Gamma-ray Astronomy: Latest Results and Prospects

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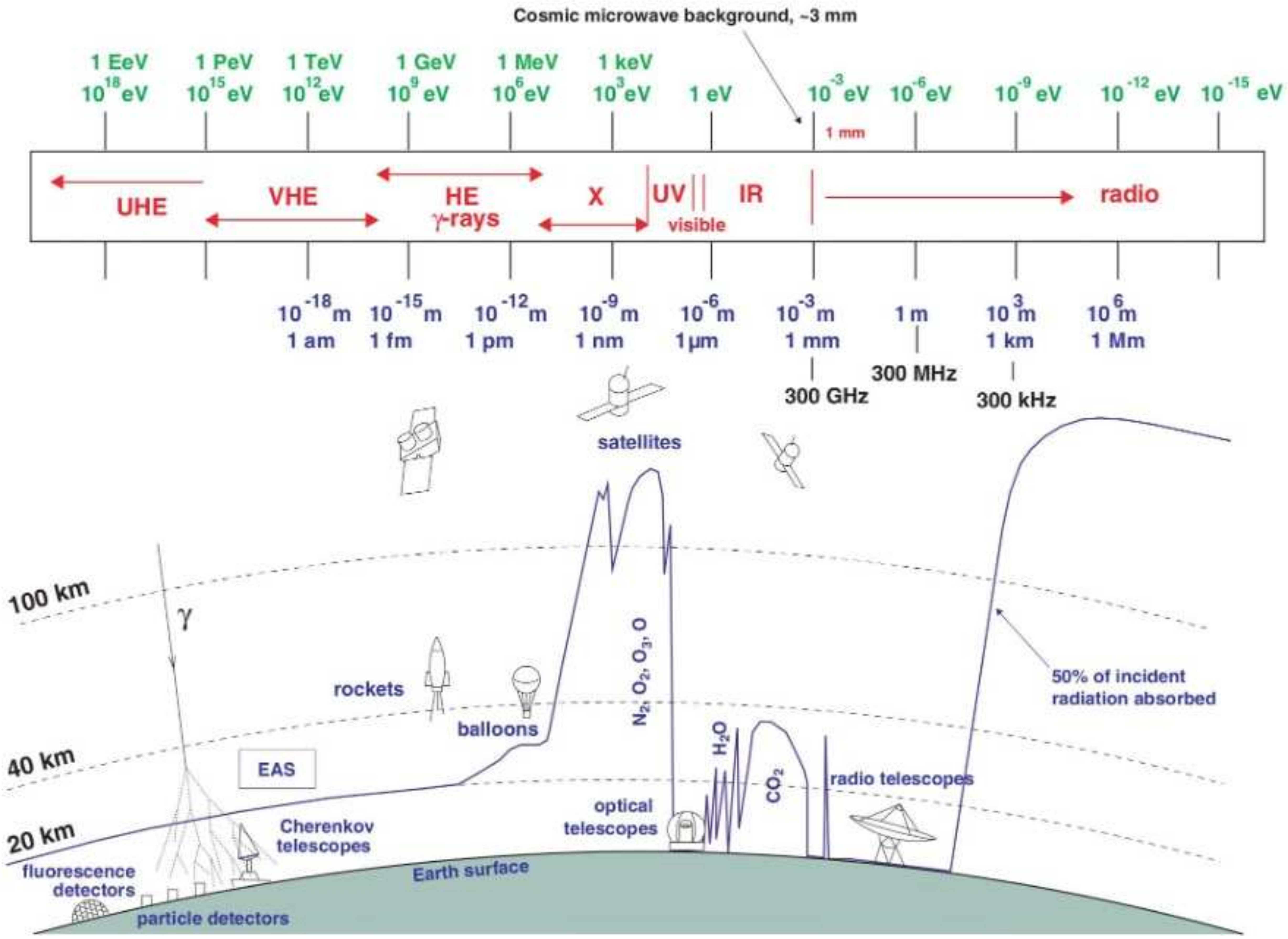
EPS-HEP Marseille 2024

Artwork by Sandbox Studio, Chicago with Lexi Fodor

Gamma-ray astronomy

- γ-rays indicate the presence of a parental population of high-energy massive particles
- Little effect from absorption in the galaxy
- Carry information directly from the sites of acceleration

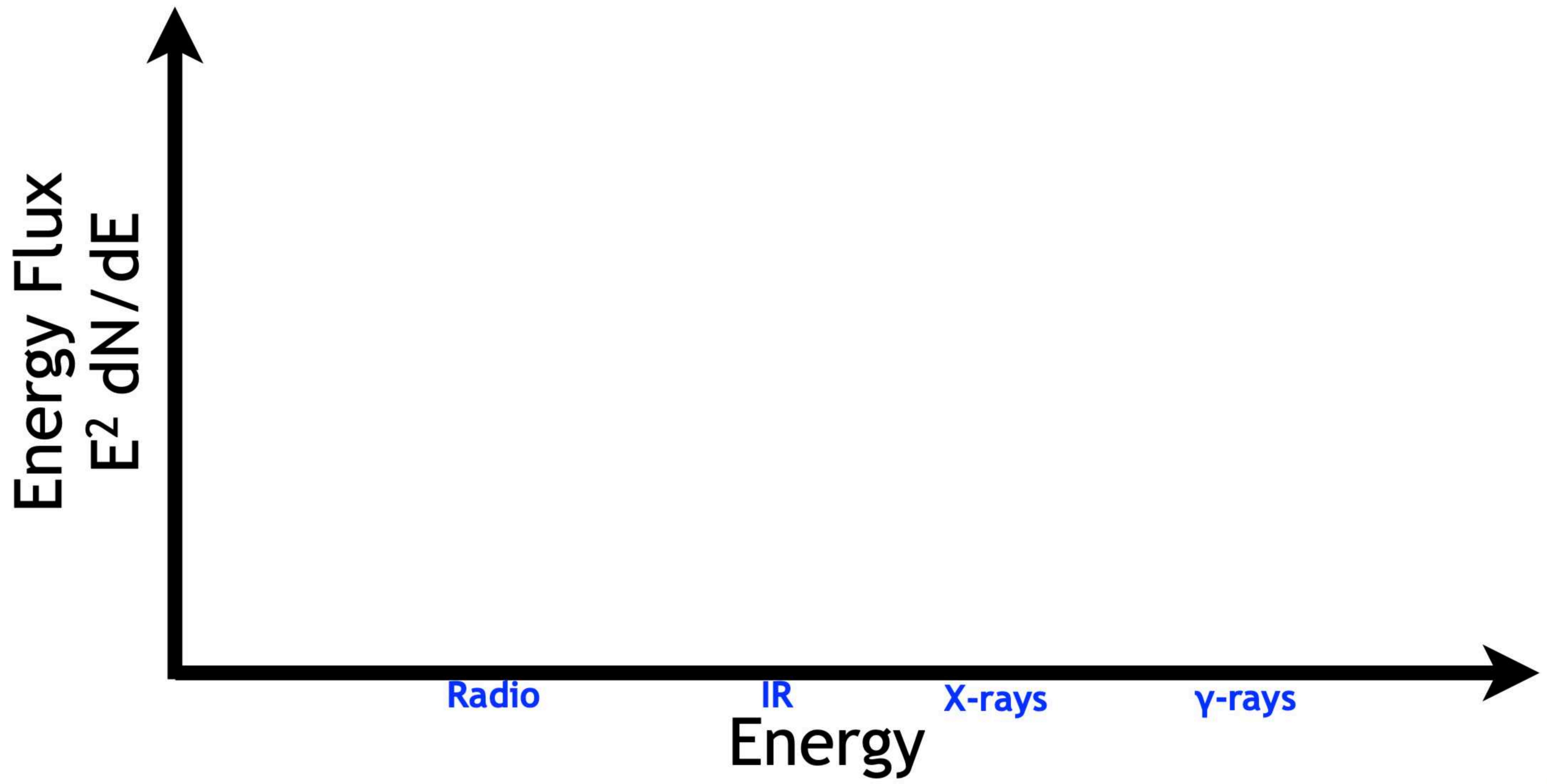


Credit: K. Satalecka

Very High Energy gamma-rays

Only produced by non-thermal processes

ELECTRON POPULATION **PROTON POPULATION**

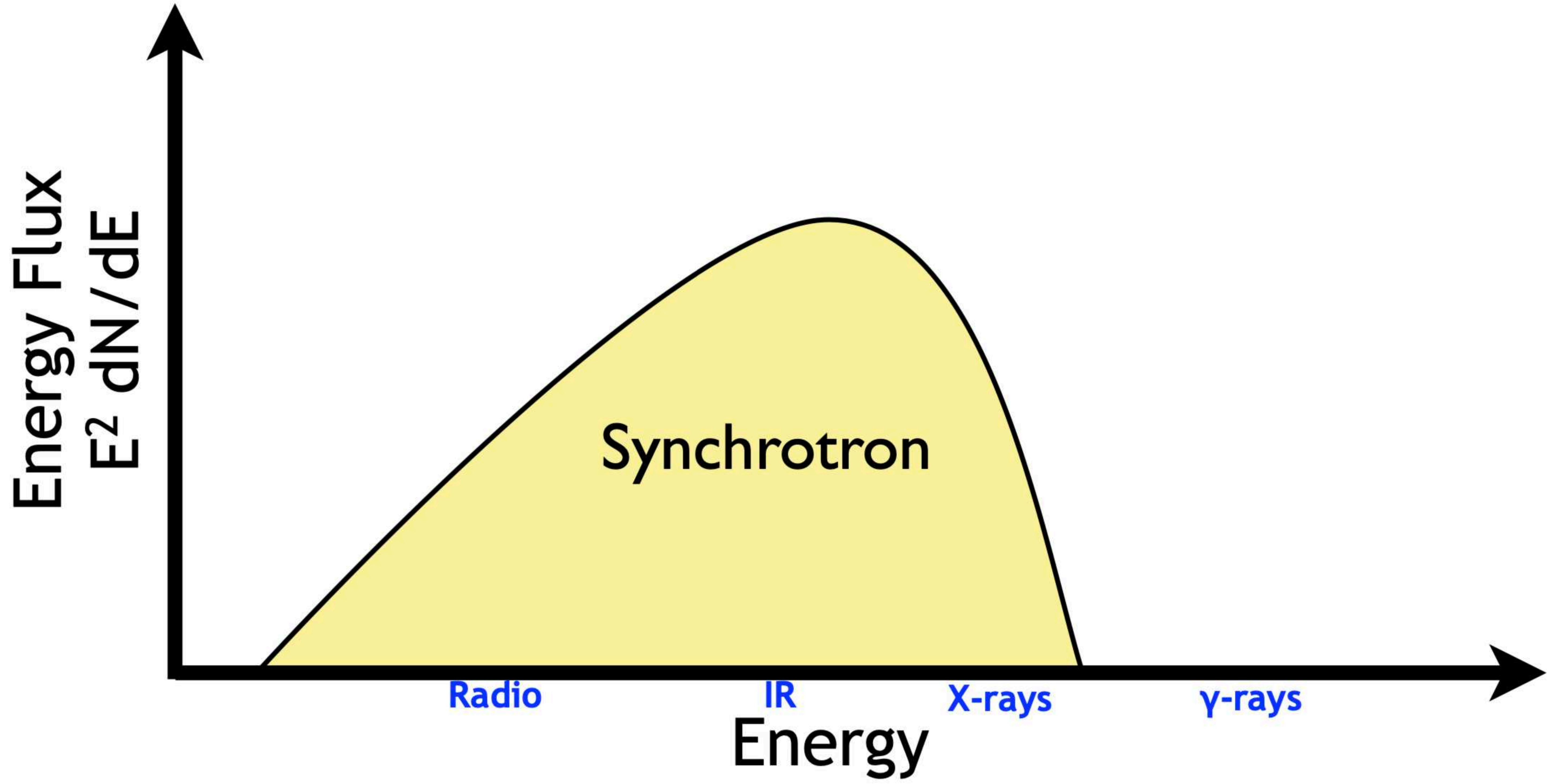


Very High Energy gamma-rays

Only produced by non-thermal processes

ELECTRON POPULATION $+ \vec{B}$ **FIELD**

PROTON POPULATION

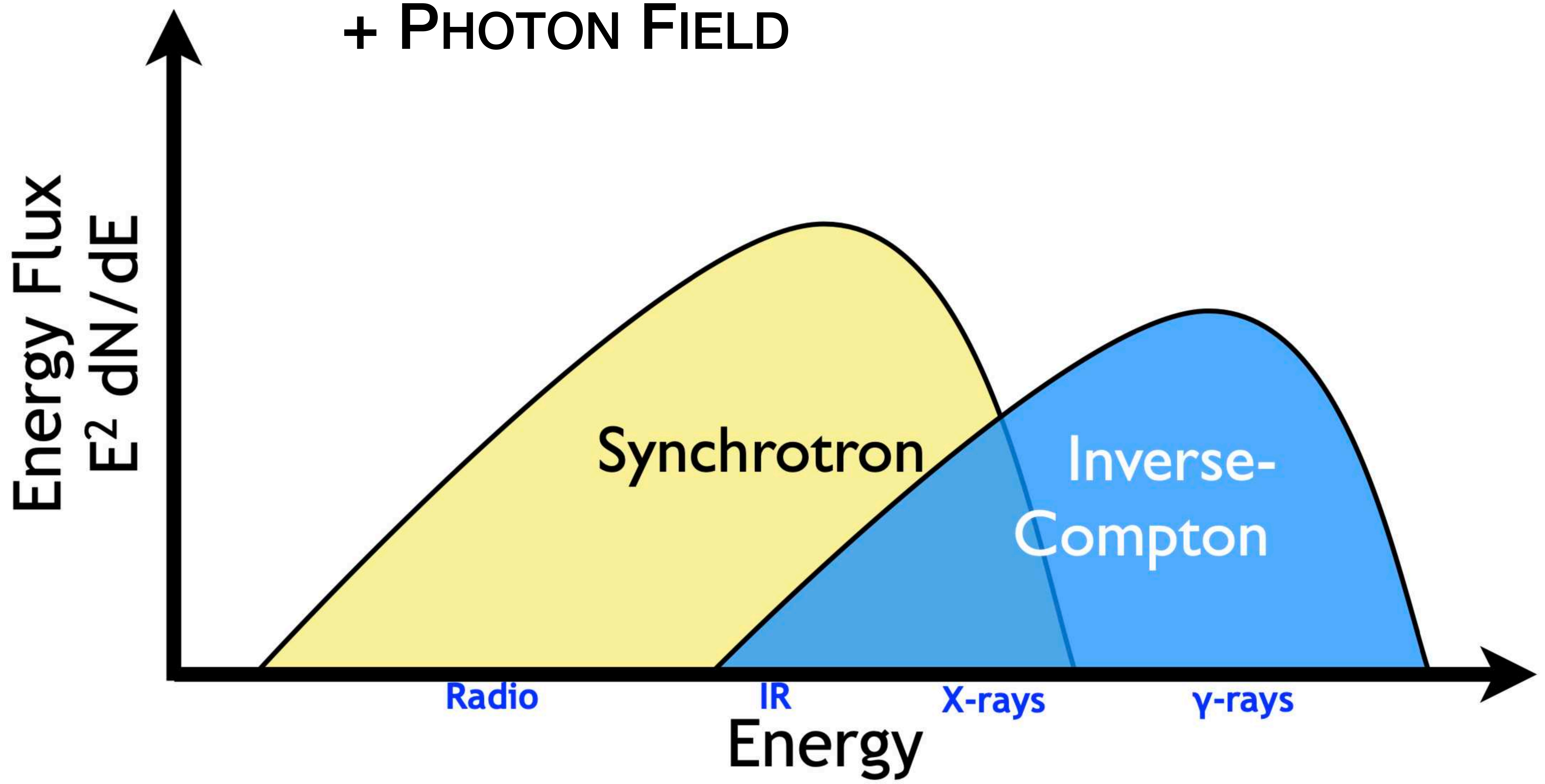


Very High Energy gamma-rays

Only produced by non-thermal processes

ELECTRON POPULATION
$+\vec{B}$ FIELD
+ PHOTON FIELD

PROTON POPULATION

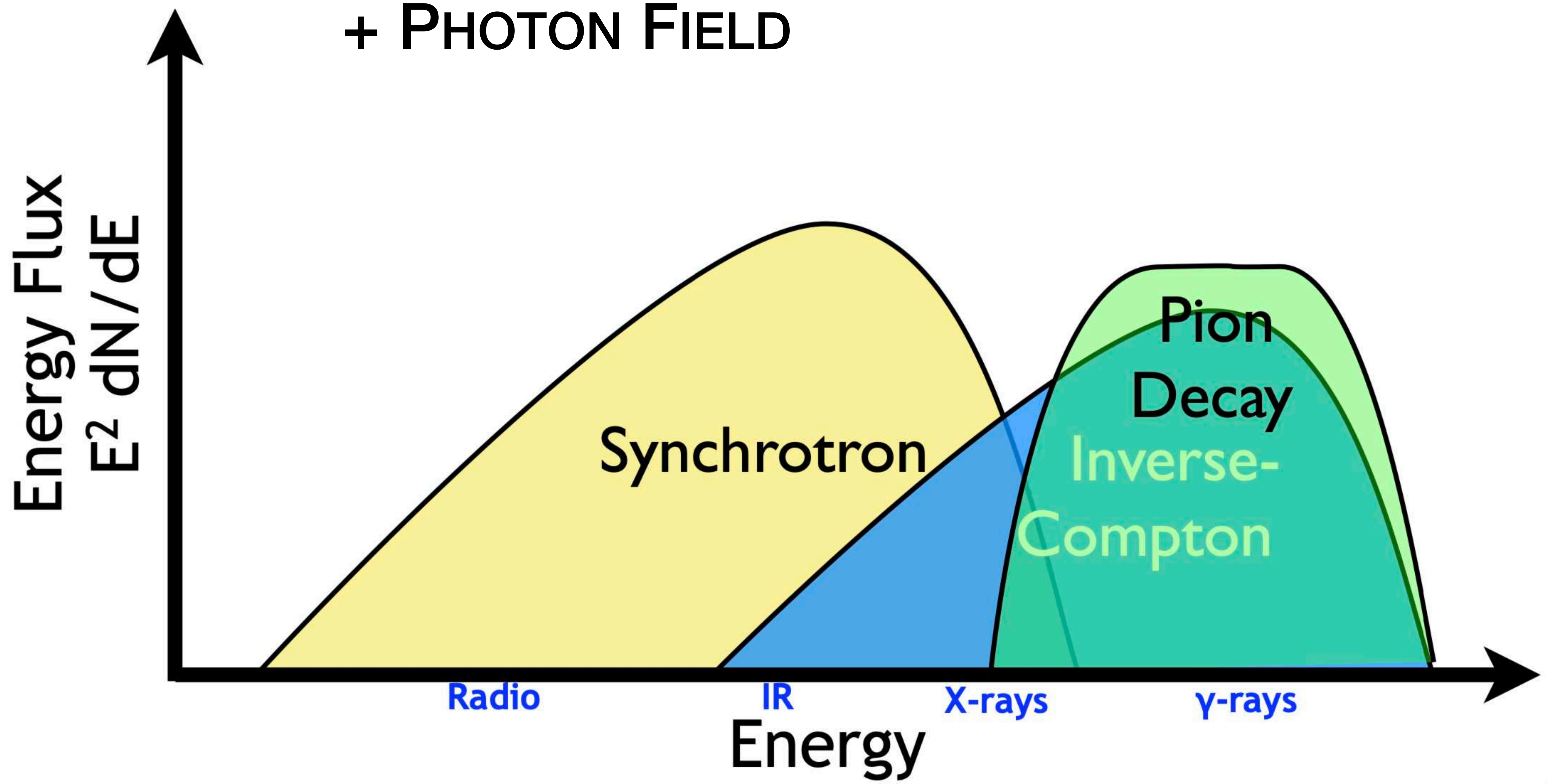


Very High Energy gamma-rays

Only produced by non-thermal processes

ELECTRON POPULATION
+ $\vec{B}$ FIELD
+ PHOTON FIELD

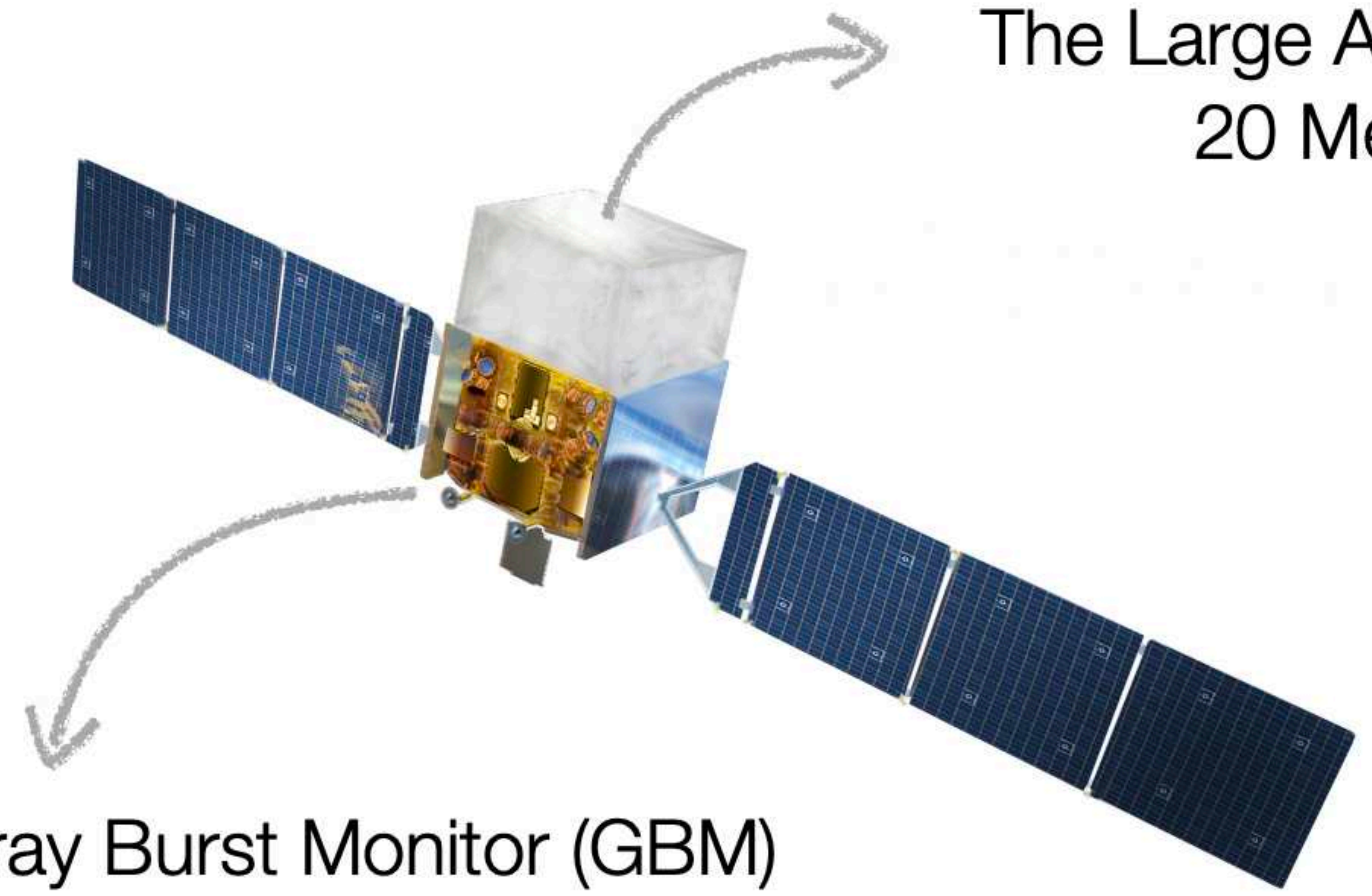
PROTON POPULATION
+ TARGET MATERIAL



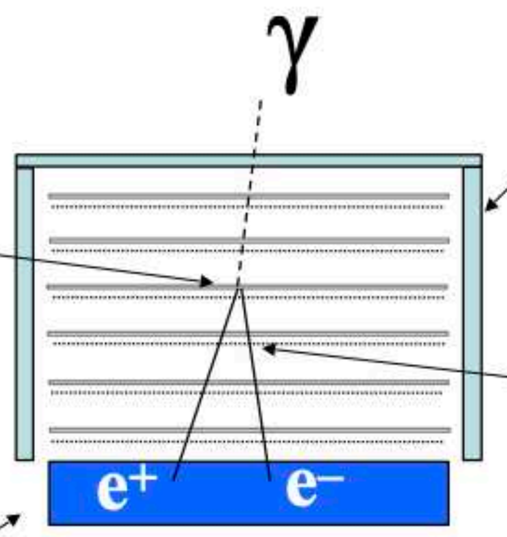
γ-ray observatories

Space-based: Fermi-LAT

The Large Area Telescope (LAT)
20 MeV - 400 GeV



Gamma ray **converts** to an e^+ e^- pair in a high density foil layer.

