Neutrinos from gamma-ray bursts, and tests of the cosmic ray paradigm

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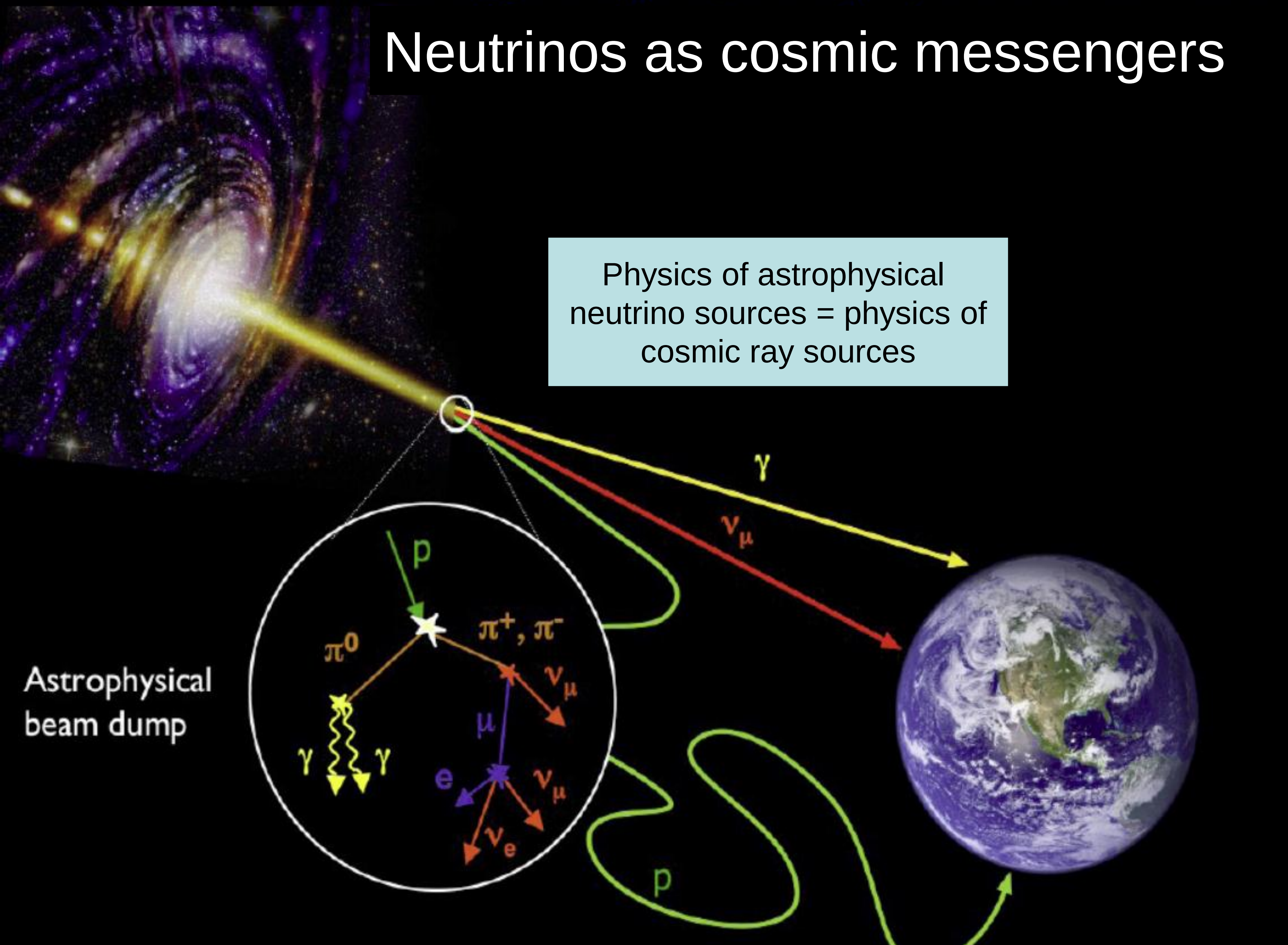
Walter Winter
Universität Würzburg

