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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Magnetic field and flavor effects on the neutrino fluxes from cosmic accelerators

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Magnetic field and flavor effects on the neutrino fluxes from cosmic accelerators

NUSKY 2011

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ICTP Trieste, Italy

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- Simulation of sources
- Neutrino propagation and detection; flavor ratios
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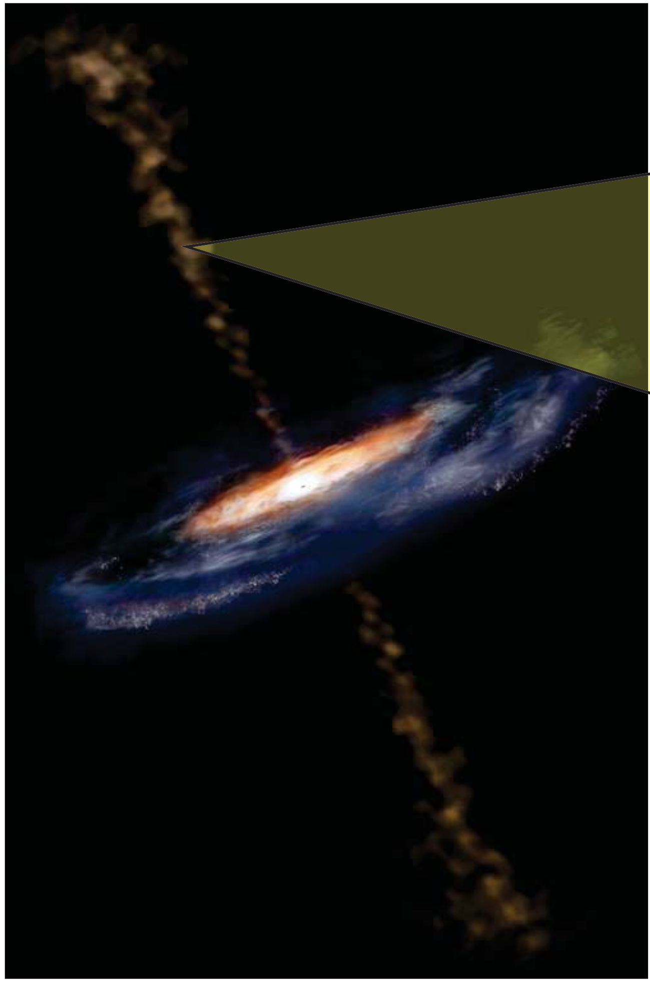
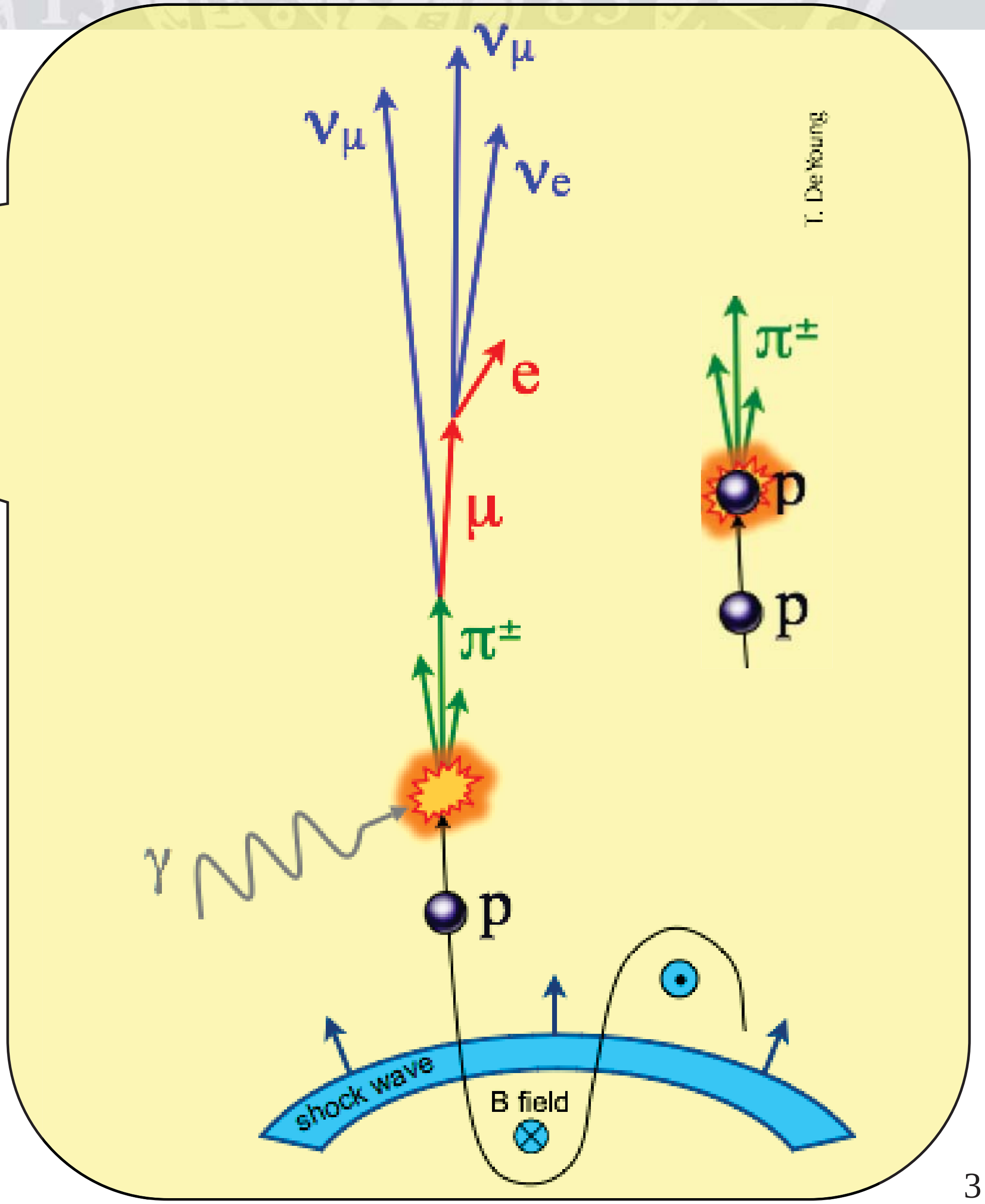
- Summary

Neutrino production in astrophysical sources

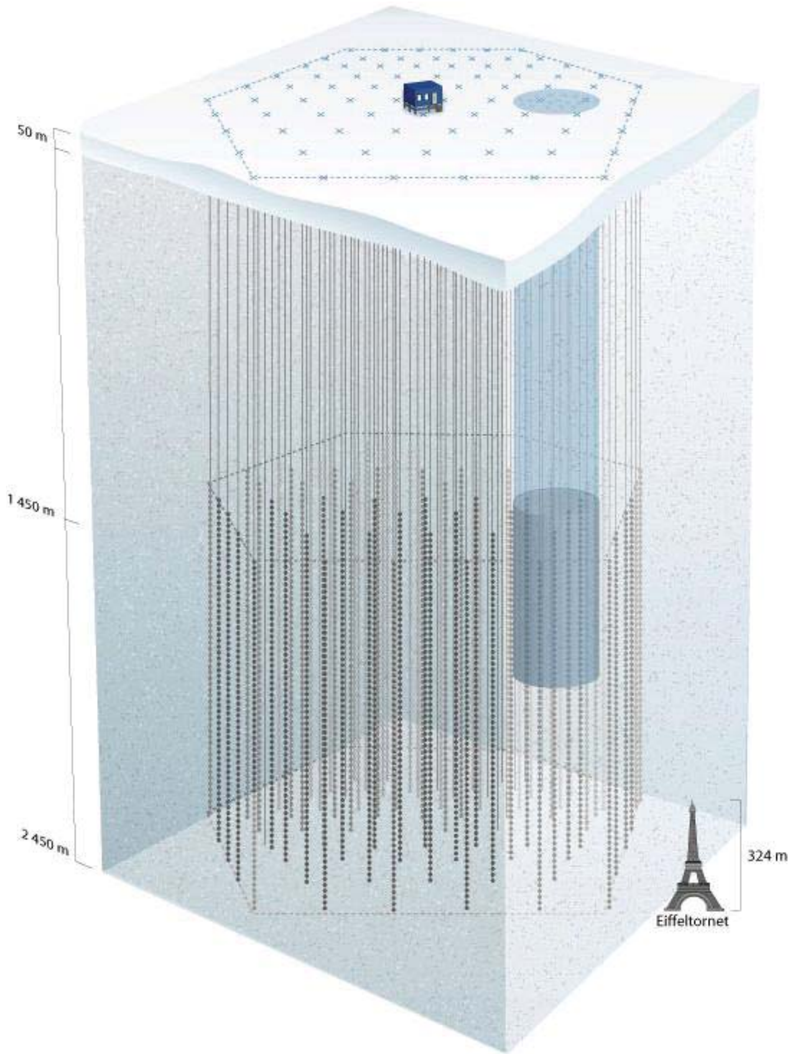


Example: Active galaxy
(Halzen, Venice 2009)



Neutrino detection: IceCube

- 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
    arXiv:1101.1448
  - Cascade detection IC-22
    arXiv:1101.1692
- Have not seen anything (yet)
  - ➢ What does that mean?
  - ➢ Are the models too optimistic?
  - ➢ Which parts of the parameter space does IceCube actually test?



http://icecube.wisc.edu/

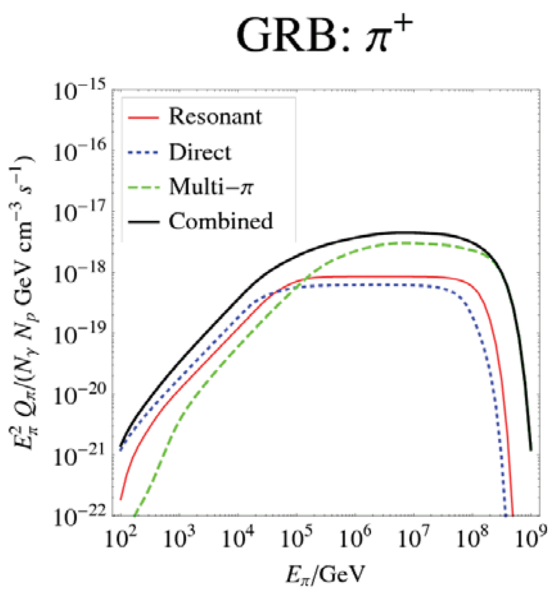
Simulation of sources

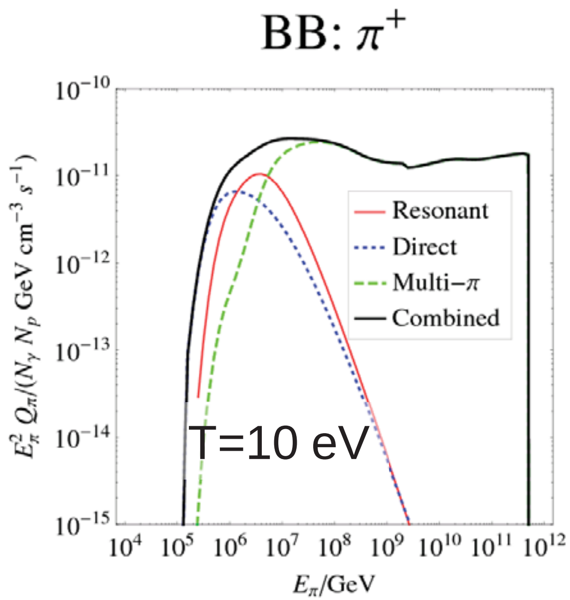
Meson photoproduction

- Often used: $\Delta(1232)$-resonance approximation

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

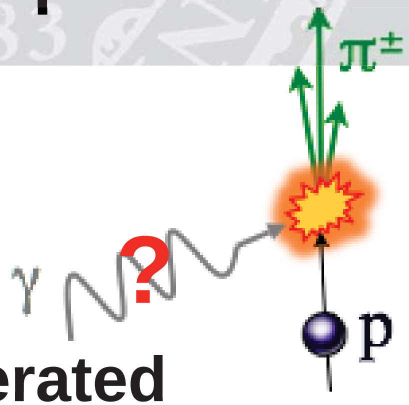
- Limitations:
  - No π^- production; cannot predict π^+/π^- ratio (affects neutrino/antineutrino)
  - High energy processes affect spectral shape
  - Low energy processes (t-channel) enhance charged pion production
  - ➢ Charged pion production underestimated compared to π^0 production by factor of 2.4 (independent of input spectra!)





