High-energetic cosmic neutrinos, and the test of fundamental physics

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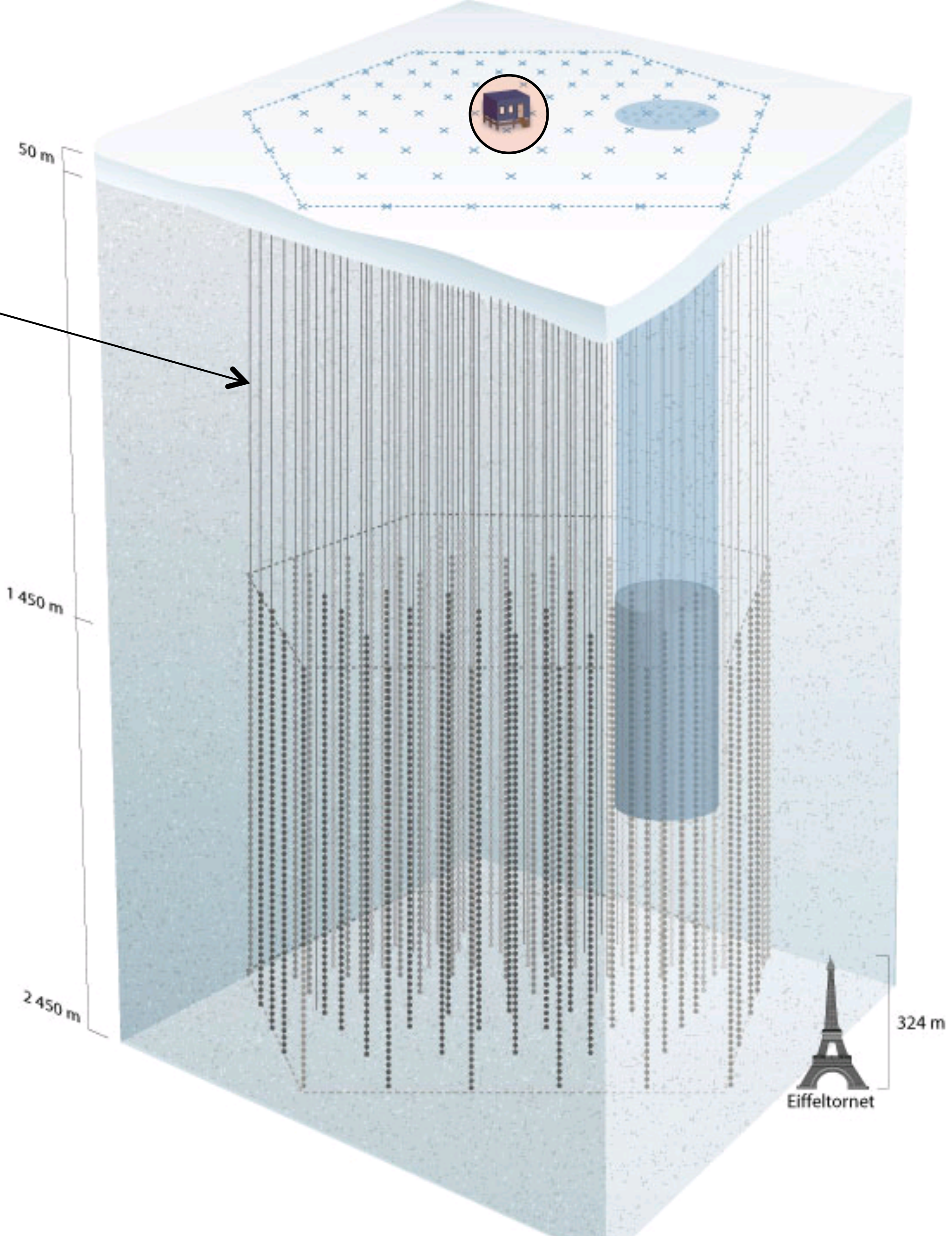
- Introduction
- Particle astrophysics of neutrino sources
- Where do the observed cosmic neutrinos come from?
- Fundamental physics tests with cosmic neutrinos:
  - Flavor composition
  - Propagation effects over cosmological distances
- Conclusions

IceCube neutrino observatory at the South Pole

- Target material: ~1 km^3 of Antarctic ice

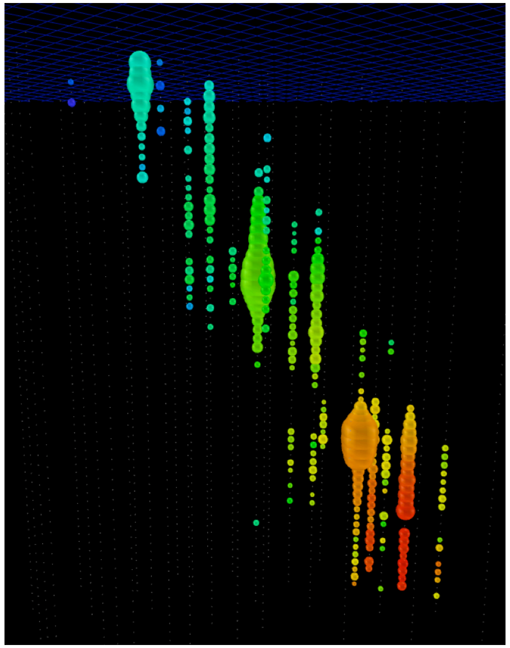


Source: IceCube

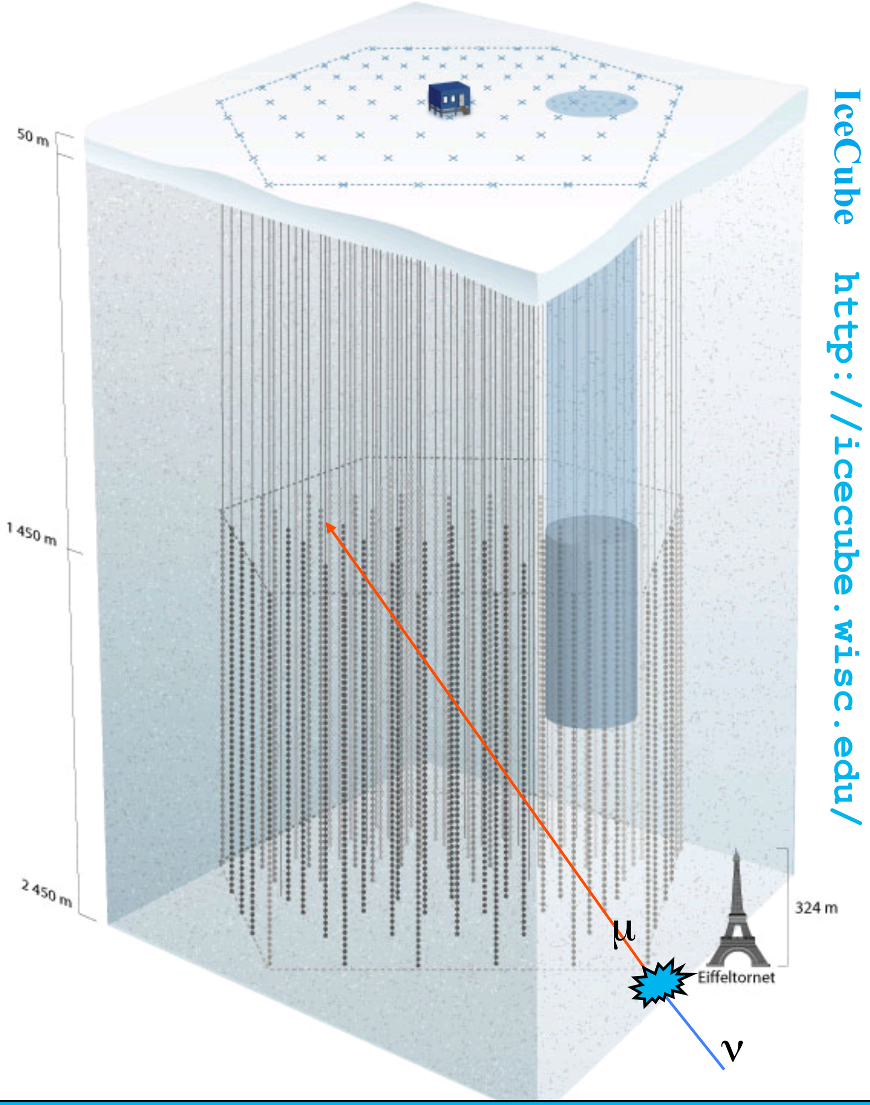
IceCube: Event topologies?

Muon track:

- From ν_μ (mostly)

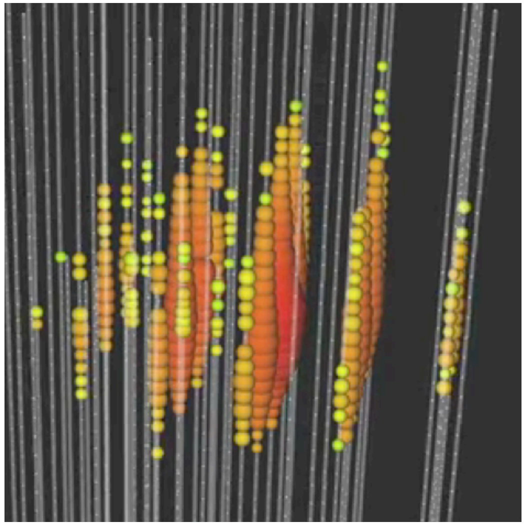


Better directional info



Cascade (shower):

- From ν_e
- From ν_τ
- [From ν_e, ν_μ, ν_τ neutral current interactions]



Better energy info

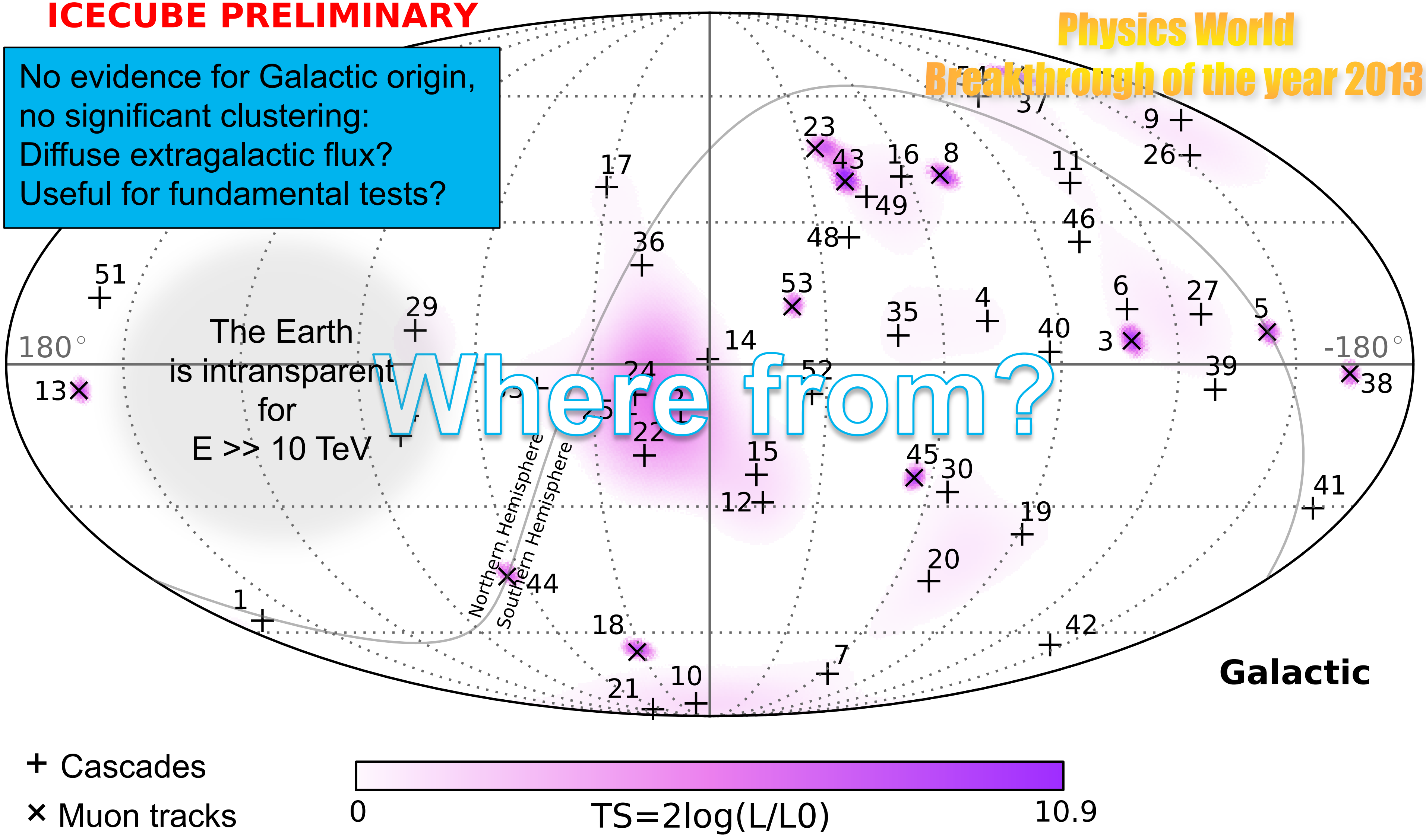
The ratio between muon tracks and showers ~ $\nu_\mu/(\nu_e+\nu_\tau)$, roughly

2015: 54 high energy cosmic neutrinos

ICECUBE PRELIMINARY

No evidence for Galactic origin,
no significant clustering:
Diffuse extragalactic flux?
Useful for fundamental tests?

