Cosmic Rays

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Disclaimer

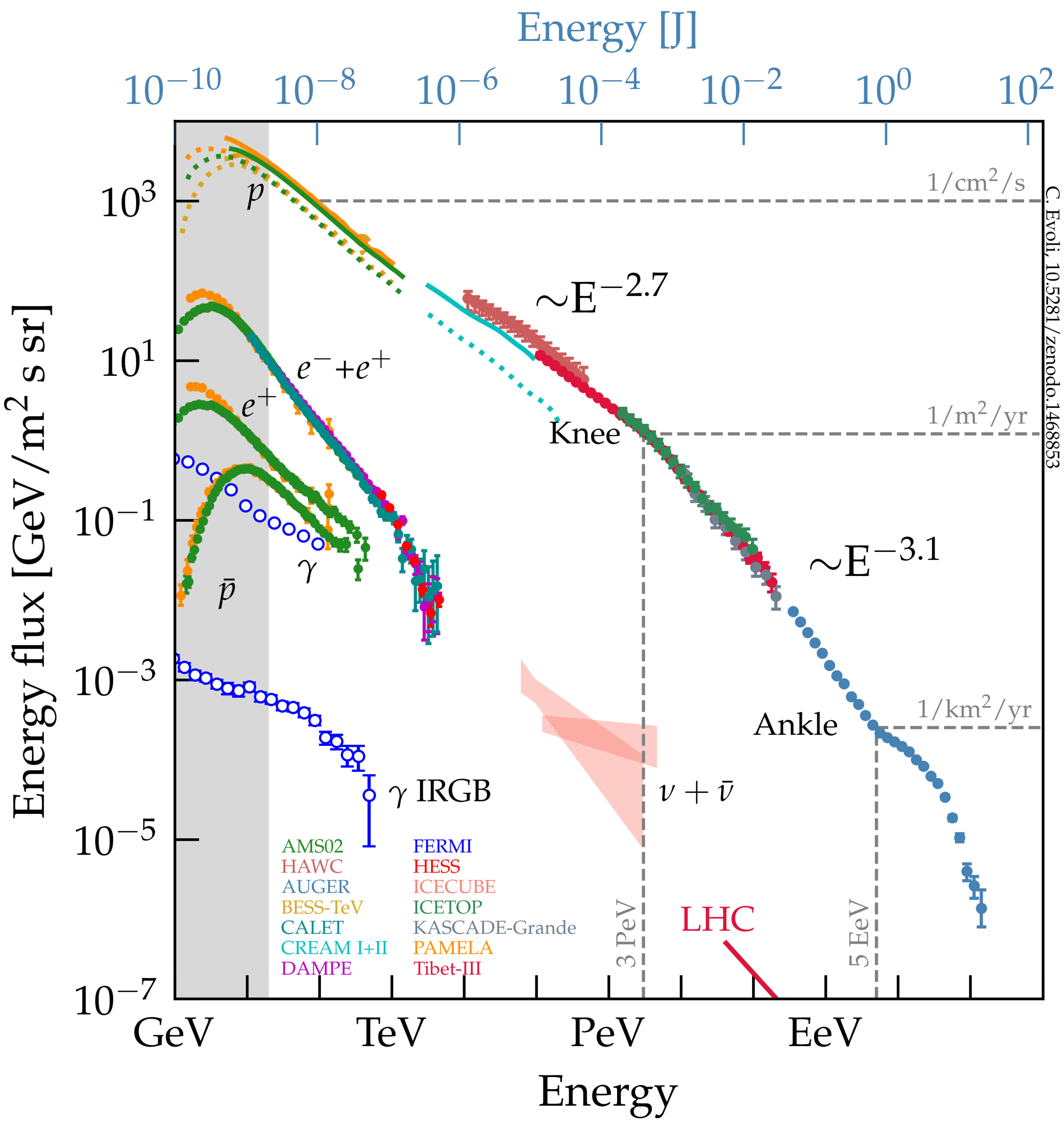
This talk will be focussed mainly on Galactic cosmic rays (because the speaker does not feel he has much to say about extragalactic ones…). A large fraction of the stuff shown in the following slides comes from two recent review articles:

- Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, Int. J. Mod. Phys. D (2019) -> high energy CRs
- Tatischeff & Gabici, Ann. Rev. Nucl. Part. Sci. (2018) -> low energy CRs

Outline of the talk

- The orthodoxy: a critical review
  - The three pillars of orthodoxy
  - Recent observations and open questions
- Galactic cosmic rays and neutrinos
  - The link with gamma rays
  - Neutrinos from the Galactic disk
  - Neutrinos from the Galactic halo
  - Neutrinos from Galactic sources of CRs
- Conclusions

The cosmic ray spectrum



Evoli 2018

A classic set of questions

[1] **Which classes of sources** contribute to the CR flux in different energy ranges? How many types of sources provide a significant contribution to the overall CR flux?

[2] Are CR **nuclei and electrons** accelerated by the same sources?

[3] Which sources are capable of reaching the **highest particle energies** and how?

[4] Which are the processes responsible for **CR confinement in the Galaxy**?

[5] Where is the **transition between Galactic and extra-Galactic CRs** and how can we explain the well-known features such as knee, second knee, ankle?

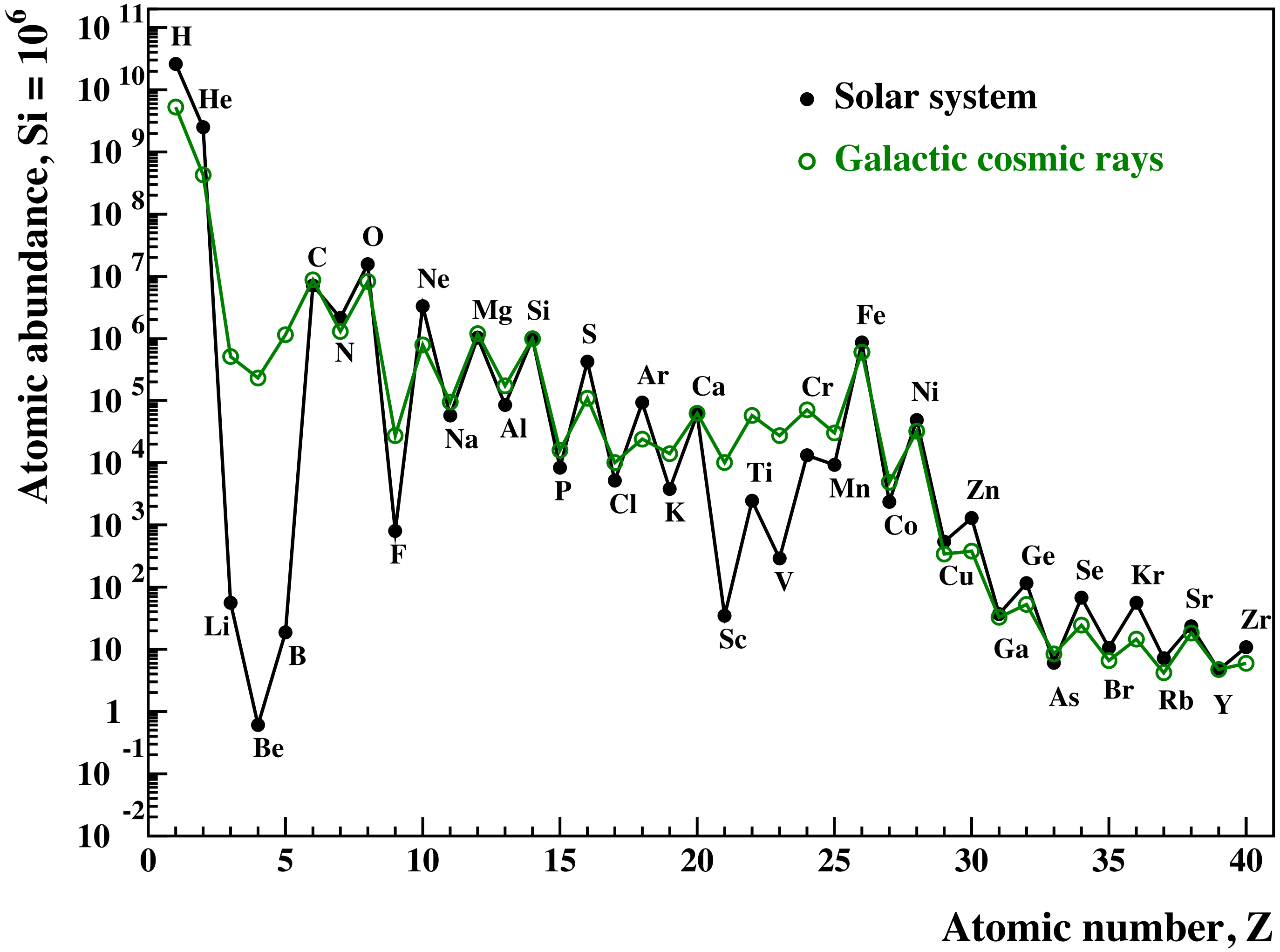
[6] What is the origin of the difference between the **chemical composition of CRs** and the solar one?

The orthodoxy (1)

- The bulk of the energy of cosmic rays originates from supernova explosions in the Galactic disk

The orthodoxy (1)

The bulk of the energy of CRs originates from SN explosions in the Galactic disk



Tatischeff & SG 2018

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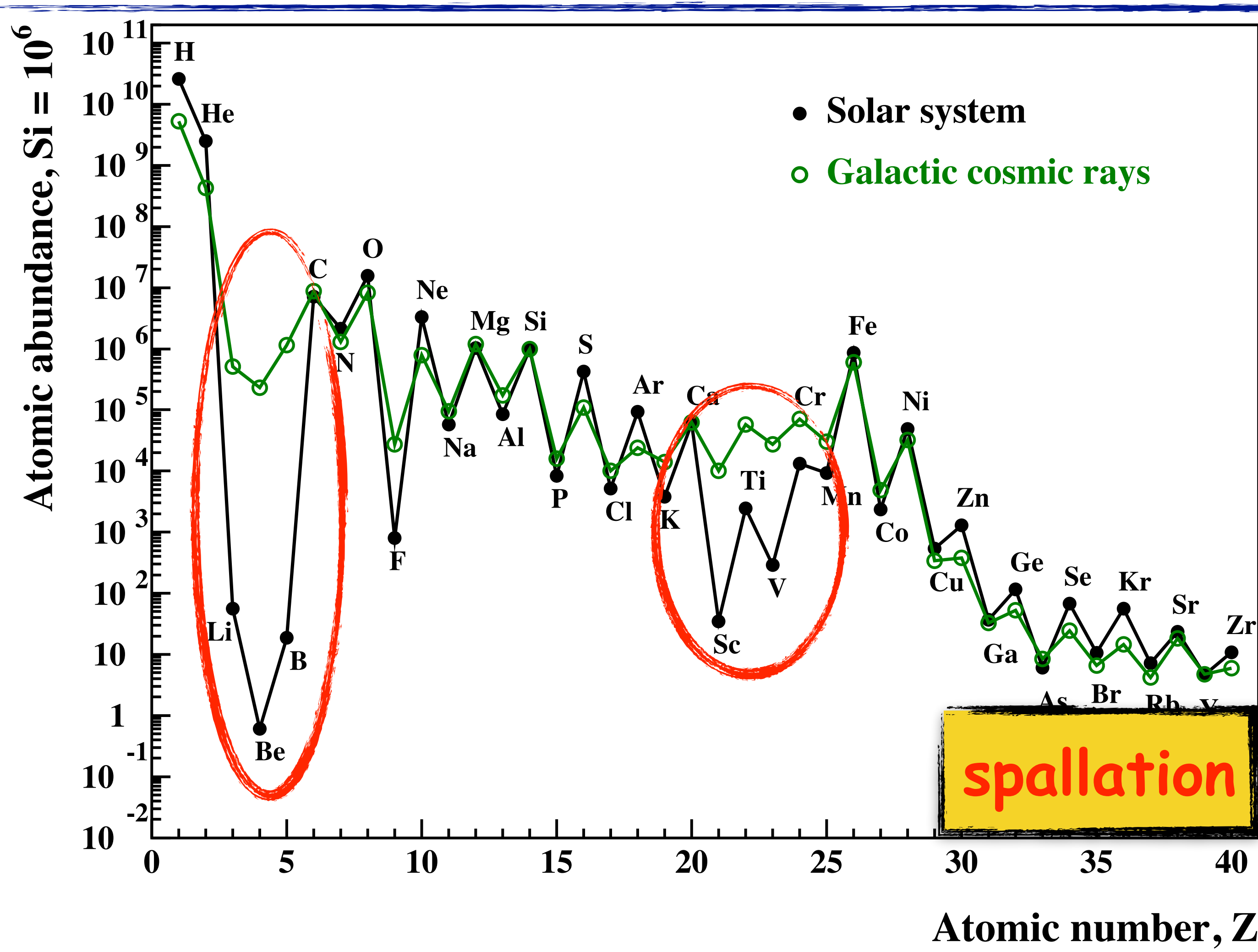

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- energy/nucleon is conserved in spallation reactions
- Boron (secondary) is produced mainly in spallation reactions involving Carbon (primary)

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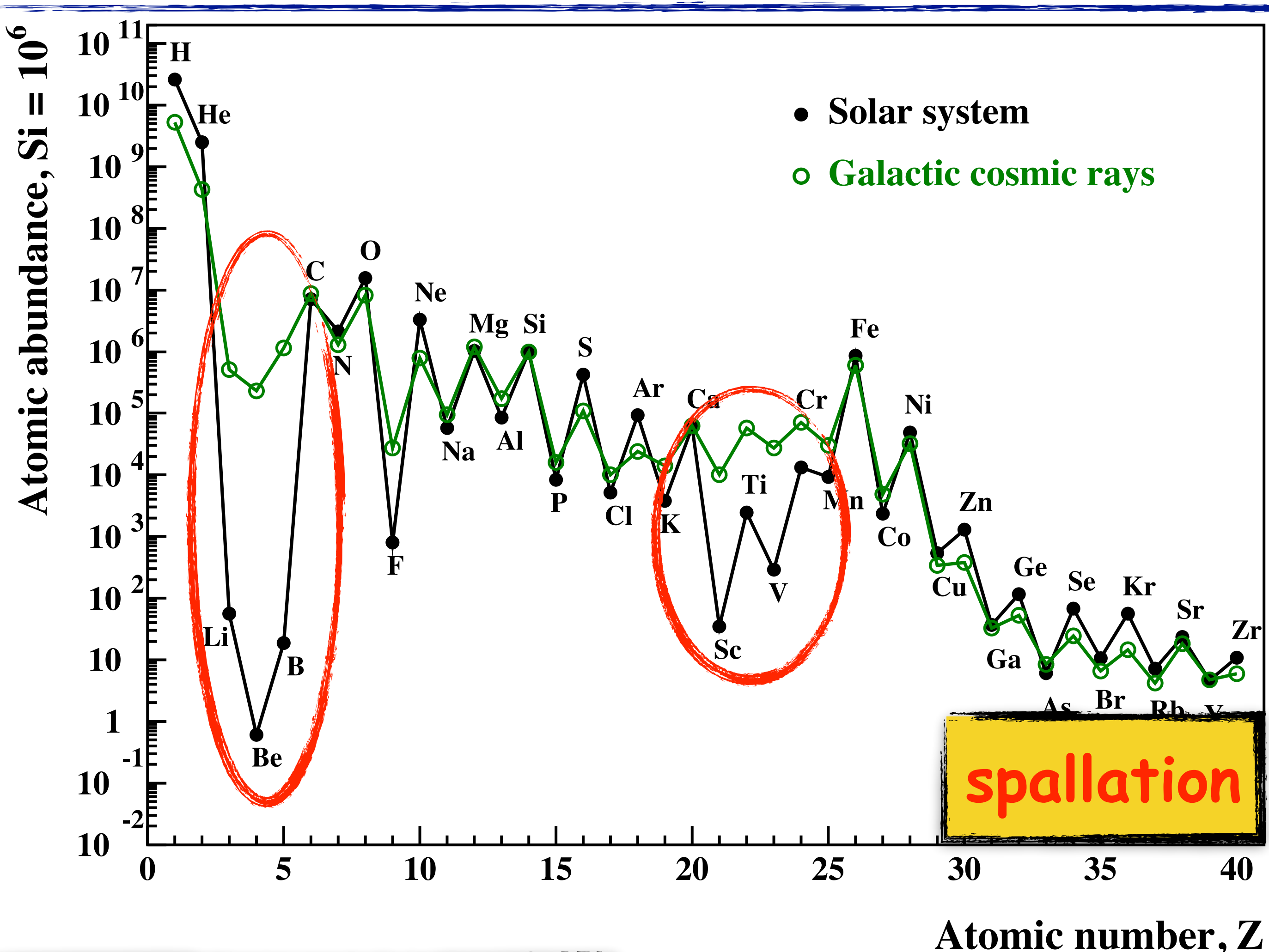

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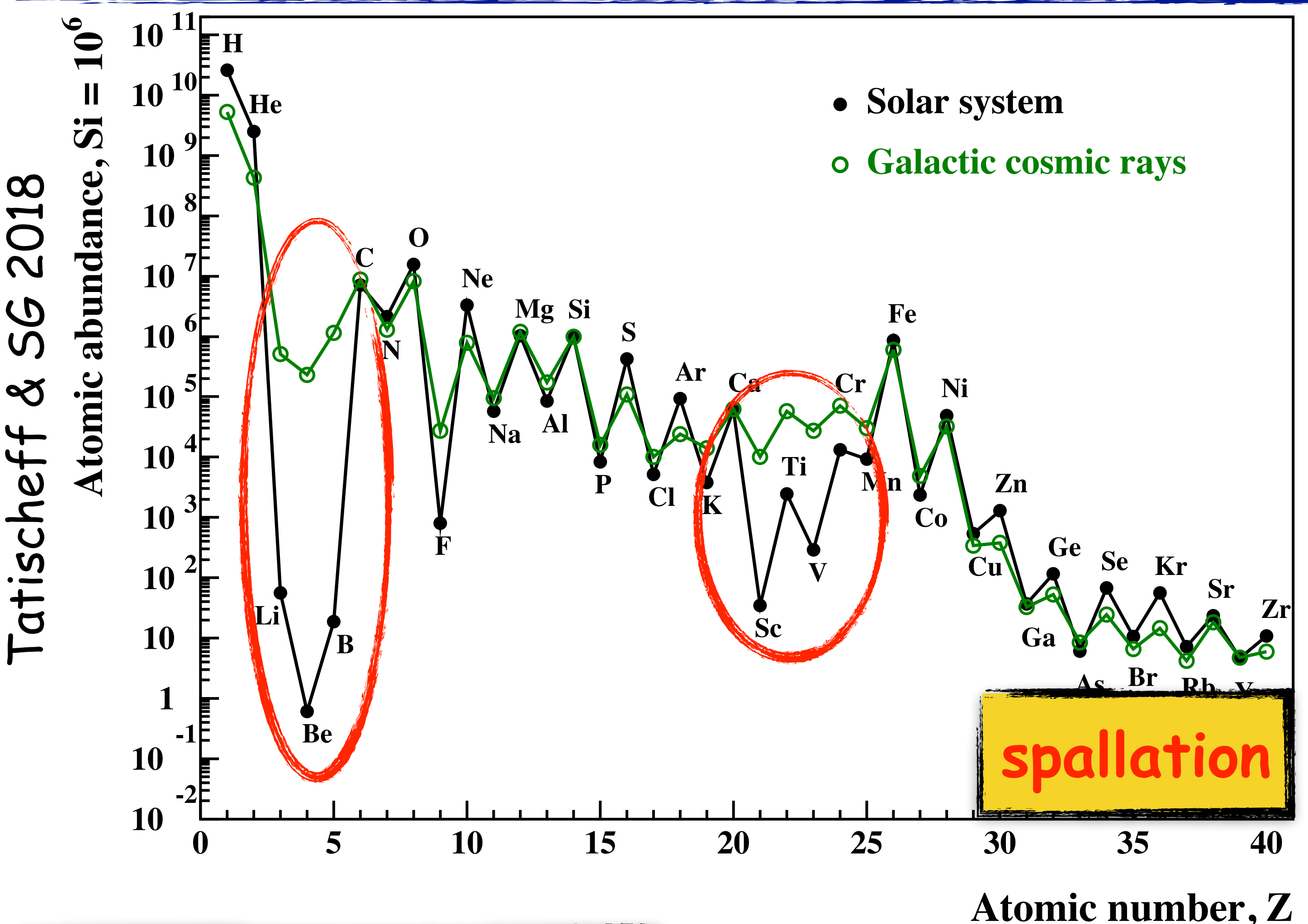

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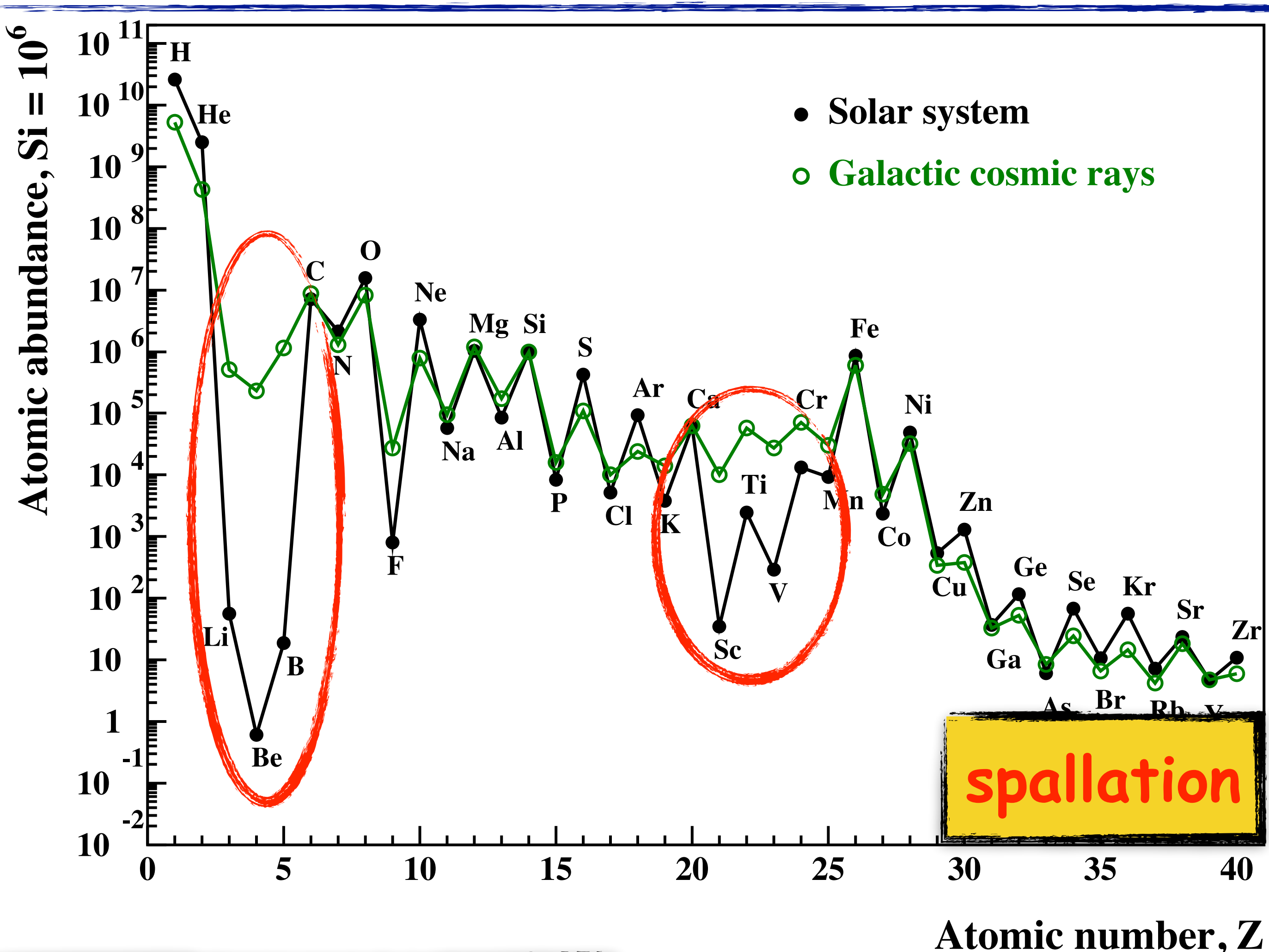

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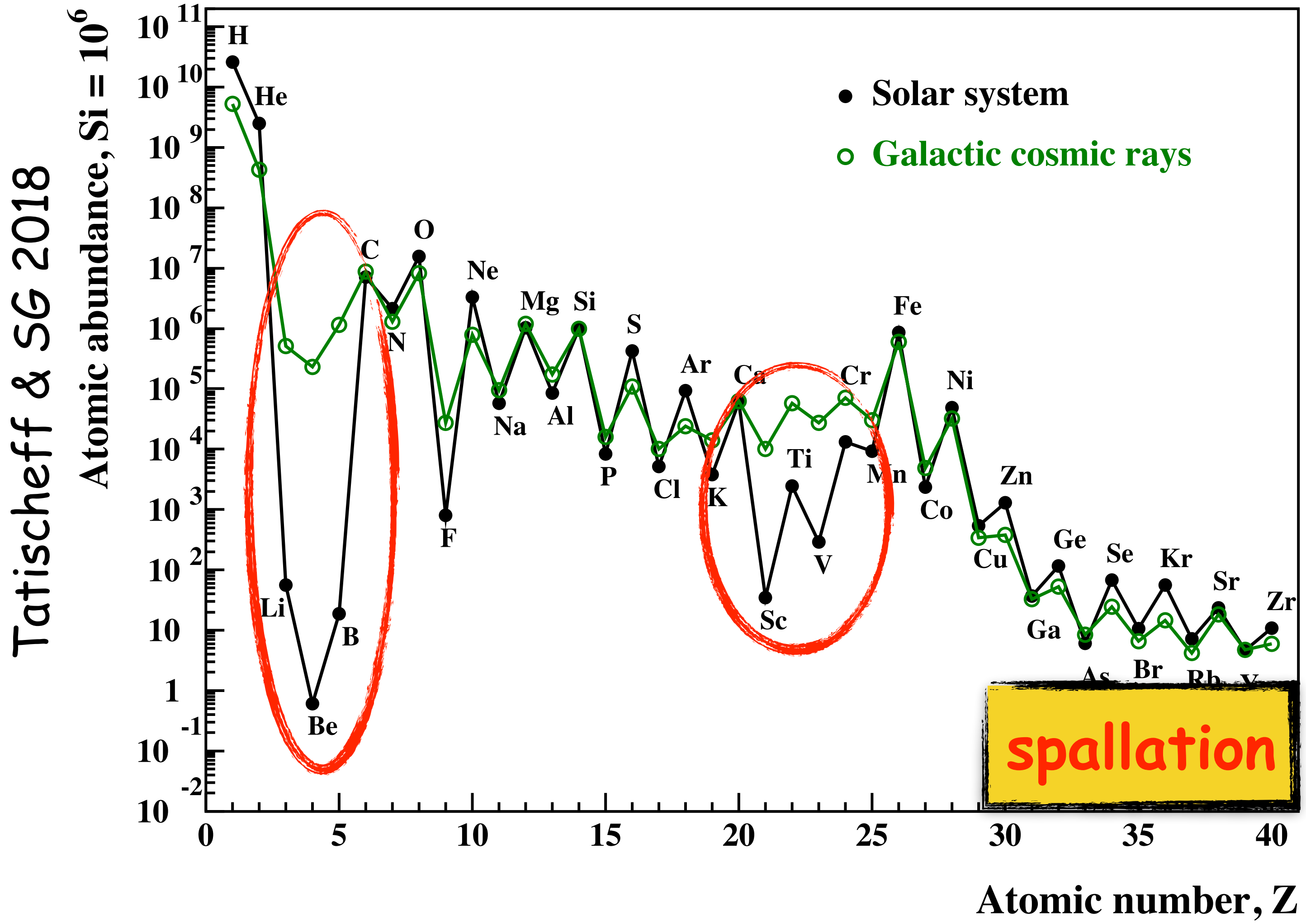

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grammage

$$\Lambda_g = \mu m_p \, n_{ISM} \, \tau_{disk} \, c \longrightarrow \boxed{\frac{n_B}{n_C} \sim \frac{\sigma_s}{\mu m_p} \Lambda_g}$$

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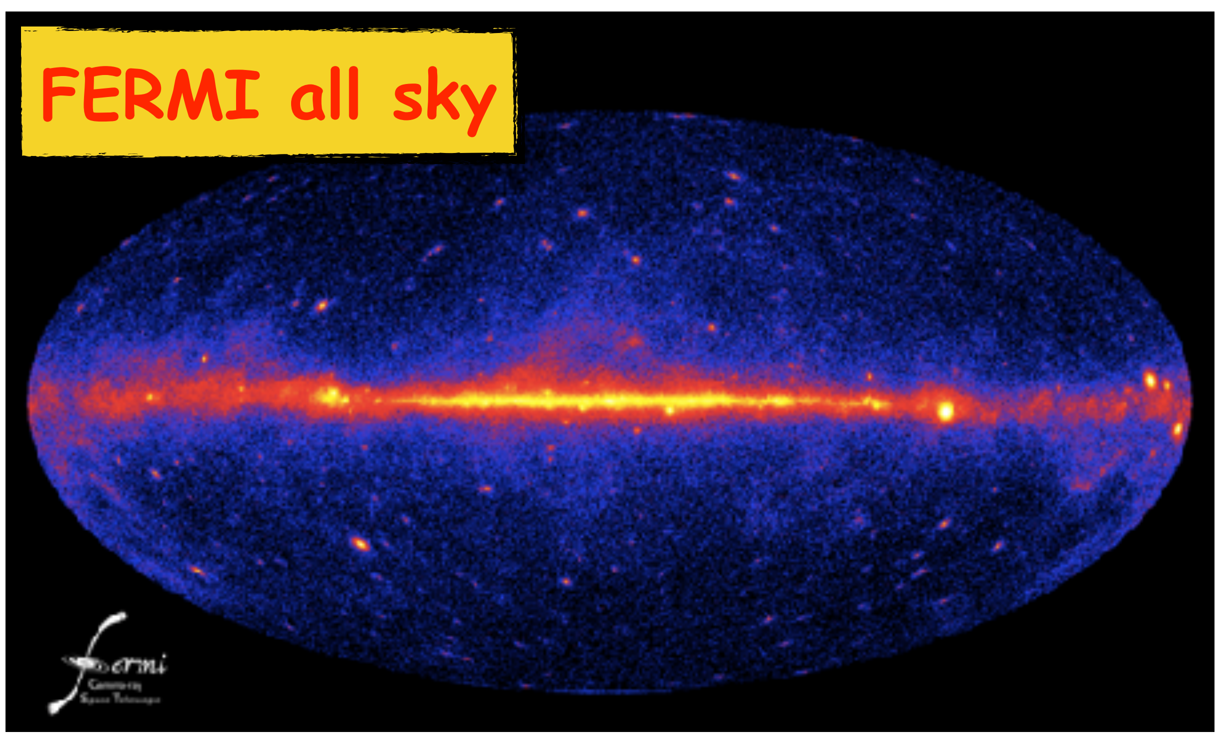
CR energy density

total CR energy in the disk

MW disk volume

$$w_{CR} \sim 1 \text{ eV/cm}^3 \longrightarrow \mathcal{E}_{CR} = w_{CR} V_{disk}$$

Small spatial gradient



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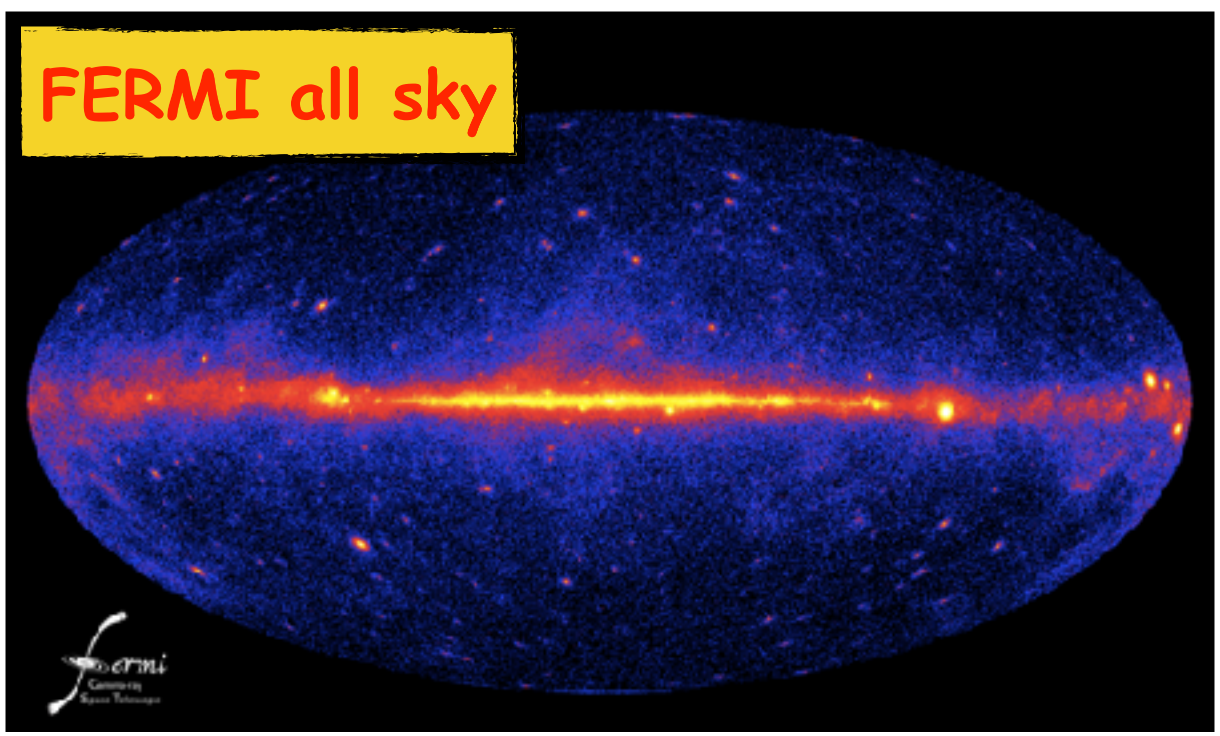

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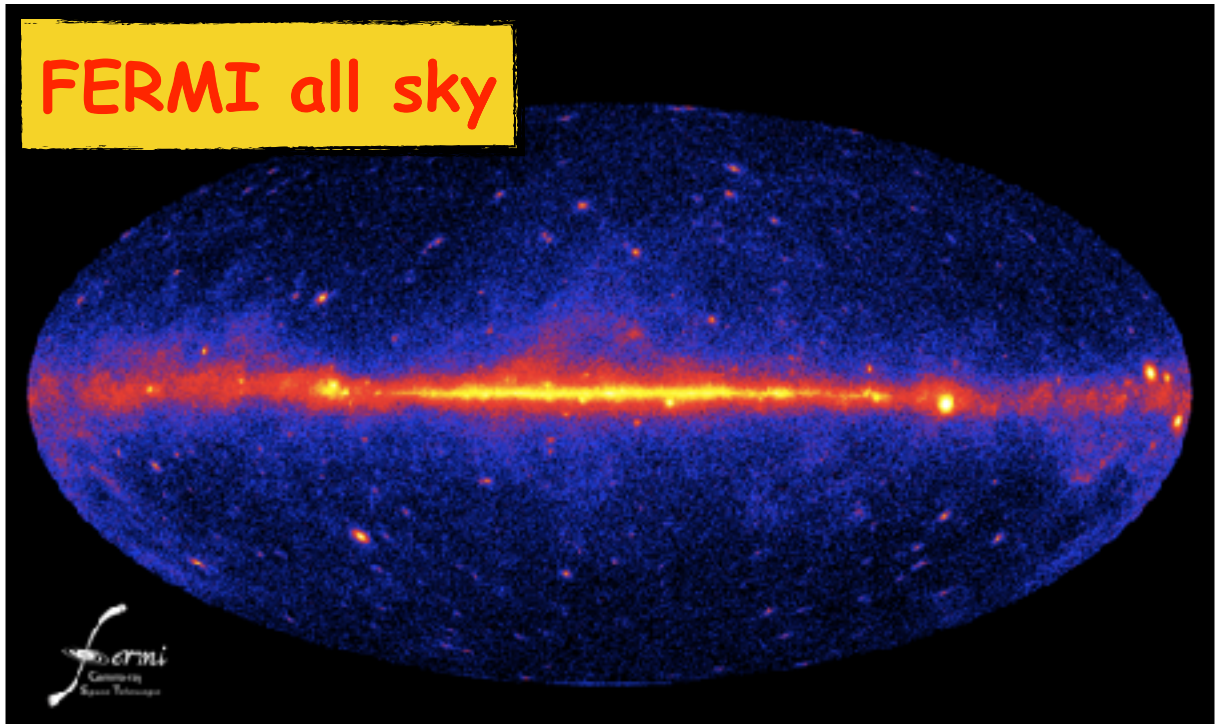

Power of CR sources in the disk

$$L_{CR} = W_{CR}/\tau_{disk} \sim 10^{41} \text{erg/s}$$

Power of Galactic SN explosions

10^{51} erg

3/century

$$L_{SN} = E_{SN} \nu_{SN} \sim 10^{42} \text{erg/s}$$

The orthodoxy (2)

- Cosmic rays are diffusively confined within an extended and magnetised Galactic halo

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$$\tau(^{10}\text{Be}) \sim 1.4 \text{ Myr}$$

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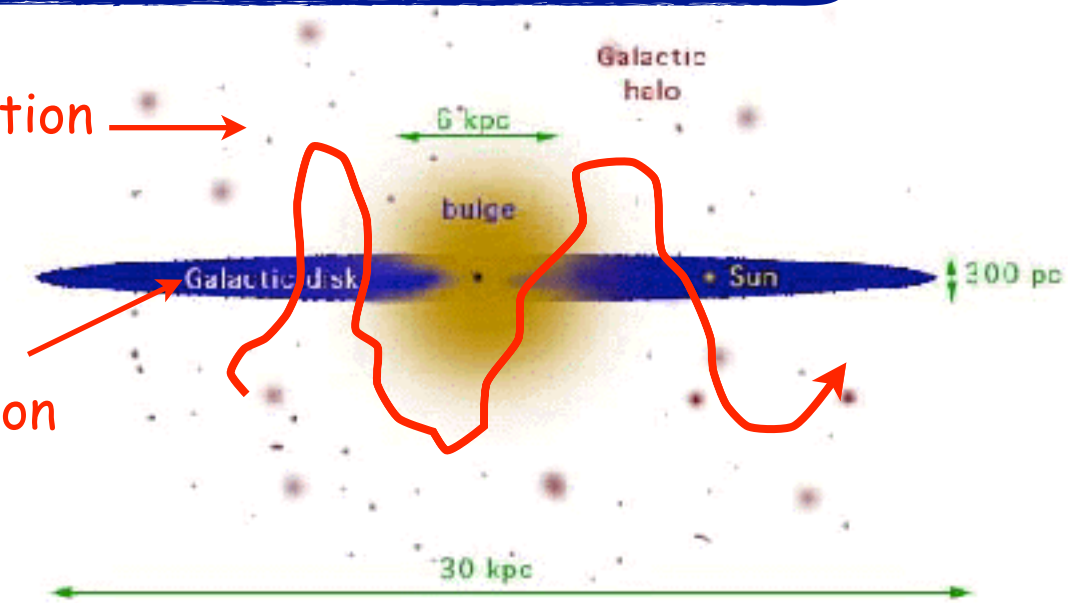
no spallation

spallation



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zero-order prediction -> small dipole anisotropy towards the Gal. centre

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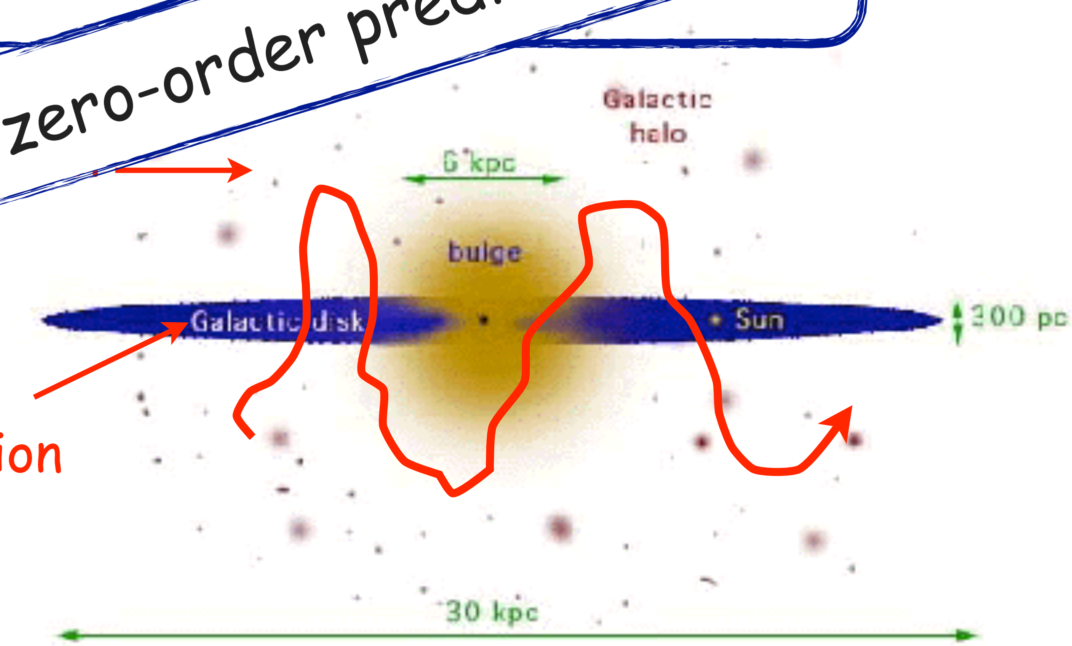


spallation

The orthodoxy (3)

- Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

The orthodoxy (3)