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

A self-consistent approach



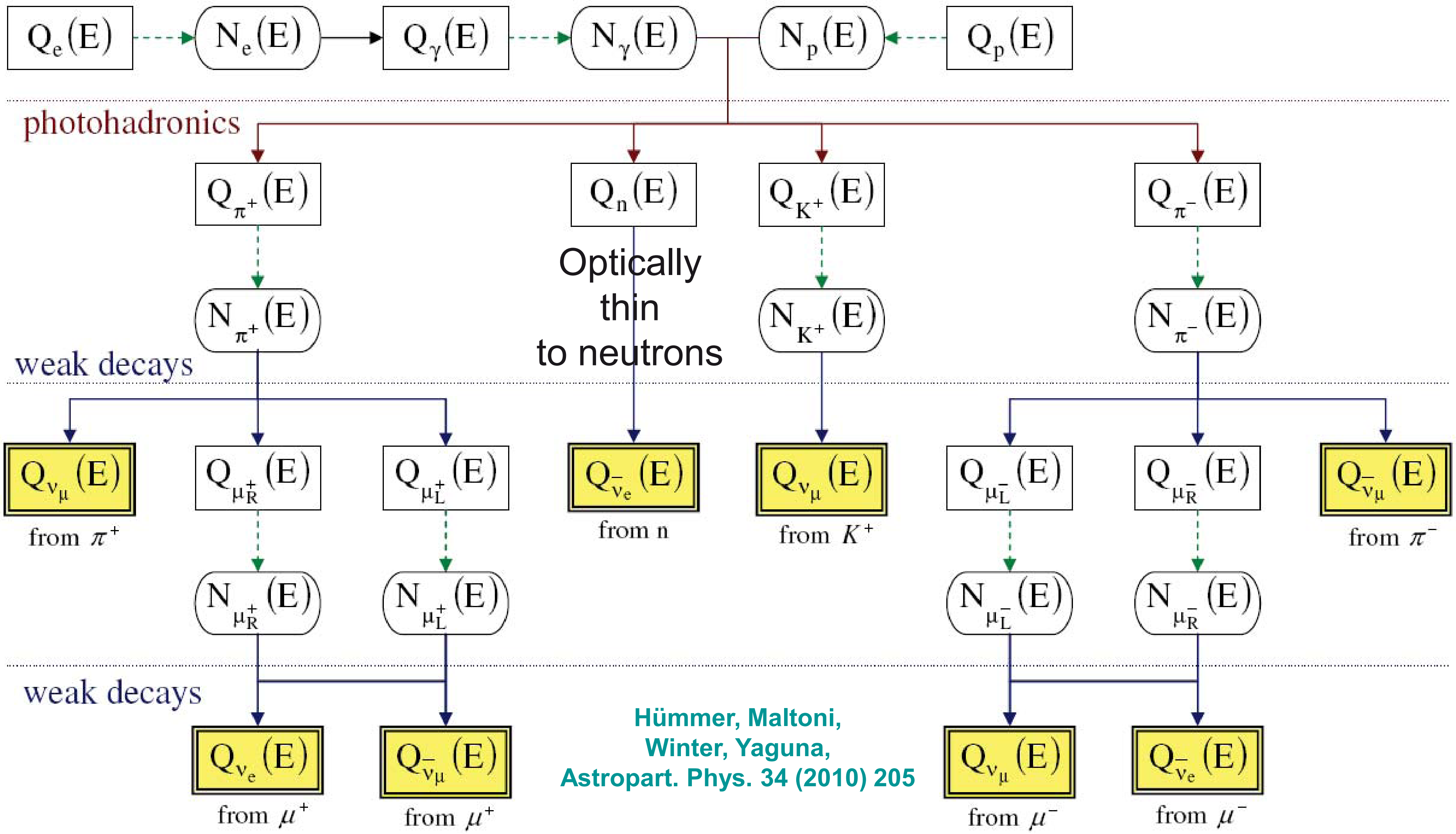
- Target photon field typically:
  - Put in by hand (e.g. obs. spectrum: GRBs)
  - Thermal target photon field
  - **From synchrotron radiation of co-accelerated electrons/positrons (AGN-like)**
- Requires few model parameters, mainly

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;
  ⇨ minimal set of assumptions for ν production?

Model summary

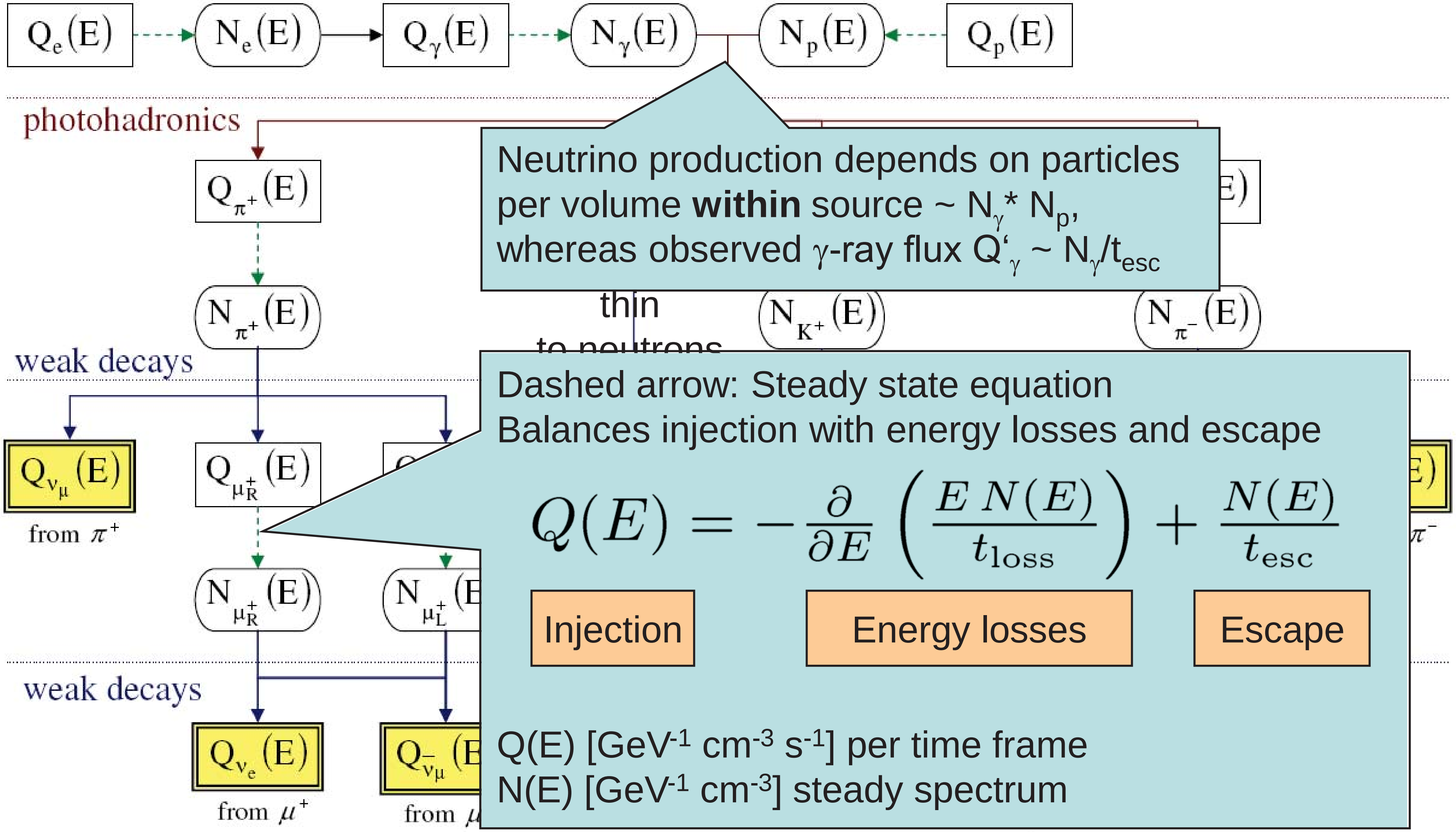
Dashed arrows: include cooling and escape



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

Model summary

Dashed arrows: include cooling and escape



Neutrino production depends on particles per volume **within** source ~ N_γ* N_p, whereas observed γ-ray flux $Q'_\gamma \sim N_\gamma/t_{esc}$

Dashed arrow: Steady state equation
Balances injection with energy losses and escape

$$Q(E) = -\frac{\partial}{\partial E}\left(\frac{E\,N(E)}{t_{\mathrm{loss}}}\right) + \frac{N(E)}{t_{\mathrm{esc}}}$$

Injection | Energy losses | Escape

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

An example: Secondaries

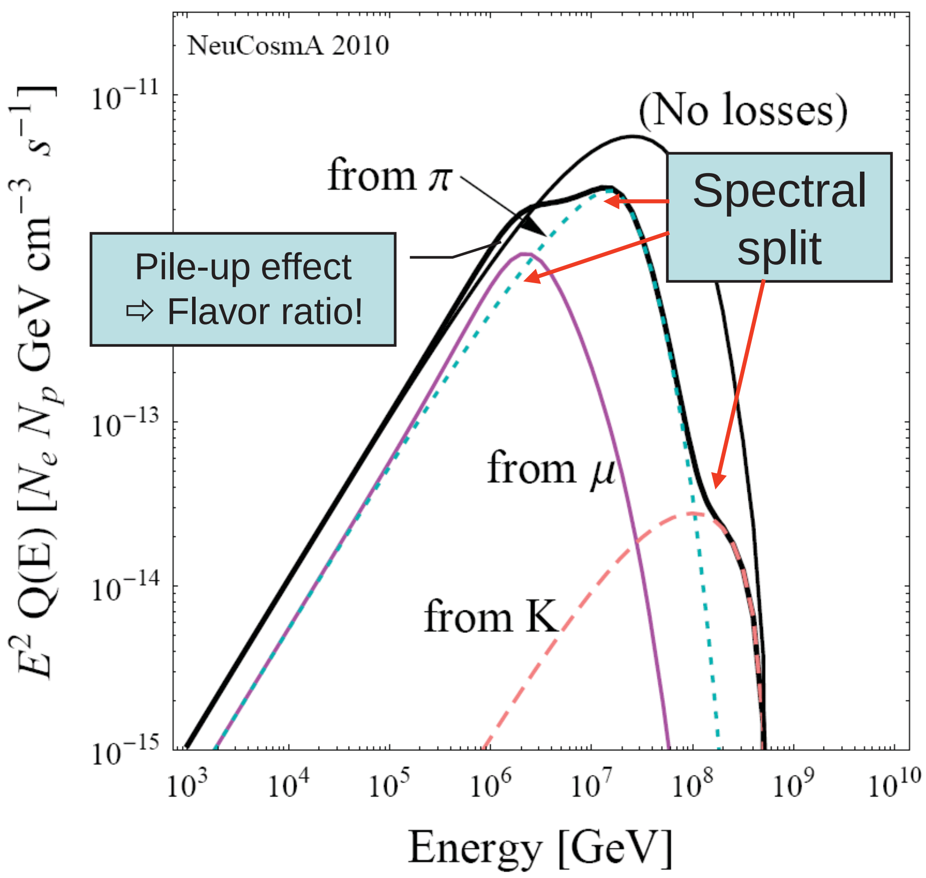
α=2, B=10^3 G, R=$10^{9.6}$ km

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

$$E_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^5}{\tau_0 e^4 B^2}}$$

  - ➢ E_c depends on particle physics only (m, τ_0), and **B**
  - ➢ Leads to characteristic flavor composition
  - ➢ Any additional cooling processes mainly affecting the primaries will not affect the flavor composition
  - ➢ Flavor ratios most robust predicition for sources?
  - ➢ The only way to directly measure B?

