High energy Neutrino Astrophysics

- experimental overview

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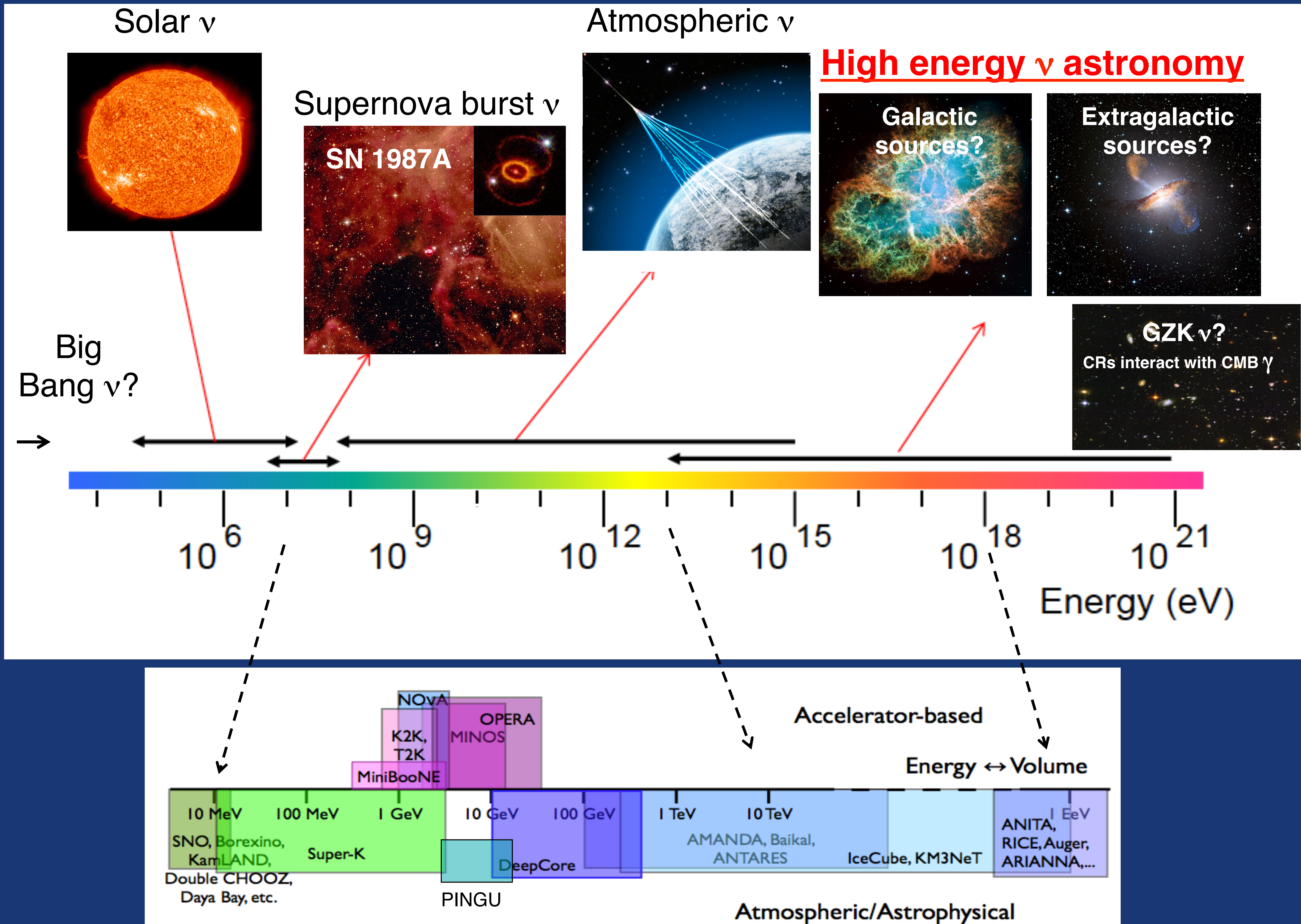
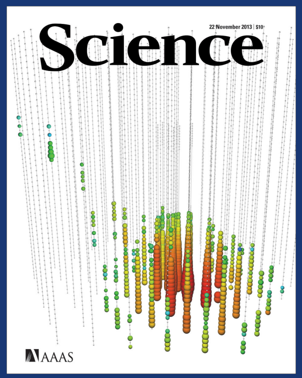
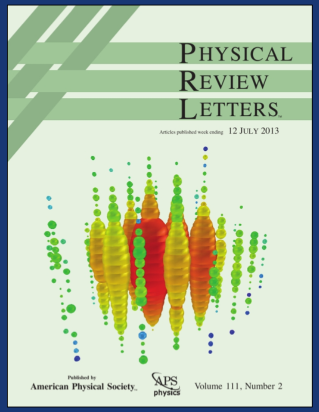
Neutrino Sources / Energies



Outline:





1. Introduction

2. HE astrophysical neutrinos – recent results
   - ✓ Diffuse flux - discovery by IceCube
   - ✓ Point source – searches
   - ✓ Multi-messenger astronomy

3. Indirect detection of Dark Matter

4. Upgrades / future experiments

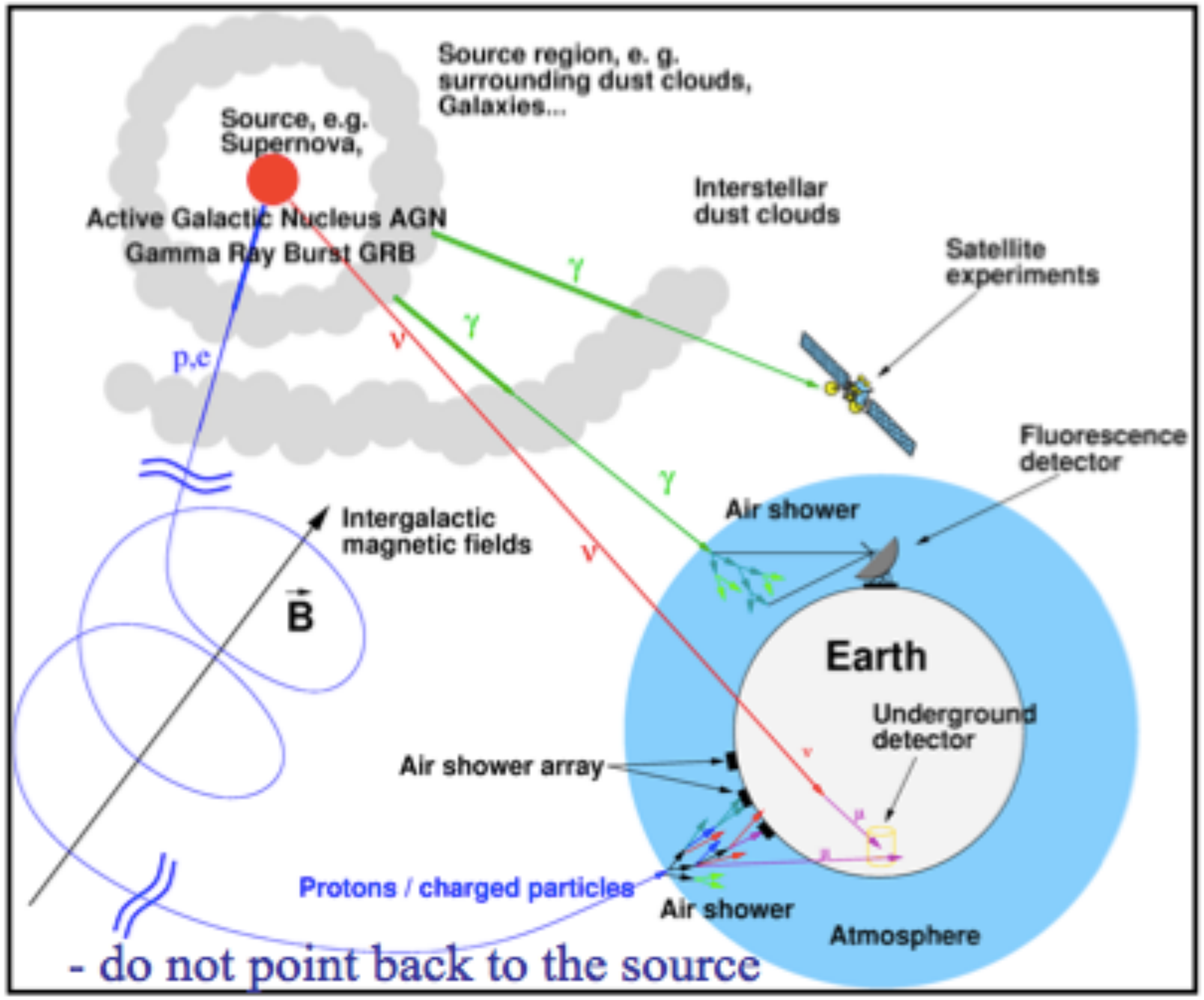
5. Summary and Outlook

High Energy Neutrinos – Introduction

look for cosmic accelerators

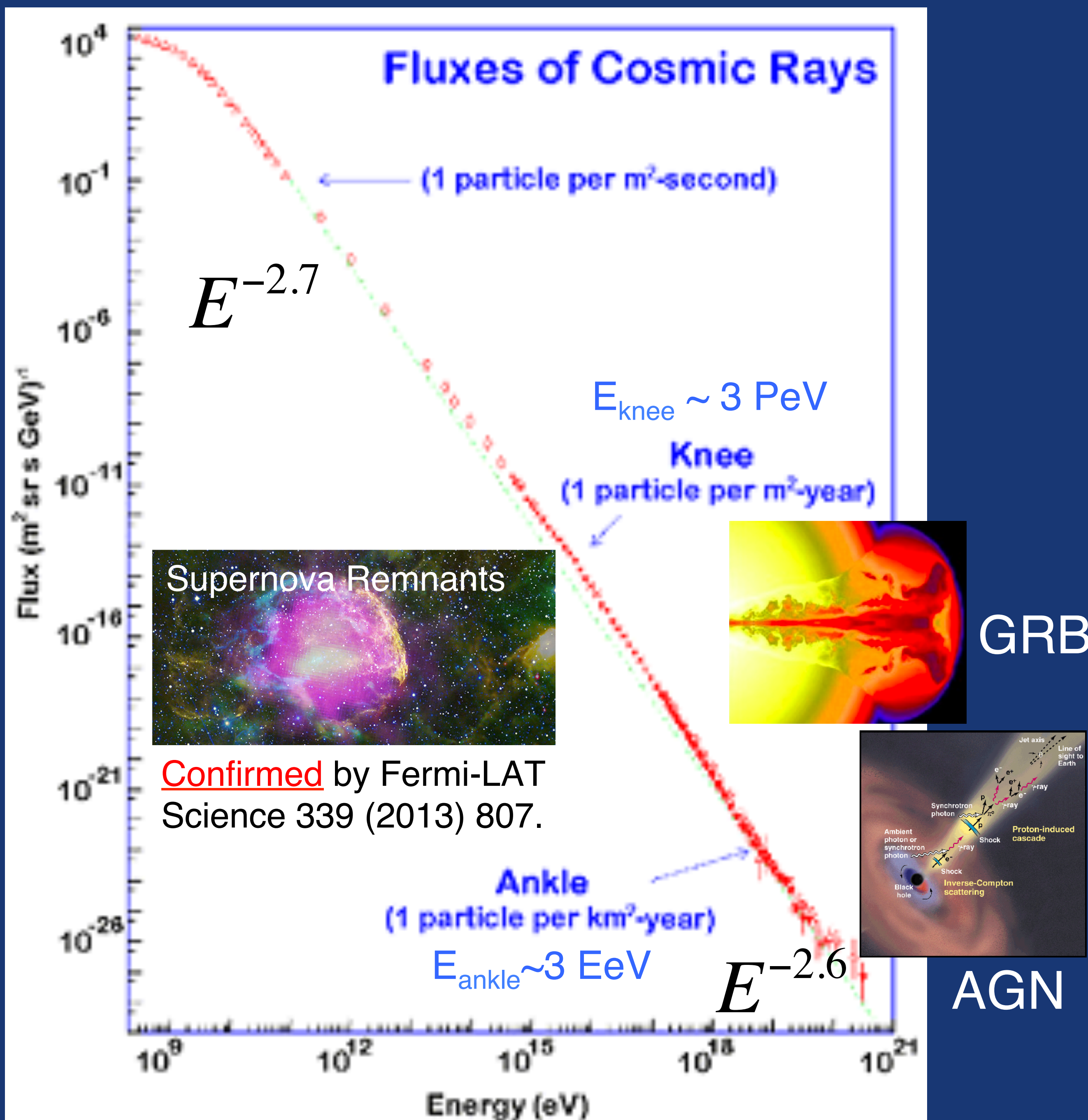
Neutrinos as probes of the high-energy Universe

- Protons with E_p< 10 EeV directions scrambled by magnetic fields
- γ-rays: straight-line propagation but reprocessed in the sources; TeV γ−ray astronomy: many newly discovered (galactic and extragalactic sources)
- Neutrinos: straight-line propagation, unabsorbed, not GZK suppressed, will provide evidence of hadronic acceleration; but difficult to detect



High Energy Neutrinos – Introduction

What is the origin of Cosmic Rays with E up to 10^{20} eV ?



Greisen-Zatsepin-Kuzmin (GZK)
cut-off

TeV-PeV neutrino production

$p+p \rightarrow \pi + \ldots \rightarrow \nu + \ldots$

hadro production

$p+\gamma \rightarrow \Delta \rightarrow \left(p+\pi \rightarrow p+\gamma\gamma\right)$
$\rightarrow n+\pi \rightarrow n+\nu+\ldots$

photo production

- CR spectrum formation
- CR acceleration
  - Fermi mechanism: γ_{CR}~2
- CR propagation

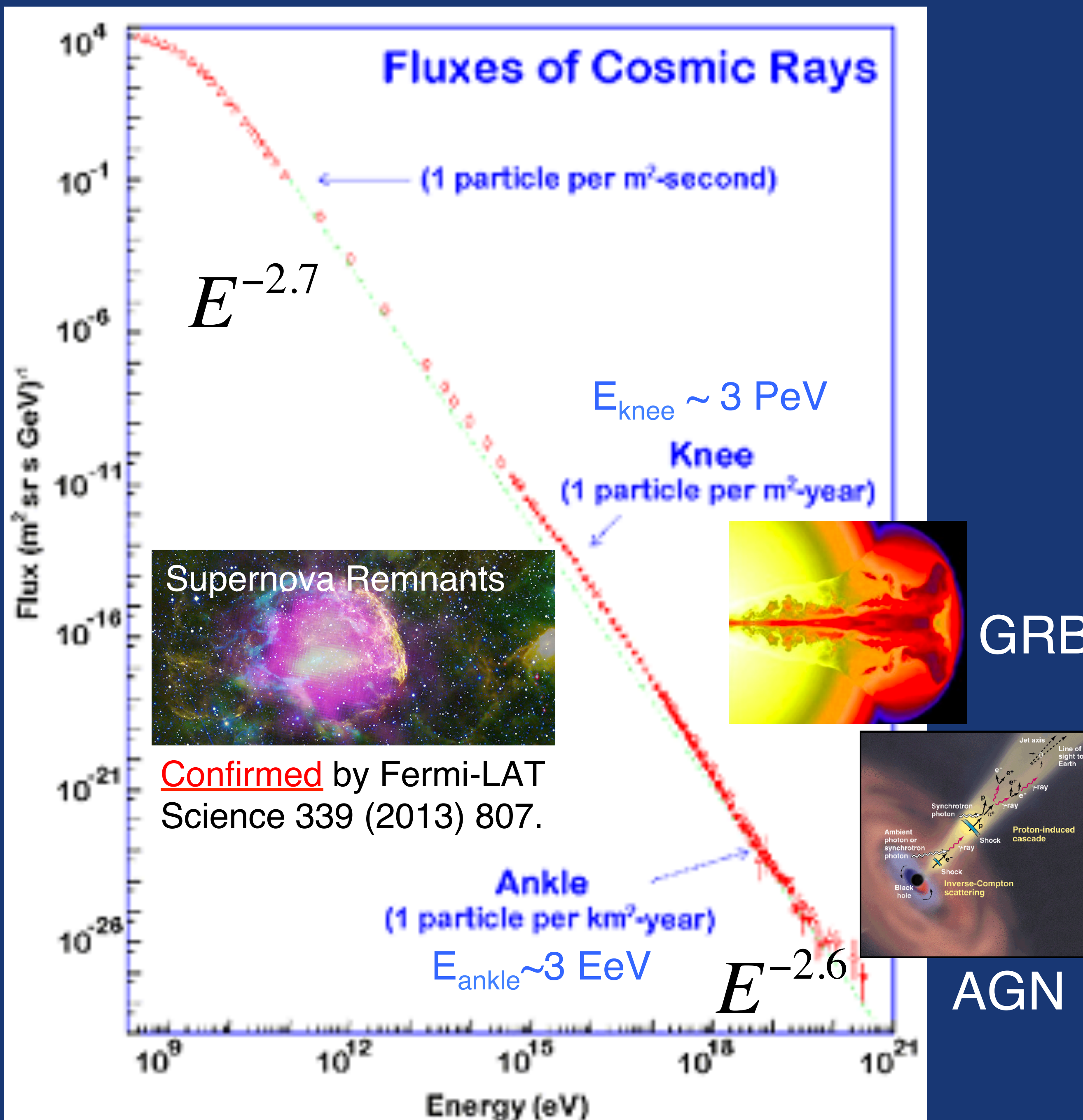
$\Phi_{CR} \sim E_{CR}^{-\gamma_{CR}}$

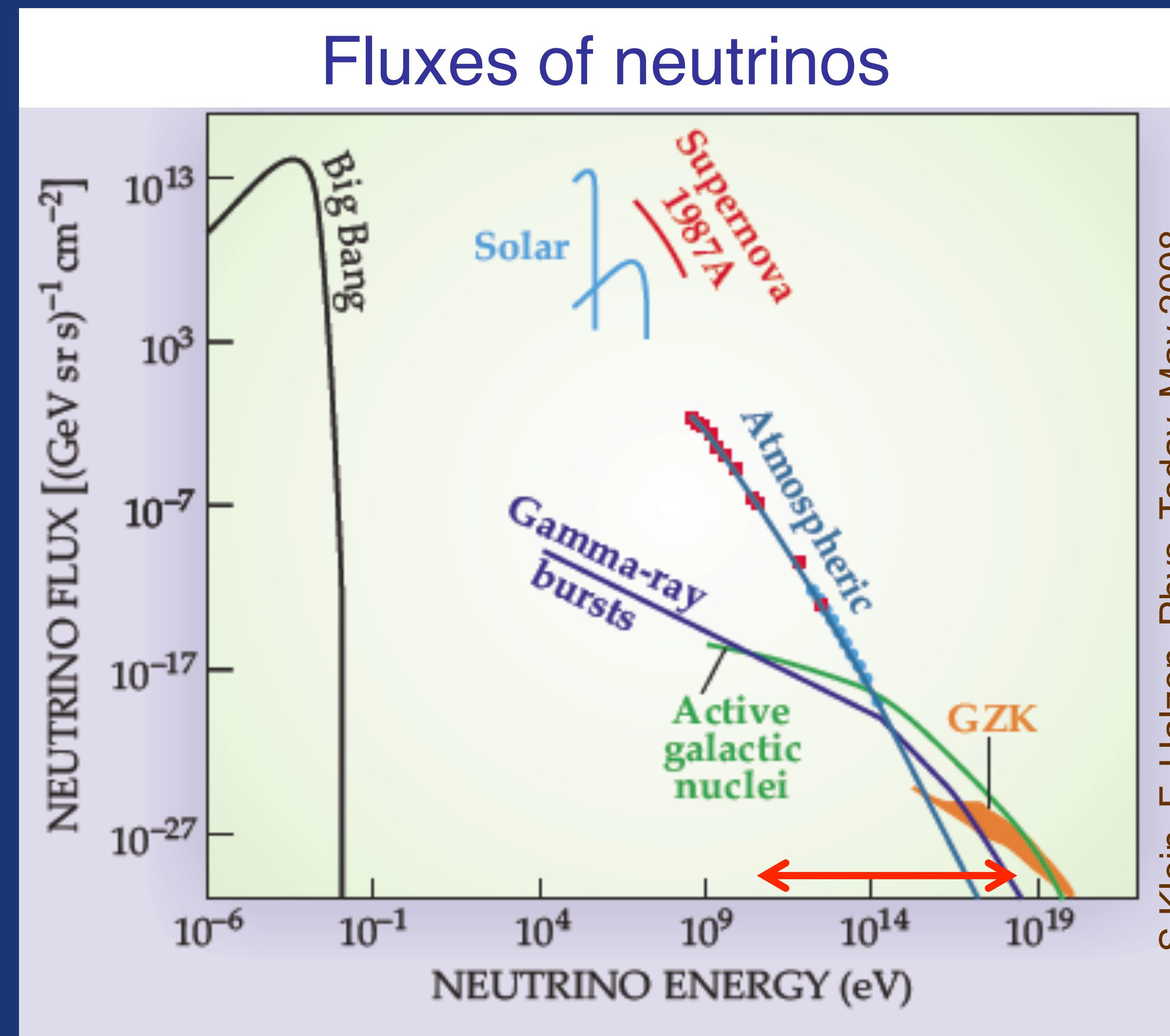
- ν benchmark model: γ_ν~2

$\Phi_\nu \sim E_\nu^{-\gamma_\nu}$

High Energy Neutrinos – Introduction

What is the origin of Cosmic Rays with E up to 10^{20} eV ?





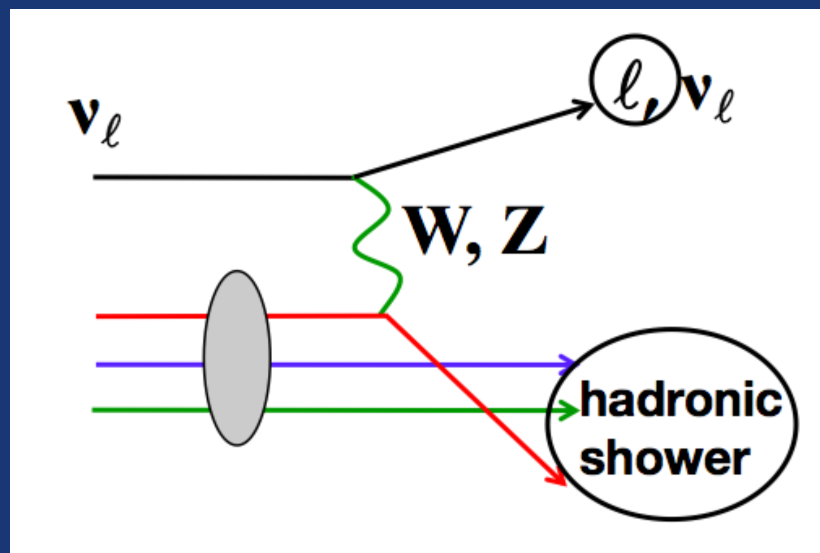
E_ν: 10^{10} eV - 10^{18} eV

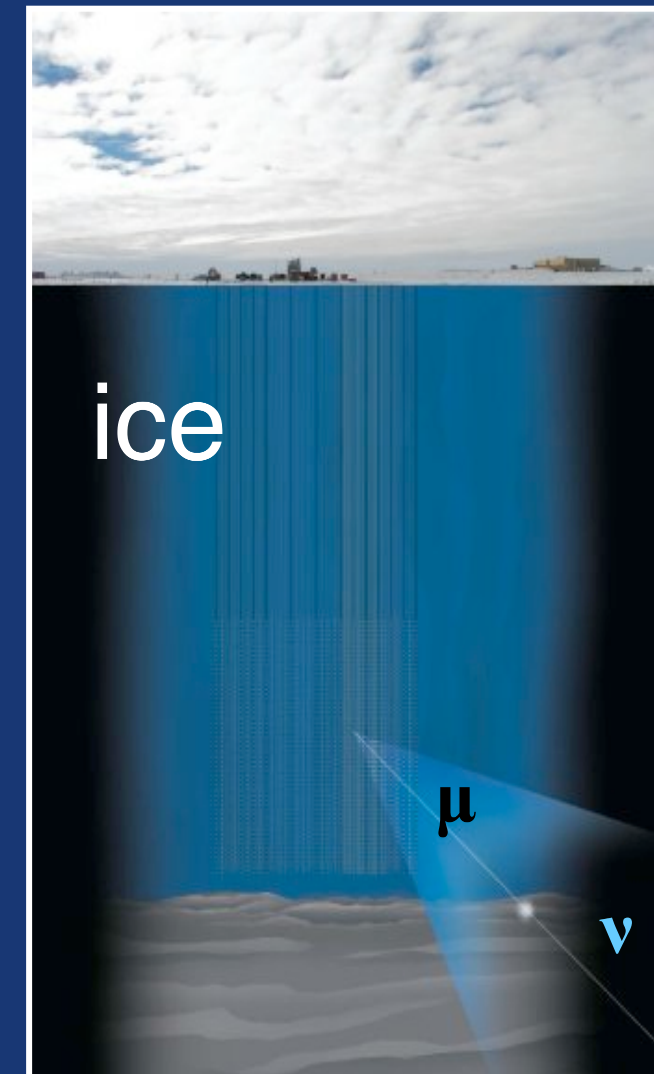
Greisen-Zatsepin-Kuzmin (GZK) cut-off

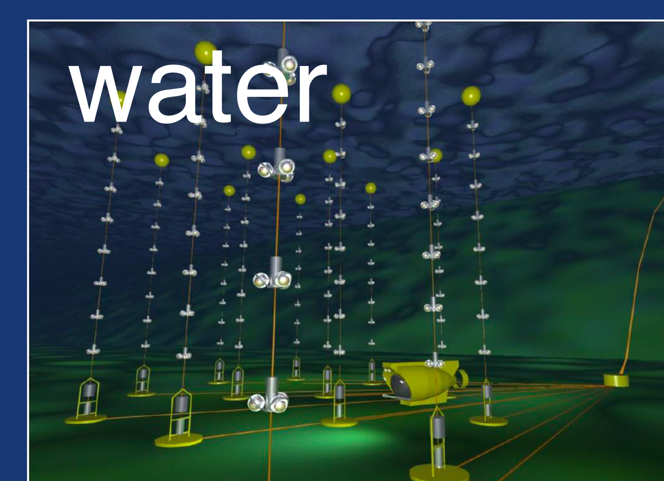
Low ν fluxes and small interaction cross section: need for 1 km³ detector- Neutrino Telescopes

High Energy Neutrino Telescopes: Optical Detection

Neutrinos of all flavors interact in or near the detector through charged current (CC) or neutral current (NC) weak interaction:







Neutrino interaction identification method:

Idea: 1960, M. Markov

Observe the secondaries

- O(km) muon tracks from ν_μ CC

  1 TeV ~ 2.5 km, 1PeV ~ 15 km

- O(10 m) e-m and/or hadronic cascades from ν_e CC, low energy ν_τ CC, and ν_x NC

via Cherenkov radiation detected by a 3D array of optical sensors

Neutrino Observatories (in operation and future)

