Are GRBs the sources of the UHECRs?

GRB: Gamma-Ray Burst   UHECR: Ultra-High Energy Cosmic Rays

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Nordita, Stockholm, 24.04.2014

HELMHOLTZ ASSOCIATION

DESY

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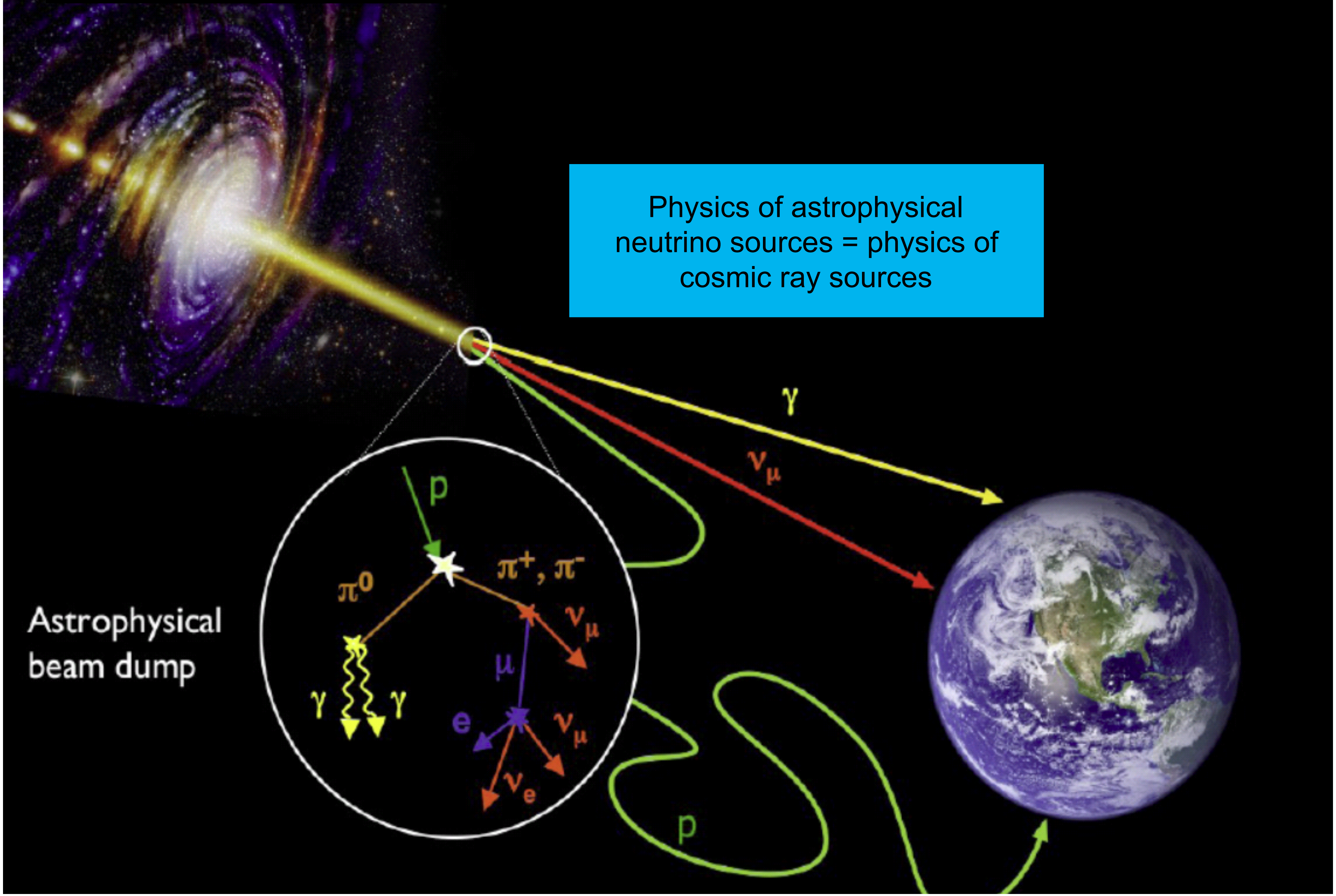
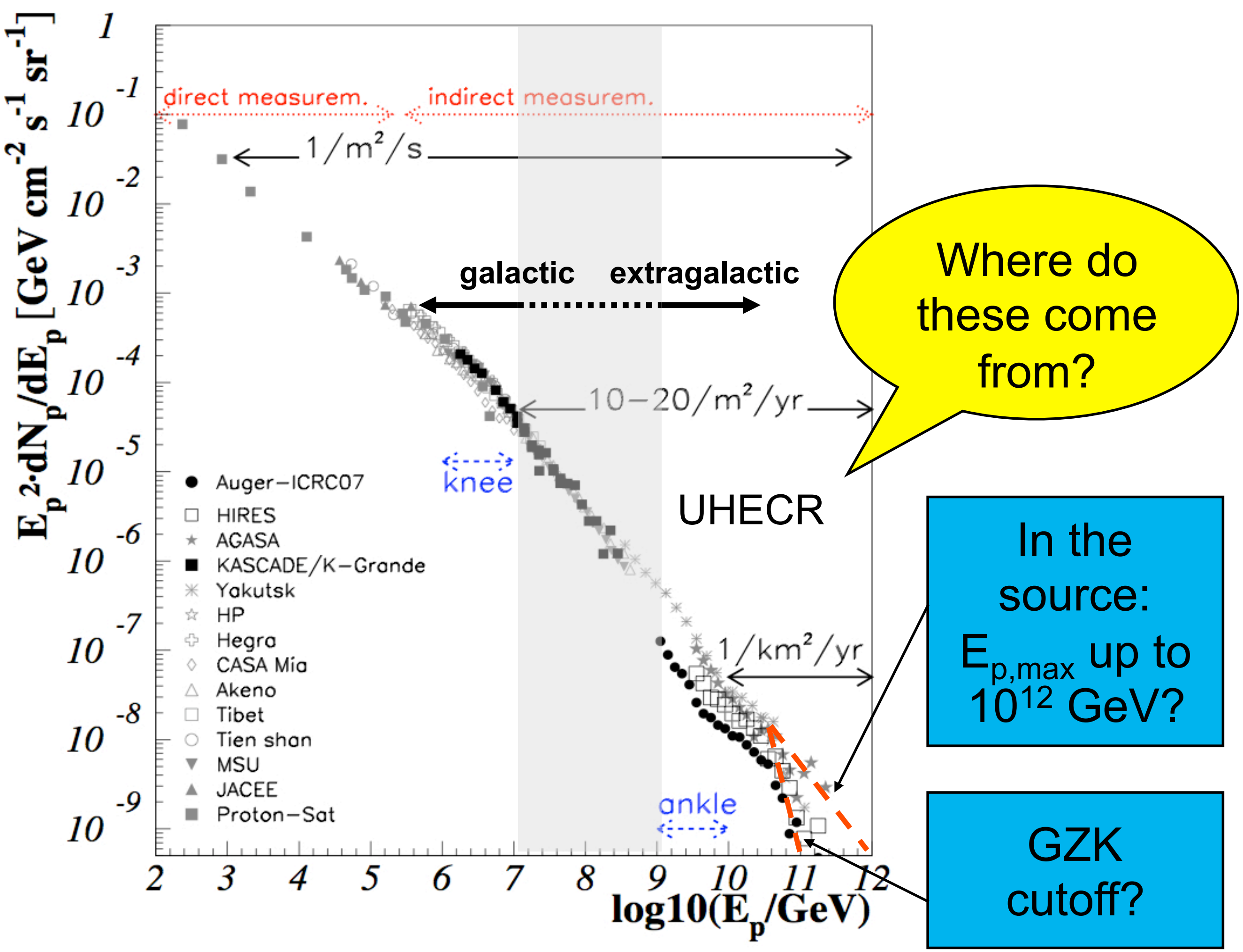
Cosmic messengers

Physics of astrophysical neutrino sources = physics of cosmic ray sources



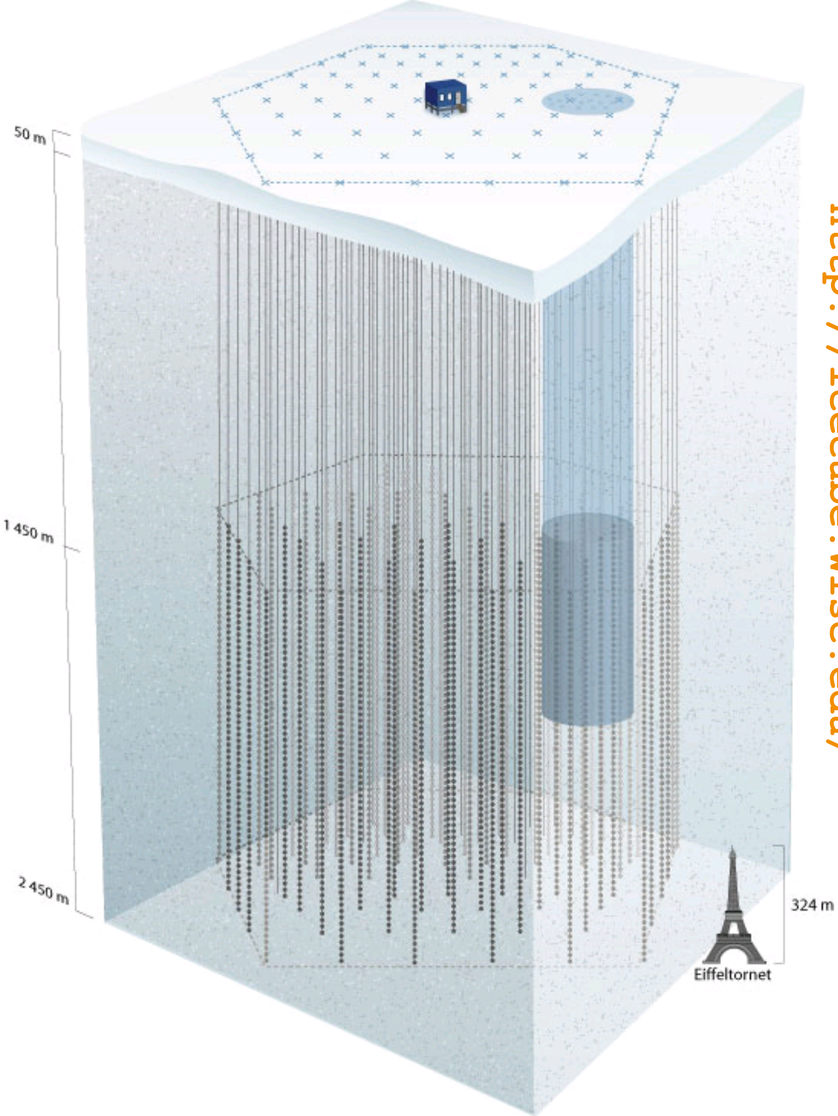
Cosmic ray observations

- Observation of cosmic rays: **need to accelerate protons/ nuclei 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



Neutrino detection: Neutrino telescopes

- Example: IceCube at South Pole.
  Detector material:
  ~ 1 km^3 antarctic ice
- Completed 2010/11 (86 strings)
- Recent major successes:
  - Constraints on GRBs
    Nature 484 (2012) 351
  - 28 events in the TeV-PeV range
    Science 342 (2013) 1242856
- **Neutrinos established as messengers of the high-energy universe!**

