Neutrinos from cosmic accelerators, and the multi-messenger connection

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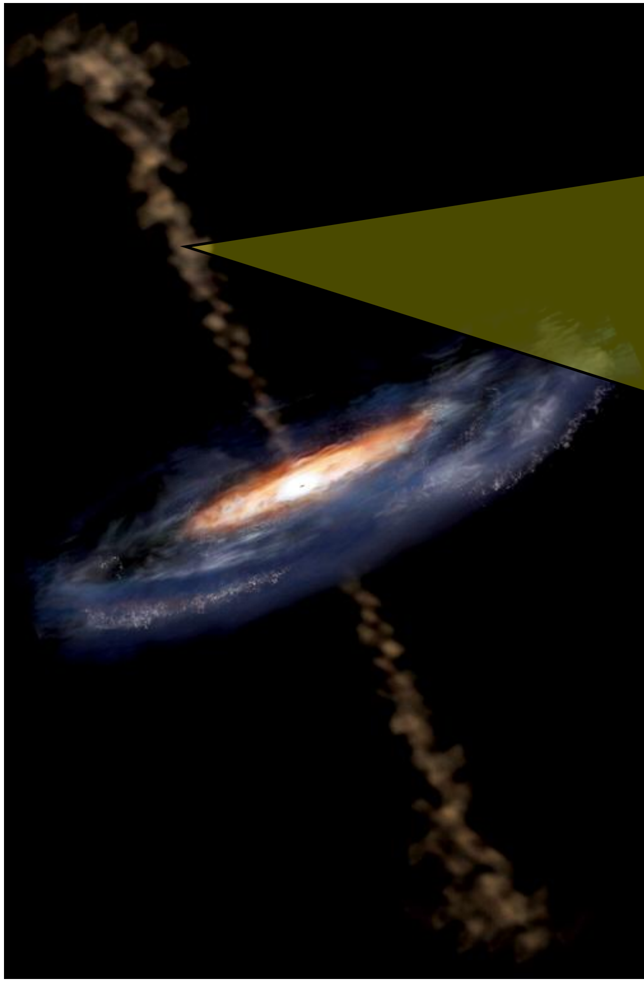
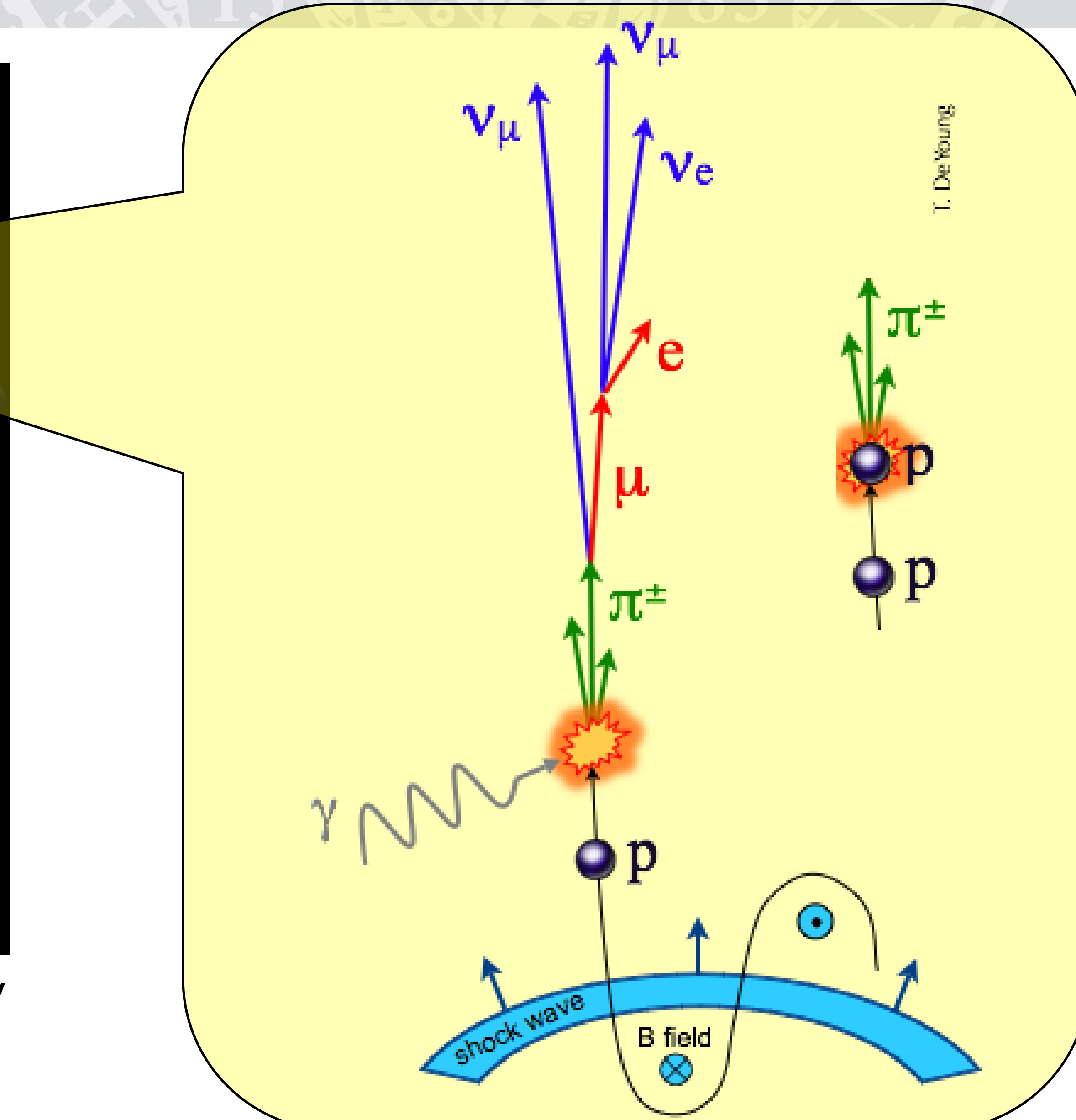
Neutrino production in astrophysical sources

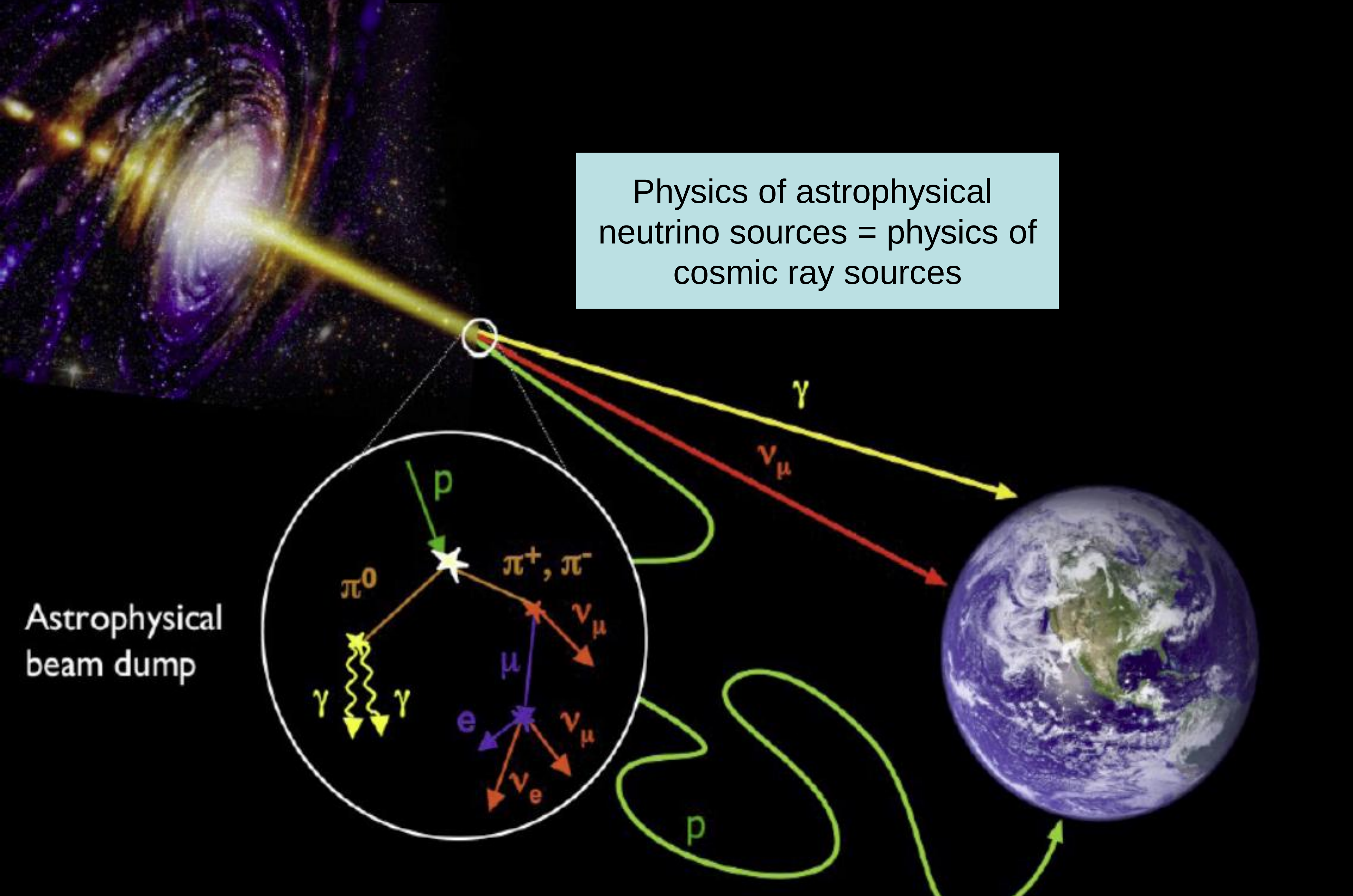


Example: Active galaxy



Neutrinos as cosmic messengers

Physics of astrophysical neutrino sources = physics of cosmic ray sources



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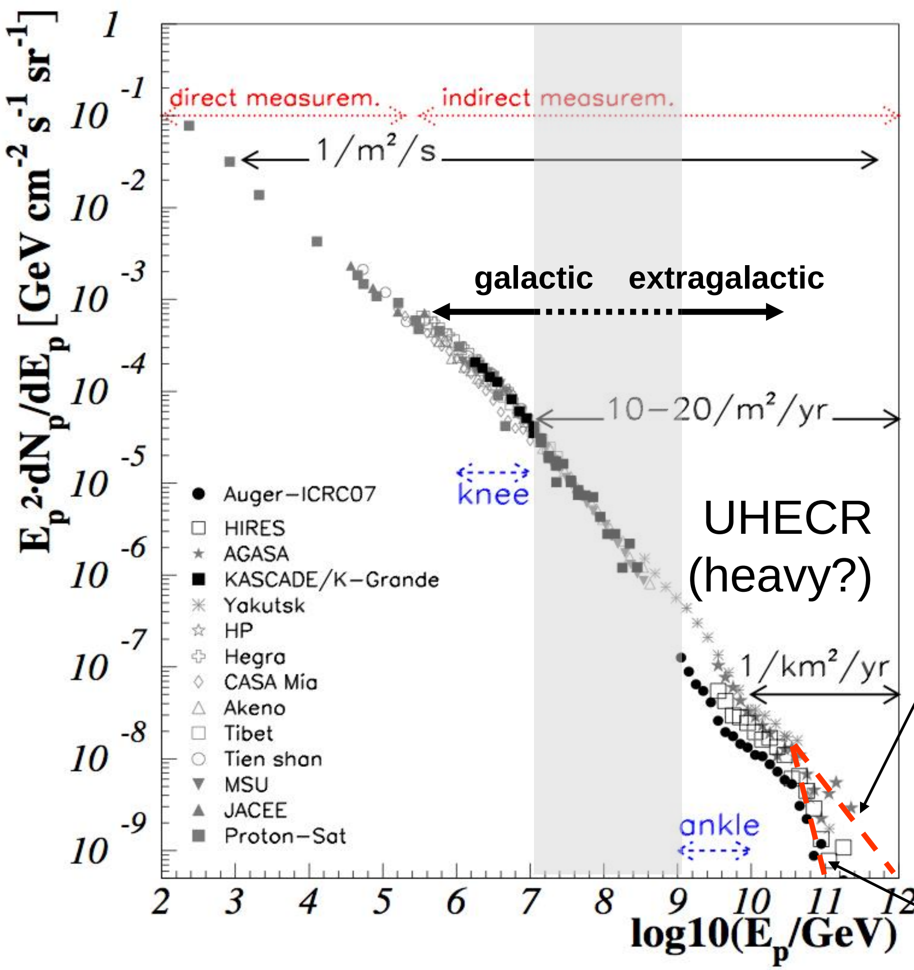
Evidence for proton acceleration, hints for neutrino production

