

See
 Aartsen et al, Science, Nov (2013) for IceCube signal
 Becker, Phys. Rep. (2008), arXiv: 0710.1557 for ν review

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The dawn of neutrino astronomy: implications from the first IceCube detection

Julia Tjus (born: Becker)

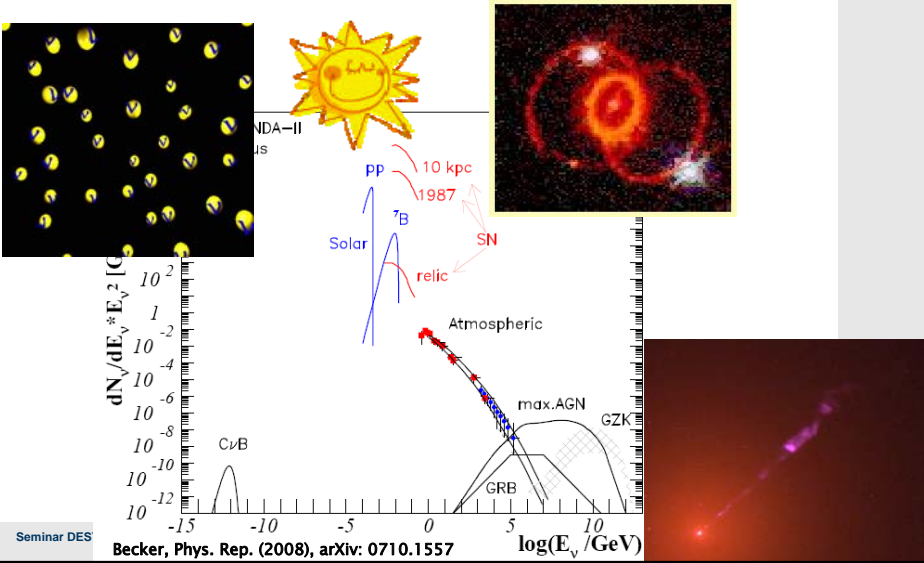
FAKULTÄT FÜR PHYSIK & ASTRONOMIE
 Theoretische Physik IV: Plasma-Astroparticle Physics

Seminar DESY Hamburg | May 20, 2014

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Neutrinos in the Universe



pp 10 kpc 1987 SN
 Solar 7B relic
 Atmospheric
 max.AGN GZK
 GRB

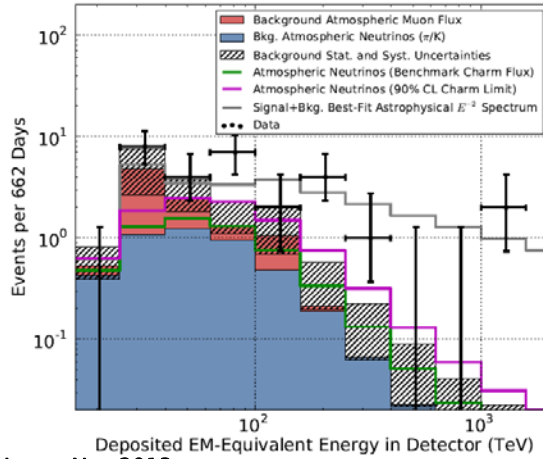
$dN_{\nu}/dE_{\nu} * E_{\nu}^2 [C]$

$\log(E_{\nu} / \text{GeV})$

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 Becker, Phys. Rep. (2008), arXiv: 0710.1557

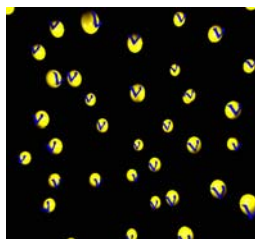
First evidence (2013): Extraterrestrial high energy vs

- 28 events (expected ~ 10 atmospheric events)
- Significance ~ 4σ



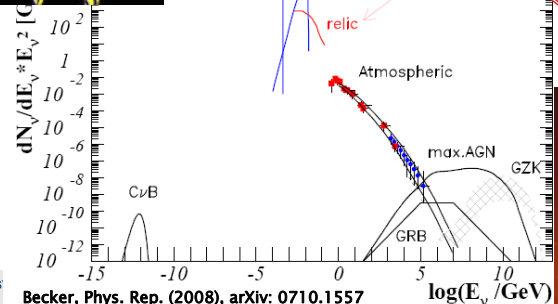
Aartsen et al (IceCube Coll), Science, Nov 2013

