

# The pion bump and the hadronic component of gamma rays

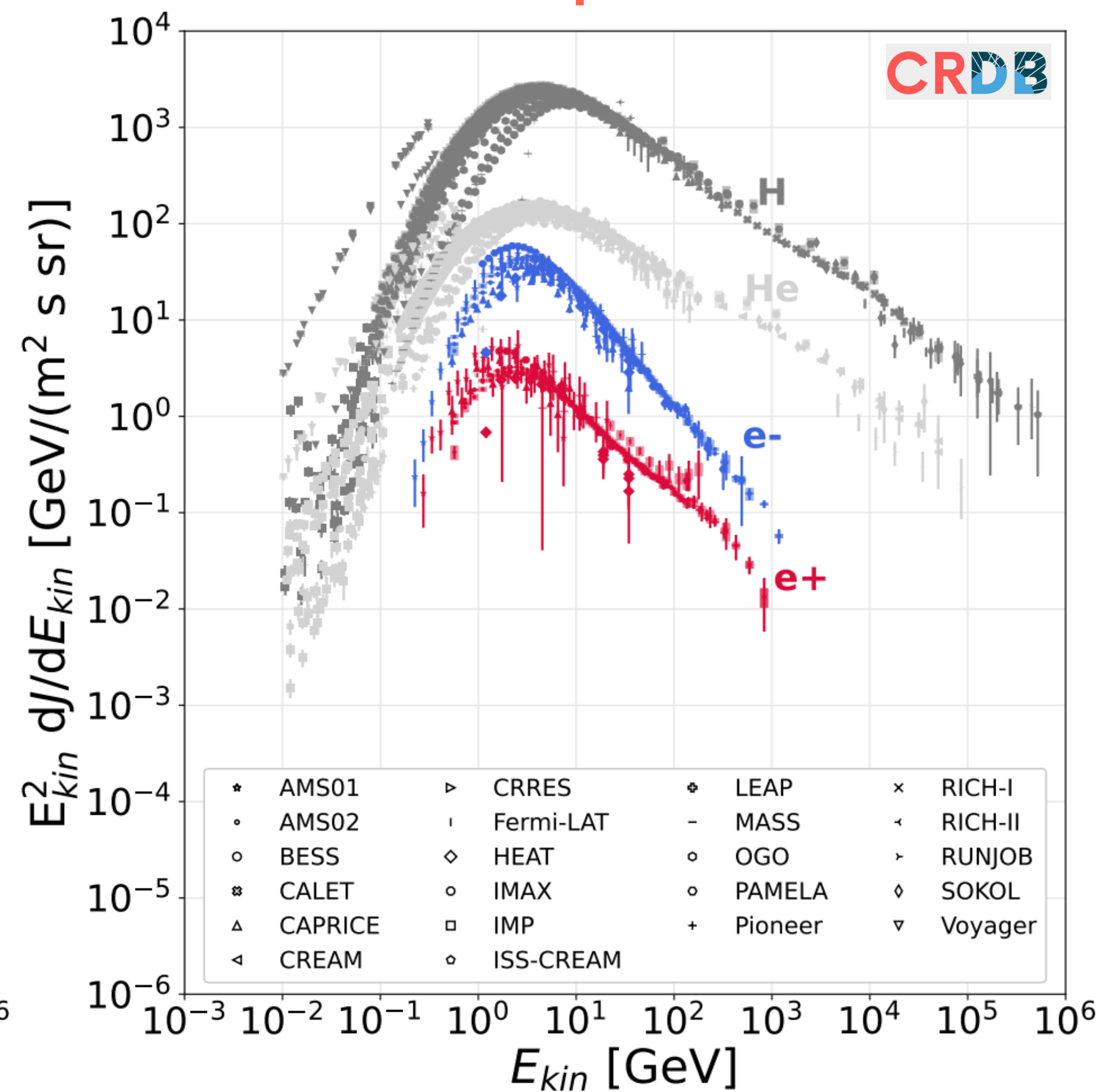
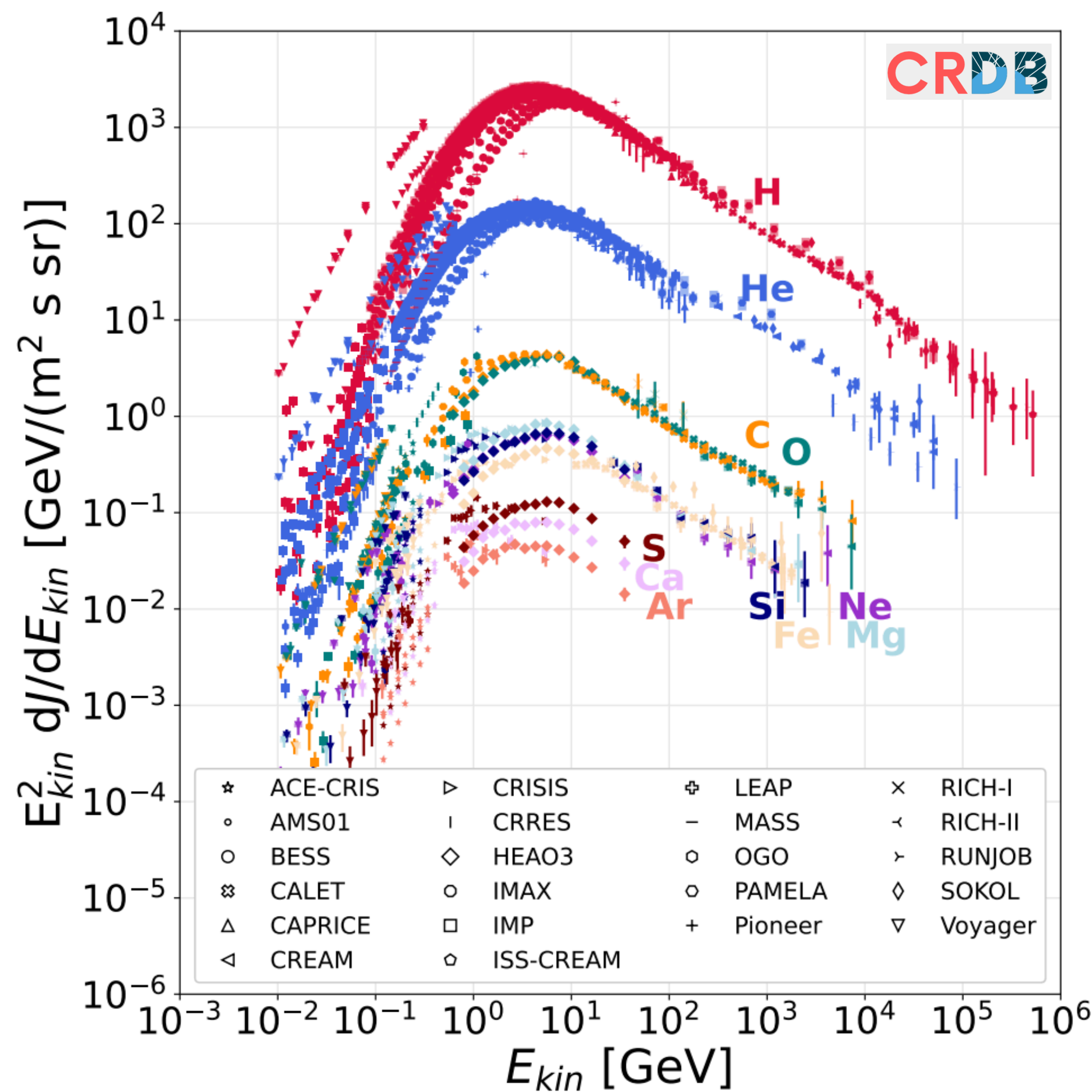
**-The extreme non-thermal Universe- CDHY Seminars**

**Giada Peron — 29.04.2026**

**Why are we interested in hadronic emission?**

# Why we want hadrons

Cosmic rays measured at Earth are **Hadrons ~ 99%**  
**Leptons ~ 1%**



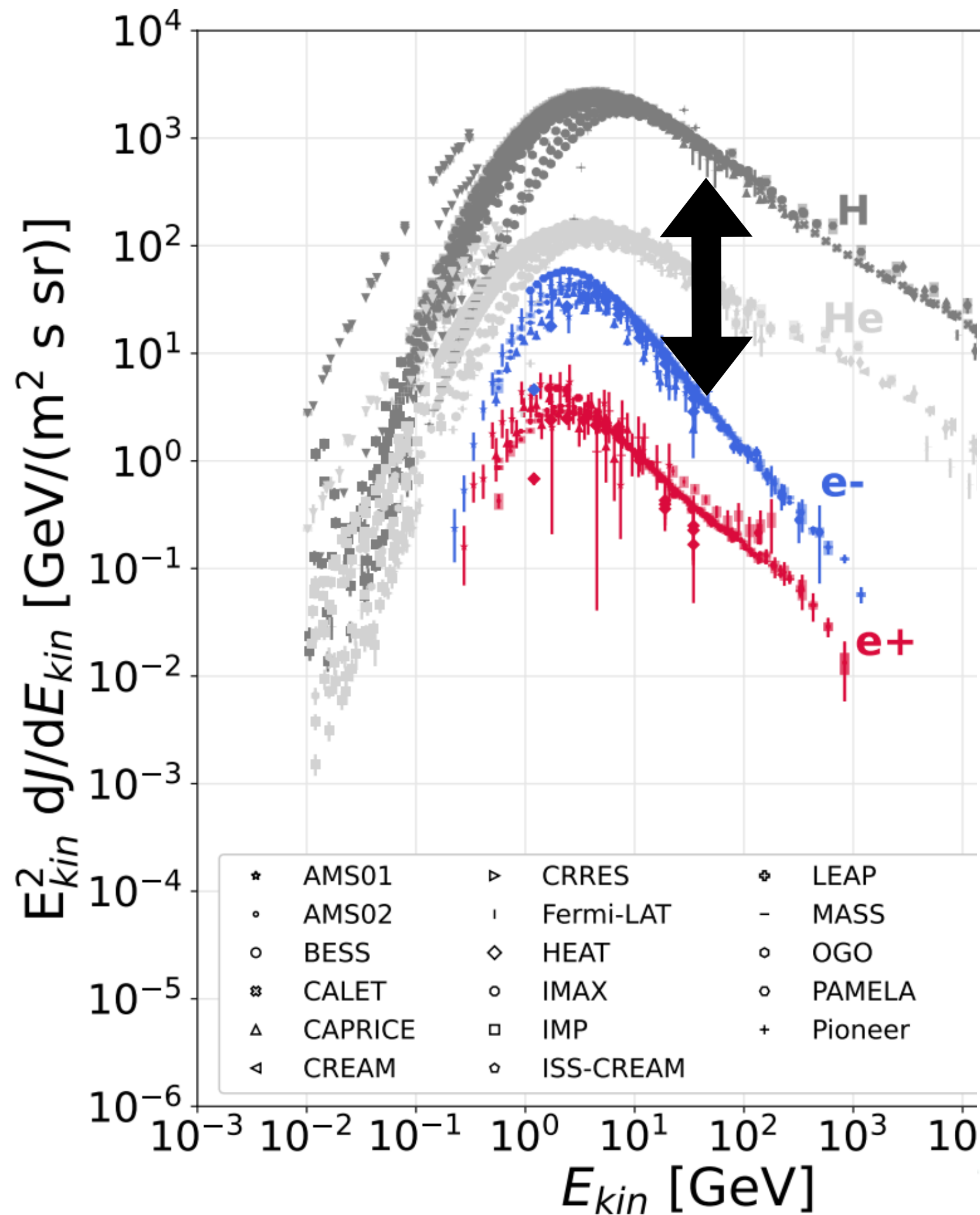
GP et al. 2026



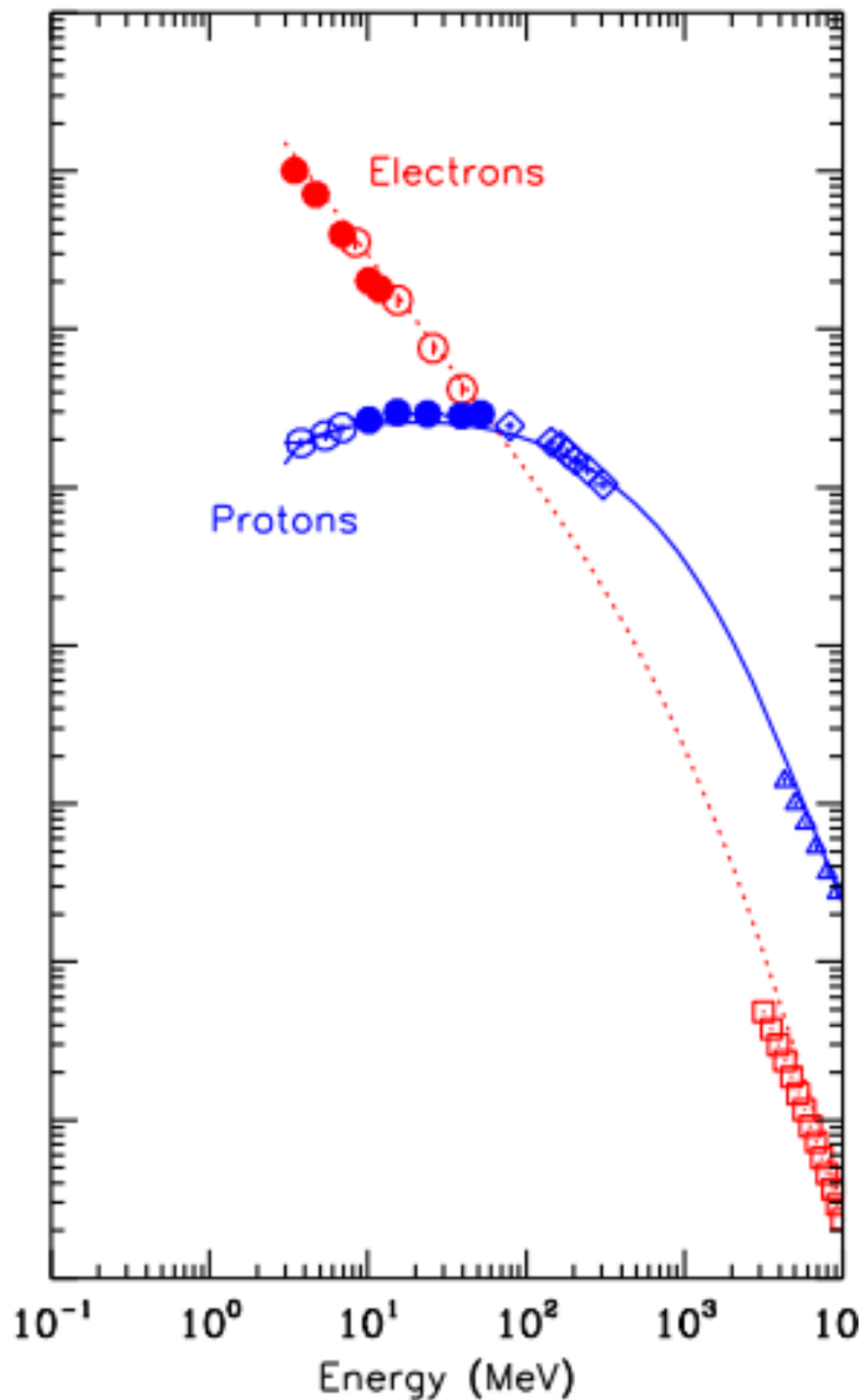
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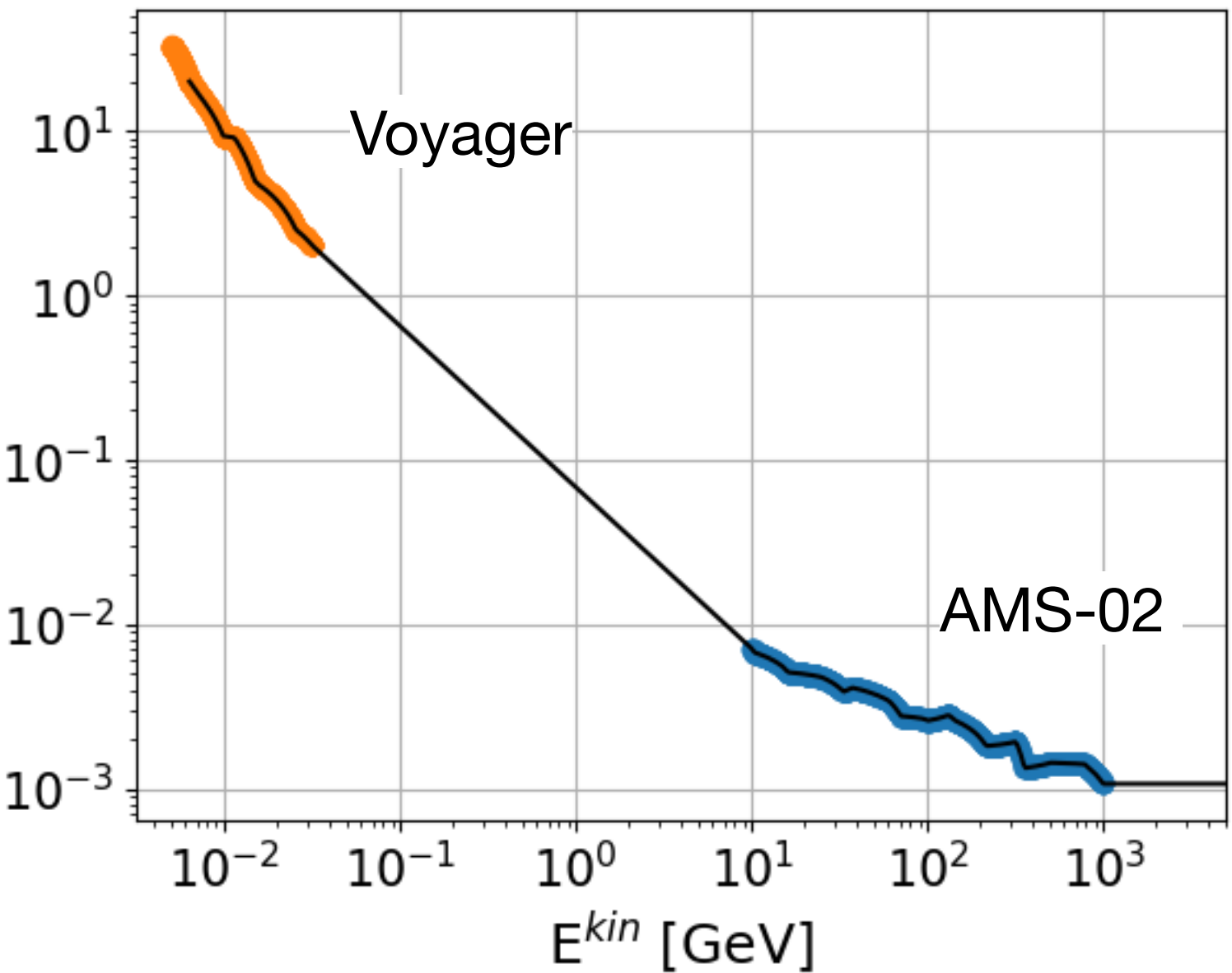


Voyager Cummings et al. 2016



$$K_{ep}^{CR} < 10^{-2} \quad >10 \text{ GeV}$$

electron/protons  
at Earth

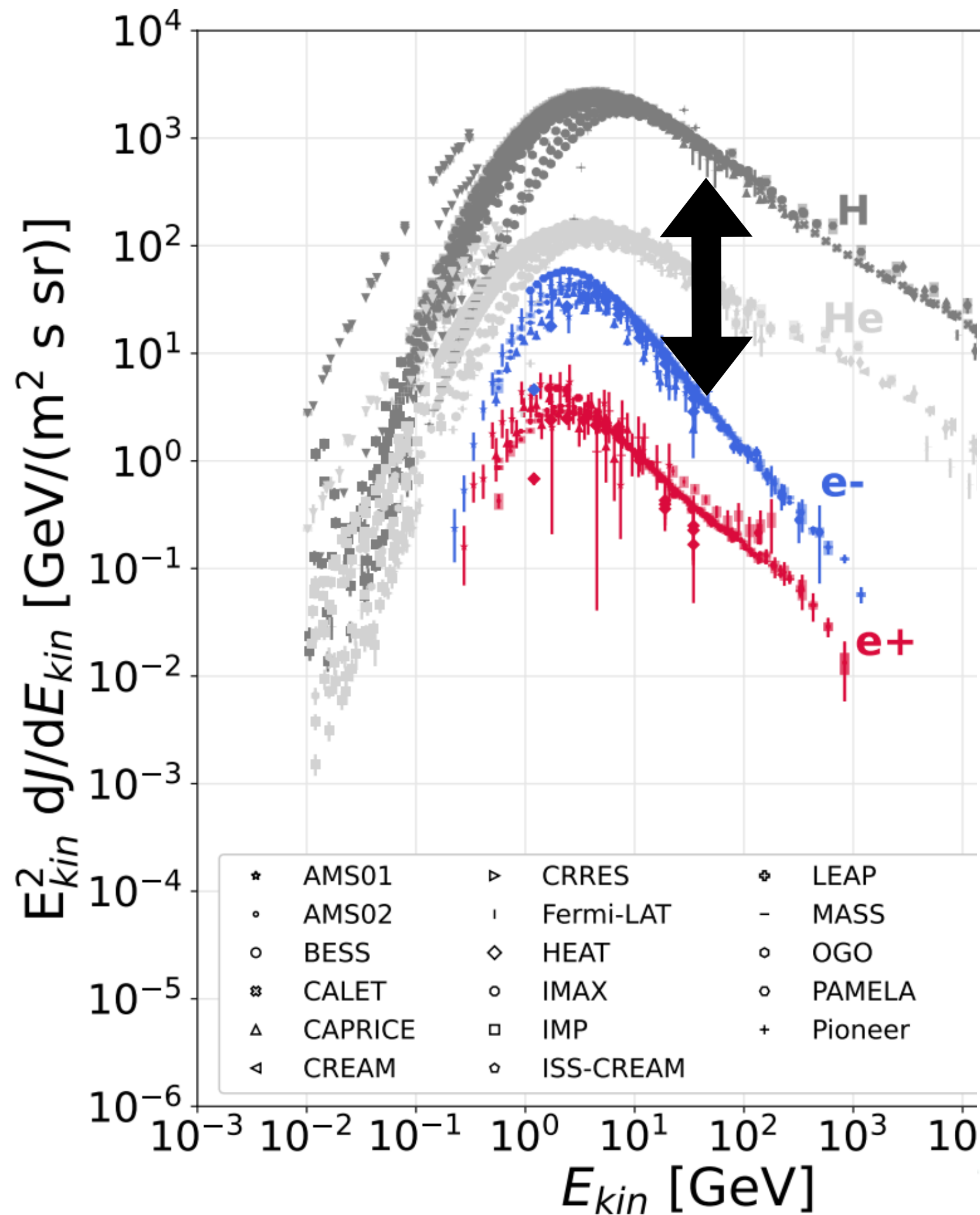




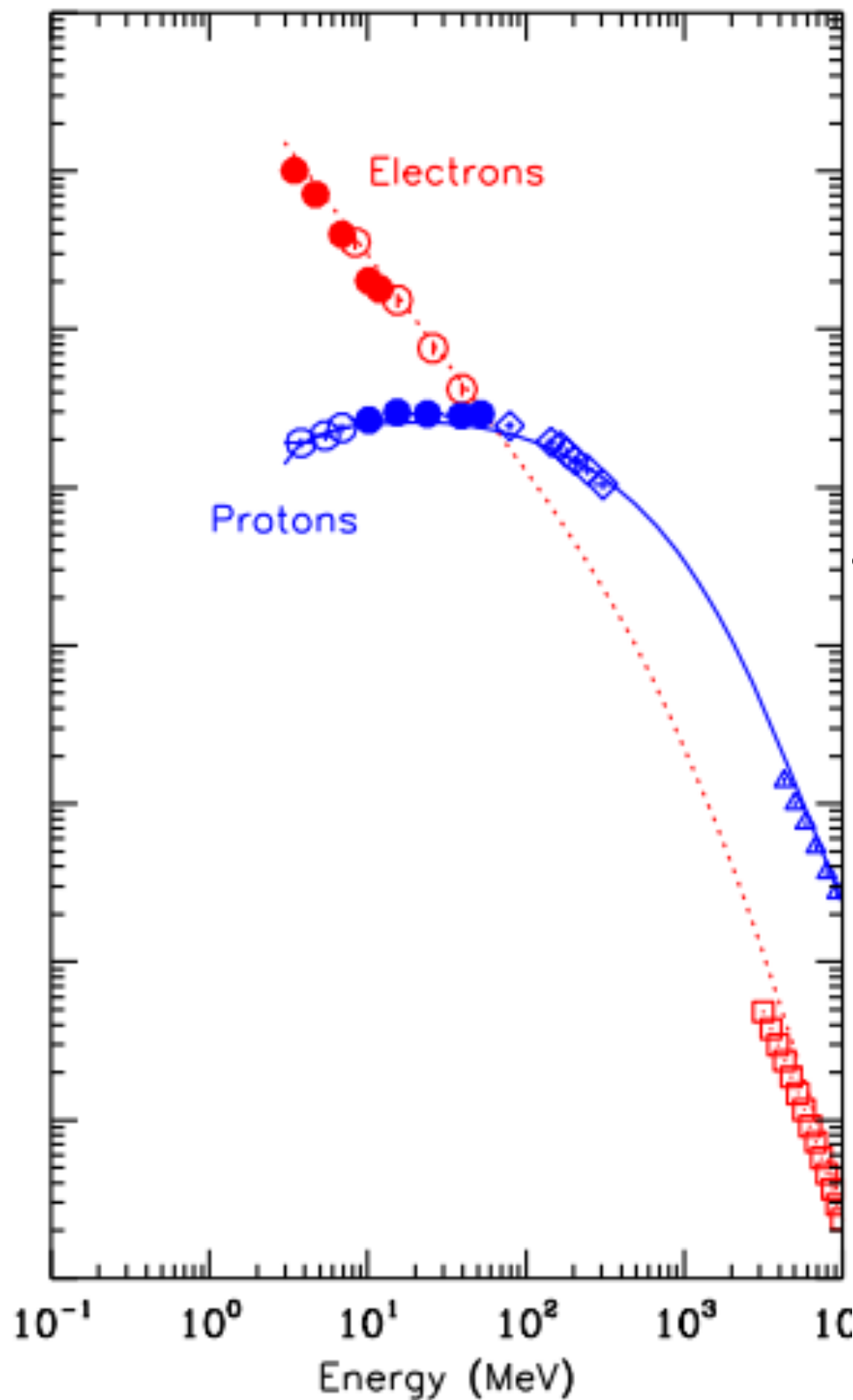
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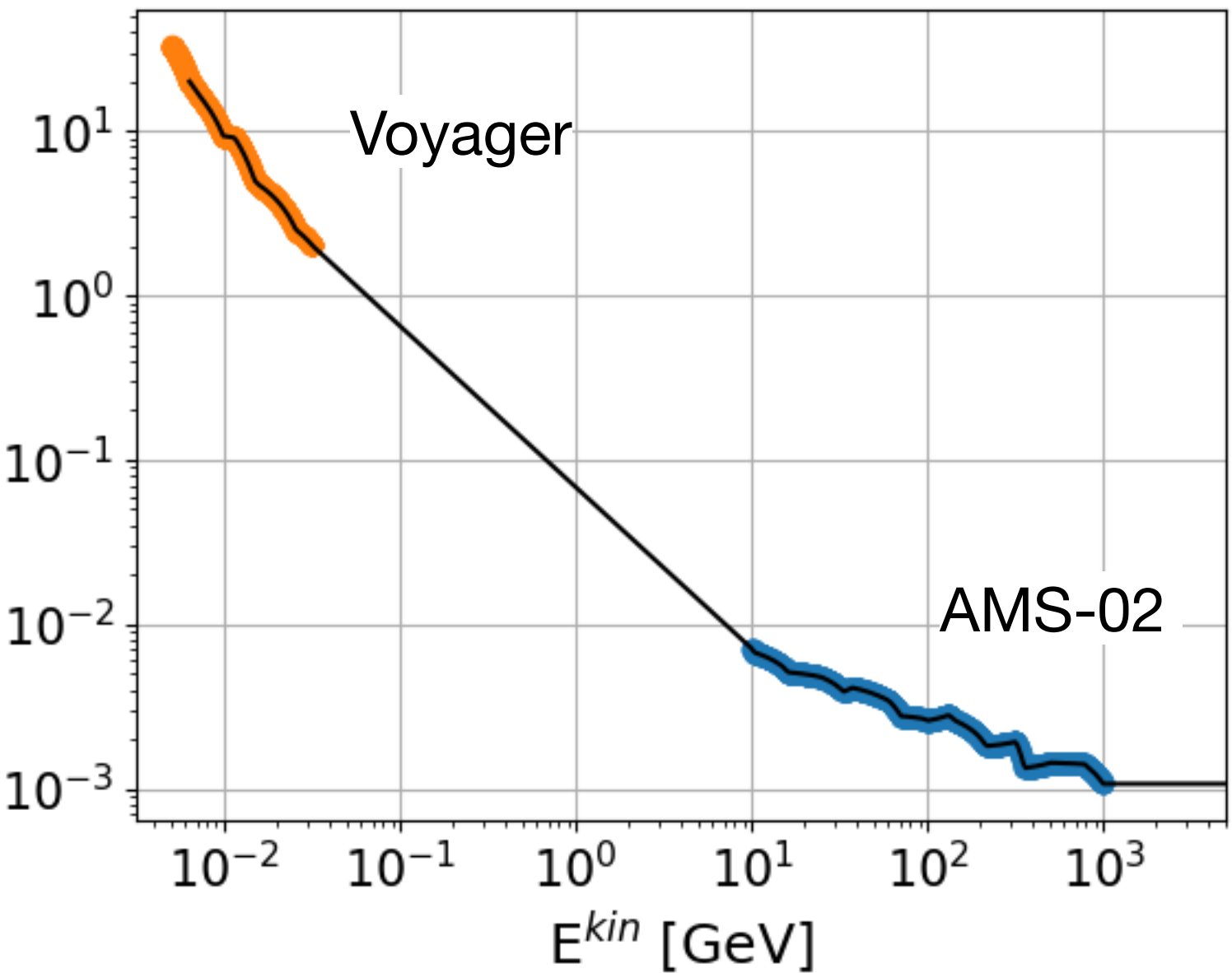


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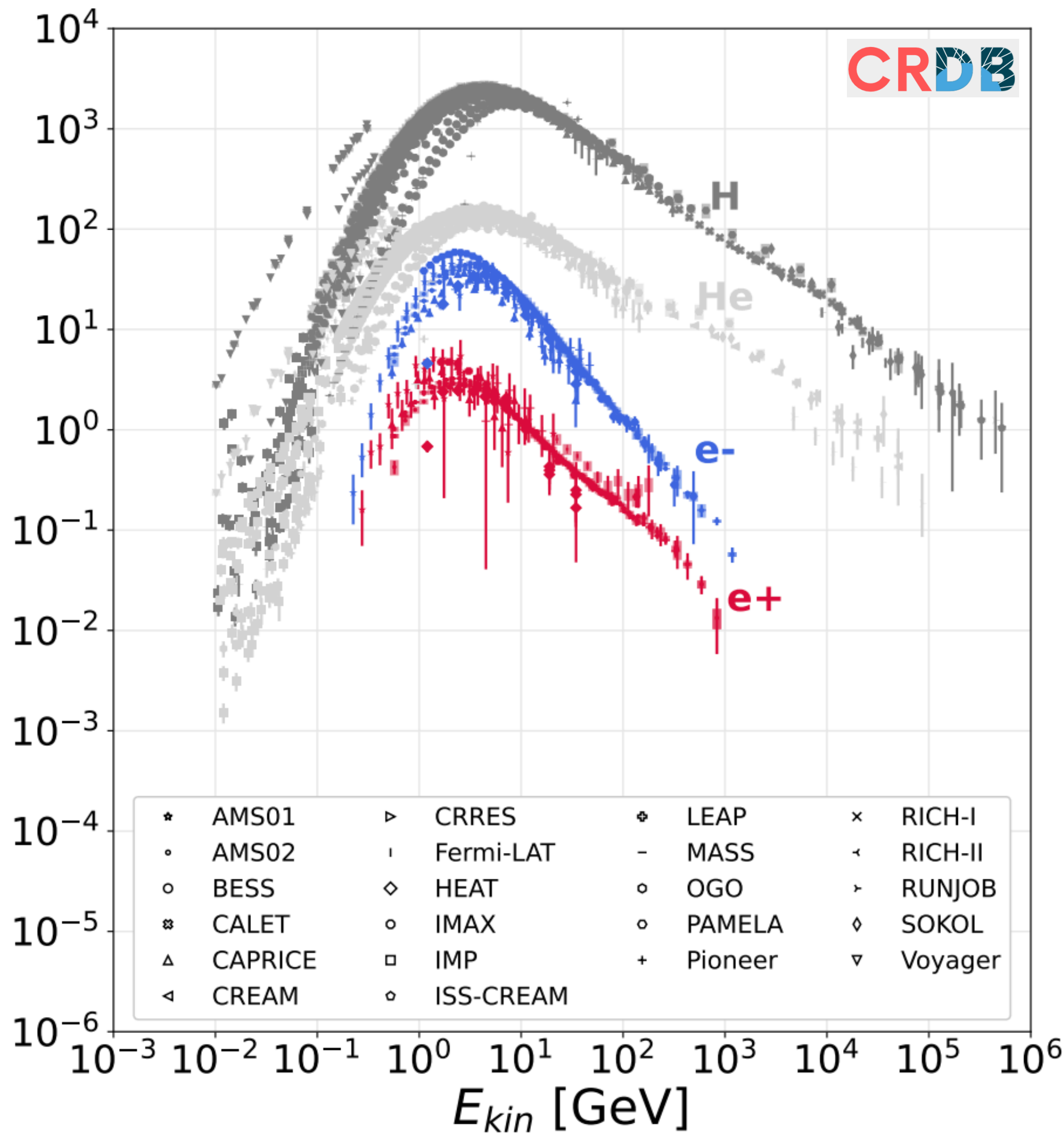
$$K_{ep}^{inj}?$$

electron/protons  
at source



# Why we want hadrons

Cosmic rays measured at Earth are **Hadrons ~ 99%**  
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Back-of-the-envelope calculation

If stationary:

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electron/protons at Earth

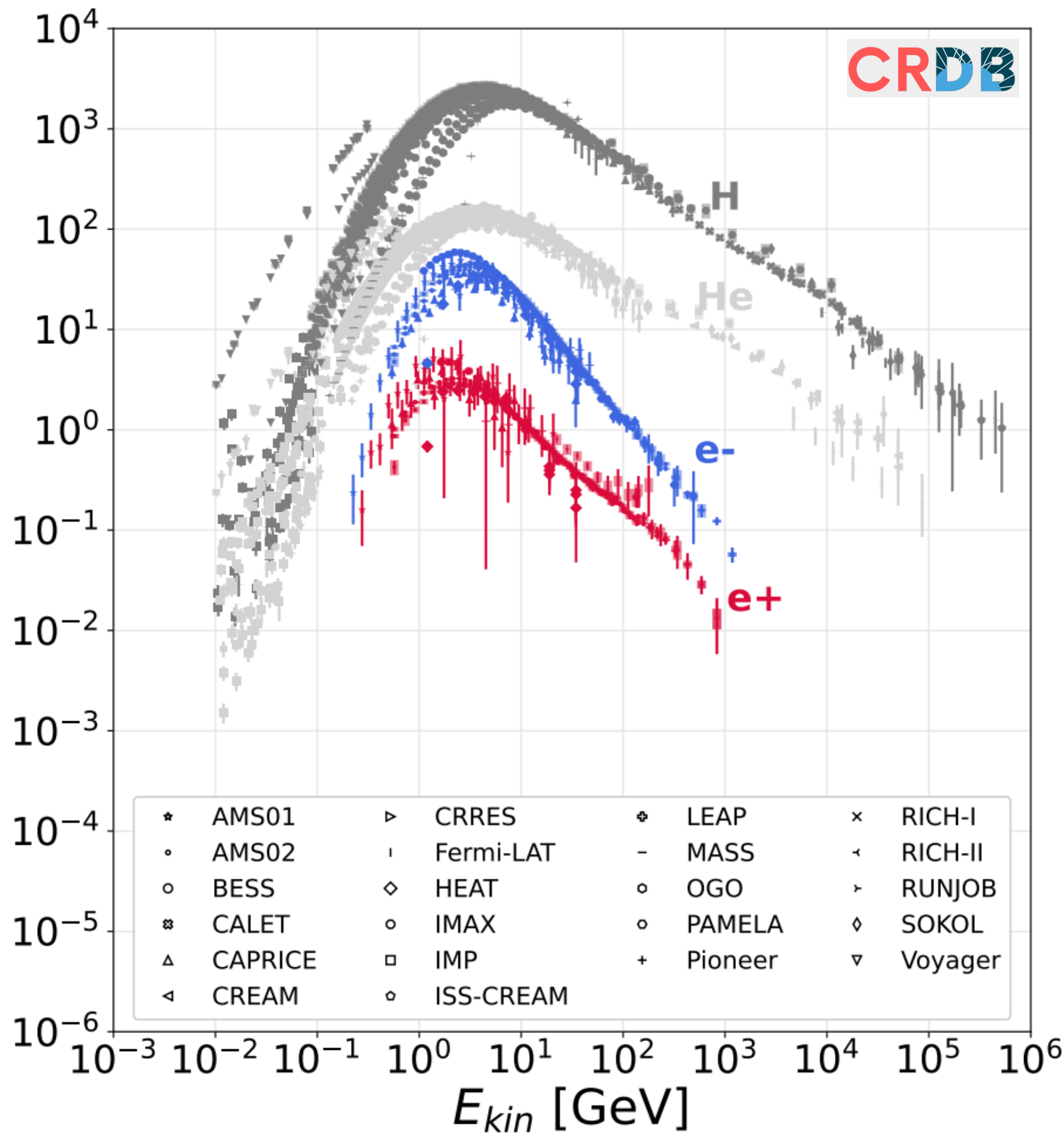
$$\frac{N_p}{\tau_p} - Q_p = 0$$

$$\frac{N_e}{\tau_e} - Q_e = 0 = \frac{K_{ep}^{CR} N_p}{\tau_e} - K_{ep}^{inj} Q_p$$

$$K_{ep}^{inj} = K_{ep}^{CR} \frac{\tau_{esc}}{\min[\tau_{loss}, \tau_{esc}]}$$

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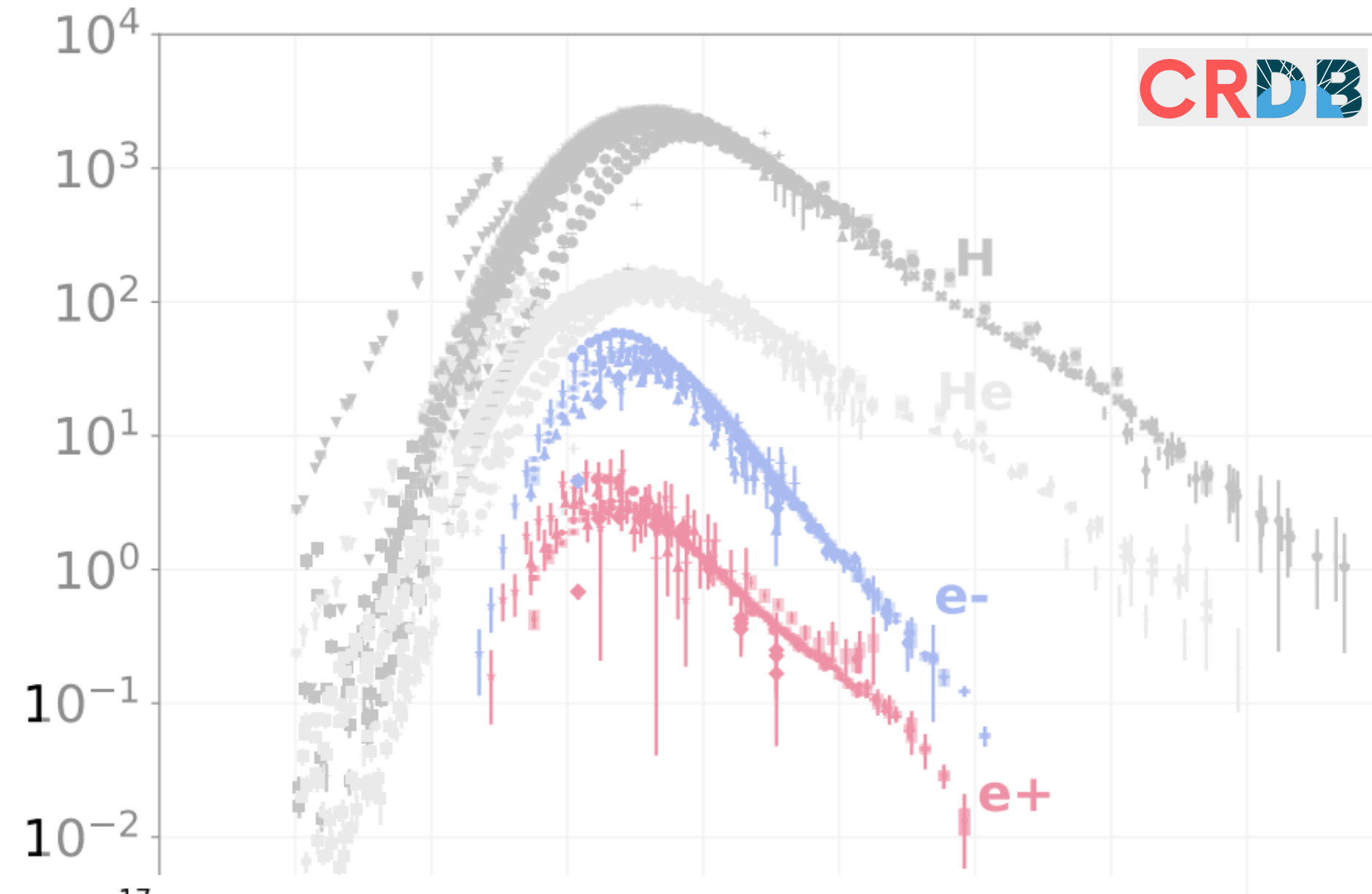
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electron/protons  
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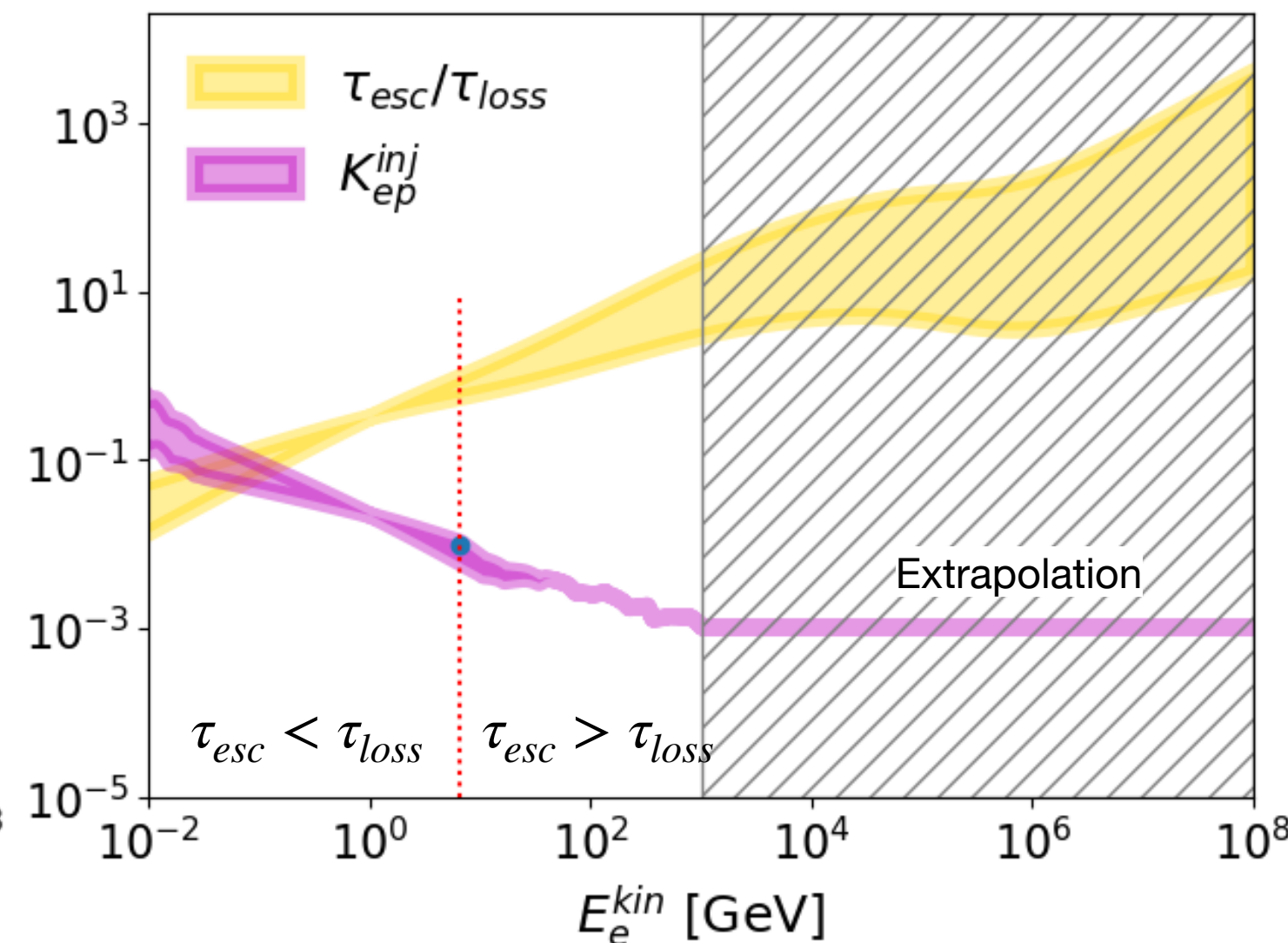
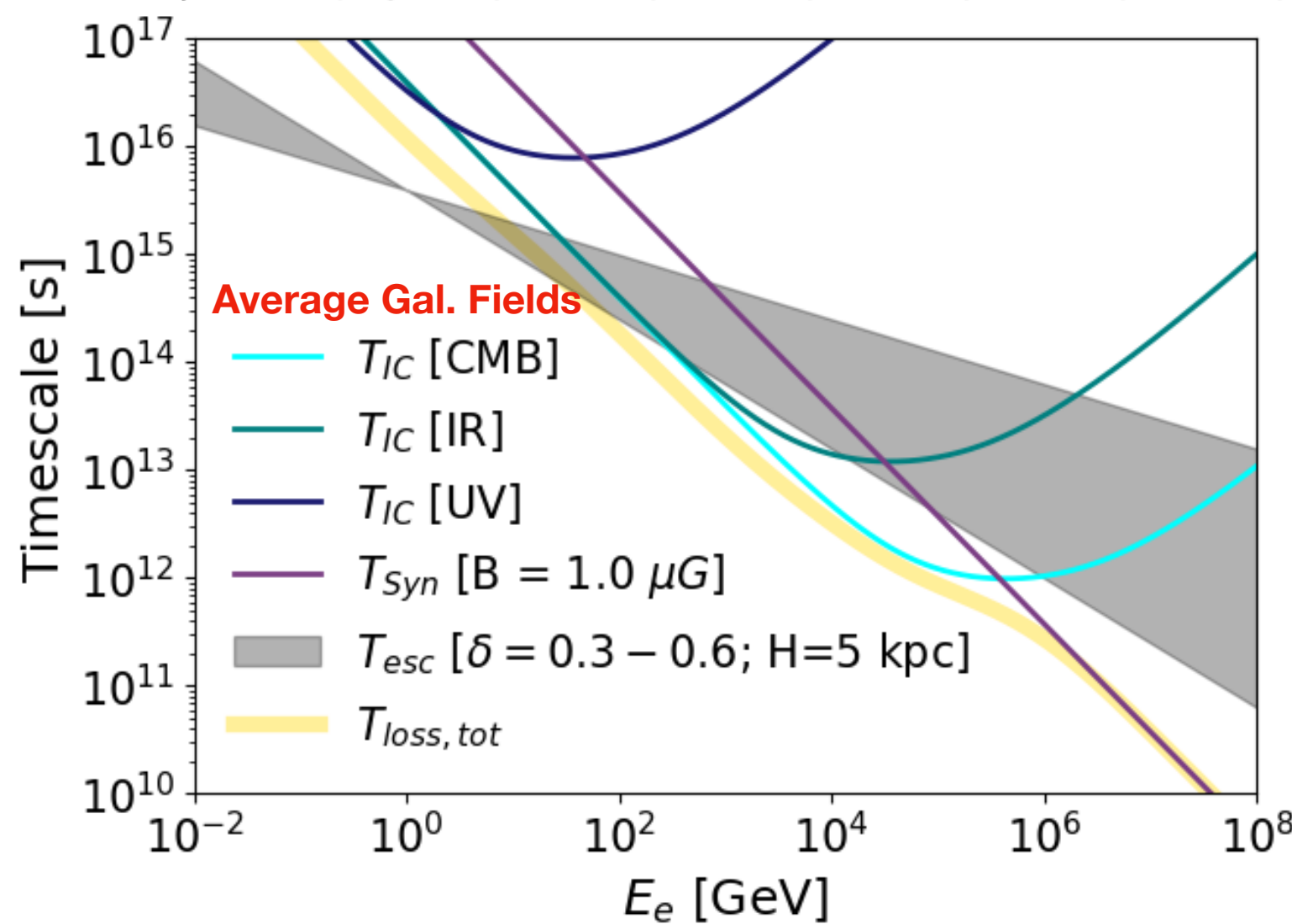
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$$K_{ep}^{inj} \sim K_{ep}^{CR} \quad >10 \text{ GeV}$$

electron/protons  
at source

$$K_{ep}^{inj} \sim 10^{-2} - 10^{-3}$$





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Back-of-the-envelope calculation

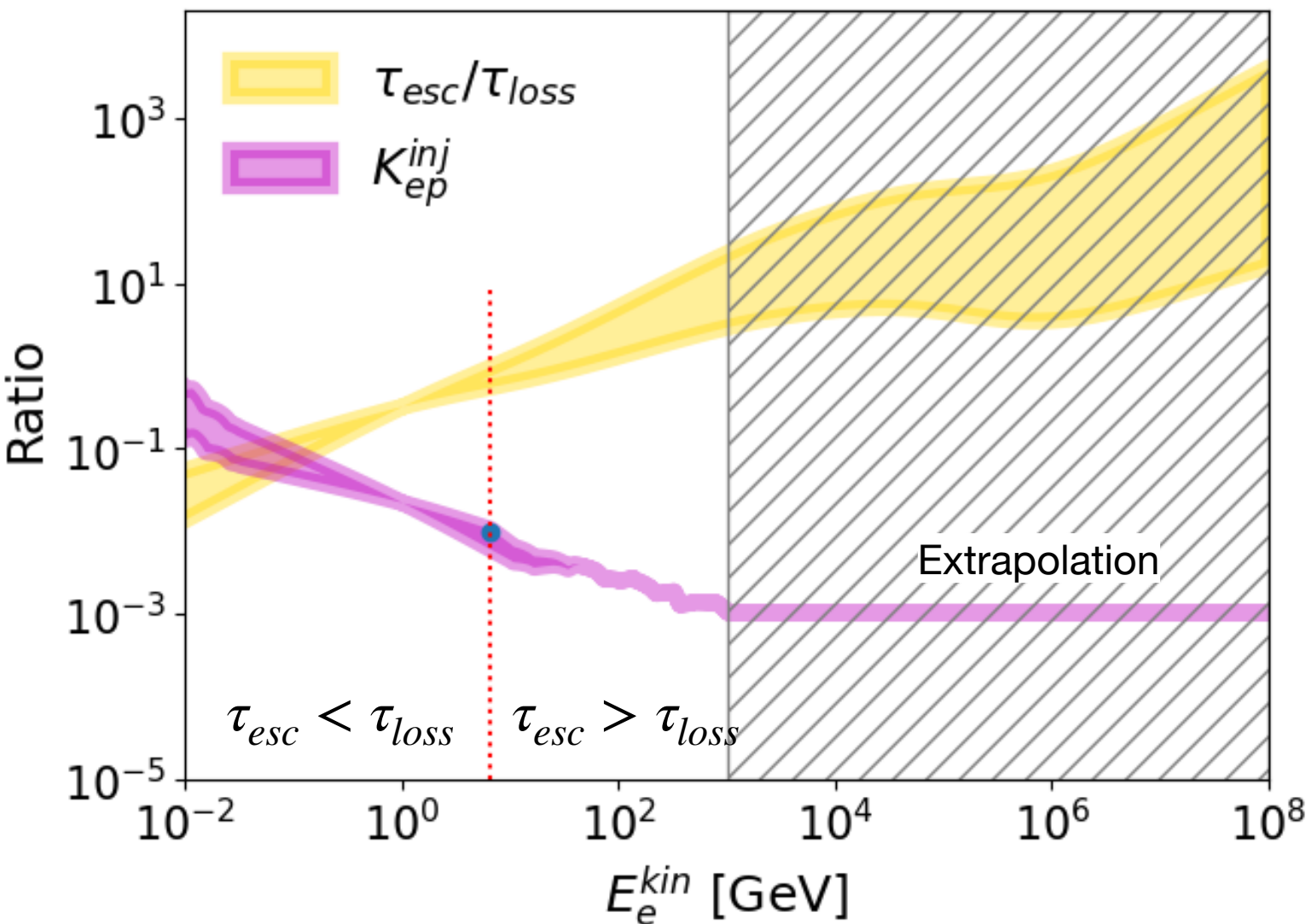
$$K_{ep}^{CR} < 10^{-2} \quad >10 \text{ GeV}$$

electron/protons at Earth

If stationary:

$$K_{ep}^{CR} = K_{ep}^{CR}(E) \quad \Delta s_{ep} \sim 0.3$$
$$K_{ep}^{inj} = K_{ep}^{inj}(E)$$

$$\frac{N_p}{\tau_p} - Q_p = 0$$
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$K_{ep}^{CR} < 10^{-2}$  **>10 GeV**  
electron/protons at Earth

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$\frac{N_p}{\tau_p} - Q_p = 0$

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**>10 GeV**  
 $K_{ep}^{inj} \sim 10^{-2} - 10^{-3}$   
electron/protons at source

electron and protons at source are accelerated in different ways?

