

High-Synchrotron Peaked Pevatron Sources in the Galaxy [A.K.A. Critical Need for Improved MeV/GeV Gamma-Ray Mission...!]

P. Coppi, Yale

Why worry: AGILE just died,
Swift (1 gyro) and Fermi no longer young.

After COSI, there is NO new mission in
~100 keV – GeV energy range that has gone beyond
concept/study stage in US/Europe/Japan. This energy range
can only be done from space. Not a key priority
in US 2020 Decadal Survey/P5 Particle Physics reports.
Maybe China will come to the rescue??



Big problem since Fermi-like mission requires 10+ years.



Physics of the Cosmos

Exploring fundamental questions regarding the physical forces of the universe

[FIG SAG Home](#)

[SAG Leadership](#)

[SAG Events](#)

Future Innovations in Gamma Rays (FIG SAG)

- [Future Innovations in Gamma Rays Science Analysis Group Terms of Reference \[PDF\]](#)

FIG SAG Workshop

Michigan Tech, Houghton, Michigan
24 – 28 June 2024

Abstract deadline: May 15
Registration deadline: May 15

This group's activity will focus on identifying future science drivers, necessary capabilities, and priorities for the future of gamma-ray astronomy.

Questions to be evaluated include:

- 1. Gamma-Ray Science Priorities:** What are the opportunities to probe astrophysical phenomena, fundamental physics, and cosmology that are uniquely afforded by gamma rays? How do these opportunities connect to the priorities of the wider astrophysics community? For each of these phenomena, how can future gamma-ray observations advance our current understanding and what is lost by not including gamma-ray constraints? What are the observational capabilities and requirements for these future studies?



News

10 May 2024

JWST Senior Project Scientist
Awarded Presidential Medal of
Freedom

» [Details](#)

Astrophysics Tech Gaps
Webinar on 14 May 2024

» [Details](#)

Reminder: Hybrid Joint
NICER/IXPE Workshop, 29 July –
1 August 2024

» [Details](#)

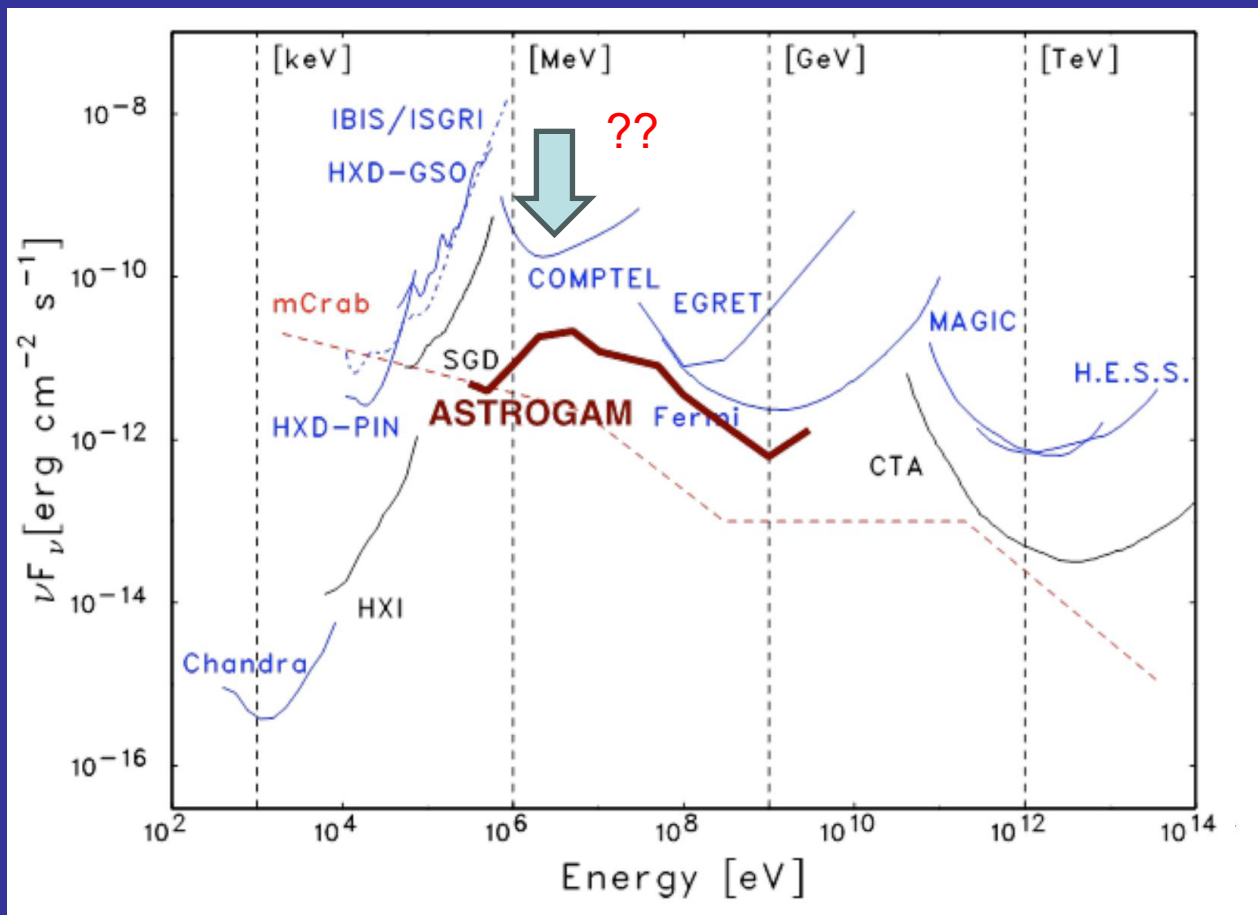
FIG SAG Face-to-Face Meeting
24 – 28 June 2024

» [Details](#)

[More News Articles »](#)

[Subscribe to PhysCOS News »](#)

Energy Coverage – ~100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at ~MeV.



Hopefully will have COSI in ~2027, but could do even better with more \$\$

Adapted from Takahashi et al. (2013)

Differential sensitivities for different X-ray and γ-ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), and the ASTRO-H/HXI,SGD are the 3σ sensitivity curves for 100 ks exposures. A spectral bin with ΔE/E = 1 is assumed for Chandra and ΔE/E = 0.5 for the other instruments.

Motivation I: MeV Gamma-ray Survey



Images: ESA

The MeV energy range is crucial for probing a wide array of sources and phenomena!

- **Spectral features in particle accelerators**
 - Transition from thermal to non-thermal emission
 - Pion bump to identify hadronic accelerators
 - Constrain magnetic properties and energetics of relativistic jets from
- **Line emissions and nucleosynthesis**
 - Measure chemical yields from CCSNe
 - r-process signatures from kilonovae and magnetar flares
 - Probe 511 keV positron annihilation excess
- **EM counterparts to multi-messenger events**
 - GRBs associated with NS merger events
 - MeV photon cascades from cosmic neutrino sources

Why $\sim$ MeV? Is there anything special there?
 [A “hidden” 100 MeV source]

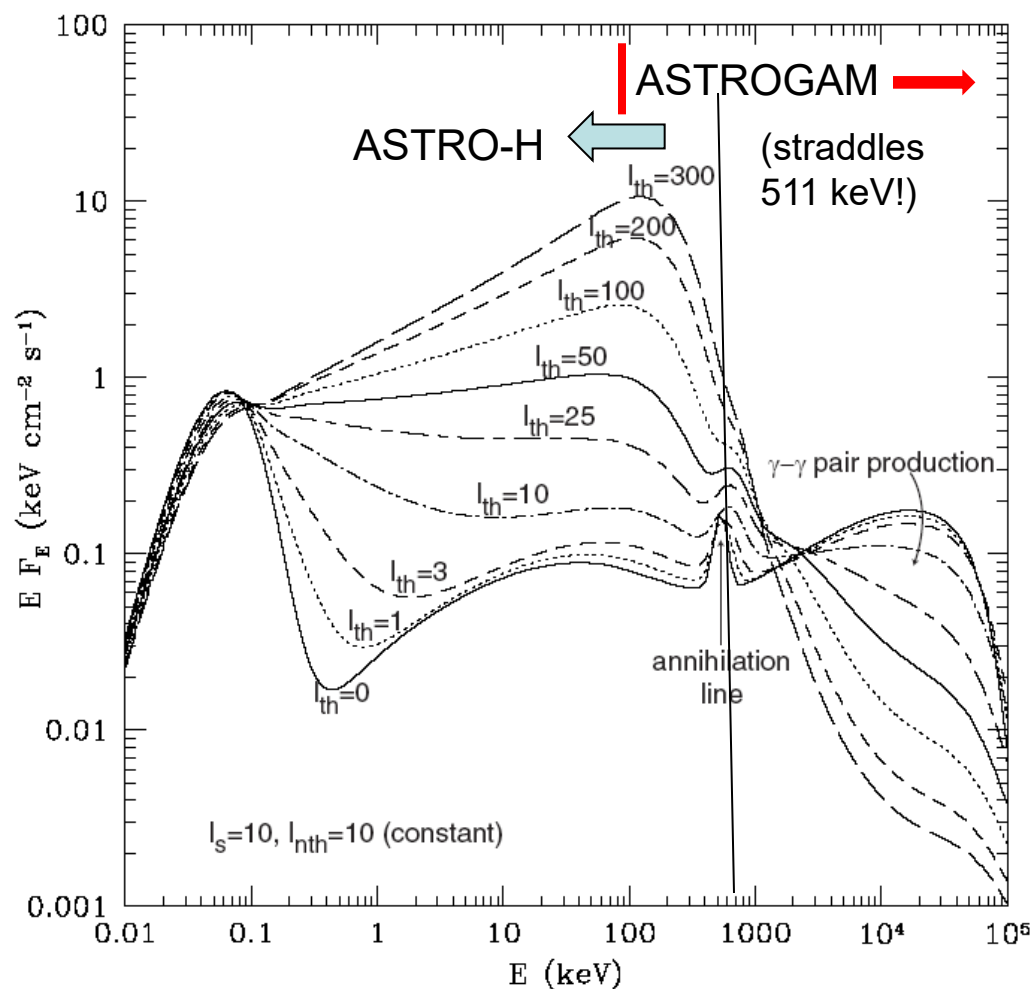


Figure 1. The transition from a non-thermal plasma ($l_{th} = 0$) to a thermally dominated plasma ($l_{th}/l_{nth} = 30$). The soft input into the source has a compactness $l_s = 10$ and has a blackbody spectrum with $T_{bb} = 15$ eV. The assumed source radius is $R = 10^{14}$ cm, and a background plasma is present with optical depth $\tau_p = 0.1$.

$E \sim 511$ keV
 special energy
 for physics:
 Klein-Nishina,
 pair production,
 pair annihilation

$\Rightarrow$ Spectral features
 expected!

$\Rightarrow$ Constraints
 if not seen!

Note: 511 keV **NOT**
 special energy from
 binding energy/particle,
 energetics, etc.
 considerations

The trouble with AGN jets and ICECUBE neutrino(s)...

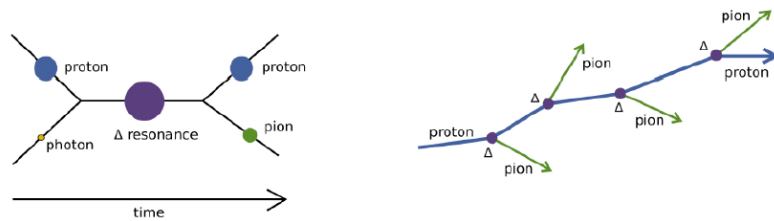


Figure 3: Left: Photo-pion production via excitation of a Δ -resonance in collision of an ultra-high energy cosmic ray proton with a CMB photon. Right: Trajectory of a super-GZK proton through the CMB, suffering attenuation due to repetitive photo-pion production [Credits: W. Bietenholz, arXiv:1305.1346].