Techniques:
- optical detection
- radio detection

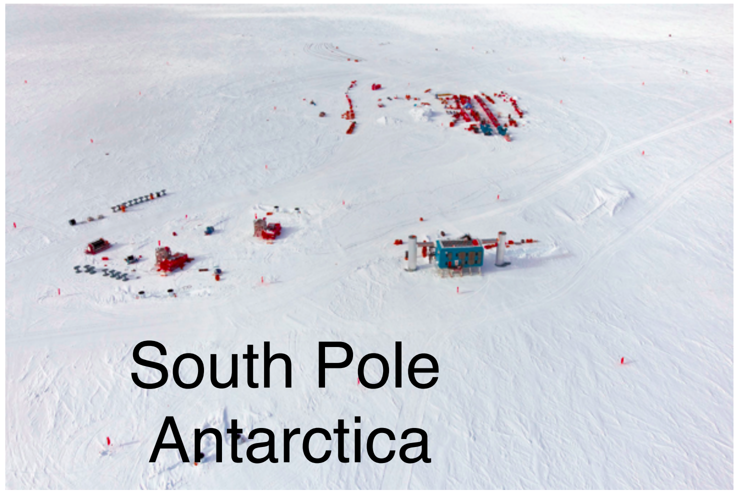
- Antares
- *Km3net (ORCA/ARCA)*

- *GNO (Greenland)*

- Lake Baikal NT200+
- *Lake Baikal-GVD*

- (PAO) ν_τ

- IceCube
- *Gen2*
- *ARA*



- Anita
- *(EVA)*
- *Arianna*

HE (optical) Neutrino Observatories (in operation)

NT-200+

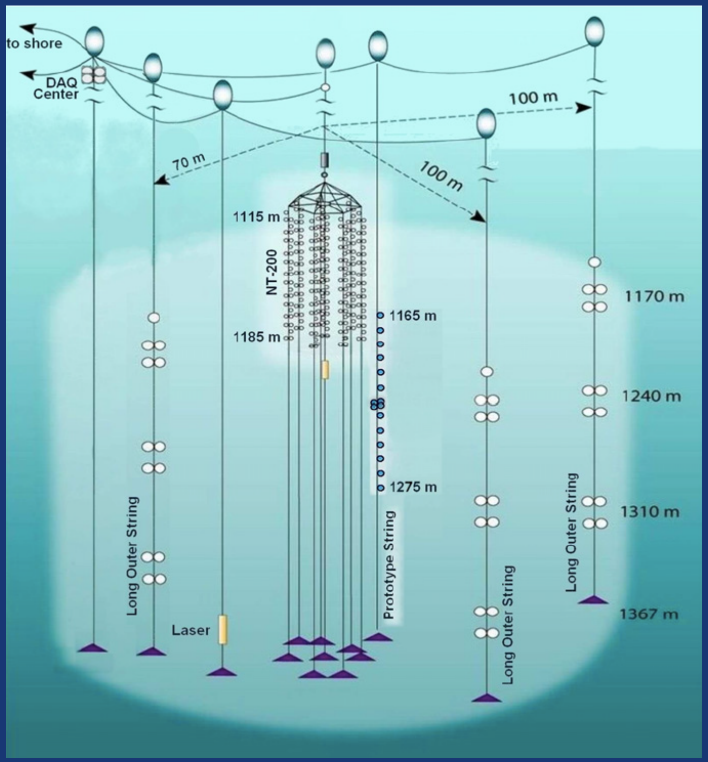
- 8+3=11 strings
- 192+36=228 PMTs
- 1/2000 km^3 of volume
- Medium: Lake Baikal
- Northern hemisphere

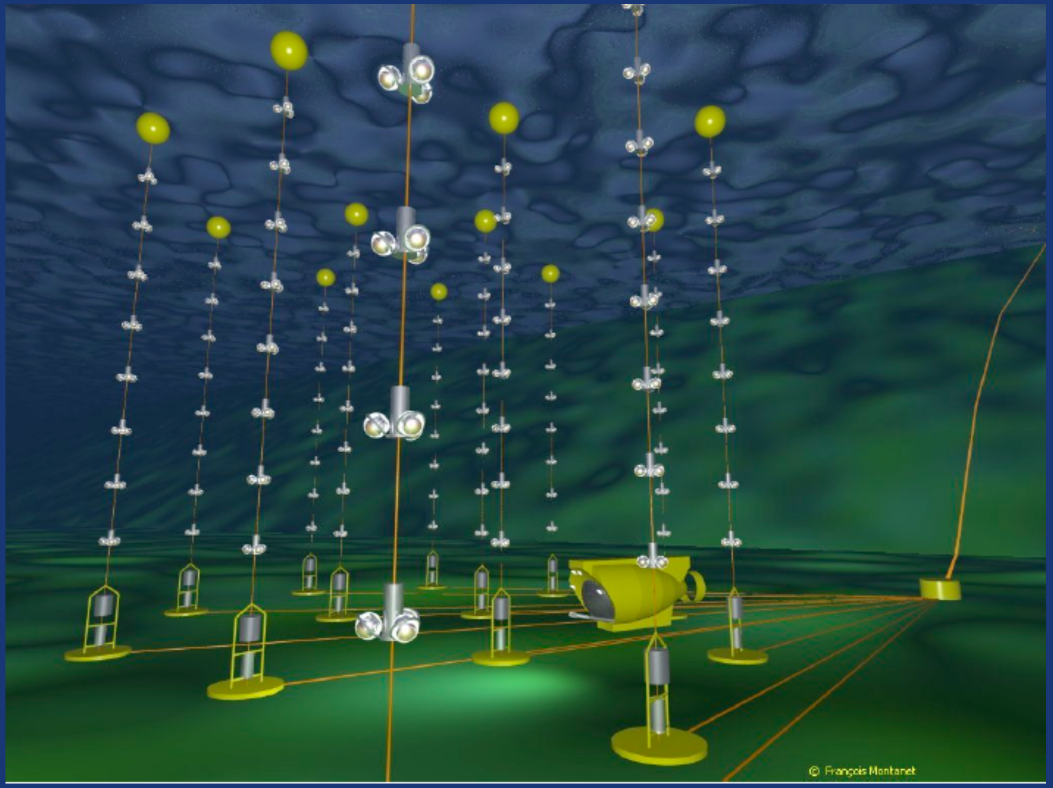
Antares

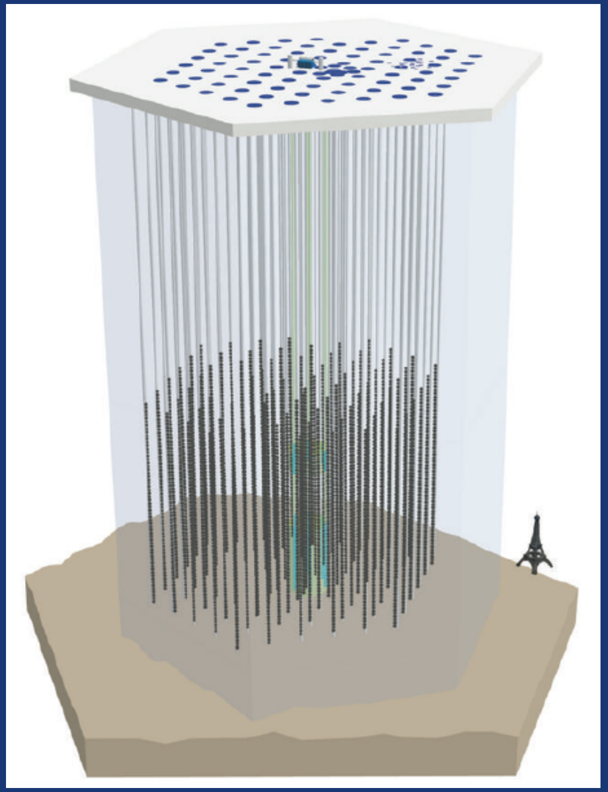
- 12 strings
- 885 PMTs
- 1/100 km^3 of volume
- Medium: Mediterranean Sea
- Northern hemisphere

IceCube

- 86 strings
- 5160 PMTs
- 1 km^3 of volume
- Medium: South Polar Ic
- Southern hemisphere

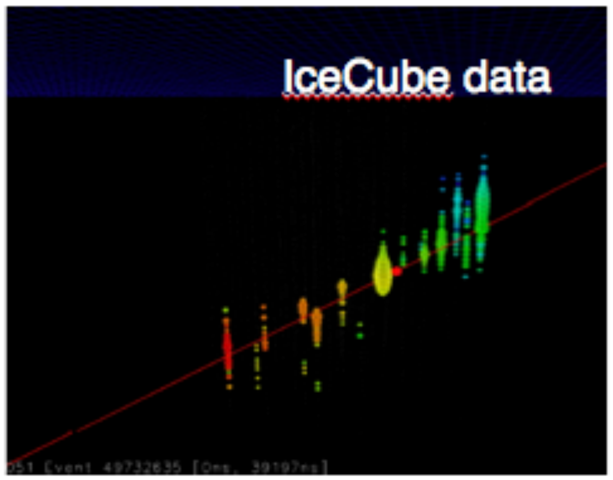


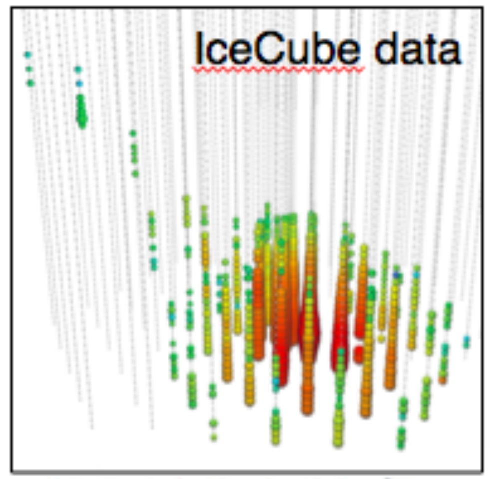


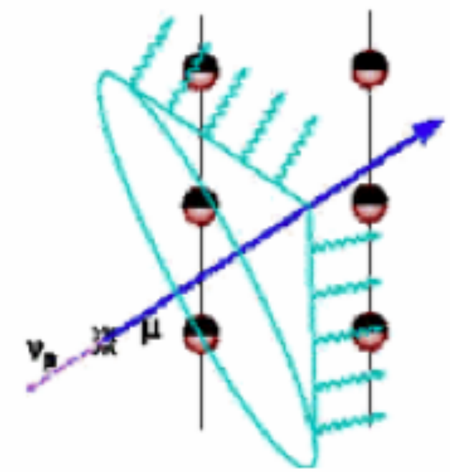


Event Signatures (example IceCube)

Neutrino interaction identification method: observe and reconstruct the secondaries (tracks, cascades/showers) via Cherenkov radiation detected by a 3D array of optical sensors

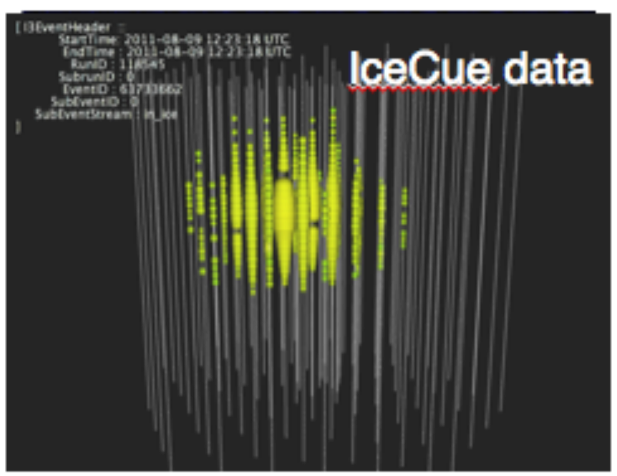


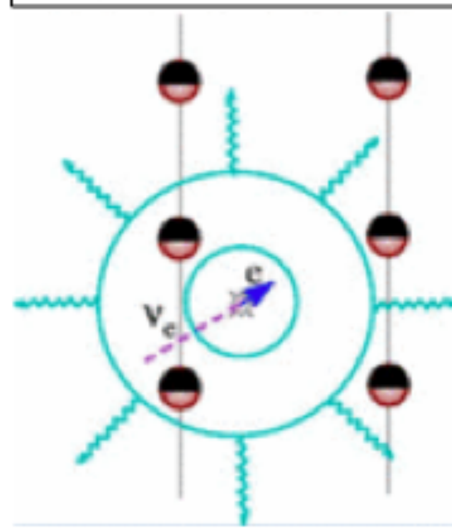




μ Tracks: (ν_μ)

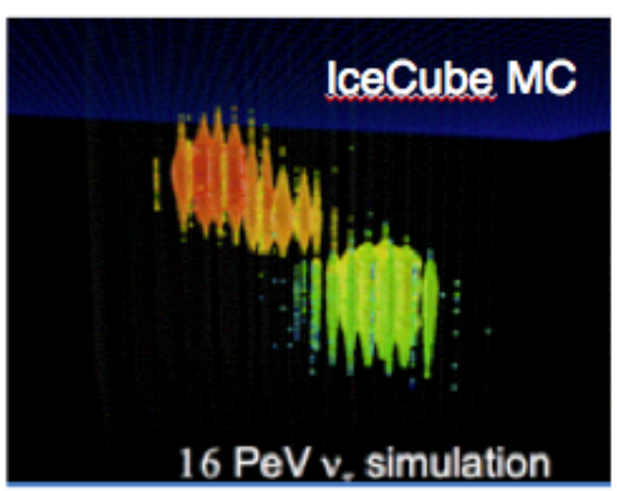
- through-going muons
- energy resolution ~ factor of 2
- pointing resolution <1°





Cascades:

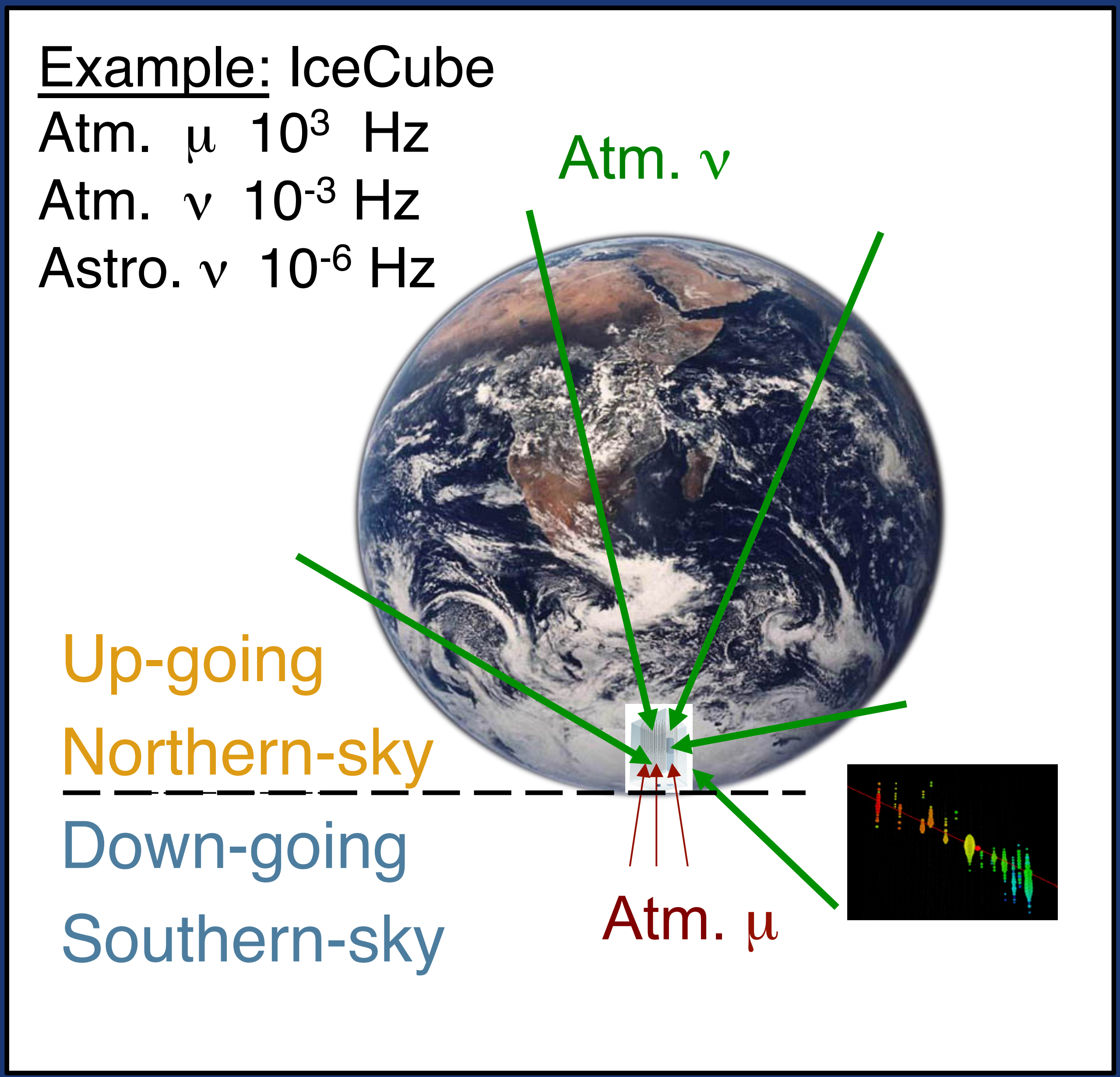
- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
  $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- Resolutions, cascades contained in detector
  - visible energy ~ 15%
  - angular ~ 10°- 40°

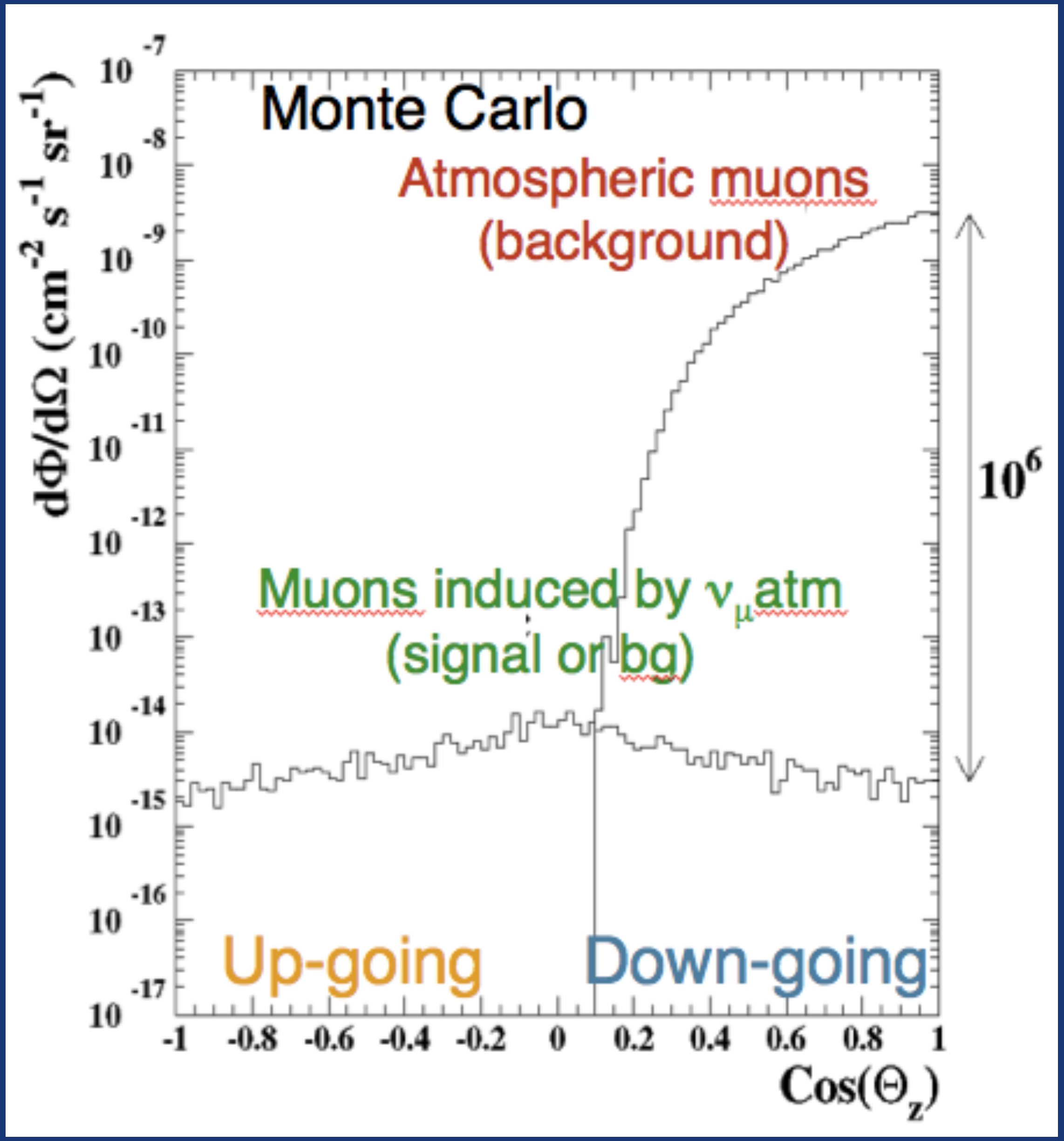


Composites

- starting events ("HESE","MESE","LESE")
- ν_τ ("double bangs" E_ν ~ 10's of PeV)
  not yet observed

ν_μ analyses: atmospheric μ bg

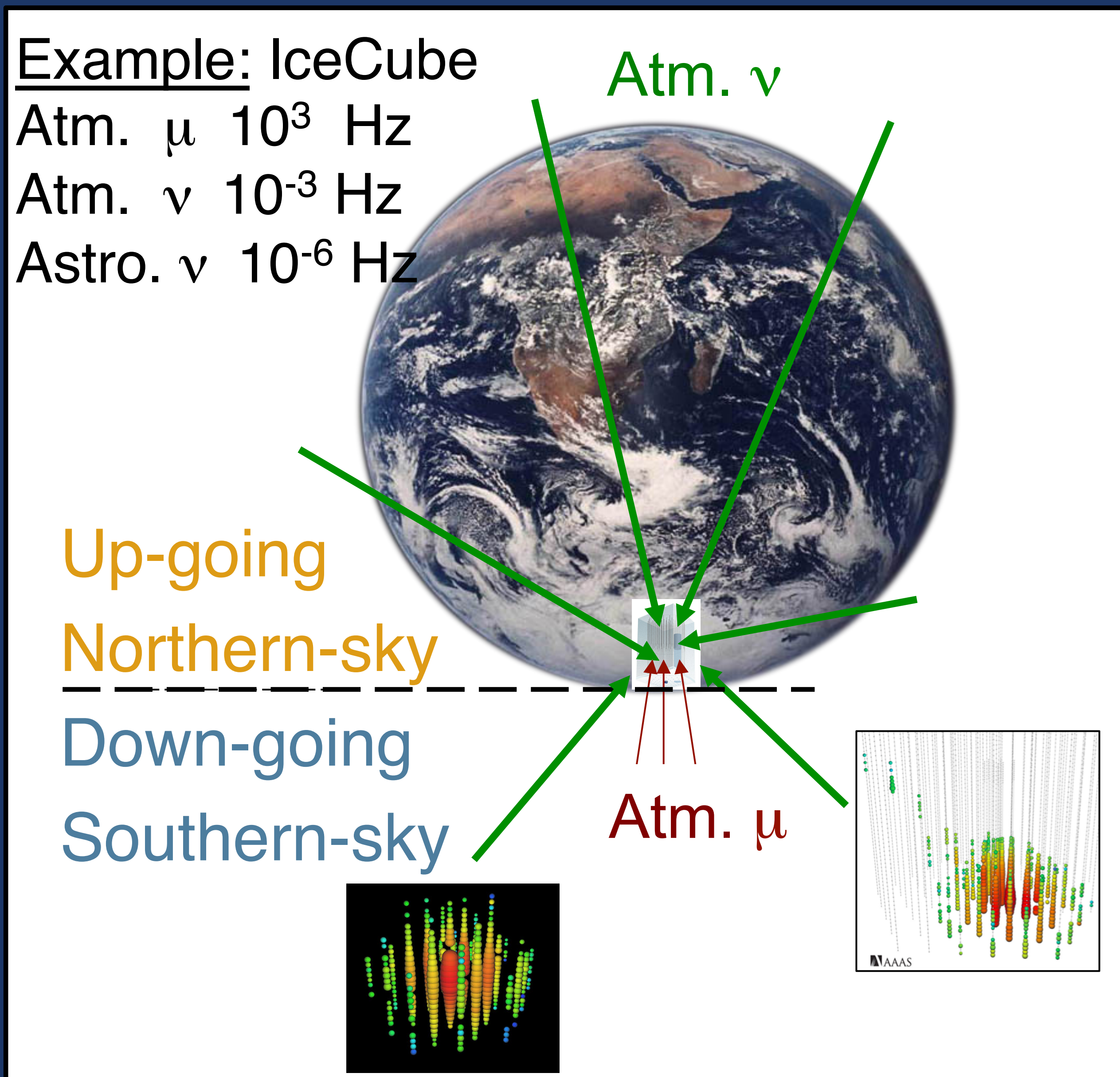




Reconstruct μ tracks and identify their origin (μ vs ν_μ)
by their direction

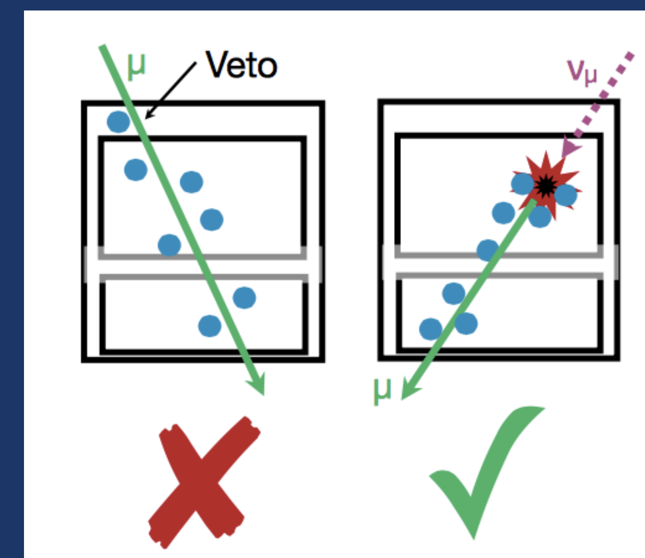
ν_μ - from the Northern sky ("up-going" μ only)

all-sky all-flavor ν analyses: atmospheric bg

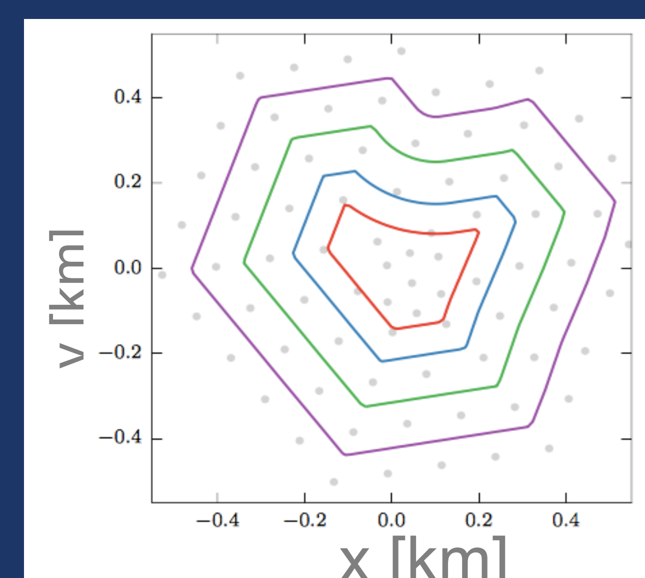


“Down-going” atm. ν rejection
Schönert et al., arXiv:0812.4308

- Starting events (cascades + tracks)

