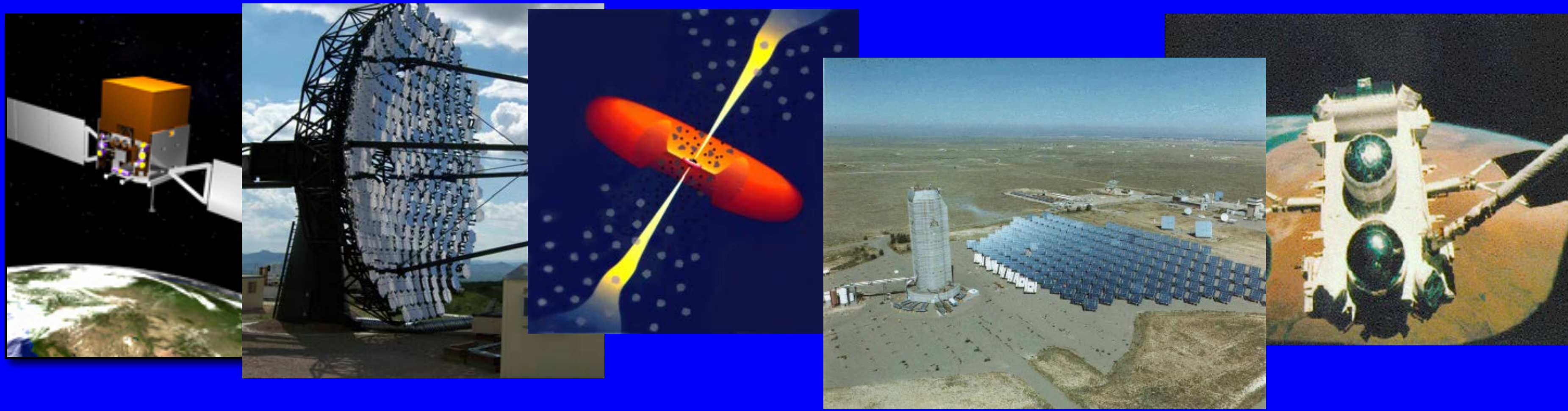


Exploring the Extreme Universe with MeV to TeV Gamma-ray Observatories

Reshmi Mukherjee[1]
[1]Barnard College, Columbia University, NY

DESY Colloquium 14 Dec 2022

Thanks to the VERITAS Collaboration

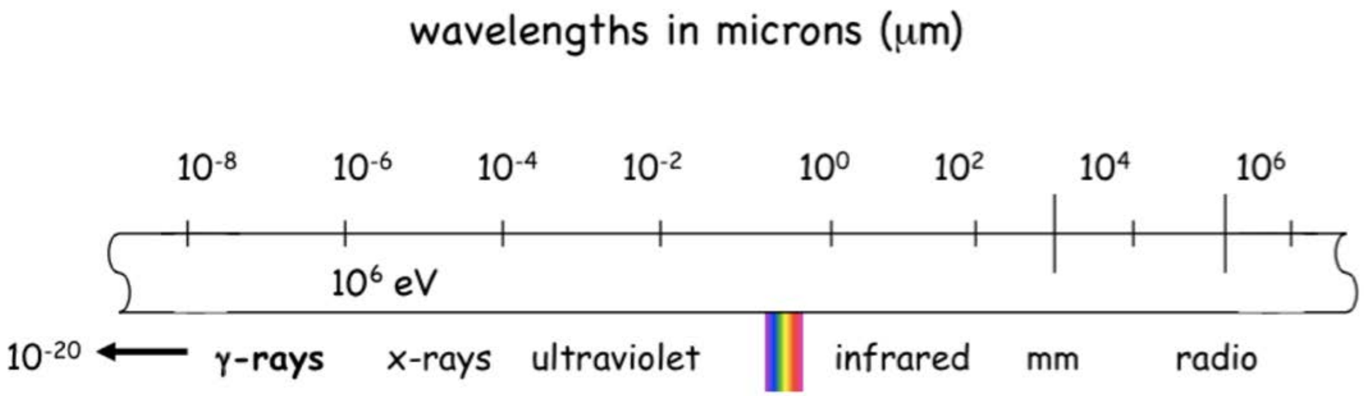
VERITAS hybrid Summer Collaboration Meeting 2022 at DESY (Zeuthen)

Outline

- Motivation and broad science goals
  - Cosmic ray and astrophysical accelerators
- Techniques in high energy gamma-ray astronomy
  - satellite, ground-based
- Science highlights
  - Open questions in Particle Astrophysics
  - What are the most energetic events in the universe?
  - (Focus on relativistic jets and blazars)
- Future – new telescopes

Why Gamma-Ray Astronomy?

- Provides crucial window in the cosmic E-M spectrum
- Exploration of non-thermal phenomena in the Universe of the most energetic and violent forms
- The "last window" in the cosmic EM spectrum covers 8+ decades



- LE or MeV : 0.1 -100 MeV
- HE or GeV : 0.1 -10 GeV
- VHE or TeV : 0.1 -100 TeV

domain of space-based astronomy

domain of ground-based astronomy

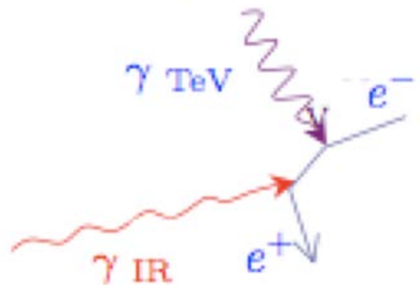
Potential & Uniqueness

- Unique for specific topics
  - e.g. for the solution of the origin of Galactic and Extragalactic Cosmic Rays

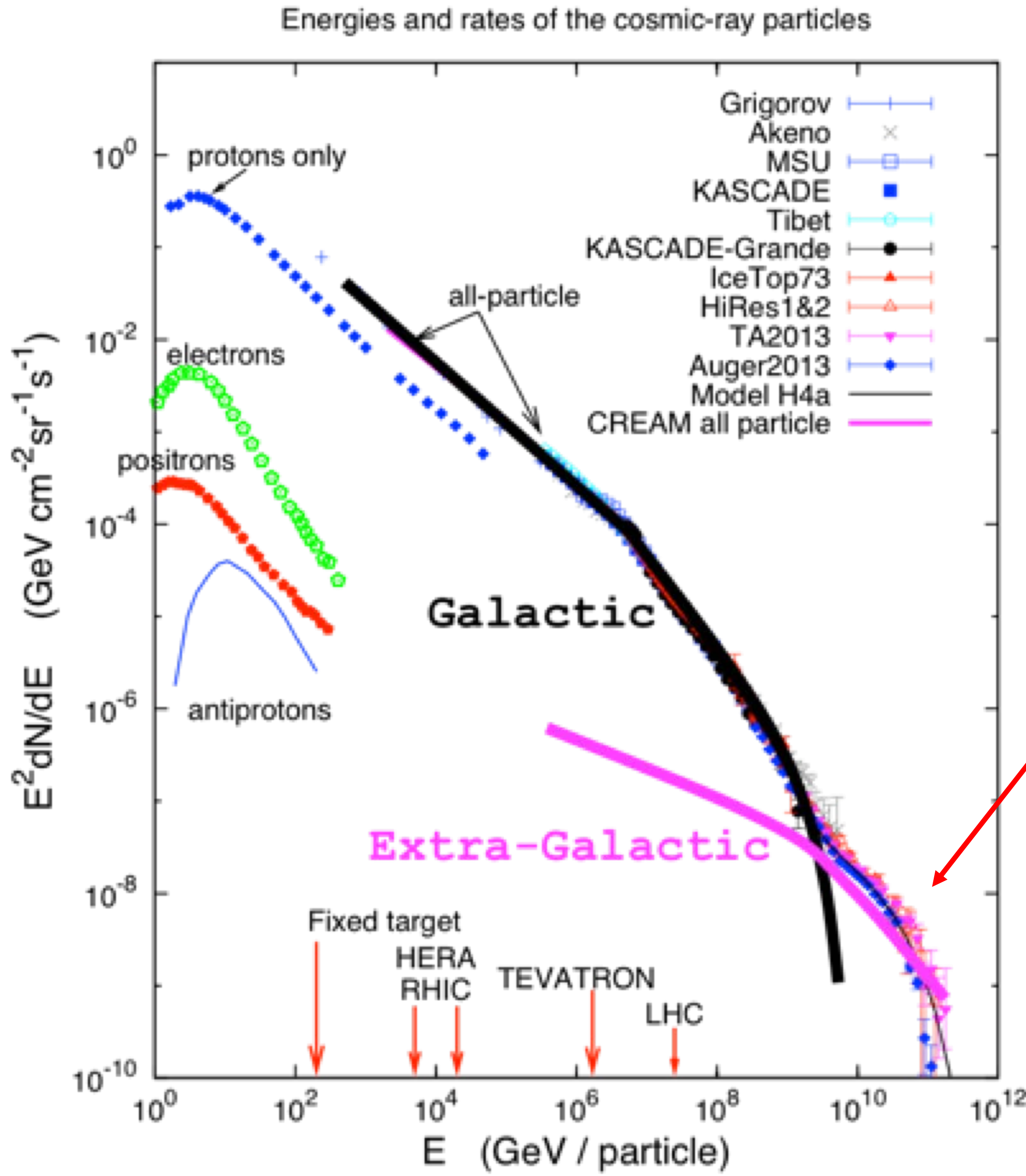
- May provide key insight into a number of astrophysics questions
  - physics and astrophysics of relativistic outflows (jets and winds)
  - HE processes at extreme conditions (e.g. close to Black Holes)
  - Physics and astrophysics of Supermassive Black Holes

- Using γ rays to probe intergalactic space
  - Diffuse radiation fields.

- Contribution to fundamental physics topics
  - violation of Lorentz invariance
  - search for Dark Matter



Energies & rates of CR particles

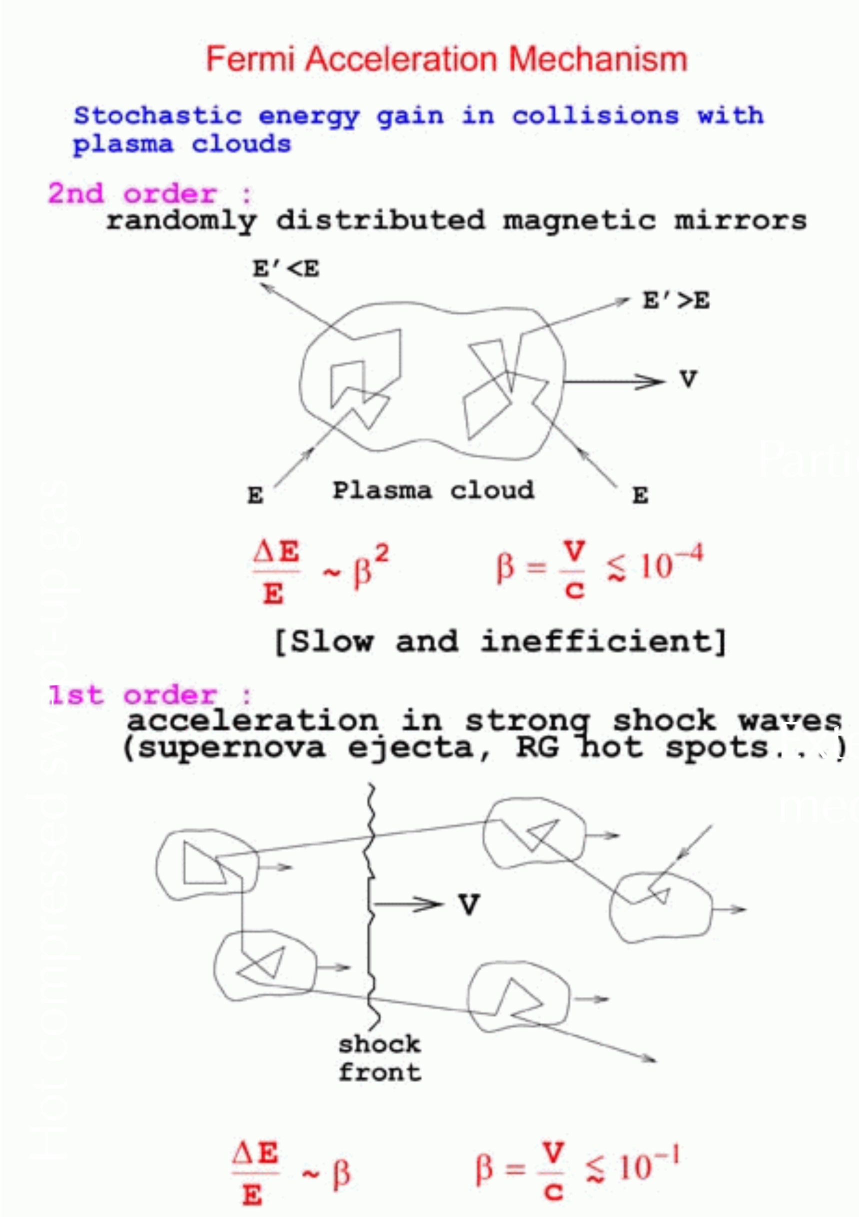


- >100 year old mystery !
- Enormous energy range
- Mostly charged particles
- ~85% protons, ~12% He nuclei, ~1% heavier nuclei, ~1% e- and e+.
- Energy density ~ 1 eV/cm^3

PeVatrons and Zevatrons are extreme accelerators

- below 10^{15} eV - G
- beyond 10^{18} eV - ExG
- between 10^{15}-10^{18} eV ?

Cosmic Ray Origins



see: http://hires.physics.utah.edu/

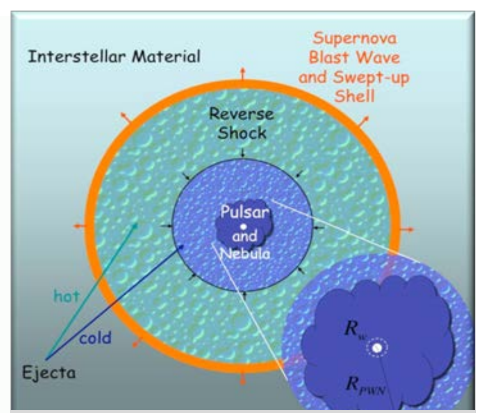
How do you get 10^{20} eV?

Diffusive shock acceleration: stochastic energy gain in collisions with plasma clouds

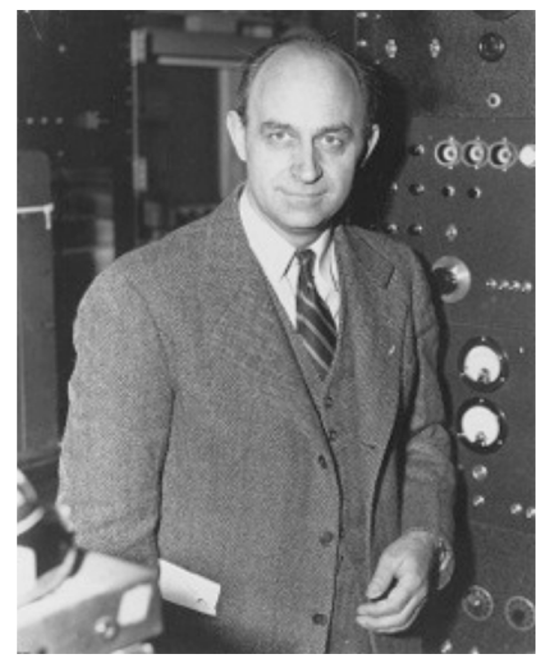
Shock waves + strong magnetic fields increase the energy of cosmic rays over time:

- Particle's perspective: crossing the shock => head-on collision with magnetic domains
- Energy gain:

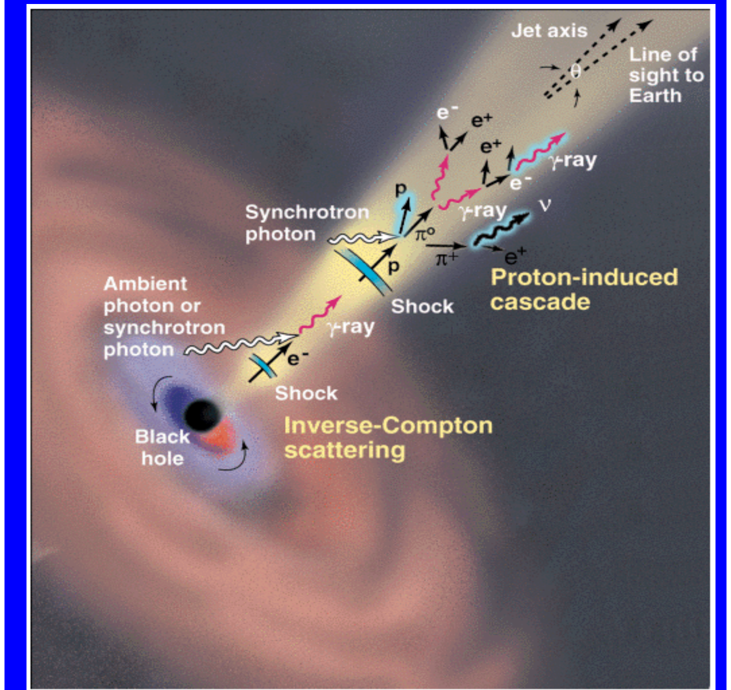
$\Delta E/E \sim 1\ \%$



Gaensler & Slane 2006



Extragalactic γ-ray Sources: Blazars



Buckley, Science 1998

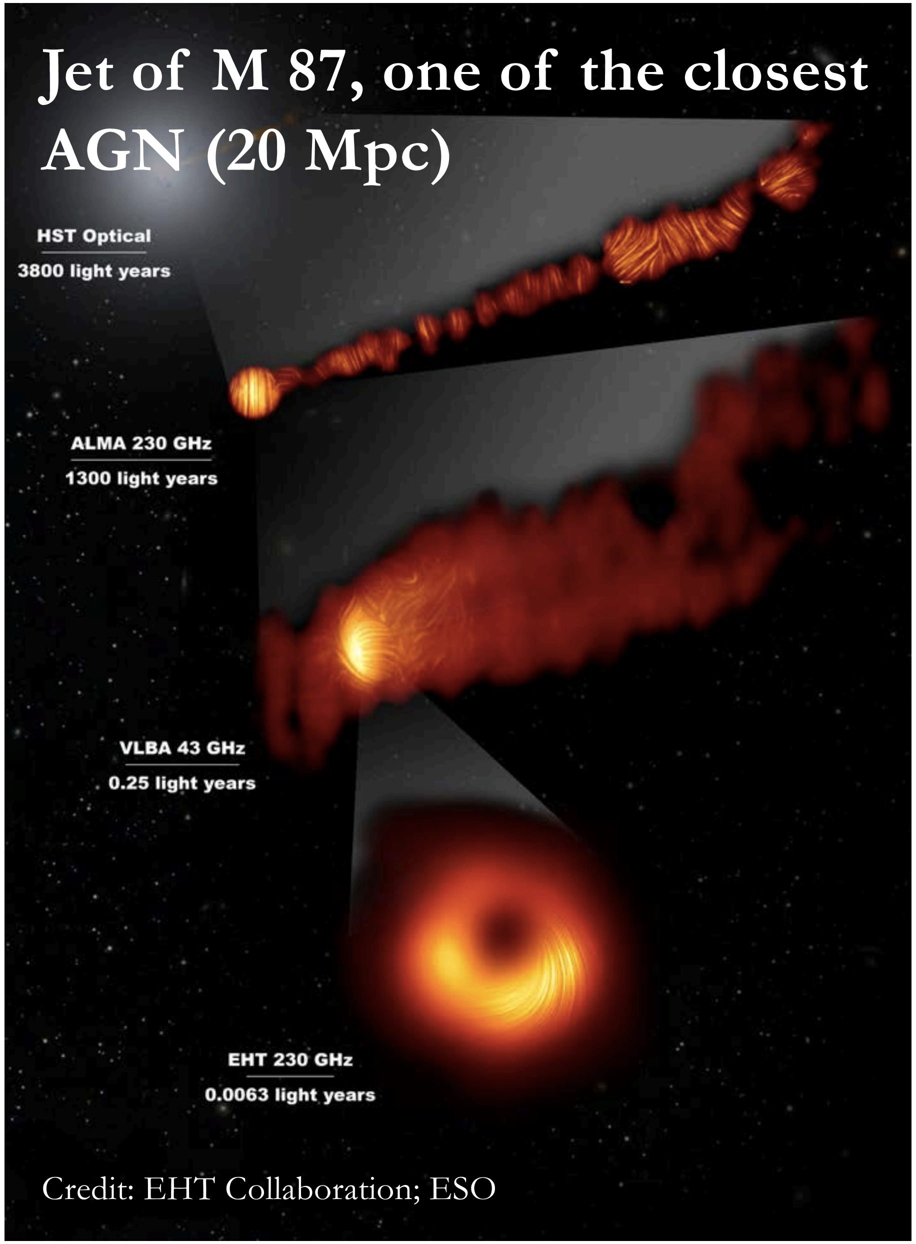
Physics of Compact Objects: AGN scales

- Active galactic nuclei occupy a tiny fraction of a galaxy:
  - $R_G \sim 10^4$ pc
  - $R_{tor} \sim 1$ pc
  - $R_{BH} \sim 10^{-5}$ pc

- Blazars: largest TeV & GeV extragalactic source class
- Ultra short time variability (~min scales)
- Extremely hard (harder than $E^{-1.5}$) energy spectra
- Jet power exceeds Eddington luminosity. High γ-ray luminosity ~ 10^{48}erg/s (isotropic)

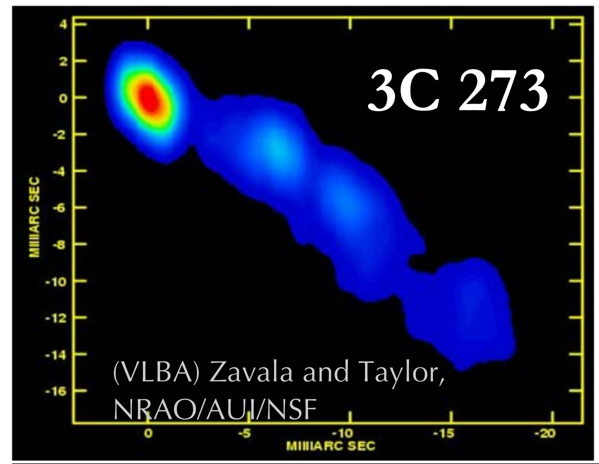
- GeV-TeV particles are needed to make VHE γ-rays
- Doppler boosting allows γ-rays to be detectable from >100 Mpc sources

Extragalactic Jets: Regime of relativistic plasmas

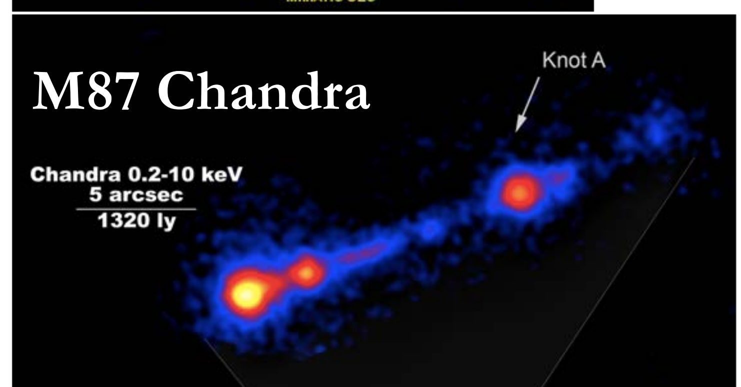


Open Questions

- Origin of fast flares?
- Physics of particle acceleration & relativistic reconnection?
- Blazars as neutrino sources?

