Variable Galactic Gamma-Ray Sources VII
University of Barcelona, May 6-8 (2025)

Observations of Galactic binaries in the sub-MeV/MeV band with future prospects

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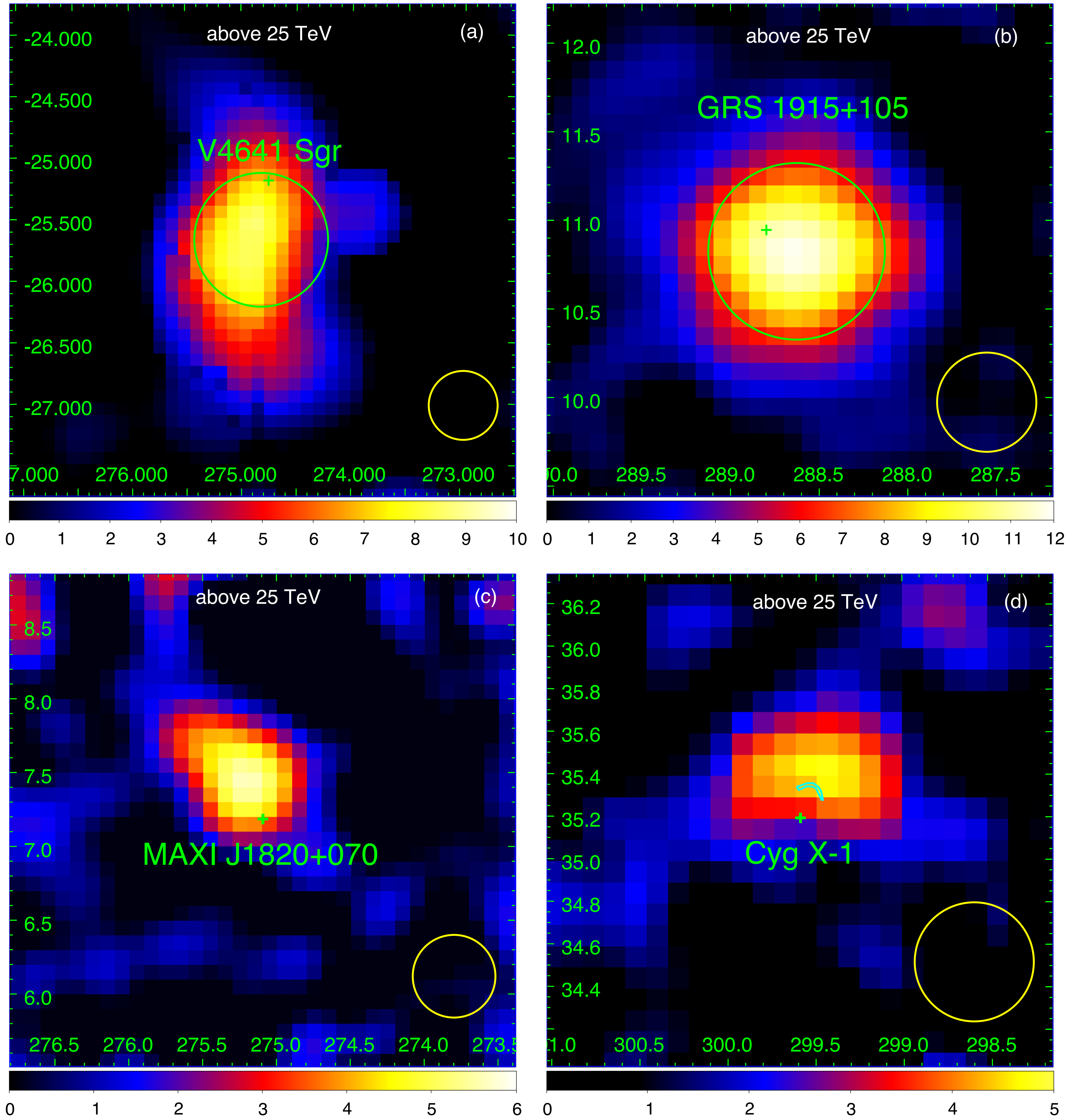
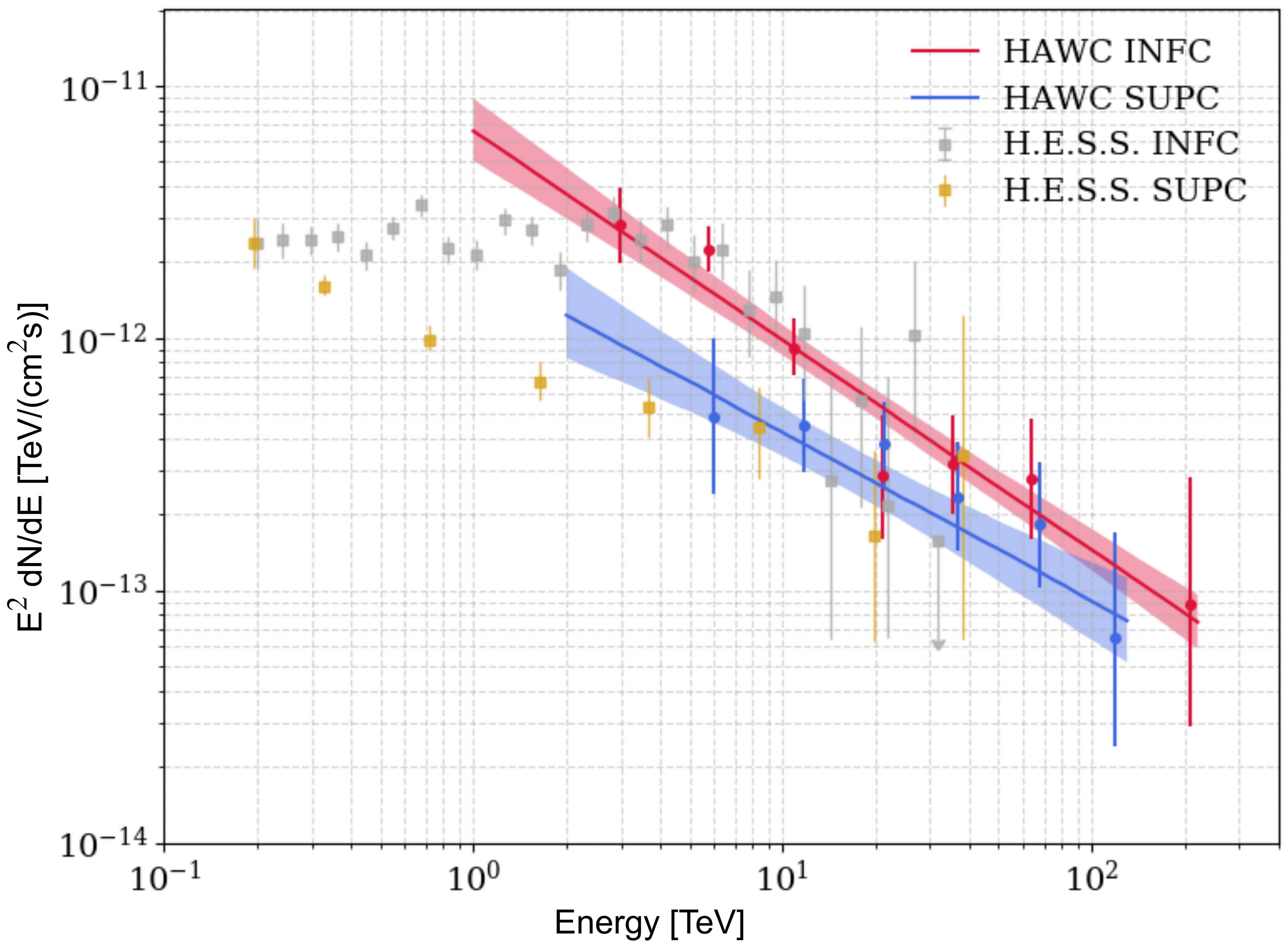
Particle acceleration in Galactic binaries

Sub-PeV gamma-ray measurement from BH-jet systems (LHASSO collab. 2024)



Extended gamma-ray emission to 200 TeV in the gamma-ray binary LS 5039 (HAWC collab. 2025)

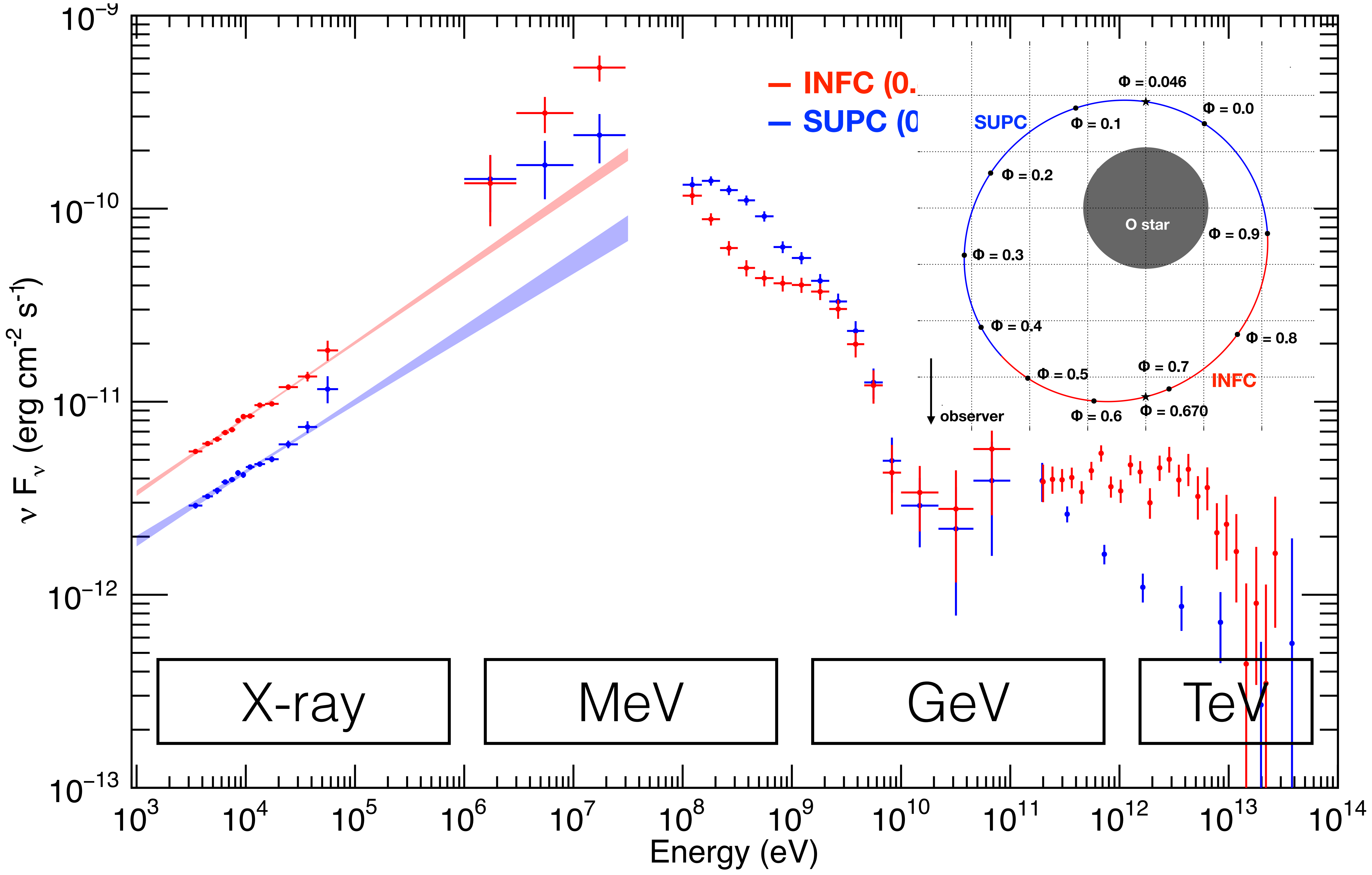


They challenge the origin of Galactic cosmic rays

- They are PeVatron sources?
- **Extremely efficient leptonic particle accelerator?**

Sub-MeV/MeV gamma-ray synchrotron from gamma-ray binaries

Broadband spectrum of LS 5039 (HY+21)



Maximum gamma-ray energy allowed in synchrotron emission

$$T_{\rm sync} = \frac{6\pi mc^2}{c\sigma_T \gamma B^2} \simeq T_{\rm acc} = \gamma mc^2/\dot{E}$$

$$E_\gamma = \hbar \frac{qB}{mc}\gamma^2 = \frac{9}{4}\frac{mc^2}{\alpha\xi} \sim 160\ \mathrm{MeV} \times \xi^{-1}$$

Gamma-ray energy

Acceleration parameter

$$\dot{E} = q_e B c \xi^{-1}$$

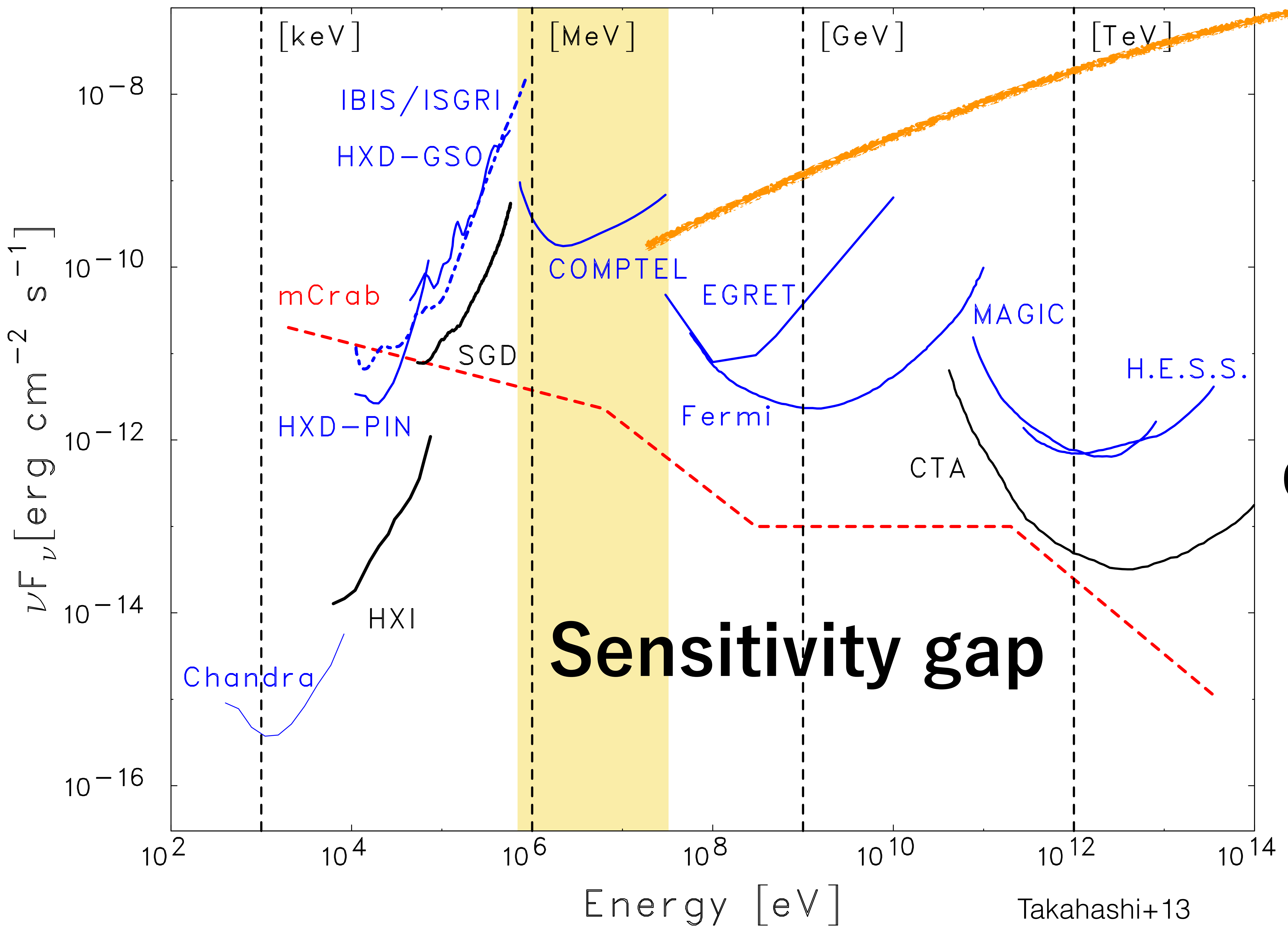
Sub-MeV/MeV synchrotron can be a smoking gun for extremely efficient leptonic acceleration $\xi \sim 1$