Heisenberg-Programm
Deutsche Forschungsgemeinschaft

Contents

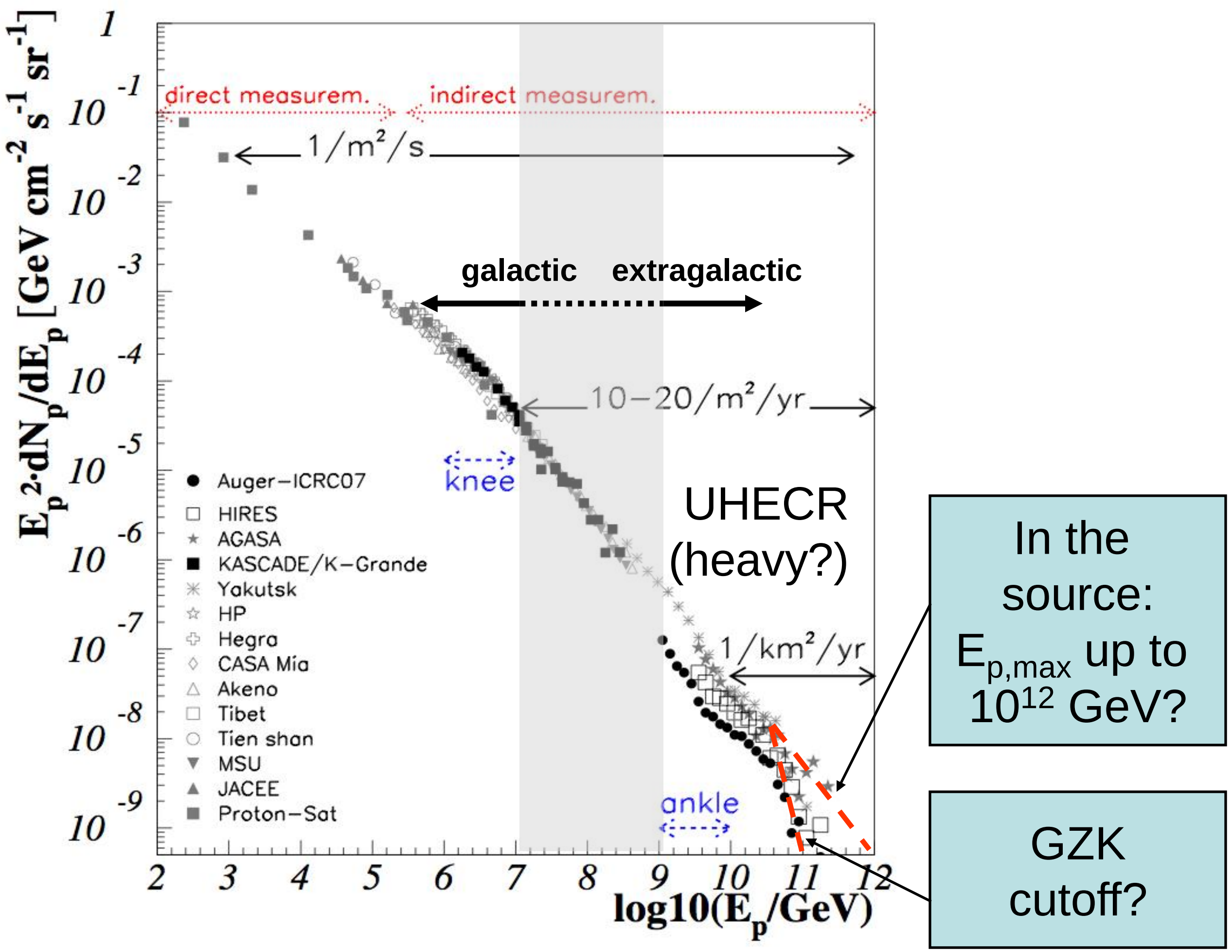
Neutrinos as cosmic messengers

Physics of astrophysical neutrino sources = physics of cosmic ray sources



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



Cosmic ray source

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

If neutrons can escape:
Source of cosmic rays

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

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

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

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

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

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

$$\pi^0 \longrightarrow \gamma + \gamma$$

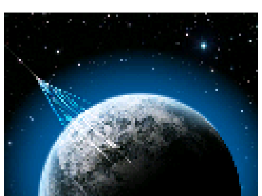
High energetic gamma-rays;
typically cascade down to lower E

Cosmic messengers

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

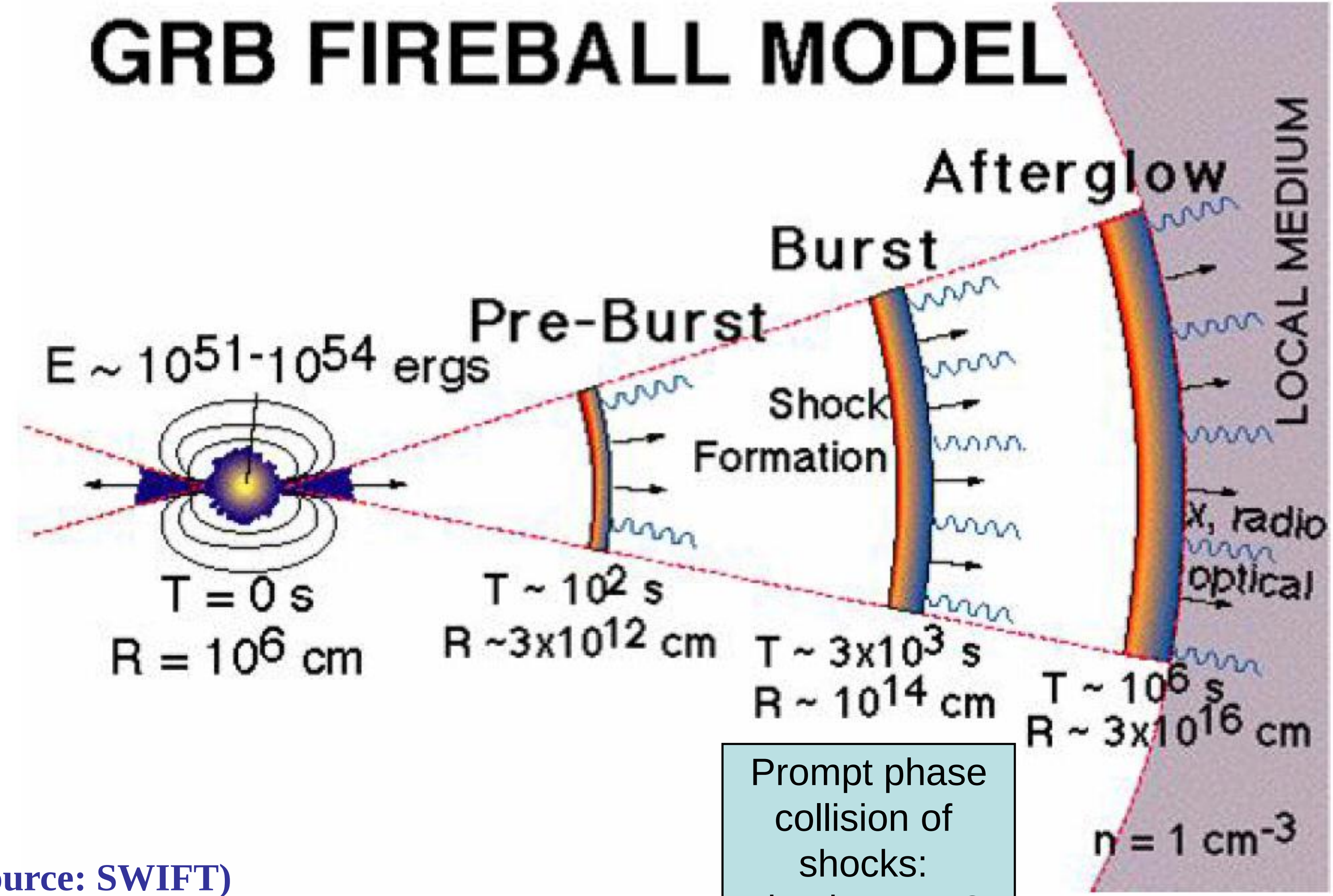


Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

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

Neutrino emission in GRBs



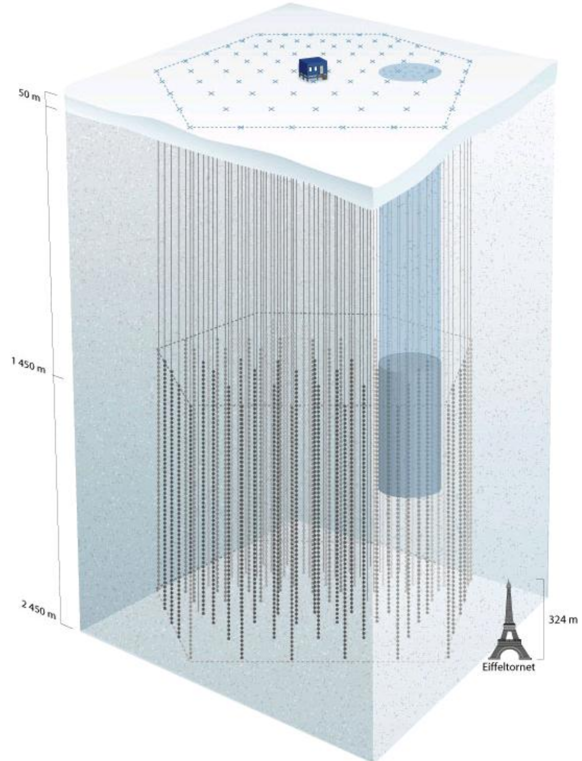
Prompt phase collision of shocks: dominant νs?