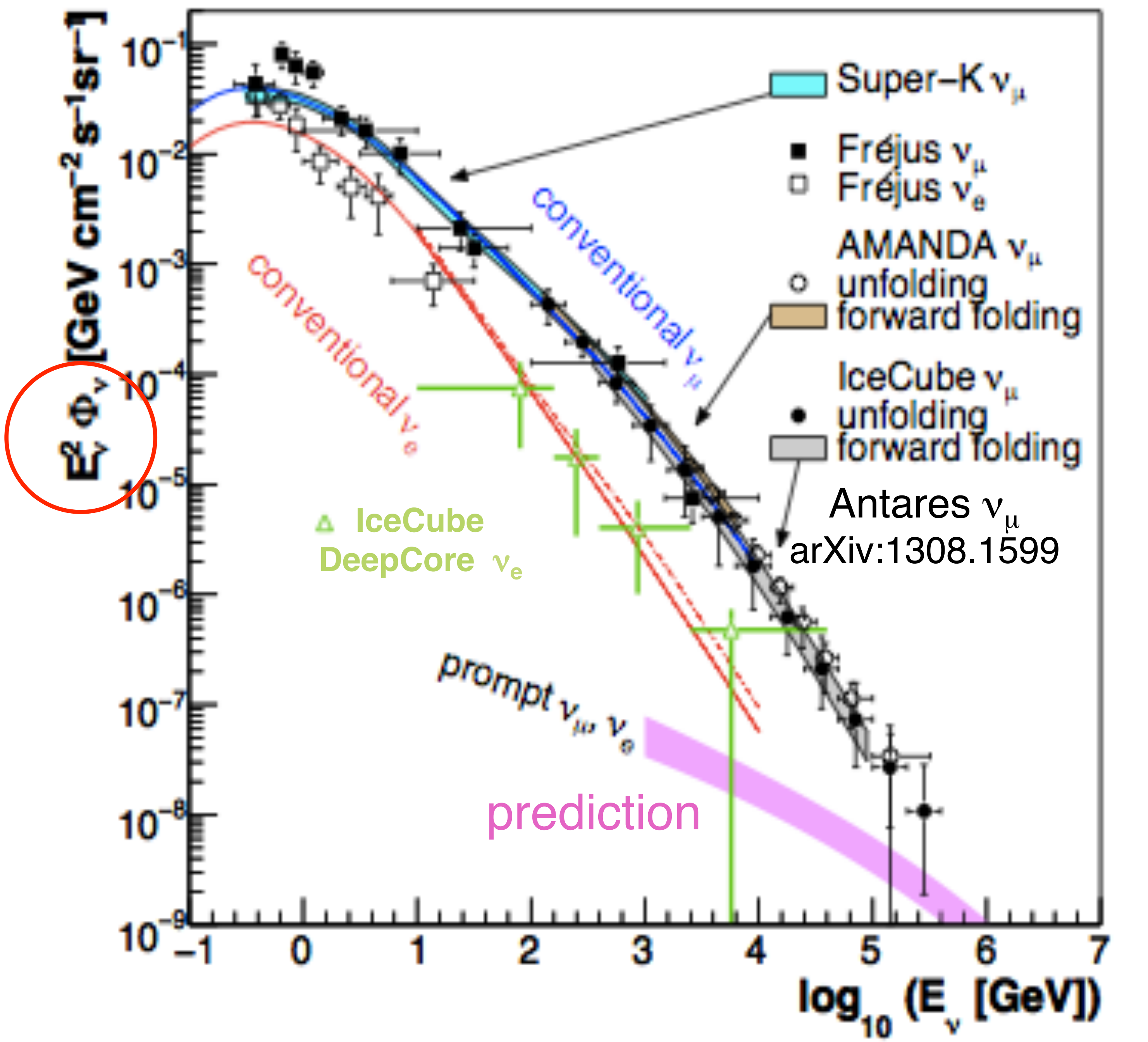


- Cascades (all-sky)
  event topology+ vertex containment



Atmospheric Neutrinos: ν_μ and ν_e

ν_e IceCube, Phys. Rev. Lett. 110 (2013) 151105
IceCube Phys. Rev. D91 (2015) 122004



Conventional neutrino flux
Decays of π,K mesons

- steeply falling spectrum ($E^{-3.7}$)
- flux peaked at horizon
- ν_μ dominated

Prompt neutrino flux
decays of D,B mesons

- spectrum follows CR ($E^{-2.7}$)
- flux isotropic
- equal parts ν_μ and ν_e

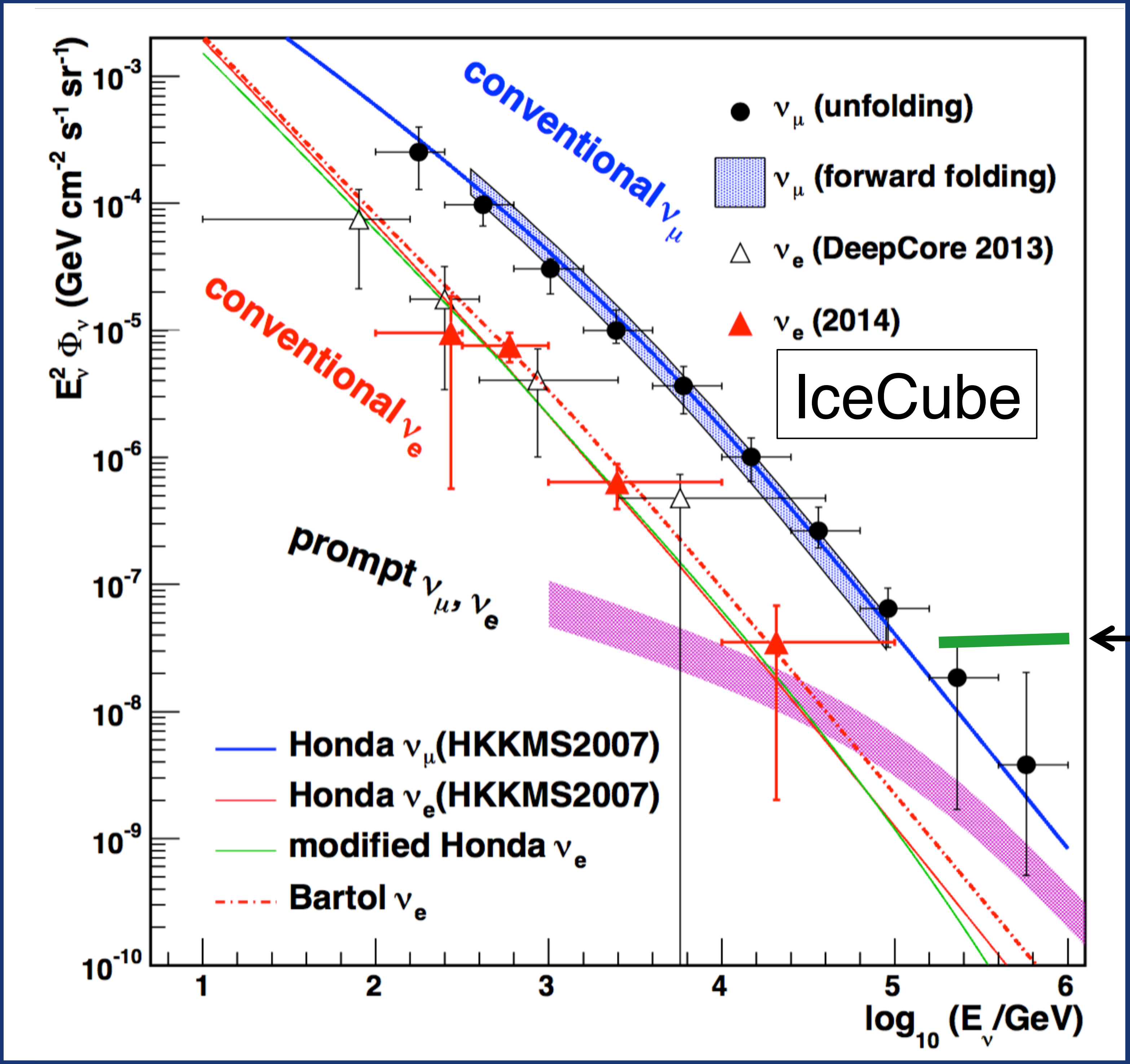
○ not yet directly observed

Prompt ν flux component depends on the assumed astrophysical flux and shape.

For: $\Phi_{astro} \sim E^{\gamma} \Rightarrow \Phi_{prompt} = 0.0^{+3.0}_{-0.0}\,\Phi_{ERS}$

ERS: R. Enberg et. Al.,Phys. Rev. D78, 043005 (2008)
A. Bhattacharya et.al. (2015), arXiv:1502.01076.

Atmospheric and Astrophysical Neutrinos



Atmospheric Neutrinos

- Signal: flux, oscillations
- Background: cosmic neutrinos

Astrophysical neutrinos

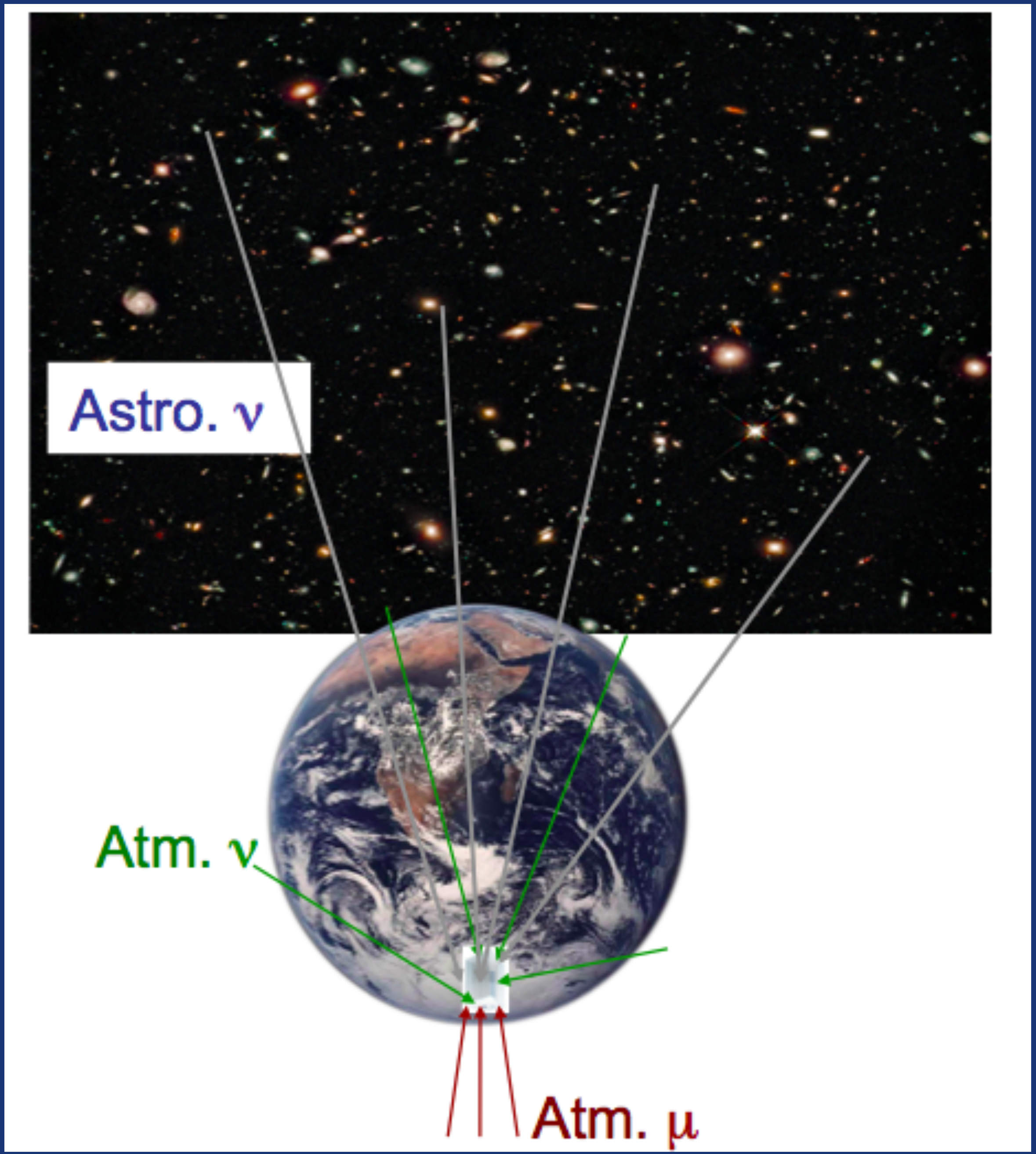
Waxman-Bahcall Bound (all flavor)

$$E_\nu^2 \Phi_{\rm WB} \approx 3.4 \times 10^{-8}\ \mathrm{GeV/cm^2\,sr\,s}$$

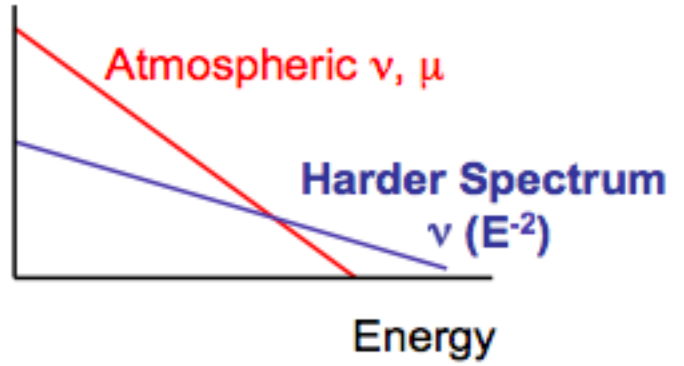
Benchmark model:
Fermi acceleration at shock fronts

Neutrino Diffuse Flux Search: Method

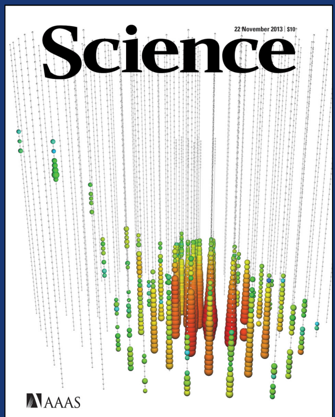
Diffuse flux = effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs) Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.



- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos using energy and direction (self-veto)



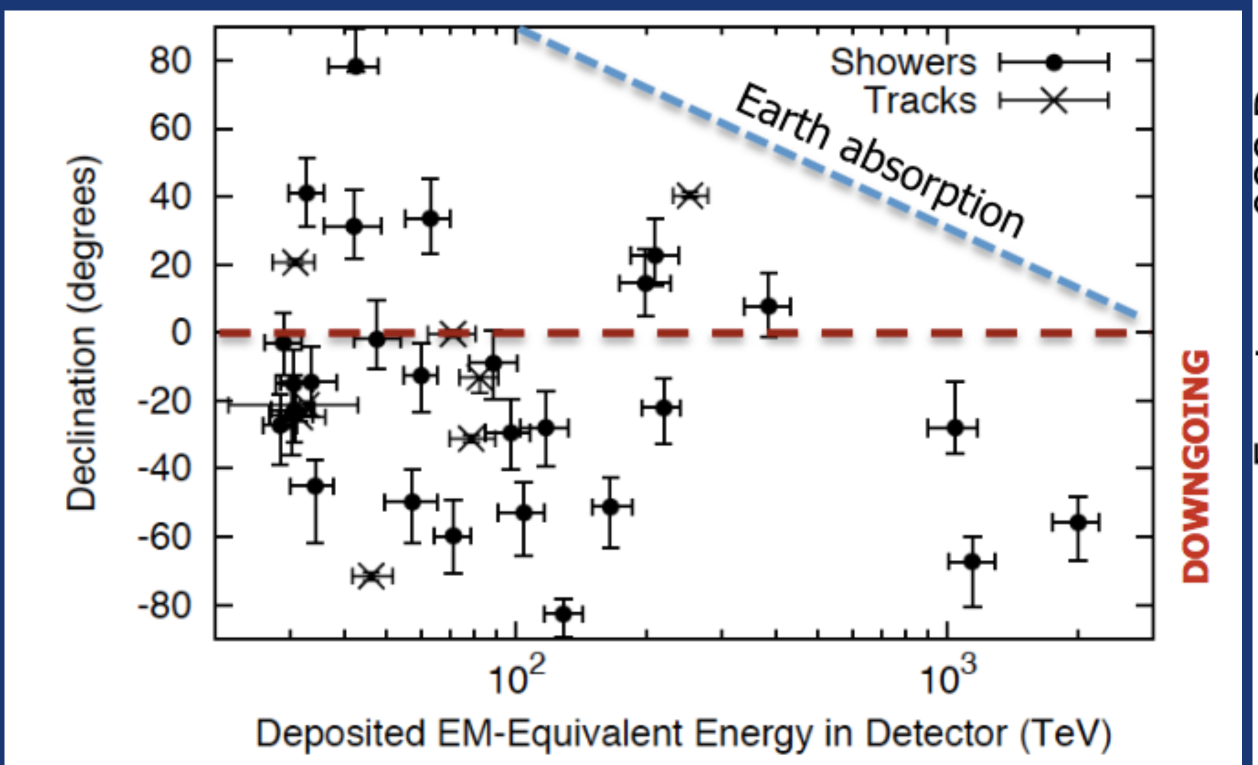
- Advantage over point source search: can detect weaker fluxes
- Sensitive to all three flavors of neutrinos
- Disadvantage: high background
  solution: containment cut / veto technique

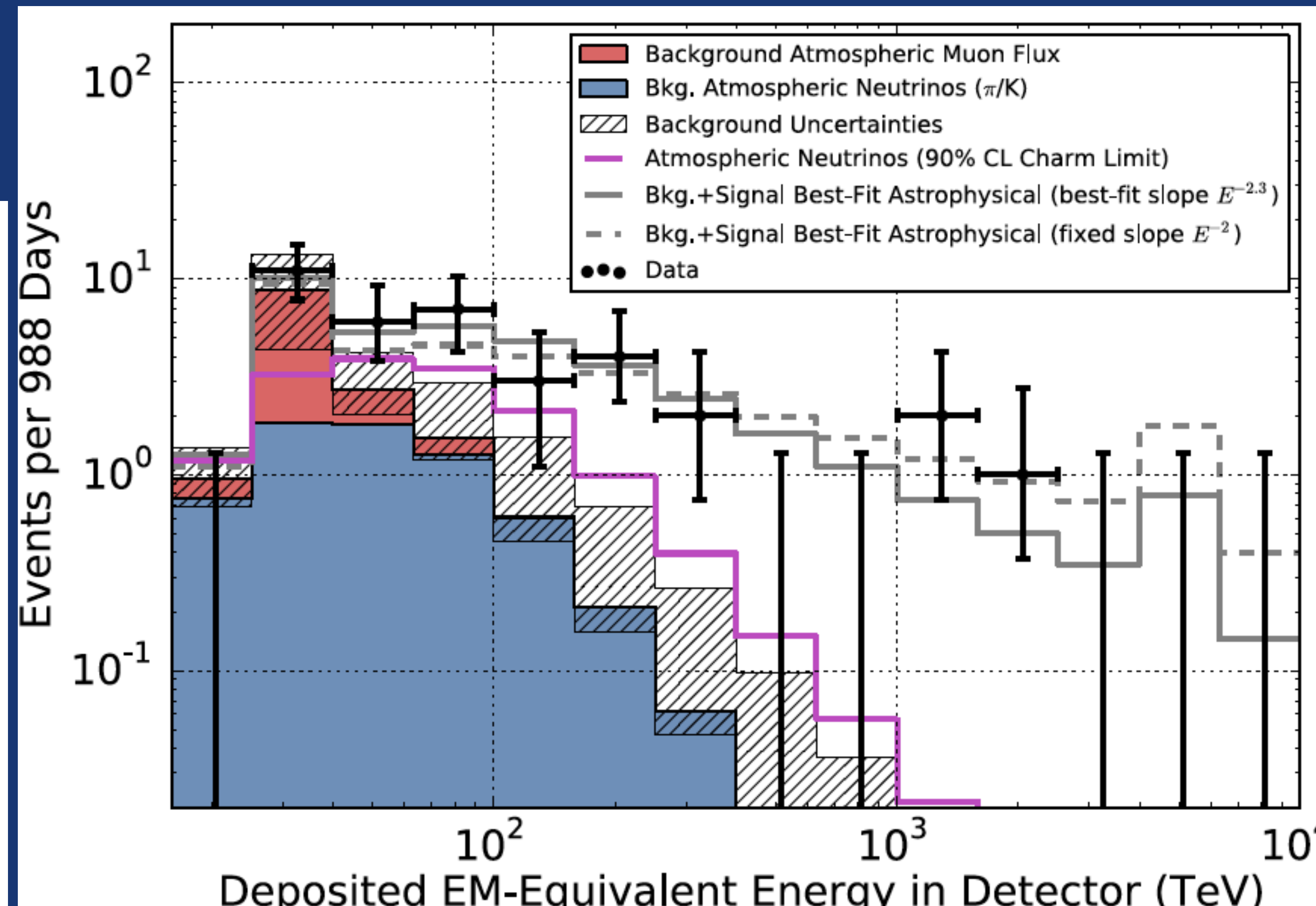


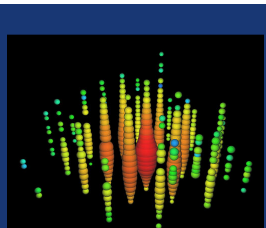
Discovery of Cosmic Neutrinos with IceCube

IC79+IC86 analysis of **2010-2013 data (3 years)** to search for "High Energy Starting Events" (HESE) <u>all-flavor neutrinos</u>

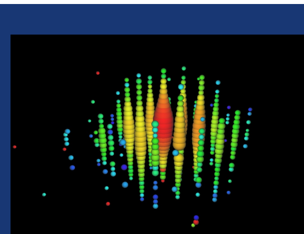
IceCube (3 yr), Phys. Rev. Lett.; arXiv:1405.5303
IceCube (2 yr), Science 22 Vol. 342 no. 6161



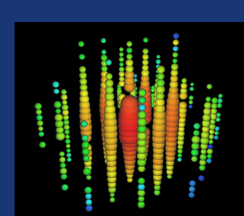




E = 1.0 PeV
Aug. 2011

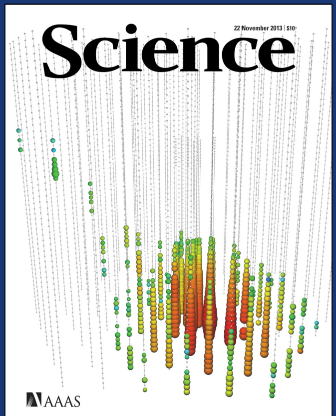


E = 2.0 PeV
Dec 2012



E = 1.1 PeV
Jan 2012

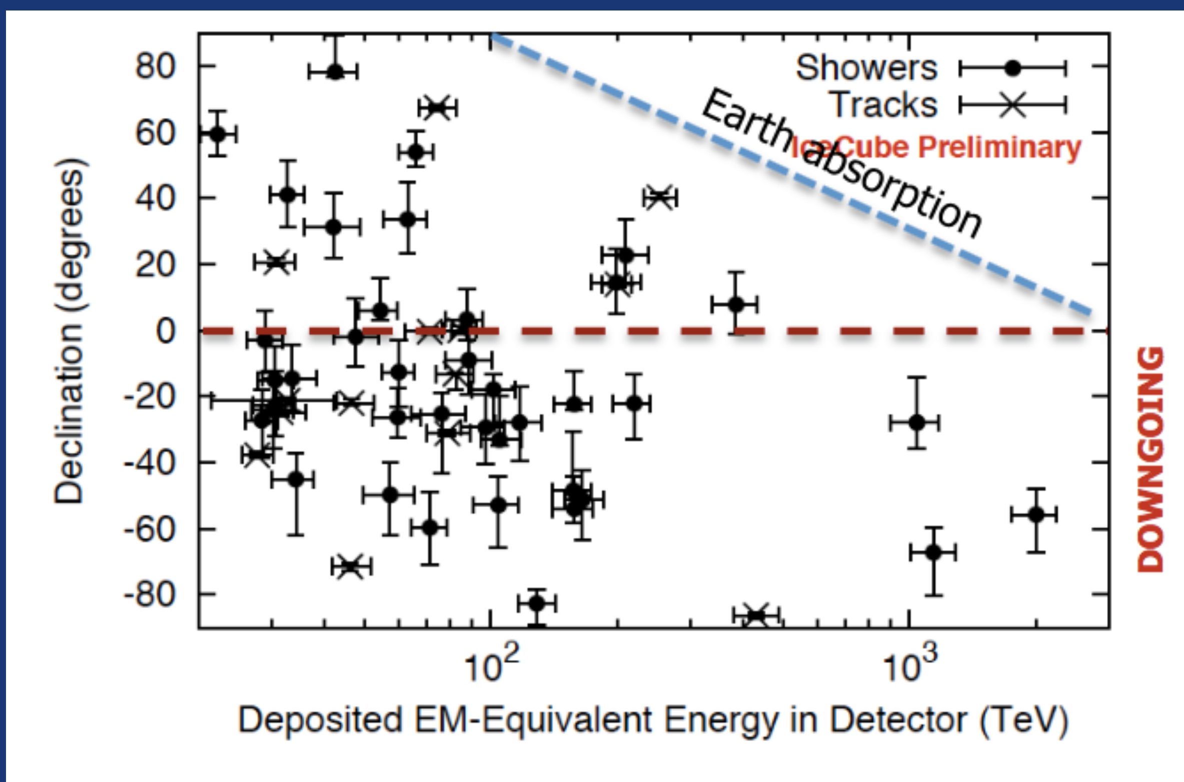
- 37 events in 988 days (3yr)
- Astro. signal dominates at E > 60 TeV
- Significance: 5.7σ

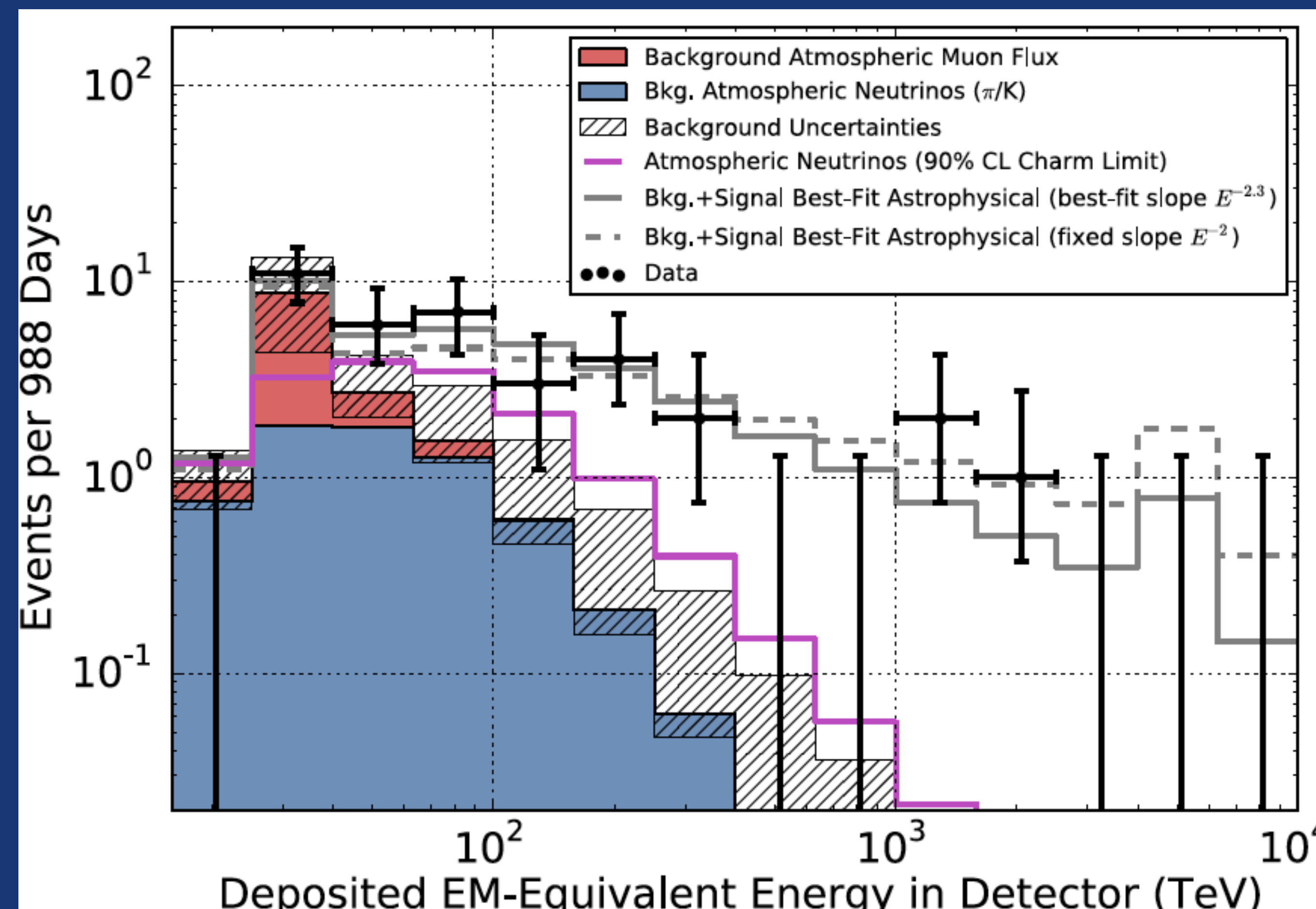


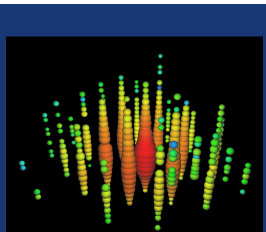
Discovery of Cosmic Neutrinos with IceCube