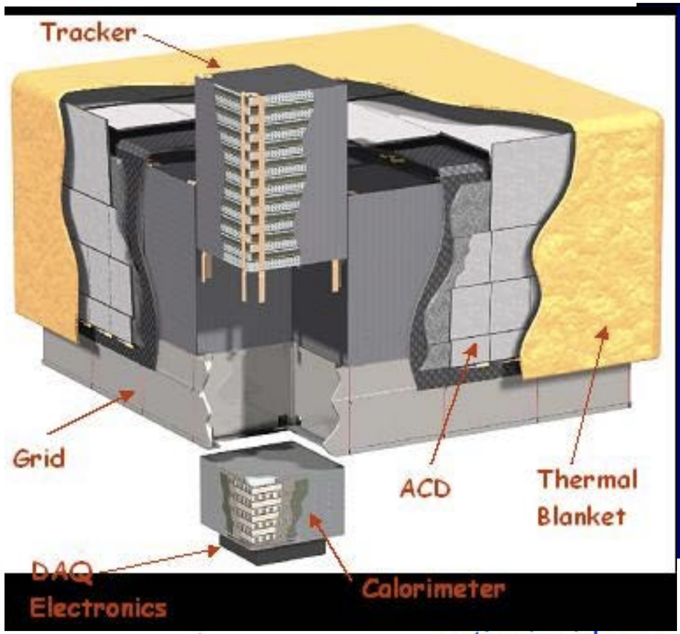


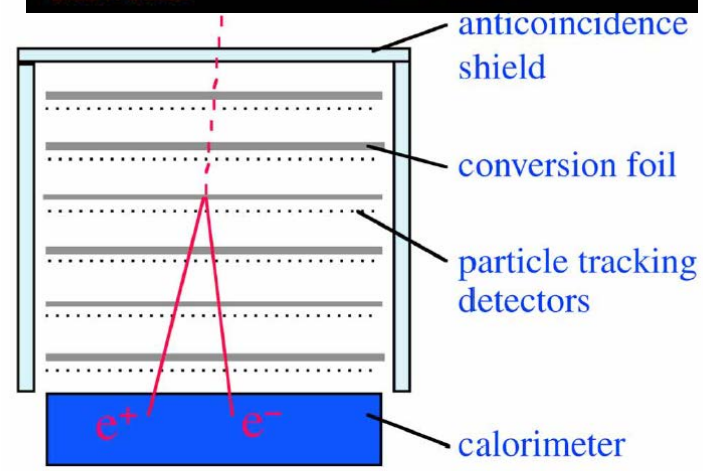
3C 273: kpc scale radio jet

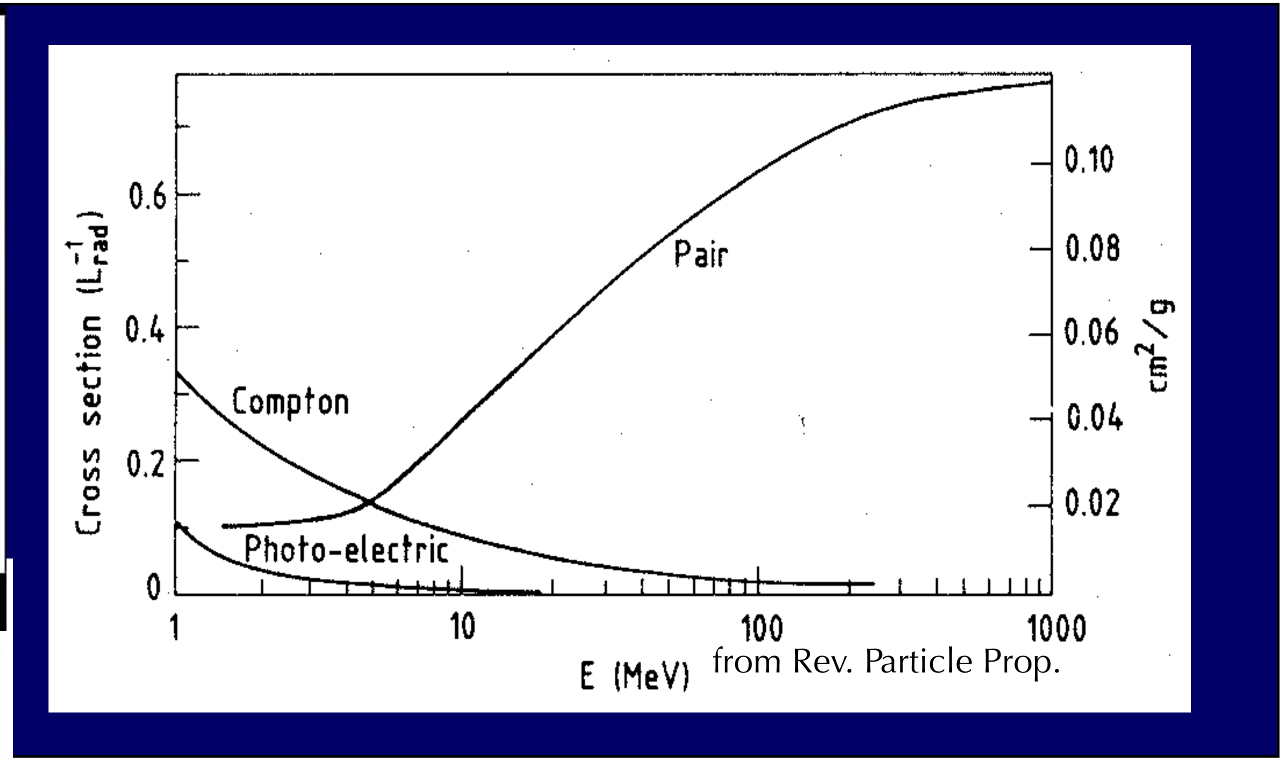


The instruments at VHE energies

In Space …

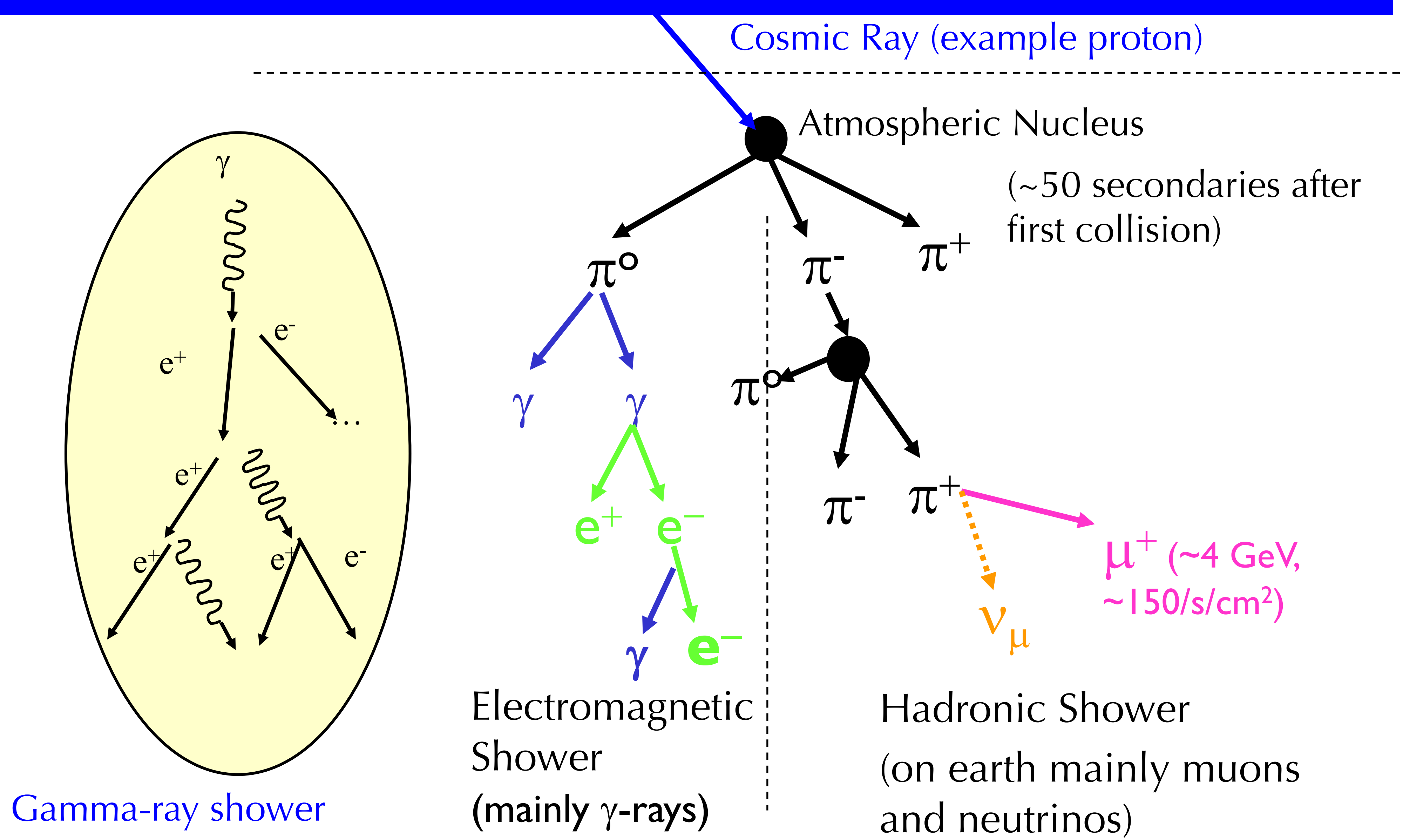




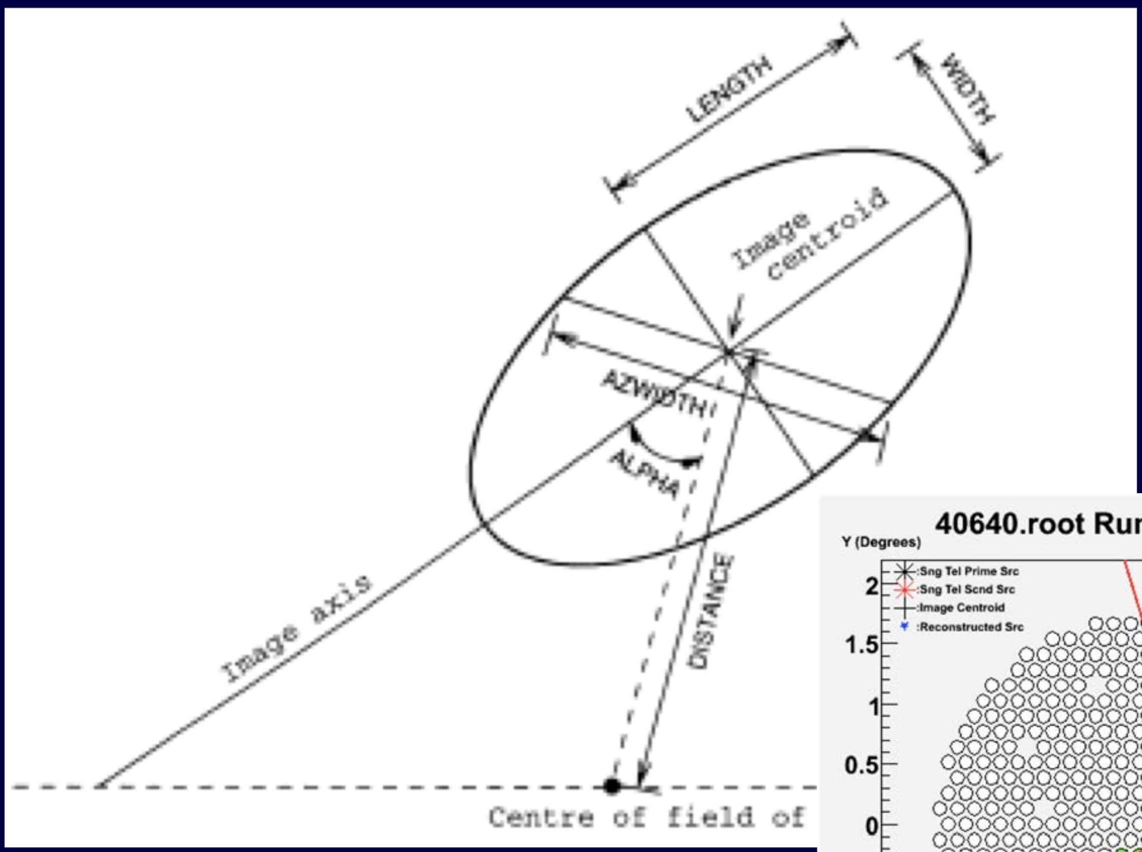


NASA's Fermi Gamma Ray Space Telescope: ~100 MeV – 50 GeV

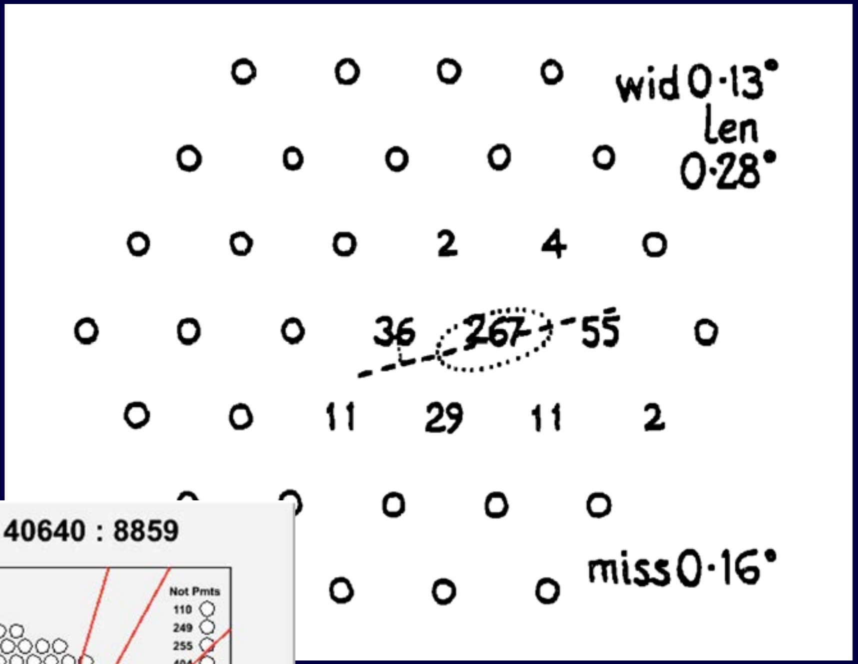
On the Ground: Physics of Extensive Air Showers



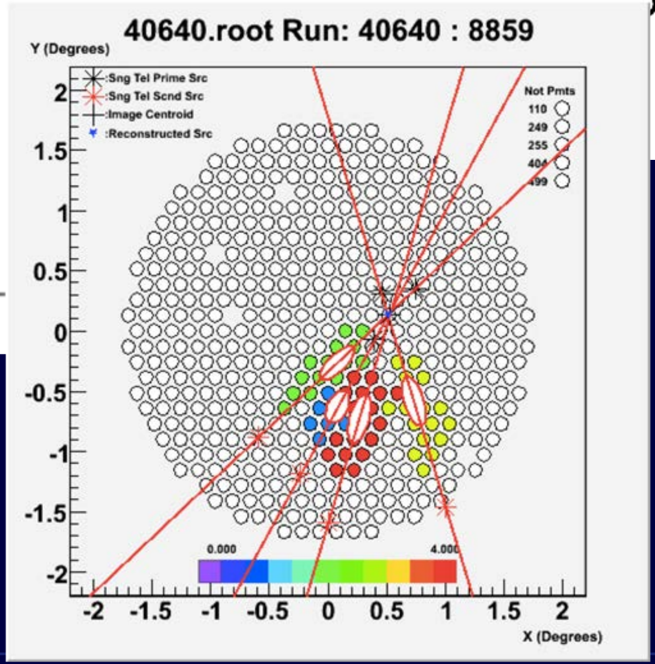
The Atmospheric Cherenkov Technique



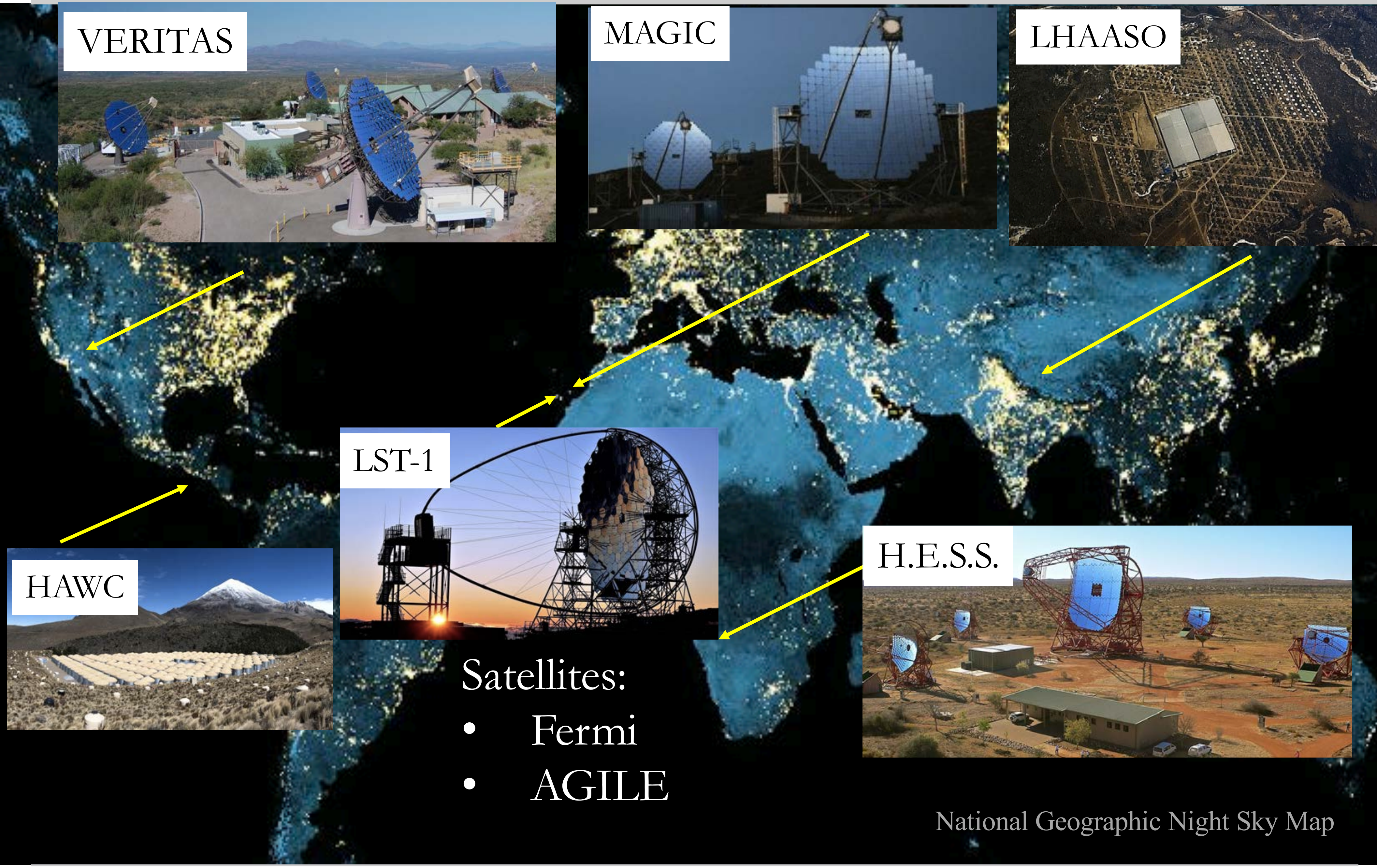
Whipple Observatory



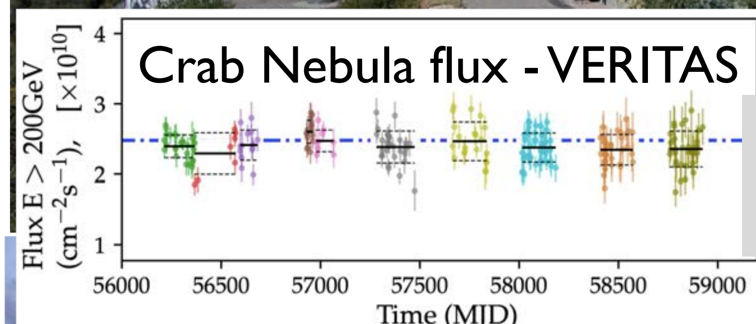
Hillas 1985



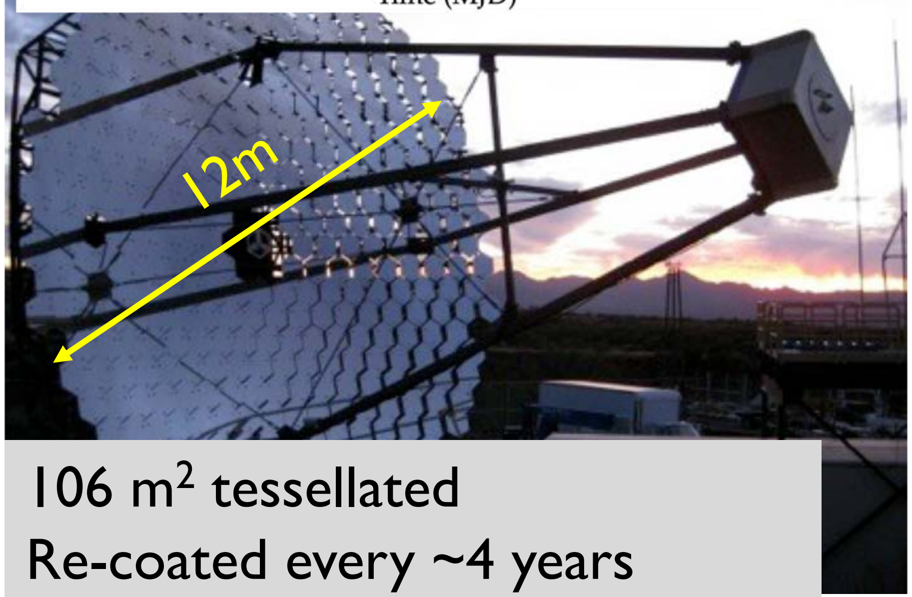
The Gamma-ray Instruments (2022)



