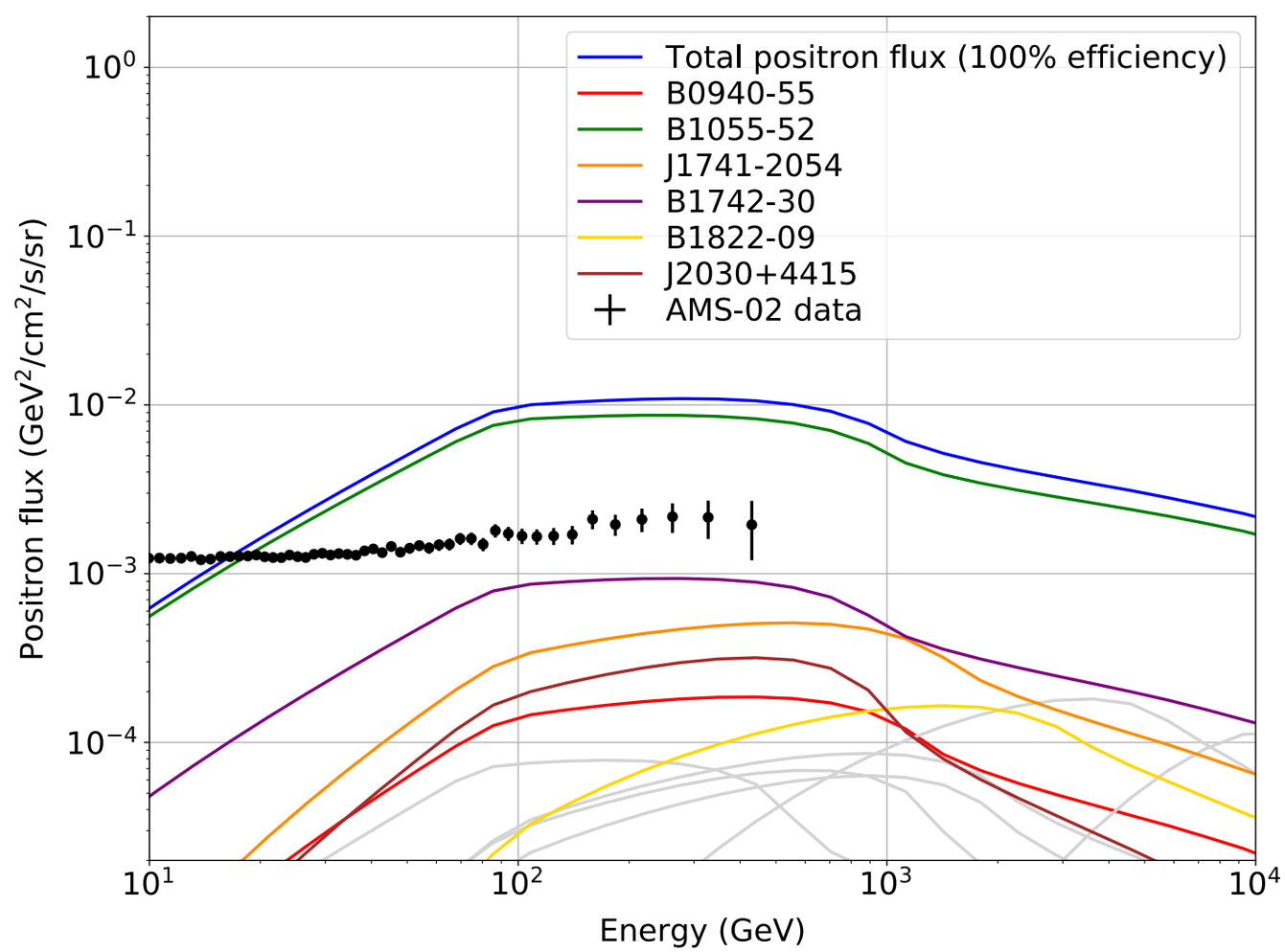
- Suppression of diffusion coefficient?
  - additional turbulence of kinetic or fluid origin
  - reduced turbulence coherence length (< 5 pc)

- Contributions to source populations and diffuse emission?
  - positrons: occurrence < 10% in local middle-aged pulsars?

Evoli+ 2018 PRD 98 6 063017



Martin+ 2022 in press arXiv:2206.11803



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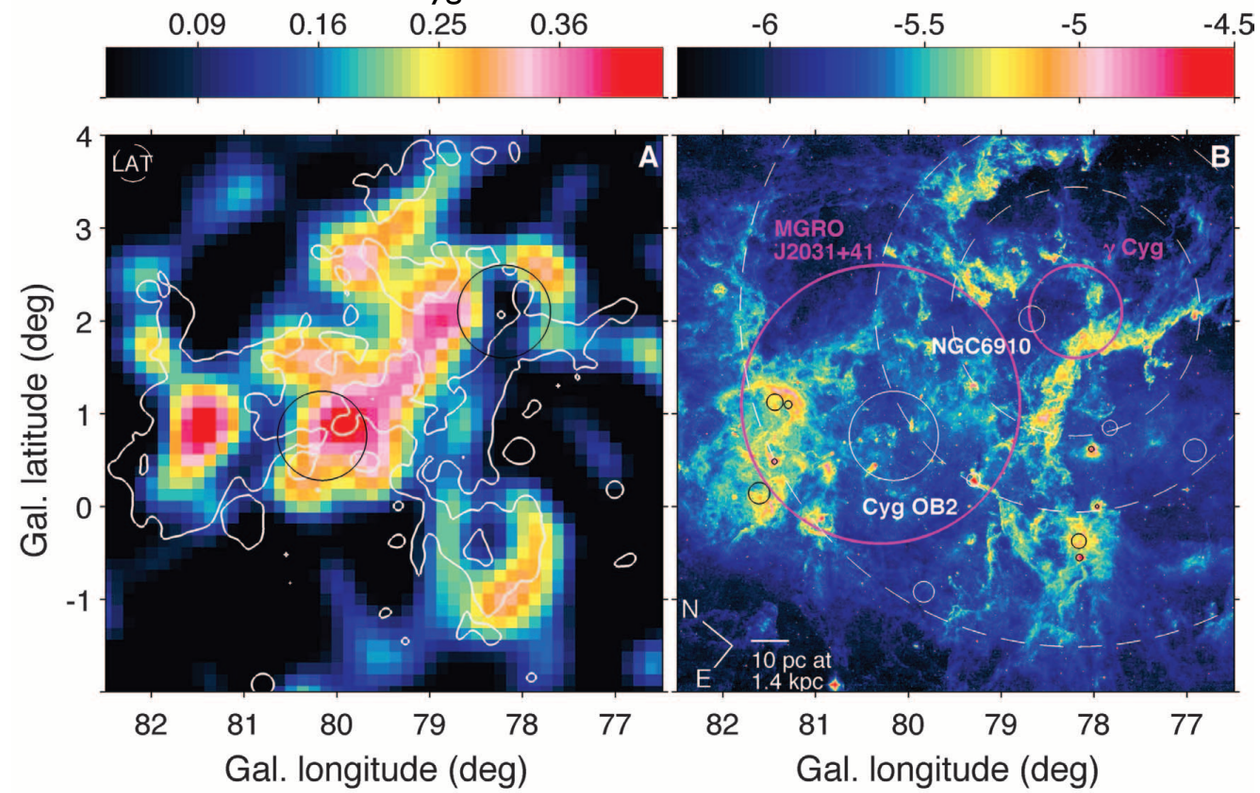
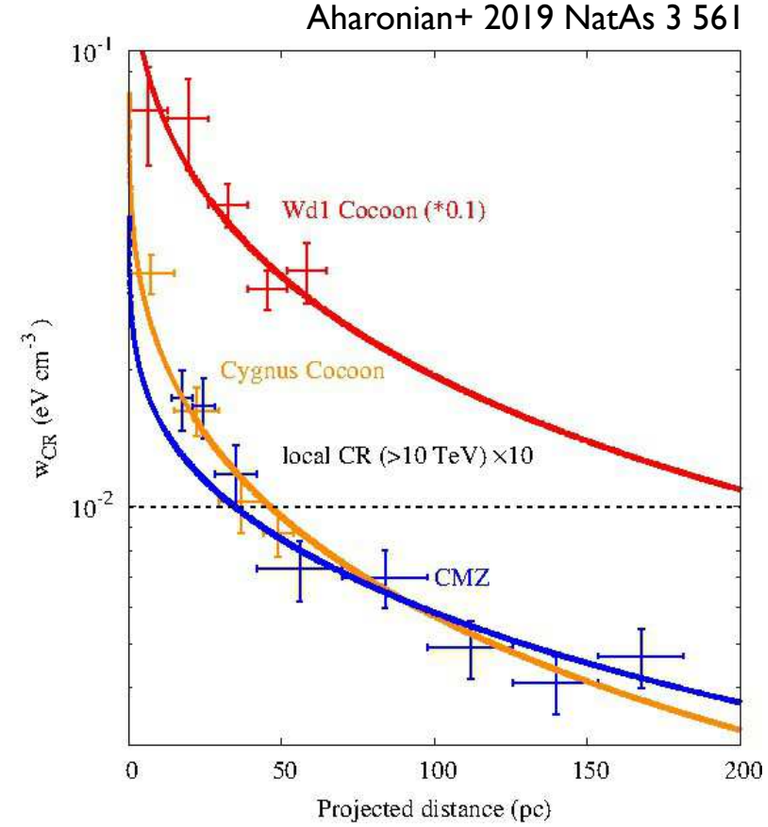
Gamma rays from star-forming regions

Cygnus cocoon: *Fermi* LAT collab. 2011 Science 334 1103



- Expected
  - good conditions for acceleration
  - targets
  - CR isotopic abundances
- More than 10 young star-forming regions possibly detected at GeV-TeV
  - caveats: limited angular resolution, foregrounds, source confusion
  - radial profiles → continuous CR injection + diffusion over few Myr