IC79+IC86 analysis of **2010-2014 data (4 years)** to search for "High Energy Starting Events" (HESE) <u>all-flavor neutrinos</u>

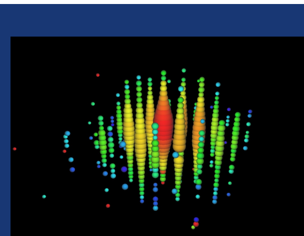
IceCube (4yr) C. Kopper et al, ICRC2015
IceCube (3 yr), Phys. Rev. Lett.; arXiv:1405.5303
IceCube (2 yr), Science 22 Vol. 342 no. 6161



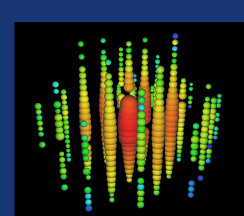




E = 1.0 PeV
Aug. 2011



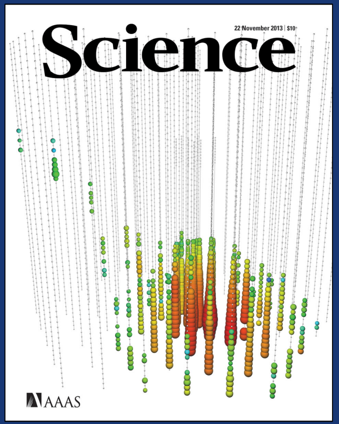
E = 2.0 PeV
Dec 2012



E = 1.1 PeV
Jan 2012

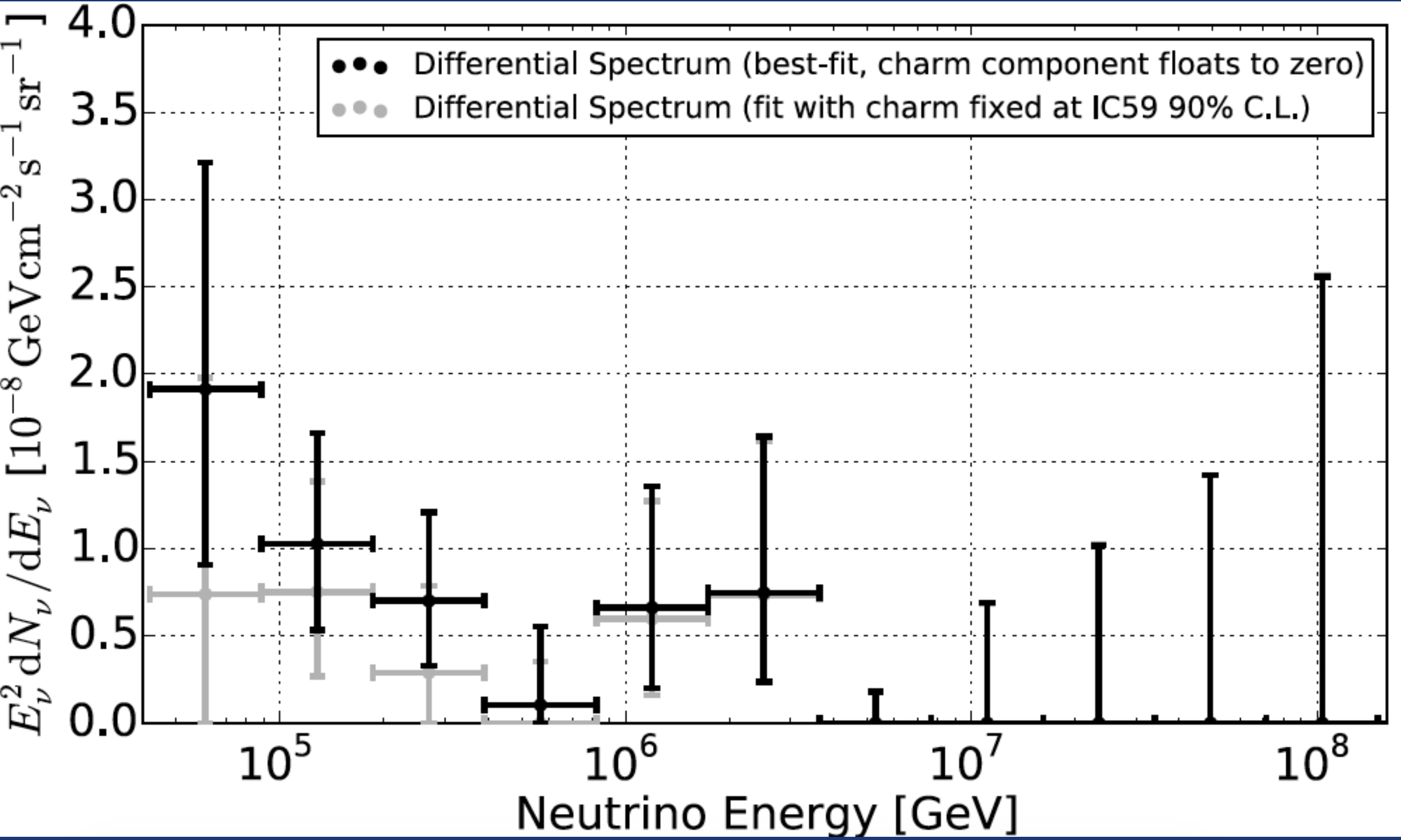
- 54 events in 1347 days (4yr)
- Astro. signal dominates at E > 60 TeV
- Significance: 7σ

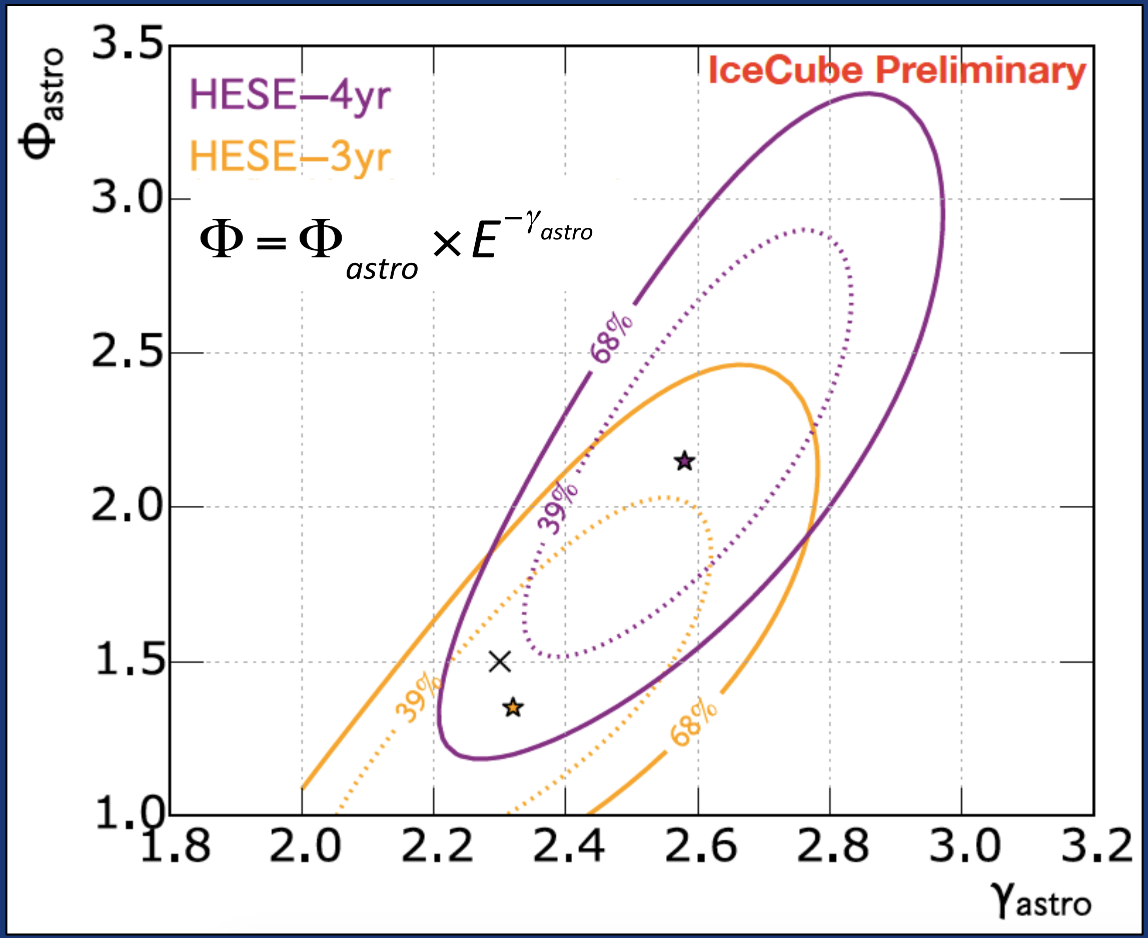
Discovery of Cosmic Neutrinos with IceCube



IC79+IC86 analysis of 2010-2013 data (3 years) to search for "High Energy Starting Events" (HESE) all-flavor neutrinos

IceCube (4yr) C. Kopper et al, ICRC2015
IceCube (3 yr), Phys. Rev. Lett.; arXiv:1405.5303
IceCube (2 yr), Science 22 Vol. 342 no. 6161





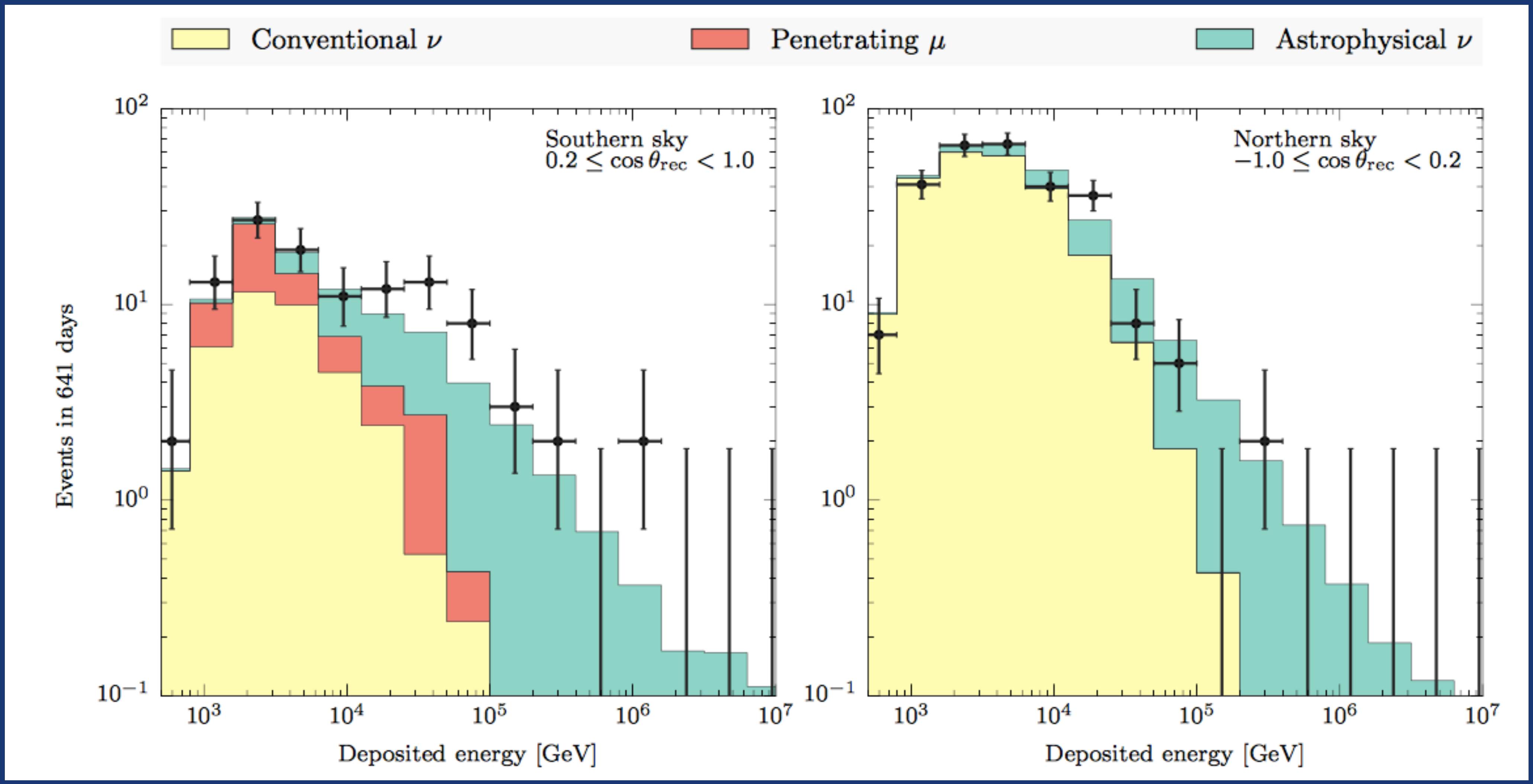
E^{-2} or softer ? (large uncertainties)

Joanna Kiryluk (Stony Brook University), PACIFIC2015

Cosmic Neutrinos at Medium Energies with IceCube

IC79+IC86 analysis of 2010-2012 data (2 years) to search for "Medium Energy Starting Events" (MESE) all-flavor neutrinos

IceCube (2yr): Phys.Rev.D91:022001 (2015)



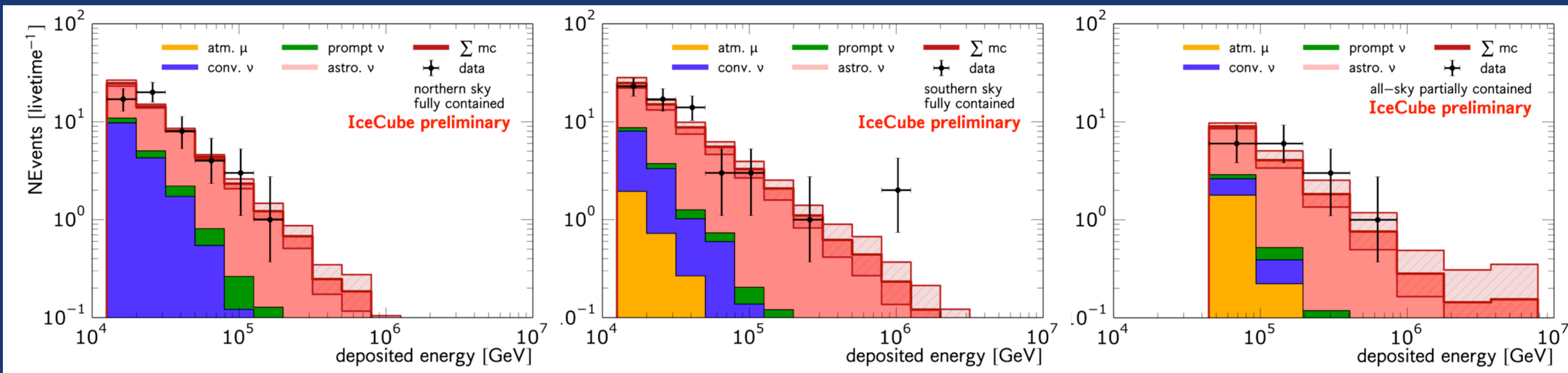
Parameter	Best-fit value	No. of events
Penetrating μ flux	$1.73 \pm 0.40\, \Phi_{\mathrm{SIBYLL+DPMJET}}$	30 ± 7
Conventional ν flux	$0.97^{+0.10}_{-0.03}\, \Phi_{\mathrm{HKKMS}}$	280^{+28}_{-8}
Prompt ν flux	$< 1.52\, \Phi_{\mathrm{ERS}}$ (90% CL)	< 23
Astrophysical Φ_0	$2.06^{+0.35}_{-0.26} \times 10^{-18}$ $\mathrm{GeV^{-1}\, cm^{-2}\, sr^{-1}\, s^{-1}}$	87^{+14}_{-10}
Astrophysical γ	2.46 ± 0.12	

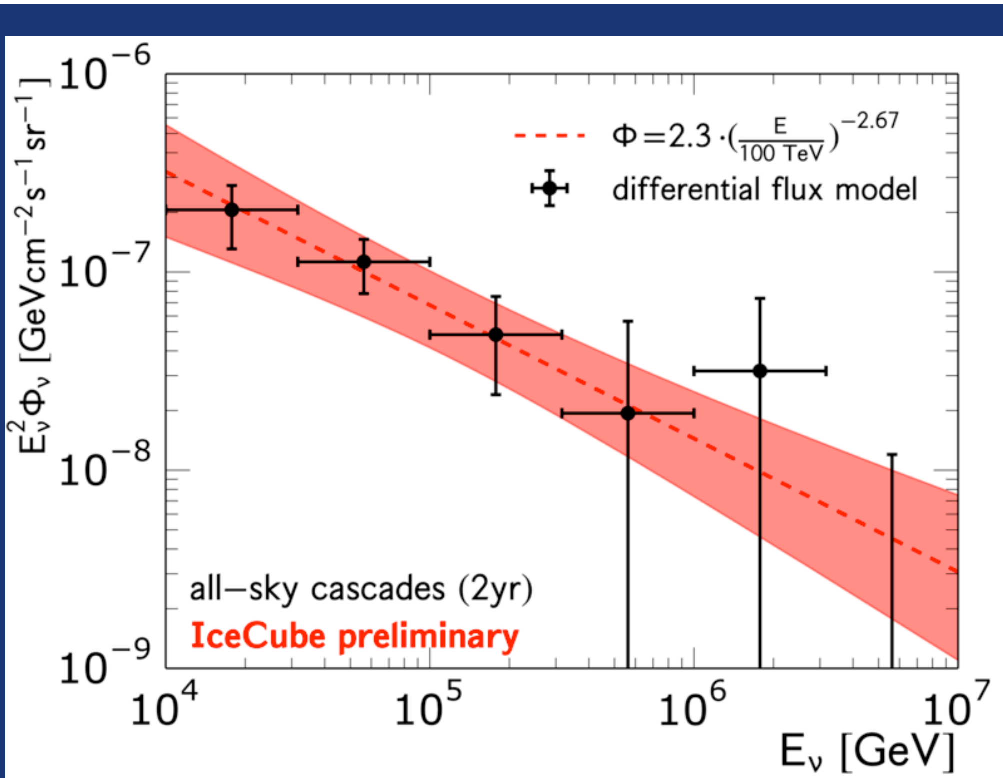
Astrophysical neutrinos remain the dominant component in the Southern sky down to a deposited energy of 10 TeV

IceCube Astrophysical Neutrinos: All-Sky Cascades ($\nu_e+\nu_\tau$)

- IC79+IC86 analysis of 2010-2012 data (2 years), cascades **(contained and partially contained)**

H. Niederhausen et al (IceCube), ICRC2015

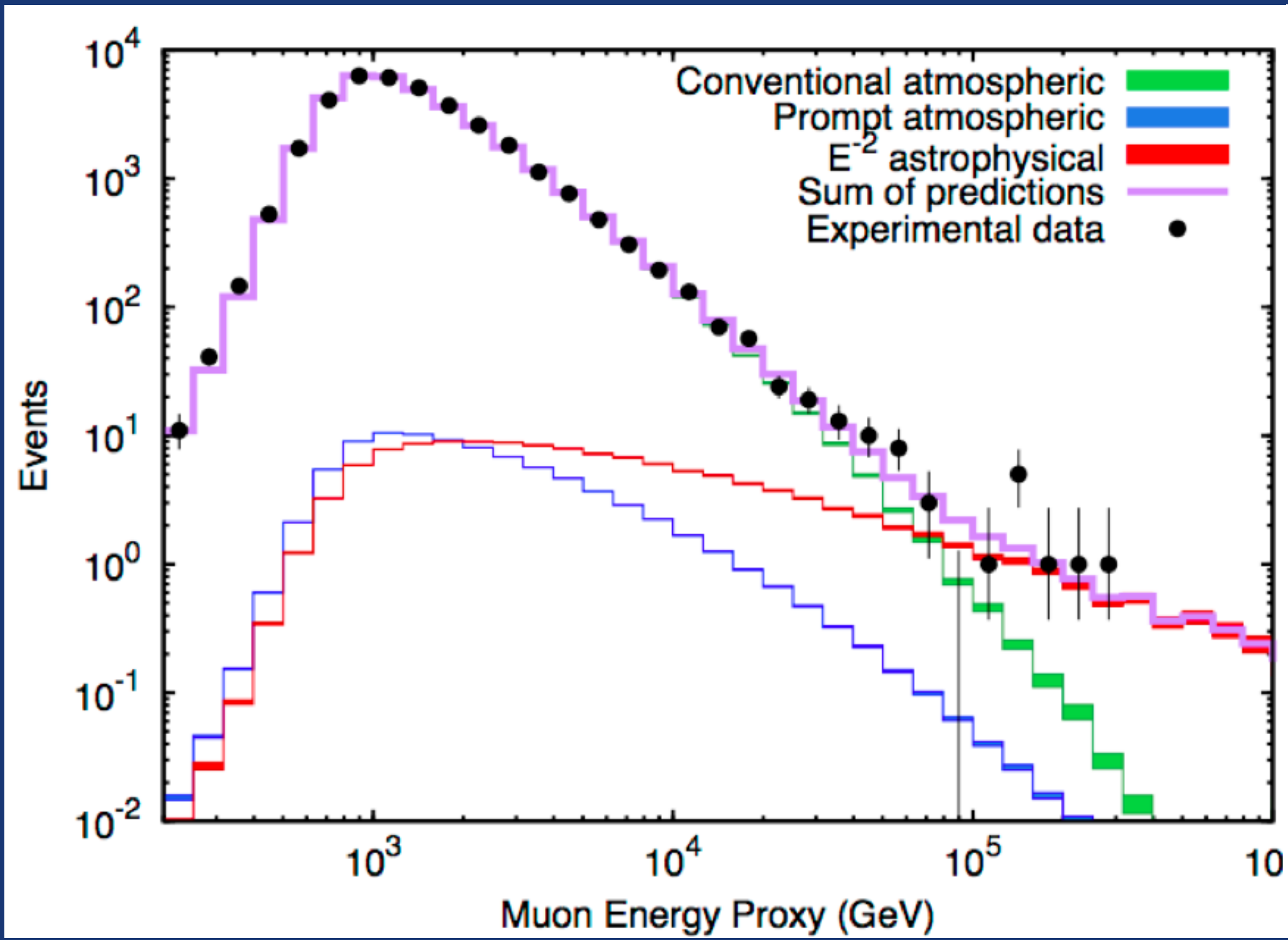


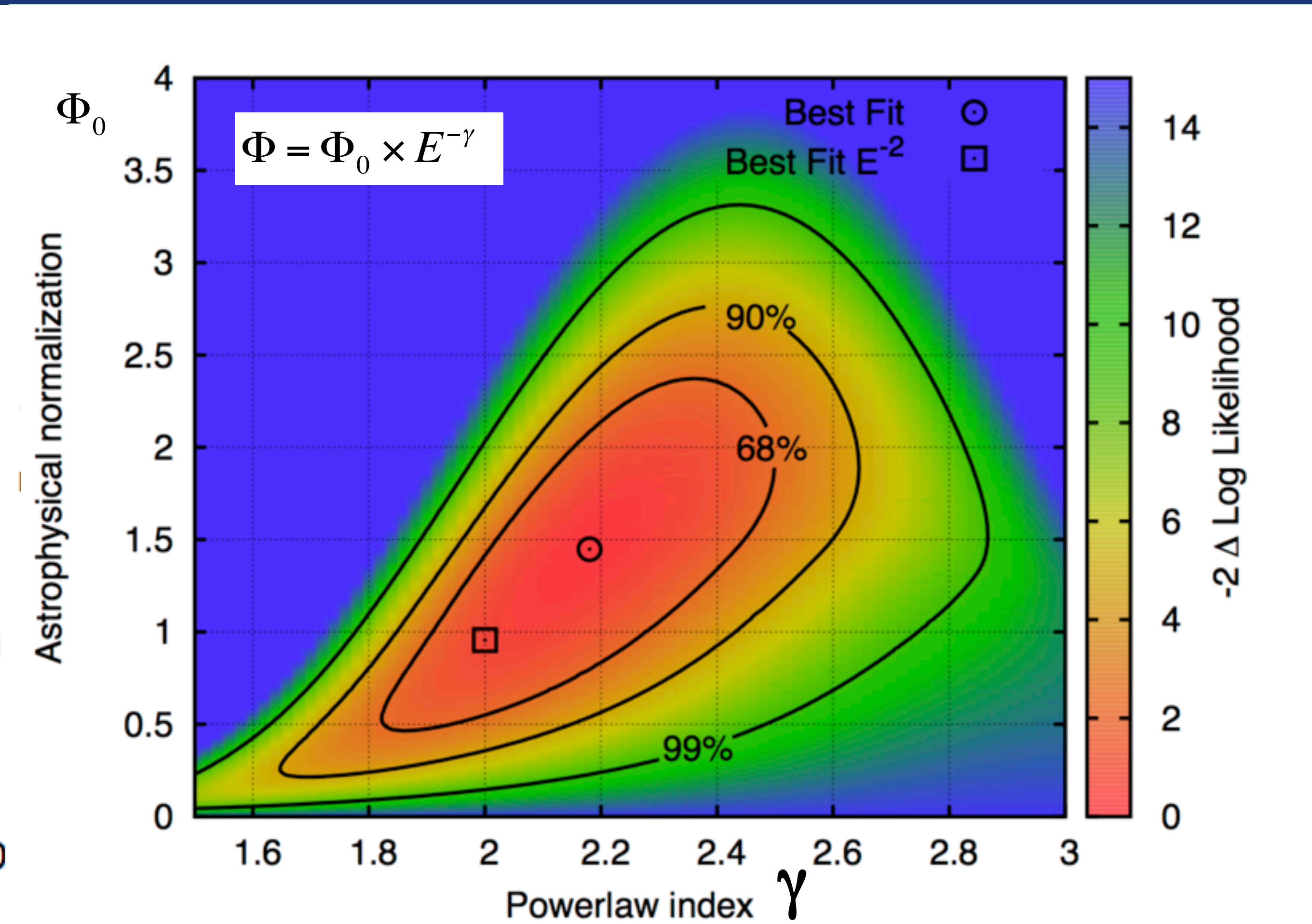


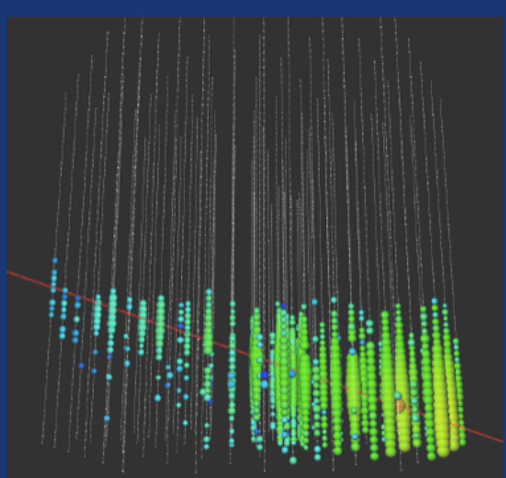
- Observed 172 events (energies 10 TeV – 1 PeV)
  μ bg < 10% , largely uncorrelated with HESE/MESE/LESE
- Bg only hypothesis rejected at 4.7σ
- Soft spectral index $\gamma = 2.67^{+0.12}_{-0.13}$ for astrophysical ν's
- Reject γ = 2.0 at 3.5σ (" E^{-2} without cutoff ")
- Astrophysical ν's: No evidence for deviation from single, unbroken power-law in the cascade channel ($\nu_e+\nu_\tau$)

