Astrophysical (PeV) neutrinos

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Neutrinos: the quest for a new physics scale
CERN

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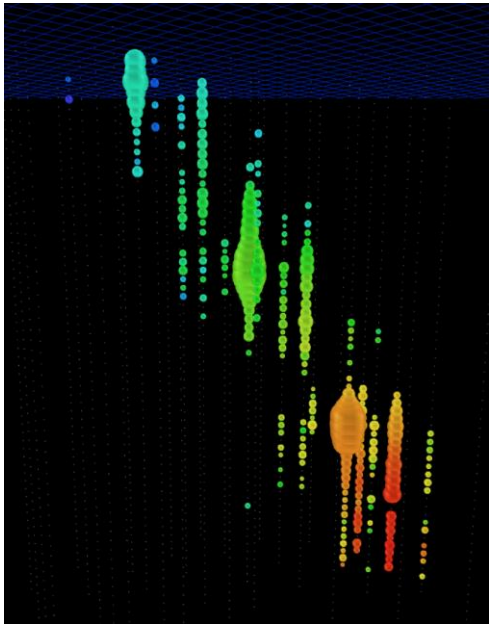
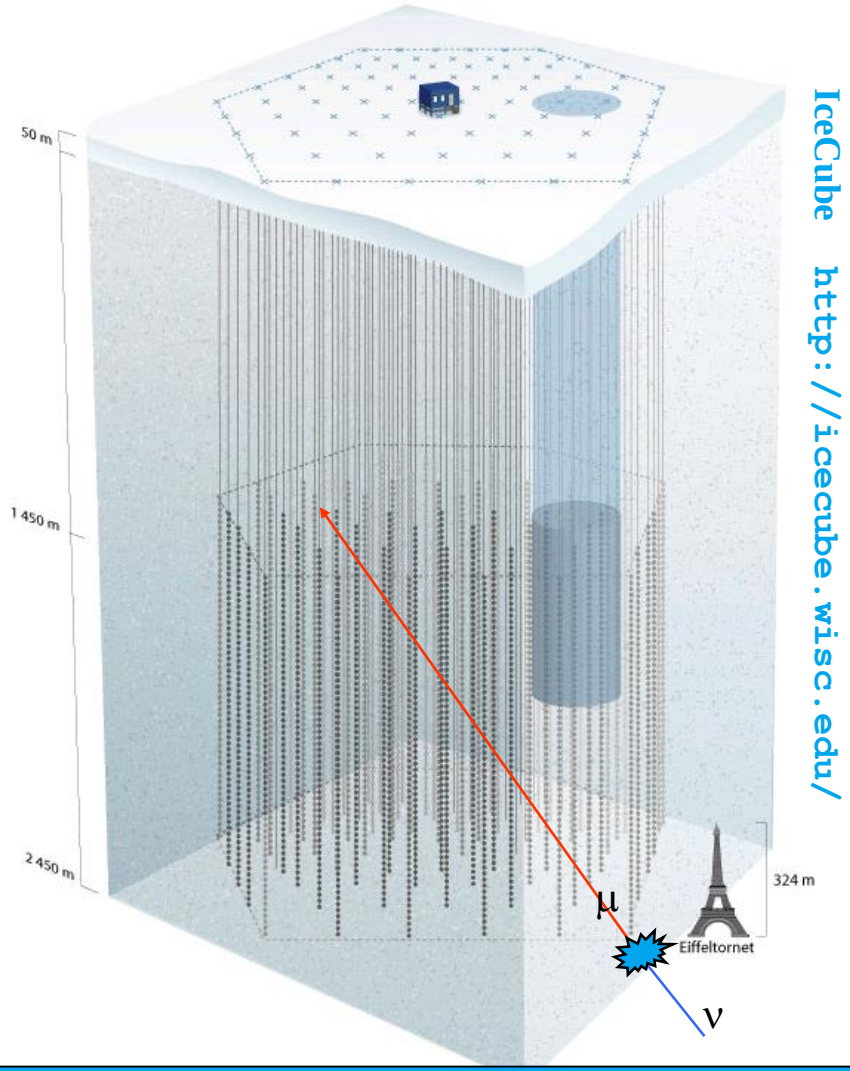
Contents

IceCube: Event topologies?

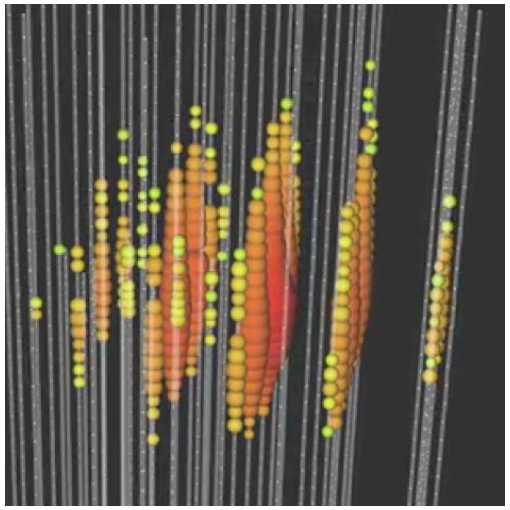
Muon track:
- From ν_μ (mostly)



Better directional info



Cascade (shower):
- From ν_e
- From ν_τ
- [From ν_e, ν_μ, ν_τ neutral current interactions]



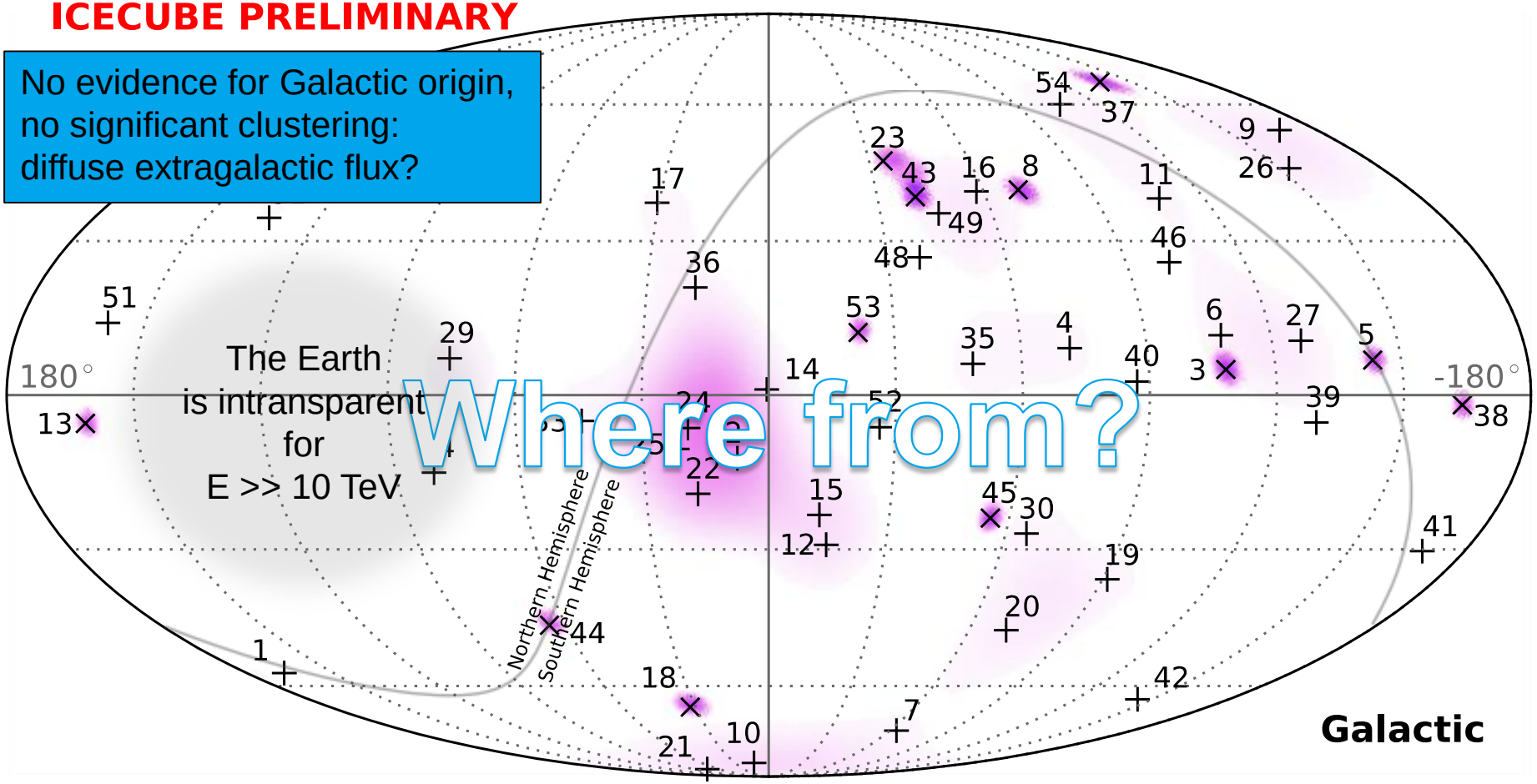
Better energy info

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

54 high energy cosmic neutrinos

ICECUBE PRELIMINARY

No evidence for Galactic origin, no significant clustering: diffuse extragalactic flux?



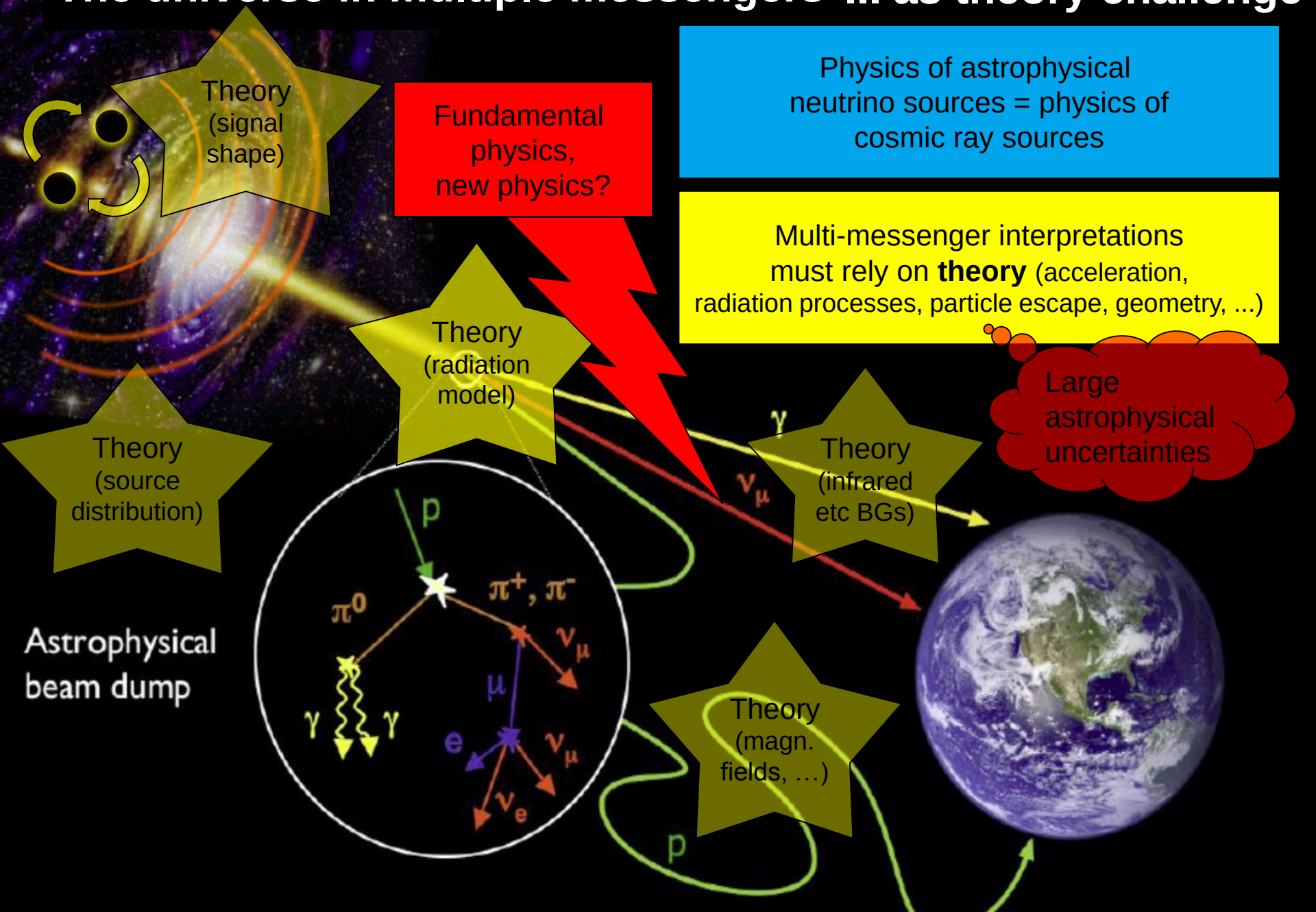
+ Cascades

× Muon tracks

0 TS=2log(L/L0) 10.9

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

The universe in multiple messengers ... as 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, ...)