Emission up to 30 MeV was reported from the gamma-ray binary LS 5039 (and LS I +61 303?) by COMPTEL

Possible MeV-TeV/PeV correlation from some leptonic particle accelerators (e.g., Crab PWN, Khangulyan+19)

The current status of MeV gamma-ray astrophysics

- **MeV gamma-ray observation is a remaining frontier in astrophysics**
  - Achieved sensitivity is x10-100 worse than X-ray/GeV



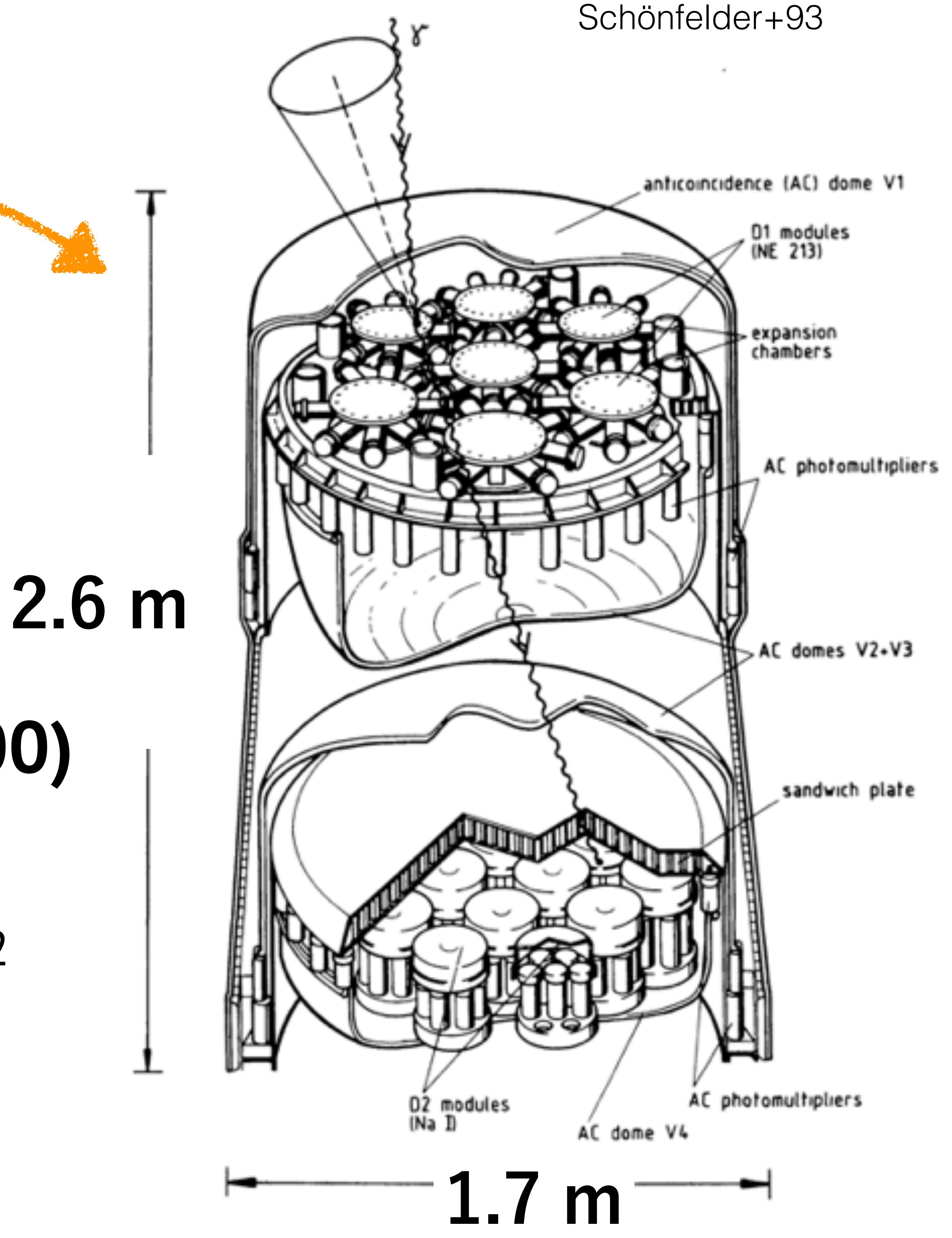
Takahashi+13

COMPTEL (1991-2000)

Effective area

→ only 20-50 cm²

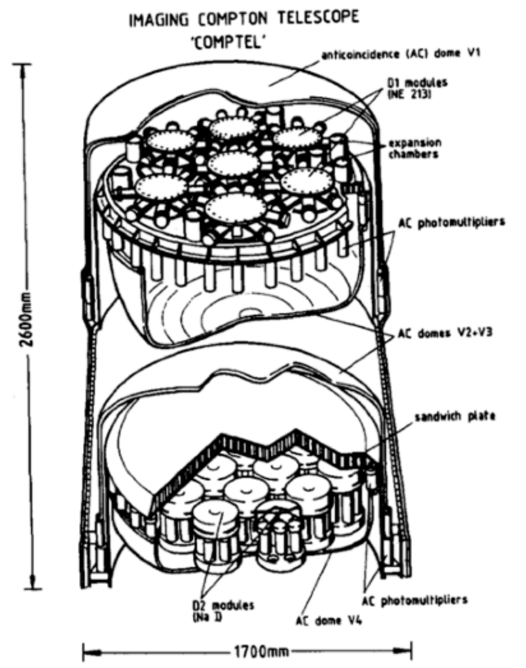
Schönfelder+93



Past, Present, Future of MeV gamma-ray observations

Past | **Present** | **Future**

1990 — 2000 — 2010 — 2020 — 2030 — 2040



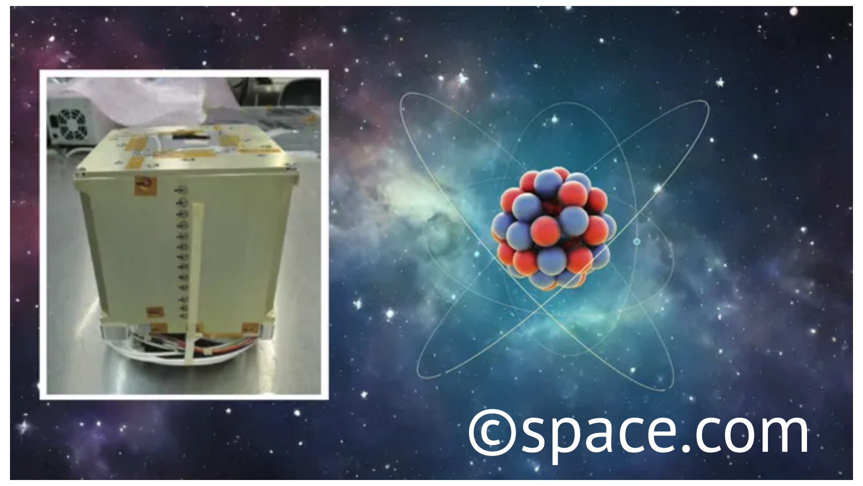
COMPTEL, NASA
(1991-2000)

INTEGRAL/ESA
(2002-2025)

SGD/Hitomi, JAXA
(2016)

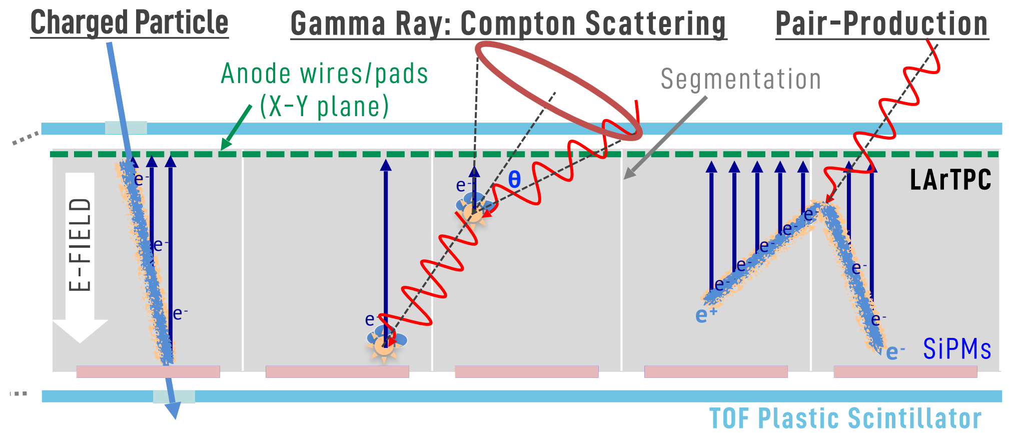
Application to nuclear experiments (Go, Tsuzuki, HY+24)

COSI, NASA
(2027-)



A large-scale mission in 2030s? 2040s?

SMILE, AMEGO, GRAMS, GECCO, MASS, MeGaT, MeVCube, HARPO, and more...

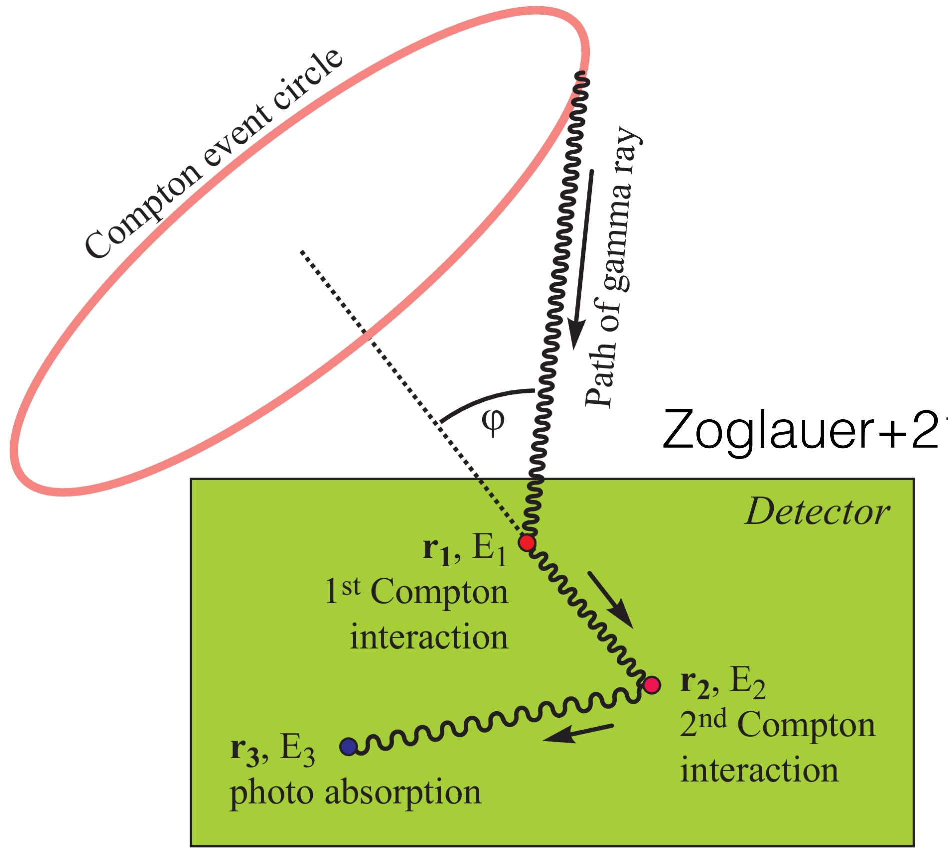


GRAMS, Japan+US

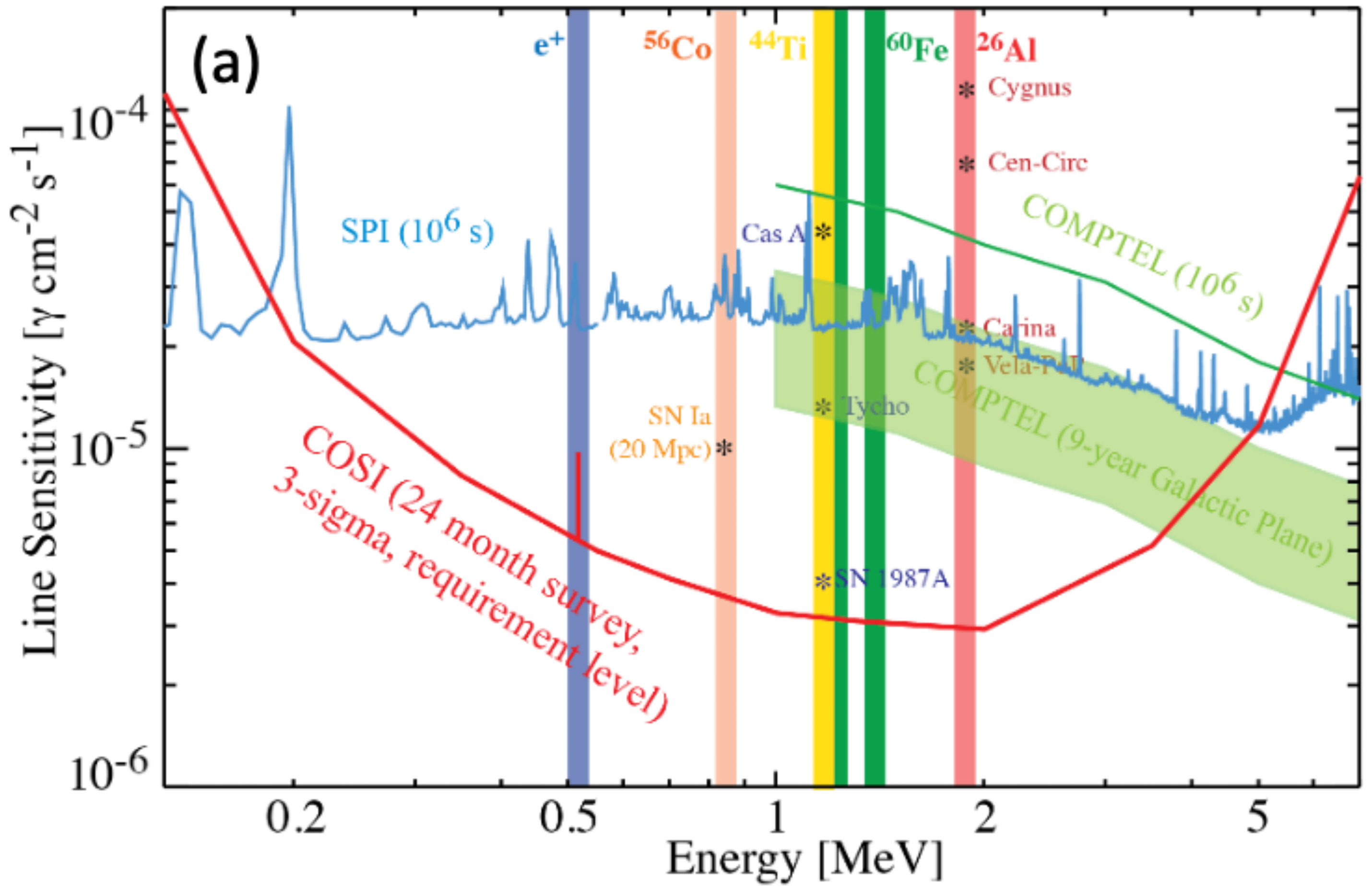
- A large-scale mission with liquid argon
  - engineer balloon flight from Japan in 2023
  - engineer balloon flight in 2025/2026

