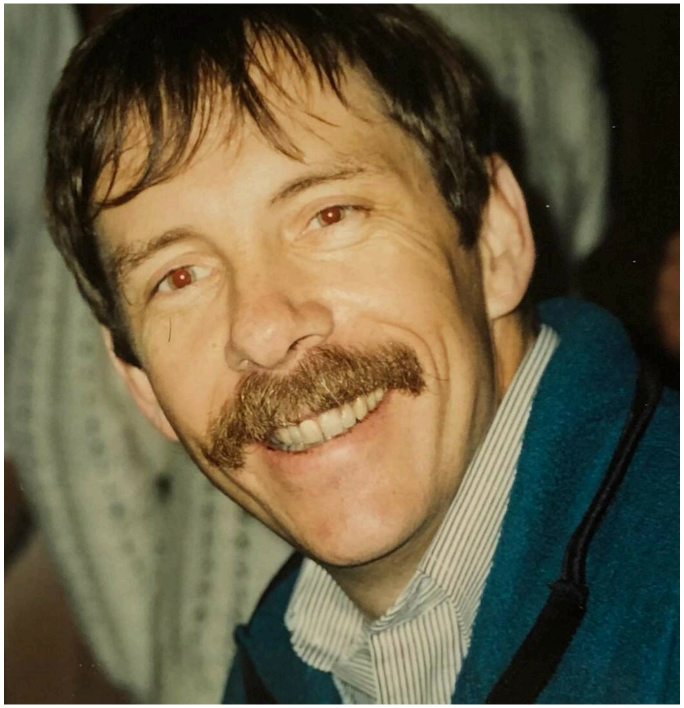
Extragalactic γ-ray sources: a status report*

Reshmi Mukherjee
Barnard College, Columbia University

Gamma 2020(2), Barcelona

Ken Gibbs (1955-2022)



A pioneer of the Imaging Atmospheric Cherenkov Technique with the Whipple Collaboration:

- PhD Dissertation title: "***Application of Imaging to the Atmospheric Cherenkov Technique: Observations of the Crab Nebula and Pulsar***" (University of Arizona 1986): a critical step for the detection of the Crab Nebula at TeV energies. In 1989

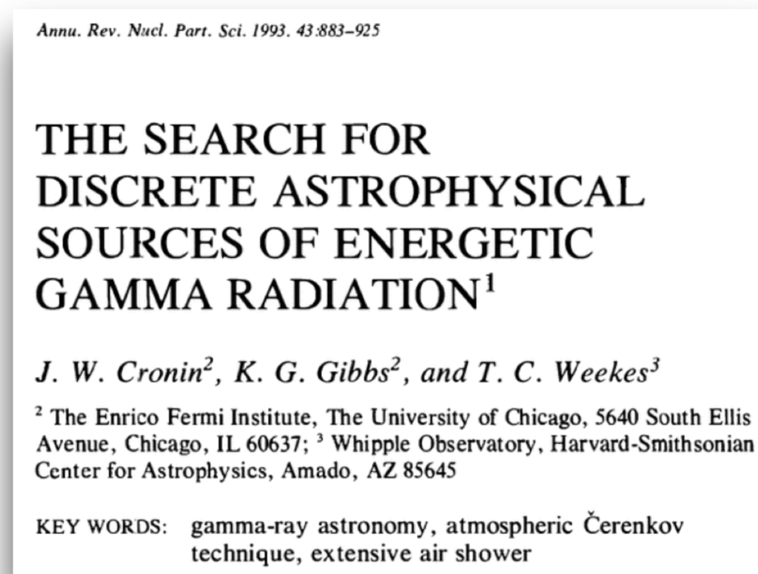
A driving force for the realisation of VERITAS:

- VERITAS Operations Manager (2001 – 2011): A leader in the the design, construction, validation, and initial operation of VERITAS.

Many additional contributions to the field of High Energy Astrophysics including:

- CASA/MIA and Auger Air Shower arrays
- CHIME project manager

Obituary:
https://www.islandssounder.com/obituaries/kenneth-gibbs-passages/


Annu. Rev. Nucl. Part. Sci. 1993. 43:883–925

THE SEARCH FOR DISCRETE ASTROPHYSICAL SOURCES OF ENERGETIC GAMMA RADIATION[1]

J. W. Cronin[2], K. G. Gibbs[2], and T. C. Weekes[3]

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KEY WORDS: gamma-ray astronomy, atmospheric Čerenkov technique, extensive air shower

Extragalactic γ-ray sources: a status report*

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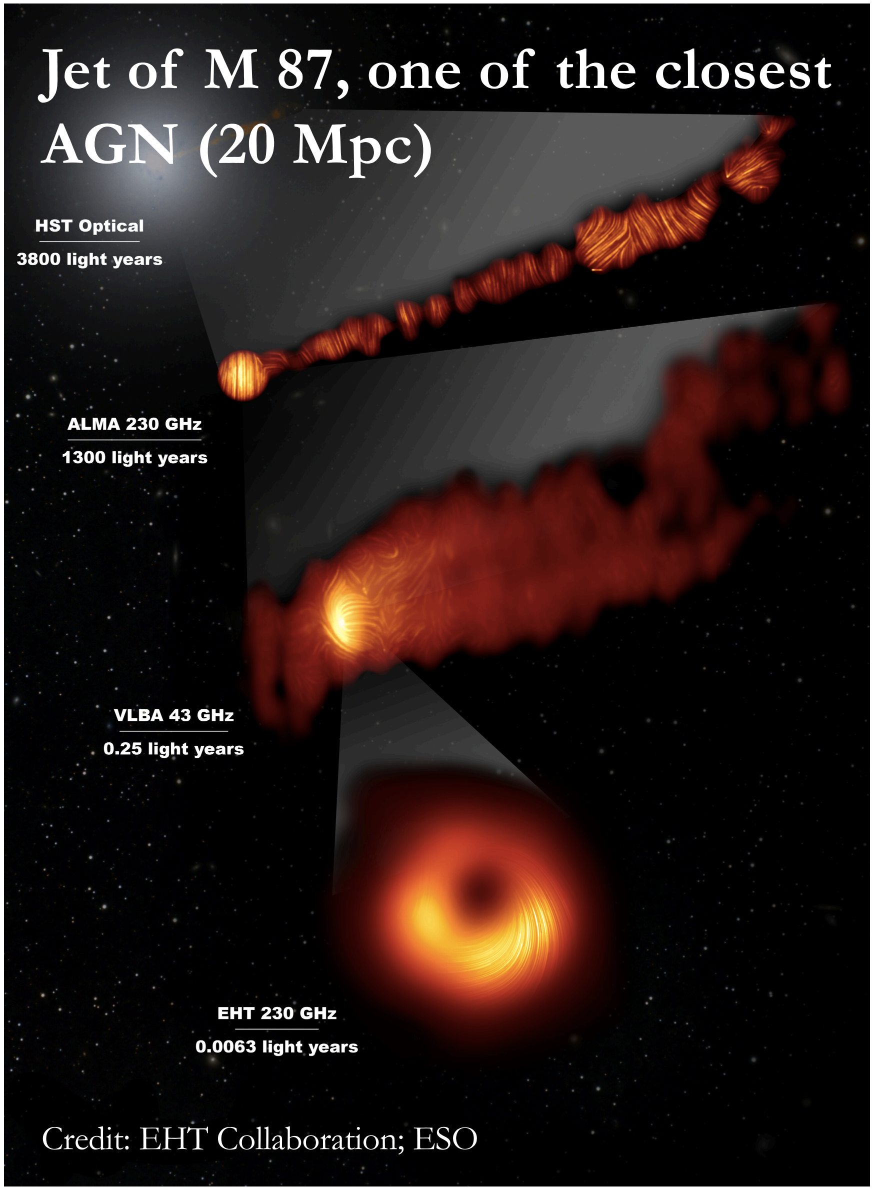
Barnard College, Columbia University

Gamma 2020(2), Barcelona

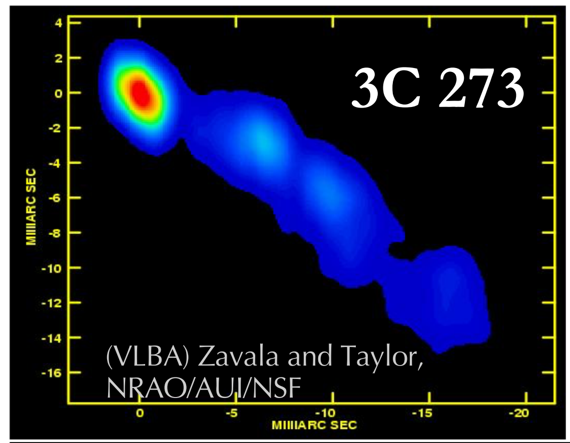
** 3 Reviews, 11 Highlight, 48 Contributed talks, 43 (?) posters over 5 days, 1275 min of talks*

Extragalactic Jets: Regime of relativistic plasmas

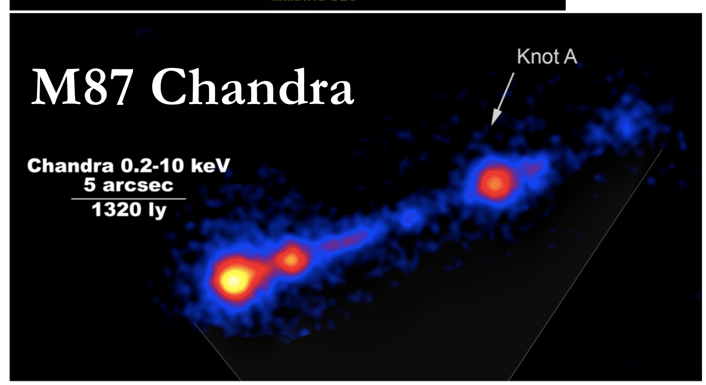


Open Questions

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



3C 273: kpc scale radio jet



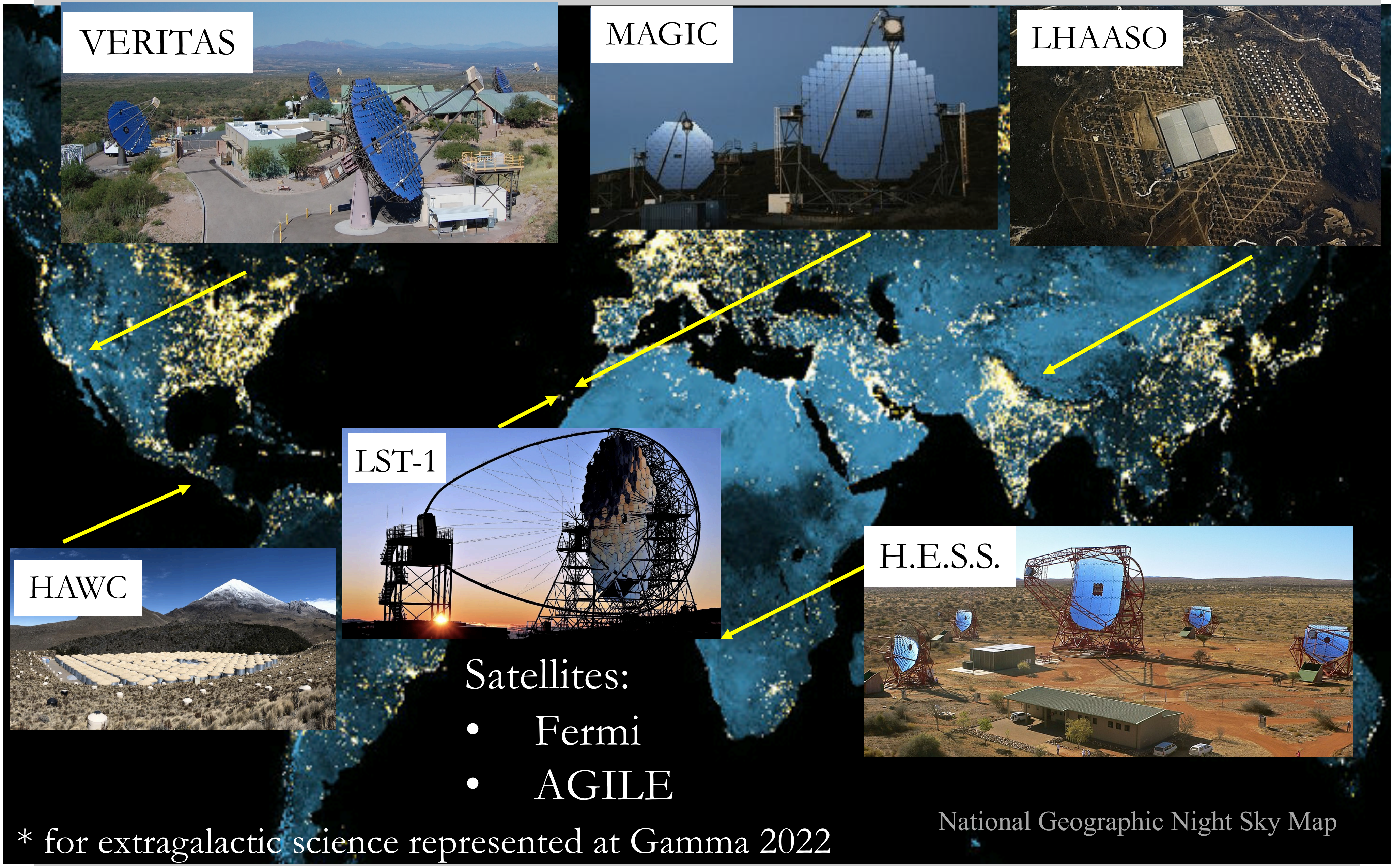
Outline

- Telescopes & Observatories
- The TeV & GeV sky maps c.2022
- New results at γ2022

Not enough time to cover:
Fast radio bursts
Theoretical modeling
Fundamental physics topics

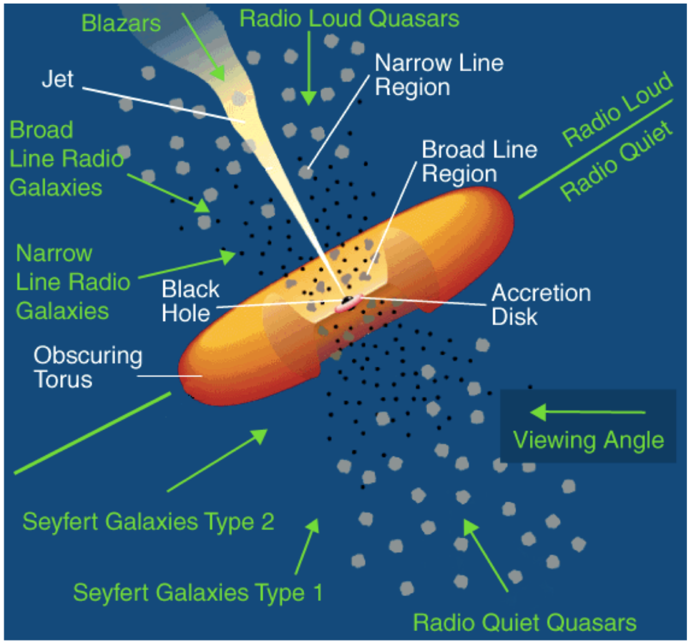
- LE or MeV : 0.1 -100 MeV
- HE or GeV : 0.1 -100 GeV } domain of space-based astronomy
- VHE or TeV : 0.1 -100 TeV   domain of ground-based astronomy

The Gamma-ray Instruments* (2022)



* for extragalactic science represented at Gamma 2022

Extragalactic γ-ray Sources: Blazars



Urry & Padovani 1995

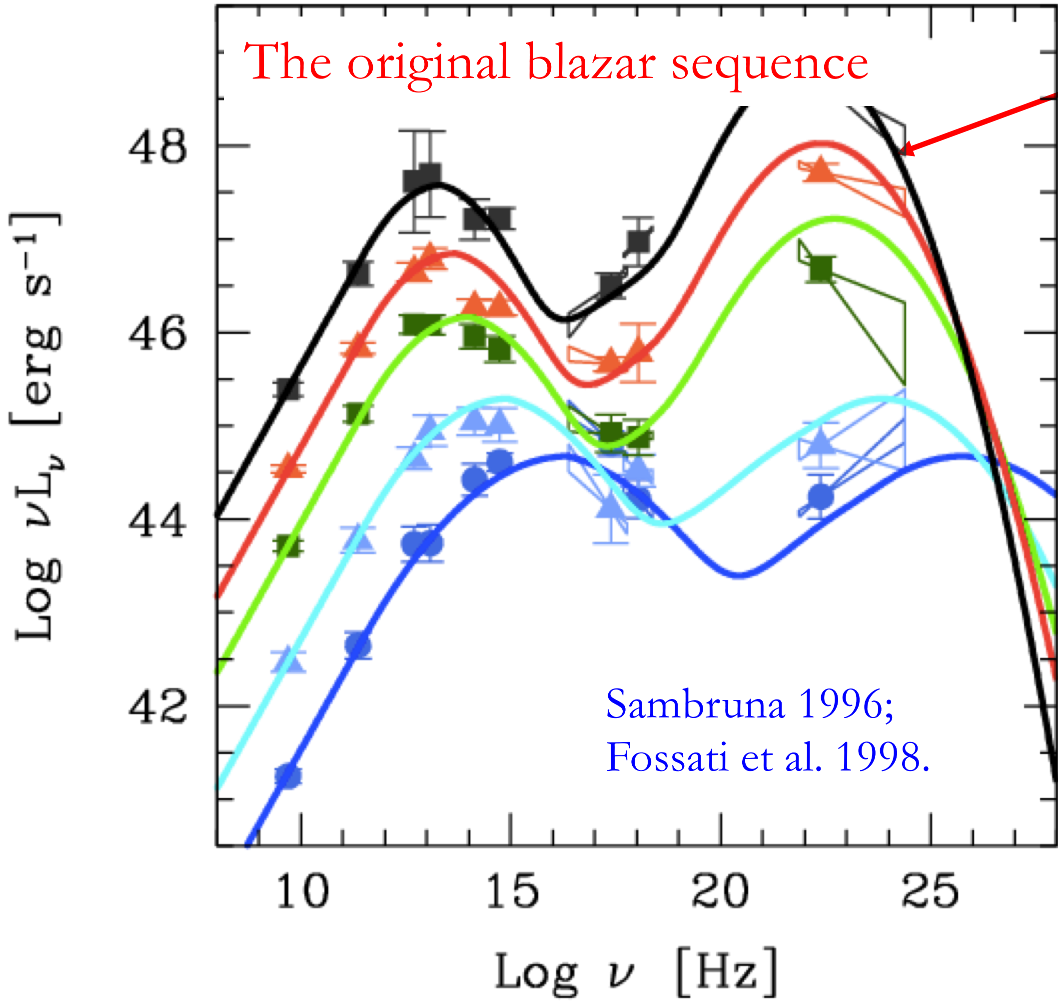
Physics of Compact Objects: AGN scales

- 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 constitute the largest TeV & GeV extragalactic source populations
- 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

