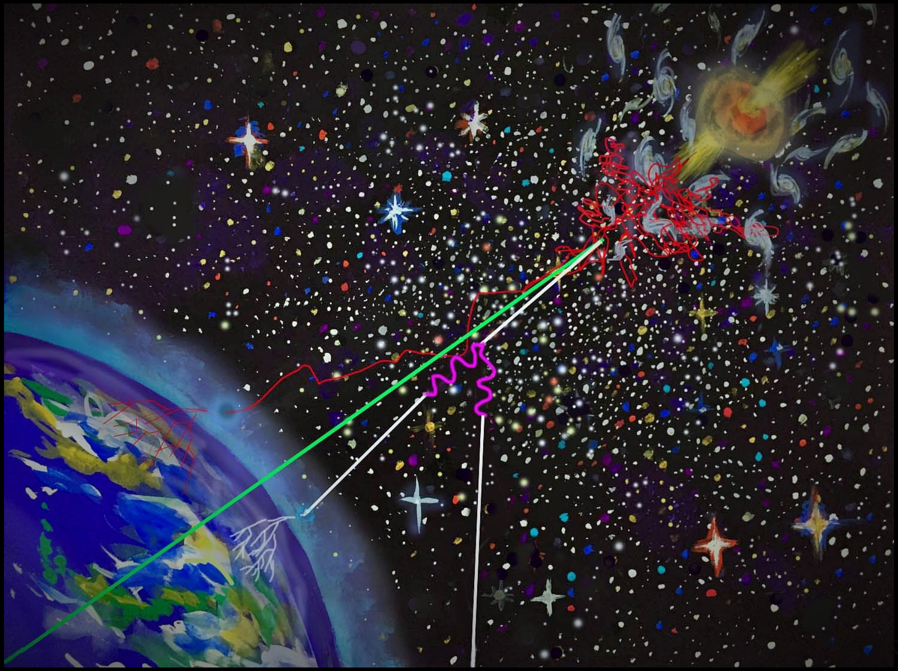
Cosmic Particles in the Multi-Messenger Era

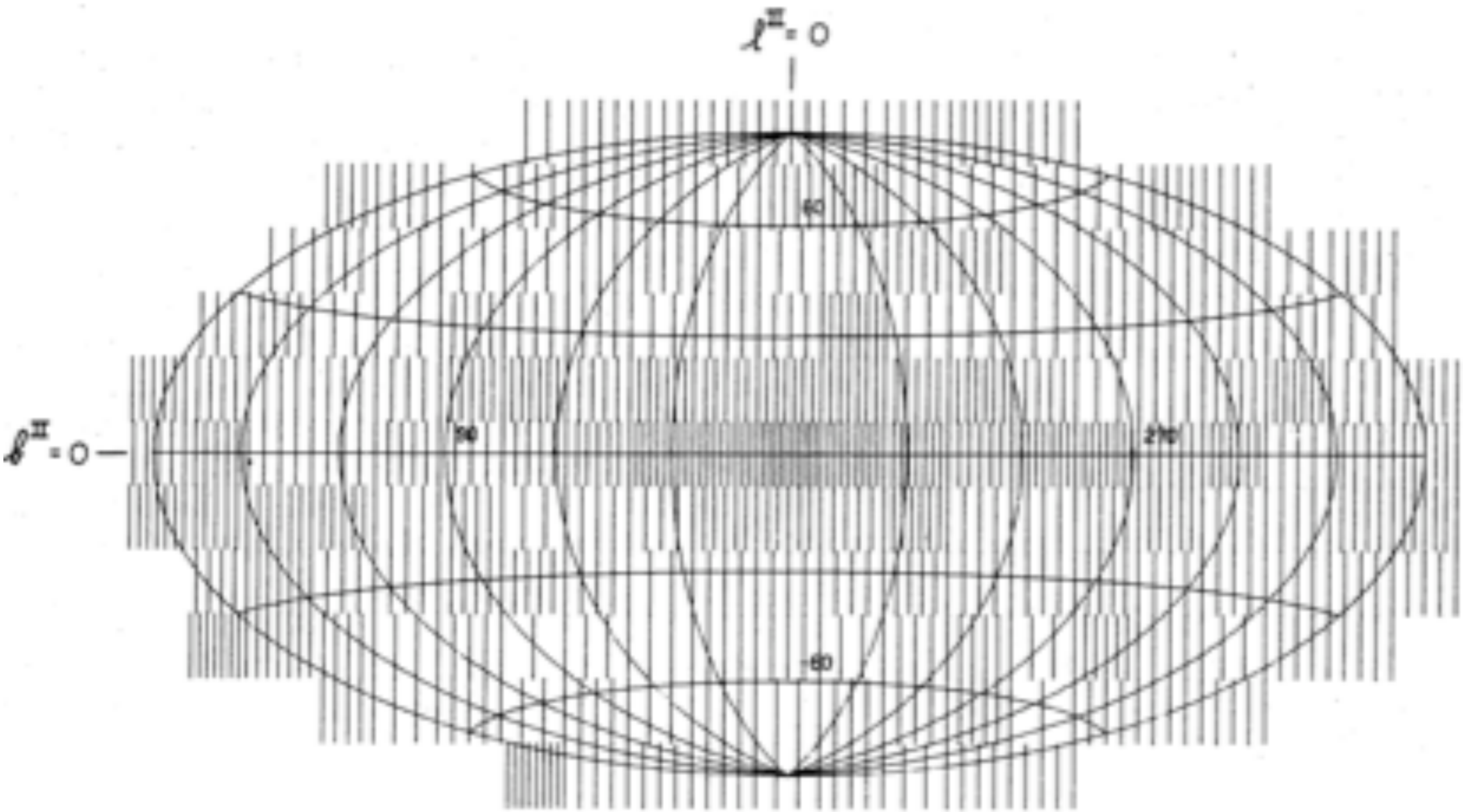


Kohta Murase

Penn State University

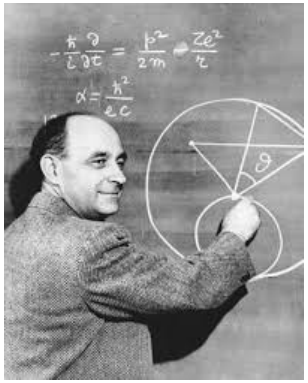
Gamma Rays
&
Blazars as Examples

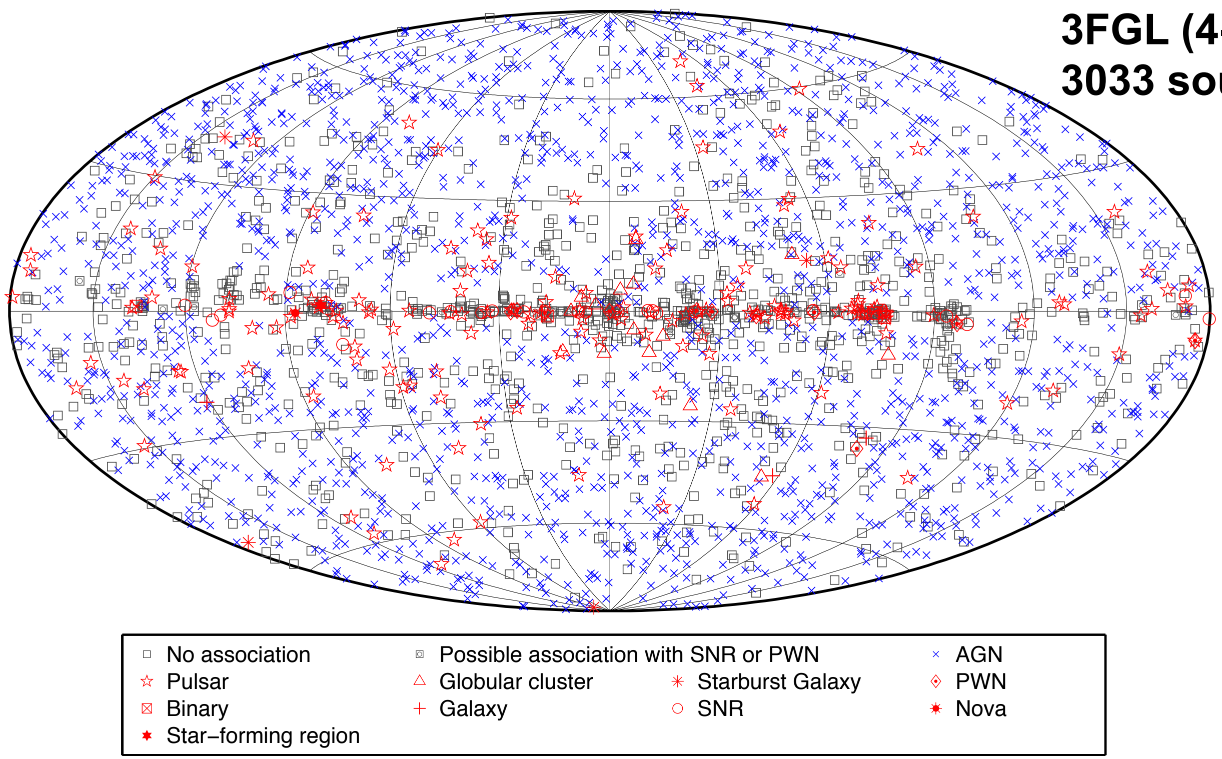
First Gamma-Ray Sky



- Third Orbiting Solar Observatory OSO-3 (Kraushaar et al. 1972)
- Sensitive to >50 MeV γ rays, 1 source (i.e. Milky Way)

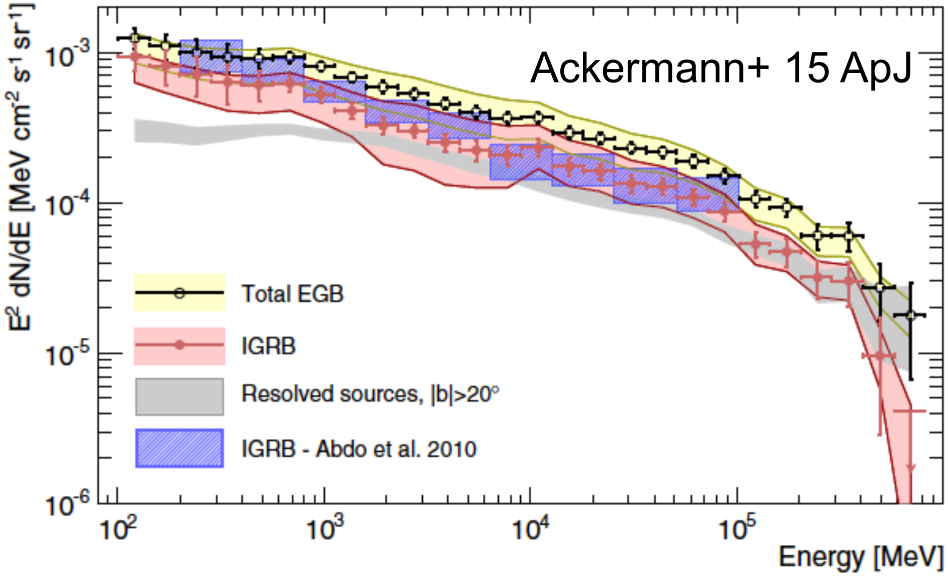
Gamma-Ray Astrophysics in the Fermi Era



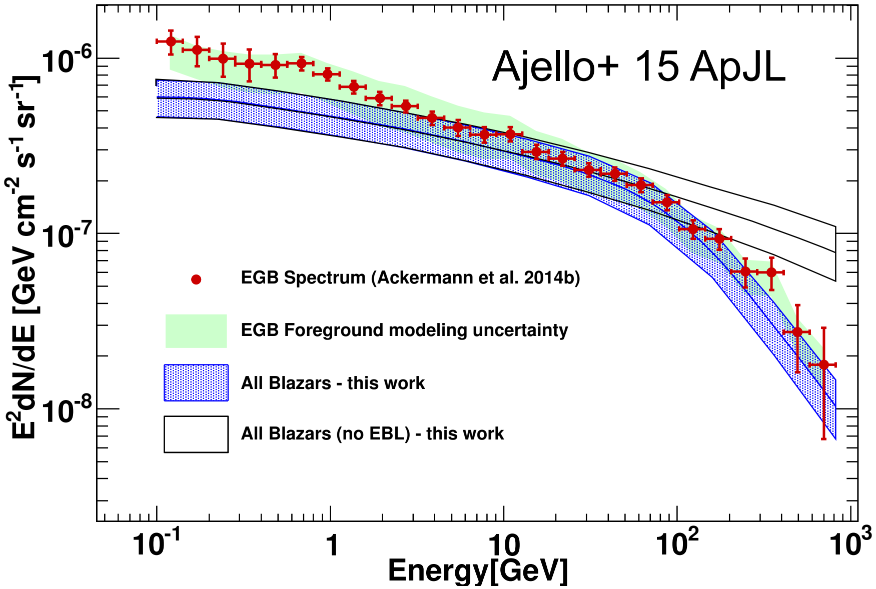


3FGL (4-year)
3033 sources

Extragalactic Gamma-Ray Background

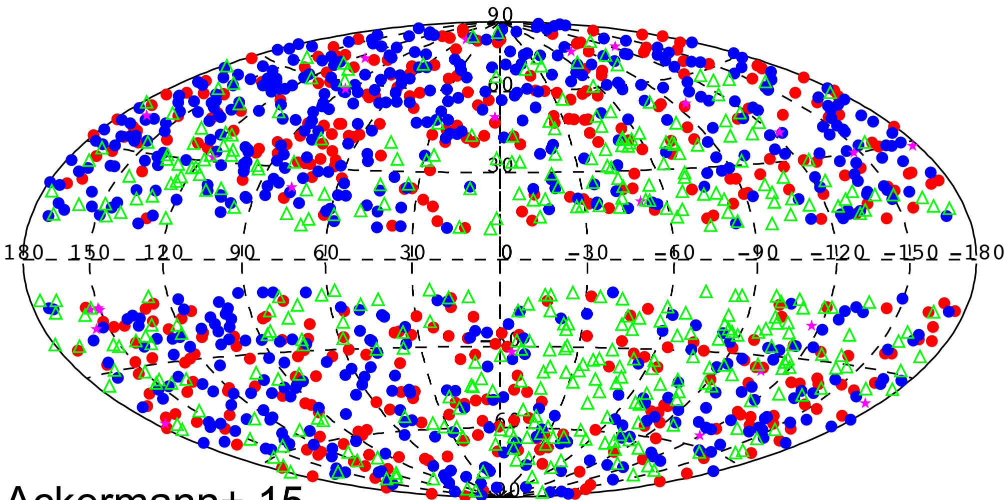


EGB: total
IGRB: unresolved



~15-30% of the EGB at > 50 GeV may come from something else
and more rooms at lower energies

Blazars: Main Extragalactic Sources in the γ-ray Sky



Ackermann+ 15

48 months of observations :

