High-Energy Neutrinos

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1. Introduction
2. IceCube events
   - properties
   - implications
3. Astrophysical sources
   - point sources versus diffuse flux
   - Galactic sources versus extragalactic
4. PeV dark matter
5. Summary

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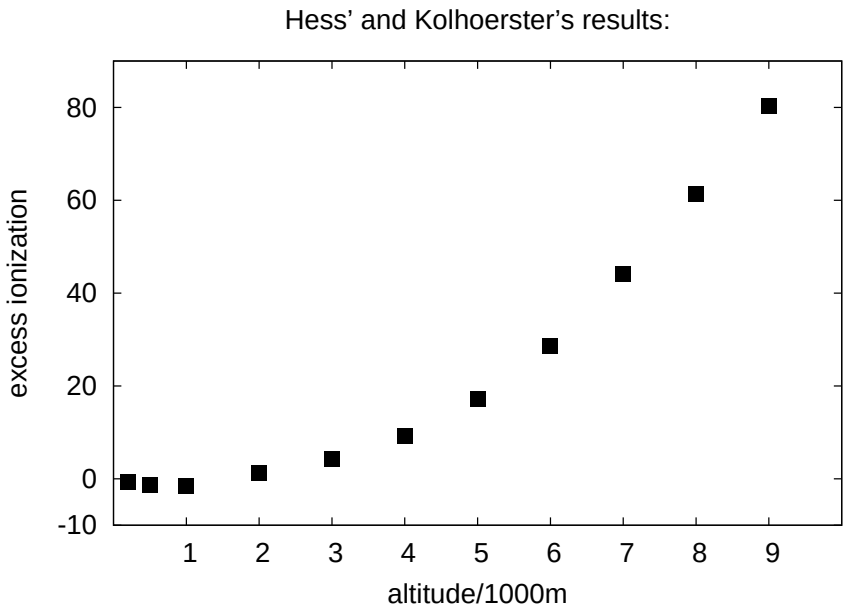
1912: Victor Hess discovers cosmic rays

"The results are most easily explained by the assumption that radiation with very high penetrating power enters the atmosphere from above; the Sun can hardly be considered as the source."



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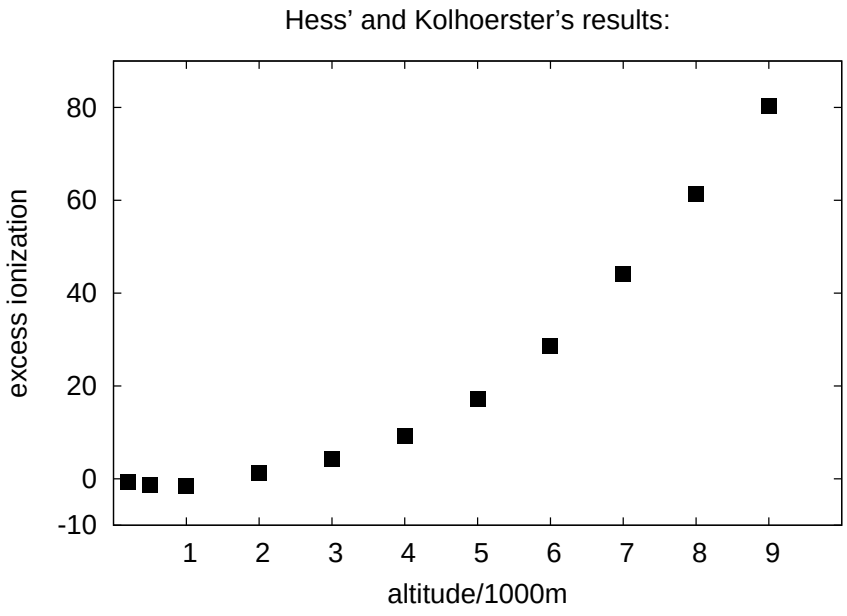
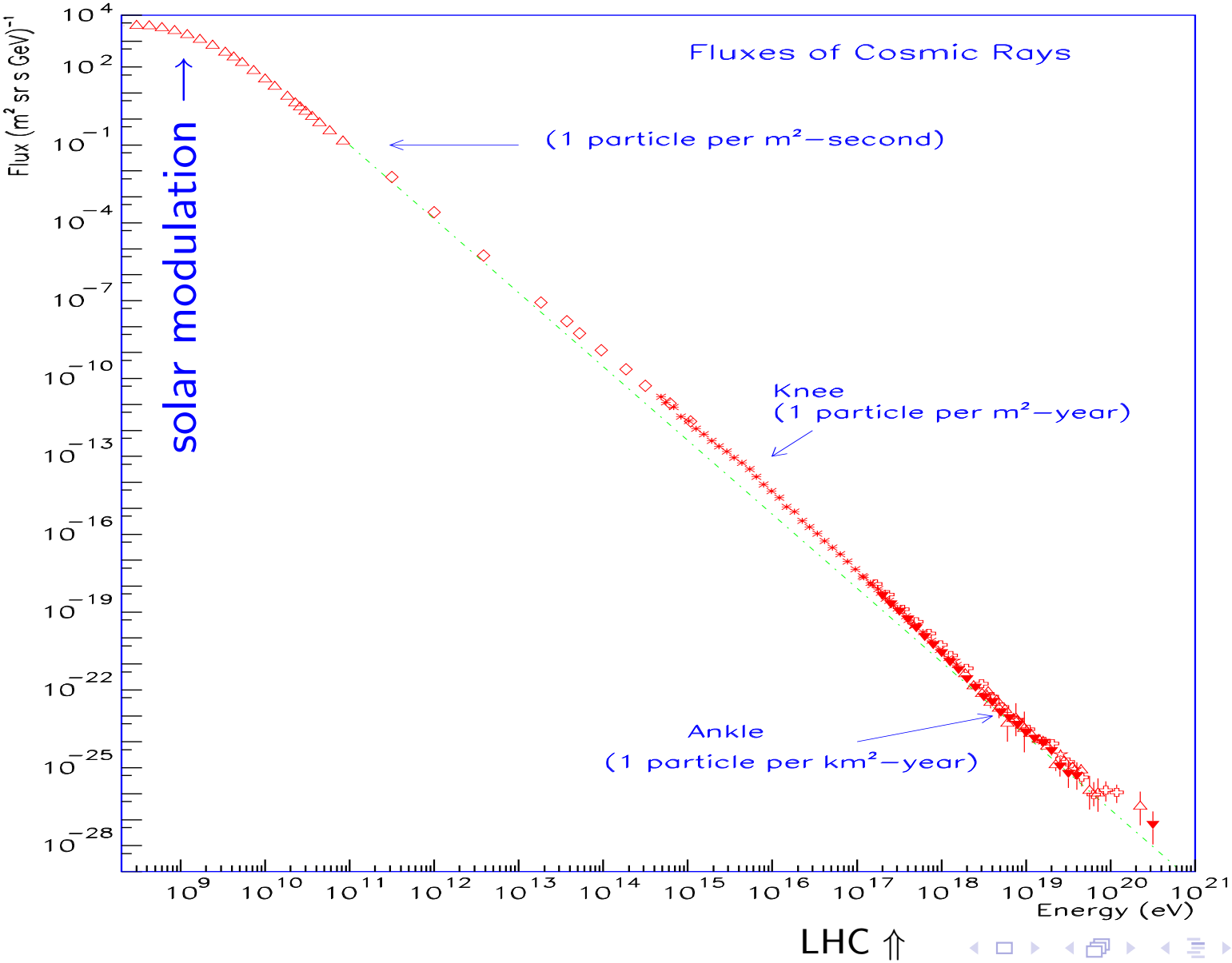
Two main questions

- what are they?
- what are their sources?



What do we know 100 years later?



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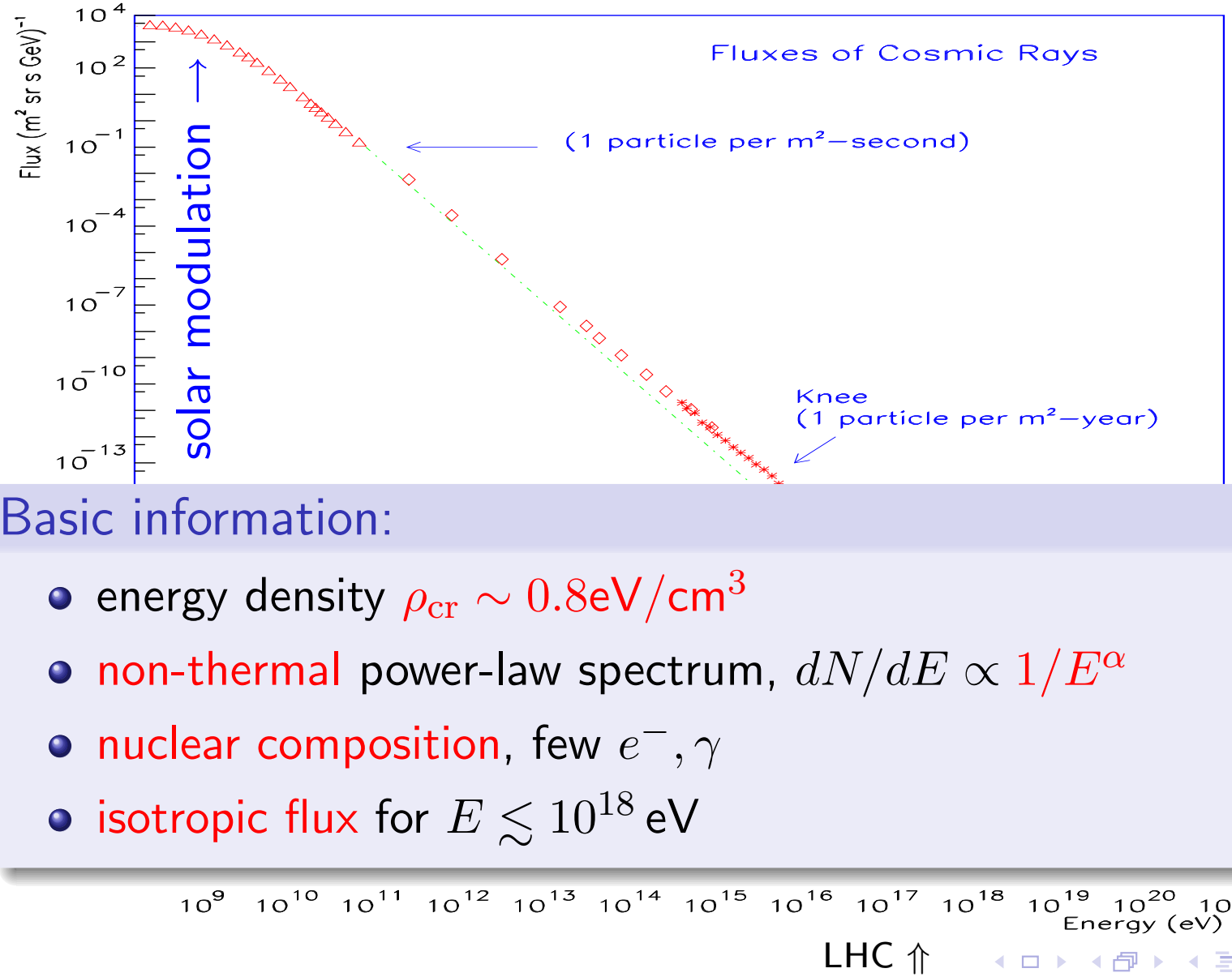

Basic information:

- energy density $\rho_{\rm cr} \sim 0.8\,{\rm eV/cm^3}$
- non-thermal power-law spectrum, $dN/dE \propto 1/E^{\alpha}$
- nuclear composition, few e^-, γ
- isotropic flux for $E \lesssim 10^{18}$ eV

The CR–γ–ν connection:

HE neutrinos and photons are unavoidable byproducts of HECRs

- astrophysical models, cosmogenic flux:
  - ratio I_ν/I_p determined by nuclear composition of UHECRs and source evolution
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- top-down DM models:
  - large fluxes with $I_\nu \gg I_p$
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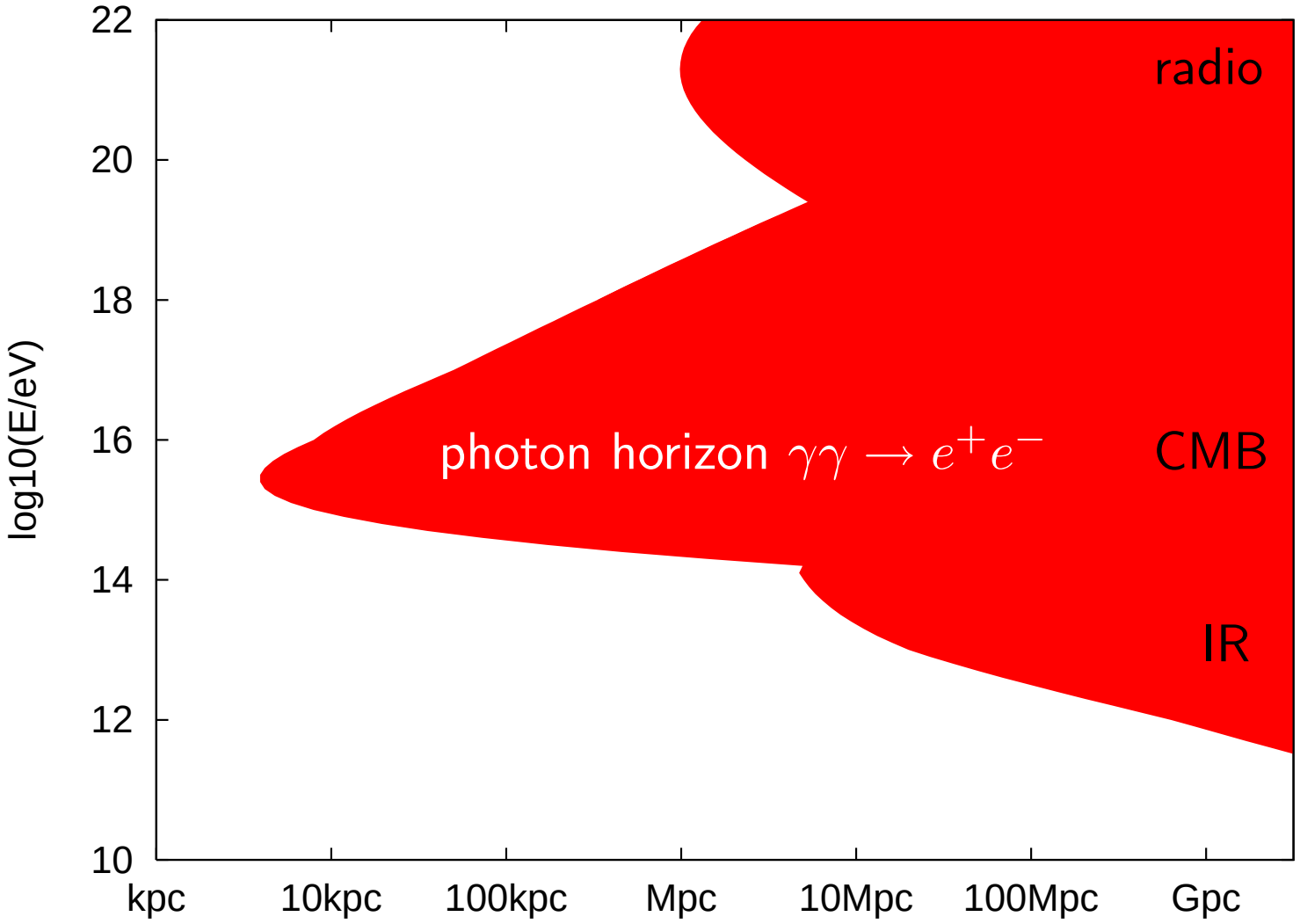
- prizes to win:
  - astronomy above 100 TeV
  - identification of CR sources
  - determination galactic–extragalactic transition of CRs
  - test/discover new particle physics

What is the bonus of HE neutrino astronomy?