Neutrinos in the Universe



confirmed (1998)

confirmed (1987)
SN1987



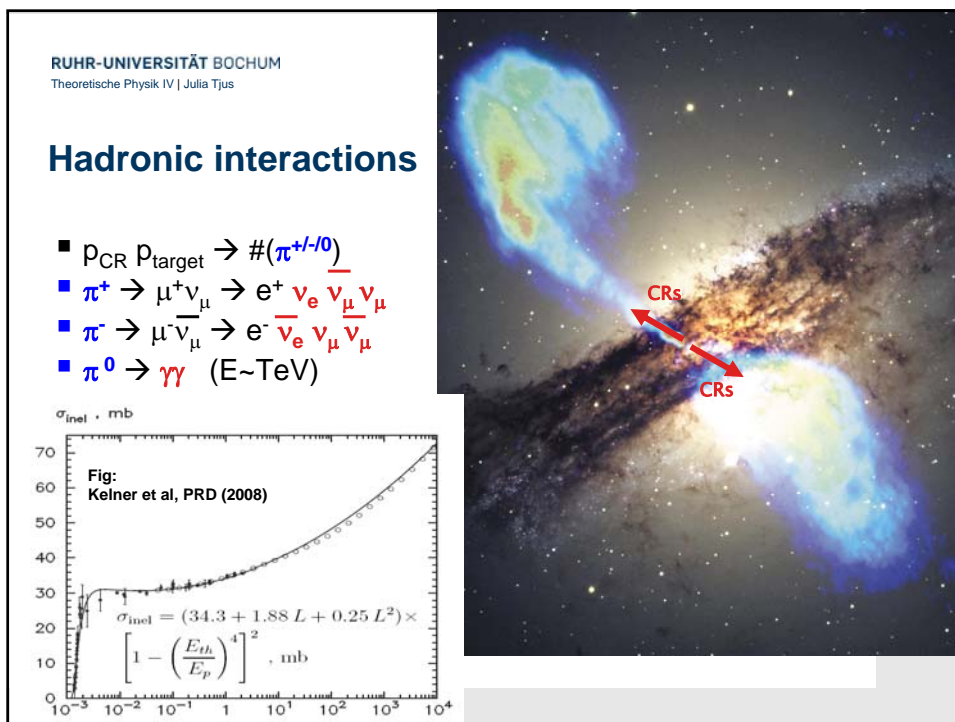
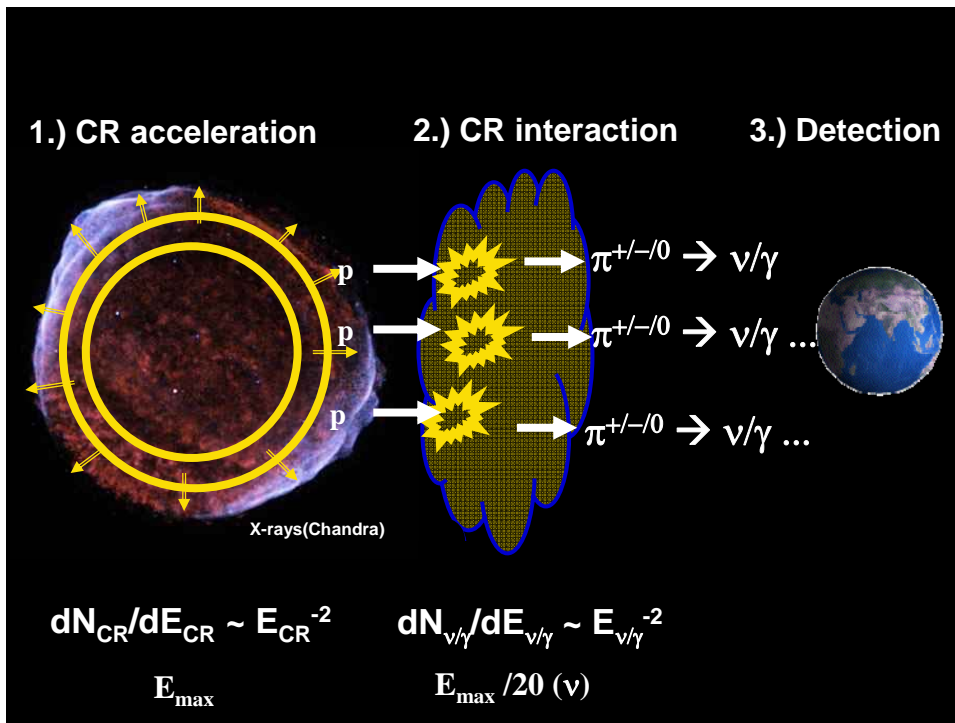
existence confirmed (2013)
sources???