Large astrophysical uncertainties

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

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

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

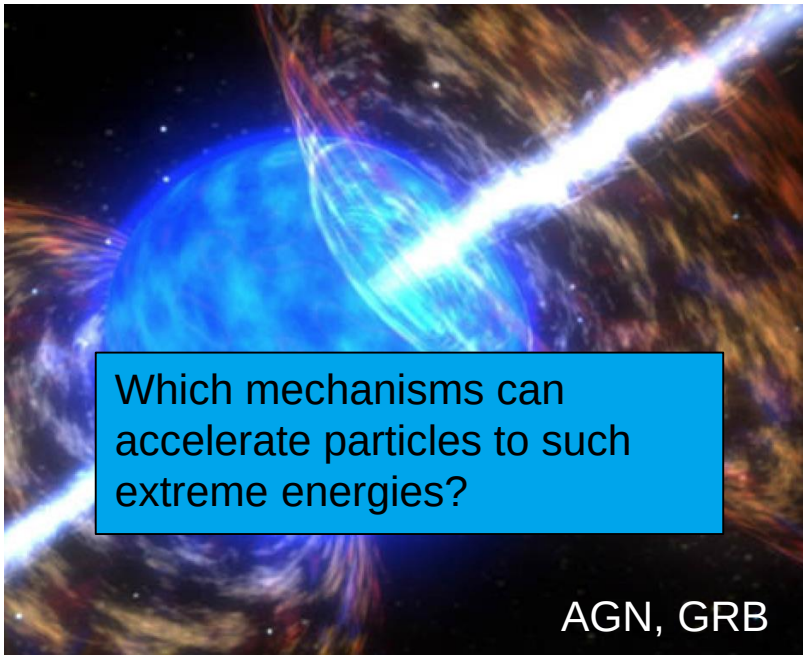
Cosmic vs. terrestrial particle accelerators

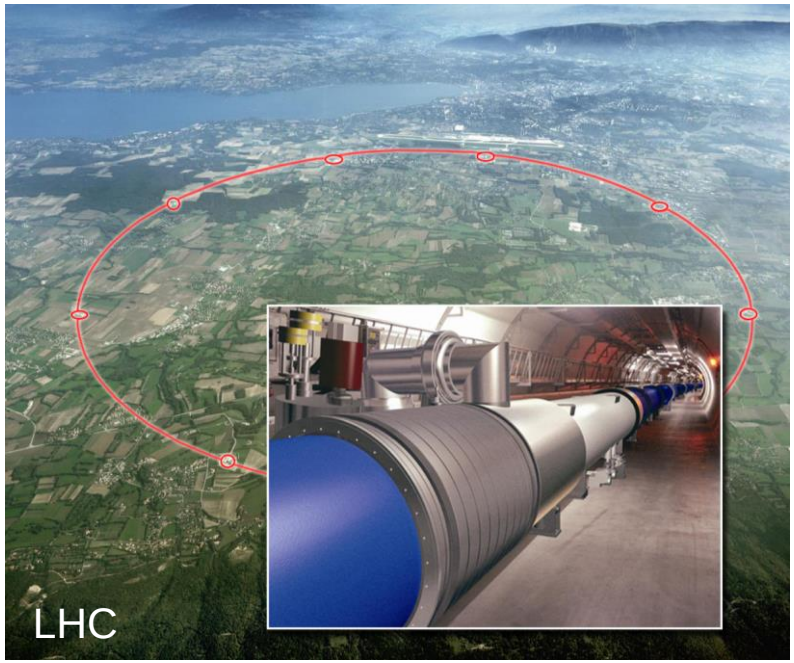
Lorentz force = centrifugal force ➔ $E_{max} \sim q\,B\,R$

Hillas

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

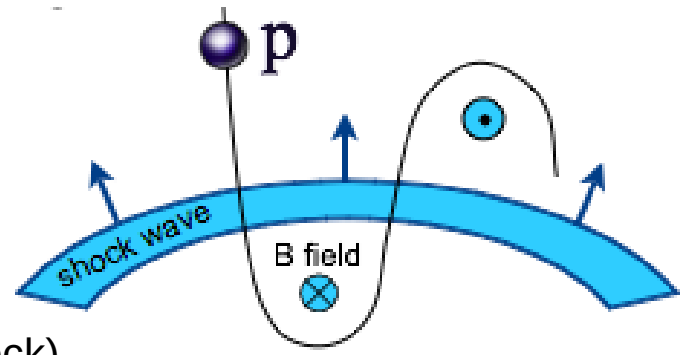
- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km





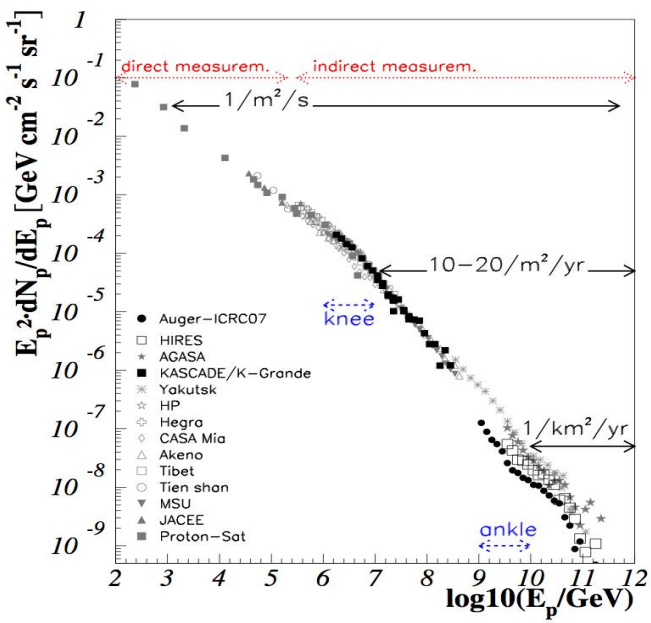
Acceleration of primaries (protons, nuclei)

Example: Fermi shock acceleration



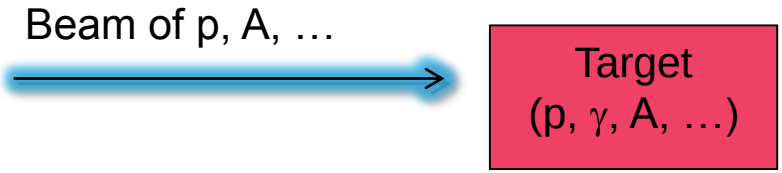
- Fractional energy gain per cycle: η
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{esc}}{\ln \eta} - 1}$
- $\ln P_{esc}/\ln \eta \sim -1$ (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical "textbook" spectrum

- 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 ...)*



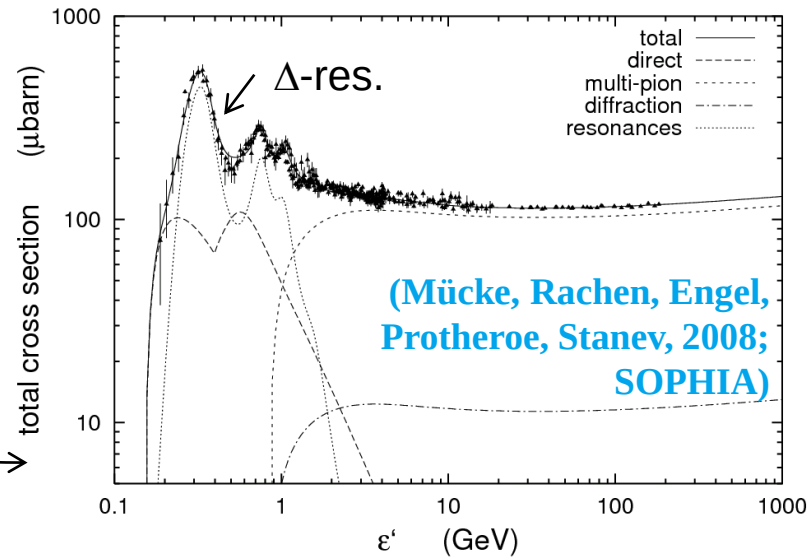
Secondary production: Particle physics 101

- Beam dump picture (particle physics)



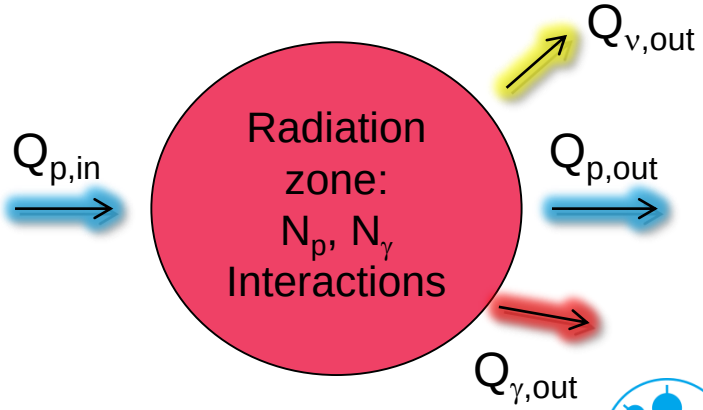
- Interaction rate $\Gamma \sim c \;\; N\,[\mathrm{cm}^{-3}] \;\; \sigma\,[\mathrm{cm}^{2}]$

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



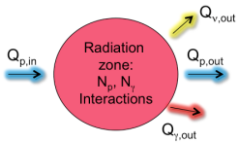
(Photon energy in nucleon rest frame)

- 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



Kinetic equations for self-consistent treatment (steady state)

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



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

Injection | Energy losses | Escape

One equation for each particle species!

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

Need N(E) to compute particle interactions

- Simple case: No energy losses b=0: $N(E) = Q(E)\, t_{\rm esc}$

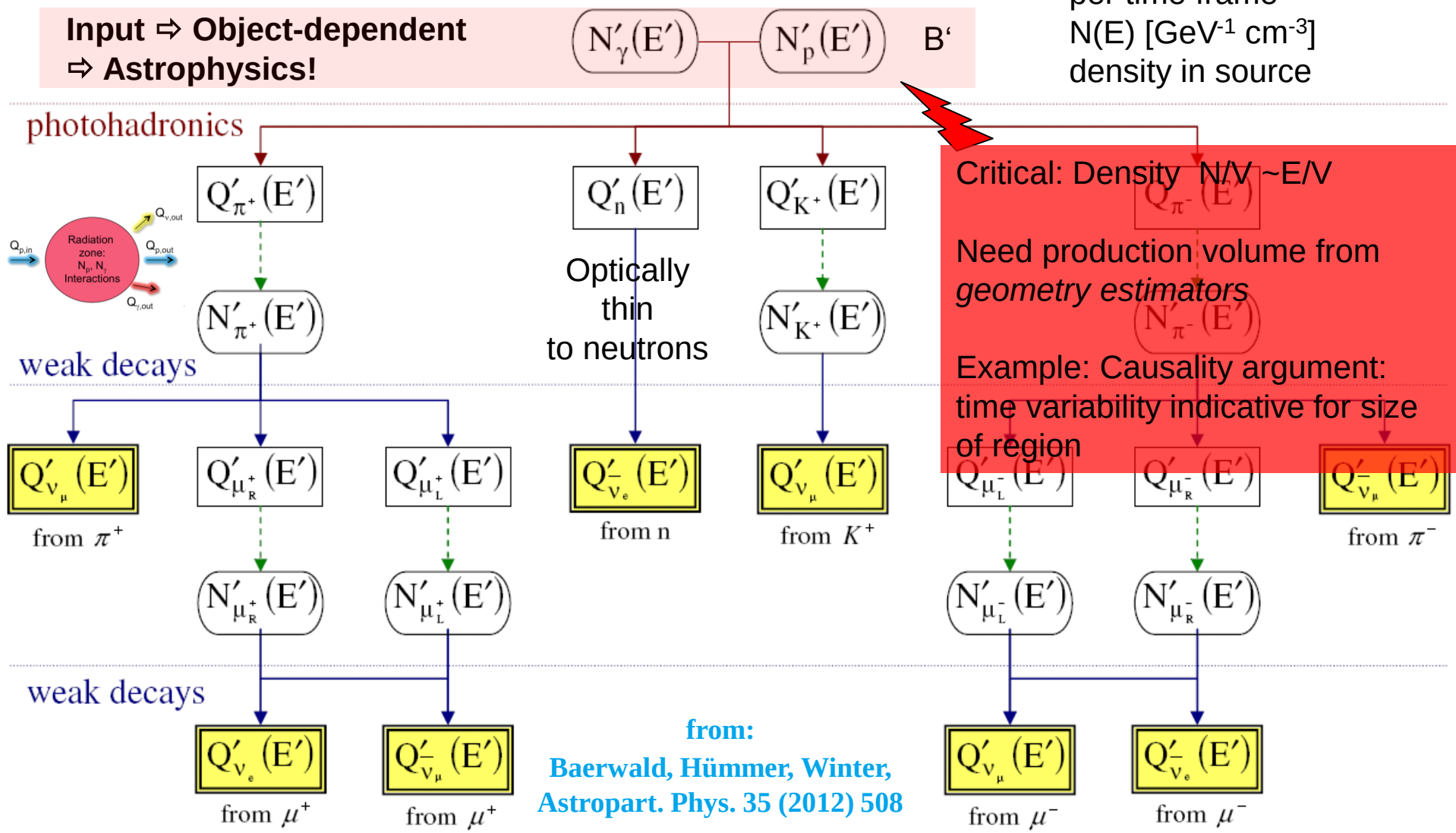
- Special case t_{esc} ~ R/c (free-streaming, aka “leaky box“)

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!