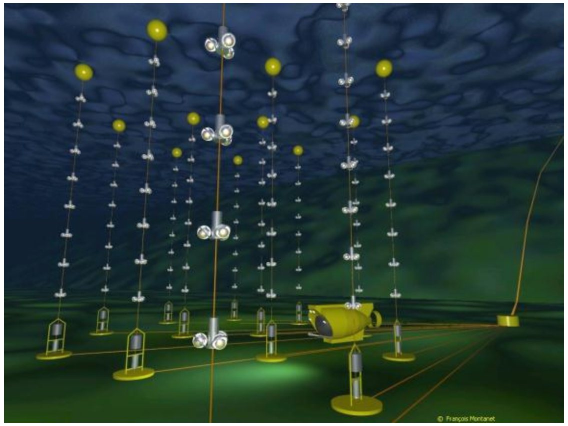
(Source: SWIFT)

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/

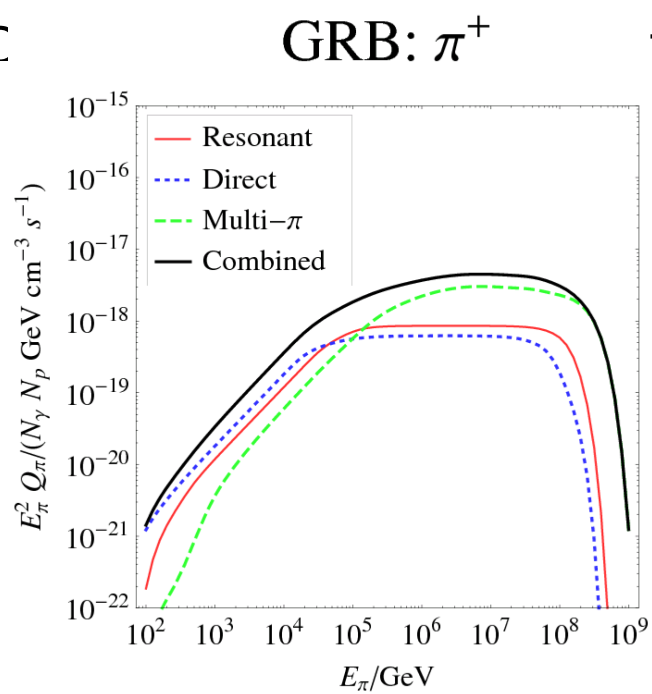
Simulation of sources

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:
  - SC … iption of physics



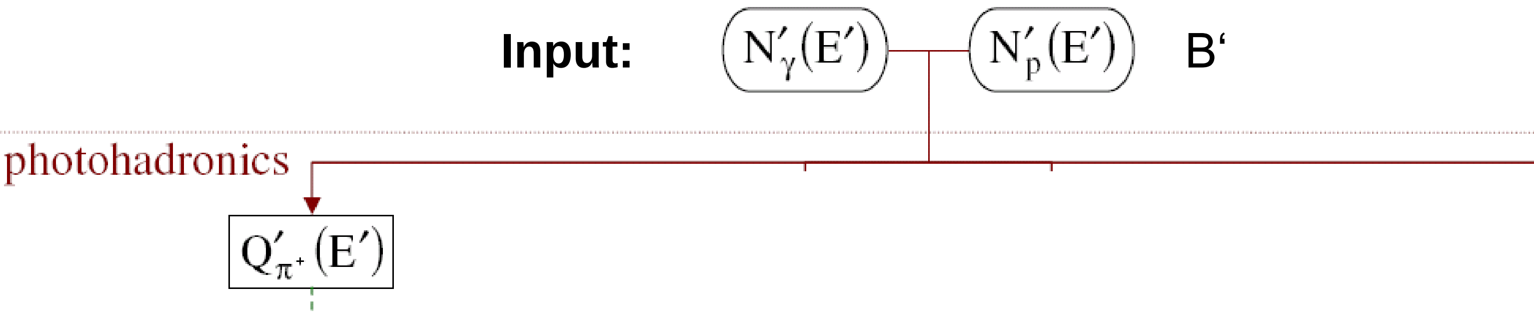
from: Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630

NeuCosmA

"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



Peculiarity for neutrinos: Secondary cooling

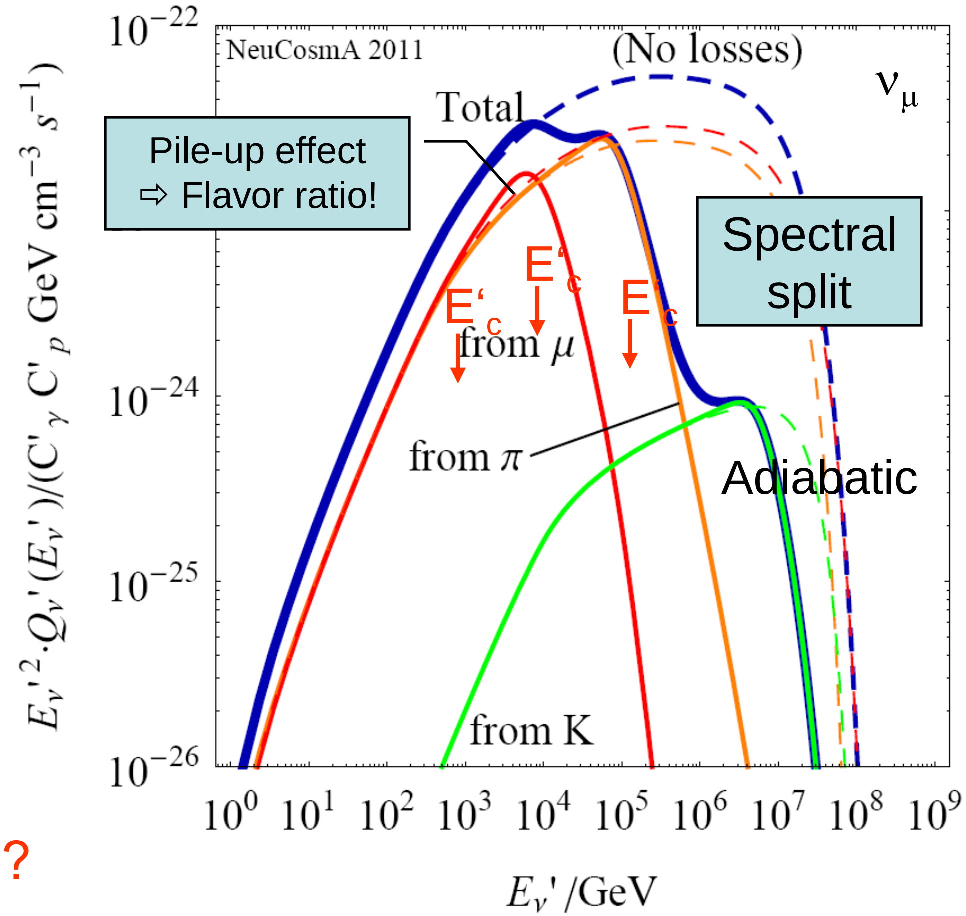
Example: GRB

Secondary spectra (μ, π, K) loss-steepend above 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‘?