- If one particle is a photon ($e_2 = p_2$ and $m_2 = 0$), then threshold energy

$$e_2 \left(\gamma_1 - \sqrt{\gamma_1^2 - 1} \cos \theta \right) = \delta m c \left(1 + \frac{\delta m}{2m_1} \right)$$

Example: Consider reaction $p + \gamma \rightarrow p + \pi^0$ on CMB photons (mean energy $E_2 = \langle h\nu \rangle \simeq 3kT \simeq 7 \times 10^{-4}$ eV [SI], $e_2 = E_2/c$). Threshold energy for most favourable collision angle ($\cos \theta = -1$ head-on) for high γ_1 :

$$\Rightarrow 2\gamma_1 \simeq \frac{m_{\pi^0} c}{e_2} \left(1 + \frac{m_{\pi^0}}{2m_p} \right) \quad \text{or} \quad \gamma_1 \simeq 10^{11}$$

Rieger lecture notes

Kelner+ 2008

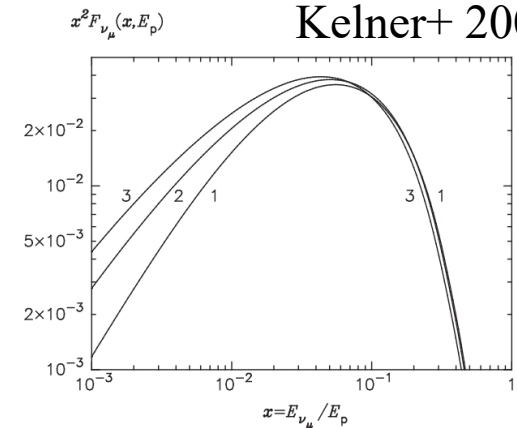


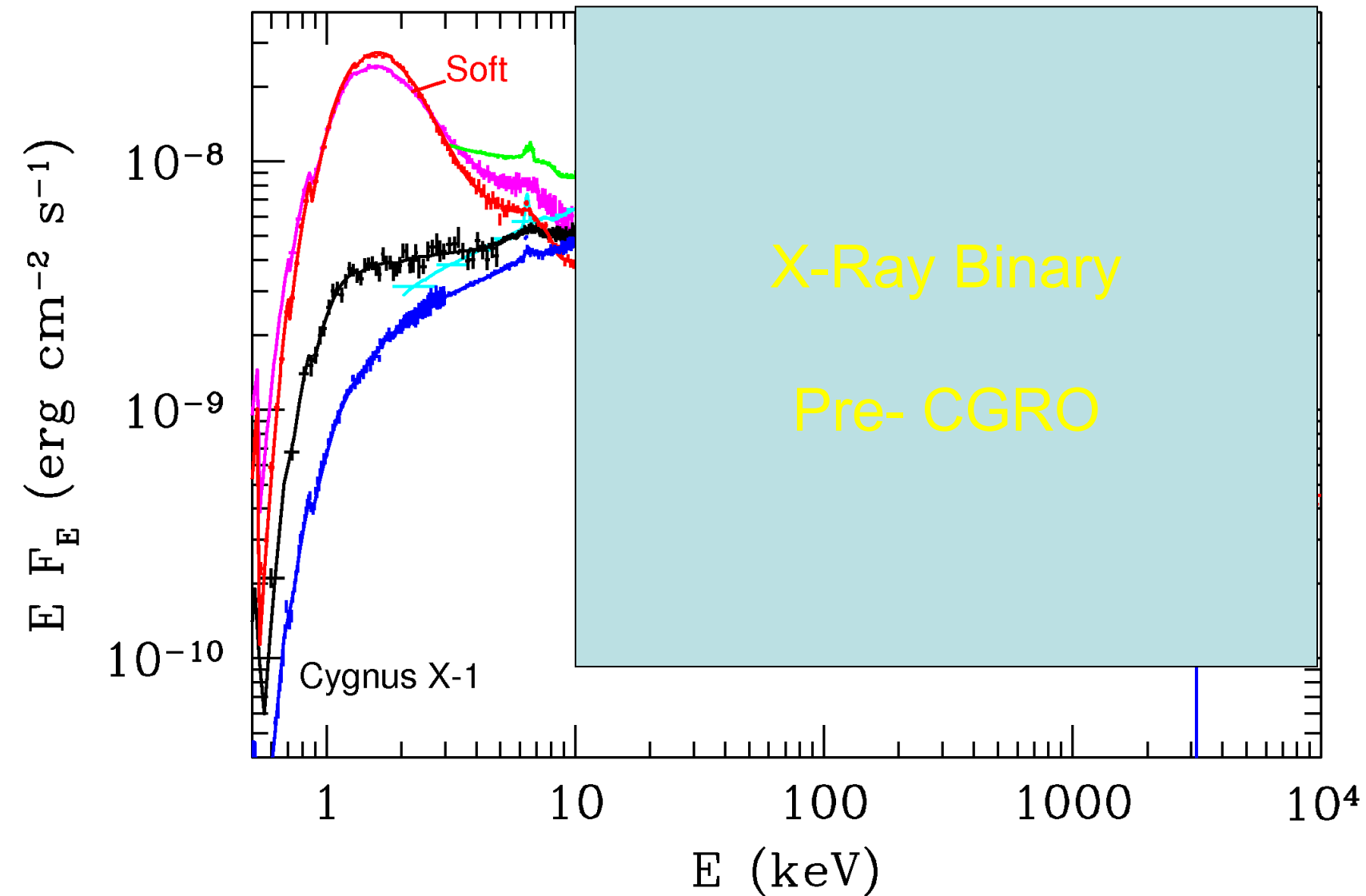
Figure 9: Energy spectra of all muonic neutrinos described by Eq.(62) and (66) for three energies of incident protons: 0.1 TeV (curve 1), 100 TeV (curve 2) and 1000 TeV (curve 3).

In delta-function approximation, pion has ~ 0.1 - 0.2 energy of proton, and neutrino has ~ 0.3 of energy of pion. ICECUBE sees neutrinos from ~ 1 TeV – 1 PeV. To make TeV neutrino, need proton of energy ~ 20 TeV, or $\gamma \sim 2 \times 10^4$. $\Rightarrow$ need target photon $E \sim 3.5$ keV [X-rays], and lots of them (for efficient production)... where do you get these? Compactness (pair production) problem...

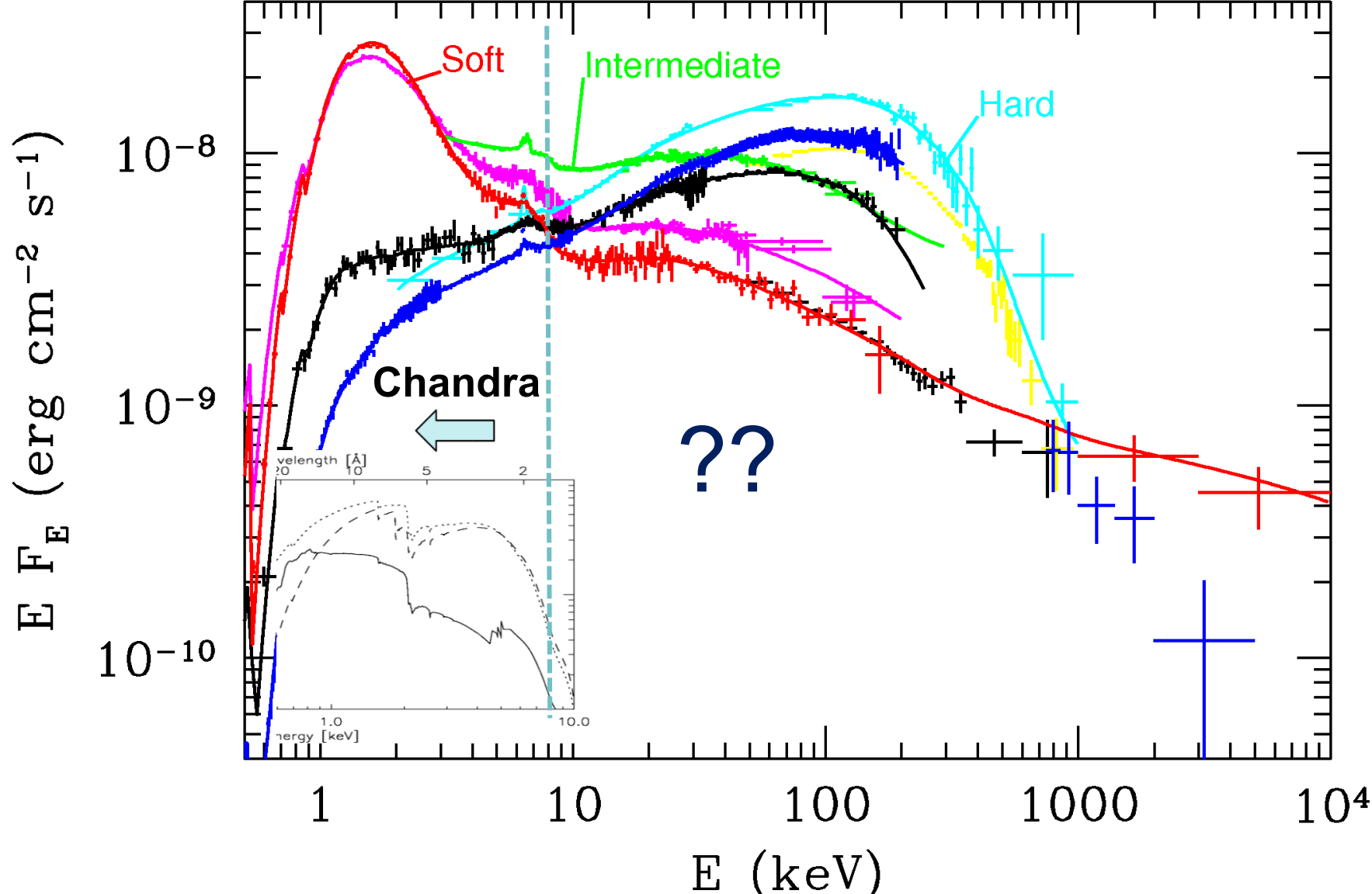
$\Rightarrow$ Cascade to MeV – GeV

$\Rightarrow$ (NOT Fermi range if X-rays come from corona...)

Why (soft) gamma-rays for non-jet AGN? Need broad-band spectra to constrain physics, reprocessing, measure bolometric luminosity, etc...

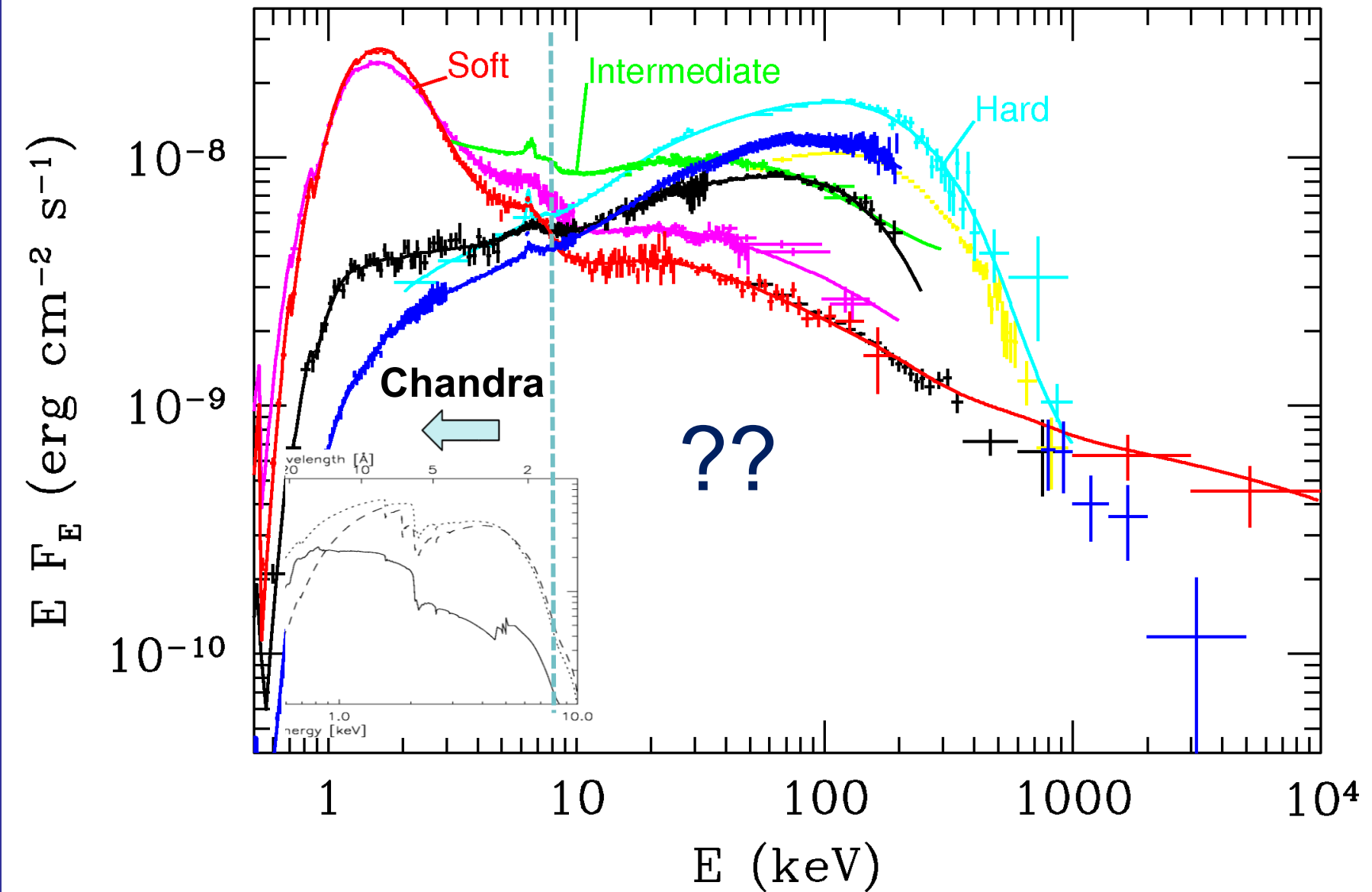


Spectra of this quality generally do not exist for AGN!