Aharonian+ 2019 NatAs 3 561



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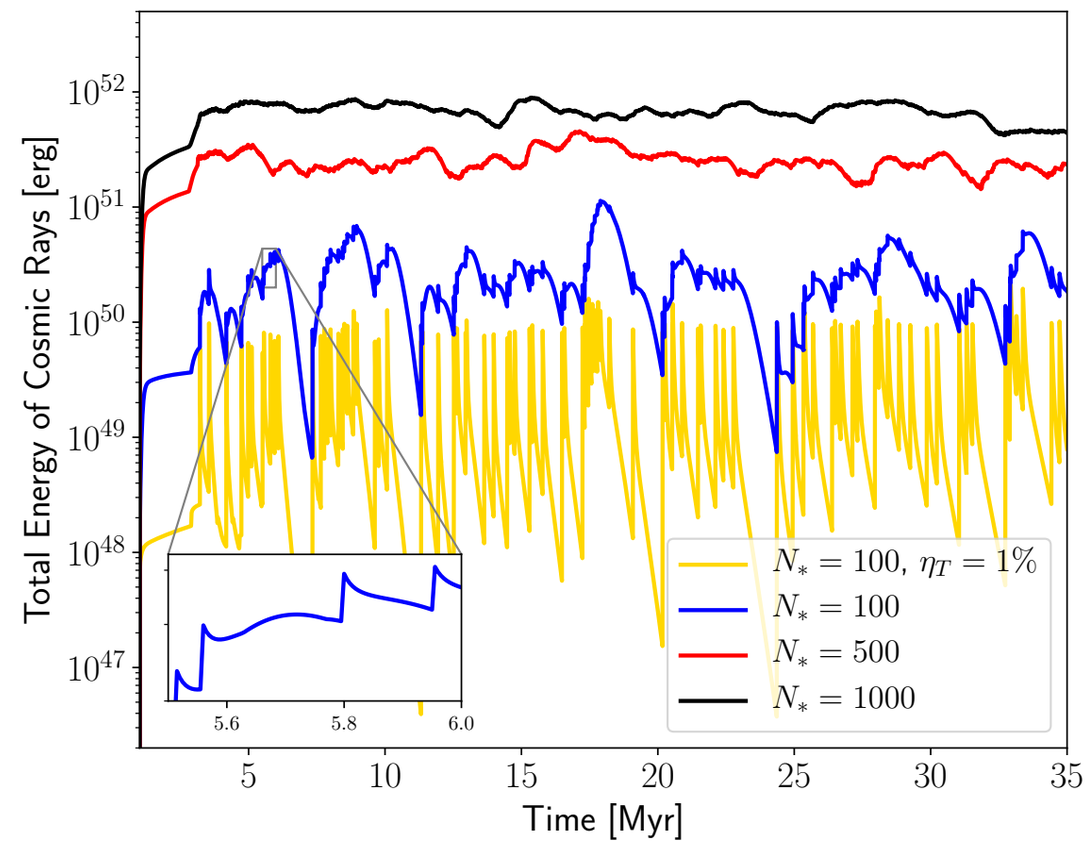
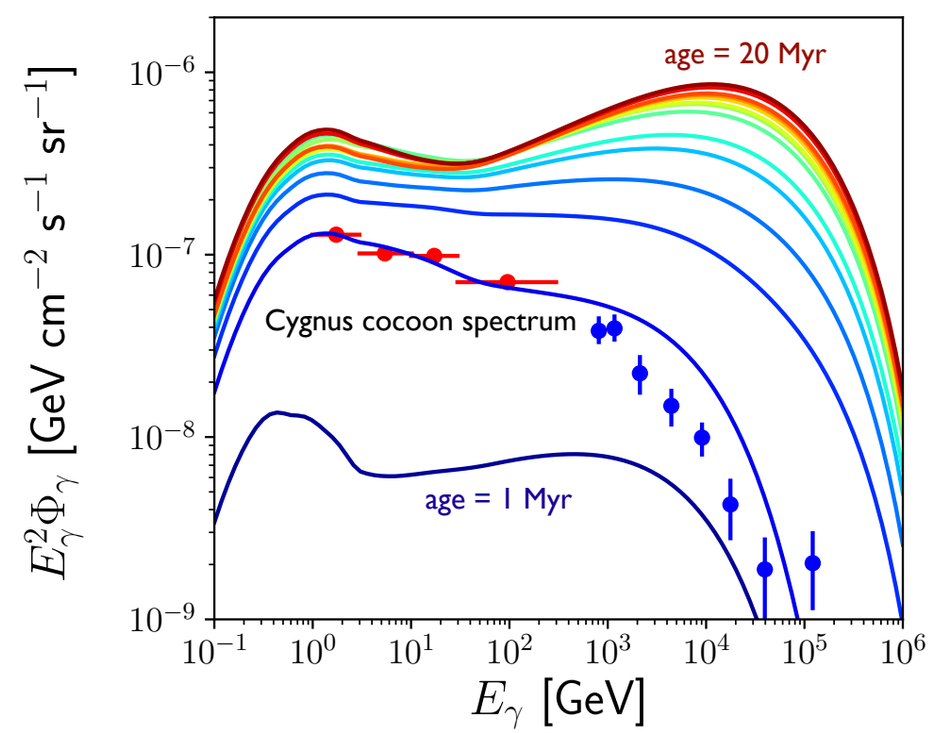
CR acceleration and gamma-ray emission

- Possible acceleration sites/ mechanisms:
  - cluster winds termination shocks
  - superbubbles/shells
  - converging flows
- Up to PeV for clusters, less clear for superbubbles
- Steady emission in wind-dominated phase, intermittent in SN-dominated phase
- Reproduces observations if good confinement

Vieu+ 2022 MNRAS 512 1 1275





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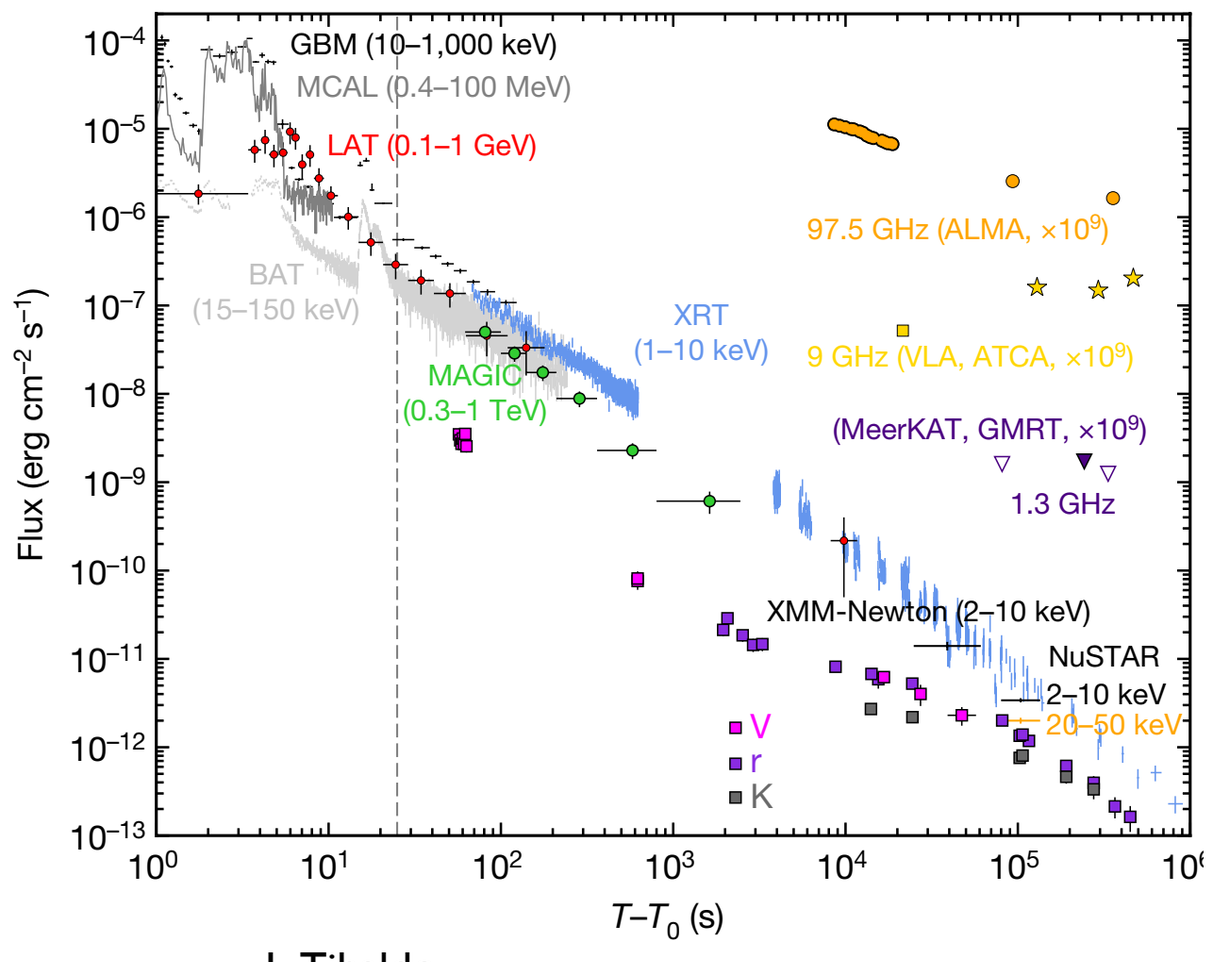
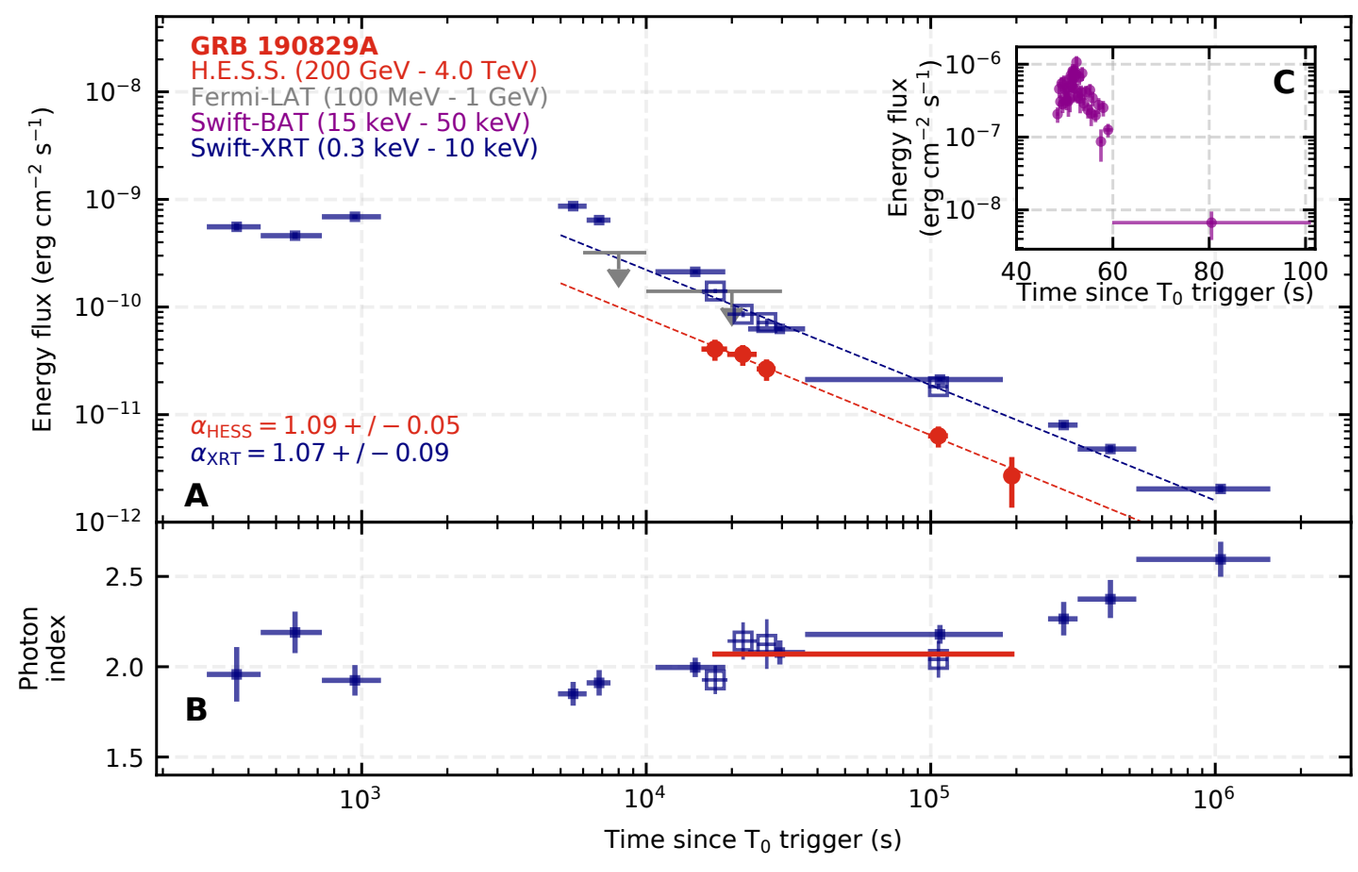
GRBs at VHE