Idea: Morlino & Celli 2021

electron and protons are injected in different ways

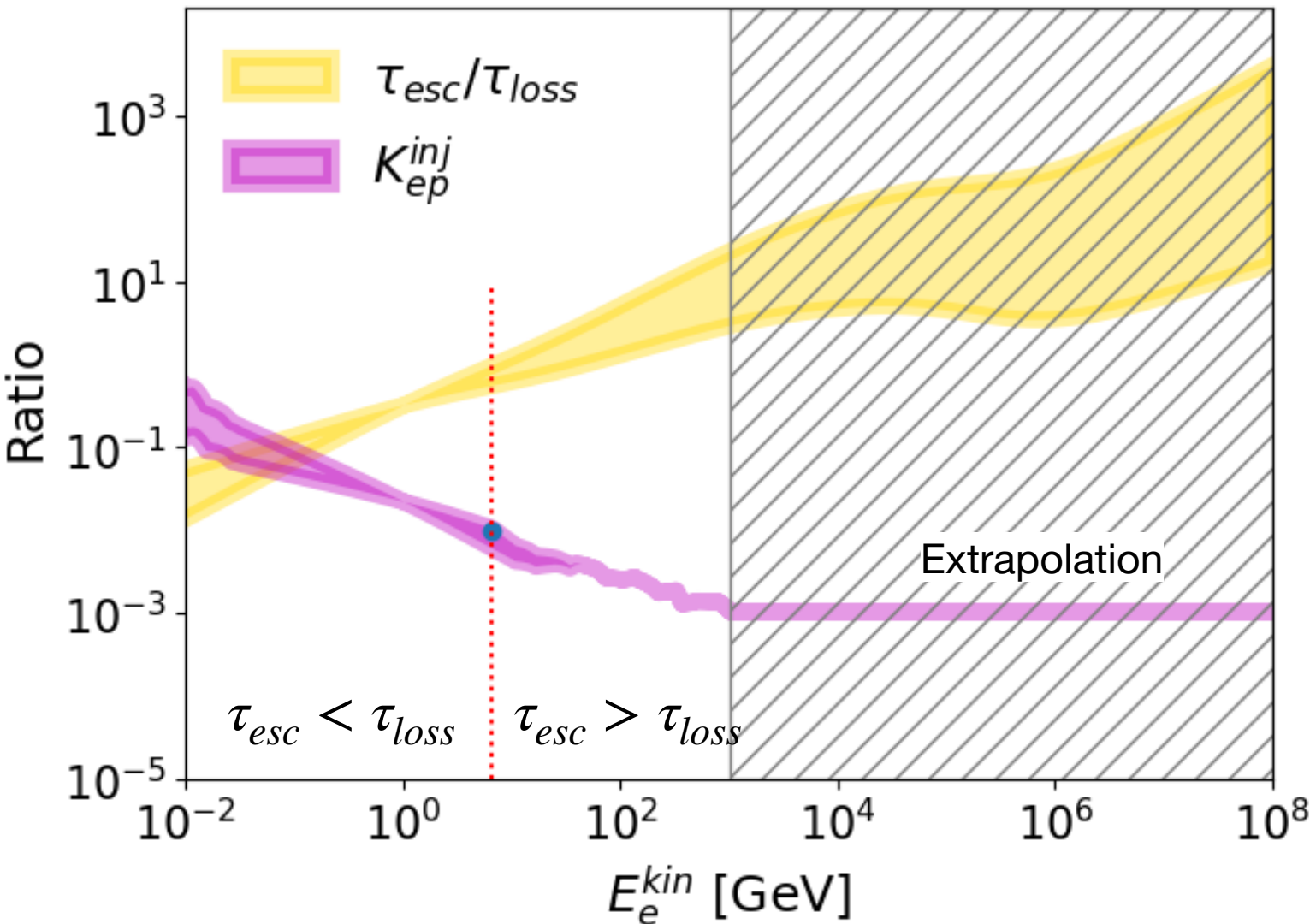
$K_{ep}^{inj} = u_{sh}^{-1}$

SNRs

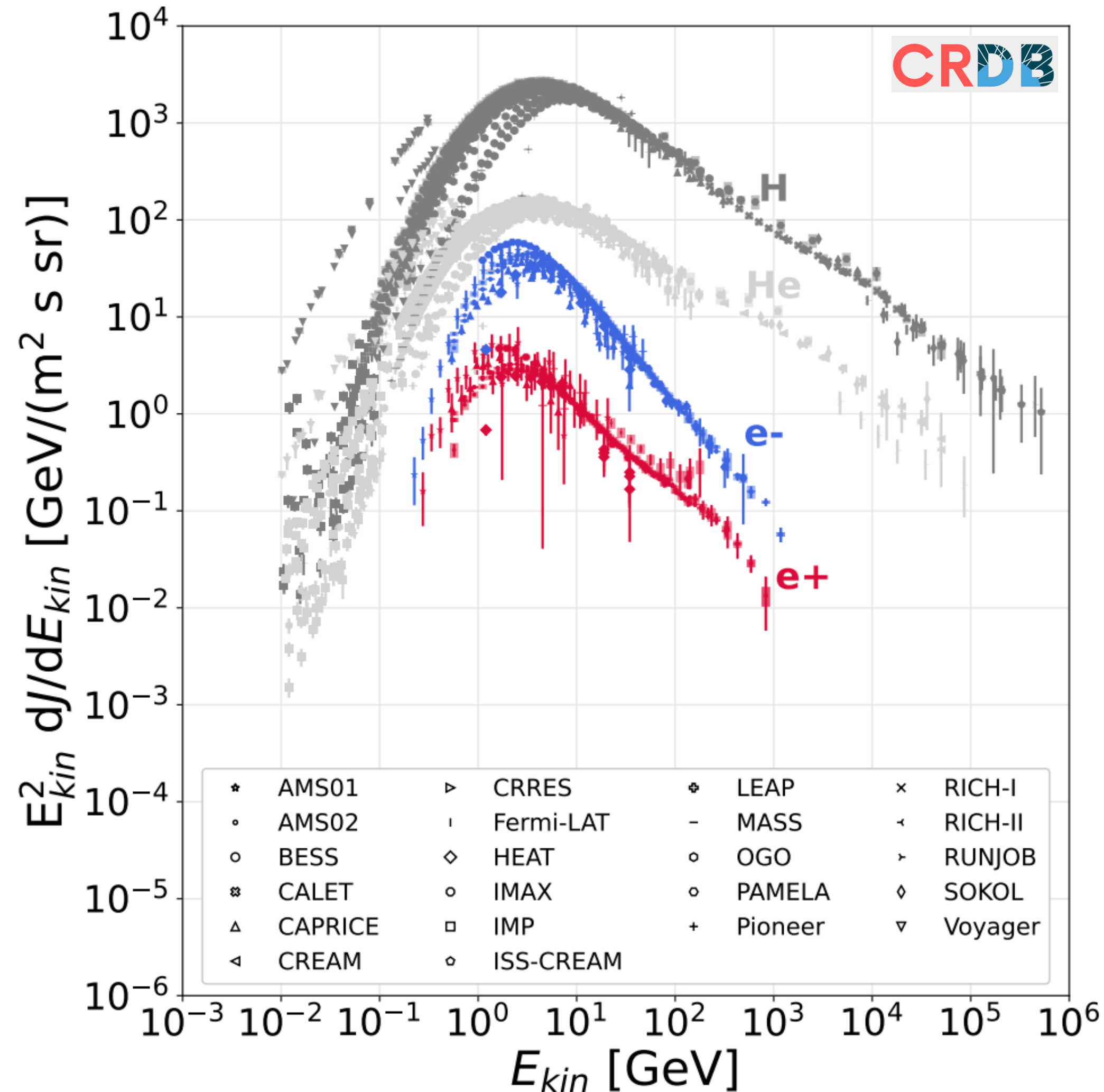
$\left[ \begin{array}{l} u_{sh} \searrow t \\ K_{ep}^{inj} \nearrow t \\ E^{max} \searrow t \end{array} \right]$

More electrons are injected when the speed is smaller and when the maximum energy is smaller: steeper integrated spectrum

$K_{ep}^{CR} = K_{ep}^{CR}(E)$   
 $K_{ep}^{inj} = K_{ep}^{inj}(E)$   $\Delta s_{ep} \sim 0.3$



# Why we want hadrons



To explain the CR spectrum at Earth

CR sources need to accelerate more protons than electrons

$$K_{ep}^{inj} \sim 10^{-2} - 10^{-3}$$

## Hadrons tell about the origin of CRs

If SNRs are the main CR contributors they must accelerate hadrons — and more hadrons than electrons: revealing hadronic emission from SNRs is needed to support the SNR paradigm

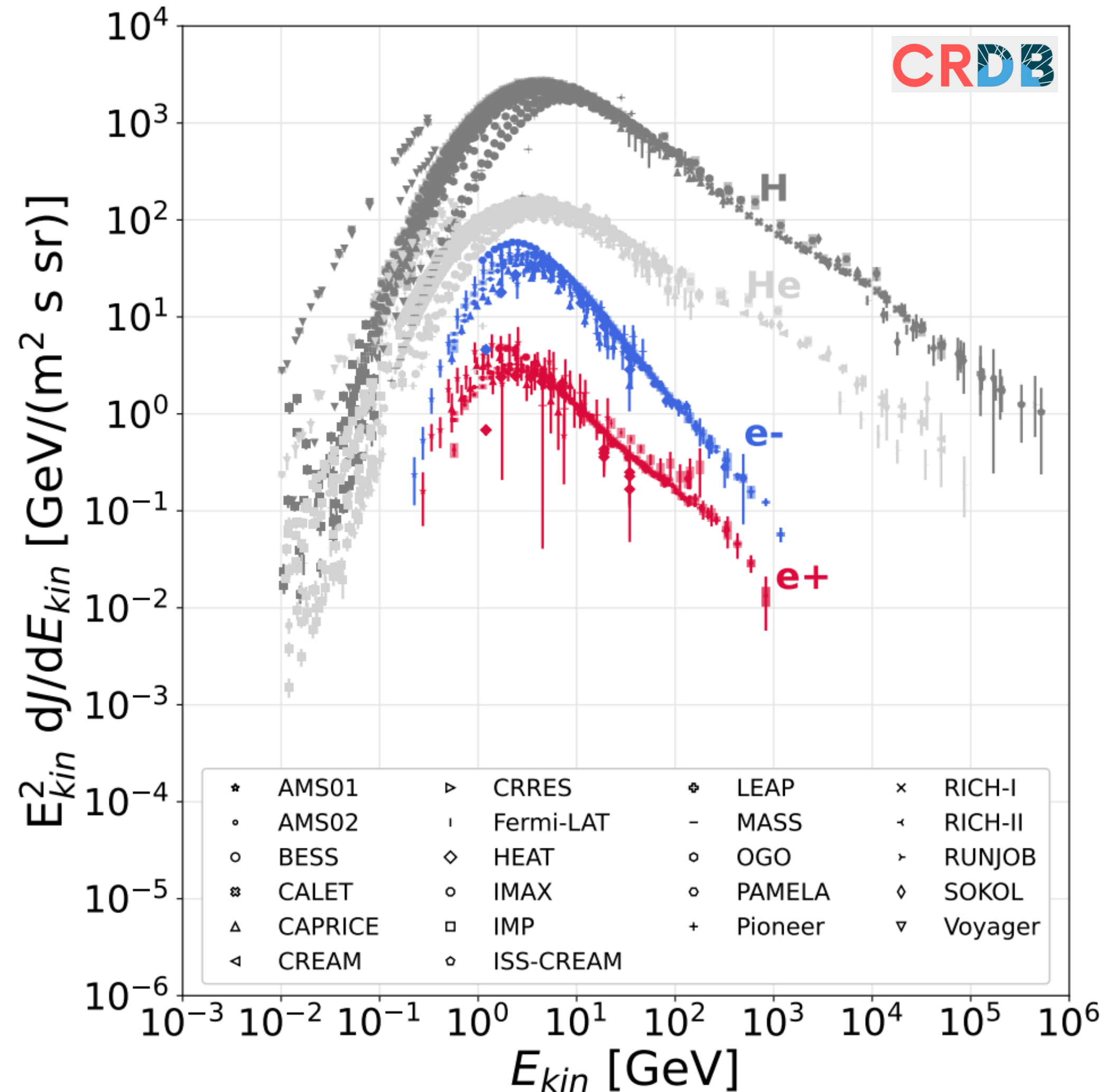
$K_{ep}^{CR}$  at Earth is contributed also by leptonic sources like PSRs, PWNe, mostly leptonic, hence:

$$\langle K_{ep}^{inj} \rangle_{SNR} \lesssim 10^{-2}$$

**Alternative CR source** should respect a similar ratio if they have a relevant contribution.



# Why we want hadrons



To explain the CR spectrum at Earth

$$K_{ep}^{inj} \sim 10^{-2} - 10^{-3}$$

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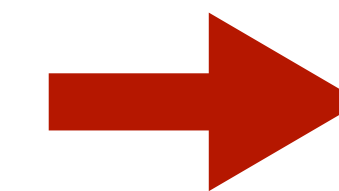
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**Search for hadronic observational signatures**

**How do we recognize hadronic emission?**

# How to recognize hadronic emission

Observational signatures of hadrons

## Hadronic interactions

Energetic nuclei impact  
on ambient nuclei or  
photons :  $pp$  /  $p\gamma$

$$p(A) + p(A, \gamma) \rightarrow \pi^{0,\pm} + X \quad \left\{ \begin{array}{l} \pi^0 \rightarrow 2\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \end{array} \right.$$

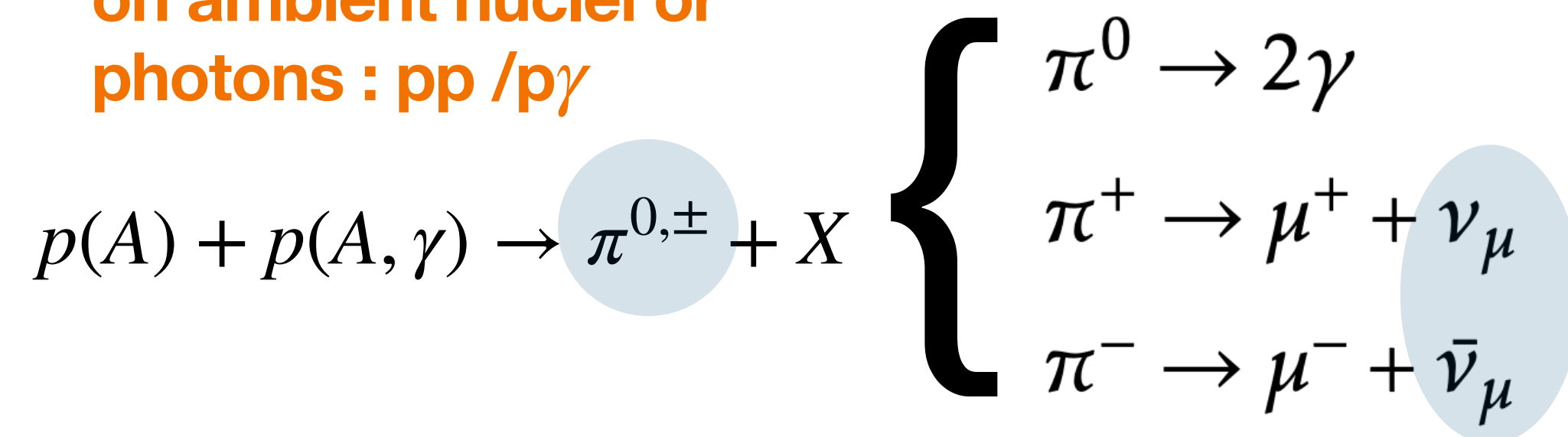


# How to recognize hadronic emission

## Observational signatures of hadrons

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### Intrinsic signatures:

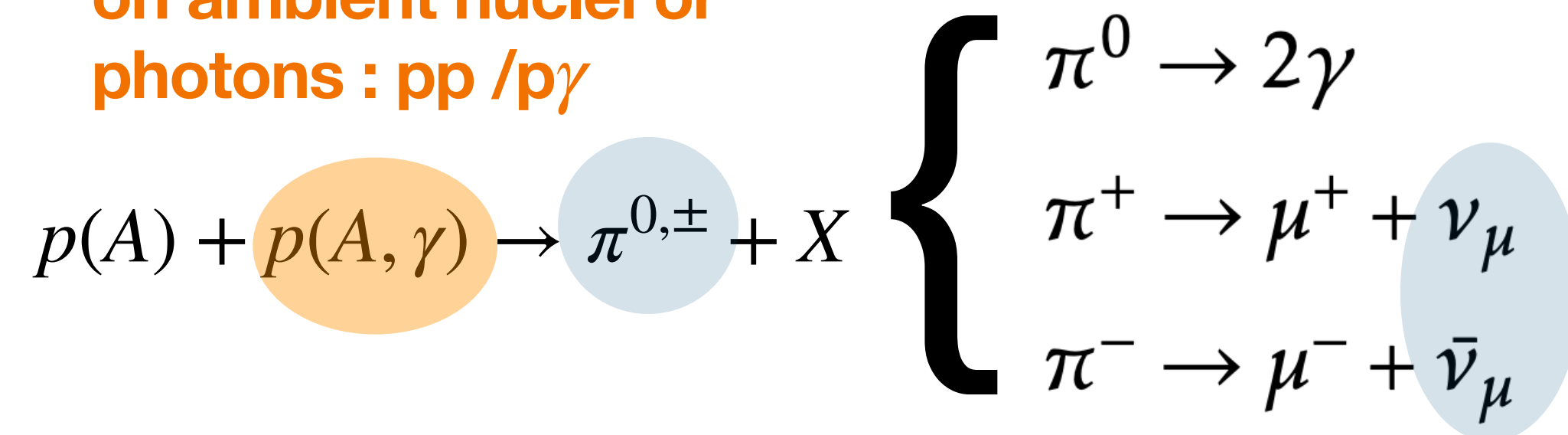
- The process has a natural threshold
- The process produces neutrinos

# How to recognize hadronic emission

## Observational signatures of hadrons

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### Intrinsic signatures:

- The process has a natural threshold
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### External signatures:

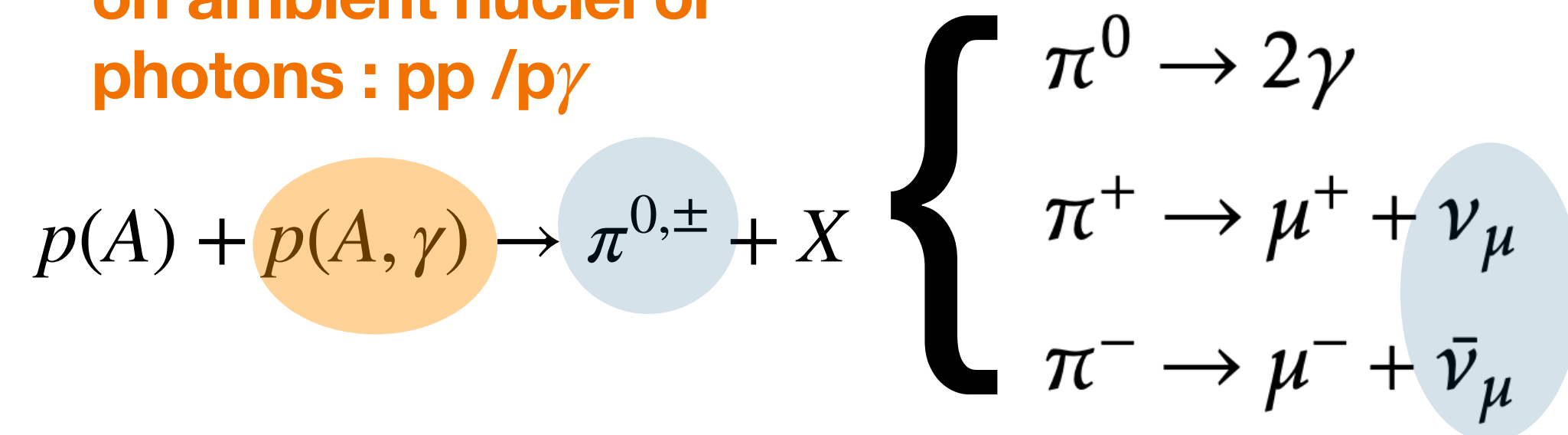
- Need for a high gas density (pp)
- Need for a high radiation density (pγ)

# How to recognize hadronic emission

## Observational signatures of hadrons

### Hadronic interactions

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### Intrinsic signatures:

- The process has a natural threshold
- The process produces neutrinos

### External signatures:

- Need for a high gas density (pp)
- Need for a high radiation density (p $\gamma$ )

### Multi-wavelength signatures:

- Constraints on lepton production from radio and X-ray observations



# The threshold for $\pi^0$ production

Production of pions requires a minimum energy in the center of mass (CoM).



$$s = (p_1 + p_2)^2 \rightarrow s_{lab} = (2m_p c^4 + 2m_p c^2 E_p)$$

$$s_{th} = (2m_p c^2 + m_{\pi^0} c^2)^2$$

$$2m_p c^2 E_p + 2m_p c^4 = (2m_p c^2 + m_{\pi^0} c^2)^2$$

$$E_p^{K,th} = 2m_{\pi^0} c^2 + \frac{m_{\pi^0}^2 c^2}{2m_p} = 280 \text{ MeV}$$



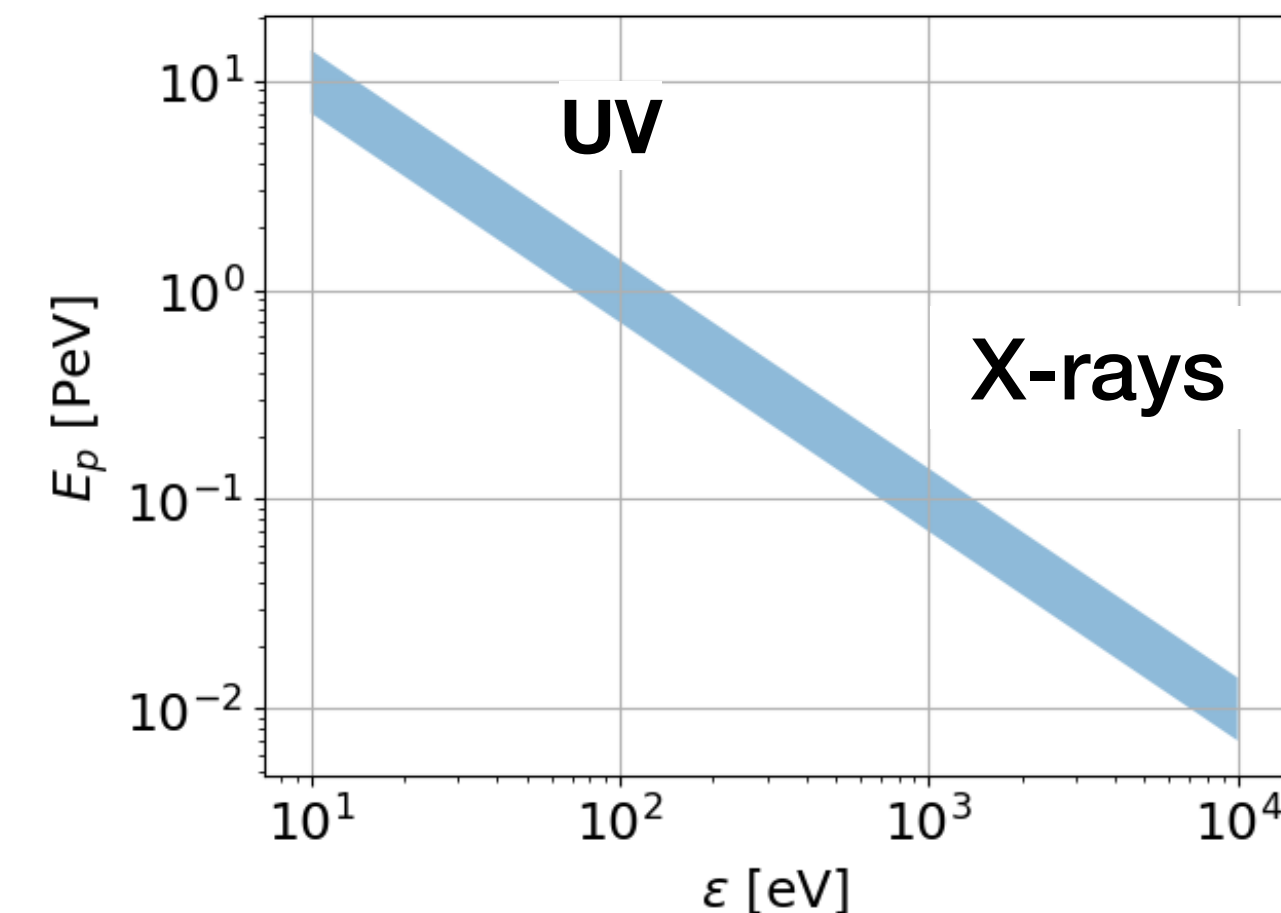
$$s_{lab} = (p_p + p_\gamma)^2 = m_p^2 c^2 + 2E_p \epsilon (1 - \cos \theta)$$

$$p_p \cdot p_\gamma = E_p \epsilon (1 - \cos \theta)$$

$$s_{lab} = (m_p c^2)^2 + 2E_p \epsilon (1 - \cos \theta)$$

$$s_{th} = (m_p c^2 + m_{\pi^0} c^2)^2$$

$$E_p^{th} = \frac{2m_p m_{\pi^0} + m_{\pi^0}^2}{2\epsilon(1 - \cos \theta)} = \frac{140 \text{ PeV}}{(1 - \cos \theta) \frac{\epsilon}{1 \text{ eV}}}$$





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Range probed by  
Fermi-LAT / AGILE



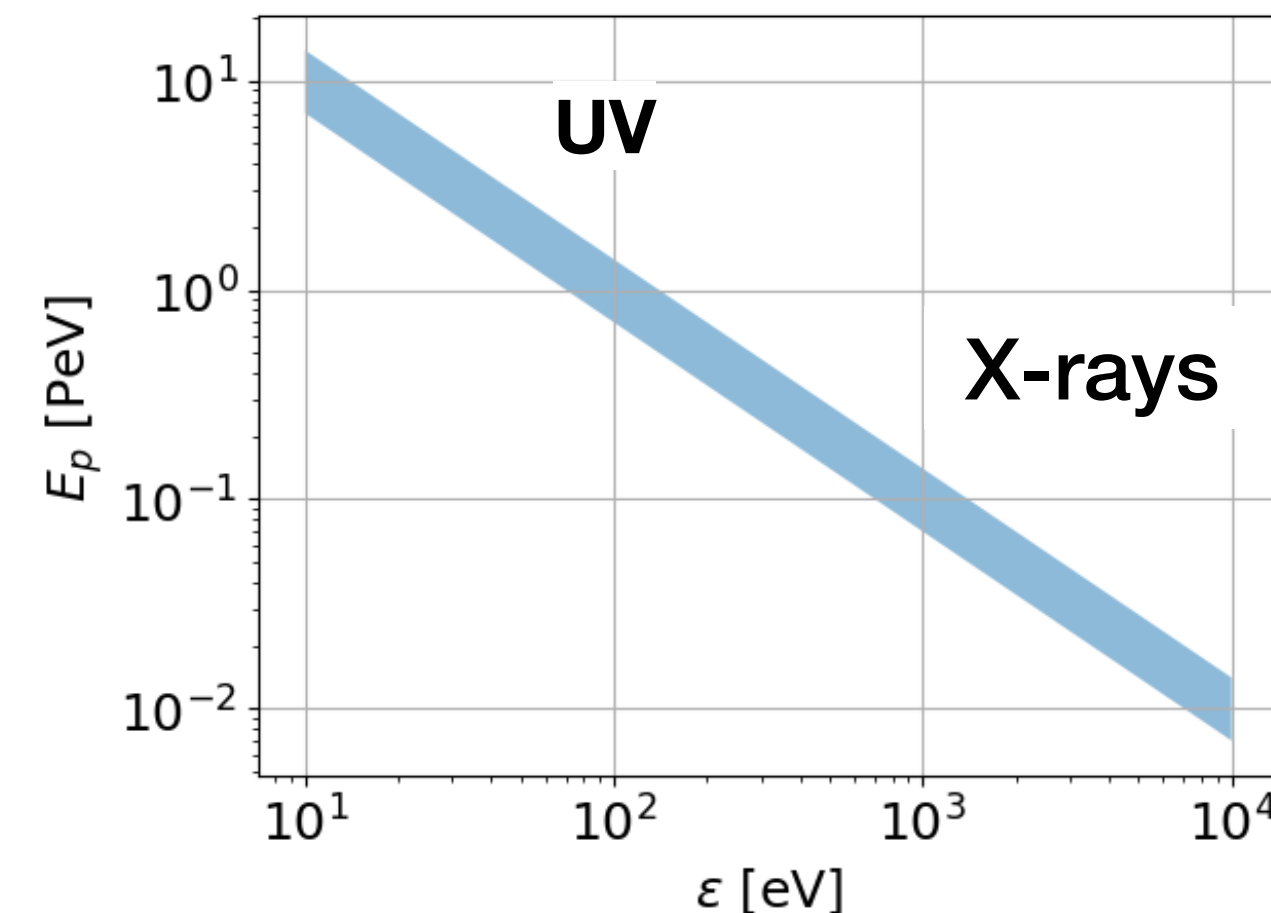
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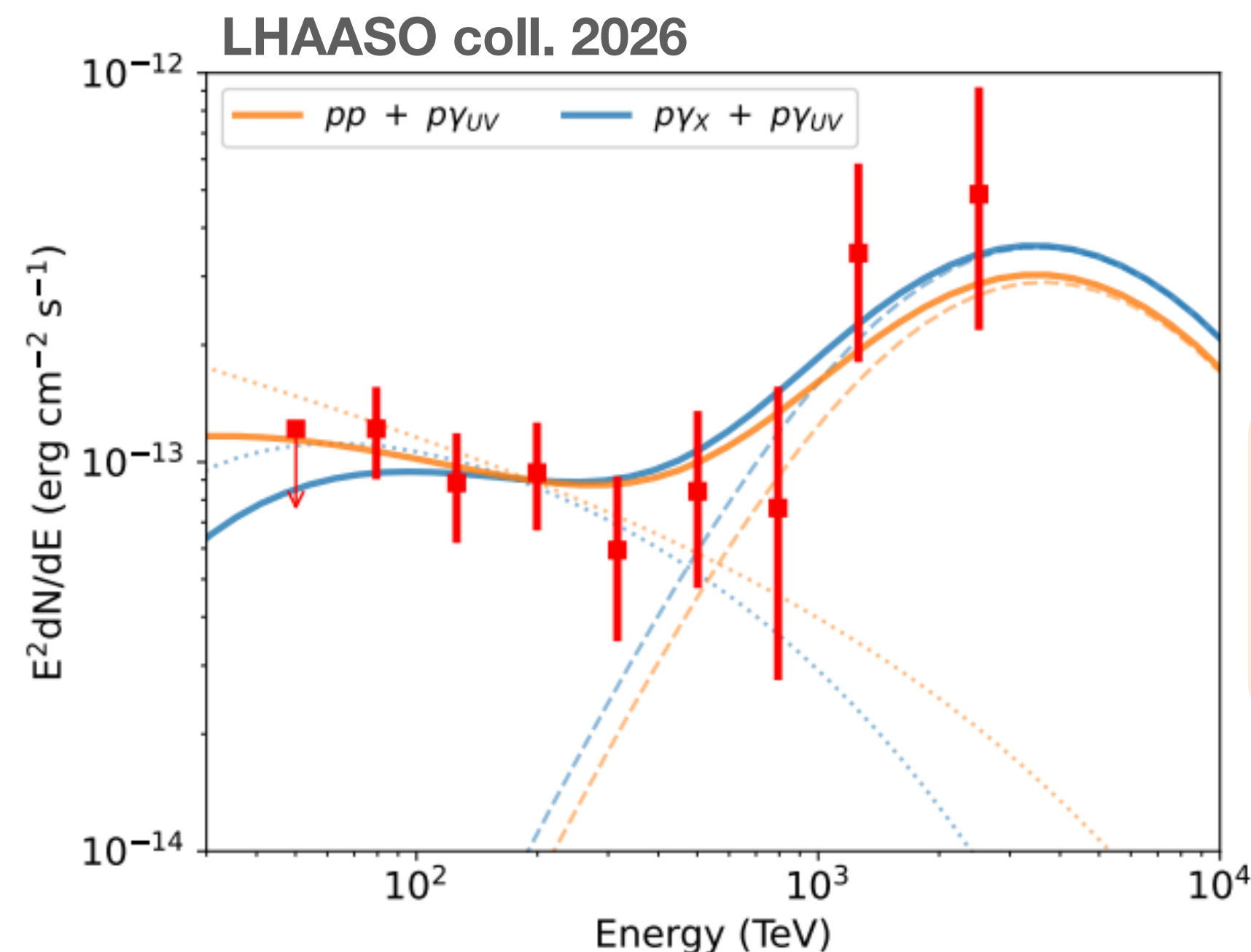


Range probed  
by LHAASO

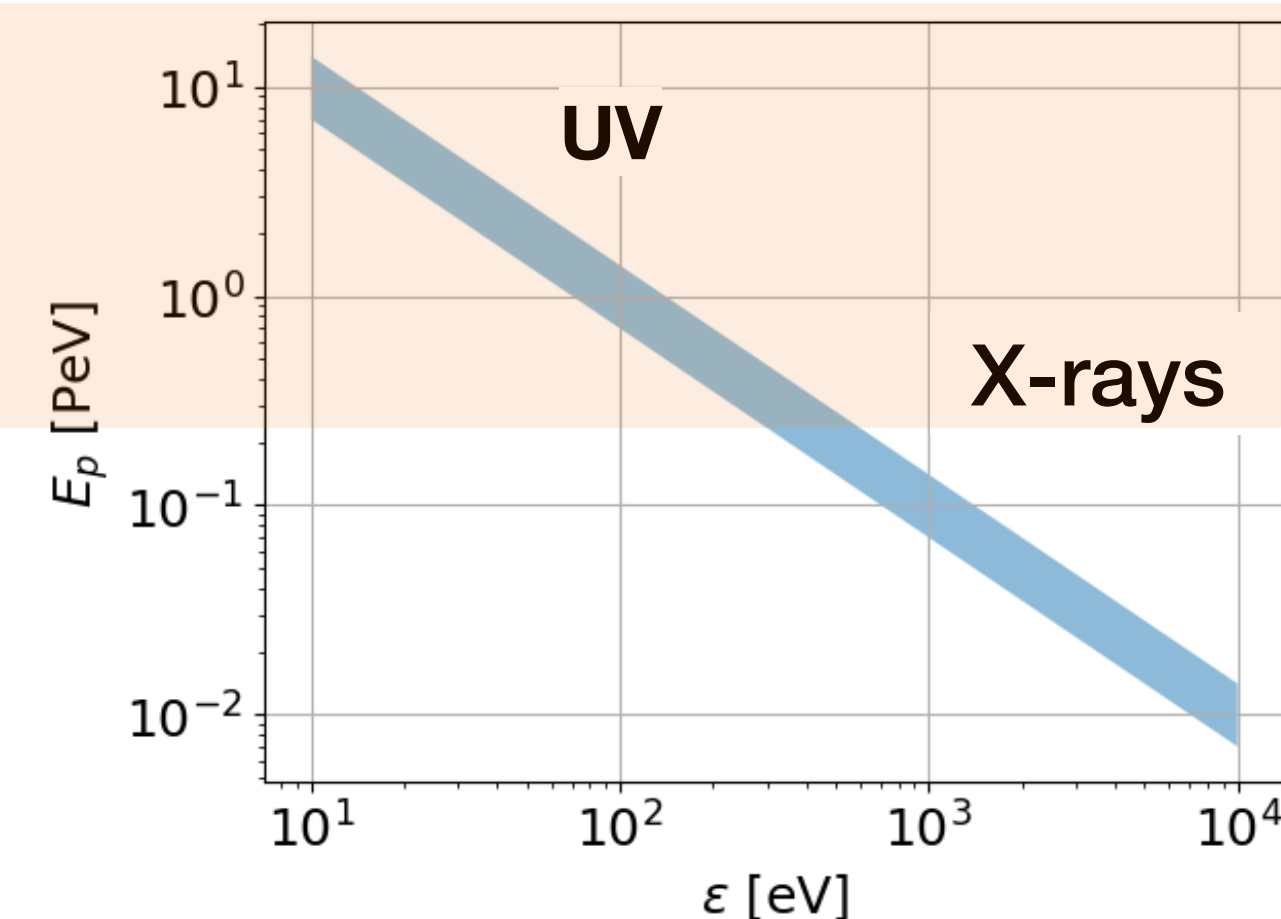
# The threshold for $\pi^0$ production

Production of pions requires a minimum energy in the center of mass (CoM).

The case of Cygnus X-3:  
spectrum rise above 100 TeV: as  
a proof of UHE protons



Ideal environment  
for  $p\gamma$  thanks to  
the high UV and  
X-ray field



Range probed  
by LHAASO

$$p + \gamma \rightarrow p + \pi^0$$

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# The pion bump



# The pion bump

In the rest frame of pion photons are emitted isotropically

$$\pi^0 \rightarrow 2\gamma$$

$$\beta = \sqrt{1 - \frac{1}{\Gamma^2}}$$

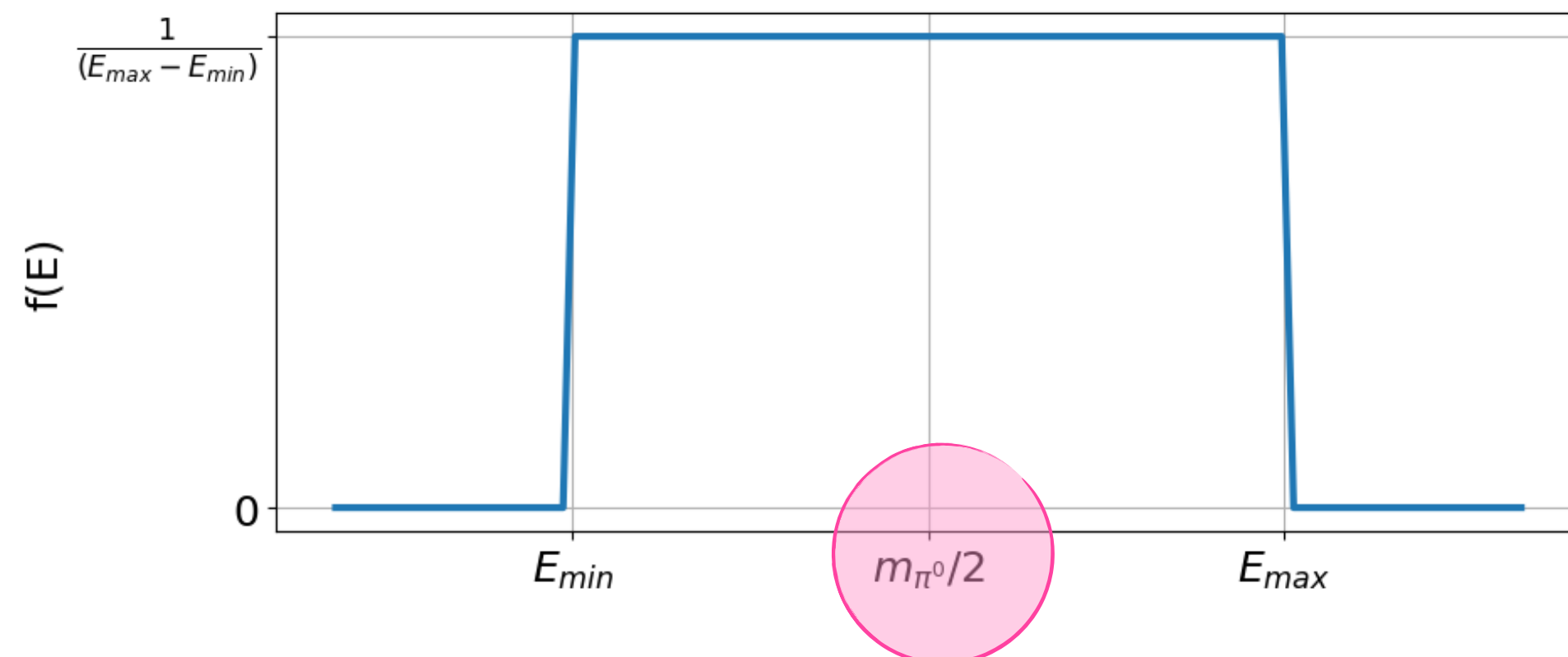
Pion rest frame:  $E^*_\gamma = \frac{m_{\pi^0}}{2}$

$$\Gamma = \frac{E_\pi}{m_{\pi^0}} = \frac{\eta E_p}{m_{\pi^0}}$$

Lab. frame:  $E_\gamma = \Gamma E^*_\gamma (1 + \beta \cos \theta^*) \rightarrow -1 < \cos \theta^* < 1$

Photon distribution for each pion of energy  $E_\pi$

$$f(E_\gamma) = \frac{dN_\gamma}{dE_\gamma} = \frac{1}{E_{E_{\max}} - E_{E_{\min}}}$$



$$\begin{cases} E_{\gamma, \min} < E_\gamma < E_{\gamma, \max} \\ E_{\gamma, \min} = \Gamma E^*_\gamma (1 - \beta) = E_\gamma(E_\pi) \\ E_{\gamma, \max} = \Gamma E^*_\gamma (1 + \beta) = E_\gamma(E_\pi) \end{cases}$$

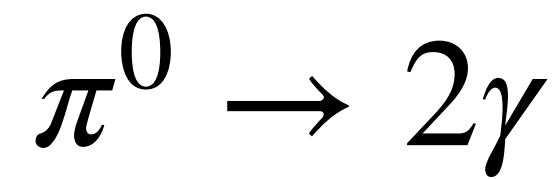
$$\log(E_{\text{mean}}) = (\log(E_{\min}) + \log E_{\max})/2$$

$$E_{\text{mean}}^{\log} = (E_{\min} E_{\max})^{1/2} = \frac{m_{\pi^0}}{2}$$



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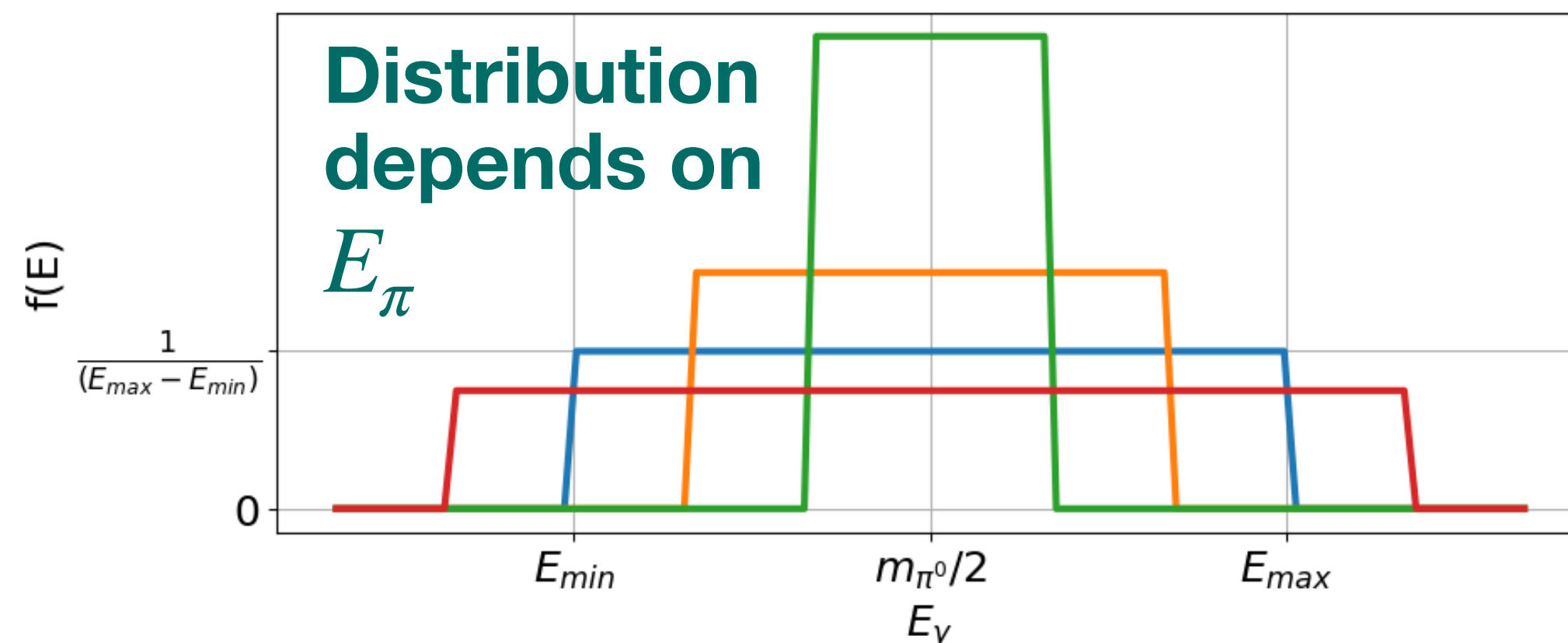
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Mean does not depend on  $E_\pi$ :

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Photon distribution for a power-law distribution of pions:

$$\frac{dN_\gamma}{dE_\gamma} = \int_{E_\pi^{min}(E_\gamma)} dE_\pi \frac{dN_\pi}{dE_\pi} \frac{1}{\sqrt{E_\pi^2 - m_{\pi^0}^2}} = \int_{E_\pi^{min}(E_\gamma)} dE_\pi E_\pi^{-s} \frac{1}{\sqrt{E_\pi^2 - m_{\pi^0}^2}} \approx (E_\pi^{min}(E_\gamma))^{-s}$$

If  $s > 0$  Dominated by lower boundary

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Photon distribution for a power-law distribution of pions:

$$\approx (E_\pi^{min}(E_\gamma))^{-s}$$

Dominated by lower boundary

$$(B) \rightarrow E_\pi^{min} = E_\gamma + \frac{m_{\pi^0}^2}{4E_\gamma}$$

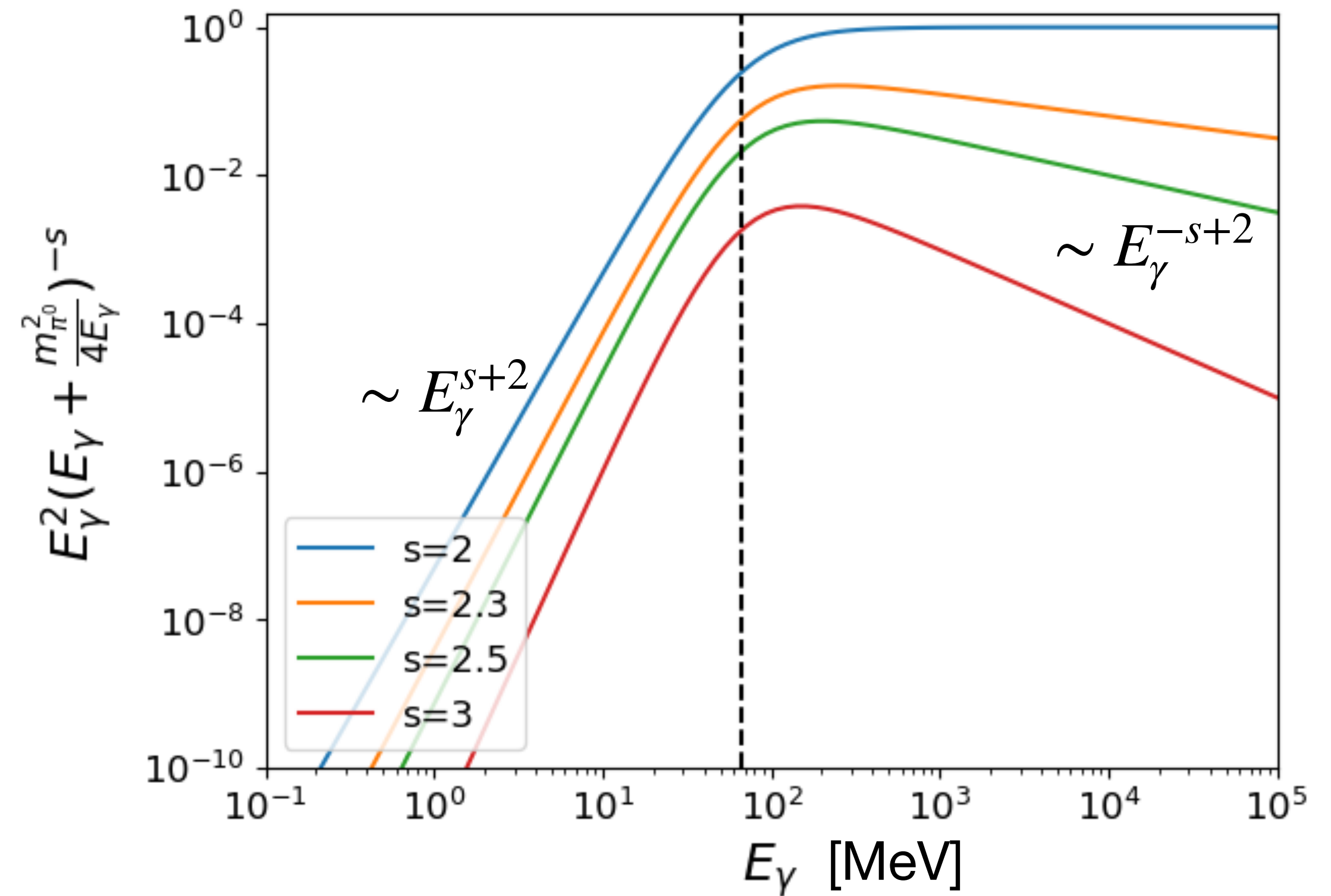
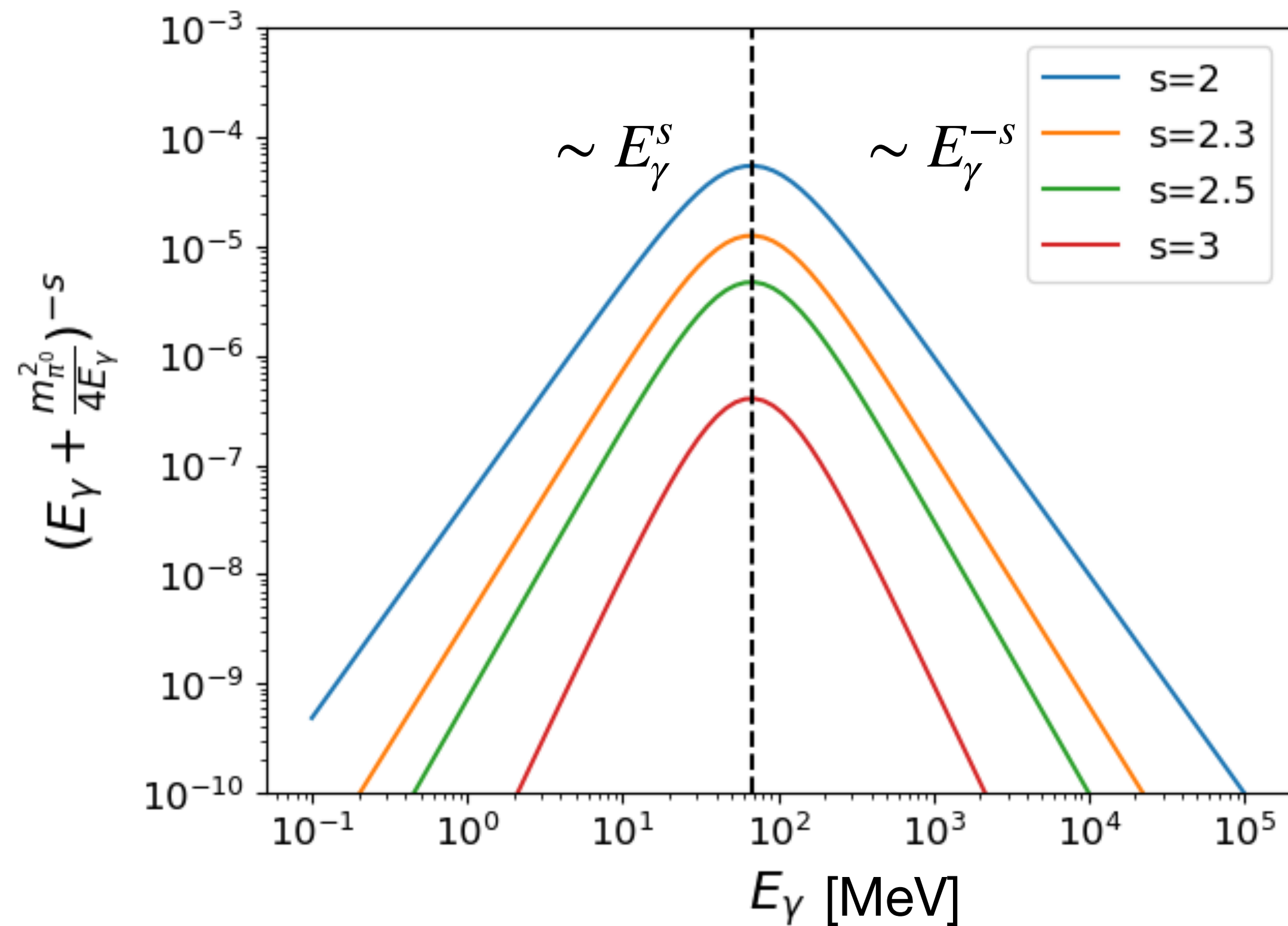
The minimum energetic pion to obtain the same photon energy



