# Interpretation of astrophysical neutrino signal, and the multi-messenger context

## (a particle physics theorist's perspective)

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KITP conference
*Neutrinos: Recent developments*
*... and future challenges*
Nov 3-7, 2014

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KITP conference

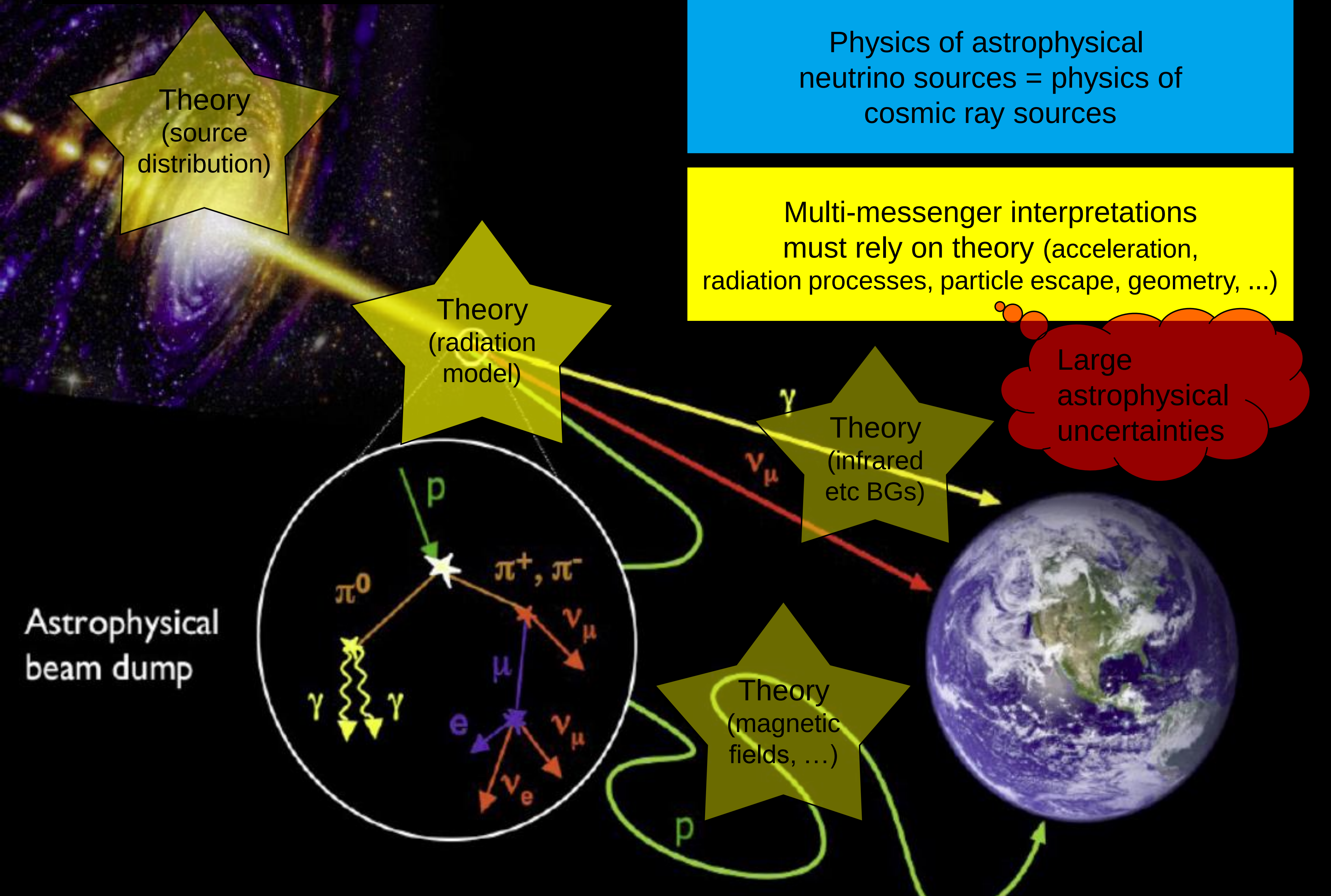
*Neutrinos: Recent developments*

***... and future challenges***

# Cosmic messengers

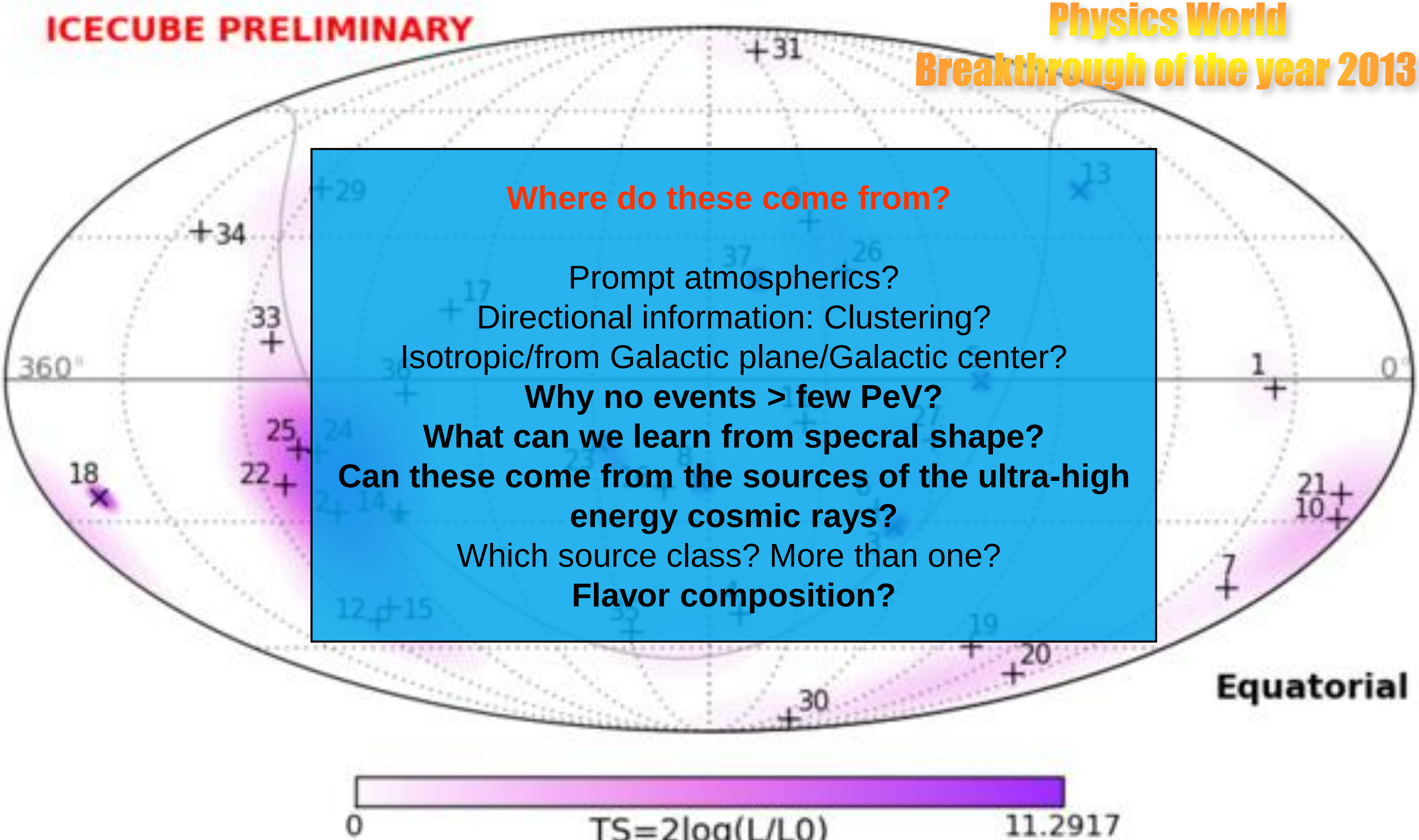
Physics of astrophysical neutrino sources = physics of cosmic ray sources

Multi-messenger interpretations must rely on theory (acceleration, radiation processes, particle escape, geometry, ...)



# 2014: 37 neutrinos in the TeV-PeV range

**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?**
**What can we learn from specral shape?**
**Can these come from the sources of the ultra-high energy cosmic rays?**
Which source class? More than one?
**Flavor composition?**

Science 342 (2013) 1242856; update by Gary Hill @ Neutrino 2014

# Simulation of neutrino sources

# Neutrino and cosmic ray source
## (illustrative proton-only scenario, pγ interactions)

If neutrons can escape:
Source of cosmic rays

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

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

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

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

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

Delta resonance approximation:

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

$\pi^+/\pi^0$ determines ratio between neutrinos and high-E gamma-rays

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

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

Cosmic messengers



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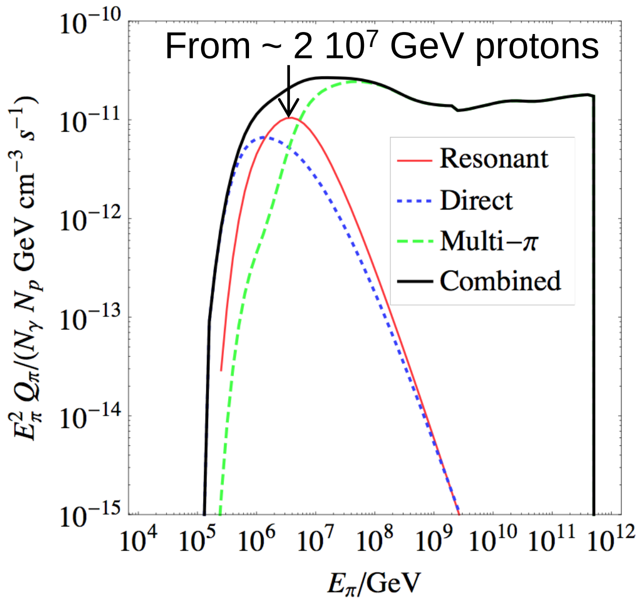
# Source simulation: pγ (particle physics)

- Δ(1232)-resonance approximation:

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

  Resonance condition: Proton energy [GeV] x Photon energy [GeV] ~ 0.2

- Limitations:
  - No $\pi^-$ production; cannot predict $\pi^+/\pi^-$ ratio (Glashow resonance!)
  - High energy processes affect spectral shape (X-sec. dependence!)
  - Low energy processes (t-channel) enhance charged pion production
- Example: Peak at PeV energies (here pions) from thermal target photons?