Blazars – Multiwavelength Power Spectra



Non-thermal, continuum spectra
Dramatic peak at γ-ray energies.
Emission extends to GeV-TeV

The blazar sequence? Or selection effects? Two classes:

- jetted vs
- non-jetted AGN

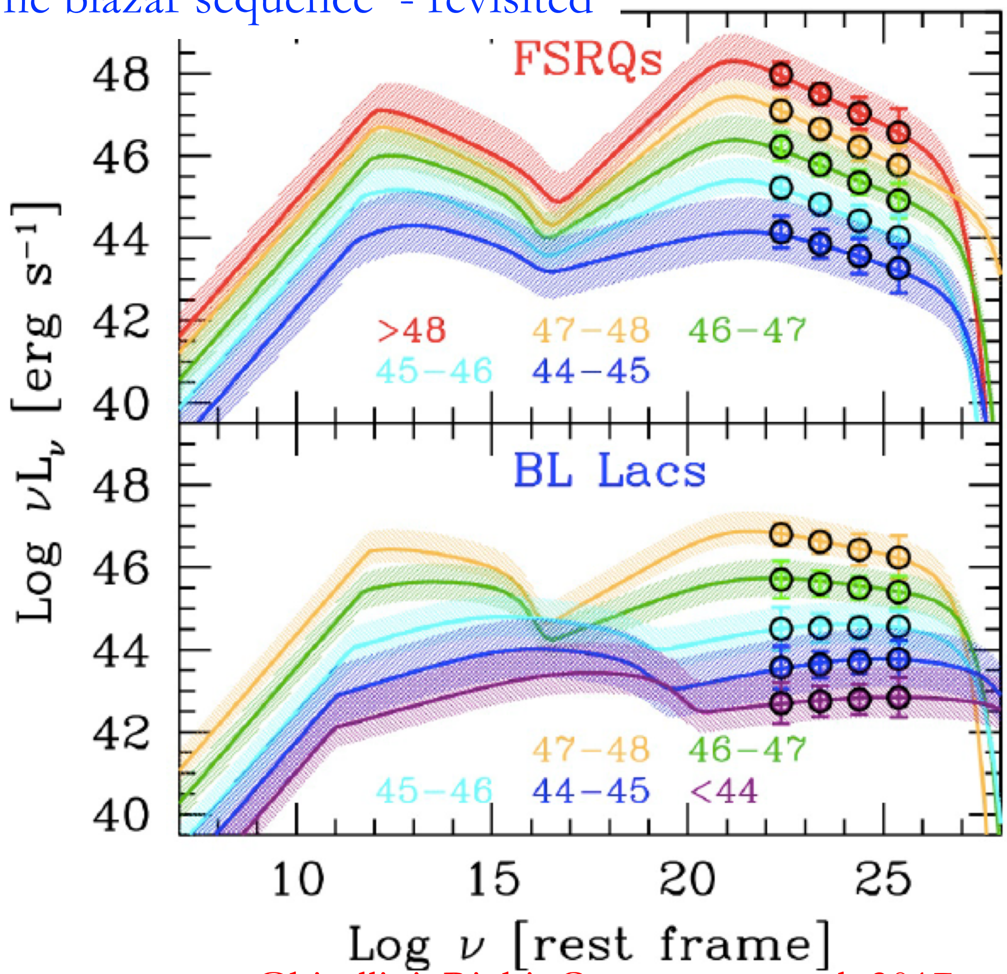
See P. Padovani γ2022

- HBLs: $\nu_{pk} \sim 10^{16\text{-}18}$ Hz
- IBLs: $\nu_{pk} \sim 10^{15\text{-}16}$ Hz
- LBLs: $\nu_{pk} \sim 10^{13\text{-}15}$ Hz
- "Extreme" HBLs $> 10^{18}$ Hz

Absence of intrinsic γγ pair absorption ---> beaming in blazars
High luminosity -- γ-ray emission originates in strongly beamed sources

Blazars – Multiwavelength Power Spectra

The blazar sequence - revisited



Ghisellini, Righi, Costamante et al. 2017

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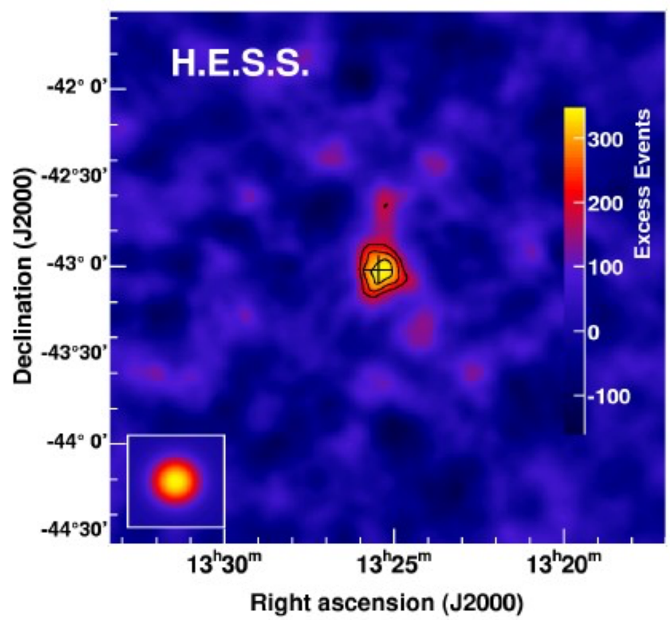
Highlights from γ-2016 (Heidelberg)

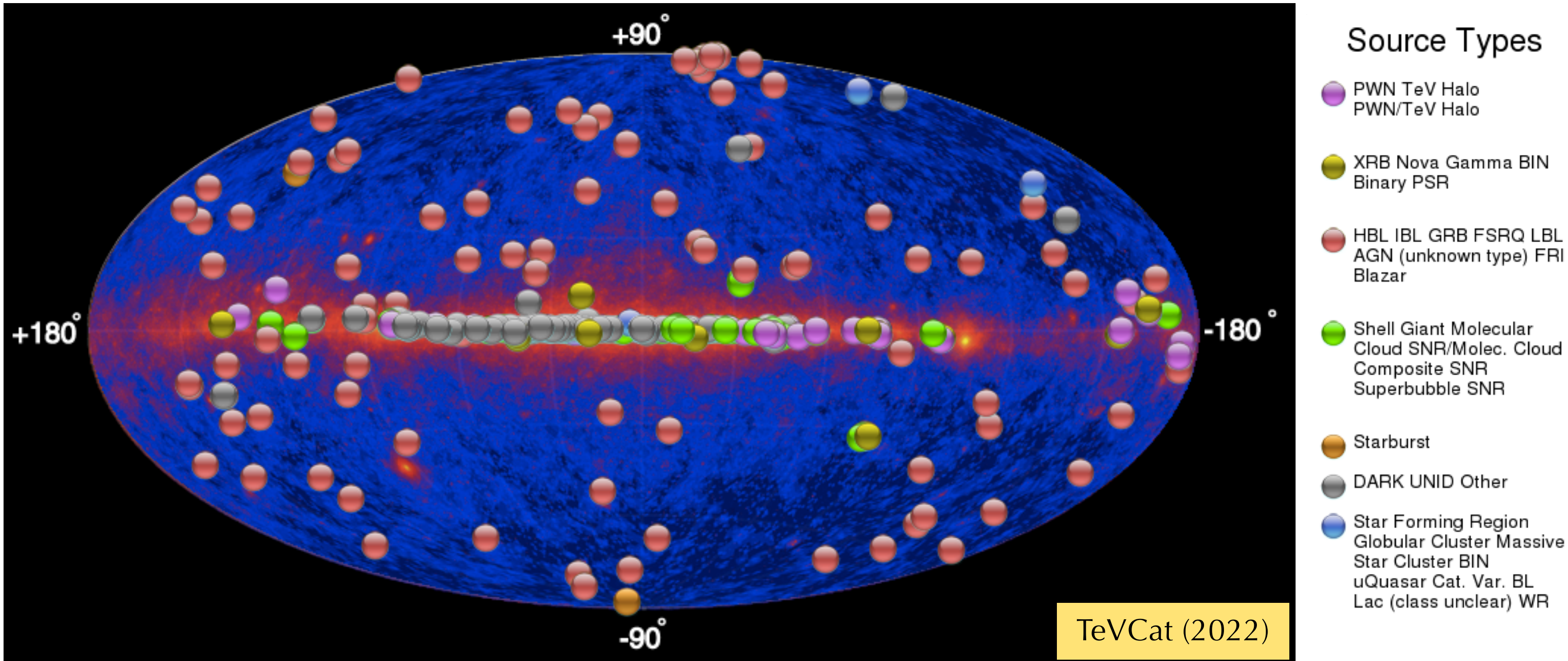
(Extragalactic rapporteur: Andrew Taylor)

- Results from recently-upgraded IACTs, FACT monitoring & partial HAWC
- **~ 60 extragalactic sources**
- Remarkable detection by MAGIC and VERITAS, of a flaring outburst from the FSRQ PKS 1441+25 (redshift z ~1)
  - EBL component constrained by the observations of PKS 1441+25
- Detection of gravitationally-lensed system by MAGIC:
  - first VHE γ-ray gravitationally lensed system, B0218+357
  - Source AGN at a z ~ 0.94.
  - Lensing galaxy at z ~ 0.68

- Fast variability and outbursts in 3C 279.
- Discovery of quasi-periodicity in the emission of PG 1553+113
- Spatially-resolved AGN Cen A at 3.8 Mpc by H.E.S.S.



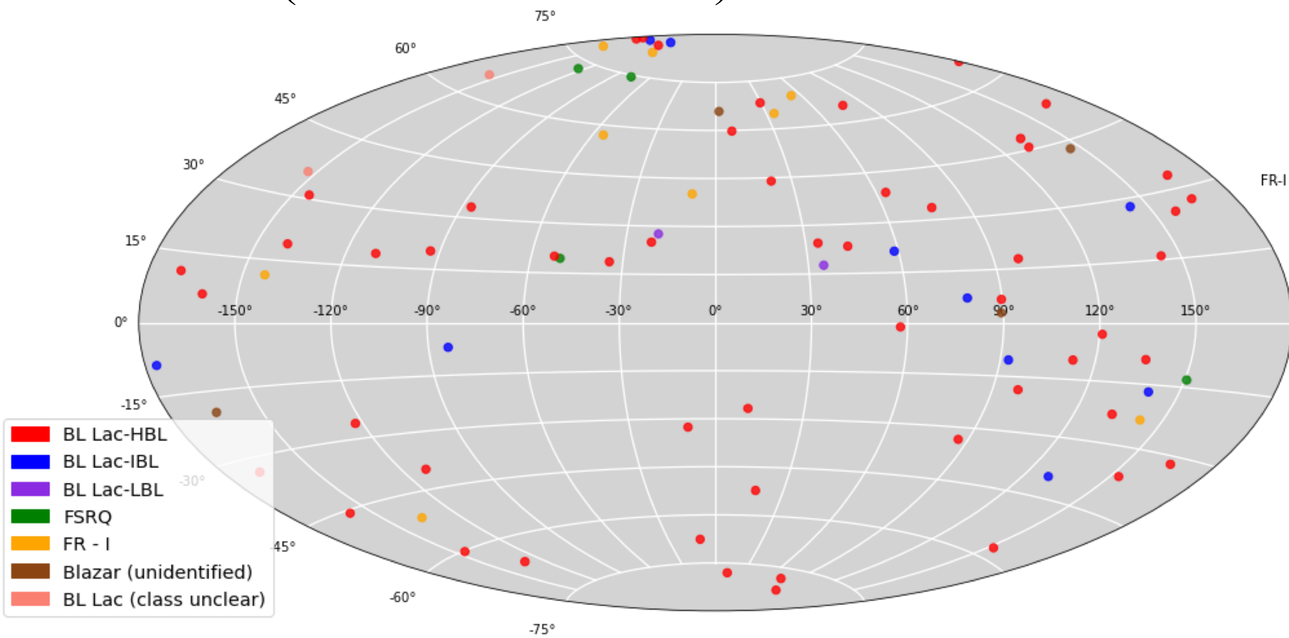
VHE Gamma-Ray Sky (2022)

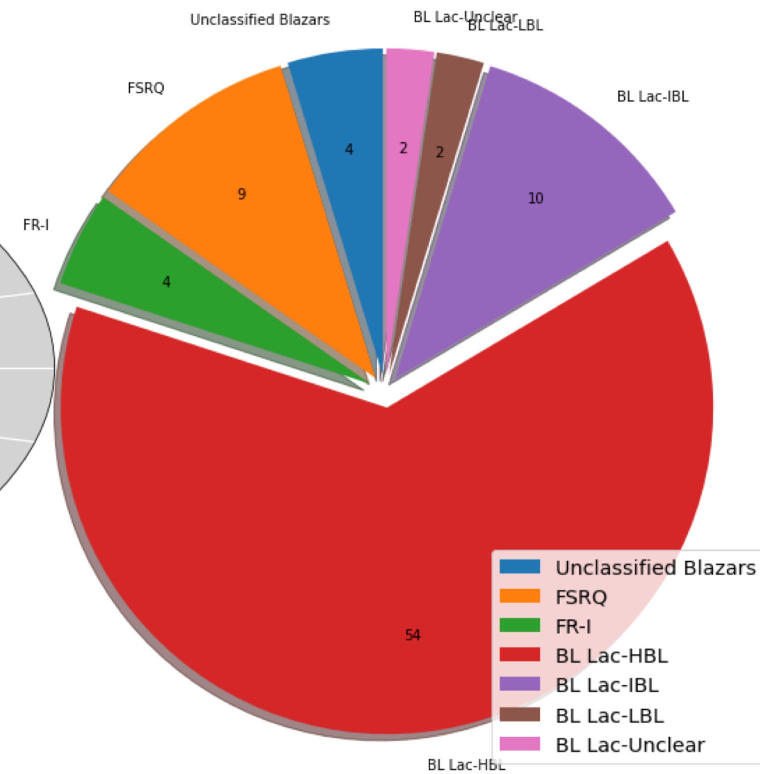


- More than 250 sources
- 10 different source classes
- ~90 extragalactic sources (86 AGN + 3 starbursts)
  - Expansion of radio galaxy counts
  - Detection of starburst galaxies ⟶ See E. Peretti γ2022
  - **GRBs detected as TeV sources (after a > 15 yr search)**
- Detection of powerful and ultrashort flares of AGN (Fermi, IACTs)

The Extragalactic TeV γ-ray Sky

TeV Blazars (TeVCat March 2022)

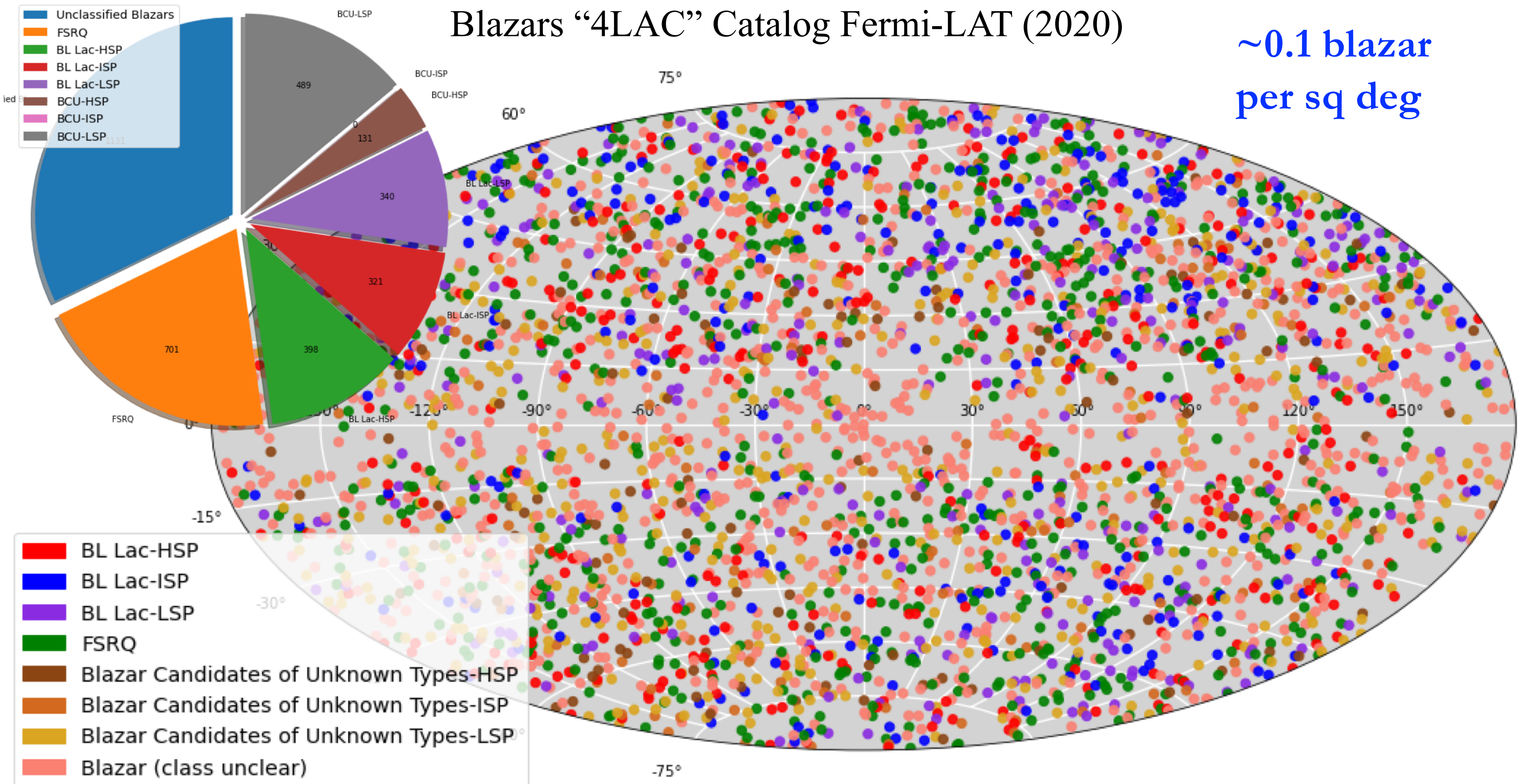




- Blazar population studies: SED-based distributions of low-, intermediate-, high-Synchrotron-Peaked sources
- Of the TeV blazars, 90% of blazars with known redshift have $z < 0.5$
- Possible to do GeV-TeV blazar studies. Probe EBL, IGMF, ALP studies
- Build blazar luminosity functions