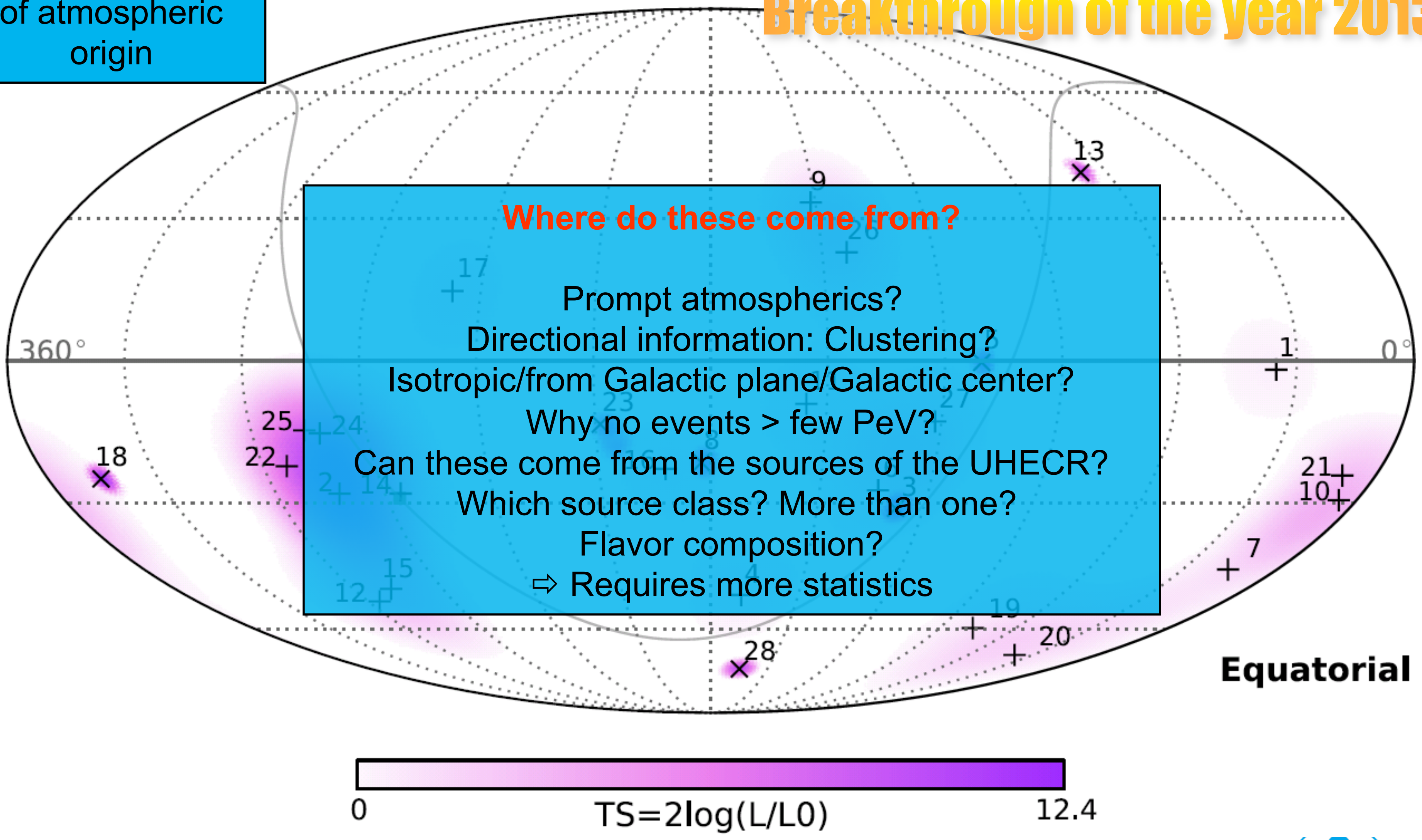


http://icecube.wisc.edu/

Neutrinos in the TeV-PeV range

~ 11 events
of atmospheric
origin

Physics World
Breakthrough of the year 2013



Where do these come from?

Prompt atmospherics?
Directional information: Clustering?
Isotropic/from Galactic plane/Galactic center?
Why no events > few PeV?
Can these come from the sources of the UHECR?
Which source class? More than one?
Flavor composition?
⇨ Requires more statistics

Science 342 (2013) 1242856

The two paradigms for extragalactic UHECR 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

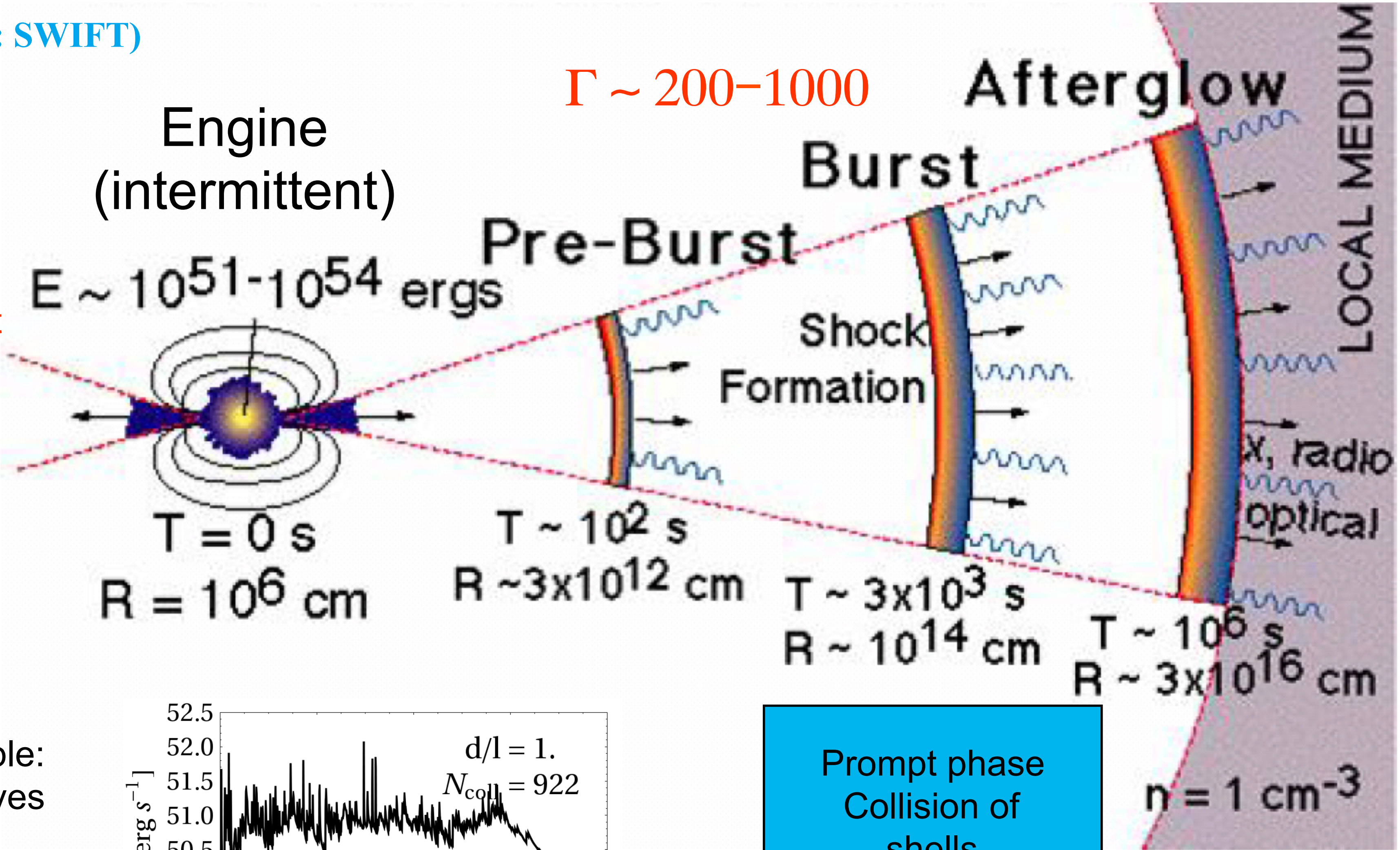
Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

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

GRB - Internal shock model

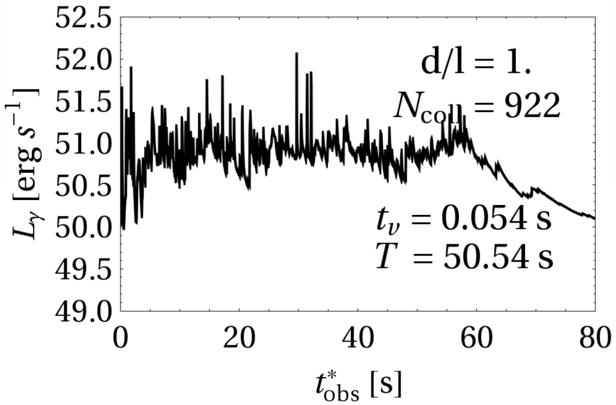
(Source: SWIFT)



"Isotropic equivalent energy"

Observable:
Light curves

(Simulation by
M. Bustamante)



Prompt phase
Collision of
shells
⇨ Shocks
⇨ Particle acc.

Simulation of cosmic ray and neutrino sources

(focus on proton composition …)

Cosmic ray source
(illustrative proton-only scenario, pγ 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

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

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

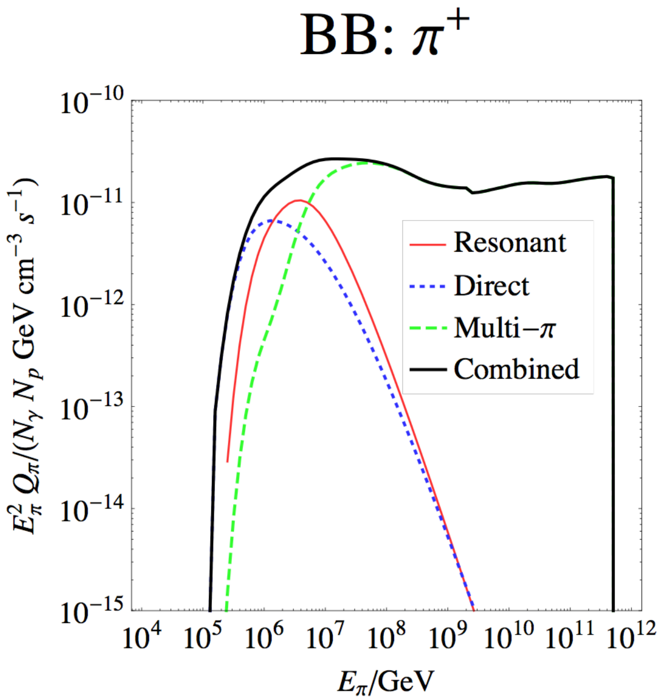
Cosmic messengers

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:



Example: 10 eV blackbody target photon spectrum
Multi-pion processes exclude this as explanation for observed neutrinos!