Critical: Density N/V ~E/V

Need production volume from *geometry estimators*

Example: Causality argument: time variability indicative for size of region

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

In the presence of strong B: Secondary cooling

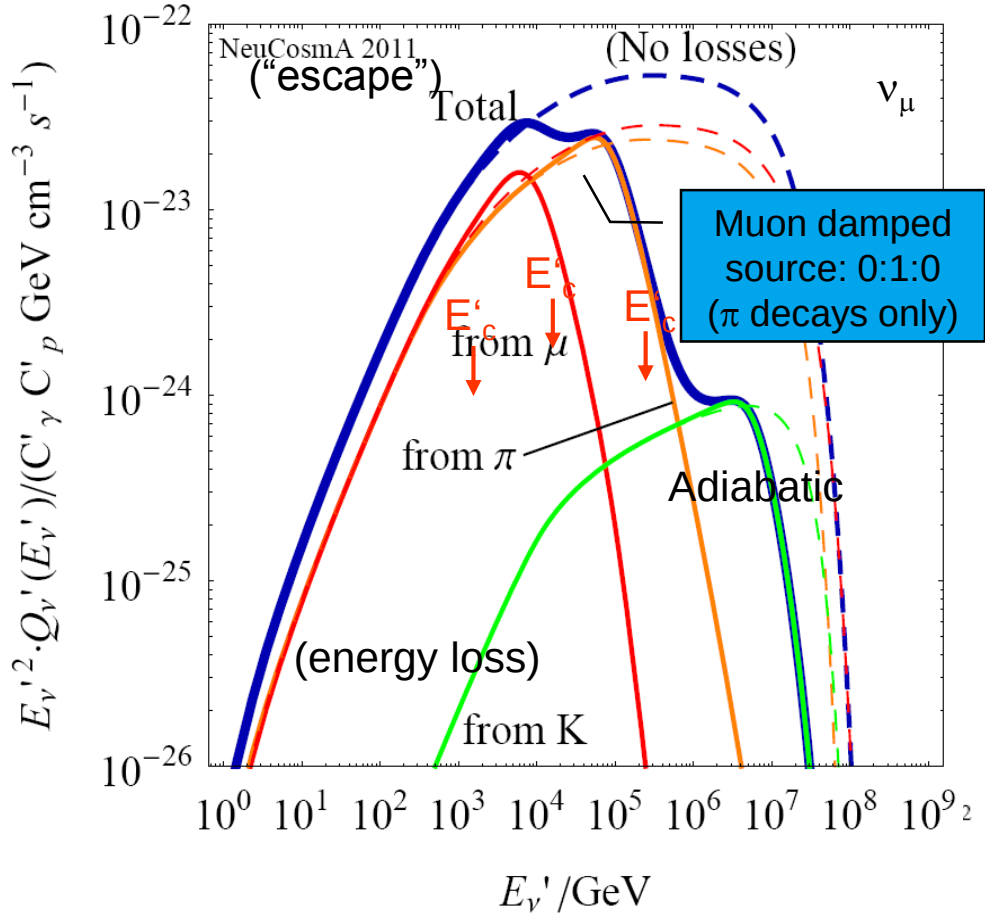
Example: GRB

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



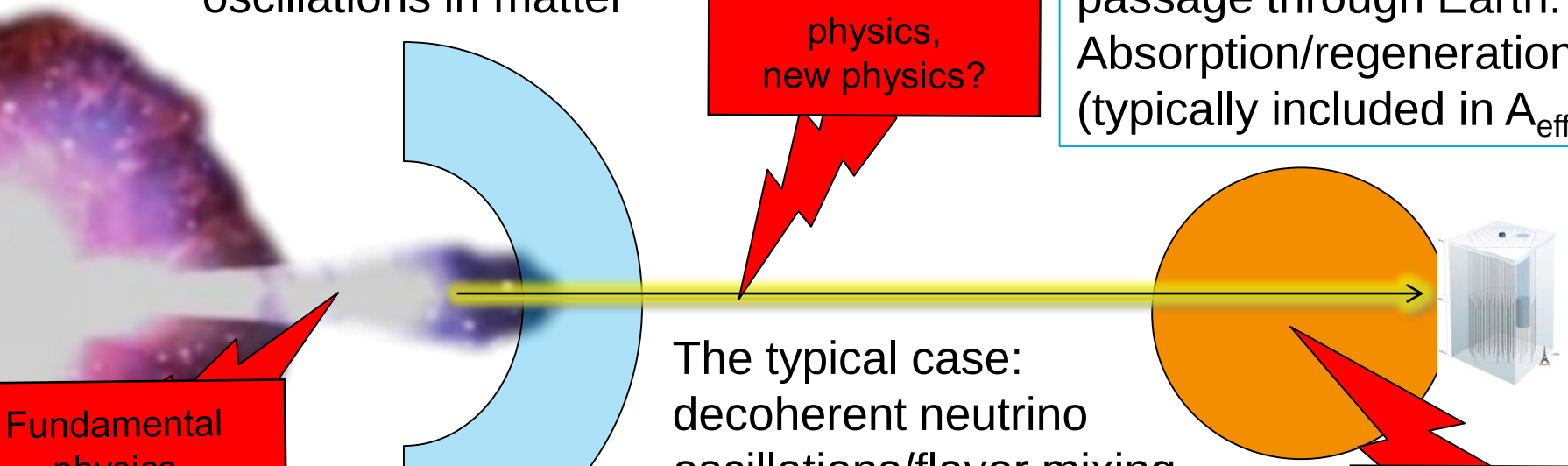
Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

Neutrino propagation: From source to detector

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

Fundamental physics, new physics?

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



Fundamental physics, new physics?

Fundamental physics, new physics?

Fundamental physics, new physics?

The typical case: decoherent neutrino oscillations/flavor mixing

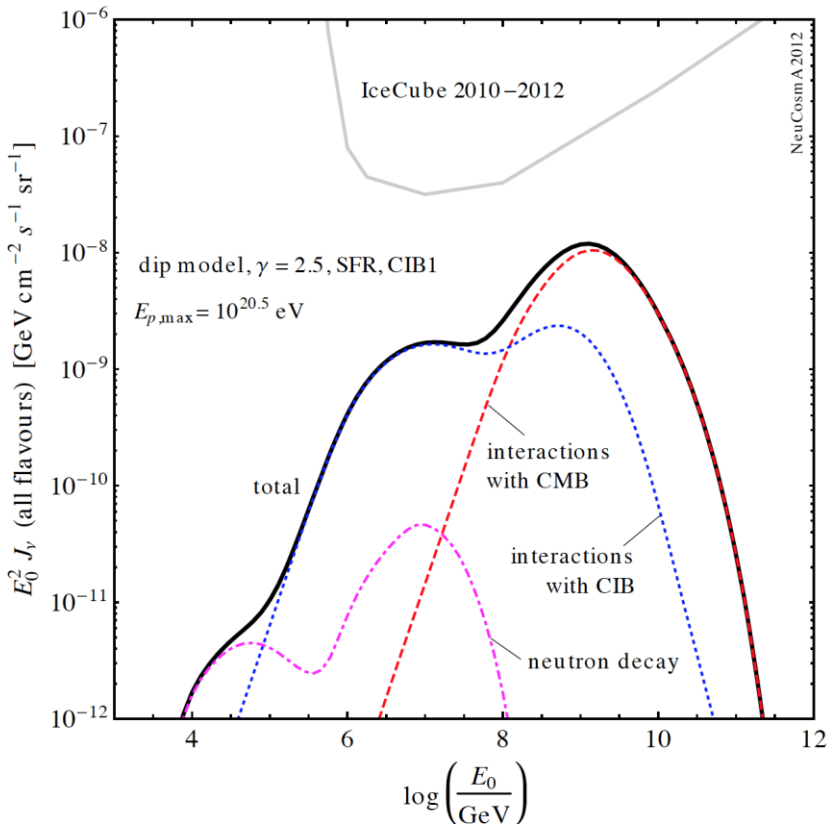
$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

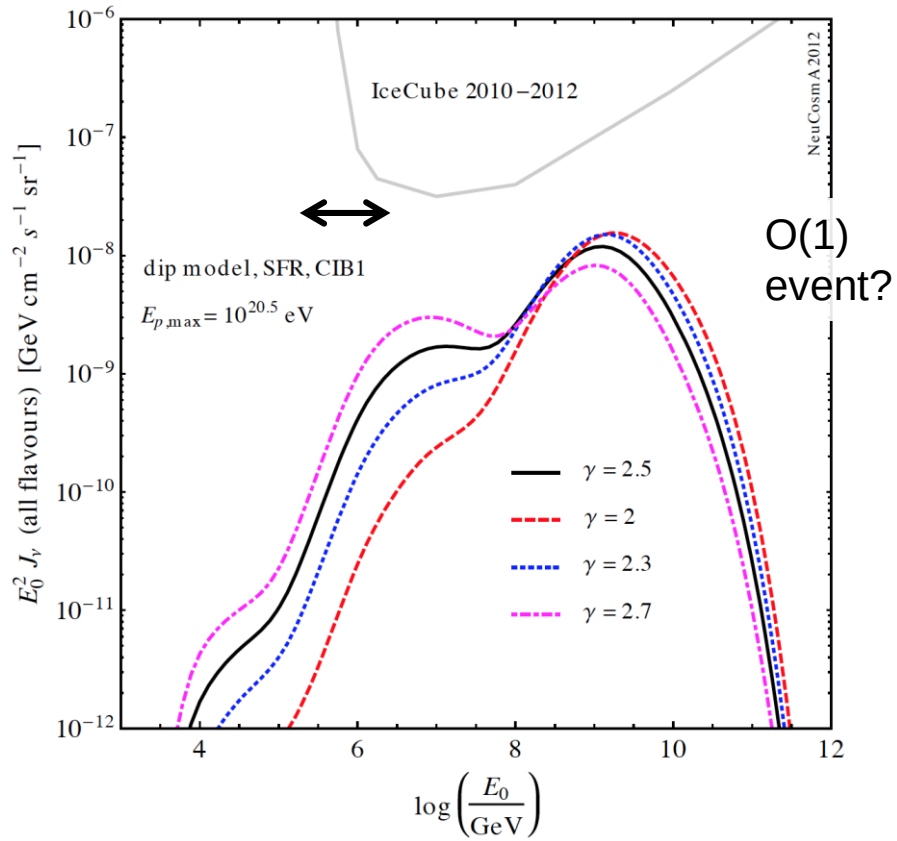
Source $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 ➔ Detector 1:1:1
+ redshift of energy if cosmological distance

On the signal interpretation

Can the signal come from cosmogenic neutrinos?
(or other contributions which we know that they are there?)

- PeV neutrinos from extragalactic (infrared) background interactions of UHECRs (here: protons)
- Even if protons, soft spectra etc, difficult to reach required flux





Figures: Bustamante. See also Roulet, Sigl, van Vliet, Mollerach, JCAP 1301 (2013) 028

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

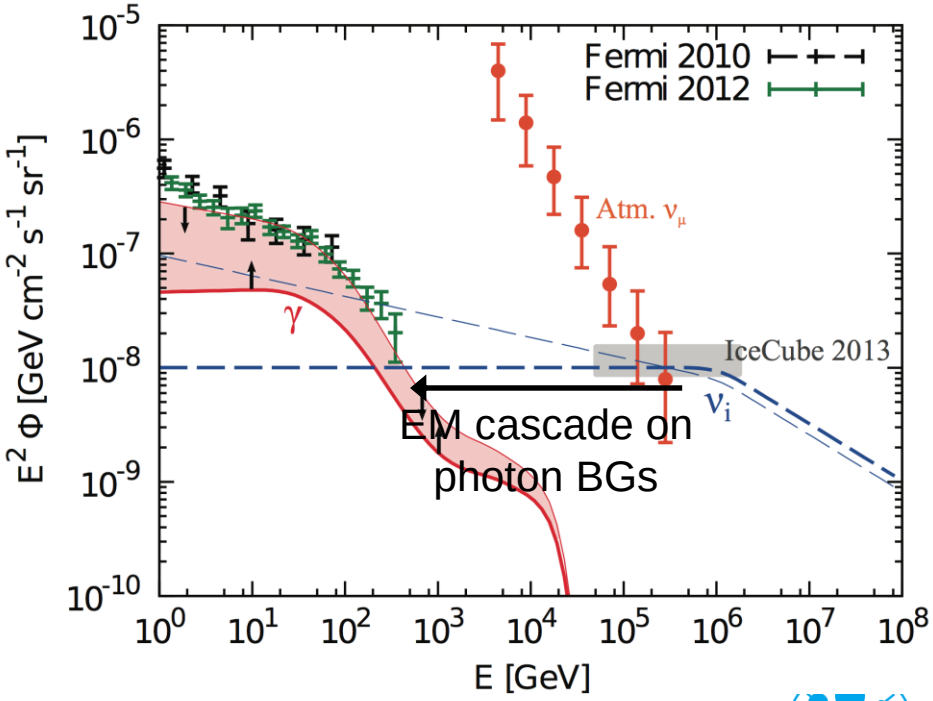
Astrophysics > High Energy Astrophysical Phenomena

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)

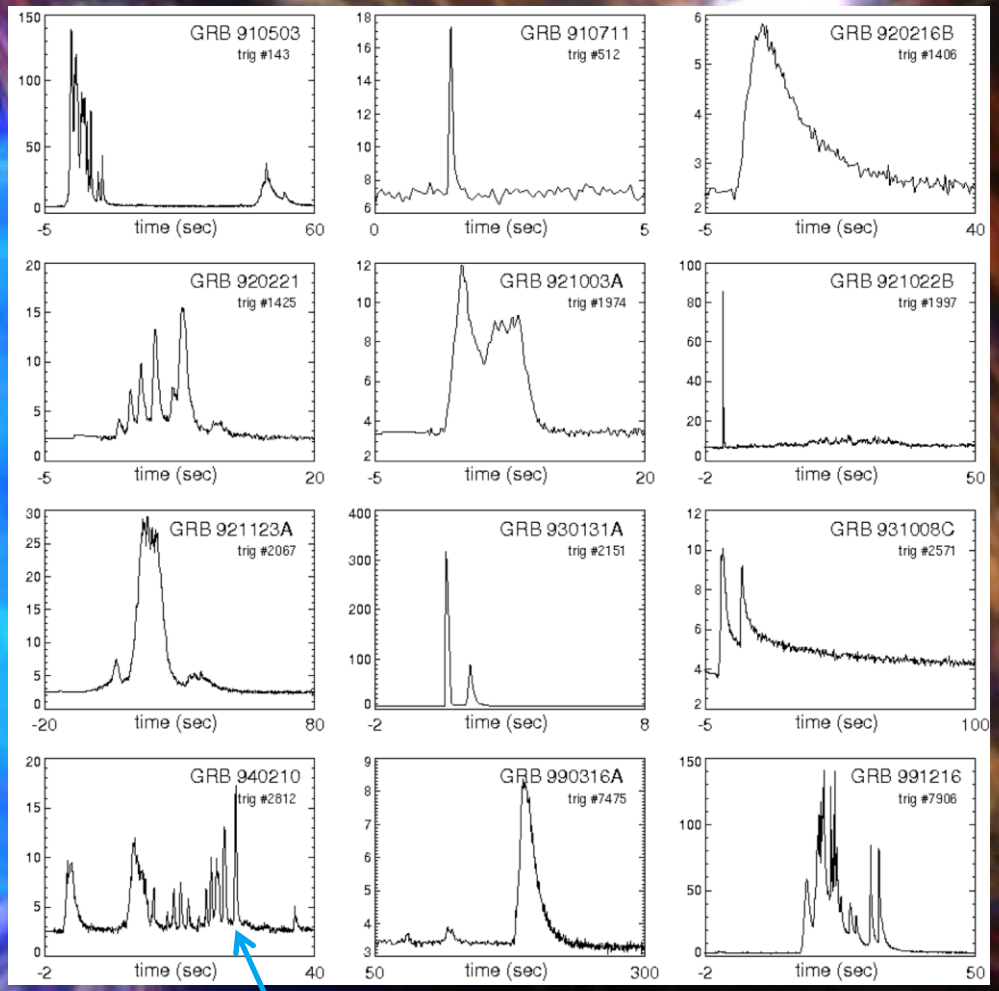
- For pp interactions: π^+, π^-, and π^0 same production spectrum
- Constraints from Fermi diffuse extragalactic background flux **Murase, Ahlers, Lacki, 2013**
- Problem may be even more severe: A large fraction of that background can be attributed to blazars **Bechtol et al, 2015**



Gamma-ray bursts (GRBs)

- Most energetic 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?
- Typical redshift ~ 1-3 (cosmological distances) Useful as “standard candles”?
- Observed light curves come in large variety

Daniel Perley

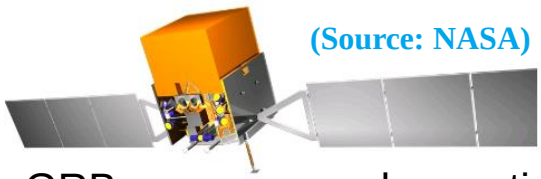


t_v: variability timescale

Source: NASA

Neutrino constraints on GRBs (one zone model)

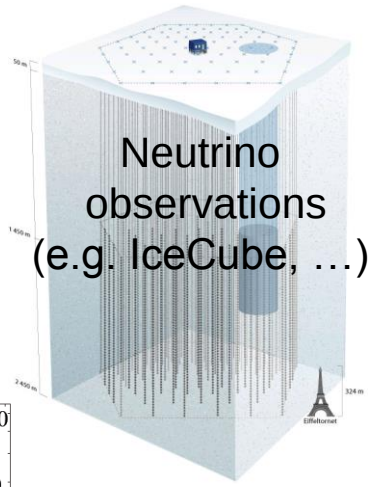
- Idea: Use timing and directional information to suppress atm. BGs



(Source: NASA)

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

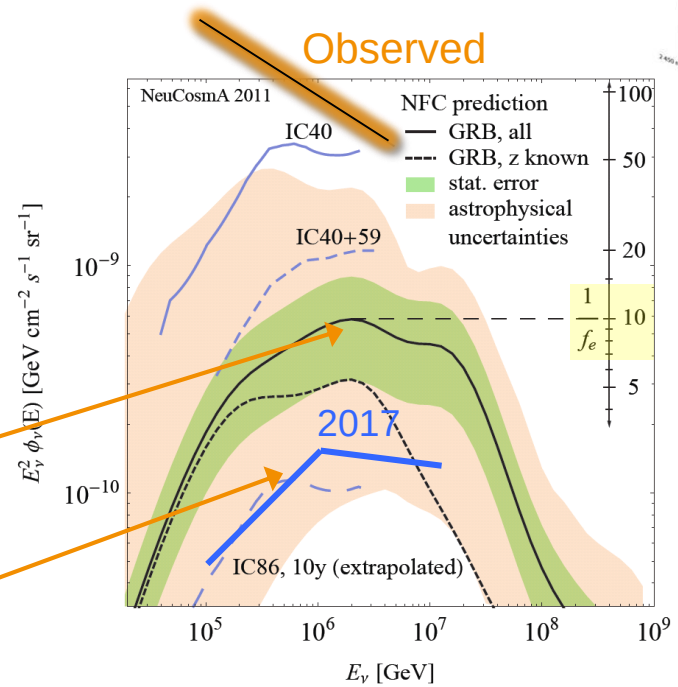
Coincidence!