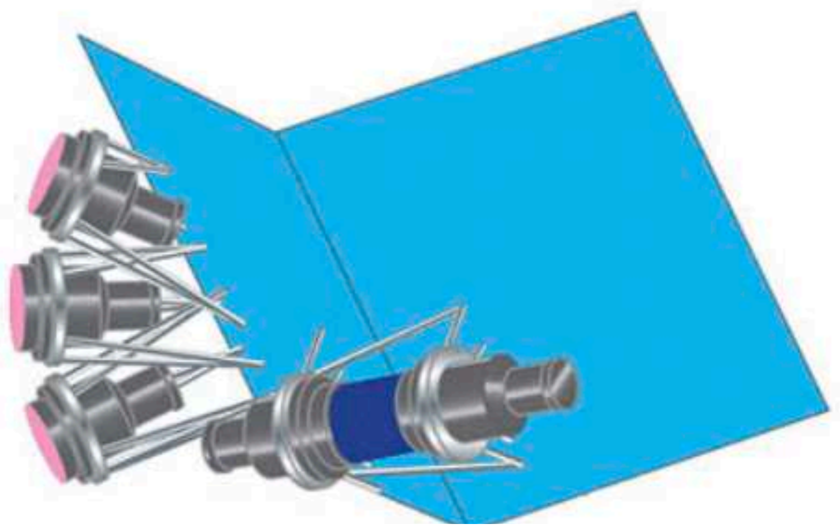


An **anti-coincidence detector** identifies and rejects incoming charged particles.

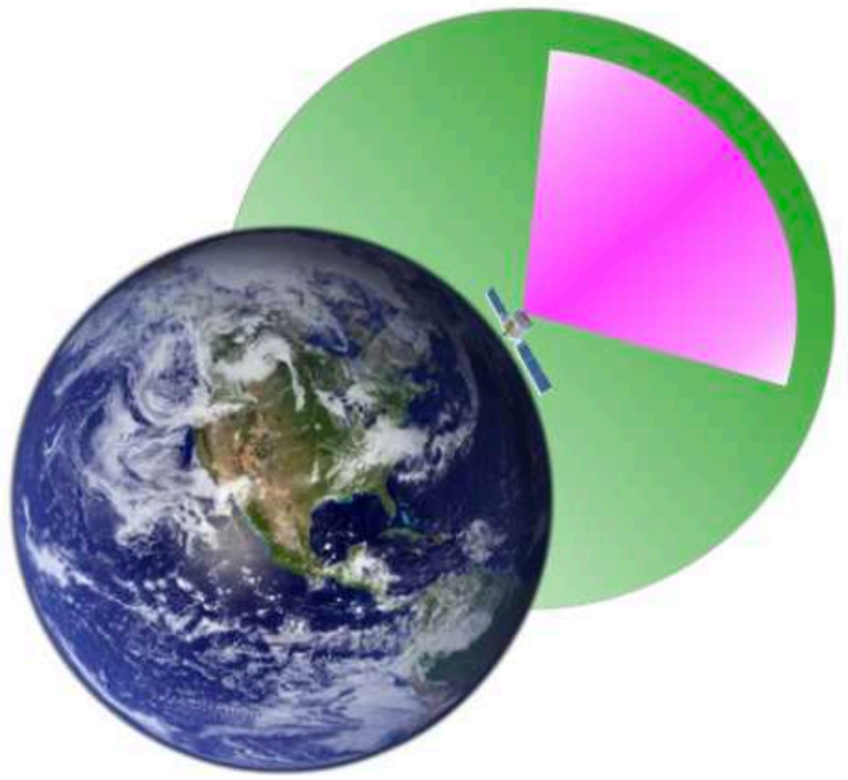
The **tracks** of charged particles in the instrument are recorded by sensors. They are used to determine the direction of the gamma-ray source.

The photon energy is determined from measured energy deposited in the **calorimeter**.

The Gamma ray Burst Monitor (GBM)
8 keV - 30 MeV



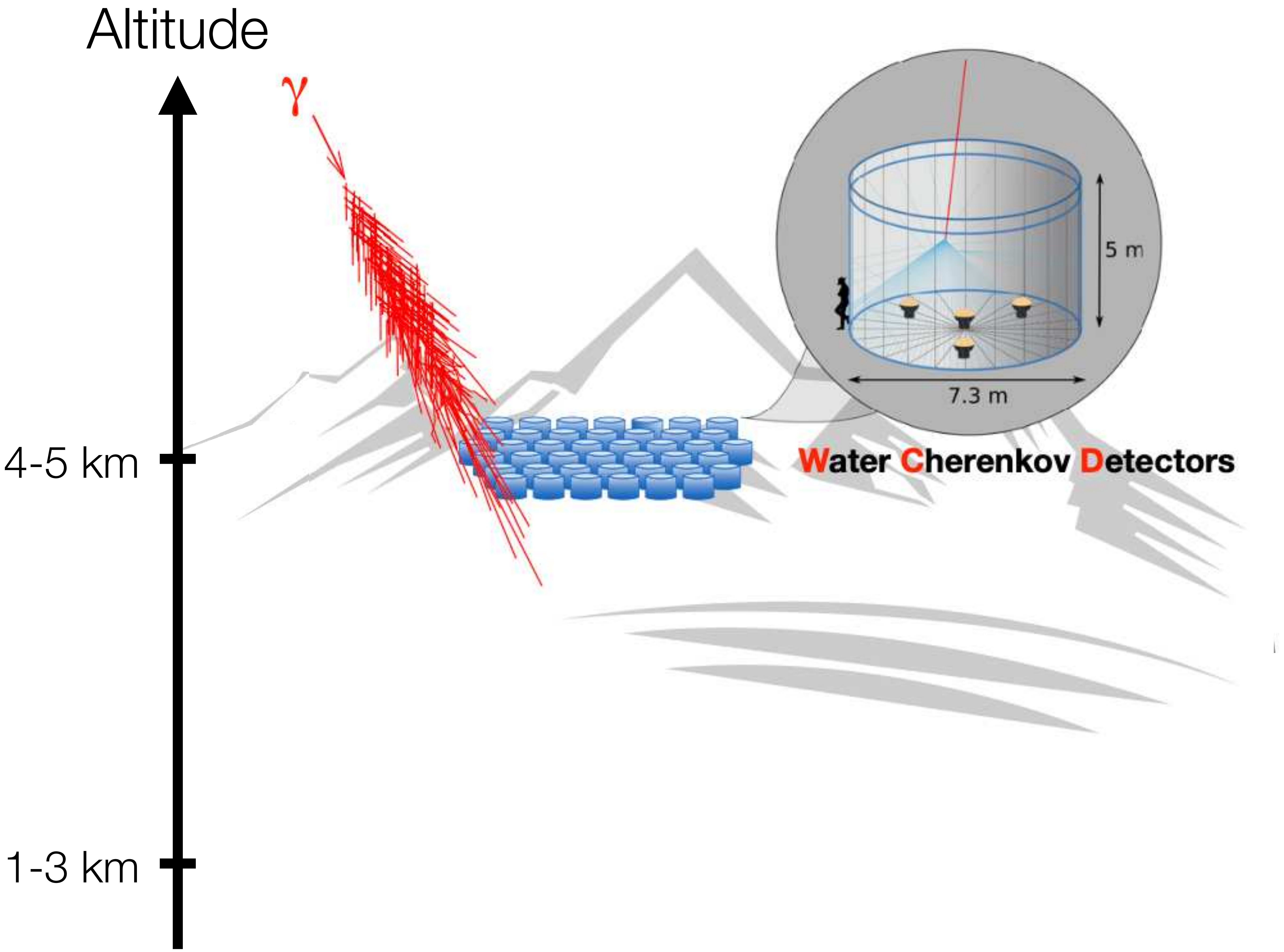
Scintillation detectors are distributed around the spacecraft with different viewing angles in order to determine the direction of a burst by comparing the count rates of different detectors

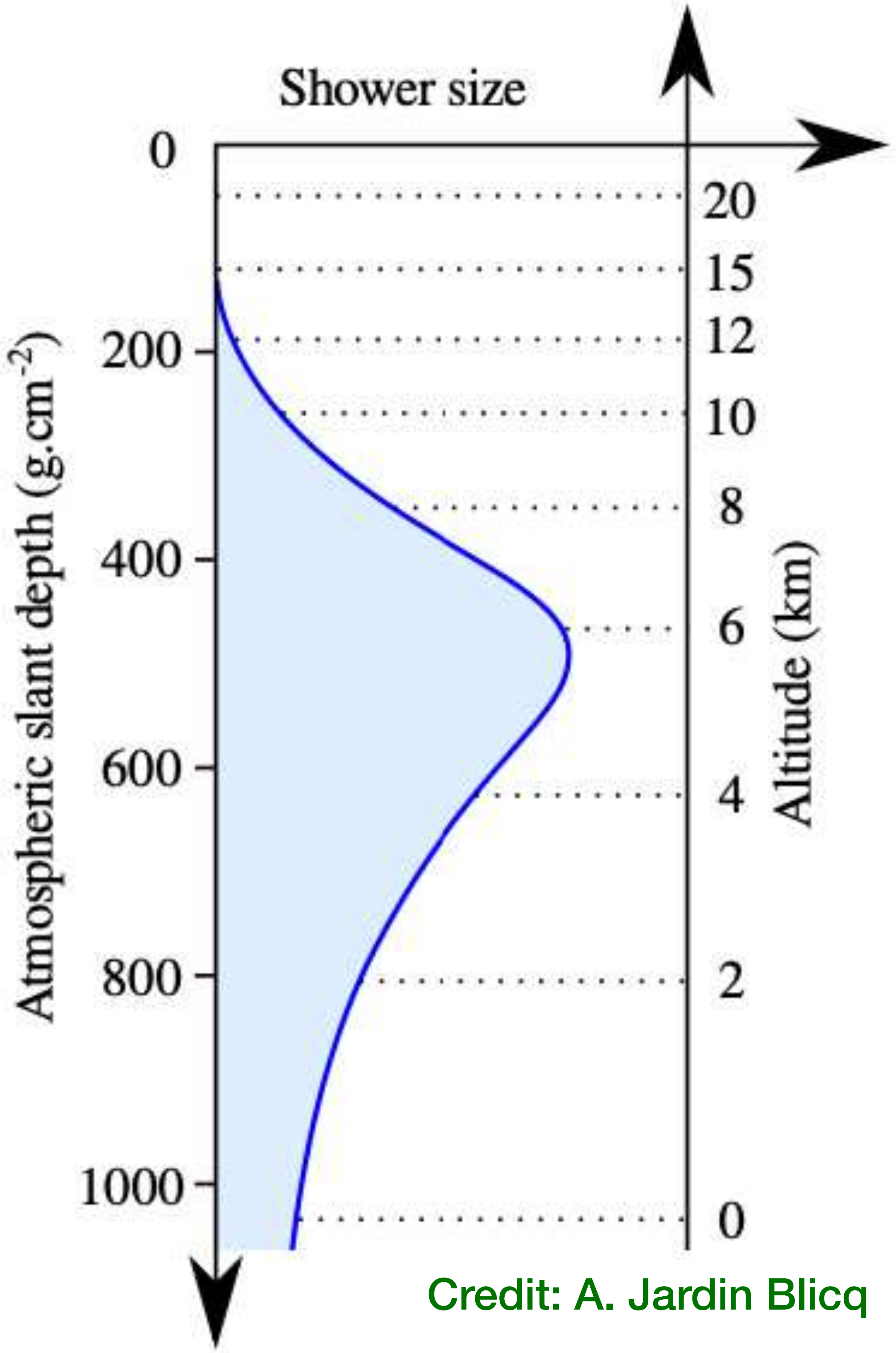


Credit: Liz Hays and Judy Racusin (Fermi school 2021)

γ-ray observatories

Ground-based: WCD and IACTs

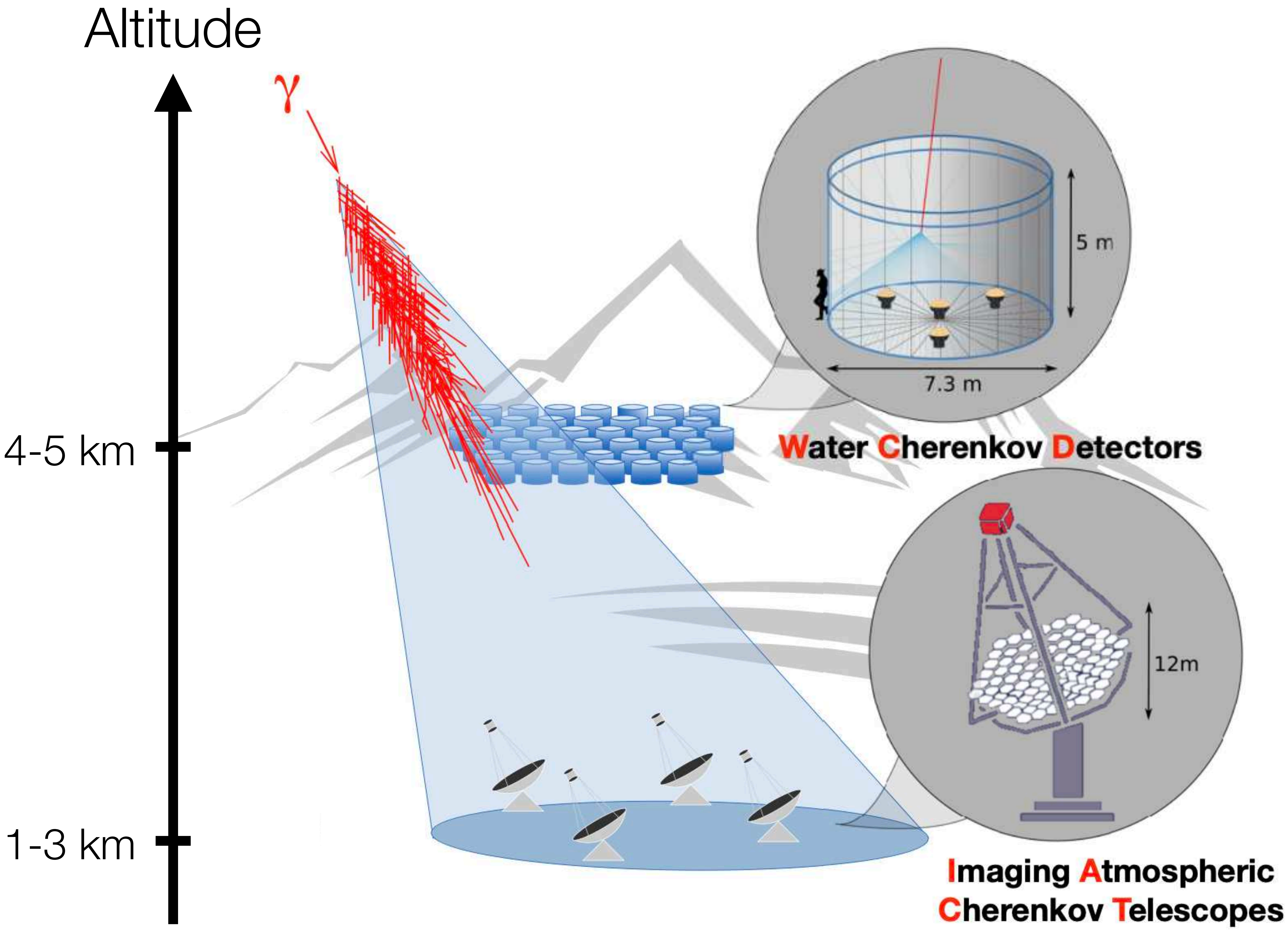


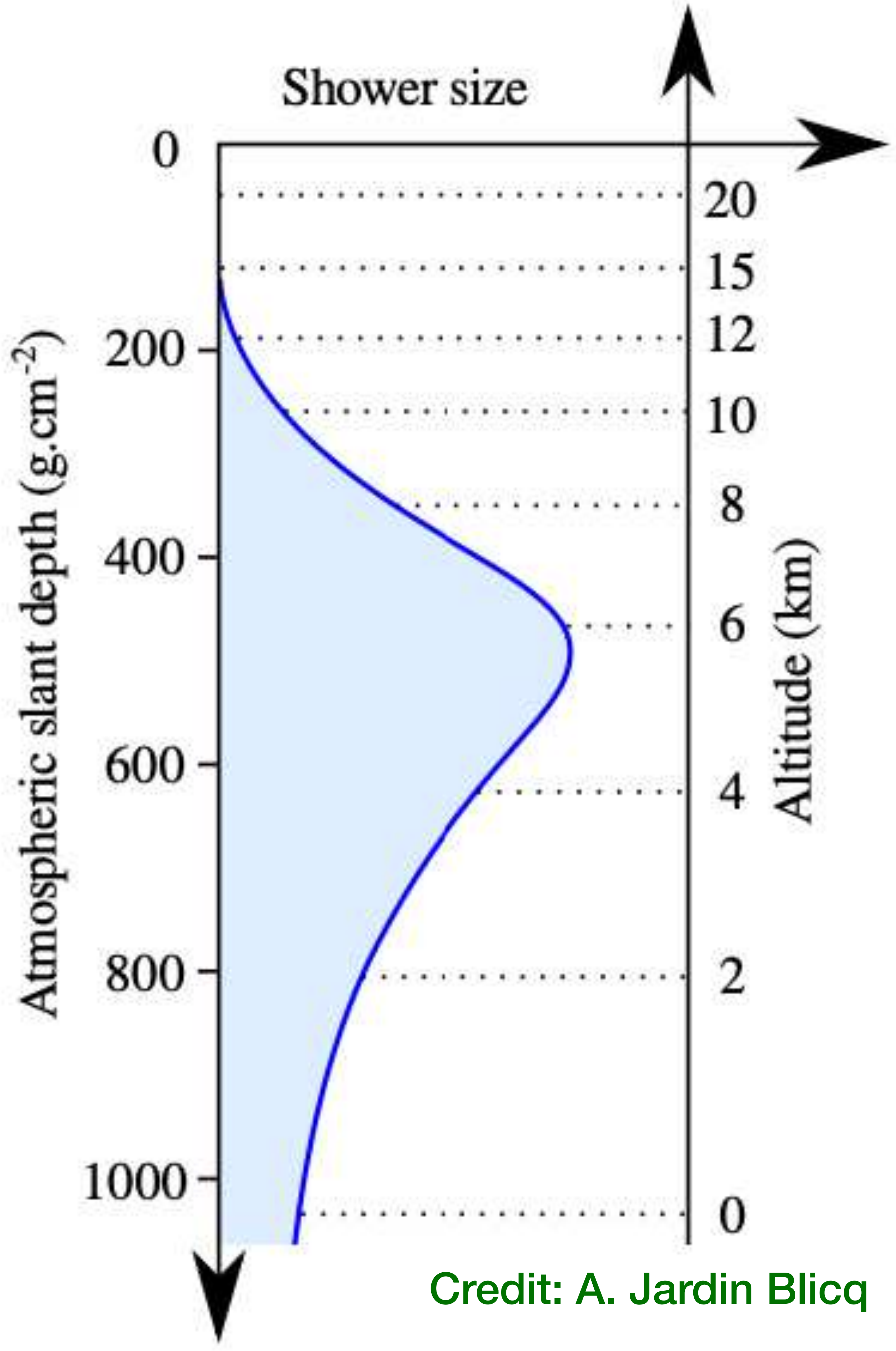


Credit: A. Jardin Blicq

ɣ-ray observatories

Ground-based: WCD and IACTs





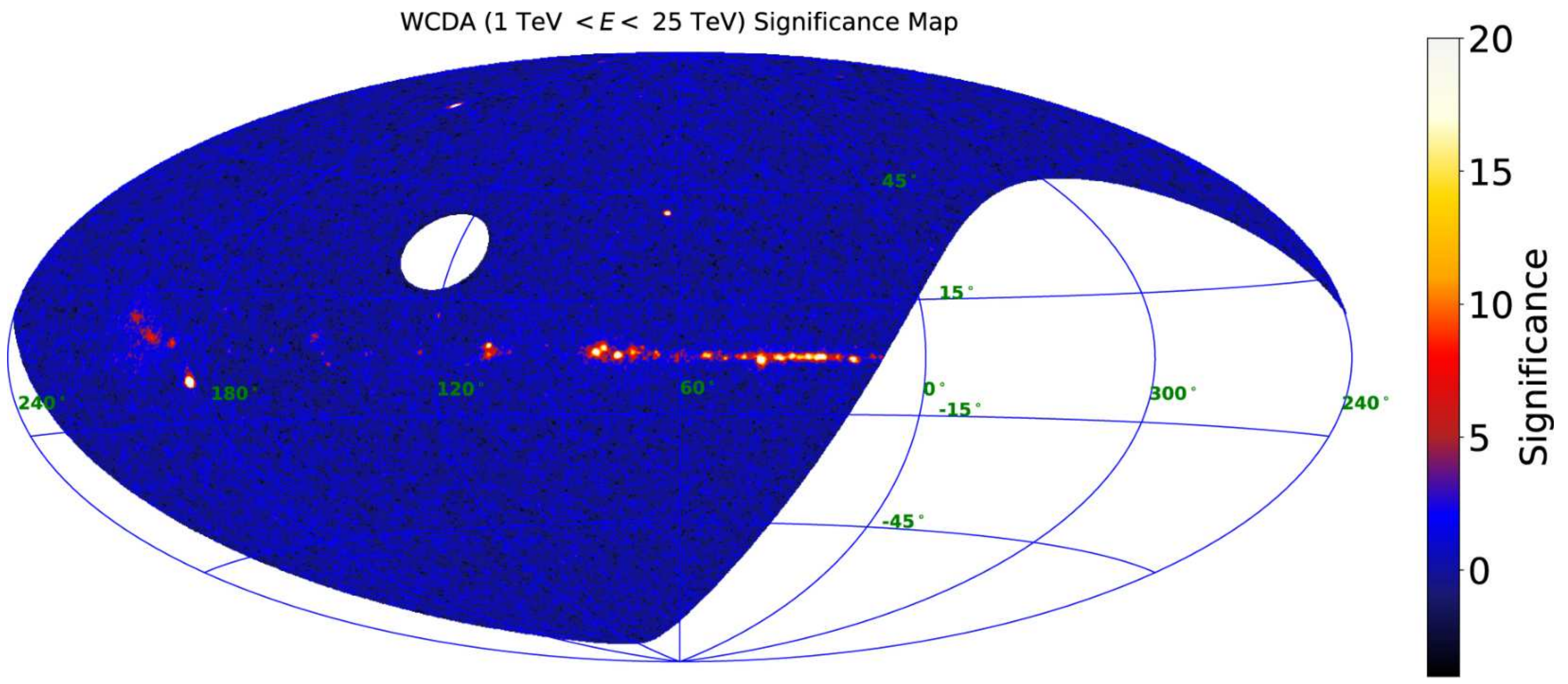
Credit: A. Jardin Blicq

ɣ-ray observatories

WCDs vs IACTs

WCD

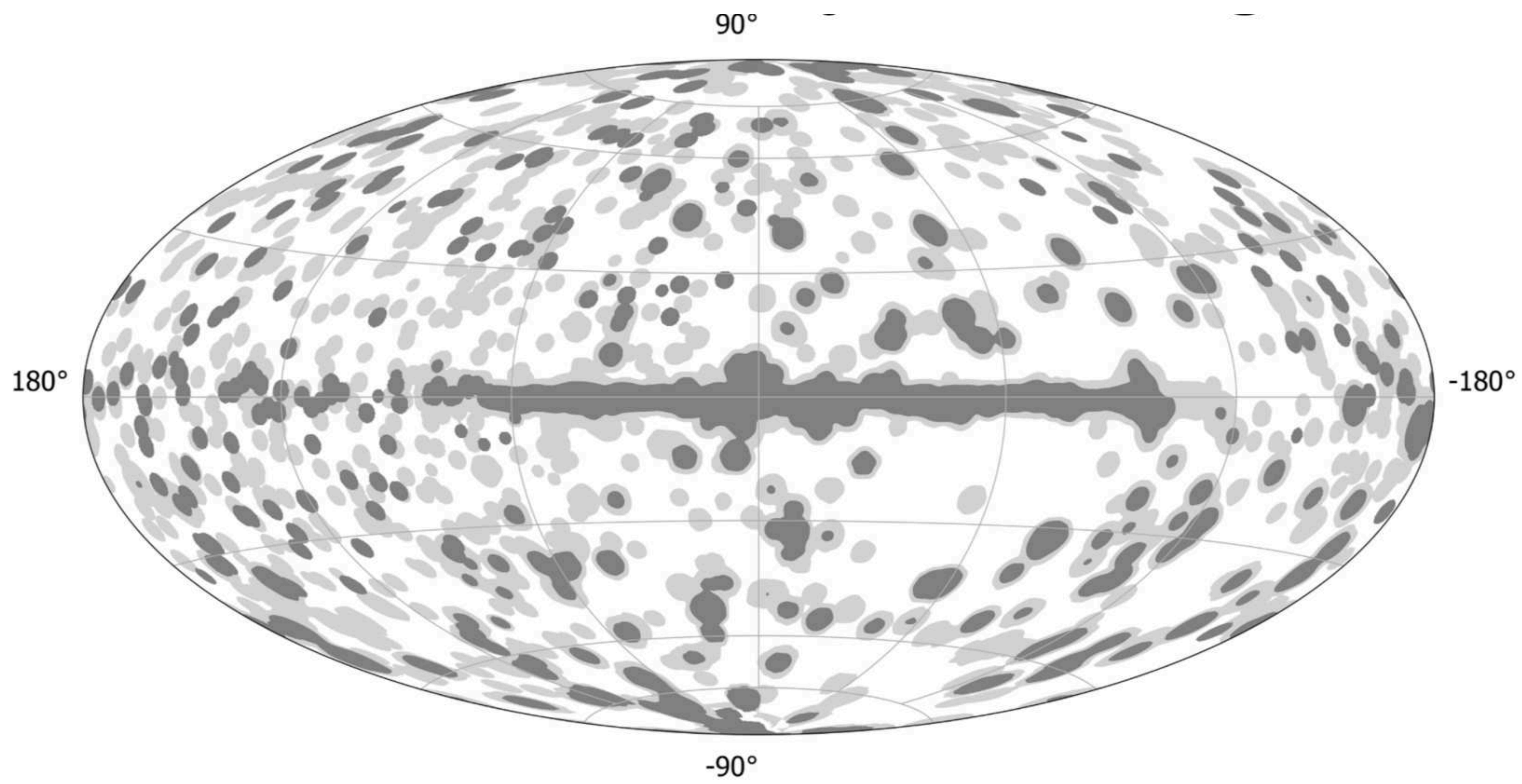
0.5-1° resolution @ 0.5 TeV,
with **wide** sky coverage
100% duty-cycle