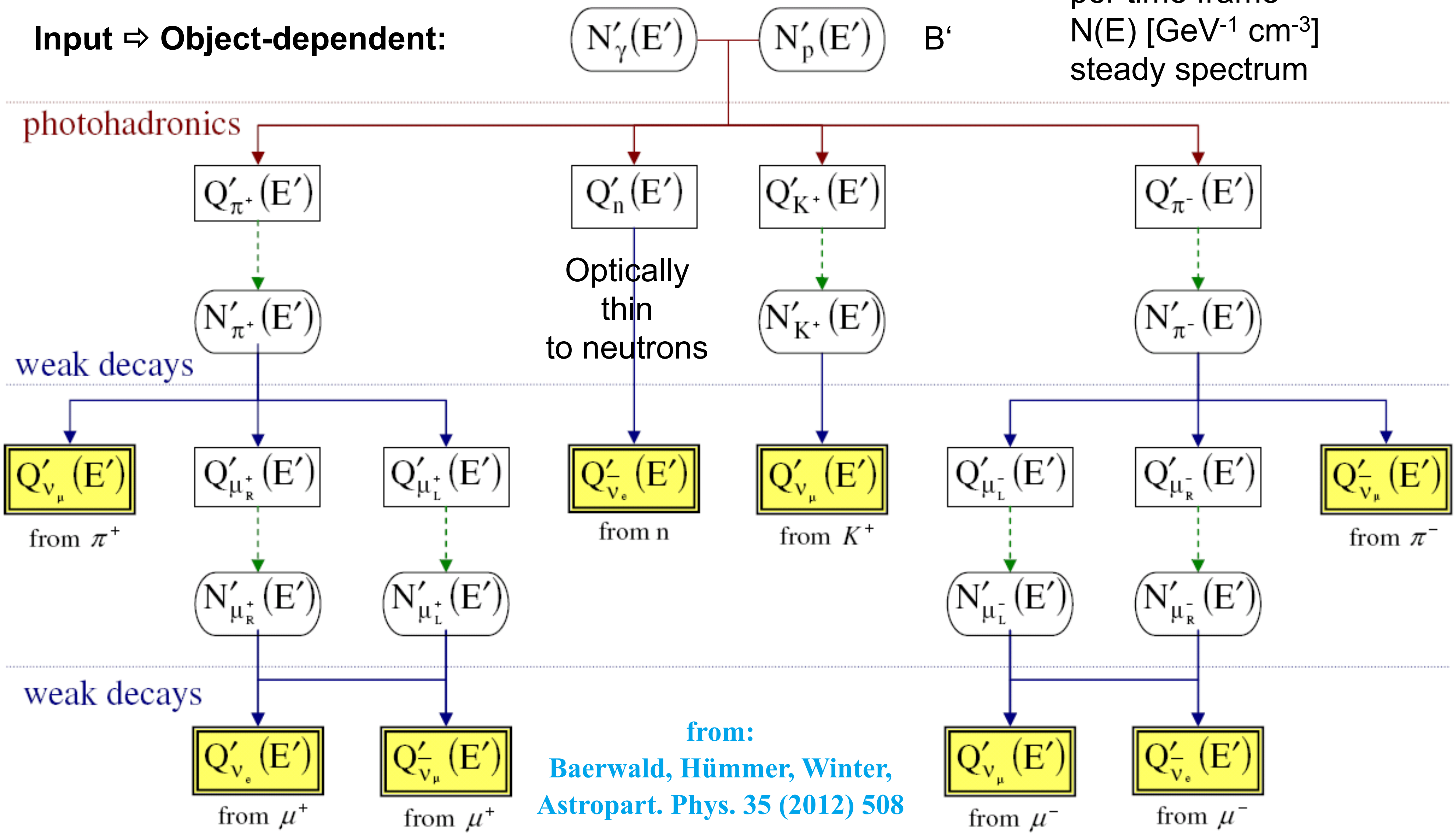
from:
Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630

Neutrino production

Dashed arrows: kinetic equations include cooling and escape

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

Input ⇨ Object-dependent:



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

Peculiarity for neutrinos: Secondary cooling

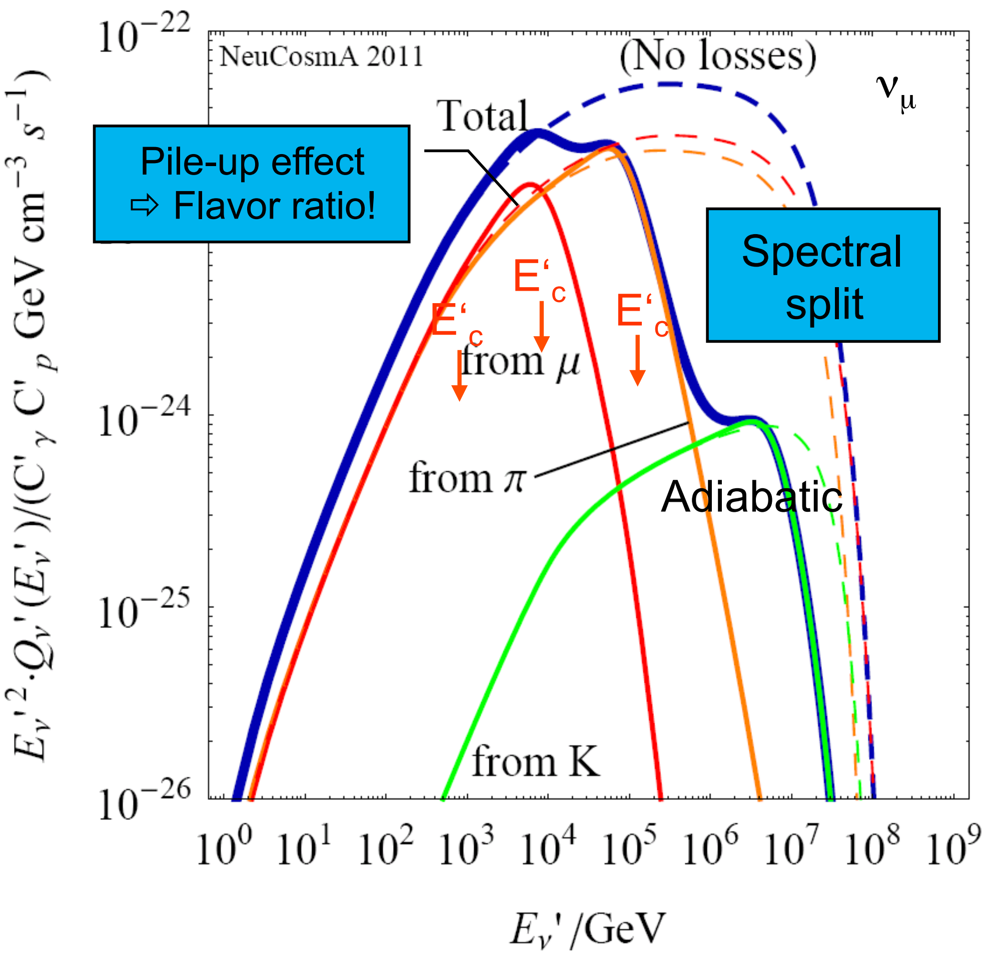
Example: GRB

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]

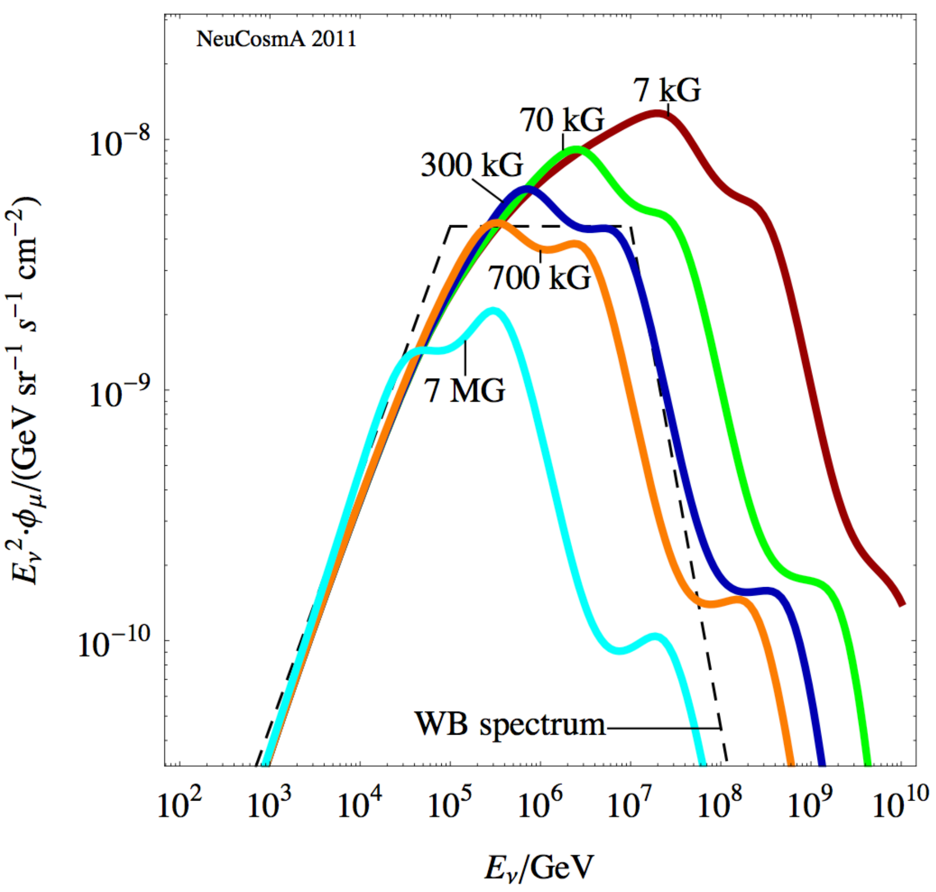
Decay/cooling: charged μ, π, K

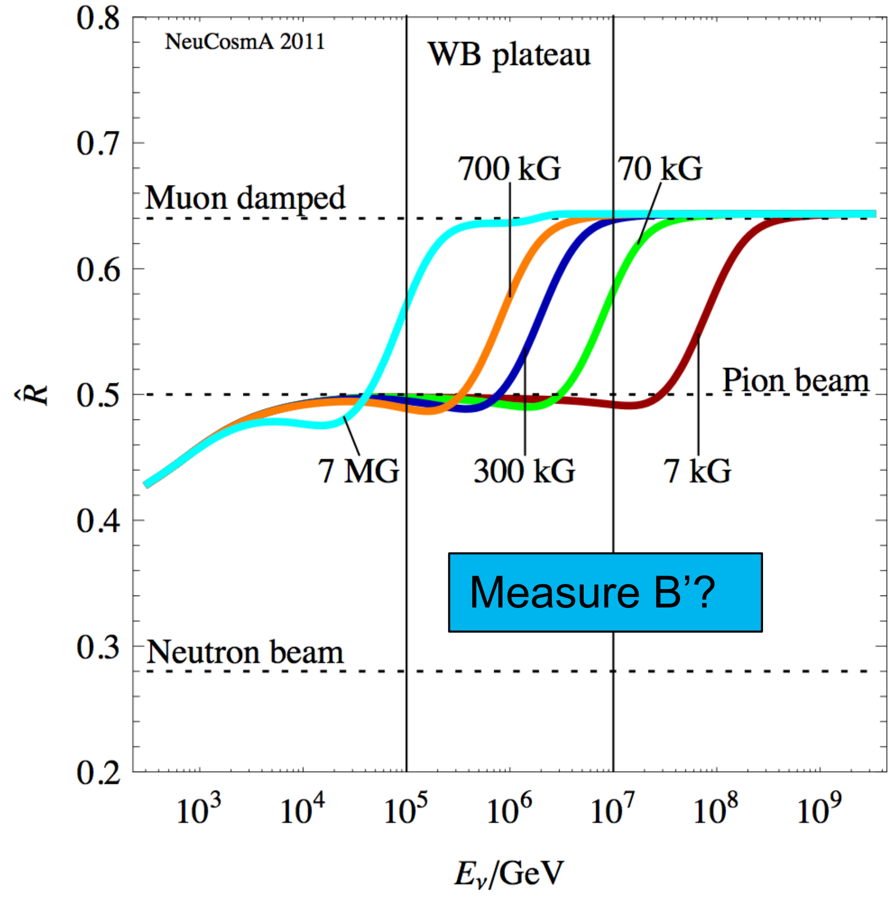


Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007

Impact on flavor composition

> Muon track to cascade ratio (R) changes as a function of B':