Contents

- Predicted sources of high-energy neutrinos
- High-energy neutrino detection with IceCube
- What can we learn from the first IceCube results?
- Summary & Outlook

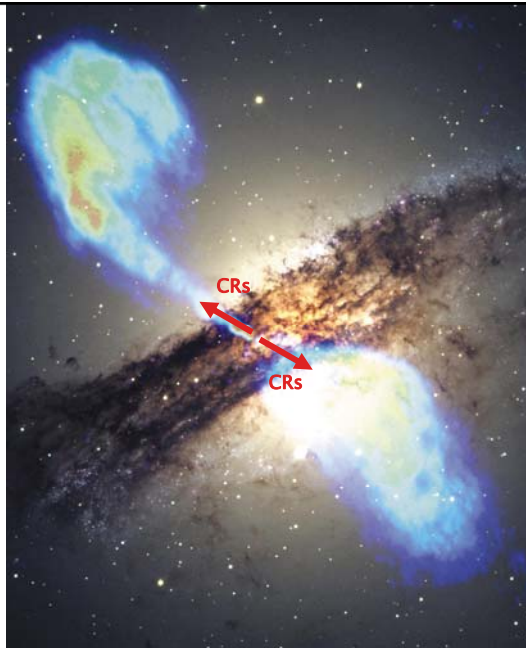
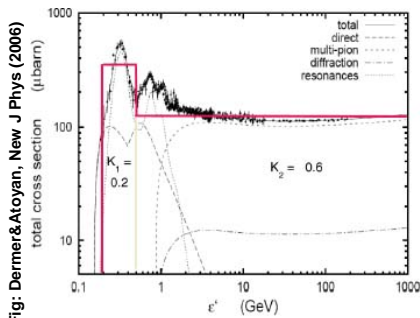
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Photohadronic interactions

- $p_{CR} \gamma_{target} \rightarrow \Delta^+ \rightarrow \pi^{+/-} N$
- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$
- $\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$
- $\pi^0 \rightarrow \gamma\gamma$ (E~TeV)



Neutrinos VS Gammas

▪ Neutrinos:

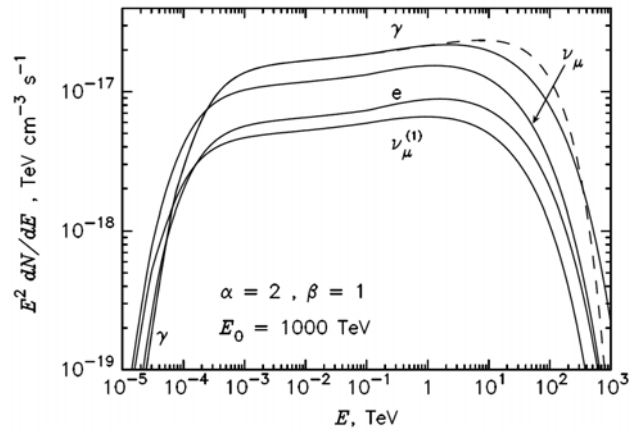
- + without doubt of hadronic nature
- difficult to detect

▪ Gammas:

- + # ~100 (TeV); ~2000 (GeV) sources already detected
- ambiguous signal (π^0 VS brems VS Inverse Compton)

Focus for this talk: **neutrinos**

Neutrino Signal: $\sim E^{-\beta}$ spectrum



- Kinematic threshold: $E_{p,\min} \sim 280\text{MeV}$ ($\sim 100\text{ MeV}$ gamma energy)
- Above threshold: spectral behavior follows CR spectrum $\rightarrow \sim E^{-\beta}$

