Astrophysical neutrinos

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1 Introduction

2 IceCube events
  - implications

3 Astrophysical sources
  - point sources versus diffuse flux
  - Galactic sources versus extragalactic

4 PeV dark matter

5 Summary

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   - or better speculations. . .

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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
    - ratio E_ν/E_γ determined by isospin

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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?

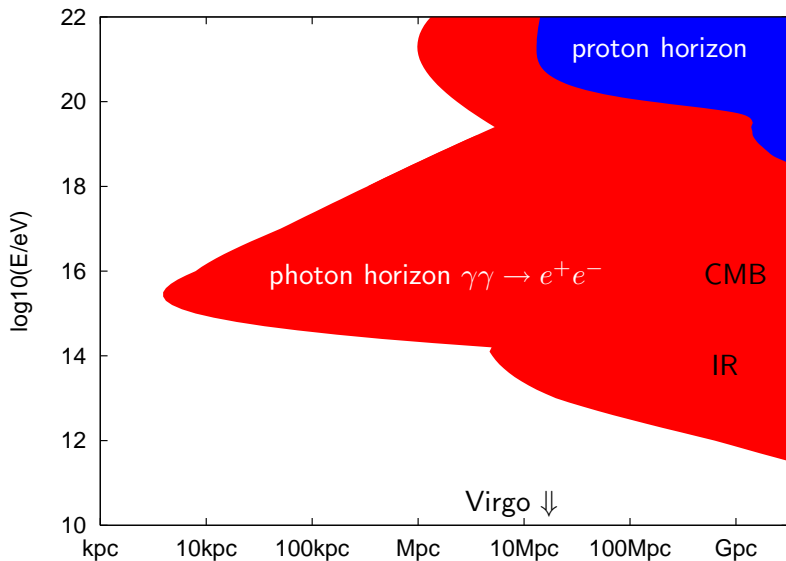- astronomy with VHE photons restricted to few Mpc:
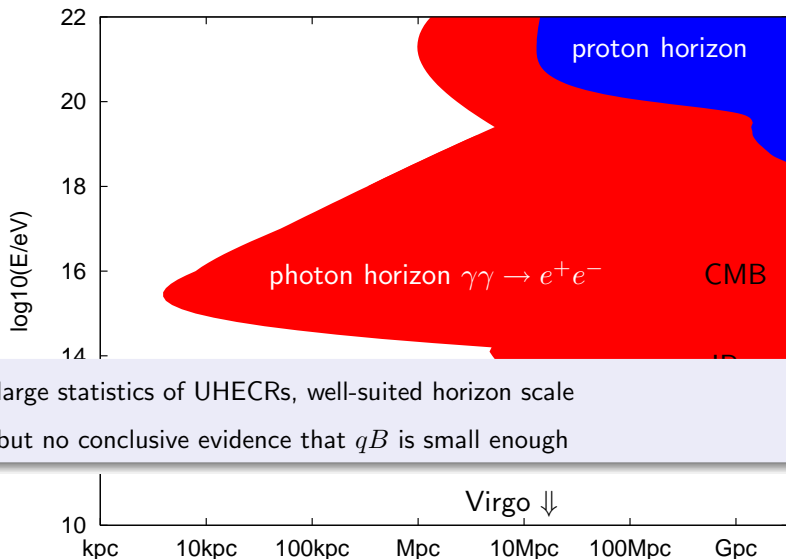
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ambiguity: leptonic/hadronic origin
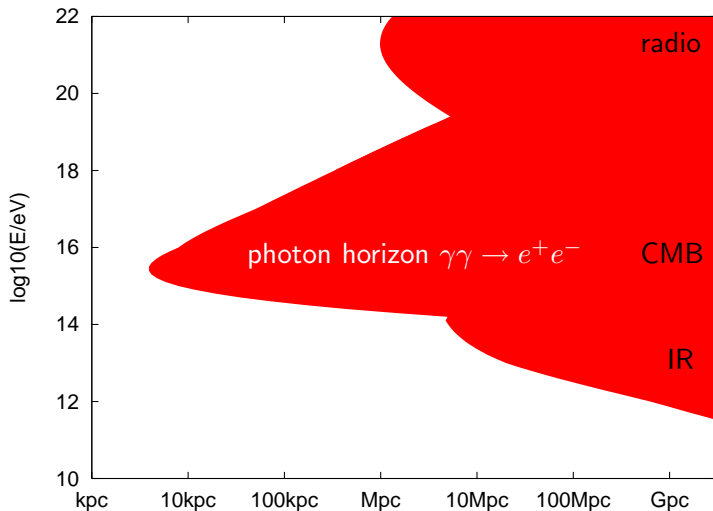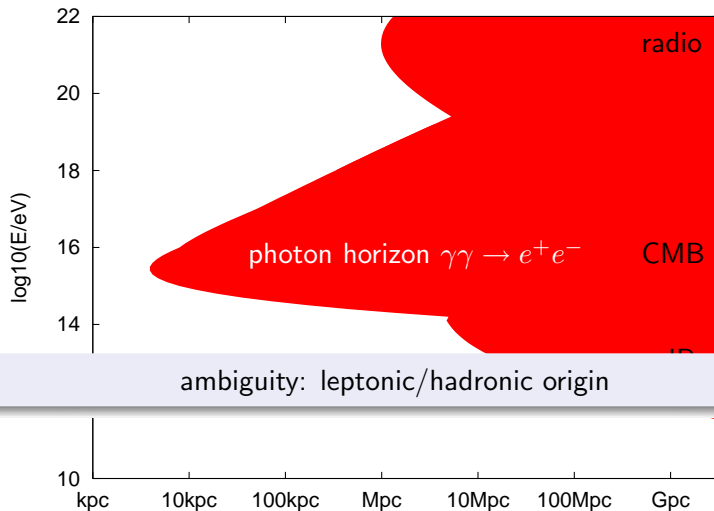
HE neutrino astronomy vs UHECRs?