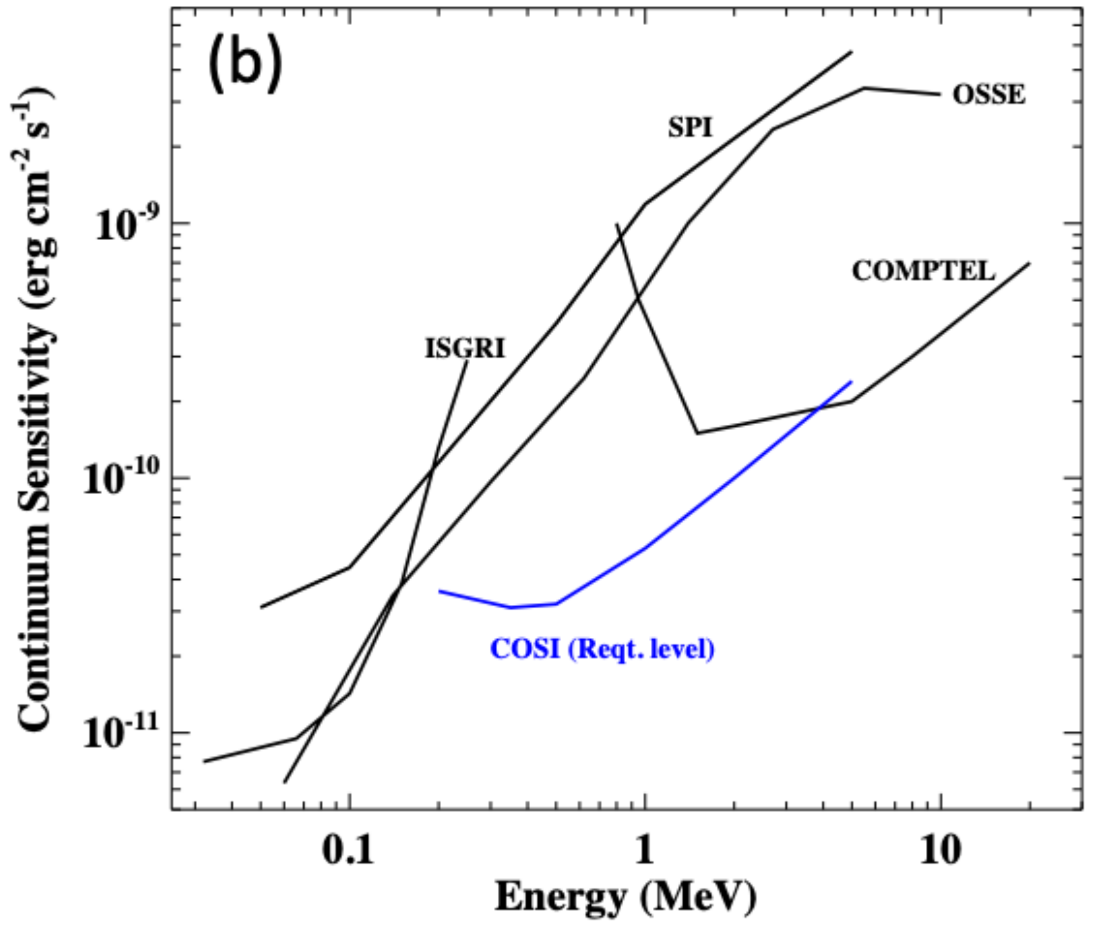
COSI (The Compton Spectrometer and Imager)

- ✦ was selected as a NASA SMEX satellite to be launched in 2027
- ✦ a Compton telescope observing gamma-rays in 0.2 - 5.0 MeV



Zoglauer+21





Tomsick+23

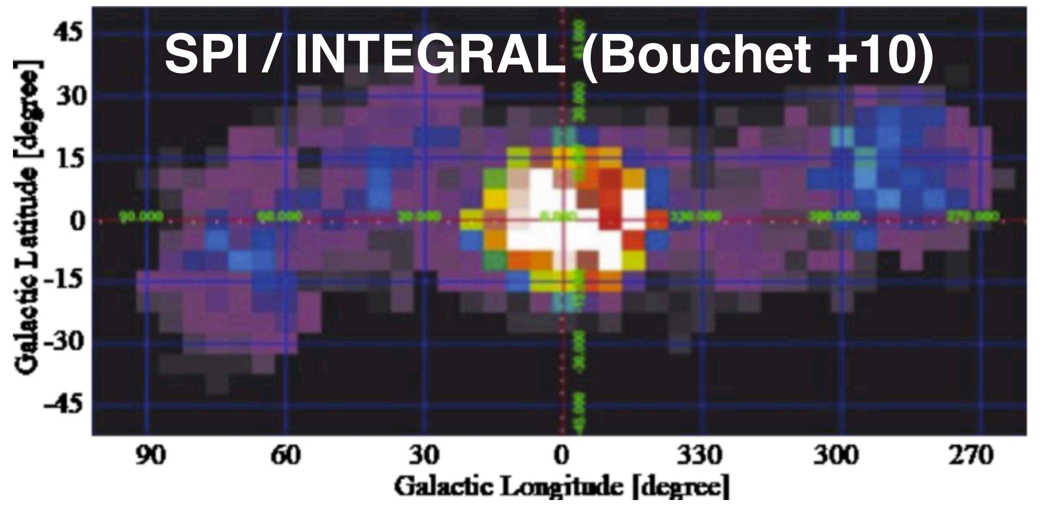
Key capabilities

- ✦ Cryogenically-cooled germanium detectors
  - ➔ gamma-ray line imaging with excellent energy resolution ~1%
- ✦ Instantaneous field-of-view is ~25% of the sky
  - ➔ all-sky monitoring (whole sky observation in a day)