Example: $E^{-2}$ proton spectrum interacting with 10 eV blackbody target photon spectrum
Multi-pion processes exclude this as explanation for observed neutrinos unless $E_{p,max} < 10^8$ GeV!

**From: Hümmer et al, ApJ 721 (2010) 630 parameterization based on SOPHIA – Mücke, Rachen, Engel, Protheroe, Stanev, 2000**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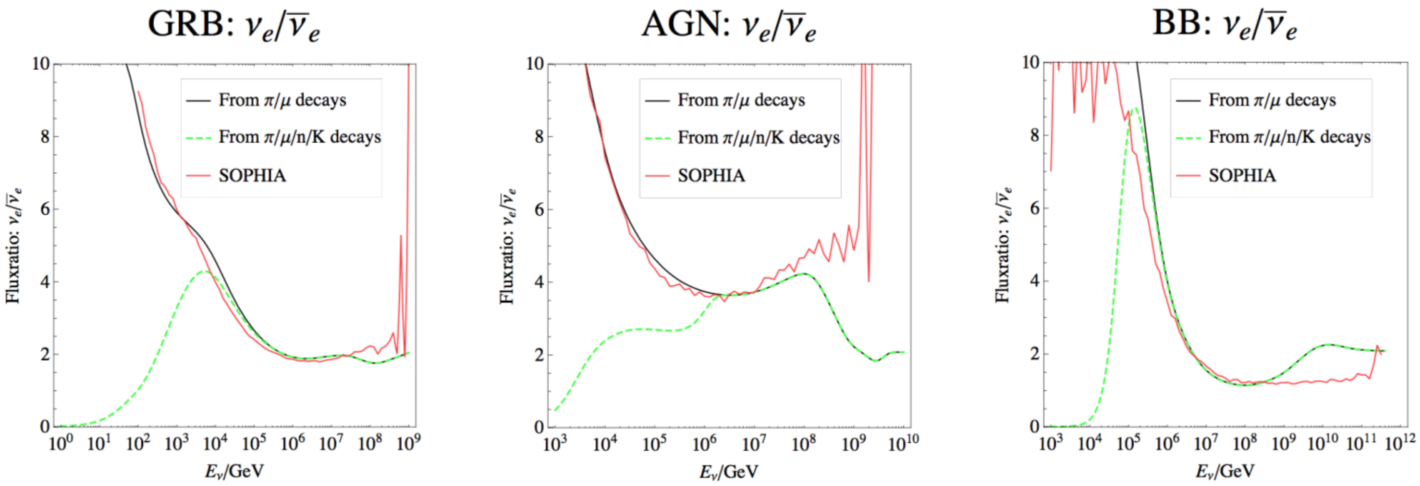
# pp versus p$\gamma$ interactions: commons and differences

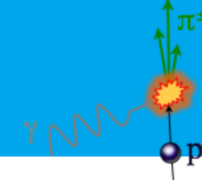
- In pp and p$\gamma$ interactions, the secondary pions take about 20% of the proton energy, the neutrinos about 5% (per flavor)
  ➔ PeV neutrinos must come from 20 PeV (pp/p$\gamma$) to 1 EeV (Fe-p)
- The charged to neutral pion ratio is roughly 50-50 (both pp and p$\gamma$)
- The spectral shape of the neutrinos follows the primary nuclei for pp interactions, for p$\gamma$ it depends on that of the target photons as well
- There are typically (not necessarily) more electron neutrinos than antineutrinos at the source for p$\gamma$ interactions (if Glashow resonance used for discrimination, proposed in **Anchordoqui et al, hep-ph/0410003; Barger et al, 1407.3255 etc**!)




$\Delta$-resonance prediction: infinity!

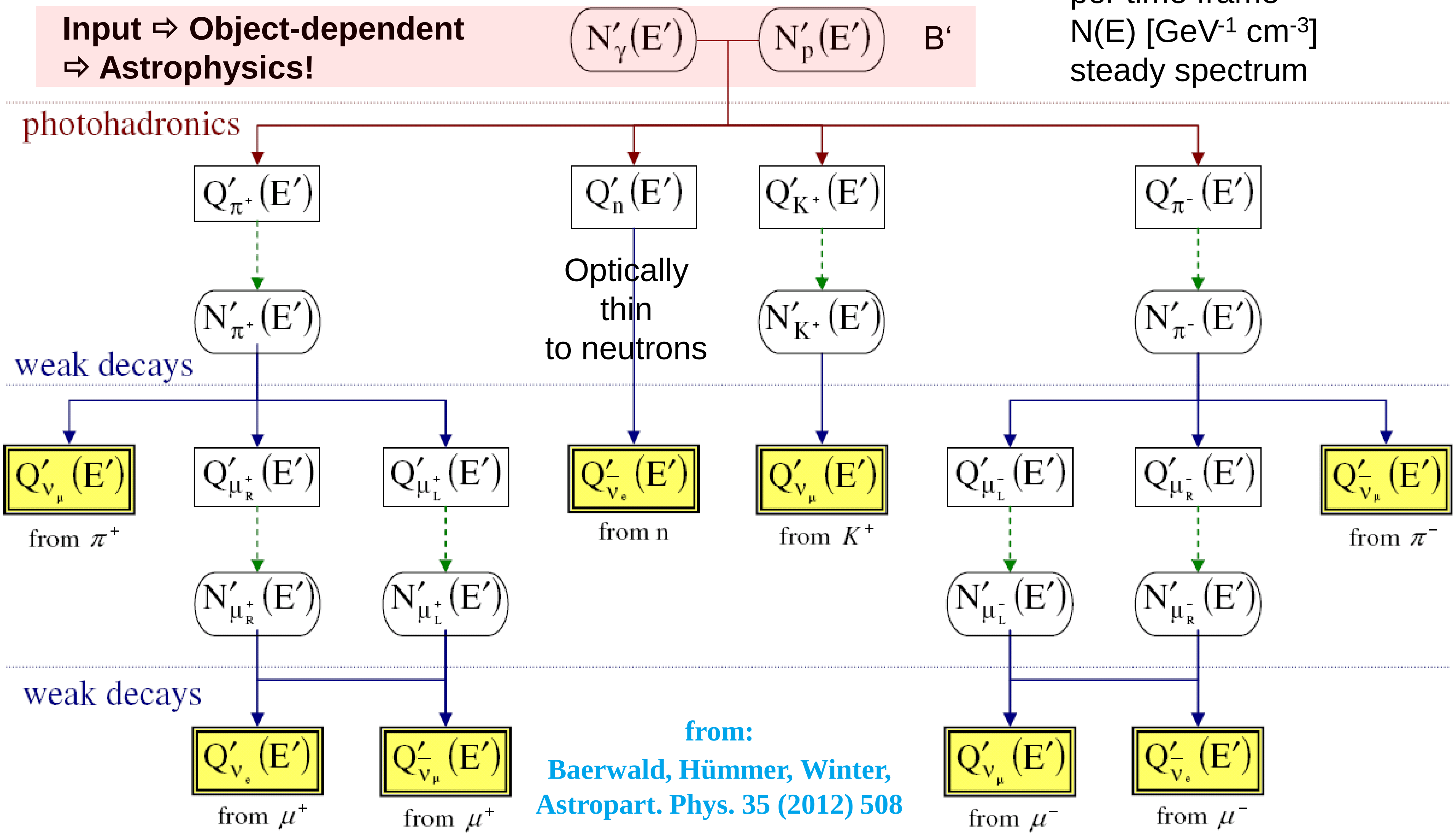
**Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630**

# Neutrino production (example: pγ)




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




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

# Kinetic equations (steady state)

- Treat energy losses/escape in continuous limit:

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

| Injection | Energy losses | Escape |
|---|---|---|

$b(E) = -E\, t^{-1}_{\mathrm{loss}}$
$Q(E,t)$ [$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}$] injection per time frame (e. g. from acc. zone)
$N(E,t)$ [$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}$] particle spectrum including spectral effects

NB: Need N(E) to compute particle interactions

- Simple case: No energy losses b=0: $N(E) = Q(E)\, t_{\mathrm{esc}}$
- Special cases:
  - $t_{esc}$ ~ R/c (free-streaming, aka "leaky box")
  - $t_{esc} \sim E^{-\alpha}$ . Consequence: $N(E) \sim Q_{inj}(E)\, E^{-\alpha}$, Escape: $Q_{esc}(E) = N(E)/t_{esc} \sim Q_{inj}$

