Neutrino spectra and flavor composition on the Hillas plot

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- Simulation of sources,
  magnetic field and flavor effects
- Neutrino detection
- New physics tests
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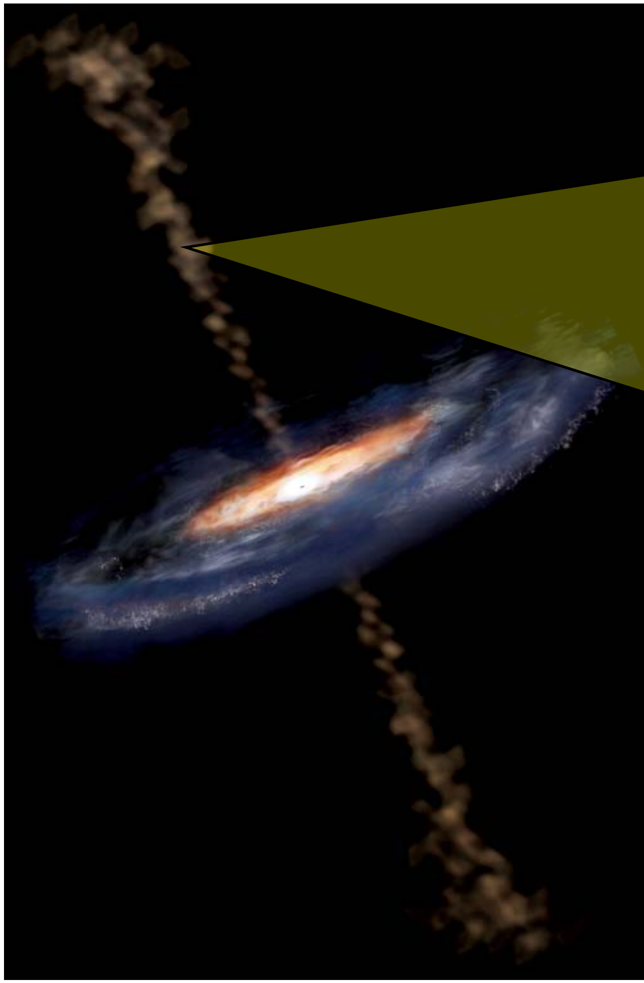
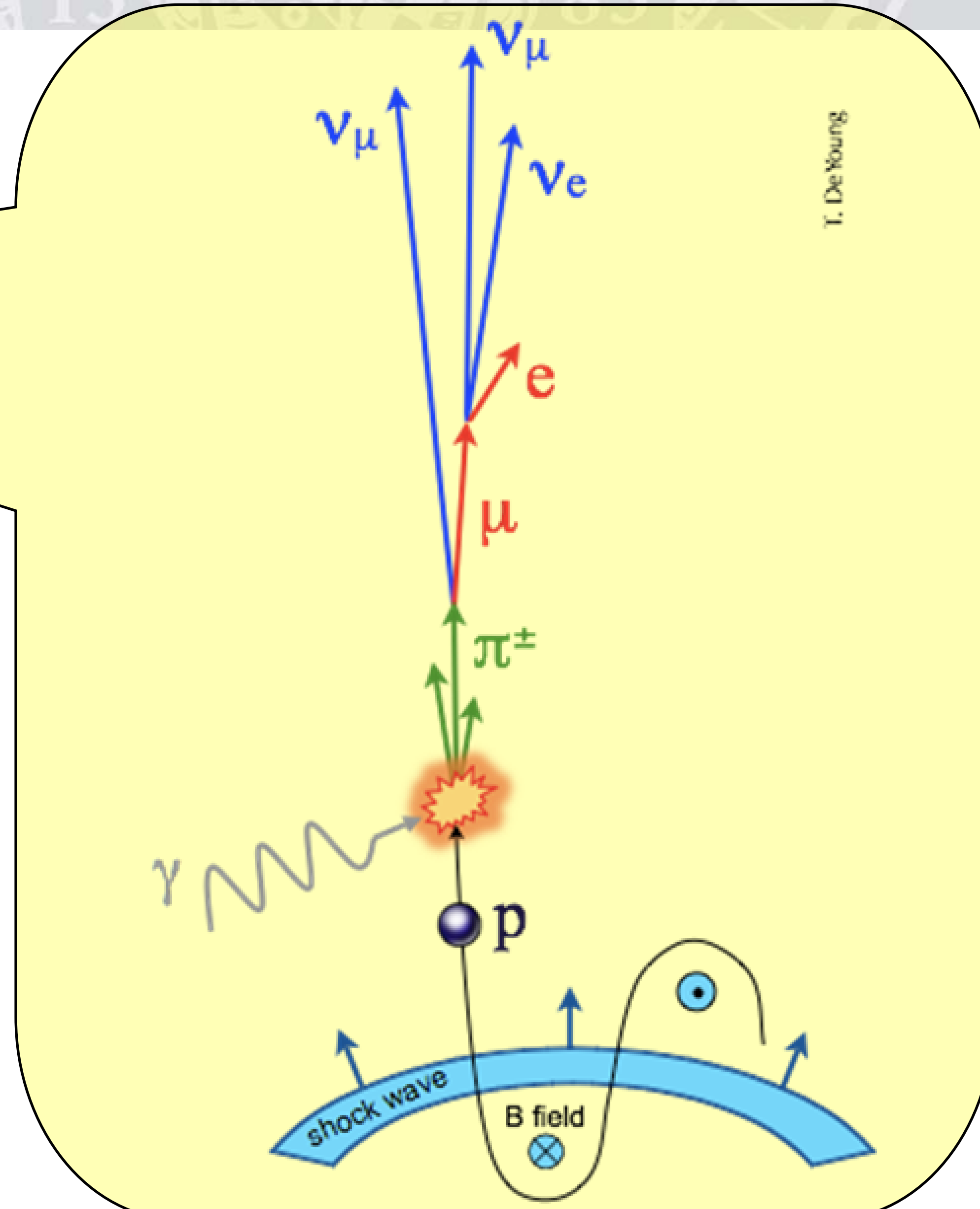
Neutrino production in astrophysical sources

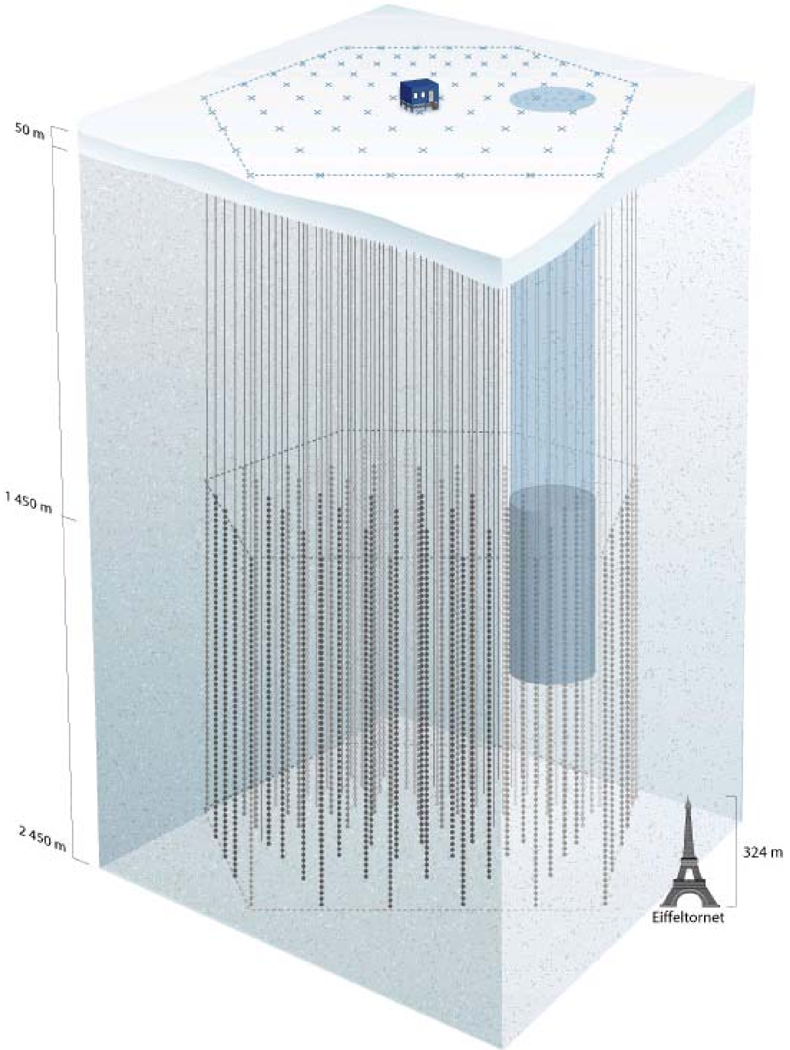


Example: Active galaxy
(Halzen, Venice 2009)



