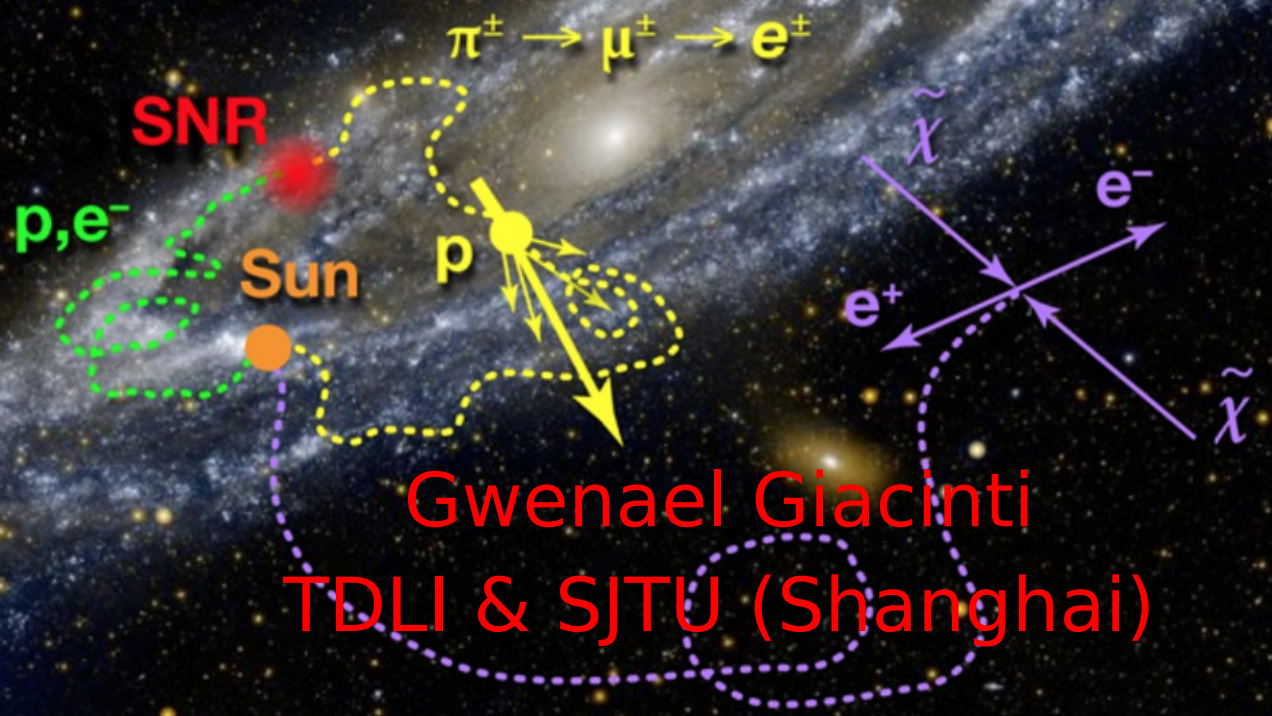
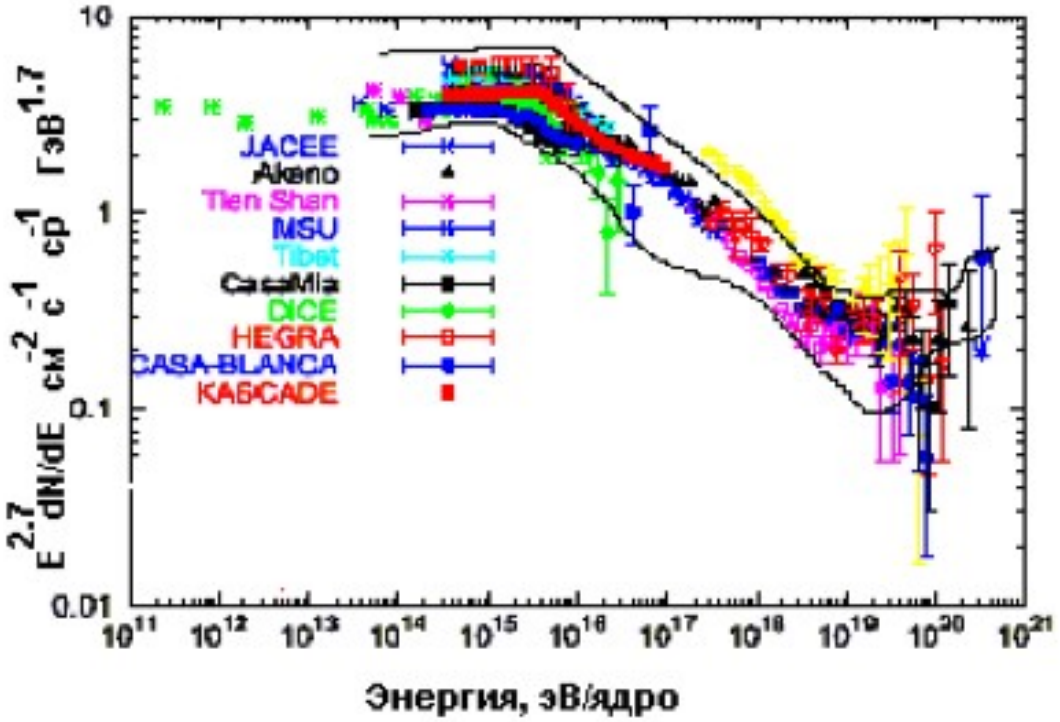
Modelling the cosmic ray spectrum at the knee



Gwenael Giacinti
TDLI & SJTU (Shanghai)

Experimental data (knee)

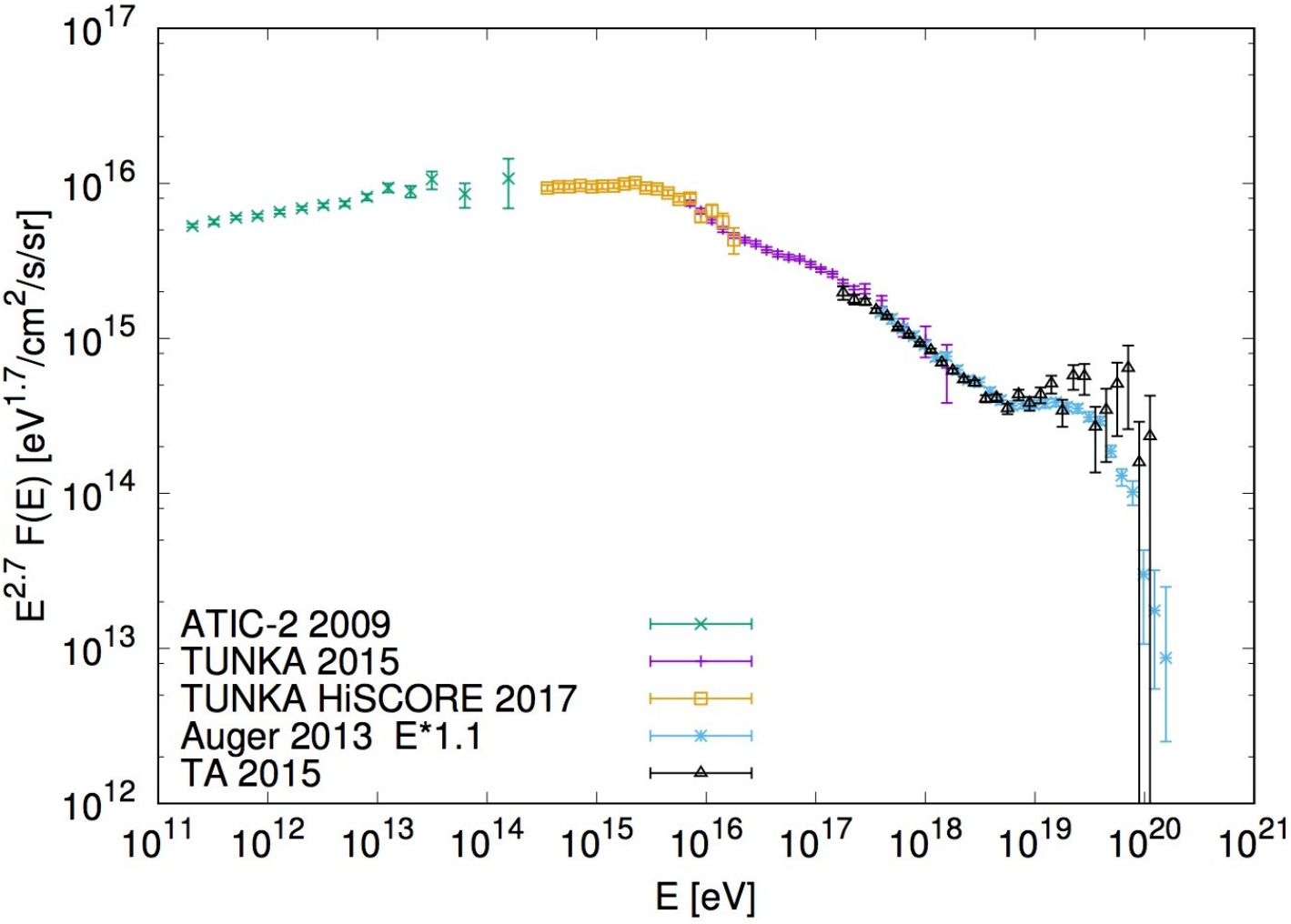
The knee in the CR spectrum



Knee was discovered by Kulikov and Khristiansen in data of MSU Experiment in 1958.
It was confirmed by all new independent experiments.

For a long time there were 2 explanations: either astrophysical and from particle physics. In the ‘particle physics’ explanation, it was assumed that either interactions change or a new particle dominates. LHC finally dismissed this interpretation.

The knee in the CR spectrum



Astrophysical interpretations of the knee

→ Knee is due to the maximum energy of the dominant type of sources.
Problem: Observed knee is too sharp.

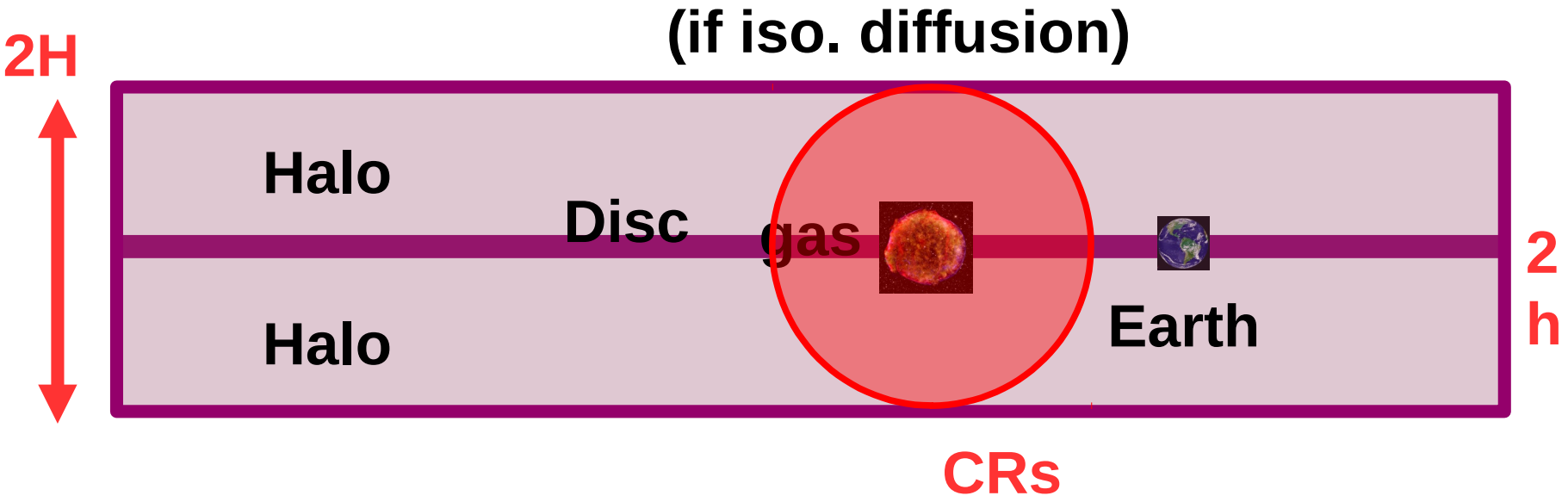
→ One single source dominates everything around the knee.
Problem: Dipole anisotropy is too small.

→ Knee is due to a change in the CR propagation properties in the interstellar medium.
Problem: Not the end of the Galactic CR spectrum.
=> Galactic CR sources have to accelerate particles above the knee.

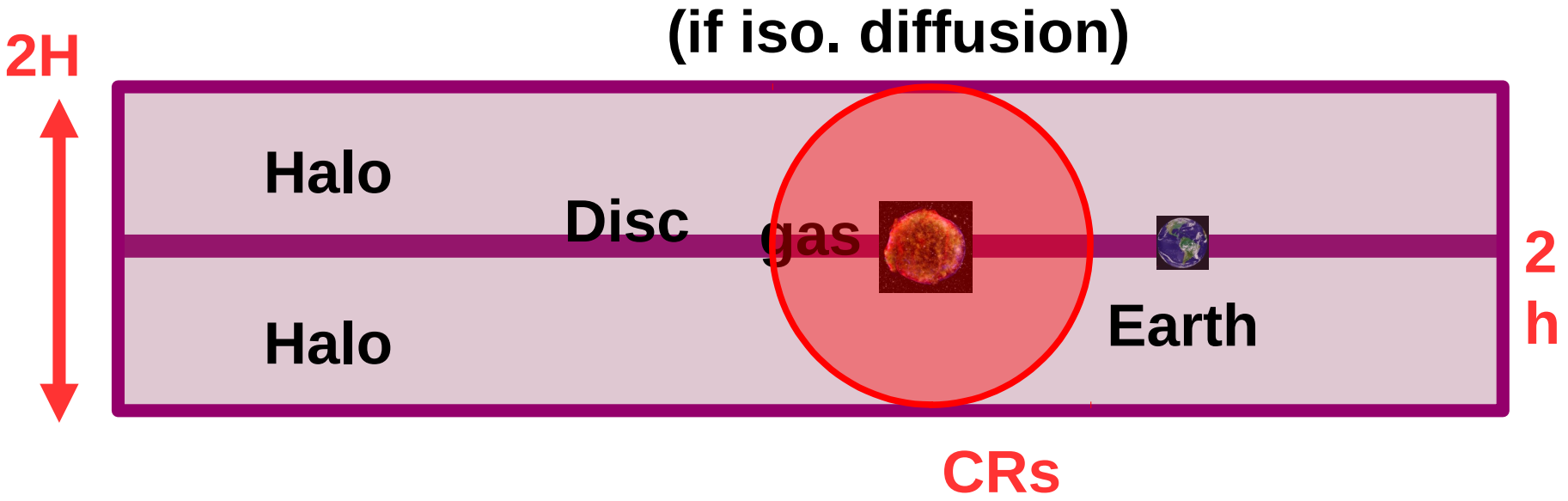
The standard paradigm for Galactic CRs

Simplified Milky Way seen edge-on :

Simplified Milky Way seen edge-on :



Simplified Milky Way seen edge-on :



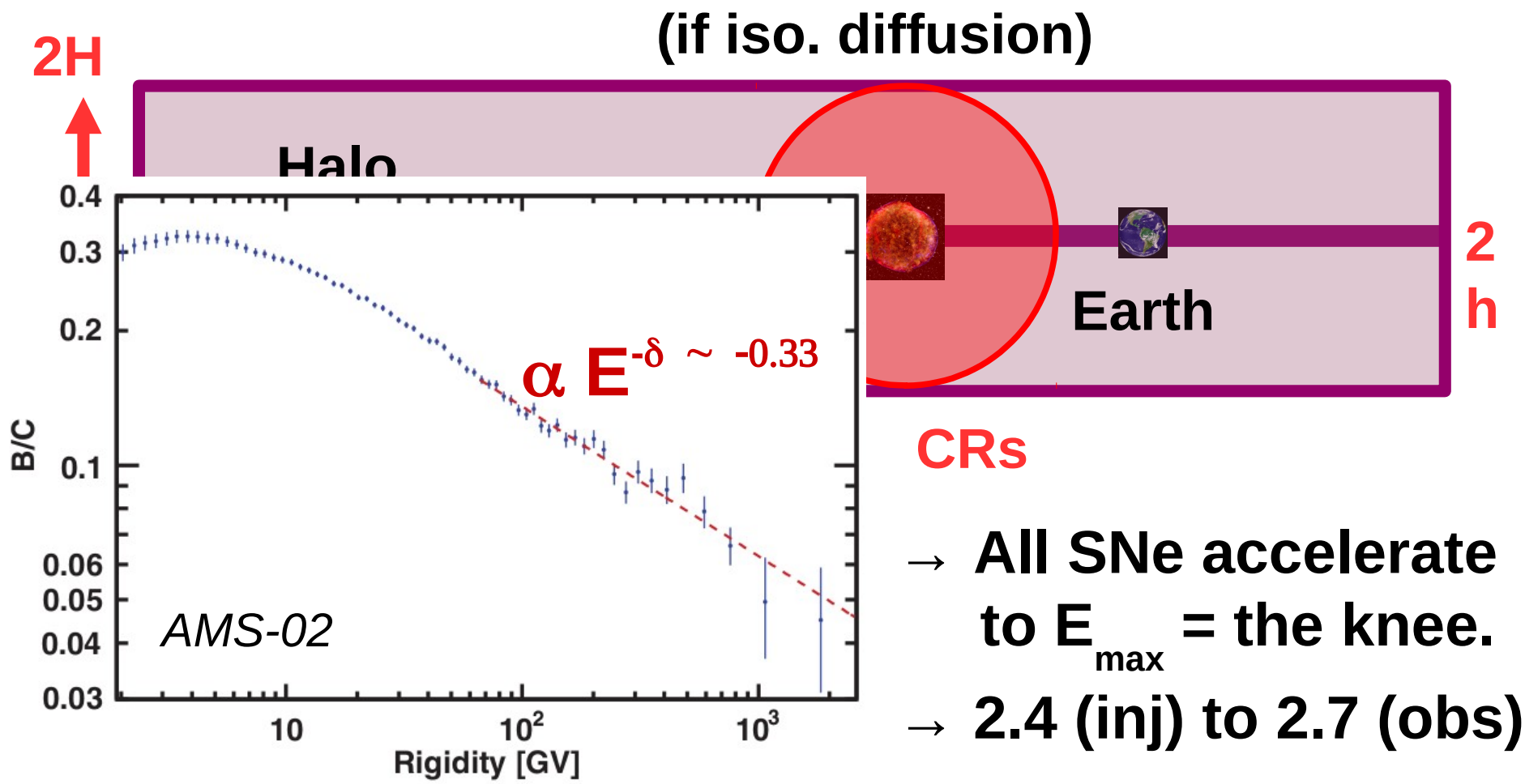
CR spectrum at sources: $\alpha\ E^{-\beta}$

D: $\alpha\ E^{\delta}$; B/C, conf. time: $\alpha\ E^{-\delta}$

CR spectrum at Earth: $\alpha\ E^{-\beta-\delta}$

("no wind" case)

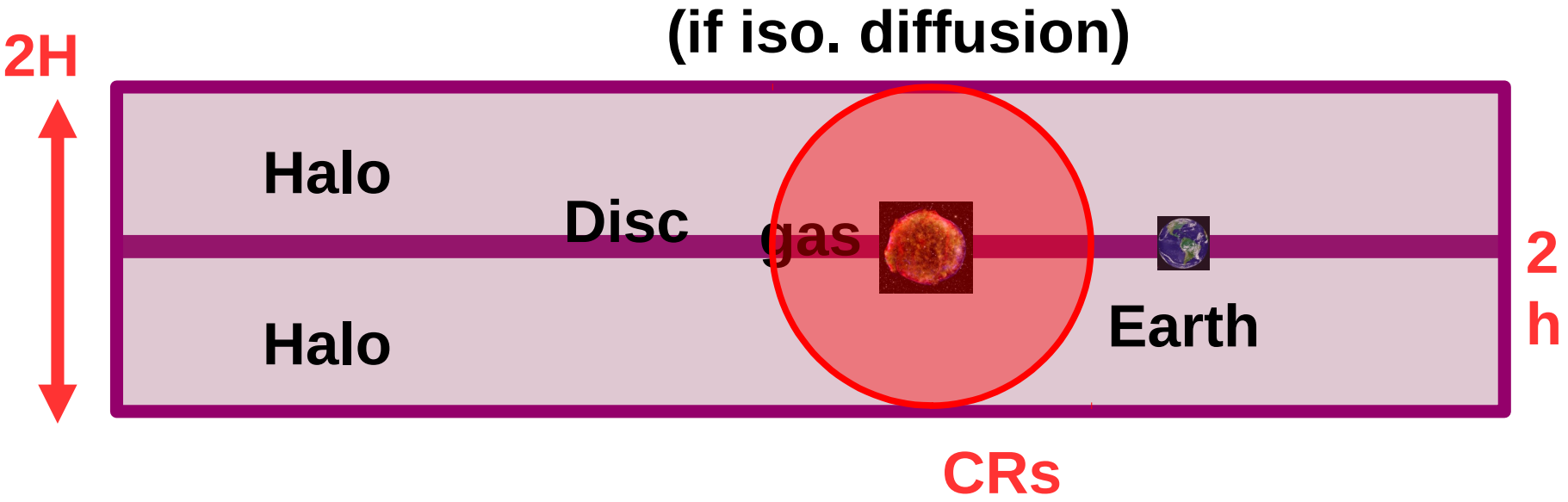
Simplified Milky Way seen edge-on :



→ All SNe accelerate to E_{max} = the knee.