Injection: ν_μ



Hümmer et al, Astropart. Phys. 34 (2010) 205

Parameter space: Hillas plot

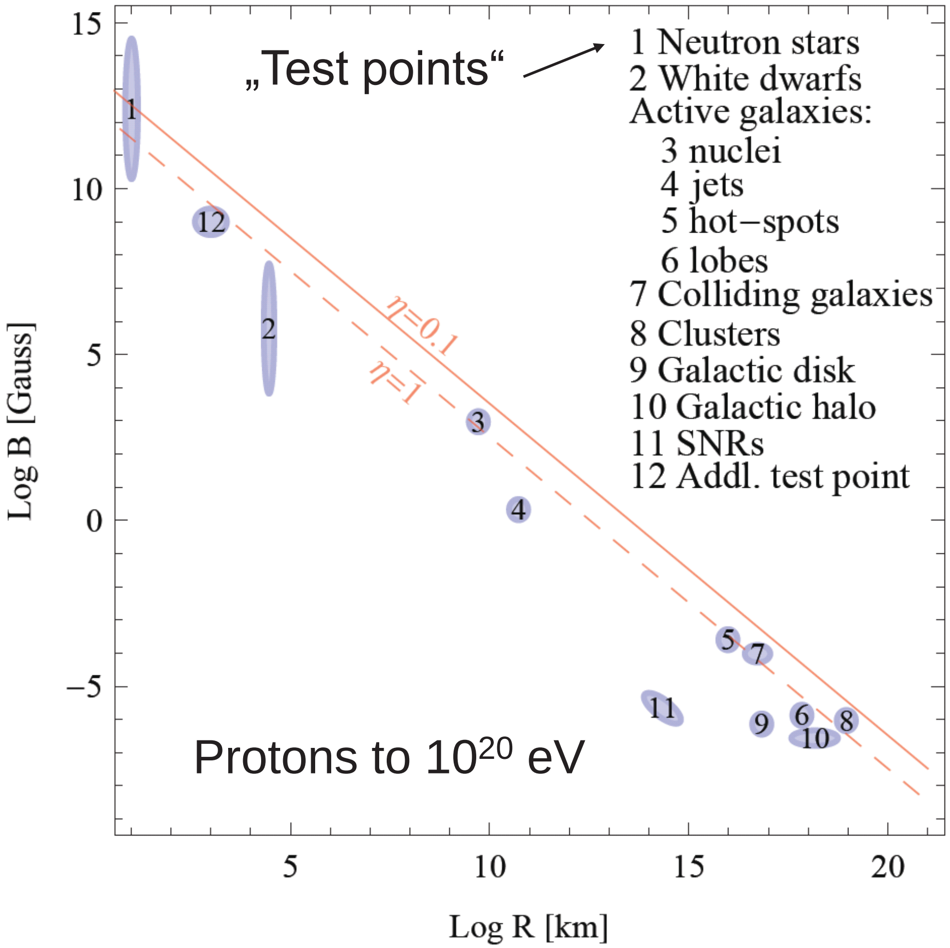
- Model-independent (necessary) condition for acceleration of cosmic rays:

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

  (Larmor-Radius < size of source; 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

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Flavor composition at the source

(Idealized – **energy independent**)

- Astrophysical neutrino sources produce certain flavor ratios of neutrinos (ν_e:ν_μ:ν_τ):
- Pion beam source (1:2:0)
  Standard in generic models
- Muon damped source (0:1:0)
  at high E: Muons loose energy before they decay
- Muon beam source (1:1:0)
  Cooled muons pile up at lower energies (also: heavy flavor decays)
- Neutron beam source (1:0:0)
  Neutron decays from pγ
  (also possible: photo-dissociation of heavy nuclei)

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

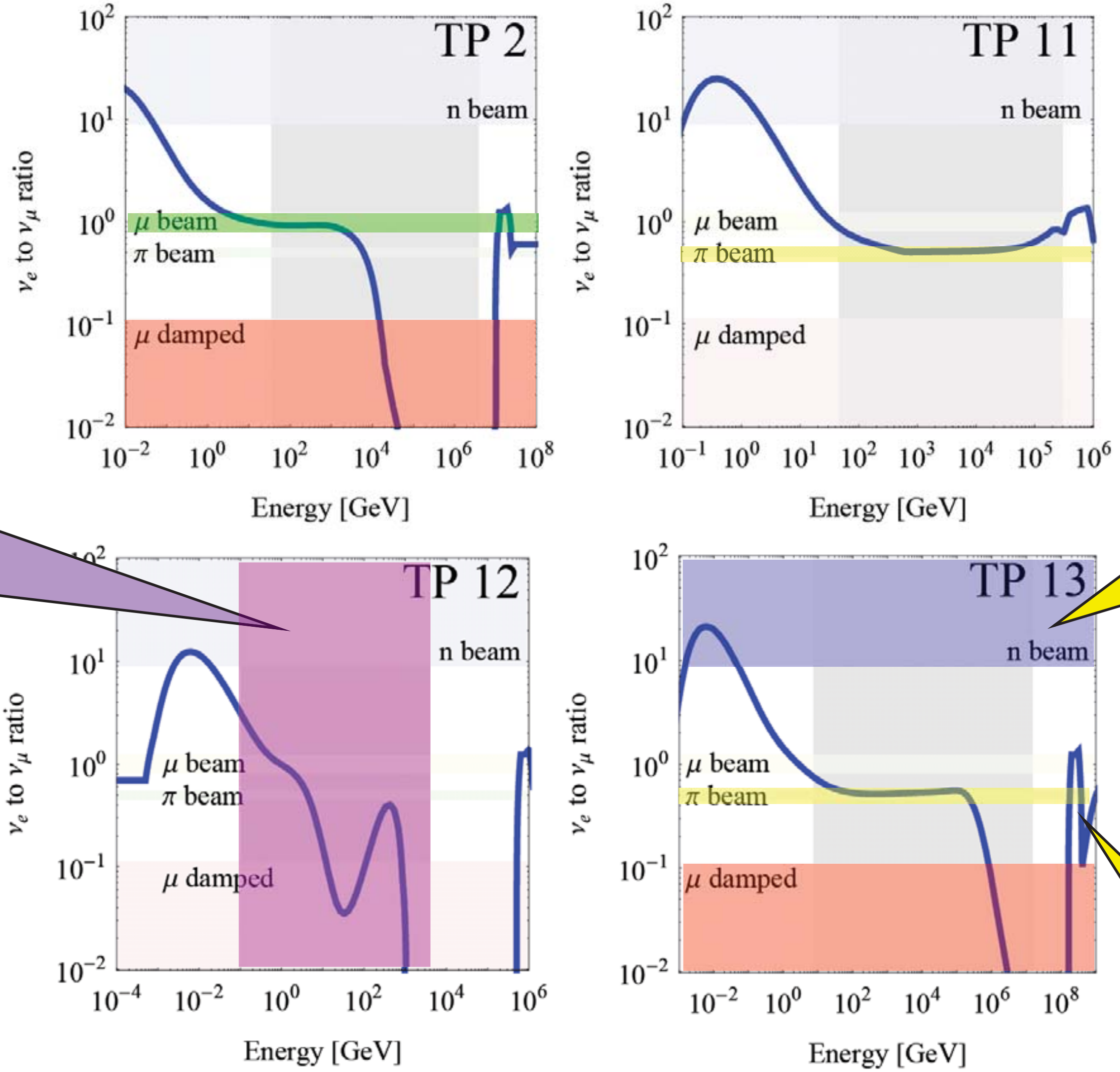
➢ At the source: Use ratio ν_e/ν_μ (nus+antinus added)

However: flavor composition is energy dependent!

Muon beam
⇨ muon damped

Energy window with large flux for classification

Undefined (mixed source)



Pion beam

Typically n beam for low E (from pγ)

Pion beam
⇨ muon damped

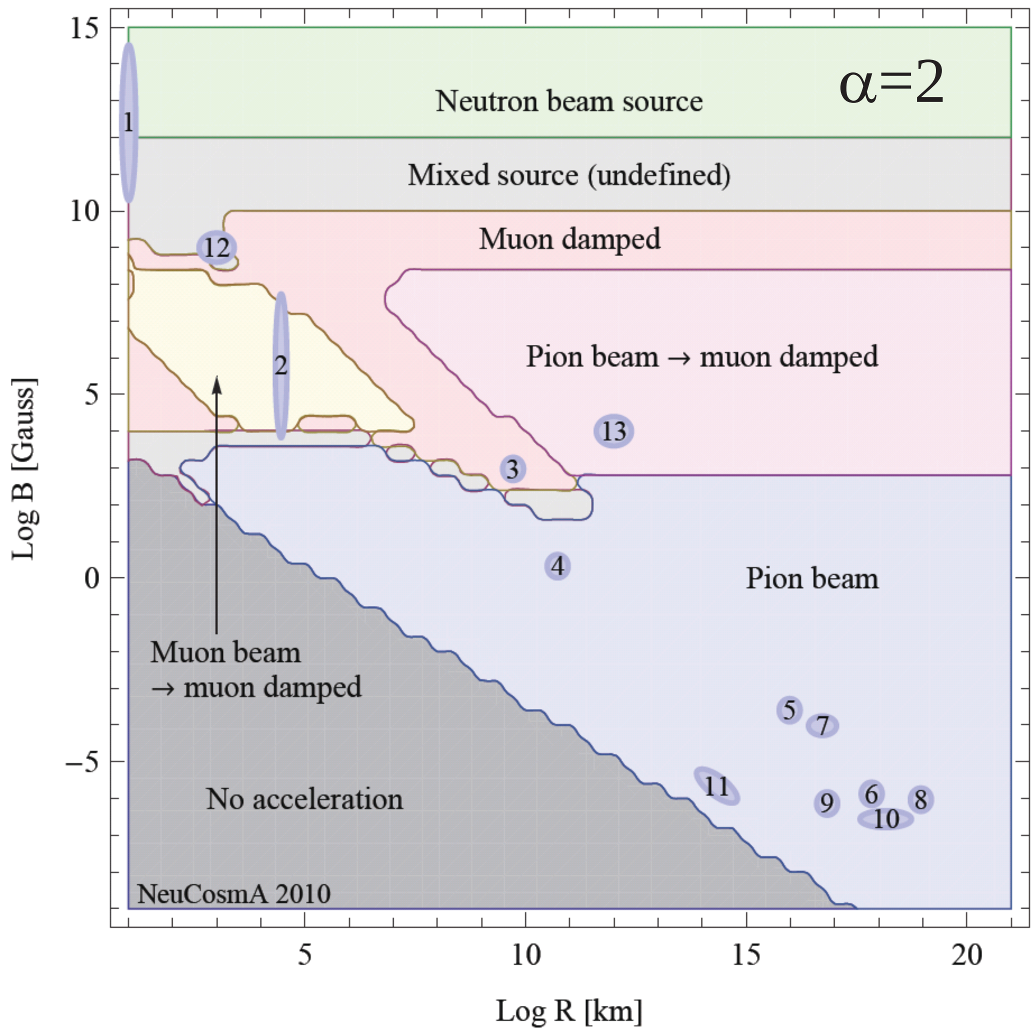
Behavior for small fluxes undefined

(from Hümmer et al, Astropart. Phys. 34 (2010) 205;
see also: Kashti, Waxman, 2005; Kachelriess, Tomas, 2006, 2007; Lipari et al, 2007)

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 et al, 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 $\theta_{13}=0$, $\theta_{23}=\pi/4$:

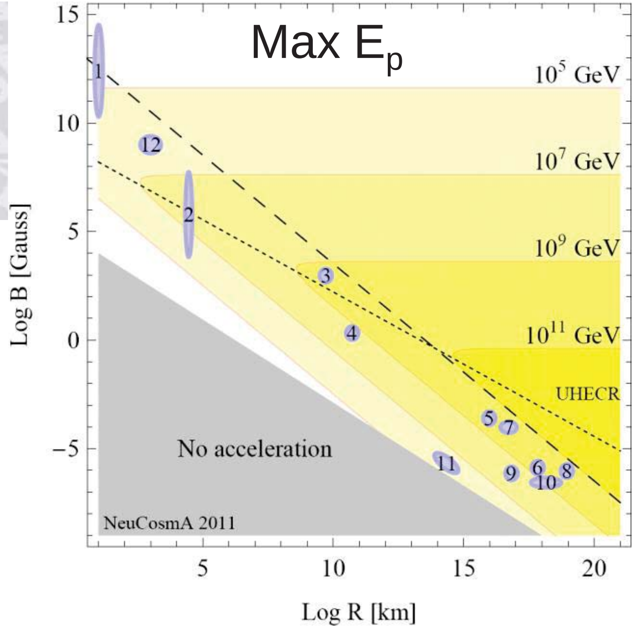
(see Pakvasa review, arXiv:0803.1701, and references therein)