Possible AGN spectral “states” not well-sampled!

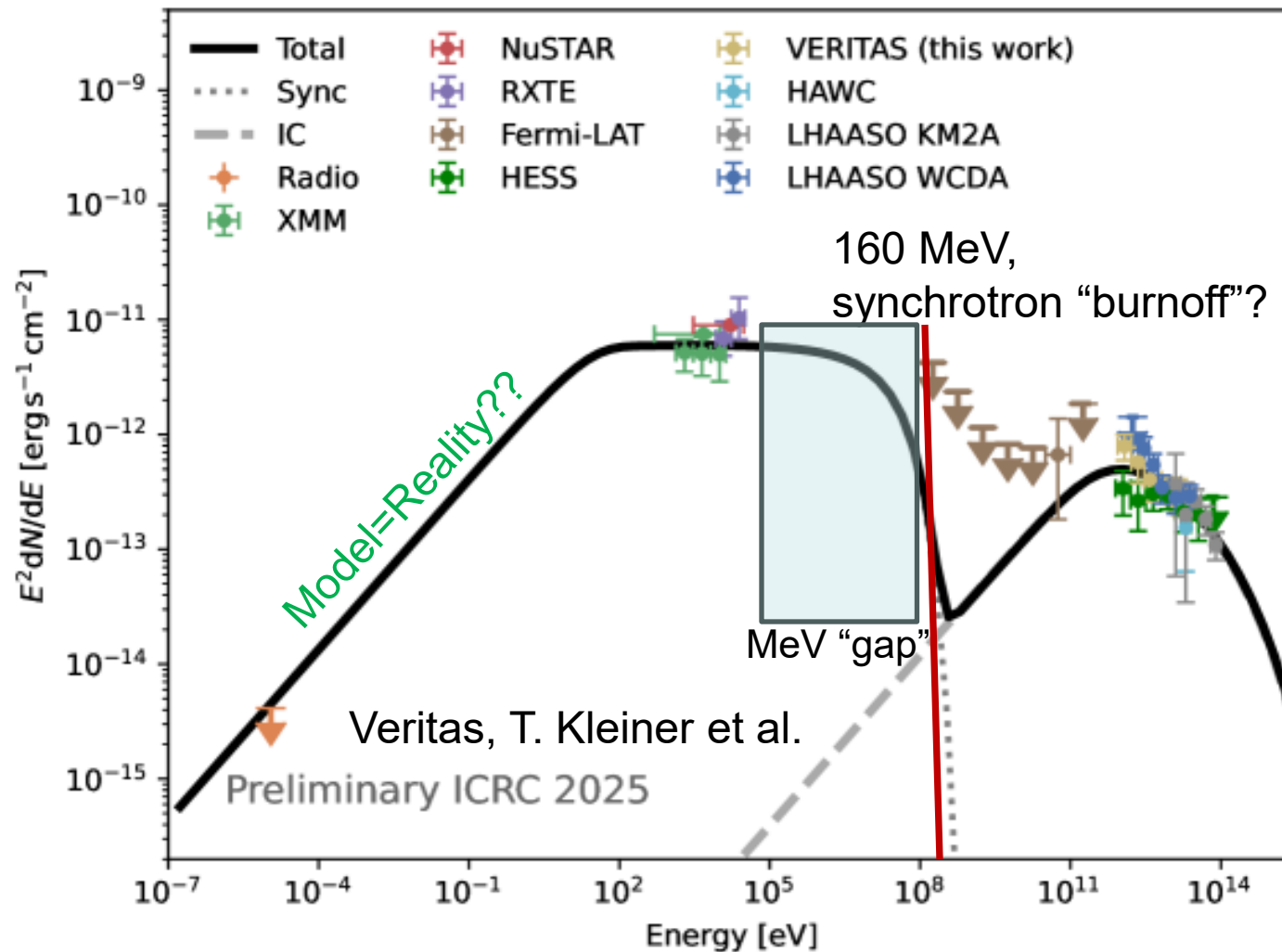
Polarization: broad energy coverage important too!



Possible AGN spectral “states” not well-sampled!

What about a jetted source, e.g., microquasar pevatron?

SS 433
Eastern Lobe



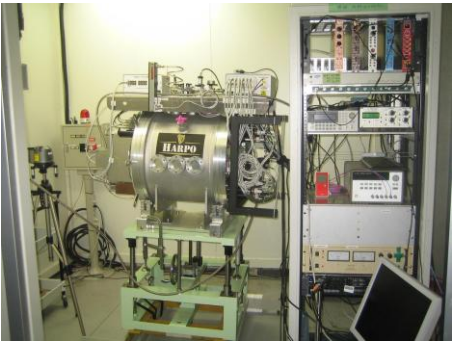
~PeV gamma-rays (even if from pion decay) => PeV+ electrons
=> For micro-milli Gauss magnetic fields => ~100 keV – MeV+ synchrotron!

MeV Gamma-ray Instrument Landscape

Understanding the MeV universe requires a *multi-instrument, multi-technique* approach.

Time Projection Chambers (pair):

(AdEPT, HARPO, LArGO) high angular resolution, good polarization capability, no background veto



Coded mask/Occultation

(Theseus, Swift-BAT, Fermi-GBM, LOX...), no background veto, very good for transients

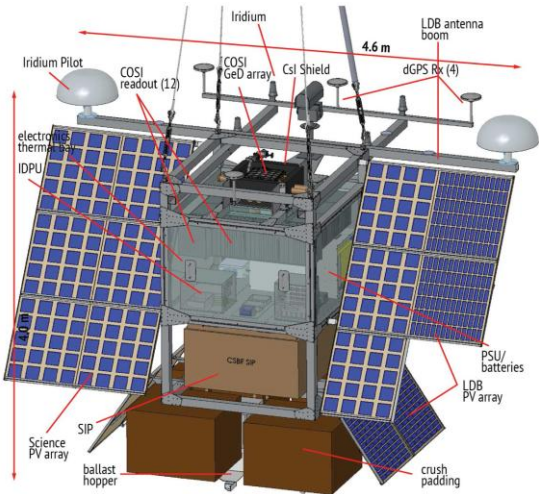
Continuum / survey mappers (Pair

& Compton): (AMEGO, ComPair, MEGA, AstroGAM) high flux sensitivity, moderate resolution spectroscopy, wide field of view, broad energy coverage, some polarization capability



Spectrometers / mappers (Compton):

(COSI, GRX) high resolution spectroscopy, wide field of view, some polarization capability
2016 COSI Balloon Flight!



COSI [Solid-State Compton Telescope] – launch 08/2027 ? [or never ☹️]

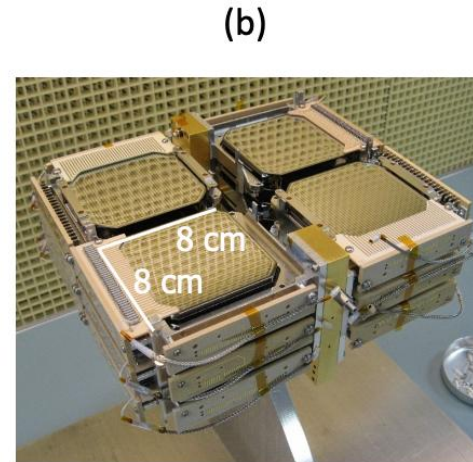
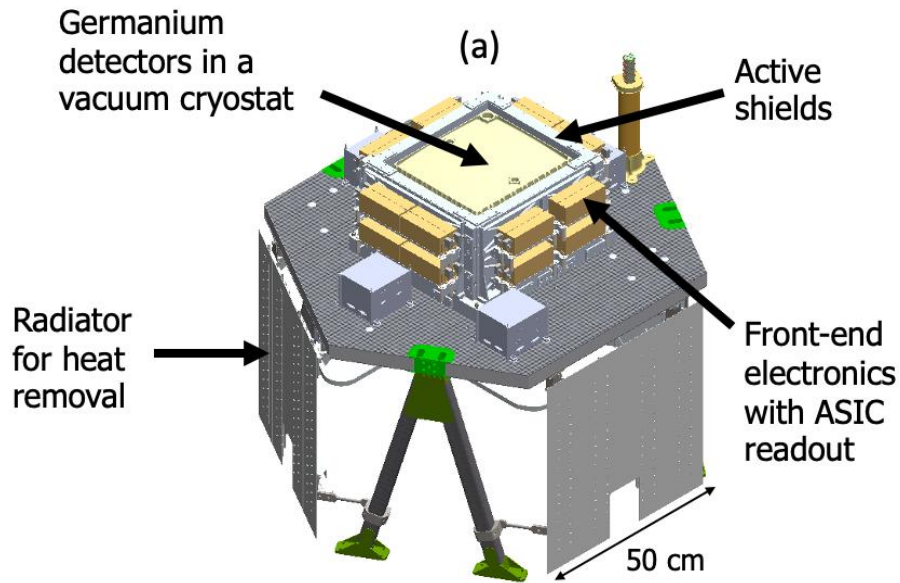


Table 1: COSI Requirements

Parameter	Requirement
Sky Coverage	25%-sky instantaneous field of view (all-sky every day in survey mode)
Spectral Resolution (FWHM)	6.0 keV at 0.511 MeV and 9.0 keV at 1.157 MeV
Angular Resolution (FWHM)	4.1° at 0.511 MeV and 2.1° at 1.809 MeV
Line Sensitivity ^a	1.2×10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$ at 0.511 MeV 3.0×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ at 1.157 MeV (^{44}Ti) 3.0×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ at 1.173 MeV (^{60}Fe) 3.0×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ at 1.333 MeV (^{60}Fe) 3.0×10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ at 1.809 MeV (^{26}Al)
Flux limit for polarization ^b	1.4×10^{-10} erg $\text{cm}^{-2} \text{s}^{-1}$ (0.2-0.5 MeV)
Reporting short GRB detections	<1 hour reporting time ~1° localizations (accuracy depends on GRB fluence) 100 ms absolute time accuracy

^a3 σ narrow line point source sensitivity in 2-years of survey observations.

^bFor 50% minimum detectable polarization in 2-years of survey observations.