- astronomy with VHE photons restricted to few Mpc:



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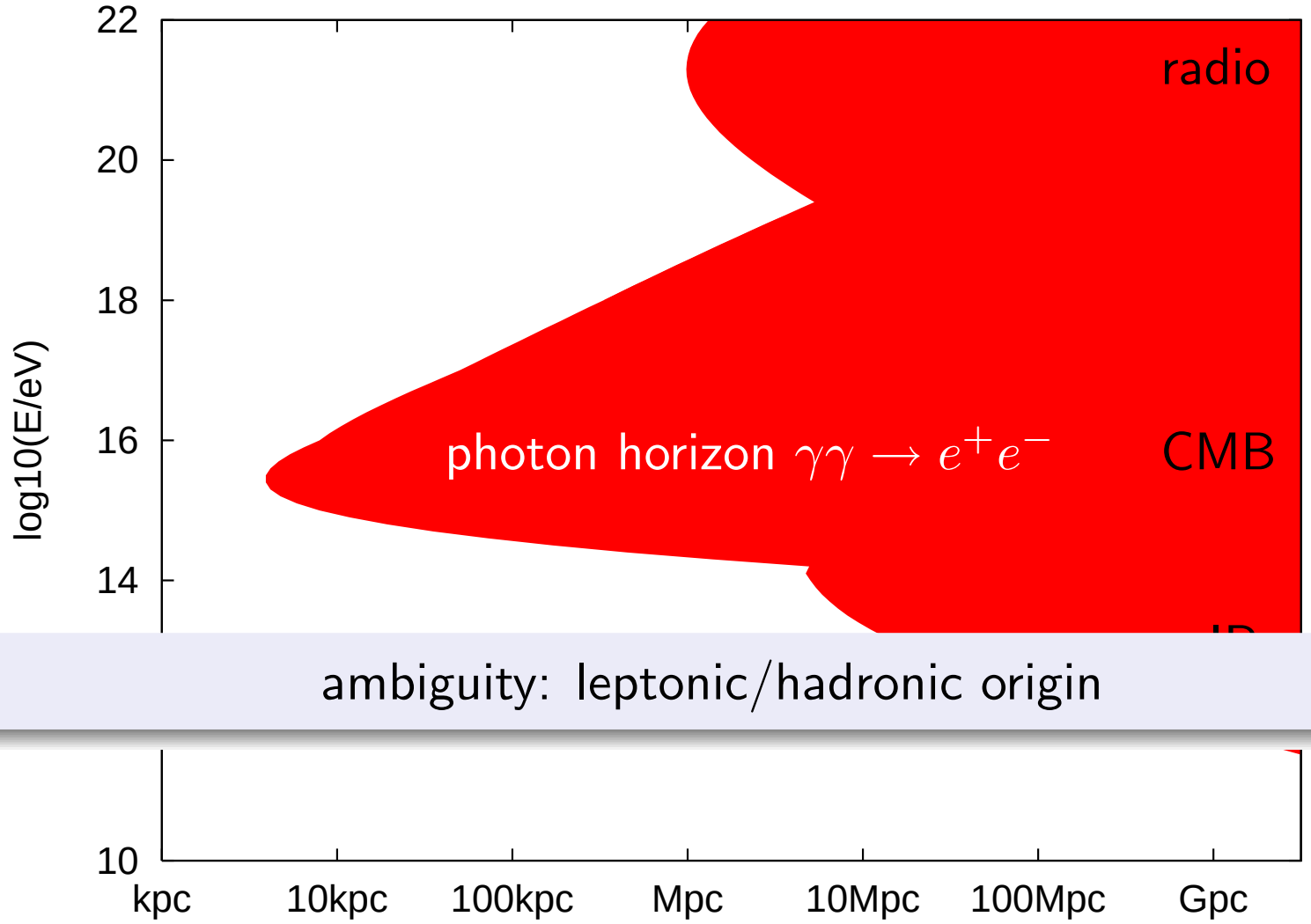
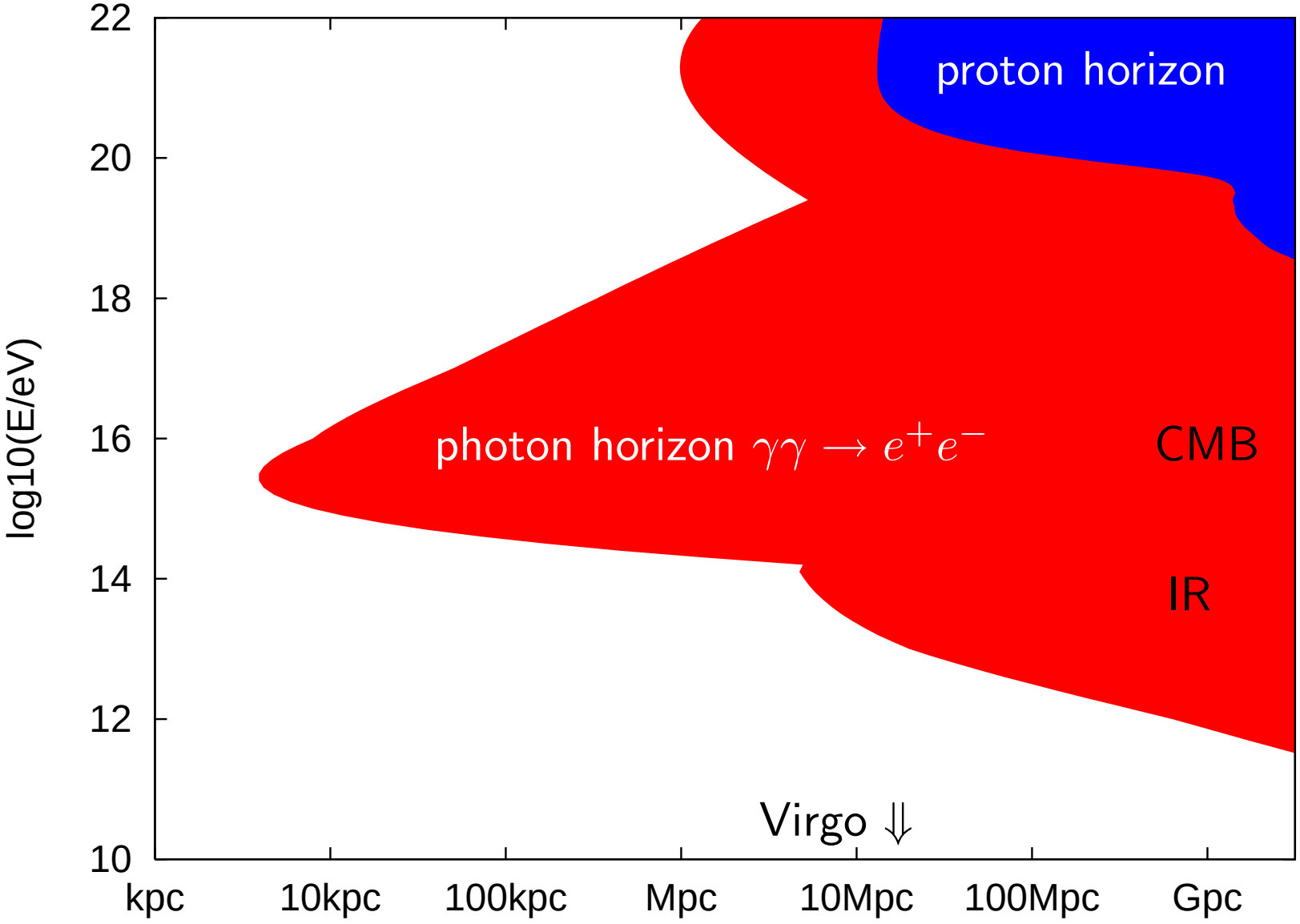


ambiguity: leptonic/hadronic origin

HE neutrino astronomy vs UHECRs?



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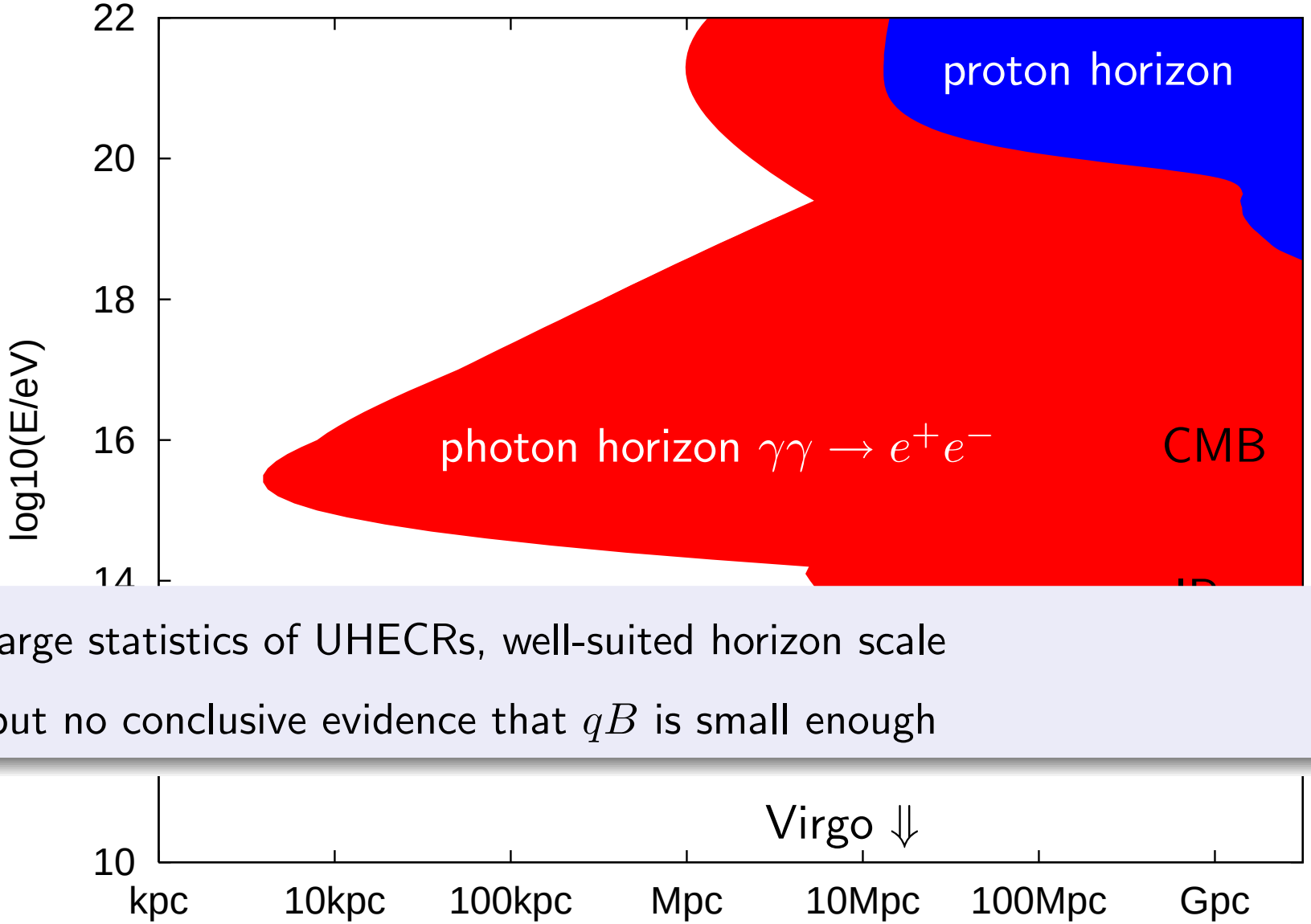

- large statistics of UHECRs, well-suited horizon scale
- but no conclusive evidence that qB is small enough

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Neutrino astronomy: small $\sigma_{\nu N}$

- large λ_ν but also "large" uncertainty $\langle \delta\vartheta \rangle \gtrsim 0.1^\circ - 1^\circ$

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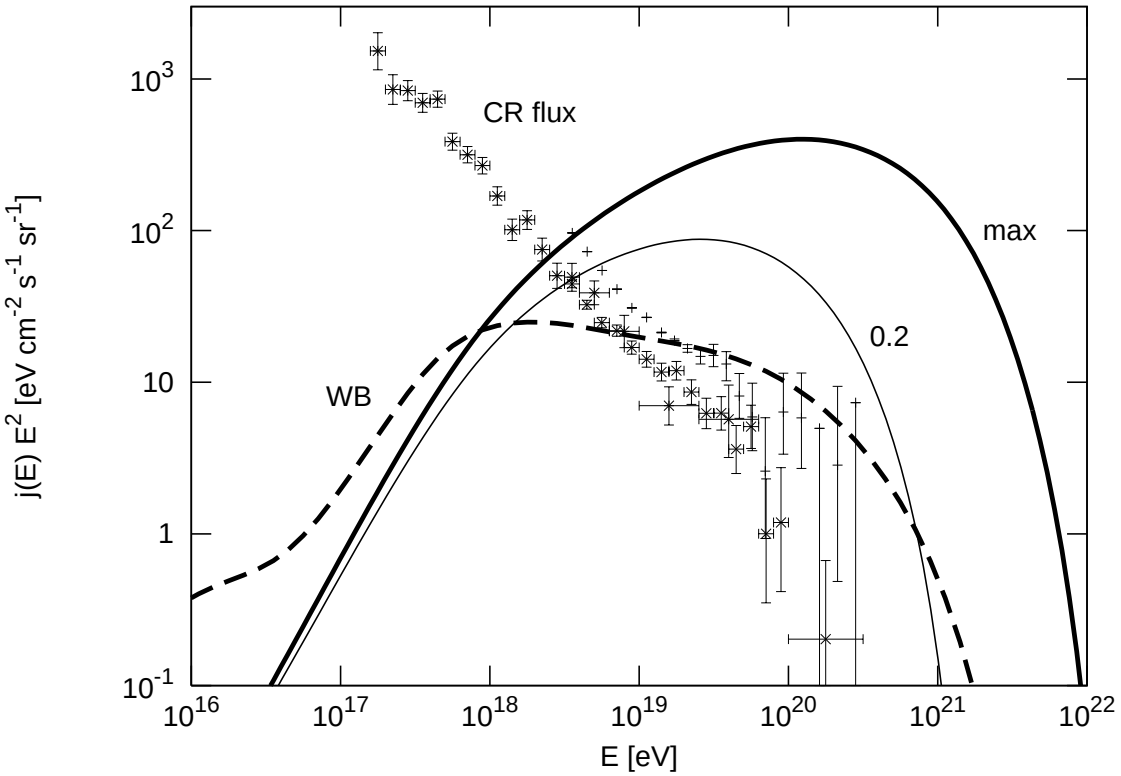

$\Rightarrow$ identification of steady sources challenging

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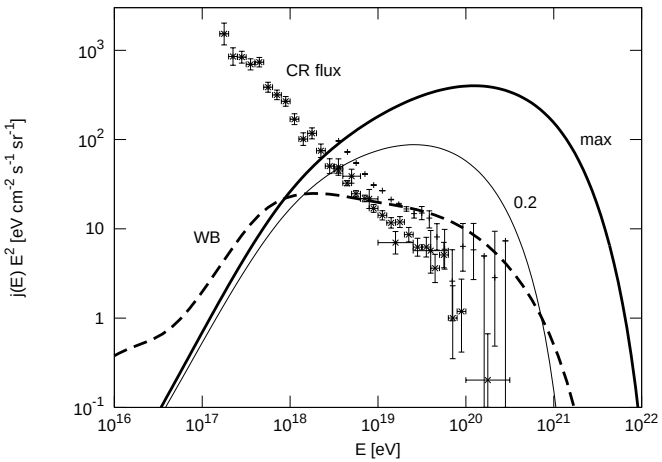
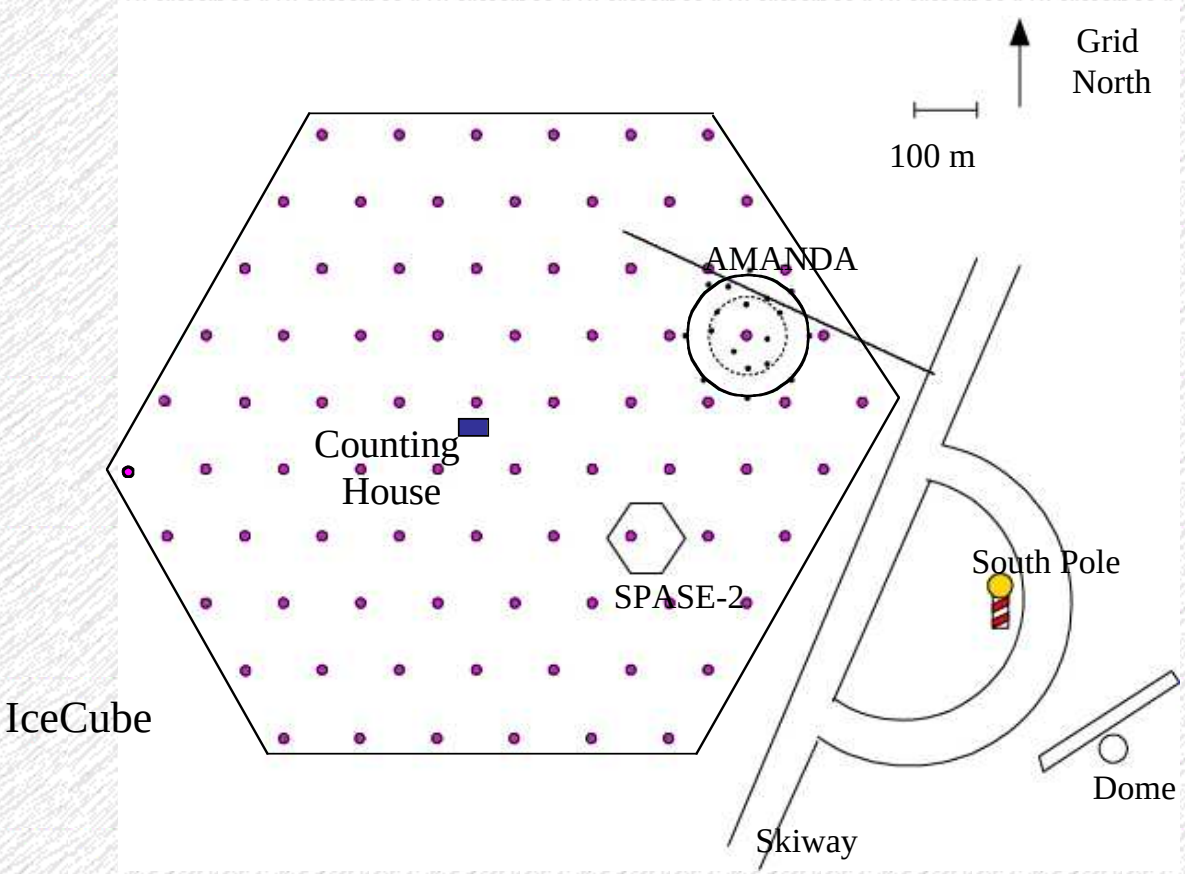