- Long hunt for GRB afterglow
  - relativistic shock acceleration in its simplest realisation
  - likely SSC (beyond synchrotron burnoff): constraints on downstream conditions
- 4 (6) detections since 2019

GRB 190114C MAGIC collab. 2019 Nature 575 459



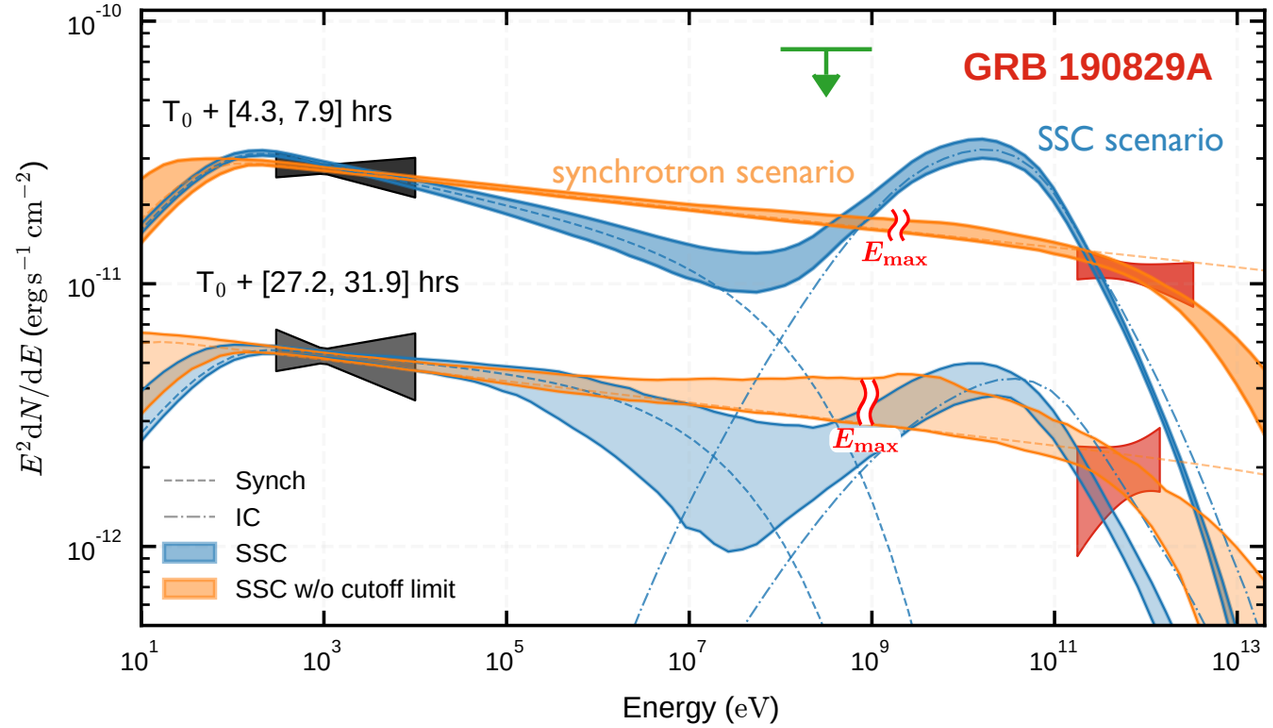
GRB 190829A H.E.S.S. collab. 2021 Science 372 1081



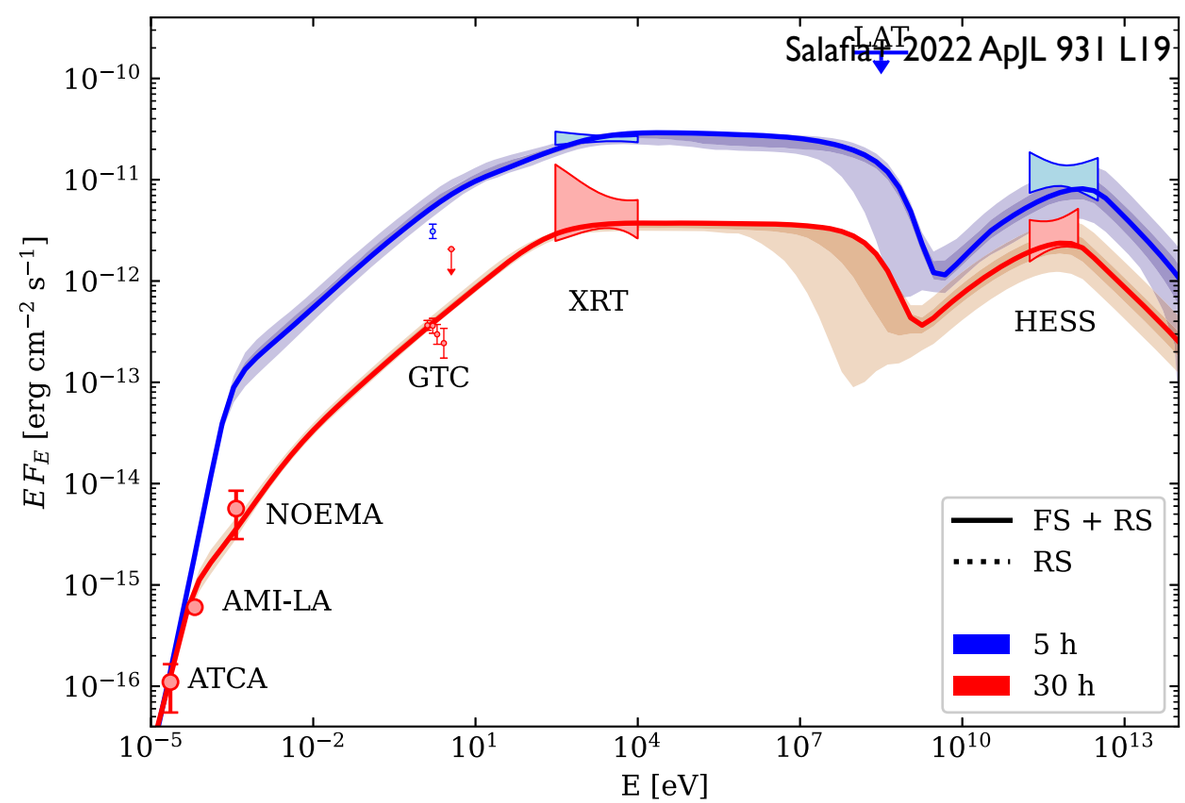
GRB 190829A

- z = 0.08 → no EBL uncertainties
- Klein-Nishina suppression + photon-photon absorption → one zone SSC scenario challenged
- extend synchrotron beyond burnout limit?
- few % of accelerated e + rapid decay of B in reverse shock→ SSC scenario viable from radio to TeV
- alternative explanations: blast wave + pair enriched shell, magnetar …