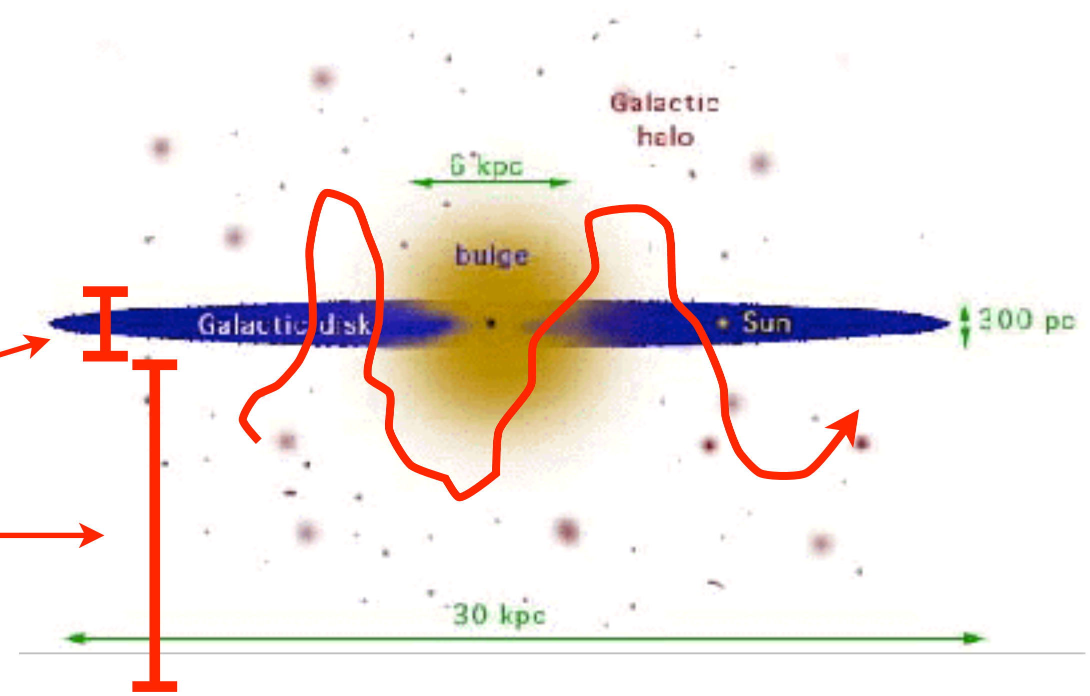
- CRs are accelerated out of the (dusty) ISM through DSA in SNRs

effective grammage

$$\Lambda_g \sim \bar{\varrho}\; \tau_{esc}\; c$$

mean density

$$\bar{\varrho} = \mu m_p n_{ISM} \left(\frac{h}{H}\right)$$



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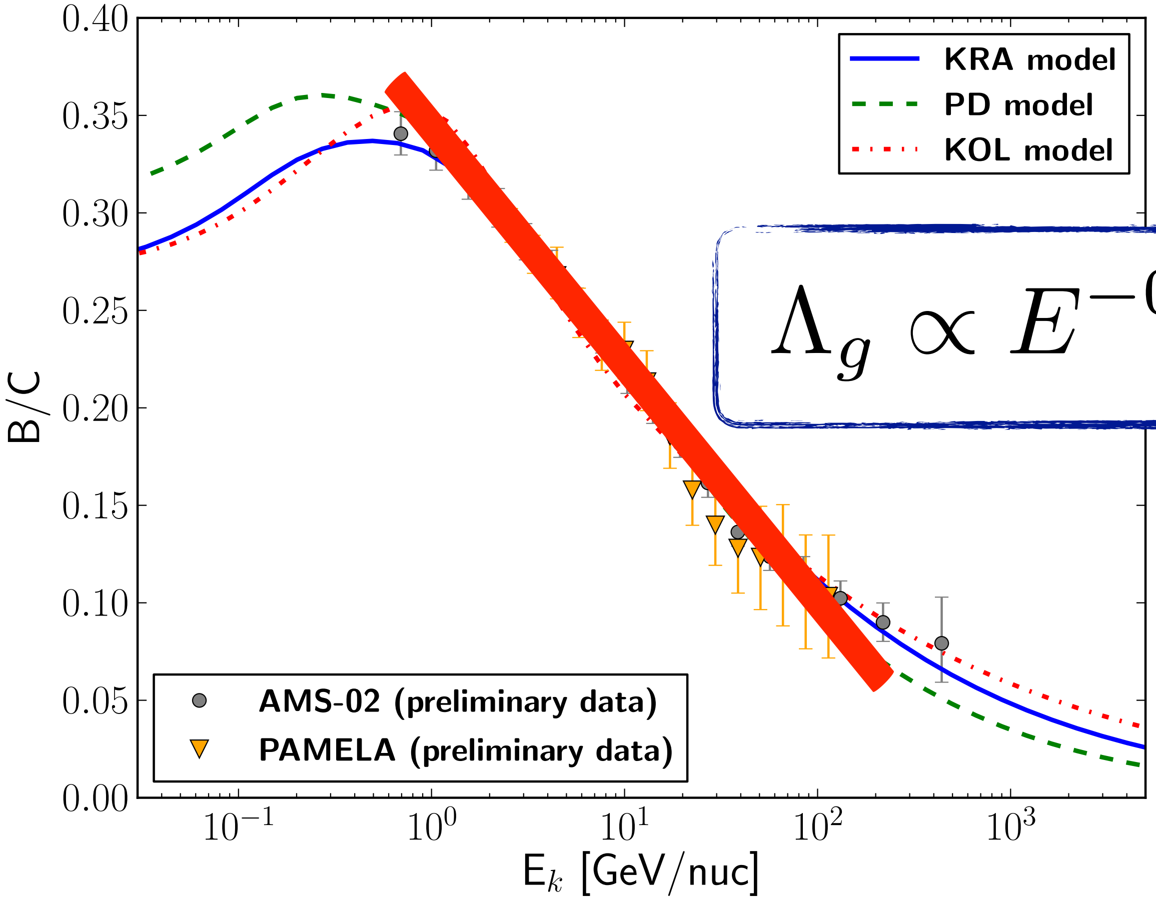
Gaggero et al (2014)



$$\Lambda_g \propto E^{-0.3}$$

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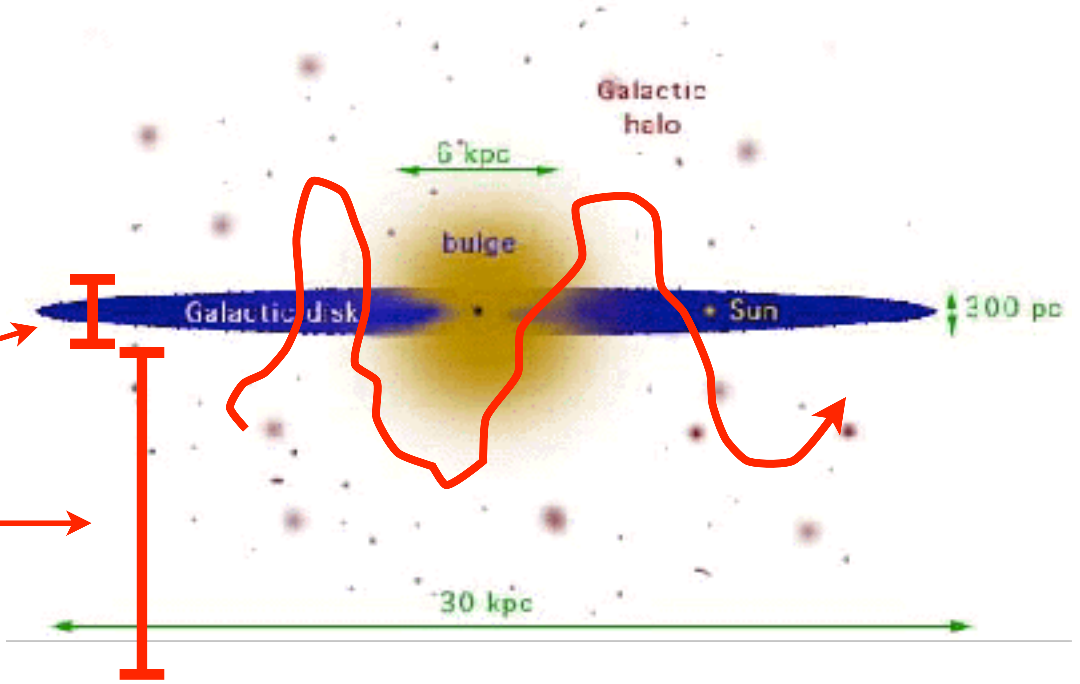

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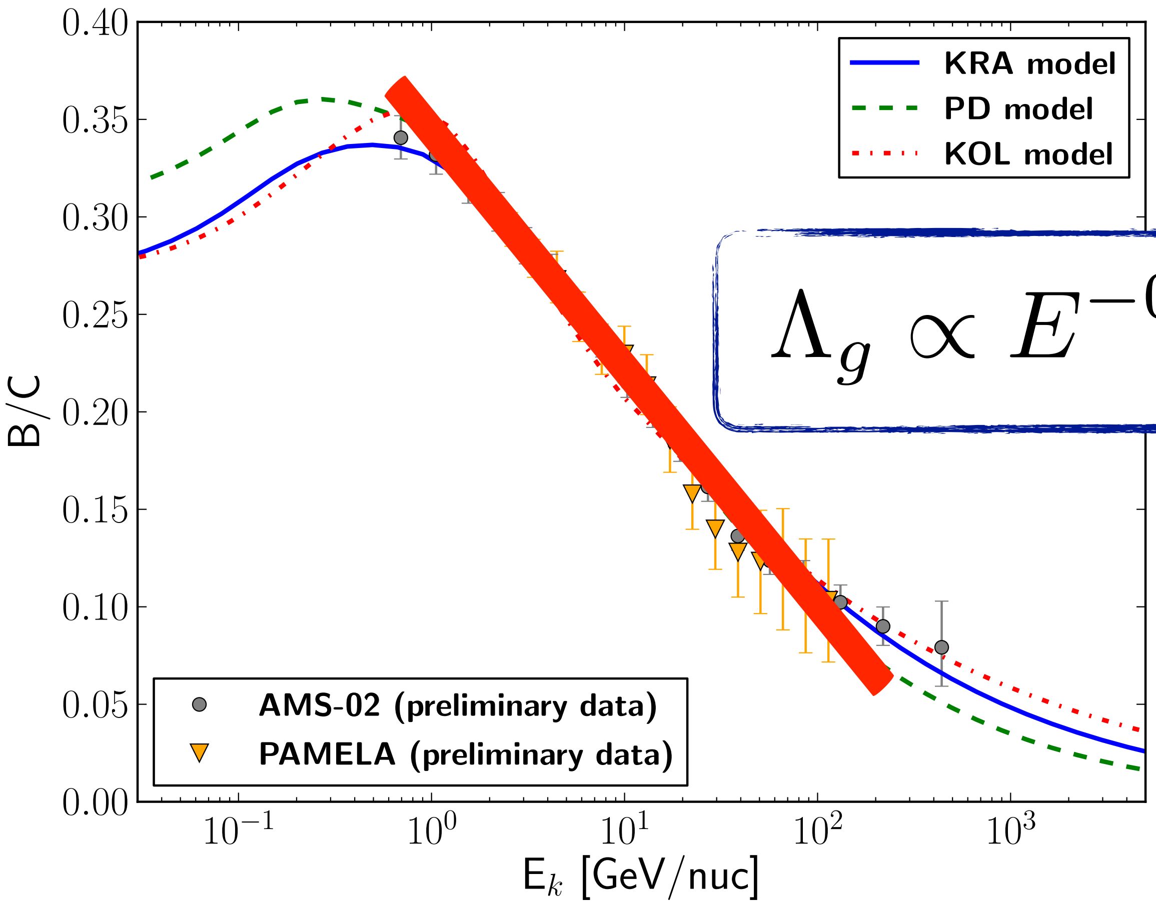

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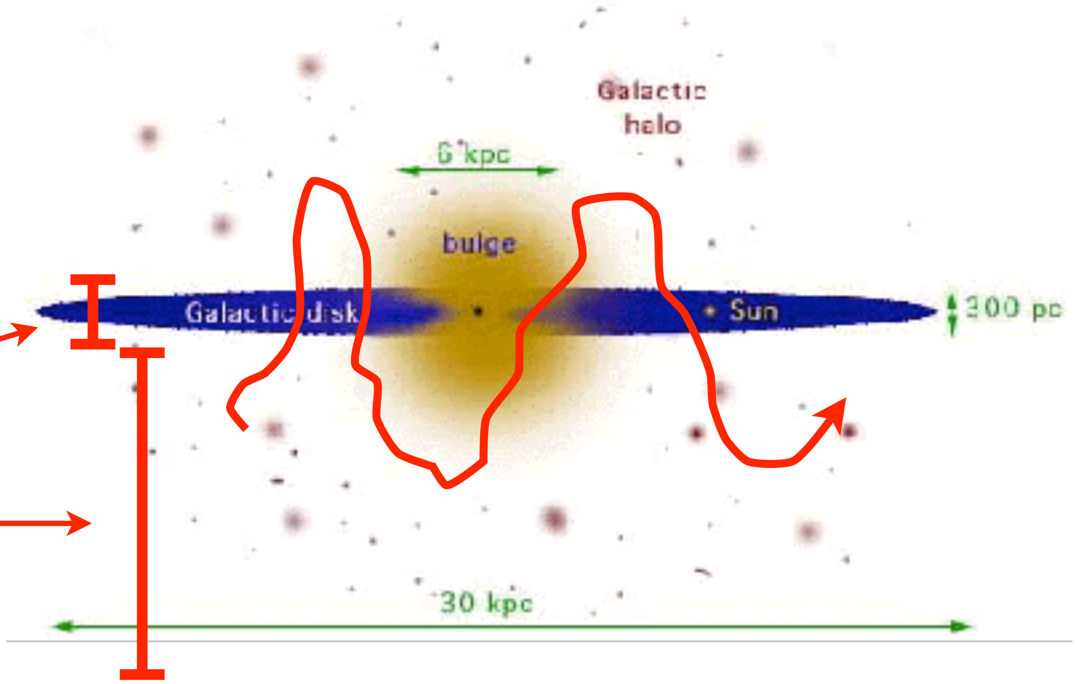

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$$n_p(E) \sim q_p(E) \times \tau esc \longrightarrow \boxed{q_p \propto E^{-2.4}}$$

quite close to the predictions of diffusive shock acceleration -> $\propto E^{-2}$

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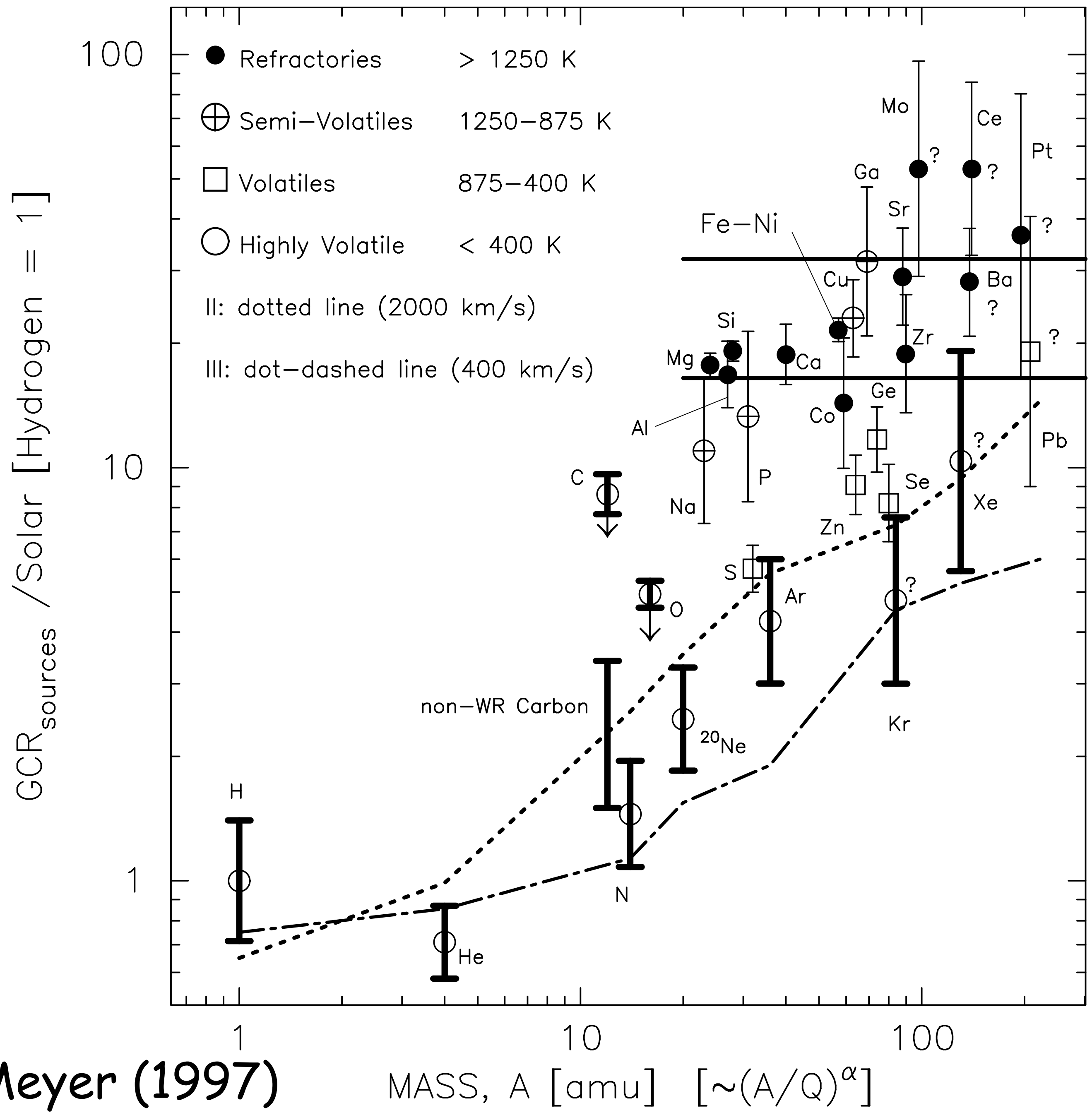
why dusty?



Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

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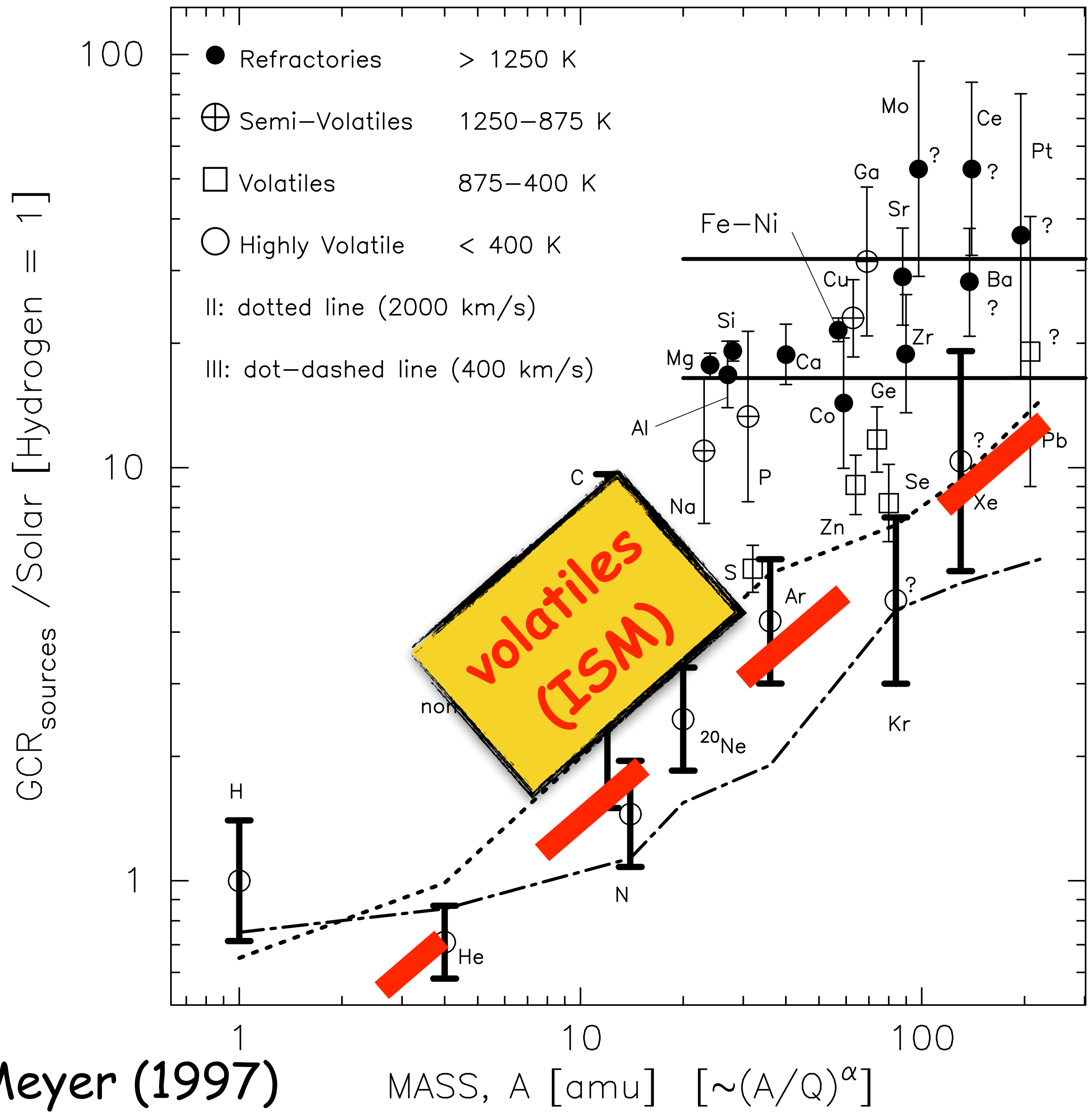

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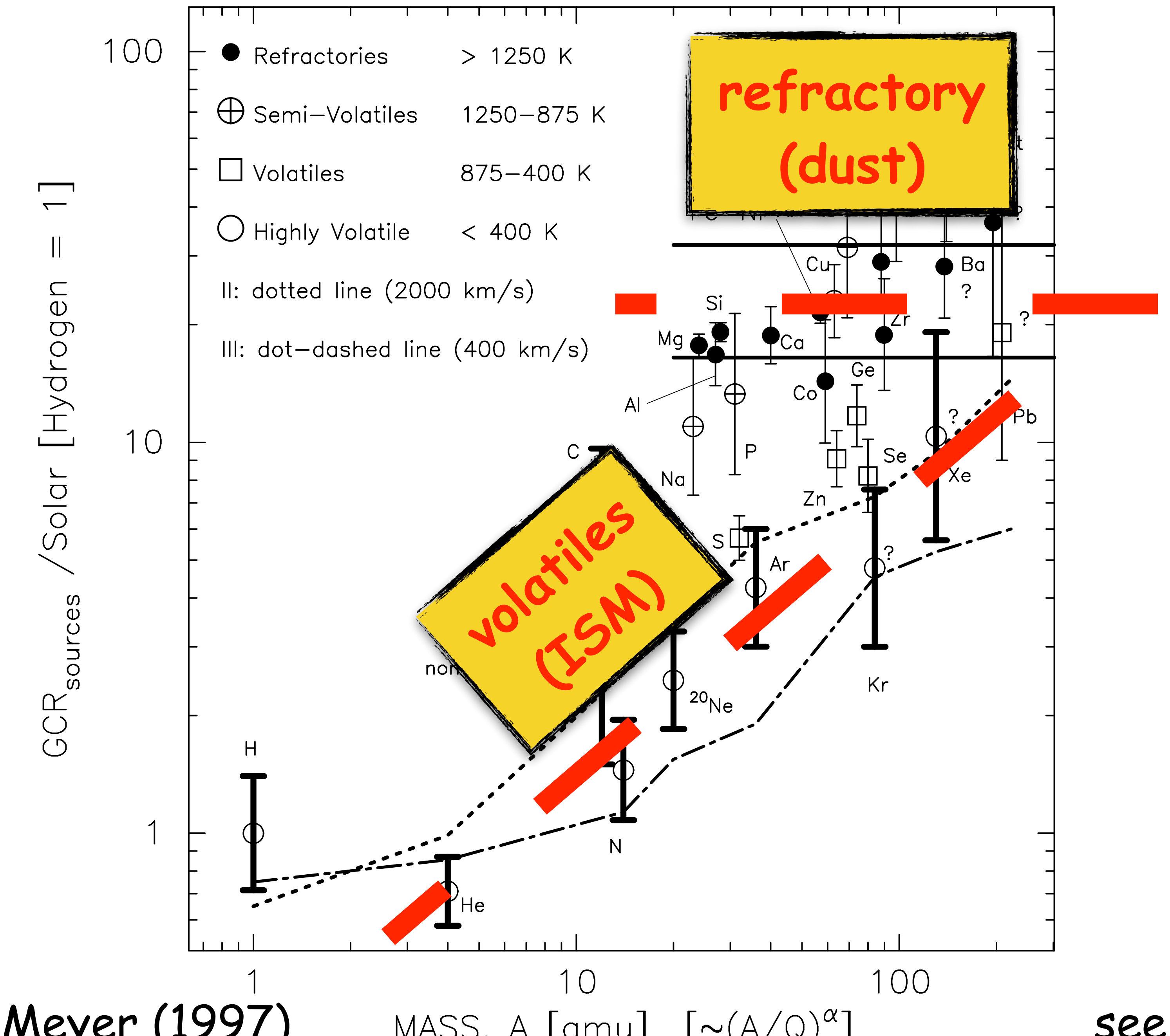

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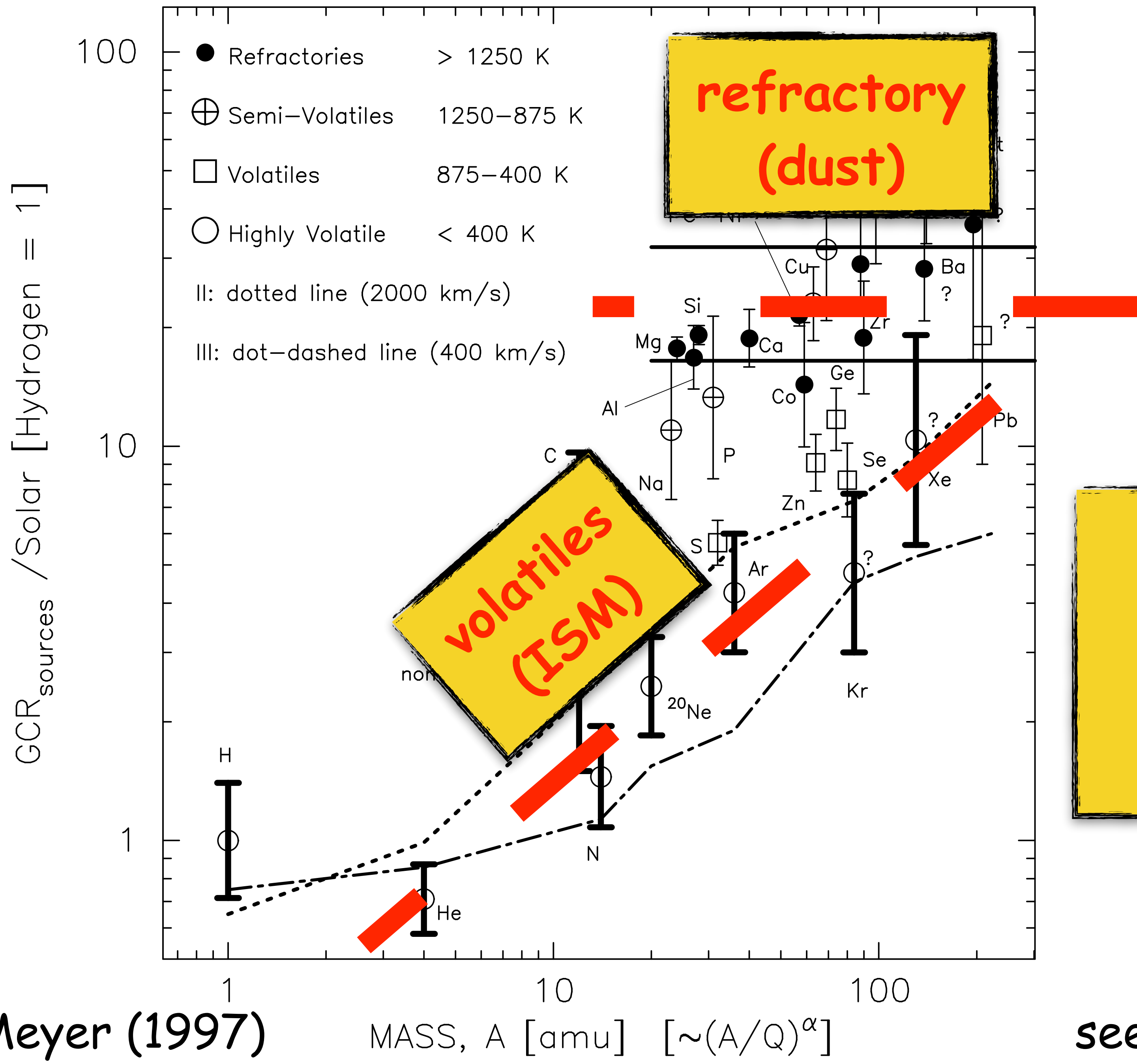
Data are best explained if refractory CRs are injected at shocks through sputtering of pre-accelerated dust grains



why dusty?

MESSAGE
CR composition deserves more attention

Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

Answers to classic questions?

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How many types of sources provide a significant contribution to the overall CR flux?

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Problems with LiBeB versus cosmic time, $^{22}Ne/^{20}Ne$...

10 questions

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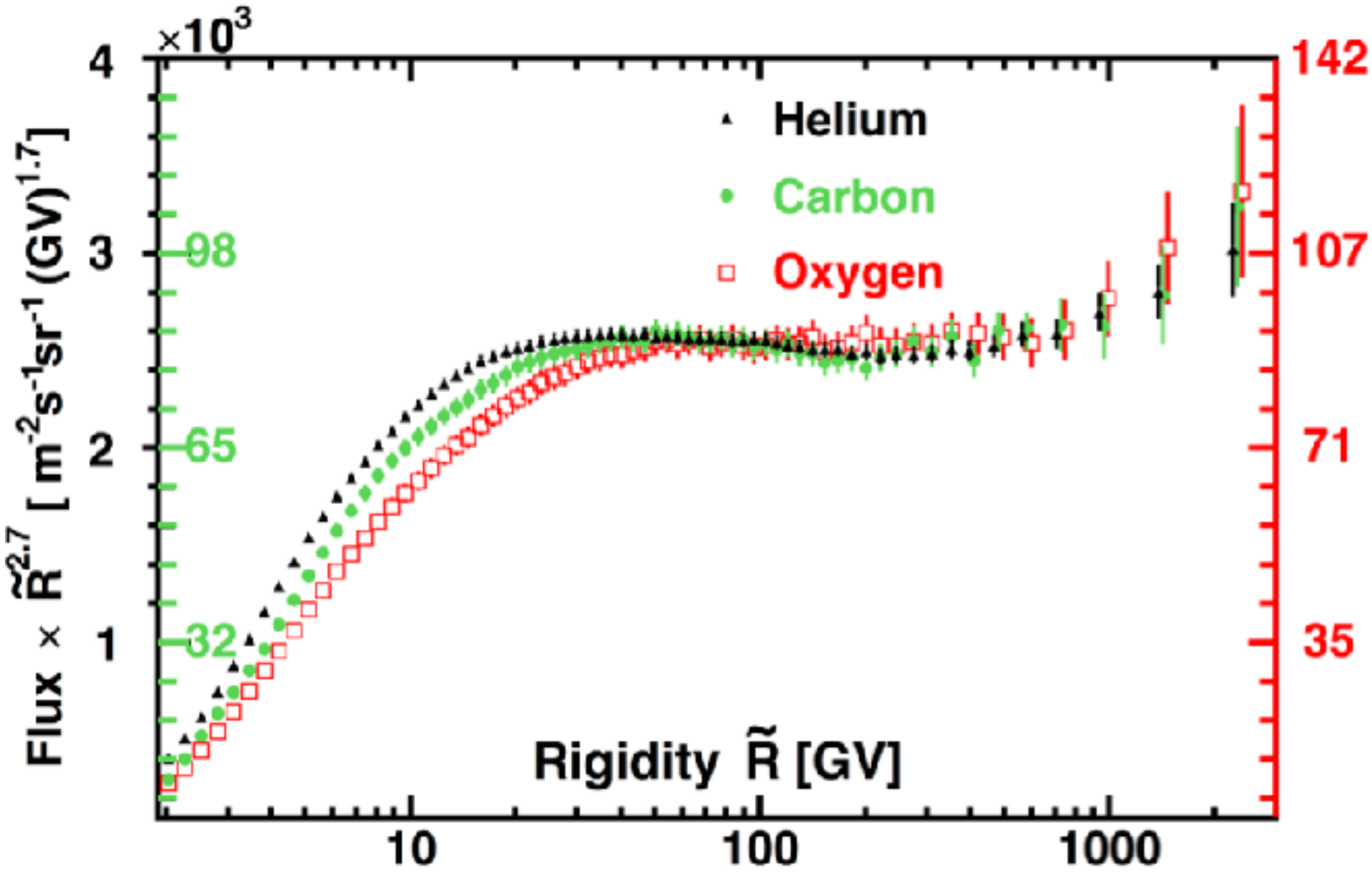

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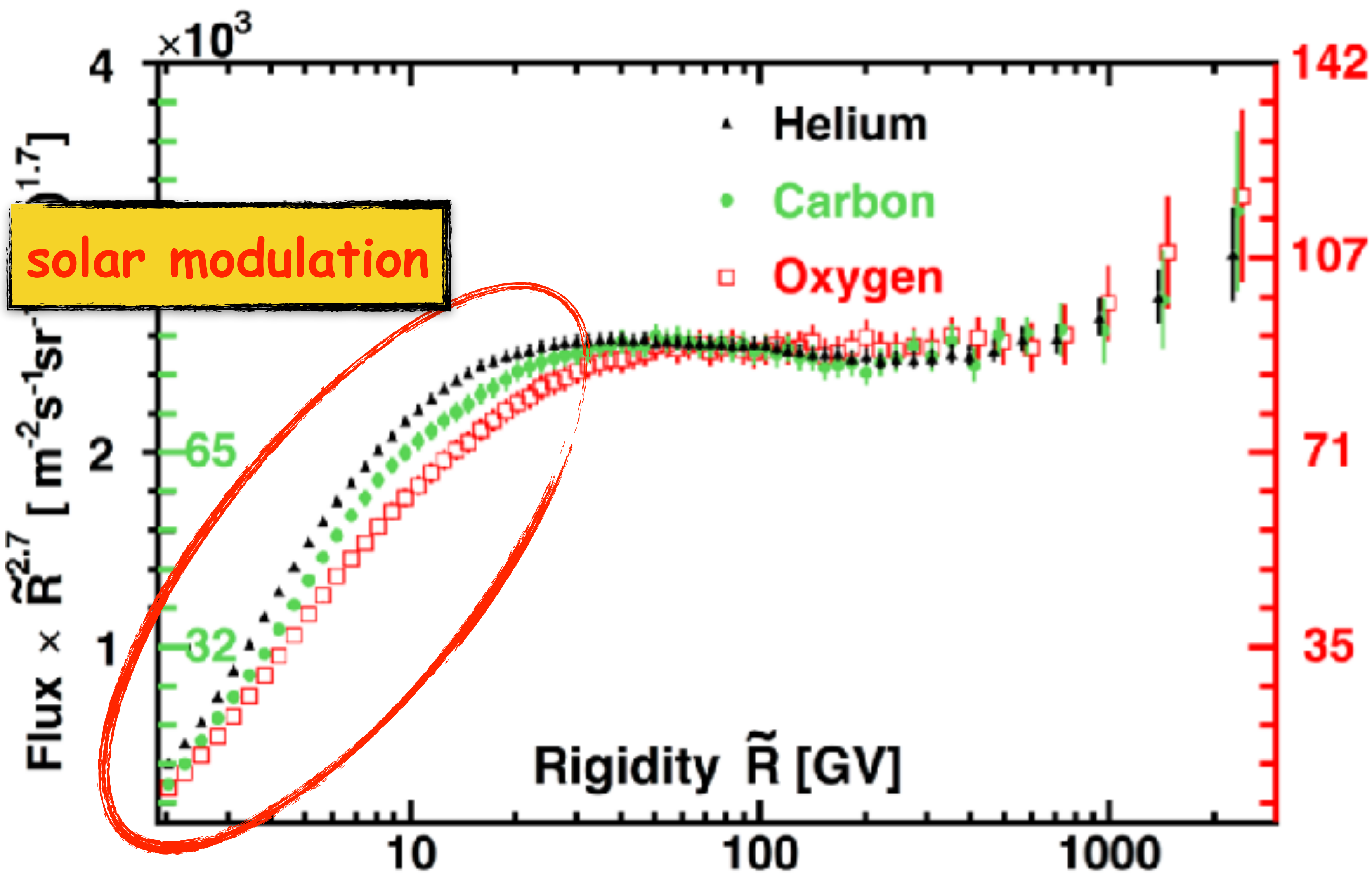

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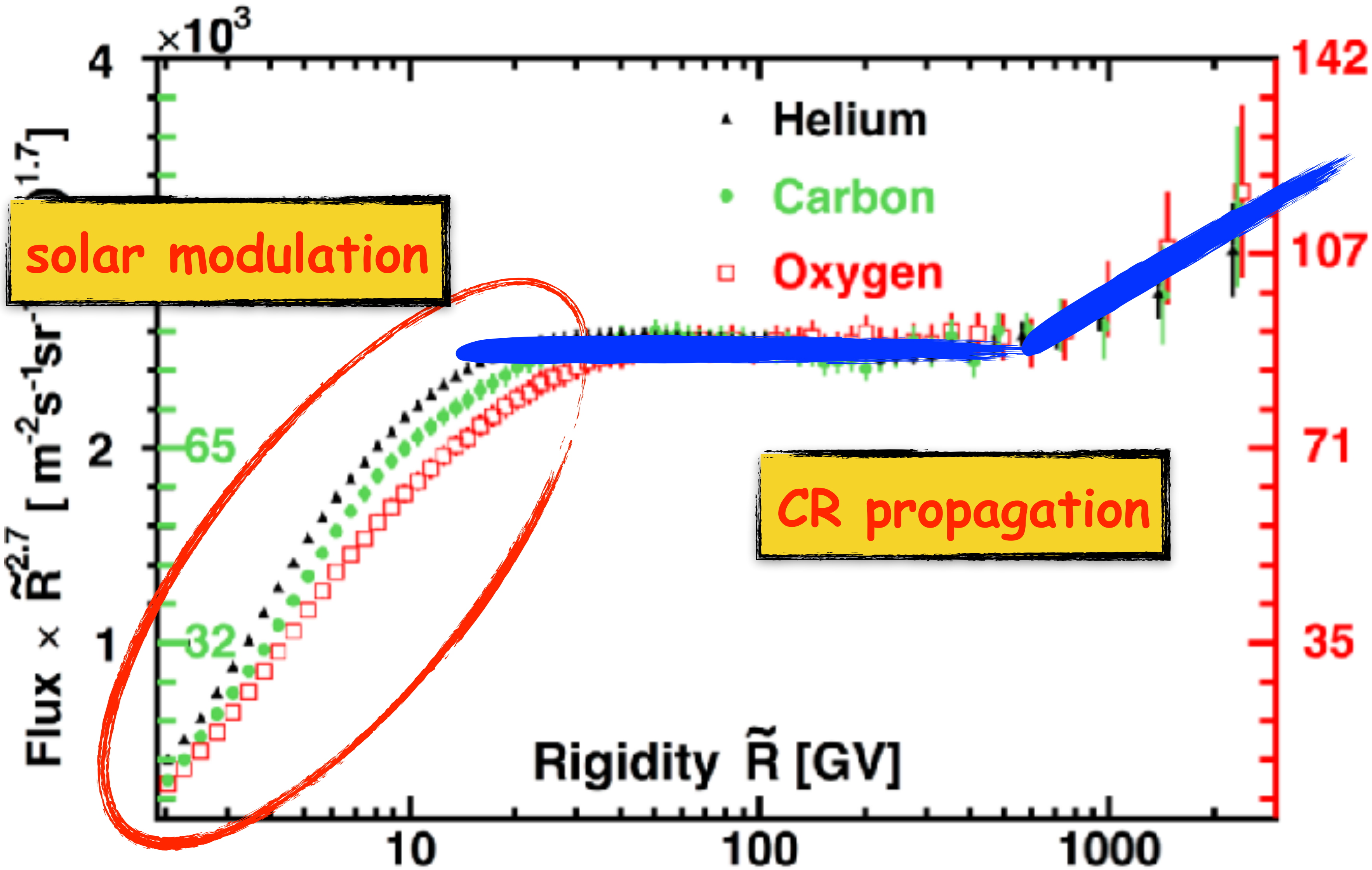

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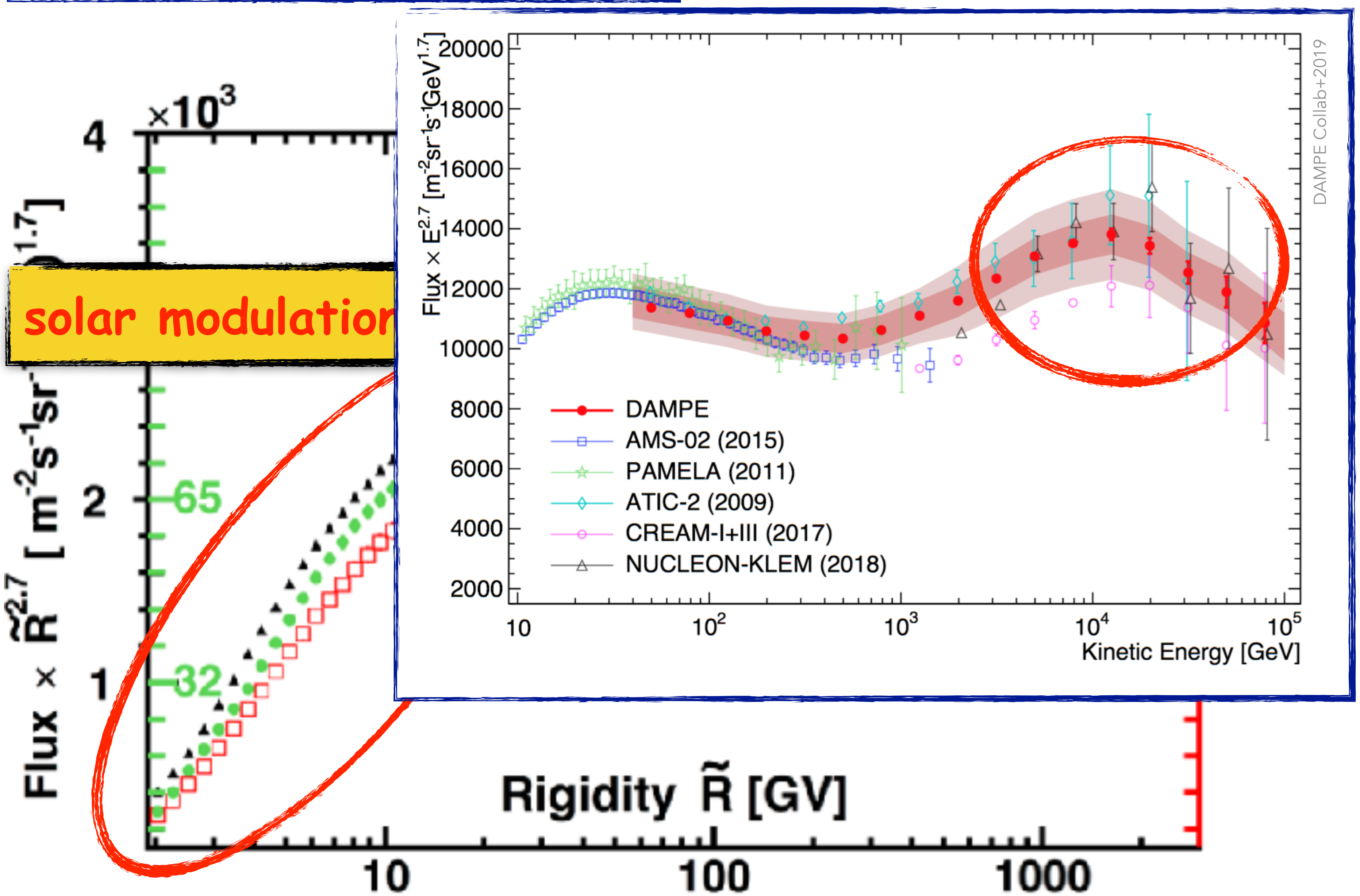