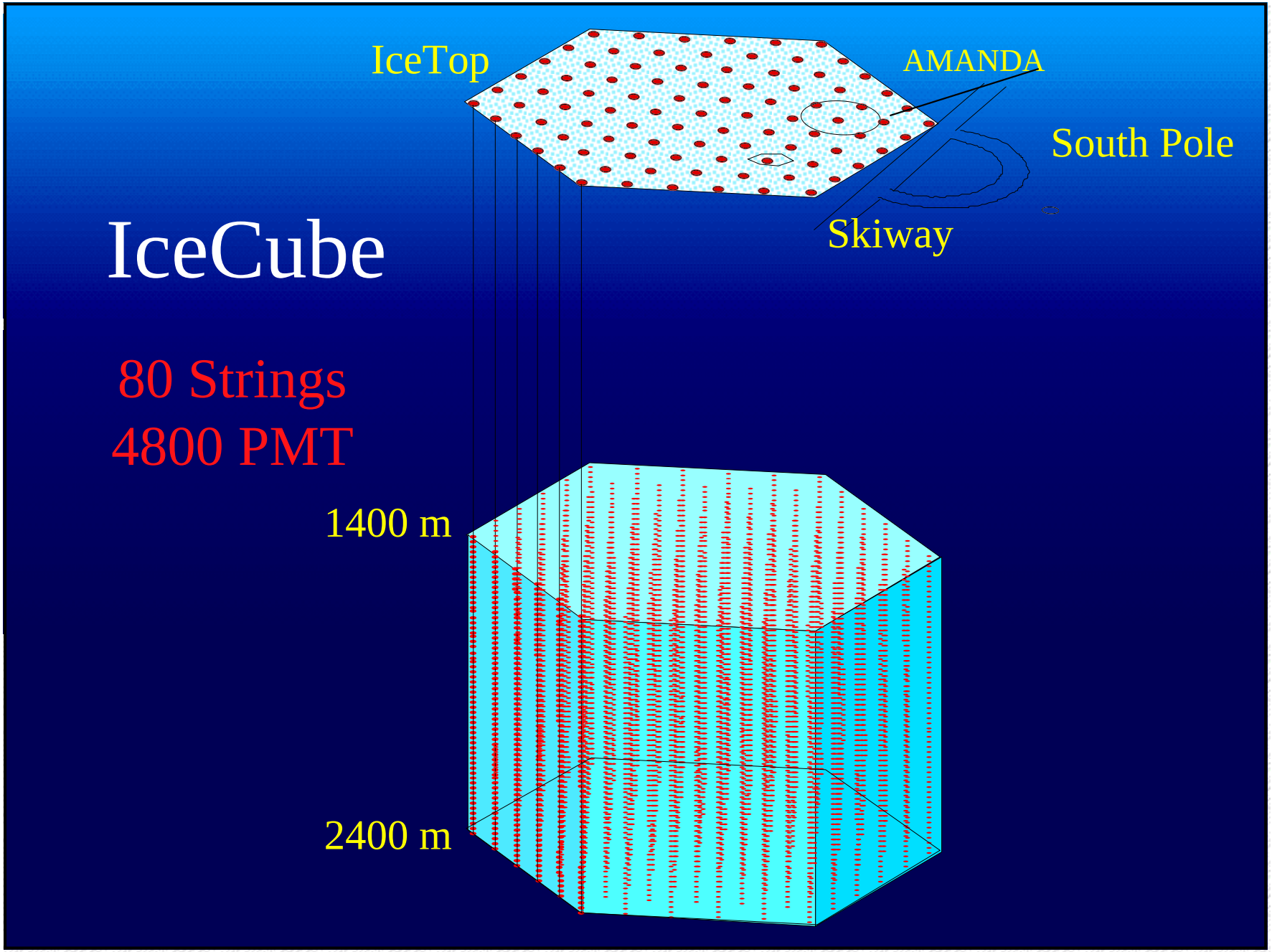
$\Rightarrow$ identification of steady sources challenging

- correlation with AGN flares, GRBs
- diffuse flux detected first

IceCube

IceCube:Top View



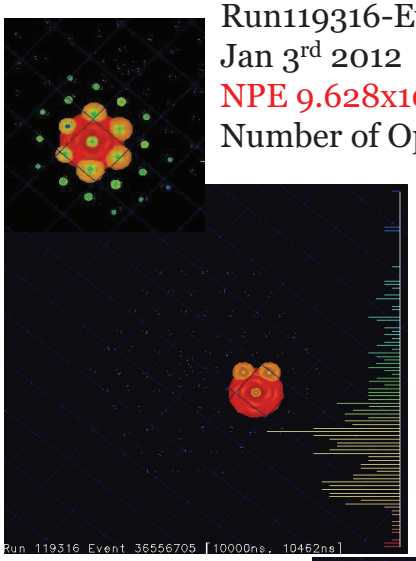

IceTop
AMANDA
South Pole
Skiway
IceCube
80 Strings
4800 PMT
1400 m
2400 m

Icecube: 2 events presented at Neutrino 2012

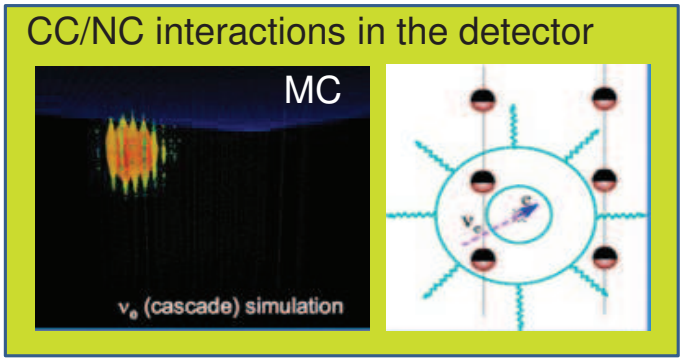
- 2 cascade events close to $E_{\min} = 10^{15}$ eV, bg $= 0.14$

Two events passed the selection criteria

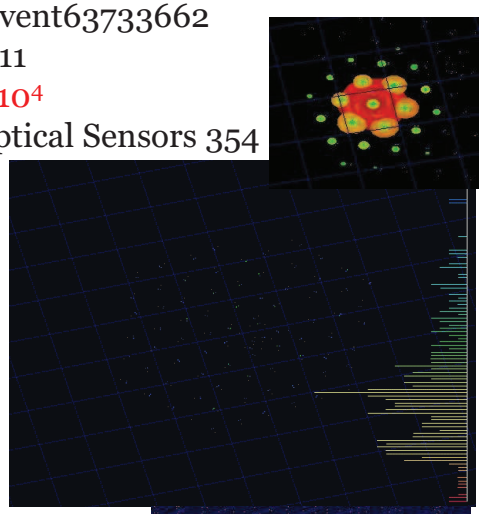
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events
preliminary p-value: 0.0094 (2.36σ)

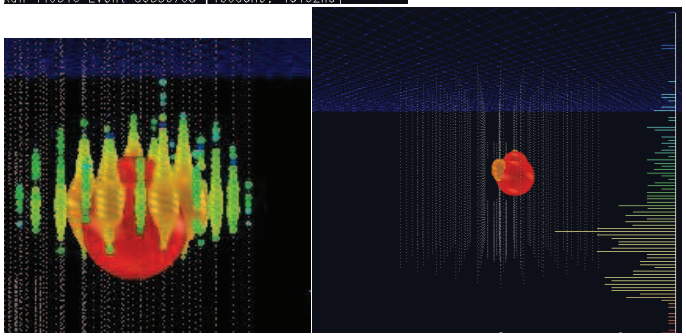


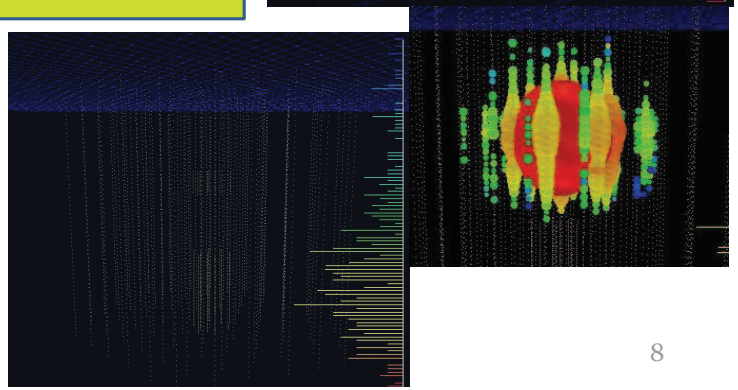
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10⁴
Number of Optical Sensors 312



Run118545-Event63733662
August 9th 2011
NPE 6.9928x10⁴
Number of Optical Sensors 354





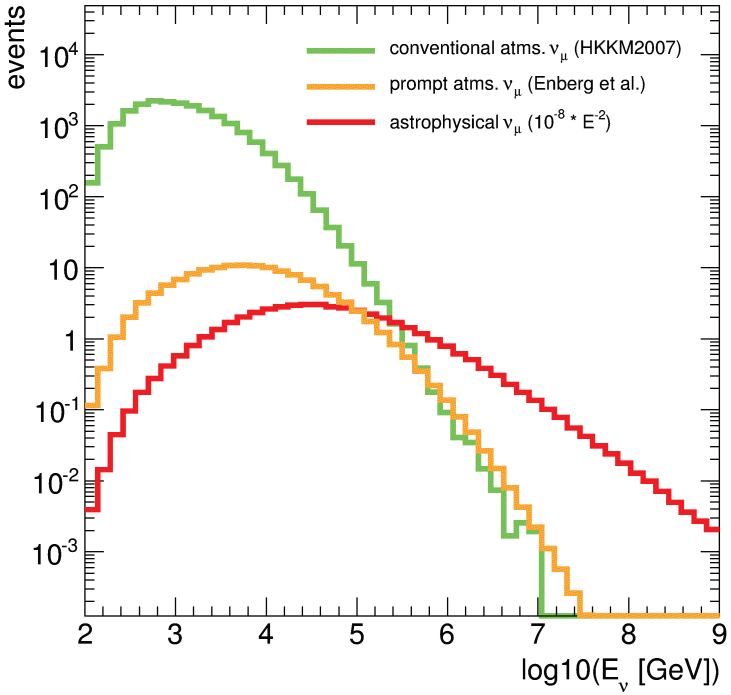


Icecube: prompt neutrino analysis

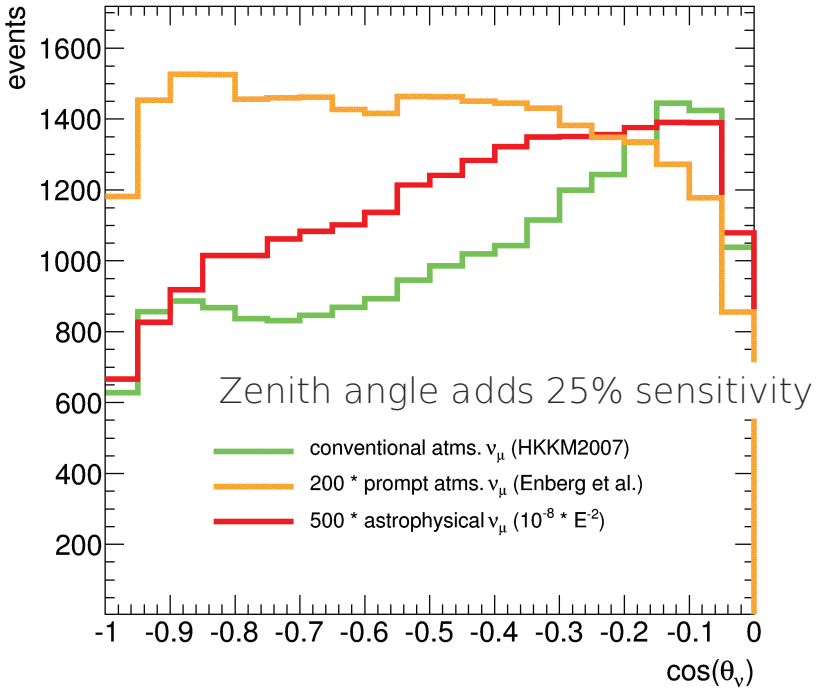
[A. Schukraft, NOW2012]

Signatures of high energy ν_μ in IceCube

Energy distribution
The three neutrino components have different spectral slopes



Zenith angle distribution
Additional sensitivity through characteristic angular distributions



Conventional, prompt and astrophysical neutrinos can't be decoupled and need to be looked at together in a HE neutrino analysis.

IceCube events: specifications for candidate sources

36 events with ~ 14 bg: flukes are possible...

