Neutrinos and the origin of cosmic rays

Walter Winter
DESY, Zeuthen, Germany

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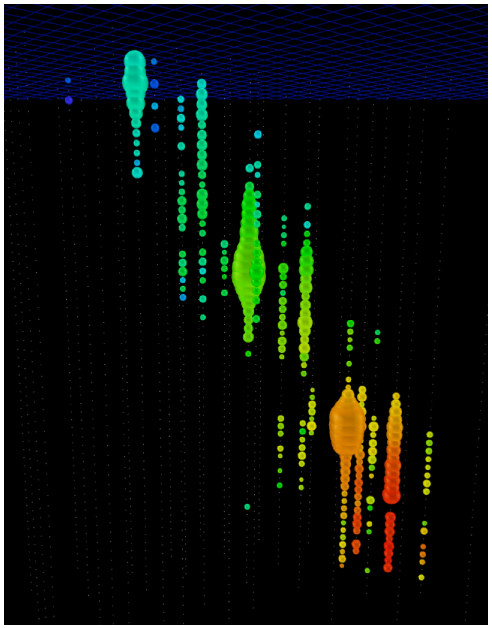
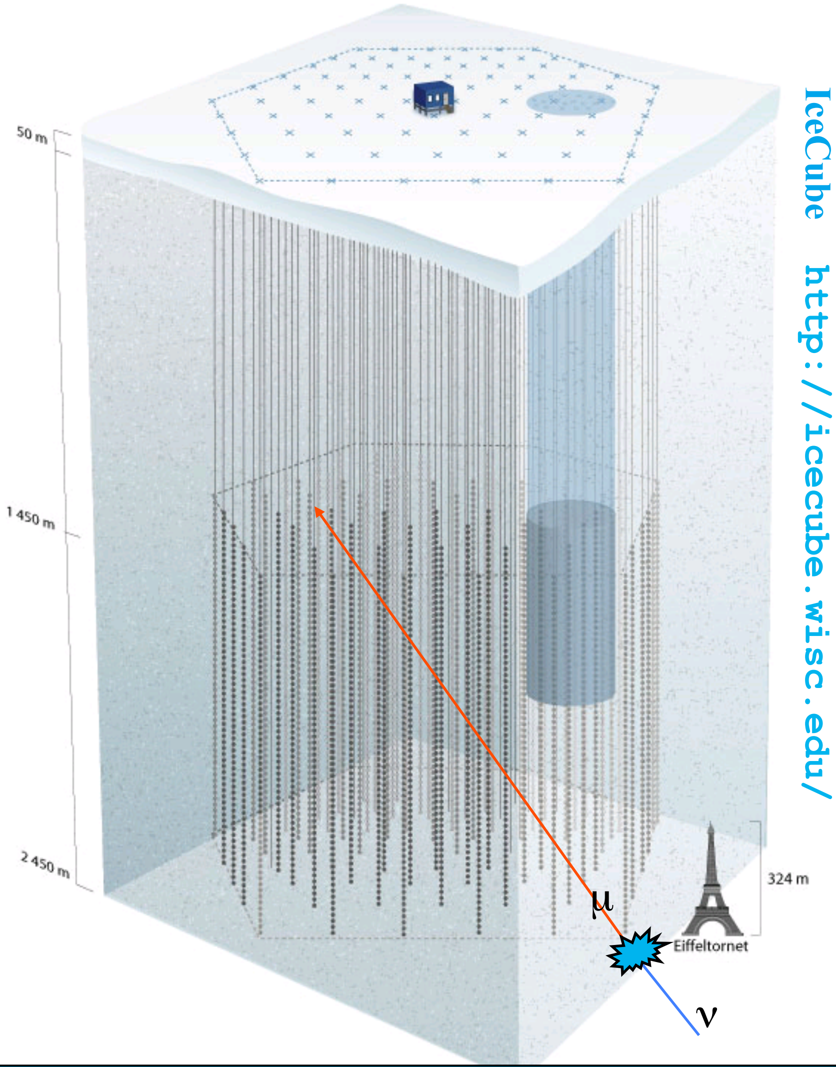
Contents

Observing TeV-PeV neutrinos with IceCube

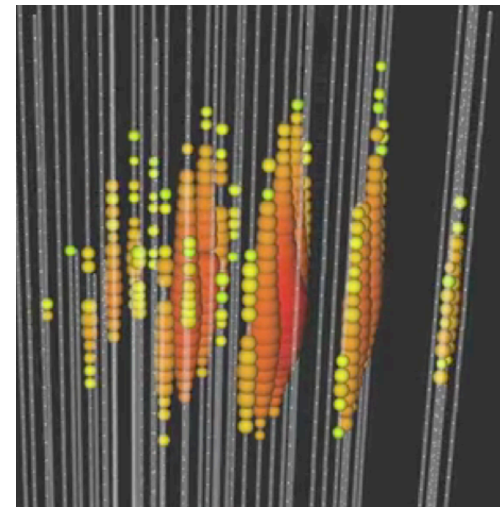
Muon track:
- From ν_μ (mostly)



