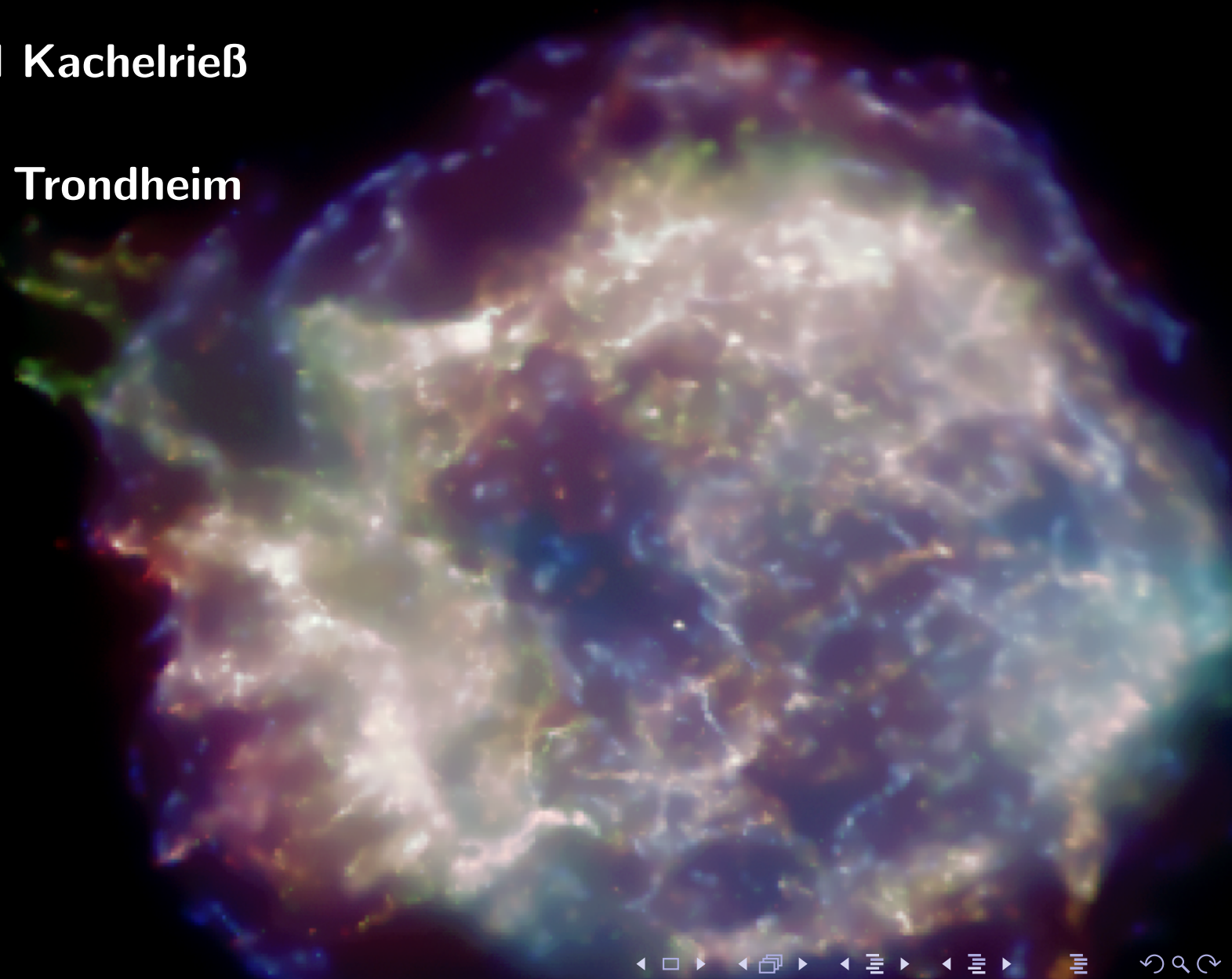
Galactic Neutrinos

Michael Kachelrieß

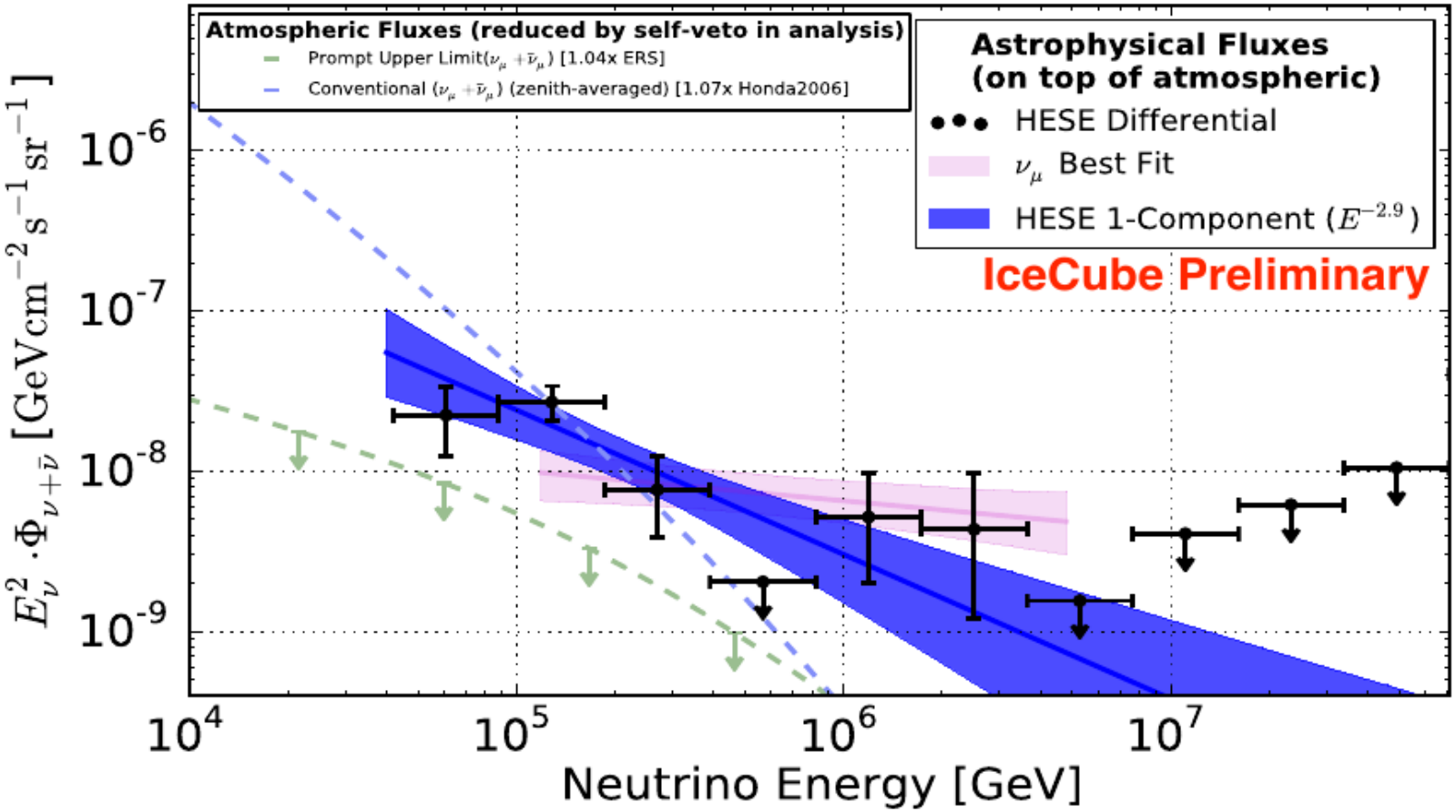
NTNU, Trondheim



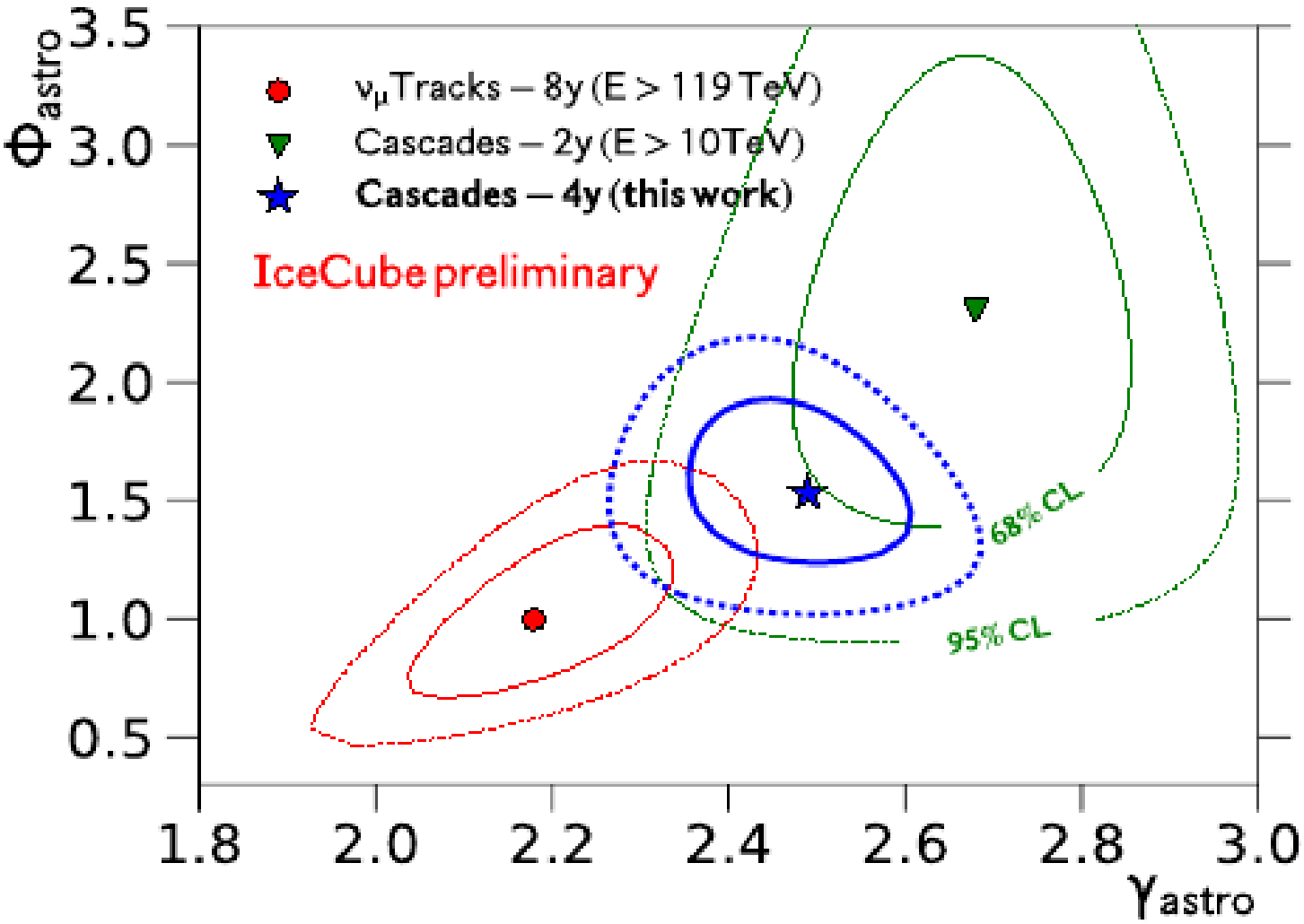
Outline of the talk

1. Introduction
   - Observations
   - Cascade limit and implications
2. Neutrinos from the Galactic CR sea – Galactic plane
3. Neutrinos from Galactic CR sources
4. Neutrinos from extended sources
   - TeV γ-ray excess in Fermi-LAT
   - Interpretations
5. Conclusions

IceCube events: Soft "low-energy" spectrum?



IceCube events: power-law fit of energy spectrum



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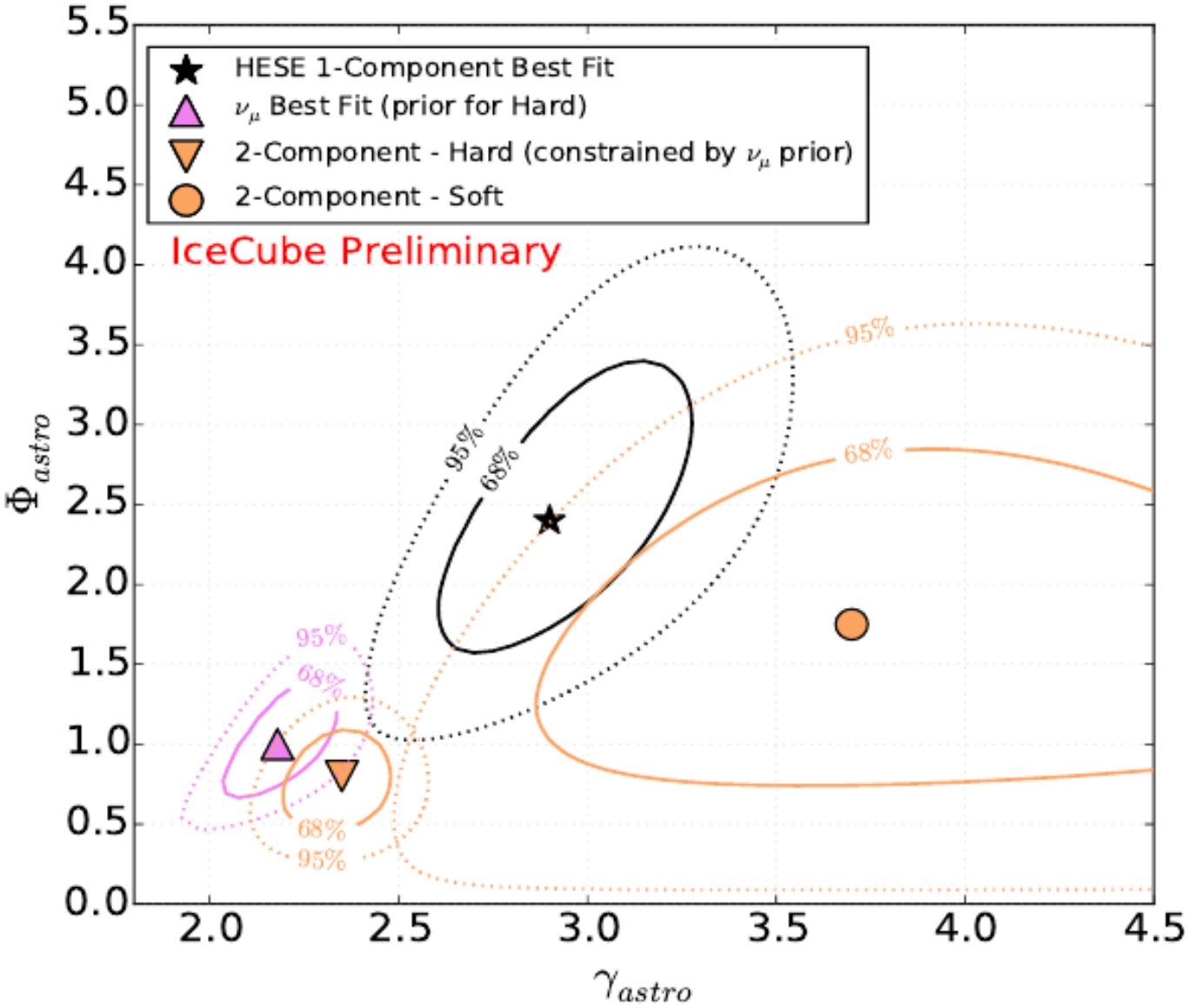
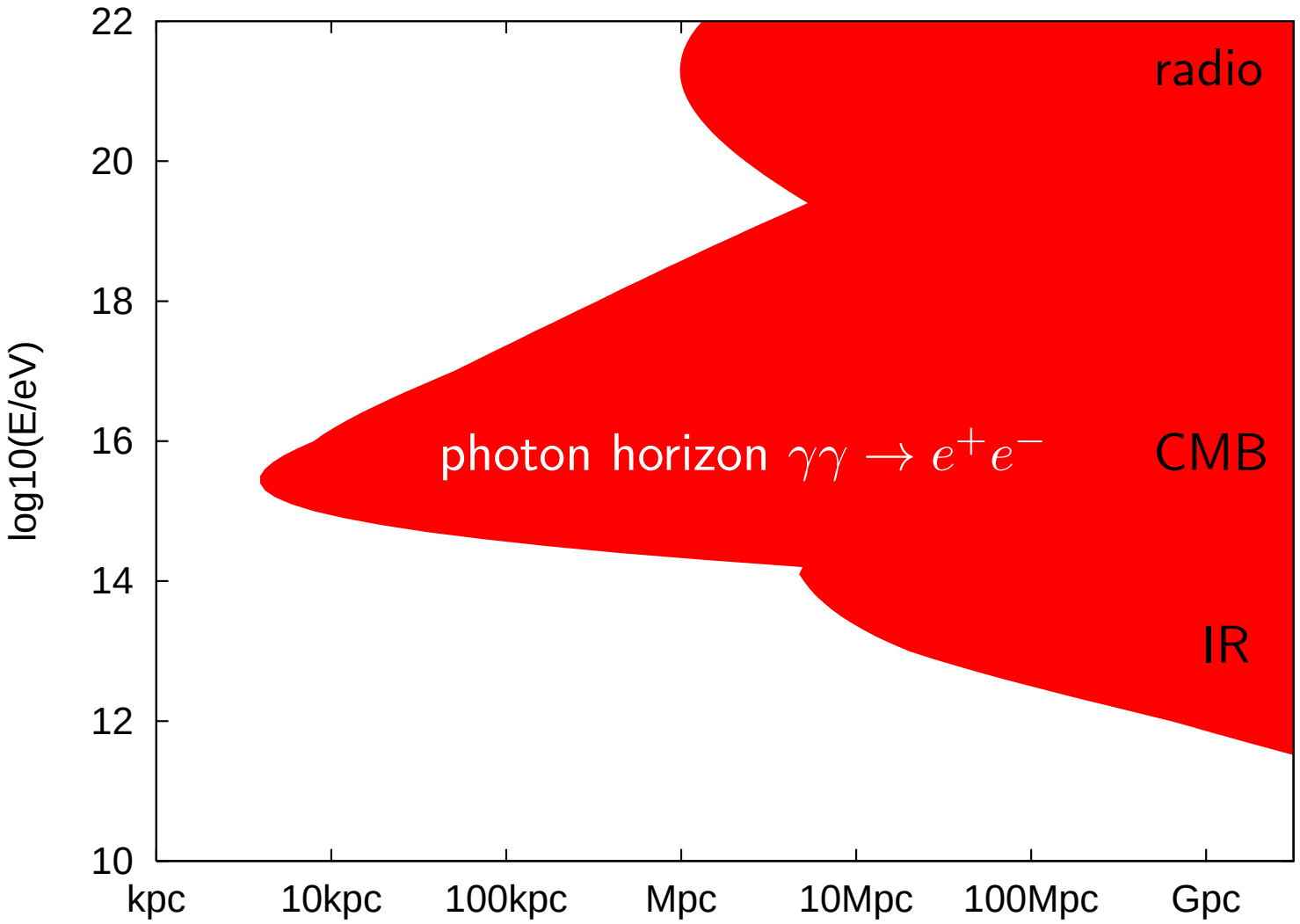
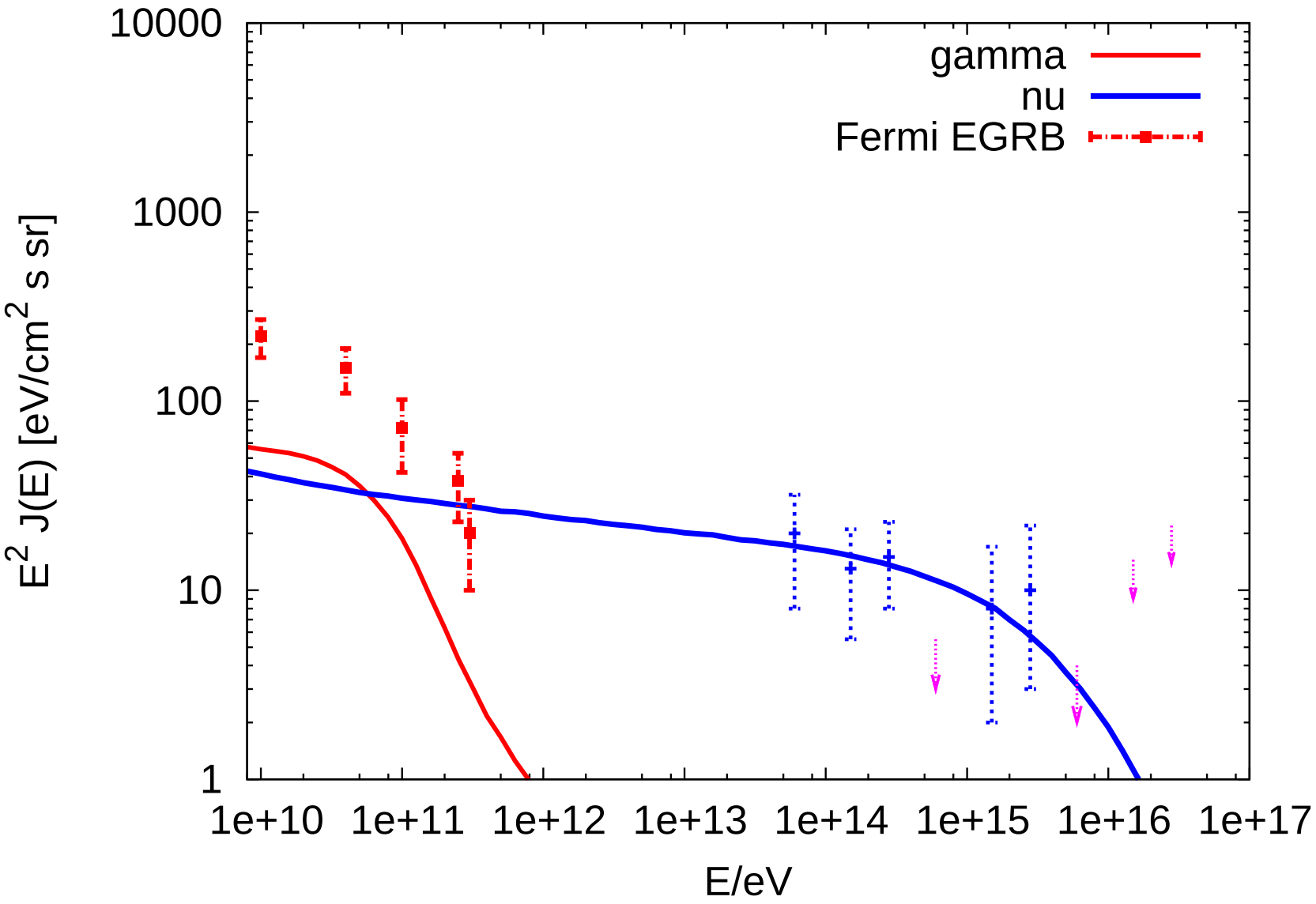