# The pion bump

Photon distribution for a power-law distribution of pions

$$(E_{\pi}^{min})^{-s} = \left( E_{\gamma} + \frac{m_{\pi^0}^2}{4E_{\gamma}} \right)^{-s}$$

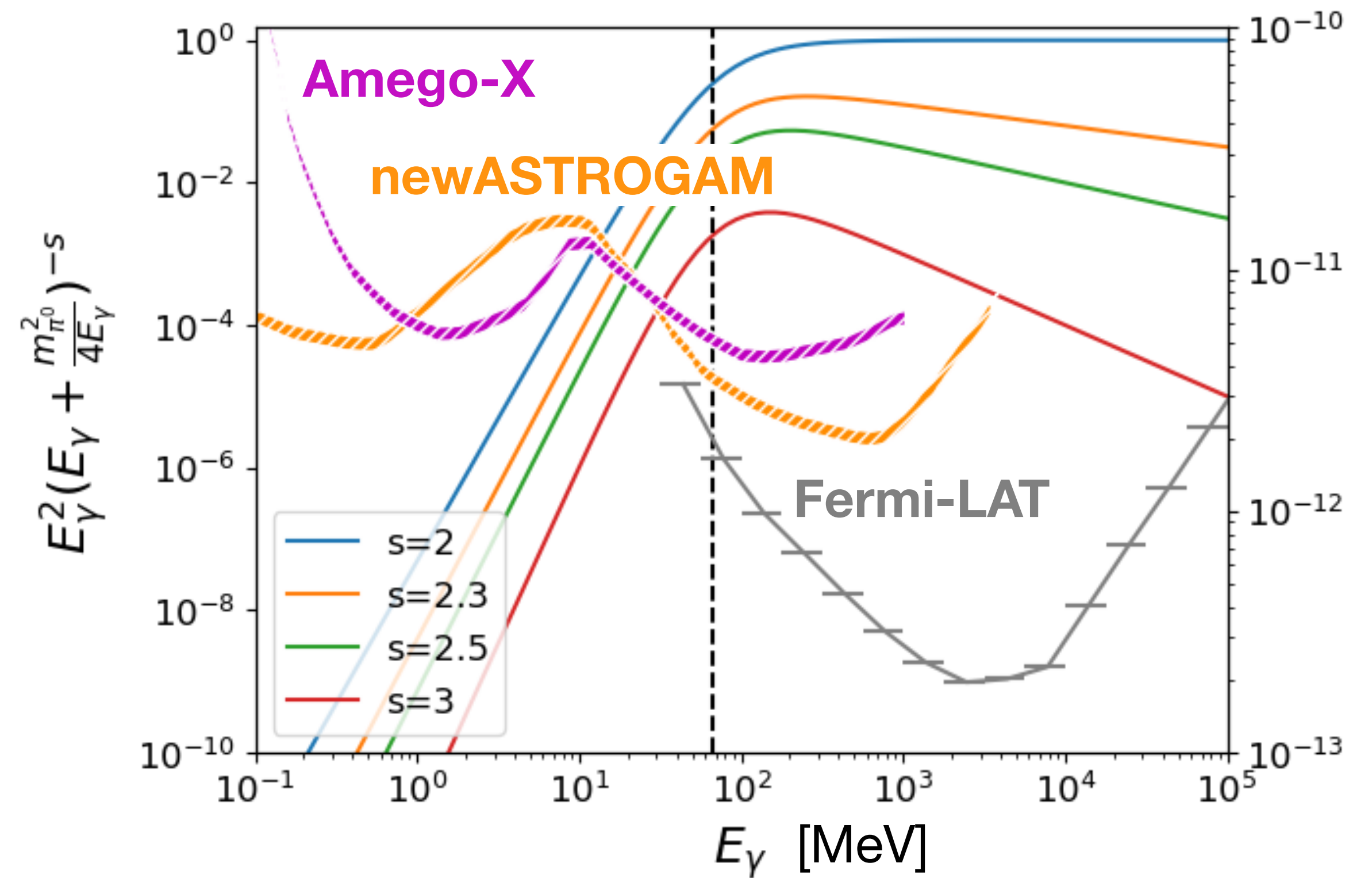
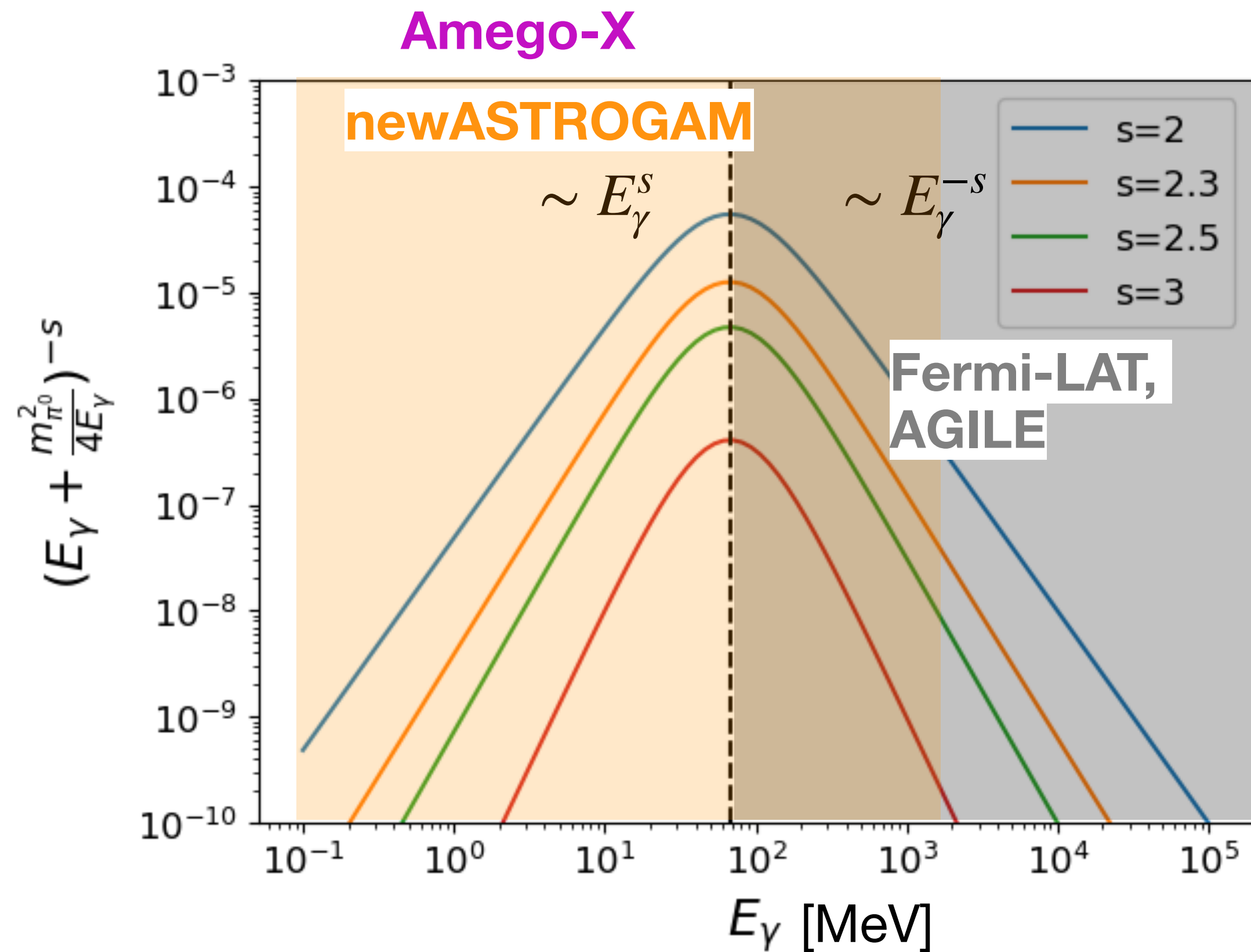




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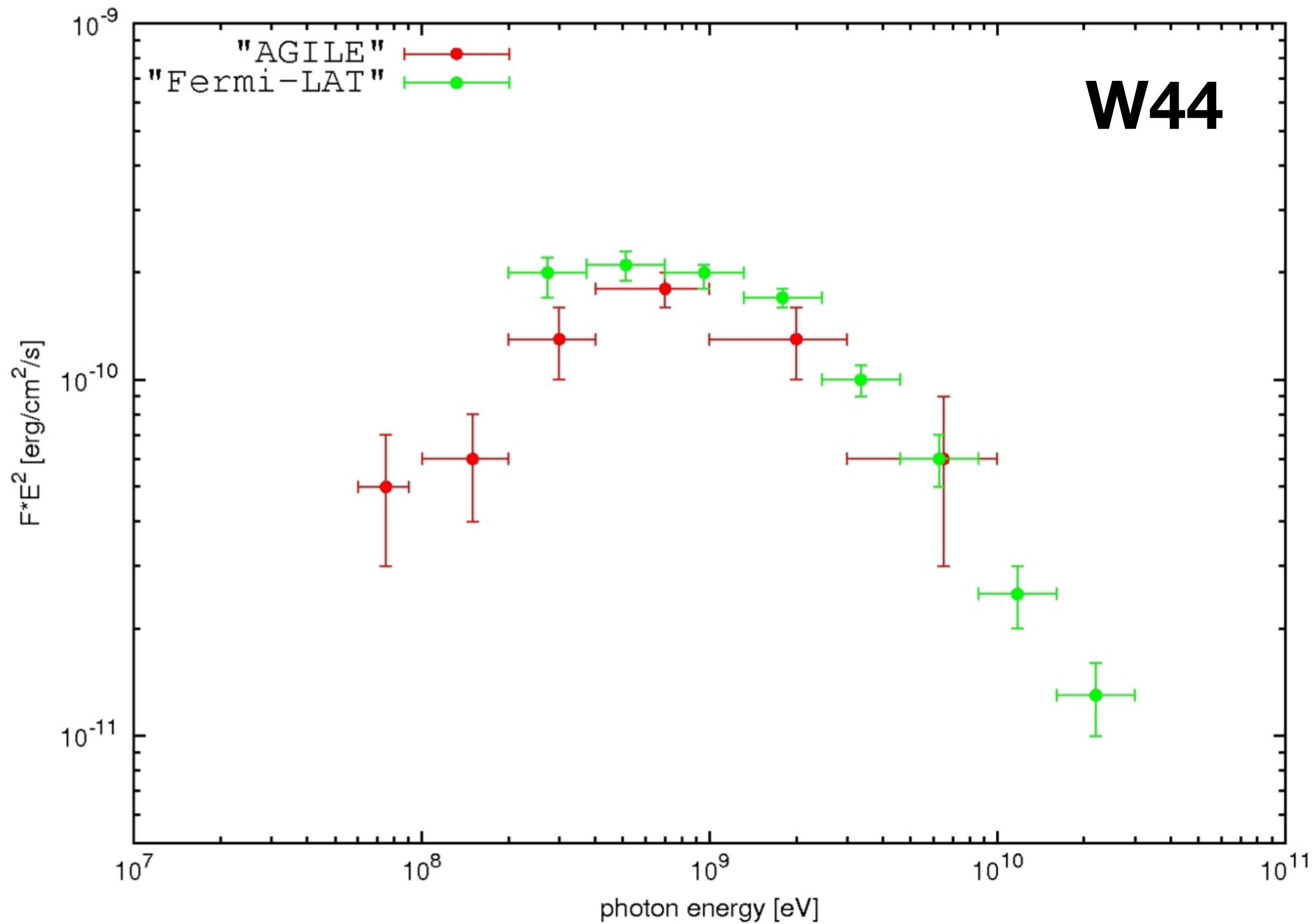
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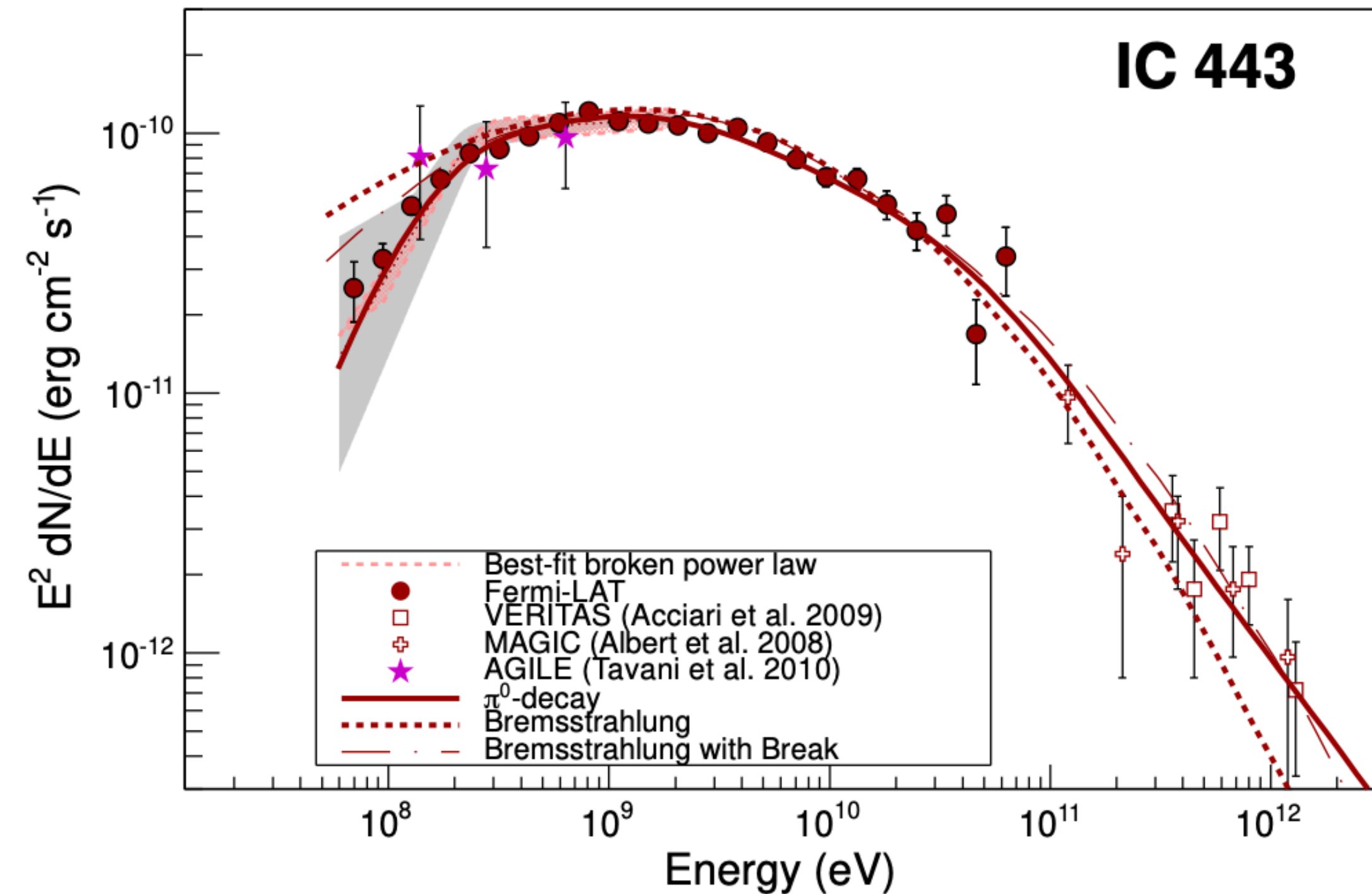
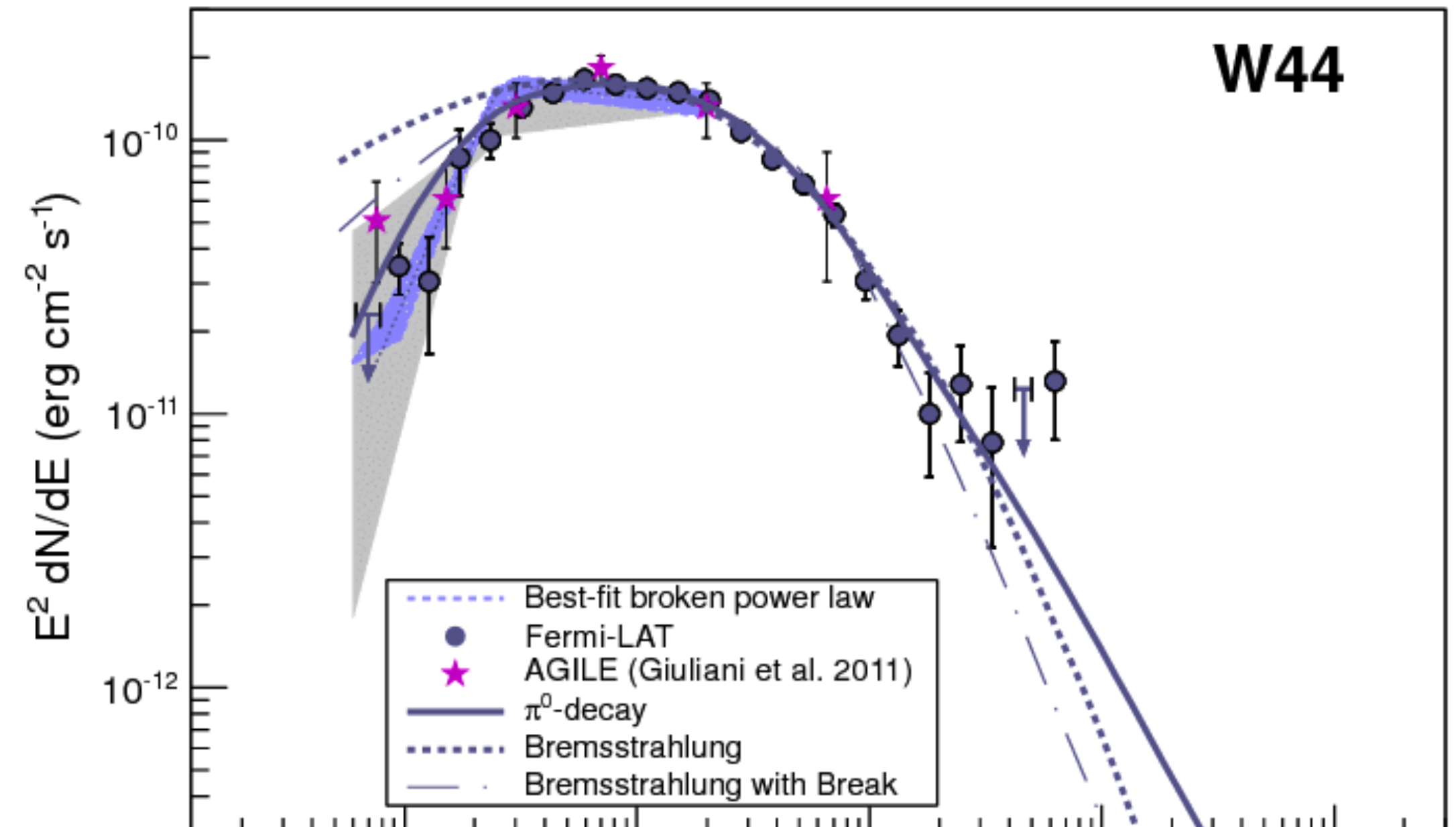


# The pion bump: examples of detection

AGILE, Giuliani et al. 2011

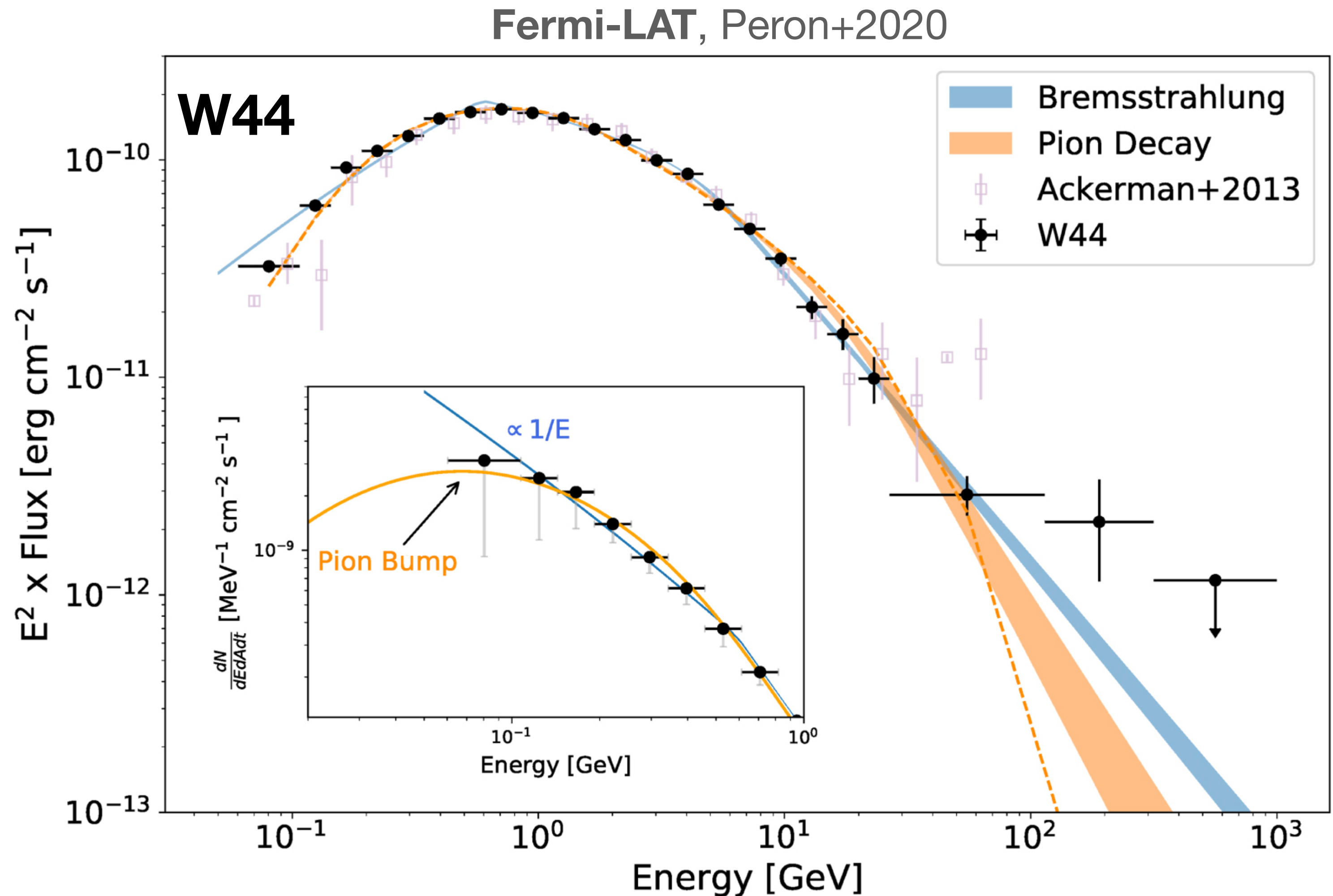
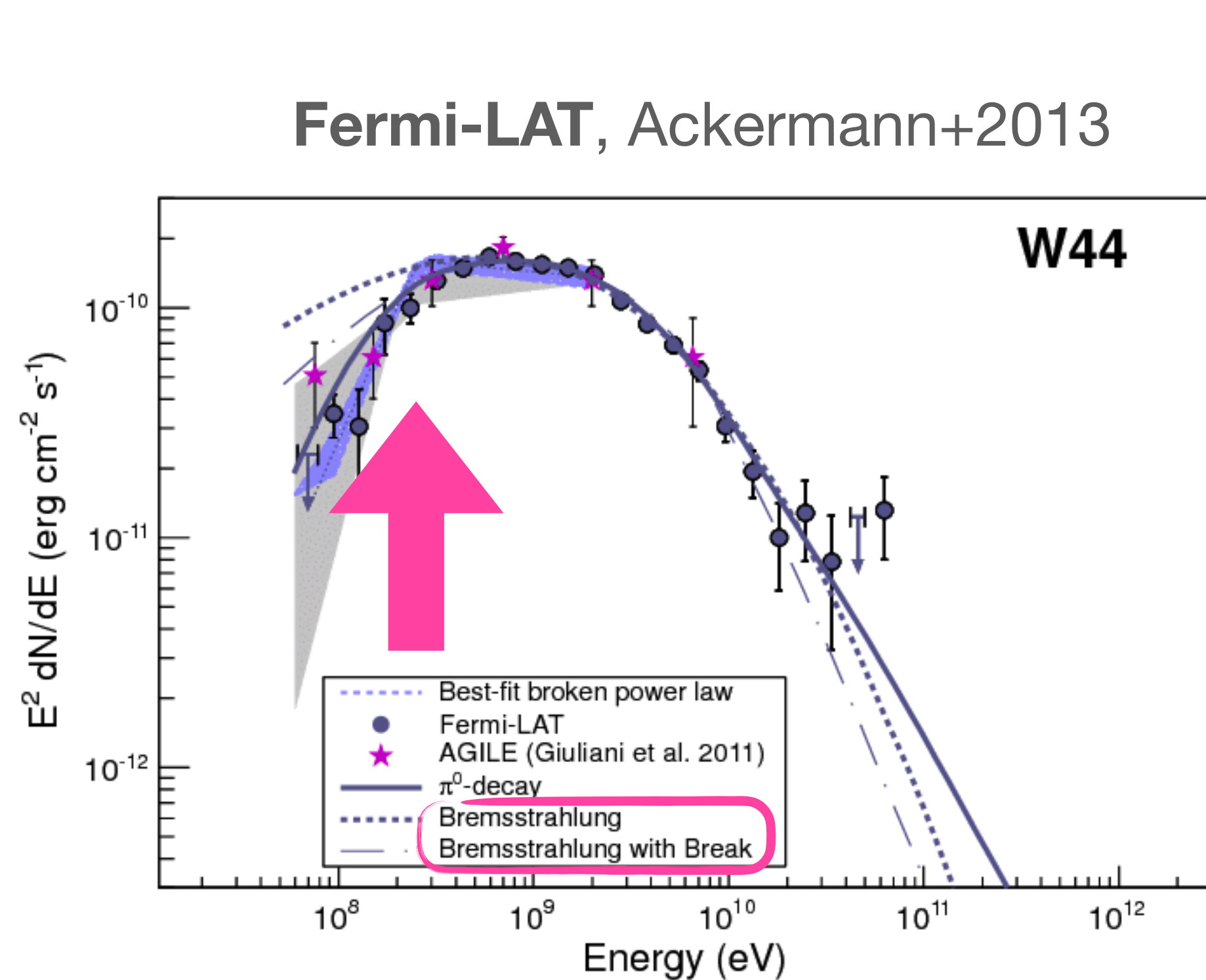


Fermi-LAT, Ackermann+2013



# The pion bump: examples of detection?

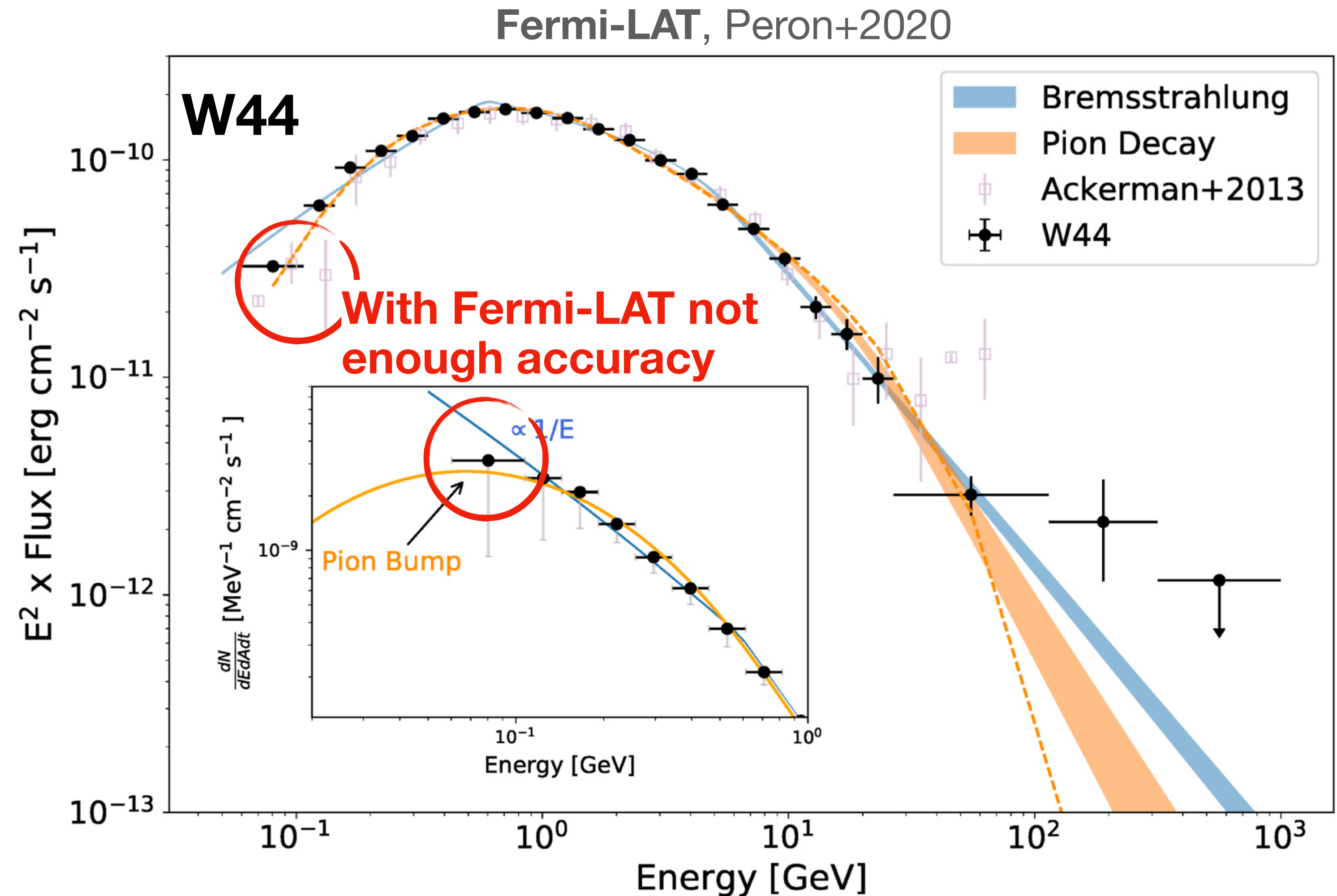
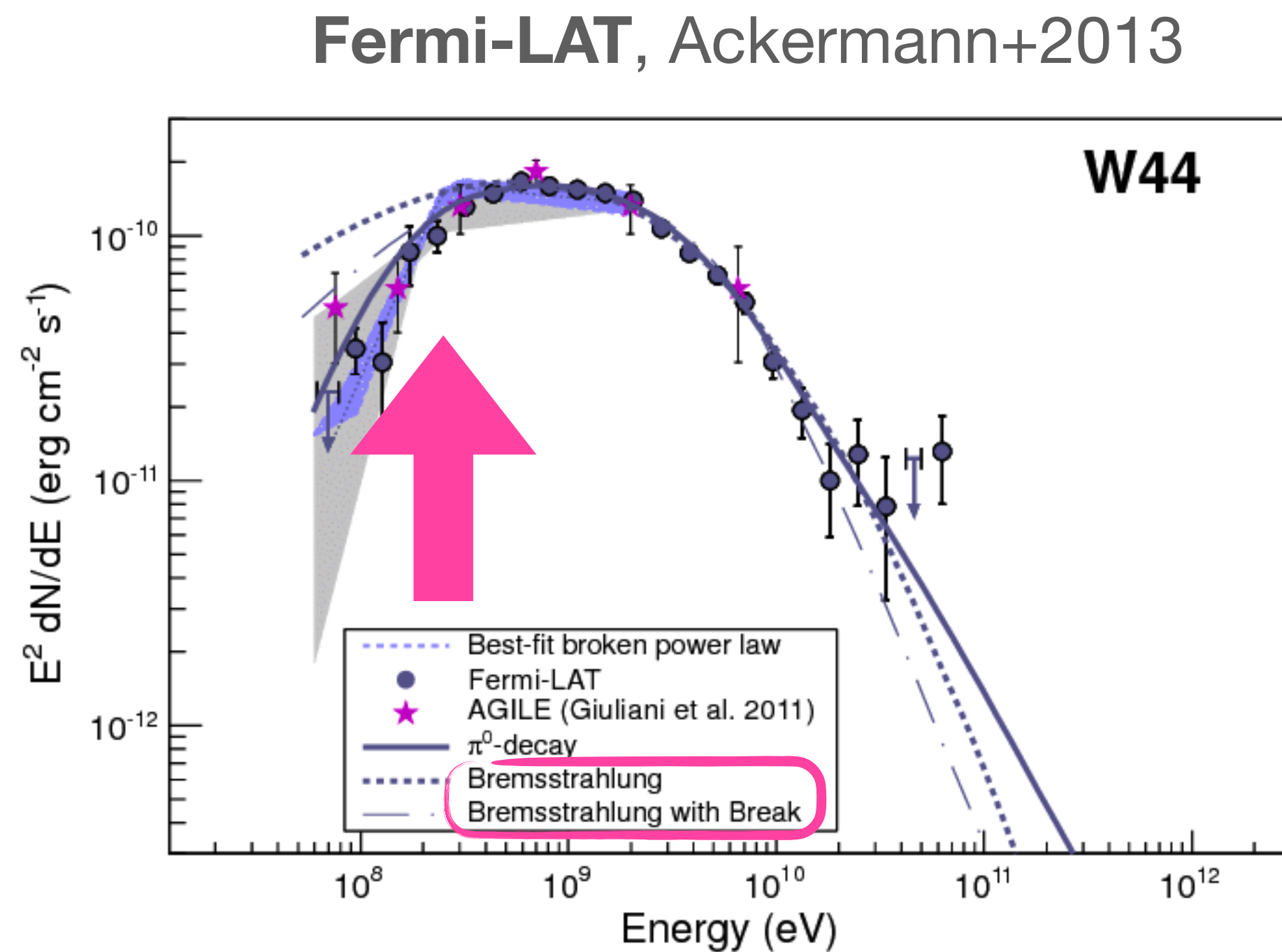
Are we really seeing the pion bump or is it broken bremsstrahlung?





# The pion bump: examples of detection?

Are we really seeing the pion bump or is it broken bremsstrahlung?

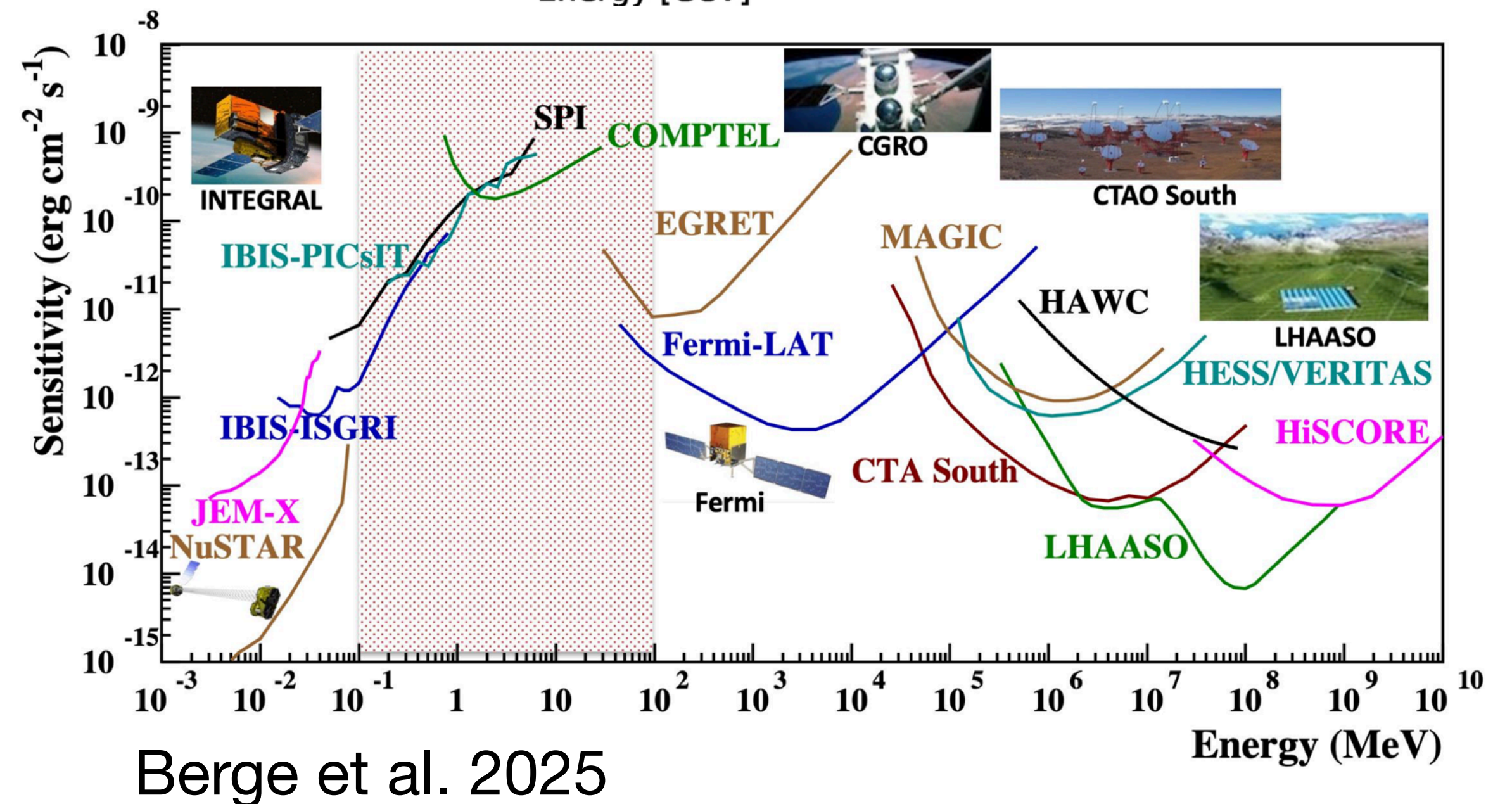
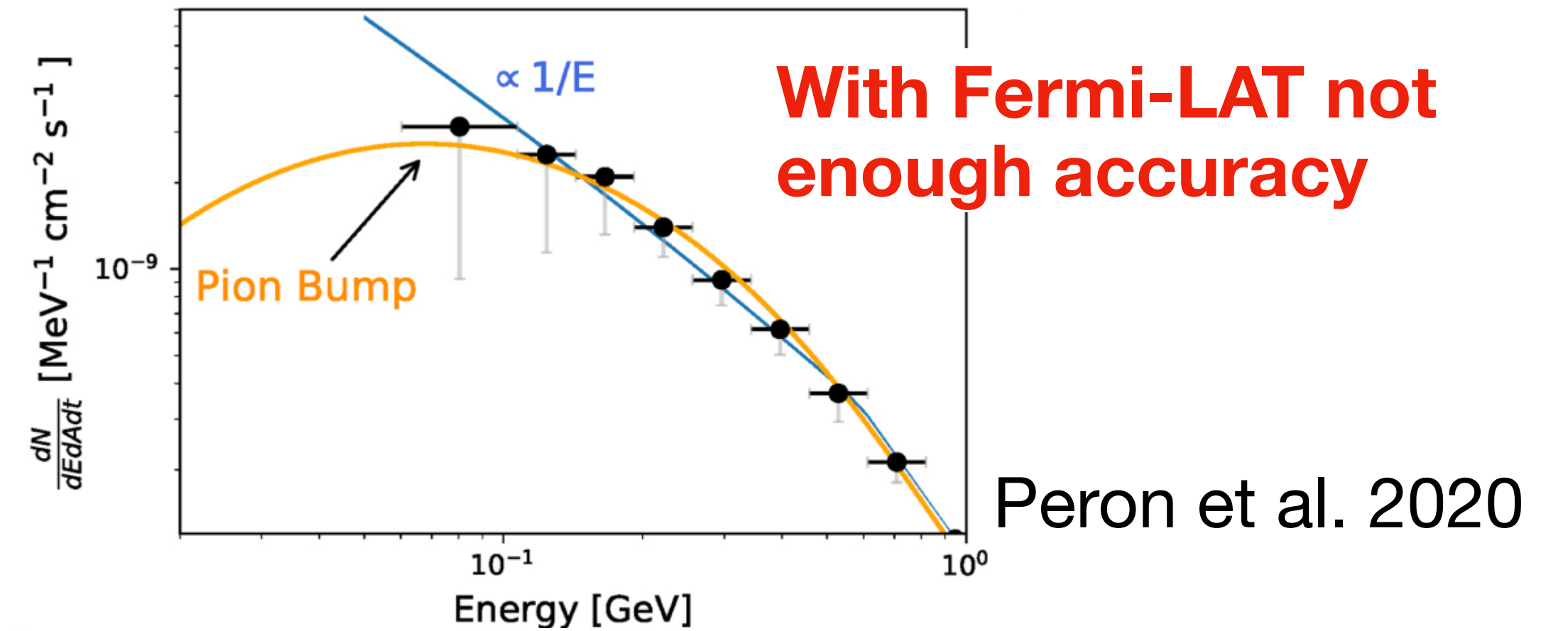
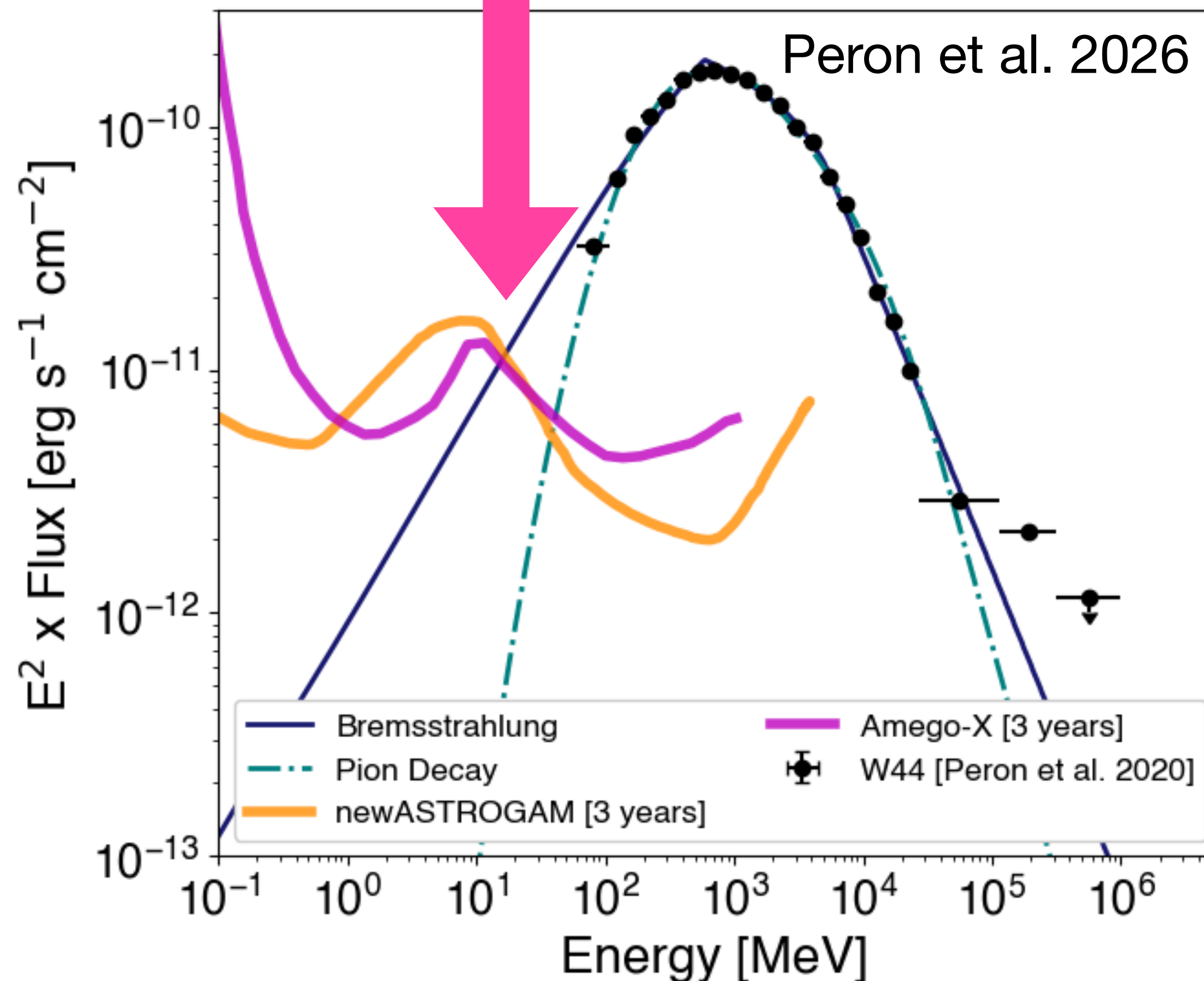




# The pion bump: examples of detection?

Are we really seeing the pion bump or is it broken bremsstrahlung?

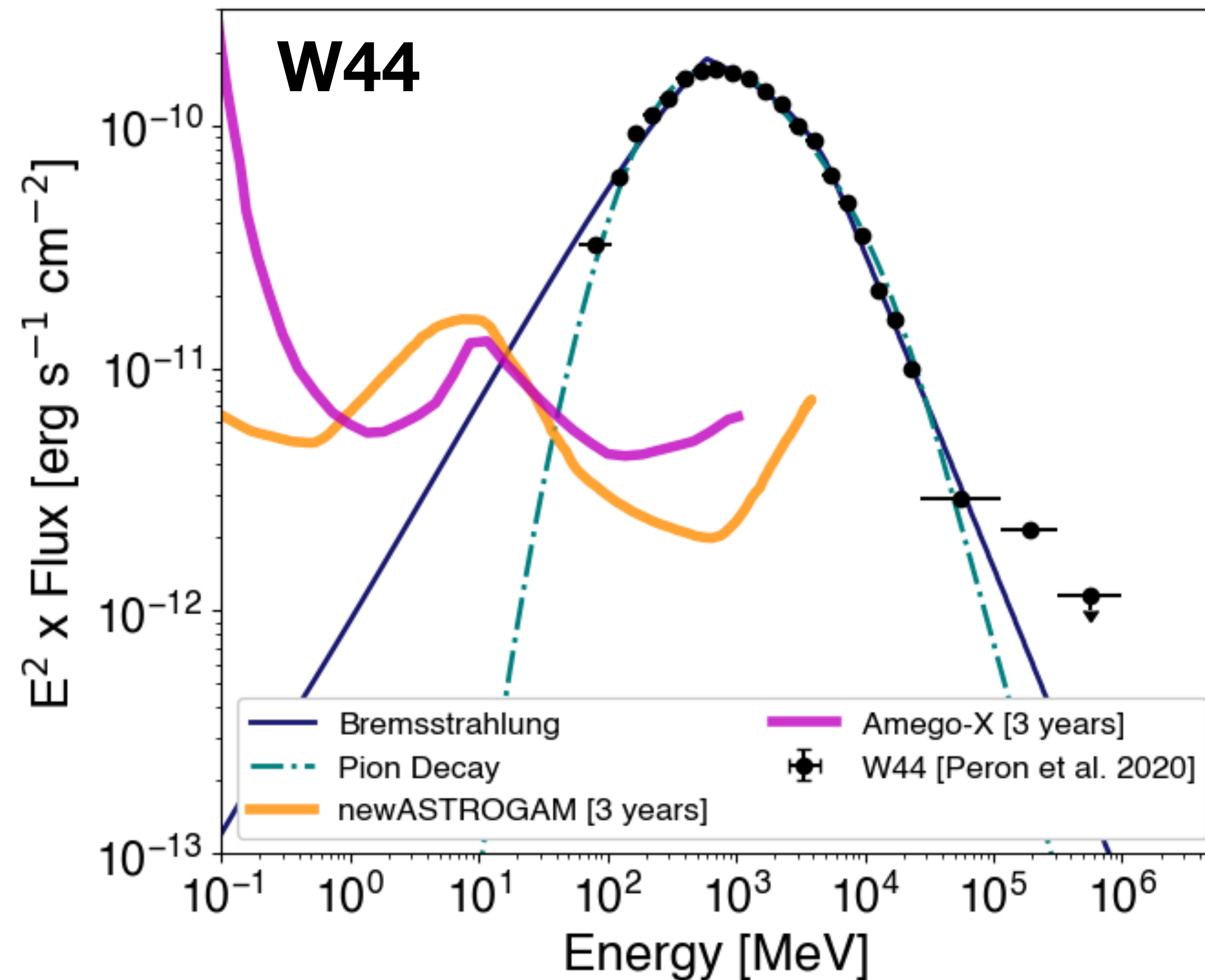
Solution is in the MeV range!



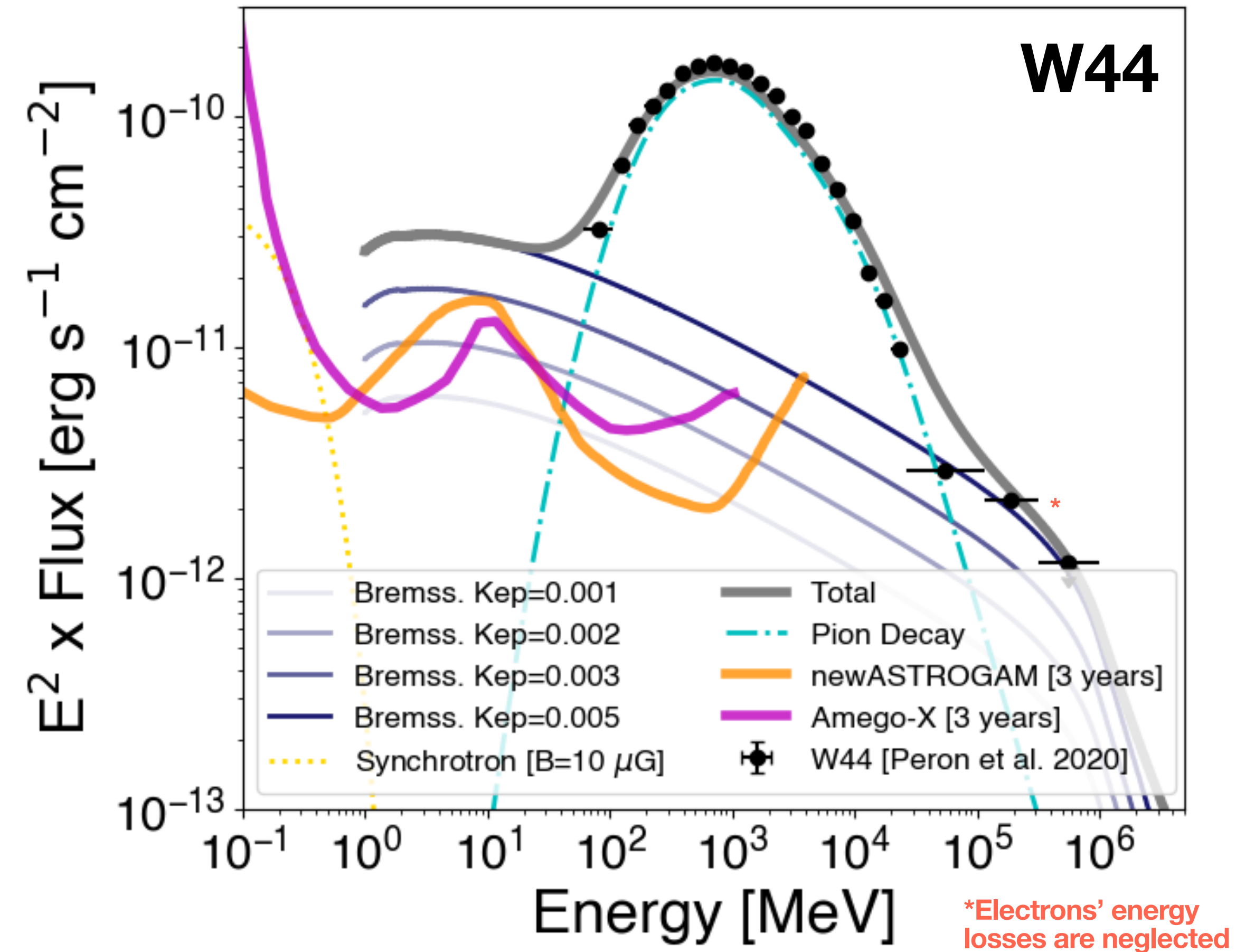


# The potential of future MeV detectors

Understand the nature of the emission:  
Is it Pion bump or broken bremsstrahlung?