HE neutrino astronomy vs UHECRs?

- ▸ large statistics of UHECRs, well-suited horizon scale
- ▸ but no conclusive evidence that qB is small enough
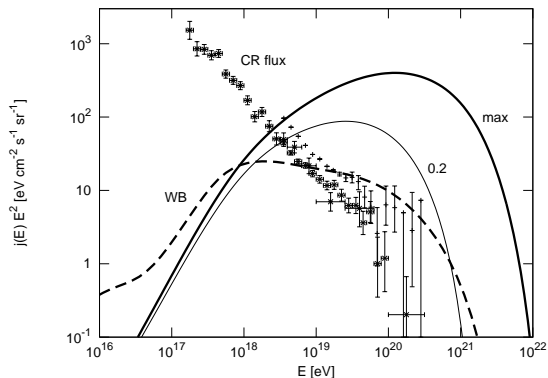
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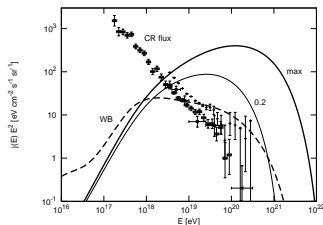- small event numbers: $\lesssim 1/\text{yr}$ for PAO or ICECUBE

$\Rightarrow$ identification of steady sources challenging

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$\Rightarrow$ identification of steady sources challenging

- correlation with AGN flares, GRBs

- which AGNs? GeV/TeV photon sources?

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 9.628x10^4
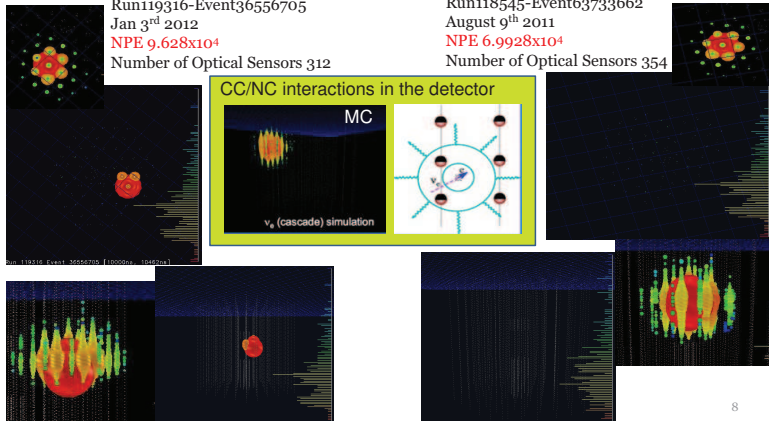Number of Optical Sensors 312

Run118545-Event63733662
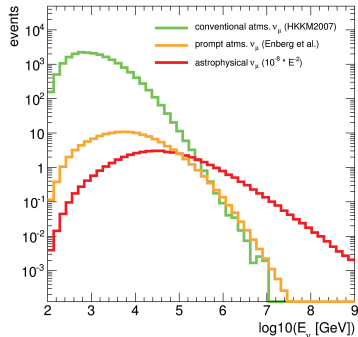August 9th 2011
NPE 6.9928x10^4
Number of Optical Sensors 354

CC/NC interactions in the detector

MC

ν_e (cascade) simulation

8

Icecube: prompt neutrino analysis [A. Schukraft, NOW2012]

Signatures of high energy ν_μ in IceCube
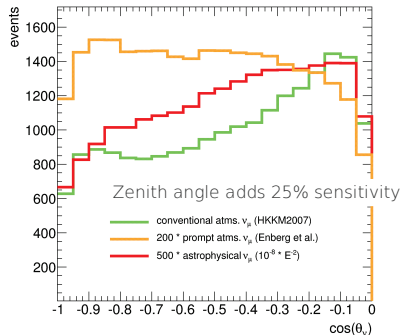
Conventional, prompt and astrophysical neutrinos can't be decoupled and need to be looked at together in a HE neutrino analysis.

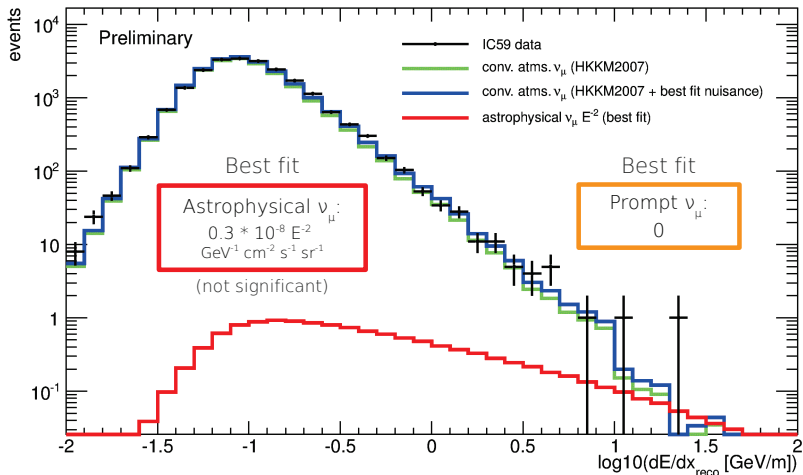# Icecube: prompt neutrino analysis

[*A. Schukraft, NOW2012*]

