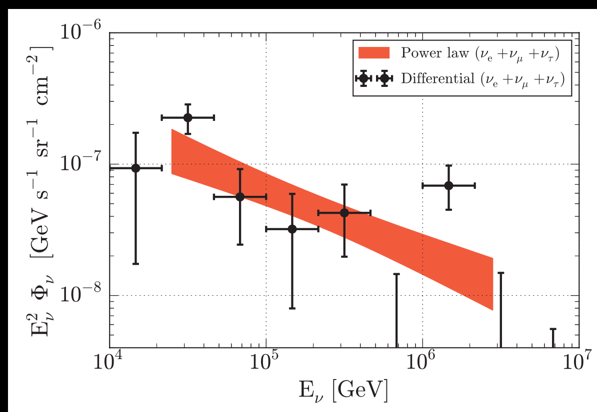
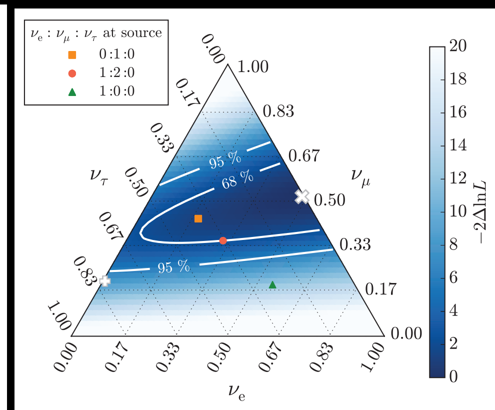
Need for Global Fit
Theorists Wish List





Kohta Murase (Penn State)

September 14 @ U. Tokyo

PENNSTATE

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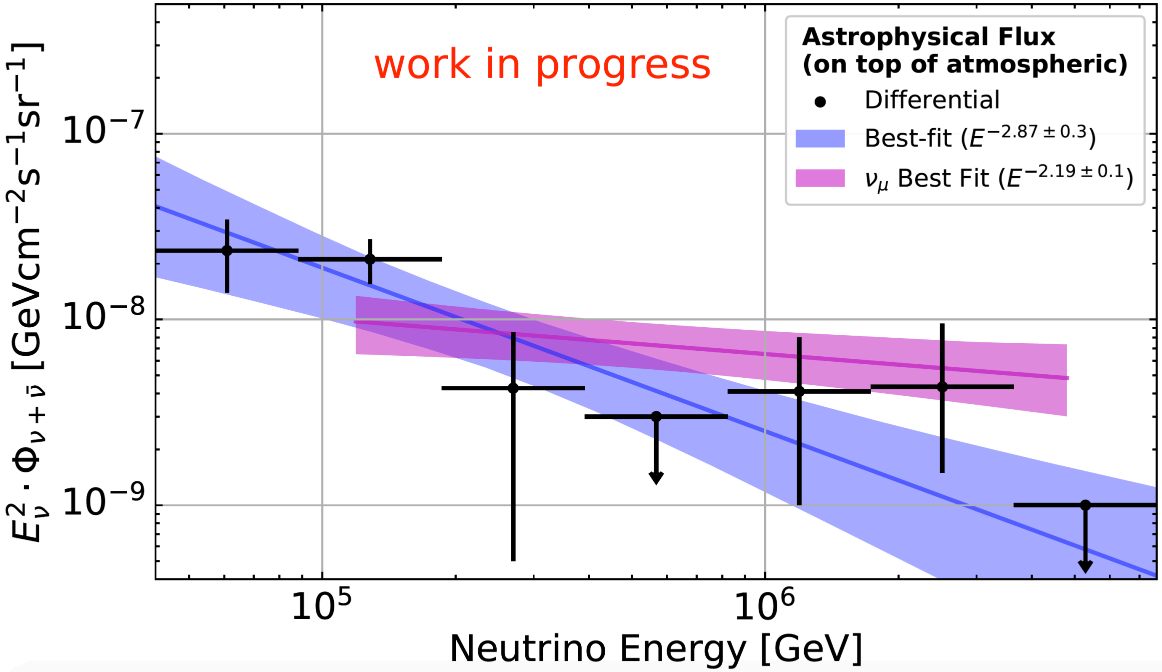
NSF

AMON
Astrophysical Multimessenger Observatory Network

Diffuse Neutrino Flux Spectrum

IceCube @ Neutrino 2018



diffuse ν flux per flavor

$E_\nu{}^2\Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at $E_\nu > 200$ TeV

- 7.5-yr HE Starting Events
  103 events
  (60 events > 60 TeV)
  Best-fit: s=2.87±0.3
- Updates at ICRC 2019
  Best-fit: s=2.89+0.2-0.19
- 8-yr upgoing ν_μ "track"
  36 events at >200 TeV (6.7σ)
  Best-fit: s=2.19±0.10
- Updated at ICRC 2019
  9.5-yr upgoing ν_μ "track"
  Best-fit: s=2.28+0.08-0.09

Importance of Combined Analysis

Two basic questions

1. one component power-law or structure?
   (origin of cosmic neutrinos below 100 TeV ?)
2. neutrino flavor consistent w. 1:1:1?

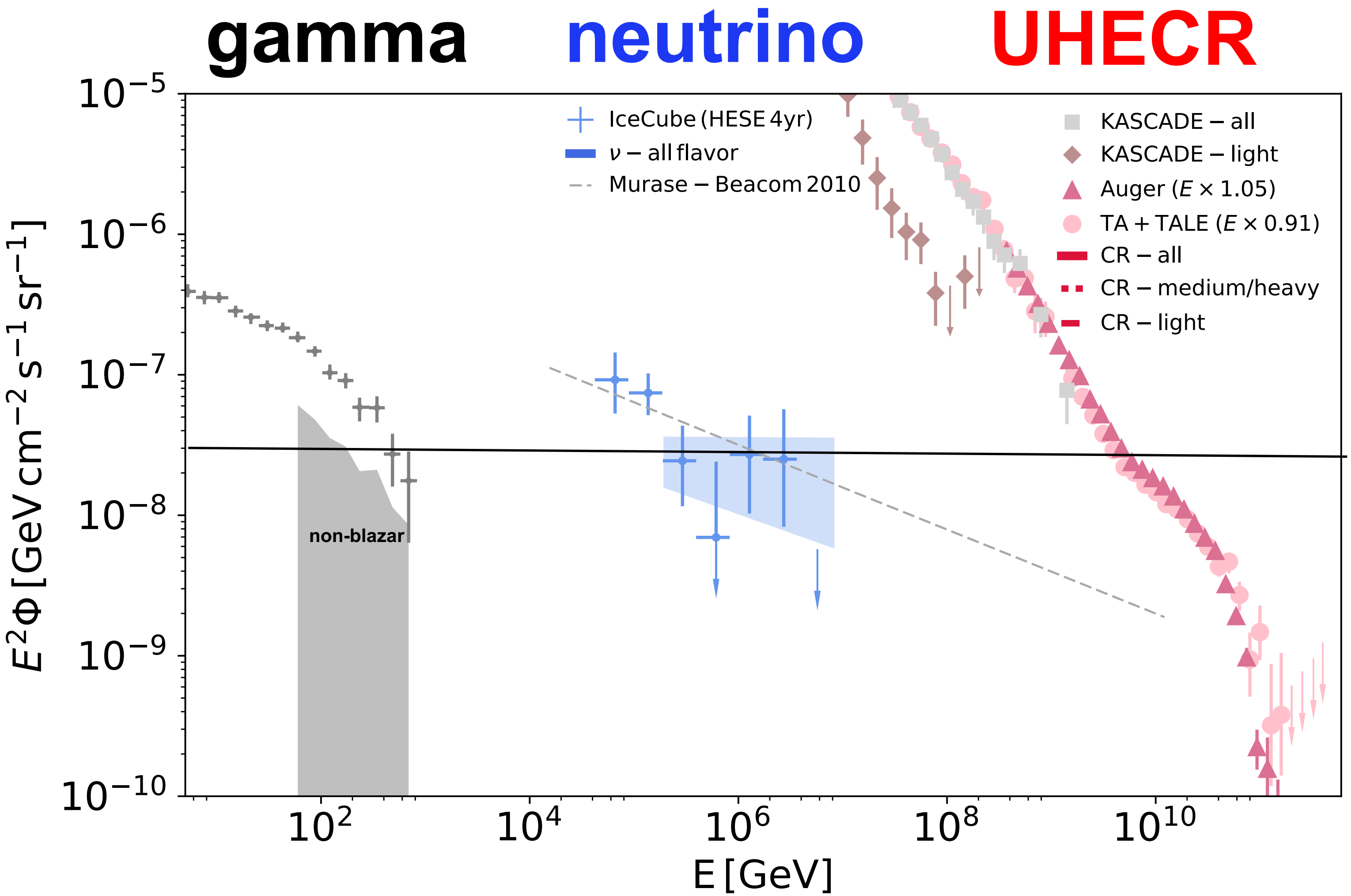
For astro/BSM model perspectives

Tests for non-power law (arbitrary) neutrino spectra with different (arbitrary) flavor ratios

- astrophysical neutrinos: may not be power-law
- flavor ratios depend on mechanisms (E-dependent)
- BSM effects can easily modify shapes & flavor ratios

HOW GLOBAL? (ULTIMATE: MULTIMESSENGER?)

Multi-Messenger Cosmic Particle "Backgrounds"

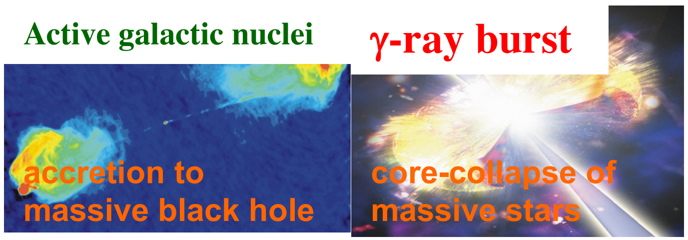


Energy generation rates are all comparable to a few x 10^{43} erg Mpc^{-3} yr^{-1}

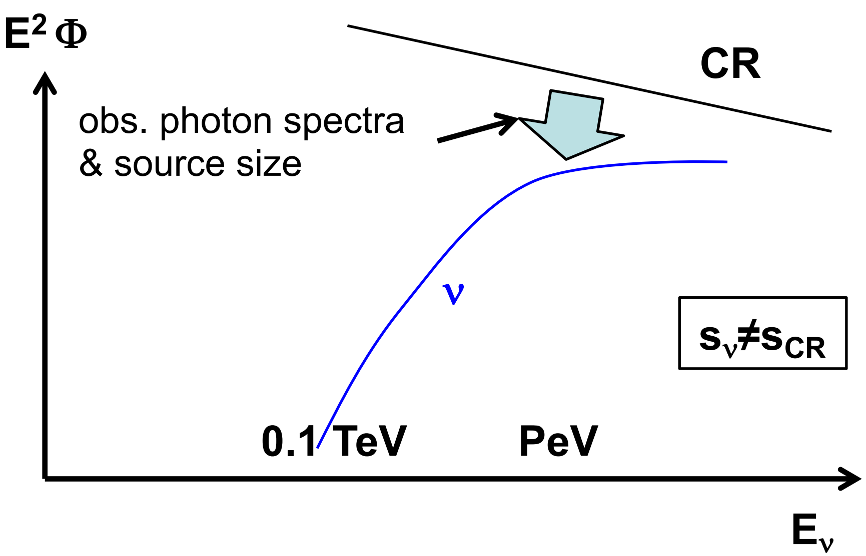
Astrophysical Extragalactic Scenarios

$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

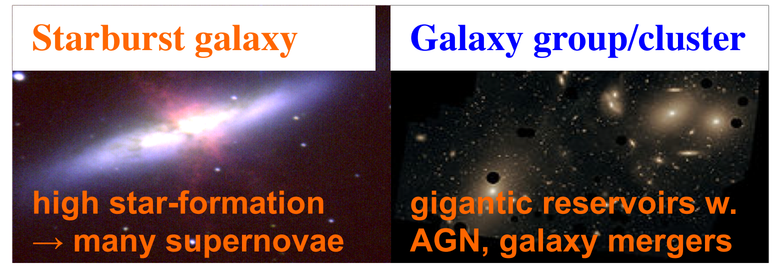
Cosmic-ray Accelerators
(ex. UHECR candidate sources)



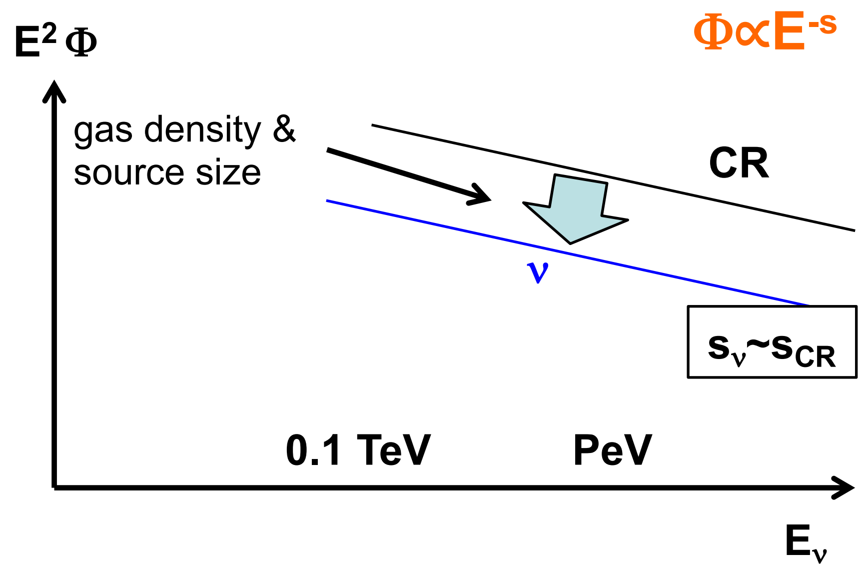
$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs



$$p + p \rightarrow N\pi + X$$



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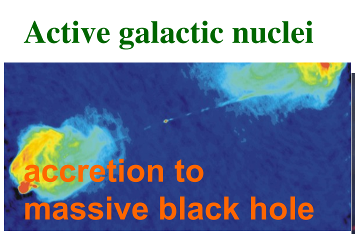

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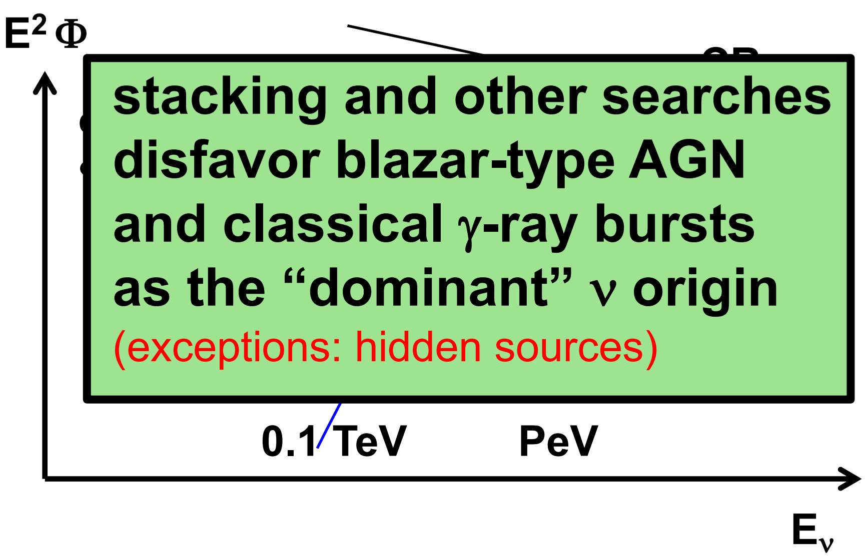
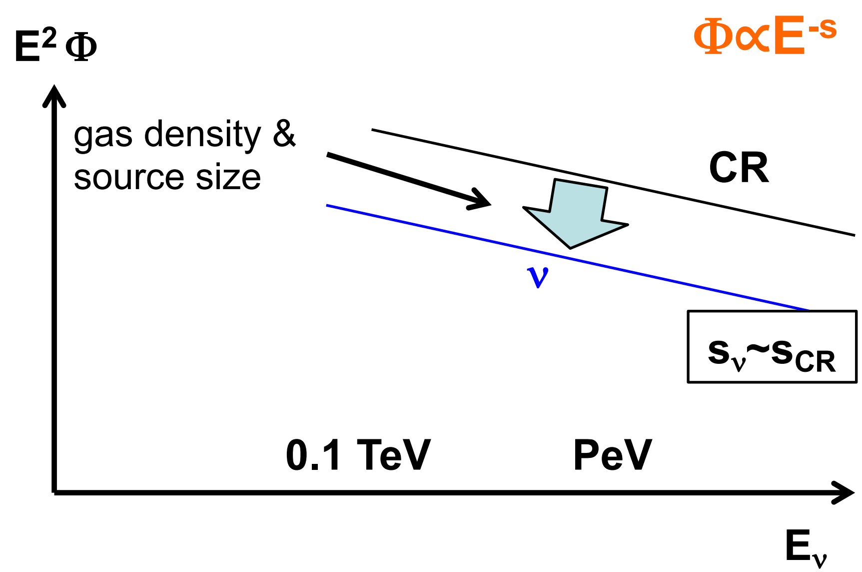