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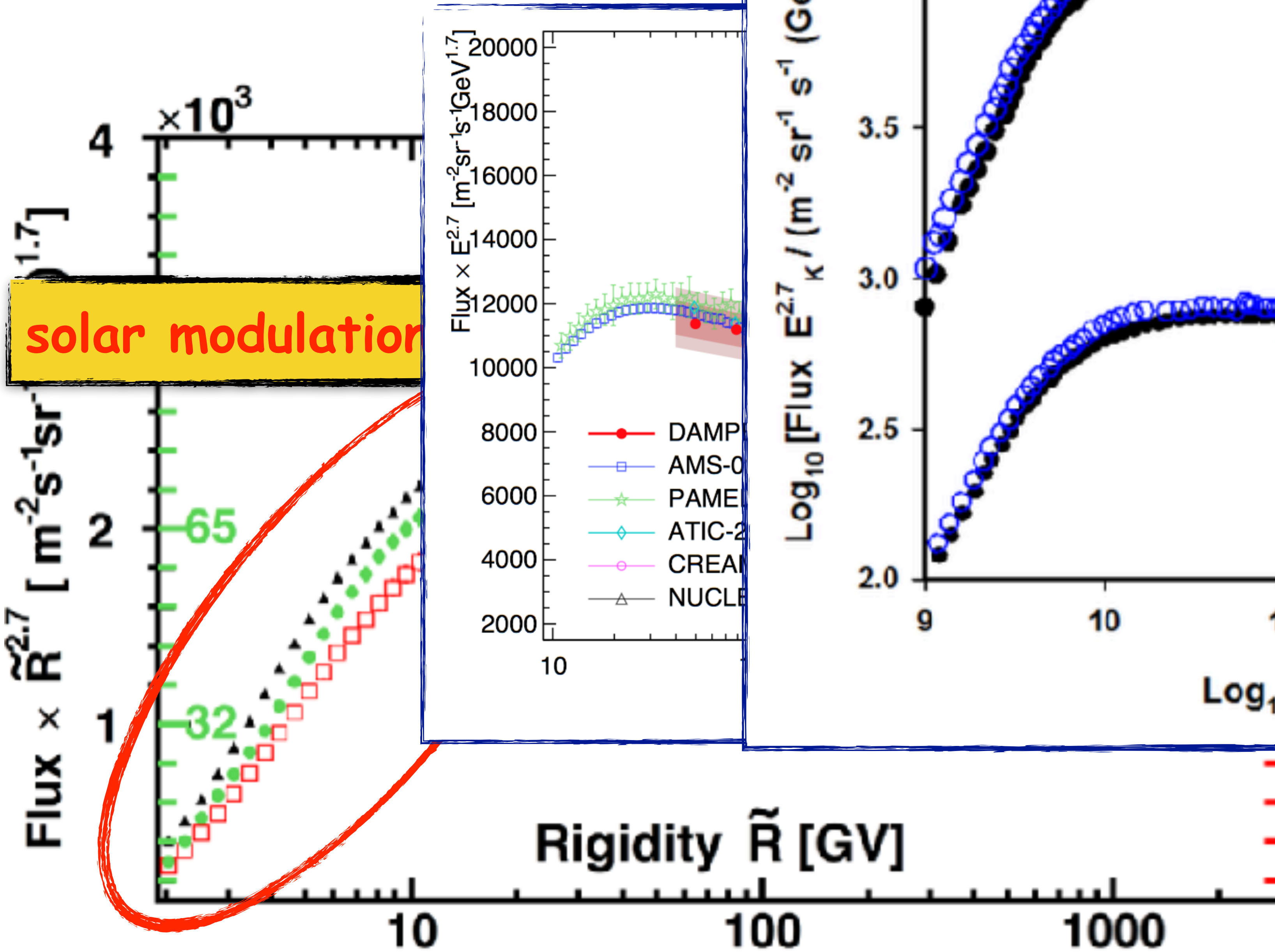

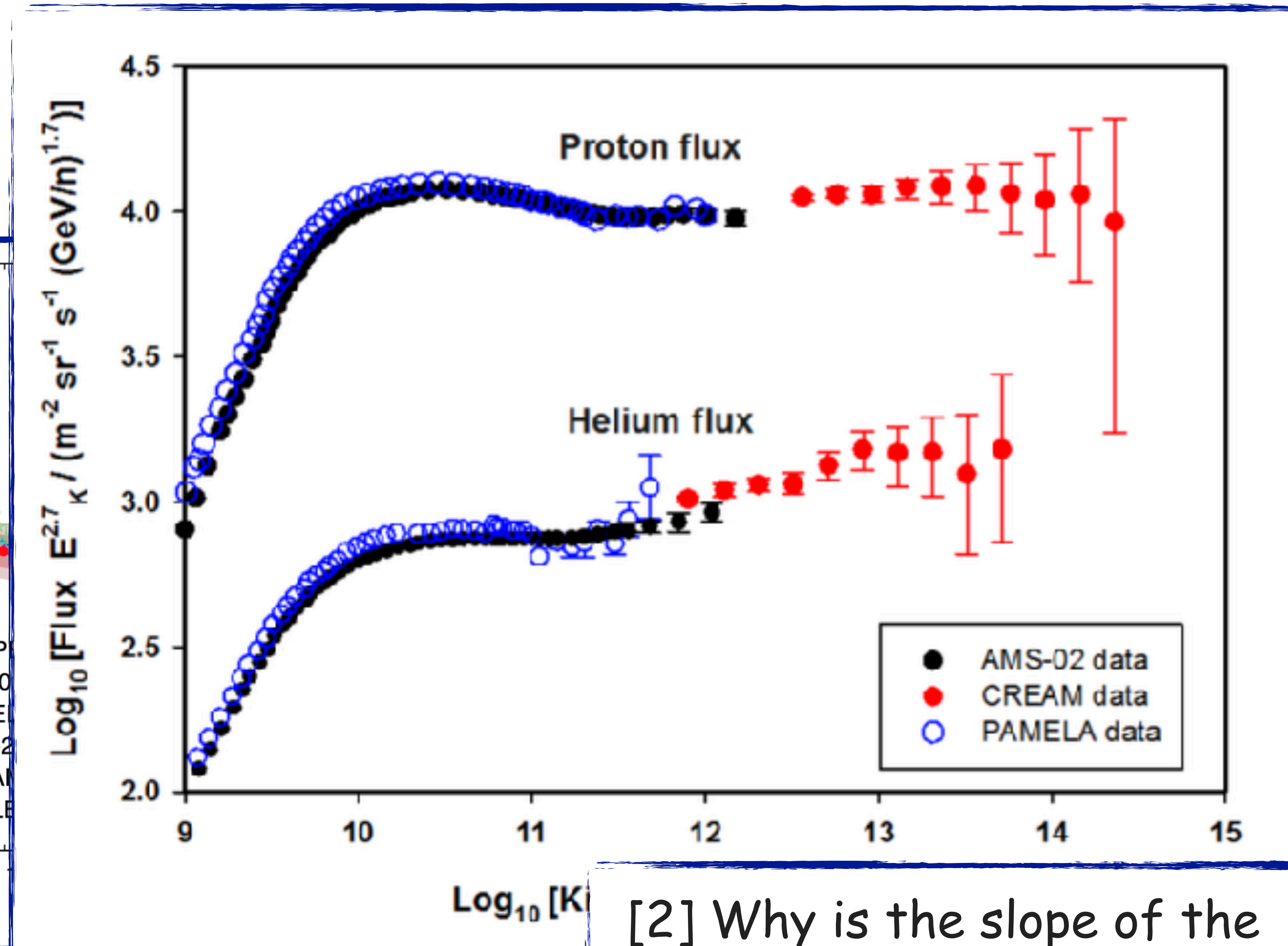

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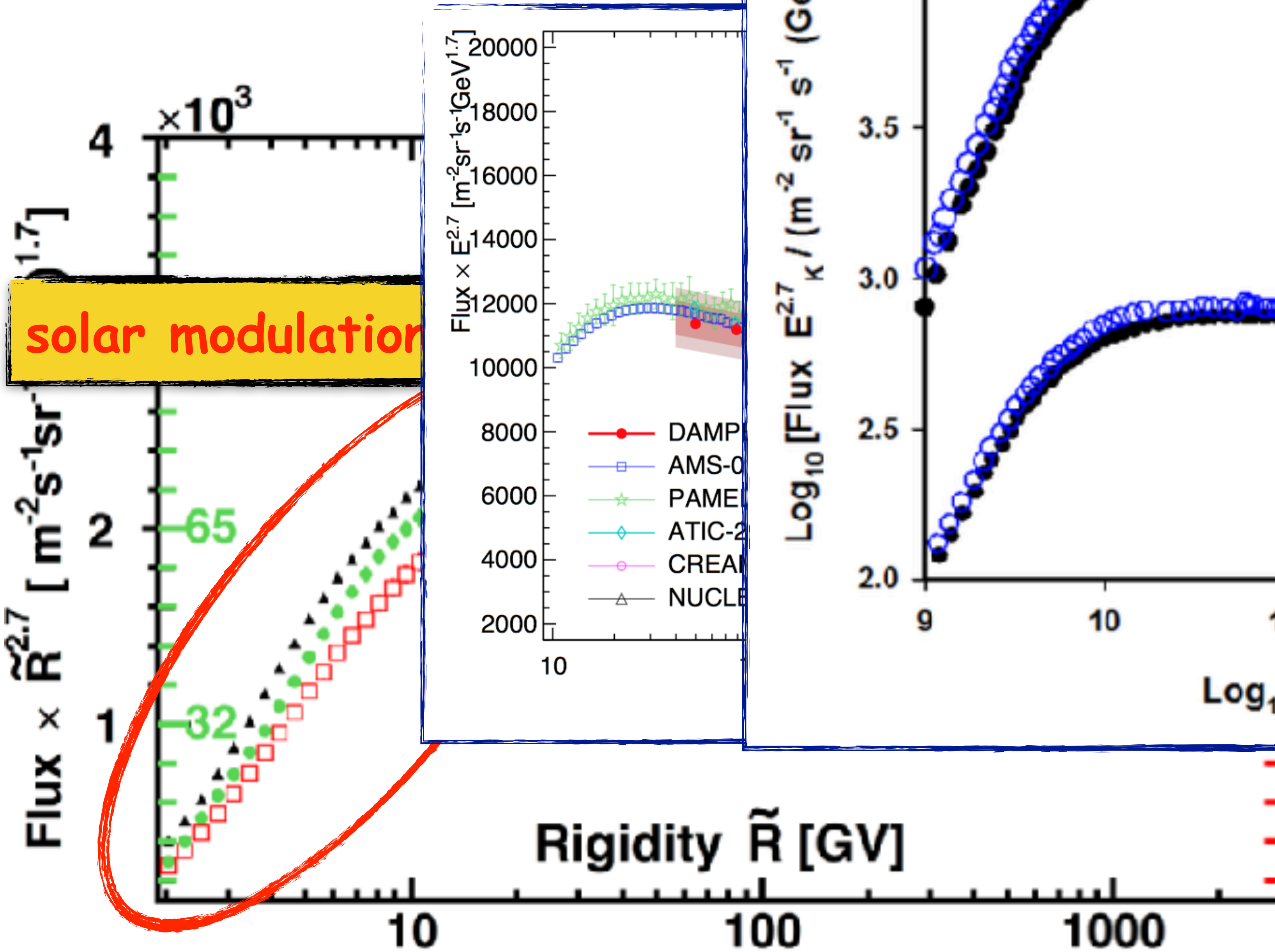

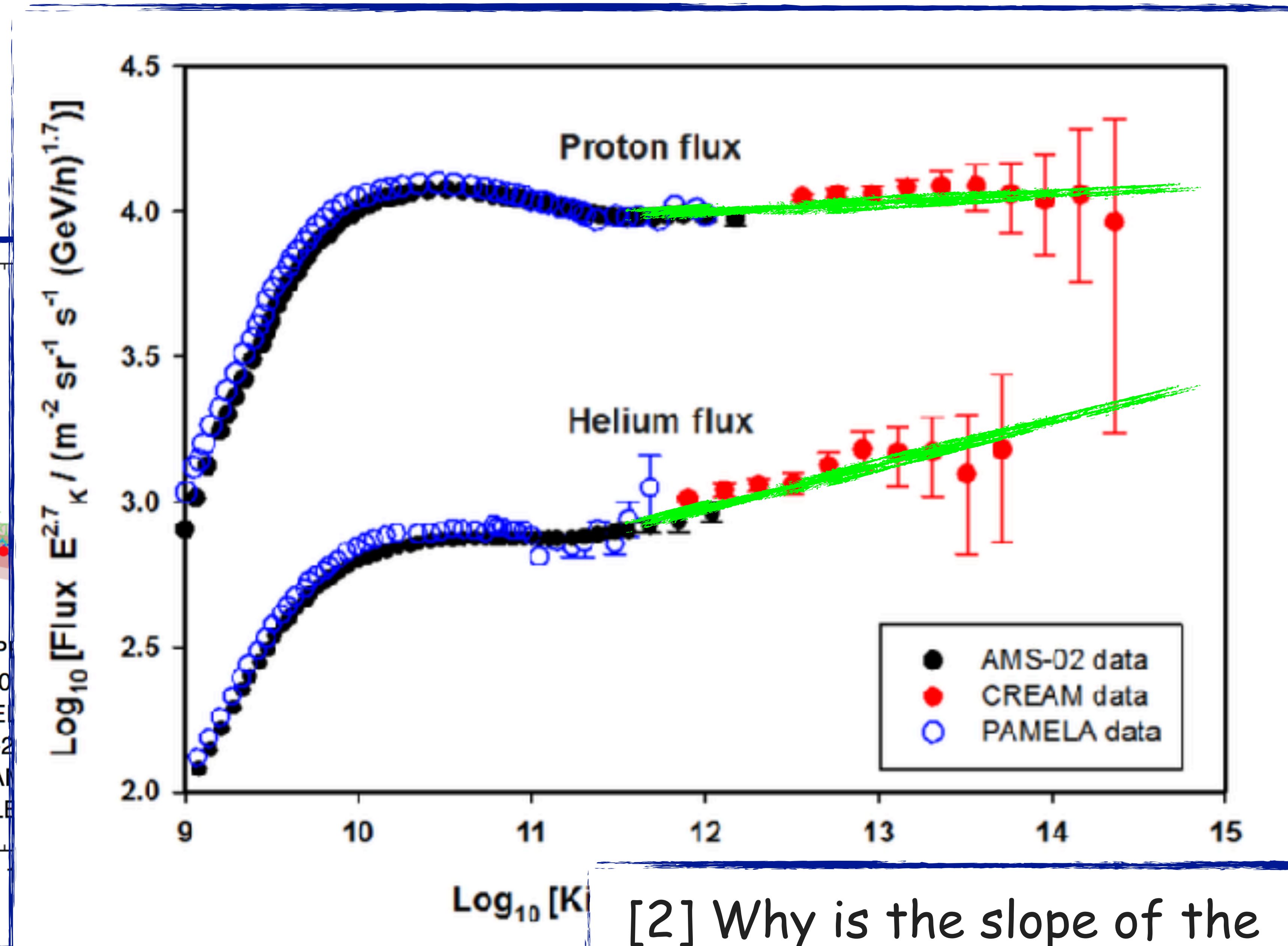

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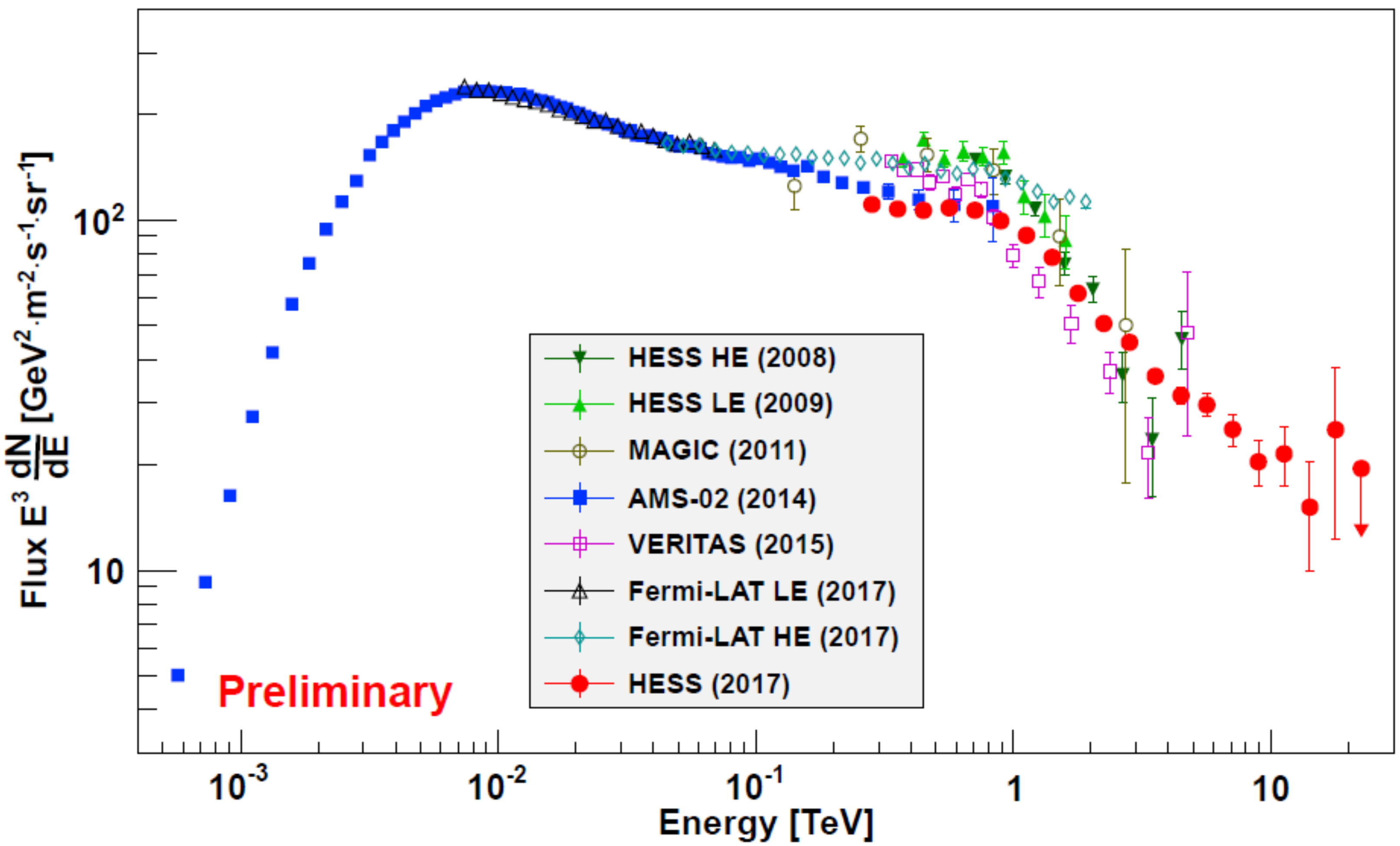
10 questions

[3] What is the origin of the prominent break observed at a particle energy of ~ 1 TeV in the electron spectrum?



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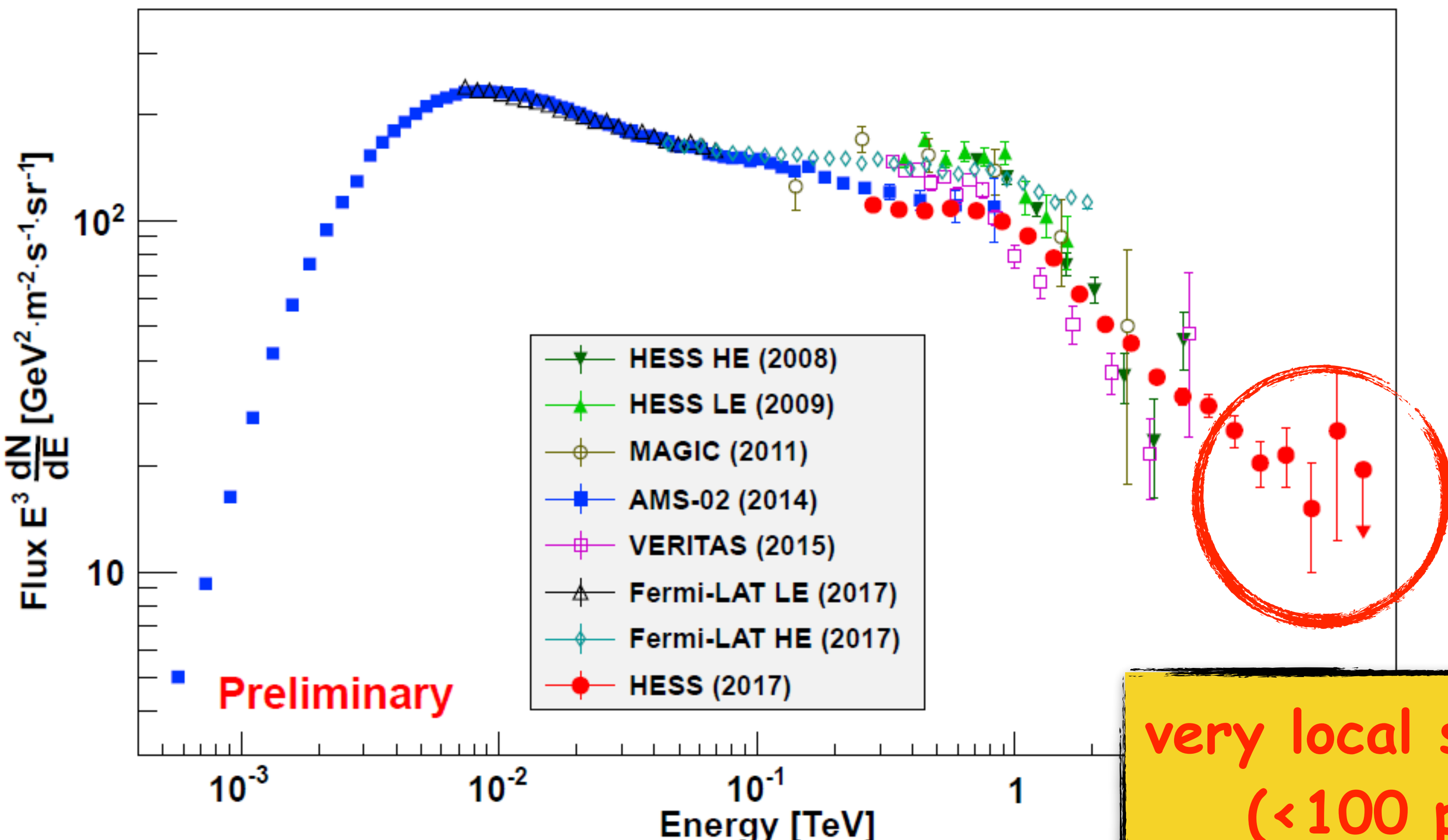

very local source (<100 pc)

10 questions

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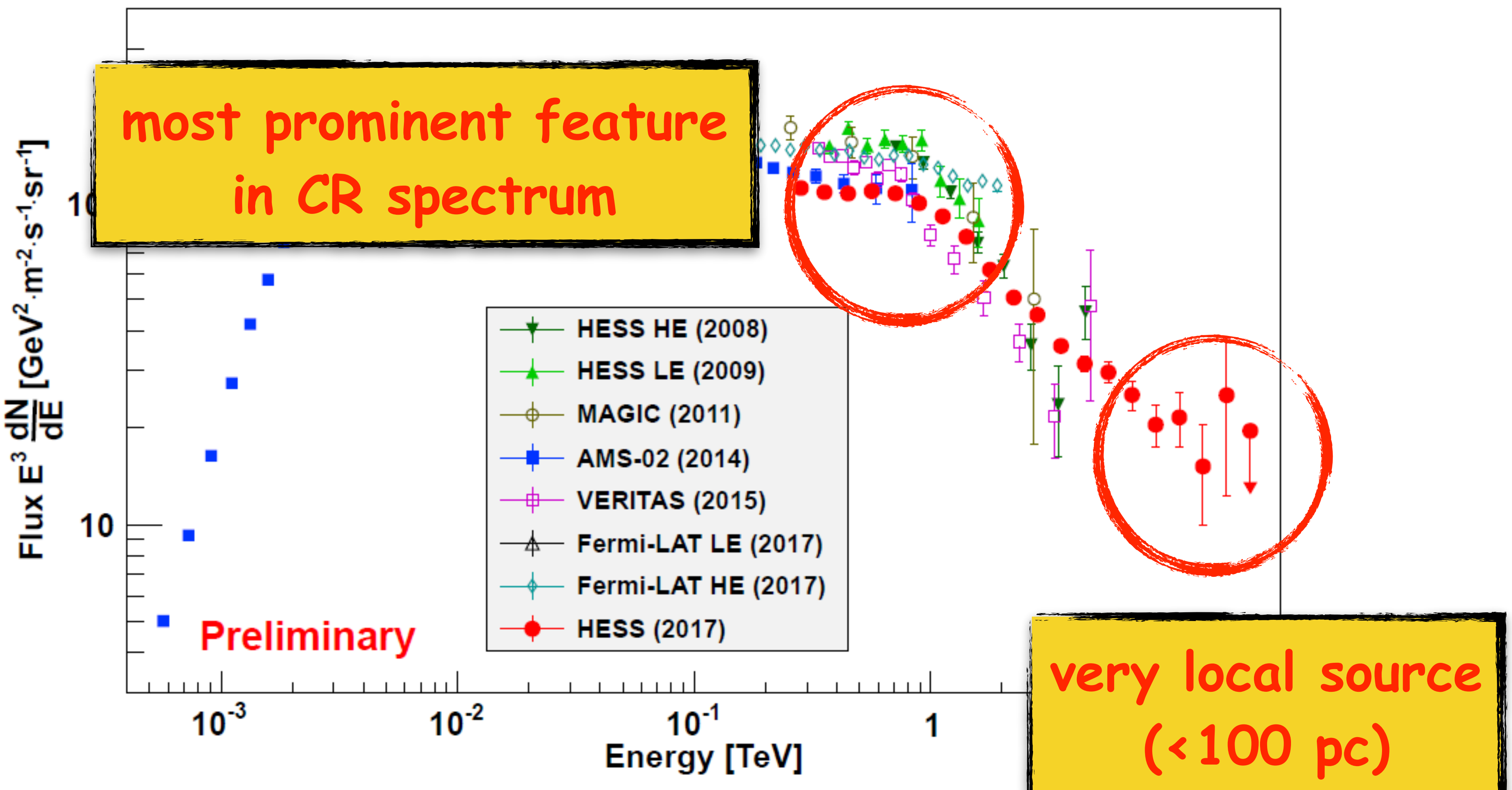

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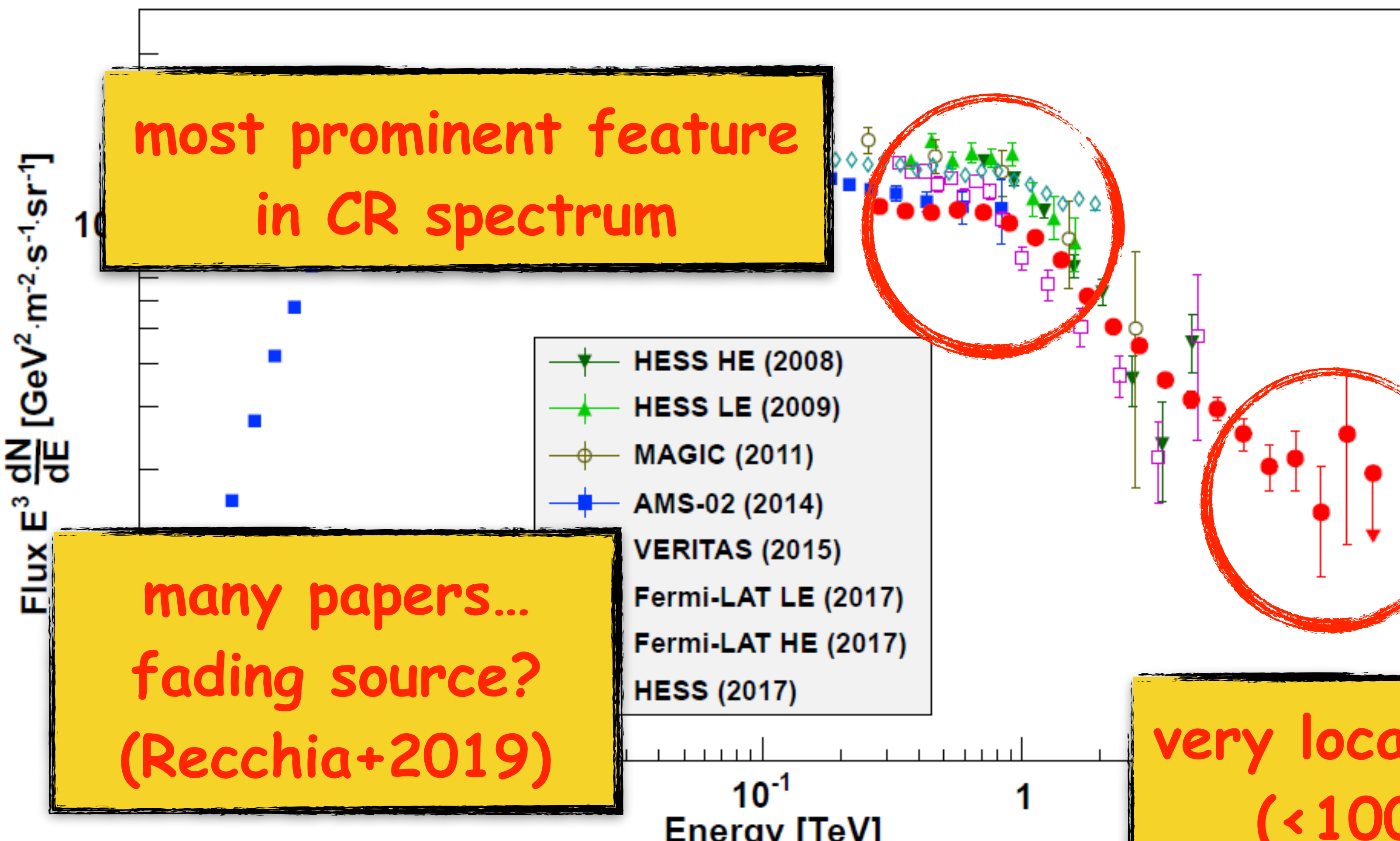
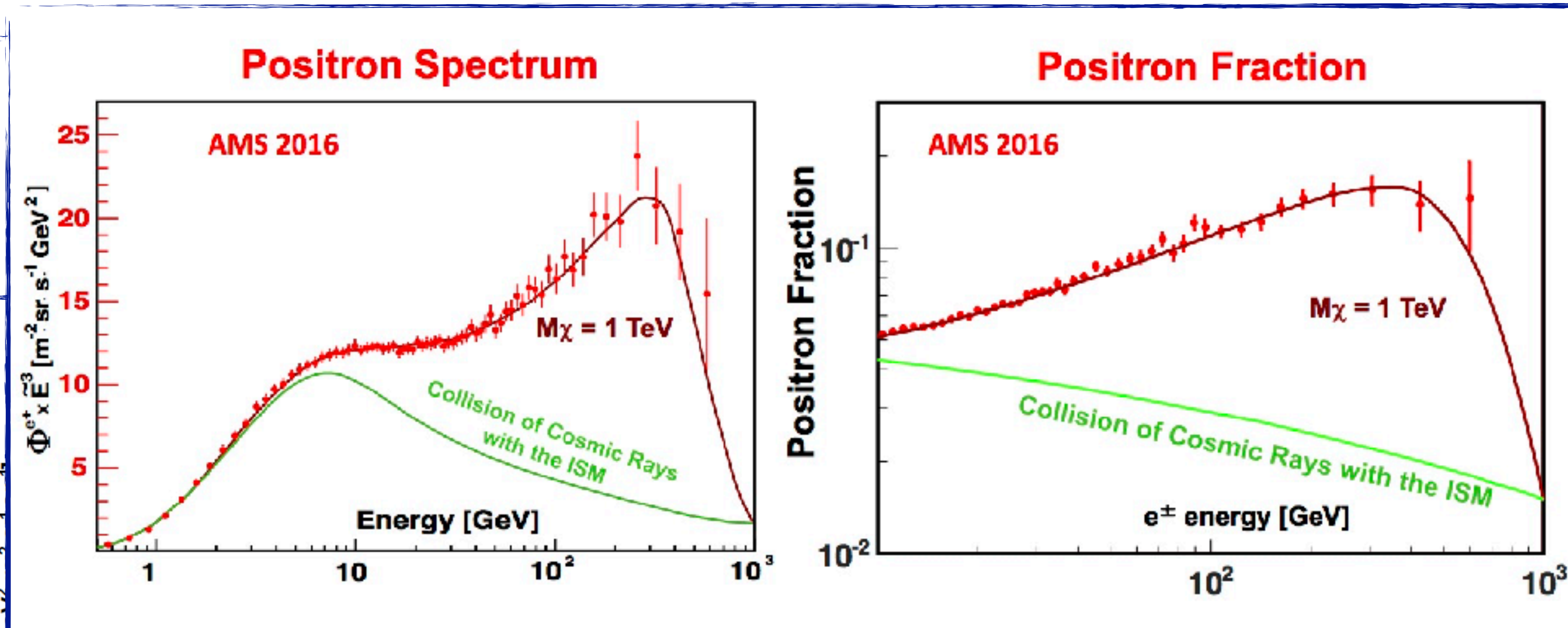


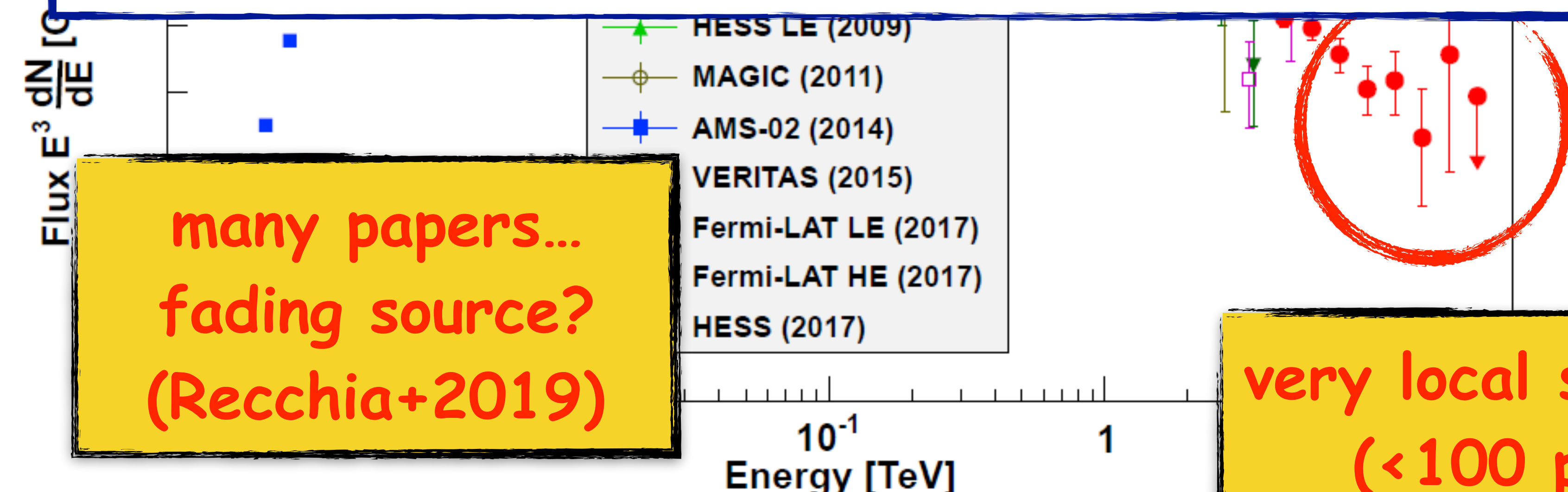
most prominent feature in CR spectrum

many papers... fading source? (Recchia+2019)

very local source (<100 pc)

10 questions





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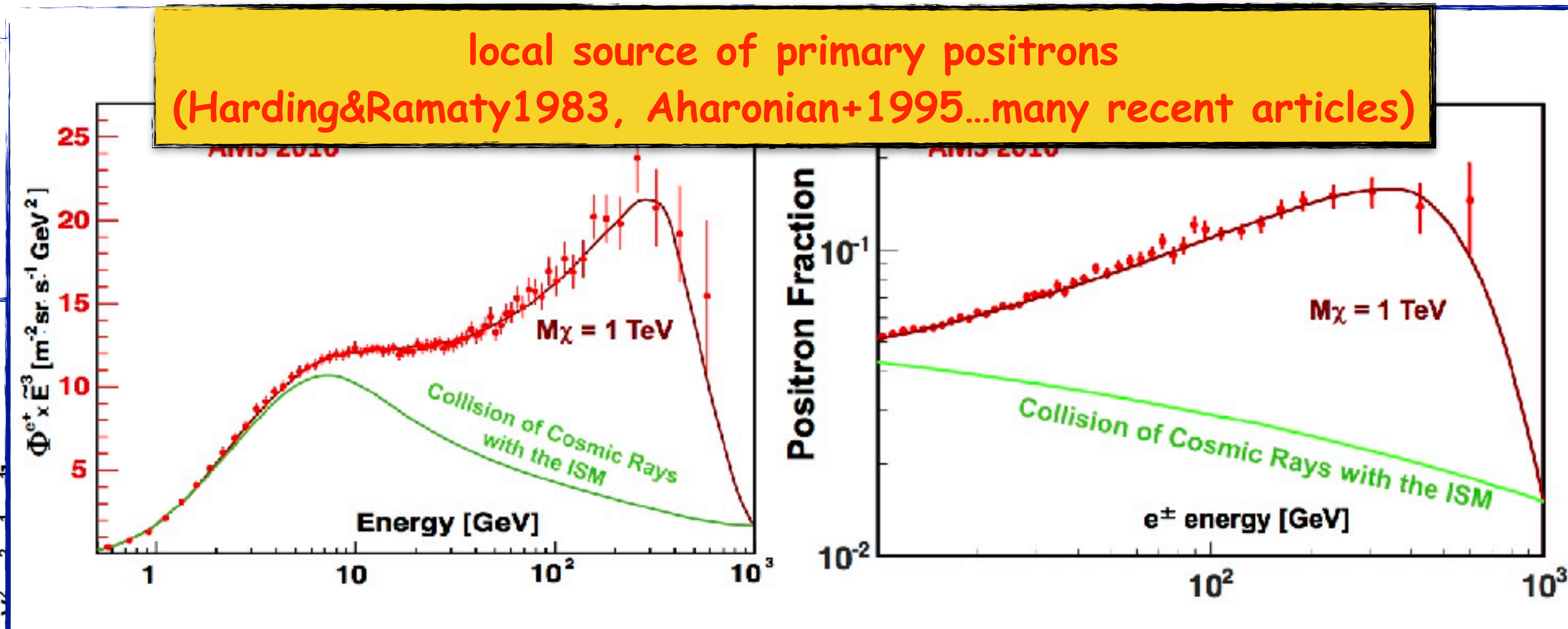
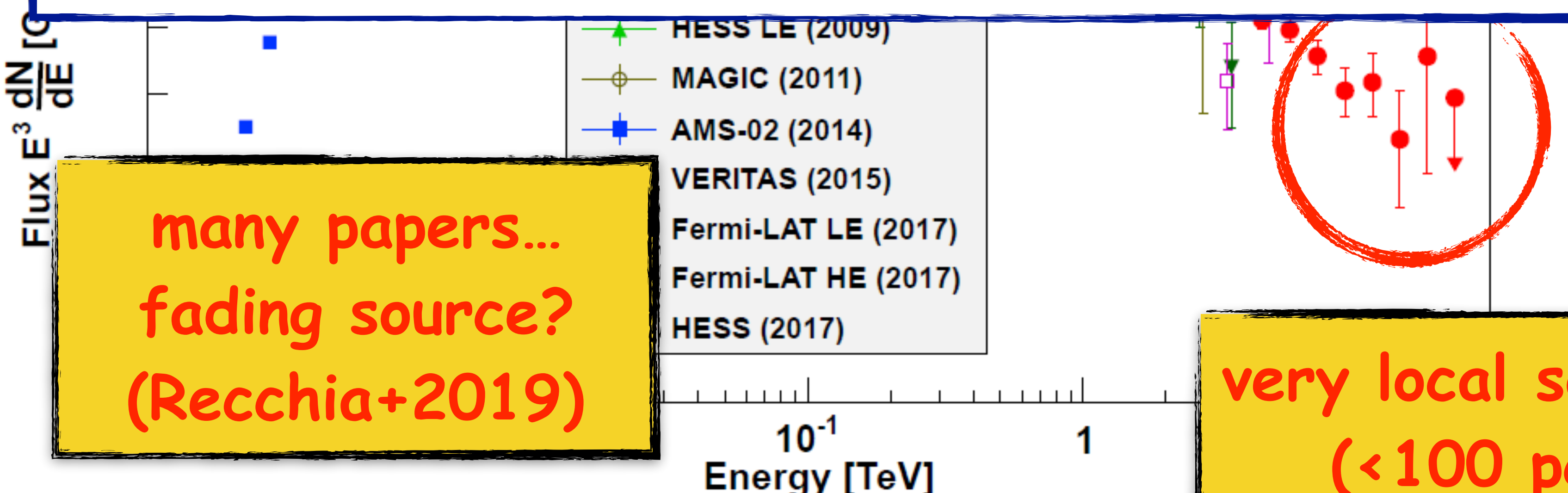
[4] What is the origin of the rise in the positron fraction at particle energies above ~ 10 GeV?