2192 TS>25, |b|>10° sources

3LAC: 1563 sources

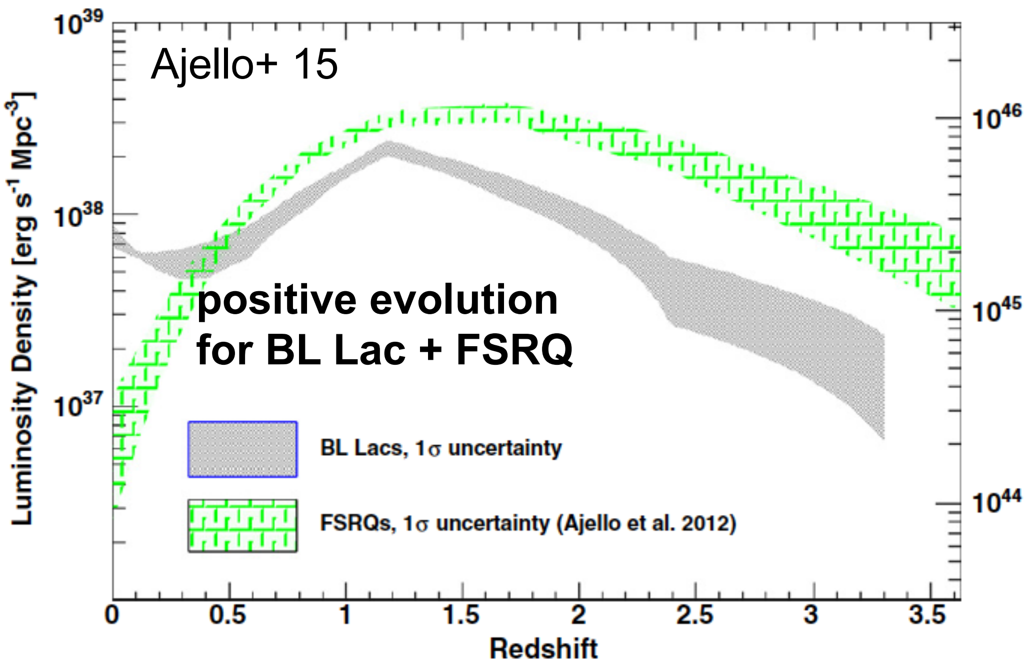
1444 AGNs in the clean sample

415 FSRQs

602 BL Lacs

413 of unknown type

23 other AGNs



Local (z=0) luminosity density

BL Lacs:

2×10^{45} erg Mpc^{-3} yr^{-1}

FSRQs:

$\sim(1\text{-}4)\times10^{44}$ erg Mpc^{-3} yr^{-1}

UHECR:

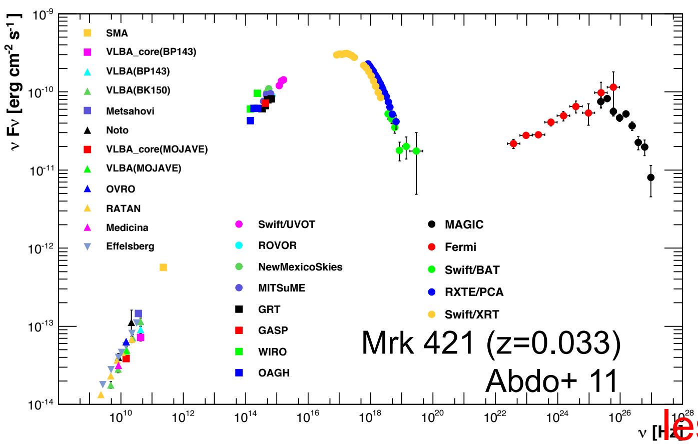
$\sim10^{44}$ erg Mpc^{-3} yr^{-1}

Candidate sources of UHECRs

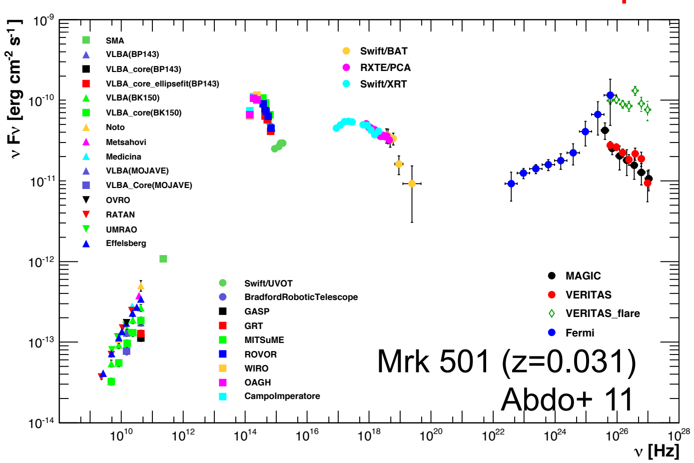
Blazars: Success of Multiwavelength Observations

Spectral energy distribution (SED): typically "two hump" structure

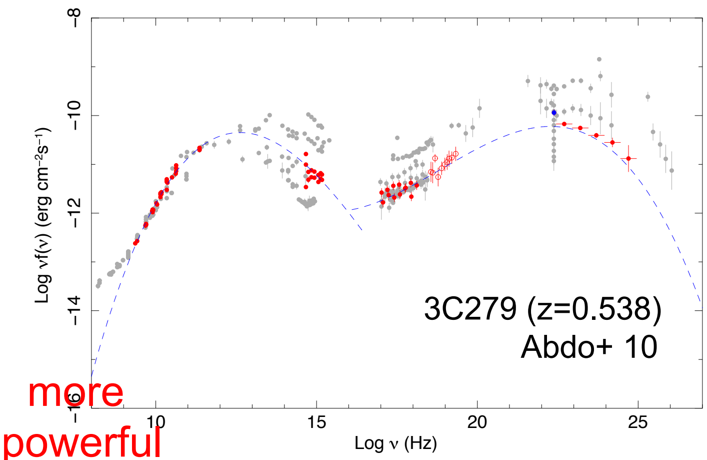
BL Lac objects (BL Lacs)
emission to VHE/TeV energies



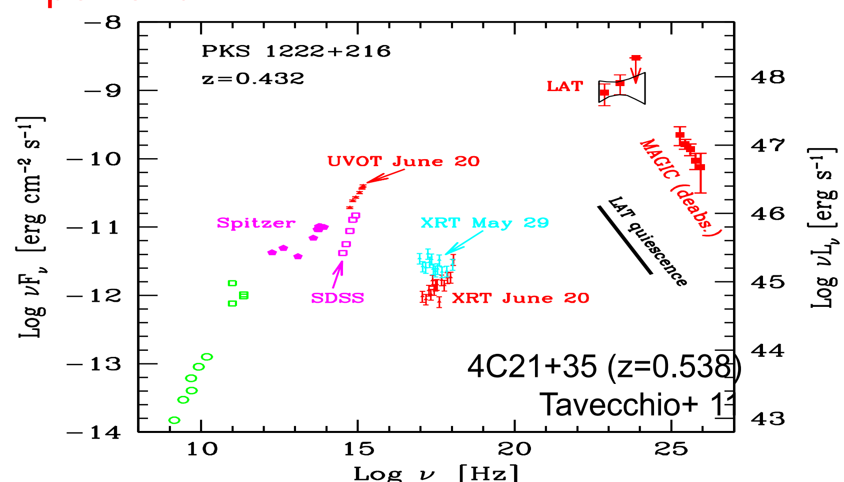
less powerful



Flat-spectrum quasars (FSRQs)
(or quasar-hosted blazars (QHBs))
mosty LSPs (ν_{pk}<10^{14} Hz), GeV break



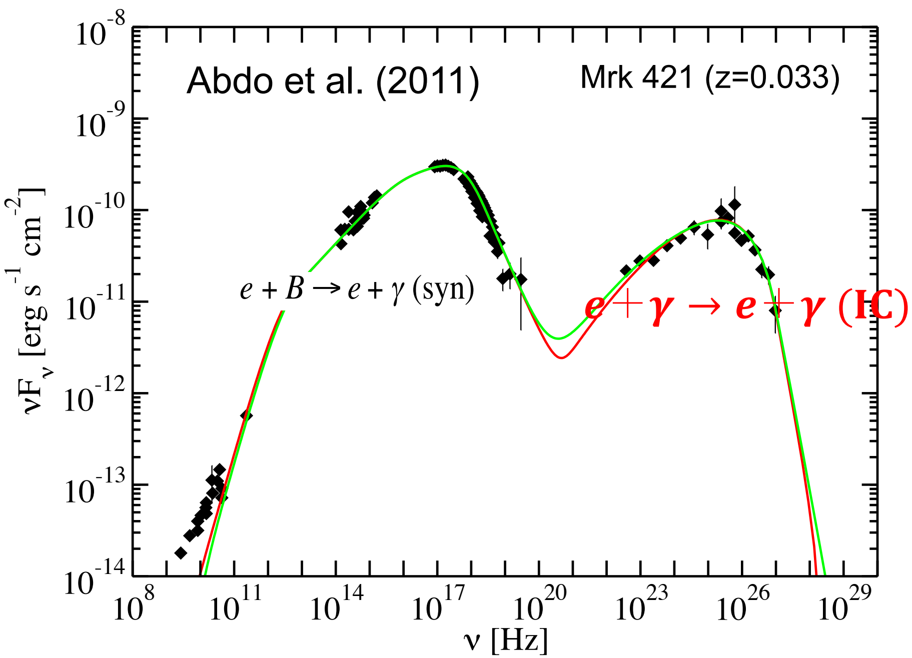
more powerful



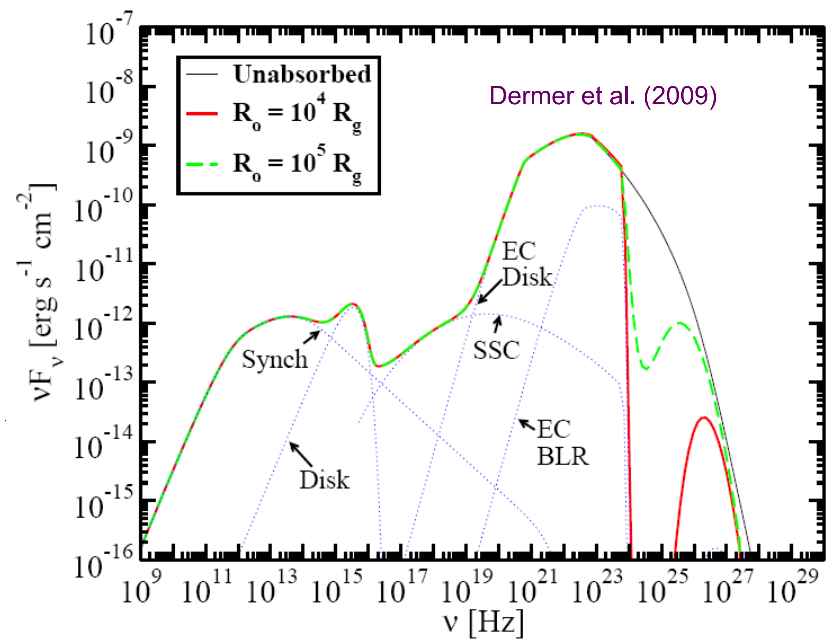
Leptonic Scenario

HE radiation: relativistic electrons accelerated in inner jets
(magnetic reconnection, shock acc., shear acc., turbulence etc.)

BL Lacs
synchrotron/SSC fitting



FSRQs or QHBs
synchrotron/SSC+EIC model fits



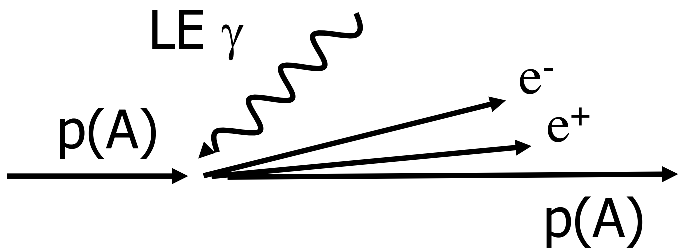
- BL Lacs: synchrotron + synchrotron self-Compton (SSC)
- FSRQ: external Compton (EC)

bloadline regions (BLR), dust torus, accretion disk

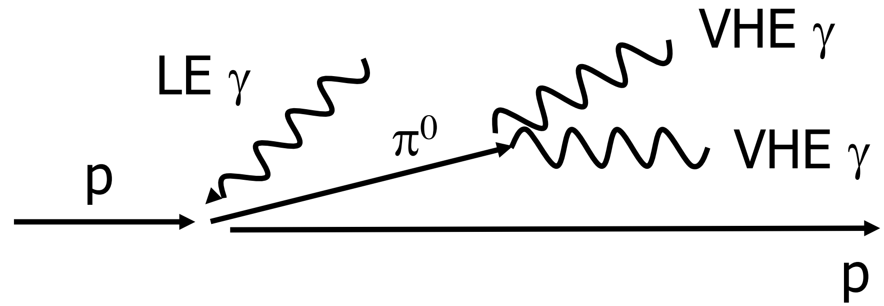
Intra-Source Cascades

VHE γ/e injection by cosmic rays

Bethe-Heitler process



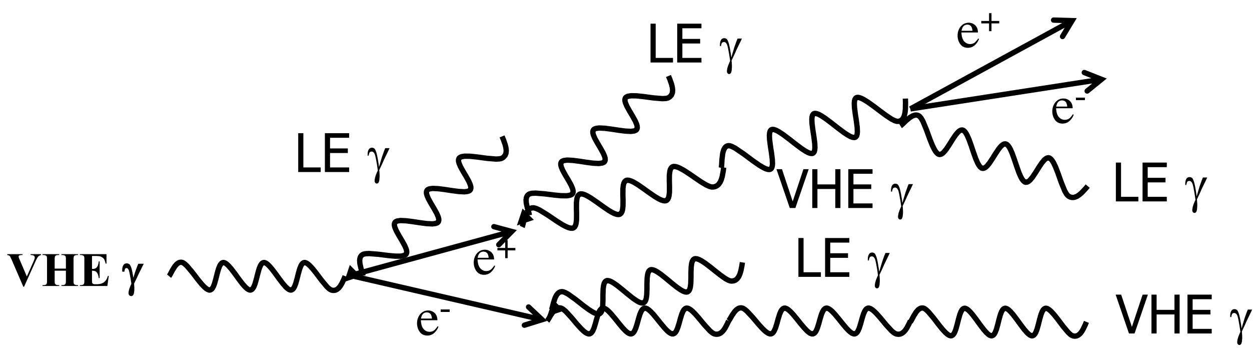
pγ meson production



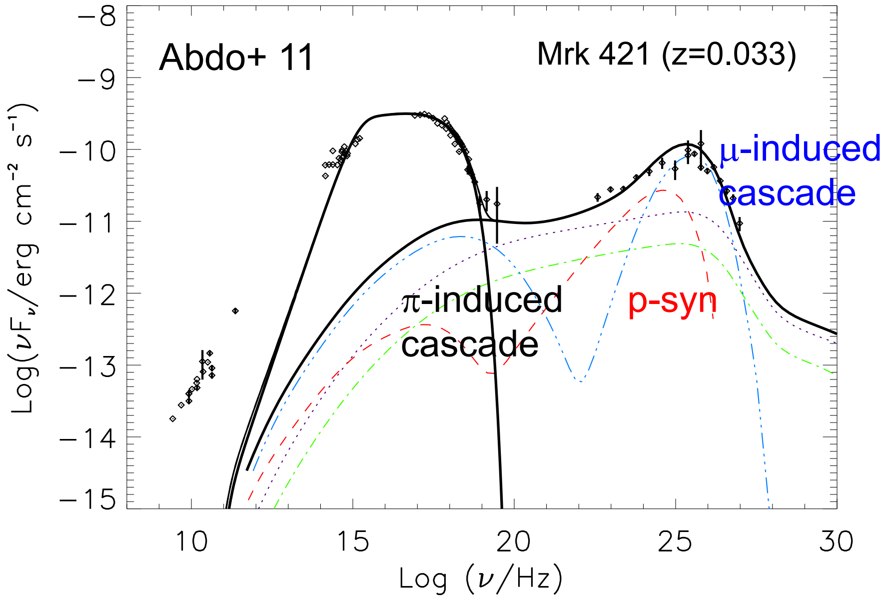
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

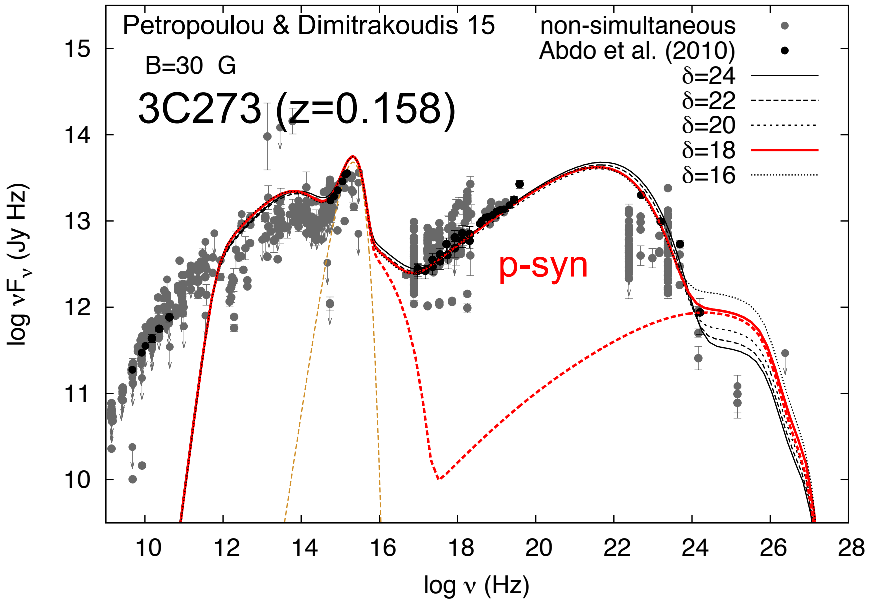
$$e + \gamma \rightarrow e + \gamma \text{ (IC)}$$

$$e + B \rightarrow e + \gamma \text{ (syn)}$$



(Lepto-)Hadronic Scenario?