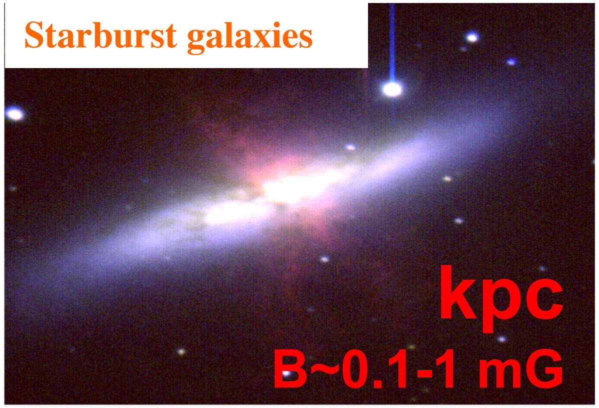
stacking and other searches disfavor blazar-type AGN and classical γ-ray bursts as the "dominant" ν origin
(exceptions: hidden sources)

Cosmic-ray Reservoirs

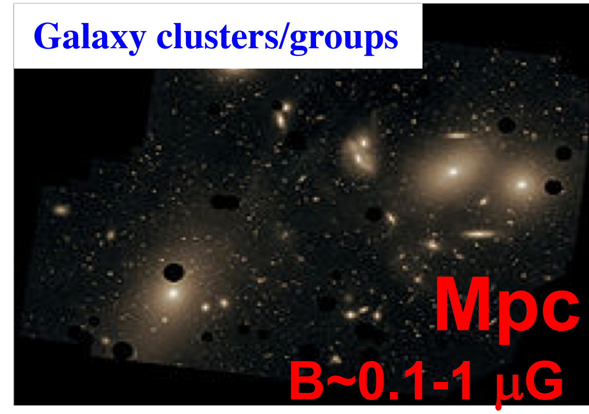
$$p + p \rightarrow N\pi + X$$

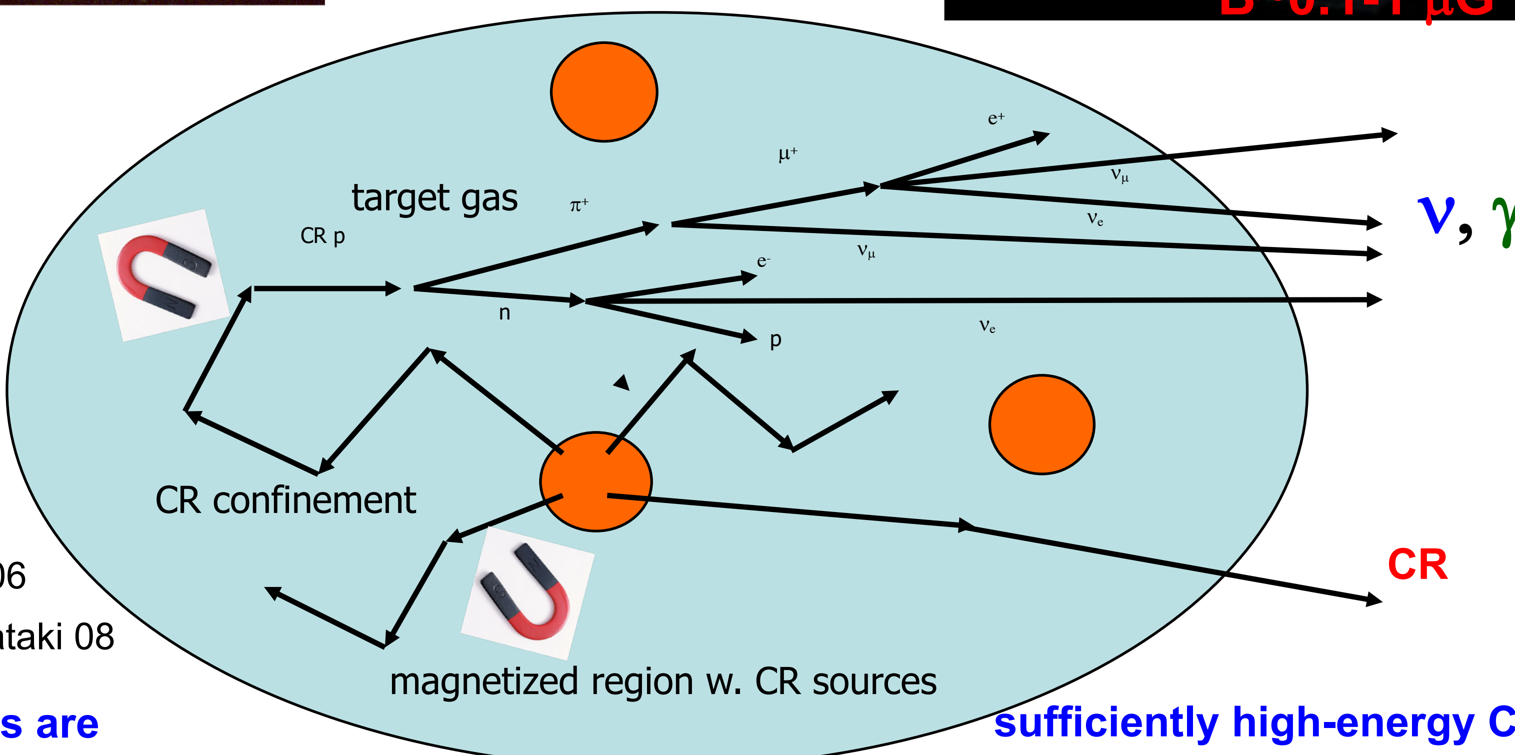


Cosmic-Ray Reservoirs



"cosmic-ray reservoirs"



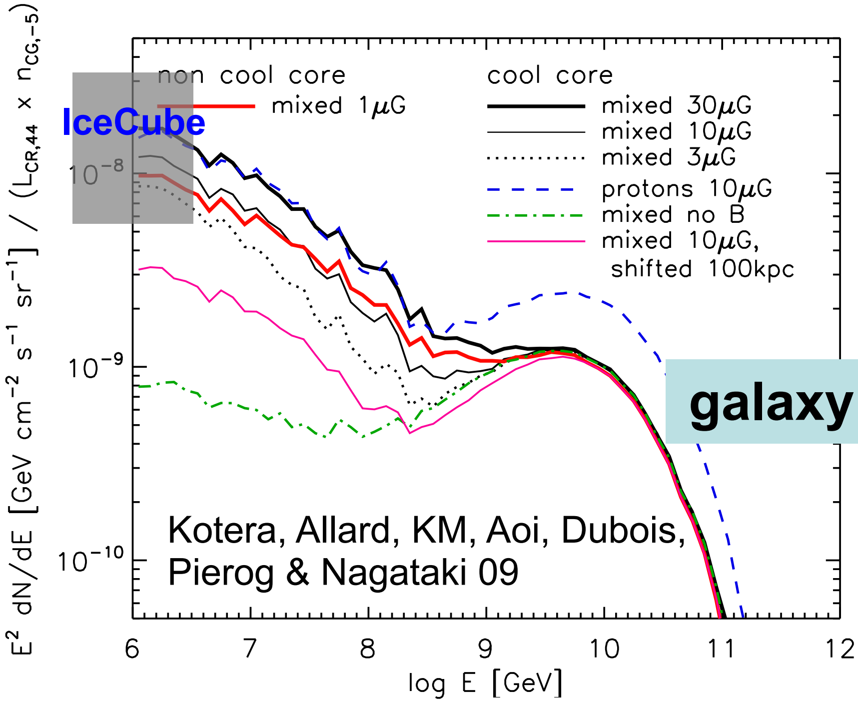


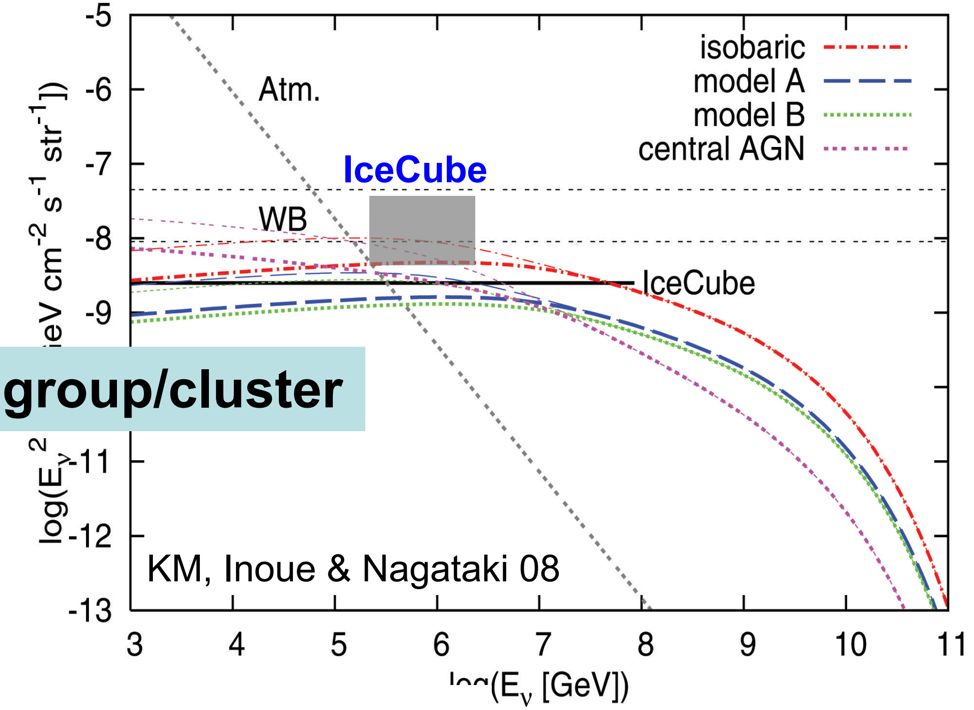
Loeb & Waxman 06

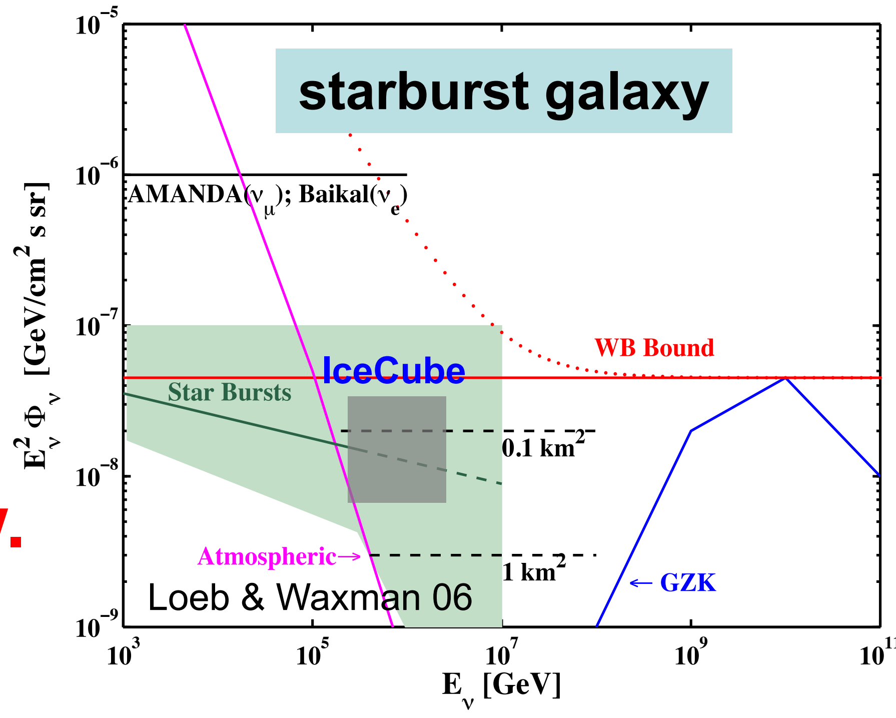
KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions



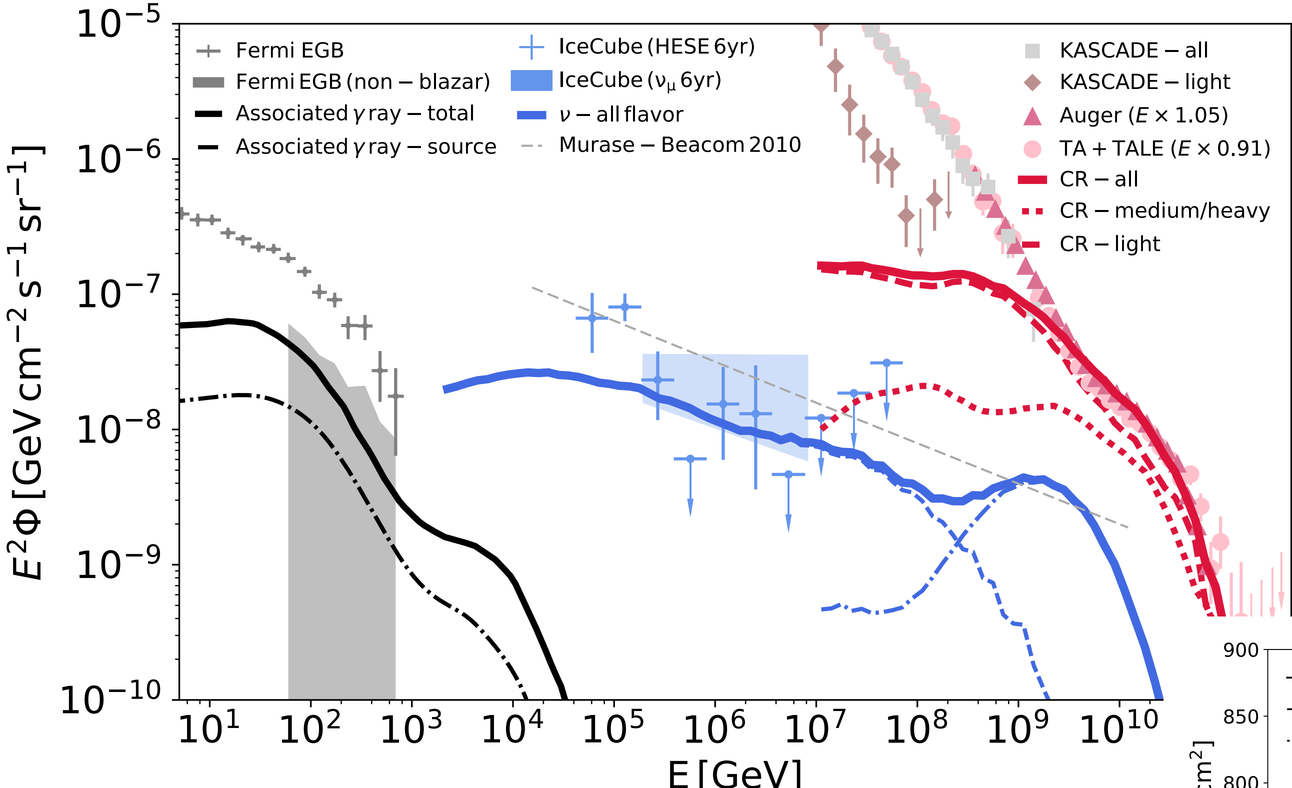




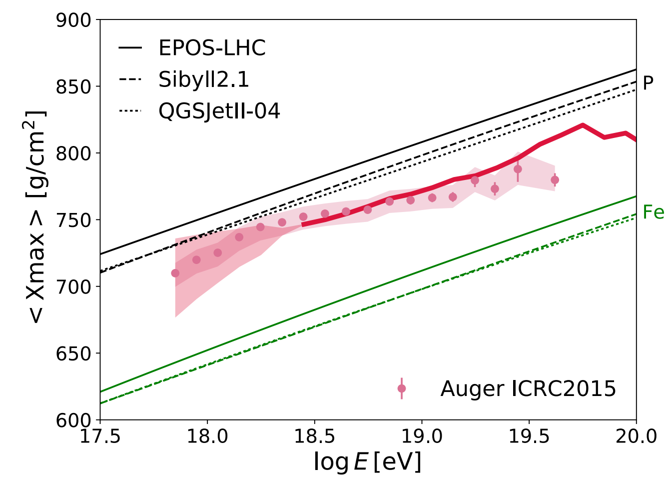
Consistent w. predictions

Ex. AGN Embedded in Galaxy Clusters/Groups

"Unifying" >0.1 PeV ν, sub-TeV γ, and UHECRs (above 2nd knee at 10^{17} eV)



Fang & KM 18 Nature Phys.