The final ν_μ energy spectrum

Preliminary

IC59 data
conv. atms. ν_μ (HKKM2007)
conv. atms. ν_μ (HKKM2007 + best fit nuisance)

21943 events

Deviation from conv. atms neutrino expectation:

1.8 σ

- Conv. atms. ν_μ are used to determine the nuisance parameters

- improves agreement between data and conv. ν_μ

- nuisance fit results are within expectations
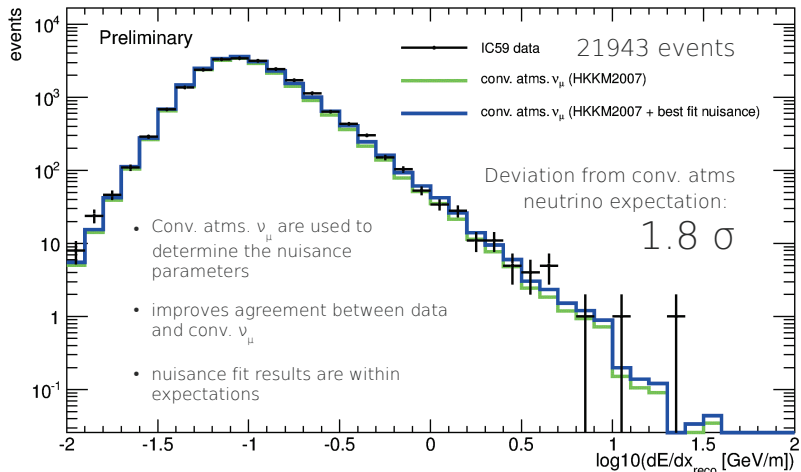
Icecube: prompt neutrino analysis [A. Schukraft, NOW2012]

The final ν_μ energy spectrum – Best fit

IceCube events
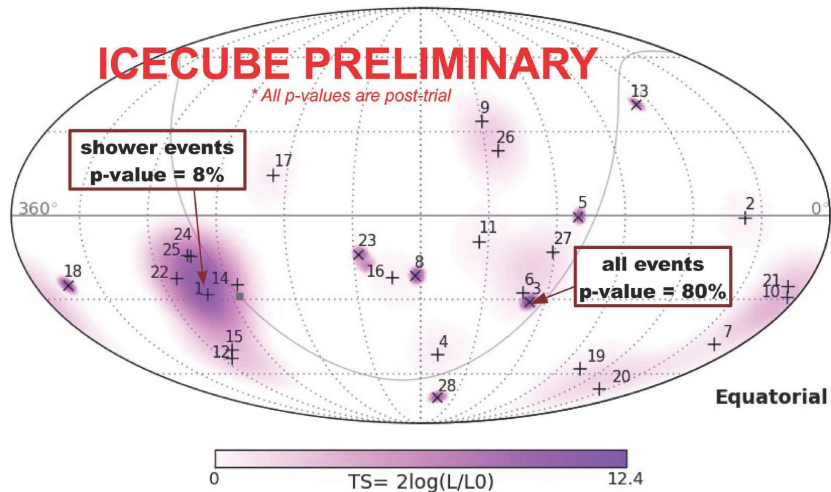
IceCube events: specifications for candidate sources

> 28 events with ~ 10 bg: flukes are possible...

- flux is large, close to
  - ▶ Waxman-Bahcall estimate
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- CR energies $E_p \sim 20 E_\nu \Rightarrow$ few$\times 10^{16}$ eV
  - ▶ high for Galactic CRs
  - ▶ lowish for cosmogenic, AGN, GRB

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- flavor ratio consistent with 1:1:1

Astrophysical sources of high-energy neutrinos

Galactic sources:

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

Extragalactic sources:

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

Galactic CRs: KASCADE-Grande 2013
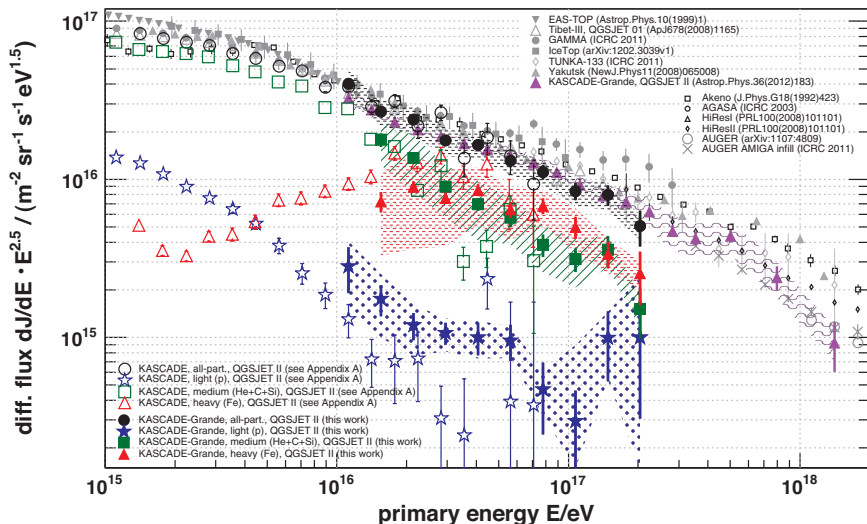
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Galactic sources

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    - ⇒ average CR sea plus few recent sources

- close to the knee:
    - ▶ CRs in PeV range spread fast
    - ▶ few extreme sources
    - ⇒ inhomogenous CR sea, extended sources
    - ⇒ no clear distinction between point sources
      vs. Galactic bulge + plane cases