The Extragalactic GeV γ-ray Sky

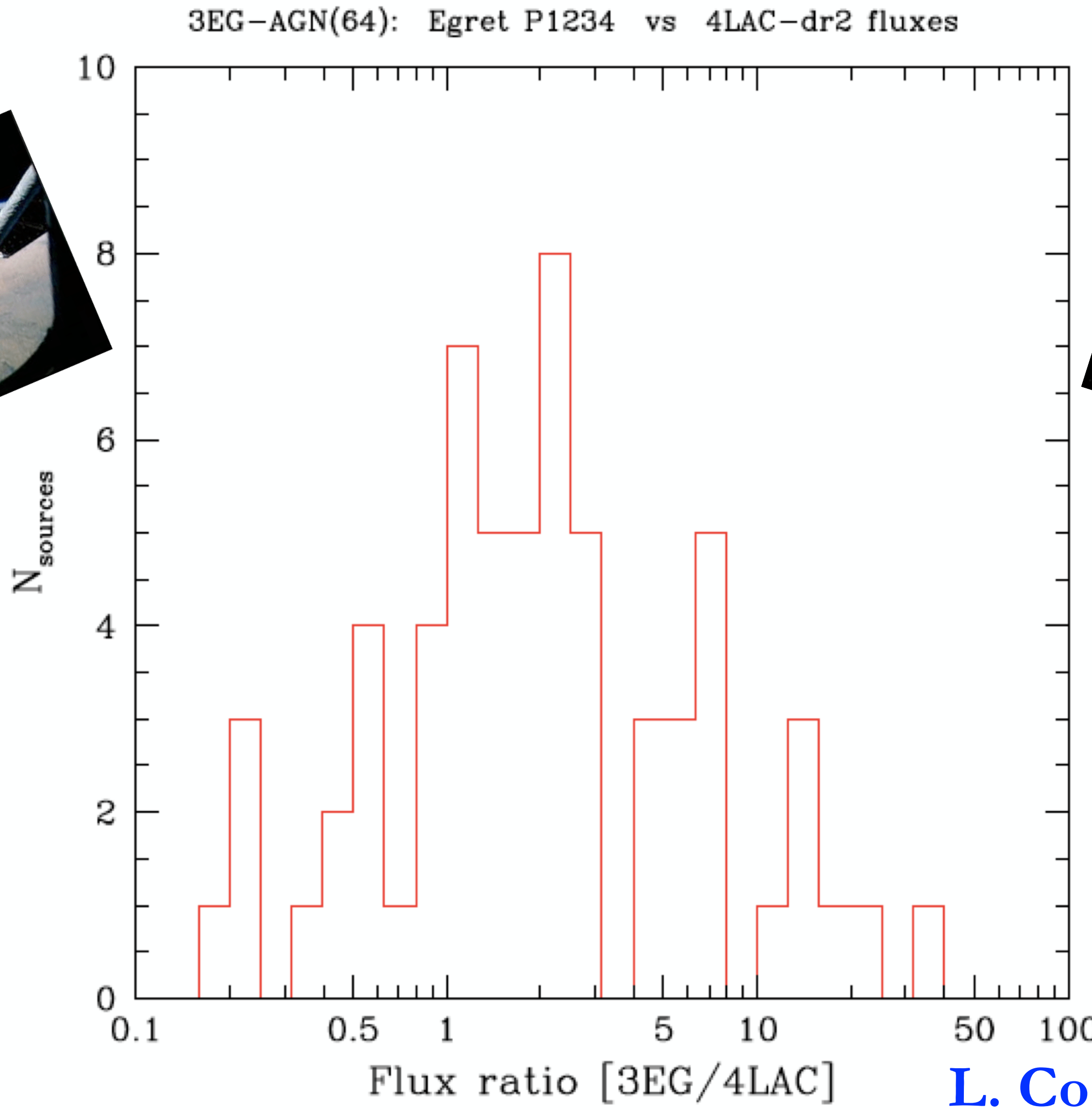
Blazars "4LAC" Catalog Fermi-LAT (2020)

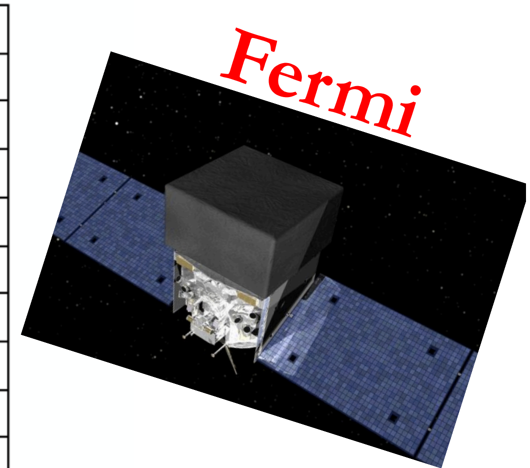


~0.1 blazar per sq deg

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

EGRET - Fermi-LAT : not the same sky





Some sources are one to 2 order of mag brighter in EGRET than Fermi

➔ Decadal variations from average emission in blazars

L. Costamante, CDY

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

Other Nearby Extragalactic Sources: Radio Galaxies

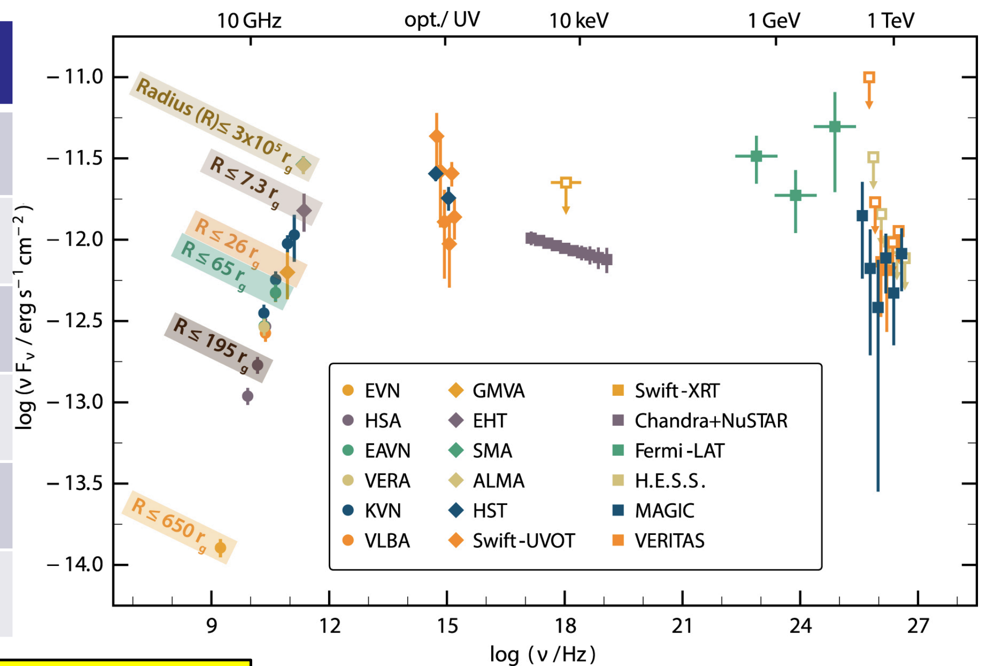
Radio Galaxies (mis-aligned jets)

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

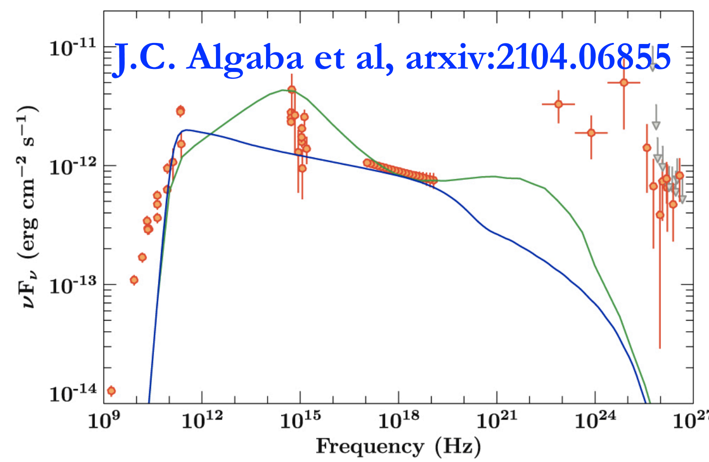
Rieger & Levinson 2018 arXiv:1810.05409

See F. Rieger γ2022

Broadband MWL for M87 with EHT



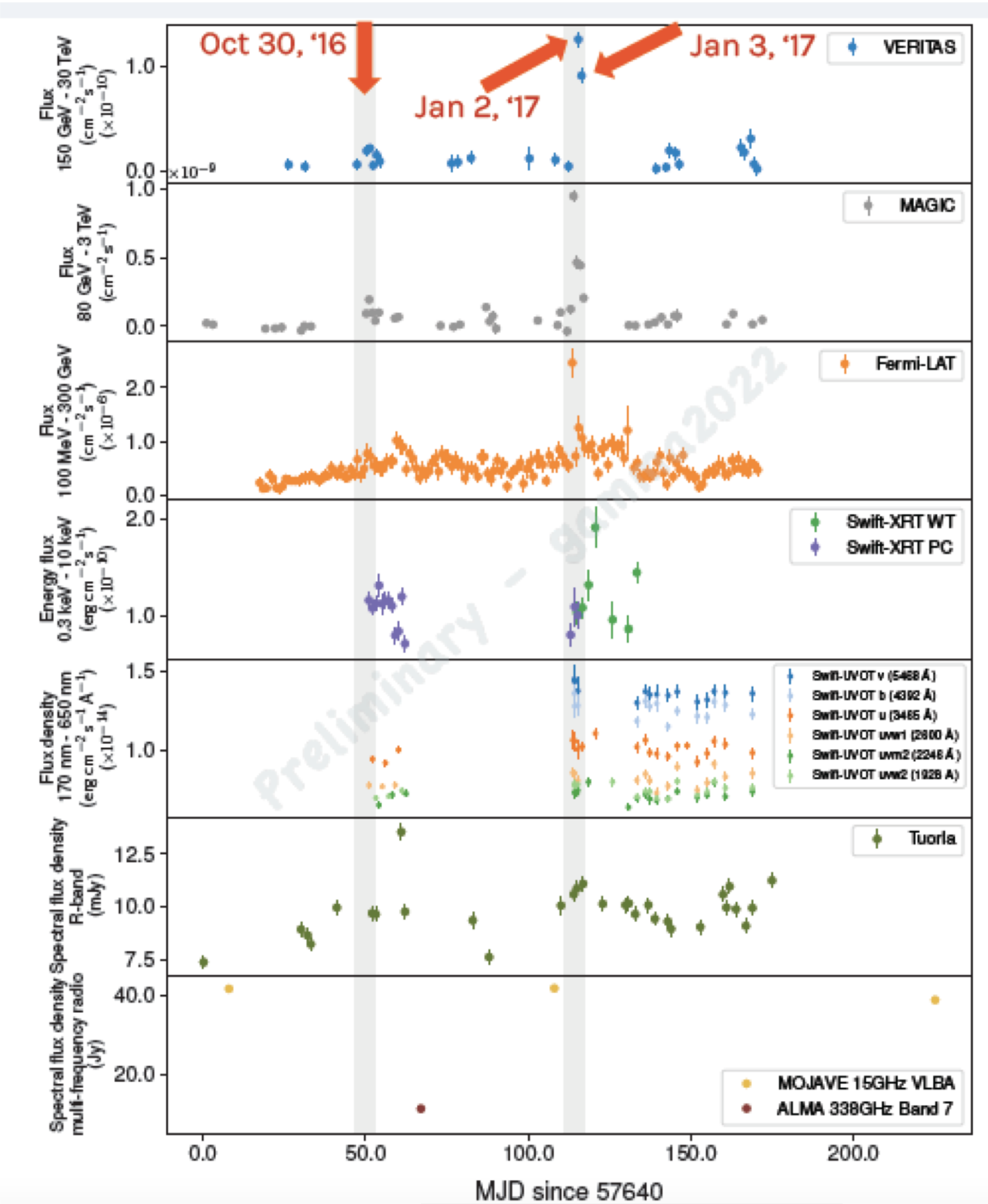
J.C. Algaba et al, arxiv:2104.06855



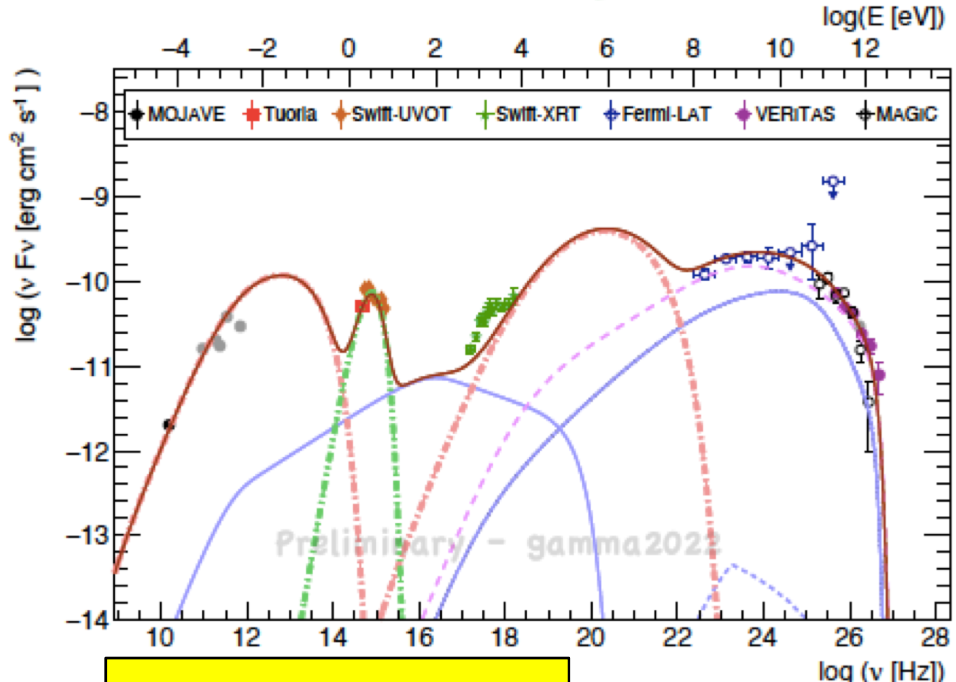
"VHE γ-ray emission cannot be produced in same region as mm-band. Need of structured jet model including time-dependence "