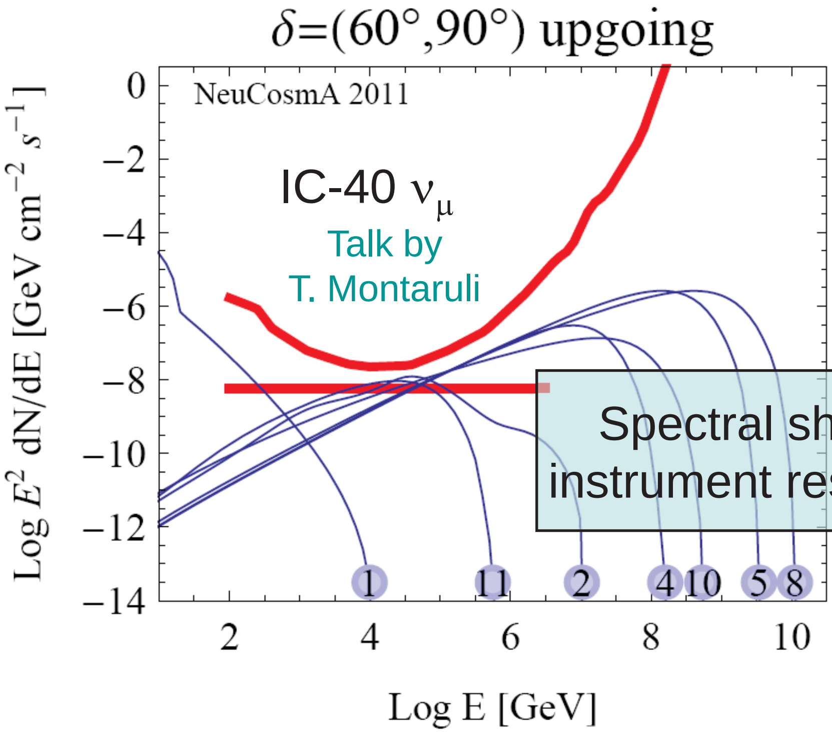
$$\begin{pmatrix} \nu_e^{source} \\ \nu_\mu^{source} \\ \nu_\tau^{source} \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \quad \Longrightarrow \quad \begin{pmatrix} \nu_e^{Earth} \\ \nu_\mu^{Earth} \\ \nu_\tau^{Earth} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

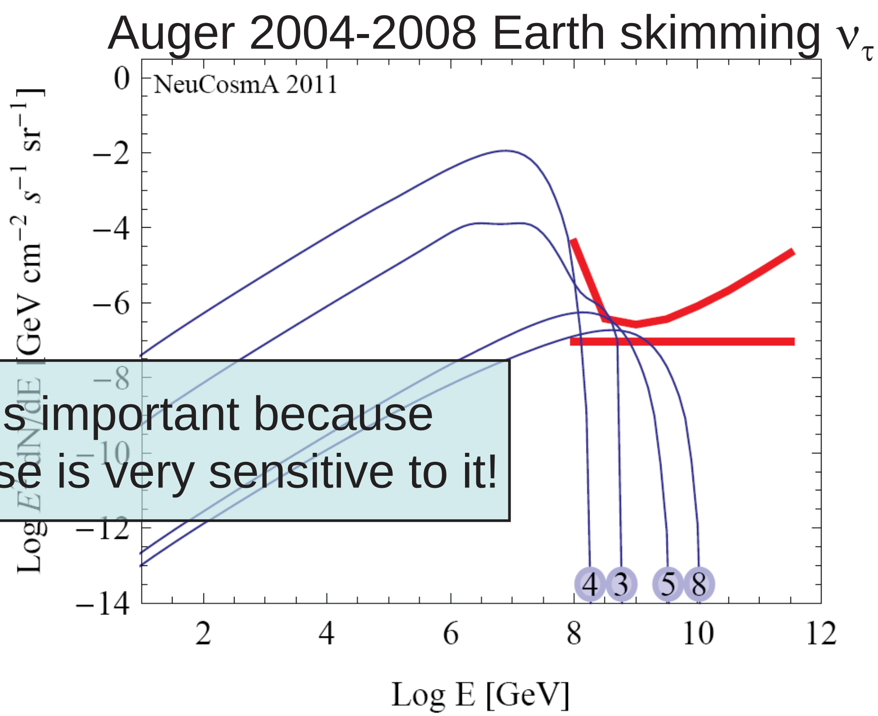
- NB: No CPV in flavor mixing only!
  But: In principle, sensitive to Re exp(-i δ) ~ cosδ
- Take into account Earth attenuation!

Individual spectra: Muon tracks

- Differential limit 2.3 $E/(A_{eff}\ t_{exp})$ illustrates what spectra the data limit best





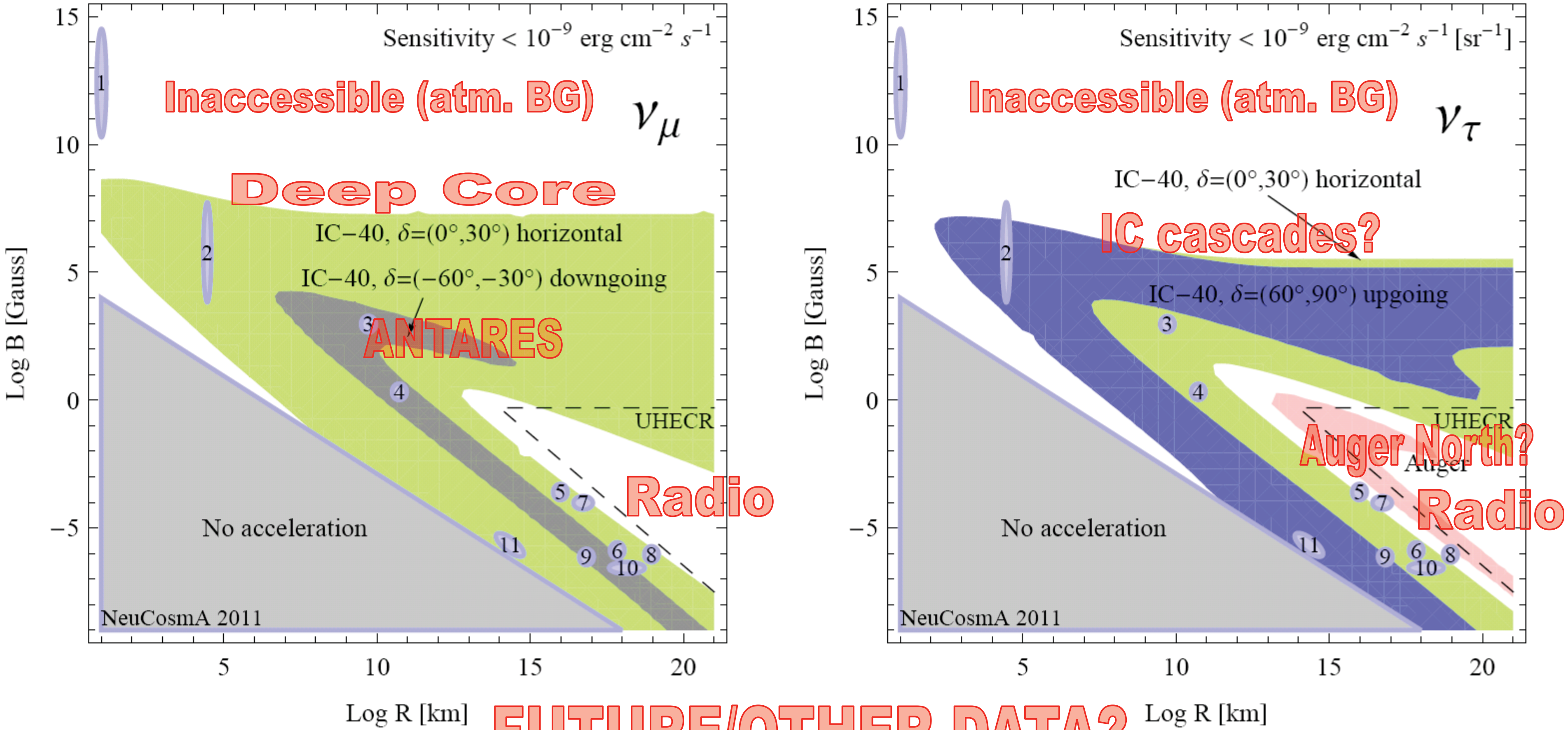


Spectral shape is important because instrument response is very sensitive to it!

(Winter, arXiv:1103.4266; diff. limits from IceCube, arXiv:1012.2137; Auger, arXiv:0903.3385)

Which point sources can specific data constrain best?

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



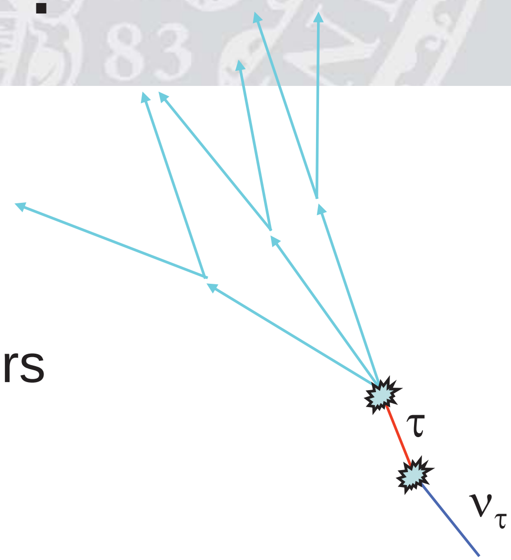
FUTURE/OTHER DATA?

(Winter, arXiv:1103.4266)

Measuring flavor?

- 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: $\overline{\nu}_e$
  - Double bang/lollipop: ν_τ

  (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

Flavor ratios at detector

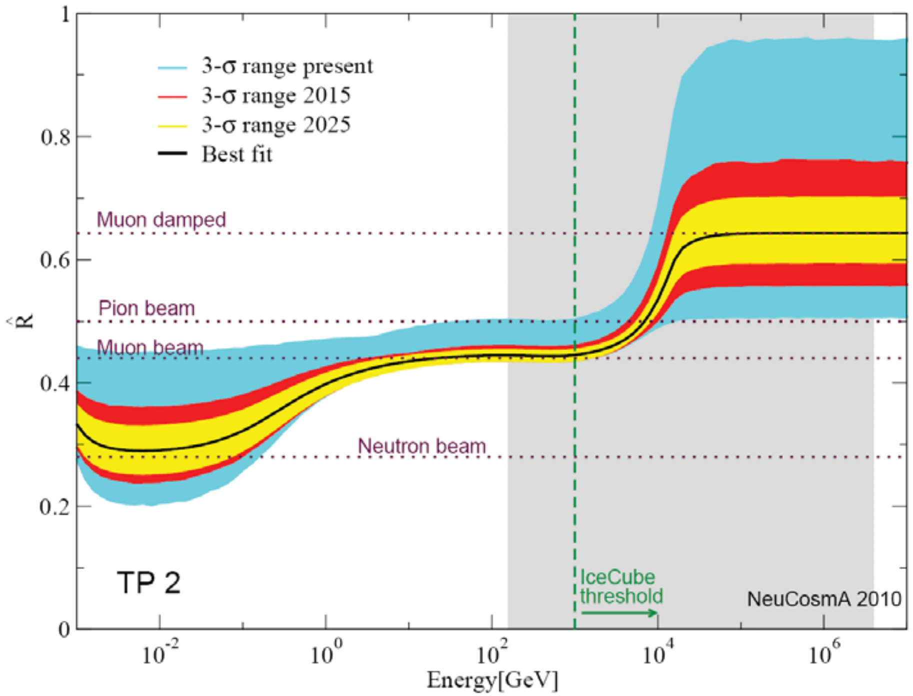
- At the detector: define observables which
  - take into account the unknown flux normalization
  - take into account the detector properties
- Example: Muon tracks to showers
  Do not need to differentiate between electromagnetic and hadronic showers!