$E = 100\,\text{TeV} \to 1\,\text{PeV} \to 10\,\text{PeV}$ $t = 500\,\text{yr} \downarrow 2000\,\text{yr} \downarrow 7000\,\text{yr}$

0   0.2   0.4   0.6   0.8   1
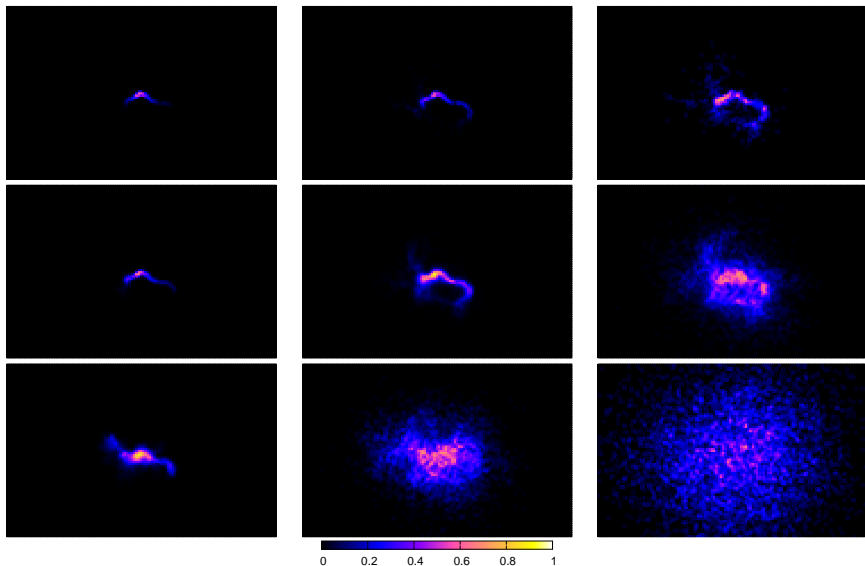
Point source in gamma-ray

- source HESS J1825-137
  [Neronov, Semikoz, Tchernin '13]
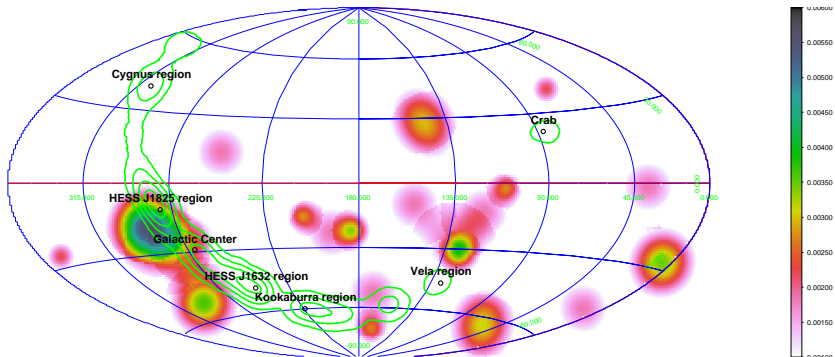
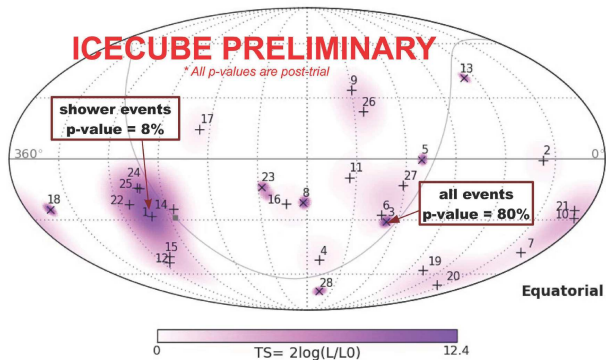# Gamma-ray point sources

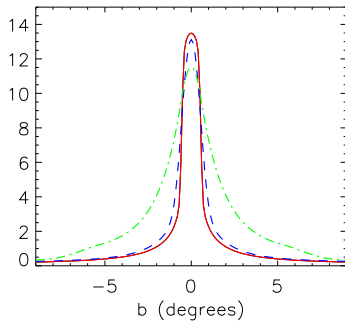- flux from HESS J1825-137, GC and GP
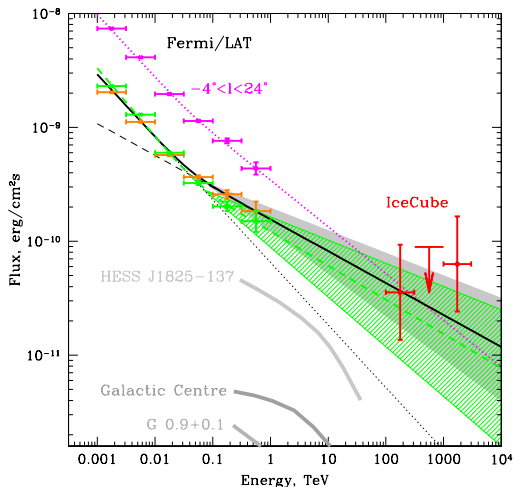
(Isotropic) photon limits
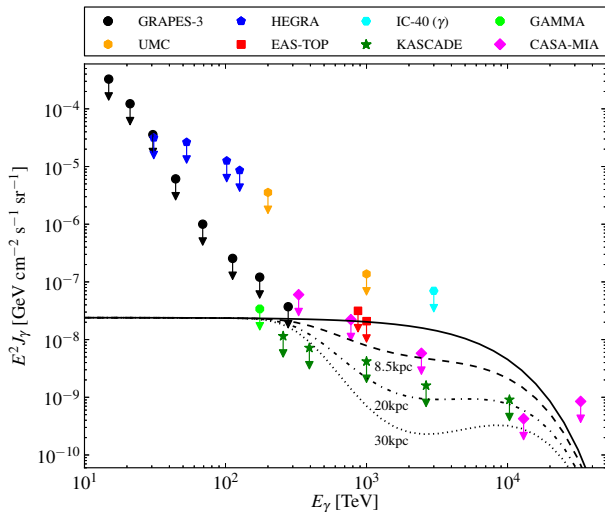
[Ahlers, Murase '13]