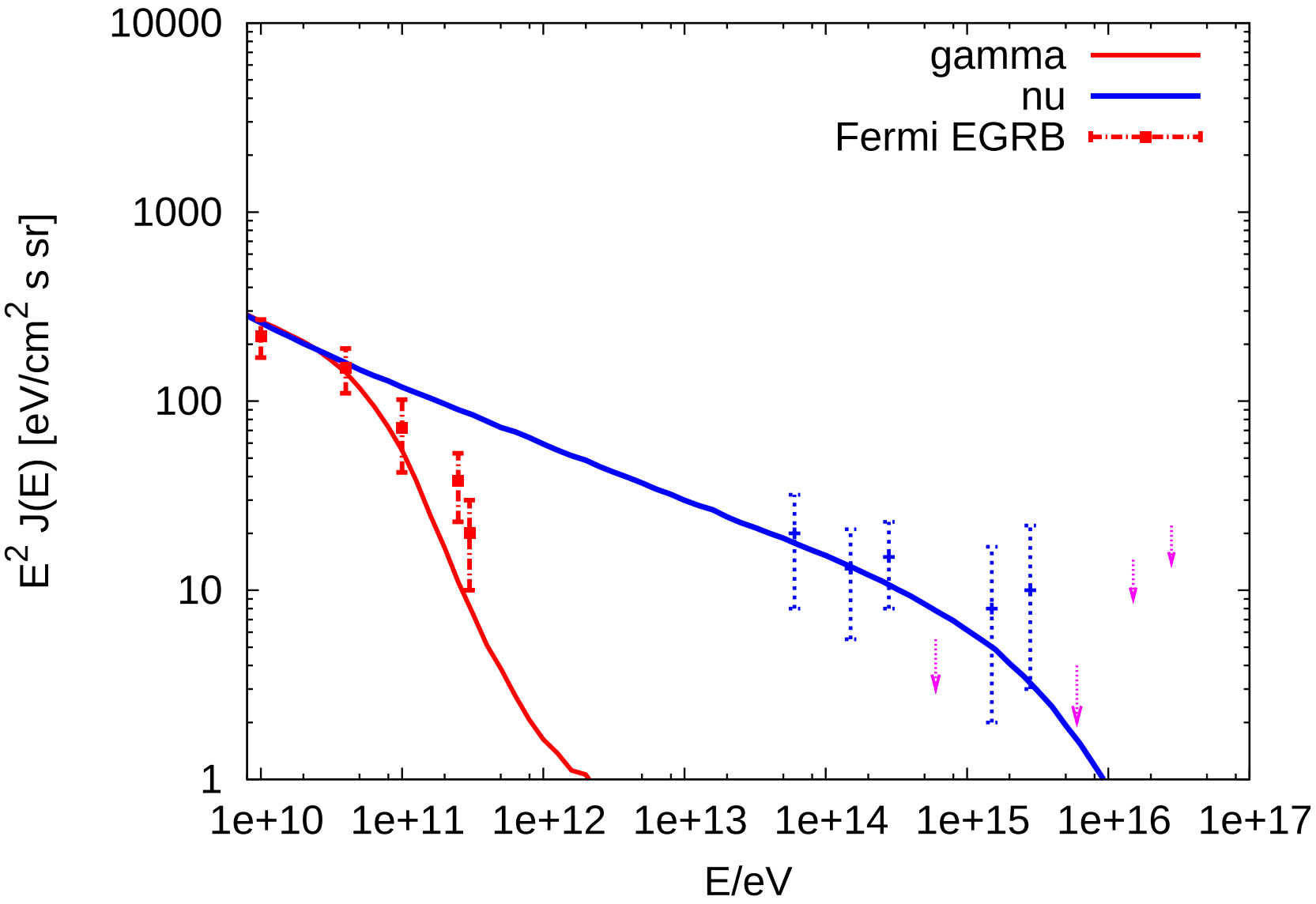
The photon horizon



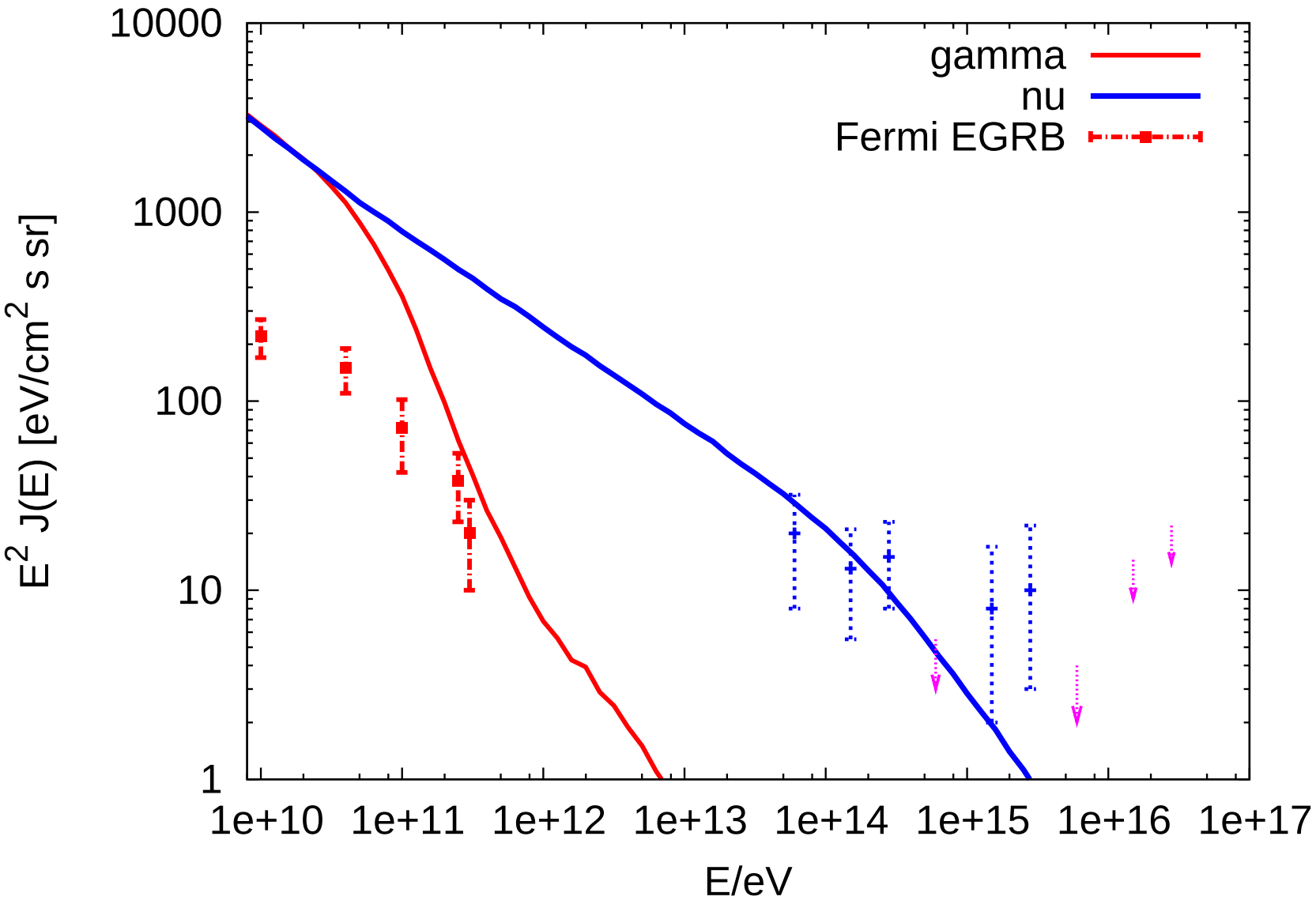
Cascade limit: $\alpha = 2.1$



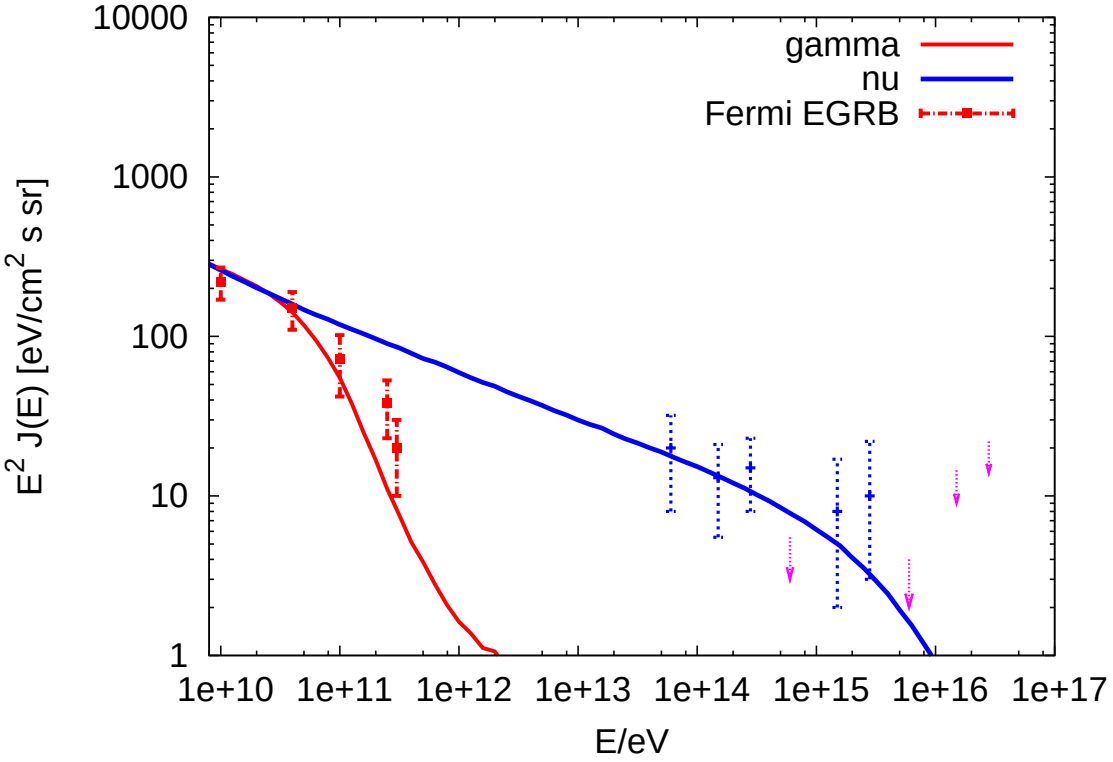
Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



Cascade limit:

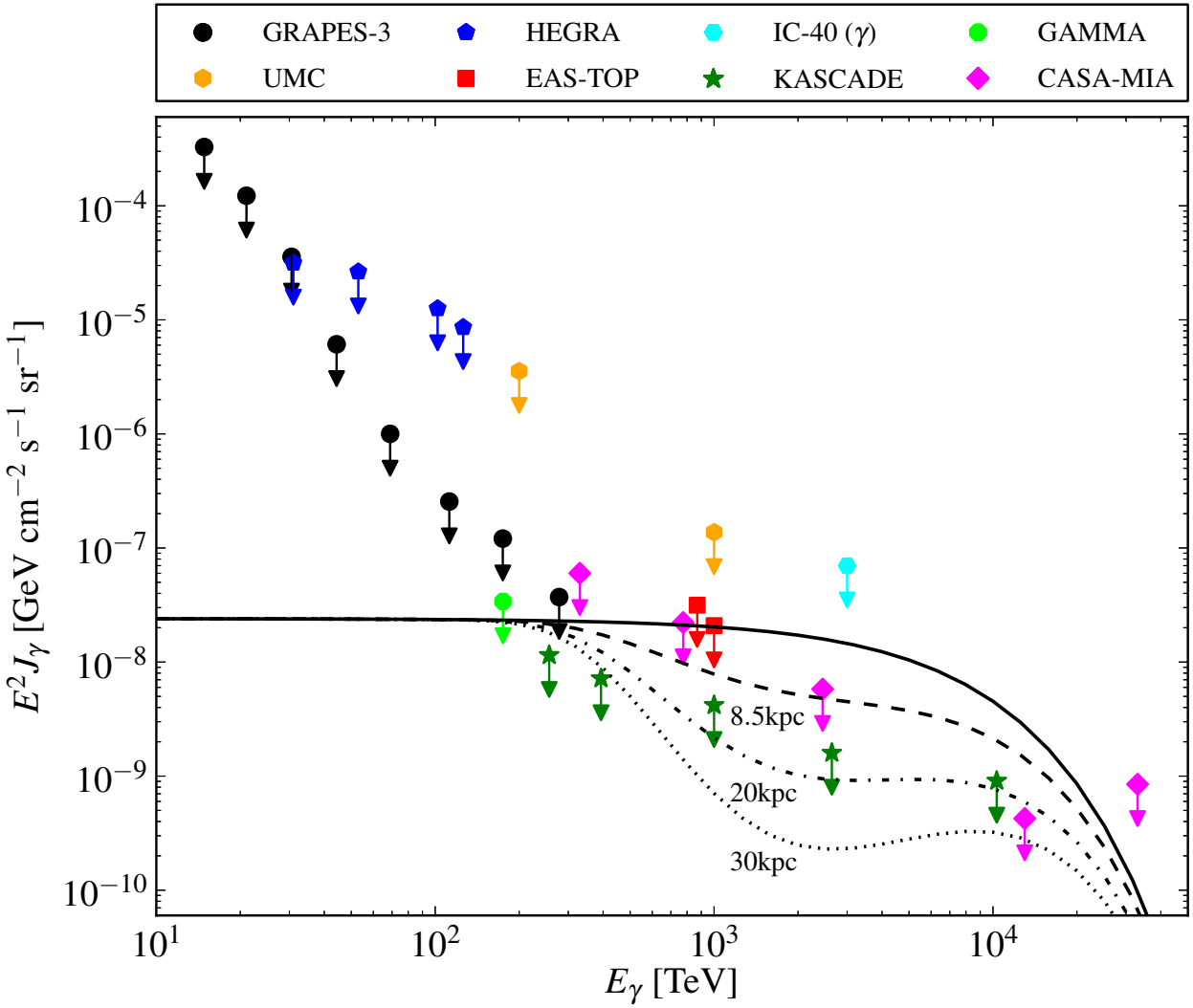


Slope $\alpha \gtrsim 2.2$

- requires "hidden sources" or
- Galactic origin

(Isotropic) photon limits

[Ahlers, Murase '13]