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/

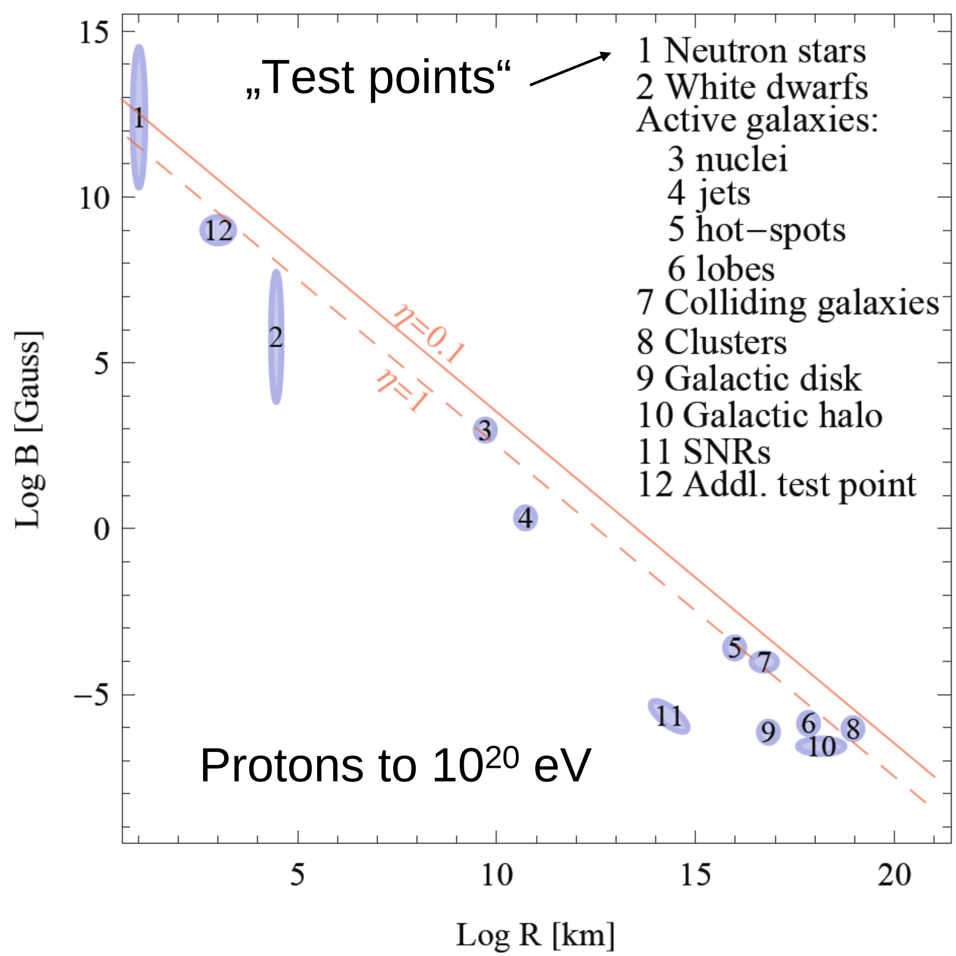
Parameter space: Hillas plot

- 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)

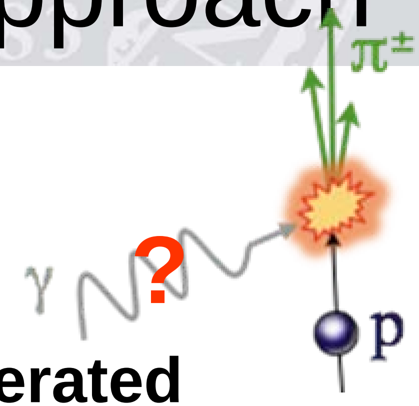
  - Particles confined to within accelerator!



Hillas 1984; version adopted from M. Boratav

Simulation of sources:

A self-consistent approach



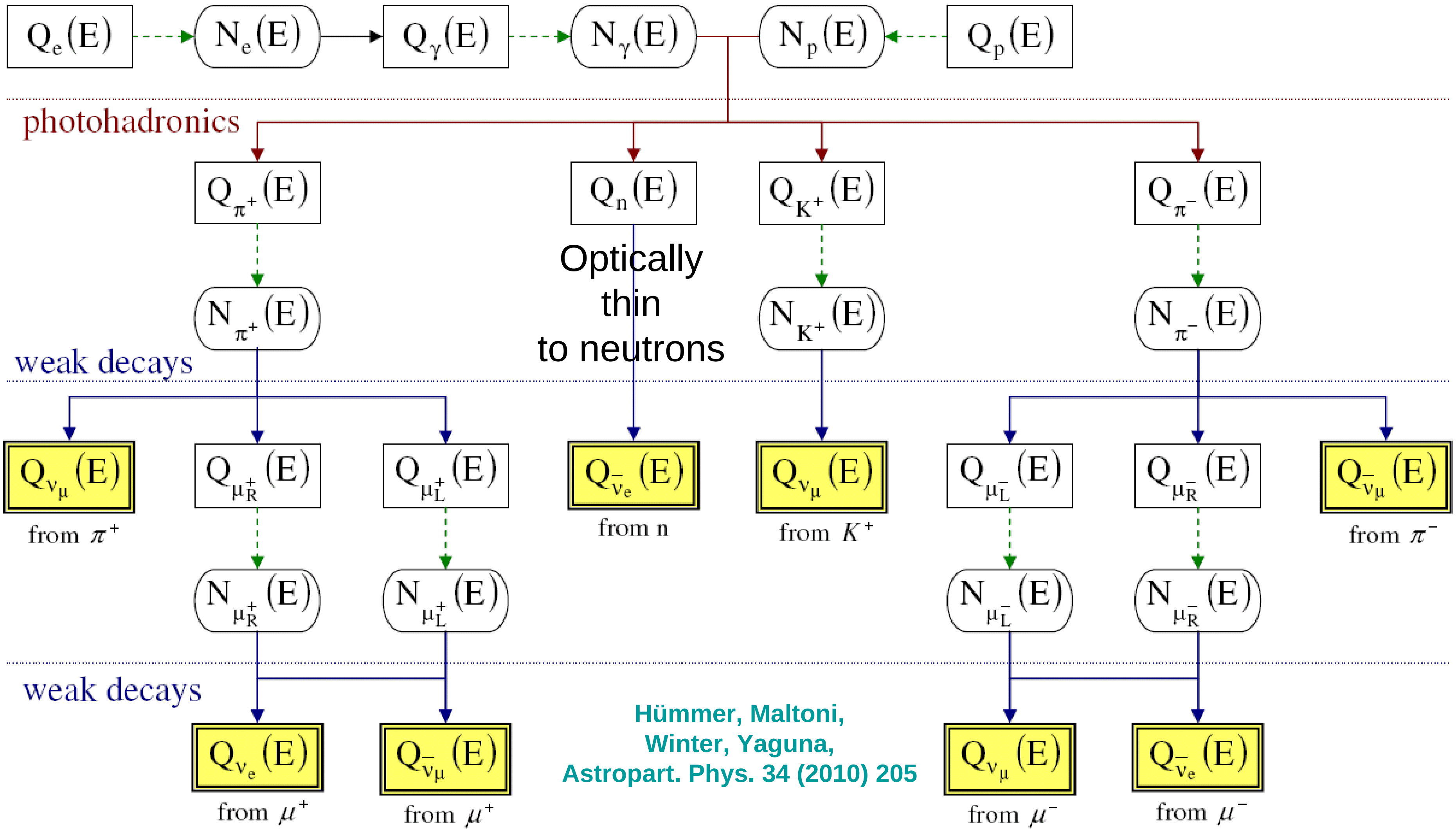
- Target photon field typically:
  - Put in by hand (e.g. obs. spectrum: GRBs)
  - Thermal target photon field
  - **From synchrotron radiation of co-accelerated electrons/positrons (AGN-like)**
- Requires few model parameters, mainly