Galactic plane

- gas is concentrated as $n(z) \sim n_0 \exp[-(z|/z_{12})^2]$ with $z_{12} \sim 0.2\,\mathrm{kpc}$
- n_0 decreases with ρ – events at GAC?
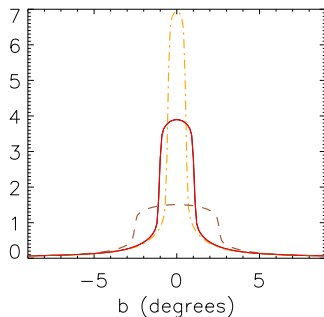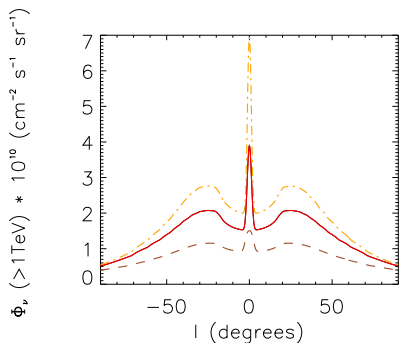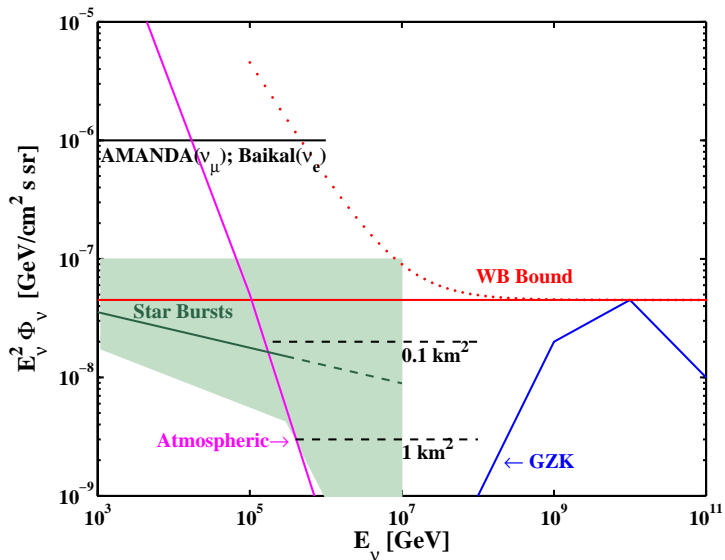
Column density of gas
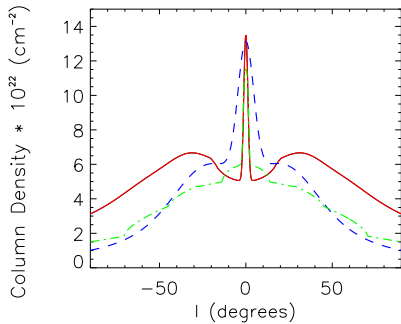
[Evoli, Grasso, Maccione '07]

Diffuse ν flux from Galactic plane

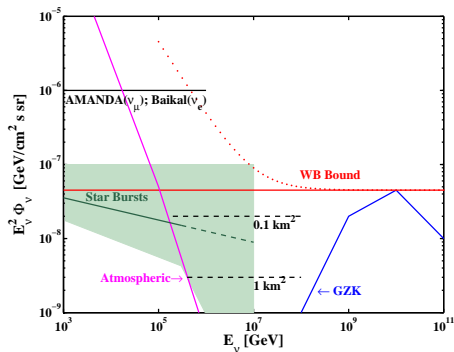[Evoli, Grasso, Maccione '07]

averaged over 1,2,5 degrees

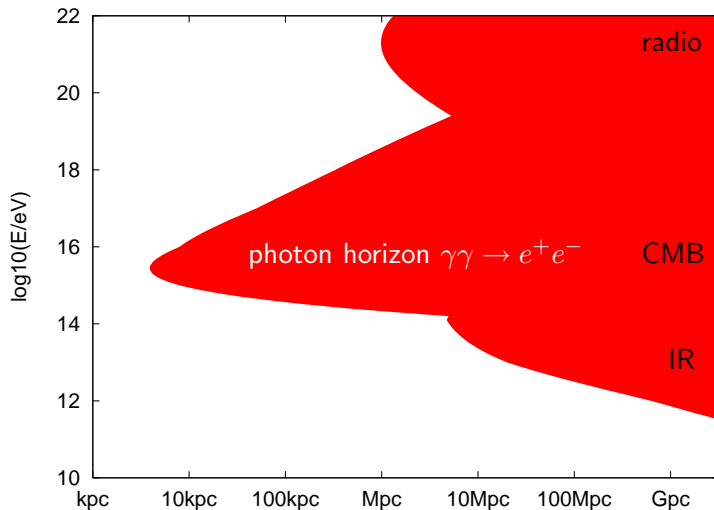# Diffuse ν flux from normal and starburst galaxies

[Loeb, Waxman '06]