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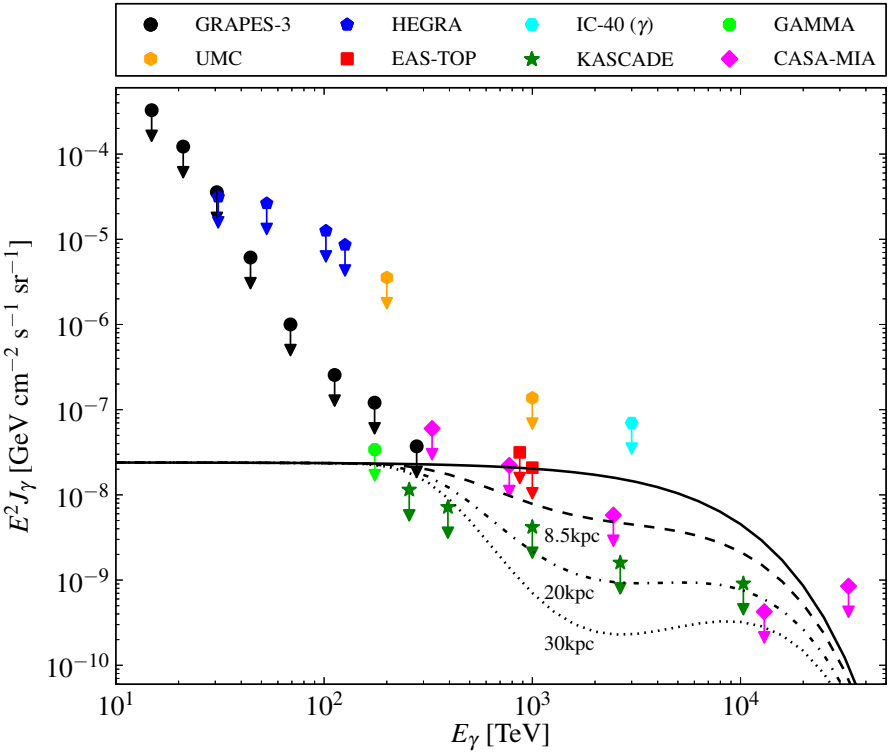
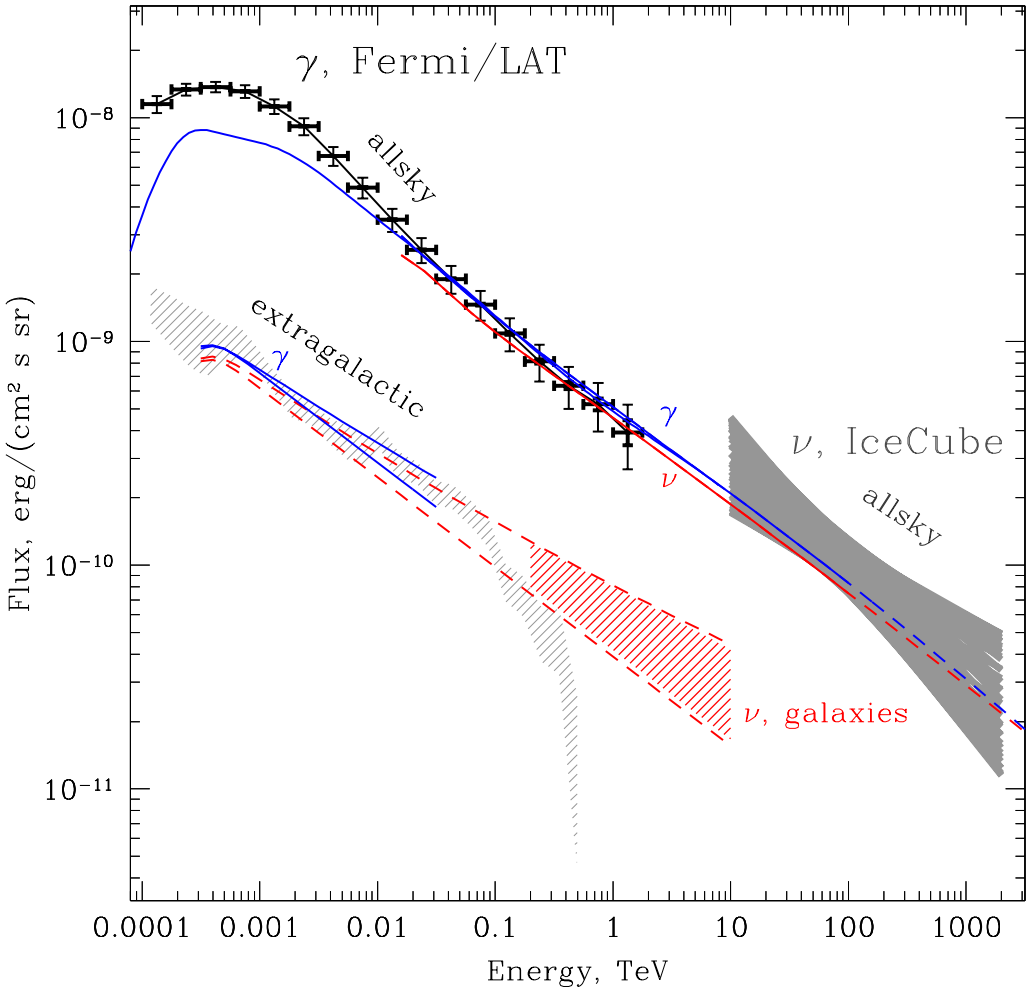


KASCADE limits

- reanalysed '17 and increased

Hints for a Galactic plane contribution?

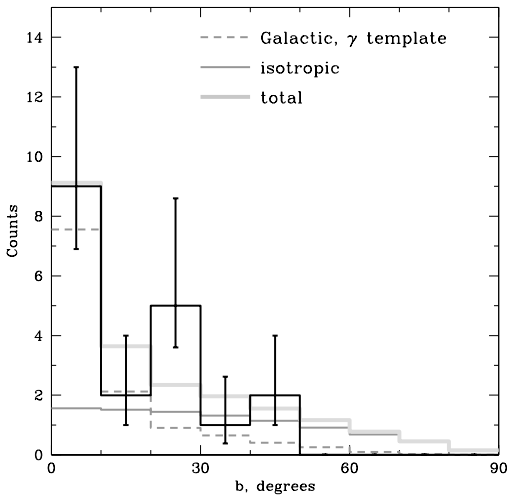
[*Neronov, Semikoz '14,'15*]



Hints for a Galactic plane contribution?

[*Neronov, Semikoz '14,'15*]

- Neronov & Semikoz '15: Galactic latitude distribution of 4yr IceCube data with $> 100\,\text{TeV}$ inconsistent at 3σ with isotropy



- Palladino & Vissani '15: Two component fit, soft Galactic $E^{-2.4}$ 25% Galactic contribution

Expectation:

- CR interactions with gas in Galactic plane give guaranteed ν flux

  . [*Berezinsky, Smirnov '75*]

  . [*Gaggero et al. '15, Pagliaroli, Evoli, Villante '17, . . .*]

- agreement: 10-20% Galactic contribution at 100 TeV

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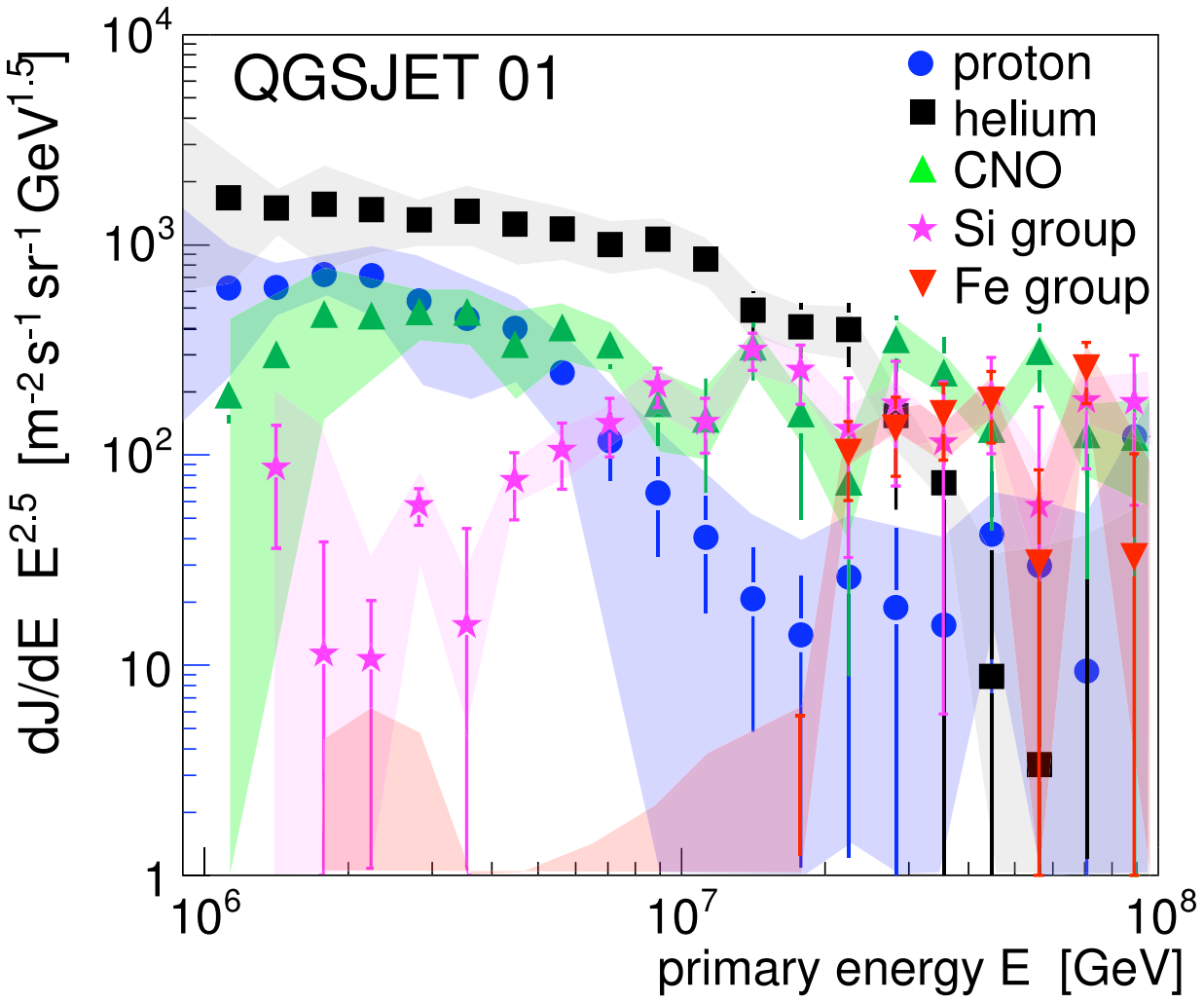
However, uncertainties are very large:

- elemental composition unclear, but $Z_\nu \propto A^{1-\gamma}$
- CRs locally measured
- close to knee diffusion may be unreliable
- gas density

Uncertainties: CR composition

Kascade-Grande: dependenc on interaction model



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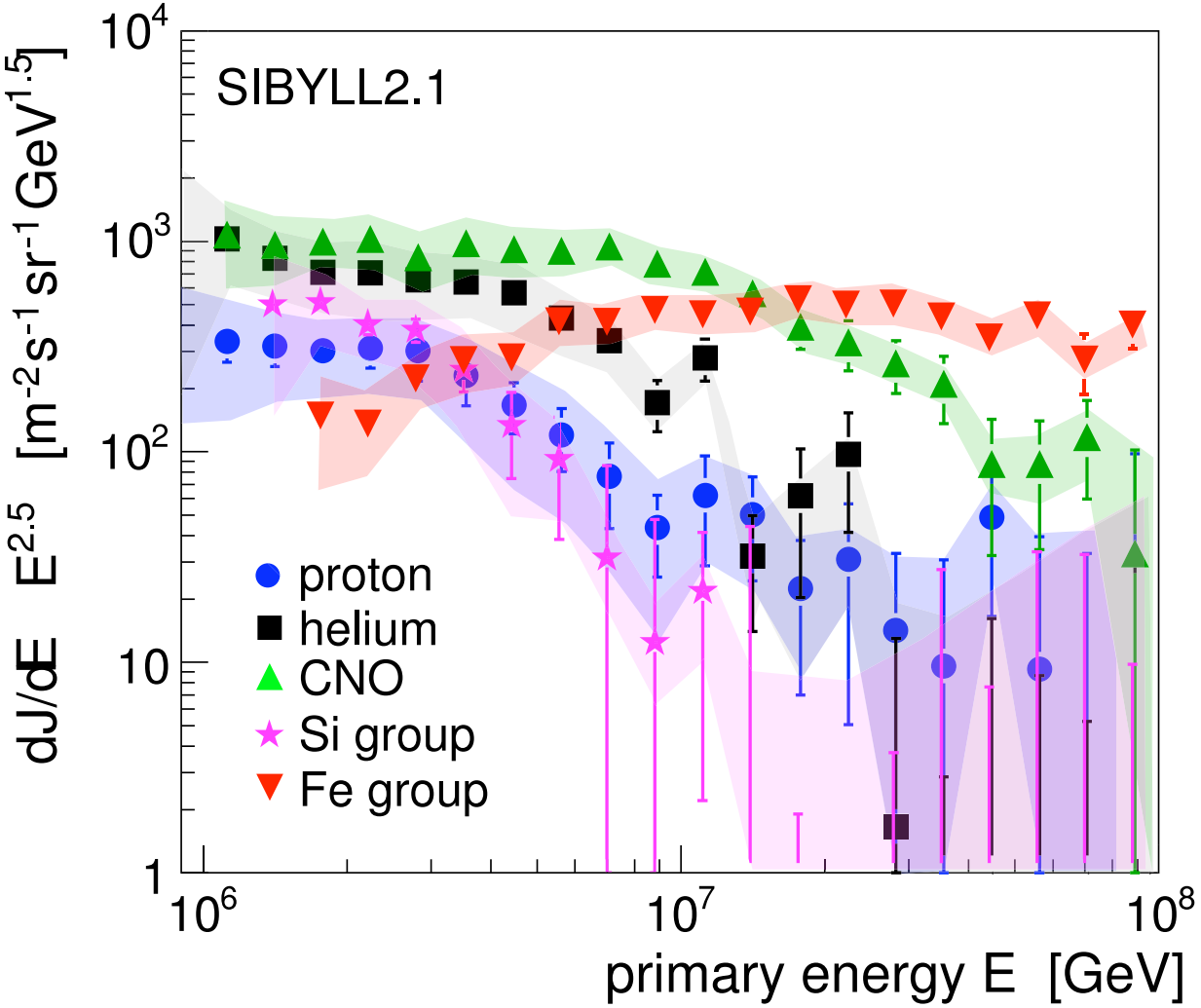

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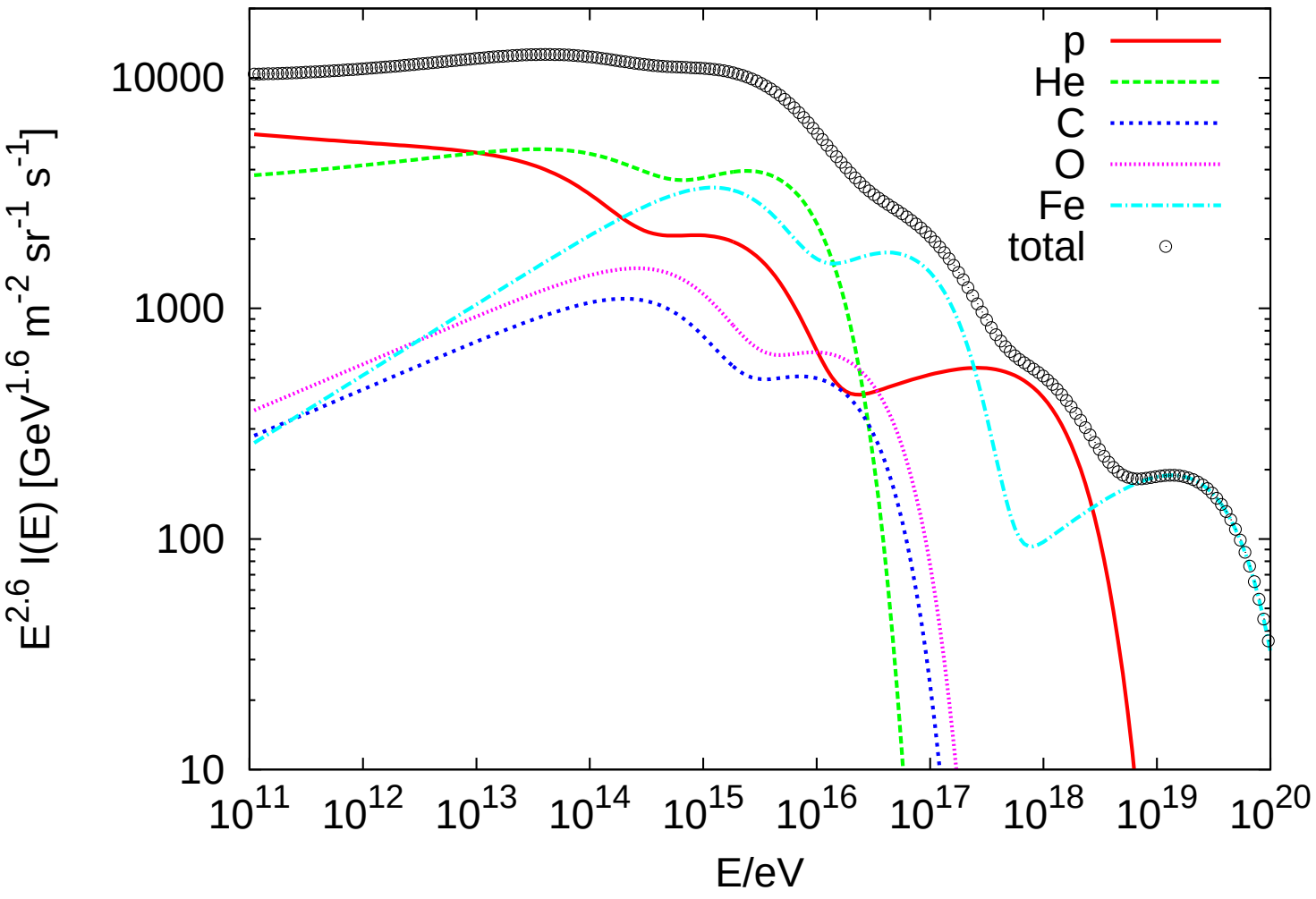
[*Gaisser, Stanev & Tilav '13*]