- Nonthermal synchrotron radiation from primary electrons for radio through optical (low-energy hump)

- Cascades via photomeson production
  $p+\gamma \rightarrow p/n, \pi \rightarrow p/n, \nu, \gamma, e$
- Proton and ion synchrotron radiation
  $p+B \rightarrow p+\gamma$

"SEDs can usually be fitted by both leptonic and leptohadronic scenarios"

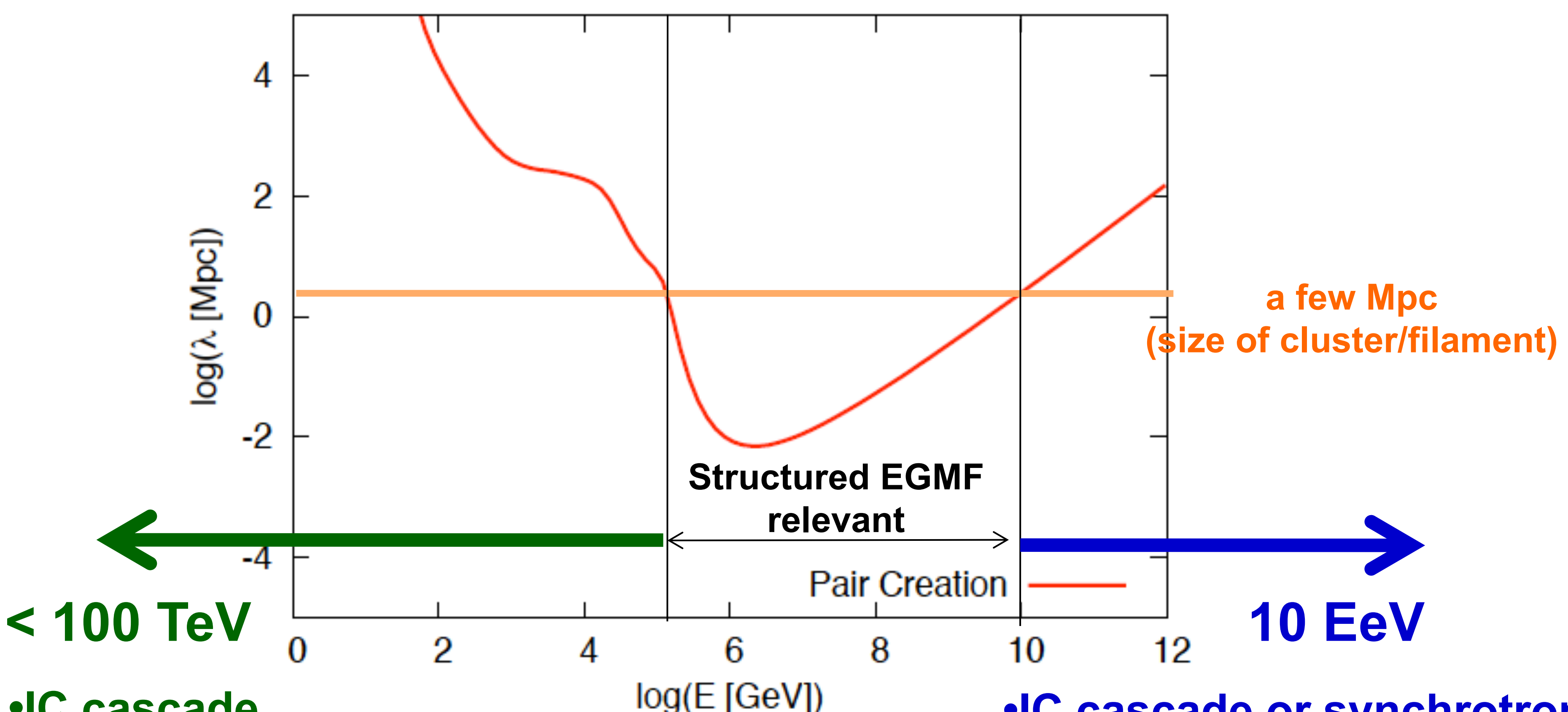
caveats:

- large CR power is necessary
  ($L_p \sim 10^{47}$-10^{49} erg/s ~ 10^3-10^6 L_e)
- much more free parameters

smoking gun? -> neutrinos!

Fate of Gamma Rays Escaping from the Sources

$$\gamma + \gamma_{\mathrm{CMB/CIB}} \rightarrow e^+ + e^-$$



- IC cascade
- distant (> 100 Mpc) sources
  (either hadronic or leptonic)

- IC cascade or synchrotron
- probe of CR accelerators

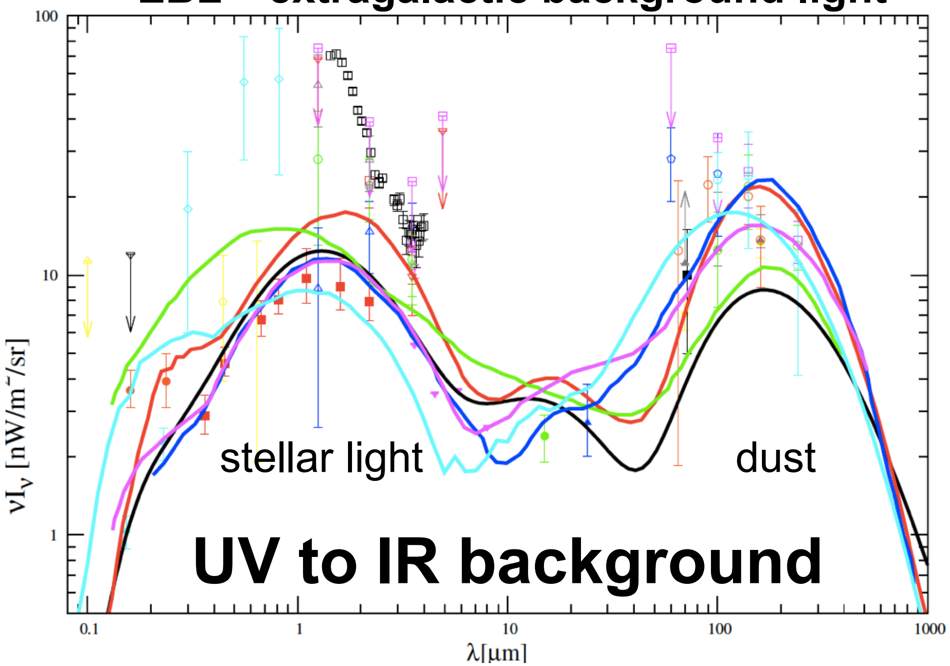
EBL Attenuation

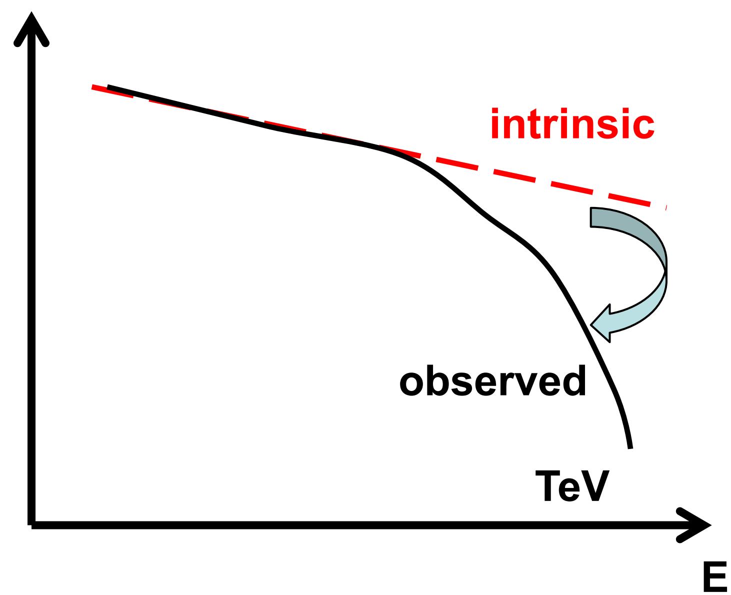
>TeV γ rays interact with CMB & extragalactic background light (EBL)

$$\gamma + \gamma_{\mathrm{CMB/EBL}} \rightarrow e^{+} + e^{-}$$

ex. $\lambda_{\gamma\gamma}$(TeV) ~ 300 Mpc
$\lambda_{\gamma\gamma}$(PeV) ~ 10 kpc ~ distance to Gal. Center

"EBL"=extragalactic background light



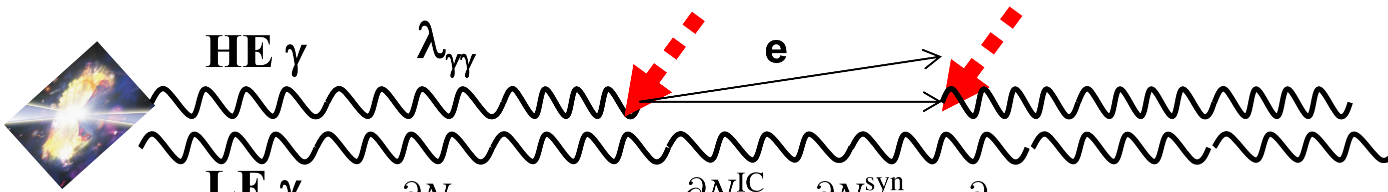


$$E' \approx \frac{m_e^2 c^4}{\varepsilon'}$$ ⇨ **E~130 GeV (eV/ε) (2/(1+z))^2**

Intergalactic Cascades

"electromagnetic cascades"

cosmic photon bkg. cosmic photon bkg.



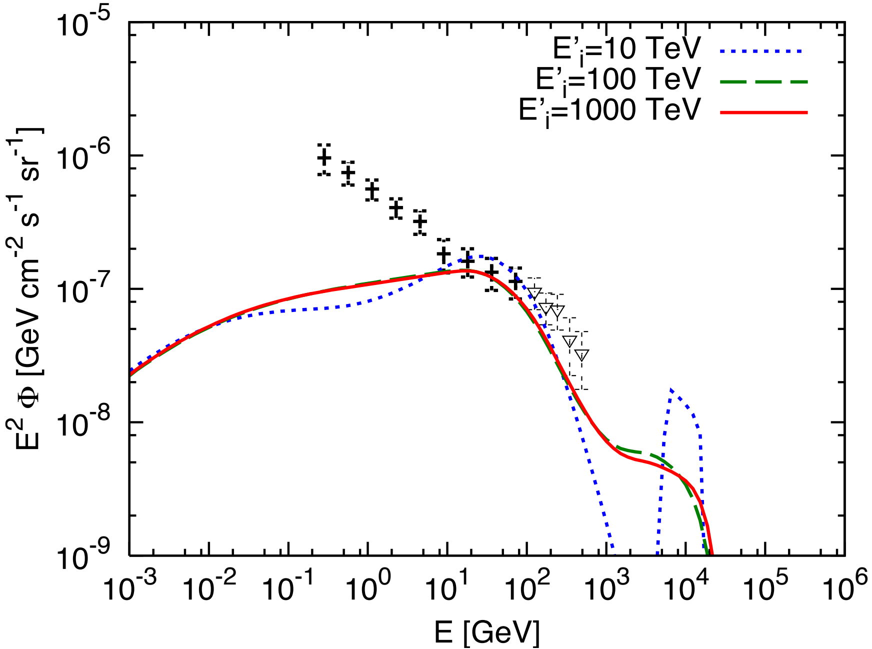
Fermi satellite

airshower detectors

Boltzmann eq.

$$\frac{\partial N_\gamma}{\partial x} = -N_\gamma R_{\gamma\gamma} + \frac{\partial N_\gamma^{\rm IC}}{\partial x} + \frac{\partial N_\gamma^{\rm syn}}{\partial x} - \frac{\partial}{\partial E}[P_{\rm ad} N_\gamma] + Q_\gamma^{\rm inj},$$

$$\frac{\partial N_e}{\partial x} = \frac{\partial N_e^{\gamma\gamma}}{\partial x} - N_e R_{\rm IC} + \frac{\partial N_e^{\rm IC}}{\partial x} - \frac{\partial}{\partial E}[(P_{\rm syn} + P_{\rm ad}) N_e] + Q_e^{\rm inj},$$



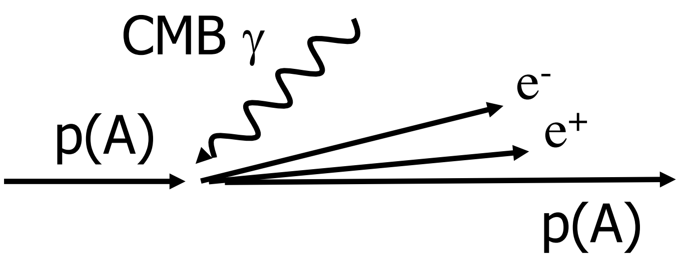
cascaded (regenerated) γ

nearly-universal spectra

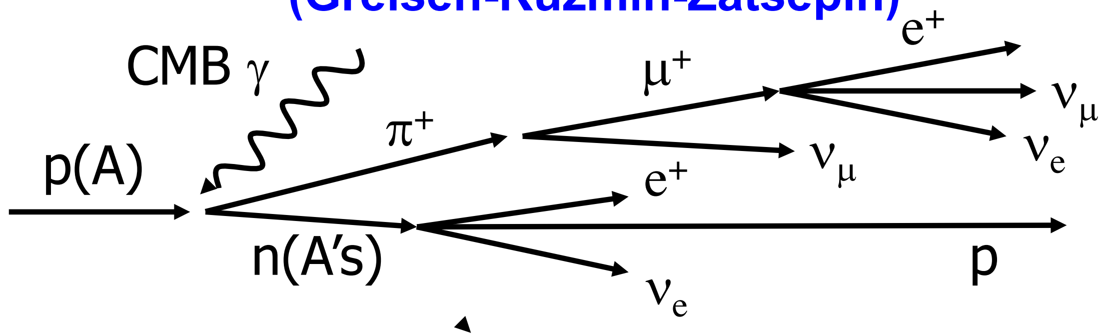
UHECR-Induced Intergalactic Cascades

Alternative explanation for gamma rays from blazars:
neutrino and hadronic gamma-ray production *outside* sources