10 questions

local source of primary positrons
(Harding&Ramaty1983, Aharonian+1995...many recent articles)





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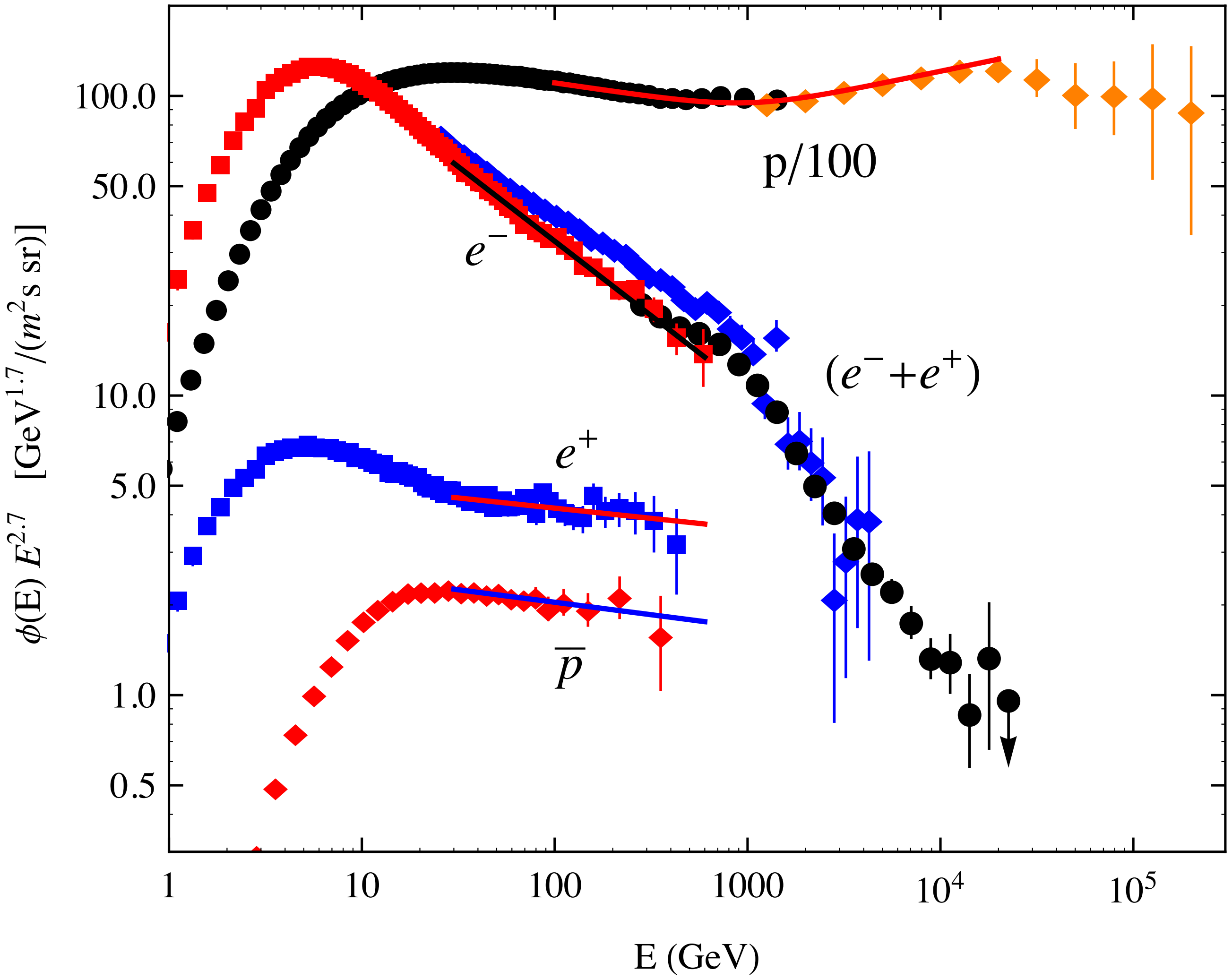

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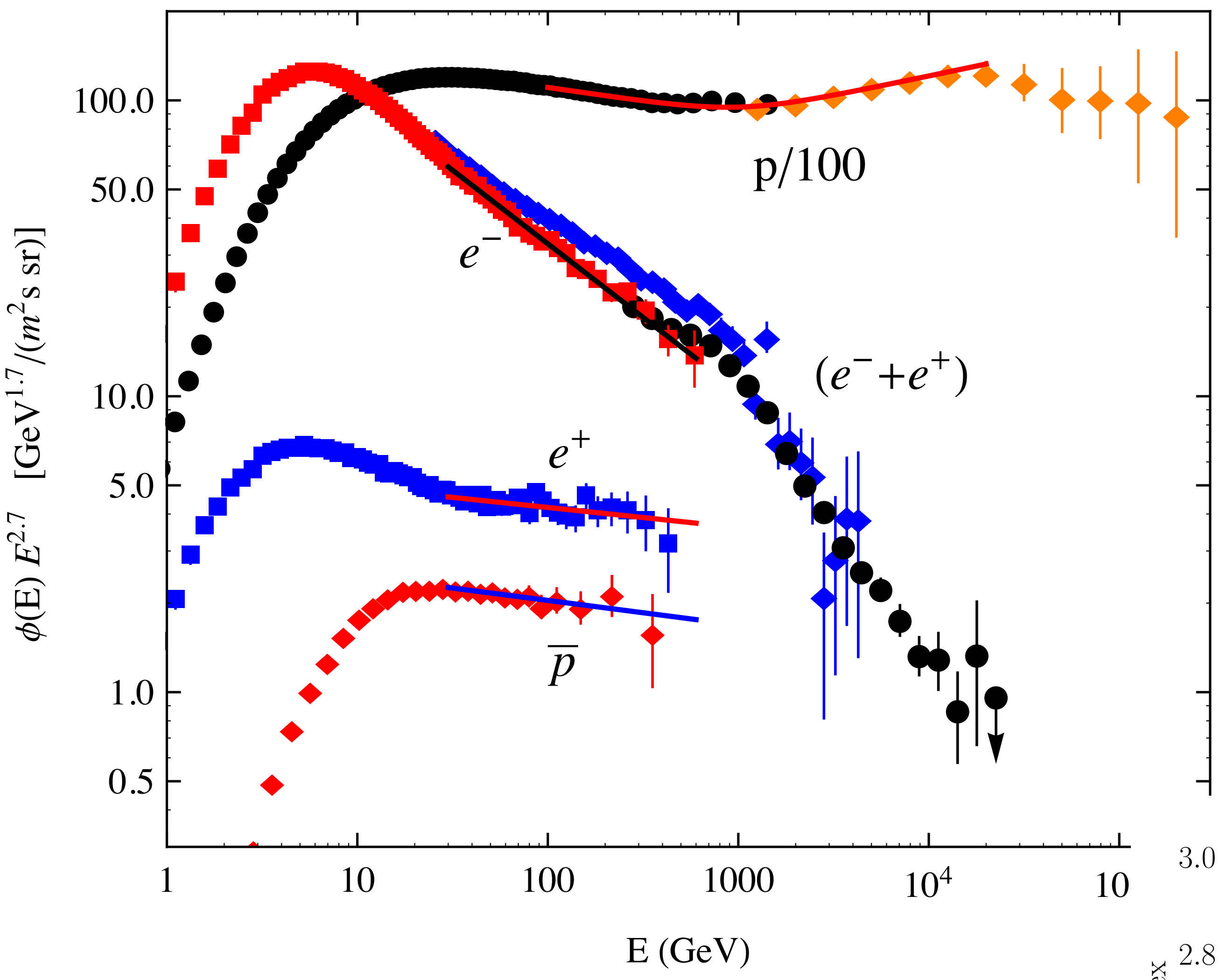
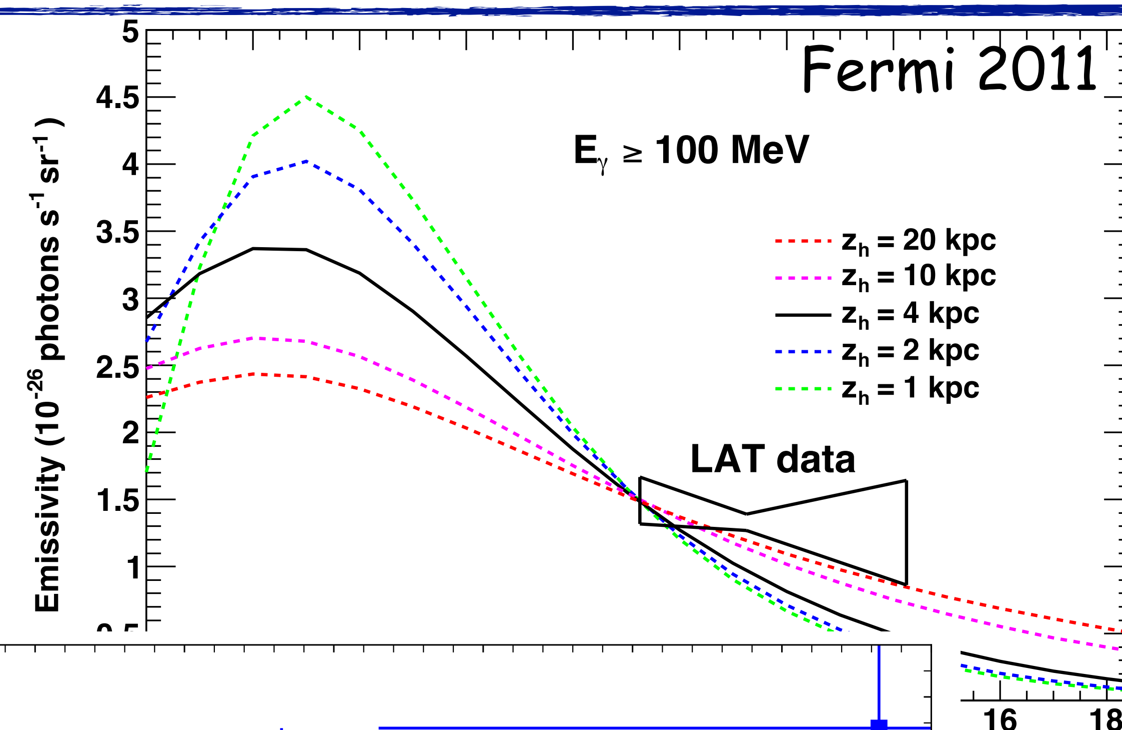
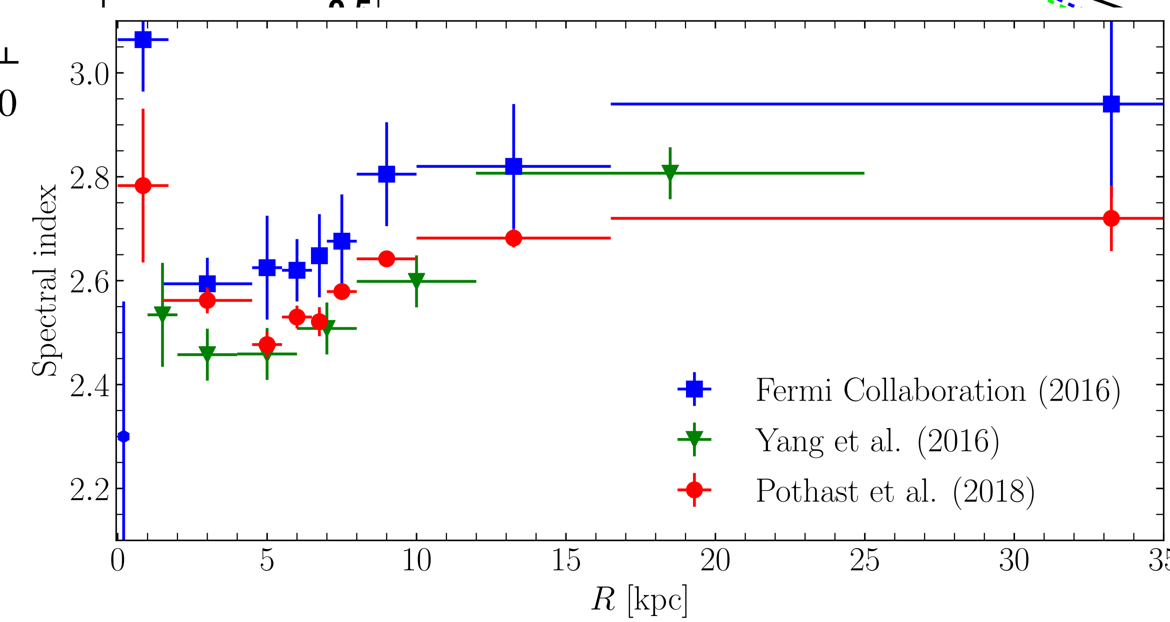


[6] Why is the spatial gradient of CRs so small? Why is the CR spectrum hardening towards the Galactic centre?





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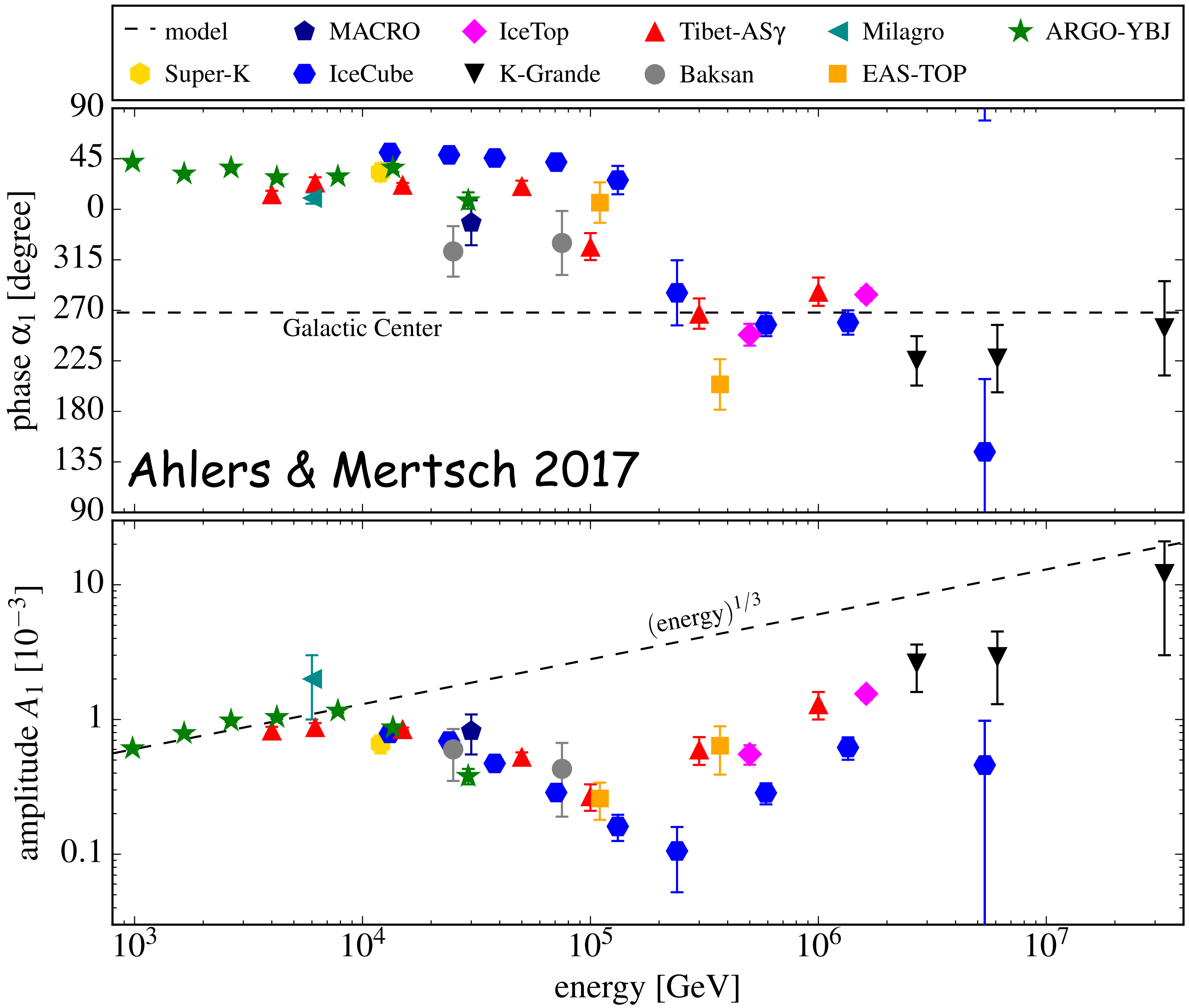

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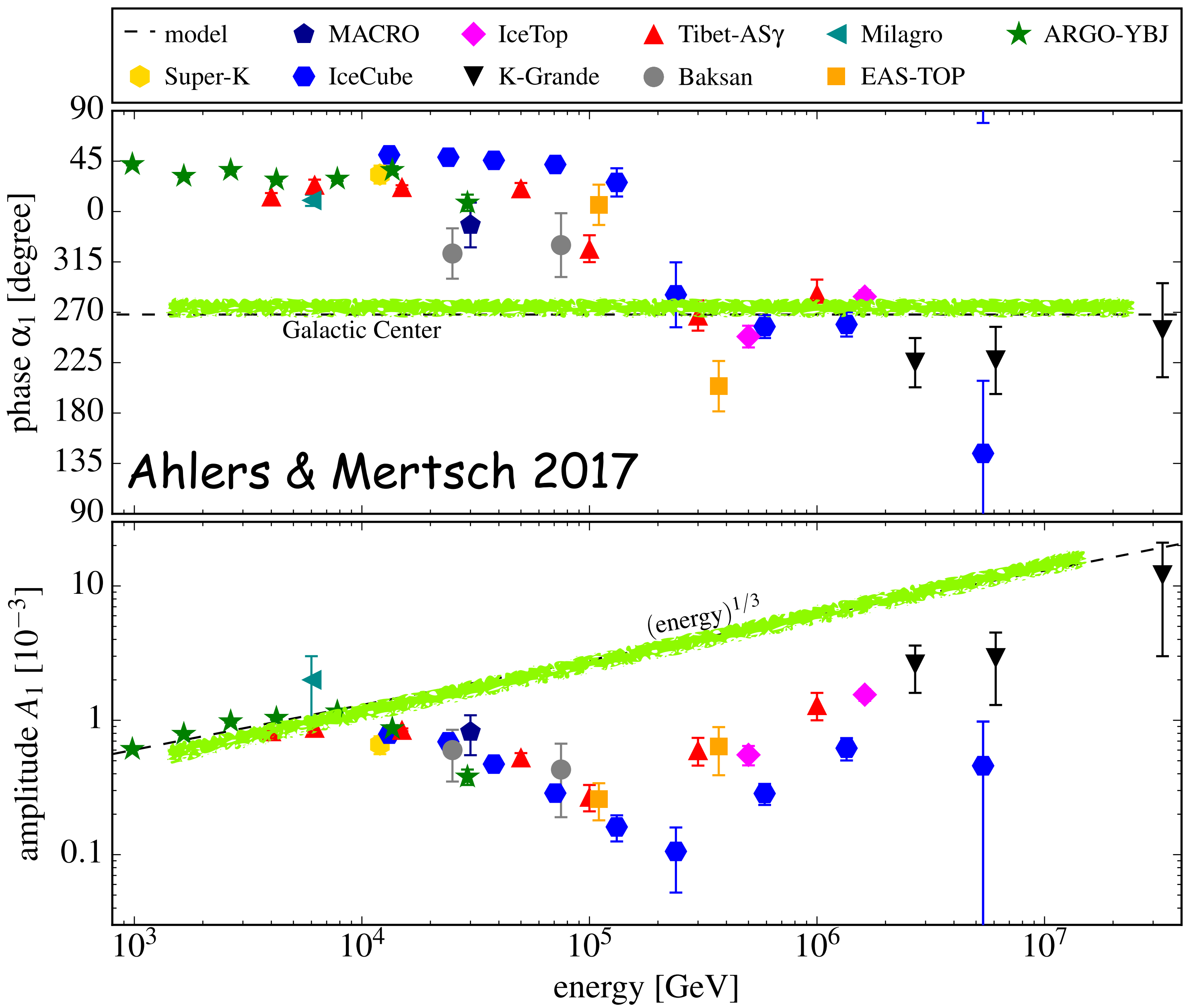

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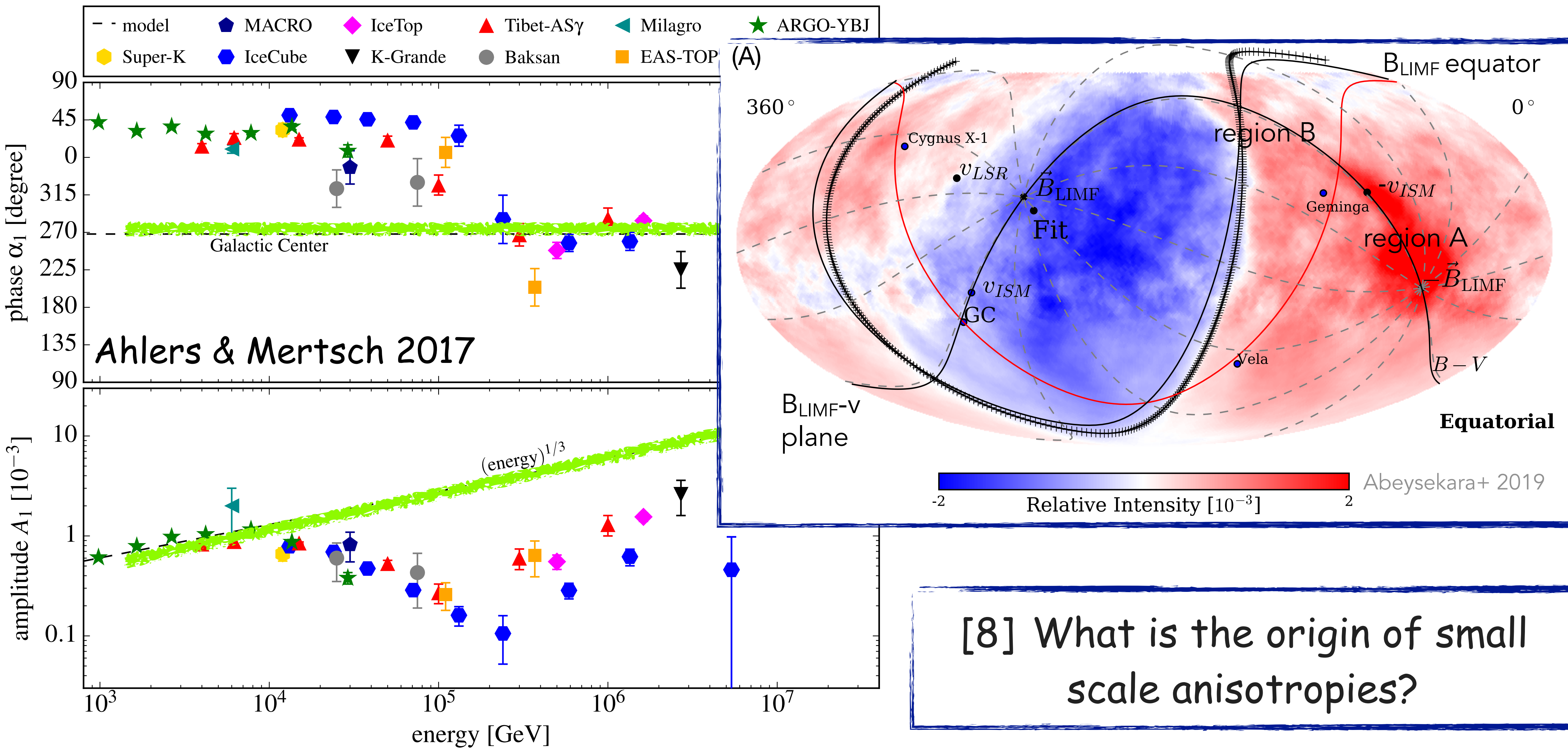
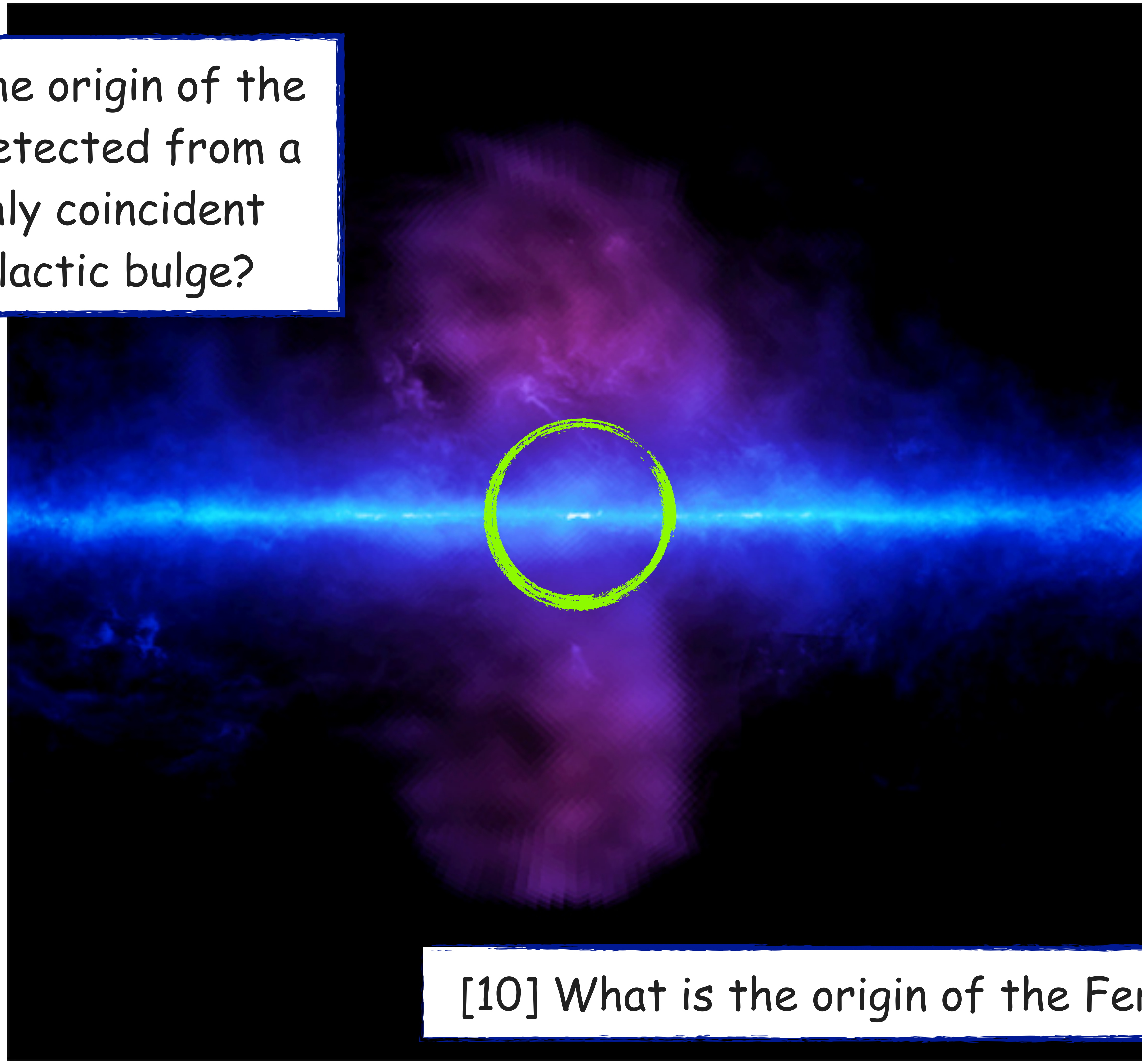


[8] What is the origin of small scale anisotropies?

intro | orthodoxy? | galactic disk | galactic halo | point sources | the end

10 questions



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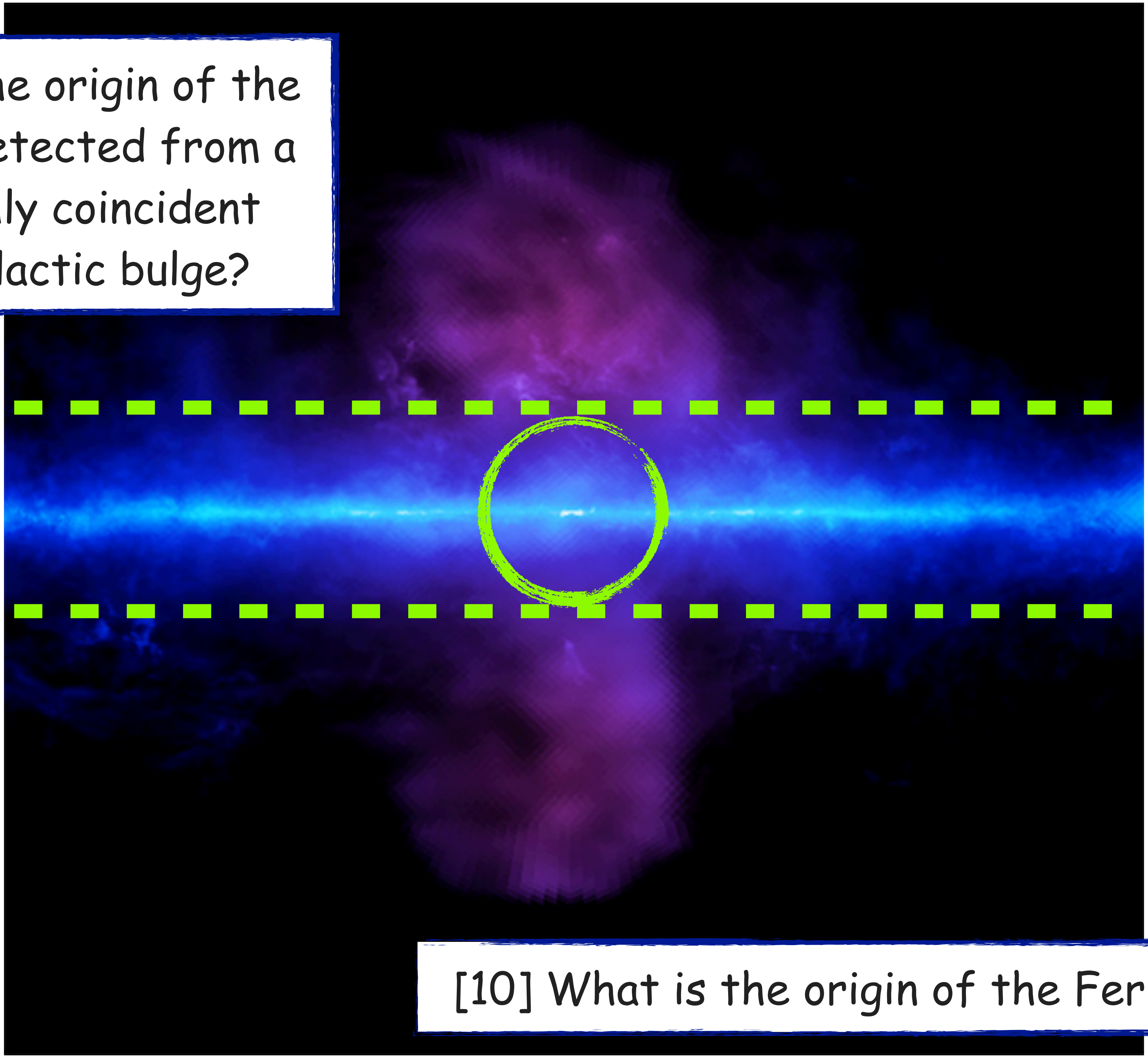

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The link gamma-neutrinos

- pp interaction $$p + p \to p + p + \pi^0 + \pi^+ + \pi^-$$

The link gamma-neutrinos

- pp interaction
  - approx. one ν per each γ

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

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

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$

The link gamma-neutrinos

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  - approx. one ν per each γ
    - approx. same energy for ν and γ

$$E_e \approx E_\nu \approx \frac{E_p}{20}$$

$$E_\gamma \approx \frac{E_p}{10}$$

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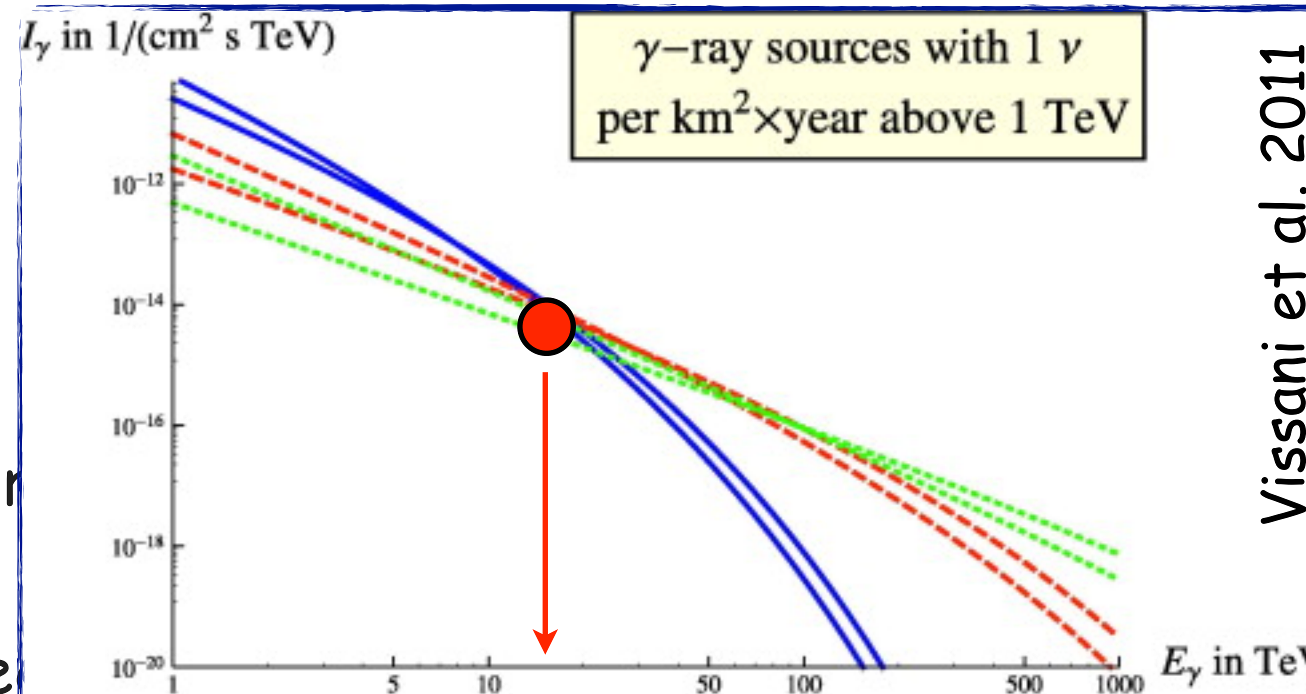

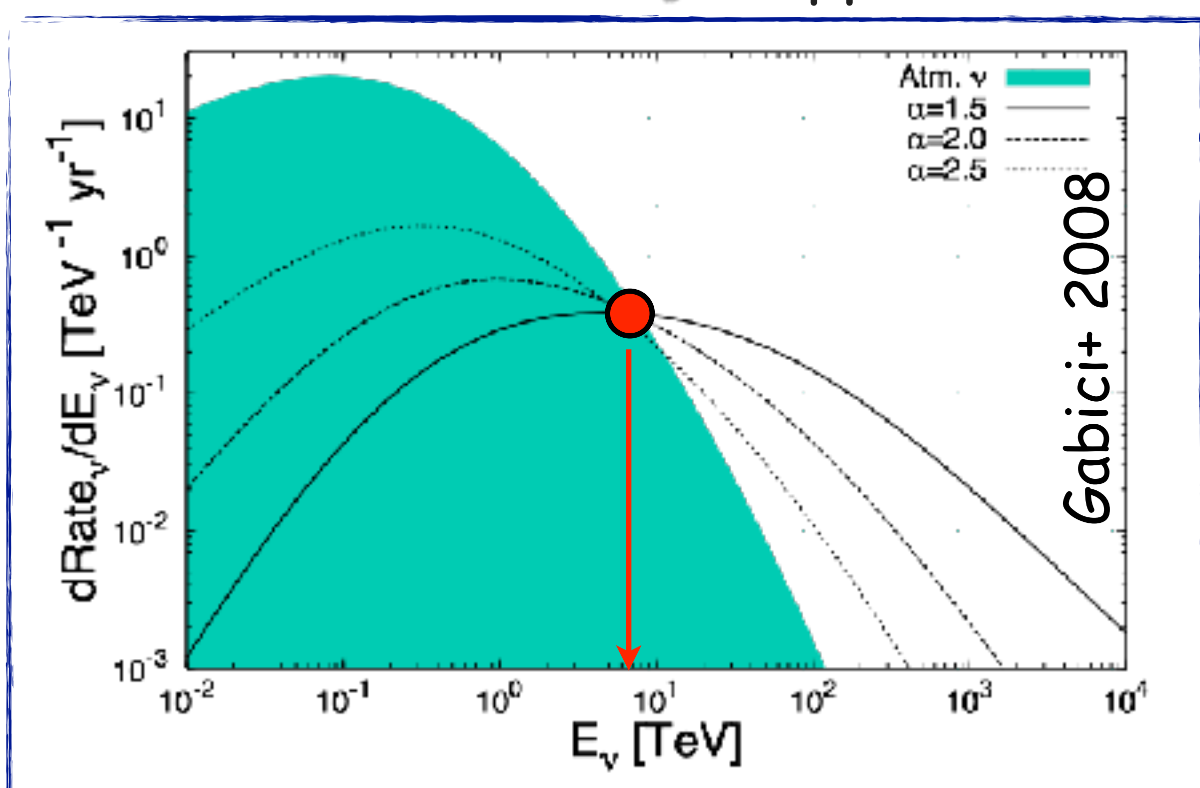

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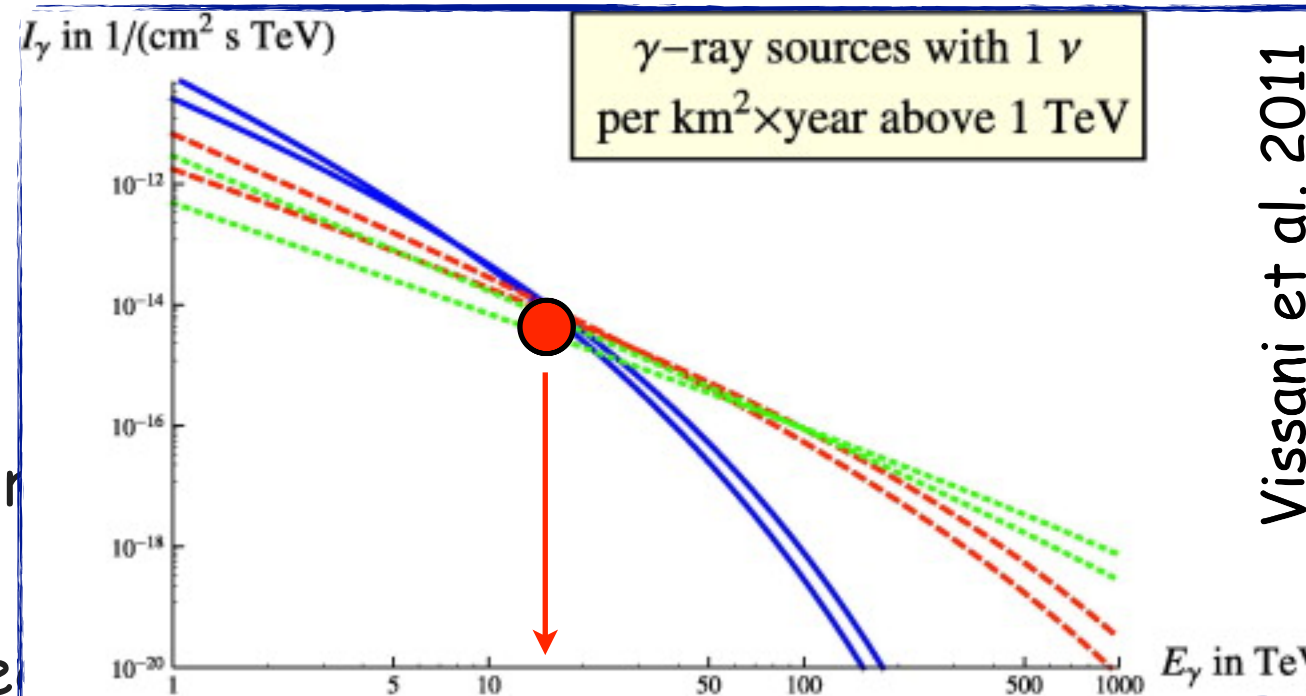
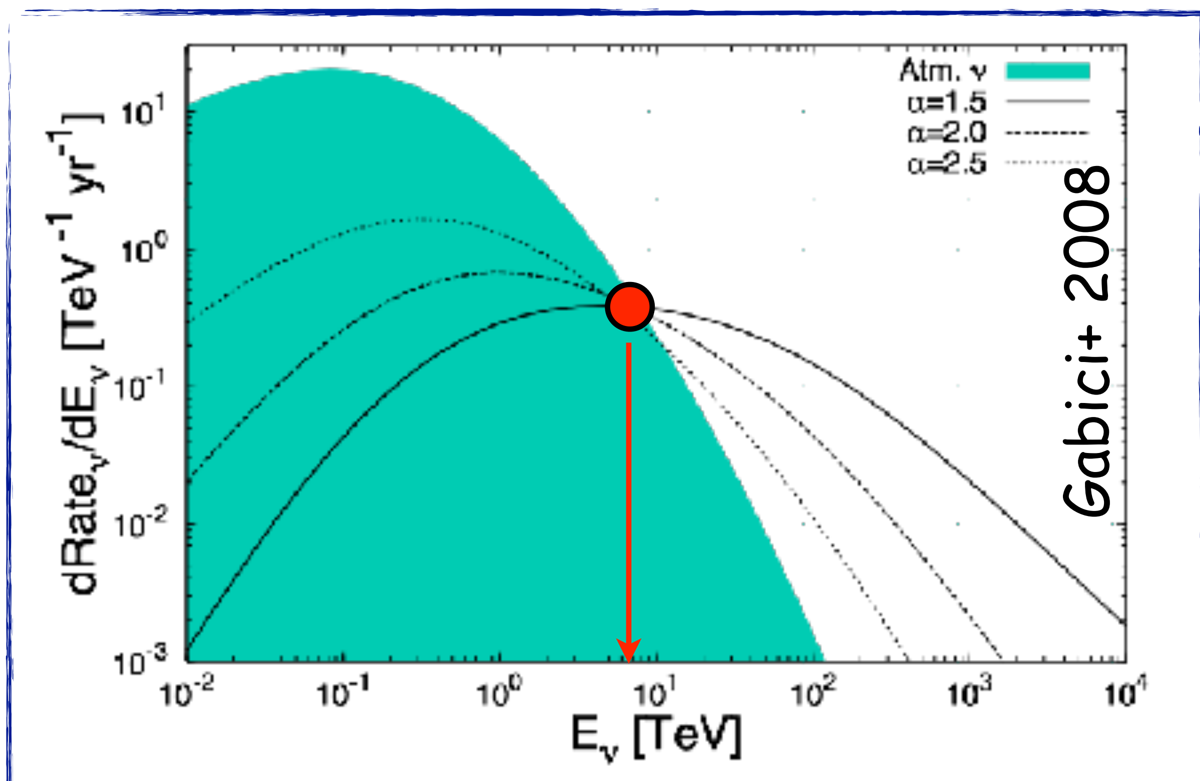
neutrino telescope: best performances in the multi-TeV domain

n γ

approx. same energy for

- approx. same spe





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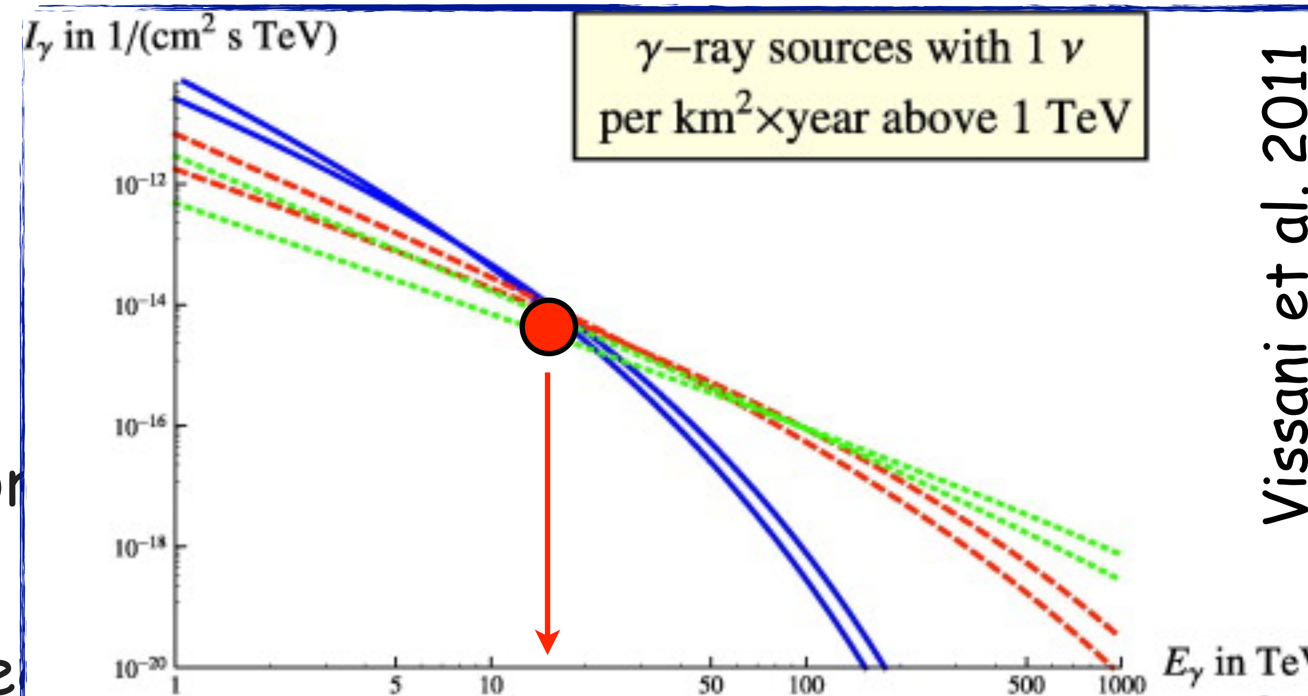