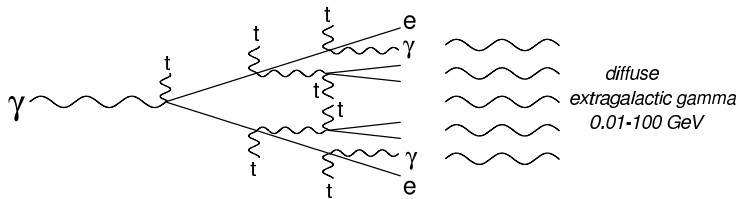# Diffuse ν flux from normal and starburst galaxies

[Loeb, Waxman '06]

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

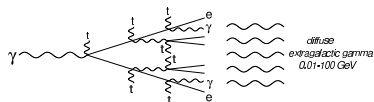# Reminder: The photon horizon

Development of the elmag. cascade:

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

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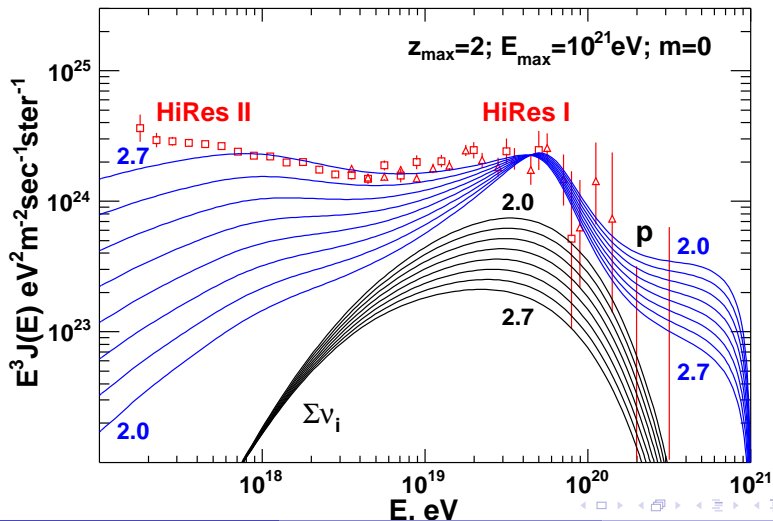$$

- three regimes:
  - ▸ Thomson cooling:

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

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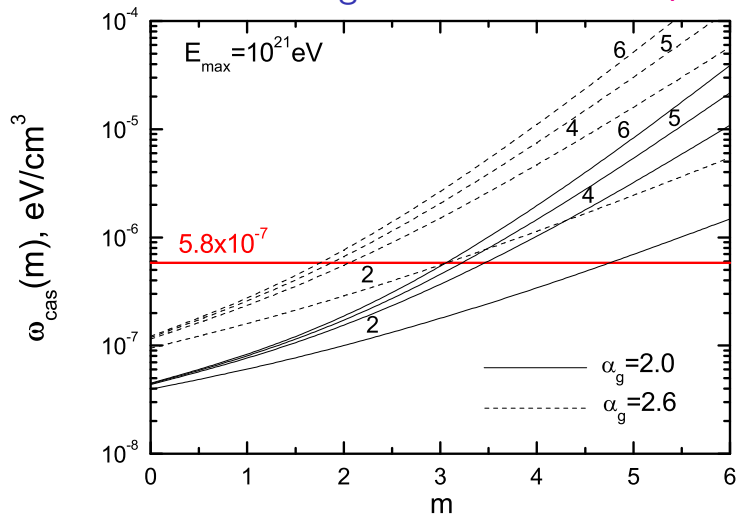 - ▸ above pair-creation threshold $s_{\min} = 4E_\gamma \varepsilon_{\mathrm{bb}} = 4m_e^2$:
    flux exponentially suppressed

Fermi limit for cosmogenic neutrinos: [Berezinsky et al. '10, Ahlers et al. '10,...]

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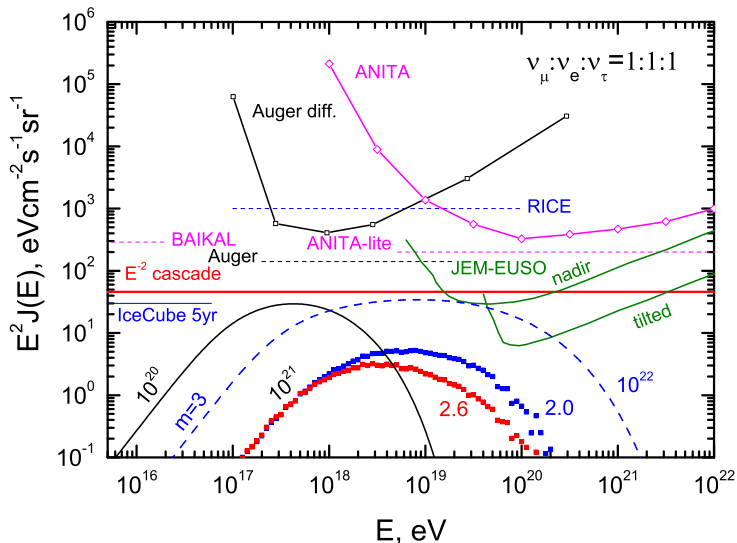

$$n(z)L(z) \propto (1+z)^m, \qquad z_{max}$$

Fermi limit for cosmogenic neutrinos: [Berezinsky et al. '10, ...]
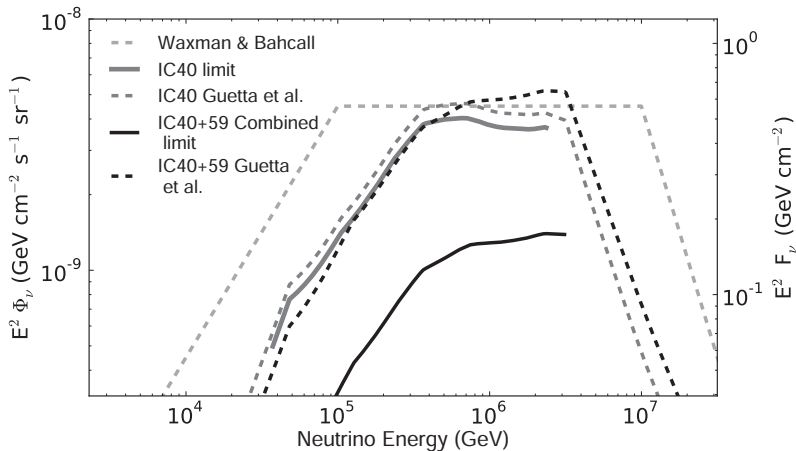
IceCube limit on GRBs