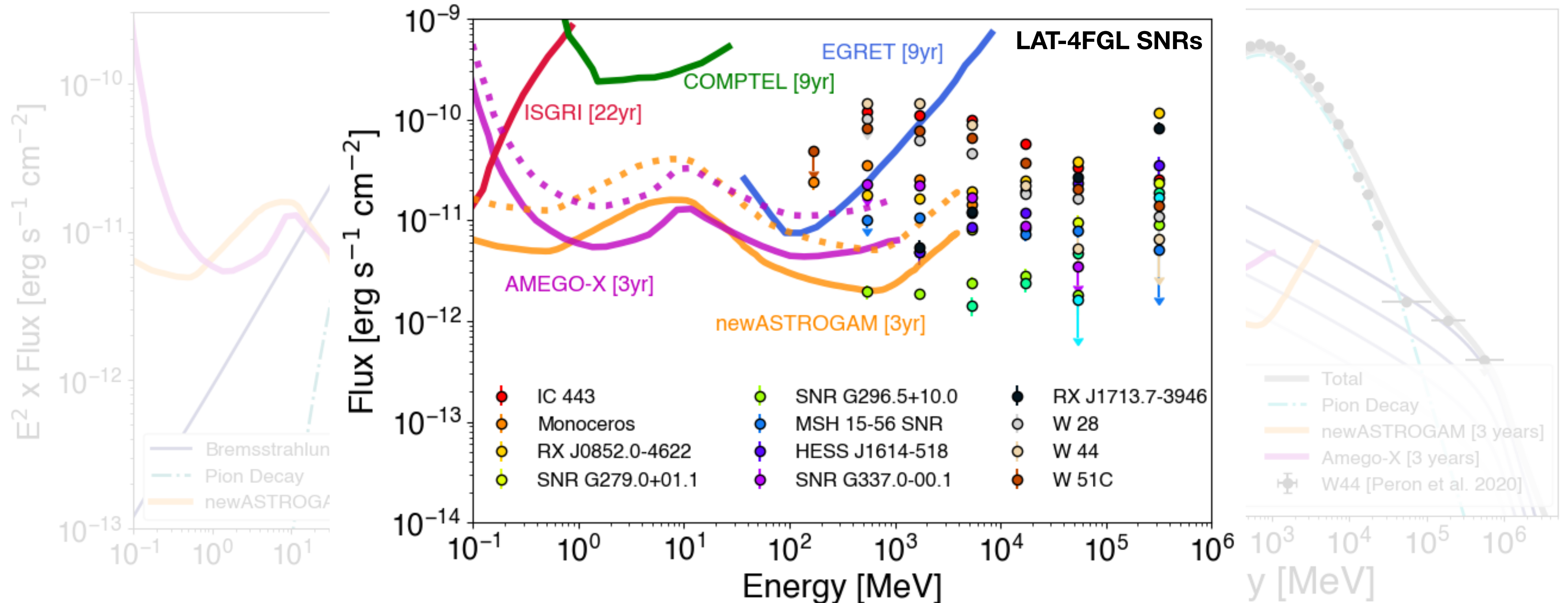
Evaluate the rate between hadronic emission  
and leptonic emission, hence estimate  $K_{ep}$



# The potential of future MeV detectors

Understand the nature of the emission:  
Is it Pion bump or broken bremsstrahlung?

Evaluate the rate between hadronic emission  
and leptonic emission, hence estimate  $K_{ep}$



**When the pion bump is not there...**



# When the pion bump is not there...

For how many gamma ray sources there has been a clear detection of a pion bump?

## ChatGPT

If by “clear detection of a pion bump” you mean **robust, widely accepted spectral identification of the characteristic  $\pi^0$ -decay feature ( $\sim 100\text{--}200\text{ MeV}$ )** in individual  $\gamma$ -ray sources, then the number is actually quite small.

### Established, unambiguous detections

So far, the community generally agrees on **only a handful ( $\approx 2\text{--}3$ ) of clear cases**, all in **middle-aged supernova remnants interacting with dense gas**, most notably:

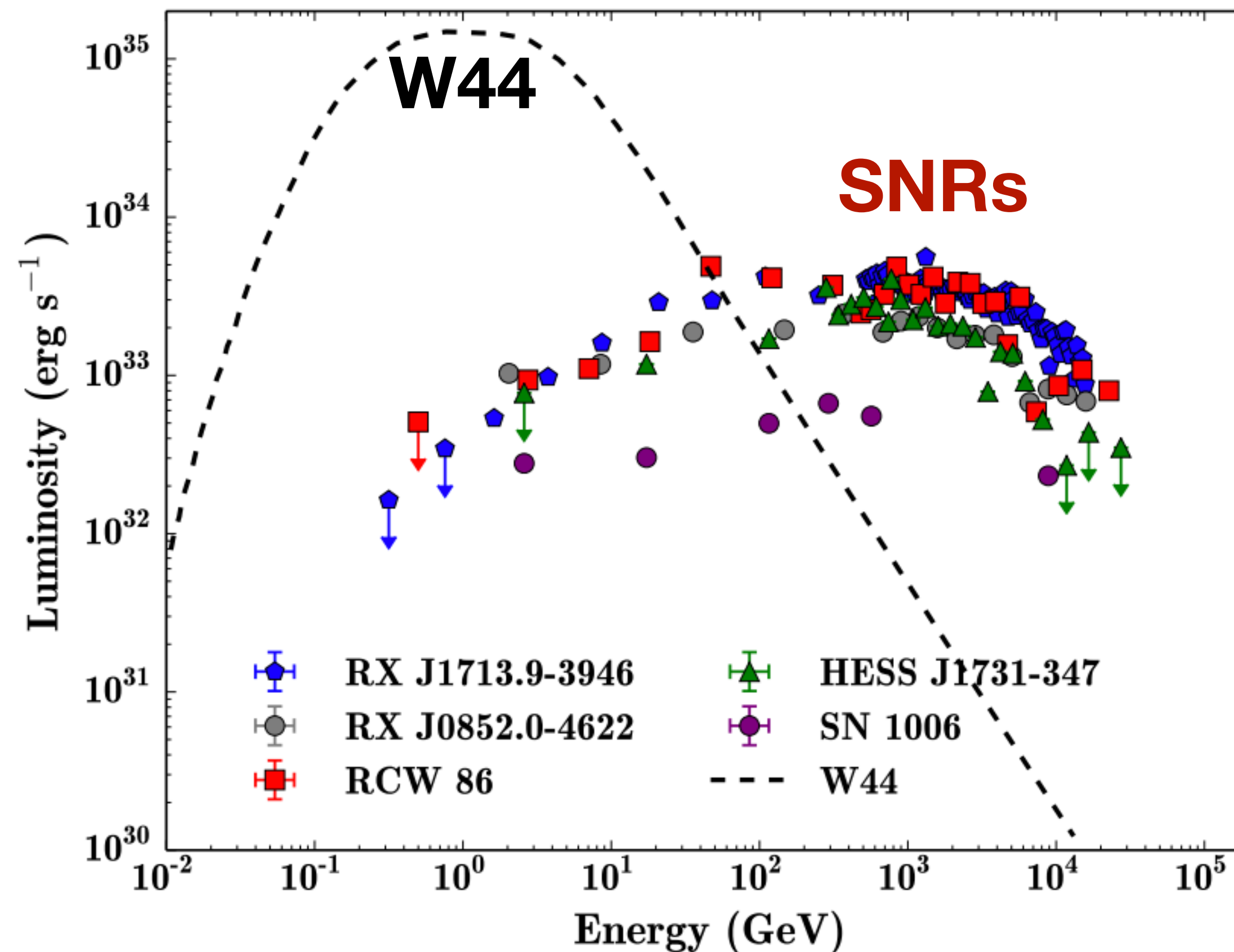
- IC 443
- W44

These are the classic examples where the pion bump has been **cleanly resolved and attributed to hadronic emission** (often cited as the first direct proof of cosmic-ray proton acceleration). [arXiv](#)

Sometimes a couple of additional SNR candidates are discussed, but the consensus “gold standard” remains at  **$\sim 2$  firm detections**.

# Interpretation of gamma-ray emission

SNRs where the bump is not there...



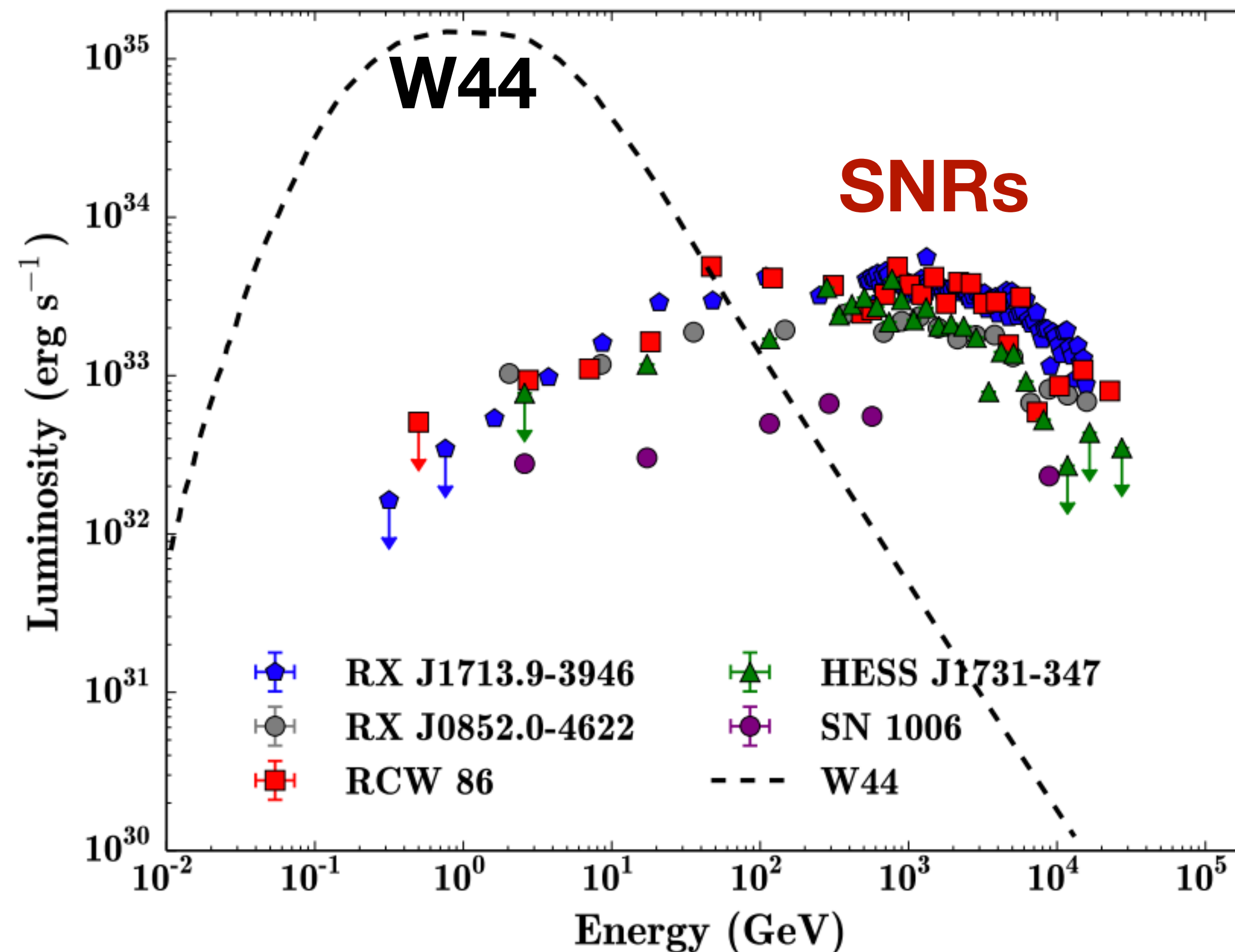
SNRs with a similar spectrum and luminosity

Hard spectrum  $\Gamma \sim 1.8$

Similar age (1-6 kyr)  
Similar environment (low density)

# Interpretation of gamma-ray emission

SNRs where the bump is not there...



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Hard spectrum  $\Gamma \sim 1.8$

Similar age (1-6 kyr)

Similar environment (low density)

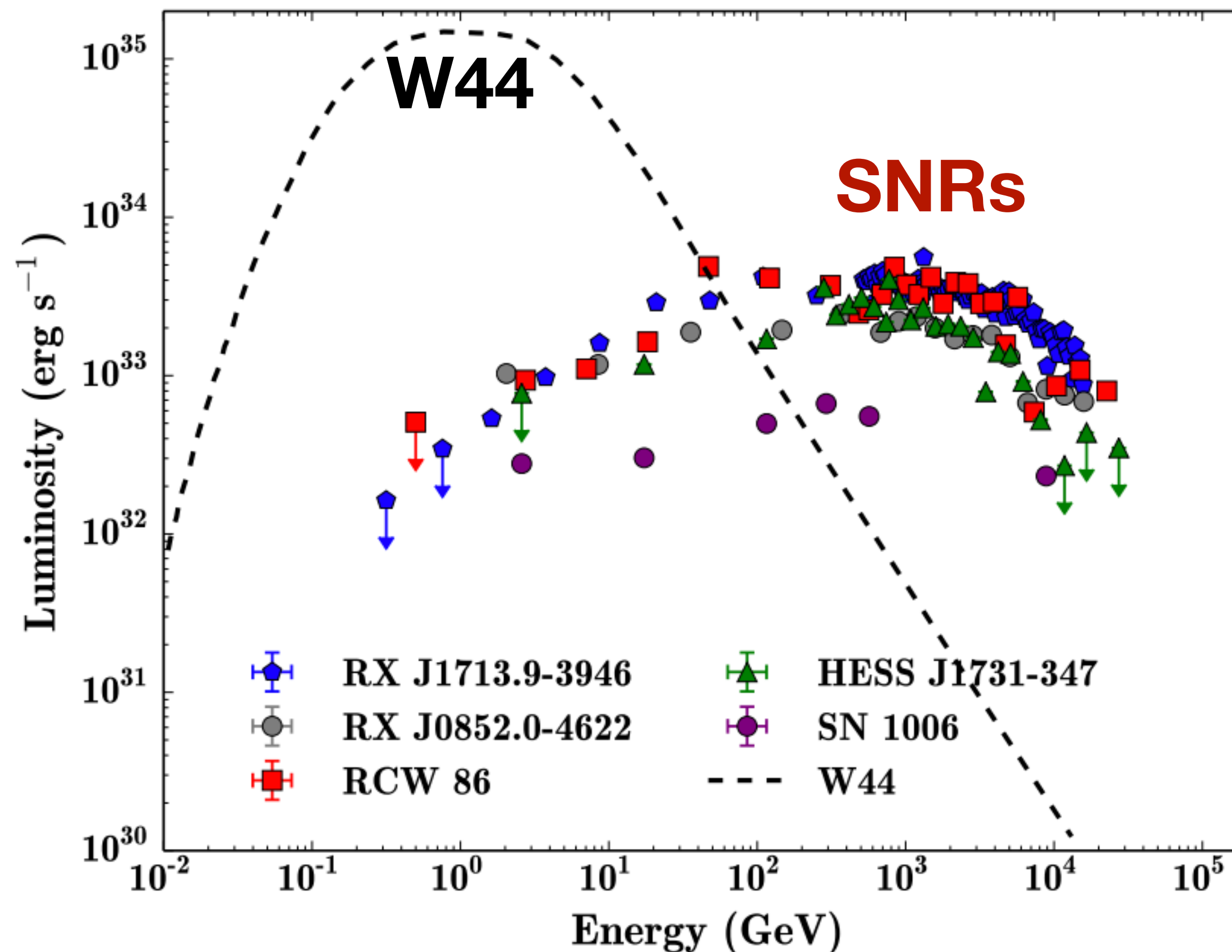
→ Similar efficiency

→ Inverse Compton on a uniform target [CMB]



# Interpretation of gamma-ray emission

SNRs where the bump is not there...



SNRs with a similar spectrum and luminosity

Hard spectrum  $\Gamma \sim 1.8$

Similar age (1-6 kyr)

Similar environment (low density)

} → **Similar efficiency**

→ **Inverse Compton on a uniform target [CMB]**

...is a leptonic model the only possibility?



# Interpretation of gamma-ray emission

SNRs where the bump is not there...

...is a leptonic model the only possibility?

## The debated case of RX J1713.7-3946

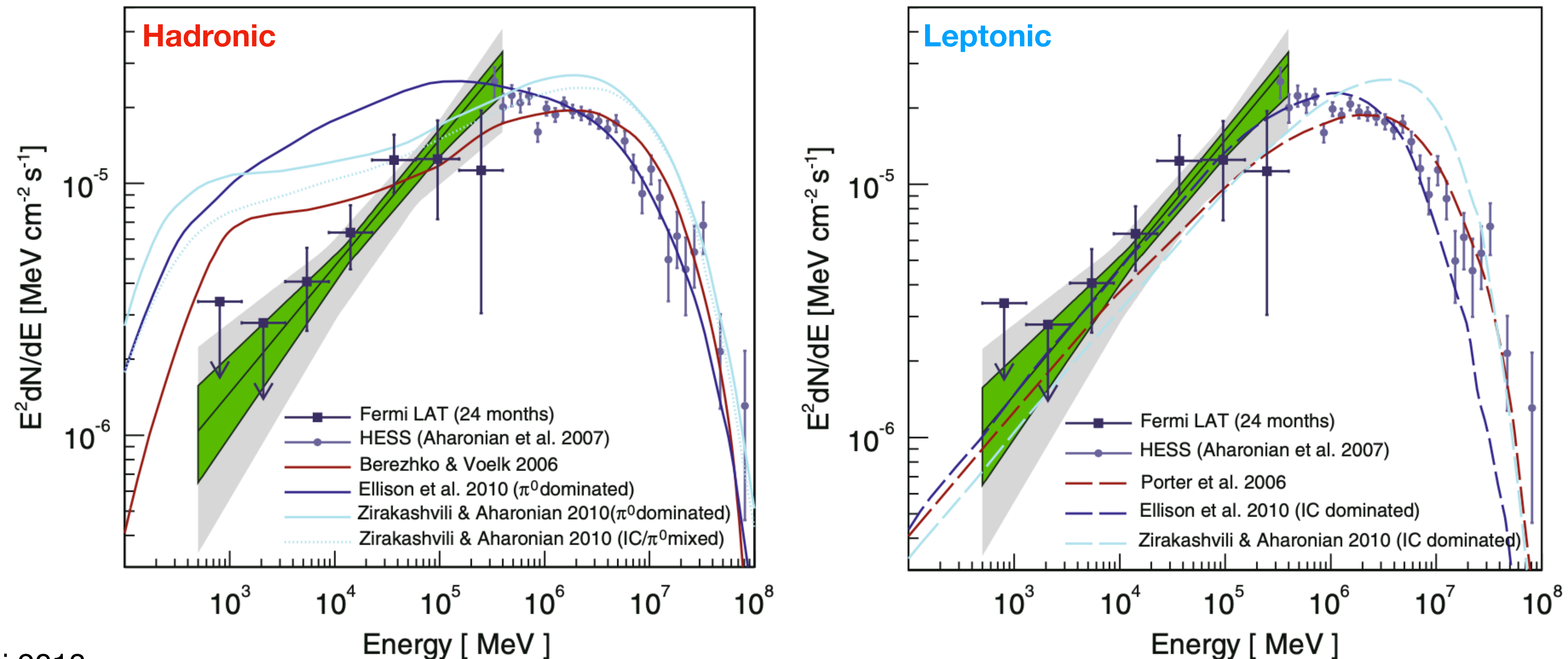


Fig from Fukui 2013

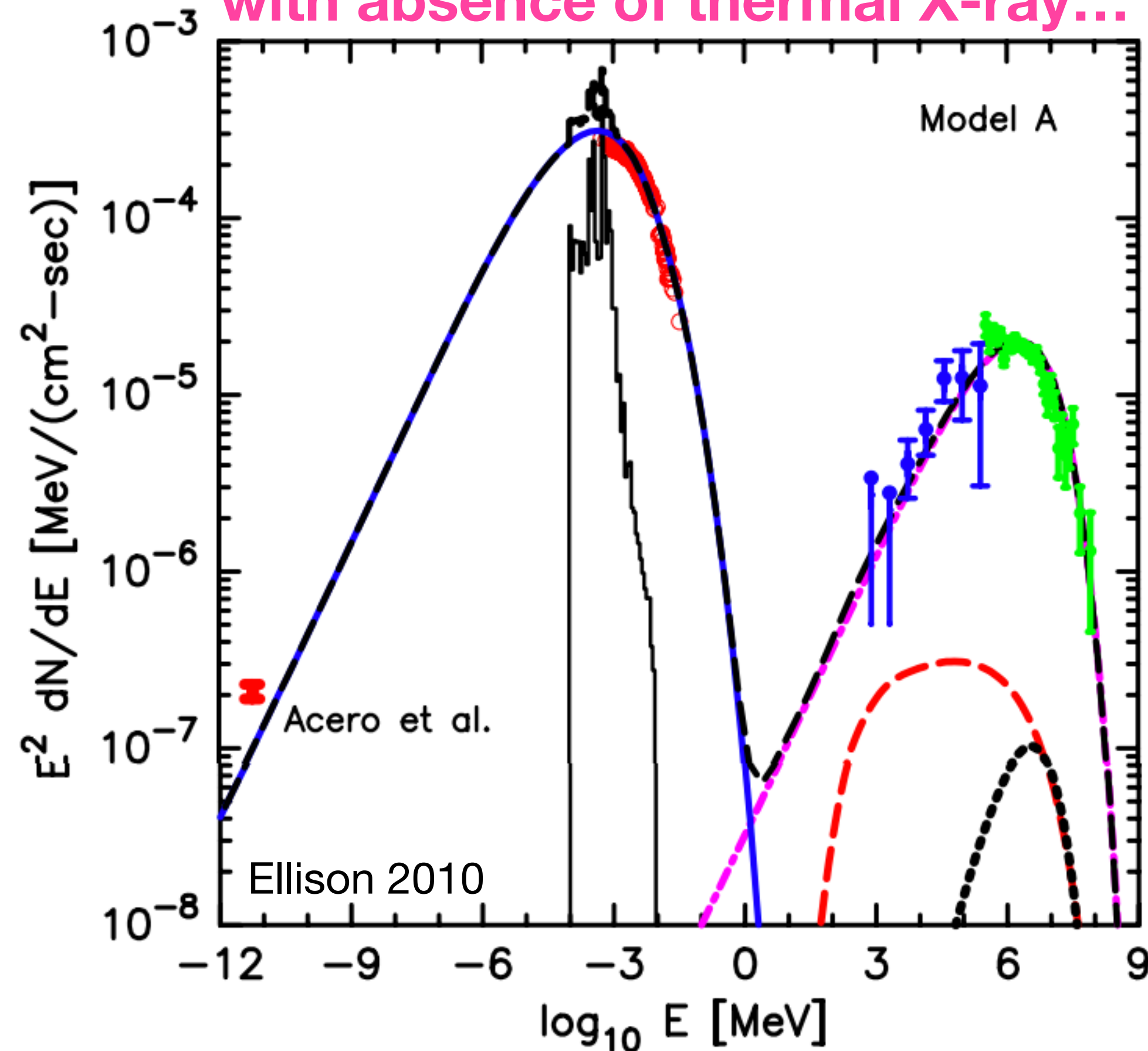
# Interpretation of gamma-ray emission

RX J1713.7-3946

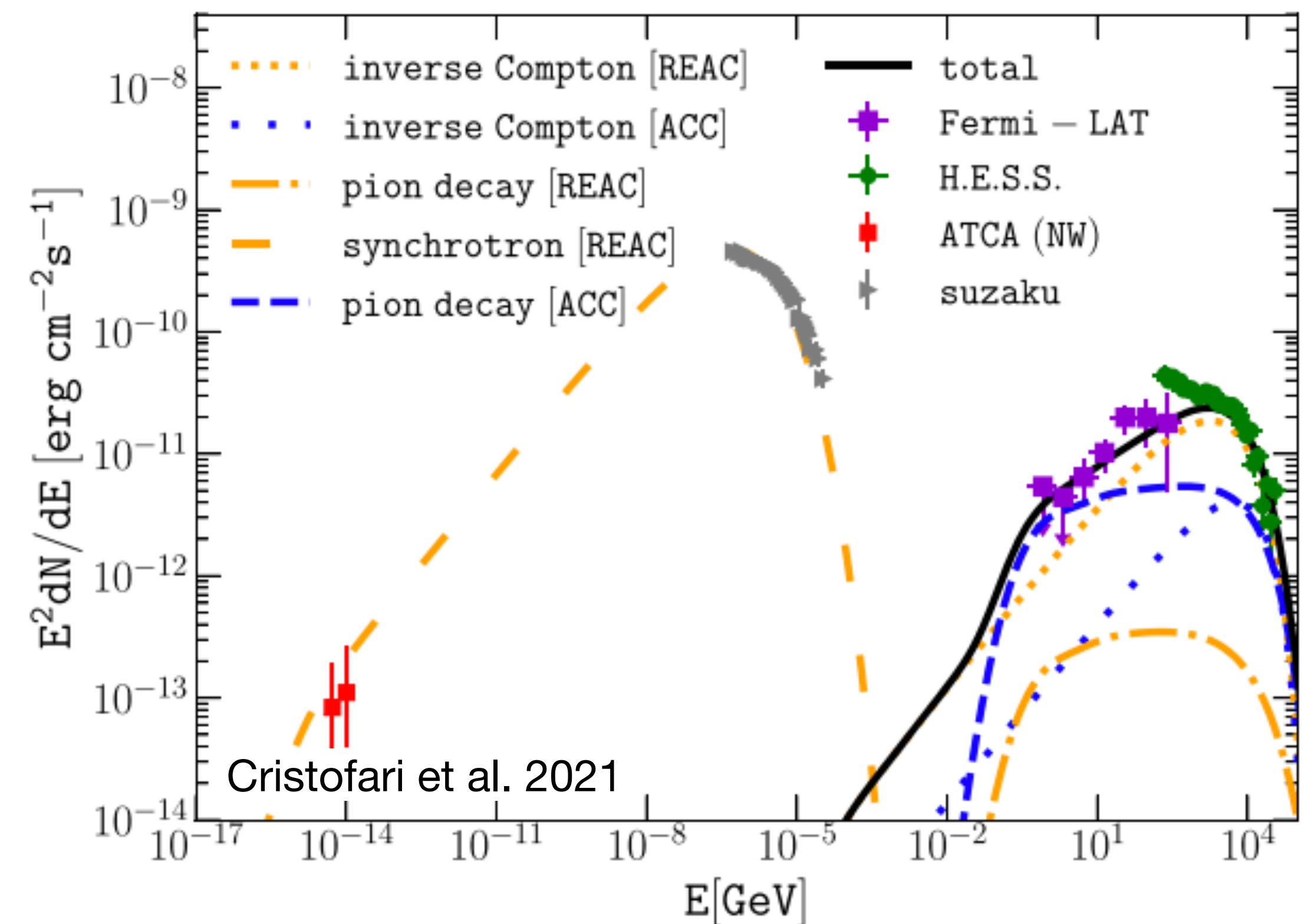
SNRs where the bump is not there...

...is a leptonic model the only possibility?

Leptonic emission is consistent with absence of thermal X-ray...



...but not easy to explain with one component



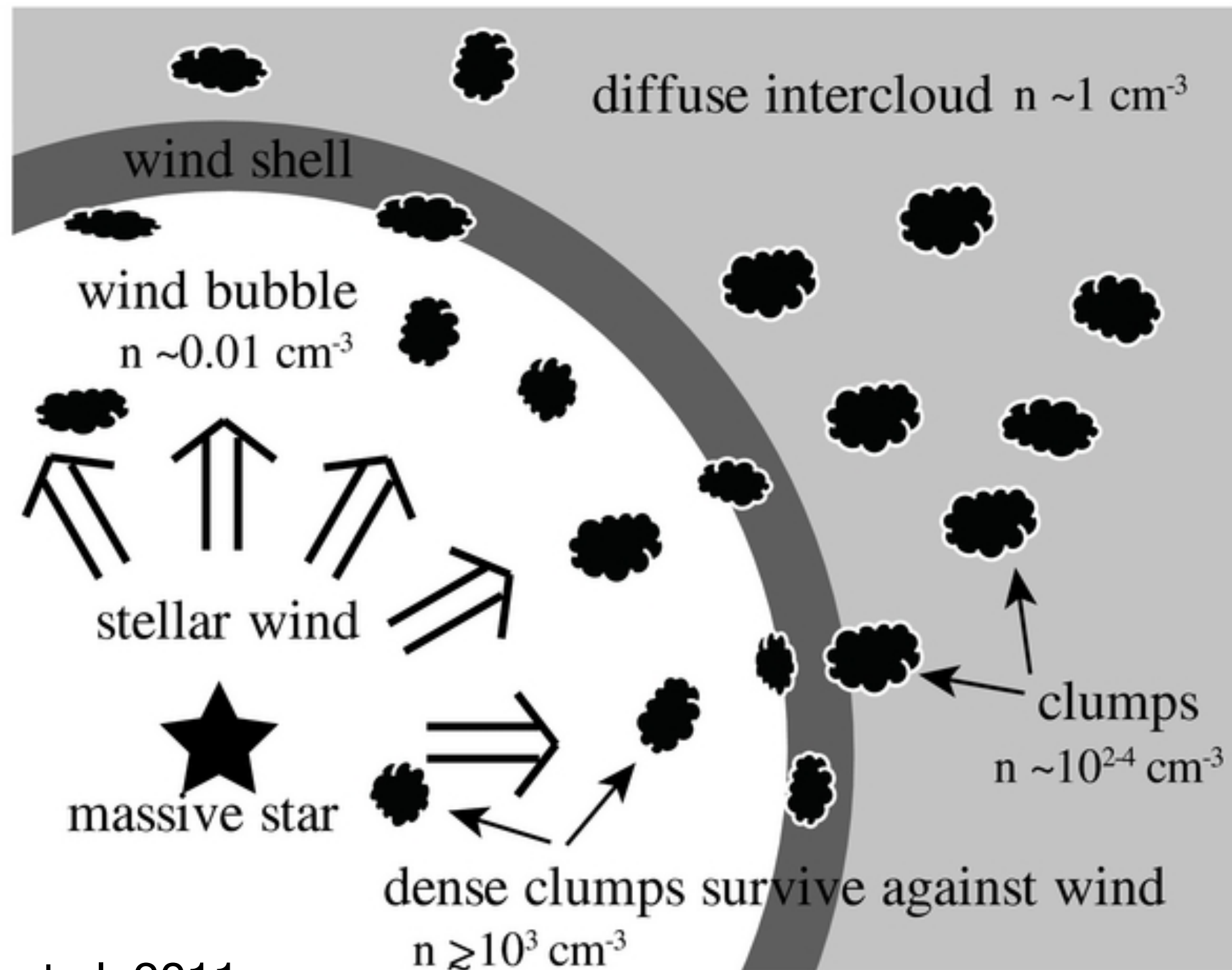


# Interpretation of gamma-ray emission

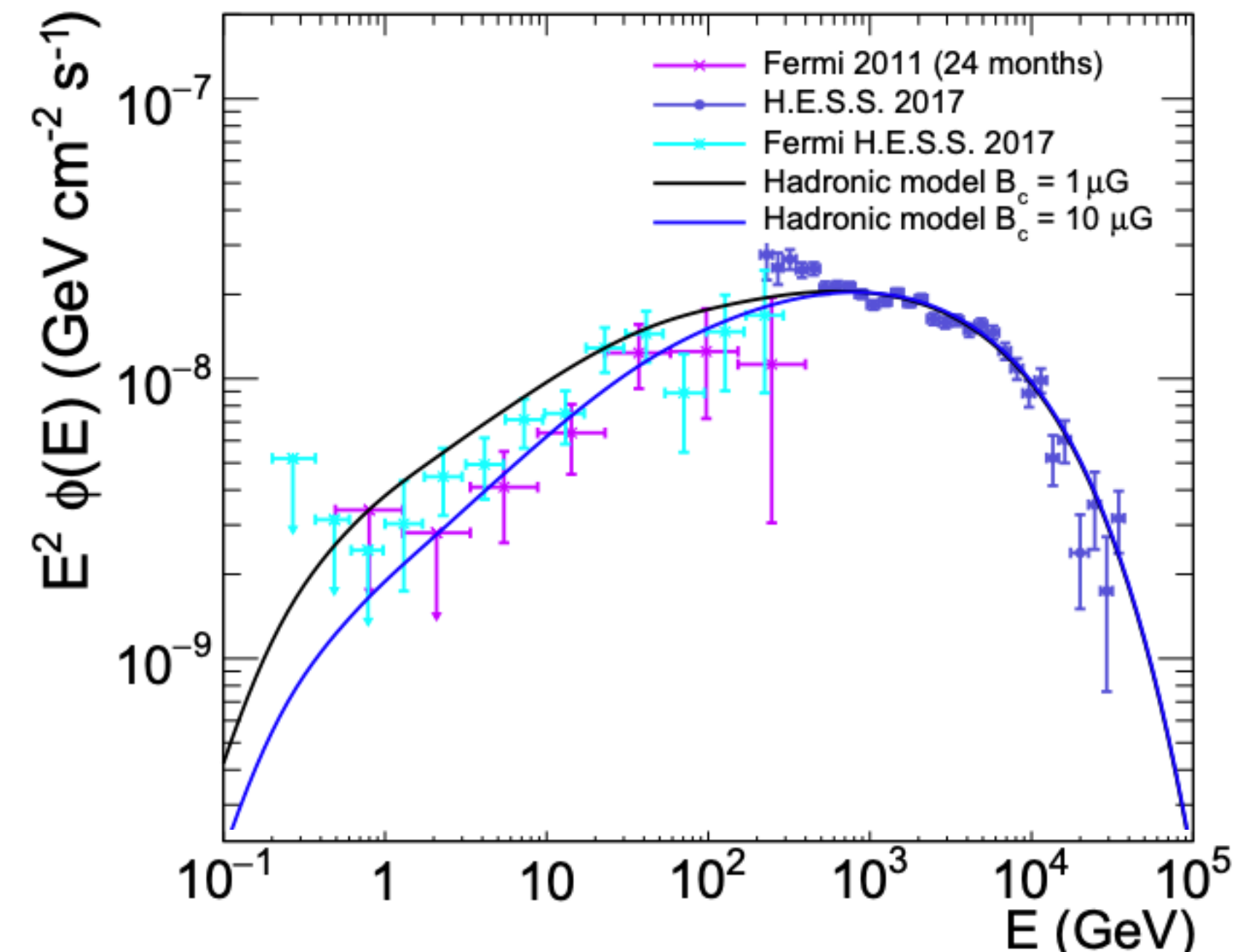
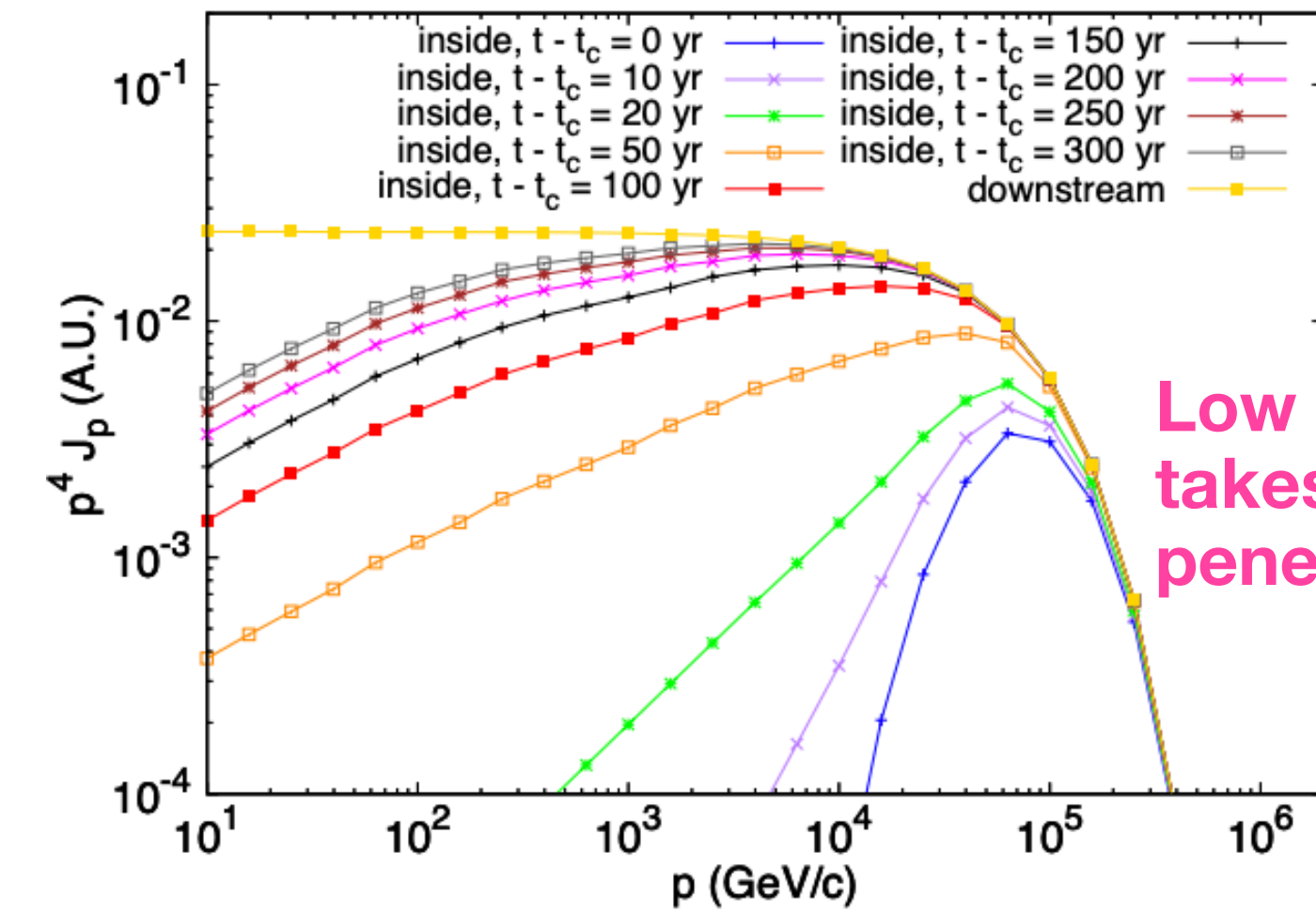
## SNRs where the bump is not there...

Celli et al. 2019 (see also Gabici & Aharonian 2013)

...an hadronic scenario is still possible: hard spectrum derives from propagation in a clumpy medium



Inoue et al. 2011



# Interpretation of gamma-ray emission

## SNRs where the bump is not there...

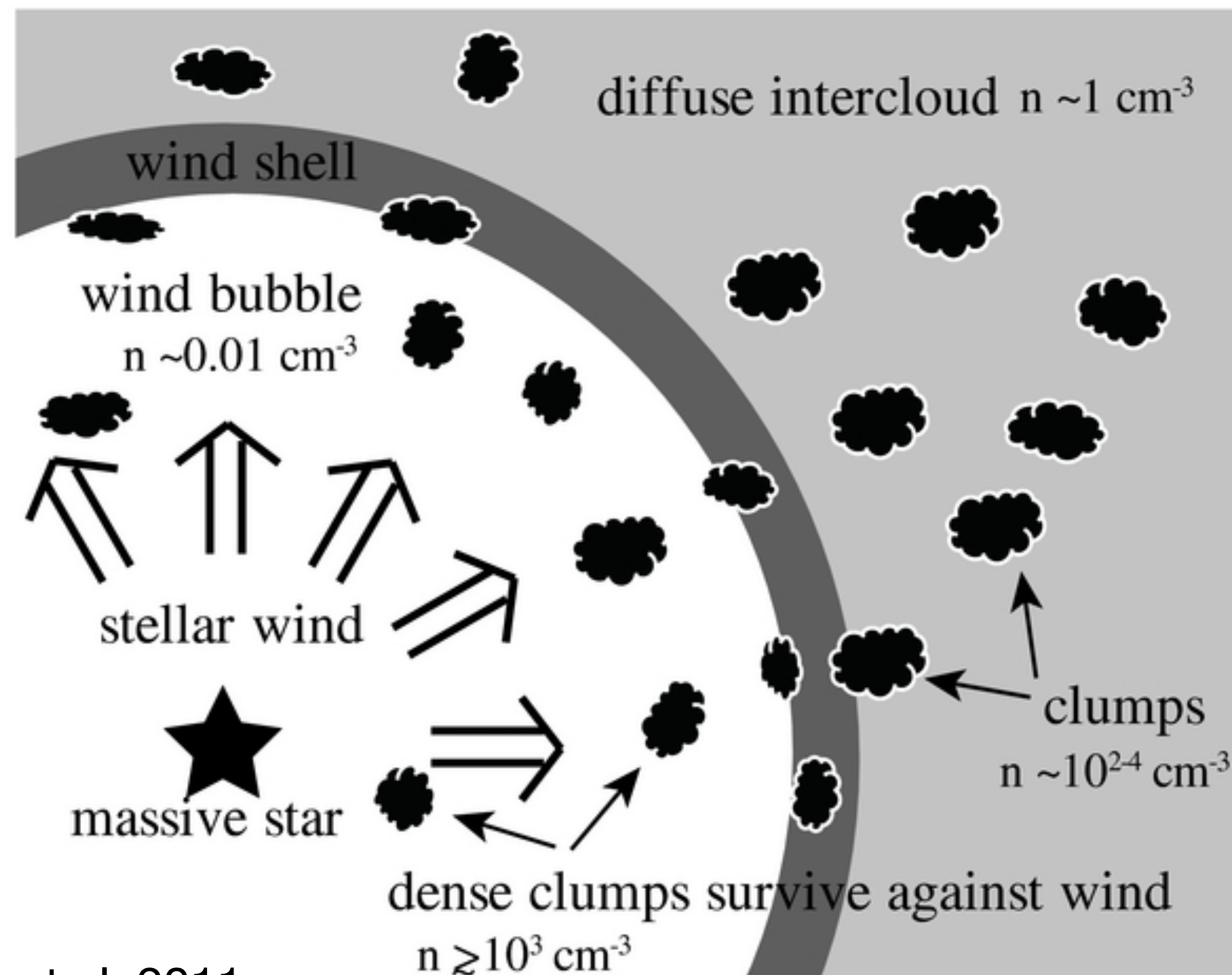
Celli et al. 2019 (see also Gabici & Aharonian 2013)

...an hadronic scenario is still possible: hard spectrum derives from propagation in a clumpy medium...

...which observables would be related to this scenario?

➡ Spatial fluctuations on the scale of clumps (~arcsec)

➡ Would produce neutrinos



Inoue et al. 2011



# Interpretation of gamma-ray emission

## SNRs where the bump is not there...

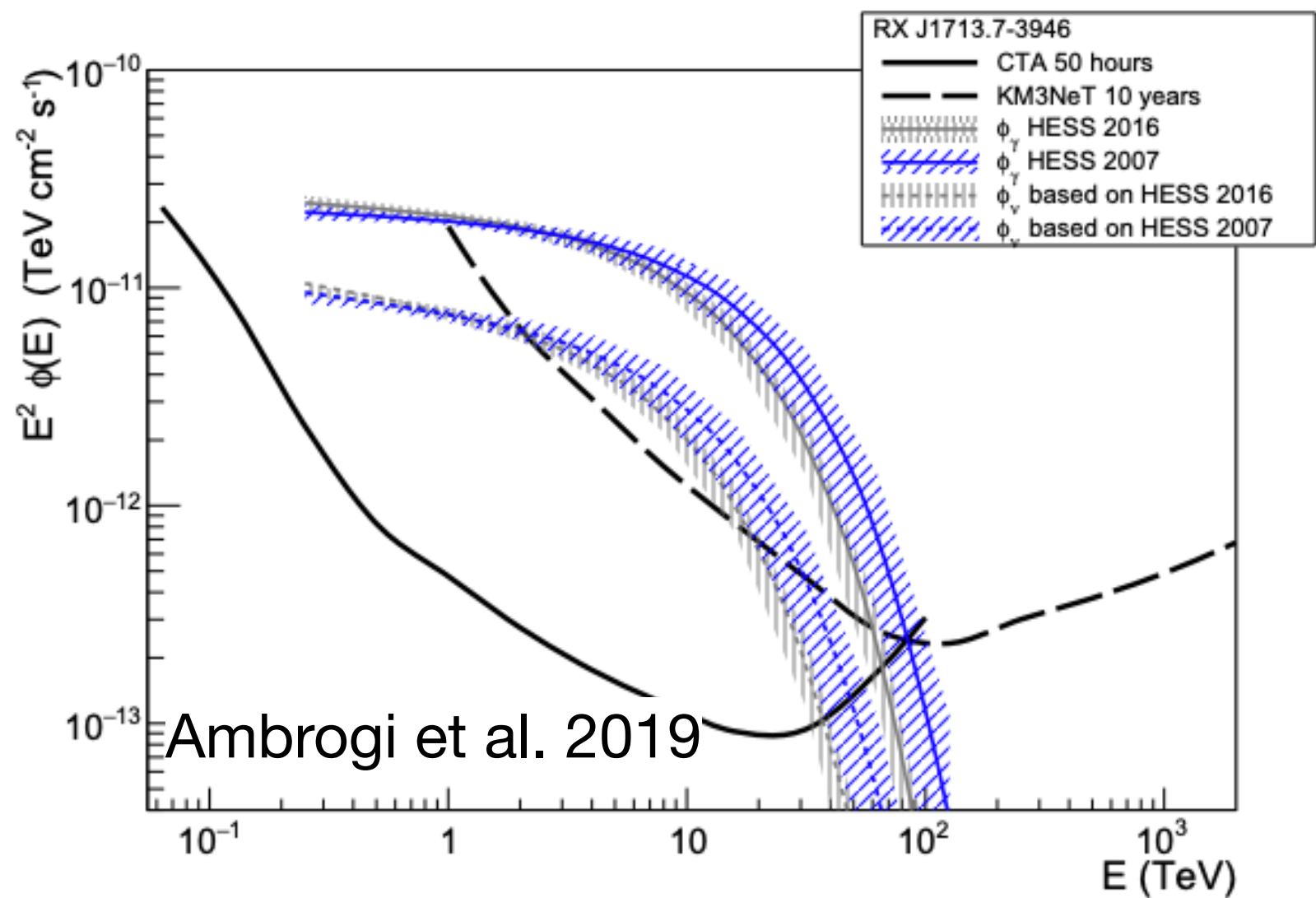
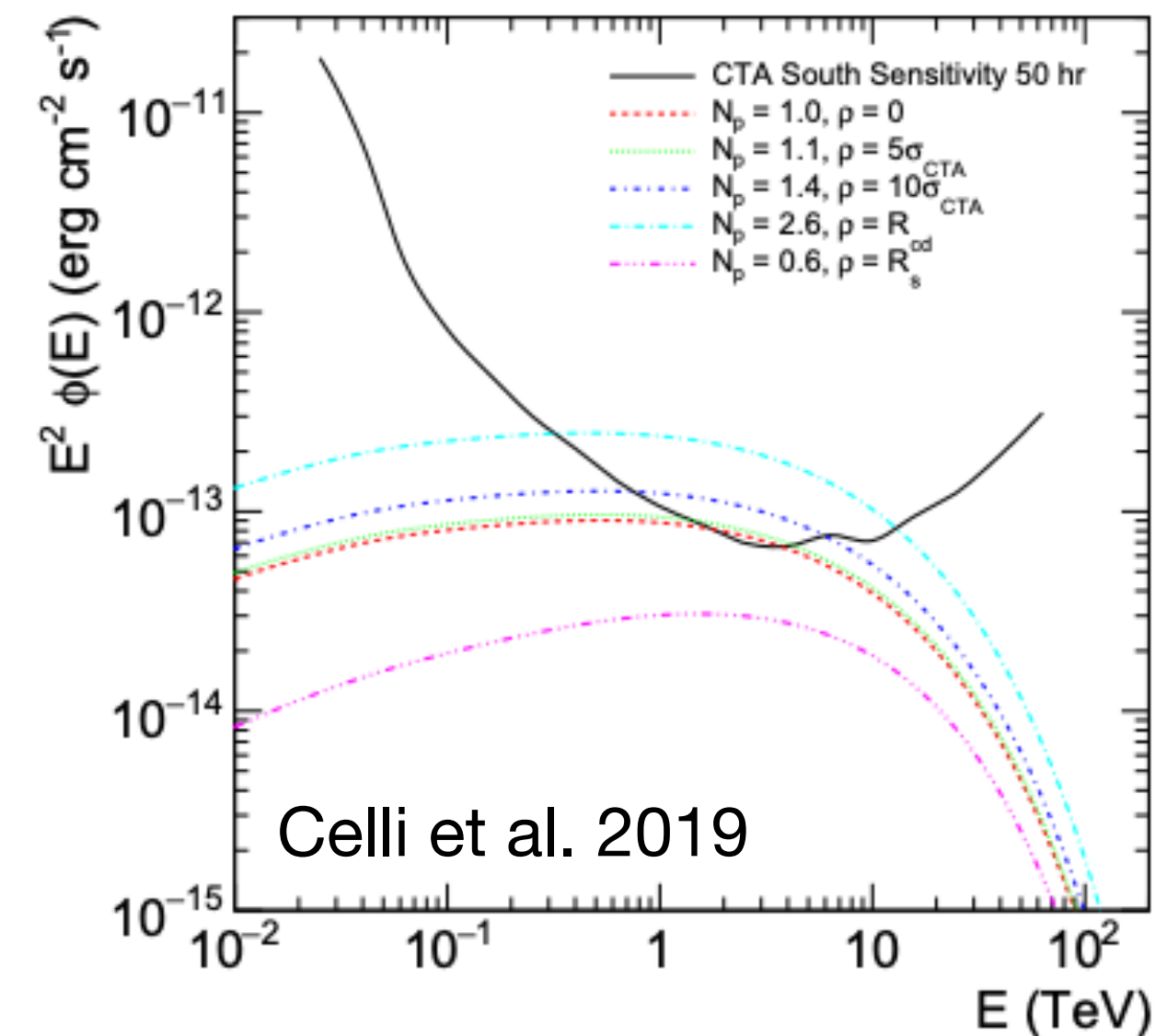
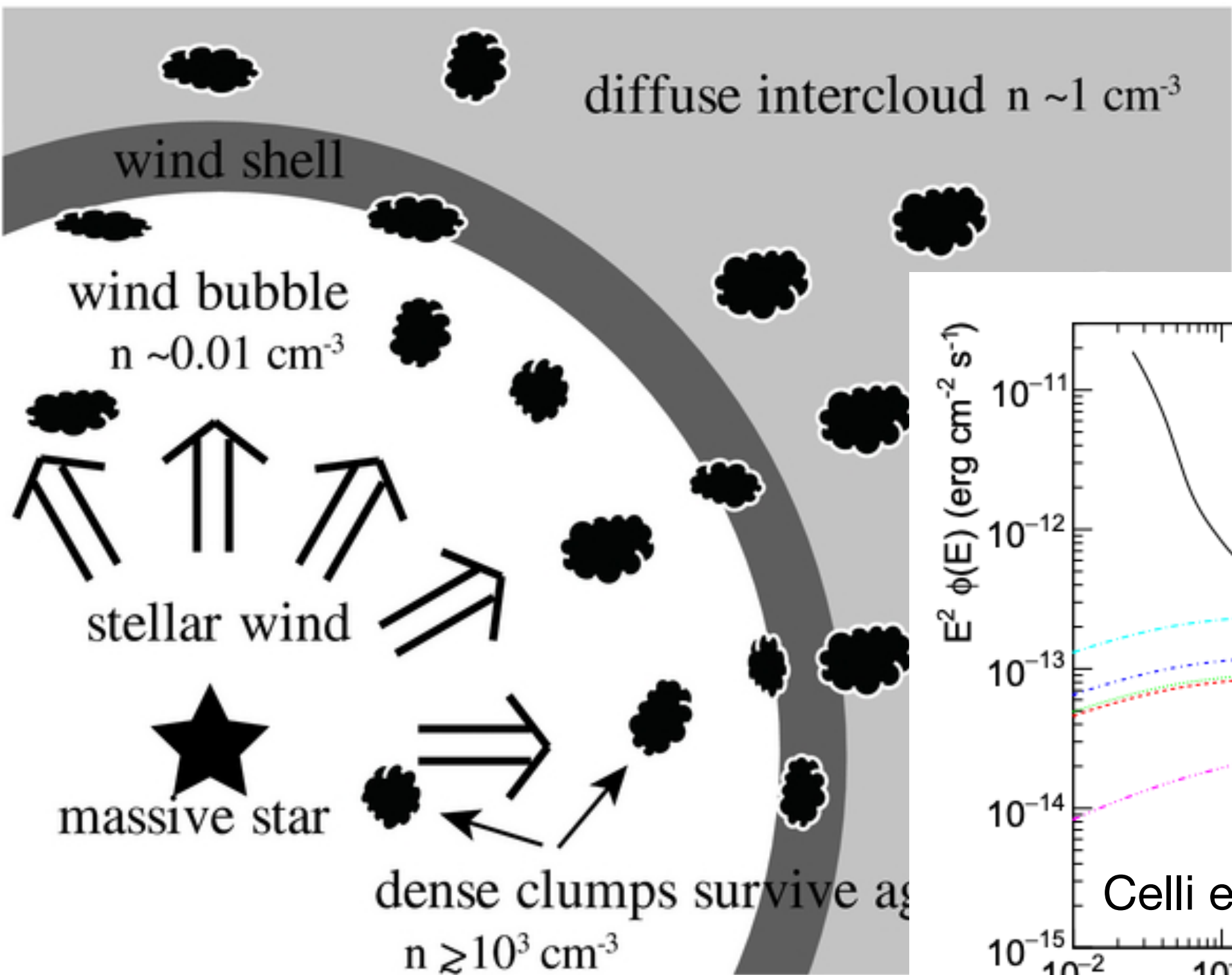
Celli et al. 2019 (see also Gabici & Aharonian 2013)

...an hadronic scenario is still possible: hard spectrum derives from propagation in a clumpy medium...