See A. Hahn γ2022

Radio Galaxy NGC 1275: Long term monitoring

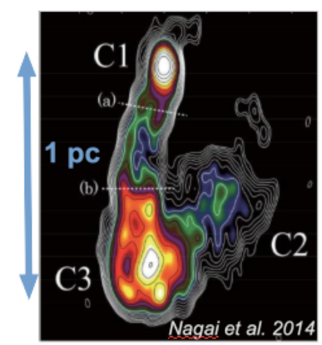


Broadband MWL for 2017 flare

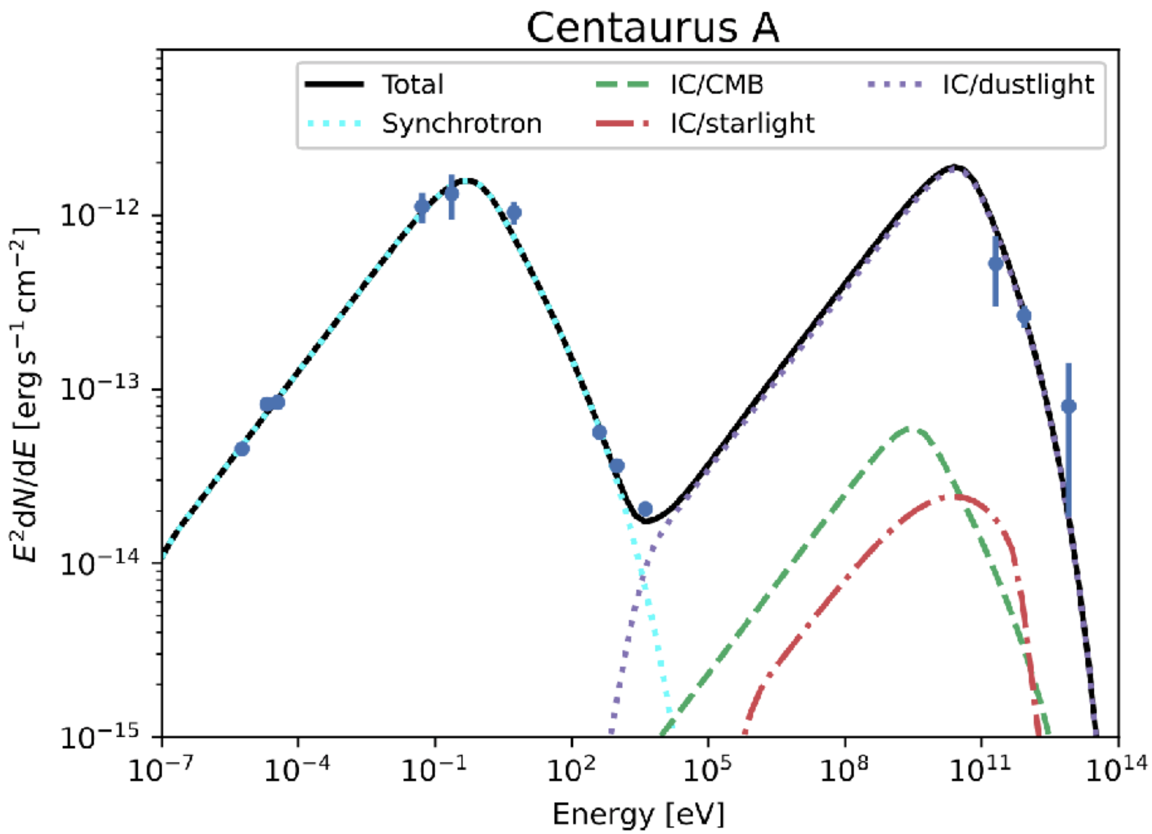


See L. Fortson γ2022

Jan 2017: MAGIC detects flare ~150% Crab.
Next day: VERITAS sees ~60% flare.
Multi-zone C3-blob-in-jet model



Model: Shear acceleration in large-scale jets



See J. Wang γ2022

Wang et al., arXiv:2105.08600

Modeling emission with a gradual shear flow particle acceleration - can produce cutoff power-law spectra

- Velocity-shear stratification is naturally expected in large-scale X-ray jets
- Energetic seed particles can be accelerated by interacting with the magnetic field inhomogeneities frozen in stratified layers
- IC and synchrotron from one population of electrons

AGN Physics - a Multi-scale Problem

A modelling challenge .....

See F. Rieger γ2022

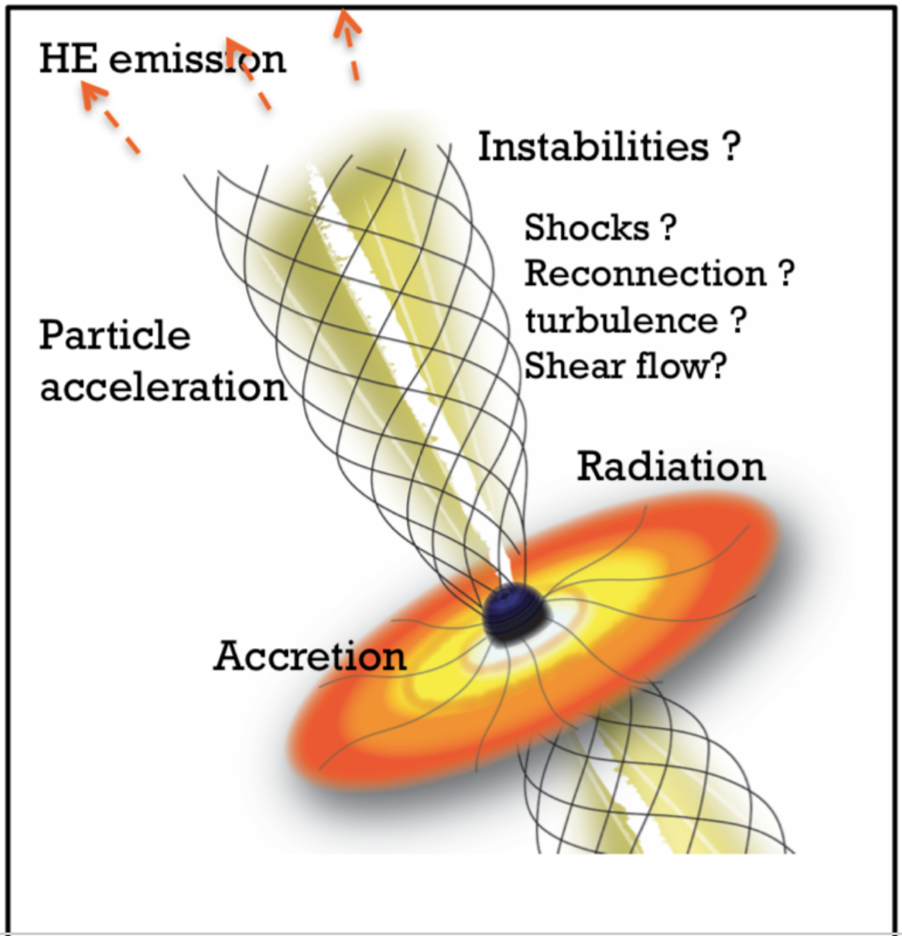
BH magnetosphere and jet are multi-scale systems

Global scales
formation and dynamics

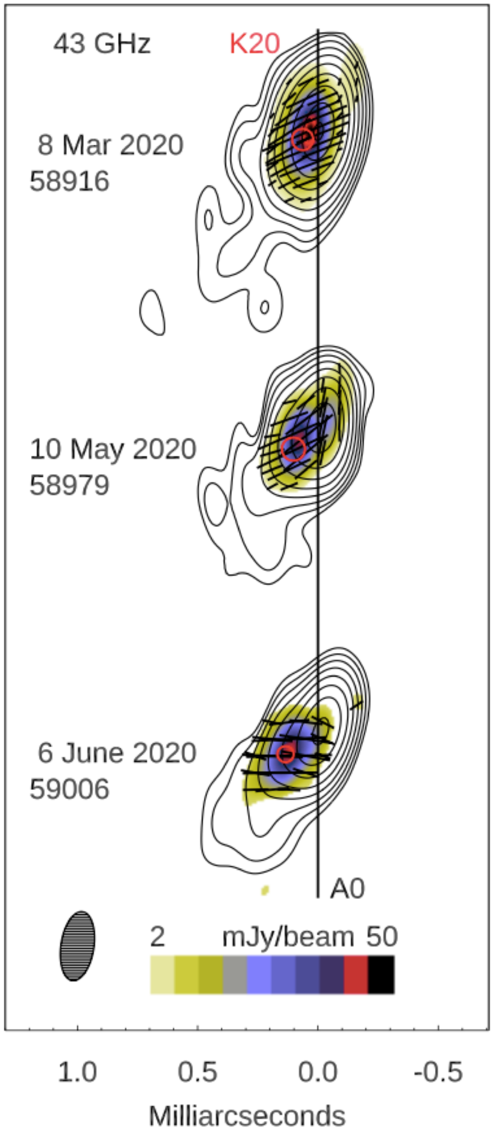
Radiation scales
Sync, IC, pp

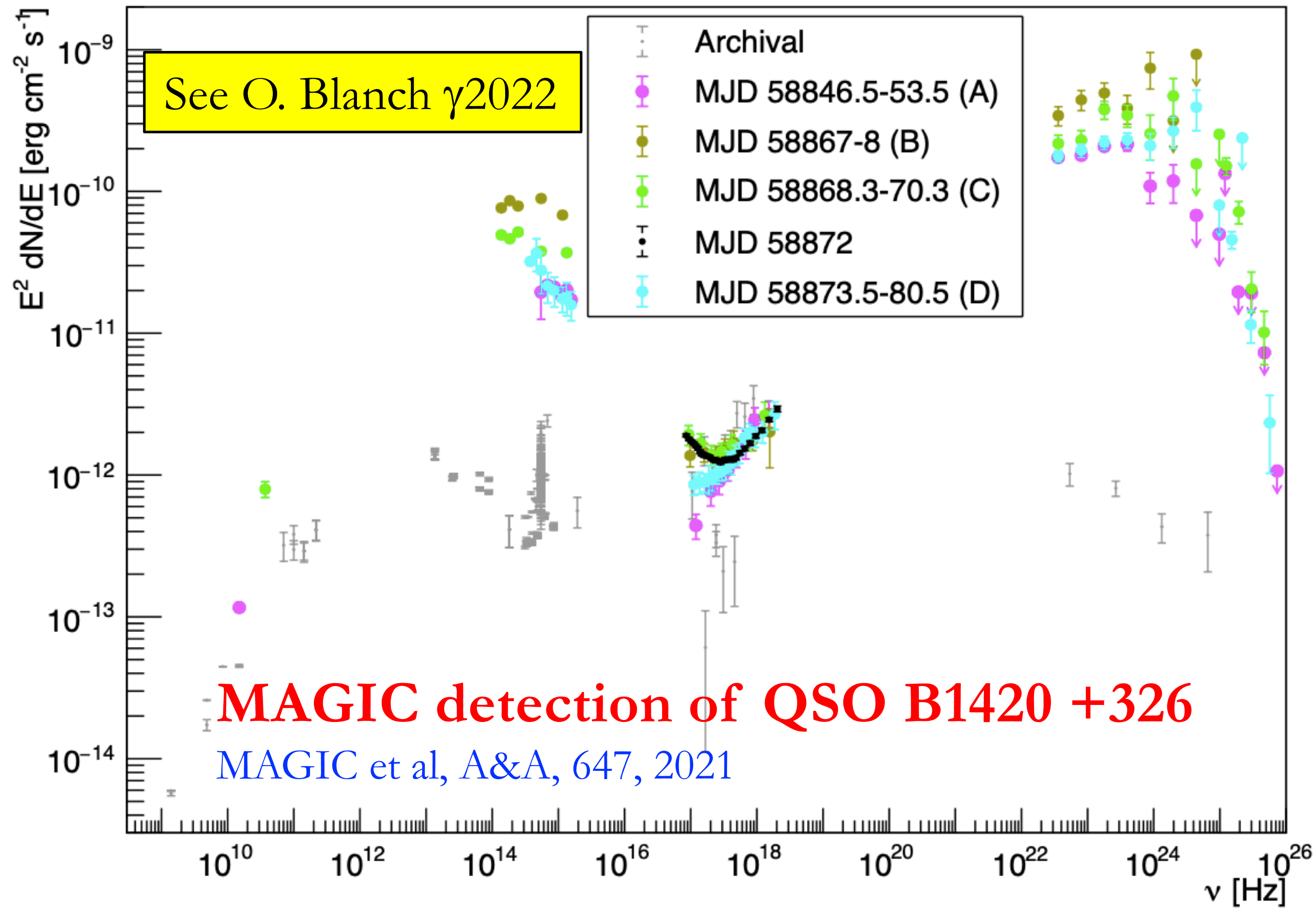
Dissipation scales
shocks, reconnection, turbulence

How are they connected?



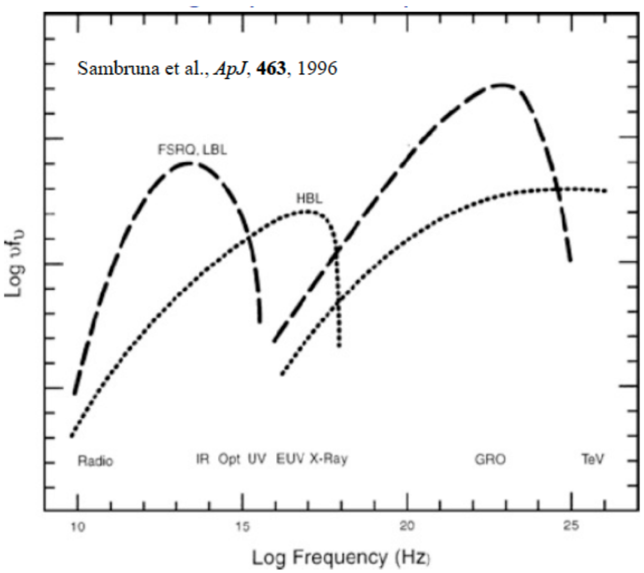
FSRQs: Rare at TeV Energies





- 8^{th} FSRQ detected at TeV energies
- SED shows peak shift to higher energies
- Modelling — e- accelerated in shock beyond BLR, external Comp.

Extreme High Frequency peaked BL Lacs

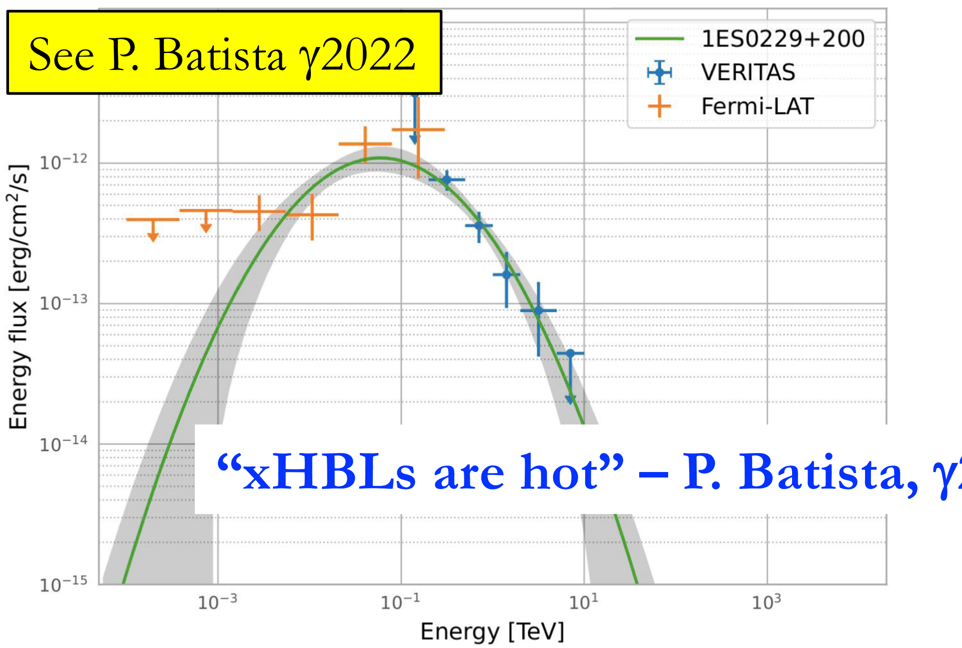


- Brightest in X-ray, SED peak at X-ray energies
- TeV peak at energies > 1 TeV (~10^{26} Hz)
- Hard intrinsic spectrum at sub-TeV energies
- New eHBL reported by VERITAS: RBS 1366,

log ν_{pk} ~ 17.2 See J. Quinn γ2022

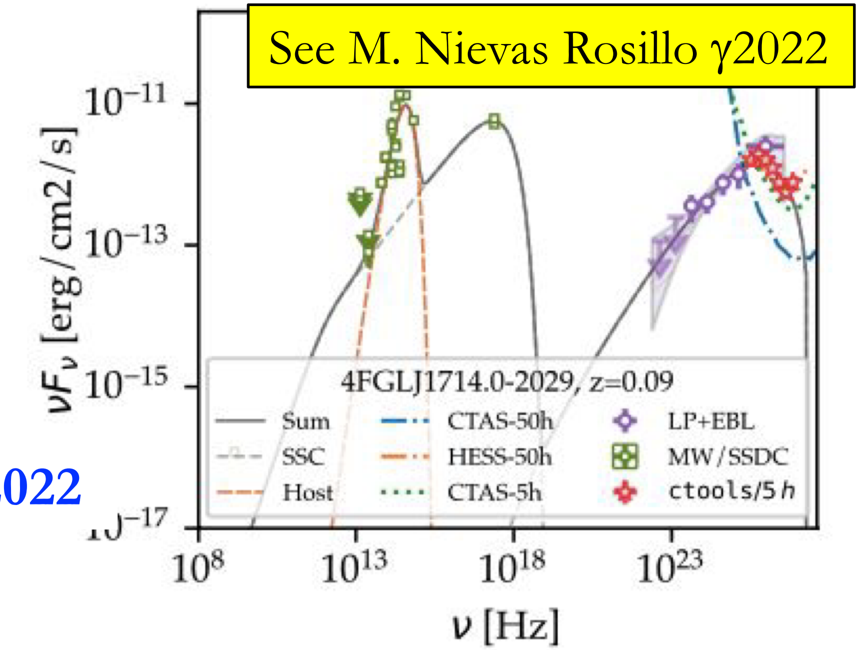
- New eHBLs reported by H.E.S.S.: MRC 0910-208 and 1RXS J195815.6-301119 See S. Wagner γ2022