Better directional info



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

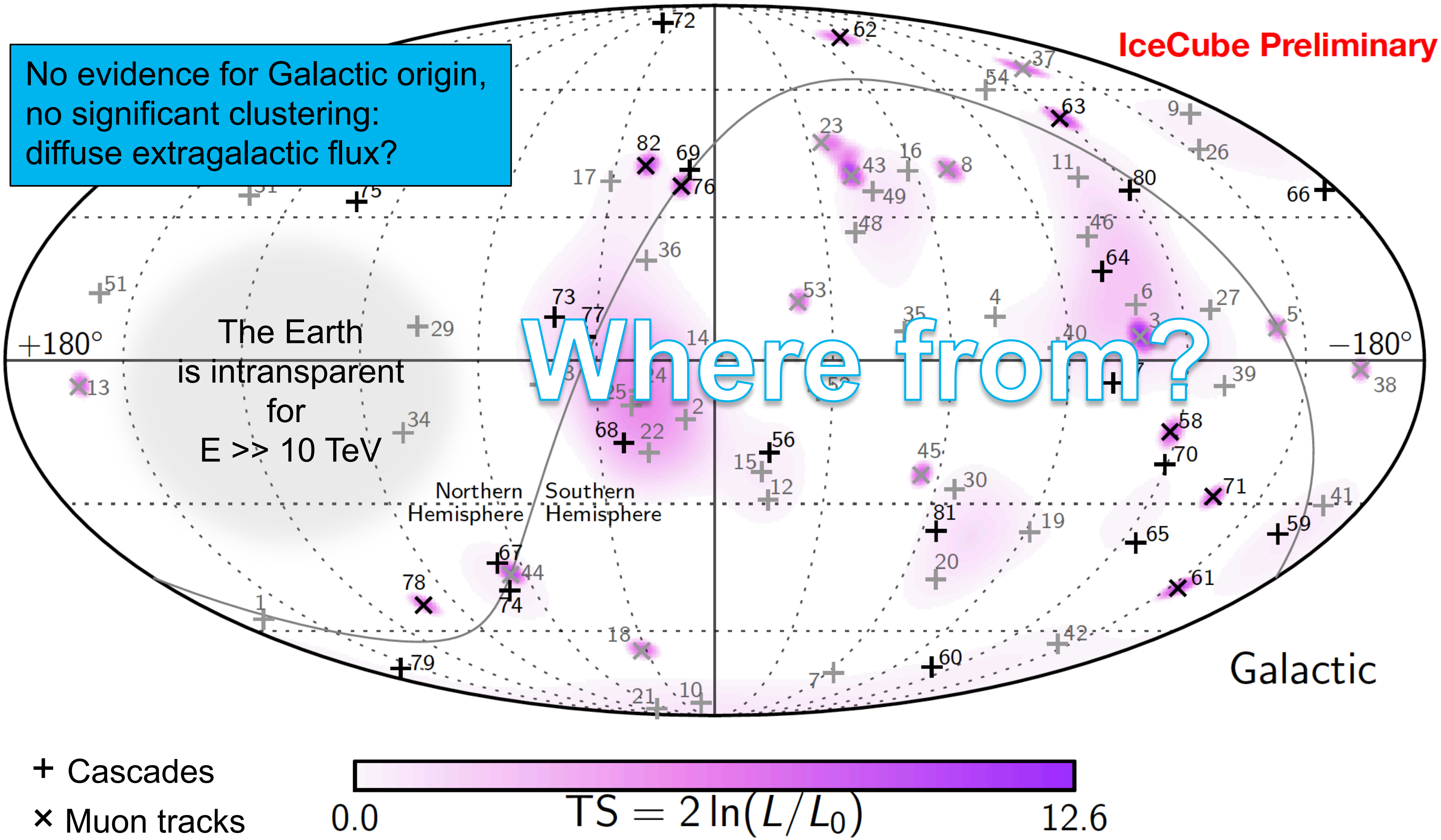


Better energy info

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

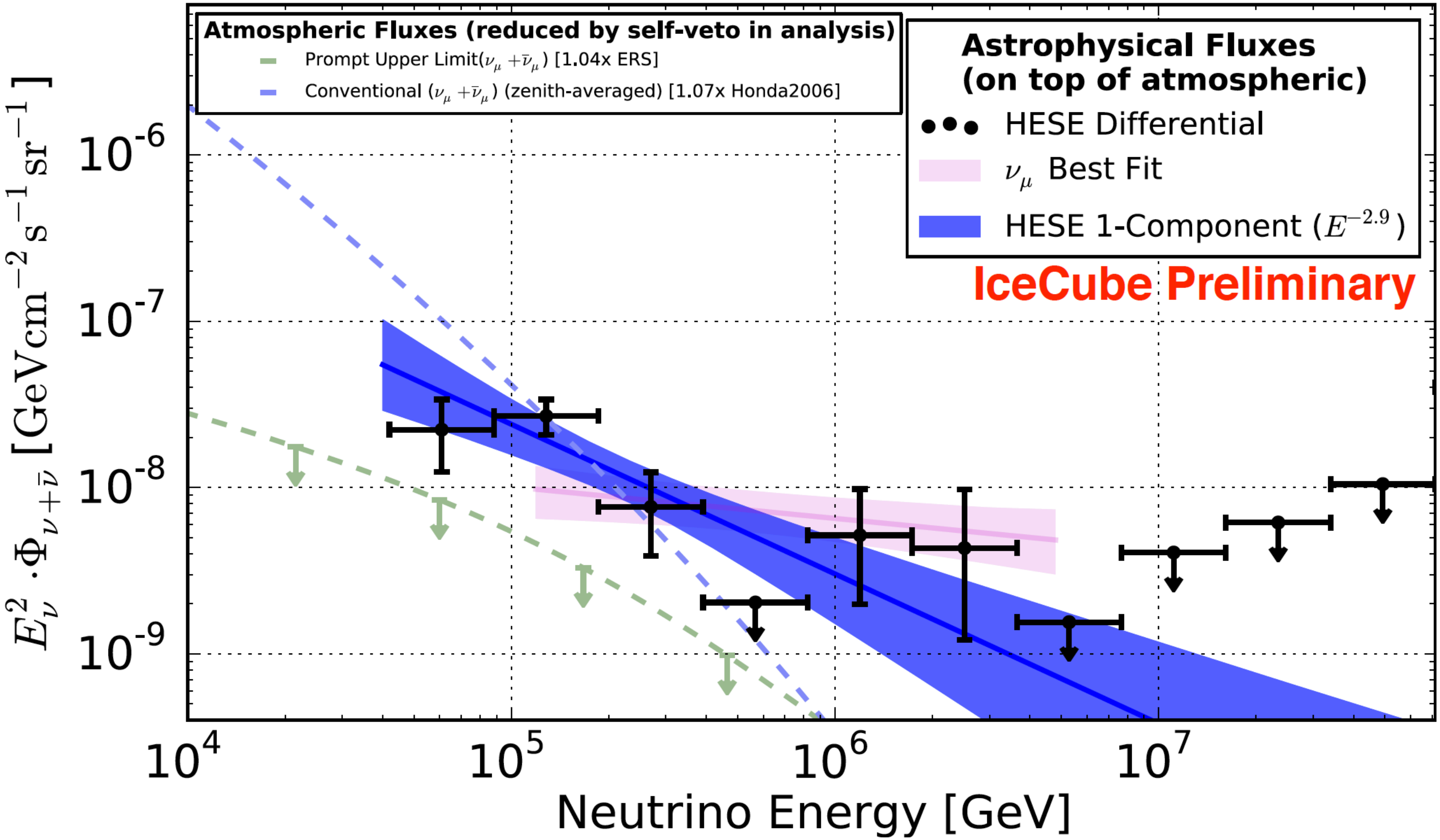
A flux of high energy cosmic neutrinos

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



IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

Observed neutrino flux

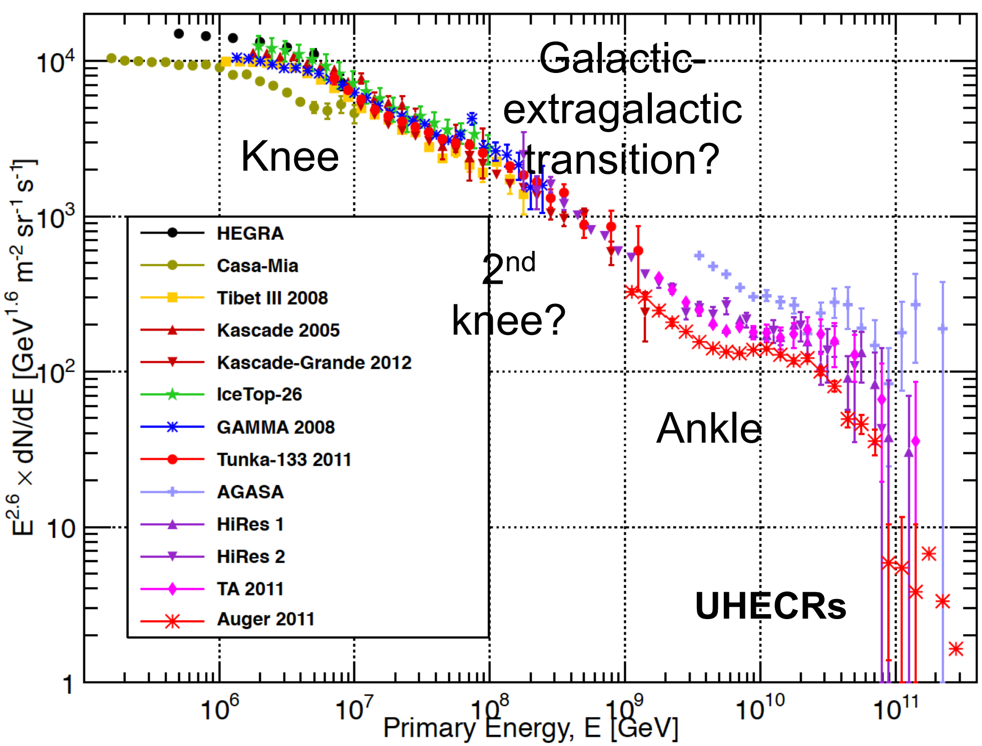


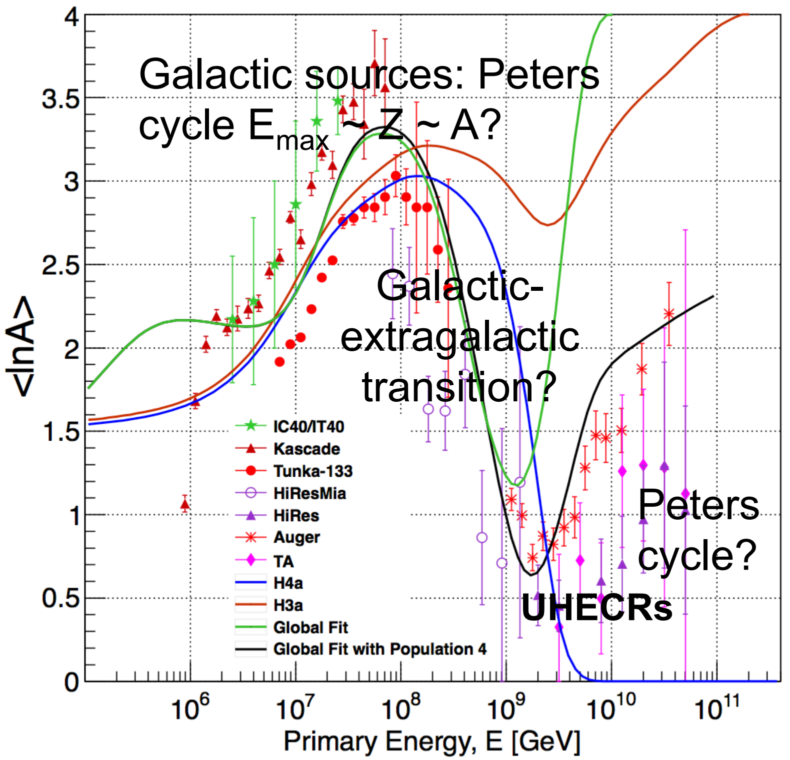
> Could be a two-component flux, but not yet statistically evident

IceCube/Claudio Kopper at ICRC 2017

Cosmic rays: Spectrum and composition