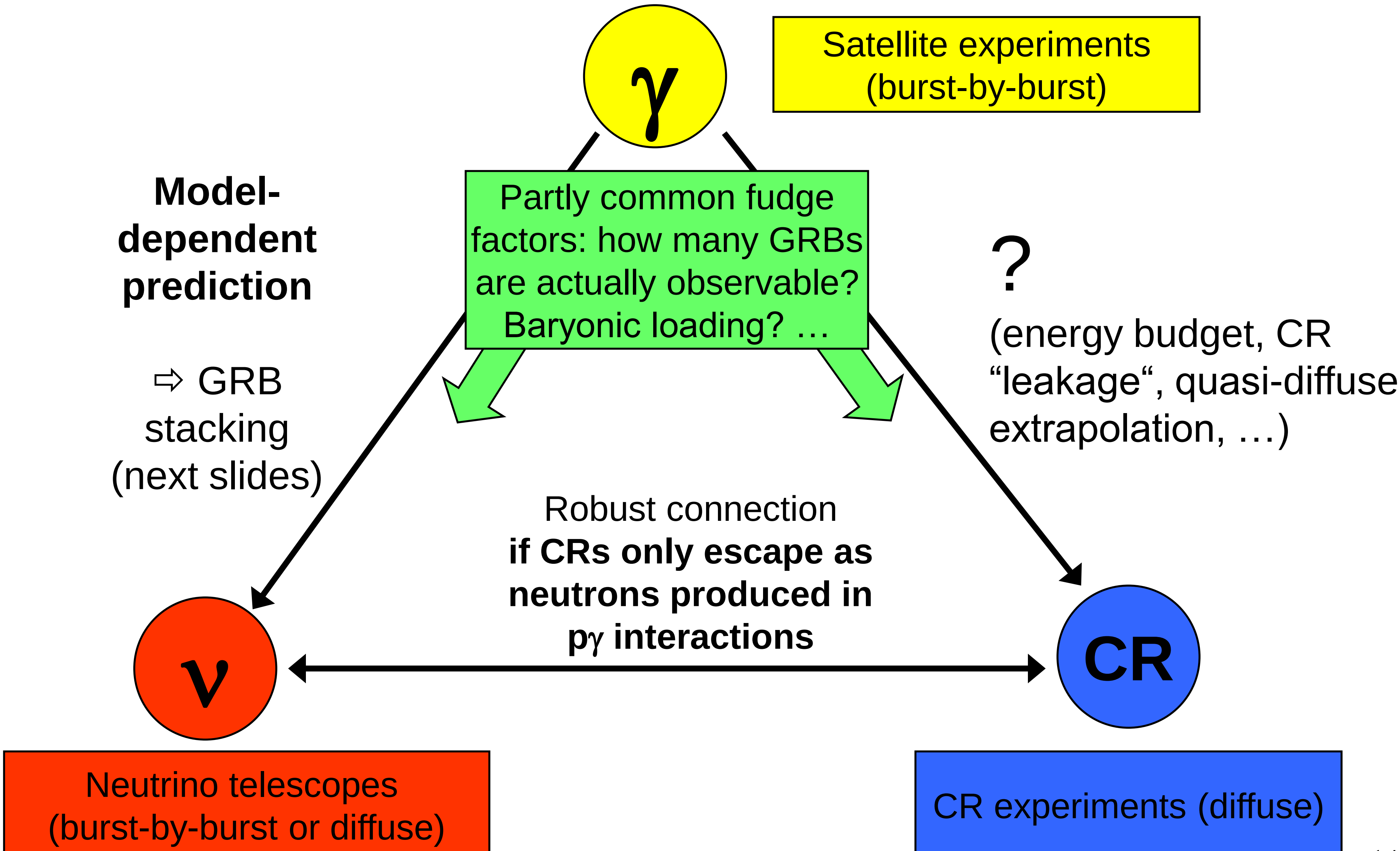
Decay/cooling: charged μ, π, K



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007

Neutrinos from GRBs

The “magic“ triangle



Julius-Maximilians-
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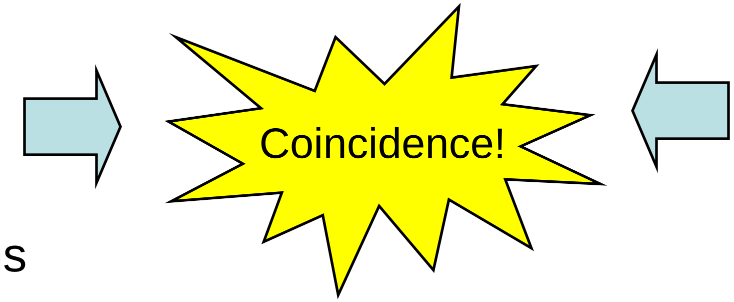
GRB stacking

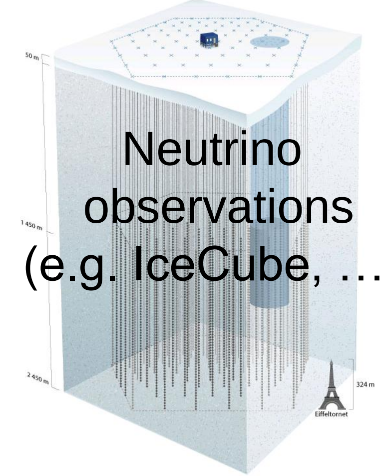
- Idea: Use multi-messenger approach

(Source: NASA)

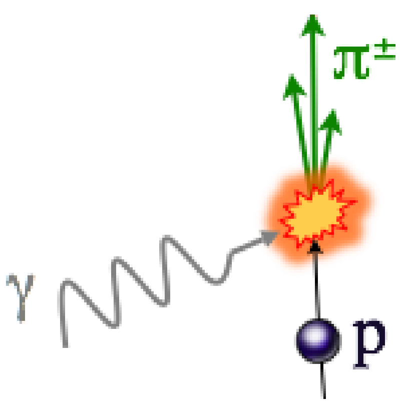
GRB gamma-ray observations
(e.g. Fermi GBM, Swift, etc)



(Source: IceCube)

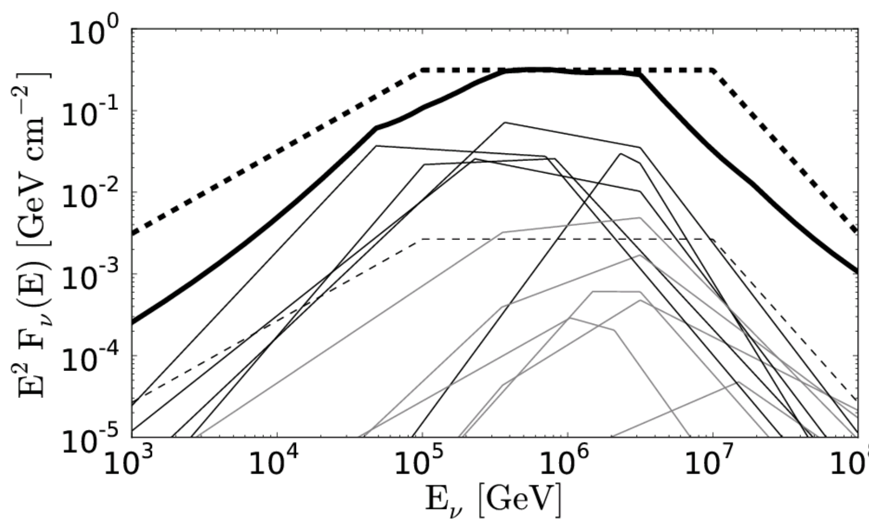


- Predict neutrino flux from observed photon fluxes event by event



Observed:
broken power law
(Band function)