...which observables would be related to this scenario?

➡ Spatial fluctuations on the scale of clumps (~arcsec) **A challenge for CTAO**

➡ Would produce neutrinos **A challenge for KM3NeT**

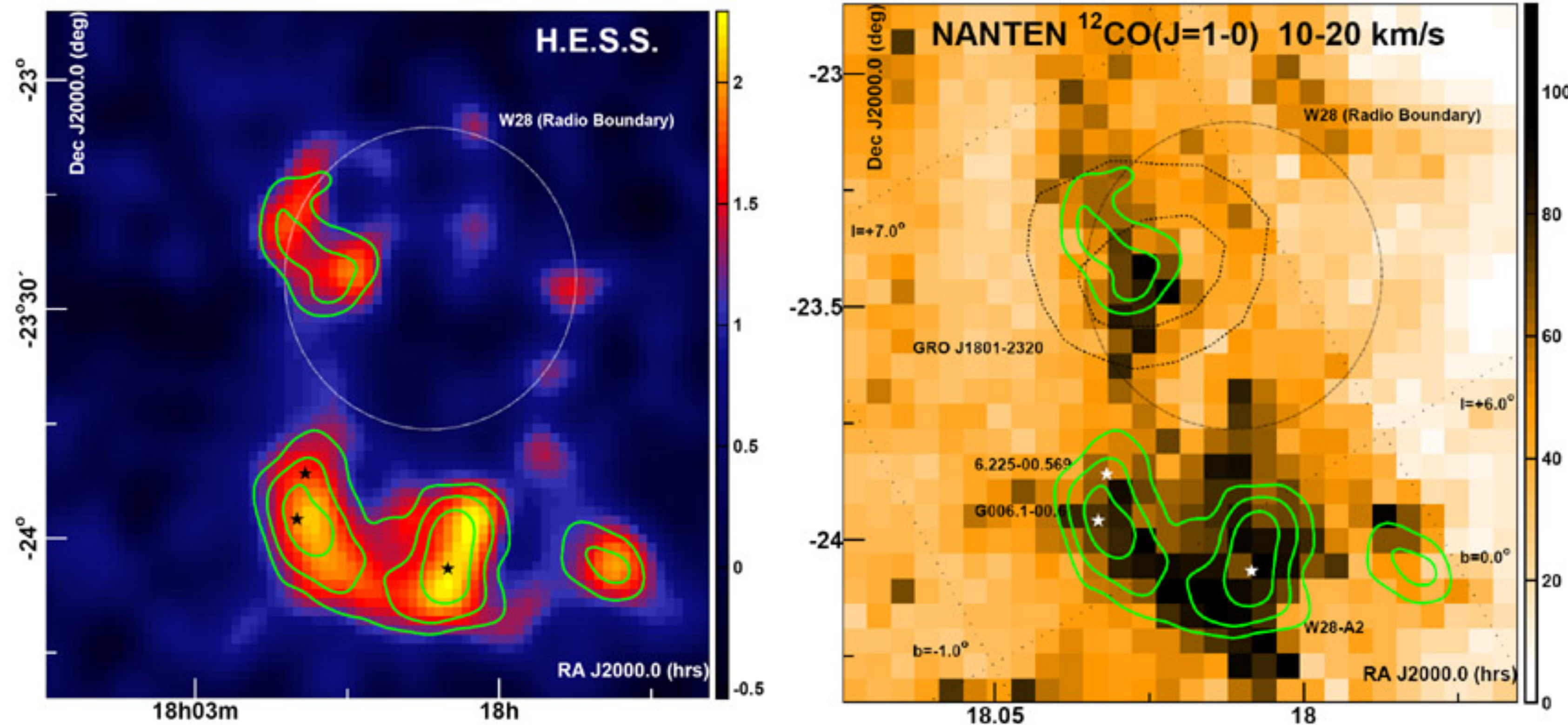


**Hadronic emission correlates with gas**



# Correlation with gas structure

TeV emission correlates with gas near W28

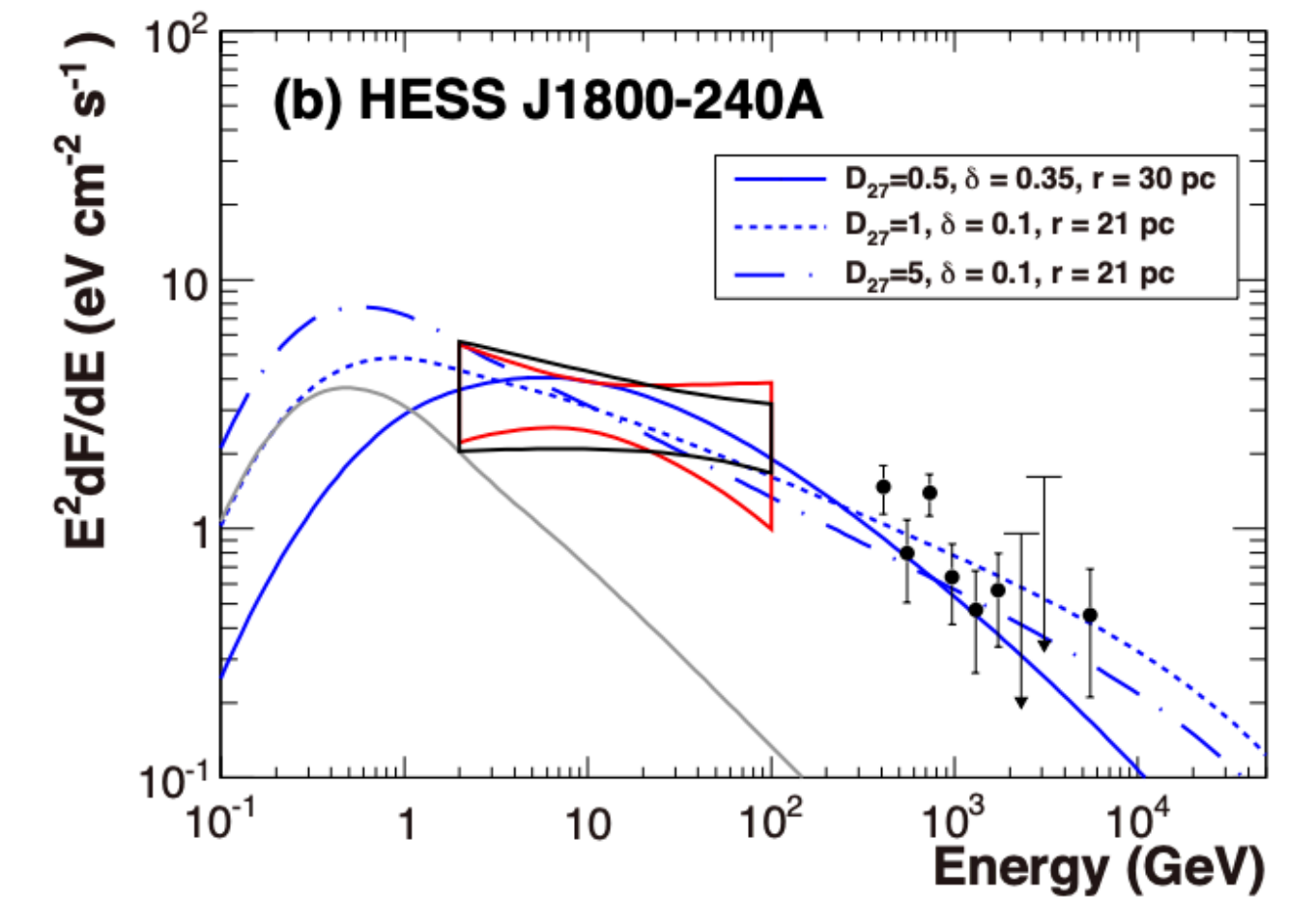
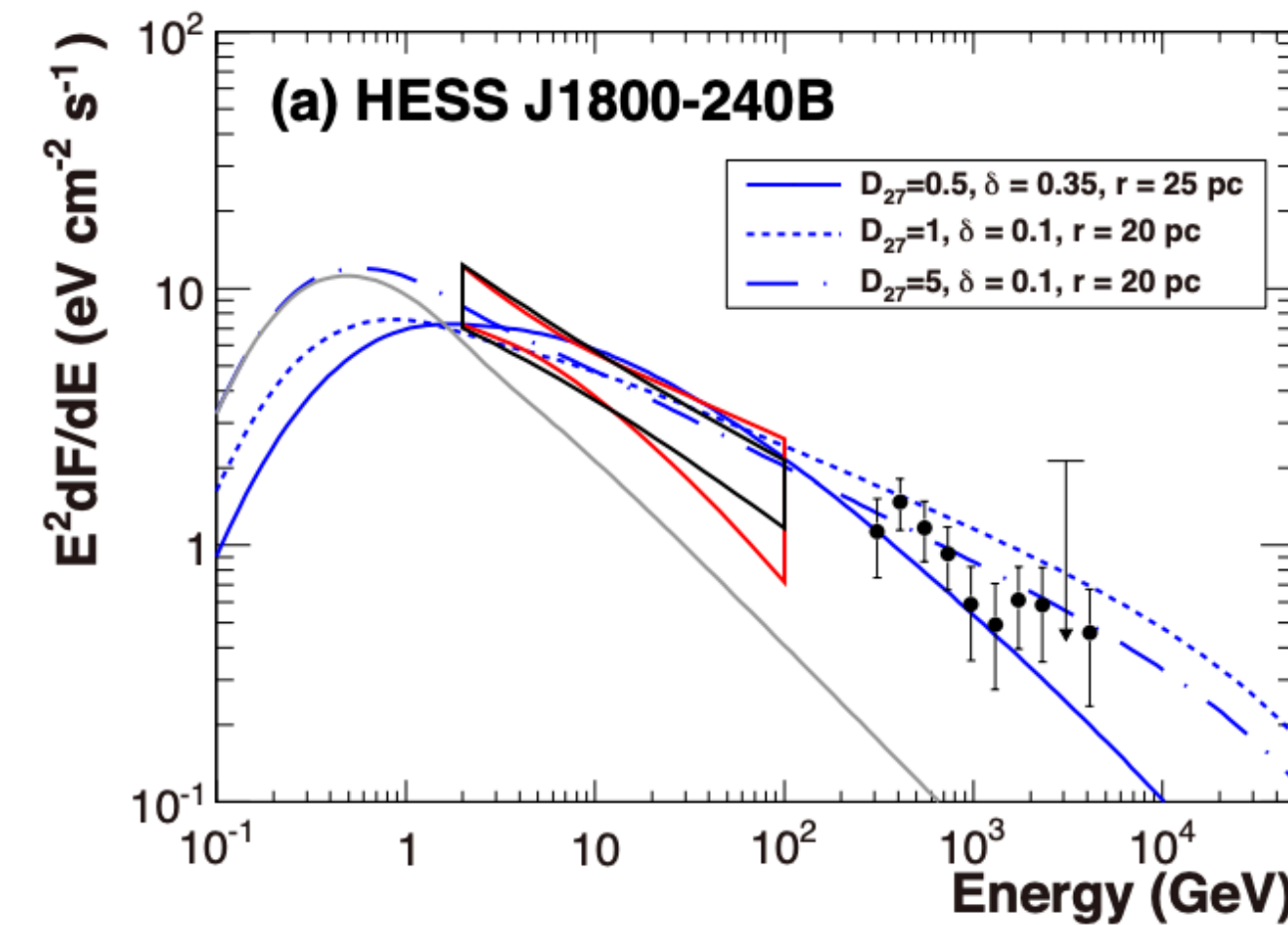
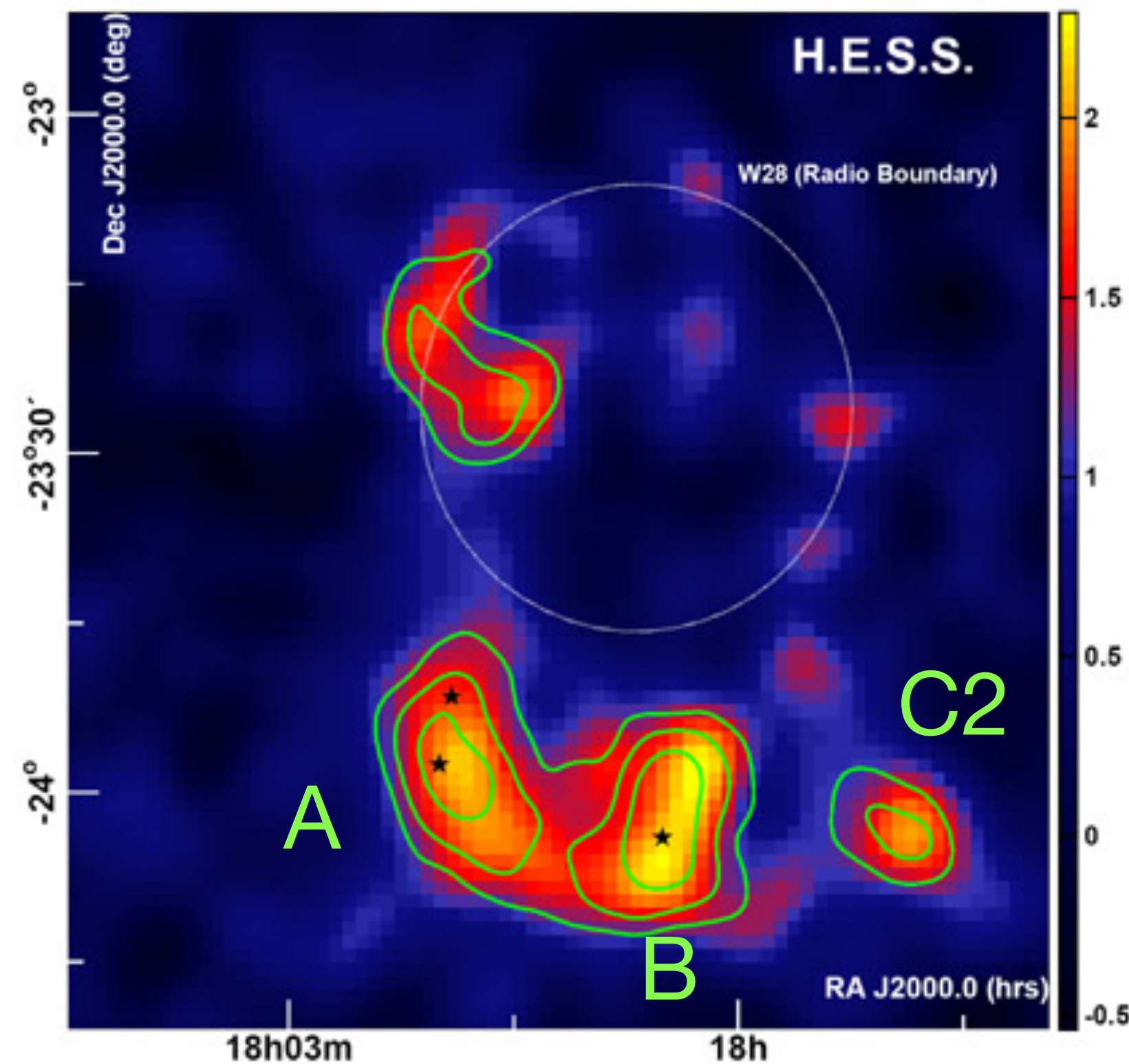




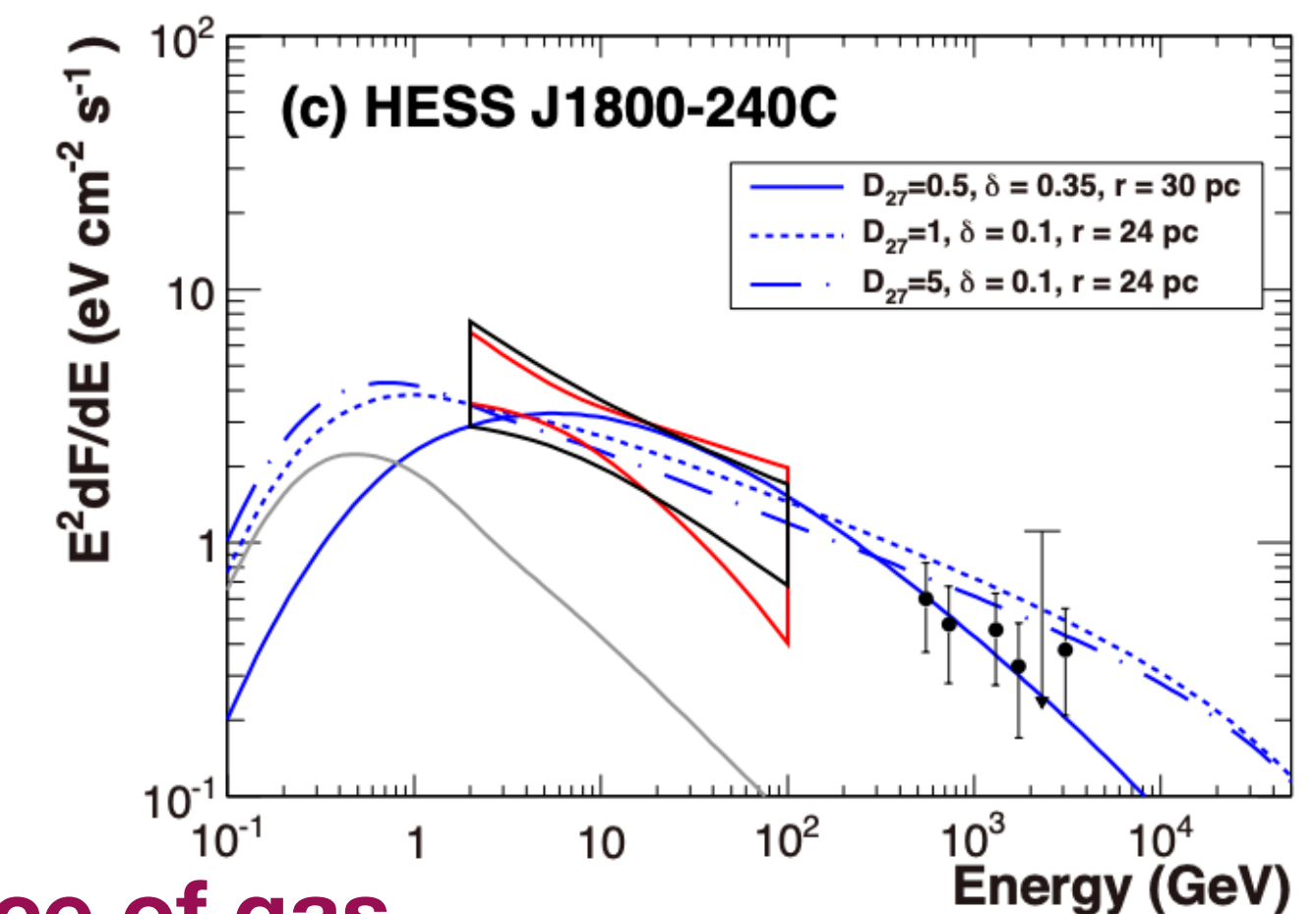
# Correlation with gas structure

## TeV emission correlates with gas near W28

Hanabata et al. 2014



Particles leave the remnant, propagate in the surrounding medium interacting with nearby clouds

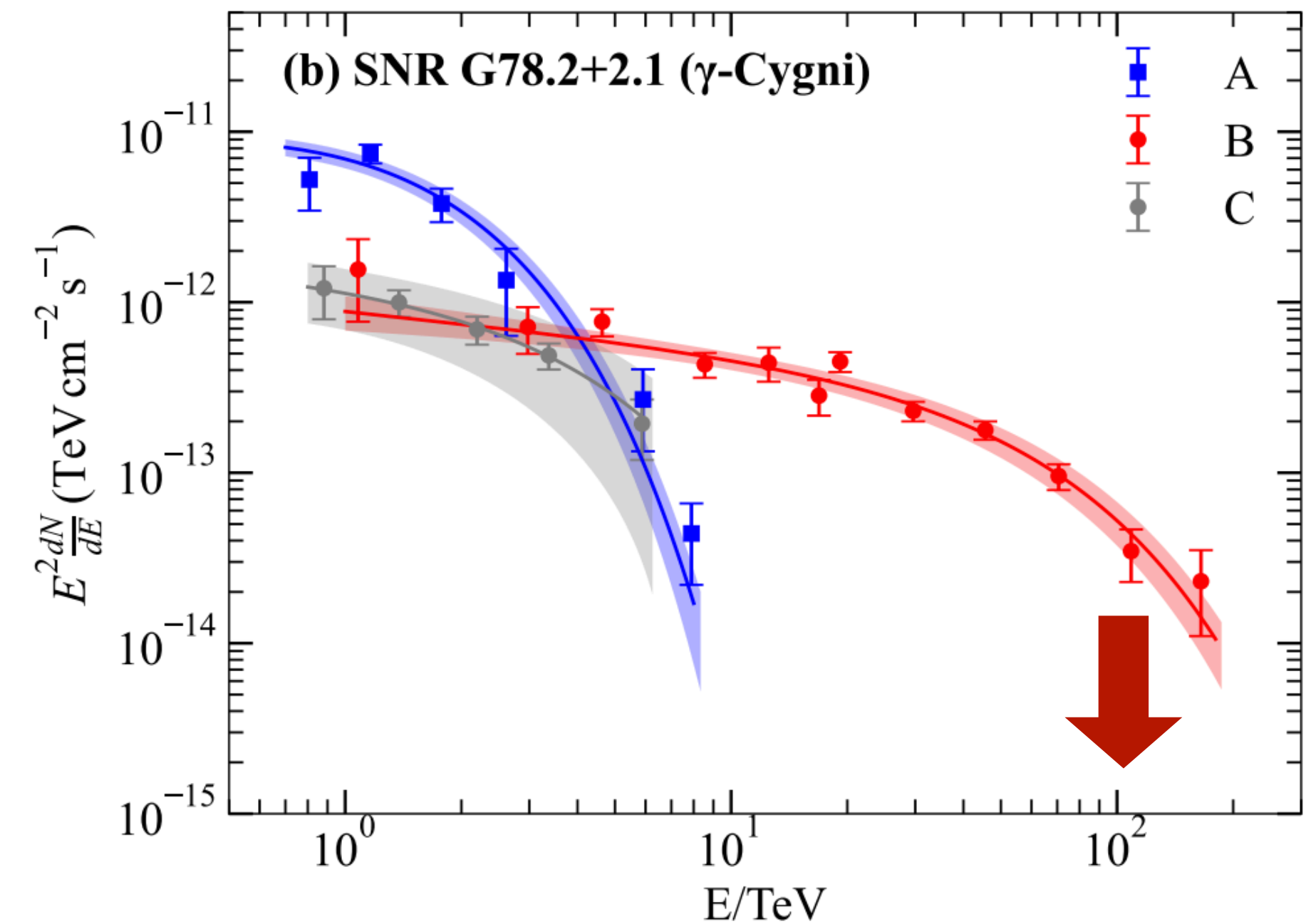
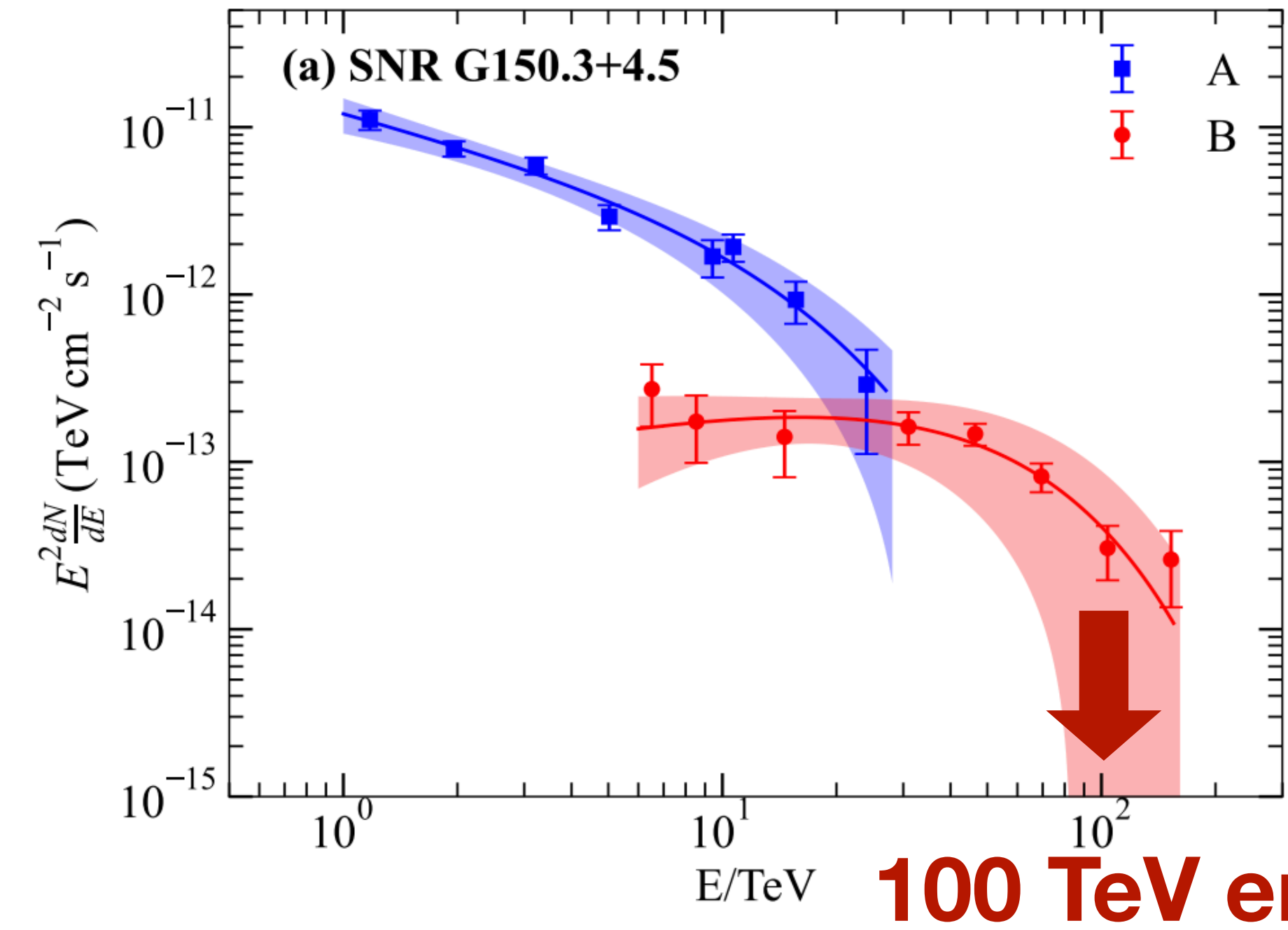
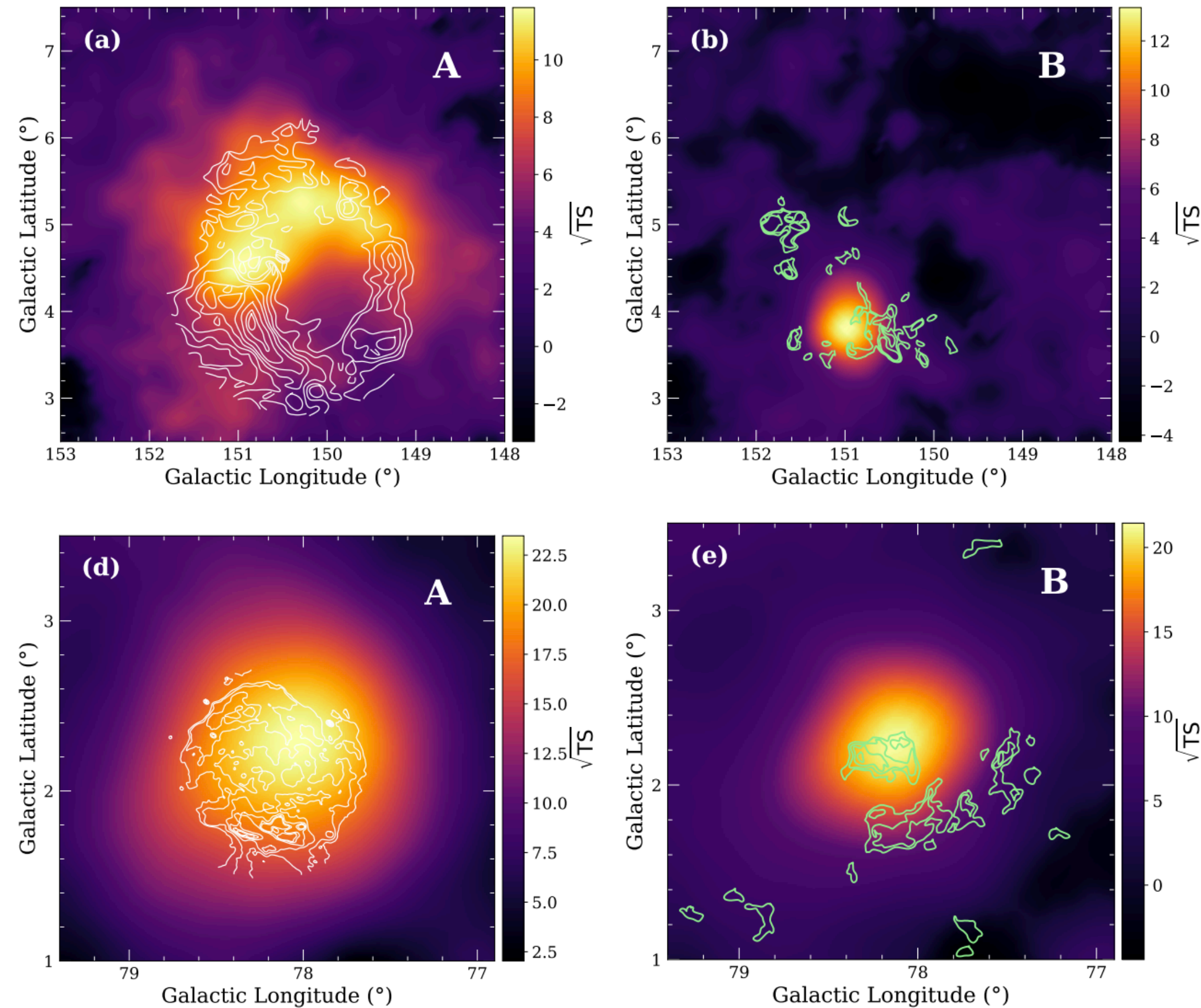


Energy-dependent effect  
Detection subject to the presence of gas



# Correlation with gas

## TeV emission near SNR G140.3+4.5 and Gamma Cygni



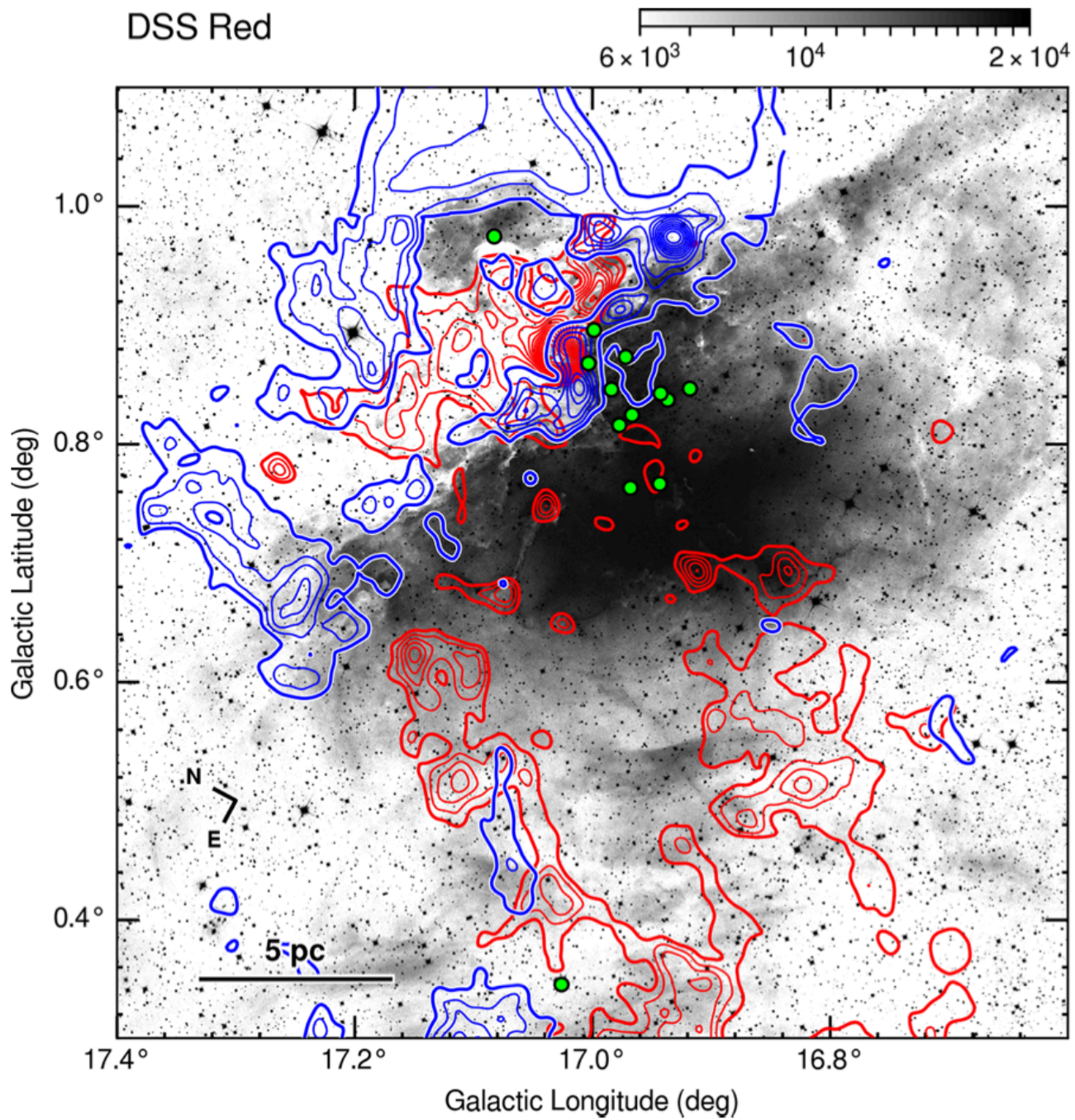
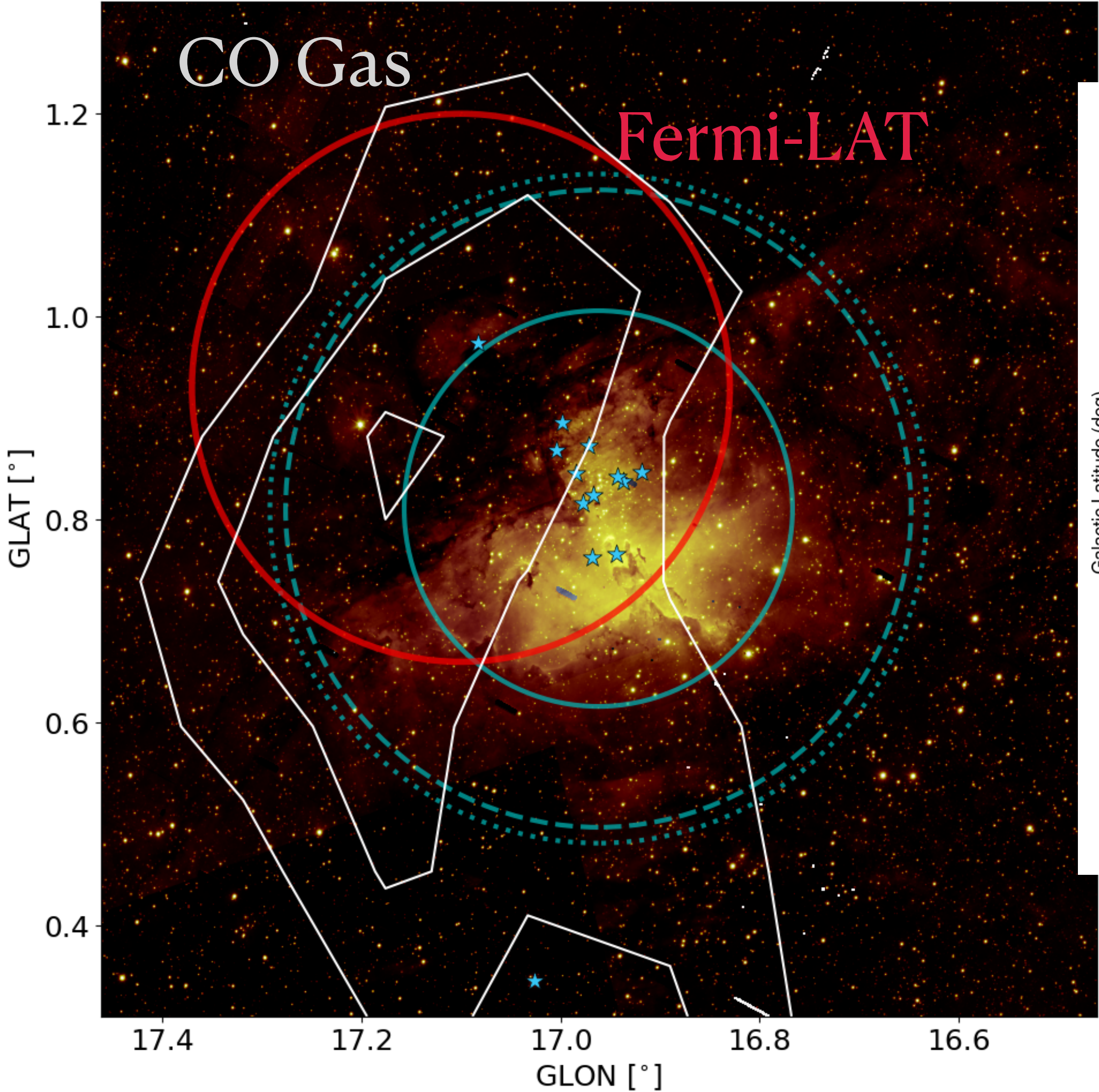


# Correlation with gas

Not only SNRs...

...Hadronic emission unveiled in  
correspondence of a gas cloud near  
NGC6611 a young massive star cluster

Peron et al. 2025



[Nishimura et al. 2021]

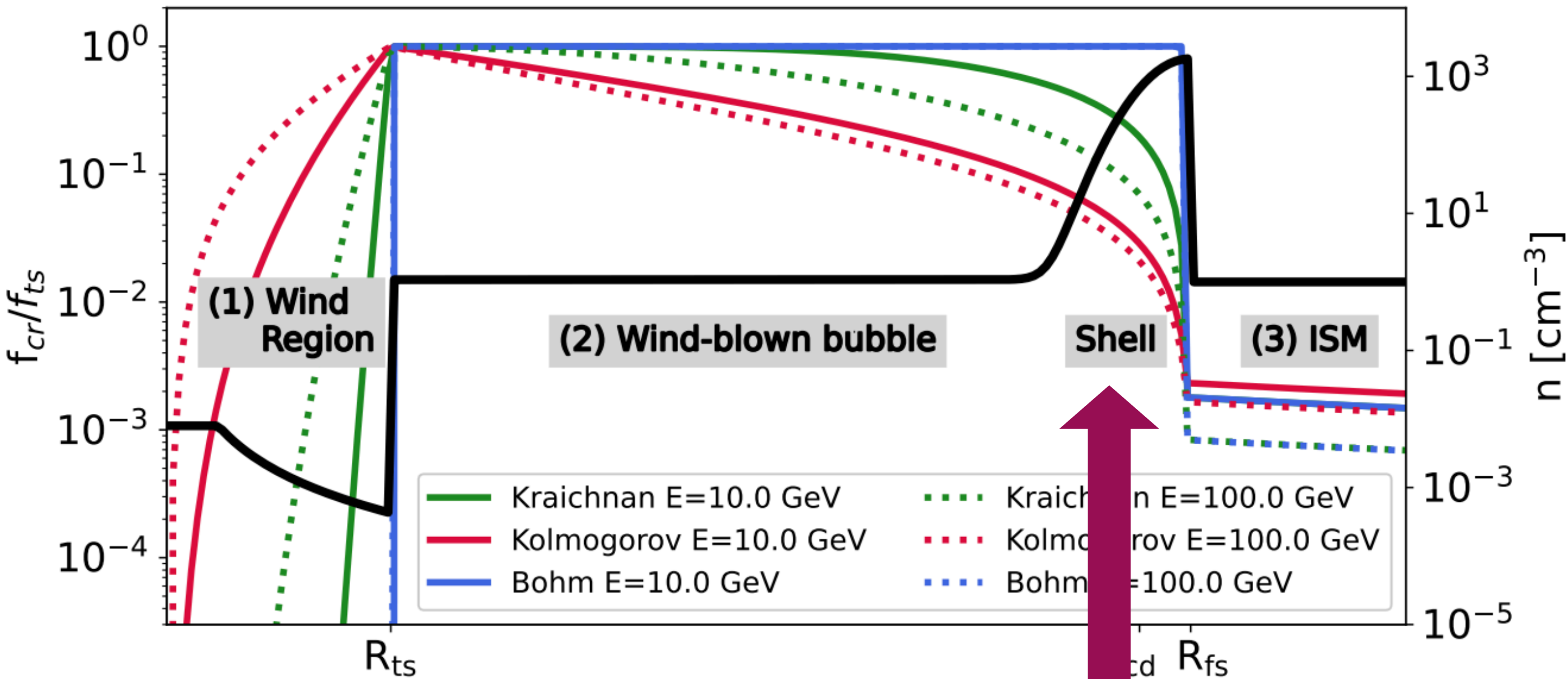
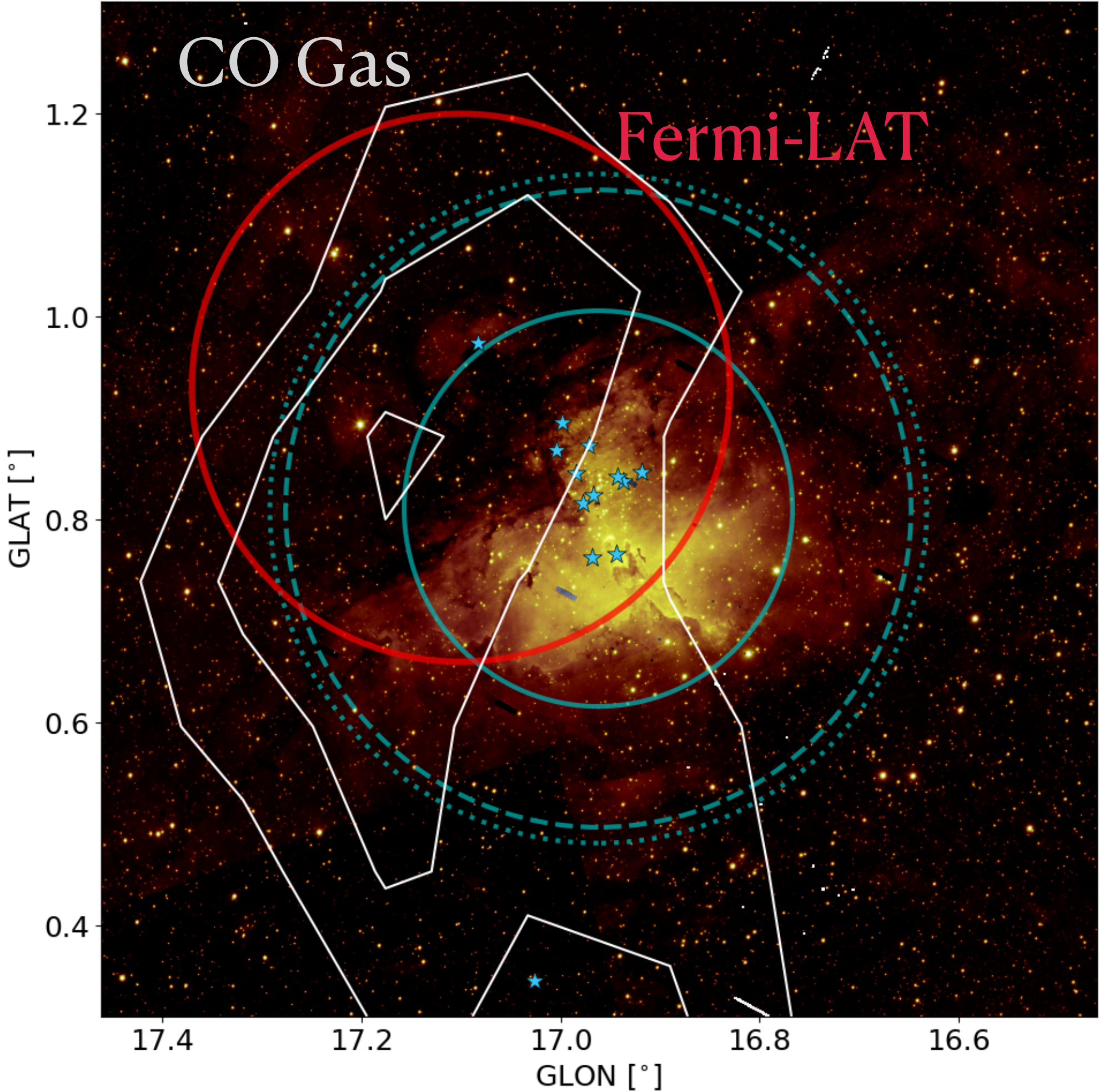


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Dense gas is found at  
the edges of SC bubbles

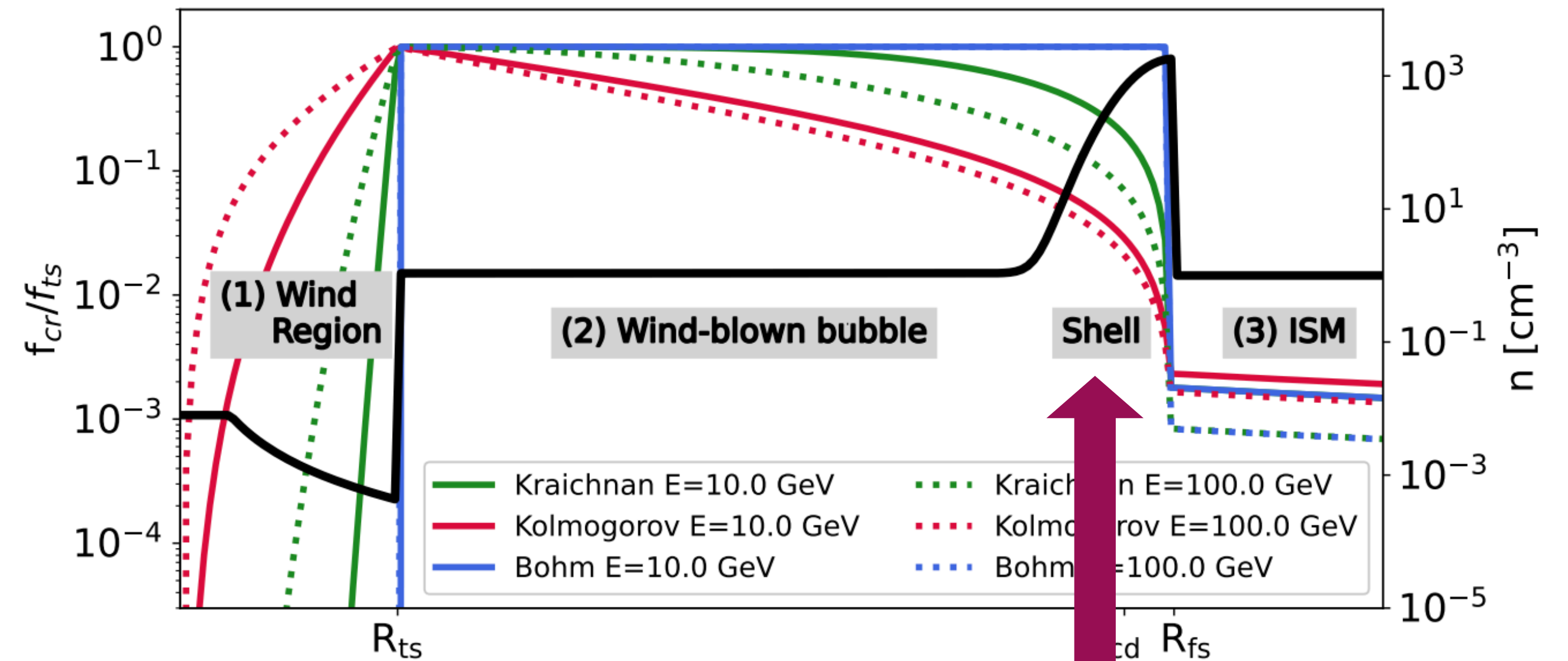
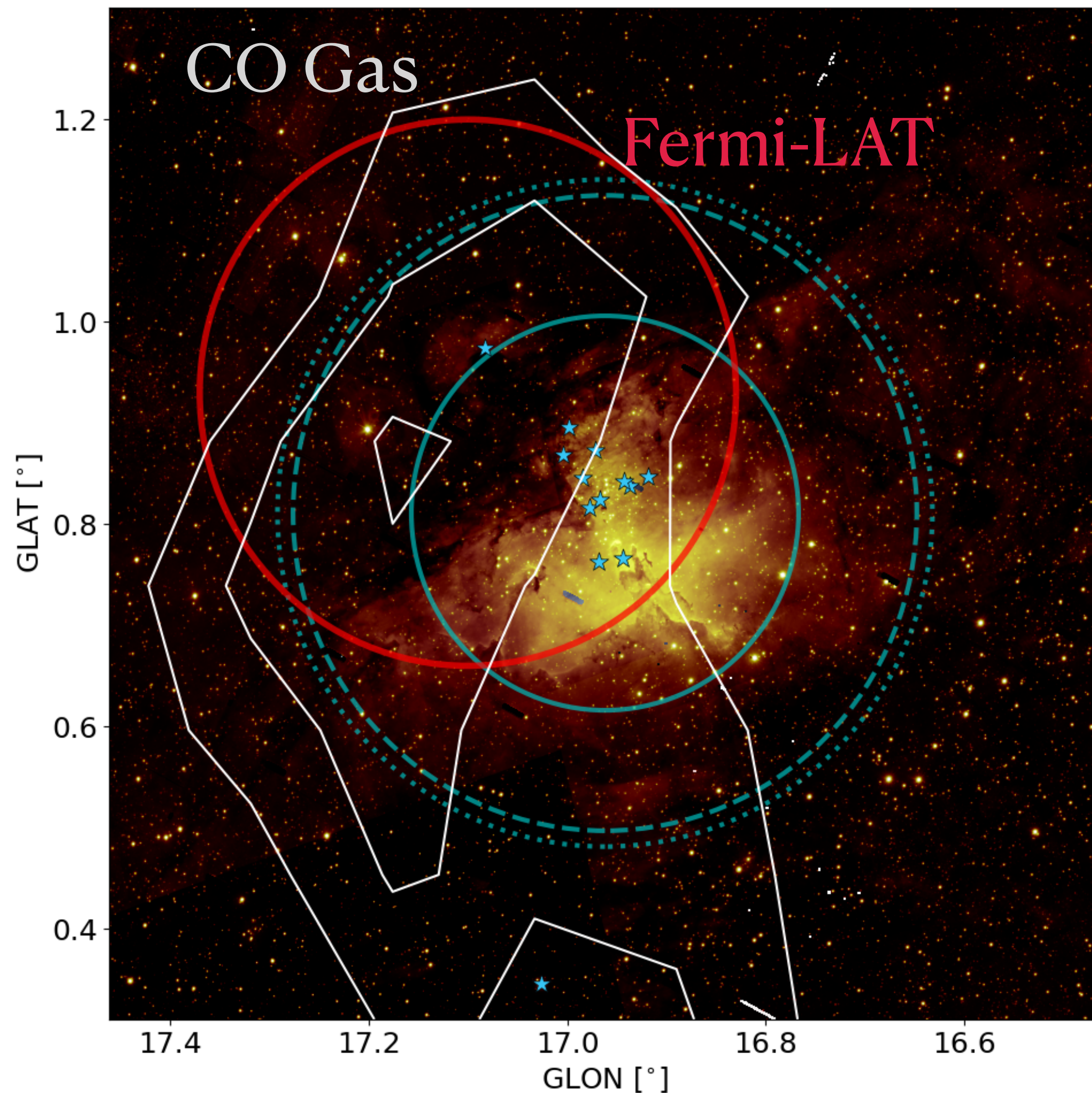


# Correlation with gas

Not only SNRs...