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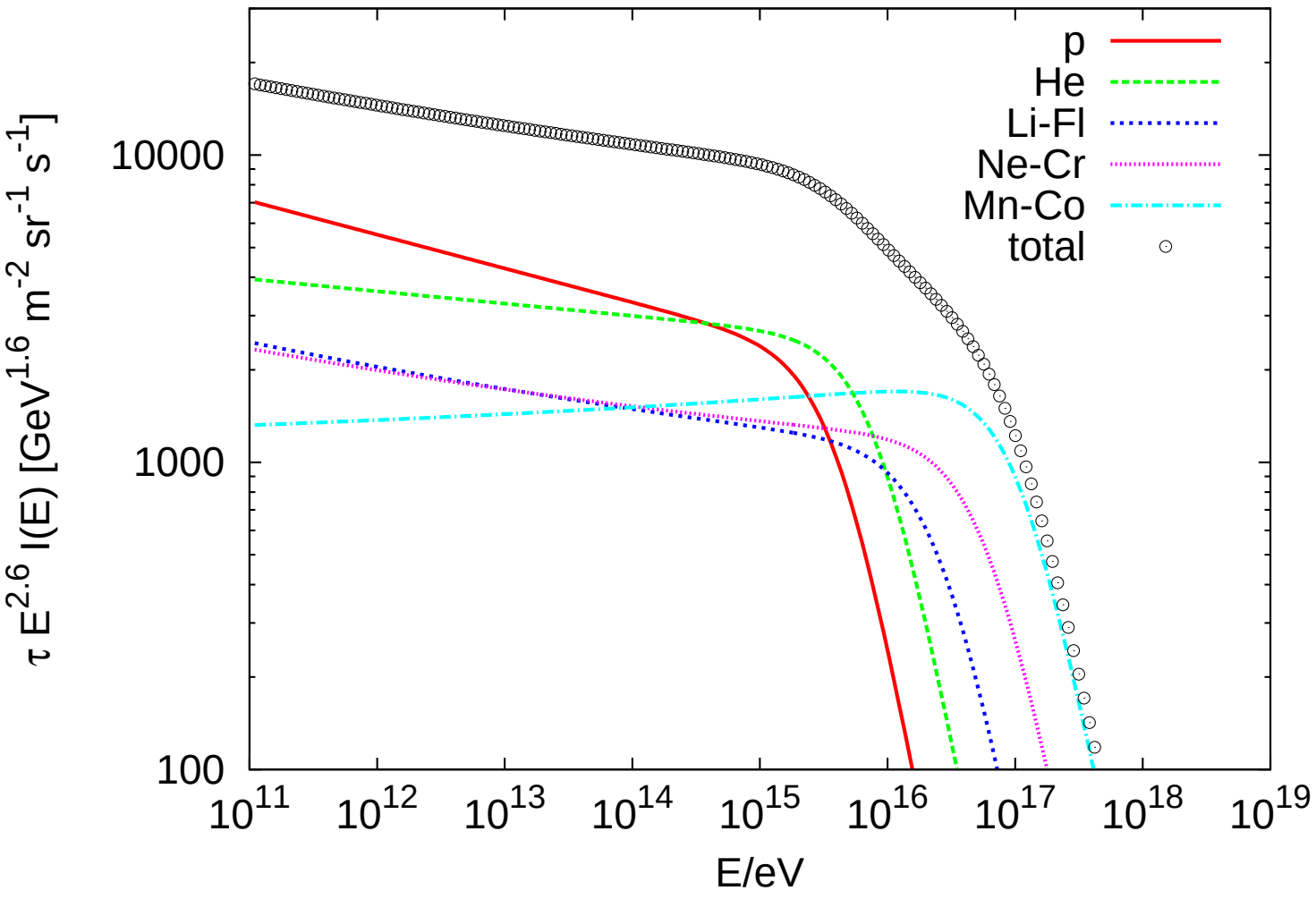
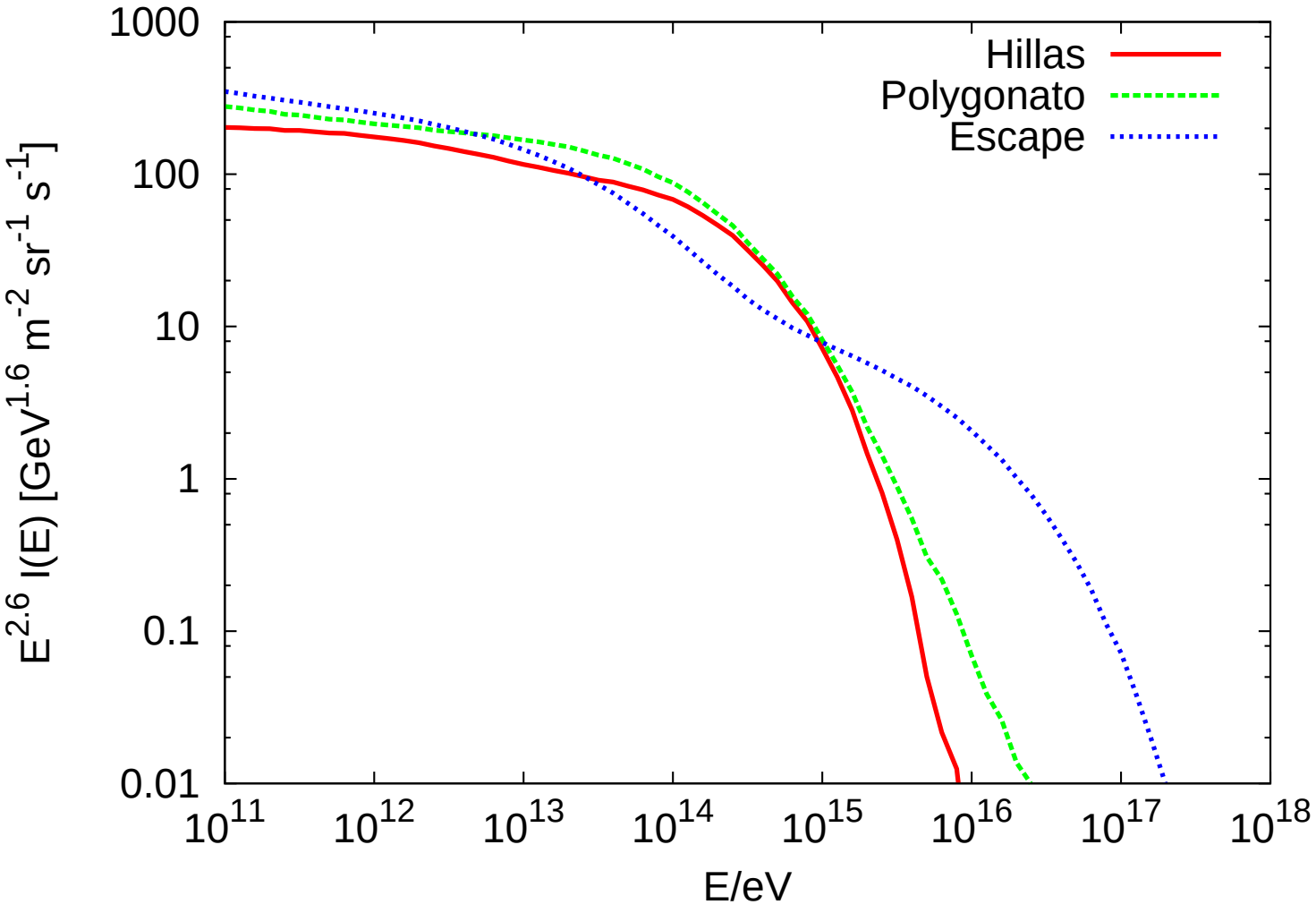
[*Hörandel '0?*]



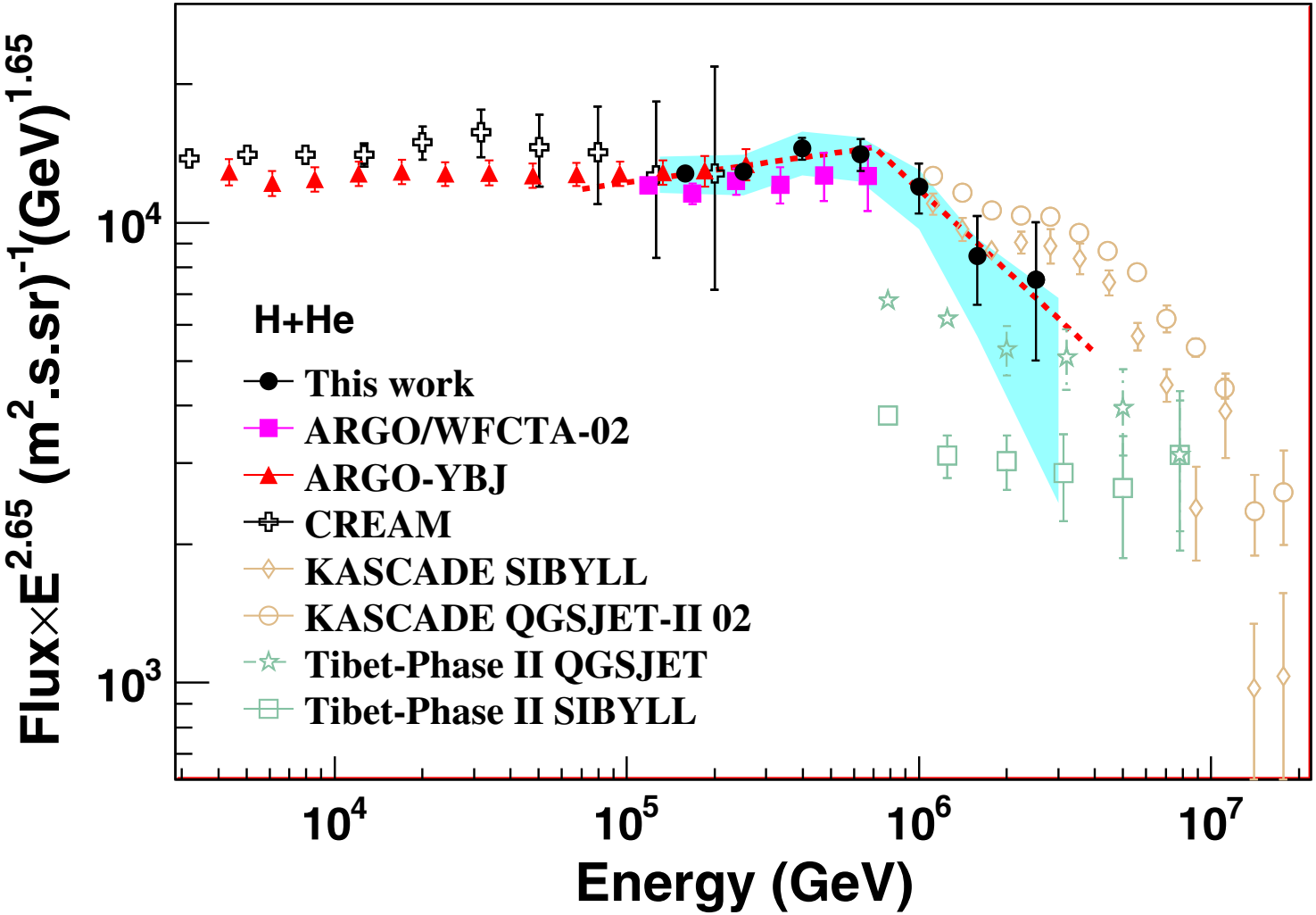
Resulting ν fluxes ($\tau = 1$ at PeV)

[MK, Ostapchenko '14]



Uncertainties: CR composition

ARGO-YBJ: position of "p+He knee" $\simeq 700$ TeV



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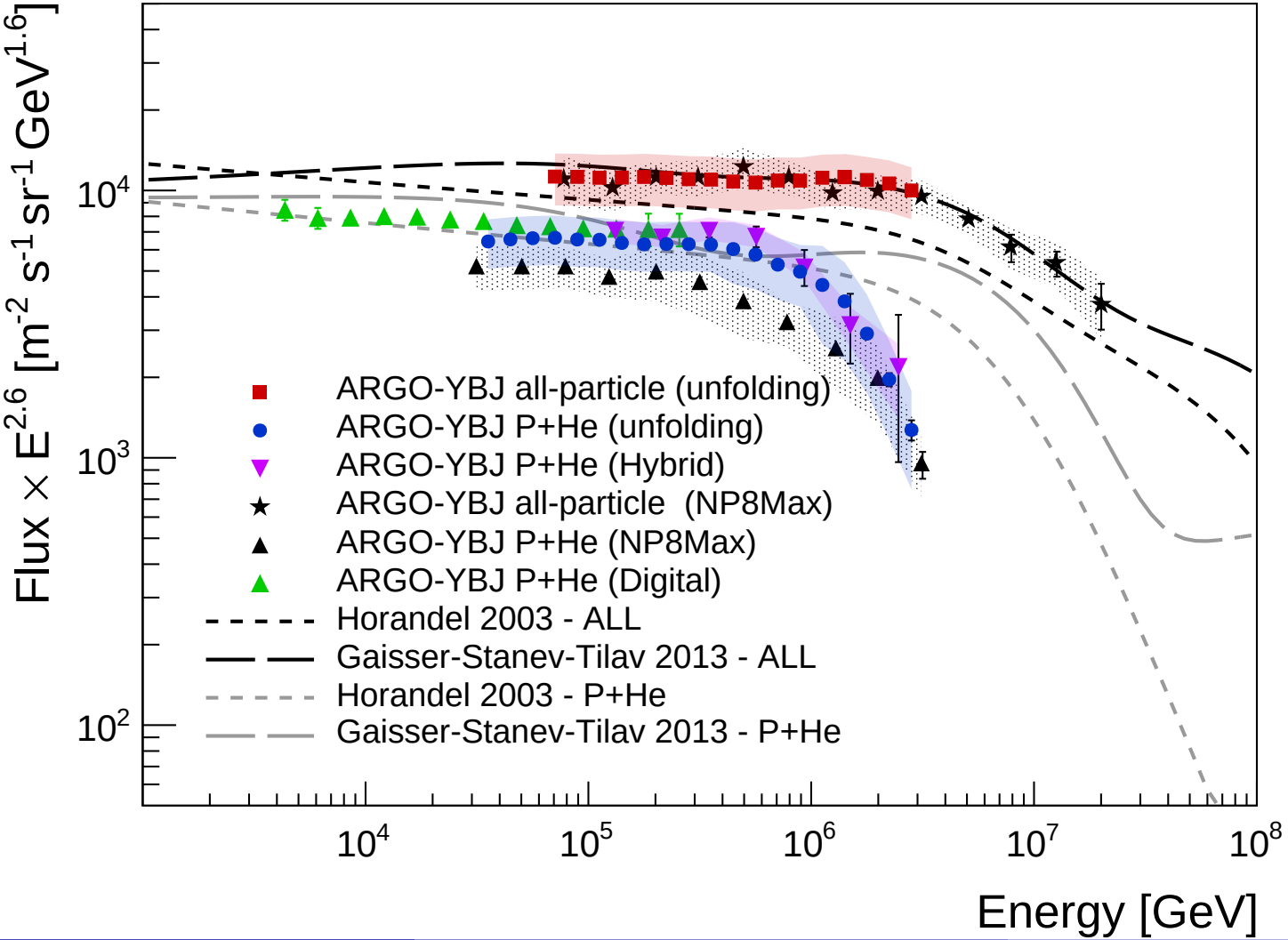

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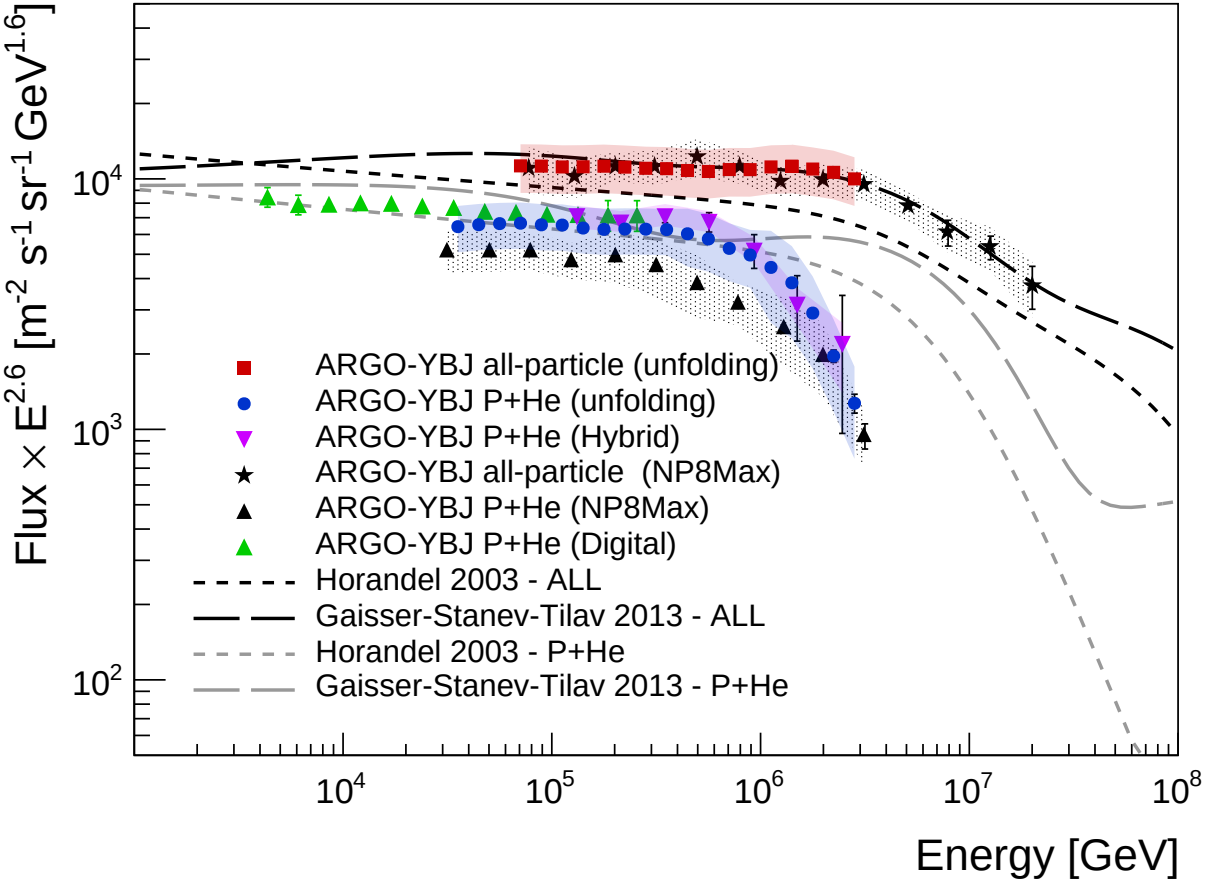

- neutrino knee at $\simeq 20$–40 TeV

Uncertainties: diffusion approach

- diffusion picture requires $R_L(E_*) \ll L_{\rm coh}/(2\pi)$
- for $L_{\rm coh} \sim 50\,$pc and $B \sim {\rm few}\mu$G: $E_* \simeq 10^{16}\,$eV

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- LOFAR: $l_{\rm coh} \lesssim 10\,$pc in disc
- diffusion has to be anisotropic [*Giacinti, MK, Semikoz '18*]
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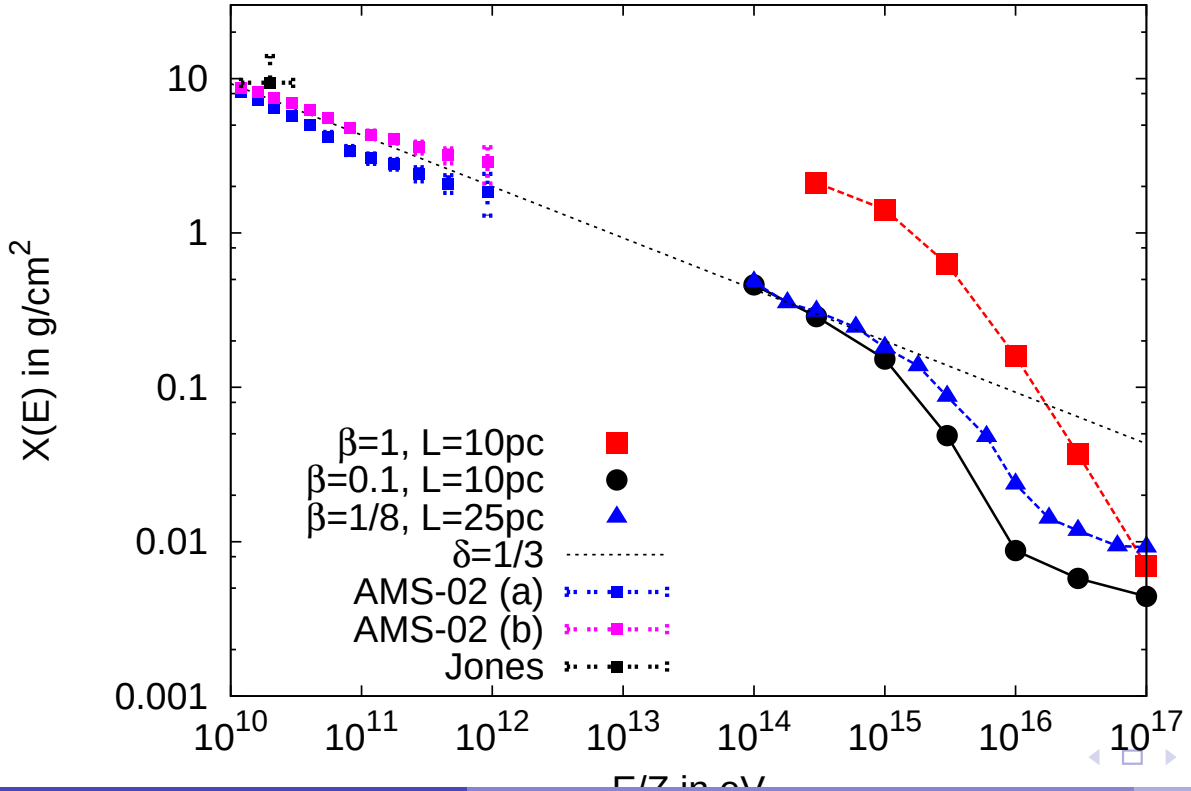