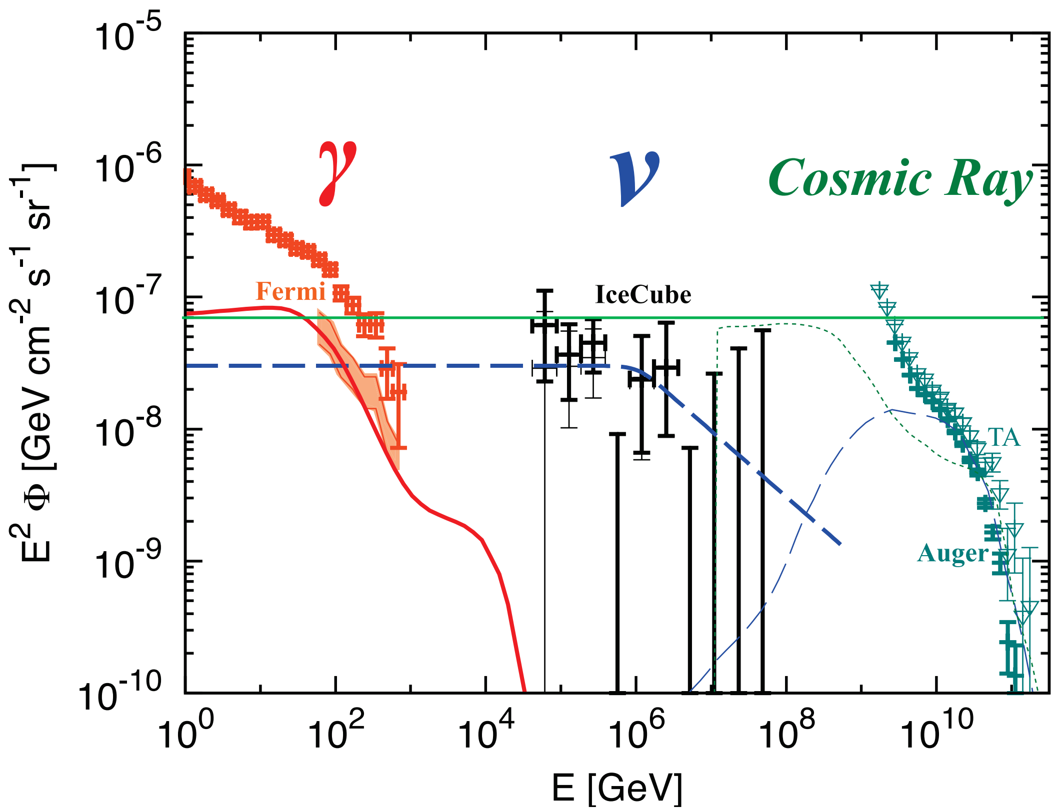
- AGN as "UHECR" accelerators
- confinement in cocoons & clusters
- escaping nuclei → "hard" spectrum
- smooth transition to cosmogenic ν spectrum

Neutrino-Gamma-UHECR Connection?

(grand-)unification of neutrinos, gamma rays & UHECRs

simple flat energy spectrum w. s~2 can fit all diffuse fluxes

- Explain >0.1 PeV ν data with a few PeV break (theoretically expected)
- Escaping CRs may contribute to the observed UHECR flux



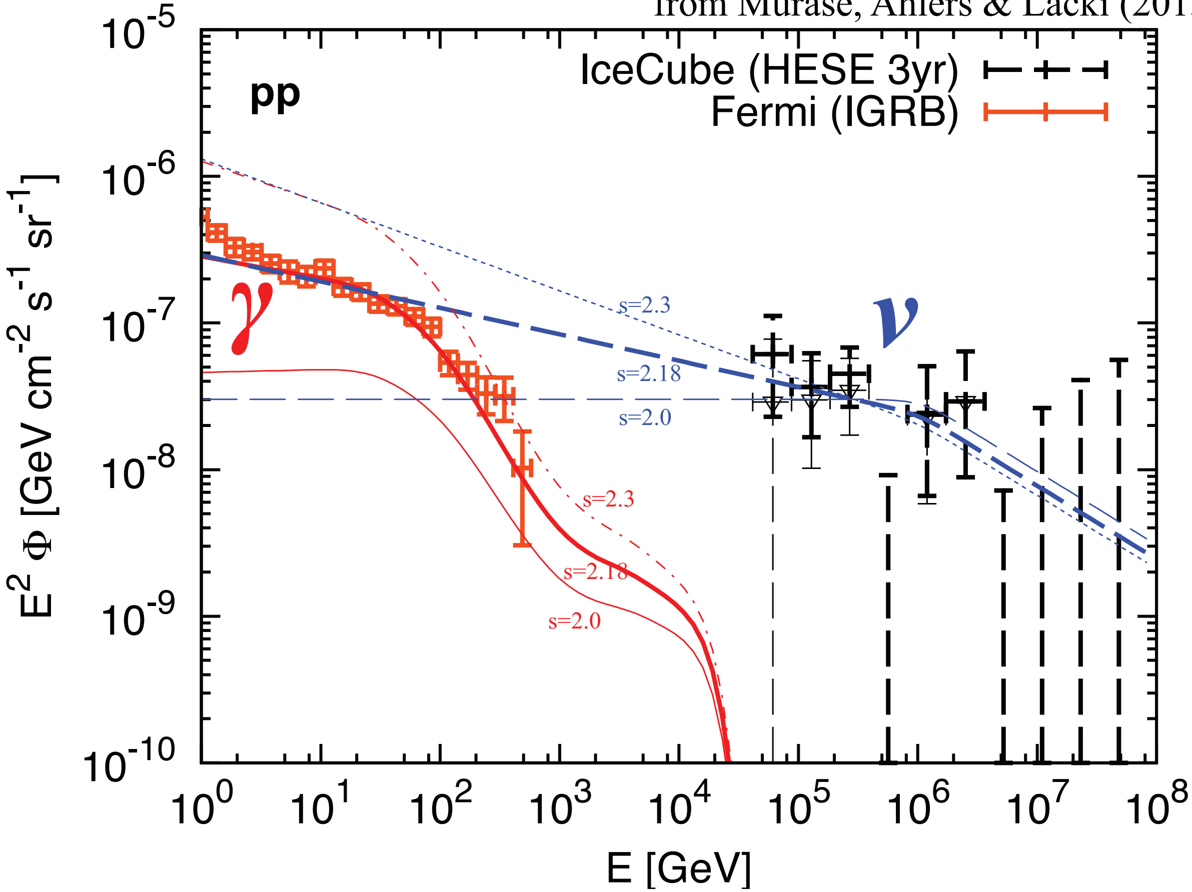
KM & Waxman 16 PRD

PeVν – confined CR
UHECR – escaping CR
sub-TeVγ – "sum"

Neutrino-Gamma Connection

Generic power-law spectrum: $\propto \varepsilon^{2-s}$, transparent to GeV-TeV γ

from Murase, Ahlers & Lacki (2013)



- **s_ν<2.1-2.2 (for extragal.); insensitive to redshift evolution of sources**
- **physical connection between ν & γ backgrounds?**
  contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)

PHYSICAL REVIEW D **88,** 121301(R) (2013)

Testing the hadronuclear origin of PeV neutrinos observed with IceCube

Kohta Murase,[1] Markus Ahlers,[2] and Brian C. Lacki[3]

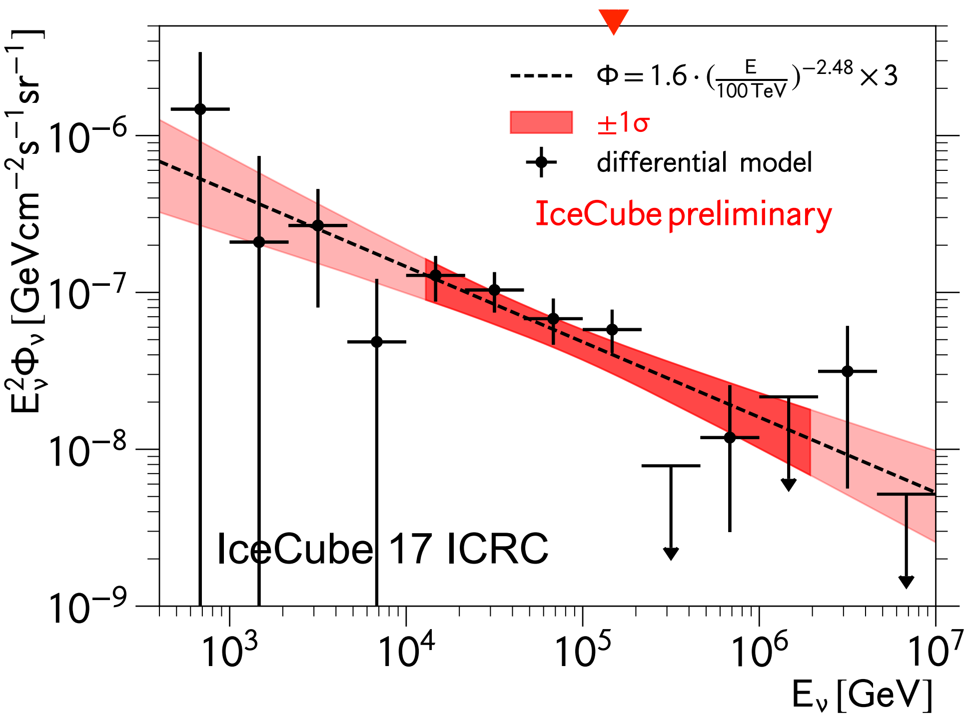
We consider implications of the IceCube signal for hadronuclear (pp) scenarios of neutrino sources such as galaxy clusters/groups and star-forming galaxies. Since the observed neutrino flux is comparable to the diffuse γ-ray background flux obtained by *Fermi*, we place new, strong *upper* limits on the source spectral index, $\Gamma \lesssim 2.1$–2.2. In addition, the new IceCube data imply that these sources contribute *at least* 30%–40% of the diffuse γ-ray background in the 100 GeV range and even $\sim$100% for softer spectra. Our results, which are insensitive to details of the pp source models, are one of the first strong examples of the multimessenger approach combining the *measured* neutrino and γ-ray fluxes. The pp origin of the IceCube signal can further be tested by constraining Γ with sub-PeV neutrino observations, by unveiling the sub-TeV diffuse γ-ray background and by observing such pp sources with TeV γ-ray detectors. We also discuss specific pp source models with a multi-PeV neutrino break/cutoff, which are consistent with the current IceCube data.

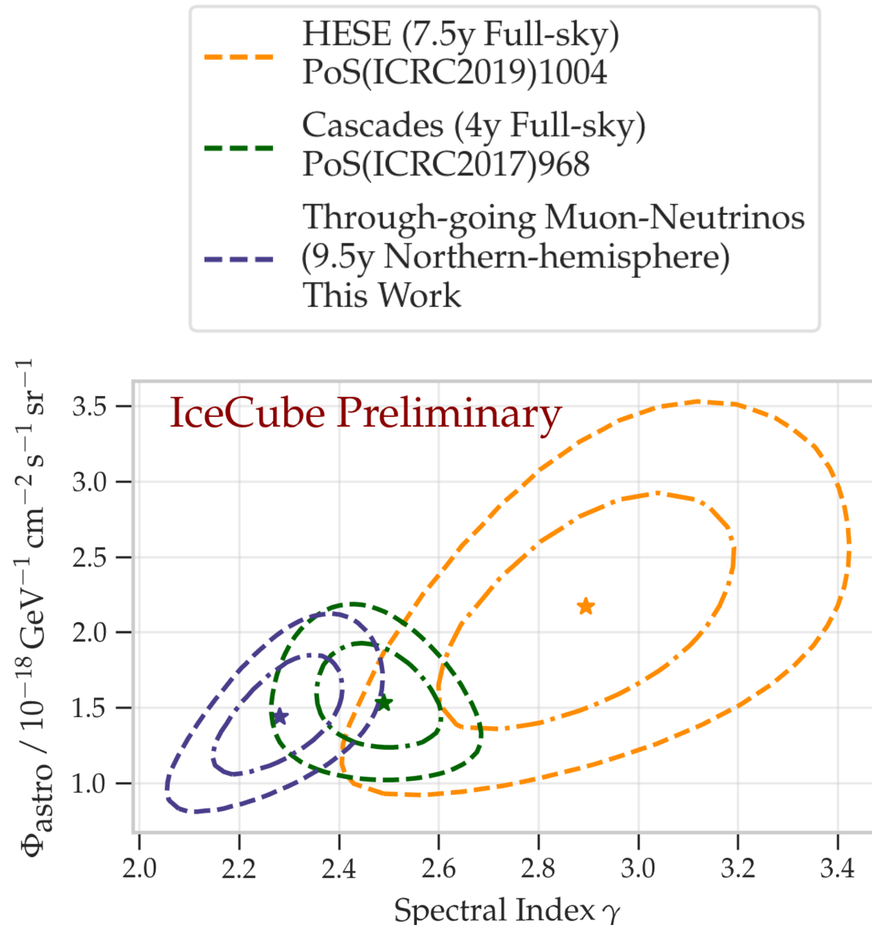
Lowering the Threshold: Medium-Energy Excess?