COSI [Solid-State Compton Telescope] – launch 08/2027 ? [or never ☹️]

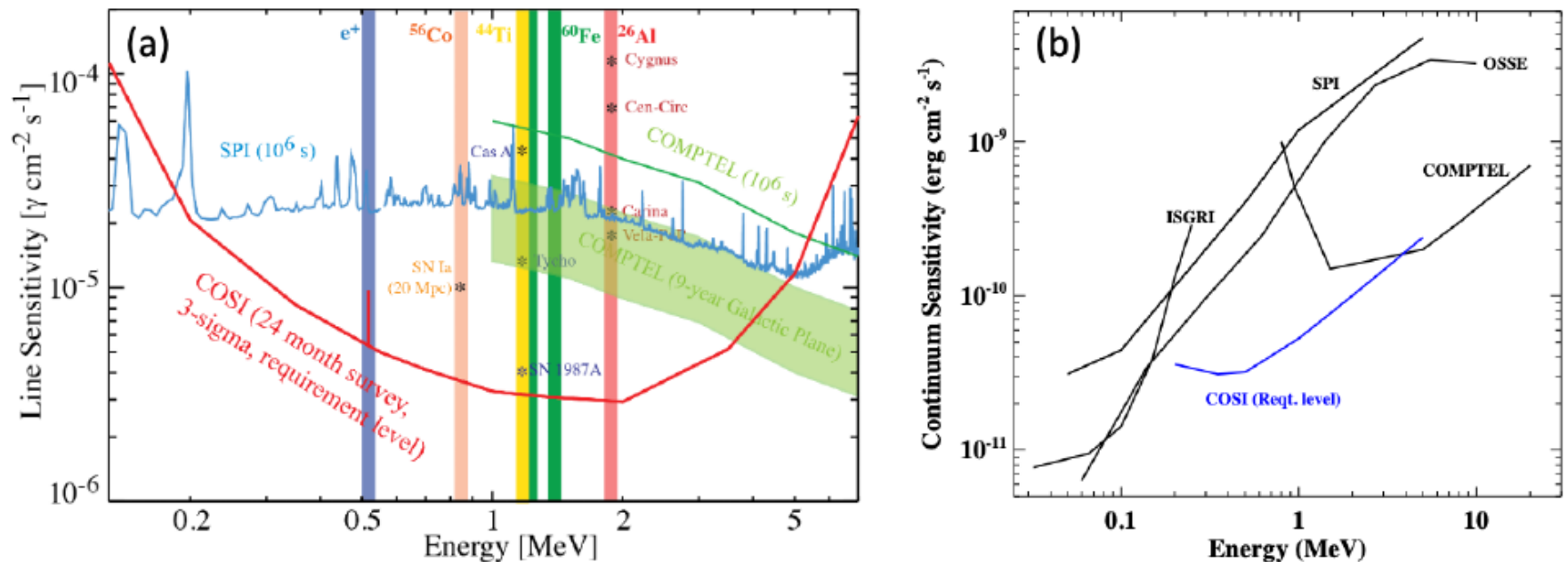
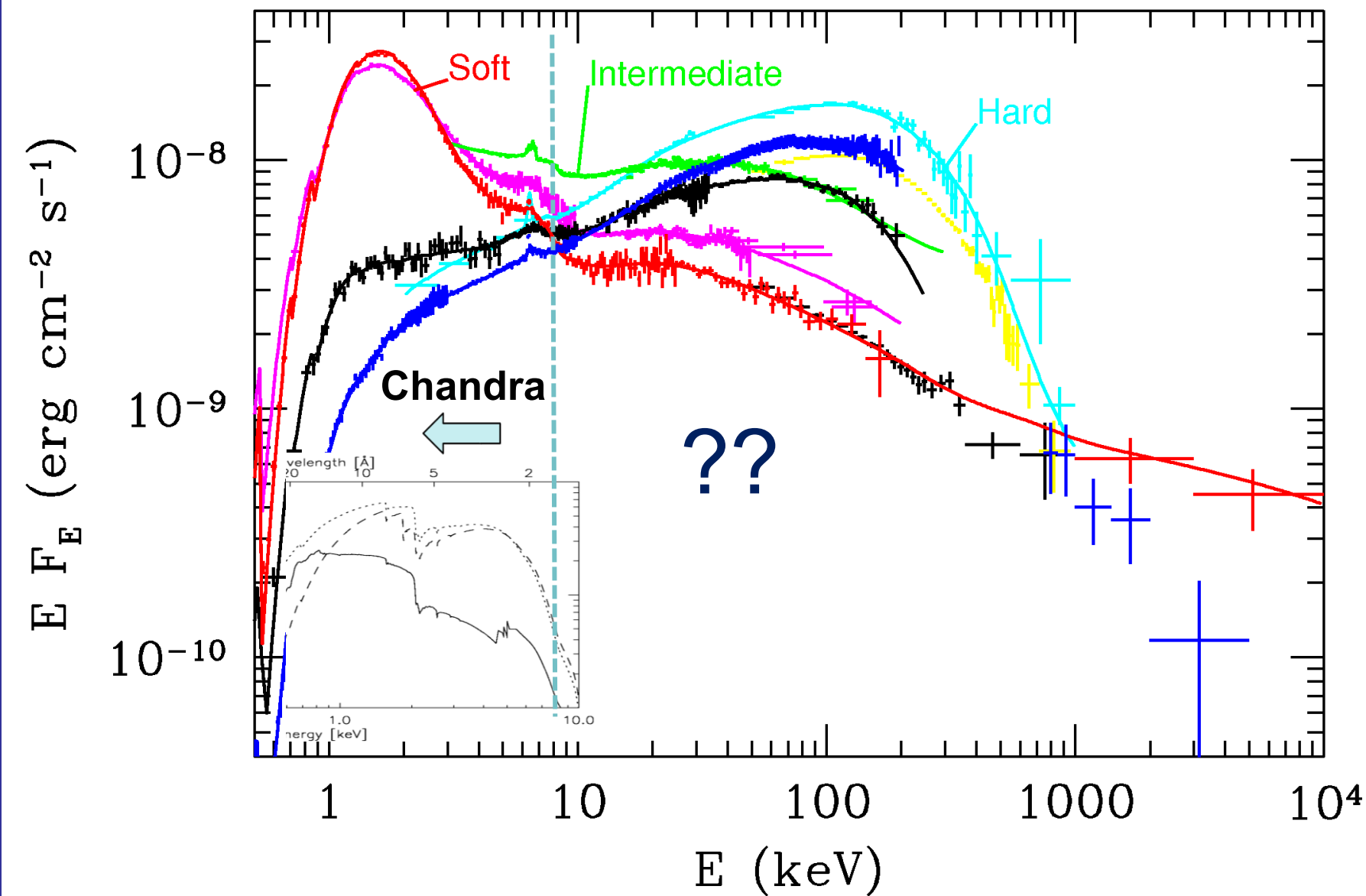
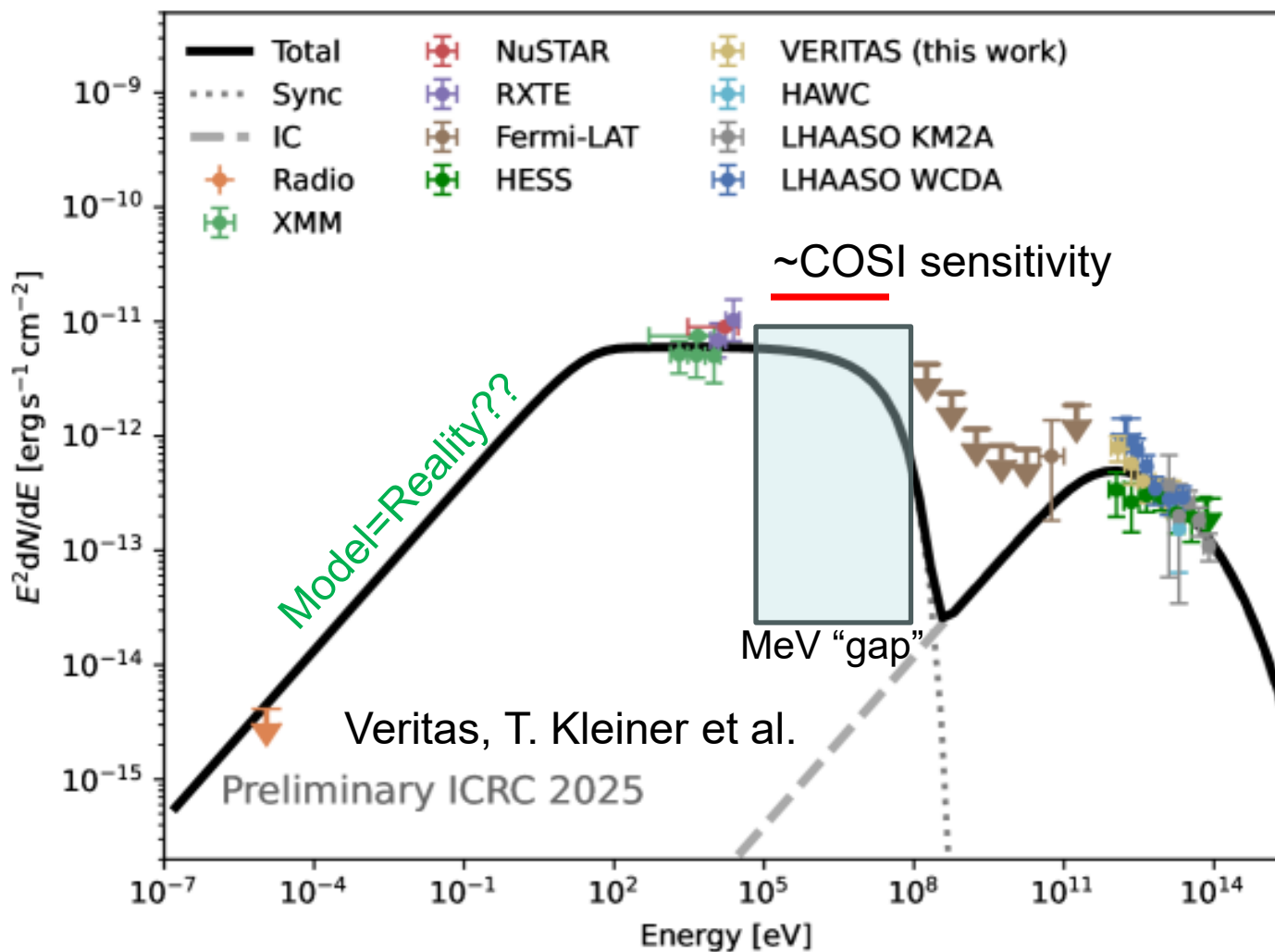


Figure 2: Narrow-line (a) and continuum (b) sensitivities based on COSI's requirements compared to current and previous instruments. The sensitivity curves are for point sources at the $3\text{-}\sigma$ level during 2 years of COSI survey time. Due to the all-sky coverage that COSI obtains, these sensitivities will be reached for every source in the sky.

COSI great for Cyg X-1 – but, one of brightest sources...



Not so o.k. for $\sim$ pevatrons, and LHAASO/CTA/SWGO sources



SS 433
Eastern Lobe

Can we
do better
than COSI?

Yes, \$\$ $\rightarrow$
solid state,
SMEX
to M-Class/
MIDEX/Probe

$\sim$ PeV gamma-rays (even if from pion decay) $\Rightarrow$ PeV+ electrons
 $\Rightarrow$ For micro-milli Gauss magnetic fields $\Rightarrow$ $\sim$ 100 keV – MeV+ synchrotron!

MeGaT: conceptual design

▣ TPC based technique

§ 30cm cubic volume (prototype)

§ four 50cm cubic or a single 100 cm $\times$ 100cm $\times$ 50(or larger)cm volume (satellite)

§ 3-10 bar high pressure

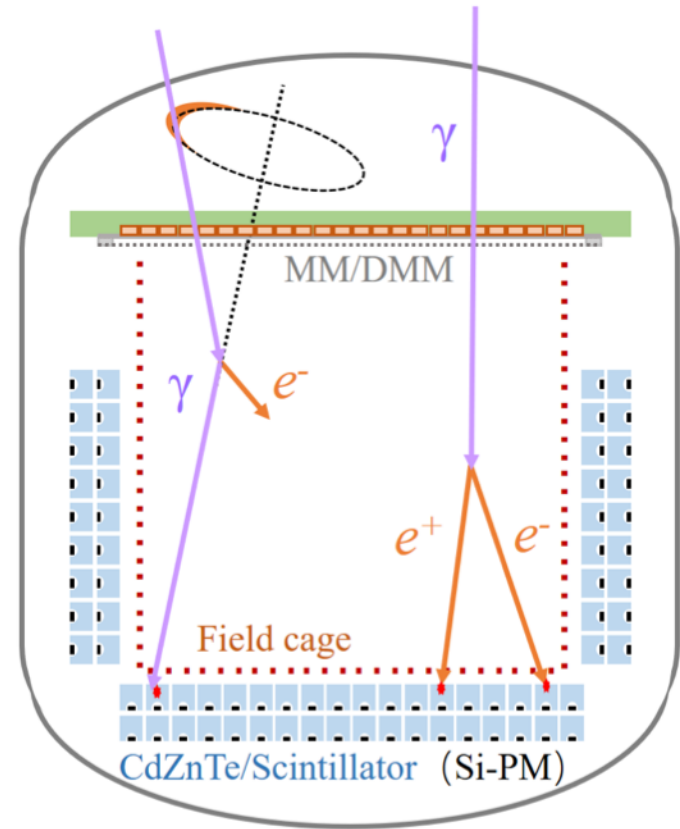
▣ Expected performance

§ High dynamic range:

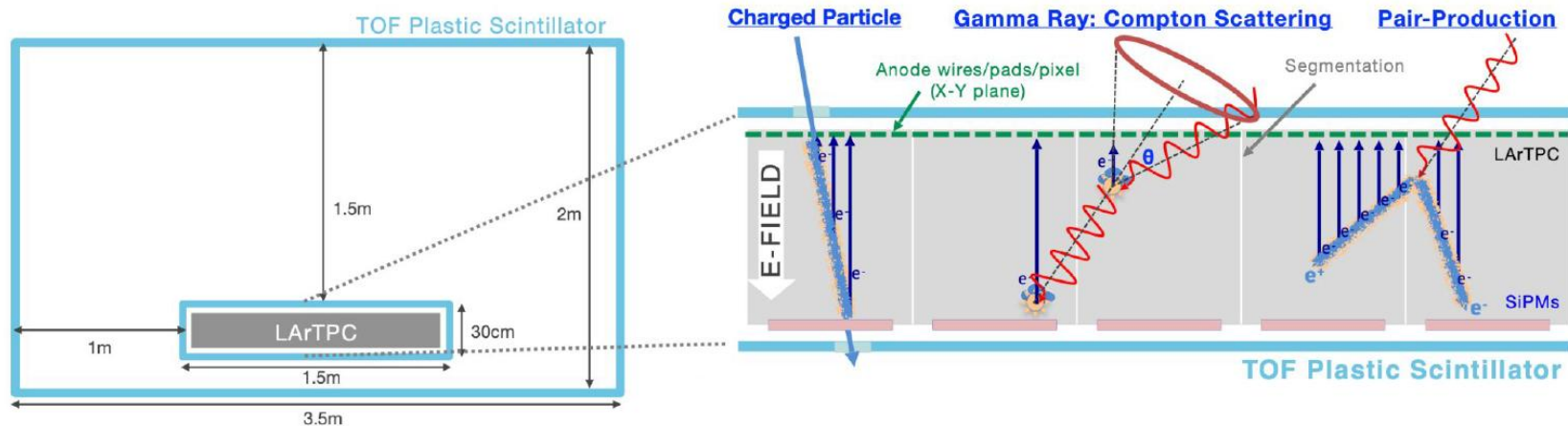
0.3MeV -100 MeV

§ Angle resolution (PSF) :

2 ° @MeV, 0.5 ° @100 MeV



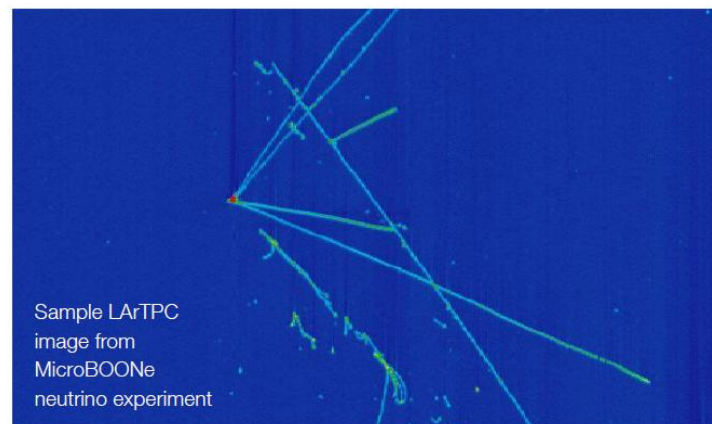
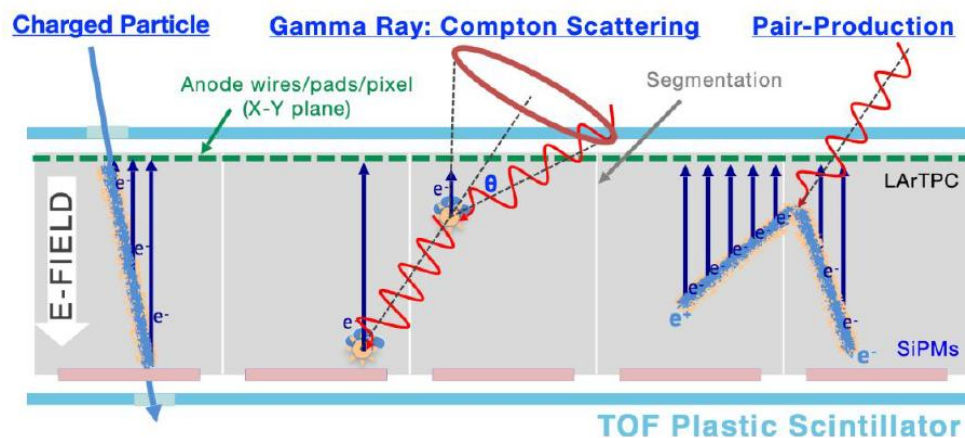
Detection Concept: MeV Gamma-rays



LArTPC = Liquid Argon Time Projection Chamber

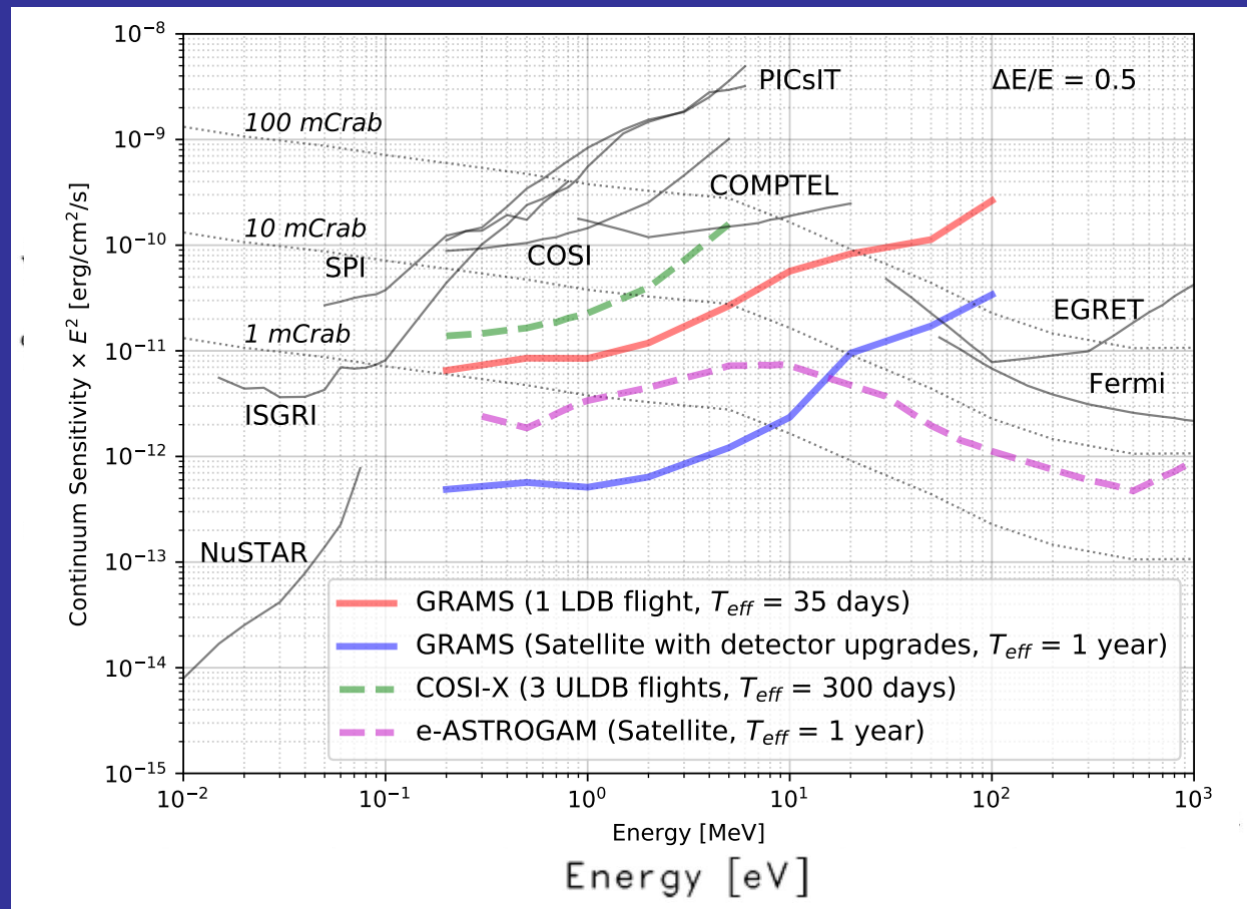
- Incoming gamma-ray Compton scatters or pair-produces in detector volume
 - Daughter particles ionize Argon atoms
 - Ionized electrons are drifted towards pixelated readout anode
 - Event readout triggered via Argon scintillation

Detection Concept: MeV Gamma-rays



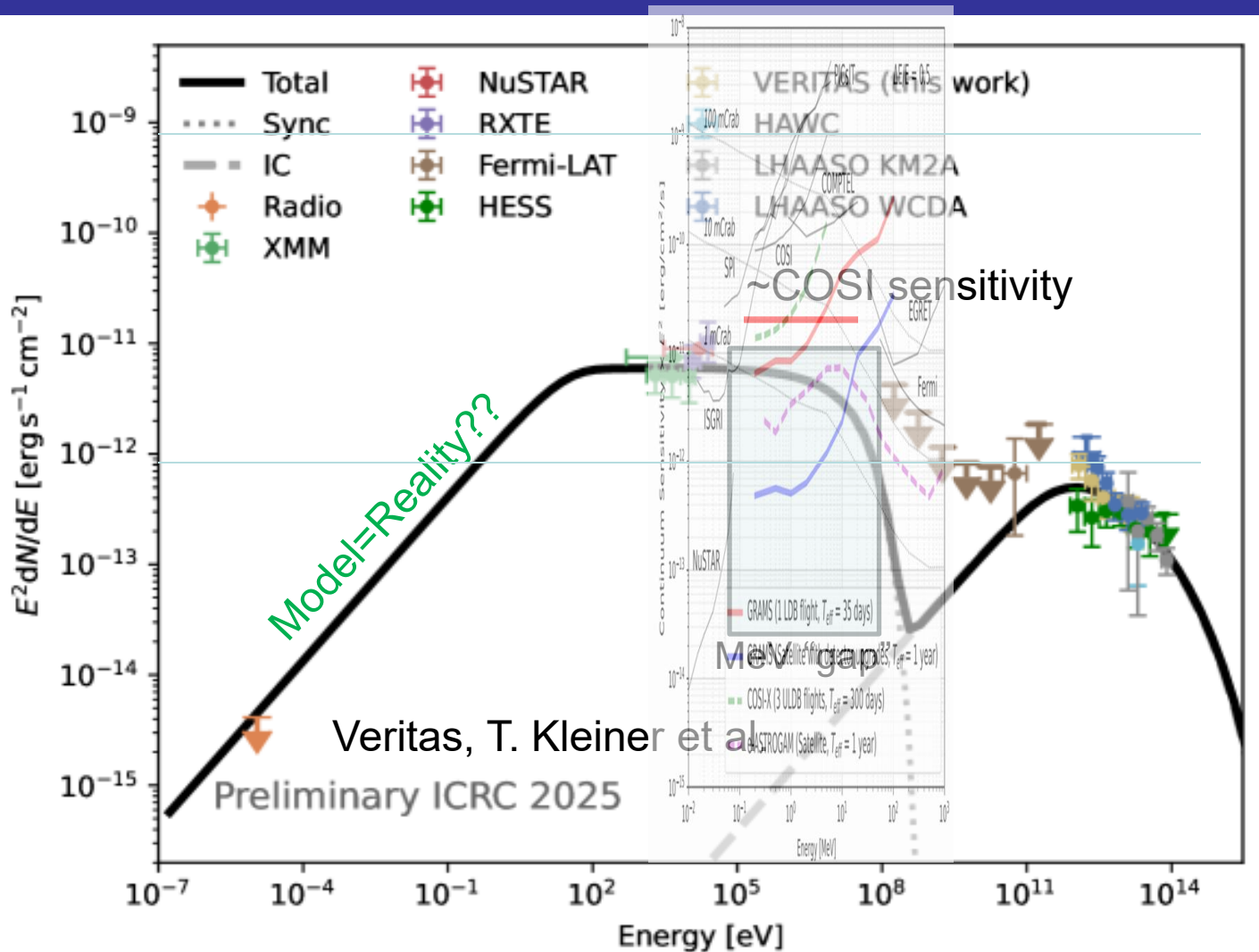
- LArTPC technology is already **well-studied** and **widely-used** in underground dark matter and neutrino experiments
- **Cost-effective** and **easily scalable**, with little to no dead volume
- Excellent 3D track reconstruction without need for dense multi-layer design
- Neutron background rejection via pulse shape of scintillation light

Why now? Energy Coverage – ~ 100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at $\sim$ MeV.