Neutrino observations
(e.g. IceCube, …)

(Source: IceCube)

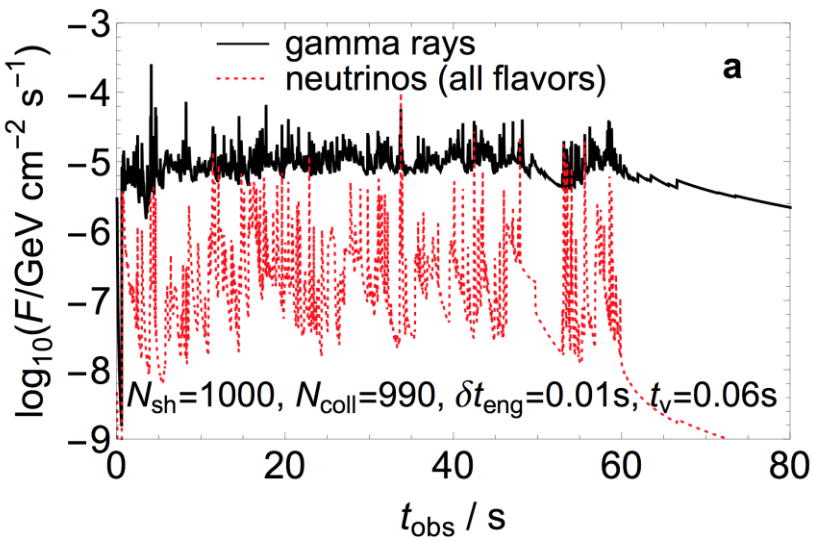
- Best tested astrophysical object class from stacking
  IceCube, Nature 484 (2012) 351; see arXiv:1702.06868 for latest update
- Not the dominant source of observed diffuse ν flux!
- Nominal prediction (depends on GRB sample)
- Current limit constrains average parameters relevant for ν production
  (e.g. **baryonic loading f_e^{-1}**, Γ, z)

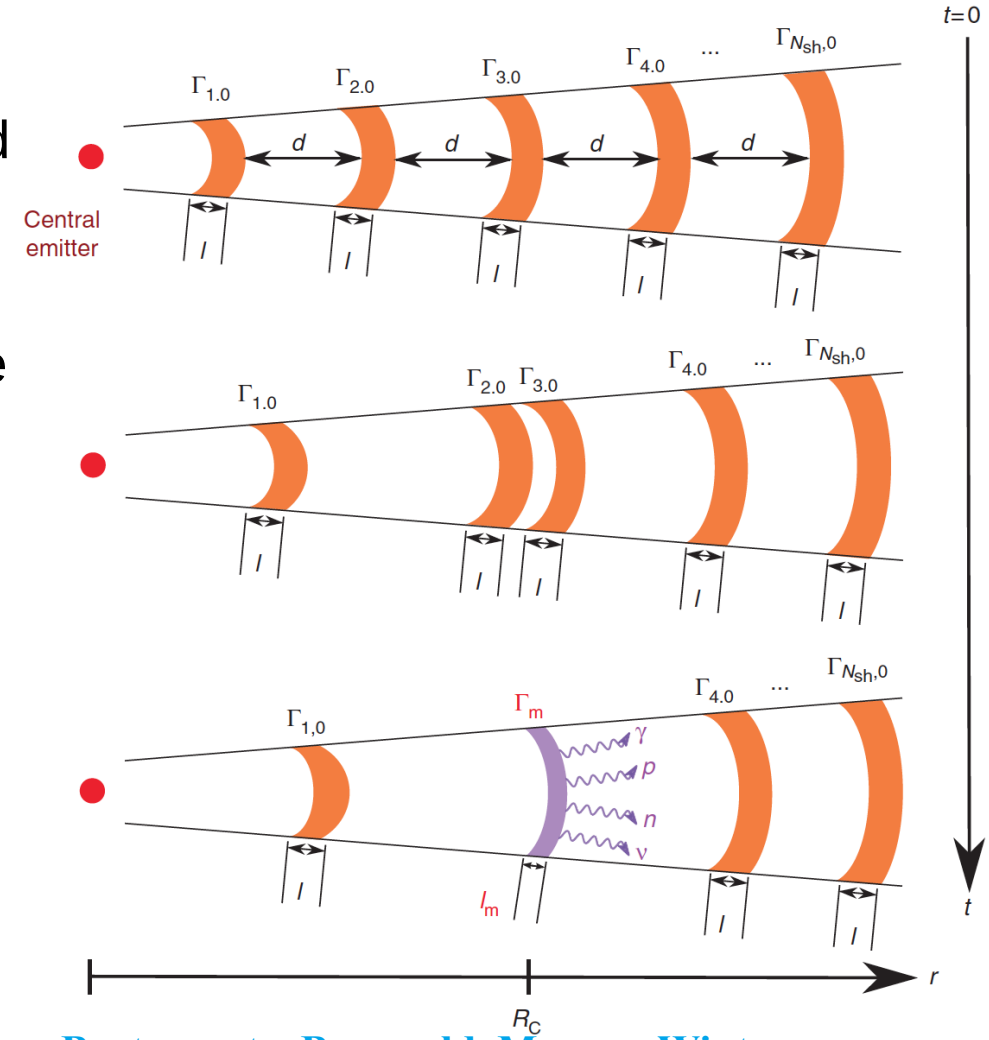


(from: Hümmer, Baerwald, Winter, PRL 108 (2012) 231101)

But: are these models realistic? Multi-zone models

- Set our shells with Γ distribution
- The light curves can be predicted as a function of the engine parameters
- Consequence: Collsions radii are widely distributed!
- Neutrino flux not linearly proportional to gamma-ray flux!

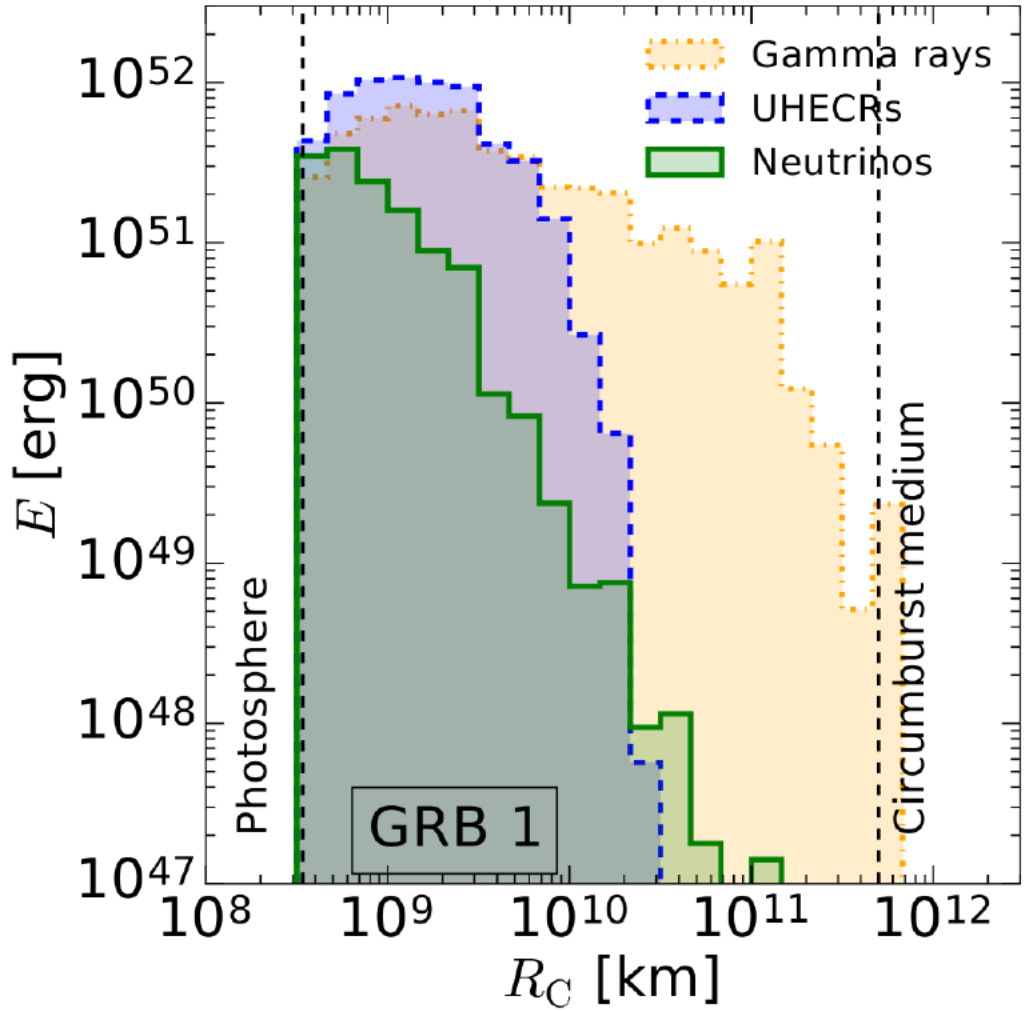




Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

Consequences for multiple messengers from one GRB

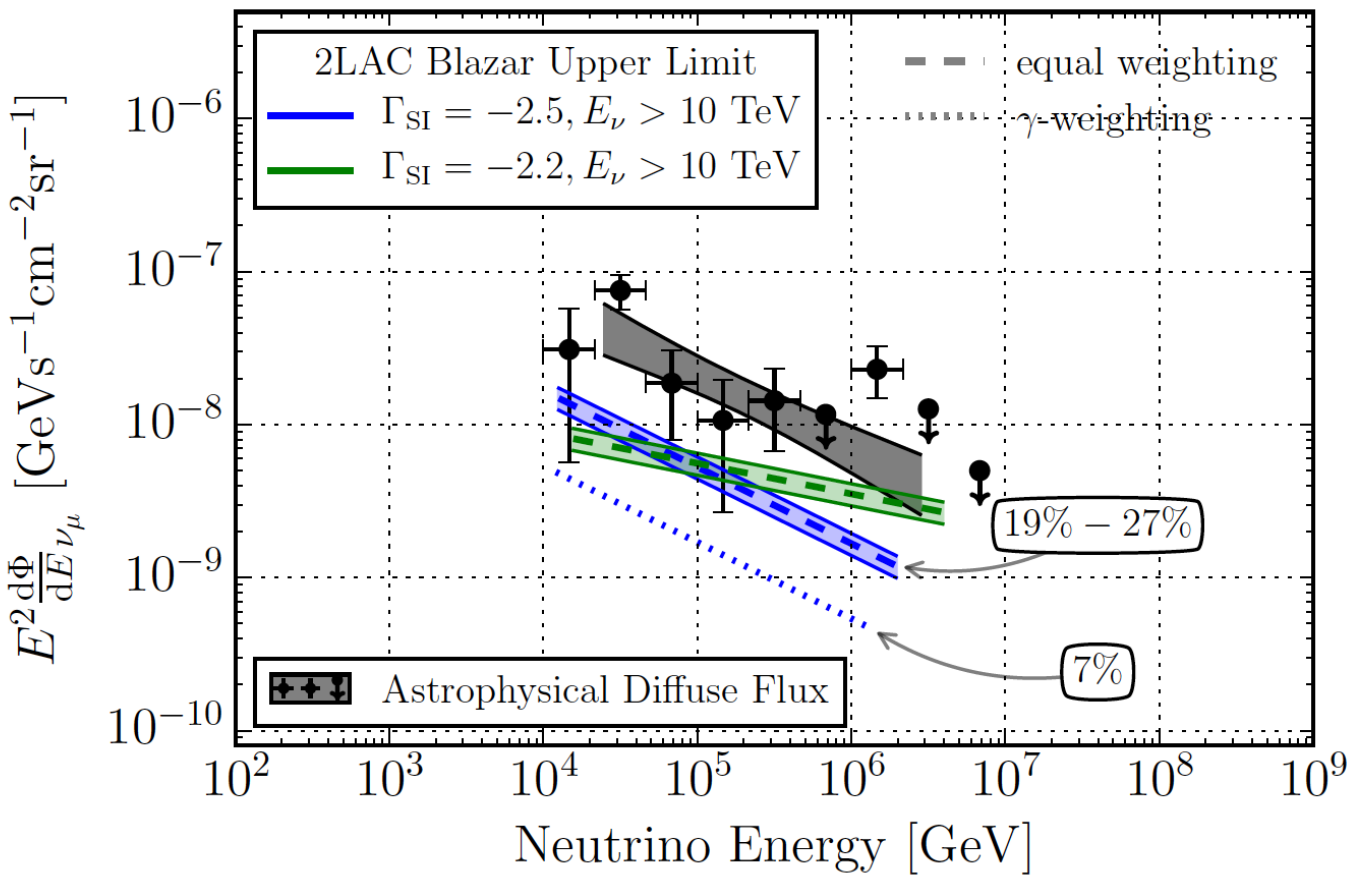
- The different messengers originate from different regimes of the GRB *where the photon densities are very different*
- Fundamental problem?Quantities inferred from γ-ray observations not representative for neutrinos and UHECRs?
- Neutrino flux prediction from collisions beyond photosphere
  $E^2 \phi \sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}



Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015); Bustamante, Heinze, Murase, Winter, Astrophys. J. 837 (2017) 33

So how about AGN blazars?