[Zhen Cao et al. (2021) Nature **594**, 33-36]

IACT

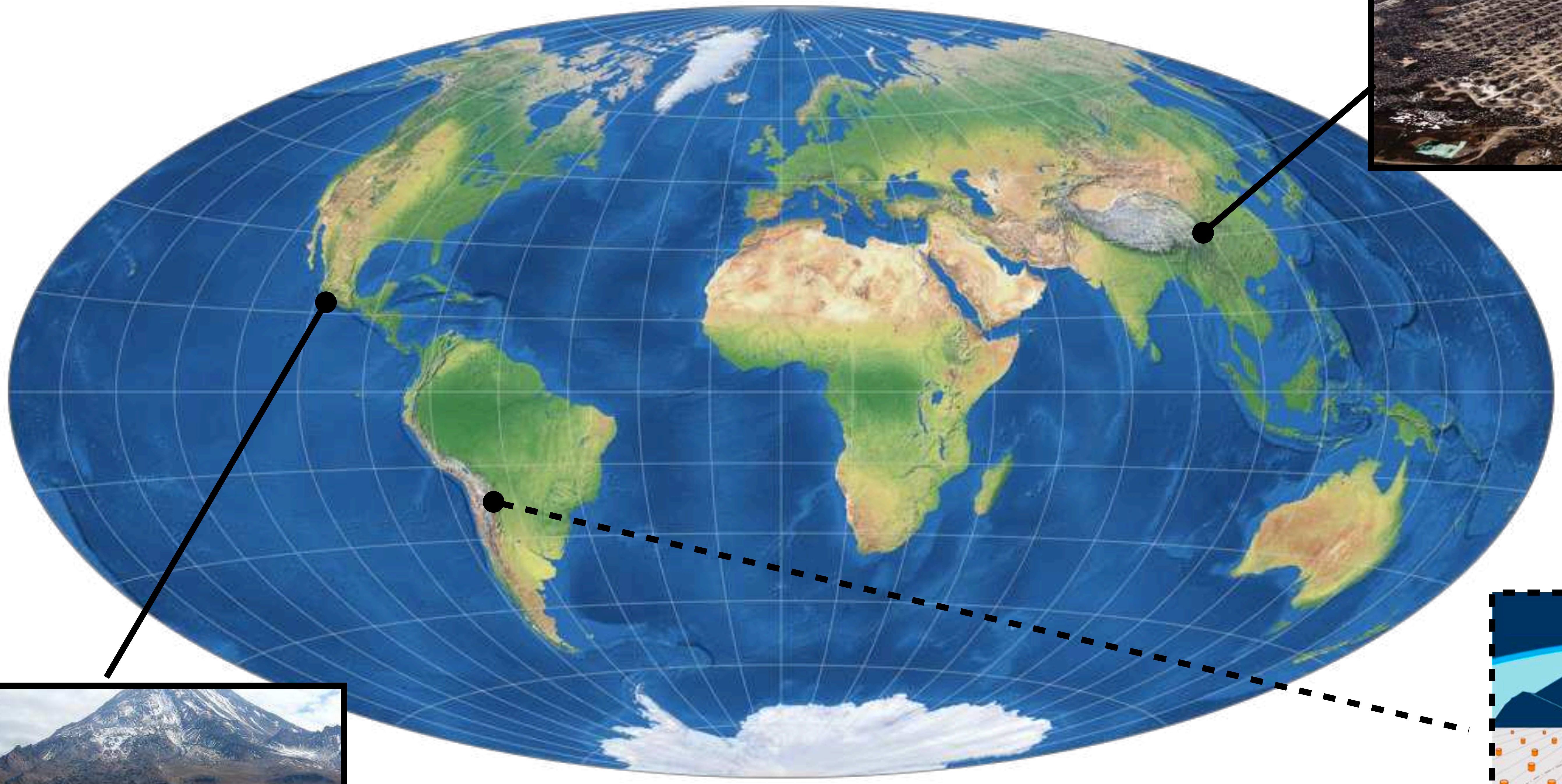
4' resolution @ 0.5 TeV,
with **limited** sky coverage
15% duty-cycle



[Mukherjee & Zanin, 2025]

γ-ray observatories

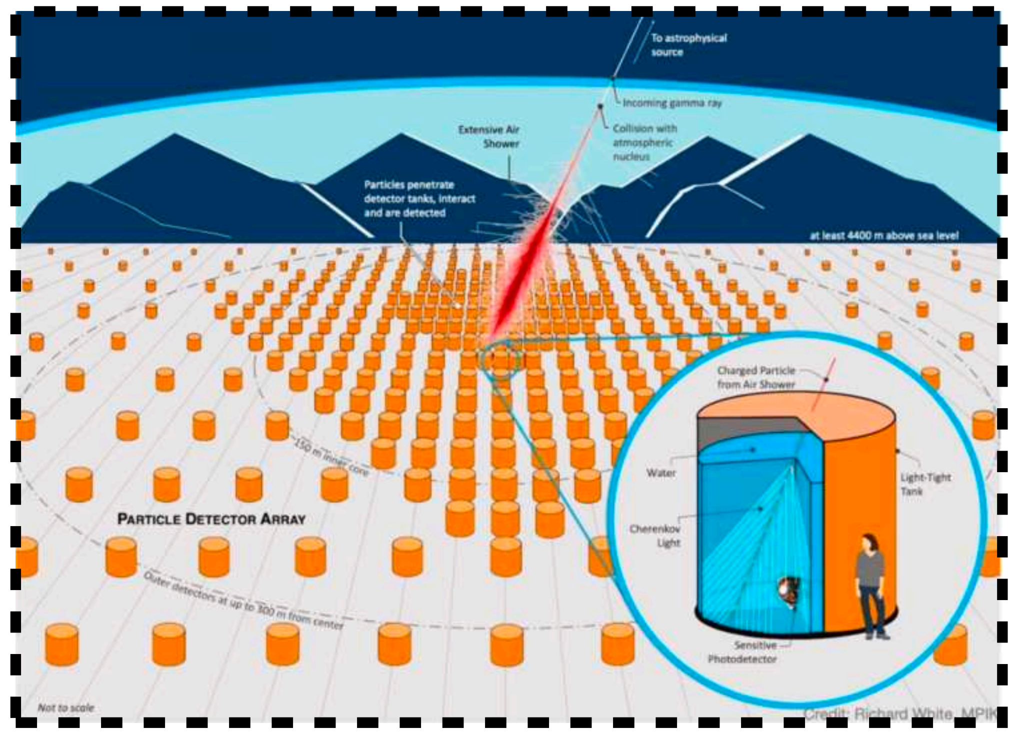
Current and future generation of WCDs



LHASSO (2021)
Daocheng, China
(4410 m)

HAWC (2015)
Puebla, Mexico
(4100 m)

SWGO
Atacama, Chile
(4770 m)