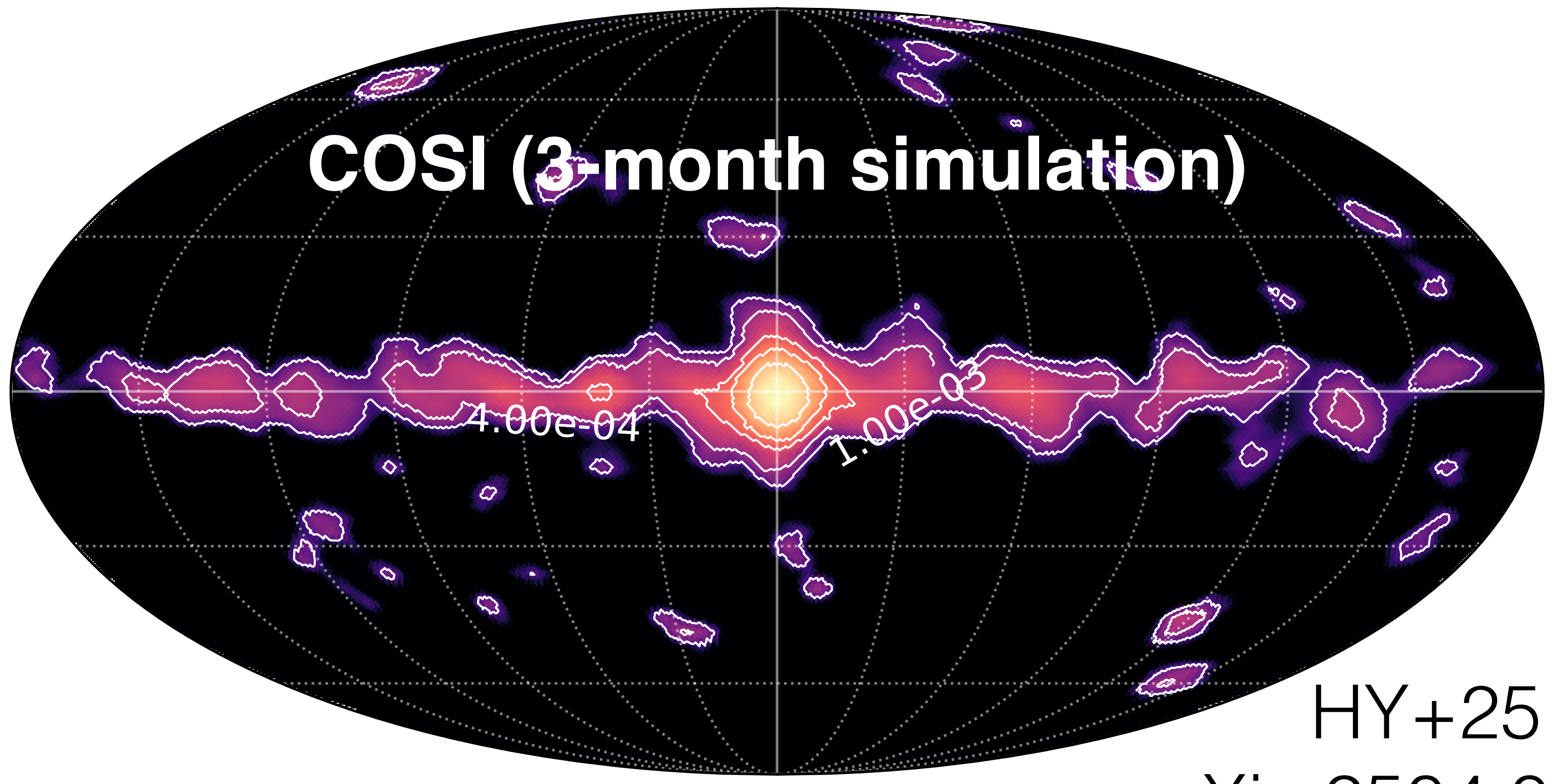
Key science goals

A. **Uncover the origin of Galactic positrons**

B. **Reveal Galactic element formation**

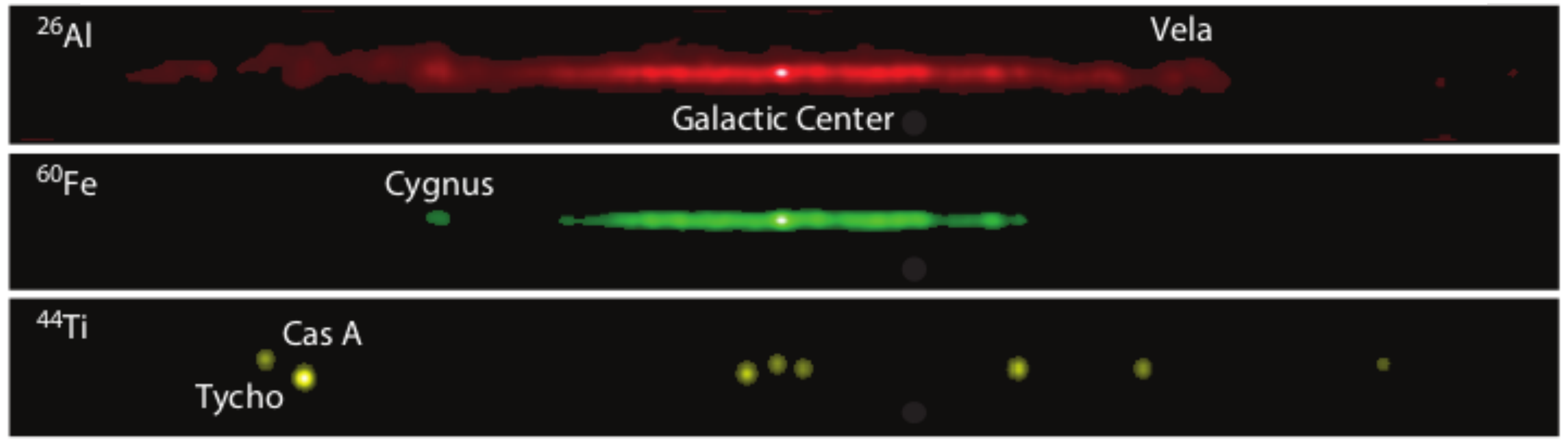


511 keV all-sky image



HY+25
arXiv:2504.02468

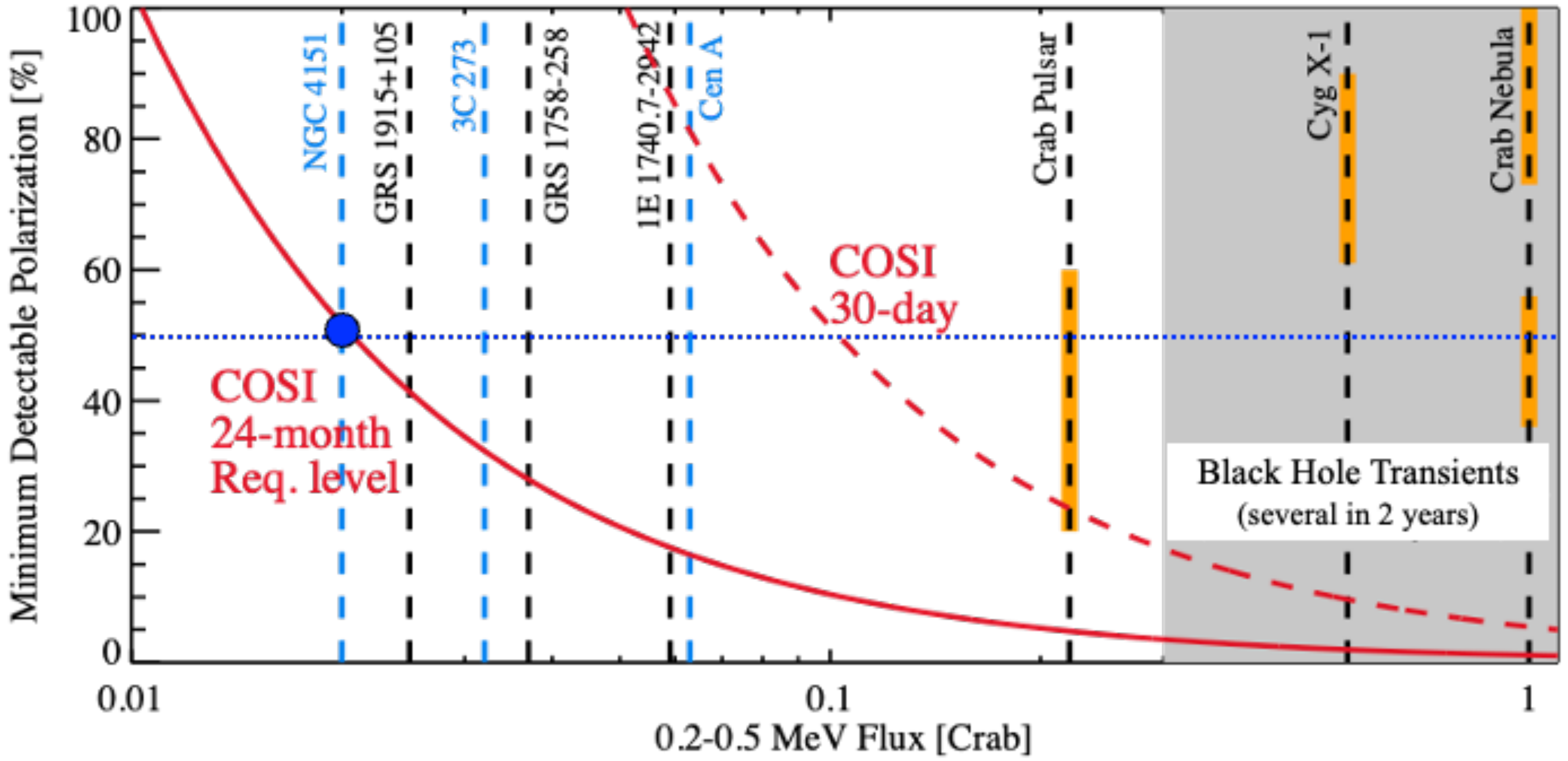
Nuclear gamma-ray lines (^{26}Al, ^{60}Fe, ^{44}Ti)



C. **Gain insight into extreme environments with polarization**

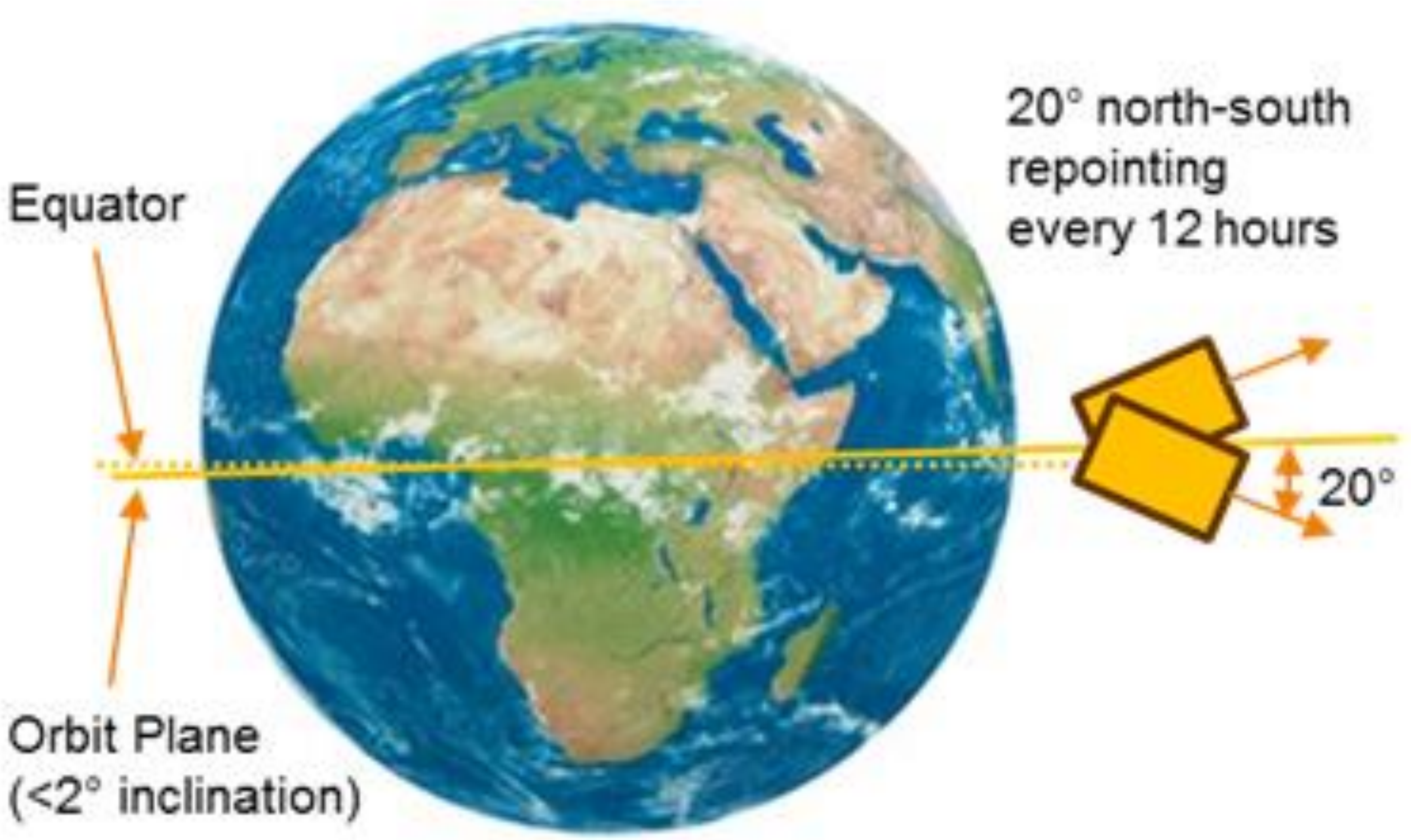
D. **Probe the physics of multimessenger events**

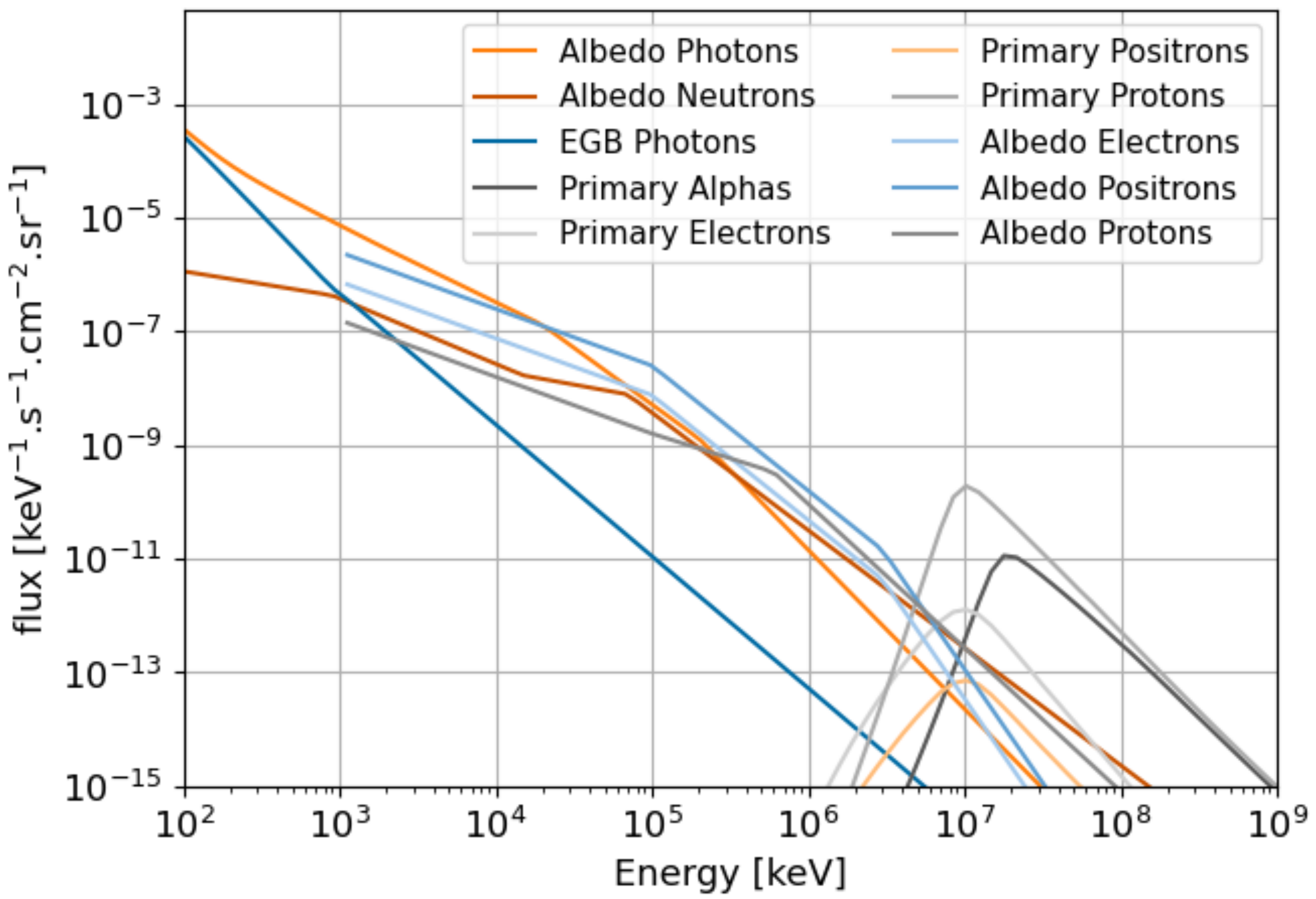
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2\left(\frac{E'_\gamma}{E_\gamma} + \frac{E_\gamma}{E'_\gamma} - 2\sin^2\theta\cos^2\chi\right)$$



Orange bars show existing measurements by INTEGRAL

Gamma-ray binaries with COSI





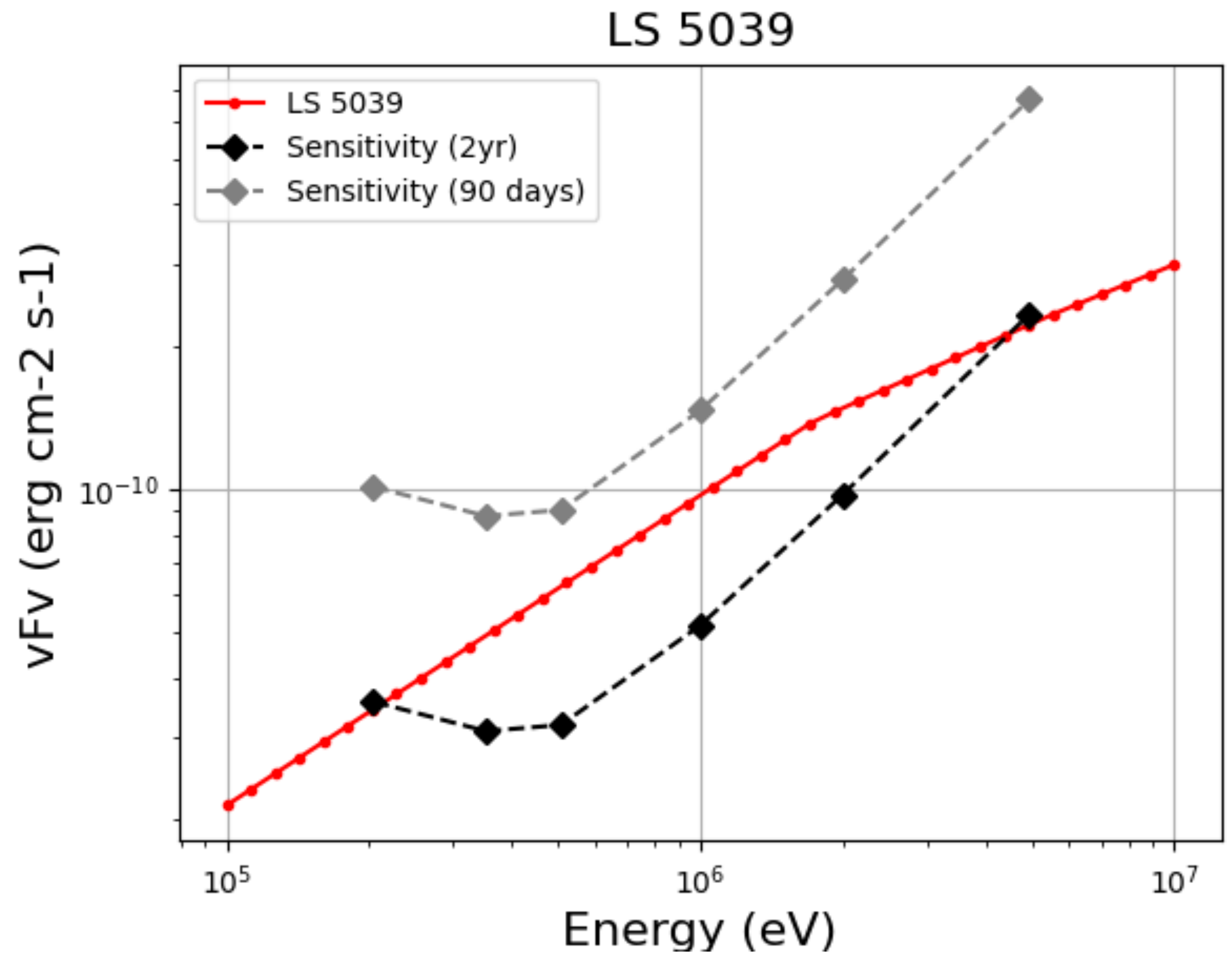
COSI Data Challenge 3 (DC3)