Parameter	Units	Description	Typical values used
R	km (kilometers)	Size of acceleration region	$10^1\,\mathrm{km}\ldots10^{21}\,\mathrm{km}$
B	G (Gauss)	Magnetic field strength	$10^{-9}\,\mathrm{G}\ldots10^{15}\,\mathrm{G}$
α	1	Universal injection index	$1.5\ldots4$

- 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

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Model summary

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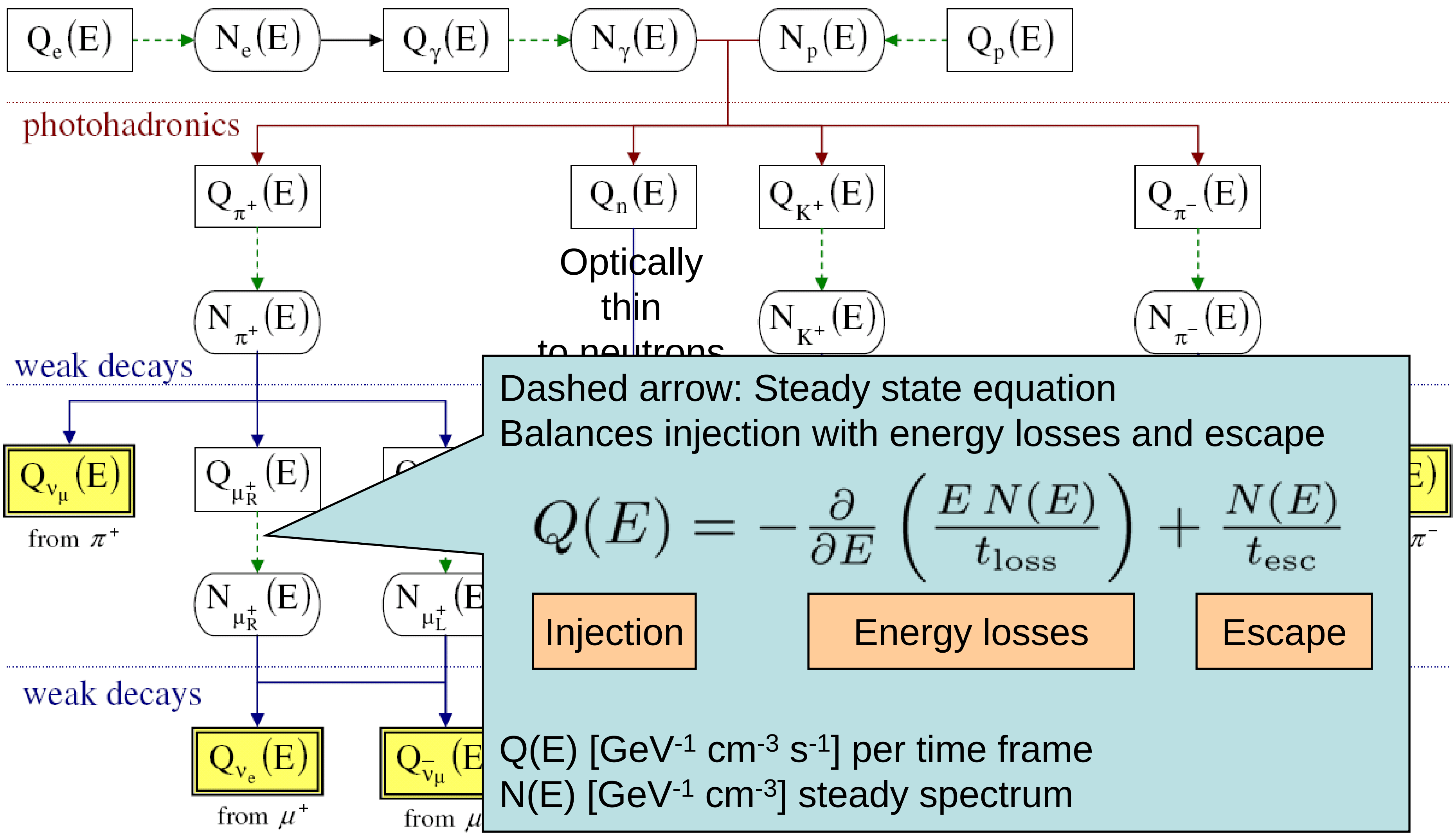


Dashed arrow: Steady state equation
Balances injection with energy losses and escape

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

Injection | Energy losses | Escape

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

An example: Secondaries

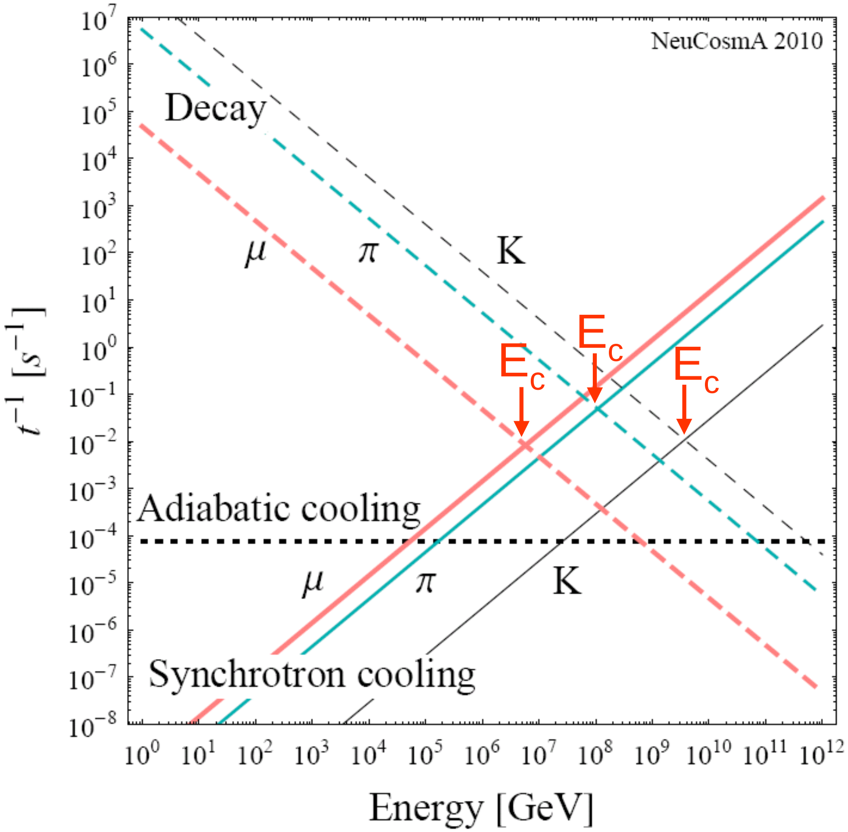
α=2, B=10^3 G, R=$10^{9.6}$ km

- 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?