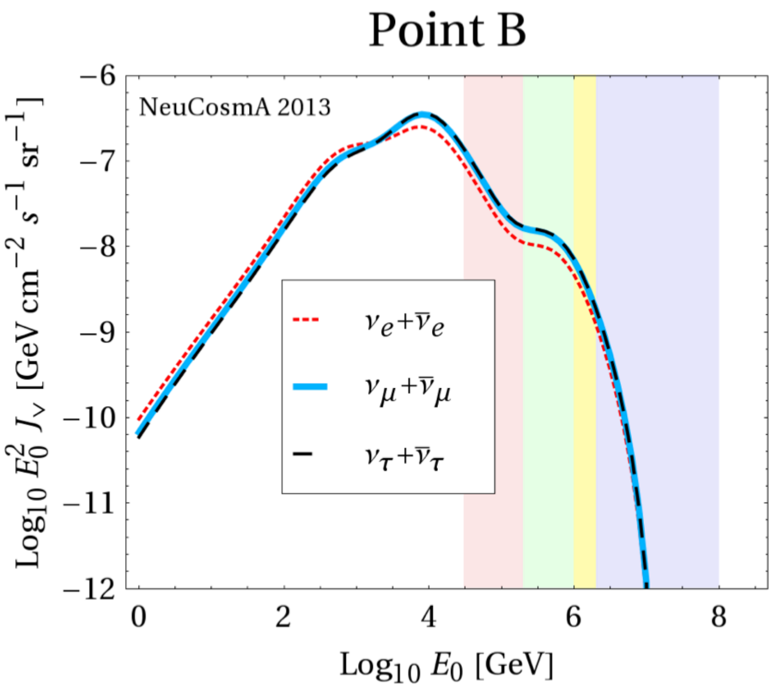




Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508

Cutoff at PeV energies, and the UHECR paradigm?

- One of the puzzles in current neutrino observations: Is there a cutoff at a few PeV?
  - Maximal proton energy limited?
  - Spectrum significantly steeper than E^{-2}
  - ➢ Both cases: difficult to re-concile with UHECR paradigm
- Can one partially decouple maximal proton and neutrino energies?
  - Yes, with magnetic fields
  - Challenge: require large Γ. GRBs again? E. g. Low luminosity GRBs?



Winter, Phys. Rev. D88 (2013) 083007

From the source to the detector: UHECR transport

> Kinetic equation for co-moving number density:

$$\dot{Y}_p = \partial_E \left(HEY_p\right) + \partial_E \left(b_{e^+e^-} Y_p\right) + \partial_E \left(b_{p\gamma} Y_p\right) + \mathcal{L}_{\rm CR}$$

Expansion of Universe

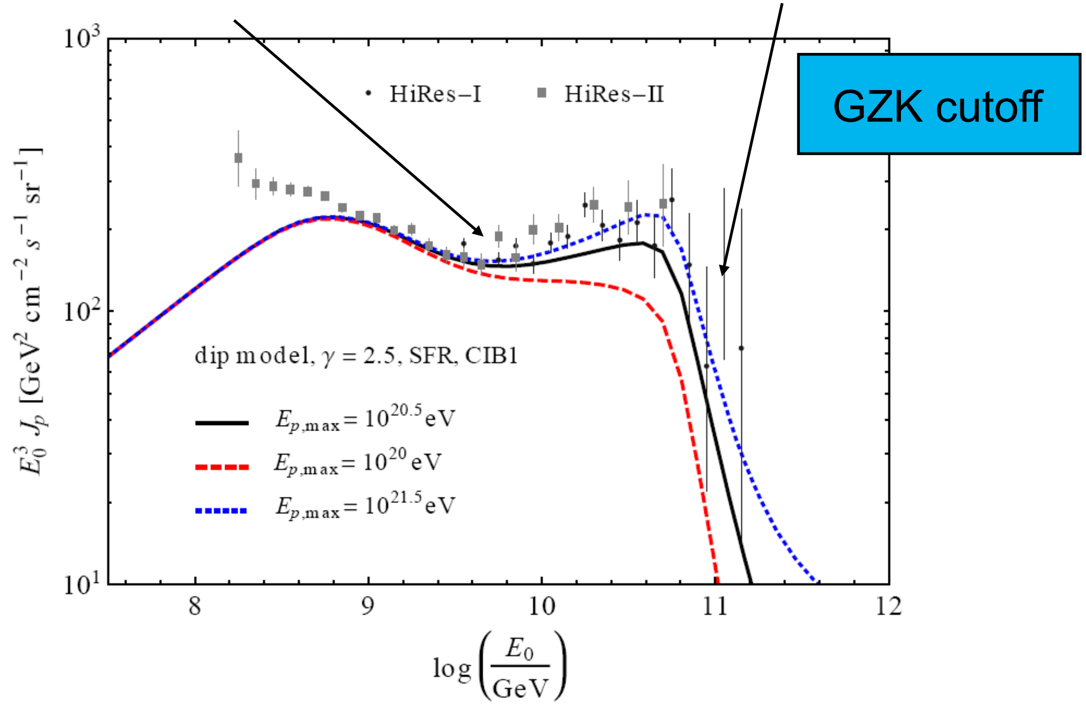
Pair production **Blumenthal, 1970**

Photohadronics **Hümmer, Rüger, Spanier, Winter, 2010**

CR inj. z-dep!

[here $b=-dE/dt=E\, t^{-1}_{loss}$]

> Energy losses
> ⇨ UHECR must from from our local environment
> (~ 1 Gpc at 10^{10} GeV, ~ 50 Mpc at 10^{11} GeV)



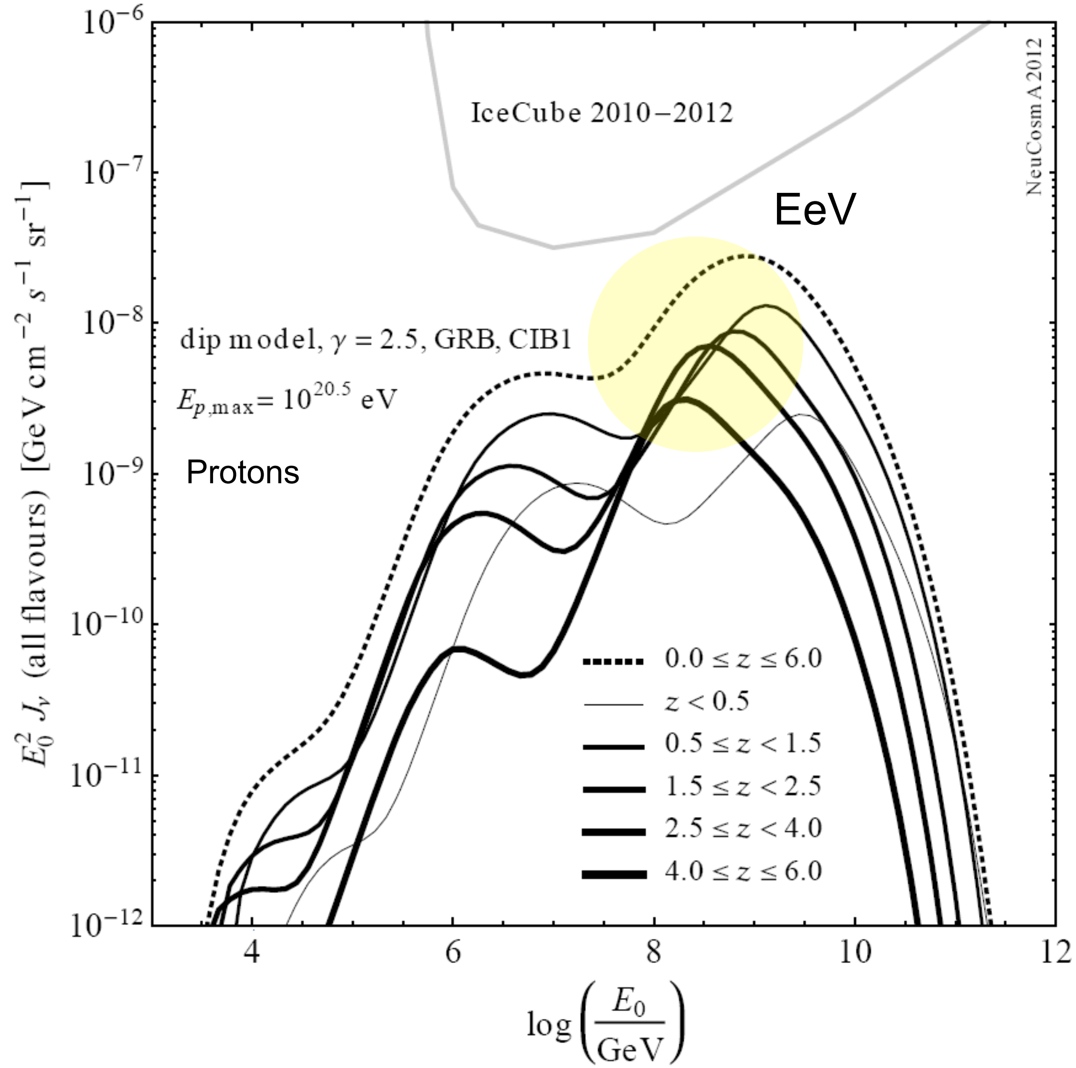
(M. Bustamante)

Cosmogenic neutrinos

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

Cosmogenic neutrinos

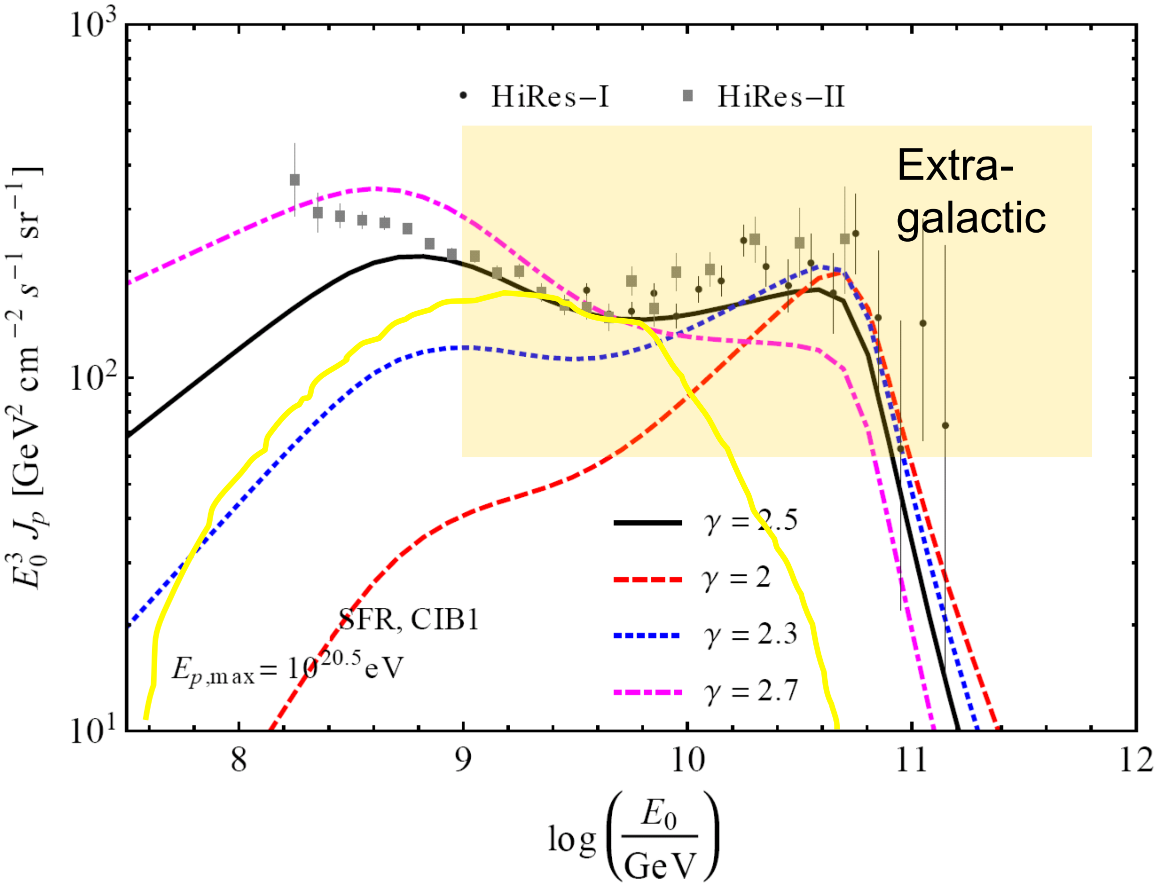
- Prediction depends on maximal proton energy, spectral index γ, source evolution, composition
- Can test UHECR beyond the local environment
- Can test UHECR injection independent of CR production model
  ⇨ constraints on UHECR escape