See P. Batista γ2022



“xHBLs are hot” – P. Batista, γ2022

See M. Nievas Rosillo γ2022



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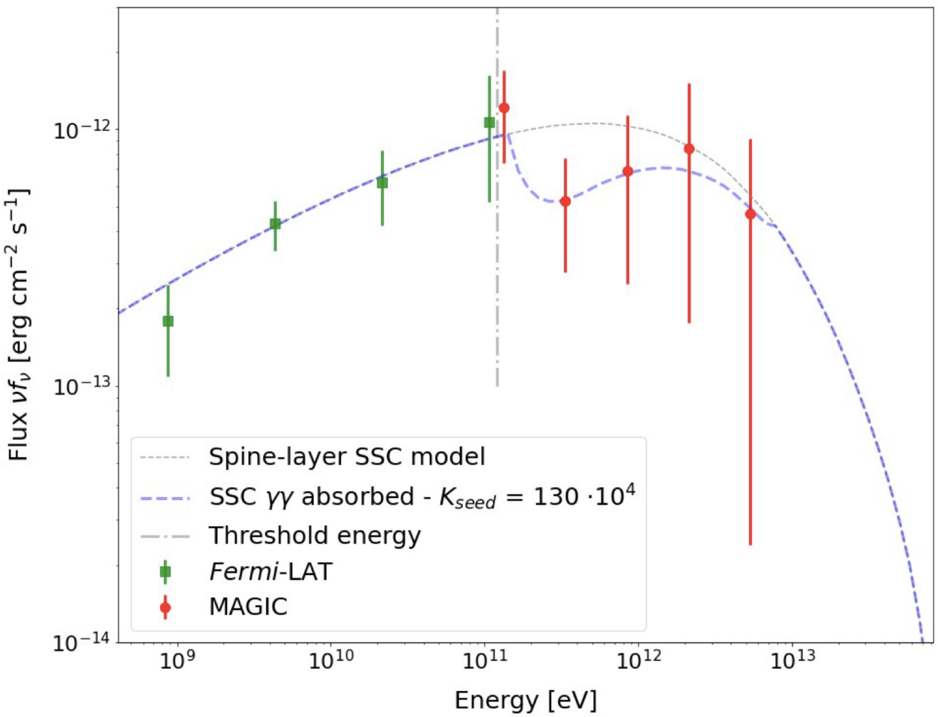
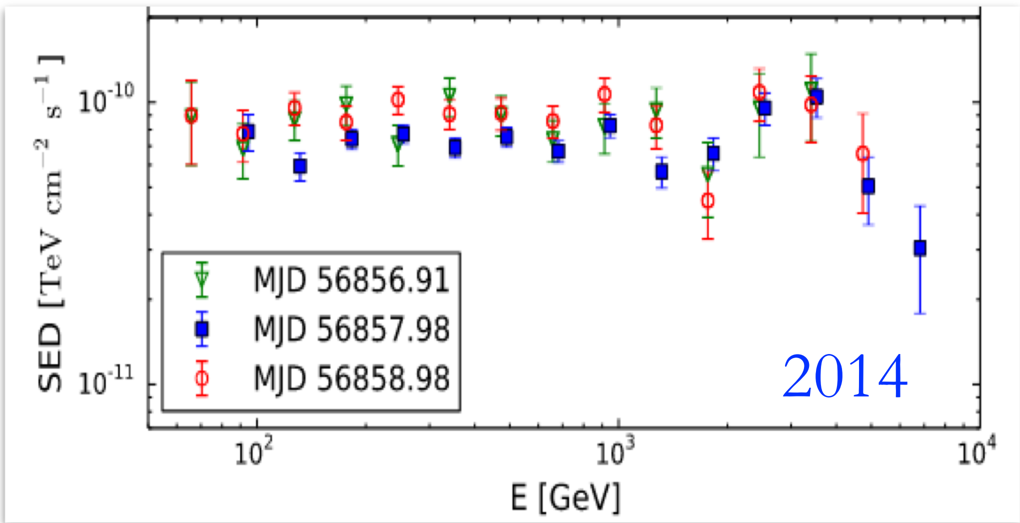


Absorption features in HBL and eHBL spectra due to γγ → Potentially identify of large-scale structures (e.g. a narrow-line region, NLR)

See L. Foffano γ2022

See M. Petropoulou γ2022



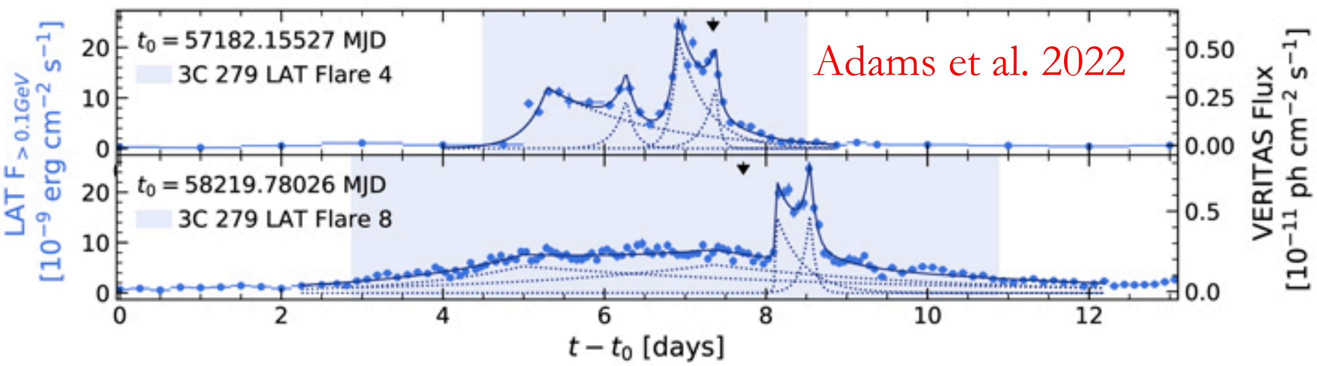
- Spectral feature at ~3 TeV detected by MAGIC in Mrk 501 during an extreme X-ray flaring activity.
- One-zone SSC incompatible
- Could the narrow features in VHE blazar spectra result from the decay of neutral pions (π0 bumps)?

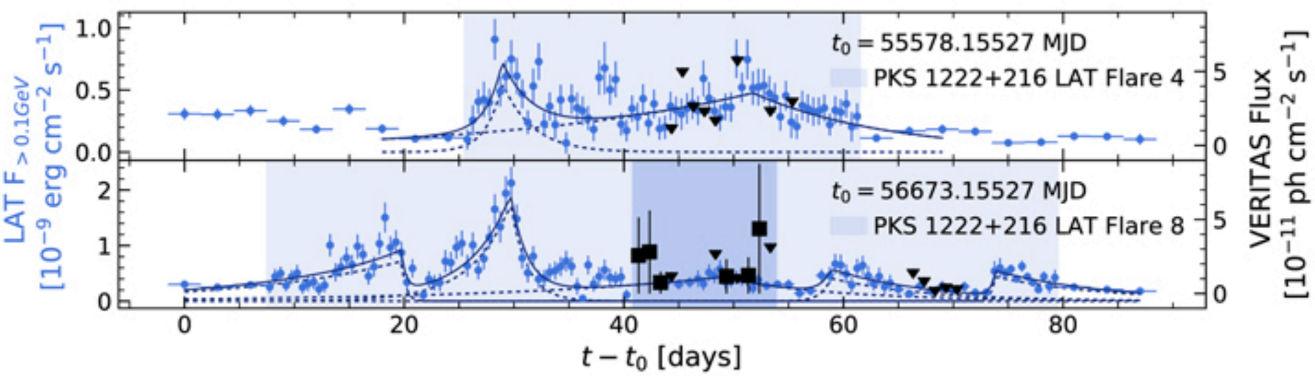
News Bulletins from HAWC, H.E.S.S., MAGIC & VERITAS

- Our old friends, H.E.S.S., MAGIC and VERITAS are strong, with new results at γ-2022, despite volcano eruptions (MAGIC), COVID-19
  - Initial COVID-19 interruptions overcome with efficient remote operations.
- Operations will continue at least until 2025: Great resource for GRBs, transients, blazar studies
- Large data sets allow long-term studies of spectral characteristics and variability – Several multi-year studies of blazars
- Unbiased study of HBLs, luminosity function studies
- HAWC: Remote operations during COVID-19
  - Creative data transfer solutions – Uber shuttle
- Better analysis "Pass5"
- Three new strong AGN detections: M87, 1ES1215+303, VER J0521+211
- Detection of microquasar jets. Not an AGN, but Galactic microquasar offer the opportunity to understand jets at all scales

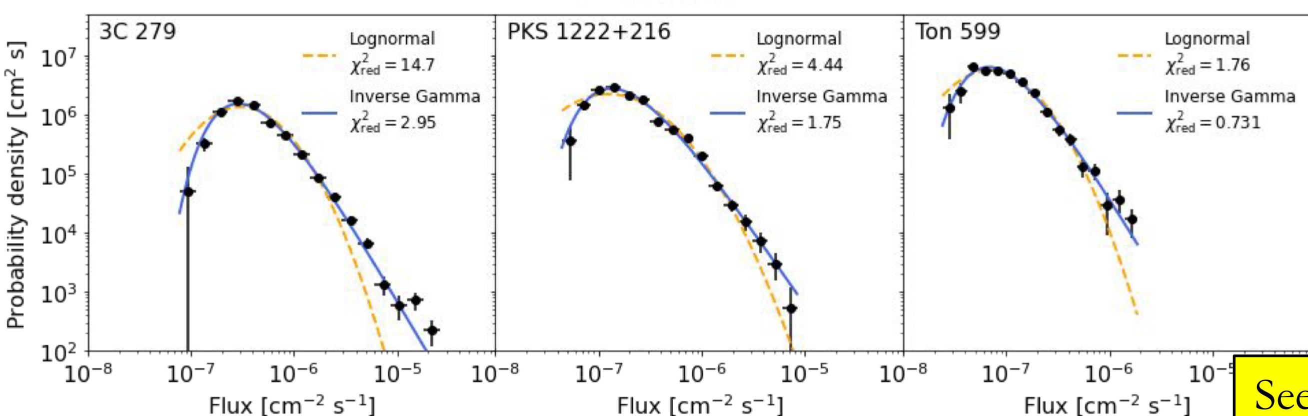
See O, Blanch γ2022 | See S. Wagner γ2022 | See J. Quinn γ2022 | See J. Goodman γ2022

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?

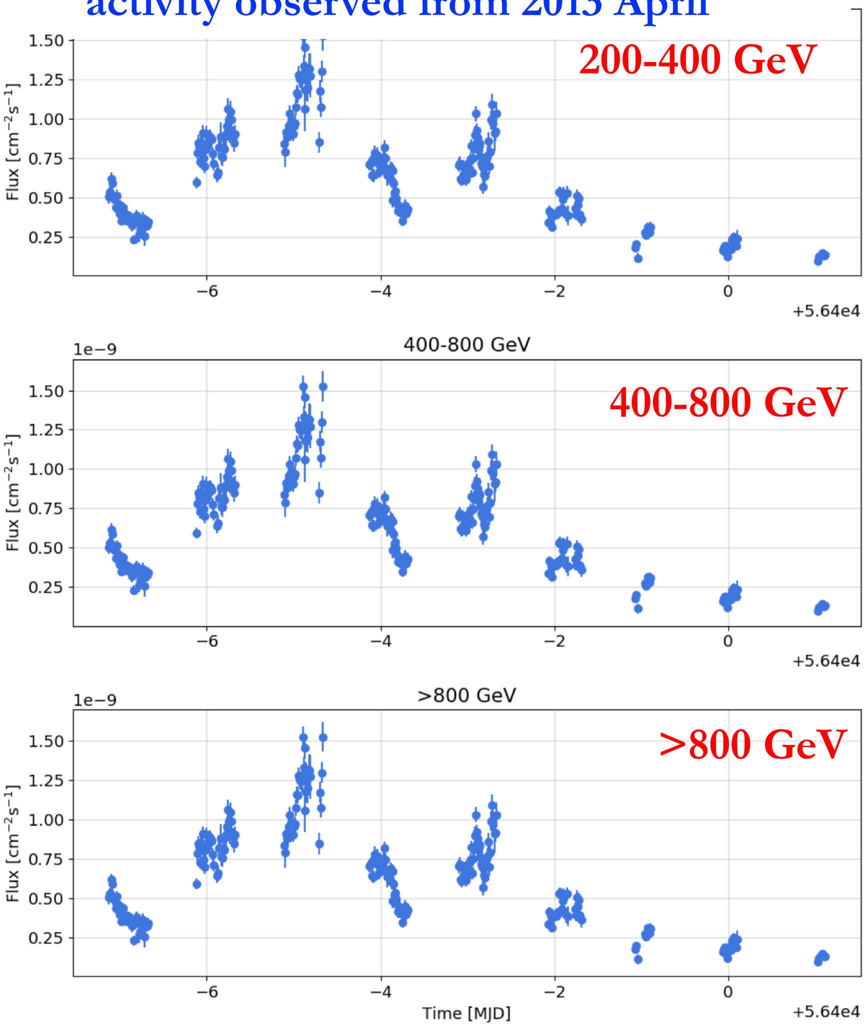


Flux distributions of 3 FSRQs, scaled as probability densities. SDE model of Tavecchio et al. (2020)

See A. Brill Poster γ2022

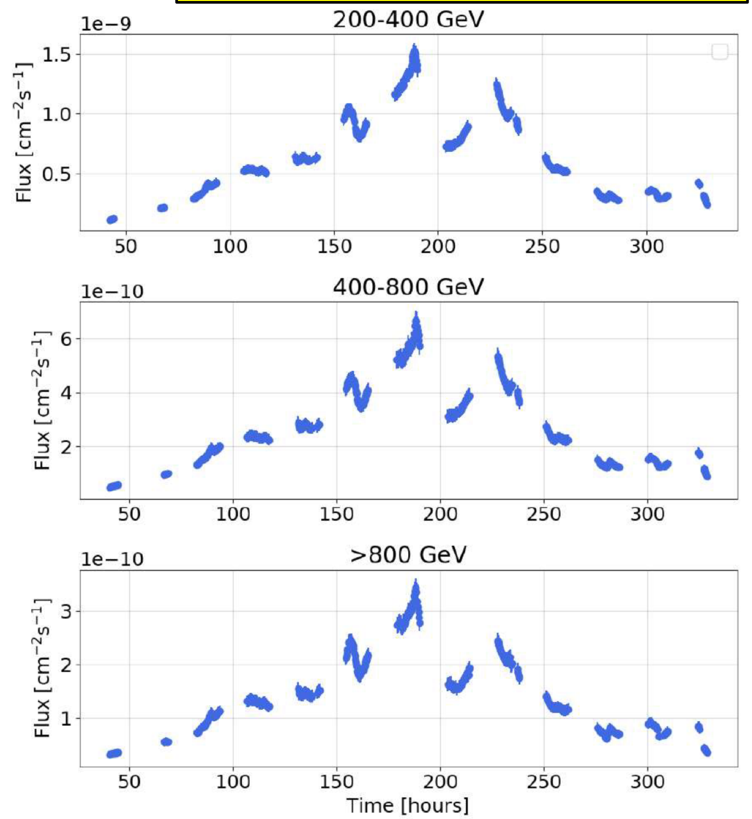
Magnetic Reconnection? Very Fast γ-ray Flares