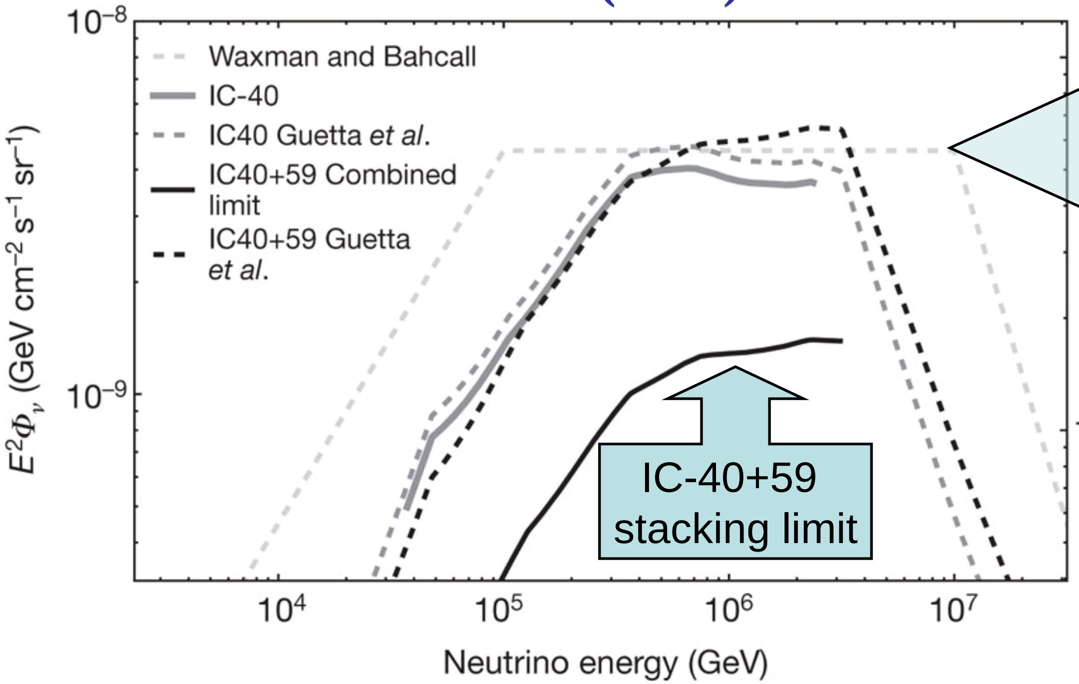
E^{-2} injection



(Example: IceCube, arXiv:1101.1448)

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?

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:

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

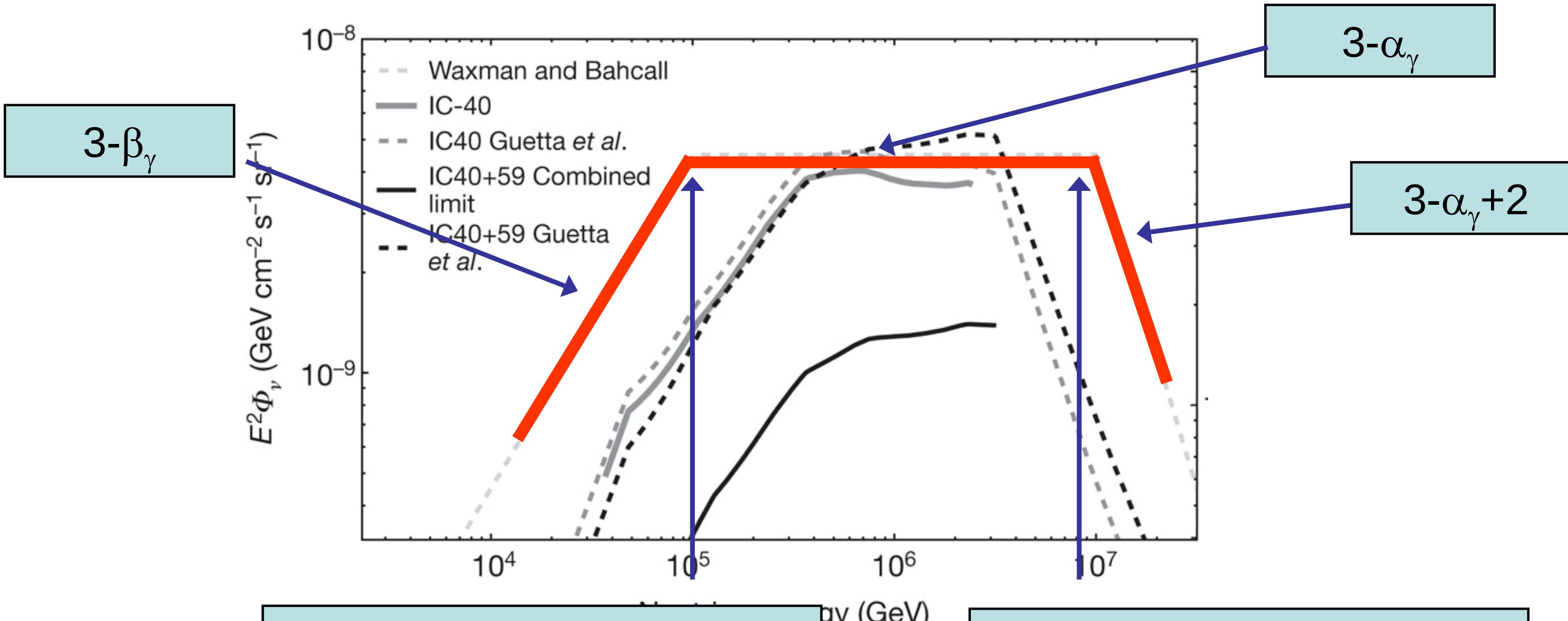
[in principle, $\lambda_{p\gamma} \sim 1/(n_\gamma\,\sigma)$; need estimates for n_γ, which contains the size of the acceleration region]