- Observation of cosmic rays: **need to accelerate protons/hadrons somewhere**
- The same sources should produce neutrinos:
  - in the source (pp, pγ interactions)
  - Proton ($E > 6\ 10^{10}$ GeV) on CMB ⇨ GZK cutoff + cosmogenic neutrino flux



In the source: $E_{p,max}$ up to 10^{12} GeV?

GZK cutoff?

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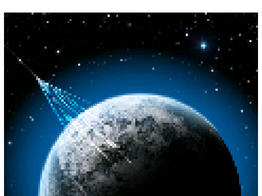
The two paradigms for extragalactic sources:
AGNs and GRBs

- Active Galactic Nuclei (AGN blazars)
  - Relativistic jets ejected from central engine (black hole?)
  - Continuous emission, with time-variability
- Gamma-Ray Bursts (GRBs): transients
  - Relativistically expanding fireball/jet
  - Neutrino production e. g. in prompt phase
    (Waxman, Bahcall, 1997)

Cosmic Rays: 100 years of mystery 2012-04-18



Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

Their result, appearing today in the journal Nature, challenges one of the two leading theories for the origin of the highest energy cosmic rays.

Nature 484 (2012) 351

Cosmic ray source

(illustrative proton-only scenario, $p\gamma$ interactions)

If neutrons can escape:
Source of cosmic rays

Neutrinos produced in
ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu\,,$$

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow$$ Cosmogenic neutrinos

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

π^+/π^0 determines ratio between neutrinos and high-E gamma-rays

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

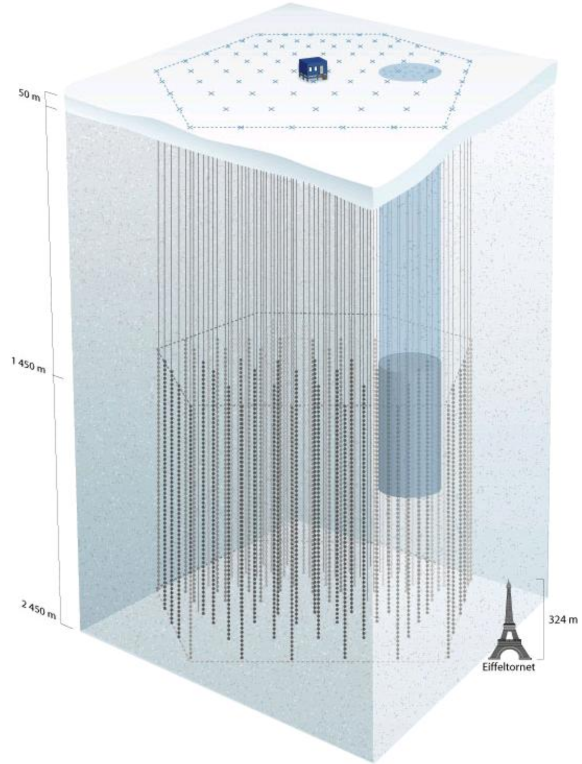
High energetic gamma-rays;
typically cascade down to lower E

Cosmic messengers

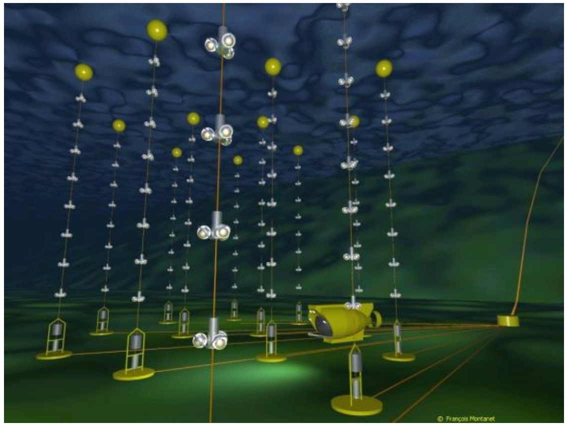
Neutrino detection:

Neutrino telescopes

- Example:
  IceCube at South Pole
  Detector material: ~ 1 km^3
  antarctic ice
- Completed 2010/11 (86 strings)
- Recent data releases, based on parts of the detector:
  - Point sources IC-40 [IC-22]
    arXiv:1012.2137, arXiv:1104.0075
  - GRB stacking analysis IC-40+IC-59
    Nature 484 (2012) 351
  - Cascade detection IC-22
    arXiv:1101.1692
- Have not seen anything (yet)
  - ➢ What does that mean?
  - ➢ Are the models too simple?
  - ➢ Which parts of the parameter space does IceCube actually test?



http://icecube.wisc.edu/



http://antares.in2p3.fr/

Parameter space - Hillas plot?

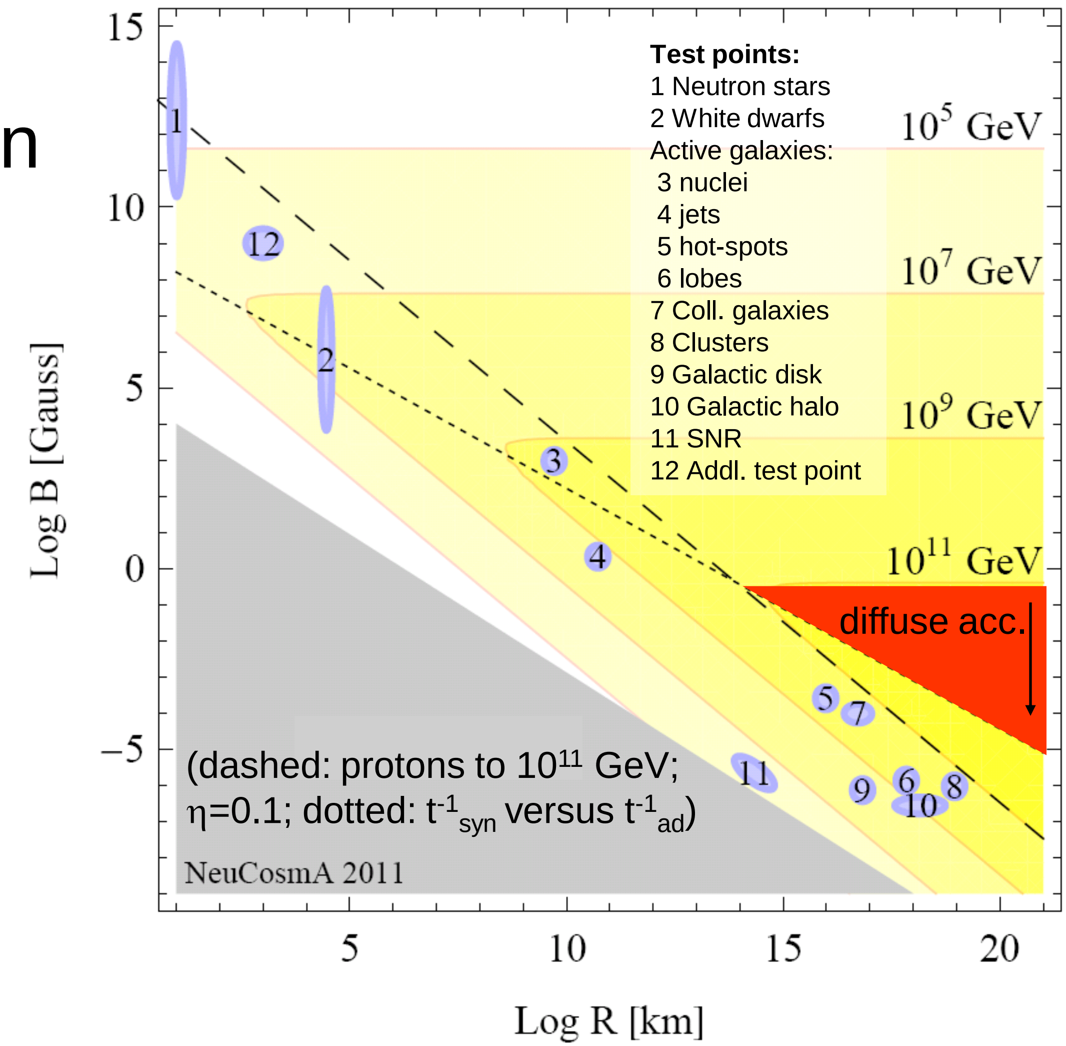
- Model-independent (necessary) condition for acceleration of cosmic rays:

  $E_{max} \sim \eta \, Z \, e \, B \, R$

  (η: acceleration efficiency)

  - Particles confined to within accelerator!