- Shower analyses

  E_{dep}: 0.4 TeV-10 PeV (2010-2015)

IceCube @ ICRC 2019





4740 events, s=2.48+-0.08

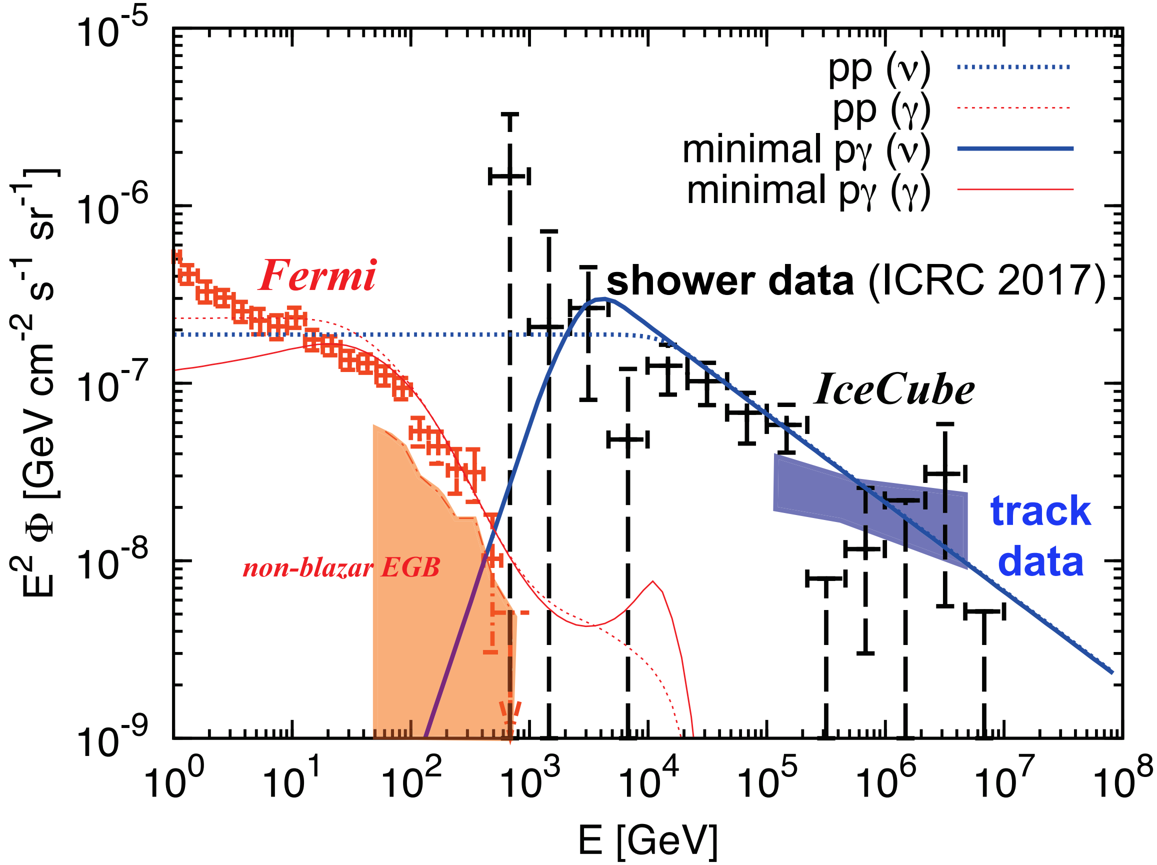
$E_\nu^2\ \Phi_\nu$=(1.57+0.23-0.22)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV (per flavor)

No evidence for north-south asymmetry

Not conclusive but perhaps a structure in the neutrino spectrum?

Medium-Energy Excess Problem

- 10-100 TeV shower data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



KM, Guetta & Ahlers 16 PRL

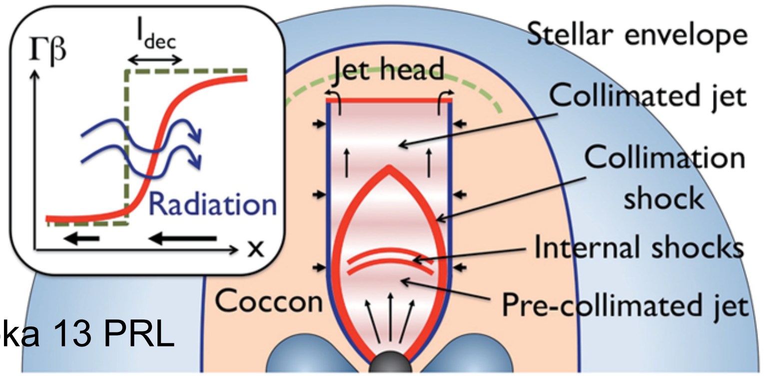
Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent

→ **existence of "hidden (γ-ray dark) sources"**

(ν data above 100 TeV can be explained by γ-ray transparent sources)

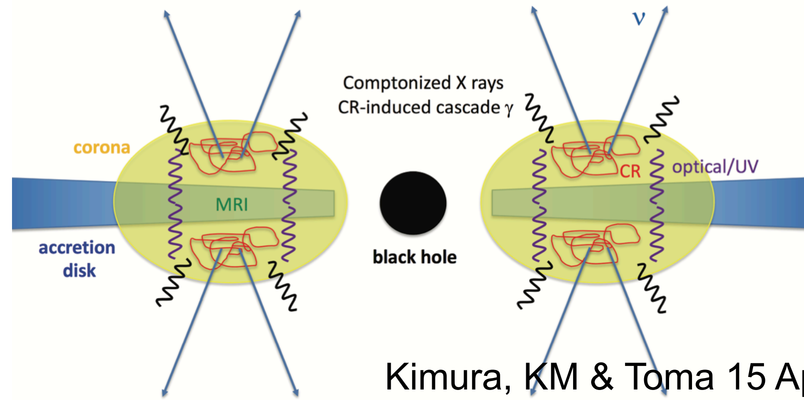
Hidden Cosmic-Ray Accelerators?

Low-power GRBs (choked jets)

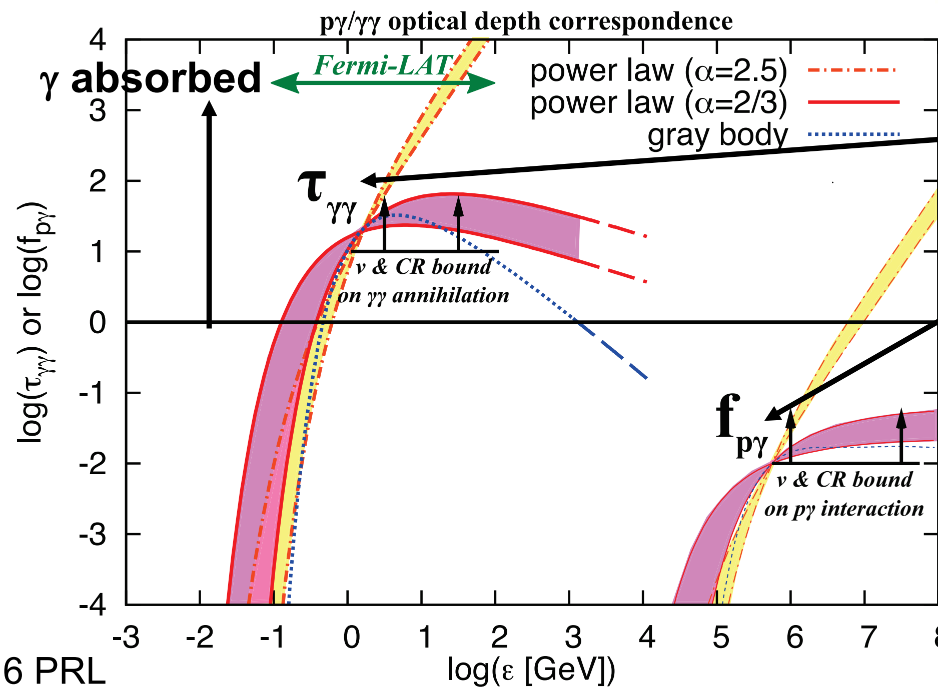


KM & Ioka 13 PRL

Supermassive black hole cores



Kimura, KM & Toma 15 ApJ



KM+ 16 PRL

$$\gamma + \gamma \rightarrow e^+ + e^-$$

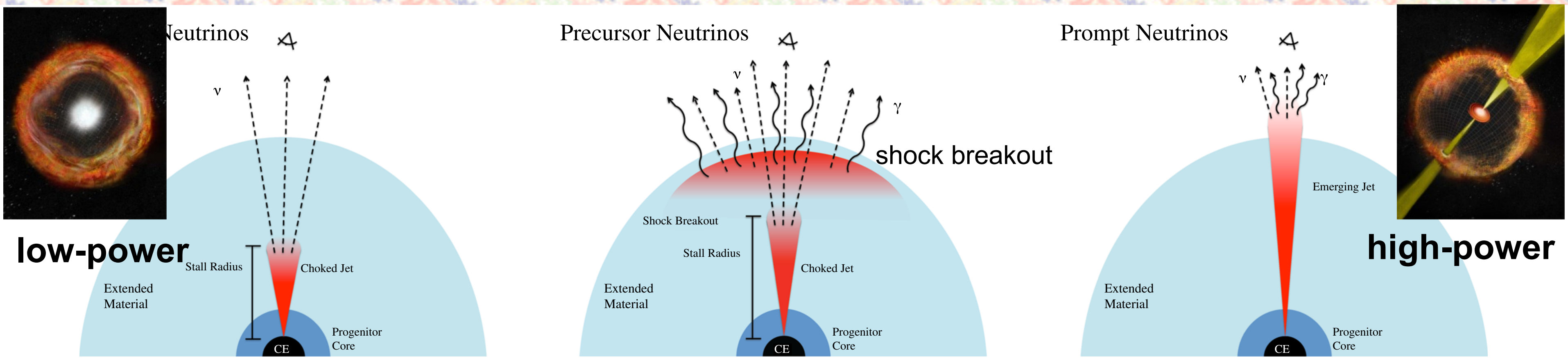
II

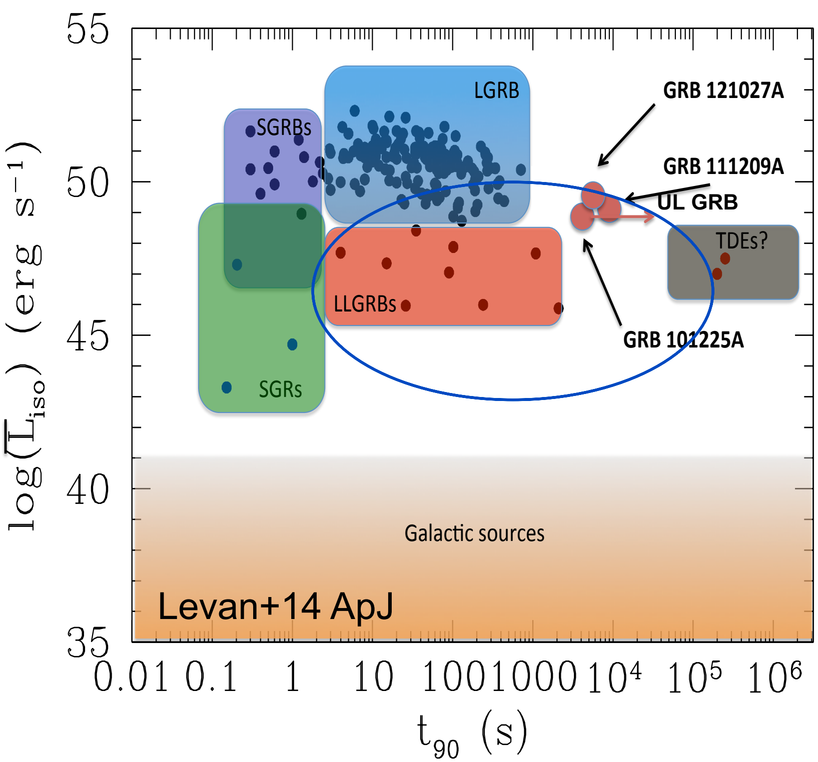
$$p + \gamma \rightarrow N\pi + X$$

$$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\text{or } \bar{\nu}_e) + e^\pm$$

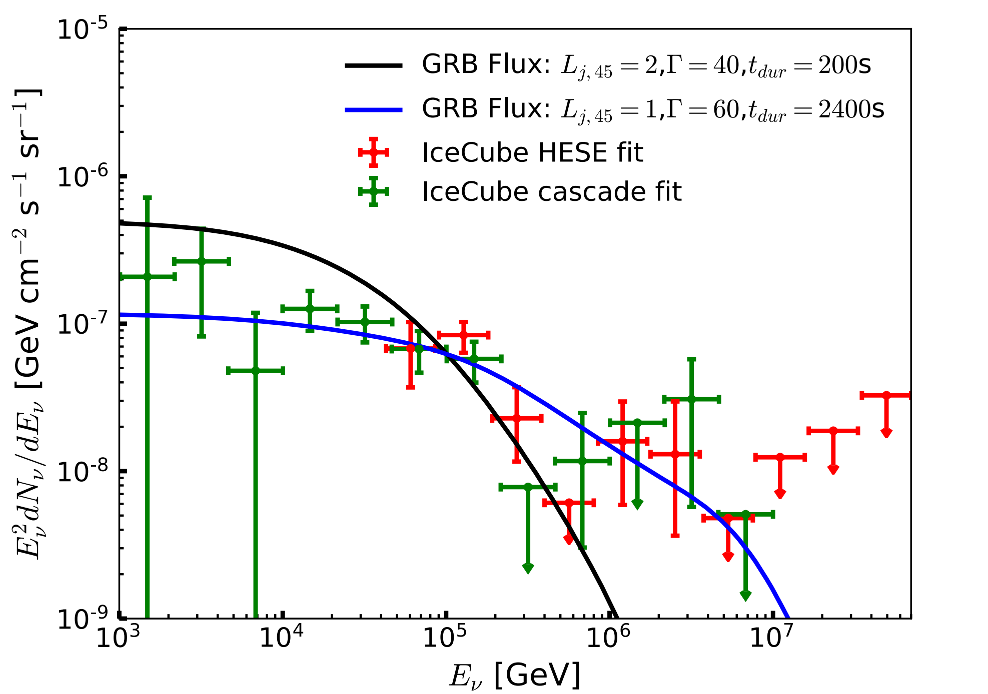
Interaction probability of γγ ~ 1000 x (effective) interaction probability of pγ collisions

Choked Jets as Hidden Neutrino Factories





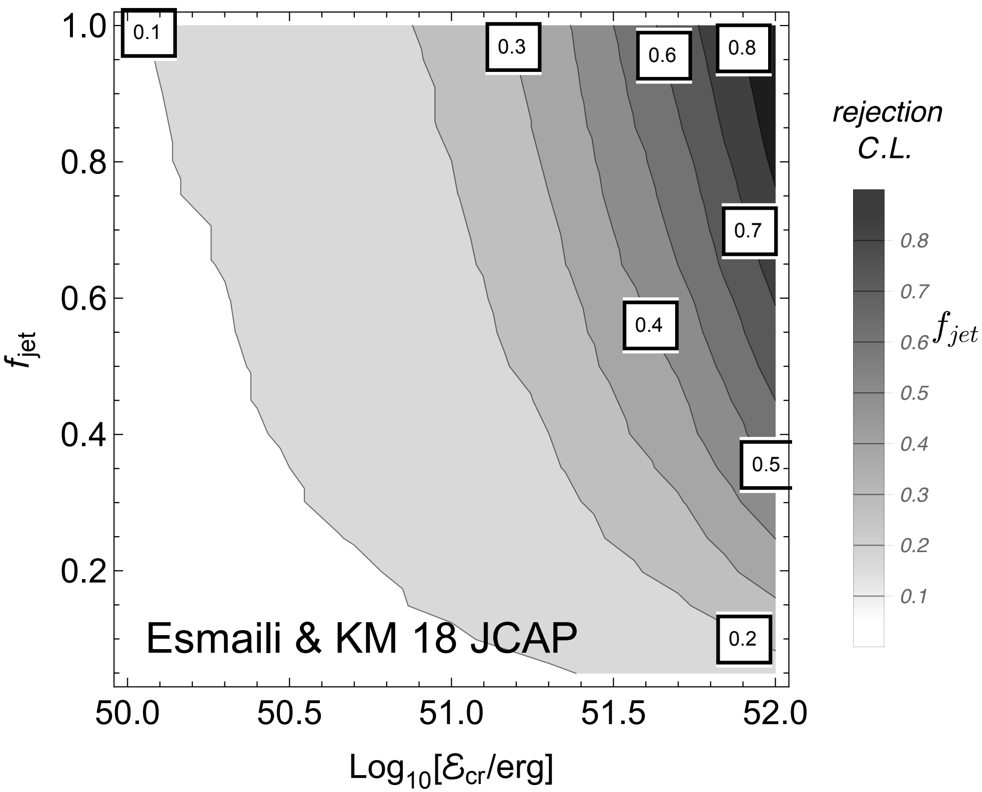
KM & Ioka 13, Nakar 15, Senno, KM & Meszaros 16, He+ 18