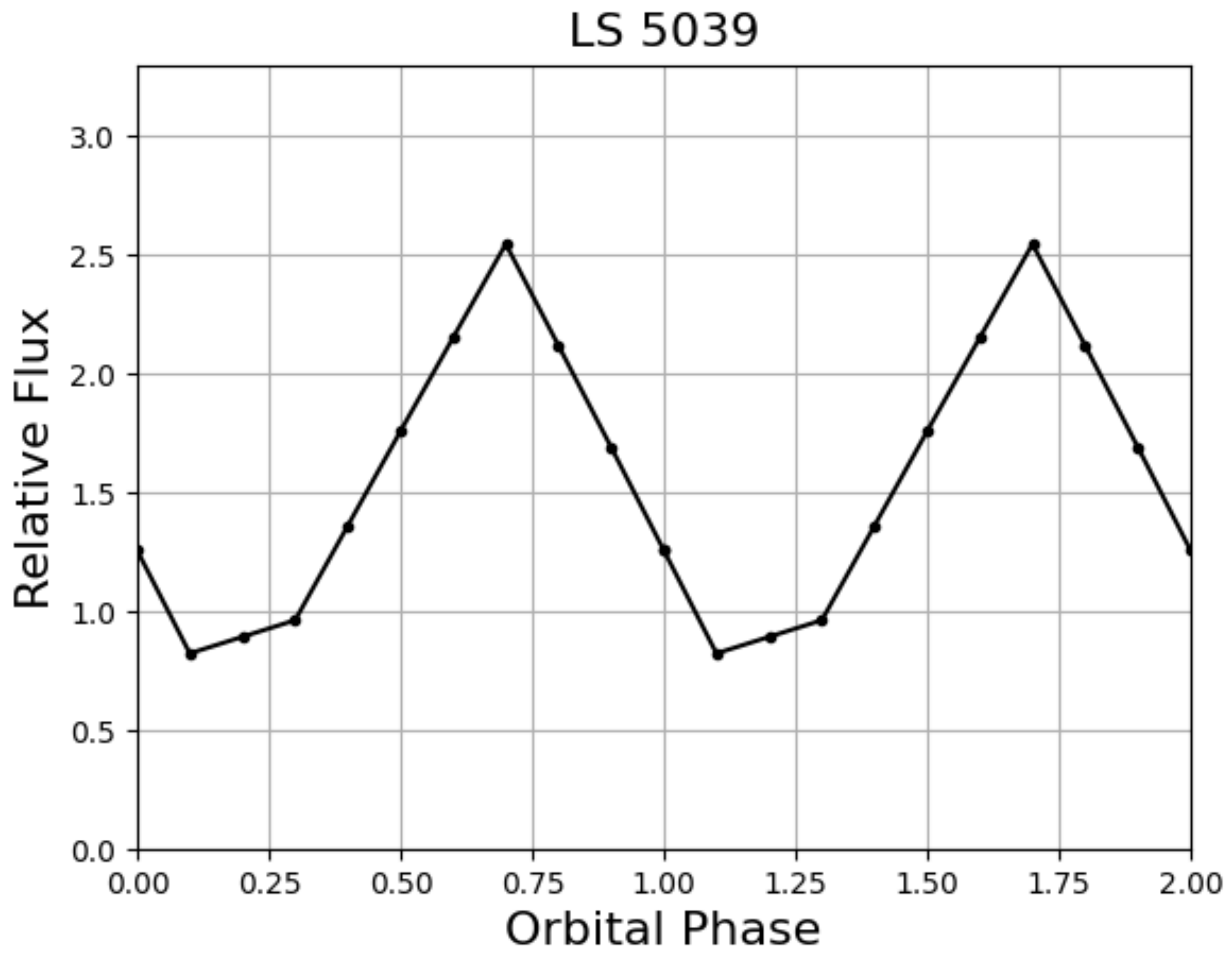
- provides simulated data designed to closely mimic future flight data
- enhances data pipeline and analysis tools (COSItools) through scientist feedback

Feasibility studies of gamma-ray binaries

- **added two objects to DC3 datasets:** LS 5039 (a persistent gamma-ray binary) and PSR B1259 (a transient source)
- **conducted comprehensive 3-month full simulation including:**
  - complete satellite orbital parameters
  - realistic background components including South Atlantic Anomaly (SAA) and galactic diffuse emission

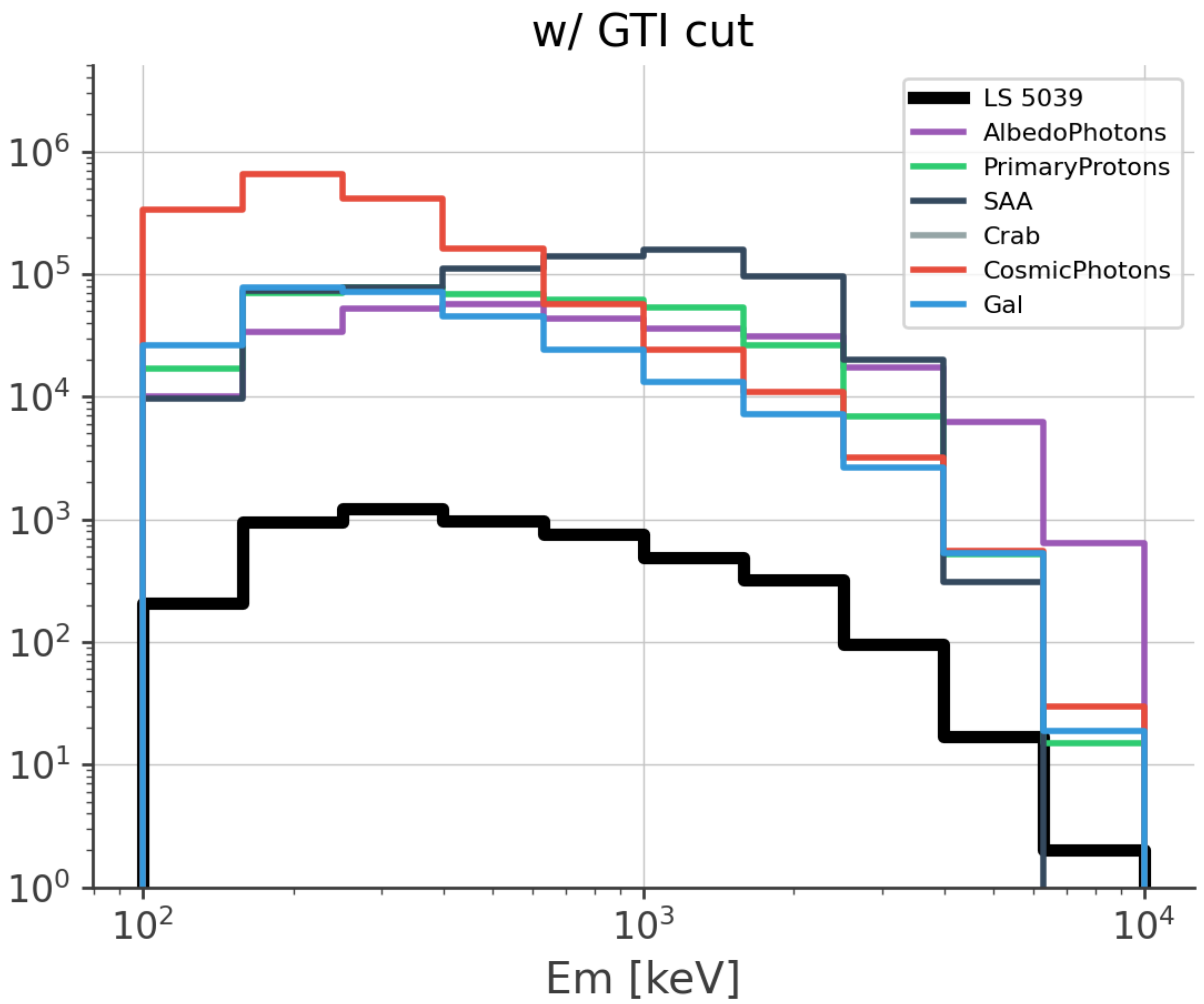
3-month simulation of LS 5039 in DC3

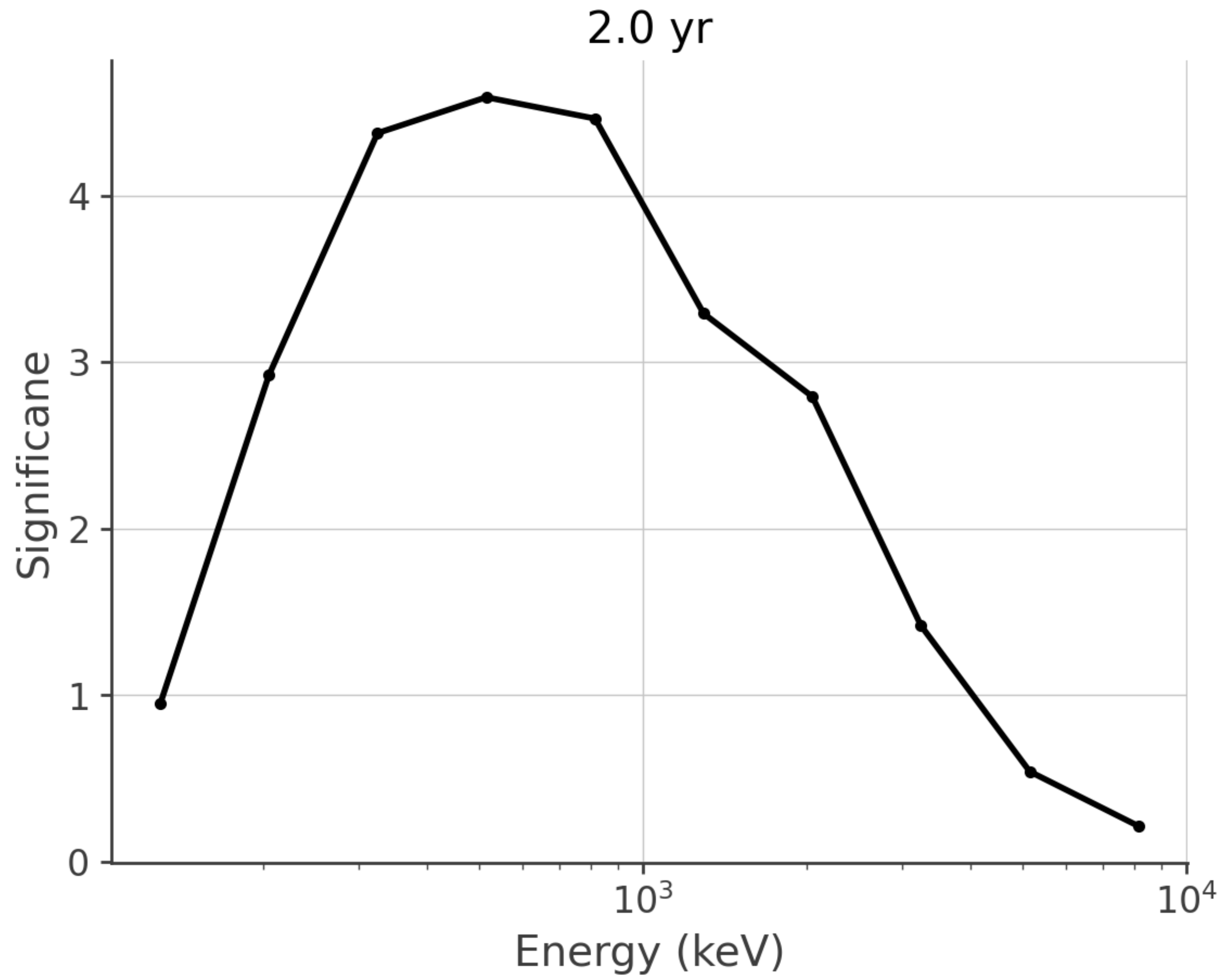




- The spectrum was generated by interpolating X-ray spectrum (HY+21) and MeV spectrum (Collmar&Zhang, 14)
- Used a spectrum averaged over the orbital period
- Orbital modulation is based on the orbital light curve