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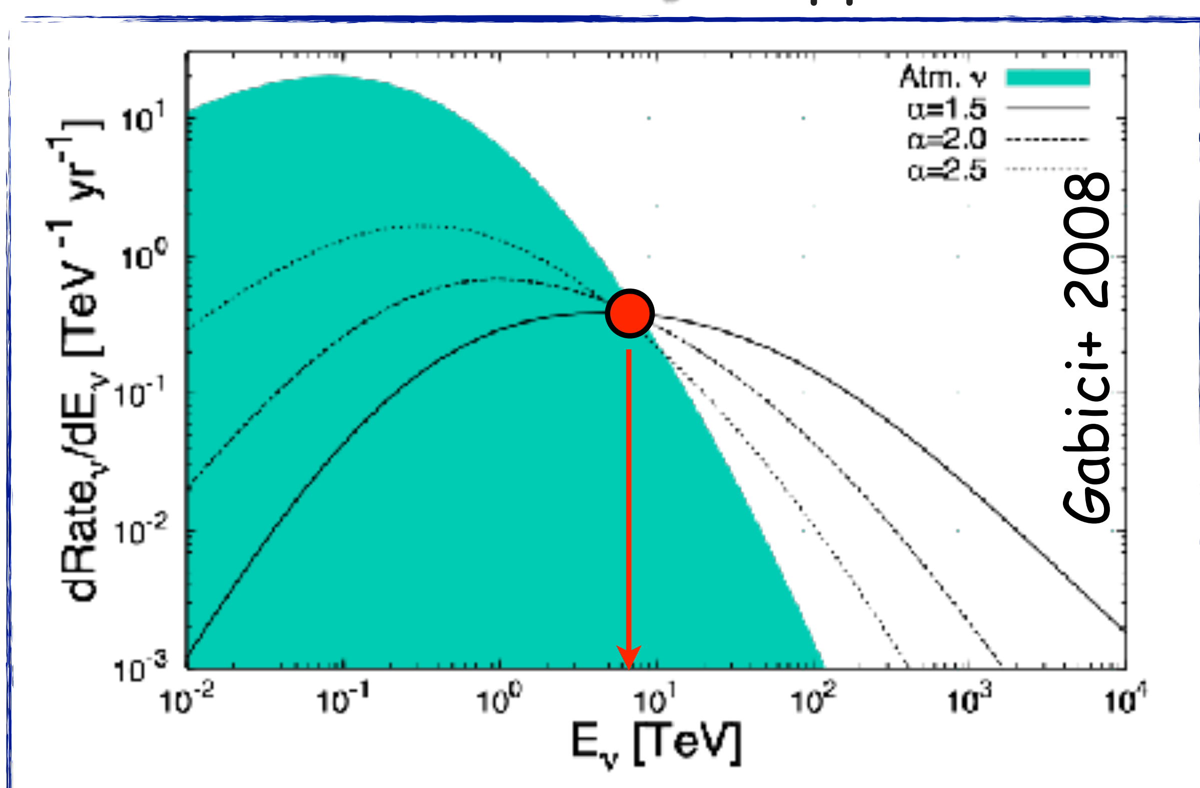

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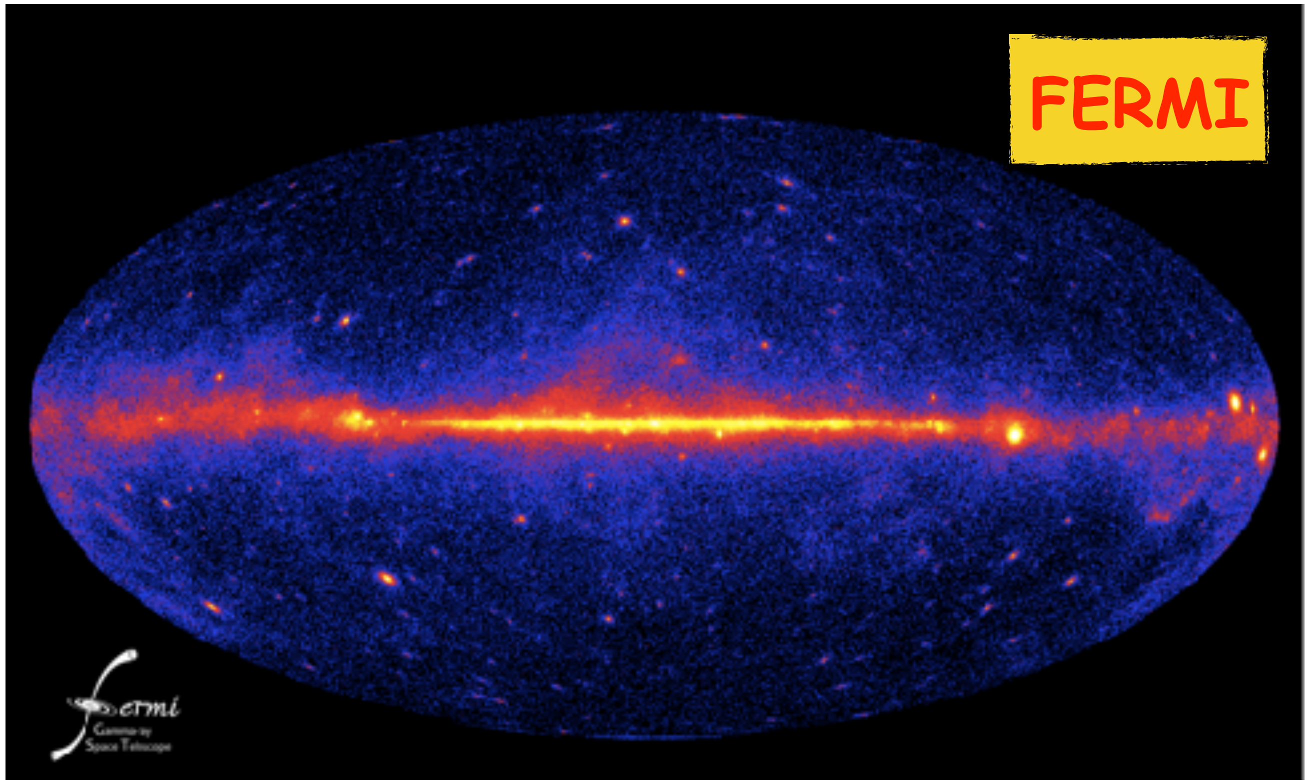
tended sour

gamma ray fluxes at the ~Crab level -> detection of neutrinos

- model in... ν's!

Neutrinos from the Galactic disk



Gabici+ 2008

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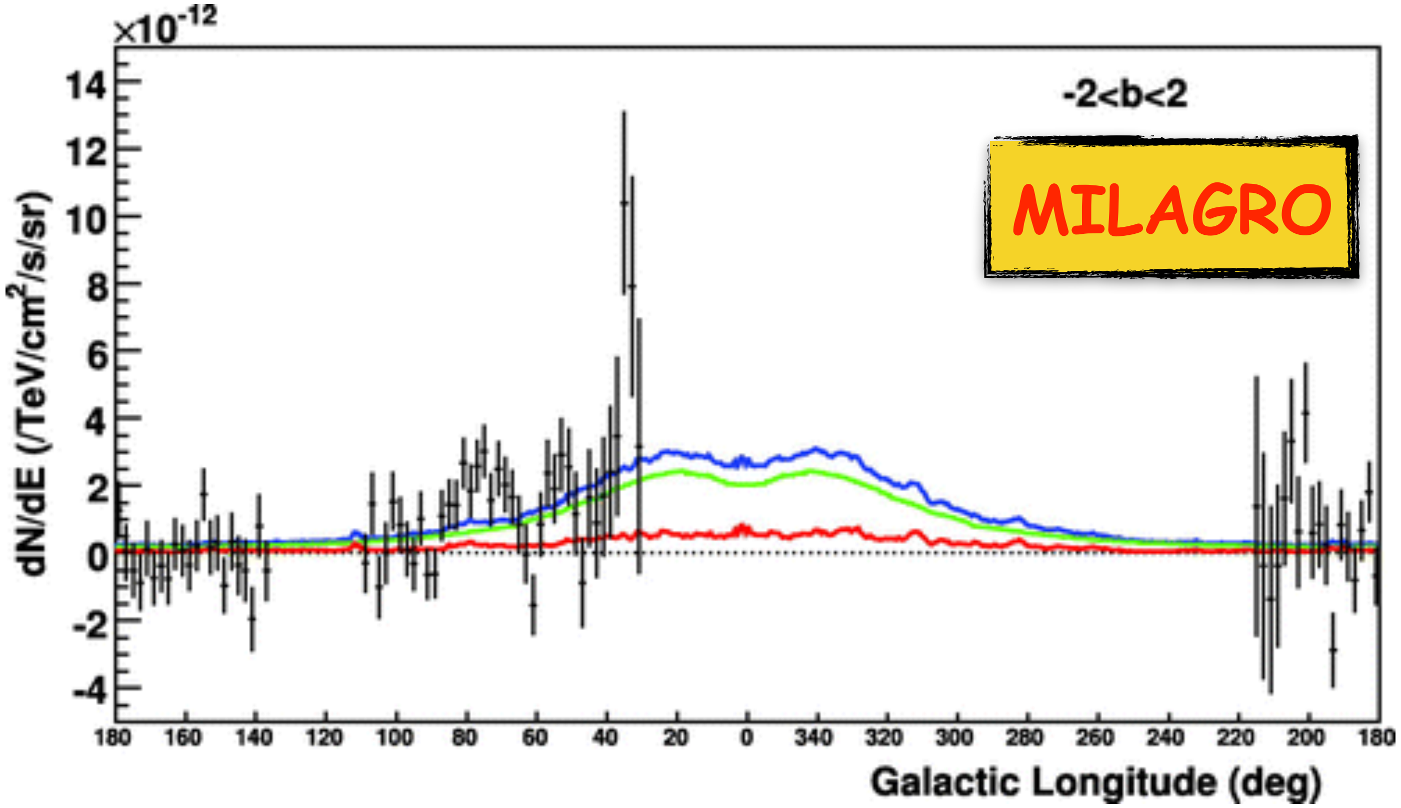

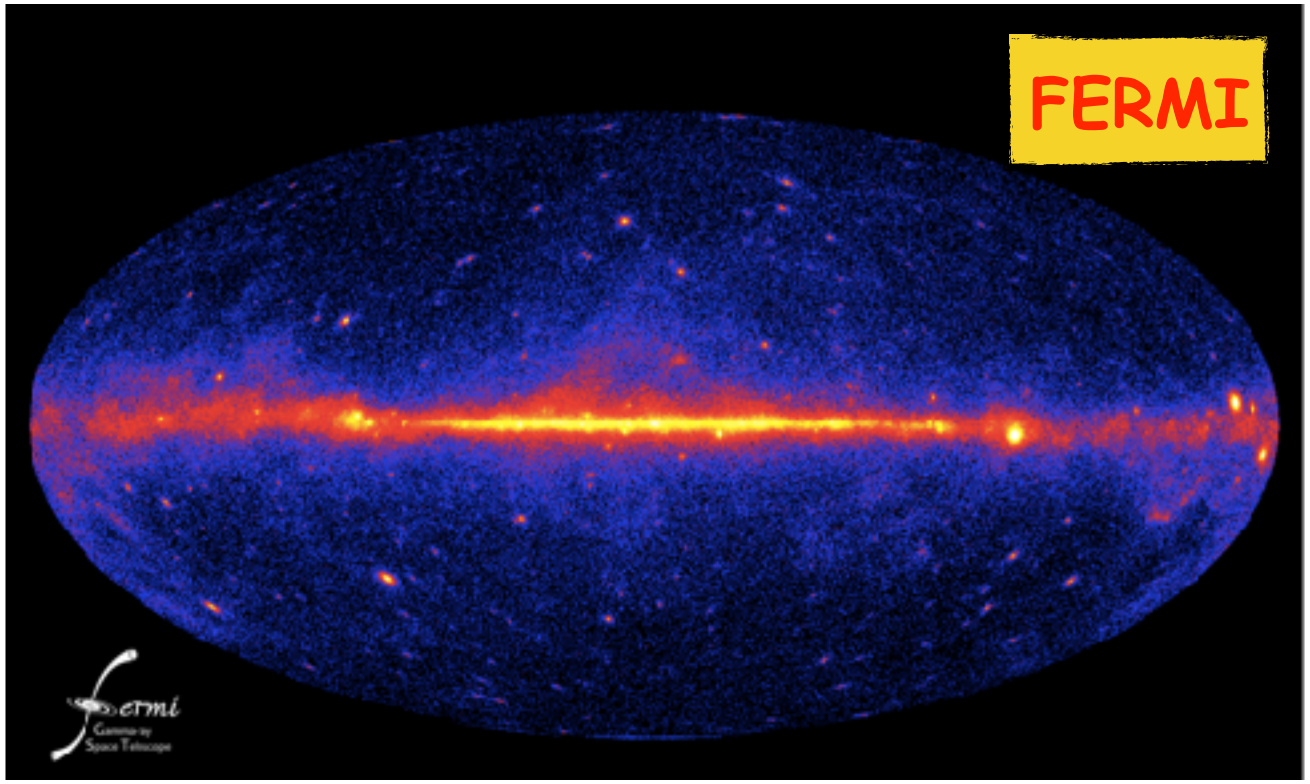

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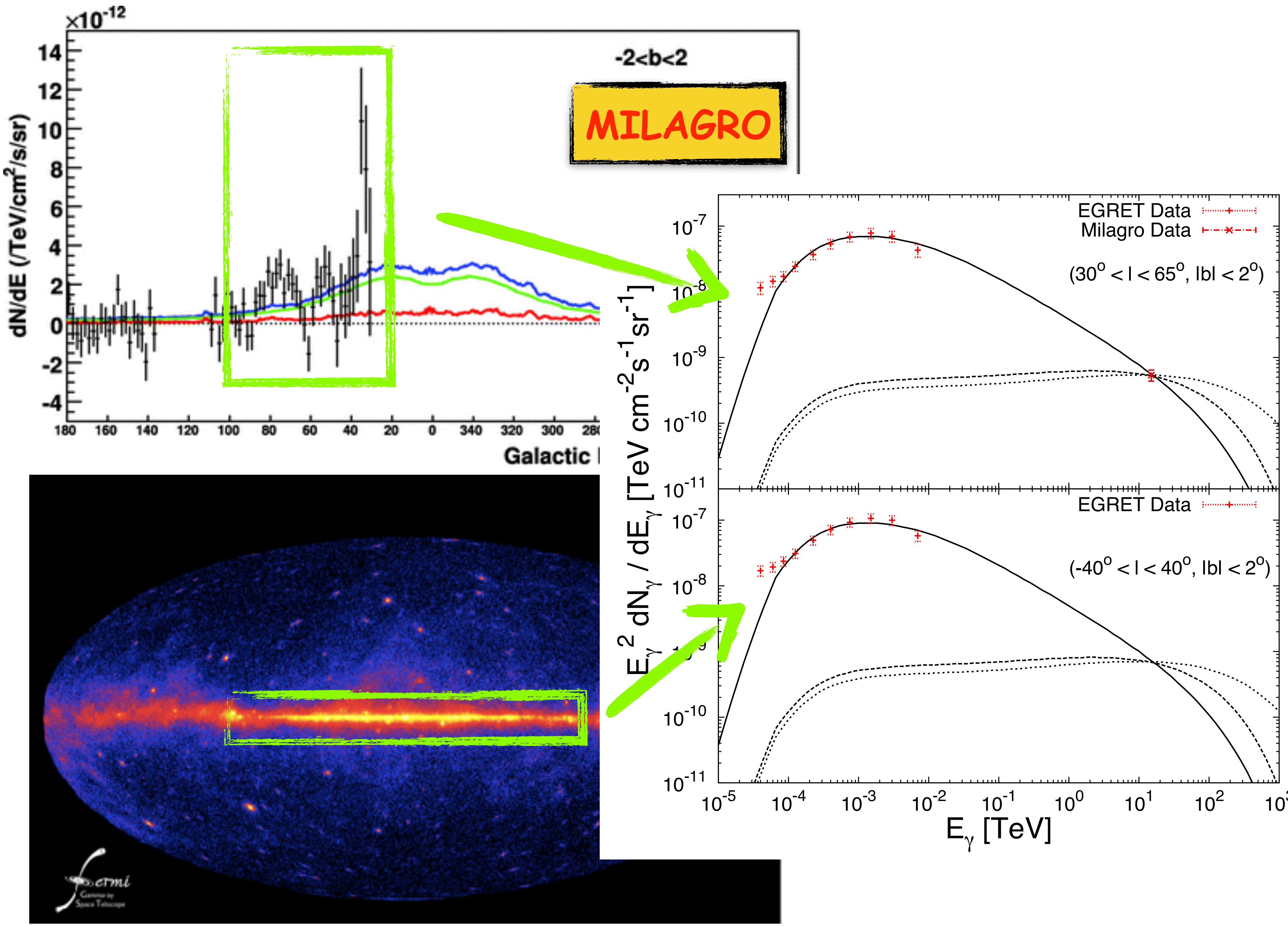

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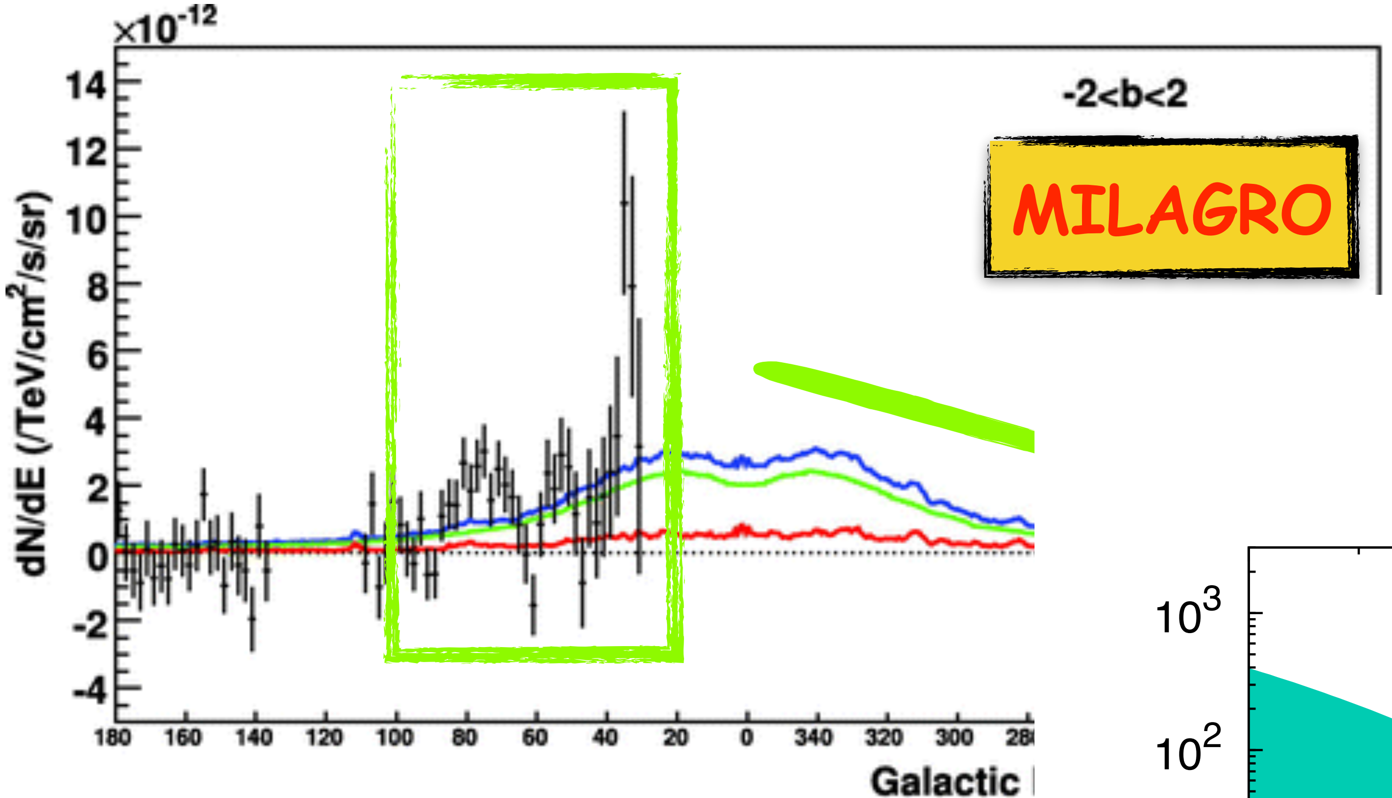

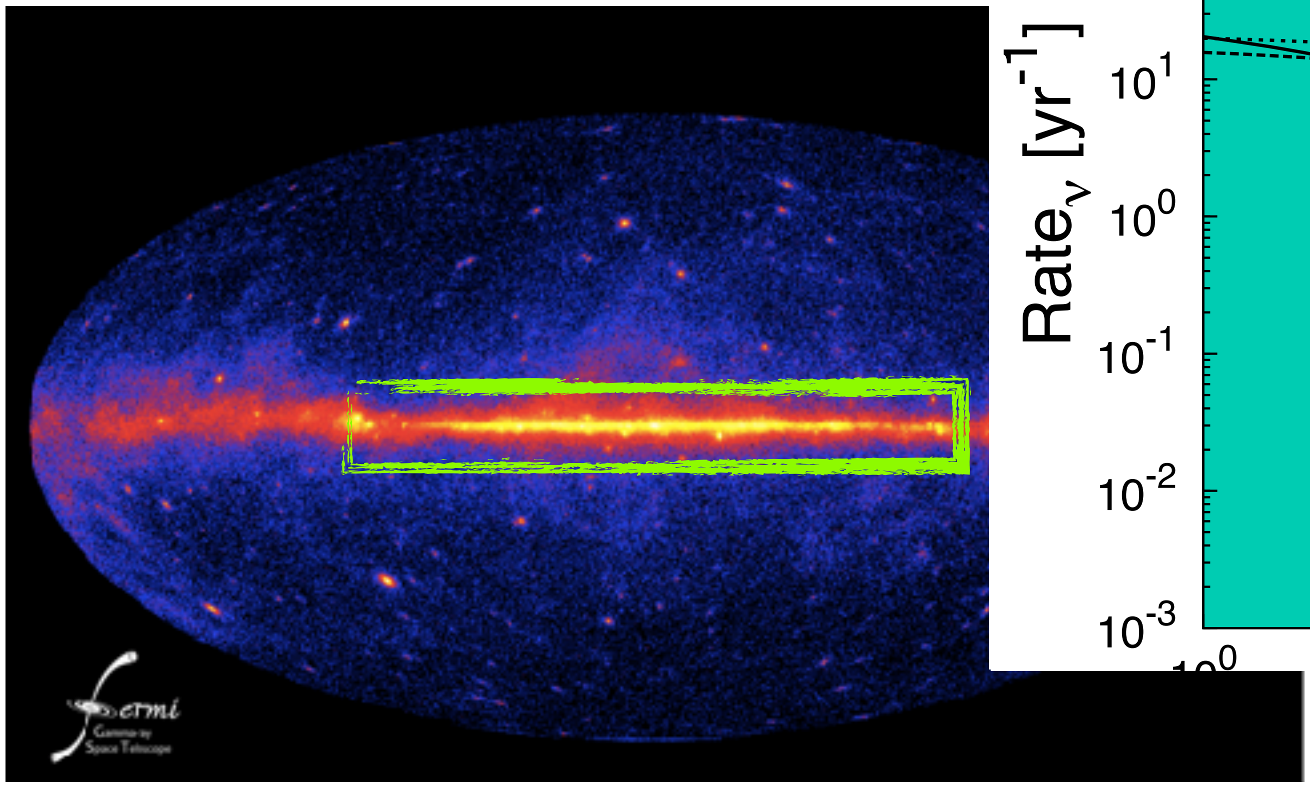

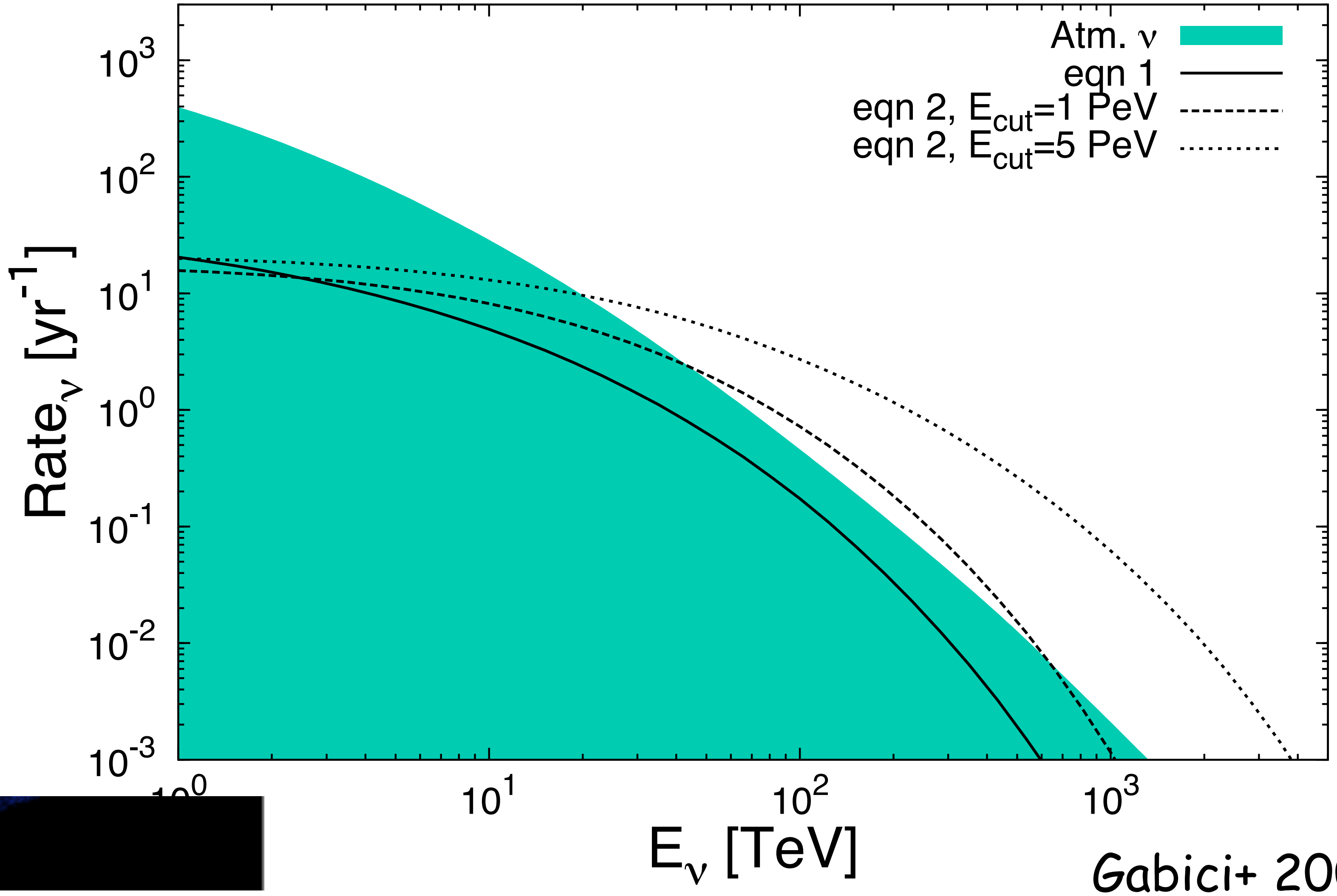

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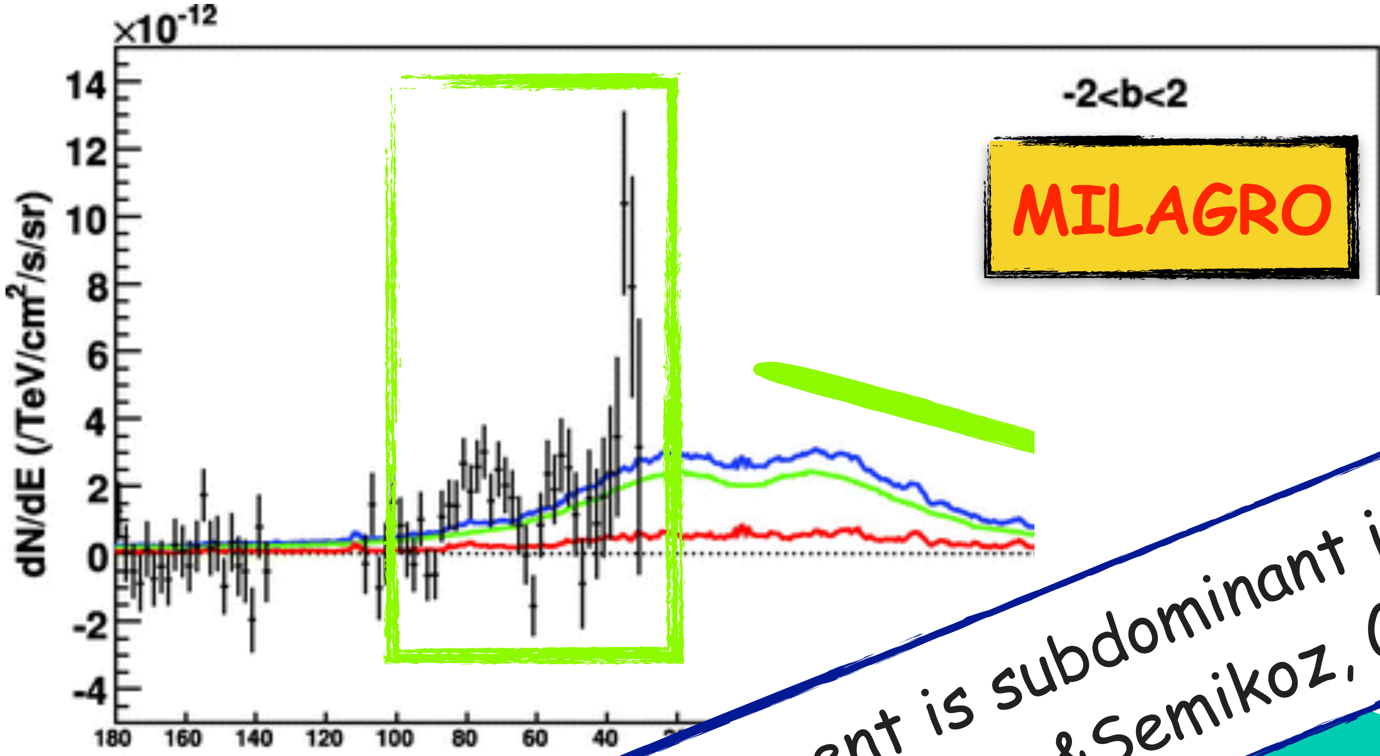
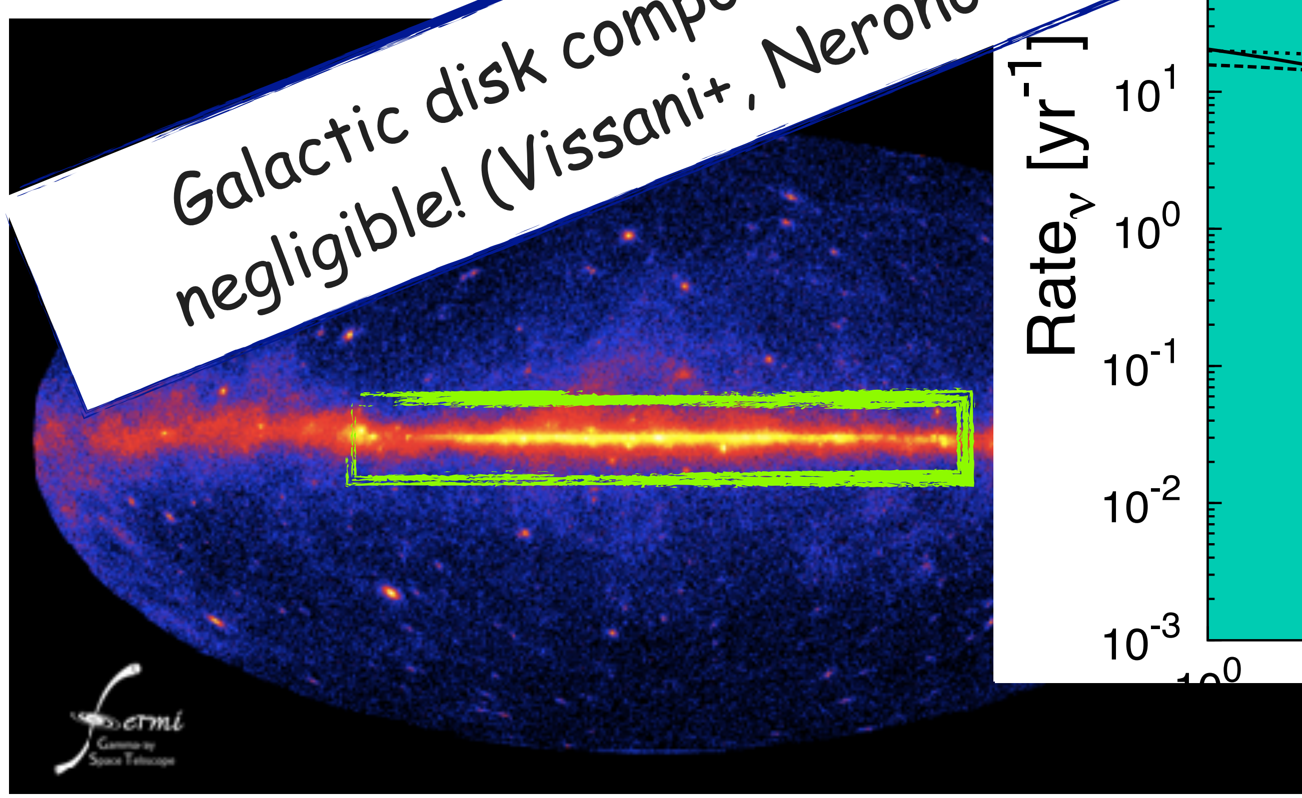
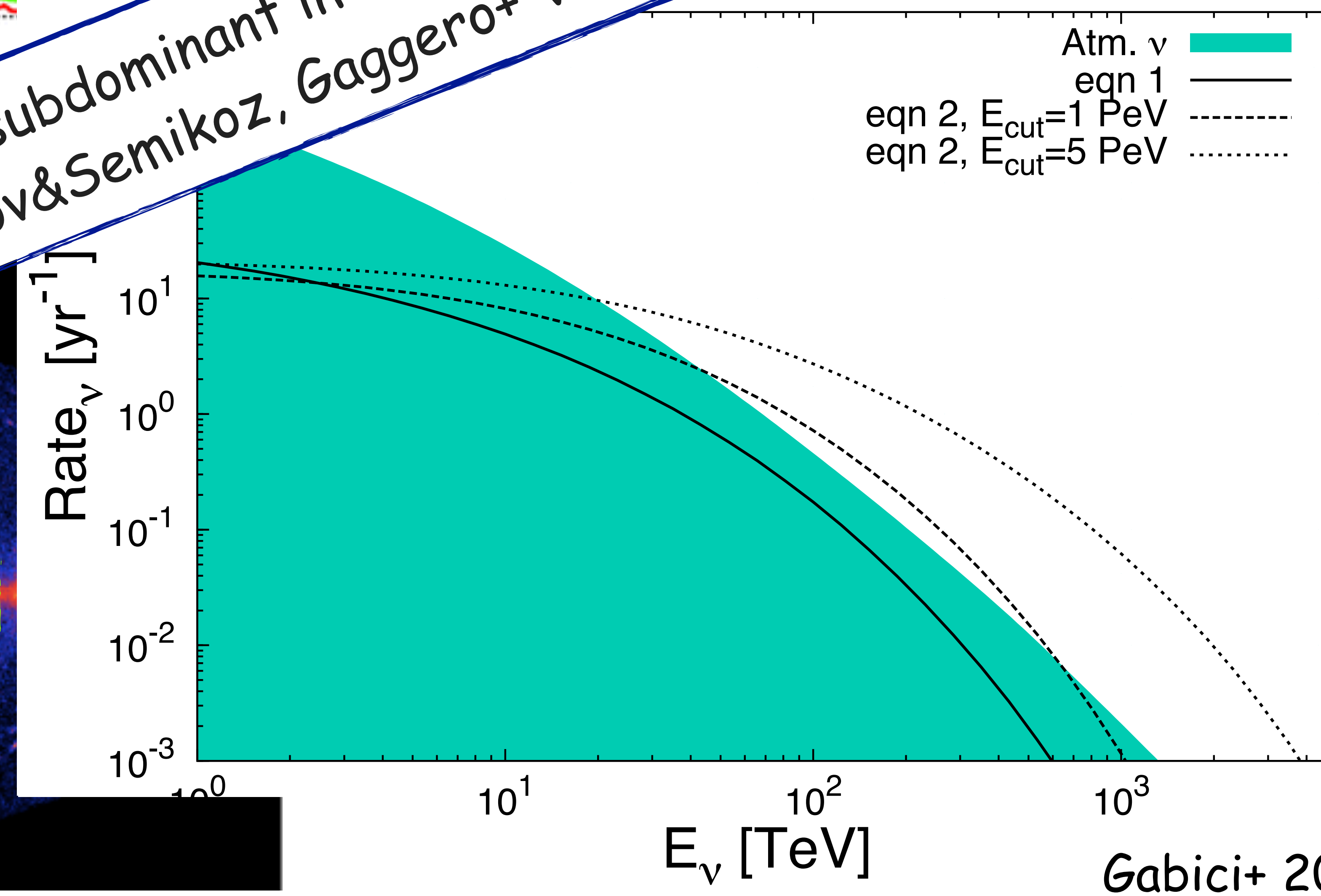


Galactic disk component is subdominant in Icecube data, but most likely not negligible! (Vissani+, Neronov&Semikoz, Gaggero+ Villante&Pagliaroli, Spurio...)