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

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

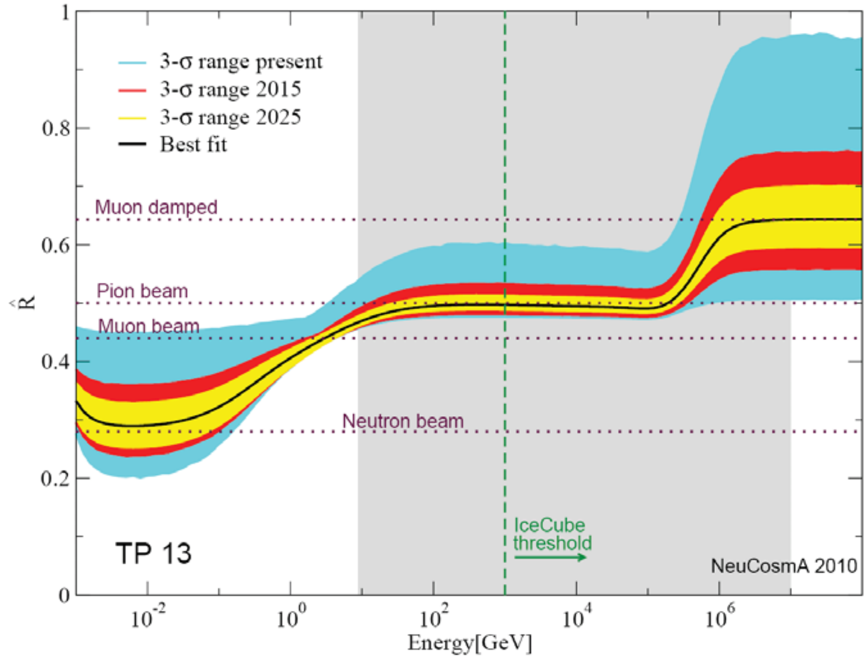
(for flavor mixing and decay: Beacom et al 2002+2003; Farzan and Smirnov, 2002; Kachelriess, Serpico, 2005; Bhattacharjee, Gupta, 2005; Serpico, 2006; Winter, 2006; Majumar and Ghosal, 2006; Rodejohann, 2006; Xing, 2006; Meloni, Ohlsson, 2006; Blum, Nir, Waxman, 2007; Majumar, 2007; Awasthi, Choubey, 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



- Basic dependence recovered after flavor mixing

- However: mixing parameter knowledge ~ 2015 (Daya Bay, T2K, etc) required



Hümmer et al, Astropart. Phys. 34 (2010) 205

New physics in R?

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

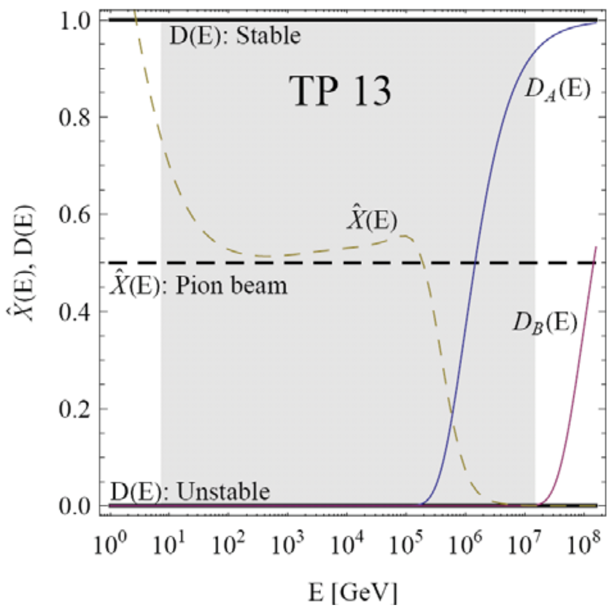
Energy dependence flavor comp. source

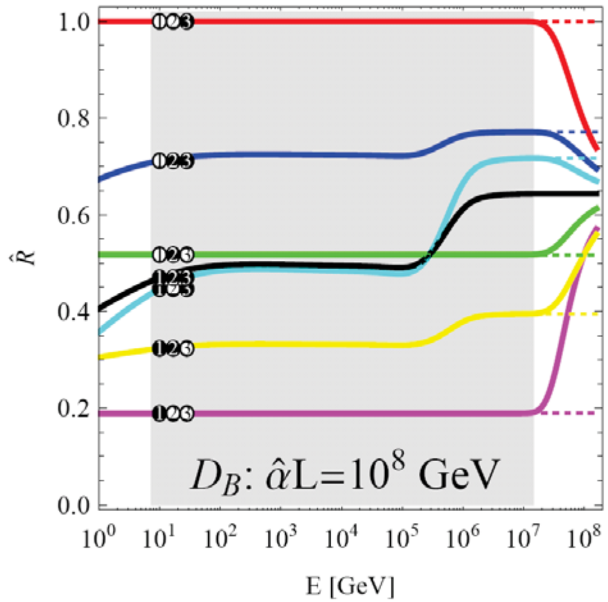
$$\widehat{R} \equiv \frac{\Phi_\mu^{\mathrm{Det}}}{\Phi_e^{\mathrm{Det}} + \Phi_\tau^{\mathrm{Det}}} = \frac{P_{e\mu}(E)\,\widehat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)]\,\widehat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

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

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

On GRB neutrino fluxes

Example: GRB stacking

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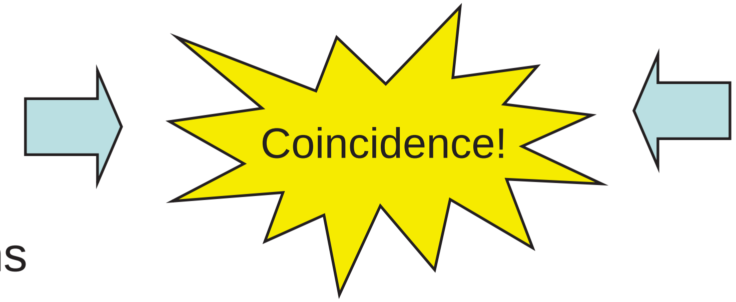
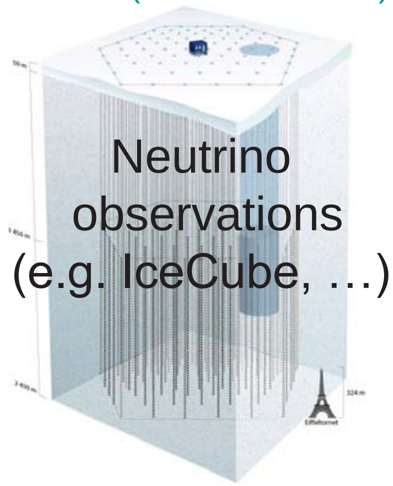
- Idea: Use multi-messenger approach

(Source: NASA)

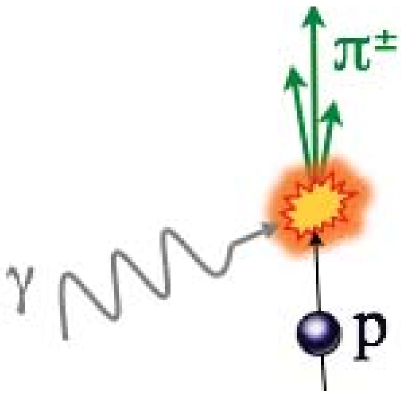
GRB gamma-ray observations
(e.g. Fermi GBM, Swift, etc)



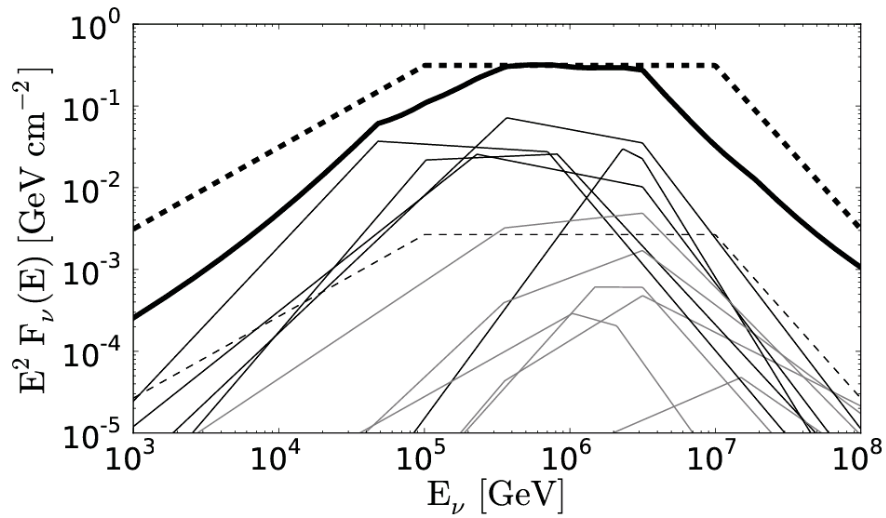
(Source: IceCube)



- Predict neutrino flux from observed photon fluxes event by event



Observed:
broken power law
(Band function)



(Example: IceCube, arXiv:1101.1448;
see also talks by P. Lipari, J. K. Becker, A. Kappes)

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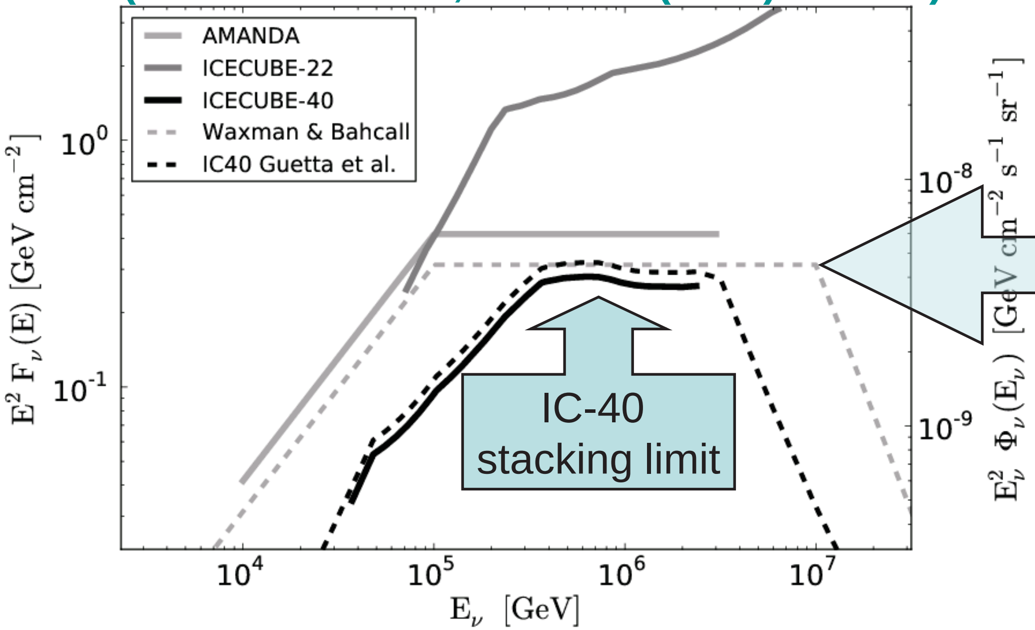
Gamma-ray burst fireball model:

IC-40 data meet generic bounds

(arXiv:1101.1448, PRL 106 (2011) 141101)