    (Neutrino spectrum from N(E) can have a break which is not present in escaping primaries $Q_{esc}(E)$)

# In the presence of strong B: Secondary cooling

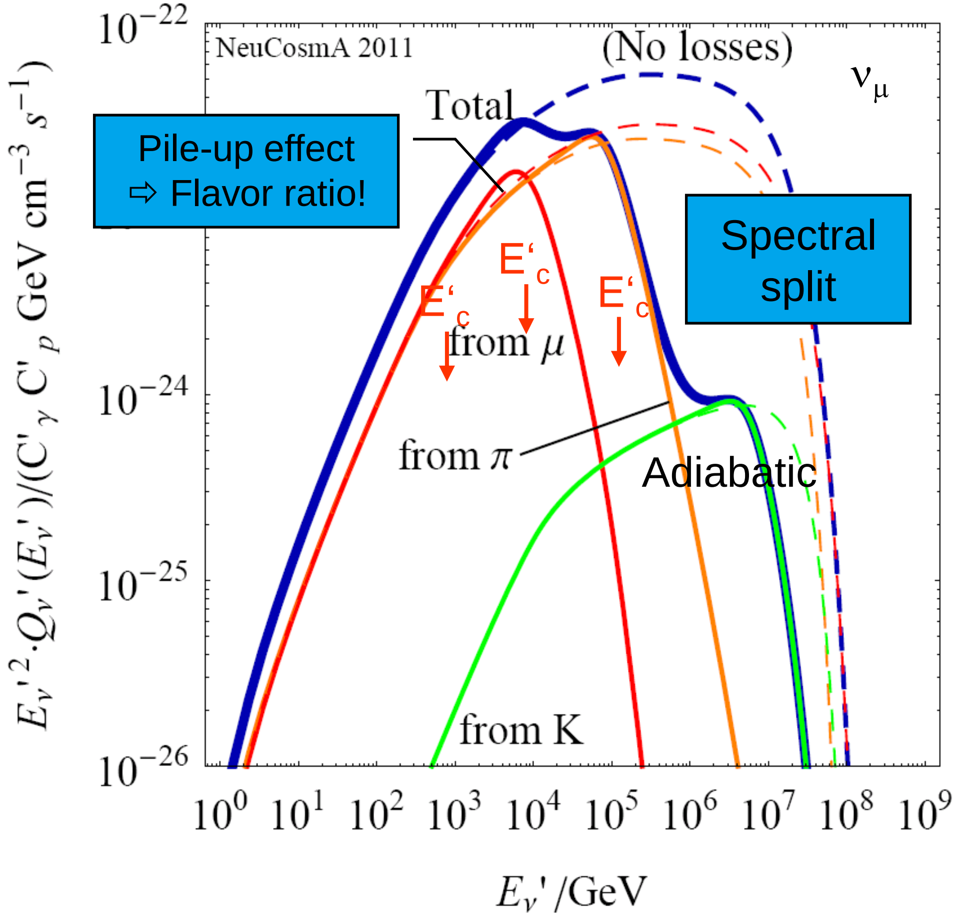
Example: GRB

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, $\tau_0$), and **B'**
- Leads to characteristic flavor composition and shape
- Very robust prediction for sources? [i.e. any additional radiation processes mainly affecting the primaries will not affect the flavor composition]

Decay/cooling: charged μ, π, K

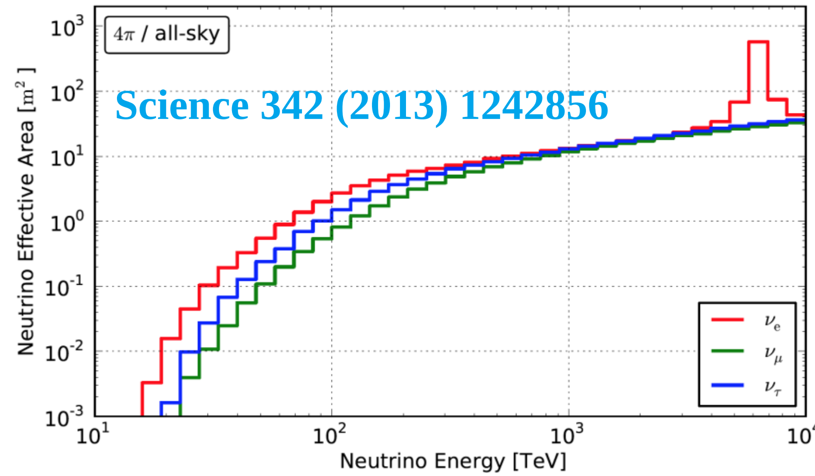


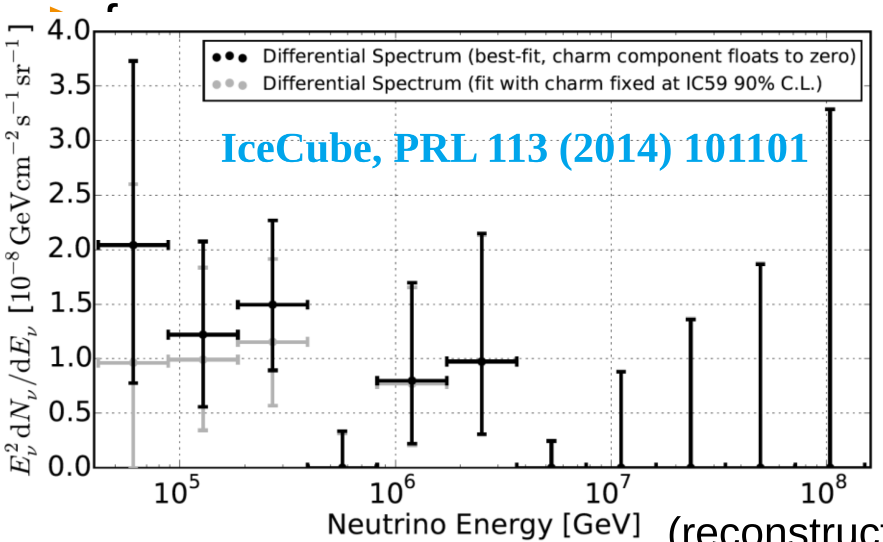

**Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007**

# Neutrino propagation and detector response

- Neutrino propagation: Flavor mixing $P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$
- Event rate computation: $N = \int_{E_{\min}}^{E_{\max}} \phi_\nu(E)\, A_{\text{eff}}(E)\, t_{\text{obs}}\, [d\Omega]\, dE$

  ($A_{\text{eff}}$ typically includes analysis cuts; $\phi$ in units of $\text{cm}^{-2}\ \text{s}^{-1}\ \text{GeV}^{-1}\ [\text{sr}^{-1}]$)
- A complication for interpretations: neutrino energy reconstruction (incident energy ➔ deposited energy ➔ reconstructed energy)



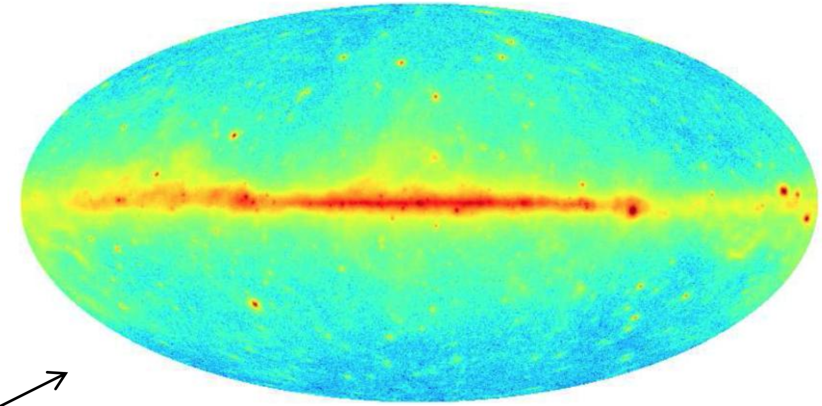

(reconstructed)

- Reconstructed distribution does not exhibit statistically signficant gap, cutoff seems to be more evident

# On the signal interpretation

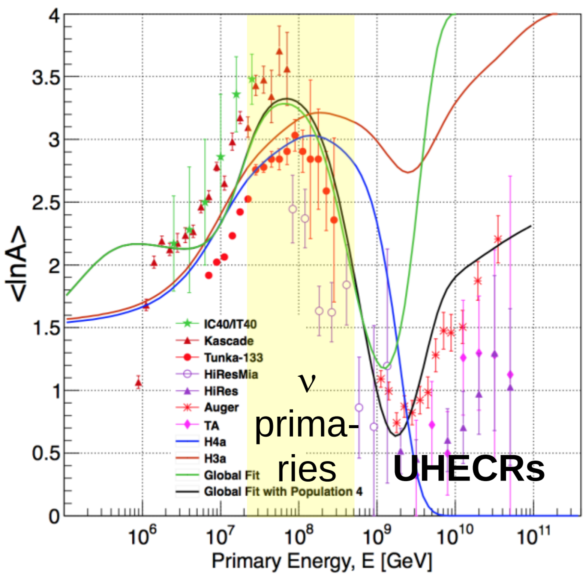
# Galactic “guaranteed” contribution?