[Caveat: condition relaxed if source heavily Lorentz-boosted (e.g. GRBs)]



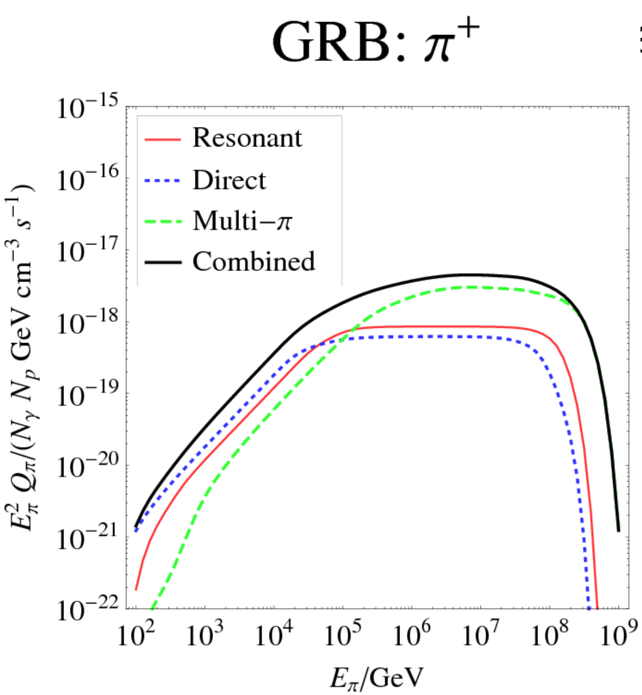
Hillas 1984; version adopted from M. Boratav
Figure from: WW, Phys. Rev. D85 (2012) 023013

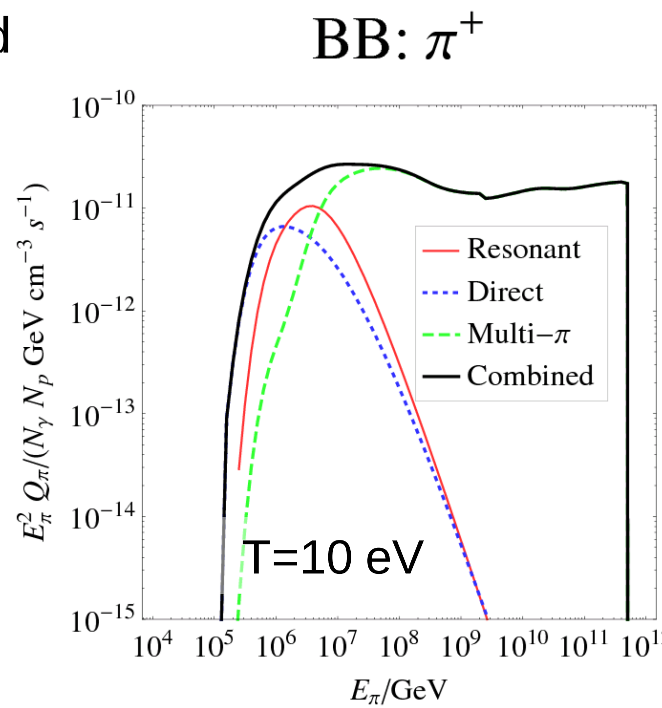
Simulation of sources

Source simulation: pγ
(particle physics)

- Δ(1232)-resonance approximation: $$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$
- Limitations:
  - No π^- production; cannot predict π^+/π^- ratio (Glashow resonance!)
  - High energy processes affect spectral shape (X-sec. dependence!)
  - Low energy processes (t-channel) enhance charged pion production
- Solutions:

e d



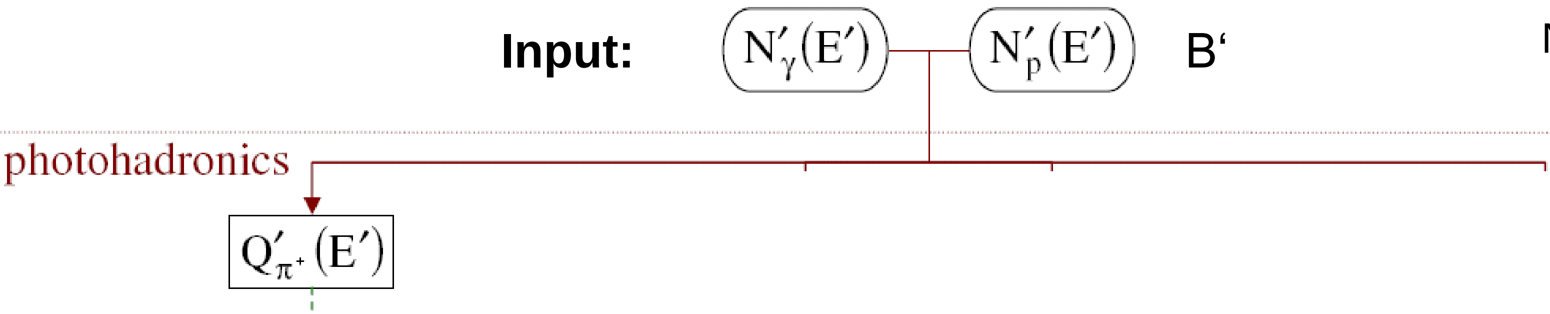


from: Hümmer, Rüger, Spanier, Winter, ApJ 72

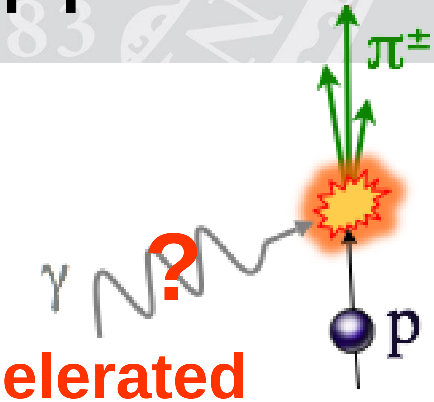
“Minimal“ (top down) ν model

Dashed arrows: include cooling and escape

Q(E) [GeV^{-1} cm^{-3} s^{-1}]
per time frame
N(E) [GeV^{-1} cm^{-3}]
steady spectrum



A self-consistent approach



- Target photon field typically:
  1) Put in by hand (e.g. GRBs) ⇨ **last part**
  2) Thermal target photon field
  3) **From synchrotron radiation of co-accelerated electrons/positrons (AGN-like)**
  4) From more complicated comb. of radiation processes
- No. 3) requires few model parameters, mainly

Parameter	Units	Description	Typical values used
R	km (kilometers)	Size of acceleration region	10^1 km ... 10^{21} km
B	G (Gauss)	Magnetic field strength	10^{-9} G ... 10^{15} G
α	1	Universal injection index	1.5 ... 4

- Purpose: describe wide parameter ranges with a simple model **unbiased by CR and γ observations**, i.e., tailor-made for neutrinos ⇨ hidden sources?

Peculiarity of neutrinos:

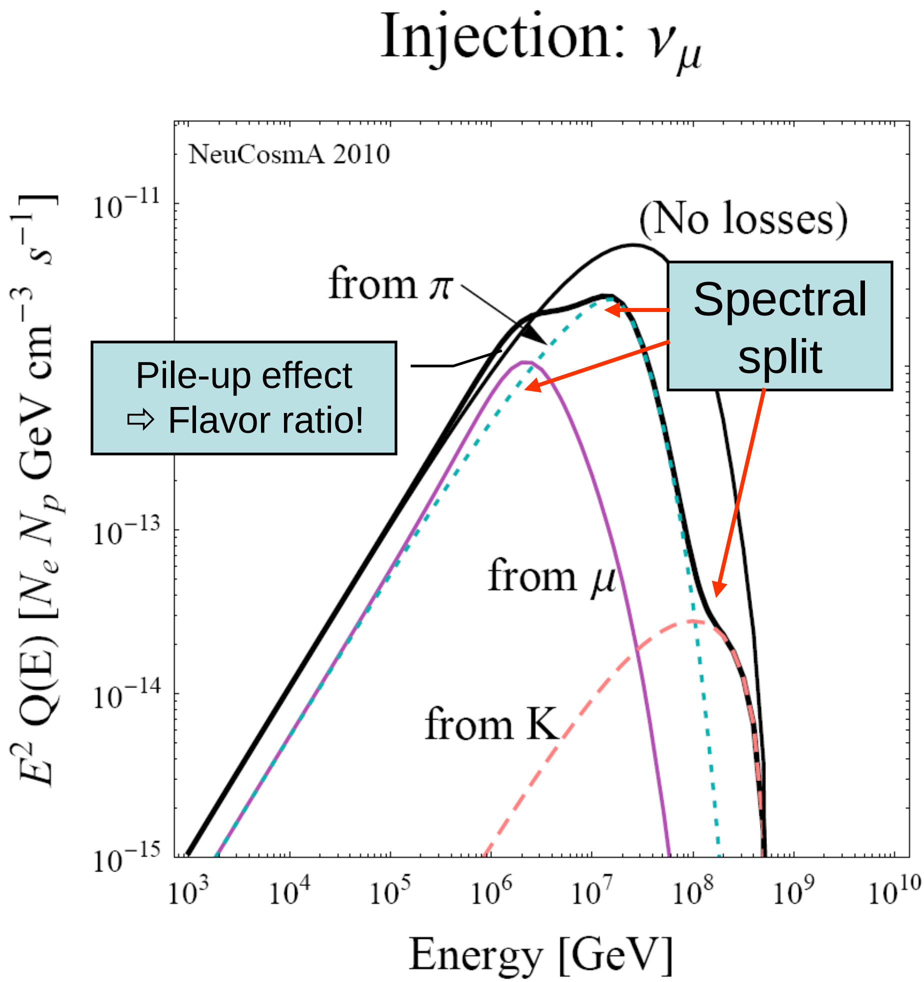
Secondary cooling

α=2, B=10^3 G, R=$10^{9.6}$ km

Secondary spectra (μ, π, K) become loss-steepend above a critical energy

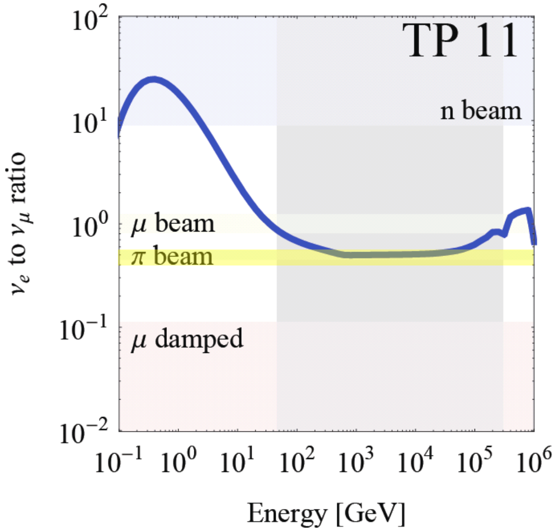
$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

- E'_c depends on particle physics only (m, τ_0), and **B'**
- Leads to characteristic flavor composition and shape
- Very robust prediction for sources? [e.g. any additional radiation processes mainly affecting the primaries will not affect the flavor composition]
- The only way to directly measure B?