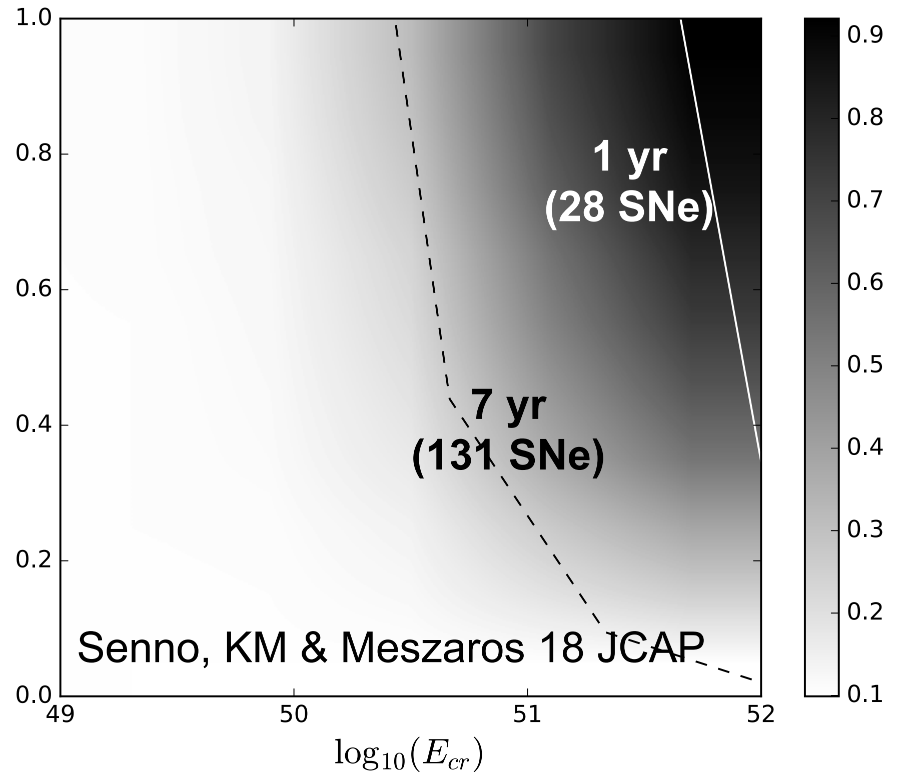
Stacking Searches for Neutrinos from Supernovae

Stacking analyses on SNe (~week) w. open SN catalogue

public 6 yr HESE data w. 222 SNe Ibc



public 1 yr upgoing ν_μ data w. 28 SNe Ibc

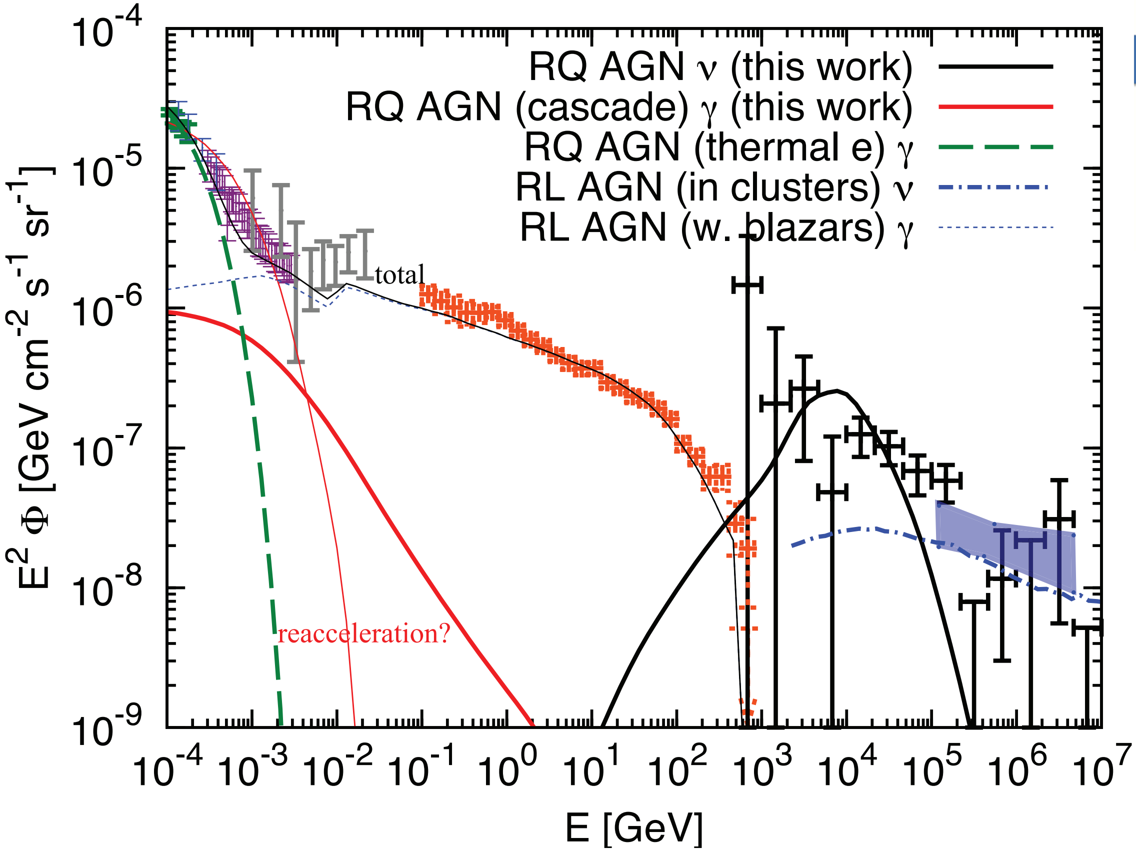


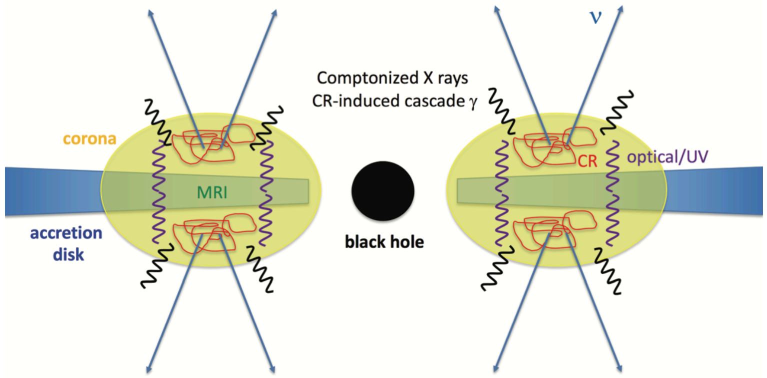
- Present constraints: $E_{cr}<10^{51}$-10^{52} erg (if all SNe emit νs)
- Stacking analyses w. shower+track (ultimately global) data? (tracks are better for transients due to time coincidence)

AGN Cores as Hidden Neutrino Factorioes

AGN corona: promising sites of CR acceleration (ex. Hoshino 12, Kimura, KM & Tomida 19)

KM, Kimura & Meszaros 19

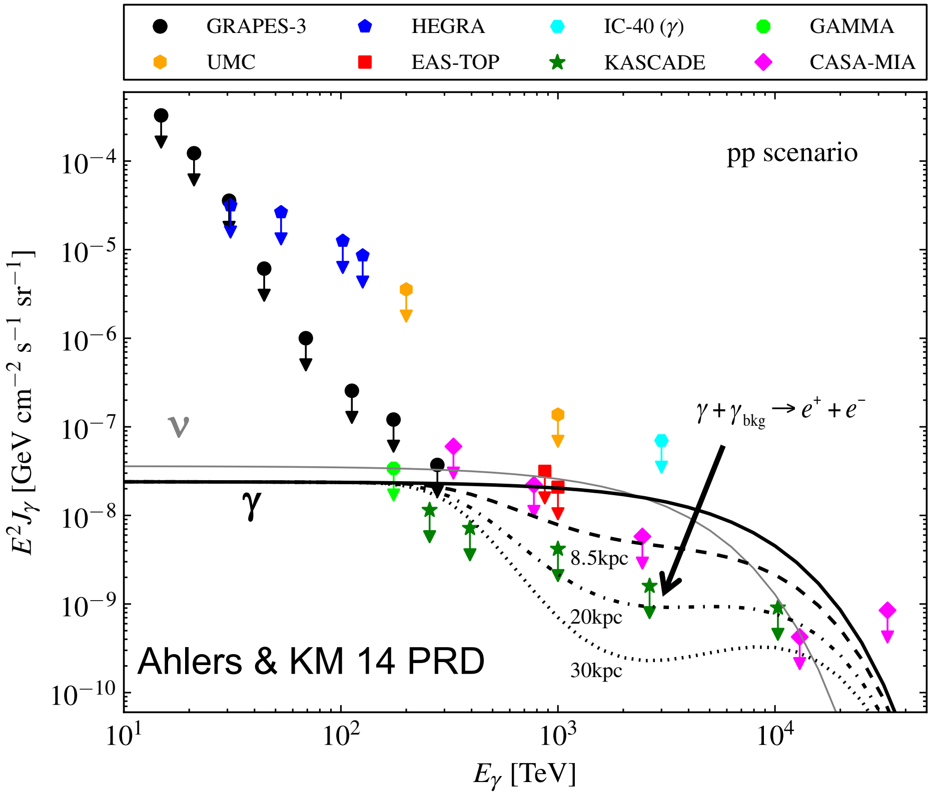


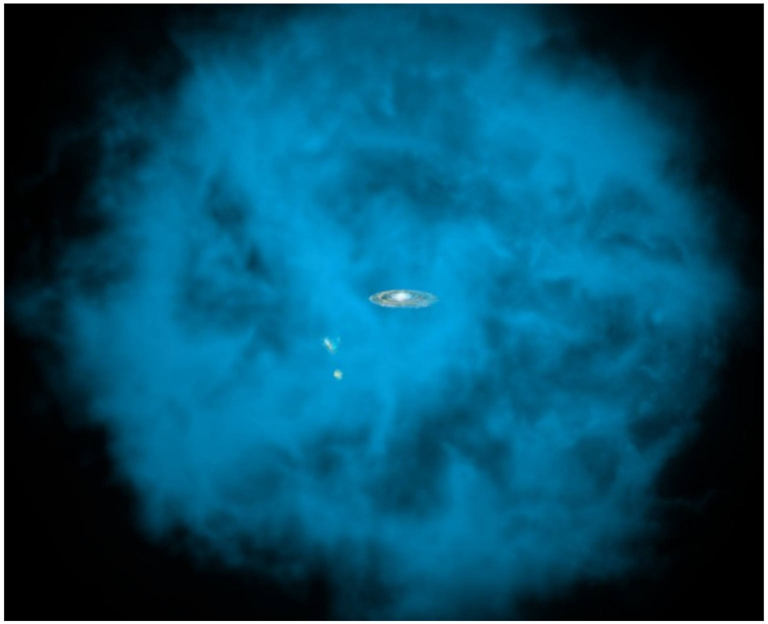


- Robust predictions for MeV γ (AMEGO) & sub-PeV ν (Gen2/KM3Net)
- Stacking analyses w. shower+track (ultimately global) data

Galactic Contribution?

Isotropic limits (Galactic halo CR model)





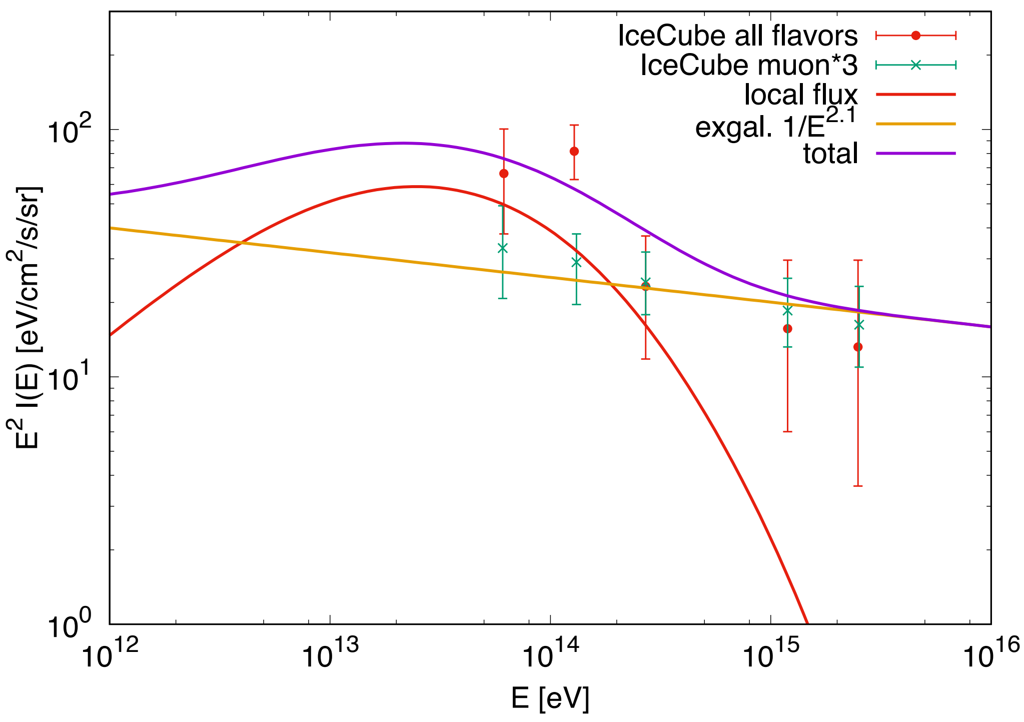
$$n_H = (10^{-4.2\pm0.25})(R/R_{vir})^{-0.8\pm0.3}$$

- Template analyses are also feasible (depending on CR distribution) (spatial information needed)

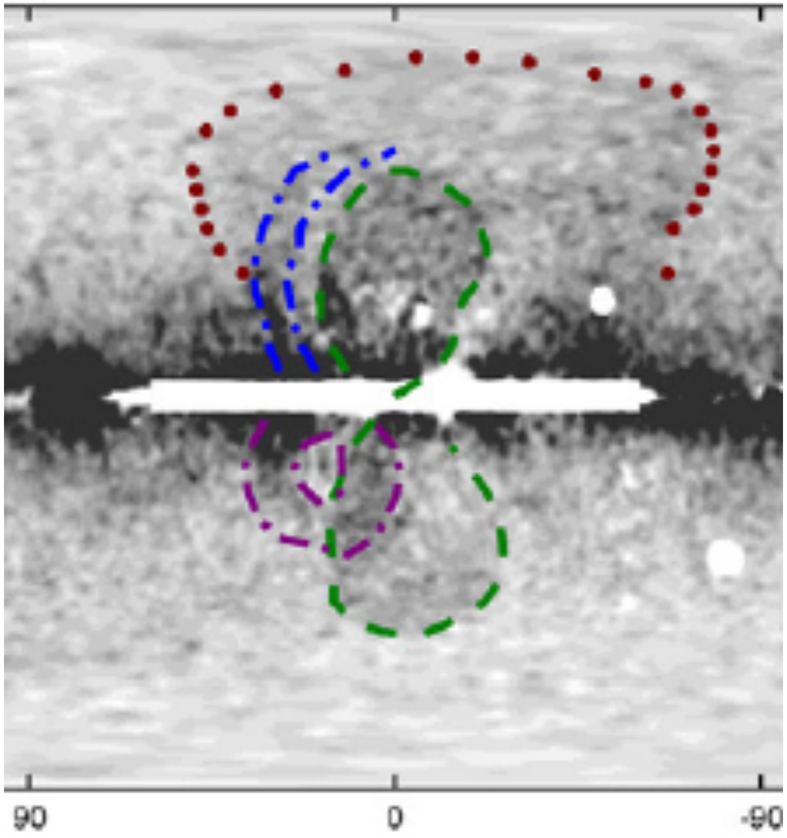
※ Airshower arrays have placed diffuse γ-ray limits at TeV-PeV
Fermi γ-ray data imply $s_\nu < 2.0$ → support extragalactic scenarios

Galactic Contribution?

