CTA大口径望遠鏡初号機によるブレーザーの観測：マルチメッセンジャー天文学時代のブレーザー観測戦略

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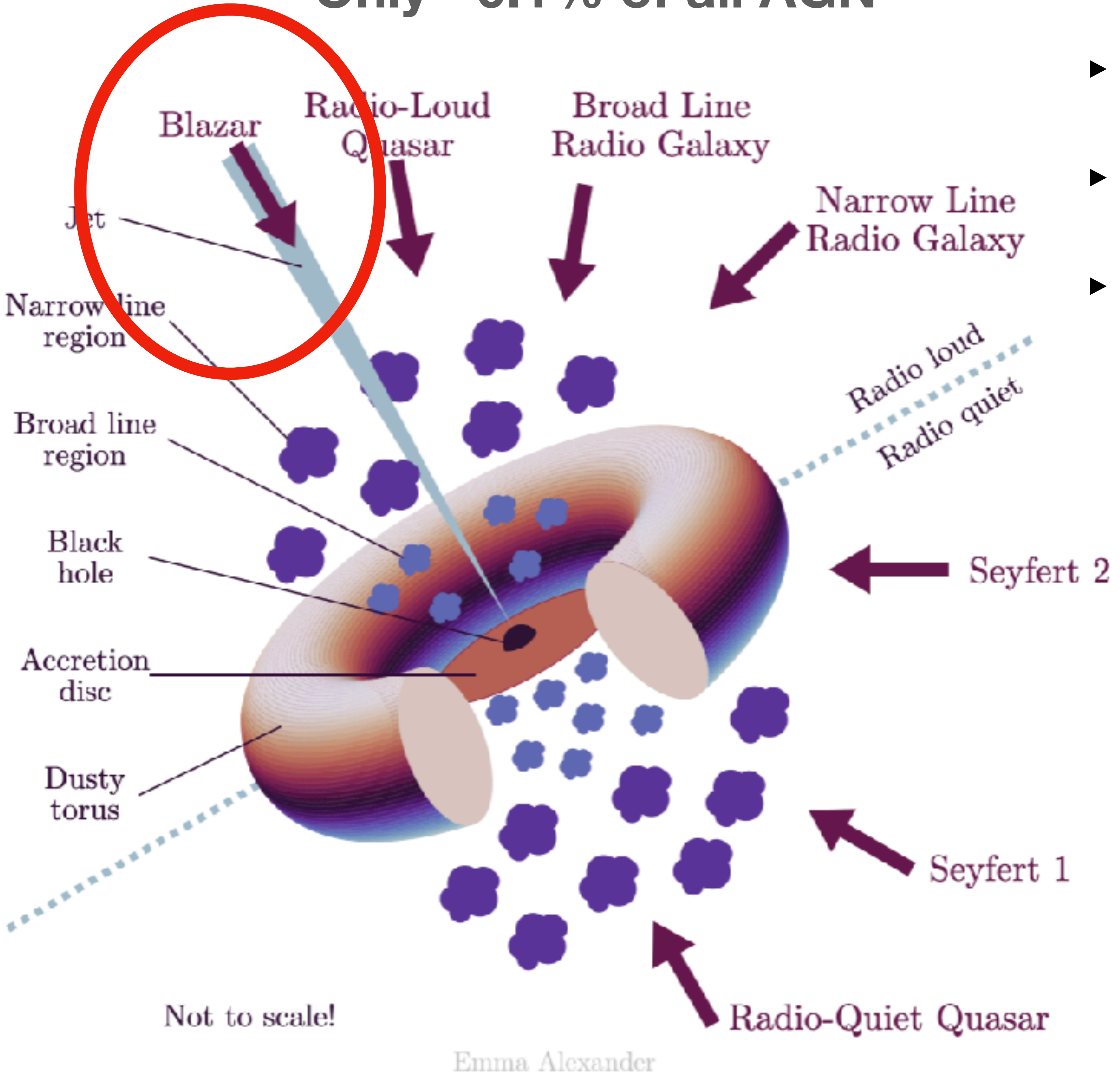
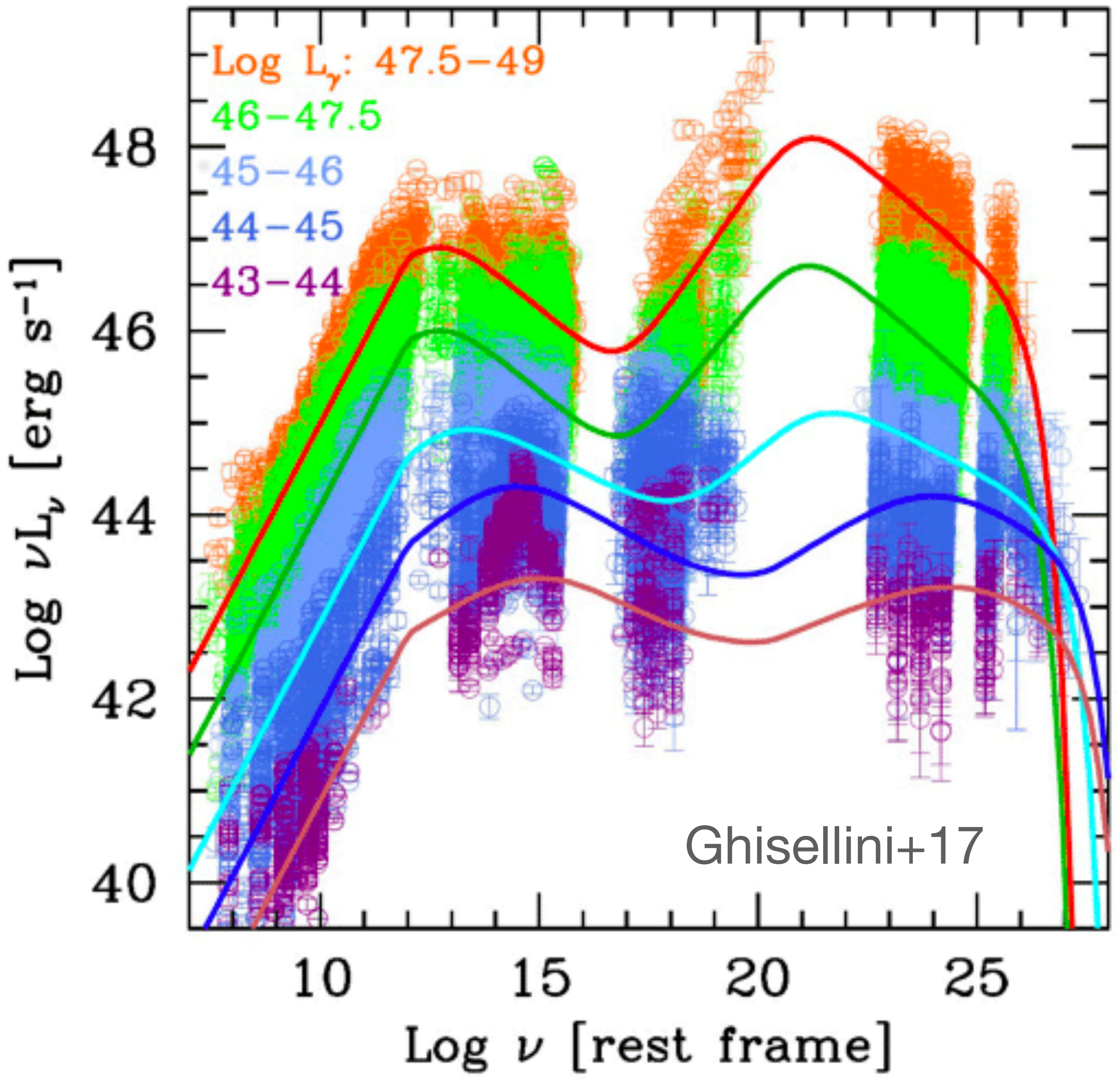
On Behalf of the CTA-LST Project

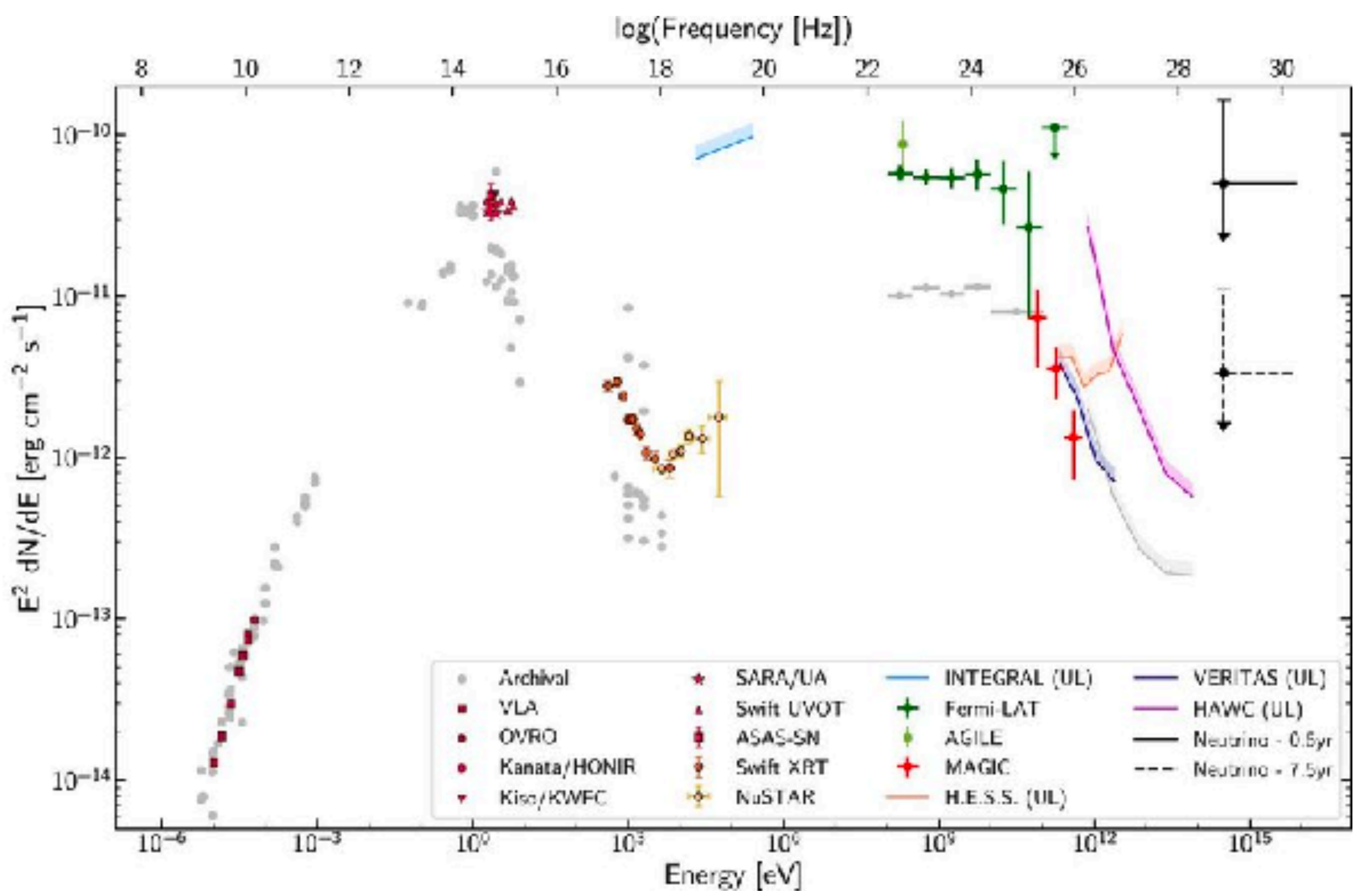
Blazars: Active Galactic Nuclei (AGN) jet pointing towards us

Only ~0.1% of all AGN



- Dominates the **HE/VHE extragalactic sky**
- **Significant variability** across the entire EM spectrum
- This talk will focus on **GeV-TeV** in particular as an individual engaged in VHE experiments (Cherenkov Telescope Array, CTA)



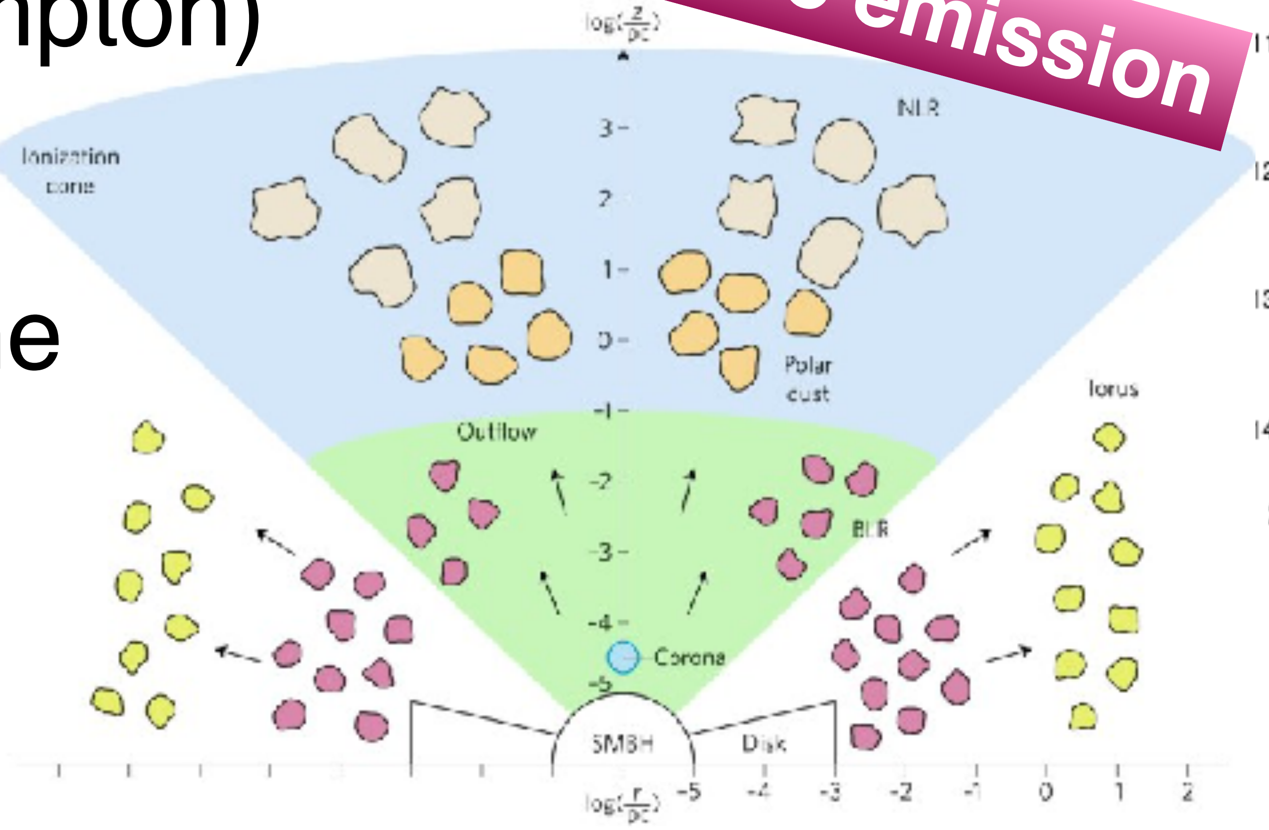


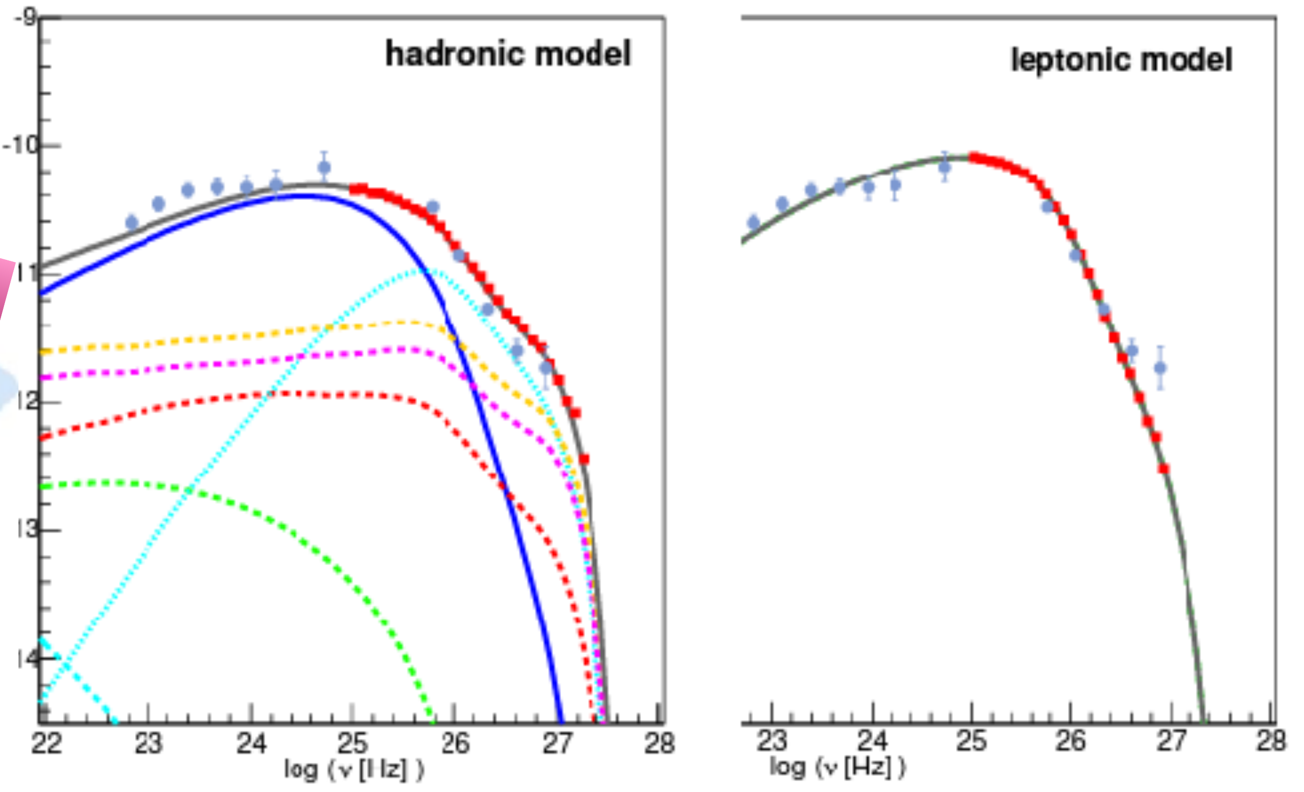
IceCube2018

What do we anticipate elucidating through the observation of blazars?

- **Astrophysical studies**:
  - Leptonic (Synchrotron Self-Compton, External Compton) or hadronic (Proton synchrotron, Photomeson...)?
  - What is the structure/role of the magnetic field in the jets?
  - Where along the jet HE/VHE emission produced?
- **Cosmological, fundamental physics**:
  - Validation of galaxy and star formation models in the universe (Extragalactic Background Light)
  - Does the intergalactic magnetic field exist?
  - Axion-Like Particle?
  - Towards the Hubble crisis; cosmological parameter measurement