→ 2.4 (inj) to 2.7 (obs)

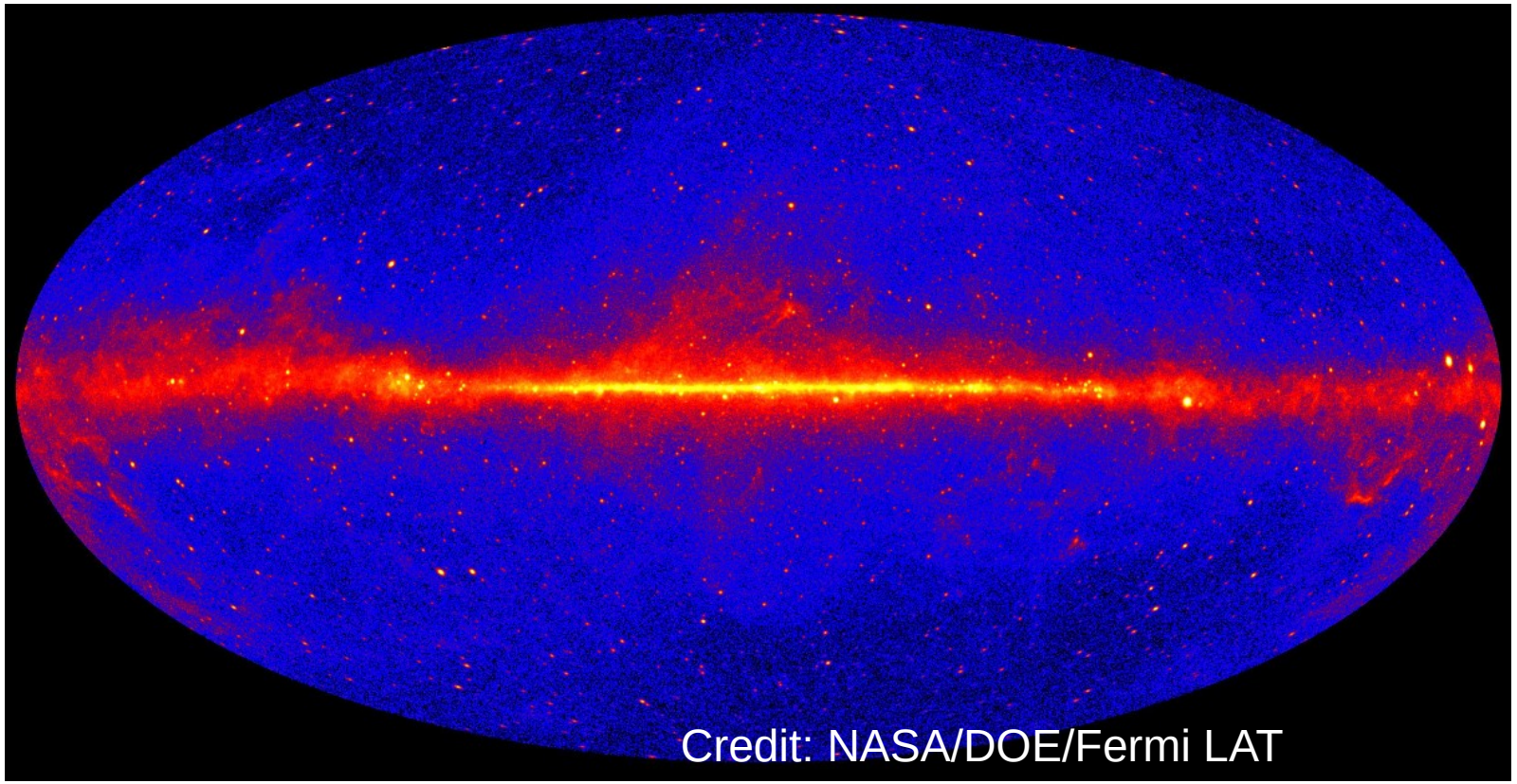
Simplified Milky Way seen edge-on :



Grammage : $X = c\rho hH/D_z$ ~ several g/cm² at GeV

D ~ 10^{28} cm²/s at GeV **for H ~ several kpc**

Fermi, 2008 – 2017 :



Diffuse emission at ~ GeV – TeV energies :

→ Globally in agreement with B/C, & SNR paradigm in terms of injected CR power…

Problems – Part 1 (sources):

→ *Where are the PeVatrons?*

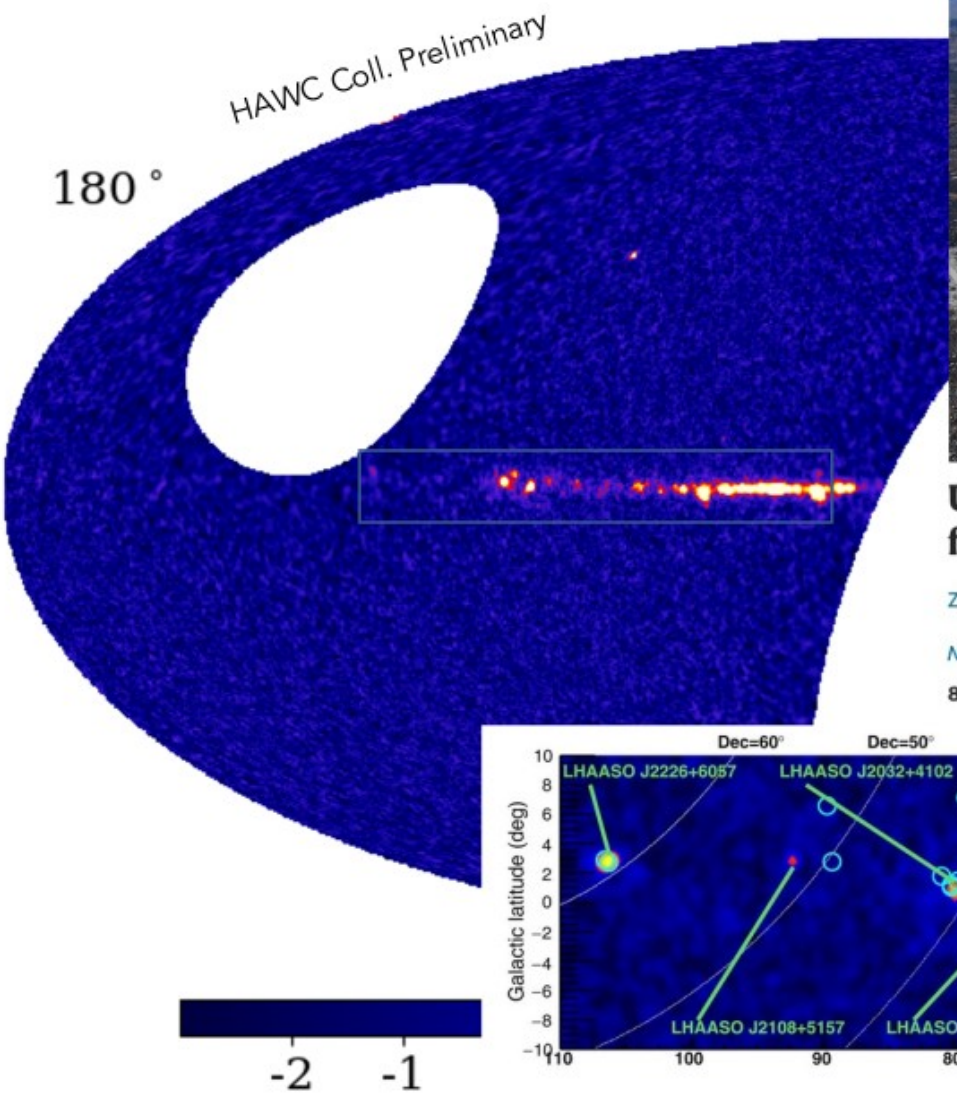
→ *Particle acceleration at SNR shocks*

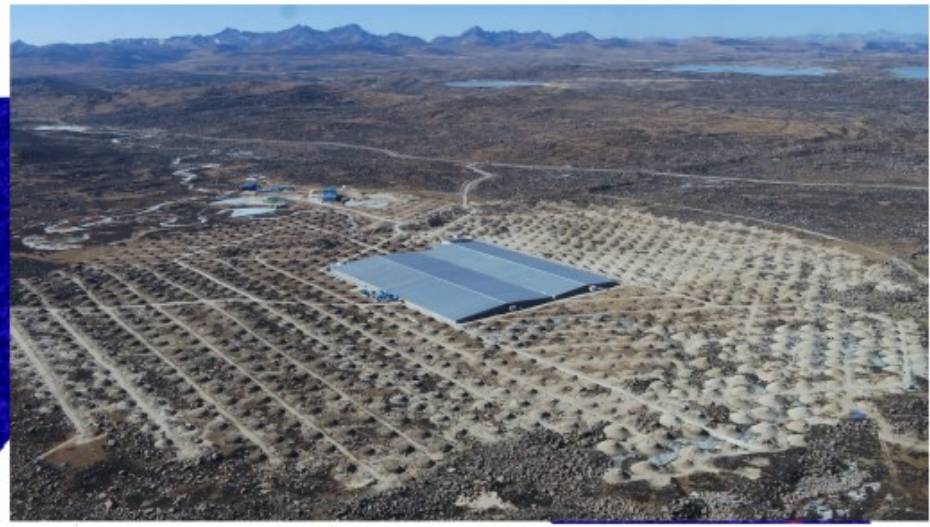
→ *Composition*

→ *~ 10 TeV bump*

The sky at VHE

LHAASO PeVatrons :



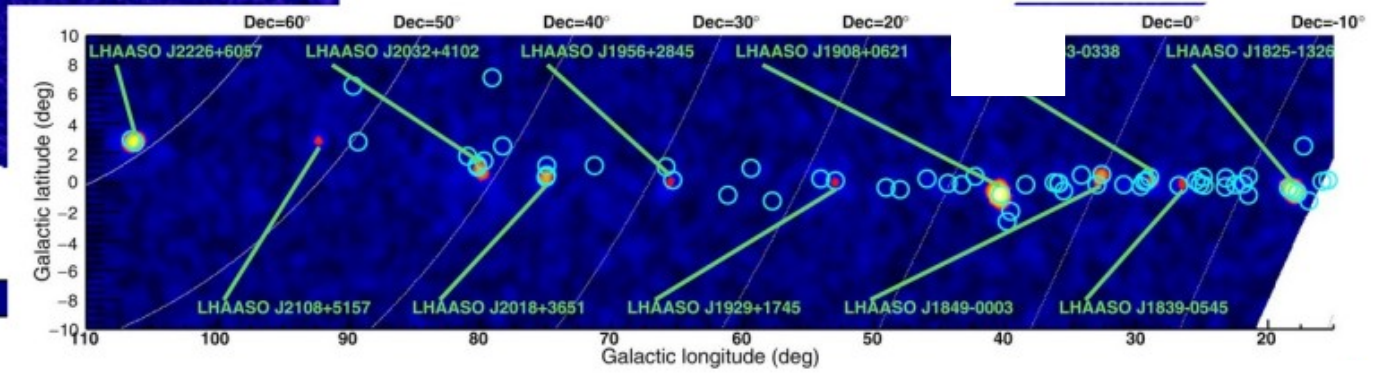


Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao ✉, F. A. Aharonian ✉, [...]X. Zuo

Nature **594**, 33–36 (2021) | Cite this article

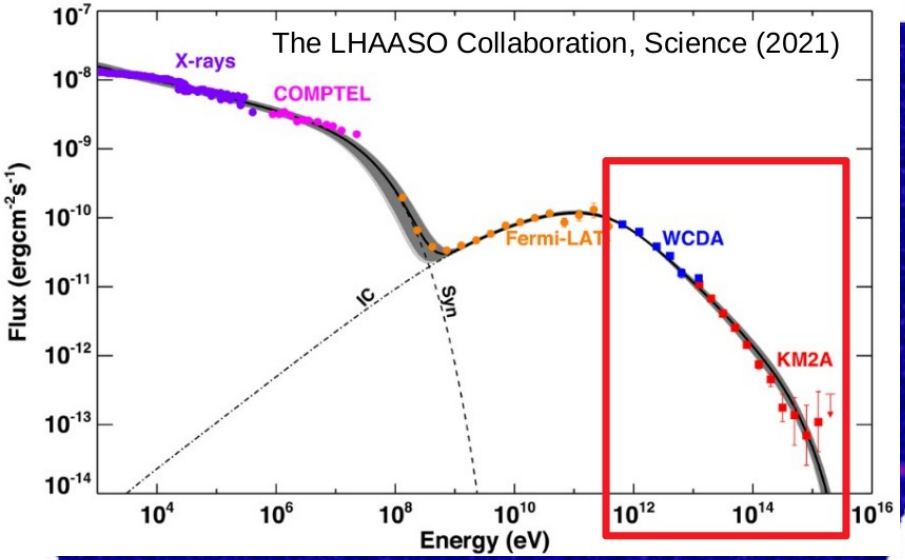
8285 Accesses | **637** Altmetric | Metrics

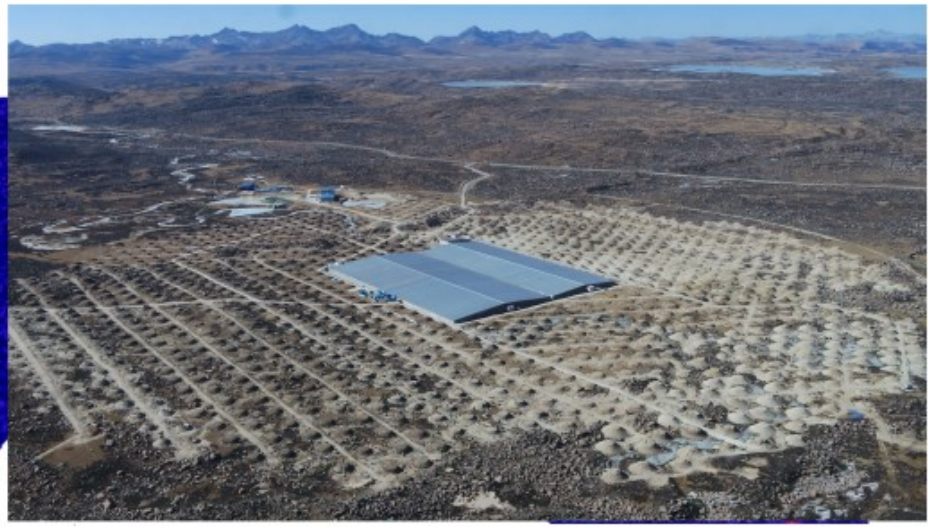


significance [σ]

For 0.4° sources

LHAASO PeVatrons :