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- anisotropies
  - event cluster around GC
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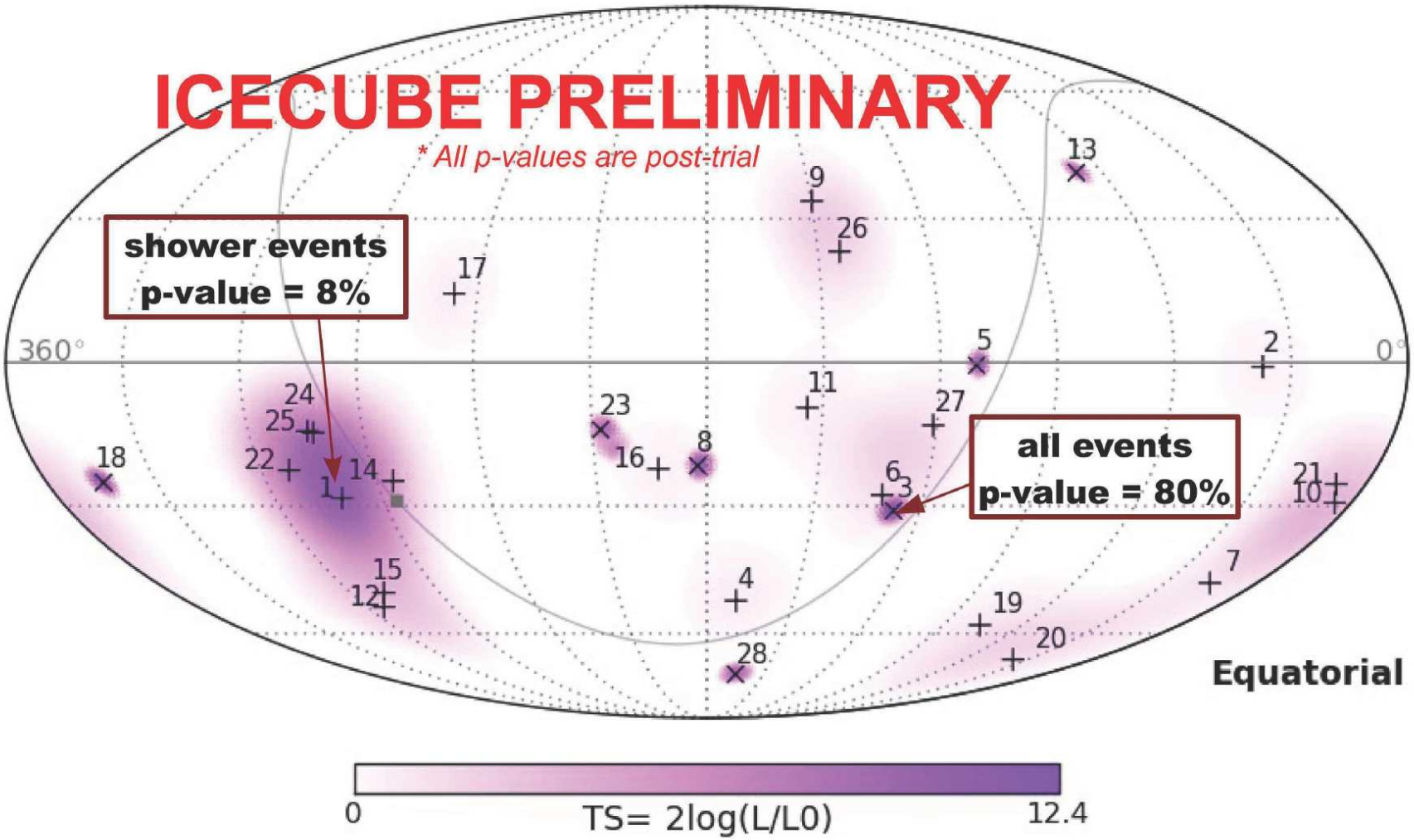
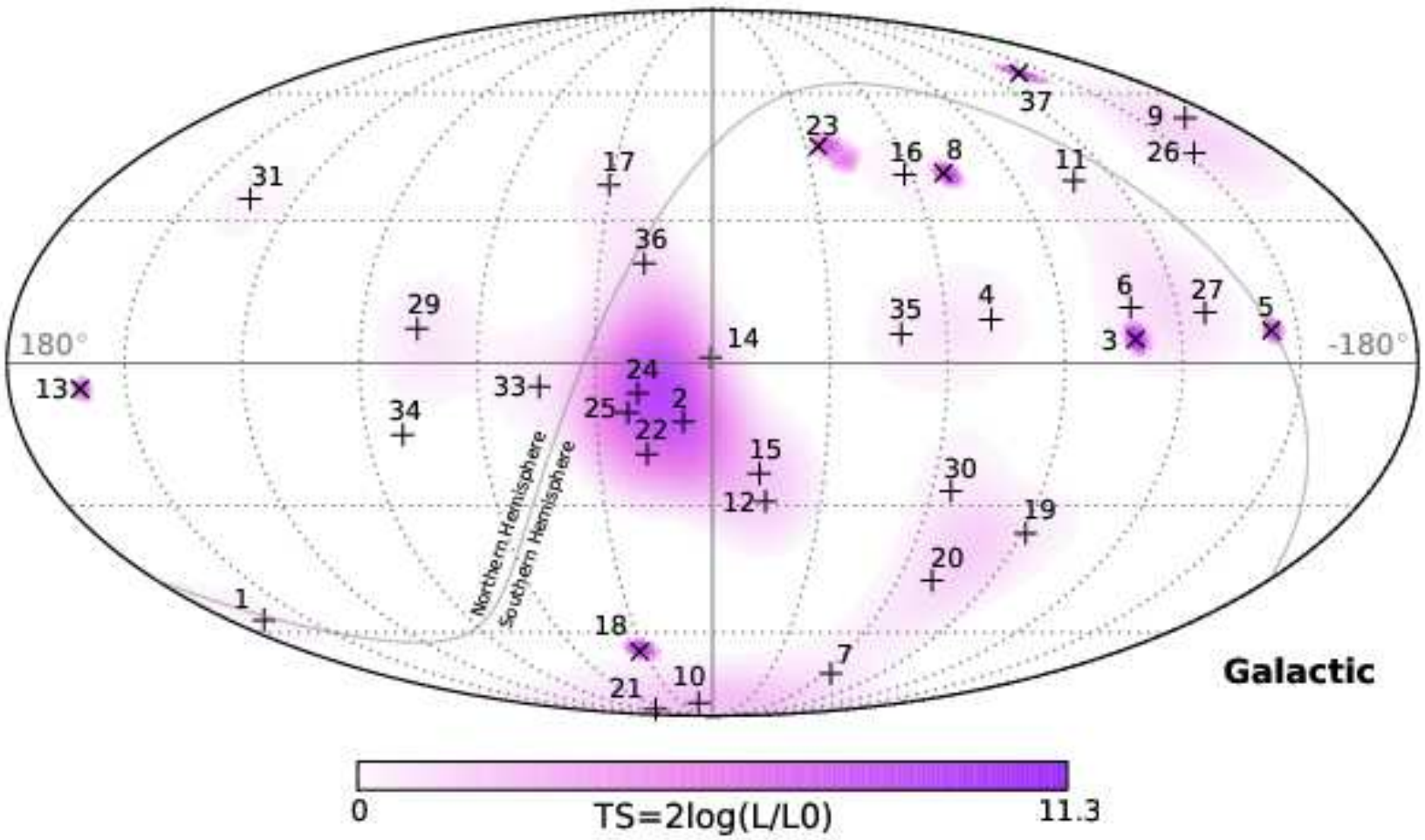
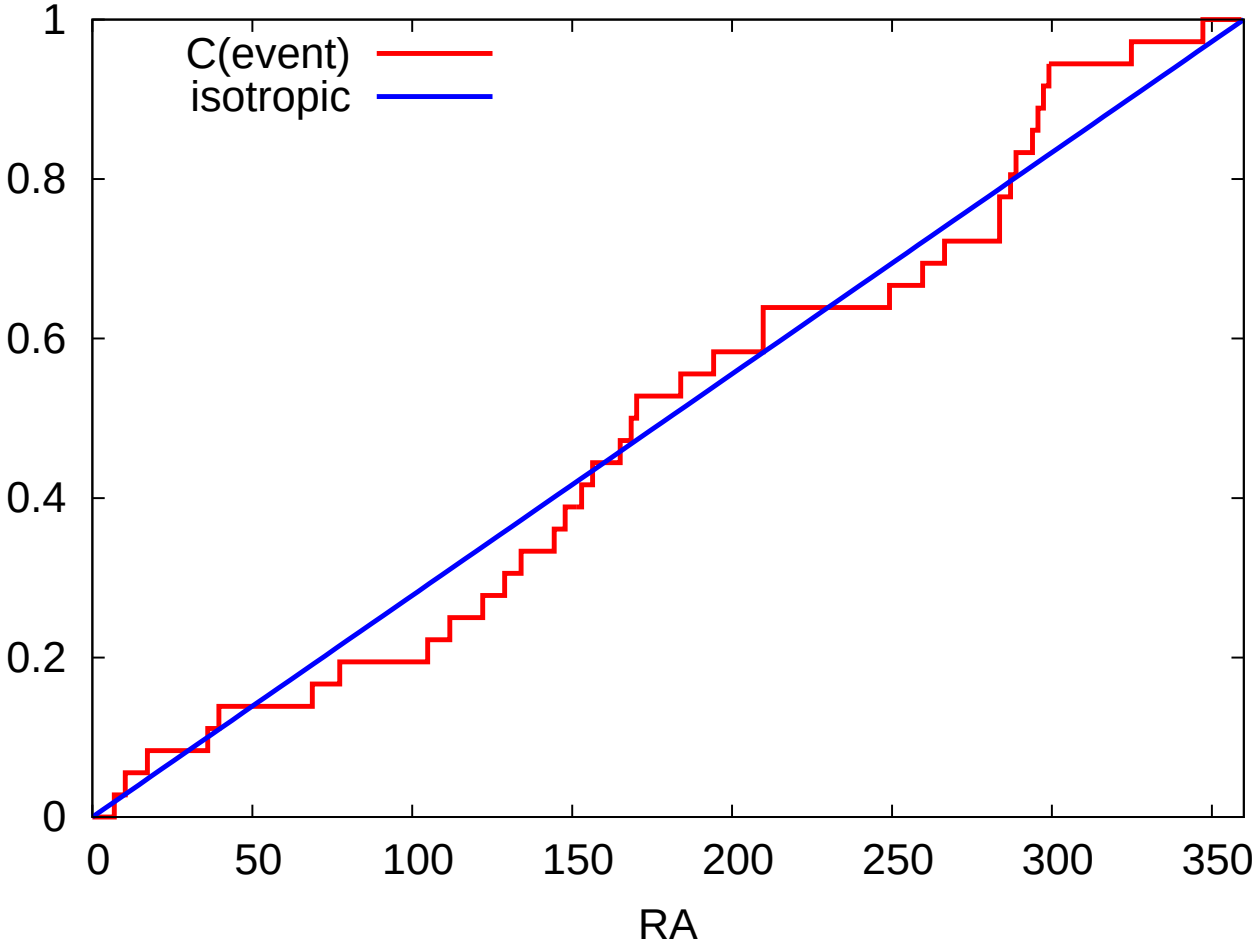
IceCube events: 2 years 28 events



IceCube events: 3 years 36 events



KS test for ansiotropy in RA



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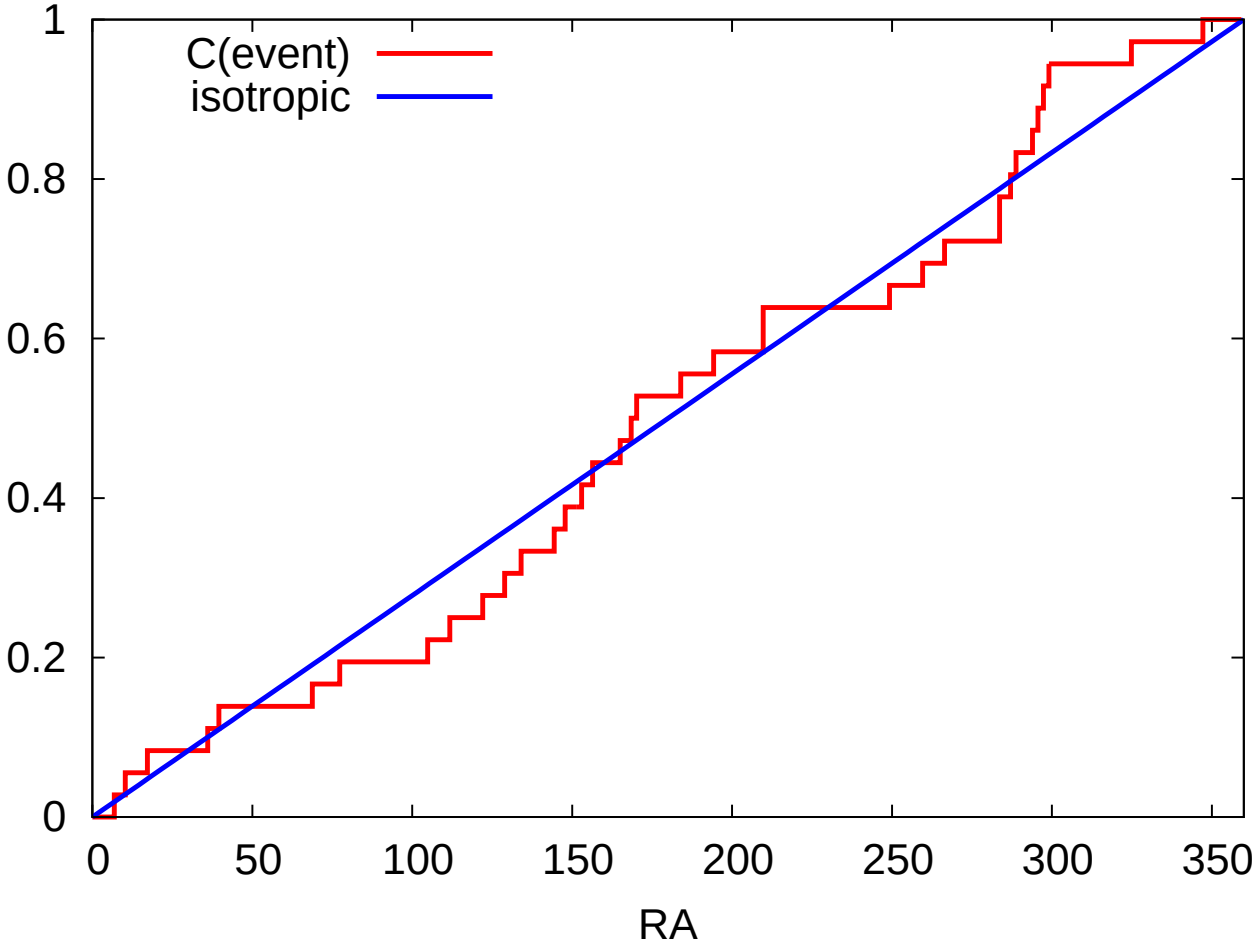

- $p = 20\%$ for 2 yr, $p = 8\%$ for 3 yr data set

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Flavour ratio

- ratio $R = N_{\rm sh}/N_{\rm tr} \sim (N_e + N_\tau)/N_\mu \sim 21/7$ consistent with 1:1:1
- including atm. bg. favors (weakly) 1:0:0 at source [*Mena, Palomares, Vincent '14*]

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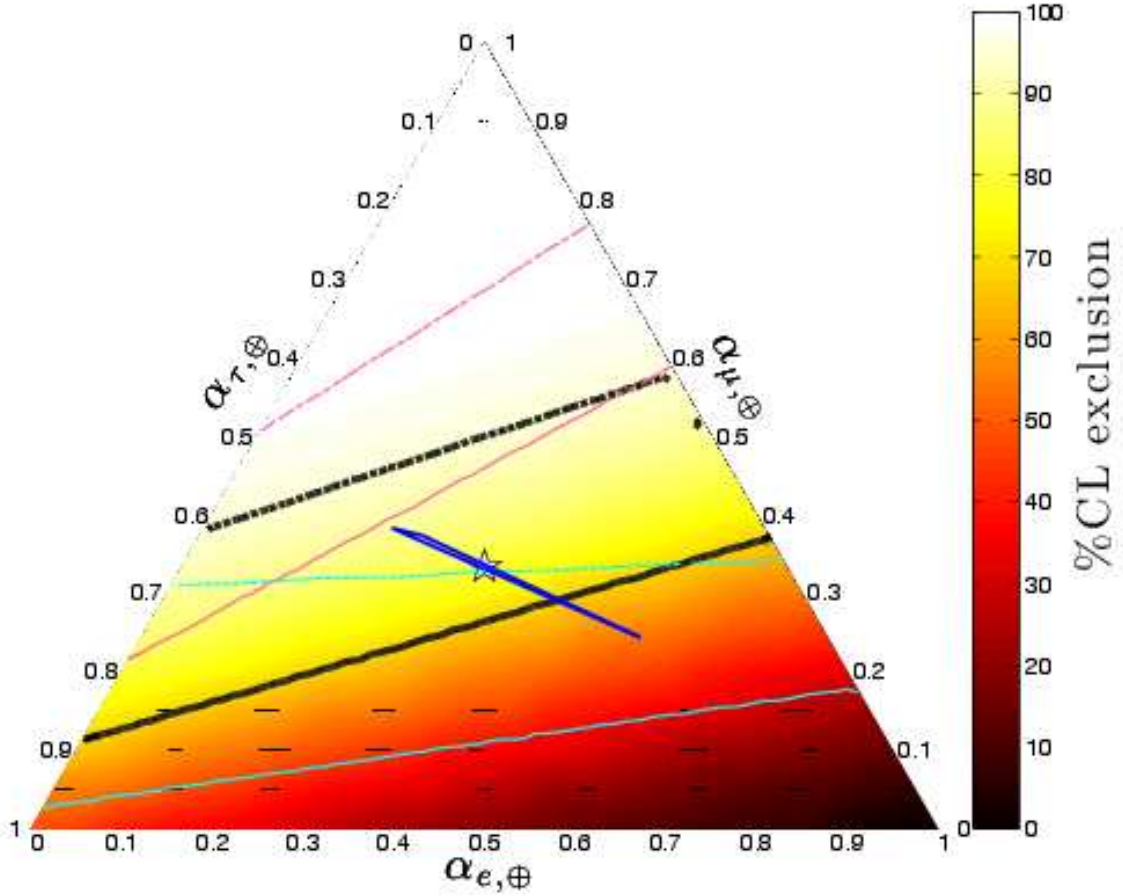


Sources of high-energy neutrinos

Galactic sources:

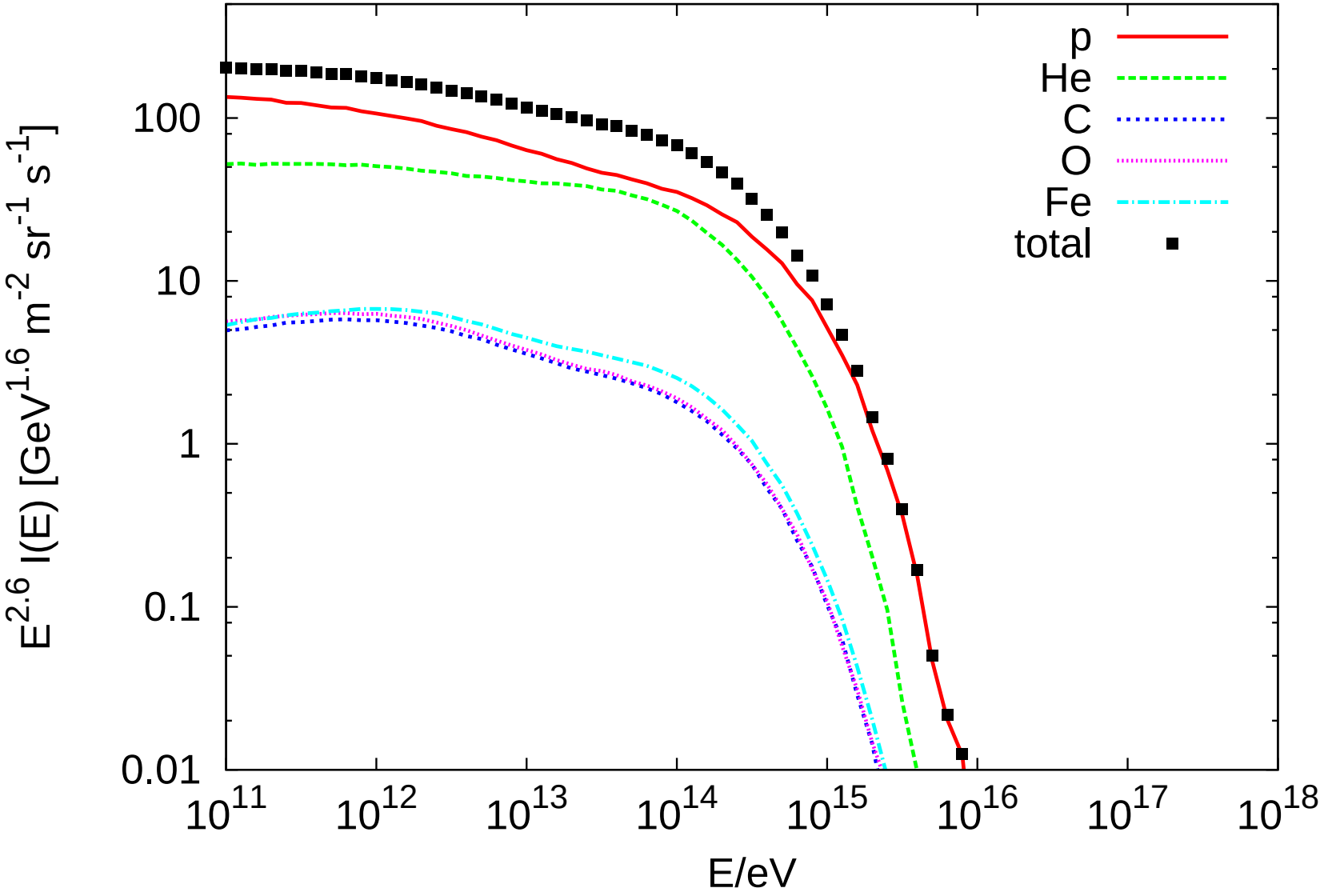
- Galactic plane and bulge
- SNR
- hypernova, GRB
- micro-quasar, ...

Extragalactic sources:

- diffuse flux from normal/starburst galaxies
- cosmogenic neutrinos
- diffuse flux from AGN
- GRB
- single AGN, ...

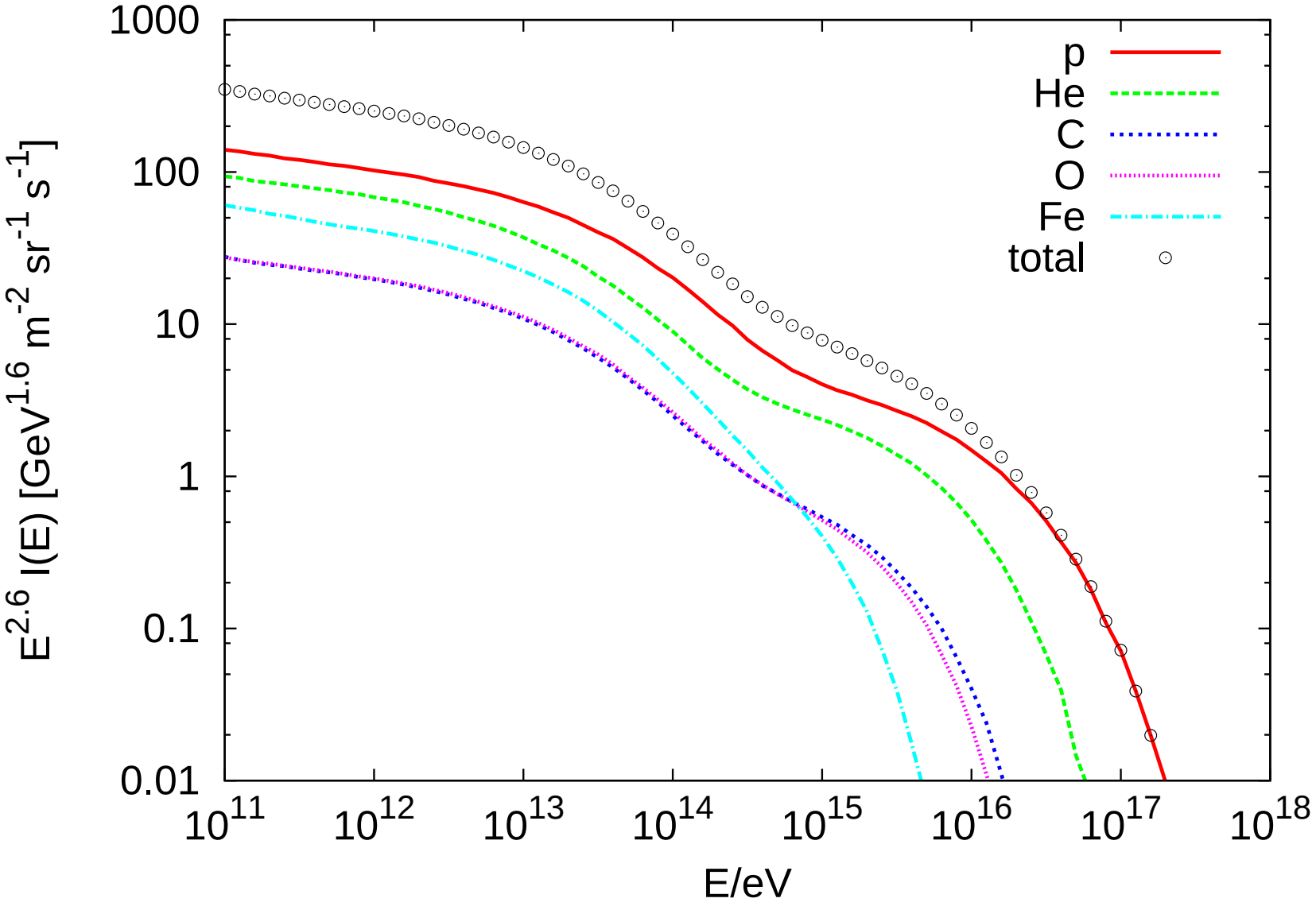
Dark matter decays, topological defects

Neutrinos from Galactic Sea CRs: "Hillas" $X = 30\,\mathrm{g/cm^2}$



[MK, S.Ostapchenko '14]

Neutrinos from Galactic Sea CRs: "escape" $X = 30\,\mathrm{g/cm^2}$



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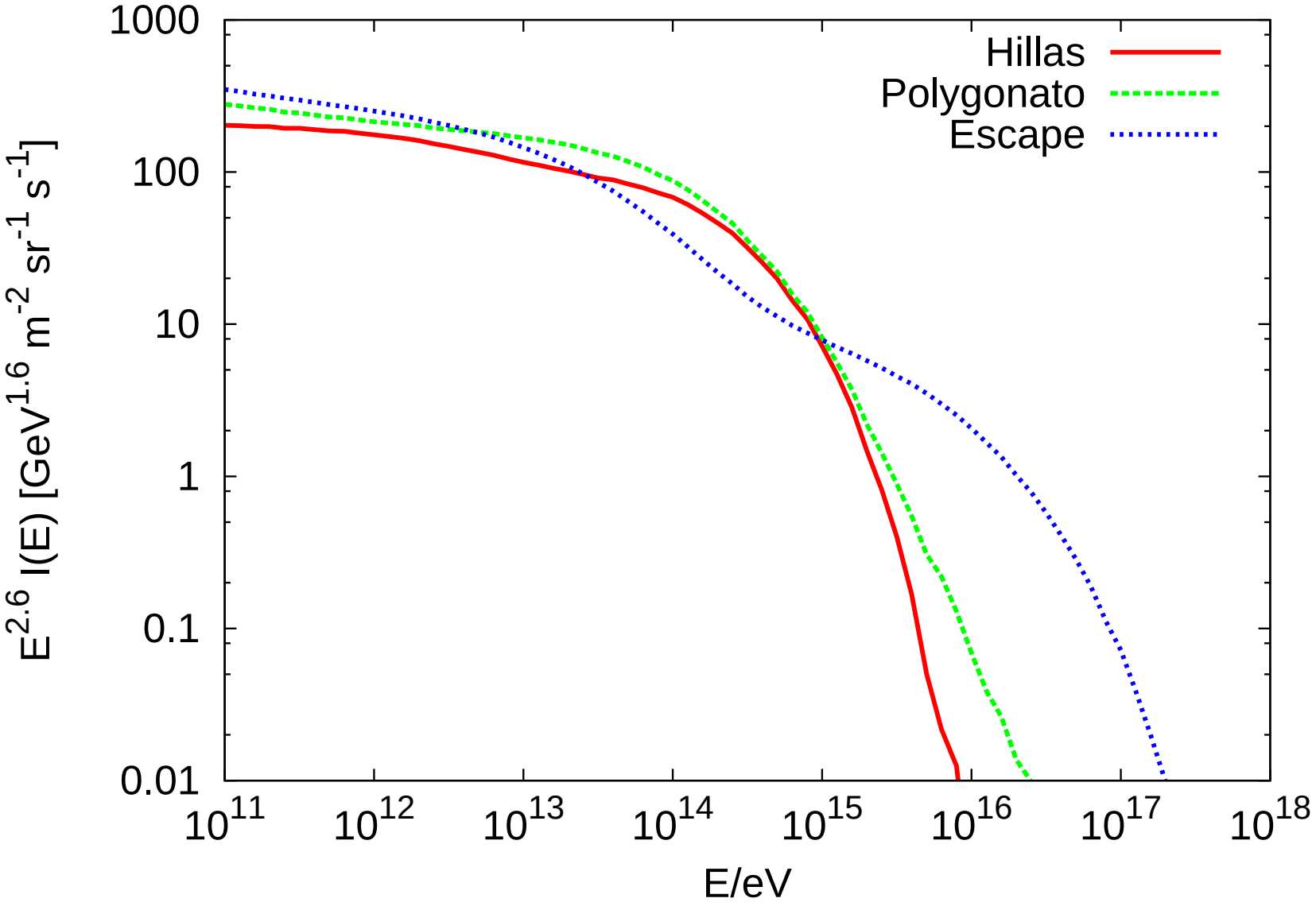

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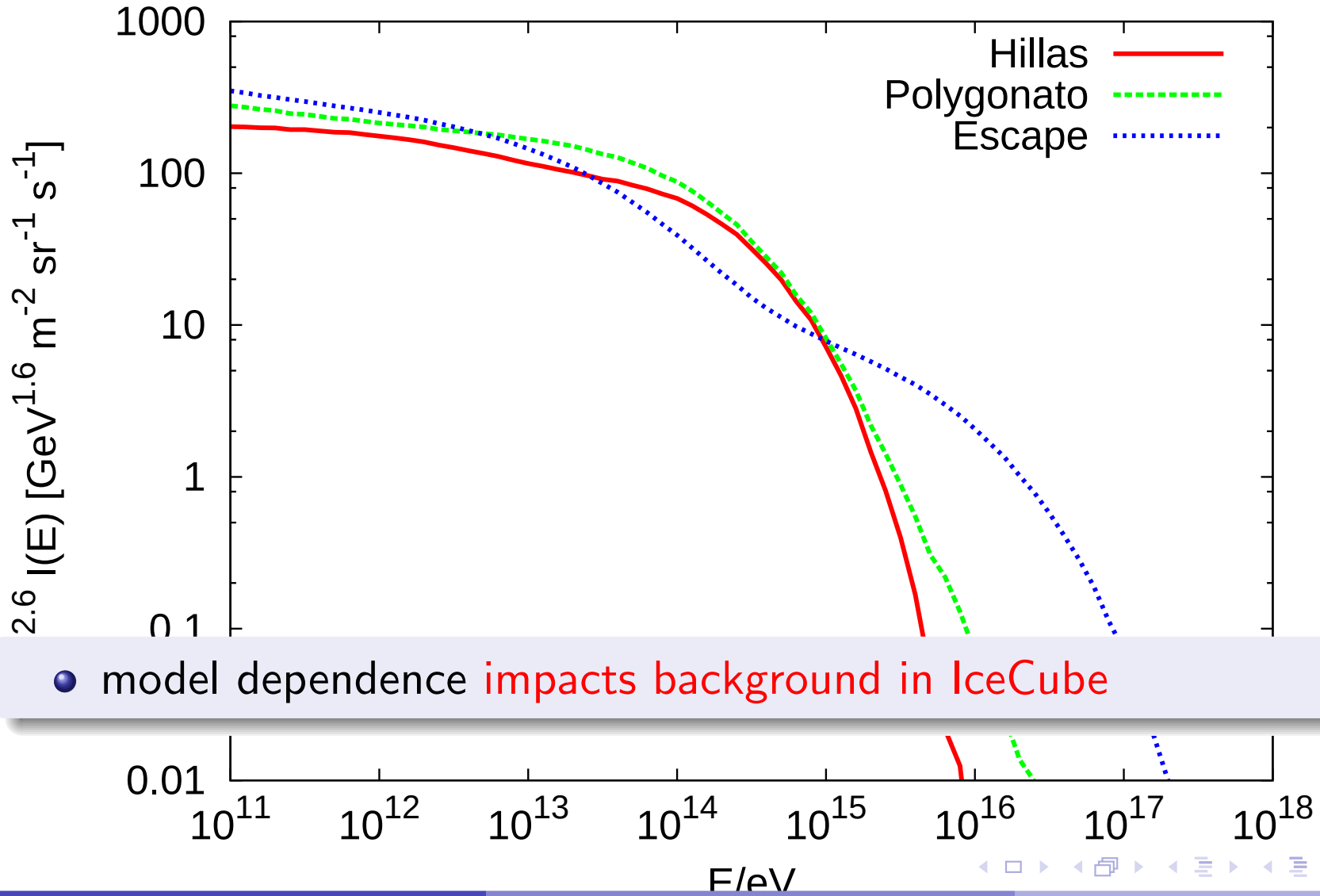

- model dependence impacts background in IceCube

Neutrinos from Galactic Sea CRs

gives negligible contribution to IceCube signal

- τ_{pp} is too small even towards GC
- gas is concentrated as $n(z) \sim n_0 \exp[-(z|/z_{12})^2]$ with $z_{12} \sim 0.2\,\mathrm{kpc}$

results apply also to other normal galaxies as starburst galaxies:

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- magnetic fields factor 100 higher:
- if knee is caused by
  - diffusion: $E_{\mathrm{cr}} \sim B$, neutrino knee at few $\times 10^{16}$ eV
  - source: $E_{\mathrm{max}} \sim B_{\mathrm{CR}}$, neutrino knee at few $\times 10^{14}$ eV