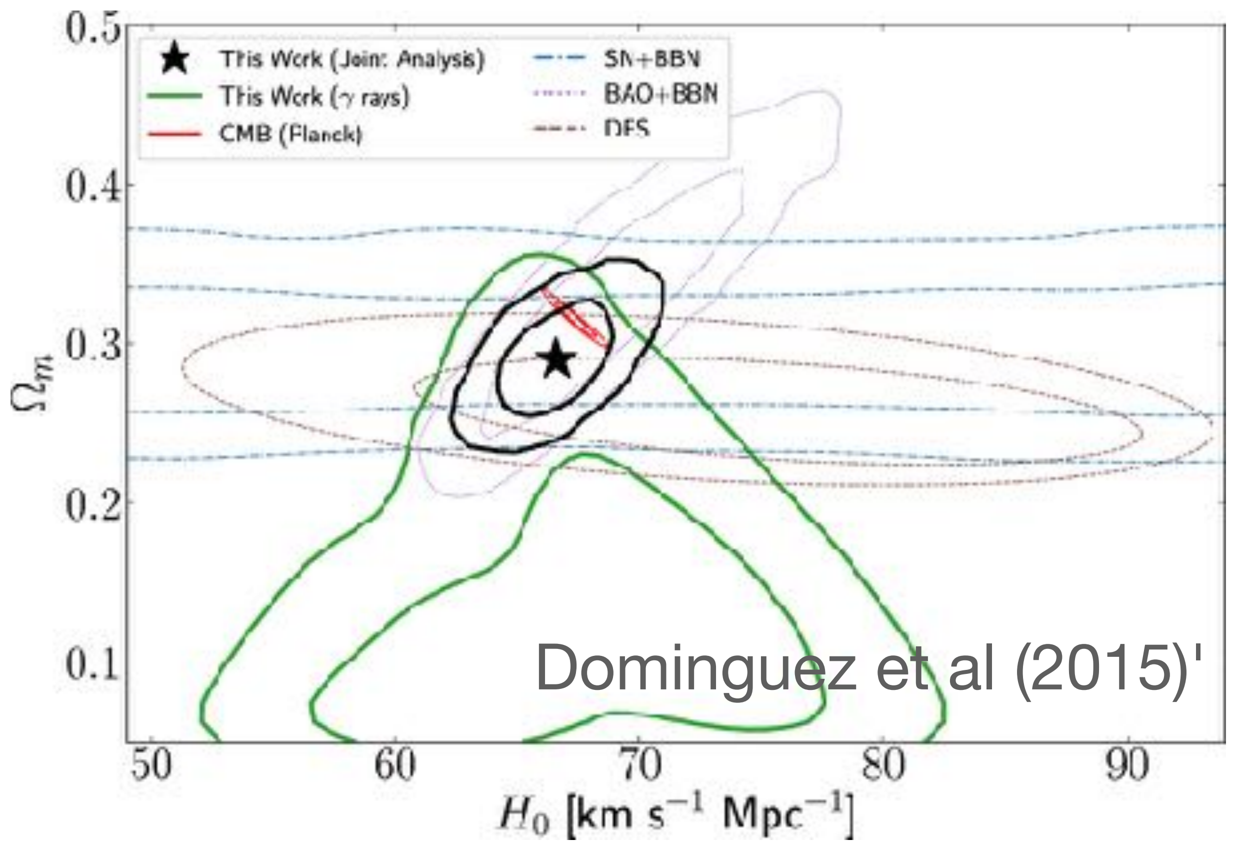
Location of the emission





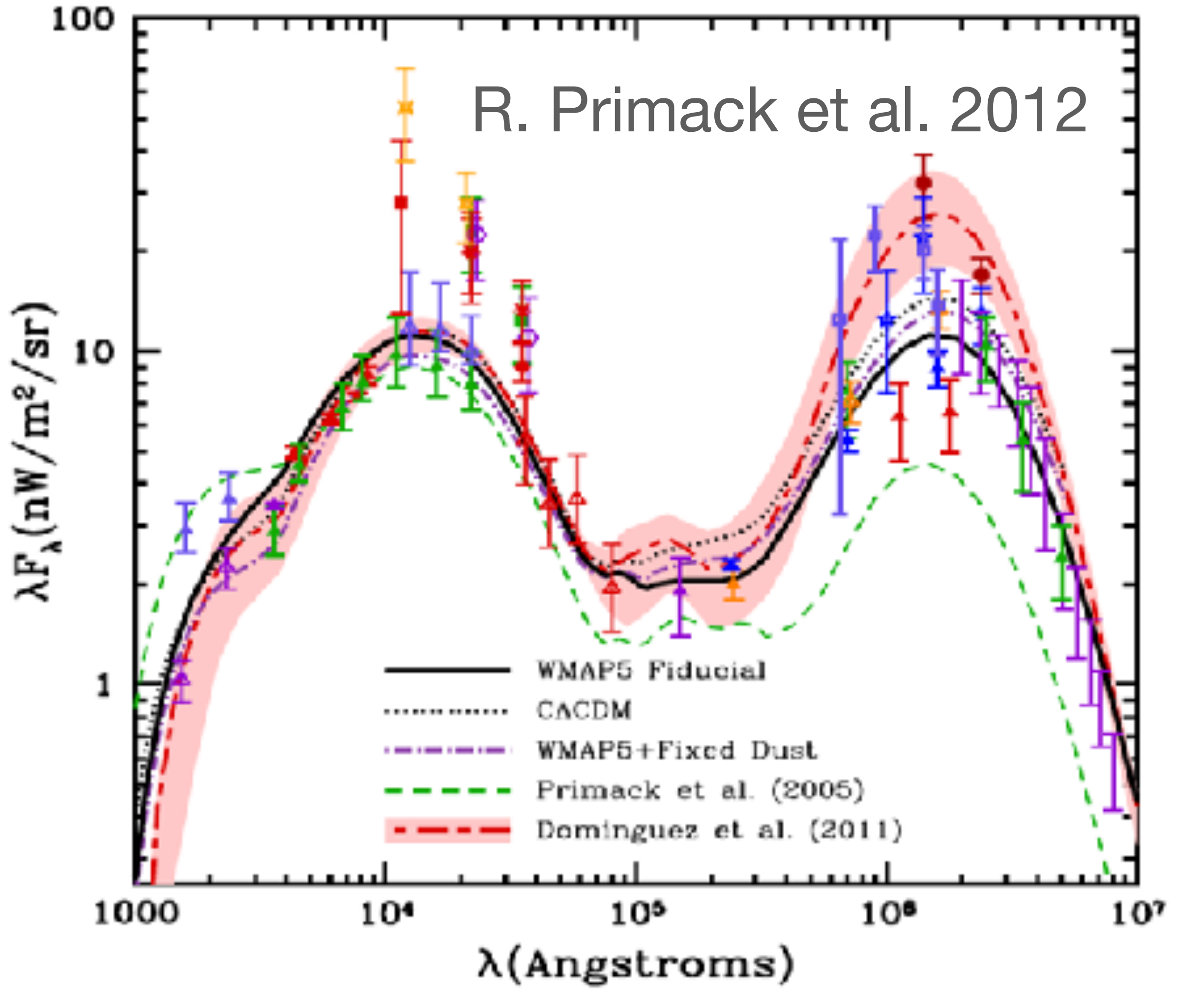
Hadronic vs Leptonic

Measurements of H0,Ωm



Dominguez et al (2015)'

Measurements of EBL



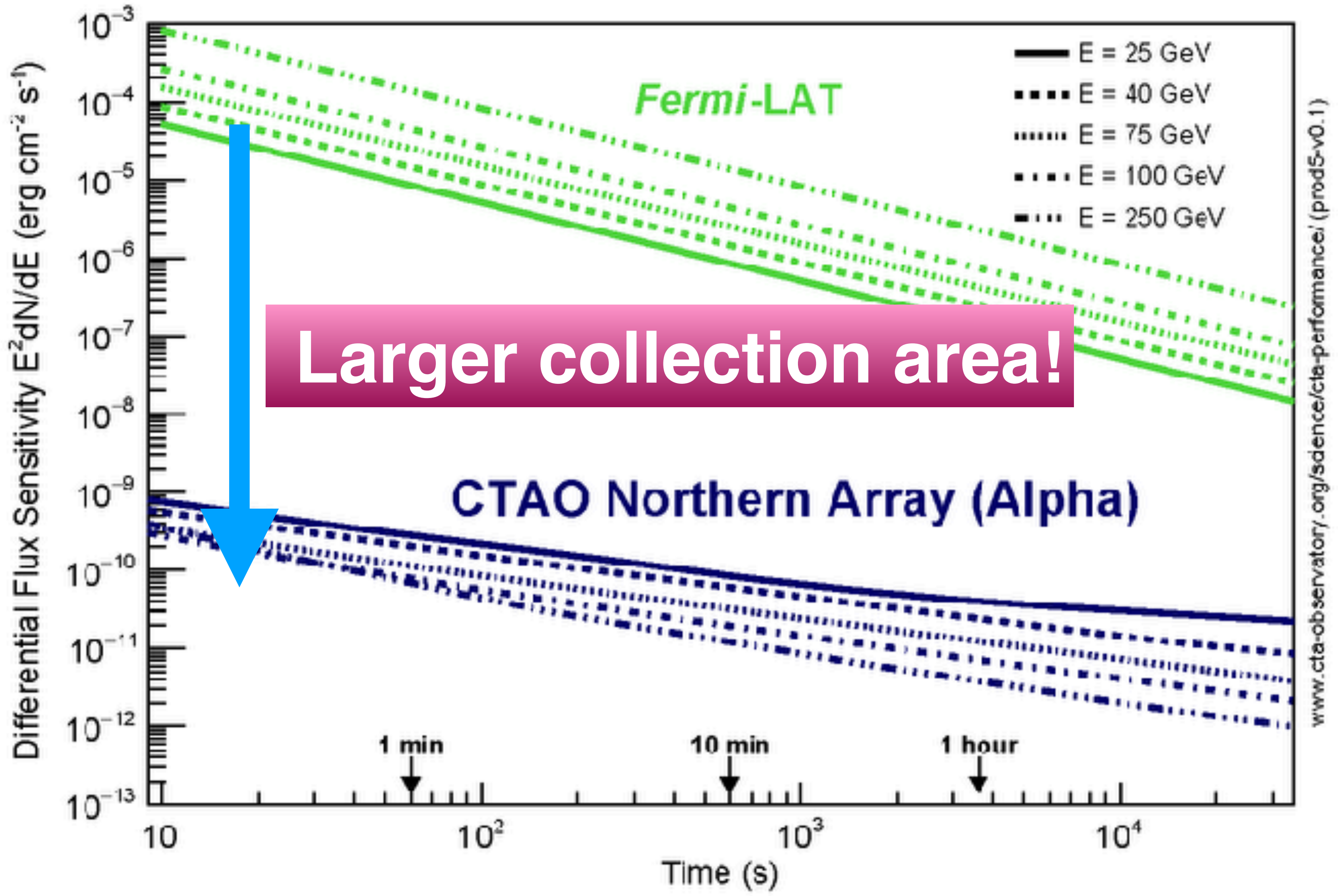
R. Primack et al. 2012

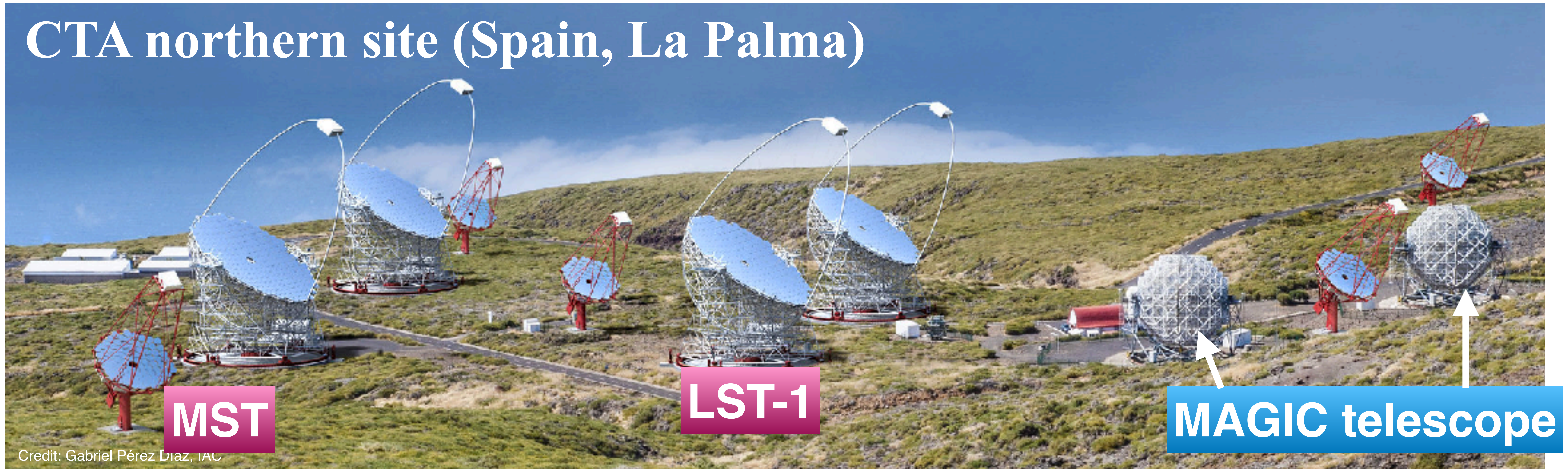
Cherenkov Telescope Array (CTA)

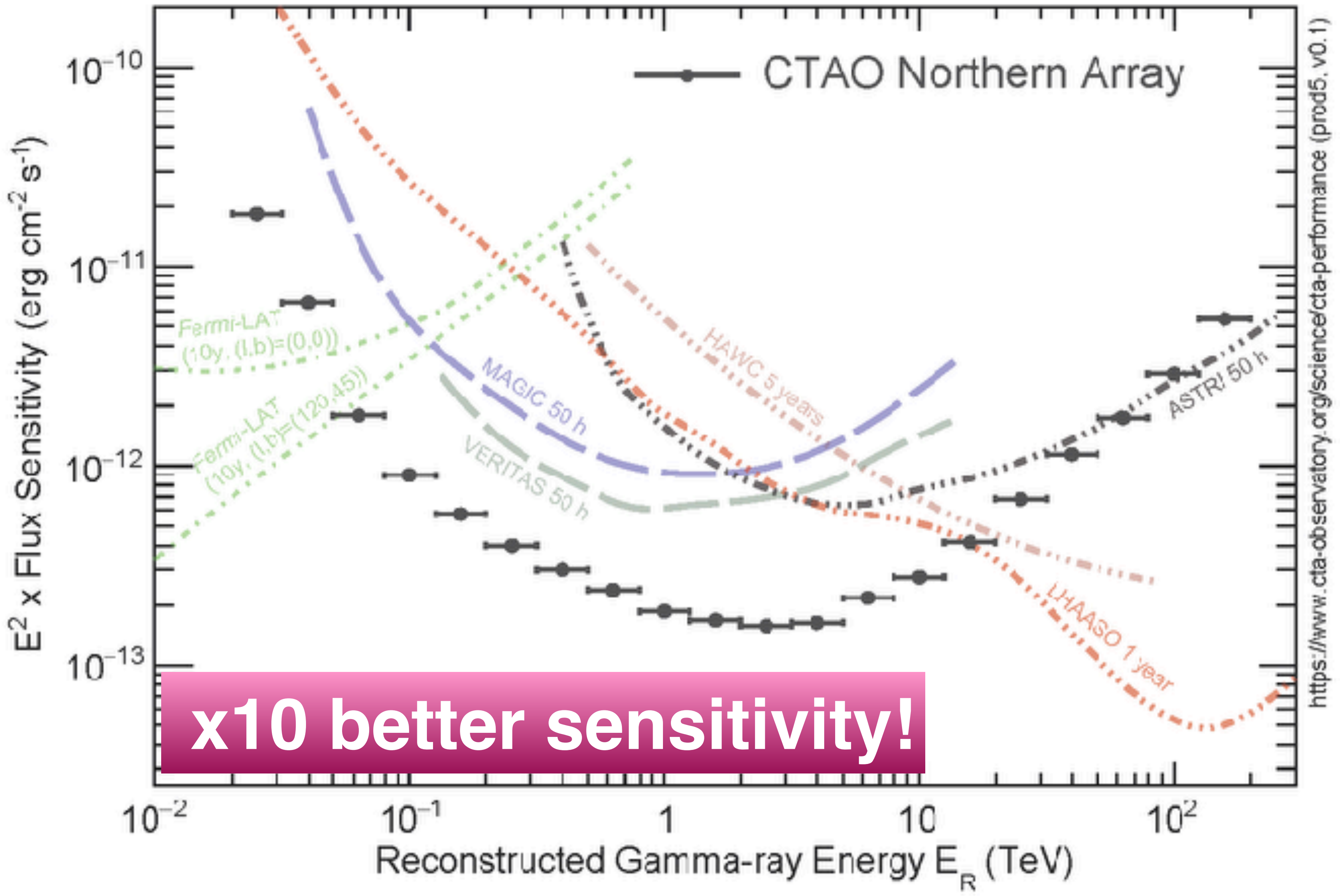
cherenkov telescope array

Next generation ground-based instrument for gamma-ray astronomy at very-high energies

- Located in the northern and southern hemispheres with 71 telescopes
- Northern CTA: 4 Large-Sized Telescopes + 9 Medium-Sized Telescopes
- **x10 better sensitivity + wide energy coverage of 20 GeV-300 TeV**
- LST-1 started observation since 2020



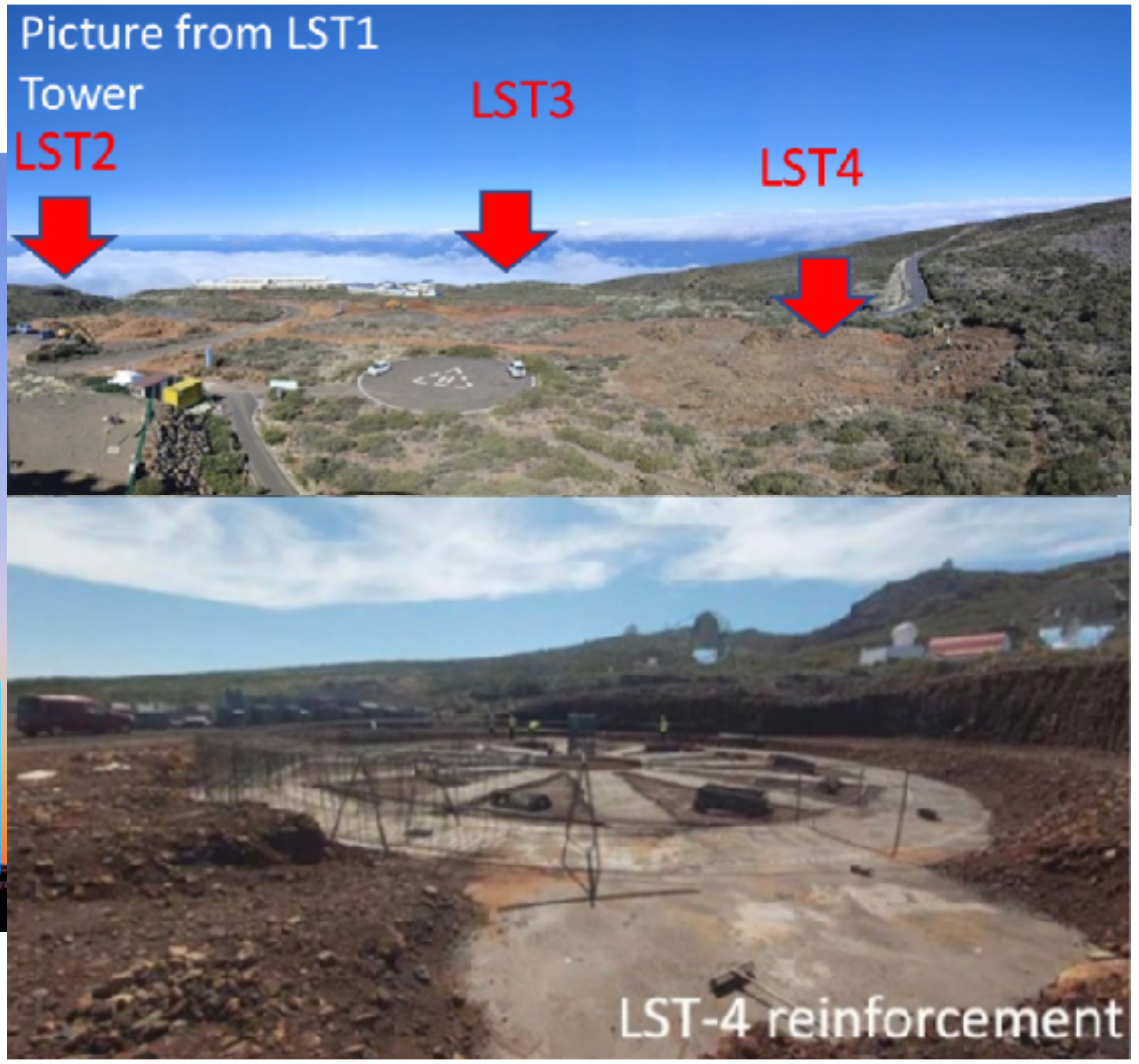


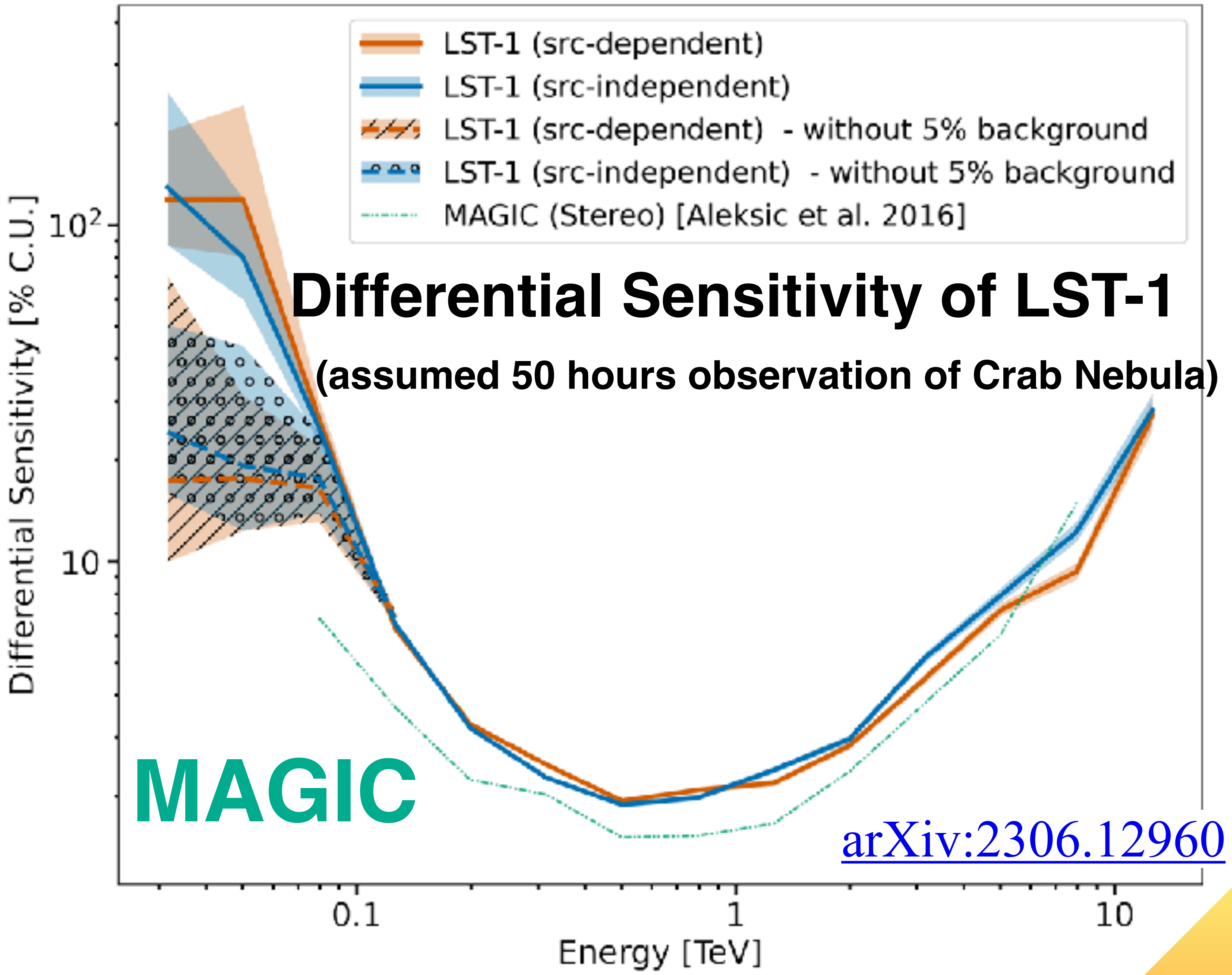


Large-Sized Telescope (LST)

LSTs are designed to give optimal performance in the lowest region of the energy range covered by CTA, down to ≃ 20 GeV