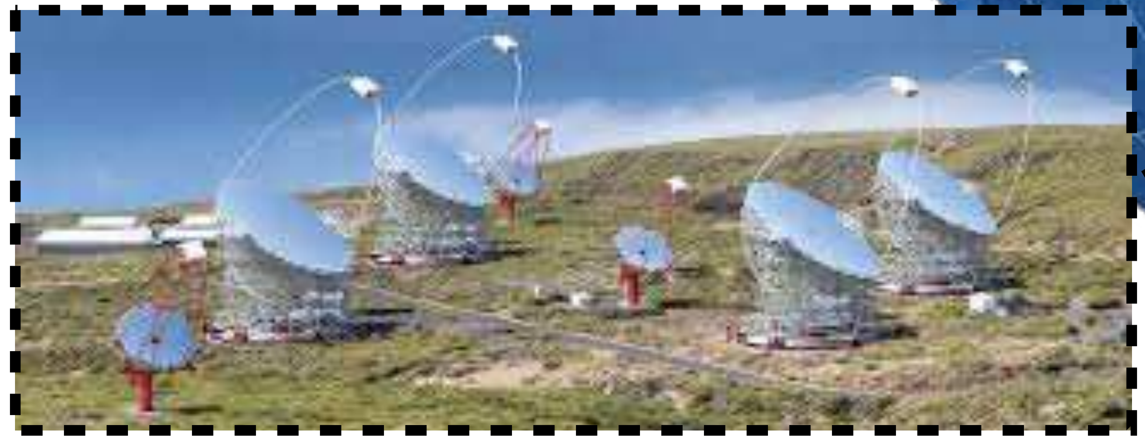


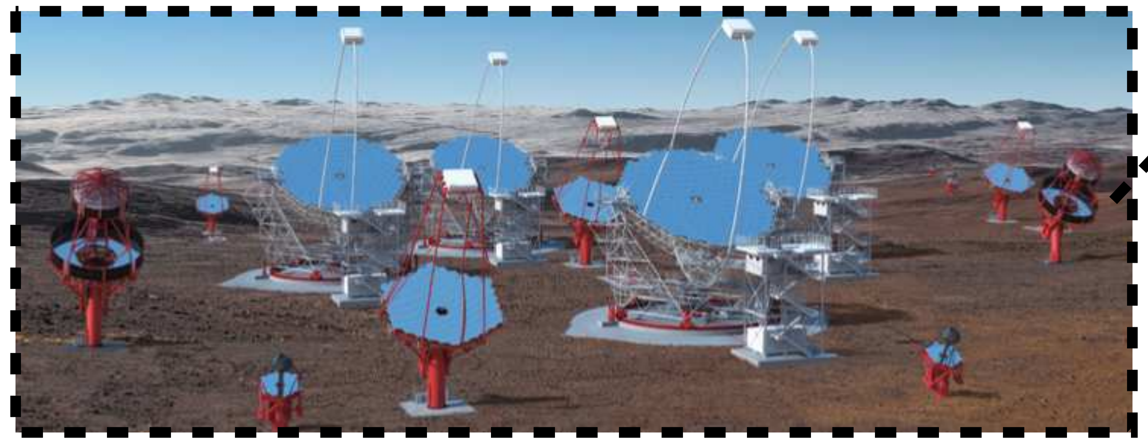
γ-ray observatories

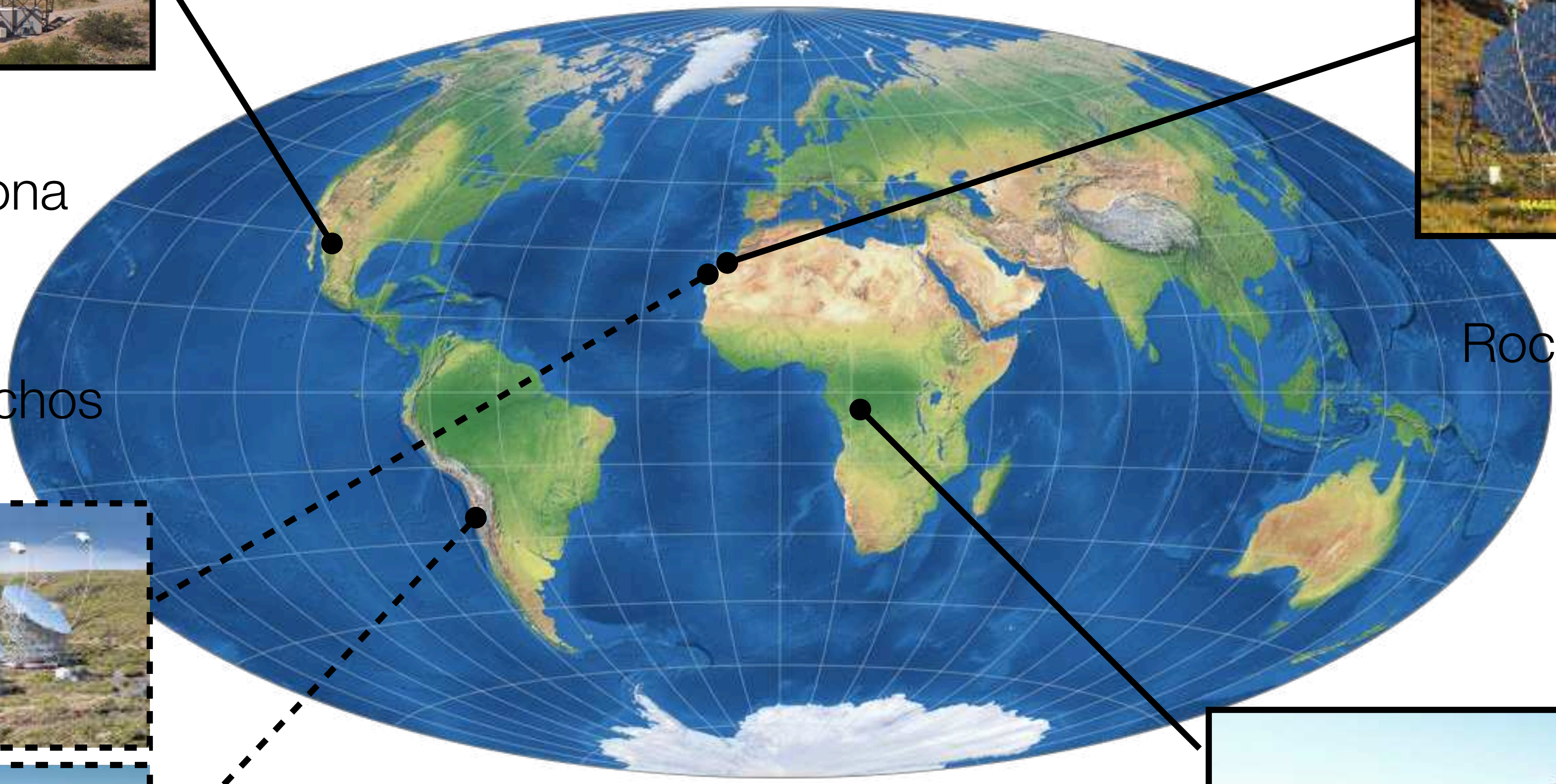
Current and future generation of IACTs

VERITAS
Mount Hopkins, Arizona

CTAO - North
Roche de los Muchachos
Canary Island



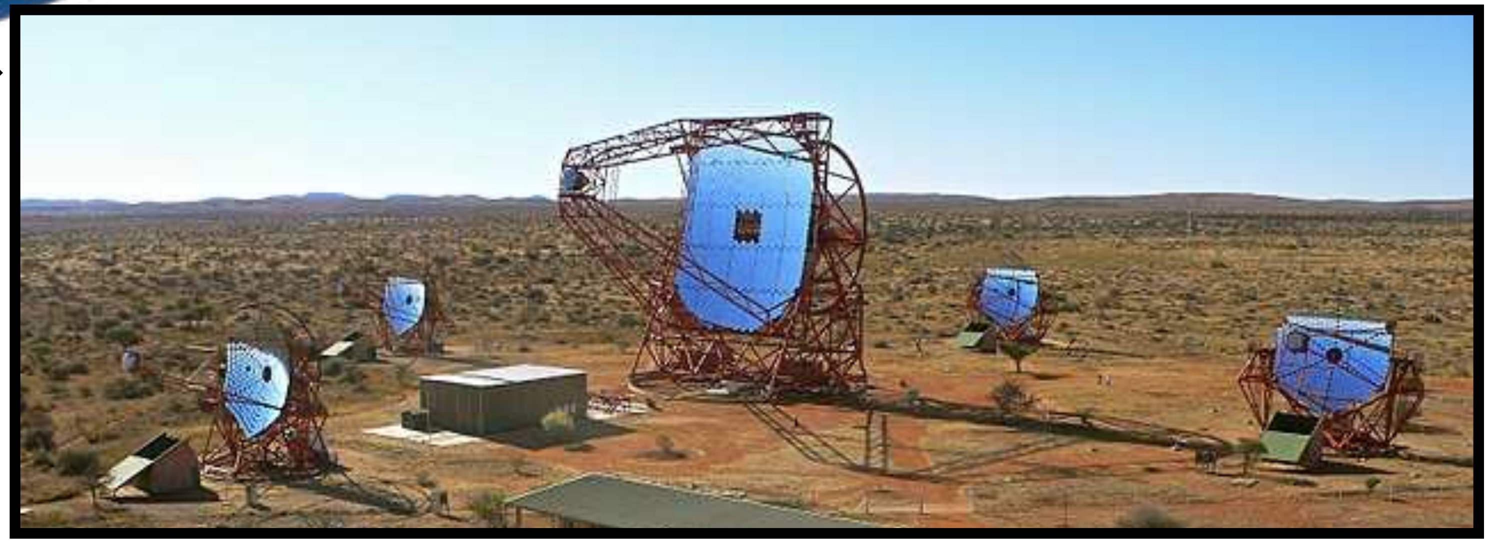




MAGIC
Roche de los Muchachos
Canary Island

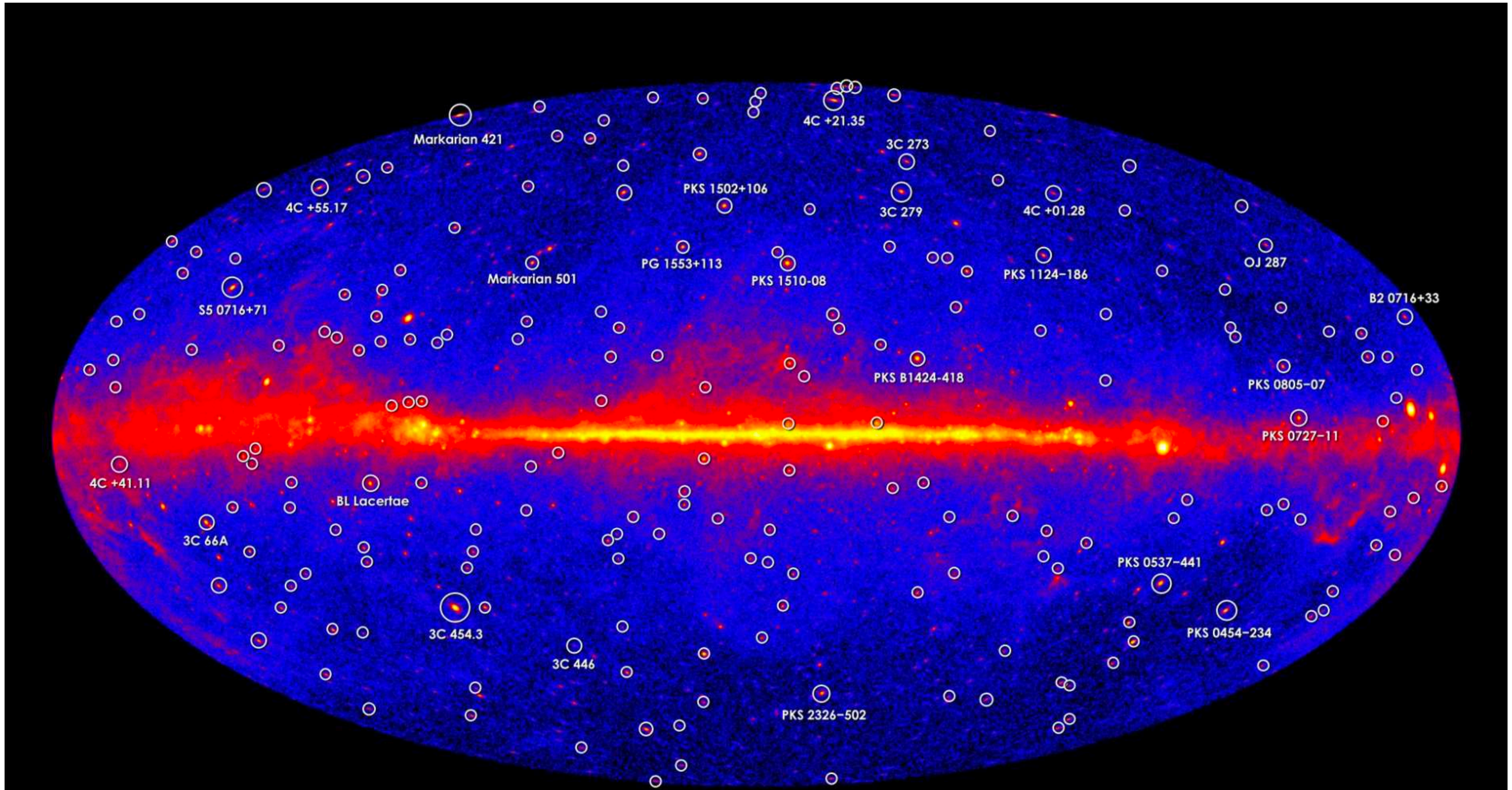
CTAO - South
Atacama, Chile

H.E.S.S. (2002)
Khomas Highland,
Namibia



The gamma-ray sky

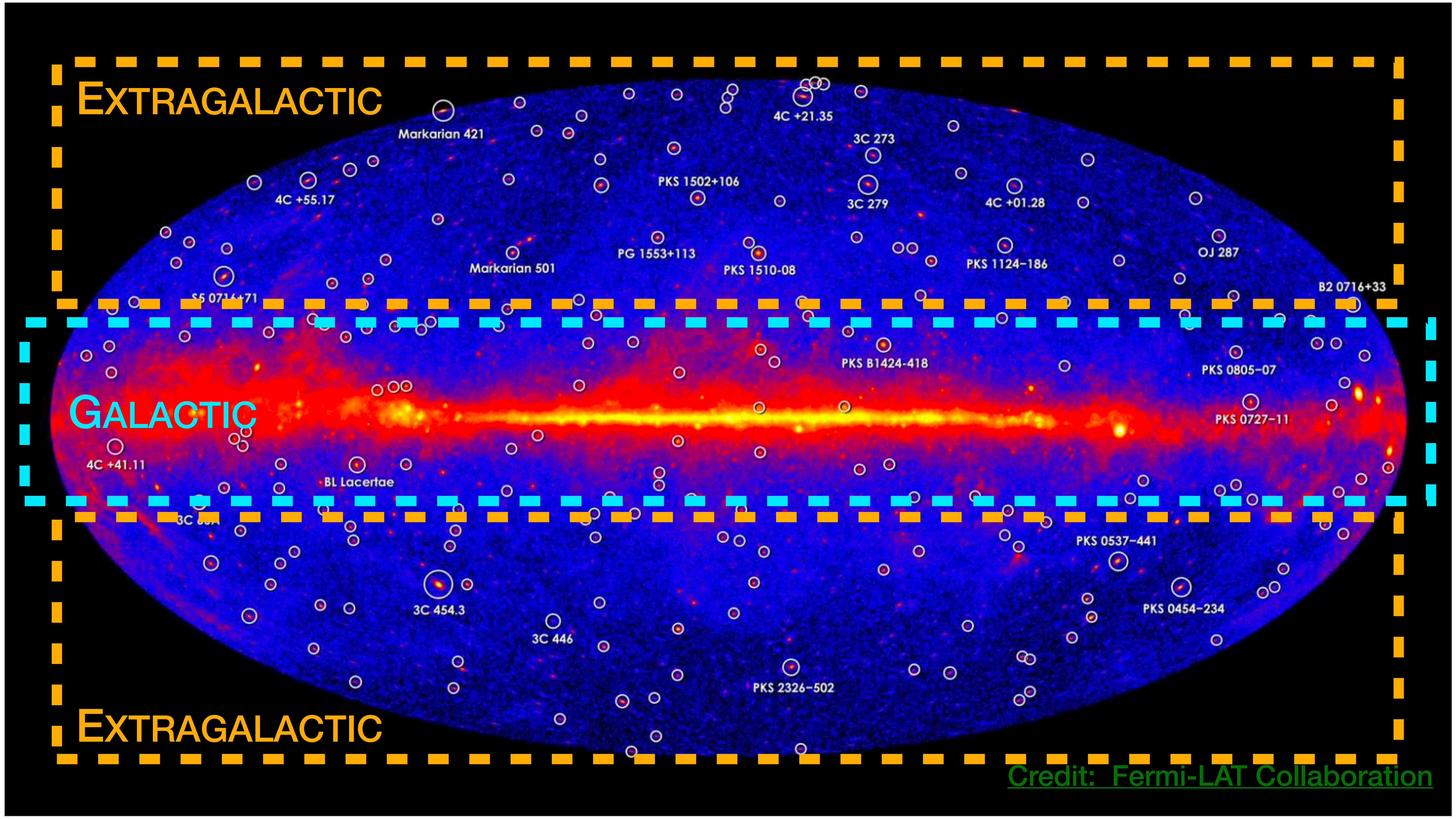
Fermi-LAT all-sky map



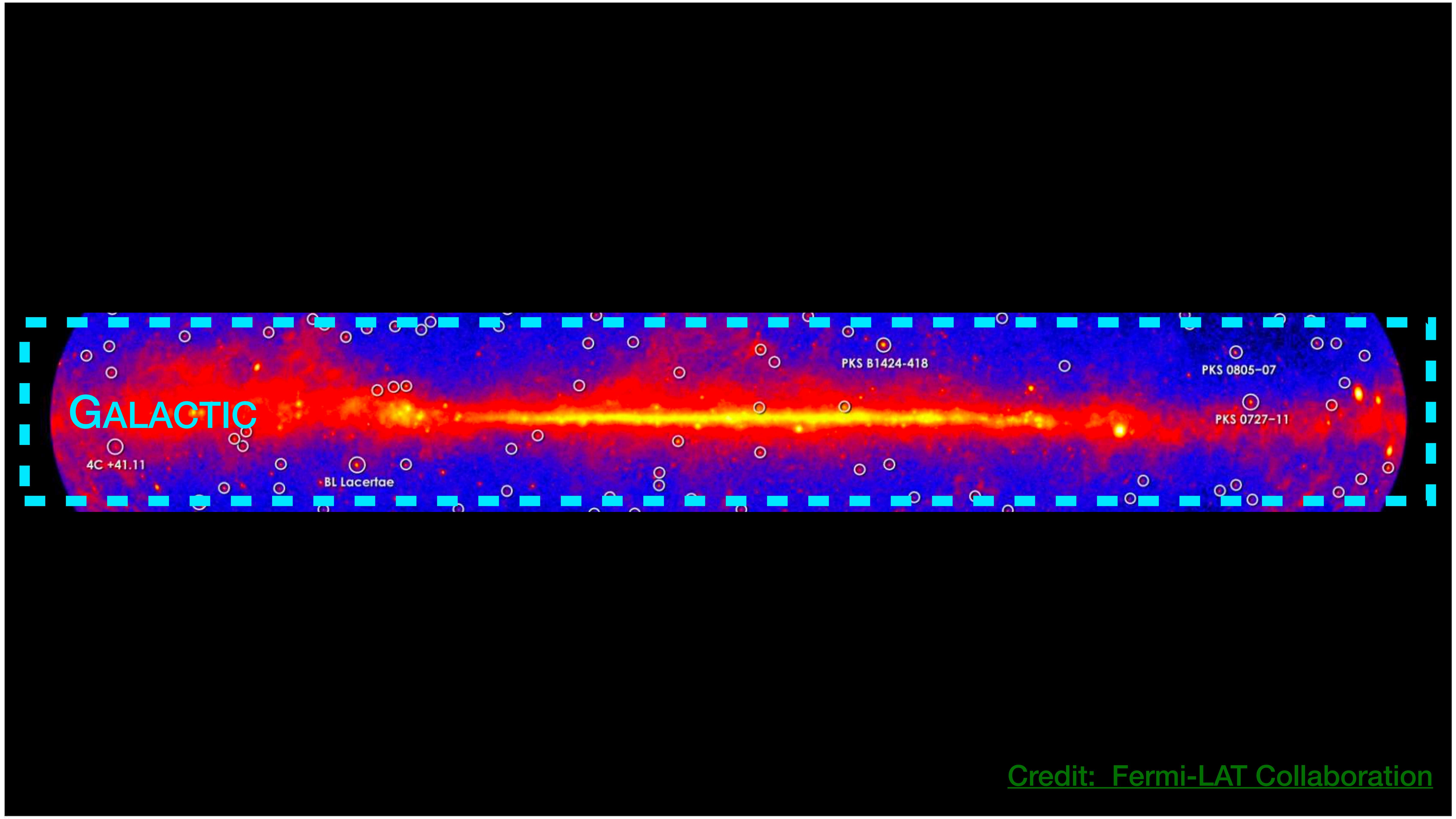
Credit: Fermi-LAT Collaboration

The gamma-ray sky

Fermi-LAT all-sky map

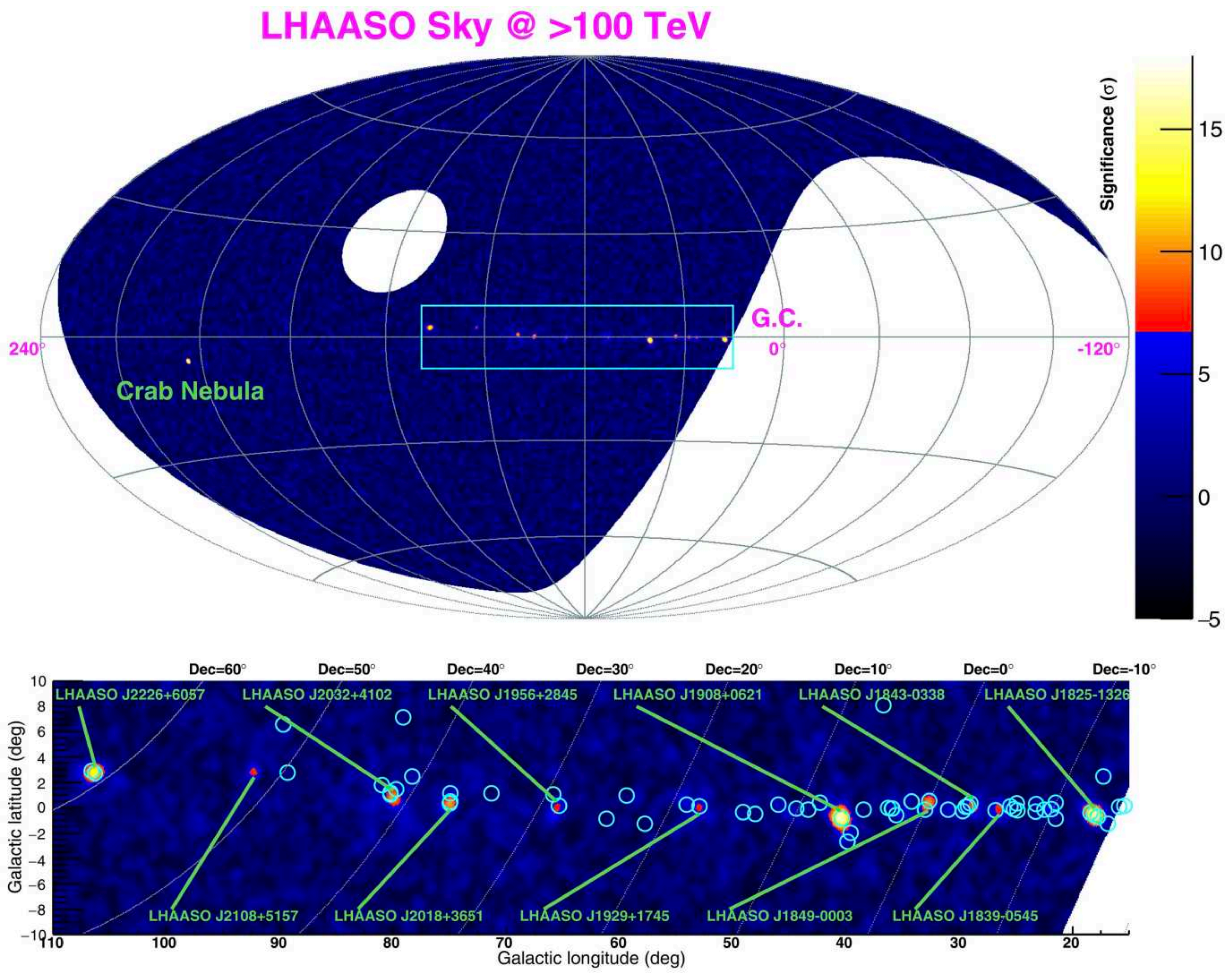


Our Galaxy


GALACTIC
4C +41.11
BL Lacertae
PKS B1424-418
PKS 0805-07
PKS 0727-11
Credit: Fermi-LAT Collaboration

PeVatrons in our Galaxy

- Detection of PeVatrons by LHAASO: sources of hadronic CRs up to PeV energies
  - 43 sources detected at E > 100 TeV with significance above 4σ
- Zoo of different galactic sources modeled to accelerate particles up to PeV
- Measurements of gamma-rays beyond PeV imply that these source must be accelerating them
  - Are they protons or electrons?



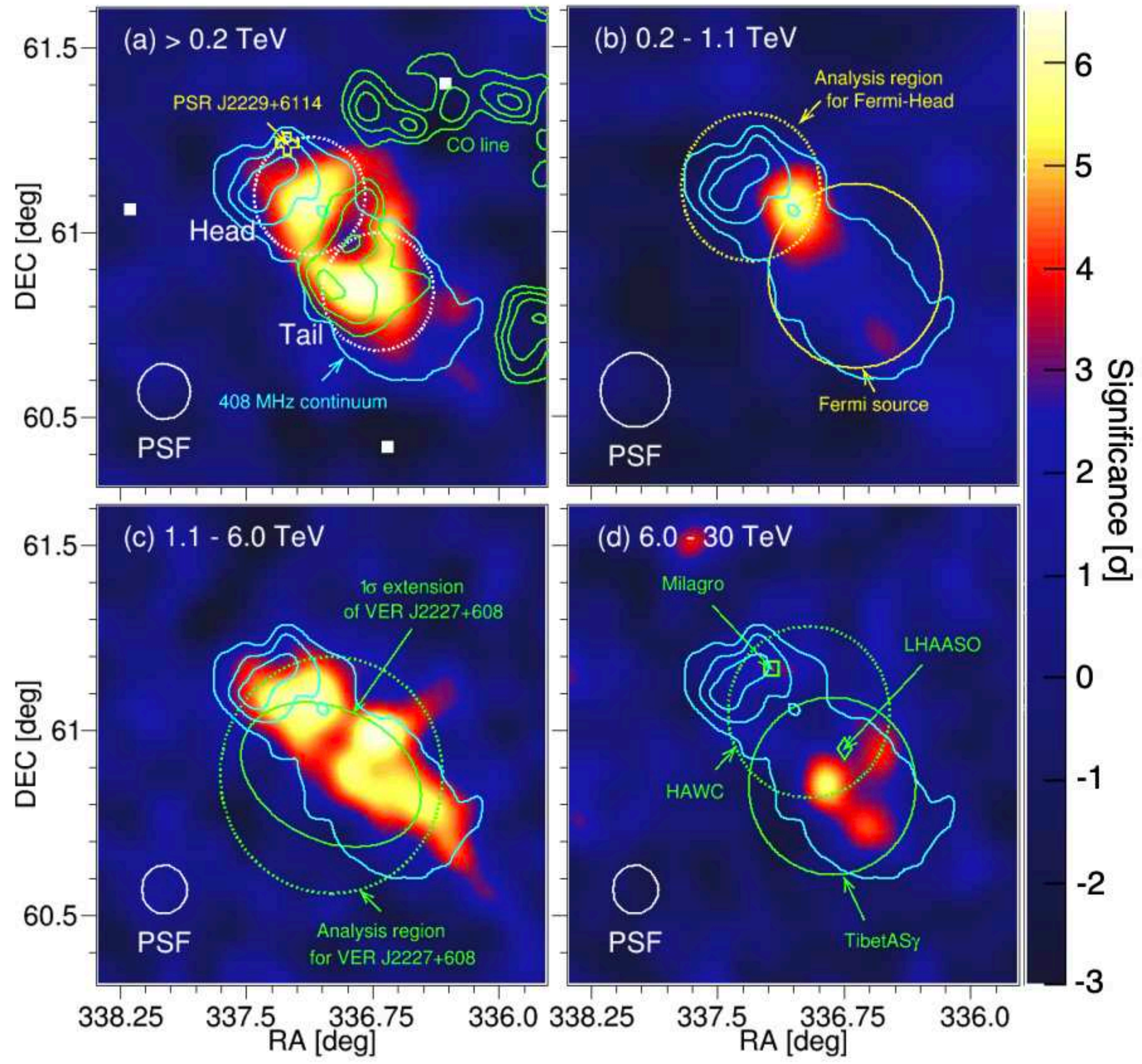
[Zhen Cao et al. (2021) Nature **594**, 33-36]

Supernova Remnants

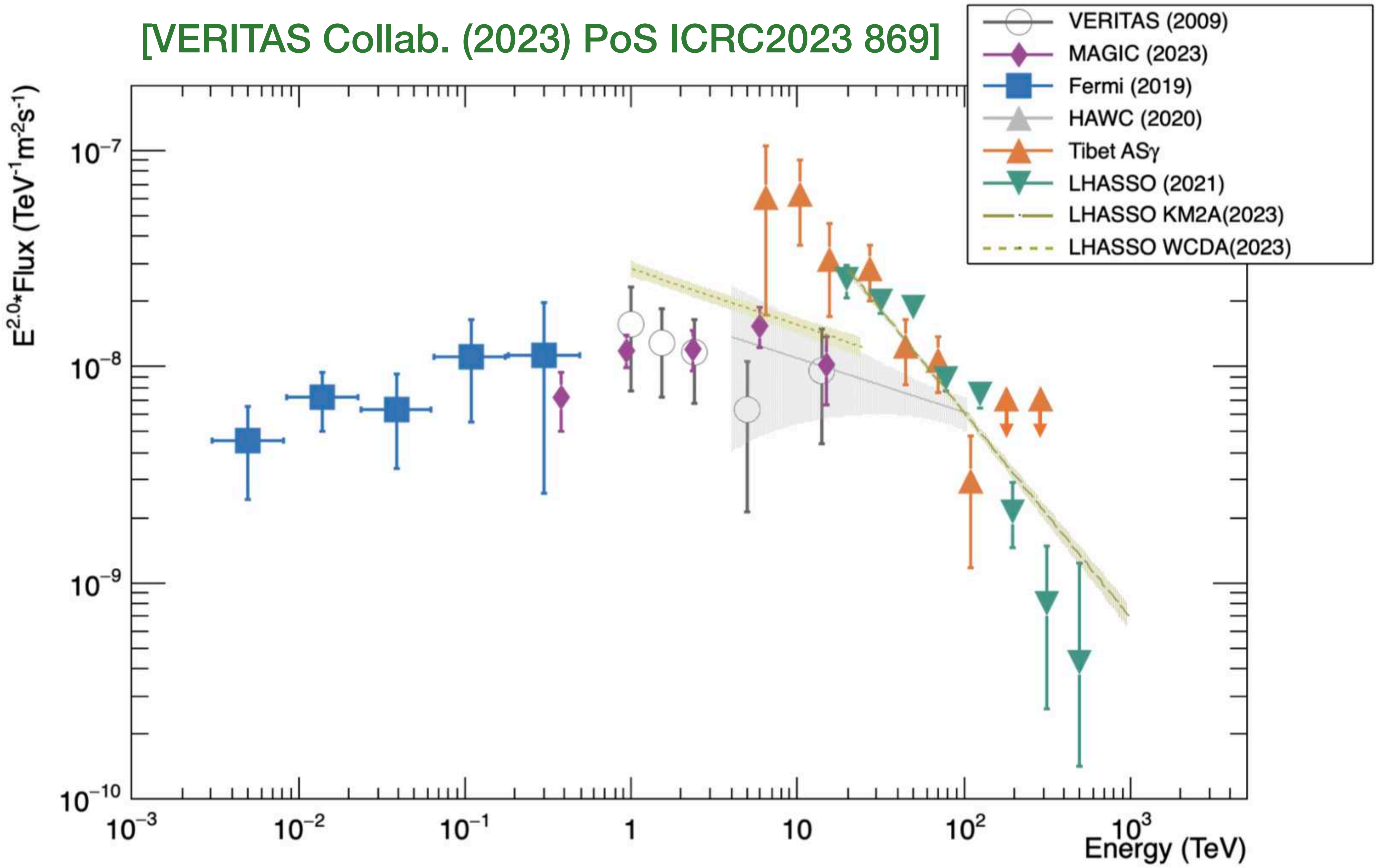
Power sufficient to explain Galactic CRs using a fraction of total energy

SNR G106.3+2.7 aka Boomerang

[MAGIC Collab. (2023) A&A 671, A12]



[VERITAS Collab. (2023) PoS ICRC2023 869]



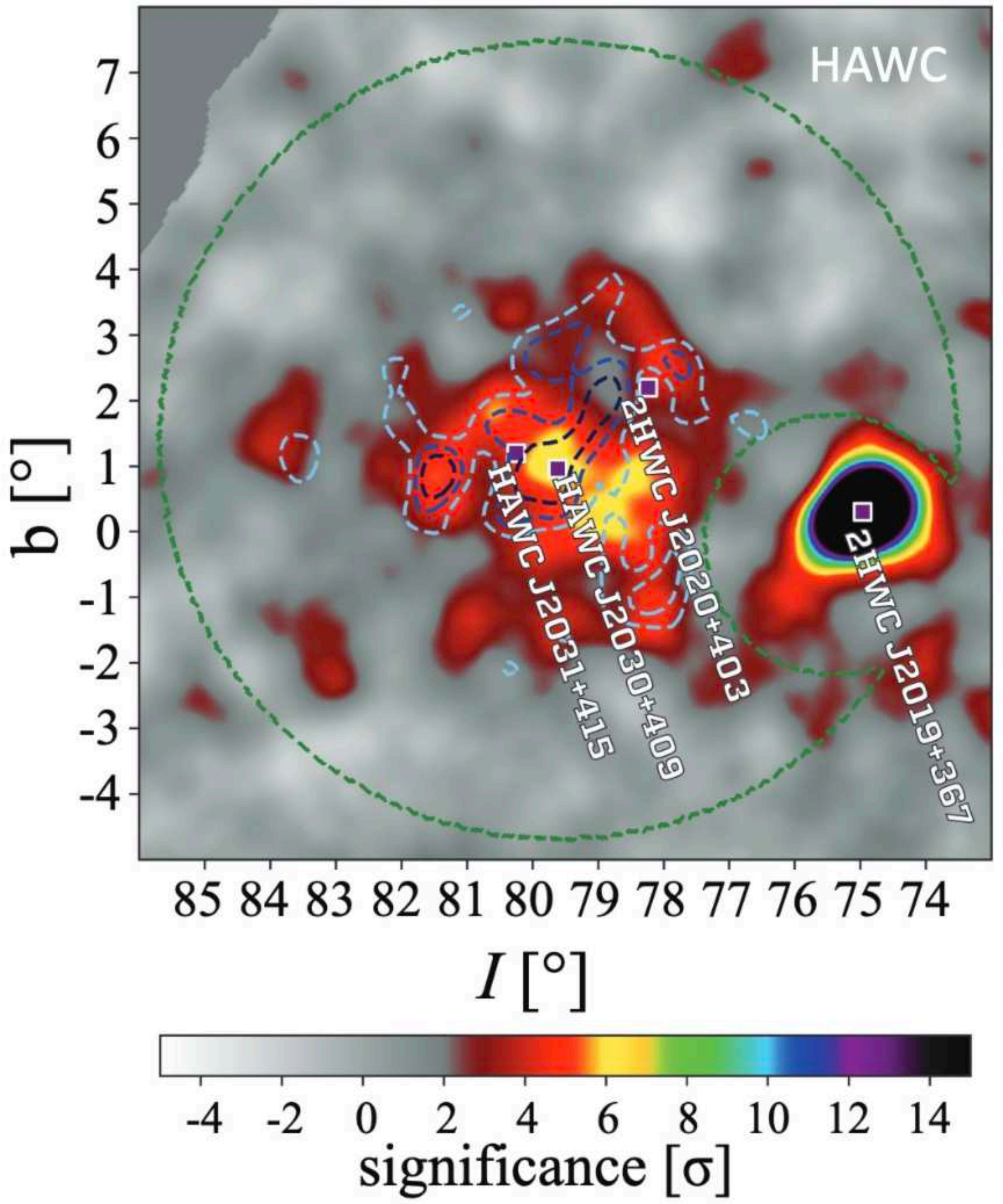
γ-ray emission originates from tail region (south-east extension of SNR) likely due to escaped PeV protons interacting with nearby dense molecular clouds

Stellar Clusters

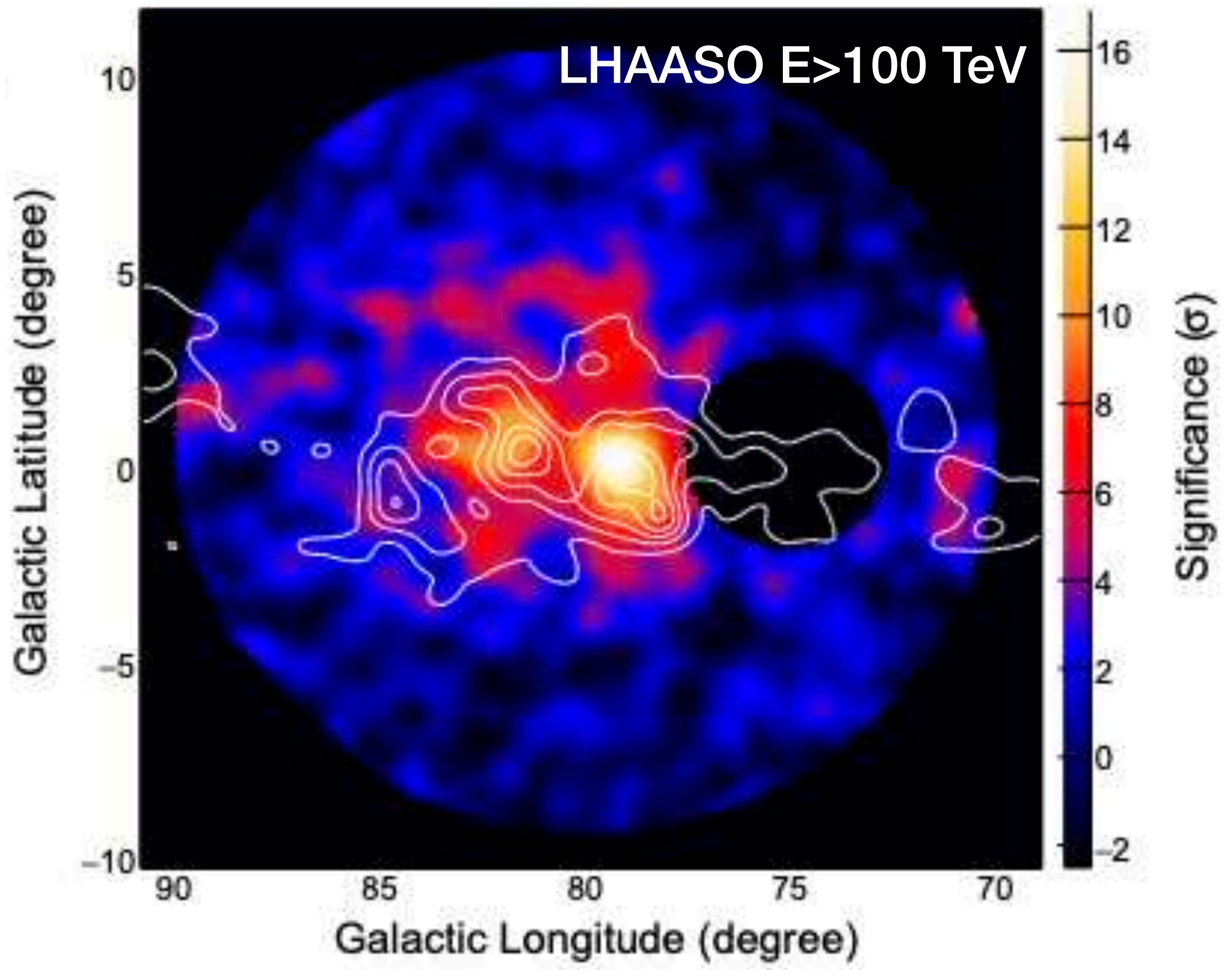
OB star winds drive shocks that can accelerate CRs

Cygnus Cocoon

[HAWC Collab. (2021) Nature Astr., 5, 465-471, A12]



[LHAASO Collab. (2024) Science Bulletin, 69, 4, 449-457]