Andesen et al. 17



Su et al. 2010



- Correlation analyses w. shower+track (ultimately global) data (spatial information needed)
- HAWC limits exist and seem to constrain the model

Why Important

Importance of identifying hidden neutrino sources

- Dense environments that can only be probed by neutrinos
- Huge non-thermal energy budget in the Universe

If 10-100 TeV neutrinos are of astrophysical & isotropic

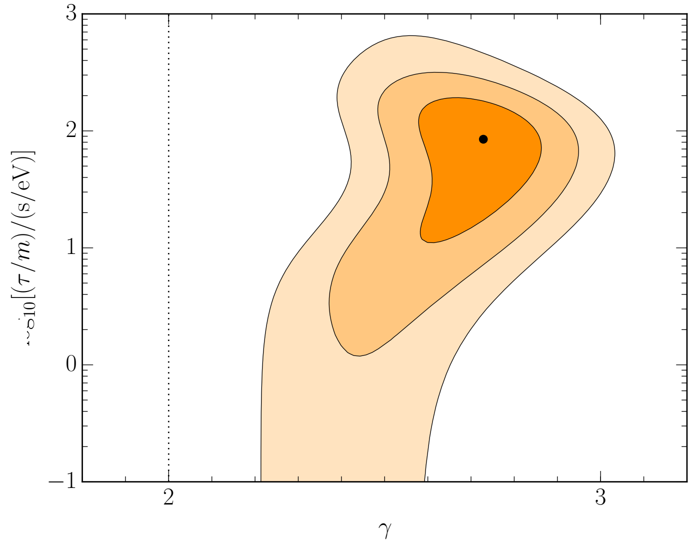
- CR reservoir models predict a structure in the spectrum (hidden source population + CR reservoir population)
- Galactic models also predict a structure in the spectrum (Galactic contribution + extragalactic contribution)
- No structure -> single hidden source population

- Unlikely to be a simple power-law (broken power law?)
- Keep the Gen-2 threshold not far from 10 TeV (~10-30 TeV) & improve angular resolutions

BSM Explanations for Medium-Energy Data?

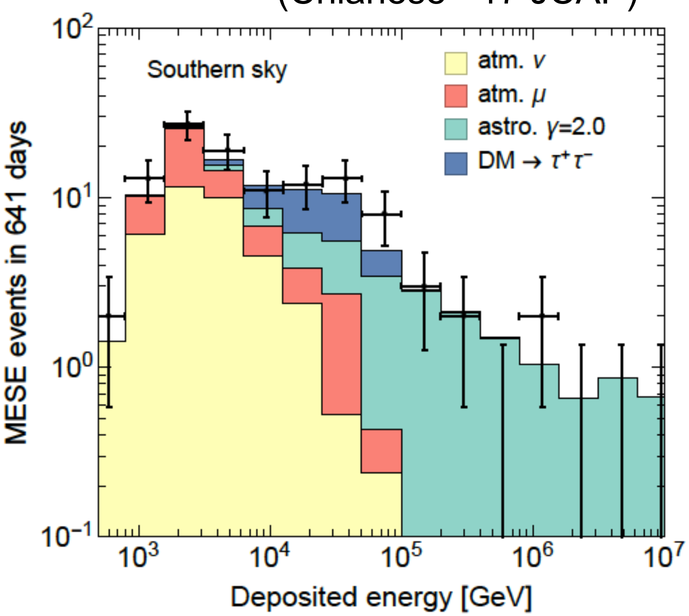
Invisible neutrino decay

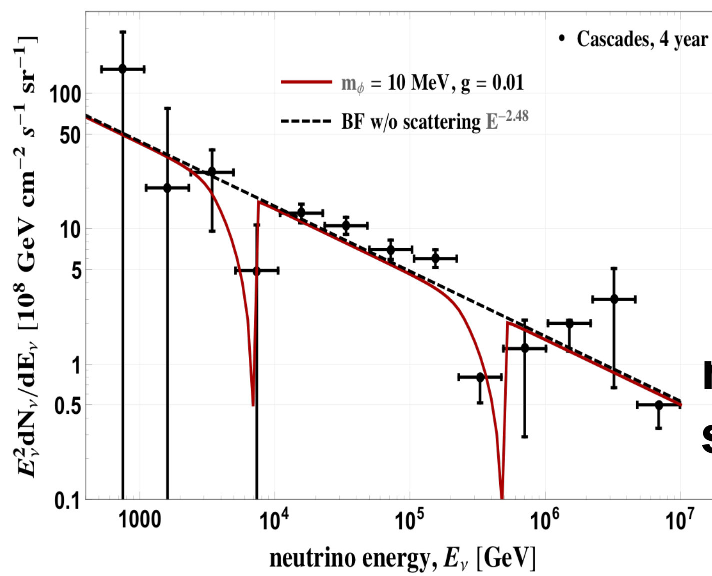
(Denton & Tamborra 18 PRL)



dark matter decay

(Chianese+ 17 JCAP)



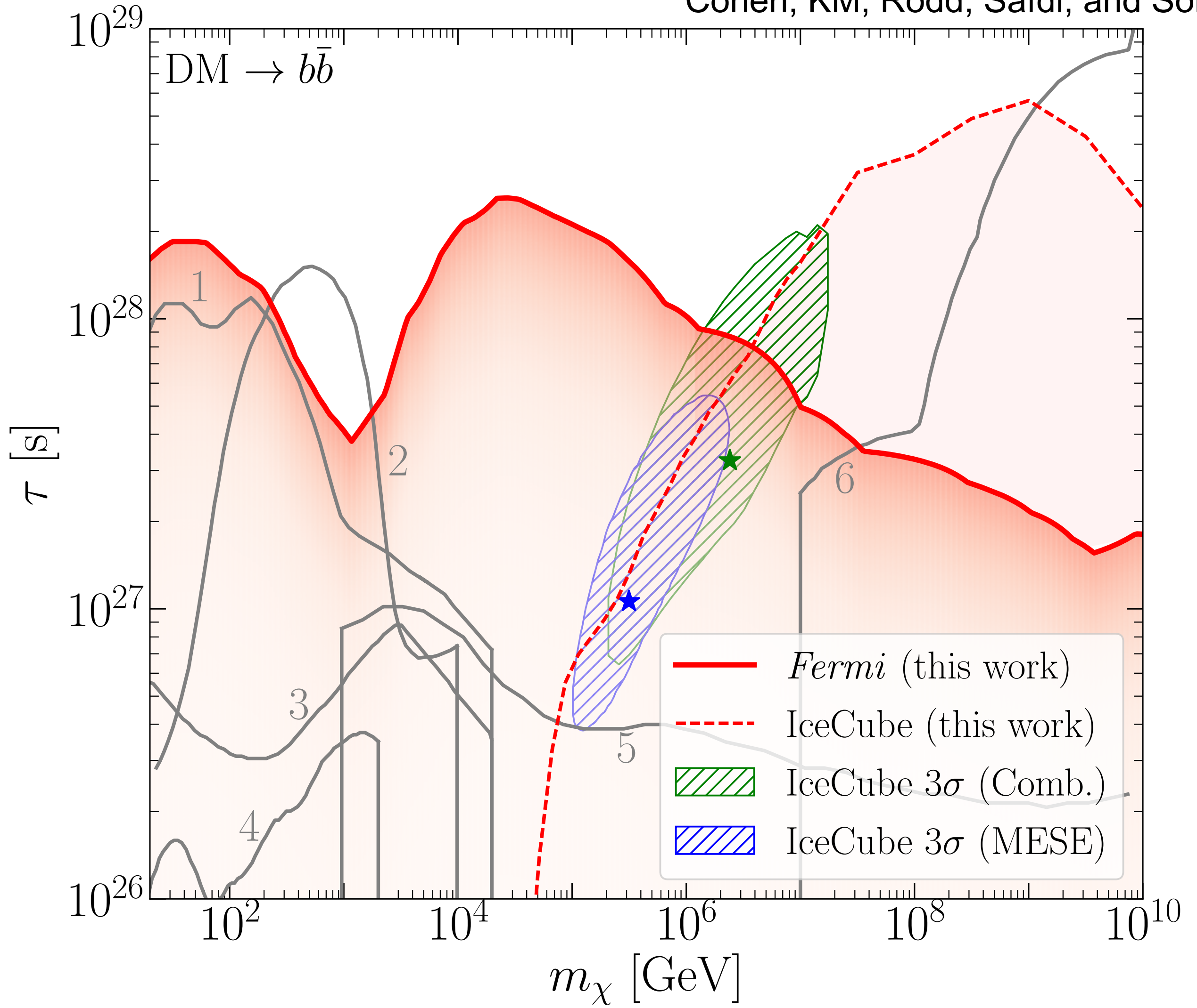


neutrino-neutrino self-interactions

(e.g., Blum, Hook & KM
Cherry+ 14
KM & Shoemaker 19)

Multi-Messenger Constraints on Decaying DM

Cohen, KM, Rodd, Safdi, and Soreq 17 PRL

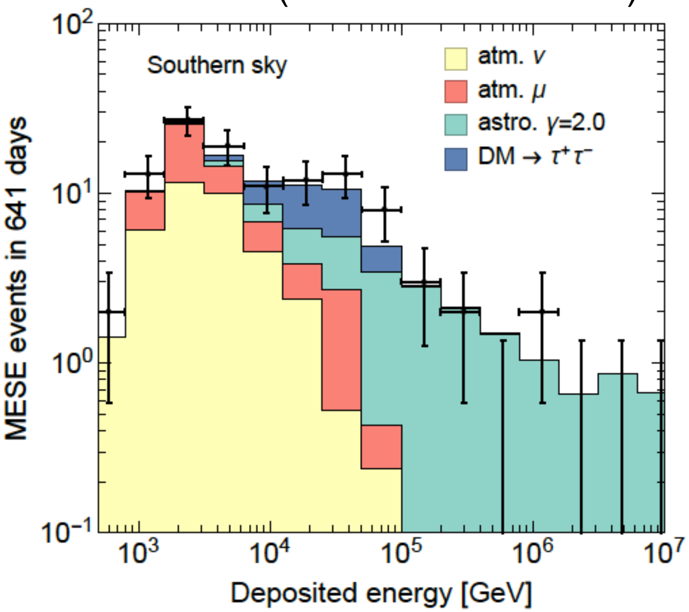


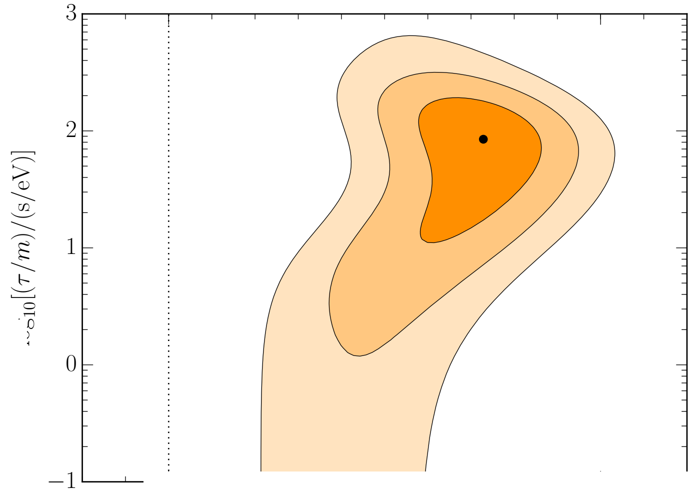
Green (DM only for global fit), Blue (DM+power law for global fit)

BSM Explanations for Medium-Energy Data?

dark matter decay

(Chianese+ 17 JCAP)



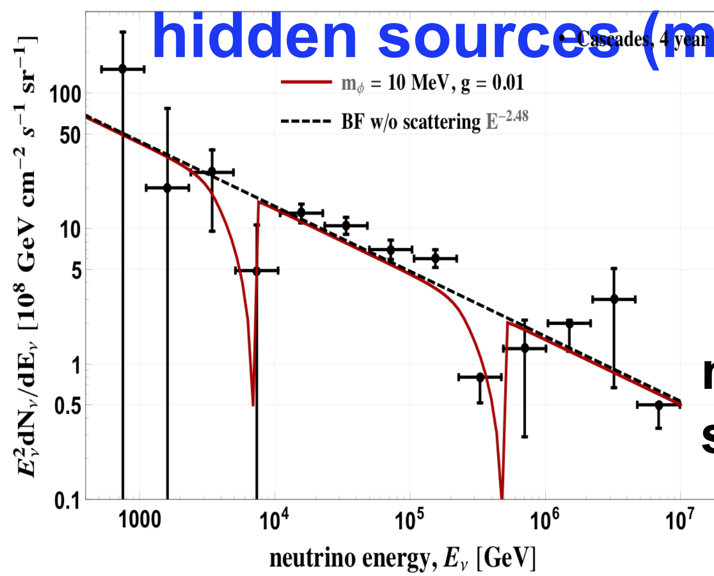


Invisible neutrino decay

(Denton & Tamborra 18 PRL)

astrophysical ν necessary

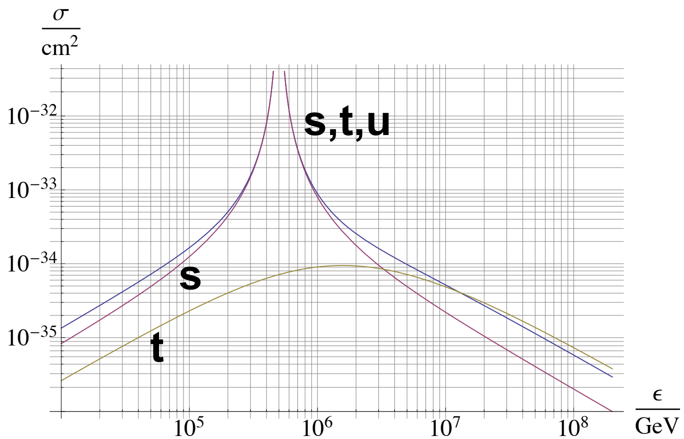
hidden sources (more) required



neutrino-neutrino self-interactions

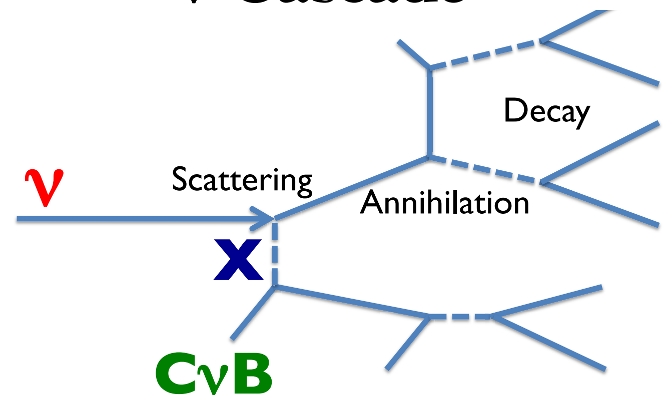
(e.g., Blum, Hook & KM
Cherry+ 14
KM & Shoemaker 19)