Physics World Breakthrough of the year 2013

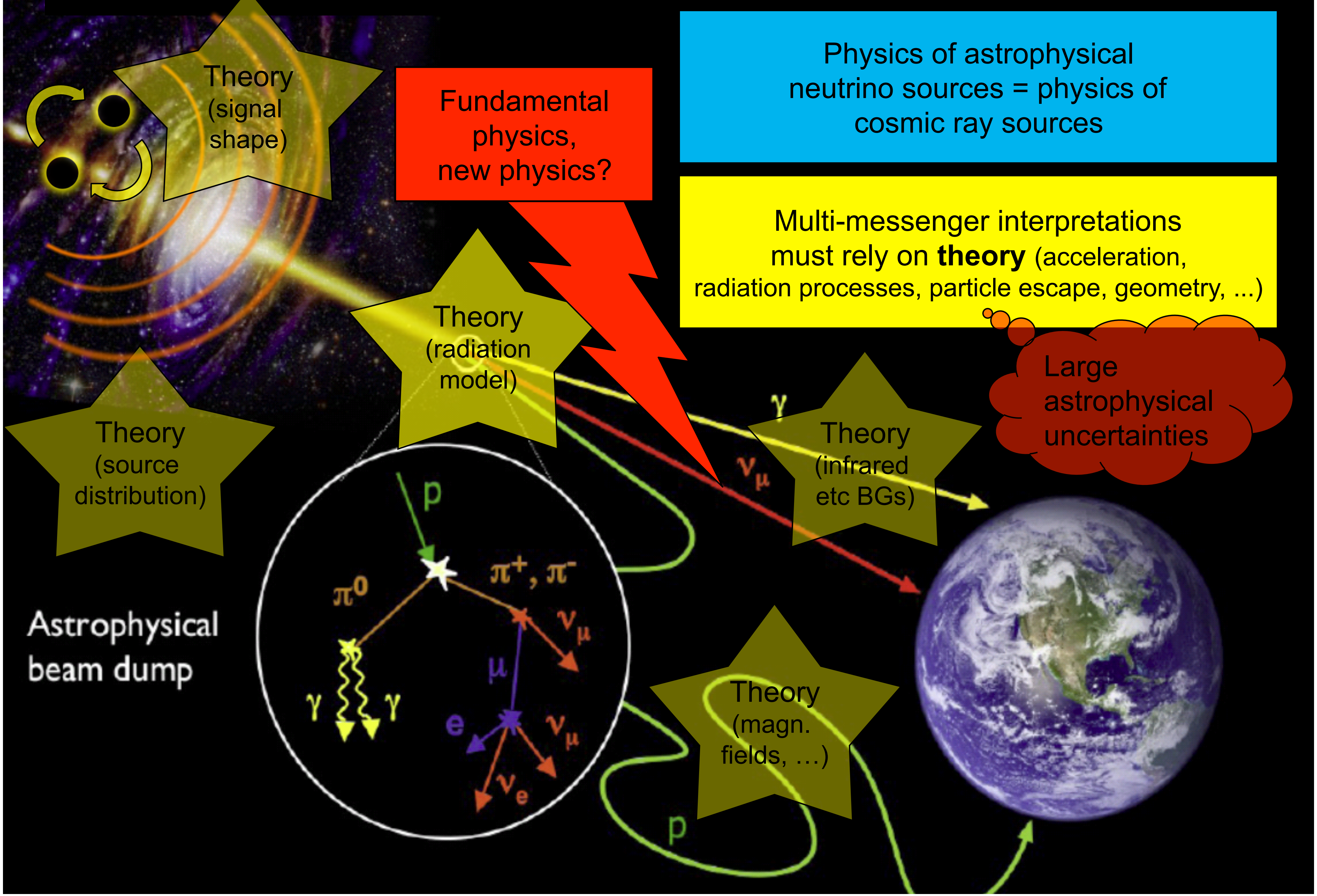


The Earth
is intransparent
for
E >> 10 TeV

Where from?

IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); Halzen at WIN 2015

The universe in multiple messengers ... a theory challenge



Physics of astrophysical neutrino sources = physics of cosmic ray sources

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

Fundamental physics, new physics?

Large astrophysical uncertainties

Theory (signal shape)

Theory (radiation model)

Theory (source distribution)

Theory (infrared etc BGs)

Theory (magn. fields, …)

A simple toy model for the source

If neutrons can escape:
Source of cosmic rays

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

Neutrinos produced in
ratio (ν_e:ν_μ:ν_τ)=(1:2:0)

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

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

Delta resonance approximation:

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

Cosmic messengers

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

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

(Same process during propagation of cosmic rays in CMB: “cosmogenic neutrinos”)

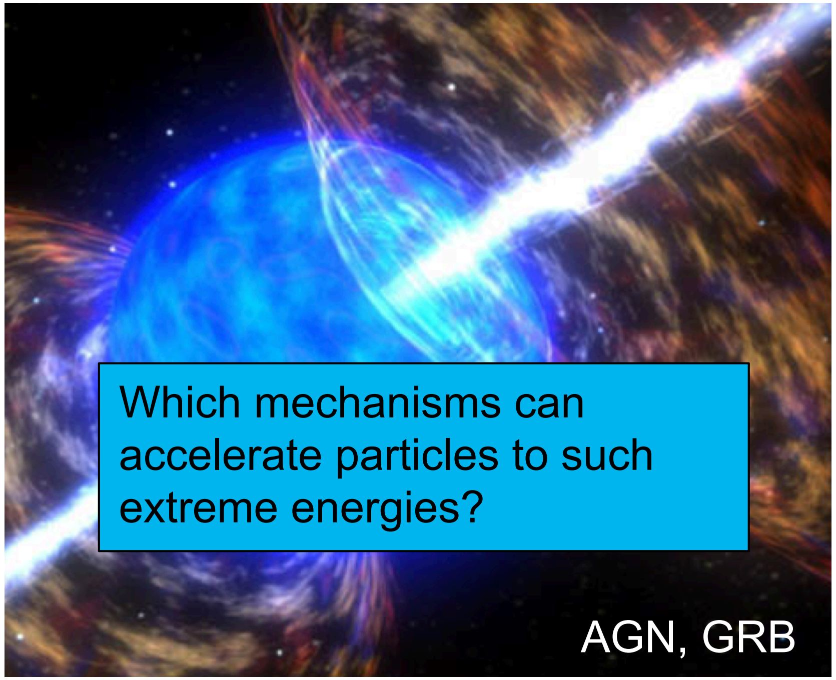
Particle astrophysics of neutrino sources

Cosmic vs. terrestrial particle accelerators

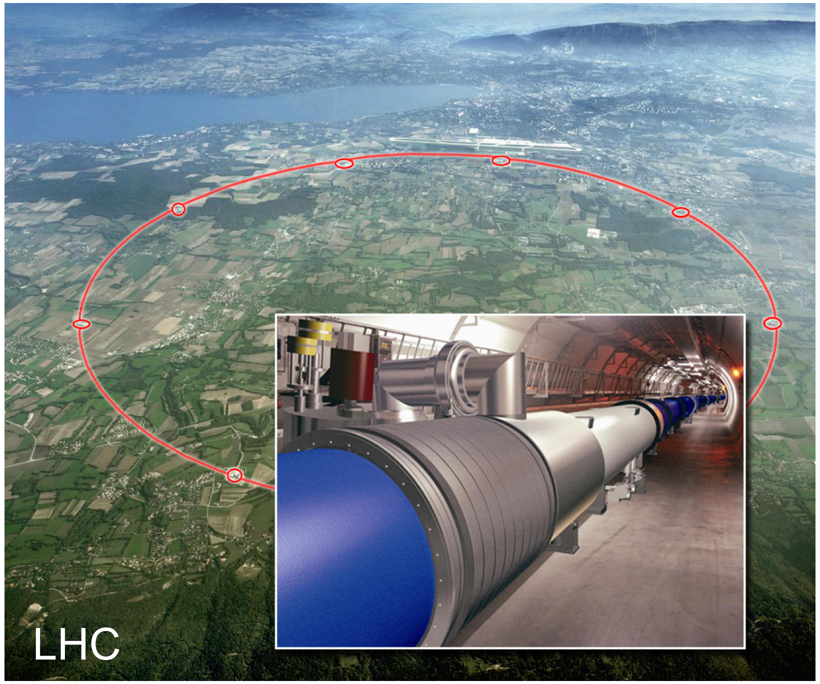
Lorentz force = centrifugal force ➔ $E_{max} \sim q\,B\,R$

- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km



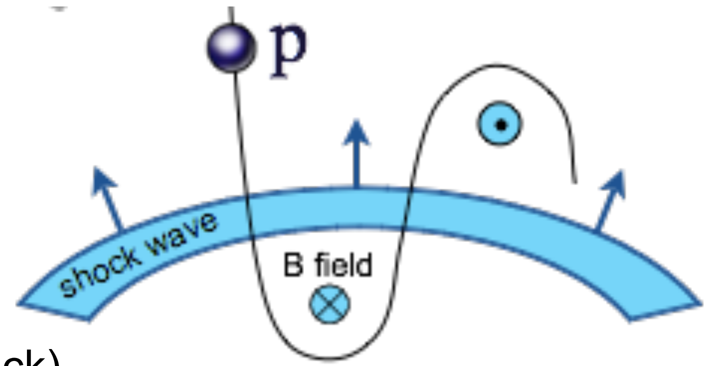
Which mechanisms can accelerate particles to such extreme energies?



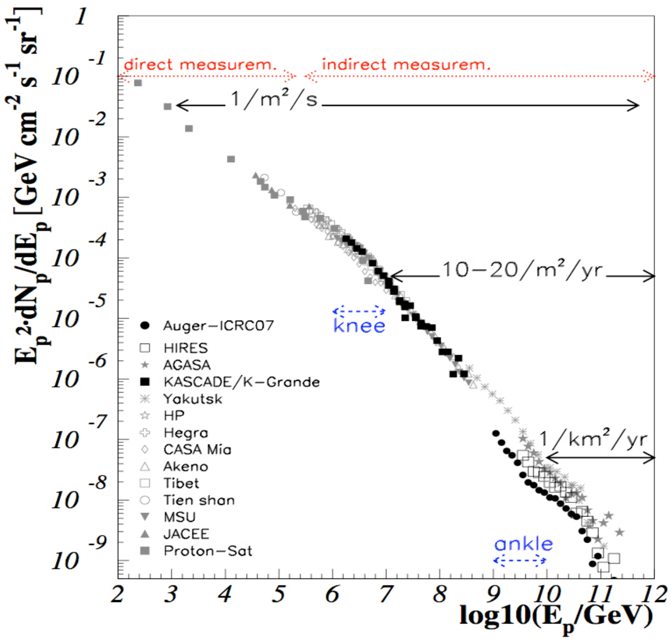
Acceleration of primaries (protons, nuclei)

Example: Fermi shock acceleration

- Fractional energy gain per cycle: η
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{esc}}{\ln \eta}-1}$
- $\ln P_{esc}/\ln \eta \sim -1$ (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical “textbook“ spectrum

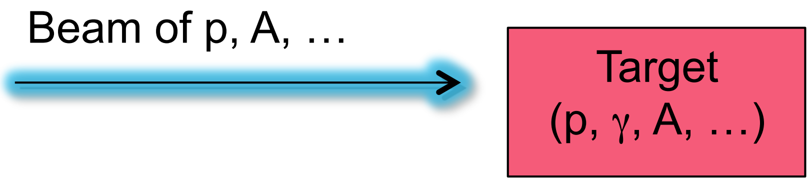


- Although theory of acceleration at relativistic shocks challenging, we **do observe** power law spectra in Nature →
- For neutrino production: adopt pragmatic point of view! *(we know that it works, somehow ...)*



Secondary production: Particle physics 101

- Beam dump picture (particle physics)

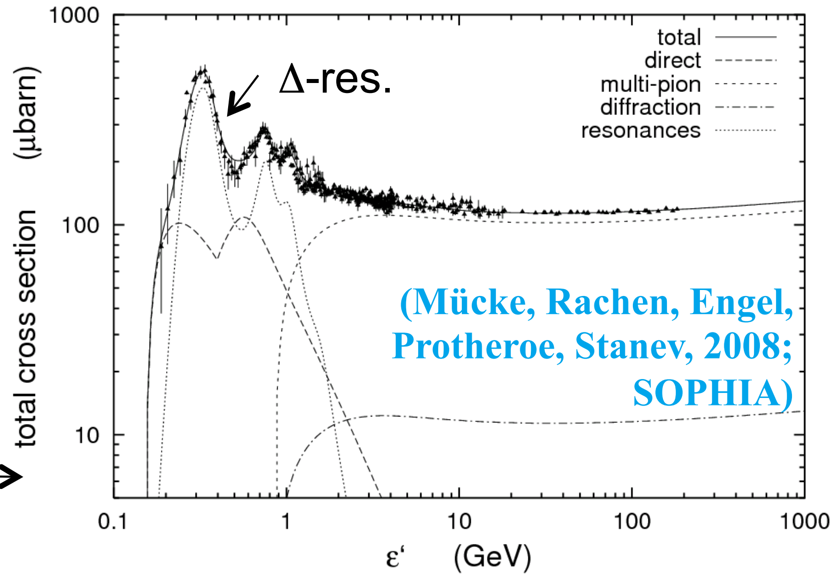

Beam of p, A, …

Target

(p, γ, A, …)

- Interaction rate $\Gamma \sim c\ \ N\ [\mathrm{cm}^{-3}]\ \ \sigma\ [\mathrm{cm}^2]$

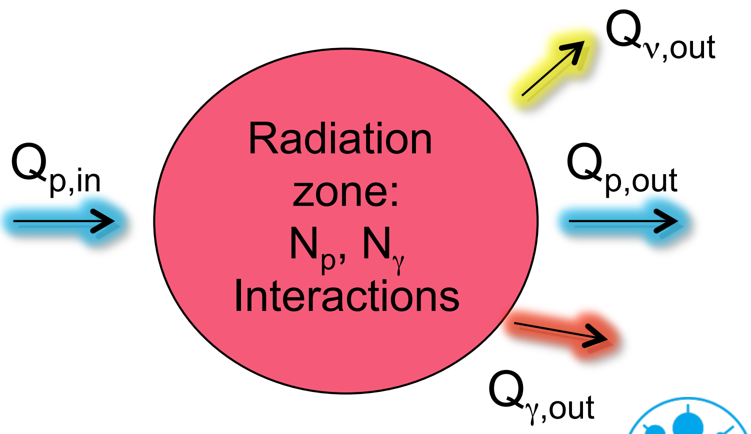
Target density (e.g. N_γ) critical for ν production!