Mrk 421 during an exceptional flaring activity observed from 2013 April



Acciari et al. 2020

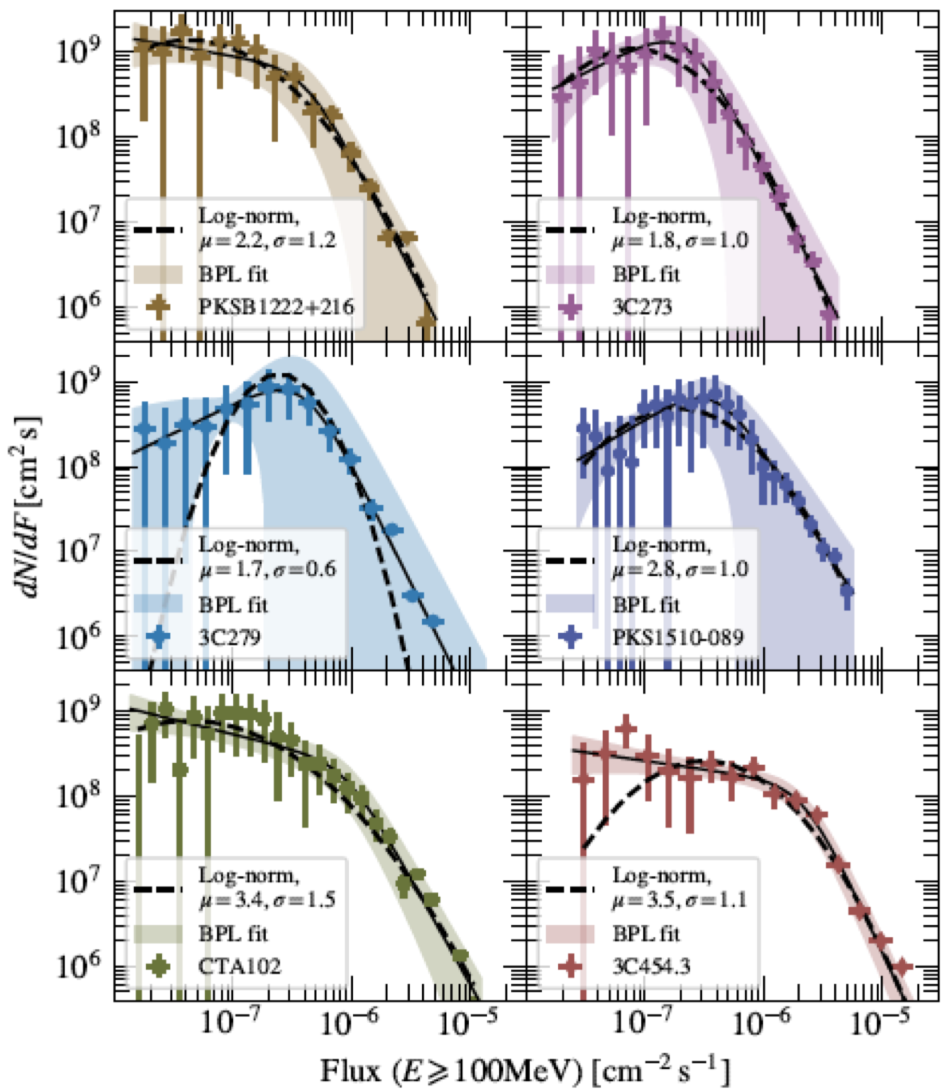
See J. Jormanainen γ2022



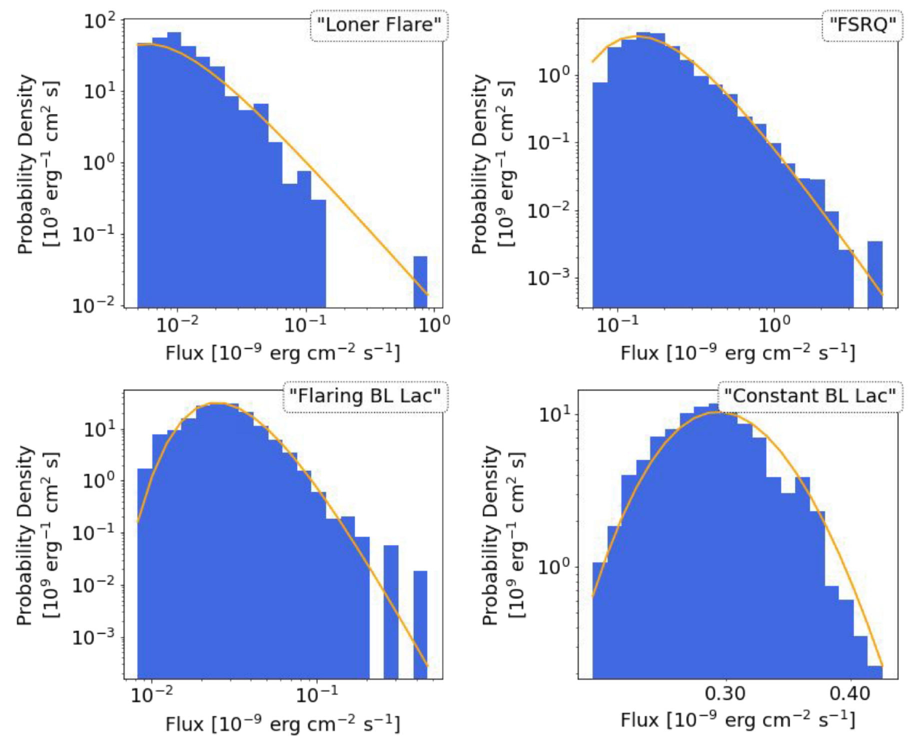
- Origin of short-duration flares is unknown
- Short flares could be due to plasmoids that produce flares with characteristic duration
- Sims being carried out for Fermi-LAT flares

Characterizing Very Fast γ-ray Outbursts

Meyer, Scargle, Blandford 2020



What causes stochastic multiwavelength variability in blazars?



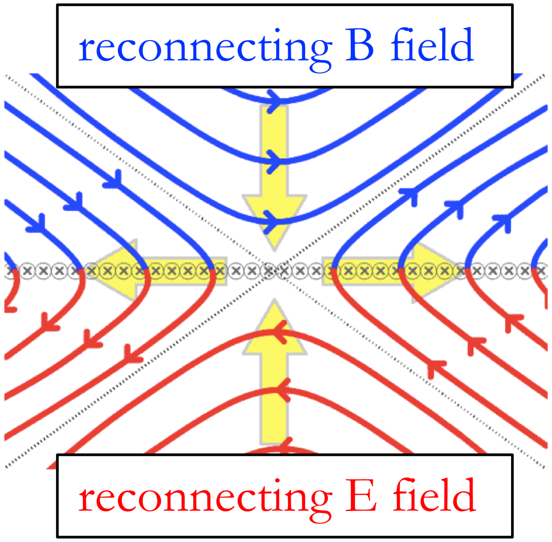
Flux distributions of simulated light curves for different types of blazars

See A. Brill poster γ2022

Relativistic Reconnection Models

Relativistic reconnection can:

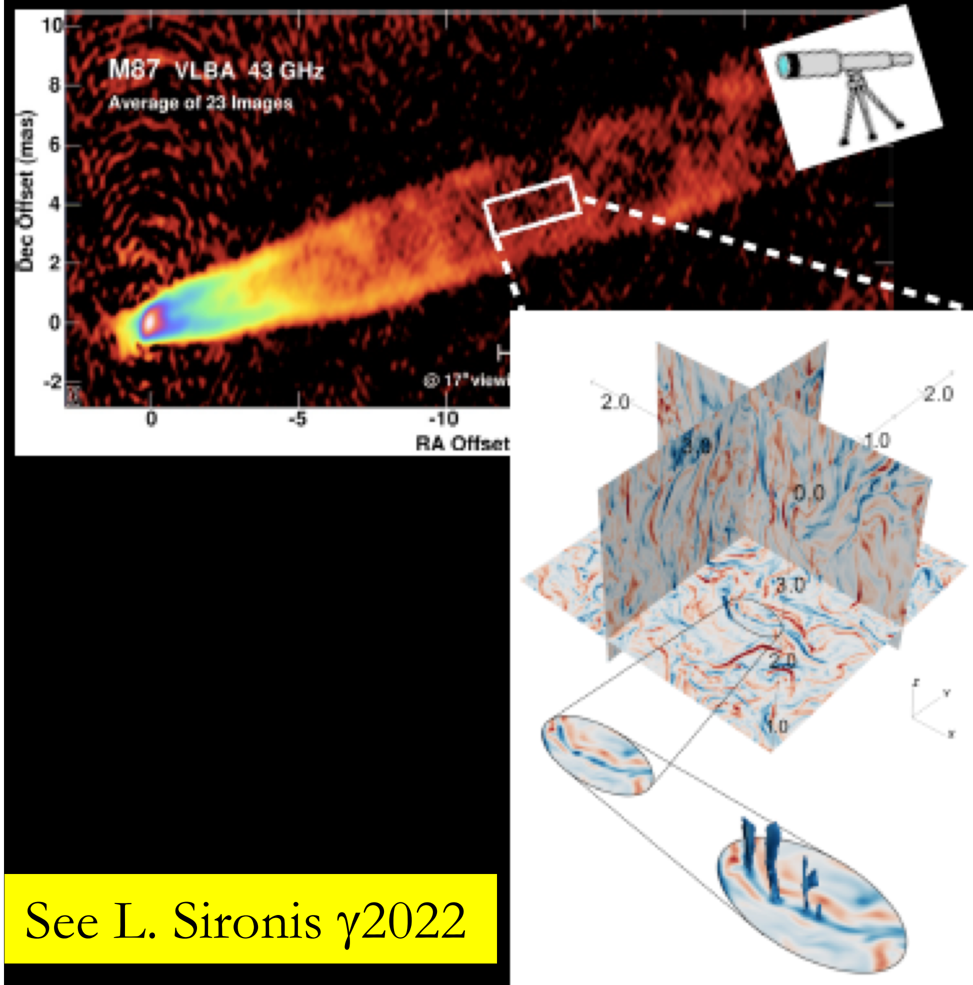
- Dissipate magnetic energy efficiently (at rate ~ 0.1 c).
- Produce non-thermal particles with hard power-law slopes.
- Serve as injection process for subsequent (non-reconnection) acceleration: e.g., Fermi acceleration at shocks, stochastic acceleration in turbulence, shear acceleration at jet boundaries.
- 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

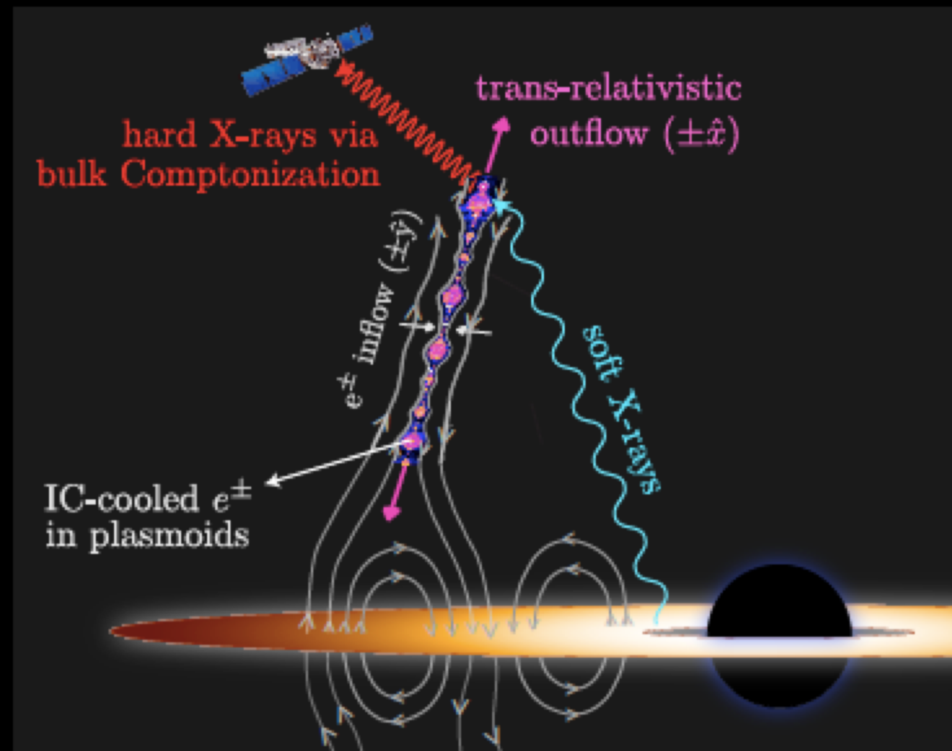
Turbulence + reconnection in blazar jets



See L. Sironis γ2022

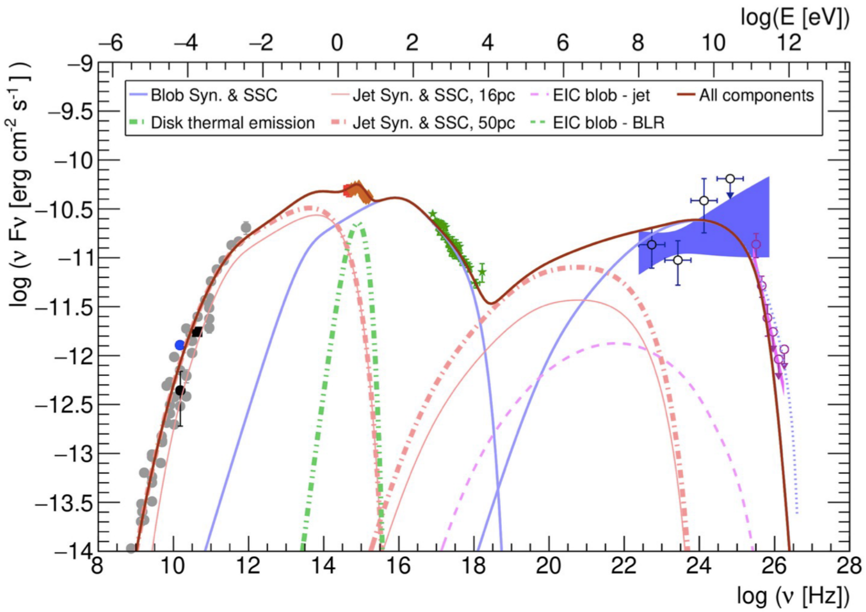
- non-thermal particles with hard power-law slopes.
- “orphan” gamma-ray flares (due to pitch angle anisotropy).

Radiative relativistic reconnection in BH coronae



- cold plasmoids moving at trans-relativistic speeds.
- plasmoid chain Comptonization with effective temperature ~ 100 keV.
- hard state spectra of X-ray binaries.

Blazar SED Modeling



See O. Hervet

OJ 287, complex blazar with X-ray jet and binary black hole system

Feb 2017 flare in TeV, coincident with radio knot ejecta: Variability can be explained by an abrupt change of the blob's Doppler factor (19 → 27)

Locating the blazar γ-ray zone from astrometric VLBI and Gaia data? See H. Sol

Revisiting particle acceleration at ultra-relativistic shocks, in AGN, GRBs (GRB 190829A): See Z. Huang

A shock-in-jet synchrotron mirror model – applied to 3C 279 orphan γ-ray flare: See M. Boettcher

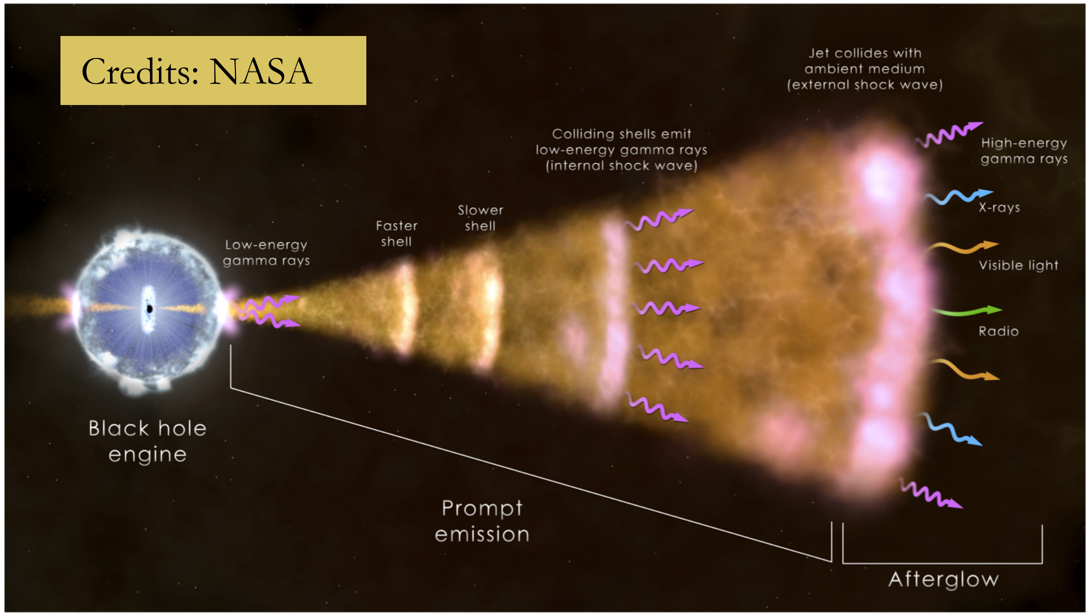
Several talks and posters on Relativistic MHD & PIC simulations

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**

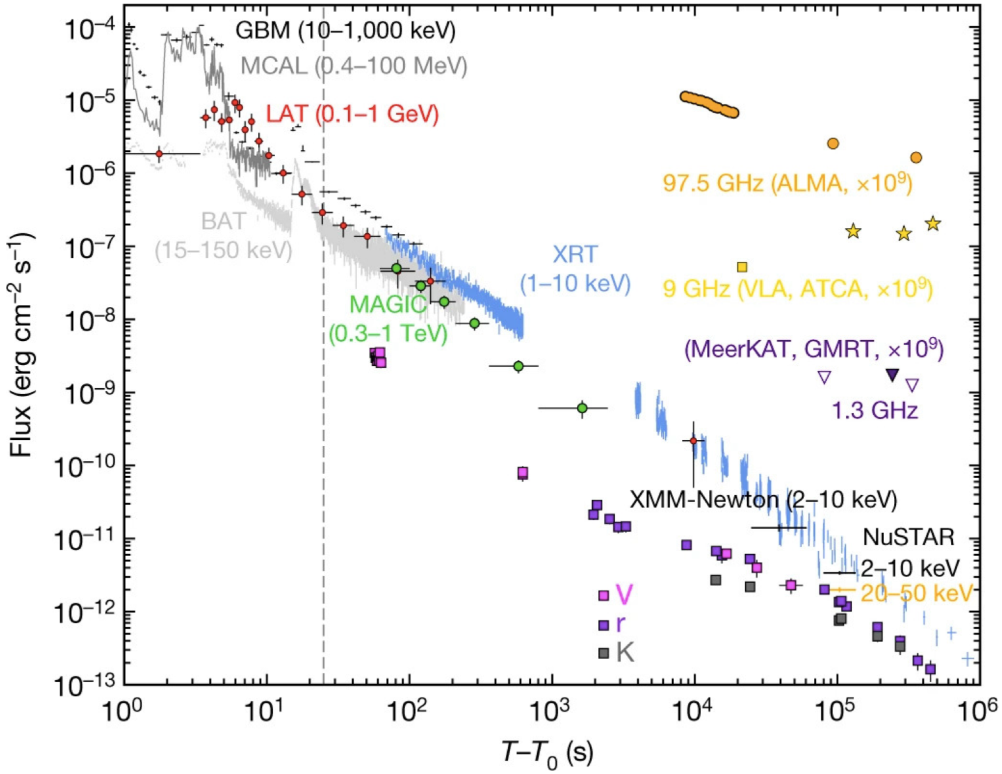
GRB 201216C(MAGIC Coll. ICRC021, S.Fukami)

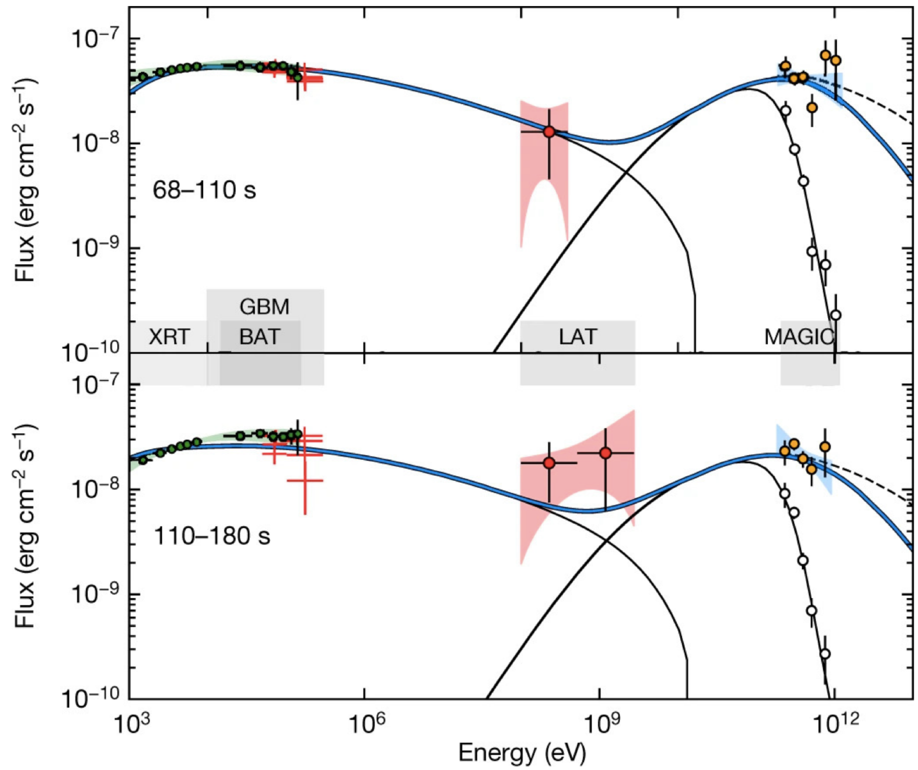
- long GRB, **z=1.1**
- for 20' after T0+

GRB 190114C

First GRB detected at VHE energies: 50 σ detection!