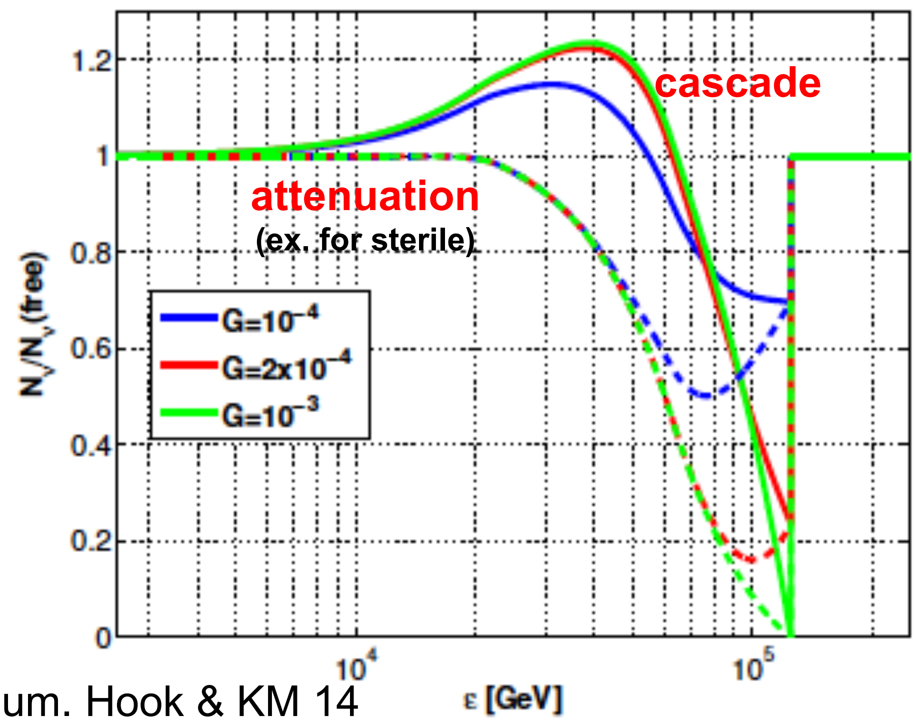
Effects on Cosmic Neutrino Spectra



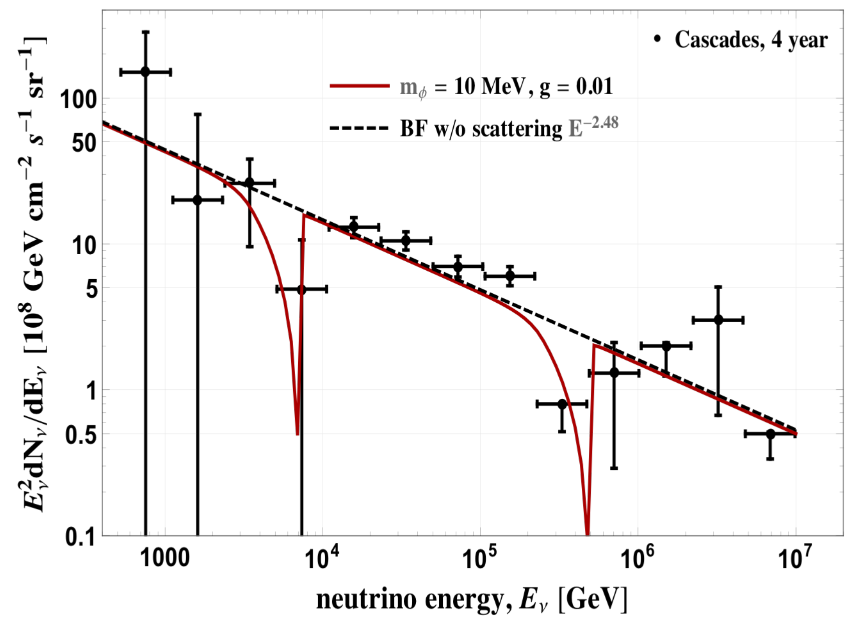
ν Cascade

Ioka & KM 14





Blum. Hook & KM 14



KM & Shoemaker 19

Neutrino Flavors

Neutrino oscillation

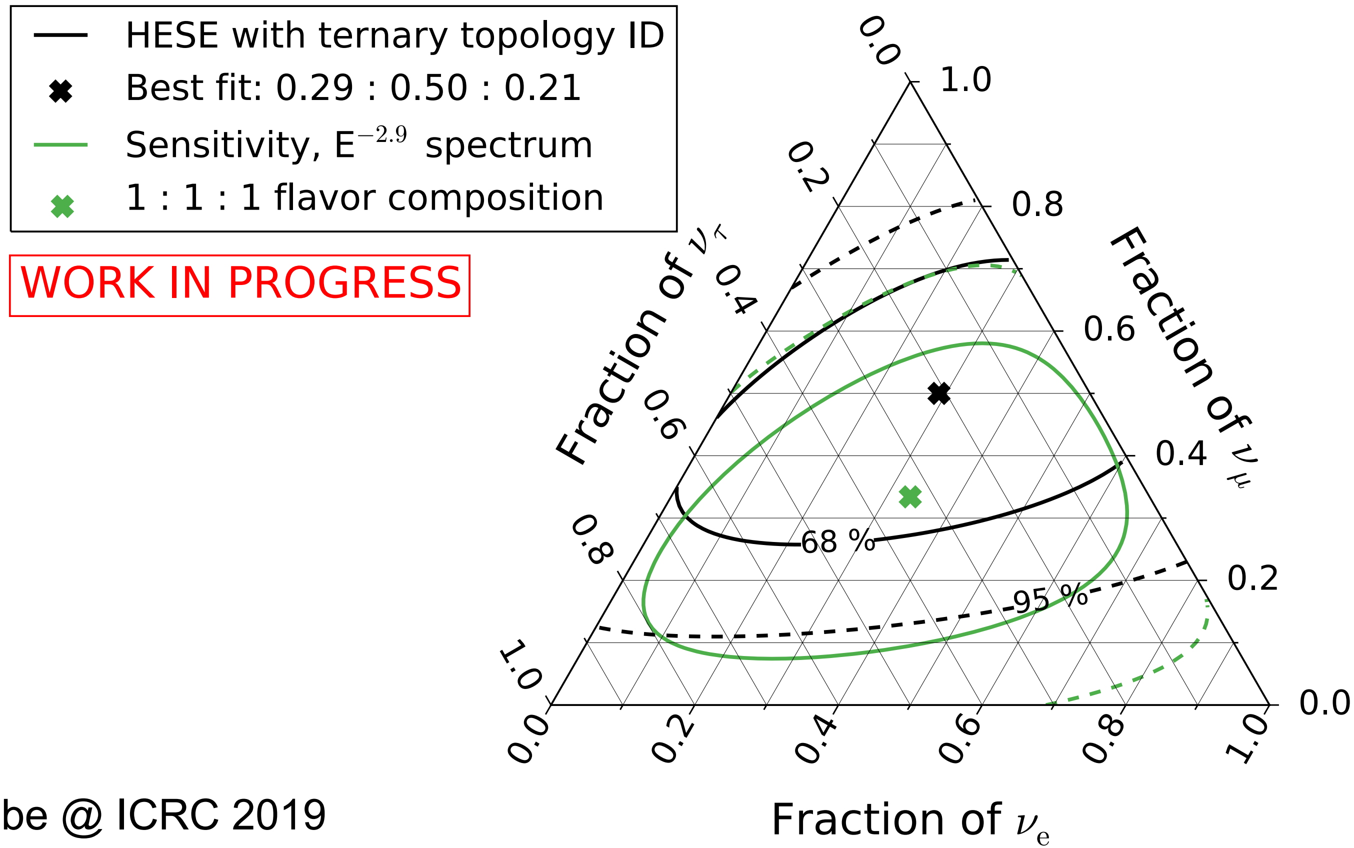
$$P_{\alpha\to\beta}(t) = \left| \sum_{k=1}^{n} U_{\beta k}^{*} \exp(-iEt) U_{\alpha k} \right|^2$$

U: lepton mixing matrix (Maki-Nakagawa-Sakata)

long baseline limit:

$\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$

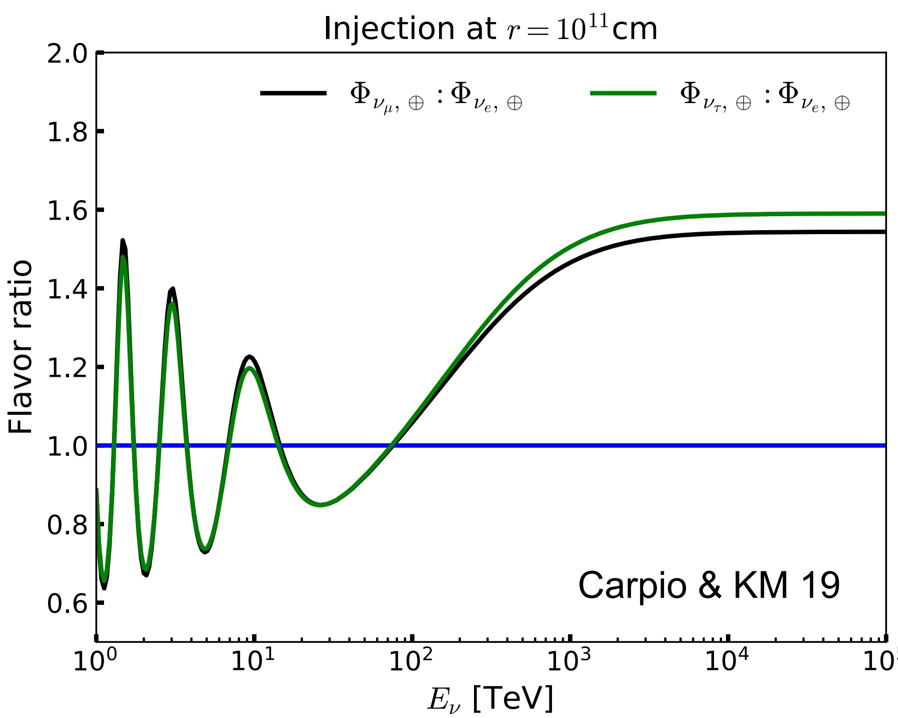
(if no astrophysical complications)

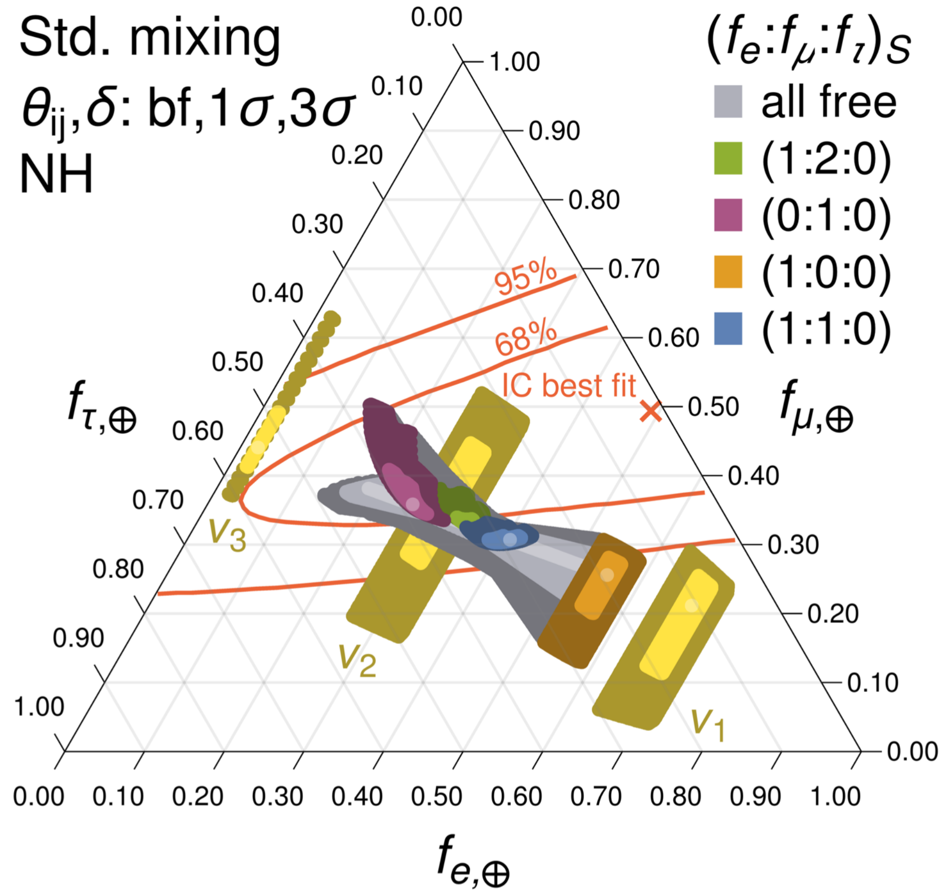


IceCube @ ICRC 2019

Flavor Ratios are E-Dependent

ν oscillation in choked jets





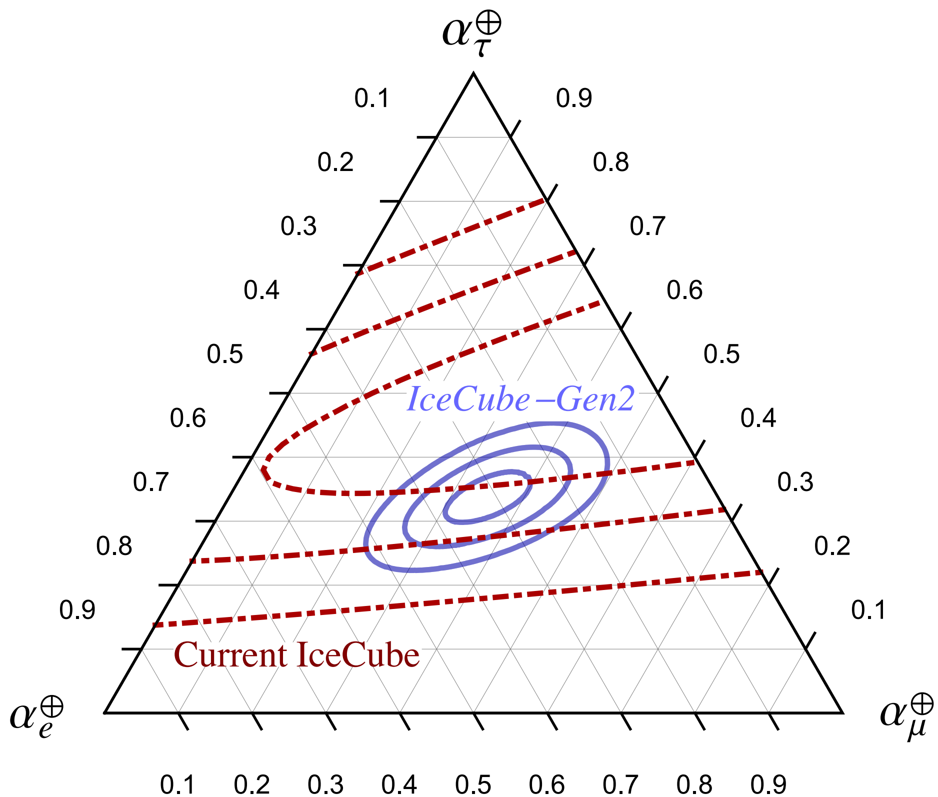
- Low: matter effect
- High: muon cooling