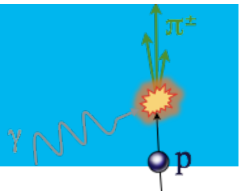
(Mücke, Rachen, Engel, Protheroe, Stanev, 2008; SOPHIA)

(Photon energy in nucleon rest frame)

- Astrophysical challenges:
  - Feedback between beam and target (e.g. photons from π^0 decays); need self-consistent description called **radiation model**
  - *What you see is*, in general, **not** *what you get* in the source

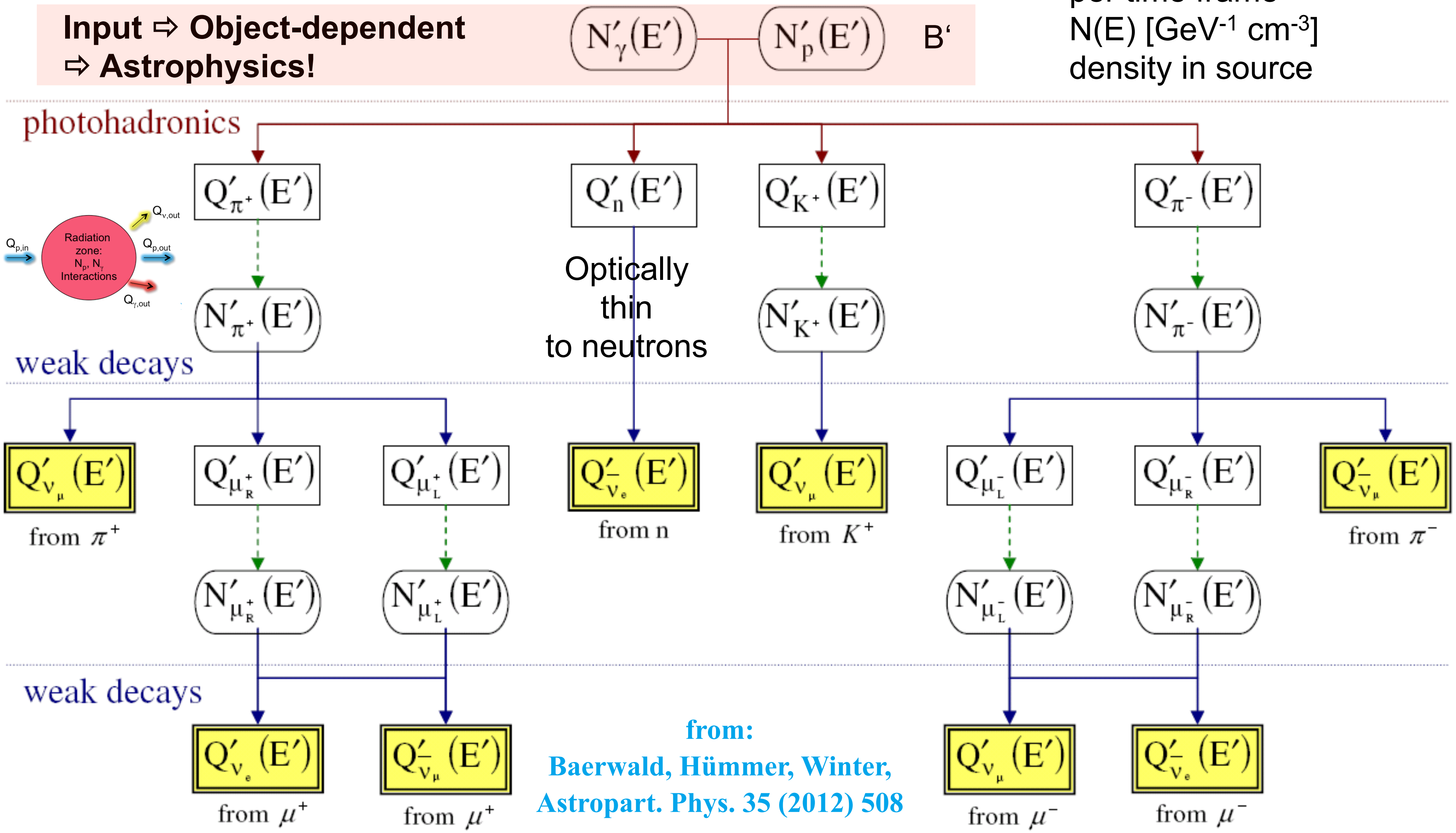


Neutrino production (example: pγ interactions)



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}]
density in source



Input ⇨ Object-dependent
⇨ Astrophysics!

$N'_\gamma(E')$ $N'_p(E')$ B‘

photohadronics

$Q'_{\pi^+}(E')$ $Q'_n(E')$ $Q'_{K^+}(E')$ $Q'_{\pi^-}(E')$

$N'_{\pi^+}(E')$ $N'_{K^+}(E')$ $N'_{\pi^-}(E')$

Optically
thin
to neutrons

weak decays

$Q'_{\nu_\mu}(E')$ from π^+
$Q'_{\mu^+_R}(E')$
$Q'_{\mu^+_L}(E')$
$Q'_{\bar{\nu}_e}(E')$ from n
$Q'_{\nu_\mu}(E')$ from K^+
$Q'_{\mu^-_L}(E')$
$Q'_{\mu^-_R}(E')$
$Q'_{\bar{\nu}_\mu}(E')$ from π^-

$N'_{\mu^+_R}(E')$ $N'_{\mu^+_L}(E')$ $N'_{\mu^-_L}(E')$ $N'_{\mu^-_R}(E')$

weak decays

$Q'_{\nu_e}(E')$ from μ^+
$Q'_{\bar{\nu}_\mu}(E')$ from μ^+
$Q'_{\nu_\mu}(E')$ from μ^-
$Q'_{\bar{\nu}_e}(E')$ from μ^-

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

Kinetic equations for self-consistent treatment (steady state)

- Treat energy losses/escape in continuous limit in radiation zone:

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

One equation for each particle species!

Injection | Energy losses | Escape

$b(E)=-E\, t^{-1}_{\mathrm{loss}}$

$Q(E,t)$ [GeV^{-1} cm^{-3} s^{-1}] injection per time frame (e. g. from acc. zone)

$N(E,t)$ [GeV^{-1} cm^{-3}] particle spectrum including spectral effects

Need N(E) to compute particle interactions

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

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

In the presence of strong B: Secondary cooling

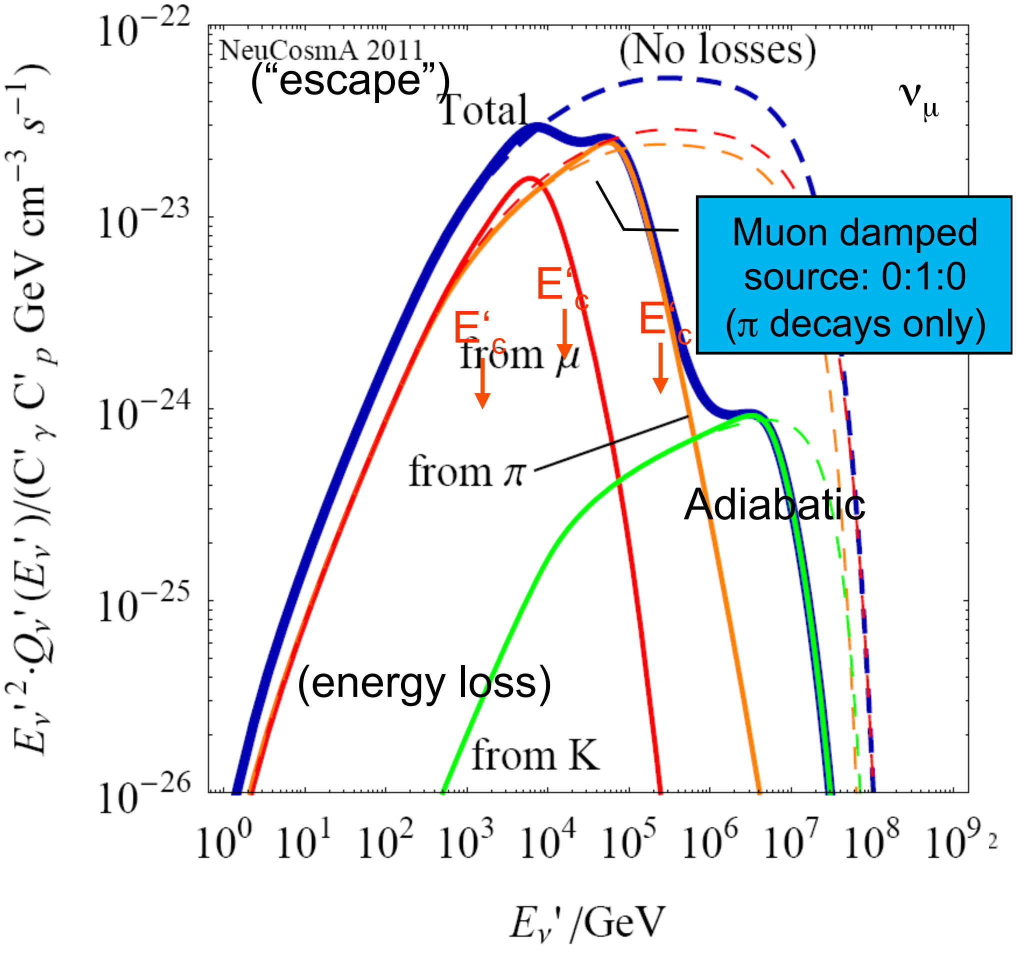
Example: GRB

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, τ_0), and **B‘**
- Leads to characteristic flavor composition and shape

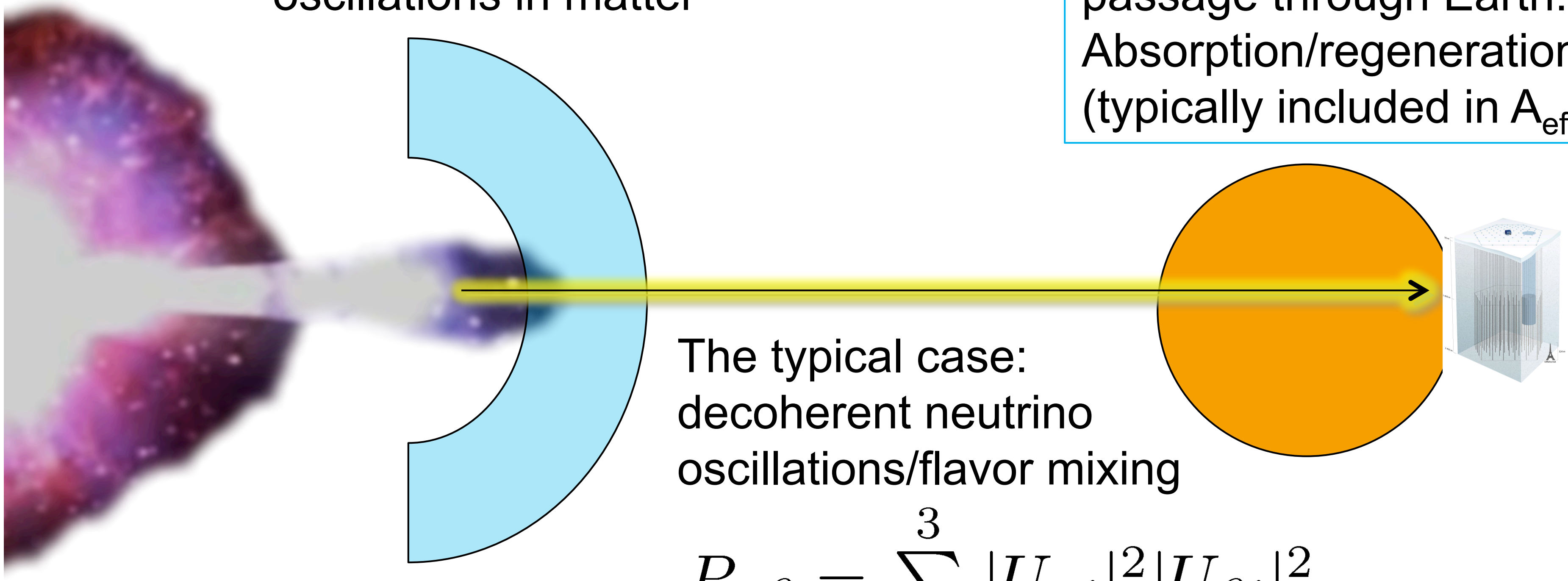
Decay/cooling: charged μ, π, K



Muon damped source: 0:1:0 (π decays only)

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

Neutrino propagation: From source to detector



In environments with high densities (e.g. jets choked in envelope): neutrino oscillations in matter

If E >> 10 TeV and passage through Earth: Absorption/regeneration (typically included in A_{eff})

The typical case: decoherent neutrino oscillations/flavor mixing

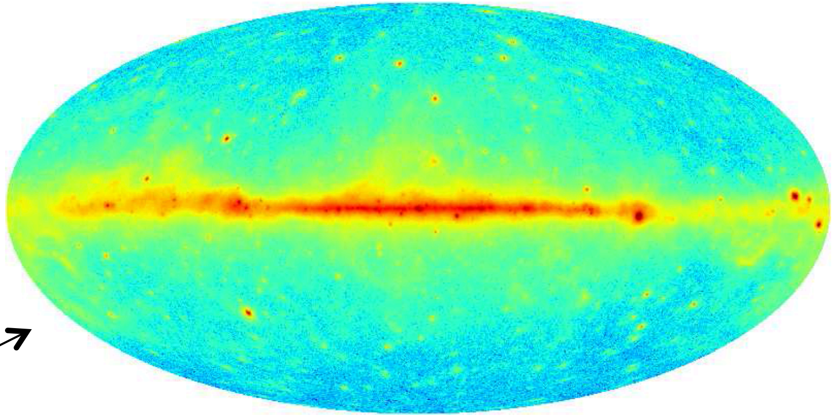
$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Source $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 ➔ Detector 1:1:1
+ redshift of energy if cosmological distance

On the signal interpretation

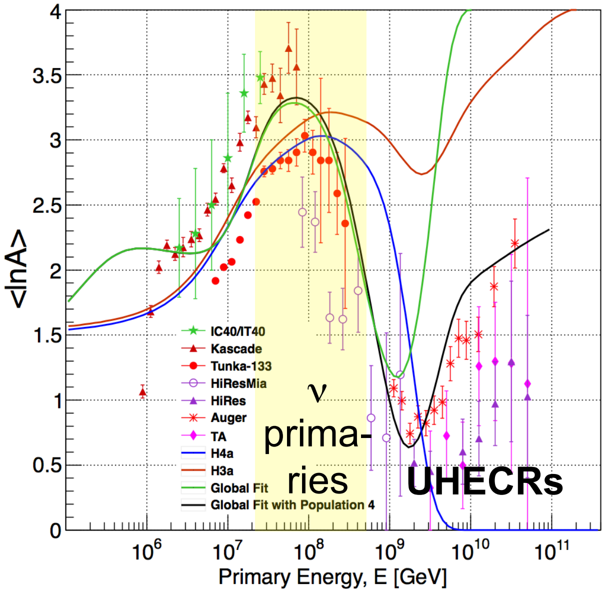
Guaranteed contribution (one example):
Neutrinos from cosmic ray interactions in the Milky Way?