**(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)

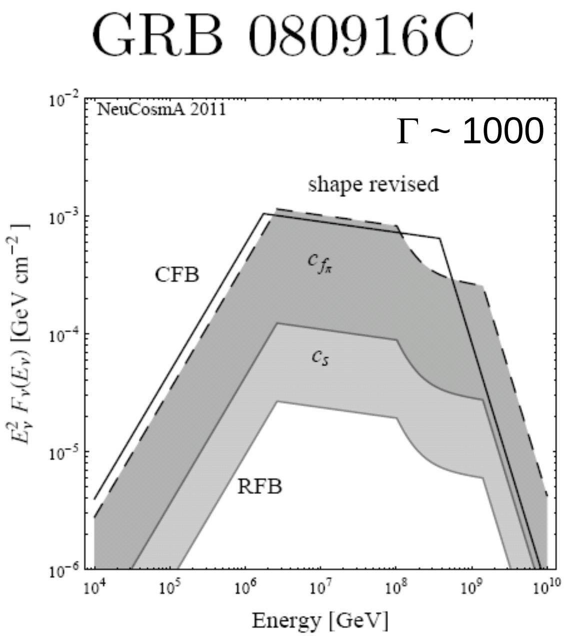
Revision of neutrino flux predictions

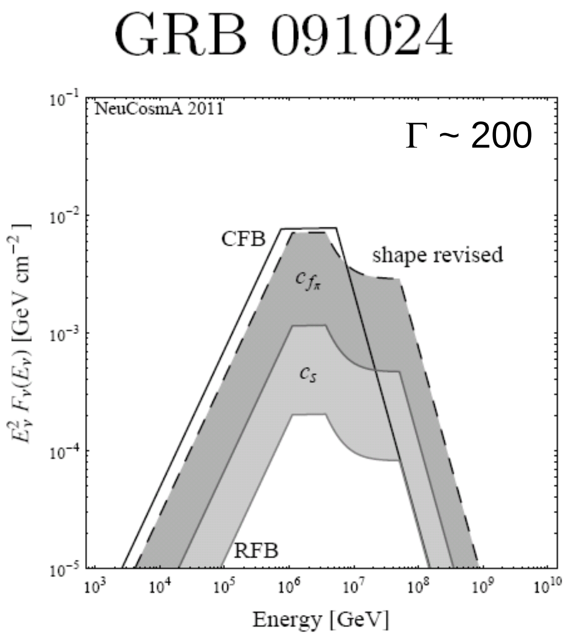
Analytical recomputation of IceCube method (CFB):

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

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

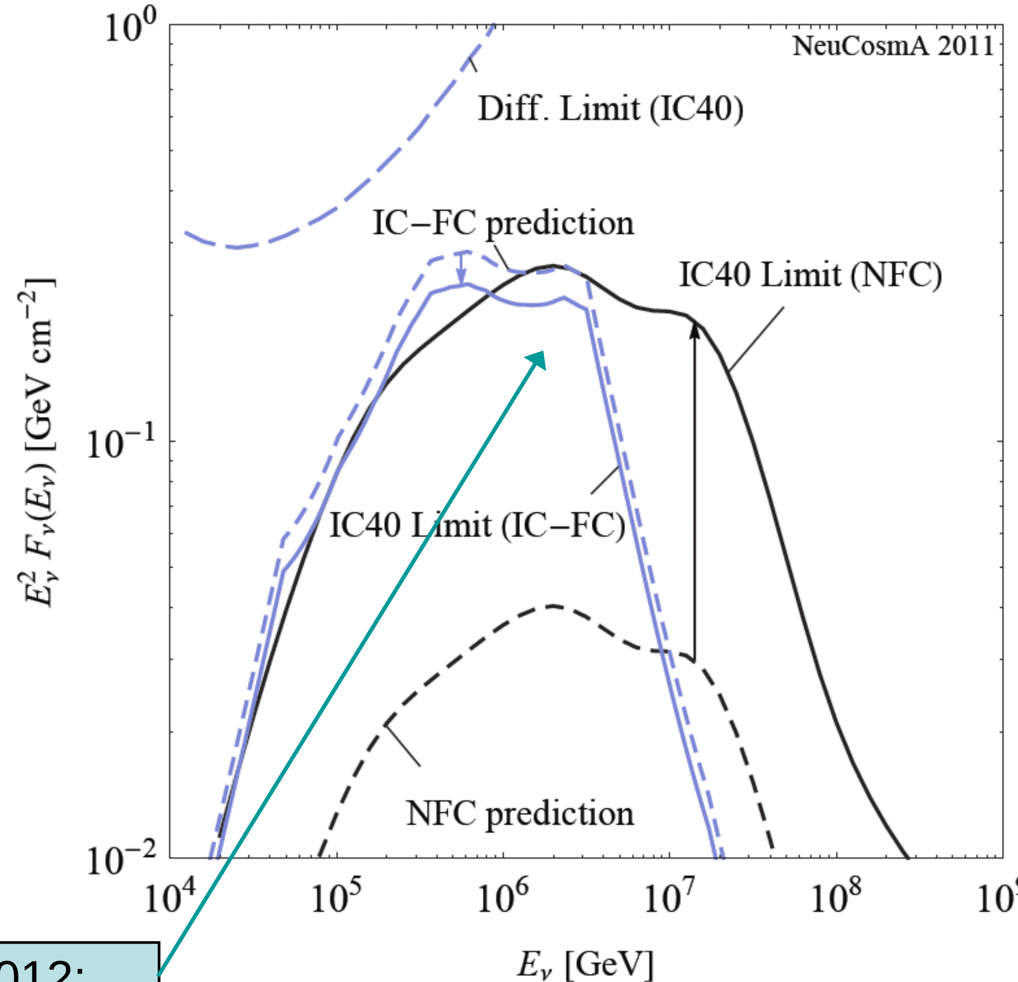
(see also Li, 2012, PRD)





Consequences for IC-40 analysis

- Diffuse limit illustrates interplay with detector response
- Shape of prediction used to compute sensitivity limit
- Peaks at higher energies