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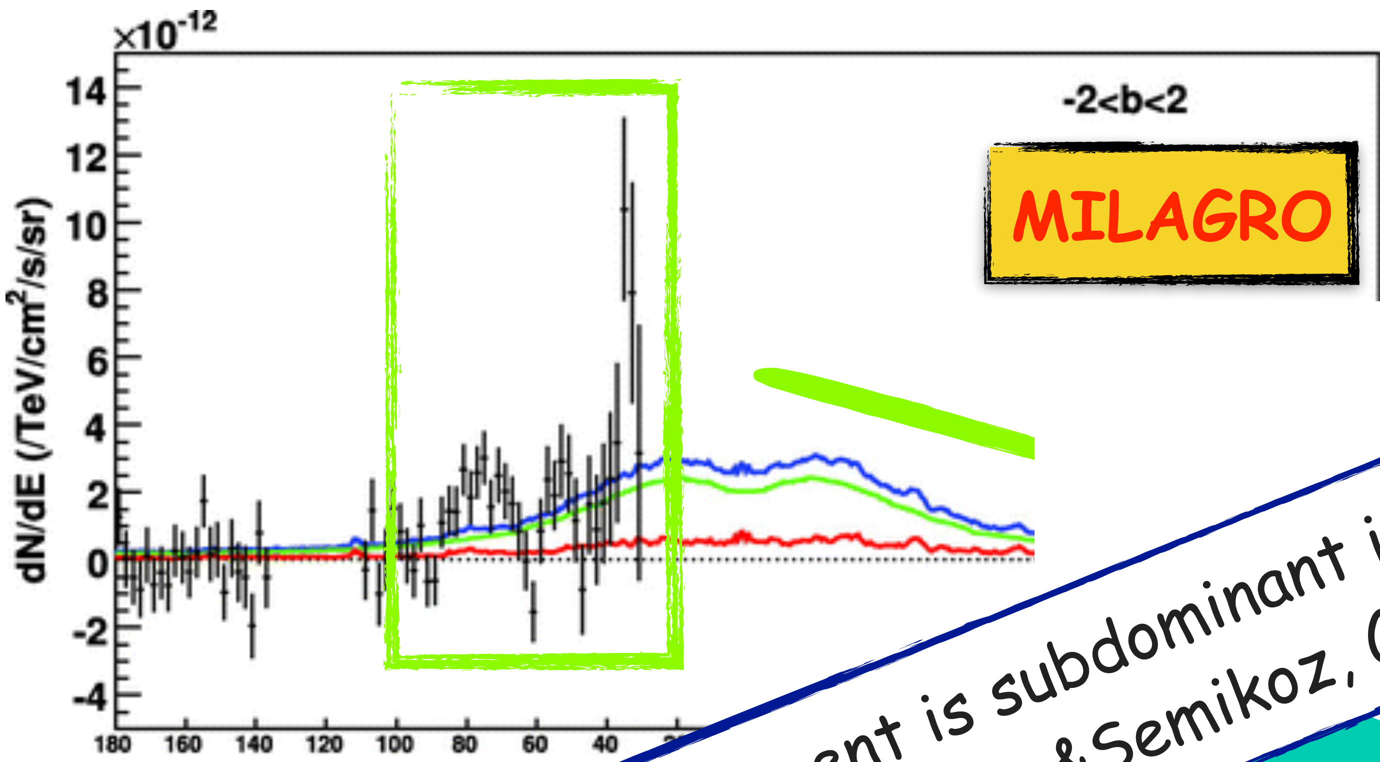

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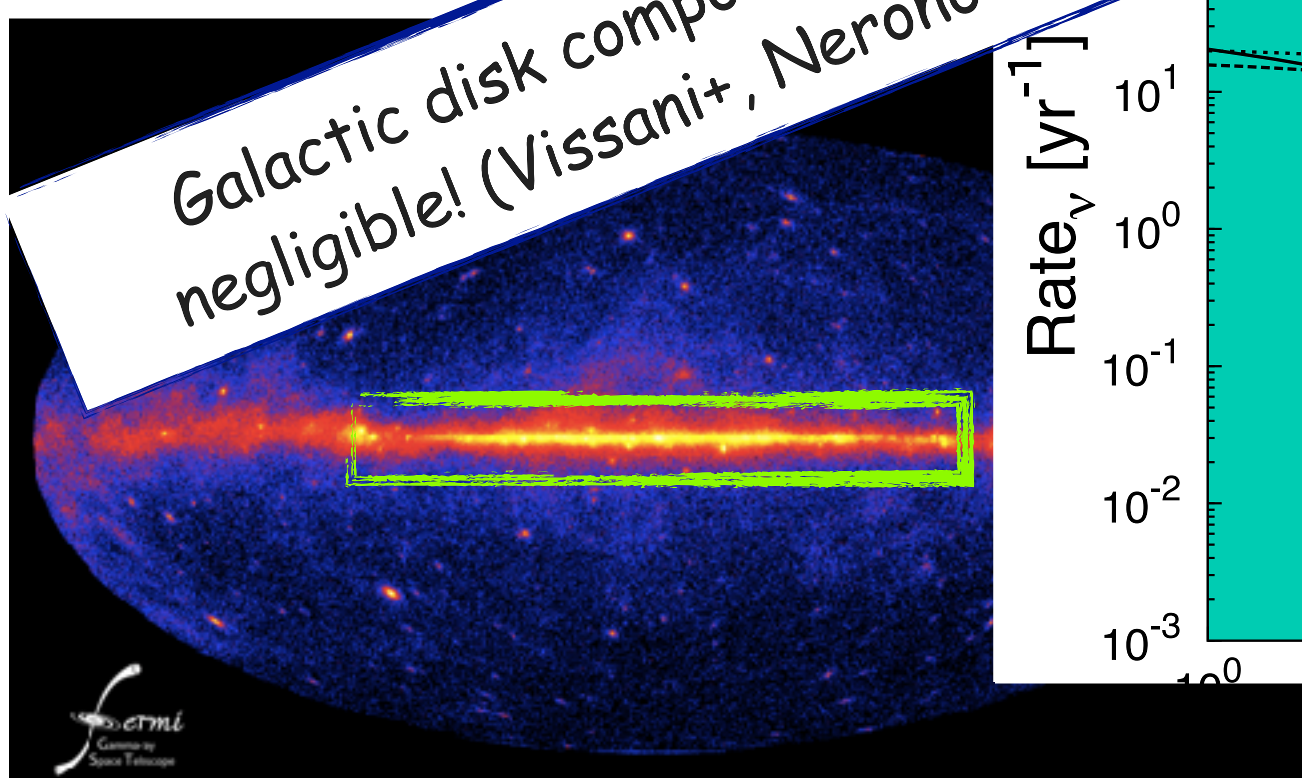
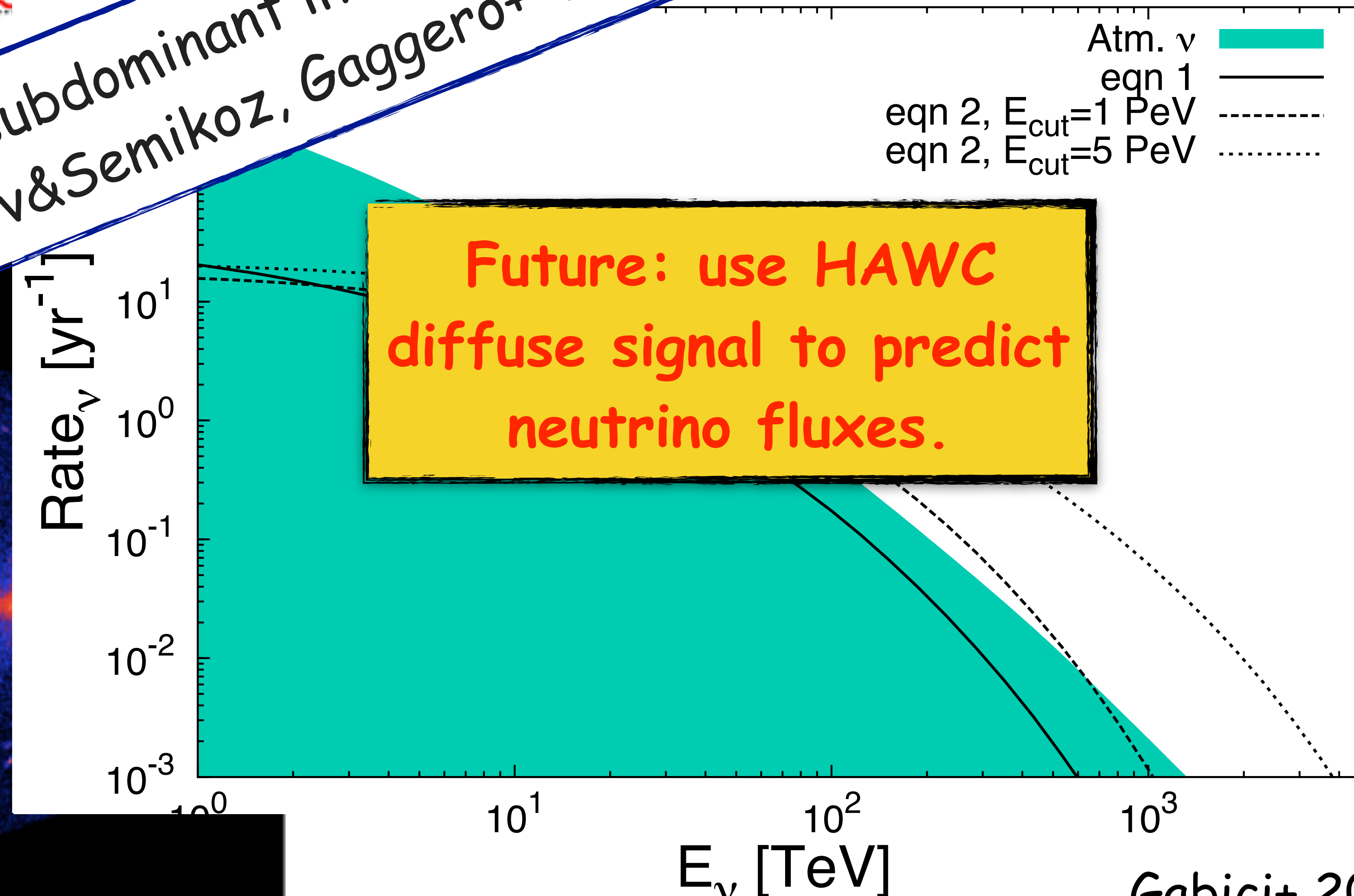


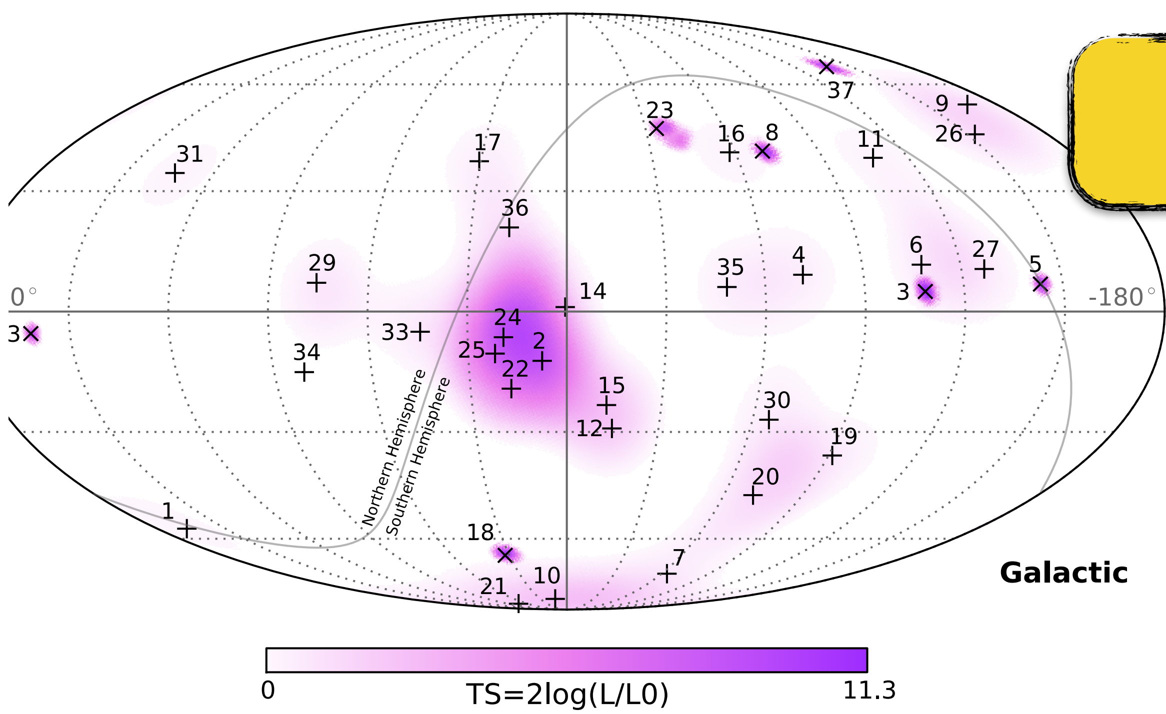


Future: use HAWC diffuse signal to predict neutrino fluxes.

Gabici+ 2008

Neutrinos from the Galactic halo

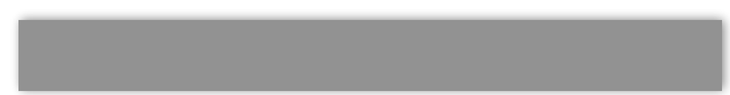
Aartsen et al. 2014



isotropy?

extragalactic?

Neutrinos from the Galactic halo



Galactic plane

# of neutrinos

$subdominant$

Taylor, SG, Aharonian 2014

Neutrinos from the Galactic halo

Galactic halo
(homogeneous CRs)

Galactic plane

# of neutrinos

≈ 0

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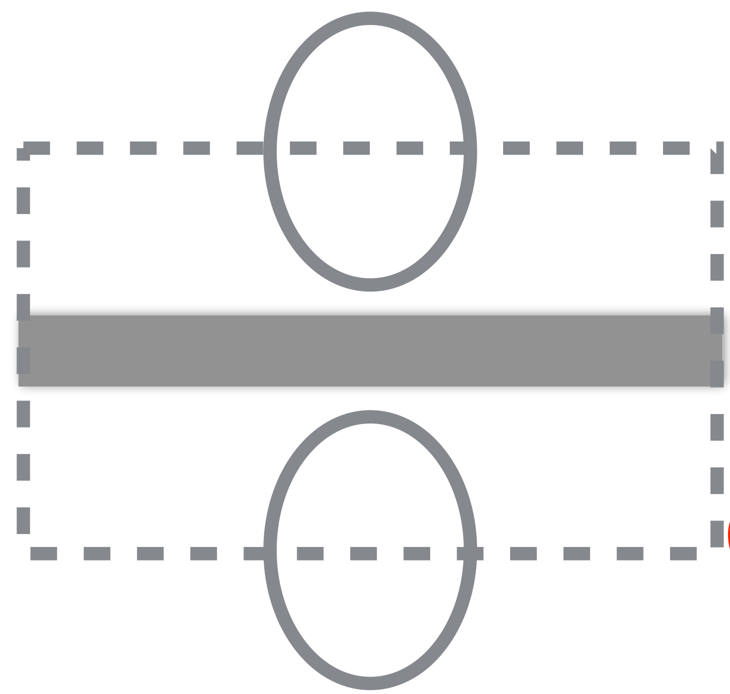

	# of neutrinos
Fermi bubbles	?
Galactic halo (homogeneous CRs)	≈ 0
Galactic plane	*subdominant*

Taylor, SG, Aharonian 2014

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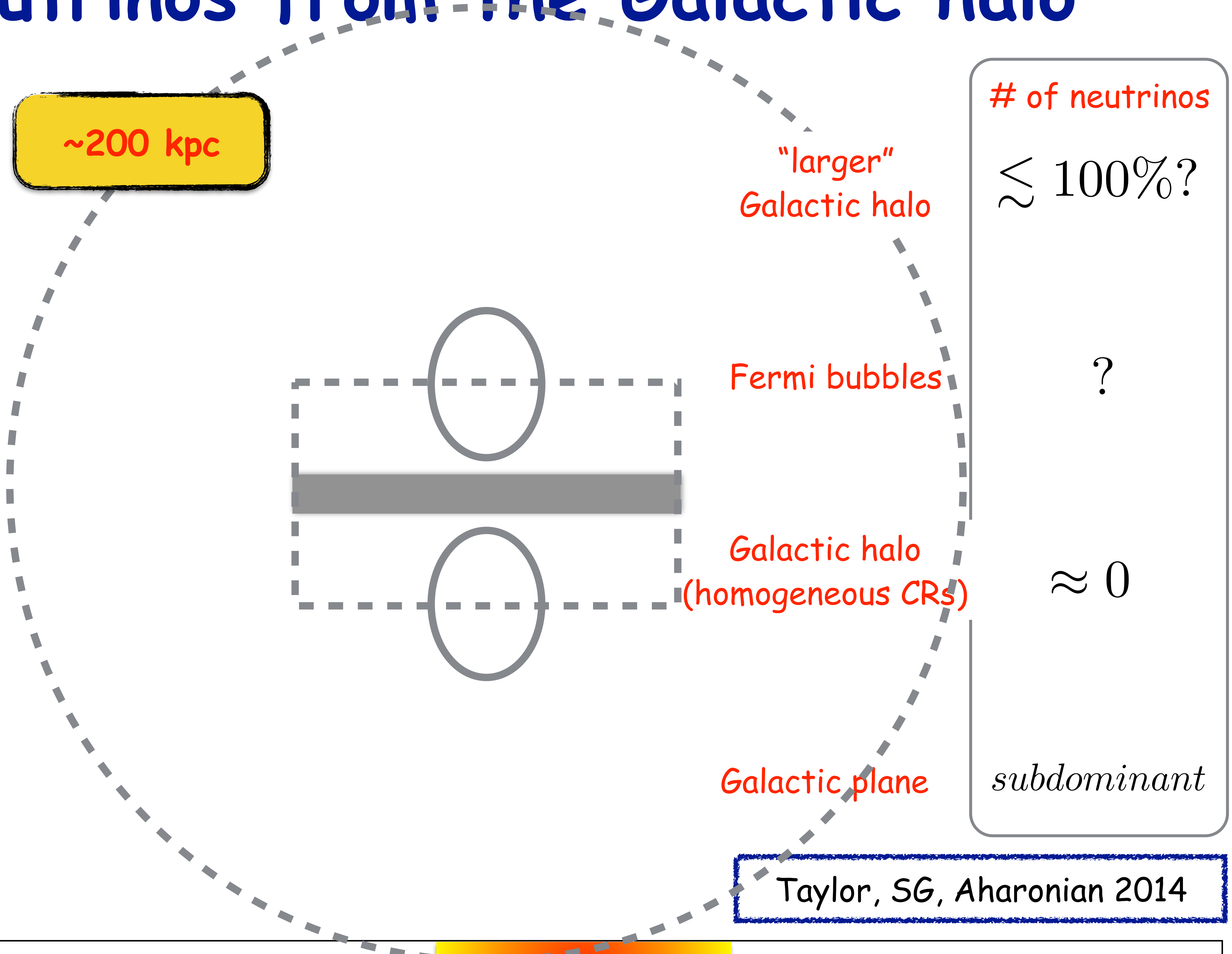

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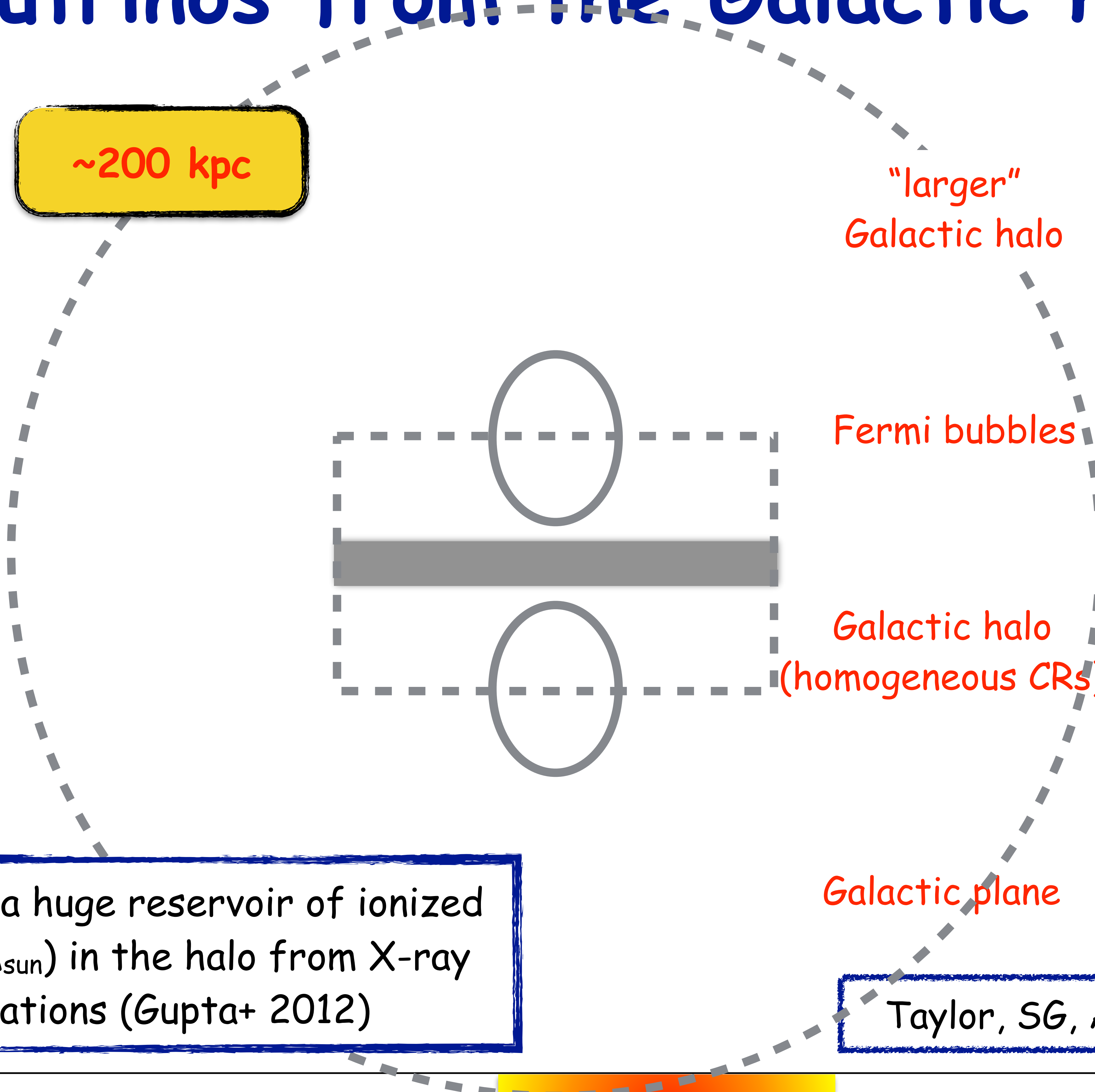

	# of neutrinos
"larger" Galactic halo	$\lesssim 100\%?$
Fermi bubbles	$?$
Galactic halo (homogeneous CRs)	≈ 0
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evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)

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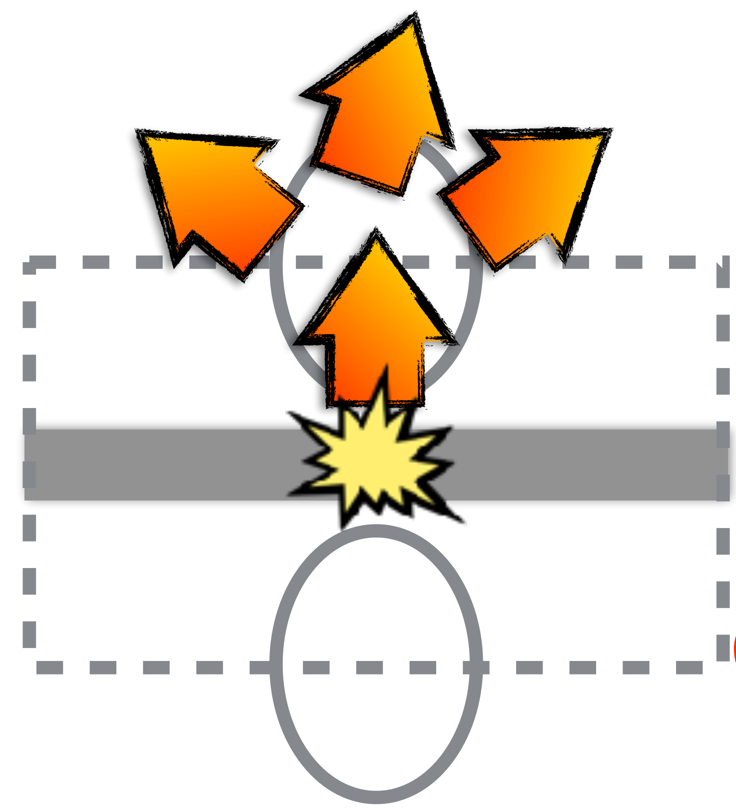
Neutrinos from the Galactic halo

~200 kpc

$L_{CR} \approx 10^{39}$ erg/s



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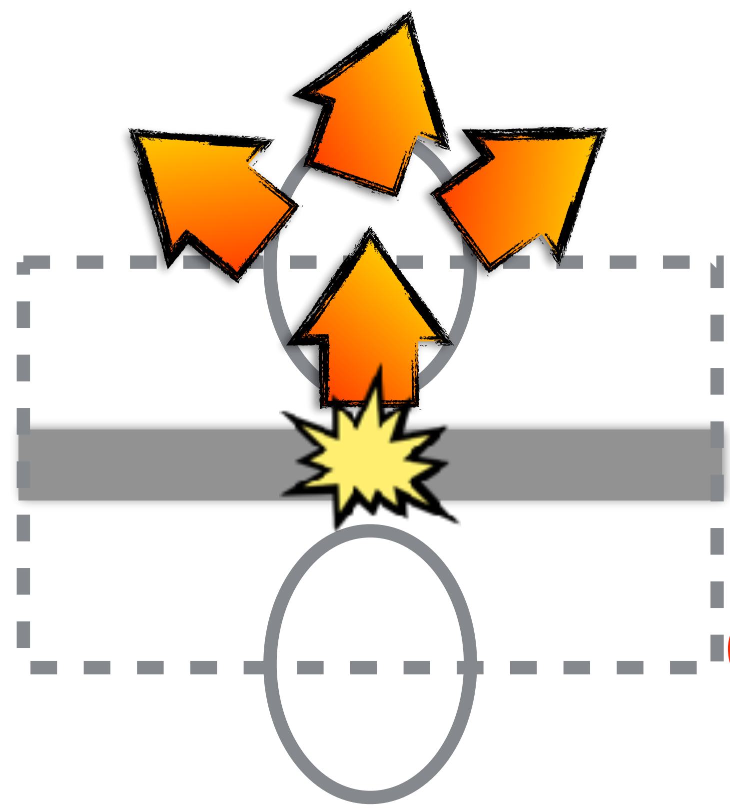

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Halo MUST be large (to absorb γ-rays)

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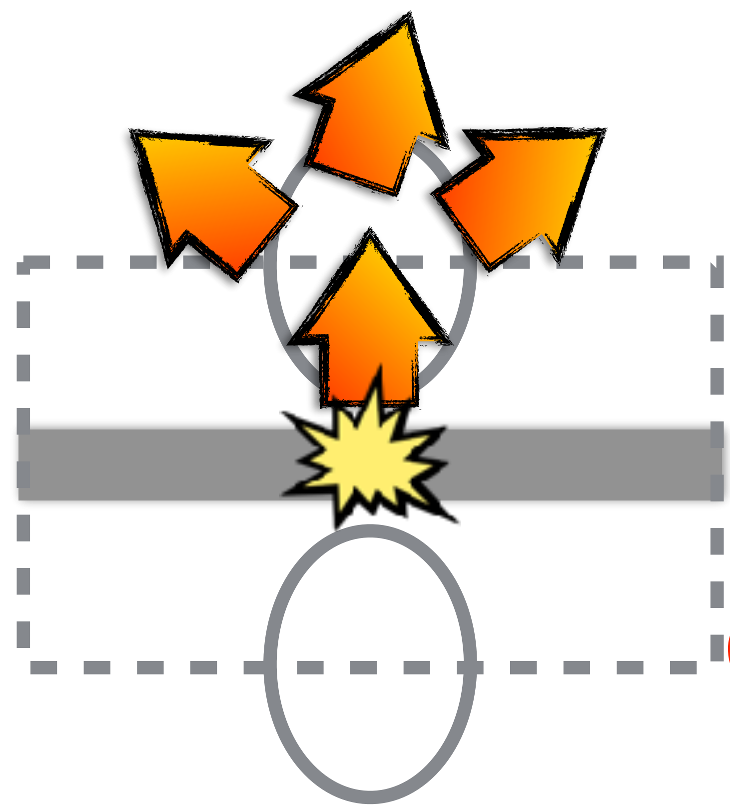

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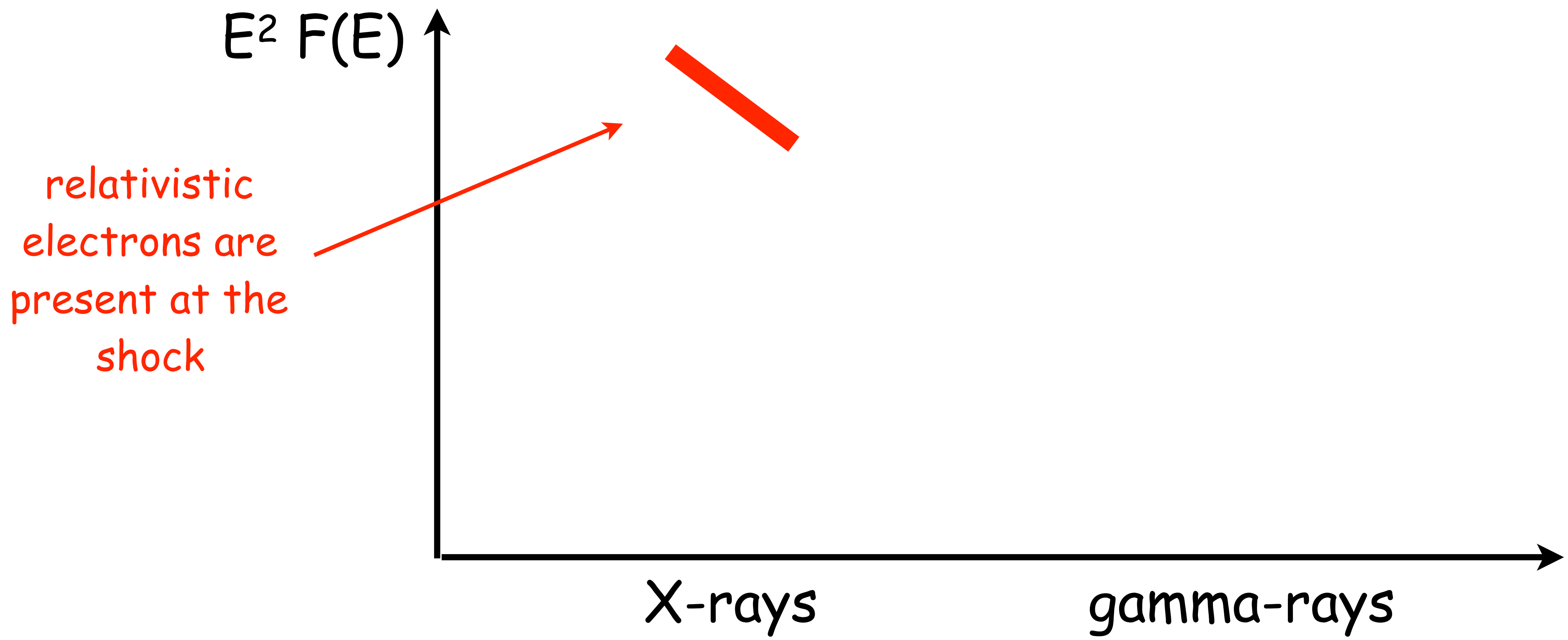
“Point” sources

Hadronic versus leptonic emission: the role of the magnetic field

X-ray synchrotron emission observed from some TeV SNRs (RXJ1713, Vela Jr)



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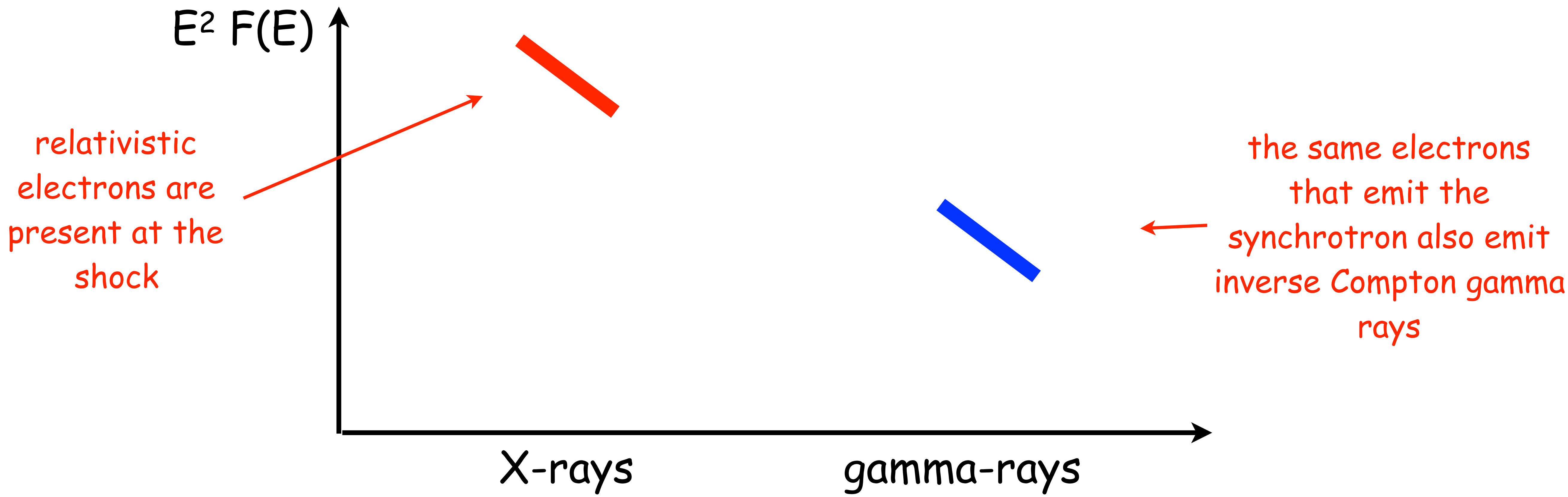

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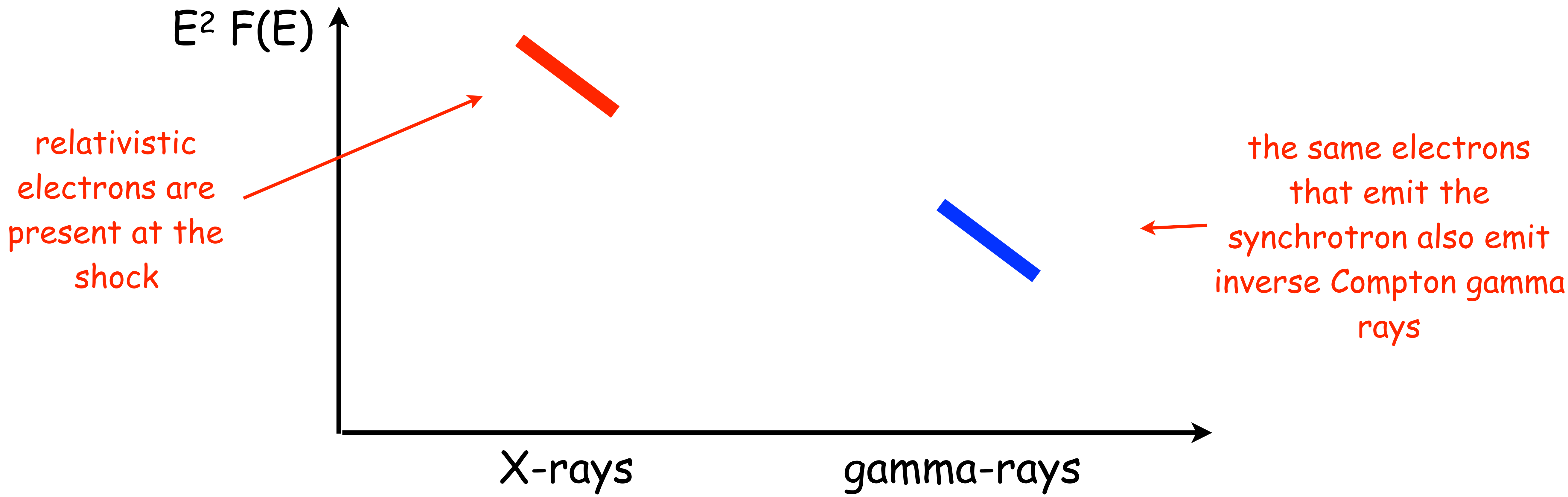

synchrotron -> $F_s \propto n_e B^\beta$ inverse Compton -> $F_{IC} \propto n_e w_{soft}$

this product is fixed by X-ray obs. we know this

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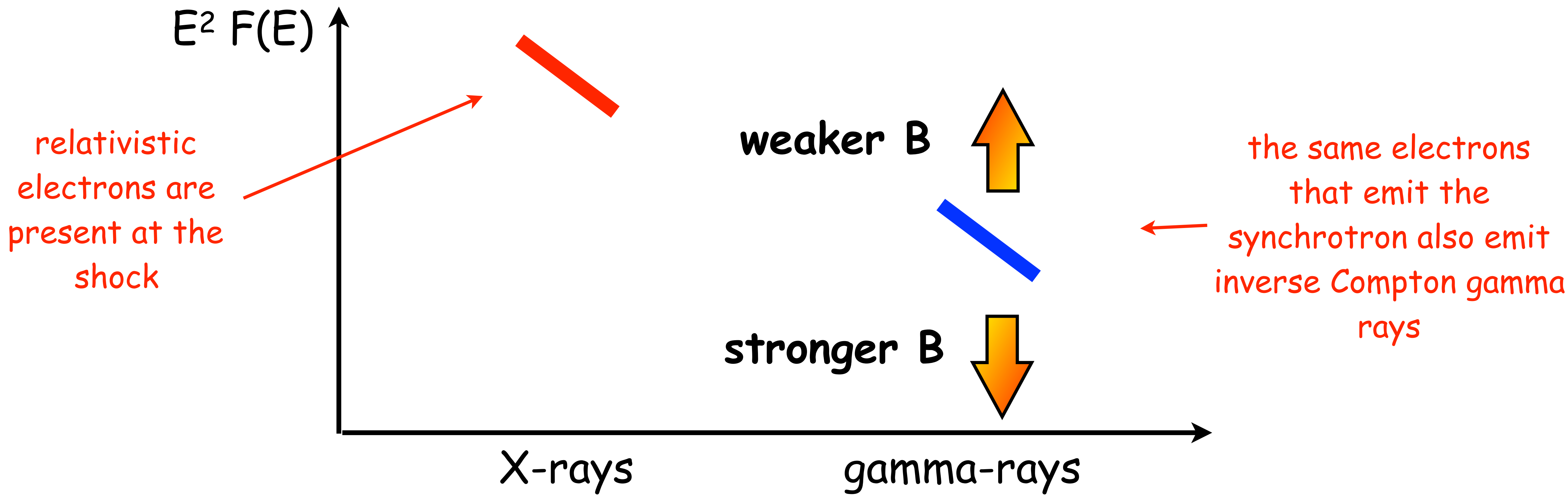