Cooling: charged μ, π, K



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

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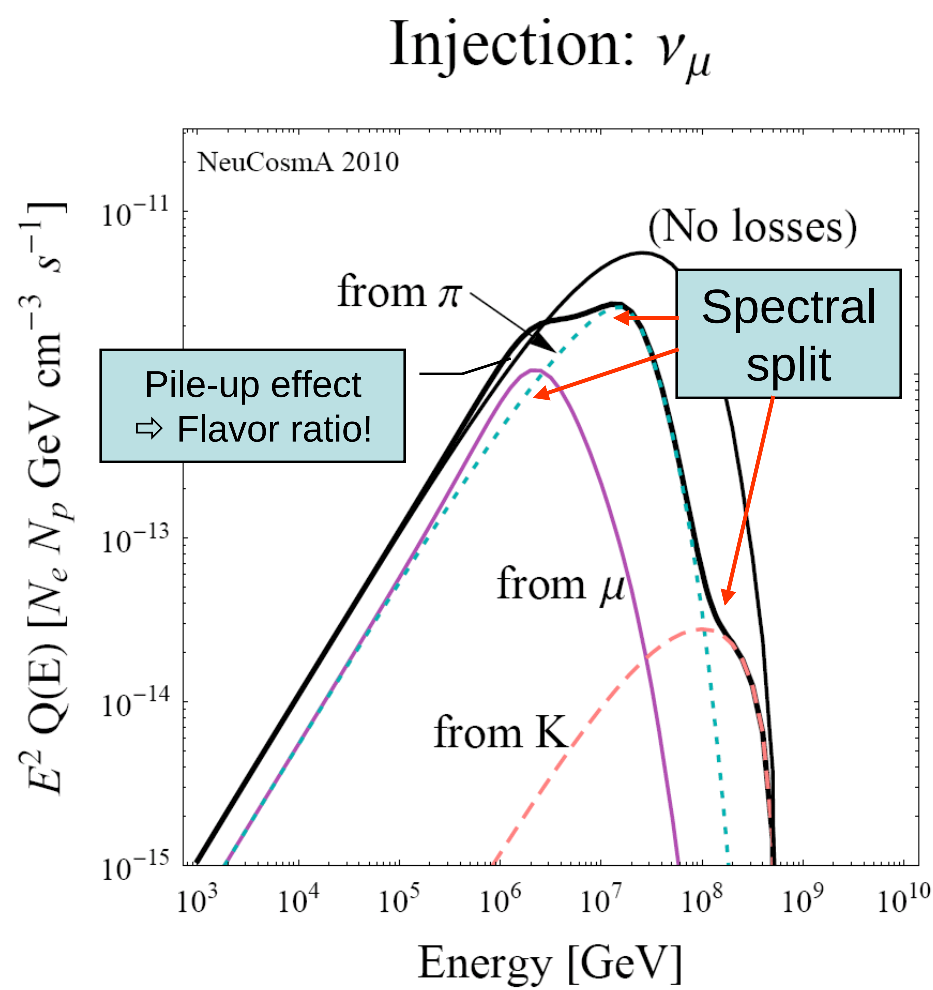

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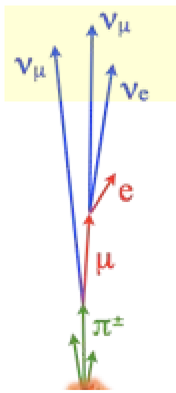
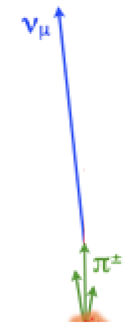
Flavor composition at the source

(Idealized – **energy independent**)

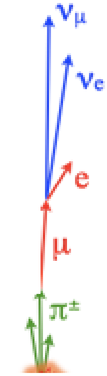
- Astrophysical neutrino sources produce certain flavor ratios of neutrinos (ν_e:ν_μ:ν_τ):
- Pion beam source (1:2:0)
  Standard in generic models



- 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)

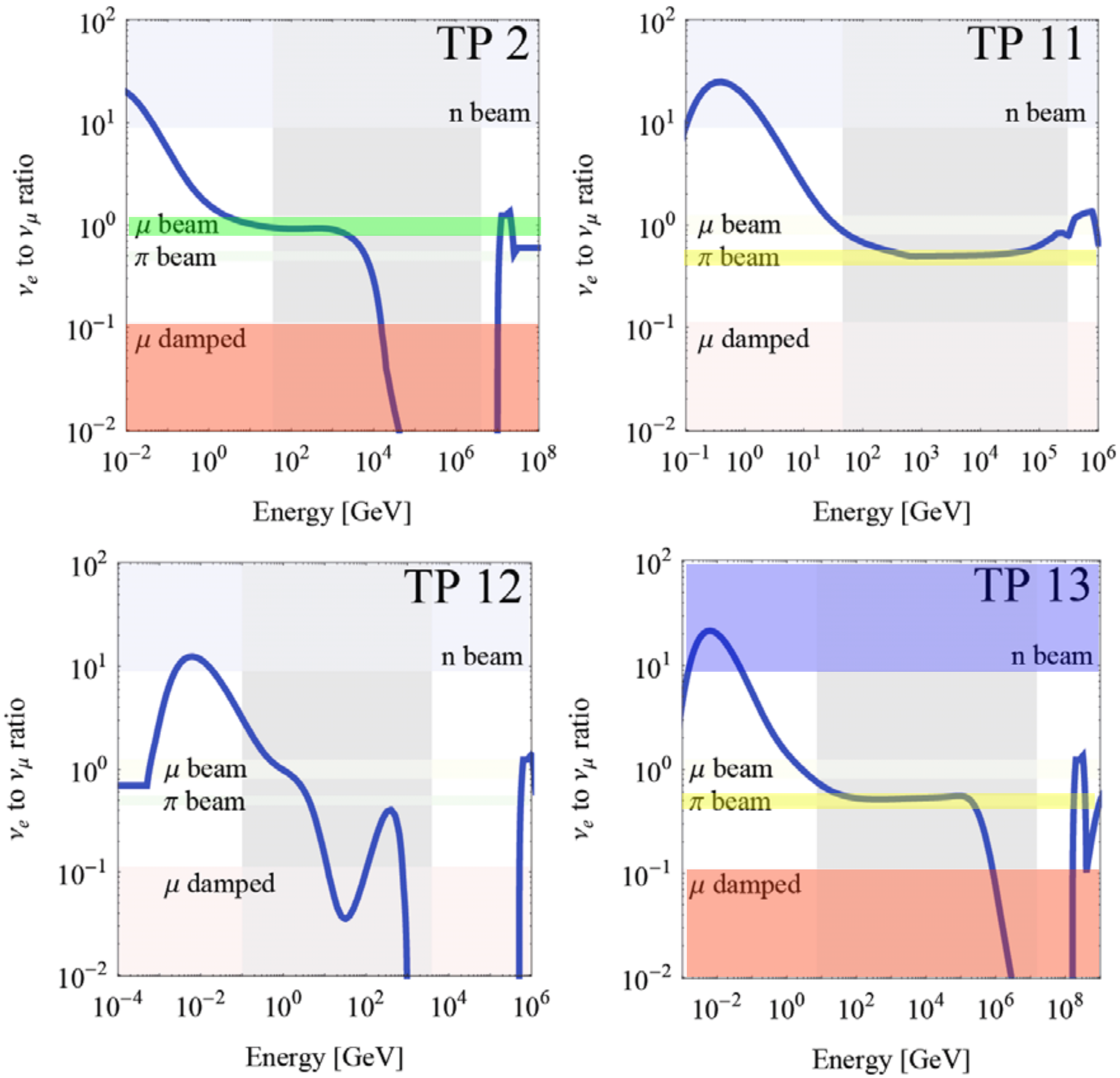
$$n \to p + e^- + \bar{\nu}_e$$

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

However: flavor composition is energy dependent!