IceCube Astrophysical Neutrinos: Northern-Sky ν_μ

IC79+IC86 analysis of 2010-2012 data (2 years)
IceCube, PRL (2015)







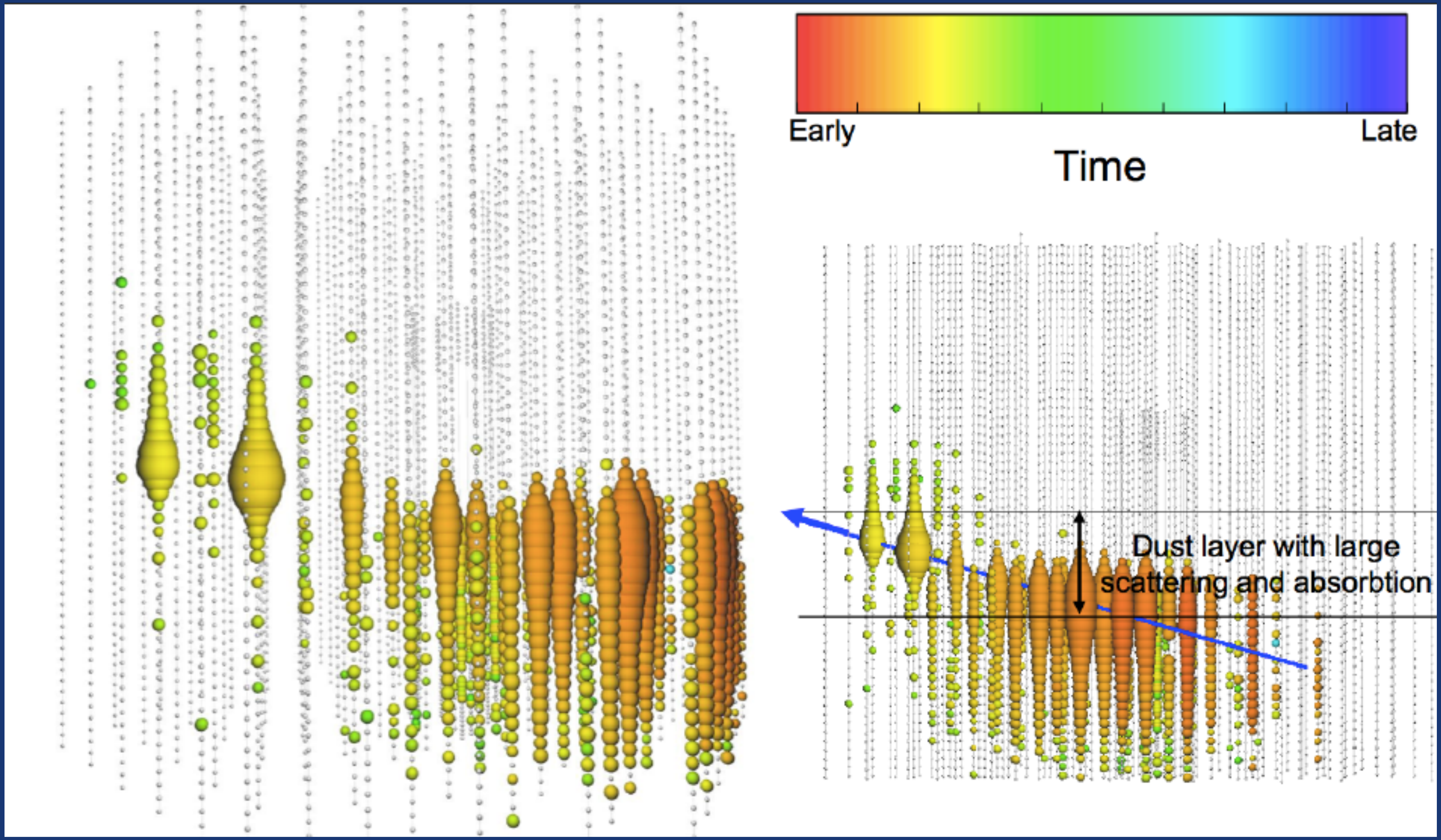
Best-fit E^{-2} result: $E_\nu^2 \cdot \Phi_{astro}(E_\nu) = 1.0 \times 10^{-8}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$

flux normalizations only

Flux consistent with other IceCube results (all-sky)
Background only hypothesis disfavored at 3.9σ

IceCube Astrophysical Neutrinos: Northern-Sky ν_μ

L. Radel, S. Schonen (for the IceCube collab.) ICRC2015



- date: June 11, 2014
- deposited energy: 2.6 ± 0.3 PeV (lower limit on ν energy)
- direction: 11.48° dec / 110.34° RA

Outside
GCN
IAUCs

Other
ATel on Twitter and Facebook
ATELstream
ATel Community Site
MacOS: Dashboard Widget

The Astronomer's Telegram

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15 Sep 2015; 03:17 UT

This space for free for your conference.

[Previous | Next | ADS]

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; ***Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration***
*on **29 Jul 2015; 20:47 UT***
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

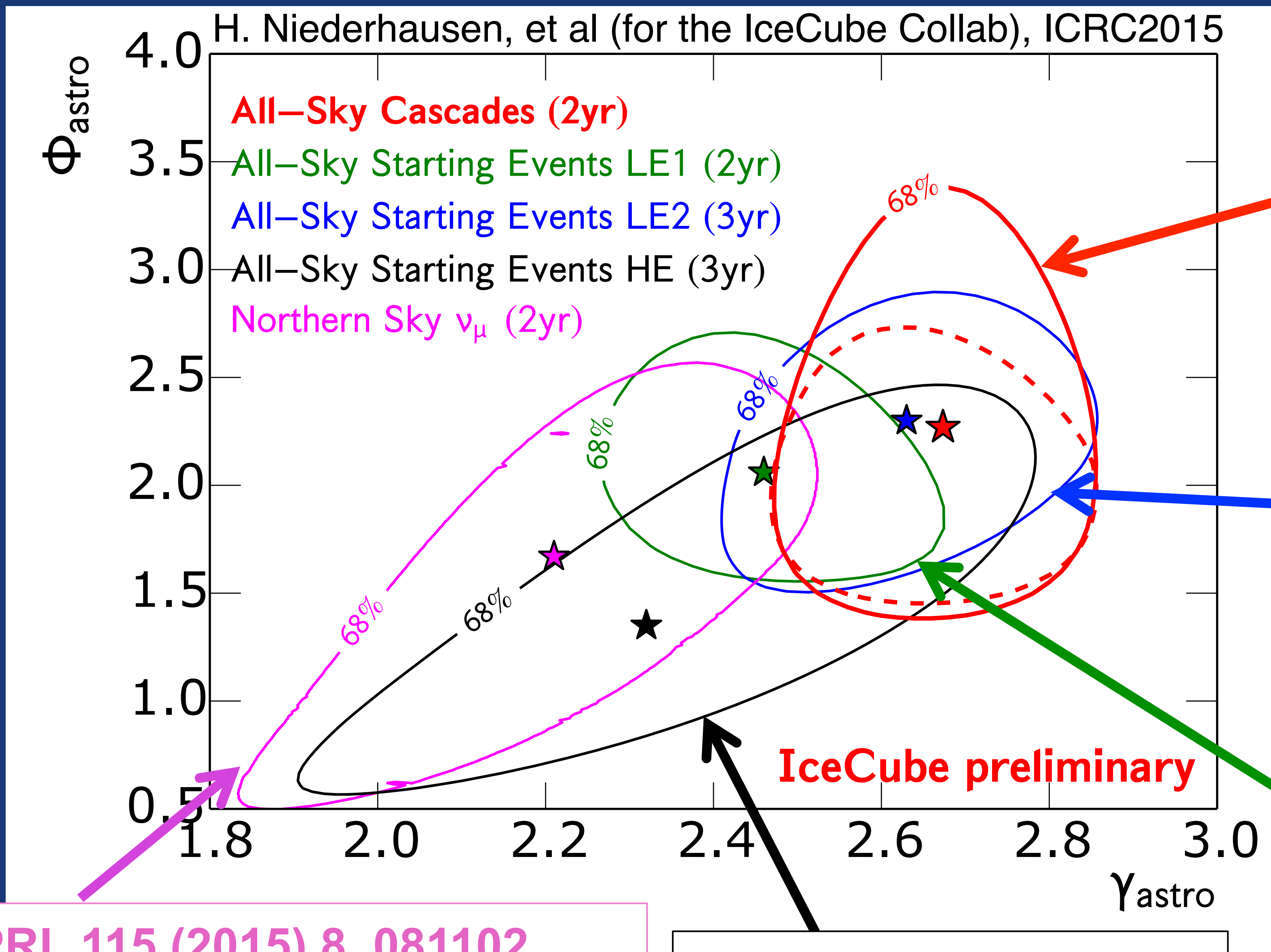
We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)

Related

7868	HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event
7856	Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

[**Telegram Index**]

IceCube Astrophysical Neutrinos: Flux Results Comparison



IceCube Preliminary
H. Niederhausen et at
ICRC2015 proc.
Cascades ($\nu_e + \nu_\tau$)

PRL114, 171102 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

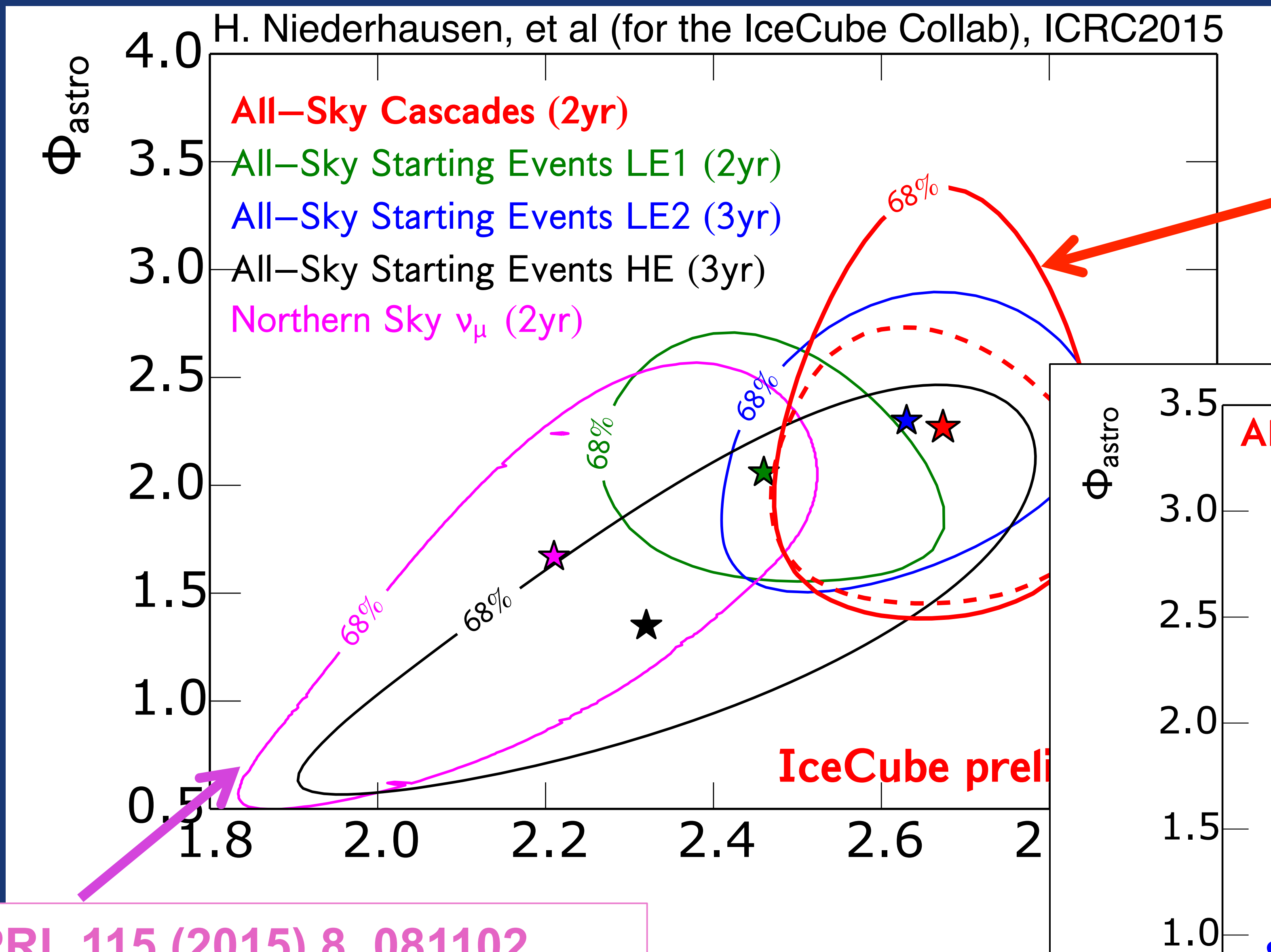
PRD 91, 022001 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

PRL 115 (2015) 8, 081102
ν_μ (Northern Sky only)

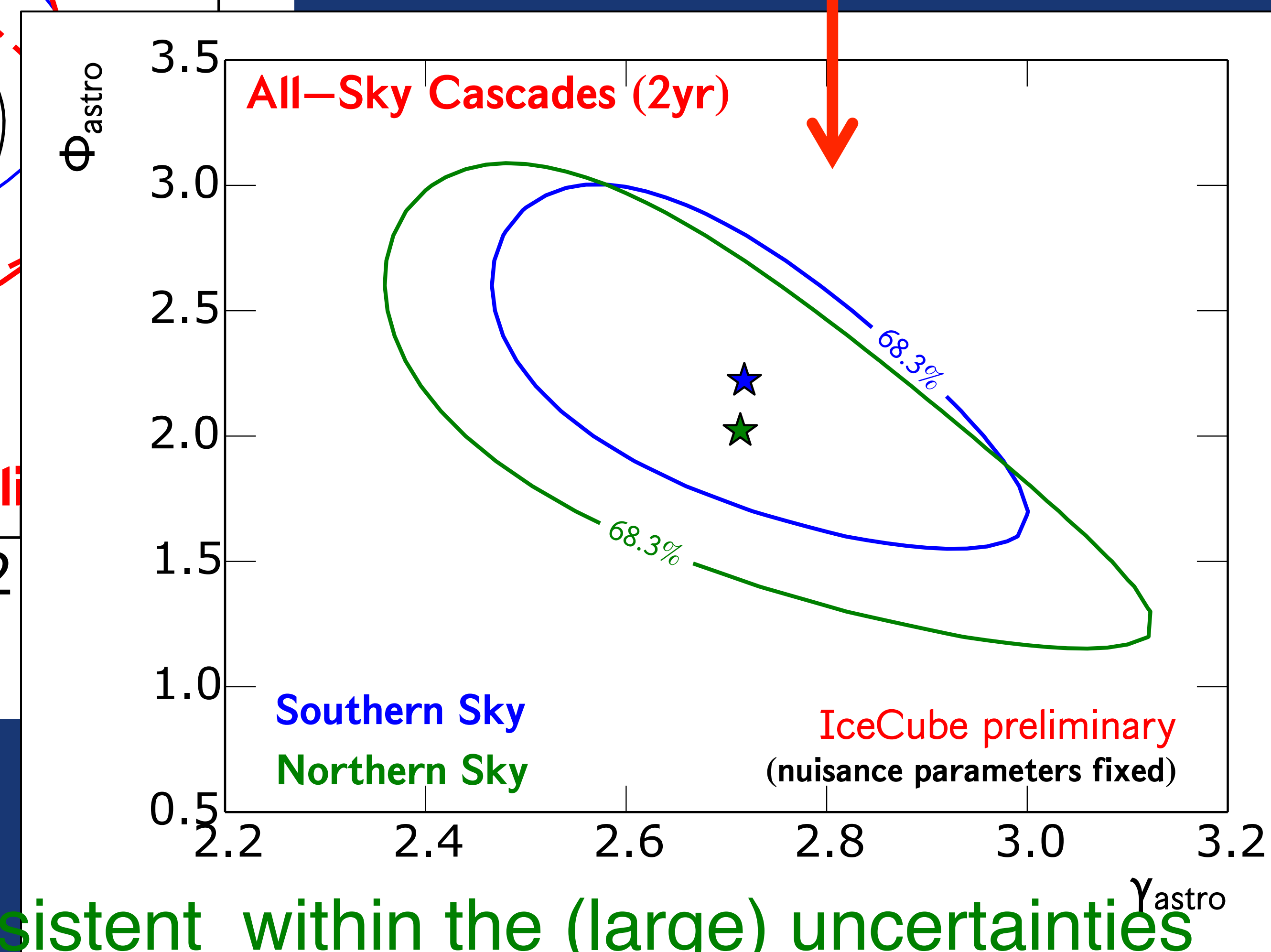
PRL 113, 101101 (2014)
$\nu_e + \nu_\mu + \nu_\tau$

IceCube Diffuse ν results consistent
Insignificant < 2σ tension between cascade result with northern sky ν_μ results

IceCube Astrophysical Neutrinos: Flux Results Comparison



IceCube Preliminary
H. Niederhausen et at
ICRC2015 proc.
Cascades ($\nu_e + \nu_\tau$)



PRL 115 (2015) 8, 081102
ν_μ (Northern Sky only)

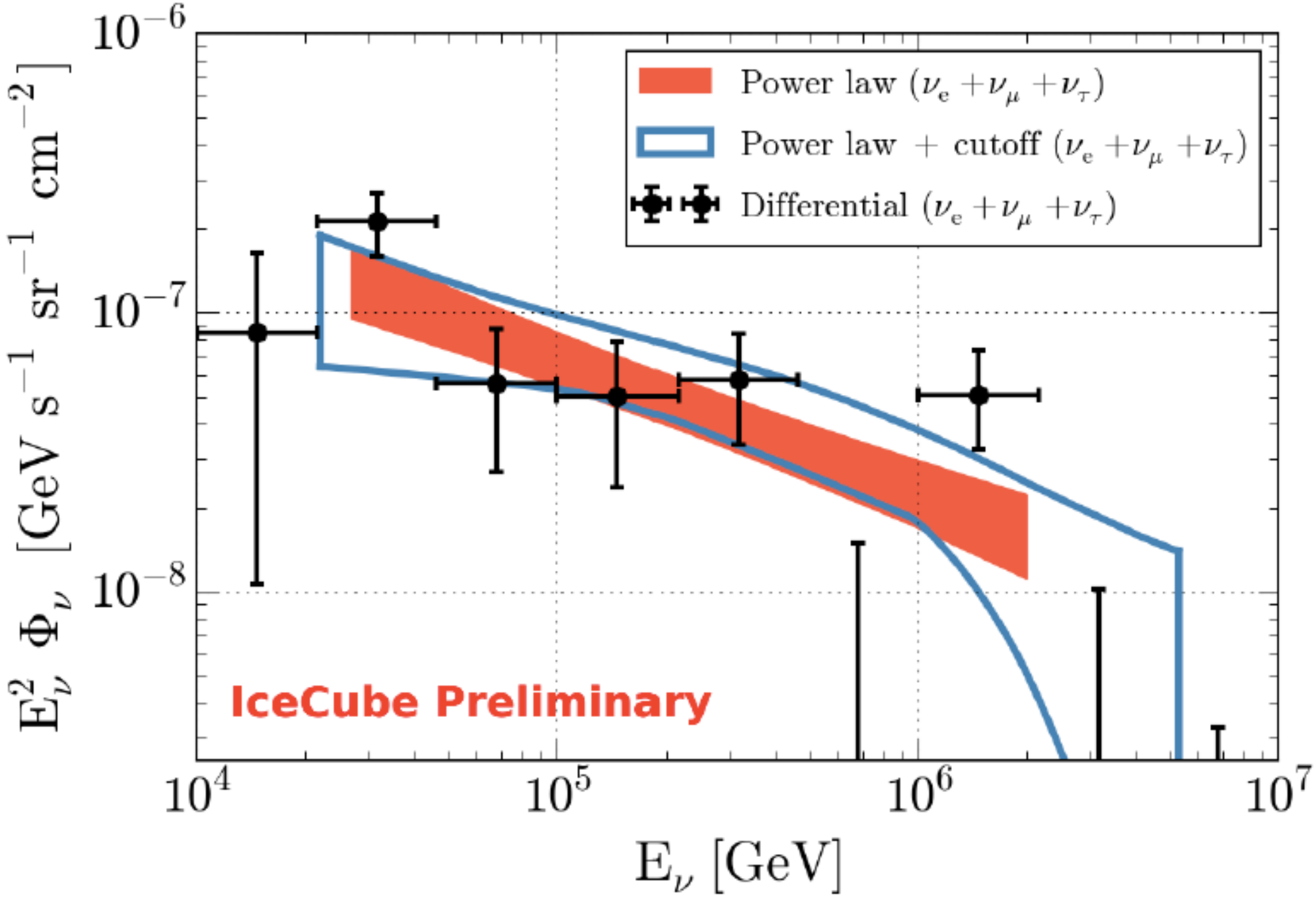
($\nu_e + \nu_\tau$) North/South Fits consistent within the (large) uncertainties
… as expected from an isotropic extragalactic neutrino flux

IceCube Astrophysical Neutrinos: Global Fit

IceCube diffuse ν results consistent → combine 8 analyses in the global fit

L. Mohrmann, (for the IceCube collab.) ICRC2015; IceCube ApJ 809 (2015), 98

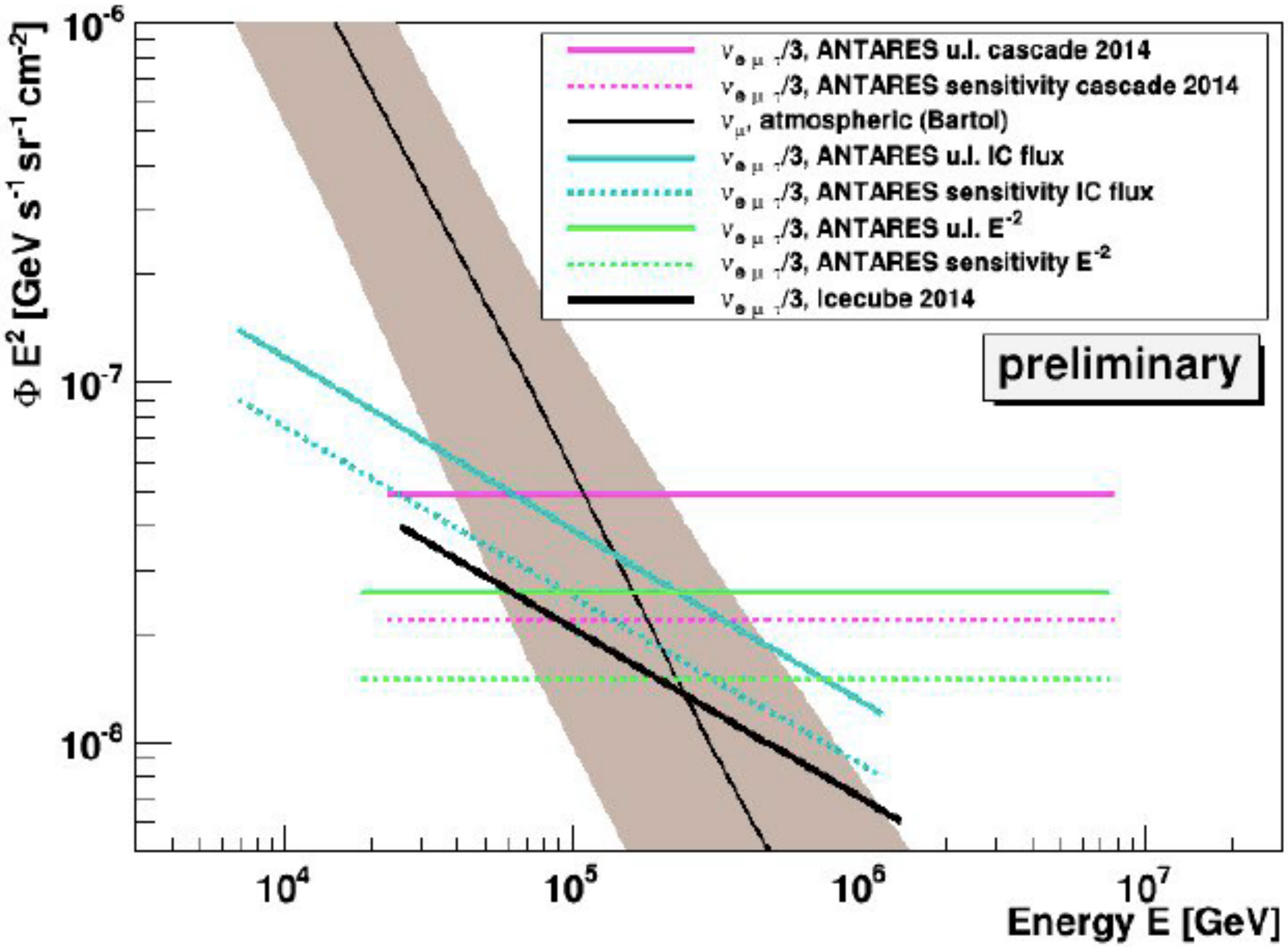
Assume isotropic flux and $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$



Antares Astrophysical Neutrinos

J. Schnabel (Antares) ICRC2015 (ID 483)

Diffuse flux search: tracks + cascades



- Expected:
  - 9.5 ± 2.5 bkgd
  - 5.0 ± 1.1 IC flux
- Observed:
  - 12 events
- Results:
  - Consistent w bkgd
  - Consistent w IC

Astrophysical Neutrinos: Flavor composition

$(f_e : f_\mu : f_\tau)_S$ at Source:

□ (0 : 1 : 0)
○ (1 : 2 : 0)
△ (1 : 0 : 0)