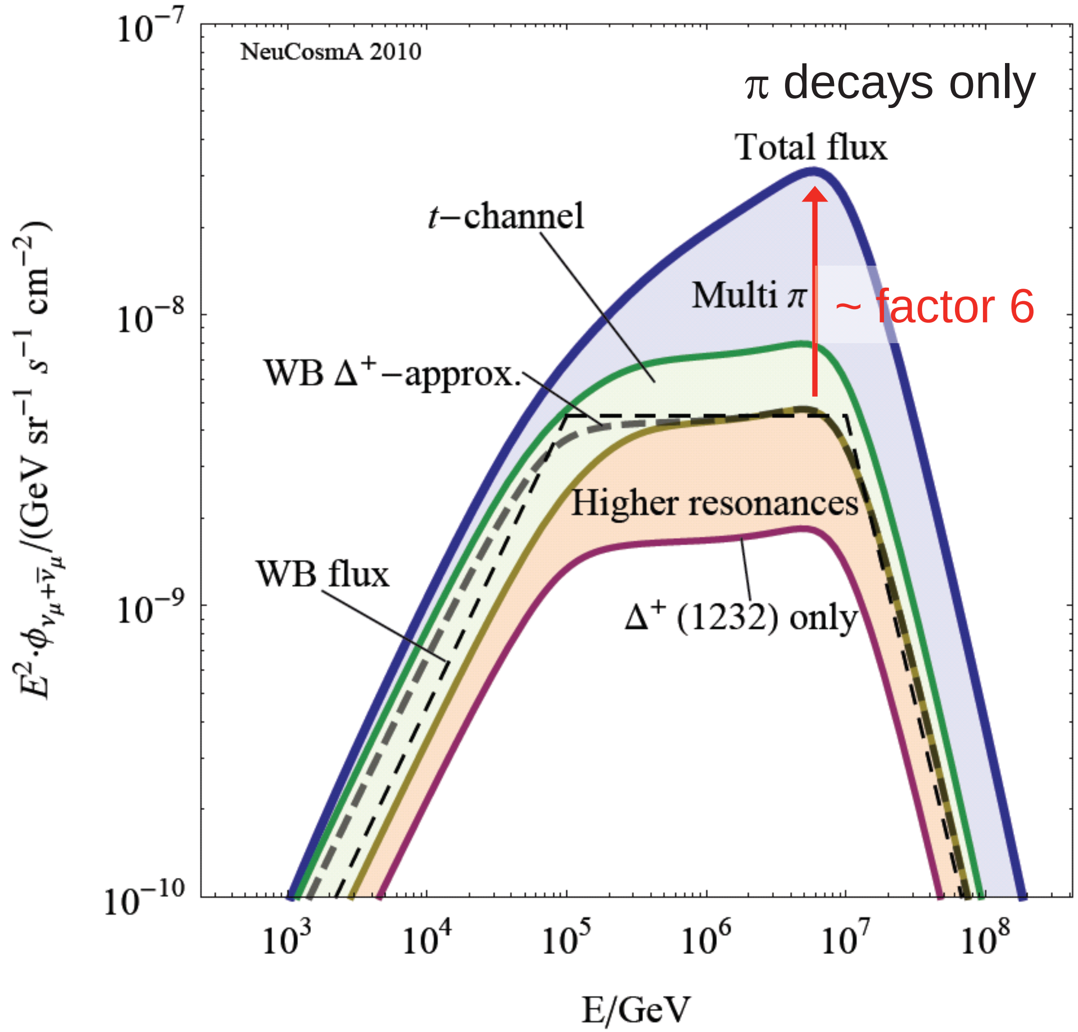
Generic flux based on the assumption that GRBs are the sources of (highest energetic) cosmic rays

(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? [from a purely technical point of view]

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

Waxman-Bahcall, reproduced

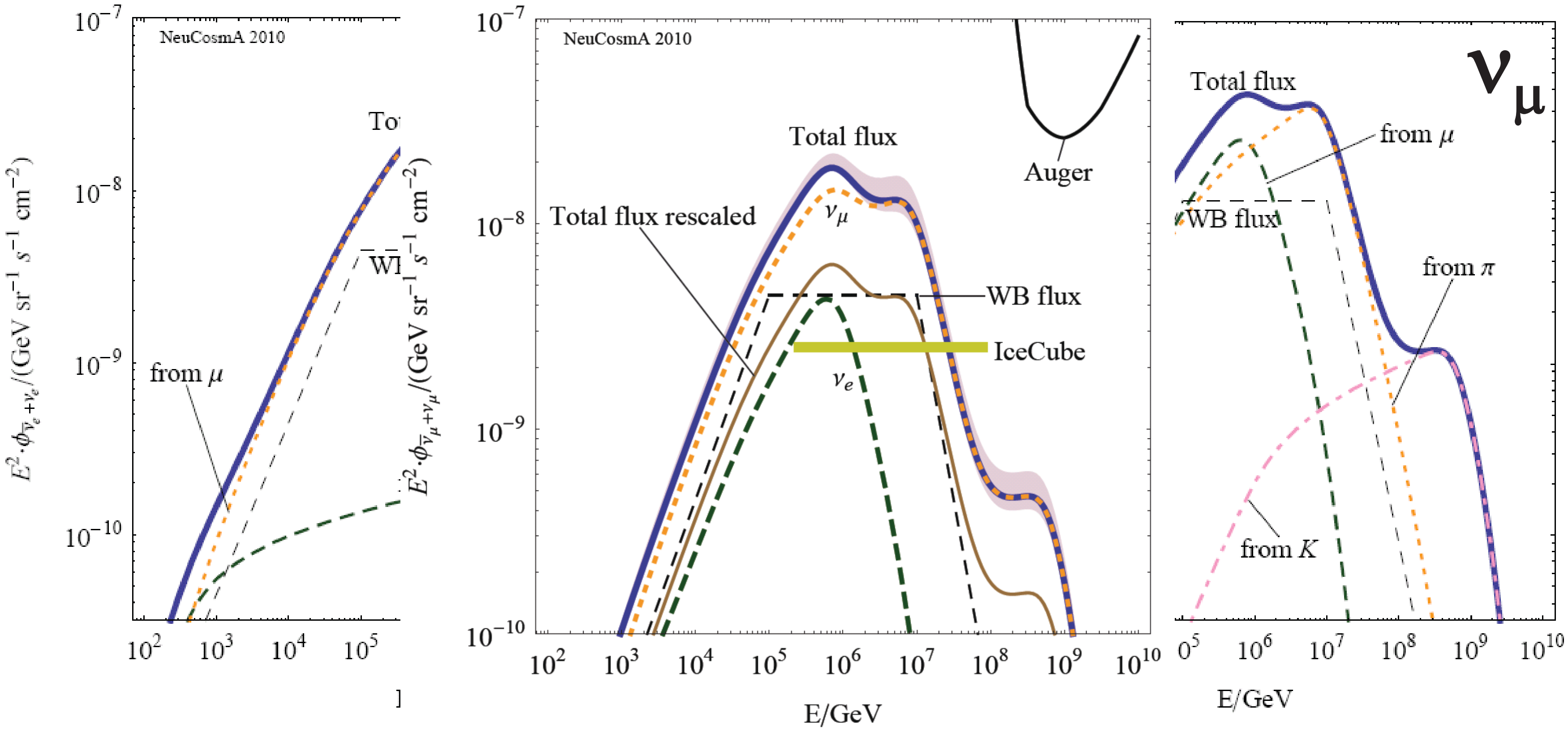


- Reproduced original WB flux with similar assumptions
- Additional charged pion production channels included, also π^-!

Baerwald, Hümmer, Winter, Phys. Rev. D83 (2011) 067303

Fluxes before/after flavor mixing

BEFORE FLAVOR MIXING

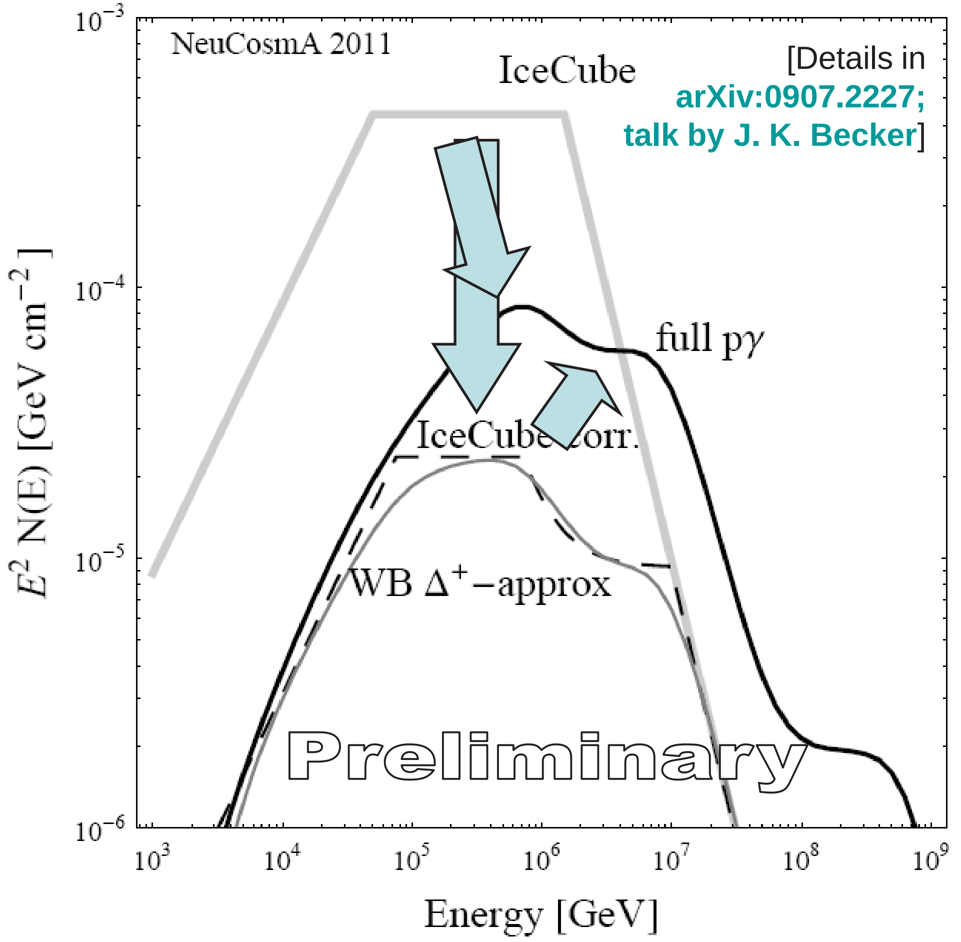


Baerwald, Hümmer, Winter, Phys. Rev. D83 (2011) 067303; see also: Murase, Nagataki, 2005; Kashti, Waxman, 2005; Lipari, Lusignoli, Meloni, 2007

Re-analysis of fireball model

- Correction factors from:
  - Cosmological expansion (z)
  - Some rough estimates, e.g. in f_π (frac. of E going into pion production)
  - Spectral corrections (e. g. compared to choosing the break energy)
  - Neutrinos from pions/muons
- Photohadronics change spectral shape
  Baerwald, Hümmer, Winter, PRD83 (2011) 067303
- **Conclusion (preliminary): Fireball flux ~ factor of five lower than expected, with different shape [but: depends on burst!]**

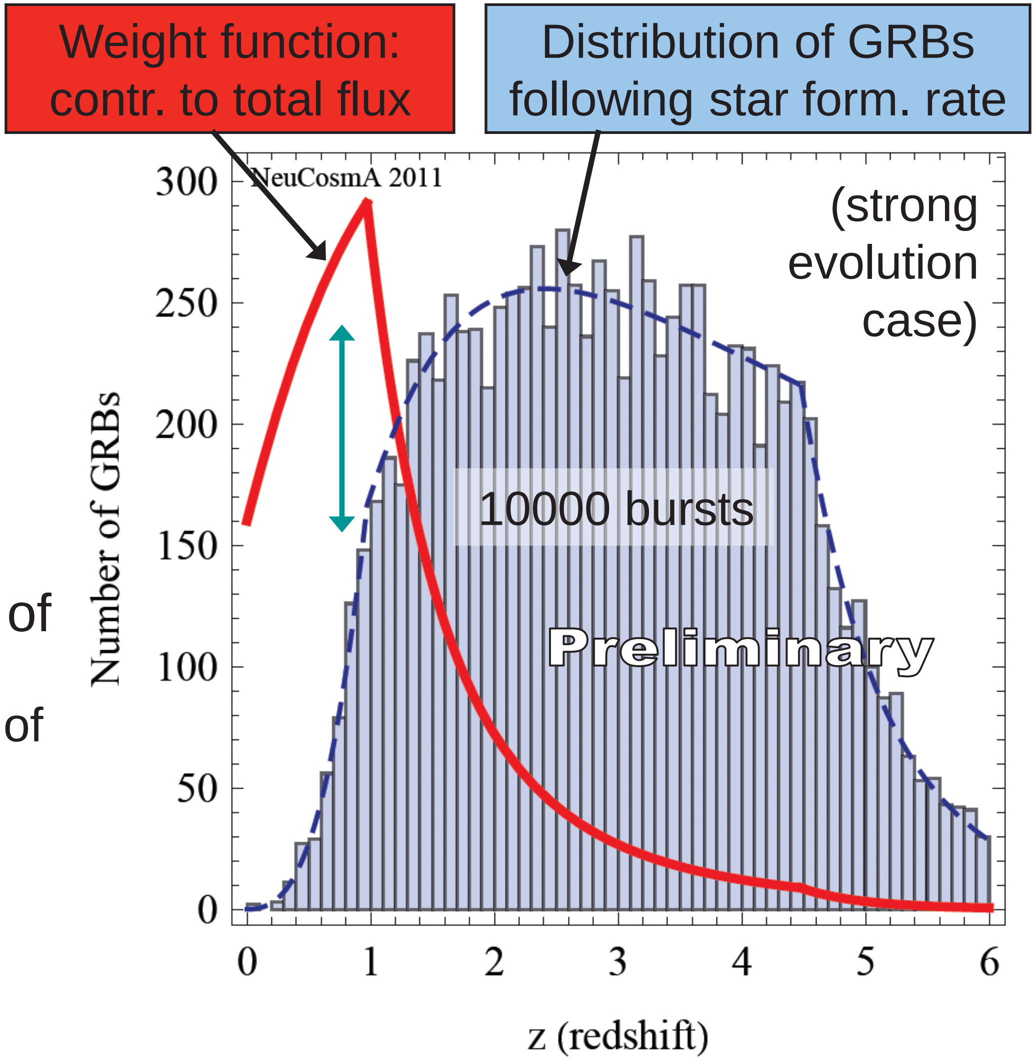
(one example/set of parameters)



(Hümmer, Baerwald, Winter, work in progress)

Systematics in aggregated fluxes

- IceCube: Signal from 117 bursts "stacked" (summed) for IC-40 limit **(arXiv:1101.1448)**
  - ➢ Is that sufficient?
- Some (preliminary) results:
  - z ~ 1 "typical" redshift of a GRB
    - ➢ Flux overestimated if z ~ 2-3 assumed (unless z measured)
  - Peak contribution in a region of low statistics
    - ➢ Probability to be within 20% of the diffuse flux is (roughly)
      - 40% for 100 bursts
      - 50% for 300 bursts
      - 70% for 1000 bursts
      - 95% for 10000 bursts
    - ➢ Need O(1000) bursts for reliable stacking limits!