Muon beam
⇨ muon damped

Pion beam



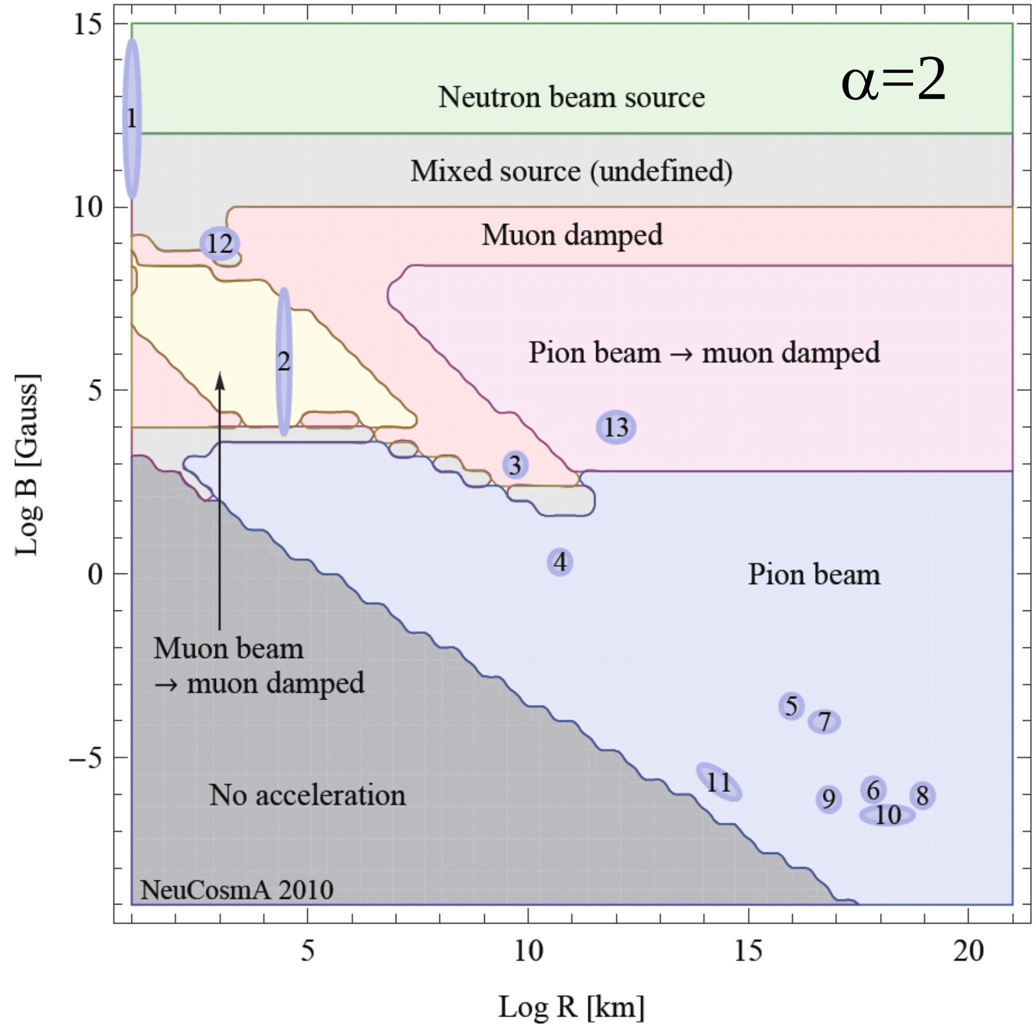
Undefined
(mixed source)

Pion beam
⇨ muon damped

(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

- Sources on galactic scales or larger: typically pion beams
- More compact sources: non-trivial flavor ratio



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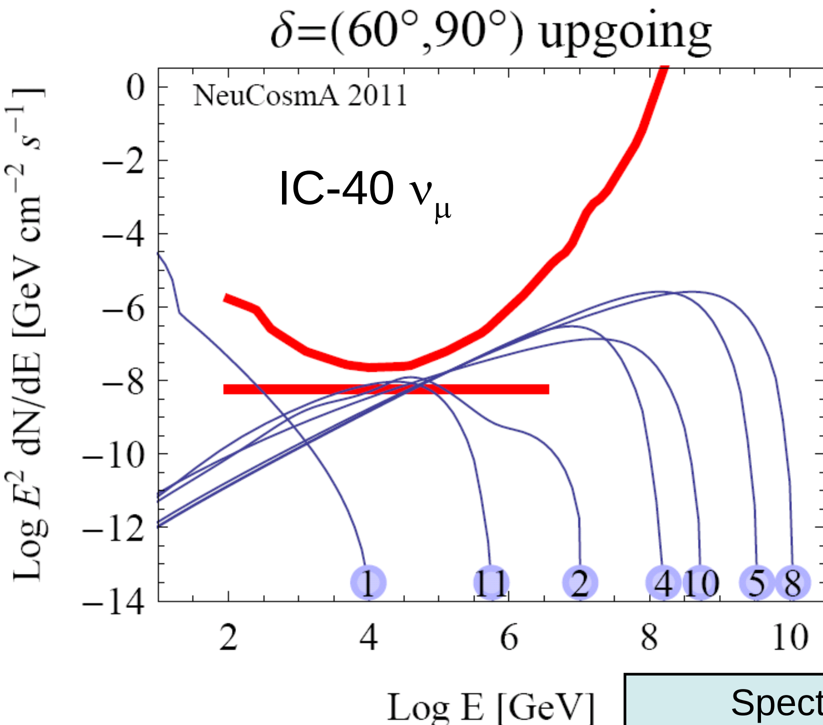
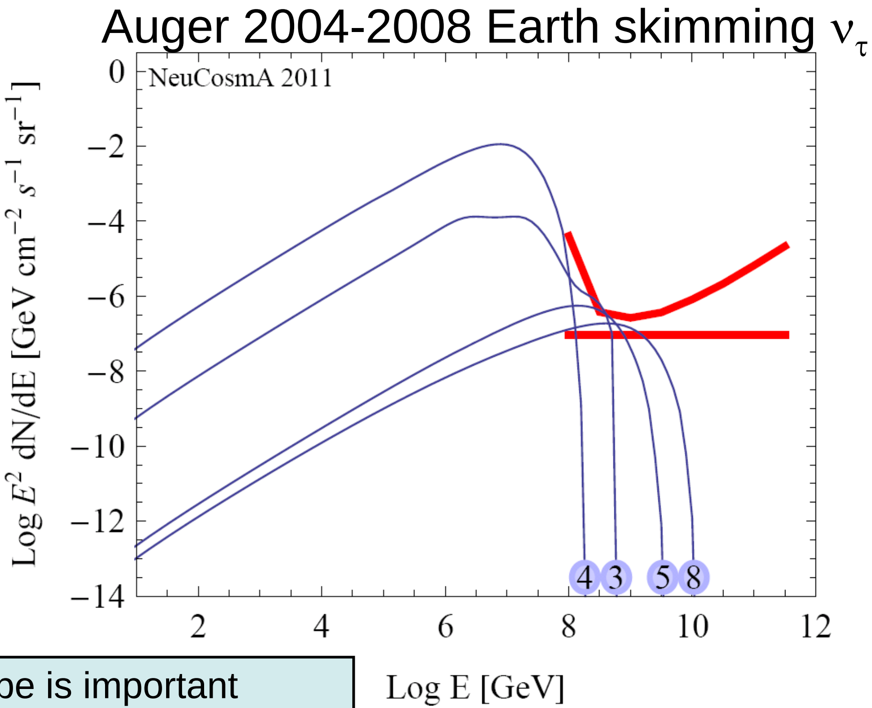
Neutrino detection: Muon tracks