(courtesy M. Bustamante; see also Kotera, Allard, Olinto, JCAP 1010 (2010) 013)

UHECR transition models

- Transition between Galactic (?) and extragalactic cosmic rays at different energies:



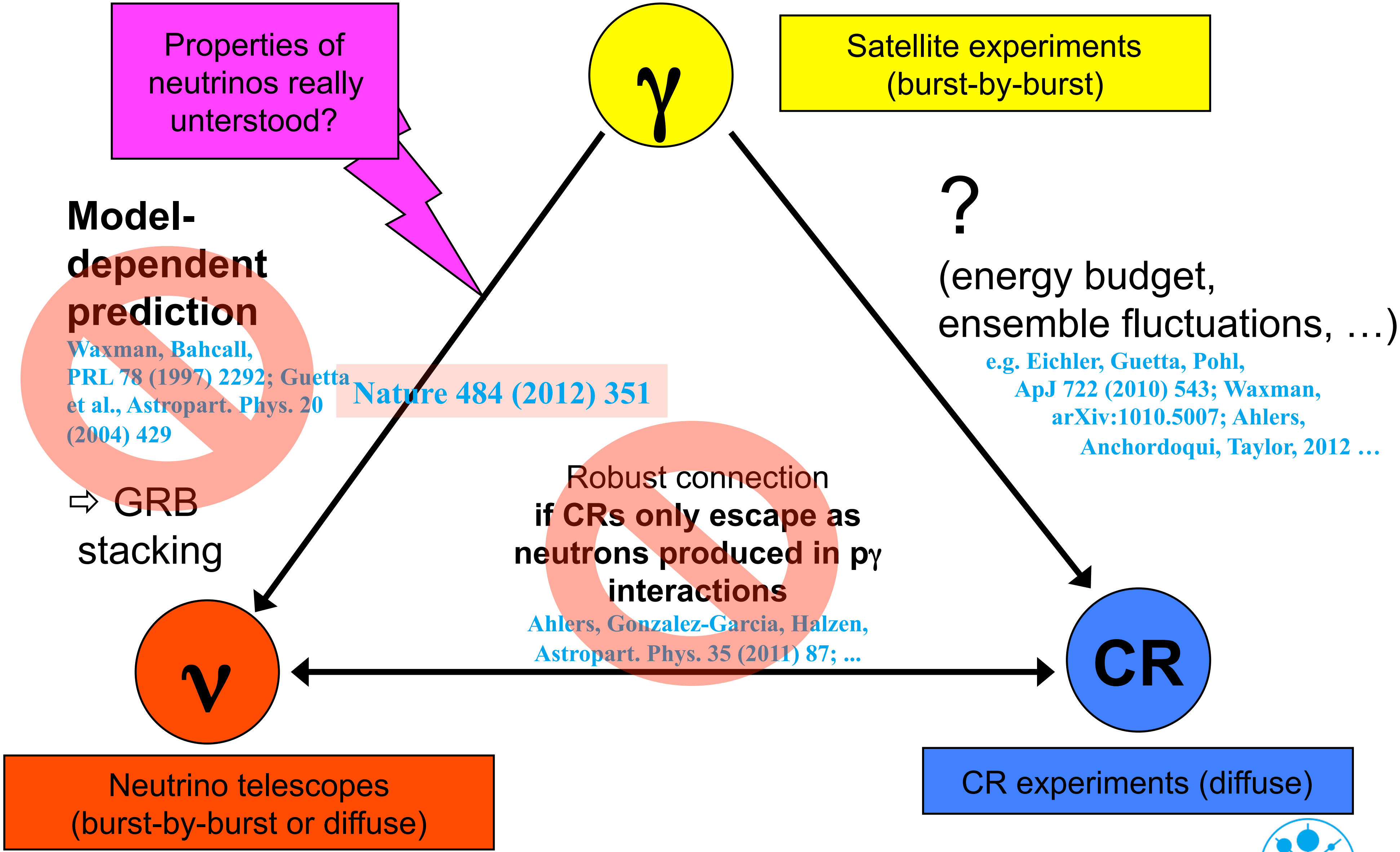
- Ankle model:
  - Injection index γ ~ 2 possible (⇨ Fermi shock acc.)
  - Transition at > 4 EeV
- Dip model:
  - Injection index γ ~ 2.5-2.7 (how?)
  - Transition at ~ 1 EeV
  - Characteristic shape by pair production dip

Figure courtesy M. Bustamante; for a recent review, see Berezinsky, arXiv:1307.4043

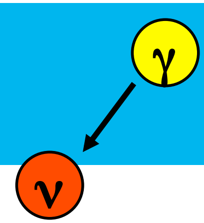
Multi-messenger physics with GRBs

… some results

Multi-messenger physics

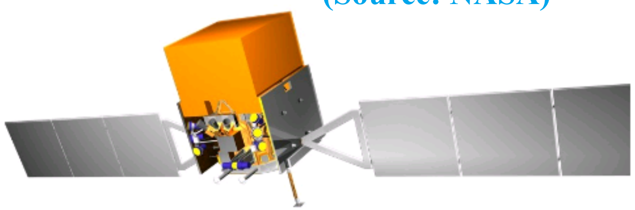


GRB stacking analysis

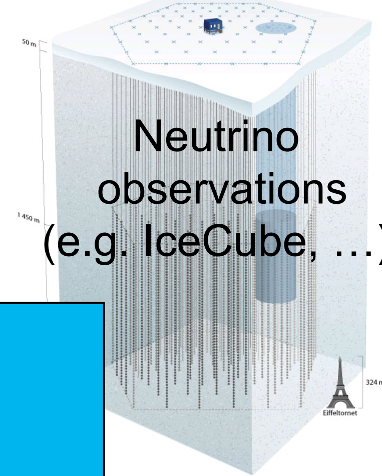


> Idea: Use multi-messenger approach (BG free)

(Source: NASA)



(Source: IceCube)

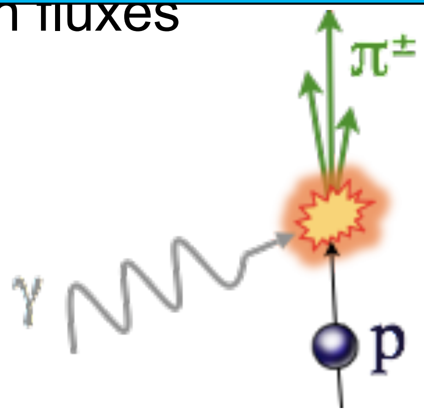


Coincidence!

GRB gamma-r
(e.g. Ferm

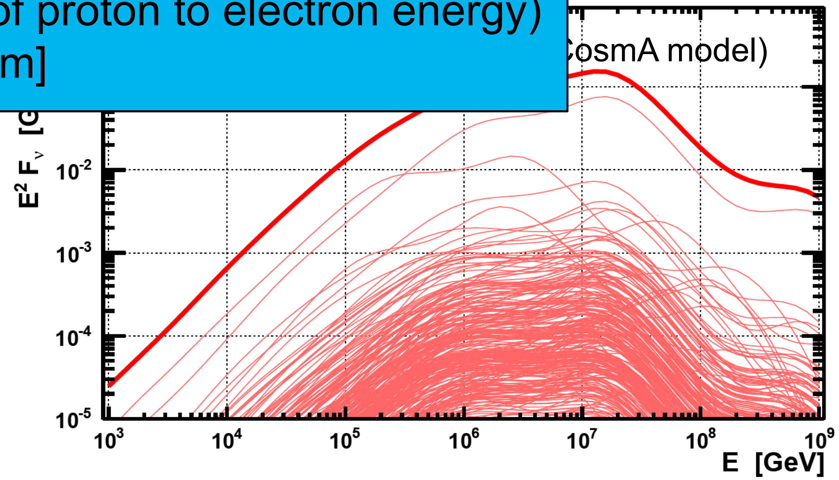
Model ruled out by IceCube **Nature 484 (2012) 351**
Based on a generic model with several "fudge" factors
- Number of GRBs in observable universe 667/year,
- Baryonic loading f_e^{-1} (fraction of proton to electron energy) 10 [motived by UHECR paradigm]