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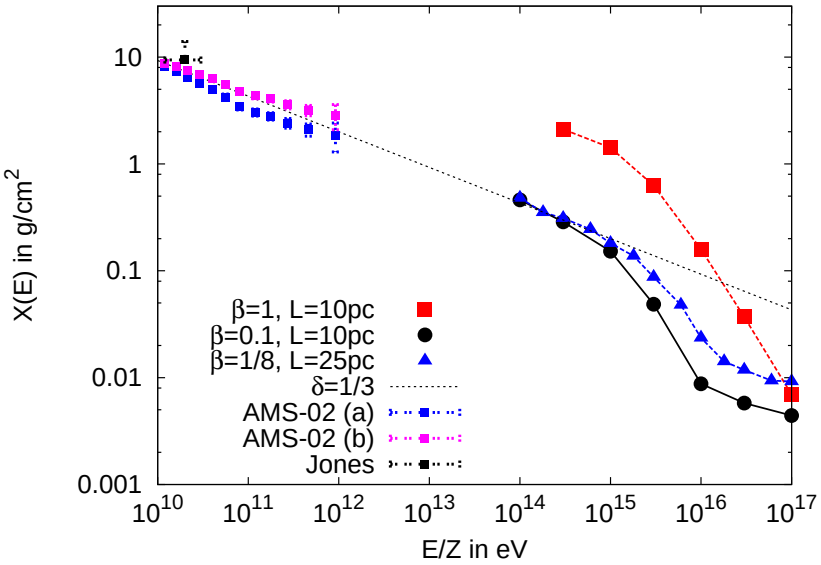
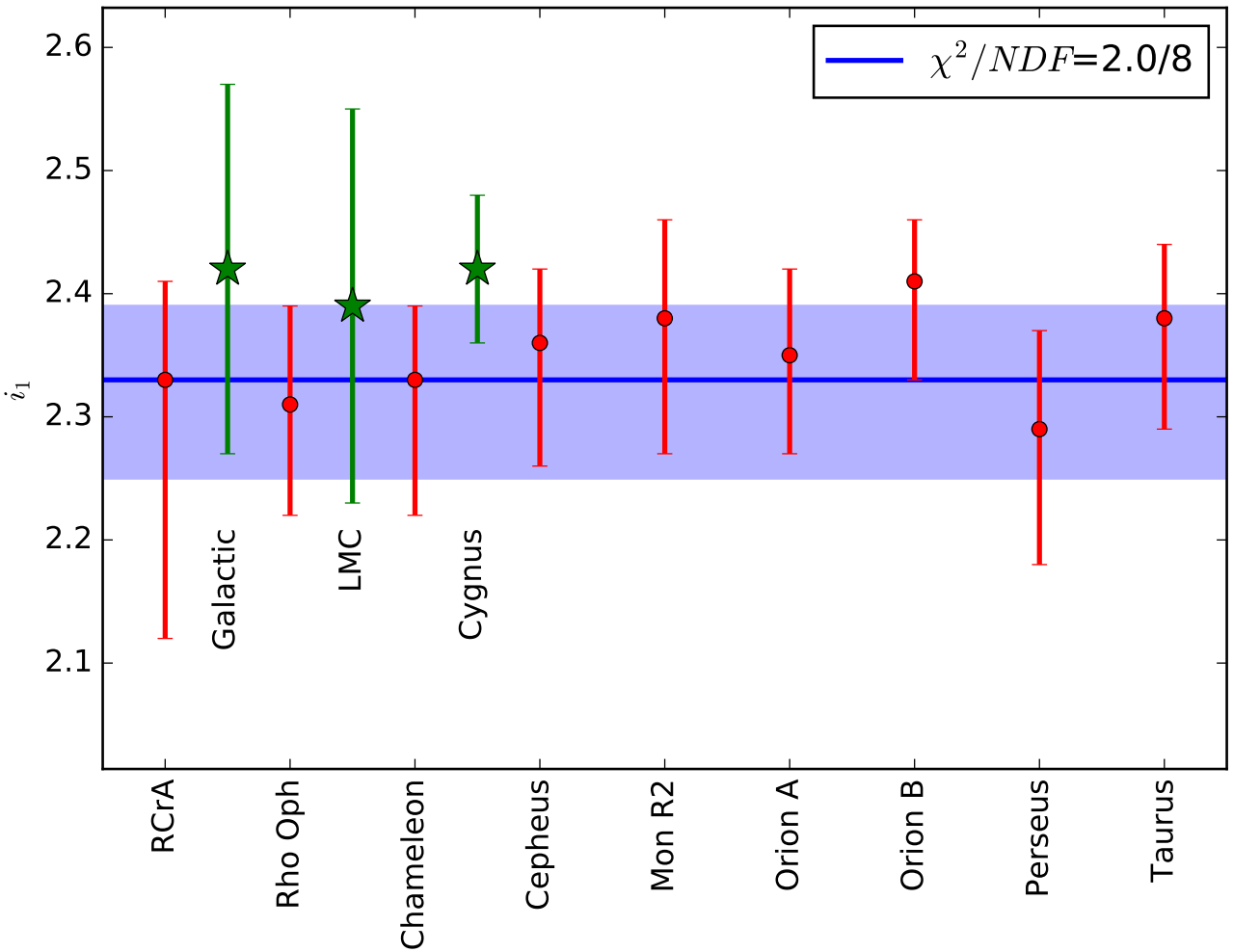


$\Rightarrow$ reduced τ above few$\sim 10^{15}\,$eV

Uncertainties: deviations from local spectrum

- CR slope from molecular clouds: $\alpha \simeq 2.4$ [Neronov, Malyshev, Semikoz '17]



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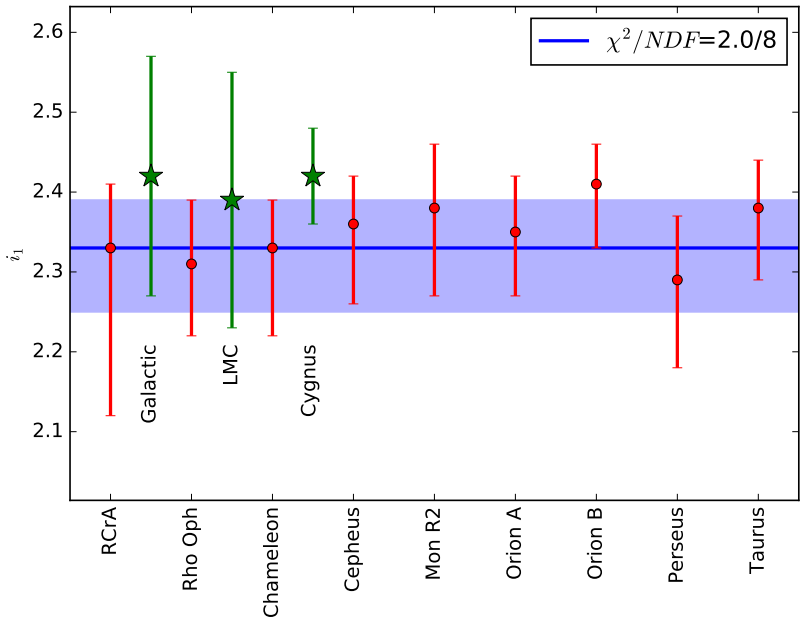
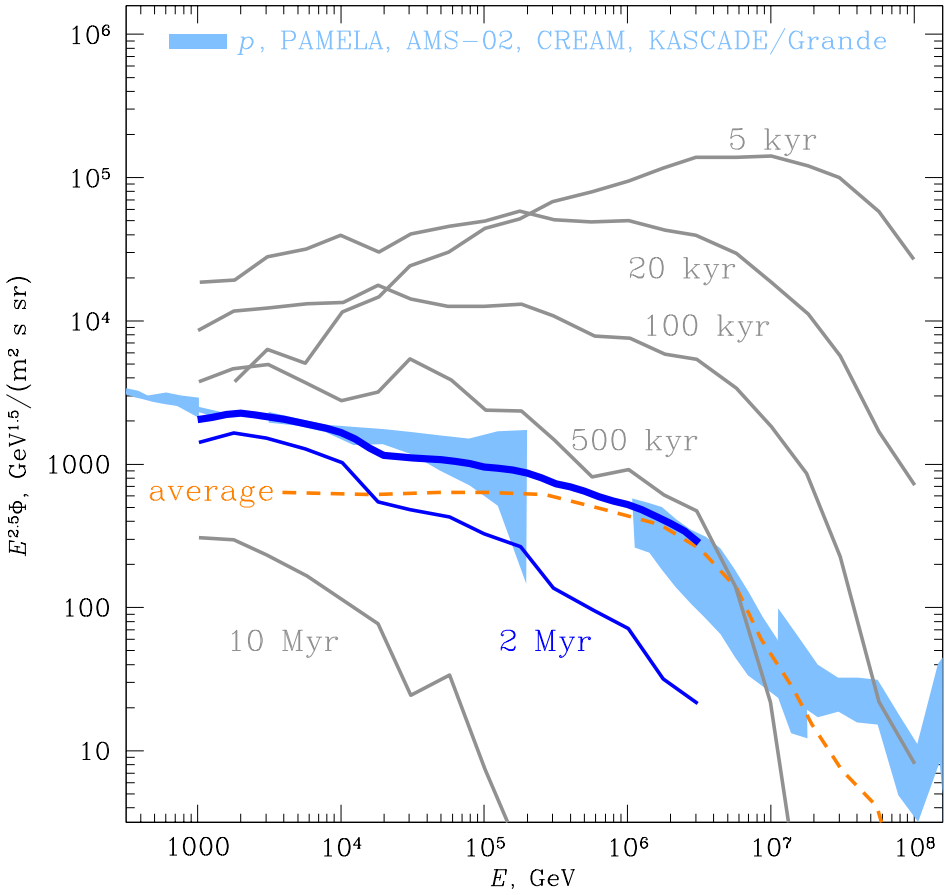


- agrees with local slope of nuclei (and $\delta = 1/3$).
- deviation of $\alpha_p \simeq 2.7$ vs $\alpha_{\rm nuc} \simeq 2.5$ local effect?

Uncertainties: deviation from local spectrum

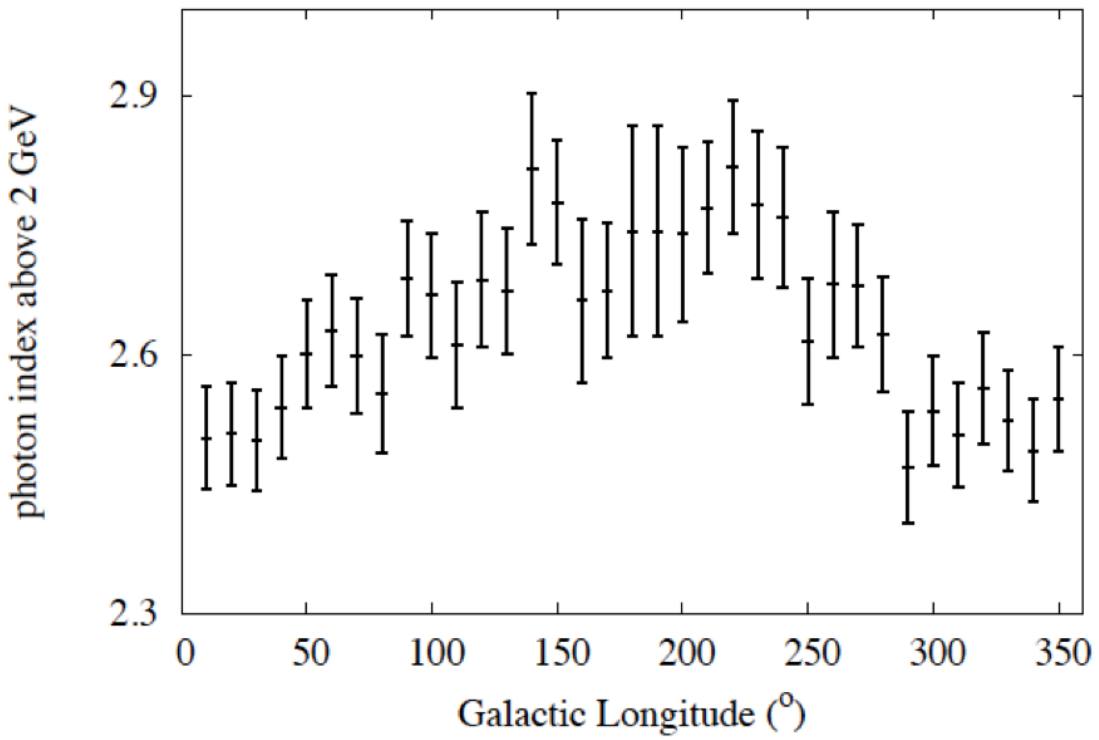
- explanations: local source

[MK, Neronov, Semikoz '15]



Uncertainties: deviation from local spectrum

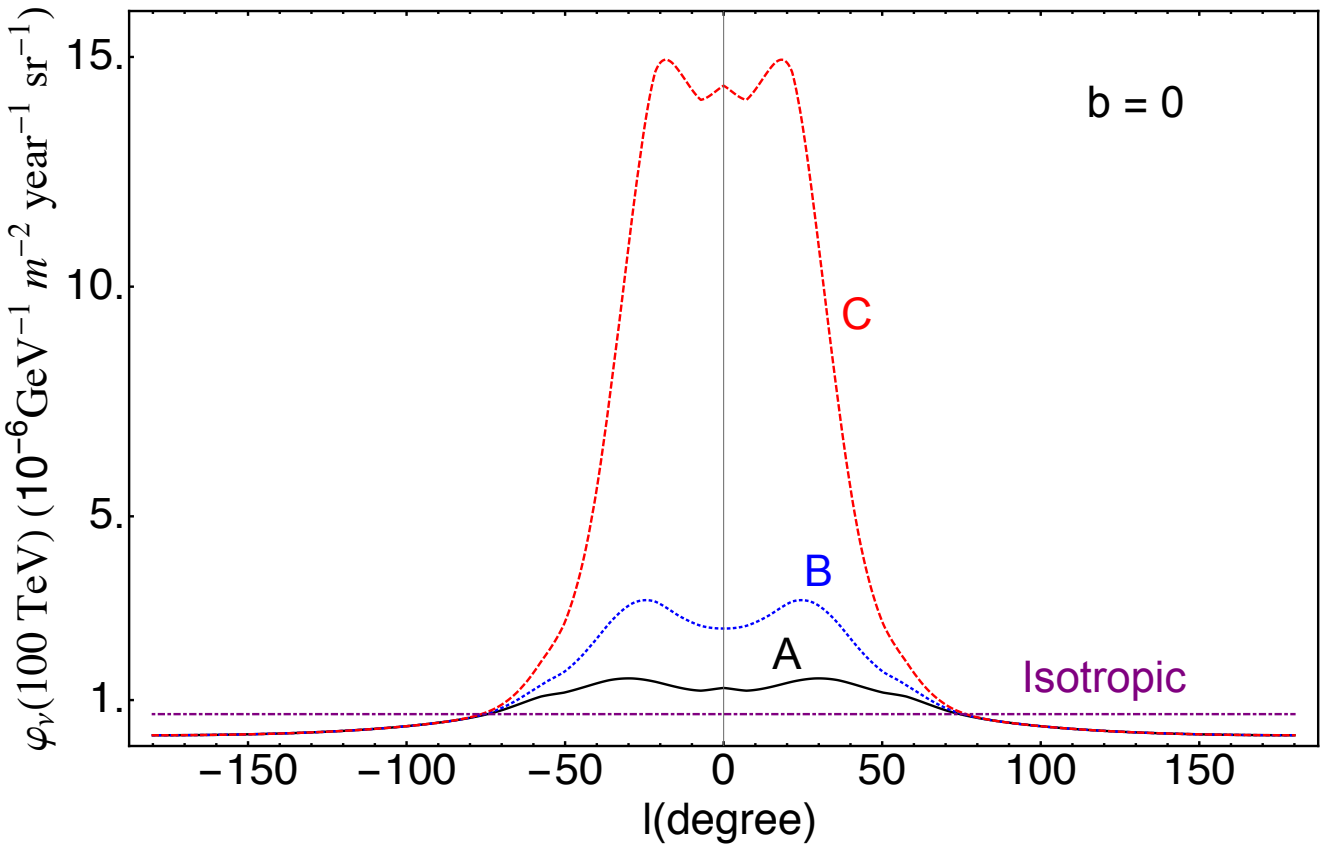
- explanations: local source [*MK, Neronov, Semikoz '15*]
- diffusion depends on ρ, $D = D(\rho)$



[*Yang, Aharonian, Evoli '16*]

Detection prospects:

[*Pagliaroli, Evoli, Villante '16*]



A: local; B: $\propto n_{\mathrm{sources}}$, C: $\propto E^{\delta(r)}$

Detection prospects:

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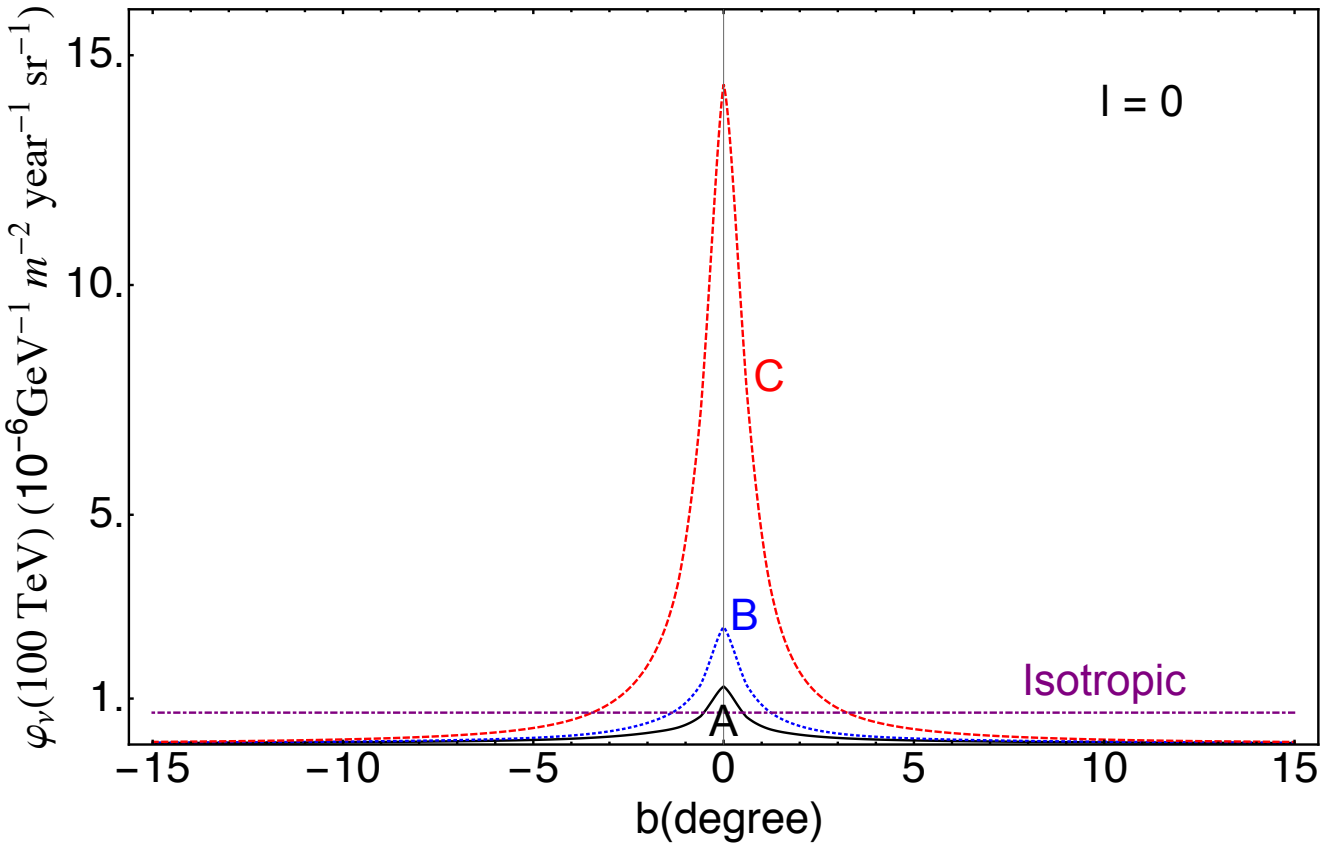

- Close to GC: always an excess rel. extragal.
- detectability requires good angular resolution

Galactic sources

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  - many sources, large confinement times

  $\Rightarrow$ average CR sea plus few recent sources

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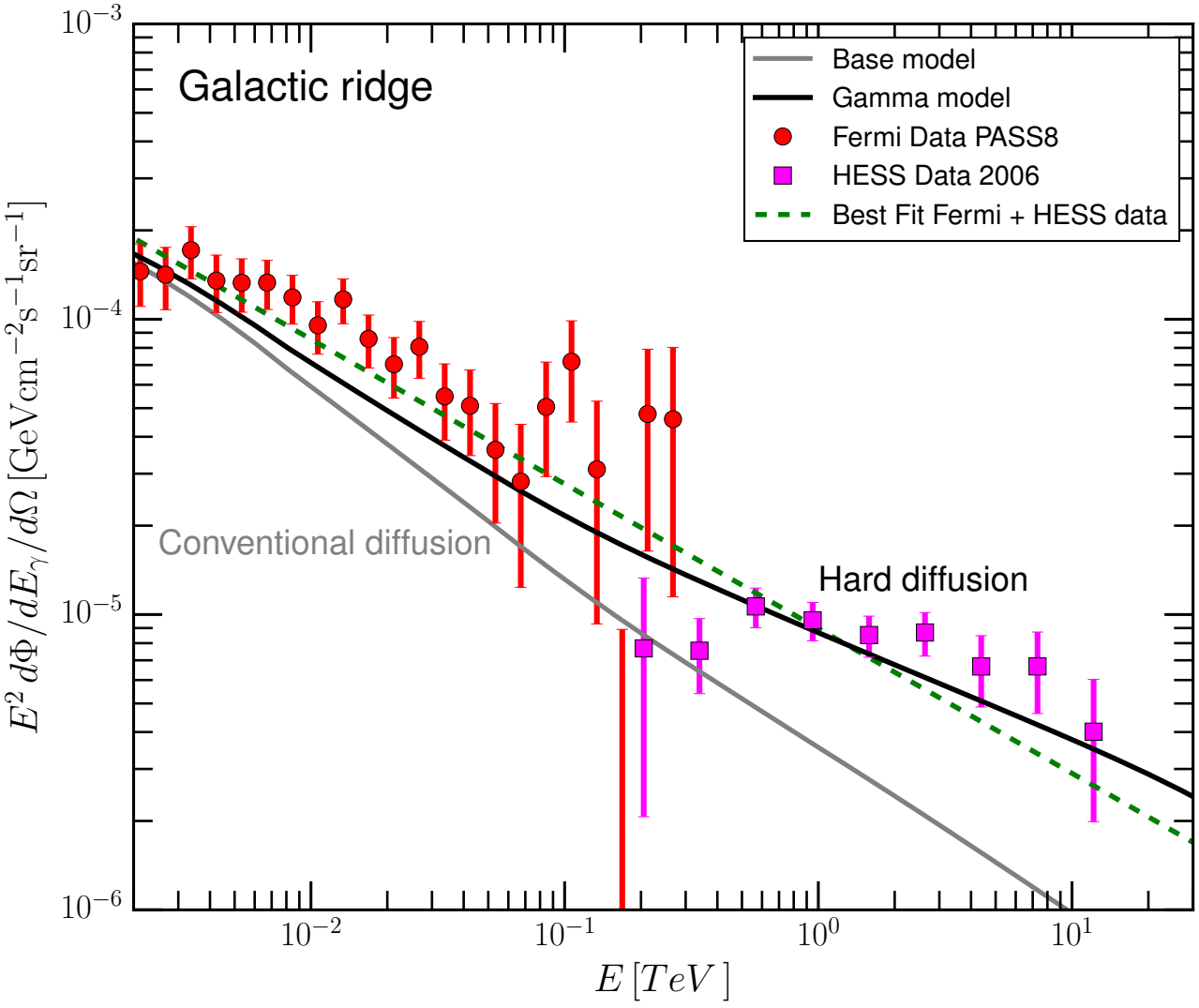
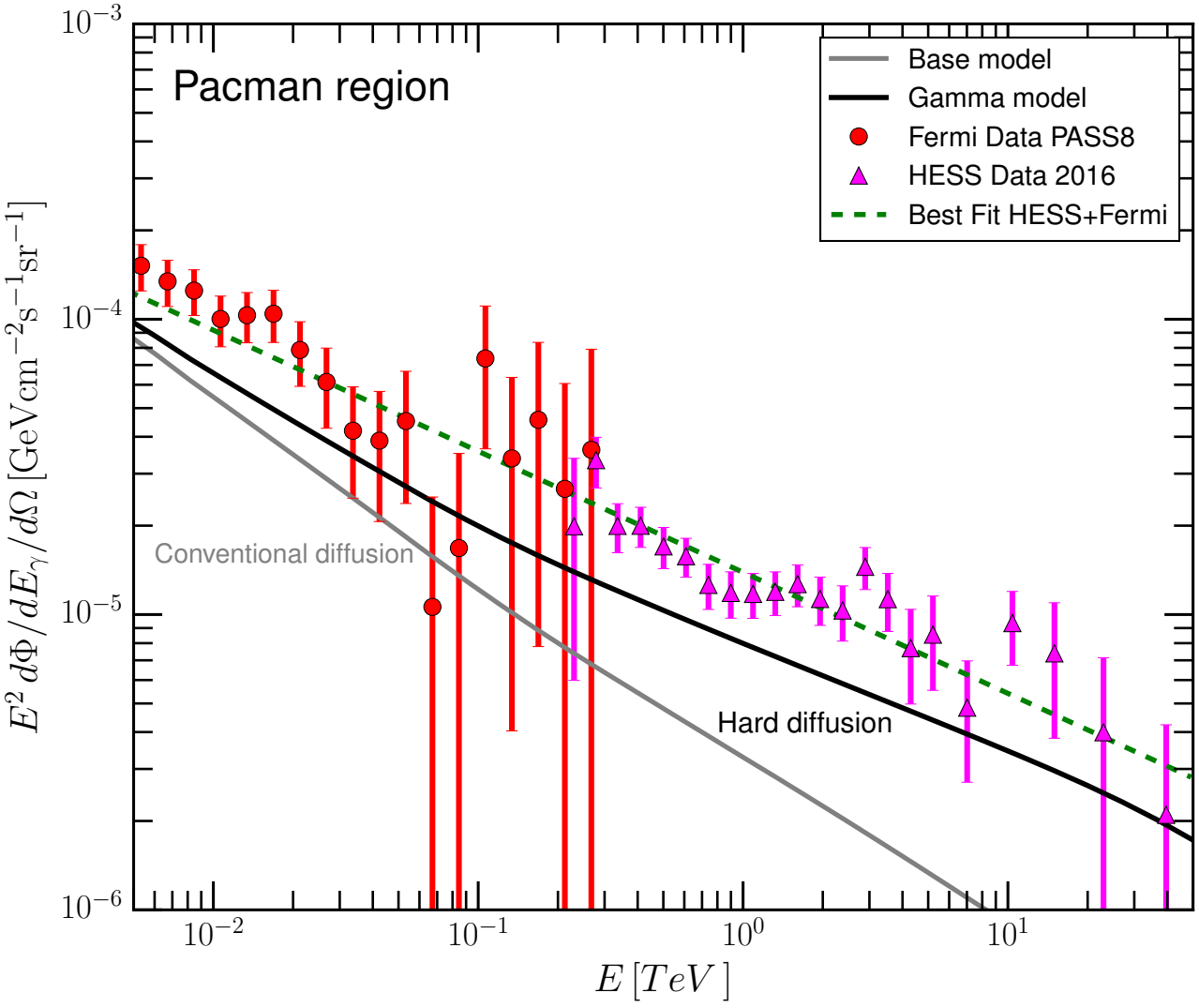
- connection to γ rays:
  - sources transparent: $\varphi_\gamma(E) \leftrightarrow \varphi_\nu(E)$
  - but requires extrapolation above 10 TeV
- young SNRs, Cygnus region, Fermi bubbles, Galactic center

Galactic center



[Gaggero et al. '17]

Galactic center



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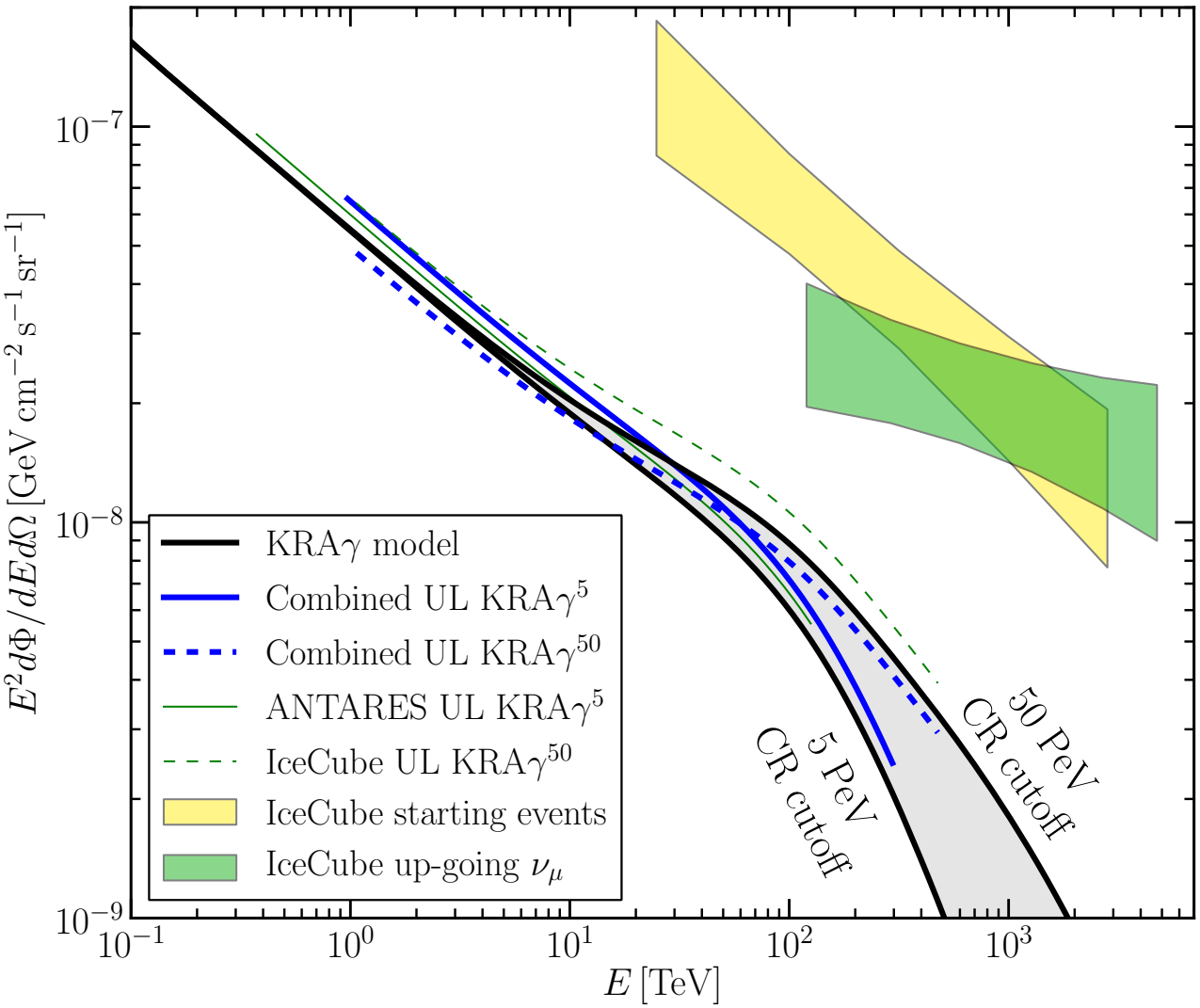
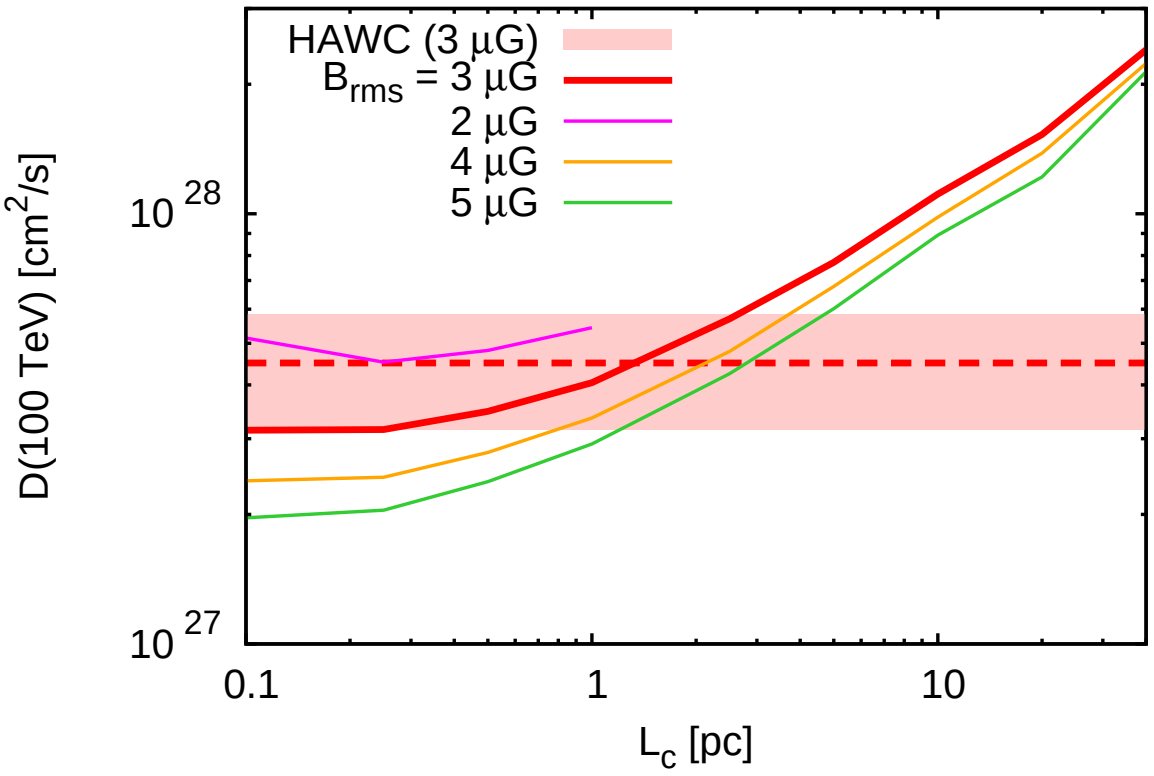
Antares–IceCube limit



Slow diffusion around sources: Geminga



[*López-Coto, Giacinti '17*]

- possible explanations:
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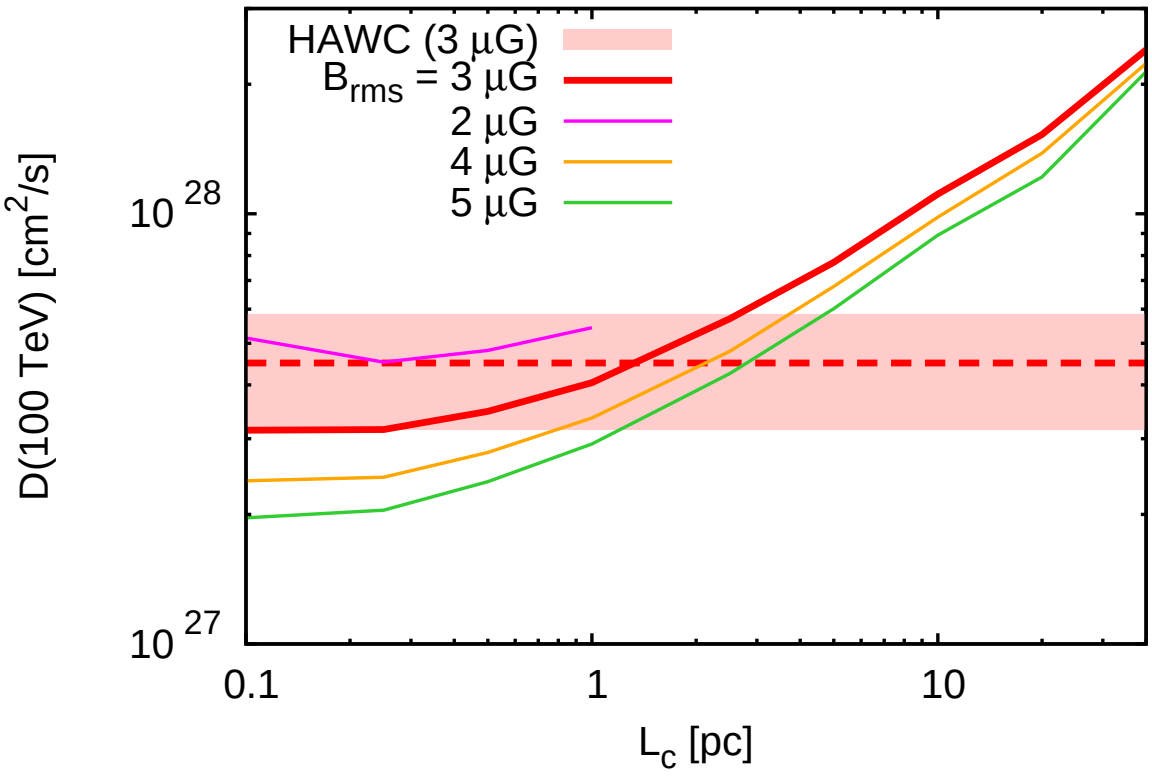