- Cosmic rays interact with hydrogen in our Galaxy (pp)
- 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)

- Complications:
  - CR composition changes in relevant range
  - Neutrino flux dominated by components sub-leading in cosmic rays
  - CR distribution and hydrogen halo extension in Milky Way disputed (may lead to higher rates)

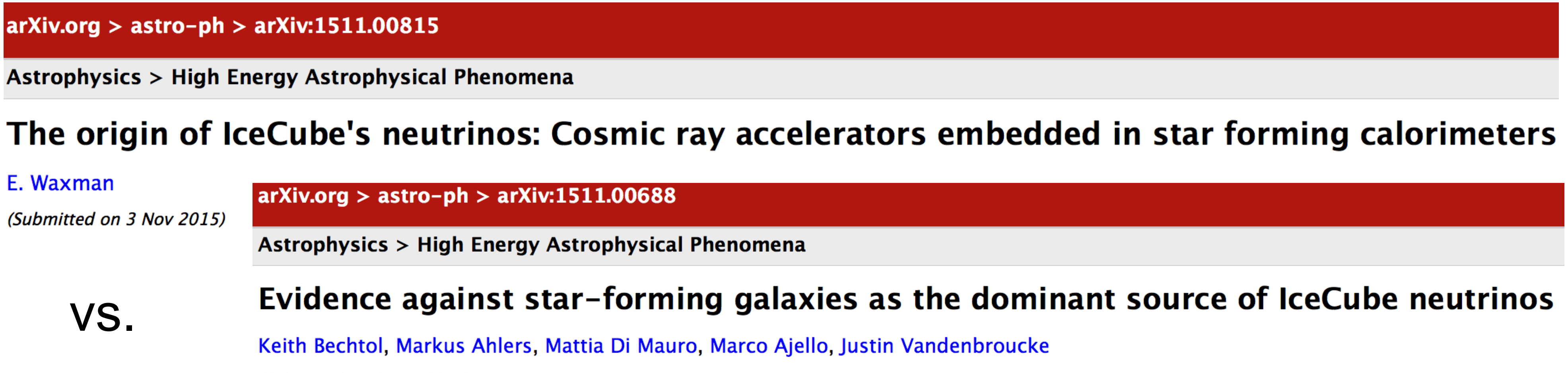


Gaisser, Stanev, Tilav, 2013

- From local cosmic ray density and observed cosmic ray flux: about 0.6 events expected
  Joshi, Winter, Gupta, MNRAS, 2014

(see discussions in Evoli, Grasso, Maccione, 2007; Ahlers, Murase, 2014; Joshi, Winter, Gupta, 2014; Kachelrieß, Ostapchenko, 2014; Neronov, Semikoz, Tchernin, 2014; Ahlers, Bai, Barger, Lu, 2015; …)

Source candidates: Starburst galaxies?



arXiv.org > astro-ph > arXiv:1511.00815

Astrophysics > High Energy Astrophysical Phenomena

The origin of IceCube's neutrinos: Cosmic ray accelerators embedded in star forming calorimeters

E. Waxman

(Submitted on 3 Nov 2015)

vs.

arXiv.org > astro-ph > arXiv:1511.00688

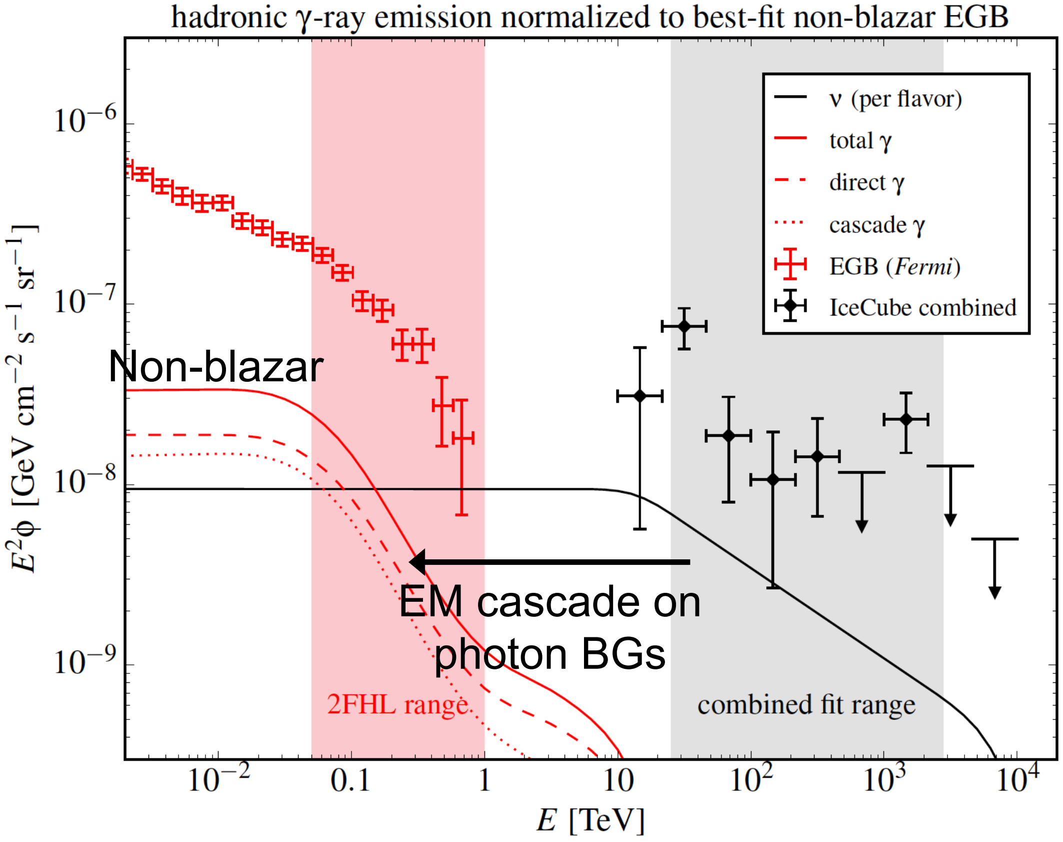
Astrophysics > High Energy Astrophysical Phenomena

Evidence against star-forming galaxies as the dominant source of IceCube neutrinos

Keith Bechtol, Markus Ahlers, Mattia Di Mauro, Marco Ajello, Justin Vandenbroucke

(Submitted on 2 Nov 2015)

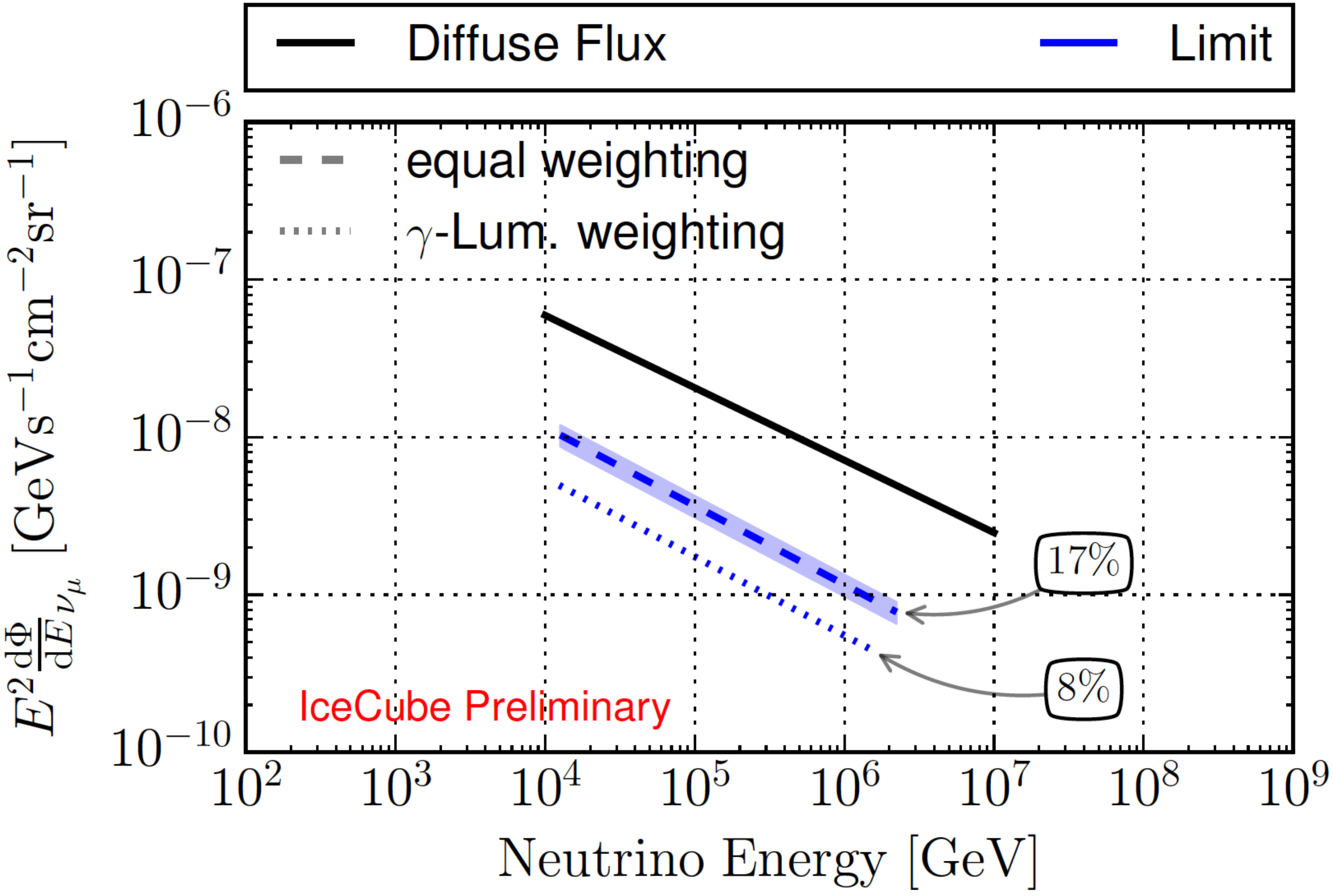
- For pp interactions: π^+, π^-, and π^0 produced together; secondary spectra follow primary cosmic ray spectrum
- Constraints from Fermi diffuse extragalactic background flux
  Murase, Ahlers, Lacki, PRD88 (2013) 121301
- A large fraction of that can be attributed to AGN blazars; pp sources challenged



Source candidates: So, how about AGN blazars?

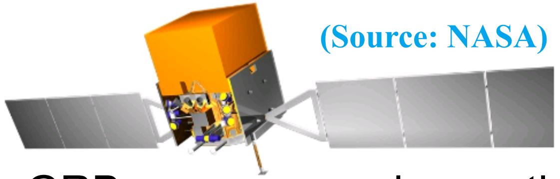
- AGN blazar search with 2nd Fermi-LAT catalogue
- Contribution to diffuse flux small

(Thorsten Glüsenkamp, arXiv:1502.03104; IceCube paper to appear)



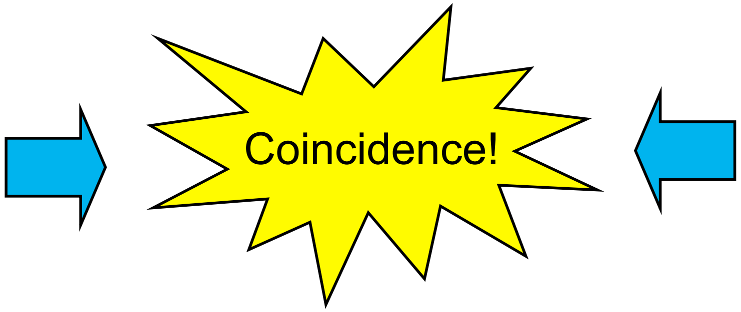
Source candidates: Gamma-Ray Bursts?

- Idea: Use timing and directional information to suppress atm. BGs

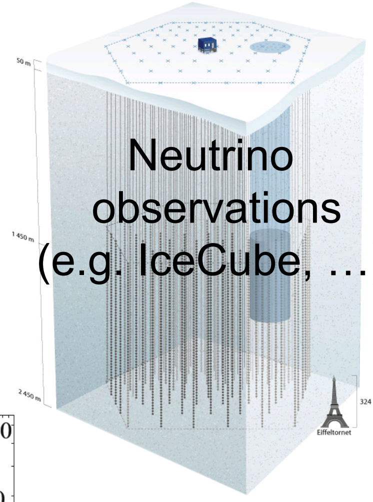


(Source: NASA)

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



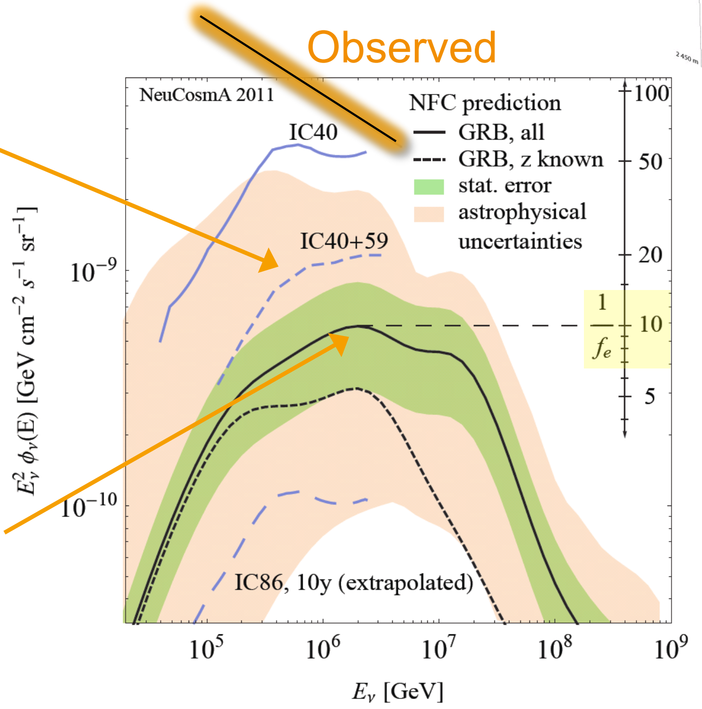
Coincidence!