Bustamante, Beacom & Winter 15 PRL
see also Arguelles, Katori & Salvado 15 PRL

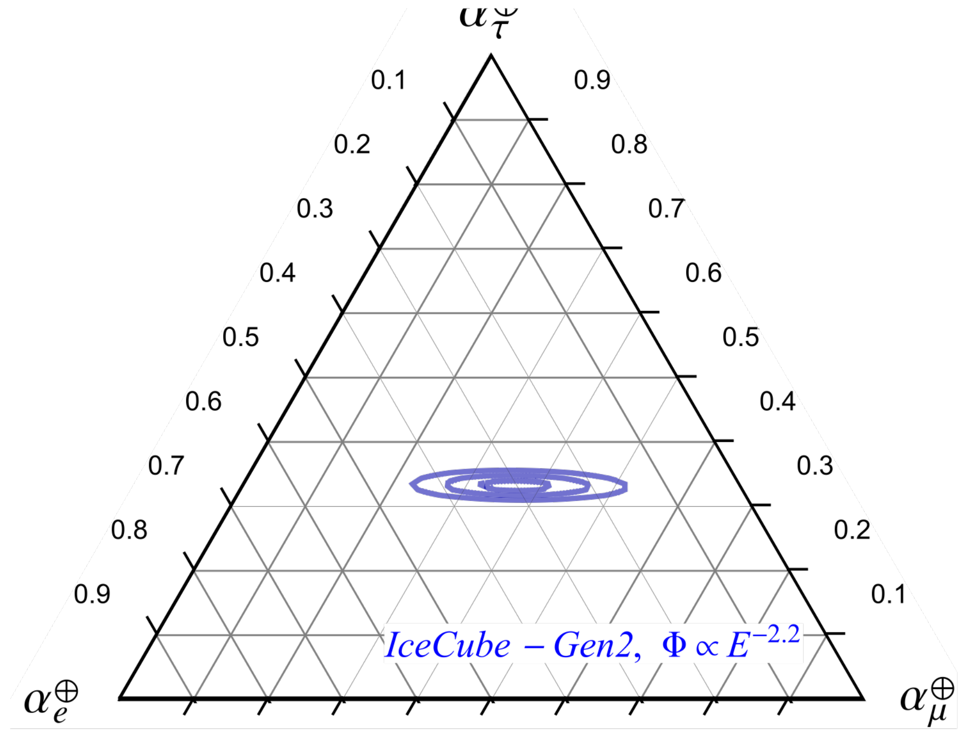
Constraints from Neutrino Flavors

Shower-to-track ratio -> flavor information (ex. IceCube Collaboration 15 ApJ)

BSM physics tests w. sufficient statistics (especially by Gen2)



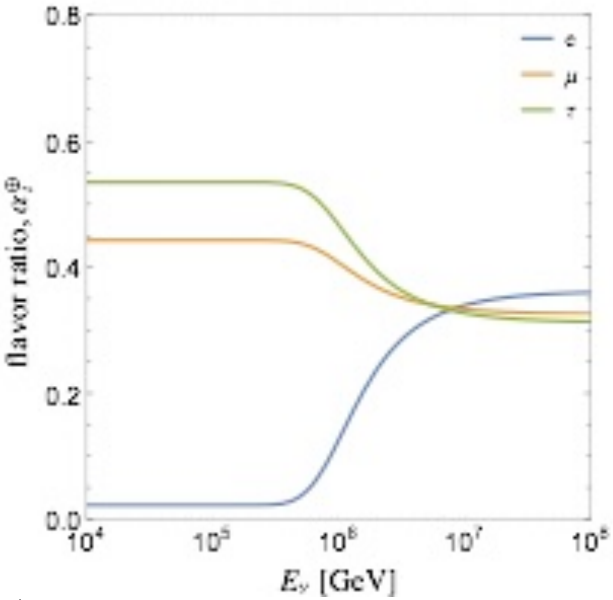
HESE w. Gen2



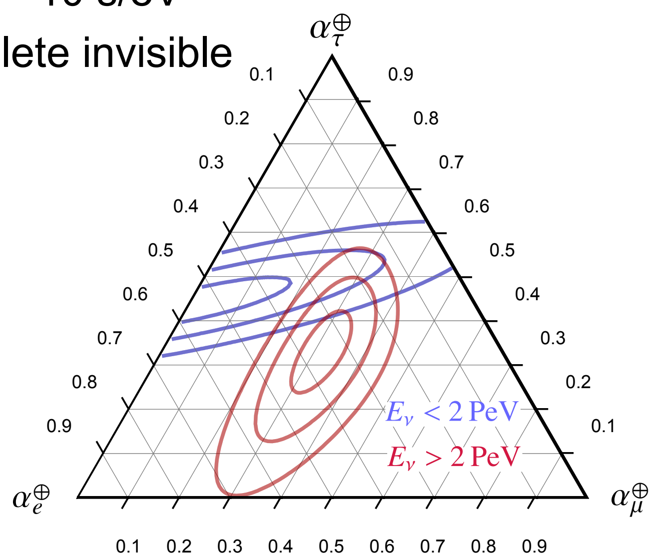
Theorist approach (shower+track)

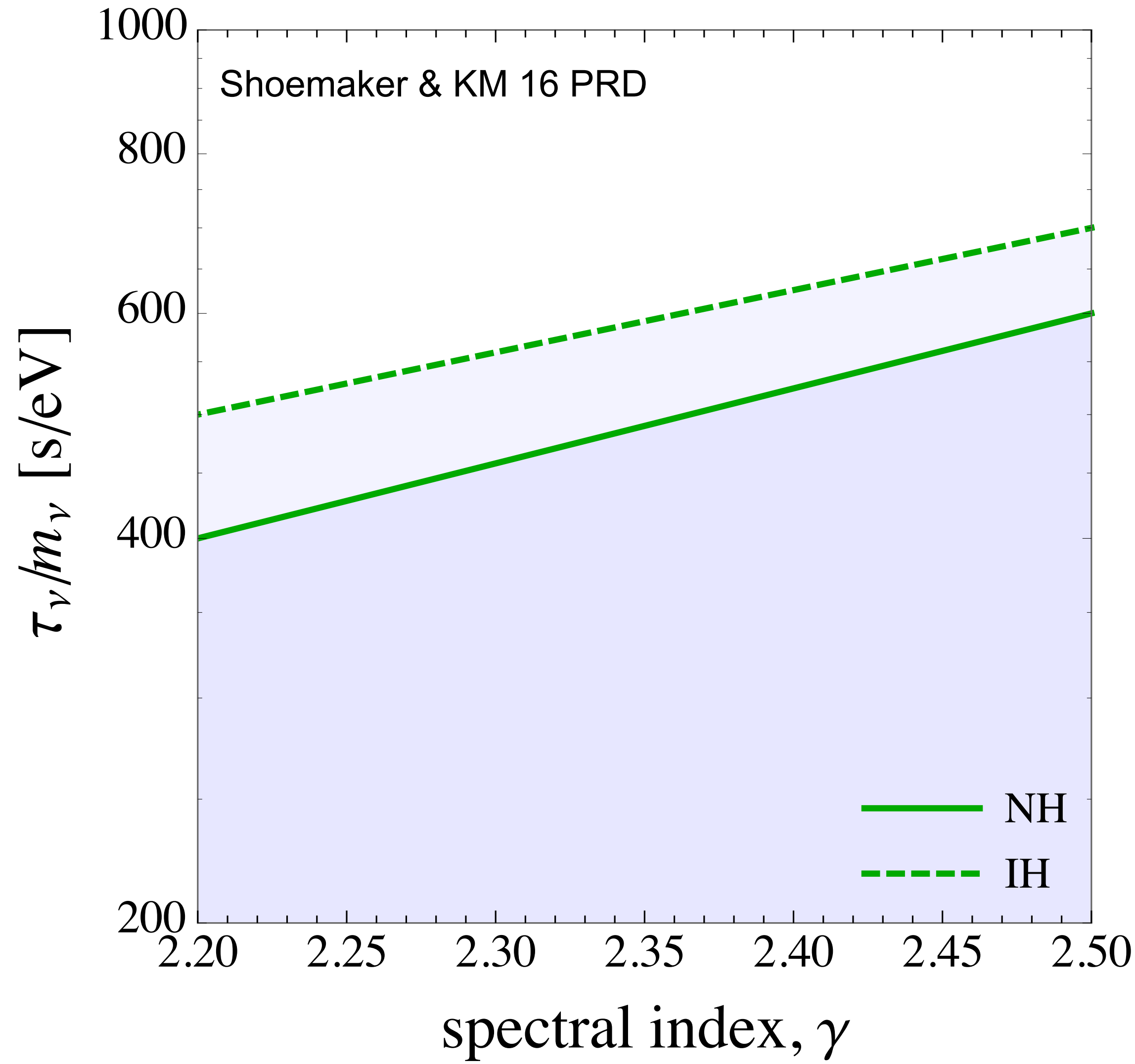
Shoemaker & KM 16 PRD

Future Constraints on Neutrino Decay

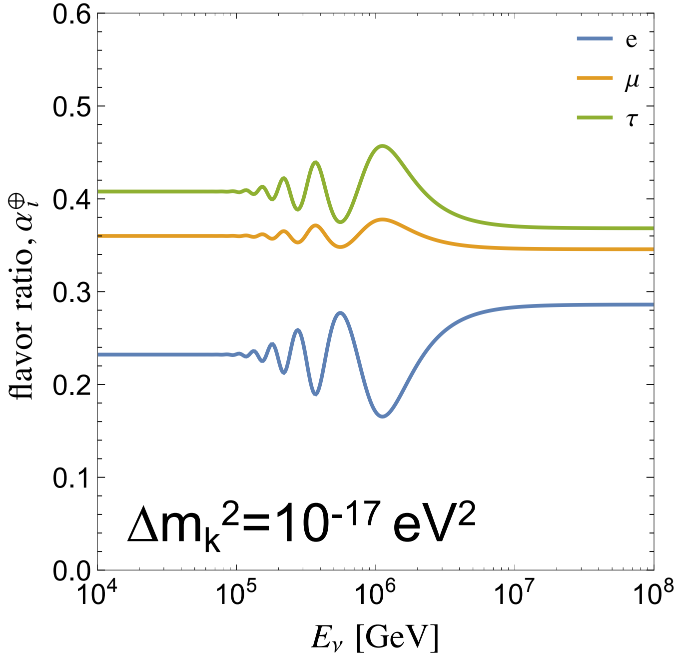


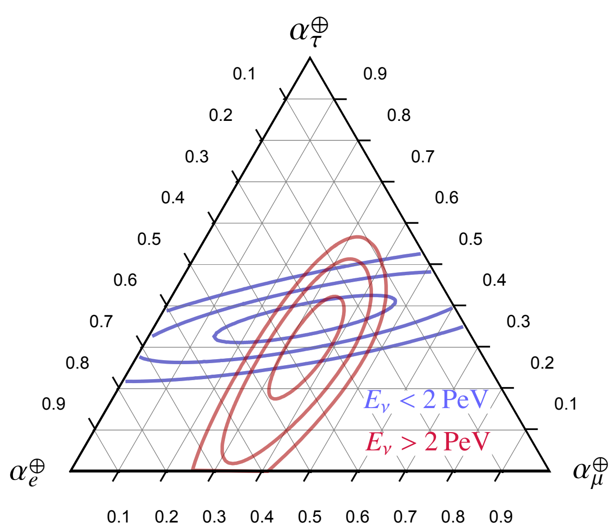
IH: κ^{-1}=10 s/eV
complete invisible





Pseudo-Dirac Neutrinos



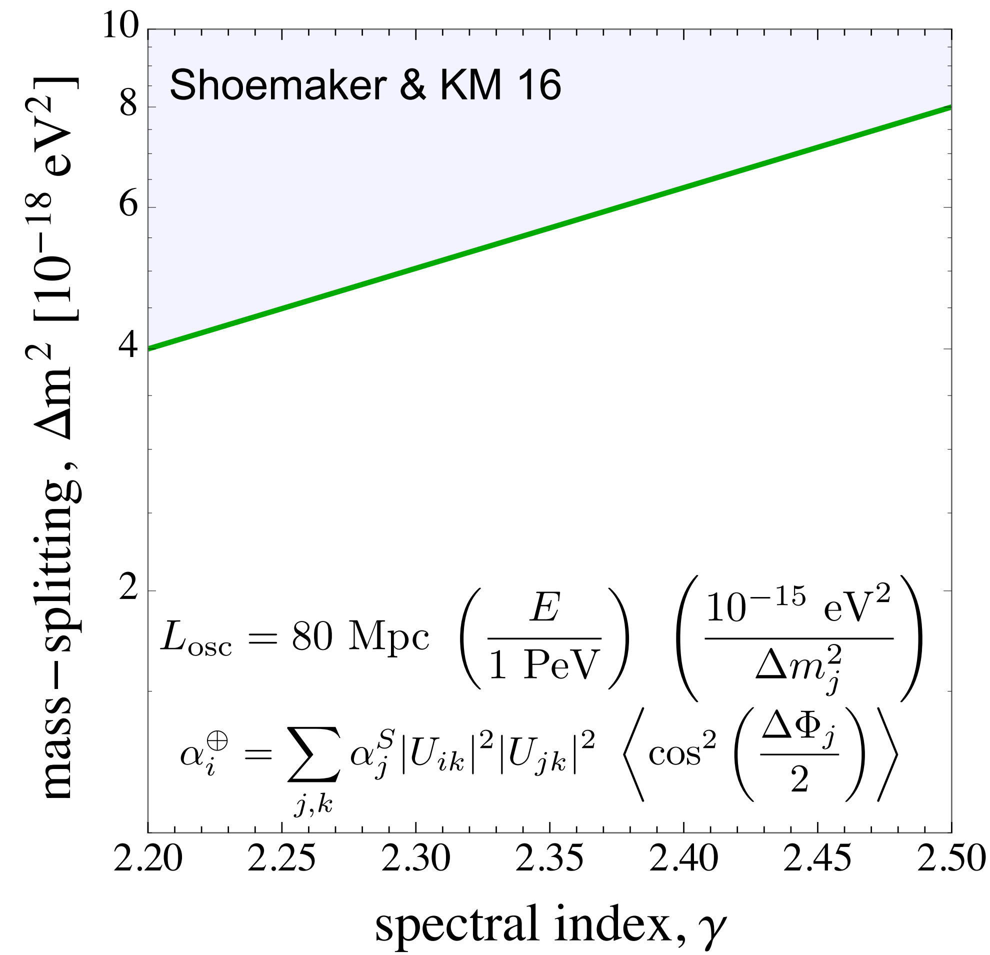


- Tiny mass splitting w. sterile neutrinos

Wolfenstein 81, Petcov 81

- Cosmic neutrinos can be used as a probe

Beacom et al. 04, Karanen et al. 03



Summary

Global fit results could address whether a single power-law works or not
Shower/MESE data may bring us “surprises” about the non-thermal universe

HE Neutrino Origin?

pp scenarios (cosmic particle unification) require two component models
10-100 TeV data: hidden CR accelerators (neutrinos are “unique”)
must be a broken power-law or other complicated spectra

BSM physics?.
Decaying dark matter, neutrino decay, neutrino self-interactions etc.

Wish list?.
“ideal”: tool enabling one to tests arbitrary spectra & flavor ratios
Not only isotropic background but also extended Galactic sources
- different astrophysical spectral (and spatial) templates: provided by theorists
- different astrophysical flavor ratios: could be treated as systematics
- BSM tests: dedicated analysis by experimentalists/tool available for theorists