Differential sensitivities for different X-ray and γ -ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), and the ASTRO-H/HXI,SGD are the 3σ sensitivity curves for 100 ks exposures. A spectral bin with $\Delta E/E = 1$ is assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.

Not so o.k. for $\sim$ pevatrons, and LHAASO/CTA/SWGO sources



SS 433
Eastern Lobe

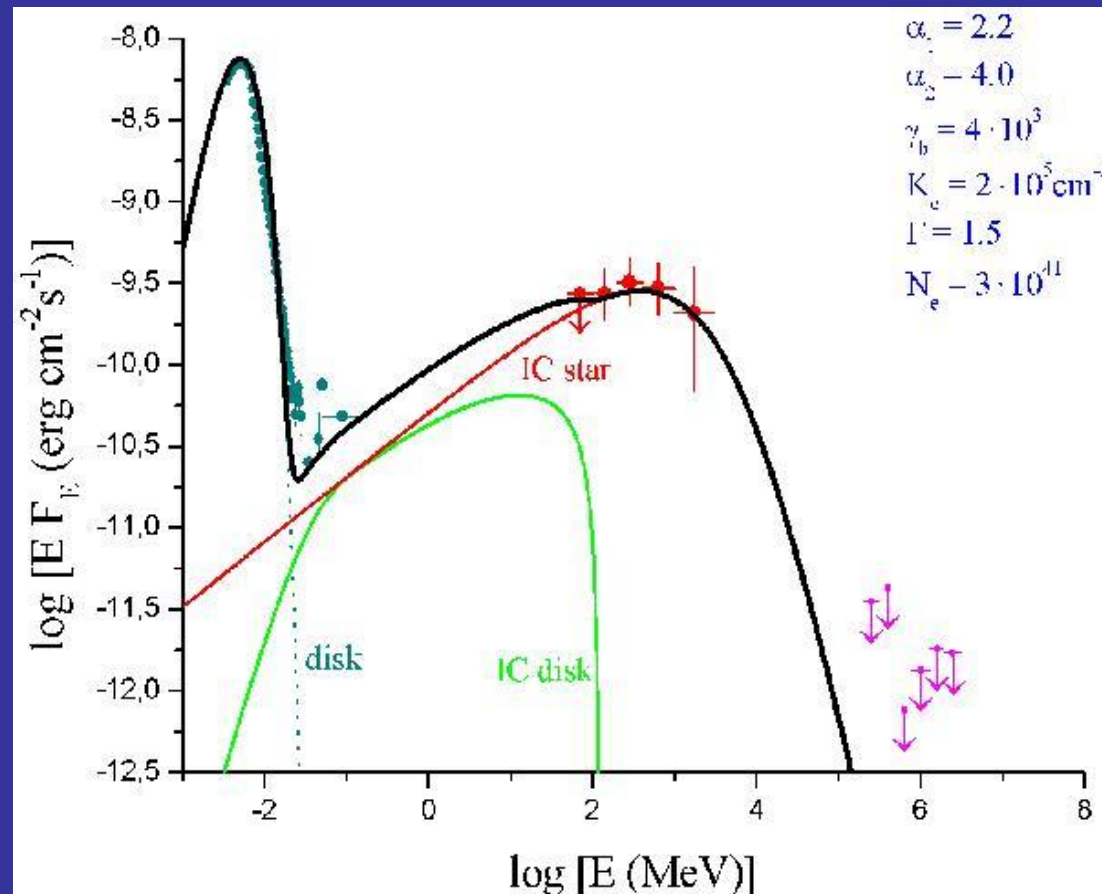
Can we
do better
than COSI?

Yes, \$\$ $\rightarrow$
solid state,
SMEX
to M-Class/
MIDEX/Probe

$\sim$ PeV gamma-rays (even if from pion decay) $\Rightarrow$ PeV+ electrons
 $\Rightarrow$ For micro-milli Gauss magnetic fields $\Rightarrow$ $\sim$ 100 keV – MeV+ synchrotron!

Why now? Energy Coverage – ~ 100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at $\sim$ MeV.

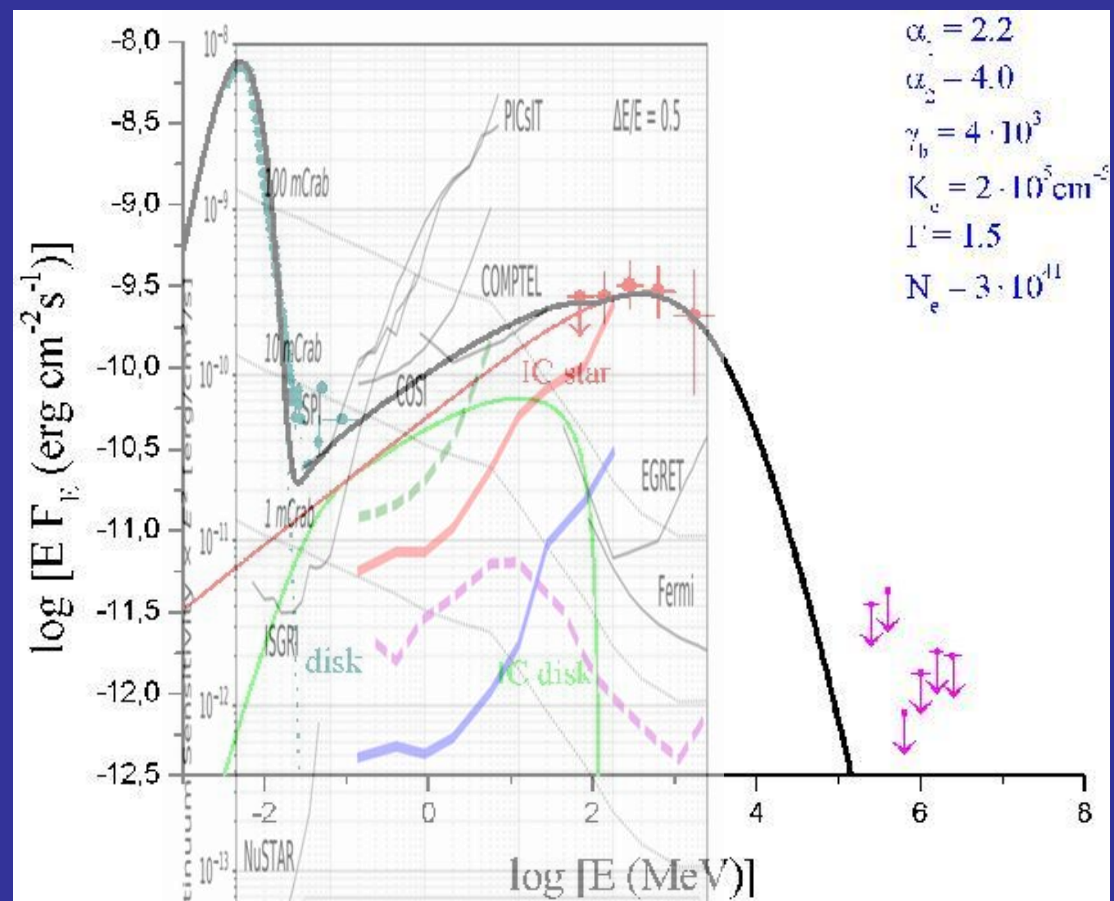
Piano et al. 2013,
Cyg X-3 flare
AGILE,
Leptonic



Differential sensitivities for different X-ray and γ -ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), and the ASTRO-H/HXI,SGD are the 3σ sensitivity curves for 100 ks exposures. A spectral bin with $\Delta E/E = 1$ is assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.

Why now? Energy Coverage – ~100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at ~MeV.

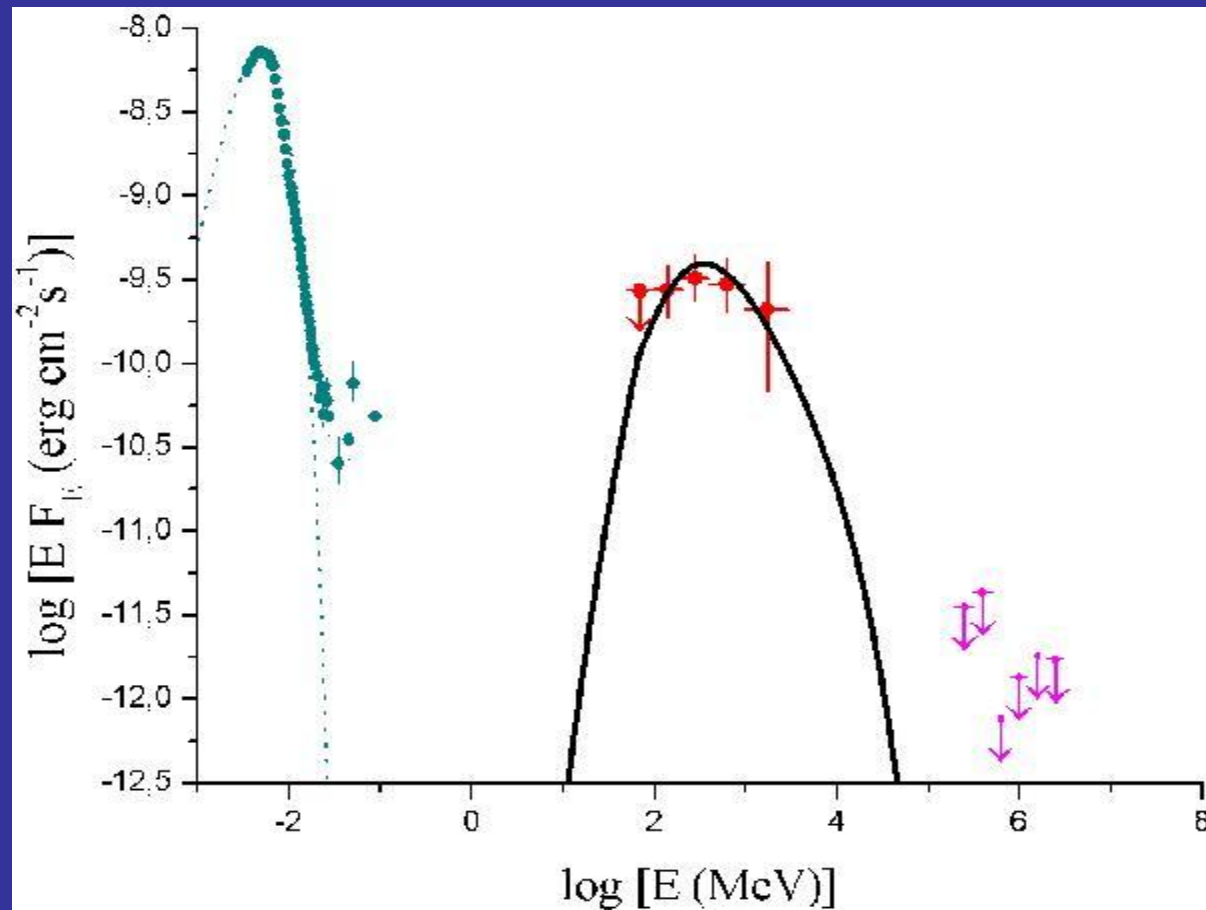
Piano et al. 2013,
Cyg X-3 flare
AGILE,
Leptonic



Differential sensitivities for different X-ray and gamma-ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-I, the Swift/BAT, the Fermi/LAT, the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), the ASTRO-H/HXI,SGD are the 3 σ sensitivity curves for 100 ks exposures. A spectral bin with $\Delta E/E = 1$ is assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.