GRB 190829A H.E.S.S. collab. 2021 Science 372 1081



Salafia+ 2022 ApJL 931 L19



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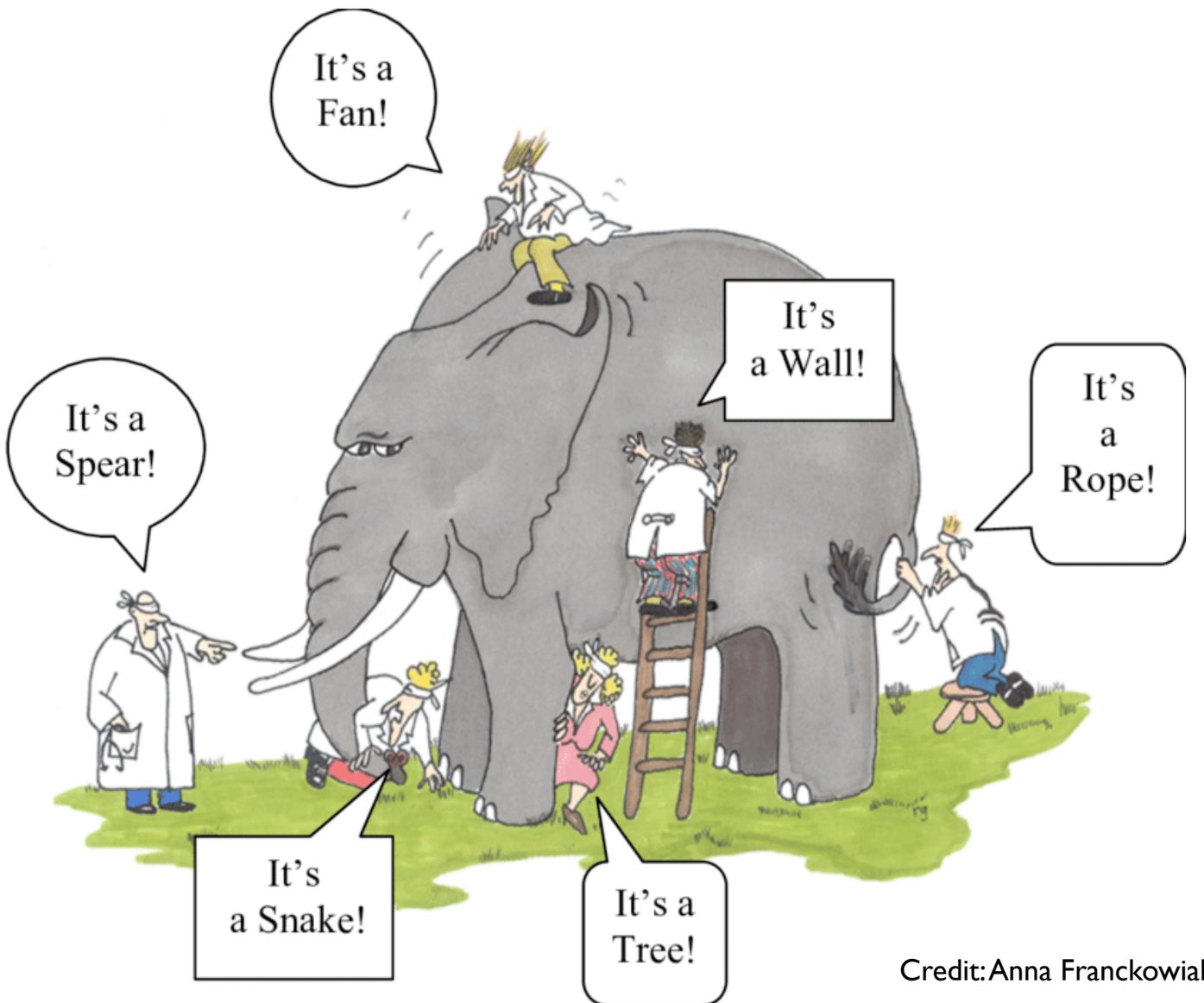
Multimessenger astronomy with gamma rays

- Firsts
  - GW 170817 (LIGO-Virgo) / GRB 170817A (*Fermi*/GBM & *INTEGRAL*/SPI)
  - IC 170922A (IceCube) and flare in blazar TXS 0506+056 (*Fermi*-LAT, MAGIC)
- See review by F. Oikonomou for neutrinos

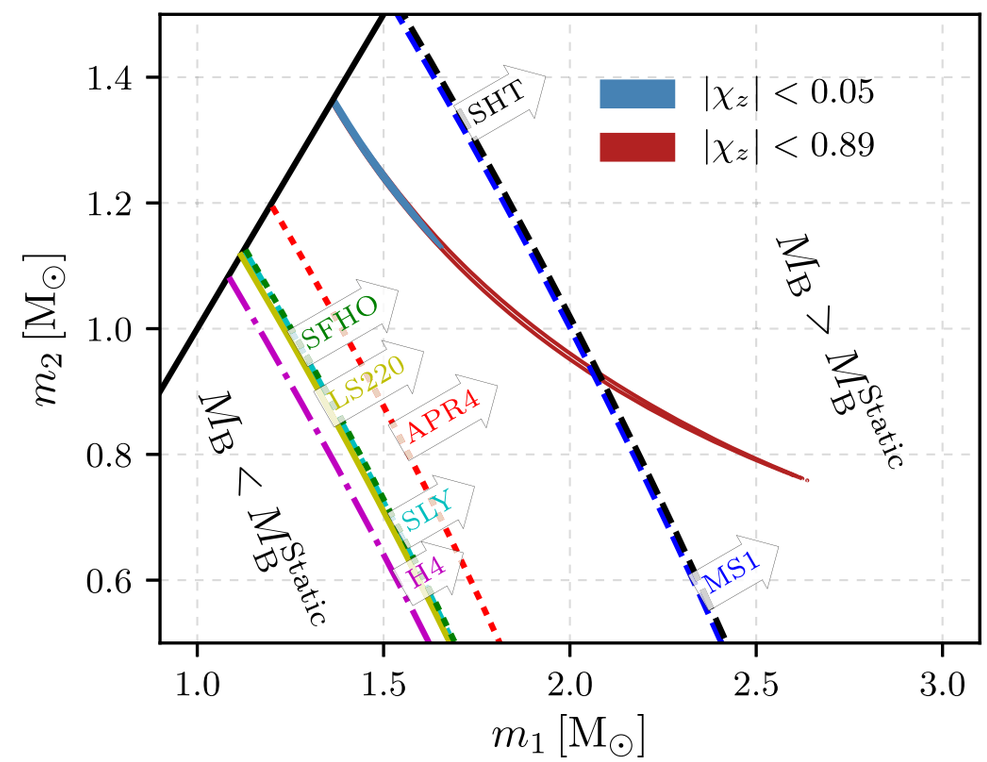


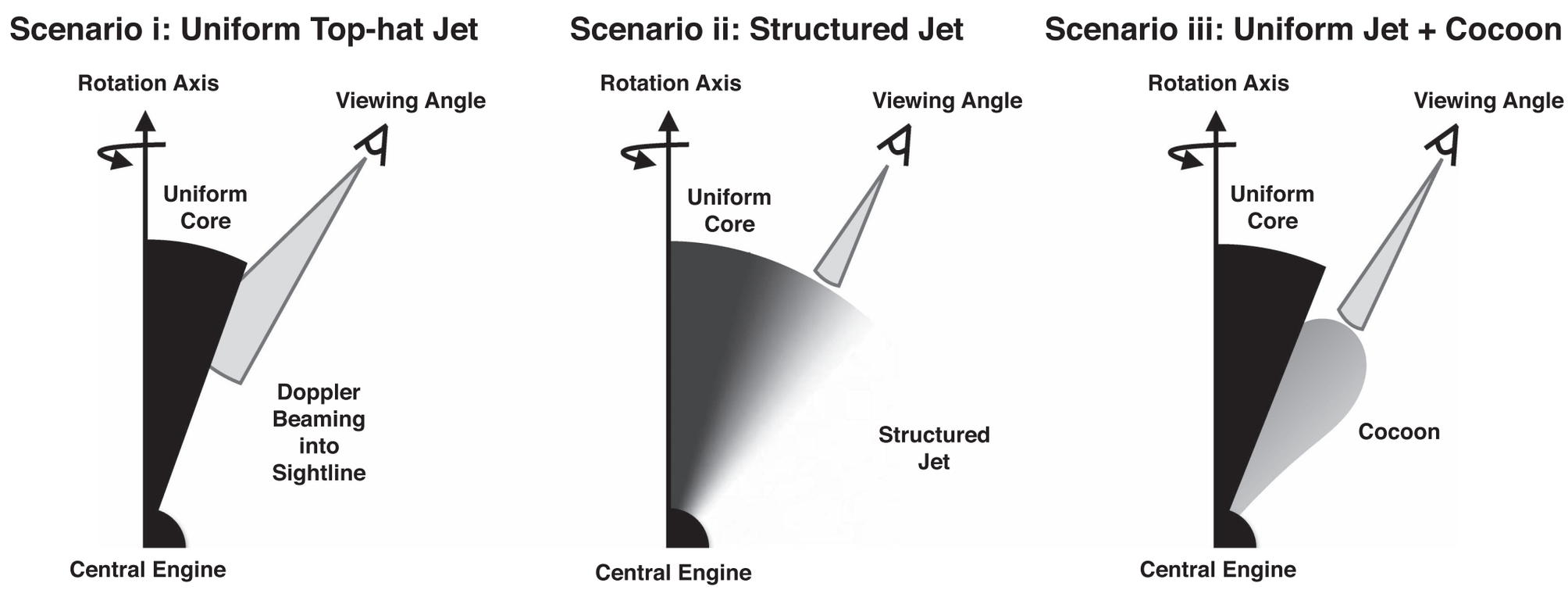
Credit: Anna Franckowiak

GW 170817: implications

- fractional GW/photon speed difference $-3 \times 10^{-15} \leq \Delta v/v_{photon} \leq 7 \times 10^{-16}$
- improvement of a few to 10 on minimal Lorentz invariance violation scenarios
- $\Delta t_{decay}/t_{delay} \sim 1$: internal shock with small difference in shells γ or external shock with $\gamma \sim 300$
- Equation of state of neutron star matter
- Dimness of the GRB → engine structure and viewing geometry