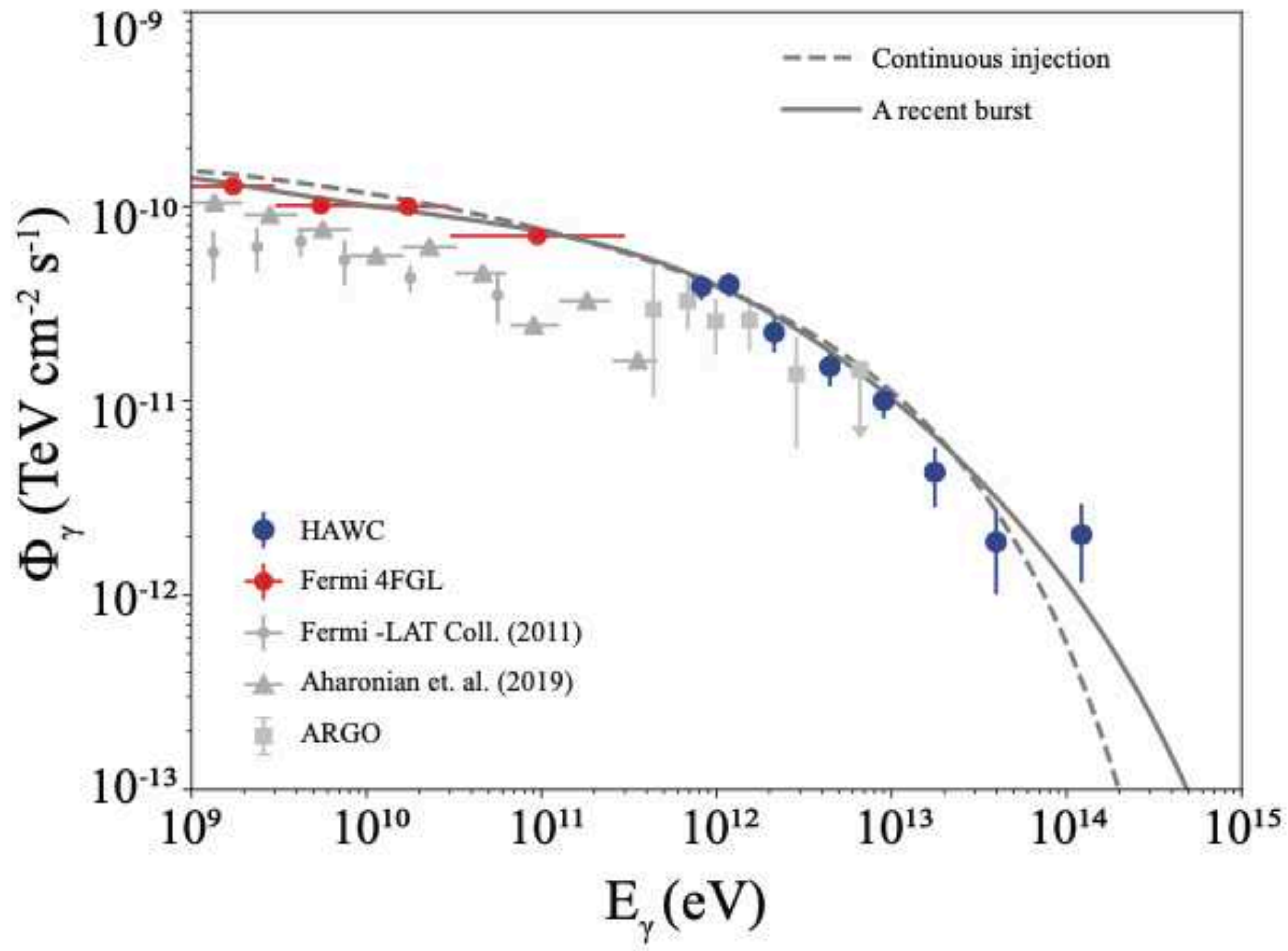
Large-scale diffuse emission GeV-PeV around star-forming region Cyg OB2 in Cygnus

Stellar Clusters

OB star winds drive shocks that can accelerate CRs

Cygnus Cocoon

[HAWC Collab. (2021) Nature Astr., 5, 465-471, A12]



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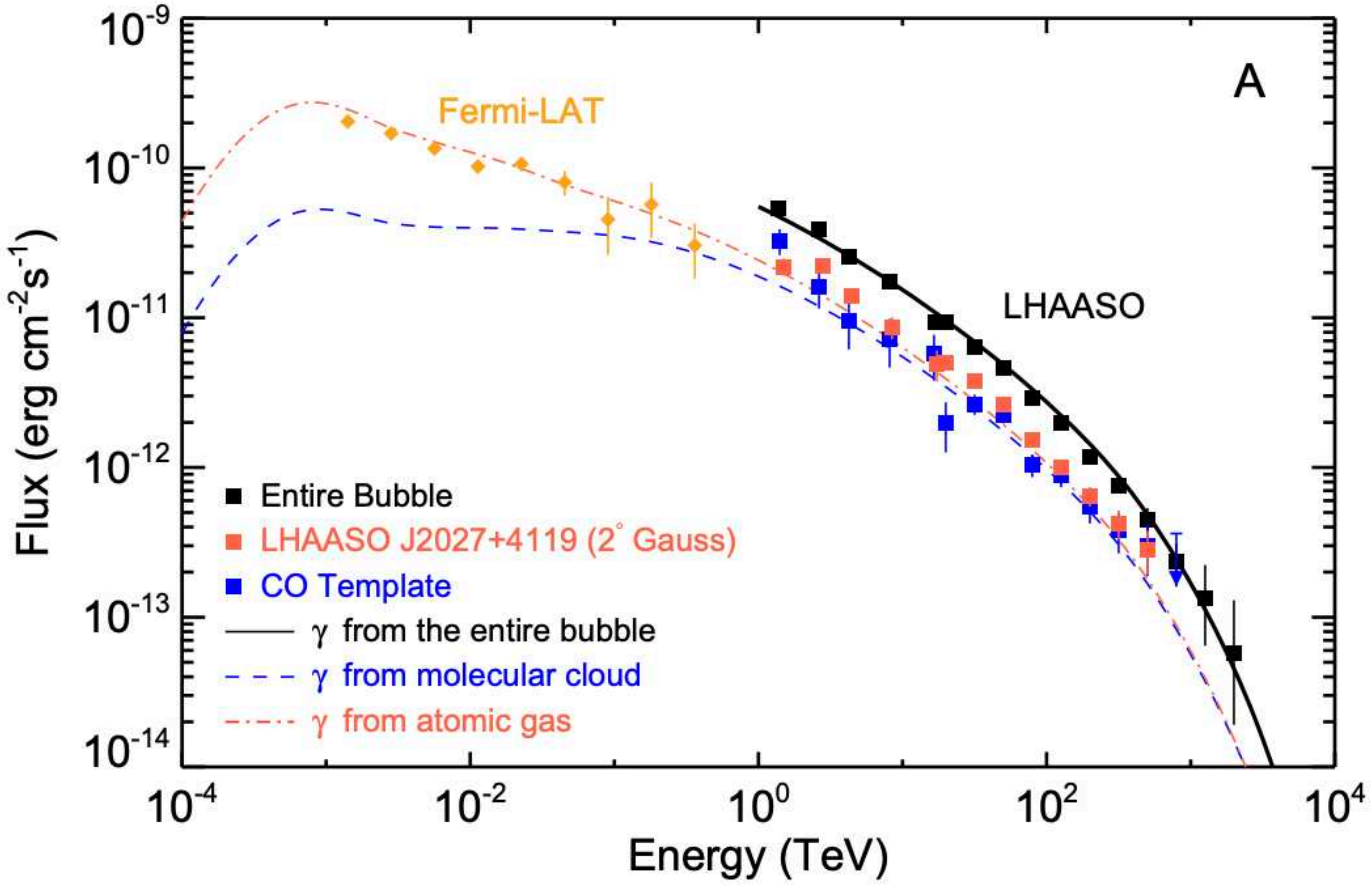
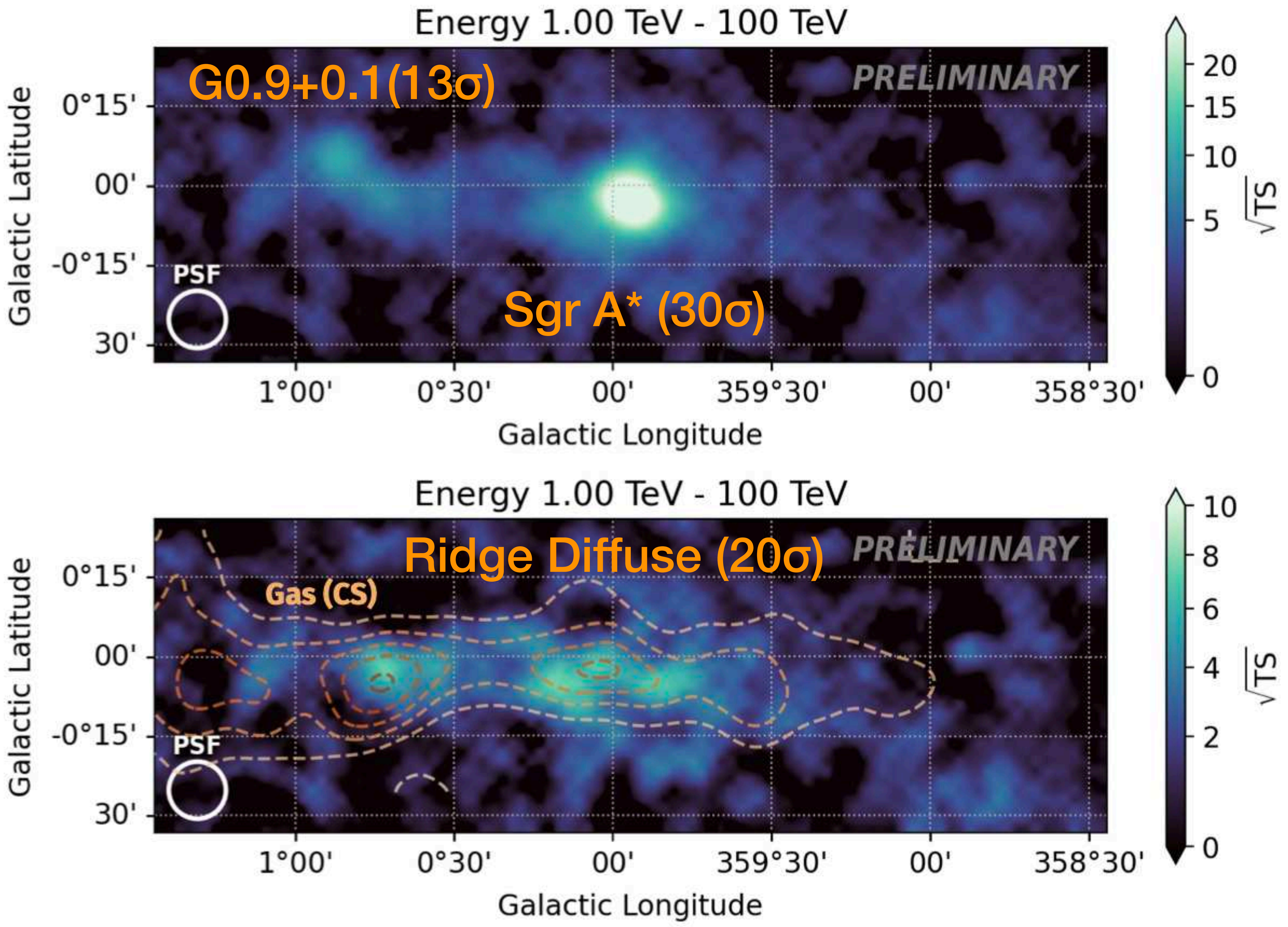
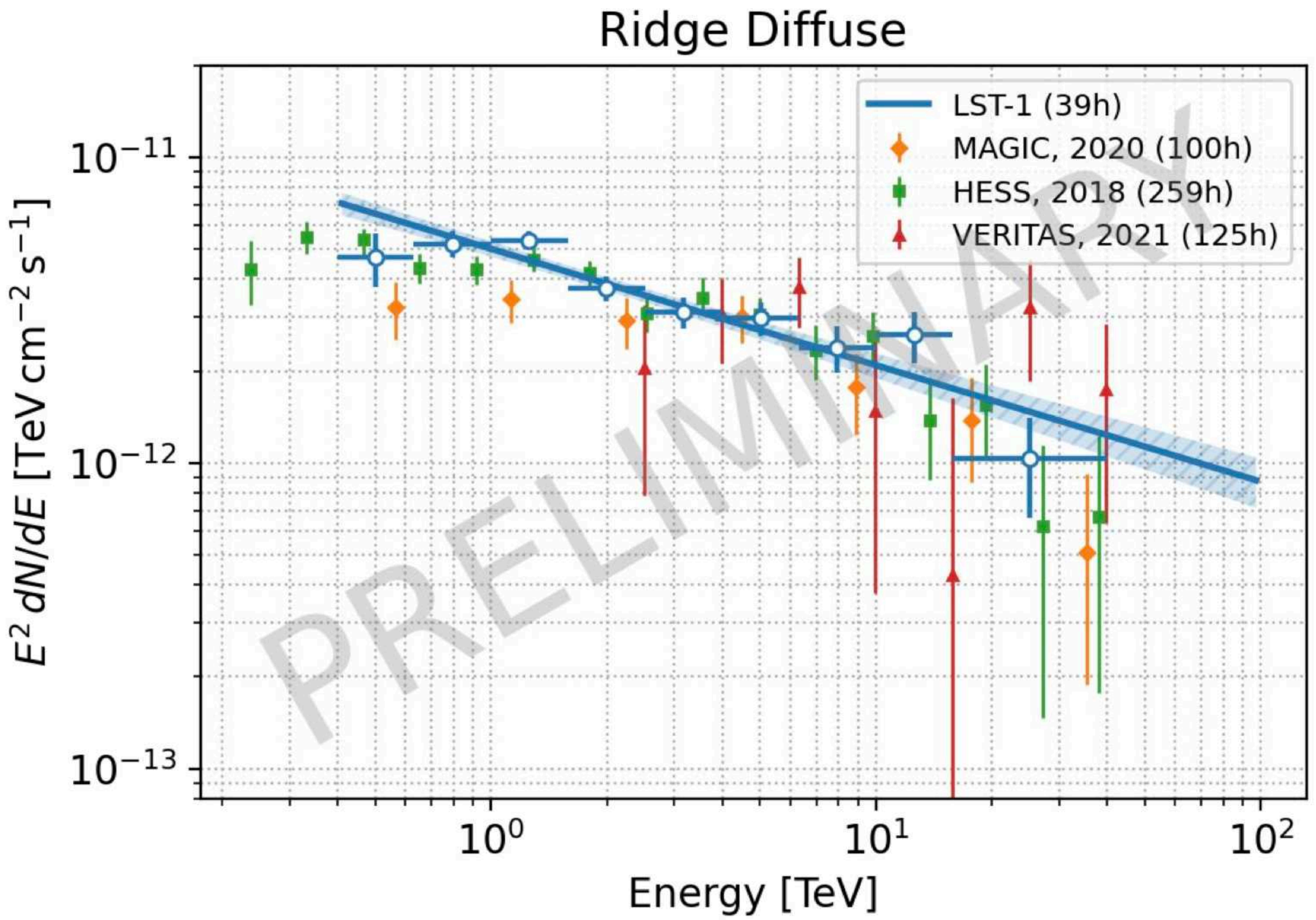


Energy spectrum beyond PeV indicates a hadronic super-PeVatron

Galactic Center

- Multiple Sources of VHE γ-Ray Emission: Massive Stellar Clusters, PWN, SNR
- **Latest VHE survey by CTAO's LST (40h)**



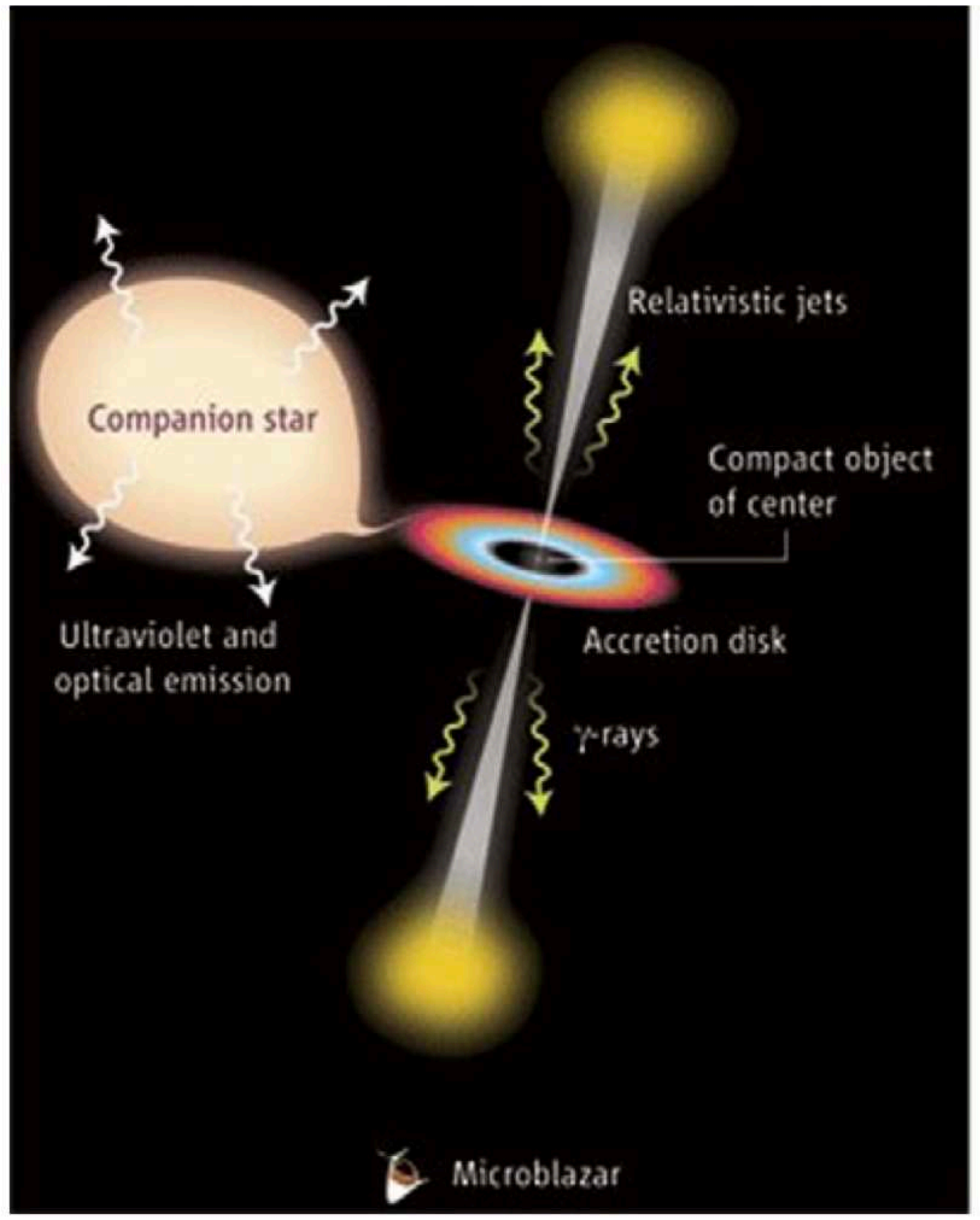


[LST Collab. PoS ICRC2023 (2023), 574]

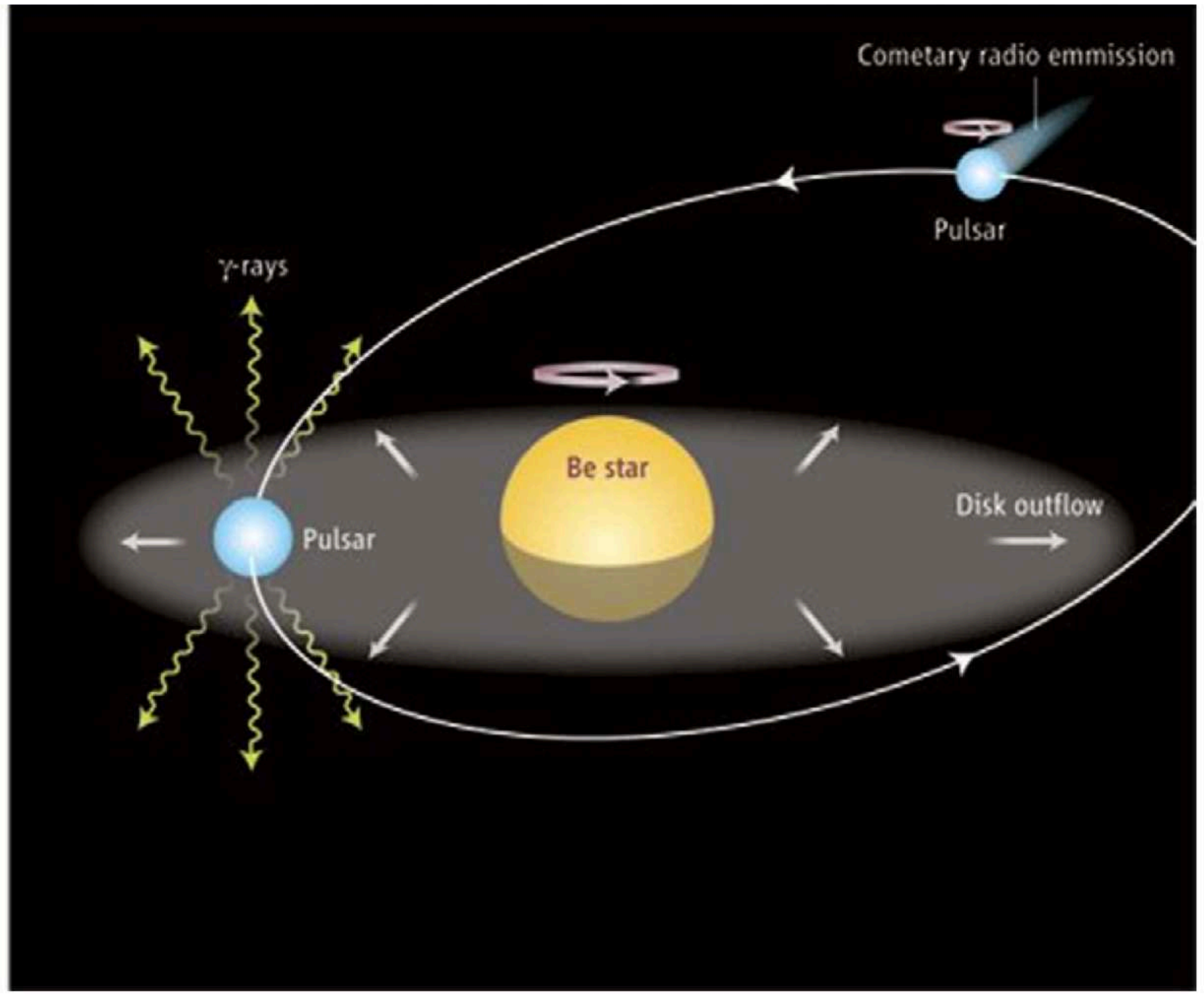
No cutoff or breaks up to 30 TeV in Ridge diffuse ⇒Acceleration of PeV cosmic rays?

