

MeV-GeV Gamma-Ray Observations: Constraining Cosmic Ray-Mediated Feedback and Star Formation Activity

P. Coppi, Yale + FIGSAG

[\[https://pcos.gsfc.nasa.gov/sags/figsag.php\]](https://pcos.gsfc.nasa.gov/sags/figsag.php)

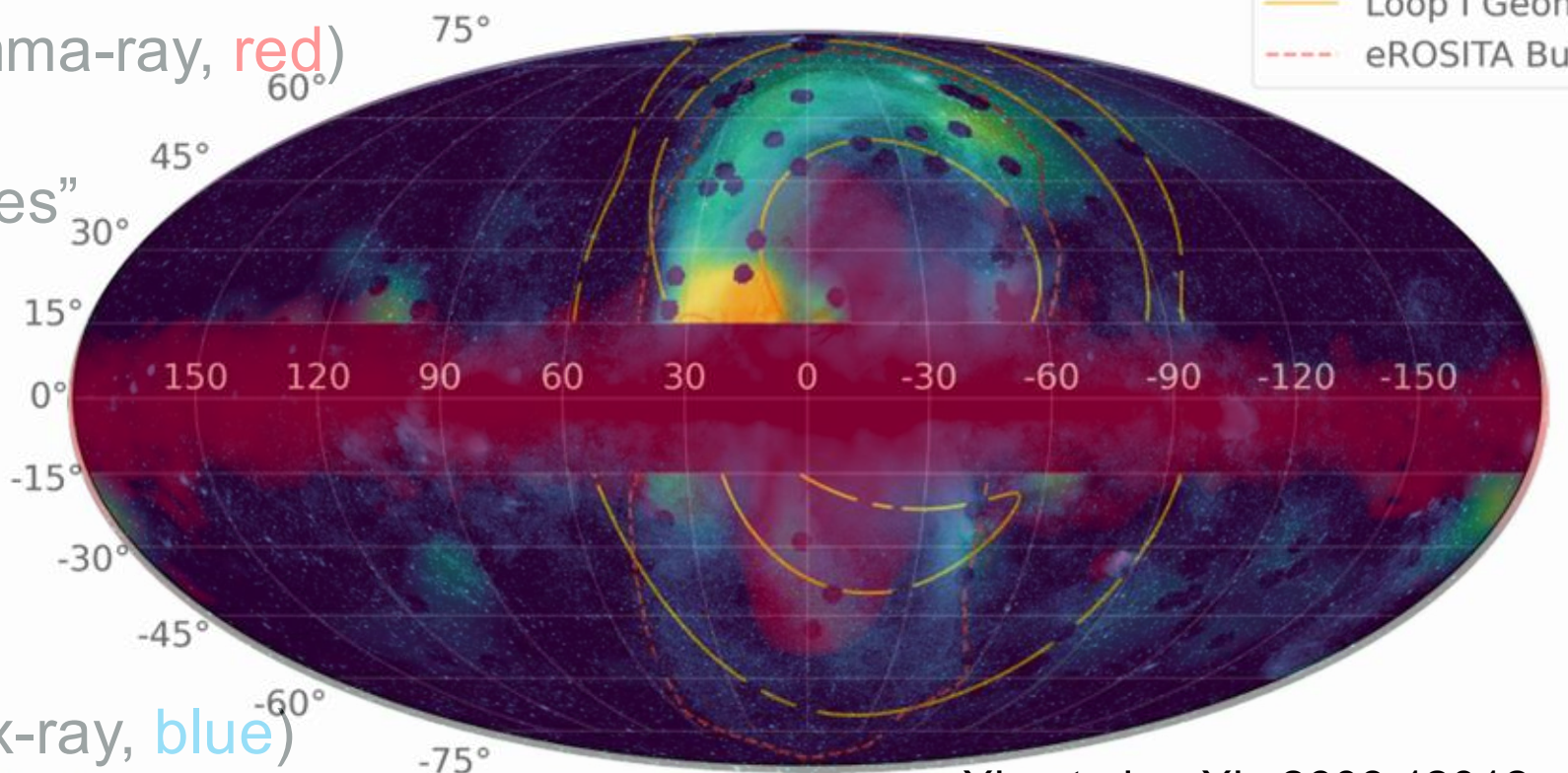


Fermi (gamma-ray, red)

The “Bubbles”
=outflows?
AGN or
stellar
feedback?

eROSITA (x-ray, blue)

Credit: Peter Predehl *Nature*, vol. 588, pp 227-231



Xie et al. arXiv:2608.12012v1

The eRosita bubbles could just be hot (thermal), maybe shocked $\sim$ keV gas ...but the Fermi bubbles [which now could have component associated with eRosita bubbles too!] are *not* ...

How do we know? **Gamma-Rays! (Fermi)**

Gamma-rays
point back to
location of
emitting particles

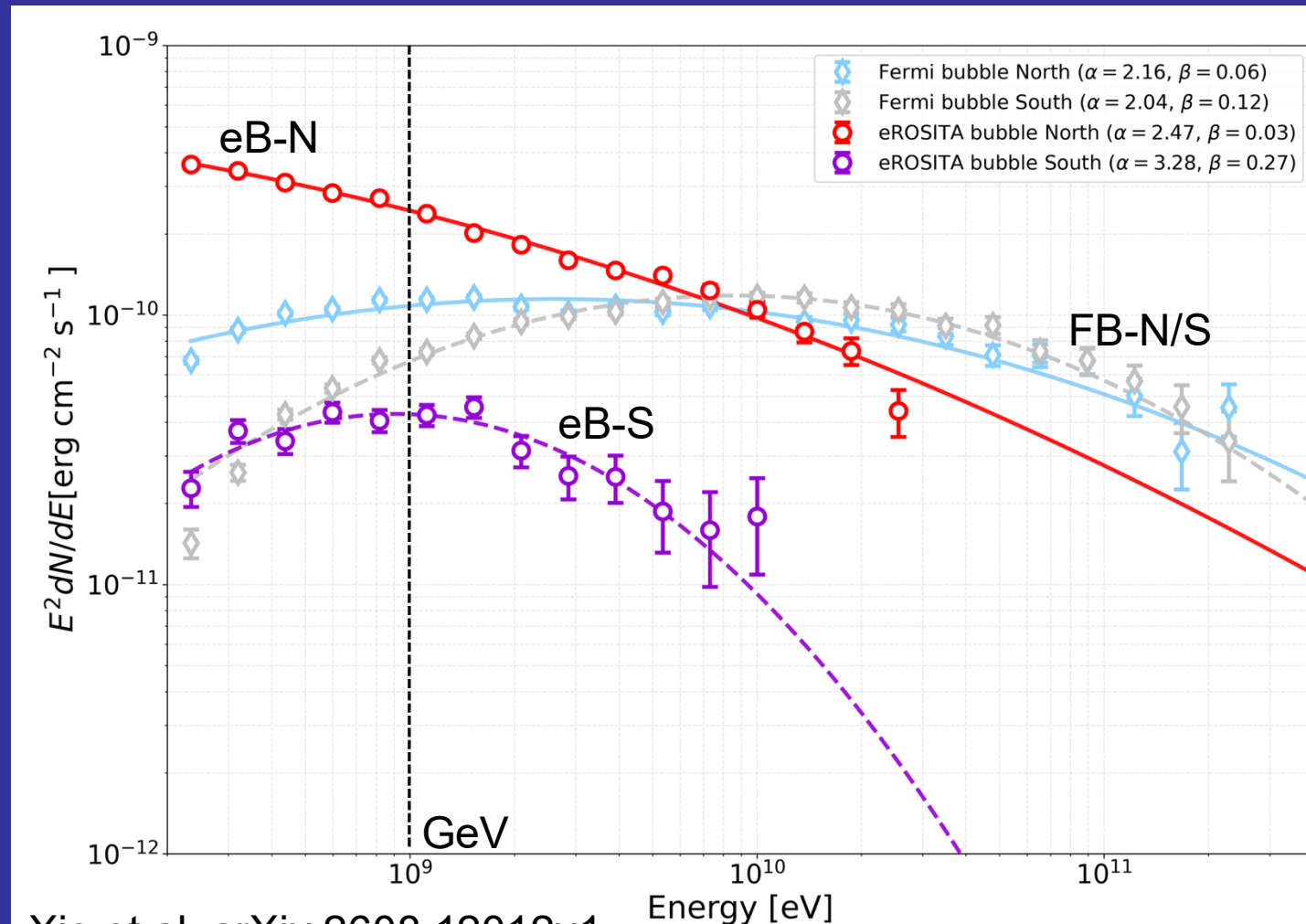
+

$E_{\text{part}} > E_{\text{gamma}}$

+

Minimal
reprocessing
= direct probe

$\Rightarrow$ Cosmic Rays!