- Charged particles, proton or heavier nuclei
- Spectrum with breaks (knee, 2nd knee, ankle)
- Composition non-trivial function of energy

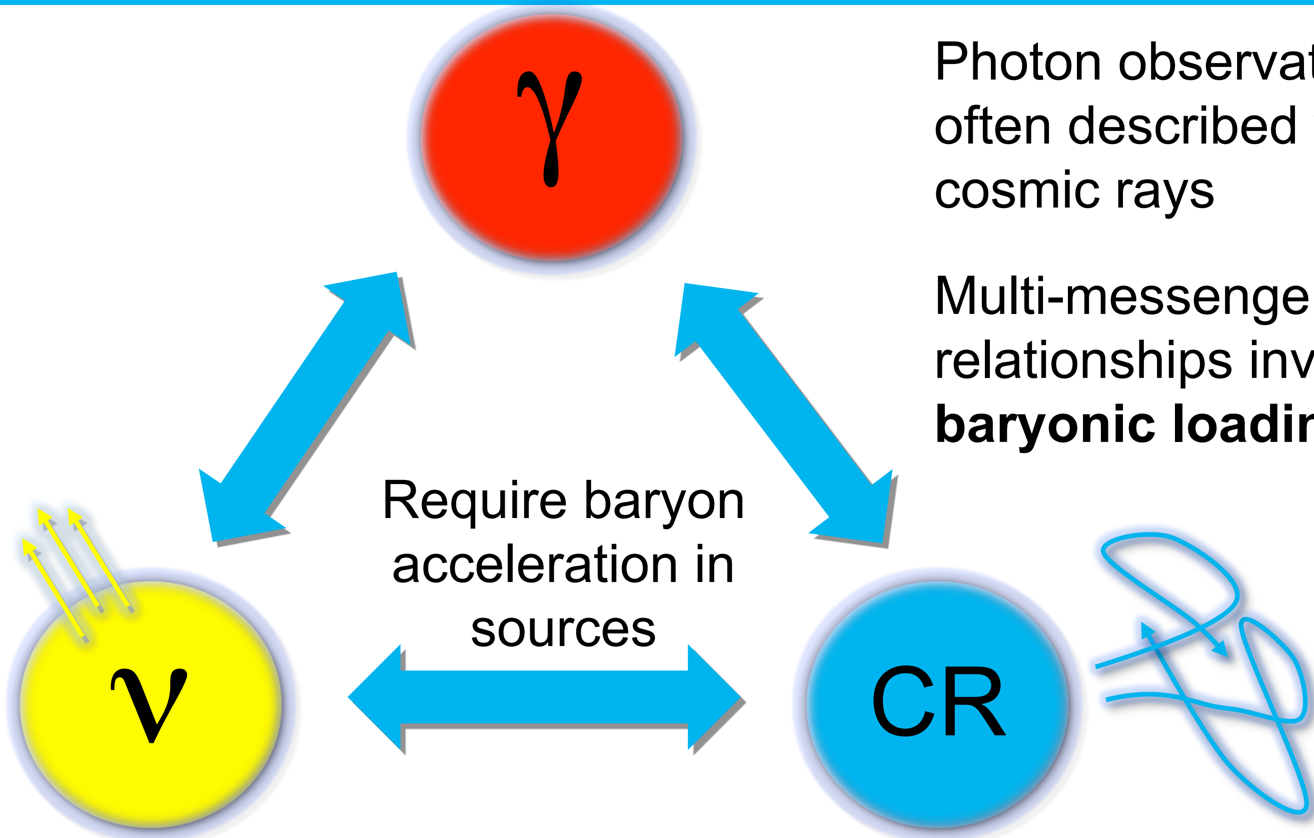




Lorentz force = centrifugal force ➔ E_{max} ~ Z c B R ~ Z (Peters cycle)

Gaisser, Stanev, Tilav, 2013

Neutrinos and the origin of cosmic rays



Photon observations can be often described without cosmic rays

Multi-messenger relationships involve **baryonic loading**

Most of these of extragalactic origin

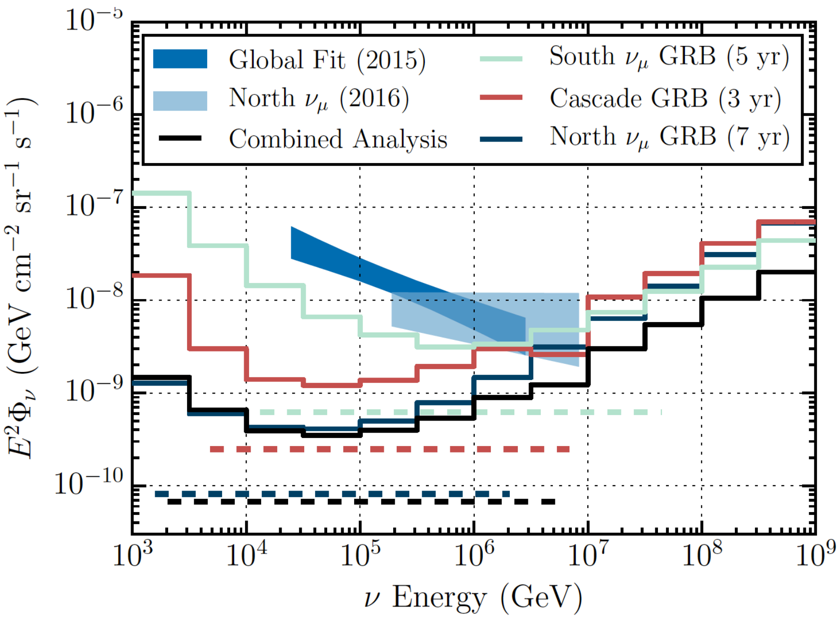
Extragalactic origin?
- Beyond ankle: Yes
- Beyond 10^9 GeV (UHECR): Probably
- Between knee and ankle: Maybe