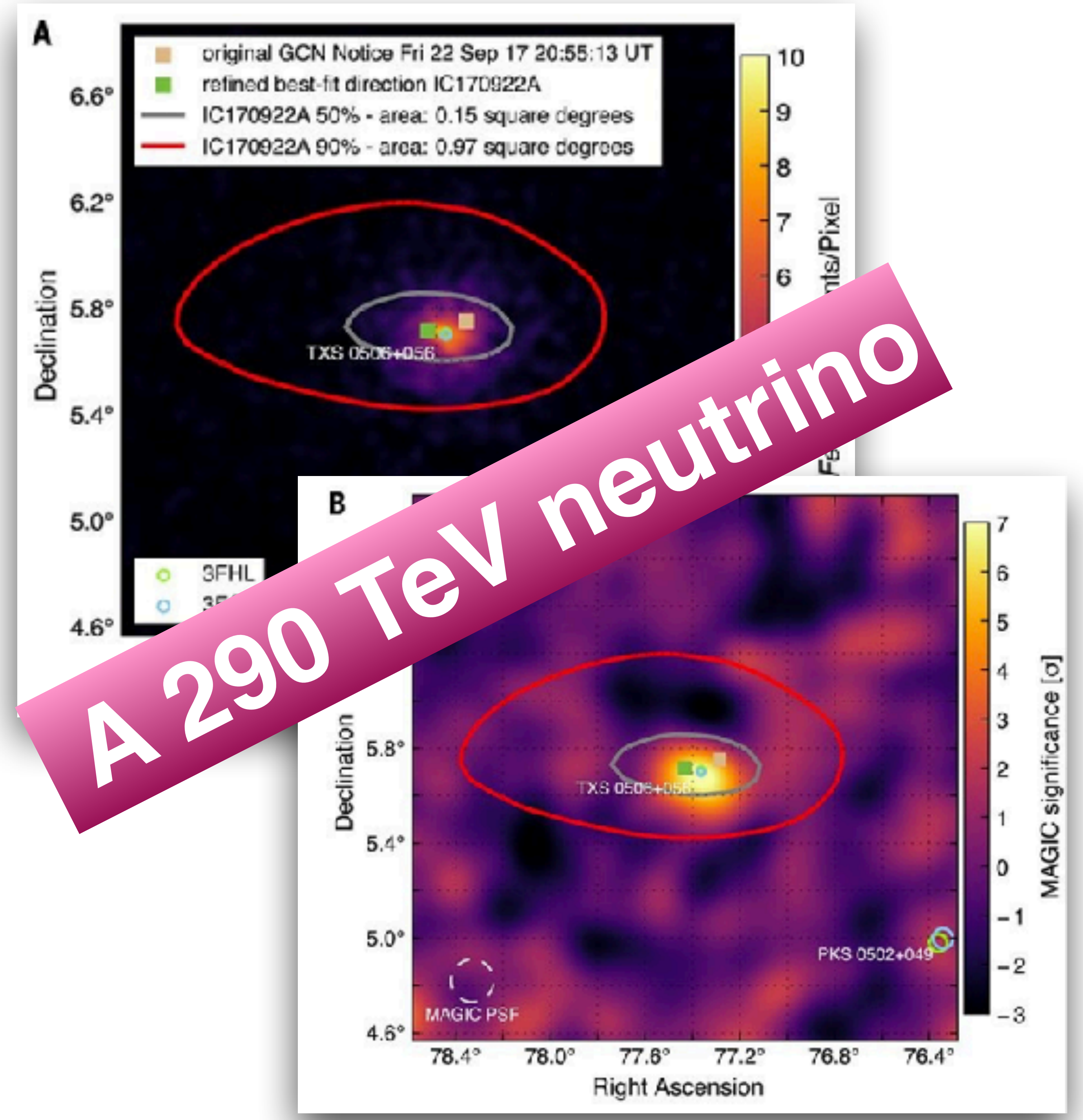
- Reposition to any point in the sky **within 20 seconds**
- A performance paper on LST-1 was published based on the observational data of the Crab Nebula
  - The energy threshold at trigger level estimated to be **20 GeV**, increasing to ≃ **30 GeV after data analysis**
- Suitable for **transient/soft/distant** sources

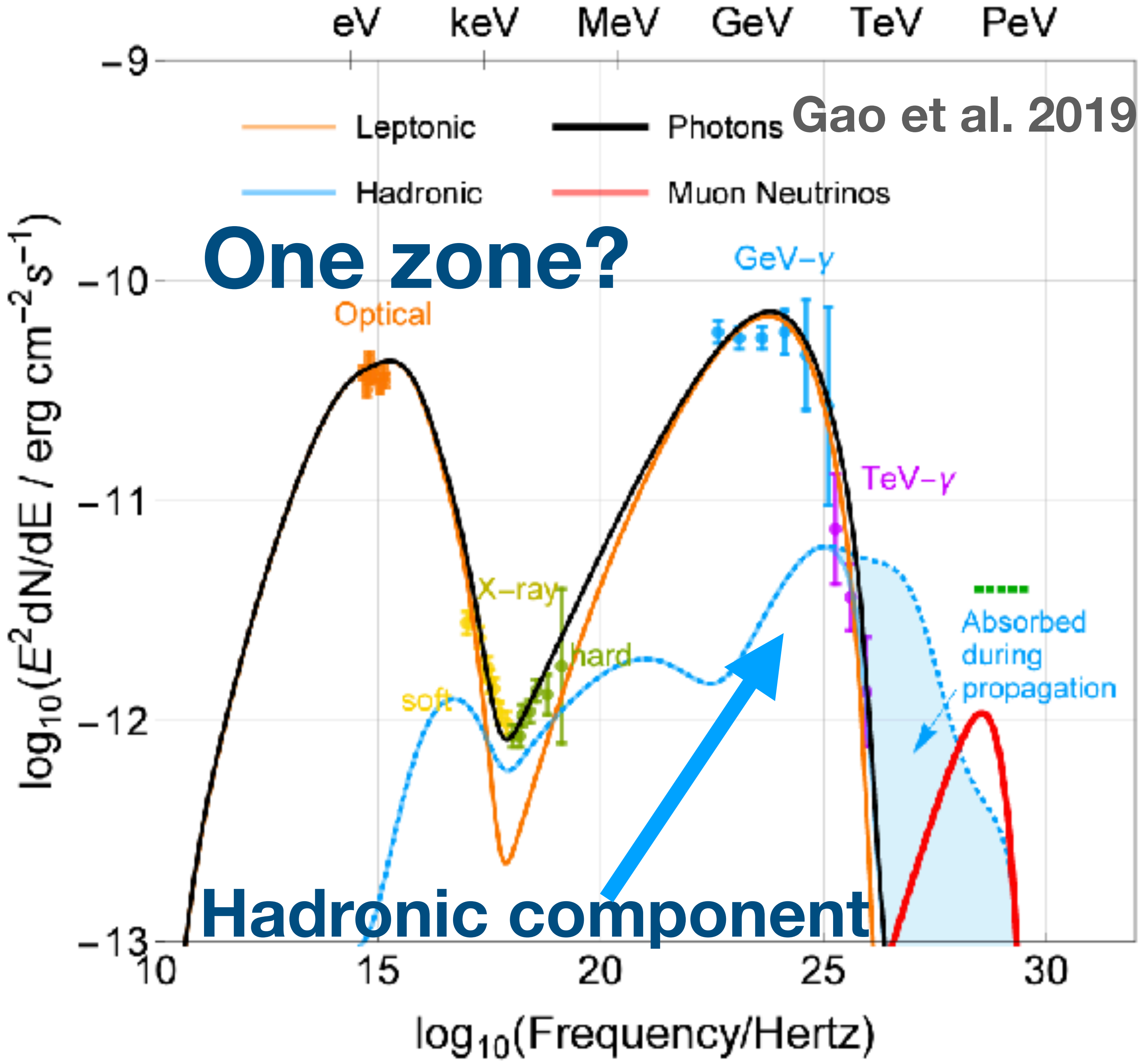


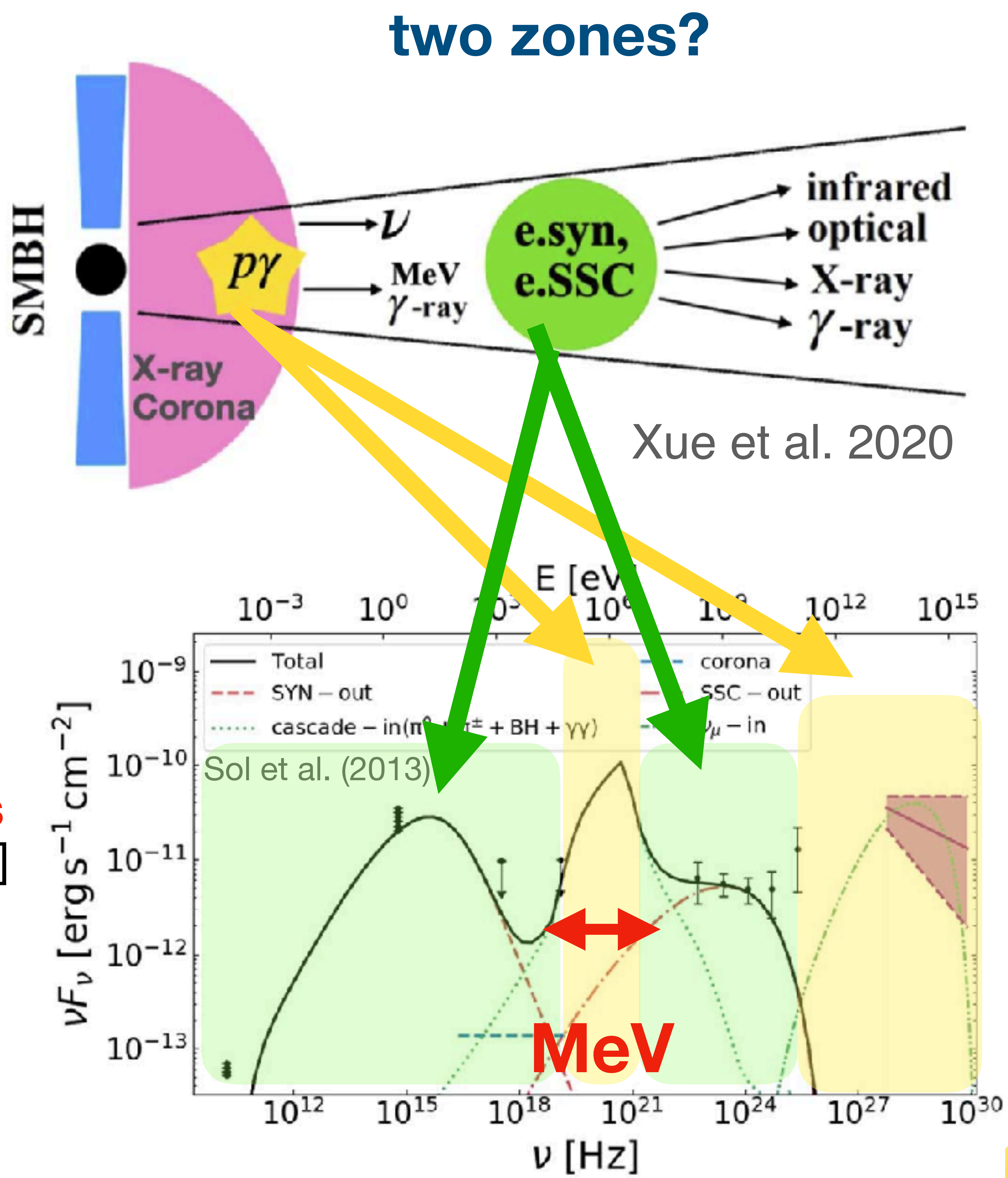


arXiv:2306.12960

Blazar Observation: Recent Trends in Astrophysics







- Modeling TXS 0506+056/IC-170922A needs **a leptonic genesis for γ-rays** [Ansoldi et al. 2018, Keivani et al. 2018, Cerruti et al. 2019, Gao et al. 2019]
  - photo-hadronic cascades in jets should **manifest as X-ray/UV emissions**, potentially **a more reliable neutrino-activity indicator**
- The EM emission observed from the blazar is **not coincident with the site of neutrino production**
  - **MeV/UV band observations could lead to model rejection**; observations are awaited!

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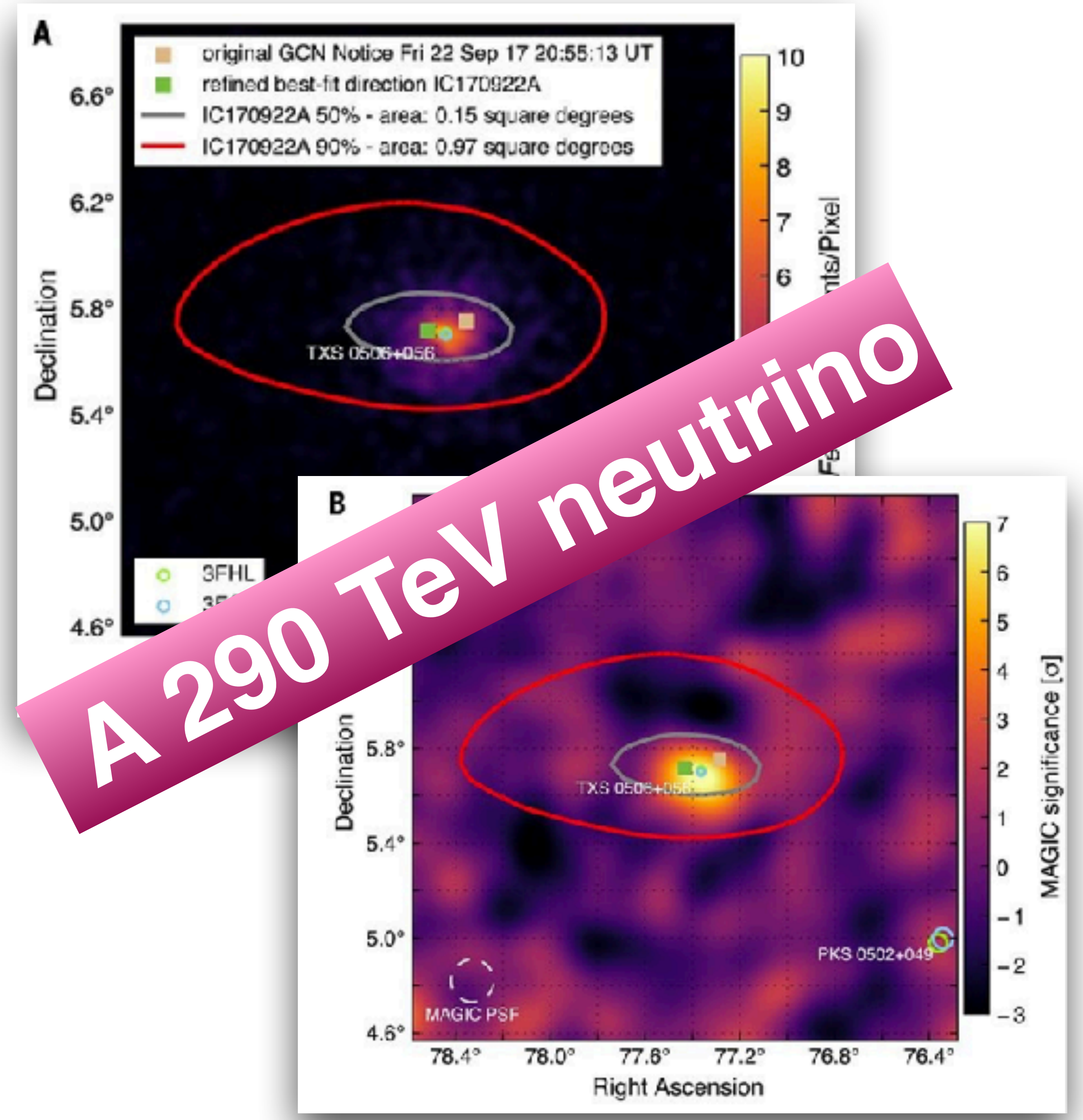