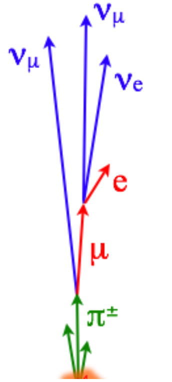


from: Hümmer et al,
Astropart. Phys. 34 (2010) 205
[GRBs: Kashti, Waxman, 2005, Lipari et al …]

Flavor composition at source



Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



(from Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205)

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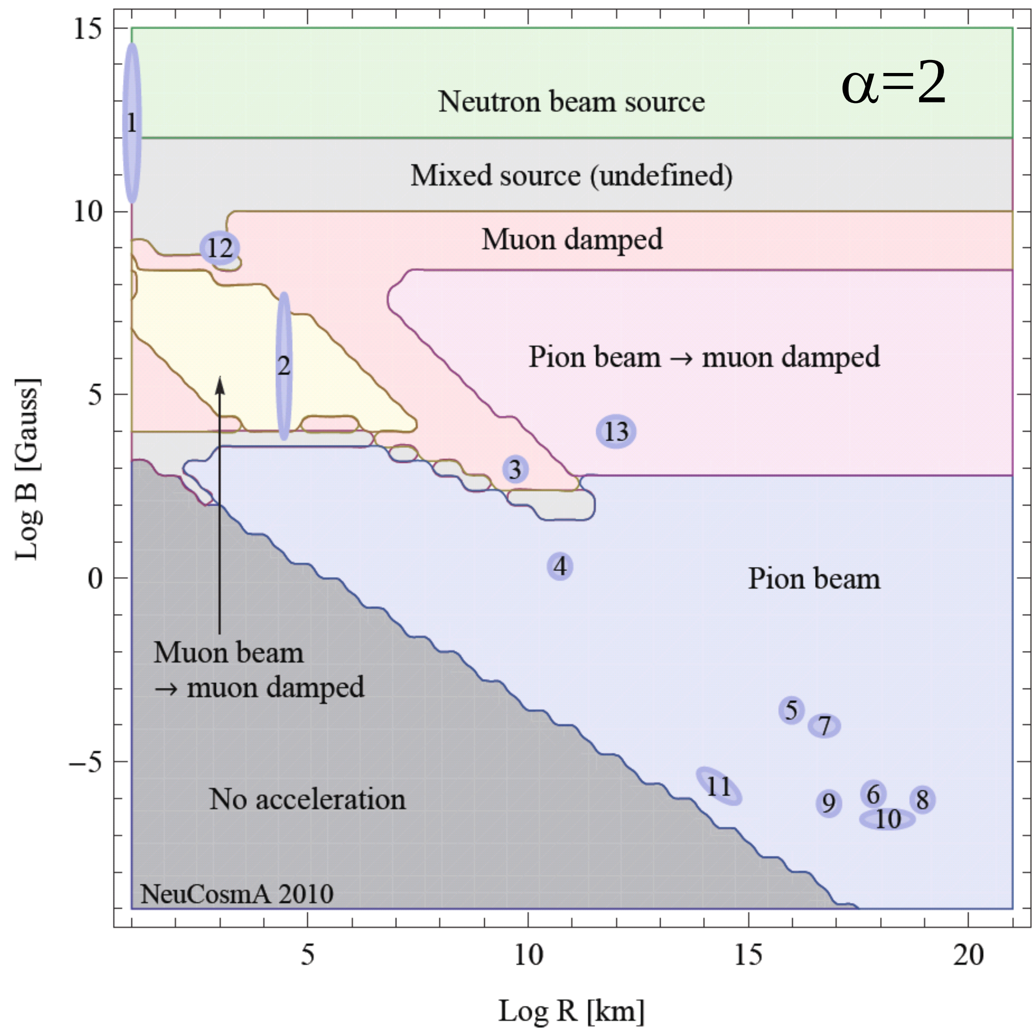
Parameter space scan

- All relevant regions recovered
- GRBs: in our model α=4 to reproduce pion spectra; pion beam ⇨ muon damped

  (confirms Kashti, Waxman, 2005)
- Some dependence on injection index



Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

Neutrino propagation and detection

Neutrino propagation

- Key assumption: Incoherent propagation of neutrinos
- Flavor mixing: $P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$
- Example: For $\theta_{13} = 0$, $\theta_{23} = \pi/4$:

$$\begin{pmatrix} \nu_e^{source} \\ \nu_\mu^{source} \\ \nu_\tau^{source} \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} \nu_e^{Earth} \\ \nu_\mu^{Earth} \\ \nu_\tau^{Earth} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

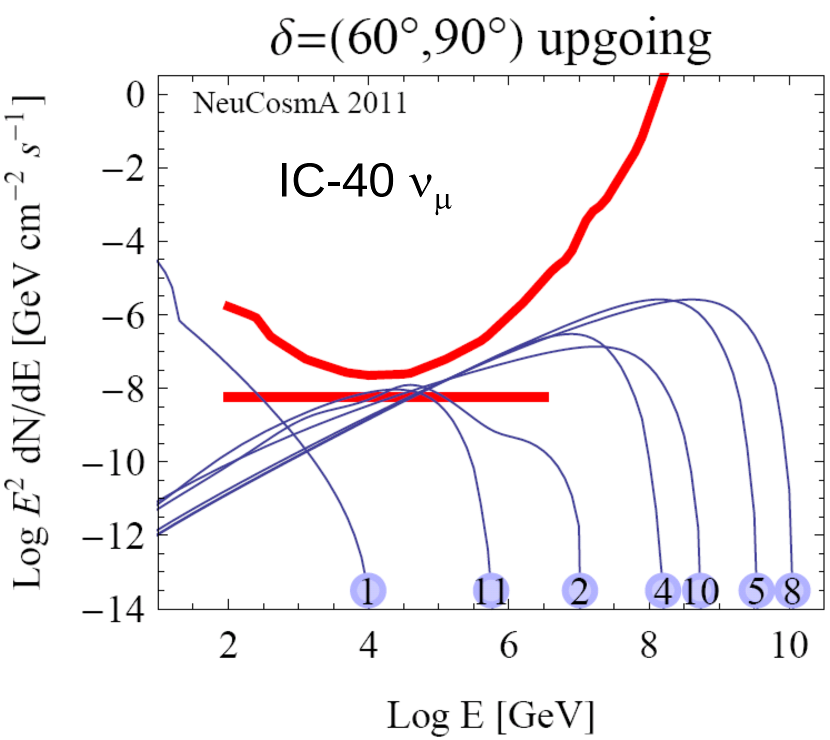
- NB: No CPV in flavor mixing only!
  But: In principle, sensitive to Re exp(-i δ) ~ cosδ

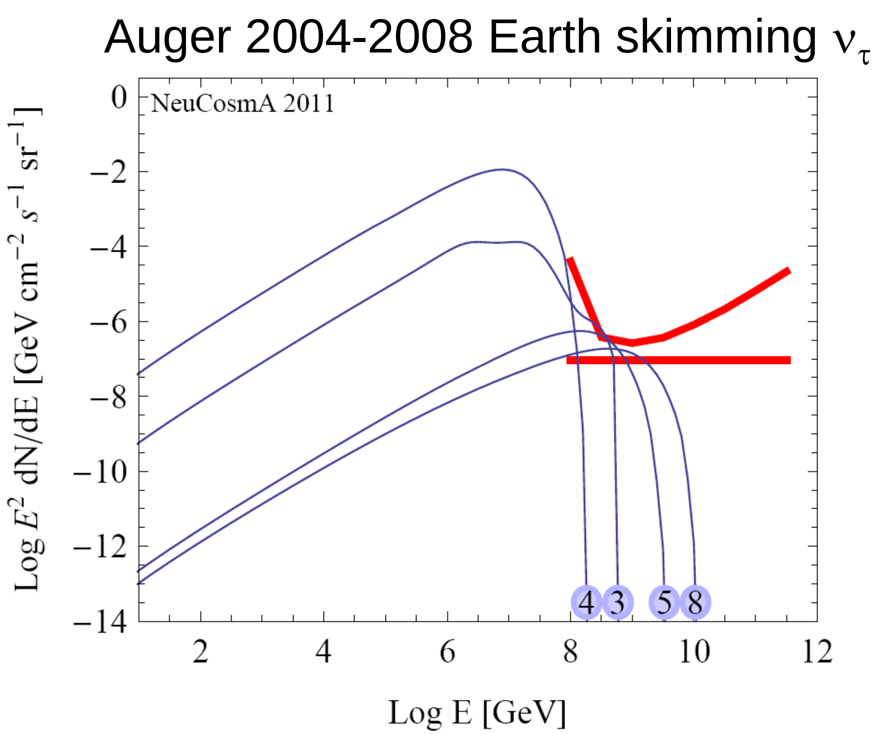
(see Pakvasa review, arXiv:0803.1701, and references therein)

Interplay: source – detection

pγ interactions: $E_p^{-\alpha}$, $\varepsilon^{-\beta}$ ⇨ $E_\nu^{-\alpha+\beta-1}$ (no cooling)

- E_ν^{-2} very special case, impossible for synchrotron photons! [typical if pp with “cold“ p; supernova remnants?]
- Production and detector response intimately connected!

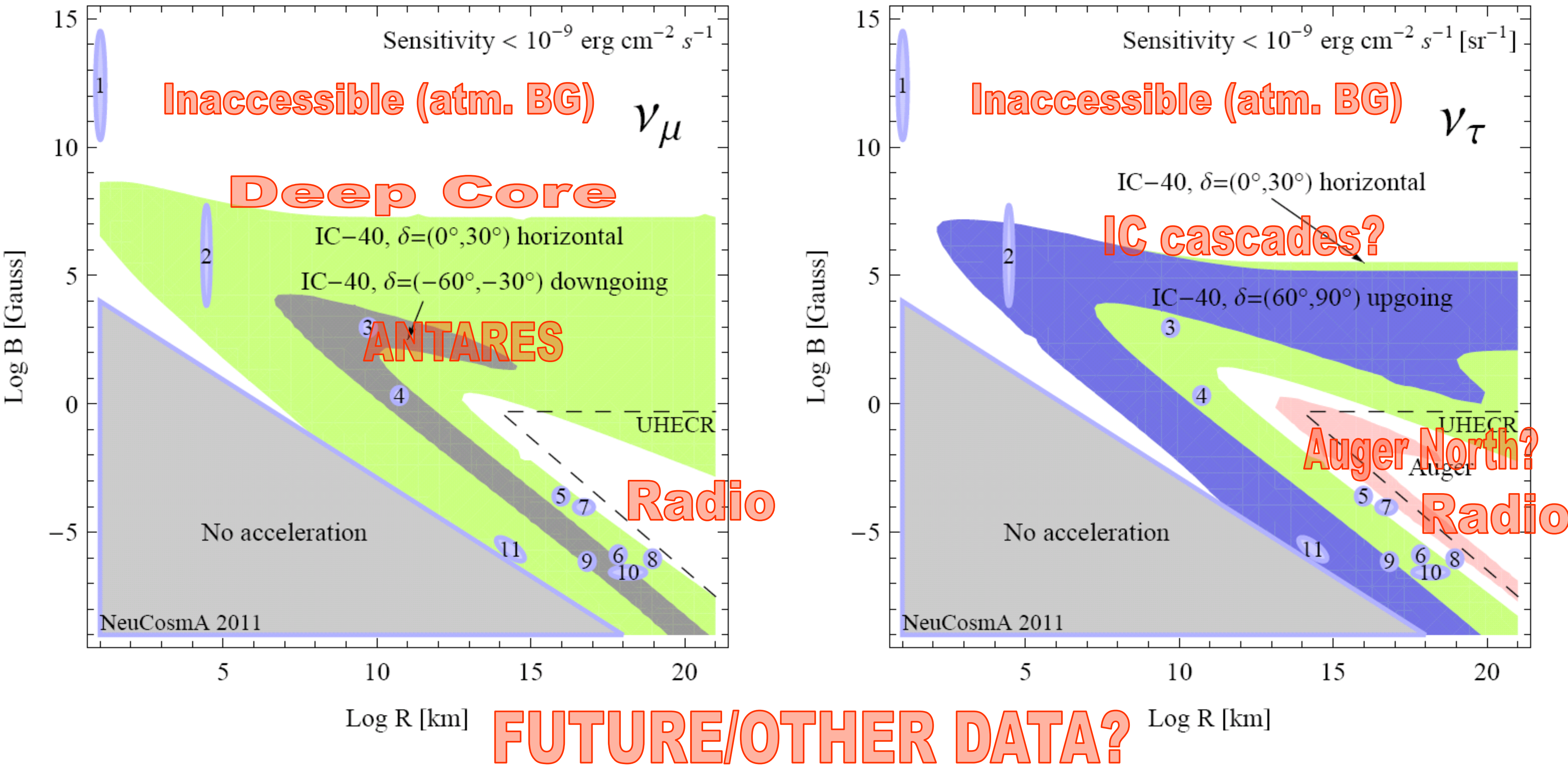




(Winter, Phys. Rev. D85 (2012) 023013)

Which point sources can specific data constrain best?