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Neutrinos ($p\gamma$)

- Kinematic threshold for pion production
 - $E_p * E_\gamma > (m_\Delta^2 - m_p^2)/4$
- Above threshold:
 - simple assumptions \rightarrow follows $E^{-\beta}$;
 - including photon field energy dependence etc \rightarrow more complicated

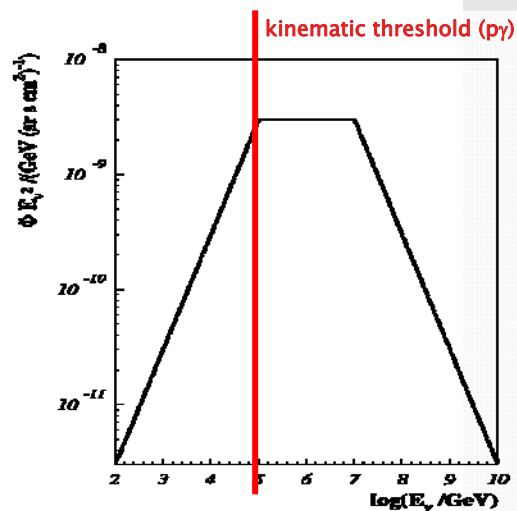
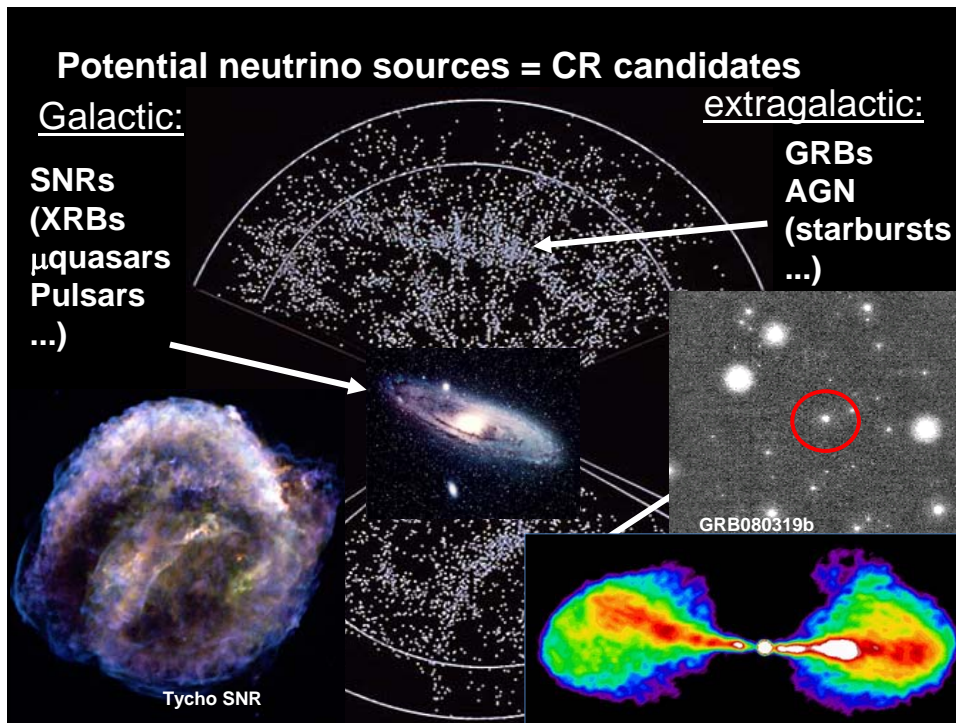


Fig: example neutrinos from GRBs
[from Becker, Phys.Rep. 2008]

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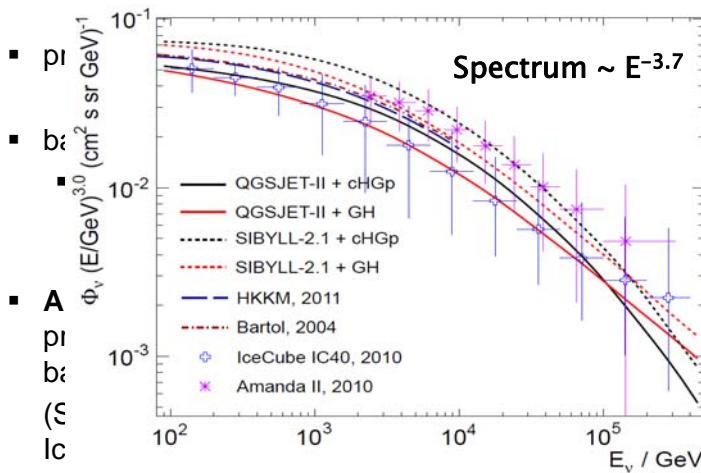
ν Background: Atmospheric ν