Bethe-Heitler process



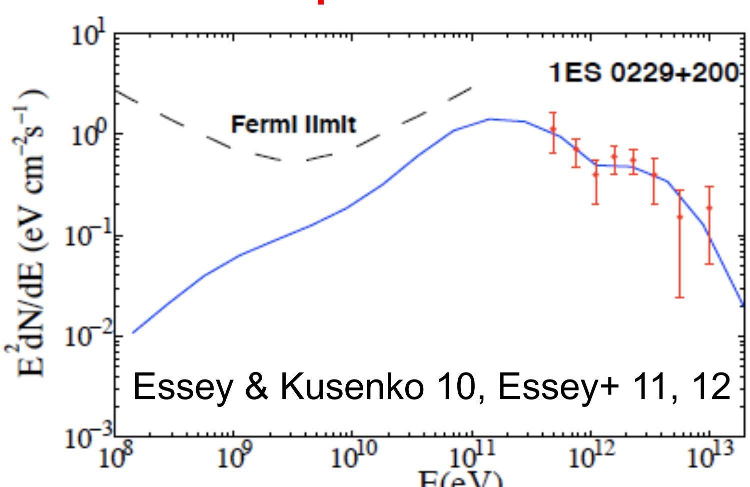
pγ meson production
(Greisen-Kuzmin-Zatsepin)



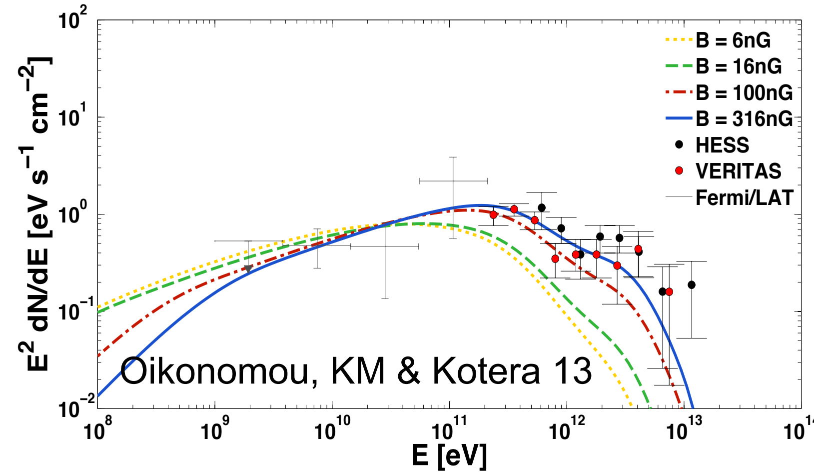
$e + \gamma \rightarrow e + \gamma$ (IC) $\gamma + \gamma \rightarrow e^+ + e^-$

$e + B \rightarrow e + \gamma$ (syn)

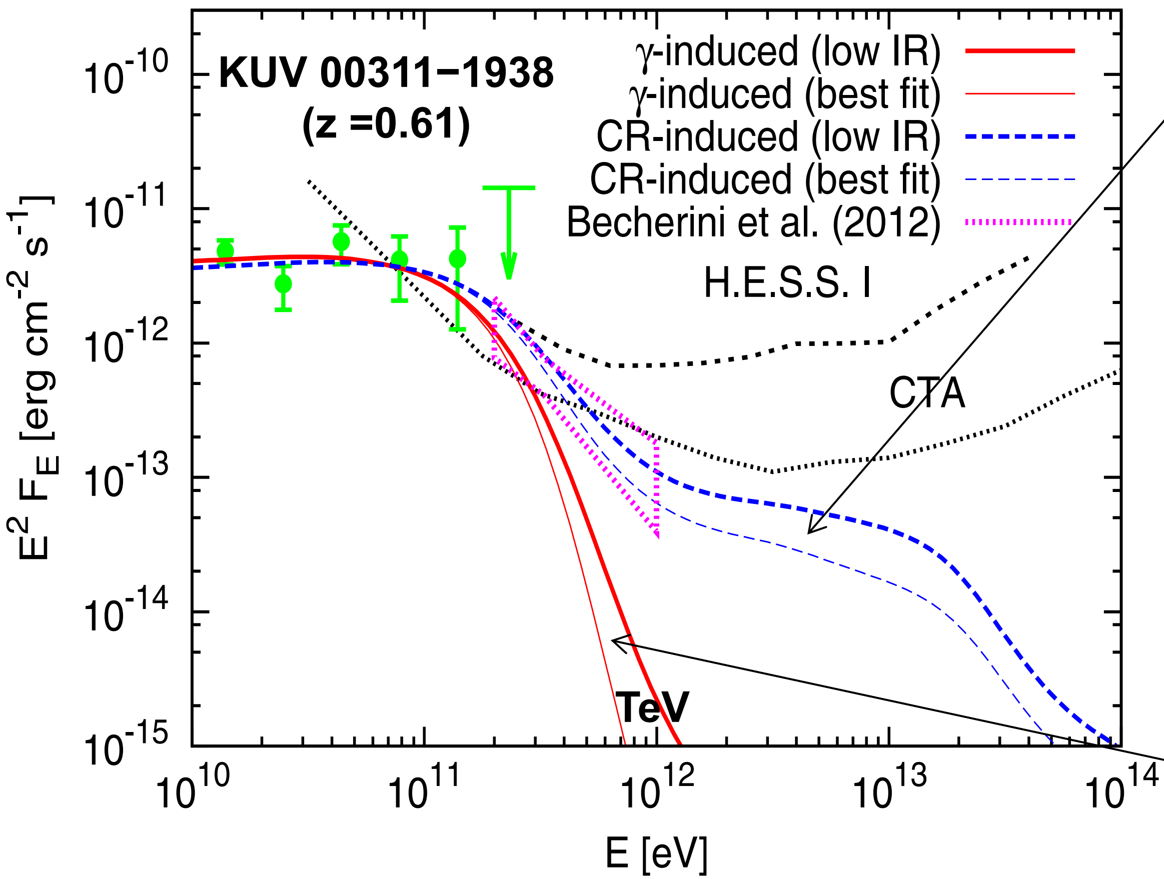
Inverse-Compton cascades in voids



Synchrotron cascades in filaments/clusters



Gamma-Ray Smoking Gun: High-Energy Tail



Primary UHECR-induced:

$dI_\gamma \sim -(1/\lambda_{\gamma\gamma})\, I_\gamma\, dr + (1/\lambda_{BH})\, I_{CR}\, dr$

$\rightarrow \propto (1-\exp(-\tau_{\gamma\gamma}))/\tau_{\gamma\gamma}$

Primary γ-induced:

$dI_\gamma \sim -(1/\lambda_{\gamma\gamma})\, I_\gamma\, dr$

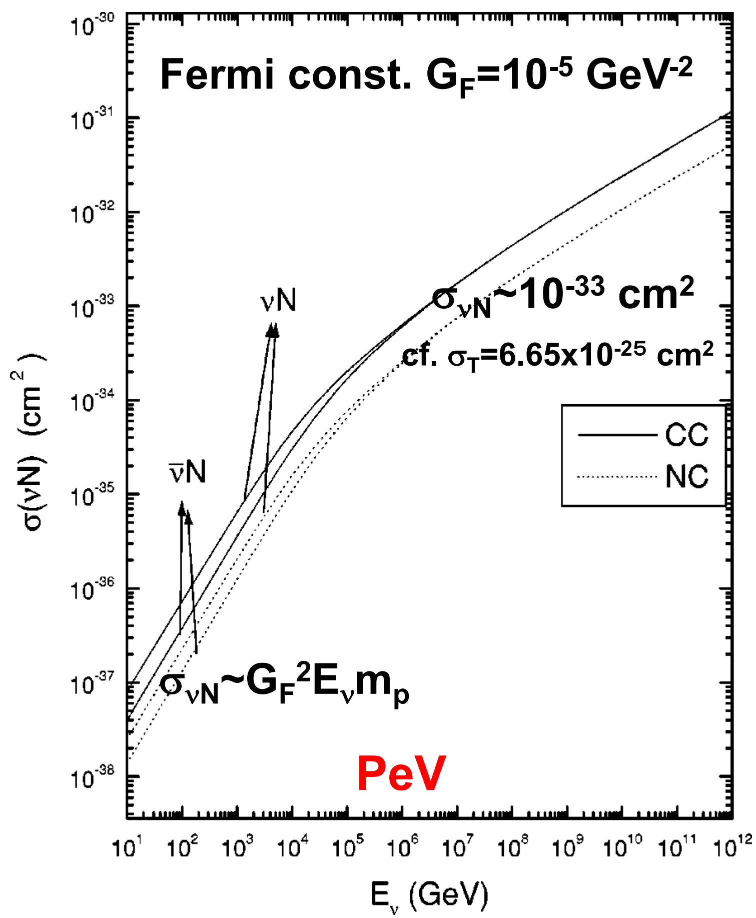
$\rightarrow \propto \exp(-\tau_{\gamma\gamma})$

KM, Dermer, Takami & Migliori 12 ApJ
Takami, KM & Dermer 13 ApJL
Aharonian+ 13 PRD

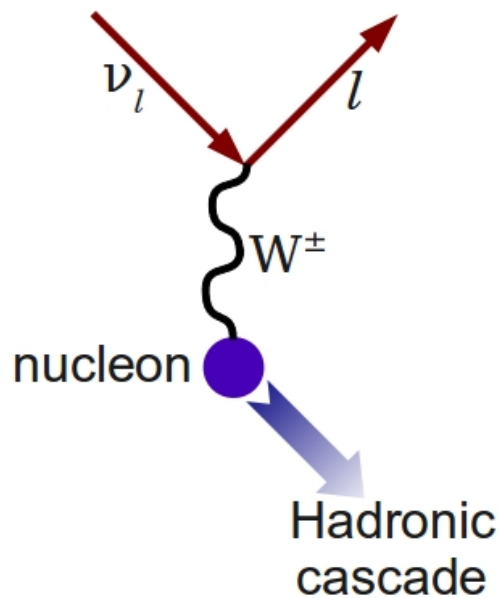
Need CTA for the discrimination

Neutrinos

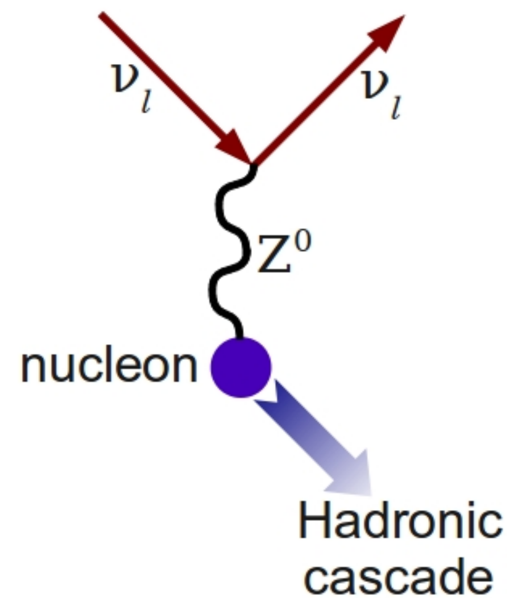
Neutrinos: Weak Interaction



$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \qquad \mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



Charged-Current

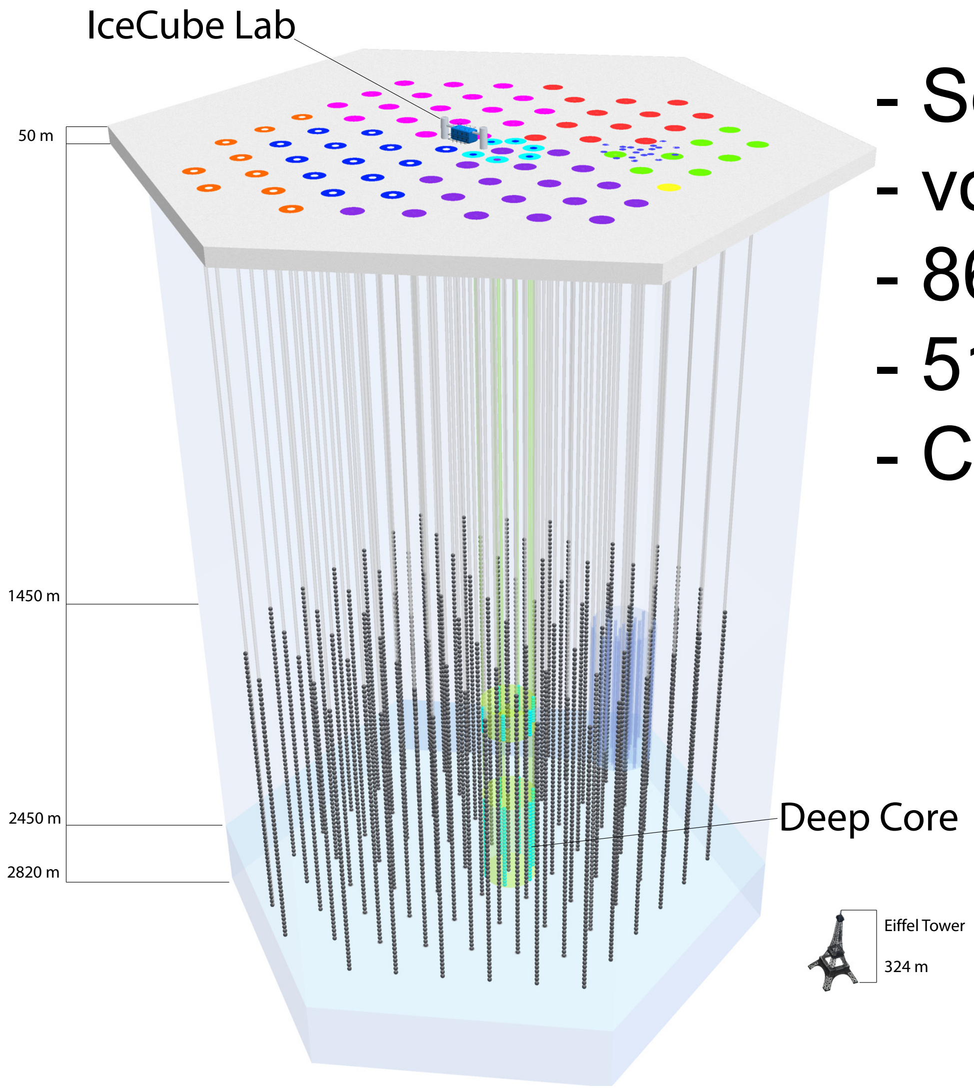


Neutral-Current

How big should a detector be? A crude estimate at PeV energies

$$\mathcal{N} \sim (\varepsilon_\nu \Phi_\varepsilon)\sigma_{\nu N}(2\pi N_A \rho V) \simeq 10 \text{ yr}^{-1} \left(\frac{\varepsilon_\nu^2 \Phi_\varepsilon}{10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}}\right)\left(\frac{V}{\text{km}^3}\right)$$