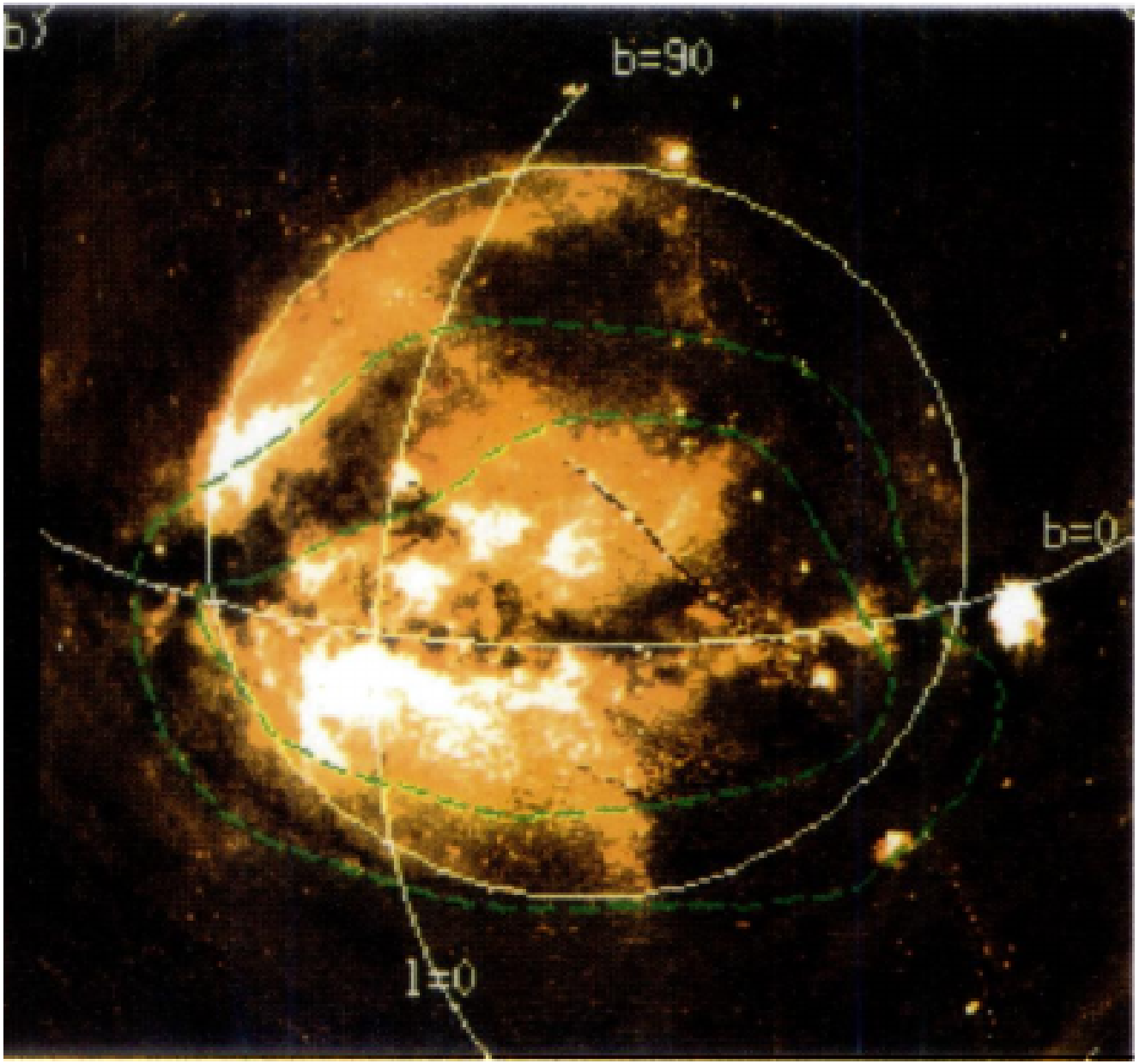
[*López-Coto, Giacinti '17*]

- possible explanations:
  - weak regular field, smallish $L_{\rm coh}$
  - self-generated turbulence by CRs

[*Evoli, Linden, Morlino '18*]

Sources in Local & Loop I superbubble

[*Andersen, MK, Semikoz '17*]



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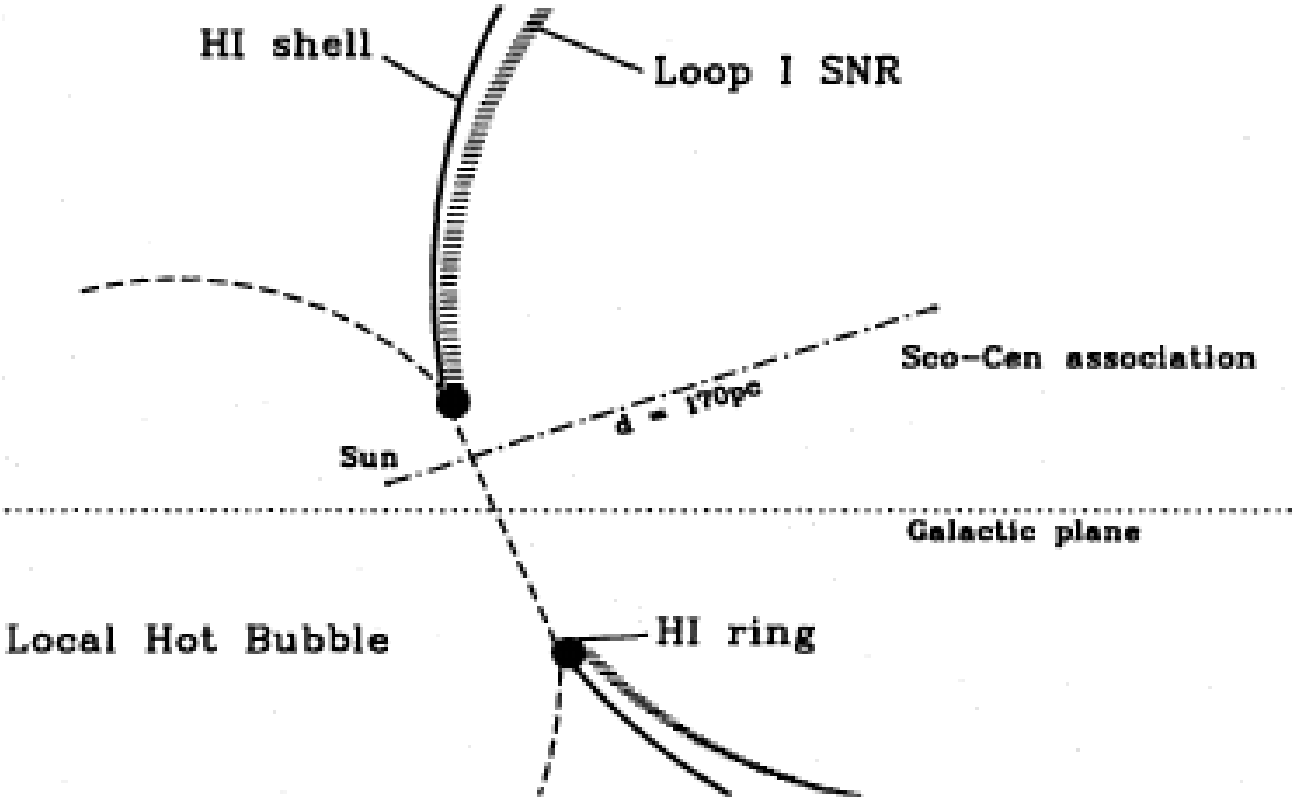

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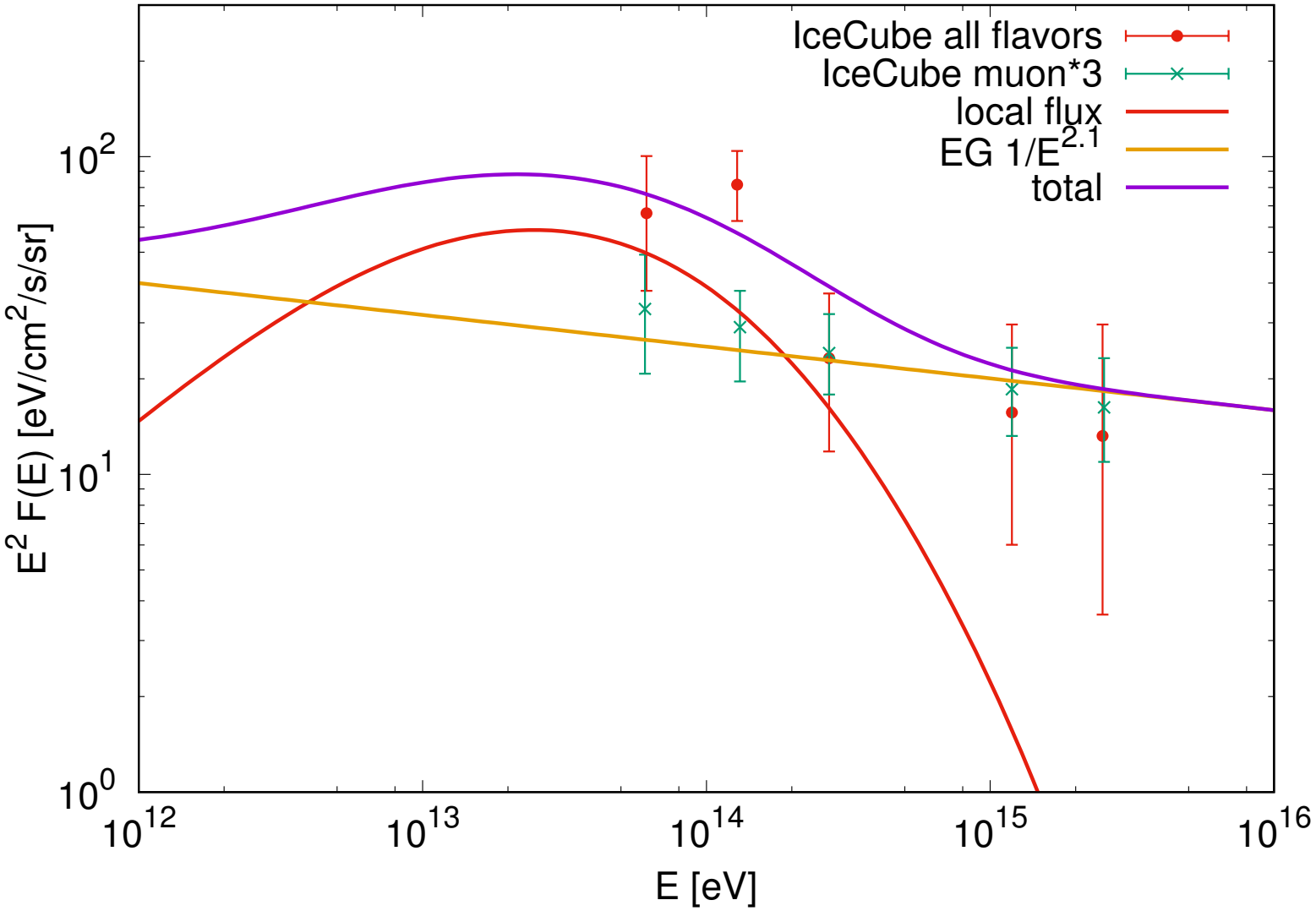

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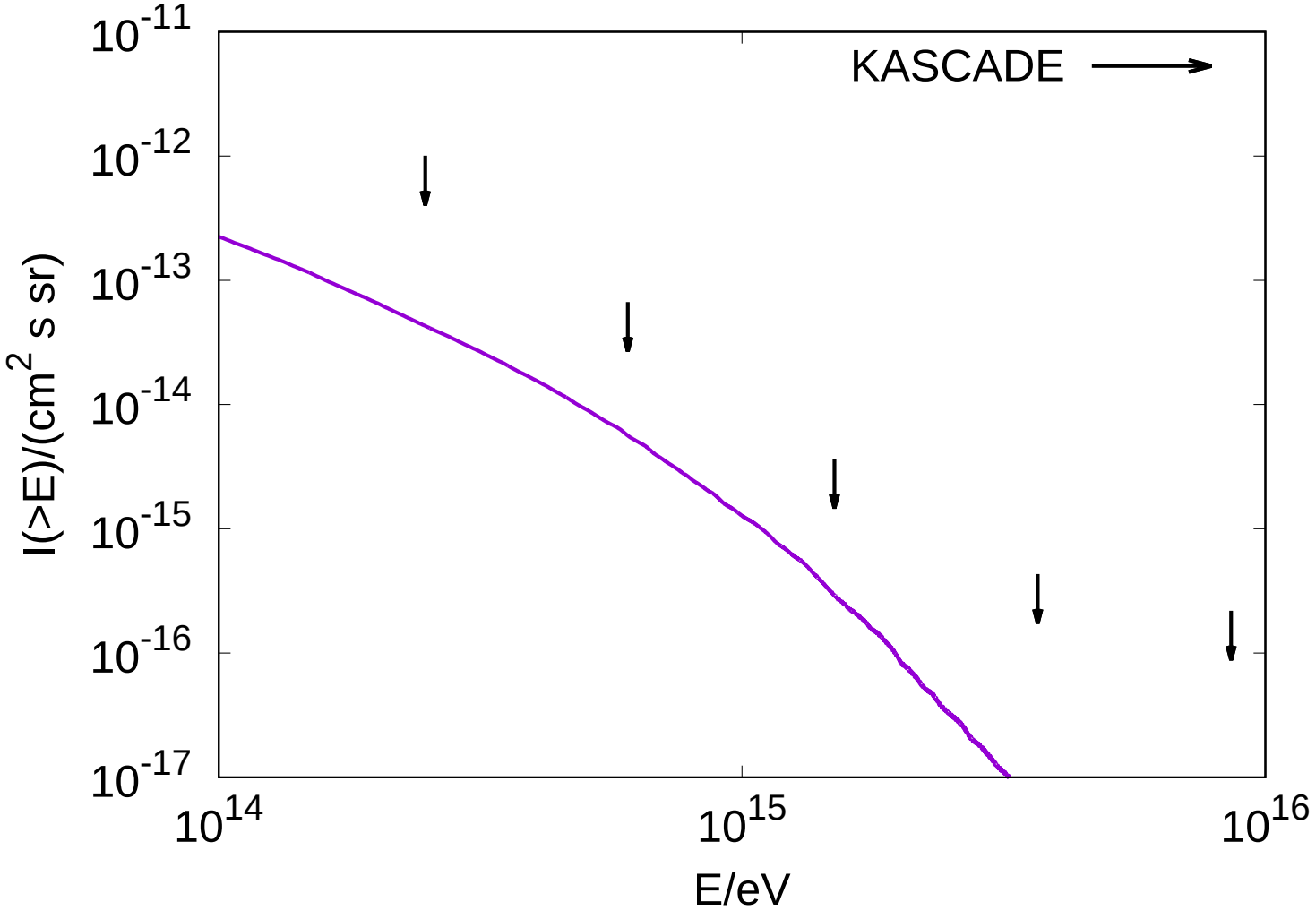

Are multi-TeV photons in the Fermi data?

[*Neronov, MK, Semikoz '18*]

Caveats Analyzing LAT Pass 8 Data:

- "...because the validation process was hampered by lack of statistics, using data below 30 MeV or above 1 TeV is discouraged."