Neutrino
observations
(e.g. IceCube, …)

(Source: IceCube)

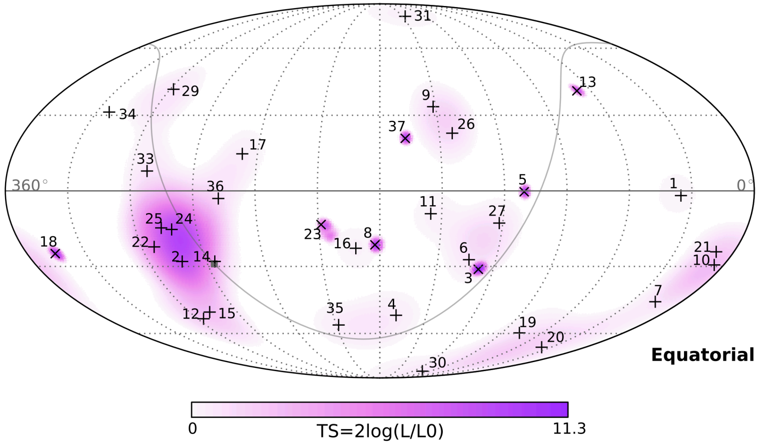
- Strong constraints from GRB stacking
  IceCube, Nature 484 (2012) 351; see arXiv:1412.6510 for update
- Not the dominant source of observed diffuse ν flux!
- Current limit close to prediction **from gamma-rays**; however: many assumptions
  (e.g. **baryonic loading f_e^{-1}**, Γ, z)



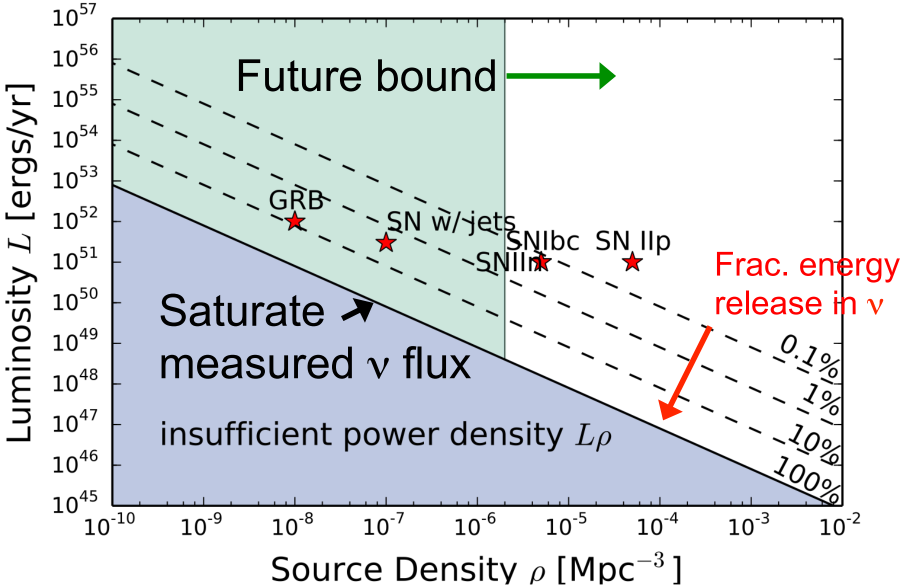
(from: Hümmer, Baerwald, Winter, PRL 108 (2012) 231101)

Observational search strategies (examples)

- Clustering of signal events?
  (e.g. in IceCube, Phys. Rev. Lett. 113 (2014) 101101)



- Anisotropies, point source searches?
  (e.g. IceCube, arXiv:1408.0634;
  ANTARES, arXiv:1402.6183)
- Correlations with known objects/ events in gamma-ray catalogues?
  (e. g. Padovani, Resconi, arXiv:1406.0376
  for BL Lacs and Pulsar Wind Nebulae)
- Use constraints on event multiplets to constrain source density
  (from Kowalski, arXiv:1411.4385;
  see also Ahlers, Halzen,
  arXiv:1406.2160)

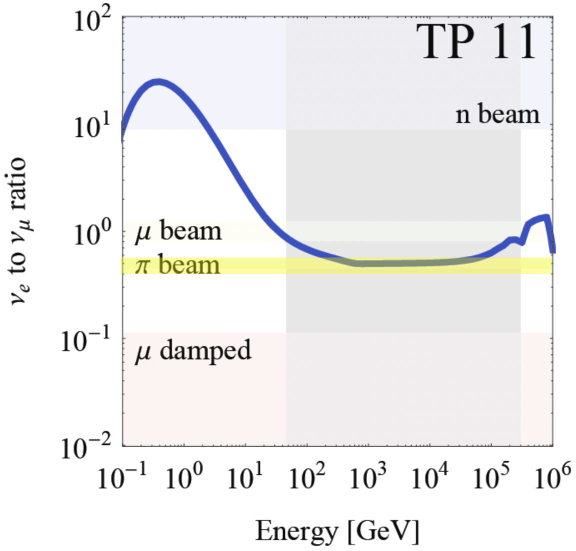


- Multi-messenger triggers and offline analyses for transients (e.g. supernova explosions, GRBs, etc)

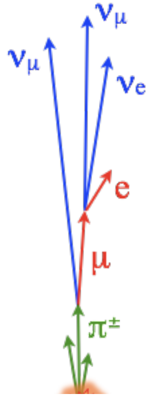
Flavor composition for tests of fundamental physics

Flavor composition at source from numerical simulations

Example: pγ, target photons from synchrotron emission of co-accelerated electrons



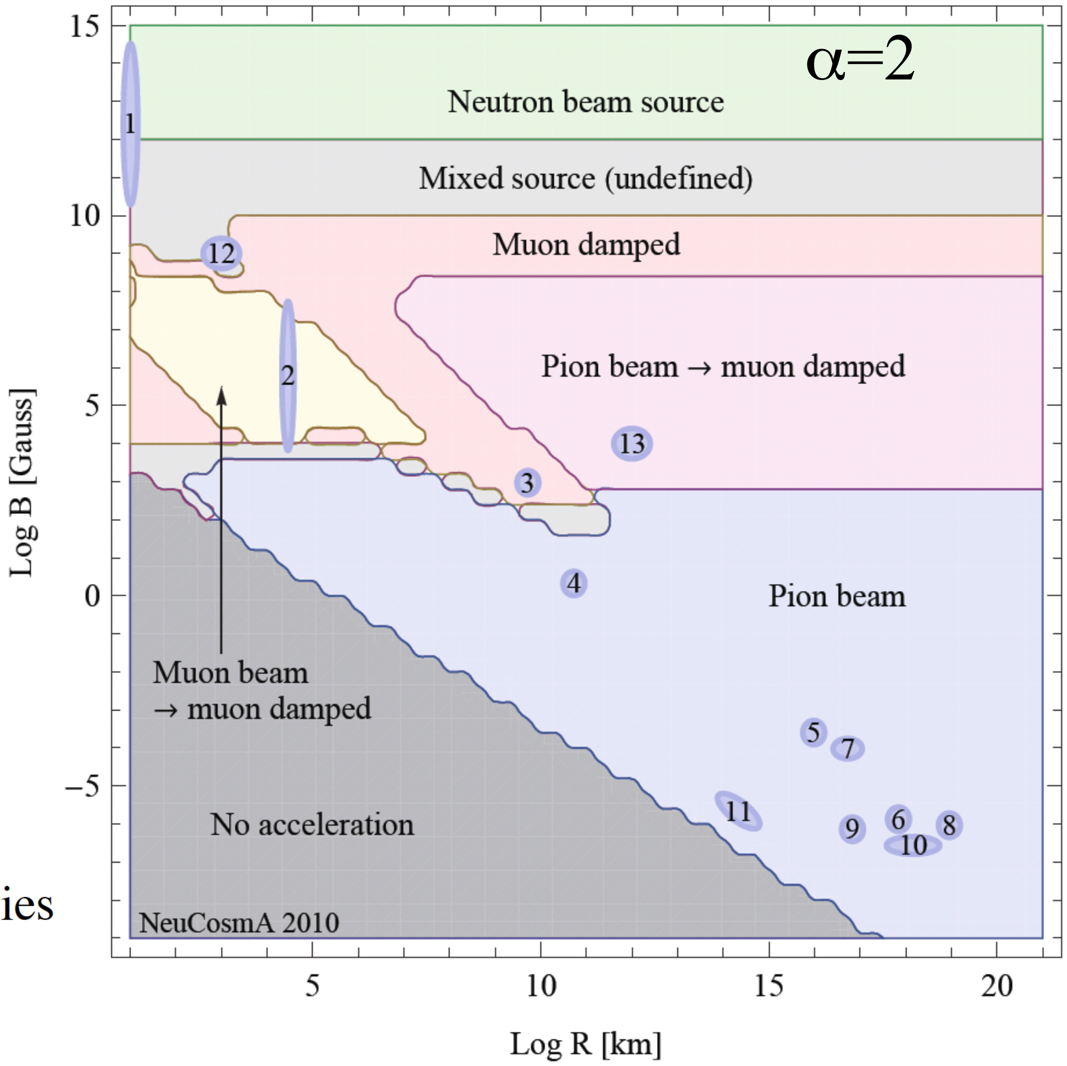
Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



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

Parameter space scan of Hillas plot

- All relevant regions recovered
- Some dependence on injection index
- Flavor composition is, in all realistic cases, a function of energy!



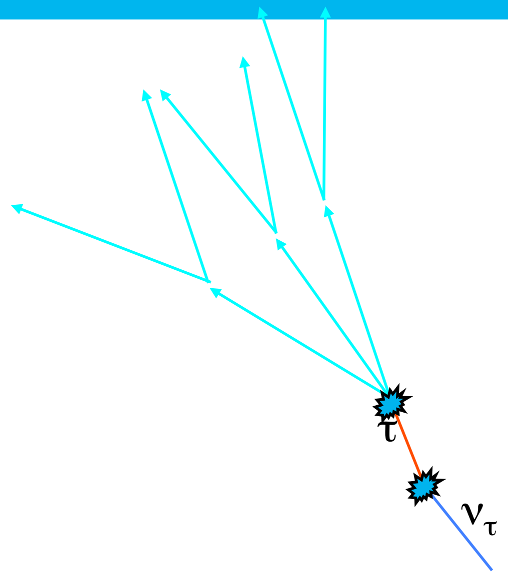
1 Neutron stars
2 White dwarfs
Active galaxies:
    3 nuclei
    4 jets
    5 hot−spots
    6 lobes
7 Colliding galaxies
8 Clusters
9 Galactic disk
10 Galactic halo
11 SNRs

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

Measuring flavor? (experimental viewpoint)

- 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 (6.3 PeV): bar ν_e
  - Double bang/lollipop: ν_τ (sep. tau track) ⟶

  (Learned, Pakvasa, 1995; Beacom et al, 2003)



- Early theoretical approaches:

  Use flux ratios which take into account detector properties and unknown flux normalization, e.g. muon tracks/cascades:

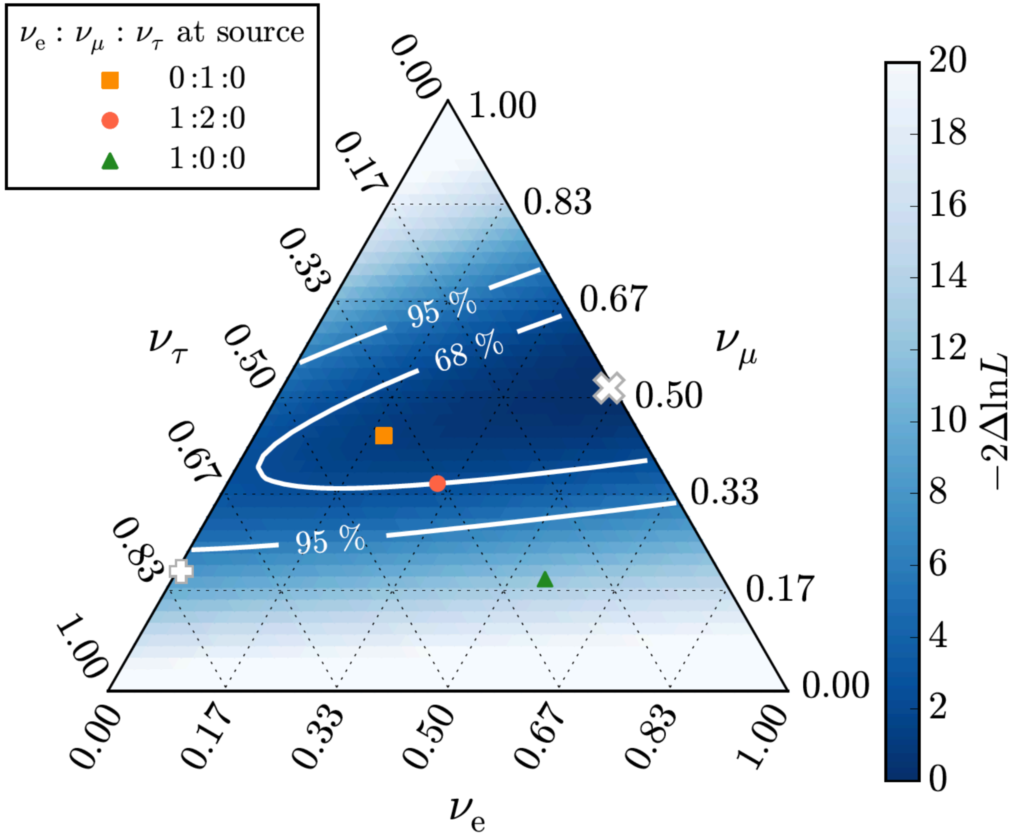
$$\hat{R} = \frac{\phi_\mu^{\mathrm{Det}}}{\phi_e^{\mathrm{Det}} + \phi_\tau^{\mathrm{Det}}}$$

(for flavor mixing and decay only until about 2011: 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; many others …)

- IceCube results actually contain more information IceCube, Astrophys. J. 809 (2015) 1, 98
  Needs ways to represent all information simultaneously:
  Concept of „flavor triangles“ Barenboim, Quigg, 2003