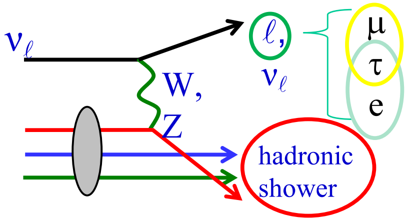
IceCube: Gton Neutrino Detector

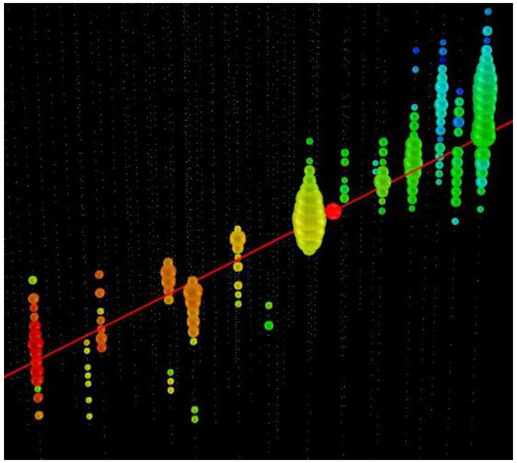
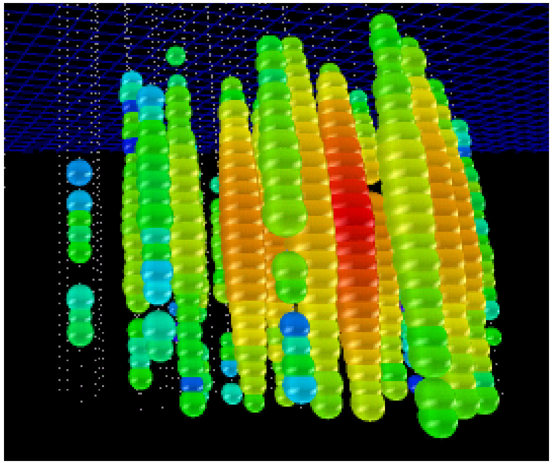
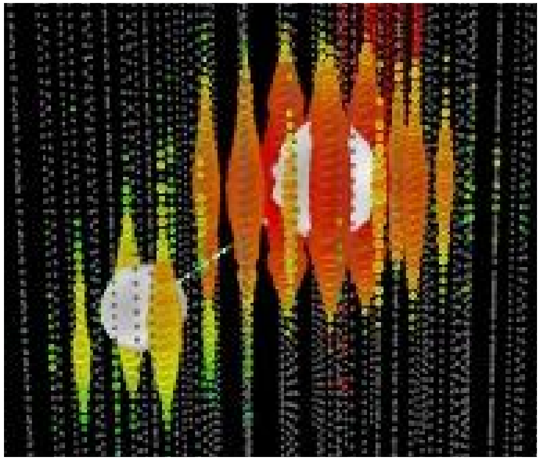


- South pole
- volume~1 km^3, mass~Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)
- Completed in 2010

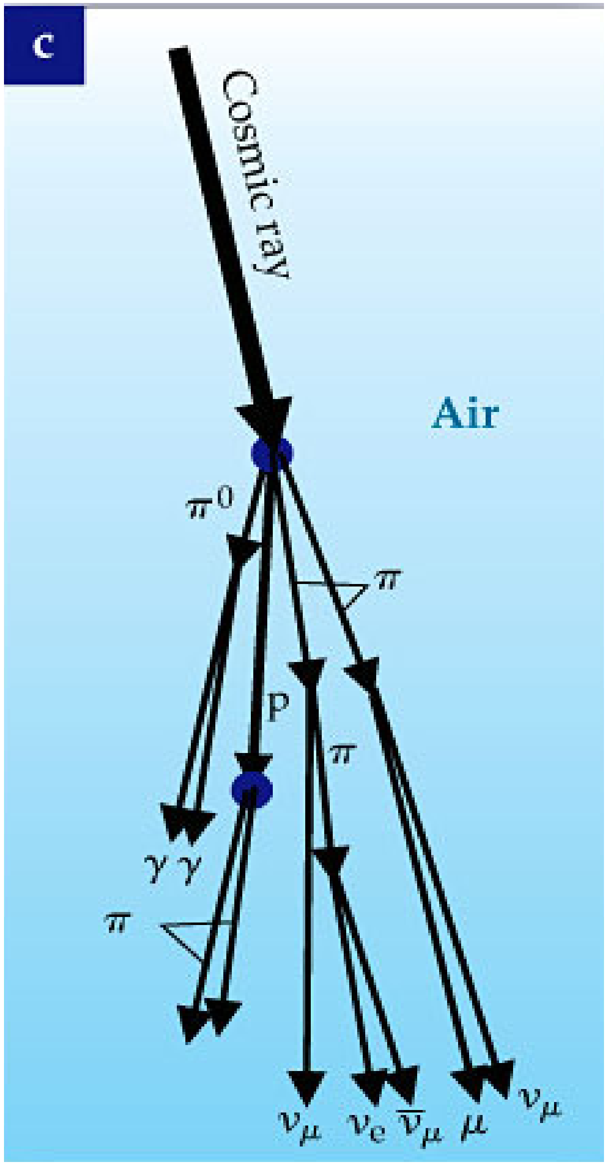
How to Detect Neutrinos?

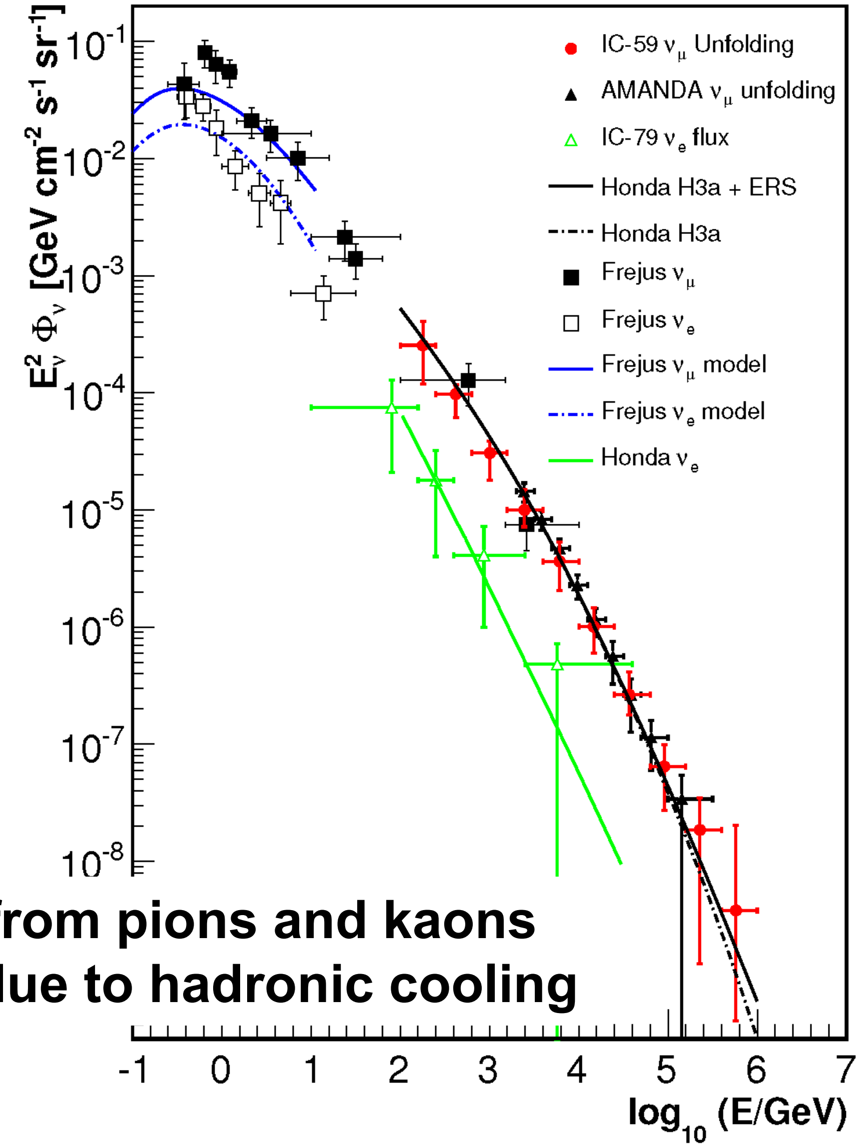
- 3 main event types



"Track" (detected)	"Shower" (detected)	"Double-bang & others" (not detected)
		
ν_μ+N → μ+X	ν_e+N → e+X ν_X+N → ν_X+X	ν_τ+N → τ+X
~2 energy res. <1 deg ang res.	~15% energy res. ~10 deg ang res. seen at >100 TeV	observable at higher E

Background: Atmospheric Neutrinos & Muons

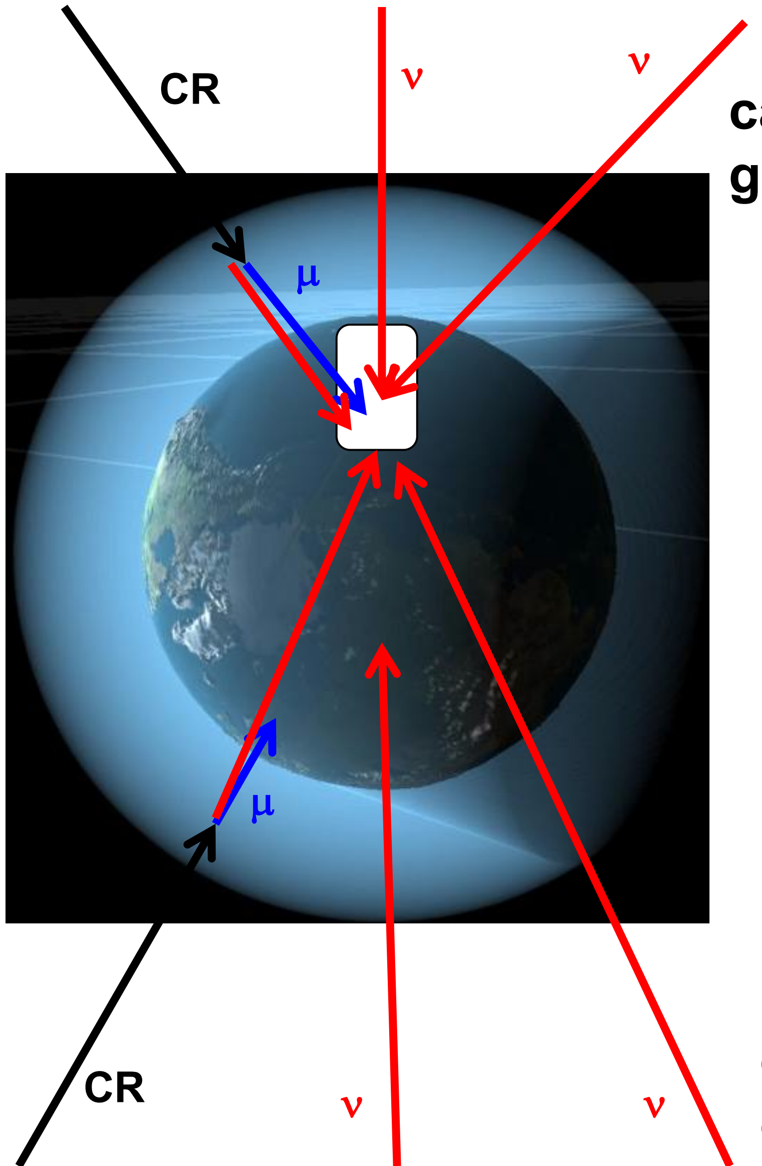




atm. ν from pions and kaons

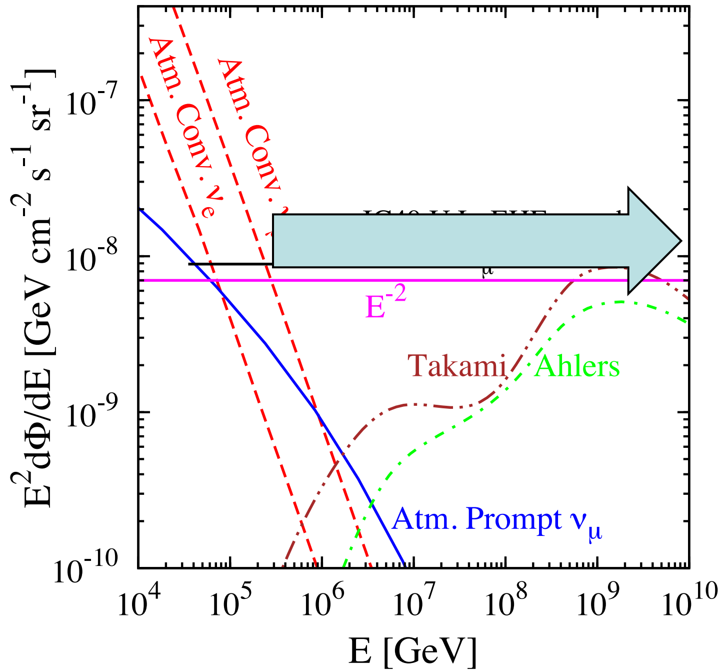
~ $E^{-3.7}$ due to hadronic cooling

Upgoing & Downgoing Neutrinos



Downgoing neutrinos

caveat: atm. muons (rapidly decreasing as E)
good: avoid attenuation by Earth

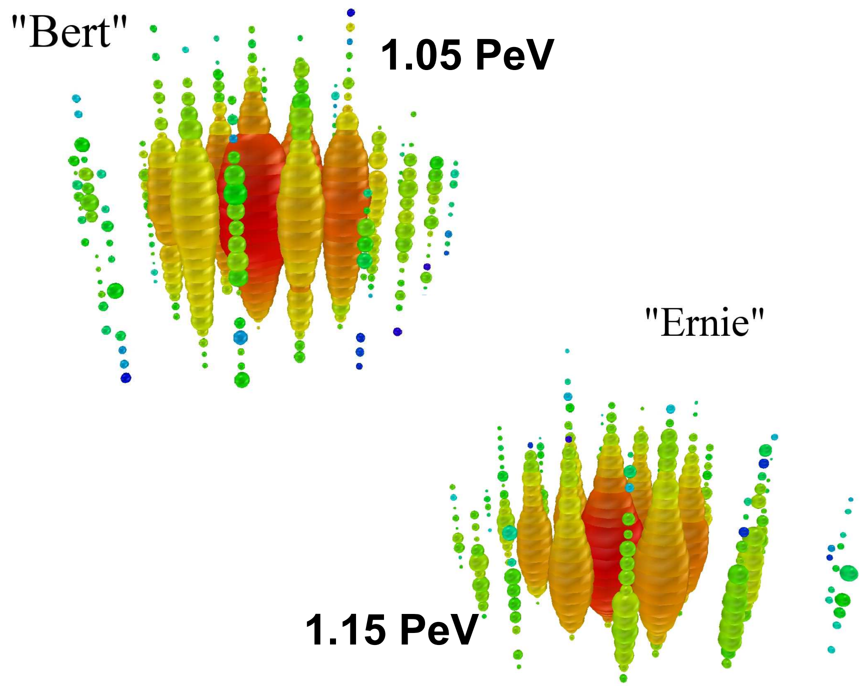


Upgoing neutrinos

good: avoid atmospheric “muons”
caveat: attenuation by Earth at > 0.1-1 PeV

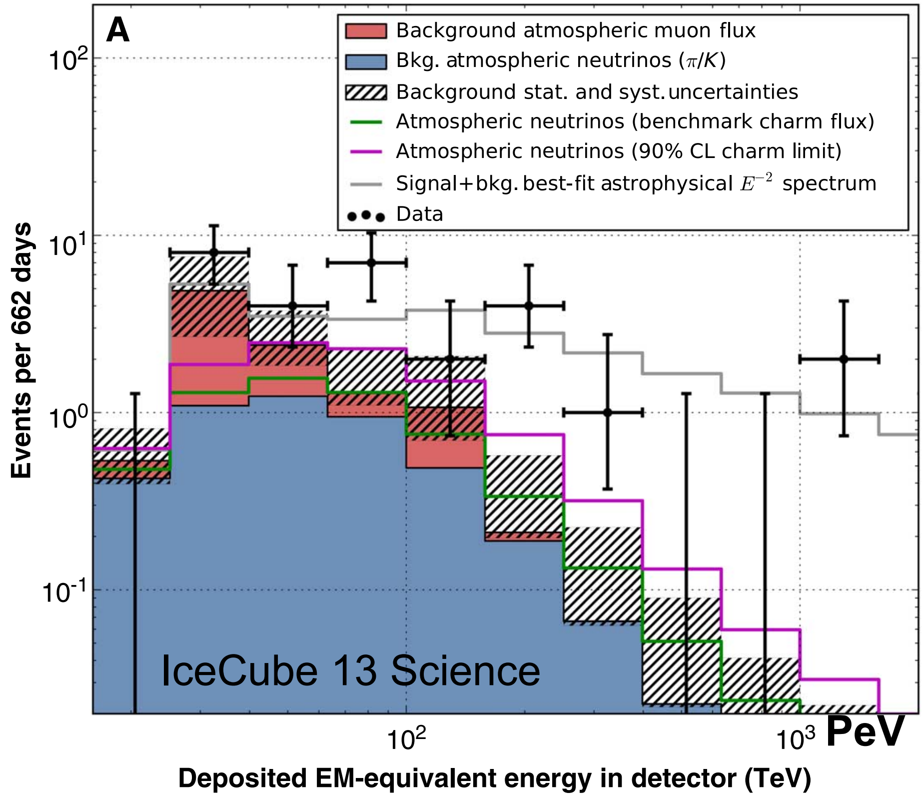
Discovery: Results Published in 2012-2013