See D. Khangulyan,





Bright late prompt emission, early afterglow emission

Photons detected above the synchrotron burn off limit

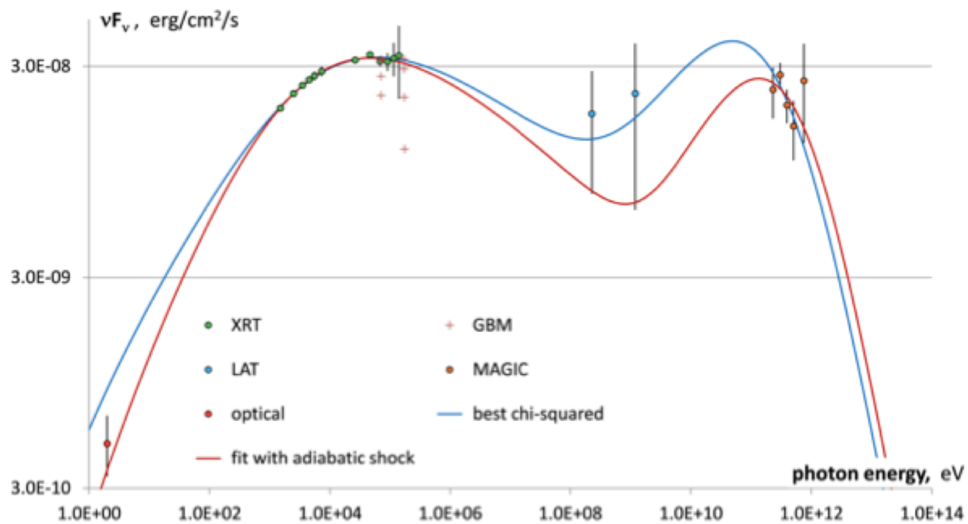
VHE and X-ray fluxes have a similar (not identical) time evolution

Evidence (or at least hints) for a two-component SED

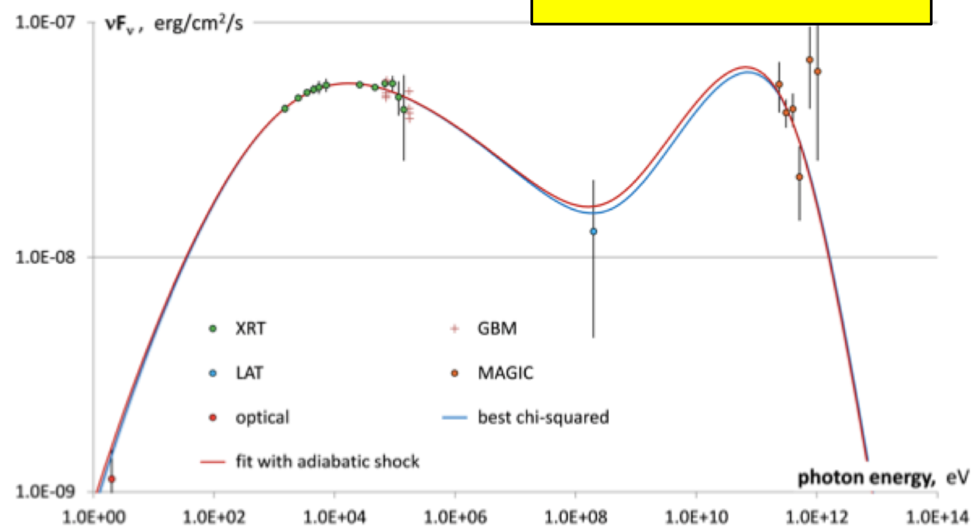
Understanding TeV Emission from GRBs

GRB models – Afterglow emission: Need to deal with degeneracies

See T. Piran



Early – 90 sec



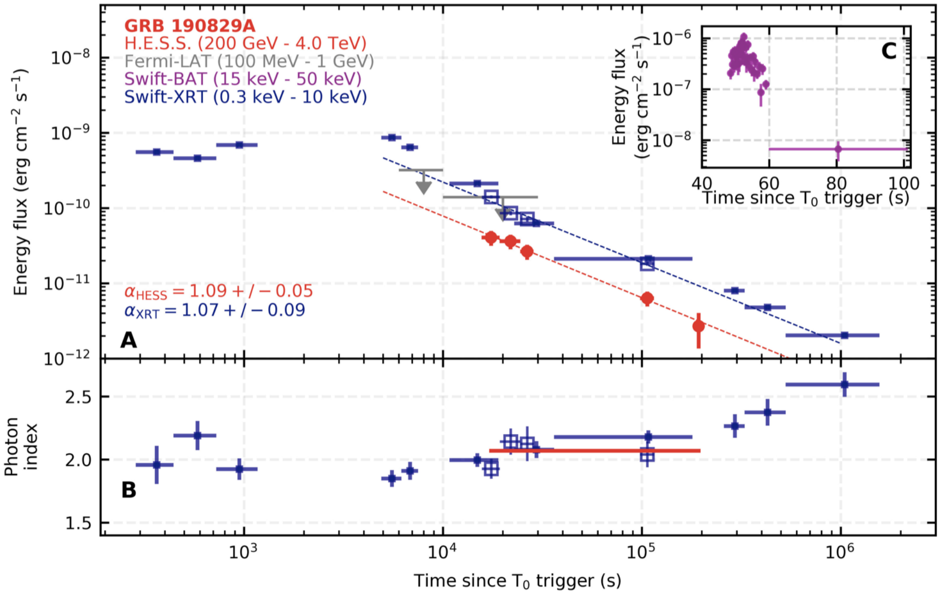
Late – 145 sec

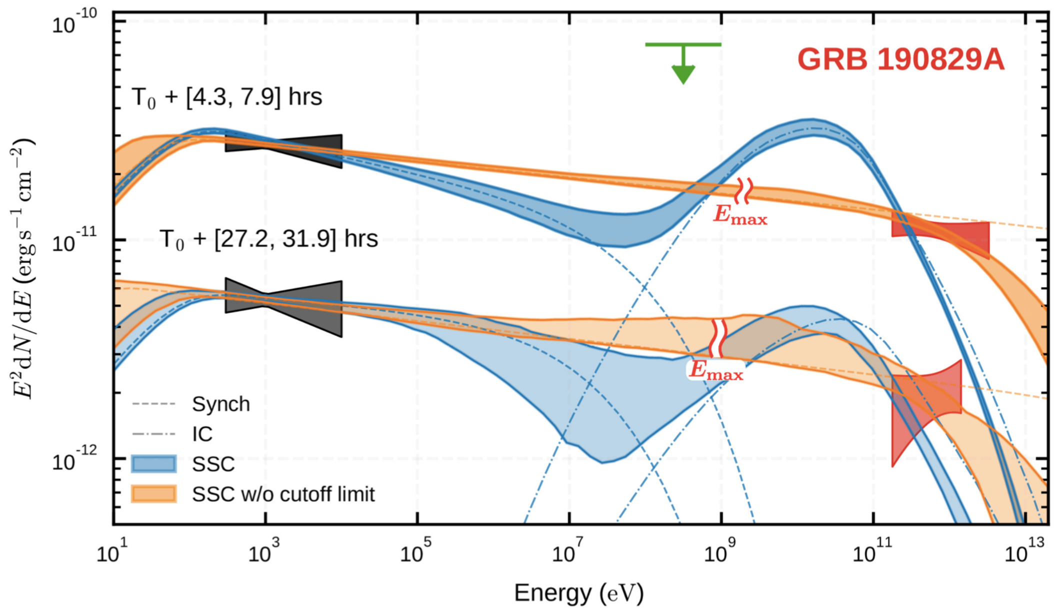
- New numerical fit from optical to sub-TeV suggests fast cooling regime.
- **"TeV observations of both early and late 190114c seems to require significant modification of the simple afterglow model. -- consistent with the "Pair Balance model".** (arxiv.org/abs/2106.12035)
- Also see: Intergalactic magnetic field studies by means of γ-ray emission from GRB 190114C See P. Da Vela

Exceptionally long TeV Emission

GRB 190829A

See D. Khangulyan,





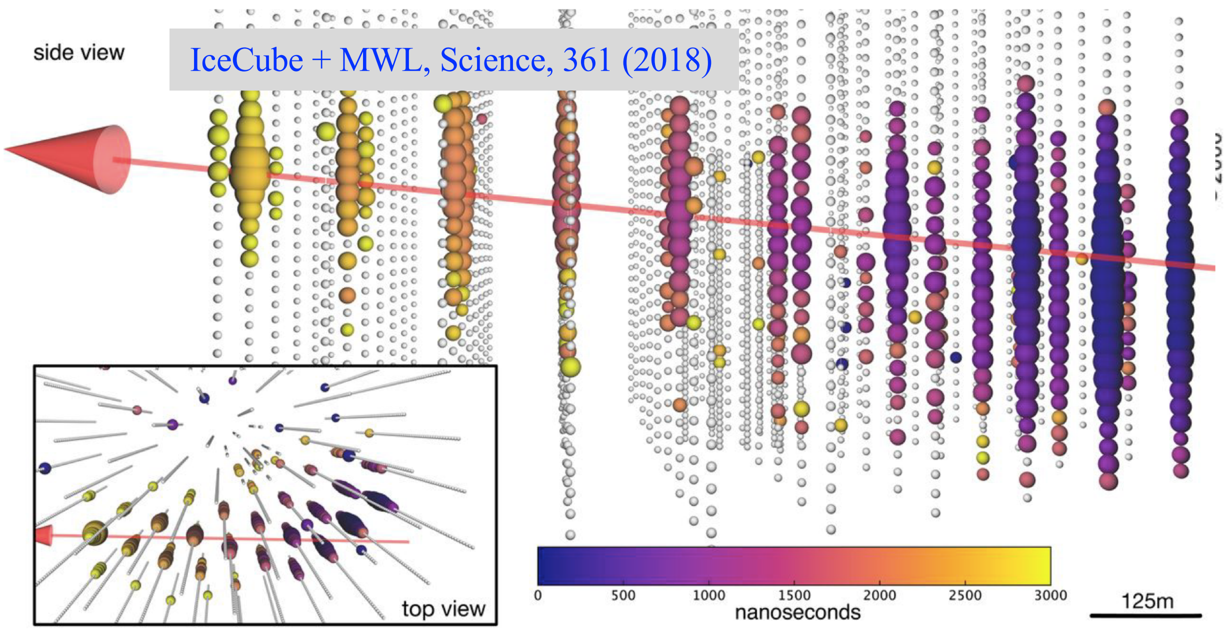
- H.E.S.S. detection exceptionally long: the signal up to 56 h (over three nights)
- Broadband SED γ rays measured between 0.18 and 3.3 TeV
- VHE and X-ray fluxes have a similar time evolution
- Extrapolation of the X-ray spectrum to the VHE domain matches the slope and flux level measured with H.E.S.S.
- **Evidence of 2-component SED? One-zone SSCmodel? Model has to explain X-ray to VHE flux ratio, X-ray & VHE spectral index.**

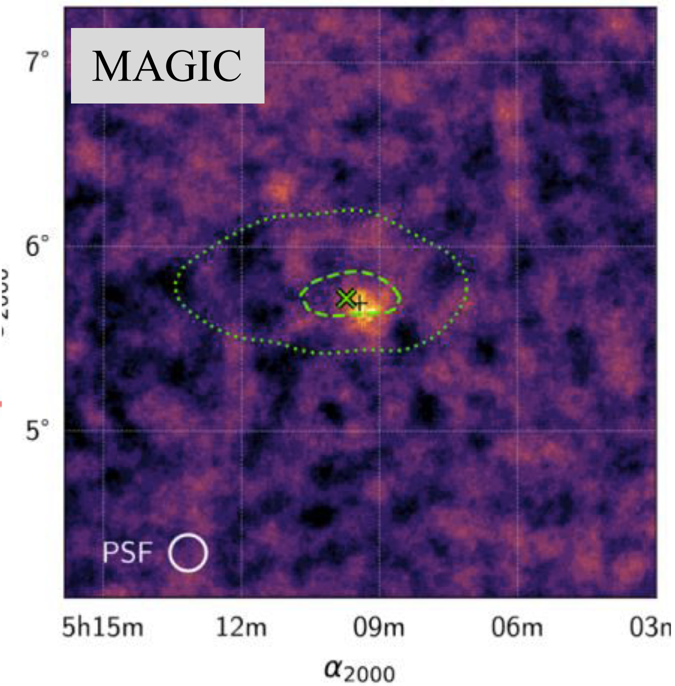
Multimessenger: UHE Cosmic Rays and Neutrinos