(Baerwald, Hümmer, Winter, to appear; talk by P. Baerwald at ICRC!)

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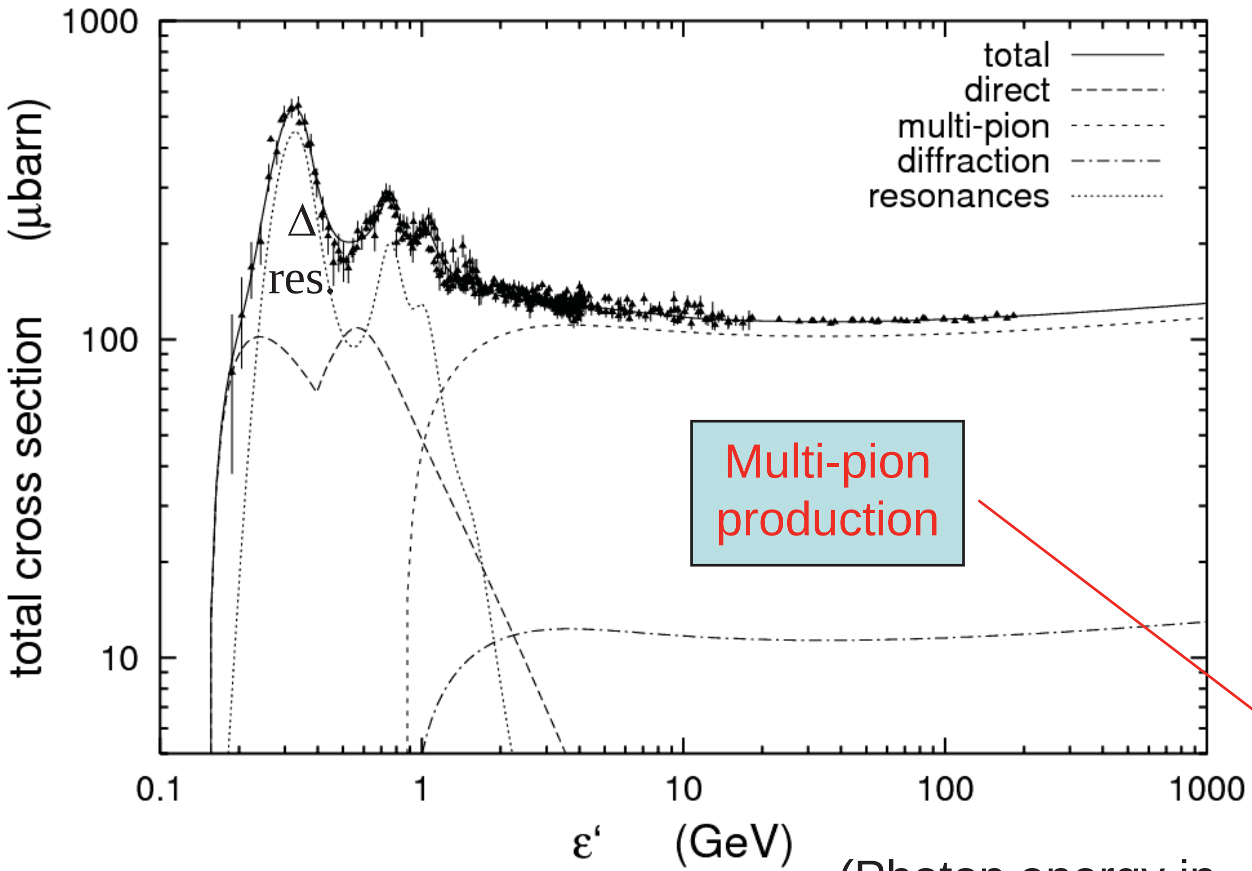
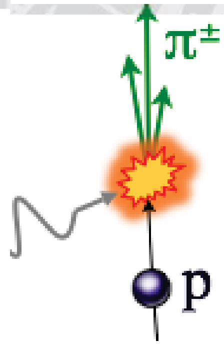
Summary

- Particle production, flavor, and magnetic field effects change the shape of astrophysical neutrino fluxes
  - ➢ Description of the „known“ (particle physics) components should be as accurate as possible for data analysis
  - ➢ Example: GRB neutrino flux shape and normalization
- 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)
- The flux shape and flavor ratio of a point source can be predicted in a self-consistent way if the astrophysical parameters can be estimated, such as from a multi-messenger observation
  (R: from time variability, B: from energy equipartition, α: from spectral shape)

BACKUP

Pion photoproduction





Power law injection spectrum from Fermi shock acc.

Multi-pion production

(Photon energy in nucleon rest frame)

Resonant production, direct production

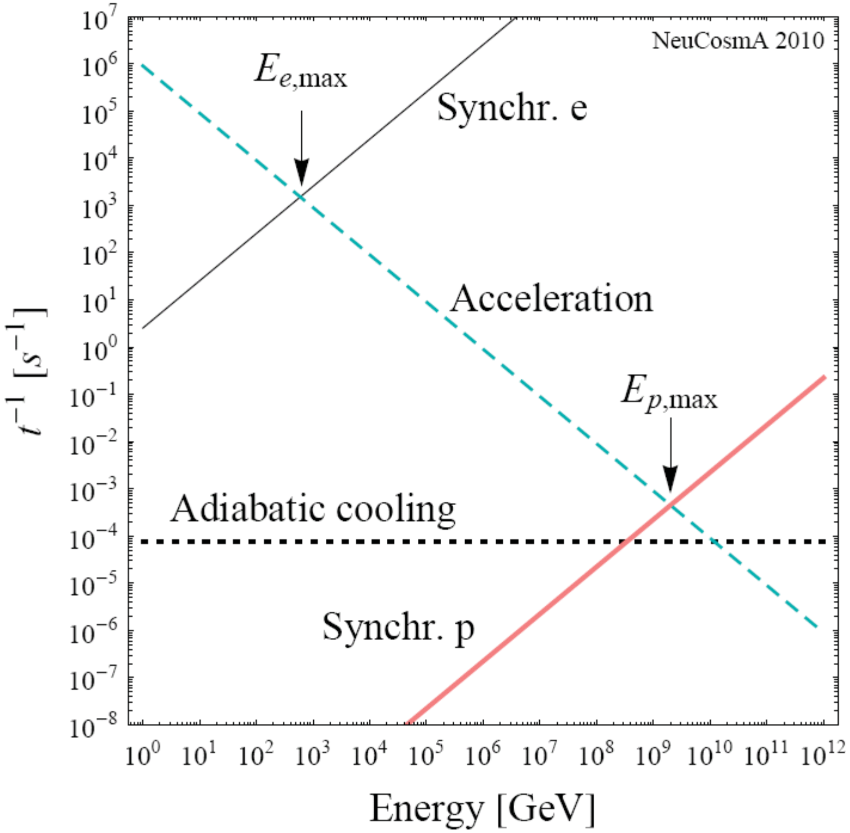
Different characteristics (energy loss of protons; energy dep. cross sec.)

(Mücke, Rachen, Engel, Protheroe, Stanev, 2008; **SOPHIA**)

An example (1)

α=2, B=10^3 G, R=$10^{9.6}$ km

Maximum energy: e, p



Hümmer, Maltoni, Winter, Yaguna, 2010

- Meson production described by

$$Q_b(E_b) = \int \frac{dE_p}{E_p} N_p(E_p) \int d\varepsilon \, N_\gamma(\varepsilon) \, R_b(x,y)$$

$$x = E_b/E_p$$
$$y \equiv (E_p \varepsilon)/m_p$$

(summed over a number of interaction types)

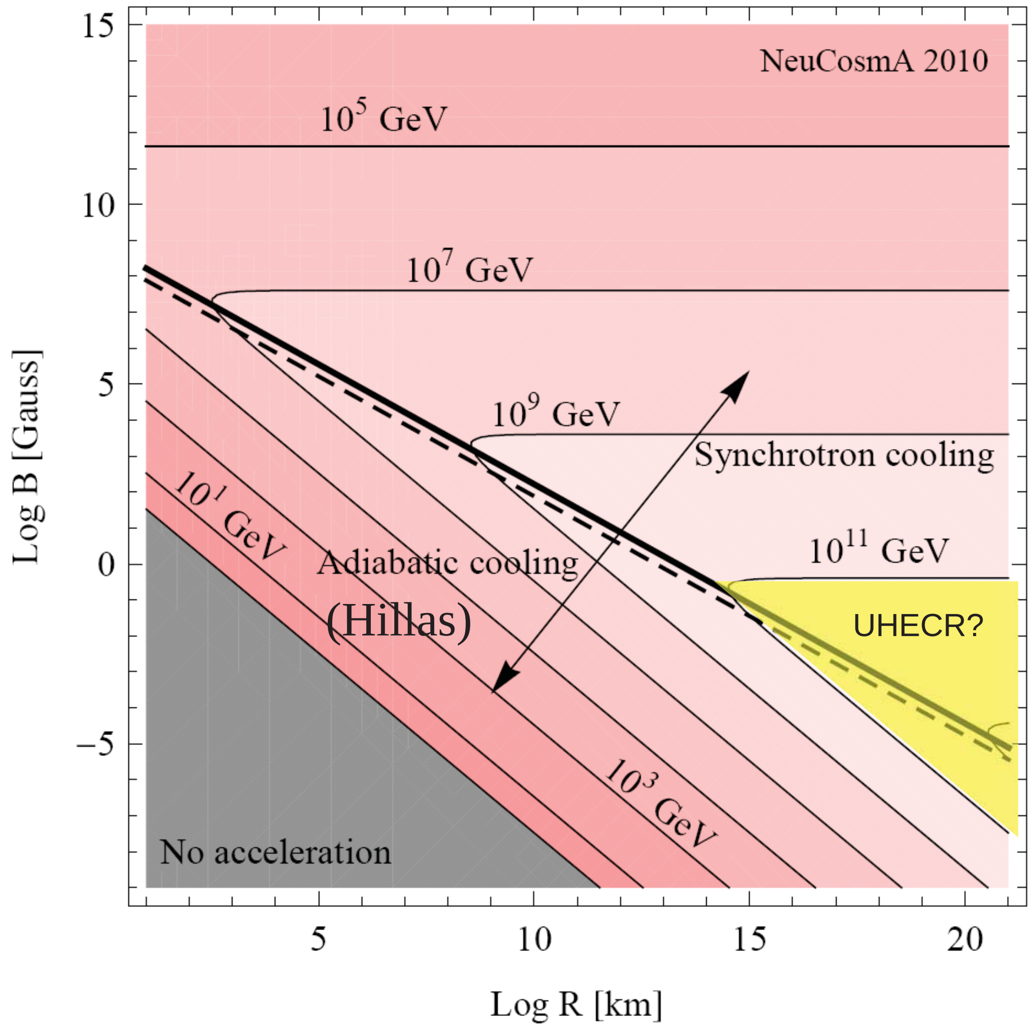
  - Only product normalization enters in pion spectra as long as synchrotron or adiabatic cooling dominate