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



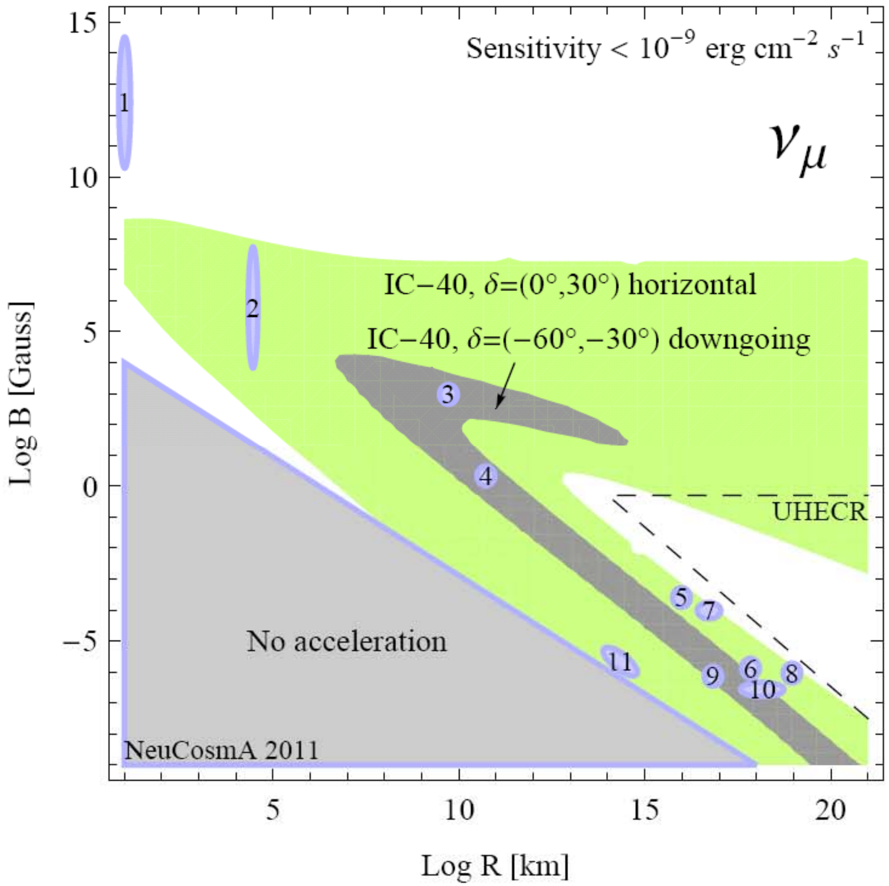


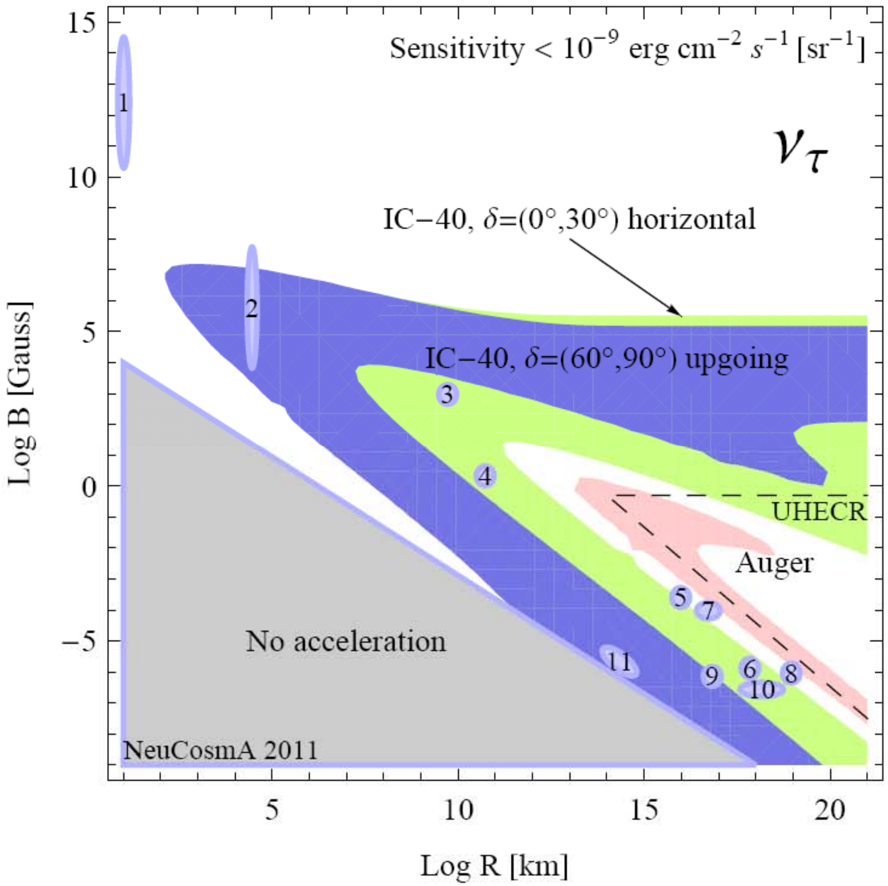
Spectral shape is important because instrument response is very sensitive to it!

(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 $\phi = \int E \frac{dN(E)}{dE} dE$





(Winter, arXiv:1103.4266)

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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 cascades

  Observable corresponds to combined muon track and cascade analysis

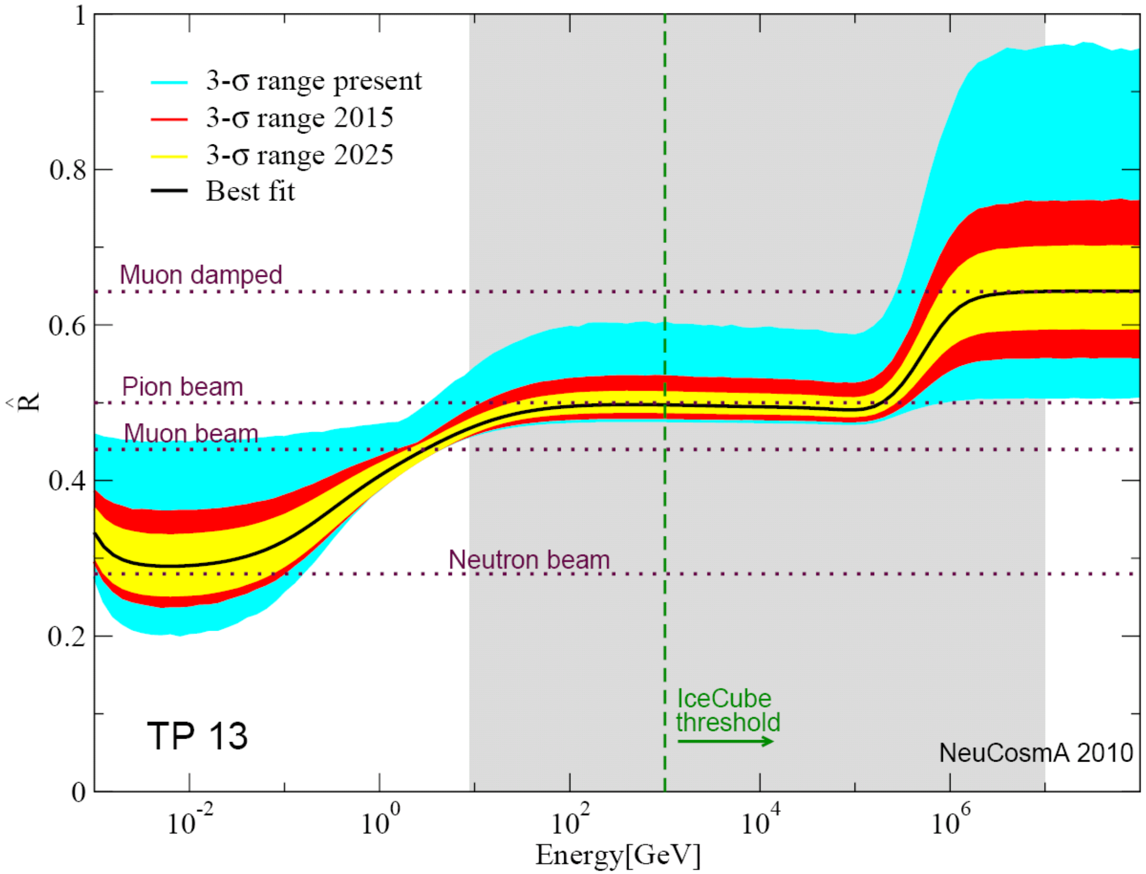
  (see arXiv:1101.1692 for IC-22 cascades)