Focus on extragalactic, baryonically loaded sources at extremest energies

Neutrino and UHECR candidate classes (examples)

Gamma-Ray Bursts (GRBs)

- Transients (e.g. from explosion of massive star)
- High luminosity over short time

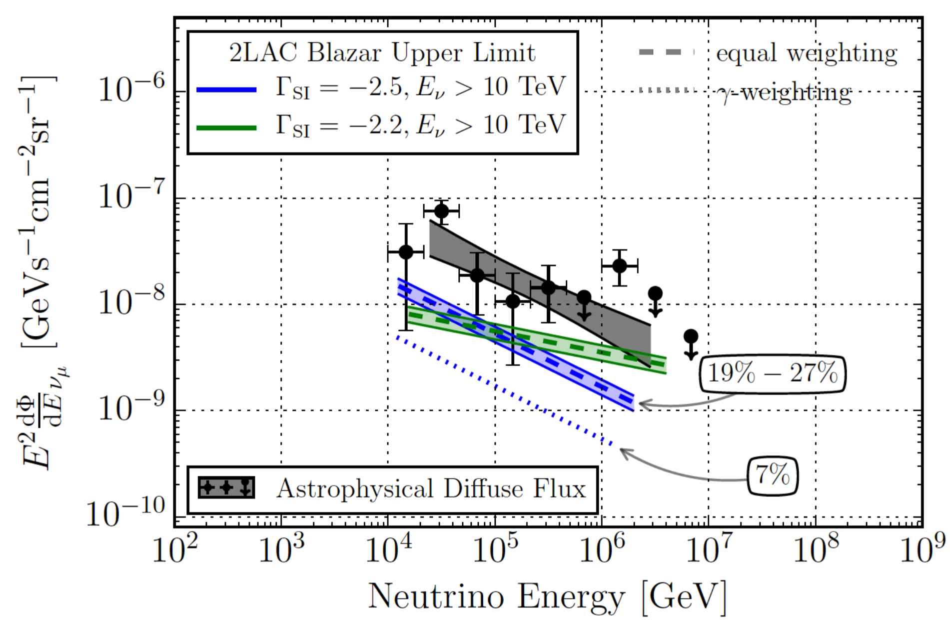


- Less than ~1% of observed ν flux

IceCube, Nature 484 (2012) 351;
Newest update: arXiv:1702.06868

Active Galactic Nucei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



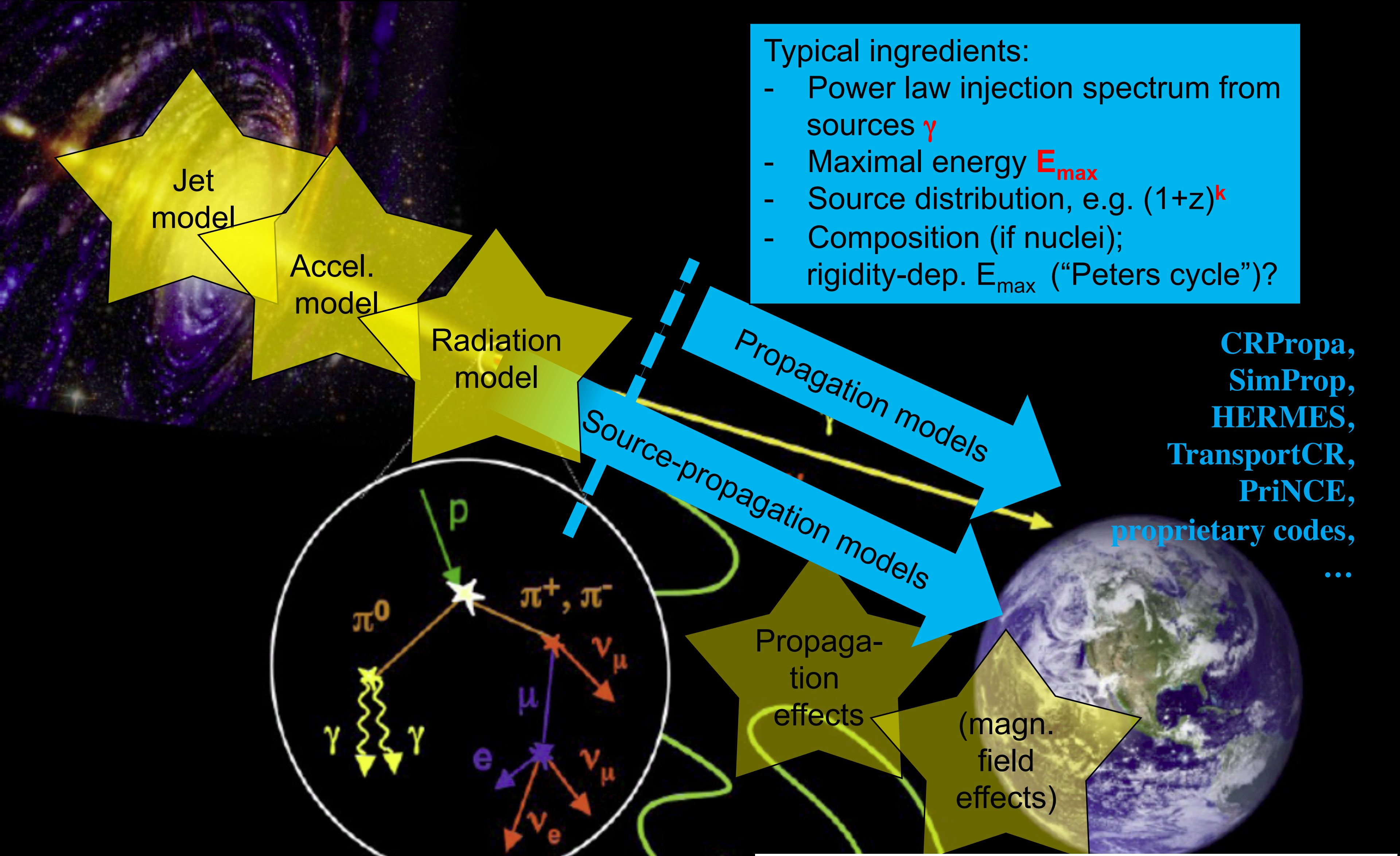
- Less than ~10% of observed ν flux

IceCube, Astrophys. J. 835 (2017) 45
(see proceedings of ICRC 2017 for updates)

Ultra-high energy cosmic rays: Models

Typical ingredients:
- Power law injection spectrum from sources γ
- Maximal energy E_{max}
- Source distribution, e.g. $(1+z)^k$
- Composition (if nuclei); rigidity-dep. E_{max} ("Peters cycle")?