Constraints to energy flux density $\phi = \int E \frac{dN(E)}{dE} dE$ ~ L_{int} x f_π



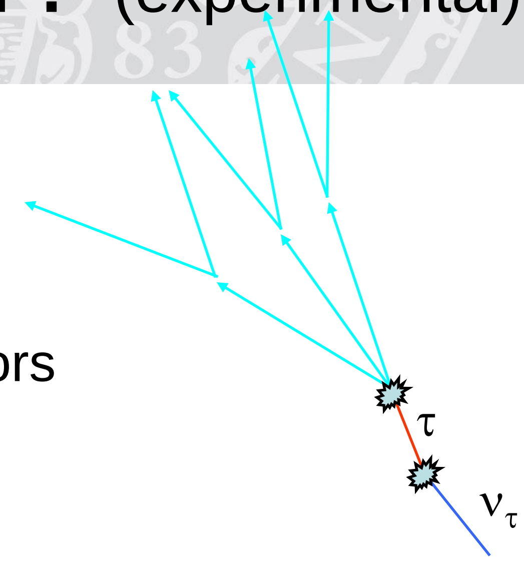
(Winter, Phys. Rev. D85 (2012) 023013)

Measuring flavor?

Measuring flavor? (experimental)

- In principle, flavor information can be obtained from different event topologies:
  - Muon tracks - ν_μ
  - Cascades (showers) – CC: ν_e, ν_τ, NC: all flavors
  - Glashow resonance (6.3 PeV): $\overline{\nu}_e$
  - Double bang/lollipop: ν_τ (sep. tau track) ⟶

  (Learned, Pakvasa, 1995; Beacom et al, 2003)



- In practice, the first (?) IceCube "flavor" analysis appeared recently – IC-22 cascades **(arXiv:1101.1692)**

  Flavor contributions to cascades for E^{-2} extragalatic test flux (after cuts):
  - Electron neutrinos 40%
  - Tau neutrinos 45%
  - Muon neutrinos 15%

➢ Electron and tau neutrinos detected with comparable efficiencies

➢ Neutral current showers are a moderate background

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Flavor ratios at detector

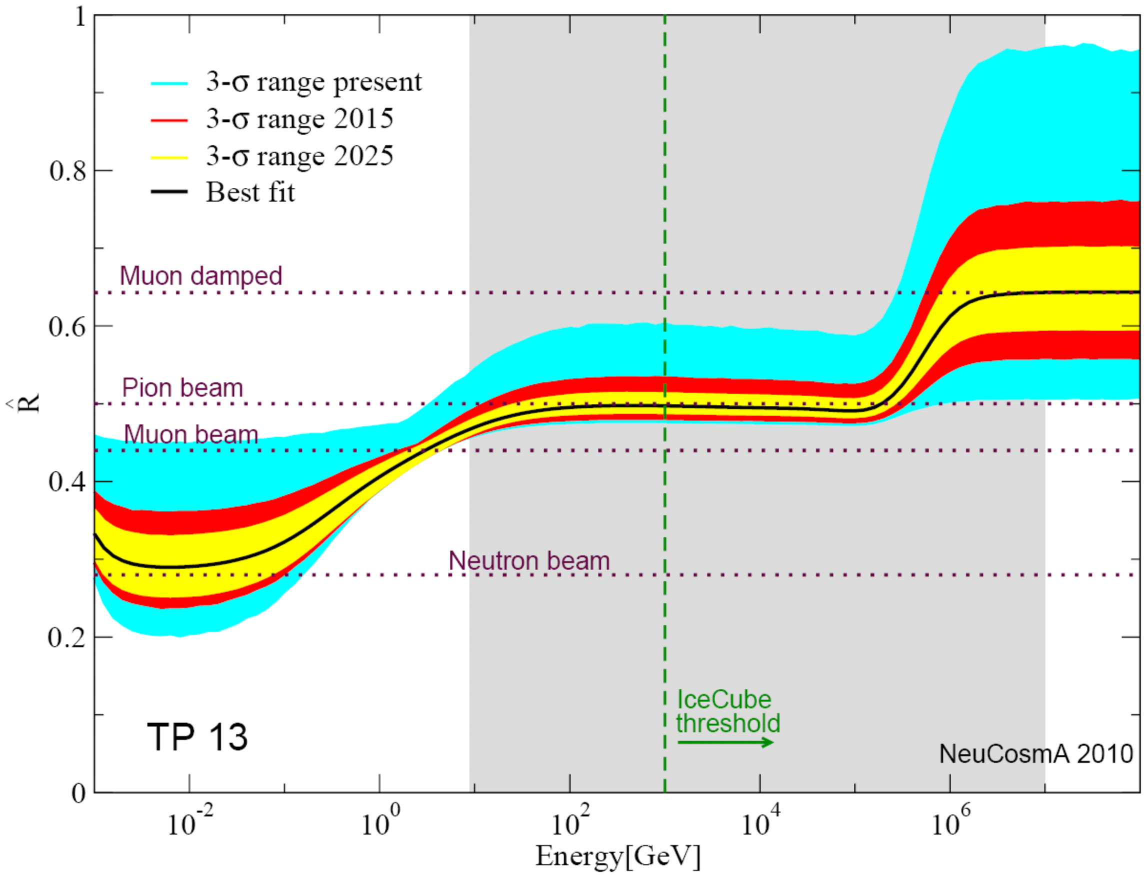
- At the detector: define observables which
  - take into account the unknown flux normalization
  - take into account the detector properties
- Example: Muon tracks to showers
  Do not need to differentiate between electromagnetic and hadronic showers!

$$\hat{R} = \frac{\phi_\mu^{\mathrm{Det}}}{\phi_e^{\mathrm{Det}} + \phi_\tau^{\mathrm{Det}}}$$

- Flavor ratios have recently been discussed for many particle physics applications

(for flavor mixing and decay: Beacom et al 2002+2003; Farzan and Smirnov, 2002; Kachelriess, Serpico, 2005; Bhattacharjee, Gupta, 2005; Serpico, 2006; Winter, 2006; Majumar and Ghosal, 2006; Rodejohann, 2006; Xing, 2006; Meloni, Ohlsson, 2006; Blum, Nir, Waxman, 2007; Majumar, 2007; Awasthi, Choubey, 2007; Hwang, Siyeon, 2007; Lipari, Lusignoli, Meloni, 2007; Pakvasa, Rodejohann, Weiler, 2007; Quigg, 2008; Maltoni, Winter, 2008; Donini, Yasuda, 2008; Choubey, Niro, Rodejohann, 2008; Xing, Zhou, 2008; Choubey, Rodejohann, 2009; Esmaili, Farzan, 2009; Bustamante, Gago, Pena-Garay, 2010; Mehta, Winter, 2011…)

Parameter uncertainties



Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

- Basic dependence recovered after flavor mixing
- However: mixing parameter knowledge ~ 2015 (Daya Bay – θ_{13}, T2K – θ_{23}, etc) required

New physics in R?

$$\widehat{X}(E) = \frac{\Phi_e^0(E)}{\Phi_\mu^0(E)}$$

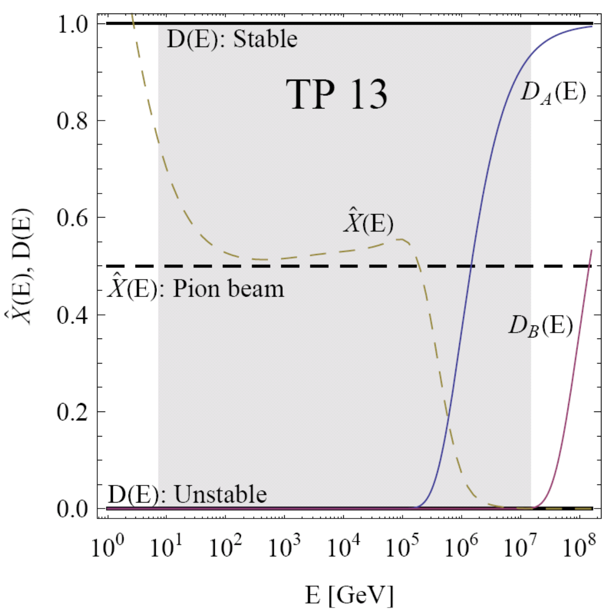
Energy dependence flavor comp. source

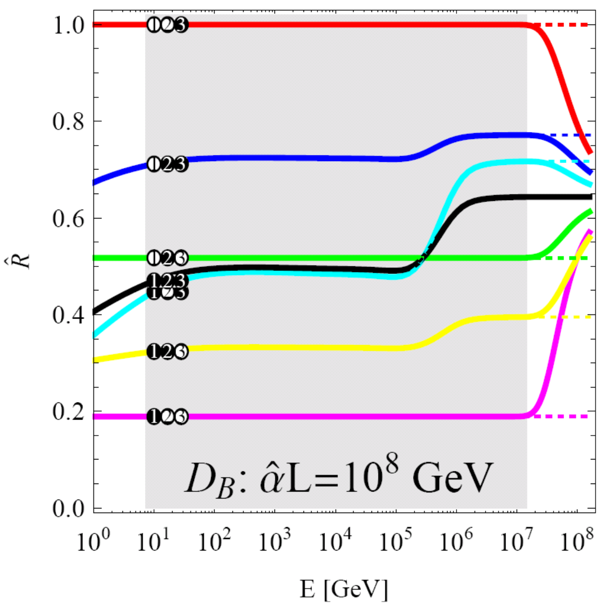
$$\widehat{R} \equiv \frac{\Phi_\mu^{\mathrm{Det}}}{\Phi_e^{\mathrm{Det}} + \Phi_\tau^{\mathrm{Det}}} = \frac{P_{e\mu}(E)\,\widehat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)]\,\widehat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\beta i}|^2\,|U_{\alpha i}|^2\; D_i(E) \quad \text{with} \quad D_i(E) = \exp\left(-\hat{\alpha}_i \frac{L}{E}\right)$$

Energy dep. new physics

(Example: [invisible] neutrino decay)





1 Stable state

1 Unstable state

Mehta, Winter, JCAP 03 (2011) 041; see also Bhattacharya, Choubey, Gandhi, Watanabe, 2009/2010

Neutrinos and the multi-messenger context

Example: Gamma-ray bursts (GRBs)

GRB stacking

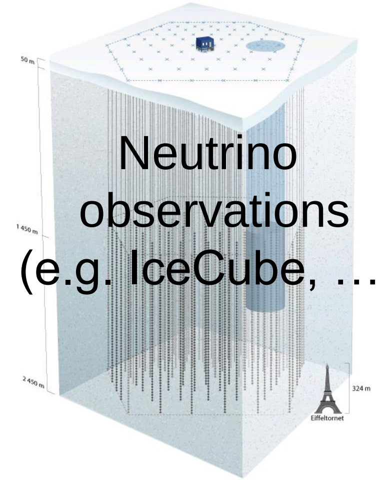
- Idea: Use multi-messenger approach

(Source: NASA)

GRB gamma-ray observations
(e.g. Fermi GBM, Swift, etc)

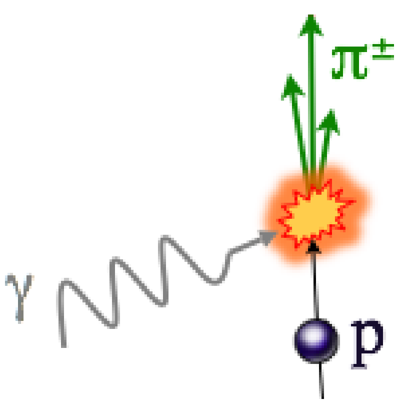
Coincidence!