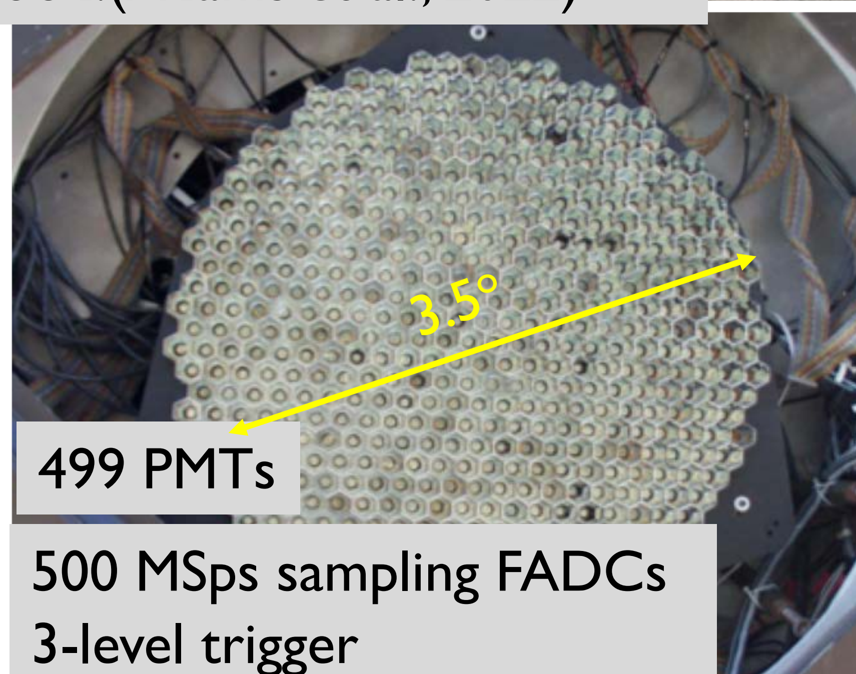
VERITAS Cherenkov Telescope



Long-term instrument response well understood:(Adams et al., 2022)



106 m^2 tessellated
Re-coated every ~4 years



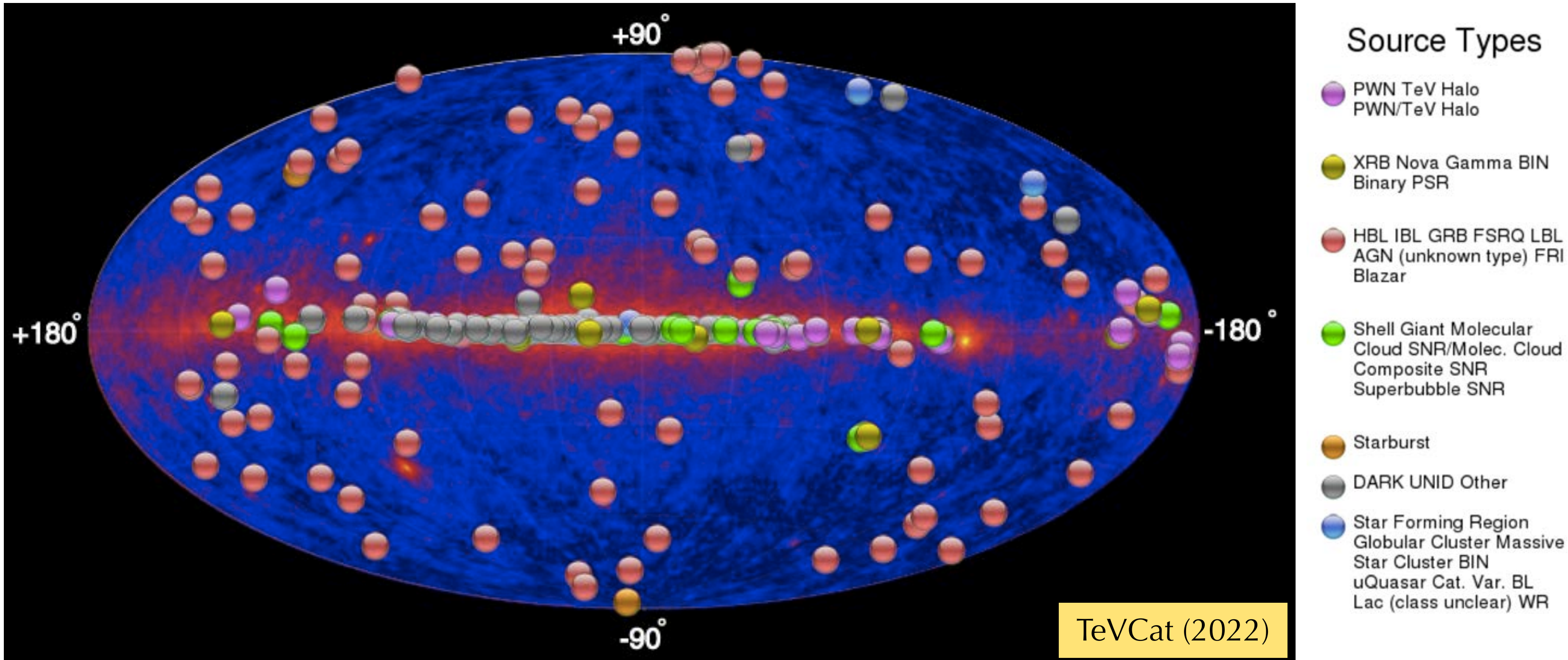
499 PMTs

500 MSps sampling FADCs
3-level trigger

Sources of VHE radiation

- Pevatrons & Tevatrons in the outer Galaxy
- Relativistic Jets

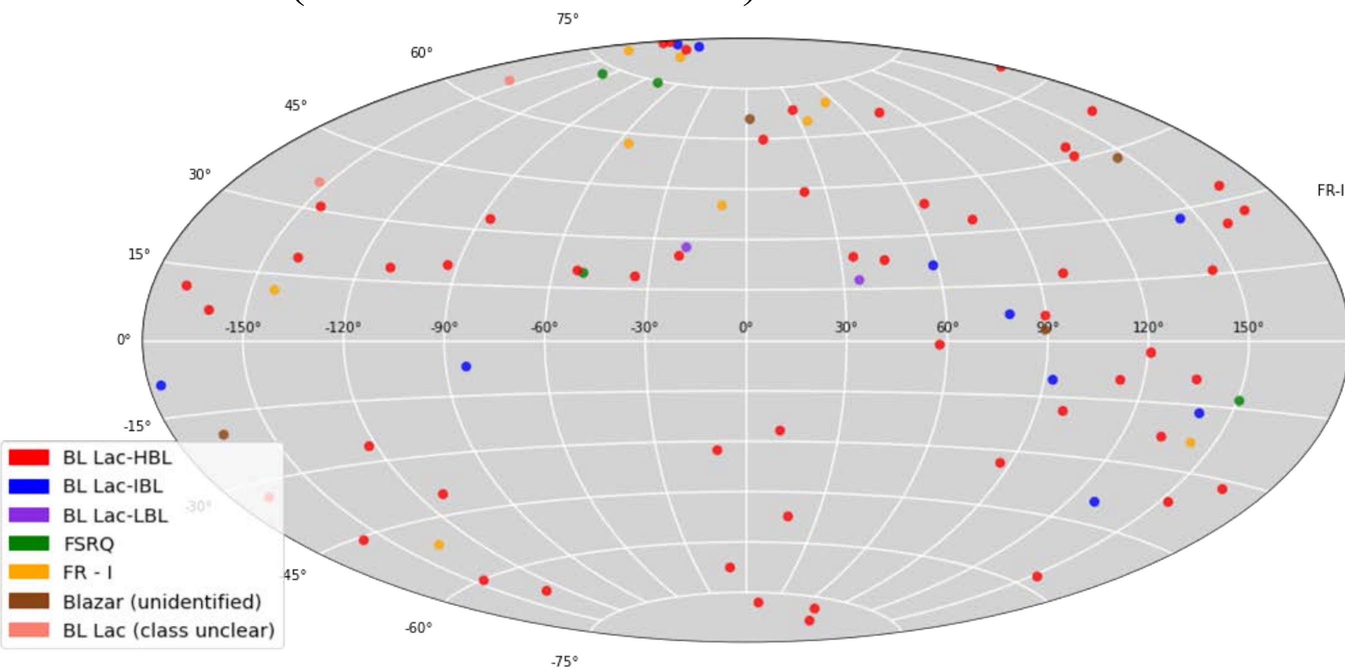
VHE Gamma-Ray Sky (2022)

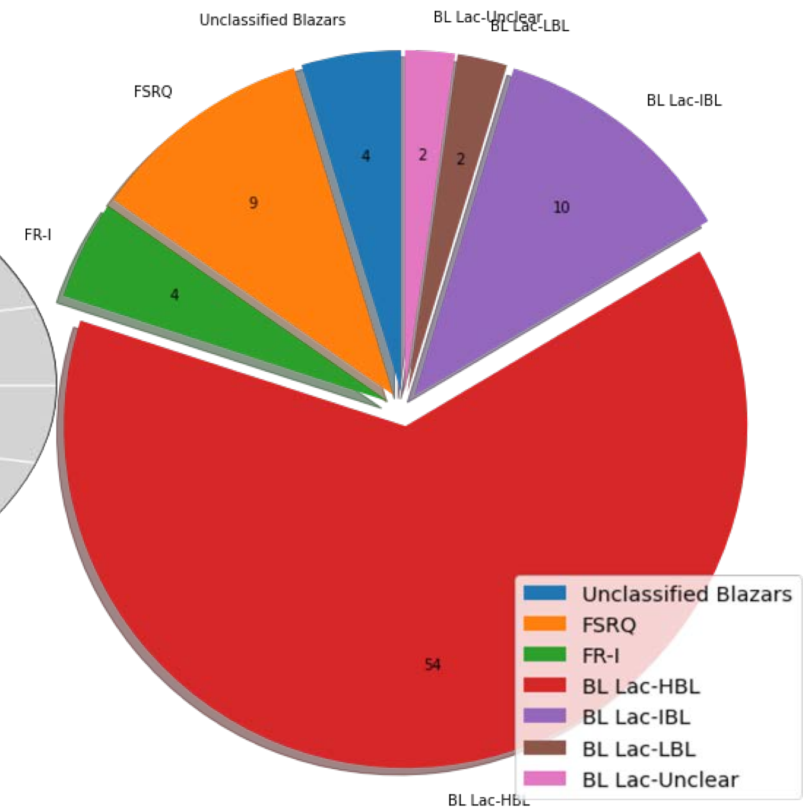


- More than 250 sources
- 10 different source classes
- ~90 extragalactic sources (86 AGN + 3 starbursts)
  - Expansion of radio galaxy counts
  - Detection of starburst galaxies
  - **GRBs detected as TeV sources (after a > 15 yr search)**
- Detection of powerful and ultrashort flares of AGN (Fermi, IACTs)

The Extragalactic TeV γ-ray Sky

TeV Blazars (TeVCat March 2022)



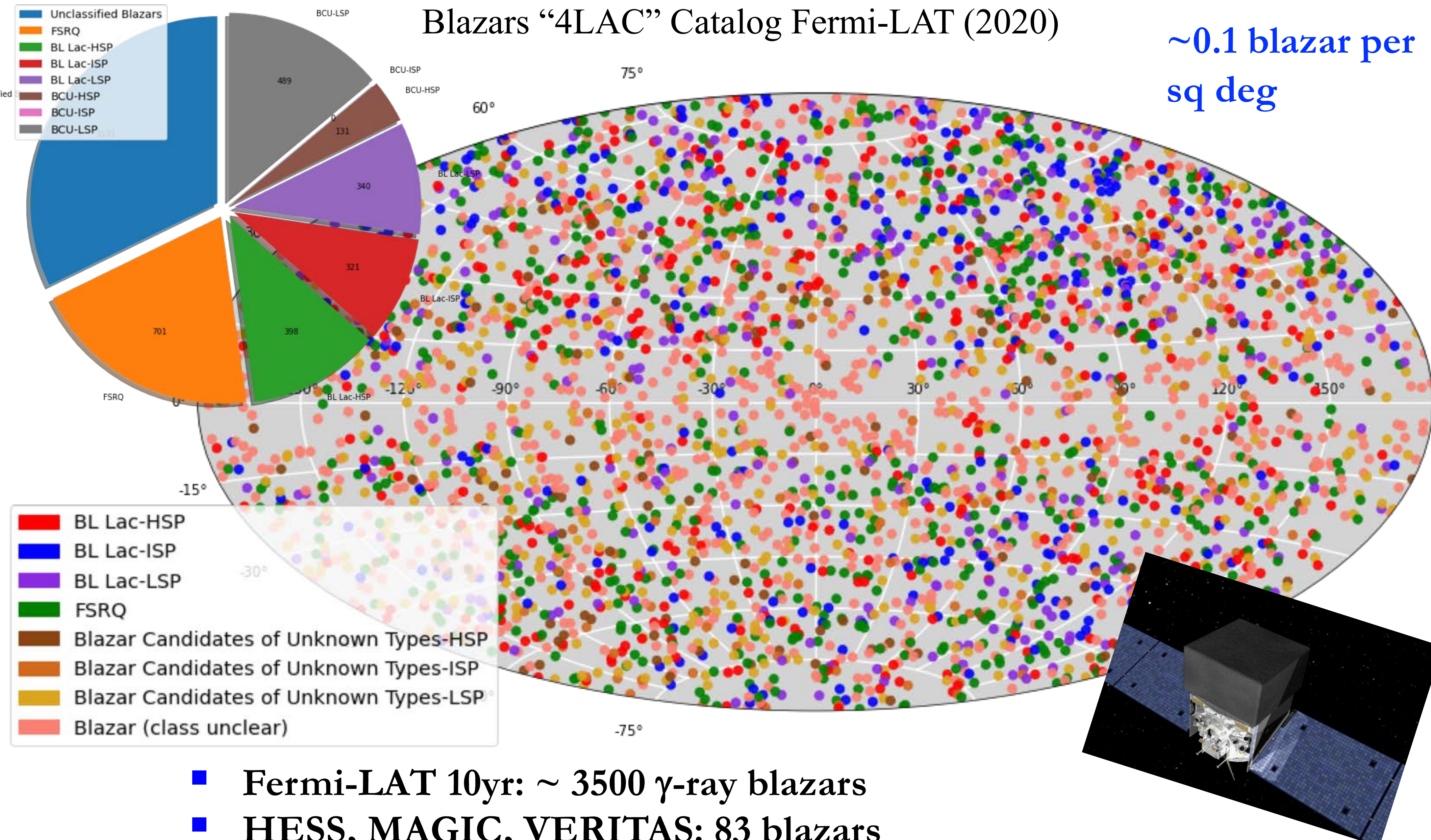


- Blazar population studies: SED-based distributions of low-, intermediate-, high-Synchrotron-Peaked sources
- Of the TeV blazars, 90% of blazars with known redshift have $z < 0.5$
- Possible to do GeV-TeV blazar studies. Probe EBL, IGMF, ALP studies
- Build blazar luminosity functions

The Extragalactic GeV γ-ray Sky

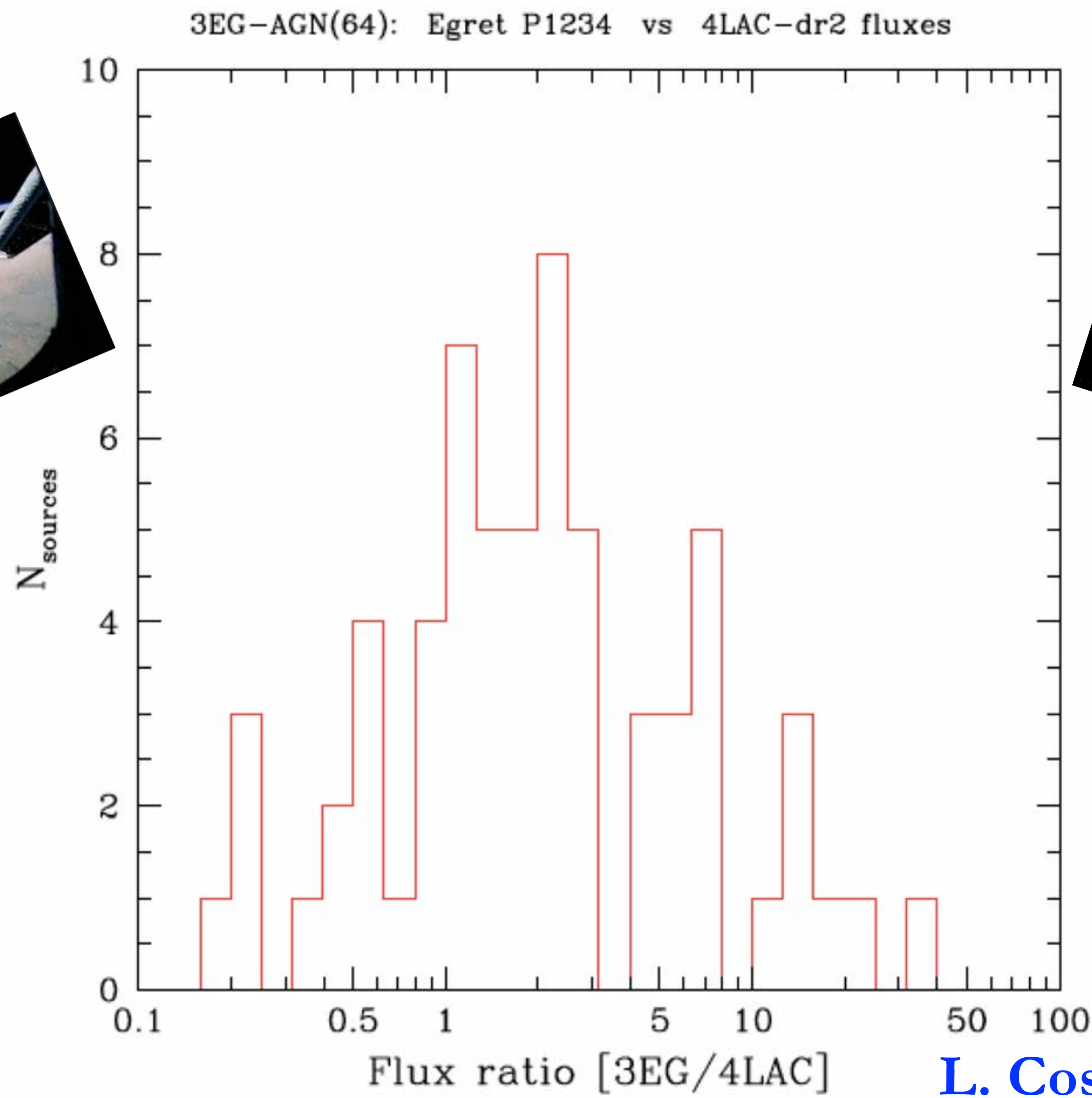
Blazars “4LAC” Catalog Fermi-LAT (2020)

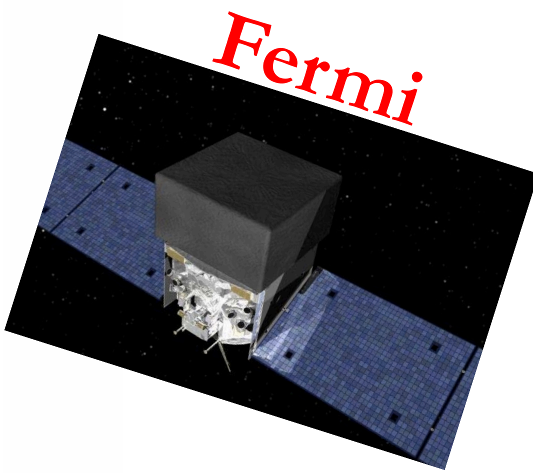
~0.1 blazar per sq deg



- Fermi-LAT 10yr: ~ 3500 γ-ray blazars
- HESS, MAGIC, VERITAS: 83 blazars

EGRET - Fermi-LAT : not the same sky





L. Costamante, CDY

https://cdy-institute.ie/index.php/events/

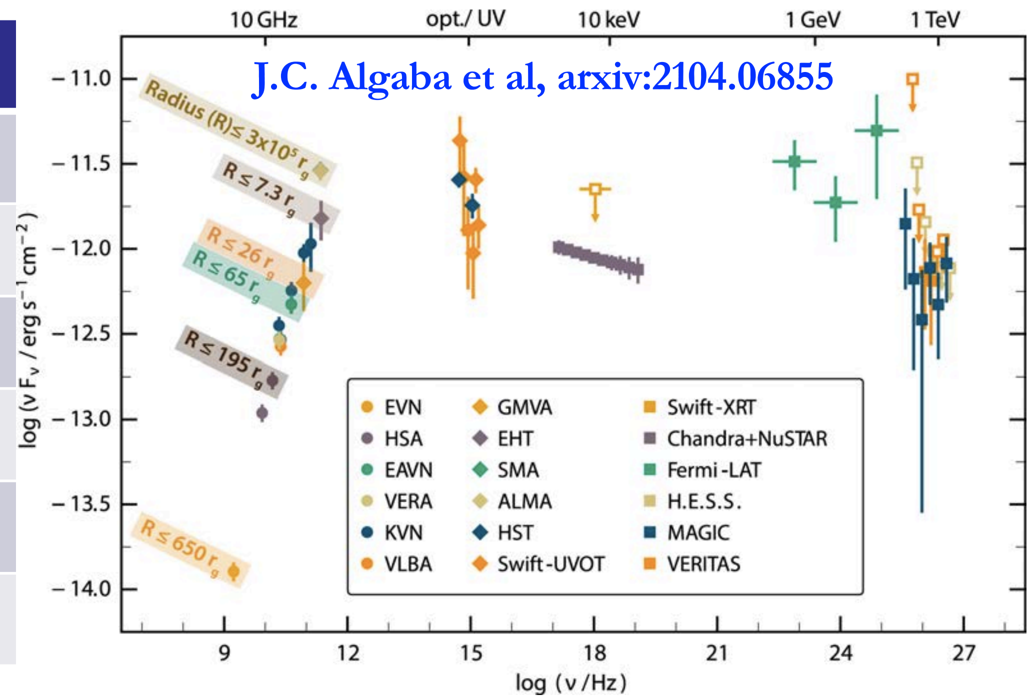
Nearby Extragalactic Sources: Radio Galaxies