First detection of PeV events (~3σ)



IceCube 13 PRL

Follow-up analysis (~4σ)



- $E_\nu^2\,\Phi_\nu$=(1.2±0.4)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} (per flavor)
- Consistent w. flavor ratio $\nu_e:\nu_\mu:\nu_\tau$=1:1:1
- Favoring cutoff at ~2 PeV for E_ν^{-2} or steeper than $E_\nu^{-2.2}$

Dawn of Neutrino Astrophysics

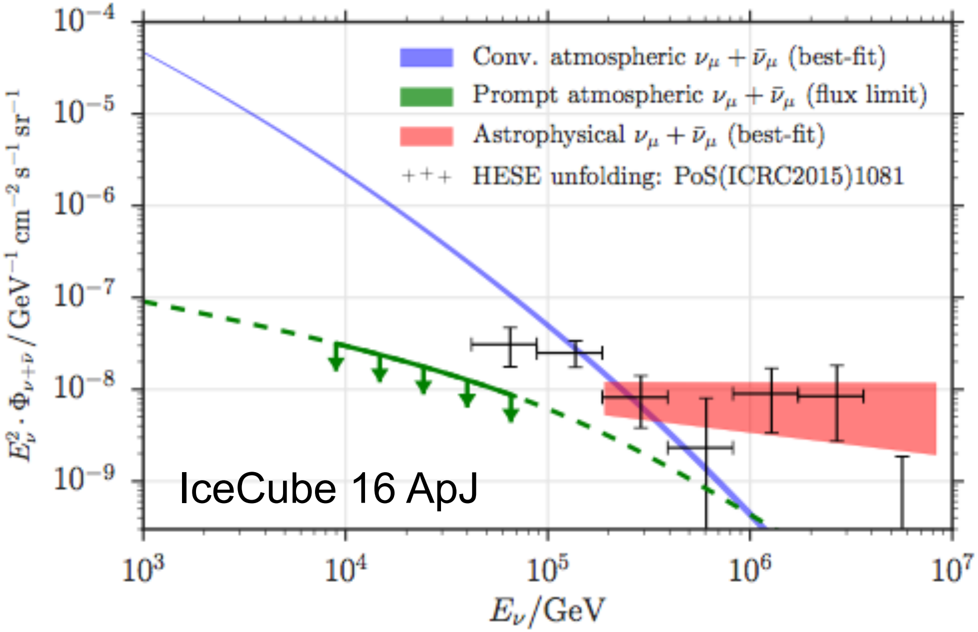
#1 of top 10 breakthroughs in 2013

Selected for a Viewpoint in *Physics*

PRL **113,** 101101 (2014) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014

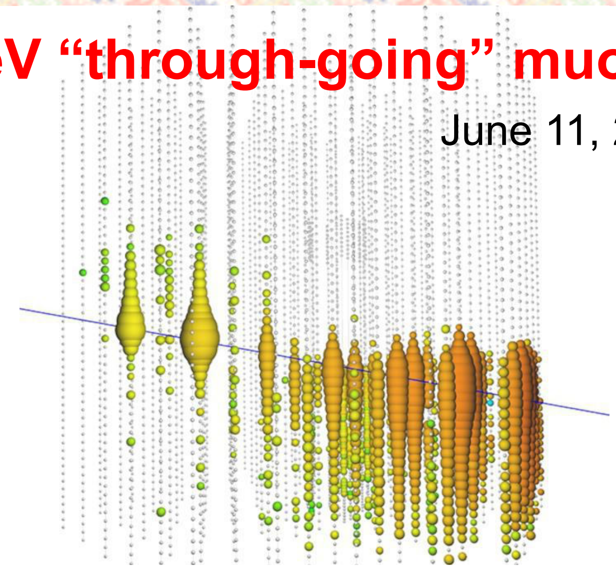
Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data

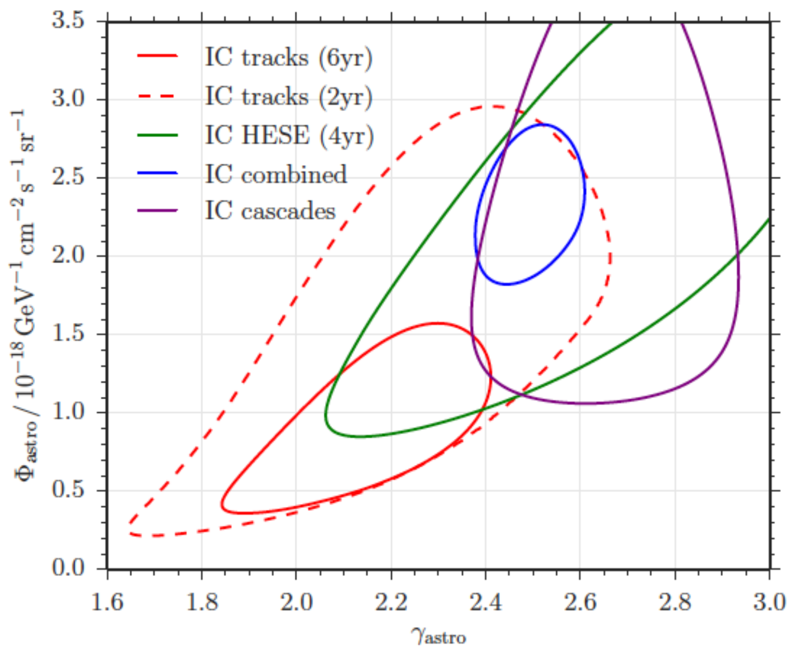
Upgoing Muon Tracks: Hard Spectra?



2.6 PeV "through-going" muon

June 11, 2014



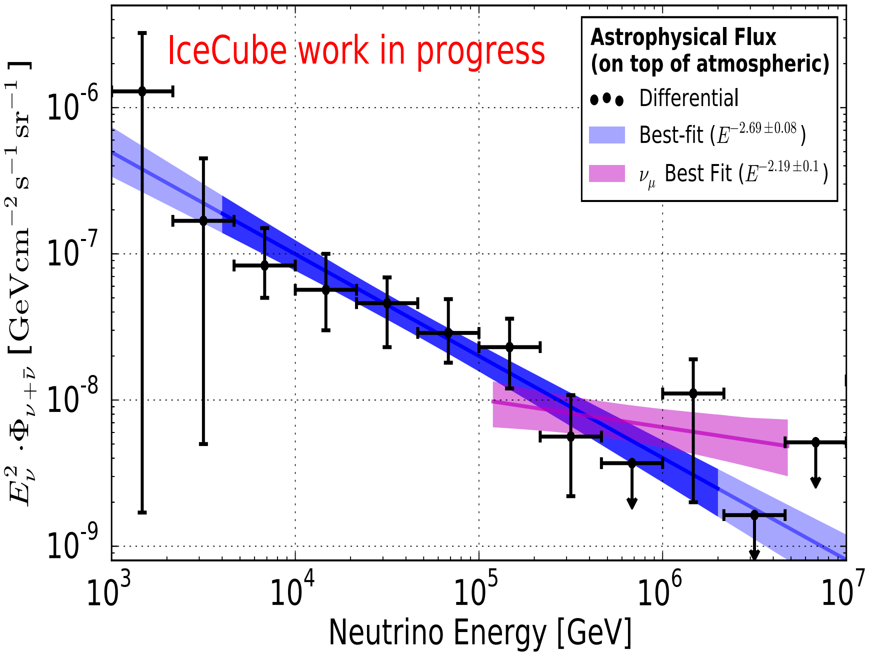


- 6-yr Upgoing muon ν (29 events at >200 TeV): only bkg. rejected at 5.9σ
- Best-fit index: $s=2.13\pm0.13$
- Muon ν flux above 100 TeV: $E_\nu^2\Phi_\nu=(0.82+0.3-0.26) \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
- Consistent w. low-energy analyses but there is a 2-3σ tension

Lowering the Threshold: Medium-Energy Excess?

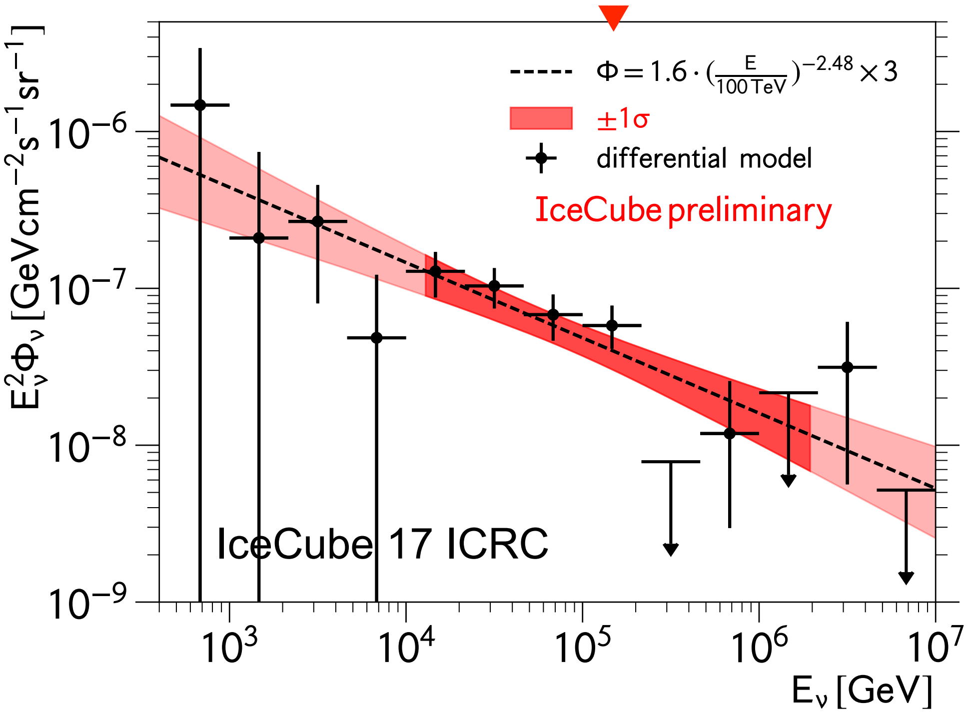
- Medium-energy starting events
  E_{dep}>~1 TeV (2010-2016)

IceCube 17 ICRC



best-fit simple PL: s=2.69±0.08
systematics is not included

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



4740 events, s=2.48+-0.08

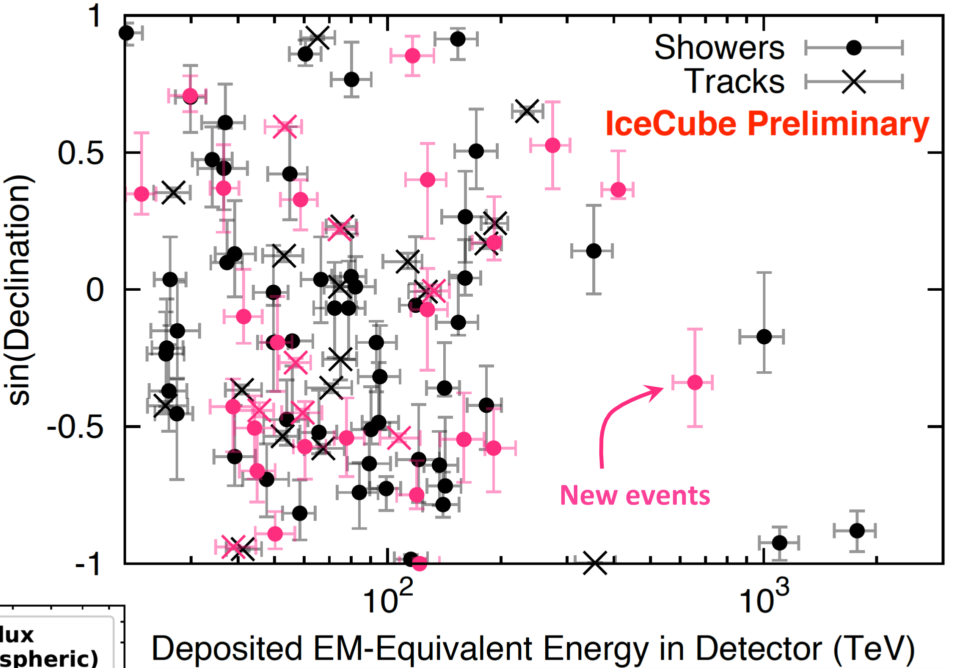
$E_\nu^2\, \Phi_\nu$=(1.57+0.23-0.22)x10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV (per flavor)

No evidence for north-south asymmetry

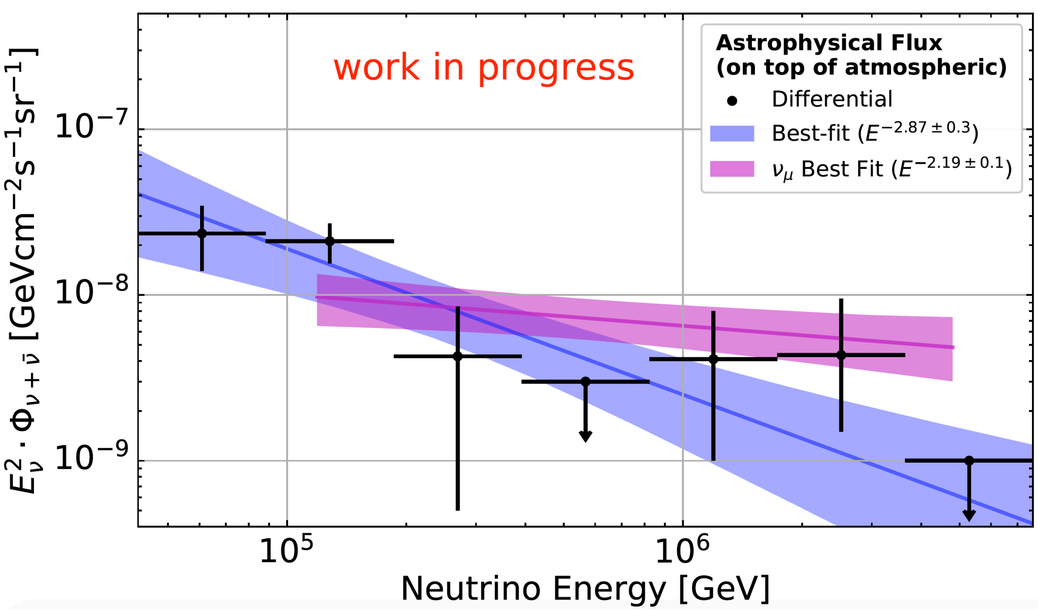
-3σ tension w. ν_μ: hint about the structure in neutrino spectra?