Galactic sources

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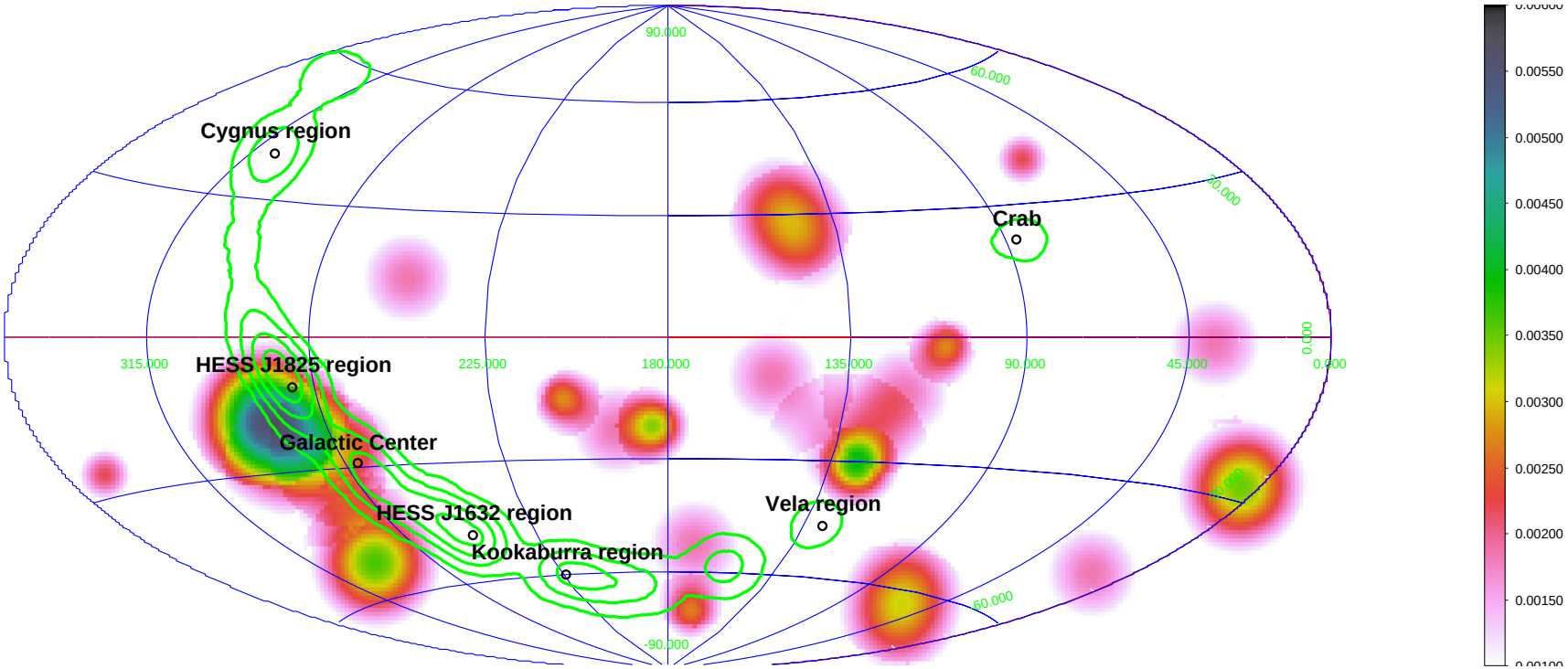
- at low energies:
  - many sources, large confinement times
  - $\Rightarrow$ average CR sea plus few recent sources
- close to the knee:
  - CRs in PeV range spread fast
  - few extreme sources
  - $\Rightarrow$ inhomogenous CR sea, extended sources
  - $\Rightarrow$ no clear distinction between point sources vs. Galactic bulge + plane cases

Point source in gamma-ray

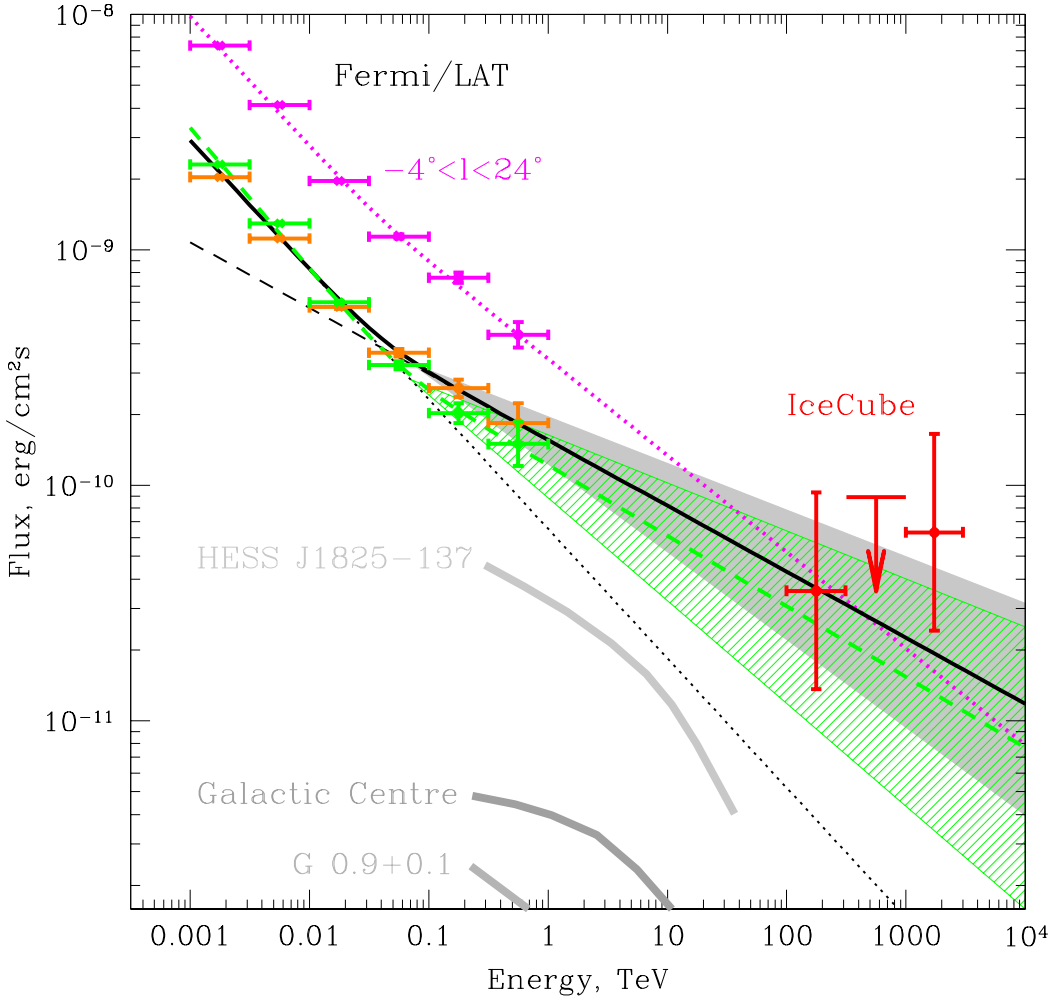
- source HESS J1825-137

[*Neronov, Semikoz, Tchernin '13*]

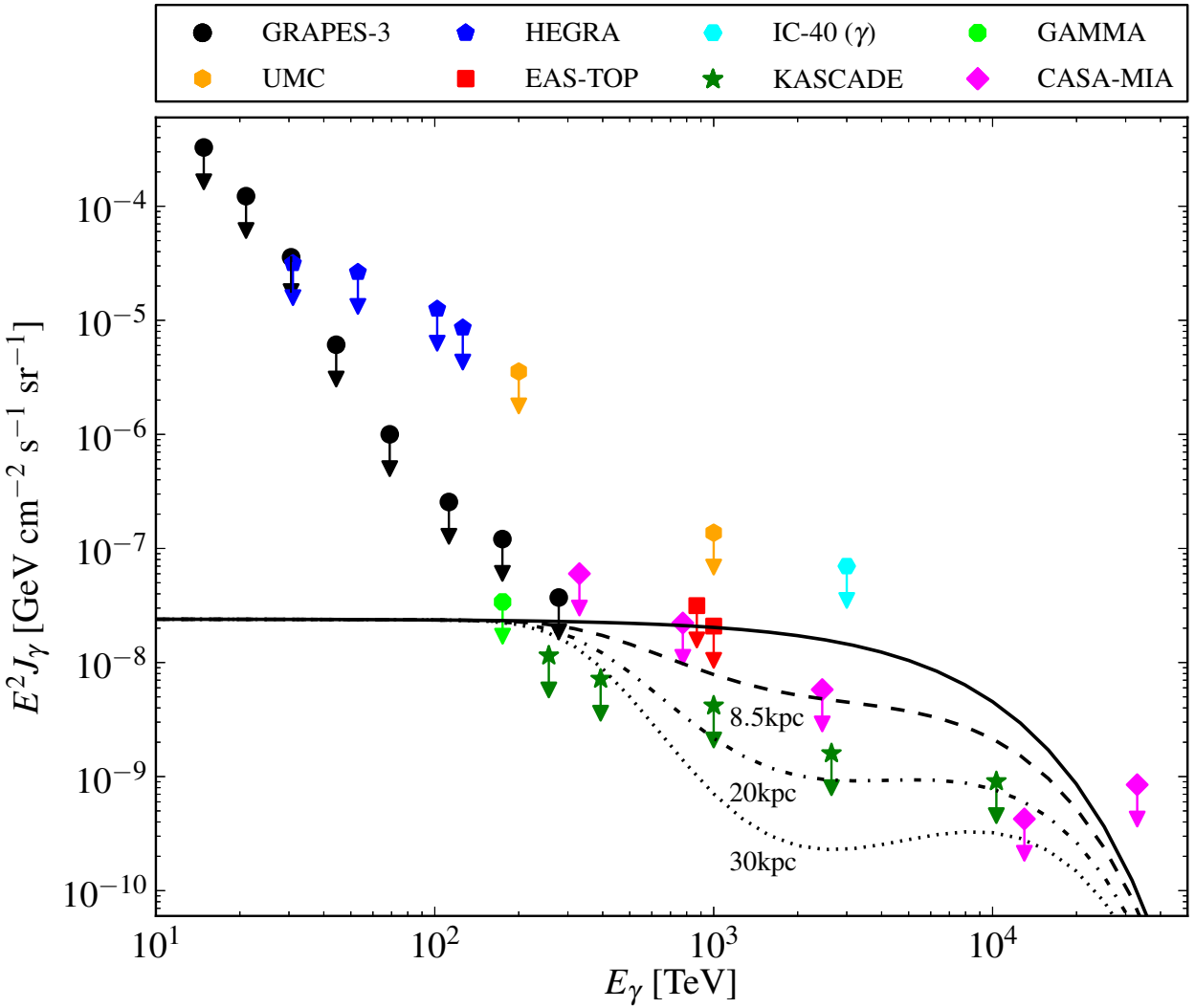


Gamma-ray point sources

- flux from HESS J1825-137, GC and GP

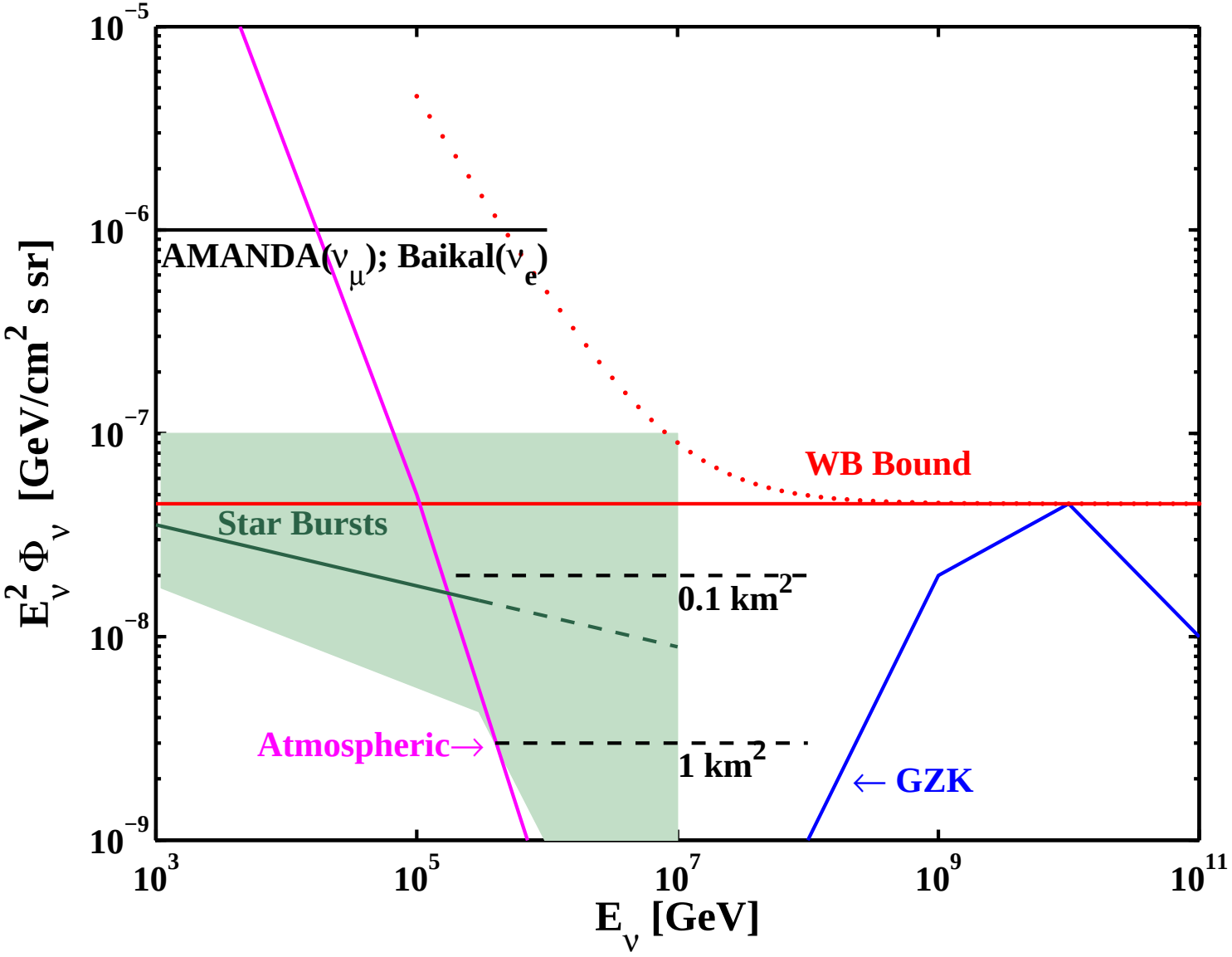


(Isotropic) photon limits



[Ahlers, Murase '13]

Diffuse ν flux from normal and starburst galaxies



[Loeb, Waxman '06]

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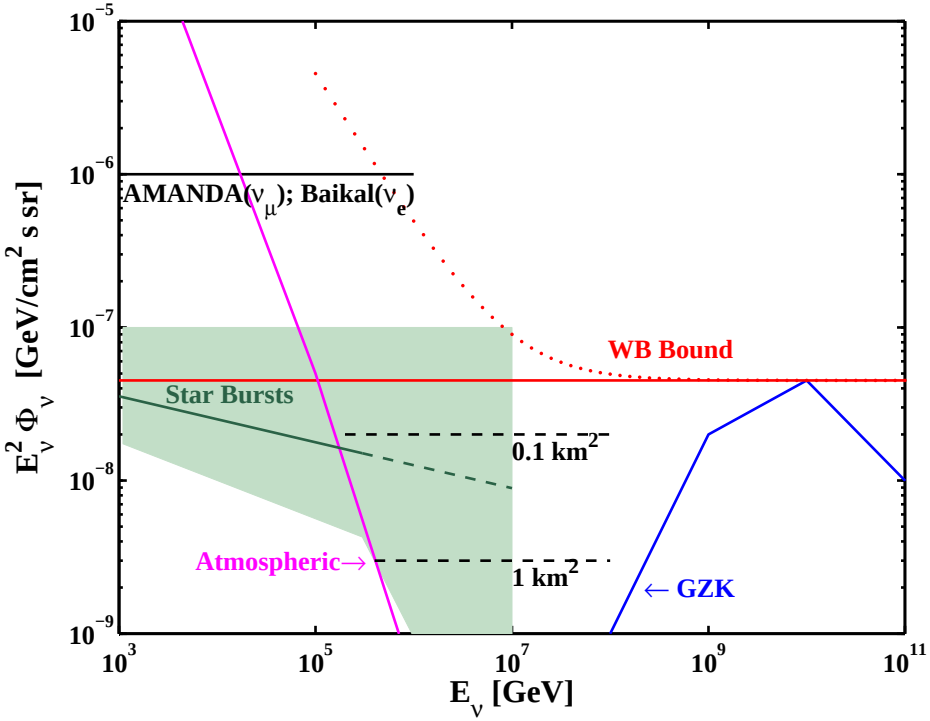
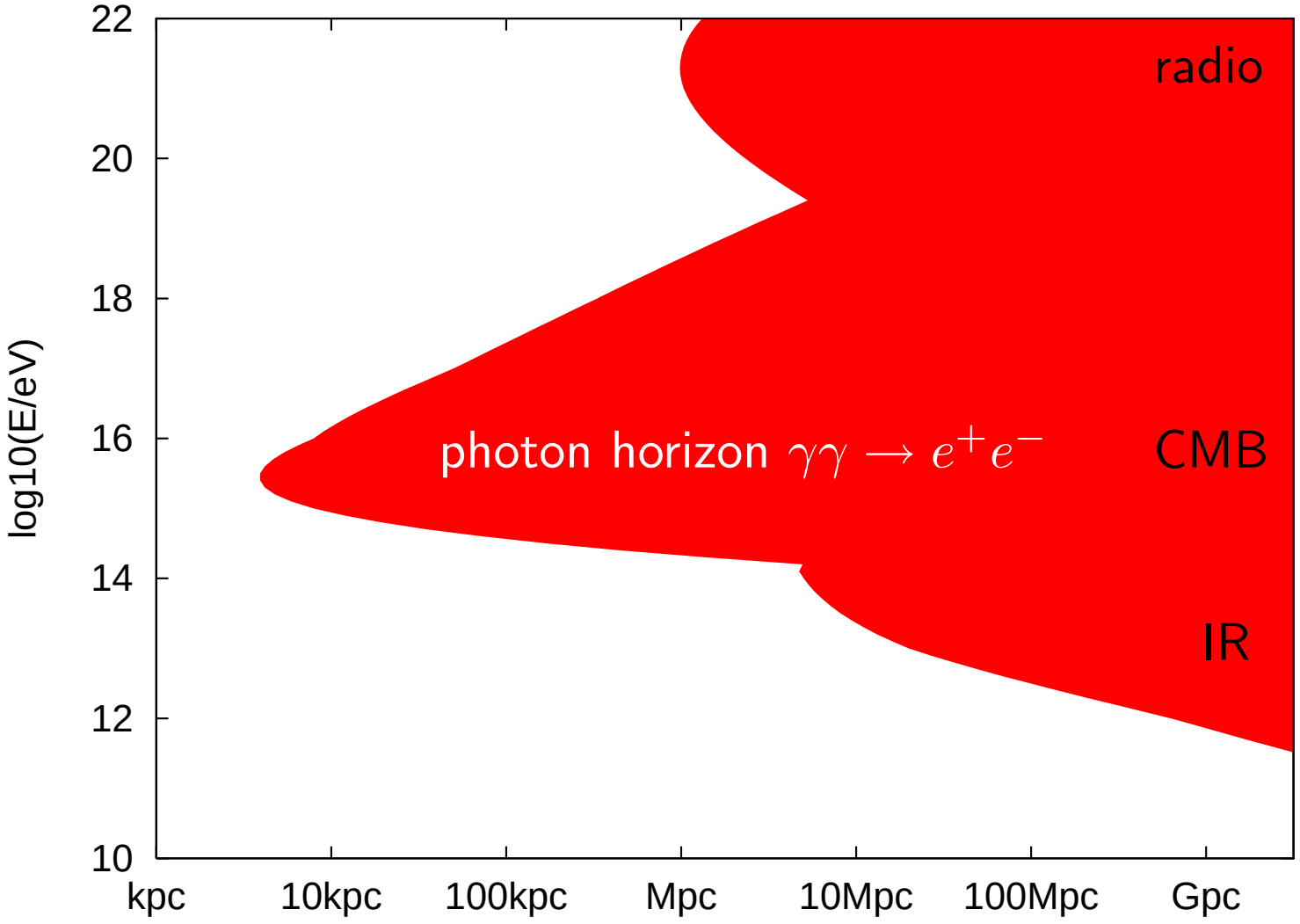