Sources

$$p+\gamma \rightarrow \Delta^+ \rightarrow n+\pi^+$$

$$p+p \rightarrow N\left[\pi^0+\pi^++\pi^-\right]+X$$

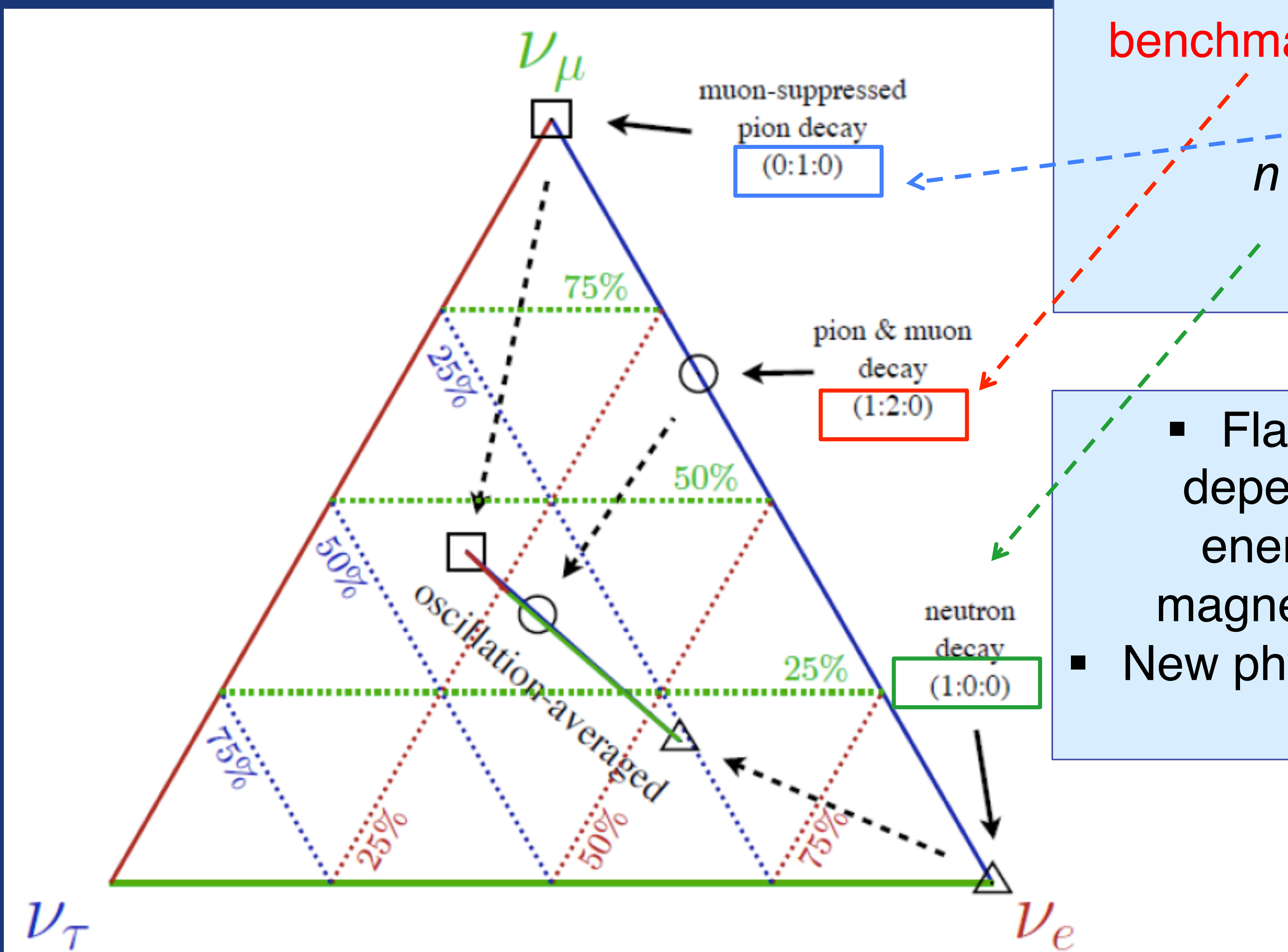
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \left(e^+ + \nu_e + \bar{\nu}_\mu\right) + \nu_\mu$$

benchmark model $(f_e : f_\mu : f_\tau)_S = (1 : 2 : 0)$

$(f_e : f_\mu : f_\tau)_S = (0 : 1 : 0)$ *Synchrotron cooling*

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

$(f_e : f_\mu : f_\tau)_S = (1 : 0 : 0)$

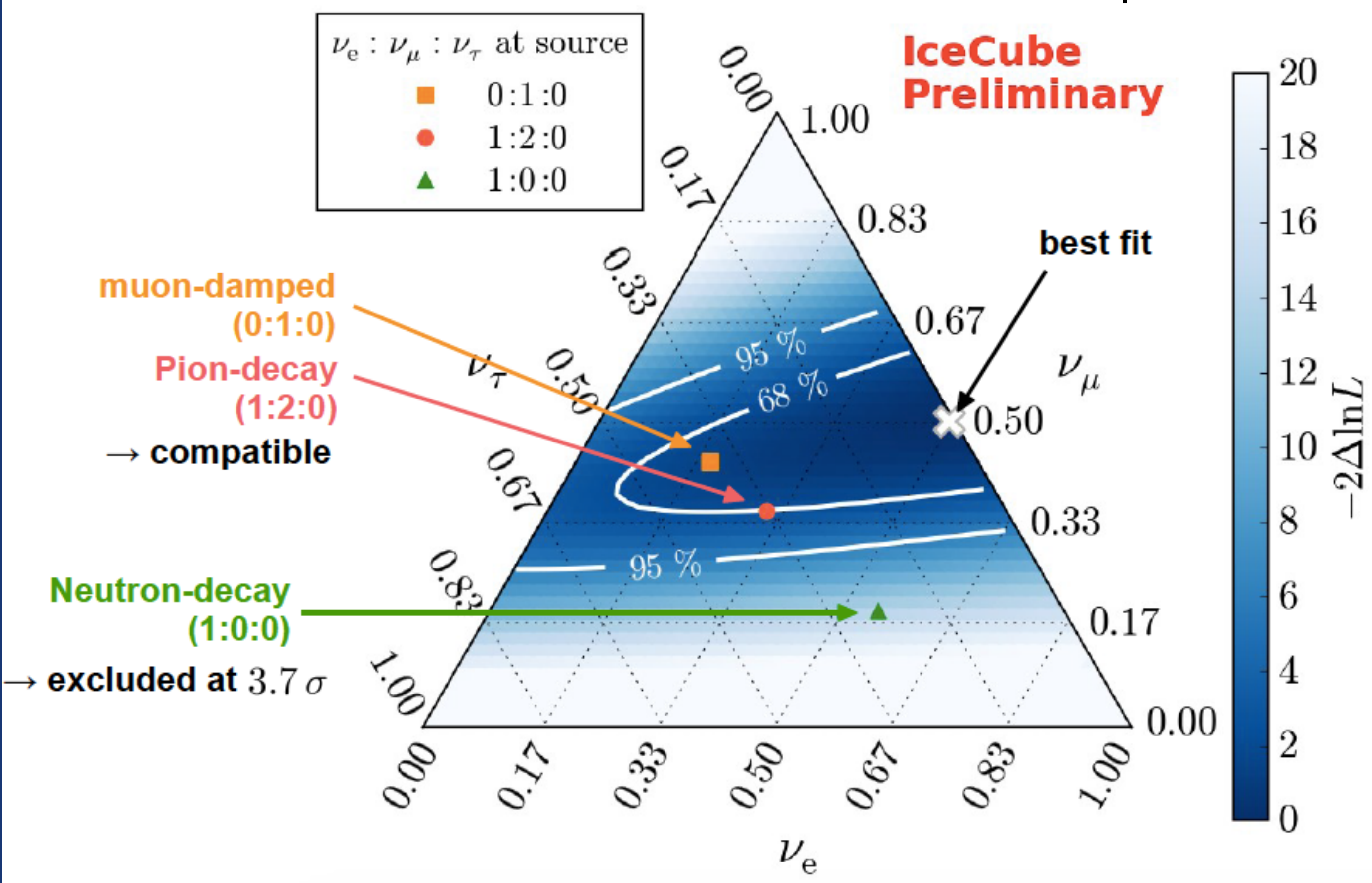


- Flavor composition likely energy dependent, may provide insight into energy losses of π's and μ's in the magnetic fields of cosmic accelerators
- New physics in neutrino propagation may modify flavor composition

IceCube Astrophysical Neutrinos: Flavor composition

L. Mohrmann, (for the IceCube collab.) ICRC2015; IceCube ApJ 809 (2015), 98
IceCube: Phys.Rev.Lett. 114 (2015) 17, 171102

The exclusion regions for astrophys. ν flavor ratios $(f_e:f_\mu:f_\tau)_\oplus$ at Earth

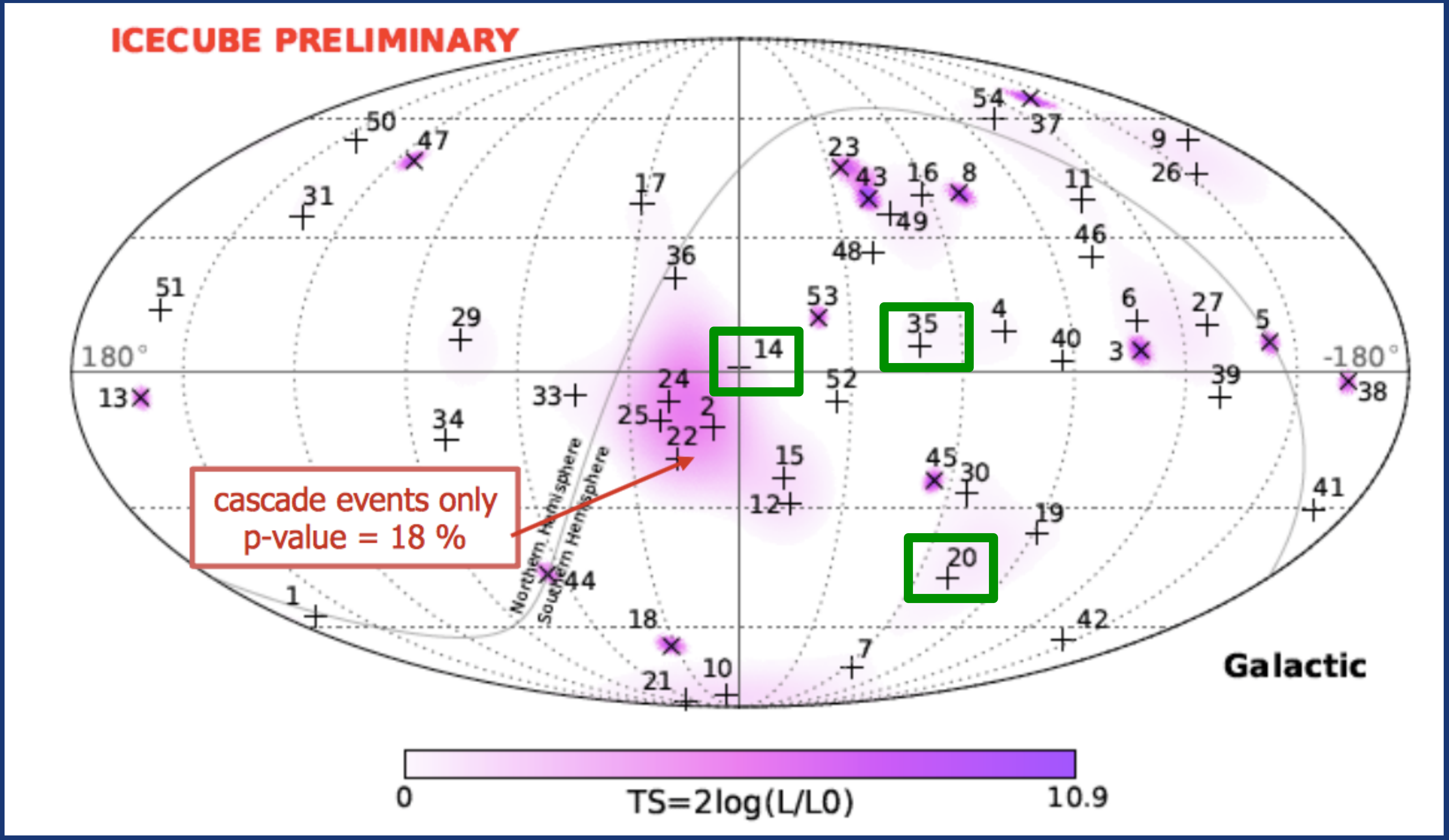


The limits are consistent (at < 68% CL) with $(1:1:1)_\oplus$ flavor ratio at Earth, expected from the averaged oscillations of ν's produced by π's decay in astrophysical sources

Astrophysical Neutrinos: Where do they come from?

IC79+IC86 analysis of 2010-2014 data (4 years) to search for "High Energy Starting Events" (HESE) all-flavor neutrinos

IceCube (4yr) C. Kopper et al, ICRC2015
Observed 54 events (tracks and cascades)



- Significance of the warm spot has decreased 3yr → 4yr (p-value 7% → 18%)
- No evidence of (significant) correlation (neither spacial nor temporial e.g. GRB's)

Astrophysical Neutrinos: Where do they come from?

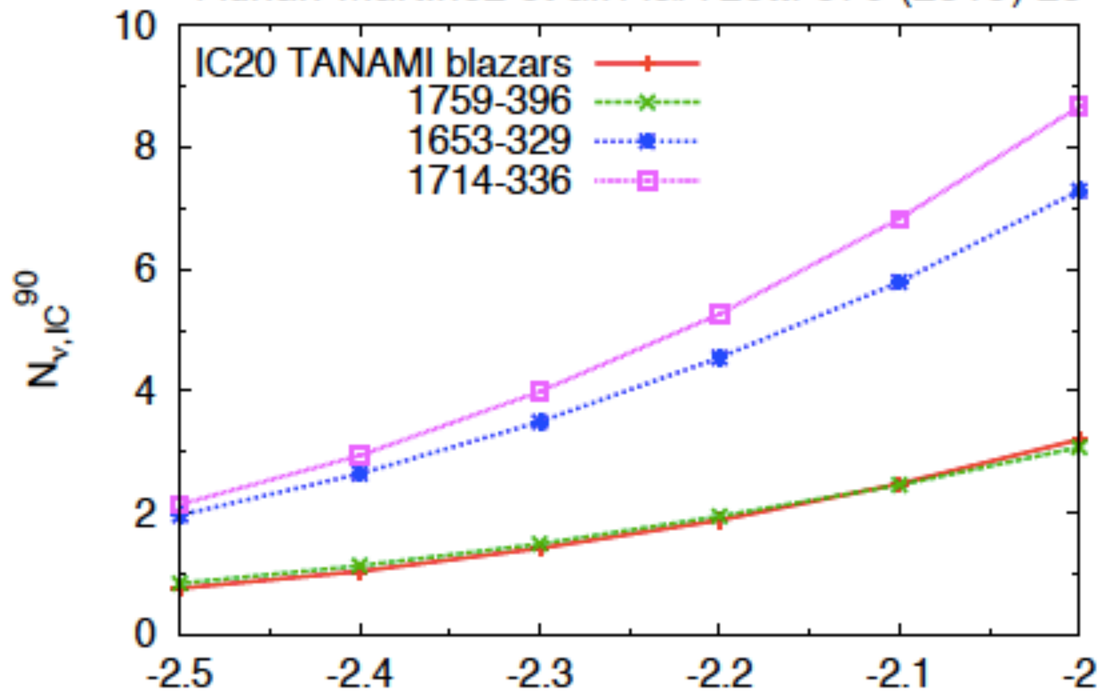
Can blazars produce the HESE PeV events?

- TANAMI multi-wavelength collaboration:
  - Six bright blazars identified with Bert (IC 14) and Ernie (IC 20)

Krauß, F. et al., 2014, A&A 566, L7

Source	F_γ [GeV cm^{-2} s^{-1}]	N_{ν_e}	IC
0235–618	$(6.2^{+3.1}_{-3.1}) \times 10^{-8}$	$0.19^{+0.04}_{-0.04}$	20, 7
0302–623	$(2.1^{+0.4}_{-0.4}) \times 10^{-8}$	$0.06^{+0.01}_{-0.01}$	20
0308–611	$(4.7^{+1.8}_{-1.8}) \times 10^{-8}$	$0.14^{+0.05}_{-0.05}$	20
1653–329	$(2.8^{+0.3}_{-0.3}) \times 10^{-7}$	$0.86^{+0.10}_{-0.10}$	14, 2, 25
1714–336	$(1.5^{+0.3}_{-0.4}) \times 10^{-7}$	$0.46^{+0.10}_{-0.12}$	14,2,25
1759–396	$(7.5^{+1.9}_{-1.9}) \times 10^{-8}$	$0.23^{+0.50}_{-0.40}$	14, 2, 15, 25

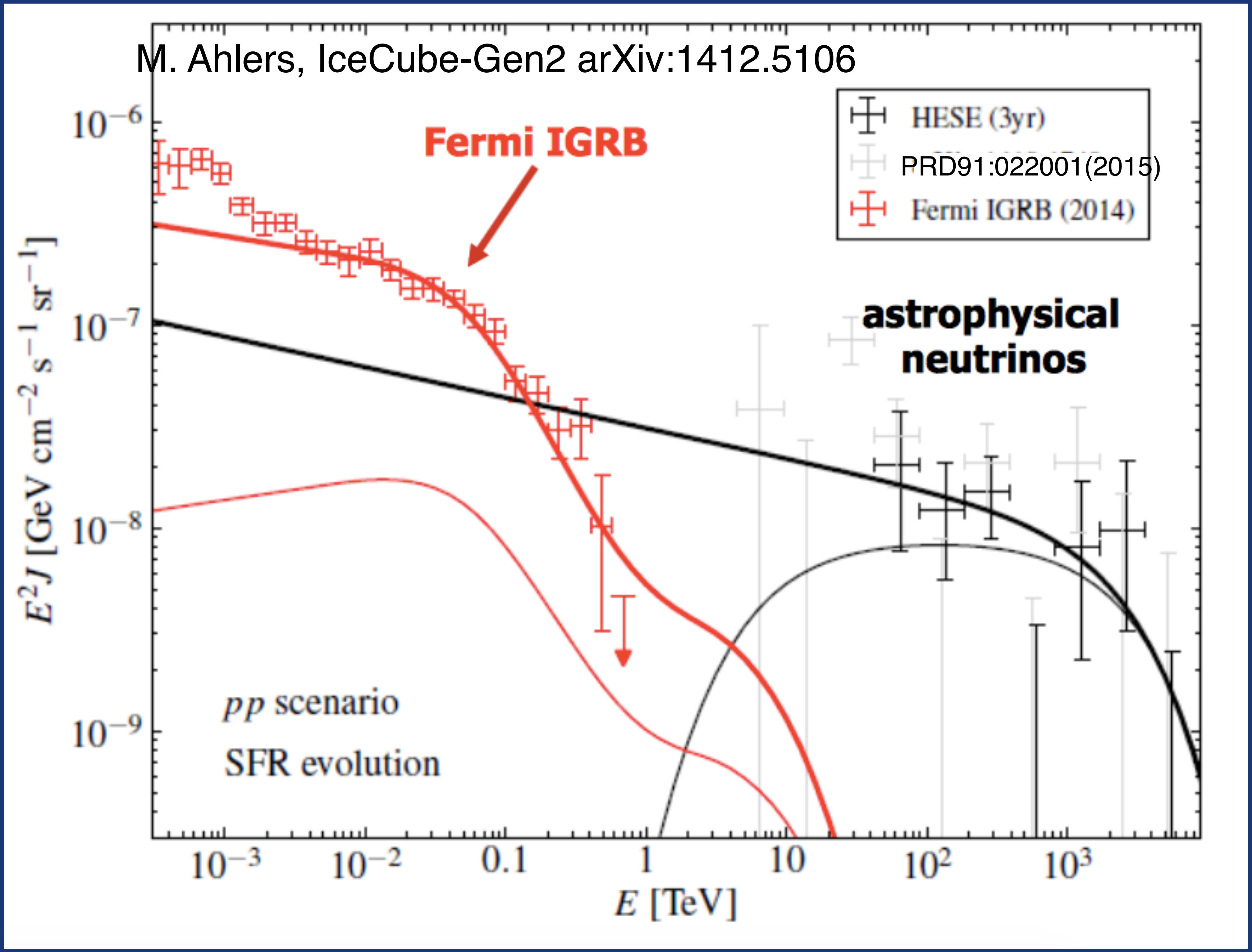
Adrián-Martínez et al. A&A Lett. 576 (2015) L8



Results. Both blazars predicted to be the most neutrino-bright in the TANAMI sample (1653−329 and 1714−336) have a signal flux fitted by the likelihood analysis corresponding to approximately one event. This observation is consistent with the blazar-origin hypothesis of the IceCube event IC 14 for a broad range of blazar spectra, although an atmospheric origin cannot be excluded. No ANTARES events are observed from any of the other four blazars, including the three associated with IceCube event IC20. This excludes at a 90% confidence level the possibility that this event was produced by these blazars unless the neutrino spectrum is flatter than −2.4.

- Antares sees no events from IC35: M. Dadler (IC 1424)

Multi-messenger astronomy

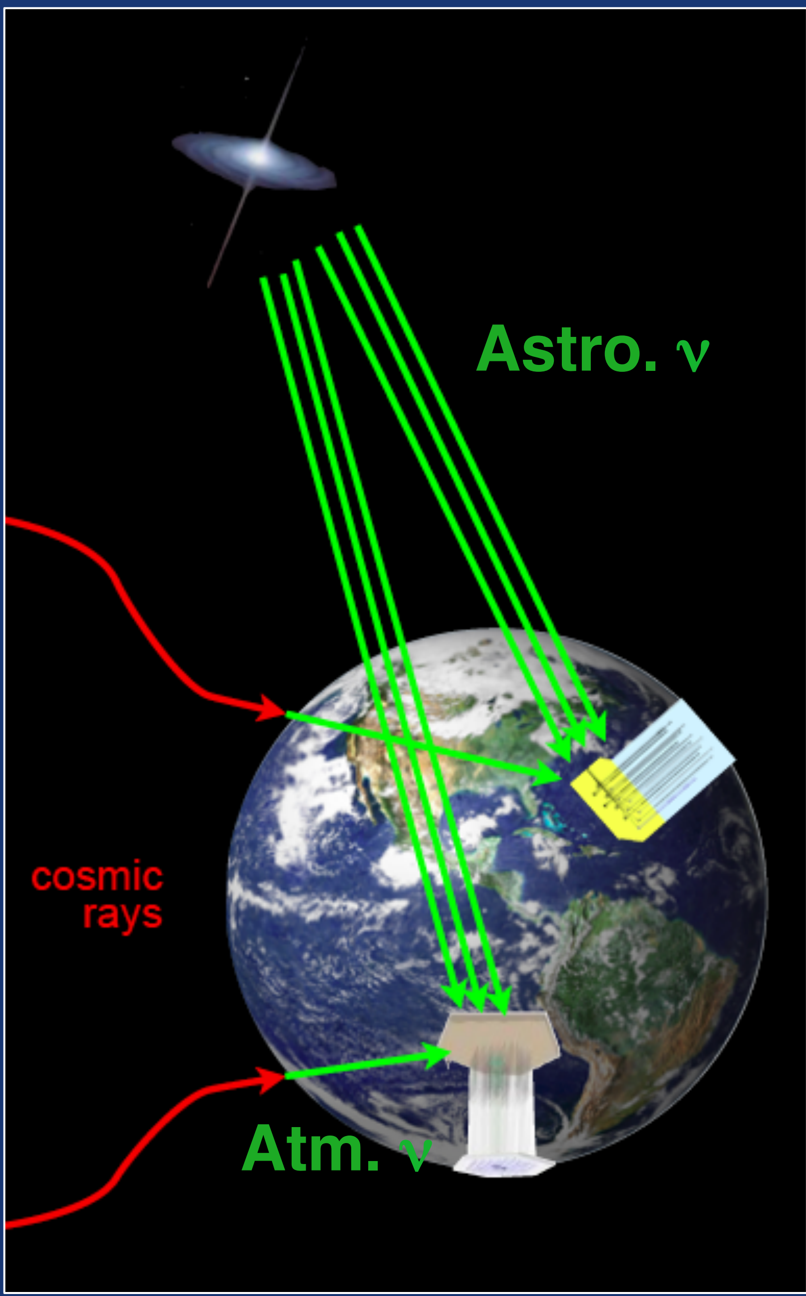


Level of astrophys. ν's compatible with IGRB (Isotropic Gamma Ray Background) measured by Fermi

Hadronic (pp) cosmic accelerators emitting comparable energy in γ's and ν's

Point Source Neutrino Search (ν_μ)

All-Sky search: Search for excess of astrophysical ν from a common direction over the background of atmospheric ν (IceCube: Northern Sky) or μ (IceCube: Southern Sky)

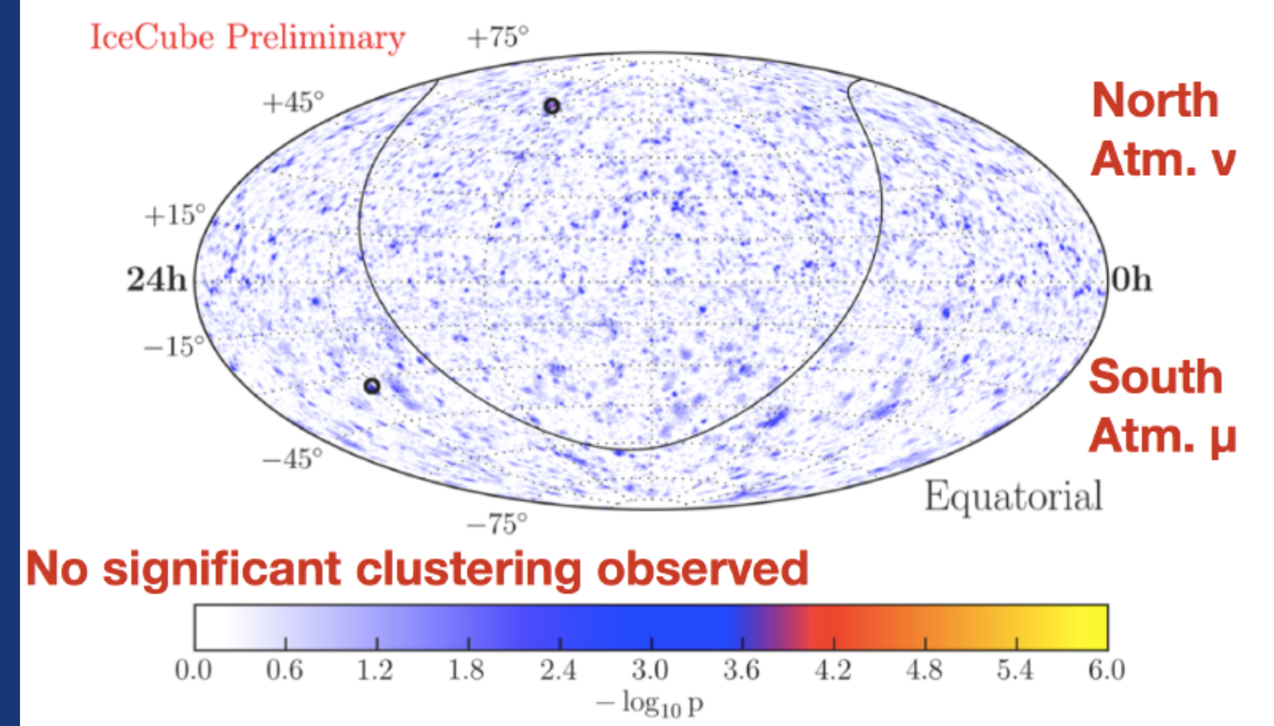


IceCube:

6yr data (2008-2014)
Hottest spots: not significant

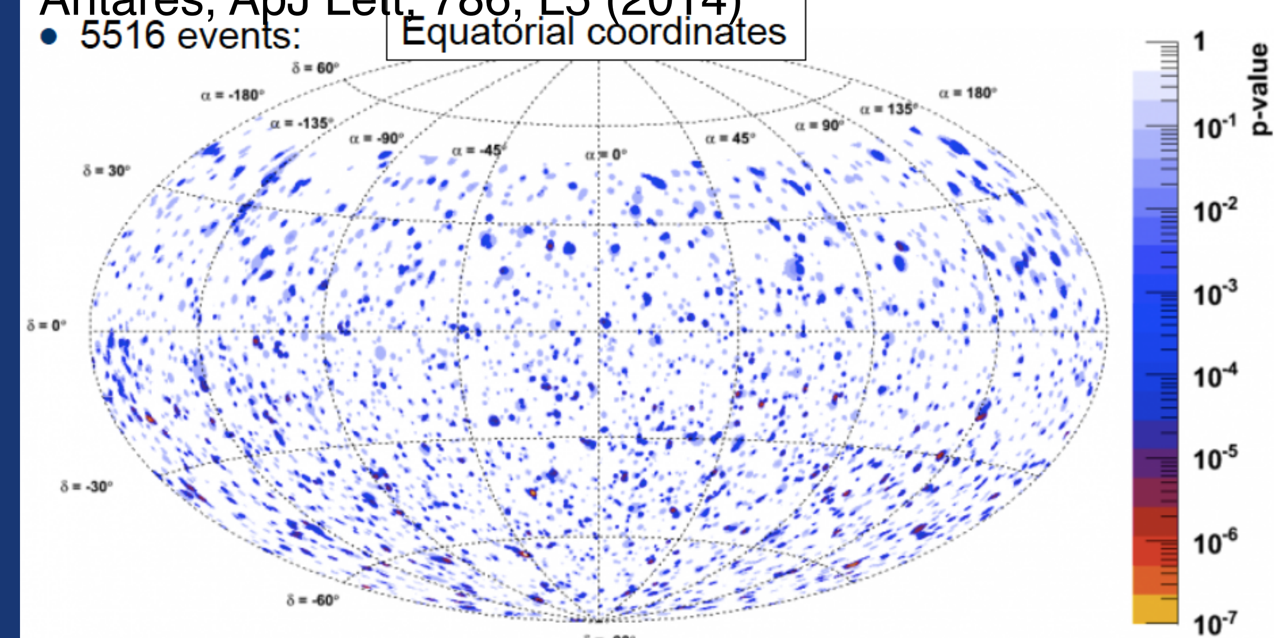
e.g. Northers Sky: 35 % of trials have significance > hottest spot

S. Coenders (IceCube) ICRC2015



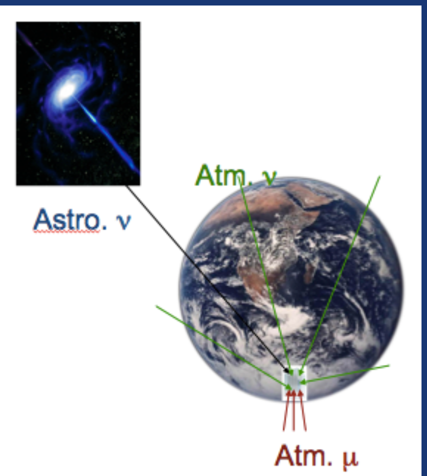
Antares:

Antares, ApJ Lett. 786, L5 (2014)



… a mostly uniform structure …

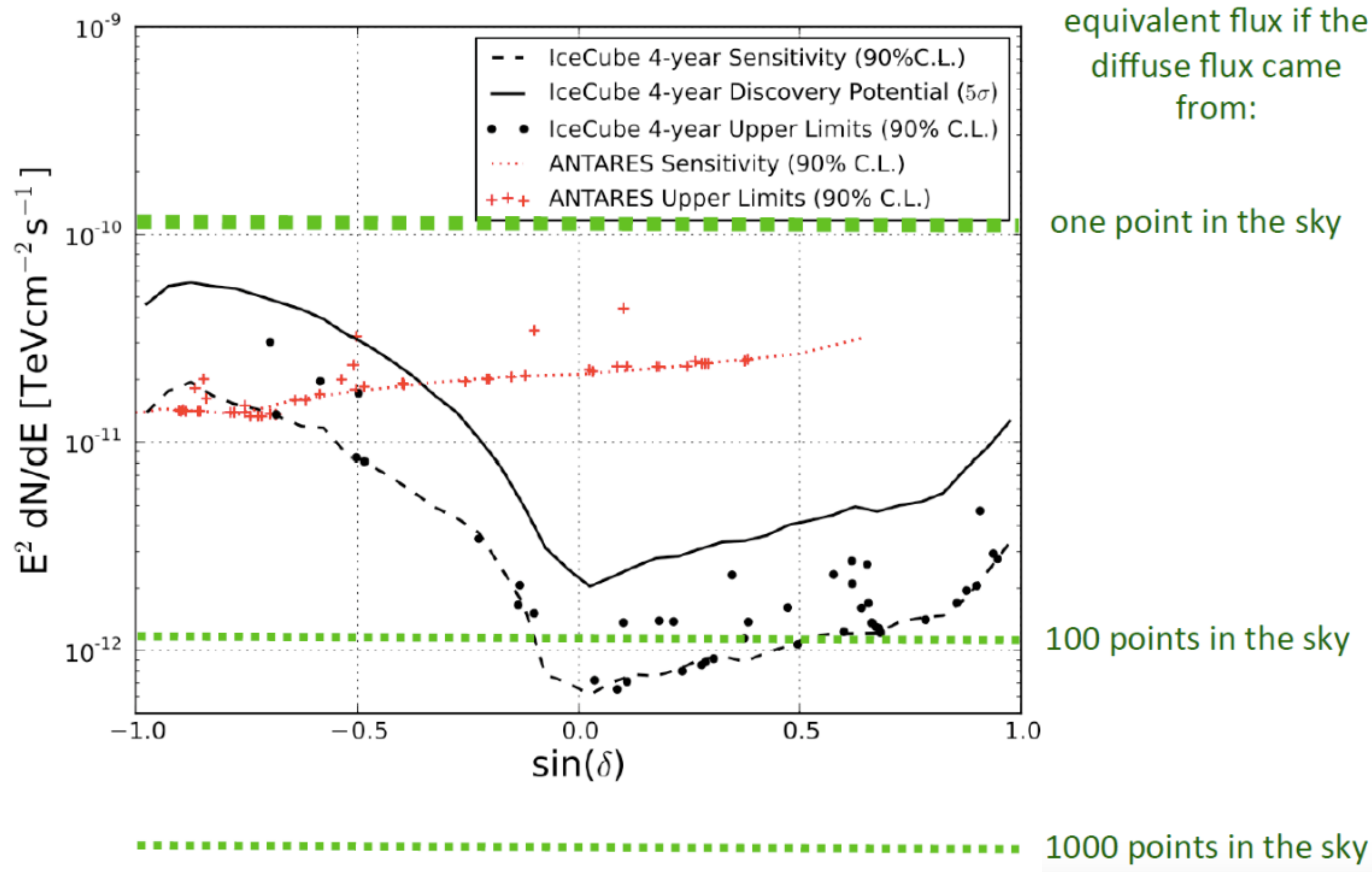
Point Source Neutrino Search (ν_μ)



Search for excess of astrophysical ν from a common direction over the background of atmospheric ν (Northern Sky) or μ (Southern Sky)

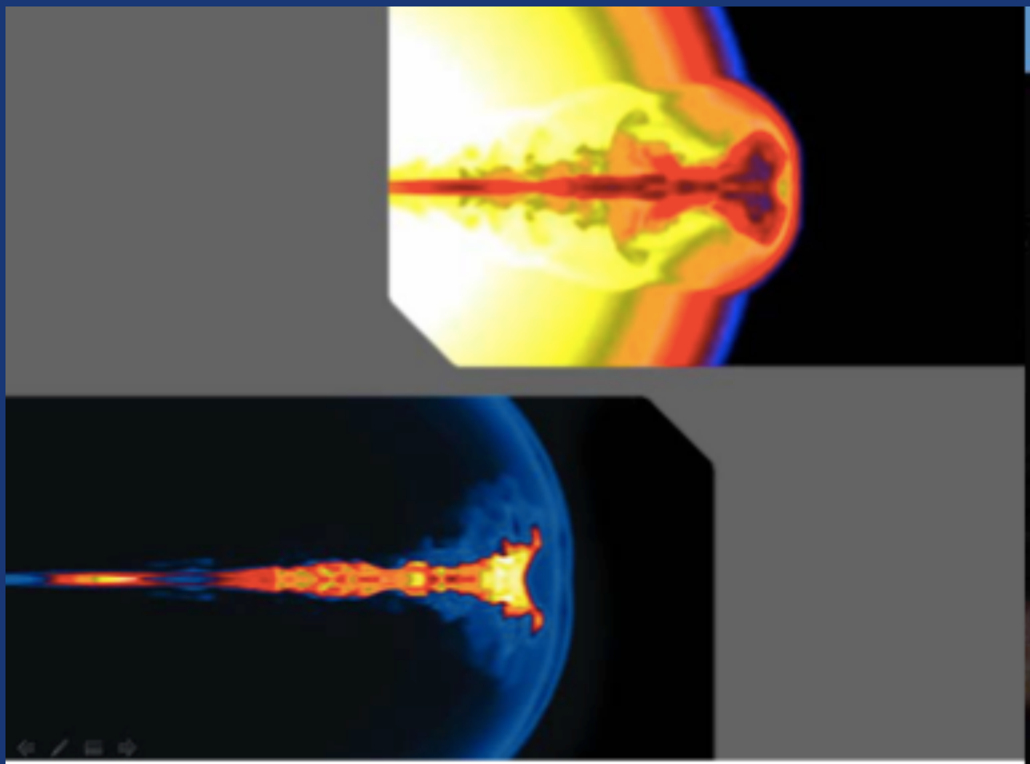
IceCube, Astrophys.J. 796:109 (2014) (4 years of data)

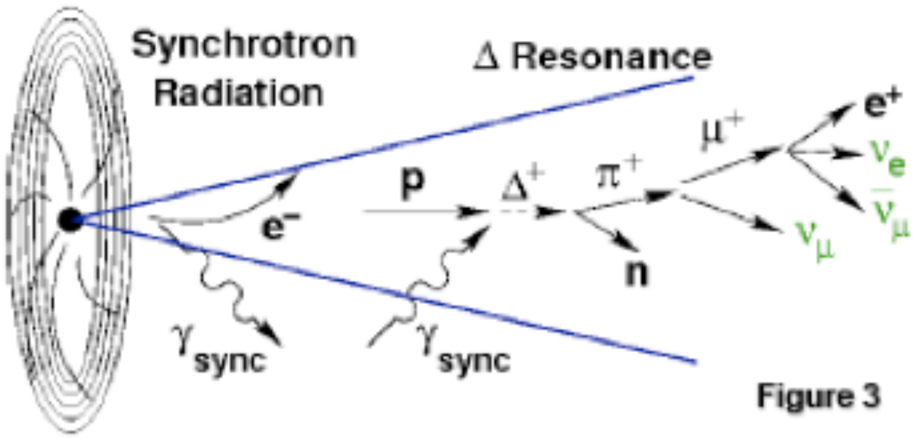
Point-source equivalent flux if the diffuse flux came from:

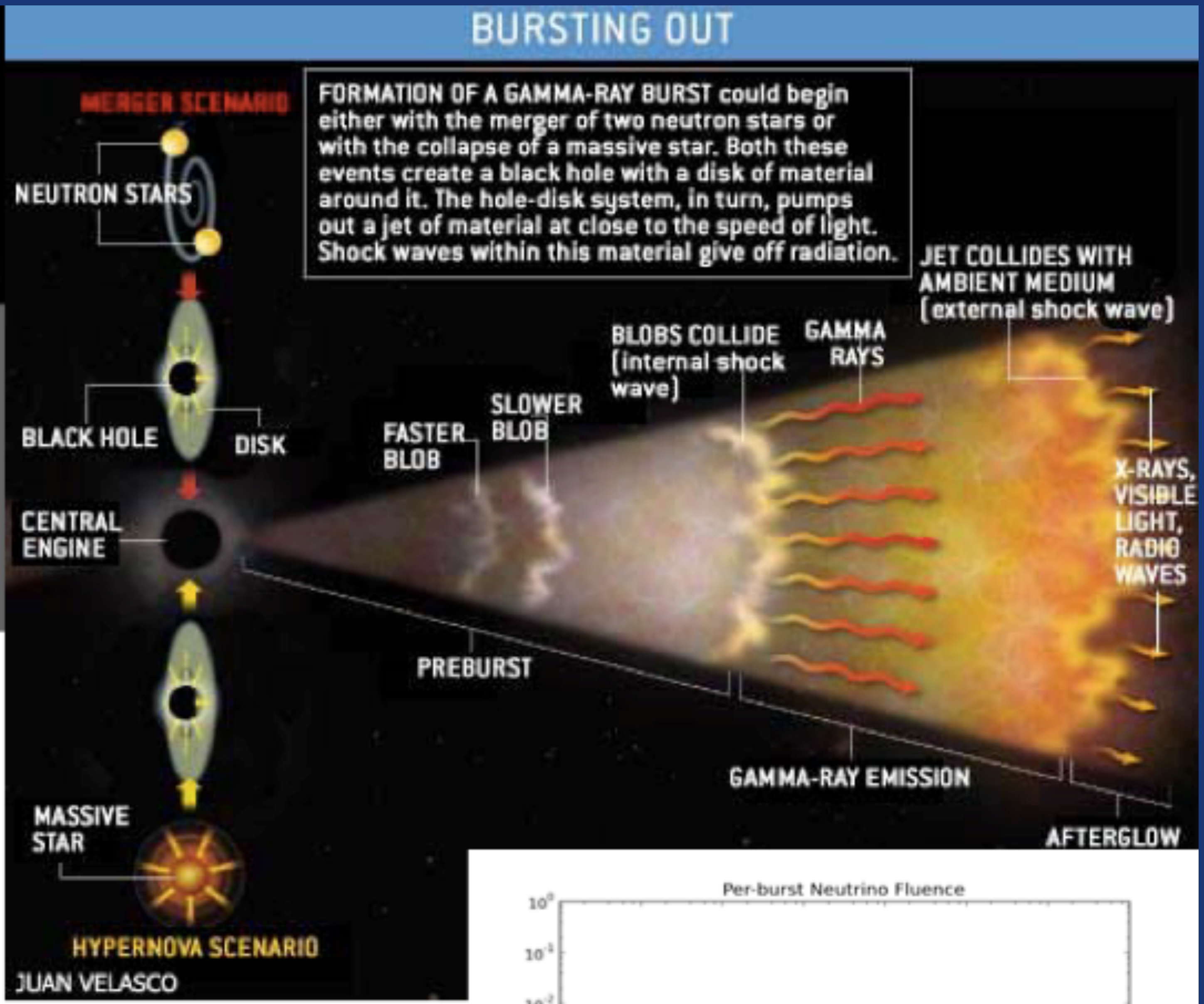


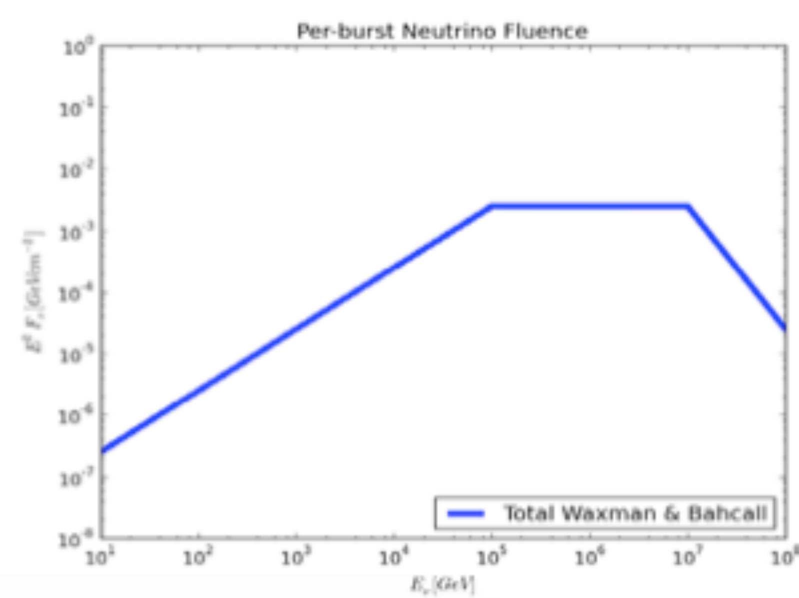
C.Finley (RICAP 2014)

Neutrinos From Gamma Ray Bursts





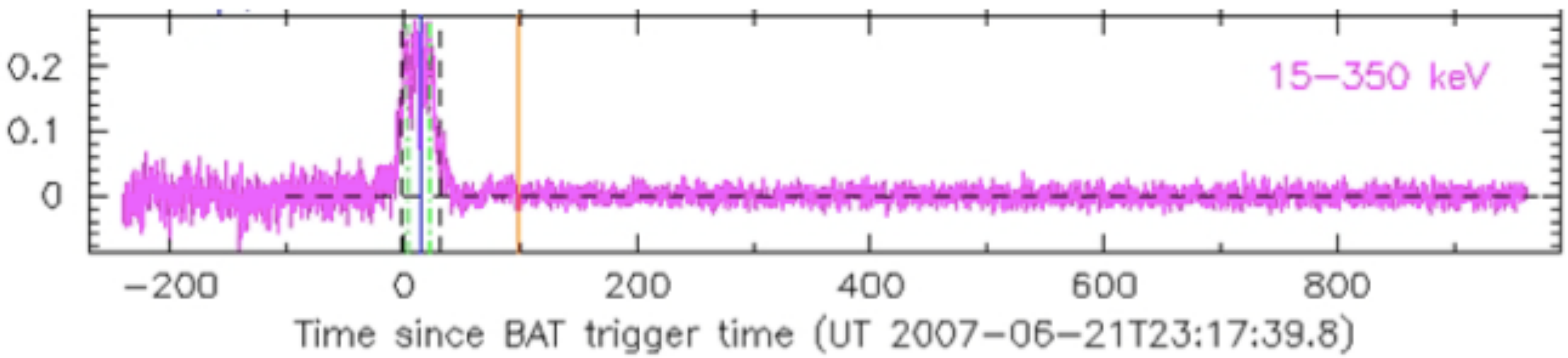




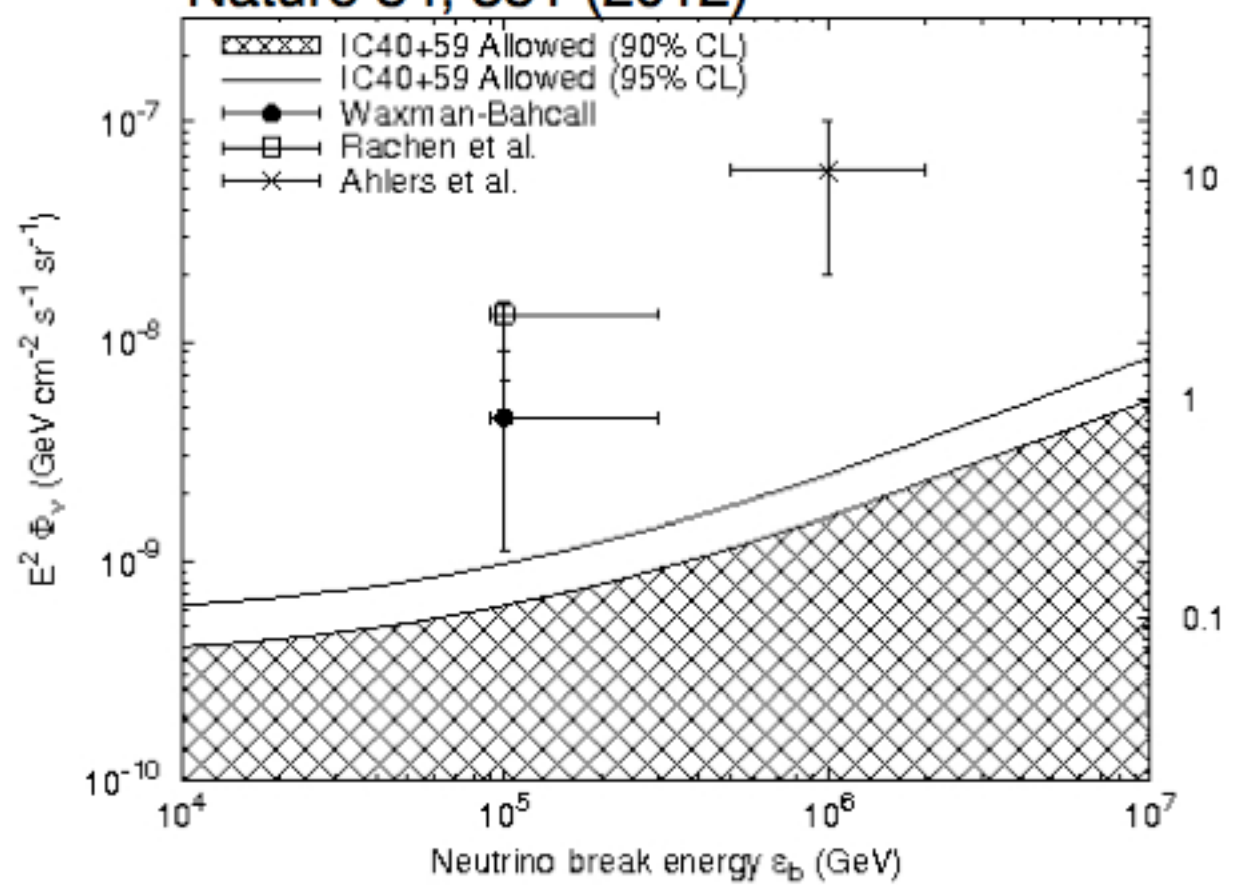
Fireball model:
Internal shocks in GRBs → acceleration for UHECRs
Neutrino production in p-γ interactions in fireball

Neutrinos From Gamma Ray Bursts

Search for neutrinos from direction of GRB in short time window (<±1 day) around trigger time (=satellite measurement of GRB):



Nature 84, 351 (2012)



Results:

- 215 GRBs in Northern sky
- 2 events observed:
  both trigger IceTop, likely atm. muons
- Neutrino flux limits in tension with fireball model

Neutrinos From Gamma Ray Bursts

- **506 GRB**
- **One single low-significance coincidence, consistent with atmospheric background**
- **IceCube has ruled out neutron escape models**

$$\Phi_\nu(E) = \Phi_0 \cdot \begin{cases} E^{-1}\varepsilon_b^{-1} & E < \varepsilon_b, \\ E^{-2} & \varepsilon_b \le E < 10\varepsilon_b \\ E^{-4}(10\varepsilon_b)^2 & 10\varepsilon_b \le E\,. \end{cases}$$

IceCube, Astrophys.J. 805 (2015) 1, L5

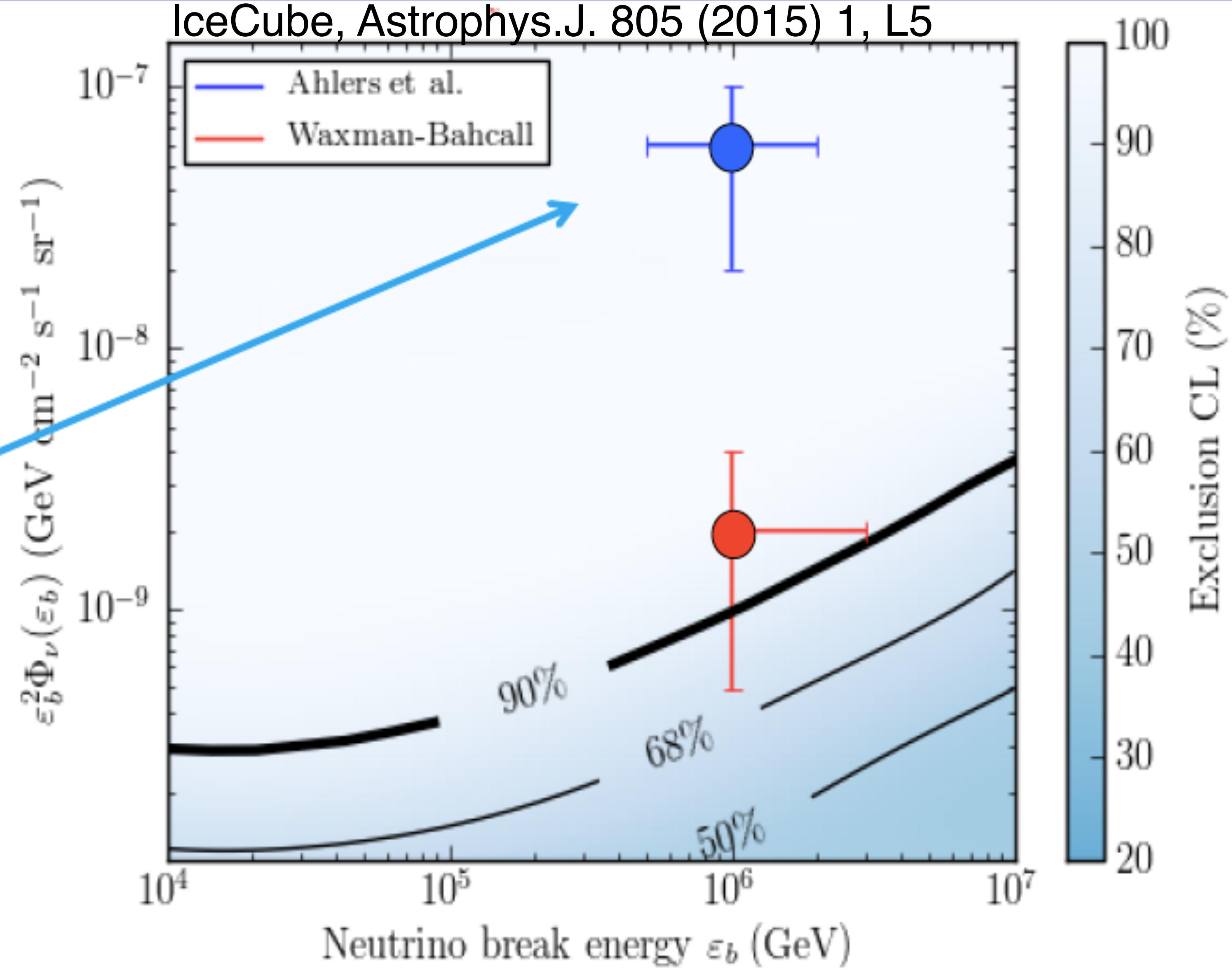


Fig. 1.— Constraint on generic doubly-broken power law neutrino flux models as a function of first break energy ε_b and normalization Φ_0. The model by Ahlers et al. (2011) assumes that only neutrons escape from the GRB fireball to contribute to the UHECR flux. The Waxman-Bahcall model (1997), which allows all protons to escape the fireball, has been updated to account for more recent measurements of the UHECR flux (Katz et al. 2009) and typical gamma break energy (Goldstein et al. 2012).