- AGN blazar search with 2nd Fermi-LAT catalogue (stacking analysis)
- No excess found, contribution to diffuse flux < 27%
- Not dominant contribution to neutrino flux
- Nevertheless few events from individual AGNs plausible



IceCube, Astrophys. J. 835 (2017) 45

PeV neutrino diffuse flux budget table (biased)

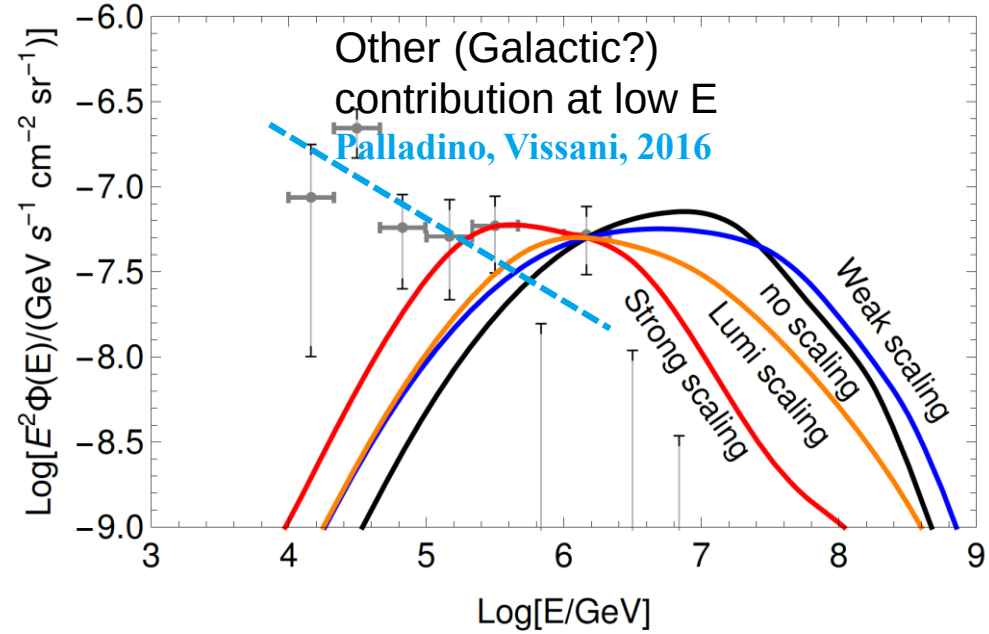
Object class	Contr.	Comments
Starburst galaxies + other “pp-calorimeters”	20%	From diffuse extragalatic gamma-ray background
AGN blazars	7-27%	From AGN stacking
Gamma-Ray Bursts	<5%	From GRB stacking
Cosmogenic neutrinos	<10%	Composition+model dependent
Galactic cosmic ray-hydrogen interactions	<10%	Disputed (depends on Galactic cosmic ray distribution)
Other Galactic sources	1-16%	See e.g. arXiv:1610.07015, arXiv:1703.09721
Choked jets	?	Very speculative

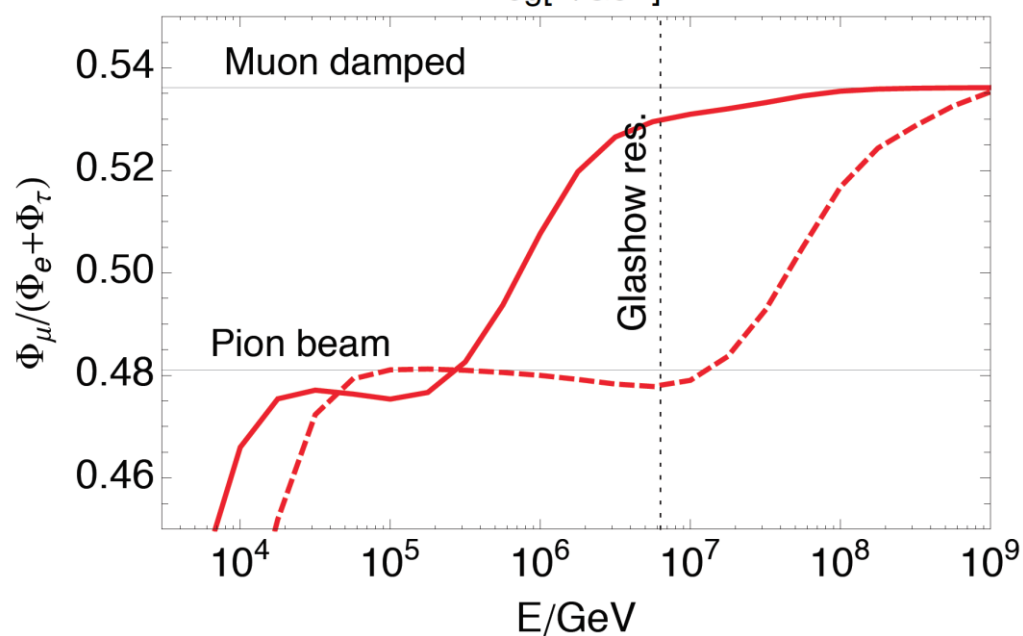
- Dominant source class not yet identified?
- Many source classes contribute at similar levels?
- Or just manifestation of what we have seen at the GRB example: efficient neutrino producers (compact) ≠ efficient gamma-ray emitters?

Unconventional possibilities? Ex.: Tidal Disruption Events

- Tidal disruption of a massive star can lead to jet formation
- Can describe/saturate diffuse neutrino flux (spectrum+normalization) for appropriate scaling choice of Γ, t_v with black hole mass function
  Lunardini, Winter, arXiv:1612.03160
- However: yet too low TDE statistics for meaningful statements
- Smoking gun signature: muon damping at high energies ⟶

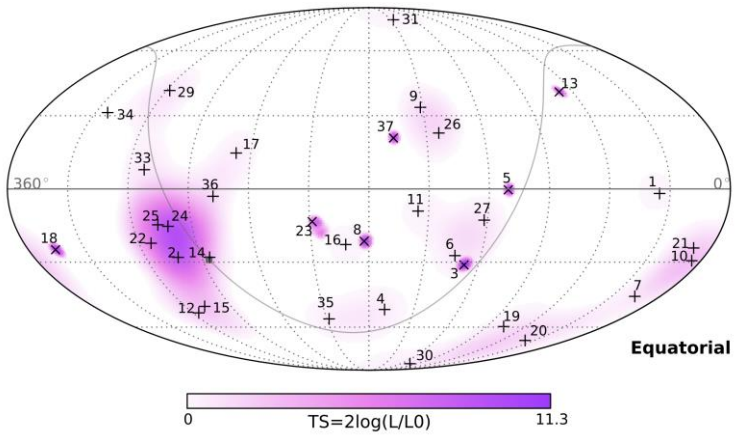
Wang, Liu, Dai, Cheng, 2011; Wang, Liu, 2016; Dai, Fang, 2017; Senno, Murase, Meszaros, 2017; Lunardini, Winter, 2017





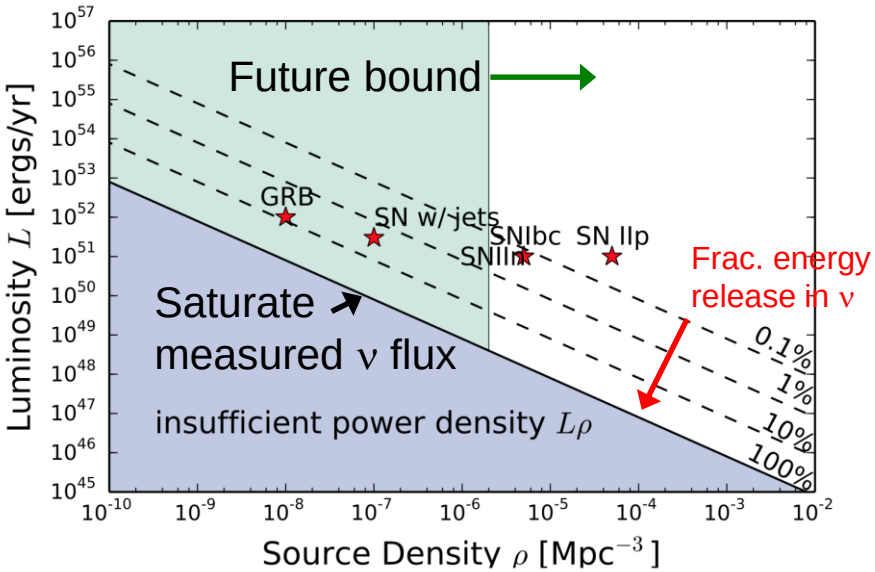
Observational search strategies (examples)

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

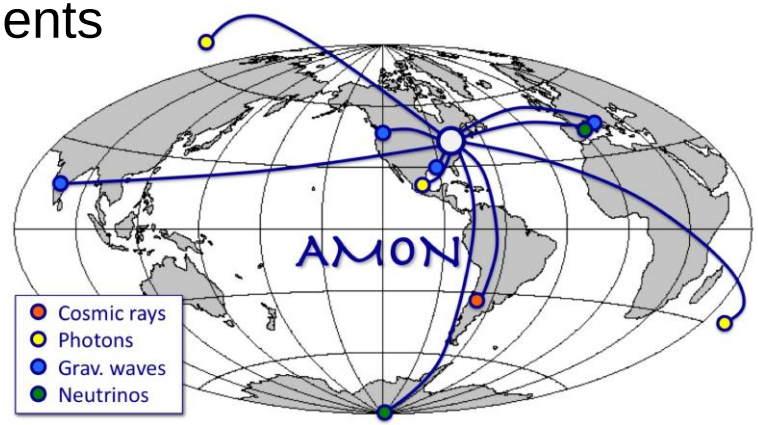


- Correlations with known objects/ events in gamma-ray catalogues?
  (e. g. Padovani, Resconi, arXiv:1406.0376; Mertsch, Rameez, Tamborra, arXiv:1612.07311, …)

- Use constraints on event multiplets to constrain source density
  (from Kowalski, arXiv:1411.4385; see also Ahlers, Halzen, arXiv:1406.2160; Murase, Waxman, arXiv:1607.01601)

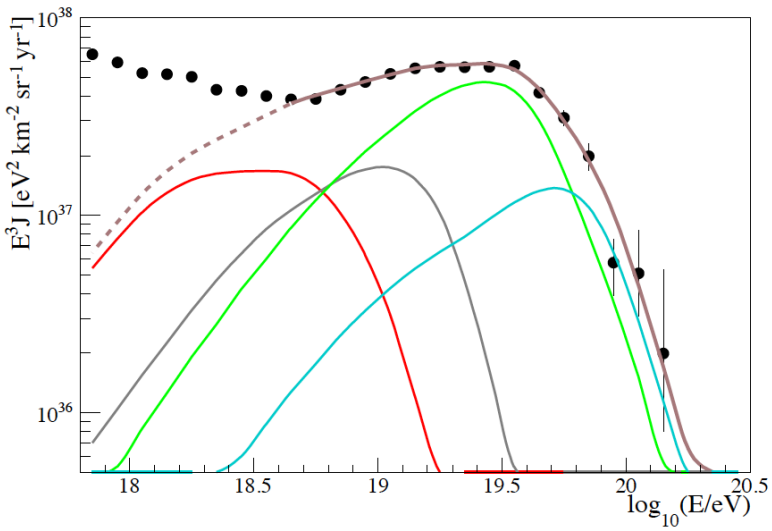


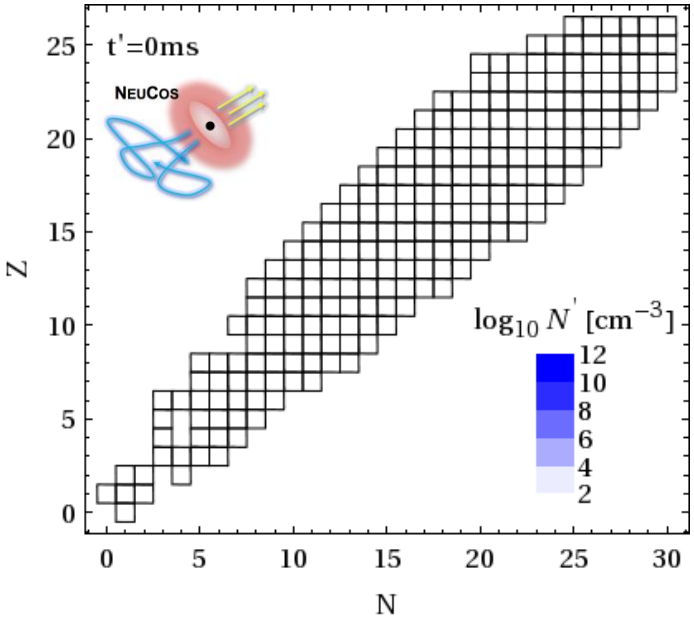
- Multi-messenger triggers for transients

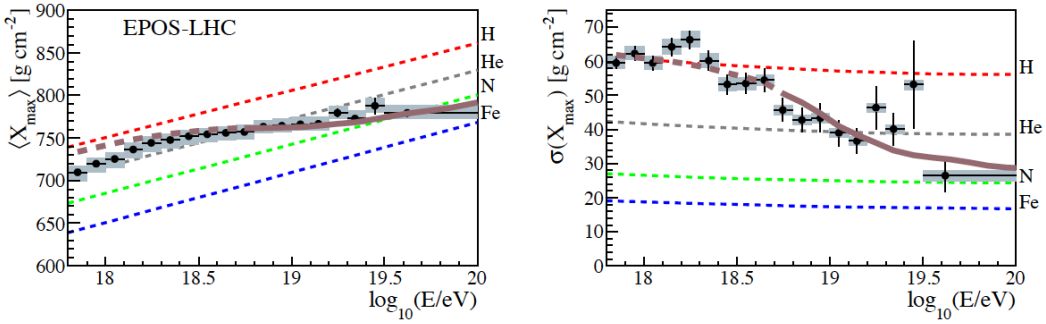


Neutrinos to test origin of cosmic rays: Theory challenges

- Auger data indicate that cosmic rays at highest energies are not protons. Best fit propagation model ⟶
- Implications for neutrino flux from sources in which a nuclear cascade can develop?