Xie et al, arXiv:2608.12012v1

Why Gamma-Rays?

On Gamma-Ray Astronomy.

P. MORRISON

Department of Physics, Cornell University - Ithaca, N. Y.

(ricevuto il 22 Dicembre 1957)

Summary. — Photons in the visible range form the basis of astronomy. They move in straight lines, which preserves source information, but they arise only very indirectly from nuclear or high-energy processes. Cosmic-ray particles, on the other hand, arise directly from high-energy processes in astronomical objects of various classes, but carry no information about source direction. Radio emissions are still more complex in origin. But γ -rays arise rather directly in nuclear or high-energy processes, and yet travel in straight lines. Processes which might give rise to continuous and discrete γ -ray spectra in astronomical objects are described, and ...

[Same goes for neutrinos!! But they're even harder to detect...]

Why γ -rays [~ 100 keV-GeV+]?

- Clean signature of extreme, non-thermal & nuclear universe (don't have to worry about thermal/stellar contamination, e.g., in soft X-rays and optical) -
- In hindsight you could have deduced existence of eROSITA and Fermi bubbles from Planck/WMAP “haze” and ROSAT X-ray observations, but...
- Valuable multi-messenger partner since neutrino & cosmic ray production/propagation $\Rightarrow \gamma$ -rays! Sources relatively rare, so coincidence often significant. (TDAMM)
- Direct propagation from source, very penetrating – especially at $\sim$ MeV energies. It takes $A_V \sim 100$'s to 1000's to block.
- Compact object energy scales, physical conditions $\Rightarrow \gamma$ -rays! They can be polarized too $\Rightarrow$ source/magnetic field geometry.
- *Though “rare,” non-thermal processes and magnetic fields more important than we thought...*

3 Milky Way analogs...

γ -ray Emission Maps [5-50 GeV]

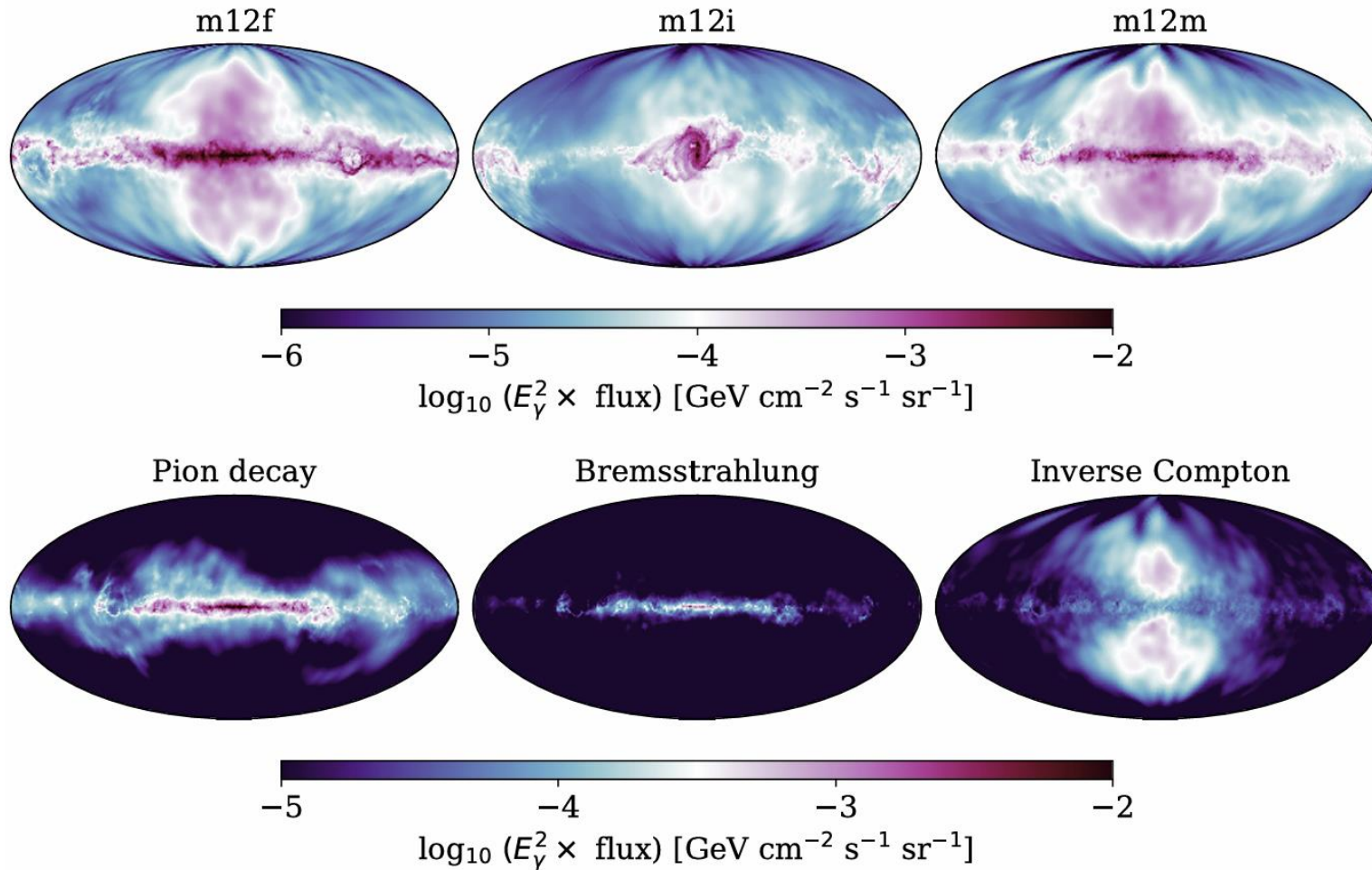


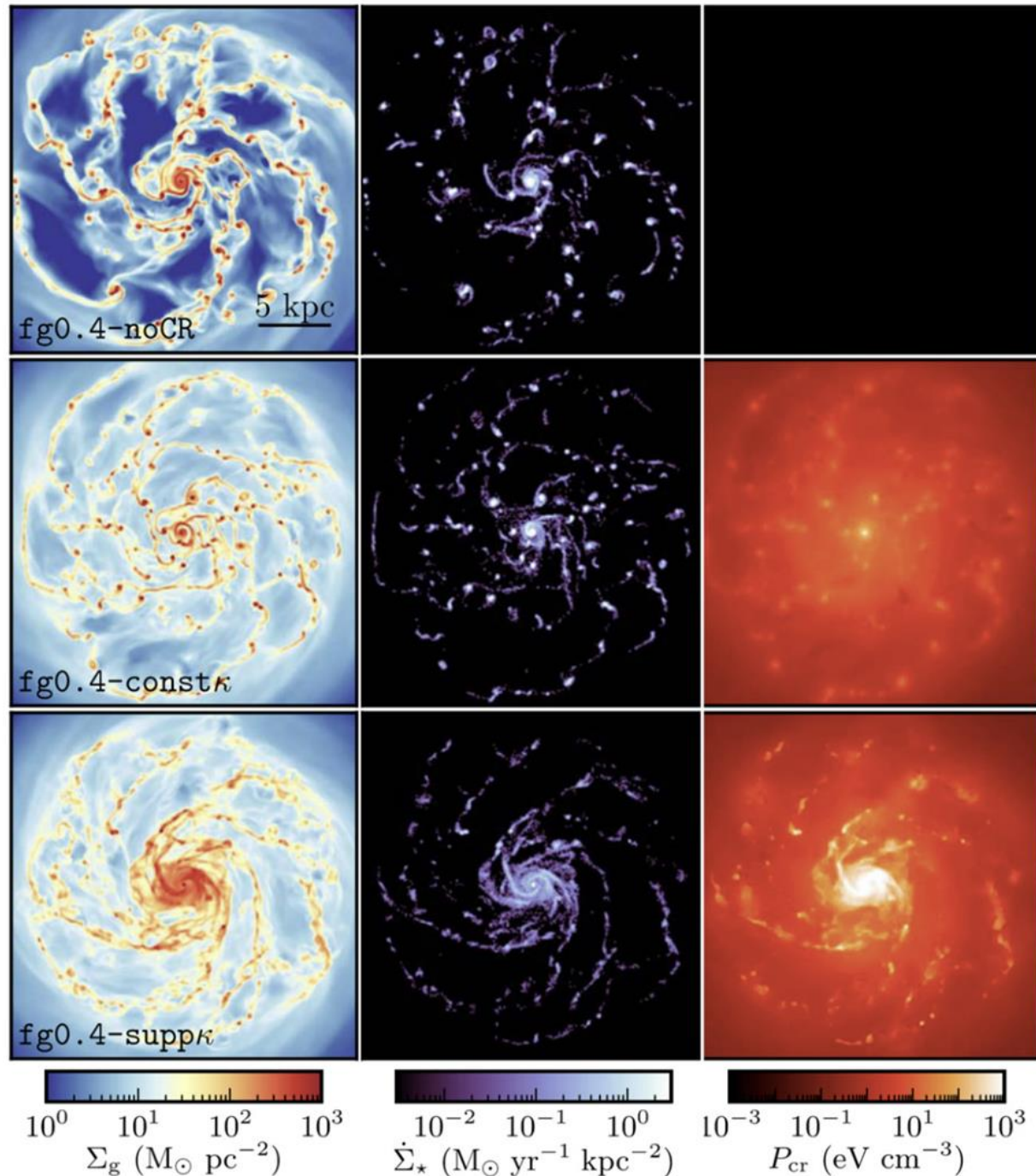
FIG. 1. **Top:** total flux of 5-50 GeV γ -rays for the three simulated MW analogs in our sample. All galaxies show a distinct bi-lobed feature above and below the plane of the galactic disk; this feature is less pronounced for **m12i**, which has a warped disk and a strong magnetic field at its center, which leads to higher CR lepton loss rates than in **m12f** or **m12m**. **Bottom:** γ -ray emission in galaxy **m12m** from the three relevant CR interactions: neutral pion decay, relativistic Bremsstrahlung, and inverse Compton scattering. ICS is responsible for most of the bubble structure, with a slight hadronic contribution at lower latitudes.