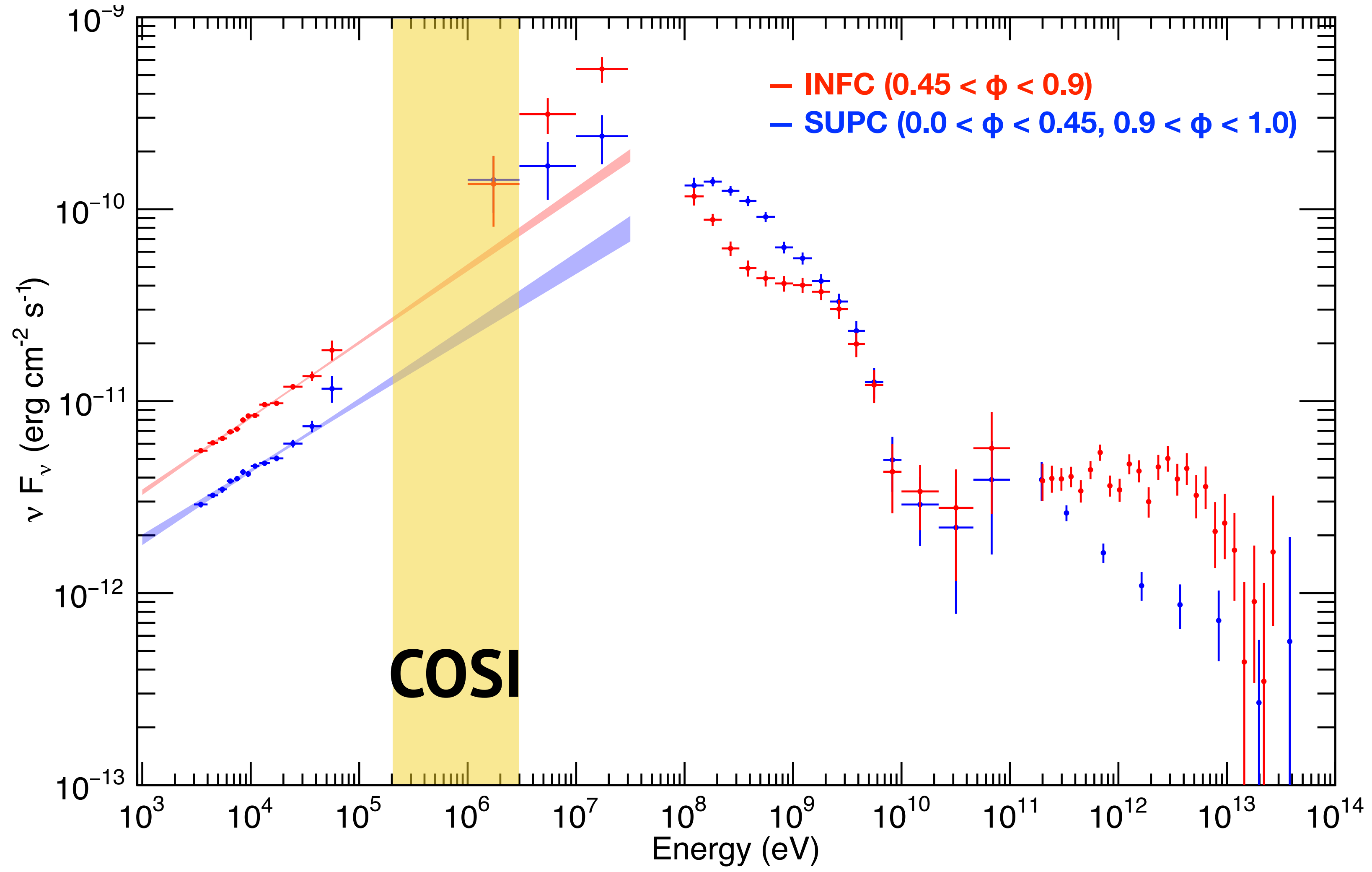
Count spectrum and significance



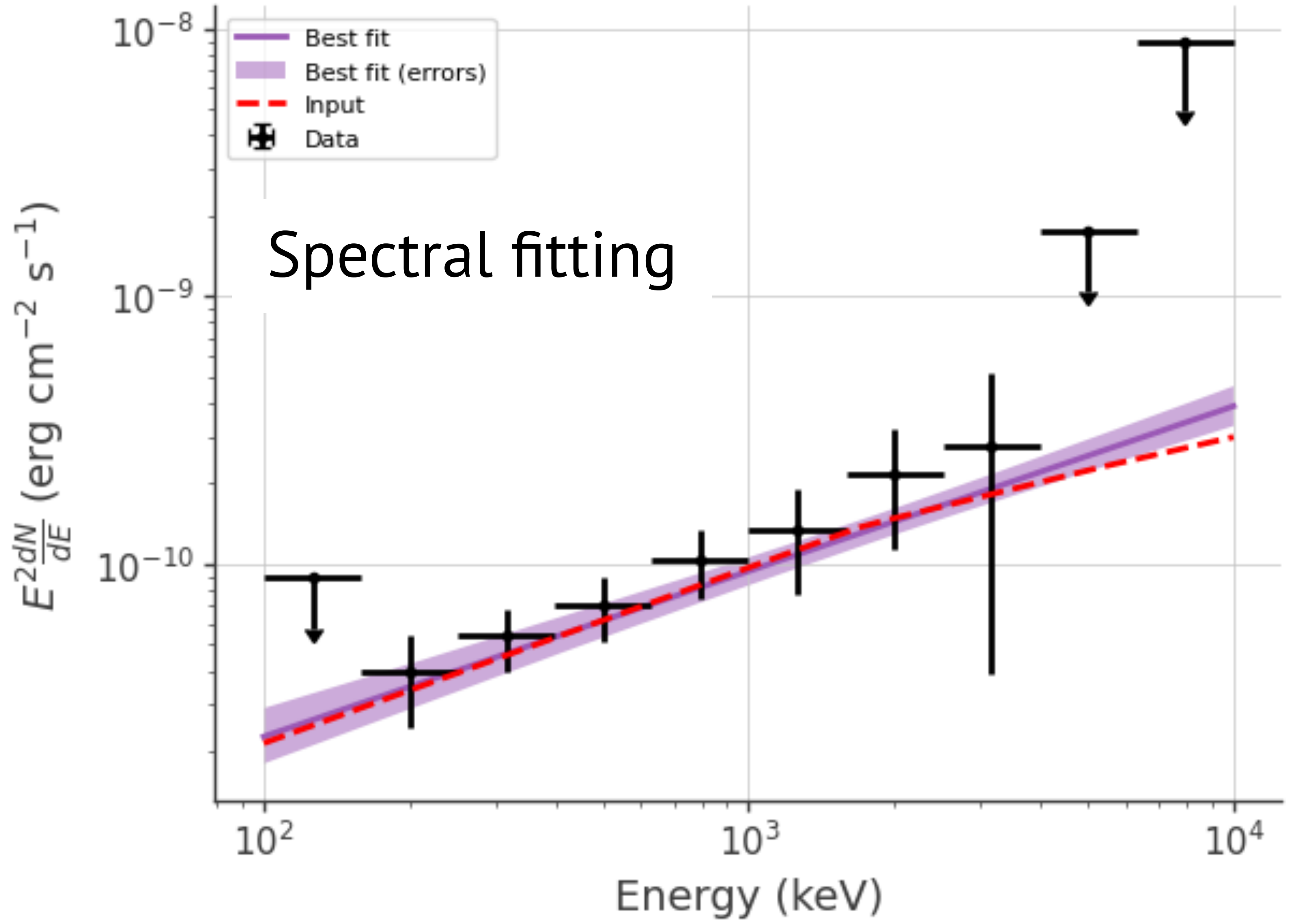


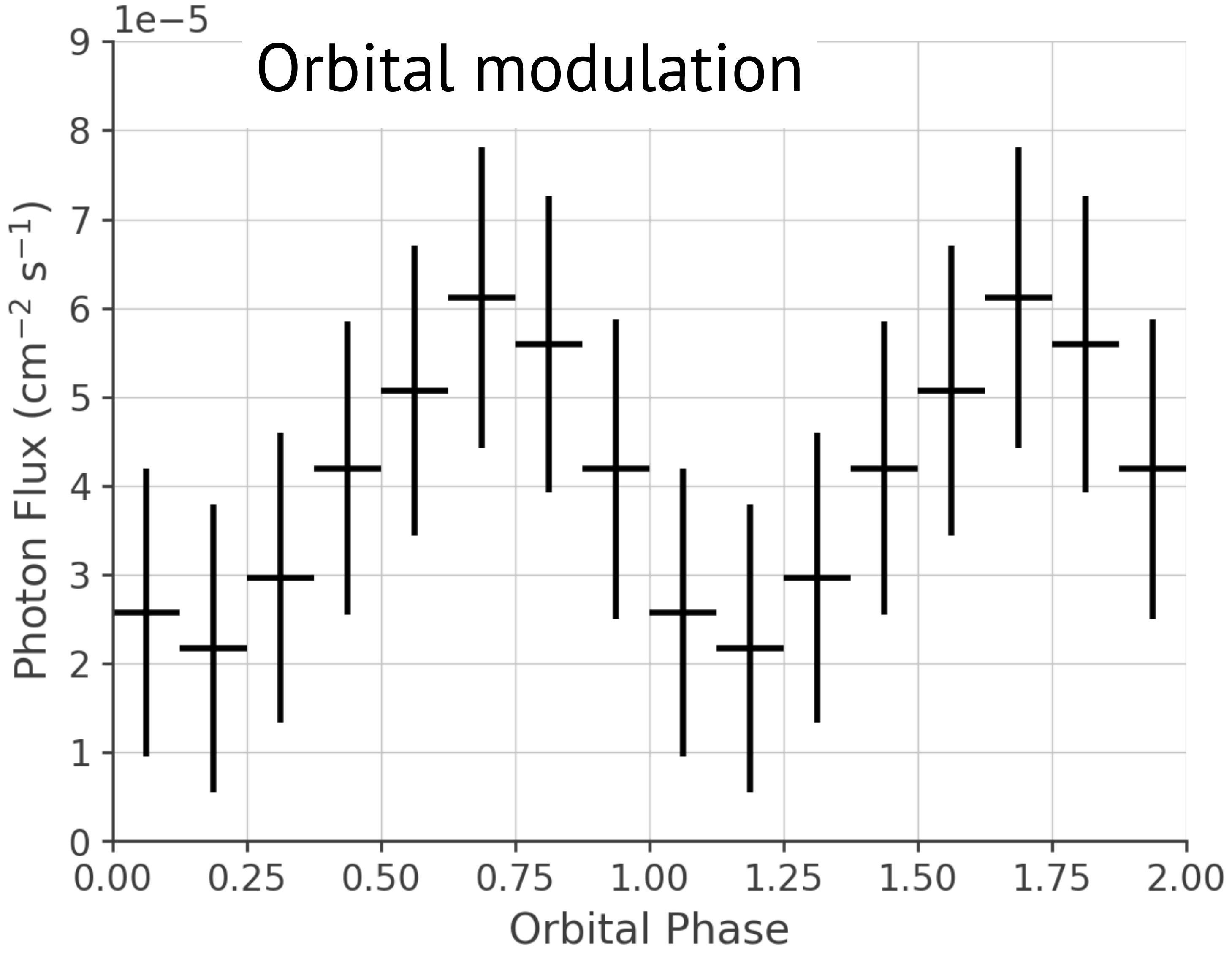
- With 3-month observation in DC3, the source and background counts are 5×10^3 and 3×10^6 on the point spread function of the Compton telescope.
- The detection significance ($= S/\sqrt{B}$) is ~3 sigma.
- By scaling it to 2 years, the spectral analysis from 0.2 to ~3 MeV can be performed

Spectral fitting and orbital modulation with 2-yr observation



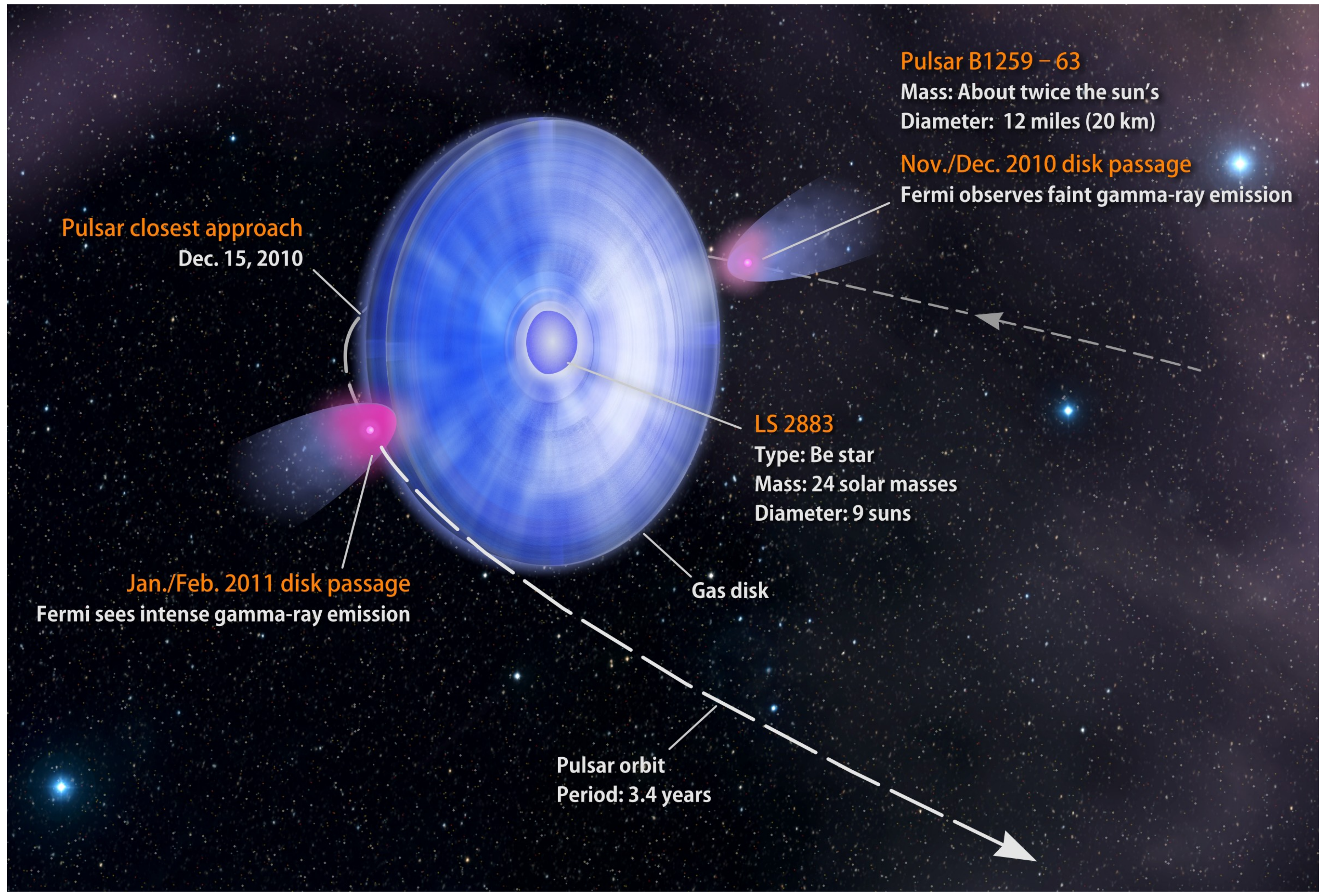
Simulation (scaled to 2-yr, DC3)