Auger, arXiv:1612.07155

Boncioli, Fedynitch, Winter, 2016; Biehl et al, 2017 (to appear)

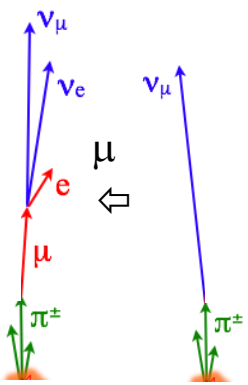
Flavor composition for tests of fundamental physics

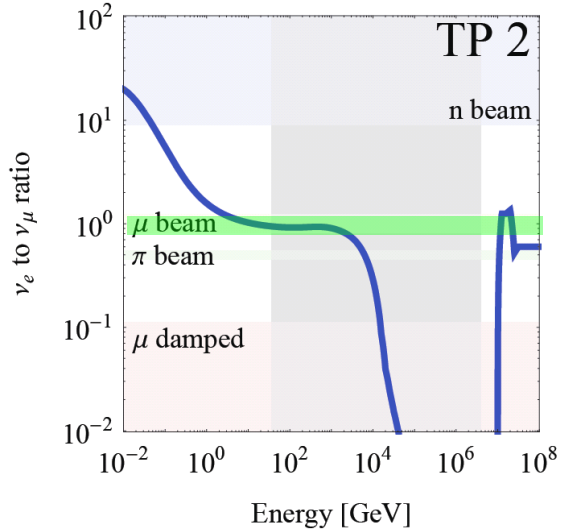
(neutrino propagation)

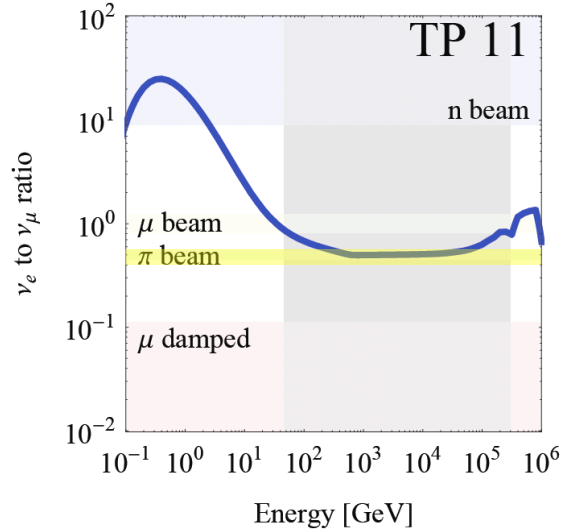
Flavor composition at source from numerical simulations

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

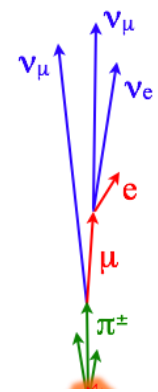
Muon beam
- muon damped





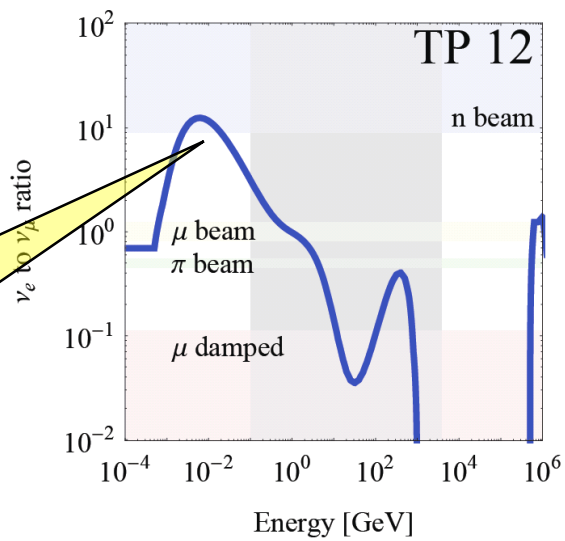


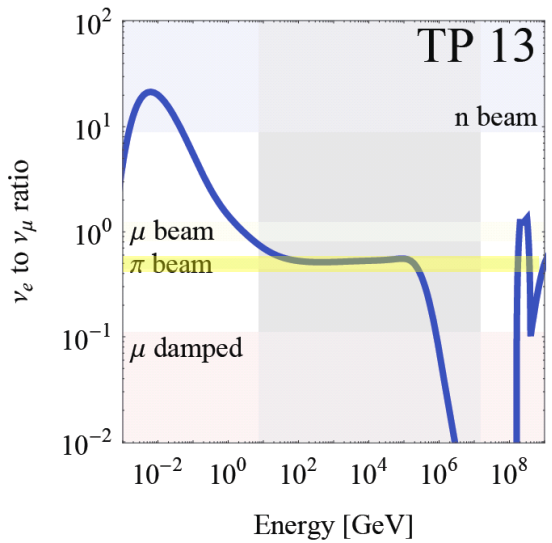
Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



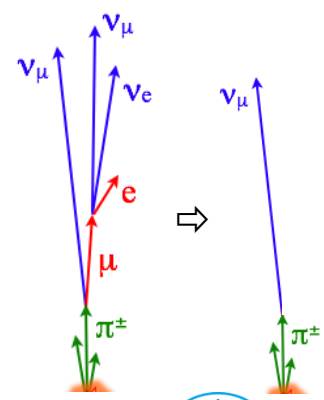
Undefined
(mixed source)

Typically
n beam
for low E
(from pγ)





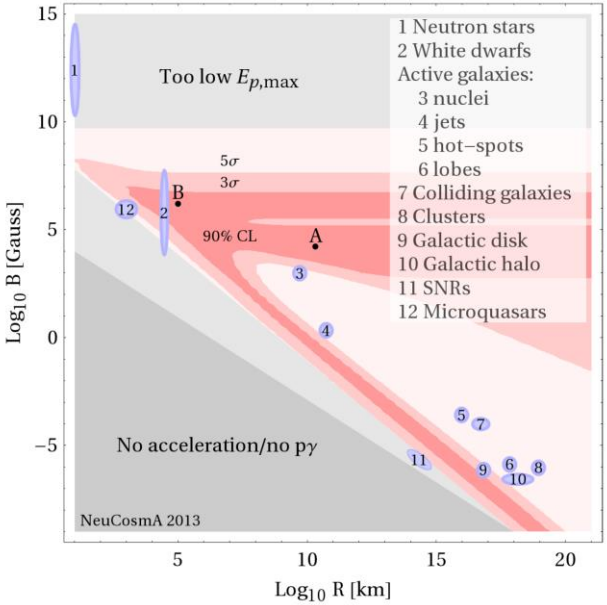
Pion beam
⇨ muon damped



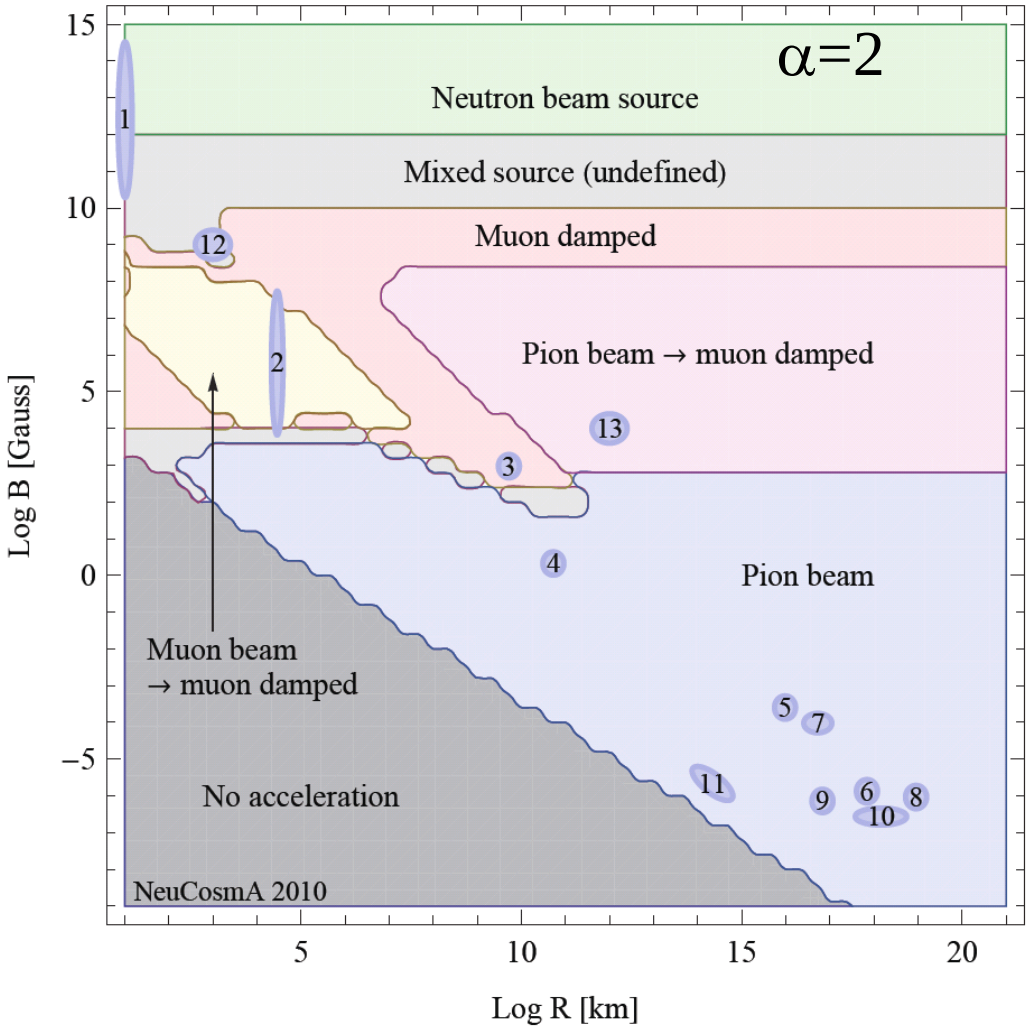
(from Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205)

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!
- Parameter fit to IC-data:



Winter, arXiv.1307.2793

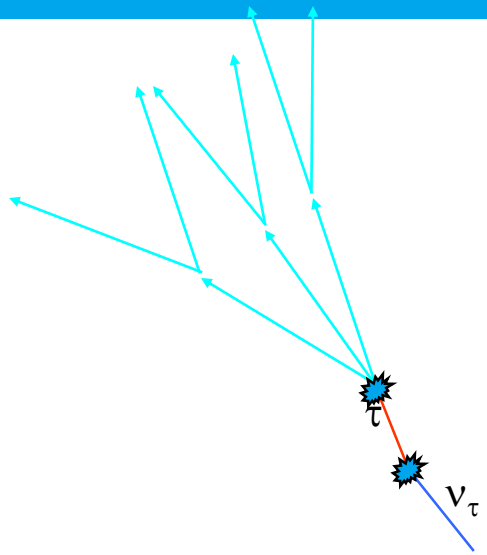


Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

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:

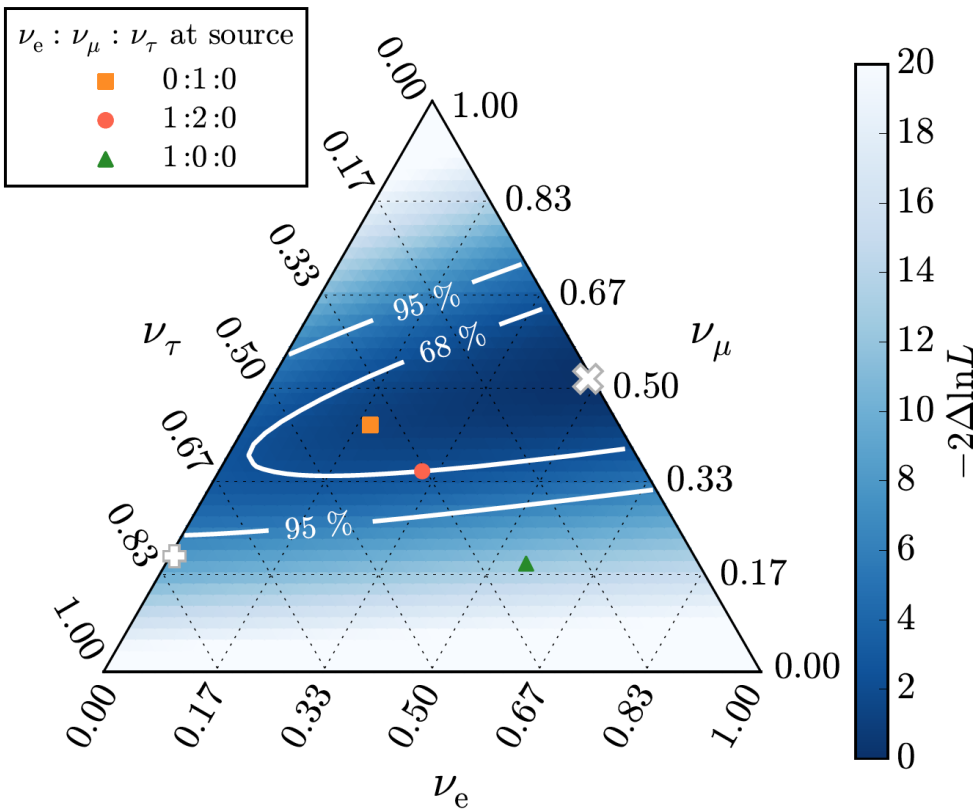
$$\hat{R} = \frac{\phi_\mu^{\rm Det}}{\phi_e^{\rm Det} + \phi_\tau^{\rm Det}}$$