> Predict neutr
observed photon fluxes
event by event



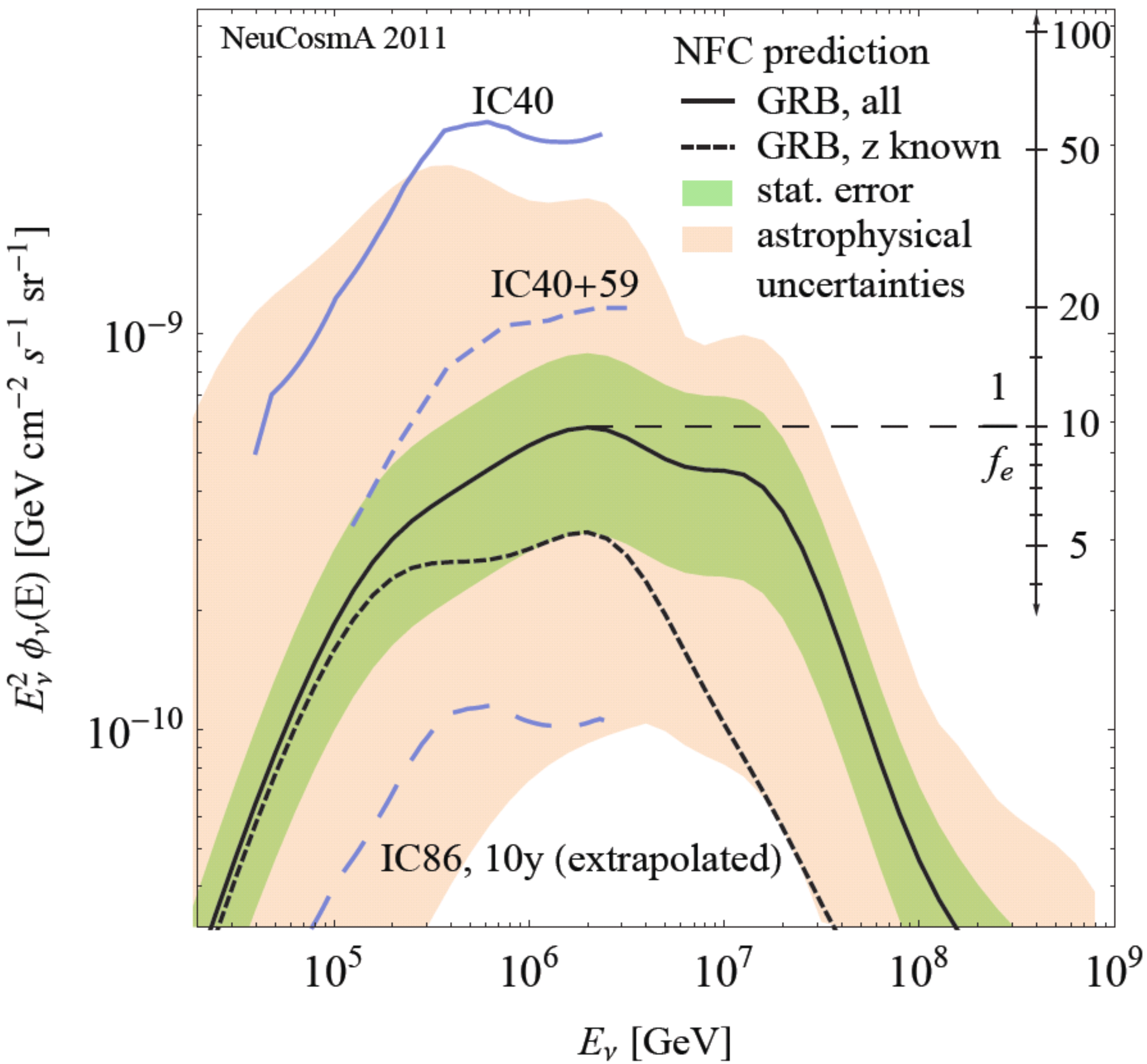
Observed:
broken power law
(Band function)

E^{-2} injection



(Example: ANTARES, arXiv:1307.0304)

Revision of predicted flux



- Revision of predicted flux based on particle physics only; about one order of magnitude lower (interactions, energy dependencies, magnetic field effects, etc)
- Numerical fireball model cannot be ruled out yet with IC40+59 for same parameters, bursts, assumptions

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

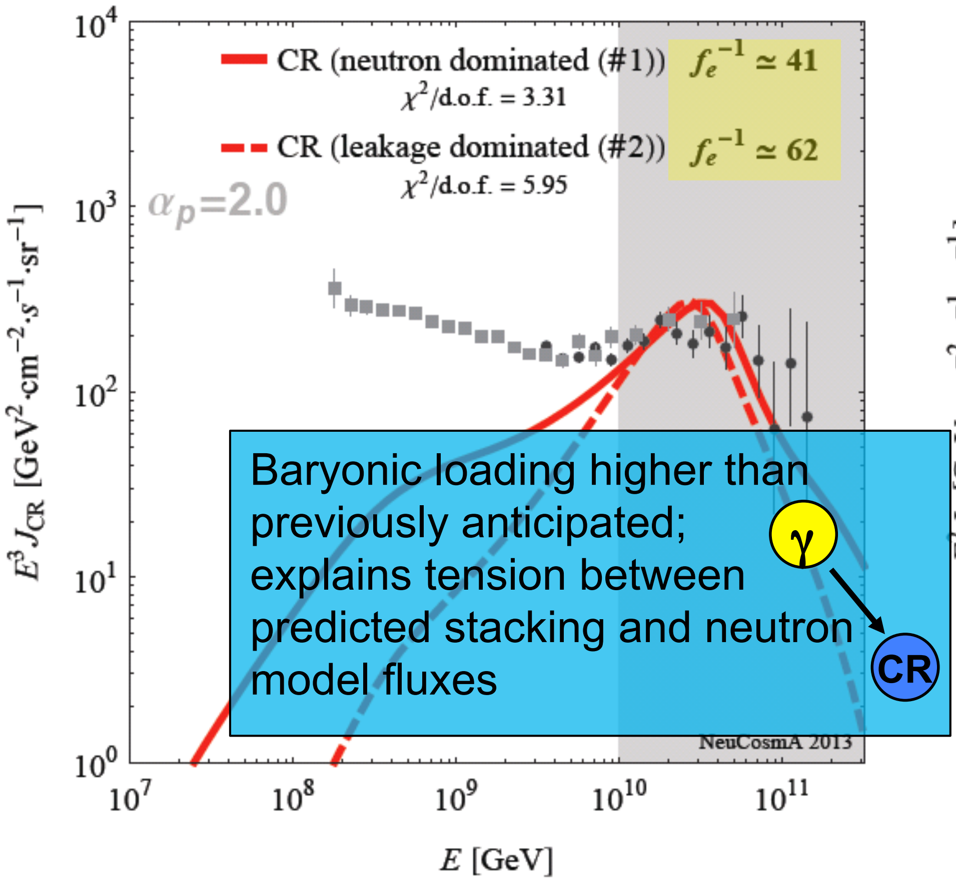
(Hümmer, Baerwald, Winter, Phys. Rev. Lett. 108 (2012) 231101)

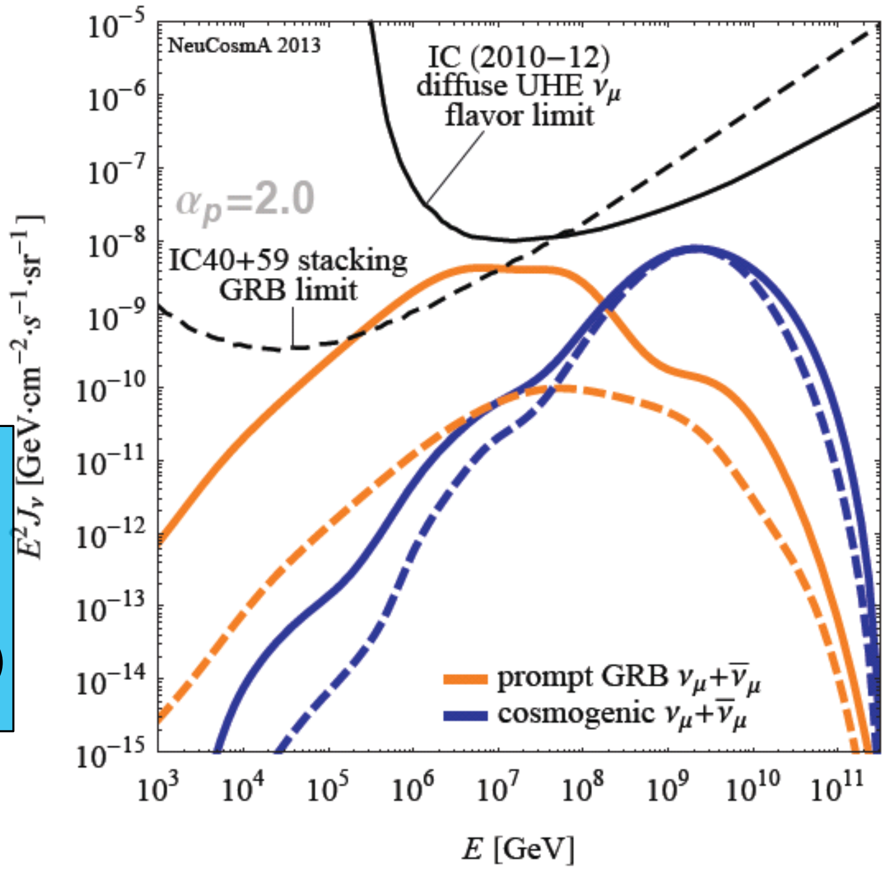
Neutron model

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

ν ⟷ CR

- Neutron model for UHECR escape can indeed be ruled out, as it leads to too many prompt neutrinos
- However: Protons will, dep. on the GRB parameters, leak from sources or escape by diffusion **Baerwald, Bustamente , Winter, ApJ 768 (2013) 186**

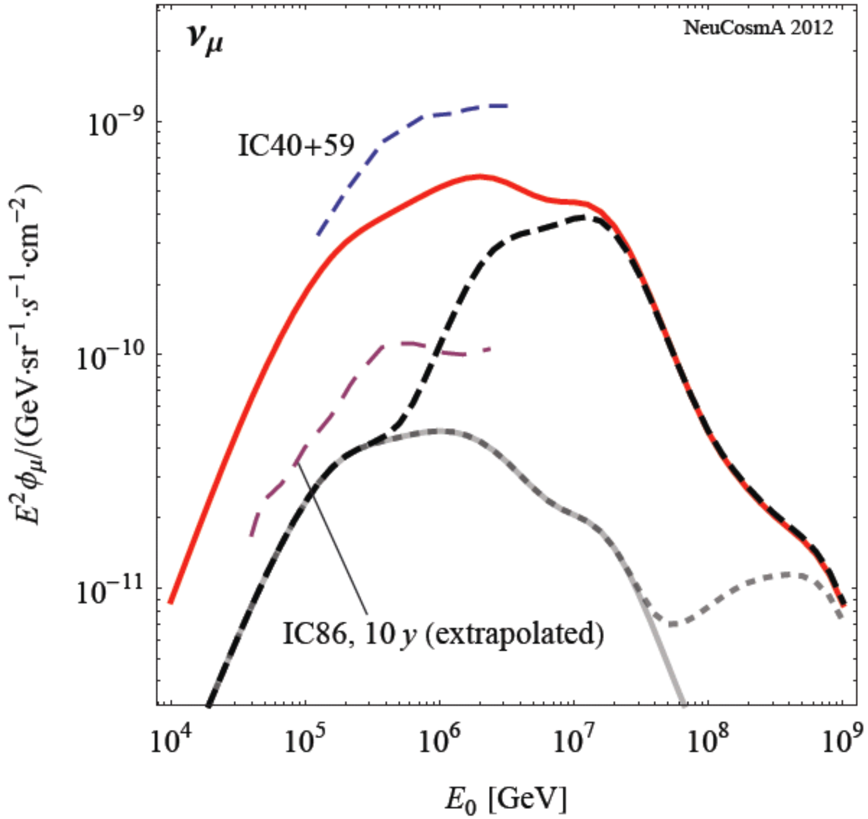


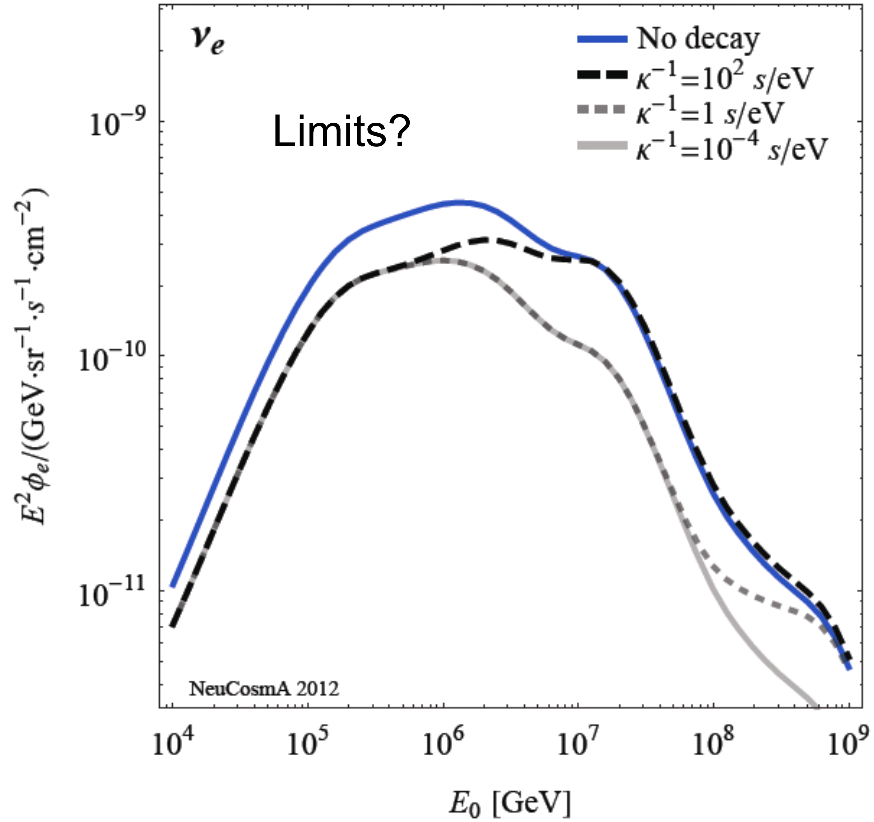


(from: Baerwald, Bustamante, Winter, arXiv:1401.1820)

What if: Neutrinos decay?