Binaries

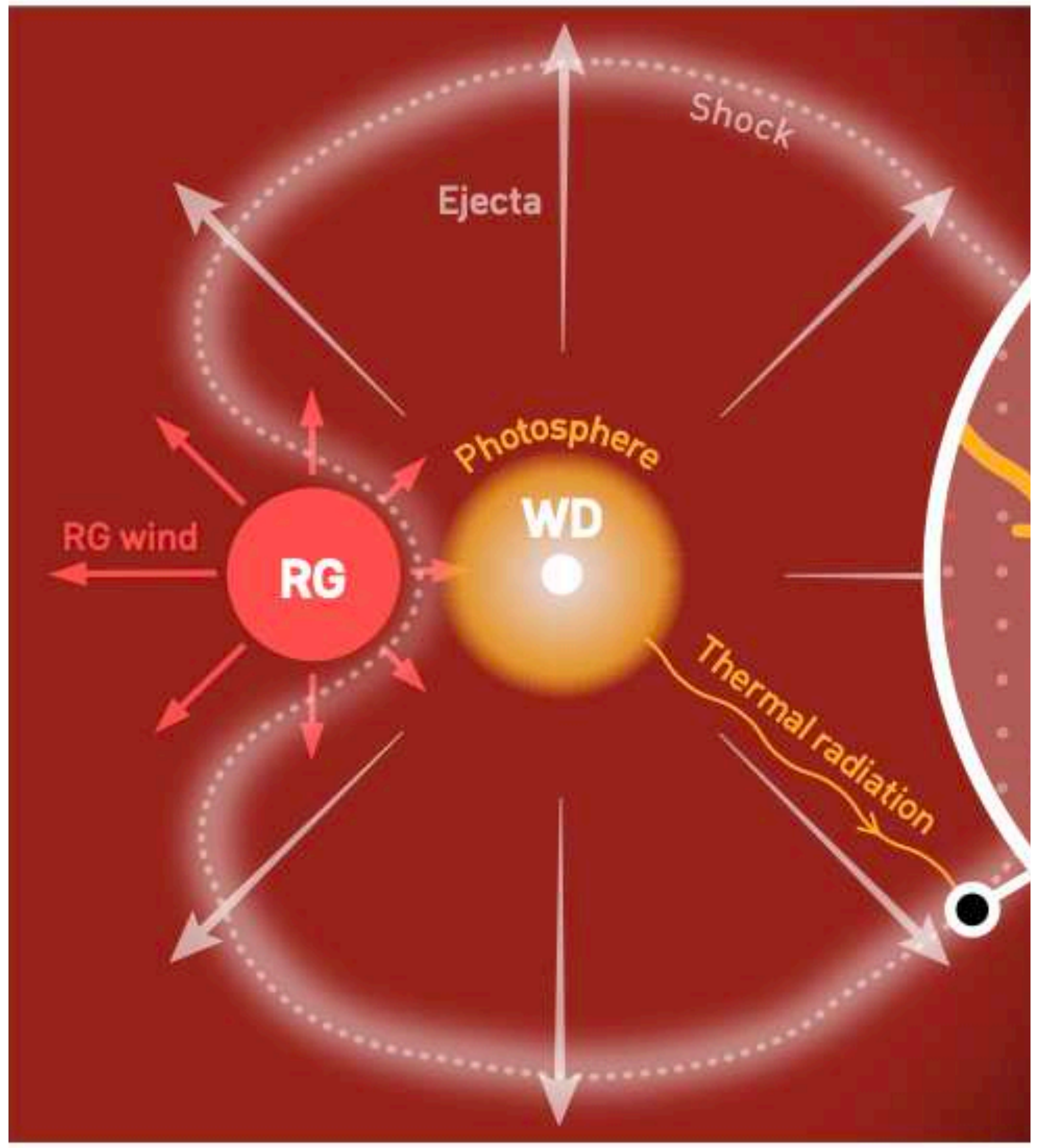
MICROQUASAR



BINARY PULSAR



NOVA



Binary system: two stars gravitationally bound to each other:

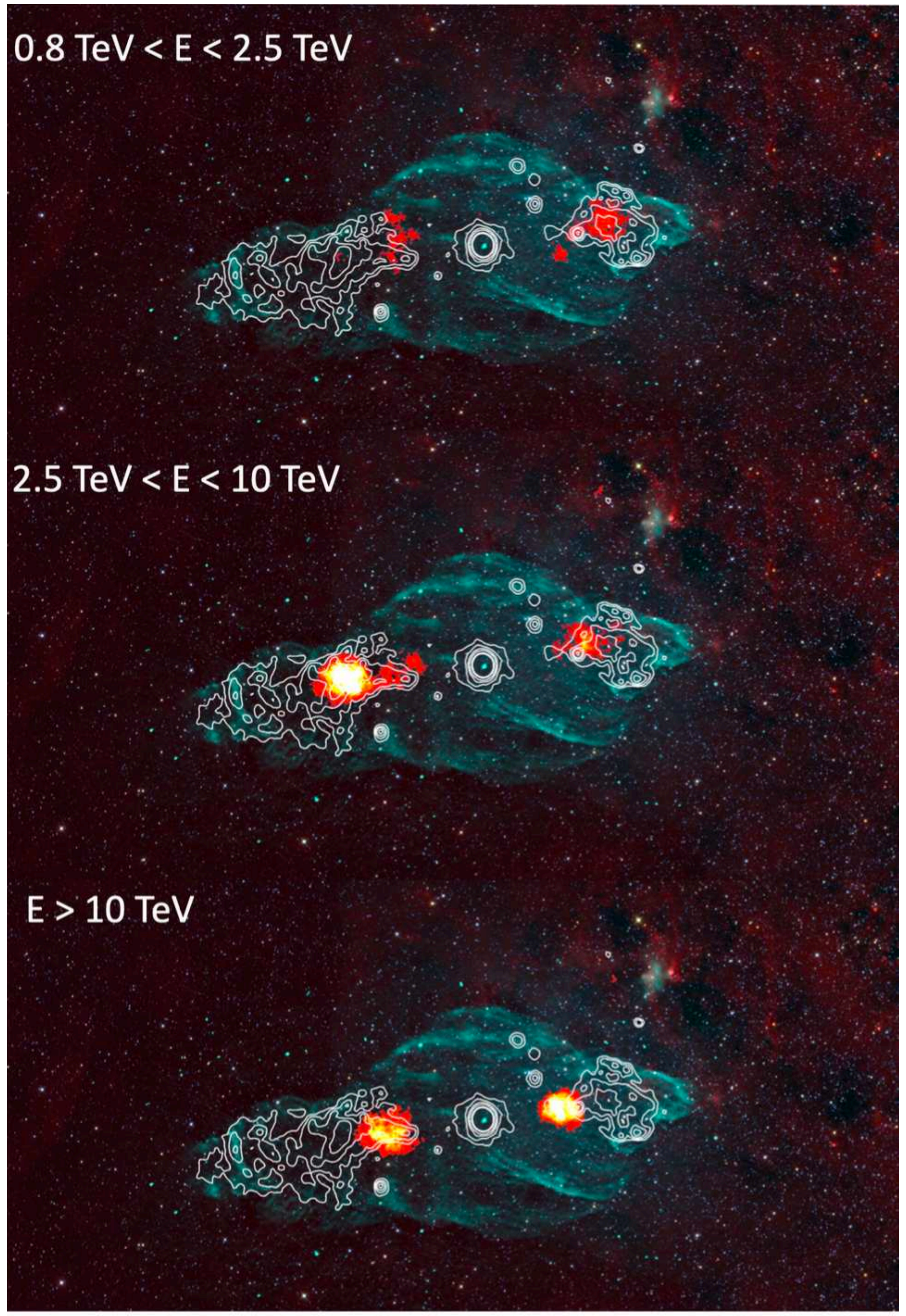
- **microquasar**: neutron star or black hole + companion massive star
- **binary pulsar**: neutrons star + Be star (pre main-sequence)
- **nova**: white dwarf + companion red giant

Microquasars

Compact obeject (BH or NS) accreting from companion star

SS 433

- First detected by HAWC (20 TeV) and deeply studied by H.E.S.S.
- First astrophysical jet resolved in gamma rays
- Favored leptonic origin of the emission: electrons propagate from the central source and cool down faster for higher energies

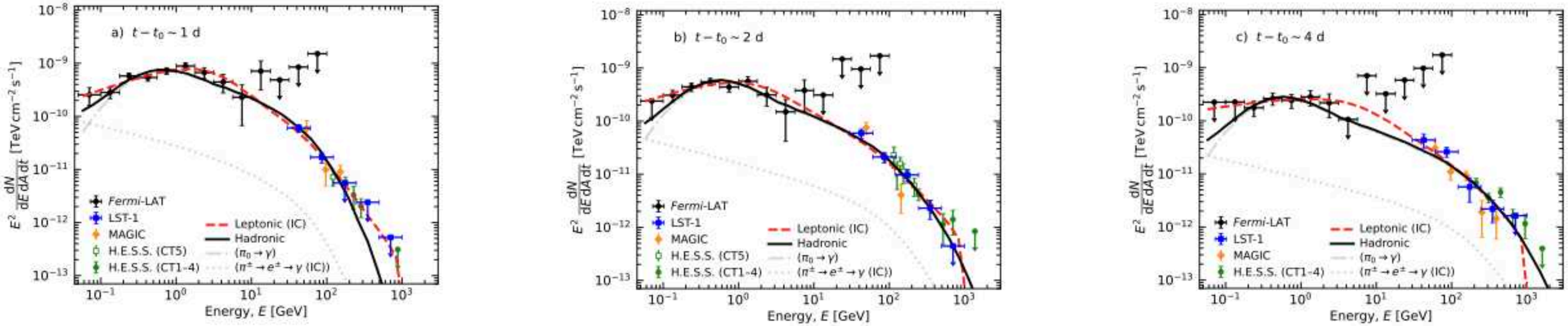


[H.E.S.S. Collab. (2024) Sience 383 6681]

Novae

White dwarf accreting from companion red giant

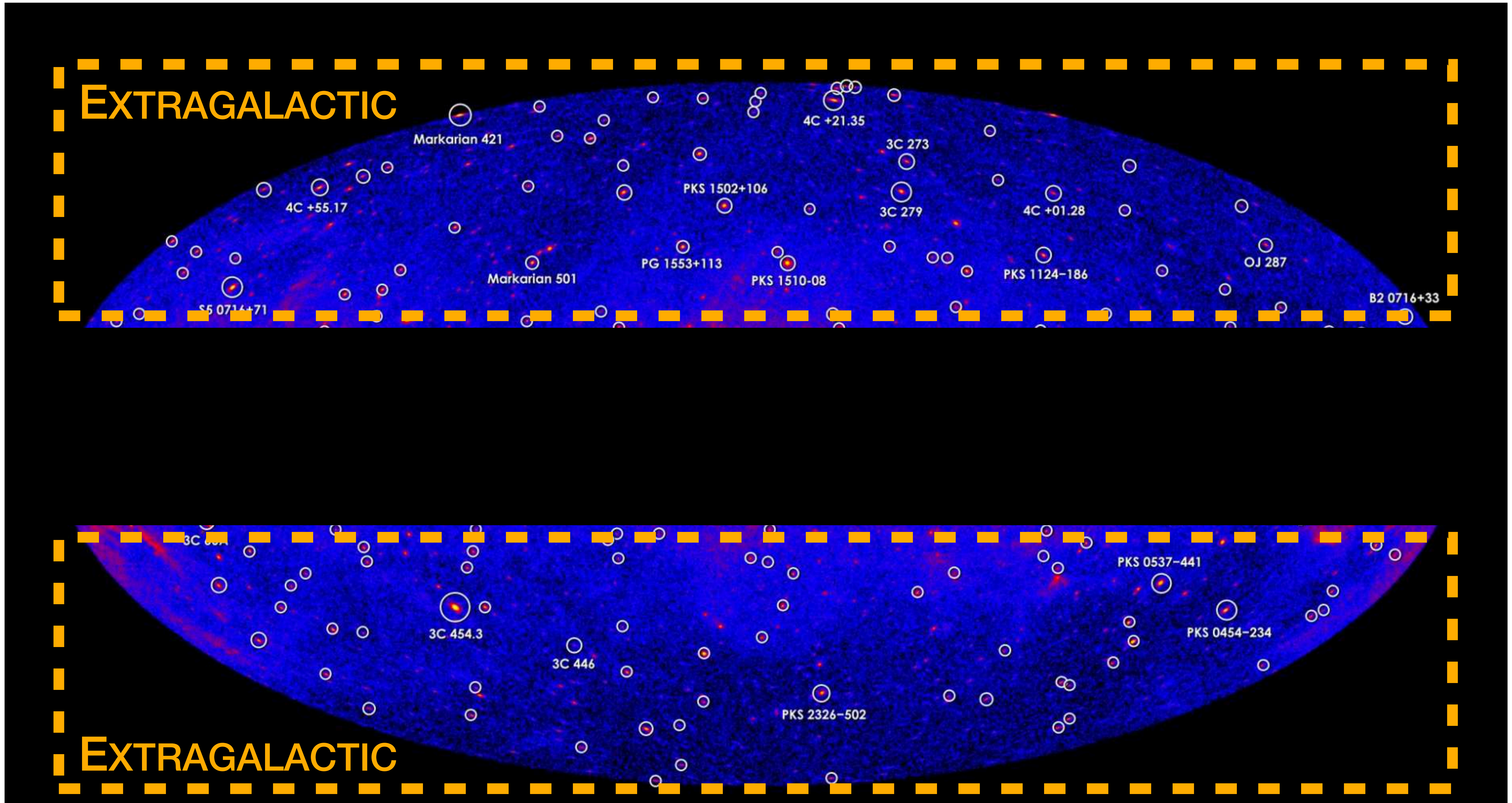
RS Ophiuchi



[LST1-1 Collab. (2025) A&A 695, A152]

- Symbiotic nova that erupted 8 Aug. 2021
- 1st time detection of VHE emission from a Nova
- Detections by HESS, MAGIC and LST-1 for several days afte the eruption
- Hadronic model favored
  - Accelerated protons will eventually escape nova shock and contribute to the sea of CRs
- Single-shock scenario disfavored to explain GeV and TeV emission

Outside our Galaxy

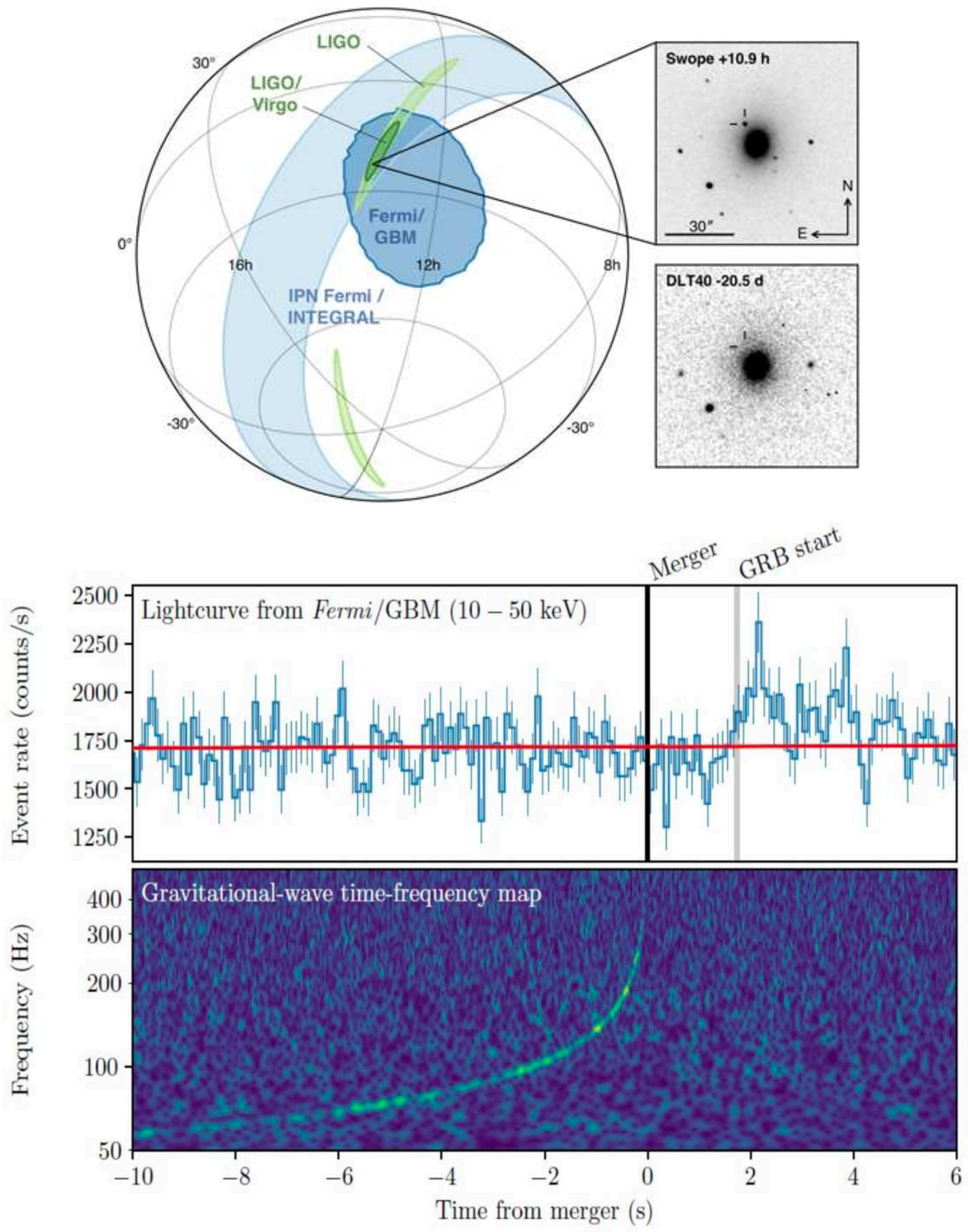


Credit: Fermi-LAT Collaboration

VHE detection of GRB

Originated by merging of two compact objects or by hypernova

- Brightest electromagnetic transient ($10^{51\text{-}53}$ erg released):
  - short, $T_{90} < 2$ s (compact objects merger, observed in GWs),
  - long, $T_{90} > 2$ s (massive star collapse);
- Continuously detected by high-energy space-borne telescopes:
  - ~ 90/yr in hard X rays by Swift-BAT, ~ 240/yr in MeV gamma rays by Fermi-GBM;
- **GRB170817A**, first multi-messenger source, GW (NS+NS merger) + hard X-ray prompt
- No GRB detected in VHE gamma rays until late 2010s

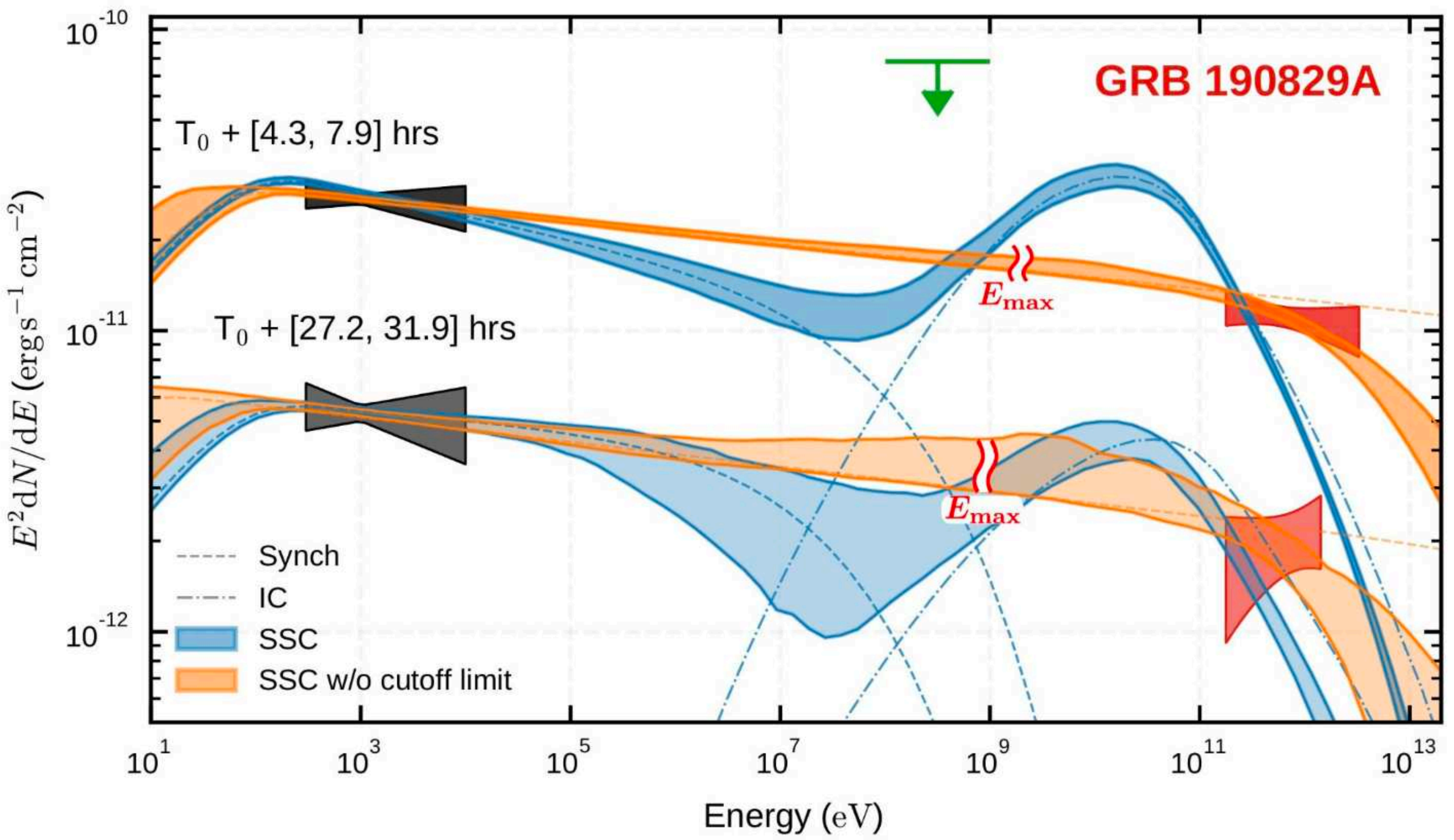


[Abbott et al. (2017) APJL 848, 2, L12, 59]

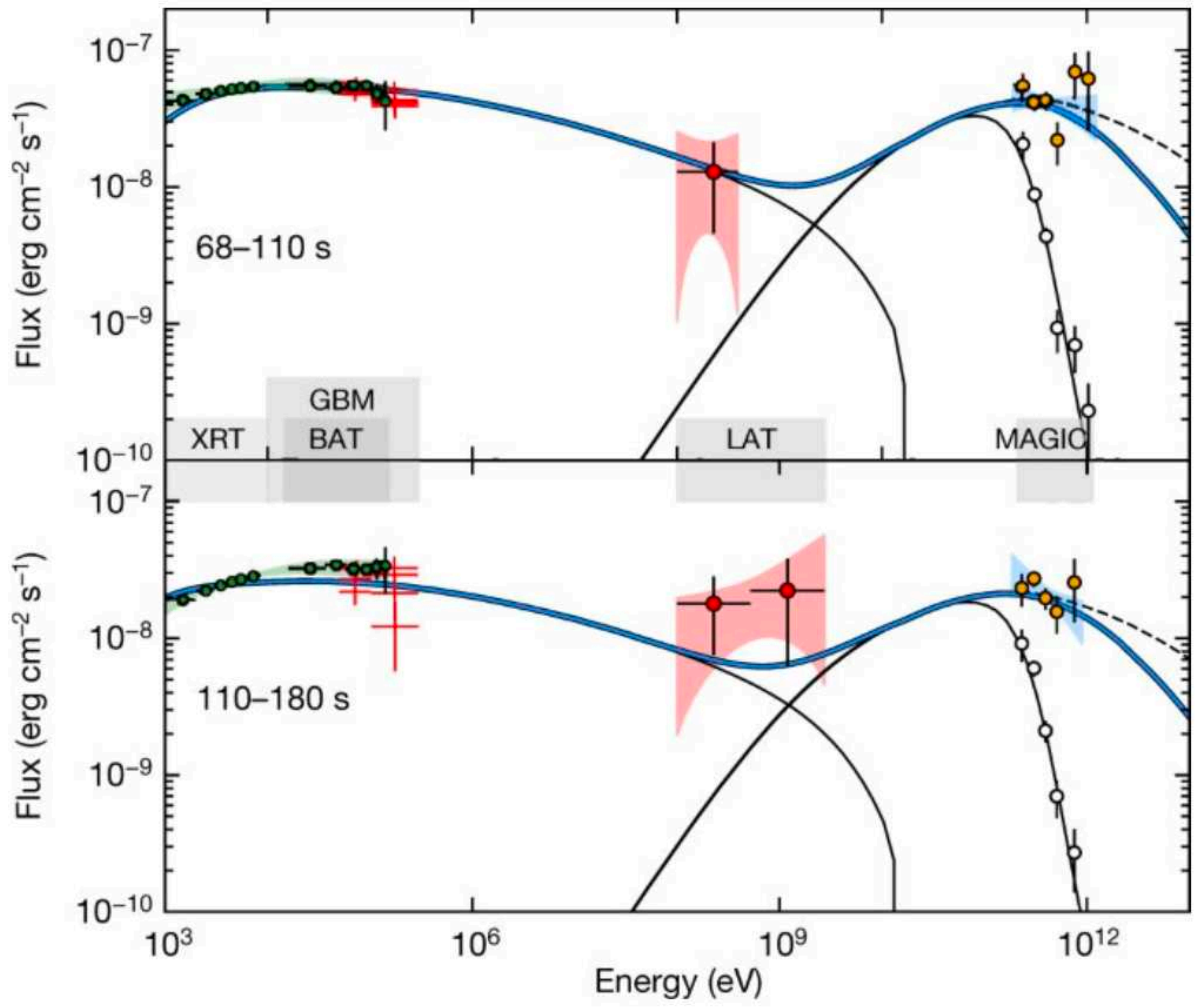
VHE detection of GRB

Originated by merging of two compact objects or by hypernova

[H.E.S.S. Collab. (2019) Nature, 575, 7783, 464-467]



[MAGIC Collab. (2019) Nature, 575, 7783, 455-458]

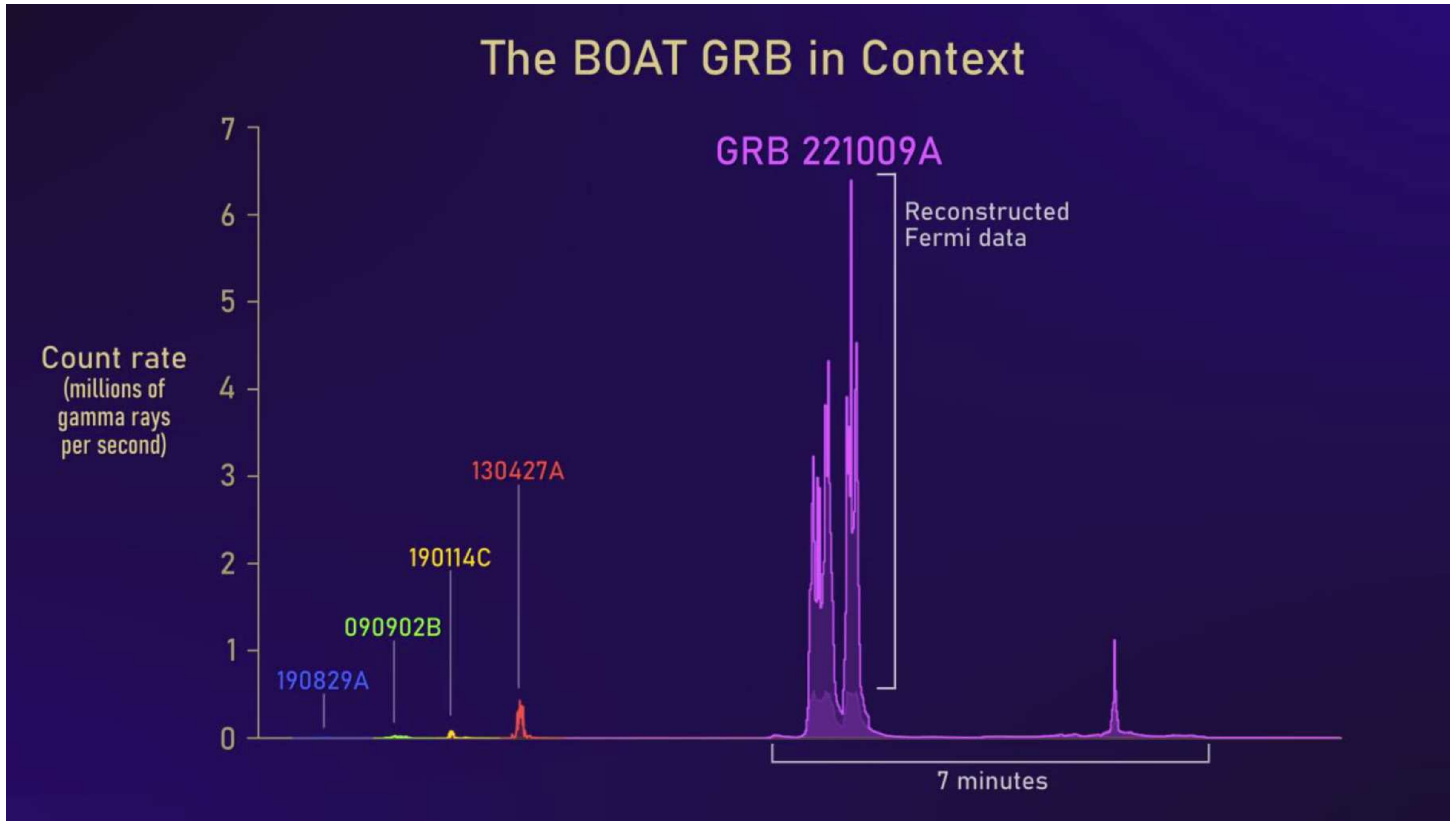


- 2019, annus mirabilis for GRBs
- Detection of GRB 190829A by H.E.S.S. and MAGIC
- Gamma-ray emission compatible with inverse Compton