- proton-air collisions
- background estimate:
 - measurement plus simulation (CORSIKA)
- **ANFlux**: tool within IceCube for proper description of atmospheric background (Schöneberg, Becker Tjus, IceCube Coll.)

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Fedynitch, Becker Tjus, Desiati, PRD (2012)

ν Background: Atmospheric ν

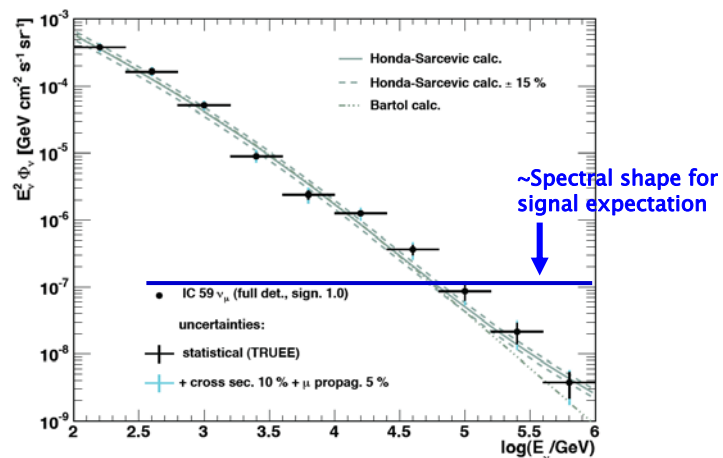


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Fedynitch, Becker Tjus, Desiati, PRD (2012)