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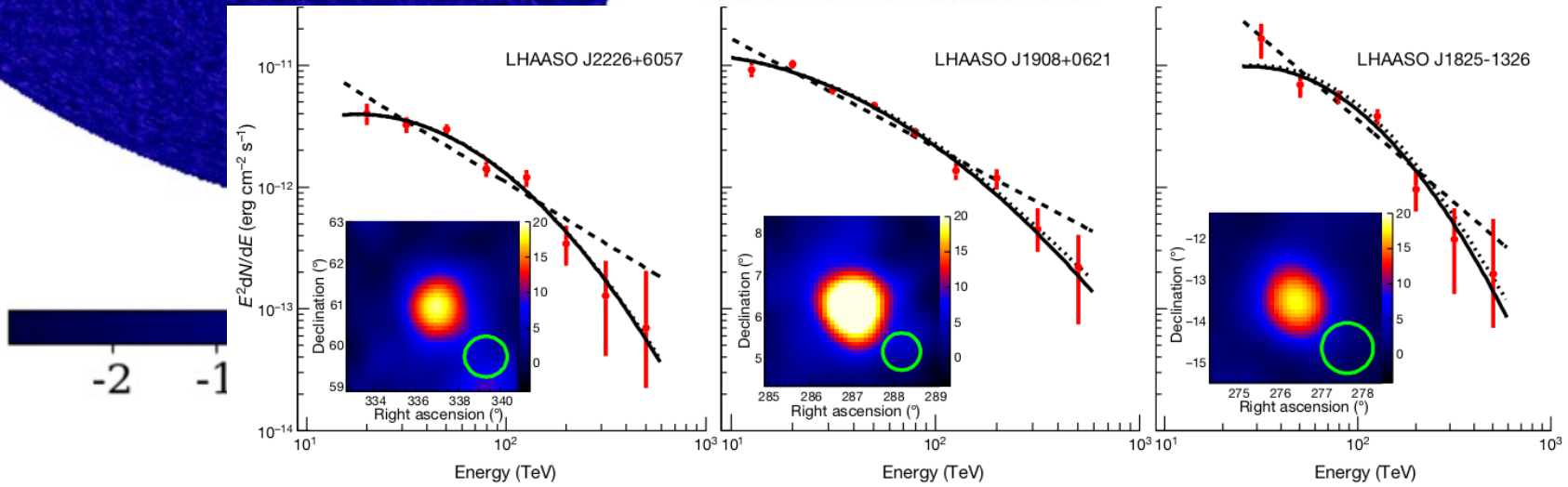
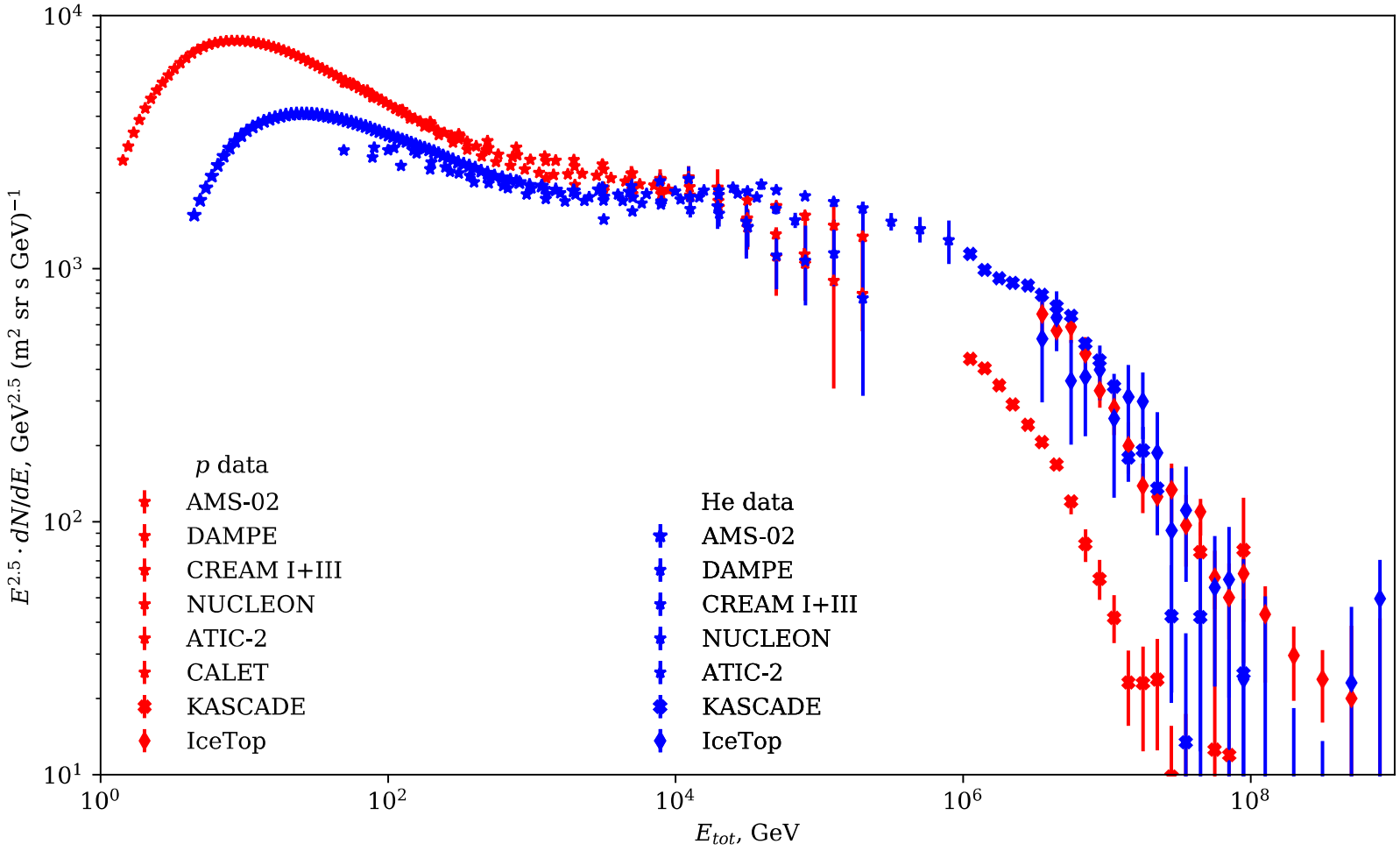
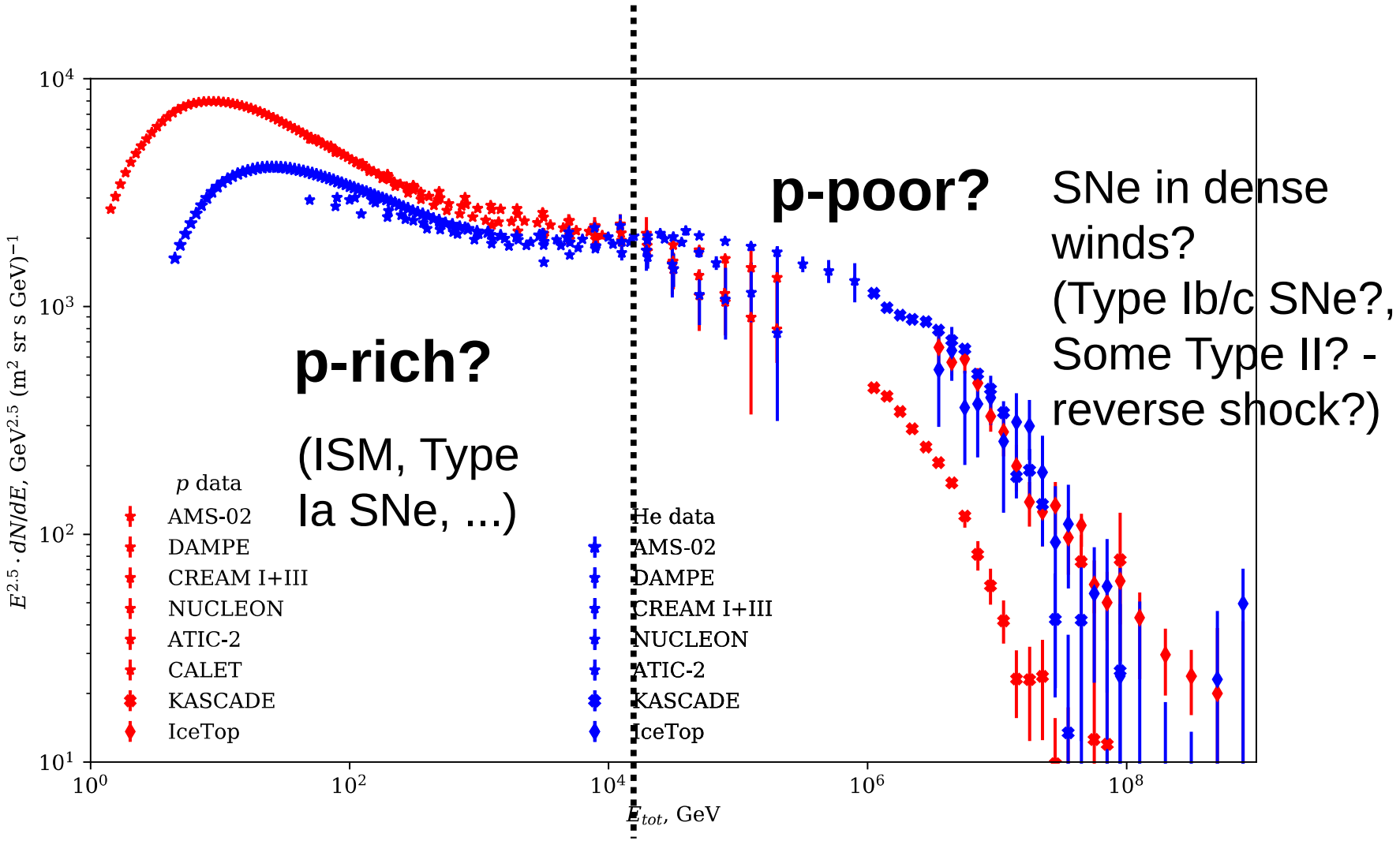


Local fluxes of CR p and He

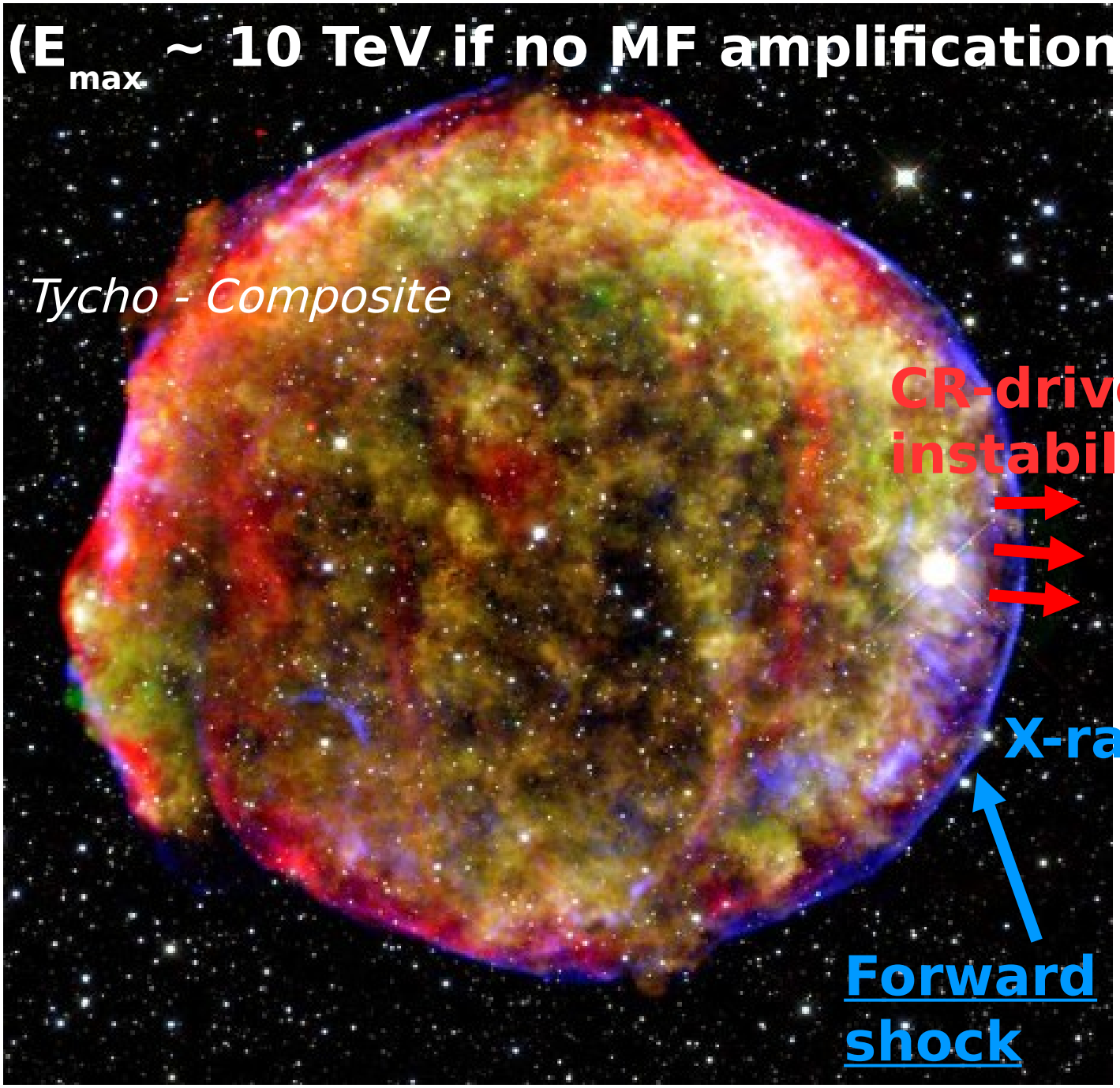


Acceleration mechanism???

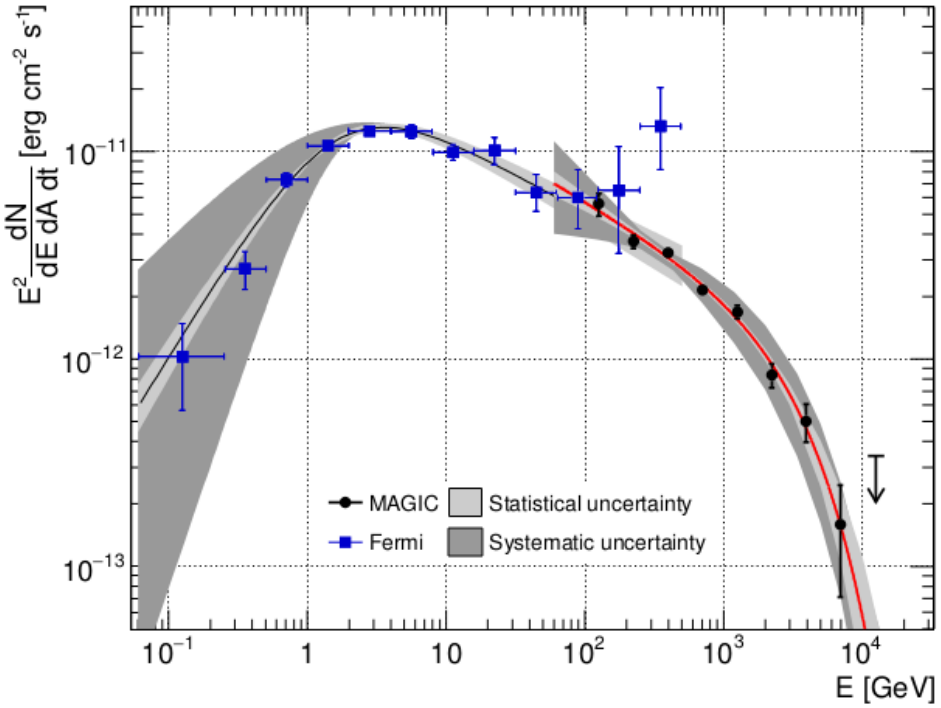
Local fluxes of CR p and He



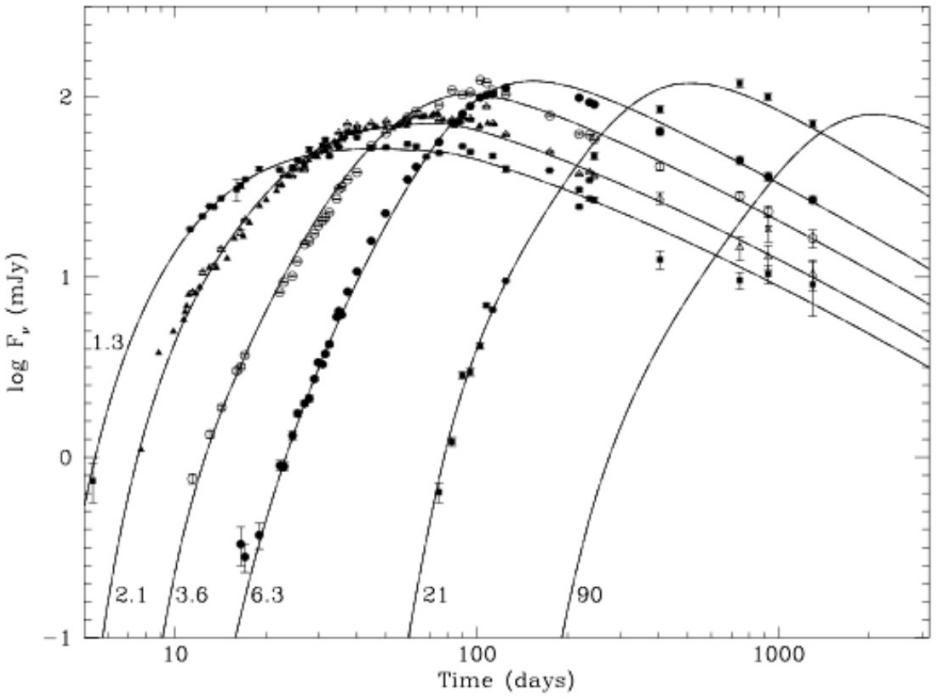
2 source populations?