Radio Galaxies (mis-aligned jets)

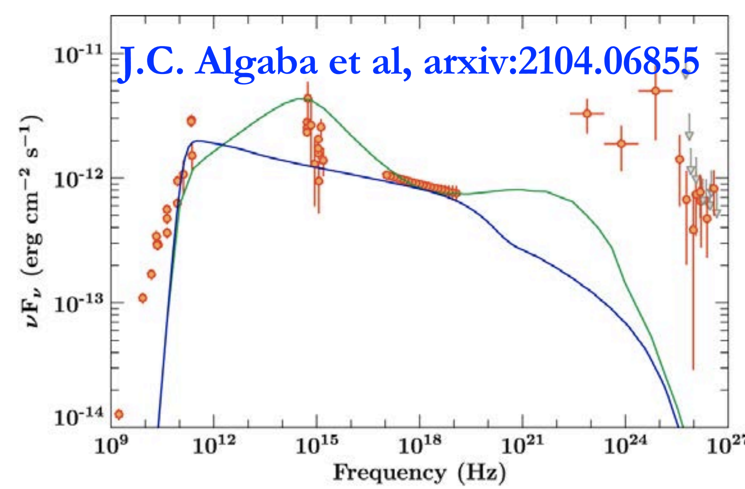
Name	Type	Distance
Cen A	FR I	3.7 Mpc
M 87	FR I	16 Mpc
NGC 1275	FR I	70 Mpc
IC 310	FR I/BL Lac	80 Mpc
3C 264	FR I	95 Mpc
PKS 0625-35	FR I/BL Lac	220 Mpc

Rieger & Levinson 2018 arXiv:1810.05409

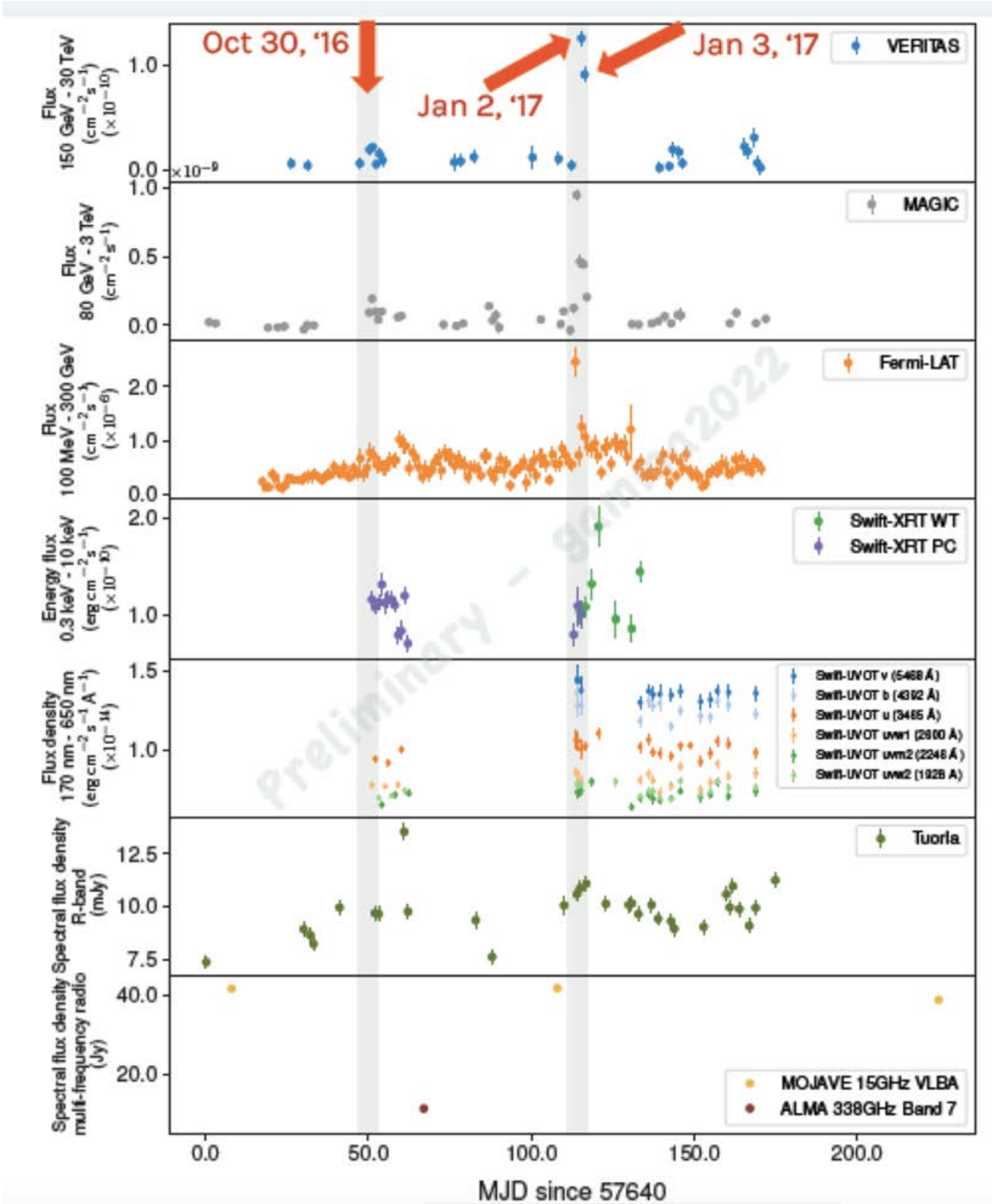
Broadband MWL for M87 with EHT



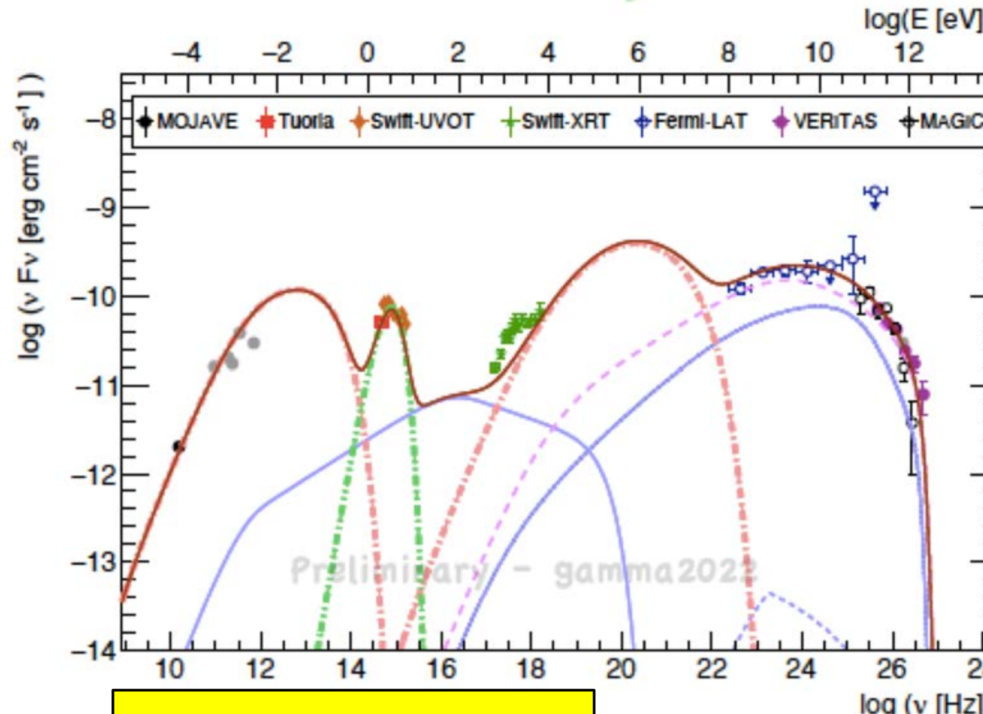
“VHE γ-ray emission cannot be produced in same region as mm-band. Need of structured jet model including time-dependence ”
(A. Hahn γ2022)



Radio Galaxy NGC 1275: Long term monitoring



Broadband MWL for 2017 flare

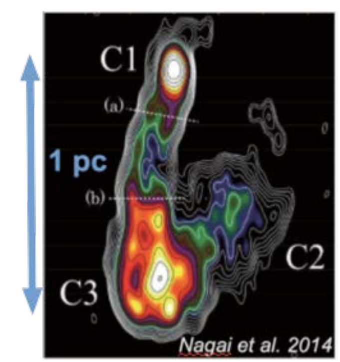


See L. Fortson γ2022

Jan 2017: MAGIC detects flare ~150% Crab.

Next day: VERITAS sees ~60% flare.

Multi-zone C3-blob-in-jet model



AGN Physics - a Multi-scale Problem

A modelling challenge .....

See F. Rieger γ2022

BH magnetosphere and jet are multi-scale systems

Global scales

formation and dynamics

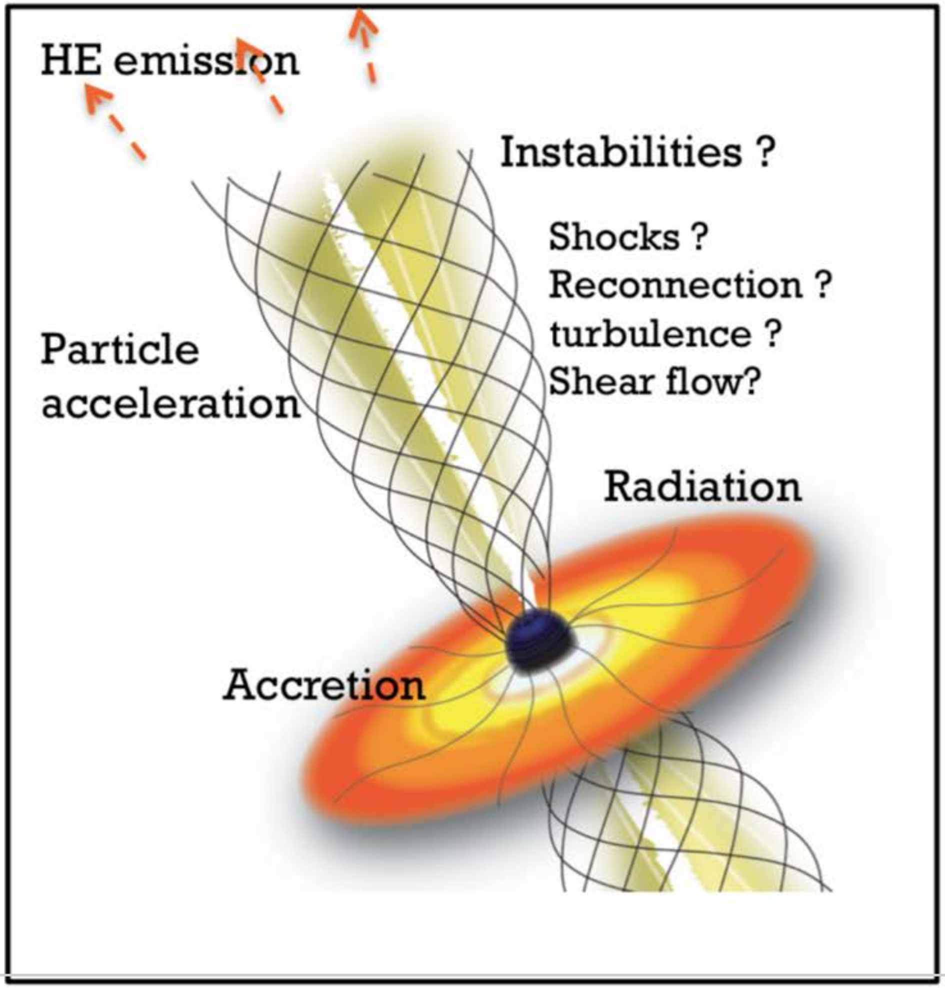
Radiation scales

Sync, IC, pp

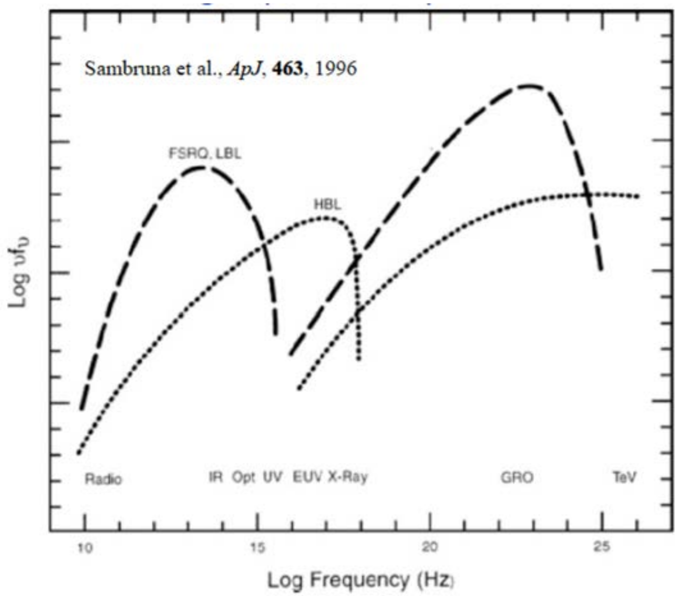
Dissipation scales

shocks, reconnection, turbulence

How are they connected?



Extreme High Frequency peaked BL Lacs



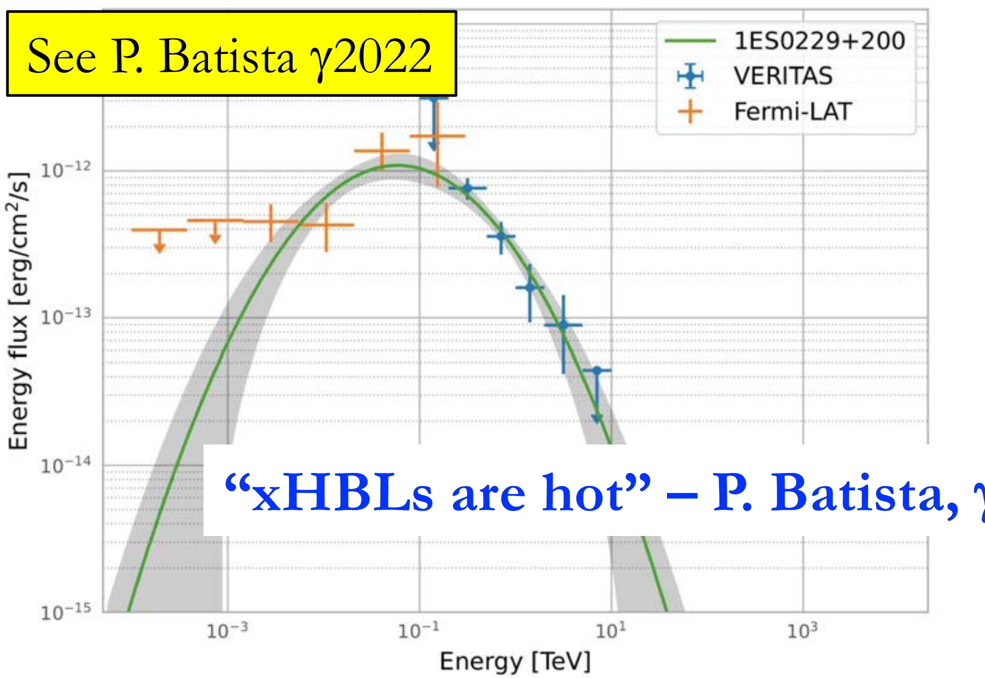
- Brightest in X-ray, SED peak at X-ray energies
- TeV peak at energies > 1 TeV (~10^{26} Hz)
- Hard intrinsic spectrum at sub-TeV energies
- New eHBL reported by VERITAS: RBS 1366, log ν_{pk} ~ 17.2

See J. Quinn γ2022

- New eHBLs reported by H.E.S.S.: MRC 0910-208 and 1RXS J195815.6-301119

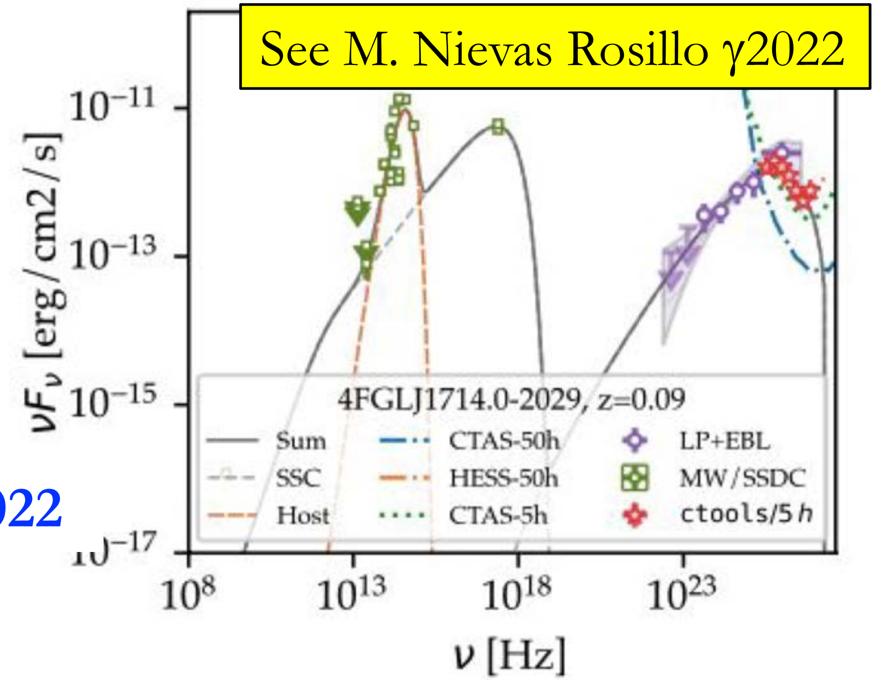
See S. Wagner γ2022

See P. Batista γ2022

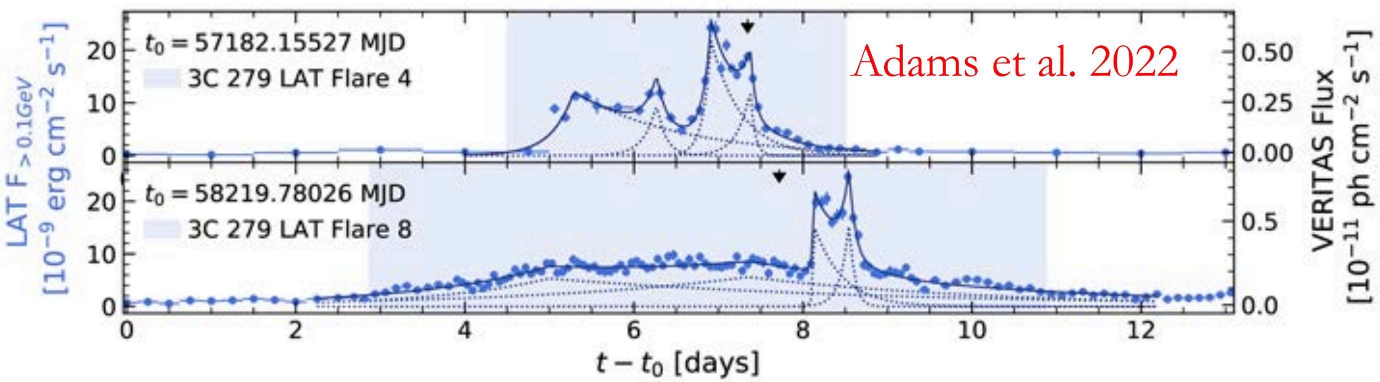


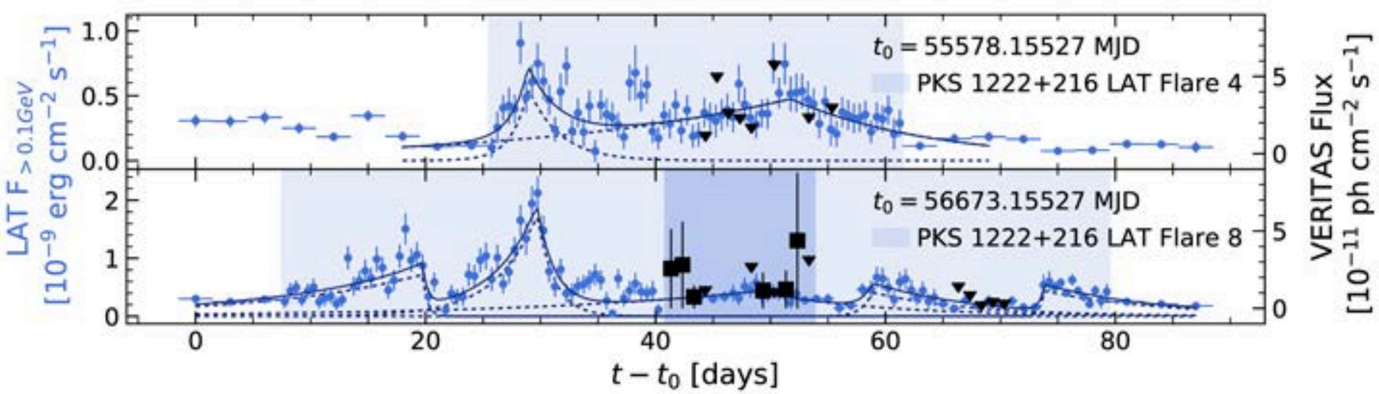
“xHBLs are hot” – P. Batista, γ2022

See M. Nievas Rosillo γ2022

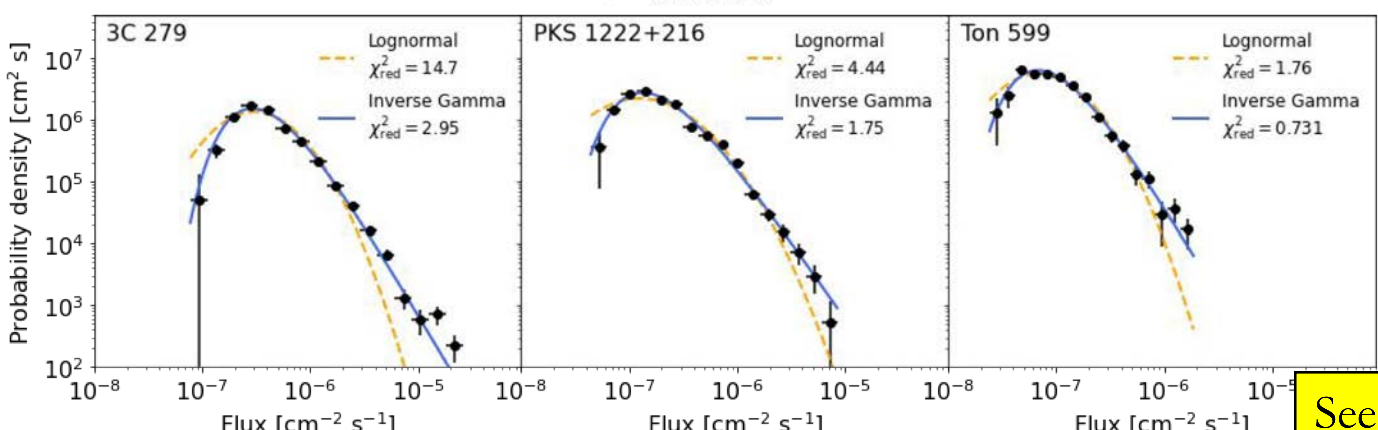


Unprecedented Light Curves in TeV Blazars





- LAT daily and sub-daily light curves for 3 FSRQs
- Models for fast flares?
  - Magnetic reconnection?
  - Slower variability explained by shocks
  - What is the origin of short-duration flares?