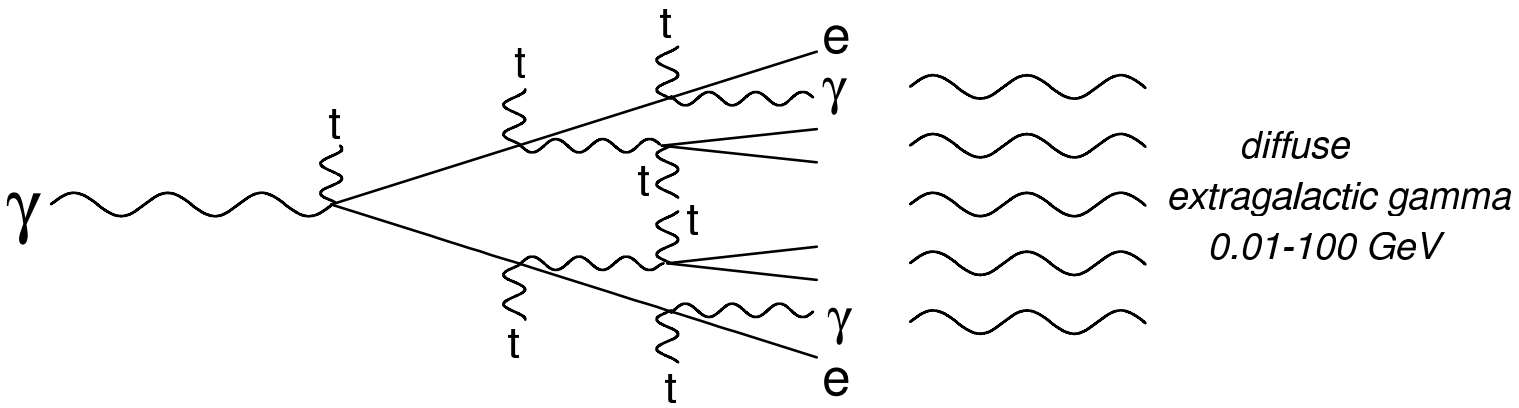
[*Loeb, Waxman '06*]

- too optimistic?
  - fraction of starbust galaxies?
  - all calorimetric?

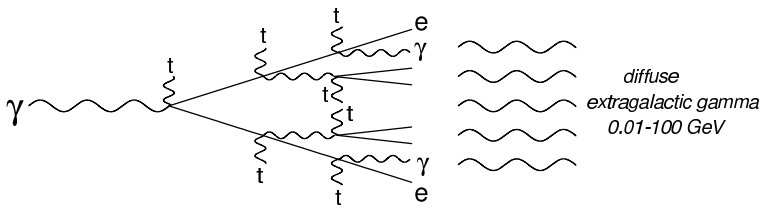
Reminder: The photon horizon



Development of the elmag. cascade:



Development of the elmag. cascade:



- analytical estimate: [*Strong '74, Berezinsky, Smirnov '75*]

$$J_\gamma(E) = \begin{cases} K(E/\varepsilon_{\rm X})^{-3/2} & \text{at} \quad E \leq \varepsilon_{\rm X} \\ K(E/\varepsilon_{\rm X})^{-2} & \text{at} \quad \varepsilon_{\rm X} \leq E \leq \varepsilon_{\rm a} \\ 0 & \text{at} \quad E > \varepsilon_{\rm a} \end{cases}$$

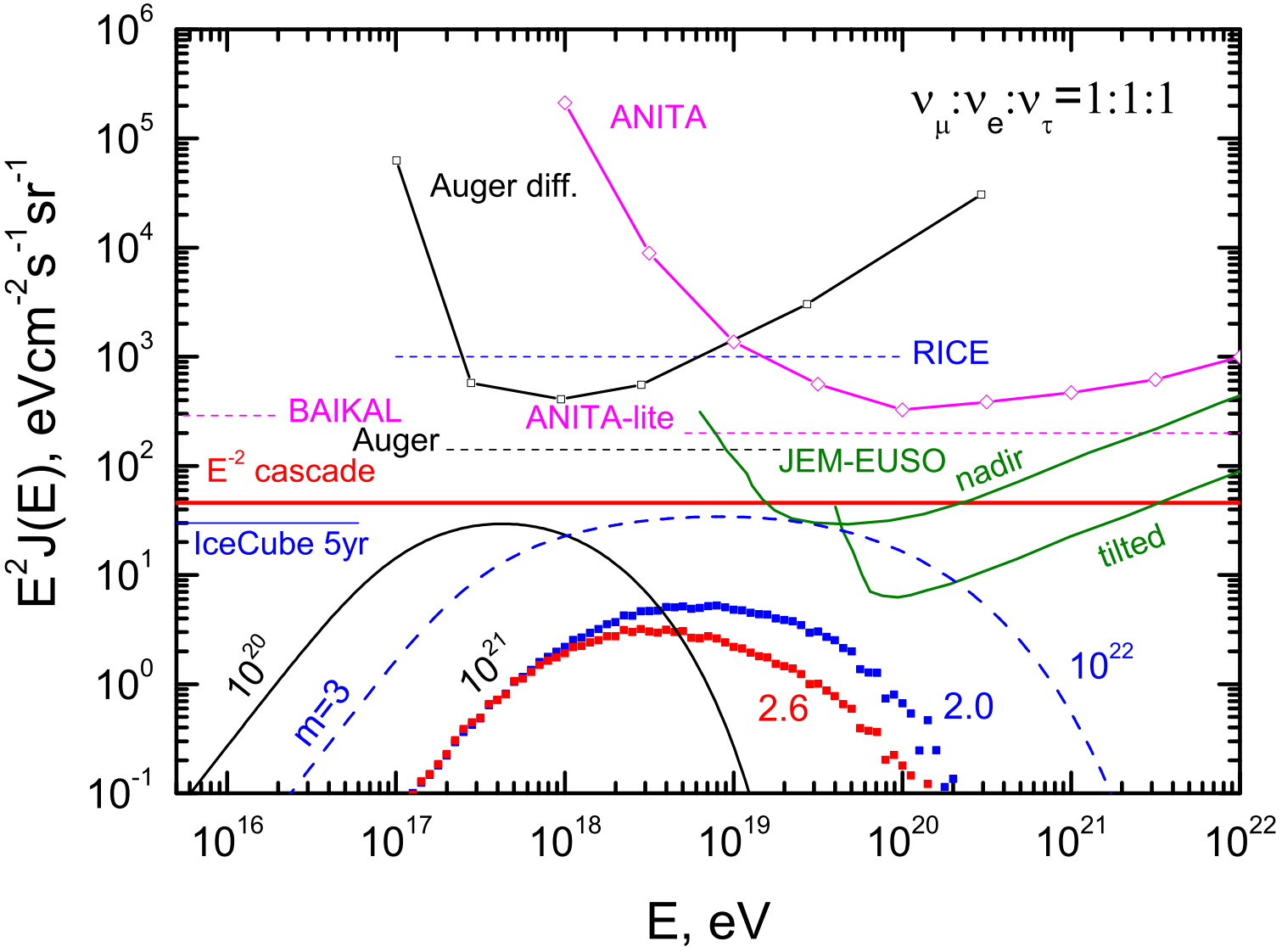
- three regimes:
  - Thomson cooling:

$$E_\gamma = \frac{4}{3}\frac{\varepsilon_{\rm bb} E_e^2}{m_e^2} \approx 100\,{\rm MeV}\left(\frac{E_e}{1{\rm TeV}}\right)^2$$

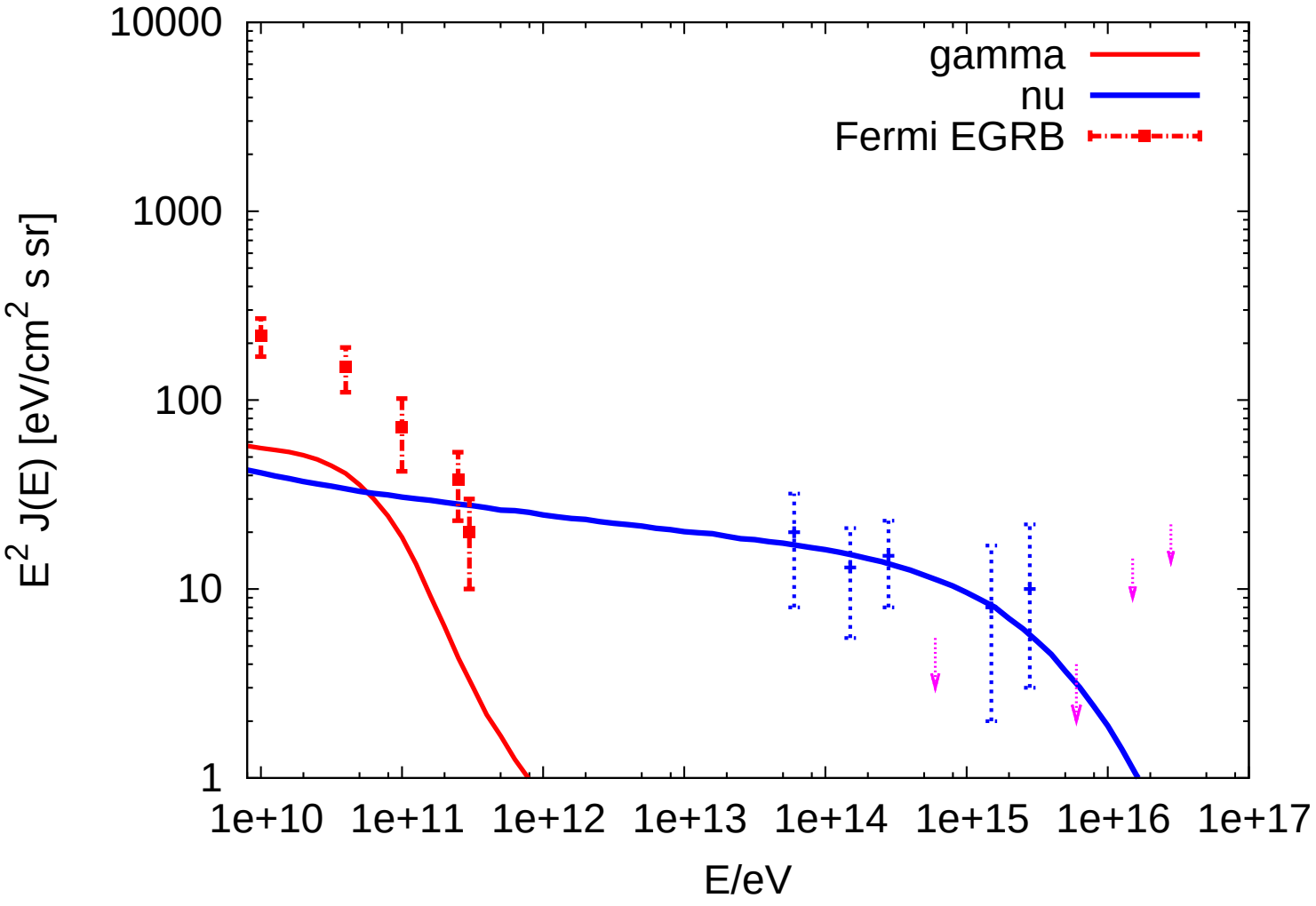
  - plateau region: ICS $E_\gamma \sim E_e$
  - above pair-creation threshold $s_{\rm min} = 4E_\gamma \varepsilon_{\rm bb} = 4m_e^2$: flux exponentially suppressed

Fermi limit for cosmogenic neutrinos:

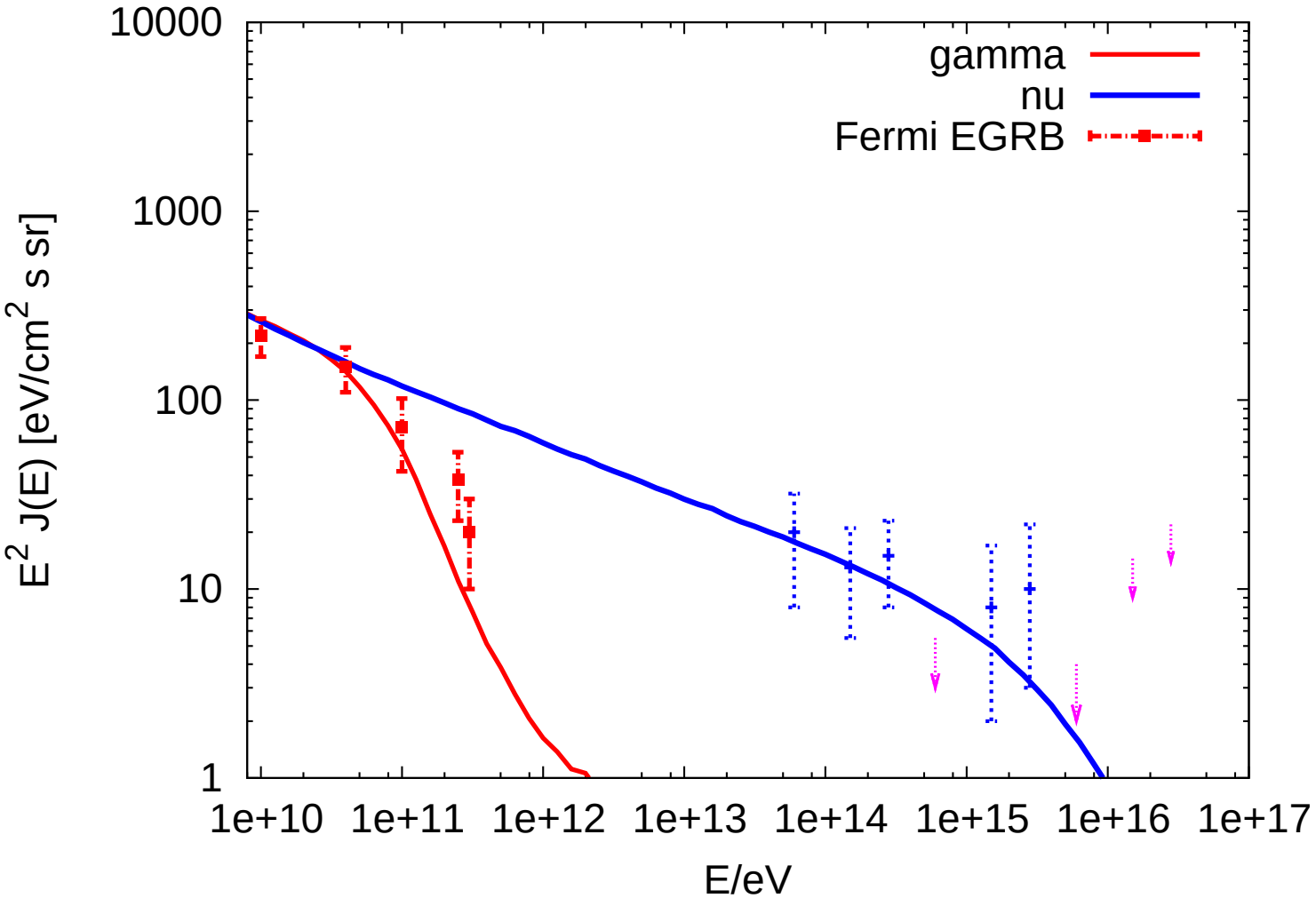
[*Berezinsky et al. '10*]