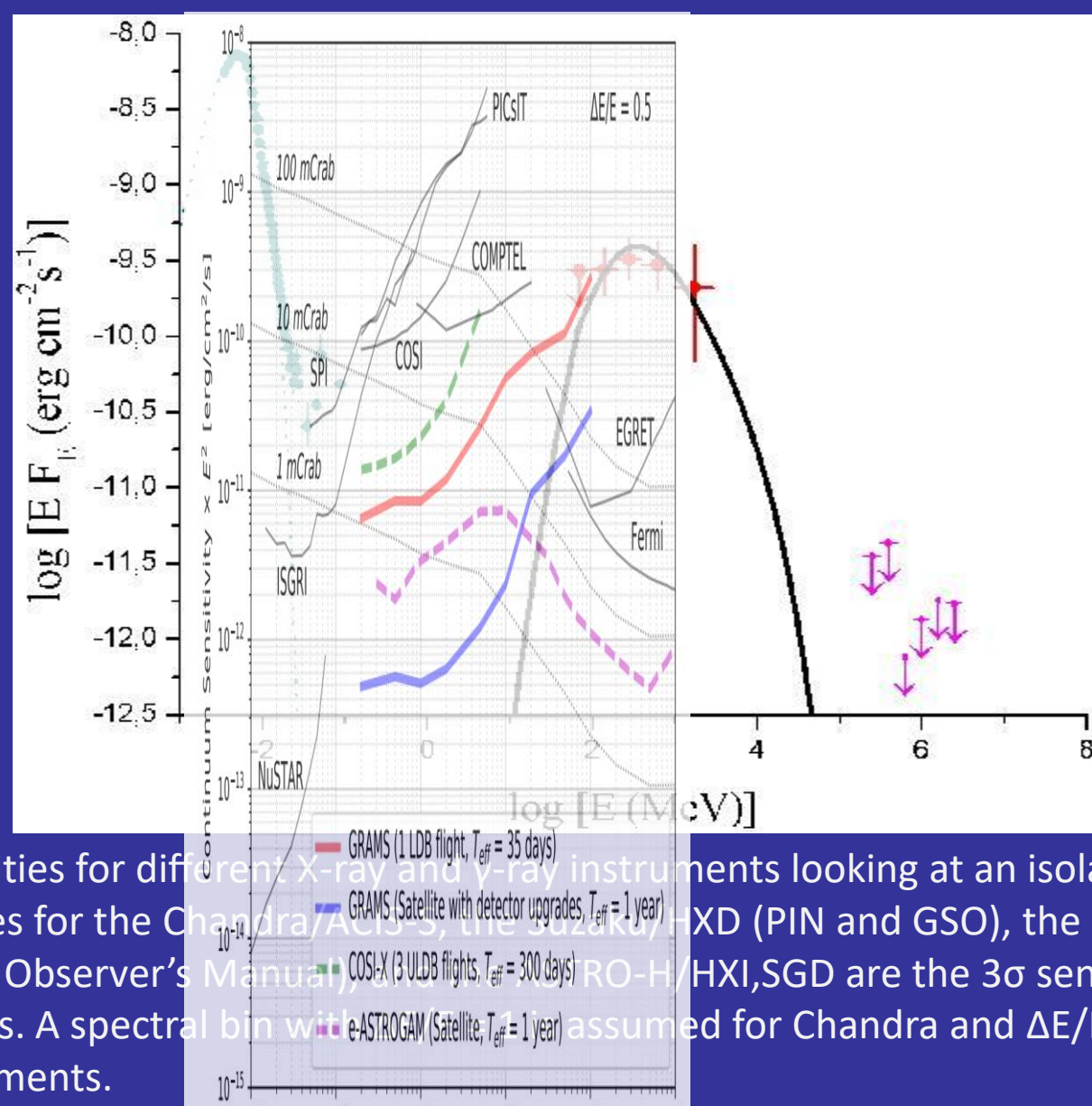
Why now? Energy Coverage – ~ 100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at $\sim$ MeV.

Piano et al. 2013,
Cyg X-3 flare
AGILE,
Hadronic

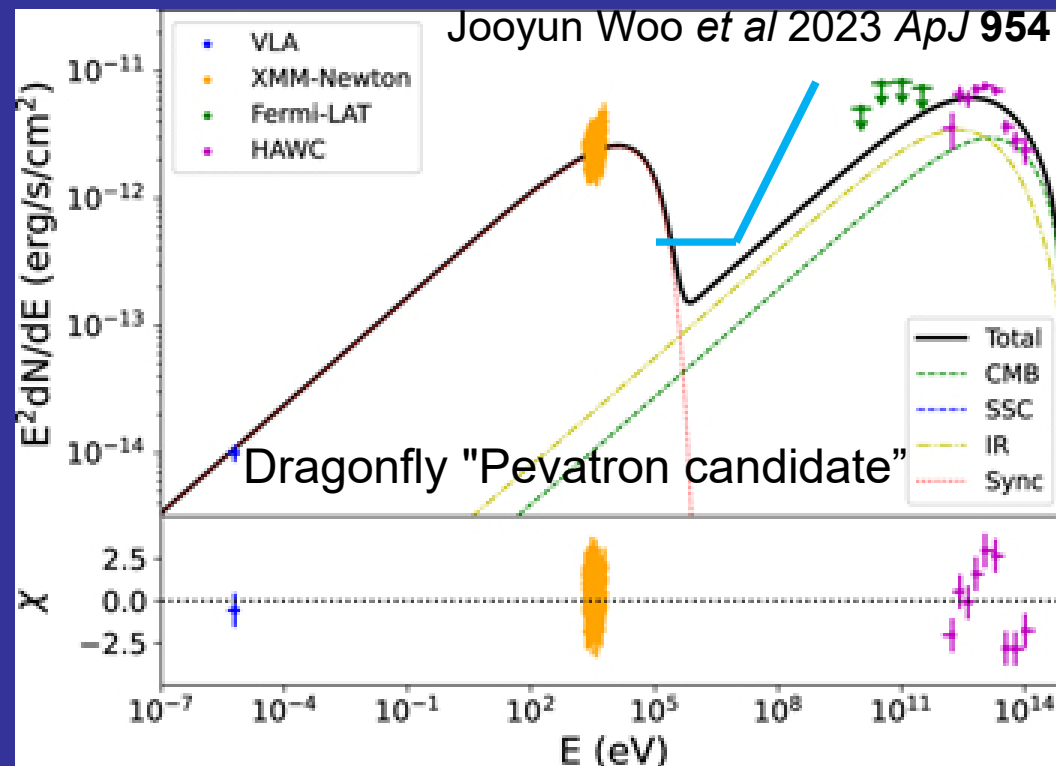


Differential sensitivities for different X-ray and γ -ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), and the ASTRO-H/HXI,SGD are the 3σ sensitivity curves for 100 ks exposures. A spectral bin with $\Delta E/E = 1$ is assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.

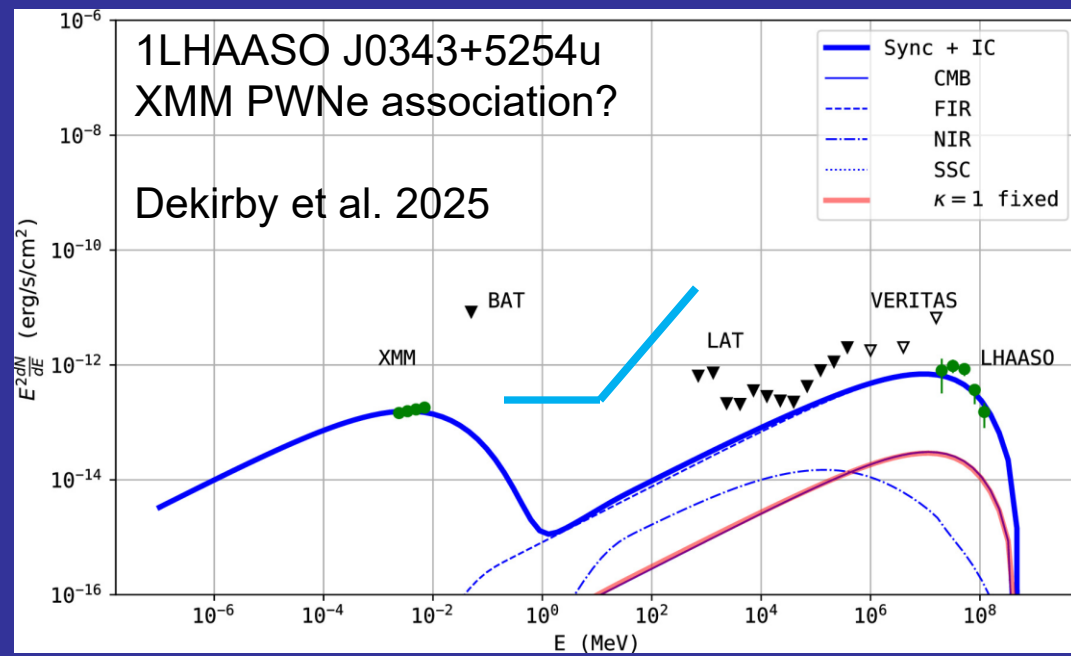
Why now? Energy Coverage – ~100 keV-MeV-GeV can only be done from space ... and there's a big gap there!! Especially at ~MeV.



Differential sensitivities for different X-ray and γ -ray instruments looking at an isolated point source. Curves for the Chandra/ACIS-S, the Suzaku/HXD (PIN and GSO), the INTEGRAL/IBIS (from the 2009 IBIS Observer's Manual), COSI-X (3 ULDB flights, $T_{\text{eff}} = 300$ days), e-ASTROGAM (Satellite, $T_{\text{eff}} = 1$ year) assumed for Chandra and $\Delta E/E = 0.5$ for the other instruments.