(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

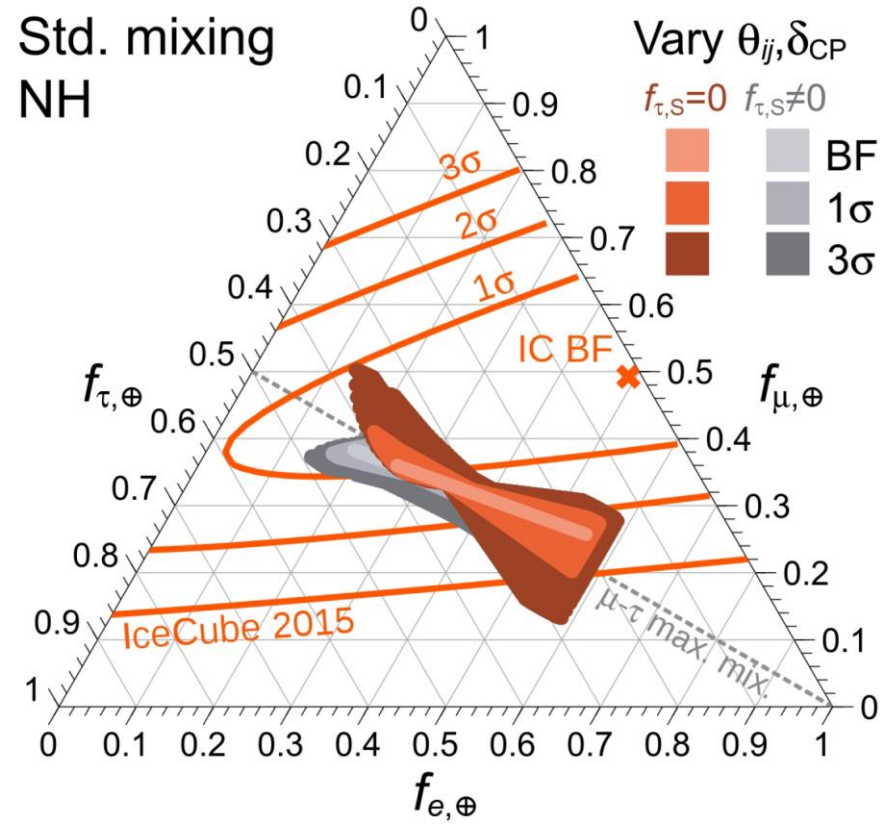
Flavor triangles

> Measurement



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

> SM expectation

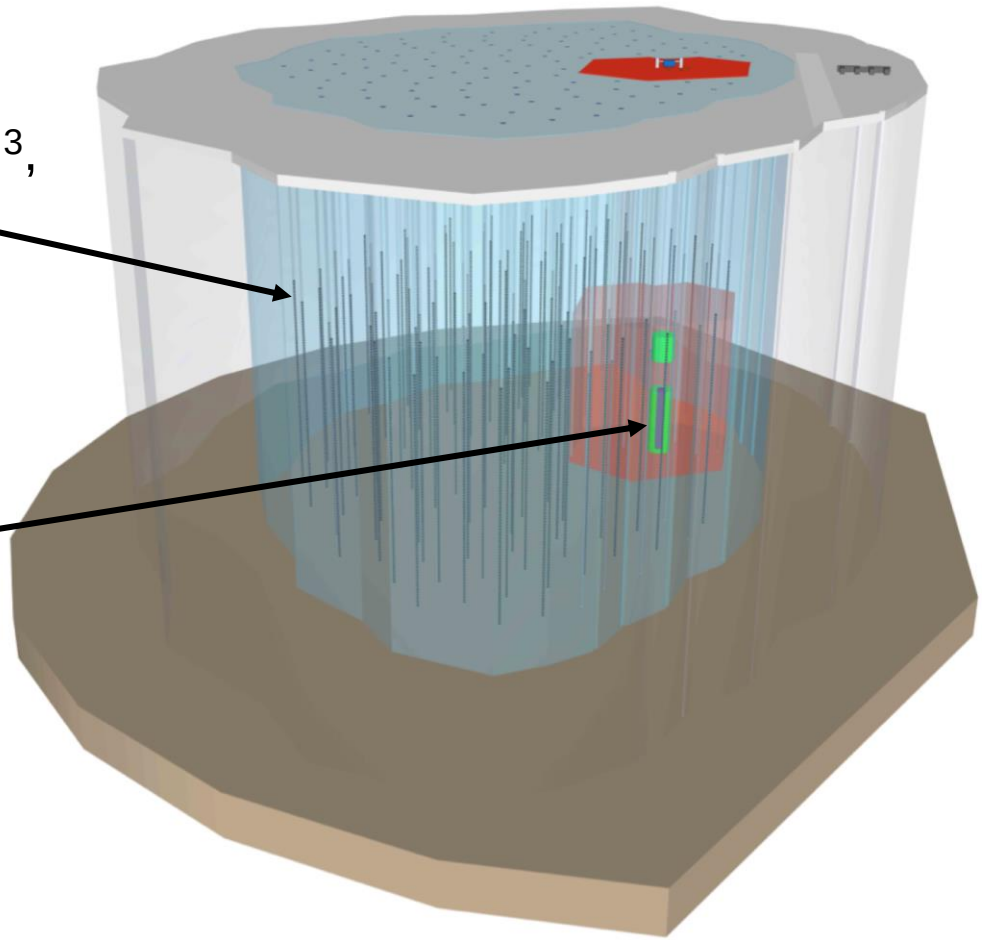


Bustamante, Beacom, Winter,
PRL 115 (2015) 16, 161302

(there is a marginal tension …)

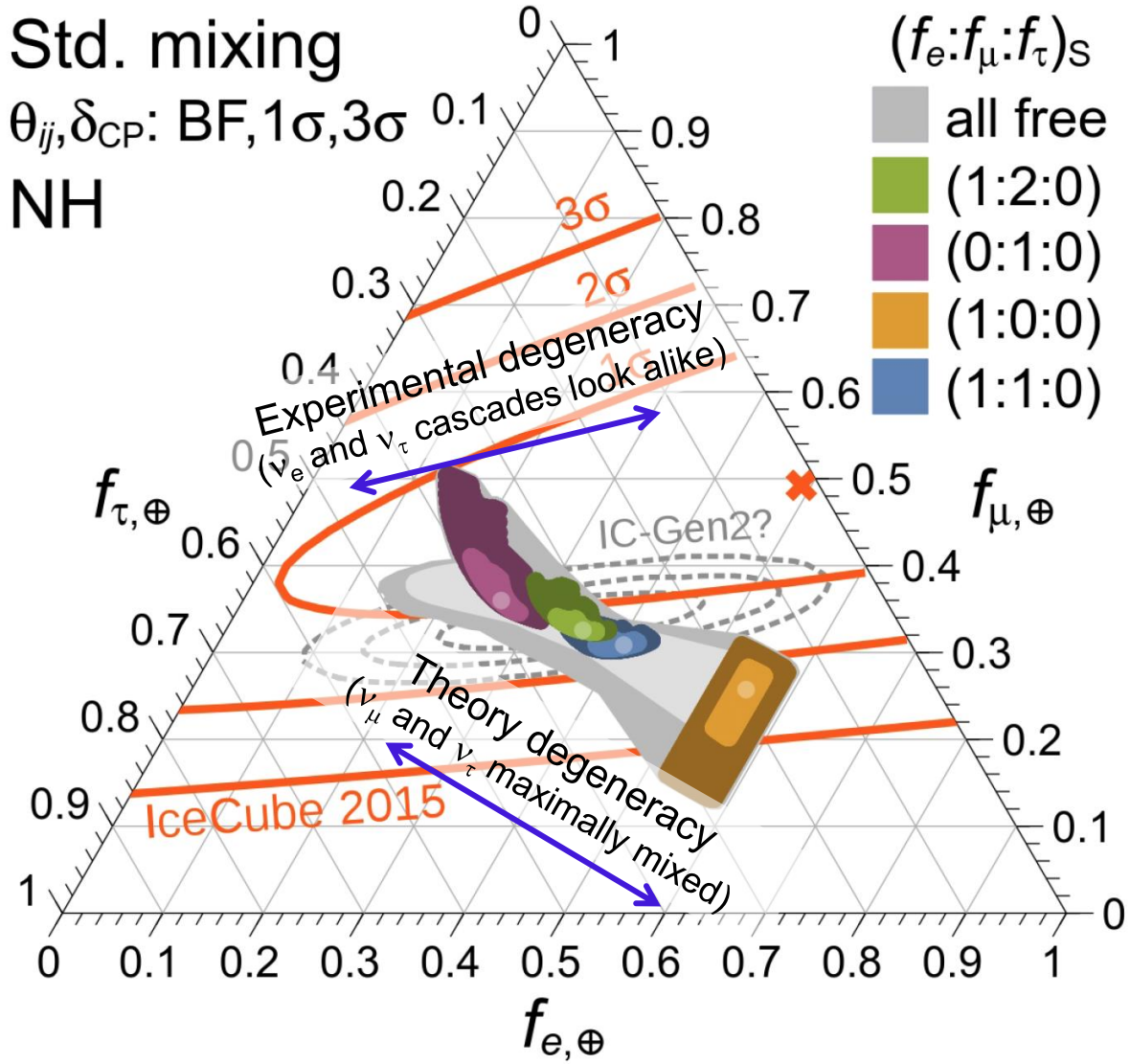
Higher precision from IceCube – Generation Two?

- 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, arXiv:1601.07459)

The future: SM expectations vs. measurement?



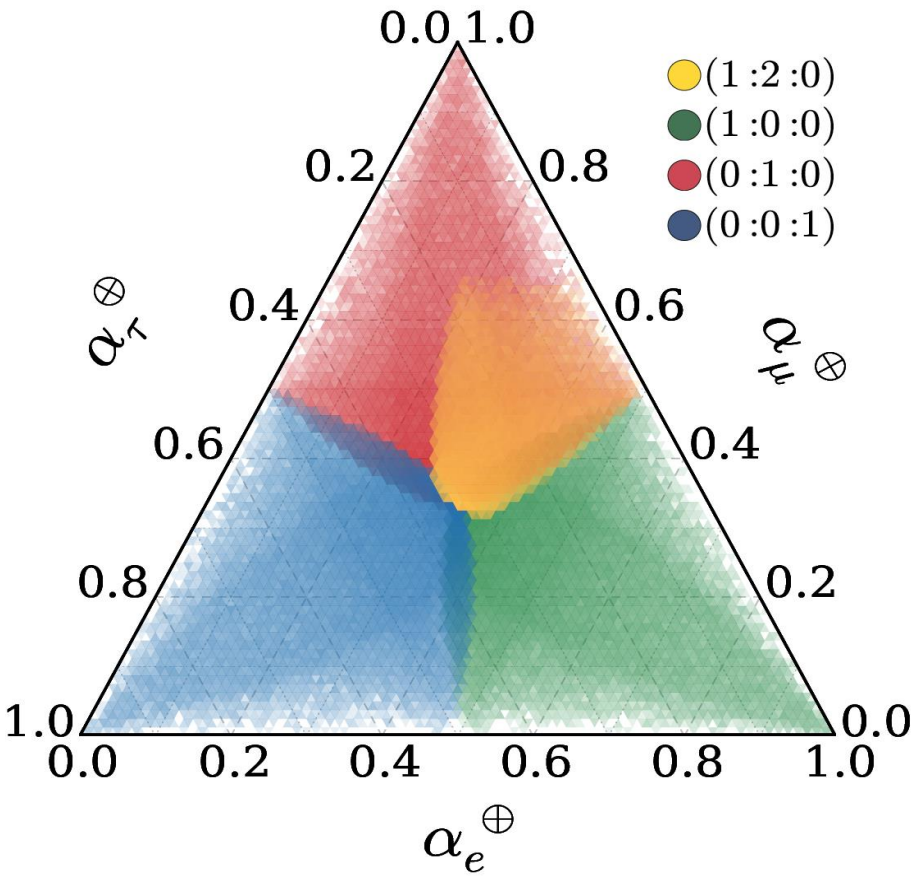
(shaded regions: current 3σ range for mixing params)

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

- IceCube-Gen2 could exclude the current best-fit point
- Allowed regions for specific flavor compositions at source even smaller

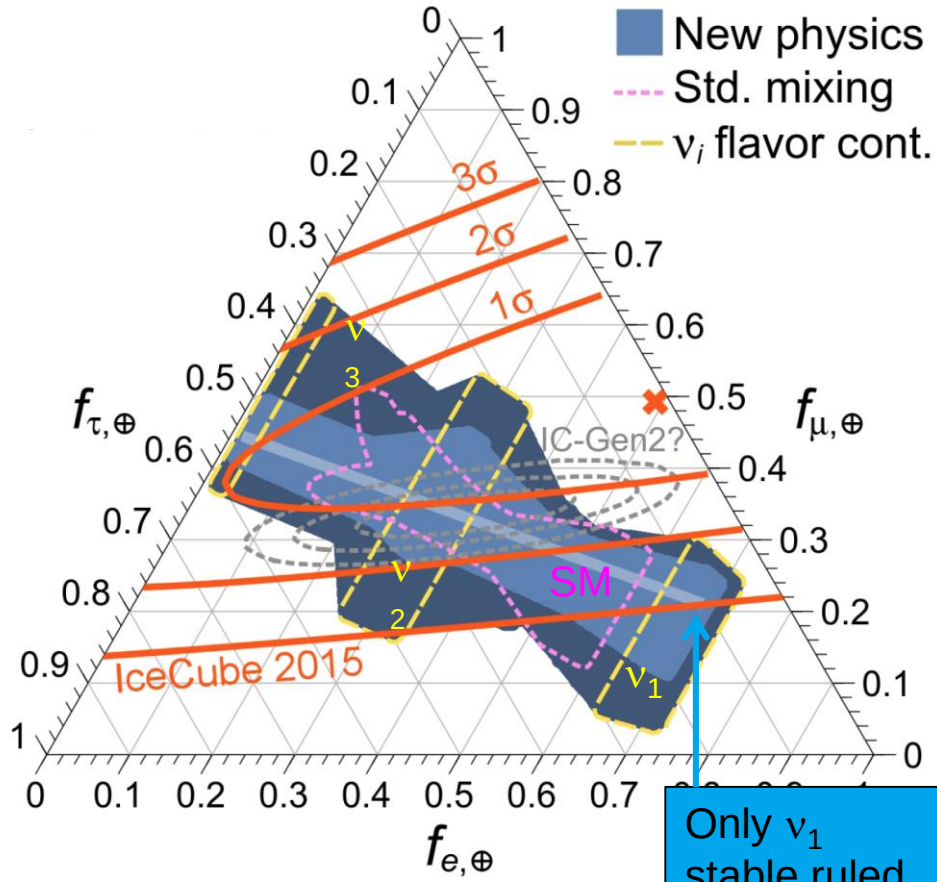
What if there is physics beyond the Standard Model?

Effective operators (CPT violation) changing Hamiltonian at high E



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

Effects leading to *incoherent* superposition of mass eigenstates



Only ν_1 stable ruled out at 2σ

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

Same issue!

Neutrino-antineutrino composition, and the Glashow resonance

The "standard" picture: Neutrino production

- Neutrino production in pγ interactions:

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

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

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

$$(\xi_e, \xi_\mu, \xi_\tau, \bar{\xi}_e, \bar{\xi}_\mu, \bar{\xi}_\tau) = \left(\frac{1}{3}, \frac{1}{3}, 0, 0, \frac{1}{3}, 0\right)$$

- Neutrino production in pp interactions:

$$\mathrm{p} + \mathrm{p} \to \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

$$(\xi_e, \xi_\mu, \xi_\tau, \bar{\xi}_e, \bar{\xi}_\mu, \bar{\xi}_\tau) = \left(\frac{1}{6}, \frac{1}{3}, 0, \frac{1}{6}, \frac{1}{3}, 0\right)$$

Yield different electron antineutrino fraction

Model discriminator?