- *gtlike* tool has limit 850 GeV

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Caveats Analyzing LAT Pass 8 Data:

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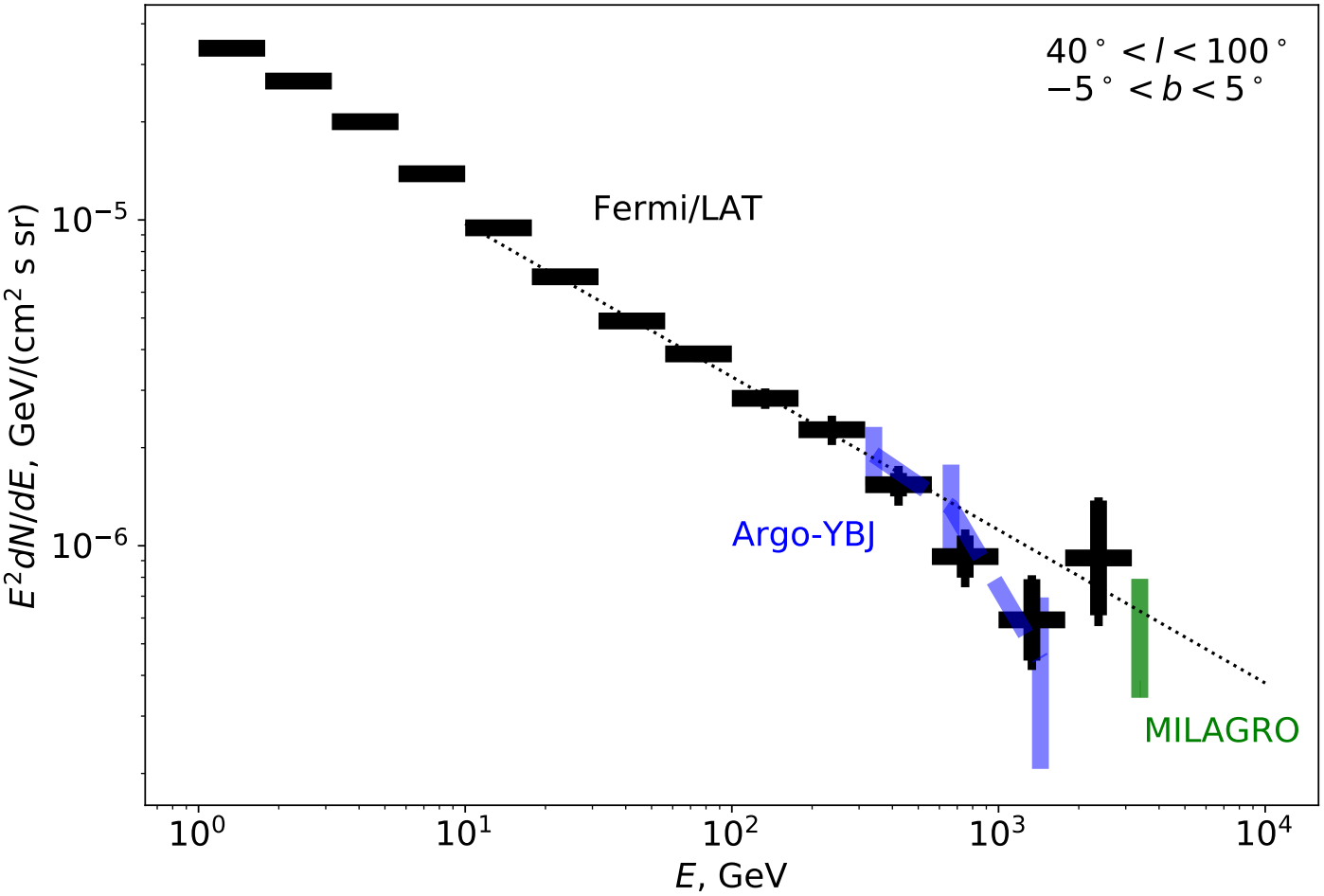
- *gtlike* tool has limit 850 GeV
- eff. area & energy resolution up to 3.2 TeV: 15% at 1 TeV & 25% at 3 TeV

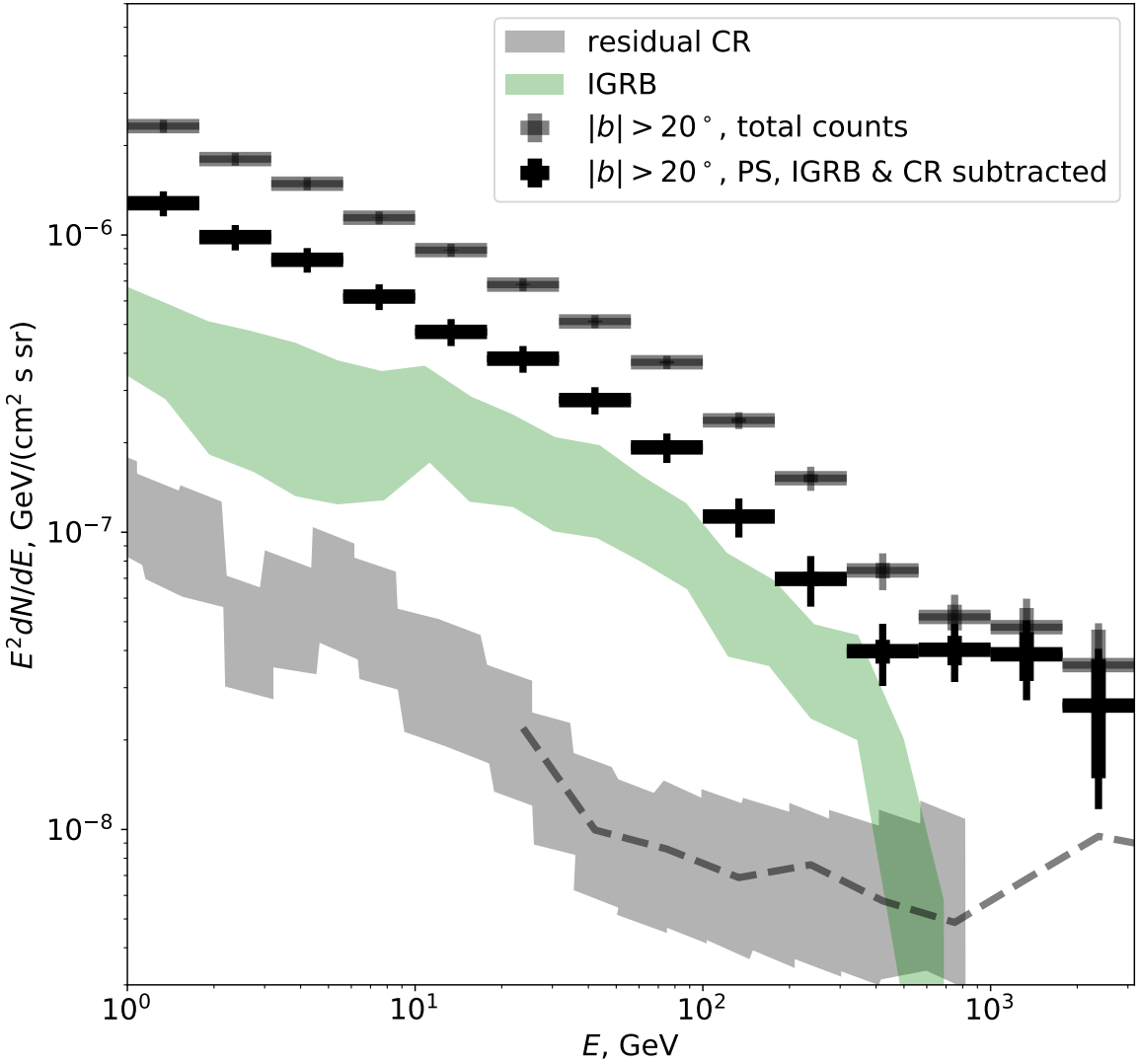
$\Rightarrow$ aperture photometry possible

Cross calibration test: Galactic plane

- Galactic plane ($|b| < 5^\circ$ and $40^\circ < l < 100^\circ$) spectrum from ARGO-YBJ and Milagro



Extension to 3 TeV for $|b| > 20°$:



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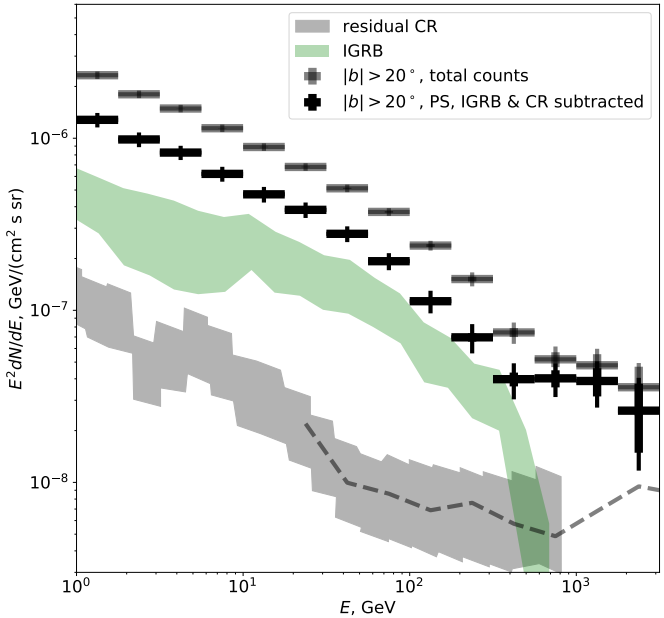
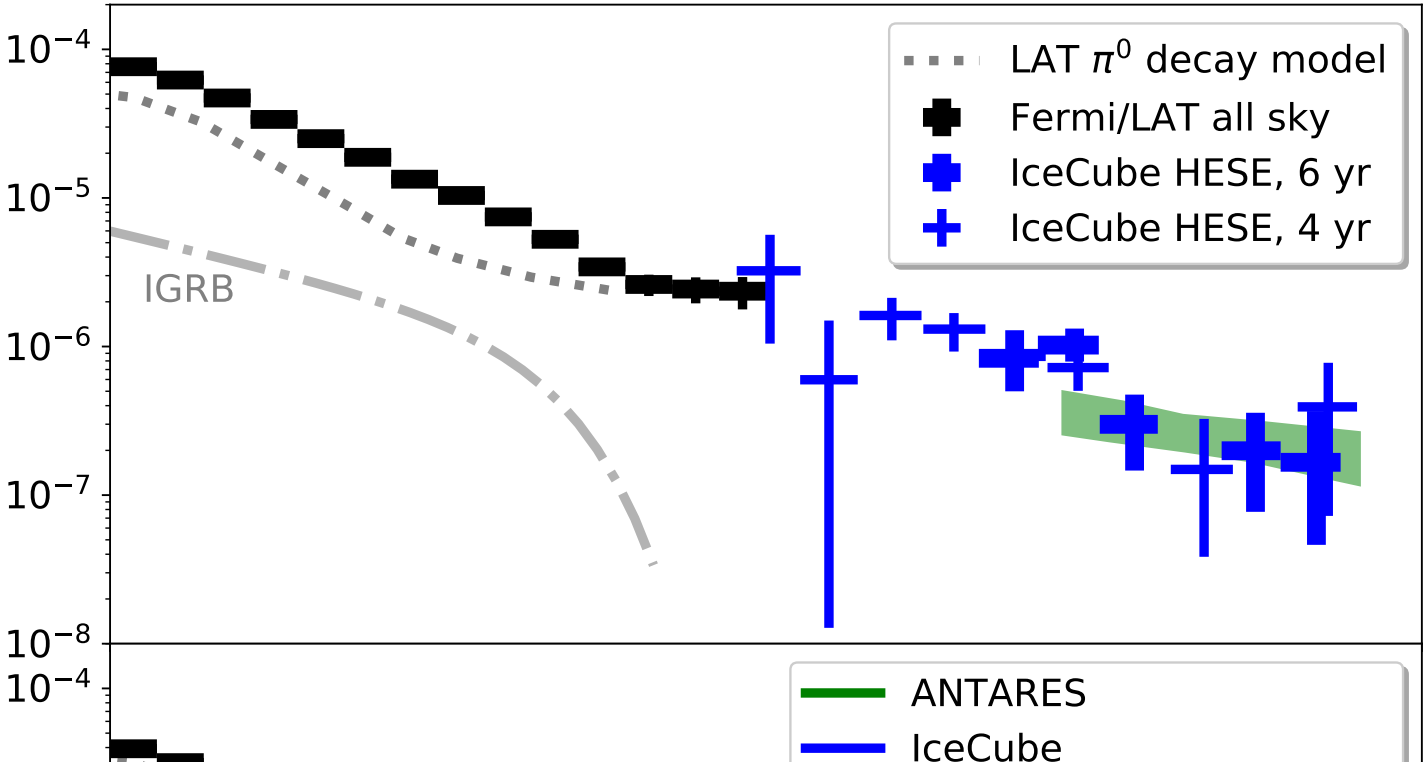


- bin 1–1.7 TeV: expected 14 (18.5) for nominal (renormalised) exposure

  observed (after subtr. CR): 47
- bin 1.7–3 TeV: expected 2.4 (3.5.5), observed 17

Adding neutrinos:



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[*Dolag '02*]

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[*Dolag '02*]

- for $B \sim 0.01\mu$ G and $L_{\rm coh} \sim 100$ pc:

$\Rightarrow$ CR with $E_* = 100$ TeV is in large-angle scattering regime

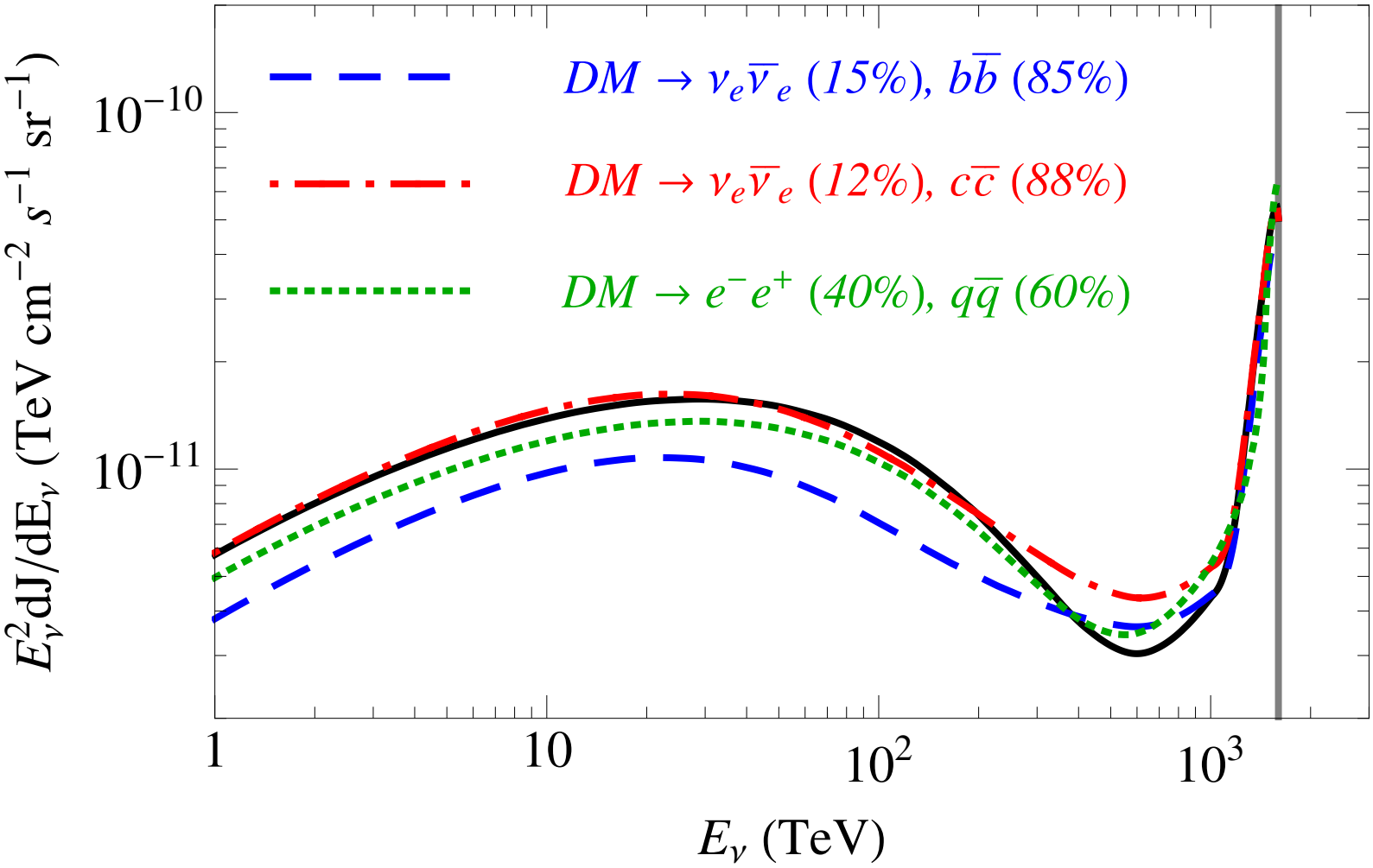
$\Rightarrow$ $D(E_*) \sim 10^{29}$cm^2/s

$\Rightarrow$ escape time $\tau = H^2/2D \sim t_0$

Possible explanations:

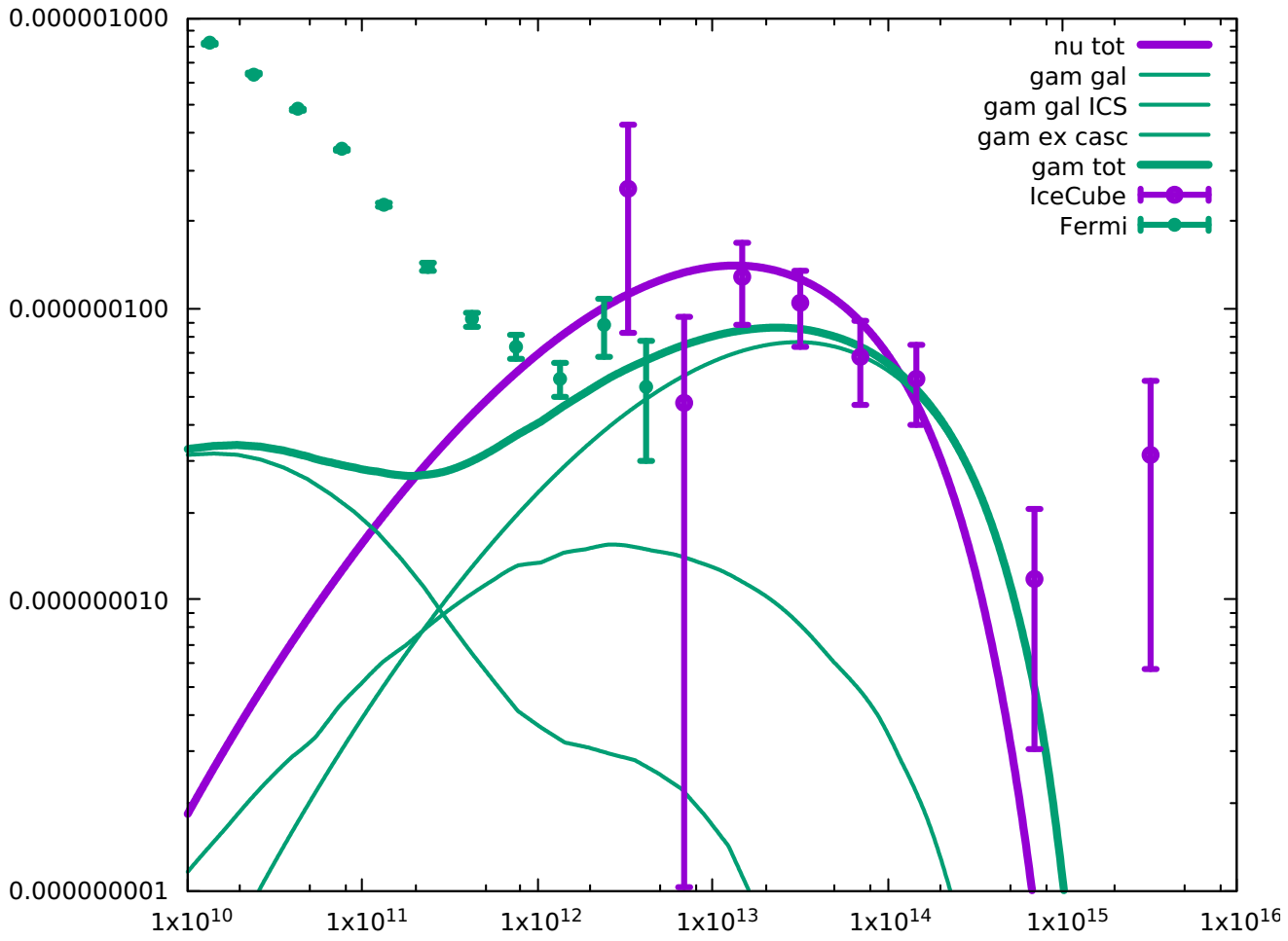
- interface Loop I/local superbubble: strong dipole?
- extended CR halo
- PeV dark matter: re-incarnation of SHDM idea for AGASA excess:
  - non-hermal DM
  - avoids cascacde limit
  - Galactic anisotropy

PeV dark matter



[Kusenko et al. '13, Esmaili, Serpico '13]

Possible explanations: heavy dark matter



Summary

1. EGRB constrains stronly neutrino sources:
   - slope of extragal. neutrino $\alpha \lesssim 2.2$
   - neutrino sources are not main source class of EGRB
2. Standard Galactic neutrinos:
   - northern km^3 telescope very useful
   - important info on propagation and acceleration
3. Soft neutrino signal in IceCube:
   - isotropy: extragalactic or large Galactic halo
   - TeV γ-ray excess consistent with neutrino flux