(E_{max} ~ 10 TeV if no MF amplification
Tycho - Composite
CR-driven instabilities
X-rays
Forward shock

Spectrum of Cas A [ArXiv:1709.00280]



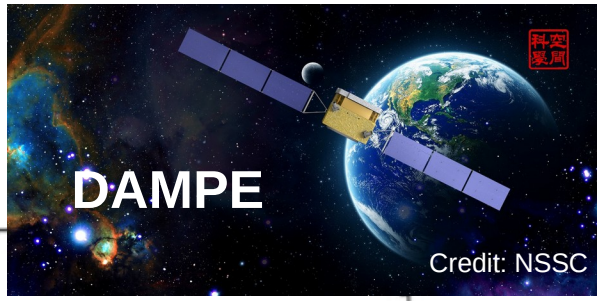
Radio SN 1993J (Fransson & Bjornsson (1998))

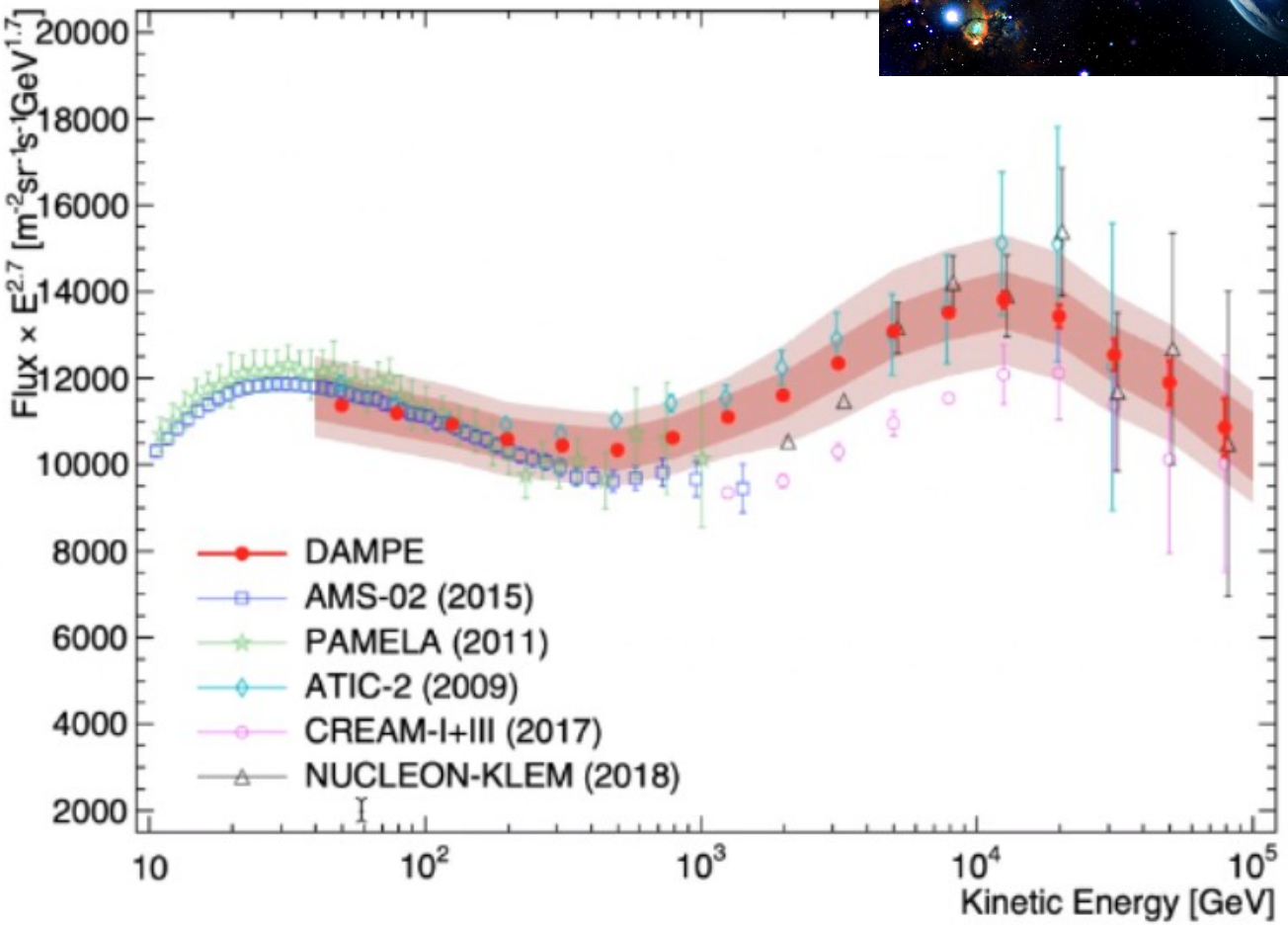


Bell et al. (2013) : **Only some supernovae in dense winds can reach multi-PeV energies.**

Tatischeff, A&A (2013) : SN 1993 J a PeVatron for 10 yr.

And the CR spectrum at Earth?





Proton spectrum with DAMPE (arXiv:1909.12860)

Problems – Part 2 (propagation):

→ *Standard picture in strong tension with GMF/ISMF observations & knowledge about CR propagation*

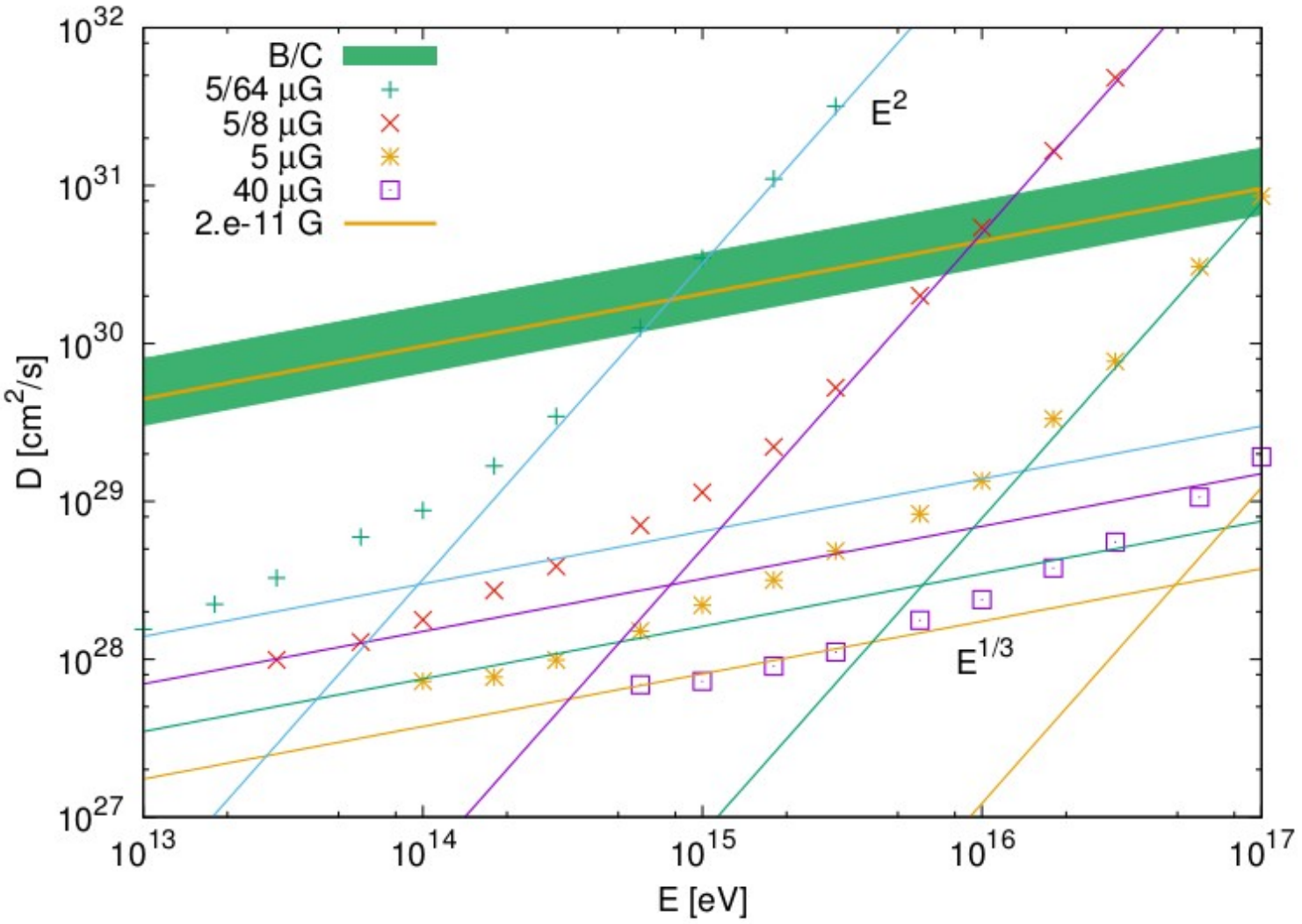
→ *Patchy diffuse Galactic γ-ray emission at VHE (~ 100 TeV +)*

Anisotropic diffusion

Isotropic diffusion

$$\mathcal{P}(k) \propto k^{-5/3}$$

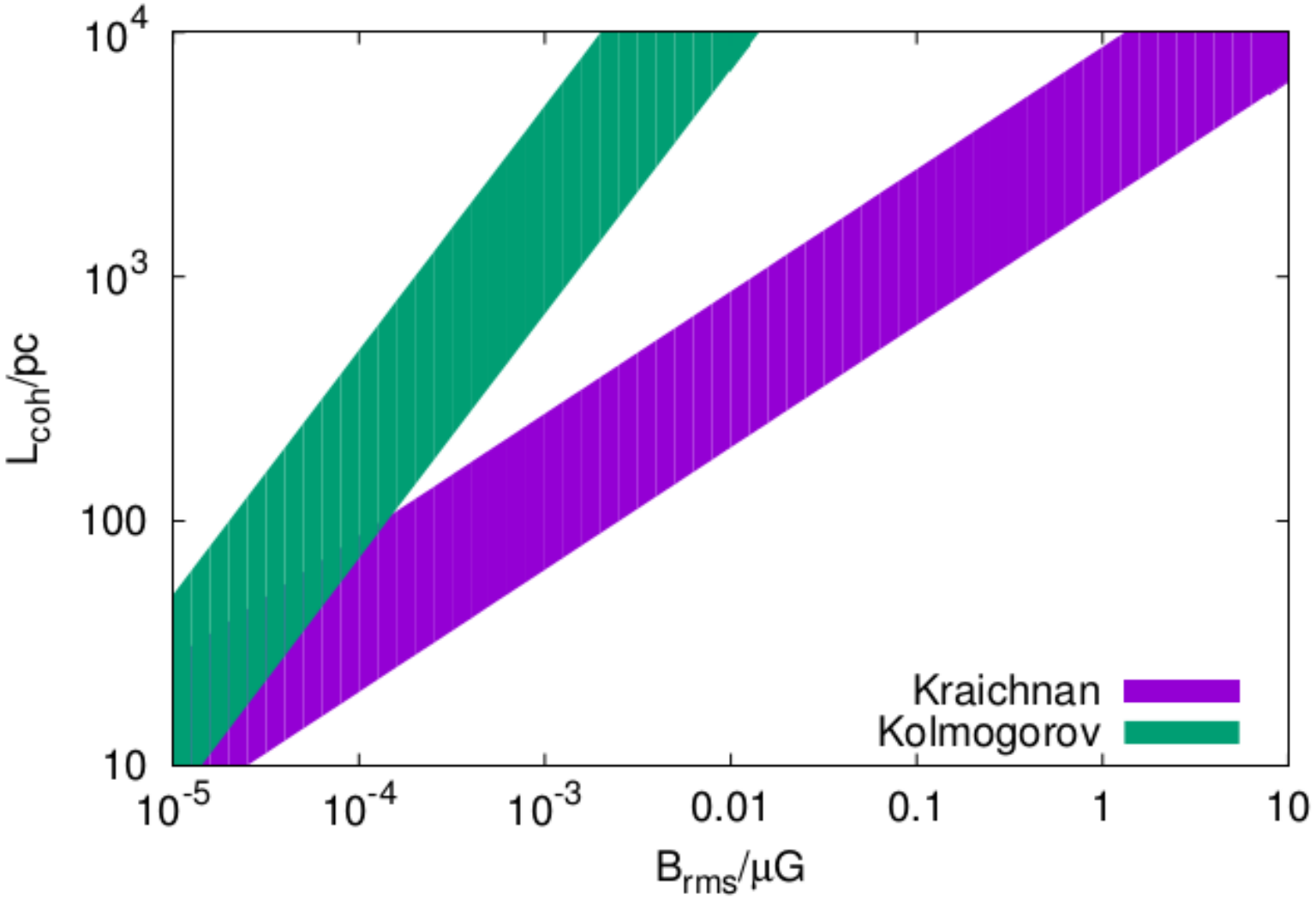
$$L_{\rm max} = 25\,{\rm pc}$$



Giacinti et al, 1710.08205

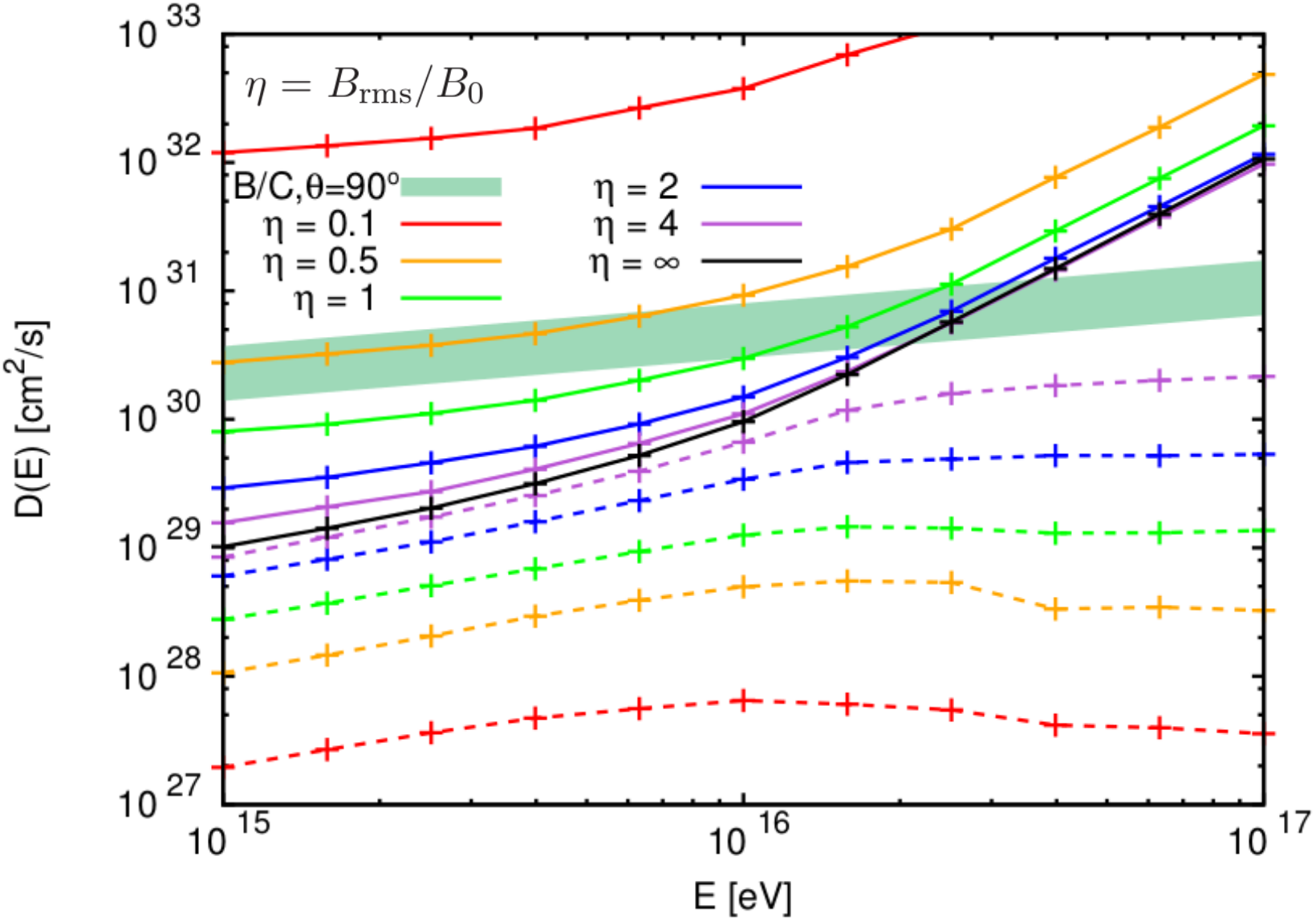
Isotropic diffusion

Allowed ranges of $B_{\rm rms}$ and $L_{\rm coh}$ compatible with $D_0 = (3-8)\times 10^{28}{\rm cm}^2/{\rm s}$ at $E_0 = 10\,{\rm GeV}$



Giacinti et al, 1710.08205

Anisotropic diffusion

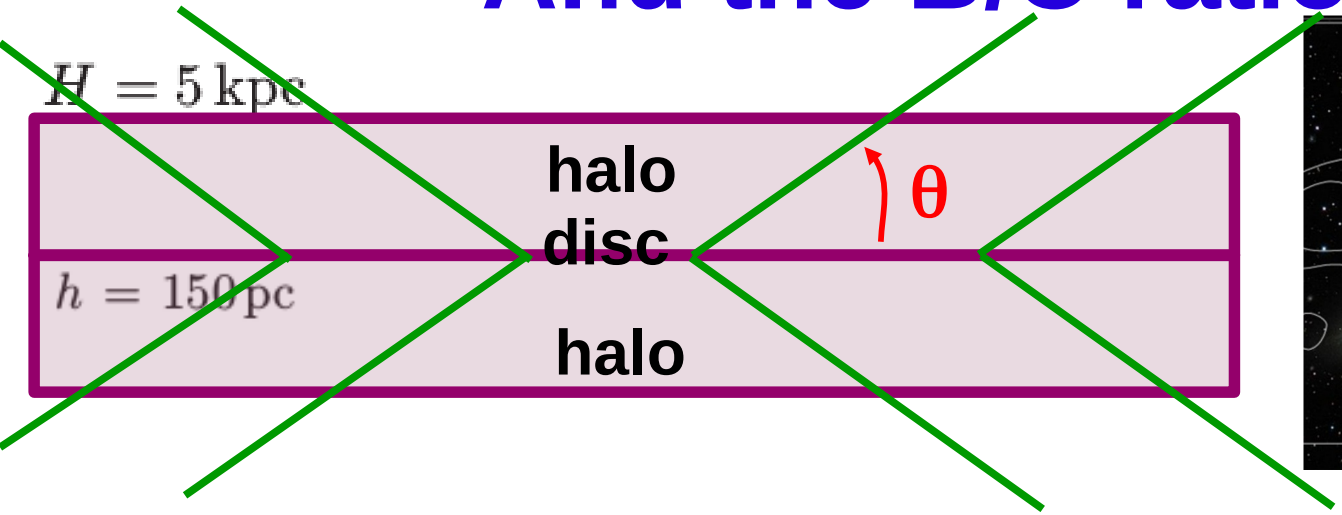


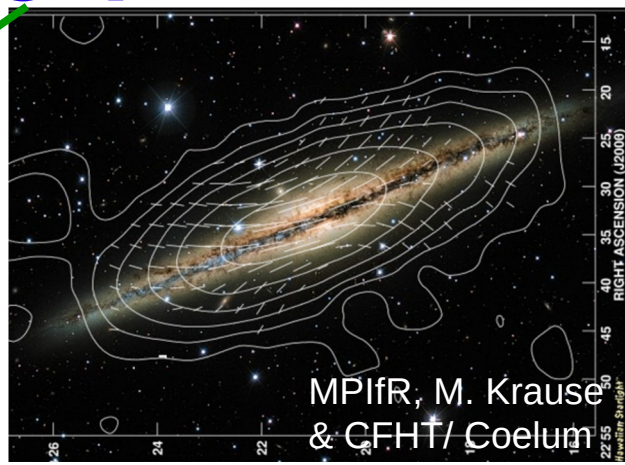
$L_{\rm max} = 100\,{\rm pc}$

Giacinti et al, 1710.08205

$B_{\rm tot} = \sqrt{B_{\rm rms}^2 + B_0^2} = 1\,\mu{\rm G}$

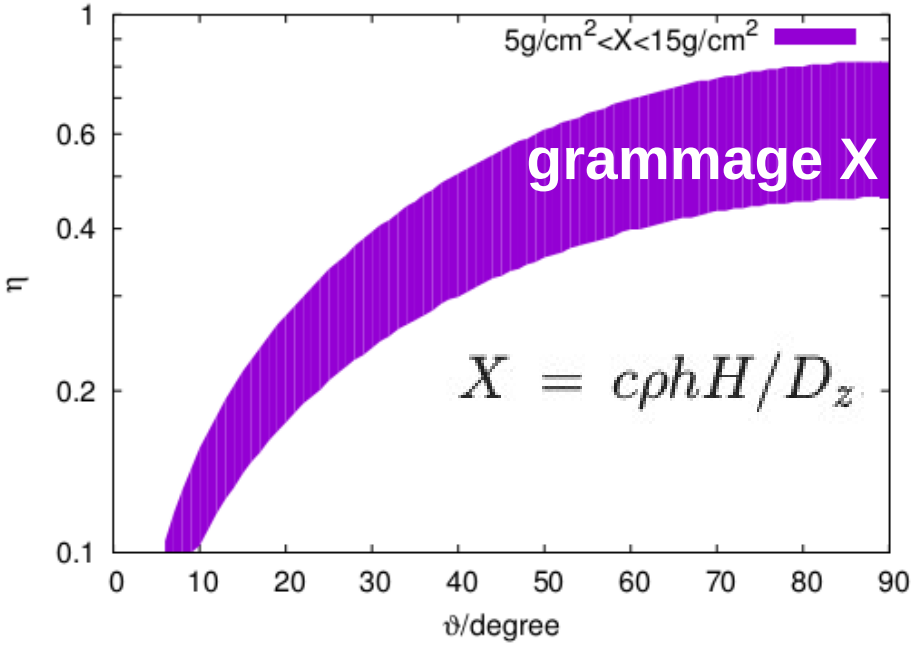
And the B/C ratio ?