- Cosmic rays interact with hydrogen in our Galaxy
- Cosmic ray density from local observations; extension of production region can be inferred from diffuse gamma-ray observations (very narrow around Galactic plane)

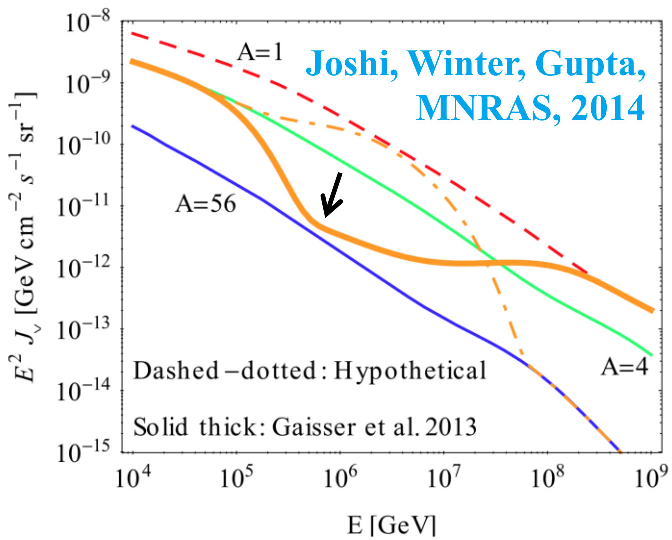


Fermi-LAT, ApJ 750 (2012) 3
(see also arXiv:1410.3696)

- Complication: the CR composition changes non-trivially in relevant range:




Gaisser, Stanev, Tilav, 2013




(all-sky averaged prediction)

O(0.1-1) event plausible to satisfy $n_H$, composition and $\gamma$-ray constraints



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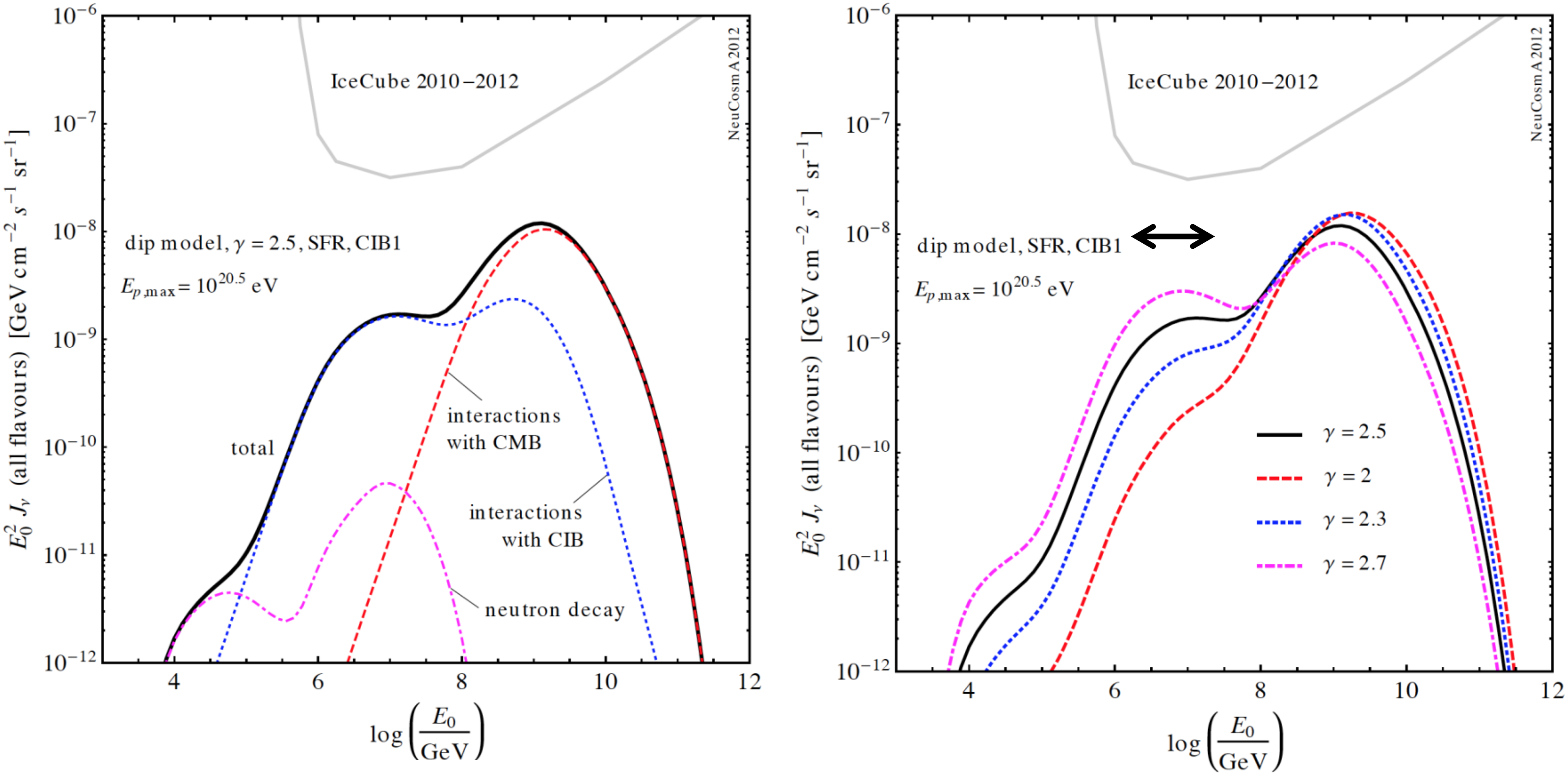
# Cosmogenic (from CR propagation) origin?

- PeV neutrinos from cosmic infrared background interactions of UHECRs (here: protons); depends somewhat on model (high-z evolution?)
- Even if protons, soft spectra etc, difficult to reach required flux




**Figures: Bustamante, Evoli, Sigl, WW, in prep. See also Roulet, Sigl, van Vliet, Mollerach, JCAP 1301 (2013) 028**

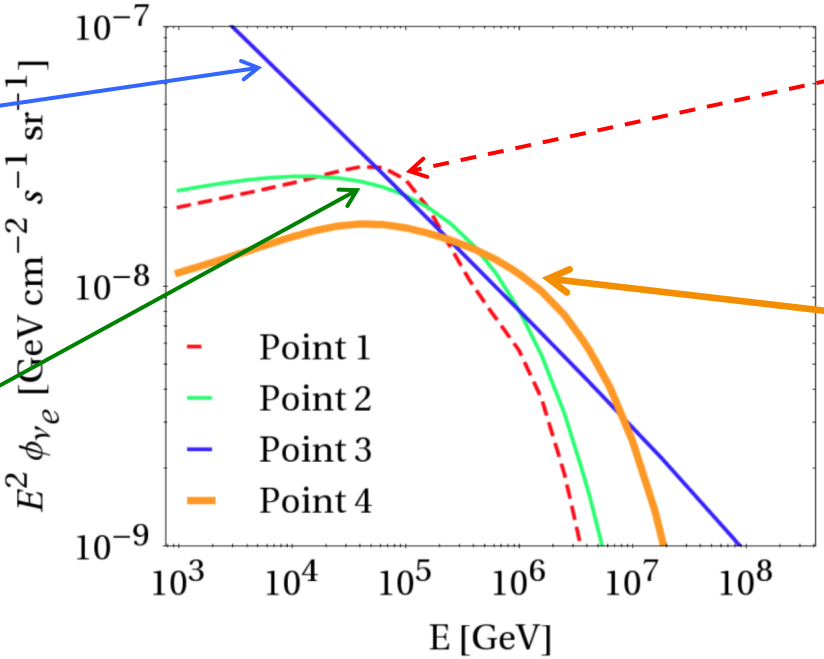
# Conceptual insights? Neutrinos from Ap interactions
## … in cosmologically distr. sources (star formation rate evolution)

- Simplest model, as the neutrino spectrum follows that of the primaries
- Possible **fits** to data:

| Parameter | Description | Unit |
|---|---|---|
| $\alpha$ | Spectral index of primary nuclei | none |
| $E_{\max}$ | Maximal energy | GeV |
| $B$ | Magnetic field | Gauss (G) |
| $A$ | Mass number | none |

Protons, $\alpha$=2.5
[Problem: Fermi diffuse $\gamma$-ray bound **Murase, Ahlers, Lacki, PRD 2013**]

Protons
$\alpha$=2
$E_{max}$=$10^{7.5}$ GeV




Protons
$\alpha$=2
B ~ $10^4$ G
(magnetic field effects on sec. pions, muons, kaons)

Nuclei
$\alpha$=2, $E_{max}$=$10^{10.1}$ GeV
Composition *at source*

$$A(E) = \max\left(1,\, 56 \times \left(\frac{E}{E_{\max}}\right)^{\beta}\right)$$

with $\beta$=0.4

**WW, arXiv:1407.7536 (PRD, in print); see also 1410.1749**

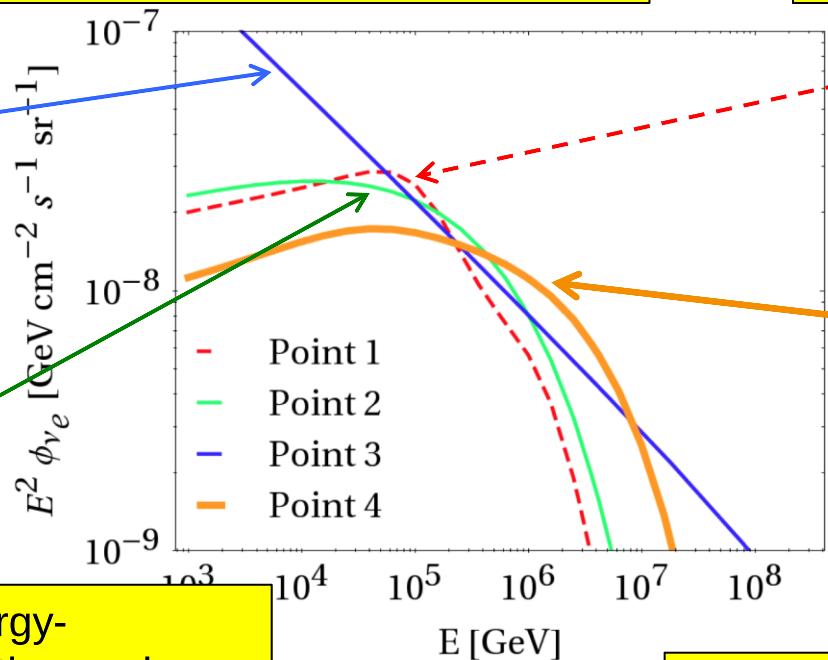
# Connection to ultra-high energy cosmic rays (UHECR)?