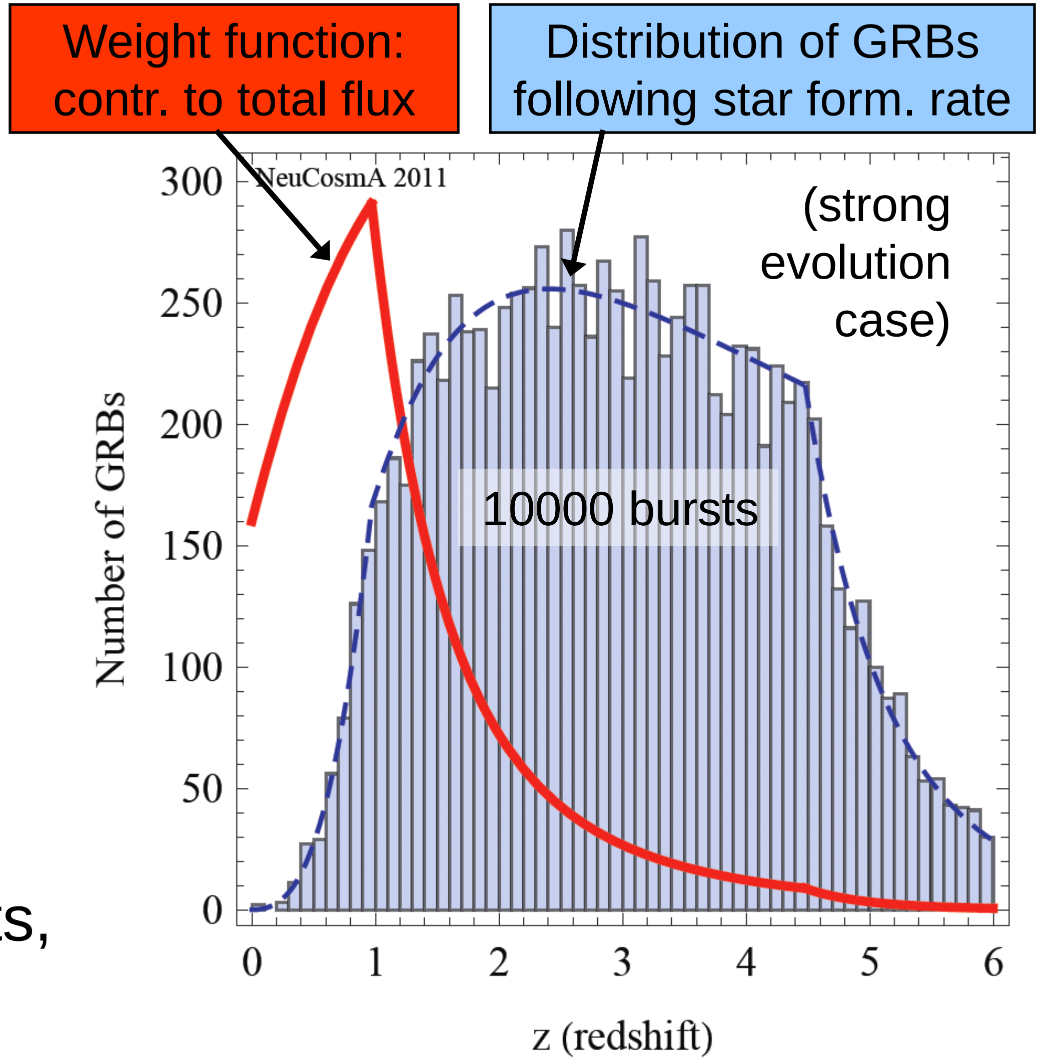


IceCube @ ν2012:
observed two events
~ PeV energies
⇨ from GRBs?

(Hümmer, Baerwald, Winter,
Phys. Rev. Lett. 108 (2012) 231101)

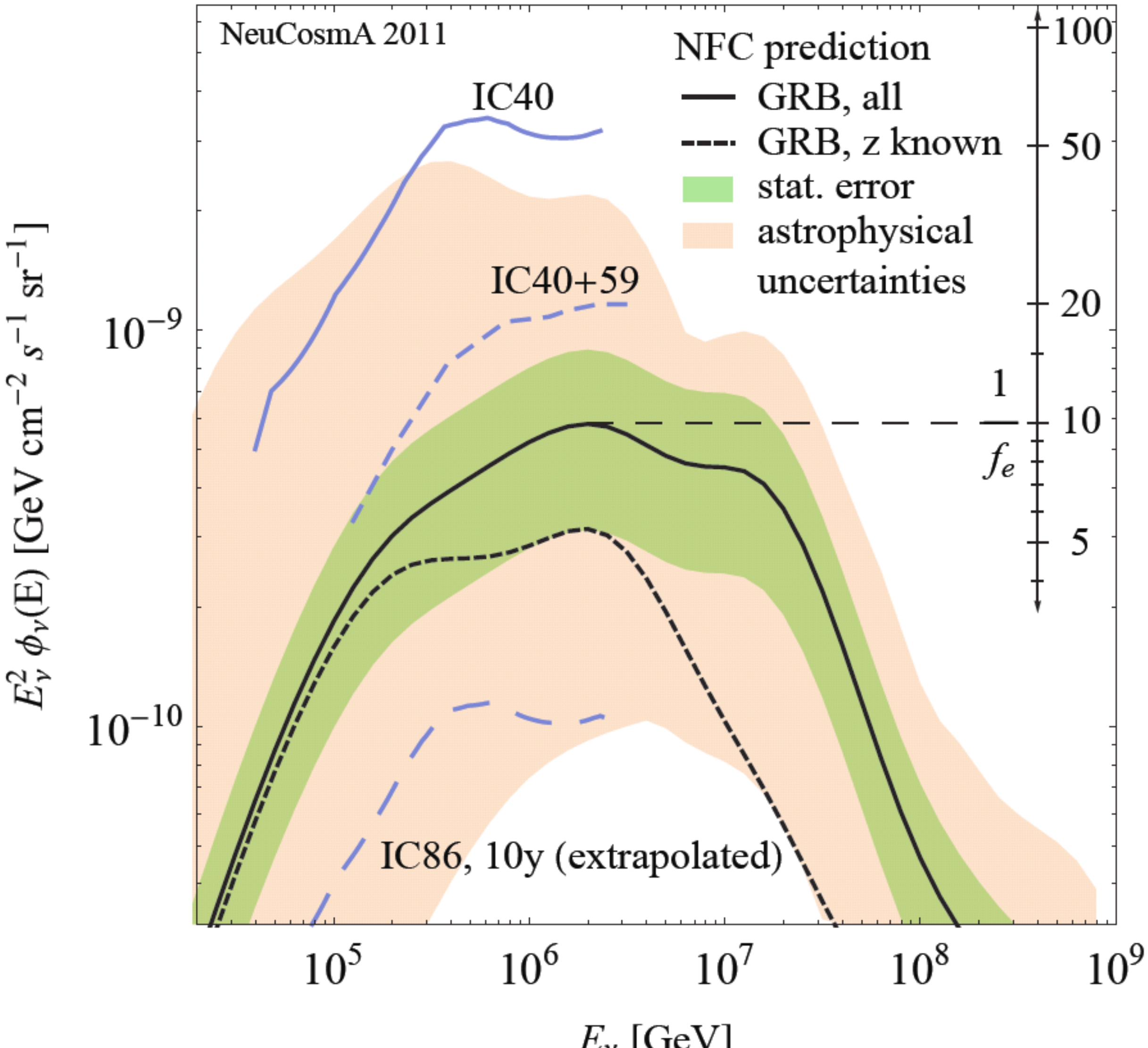
Systematics in aggregated fluxes

- 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)