Search for neutrinos

→ Signal becomes visible toward high energies

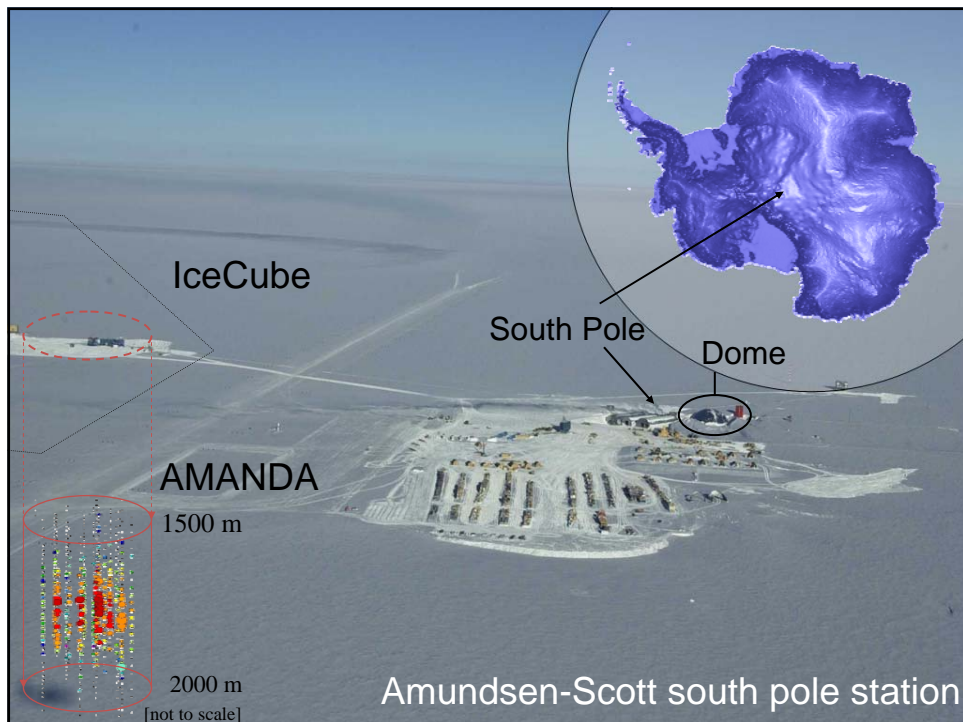


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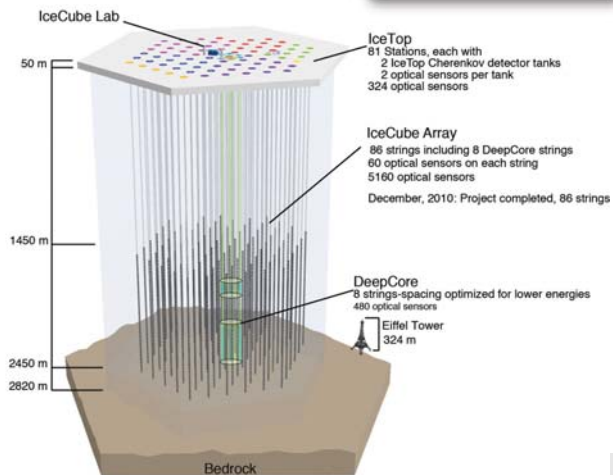
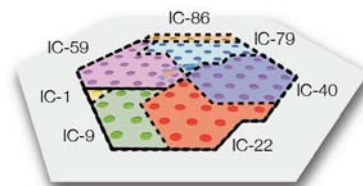
N. Milke, PhD thesis (2012), TU Dortmund

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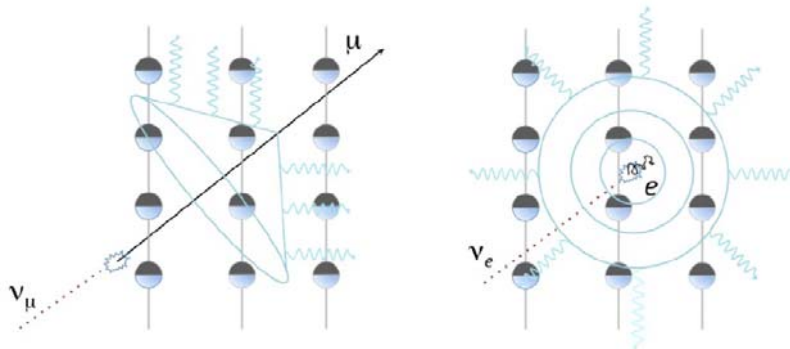