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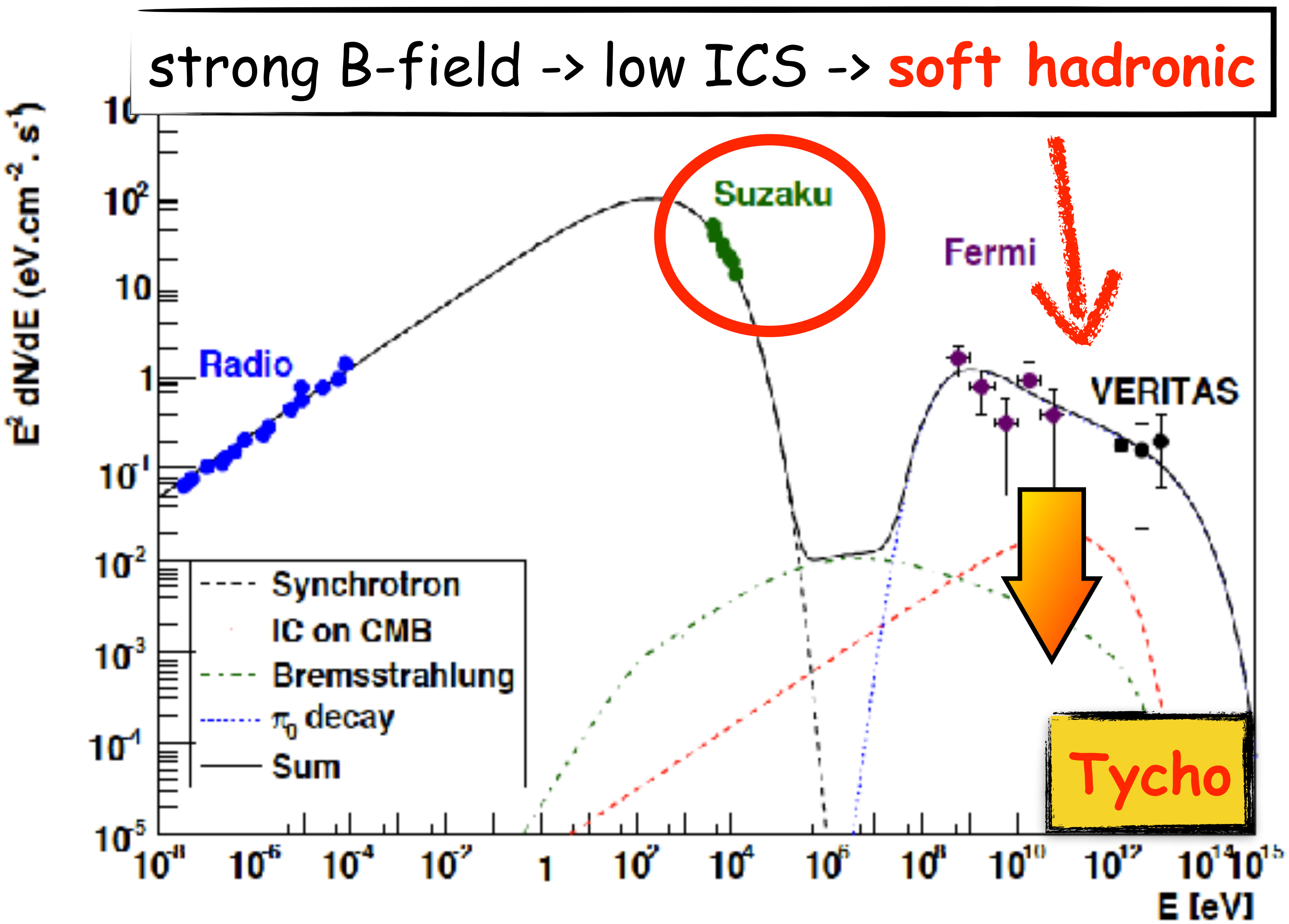
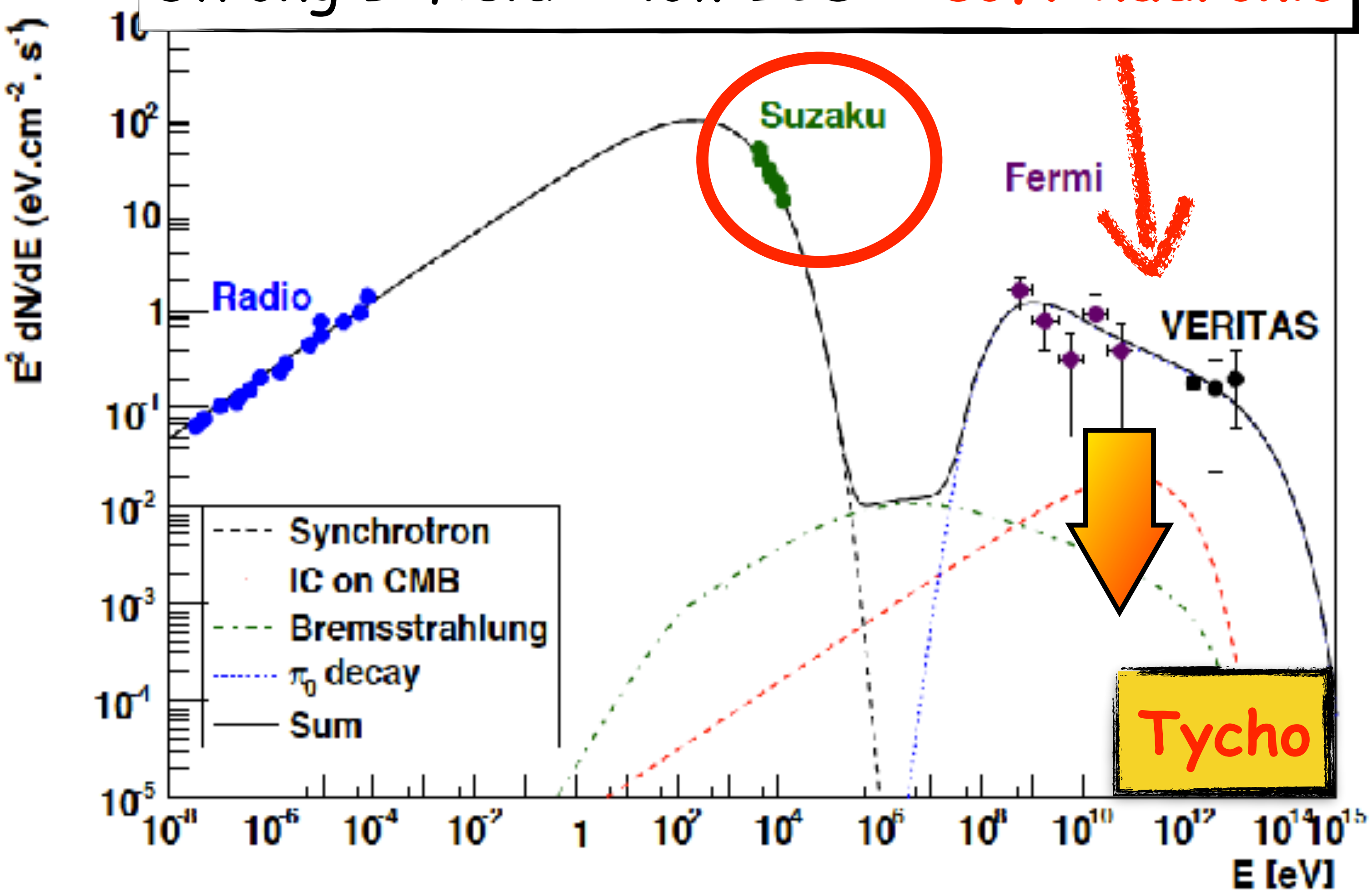
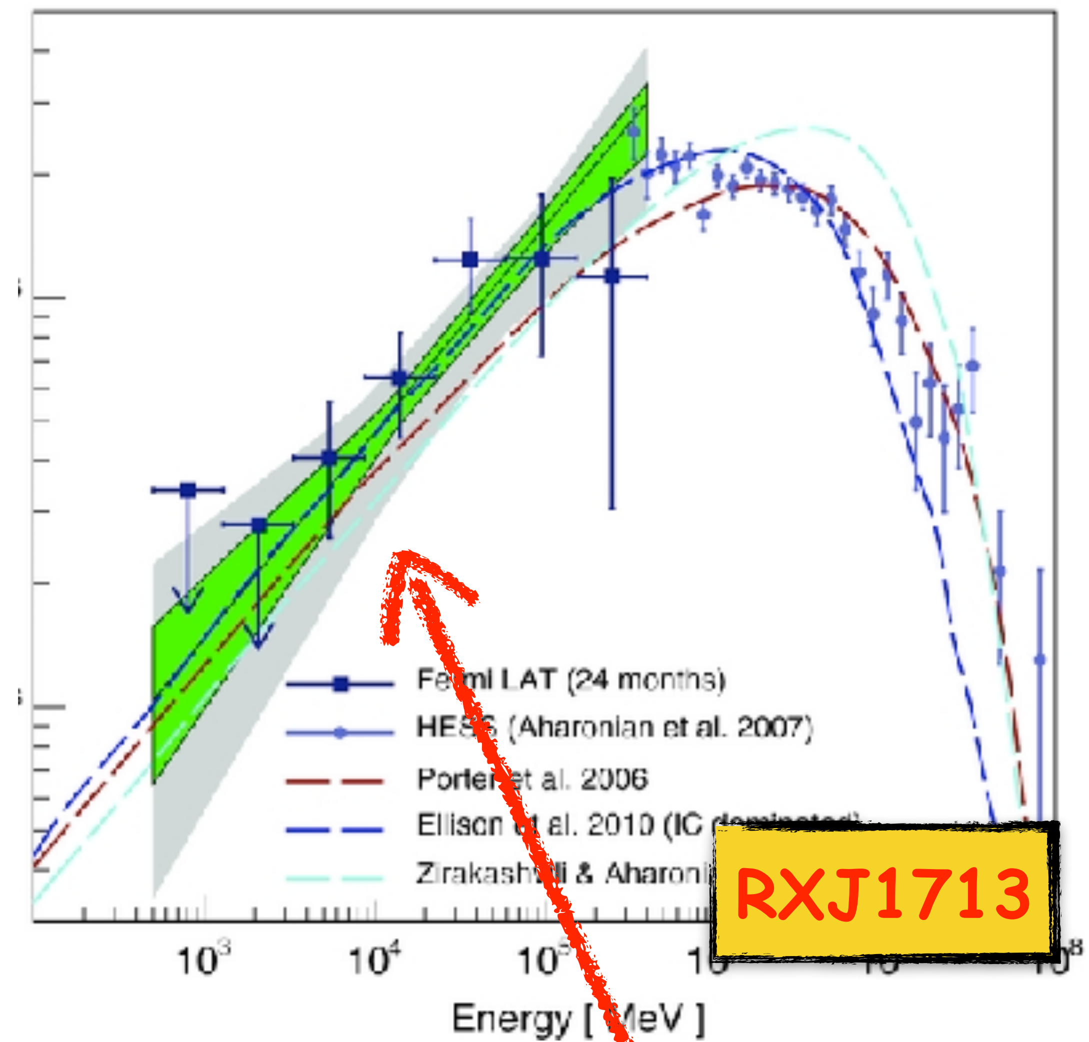
Hadronic or leptonic?



Hadronic or leptonic?

strong B-field -> low ICS -> soft hadronic

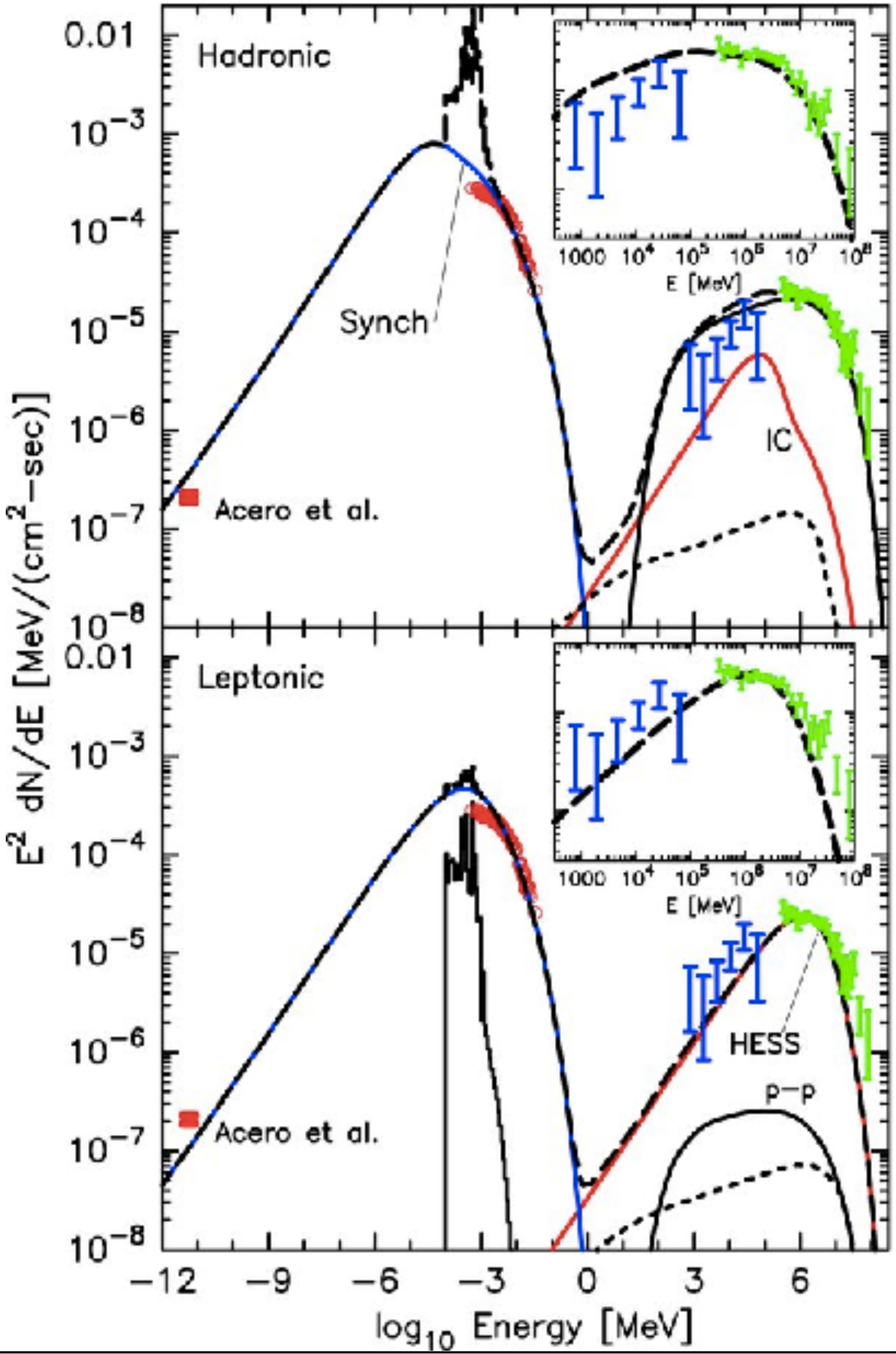




weak B-field -> uncooled e- spectrum -> hard leptonic*

* very low level of thermal X-rays from RXJ1713 -> leptonic? (Ellison+ 2010)

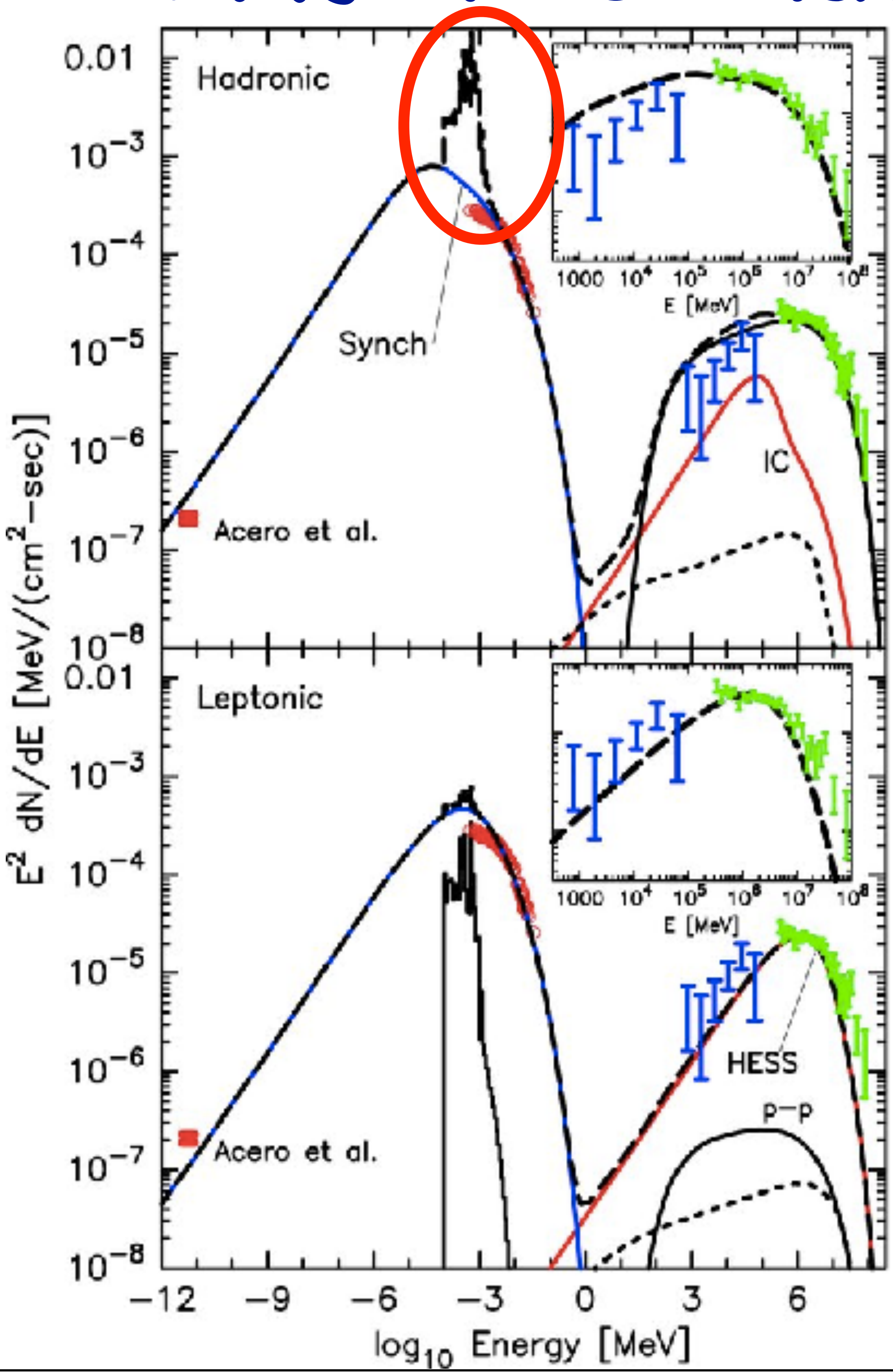
RXJ1713: hadronic or leptonic?



(Ellison et al 2010)

RXJ1713: hadronic or leptonic?

(Ellison et al 2010)



hadronic

high gas density + shock heating

-> bright X-ray thermal emission (lines)

-> NOT OBSERVED

(see also Katz&Waxman2008)

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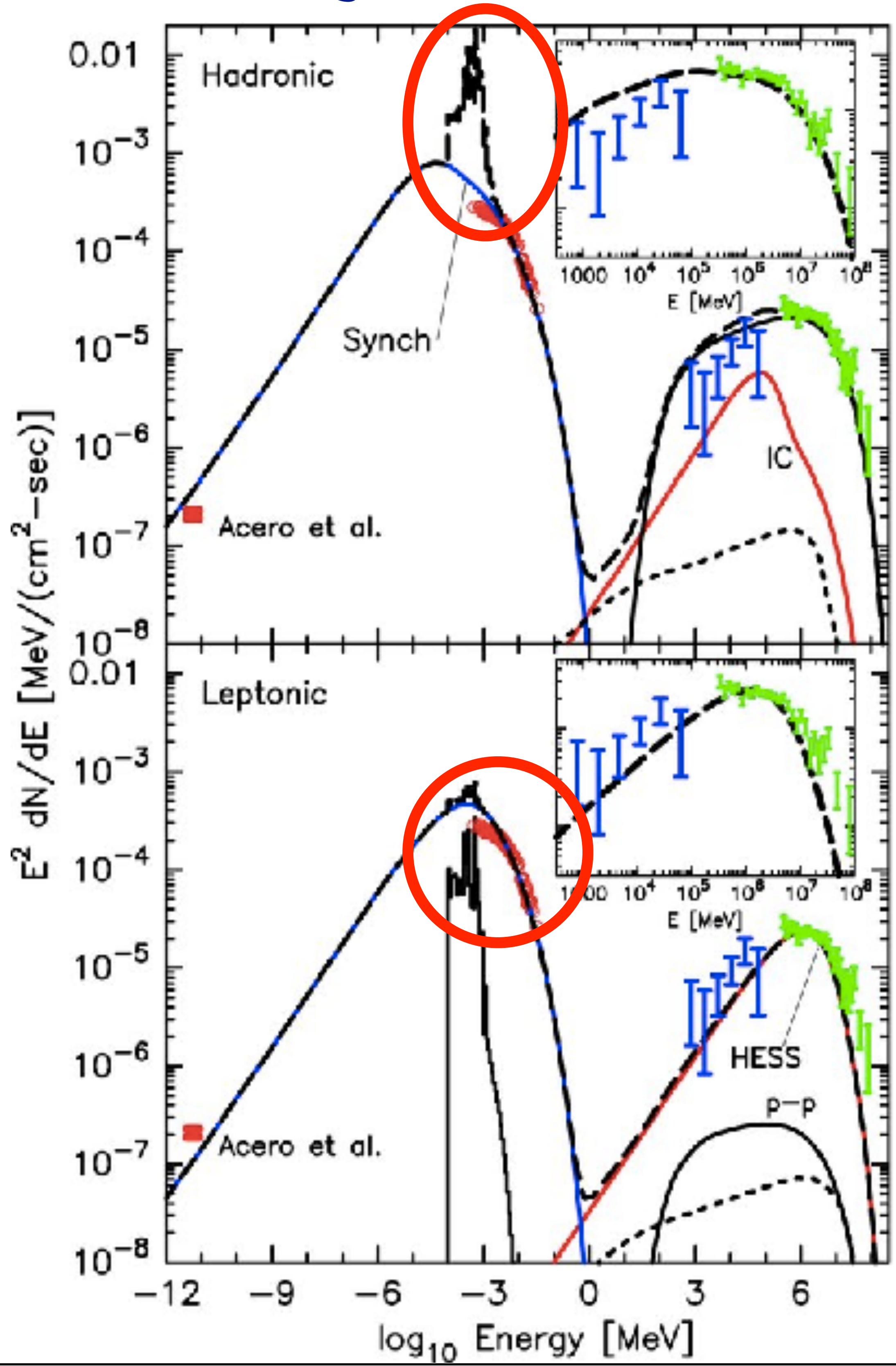

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hadronic

high gas density + shock heating
-> bright X-ray thermal emission (lines)
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(see also Katz&Waxman2008)

leptonic

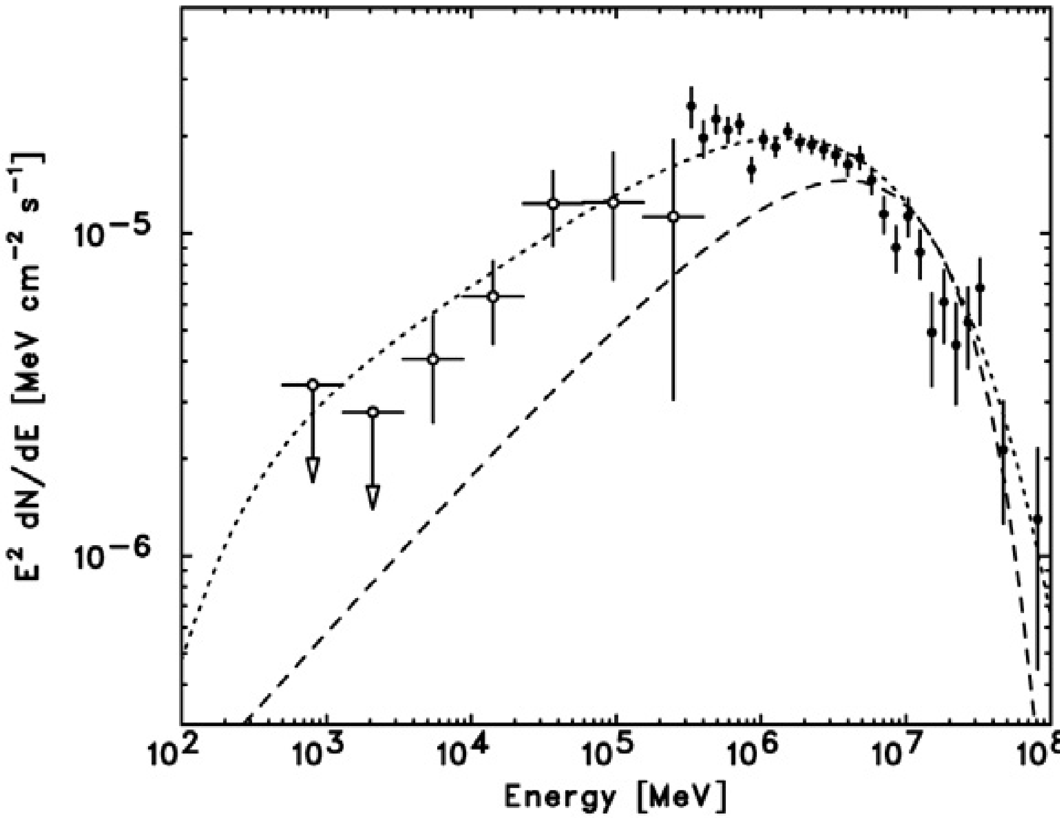
gas density is not a crucial parameter so one can tune it not to violate X-ray constraints

RXJ1713: difficulties of one-zone leptonic models

two features in the electron spectrum:

acceleration time = synchrotron loss time -> acceleration cutoff at E_{max}

SNR age = synchrotron loss time -> cooling break at E_{cool}



(Aharonian 2013)

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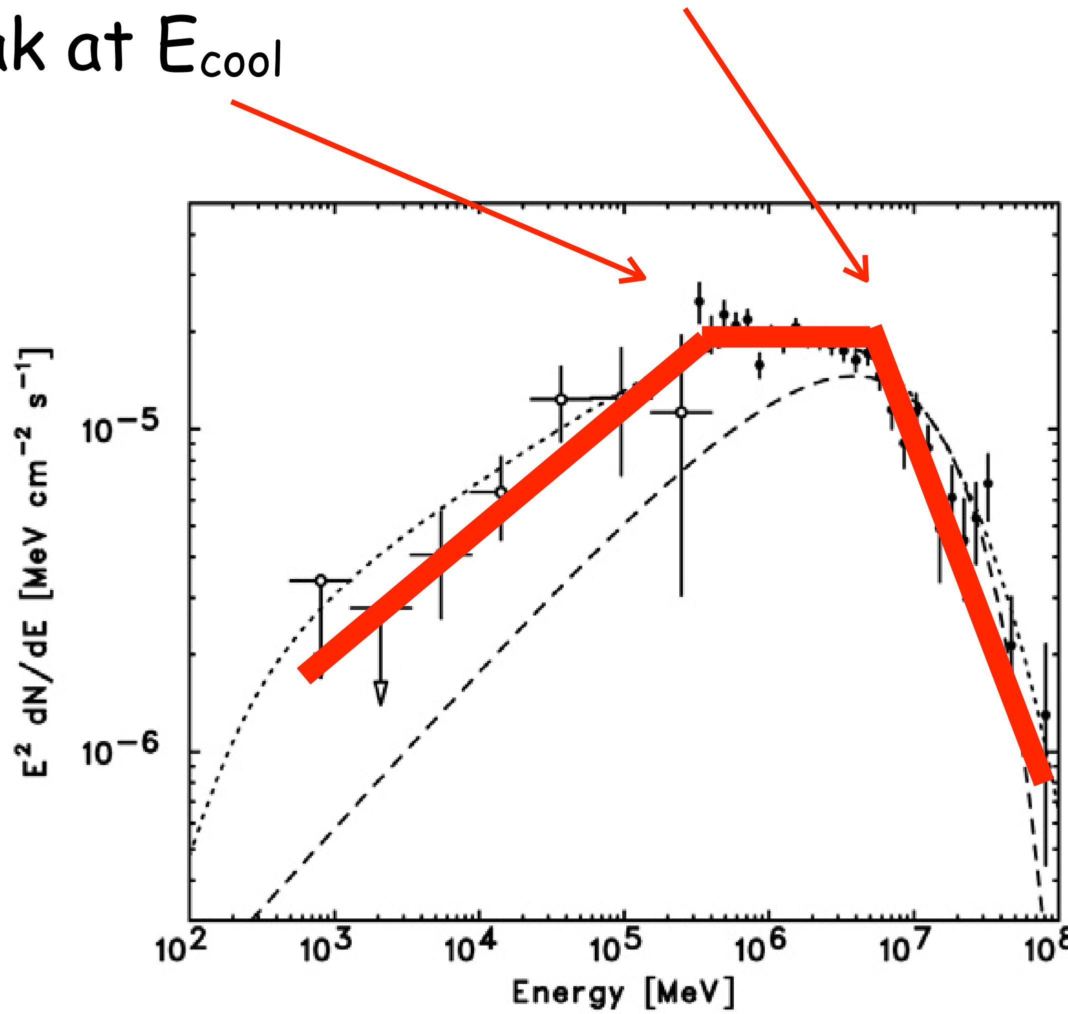

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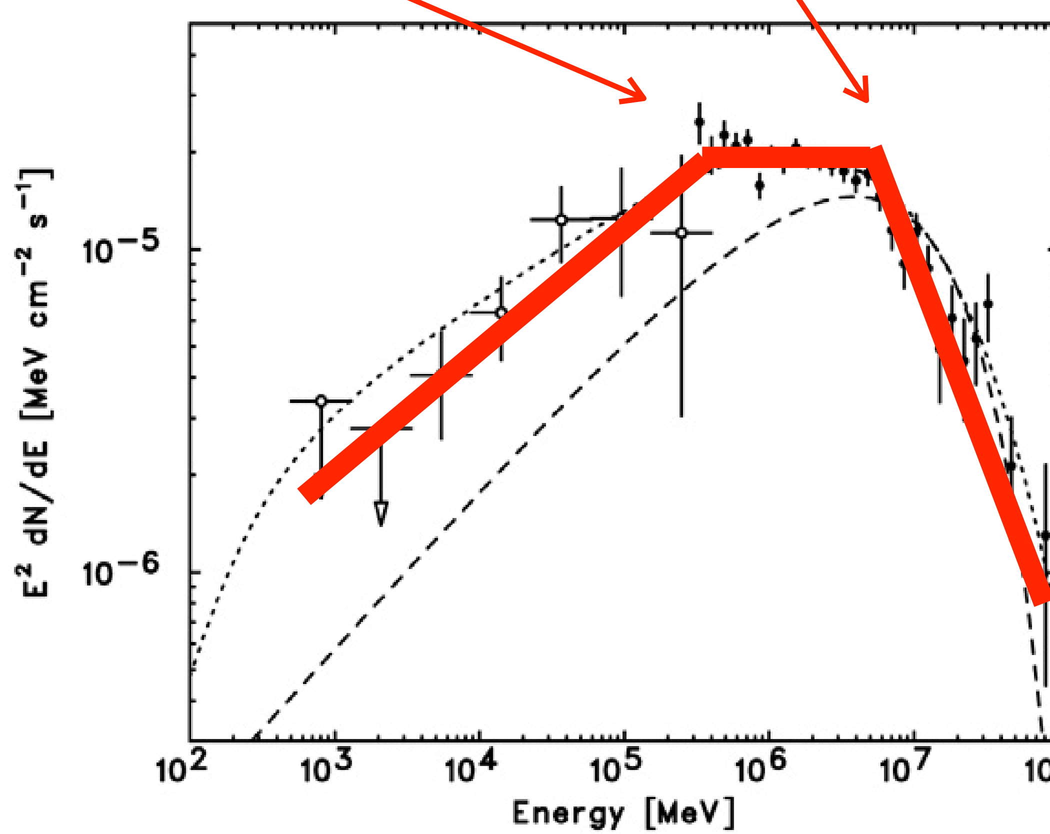
BUT!

to fit simultaneously X and gamma rays with electrons the magnetic field MUST be **at most ~10 microGauss**



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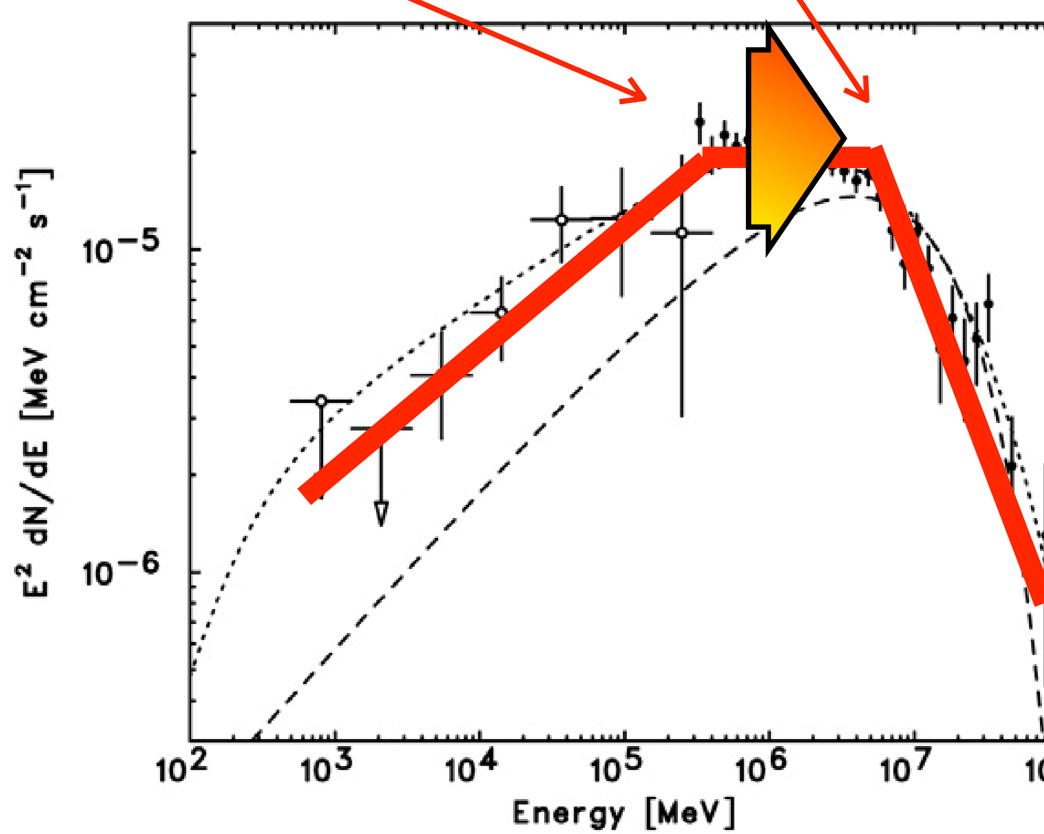

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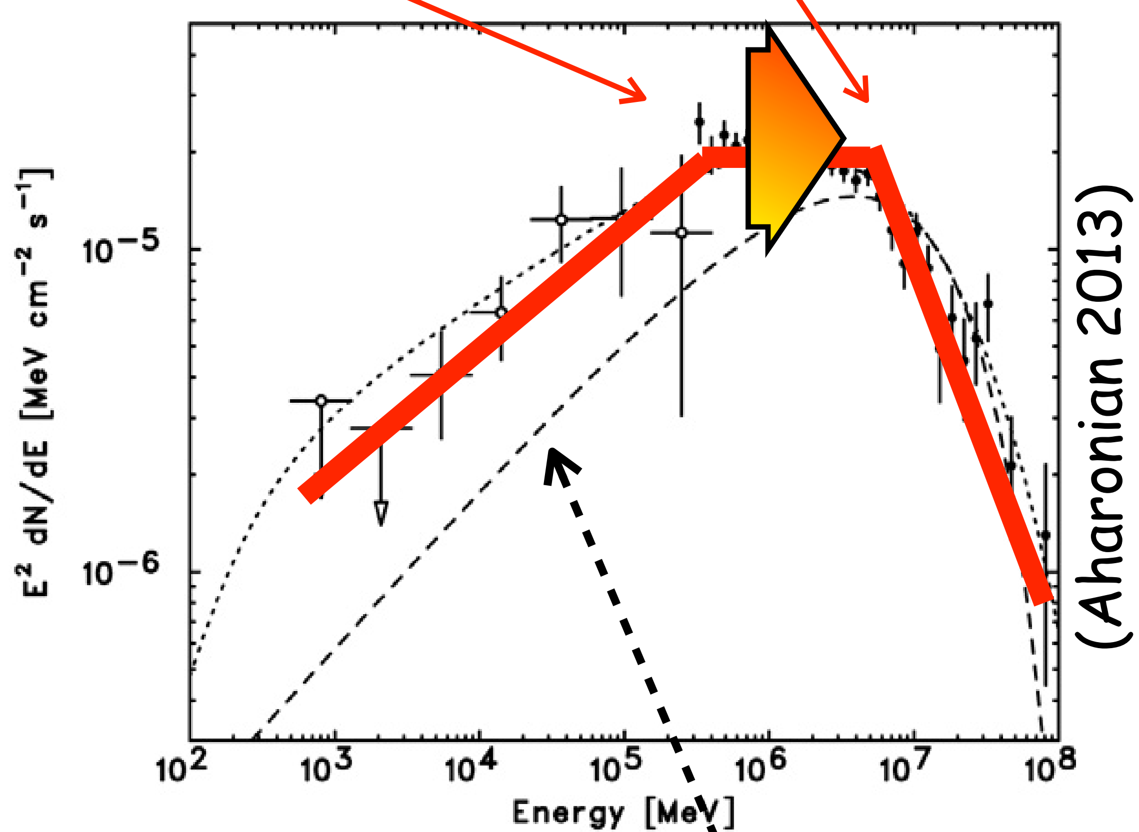


one-zone IC model

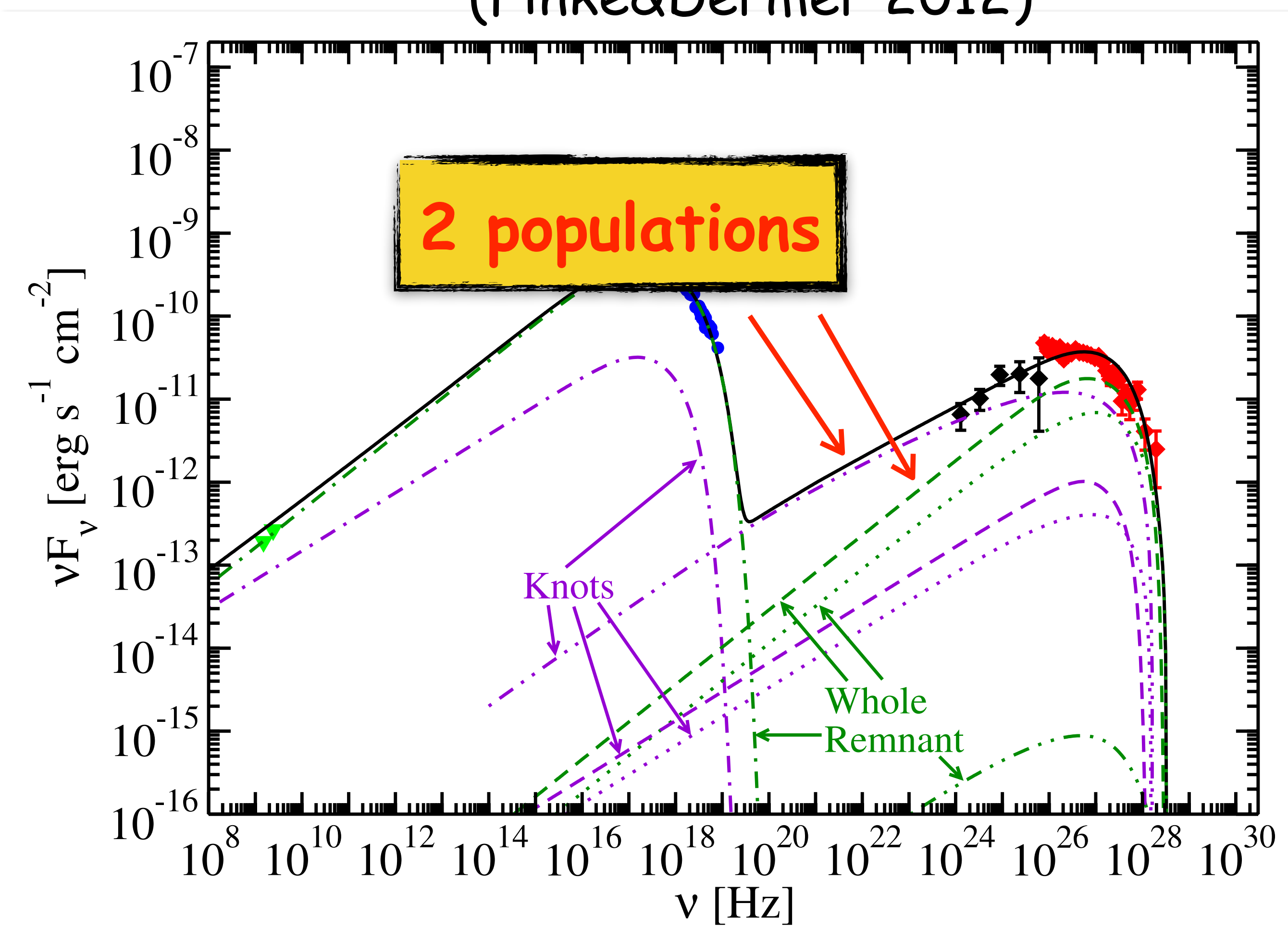
RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)

tw

ac

SN



acceleration cutoff at E_{max}

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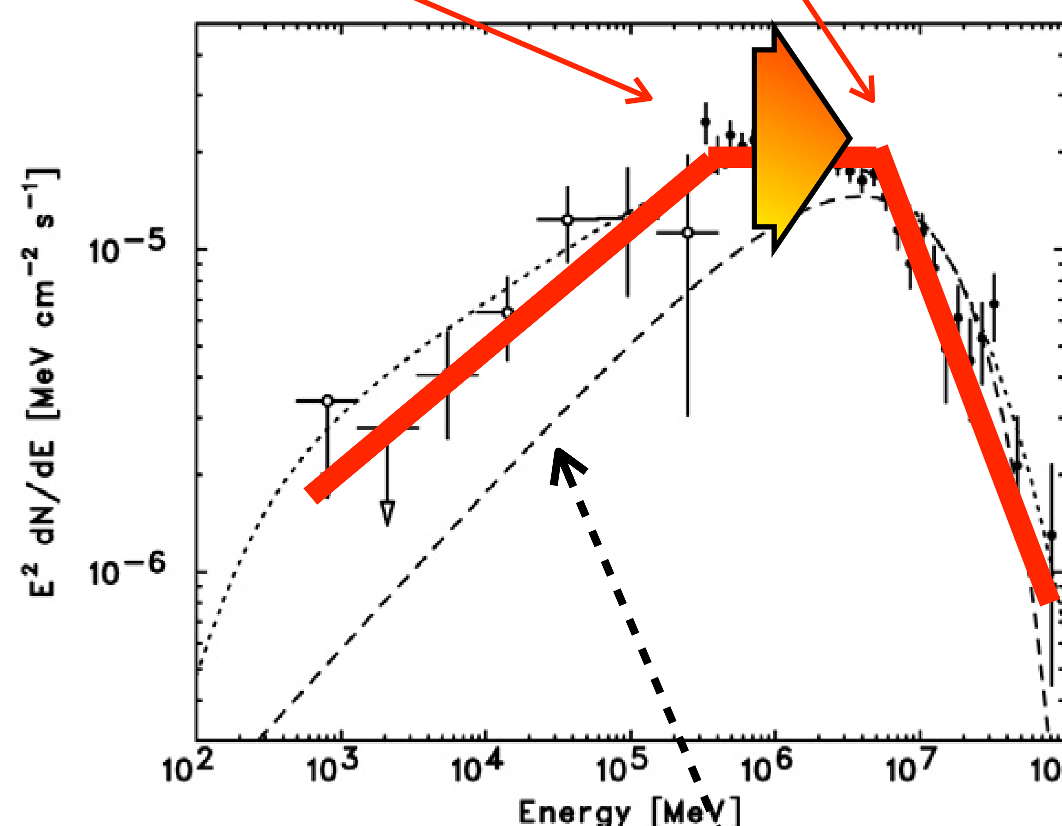

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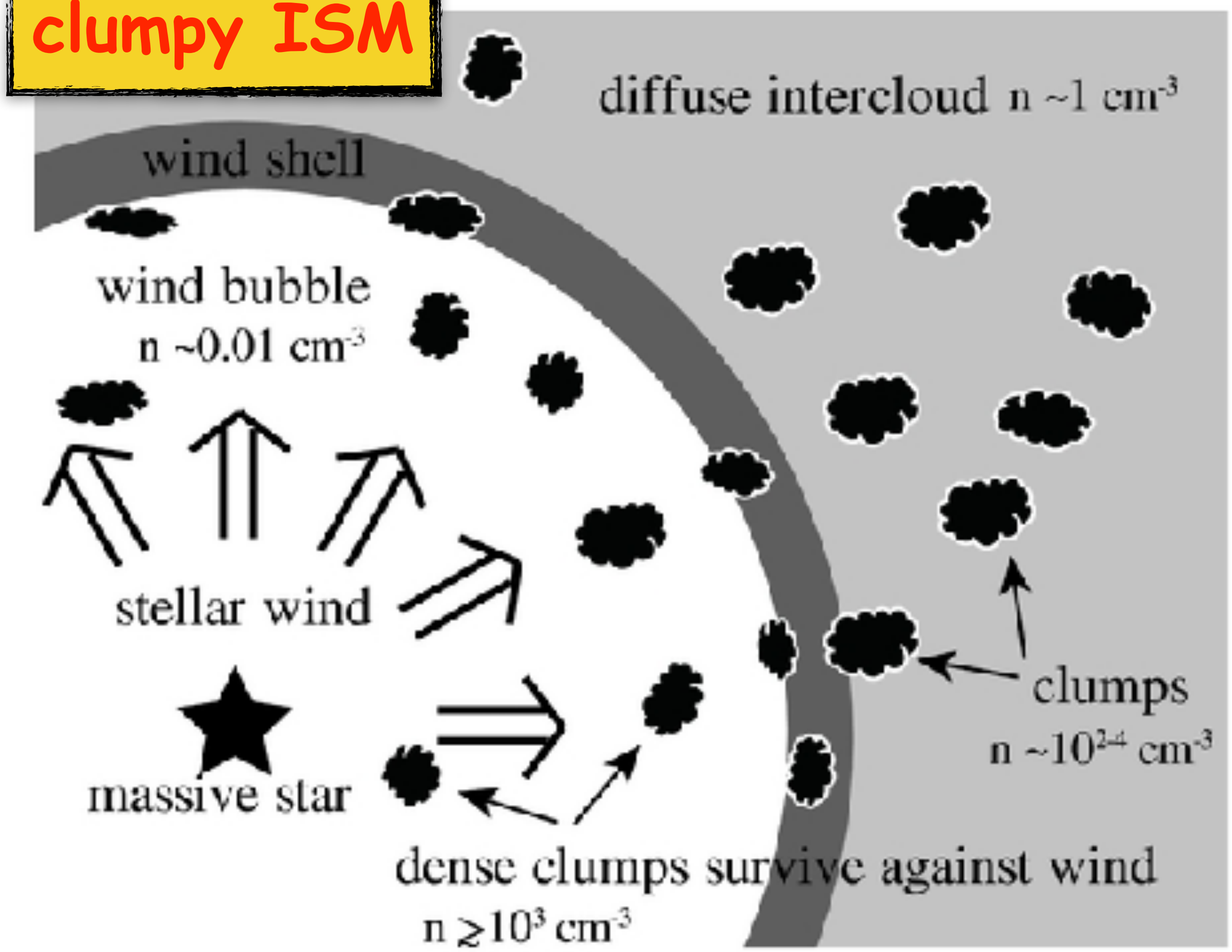
Hadronic RXJ1713: a SNR inside a MC?