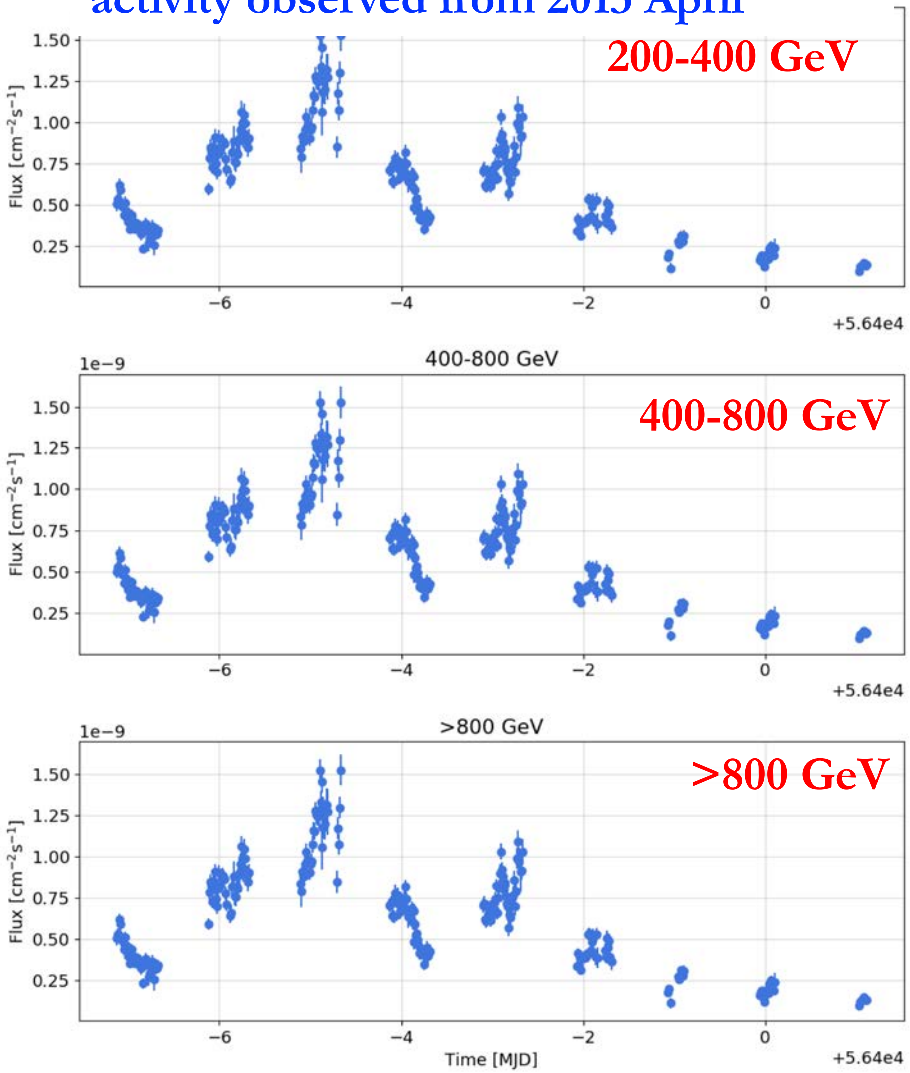


Flux distributions of 3 FSRQs, scaled as probability densities. SDE model of Tavecchio et al. (2020)

See A. Brill Poster γ2022

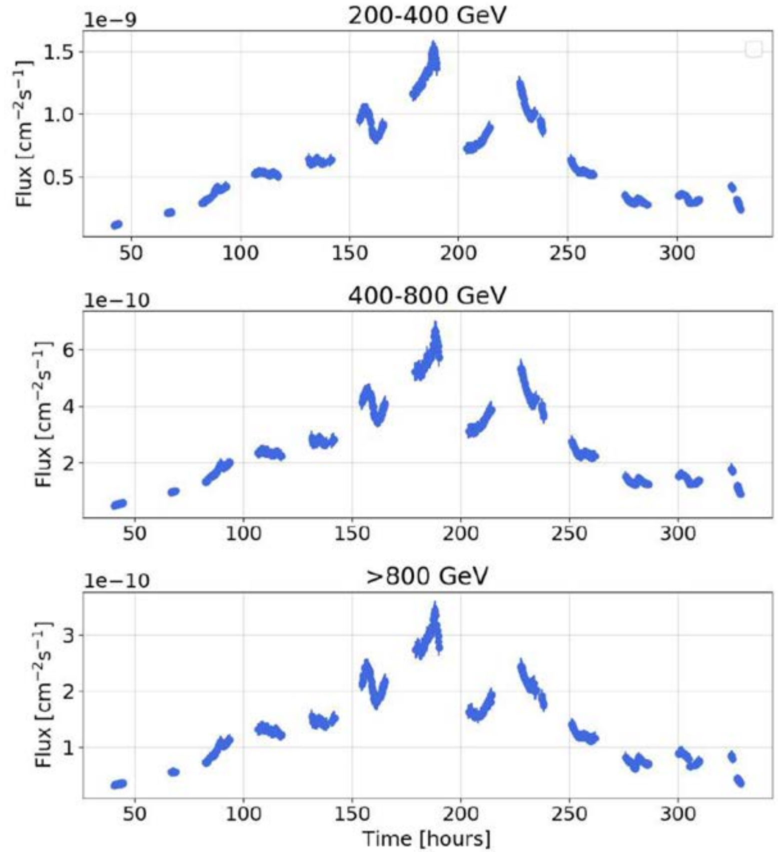
Magnetic Reconnection? Very Fast γ-ray Flares

Mrk 421 during an exceptional flaring activity observed from 2013 April



Acciari et al. 2020

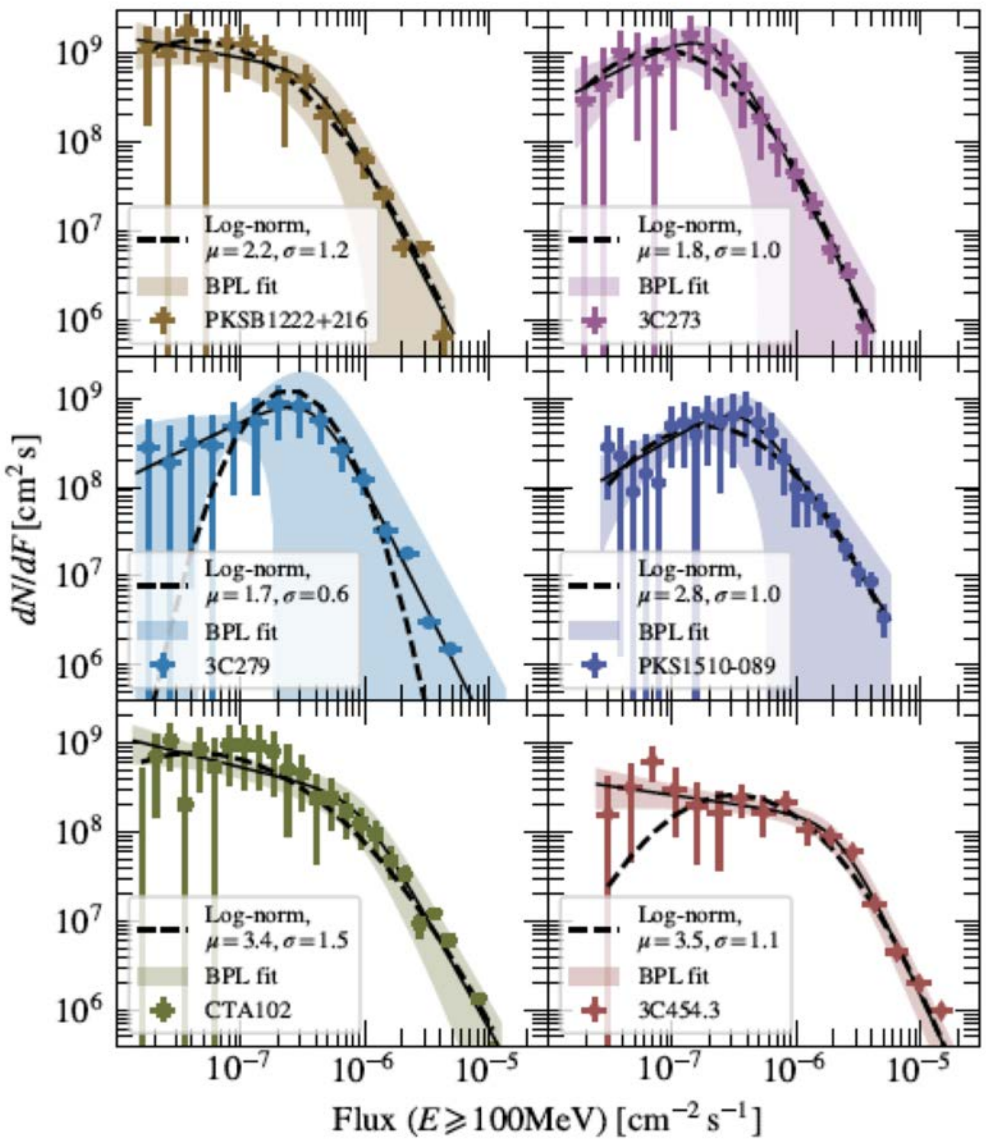
See J. Jormanainen γ2022



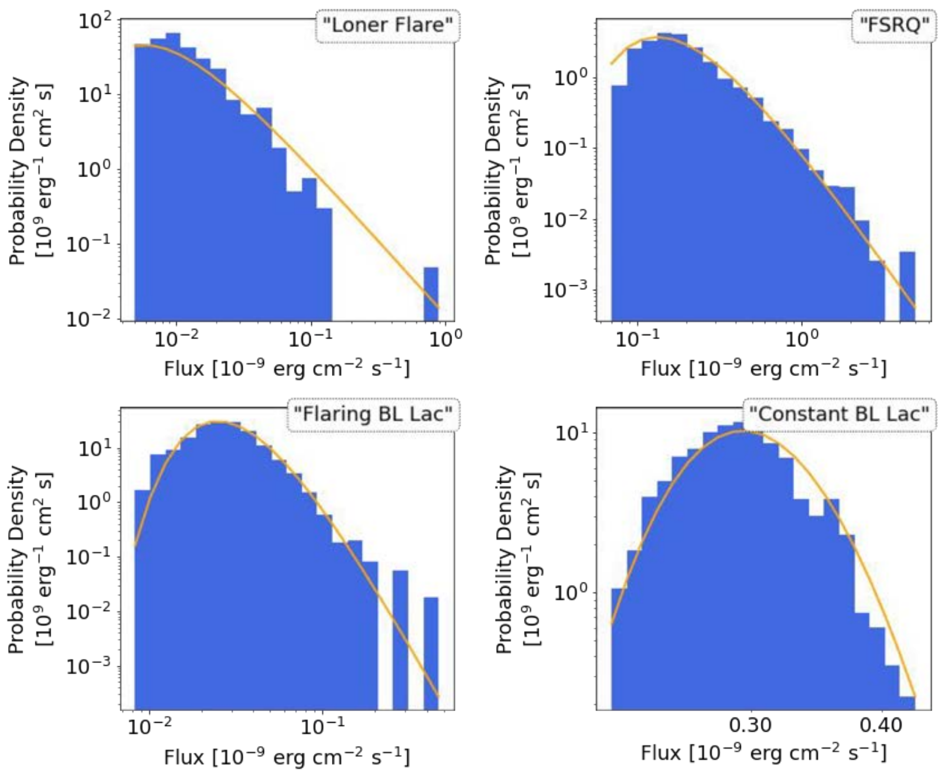
- Origin of short-duration flares is unknown
- Short flares could be due to plasmoids that produce flares with characteristic duration
- Sims being carried out for Fermi-LAT flares

Characterizing Very Fast γ-ray Outbursts

Meyer, Scargle, Blandford 2020



What causes stochastic multiwavelength variability in blazars?



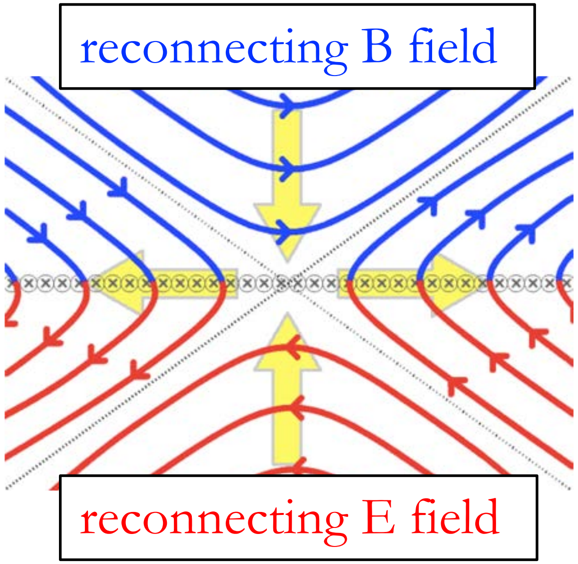
Flux distributions of simulated light curves for different types of blazars

See A. Brill poster γ2022

Relativistic Reconnection Models

Relativistic reconnection can:

- Dissipate magnetic energy efficiently (at rate ~ 0.1 c).
- Produce non-thermal particles with hard power-law slopes.
- Serve as injection process for subsequent (non-reconnection) acceleration: e.g., Fermi acceleration at shocks, stochastic acceleration in turbulence, shear acceleration at jet boundaries.
- Imprint strong pitch-angle anisotropy, and so explain orphan flares.
- Produce trans- and ultra-relativistic bulk motions, and so explain (1) fast blazar flares, and (2) hard X-ray emission from X-ray binaries.



Reconnection produces broken spectra

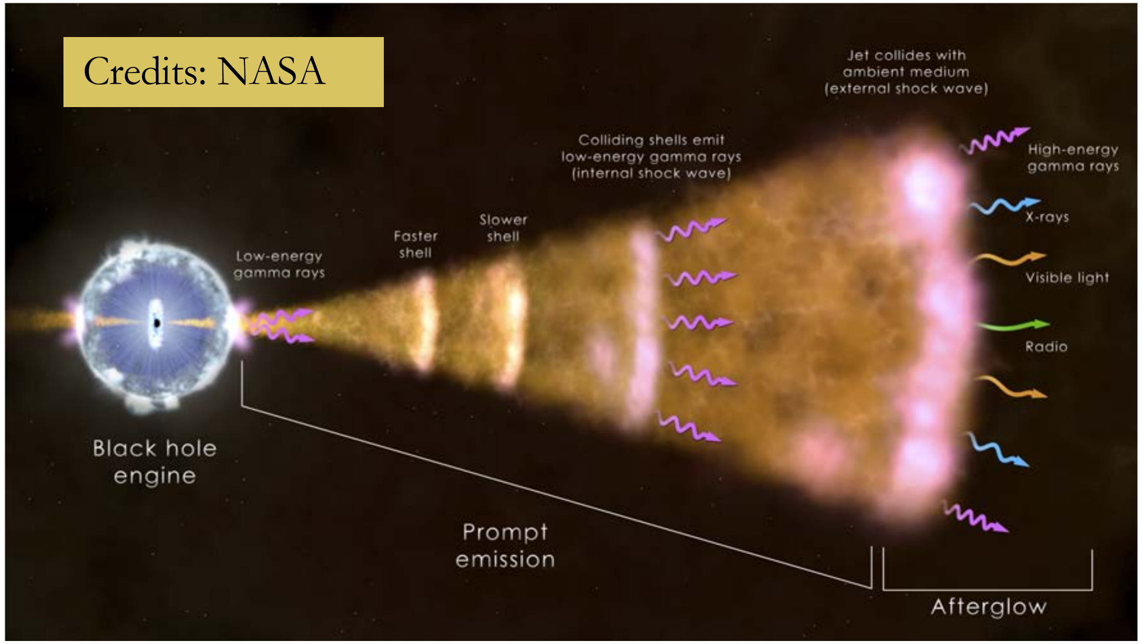
See L. Sironi γ2022

Gamma-Ray Bursts as VHE Sources

Search for TeV emission from GRBs for > 15 years – Finally!

Long GRBs detected in VHE (~0.1 TeV) during the afterglow phase

See D. Khangulyan, T. Piran



GRB 190114C (MAGIC Coll., Nature, 2020)
- long GRB, z = 0.4245 (0.2 -1 TeV)
- for 40’ after T0 +60 s
- E_{max} ~ 1 TeV, **50 σ detection**

GRB 180720B (H.E.S.S. Coll., Nature, 2020)
- long GRB, z = 0.654
- E_{max} ~ 440 GeV
- 10h after T0

GRB 190829A (H.E.S.S. Coll., Science)
- long GRB, z = 0.078 (0.18-3.3 TeV)
- for **3 nights** after T0 + 4.3h
- E_{max} ~ 3.3 TeV, **20 σ detection**

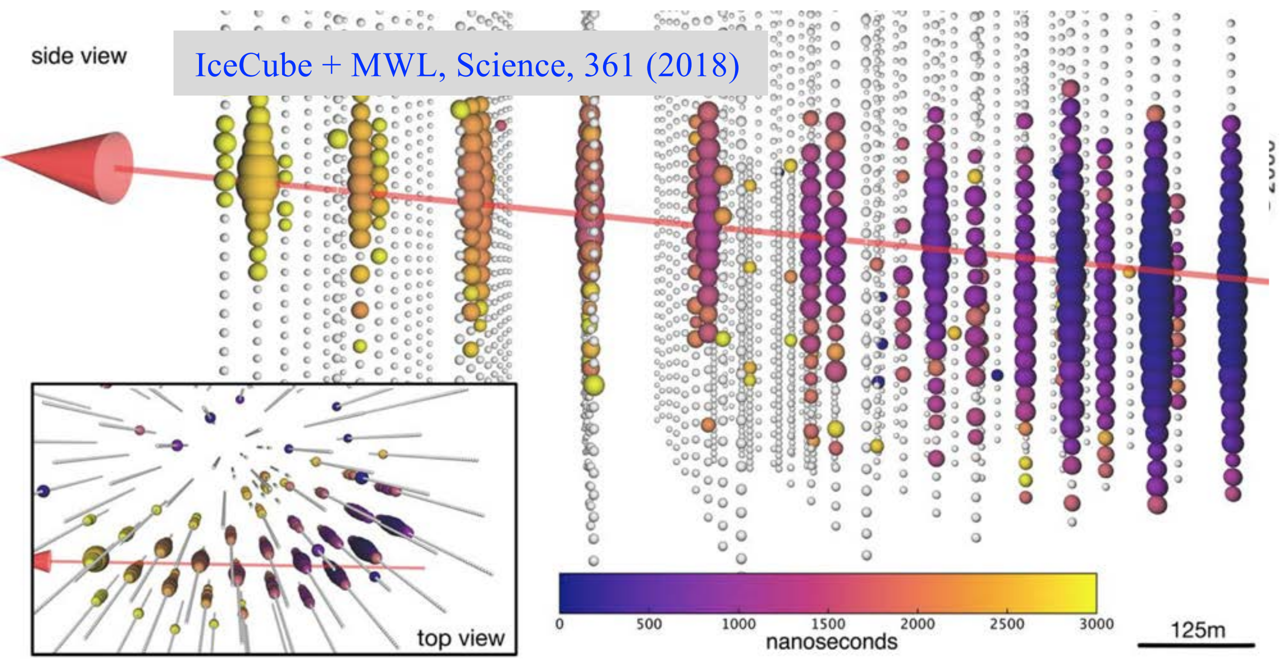
GRB 201216C(MAGIC Coll. ICRC021, S.Fukami)
- long GRB, **z=1.1**
- for 20’ after T0+

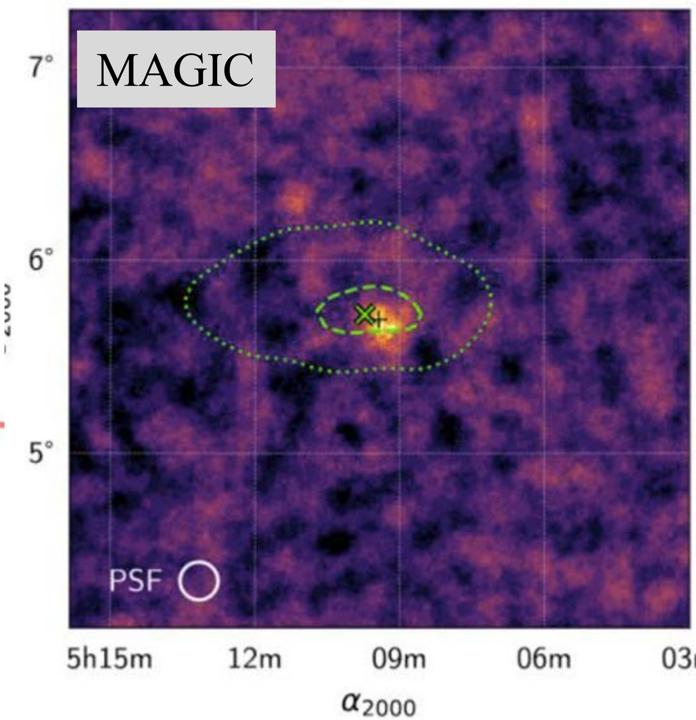
Multimessenger: UHE Cosmic Rays and Neutrinos

IC170922 and TXS 0506+056: First evidence (3σ) for a neutrino source

Are blazars the sources of the highest energy cosmic rays?