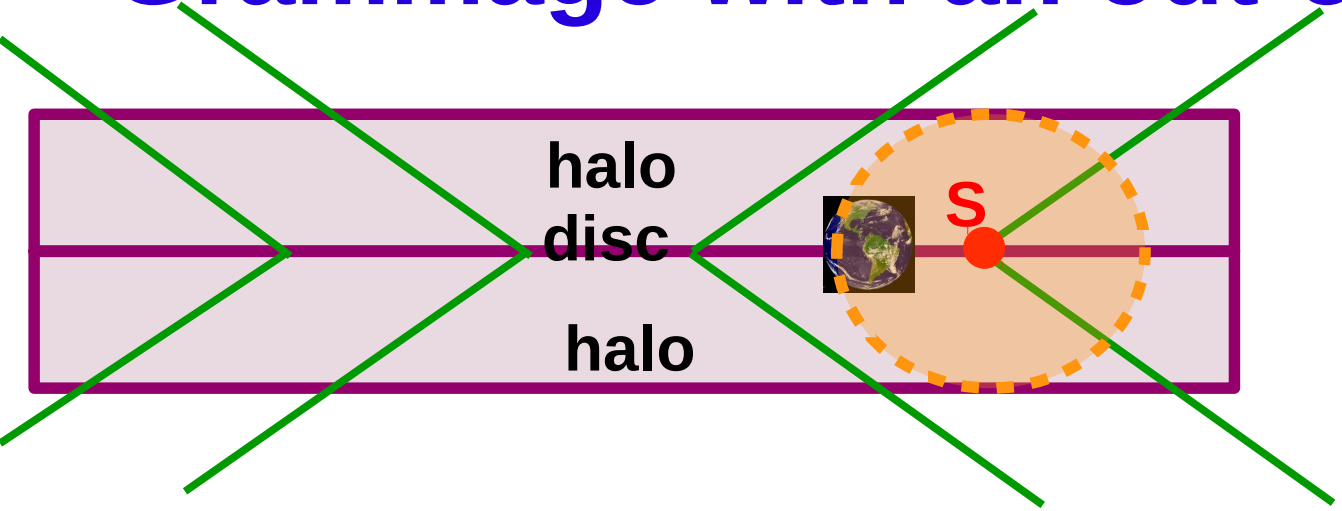


Giacinti, Kachelriess & Semikoz, JCAP (2018)

$\eta = B_{\mathrm{rms}}/B_0$



Grammage with an out-of-plane B

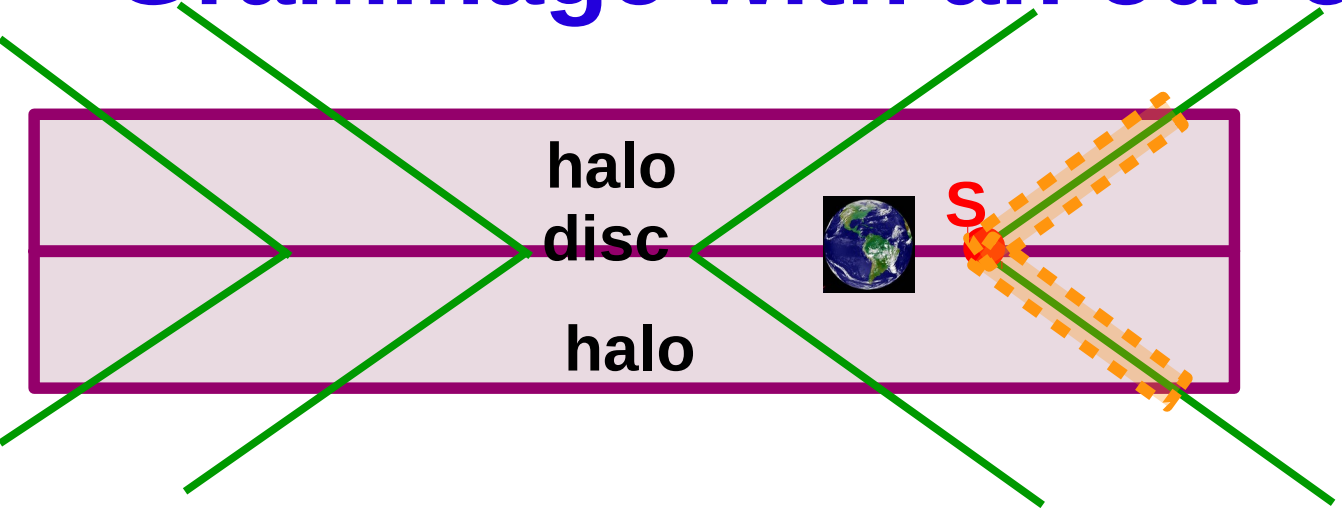


Giacinti, Kachelriess & Semikoz, JCAP (2018)

Isotropic diffusion:

Needs > 1000s sources for the local > 10 TeV CR flux.

Grammage with an out-of-plane B



Giacinti, Kachelriess & Semikoz, JCAP (2018)

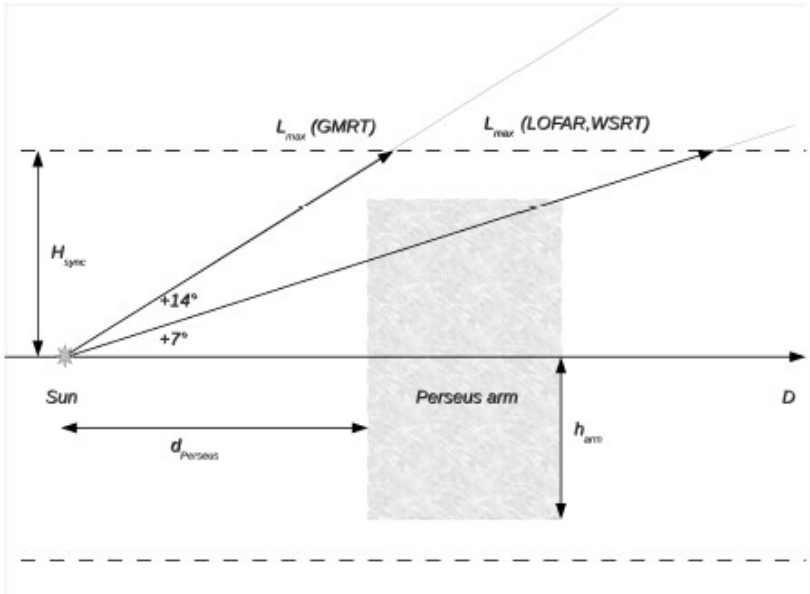
Isotropic diffusion:

Needs > 1000s sources for the local > 10 TeV CR flux.

Anisotropic diffusion:

One/Few local sources (~ 200pc) may dominate the CR flux at > 10TeV +

LOFAR measurement of maximum scale of turbulent GMF in disk



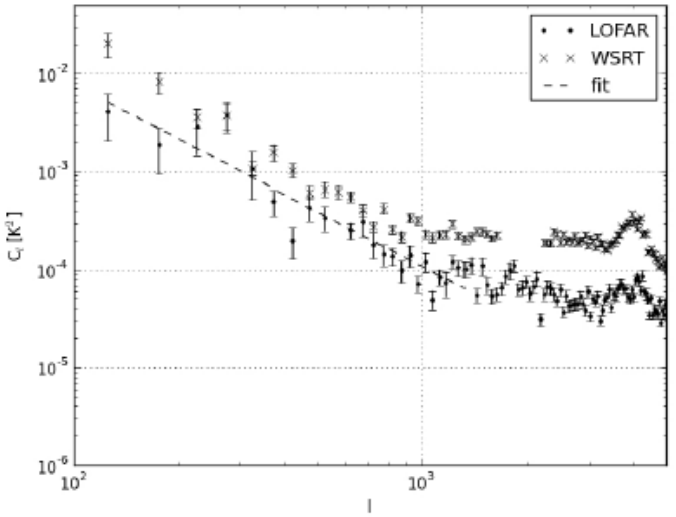


Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

Lmax ~ 20 pc +-6 pc in disk

«Escape model»

GG+ (2014, 2015)

«ESCAPE MODEL»:

- Idea:
  V. L. Ginzburg and S. I. Syrovatskii, *1962-1964; small angle diffusion at HE*

- Developement:
  V. S. Ptuskin et al., Astron. Astrophys. 268, 726 (1993);
  J. Candia, E. Roulet and L. N. Epele, JHEP 0212, 033 (2002);
  J. Candia, S. Mollerach and E. Roulet, JCAP 0305, 003 (2003).
  (*Hall diffusion)*

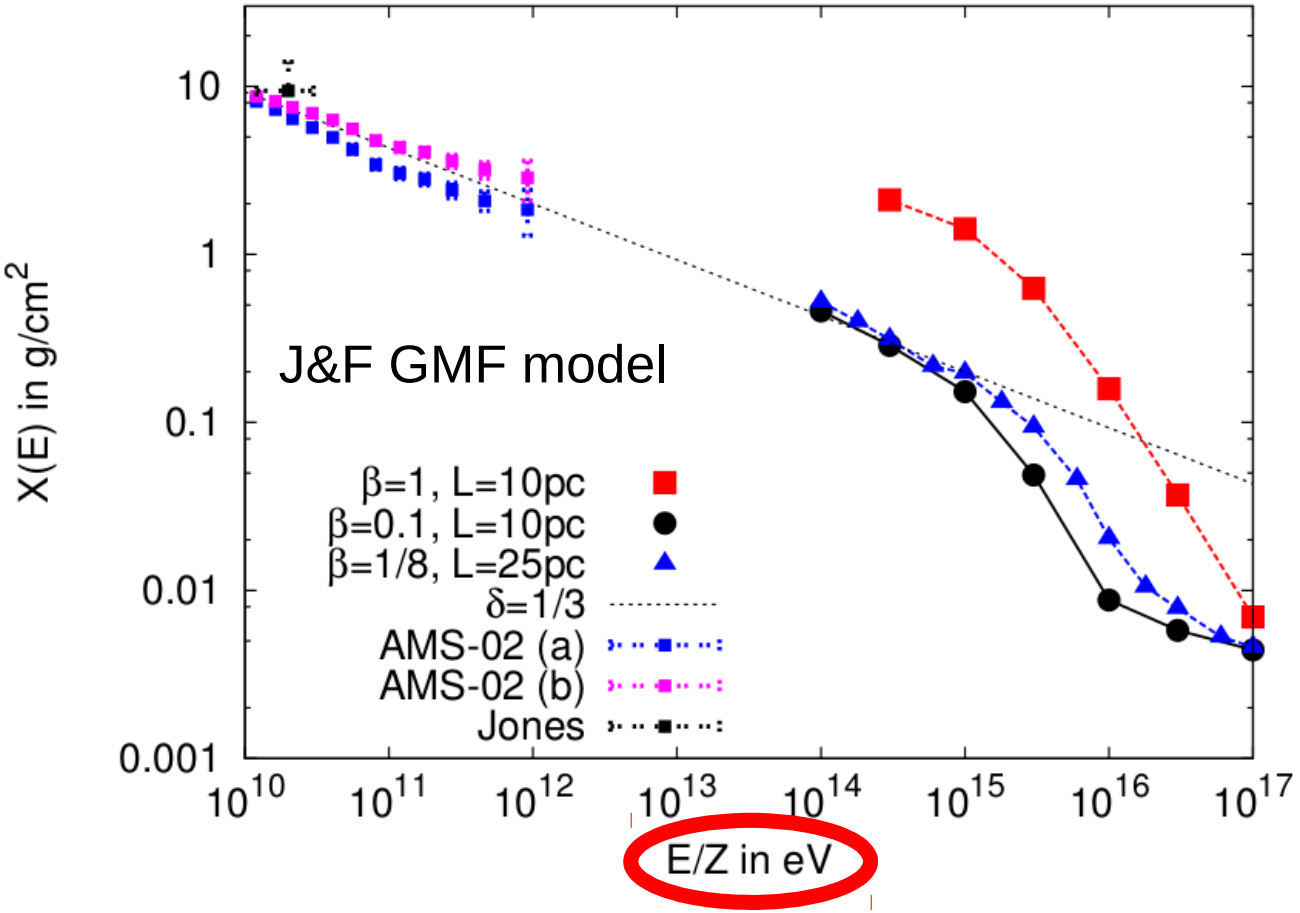
Knee

Gaz distribution

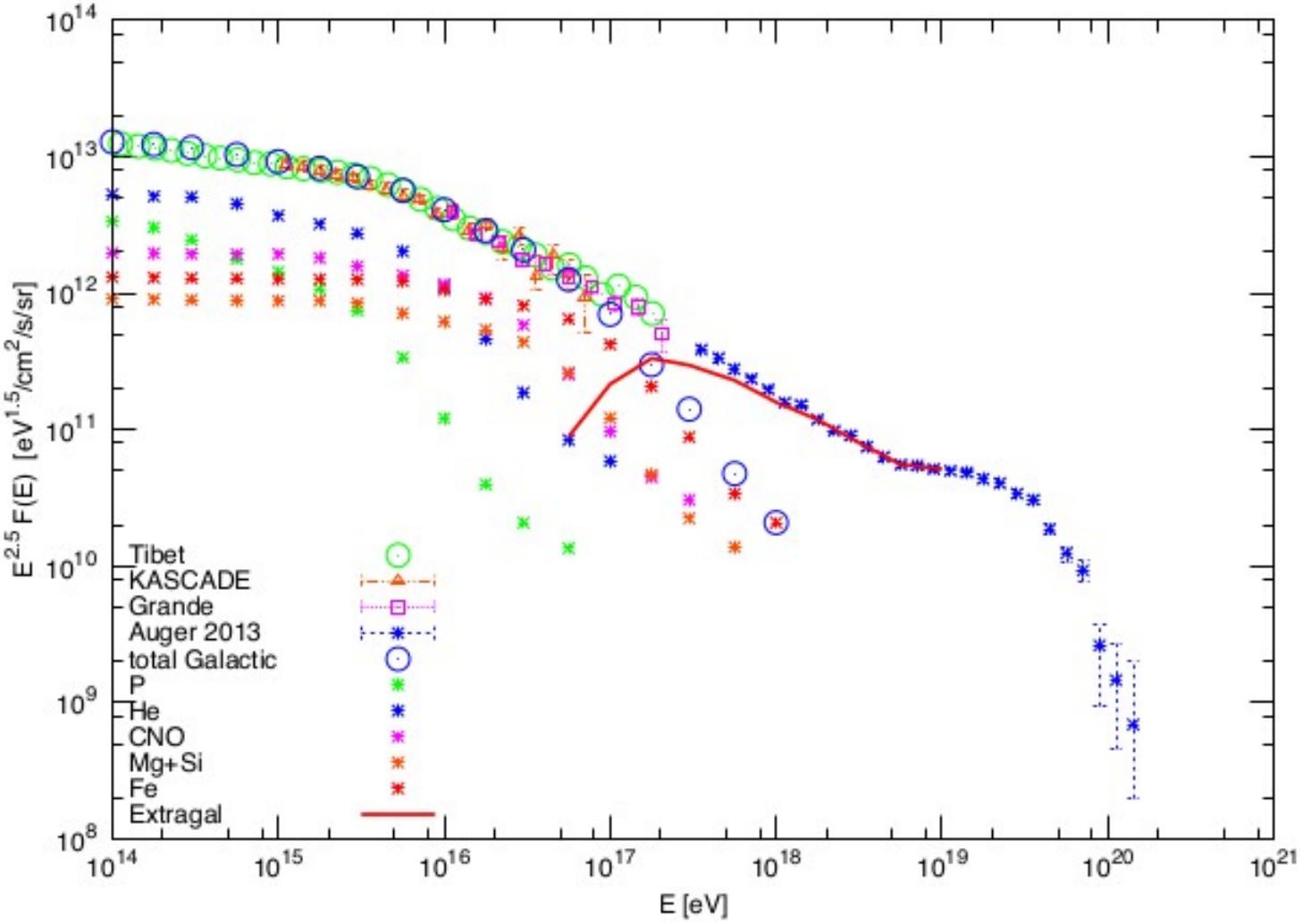
$n(z) = n_0 \exp(-(z/z_{1/2})^2)$ with $n_0 = 0.3/\mathrm{cm}^3$ at $R_\odot$ and $z_{1/2} = 0.21\,\mathrm{kpc}$