(Source: IceCube)

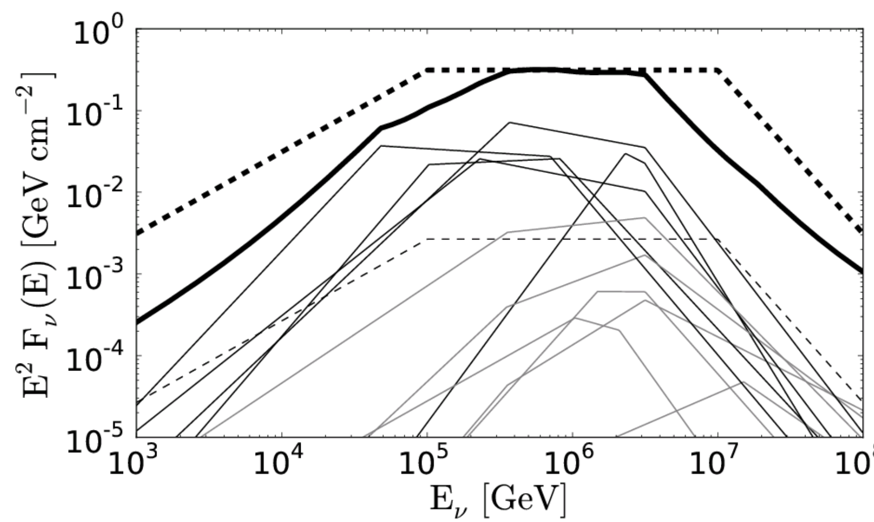


Neutrino observations
(e.g. IceCube, …)

- Predict neutrino flux from observed photon fluxes event by event



Observed:
broken power law
(Band function)



(Example: IceCube, arXiv:1101.1448)

Recent results

Cosmic Rays: 100 years of mystery

2012-04-18

Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

Their result, appearing today in the journal Nature, challenges one of the two leading theories for the origin of the highest energy cosmic rays.

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

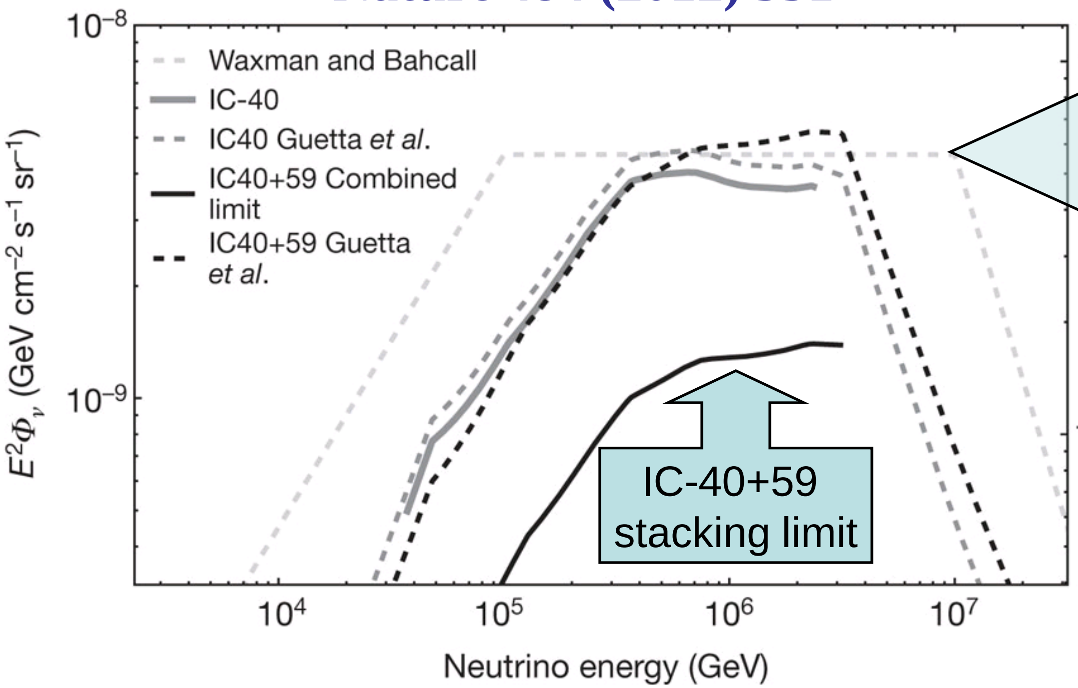
IceCube Collaboration

Affiliations | Contributions | Corresponding authors

Nature **484**, 351–354 (19 April 2012) | doi:10.1038/nature11068
Received 06 January 2012 | Accepted 08 March 2012 | Published online 18 April 2012

Gamma-ray burst fireball model:
IC-40 data meet generic bounds

Nature 484 (2012) 351



Generic flux based on the assumption that GRBs are the sources of (highest energetic) cosmic rays
(Waxman, Bahcall, 1999; Waxman, 2003; spec. bursts: Guetta et al, 2003)

- Does IceCube really rule out the paradigm that GRBs are the sources of the ultra-high energy cosmic rays?

(see also Ahlers, Gonzales-Garcia, Halzen, 2011 for a generic fit to CR data)

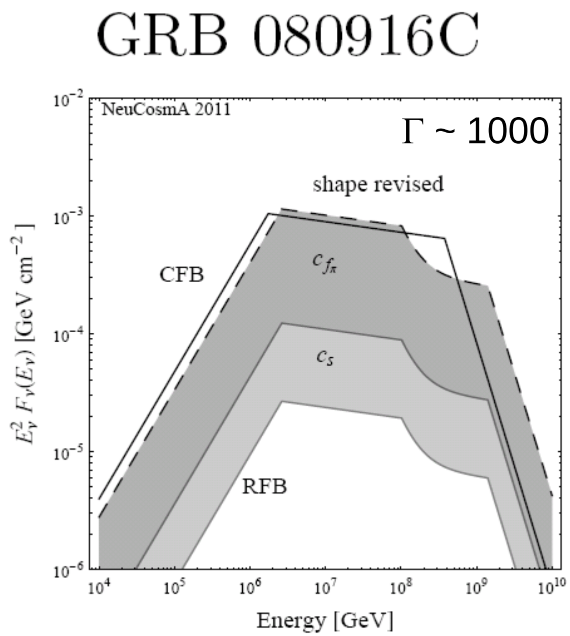
Revision of neutrino flux predictions

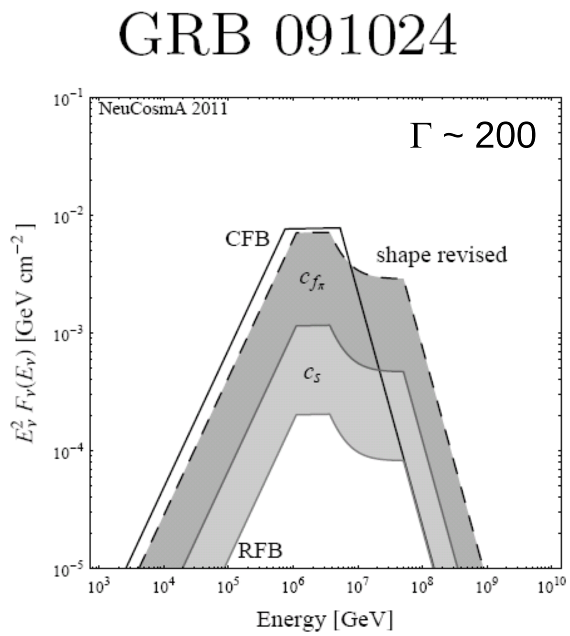
Analytical recomputation of IceCube method (CFB):

$c_{f\pi}$: corrections to pion production efficiency

c_S: secondary cooling and energy-dependence of proton mean free path

(see also Li, 2012, PRD)