Quasi-diffuse prediction

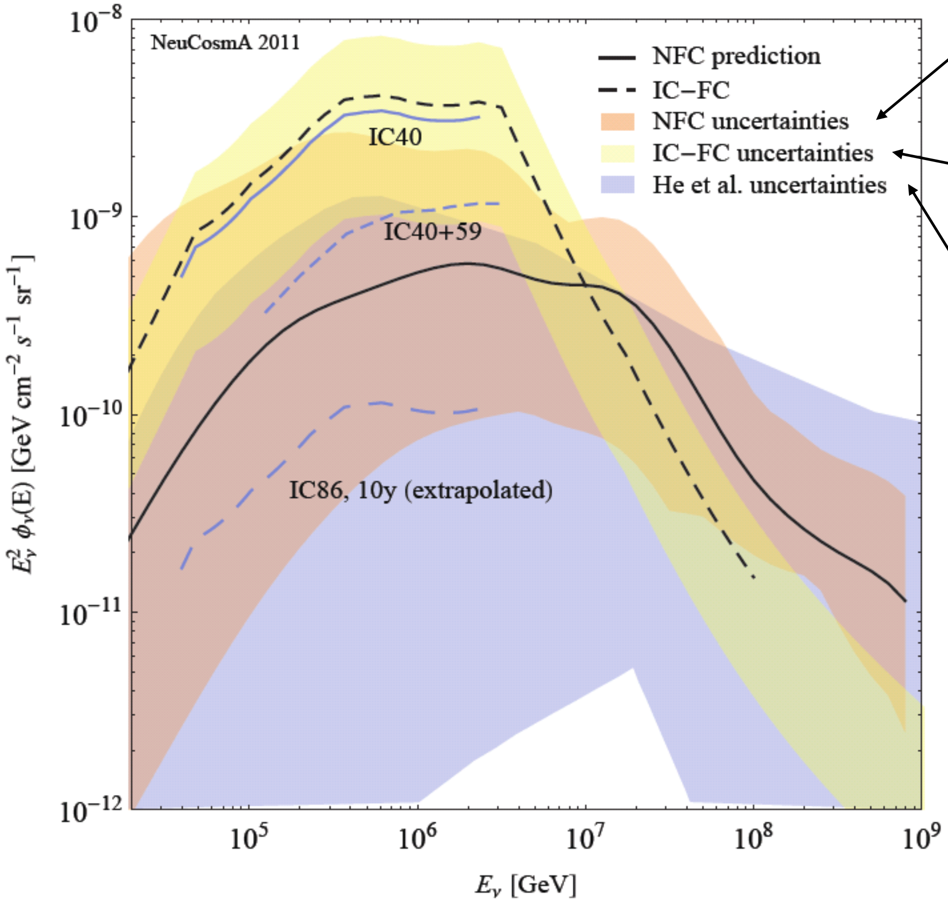


- Numerical fireball model cannot be ruled out with IC40+59 for same parameters, bursts, assumptions
- Peak at higher energy! [optimization of future exps?]

"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, Phys. Rev. Lett. 108 (2012) 231101)

Comparison of methods/models



from Fig. 3 of Hümmer et al, arXiv:1112.1076, PRL; origin of target photons not specified

from Fig. 3 of Nature 484 (2012) 351; uncertainties from Guetta, Spada, Waxman, Astroph J. 559 (2001) 2001: target photons from synchrotron emission/inverse Compton

completely model-independent (large collision radii allowed): He et al, Astrophys. J. 752 (2012) 29

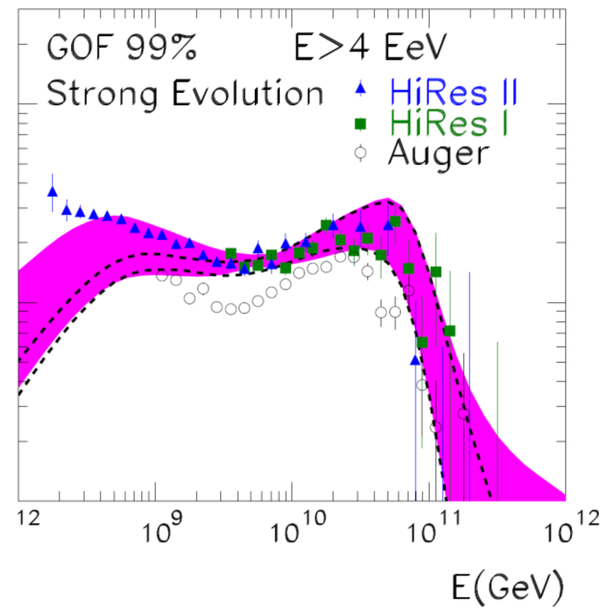
(P. Baerwald)

Neutrinos-cosmic rays ν ⟷ CR

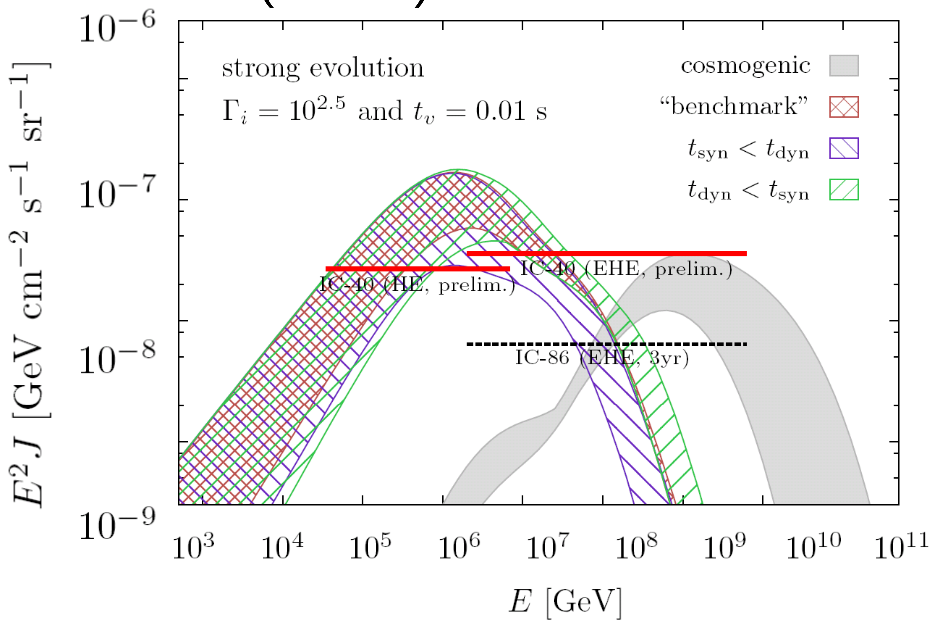
- If charged π and n produced together:

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

Fit to UHECR spectrum



Consequences for (diffuse) neutrino fluxes



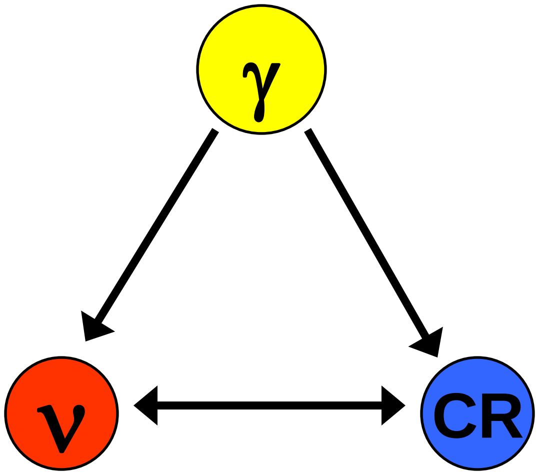
➢ GRB not exclusive sources of UHECR? CR leakage?

(Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87)

Summary

Are GRBs the sources of the UHECR?

- Gamma-rays versus neutrinos
  - Revised model calculations release pressure on fireball model calculations
  - Baryonic loading will be finally constrained (at least in “conventional“ internal shock models)



- Neutrinos versus cosmic rays
  - Cosmic ray escape as neutrons under tension
    - ➢ Cosmic ray leakage?
    - ➢ Not the only sources of the UHECR?
- Gamma-rays versus cosmic rays – in progress