...Hadronic emission unveiled in  
correspondence of a gas cloud near  
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Peron et al. 2025



Dense gas is found at  
the edges of SC bubbles

Proves the acceleration of hadrons,  
estimated to be 1-4% of  $L_w$



# Correlation with gas

Not only SNRs...

...not only NGC6611..

... Gamma-ray sources are strongly correlated with Galactic HII region <-> embedded clusters

Fig adapted from A. Adamo



**EARLY STAGE**  
Dense gas collapsing  
10-20 K



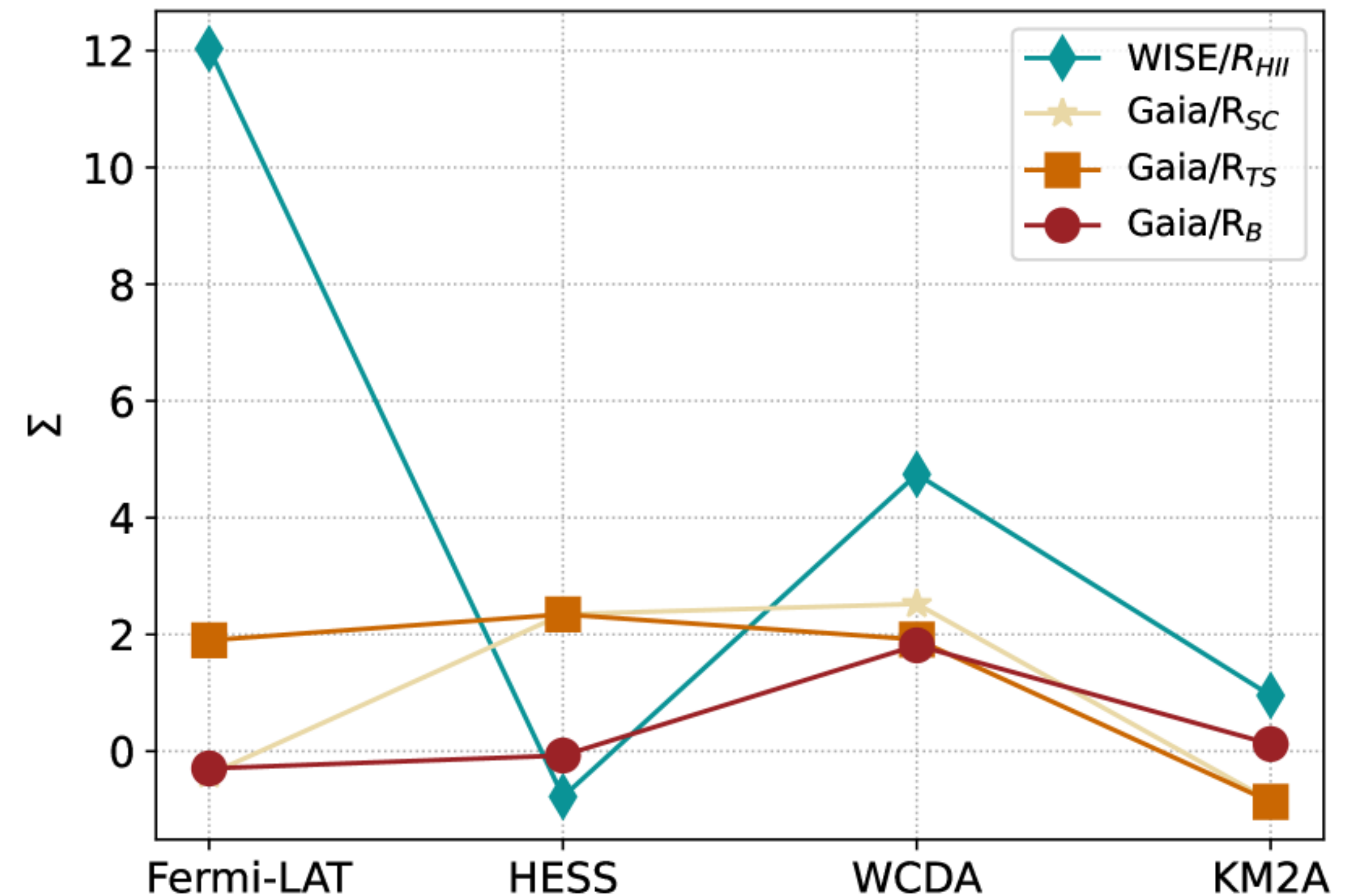
**EMBEDDED PHASE**  
Dense gas newly born stars,  
feedback HII Region  
 $T \sim 10^4$  Density  $10^2$ - $10^3$   
 $\text{cm}^{-3}$



**EXPOSED PHASE**

Young stellar clusters are naturally surrounded by gas -> ideal to test hadronic interactions

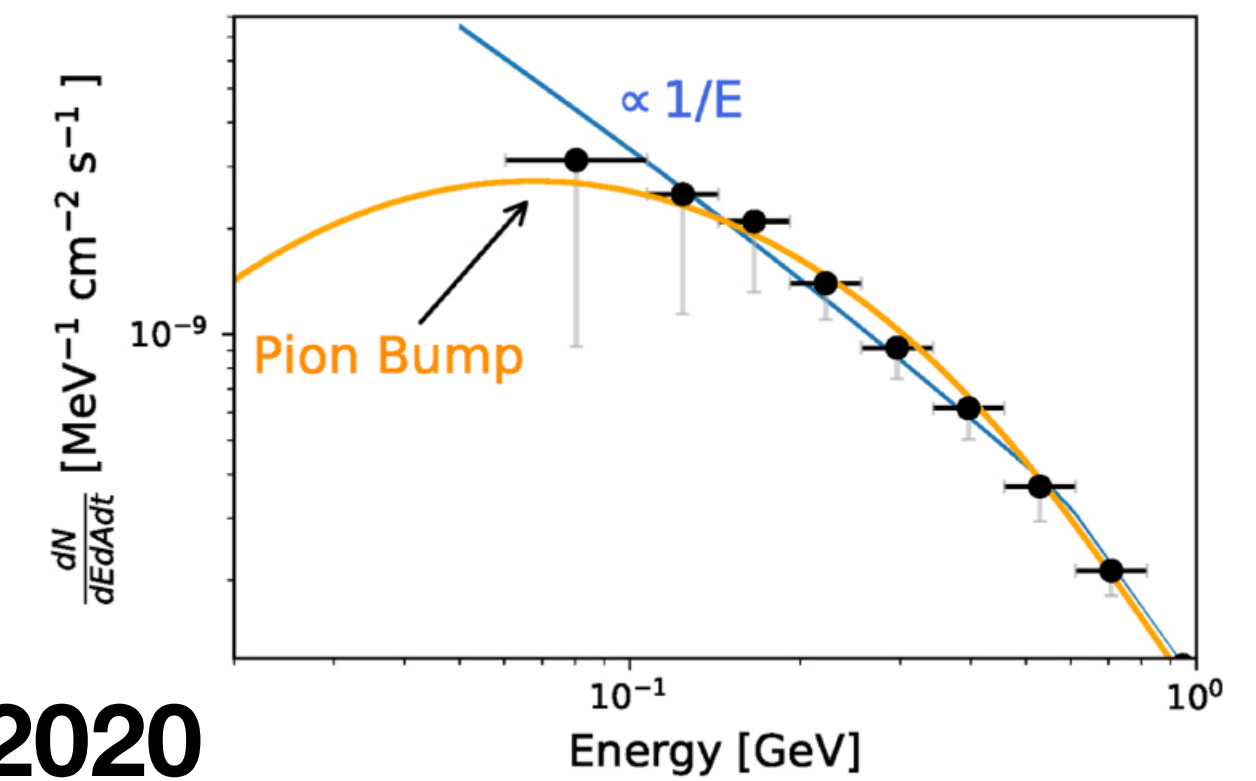
Peron et al. 2024





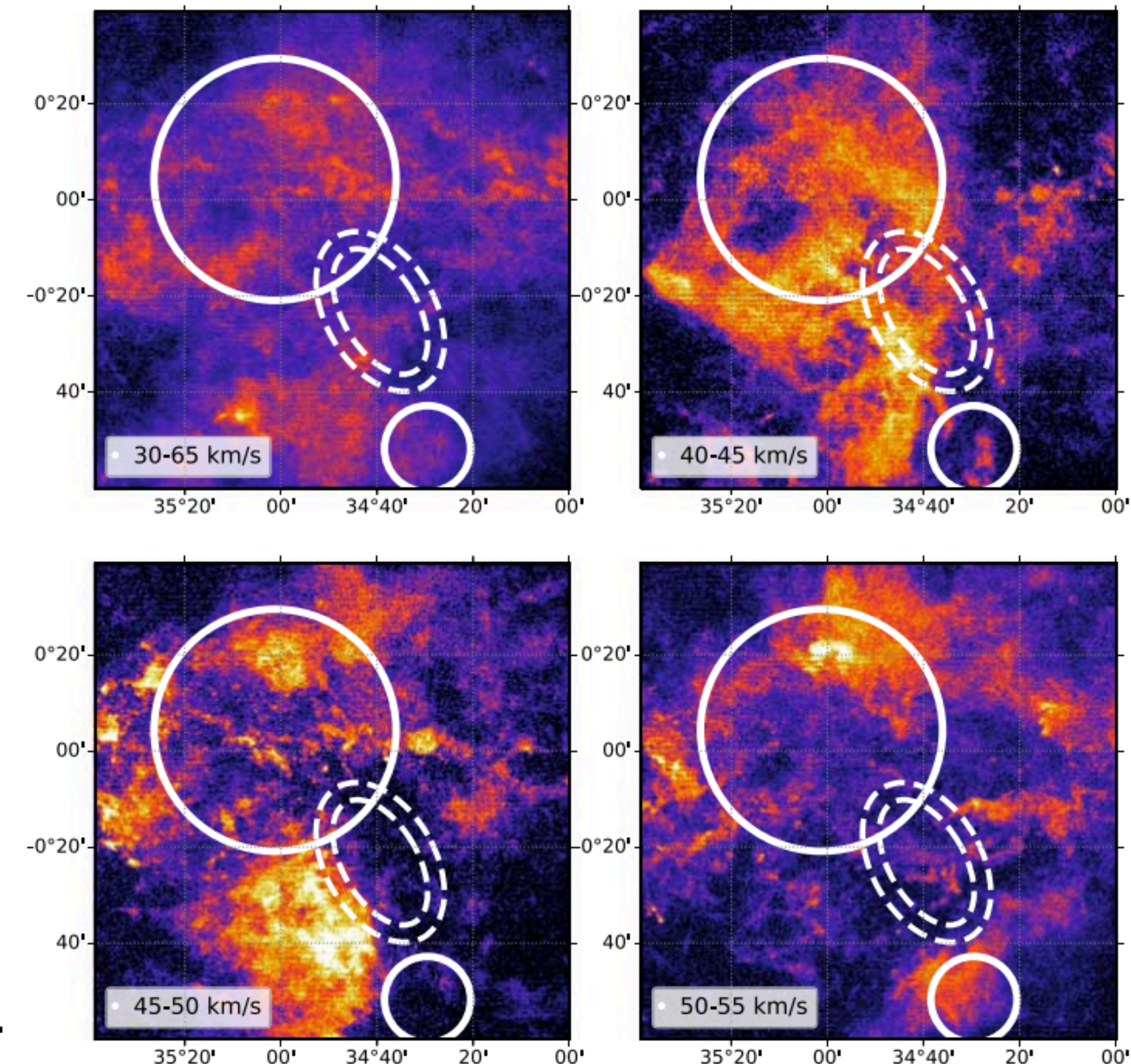
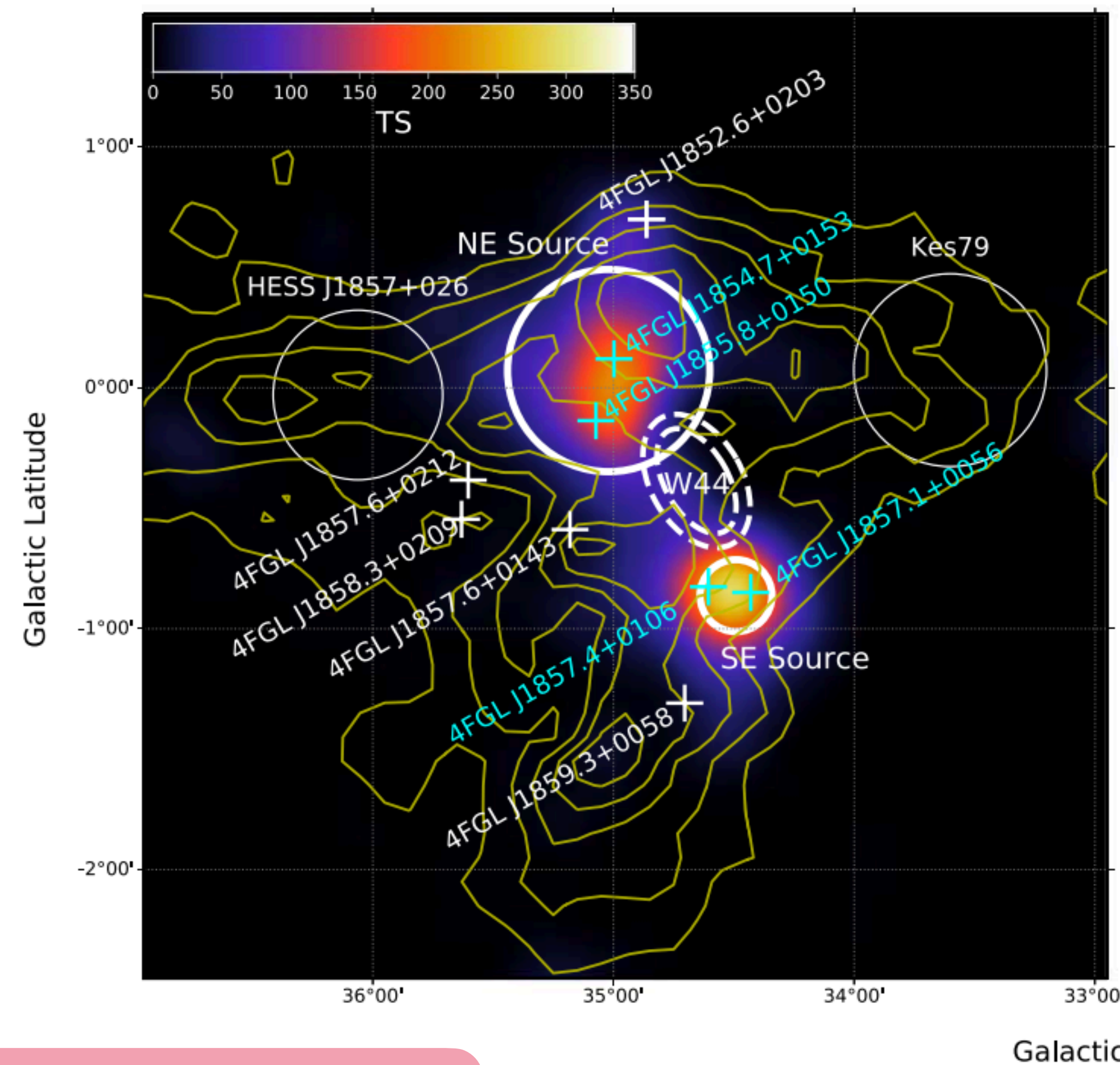
# Correlation with gas structure

GeV emission that does not correlate with gas near W44



Peron et al. 2020

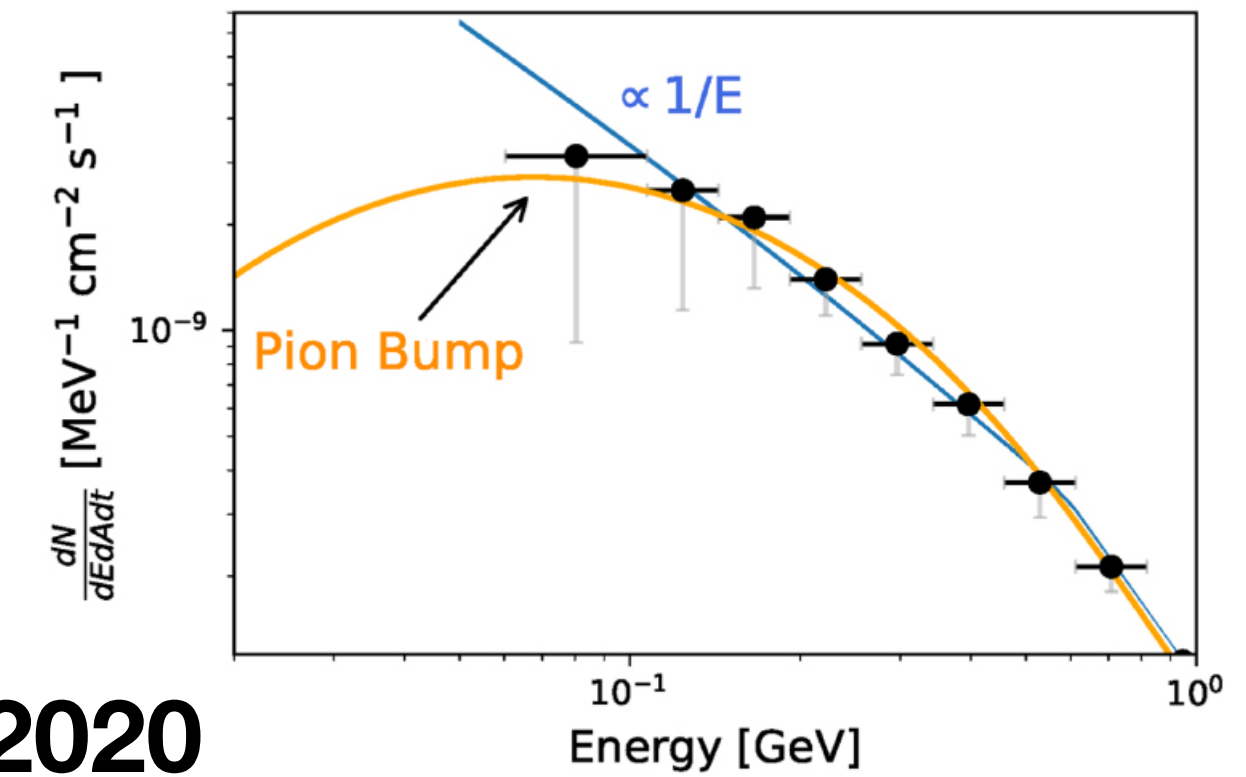
Peron et al. 2020





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GeV emission that does not correlate with gas near W44

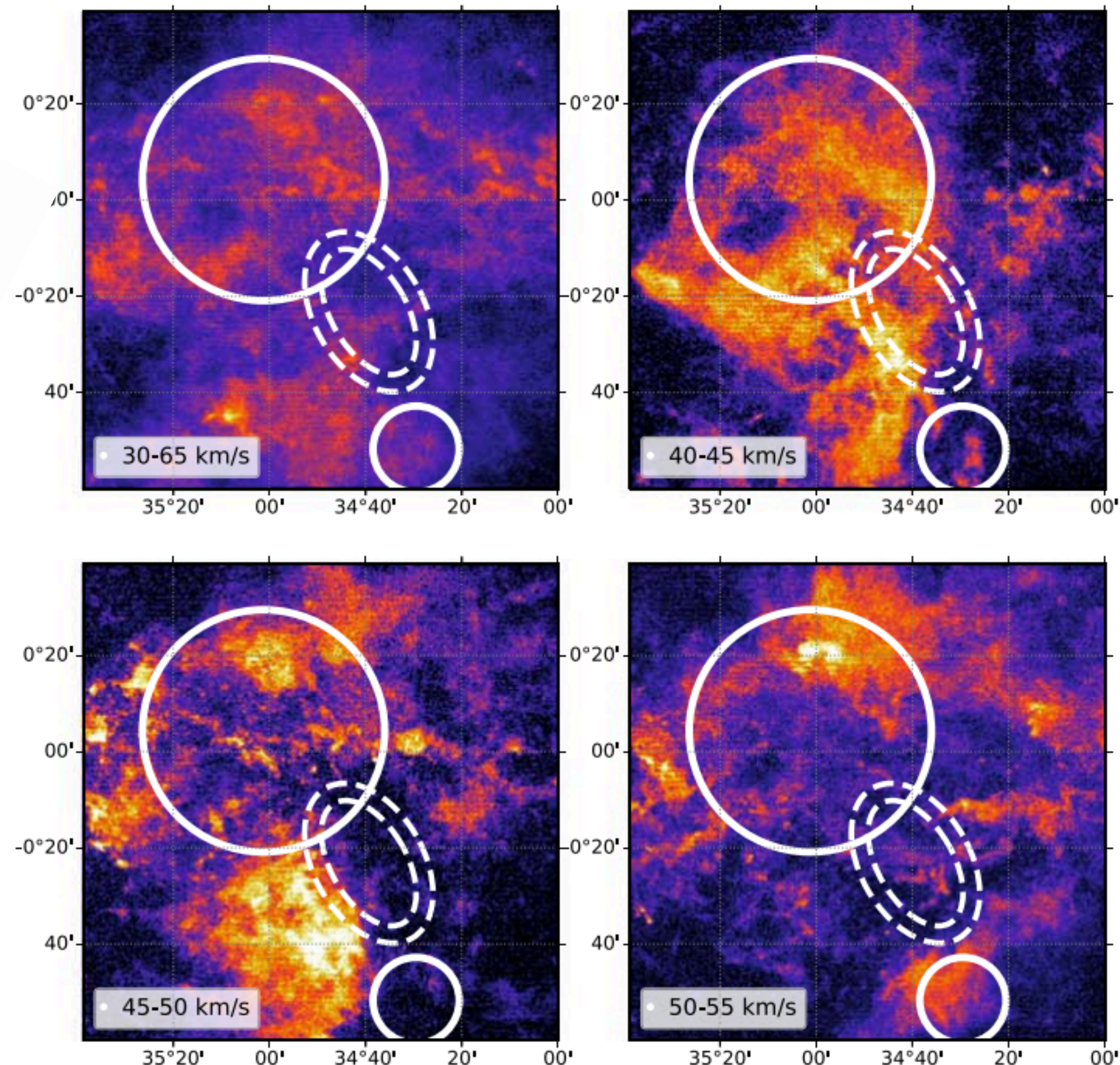
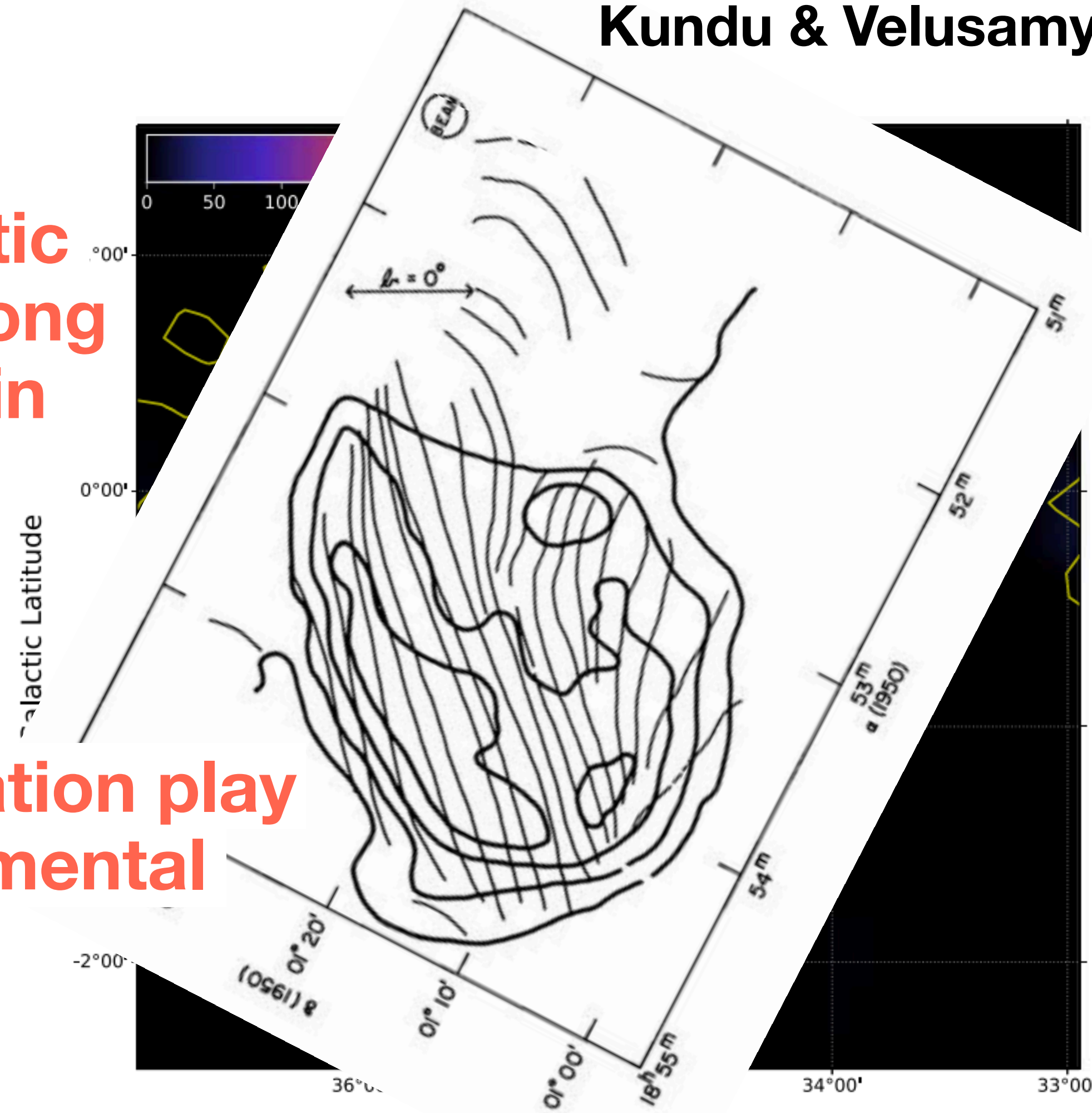


Kundu & Velusamy 1972

Peron et al. 2020

Magnetic field along the main axis

Propagation play a fundamental role

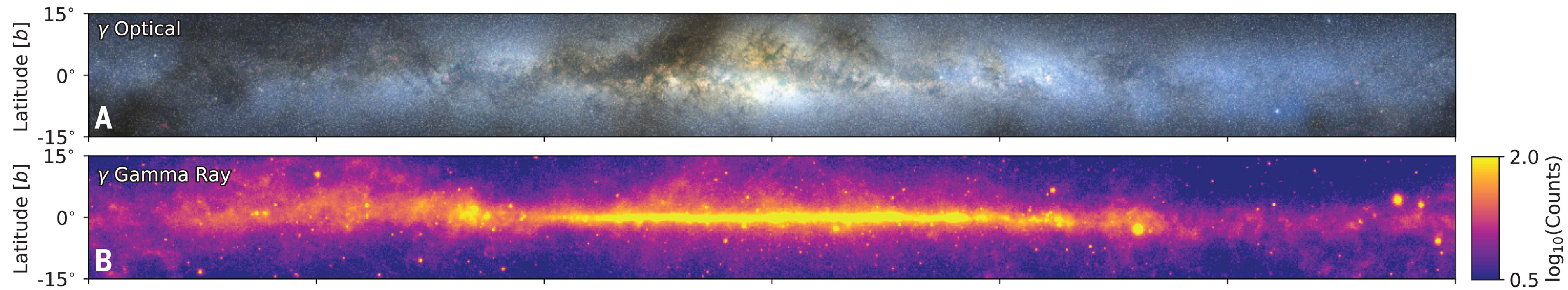




# Diffuse hadronic emission

# The hadronic component of the diffuse emission

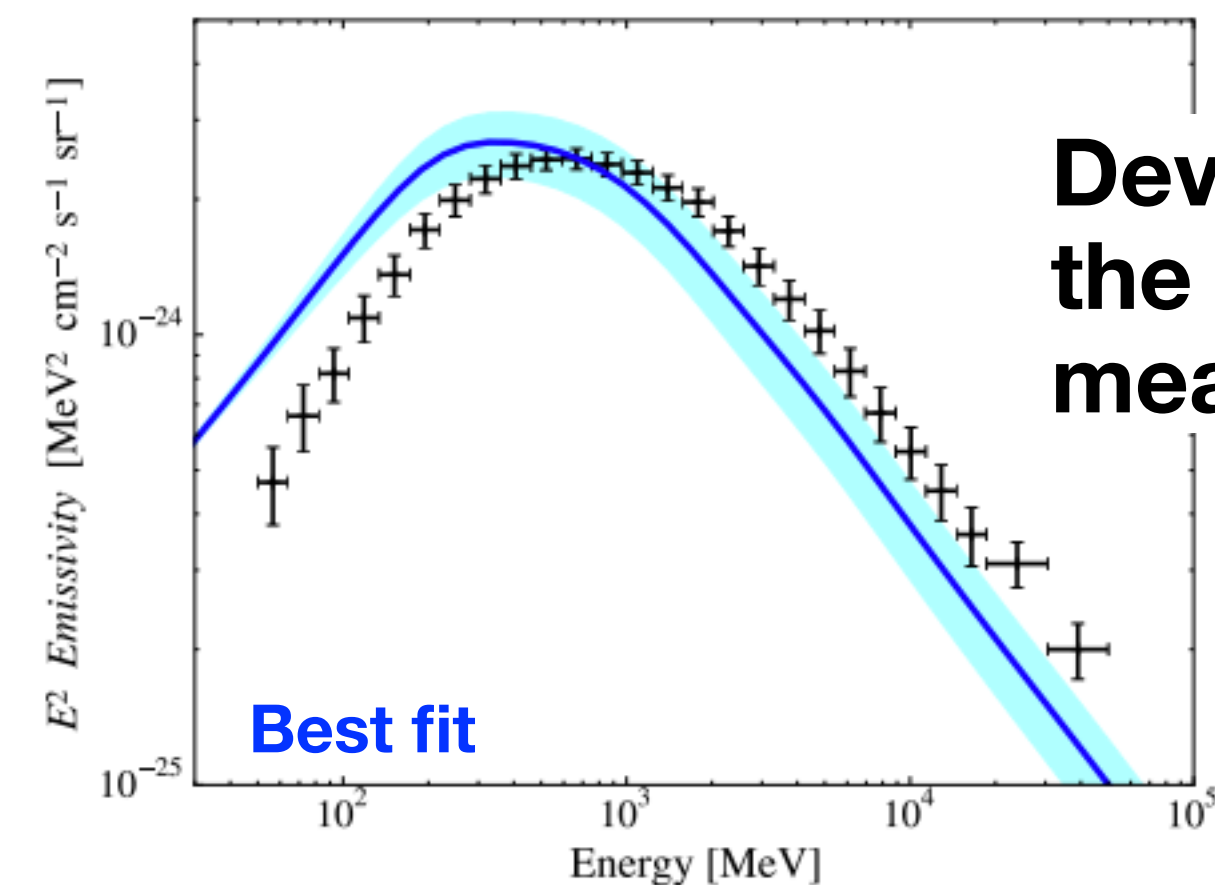
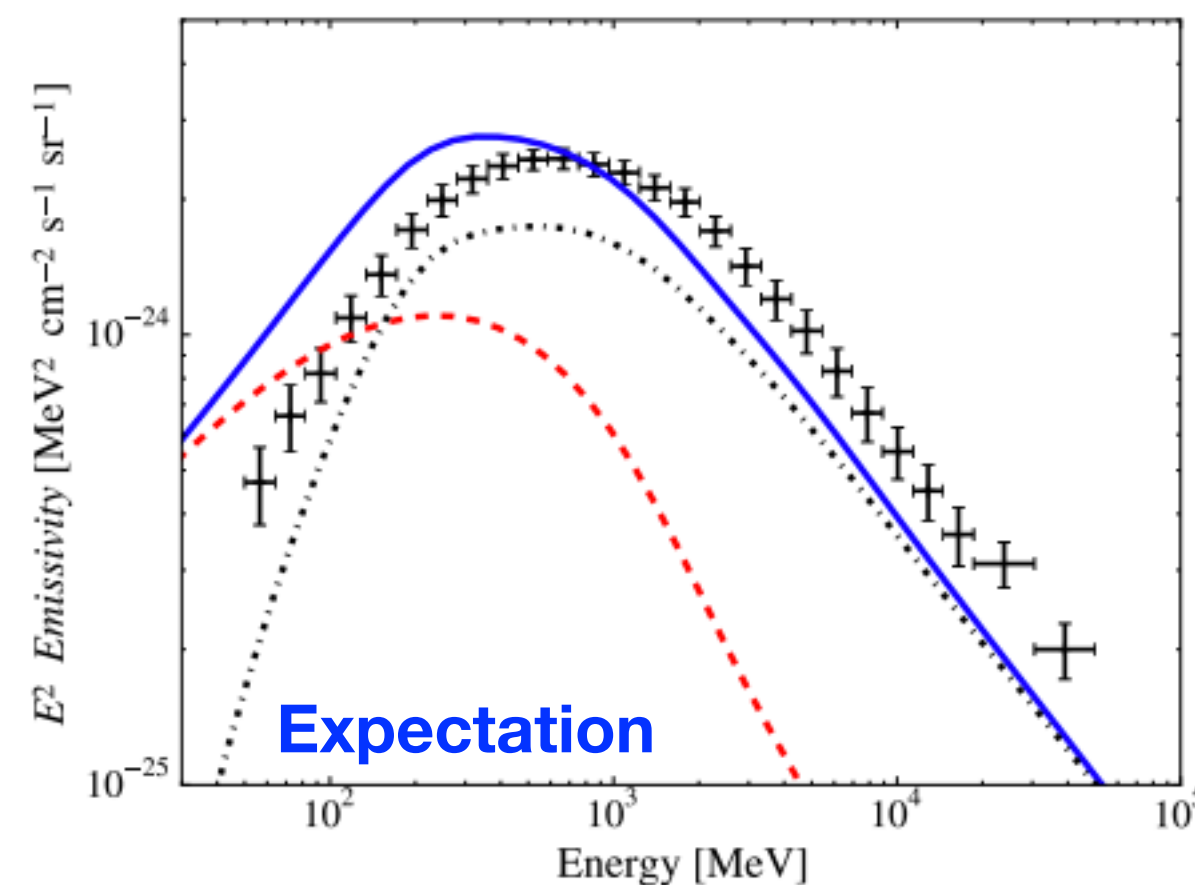
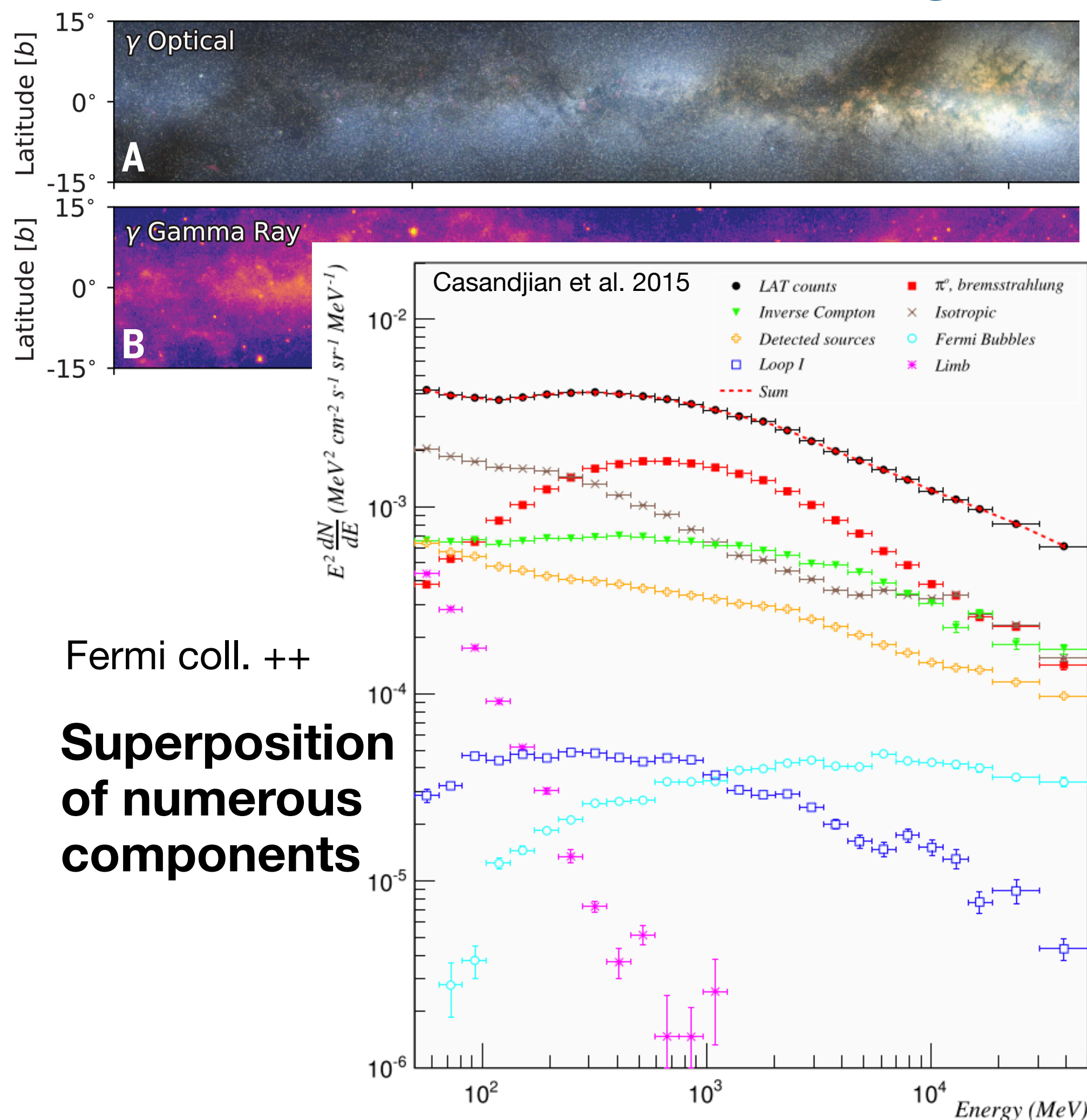
## Gamma-rays



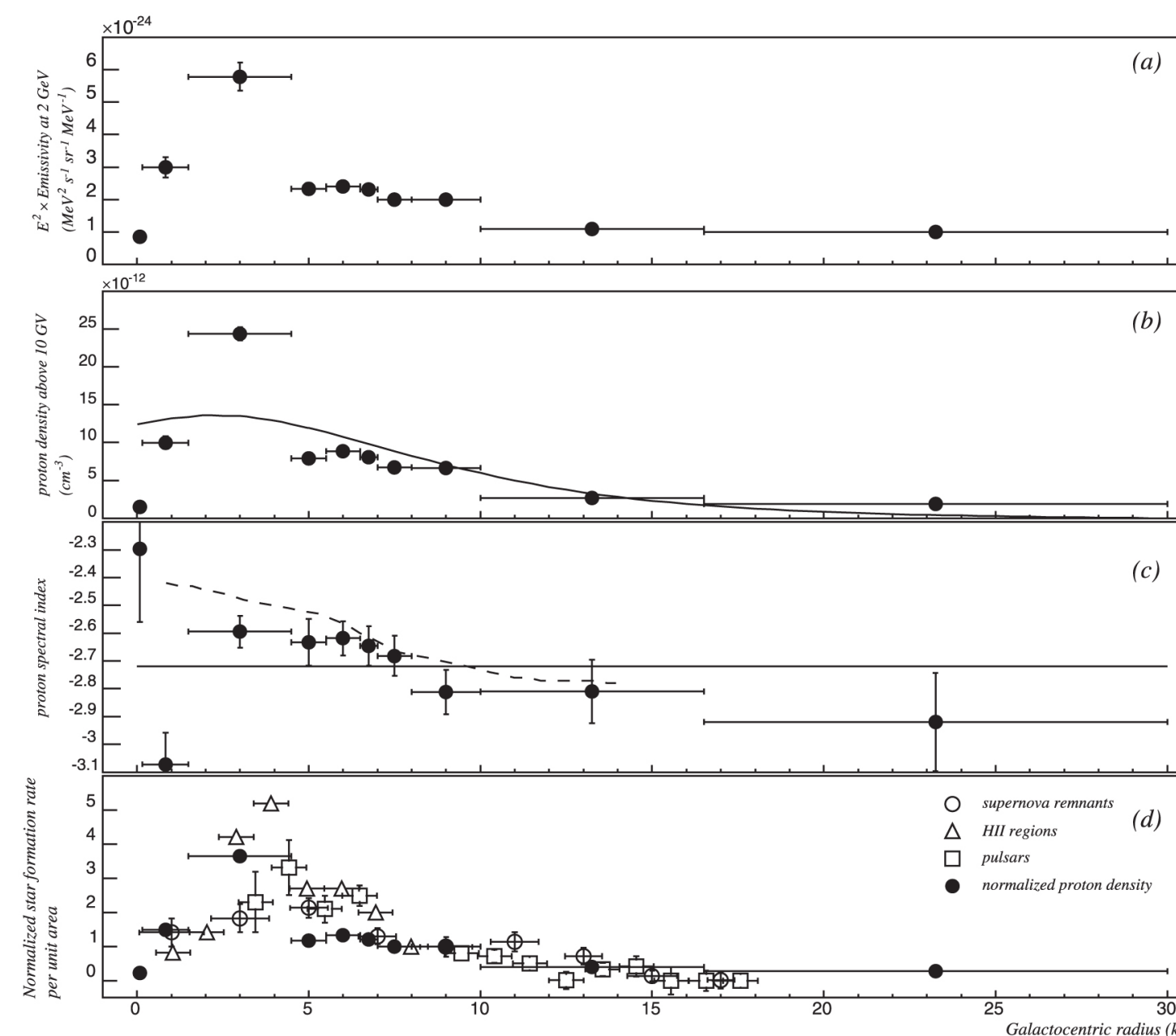


# The hadronic component of the diffuse emission

## Gamma-rays @GeV energies



Orlando et al. 2018



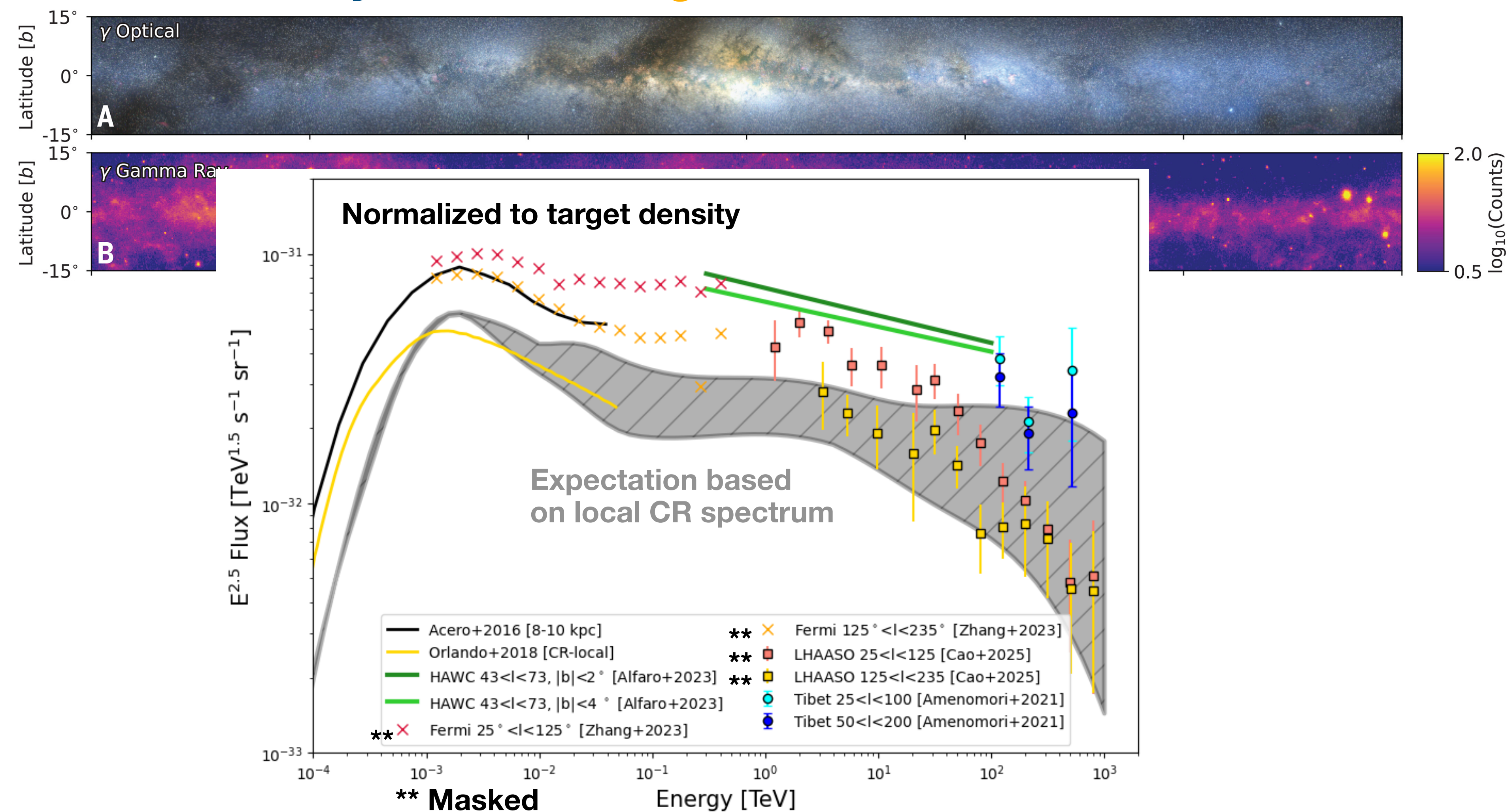
Acero et al. 2016

**Variation across the Galaxy**



# The hadronic component of the diffuse emission

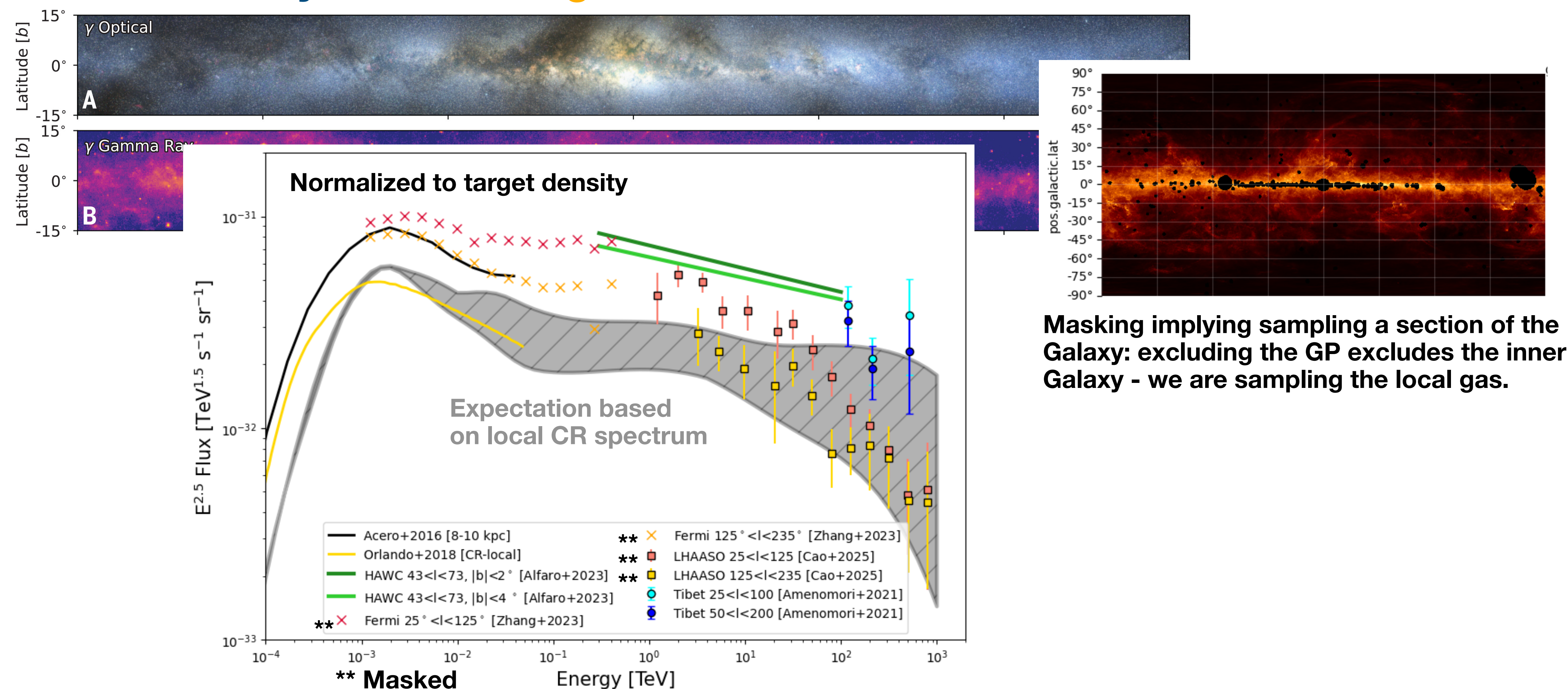
## Gamma-rays @TeV energies





# The hadronic component of the diffuse emission

## Gamma-rays @TeV energies

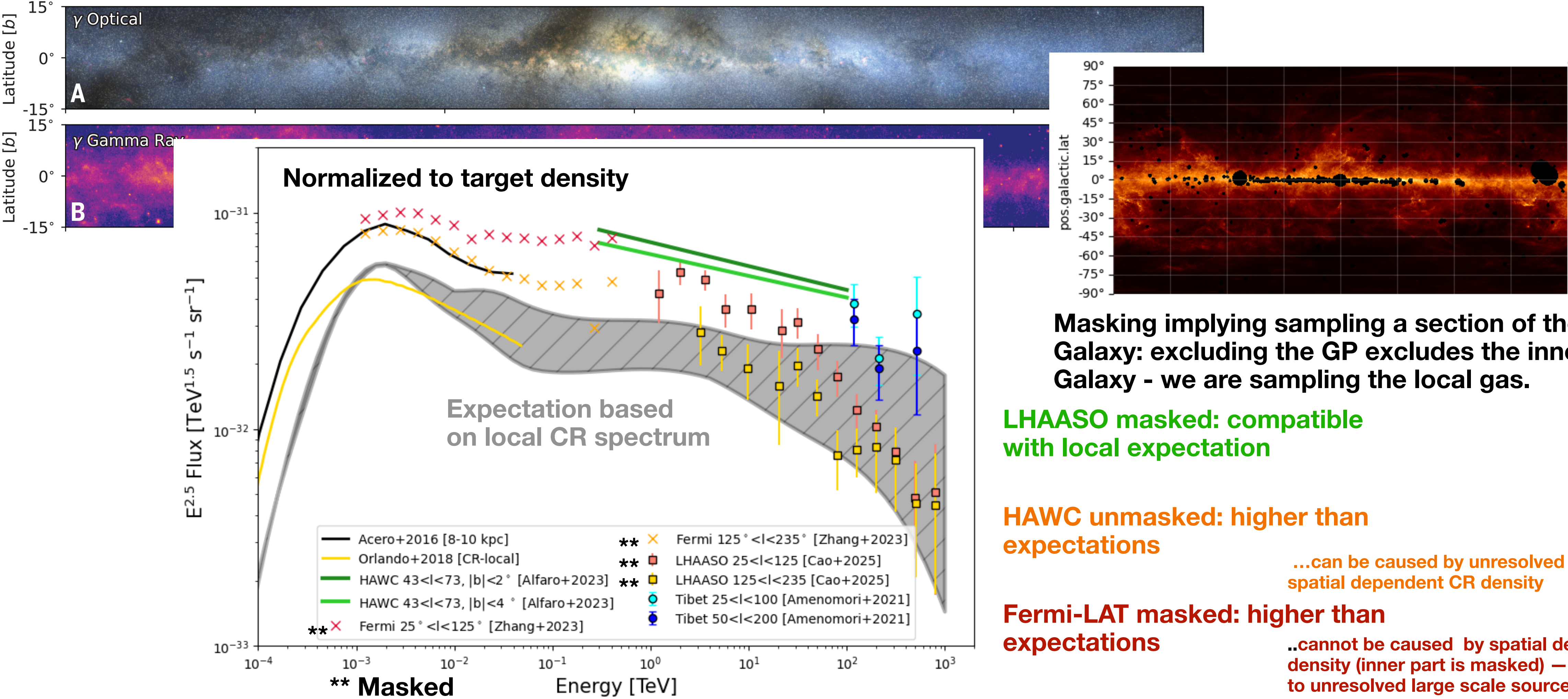


**Masking implying sampling a section of the Galaxy: excluding the GP excludes the inner Galaxy - we are sampling the local gas.**