Yes, but: Energy input per decade very different in neutrino-relevant and UHECR energy ranges (Energetics seem to favor $\alpha$~2 – Waxman/Bahcall!)
see e. g. Katz et al, 1311.0287 for generic discussion;
for GRBs specifically: extremely large baryonic loadings implied: Baerwald et al, Astropart. Phys. 62 (2015) 66

Yes, but: Synchrotron losses limit maximal proton energies as well. Need large Doppler factors (e. g. GRBs)

Protons, $\alpha$=2.5
[Problem: Fermi diffuse $\gamma$-ray bound
Murase, Ahlers, Lacki, PRD 2013]

Protons
$\alpha$=2
$E_{max}=10^{7.5}$ GeV




Protons
$\alpha$=2
B ~ $10^4$ G

Nuclei
$\alpha$=2, $E_{max}=10^{10.1}$ GeV
Composition *at source*

$$A(E) = \max\left(1,\ 56 \times \left(\frac{E}{E_{\max}}\right)^{\beta}\right)$$

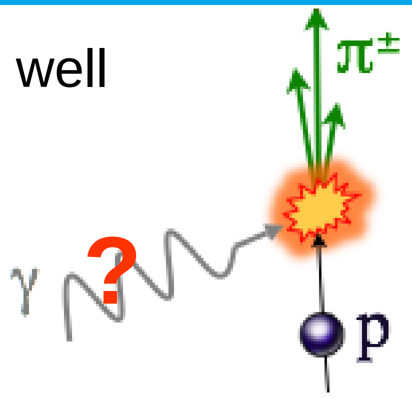
with $\beta$=0.4

Yes, but: Need energy-dependent escape timescale leading to break/cutoff within source (diff. from ejection!)
see e.g. Liu et al, PRD, 2014; arXiv:1310.1263 or starburst galaxies

WW, arXiv:1407.7536 (PRD, in print)

Yes, but: A(E) change somewhat too shallow to match observation; difference source-observation from propagation?

# Neutrinos from pγ interactions




- More freedom, as spectral shape depends on photons as well
  ➔ Strategies to address the large parameter space?
- Target photon field typically:
  - Put in by hand (derived from observed spectrum)
  - Thermal target photon field (e. g. accretion disk)
  - From interplay of radiation processes (synchrotron radiation, Bremsstrahlung, inverse Compton, pair production ...).
- One of simplest self-consistent cases:
  **From synchrotron radiation of co-accelerated electrons (AGN-like model)**
- Requires few model parameters, mainly

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

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

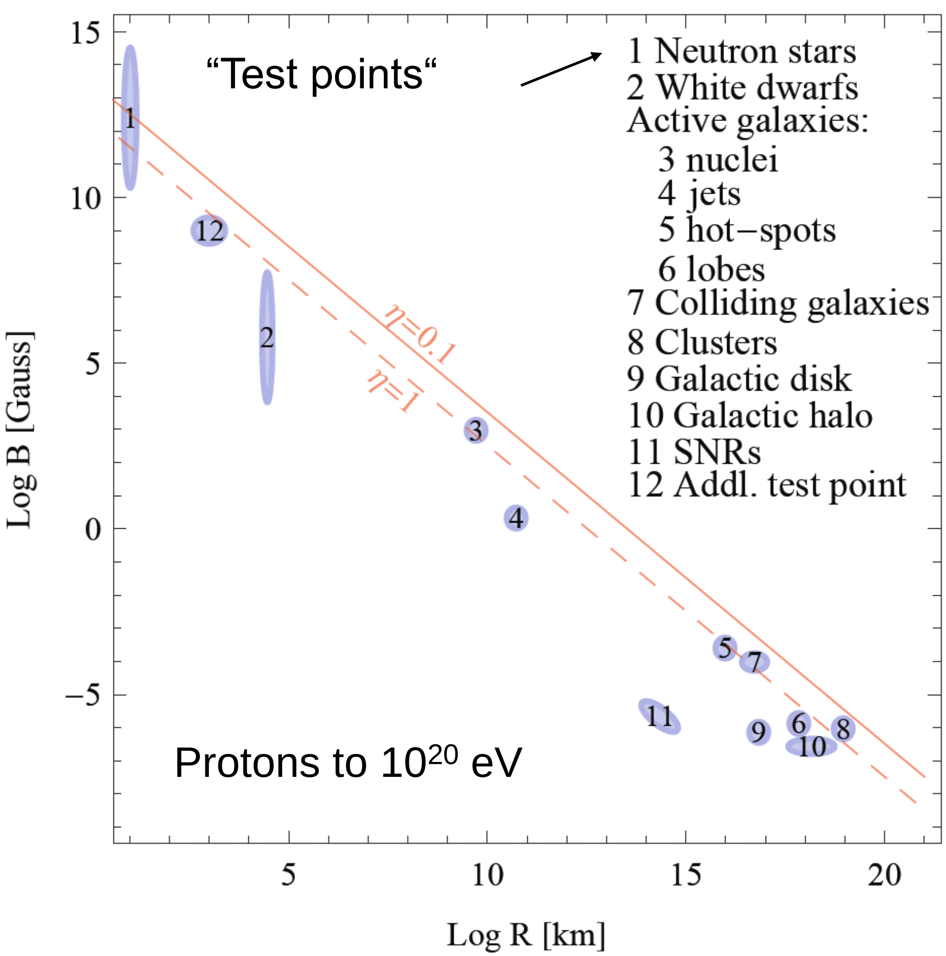
# Parameter space: Hillas plot?

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

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

  (Larmor-Radius < size of source; η: acceleration efficiency) Particles confined to within accelerator!
- Caveat: condition relaxed if source heavily Lorentz-boosted (e.g. GRBs)
- Test points in these figures not to be taken too seriously (large astrophysical uncertainties)

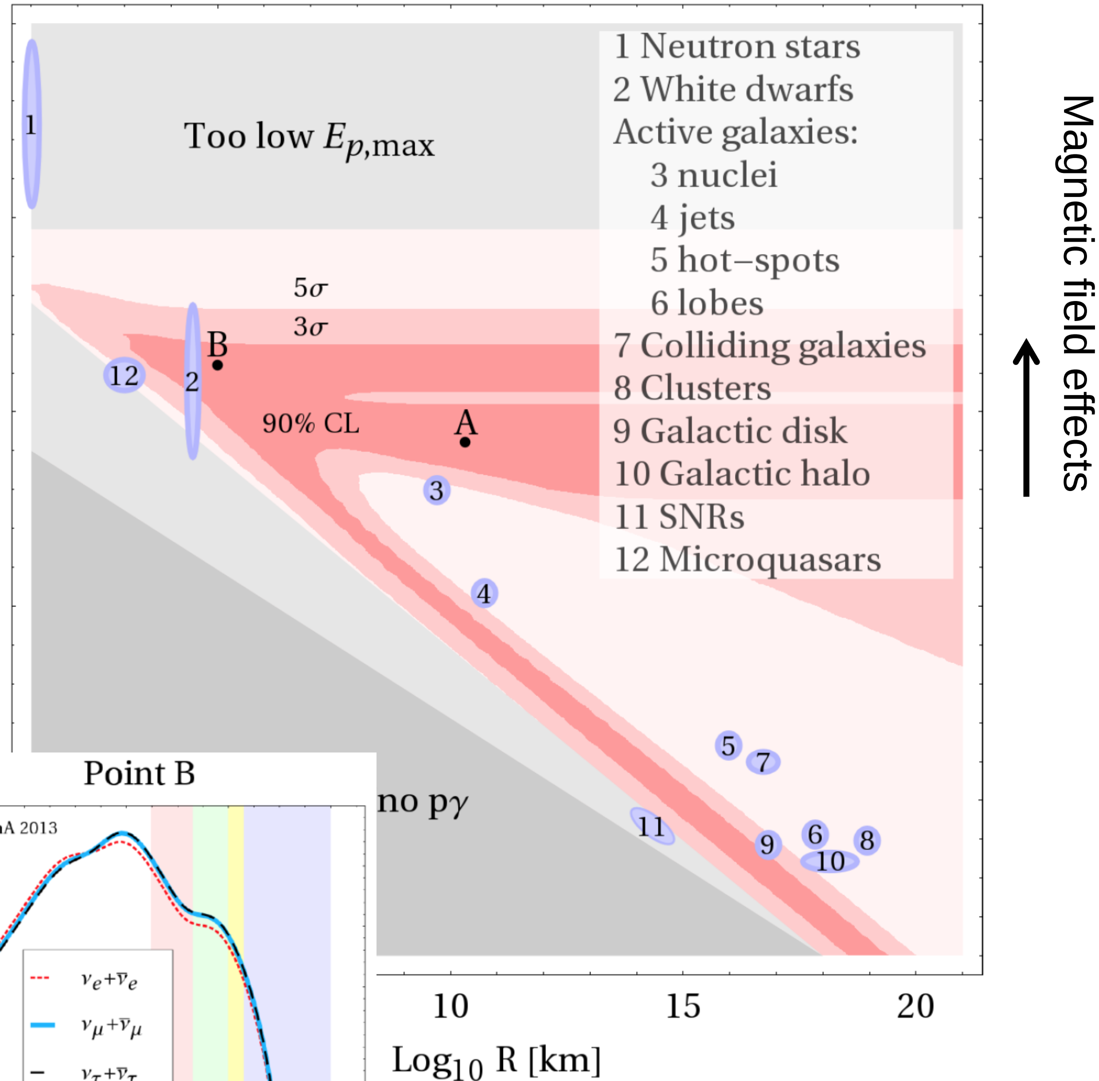
Hillas 1984; version adopted from M. Boratav