LIGO-Virgo, *Fermi*-GMB & *INTEGRAL* collab.
2017 ApJL 848 L13





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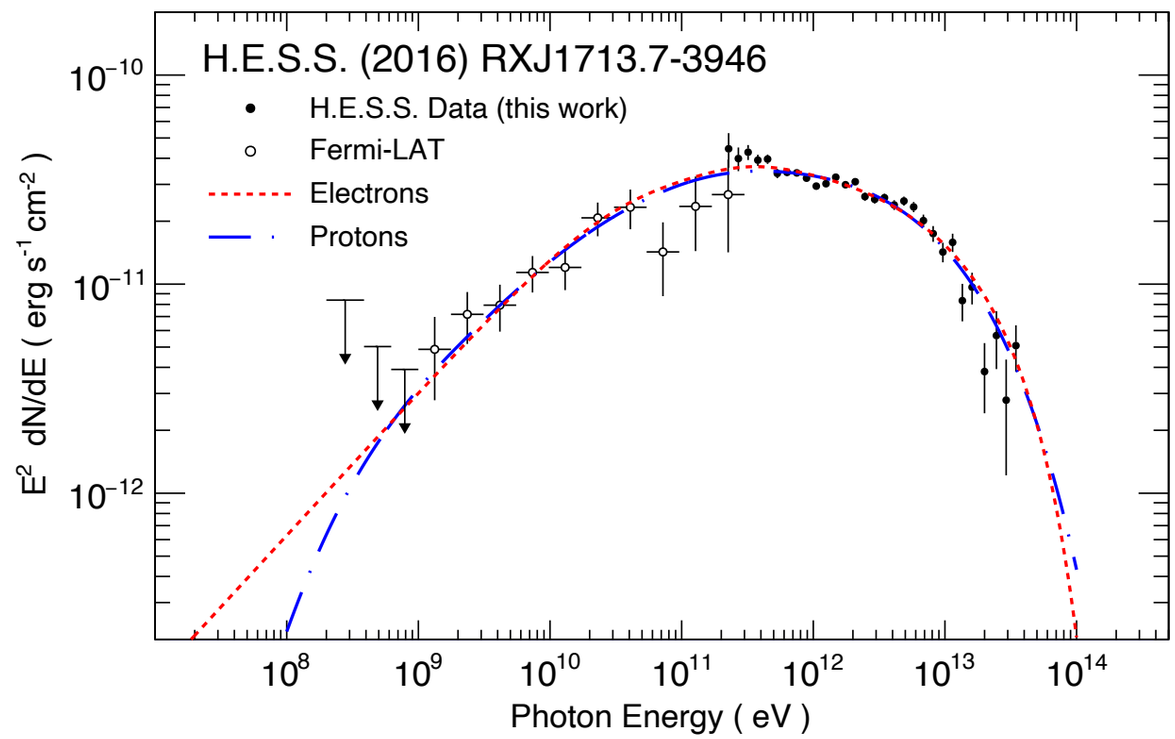
- Future prospects

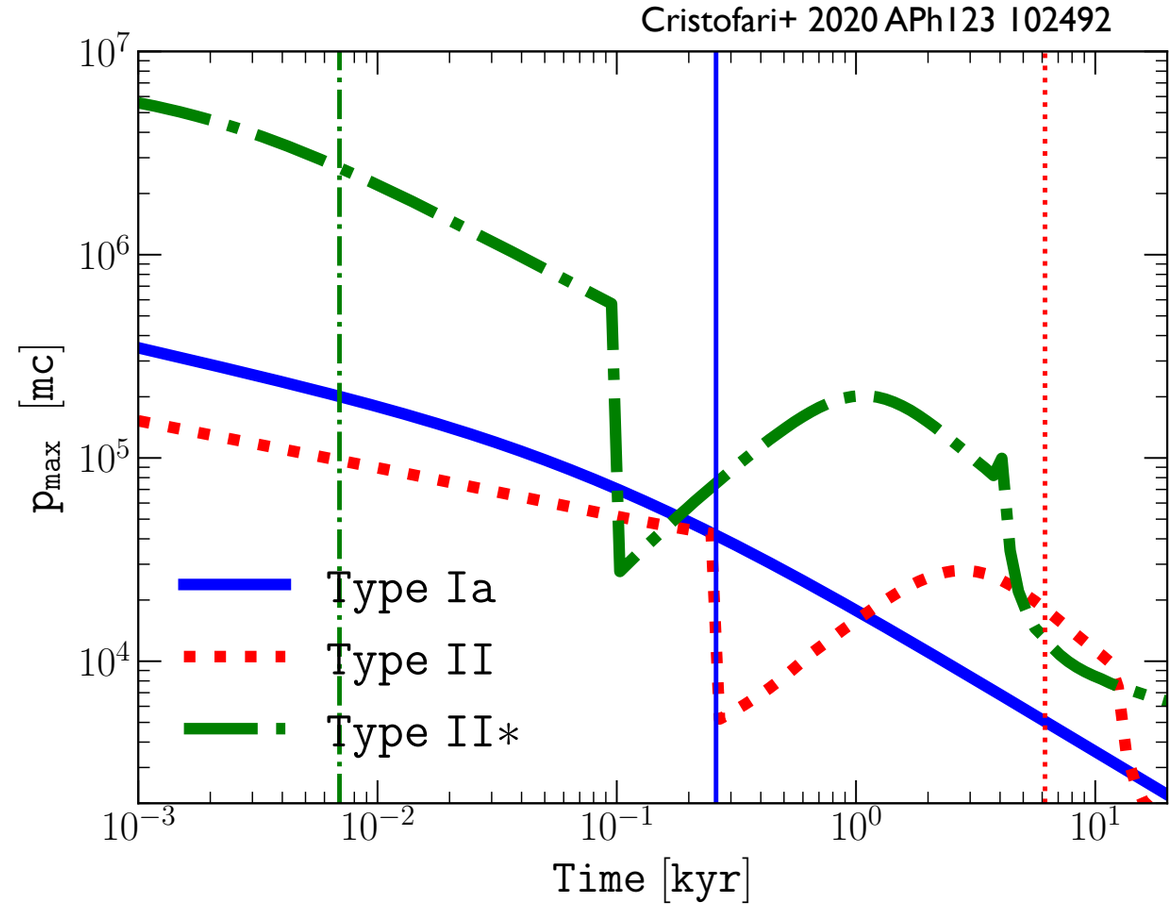
The hunt for PeVatrons

- Difficult to accelerate particles to PeV in the Milky Way
- SNRs challenged
  - observations: steep spectra, cutoffs
  - theory: maximum energy < PeV with rare exceptions
- Was generally believed
  - leptonic accelerators cannot produce effectively > 100 TeV gamma rays due to Klein-Nishina suppression
  - very rare gamma-ray sources > 100 TeV will pinpoint sources of CR nuclei in the Galaxy

H.E.S.S. collab. (2018) A&A 612 A6



Cristofari+ 2020 APh123 102492



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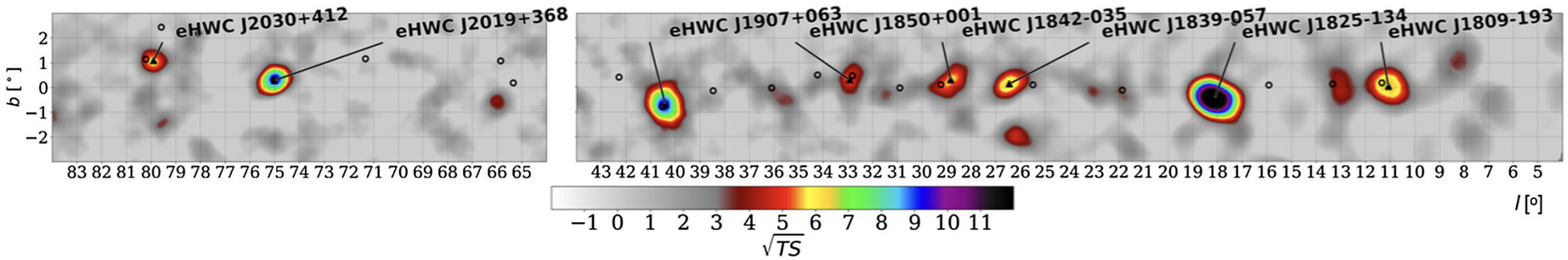
A wealth of UHE sources