Do cosmic rays matter
for feedback for galaxy
formation/structure
calculations?

YES!!

In ISM, CR energy
density (pressure)
comparable to
magnetic field and
gas thermal/turbulent
motion pressure!

ISM/CGM is complex,
multiphase medium –
can't ignore any
component.



See Ruszkowski + Pfrommer review, ARAA 2023

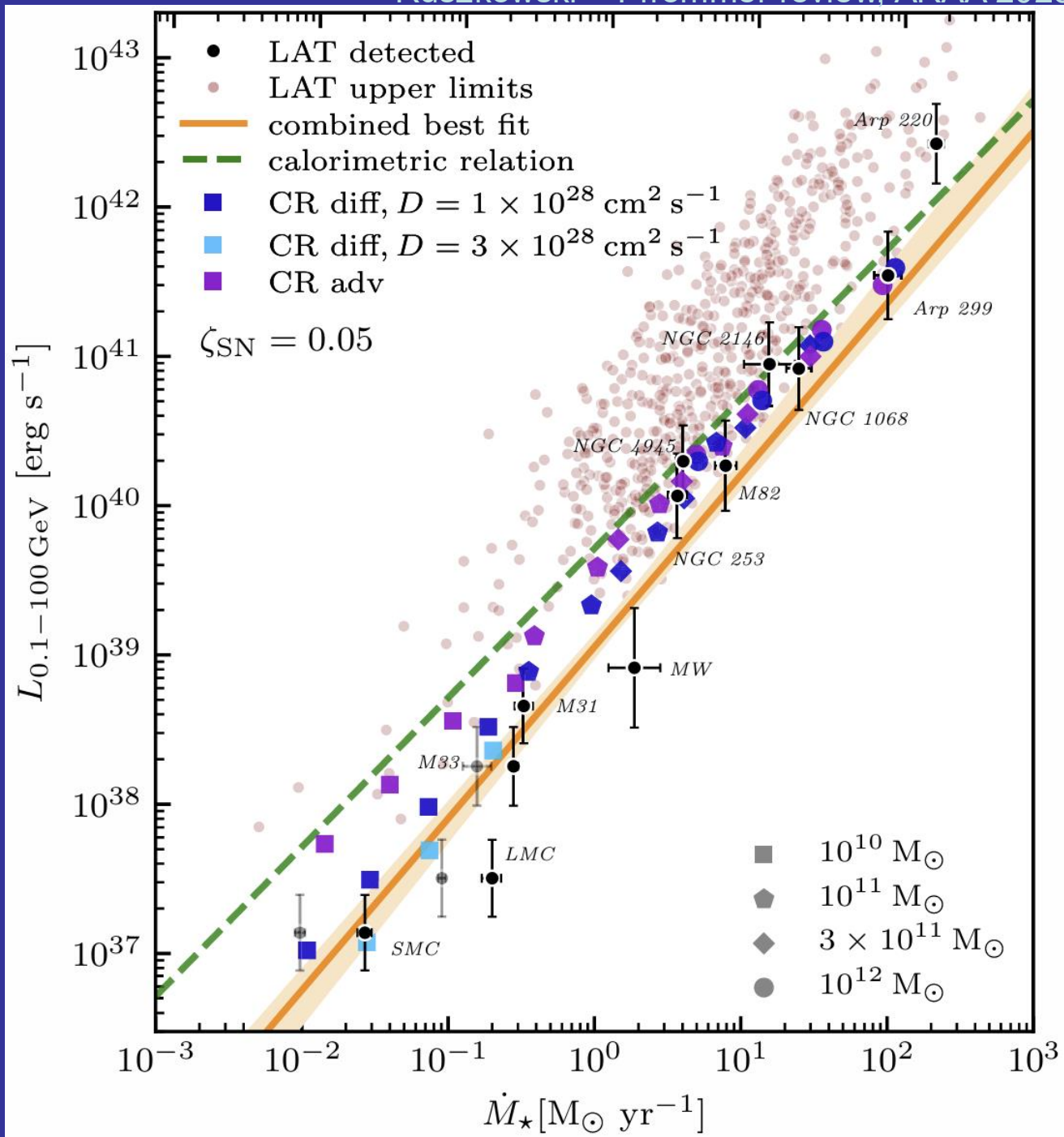
Fermi (GeV) can detect integrated flux from nearest galaxies!

Strong correlation with FIR luminosity/SFR!

Constrains global CR energetics (note: not many objects violate: "calorimetric limit" assuming CR energetics tracks SFR.)

And CR propagation/escape details matter!

Can dream of super Fermi, which detects many more galaxies and *actually images some of them!*



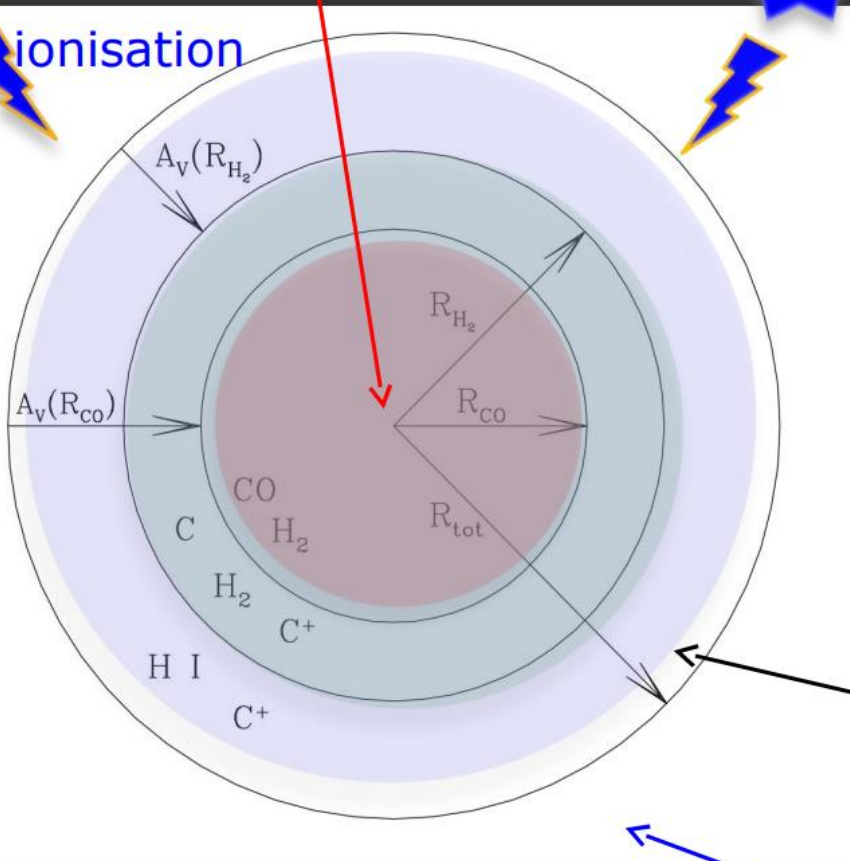
Missing Molecular Gas : “Dark” H_2

Inferred by MeV/GeV gamma-ray observations
e.g. Greiner et al 2005, Ackermann et al 2011