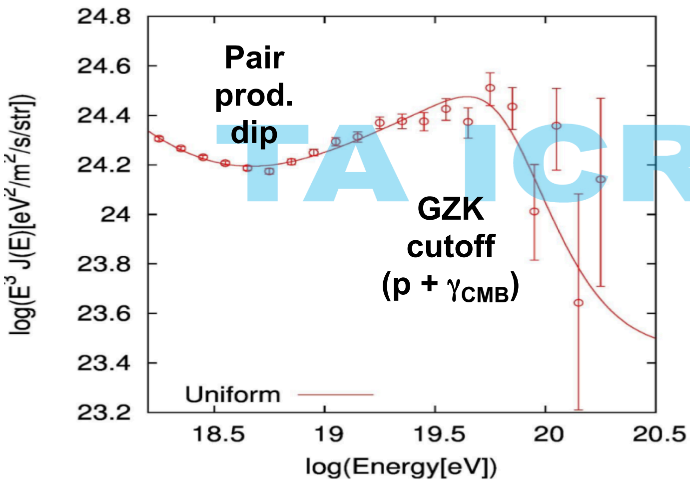
CRPropa, SimProp, HERMES, TransportCR, PriNCE, proprietary codes, …



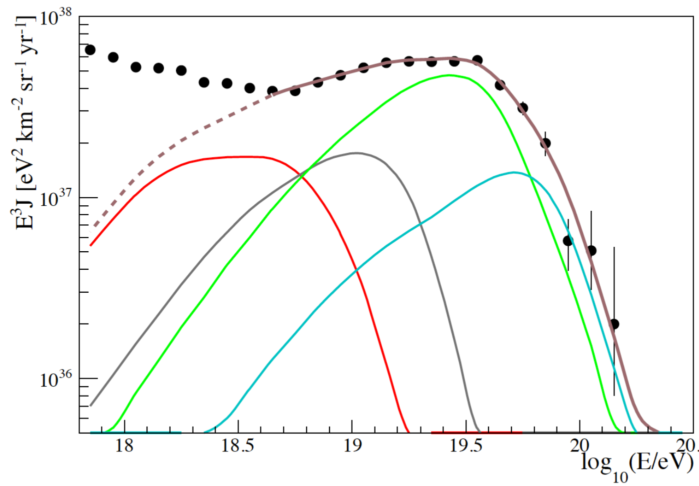
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Current theoretical paradigms (from propagation models)

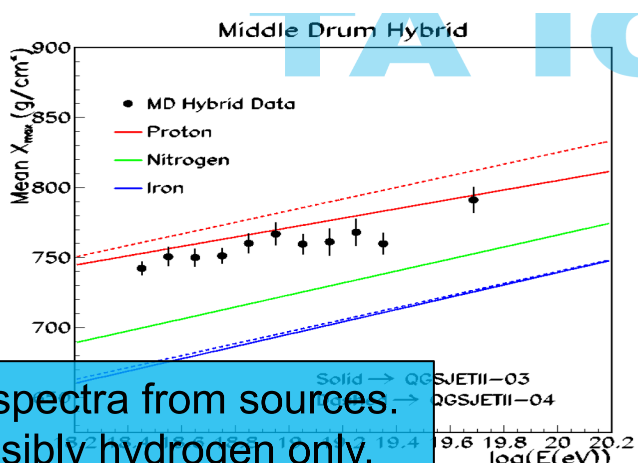
TA (Telescope Array) vs. Auger

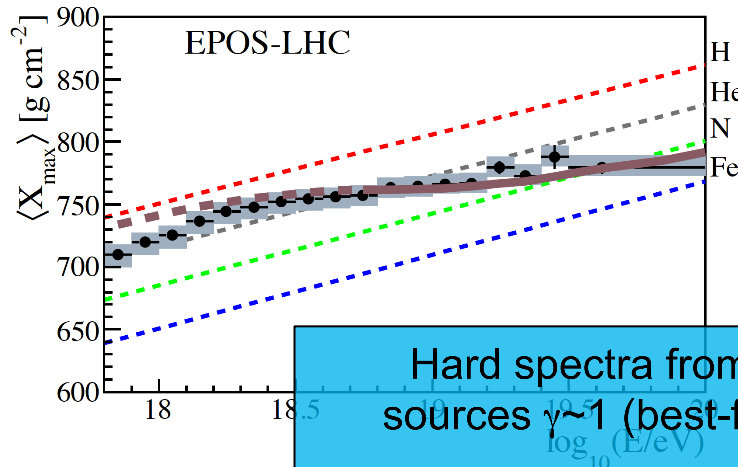


Jui @ ICRC 2015; talk by D. Ivanov



Auger global fit, 1612.07155





Soft spectra from sources. Possibly hydrogen only. Proton dip model?
Berezinsky, Gazizov, Grigorieva, 2005

What can neutrinos and γ-rays tell us?

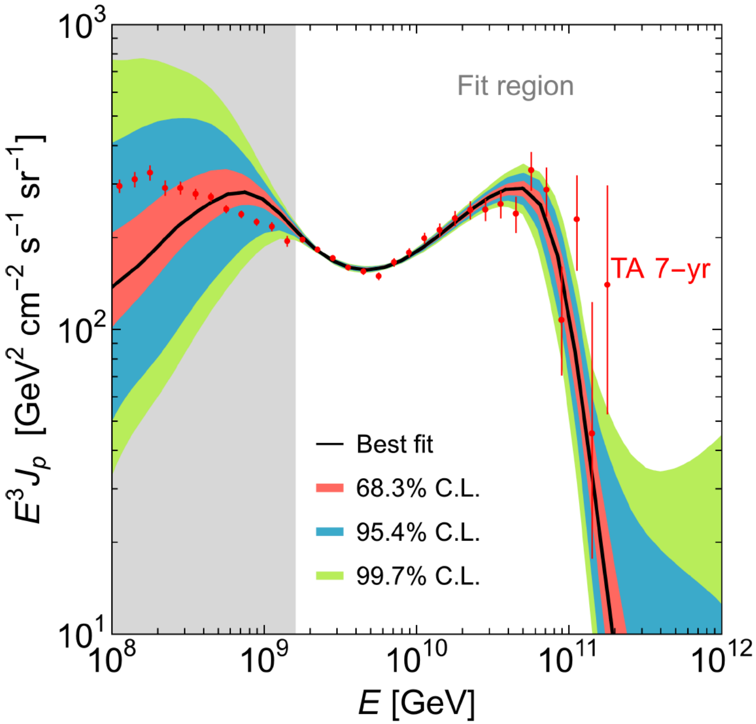
Hard spectra from sources γ~1 (best-fit).