# The hadronic component of the diffuse emission

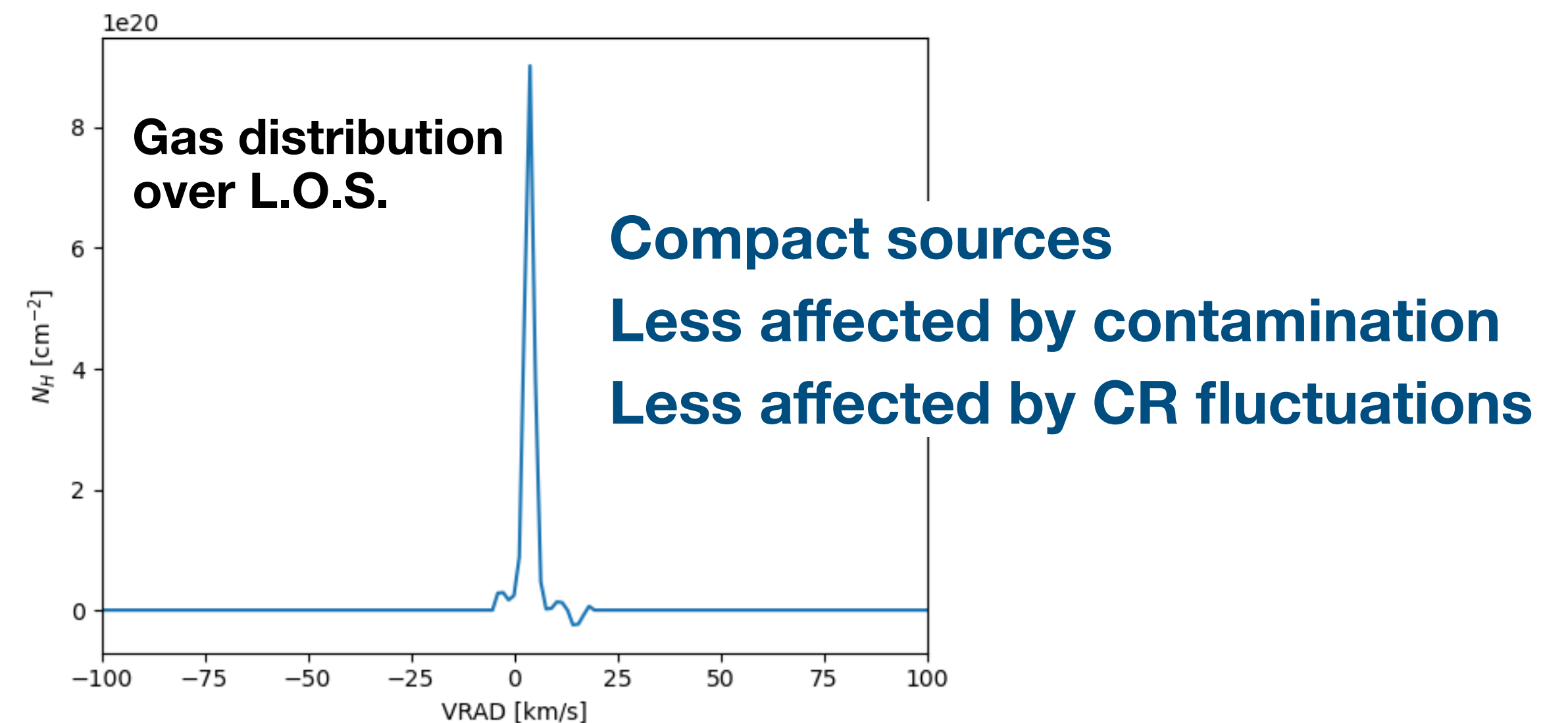
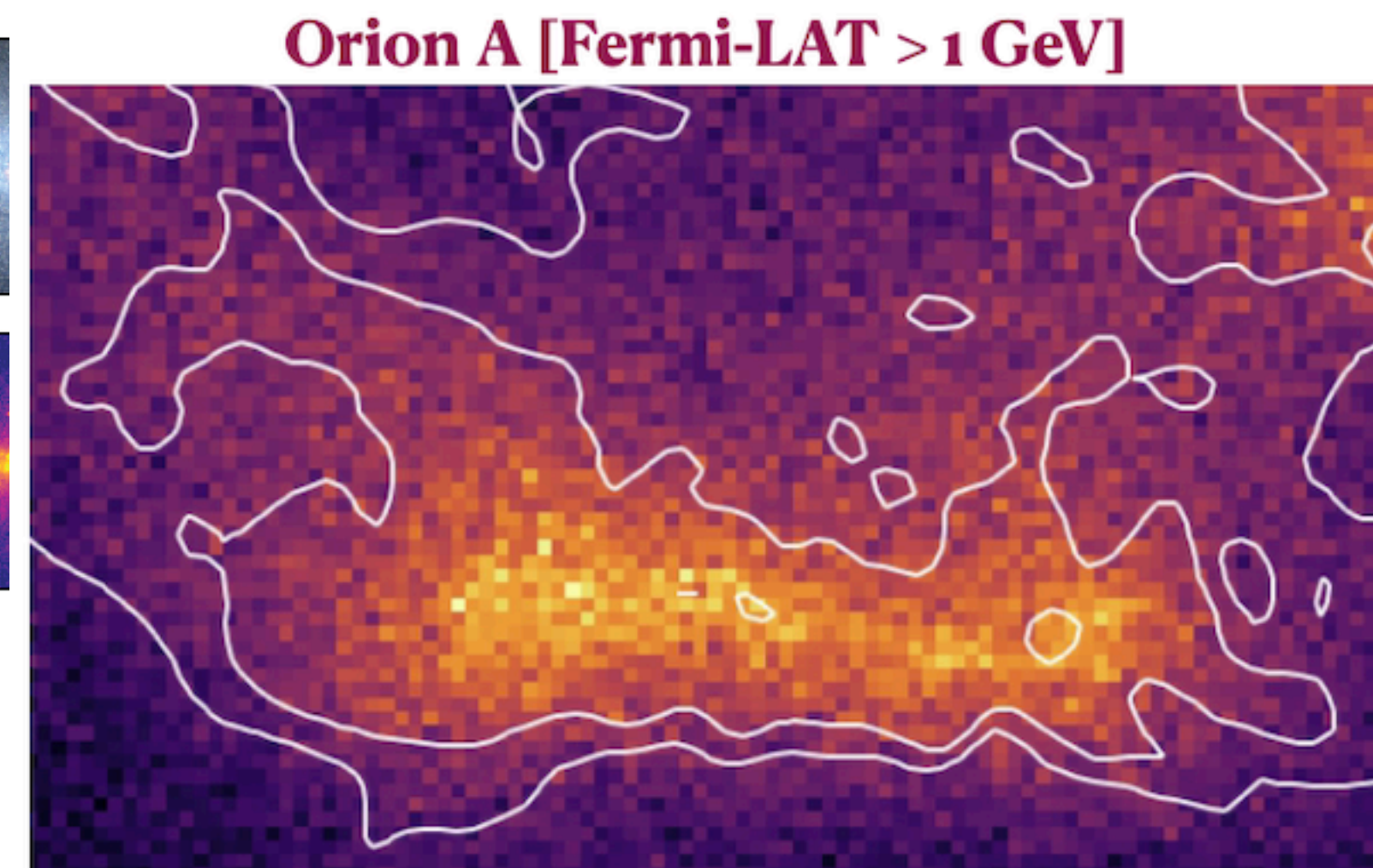
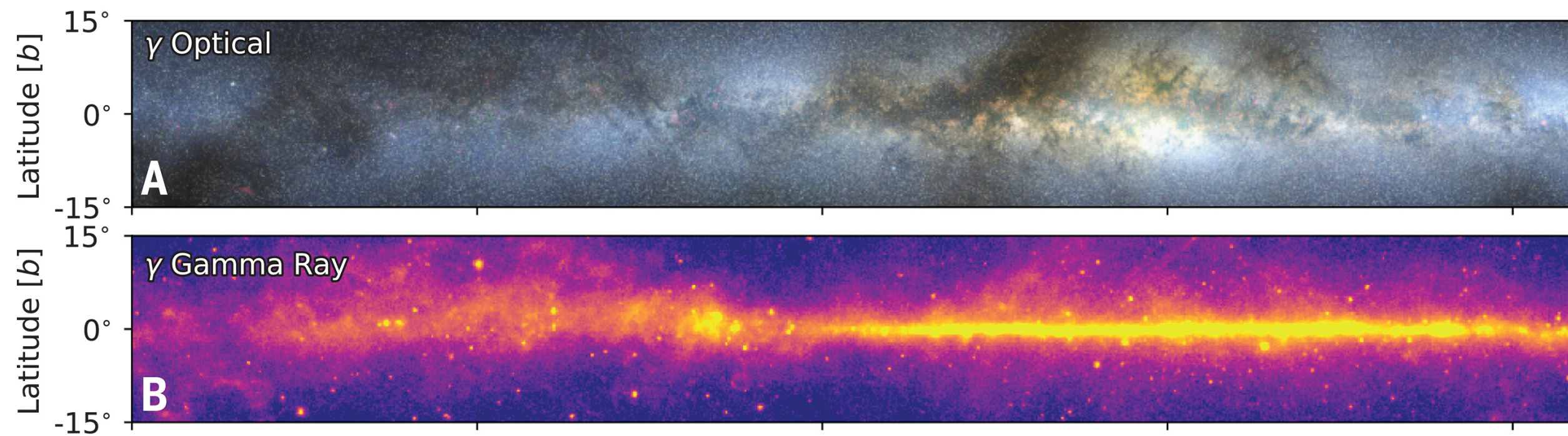
## Gamma-rays @TeV energies





# The hadronic component of the diffuse emission

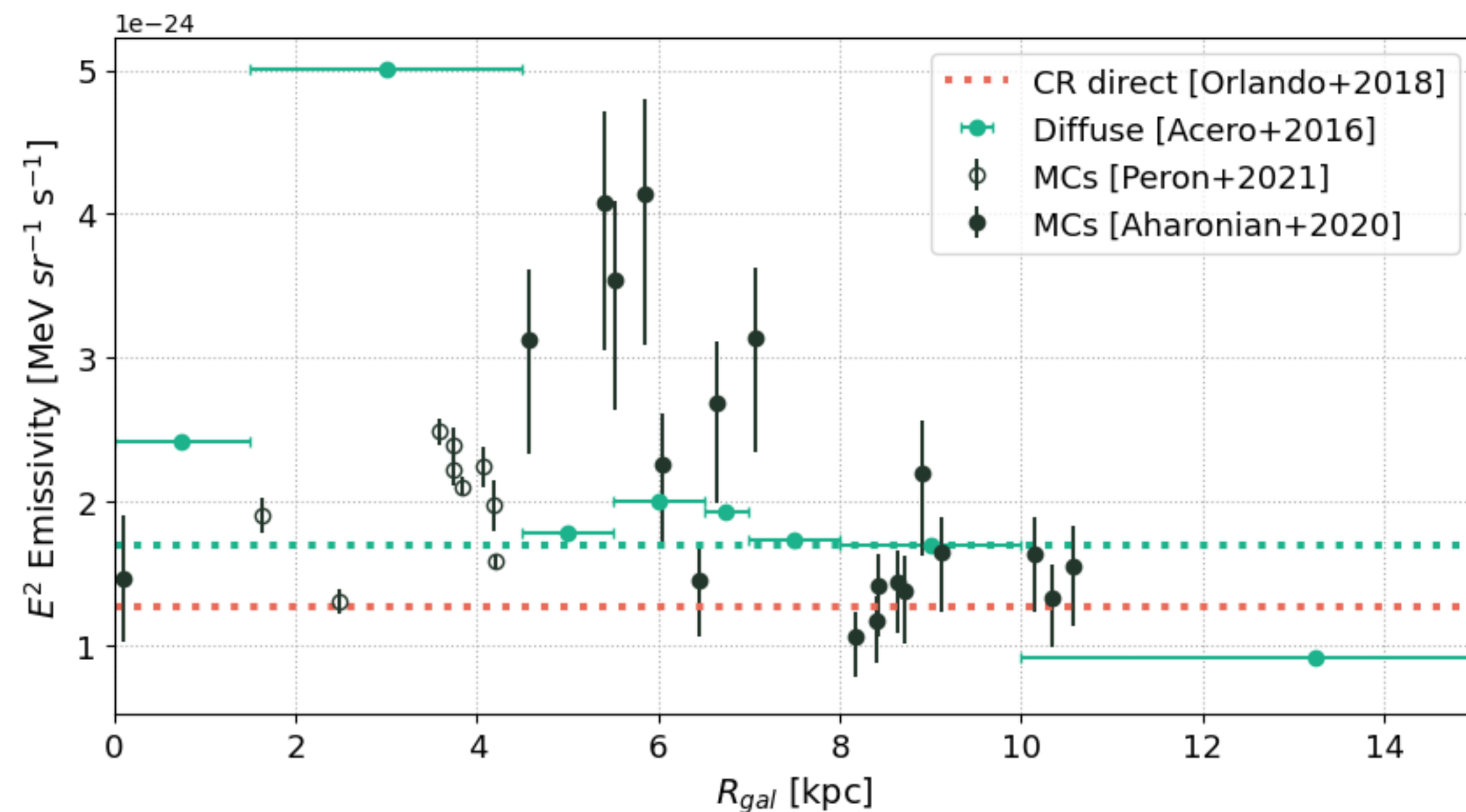
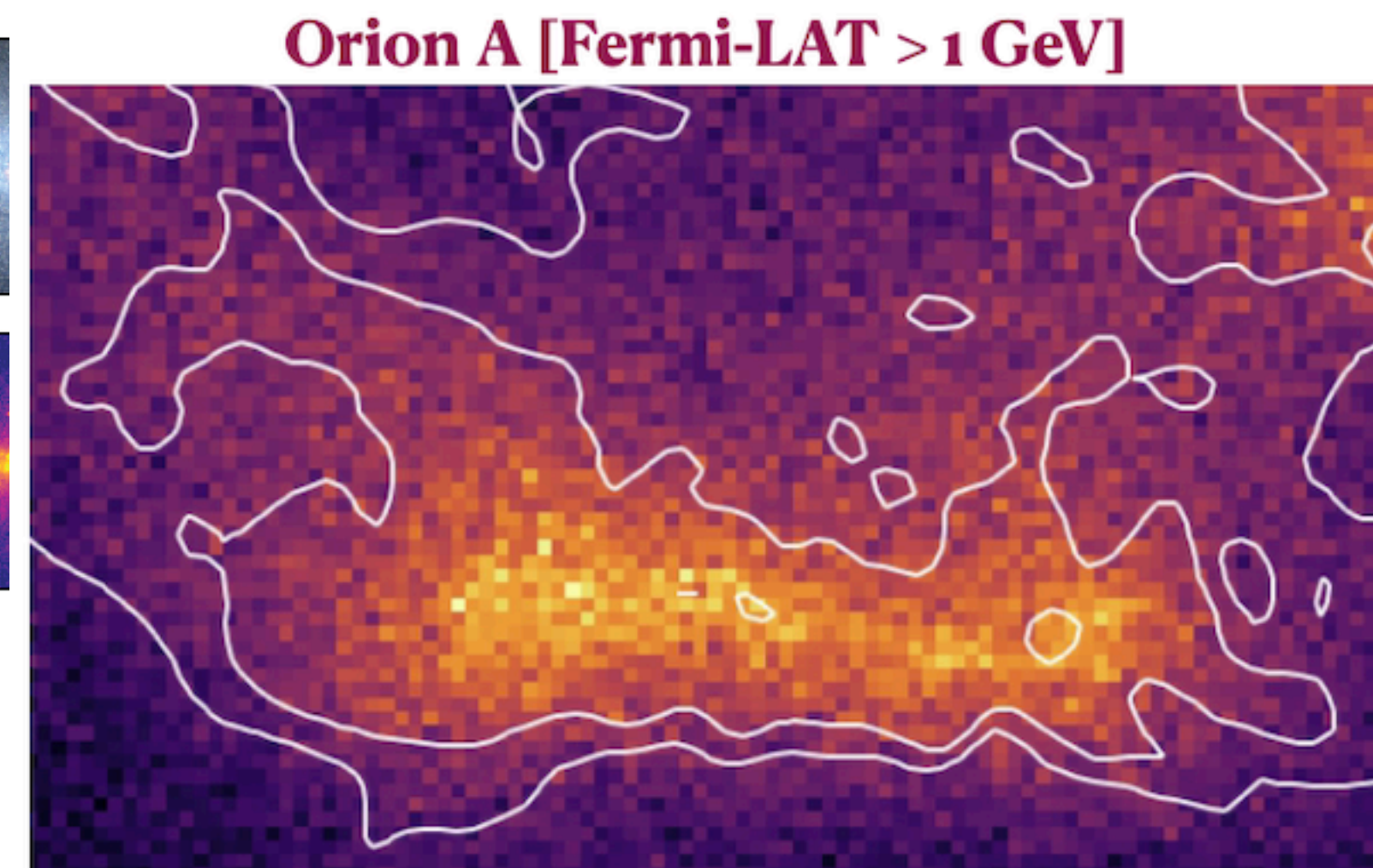
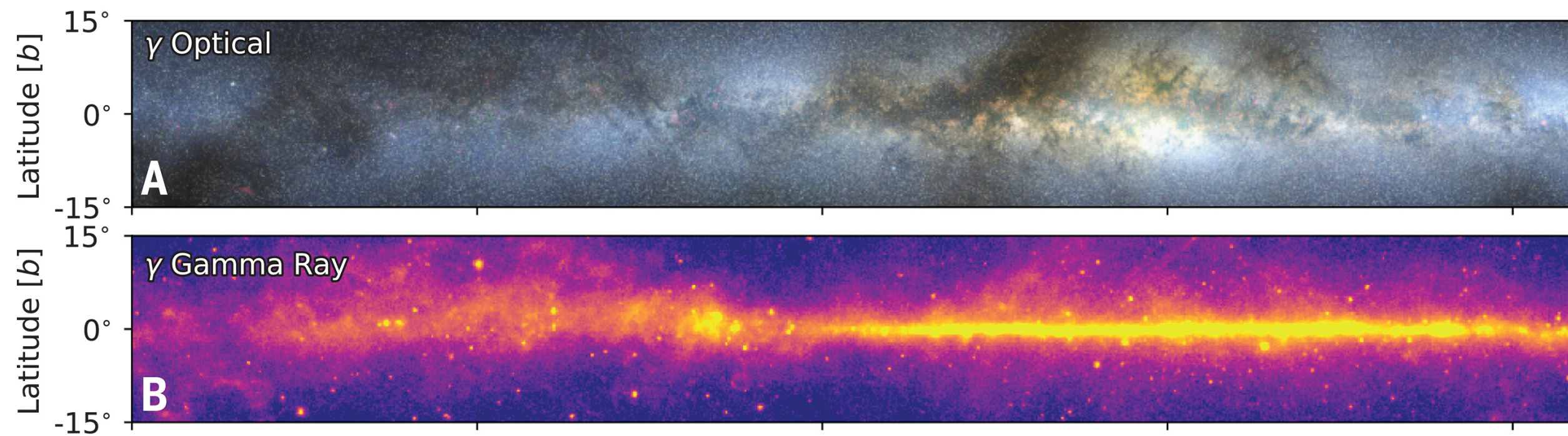
## Gamma-rays from molecular clouds





# The hadronic component of the diffuse emission

## Gamma-rays from molecular clouds

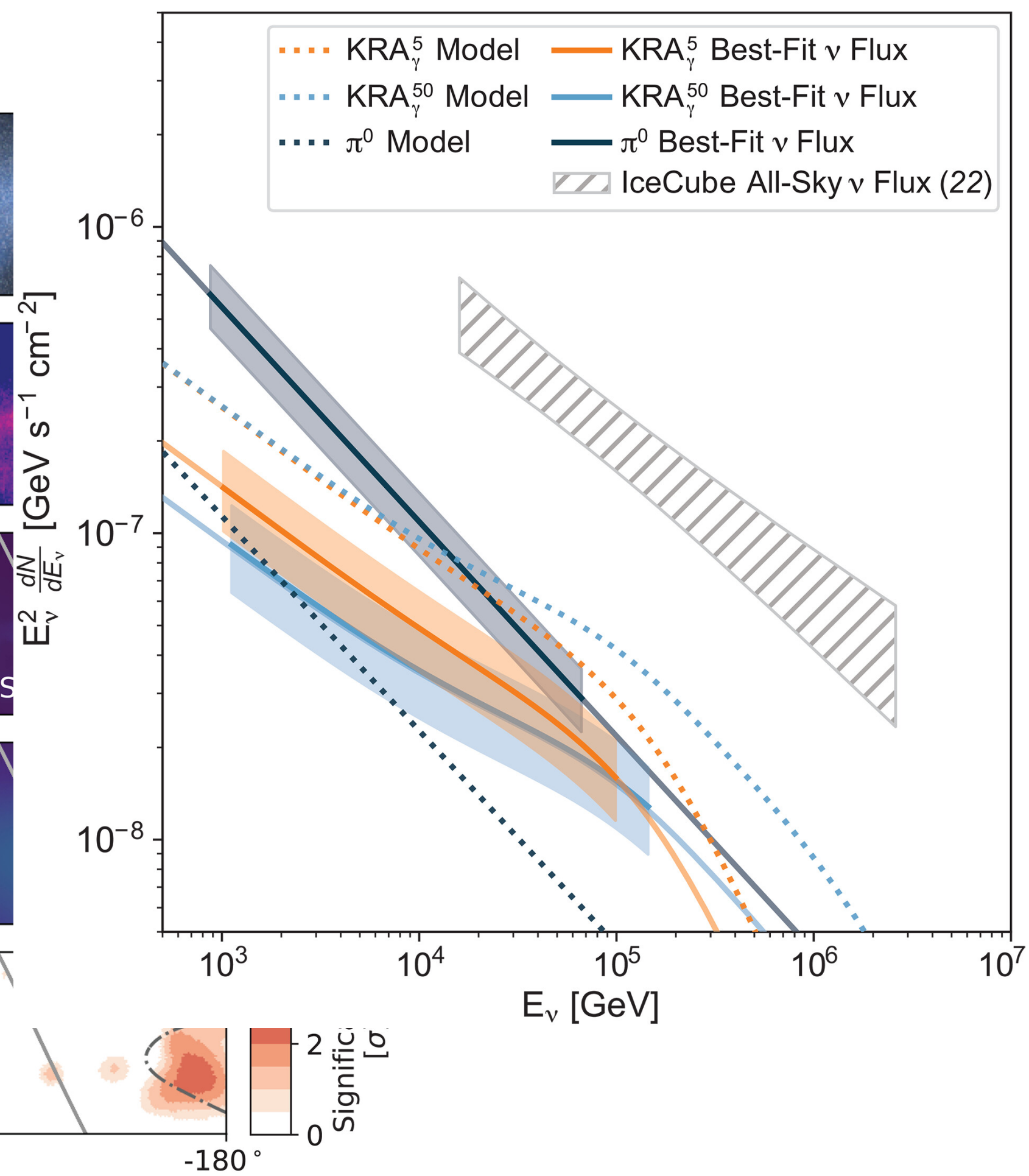
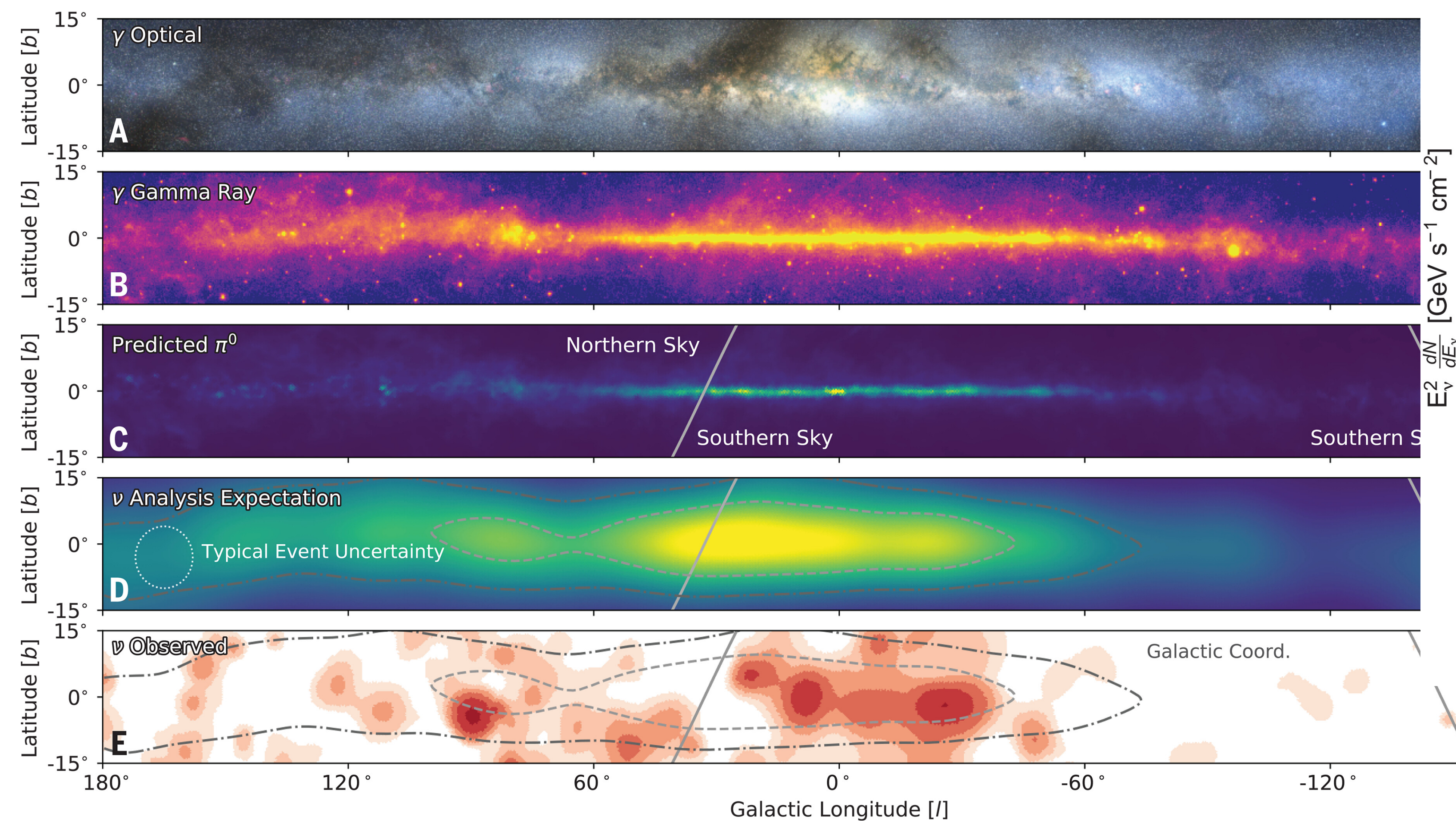


Fluctuations are revealed but  
also agreement found with CR  
local spectrum



# The neutrino diffuse emission

Abbasi et al. 2023

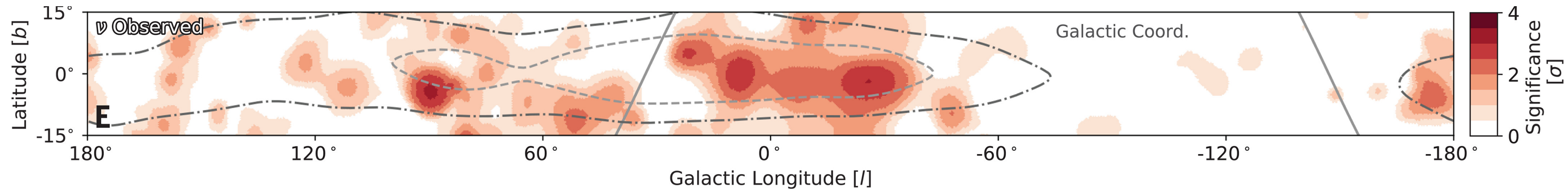


Abbasi et al. 2023



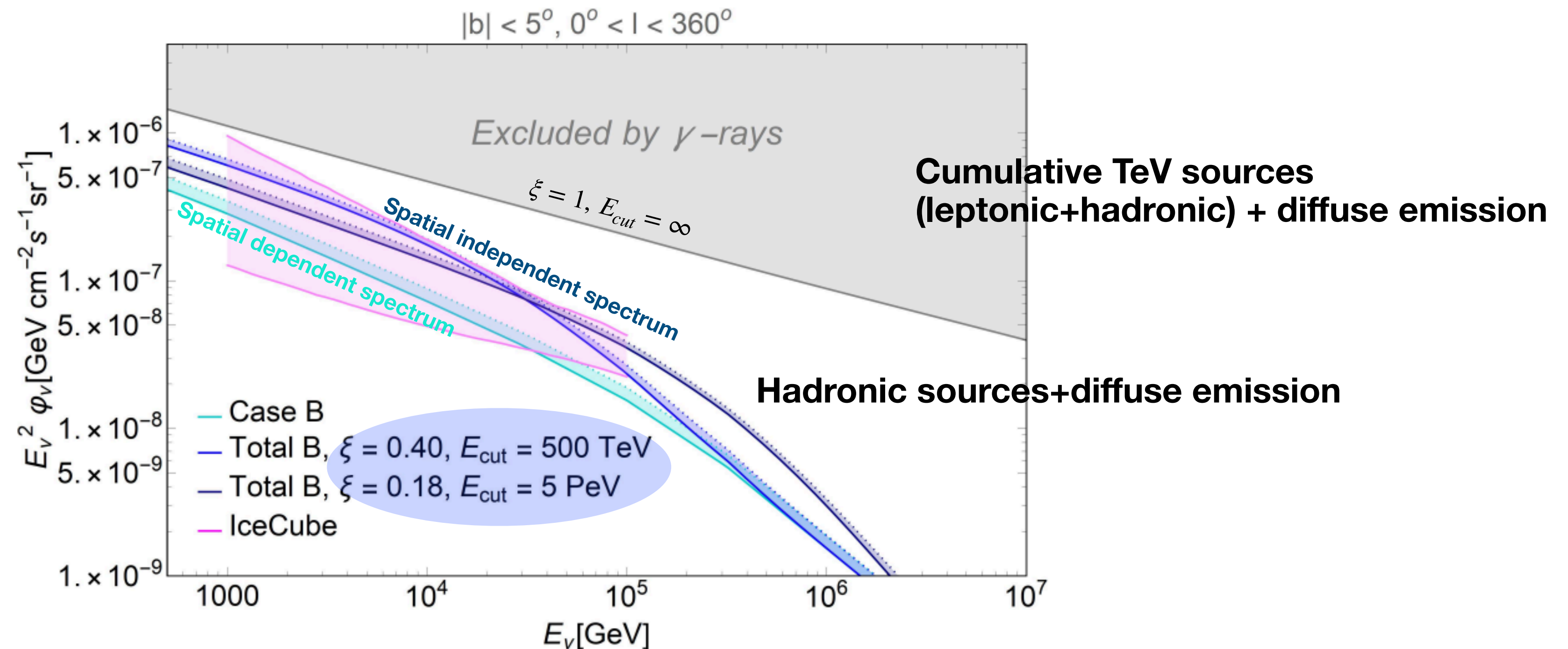
# The neutrino diffuse emission

Abbasi et al. 2023



## Constraints on the fraction of hadronic sources

$\xi$  = fraction of hadronic sources

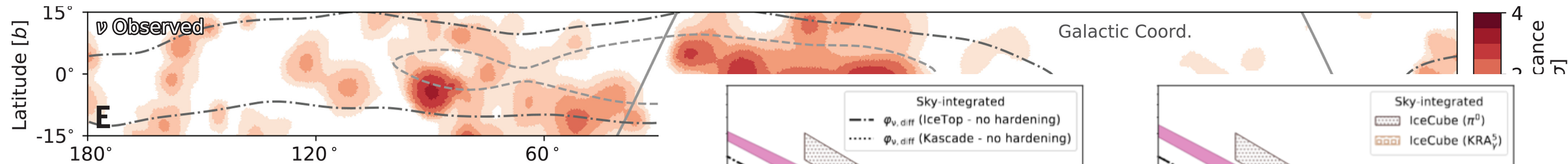


Vecchiotti et al. 2023

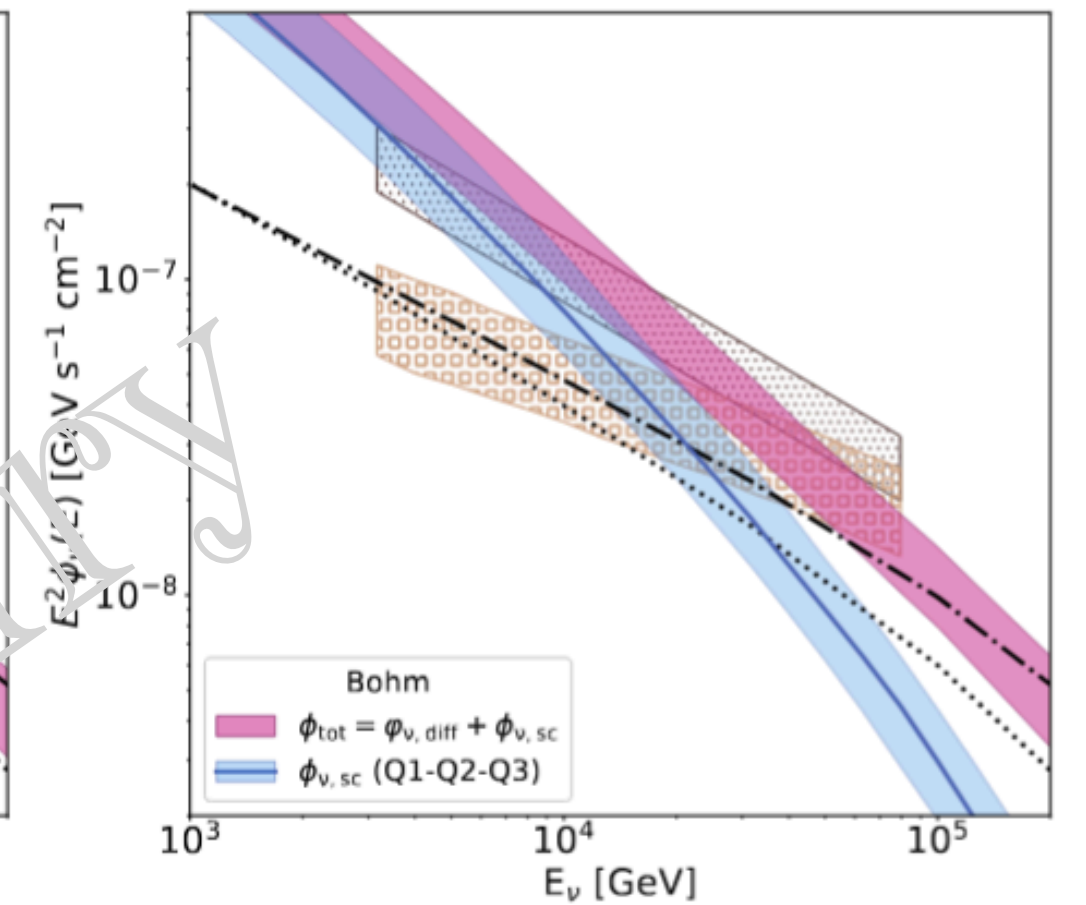
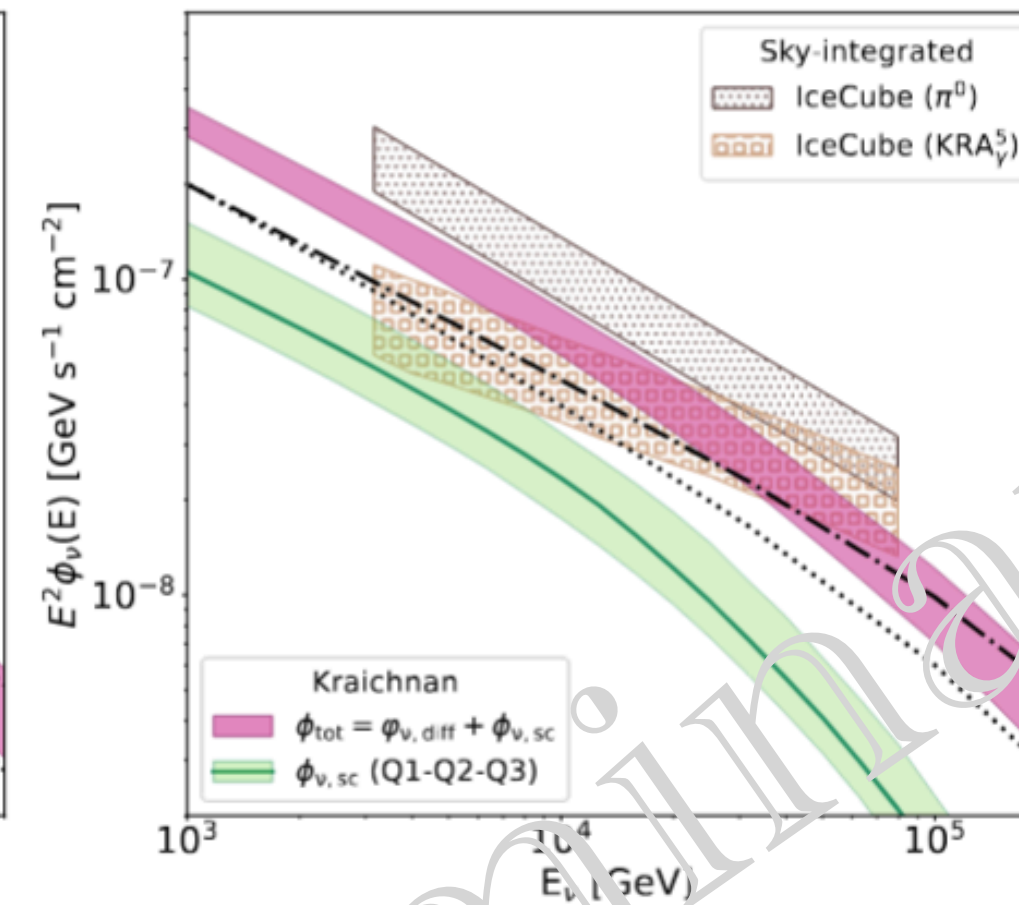
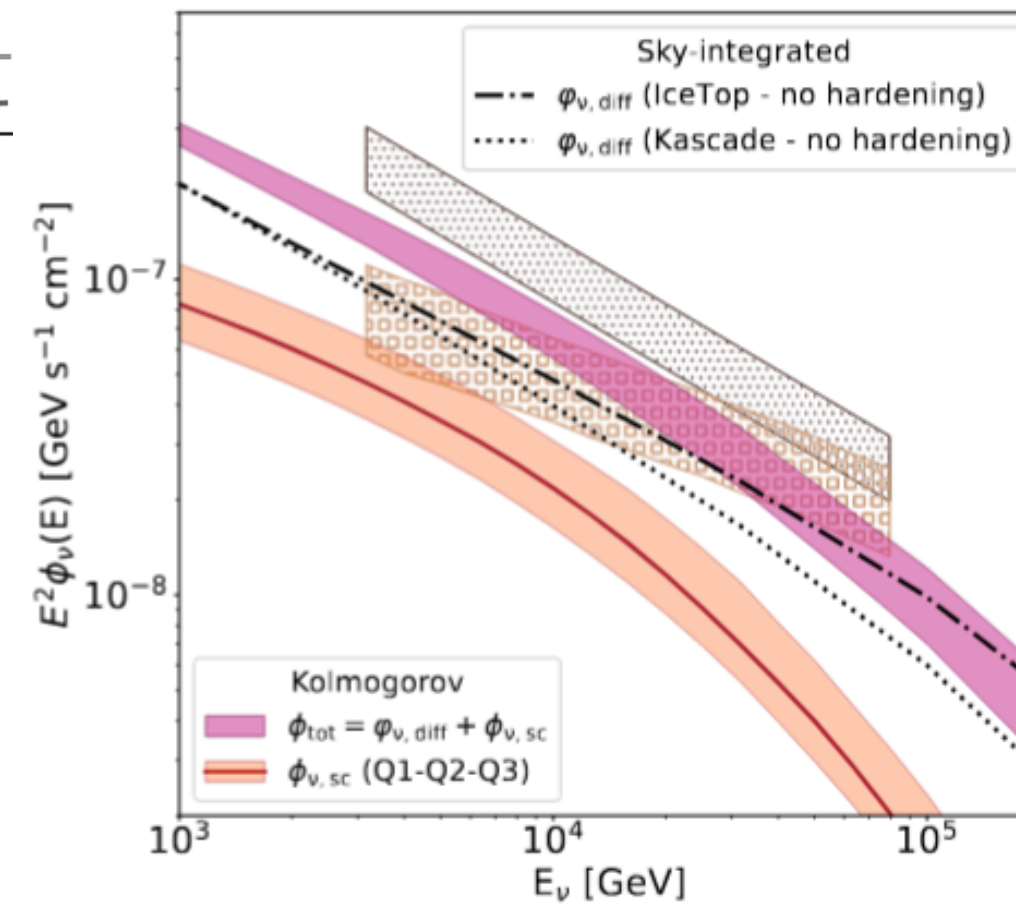


# The neutrino diffuse emission

Abbasi et al. 2023

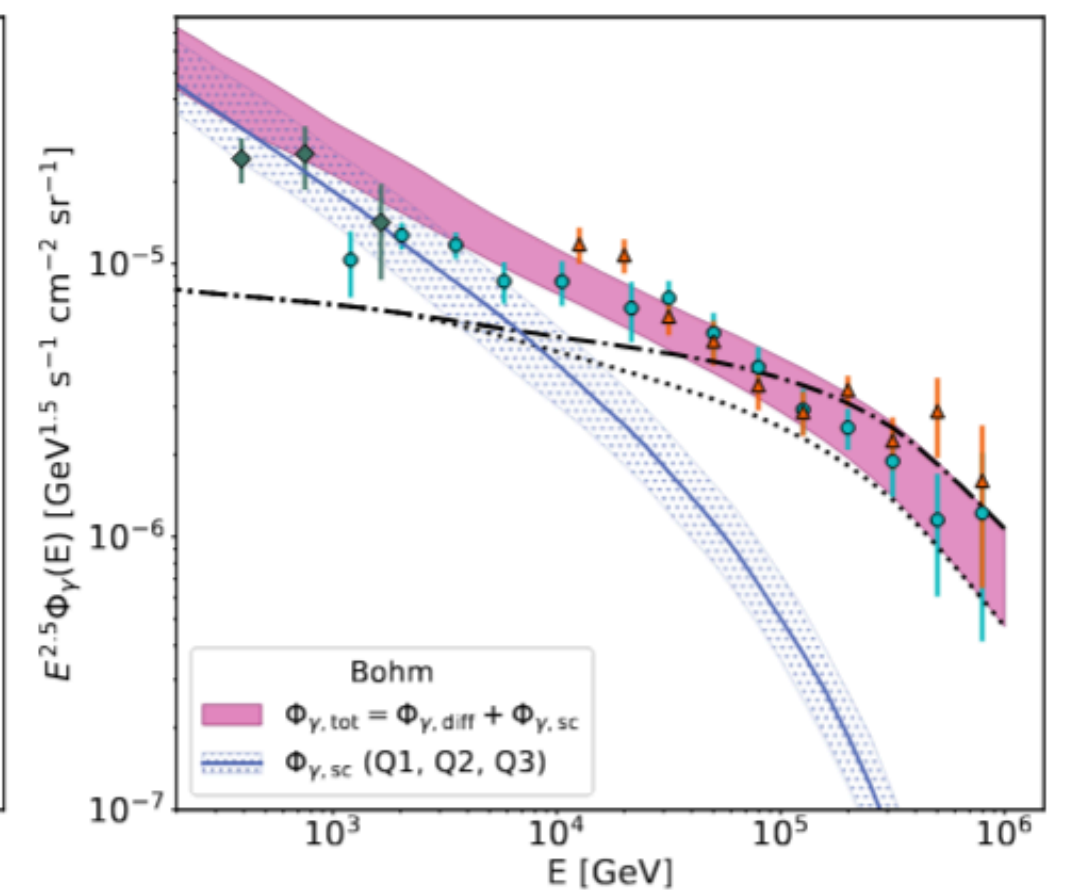
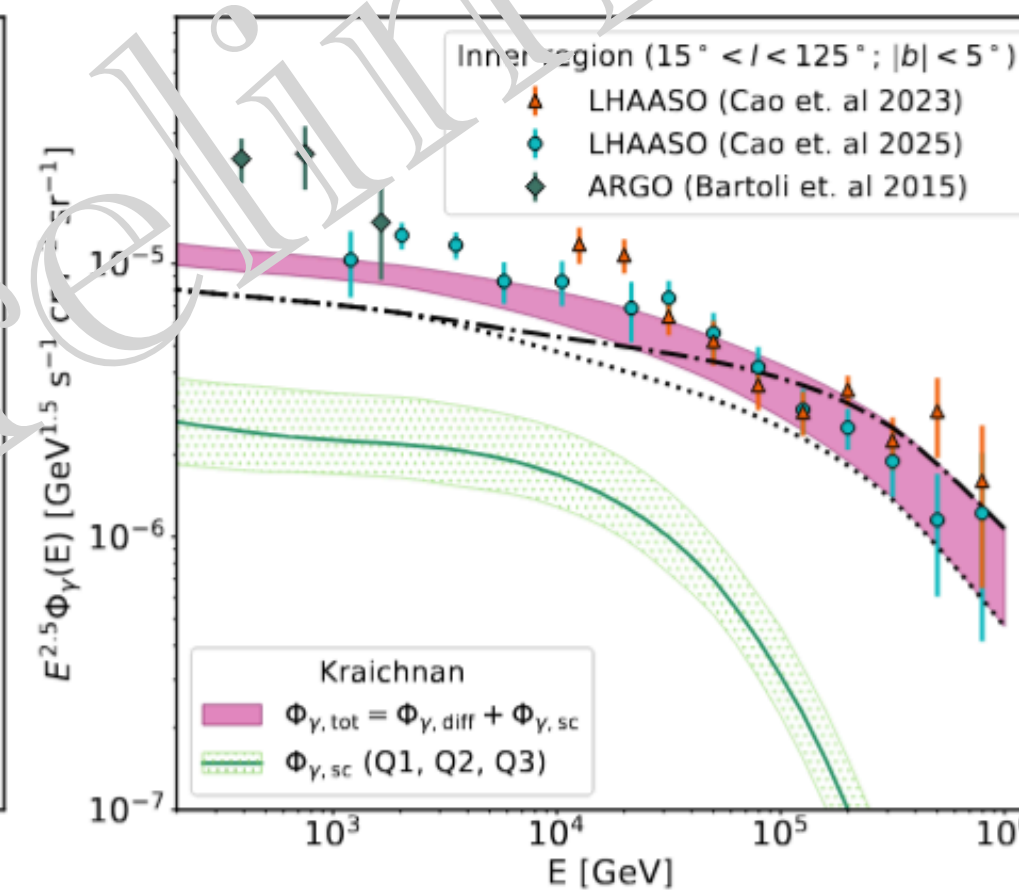
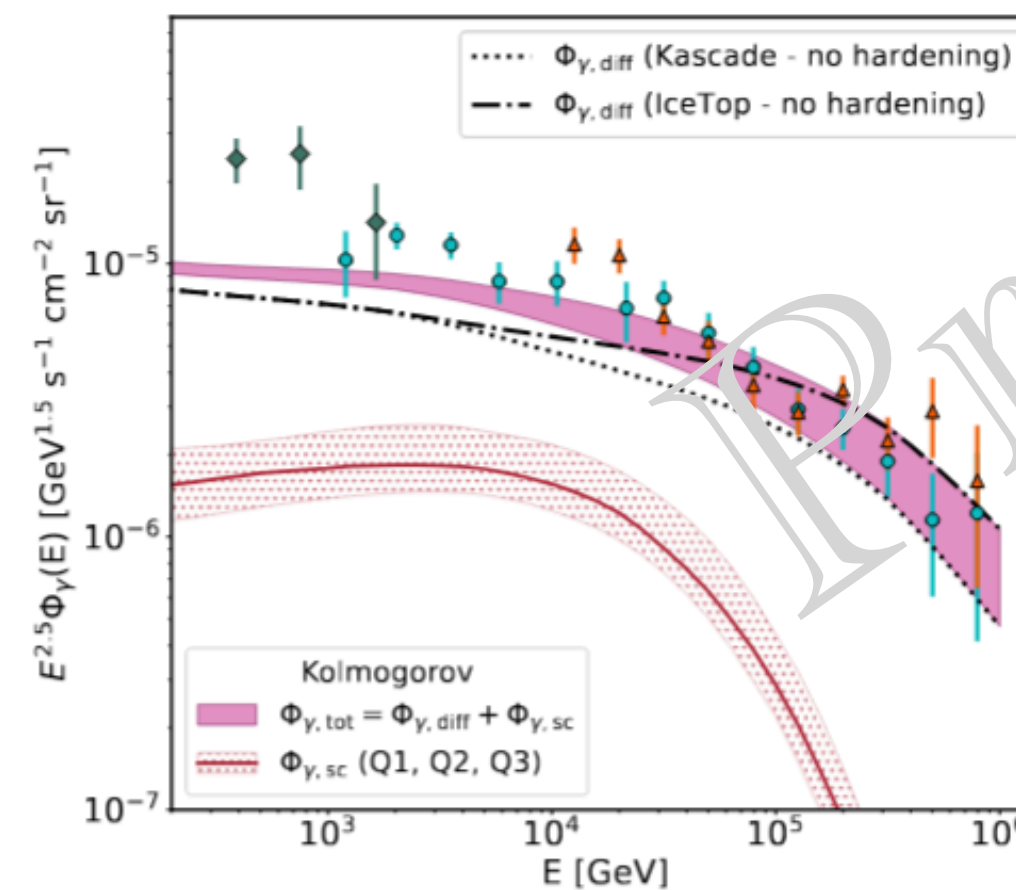


**SC+SNRs  
contribution to  
diffuse neutrinos**



Menchiari et al. 2026 In prep.