VHE detection of GRB

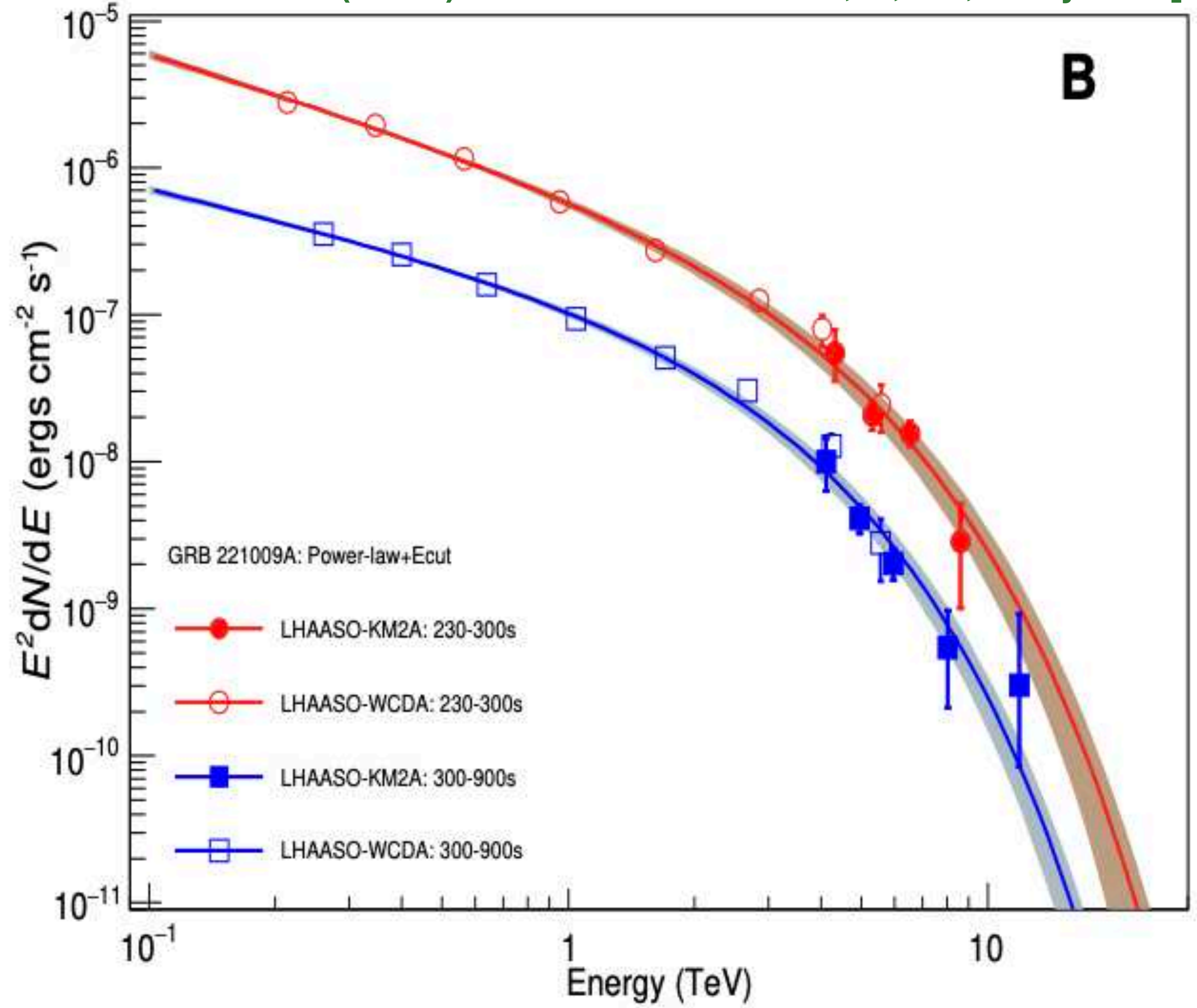
GRB 221009A: the Brightest Of All Time (B.O.A.T.)

Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)



Brightest GRB first observed (1 in 105 years events) by Fermi-GBM and Fermi-LAT up to ~400 GeV: isotropic equivalent gamma-ray energy ~$1.2 \cdot 10^{55}$ erg

[LHAASO Collab. (2023) Science Advances, 9, 46, eadj2778]



LHAASO detected photons up to 13 TeV from the afterglow (continuous monitoring + only instrument non saturable)

AGNs

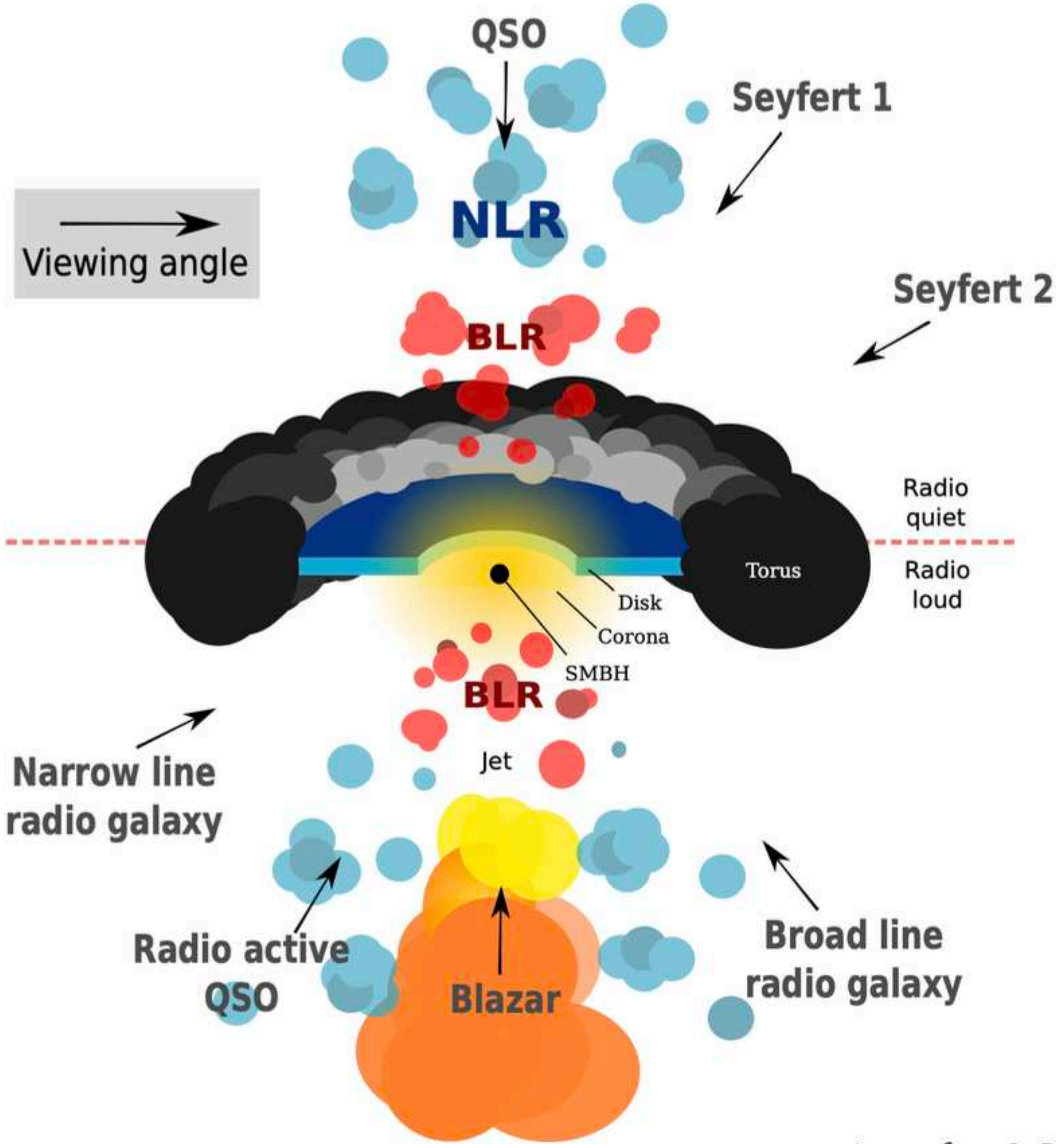


Image from L. Baronchelli

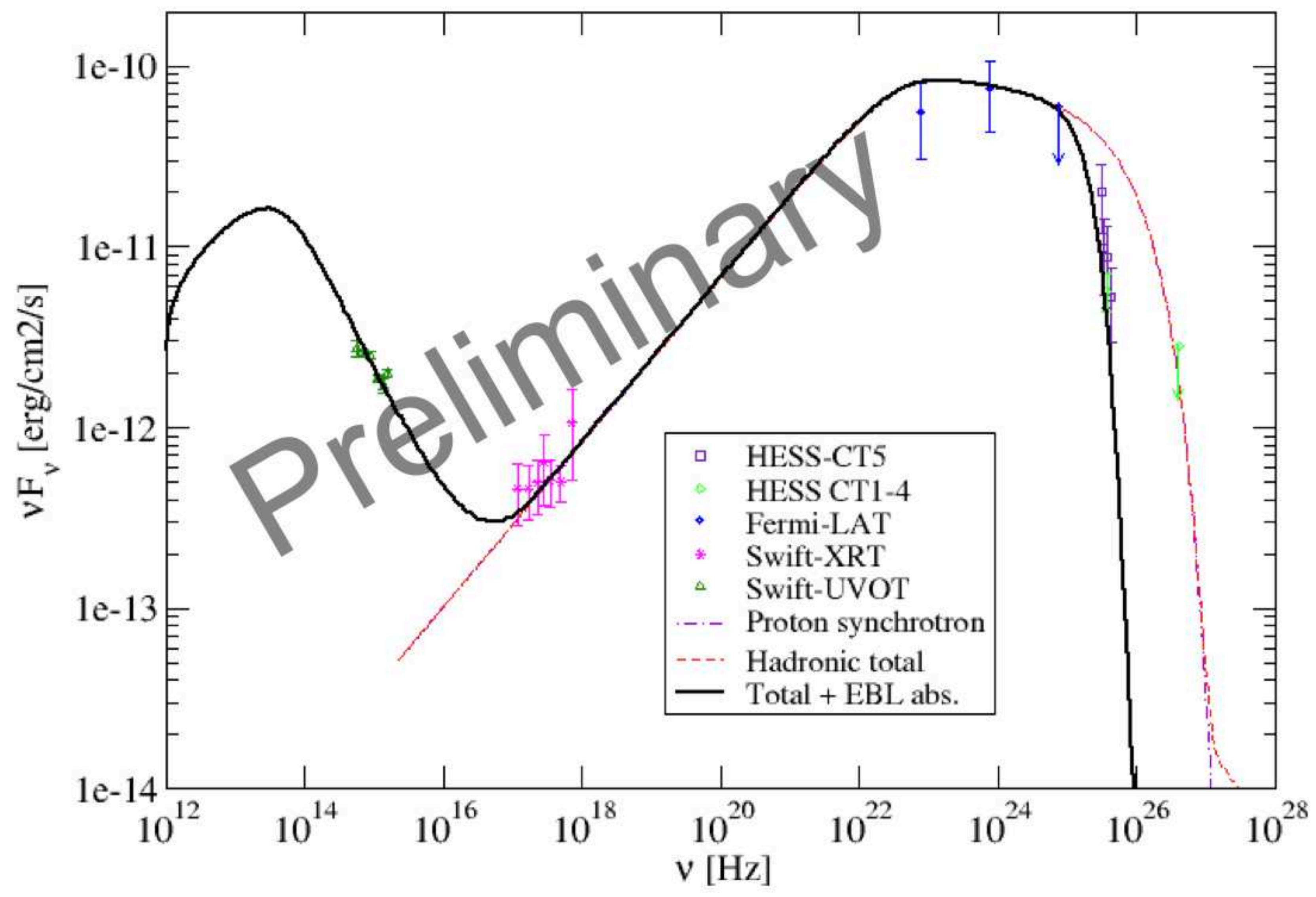
- Active galactic nuclei (AGN) with jets: collimated relativistic outflow of plasma (kpc to Mpc scale)
- Most powerful persistent emitters in the Universe
  - L ~ $10^{44\text{-}49}$ erg/s;
- Broadband, radio to gamma, non-thermal emission from the jet
- Bulk of the jet moving at relativistic speed ⇒ Doppler boost of their emission
  - Dominate the gamma-ray sky at HE and VHE

AGNs

High-redshift FSRQs (z~1)

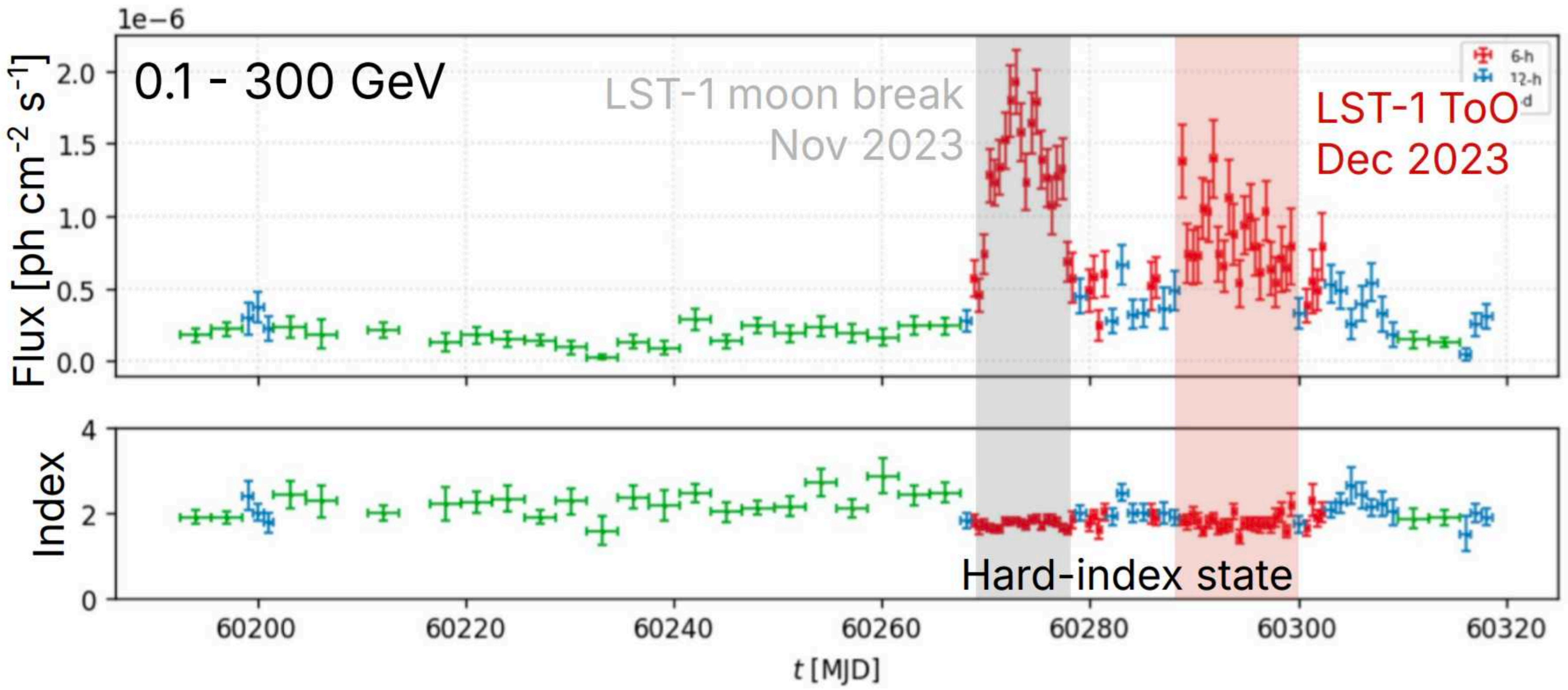
Goal: to extend the VHE blazer horizon to z>1 and probe evolution of the EBL out of z>1

PKS 0346-27 [H.E.S.S.] (z=0.991)



Detection during flaring in one night. SED modelling possible only with a hadronic model, requiring highly super-Eddington jet power

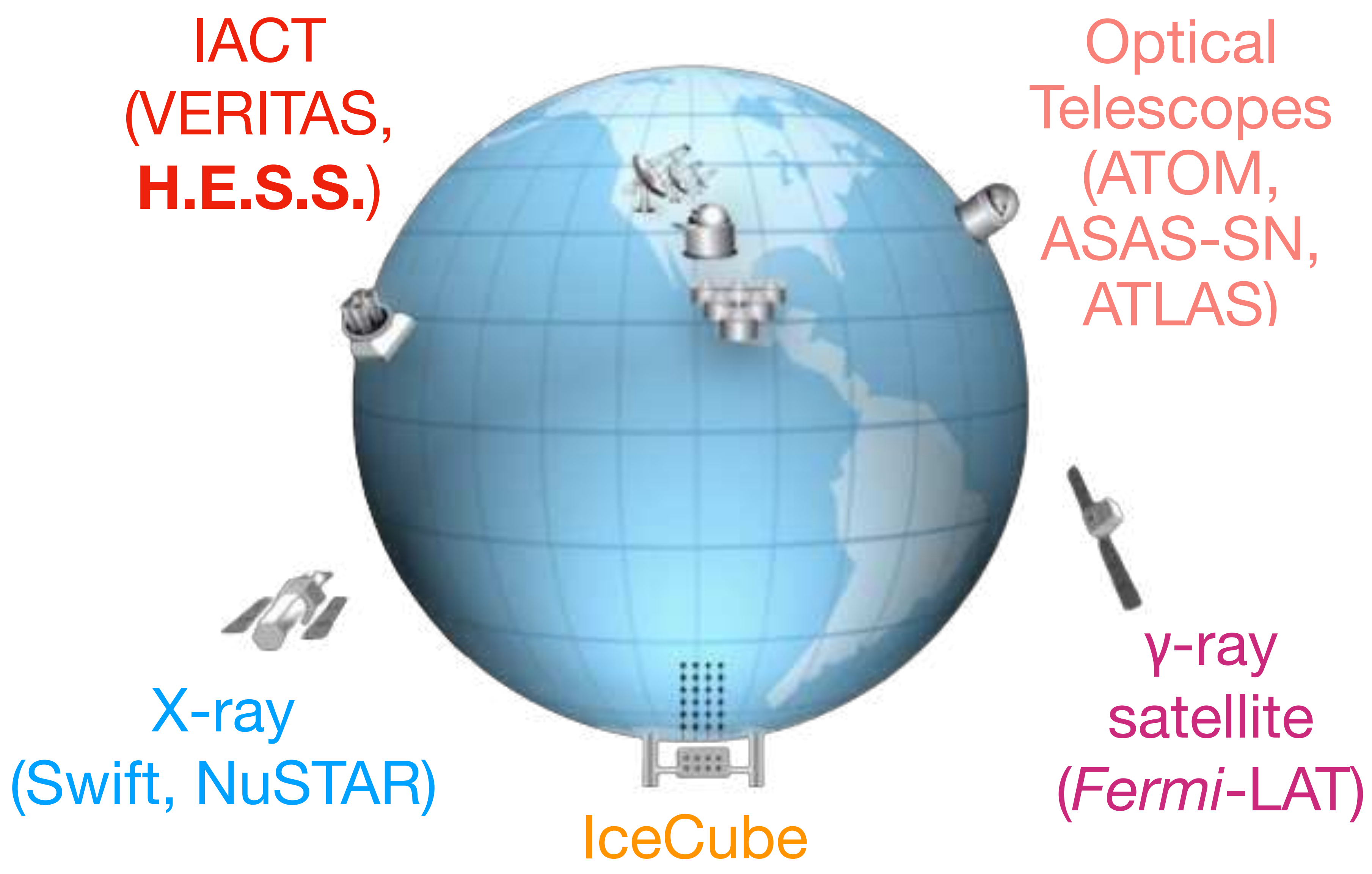
OP 313 [LST-1] (z=0.9973)

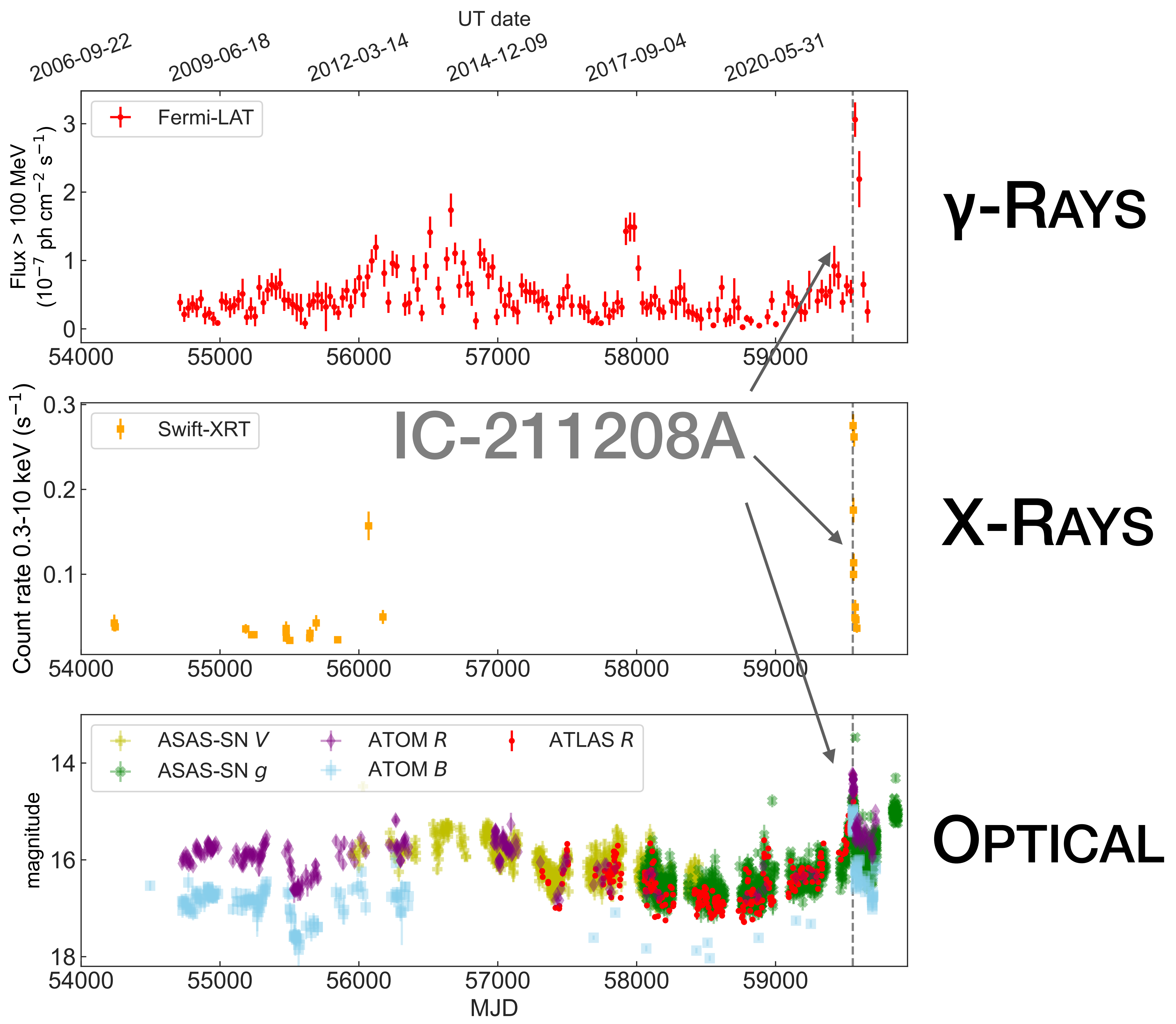


Major flare from OP313 detected with Fermi-LAT in November 2023 (Moon break) and once again December 2023 (LST-1 begins observations)

AGN Flares and Multi-Messenger Synergies

Follow-up of IC-211208A (171 TeV) in coincidence with flaring **gamma-ray blazar PKS 0735+178**





[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]