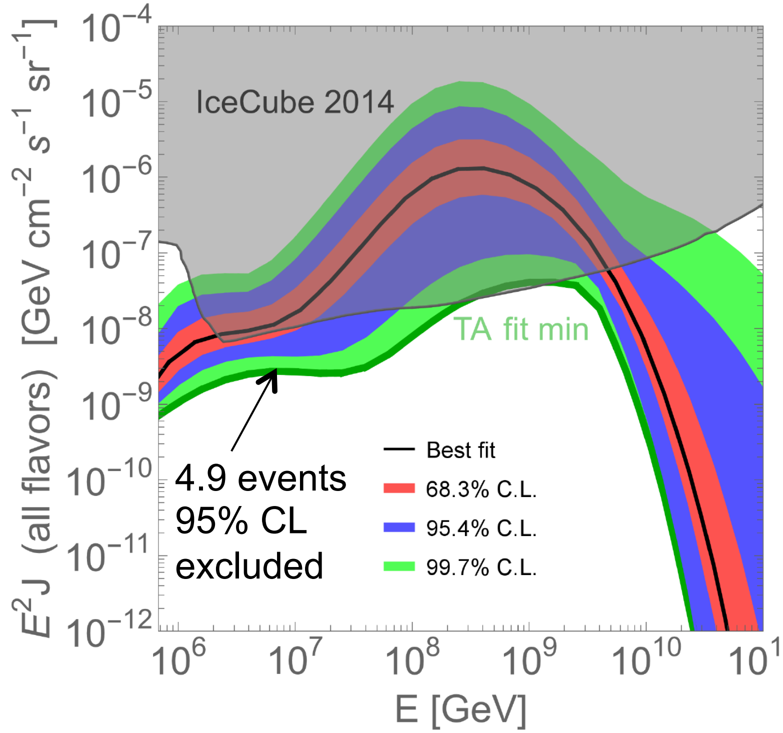
Elements up to silicon from sources

Cosmogenic neutrinos challenge the proton dip model

- 3D fit with fully marginalized parameters: TA 7-year meets IceCube 2014

  Heinze, Boncioli, Bustamante, Winter, Astrophysical Journal 825 (2016) 122

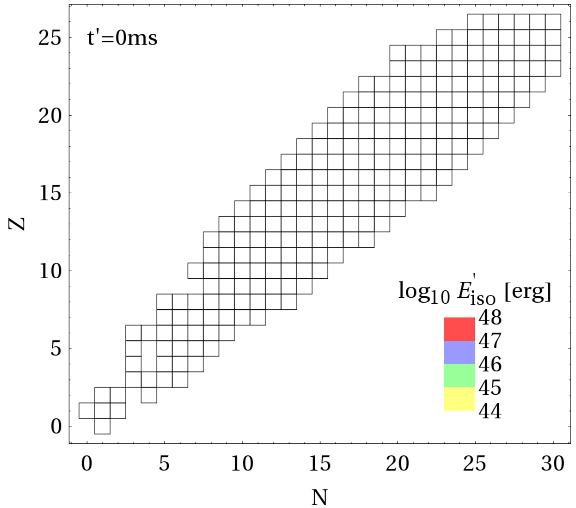




- Most likely interpretation (on consistency with Auger):
  The composition is dominated by nuclei at the highest energies
- Almost all neutrino predictions (GRBs, AGNs, …) rely on protons.
  What can be learn from neutrinos about the origin of cosmic rays in the presence of nuclei?

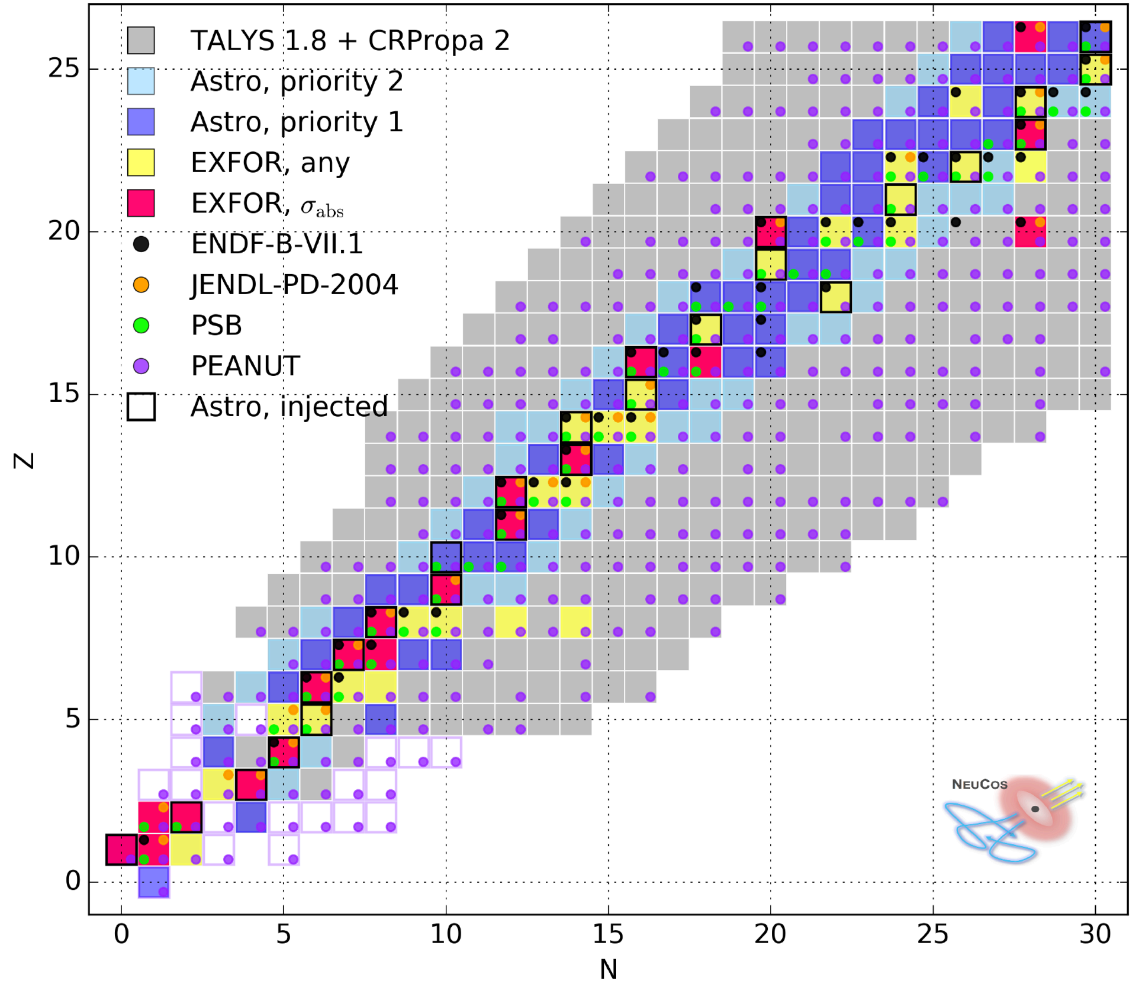
Challenge for physics of sources and propagation:
Photonuclear disintegration cross sections

- Absorption cross sections only measured for very few isotopes (red)
- Blue isotopes: populated in nuclear cascade



Ex: disintegration of ^{56}Fe ***within*** a GRB shell collision ($L_\gamma=10^{52}$ erg/s)

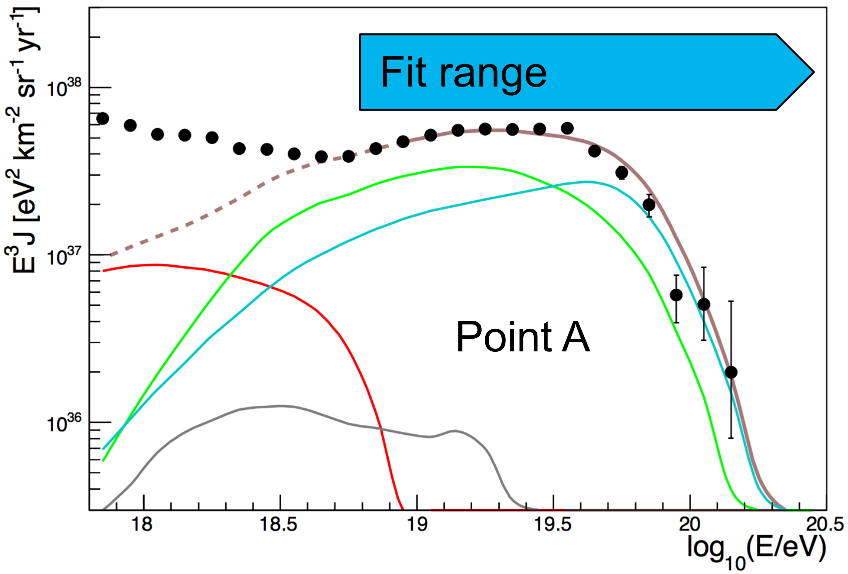
- Need future measurements and model consistency checks

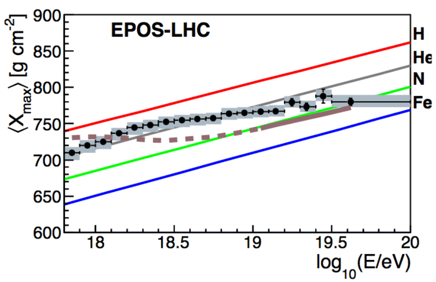


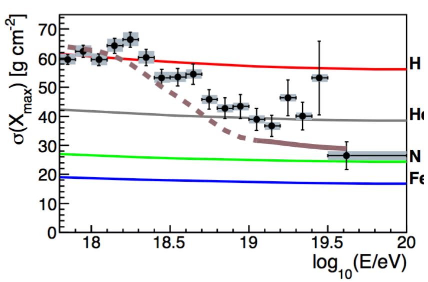
Boncioli, Fedynitch, Winter, Scientific Reports 7 (2017) 4882