- Maximal energy of primaries (e, p) by balancing energy loss and acceleration rate

$$t_{\mathrm{acc}}^{-1} = \eta \frac{c^2 e B}{E}$$

Maximal proton energy (general)

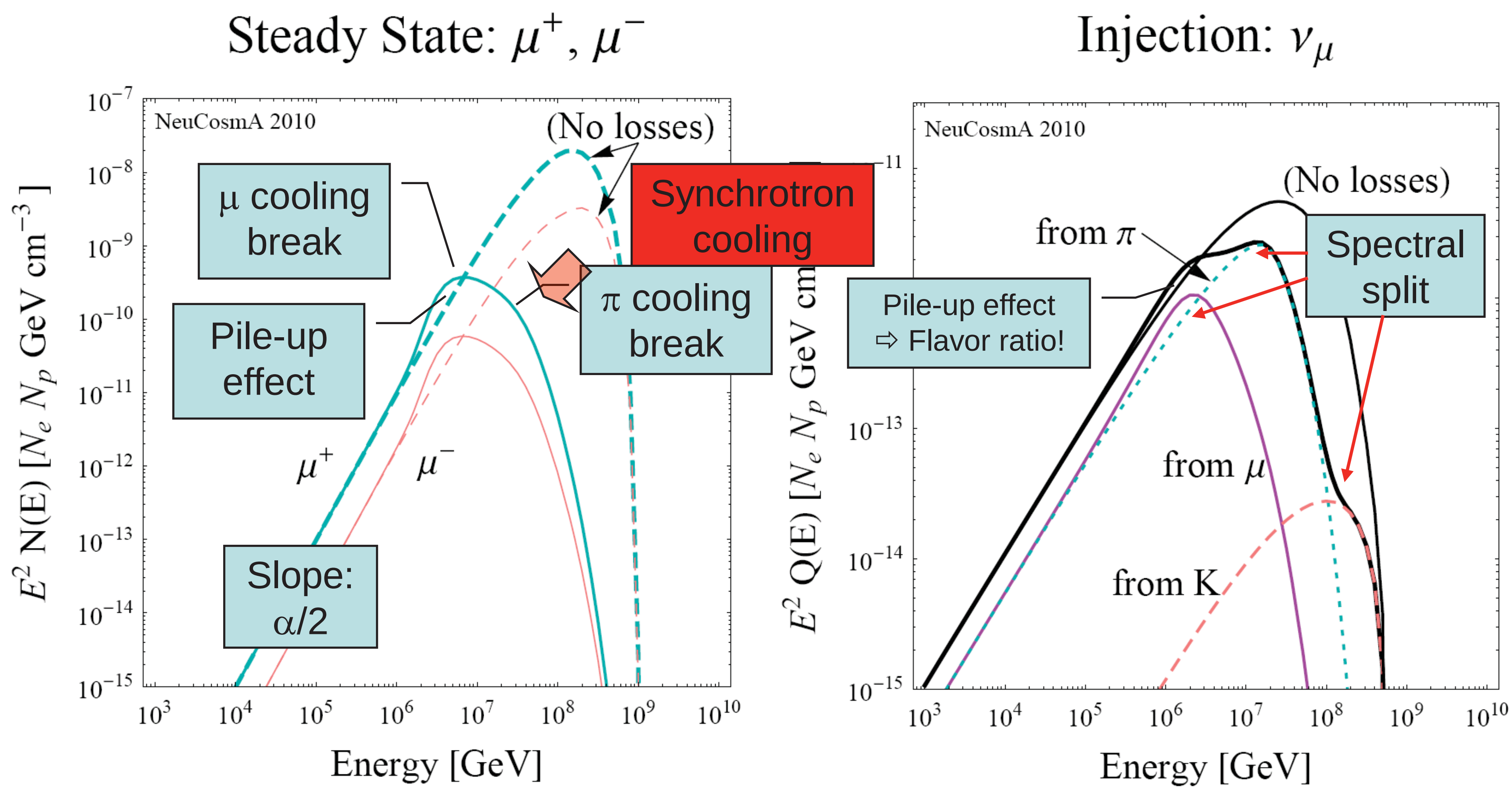
- Maximal proton energy (⇨UHECR) often constrained by proton synchrotron losses
- Sources of UHECR in lower right corner of Hillas plot?



Hümmer, Maltoni, Winter, Yaguna, 2010

An example (2)

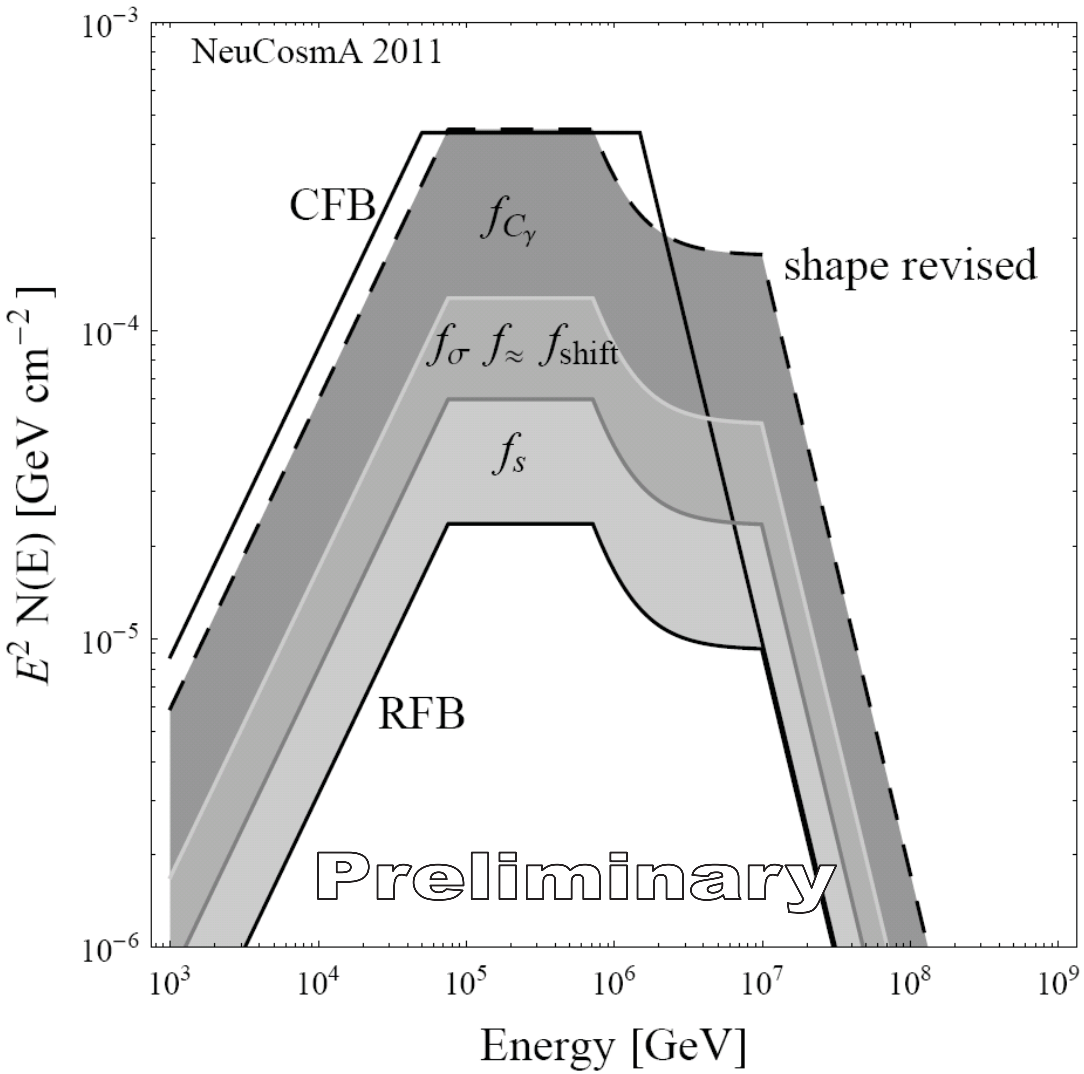
α=2, B=10^3 G, R=$10^{9.6}$ km



Hümmer, Maltoni, Winter, Yaguna, 2010

Revised fireball normalization
(compared to IceCube approach)

- Normalization corrections:
  - $f_{C\gamma}$: Photon energy approximated by break energy
    (Eq. A13 in Guetta et al, 2004)
  - f_S: Spectral shape of neutrinos directly related to that of photons (not protons)
    (Eq. A8 in arXiv:0907.2227)
  - f_σ, $f_\approx$, f_{shift}: Corrections from approximations of mean free path of protons and some factors approximated in original calcs



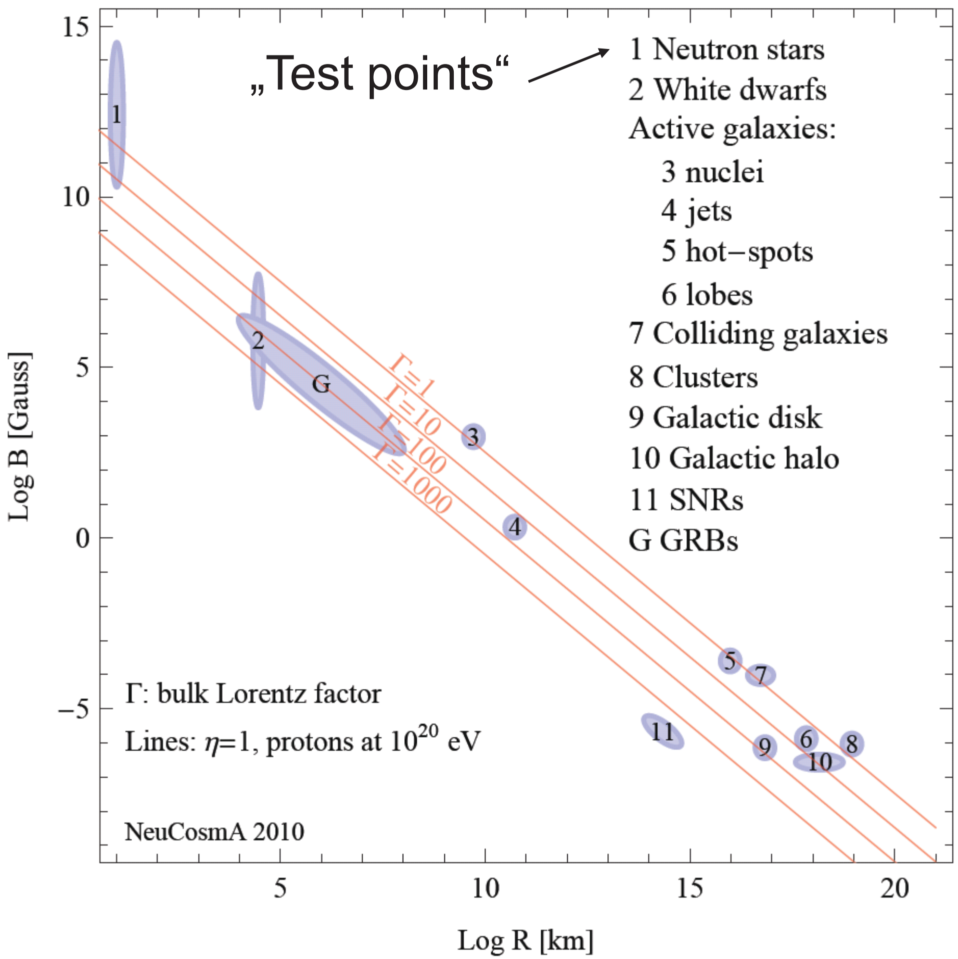
(Hümmer, Baerwald, Winter, in prep.)

Where to look for sources?

- Model-independent (necessary) condition:

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

  (Larmor-Radius < size of source)
  - ➢ Particles confined to within accelerator!
- Sometimes: define acceleration rate $t^{-1}_{acc} = \eta\ Z\ e\ B/E$ (η: acceleration efficiency)
- Caveat: condition relaxed if source heavily Lorentz-boosted (e.g. GRBs)



(Hillas, 1984; version adopted from M. Boratav)