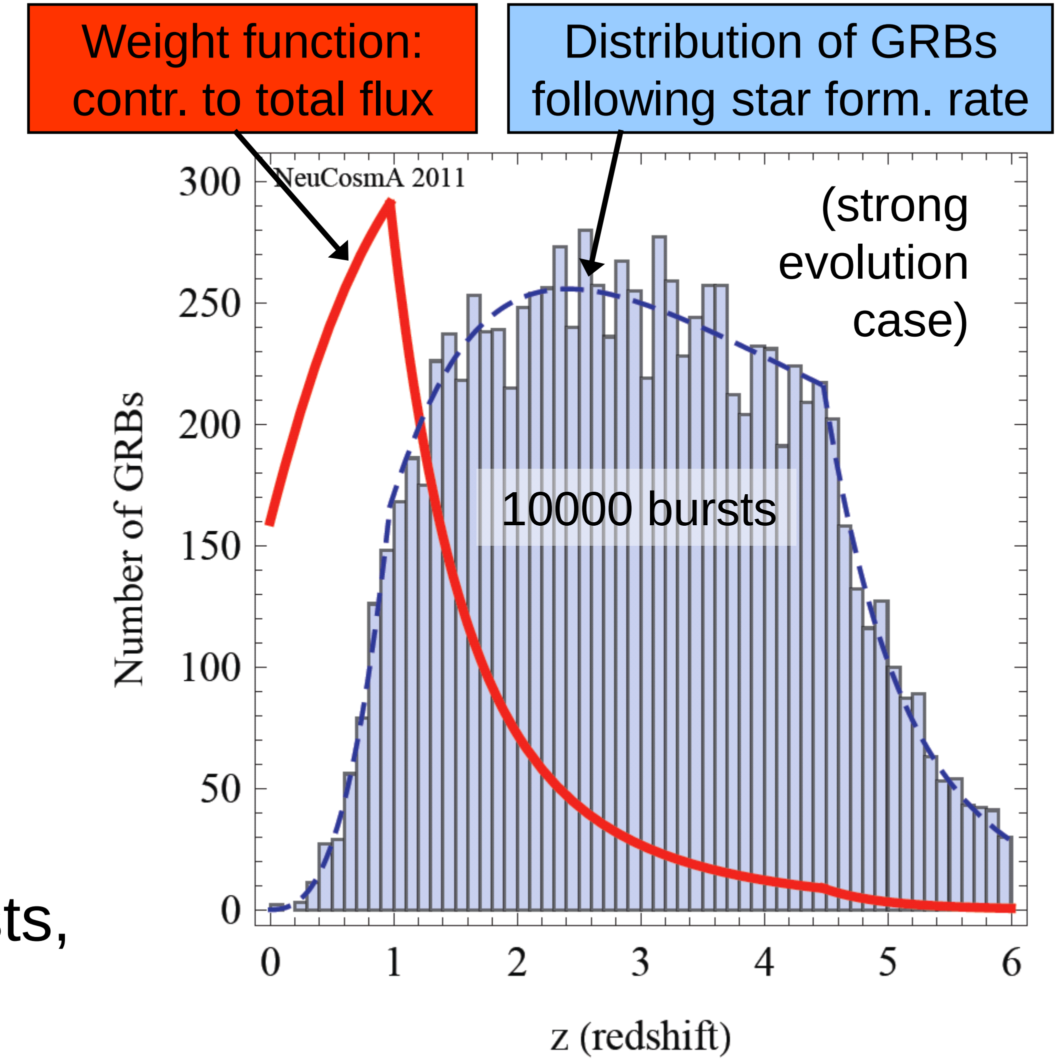




Systematics in aggregated fluxes

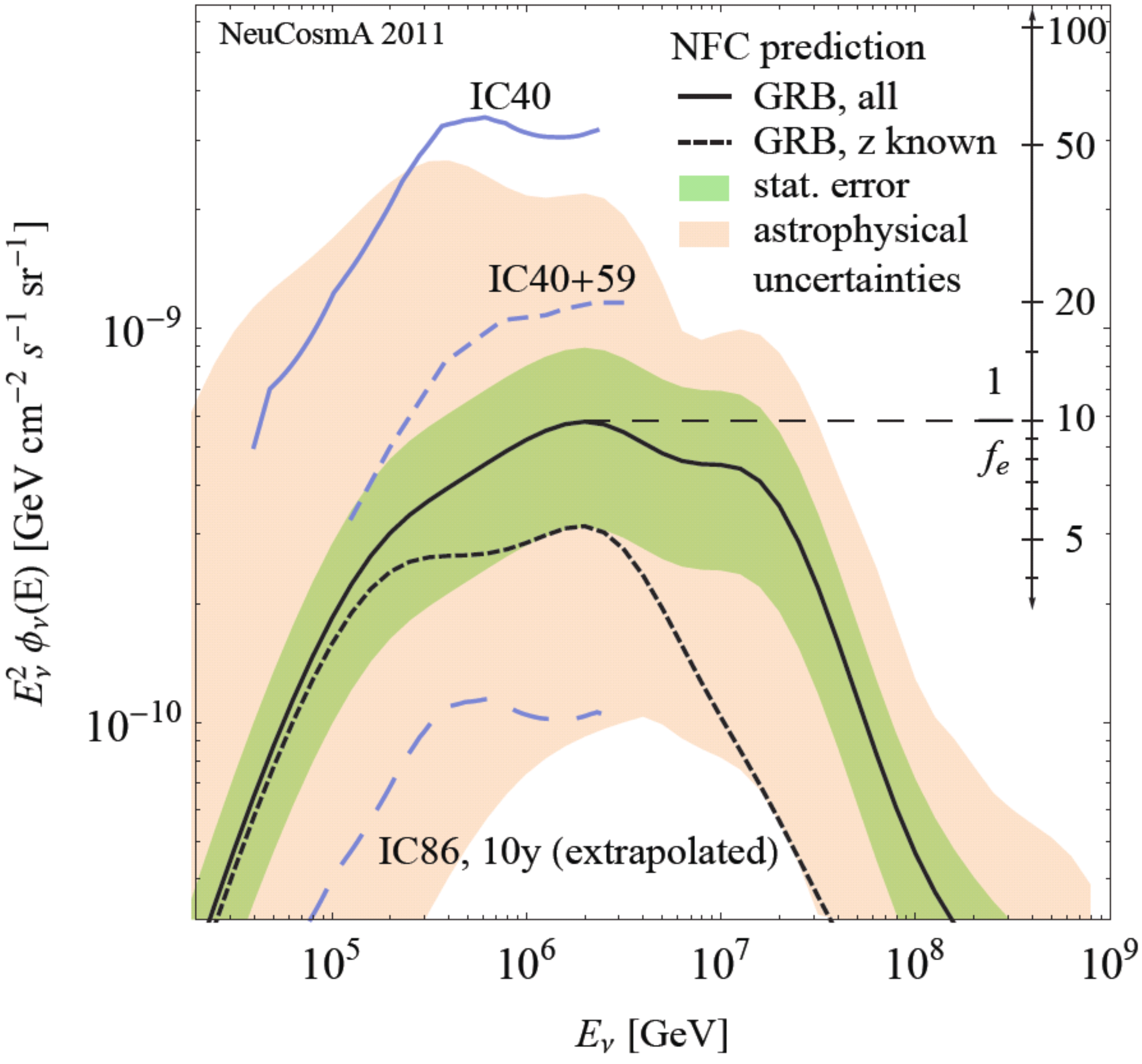
- z ~ 1 "typical" redshift of a GRB
  - Neutrino flux overestimated if z ~ 2 assumed (dep. on method)

- Peak contribution in a region of low statistics
  - Systematical error on quasi-diffuse flux (90% CL) ~ 50% for 117 bursts, [as used in IC-40 analysis]



(Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508)

Prediction for IC-40 bursts



- Numerical fireball model cannot be ruled out with IC40+59 for same parameters, bursts, assumptions
- Peak at higher energy! [optimization of future exps?]

"Astrophysical uncertainties":
t_v: 0.001s … 0.1s
Γ: 200 …500
α: 1.8 … 2.2
$\varepsilon_e/\varepsilon_B$: 0.1 … 10

(Hümmer, Baerwald, Winter, arXiv:1112.1076; accepted in PRL)

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Summary

- Peculiarity of neutrinos: Flavor and magnetic field effects change the shape and flavor composition of astrophysical neutrino fluxes
- Flavor ratios, though difficult to measure, are interesting because
  - they may be the only way to directly measure B (astrophysics)
  - they are useful for new physics searches (particle physics)
  - they are relatively robust with respect to the cooling and escape processes of the primaries (e, p, γ)
- E^{-2} flux and (1:2:0) flavor composition assumptions possibly over-simplified for neutrinos ⇨ interplay with detector response!
- More refined calculations of established model yield lower neutrino fluxes than expected ⇨ Fireball neutrinos from GRBs still to be tested

Backup

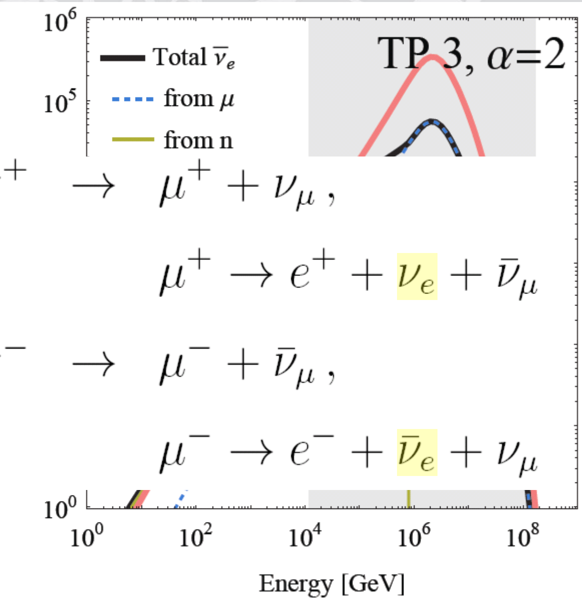
Glashow resonance

… at source

- pp: Produce π^+ and π^- in roughly equal ratio
- pγ: Produce mostly π^+
  - ➢ Glashow resonance (6.3 PeV)

    $$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow anything$$

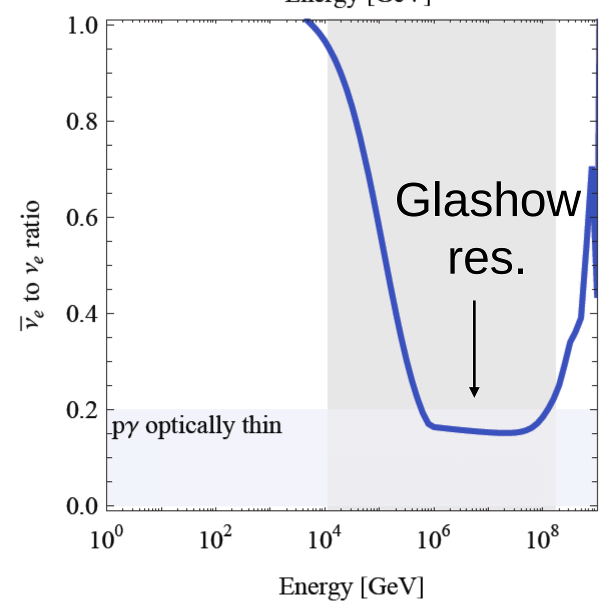
    as source discriminator?



$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu ,$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Caveats:

- Multi-pion processes produce π^-
- If some optical thickness, nγ “backreactions“ equilibrate π^+ and π^-
- Neutron decays fake π^- contribution
  - ➢ May identify “pγ optically thin source“ with about 20% contamination from π^-, but cannot establish pp source!

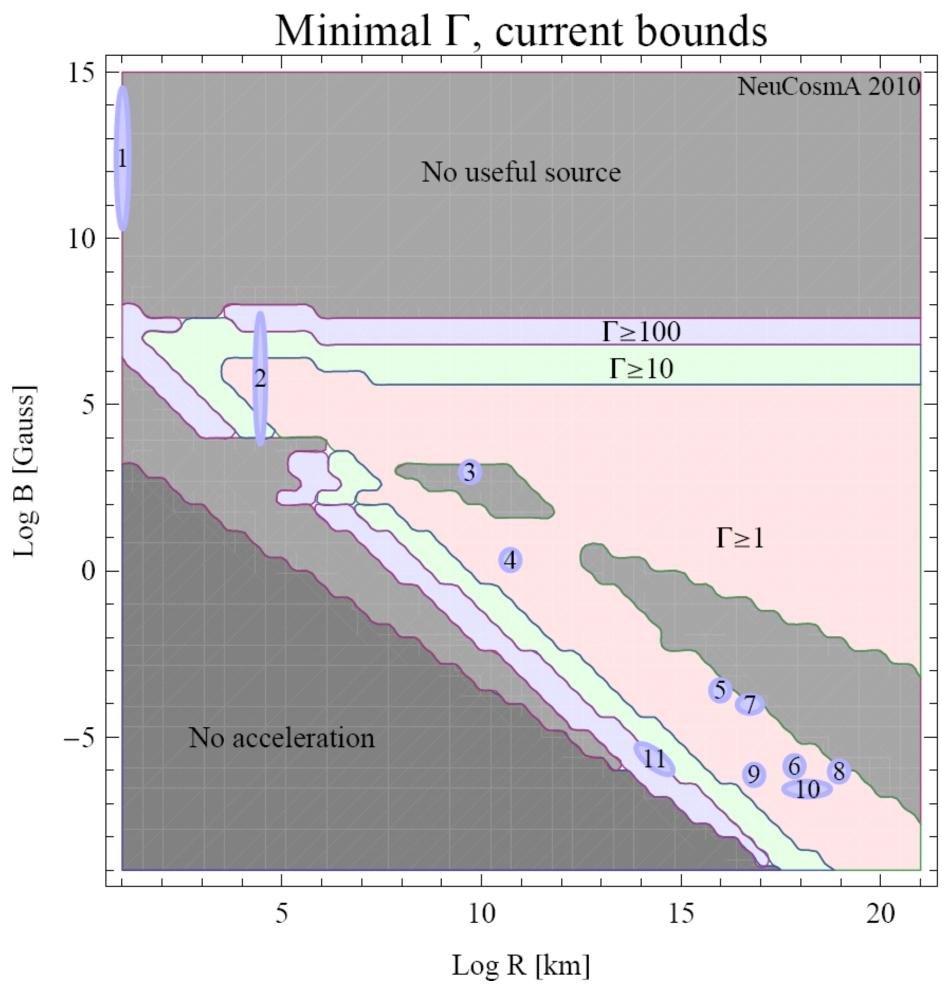


Sec. 3.3 in Hümmer, Maltoni, Winter, Yaguna, 2010; see also Xing, Zhou, 2011

Glashow resonance

… at detector

- Additional complications:
  - Flavor mixing
    (electron antineutrinos from muon antineutrinos produced in μ^+ decays)
  - Have to know flavor composition
    (e.g. a muon damped pp source can be mixed up with a pion beam pγ source)
  - Have to hit a specific energy (6.3 PeV), which may depend on Γ of the source