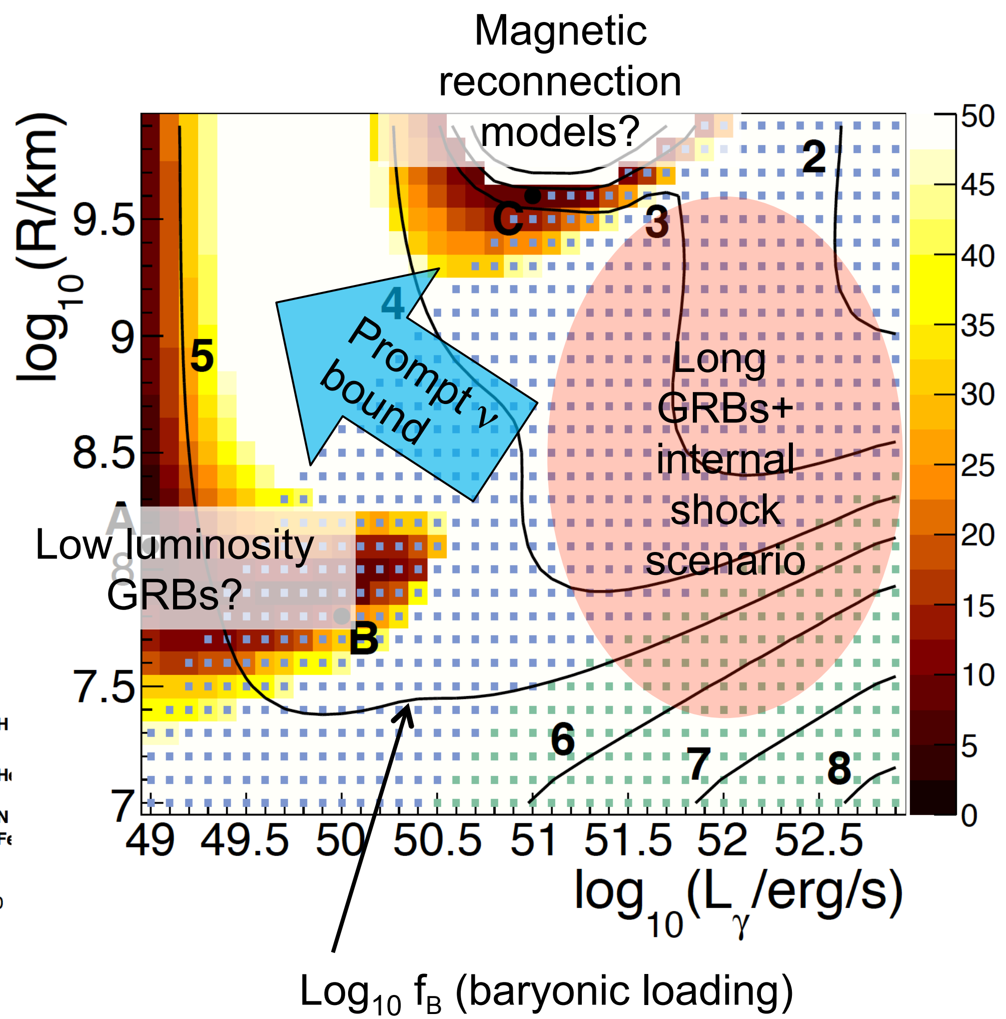
GRB stacking limits applied to source-propagation model with ^{28}Si injection: Neutrino bounds constrain UHECR models with nuclei