- 215 optically detected GRBs stacked
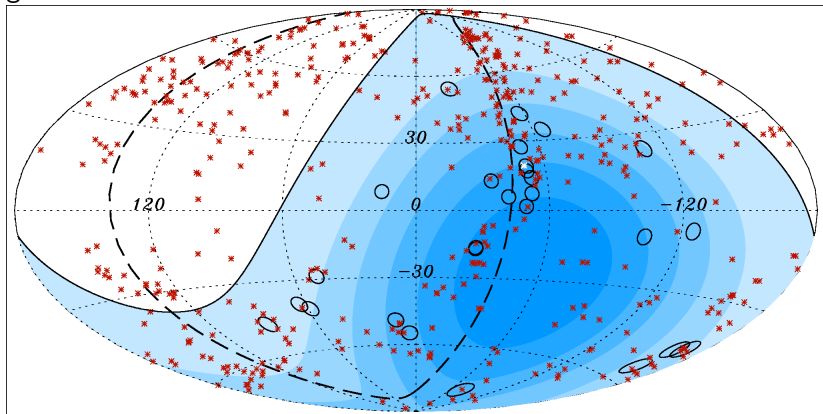
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Flux from a single AGN: Cen A

+ 2 events correlated with Cen A within $3.1°$
+ more events close-by
+ general correlation with AGN

[Gorbunov et al. '07, Fargione '08, Rachen '08]

Flux from a single AGN: Cen A

+ 2 events correlated with Cen A within $3.1°$
+ more events close-by   [*Gorbunov et al. '07, Fargione '08, Rachen '08*]
+ general correlation with AGN

− confusion with LSS?
− no confirmation by HiRes
− tension to PAO chemical composition
− E_{max} for most AGN (incl. Cen A) high enough?

Acceleration close to the core: $\alpha = 2$
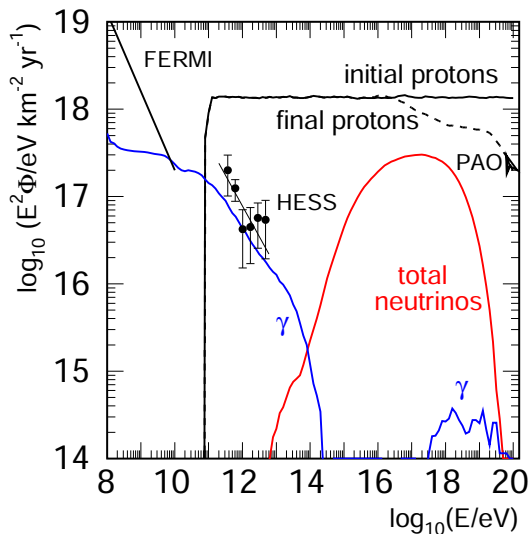
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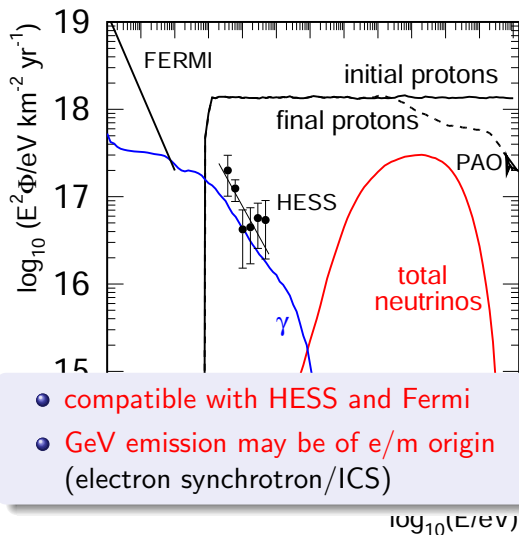
- compatible with HESS and Fermi
- GeV emission may be of e/m origin
  (electron synchrotron/ICS)

Diffuse flux from AGN - normalized to Cen A

- assume Cen A is a "typical source" with injection spectrum $j(E)$

- diffuse flux from all Cen A-like sources

$$\Phi^{\mathrm{diff}}(E) = \frac{cn_0}{4\pi} \int_0^\infty dz \left| \frac{dt}{dz} \right| \frac{dE_0(E,z)}{dE} \varepsilon(z) j(E_0) \,,$$

- enhancement between $\mathcal{O}(10)$ (no evolution) and $\mathcal{O}(100)$ (strong evolution)   [Koers, Tinyakov ('08)]