Anchordoqui, Halzen, Goldberg, Weiler, 2005; …

Neutrino detection at the Glashow resonance

- Neutrino detection at Glashow resonance

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$$

  at 6.3 PeV is sensitive to electron antineutrinos

- Neutrino mixing yields an intrinsic "contamination" from muon antineutrinos (TBM approx.):

$$\xi^f_{\bar{\nu}_e} \simeq \frac{5}{9}\,\xi_{\bar{\nu}_e} + \frac{2}{9}\,\xi_{\bar{\nu}_\mu}$$

- The π^- decay chain yields about 3.5 as many electron antineutrinos at Earth as the π^+ decay chain

- Potentially dangerous if contamination from π^-; such contaminations are expected even in $p\gamma$ interactions
  Hümmer et al, Astrophys. J. 721 (2010) 630; Hümmer et al, Astropart. Phys. 34 (2010) 205

Particle physics caveats

- Kinematics of pion/muon decays

  Deviations depending on spectral index

Production	α	ξ_{ν_e}	ξ_{ν_μ}	ξ_{ν_τ}	$\bar{\xi}_{\nu_e}$	$\bar{\xi}_{\nu_\mu}$	$\bar{\xi}_{\nu_\tau}$
Reference pp	any	0.167	0.333	0	0.167	0.333	0
Ideal pp	2.0	0.175	0.325	0	0.175	0.325	0
Ideal pp	2.3	0.179	0.321	0	0.179	0.321	0
Ideal pp	2.6	0.183	0.317	0	0.183	0.317	0
Reference pγ	any	0.333	0.333	0	0	0.333	0
Ideal pγ	2.0	0.350	0.290	0	0	0.360	0
Ideal pγ	2.3	0.358	0.273	0	0	0.369	0
Ideal pγ	2.6	0.366	0.256	0	0	0.378	0

- Monte Carlo results

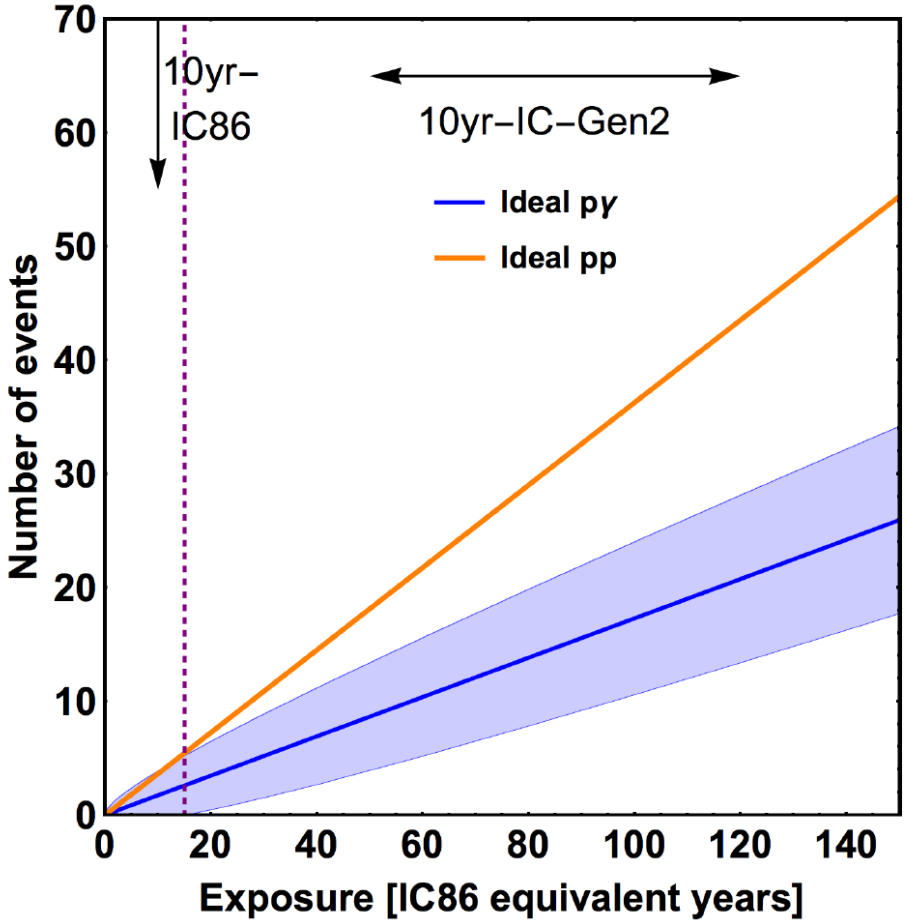
  (Sibyll 2.3, EPOS-LHC and QGSJET-II-04 yield similar results for pp)

Source	α	ξ_{ν_e}	ξ_{ν_μ}	ξ_{ν_τ}	$\xi_{\bar{\nu}_e}$	$\xi_{\bar{\nu}_\mu}$	$\xi_{\bar{\nu}_\tau}$	δ
pp	2.0	0.194	0.321	0	0.156	0.329	0	16%
pp	2.3	0.204	0.314	0	0.153	0.329	0	22%
pp	2.6	0.217	0.305	0	0.149	0.329	0	30%

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033

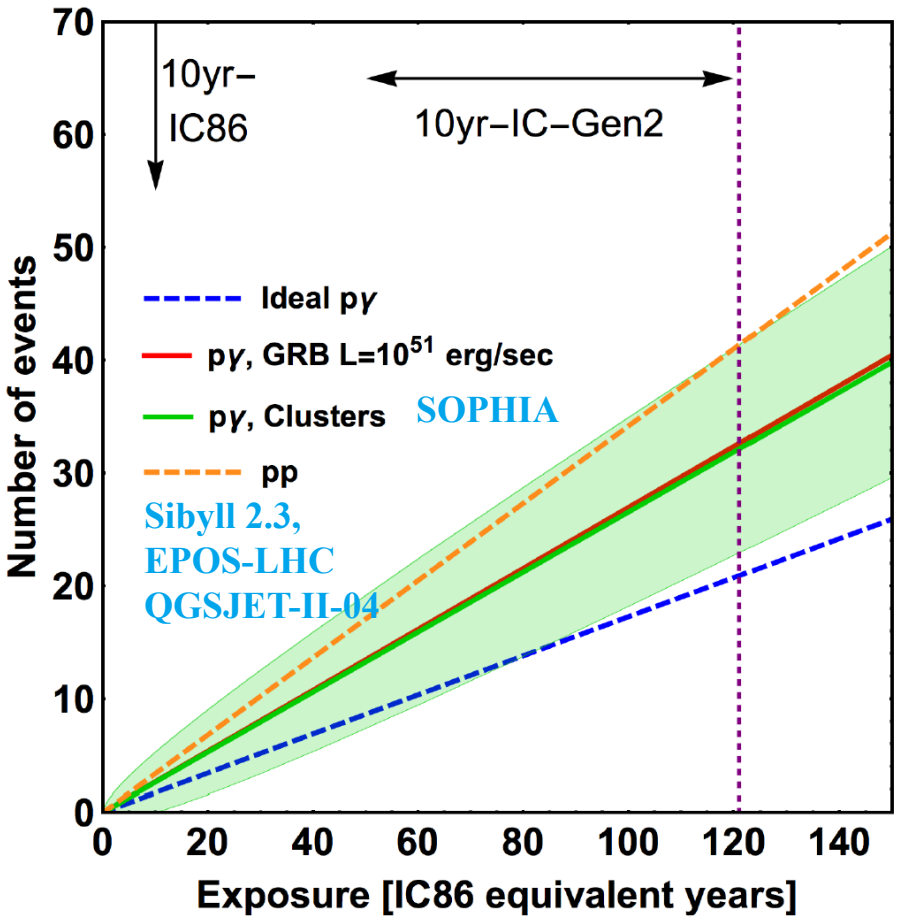
Source discrimination: pp versus pγ (optimistic case α~2)

Ideal picture



Discrimination in IceCube

Monte Carlo results

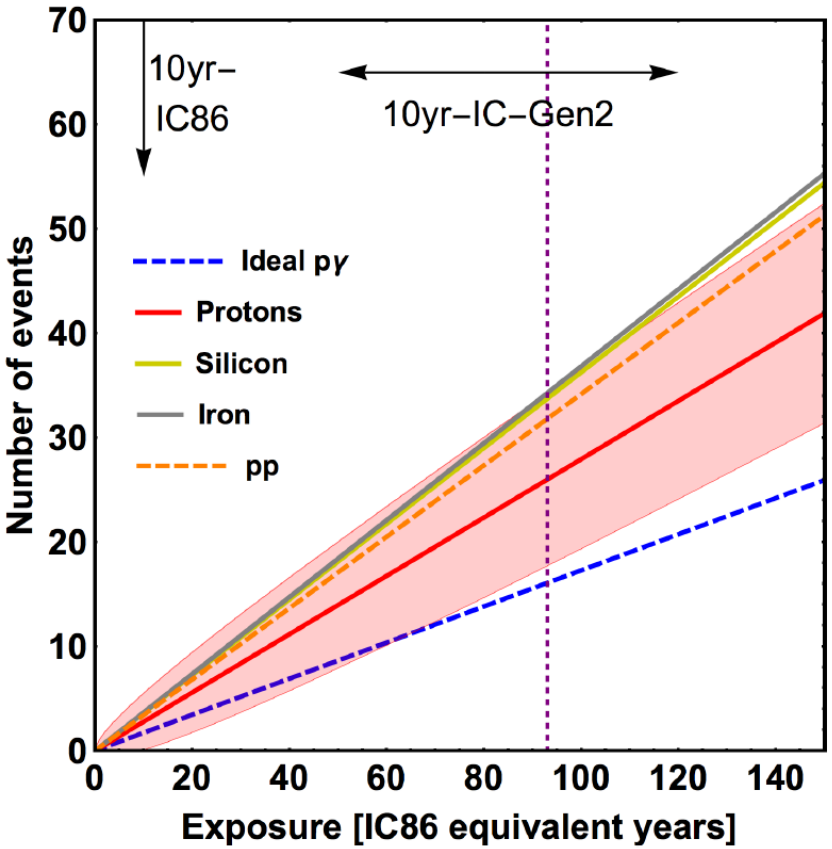


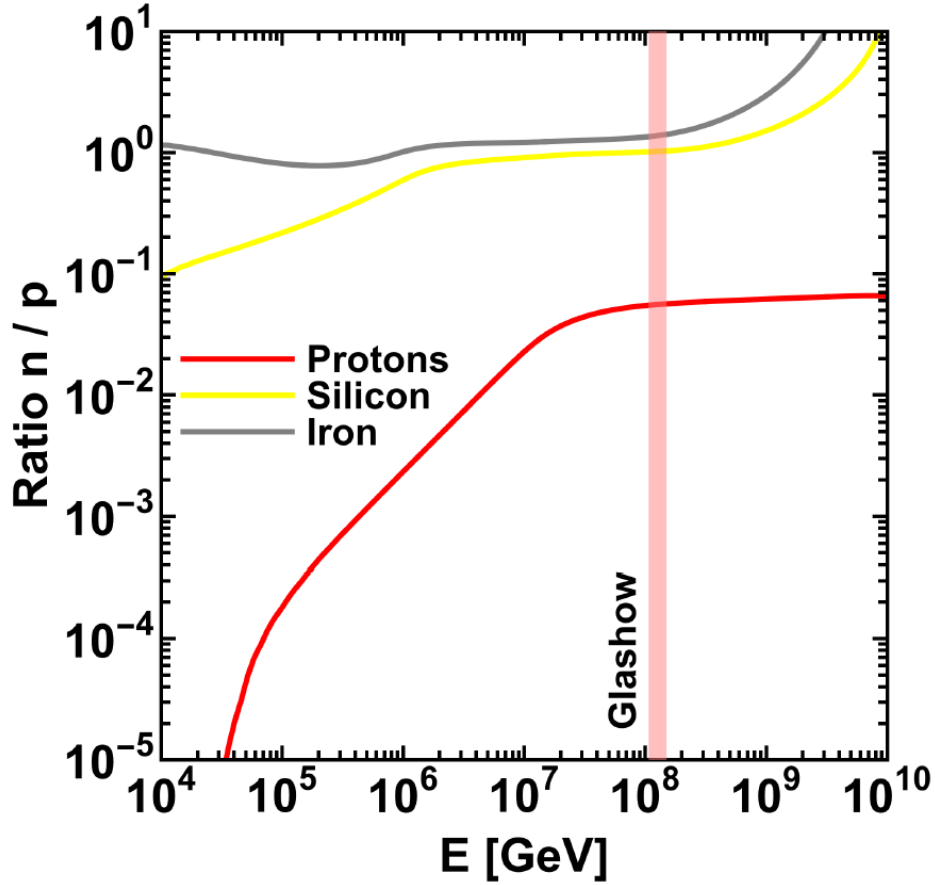
No discrimination in IC-Gen2

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033

Glashow resonance as smoking gun signature for nuclei?

- Neutrons produce more π^- than π^+, and primary nuclei are neutron-rich:





- Discrimination pγ from Aγ in IC-Gen2?

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033

So what can we learn?

- Scenario discrimination

  IceCube-Gen2 can possibly discriminate among scenarios (numbers: IC-86 equivalent years for 90% CL discrimination)

Data →	$\alpha = 2$					
Theory ↓	Ideal pγ	pγ	pp	Feγ	Damped μ	Opt. thick
Ideal pγ	·	**81**	**32**	**26**	∞	**55**
pγ	**53**	·	156	**93**	144	∞
pp	**16**	121	·	∞	**28**	∞
Feγ	**12**	**66**	∞	·	**20**	122
Damped μ	∞	∞	**48**	**37**	·	**104**
Opt. thick	**33**	∞	∞	162	**72**	·

- After what exposure do we expect to see Glashow events? (90% CL)

Dataset	Spectral index	Ideal pγ	pγ	pp	Feγ	Damped μ	Optically thick
Global fit [10]	$\alpha = 2.5$	33	22	18	16	32	20
Through-going muons [9, 11]	$\alpha \simeq 2$	15	9.7	7.6	7.1	12	8.9

"Feγ□ is the first scenario to be tested

Biehl, Fedynitch, Palladino, Weiler, Winter, JCAP 1701 (2017) 033

Summary and conclusions

- The discovery of astrophysical (PeV) neutrinos offers a new perspective of the high-energy universe
- The origin of these neutrinos is yet unclear and requires further study both from experiment and theory
- Conceptual arguments can help to identify the sources (multiplet searches, flux and flavor composition, sky distribution, Glashow resonance etc)
- An emergent discipline is multi-messenger (neutrinos, cosmic rays, gravitational waves, gamma-rays) astronomy to identify the origin of the cosmic rays and neutrinos.
- Challenge for neutrino production to test the origin of cosmic rays: what if the primaries are not protons but heavier?
- Astrophysical neutrinos may be also good to test physics beyond the SM in extreme environments, and at extreme distances and energies