> Mixed composition ankle model



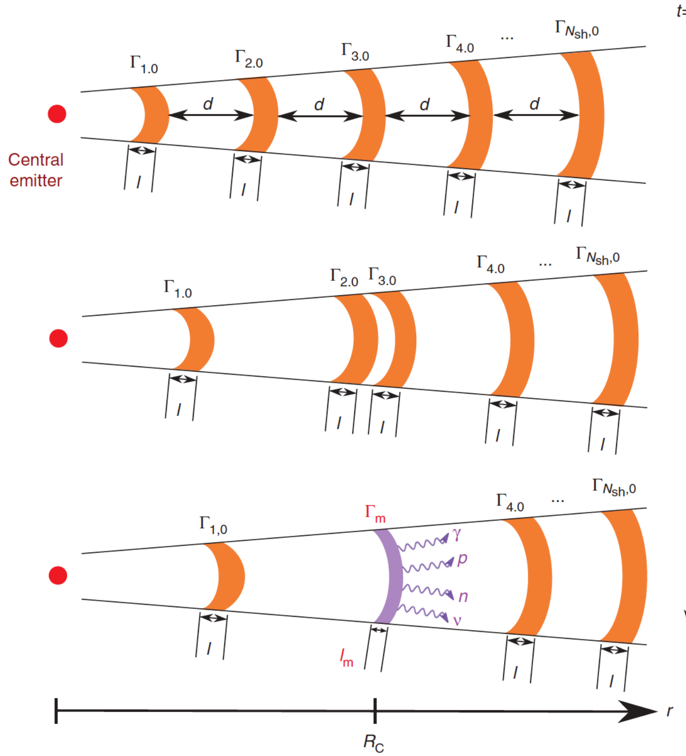


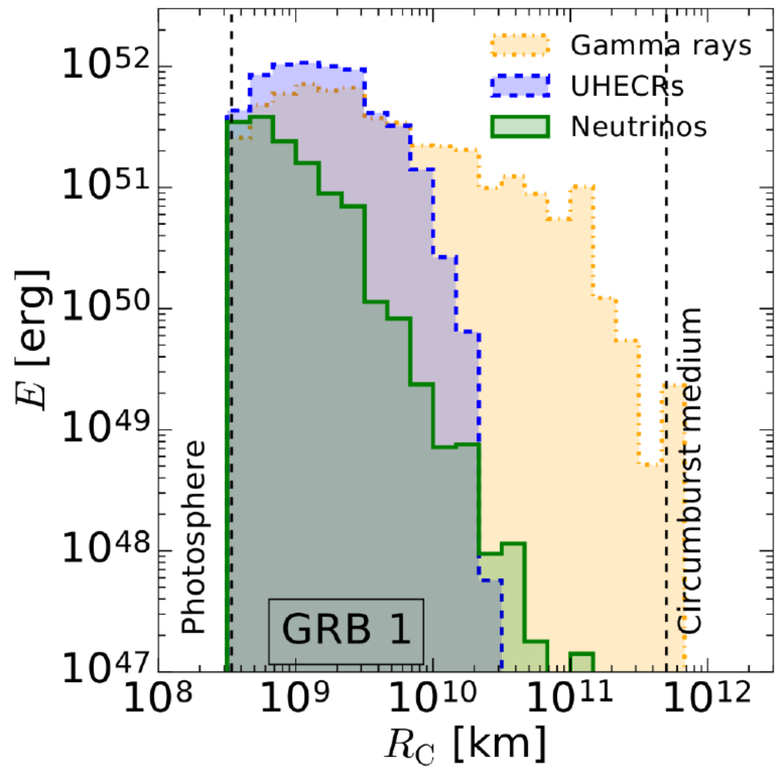




Biehl, Boncioli, Fedynitch, WW, arXiv:1705.08909

Caveat: The GRB emission comes from multiple zones



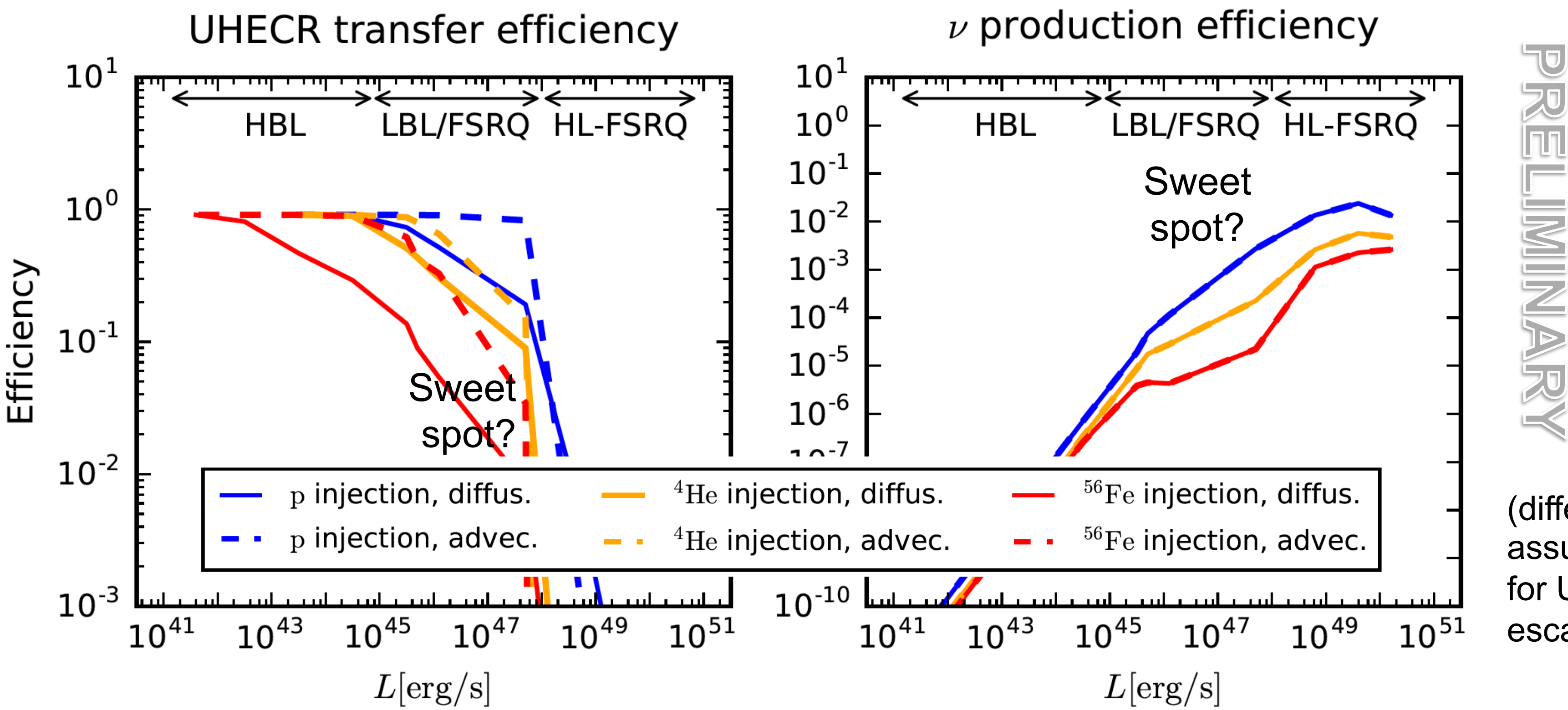


Bustamante, Baerwald, Heinze, Murase, Winter, Nature Commun. 6, 6783 (2015) + ApJ 837 (2017) 33; see also Globus et al, 2014+2015

- The different messengers originate from different regimes of the GRB *where the photon densities are very different*
- Neutrino flux is dominated by a few collisions with high densities
- More fundamental problem? Quantities inferred from γ-ray observations not representative for neutrinos and UHECRs?

A different example: AGN blazar sequence

- For AGN, one can find a relationship between luminosity and spectral energy distribution (aka "blazar sequence")
- High luminosity objects (FSRQs) produce efficiently neutrinos, low luminosity objects (HBLs) ultra-high energy cosmic rays:



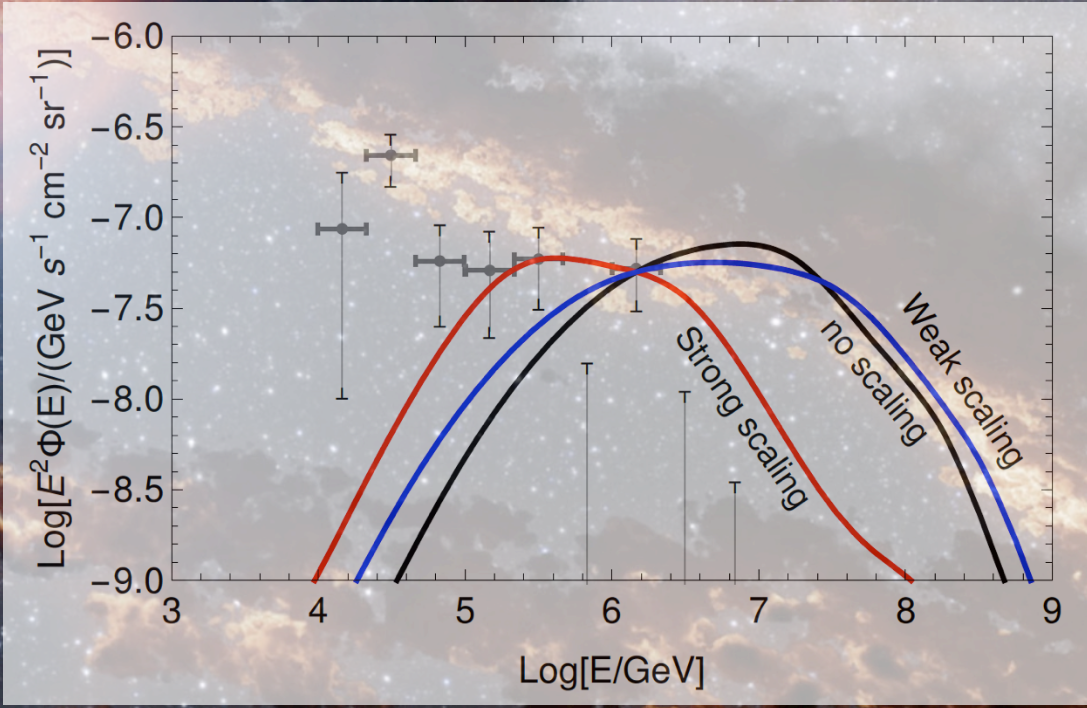
(different assumptions for UHECR escape)

Rodriguez, Fedynitch, Gao, Boncioli, WW, to appear

So where do the neutrinos and UHECRs come from?

- From different objects classes?
- Some new object class only recently thought of?
- Example: Tidal Disruption Events of massive stars? (TDEs)
- Can describe UHECR and neutrino fluxes under certain conditions

From Lunardini, Winter, 2017; see also Wang, Liu, Dai, Cheng, 2011; Wang, Liu, 2016; Dai, Fang, 2017; Senno, Murase, Meszaros, 2017; Batista, Silk, 2017; Zhang, Murase, Oikonomou, Li, 2017



Source: NASA/JPL-Caltech

Conclusions

> Neutrinos are indicative for a baryonic loading of the sources, and therefore for the origin of cosmic rays

> Cosmogenic neutrinos and gamma-rays independently confirm the Auger composition observations (substantial non-proton contribution in UHECRs)

> The nuclear composition is therefore one of the grand challenges of the field from the theory perspective; other signatures of nuclei?

> Has to be taken into account if one searches for the origin of cosmic rays with neutrinos

> Further complication: The different messengers may be dominated by different regions or objects; the interpretation of multi-messenger signals has to rely on theory or "sweet spots" in parameter space

> Neutrinos from extreme distances, environments and densities are also good for the test of fundamental physics