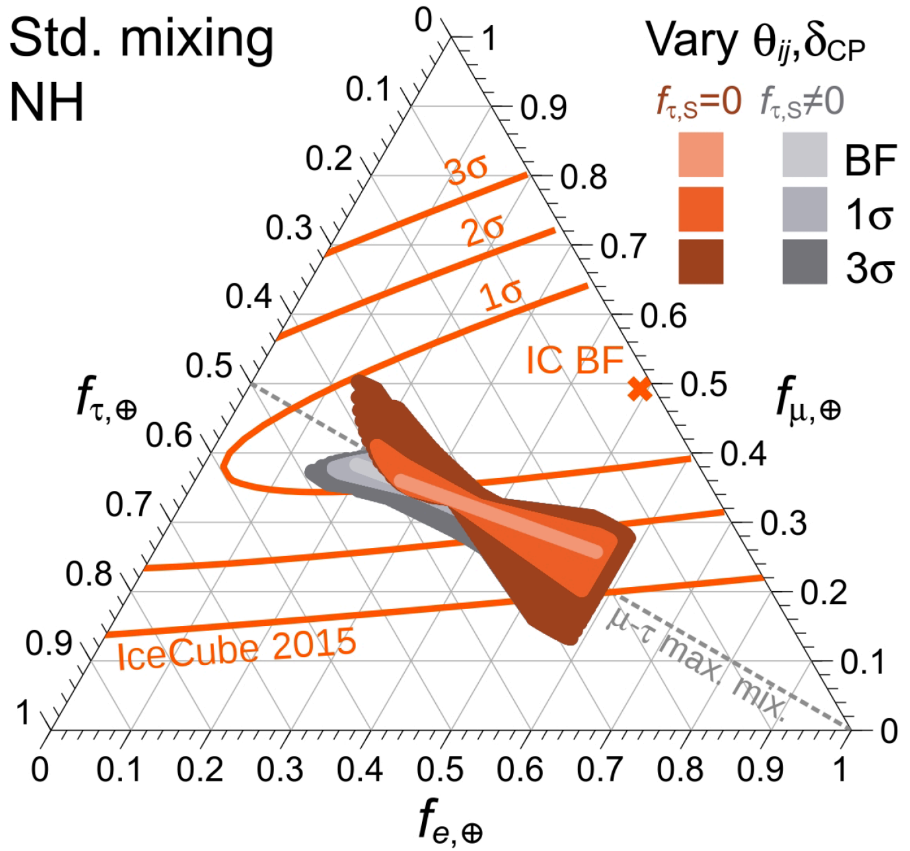
Flavor triangles

- **Measurement**



IceCube measurement
Astrophys. J. 809 (2015) 1, 98

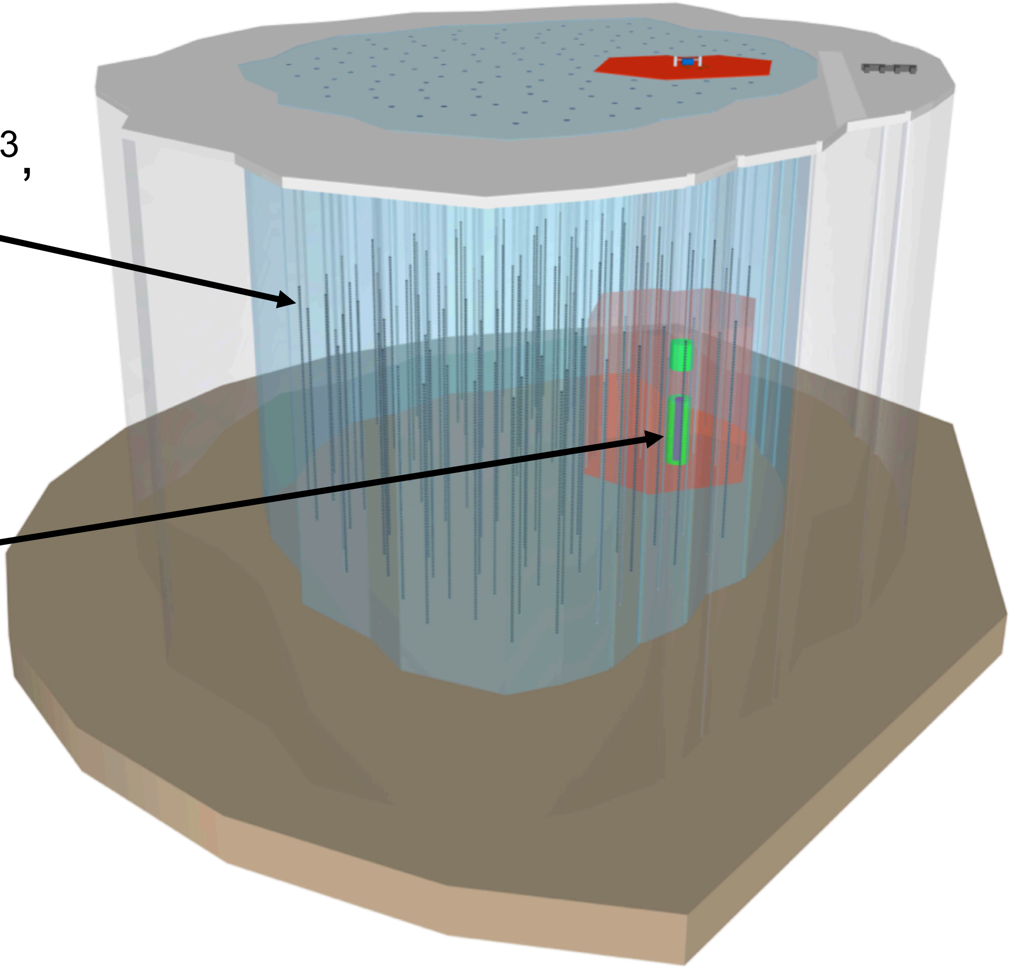
- **Standard Model expectation**



Bustamante, Beacom, Winter,
PRL 115 (2015) 16, 161302

(there is a marginal tension …)

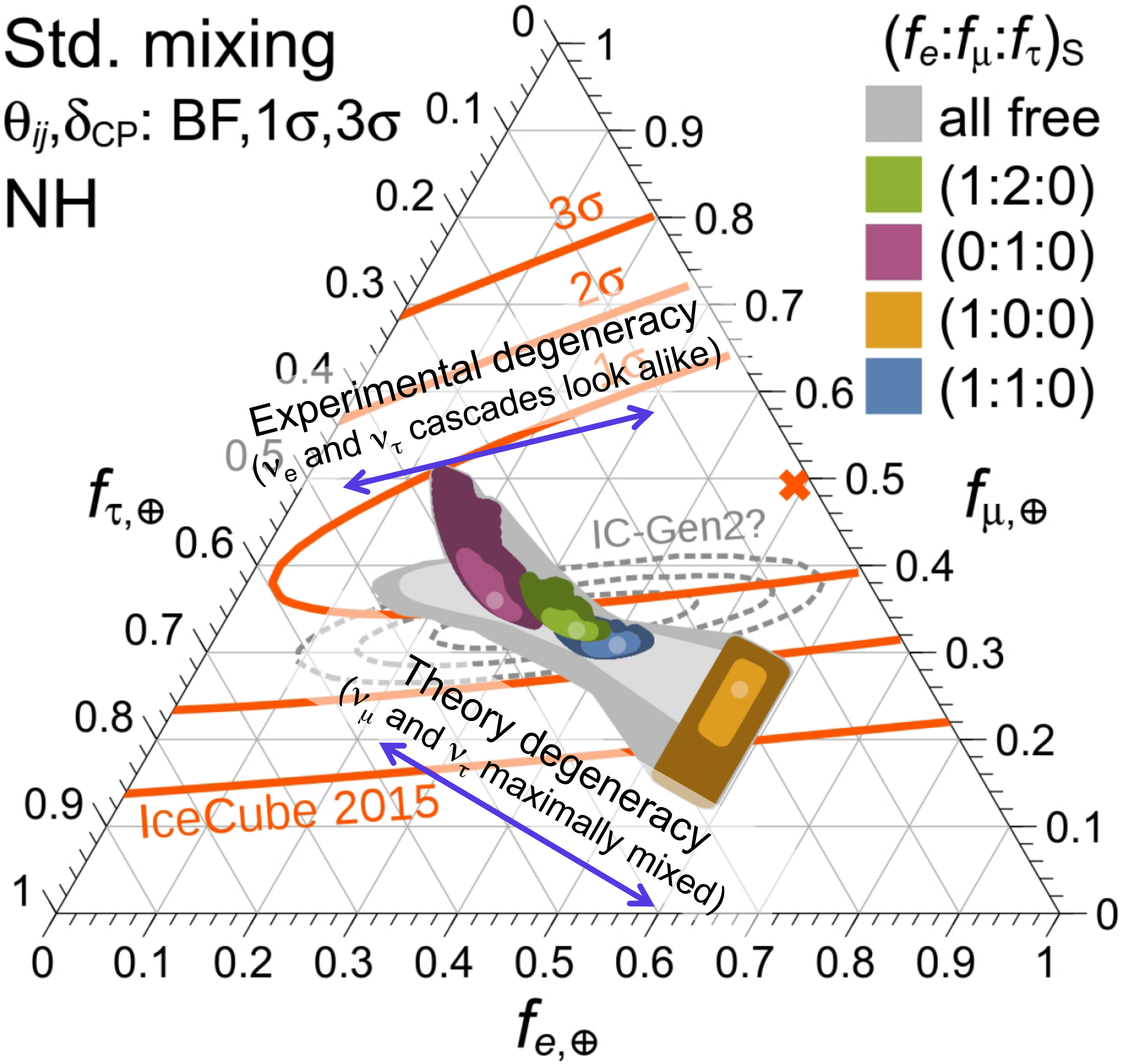
Higher precision from IceCube – Generation Two?



- Plans for upgrade of IceCube experiment
- Instrumented volume O(10) km^3, string spacing 240-300m
- Purpose: “deliver substantial increases in the astrophysical neutrino sample for all flavors”
- PINGU-infill for oscillation physics (about 40 strings for lower threshold in DeepCore region).
  Neutrino mass ordering!
- Similar ideas in sea water (KM3NeT, ORCA)

(arXiv:1401.2046, arXiv:1412.5106)

The future: SM expectations vs. measurement?



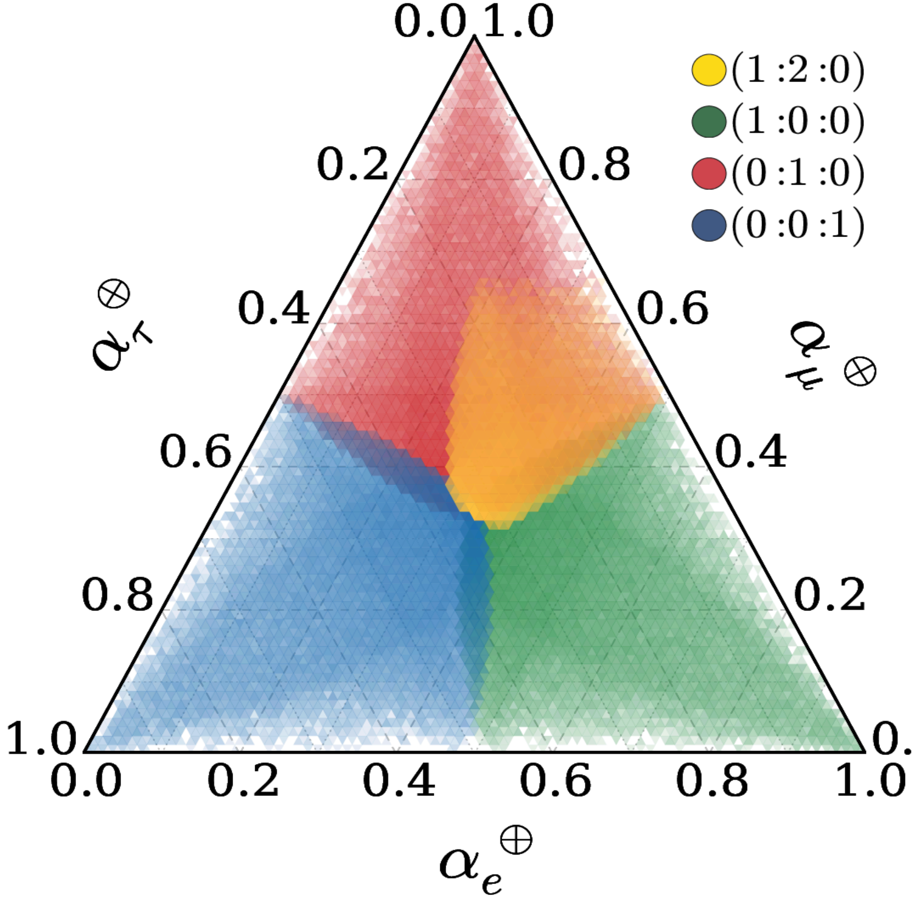
(shaded regions: current 3σ range for mixing params)

Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302

- IceCube-Gen2 could exclude the current best-fit point
- If best-fit moves, flavor composition at source can be constrained

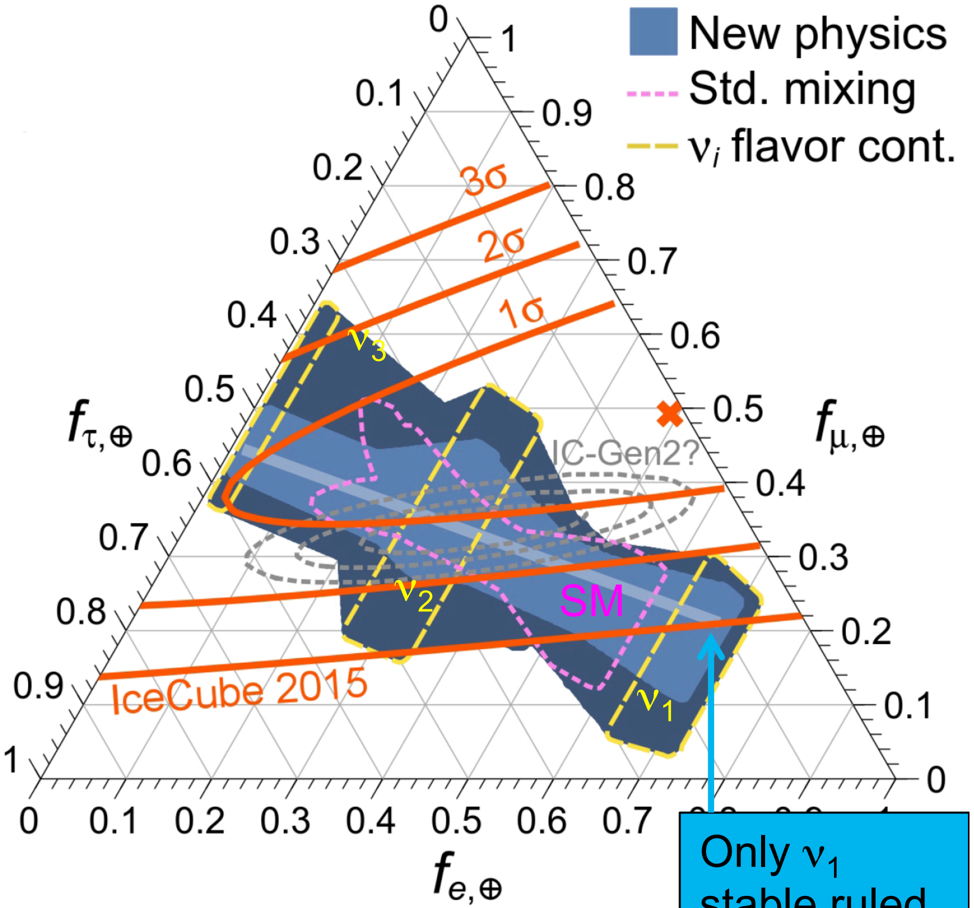
What if there is physics beyond the Standard Model?