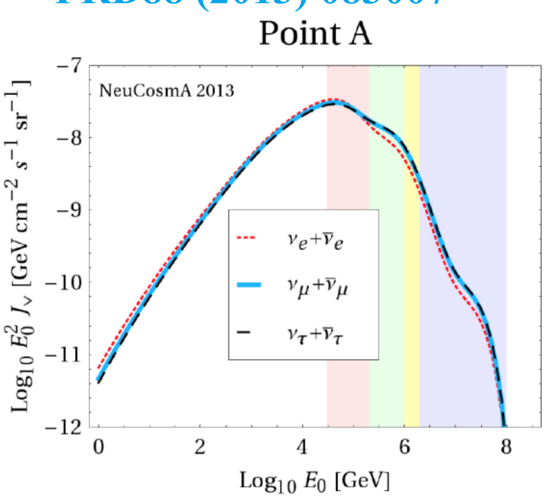


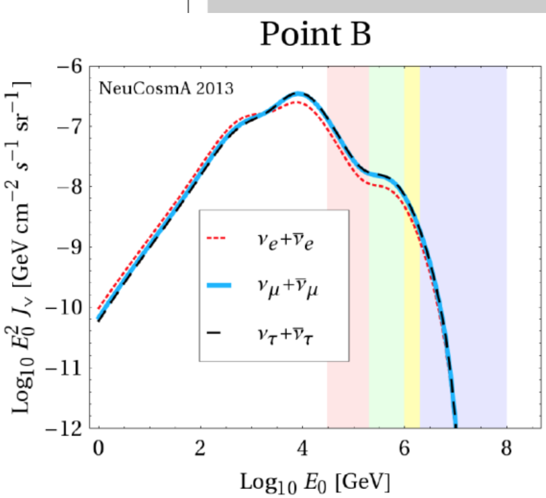
# Parameter space constraints (SFR evolution, pγ model)

- Current data start to constrain parameter space of radiation models
- Again, regions preferred where either maximal proton energy or magnetic field effects lead to cutoff

**WW, arXiv:1307.2793, PRD88 (2013) 083007**



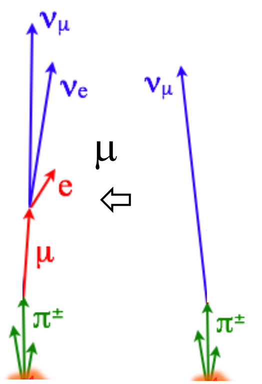
# So, where do the neutrinos come from? (my personal bias)

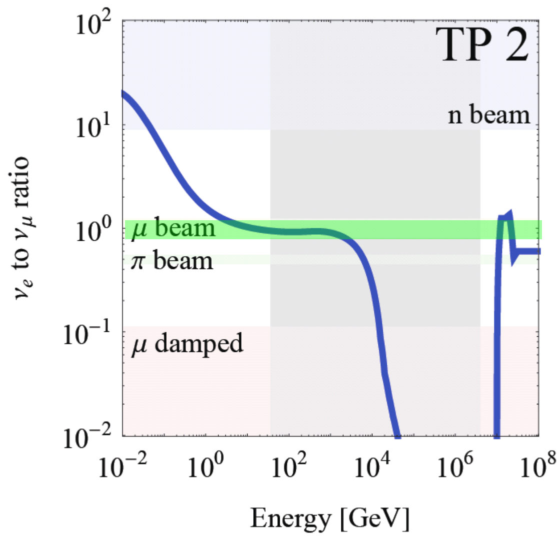
- We have no clue. There are, however, plenty of candidate classes
  - Galactic sources
    + testable by directional correlations (some workarounds in literature …)
    - no evidence, so far; perhaps only a few events
  - Gamma-ray bursts
    + may have enough power, cutoff "natural" from magnetic field effects
    - needs to be a"non-standard" population, as strong bounds on gamma-ray detected GRBs from stacking; low luminosity GRBs?
  - Active Galactic Nuclei
    + wide playground, may have enough power; there is hope for some directional/flaring correlations
    - wide playground; not easy to accommodate a cutoff (unless from primaries)
  - Starburst galaxies, hypernova remnants, … (diffuse flux contributions)
    + good to blame for if not better solution found; cutoff/break expected if energy-dependent escape timescale
    - direct evidence difficult (not easily resolvable)
  - From interactions with photon backgrounds (cosmogenic or nearby populations)
    + kind of expected fluxes (at some level)
    - models which produce IceCube flux require tweaking
    **(see Anchordoqui et al, arXiv:1312.6587 for a review)**
- There are some recent proposals for generic tests, e. g. limit source density from clustering of events
  **(see e. g. Ahlers, Halzen, arXiv:1406.2160)**

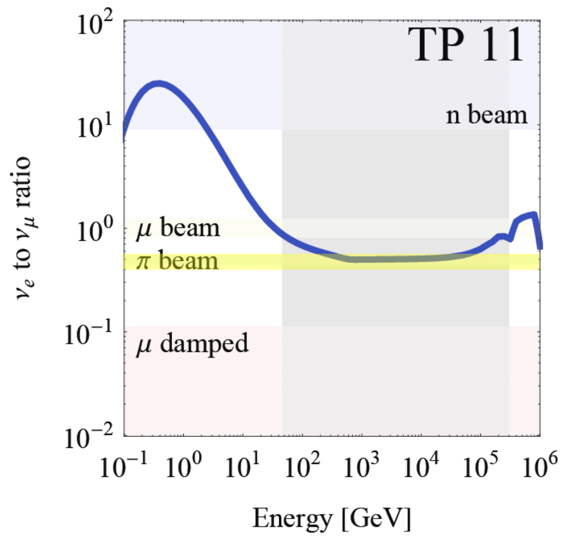
# Future challenges

# The question of flavor:
## Flavor composition is energy-dependent! (earlier pγ model)

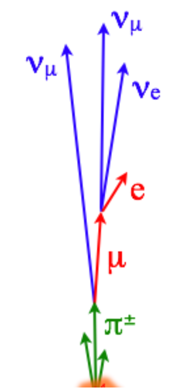
**Muon beam**
- muon damped



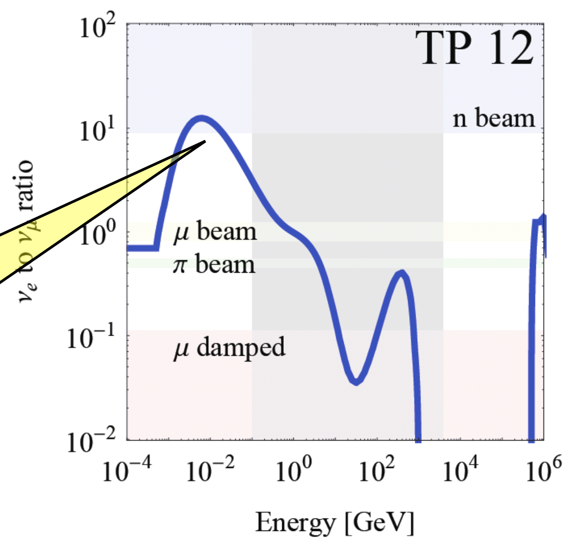



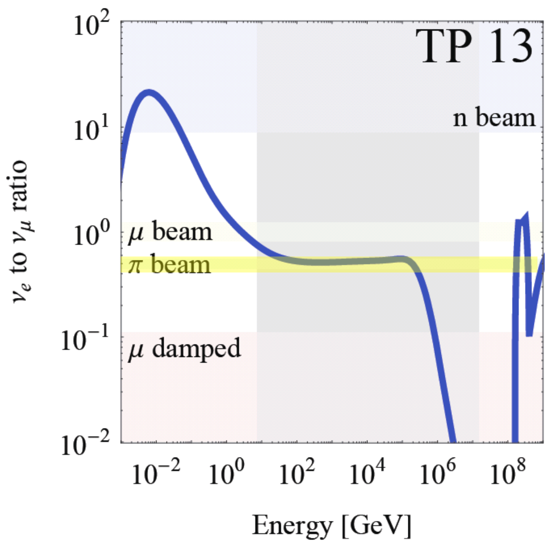

Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



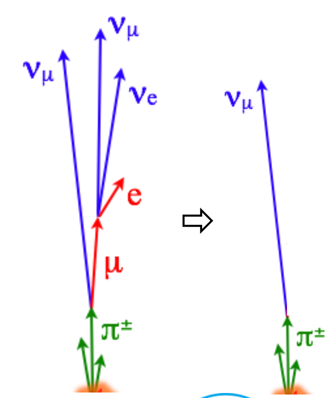

Undefined
(mixed source)