$n = 10^{-4}\mathrm{g/cm}^3$ ↔ Minimum, up to z = +/- 10 kpc

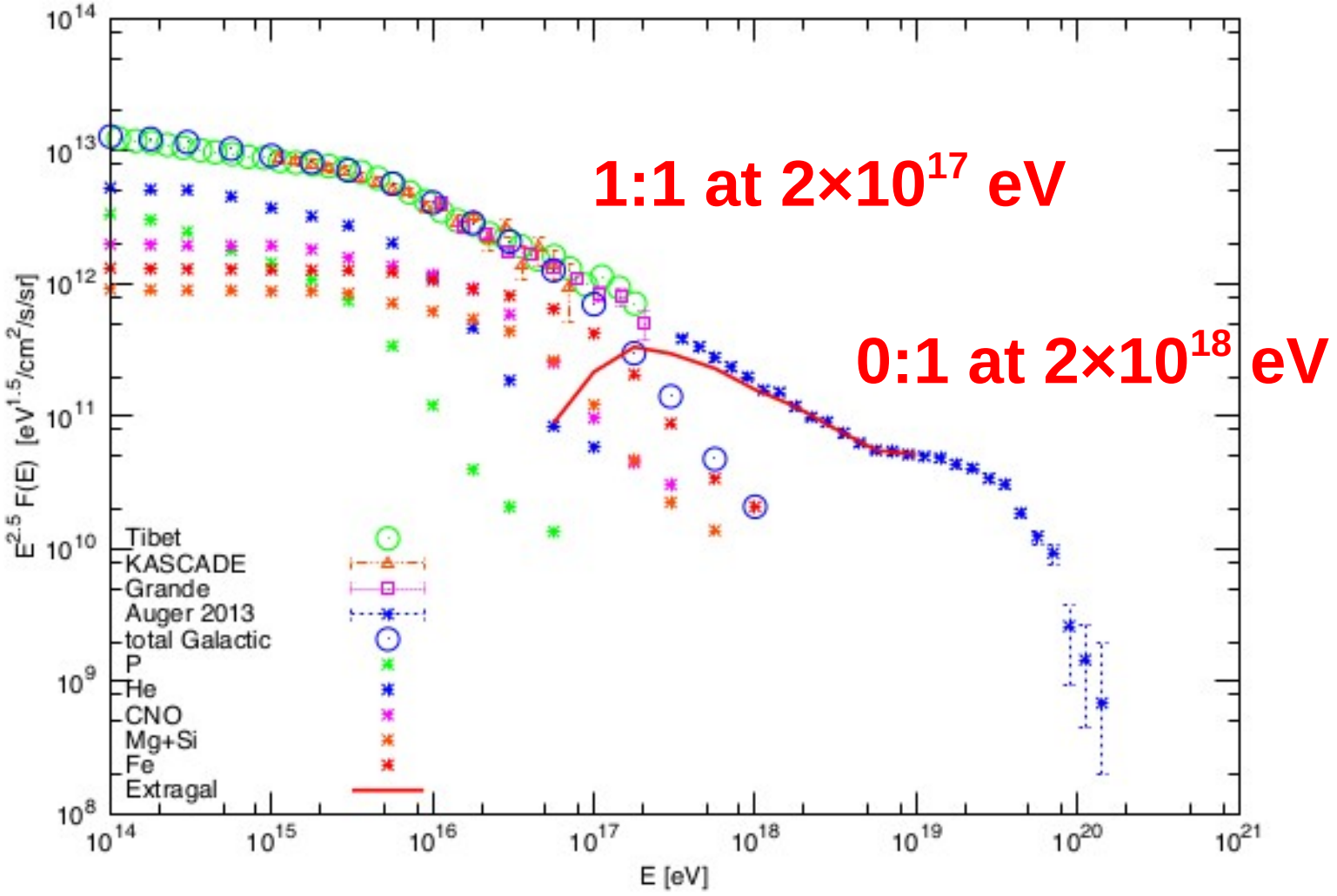
Sources : $n(r) \propto (r/R_\odot)^{0.7} \exp\left[-3.5(r - R_\odot)/R_\odot\right]$ D. A. Green, arXiv:1309.3072



Cosmic Ray Knee: all particles

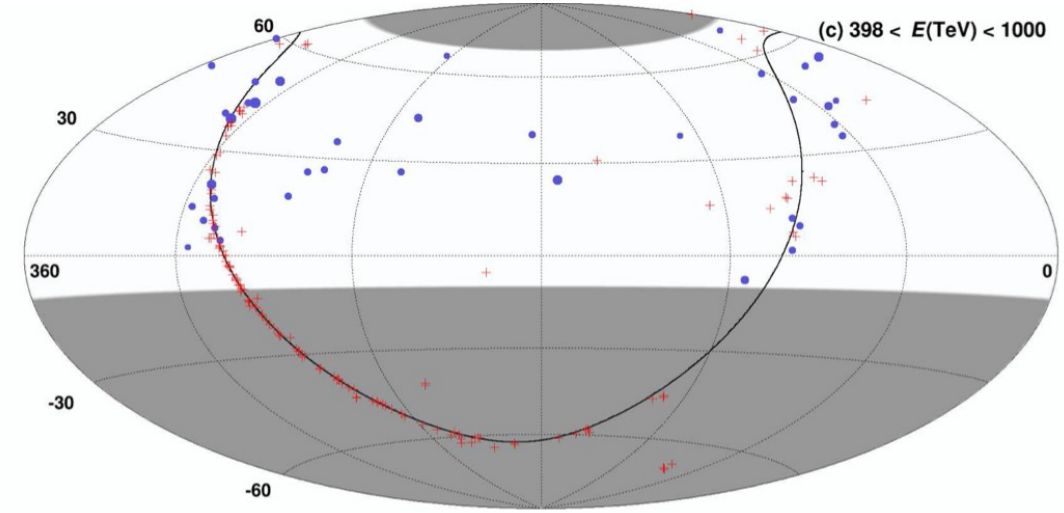


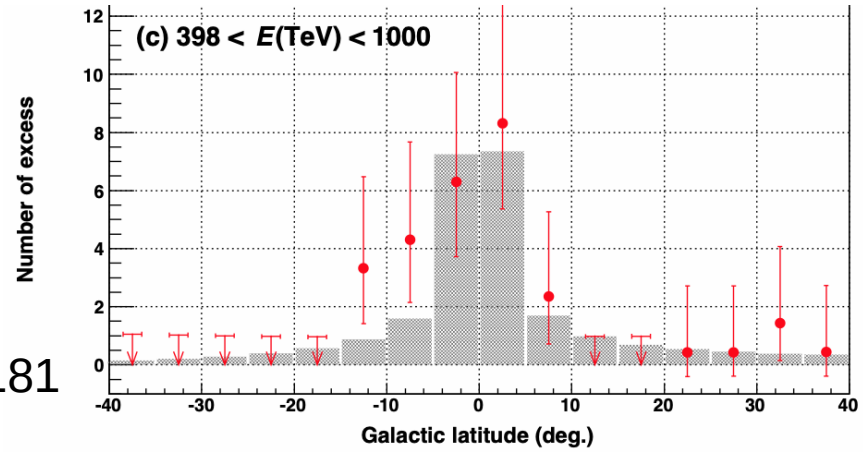
Contribution of extra-Galactic sources



Diffuse Galactic gamma-ray emission (Tibet AS-gamma)

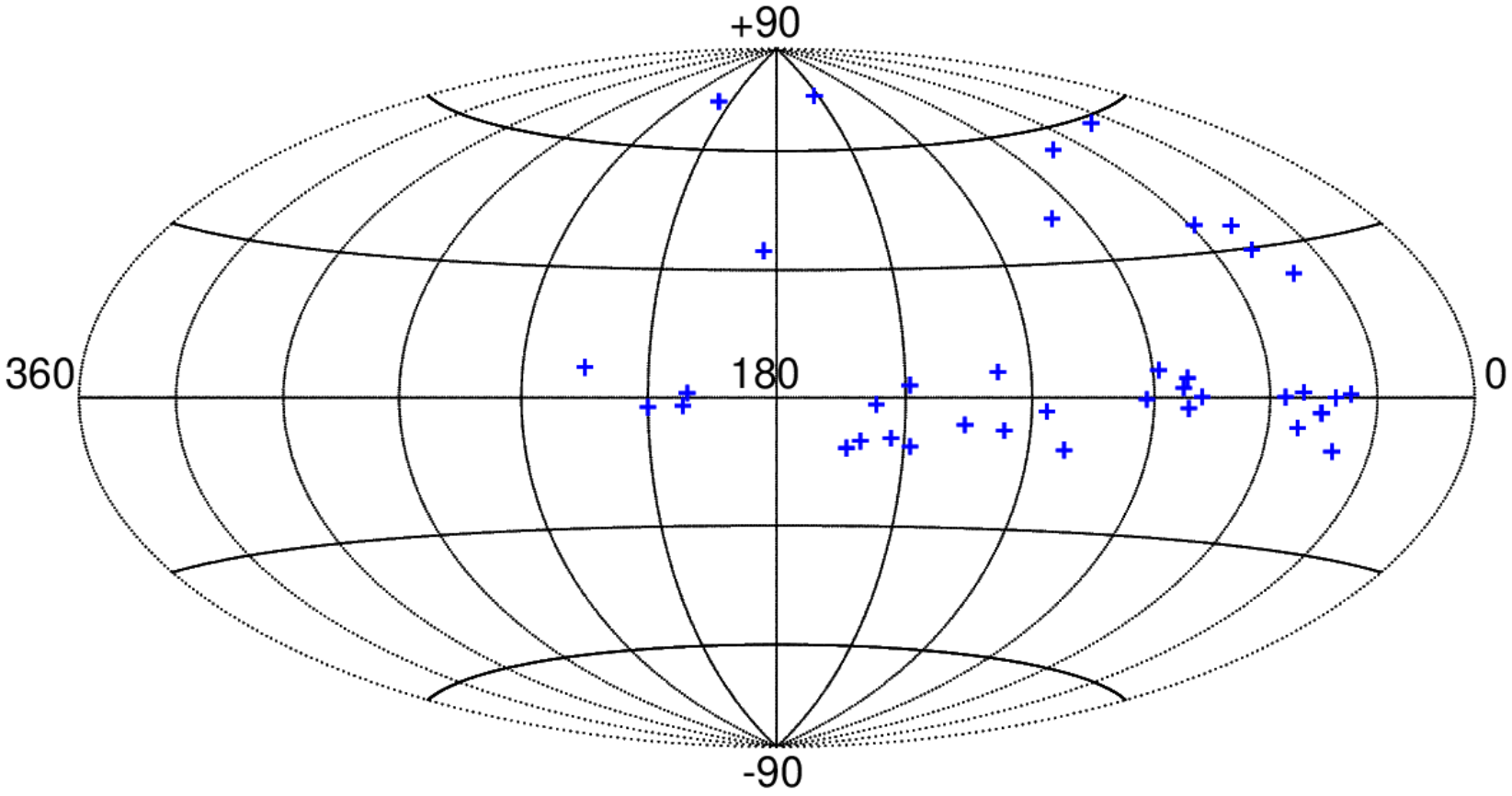
Tibet gamma-ray sky at > 400 TeV (2021)





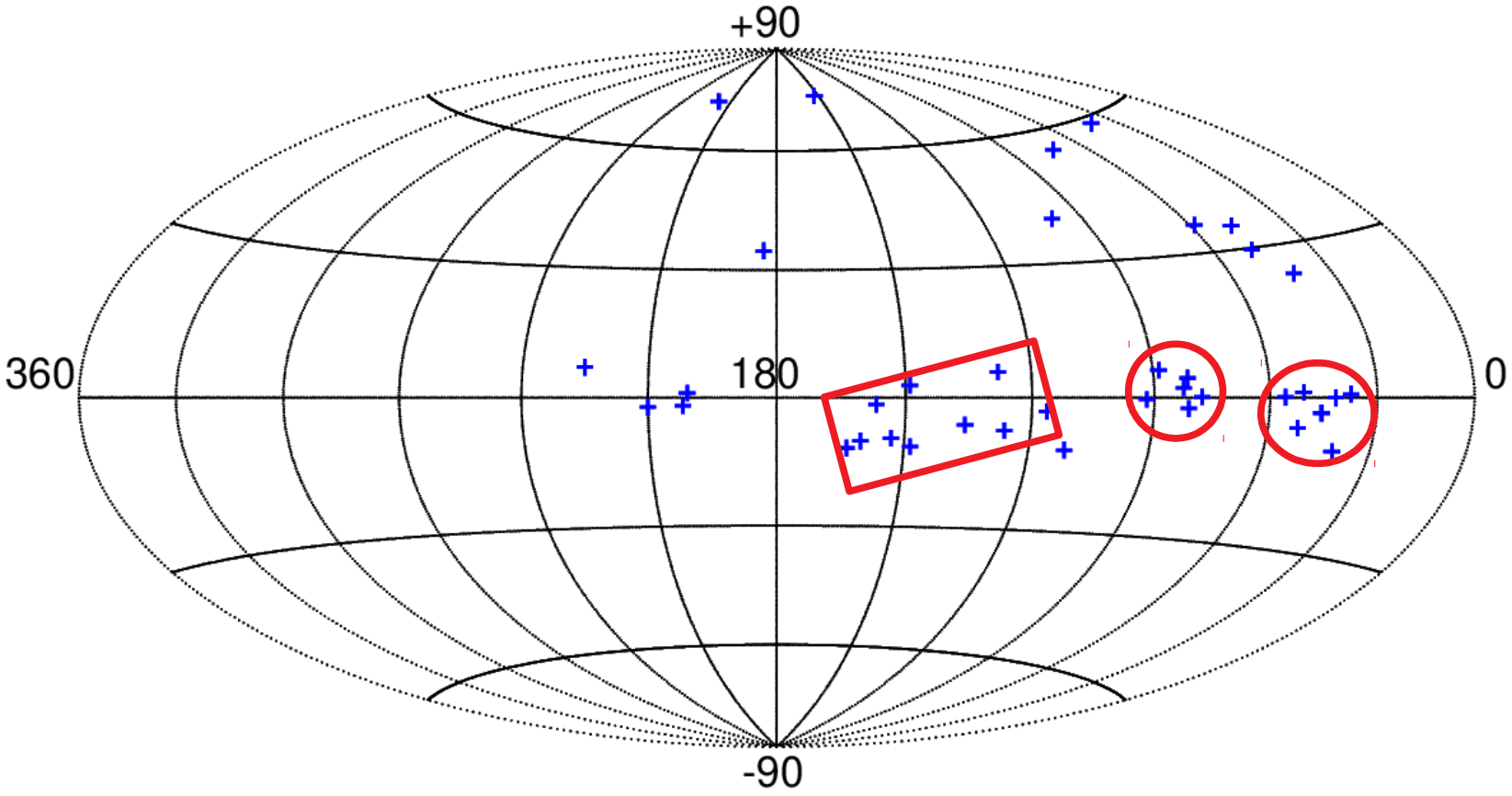
Tibet collaboration, arXiv:2104.05181

Diffuse Galactic VHE γ-ray emission



398-1000 TeV Tibet ASγ events

Diffuse Galactic VHE γ-ray emission



398-1000 TeV Tibet ASγ events

Our updated model of the knee (& >TeV CR flux) with anisotropic CR diffusion

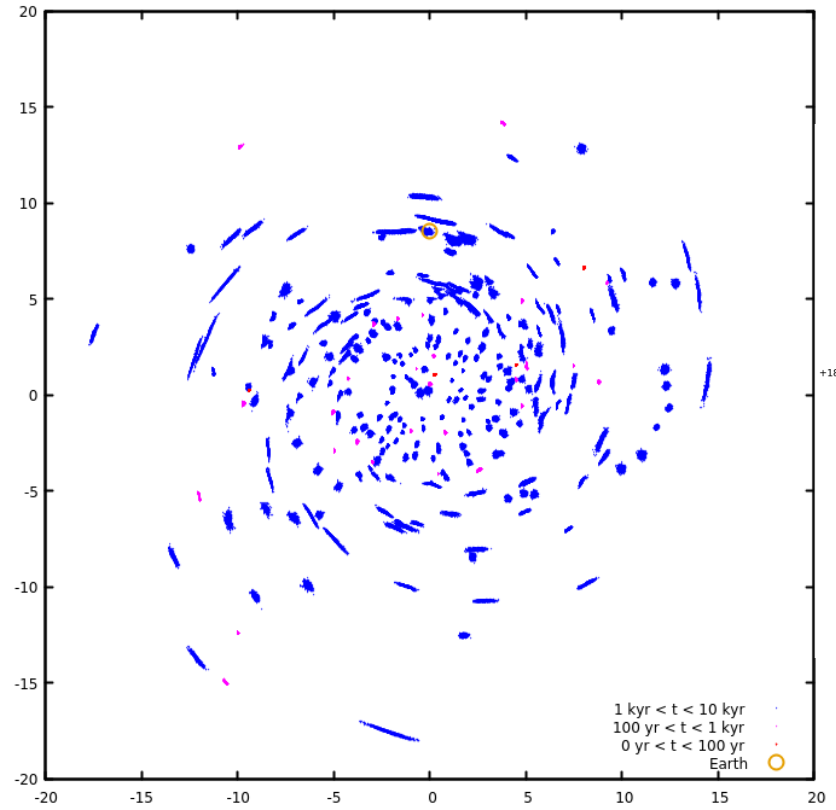
Diffuse Galactic VHE γ-ray emission

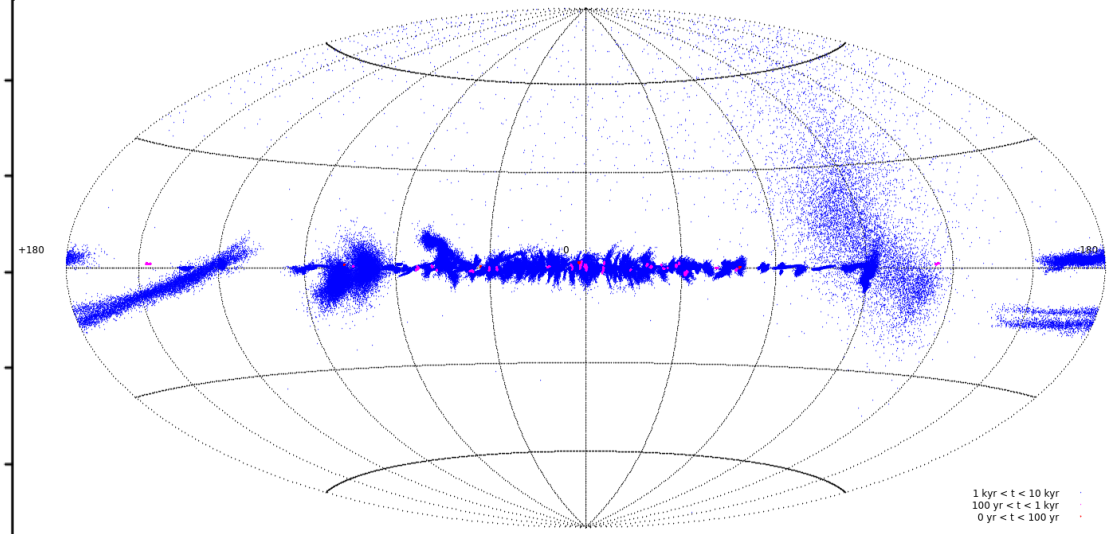
Giacinti & Semikoz, In prep.

→ Propagate CRs in Jansson&Farrar Galactic magnetic field model.