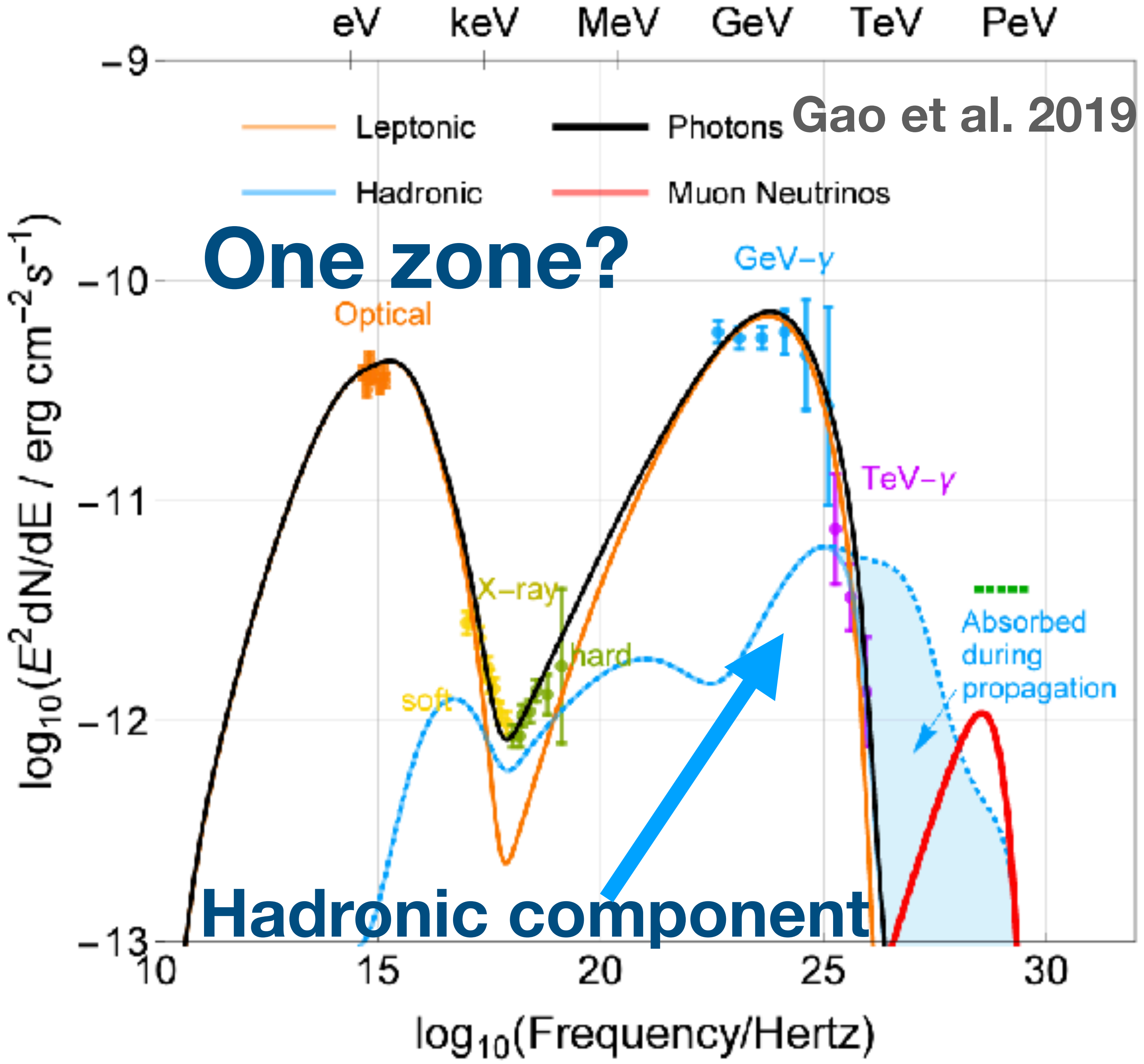

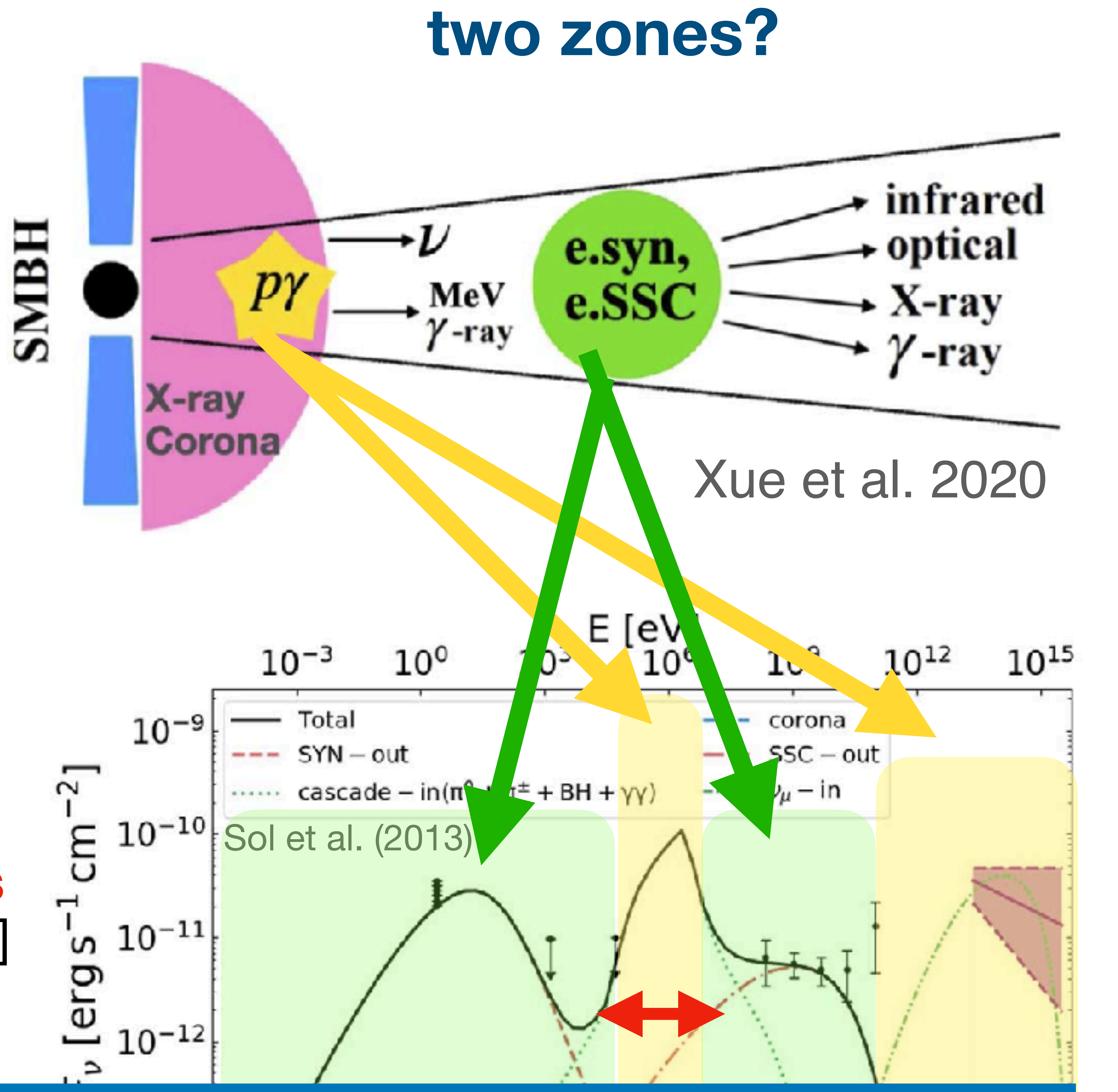

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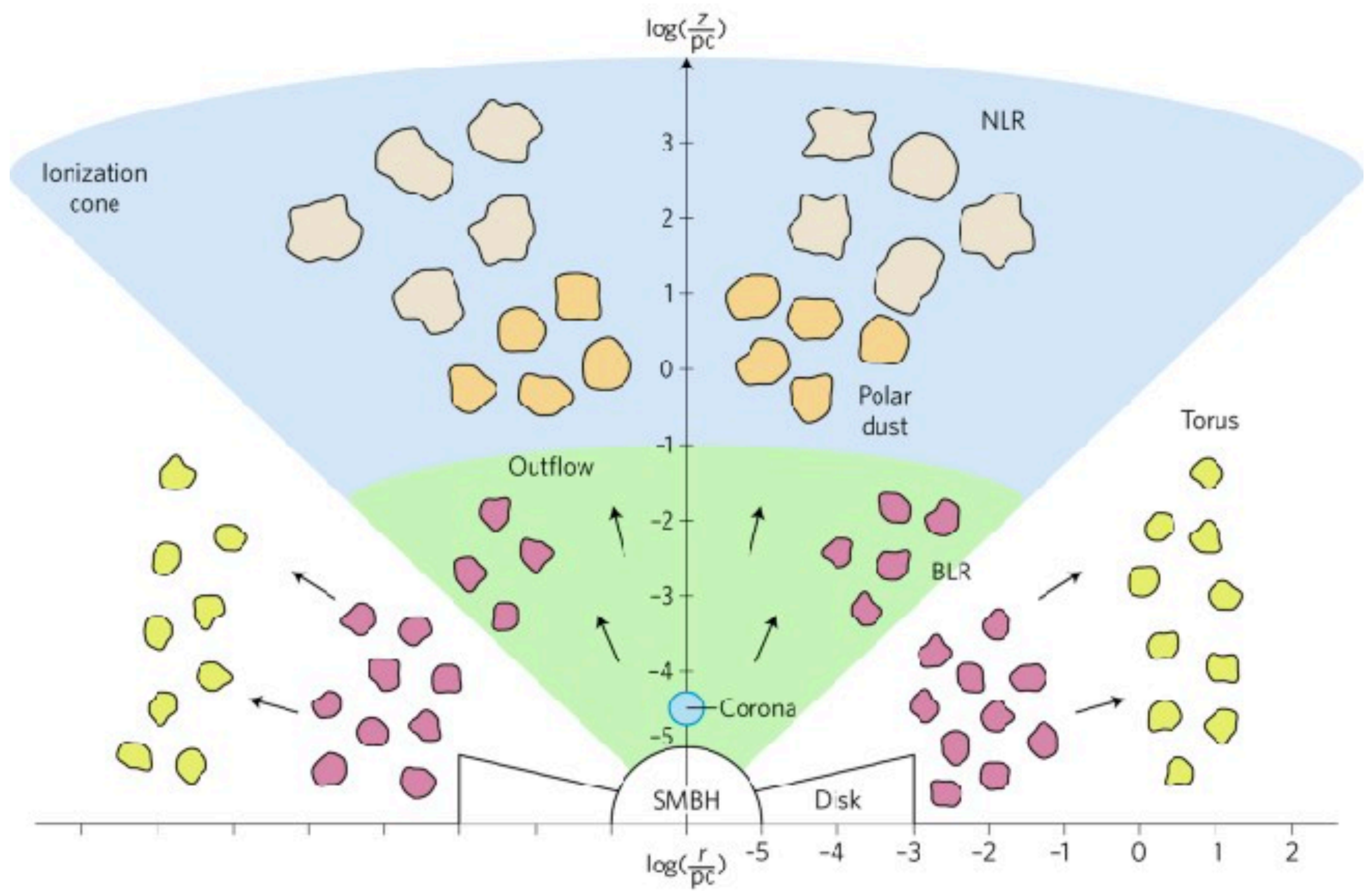
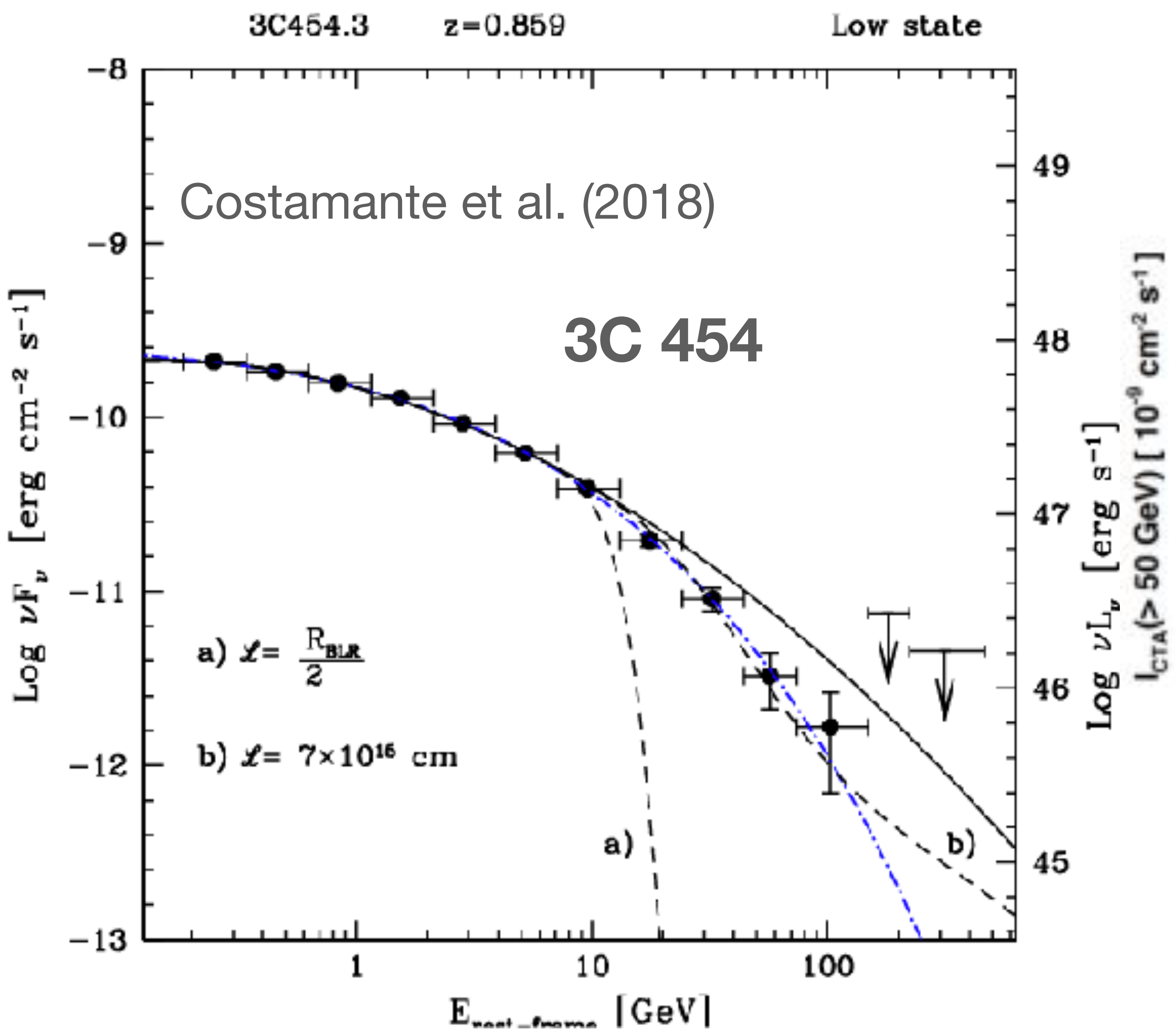
Observing a correlation between GeV-TeV gamma rays and neutrinos from the same blazar can be quite challenging!

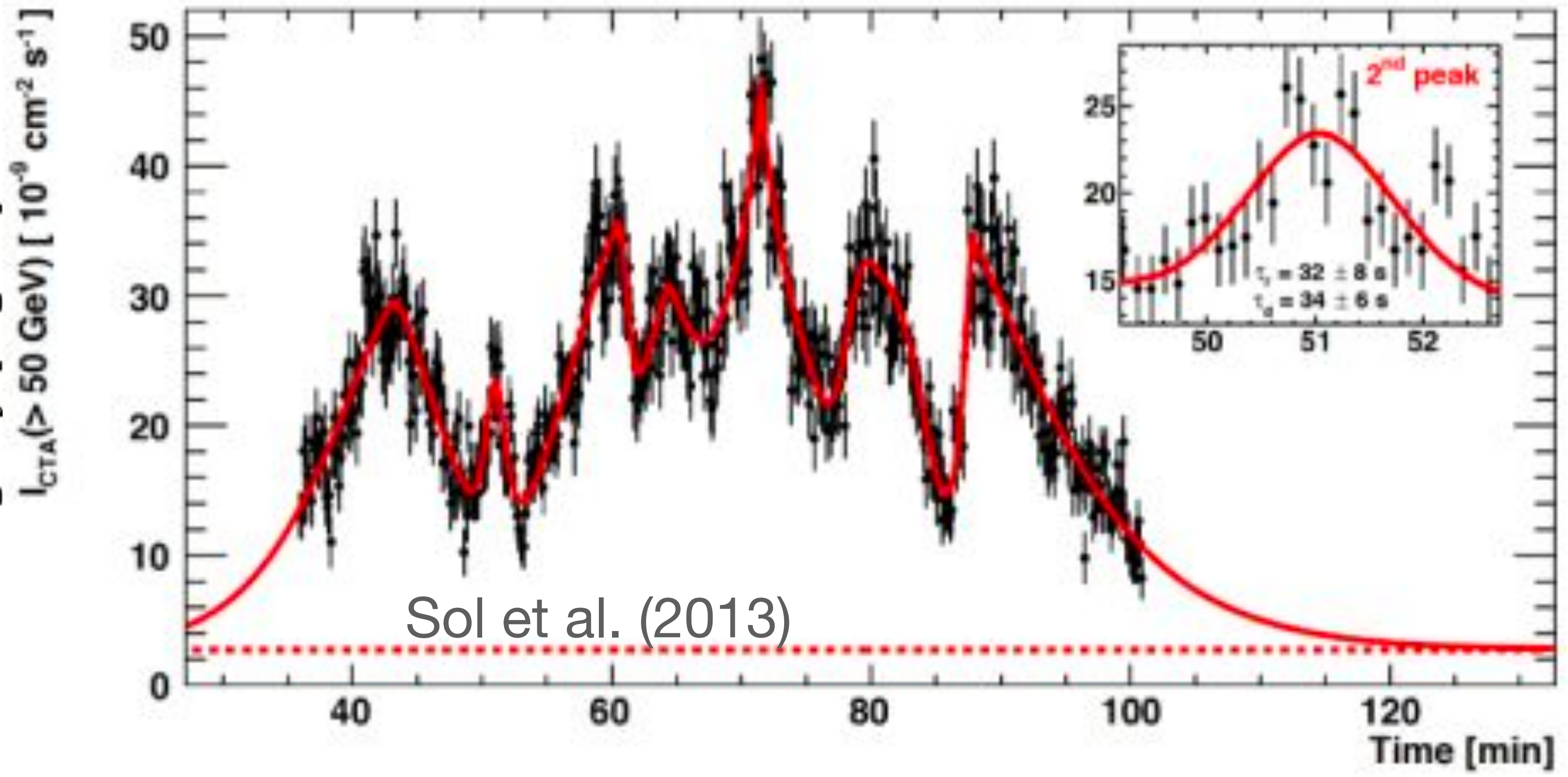
observations are awaited!

Blazar Observation: Recent Trends in Astrophysics

Where is the location of γ-ray emission region?





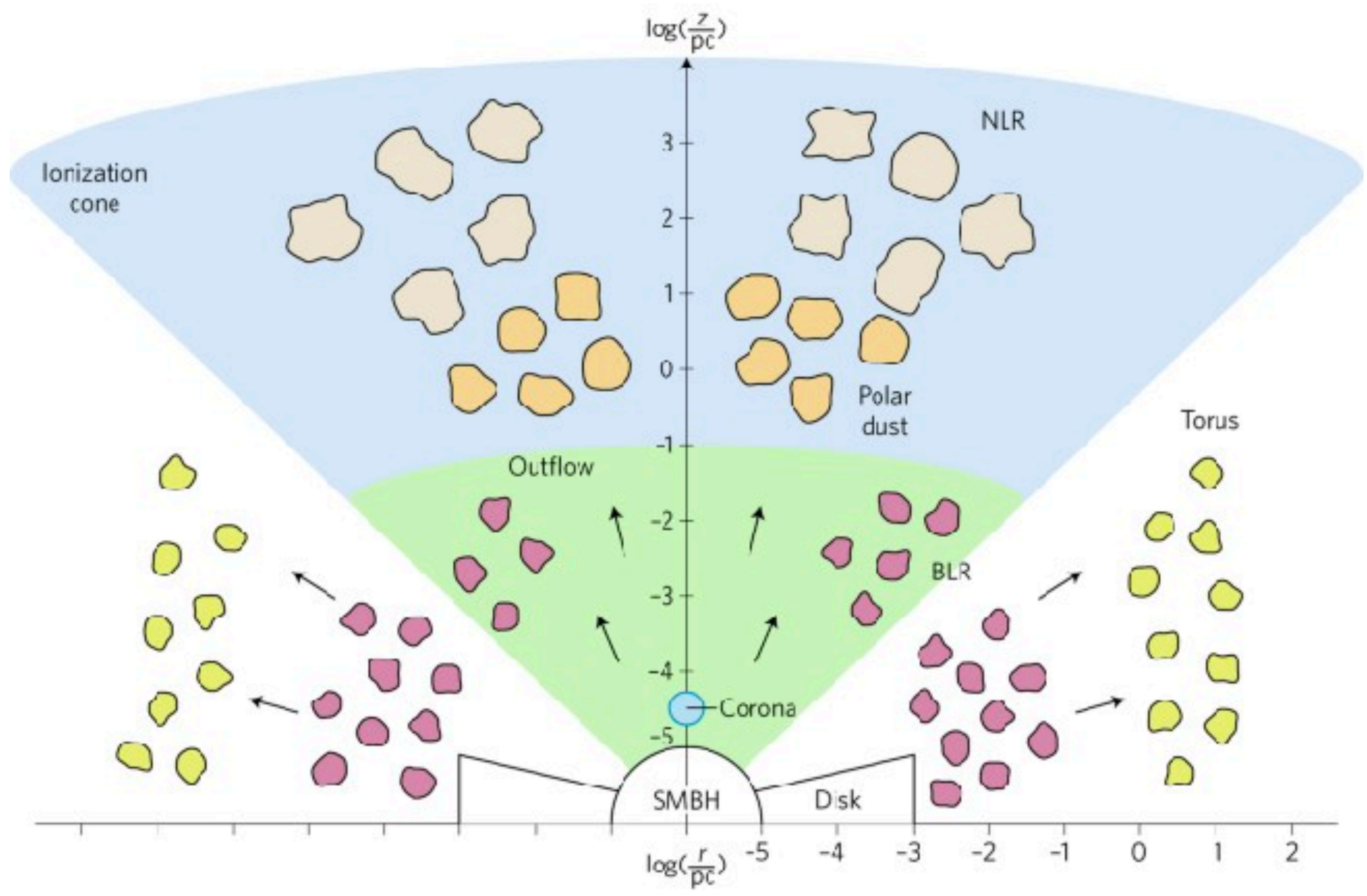


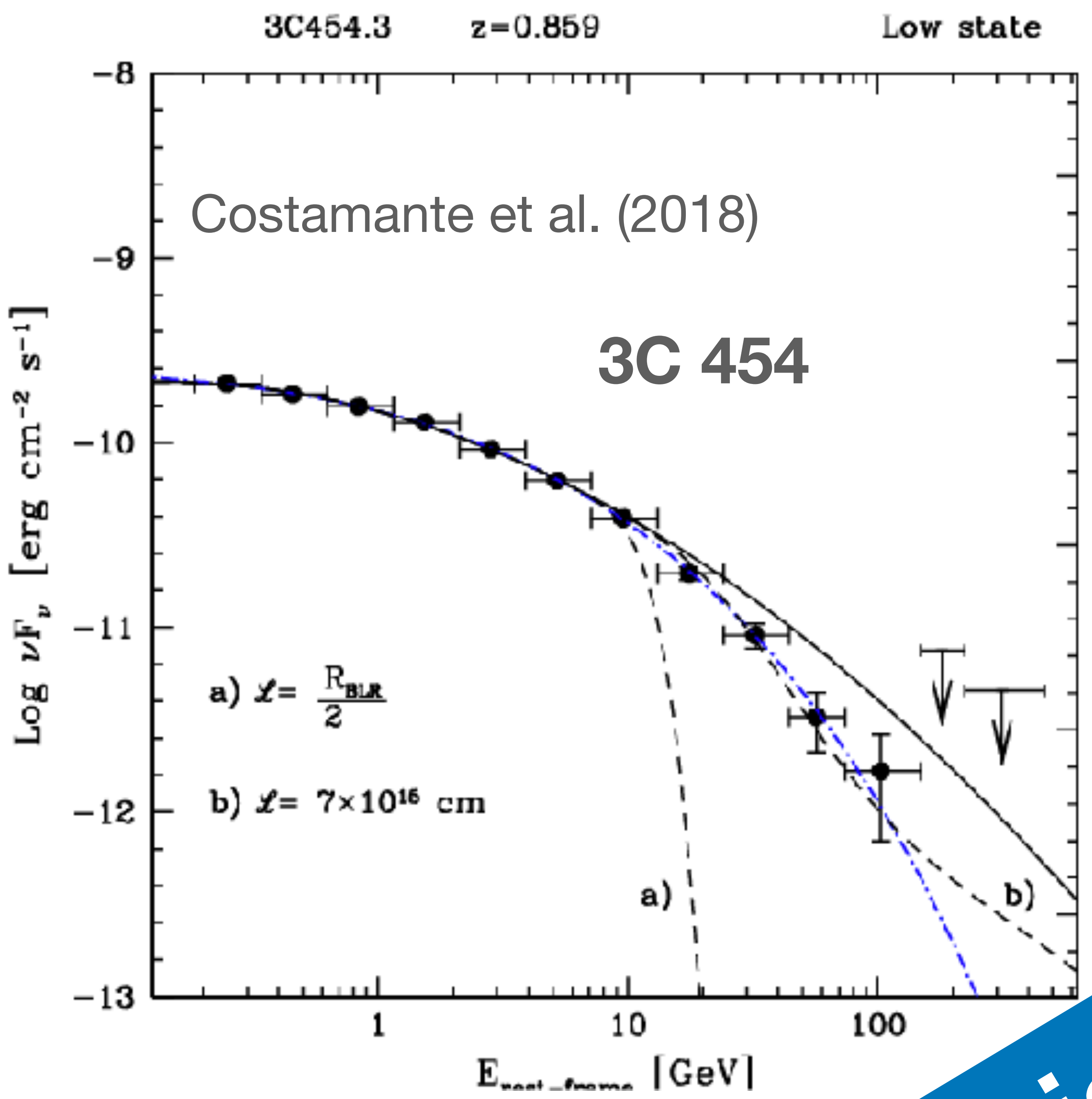
- Seeing **variability** helps us to constraints on Doppler factor, particle acceleration, and identify the location of the emission from the causality, further challenging the blazar models
- Gap of tens of pc between Radio and Optical Emission; sources like 3C 279 show no γγ absorption by BLR
  -> Gamma rays from **sub-pc** regions?
- Blazars like PKS1504 exhibit minute time scale variability
  -> Gamma-ray emission region **less than pc**? **How diverse are blazars**?

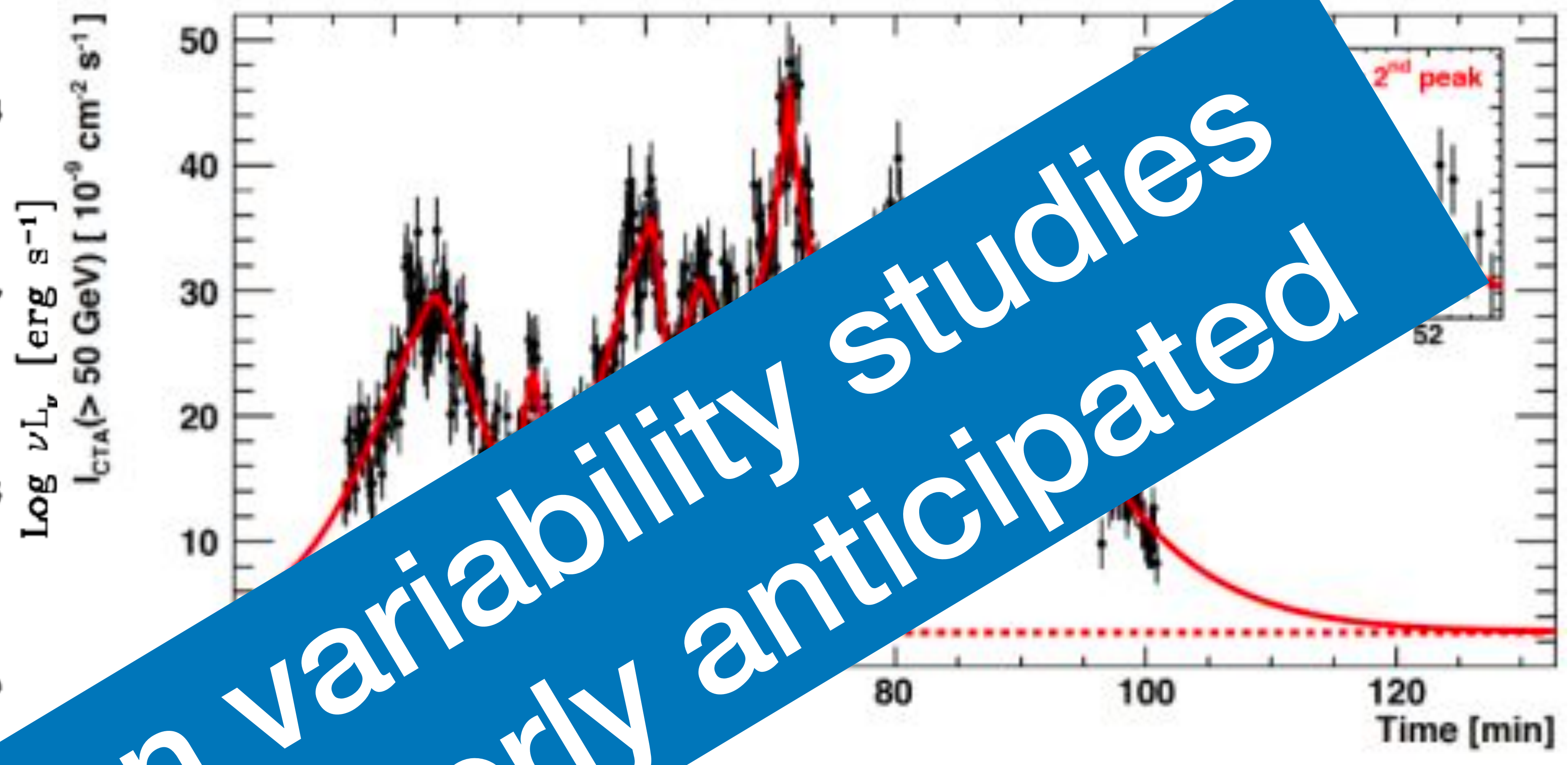
Blazar Observation: Recent Trends in Astrophysics

cherenkov telescope array

Where is the location of γ-ray emission region?