Sec. 4.3 in Hümmer, Maltoni, Winter, Yaguna, 2010

IceCube method ...normalization

- Connection γ-rays – neutrinos

½ (charged pions) x
¼ (energy per lepton)

Energy in protons

$$\int_0^\infty \mathrm{d}E_\nu\ E_\nu F_\nu(E_\nu) = \frac{1}{8}\ \frac{1}{f_e}\ \left(1-(1-\langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right) \int_{1\,\mathrm{keV}}^{10\,\mathrm{MeV}} \mathrm{d}E_\gamma\ E_\gamma F_\gamma(E_\gamma)$$

Energy in neutrinos

Fraction of p energy converted into pions f_π

Energy in electrons/ photons

- Optical thickness to pγ interactions:

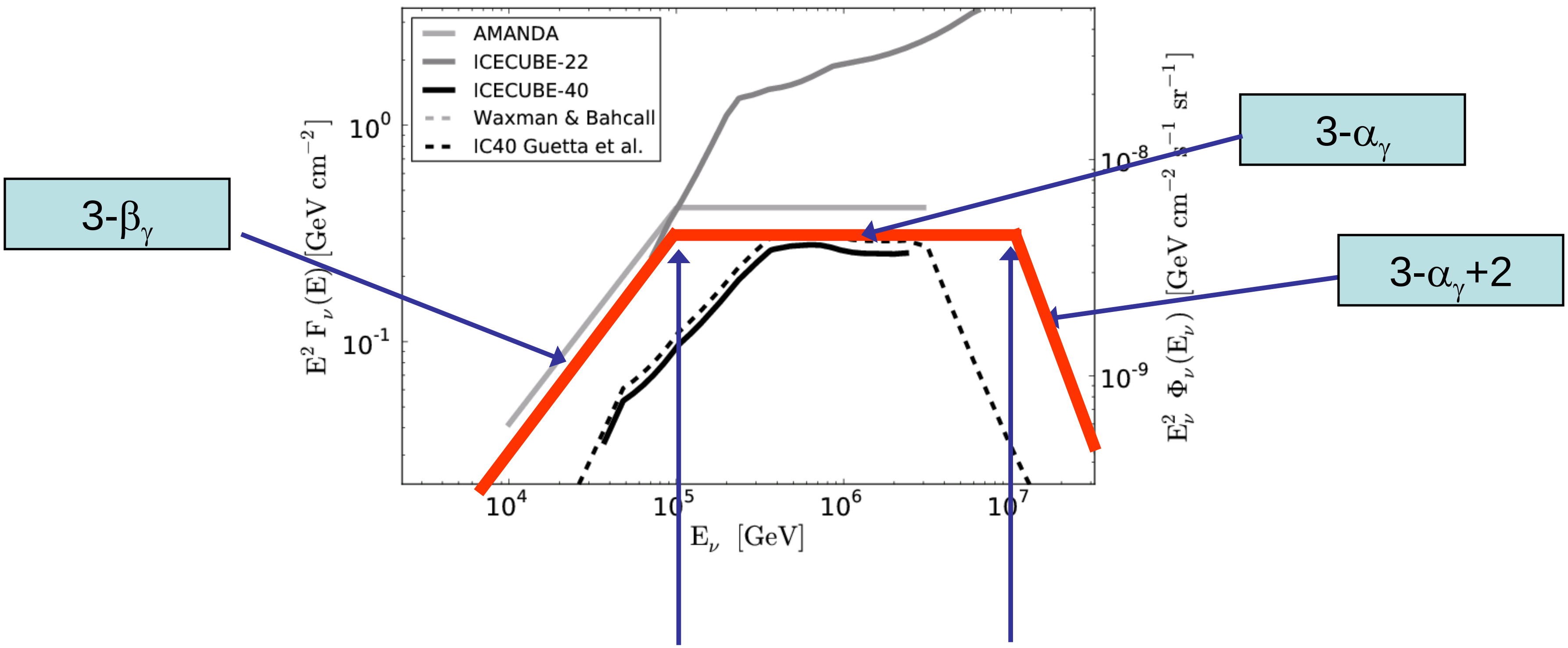
$$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right) \left(\frac{0.01\,\mathrm{s}}{t_{\mathrm{var}}}\right) \left(\frac{10^{2.5}}{\Gamma_{\mathrm{jet}}}\right)^4 \left(\frac{\mathrm{MeV}}{\epsilon_\gamma}\right)$$

[in principle, $\lambda_{p\gamma} \sim 1/(n_\gamma\ \sigma)$; need estimates for n_γ, which contains the size of the acceleration region]

(Description in arXiv:0907.2227;
see also Guetta et al, astro-ph/0302524; Waxman, Bahcall, astro-ph/9701231)

IceCube method ... spectral shape

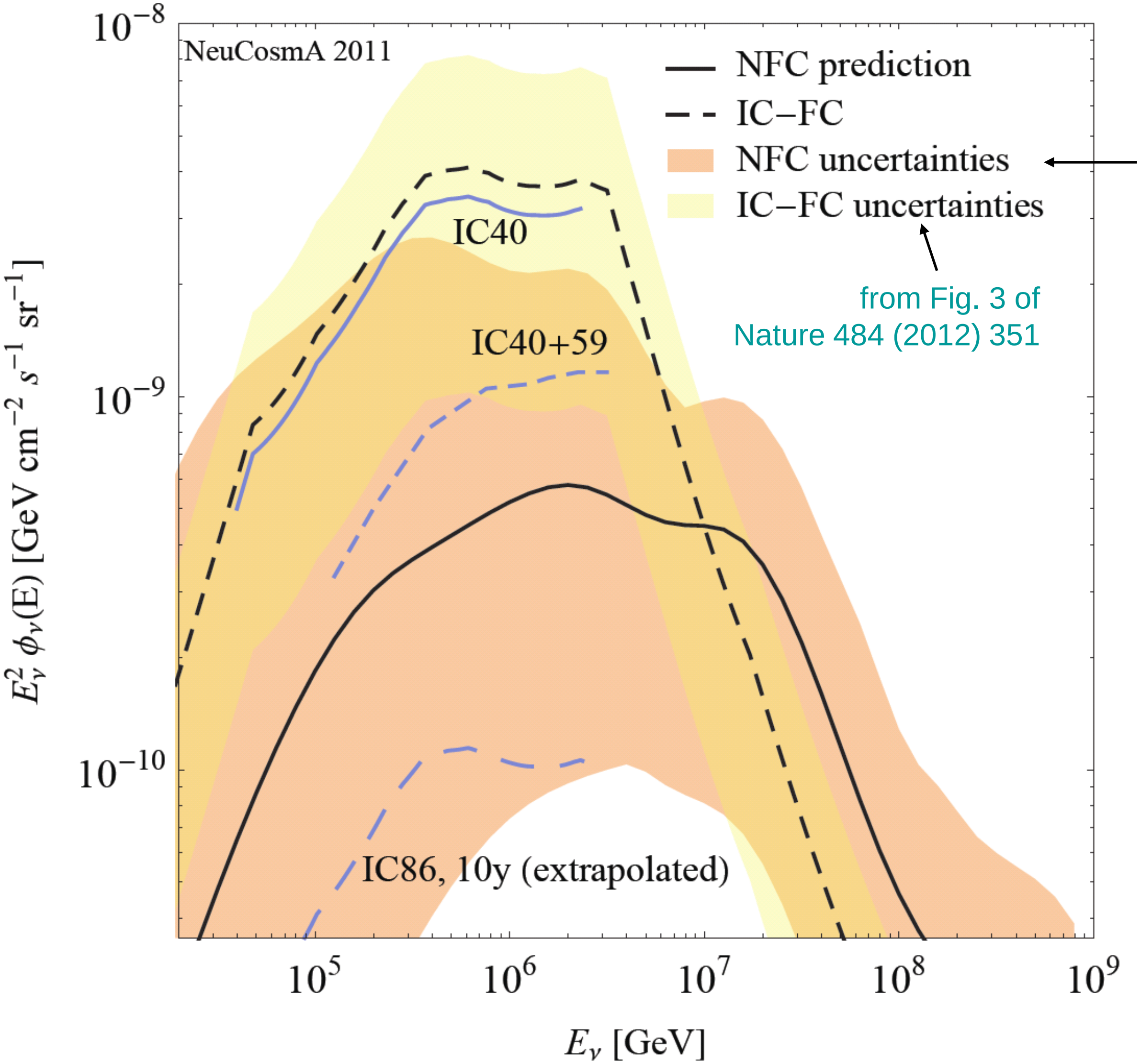
- Example: $$F_\gamma(E_\gamma) = \frac{\mathrm{d}N(E_\gamma)}{\mathrm{d}E_\gamma} = f_\gamma \times \begin{cases} \left(\frac{\epsilon_\gamma}{\mathrm{MeV}}\right)^{\alpha_\gamma} \left(\frac{E_\gamma}{\mathrm{MeV}}\right)^{-\alpha_\gamma} & \text{for } E_\gamma < \epsilon_\gamma \\ \left(\frac{\epsilon_\gamma}{\mathrm{MeV}}\right)^{\beta_\gamma} \left(\frac{E_\gamma}{\mathrm{MeV}}\right)^{-\beta_\gamma} & \text{for } E_\gamma \geq \epsilon_\gamma \end{cases}$$



First break from break in photon spectrum (here: $E^{-1} \Rightarrow E^{-2}$ in photons)

Second break from pion cooling (simplified)

Comparison of methods



from Fig. 3 of arXiv:1112.1076, PRL

from Fig. 3 of Nature 484 (2012) 351