AGN Flares and Multi-Messenger Synergies

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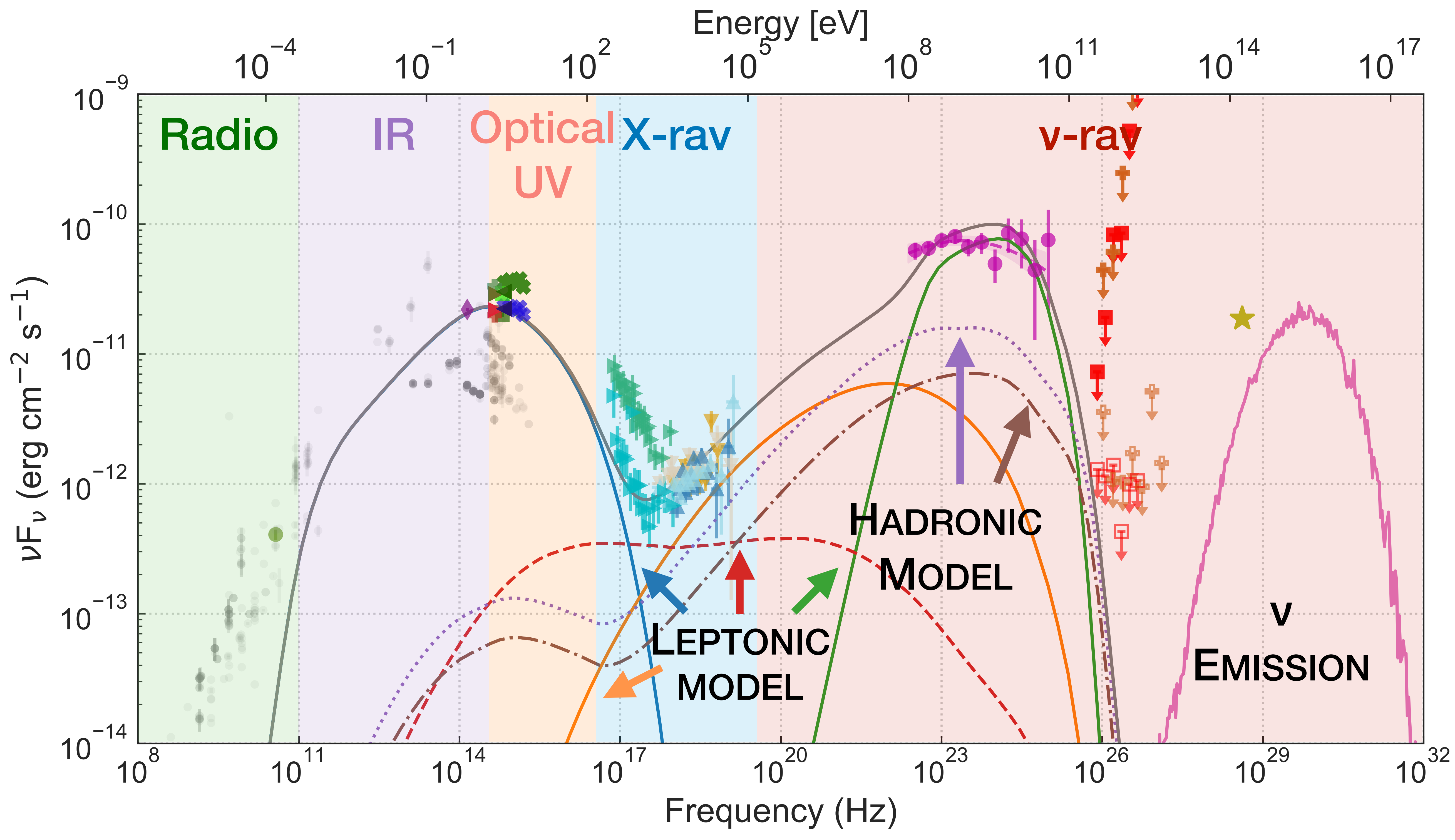
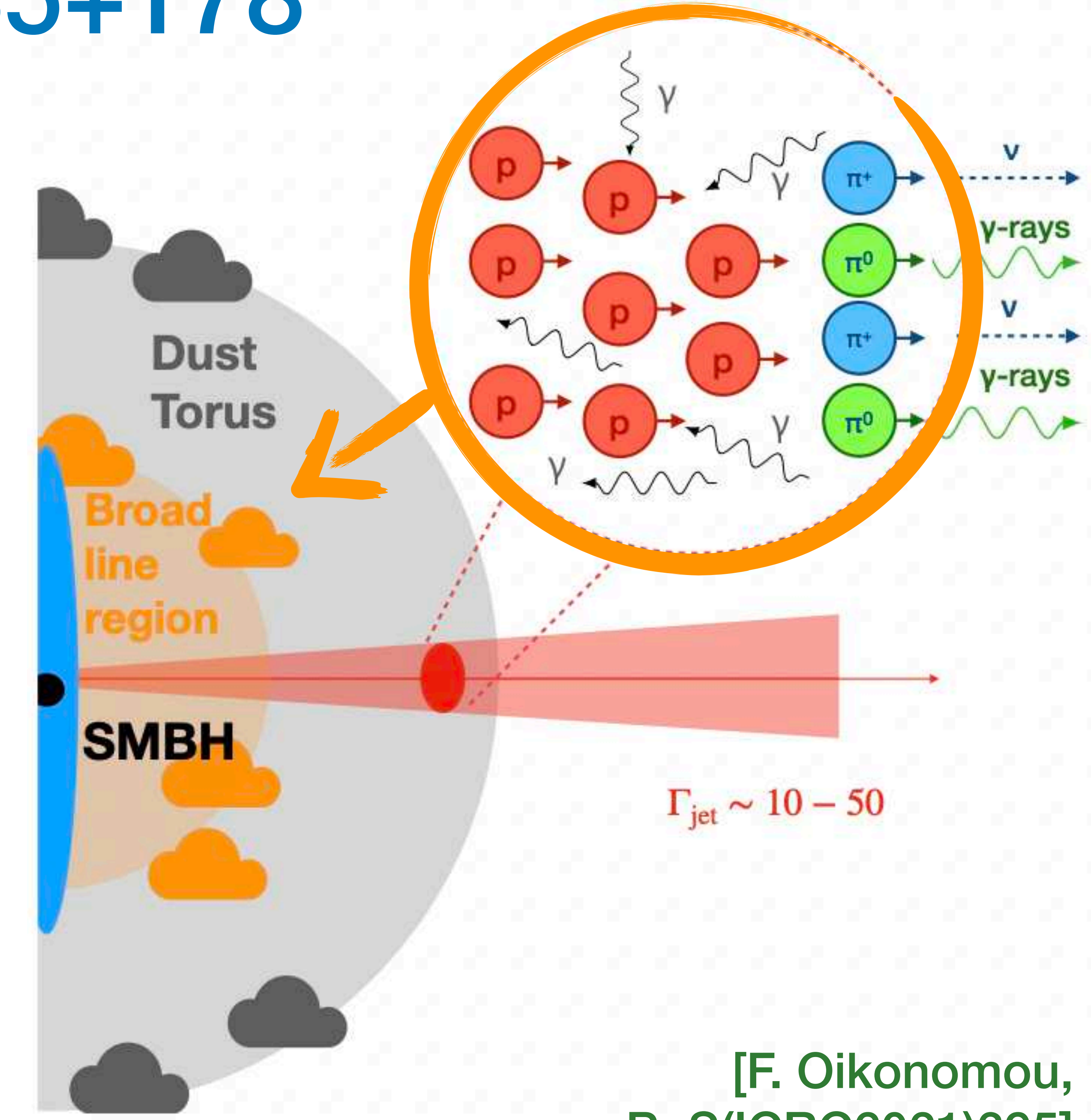


[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]

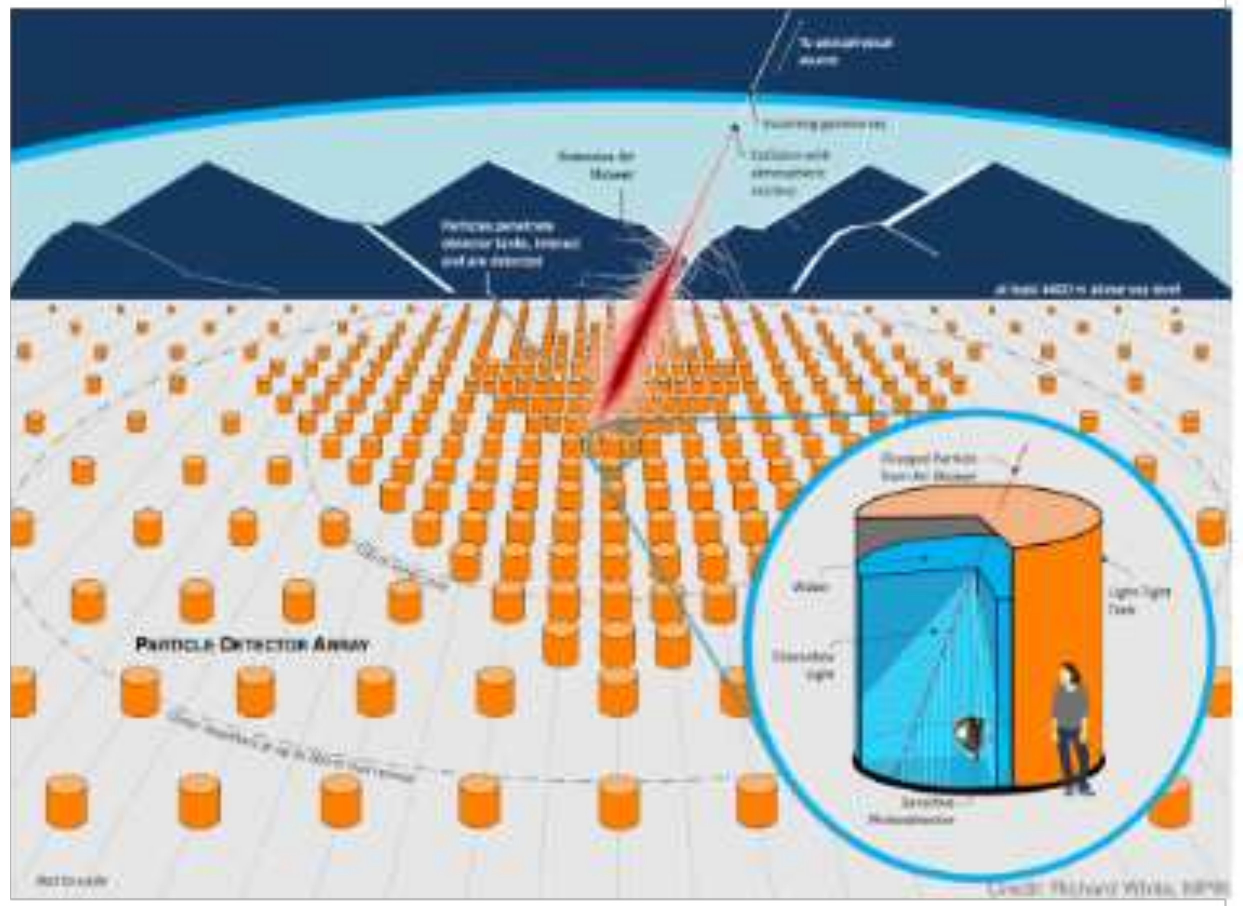


[F. Oikonomou, PoS(ICRC2021)395]

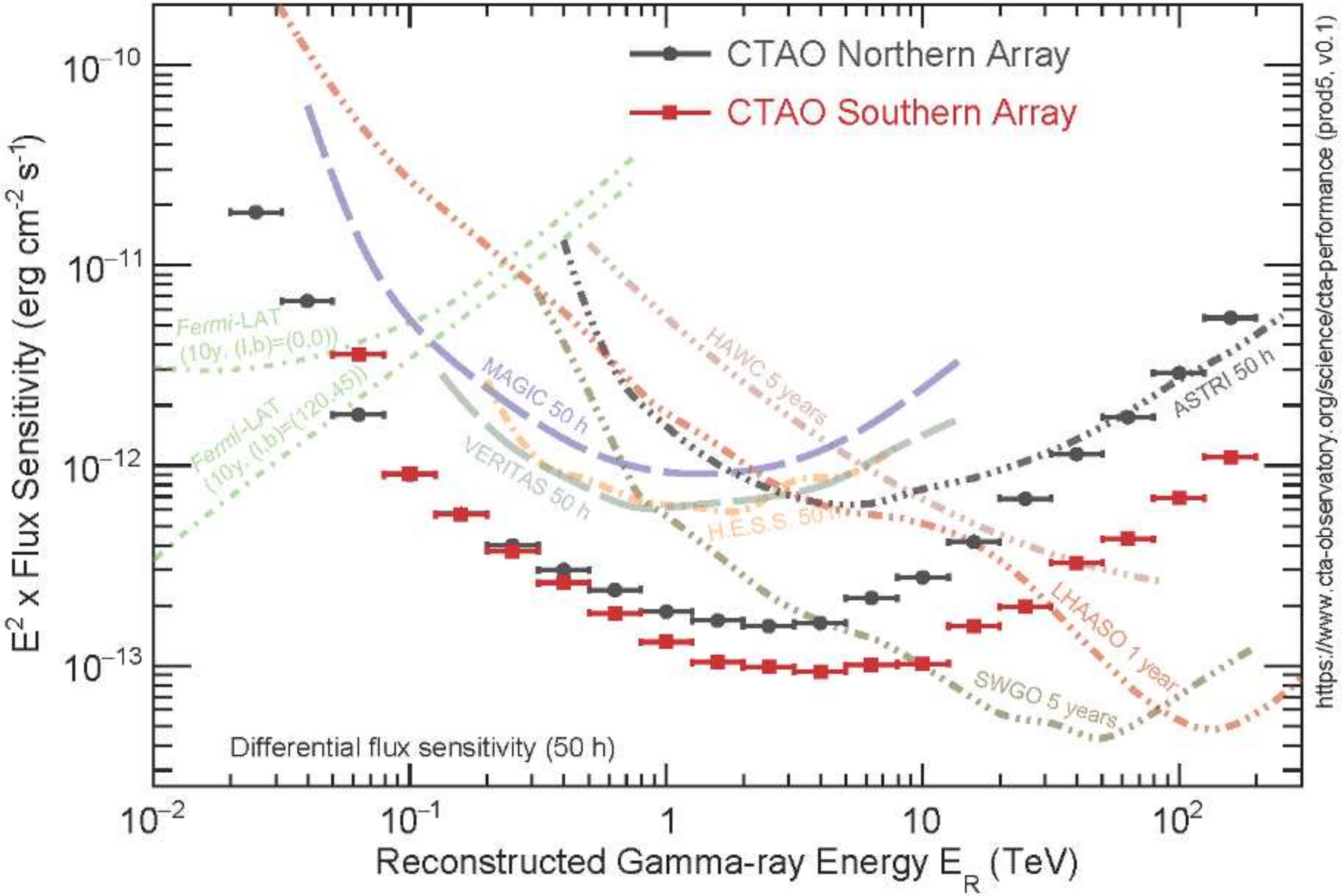
Lepto-hadronic model with external photon field target (BLR)

New generation γ-ray observatories

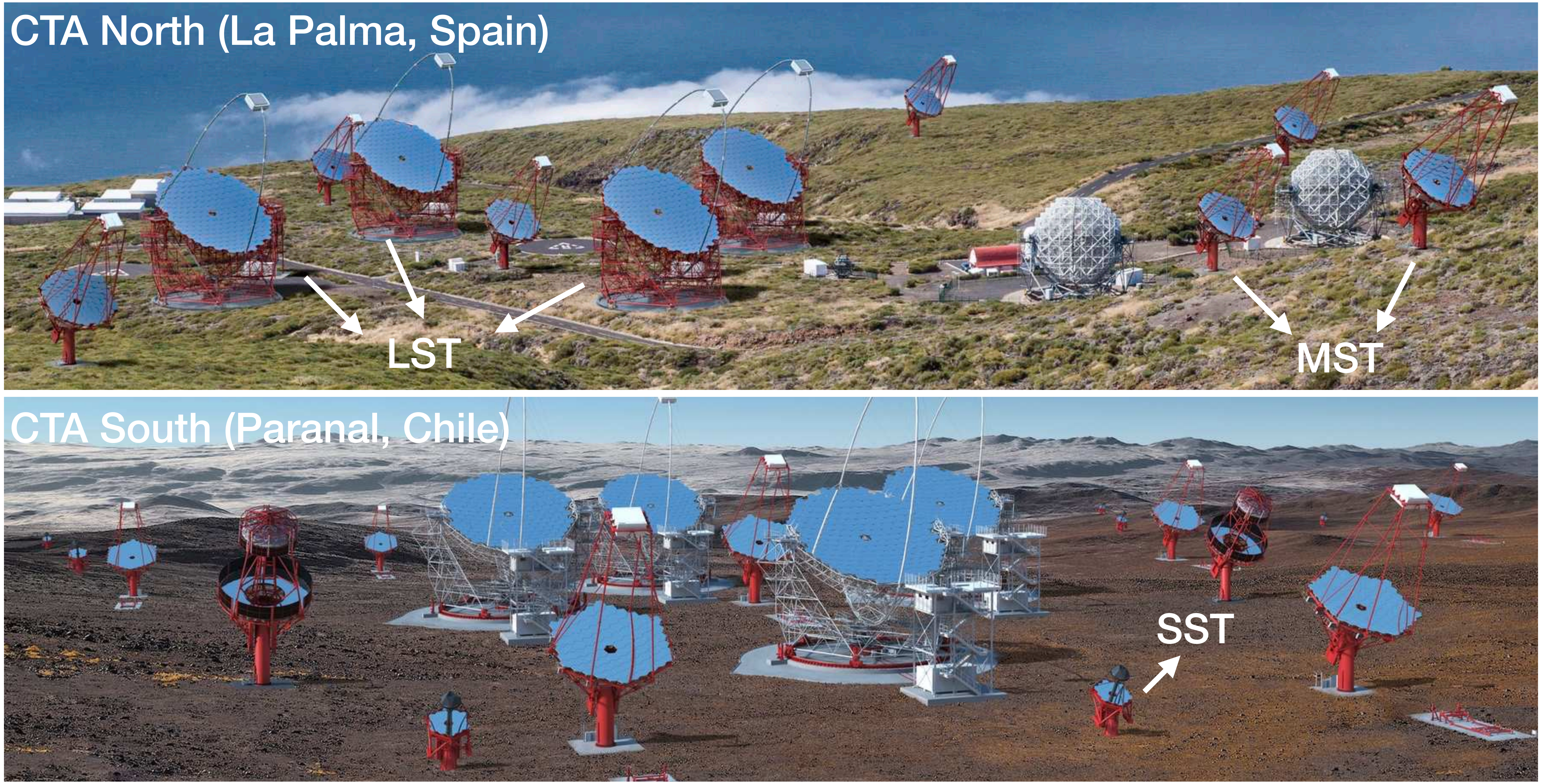
Future WCD: SWGO



Future IACT: CTAO

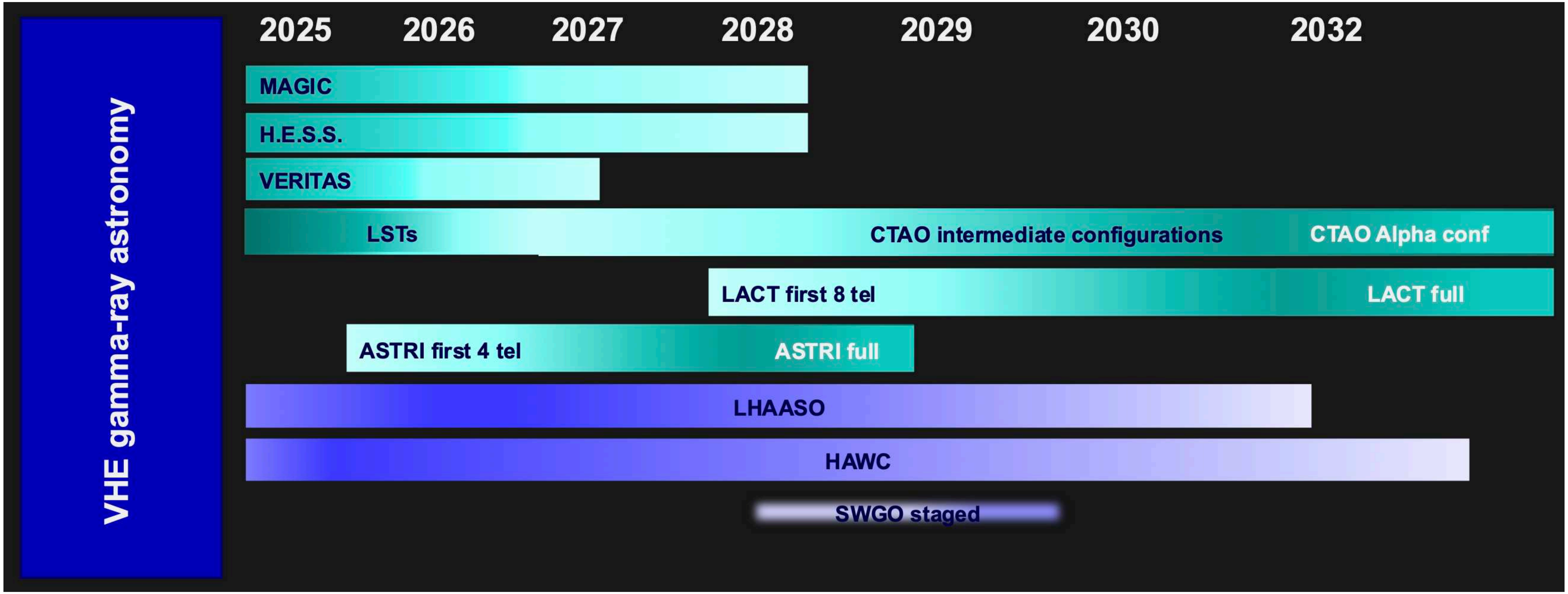


CTAO



CTAO

Timeline of VHE astronomy

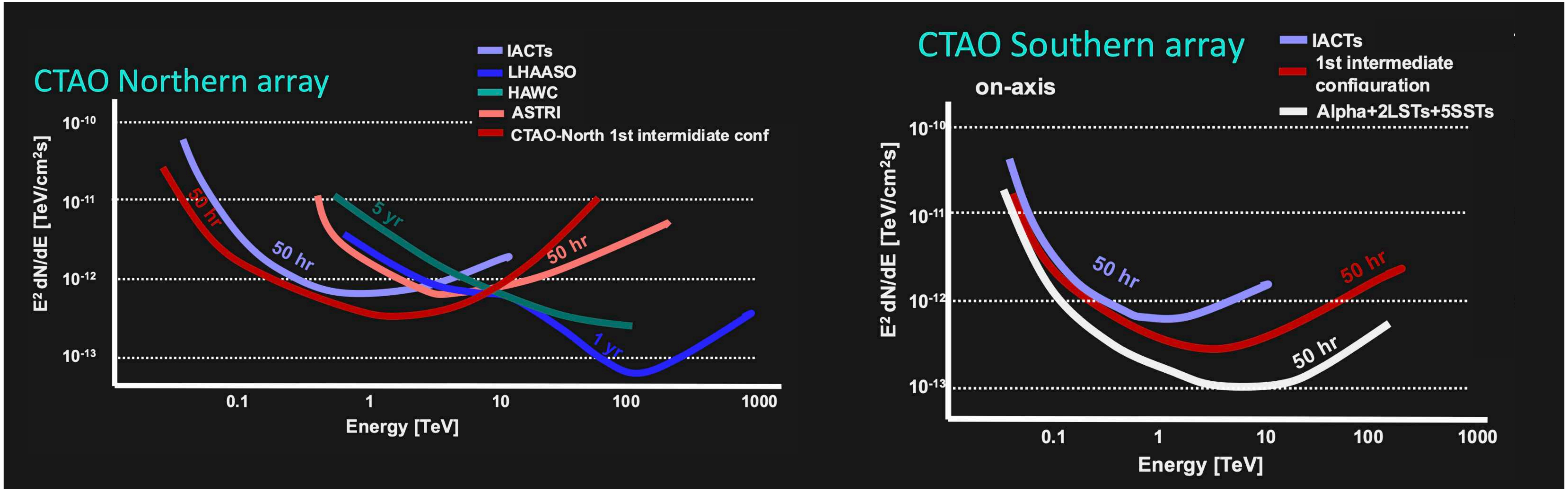


Credit: R. Zanin - gamma2024

CTAO in 3 year from now

Incremental array configurations that become progressively operative

Credit: R. Zanin - gamma2024



Performance capabilities already a factor 2 better than the existing facilities

Conclusions

- **Water Cherenkov Detectors**: HAWC, LHAASO, next: SWGO
  - → continuous, wide-field γ-ray observations.
- **Imaging Air Cherenkov Telescopes**: HESS, MAGIC, VERITAS, next: CTAO
  - → deep, precision γ-ray observations
- VHE–UHE gamma-ray measurements are a powerful tool to probe particle acceleration up to (and beyond) PeV energies, and to explore transient phenomena
- **Galactic observations**: PeVatron sources and galactic CR accelerators
- **Extragalactic observations**: GRBs, AGN, GW and neutrino follow-ups
- In the next few years new experiments and observatories will boost the covering of the gamma-ray sky with an unprecedented sensitivity that will imply an expansion in the theories explaining all the current observations