High-precision variability studies with CTA are eagerly anticipated

- Seeing **variability** helps us to constraints on Doppler factor, parti… …d identify the location of the emission from the causality, further challenging the blazar m…
- Gap of tens of pc between Radio and Optical Emissi… …279 show no γγ absorption by BLR
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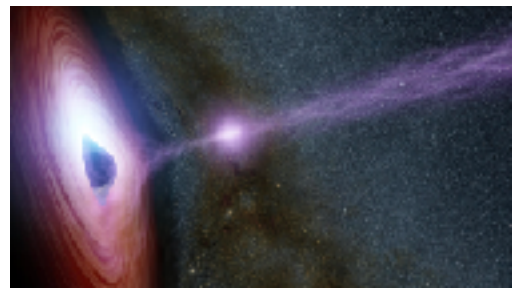
Active Galactic Nuclei Observation with LST-1



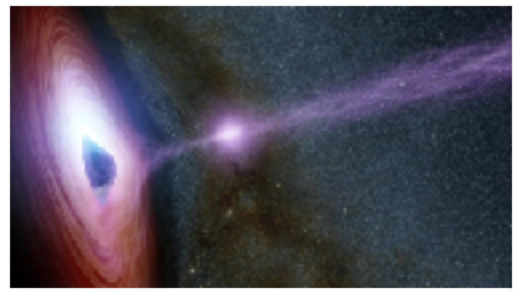
cherenkov telescope array

LST-1 detected (> 5 σ) 6 known TeV blazars:
Mrk421, Mrk501, 1ES 1959+650, 1ES 0647+250, PG 1553+113, BL Lac

- A paper is slated for publication, along with simultaneous data acquired by the Fermi-LAT
- LST-1 detected a flare from BL Lac in 2021 [icrc2023_pos]. This is a separate project and will not be covered in this talk

	Mrk421	Mrk 501	1ES1959+650	1ES0647+250	PG 1553+113
AGN type	HBL	HBL	HBL	HBL	HBL
Redshift	0.031	0.034	0.048	0.45±0.05	0.433
Obs. date	2020/12/12 -2022/05/23	2020/07/10 -2022/06/29	2020/07/11 -2022/05/05	2020/12/16 -2020/12/21	2021/04/08 -2022/05/23
Obs. time BF/AF cut (h)	68.5/32.4	67.2/39.7	21.3/11.8	8.8/8.2	12.2/9.9
Significance	34 σ	21 σ	12 σ	7 σ	16 σ
Condition	Dark (No Moon) + Clear Sky				

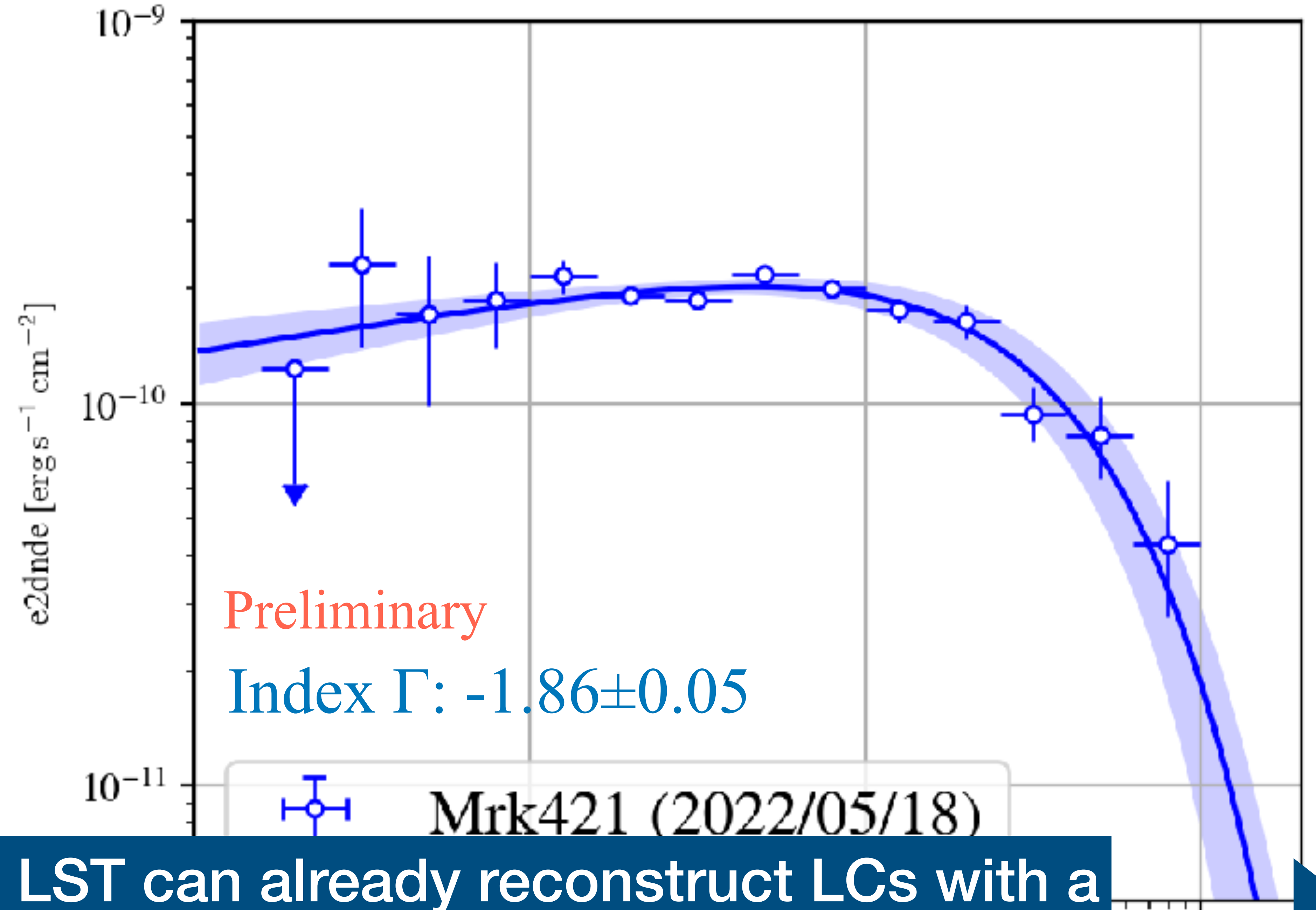
Seeing Variabilities: Mrk421 Flare in 2022-05-18

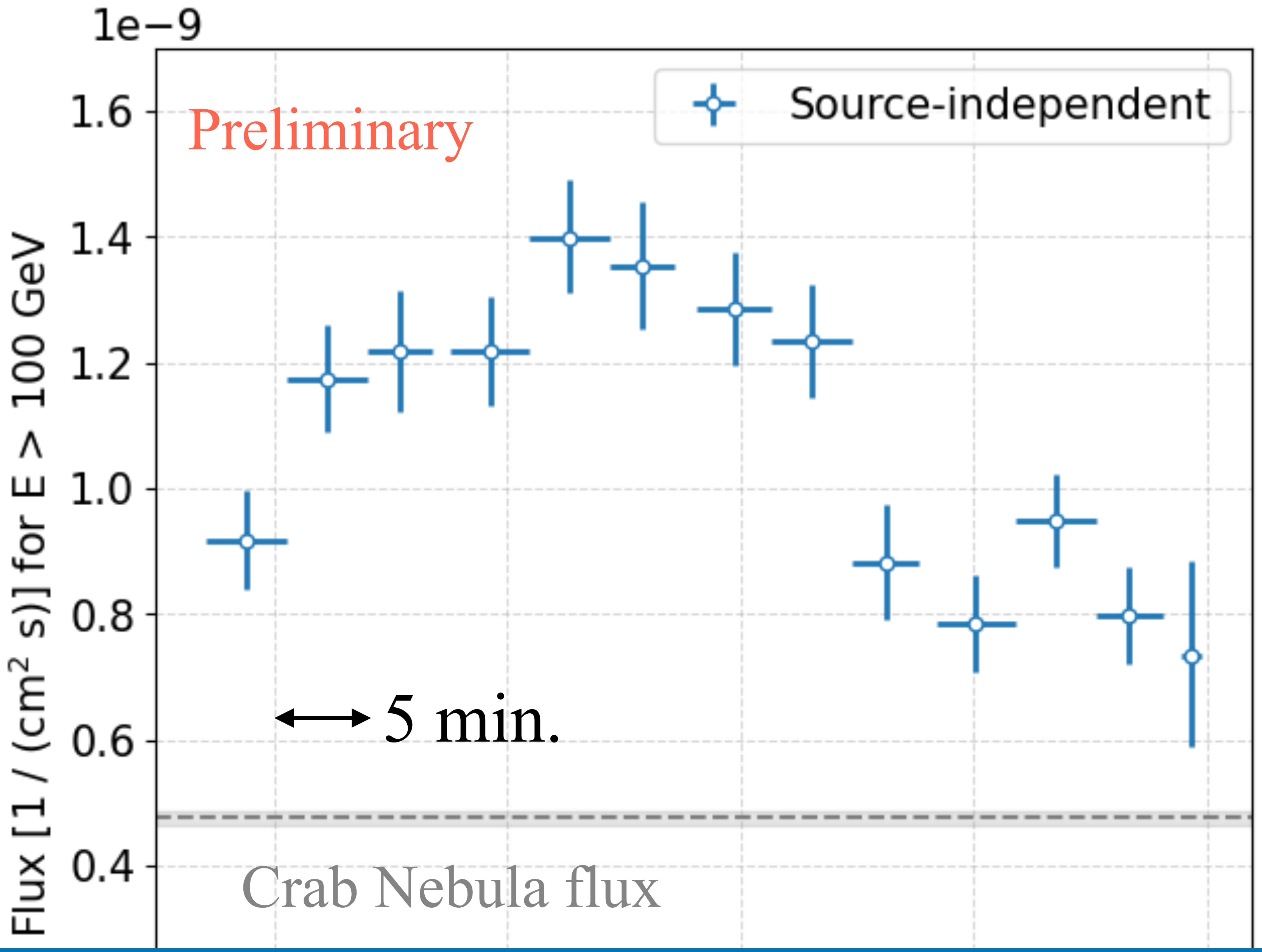


cherenkov telescope array

Mrk421 flare was detected in 2022/05/18
~3 times brighter than Crab Nebula's flux at > 100 GeV

- Spectra are measured down to ~25 GeV, and well fitted by the exponential cutoff power law (ECPL) function
- Concurrently, intra-night light curve and flux variability time scale are under examination





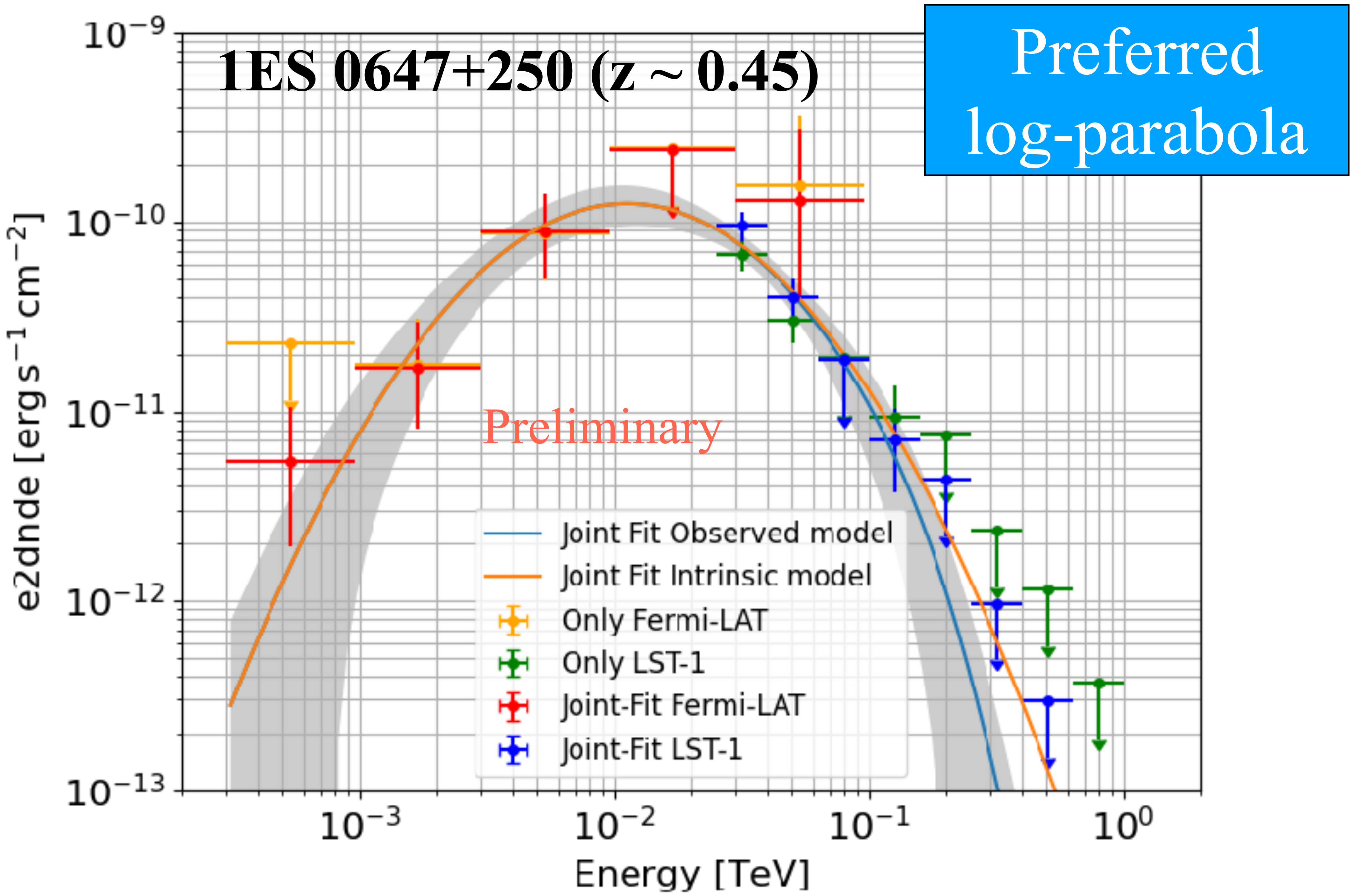
A single LST can already reconstruct LCs with a time-scale precision comparable to the current gamma-ray telescope MAGIC

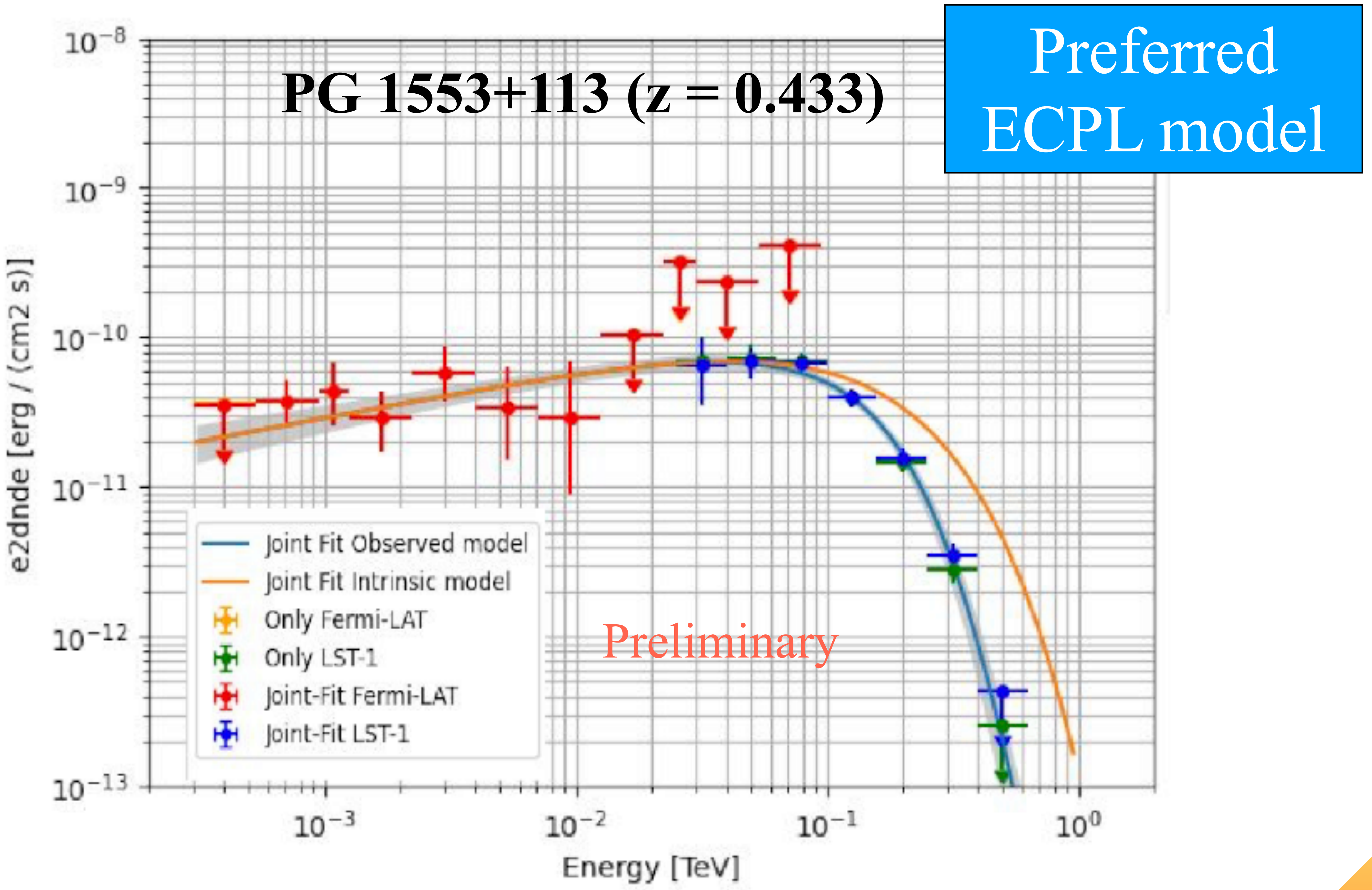
Upcoming minute-level variability studies by CTA could lead to locate the emission region, and further model constraints

Distant VHE sources: 1ES 0647+250 and PG 1553+113

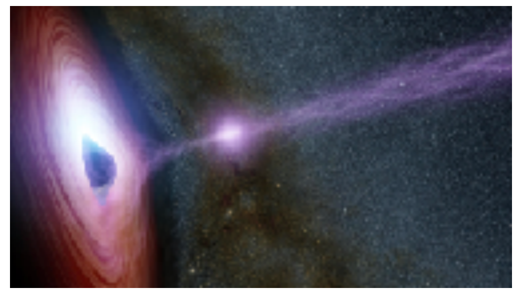
Effectively reconstructed a spectrum that seamlessly connects with the Fermi-LAT observational data from the corresponding time period

- Joint-fit with Fermi-LAT data using dedicated pipeline ***Asgardpy*** https://asgardpy.readthedocs.io/en/latest/
- Variability of these two sources is currently not confirmed by LST-1
    - The variation in PG 1553+113 has already been ascertained in Fermi-LAT observations, making it scientifically imperative to maintain ongoing surveillance through LST-1