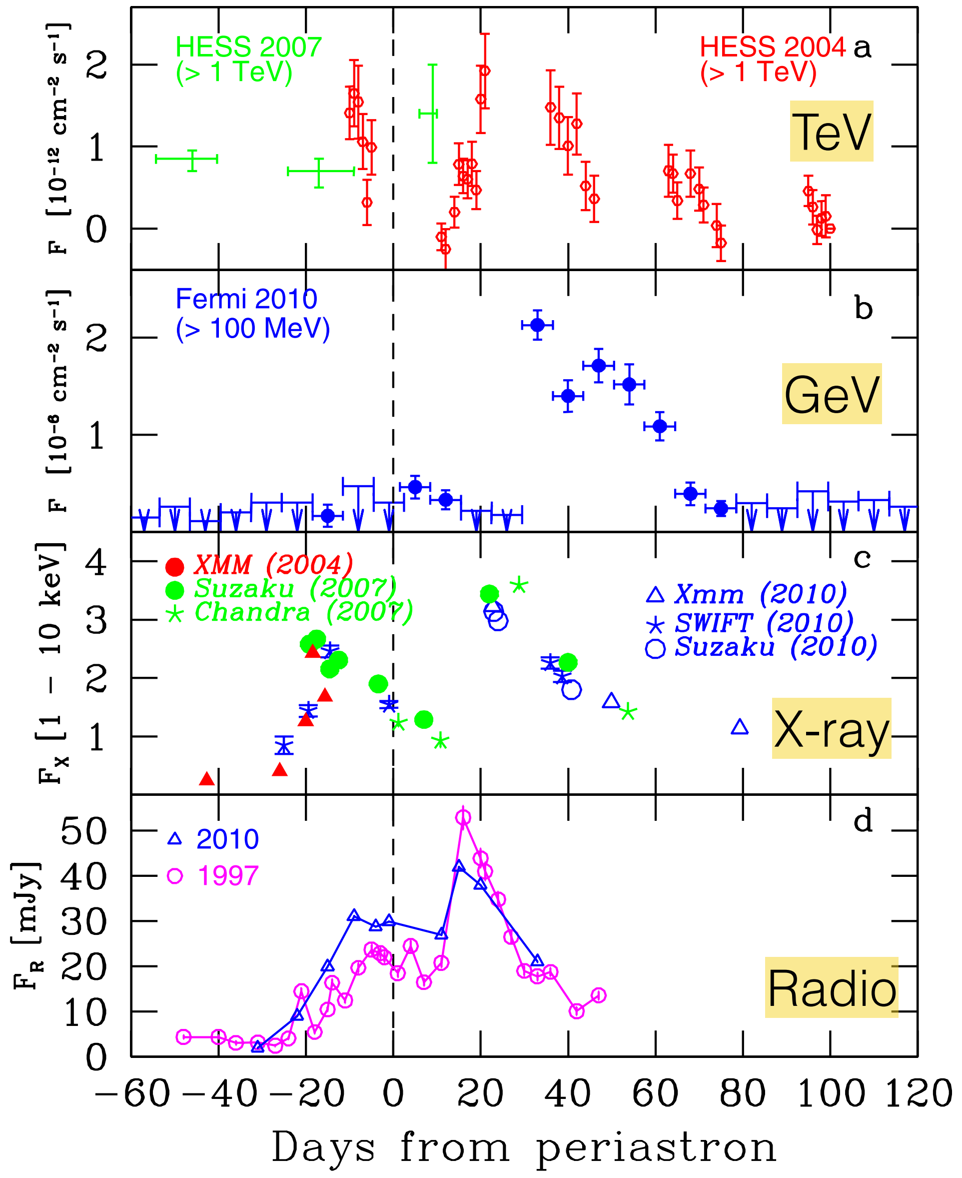


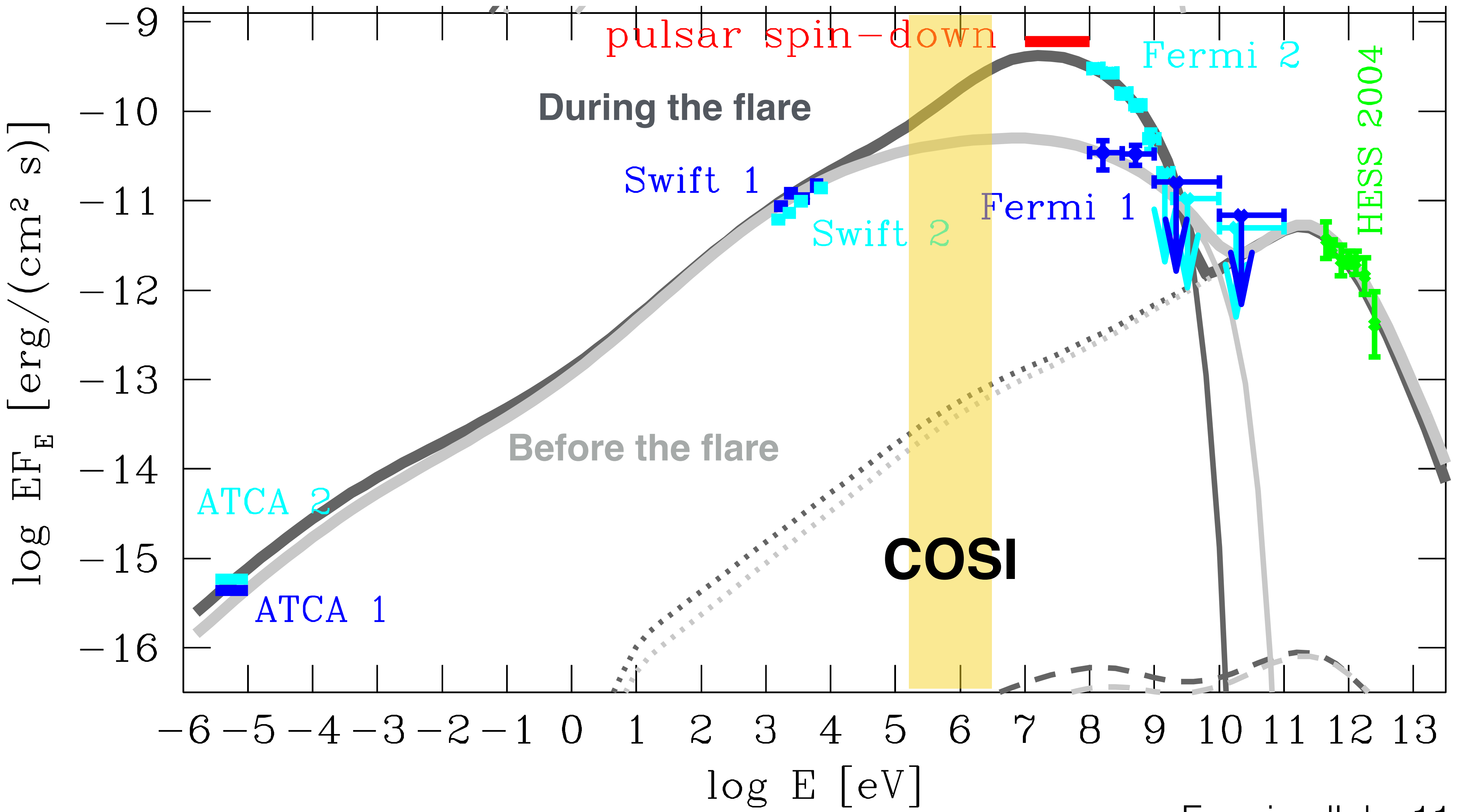


- The spectral fitting was performed with COSIpy and the threeML library
- 3σ at ~3 months; ~8σ with full 2-year mission (based on the data challenge 3 simulation)
  - We can test if the MeV peak reported by COMPTEL is real or not
- Orbital modulation can be studied within nominal mission lifetime
- Background-dominated with S/B ~0.2%, and it is crucial to model the background accurately.

3-month simulation of PSR B1259-63 in DC3







Fermi collab+11

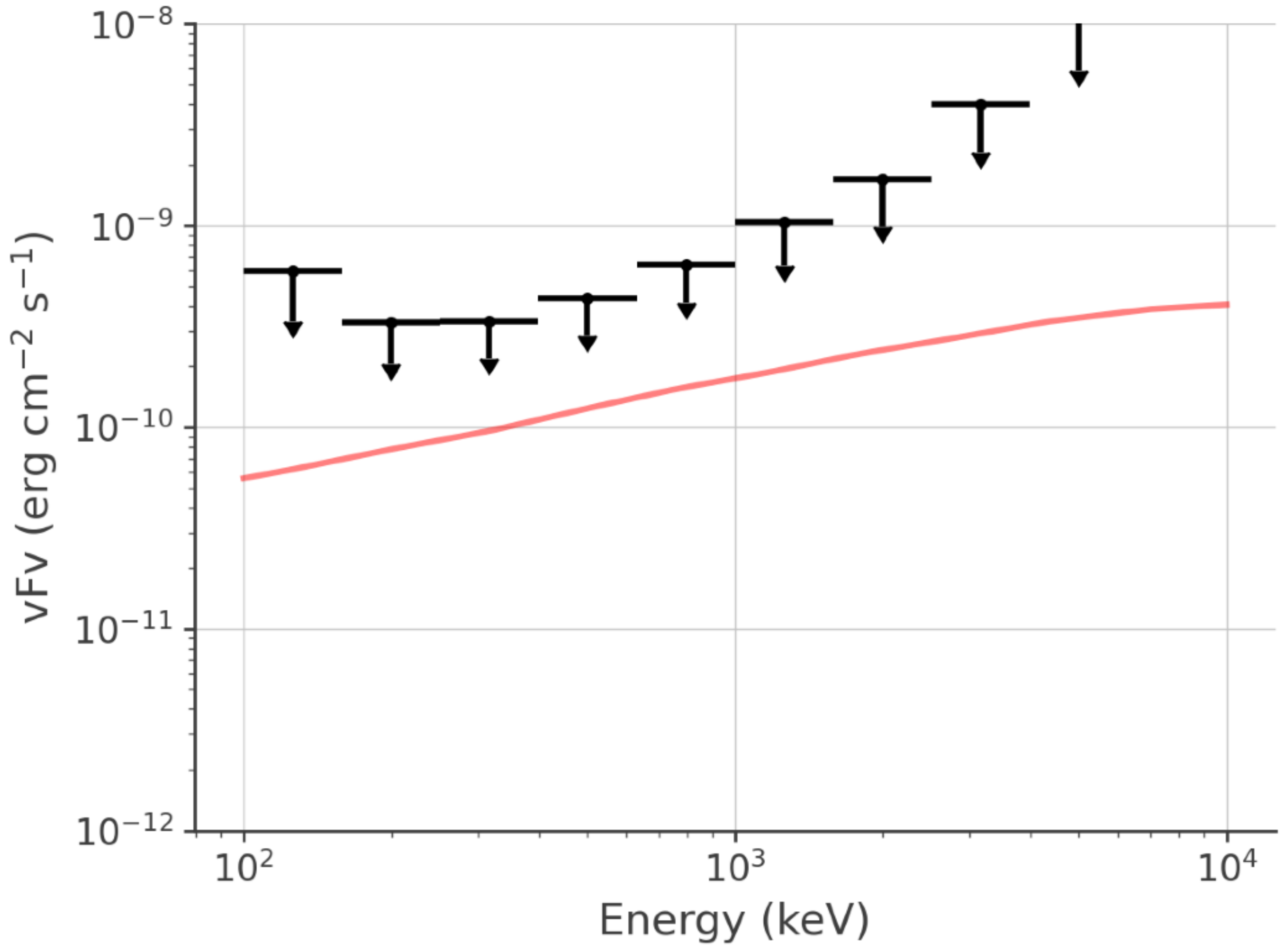
- Gamma-ray emission occurs during its periastron passage
- Its flux is brighter than the pulsar spin-down luminosity
- The flux and duration in COSI's energy band are not well understood.
- Next periastron passage: November 19, 2027 shortly after COSI launch (2027 August)

Possible constraints on the MeV emission from PSR B1259-63

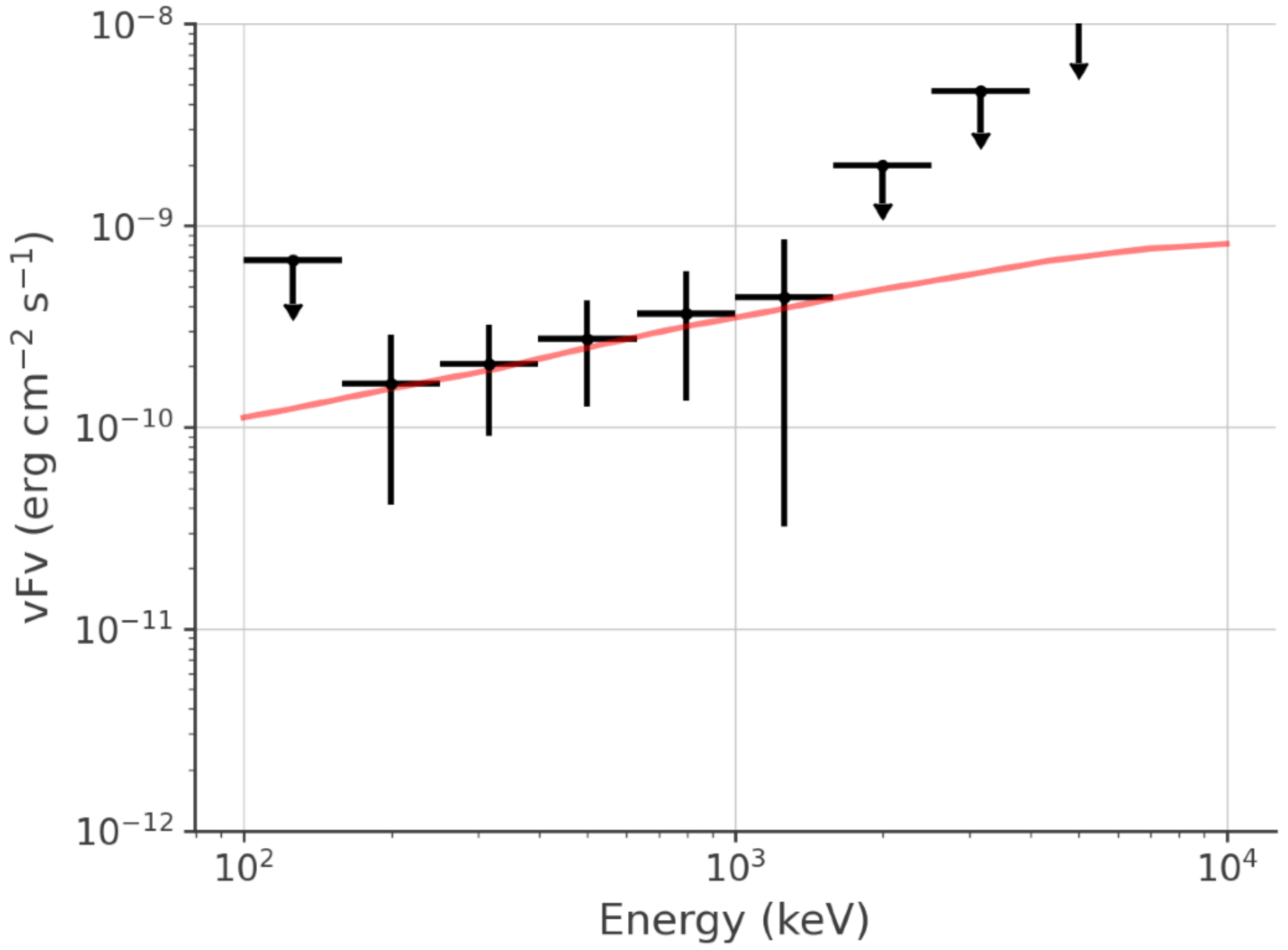
The duration of the flare is assumed as 30 days (but it is not well-known)

5×10^{-10} erg cm^{-2} s^{-1} (0.2-3 MeV)