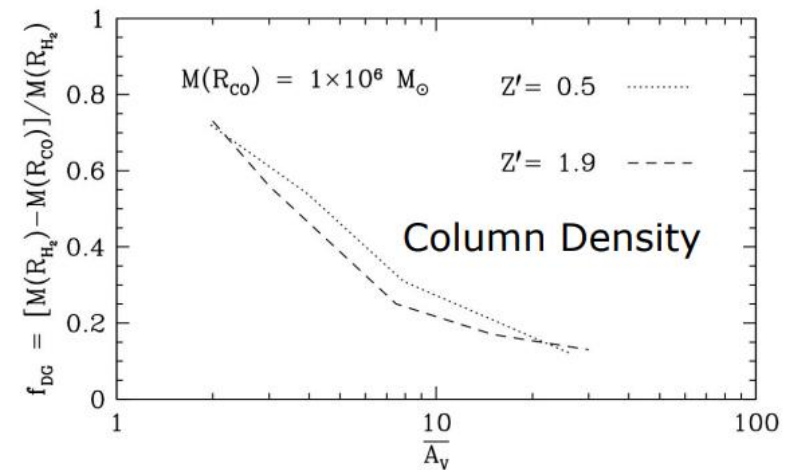
*Perhaps one-third of the
molecular gas is “dark”?!*

‘Normal’ CO Molecular Gas

ionisation



Dark H_2 Fraction



**Dark molecular gas.
No CO, but carbon
still present
→ CI, C+ ~THz lines**

Wolfire, Hollenbach & McKee, 2010

Atomic Gas

The eRosita bubbles could just be hot (thermal), maybe shocked $\sim$ keV gas ...but the Fermi bubbles [which now could have component associated with eRosita bubbles too!] are *not* ...