- Halzen, O'Murchadha ('08): all FR-I radio galaxies: 5 events/yr

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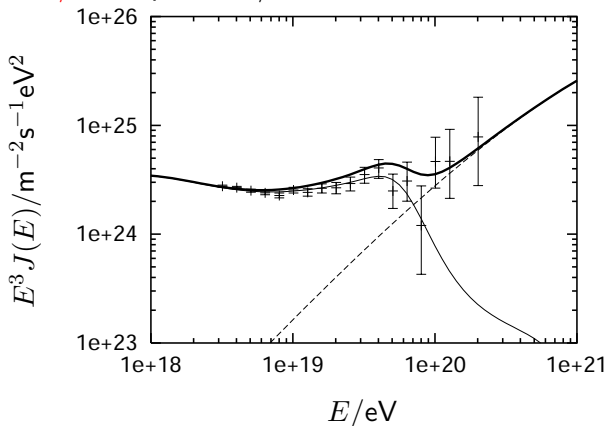
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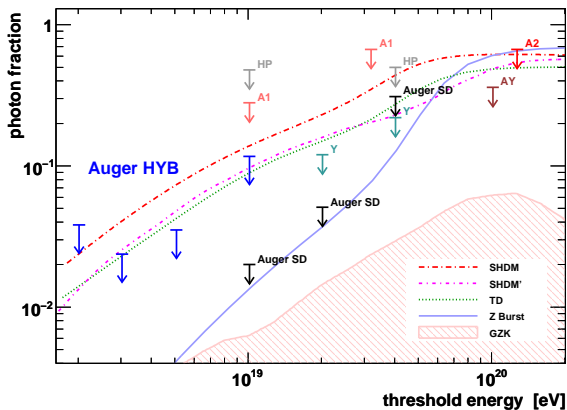- Halzen, O'Murchadha ('08): all FR-I radio galaxies: 5 events/yr

Signatures of SHDM decays

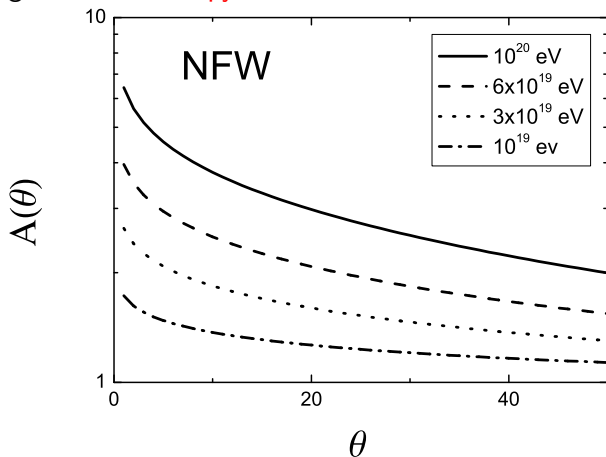- flat spectra $dE/E^{1.9}$ up to $m_X/2$

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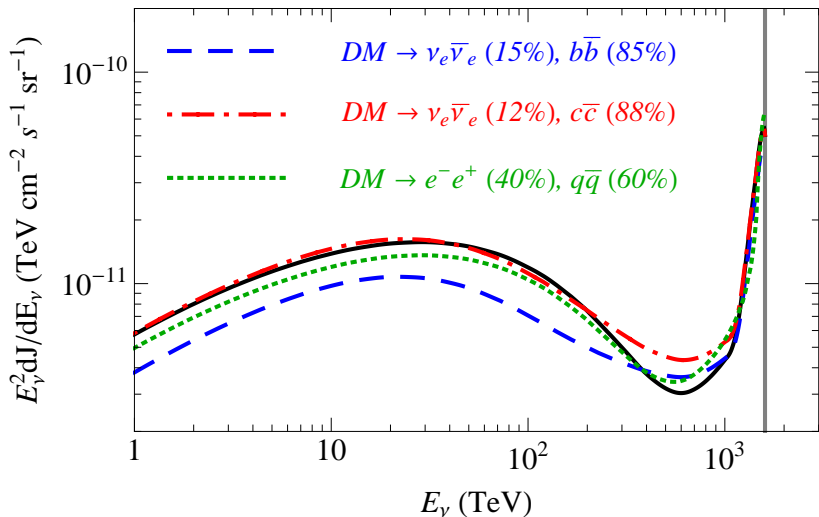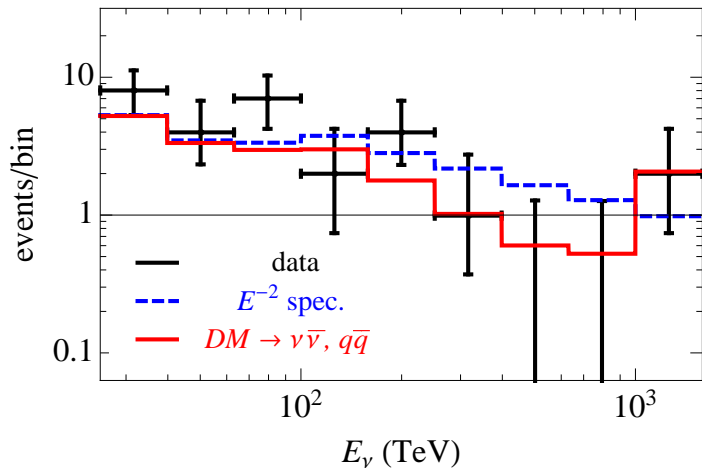- composition: $\gamma/p \gg 1$, large neutrino fluxes, no nuclei

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$
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- galactic anisotropy:

PeV dark matter

PeV dark matter

[Esmaili, Serpico '13]

Summary

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

$\Rightarrow$ at least partly Galactic origin

2. enhancement towards Galactic plane:
   - gas too narrow, flux too low

3. some tension with (Northern) γ-ray limits

4. extragalactic: (only additional?) isotropic component, diffuse, difficult to identify

5. PeV dark matter: angular distibution follows DM profile

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