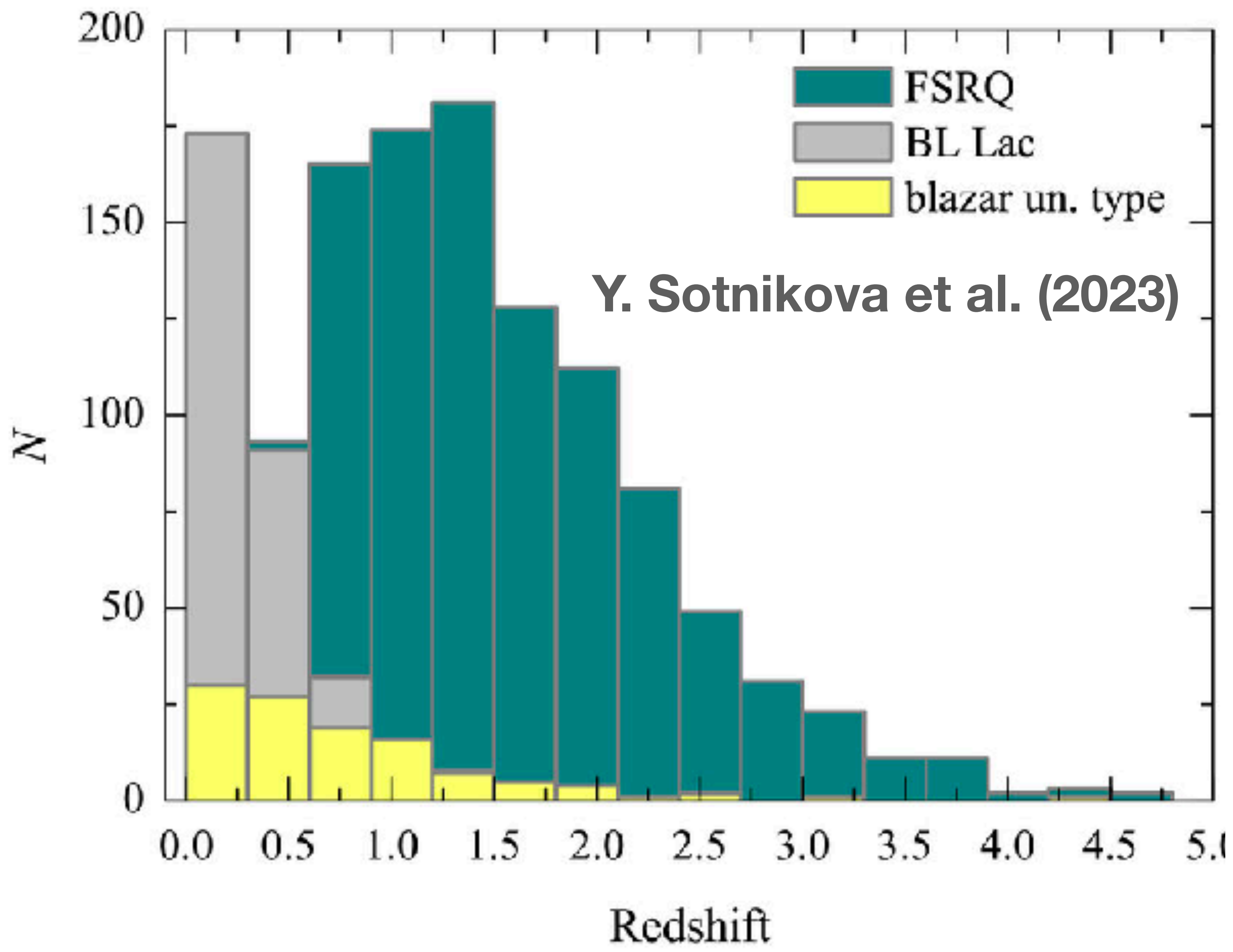


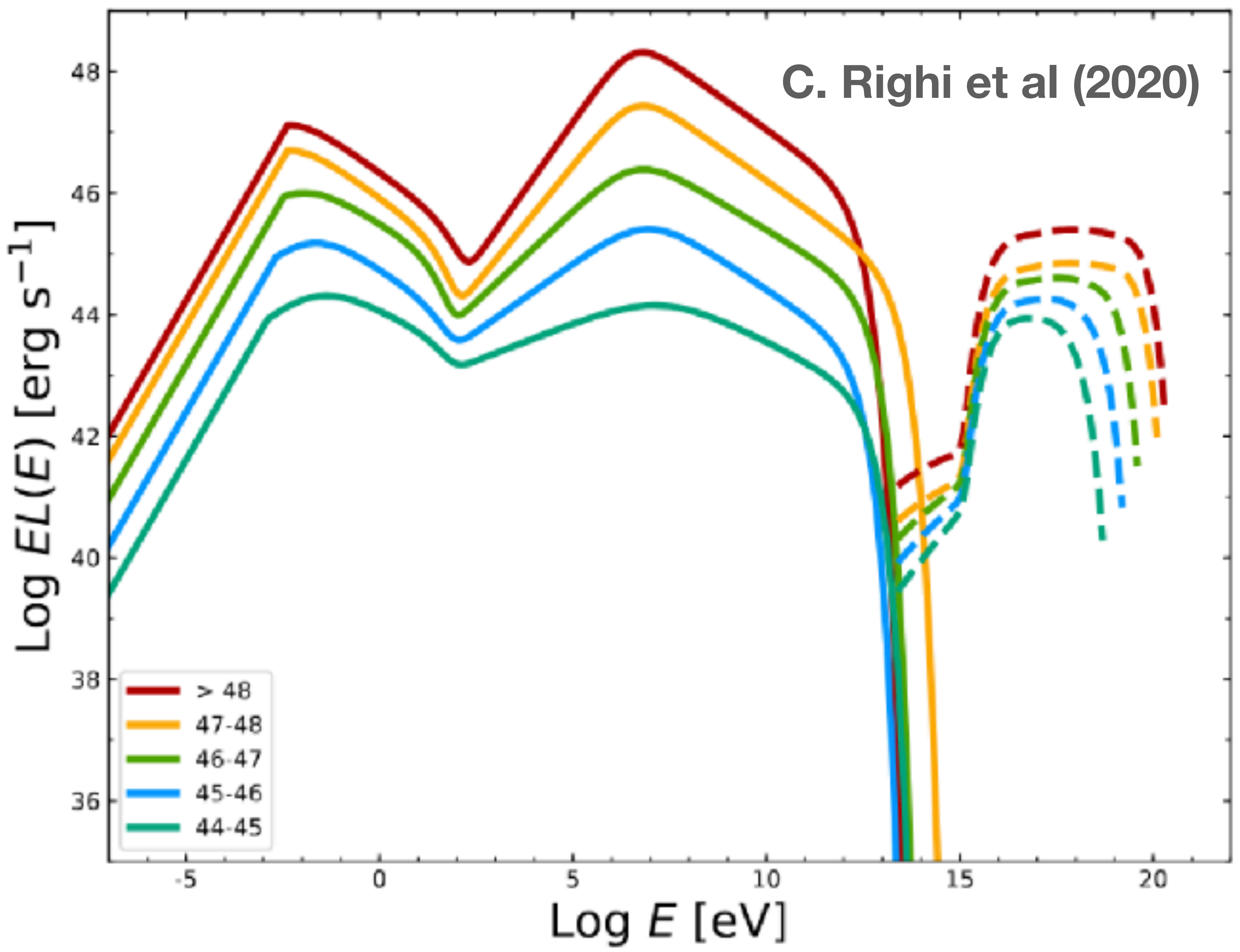


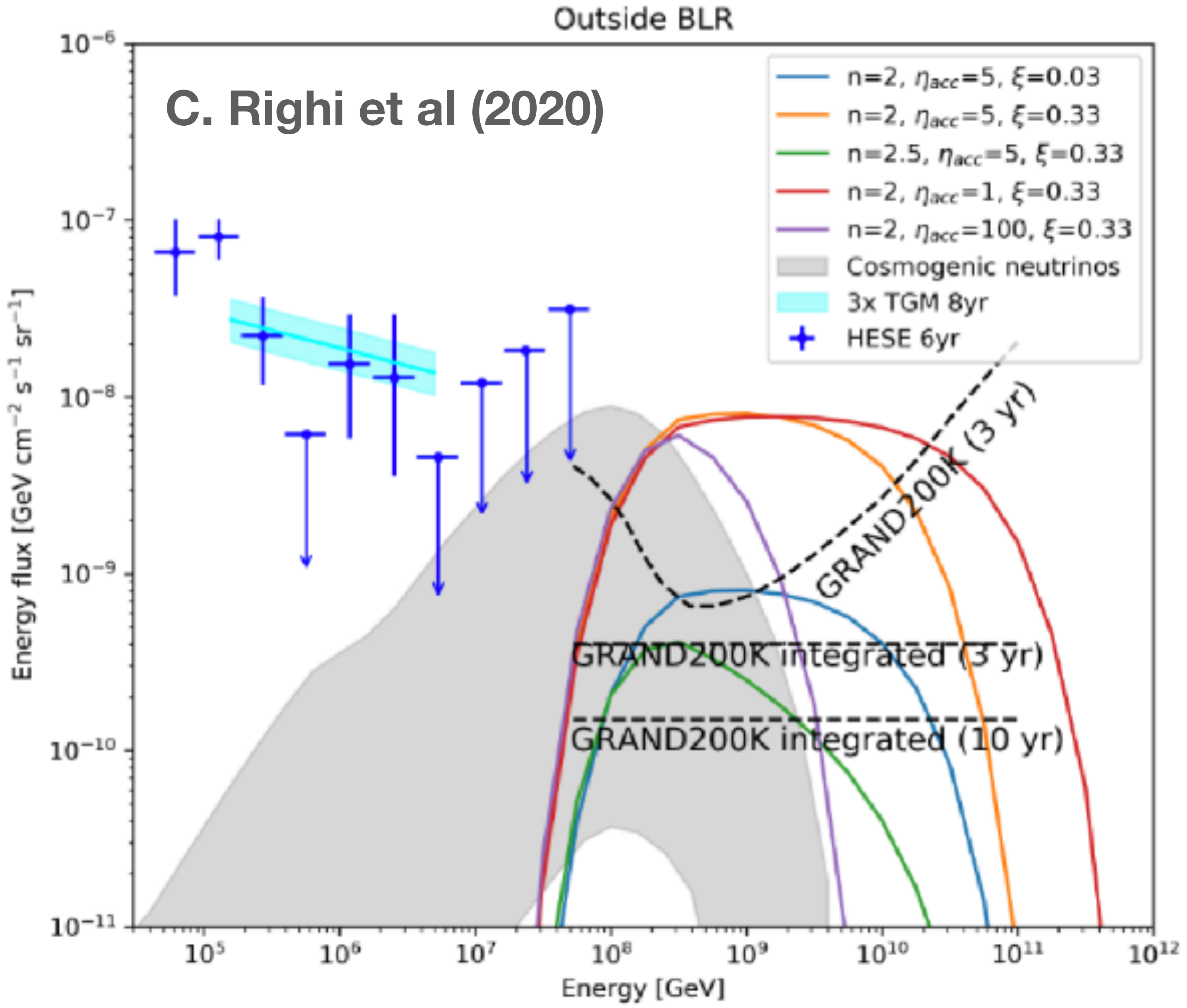
Why Distant VHE sources?



No detection of FSRQ by LST-1 so far, but...

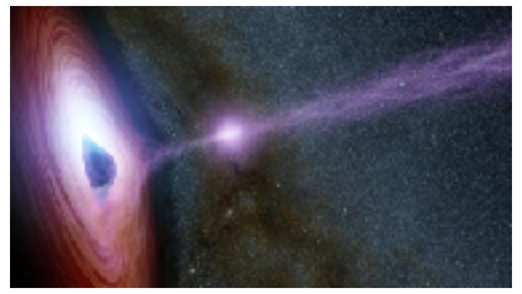






- FSRQ is a promising candidate in producing neutrino, but **no significant detection of FSRQs** up to now
  - **EeV neutrino** production in FSRQs?
  - Simply gone unobserved due to the sensitivity-wise limitation of the current neutrino detection facilities?
- Given FSRQs tend to be observed at **high redshifts** ($z > \sim 0.5$), employing **low-energy-threshold γ-ray telescope like LSTs** to increase FSRQ statistics is crucial

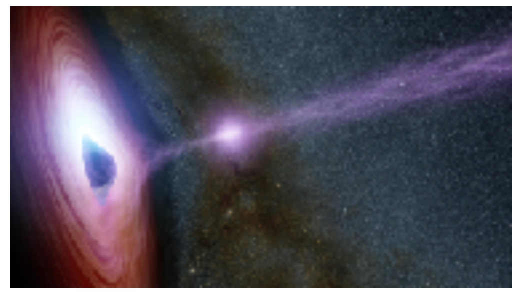
Summary



- MWL observations are essential for constraining blazar emission models
  - First neutrinos tied to a blazar observed: **TXS 0506+056/IC-170922A**
    - γ-rays likely of leptonic origin, **making γ-neutrino correlation challenging**
    - **UV/X-ray observations are awaited**
  - Monitoring variability crucial for pinpointing gamma-ray emission site
    > pc or < pc? Are blazars diverse? **Precise time-tracking by CTA is the key**
  - FSRQ may product **EeV neutrinos**
    - Given FSRQs tend to exist at high redshifts, using low-energy-threshold LSTs to increase FSRQ statistics is crucial

- LST-1 initiated scientific observations since 2020 and has already detected several known AGNs
  - Achieved reconstruction of minute-scale variability in blazars, and detection of sub-100 GeV γ-rays from distant blazars

Summary



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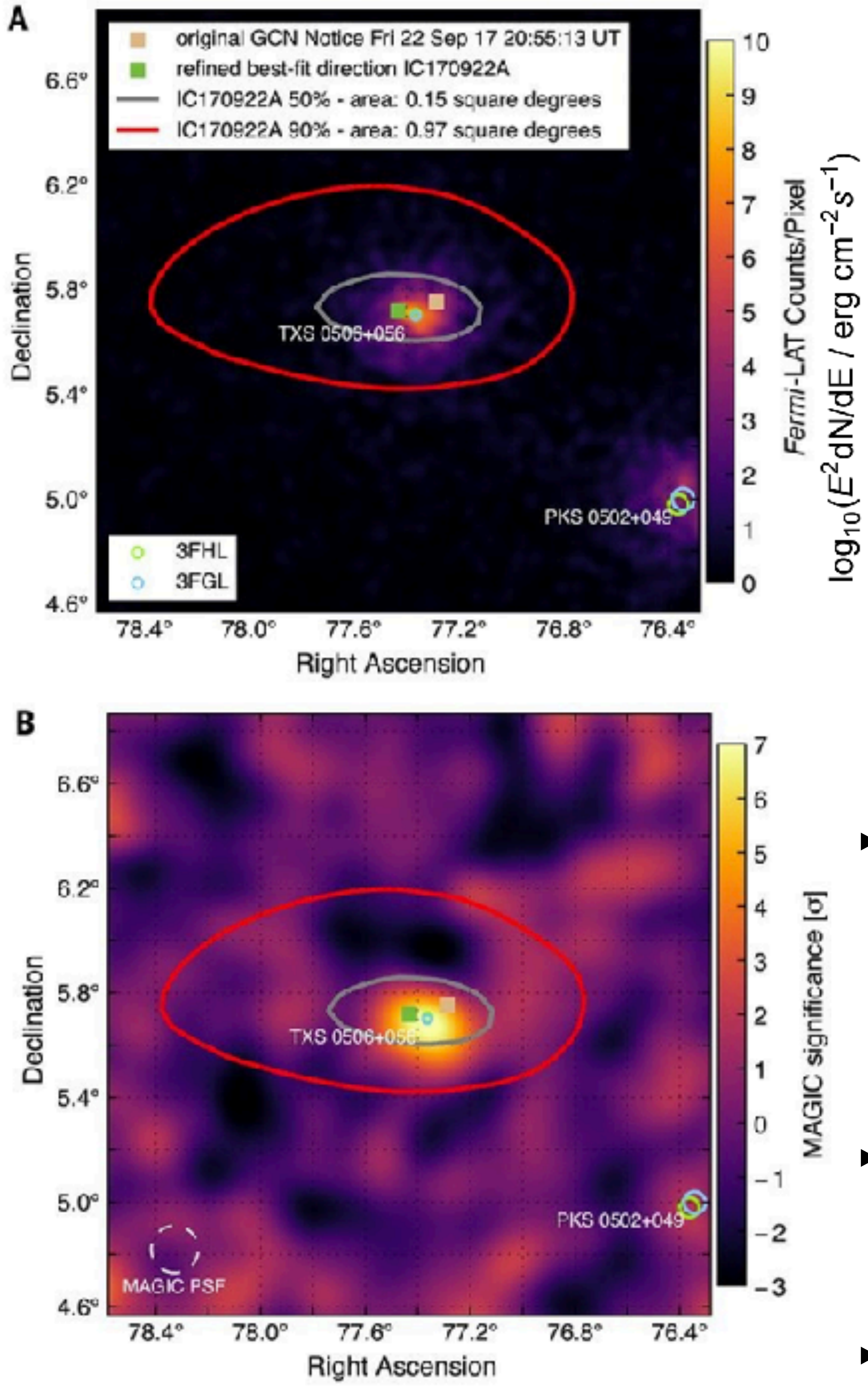
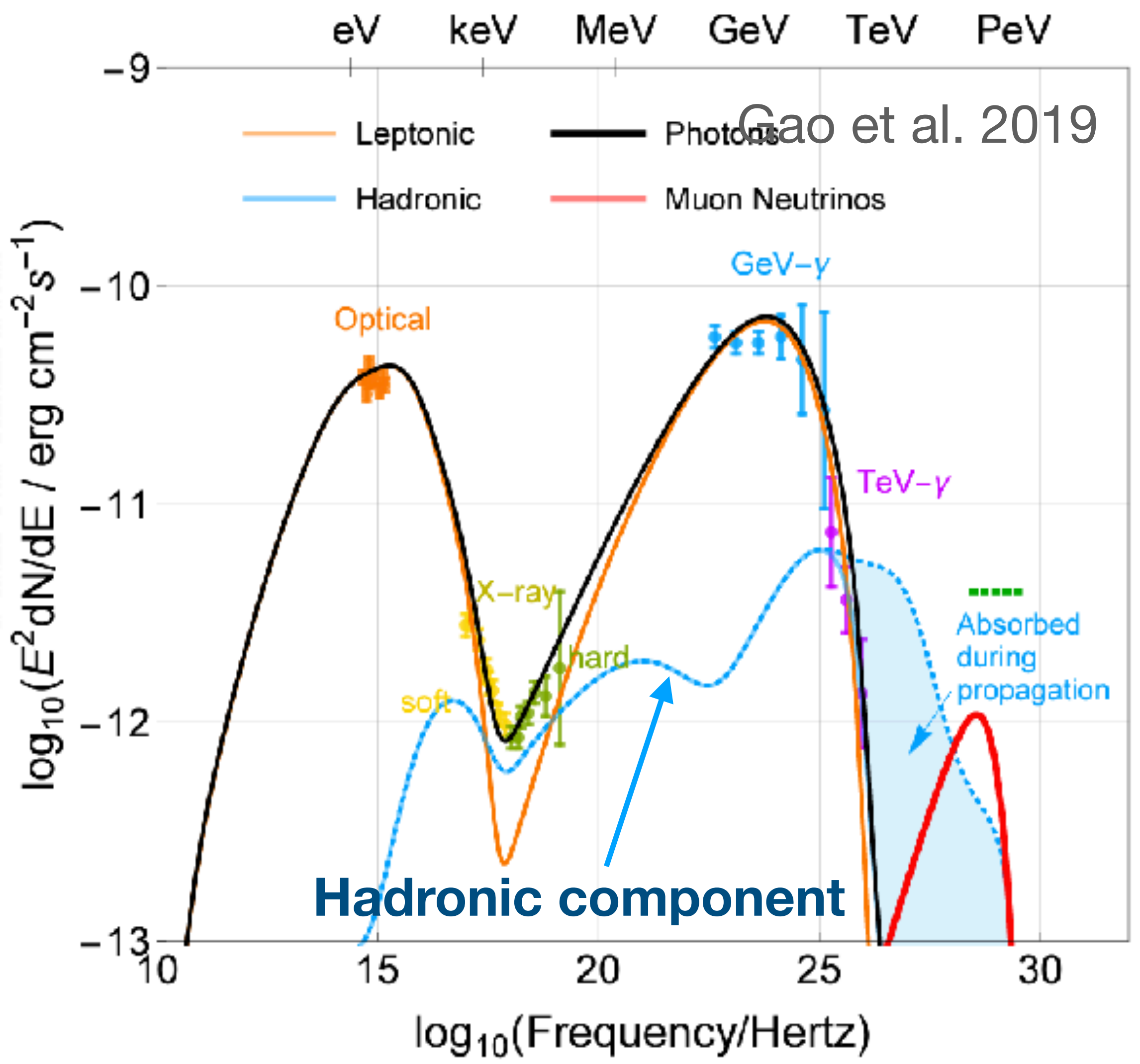
Interested in proposing observations with MAGIC/LST?