How do we know? **Gamma-Rays! (Fermi)**

Gamma-rays
point back to
location of
emitting particles

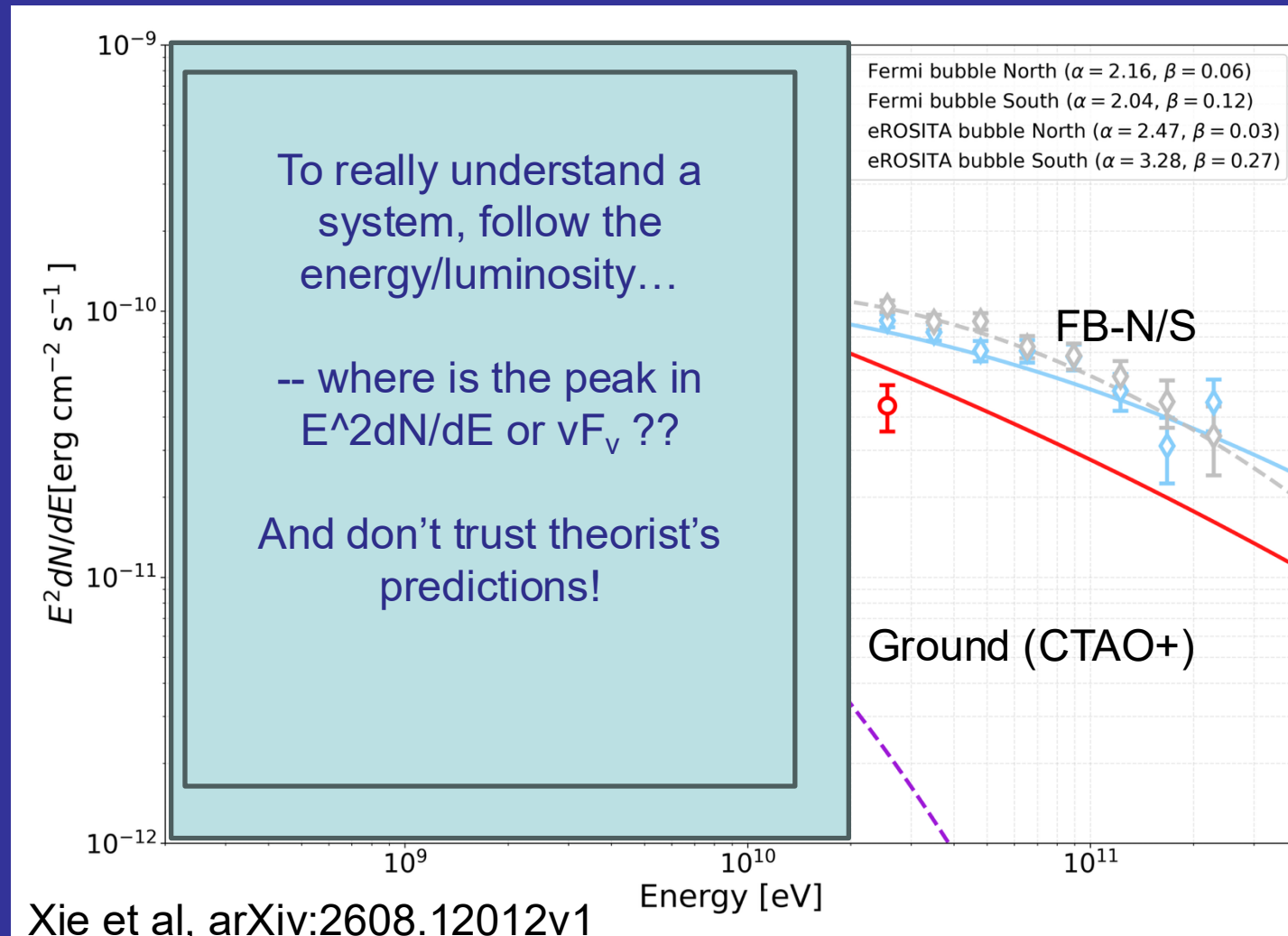
+

$$E_{\text{part}} > E_{\text{gamma}}$$

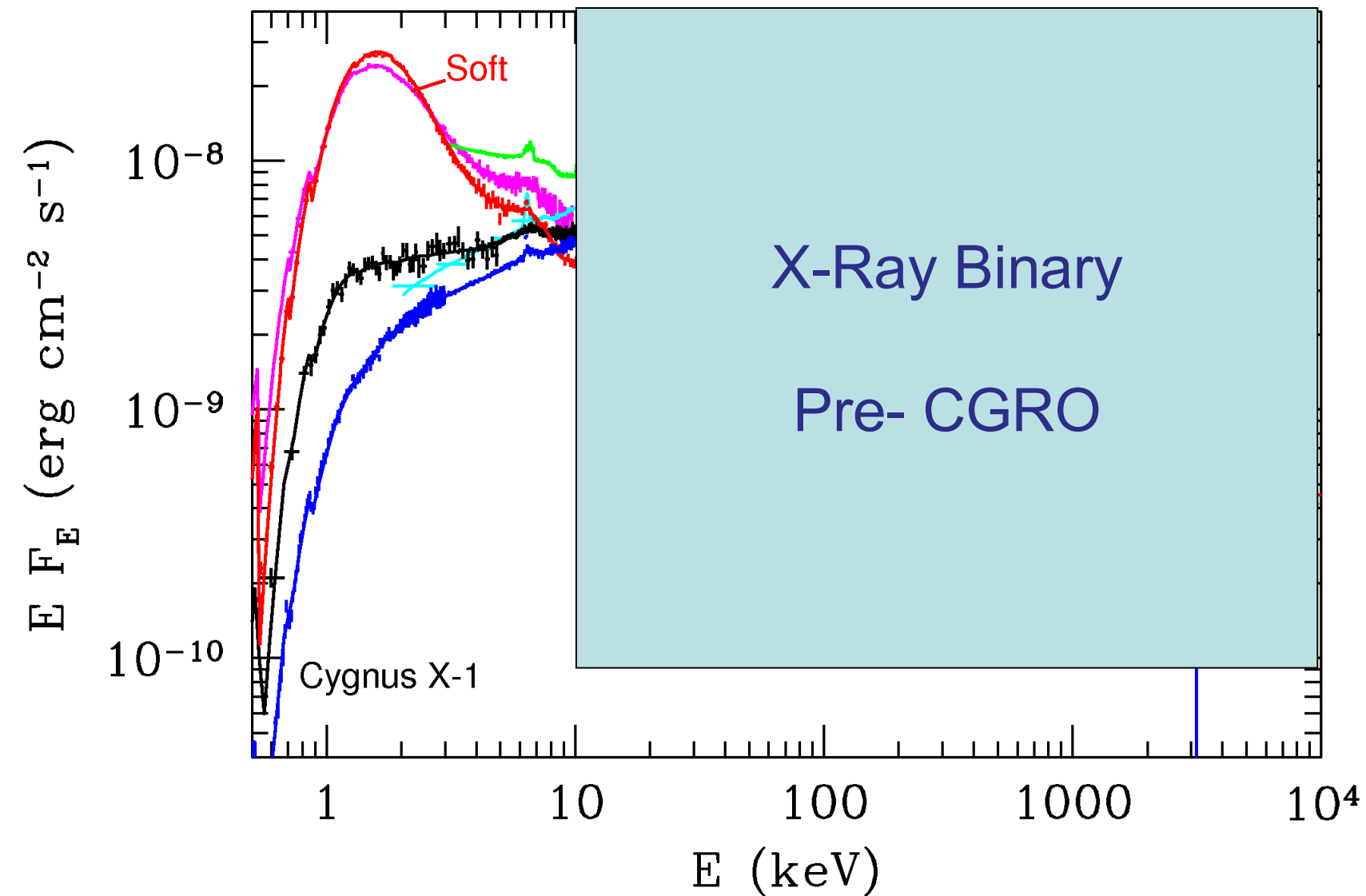
+

Minimal
reprocessing
= direct probe

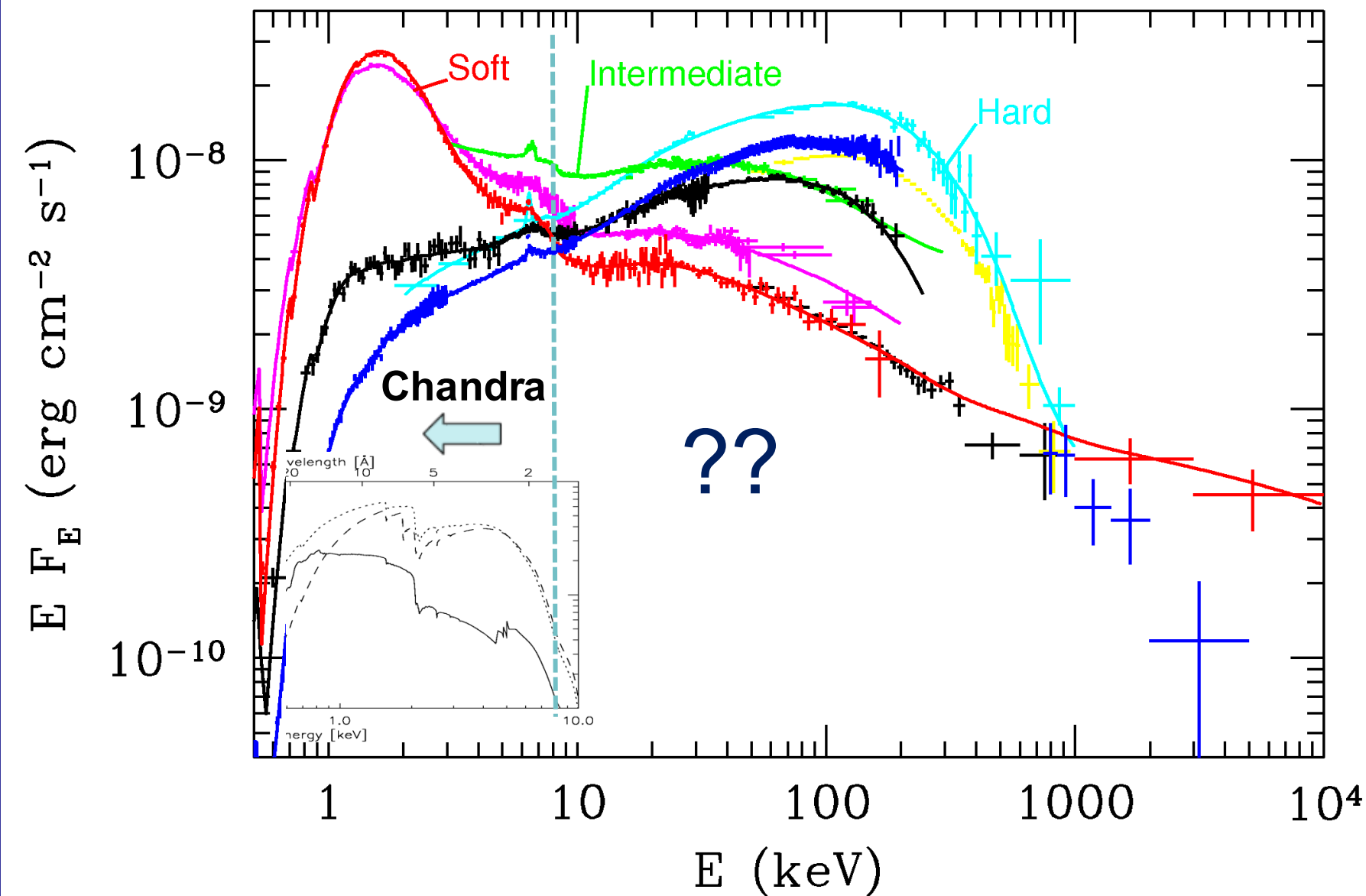
$\Rightarrow$ Cosmic Rays!



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

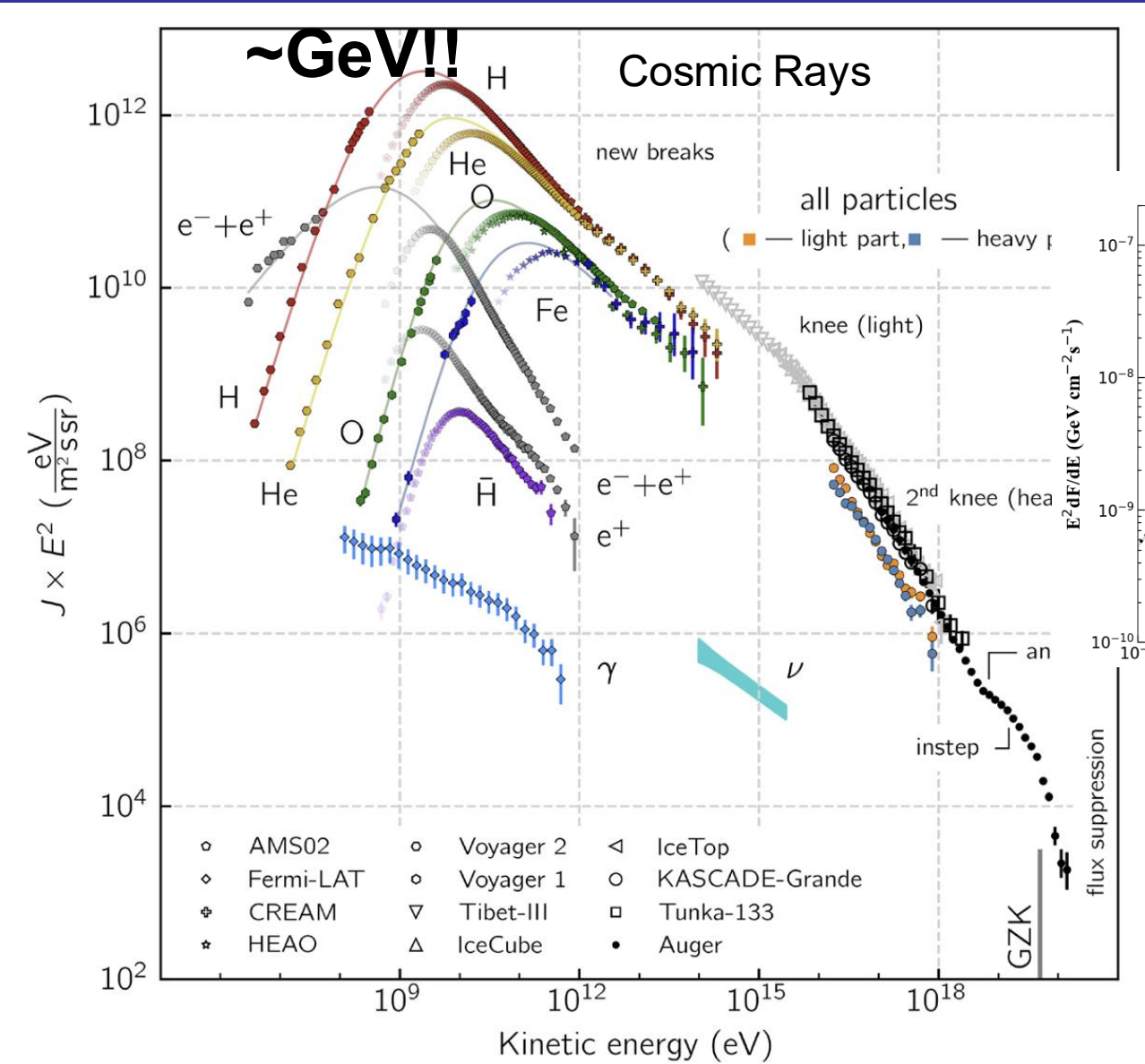


Spectra of this quality generally do not exist for AGN!