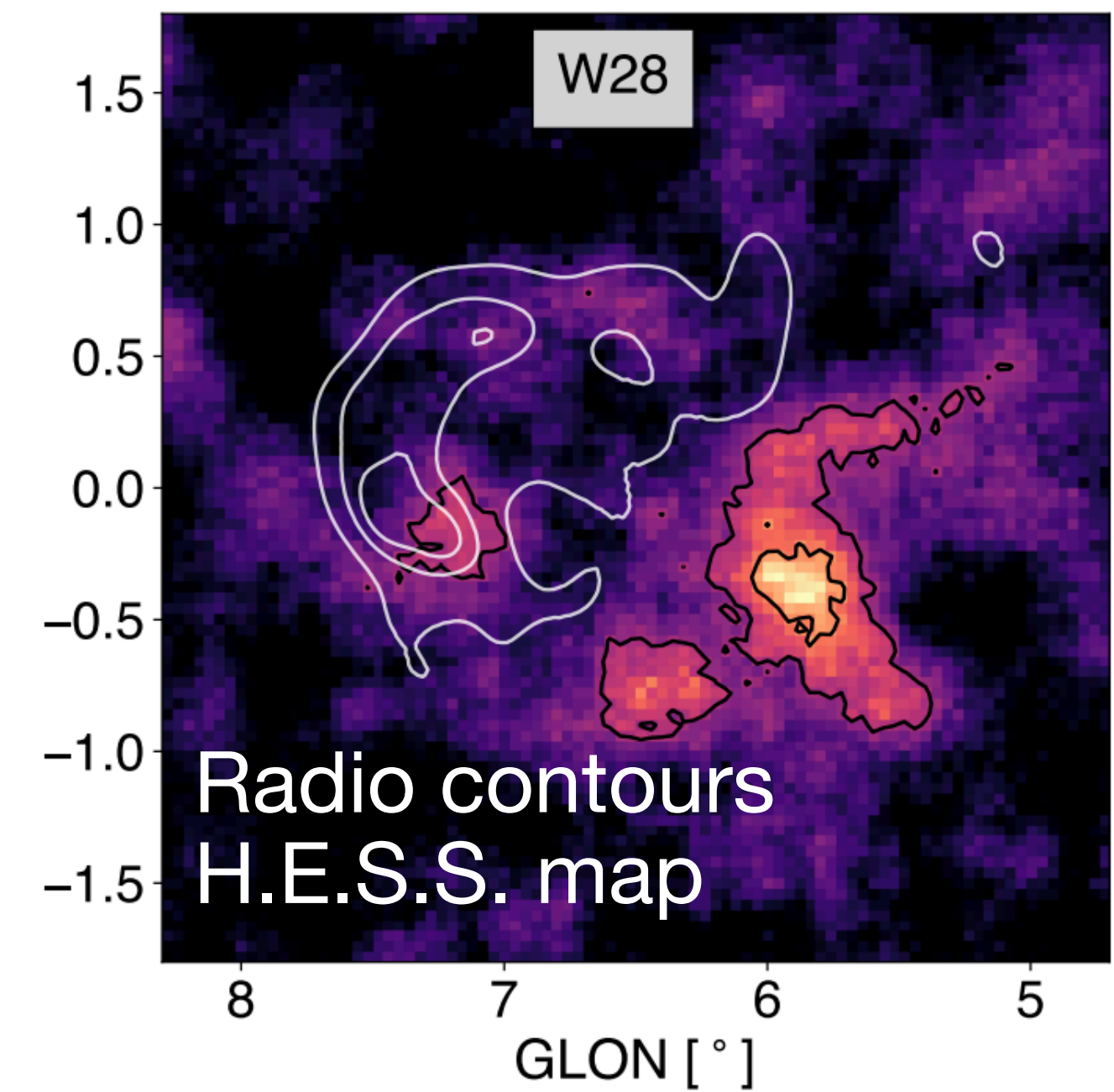
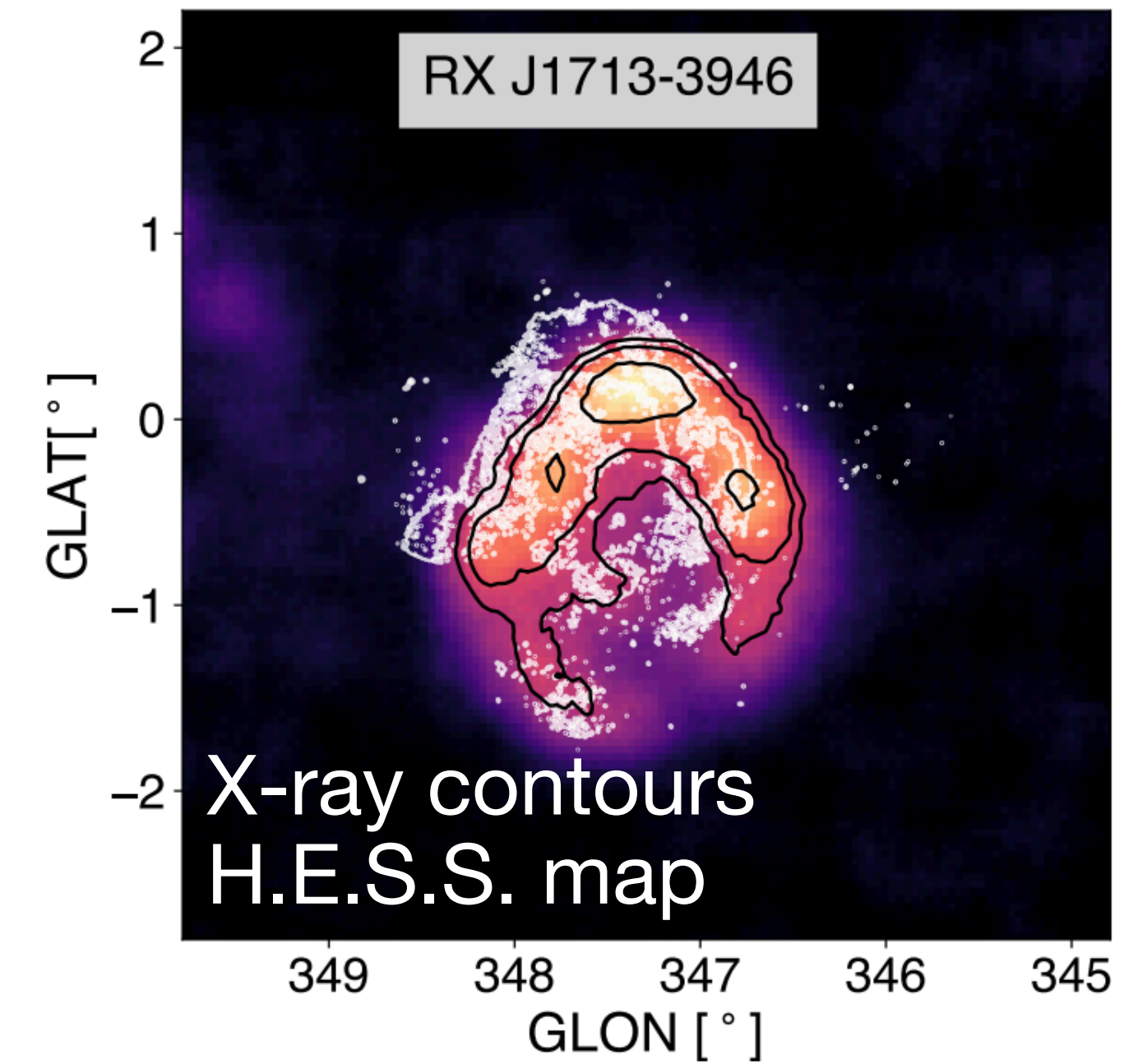
**SC+ SNRs  
contribution to  
diffuse gamma**



Not enough elements to  
conclude but the simulated  
population may contribute  
significantly

Multi-wavelength before multi-messenger

# Broadband modeling

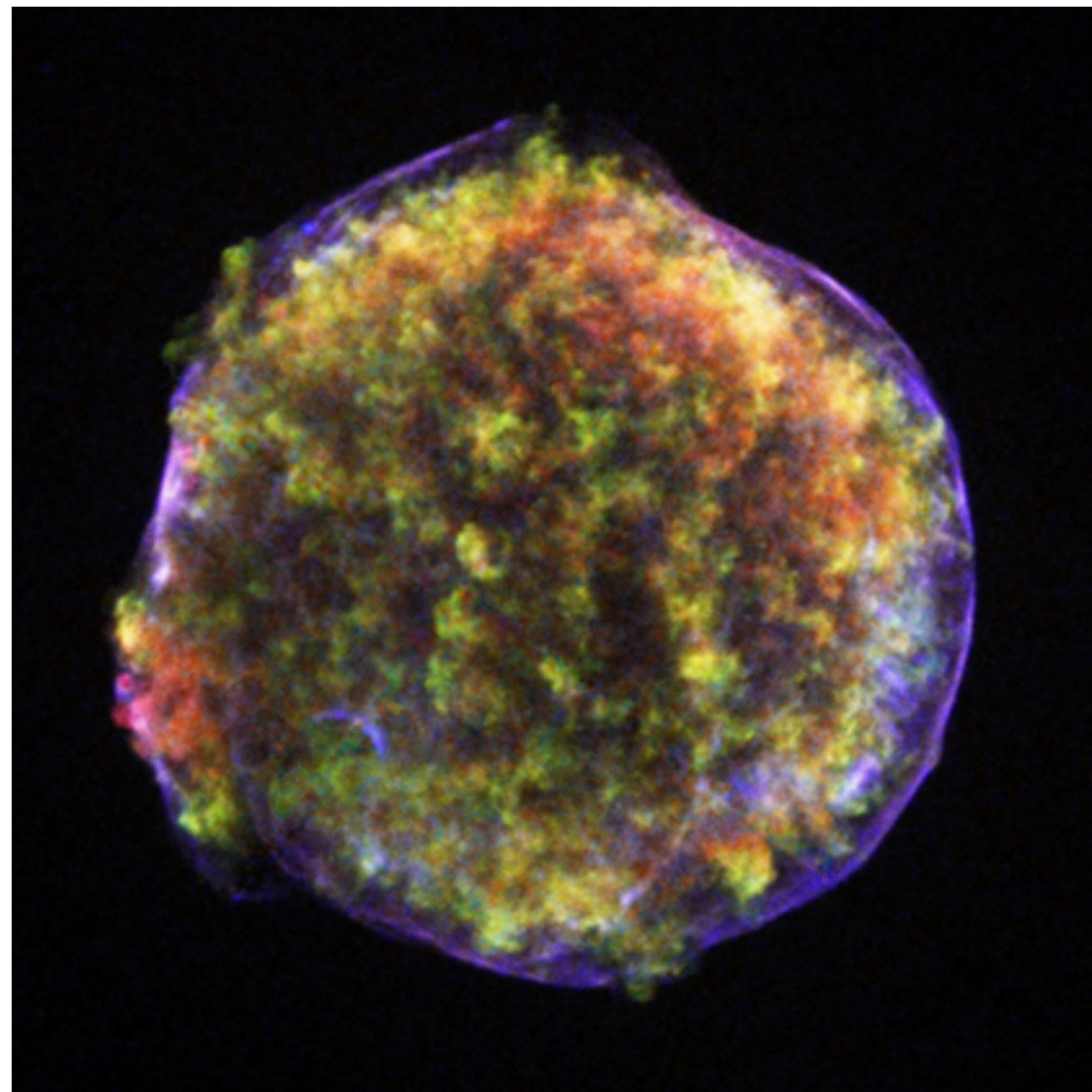




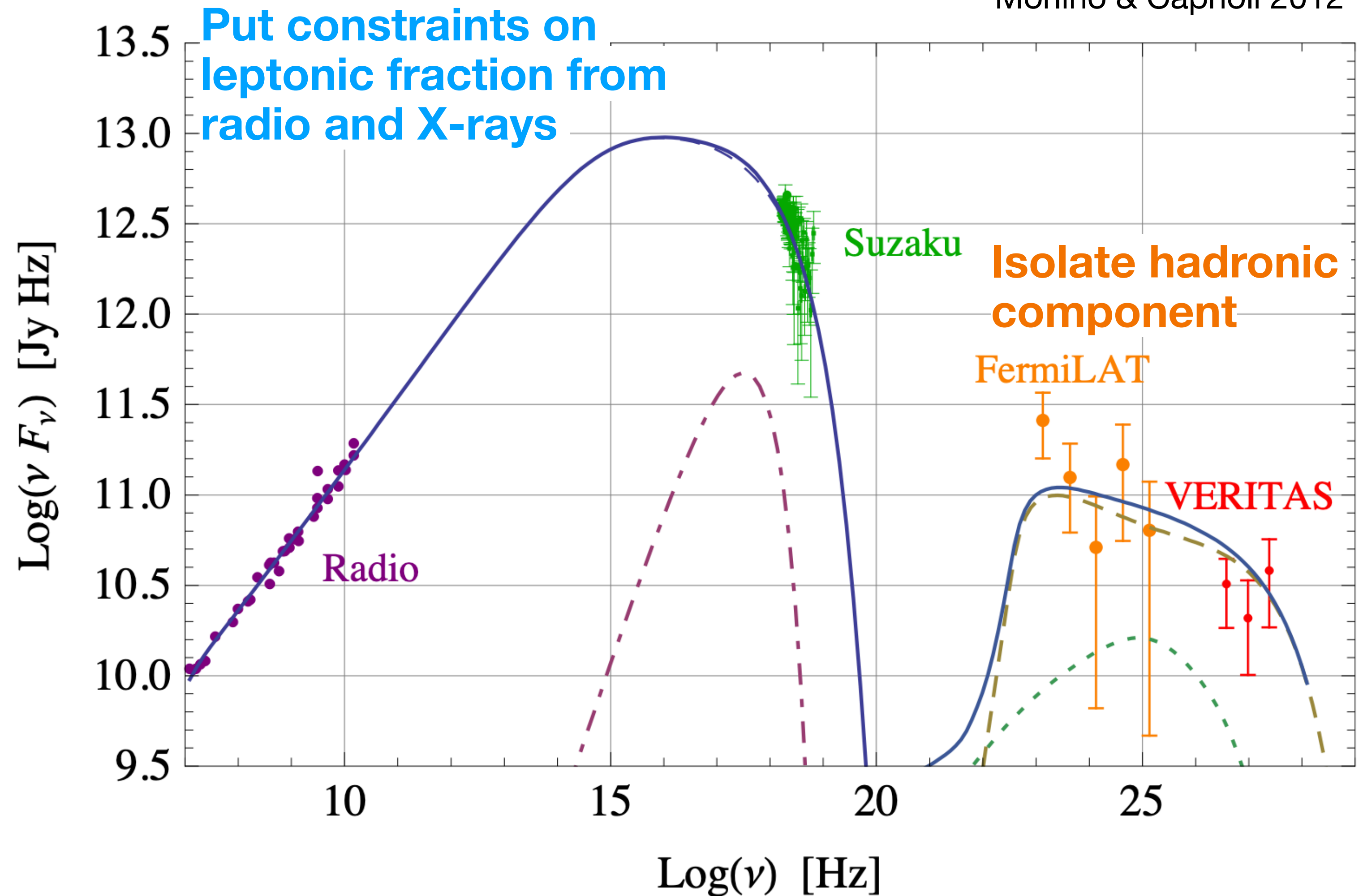
# Broadband modeling

SNR are bright in Radio due to synchrotron emission → leptonic emission

The example of Tycho



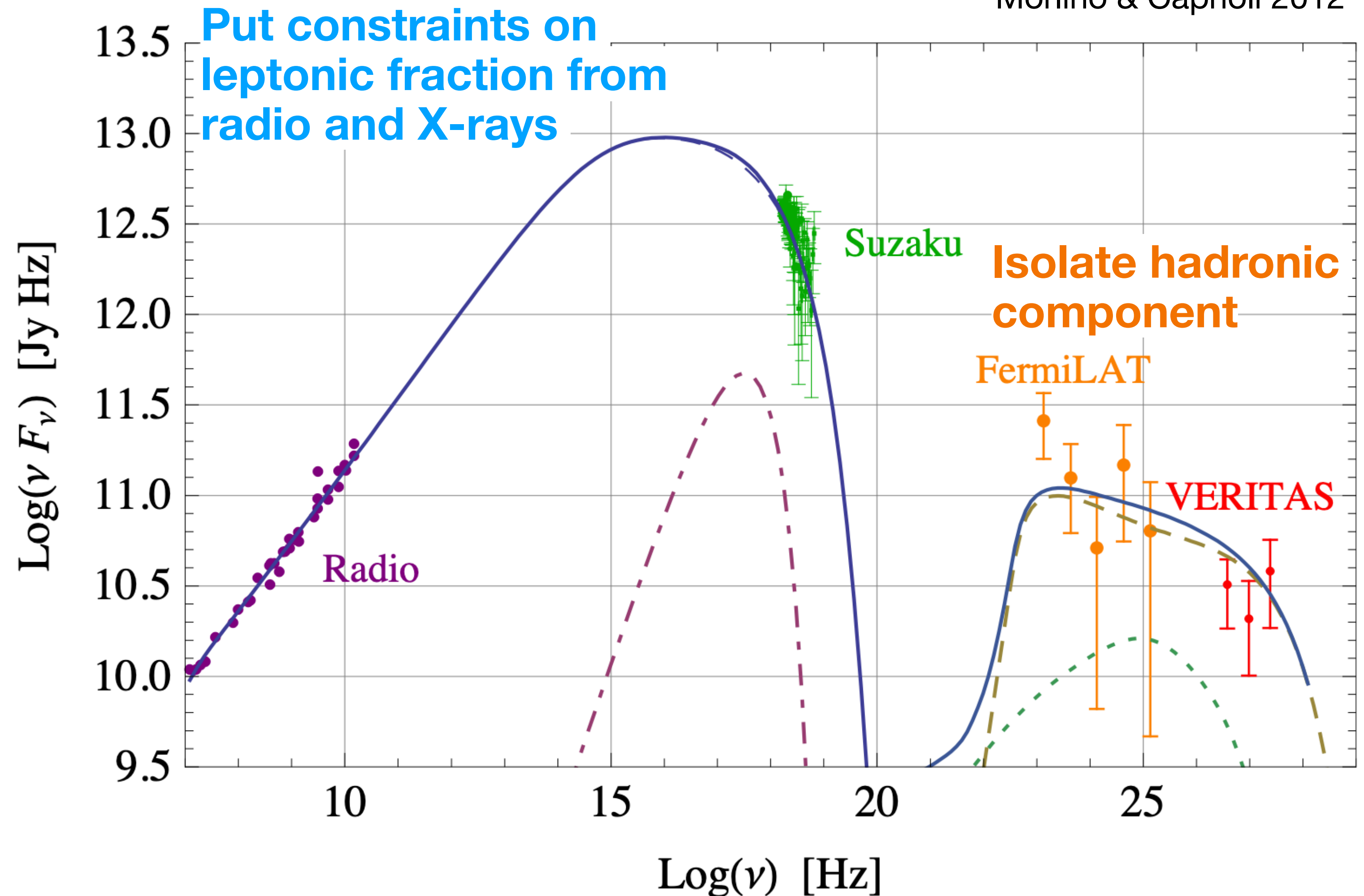
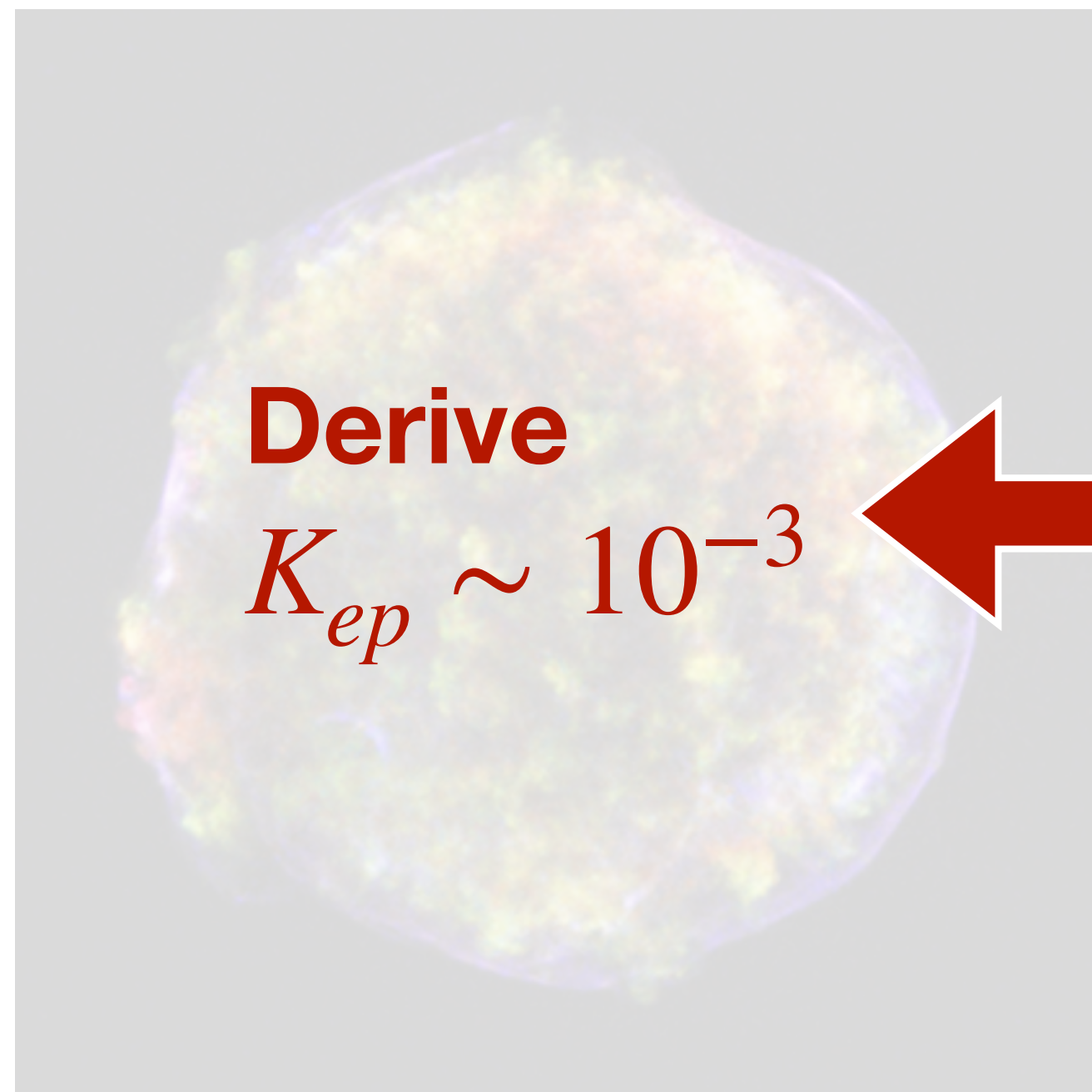
Morlino & Caprioli 2012



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SNR are bright in Radio due to synchrotron emission —> leptonic emission

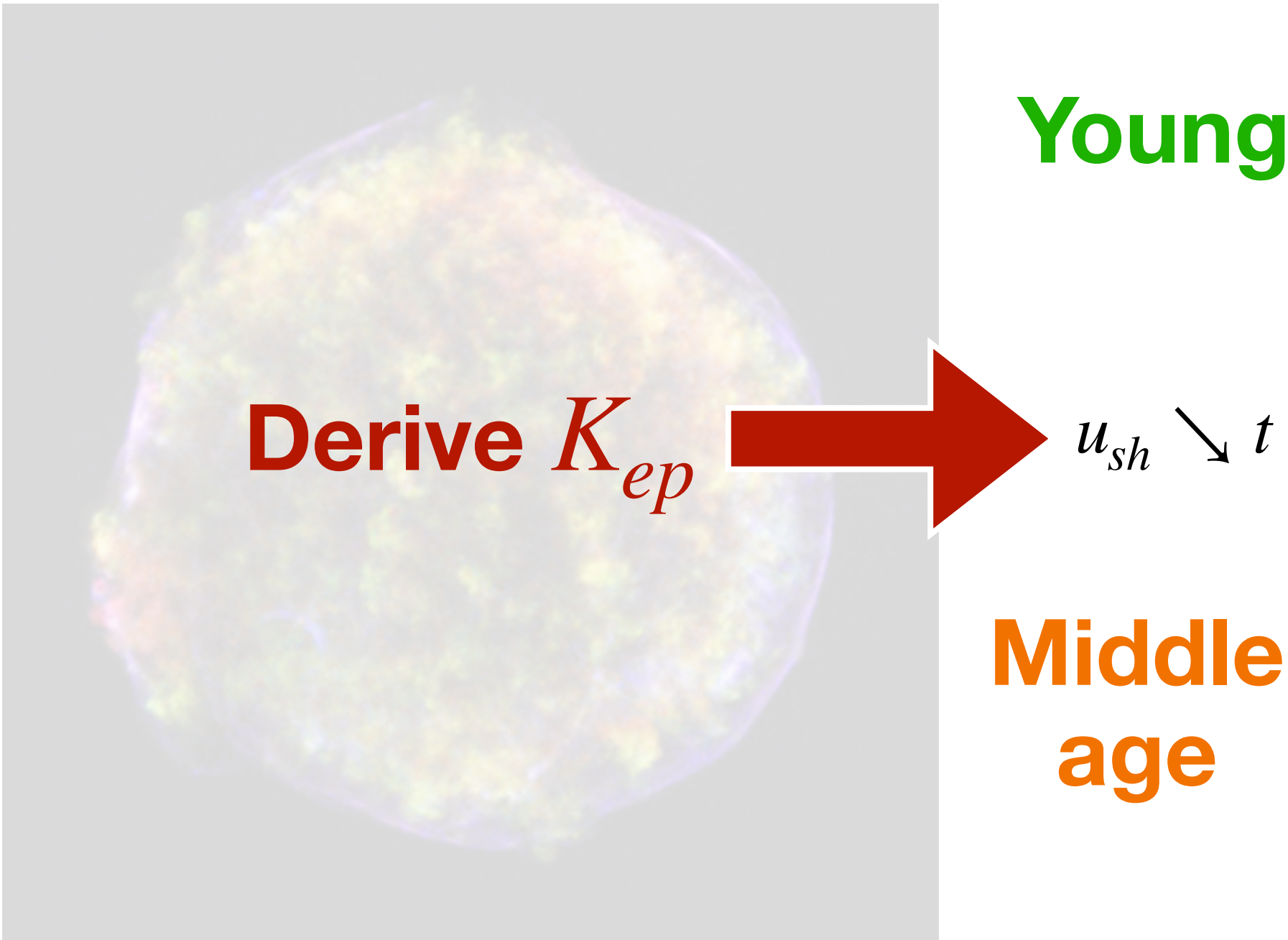
The example of Tycho





# Broadband modeling

SNR are bright in Radio due to synchrotron emission —> leptonic emission  
..not only Tycho



| SNR         | Kep   | Age     | Reference                   |
|-------------|-------|---------|-----------------------------|
| Tycho       | 1e-03 | 0.5 kyr | Morlino&Caprioli+2012       |
| Vela Jr.    | 1e-4  | 0.7 kyr | Berezhko+2009               |
| W44         | 6e-03 | 30 kyr  | Zirakashvili & Ptuskin 2016 |
| W28         | 8e-03 | 30 kyr  | Zirakashvili & Ptuskin 2016 |
| Cygnus Loop | 0.15  | 20 kyr  | Loru+2020                   |
| HB21        | 5e-03 | ~10 kyr | Ambrogi+2019                |

# Broadband modeling

..not only SNRs

**Embedded star clusters:  
some have measured non-  
thermal emission from  
radio to X-ray**

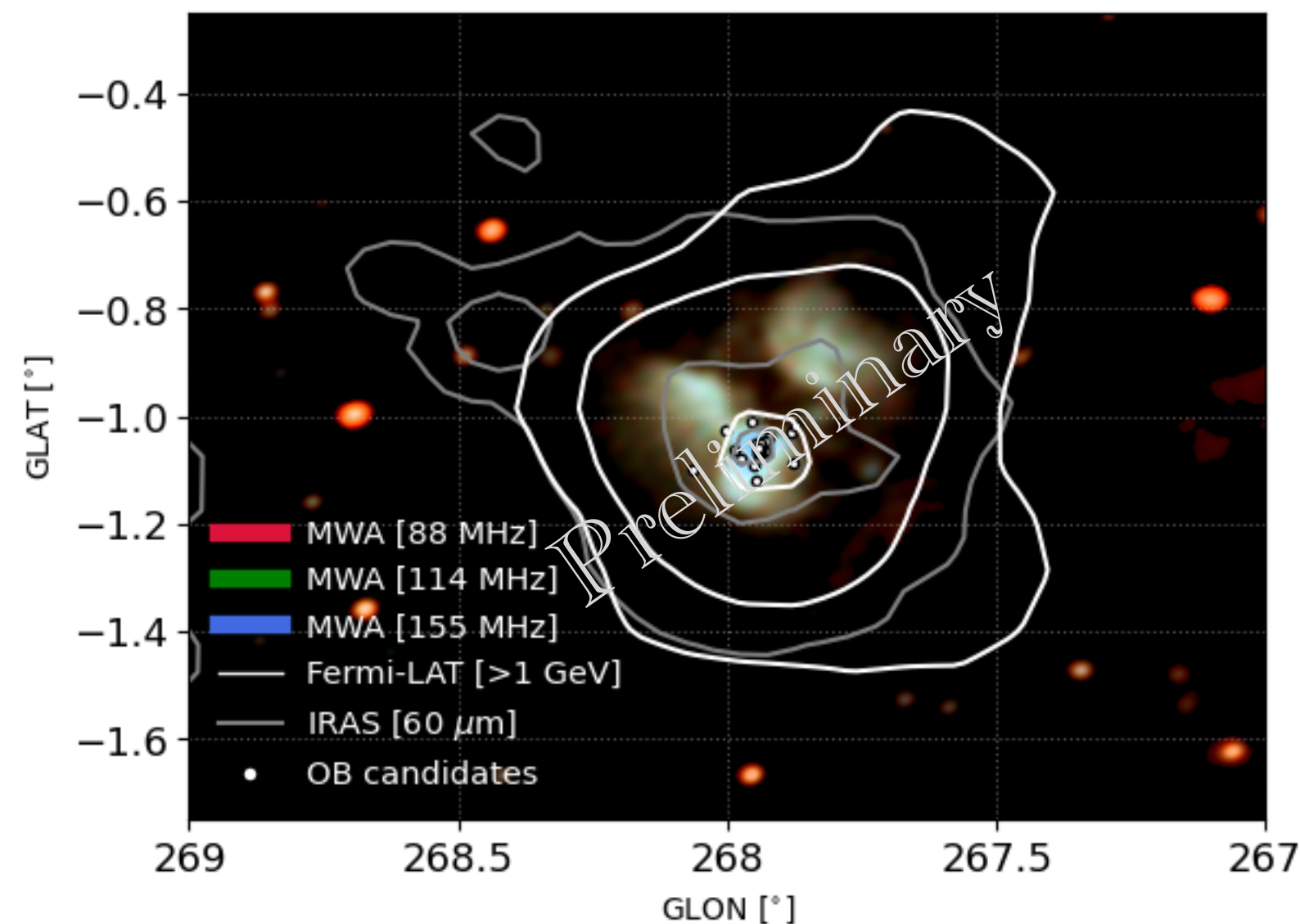


# Broadband modeling

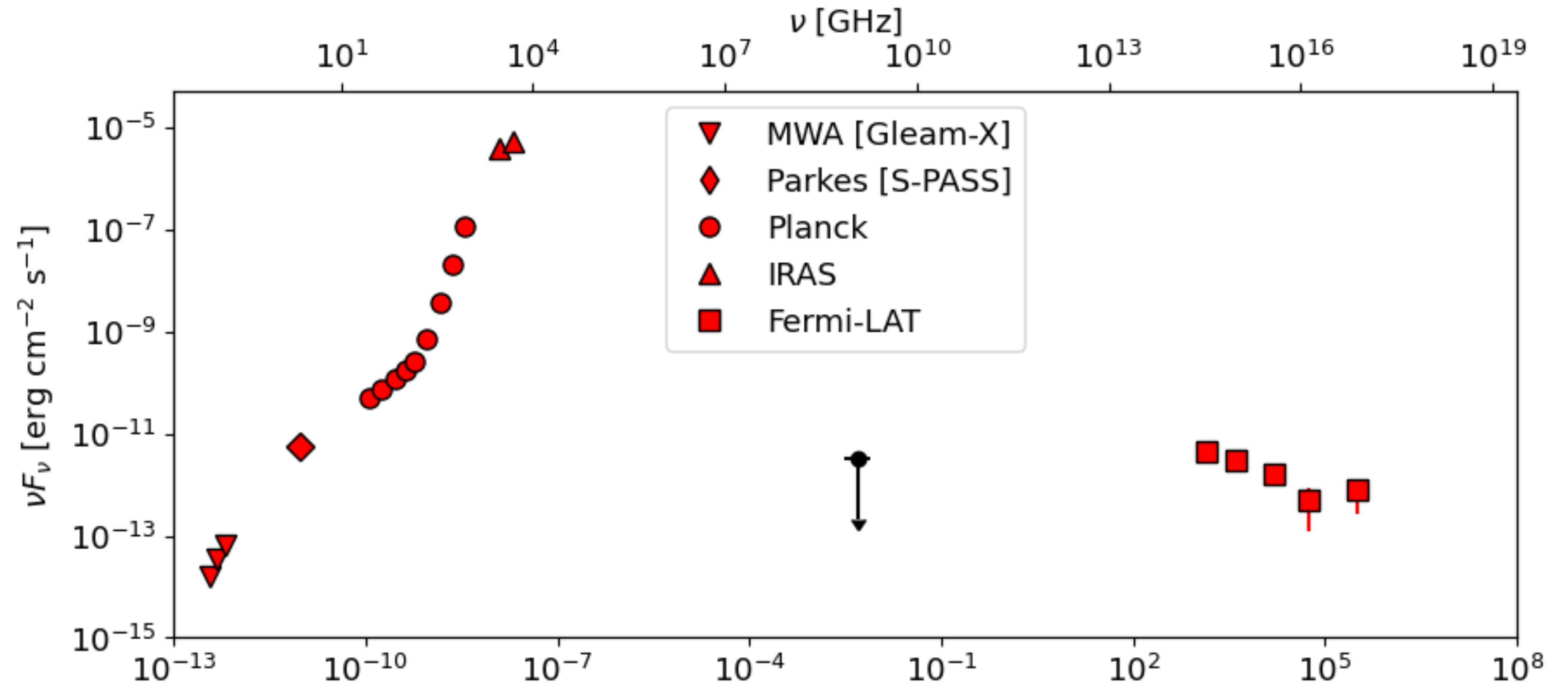
..not only SNRs

Embedded star clusters:  
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The example of RCW38



Peron et al. 2026 in prep.

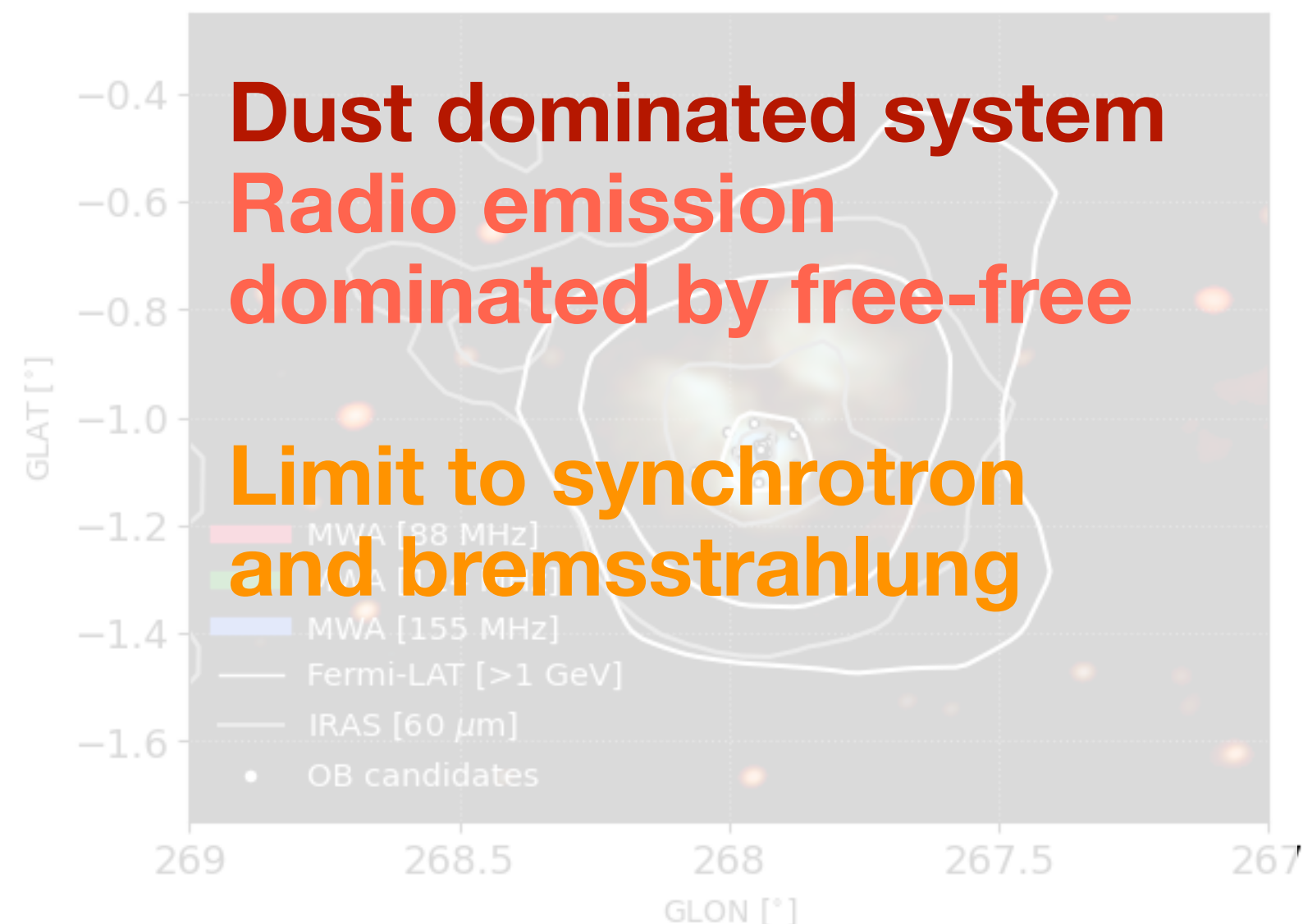


# Broadband modeling

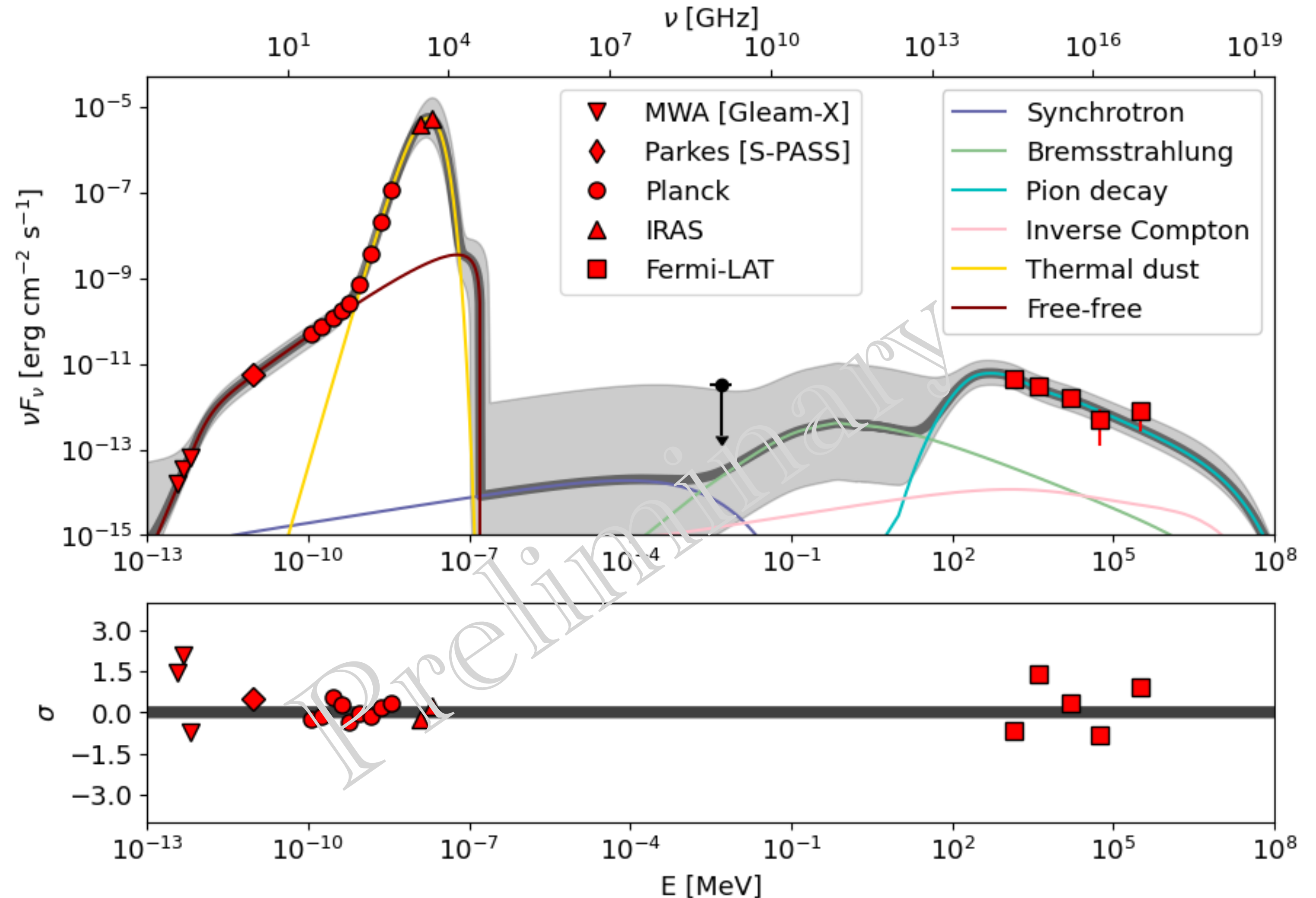
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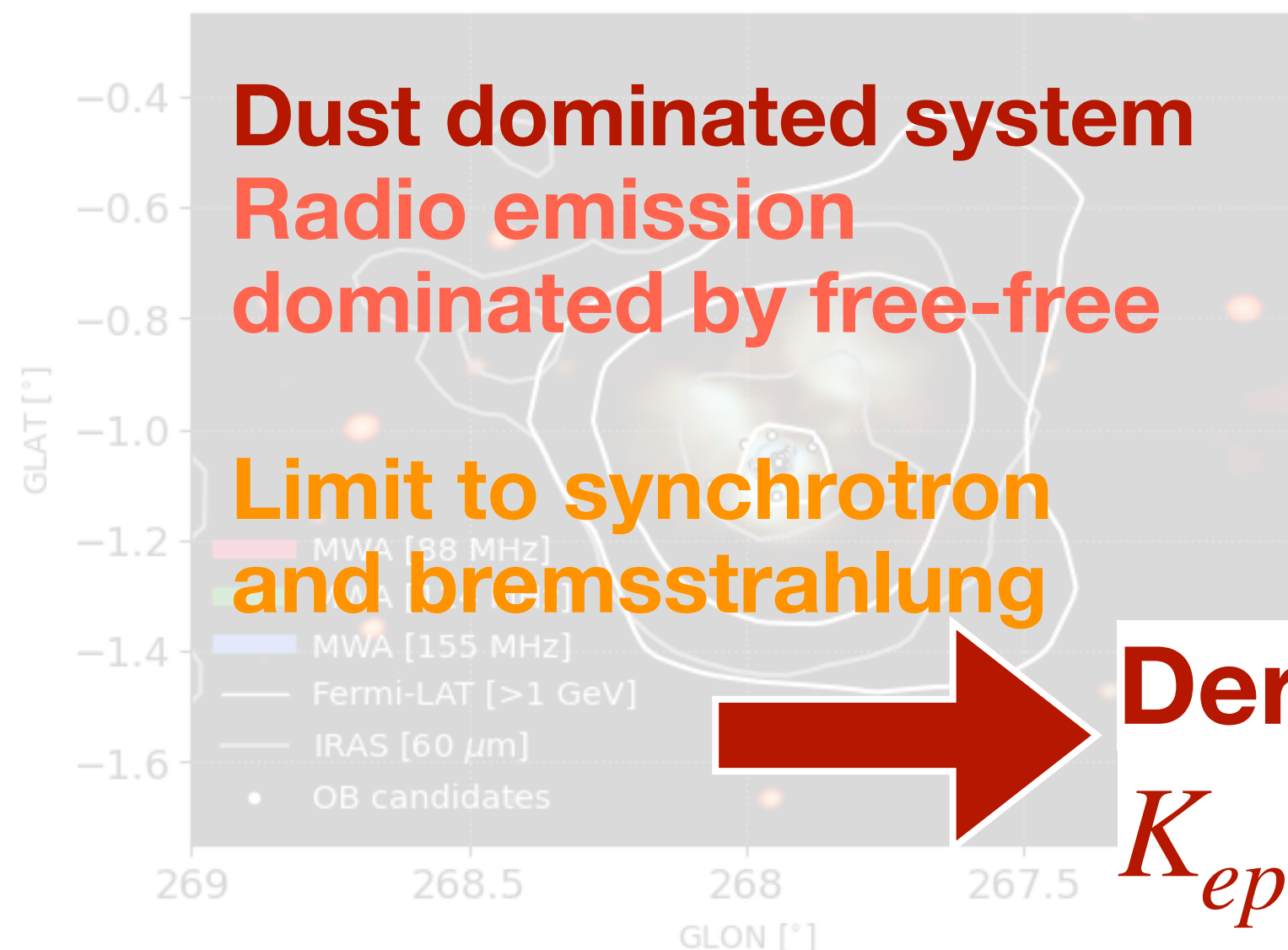


# Broadband modeling

Peron et al. 2026 in prep.

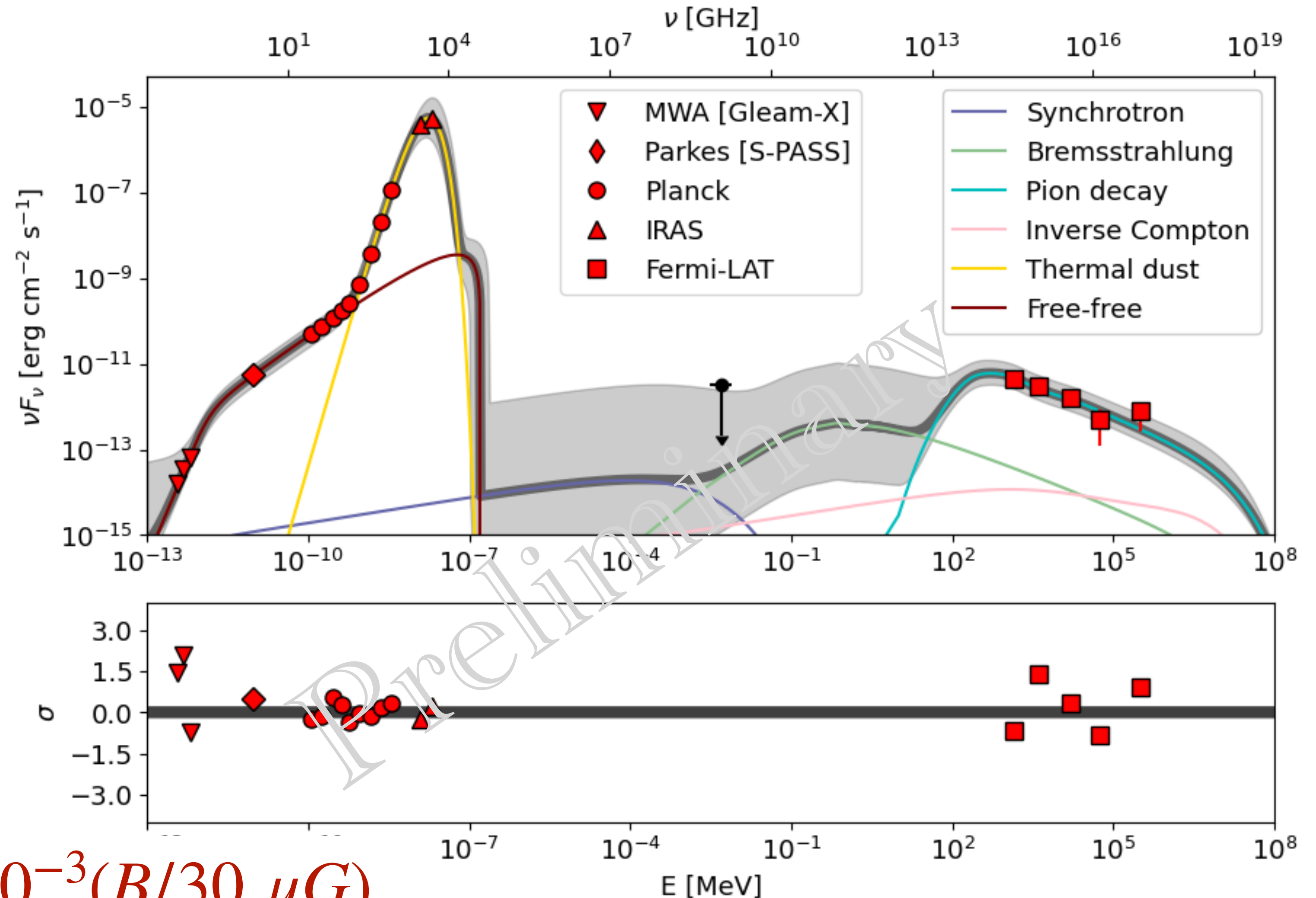
Embedded star clusters:  
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The example of RCW38



Derive

$$K_{ep} \sim 10^{-3} (B/30 \mu G)$$

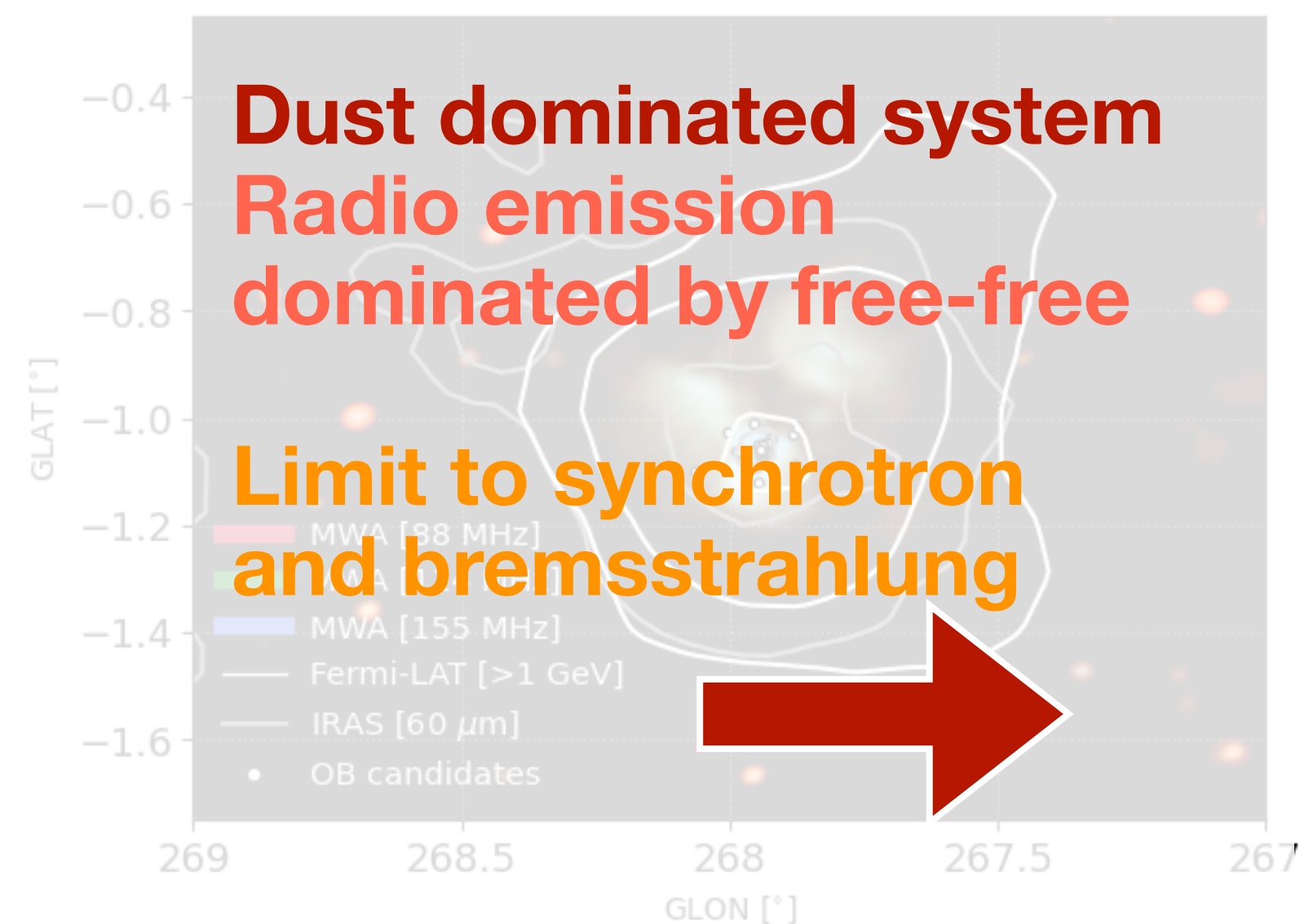


# Broadband modeling

..not only SNRs

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## The example of RCW38



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|             |       |         |                             |
| YMSC        | Kep   | Age     | Reference                   |
| RCW38       | 1e-3  | 1 Myr   | Peron 2026, in prep.        |



# Summary

- To explain cosmic-ray at Earth we need hadronic sources — sources that produce hadrons more than leptons
- To recognize hadronic sources one can rely on spectral features: threshold or pion-bump, but not always clear in the observations
- Correlation with gas structures help in recognizing and isolating hadronic emission both in the source surroundings and in the diffuse medium
- The hadronic component of diffuse cosmic rays is revealed by gamma-rays and neutrinos. Difficult to conclude at this stage but scenarios where hadronic CR distribution is consistent to hadronic CR distribution observed at Earth are possible.
- Hadronic acceleration has now been recognized not only in SNRs but also in stellar clusters and in the MQ Cygnus X-3
- Understanding the ratio of accelerated leptons over protons helps in understanding acceleration in these environments