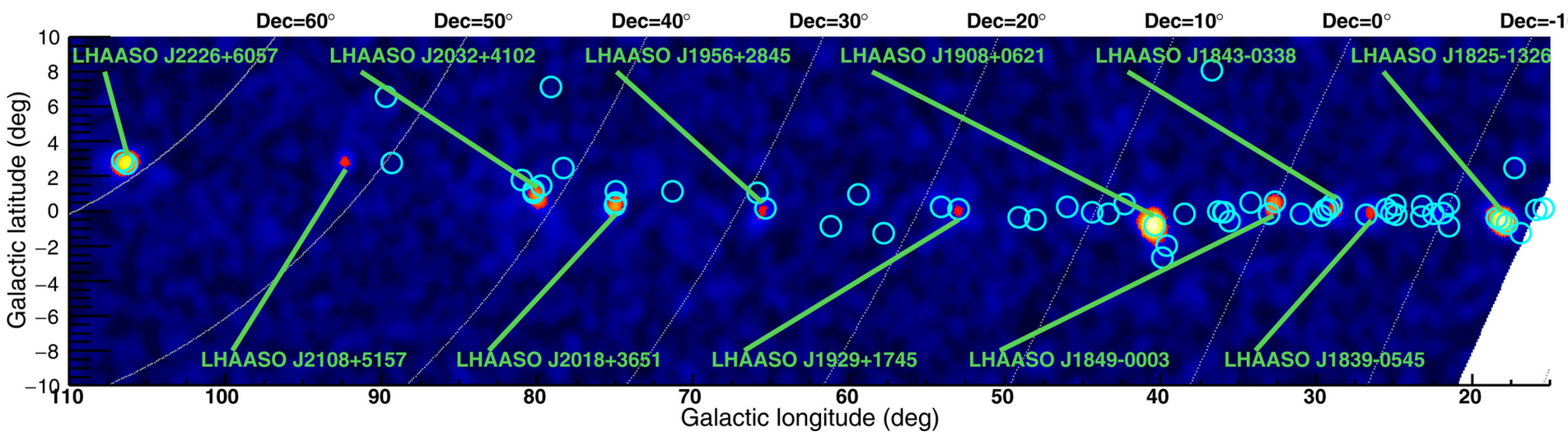
Significant emission > 56 TeV

HAWC collab. (2020) PRL 124 021102



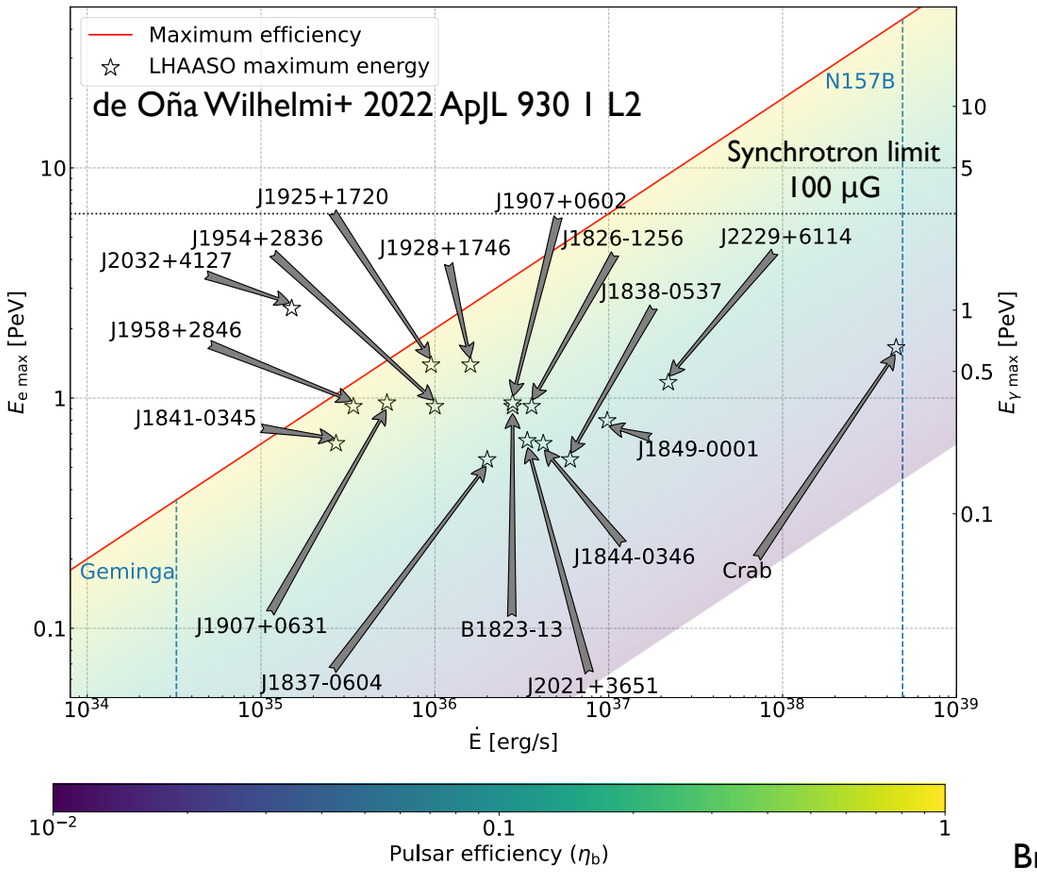
Significant emission > 100 TeV

Cao+ (2021) Nature 594 33



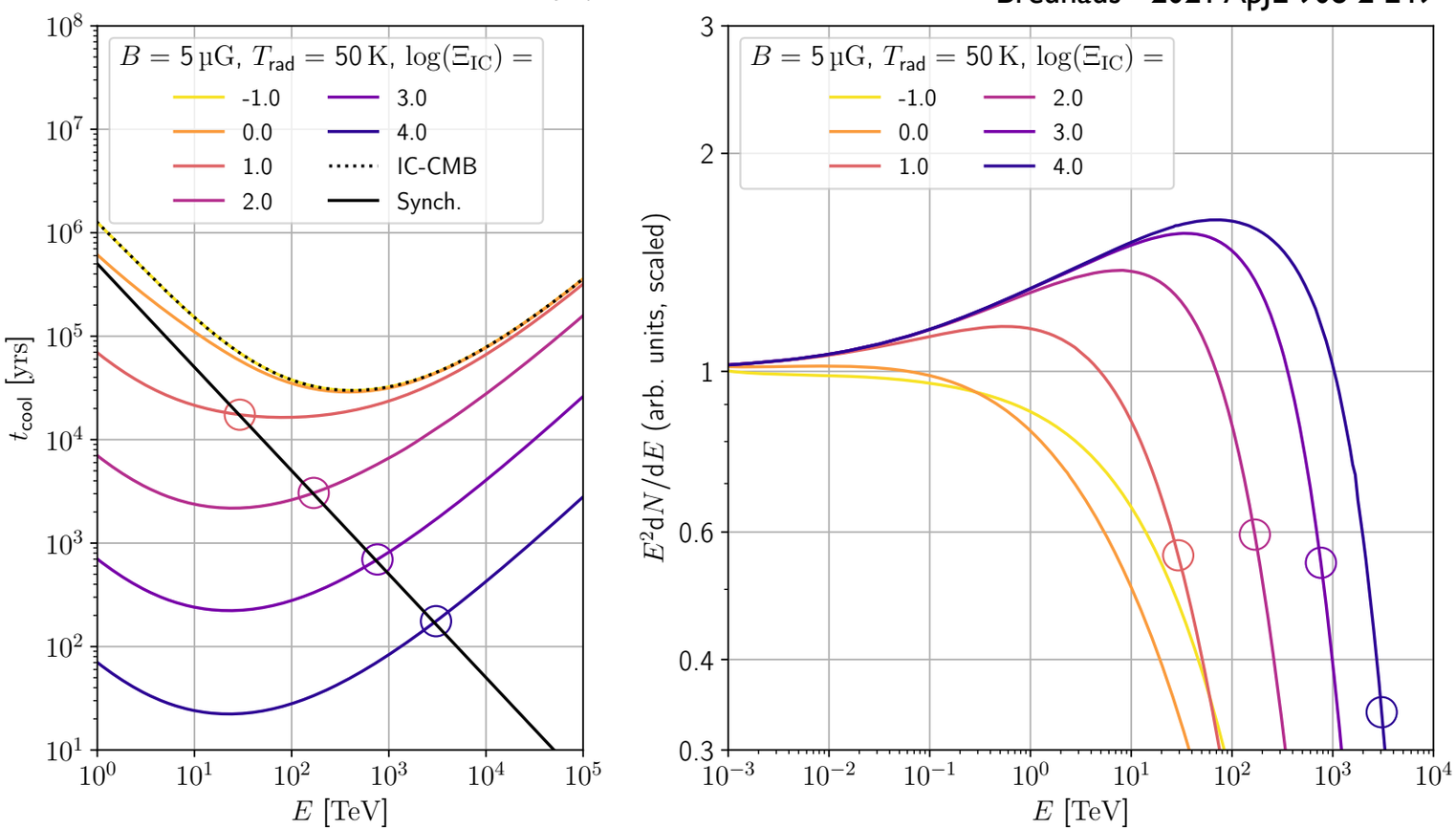
- Technological advantage of LHAASO: underground μ detectors
- Maximum photon energies 200 TeV-1.4 PeV
- Few spectral measurements: cutoff region?

Could UHE sources be leptonic?