Typically
n beam
for low E
(from pγ)




Pion beam
⇨ muon damped

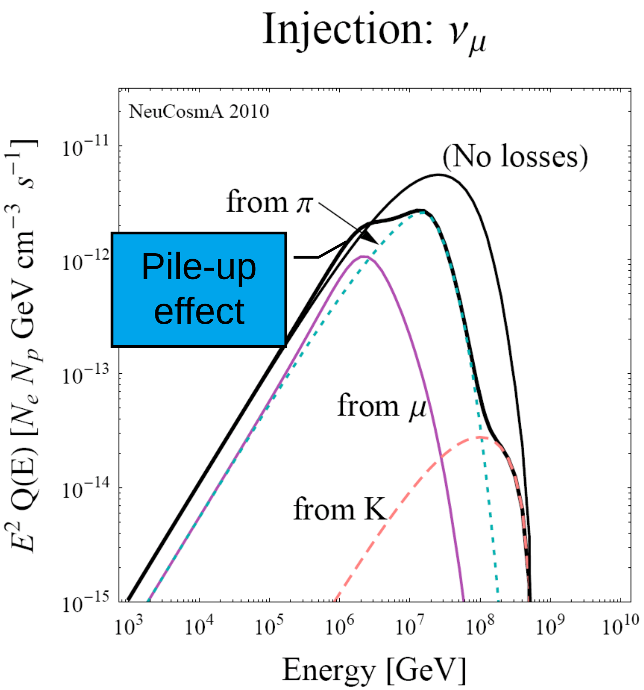




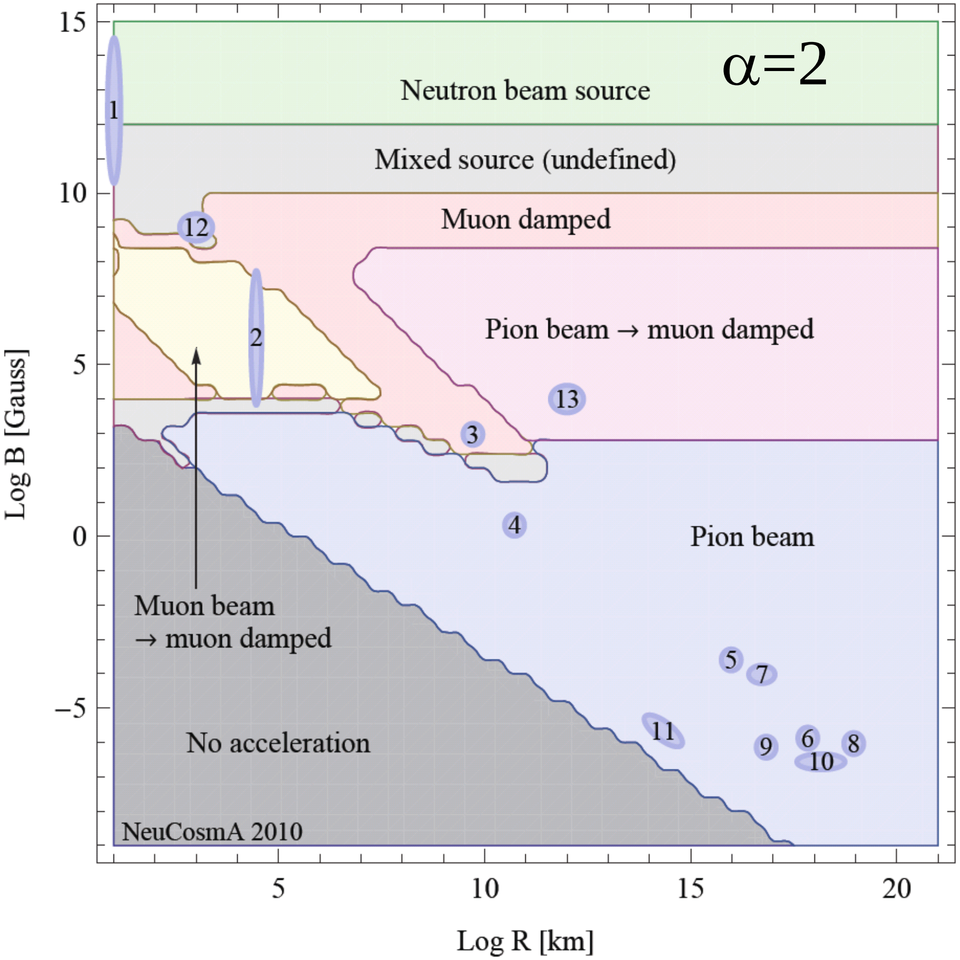

Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

# Flavor composition ... can be predicted

- Pion beam good assumption for sources on galactic scales
- Muon beam sources if muon pile-up:

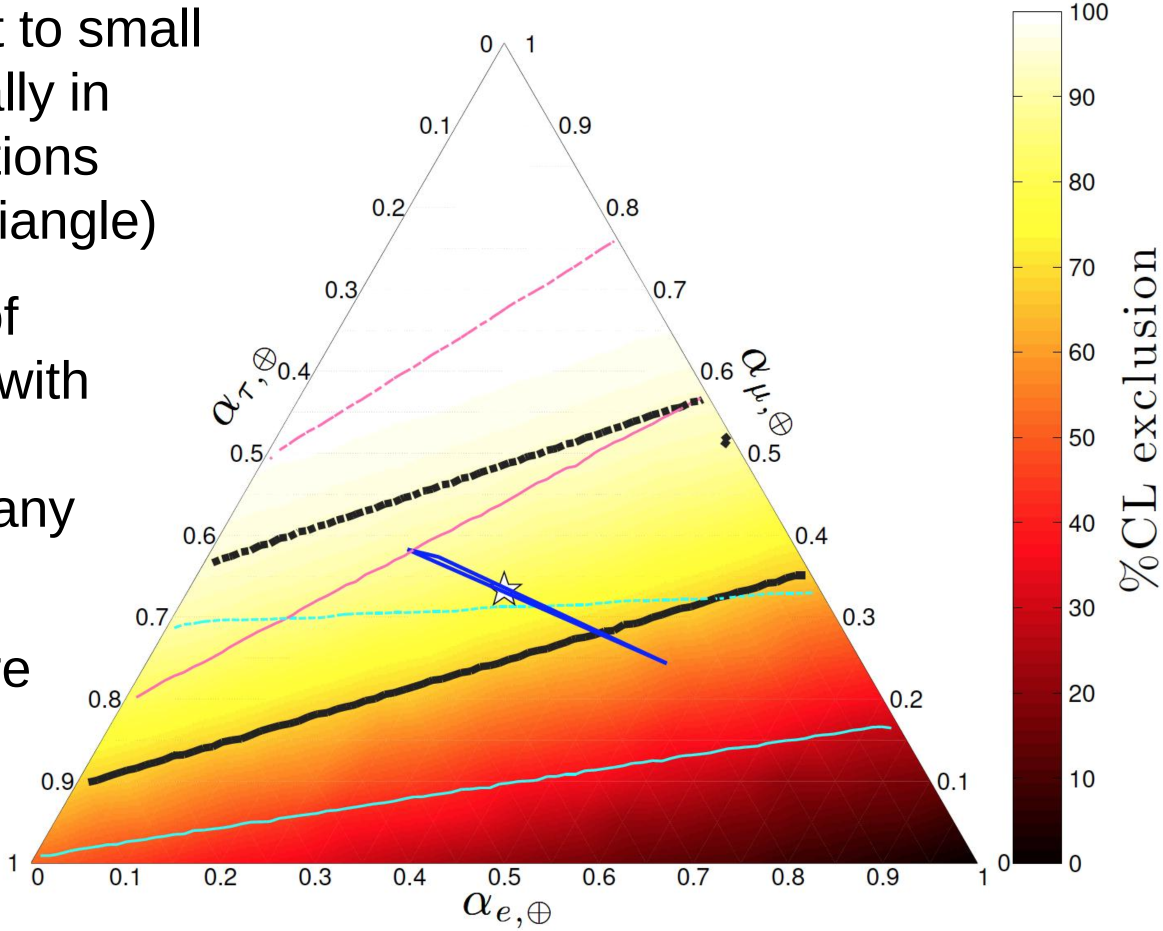



Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205



# Flavor composition … can be measured!

- Statistical significance yet to small to be meaningful, especially in region of standard predictions after flavor mixing (blue triangle)
- There is a slight tension of astrophysical predictions with data, as the background prediction contains too many muon tracks
- Future challenge: measure flavor composition with precision meaningful in blue triangle!