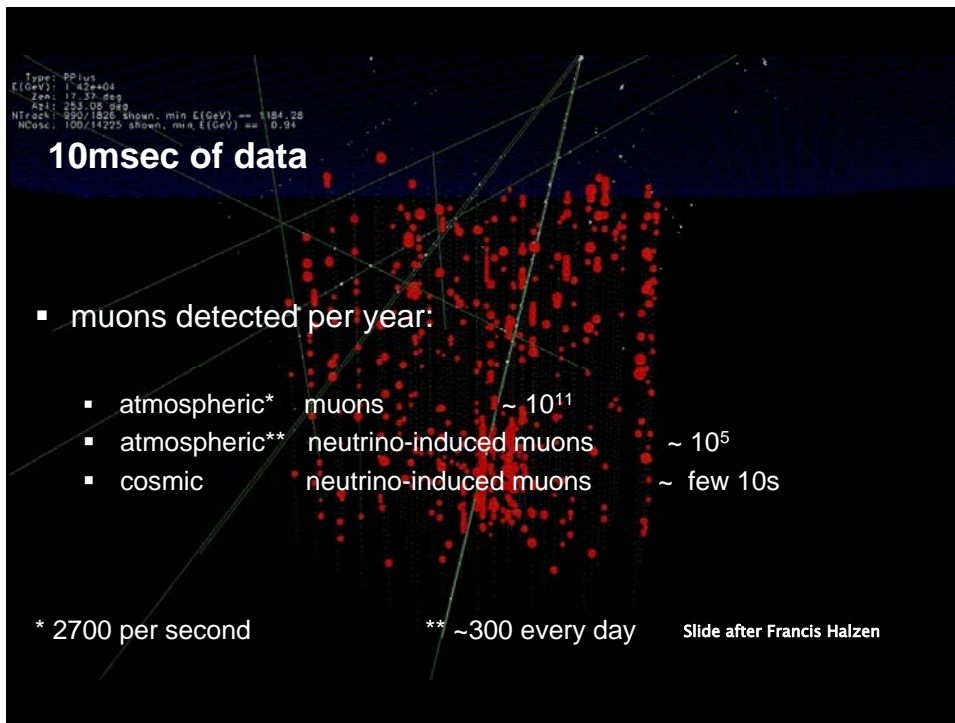
IceCube



Detection method: Cherenkov light from charged particles

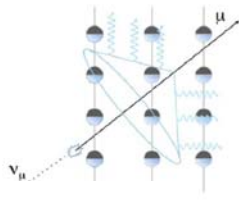
- ν_μ charged current interaction
- $(\nu_\mu)_\nu e_\tau$ charged current interaction
- $\nu_\mu \nu_e \nu_\tau$ neutral current ($\nu N \rightarrow \nu X$)





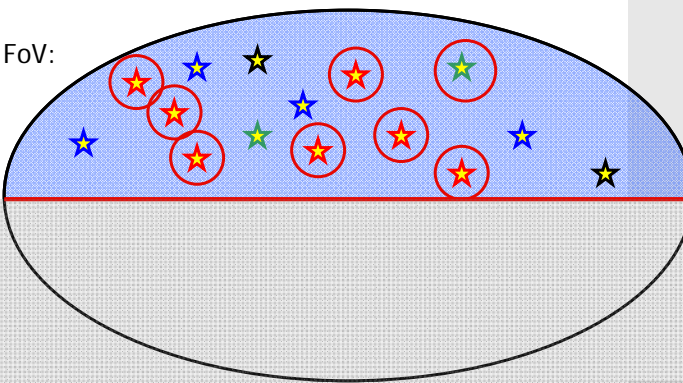
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Detection strategies: Neutrino-induced muons



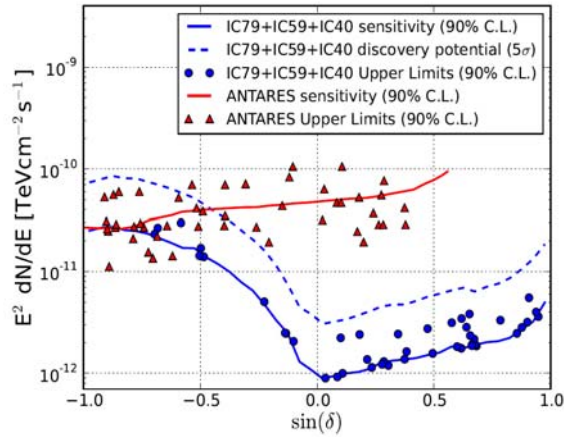
Search for a diffuse signal: use $\sim 2\pi$

AMANDA/IceCube FoV:
 $\sim 4\pi(2\pi)$



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IceCube point source sensitivity



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Aartsen et al (IceCube), arXiv:1307.6669

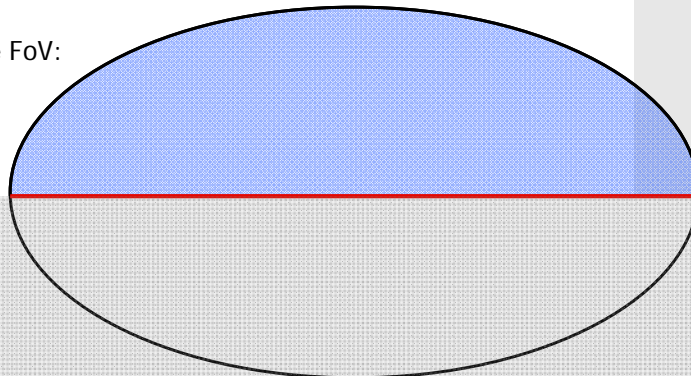
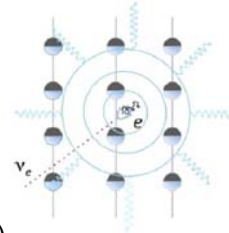
Detection strategies: Neutrino-induced cascades

Search for a diffuse signal

Very little spatial information (nearly spherical event)