Effective operators (CPT violation) changing Hamiltonian at high E



Arguelles, Katori, Salvado, PRL 115 (2015) 161303

“Known models” (e.g. neutrino decays)



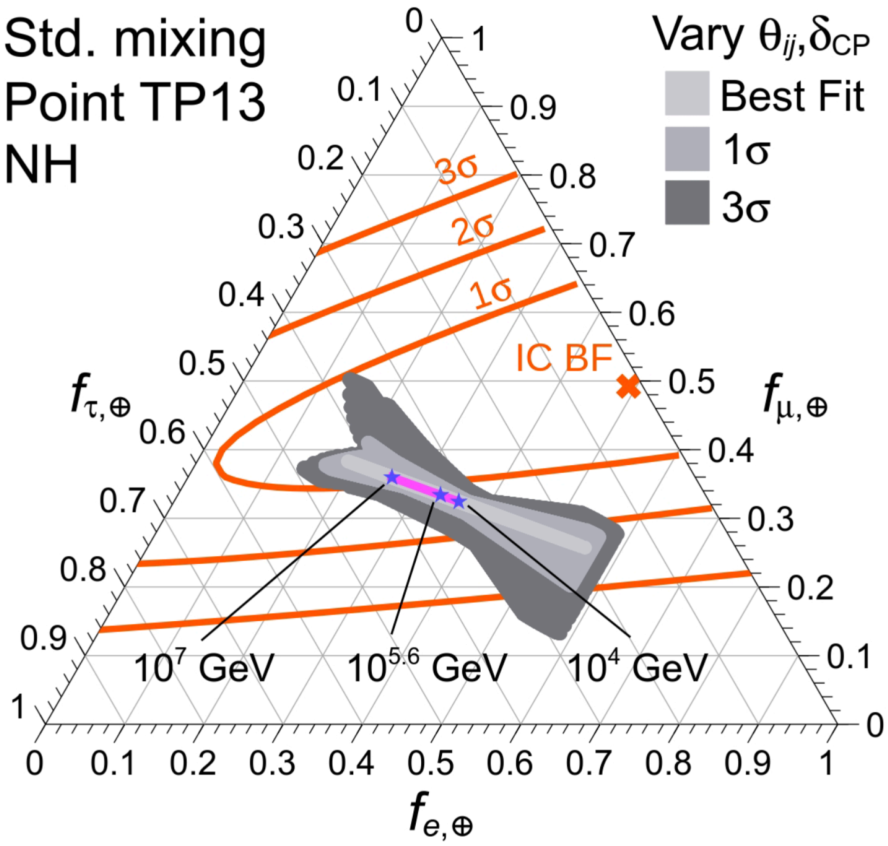
Only ν_1 stable ruled out at 2σ

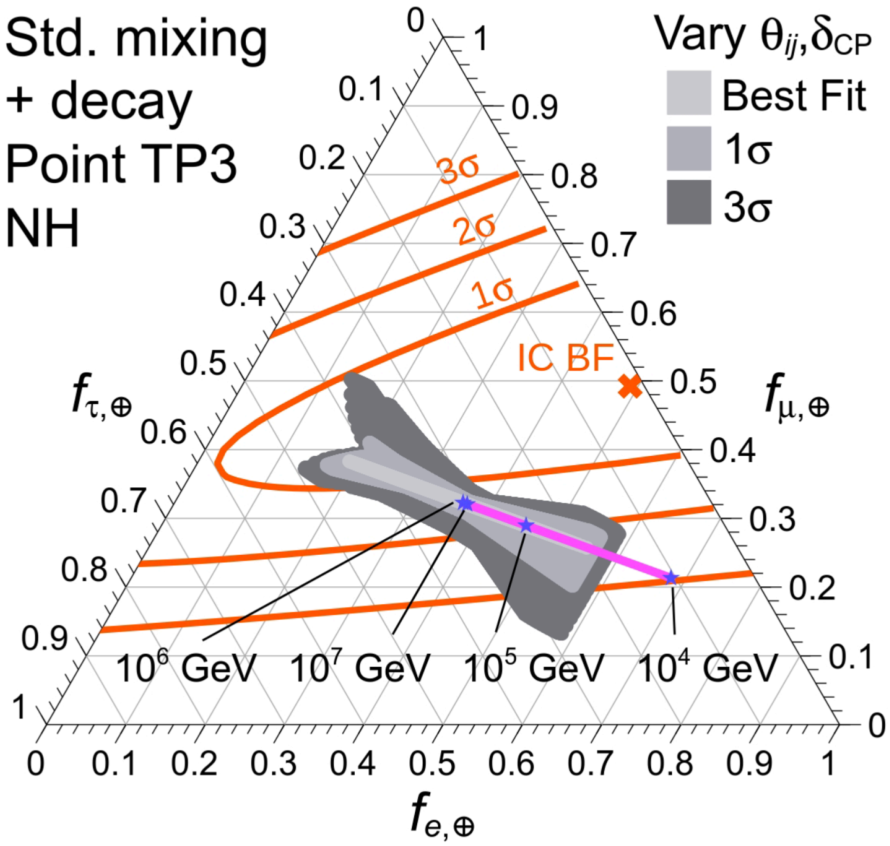
Bustamante, Beacom, Winter, PRL 115 (2015) 161302

Same issue!

Recall that flavor ratios are energy-dependent!

- **Example: Pion beam to muon damped source**
- **Example: Decays of ν_2 and ν_3, competing with energy-dep. flavor composition at source**



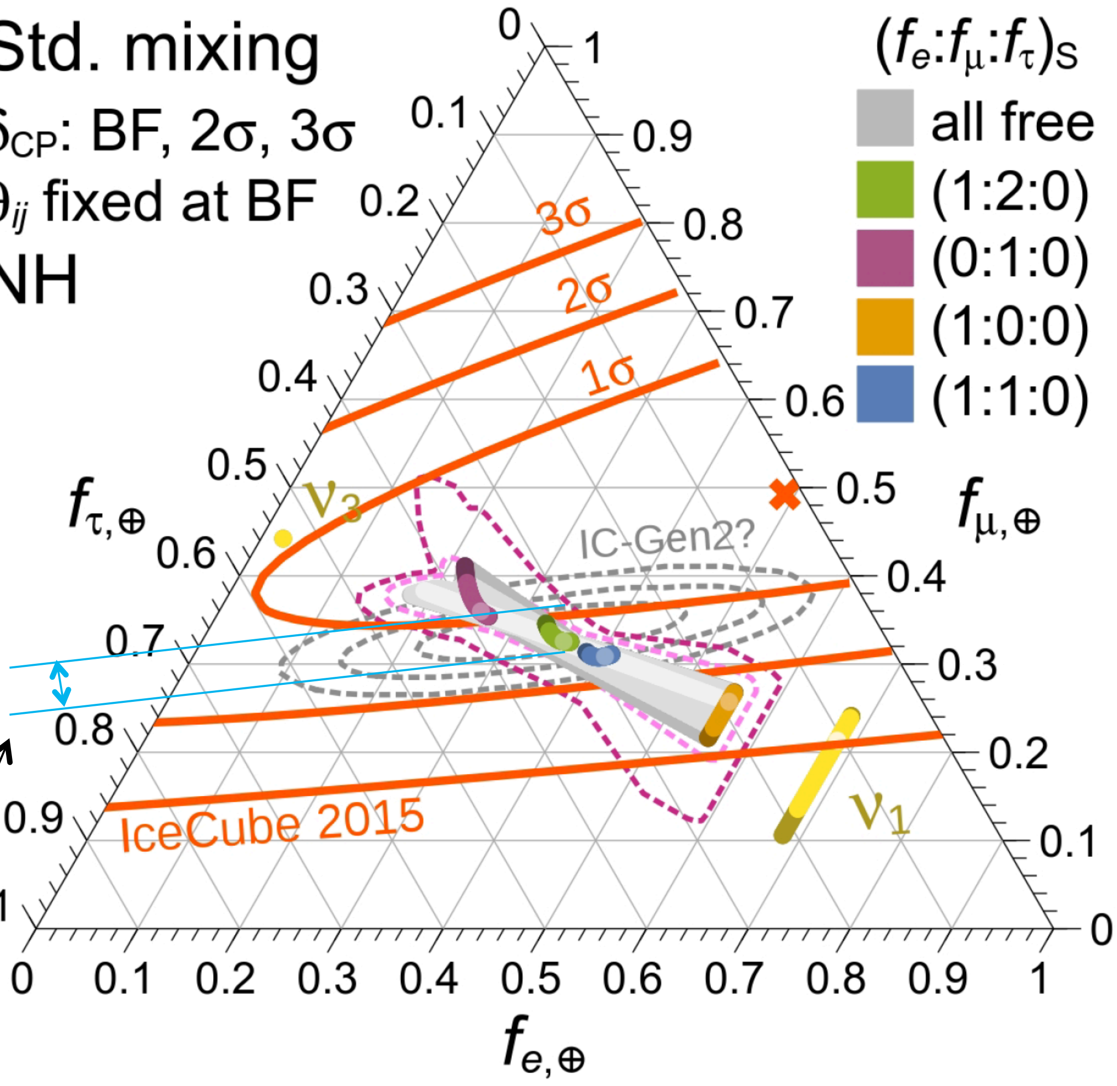


Bustamante, Beacom, Winter, PRL 115 (2015) 161302;
right example from Mehta, Winter, JCAP 03 (2011) 041

Can astrophysical measurements constrain δ_{CP}?

- Assume that all other oscillation parameters were perfectly known →
- Need to assume that type of source known
- For pion beam sources, and sources within SM, in general, challenging
- Best if only ν_1 stable
  (but this is new physics, and in tension with data already …)
  Beacom, Bell, Hooper, Pakvasa, Weiler, 2004

But: expect composition for muon tracks/showers for IC-Gen2 better than ~ 10%



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Propagation effects over cosmological distances

Example: Neutrino lifetime
… but generic thoughts apply to other classes
of new physics as well …

Neutrino lifetime: Basics

- If neutrino mass eigenstates decay: Decay rate $\lambda_i = 1/(\tau_{0,i}\ \gamma) = m_i/(\tau_{0,i}\ E)$
- Rest frame lifetime τ_0 cannot be measured. Describe by

$$\kappa^{-1} \left[\frac{\mathrm{s}}{\mathrm{eV}} \right] \equiv \frac{\tau\,[\mathrm{s}]}{m\,[\mathrm{eV}]} \simeq 10^2 \, \frac{L\,[\mathrm{Mpc}]}{E\,[\mathrm{TeV}]}$$

  (last term: estimate for sensitive L/E-range)

- Naively: need long distances and low energies to test decay!
- Best bounds from SN 1987A neutrinos: $\tau/m > 10^5$ s/eV
- Caveat: large uncertainty in neutrino flux normalization and only electron flavor measured; bound must apply to either m_1 or m_2 (or both)
- Can one obtain better bounds over cosmological distances, such as from high-z gamma-ray burst neutrinos (GRBs)?
- Have to face subtleties of new physics over cosmological distances!

Propagation effects over cosmologial distances

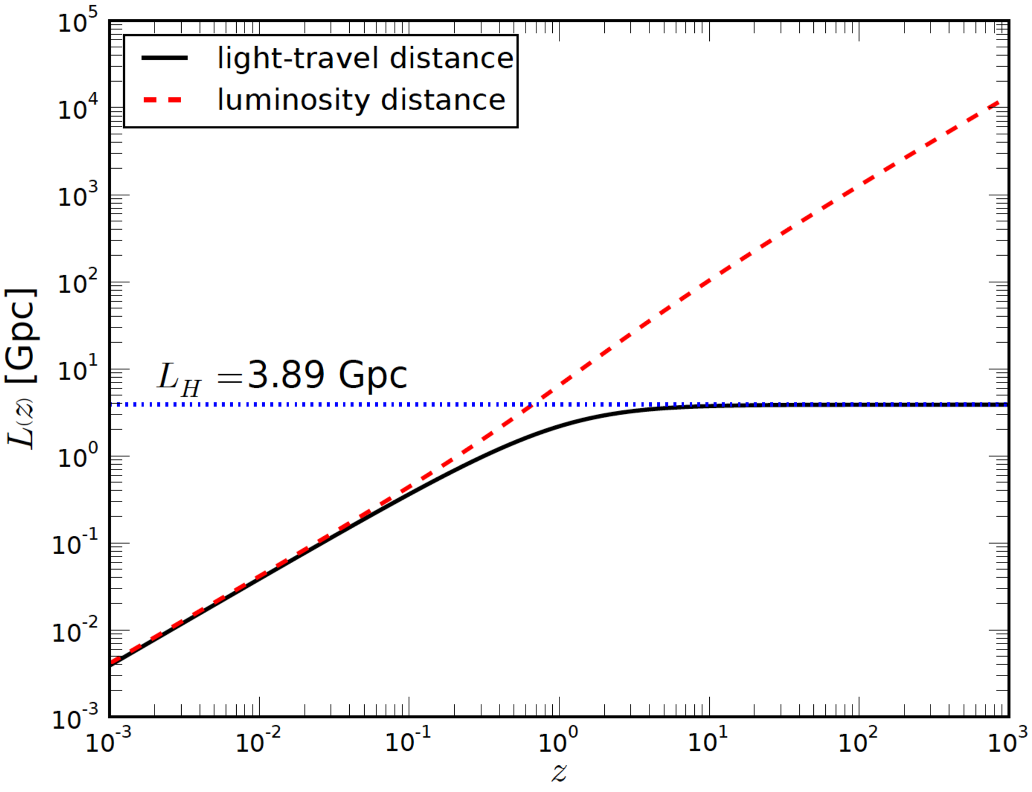
- What is the “clock” for the decay of the neutrinos? **Light-travel distance**

$$L(z) = L_H \int_0^z \frac{dz'}{(1+z')\,h(z')}$$

$$h(z) \equiv H(z)/H_0 \qquad H(z) \equiv H_0\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

- The light-travel distance is limited by the Hubble length
- Consequence: Time/distance dependent new physics effects in the propagation (including oscillations) cannot be tested for arbitrarily large distances!

e. g. Weiler, Simmons, Pakvasa, Learned, 1994; Wagner, Weiler, 1997; Beacom et al., 2004; Esmaili, Farzan, 2012; Baerwald, Bustamante, Winter, 2012



A stability paradox (… similar to Olbers' paradox)

- Invisible decays

$$P_{\alpha\beta}(E_0,z) = \sum_i |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \, \frac{N_i(E_0,z)}{\hat{N}_i(E_0)} = \sum_i |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \, D_i(E_0,z) \, ;$$

Damping factor

- Ansatz for decays: $N_i(z) = \hat{N}_i \, e^{-\lambda_i L(z)}$
- Correct decay rate for redshift: $\lambda_i = \lambda_i\,(z) = \dfrac{\kappa_i}{E_0\,(1+z)}$
- Damping factor $D_i(E_0,z) = \exp\left(-\dfrac{\kappa_i}{E_0}\,\dfrac{L\,(z)}{(1+z)}\right)$
- Re-write as $D_i(E_0,z) = \left[\mathcal{Z}_1\,(z)\right]^{-\frac{\kappa_i L_H}{E_0}}$

$$\mathcal{Z}_1\,(z) \equiv \exp\left(\frac{L(z)}{L_H \cdot (1+z)}\right)$$

For z → ∞: L → L_H and Z_1 → 1
Thus: D → 1 and neutrinos from extremely high z are stable! Stability paradox! What is wrong?