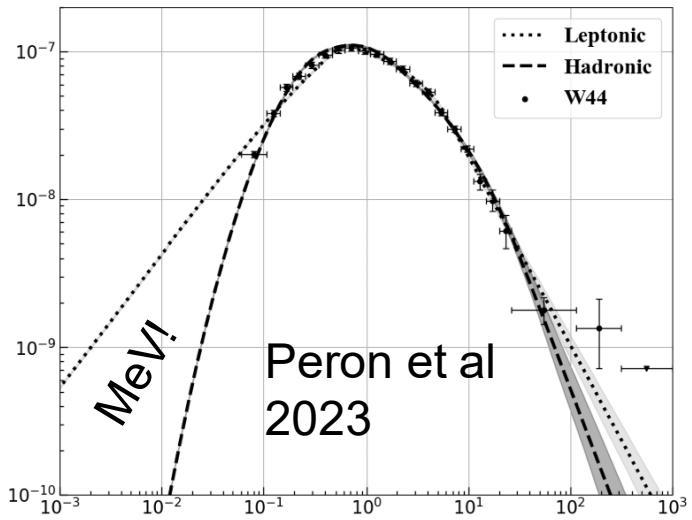


Possible AGN spectral “states” not well-sampled!

So, for galactic cosmic rays, where does $E^2 dN/dE$ peak?

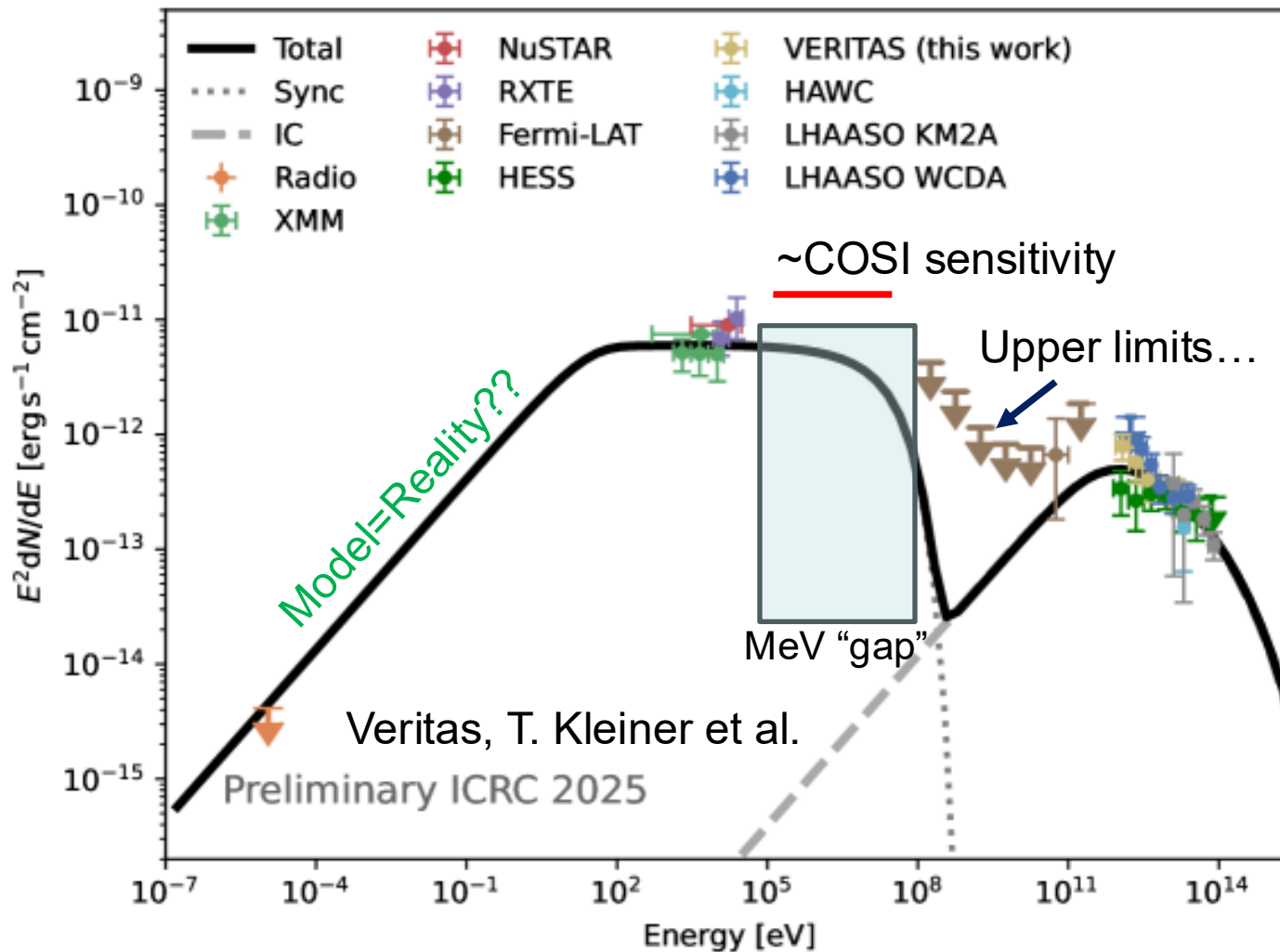


Is a CR source “hadronic” or “leptonic” ?



The pion bump “smoking gun” for SNR W44??

The MeV-GeV gap for pevatrons (latest hot VHE topic)



SS 433
Eastern Lobe
Can we
do better
than COSI?

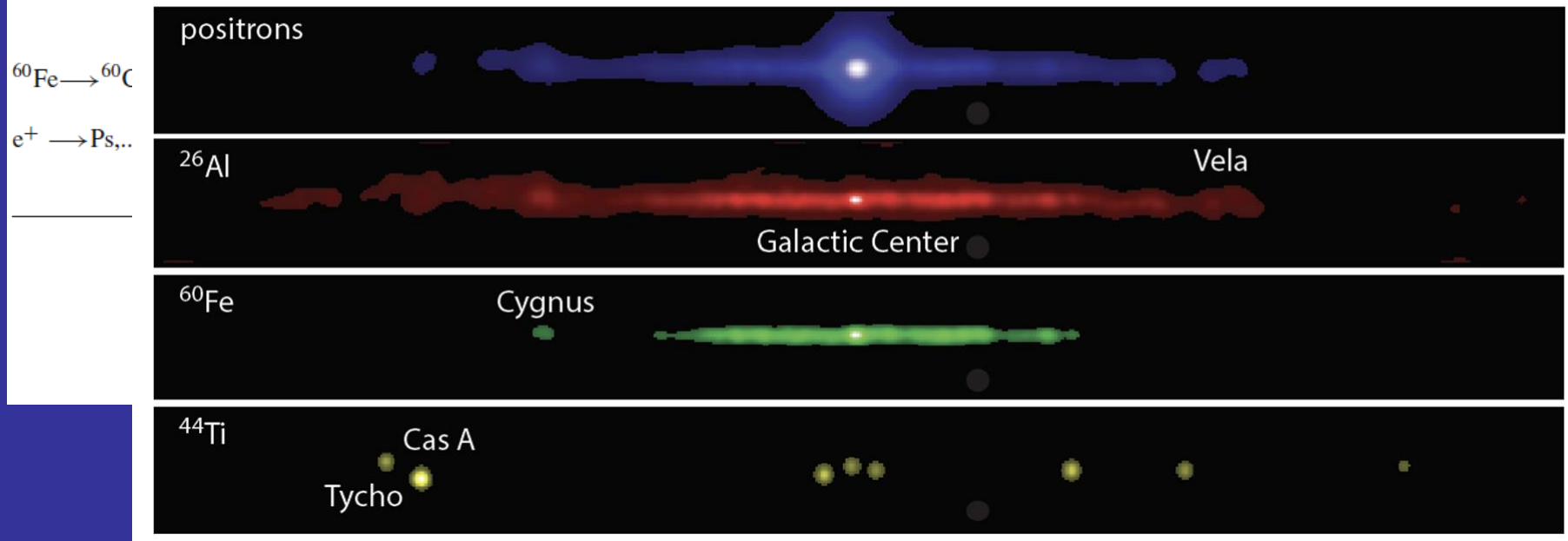
Yes, \$\$ ->
solid state,
SMEX
to M-Class/
MIDEX/Probe