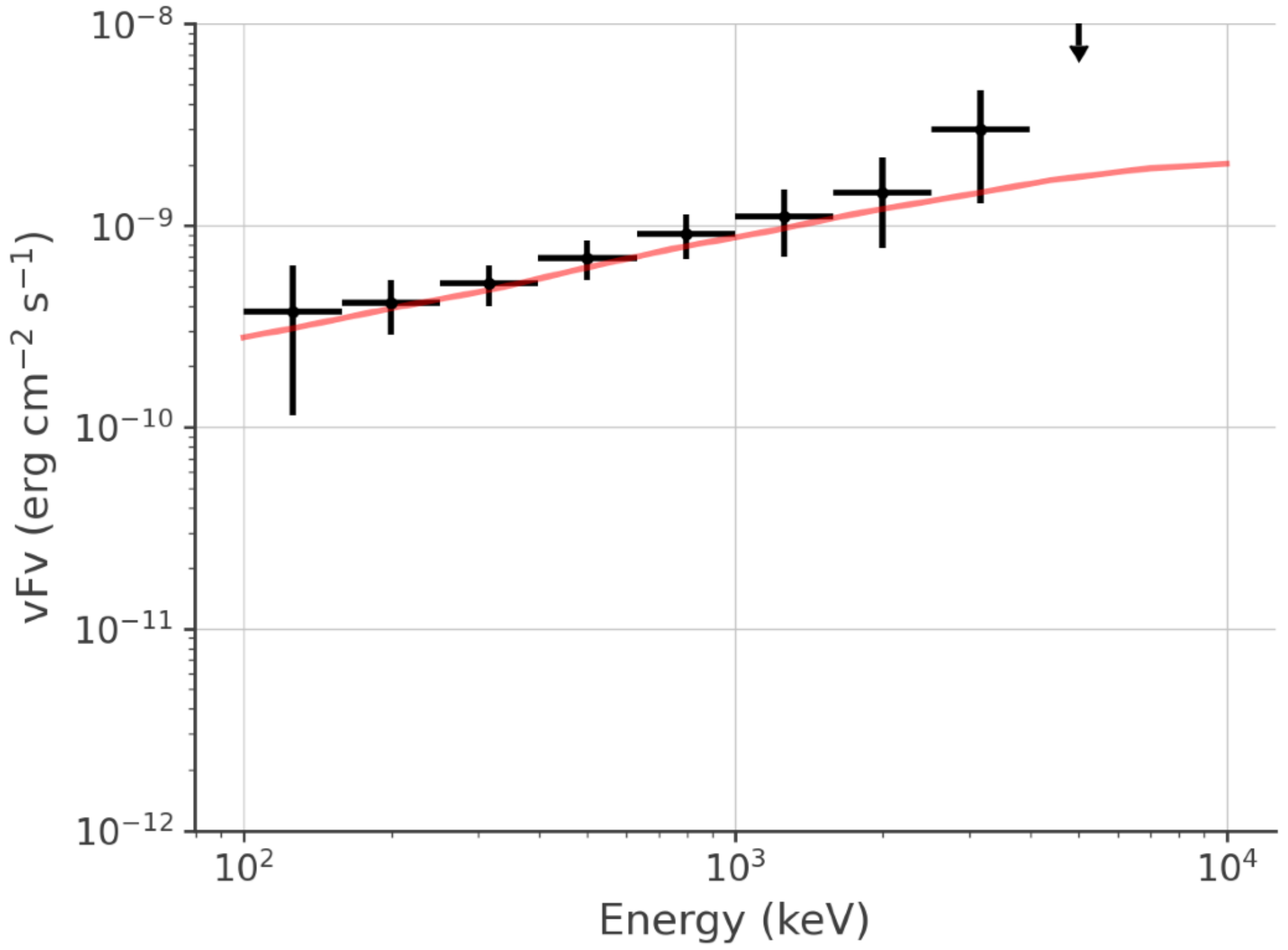
(based on Fermi+11 paper, v~0.3c)

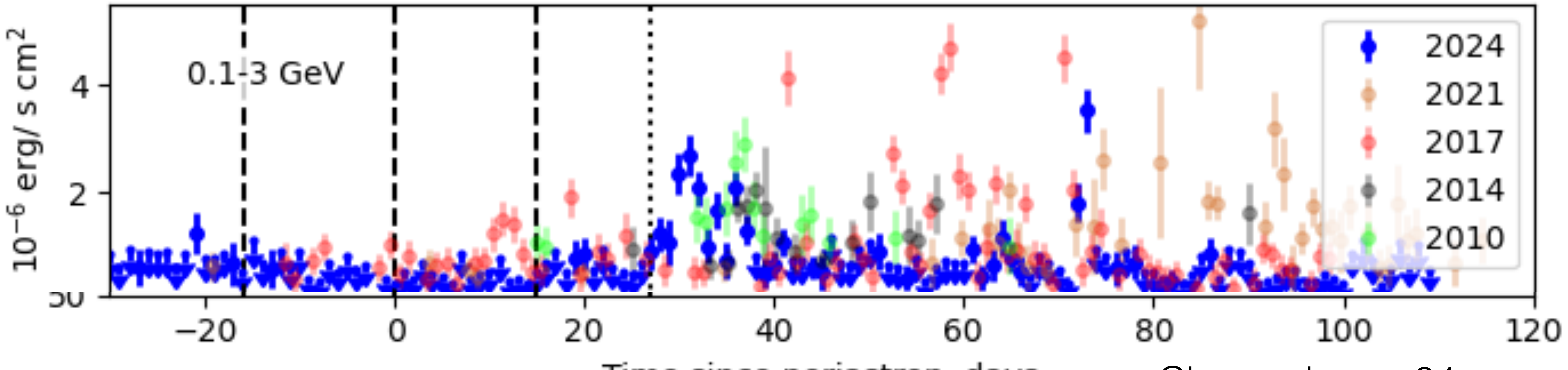


1×10^{-9} erg cm^{-2} s^{-1} (0.2-3 MeV)



2.5×10^{-9} erg cm^{-2} s^{-1} (0.2-3 MeV)





Chernyakova+24

The GeV flare varies every event and is also time-variable

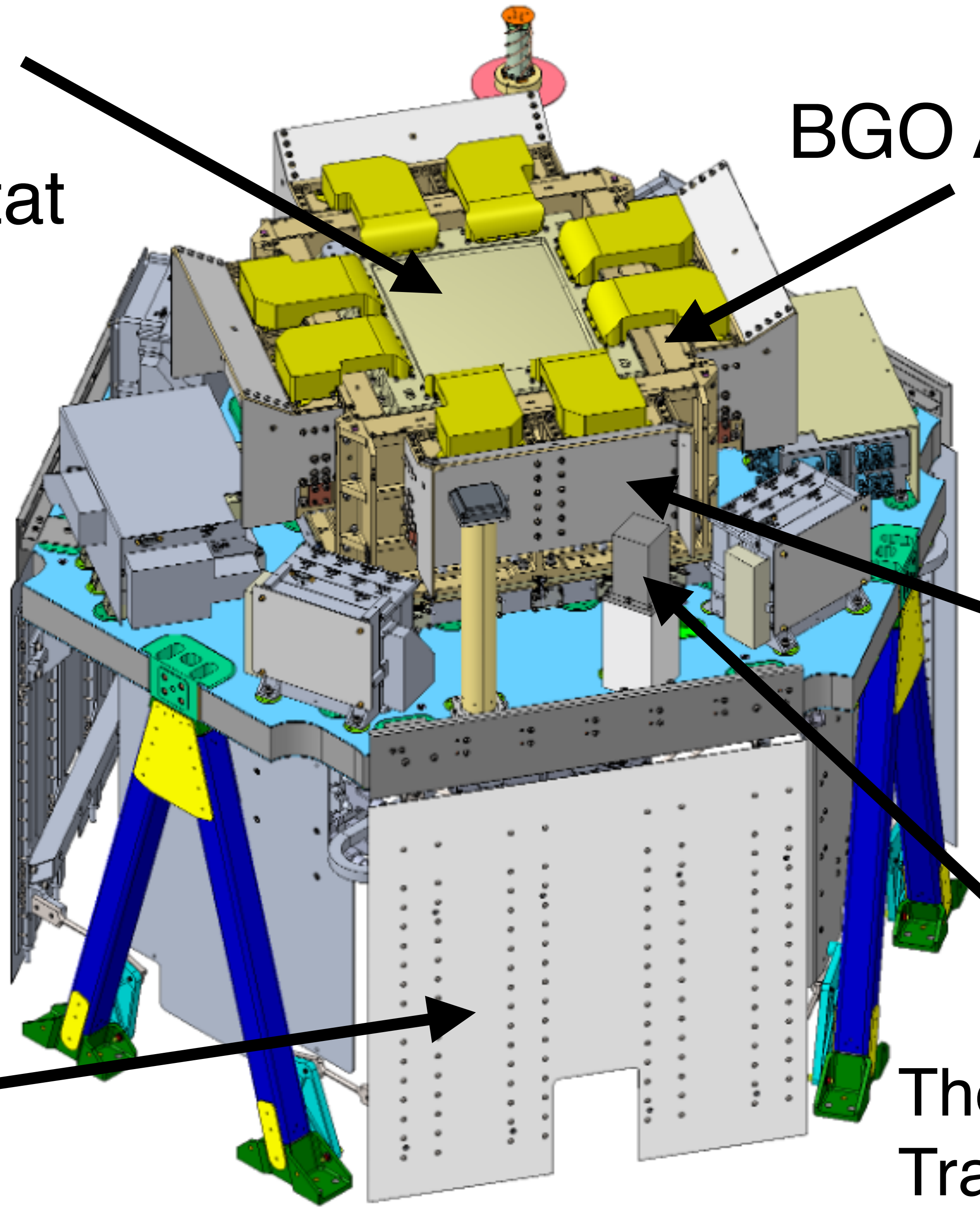
It is detectable if it is > 1e-9 erg cm^{-2} s^{-1} with 1-month duration

The multi-wavelength data would also help this analysis, e.g., selecting time intervals when the source is active in the GeV band.

Towards accurate background modeling

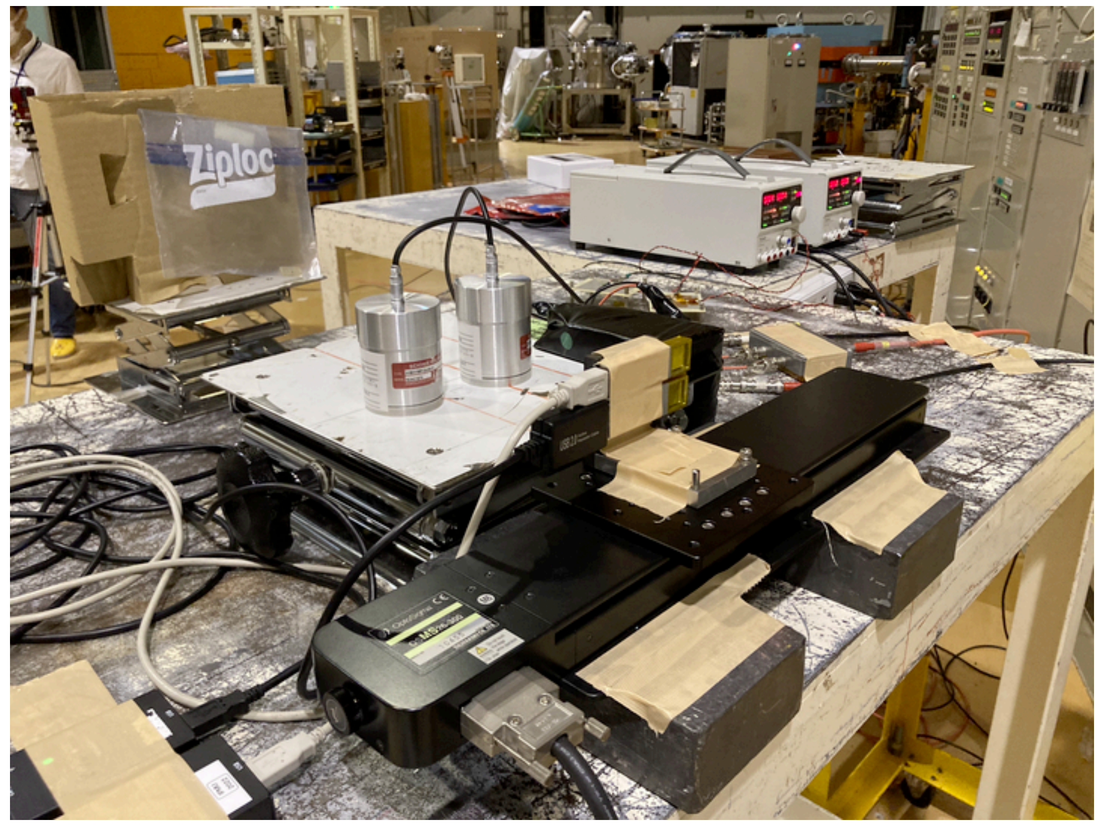
The low S/B ratio requires detailed understanding of background components

Several approaches are being investigated, e.g, full background simulation compared with 2016 balloon data (Gallego+25)



- The main Compton telescope is surrounded by the BGO active shields.
- In addition to them, scintillation detectors (NaI) will be onboard as a student collaboration project (Gulick+24,25)

The gamma-ray spectrum and saturated events will be used as a tracer of background components, which will be incorporated in the data analysis



Afterglow study (CsI, NaI) at the beamline facility HIMAC in Japan

Future of MeV gamma-ray observations

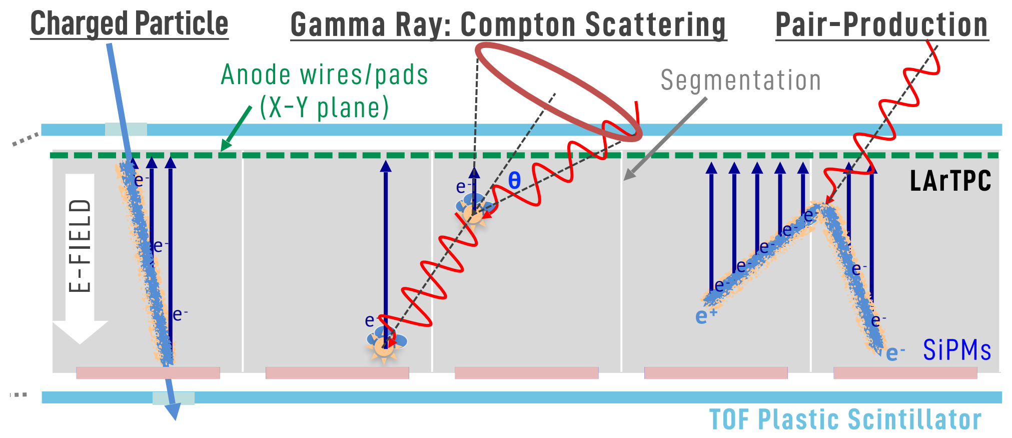
Present — **Future**

2020 — 2030 — 2040

COSI, NASA (2027-)

A large-scale mission in 2030s? 2040s?

SMILE, AMEGO, GRAMS, GECCO, MASS, MeGaT, MeVCube, HARPO, and more…



GRAMS, Japan+US

- A large-scale mission with liquid argon
  - engineer balloon flight from Japan in 2023
  - engineer balloon flight in 2025/2026

Ballon flight at Taiki-cho, Japan

2023/7/27 03:55 Launched

2023/7/27 07:07 Landed on the sea

Results of engineering flight (Nakajima+24, arXiv:2409.13209)

- Launched on 2023 July 27 03:55, experienced 3 hour flight.
- Level flight for 40 minutes at altitude of 29 km.
- The LArTPC was stable and controllable during the flight.
- Also acquired data of environmental radiation.

Successfully accomplished the first LArTPC operation at stratosphere.

Next prototype flight was accepted by NASA APRA
Balloon flight planned at 2026

Conclusions

- MeV gamma-ray observations are essential for understanding extremely efficient particle acceleration in gamma-ray binaries
- COSI to be launched in 2027 will fill the sensitivity gap between X-ray and GeV bands
- Comprehensive simulations with full orbital parameters and realistic backgrounds demonstrate:
  - LS 5039: spectral analysis and orbital modulation with 2-yr observation despite low S/B ratio
  - PSR B1259-63: Perfect timing with periastron after launch
- Multi-wavelength coordinate observations and background modeling are essential for these sources
- Join COSI Data Challenge to help prepare for closing the MeV gap!

Link to DC3