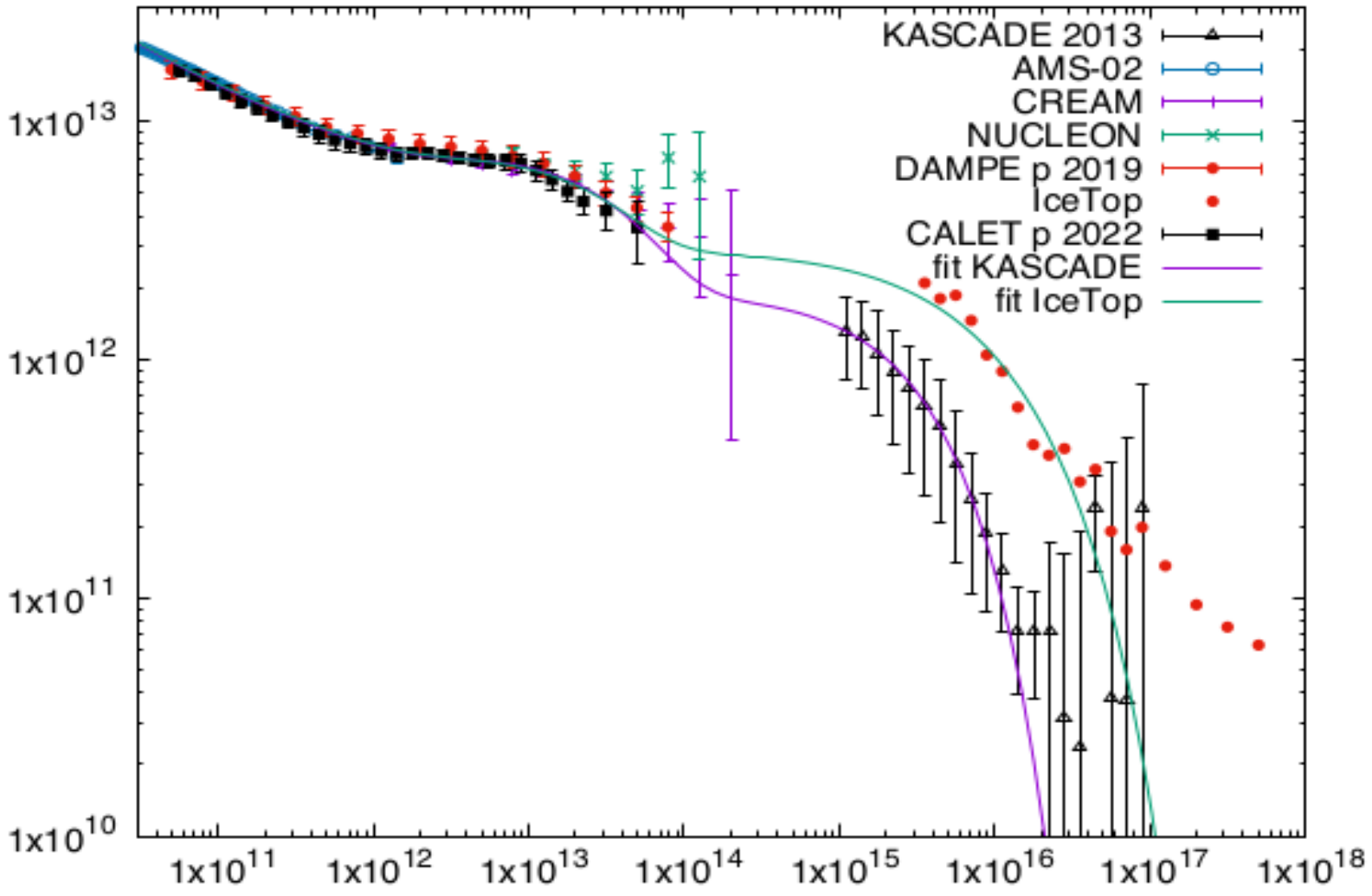
→ Stochastic PeV CR injection at SNe.

Better than Galactic CR propagation codes at these energies (E~100TeV)





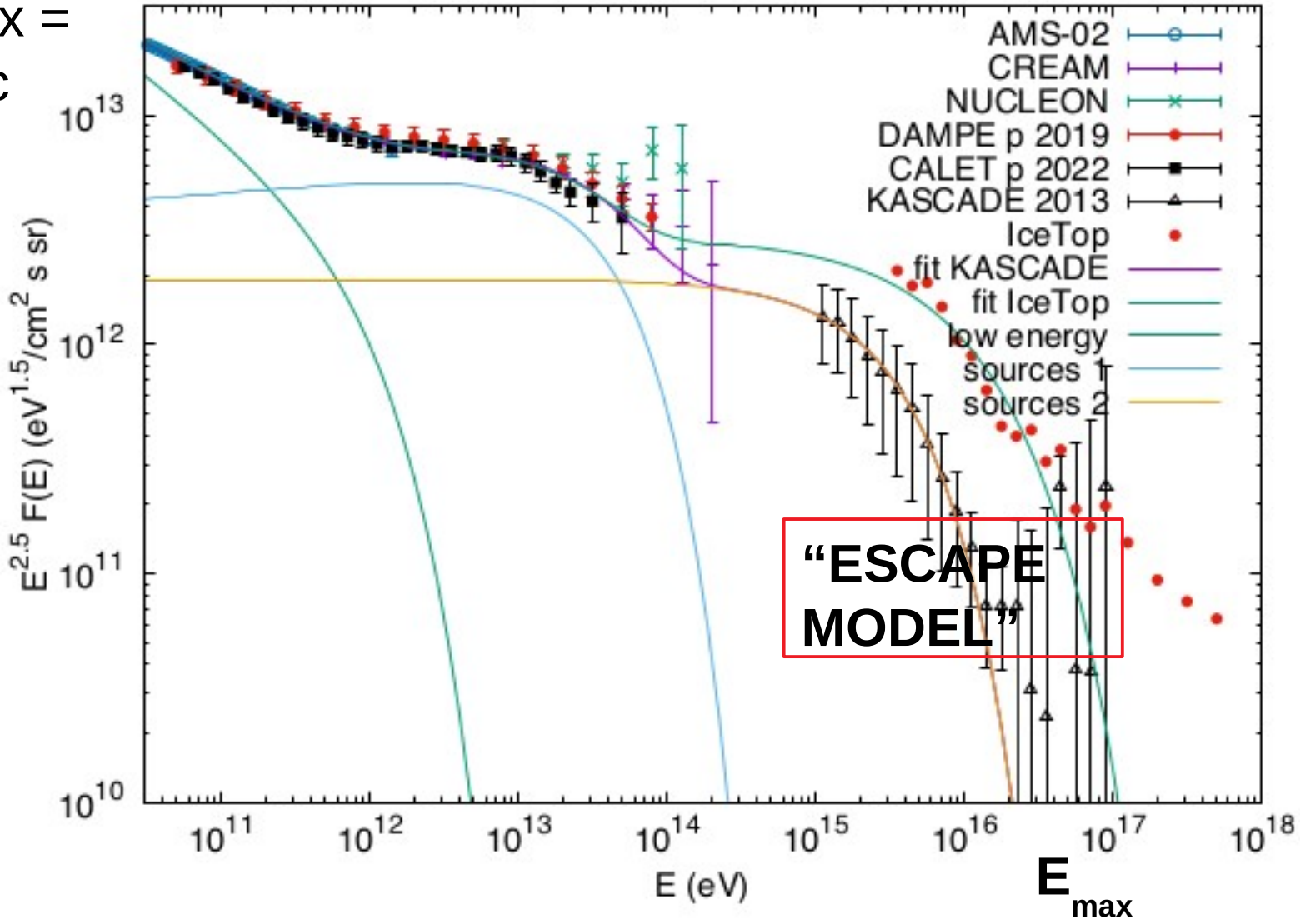
Knee – Proton flux



G.Giacinti and D.Semikoz, in preparation

Knee – Proton flux

Lmax = 25pc



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Knee – Proton flux

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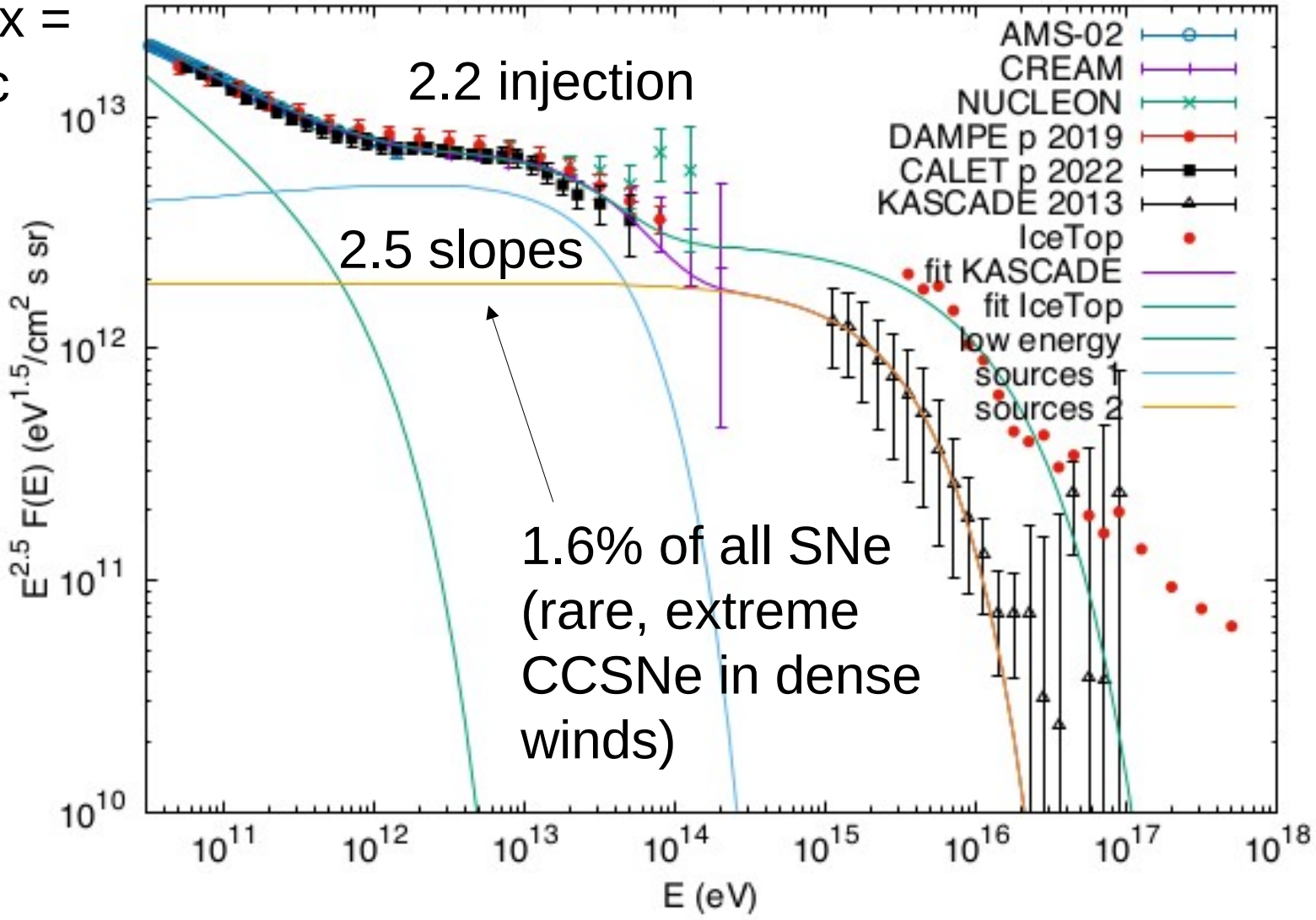
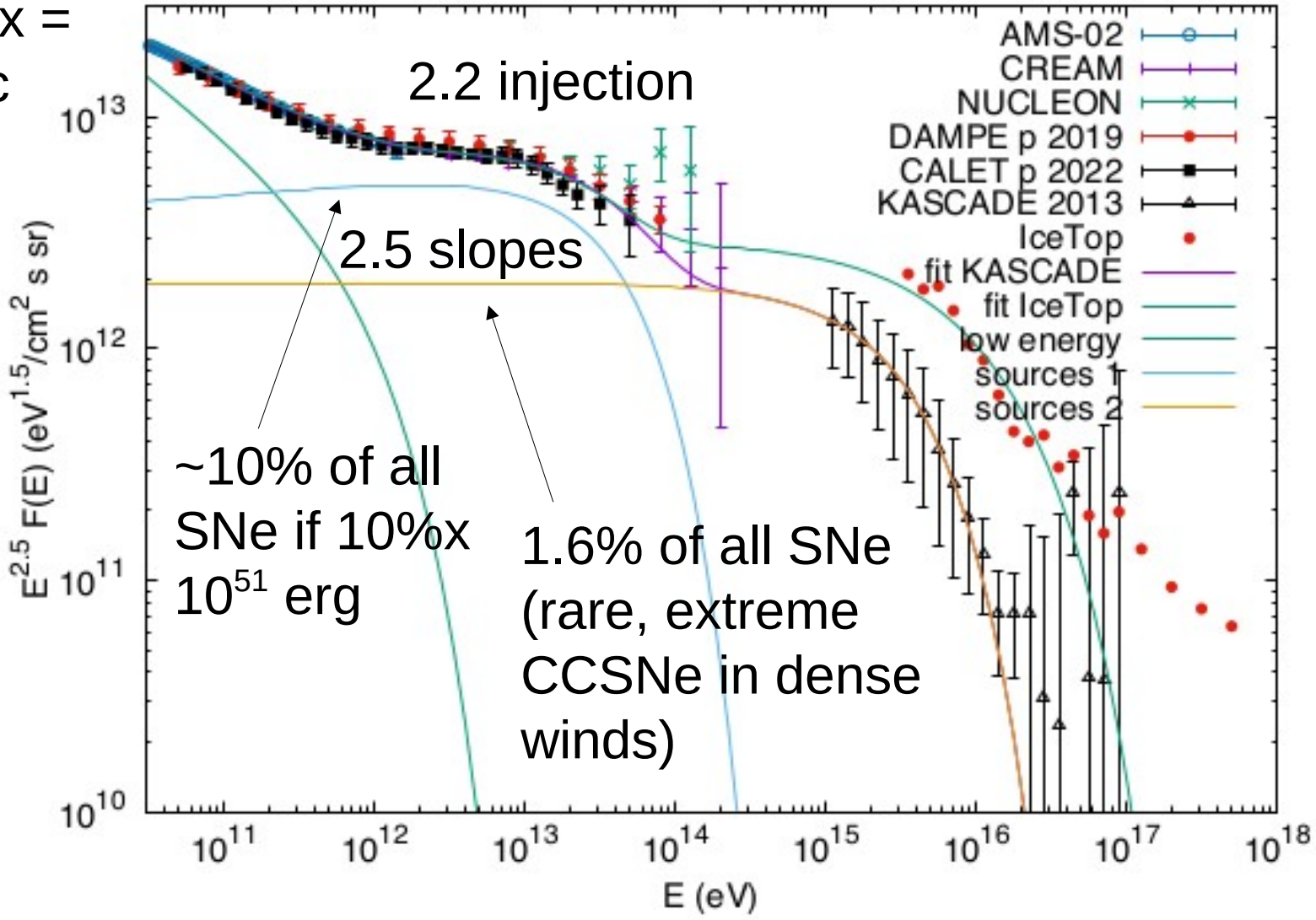