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

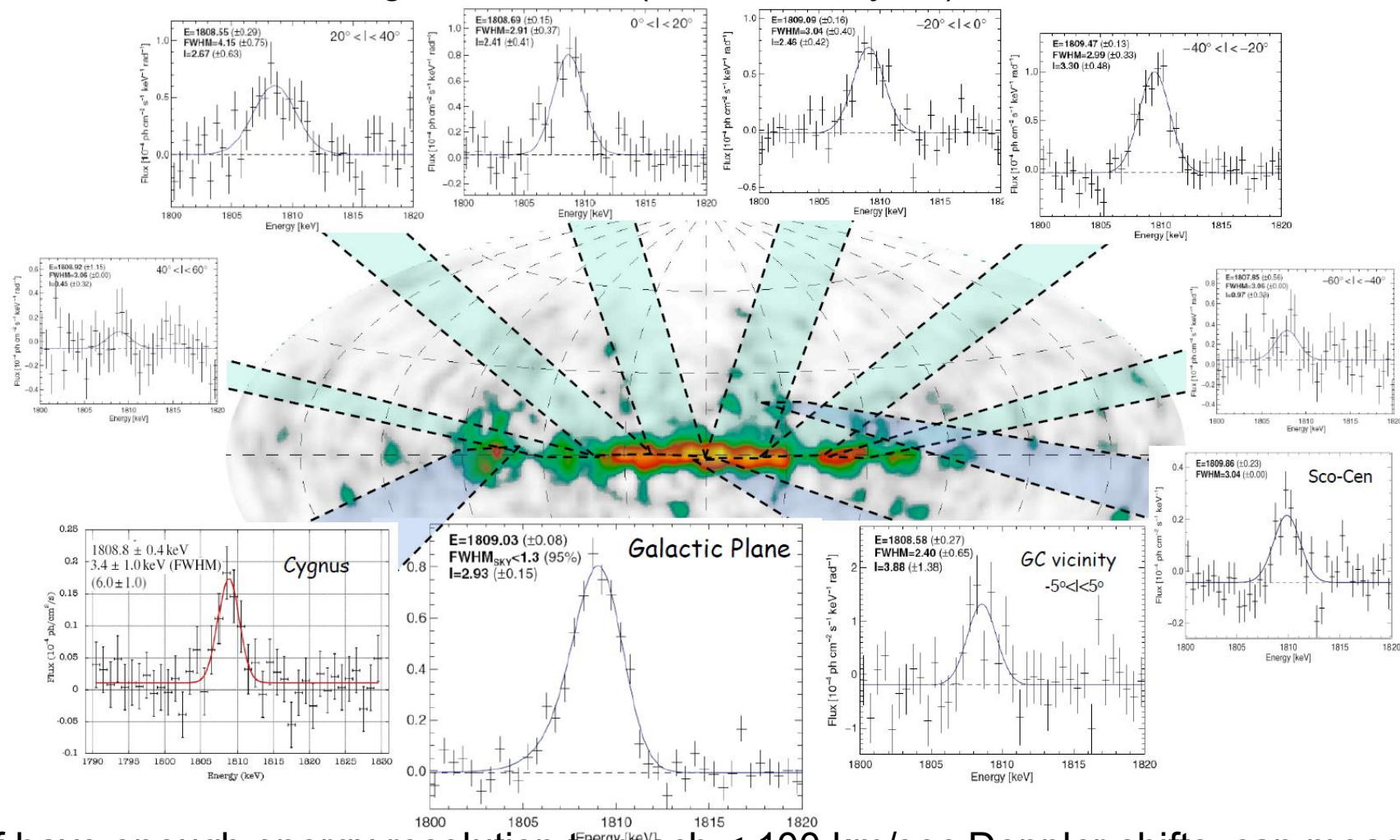
~MeV sensitivity => probe nuclear, 511 keV e⁺/e⁻ lines!

Decay chain	Lifetime(y)	γ -ray energy (keV) (branching ratio [%])	Site (detections)	Process type
${}^7\text{Be} \rightarrow {}^7\text{Li}$	0.21	478 (100)	Novae	Explosive H burning
${}^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$	0.31	847 (100), 1,238 (68) 2,598 (17), 1,771 (15) and 511 from e ⁺	SNe (SN1987A, SN1991T)	NSE burning
${}^{57}\text{Co} \rightarrow {}^{57}\text{Fe}$	1.1	122 (86), 136 (11)	SNe (SN1987A)	NSE burning
${}^{22}\text{Na} \rightarrow {}^{22}\text{Ne}$	3.8	1275 (100) and 511 from e ⁺	Novae	Explos. H burning
${}^{44}\text{Ti} \rightarrow {}^{44}\text{Sc} \rightarrow {}^{44}\text{Ca}$	89	68 (95), 78 (96) 1,156 (100)	SNe (Cas A)	NSE α freeze-

COSI Emission line science



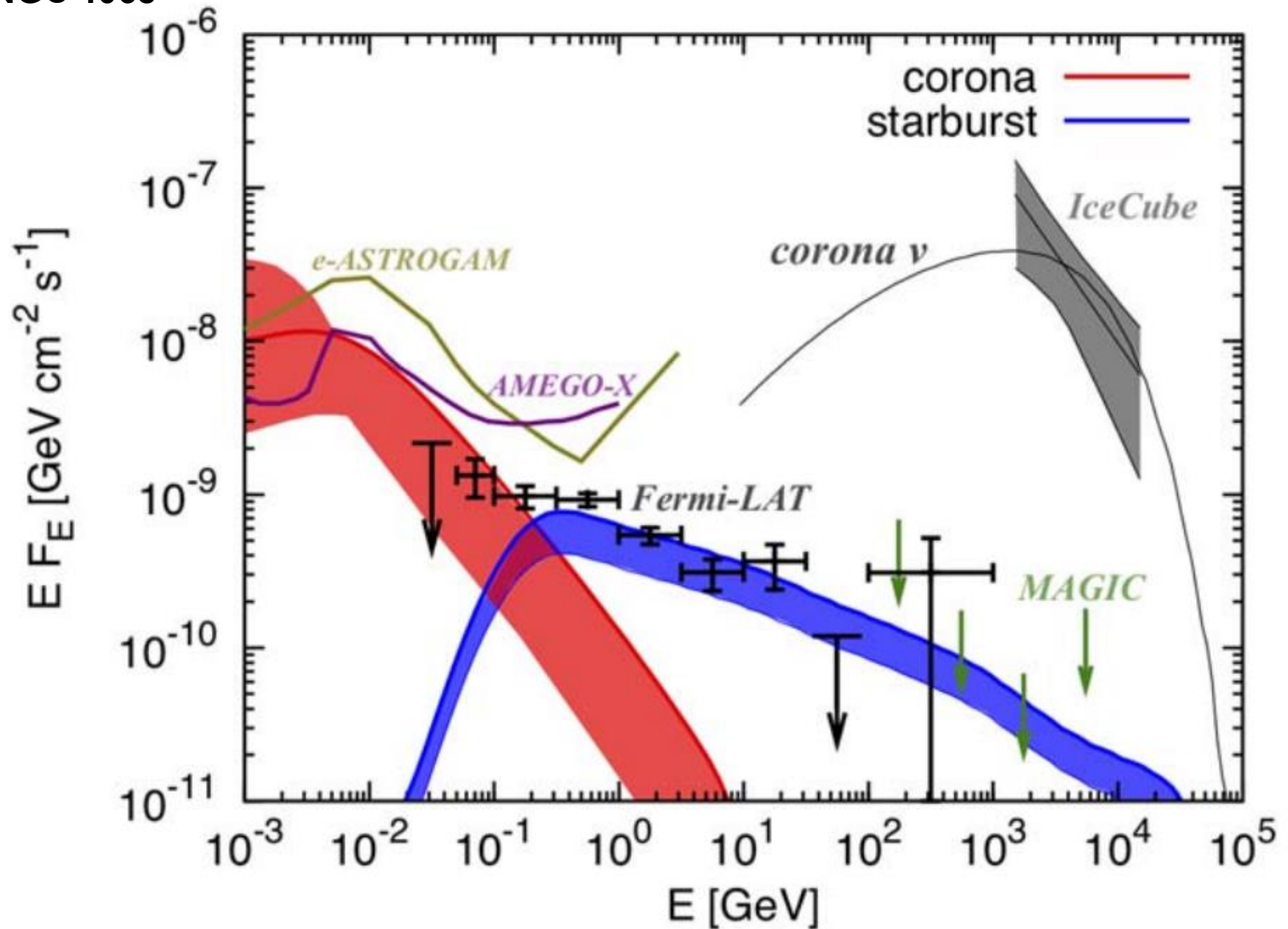
^{26}Al - Measures integrated, recent ($\sim$ few million year) SNe/star formation activity