Latest News (Neutrino 2018)

- HESE 7.5 year
  103 events
  (60 events > 60 TeV)
  Best-fit: s=2.87±0.3



per flavor



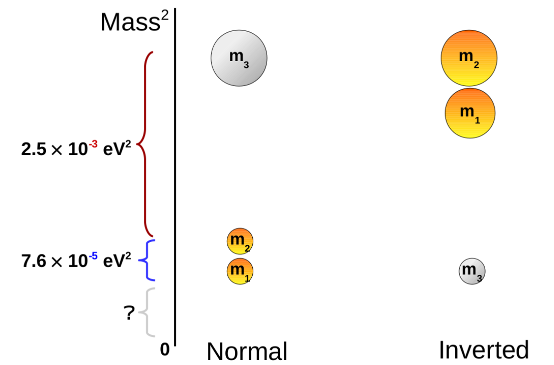
- 8-yr upgoing ν_μ "track"
  36 events at >200 TeV (6.7σ)

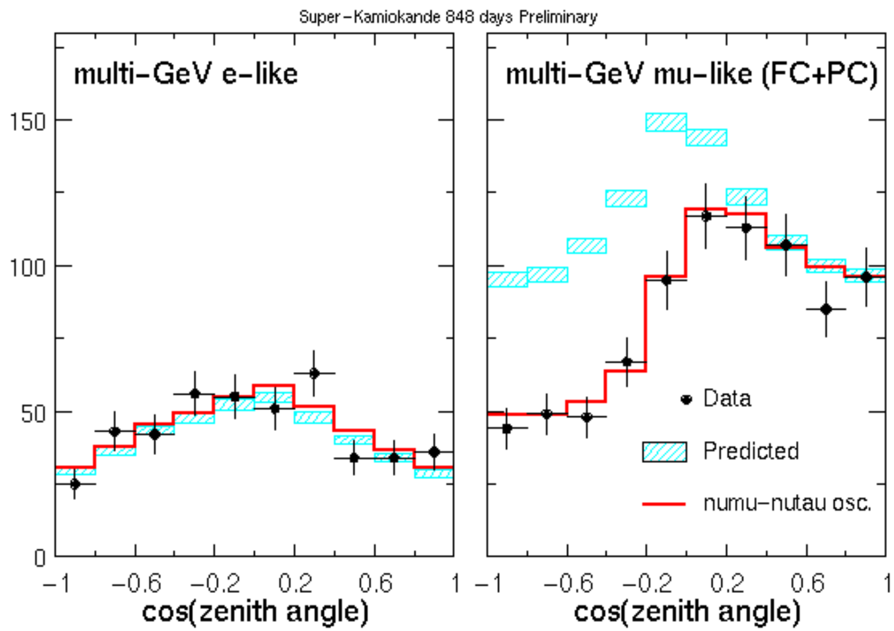
- Best-fit: s=2.19±0.10
- ν_μ flux above 100 TeV:
  $E_\nu^2\Phi_\nu=(1.01+0.26-0.23)$
  $\times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

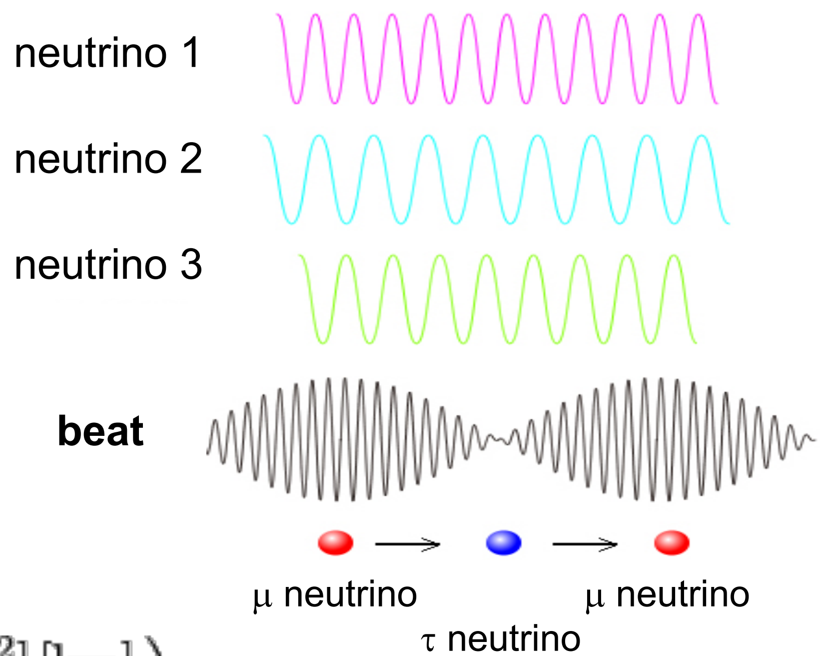
Neutrino Oscillation

- A famous example (Nobel prize 15)

"atmospheric neutrino oscillation"







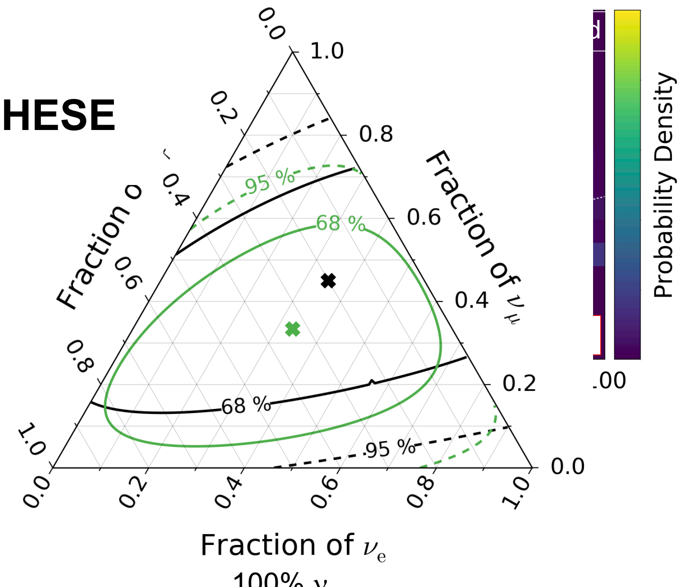
ex. 2 flavor oscillation

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right).$$

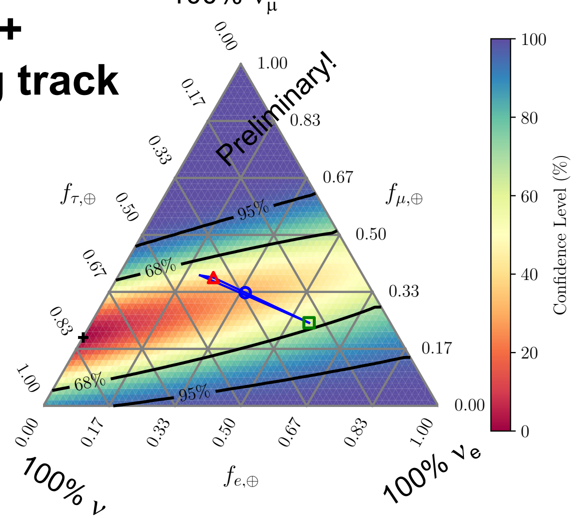
Neutrino Mixing

- Neutrino flavor

HESE



shower+ starting track



$$|\nu(t)\rangle = \sum_i U_{\alpha i}^{(\nu)} |\nu_i\rangle e^{-iEt}$$

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

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

L=ct → ∞ limit: ν_e:ν_μ:ν_τ~1:1:1
(if no astrophysical complications)

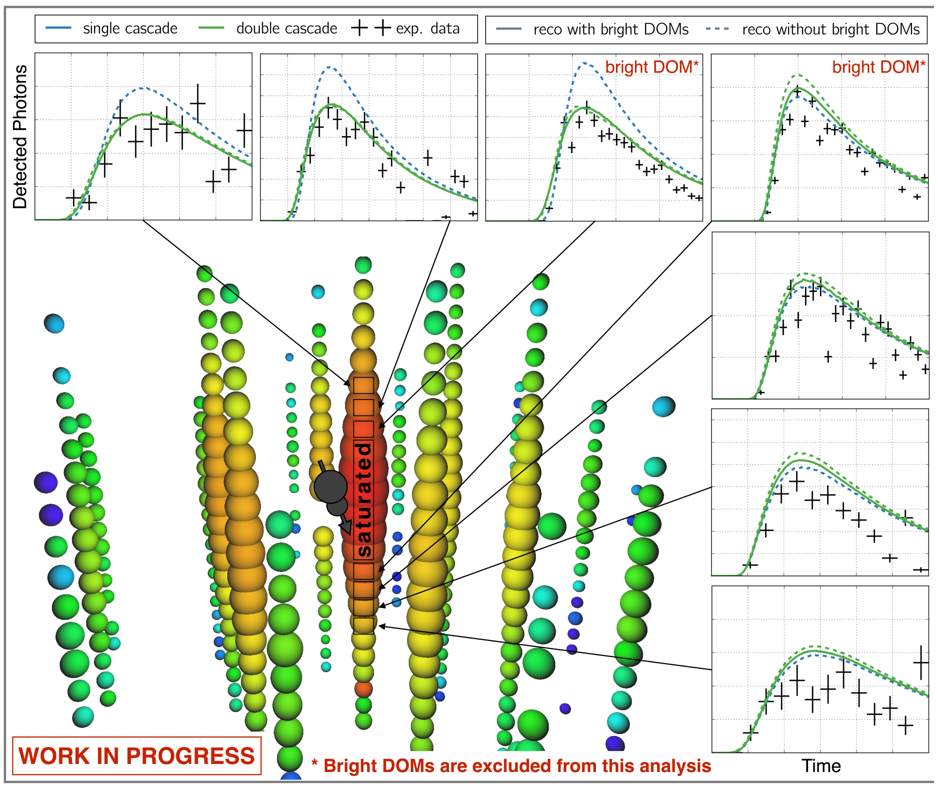
$$\phi_{\nu_e+\overline{\nu}_e} = \frac{10}{18}\phi^0_{\nu_e+\overline{\nu}_e} + \frac{4}{18}(\phi^0_{\nu_\mu+\overline{\nu}_\mu} + \phi^0_{\nu_\tau+\overline{\nu}_\tau}),$$

$$\phi_{\nu_\mu+\overline{\nu}_\mu} = \frac{4}{18}\phi^0_{\nu_e+\overline{\nu}_e} + \frac{7}{18}(\phi^0_{\nu_\mu+\overline{\nu}_\mu} + \phi^0_{\nu_\tau+\overline{\nu}_\tau}),$$

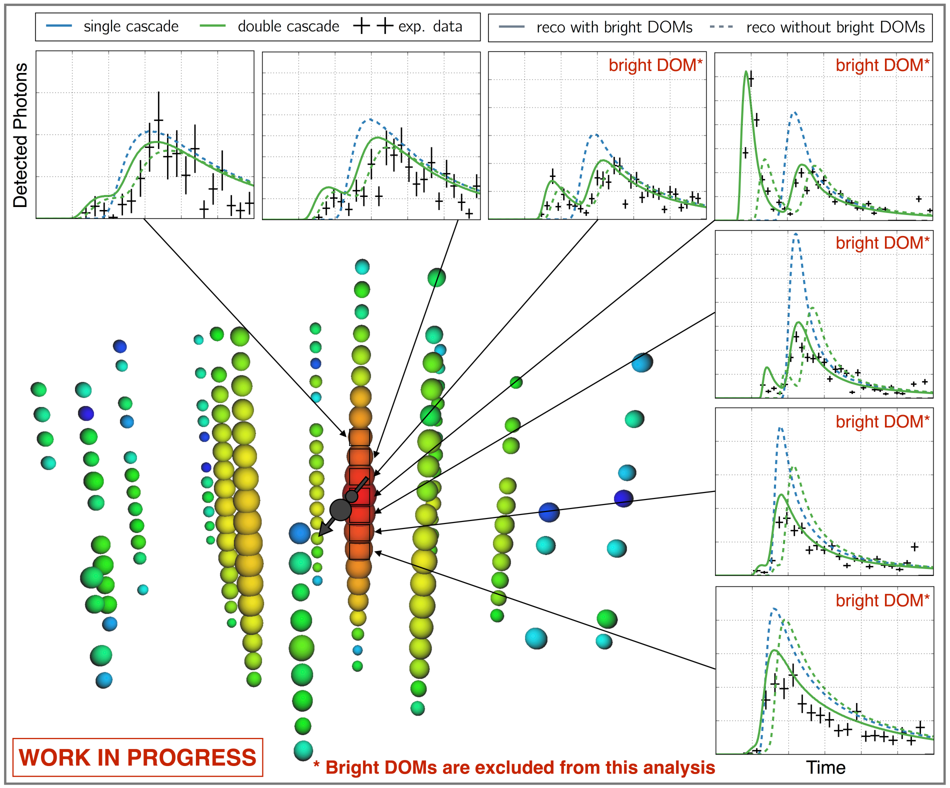
Latest News (Neutrino 2018)