G.Giacinti and D.Semikoz, in preparation

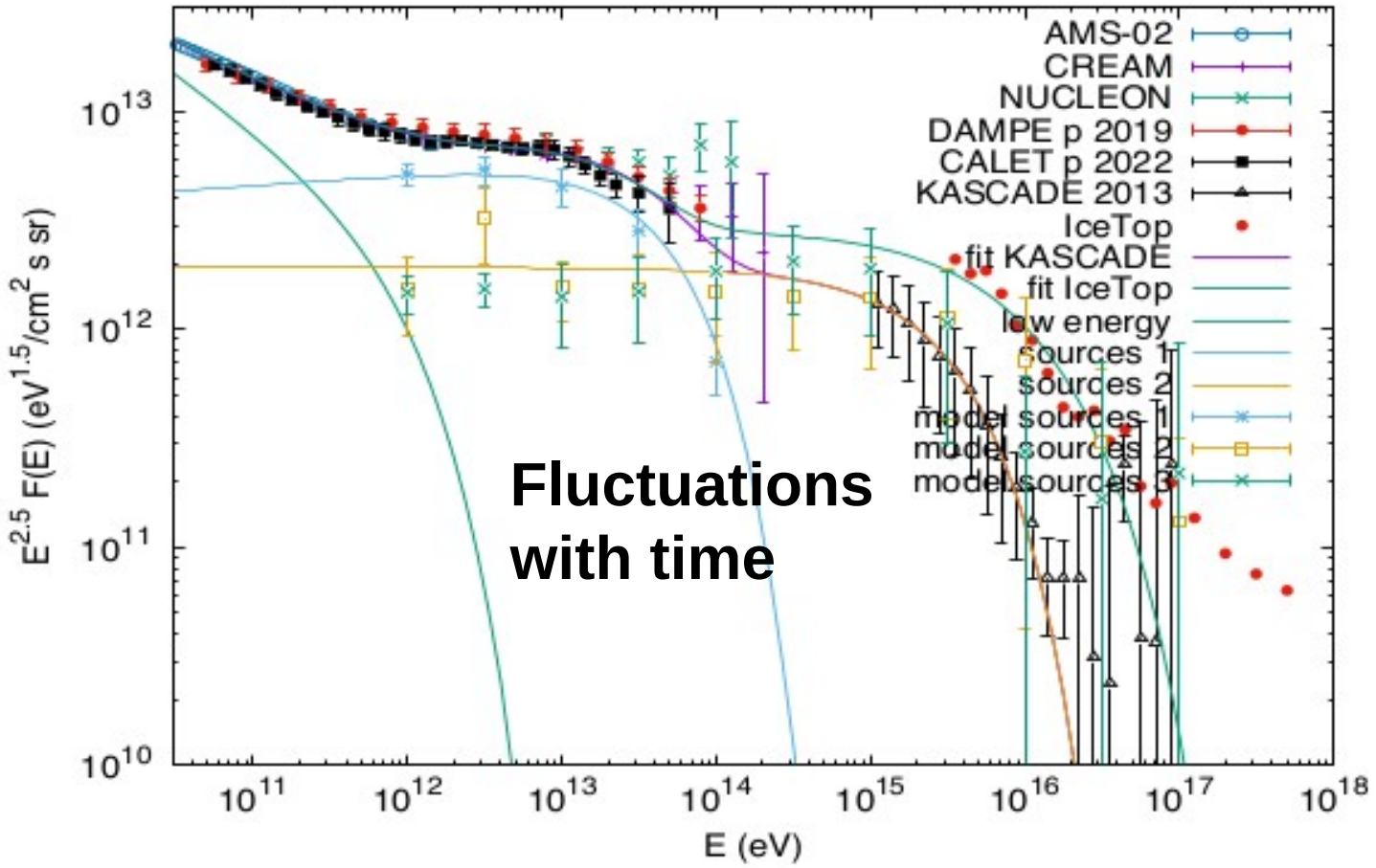
Knee – Proton flux

Lmax = 25pc



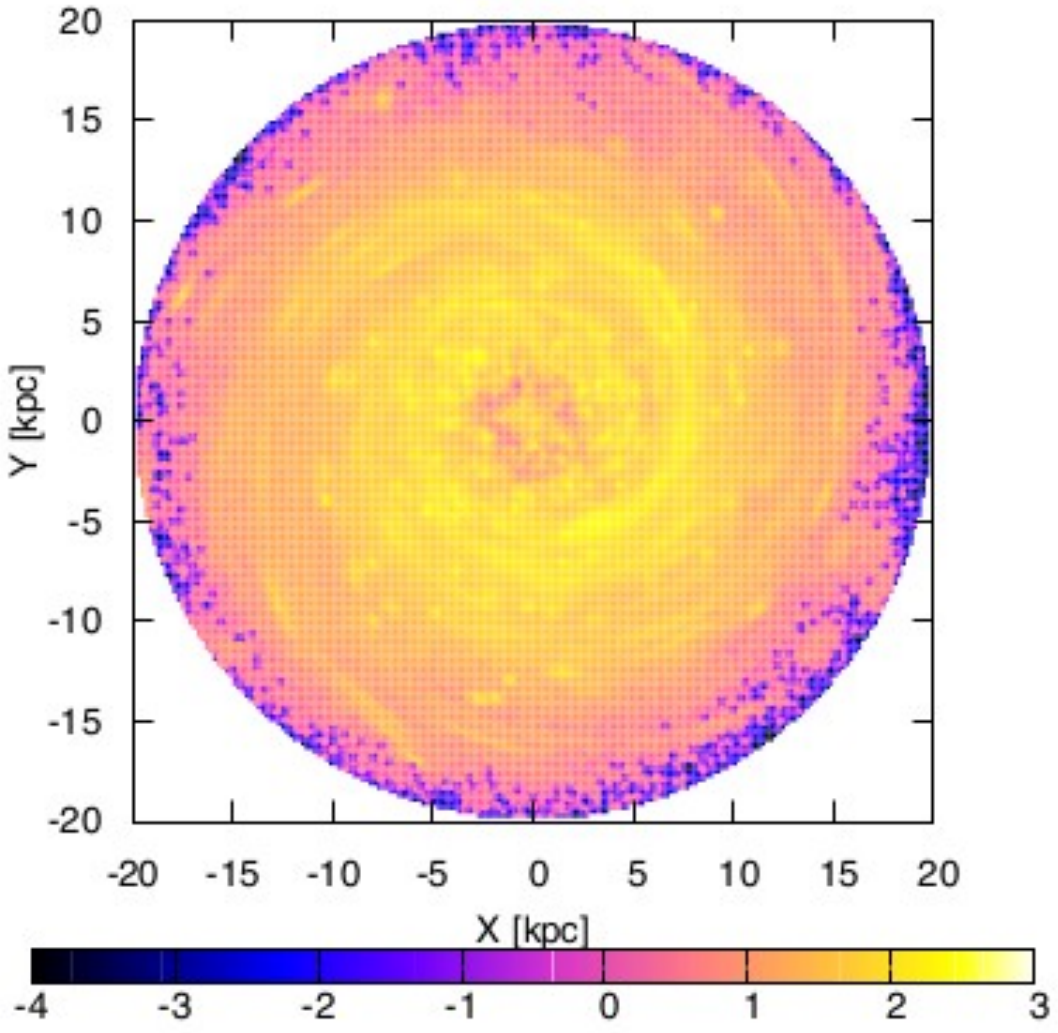
G.Giacinti and D.Semikoz, in preparation

Knee – Proton flux



G.Giacinti and D.Semikoz, in preparation

Knee – Proton flux



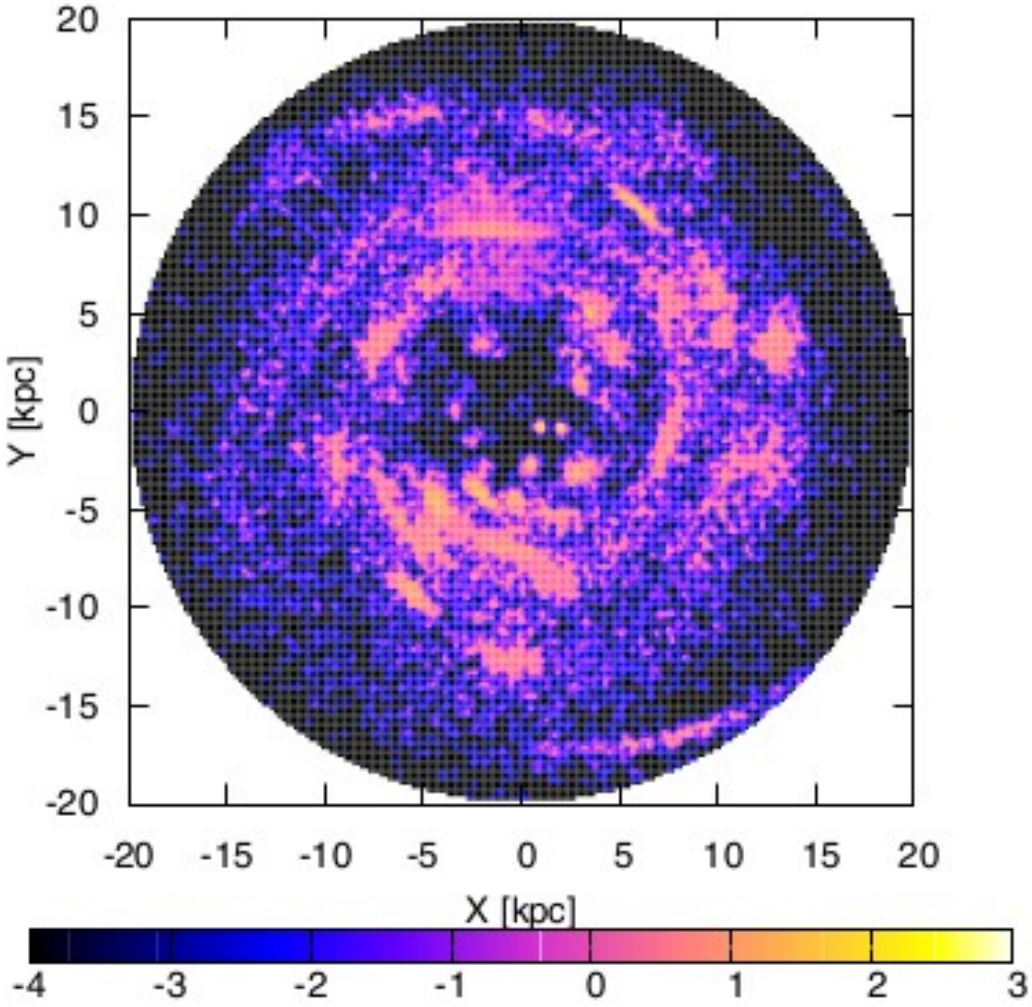
log(CR density) in the Galactic plane

1/3 of all SNe are PeVatrons (all CCSNe)

~ 'SMOOTH'? BUT MUCH MORE PATCHY THAN WITH ISO DIFF

G.Giacinti and D.Semikoz, in preparation

Knee – Proton flux



log(CR density) in the Galactic plane

1.6% of all SNe are PeVatrons (rare, extreme CCSNe in dense winds)

EXTREMELY PATCHY!!!

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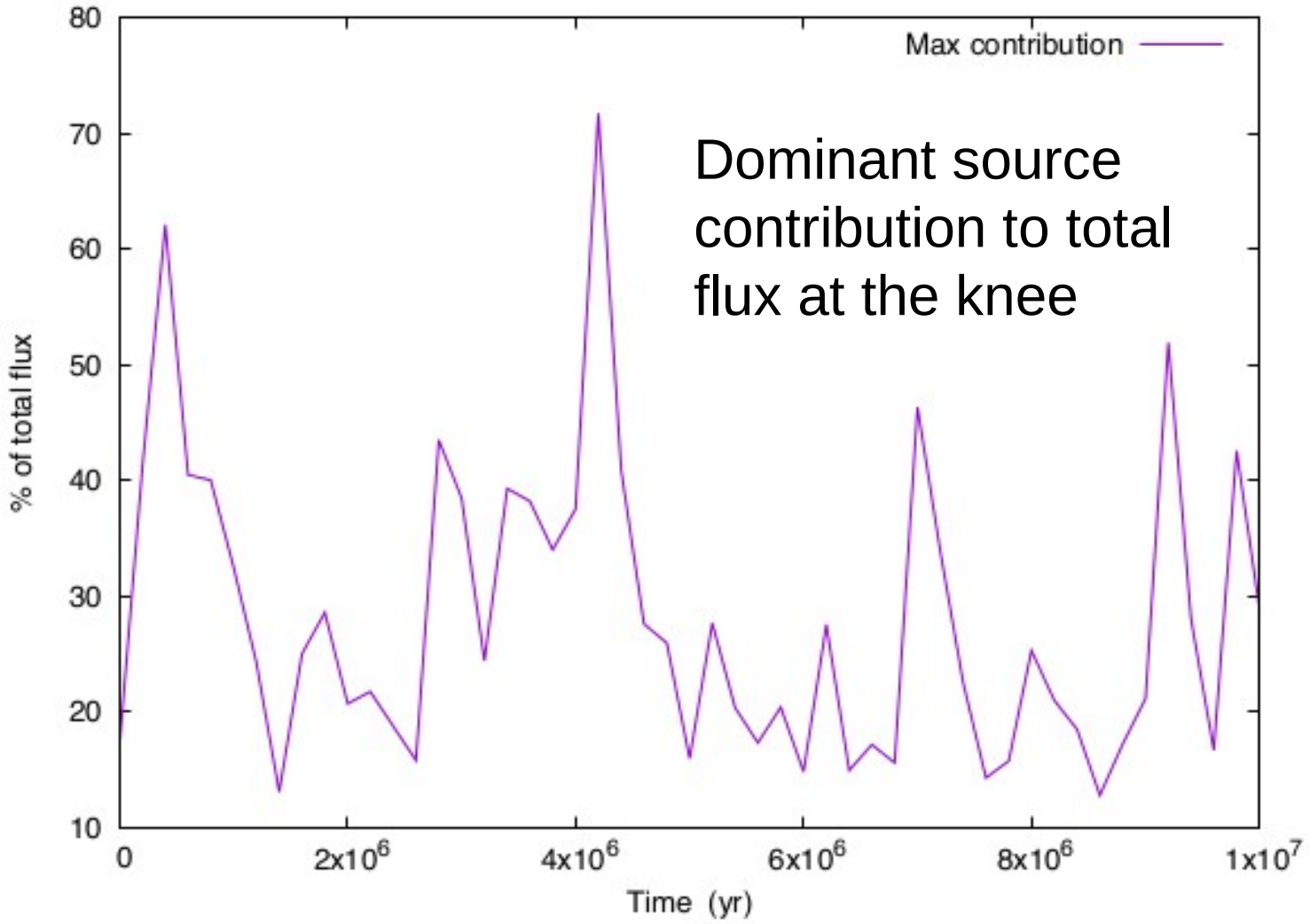
Knee – Proton flux



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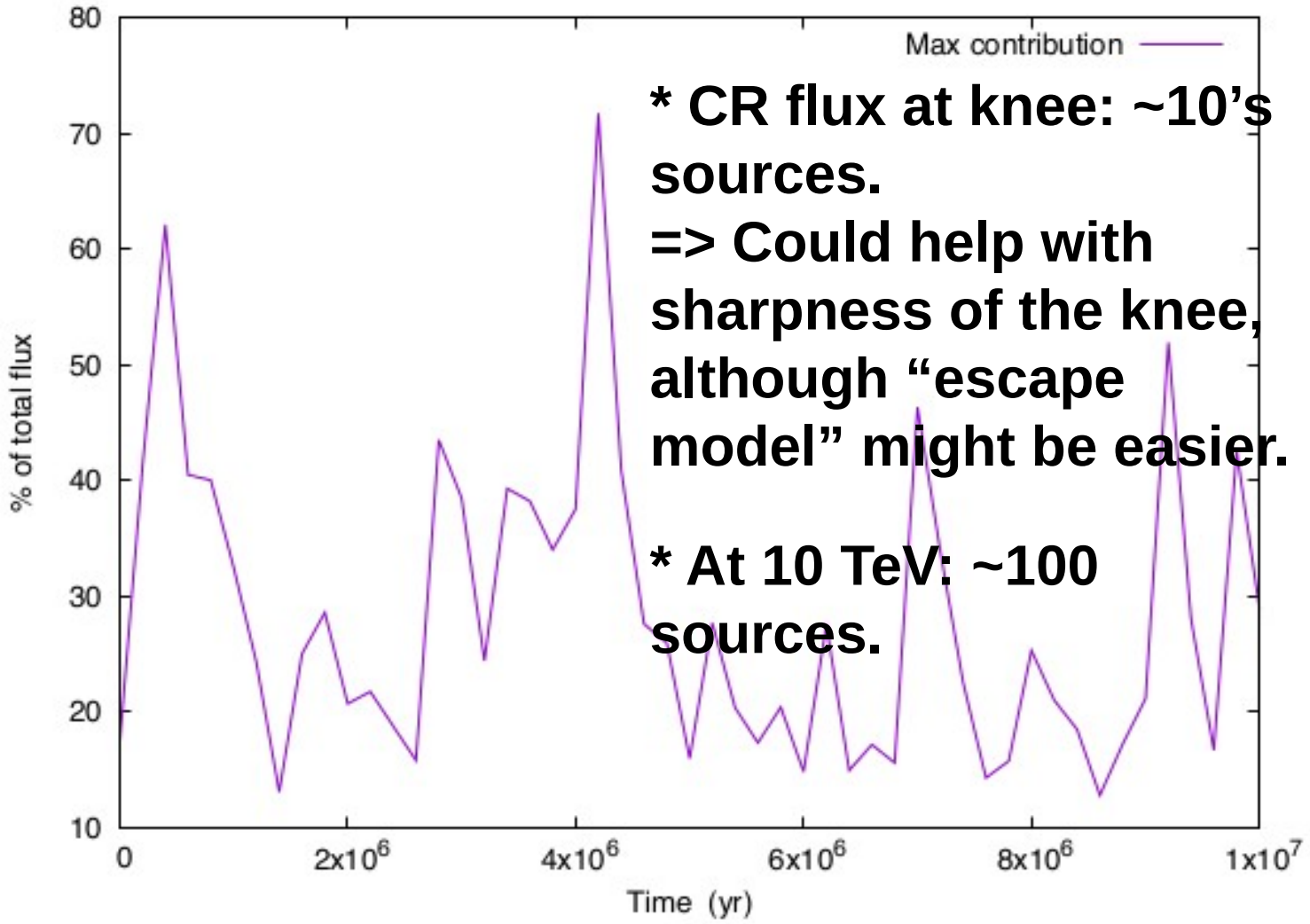
Knee – Proton flux



*** CR flux at knee: ~10's sources.**
=> Could help with sharpness of the knee, although "escape model" might be easier.

*** At 10 TeV: ~100 sources.**

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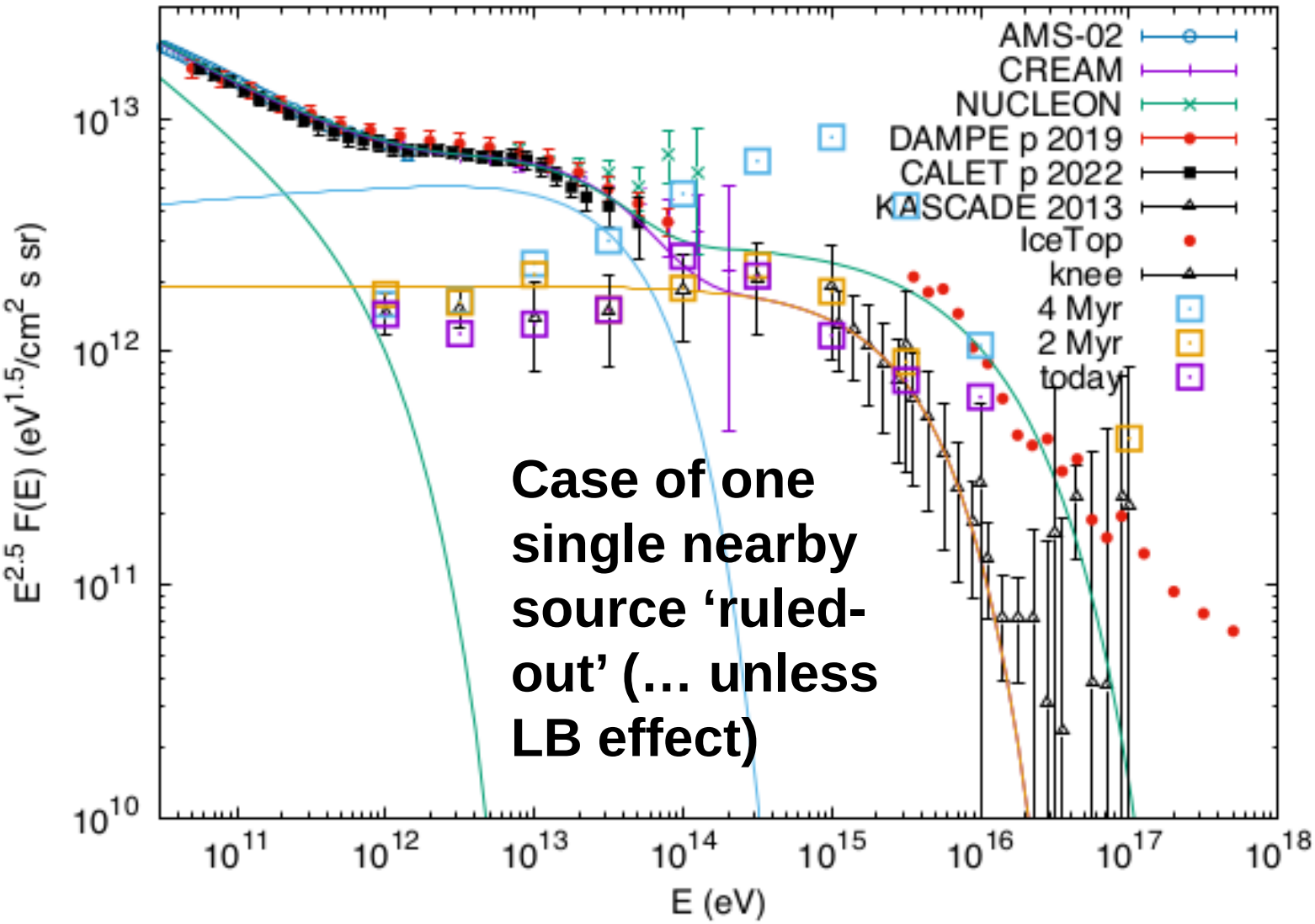
Knee – Proton flux



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Summary

- Flux at the knee is dominated by few local sources
- Flux at the knee is strongly variable
- Two classes of sources, one accelerates to ~10+ TeV, another to ~10 PeV
- Galaxy NOT uniformly filled with CRs at PeV energies (very different from GeV energies)
- Updated our escape model with this new knowledge (dynamical now) → Description of the knee.