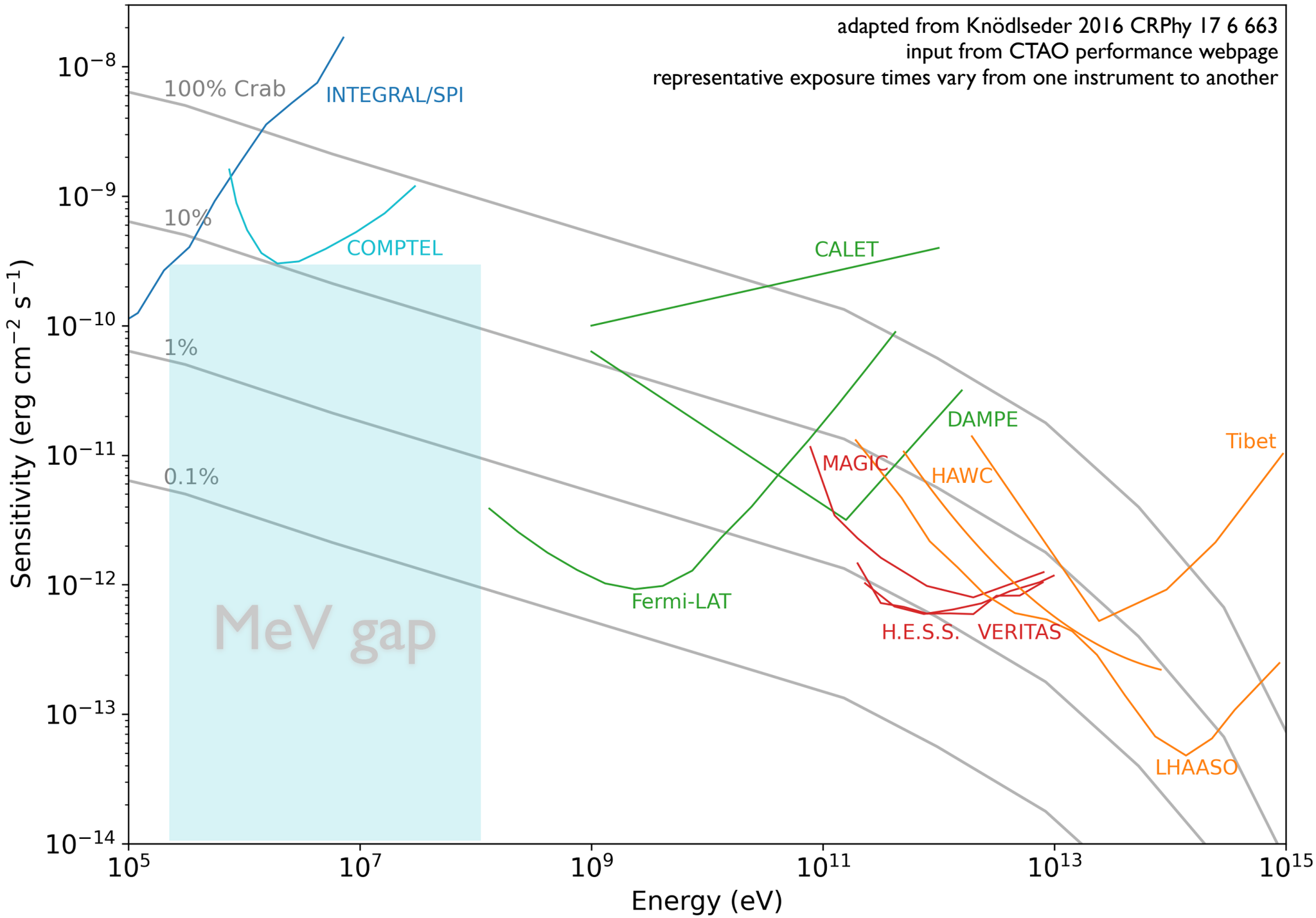
- Maximum photon energy mostly consistent with limit from pulsar potential drop
- Emission > 100 TeV can be expected if energy losses dominated by IC (intense radiation fields)

Breuhaus+ 2021 ApJL 908 2 L49

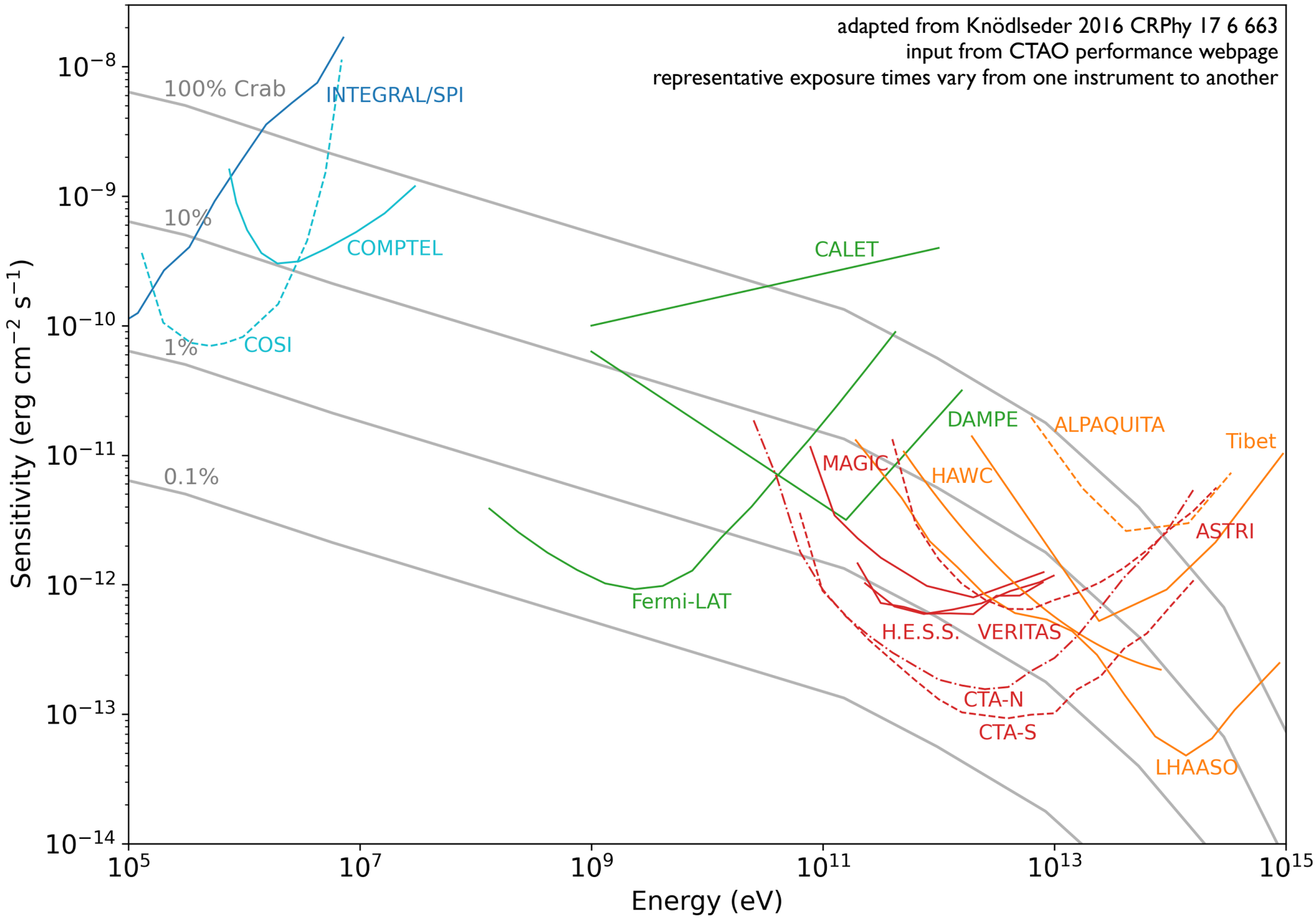


- Introduction
- The coming of age of gamma-ray astronomy
  - Sources
  - Diffuse emission
  - Highlights on recent advances
    - Pulsar halos
    - Star-forming regions
    - VHE emission from gamma-ray bursts
- Revolutions
  - Multimessenger astronomy with gamma rays
  - The PeV frontier
- Future prospects