Indirect Dark Matter searches

$\Omega_m \sim 24\%$, $\Omega_b \sim 4\%$

$\Omega_{DM} \sim 20\%$ non-baryonic and non-relativistic

(cold) DM currently favored candidate: WIMP

Look at objects where the DM particle can be gravitationaly trapped and annihilate:

Sun, Earth and galactic halo

- MSSM CDM candidate: neutralino, χ
- UED CDM candidate: lightest Kaluza-Klein (LKK)

⟶ CDM annihilation and decay to neutrinos:

$$\tilde{\chi}\tilde{\chi} \rightarrow \left\{ \begin{array}{c} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{array} \right\} \rightarrow \cdots \rightarrow \nu_{\mu}$$

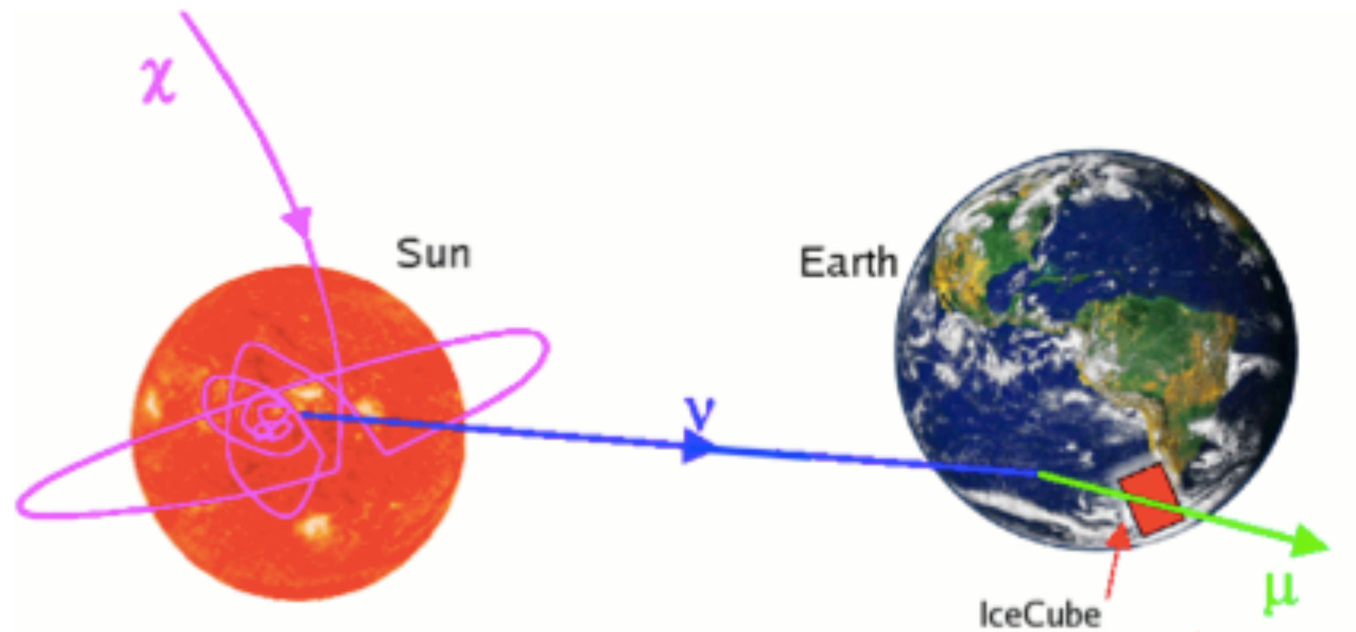
$$KK \rightarrow \nu\nu$$

Signature: neutrino excess from Sun,Earth or galactic halo direction
ν energy range: ~ 10 GeV to a few TeV

Example: WIMPs in Sun

$$\frac{dN}{dt} \sim C_c - C_A N^2 = C_c - 2\Gamma_A$$

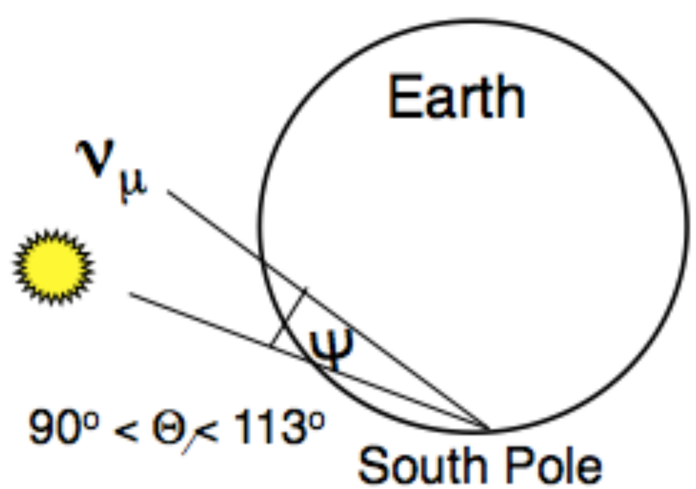
in equilibrium (dN/dt = 0)
capture rate ~ annihilation rate



Indirect Dark Matter searches: Solar WIMPs

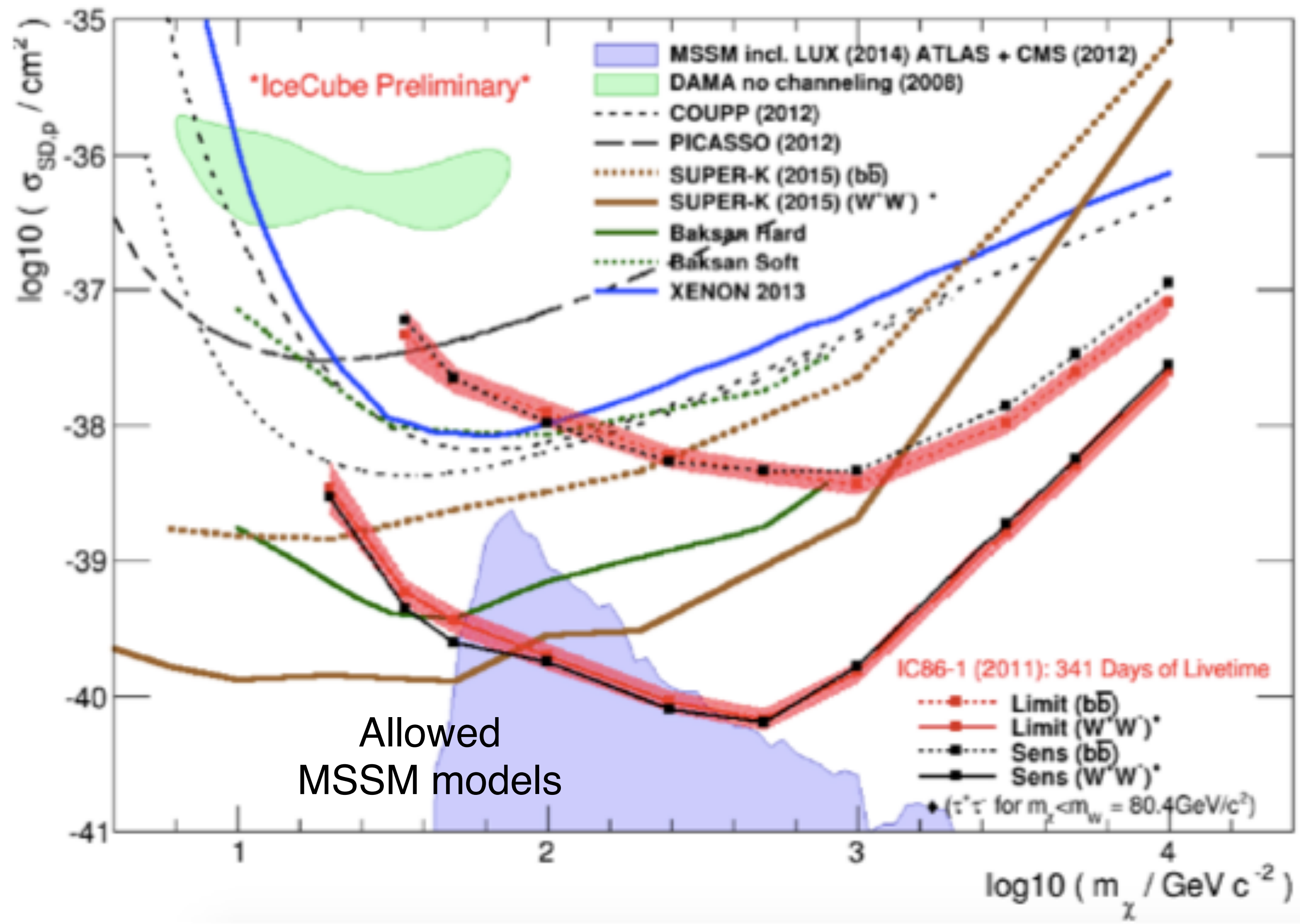
90% CL limits on the spin-dependent (SD) and spin-independent (SI) χ-p cross sections assumming equilibrium between capture and annihilation:

- $\sigma^{SI} = \lambda_{SI}(m_\chi)\Gamma_A$ and $\sigma^{SD} = 0$ $\Rightarrow$ *constrained well by direct searches*
- $\sigma^{SI} = 0$ and $\sigma^{SD} = \lambda_{SD}(m_\chi)\Gamma_A$ $\Rightarrow$ capture in the Sun dominated by σ^{SD} competitive limits by indirect searches



$$\Gamma_{\nu\to\mu} = \frac{\mu_s}{V_{eff}\times T}$$

$$\Gamma_A = \kappa^{-1}(\chi)\times\Gamma_{\nu\to\mu}$$



Joanna Kiryluk (Stony Brook University), PACIFIC2015

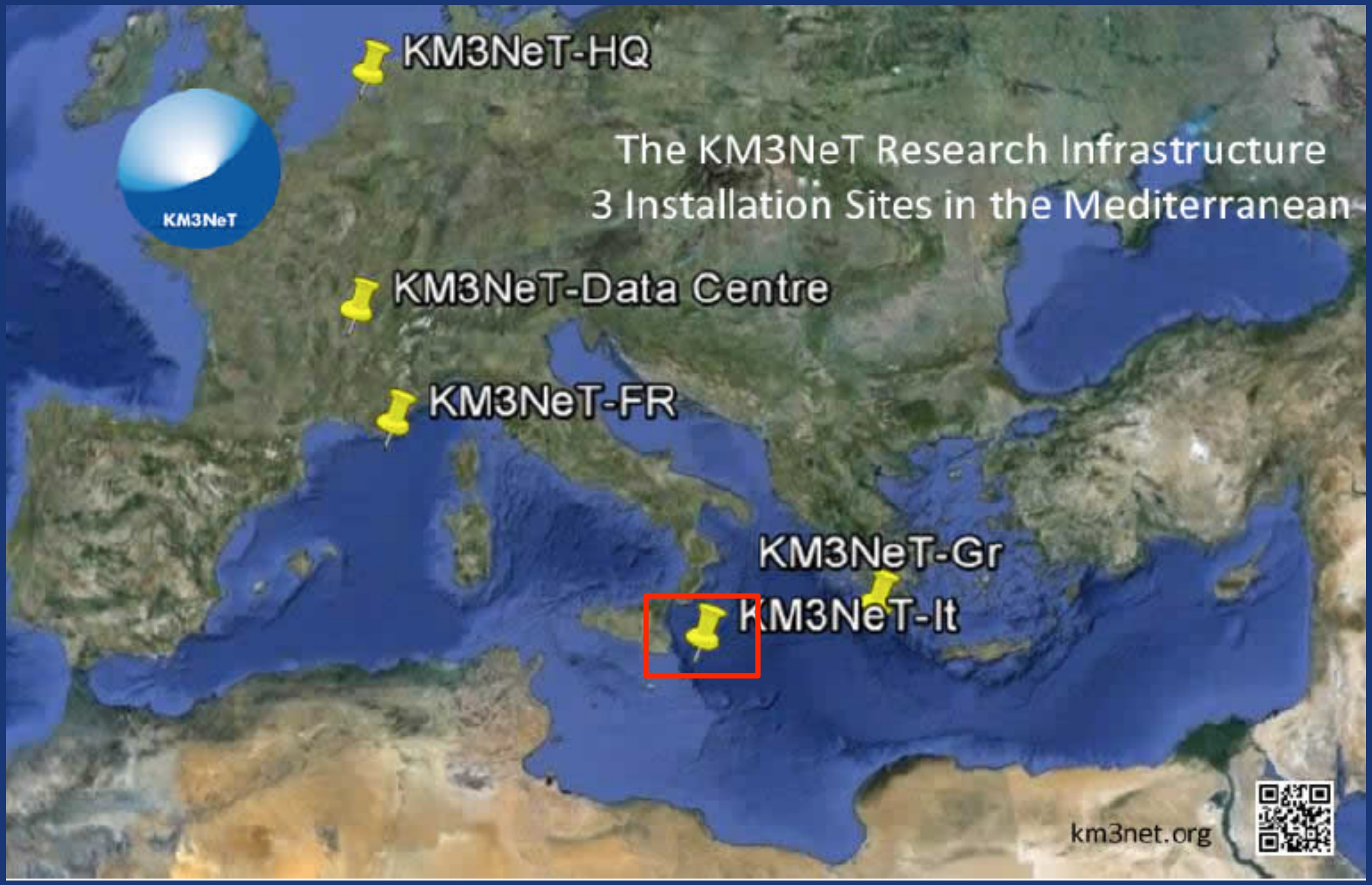
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
- No evidence for a point / extended source in several analyses

Questions:

- Where are the point sources?
- What is the spectrum? Production mechanism? Cutoff?
- What is the flavor composition?
- Multi-messenger physics?
- GZK neutrinos?

KM3NeT

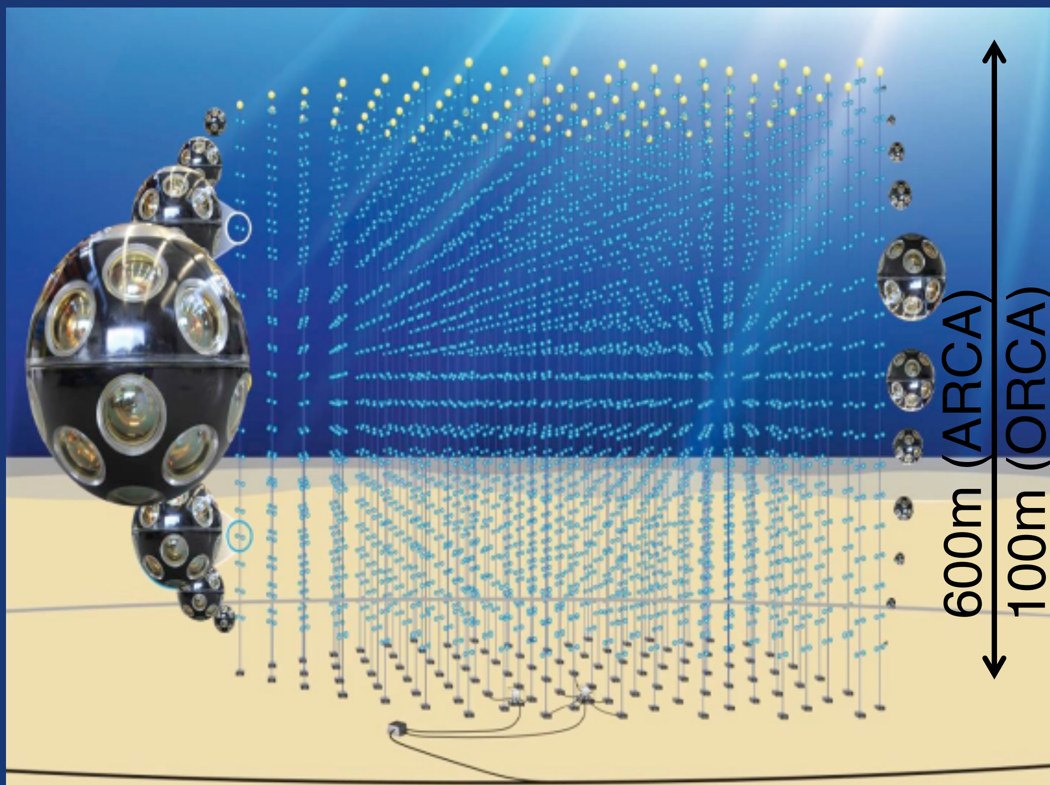
Multi-km3 sized Neutrino Telescope
Multi-site installation in the Mediterranean Sea, instrumented in “building blocks”.

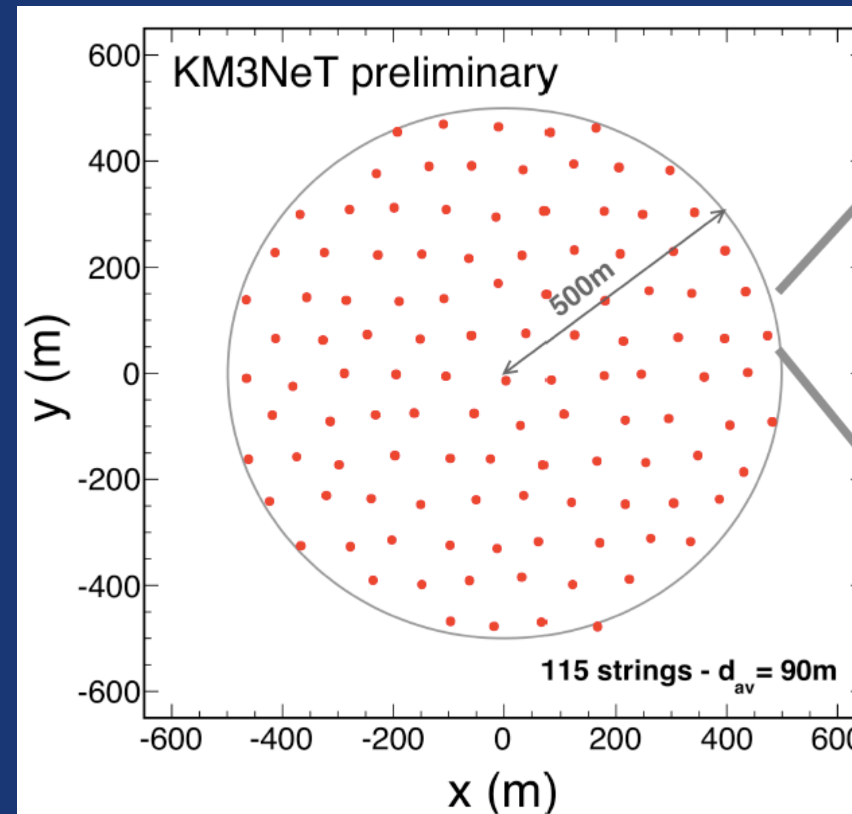


- ARCA: Astrophysical Research with Cosmic in the Abyss
  - ✓ the discovery and observation of HE (E >100 GeV) neutrino sources in the Universe
  - ✓ 2 ‘blocks’ at KM3NeT-It

- ORCA: Oscillations Research with Cosmics in the Abyss
  - ✓ the determination of the mass hierarchy of neutrinos 1 GeV < E < 100 GeV
  - ✓ 1 ‘block’ at KM3NeT-Fr

KM3NET ‘building block’





- 115 lines
- 18 OMs per line

- ARCA
  - ✓ 90m horizontal
  - ✓ 36m vertical

- ORCA
  - ✓ 20m horizontal
  - ✓ 6m vertical

Timeline

Phase	Blocks	Primary deliverables
1	0.2	Proof of feasibility and first science results;
2	2	Measurement of the neutrino signal reported by IceCube; All flavour neutrino astronomy;
	1	Determination of the neutrino mass hierarchy;
3	6	Neutrino astronomy including Galactic sources;

Table 1: Summary of the phased implementation of the KM3NeT research infrastructure.

10% ARCA
5% ORCA
funded, 2017

100% ARCA
100% ORCA
2020 (completion)

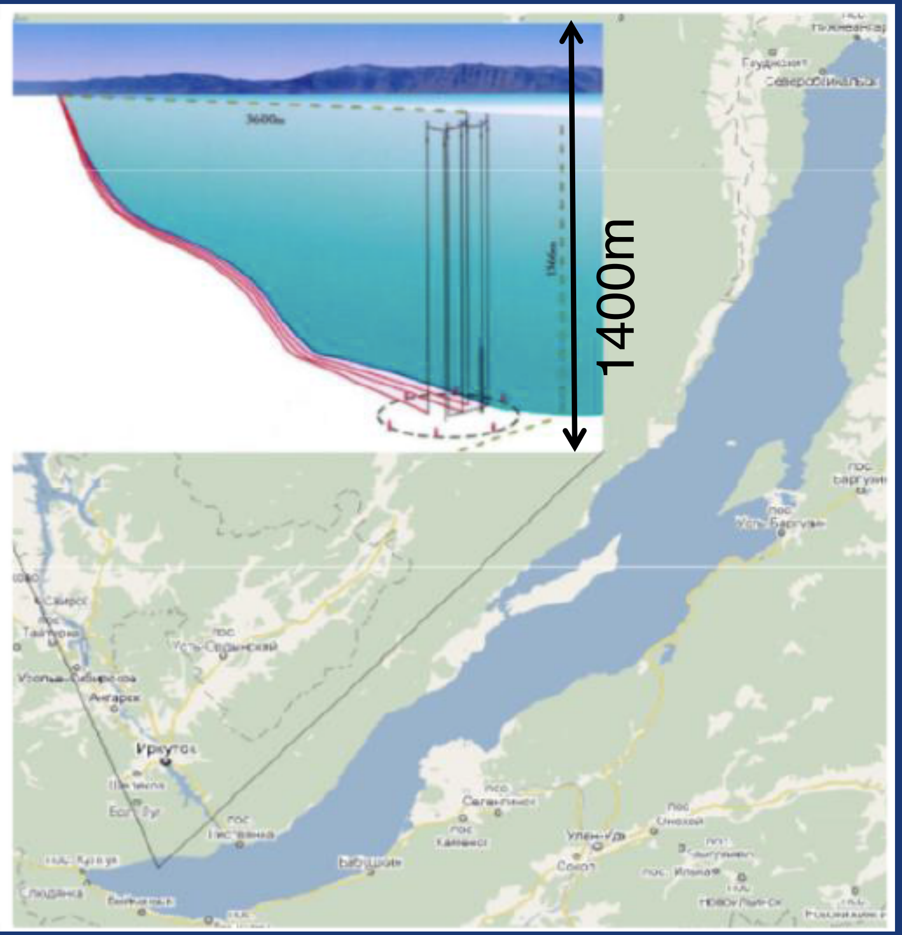
Lake Baikal-GVD (Gigaton Volume Detector)

- The most northern location allows observing the Galactic Center 18 hours per day through the Earth

- R&D stage, two possible configurations considered
  - ✓ 8 or 12 clusters (300m separation, depths 775 – 1300m or 950-1300m)

- The first cluster completed in April 2015
  - ✓ sensitive to 1 cascade event with E > 100 TeV of IC flux

- Completion of the Baikal-GVD with 2304 OMs with about of 0.4 km^3 effective volume for cascade detection is expected in 2020

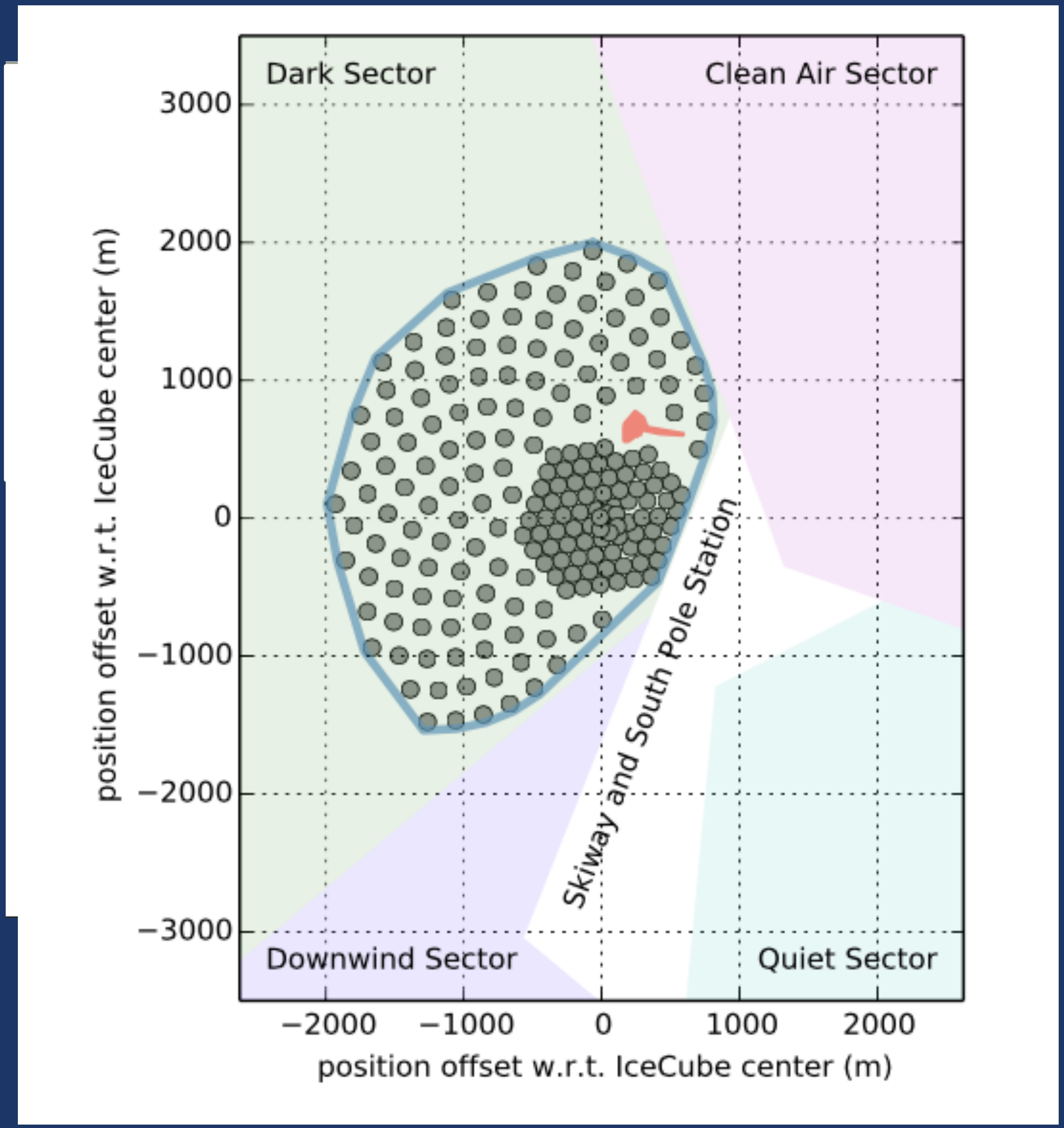


Cumulative number of clusters vs. year

Year	2015	2016	2017	2018	2019	2020
Cluster 192 OM	*1* **192**	*1* **192**	*3* **576**	*5* **960**	*7* **1344**	*10* **1920**
Cluster 288 OM	*2/3* **192**	*1* **288**	*2* **576**	*4* **1152**	*6* **1728**	*8* **2304**

IceCube-Gen2: High Energy Extension
A Vision for the Future of Neutrino Astronomy in Antarctica

arXiv:1412.5106



High Energy Extension to:

- characterize the flux of the high-energy astrophysical ν's including ν flavor composition (increase of statistics)
- identify astrophysical sources

Benchmark geometry:

- instrumented volume ~10 km^3
- 120 strings, length 1.3km
- 240 m string spacing
- Surface veto (CR physics, atm. neutrino veto)

IceCube South Pole Neutrino Observatory

The Lake Baikal Neutrino Telescope

ANTARES

KM3NeT Opens a new window on our universe

GNN The Global Neutrino Network

Era of km^3 neutrino astronomy has begun

Sensitivities/limits → *Discovery* → *Measurements* → *Models testing*

Diffuse signal → *First source* → *Catalog!*

Astrophysical neutrinos have been discovered
Diffuse flux characteristics started
Origin: Lot's of possible interpretations
Cosmic accelerator source searches continue …..

Stay tuned!