Decay hypothesis: ν_2 and ν_3 decay with lifetimes compatible with SN 1987A bound





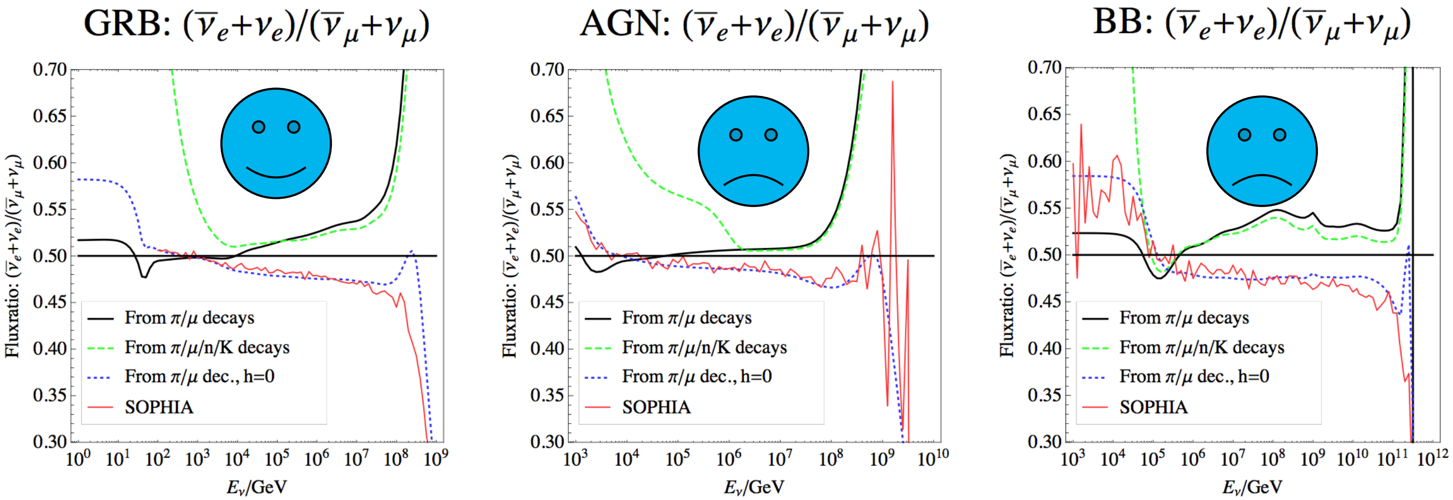
> Reliable conclusions from flux bounds require cascade (ν_e) measurements! Affects flavor composition, of course

Baerwald, Bustamante, Winter, JCAP 10 (2012) 20; see also Pakvasa, Farzan, ...

Comments on flavor and neutrino-antineutrino composition at source

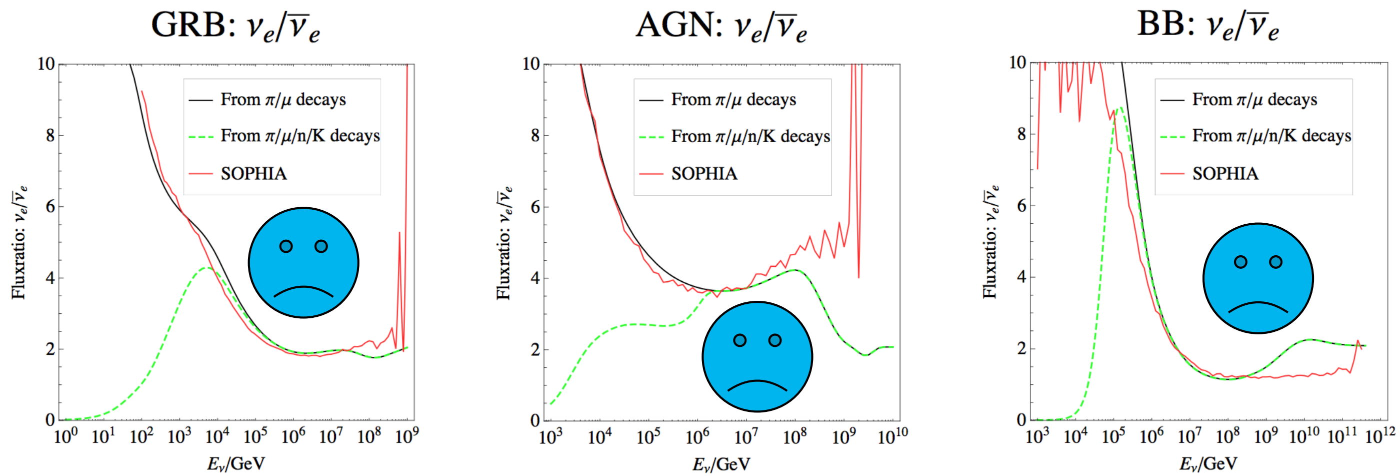
Common prejudices … without magnetic field effects

- The electron to muon-neutrino ratio is 1:1.85:0 (Lipari, Lusignoli, Meloni, 2007)



Depends on spectral shape!

- In pγ interactions, no electron antineutrinos are produced (affects Glashow resonance)



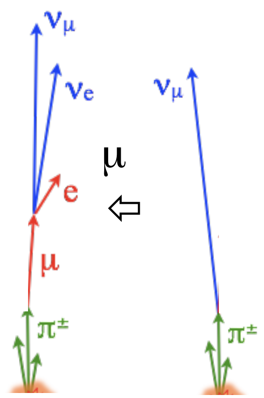
If high-E processes dominate, contamination can be as high as 100%

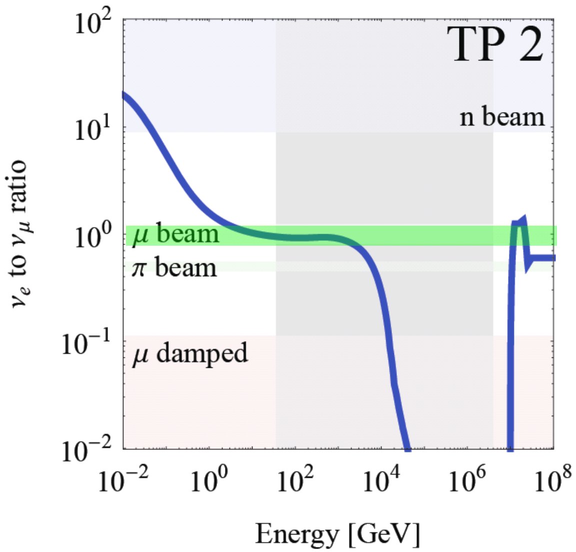
Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630

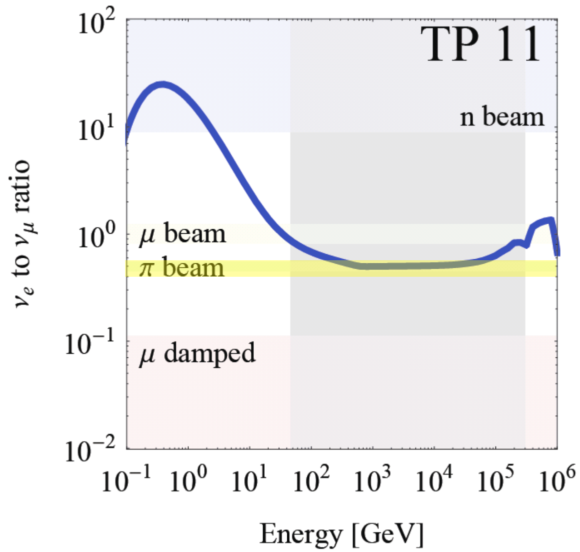
DESY

Flavor composition [including magnetic field effects] depends on energy, always

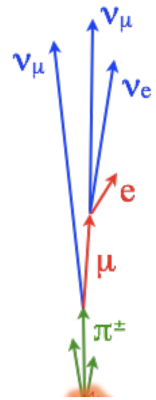
Muon beam
- muon damped





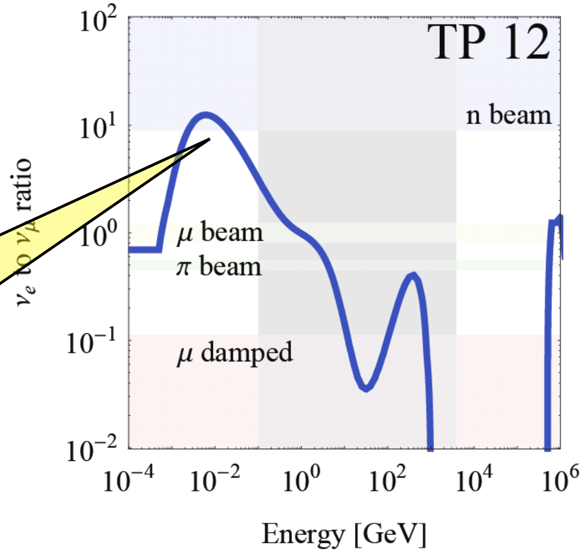


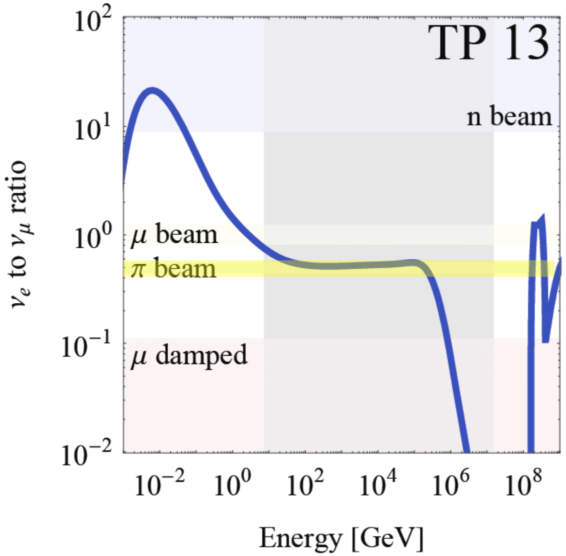
Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