Sept 22, 2017: Detection of a high-energy ν (E ~ 290 TeV) by IceCube

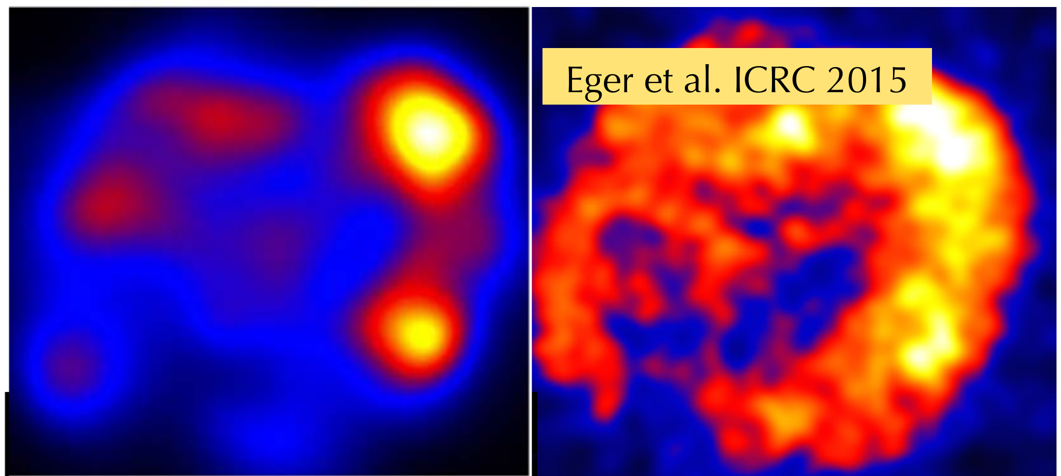




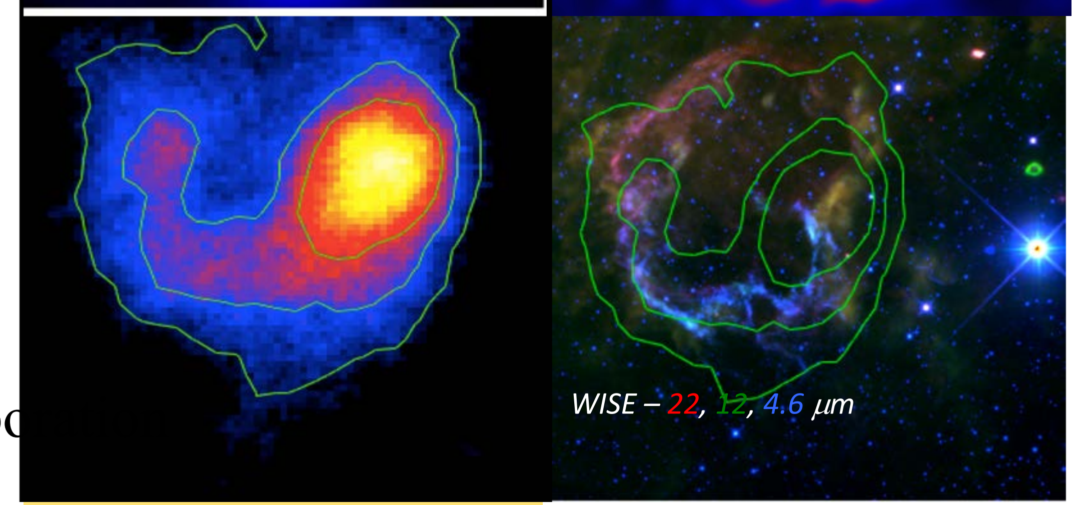
NGC 1068 as an IceCube neutrino candidate source

Supernova Remnants

- Detected at sub-TeV, TeV, sub-PeV
- Several young shell-type SNRs detected, but the main question "whether SNRs are main contributors to GCRs?" is not yet resolved.



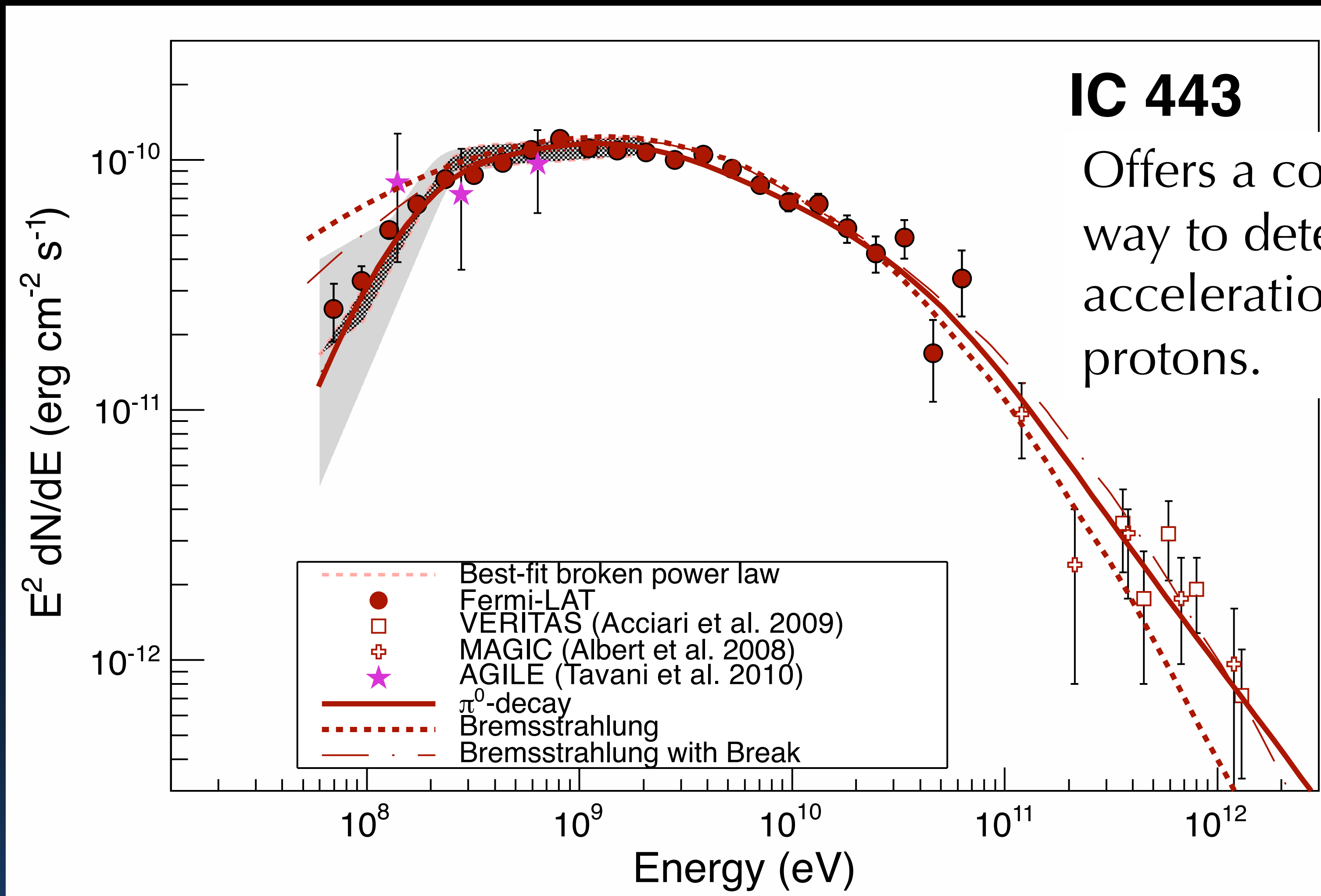
RX J1713.7–3946



IC 443
VERITAS Collabo

Cosmic rays?

Ackermann et al. 1302.3307



Offers a compelling way to detect the acceleration sites of protons.

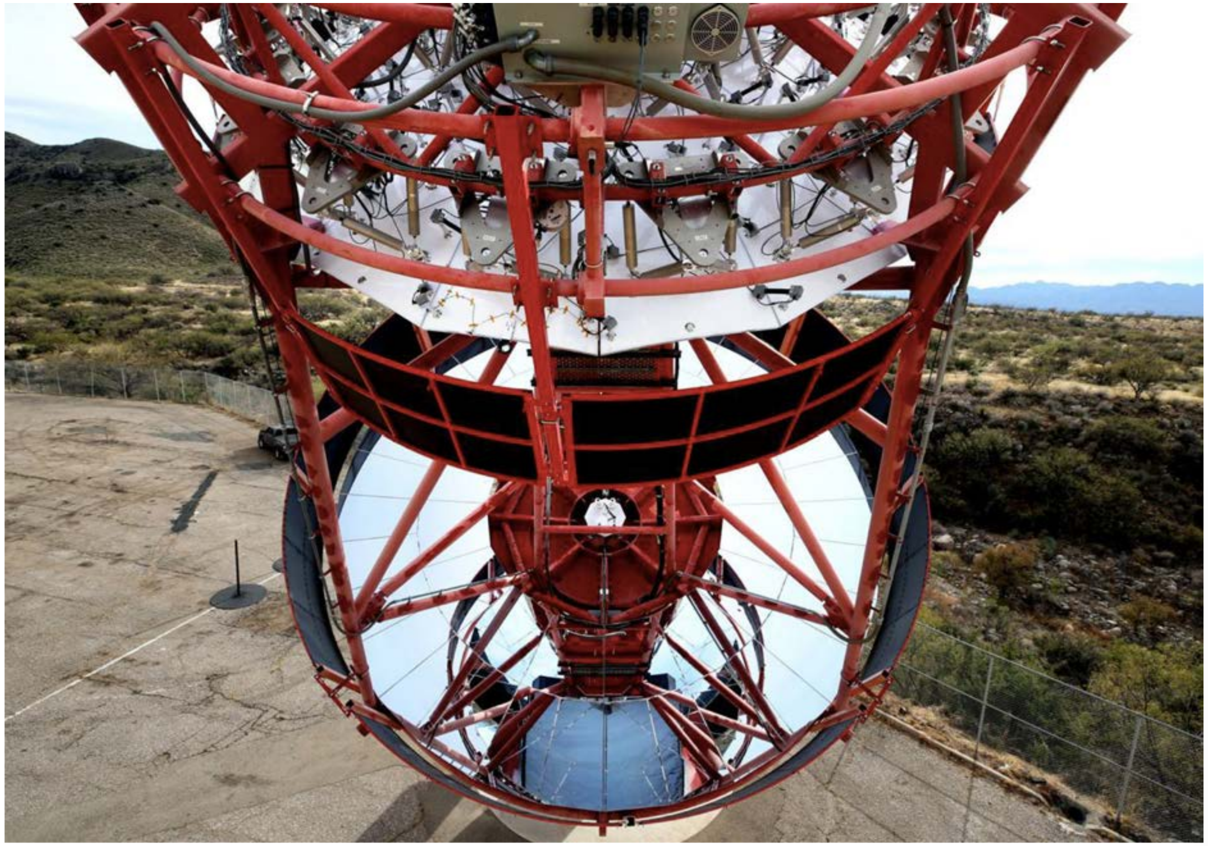
- Fermi-LAT SED cutoff around 200 MeV, "pion bump," is direct indication of hadronic interactions.

Dark Matter, Astroparticle Physics, Cosmology

- Dark matter searches (Classical & ultra faint dwarf spheroidals; PRD 2017)
- Lorentz Invariance Violation (Energy dependent speed of light differences; targets – GRBs, pulse widths of γ-ray pulsars, AGN variability)
- Primordial Black Holes (could evaporate and produce bursts of VHE γs)
- Extragalactic Background Light ($\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^-$)
- Intergalactic Magnetic Fields (look for pair cascades/halos; ApJ 2017)
- Direct Cherenkov emission (produced by the primary particle, CR heavy nuclei)
- Electron-positron measurements (Galactic CR studies)
- Multi-Messenger Astrophysics
    - Gravitational Wave EM counterpart searches
    - IceCube neutrino follow ups (BL Lac object TXS 0506+056; ApJ Lett 2018)

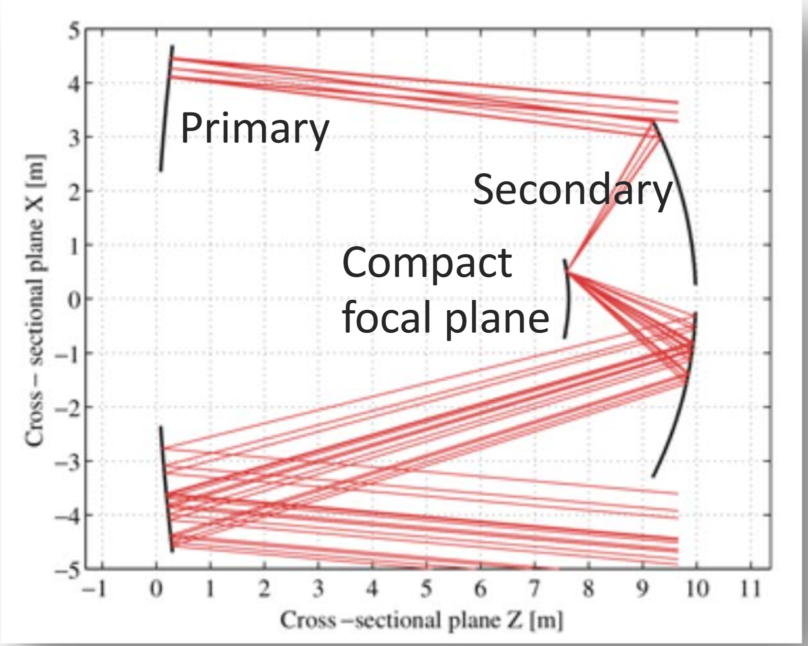
TeV Astronomy in the Future

The Schwarzschild-Couder Telescope



- Novel dual-mirror optical system
- >10,000 channel state-of-the-art SiPM camera

V. Vassiliev et al. Astroparticle Physics 28 (2007) 10

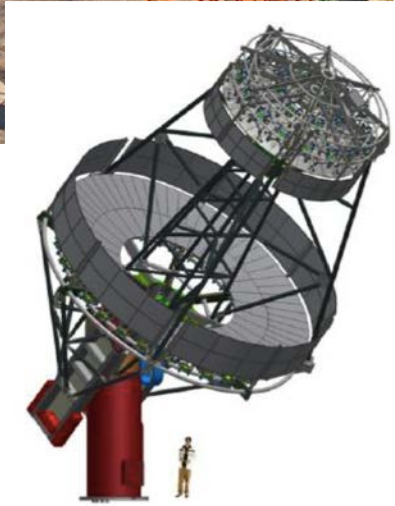


The Schwarzschild-Couder Telescope(SCT)

- **Candidate for a Medium-Sized Telescope for CTA**
  - With an advanced telescope optical system
- **Aplanatic dual-mirror optical system**
  - Increased FoV. Simultaneous correction of spherical and comatic aberrations
  - Demagnification of shower images
  - Minimization of astigmatism thanks to curved focal plane
  - Small focal plane plate scale enables use of state-of-the-art novel SiPM light sensors reducing camera dimension and costs
  - Significantly increase in imaging resolution

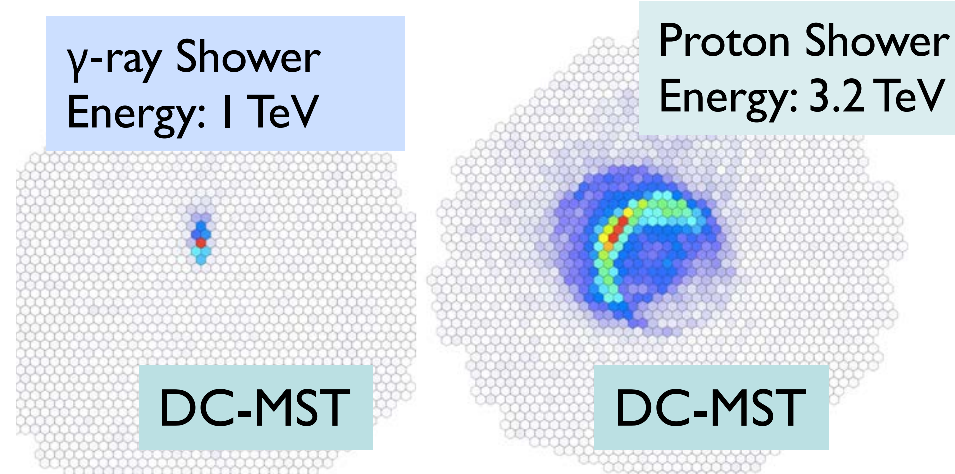
→ Main challenges: Mechanical stability and mirror alignment

- **The prototypeSCT (pSCT)**
  - Located at the Fred Lawrence Whipple Observatoryin southern Arizona (USA)
  - (At the site of the VERITAS telescopes)

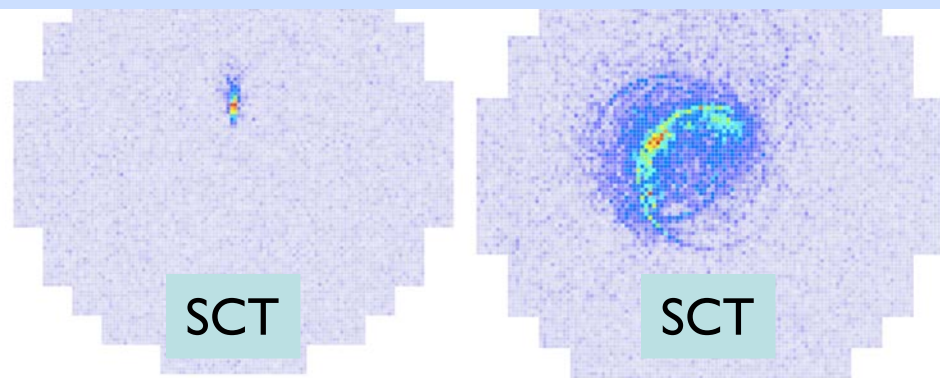


The SCT: big eyes with a sharper view

- Superior optical angular resolution over a wide (~8°) field of view
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors
- Better sensitivity and reduced observation time
- Better γ-ray PSF across the FoV for morphology, survey, and transients



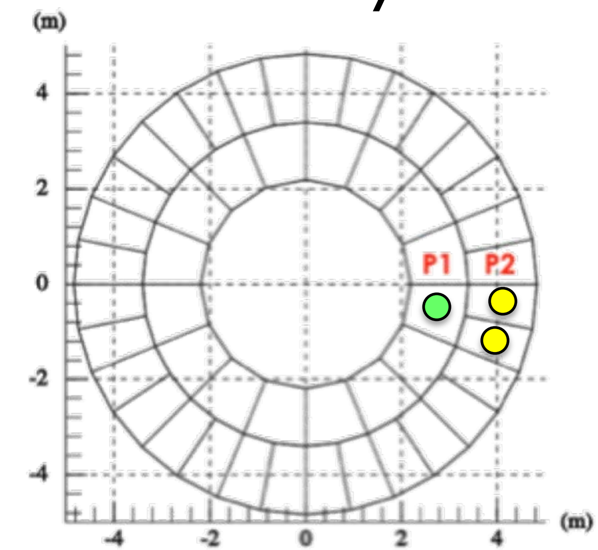
DC-MST Images
7.7° field of view, 0.17° pixels, 1,855 channels (PMTs)



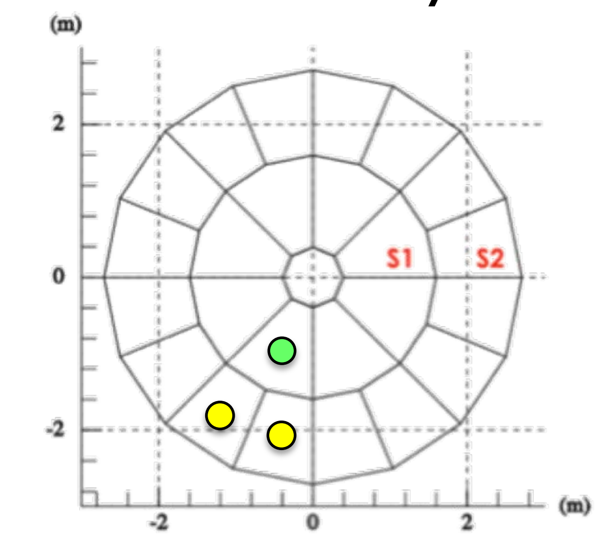
SCT Images
8° field of view, 0.067° pixels 11,328 channels`(SiPMs)