- Two double bang candidates could be CC interaction by ν_τ

$m_\tau = 1.77$ GeV
$\tau_\tau = 2.9 \times 10^{-13}$ s

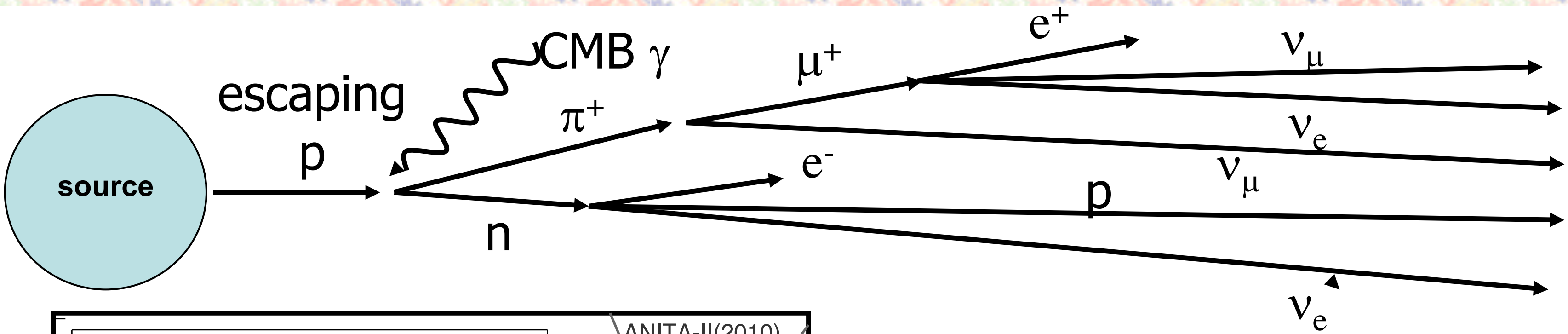


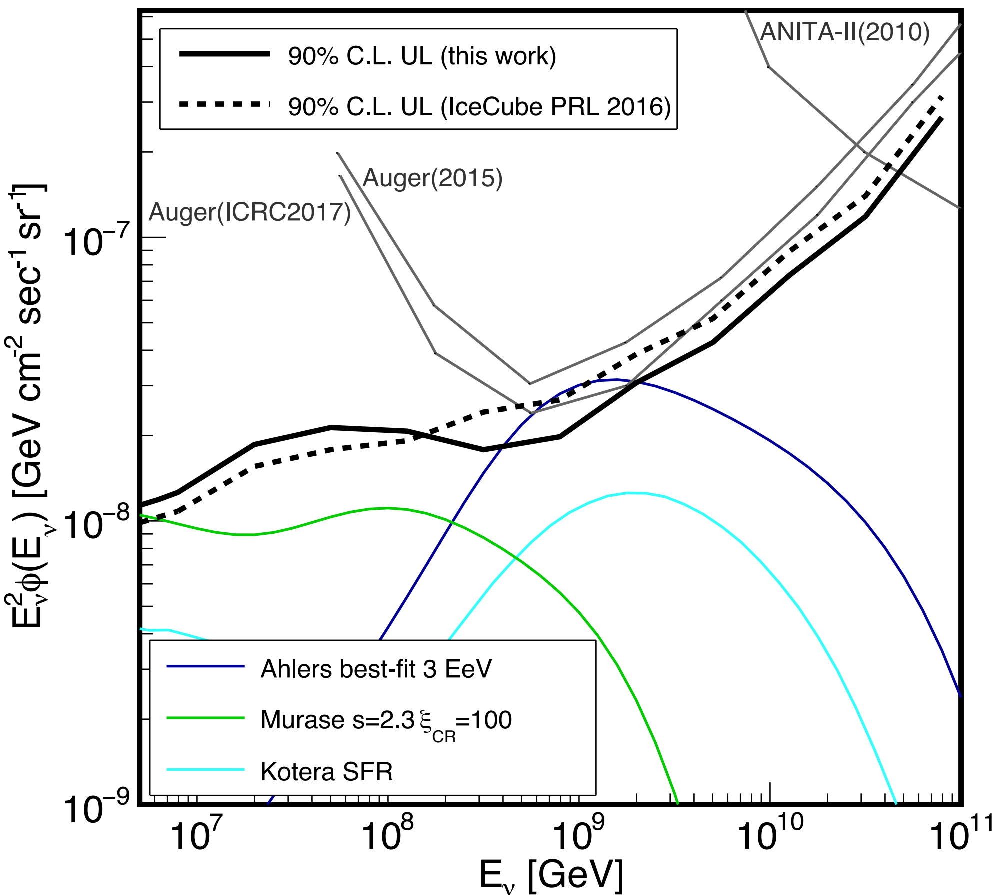
Double cascade Event #1



Double cascade Event #2

Go to Higher Energies



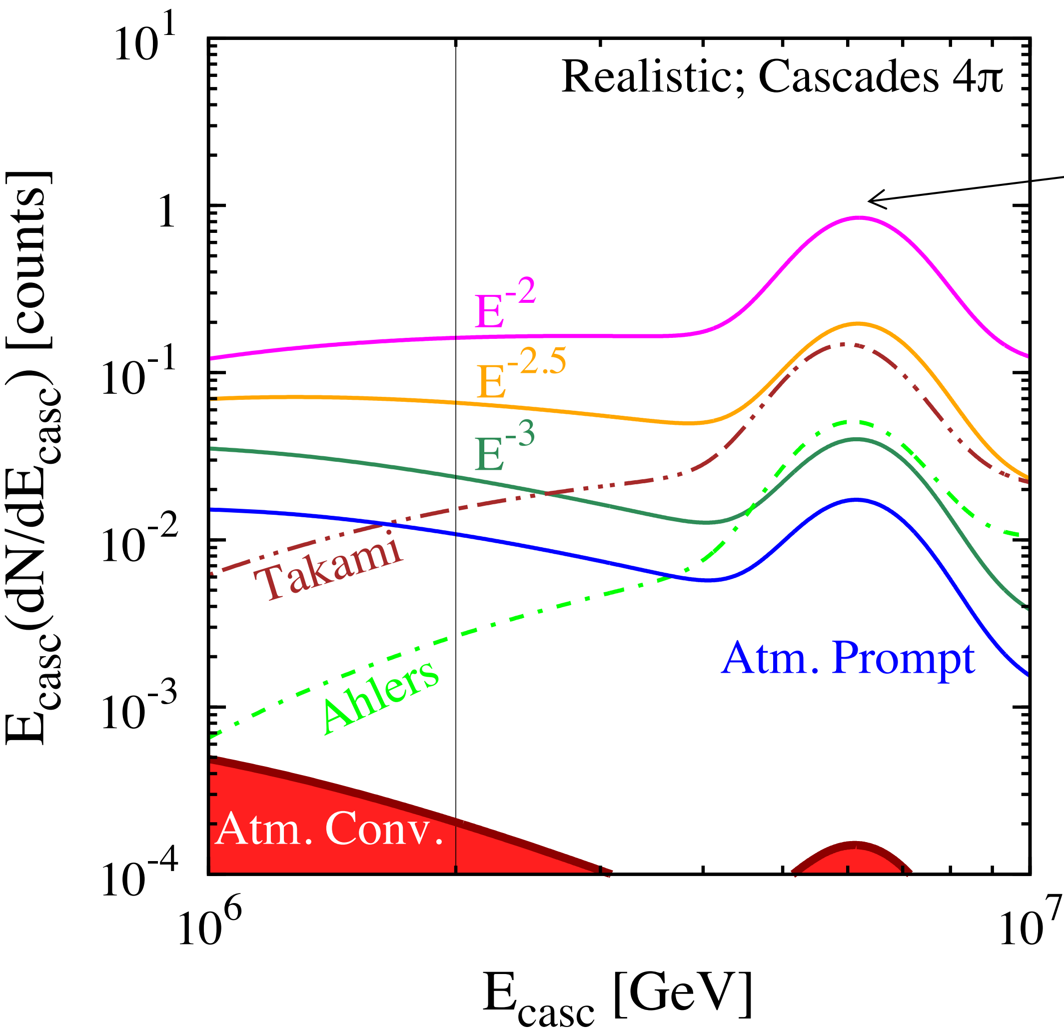


9-yr EHE analyses >1 PeV

- Neutrino spectrum cannot be extended w. s=2 up to UHE energies
- UHECR proton composition models are being constrained (strong evolution excluded)

IceCube 18

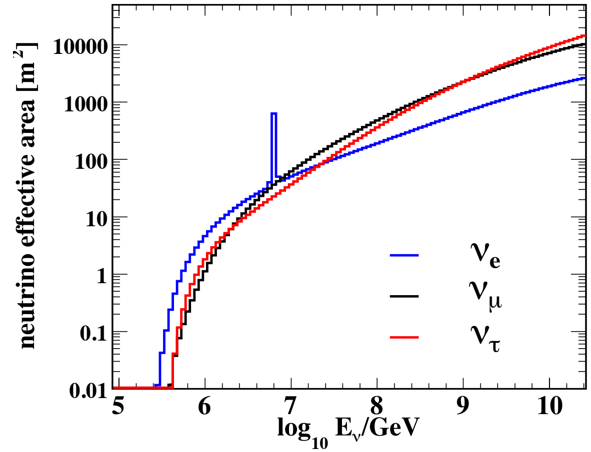
Glashow Search



Glashow resonance

$$\bar{\nu}_e\, e^- \rightarrow W^-$$

at E_ν=6.3 PeV

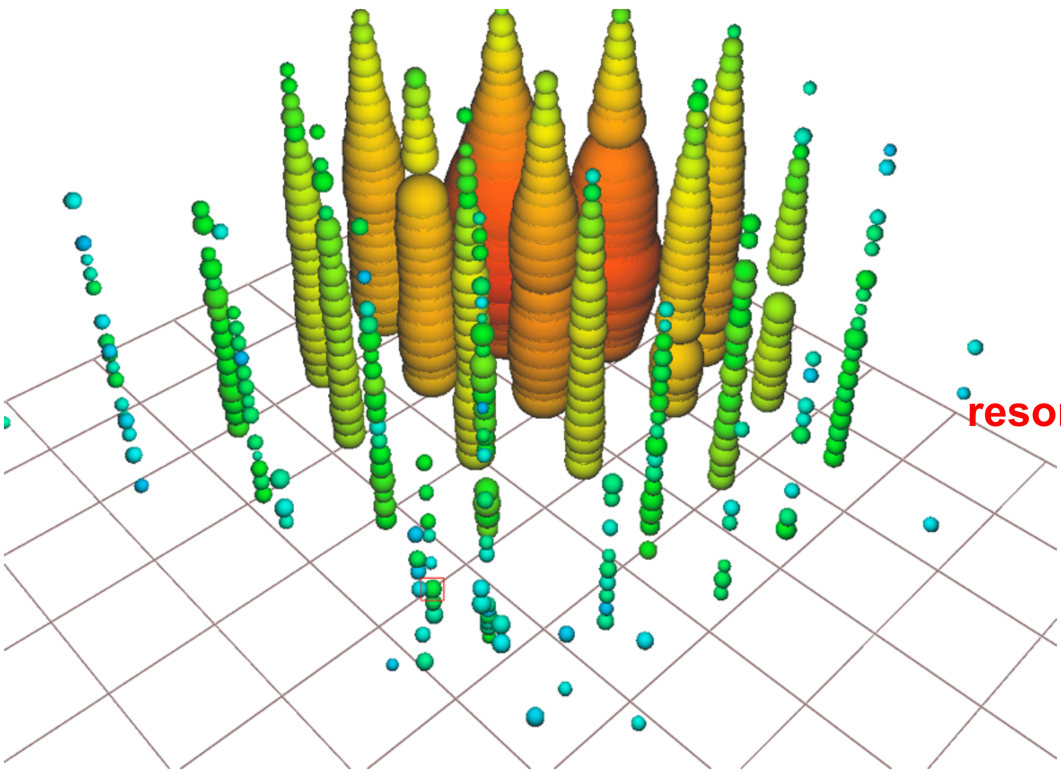


Laha, Beacom, Dasgupta, Horiuchi & KM 2013 PRD

The neutrino spectrum is soft or has a cutoff due to the absence of GR

Latest News in 2017-2018

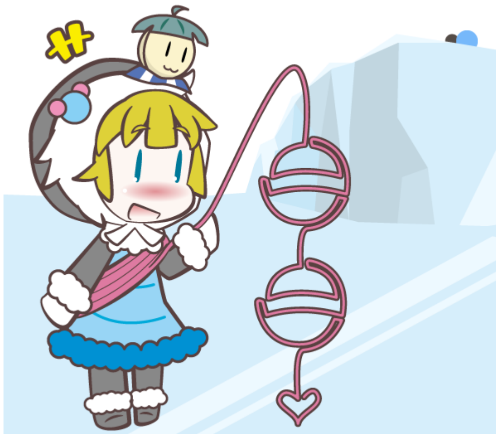
- 5.9 PeV event (deposited)
  in PEPE (PeV Energy Partially-contained Events)
- Finally we could detect a Glashow event at E=6.3 PeV?



resonant

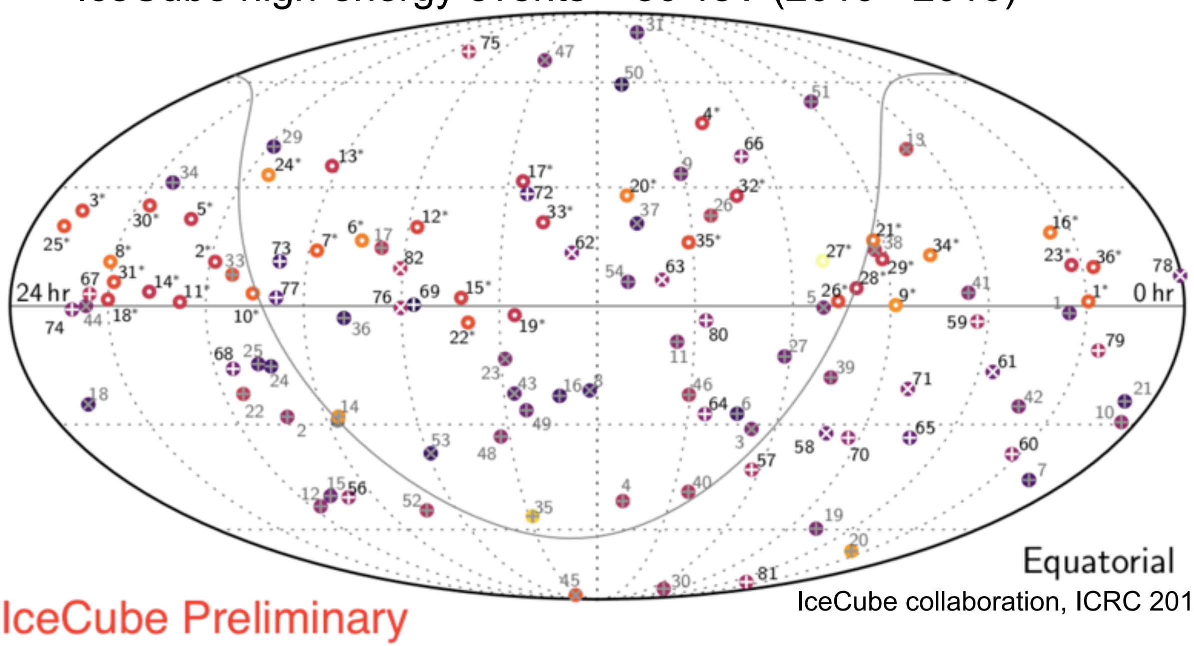
Reaction	σ [cm^2]
$\nu_\mu e \to \nu_\mu e$	5.86×10^{-36}
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	5.16×10^{-36}
$\nu_\mu e \to \mu \nu_e$	5.42×10^{-35}
$\nu_e e \to \nu_e e$	3.10×10^{-35}
$\bar{\nu}_e e \to \bar{\nu}_e e$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\mu \mu$	5.38×10^{-32}
$\bar{\nu}_e e \to \bar{\nu}_\tau \tau$	5.38×10^{-32}
$\bar{\nu}_e e \to$ hadrons	3.41×10^{-31}
$\bar{\nu}_e e \to$ anything	5.02×10^{-31}
$\nu_\mu N \to \mu^- +$ anything	1.43×10^{-33}
$\nu_\mu N \to \nu_\mu +$ anything	6.04×10^{-34}
$\bar{\nu}_\mu N \to \mu^+ +$ anything	1.41×10^{-33}
$\bar{\nu}_\mu N \to \bar{\nu}_\mu +$ anything	5.98×10^{-34}

Hunting Neutrino Sources



compatible w. isotropic distribution
no significant clustering

IceCube high-energy events > 30 TeV (2010 - 2016)



IceCube collaboration, ICRC 2017

0 source
in time-integrated search

tentative 1 source
in time-dependent search

What Can We Learn from the Neutrino Sky?

For powerful neutrino sources, searches for event clustering is powerful

1. Non-detection of ν event clustering (absence of ν "multiplet" sources)

$$N_s = b_{m,L} \left(\frac{\Delta\Omega}{3} \right) n_0^{\rm eff} d_{\rm lim}^3 < 1$$

$d_{\rm lim}$: detectable distance for a source with L

$b_{m,L}$: depends on analysis details (powerful for placing "upper limits")

"upper" limits $\mathbf{n_0 < 10^{-7}\text{-}10^{-6}\ Mpc^{-3}\ (L_\nu/10^{42}\ erg/s)^{-3/2}}$

2. IceCube flux ($E_\nu^2\Phi_\nu$ ~ 3×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}) tells us the ν energy generation rate

$\mathbf{n_0 L_\nu \sim 10^{44}\ erg\ Mpc^{-3}\ yr^{-1}}$ (for no redshift evolution)

3. Lower limits can be placed from the information 1+2

"lower" limits $\mathbf{n_0 > 10^{-5}\text{-}10^{-6}\ Mpc^{-3}}$

BL Lac objects: n_{tot}~(1-3)x10^{-7} Mpc^{-3} w. weak redshift evolution
implying that blazars are subdominant sources in the diffuse neutrino intensity
#model-dependence (e.g., cosmic evolution, luminosity weight, spectrum)

Open Questions in HE Neutrino Astrophysics

- **Origin of cosmic neutrinos?**
- production mechanism: pp or pγ?
- connection to UHECRs?
- connection to γ rays?
- Galactic contribution?
- transients?
- flavors?
- new physics?

Neutrinos & γ rays: Summary

Gamma-ray background?

main sources above 10 GeV are blazars

~15-30% (above 50 GeV) or more may come from non-blazars

intra-source cascades & intergalactic cascades

- leptonic sceanrio = self-Compton or external inverse-Compton
- hadronic scenario = p-induced cascade or p-synchrotron
- UHECR-induced intergalactic cascade

Neutrino background?

origins are unknown: spectrum may not be a power law

flavor ratios are consistent w. the standard model expectation

bulk of the neutrinos seems to come from some abundant sources

Theoretical implications will be discussed on the 3rd day