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

- 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?

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

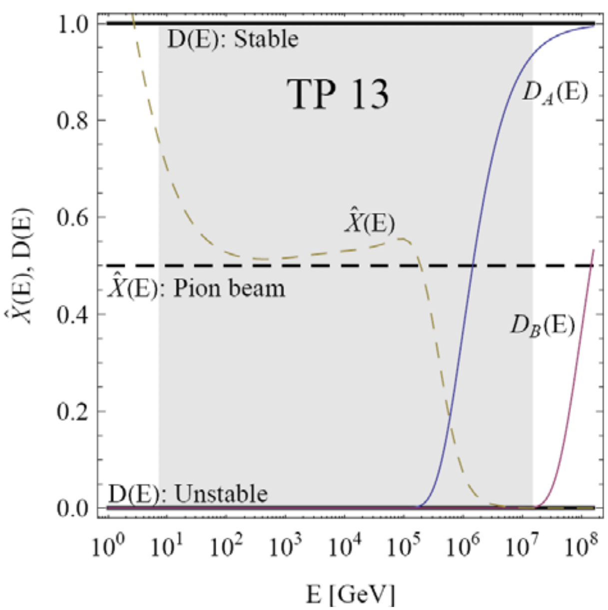
Energy dependence flavor comp. source

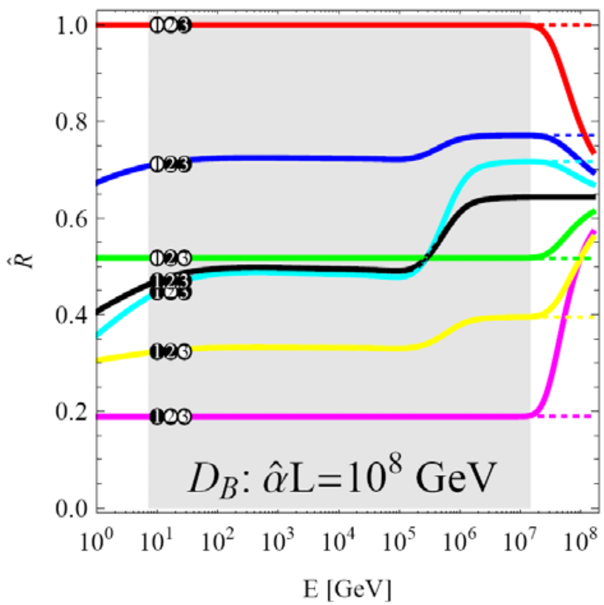
$$\hat{R} \equiv \frac{\Phi_\mu^{\mathrm{Det}}}{\Phi_e^{\mathrm{Det}} + \Phi_\tau^{\mathrm{Det}}} = \frac{P_{e\mu}(E)\,\hat{X}(E) + P_{\mu\mu}(E)}{[P_{ee}(E) + P_{e\tau}(E)]\,\hat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

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

Energy dep. new physics

(Example: [invisible] neutrino decay)





1 Stable state

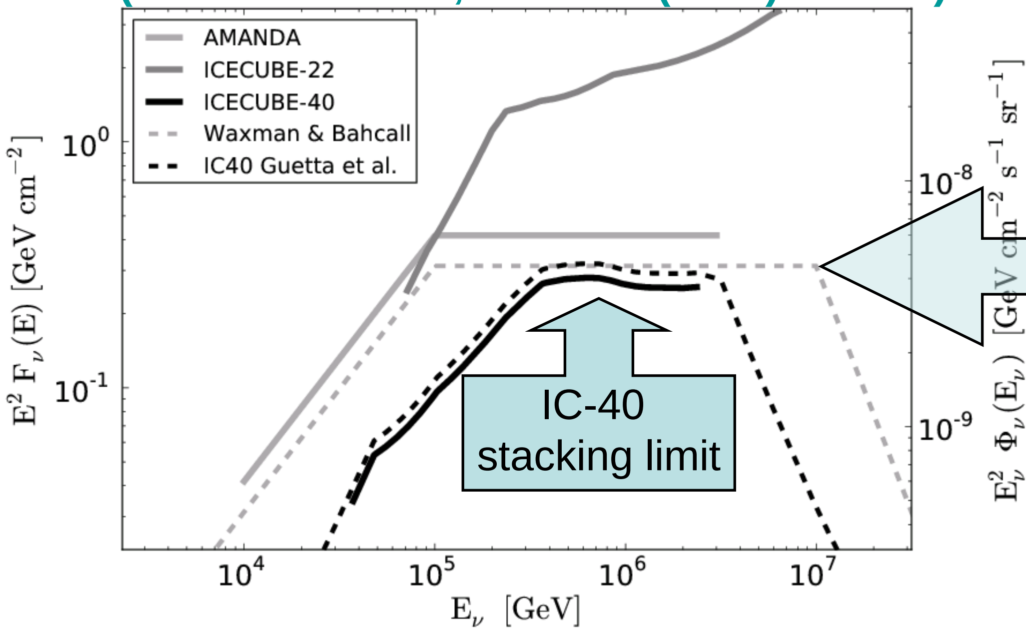
1 Unstable state

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

Gamma-ray burst fireball model:

IC-40/59 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?

➢ Systematics in stacked neutrino fluxes
➢ Re-computation of fireball phenomenology; comparison with numerical method
➢ Flavor and magnetic field effects in GRB neutrino fluxes

Poster P10
Svenja
Hümmer

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)