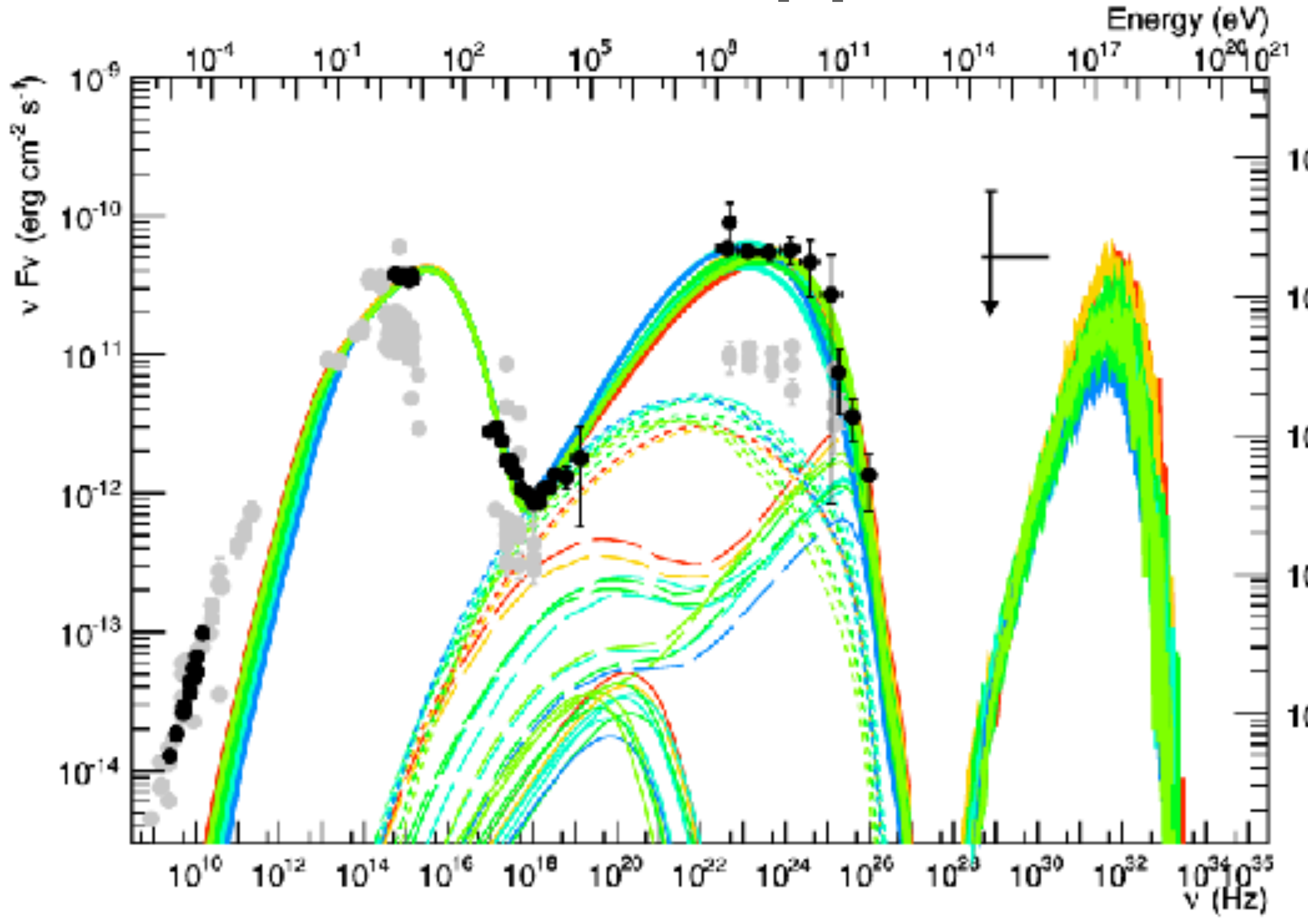
Backup

Blazar Observation: Recent Trends in Astrophysics

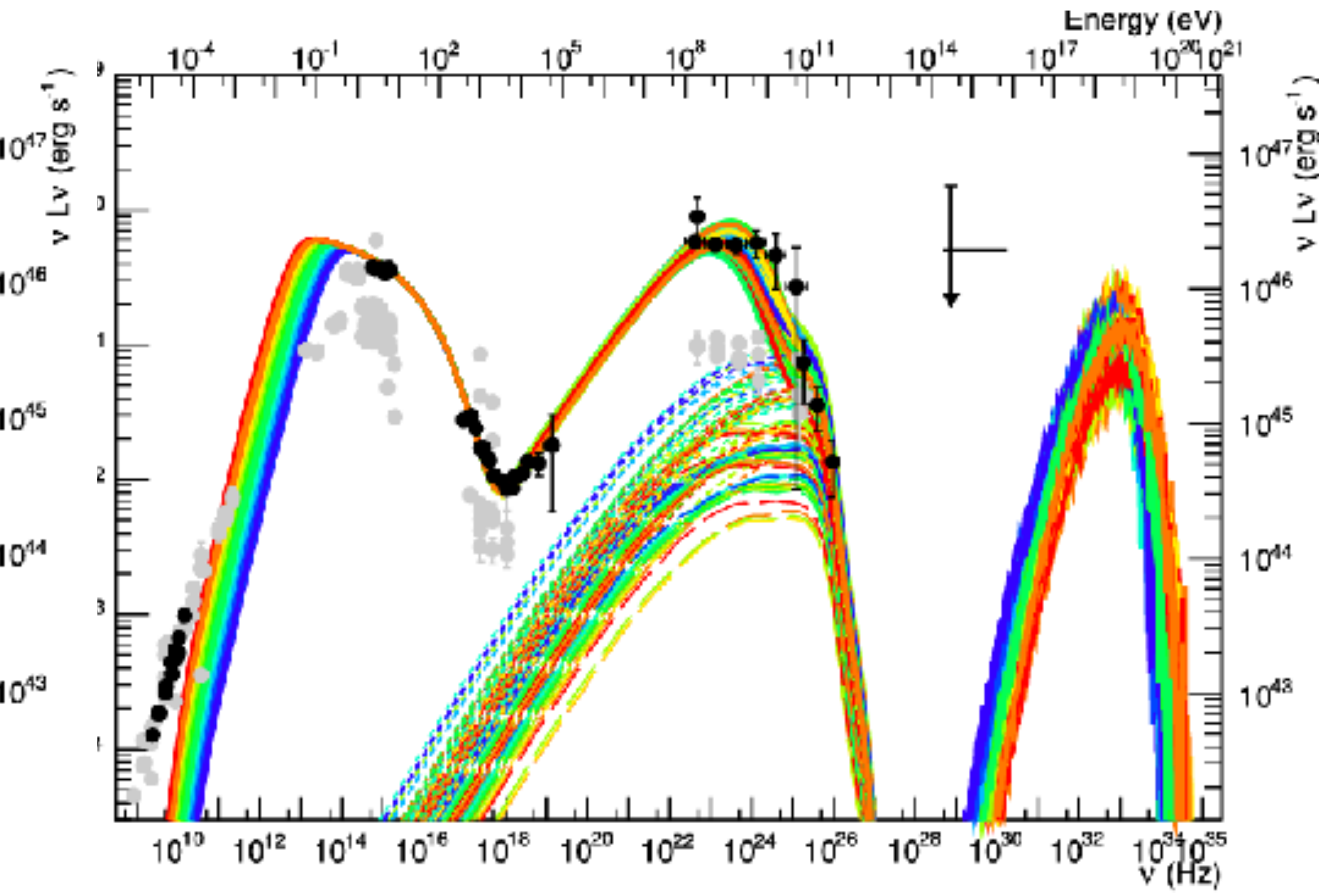




SSC-dominant +pγ cascade



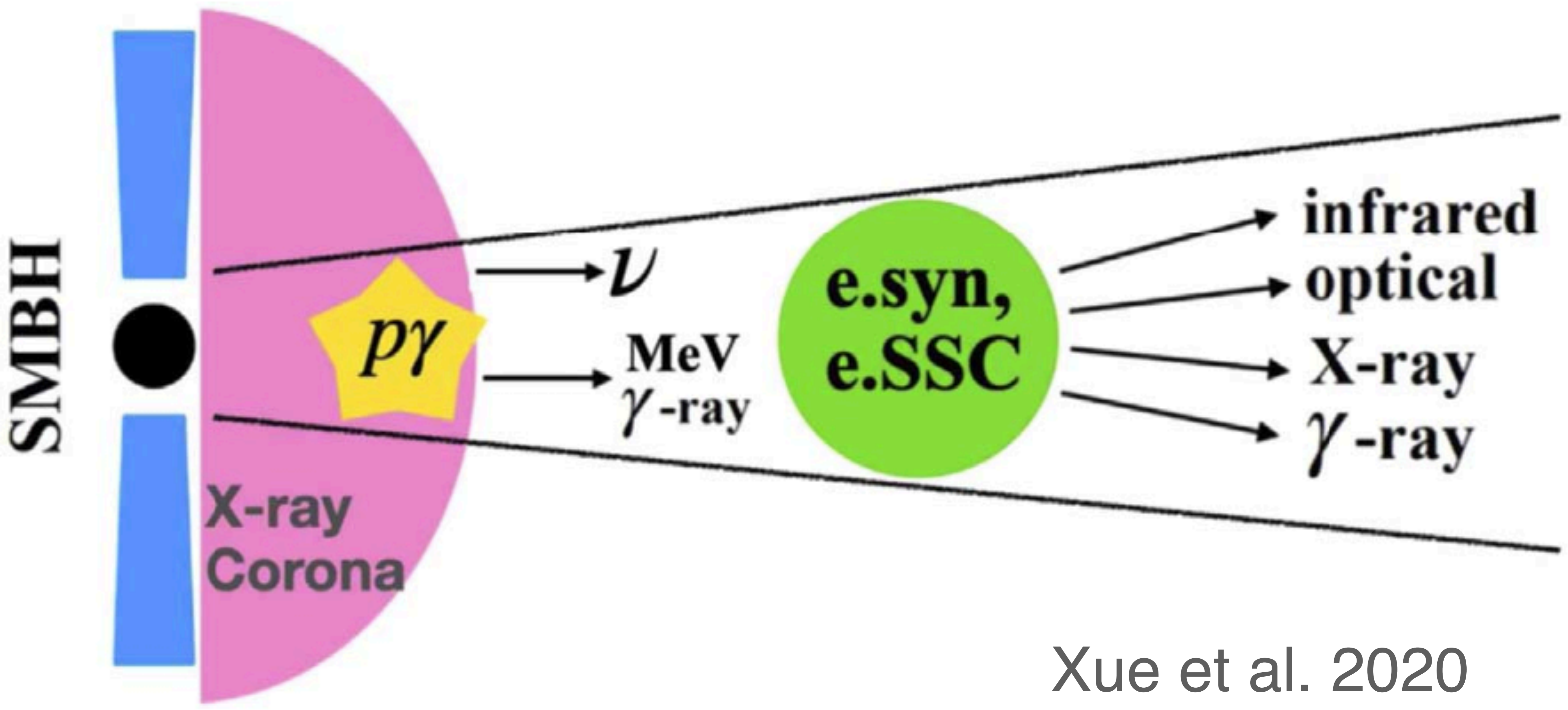
proton sync.-dominant +pγ cascade



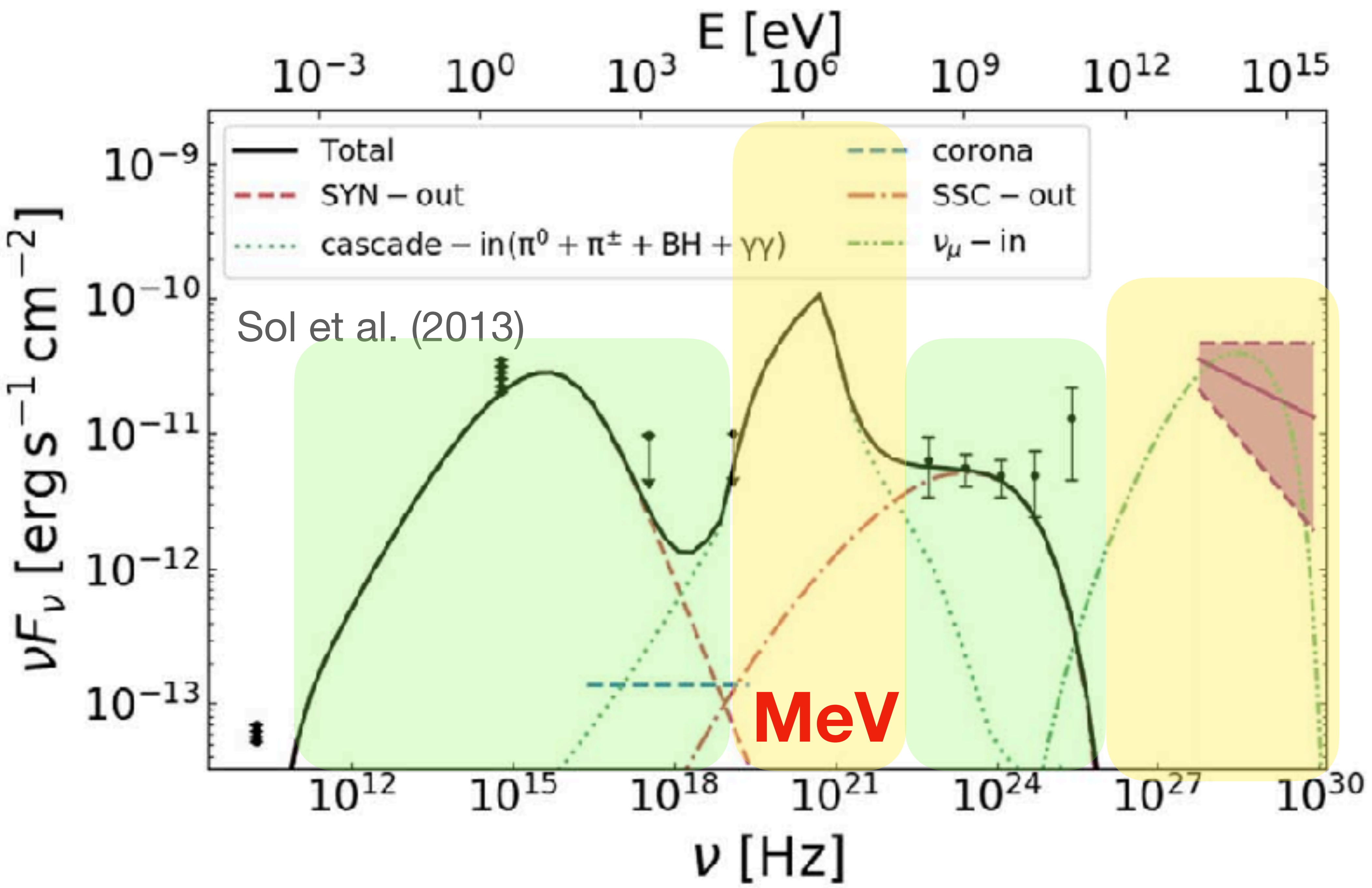
- Modeling TXS 0506+056/IC-170922A needs **a leptonic genesis for γ-rays** [Ansoldi et al. 2018, Keivani et al. 2018, Cerruti et al. 2019, Gao et al. 2019] (one zone assumed)
  - Hadronic component covered under the leptonic component
- γ-rays co-produced with IceCube neutrinos should initiate EM cascades, with their energy escaping in the optical-UV-X-ray spectrum
- Leptonic processes likely dominate their γ-ray emission, negating the need for γ-neutrino correlation
  - Instead, photo-hadronic cascades in blazar jets should **manifest as X-ray/UV emissions**, potentially **a more reliable neutrino-activity indicator**

Blazar Observation: Recent Trends in Astrophysics

Then why not two zones?



Xue et al. 2020



- Active research on modeling TXS 0506+056 assuming a two-zone framework [Xue et al. 2020, Zhang et al. 2020, Reimer et al. 2019]
- The EM emission observed from the blazar is **not coincident with the site of neutrino production**
- **MeV/UV band observations could lead to model rejection**; observations are awaited

Measurement of Cosmological Parameters using γ-ray's cosmological optical depth

- The opacity of gamma rays against Extragalactic background light (EBL) depends on H_0 and Ω_m.
  By using this fact in reverse, they gave constraints on H_0 and Ω_m from the EBL attenuation data

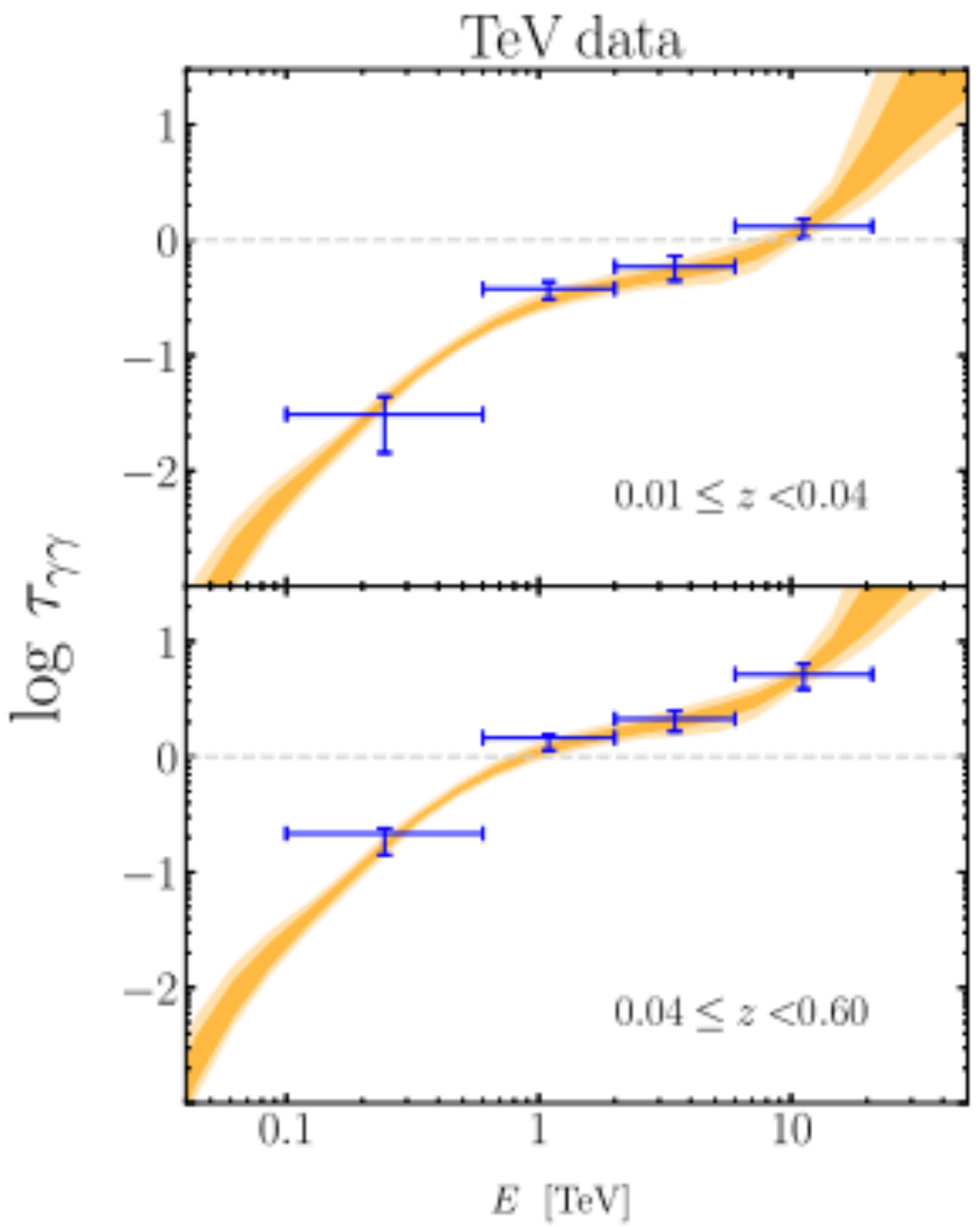
- The H0 dependence occurs at > 100 GeV and increases with energy
  The strongest constraints on H0 come from the lower redshifts

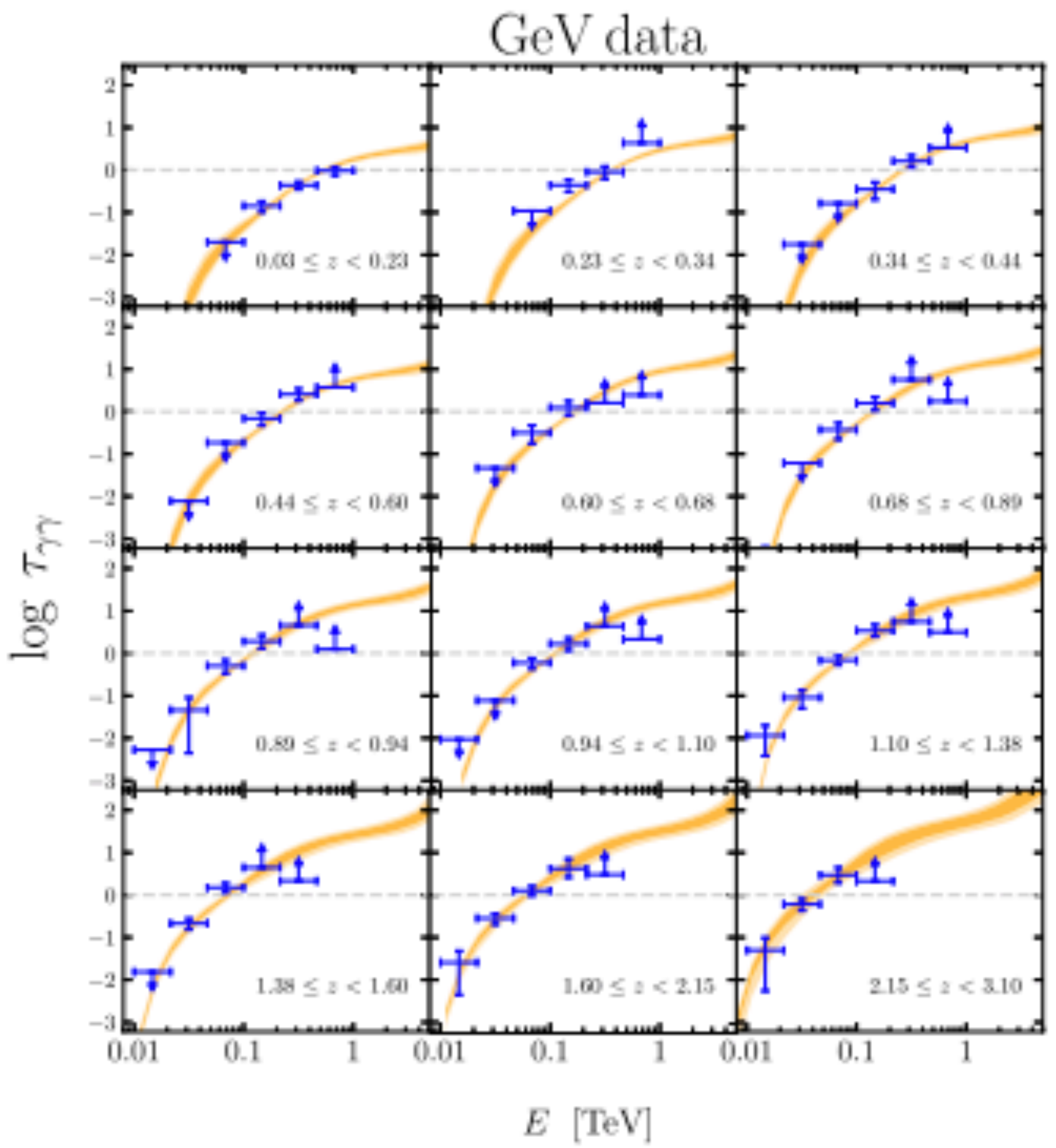
- **Ω_m dependence becomes stronger for the larger redshifts**

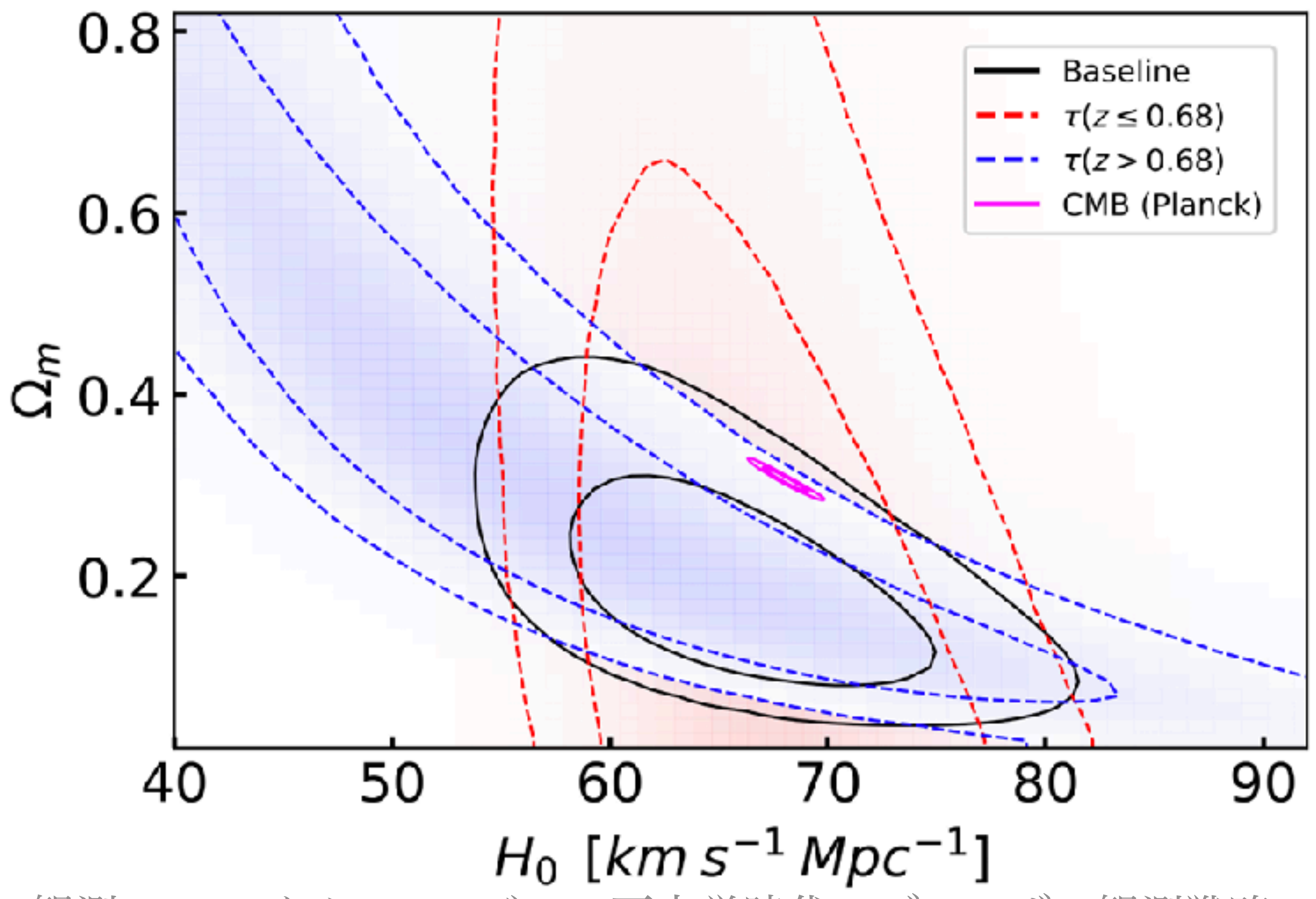
TeV optical depth $\tau\left(E_\gamma, z\right)$ data (Desai+ 2015) measured by using EBL model