Current instruments



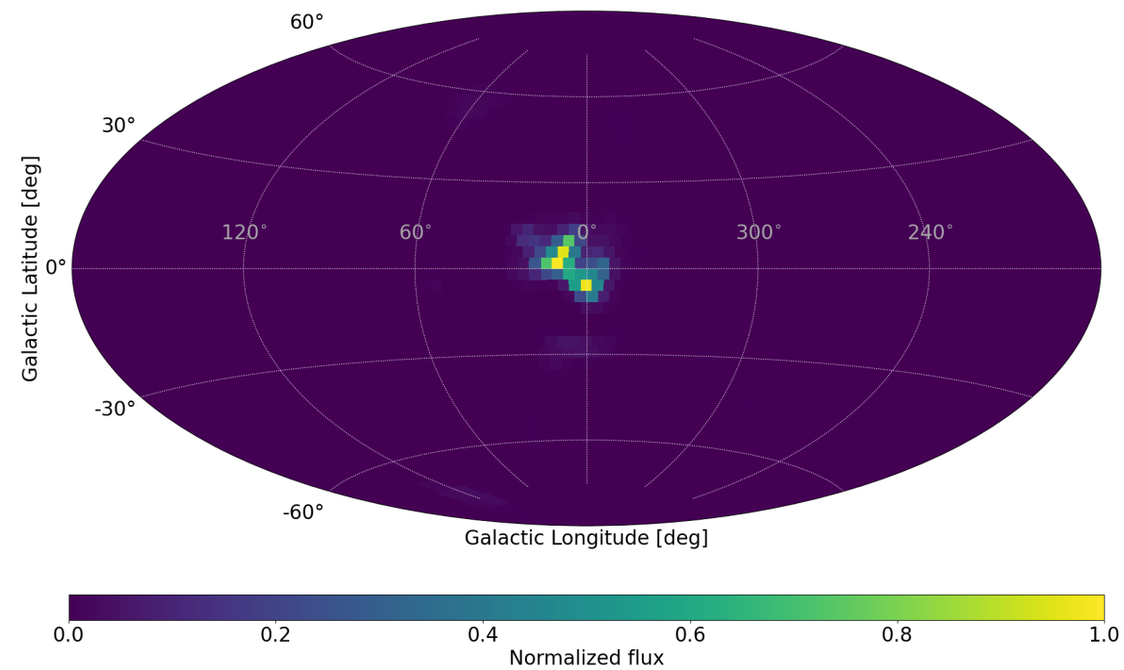
Upcoming instruments



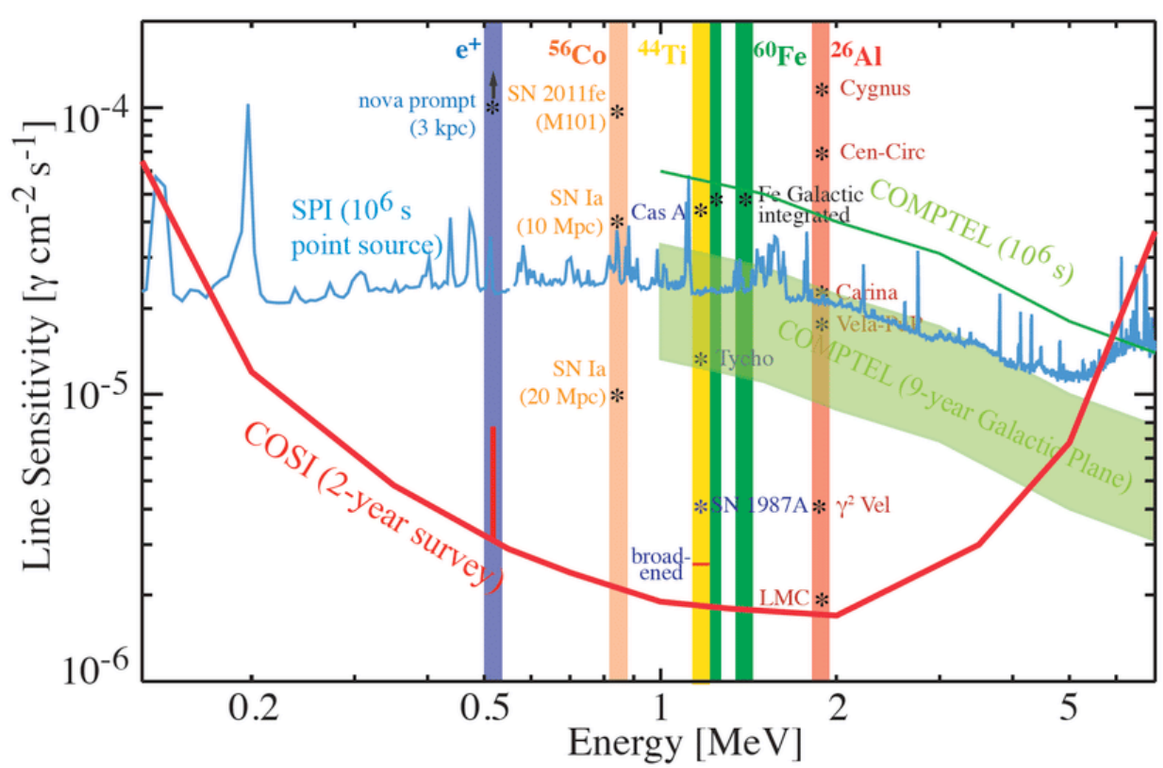
COSI SMEX

- Germanium cross-strip detectors
- Superpressure balloon → SMEX mission scheduled for launch in 2025
- Imaging + spectroscopy + polarimetry
  - positron origin
  - element formation
  - polarization in PWNe, AGNs, GRBs, …

511 keV positron annihilation map
Zoglauer+ 2021 arXiv:2102.13158



Tomsick+ 2020 Astro2020



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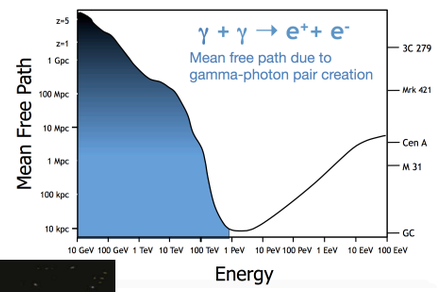
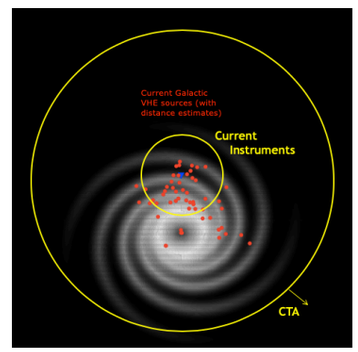
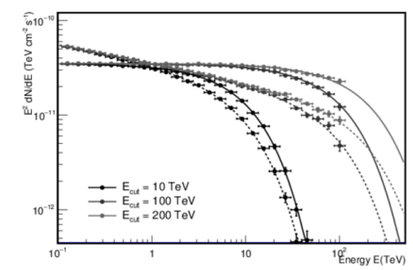
CTA

- Two arrays (N: La Palma, Spain, S: Paranal, Chile)
- > 60 Cherenkov telescopes optimised for different energy ranges
- Construction expected to start in 2023 and last 5 years



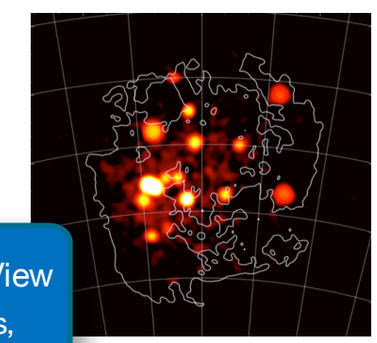


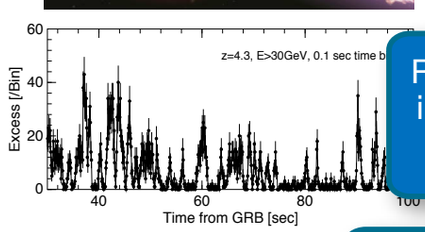


Energies down to 20 GeV
→ Cosmology++

10 x Sensitivity, Large Collection Area
→ all topics

Energies up to 300 TeV
→ Pevatrons

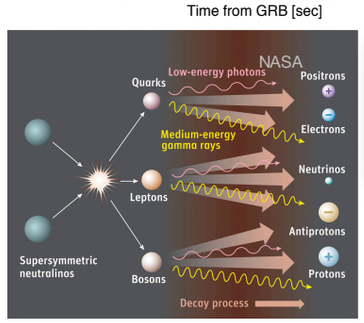




Rapid Slewing in 20 seconds
→ transients

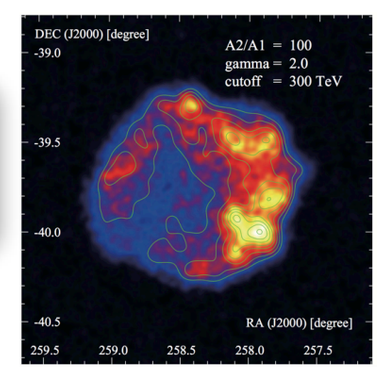
cta

8° Field of View
→ surveys, extended objects

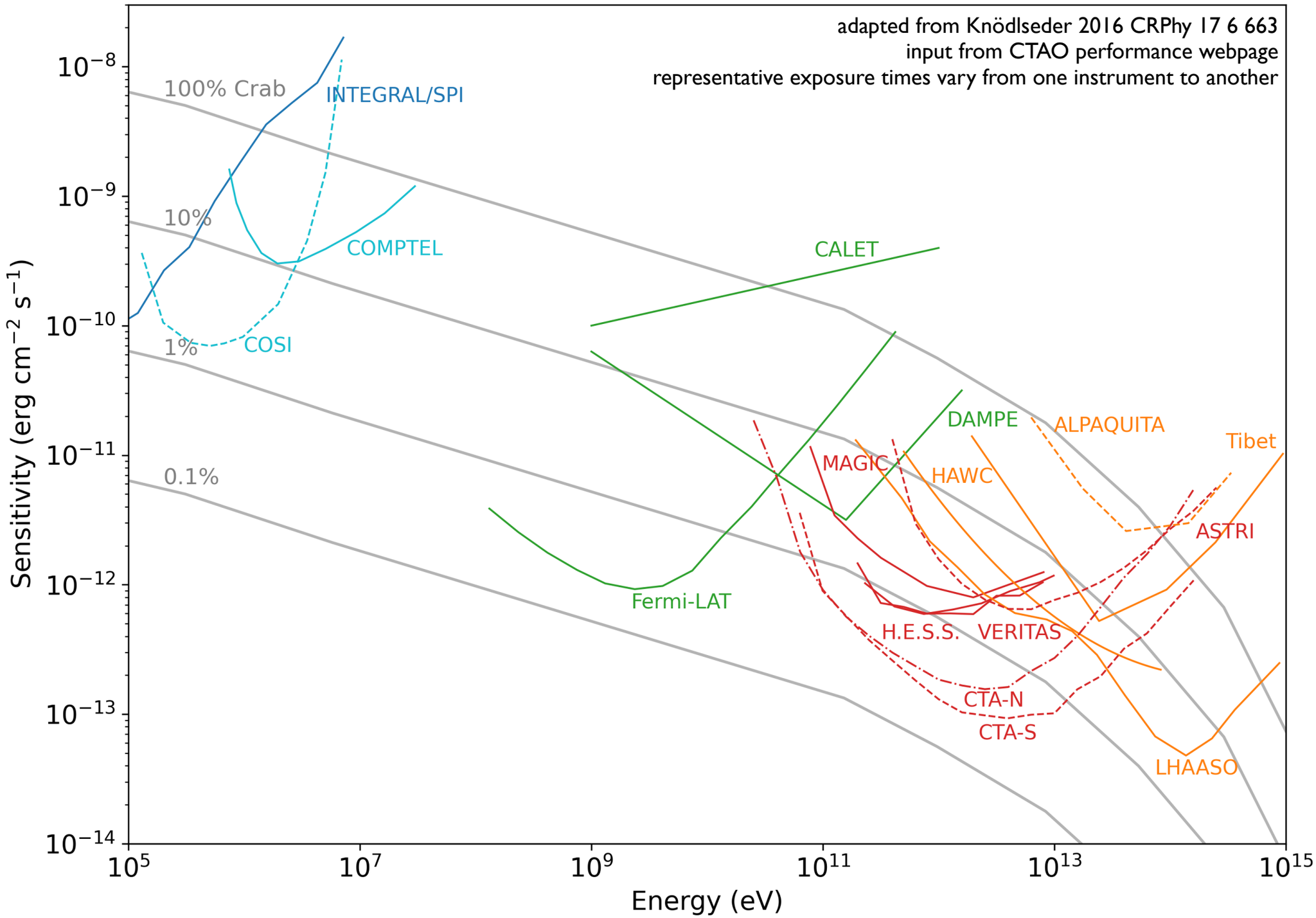


10% Energy Resolution
→ lines, features

Few ' Angular Resolution
→ morphology



Upcoming instruments



Instrument concepts