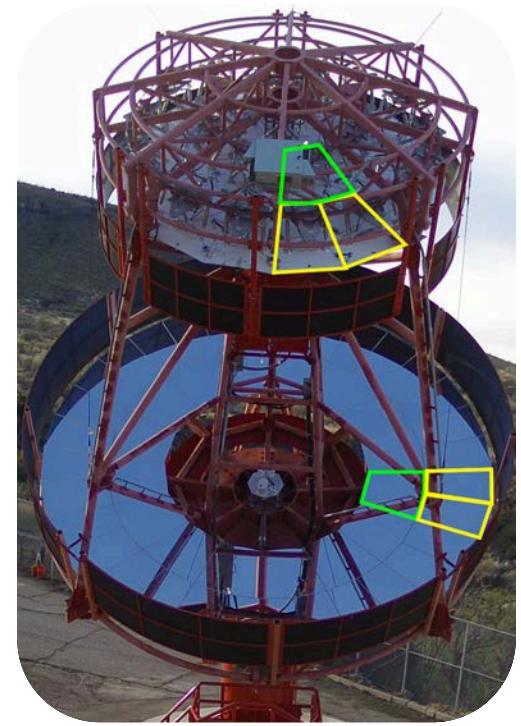
The SCT Optical System

Primary



Secondary





https://cta-psct.physics.ucla.edu/

● 16 P1 and 8 S1
● 32 P2 and 16 S2

Primary mirror: radius 4.83 m

- segmented into 48 panels
- inner-ring panel (P1) area 1.33 m^2
- outer-ring panel (P2) area of 1.16 m^2

Secondary mirror: radius 2.71 m

- Segmented into 24 panels
- inner-ring (S1) and outer ring (S2) area 0.94 m^2

SPIE. DIGITAL LIBRARY

Verification of the Optical System of the 9.7-m Prototype Schwarzschild-Couder Telescope
https://arxiv.org/pdf/2010.13027.pdf

Optical on-axis PSF commissioning

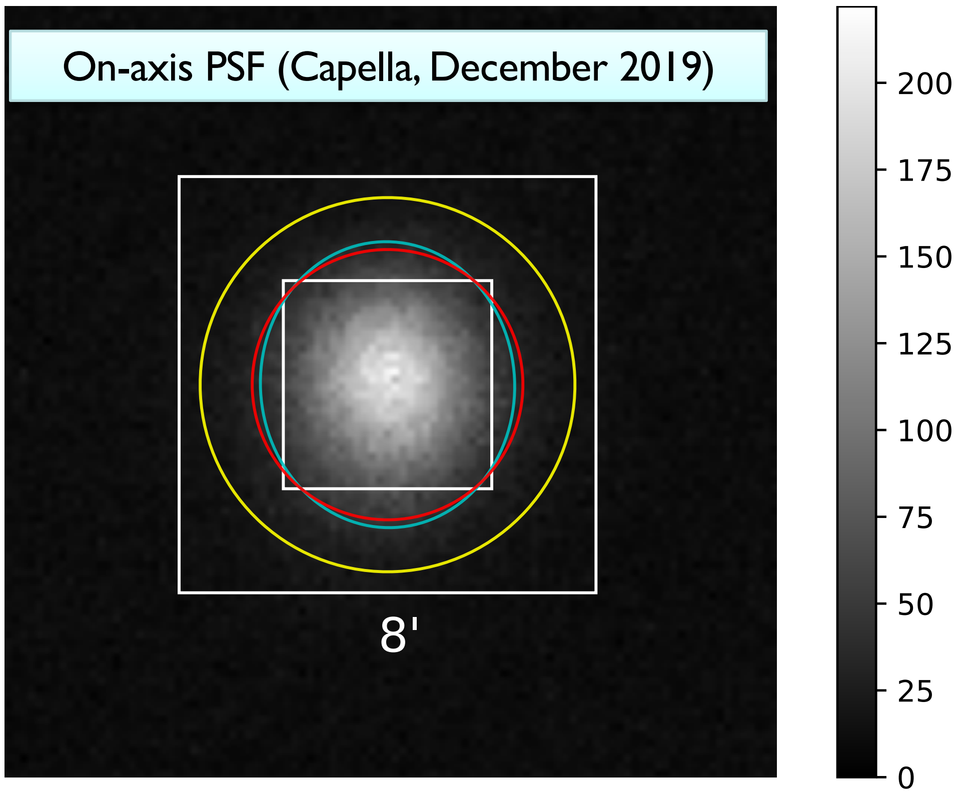


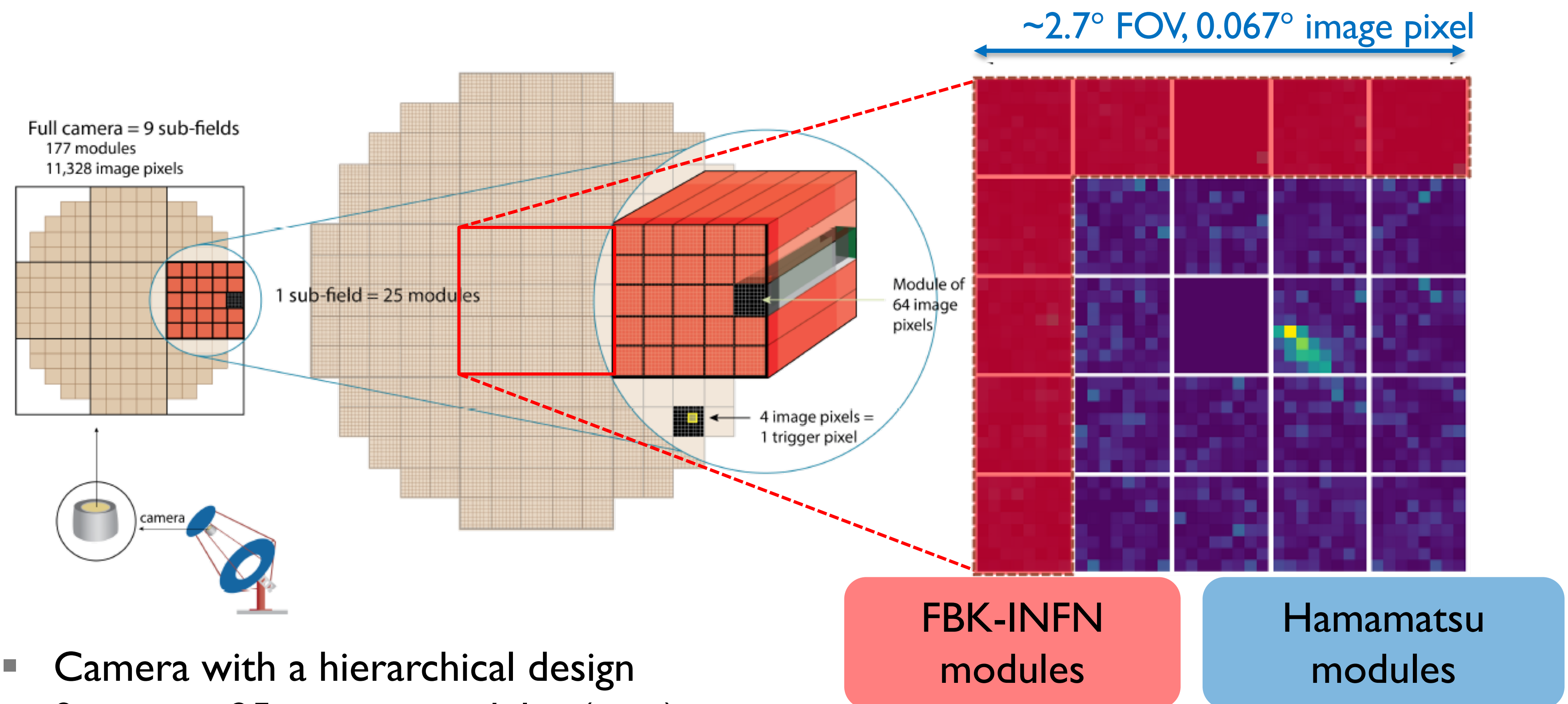
Image pixel (Inner square)
Trigger pixel (Outer square)

$$PSF = 2\times\max(\sigma_y, \sigma_x)$$ **

** corresponding to a 86.5% containment radius (for $\sigma_x = \sigma_y$)

- Commissioning on-axis optical PSF 2σ (cyan): 2.8’ (4.5 mm)
- The design “acceptable” on-axis PSF (yellow): 3.6’ and the “desirable” PSF (red): 2.6’
- Image of an on-axis star → optical PSF exceeds pre-production acceptable goal

The pSCT focal plane

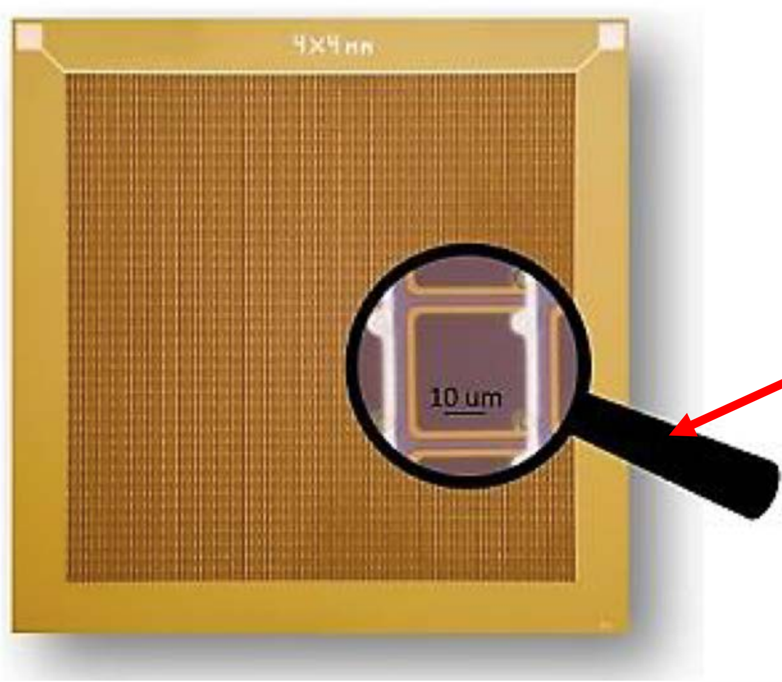


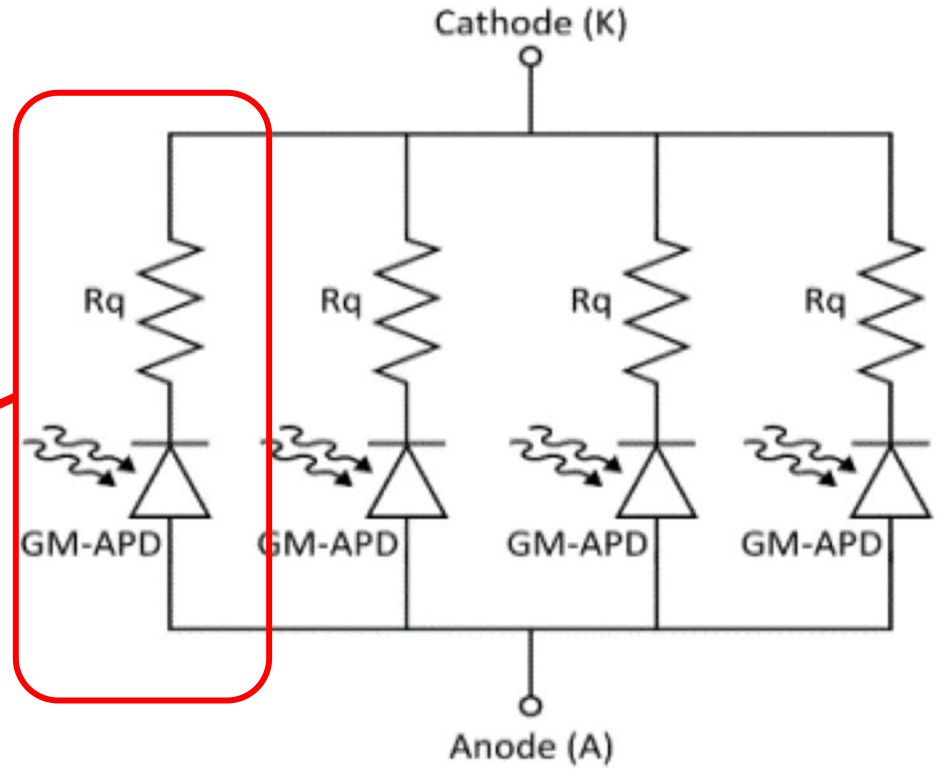
https://arxiv.org/pdf/1910.00133.pdf

- Camera with a hierarchical design
- 9 sectors, 25 camera modules (max)
- Currently 24 modules are installed
- Central sector with the central module left uninstalled for optical alignment work

The detectors: Silicon Photomultipliers

SiPMs: array of reverse-biased Single Photon avalanche Diodes (SPADs) connected in parallel



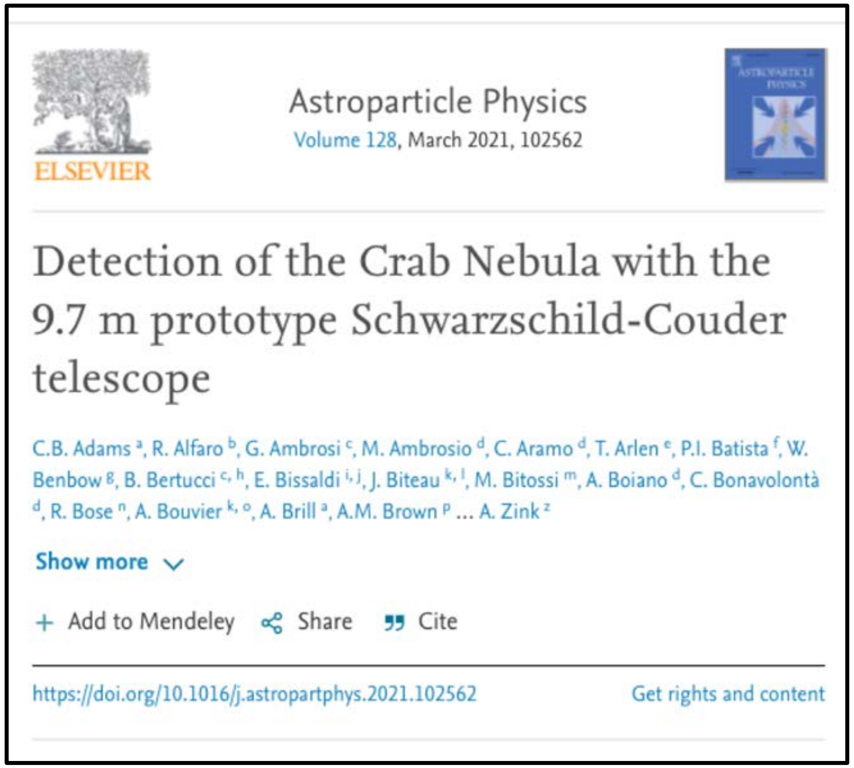


SiPM size:
From 1x1 mm^2 to 10x10 mm^2

SPAD size:
from 5 µm to 40 µm (typical)

Detection of the Crab Nebula with the Prototype SCT

https://doi.org/10.1016/j.astropartphys.2021.102562


ELSEVIER

Astroparticle Physics
Volume 128, March 2021, 102562

Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope

C.B. Adams [a], R. Alfaro [b], G. Ambrosi [c], M. Ambrosio [d], C. Aramo [d], T. Arlen [e], P.I. Batista [f], W. Benbow [g], B. Bertucci [c, h], E. Bissaldi [i, j], J. Biteau [k, l], M. Bitossi [m], A. Boiano [d], C. Bonavolontà [d], R. Bose [n], A. Bouvier [k, o], A. Brill [a], A.M. Brown [p] ... A. Zink [z]

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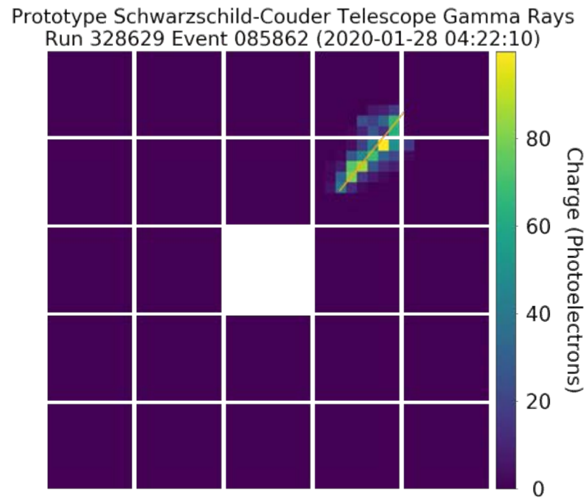
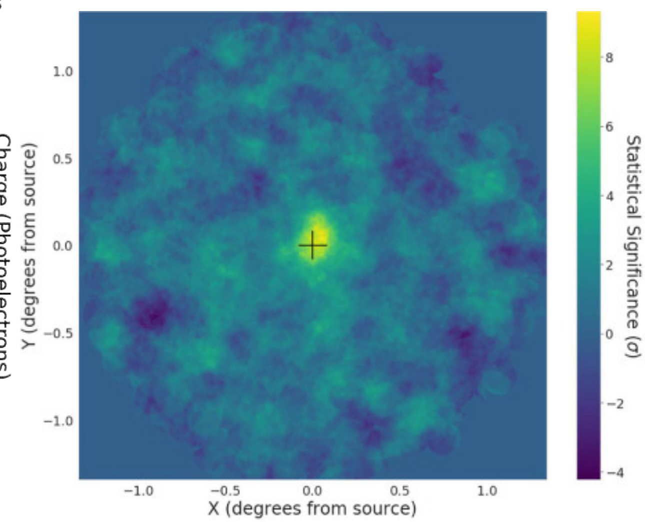
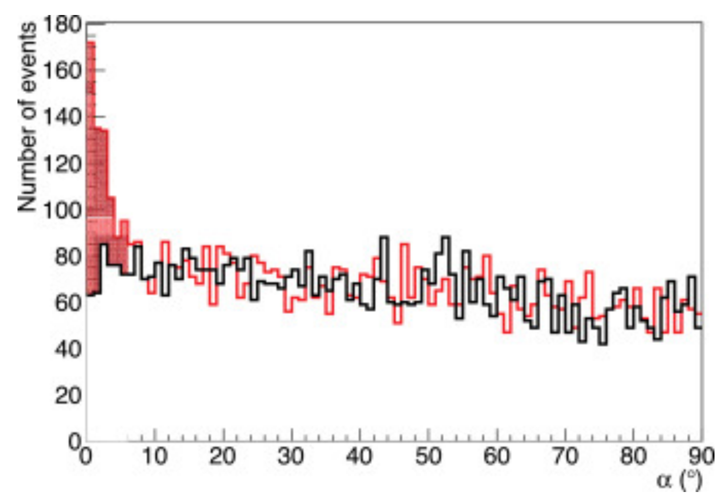
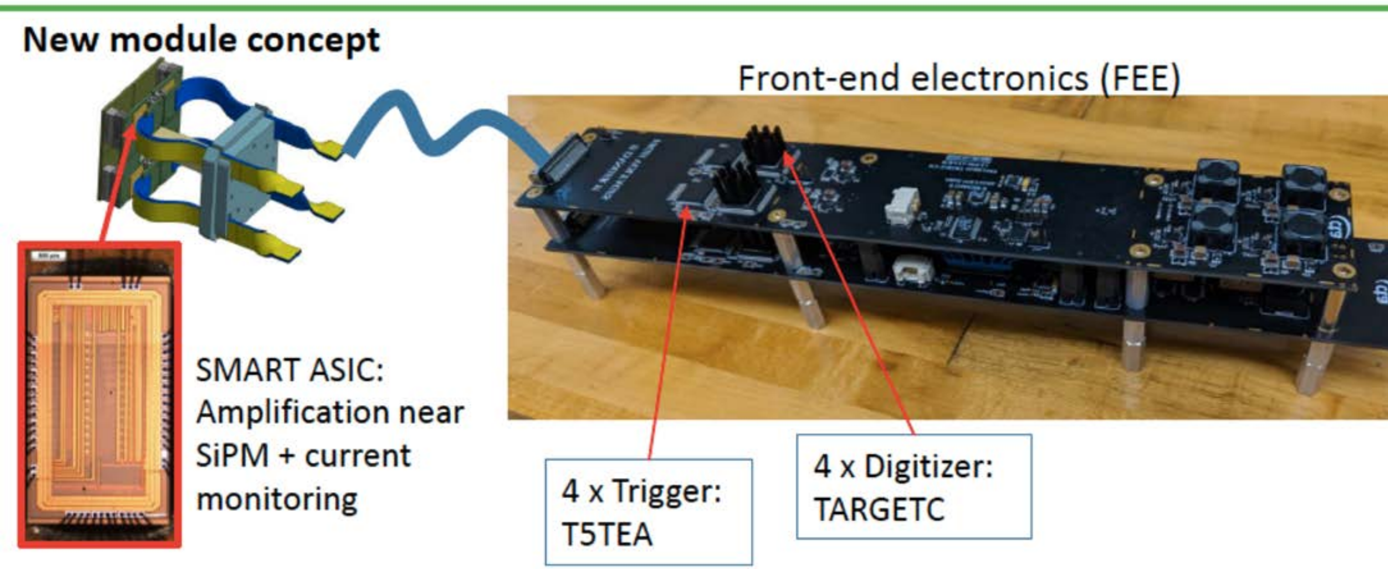