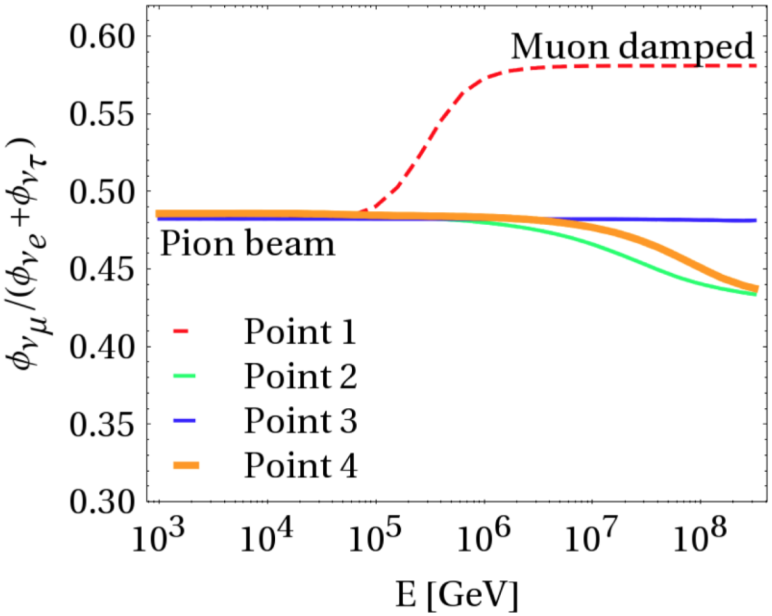


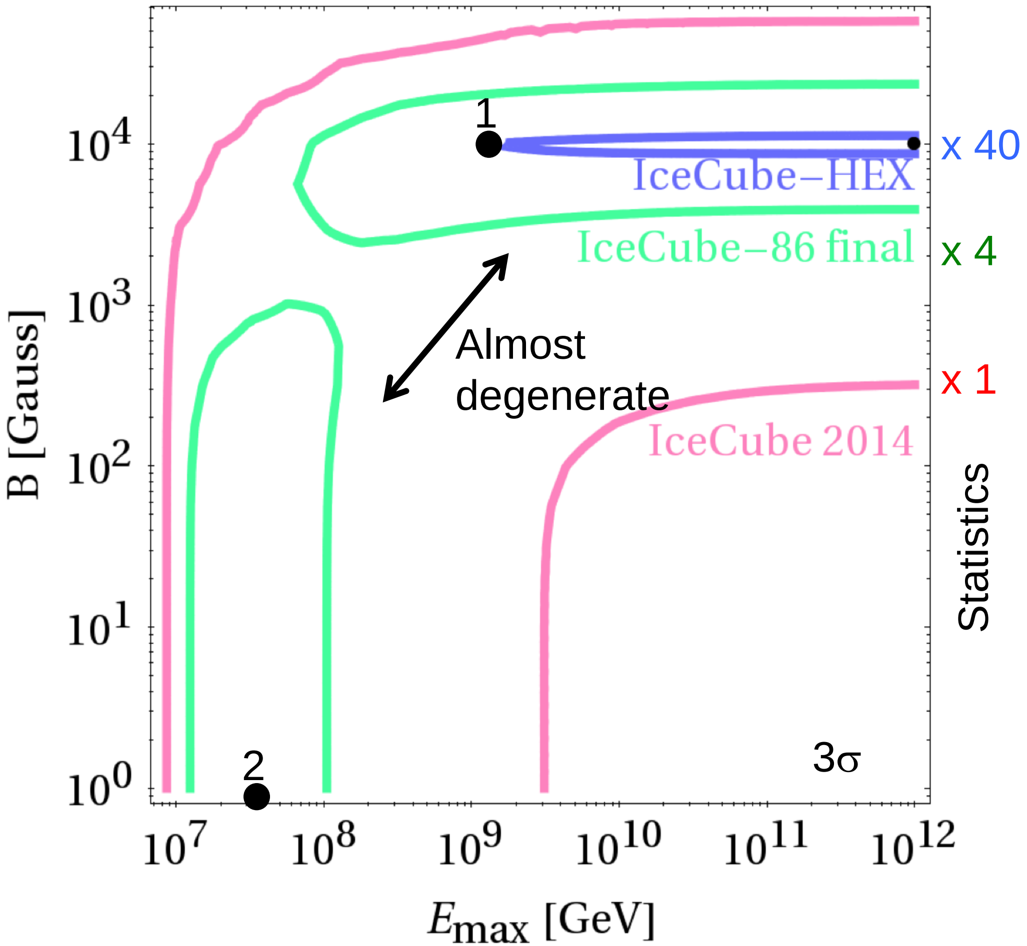

Mena, Palomares-Ruiz, Vincent, PRL 113 (2014) 091103; see also Fu, Ho, Weiler, 1411.1174 for a new related work

Discussion by Sergio Palomares-Ruiz on Oct. 2, 2014 at KITP; watch podcast at **http://online.kitp.ucsb.edu/online/neutrinos14/palomaresruiz/**

# Physics case for high-E extension? Flavor! (Ap model)

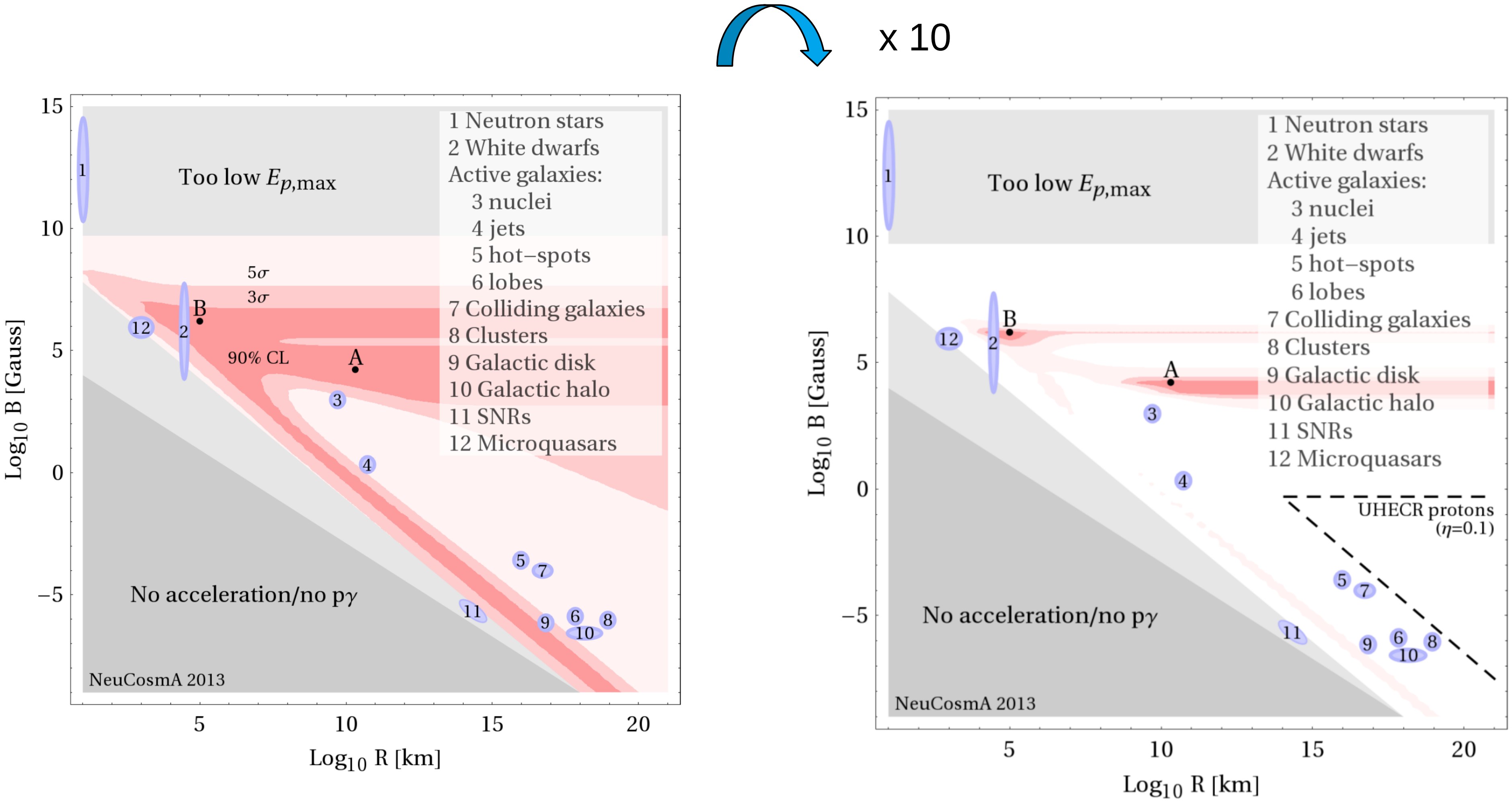
- Cutoff from magnetic field effects degenerate with maximal energy cutoff in terms of spectral shape
- Flavor composition different (see below)
- Need sufficient statistics in cutoff region (about 1 PeV)




WW, arXiv:1407.7536, PRD, in print

# Physics case for high-E extension? Precision! (pγ model)




**WW, arXiv:1307.2793, PRD88 (2013) 083007**

# Summary and conclusions

- Cosmic neutrinos are interesting, as they point towards the sources of the cosmic rays
- Next major qualitative step: resolve the sources of the neutrinos; perhaps neutrino astronomy can do better than cosmic ray observations?
- If not, we have to rely on conceptual arguments, which require the statistics of an high-energy extension:
  - Spectral shape
  - Flavor composition
  - Anisotropies
  - Multiplets, …
- Several constraints come from gamma-ray and cosmic ray observations; *theory* needed to draw a self-consistent multi-messenger picture
- Connection to UHECRs requires extrapolation over several orders of magnitude in energy, and composition; **source modeling in presence of heavier nuclei one of future key issues for CR-neutrino theory**