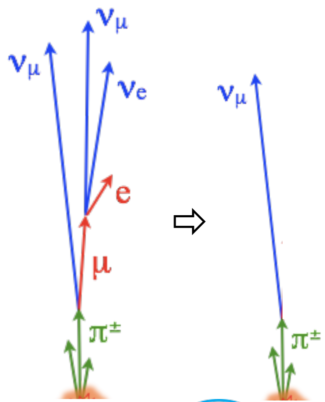
Undefined
(mixed source)

Typically
n beam
for low E
(from pγ)





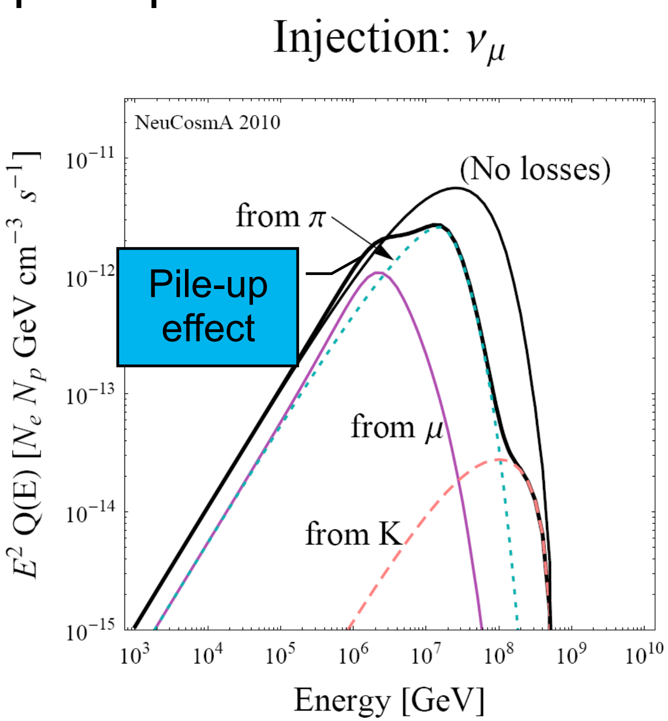
Pion beam
⇨ muon damped



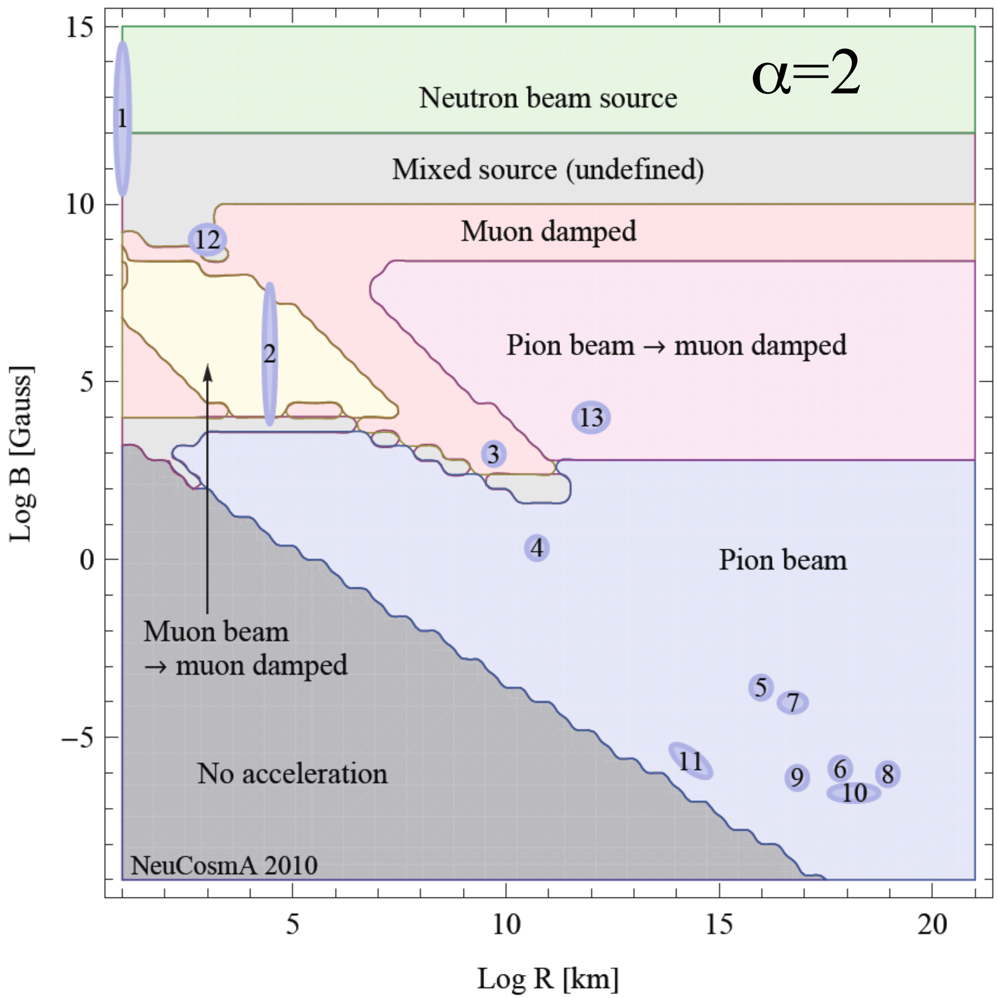
Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

Flavor composition ... can be pedicted

- Flavor composition is energy dependent
- Pion beam good assumption for sources on galactic scales
- Muon beam sources if muon pile-up:



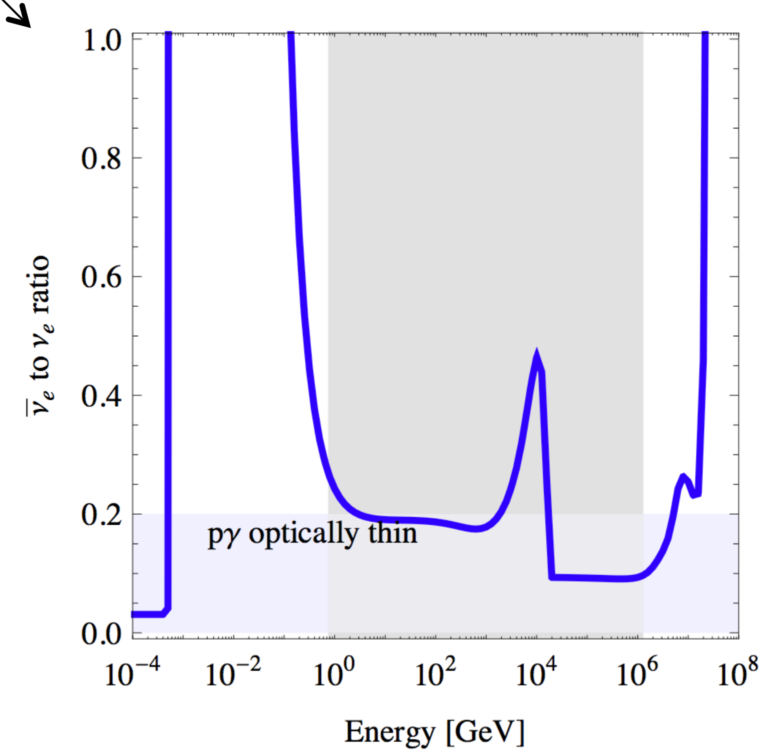
Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205



Glashow resonance? pp versus pγ interactions?

- At source: Have to accept contaminations from multi-pion processes and neutron decay at source at level of (at least) ~ 20%

  Consequence: Have to observe Glashow resonance even for pγ interactions!



- At detector: Further complications
  - Right energy (6.3 PeV)
  - Flavor mixing (electron anti-nus from muon anti-mus)
  - Degeneracy with flavor composition (e.g. muon damped pp ~ pion beam pγ)
- Perspectives: useful discriminator if flavor composition measured or source class (e. g. Galactic) established

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

Energy-dependent flavor ratio ...
... meets energy-dependent new physics

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

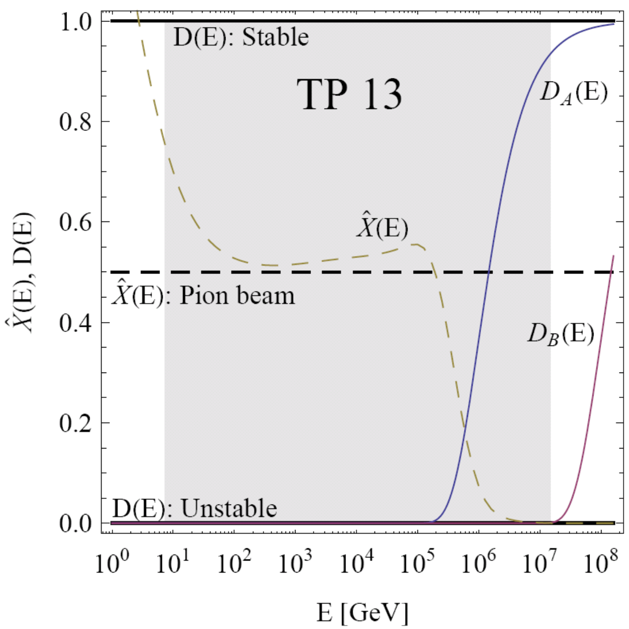
Energy dependence flavor comp. source

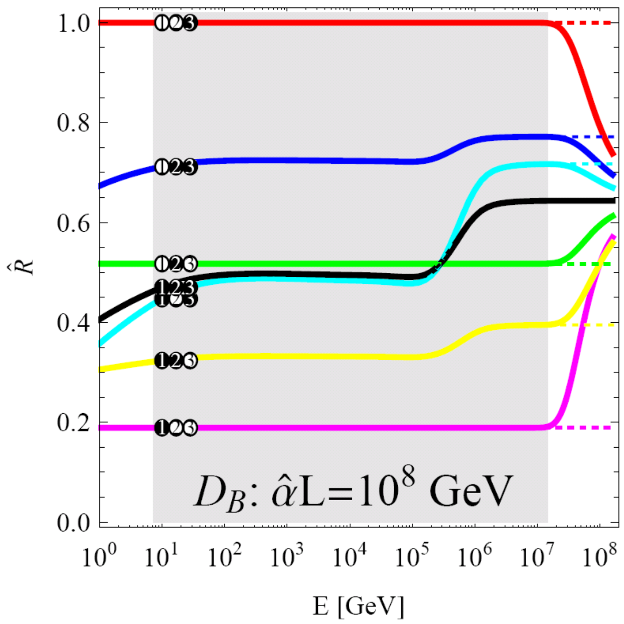
$$\widehat{R} \equiv \frac{\Phi_\mu^{\mathrm{Det}}}{\Phi_e^{\mathrm{Det}} + \Phi_\tau^{\mathrm{Det}}} = \frac{P_{e\mu}(E)\,\widehat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)]\,\widehat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

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

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

Summary

- GRB internal shell (neutrino) model has been recently tested by IceCube; however, it cannot be excluded yet that GRBs are the sources of the UHECRs if the cosmic rays can escape e.g. by diffusion
- Recent observations of cosmic neutrinos probably not from long-duration GRBs (no direct correlation), but possibly from other GRB population (e.g. low luminosity GRBs; see **Murase ,…**)
- Indirect evidence for strong magnetic fields: Cutoff at few PeV?
- Future neutrino observations in terms of flavor and neutrino-antineutrino ratios require energy-dependent predictions; particle physics perspective (X:1-X:0) flavor ratio at source "over-simplified"
- I am happy to discuss further applications etc …