Baerwald, Bustamante, Winter, JCAP 1210 (2012) 020

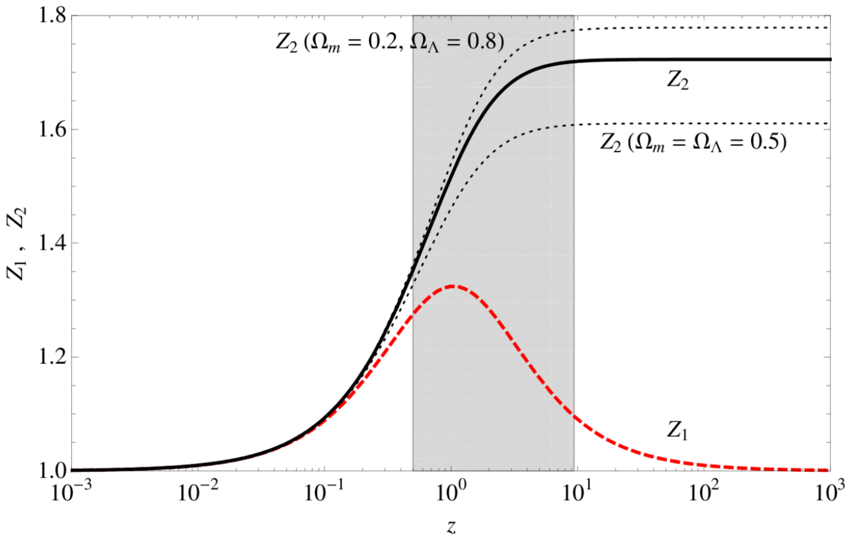
Proper solution

- Start with differential equation, re-written in terms of redshift

$$\frac{dN_i(E_0,z)}{dz} = -\frac{\kappa_i}{E_0}\frac{dL}{dz}\frac{N_i(E_0,z)}{1+z}$$

- Result

$$D_i(E_0,z) = \exp\left(-\frac{\kappa L_H}{E_0}\int_0^z \frac{dz'}{(1+z')^2\, h(z')}\right) = \left[\mathcal{Z}_2(z)\right]^{-\frac{\kappa L_H}{E_0}}$$



Neutrinos from high z decay now!

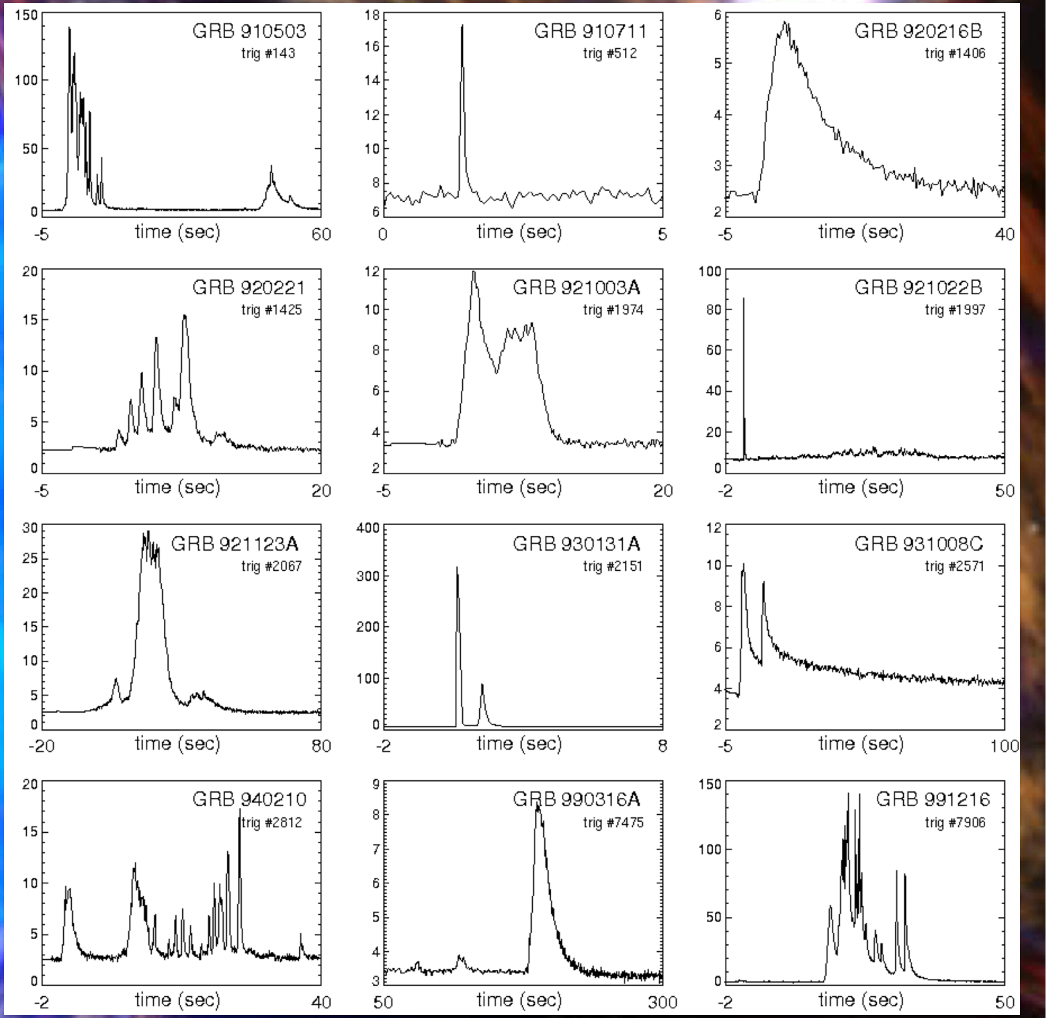
NB: Complete decays are a matter of energy, not distance! In general, the statement “the further away the better” does not apply here!

Baerwald, Bustamante, Winter, JCAP 1210 (2012) 020

Test case: Gamma-ray bursts (GRBs)

- Most energeric electromagnetic (gamma-ray) outburst class
- Several populations, such as
  - Long-duration bursts (~10 – 100s), from collapses of massive stars?
  - Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers?
- Observed in light curves come in large variety →
- Long GRBs mostly from redshifts z ~ 1-2

Daniel Perley

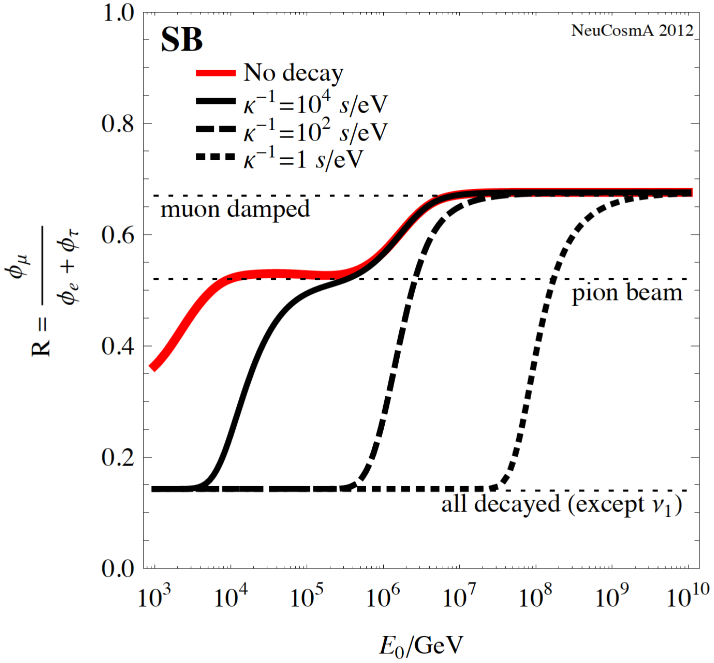


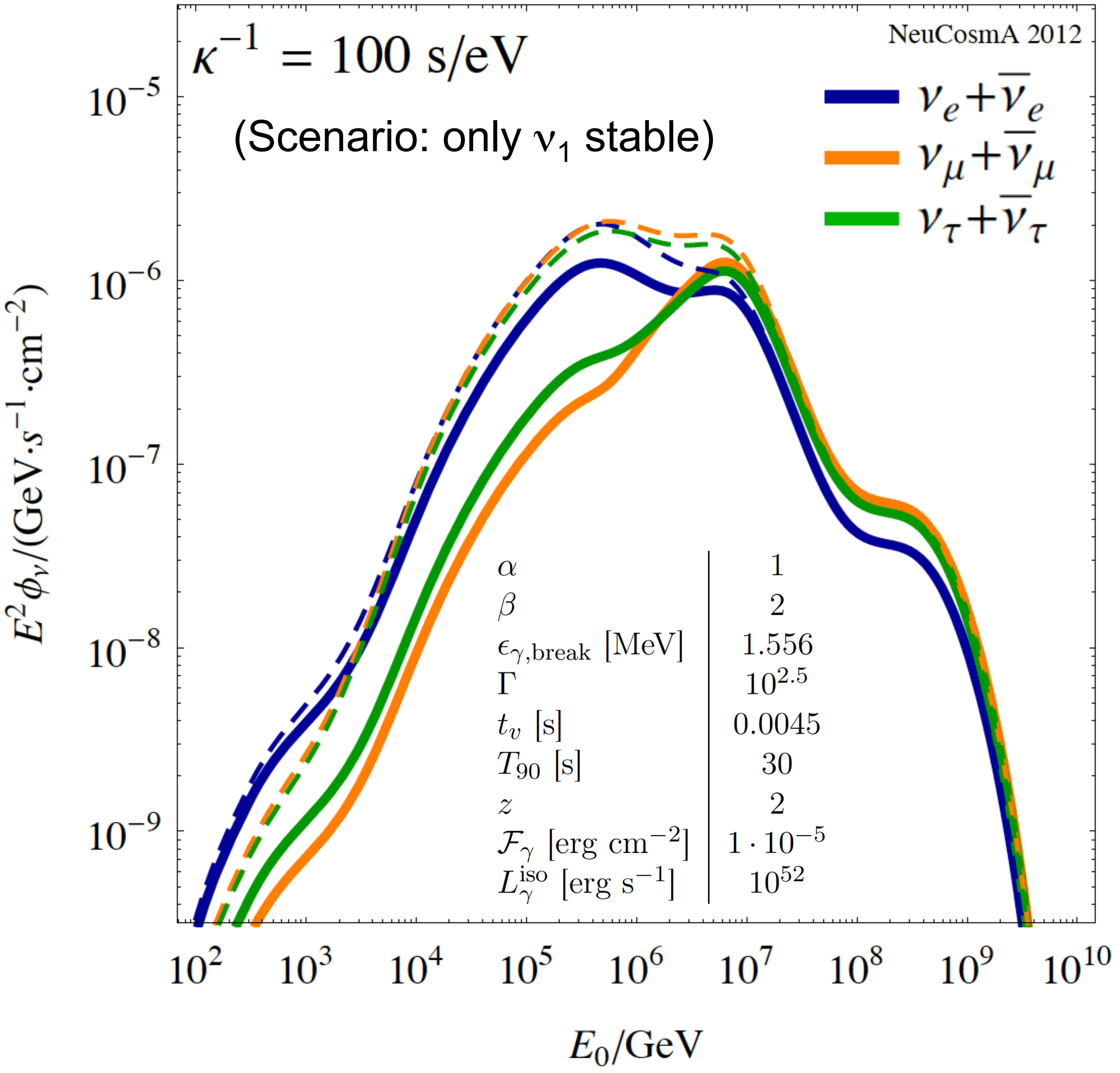
Source: NASA

Decays of GRB neutrinos?

Interesting implications:

- ν_μ from GRBs may be suppressed (current stacking analyses based on ν_μ!). Need GRB-cascade searches
- Flavor composition depends on energy





Baerwald, Bustamante, Winter, JCAP 1210 (2012) 020

Summary and conclusions

- Important clues on the neutrino signal will come from multi-messenger interpretations. This is a challenge for **theory**, as basically any multi-messenger relationship has to rely on a source model
- Origin of cosmic neutrinos yet unclear; possibly different components; partially contradictory information (also in data, not touched).
  Need more statistics: IceCube-Gen2?
- The observation of high-E cosmic neutrinos opens new possibilities for tests of SM and BSM fundamental physics
- The flavor composition of astrophysical neutrinos is relatively sensitive to physics beyond the Standard Model
- Propagation effects over cosmological distances require a dedicated treatment; naïve assumptions do not apply