Zirakashvili & Aharonian 2010, Fukui+ 2012, Inoue+ 2012, Gabici & Aharonian 2014

clumpy ISM



stellar wind sweeps the gas and creates a cavity

dense clumps survive (unshocked) both the stellar wind and the SNR shock

no thermal X-rays!

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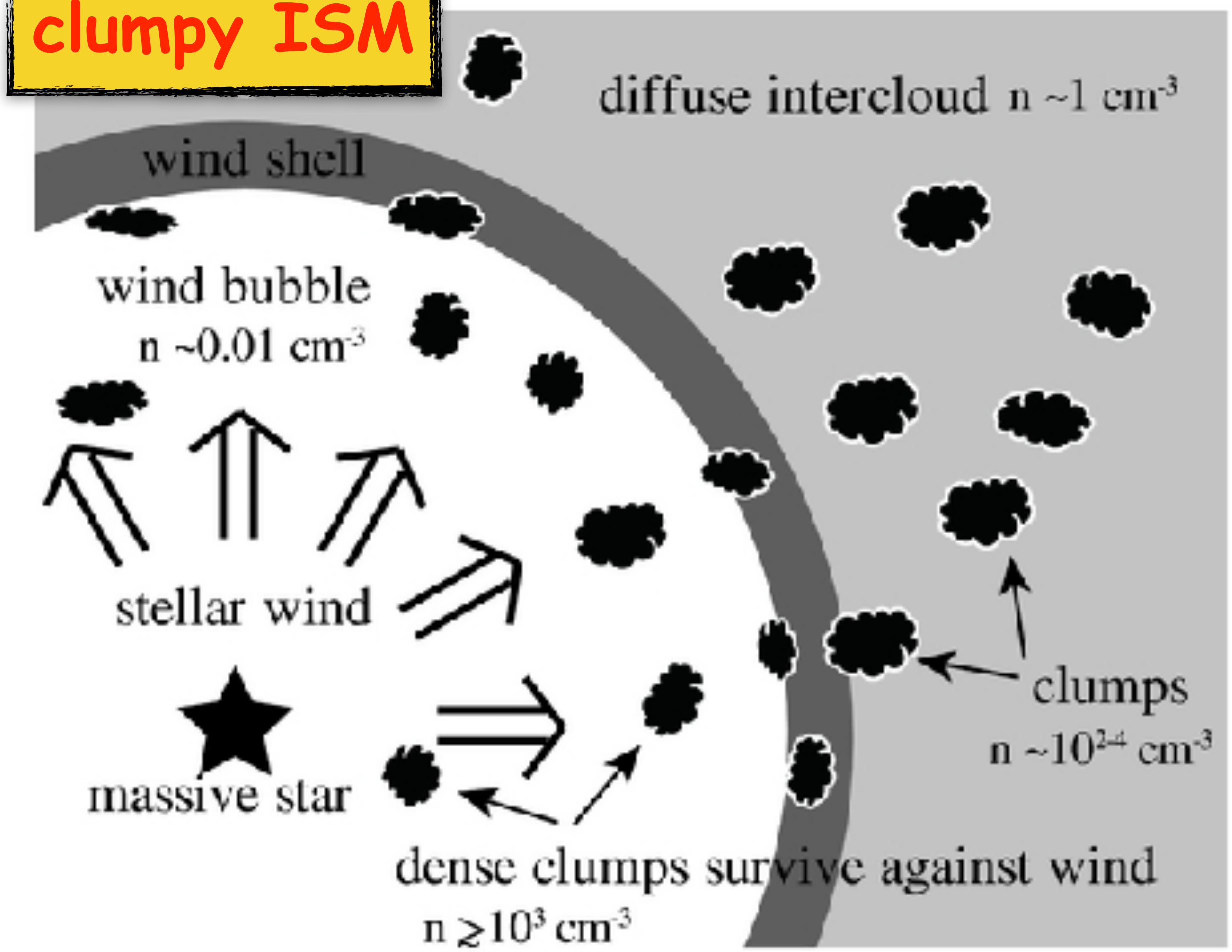

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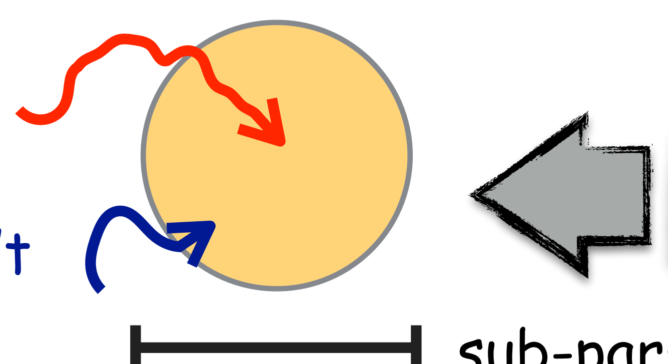
high energy CRs penetrate

low energy CRs don't



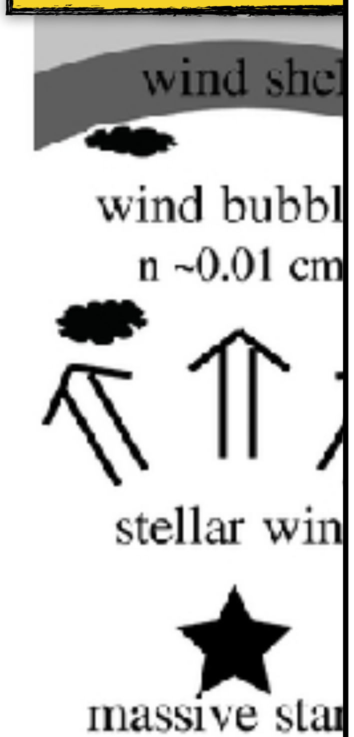
clumps!

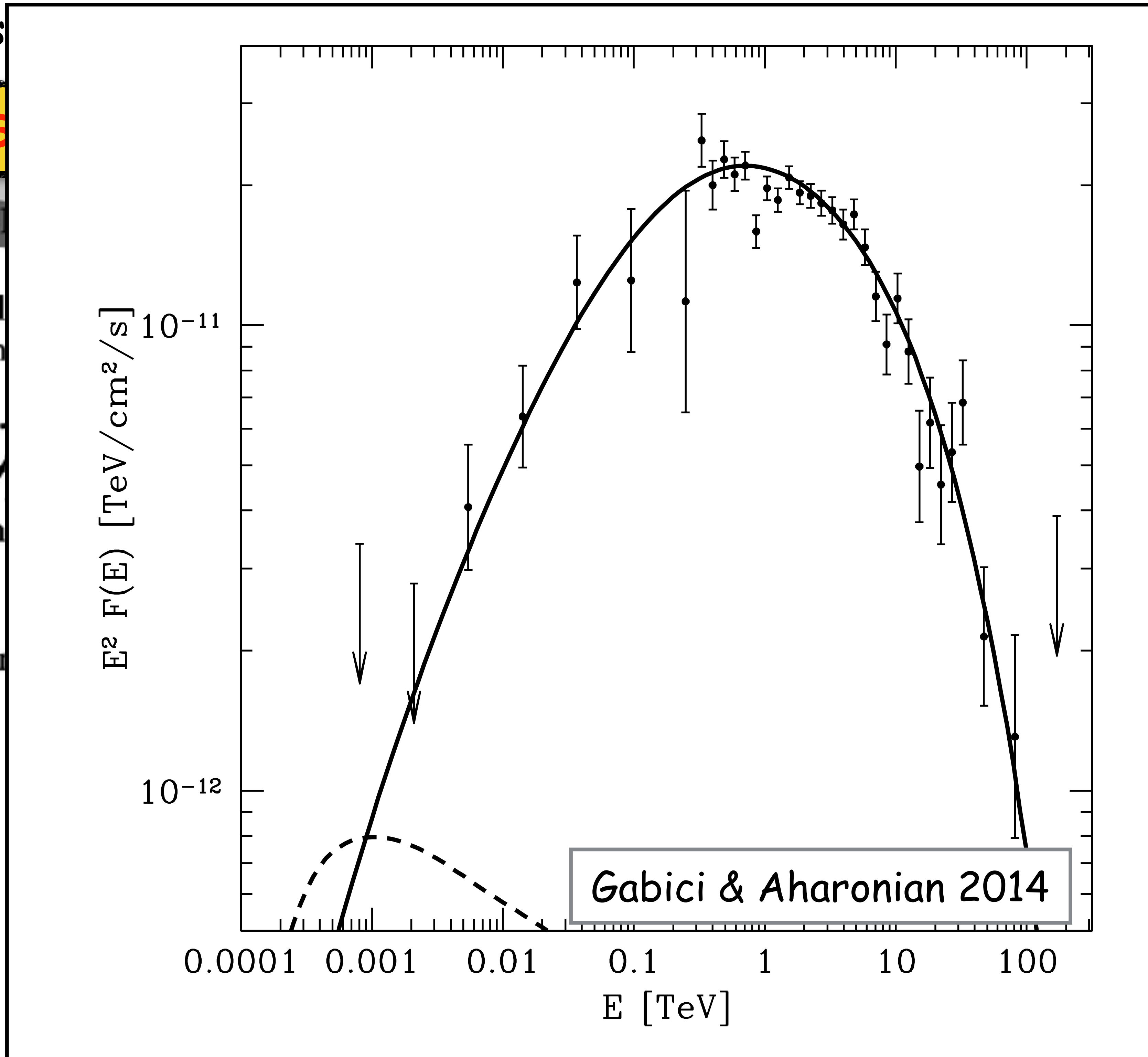
sub-parsec

Hadronic RXJ1713: a SNR inside a MC?

Zirakas … aronian 2014

clumpy IS





s the gas and
avity

unshocked) both
the SNR shock

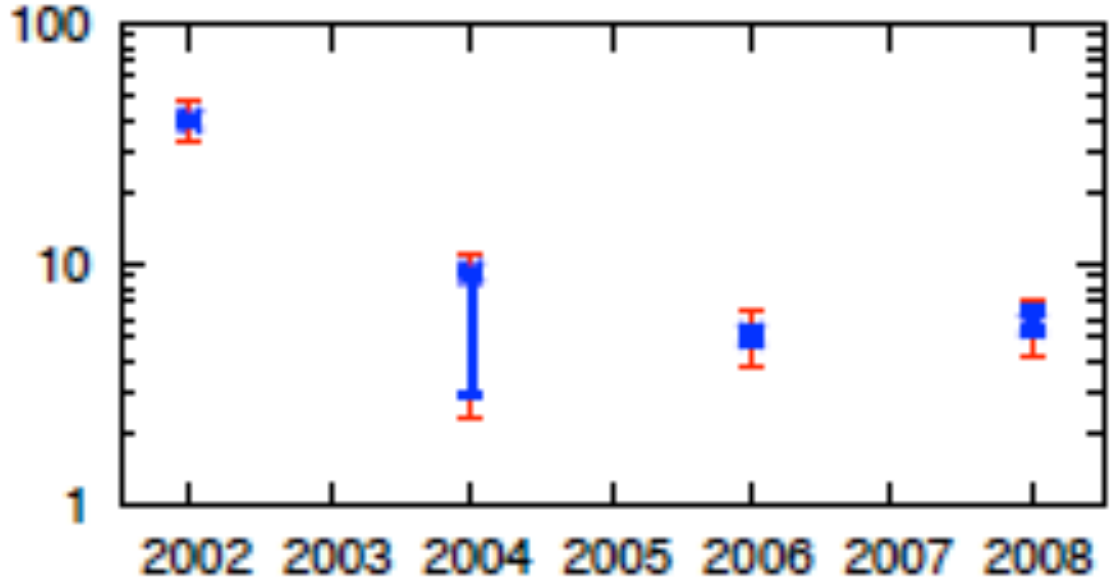
X-rays!

s!

Neutrinos

predictions of the neutrino flux (> 50 GeV)
per (km^2 x yr) from RX J1713 as a fct of time

Vissani & Aharonian 2012



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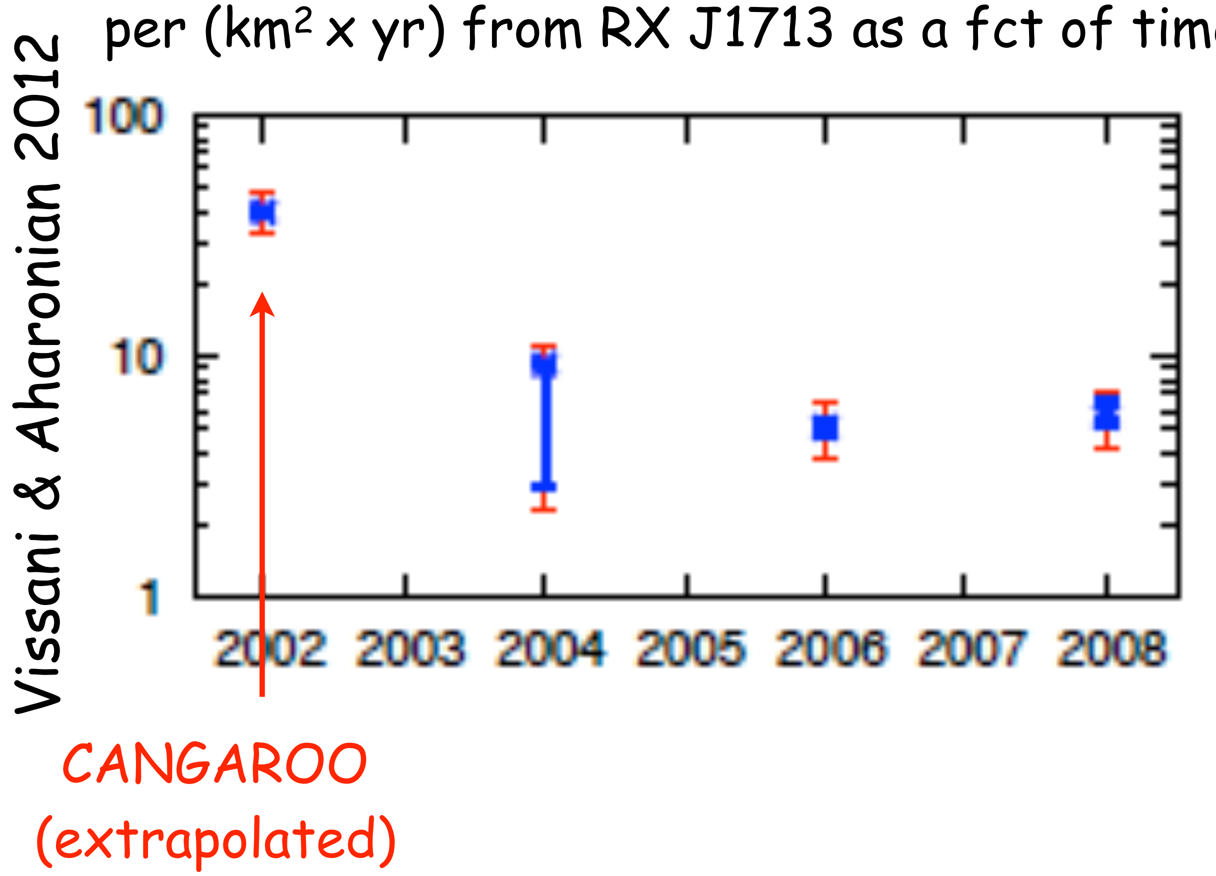

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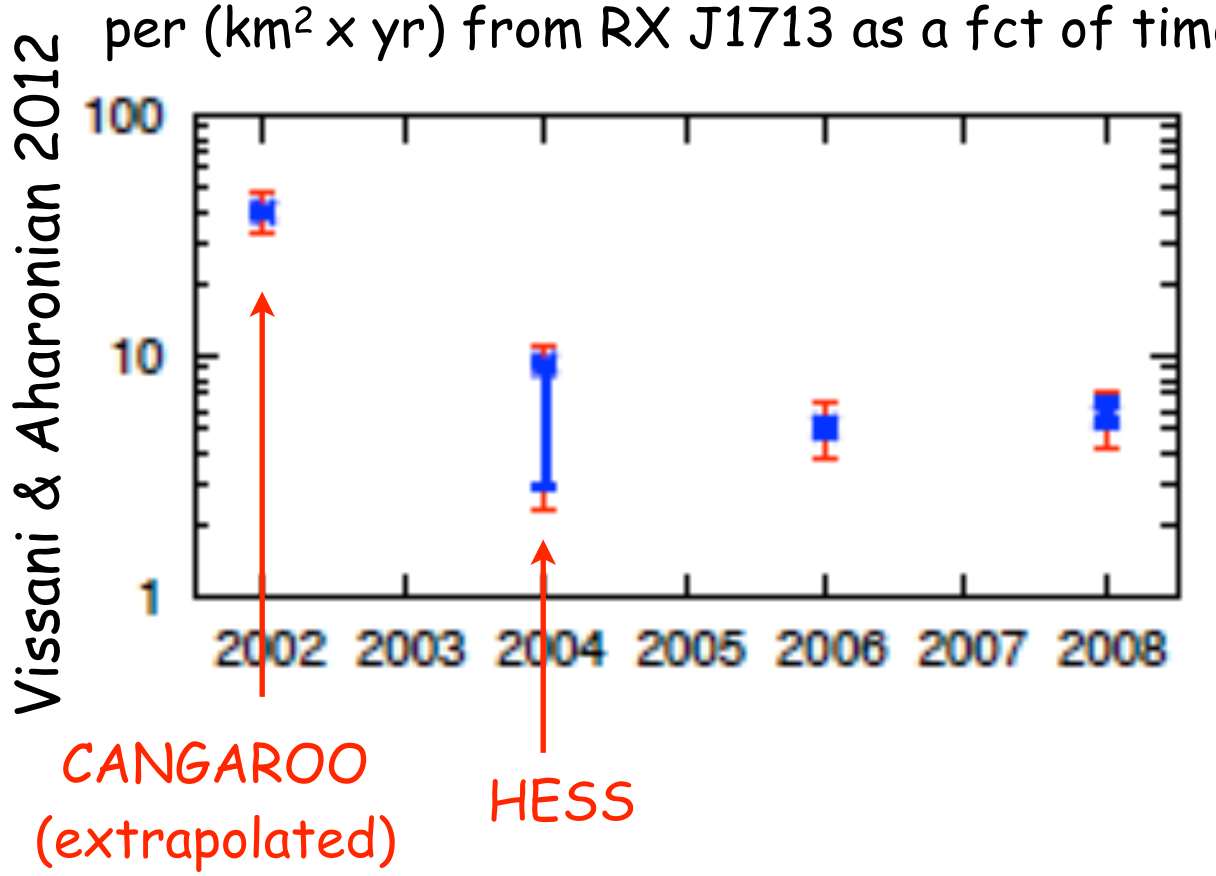

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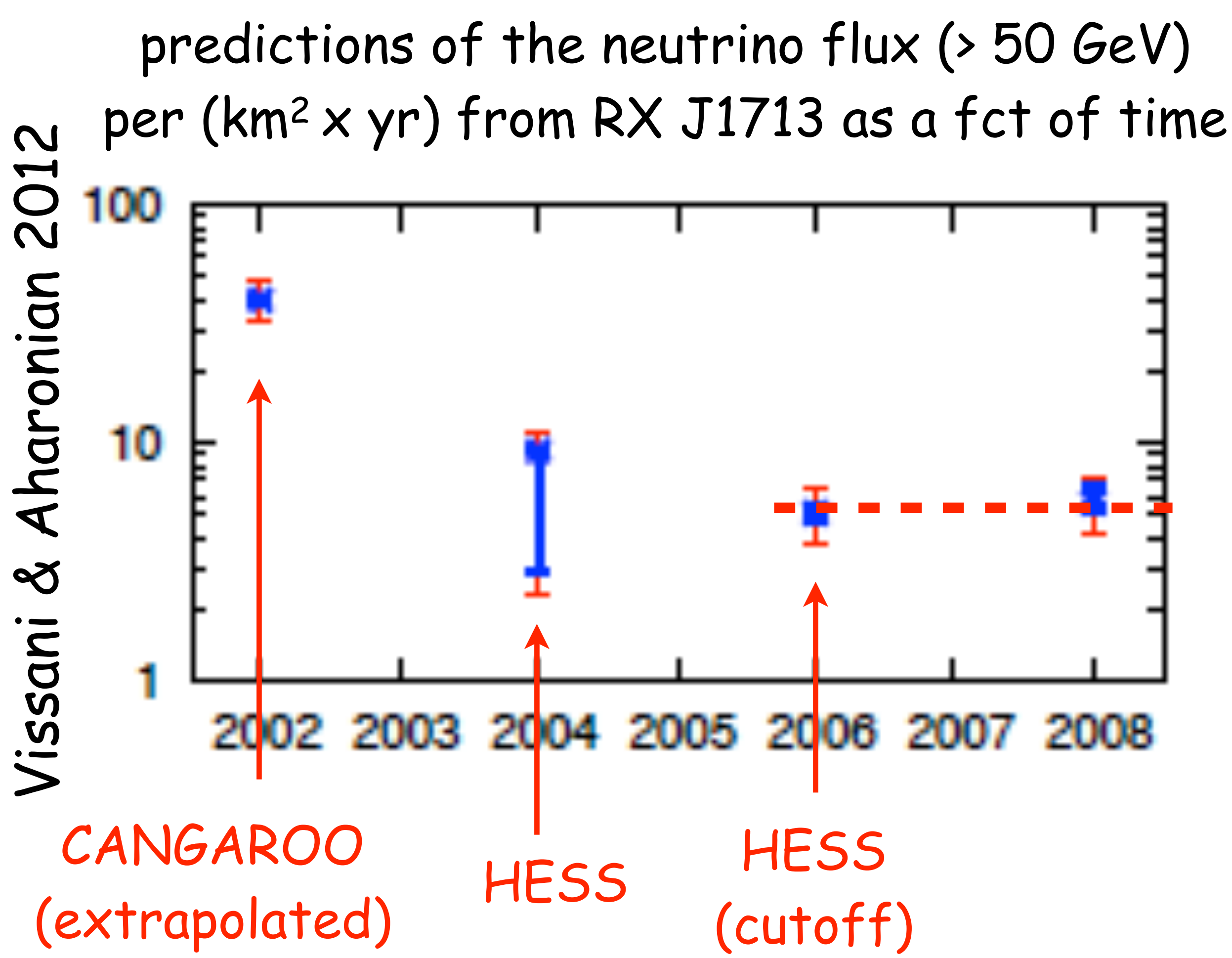

predictions of the neutrino flux (> 50 GeV)
per (km² x yr) from RX J1713 as a fct of time
Vissani & Aharonian 2012
100
10
1
2002
2003
2004
2005
2006
2007
2008
CANGAROO
(extrapolated)
HESS
HESS
(cutoff)

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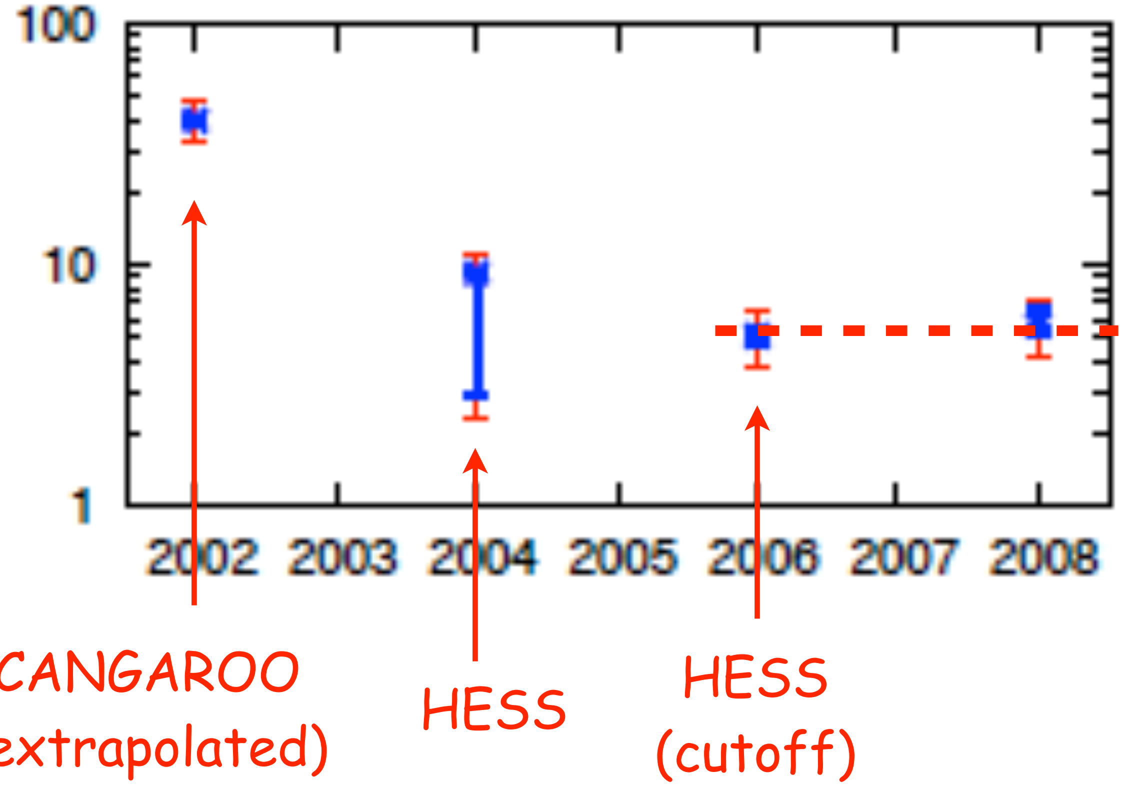
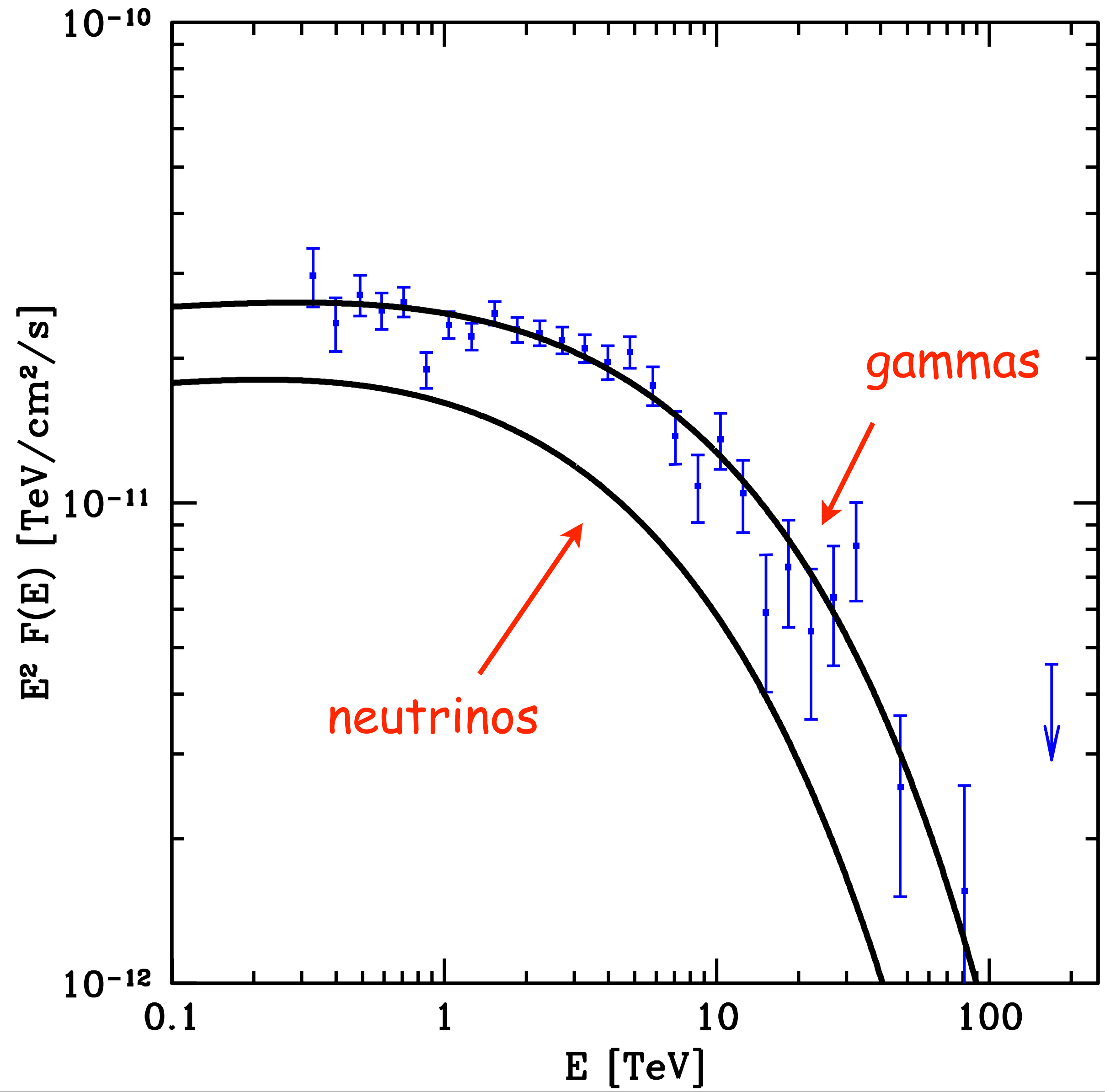


totally model independent

(SNRs are transparent sources of gamma-rays)



Gabici 2008

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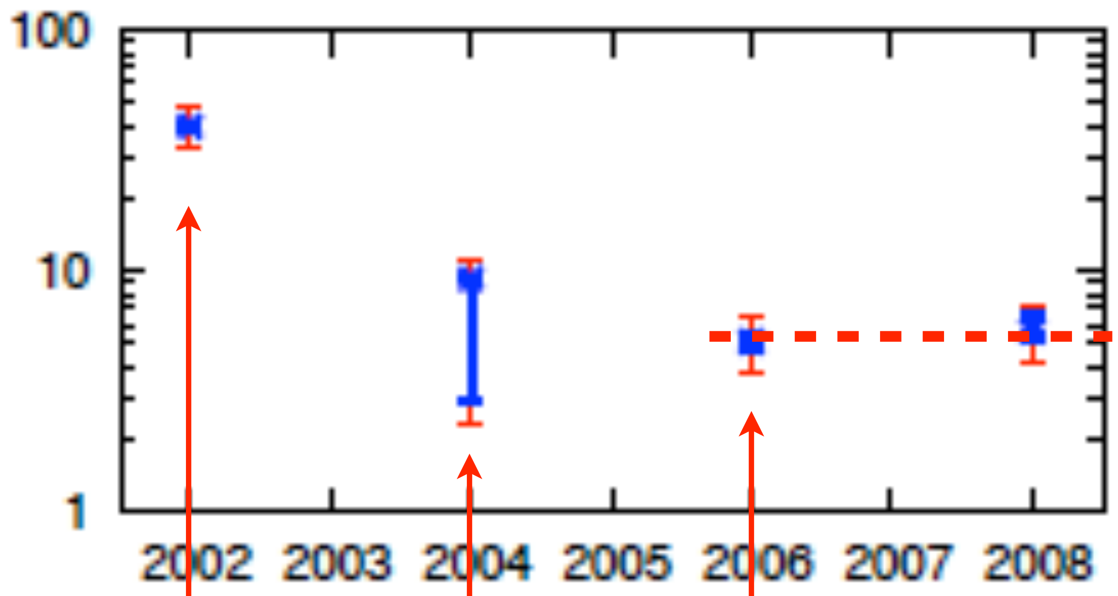

upper limit on nu emission
(gammas 100% hadronic)

$$F_\nu(>1\ \mathrm{TeV}) \;=\; 2.4\quad \nu/(\mathrm{km}^2\mathrm{yr})$$

Villante & Vissani 2008

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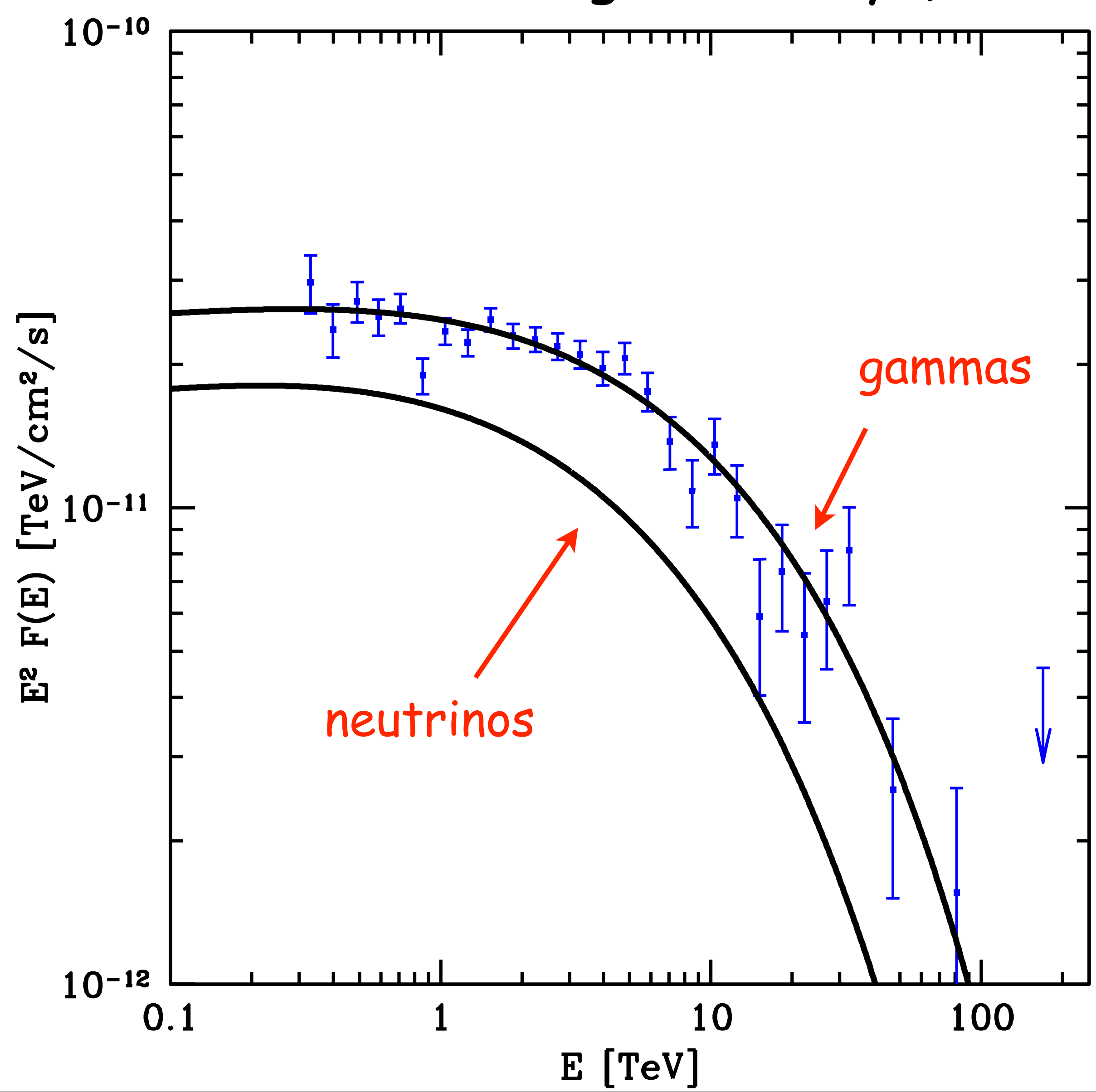

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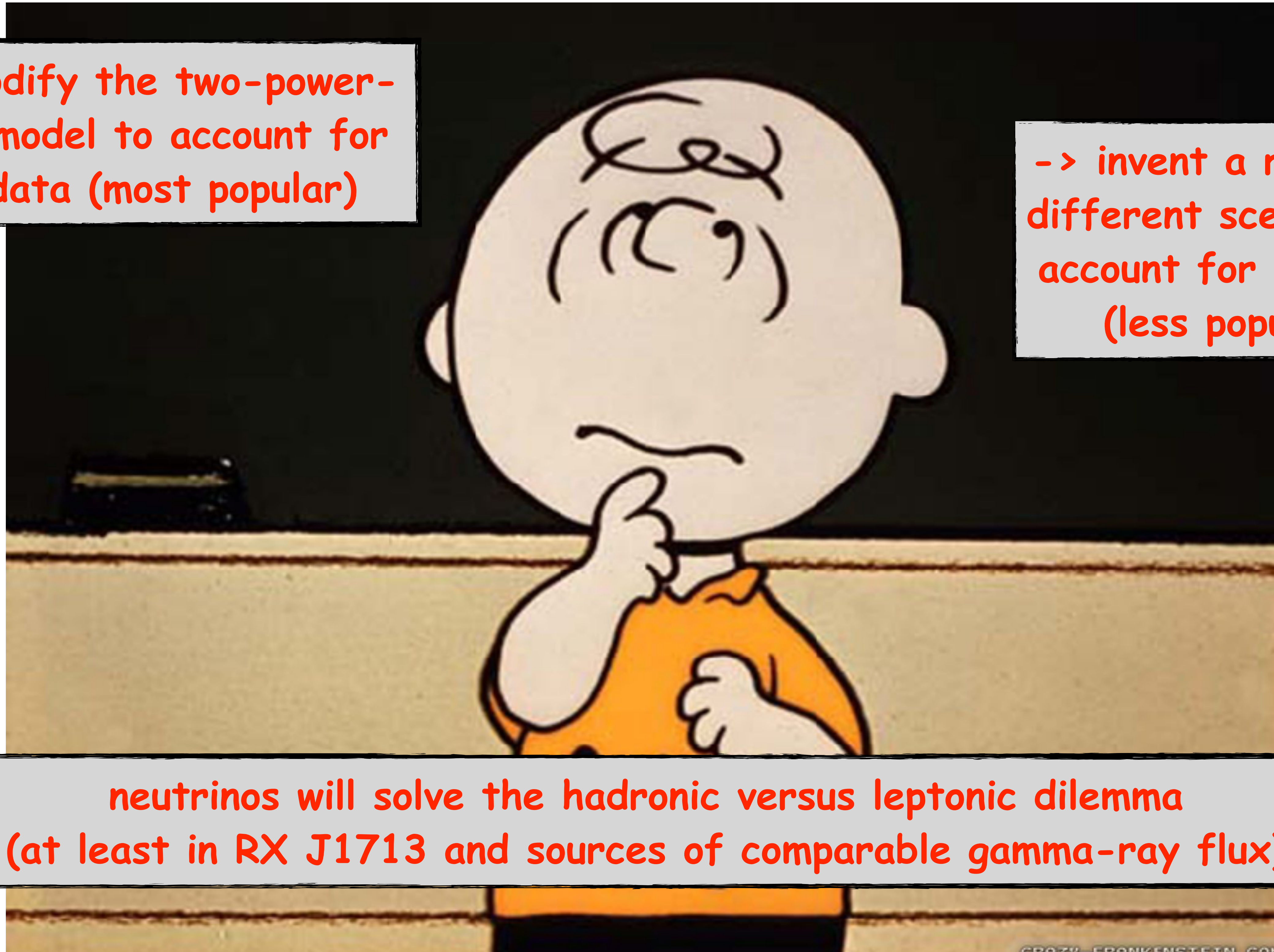
So? Two possibilities…

-> modify the two-power-laws model to account for all data (most popular)



-> invent a radically different scenario to account for all data (less popular)

neutrinos will solve the hadronic versus leptonic dilemma
(at least in RX J1713 and sources of comparable gamma-ray flux)