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

See E. Resconi γ2022

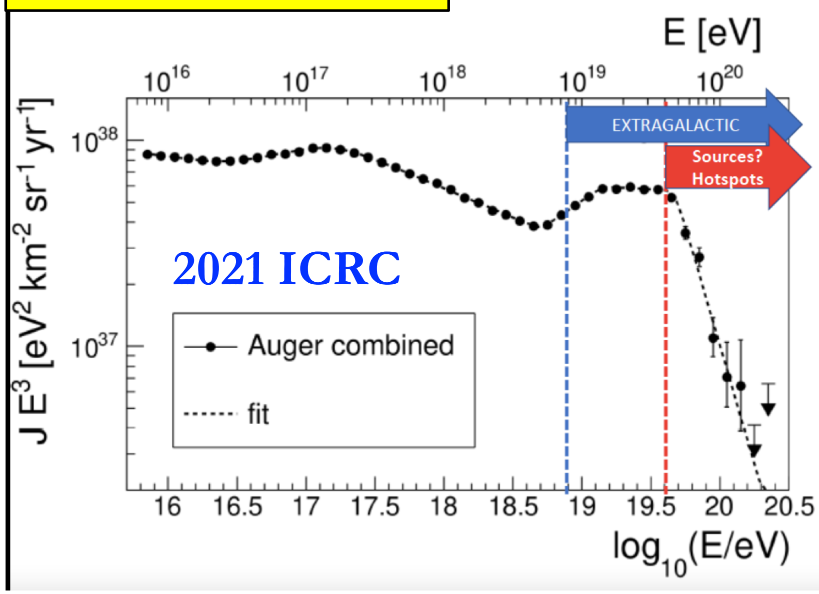
See T. Montaruli γ2022

See C. Bellenghi γ2022

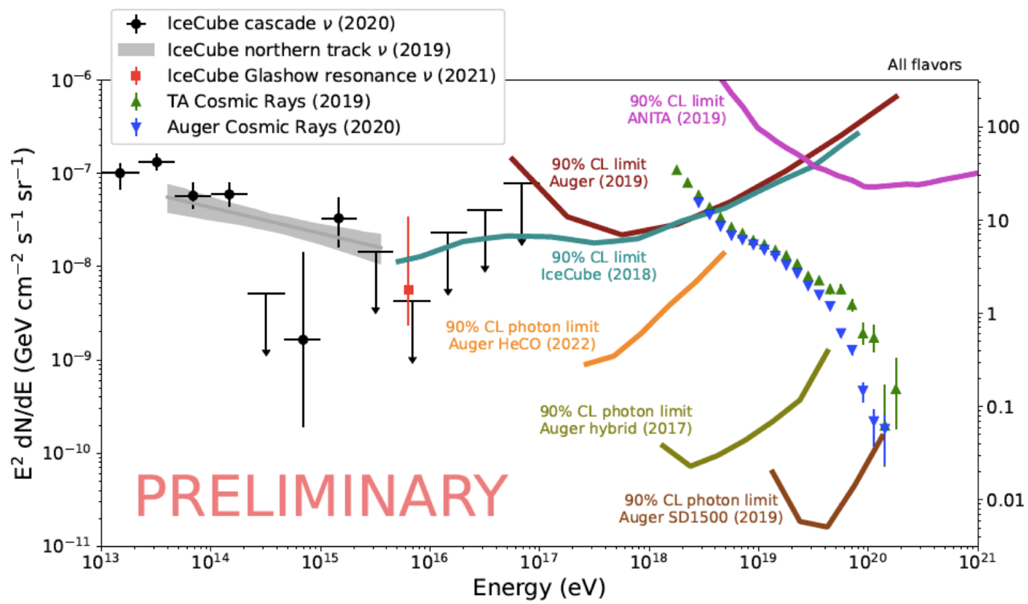
See S. Inoue γ2022

Multimessenger: UHE Cosmic Rays and Neutrinos

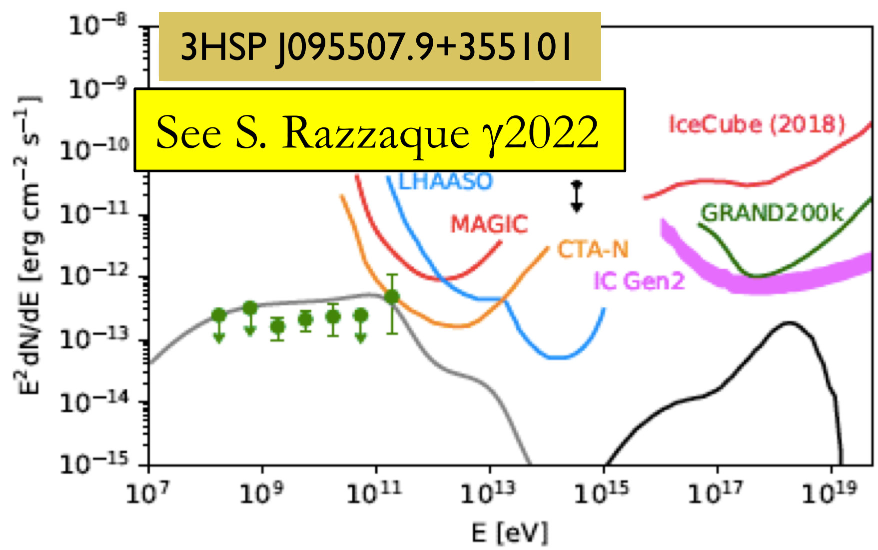
See A. Olinto γ2022



Limits on Neutrino and Gamma-Rays at UHE

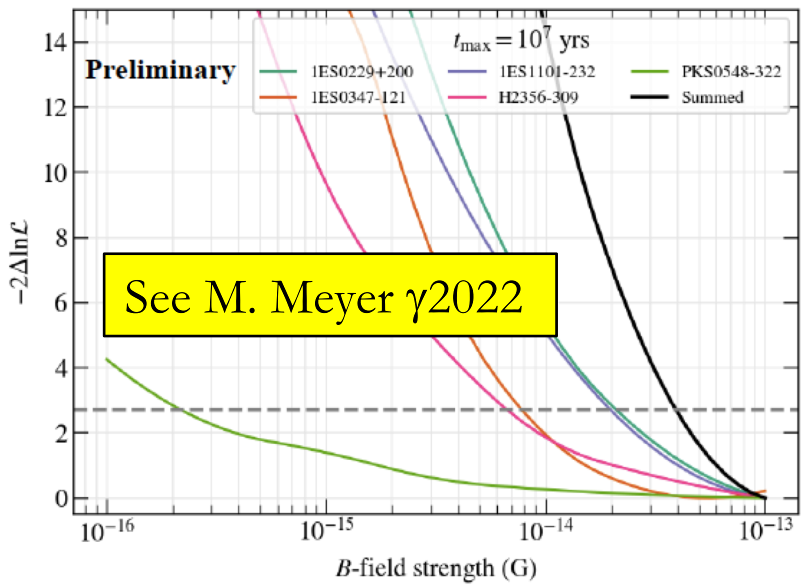


- Detection of PeV neutrinos from blazars implies acceleration of cosmic rays to ≥ 10 PeV
- Blazars are plausible candidates for UHECRs, capable of accelerating particles to 10^{20} eV
- Fits to SEDs of a few gamma-ray blazars can be improved with LoS γ-ray fluxes together with conventional source SED models

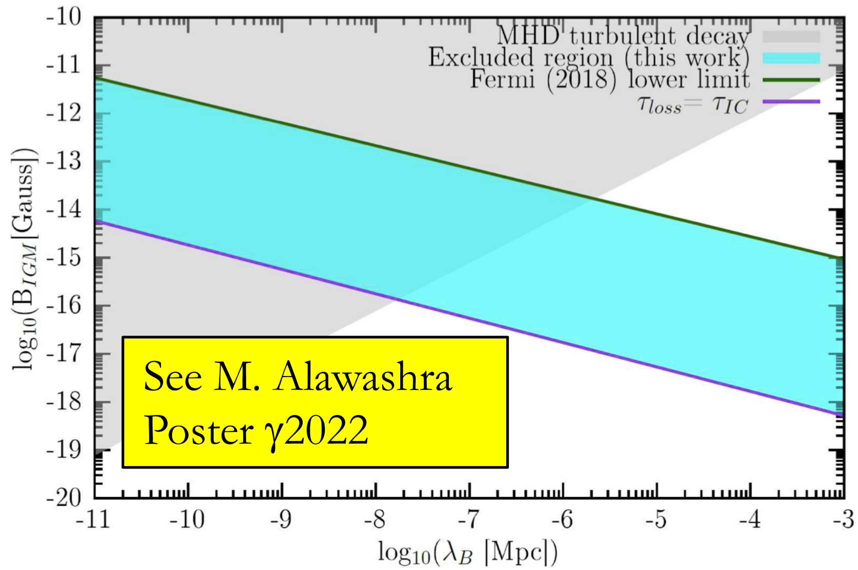


Archival Data (15+ Years)

Probing the intergalactic magnetic field
- H.E.S.S. & Fermi-LAT



CRPropa3 sims used to generate realistic cascade templates: Previous constraints improved by factor ~2



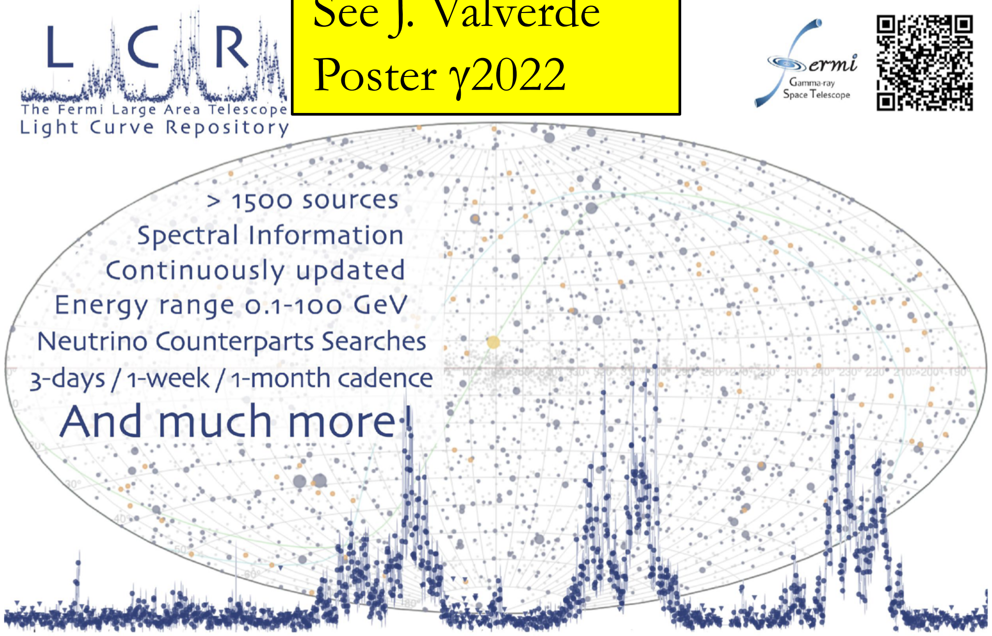
Suppression of the TeV pair-beam plasma instability by a tangled weak intergalactic magnetic field

Luminosity function studies of γ-ray blazars

- Using 8+ years of Fermi-LAT data on blazars above 100 MeV: density, evolution and origin of the Extragalactic Gamma-ray Background See L. Marcotulli γ2022
- Using 10+ years of VERITAS HBLs to produce first unbiased census of TeV emission from HBL blazars See M. Errando γ2022

Large Data Sets & Repositories & Tools

See J. Valverde Poster γ2022



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/lcr/

github.com/dankocevski/LightCurveRepository

See A. Sinha γ2022

- Flexible, open source, community driven python library
- Joint likelihood fits, spectral analysis …
- > 11 contributions at γ2022

See C. Nigro Poster γ2022

agnpy: An open-source python package modelling the radiative processes of jetted AGN

Extragalactic Astrophysics in the Future

Gamma-Ray Instruments

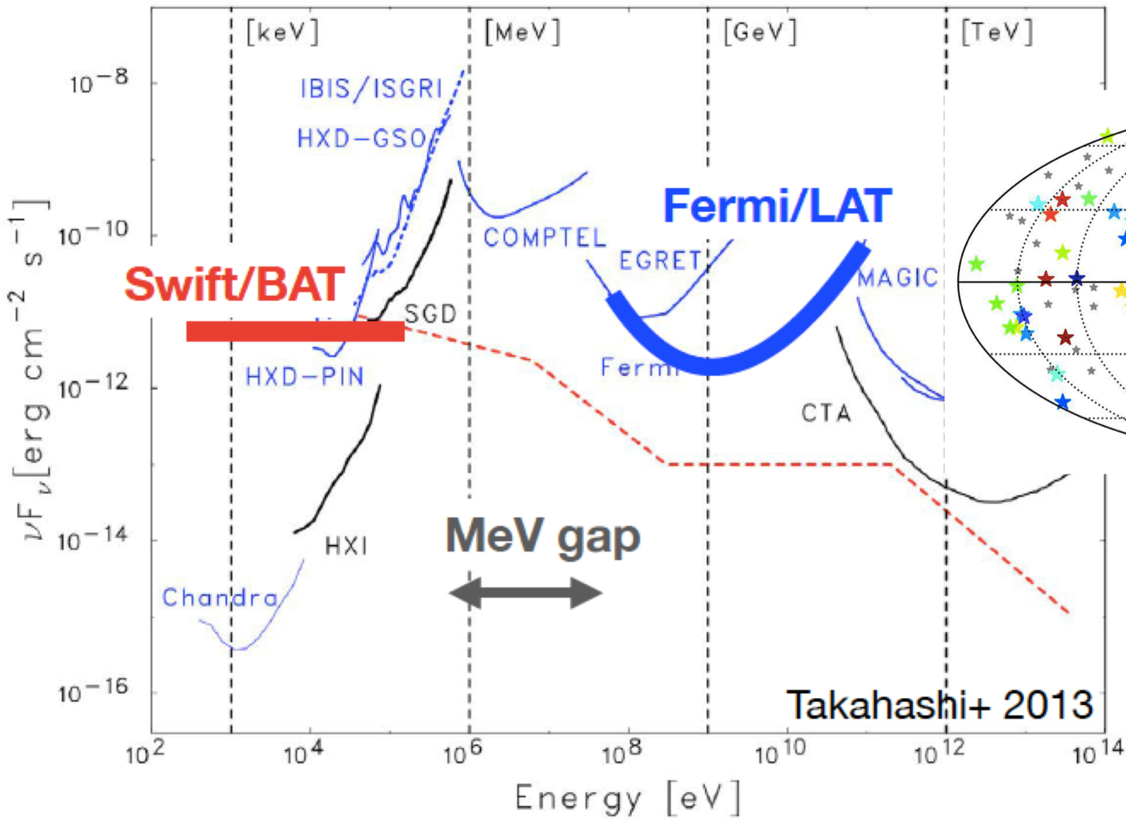
in the next decade

- LHAASO See Z. Cao
- SWGO See J. Hinton
- CTA See P. Caraveo & LST See J. Cortina
- ASTRI See A. Giuliani

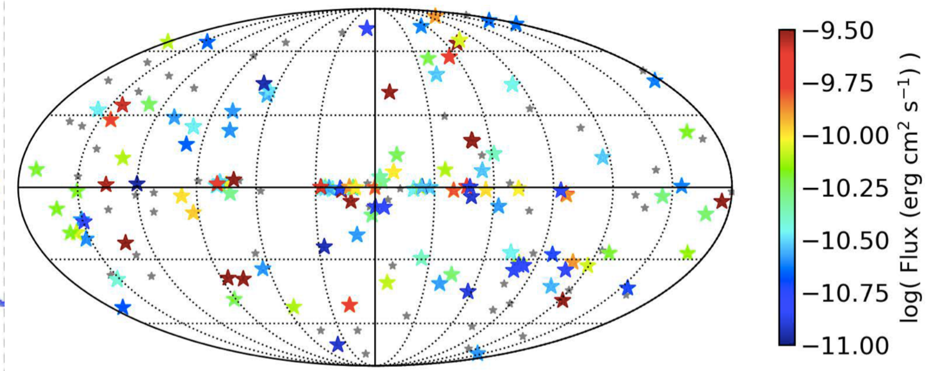
in synergy with X-ray instruments

- IXPE (Imaging X-ray polarimeter): simultaneous observations of X-ray polarization and TeV emission to determine the intensity and geometry of magnetic fields in relativistic jets. See M. Errando Poster γ2022
- eROSITA
- NuSTAR

10 MeV – Compton regime



See N. Tsuji



Potential MeV sources

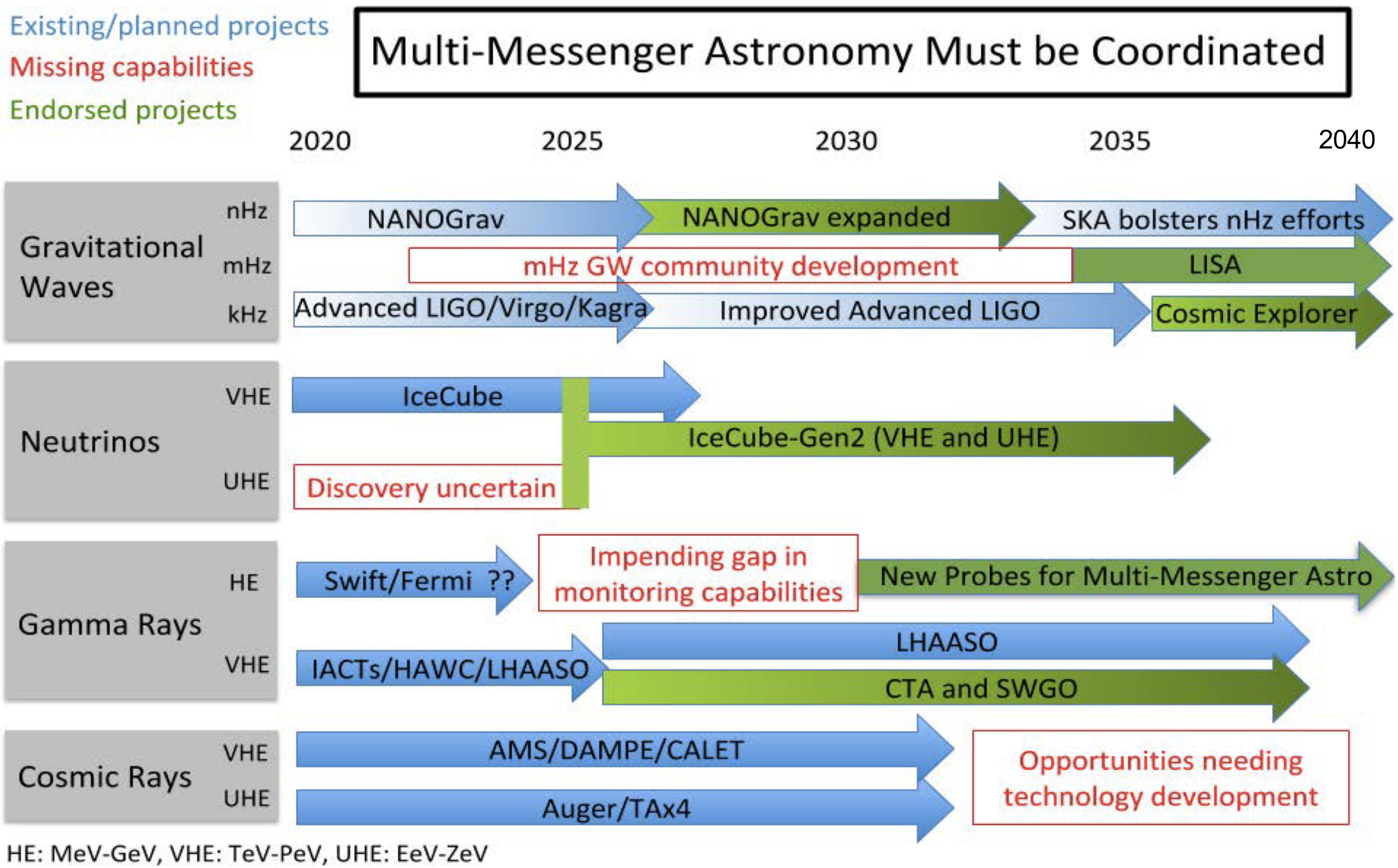
The Future of Gamma-Ray Experiments in the MeV-EeV Range,
Snowmass Whitepaper arXiv:2203.07360

- Good coverage in the Swift-BAT & Fermi-LAT, but significant MeV "gap" -- No dedicated mission since Comptel.Several potential MeV blazars
- Future: ? COSI, Amego-X, HERD, several other proposed missions

See T. Montaruli

Astro2020 Decadal Survey:

Continuity of Multi-messenger Capabilities



Concluding Remarks

We now have a rich extragalactic database of sources.

We have gone beyond source counts. Detailed spectral, morphological and temporal studies of TeV sources are possible. We will continue to build photon statistics and carry out unbiased monitoring of sources.

We have entered the temporal domain, detecting fast TeV flares and **GRBs for the first time at TeV energies**. Source counts of GRBs are still low, but we should expect to see more in the future.

We should expect to see progress in our understanding of jetted AGN: Sophisticated attempts in modeling observational data in the temporal domain are underway – orphan flares. Better understanding of fast variability will come from advances in simulations and theoretical studies.

Thank you for many exciting new results and hope to see you in γ2024!

BACKUP