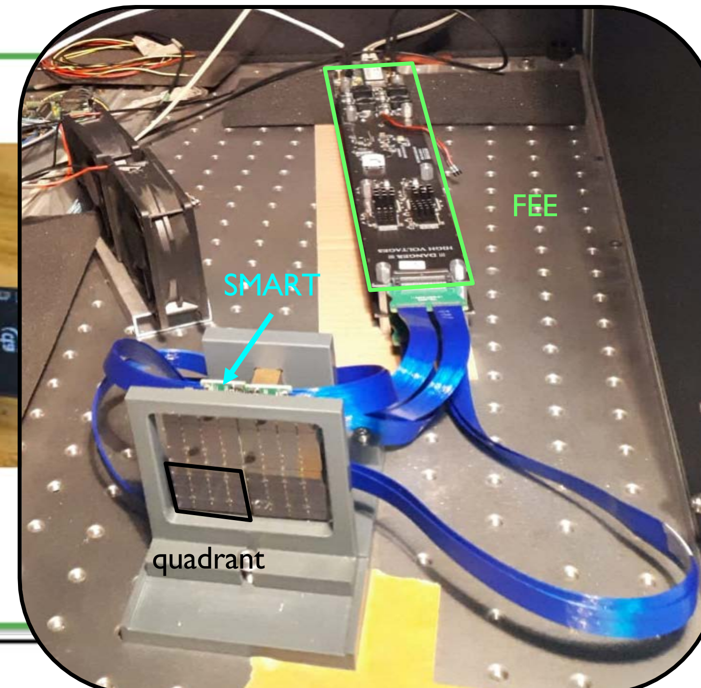


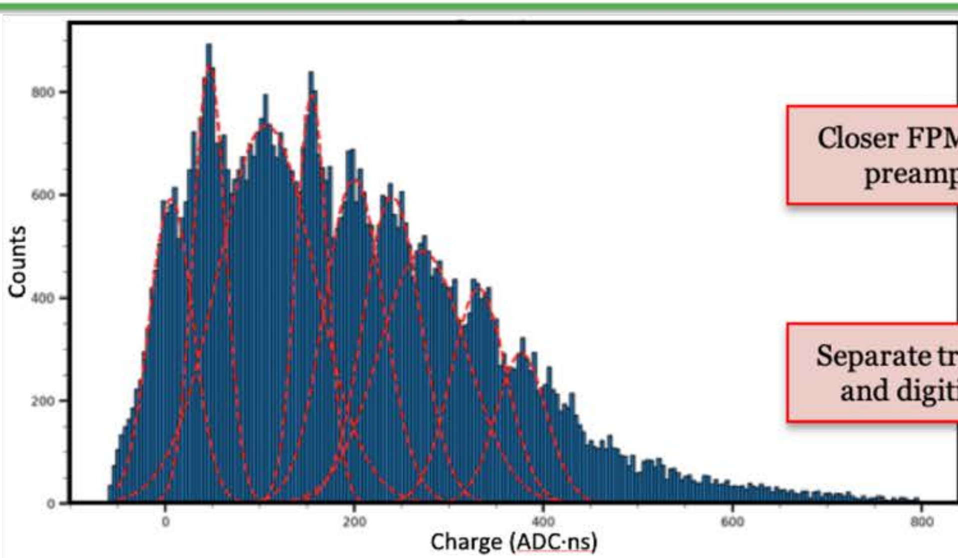


- Advantageous to have pSCT and VERITAS at the same (astronomical quality) site
- pSCT + VERITAS joint operations helpful

The pSCT Camera Upgrade – NSF Funded

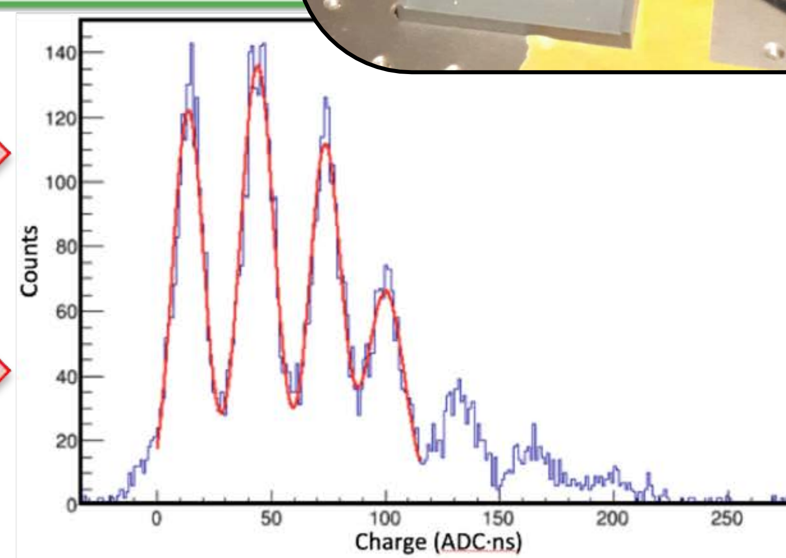






Closer FPM and preamps

Separate trigger and digitizer



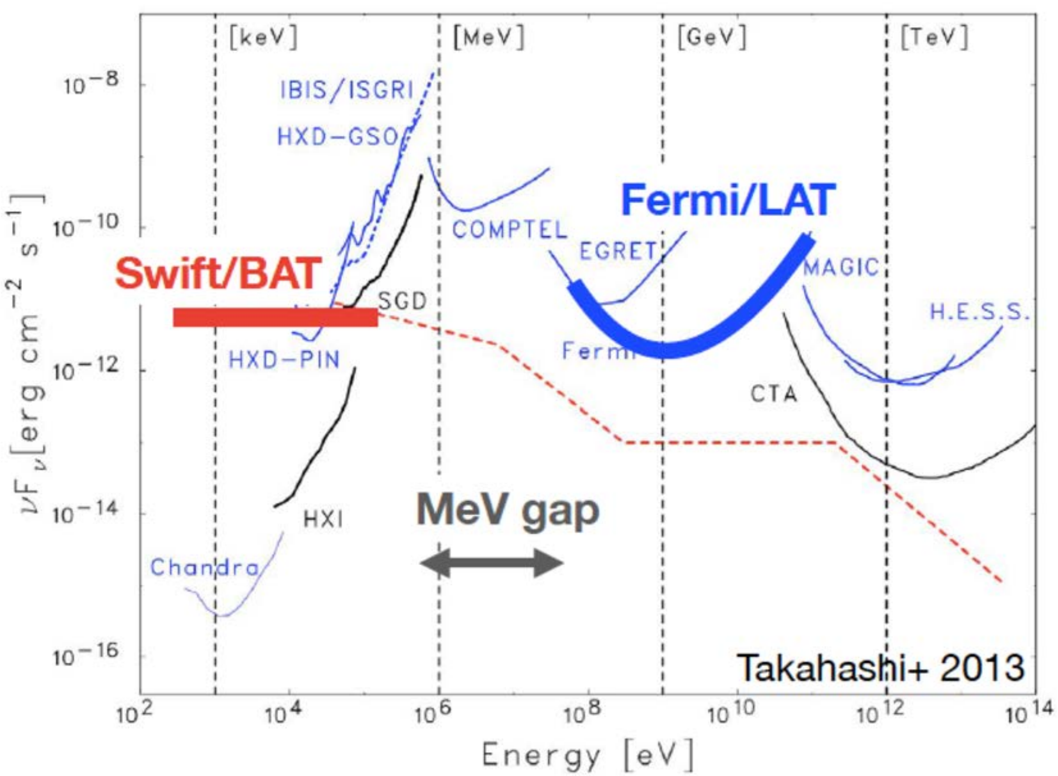
The CTA SCT Project

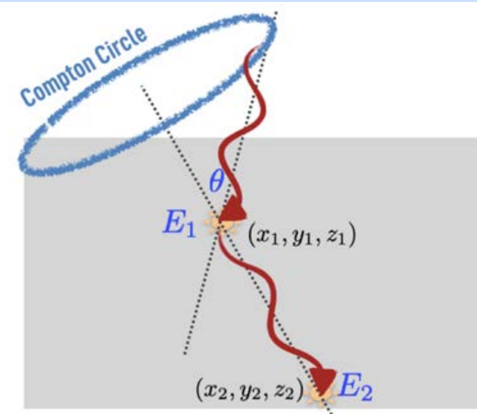
- Jan 23, 2019: First light of the prototype SCT (pSCT)
- May 2020: Detection of the Crab Nebula reported (Astropart. Phys., 128, 102562, 2021)
- Oct 2020: CTA Consortium endorses the development and construction of SCTs to enhance and complement DC-MSTs
- Ongoing: Instrumentation of the focal plane to 11k+ channels with upgraded SiPMs
- 2023: Expected completion of pSCT camera upgrade to full 8° field of view

Astro 2020 Decadal Survey endorses CTA-US contributions of SCT telescopes as an essential element of US multimessenger strategy

The Future: 10 MeV – Compton Regime

Gamma-rays in MeV region poorly explored: **“MeV Gap”**





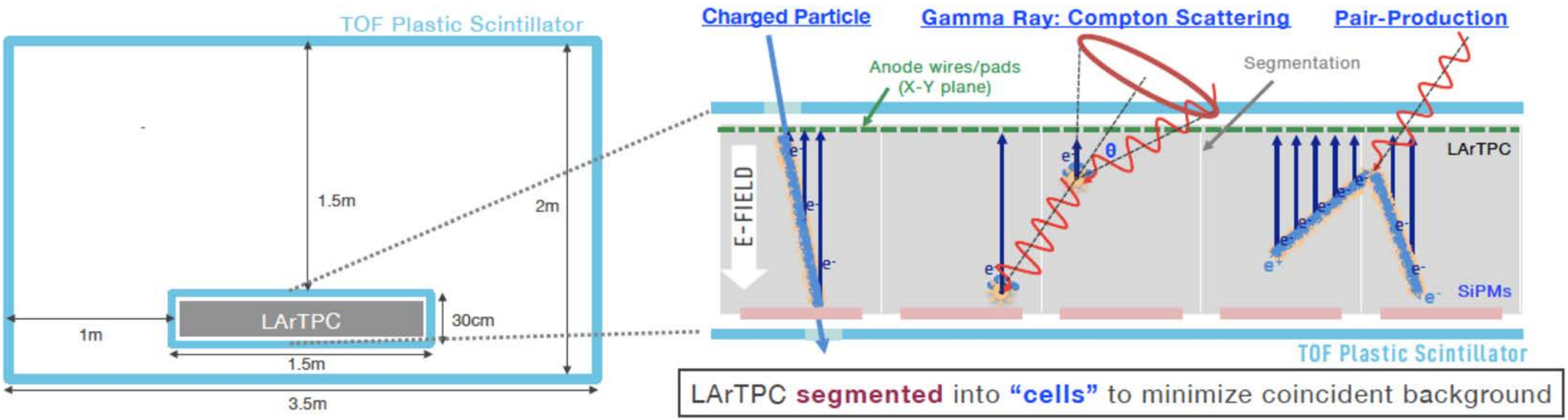
MeV gamma-ray continuum/line spectrum
- Physics processes/**nucleosynthesis** -
Multi-messenger astronomy
- Indirect **dark matter** searches/**PBH** searches

The Future of Gamma-Ray Experiments in the MeV - EeV Range, Snowmass Whitepaper arXiv:2203.07360

- Good coverage in the Swift-BAT & Fermi-LAT, but significant MeV “gap” -- No dedicated mission since Comptel.
- Future? COSI, GRAMS, Amego-X, HERD, several other proposed missions

The GRAMS Detector Design

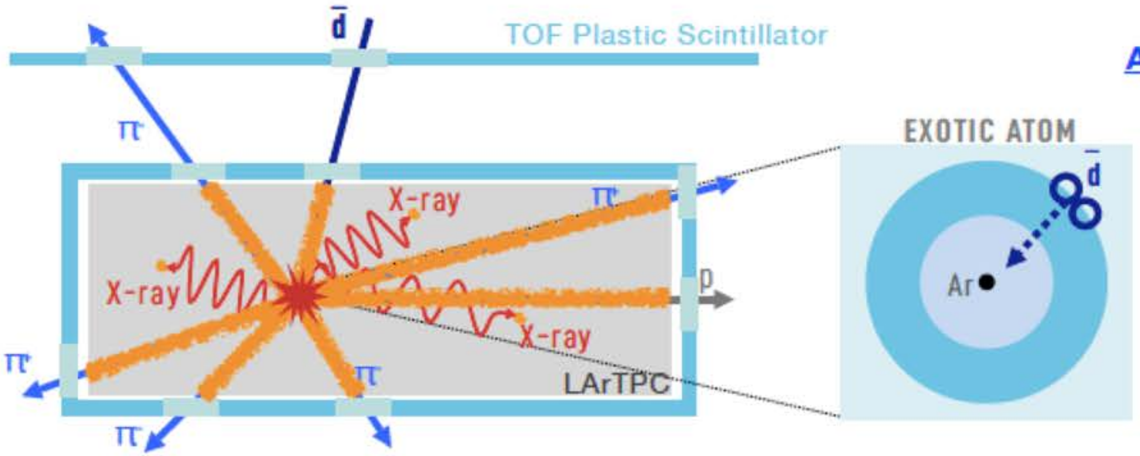
LArTPC surrounded by plastic scintillators

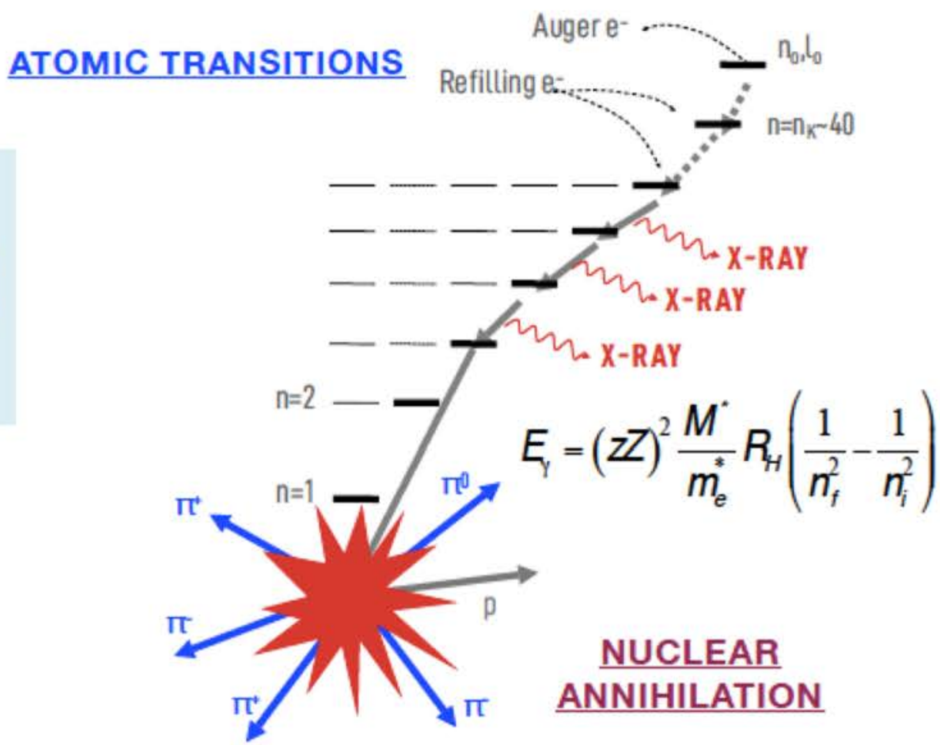


Large-scale, low-energy threshold LArTPC has been **well-studied/widely-used** in underground **dark matter/neutrino** experiments

GRAMS: Antimatter Detector

Measure atomic X-rays and annihilation products



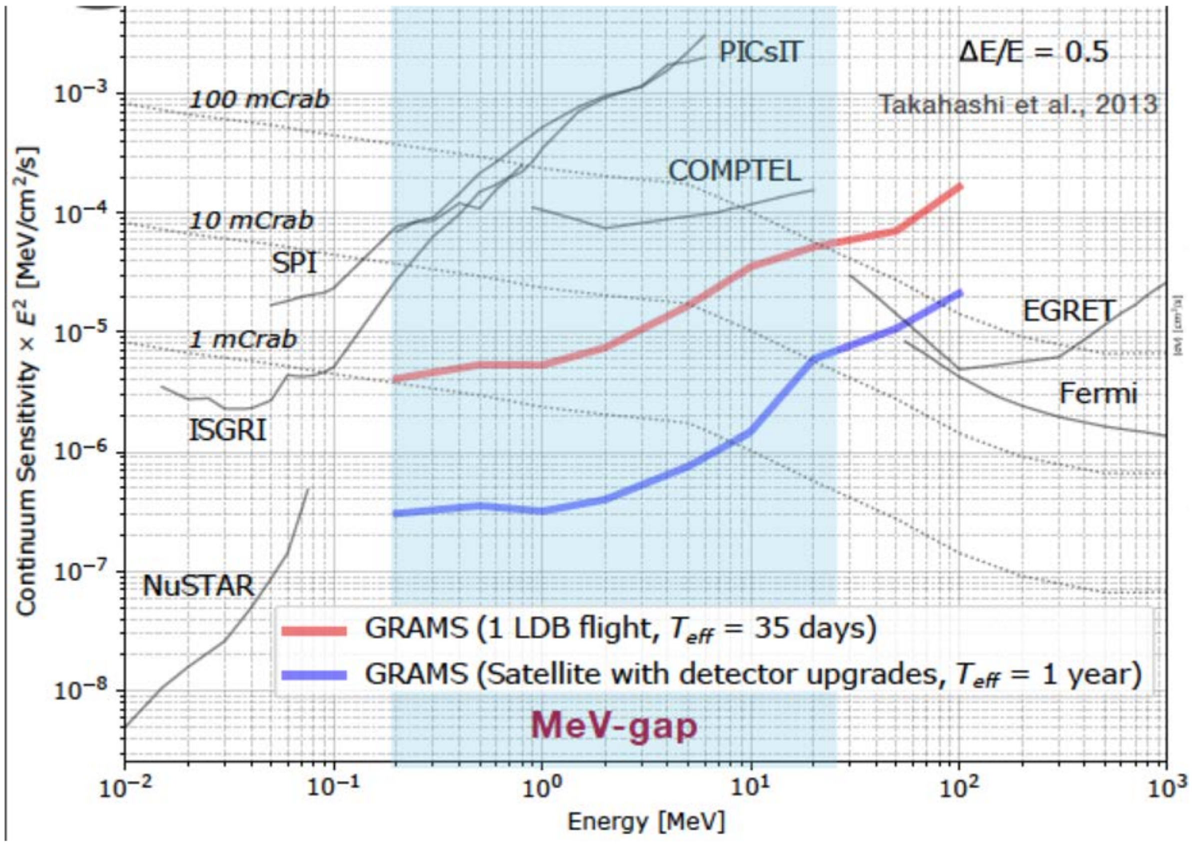


- A time of flight (TOF) system tags candidate events and records velocity
- The antiparticle slows down & stops, forming an excited exotic atom
- De-excitation X-rays provide signature
- Annihilation products provide additional background suppression

LArTPC (almost no dead volume) provides
- **Excellent** 3D particle tracking capability
- **High** particle detection efficiency

MeV Gamma-ray Observations

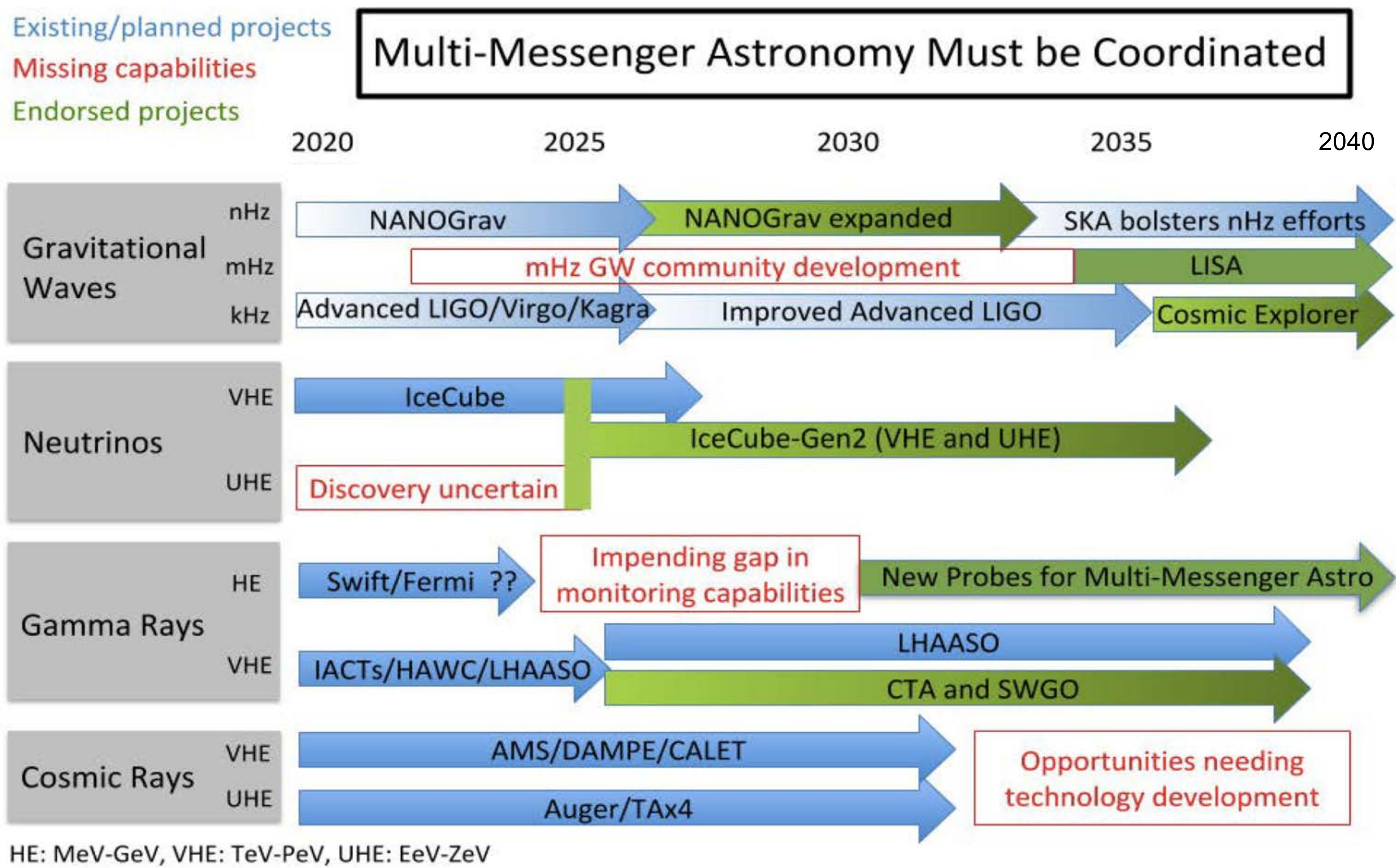
LArTPC surrounded by plastic scintillators



- **Balloon** flight: an order of magnitude improved
- **Satellite** mission: comparable to future missions

Astro2020 Decadal Survey:

Continuity of Multi-messenger Capabilities



Thank you!