↓

Possible systematic error in the method?







cherenkov telescope array

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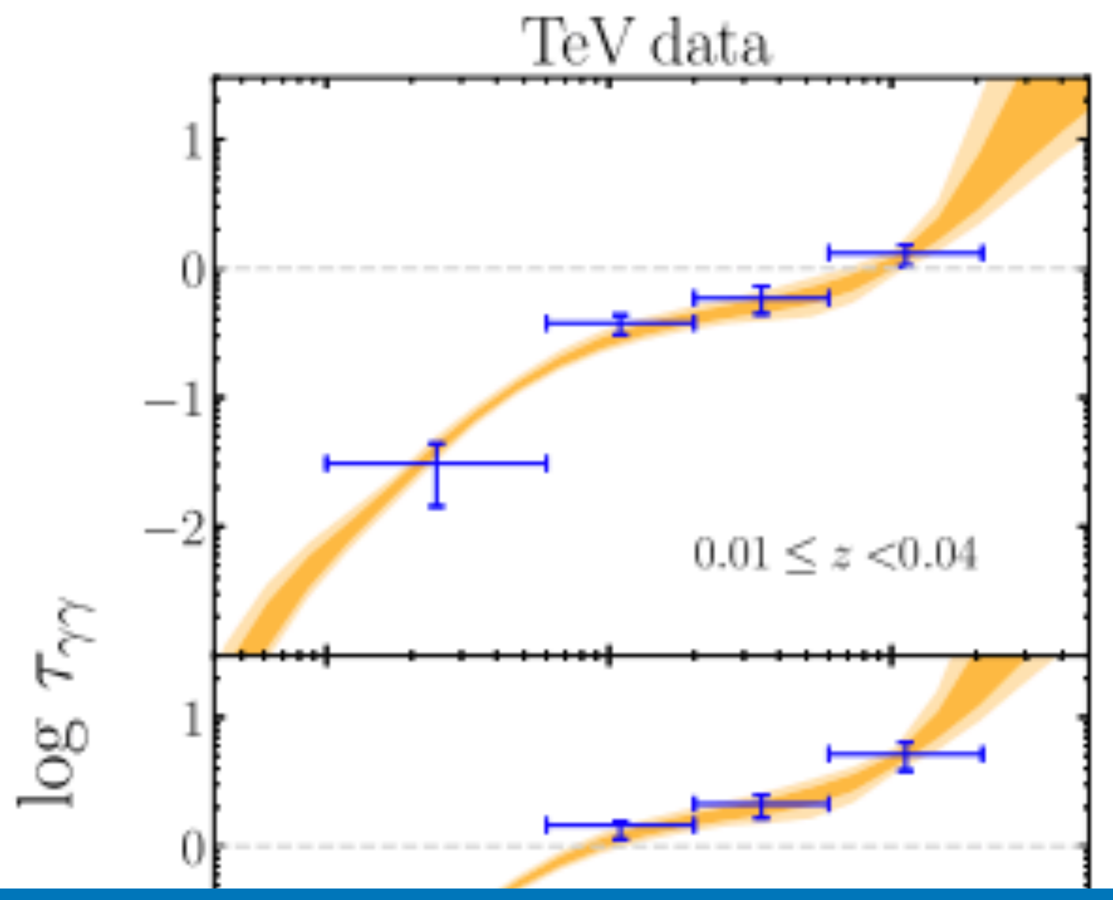
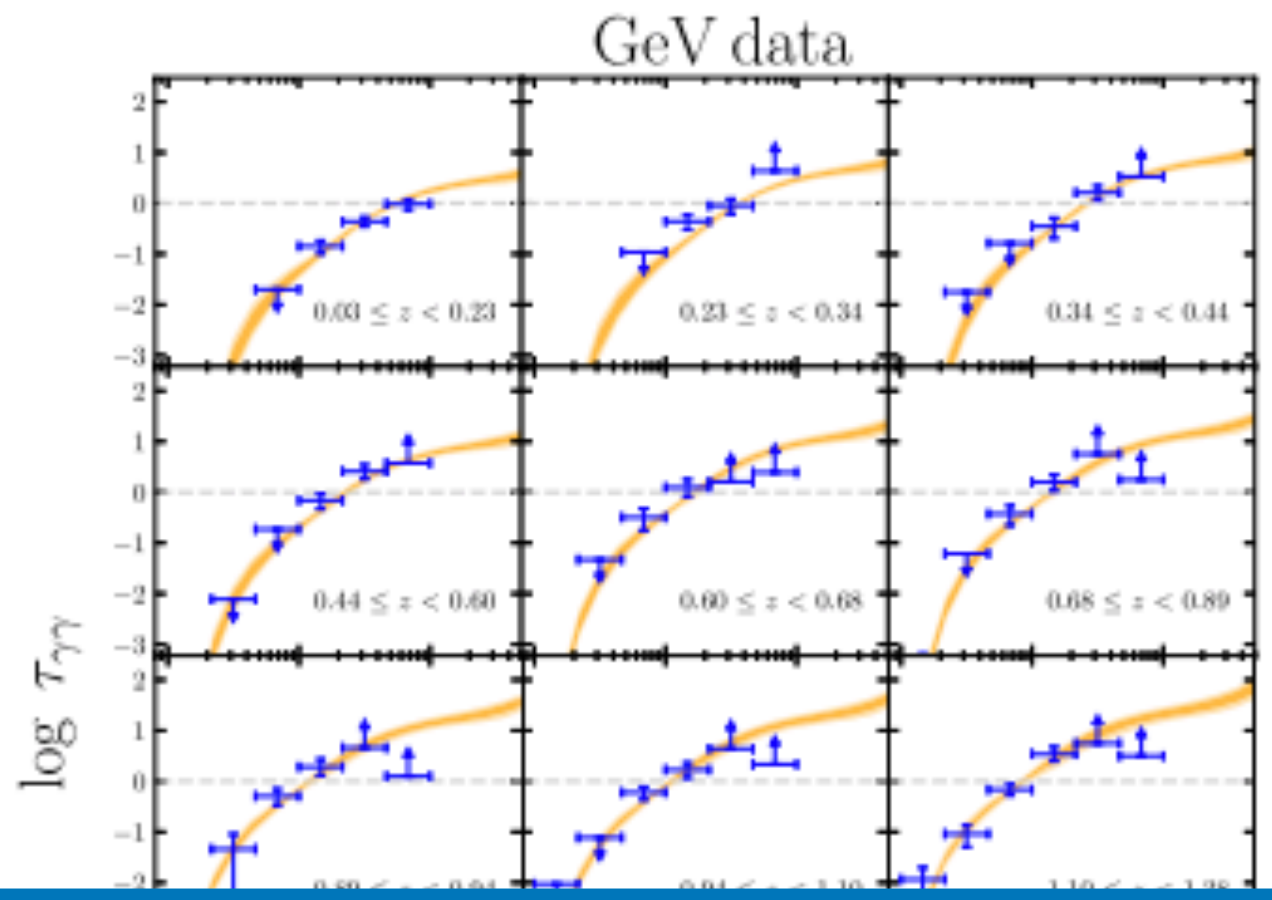
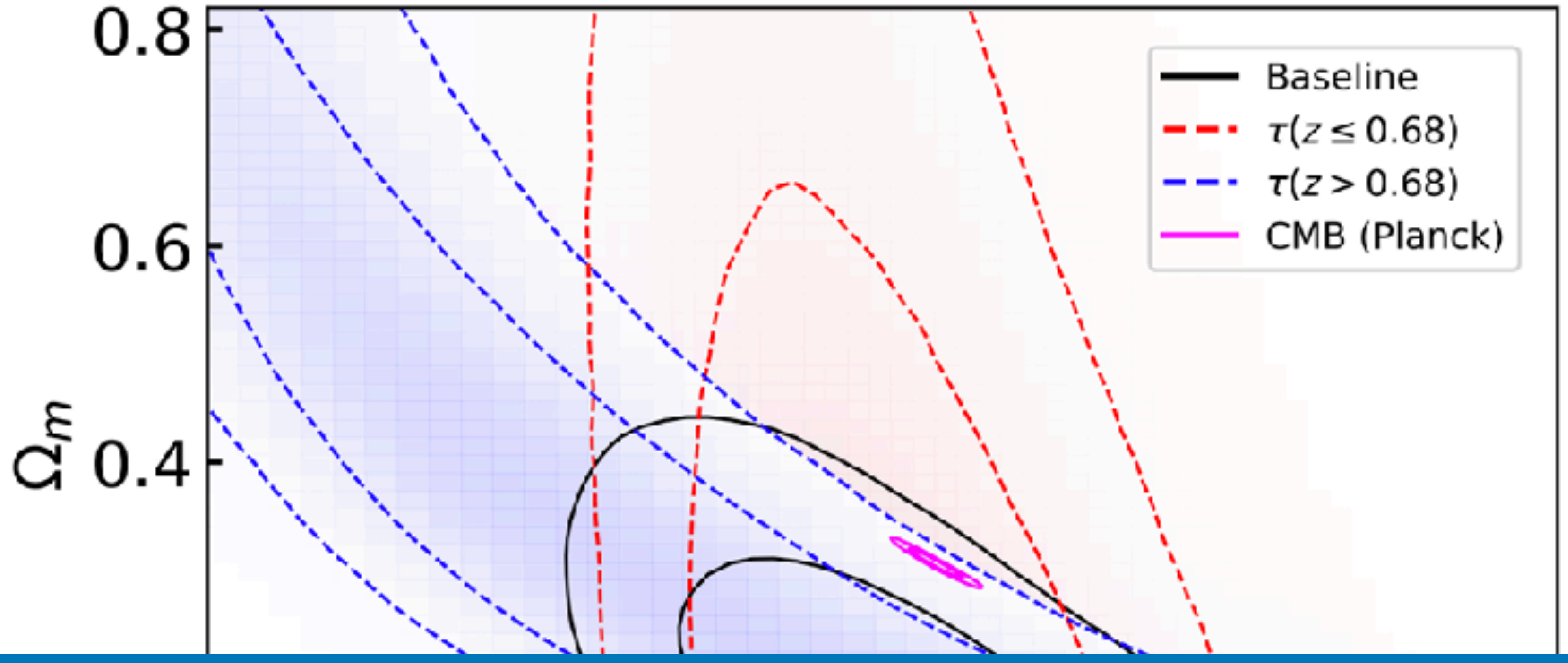




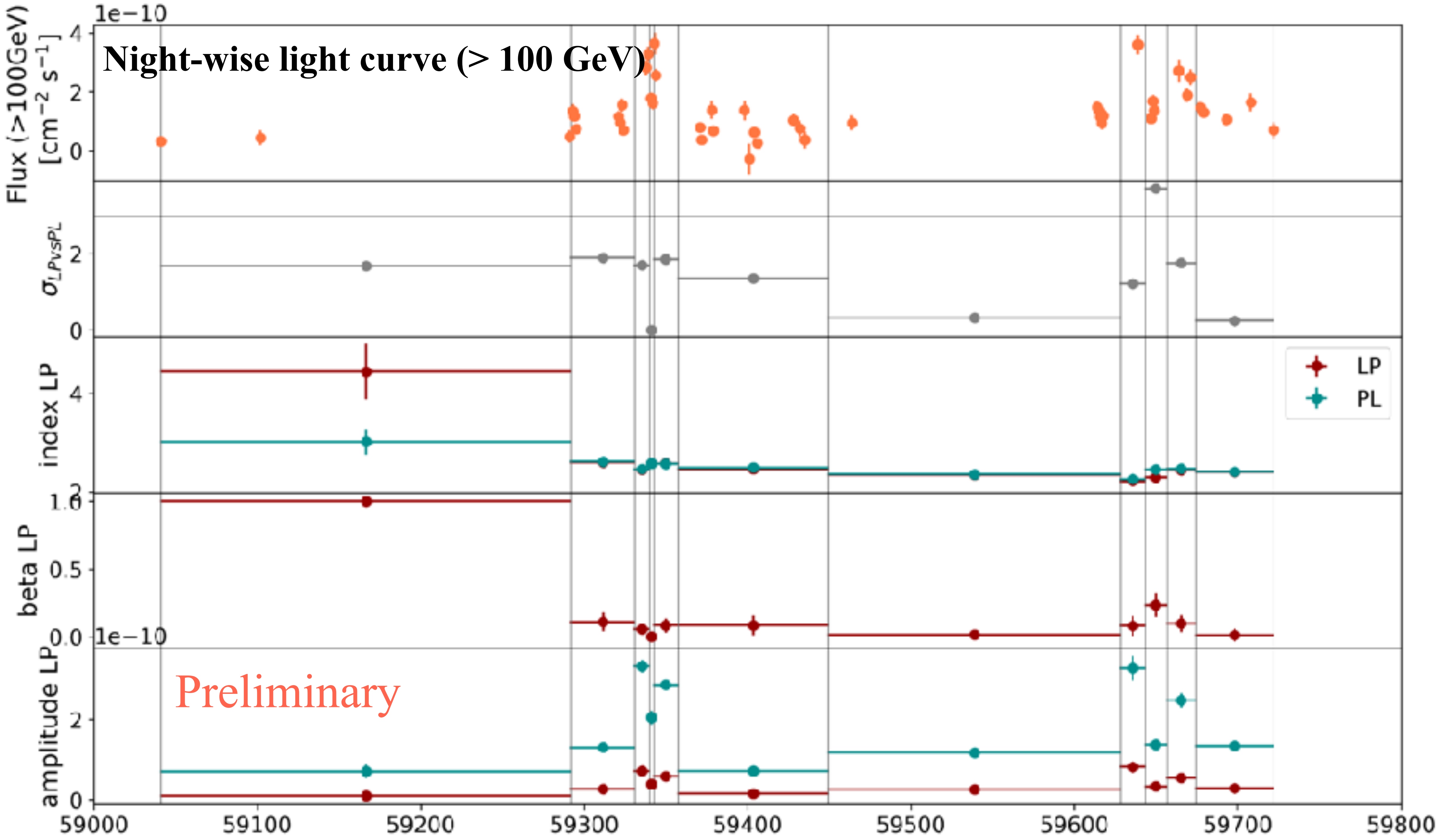


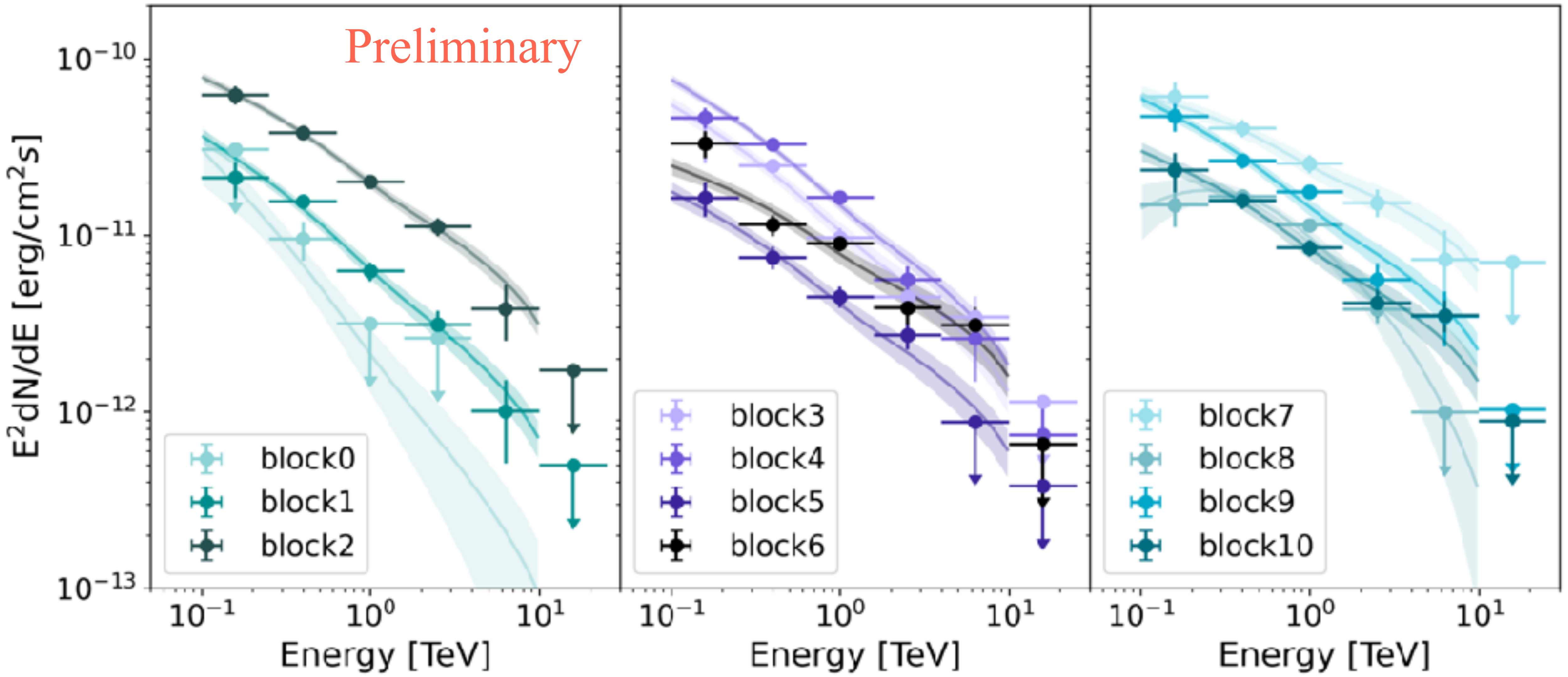
CTA could potentially offer the precision needed to tackle the Hubble Tension, given its broad energy sensitivity

Seeing Variabilities: Mrk501 Light Curves and SEDs

Tracked the temporal evolution of a spectrum consisting of 11 blocks via the application of a Bayesian block algorithm

- Data period: 2020/07/10 - 2022/05/22 (153 runs, 39.7 h)
- The spectrum variation, already verified in VHE gamma, was also properly confirmed in our data set

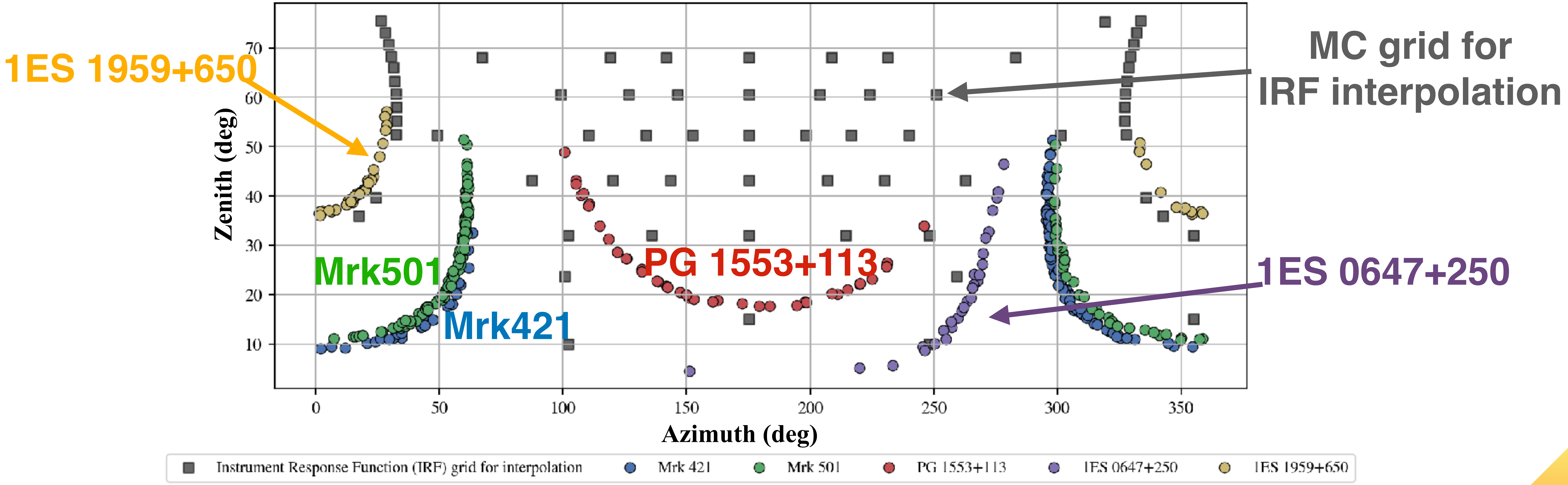




LST-1 Data Analysis Method

Perform IRF interpolation to minimize the discrepancy between Simulation and Data

- Reconstruction of primary particle information using Random Forest trained with MC simulation of gamma-ray and cosmic-ray showers as input
- The Estimation of the IRFs at given telescope pointing direction was performed through the interpolation of Monte Carlo (MC) simulations, generated on a grid in the (zenith, azimuth) plane



LST-1 Data Analysis Method

We used cta-lstchain for creating IRFs and event list, and Gammapy for subsequent processes

- Python-based pipeline **cta-lstchain v0.9.12/0.9.13** (dedicated analysis tool for LST data)
- For the generation of high-level visualizations, including SED and Light Curves, we employed **Gammapy v1.0.1**
    - **Gammapy**: open-source Python package for gamma-ray astronomy built on Numpy, Scipy and Astropy