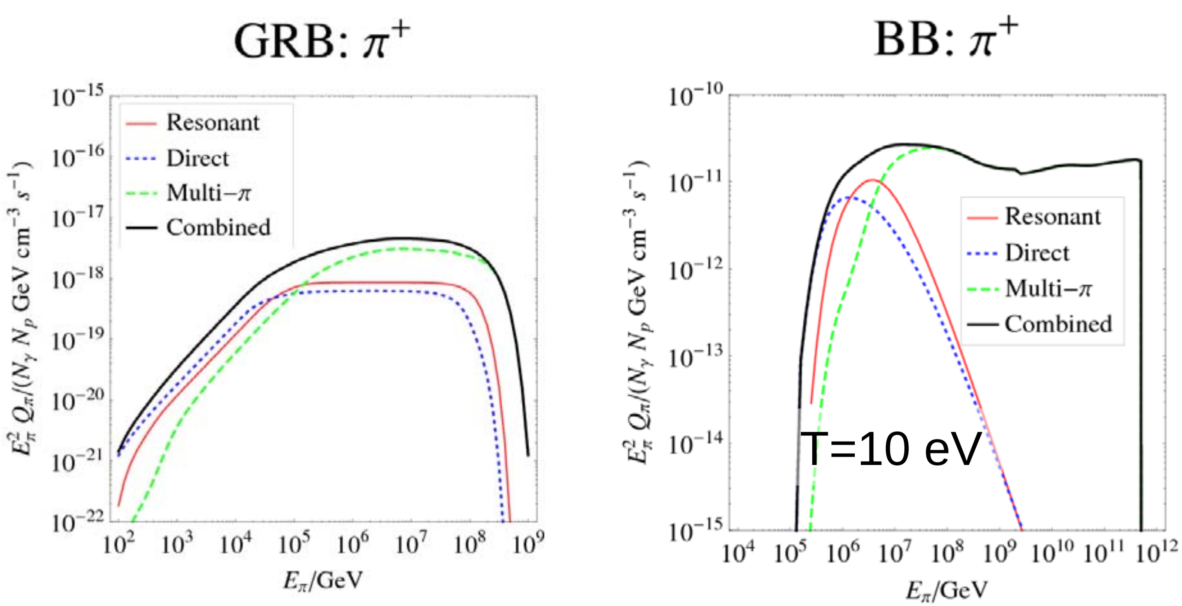
Backup

Meson photoproduction

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

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

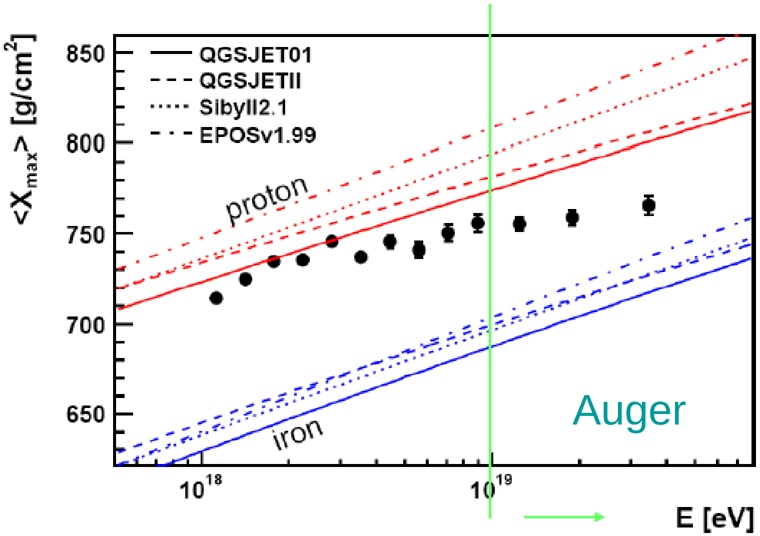
- Limitations:
  - No π^- production; cannot predict π^+/π^- ratio (affects neutrino/antineutrino)
  - High energy processes affect spectral shape
  - Low energy processes (t-channel) enhance charged pion production
  - ➢ Charged pion production underestimated compared to π^0 production by factor of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

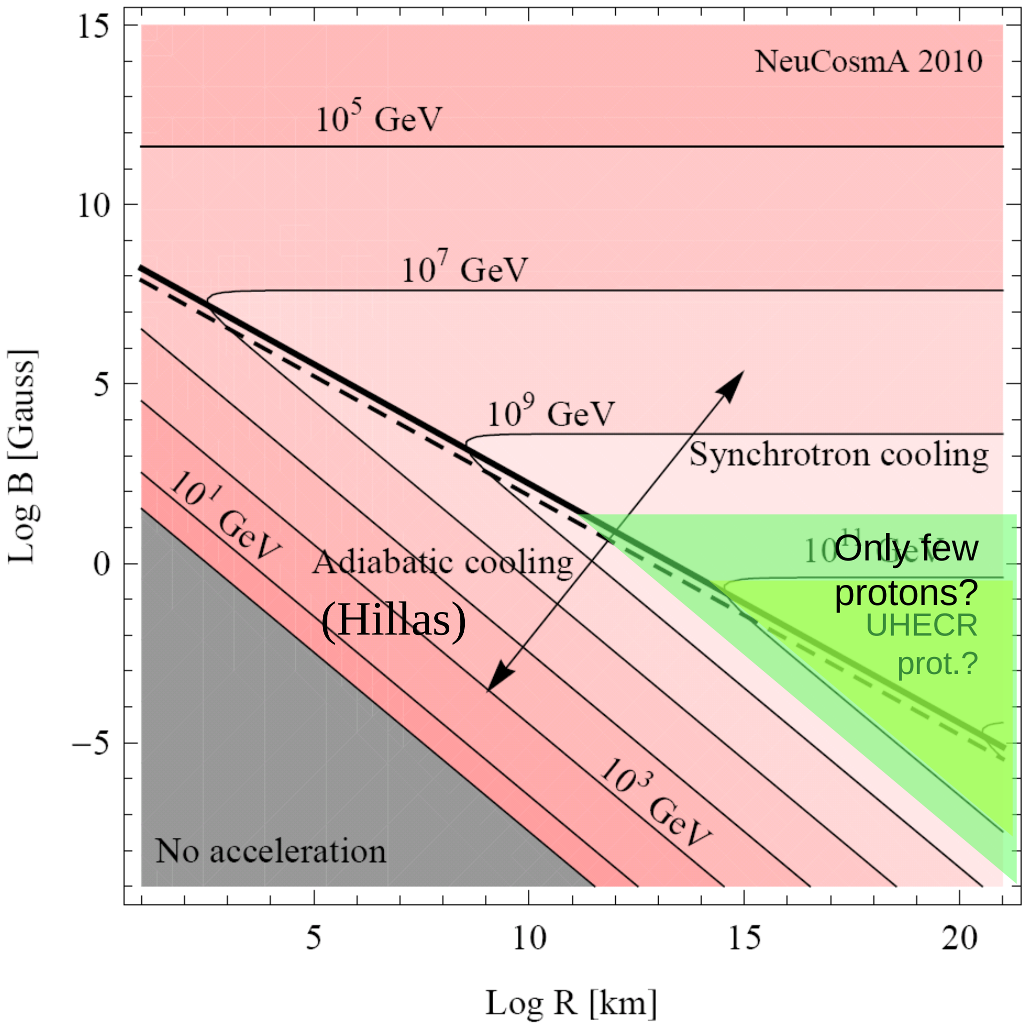


from:
Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630

Maximal proton energy (general)

- Maximal proton energy (⇨UHECR) often constrained by proton synchrotron losses
- Sources of UHECR in lower right corner of Hillas plot?
- Caveat: Only applies to protons, but …





Hümmer, Maltoni, Winter, Yaguna, 2010

Neutrino propagation

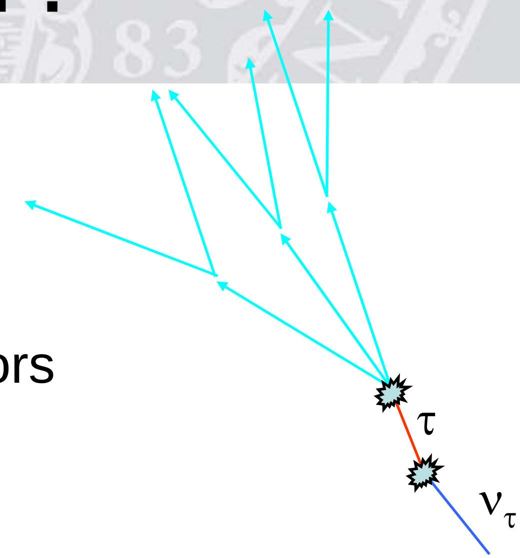
- Key assumption: Incoherent propagation of neutrinos
- Flavor mixing: $P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$

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

- Example: For $\theta_{13} = 0$, $\theta_{23} = \pi/4$:

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

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 $\longrightarrow$

  (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