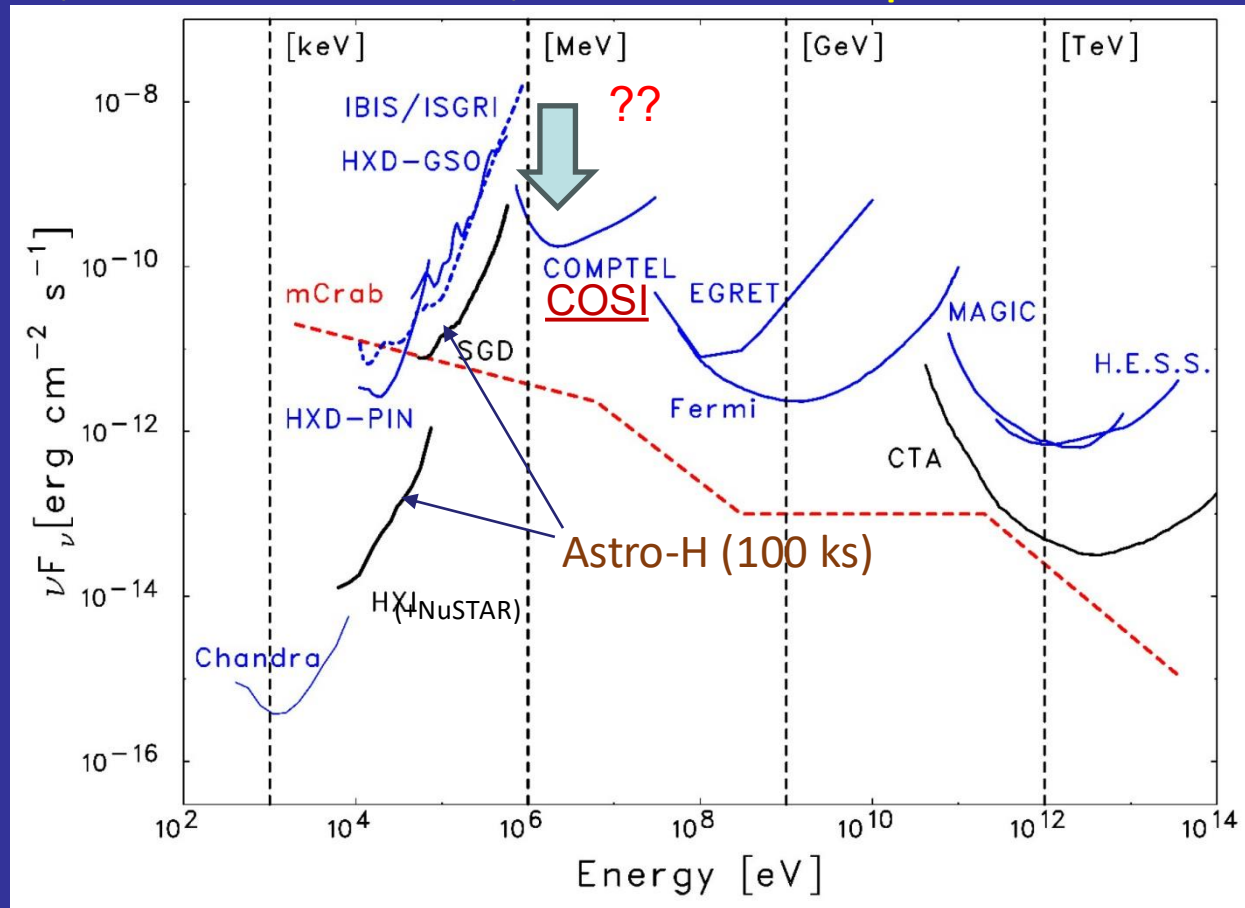
If have enough energy resolution to reach < 100 km/sec Doppler shifts, can measure galactic velocity contribution – helps constrain source distance as for molecular clouds

Figure 16. The spectra showing the ^{26}Al gamma-ray line ($E_{\text{lab}} = 1808.63$ keV) as measured by SPI from different regions along the plane of the Galaxy for ^{26}Al (Wang et al. 2009).

NGC 1068



~100 keV-MeV-GeV [only from space!] ... probes CR origin, propagation, energetics, feedback + gives direct nuclear physics constraints on star formation, stellar evolution, and element production....



Unfortunately, we have an MeV-GeV sensitivity *gap*.

Hopefully will have COSI in ~2027, but... (Fermi is not young anymore, etc)

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.

CR Diffusion *Into* Molecular Clouds

Gabici et al 2007

R = distance CR travels into molecular cloud core

$$R = 0.62 - \sqrt{6D(E_P, B)[1600 - t_0]} \quad [\text{pc}]$$

$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\text{GeV}}{B/3\mu\text{G}} \right)^{0.5} \quad [\text{cm}^2 \text{s}^{-1}],$$

$$B(n_{H_2}) \sim 100 \sqrt{\frac{n_{H_2}}{10^4 \text{ cm}^{-3}}} \quad [\mu\text{G}]$$

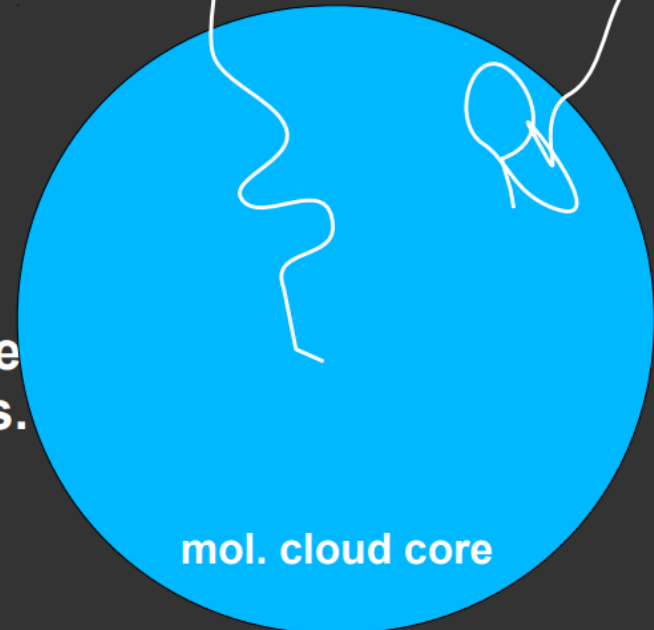
χ =diffusion suppression

- Low energy CRs can't reach cloud core
- Expect harder TeV spectra from cores.
- **Don't expect electrons to penetrate!!**
(due to sync. losses)

→ **Need to map dense cloud cores**

10 TeV proton

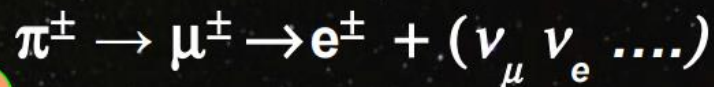
1 TeV proton



Gamma Rays from multi-TeV Cosmic-Rays (p, He ...etc)

CRs deflected by magnetic fields

Cassiopeia A



GAS CLOUD

Gamma-Rays (+ Neutrinos)

Observational Signature

- Gamma-rays and gas are ~ spatially correlated
(need to measure gas in all chemical states)
- Intimate connection with mm- radio astronomy (tracing gas)
.....we expect gamma-ray flux $F_\gamma \sim k_{CR} M_{gas}$