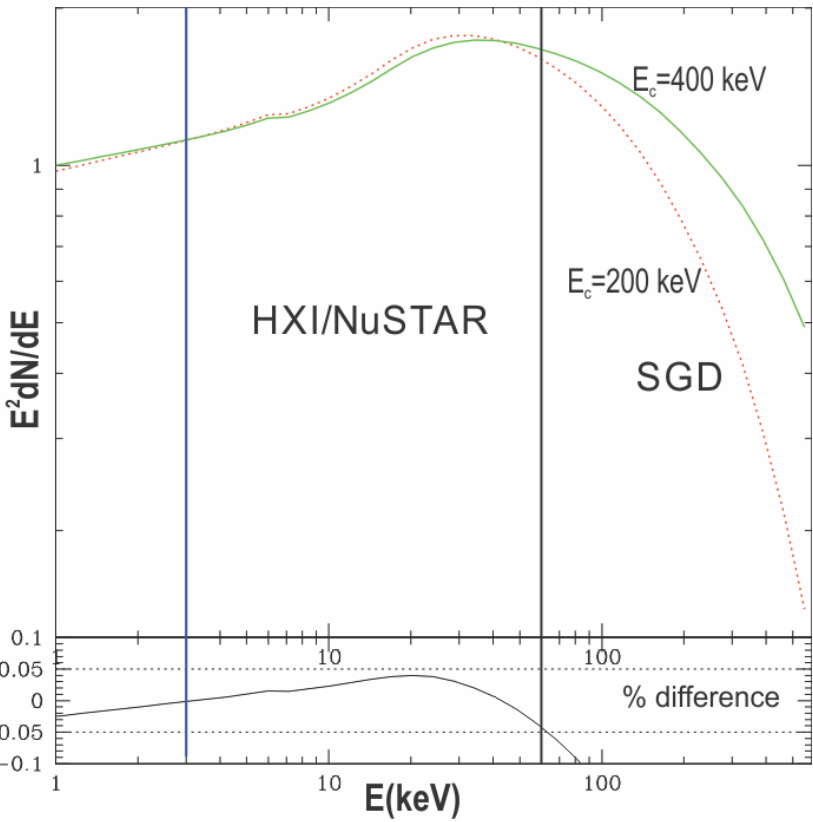
Some PWNe with SEDs



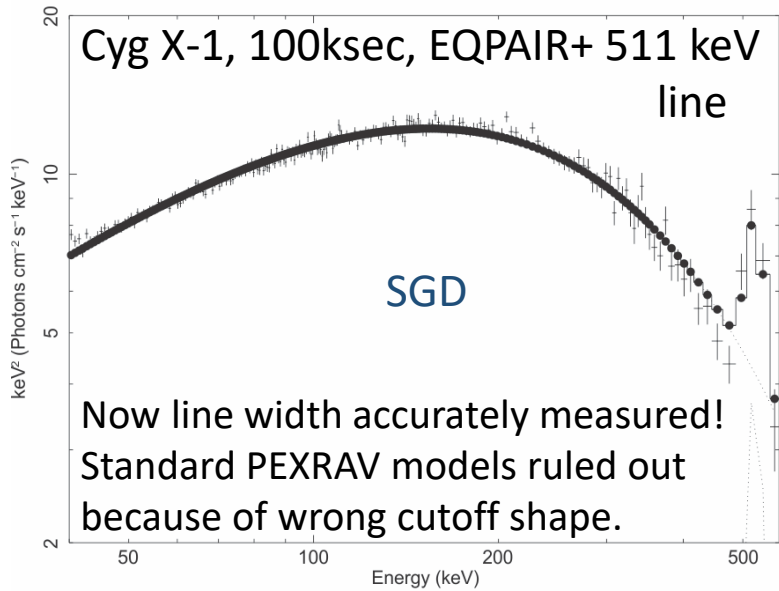
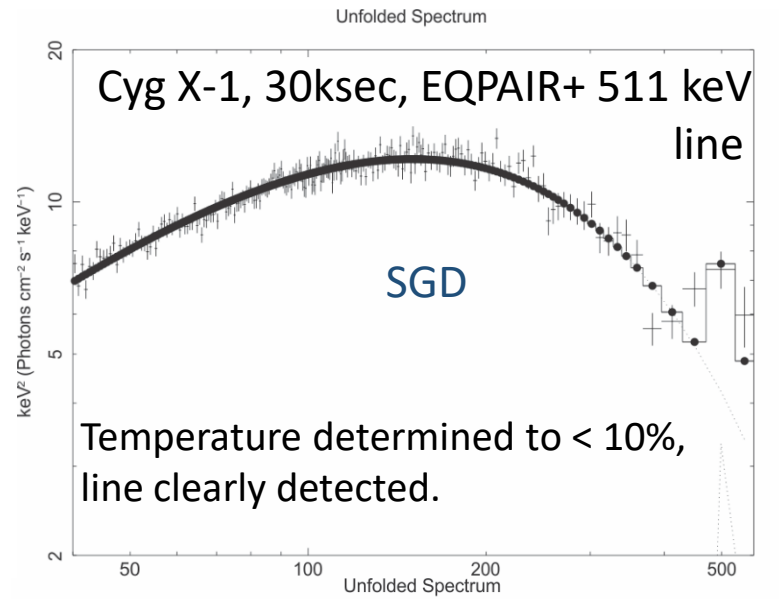
Summary

- We have an “MeV gap” problem in our current SED coverage of VHE/Pevatron sources...
- Limits our understanding of non-thermal processes (better to actually measure a cutoff than rely on theorists to predict it or draw a line from last NuSTAR point to first Fermi point).
- Filling it requires new space-based instrument(s) – not easy! If it happens, COSI is a great start (>> COMPTEL).
- But match what we are finding/will find in CTA/LHAASO/SWGO era, need >> COSI.
- LArTPC one avenue to achieve (e.g., GRAMS, actively under development, prototype balloon flight spring 2026)

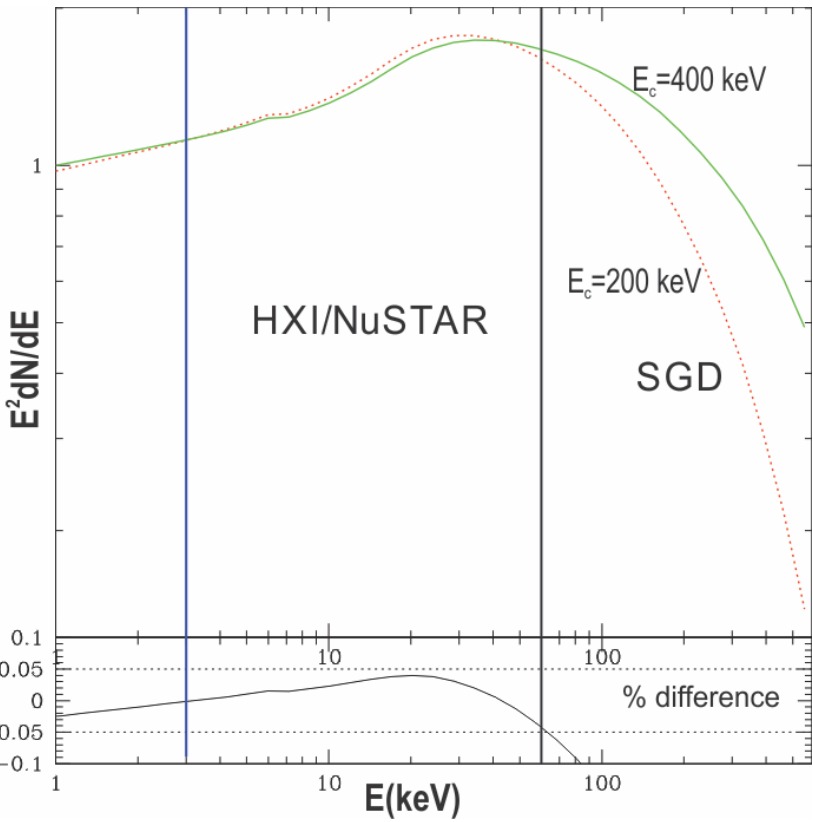
The high-energy break in the hard state of Cyg X-1: Another example of how the SGD/ASTRO-H comes into its own for brighter sources ($>10^{-10}$ erg cm² s⁻¹), e.g., enabling science that cannot be done by NuSTAR alone.



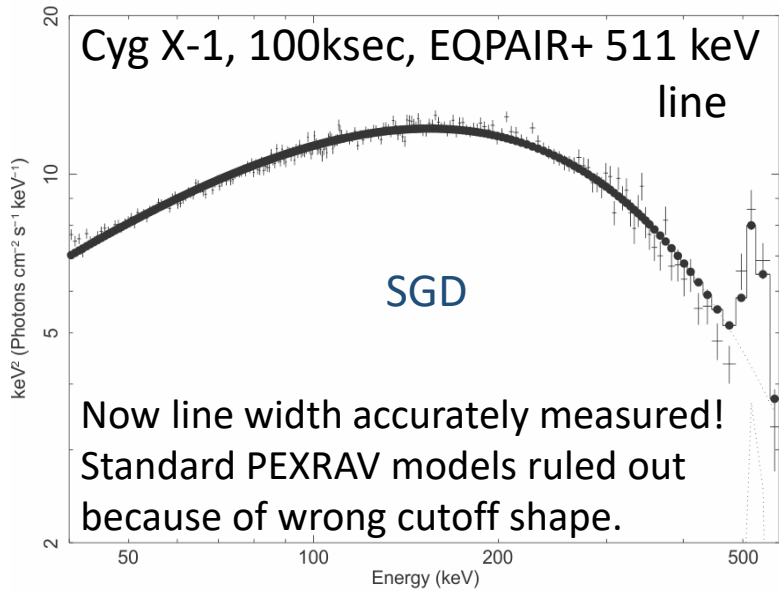
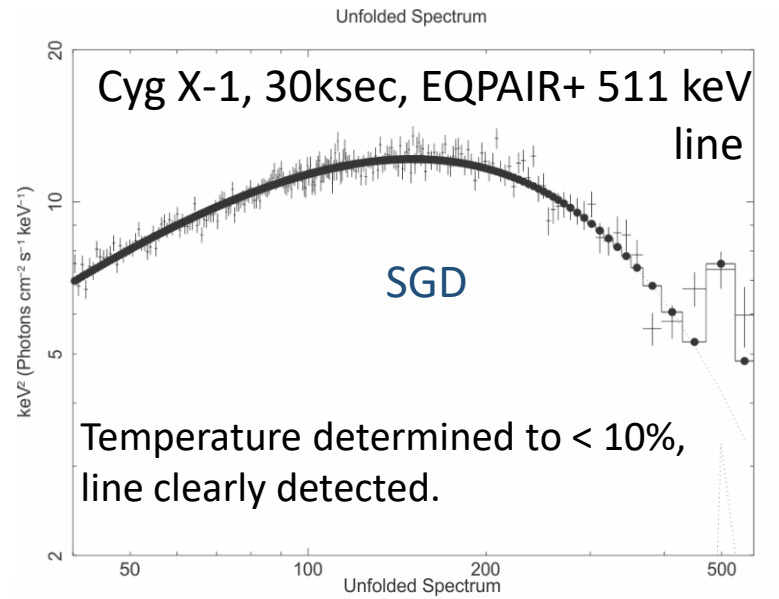
Even with sensitivity to ~ 60 keV, i.e., past the peak of the Compton reflection hump, modeling degeneracies remain for NuSTAR/HXI alone. Above, the temperature of the Comptonizing electrons cannot be constrained to better than a factor 2.



The high-energy break in the hard state of Cyg X-1: Another example of how the SGD/ASTRO-H comes into its own for brighter sources ($>10^{-10}$ erg cm² s⁻¹), e.g., enabling science that cannot be done by NuSTAR alone.



Even with sensitivity to ~ 60 keV, i.e., past the peak of the Compton reflection hump, modeling degeneracies remain for NuSTAR/HXI alone. Above, the temperature of the Comptonizing electrons cannot be constrained to better than a factor 2.



Given previous SEDs, and high compactness of coronal region, one might think Cyg X-1 could never be significant TeV source... but

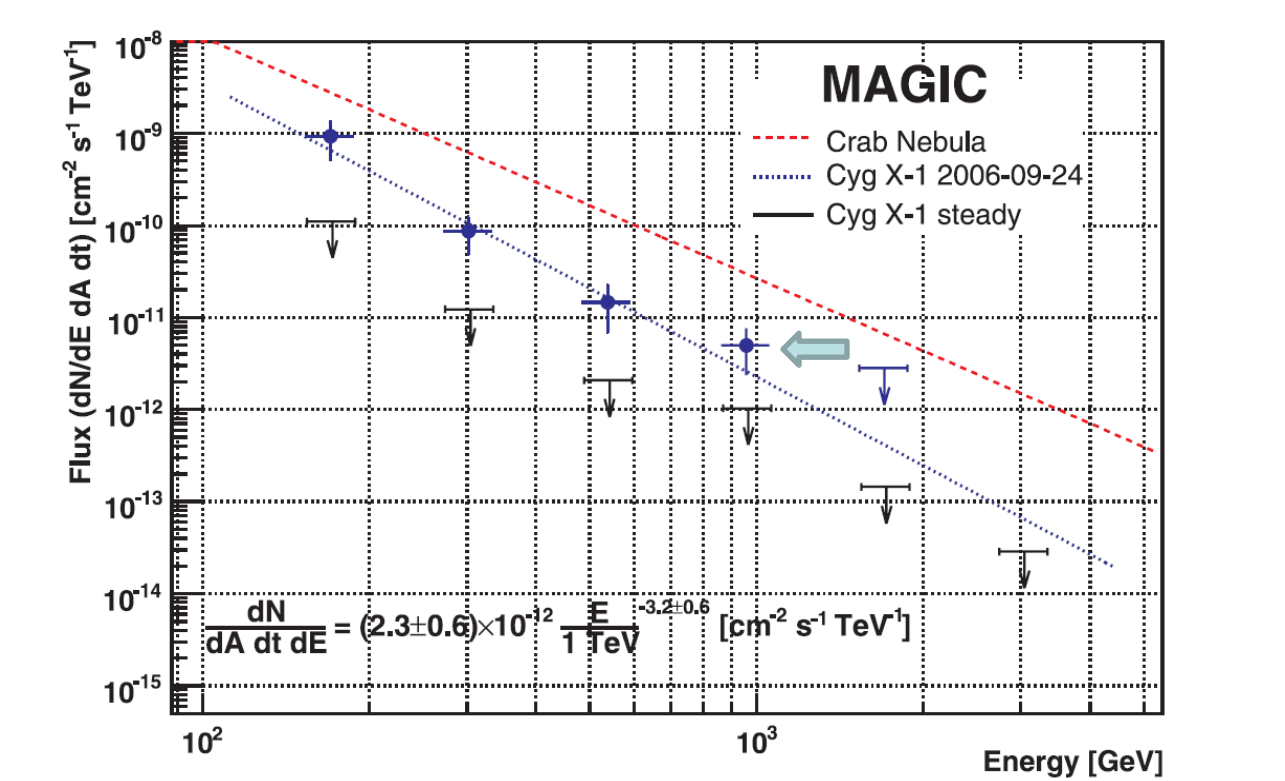


FIG. 1.—Differential energy spectrum from Cygnus X-1 corresponding to 78.9 minutes of EOT between MJD 54,002.928 and 54,002.987 (2006 Sep-tember 24). Also shown are the Crab Nebula spectrum, the best fit of a power law to the data, and the 95% confidence level upper limits to the steady γ -ray flux (Rolke et al. 2005).