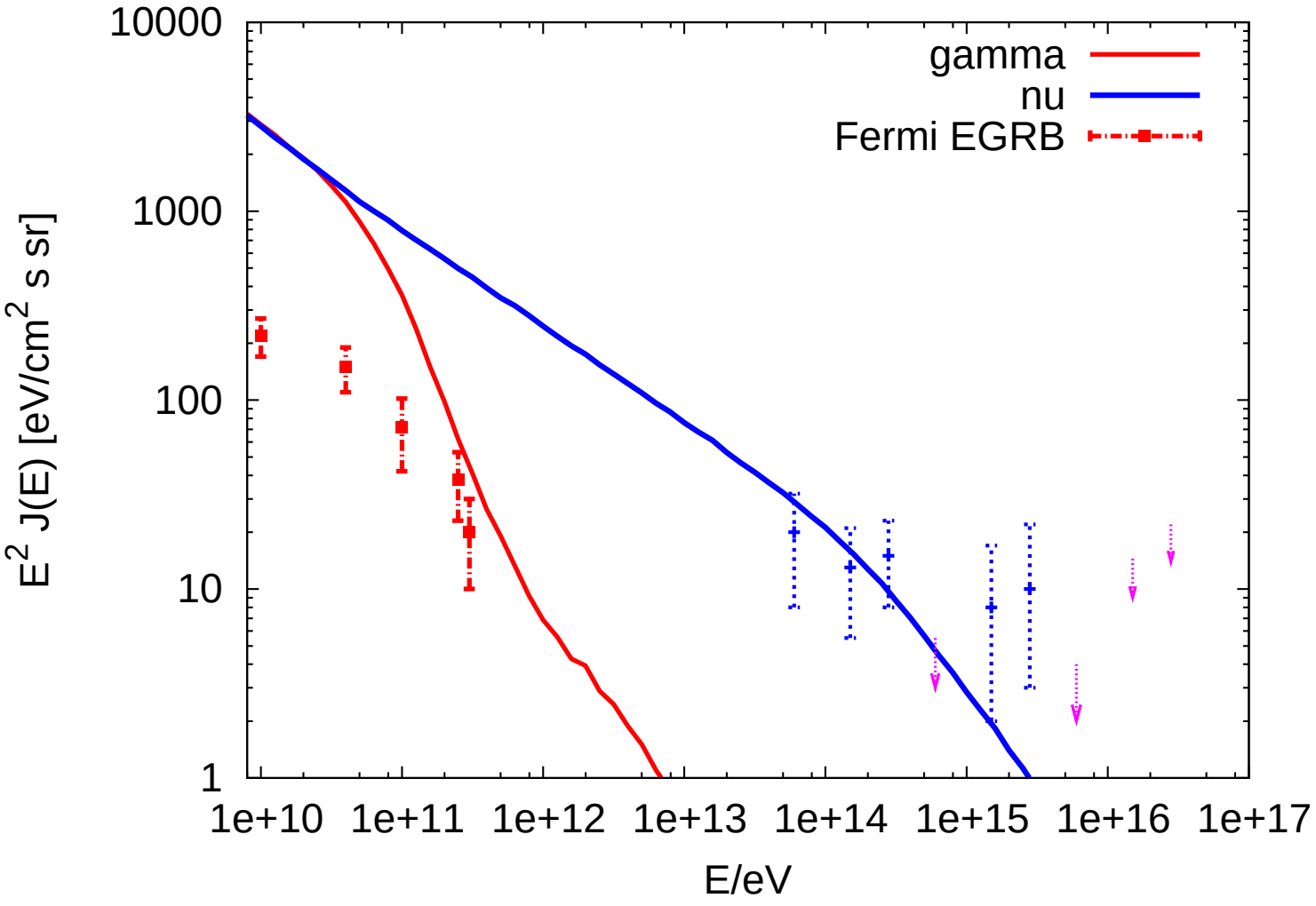
Cascade limit: $\alpha = 2.1$



Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



IceCube limit on GRBs

- 215 optically detected GRBs stacked

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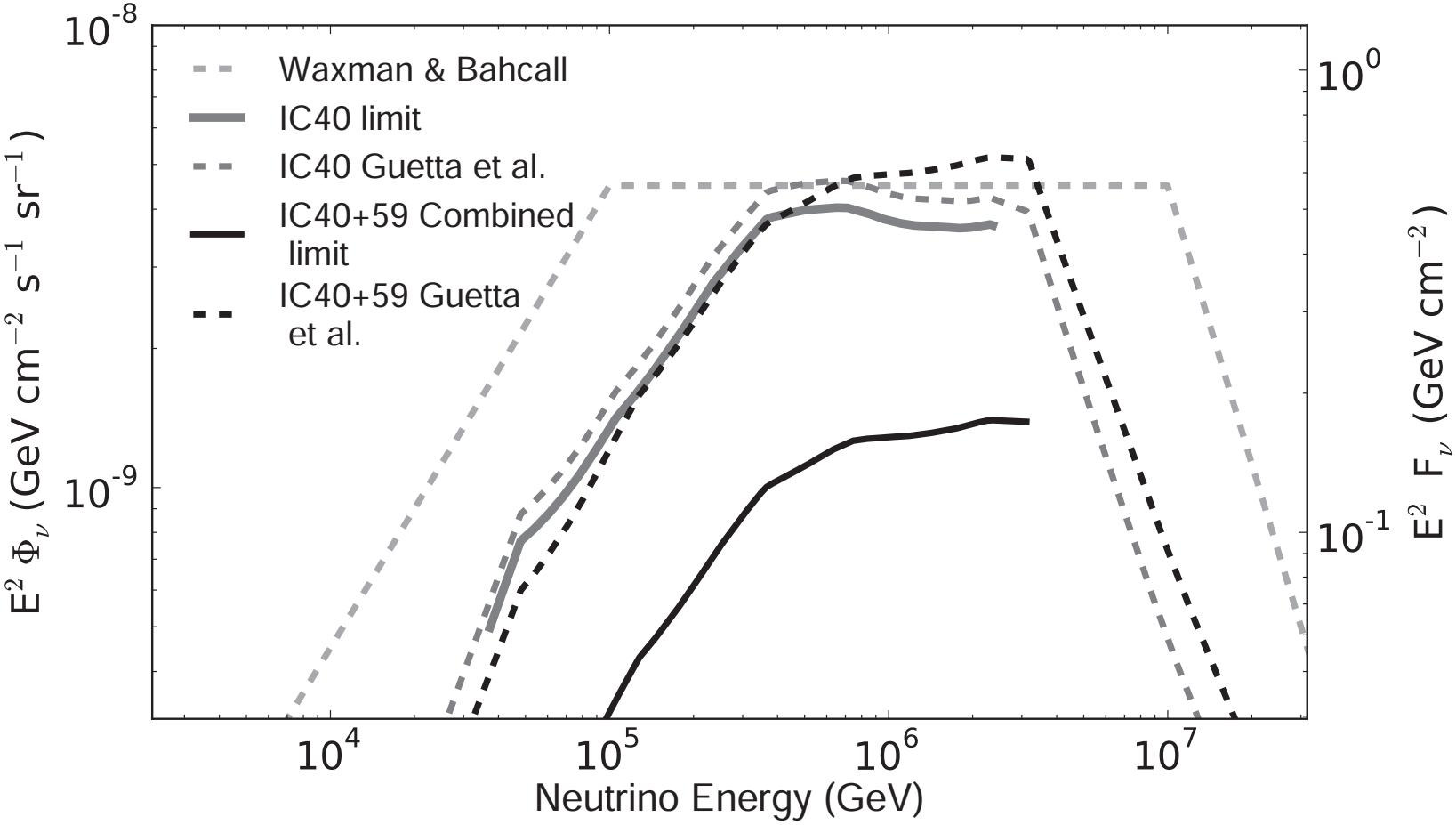

PeV dark matter

re-incarnation of SHDM idea for AGASA excess:

- non-hermal DM
- avoids cascacde limit
- Galactic anisotropy
- some option to move initial flavor ration $1:2:0$ towards $1:0:0$

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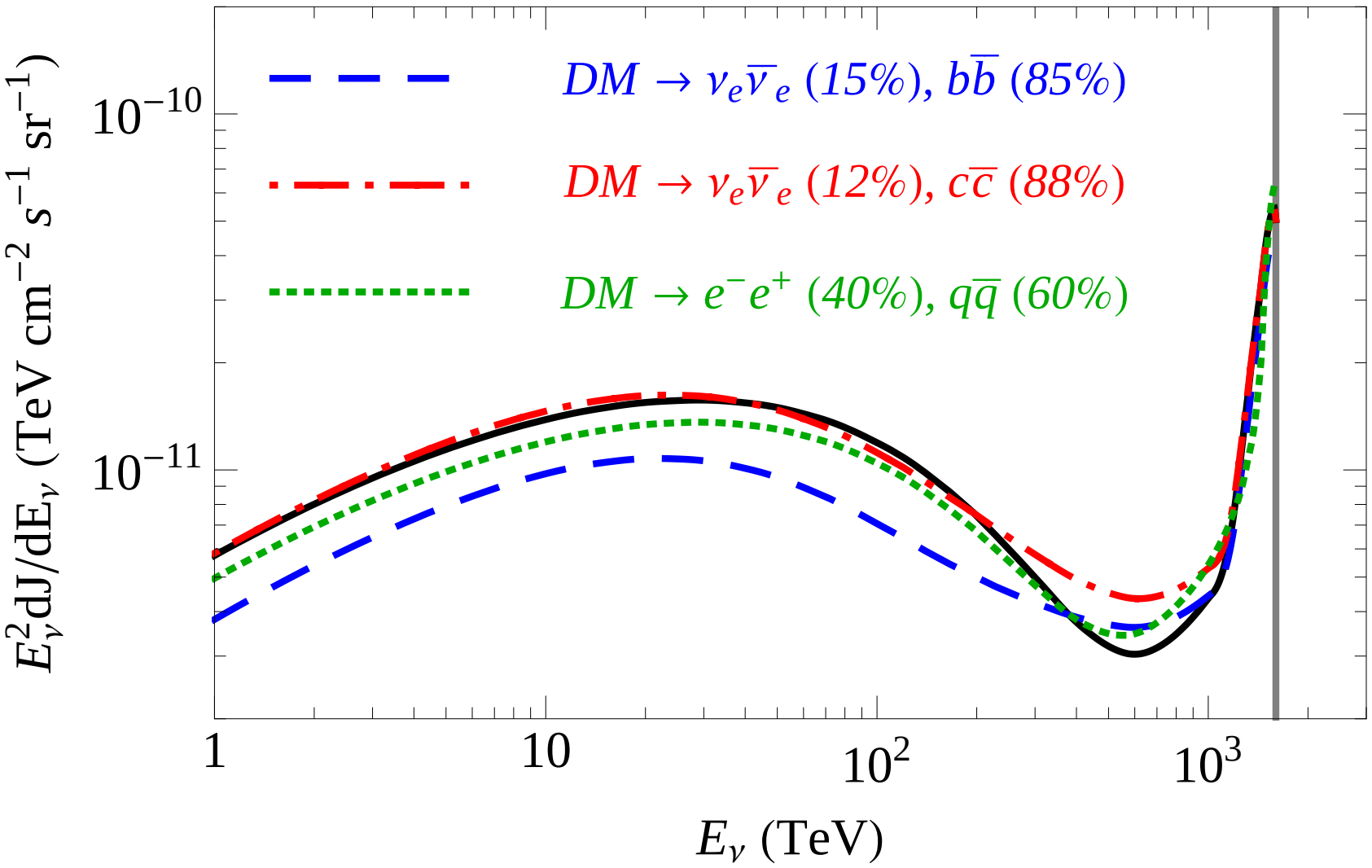

[Esmaili, Serpico '13]

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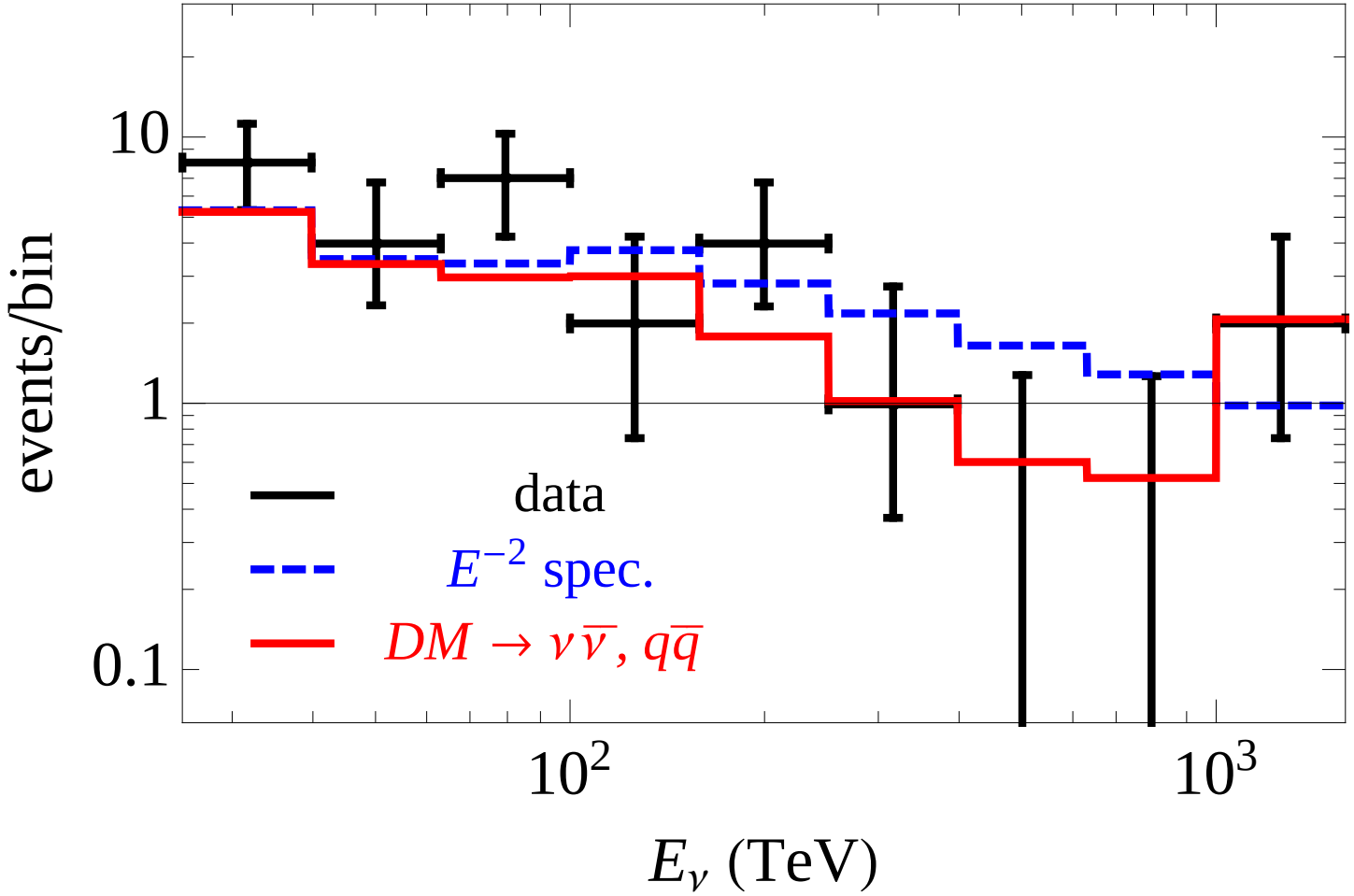

[Esmaili, Serpico '13]

Summary

1. excess towards GC, consistent (?) with γ-ray data

$\Rightarrow$ partly Galactic origin

2. no enhancement towards Galactic plane:
   - gas too narrow, flux too low
3. some tension with (Northern) γ-ray limits
4. extragalactic:
   - dominant isotropic component
   - diffuse, difficult to identify
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