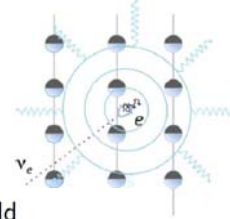
AMANDA/IceCube FoV:

$\sim 4\pi$



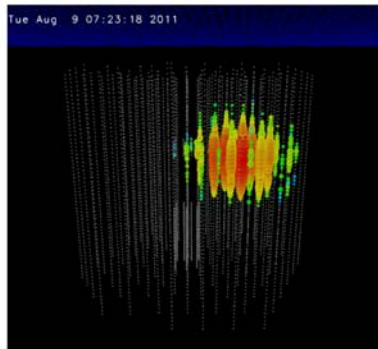
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Review: see e.g. Becker, PhysRep 2008

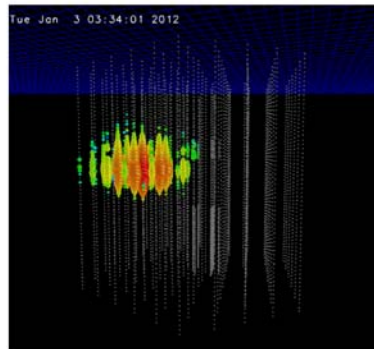


First detection of Neutrinos @ PeV energies: Cascade Channel

Appearance of ~ 1 PeV neutrinos at lower energy threshold



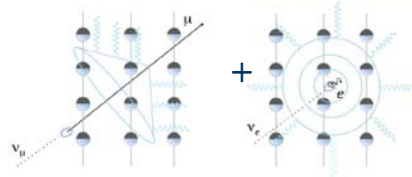
"Bert"
 ~ 1050 TeV



"Ernie"
 ~ 1150 TeV
arXiv:1304.5356

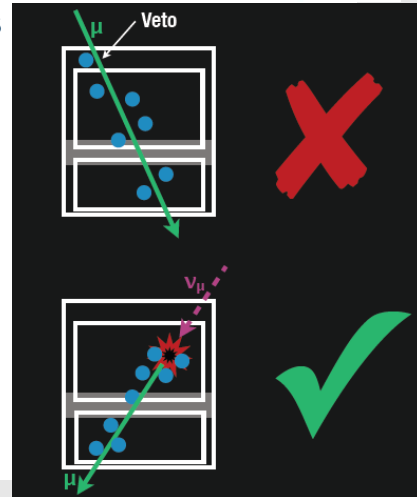
Aartsen et al (IceCube), PRL 111:021103 (2013)

How can we exploit the detector even better to extract more possible signal?



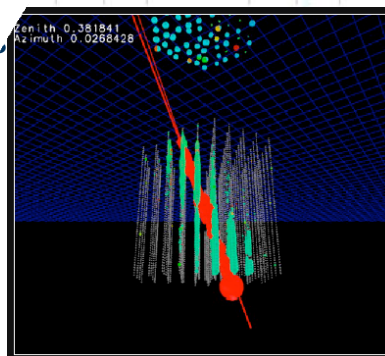
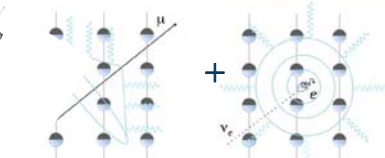
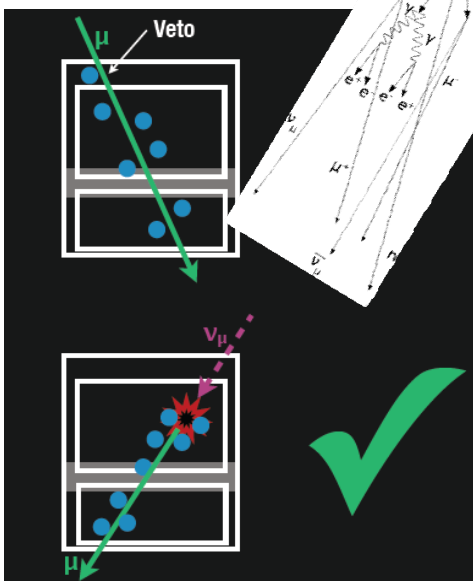
High-Energy Starting Events (HESE)

- **Idea 1:** only use contained events (veto: particles entering the detector)



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- **Idea 2:** veto for atmospheric muons



atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

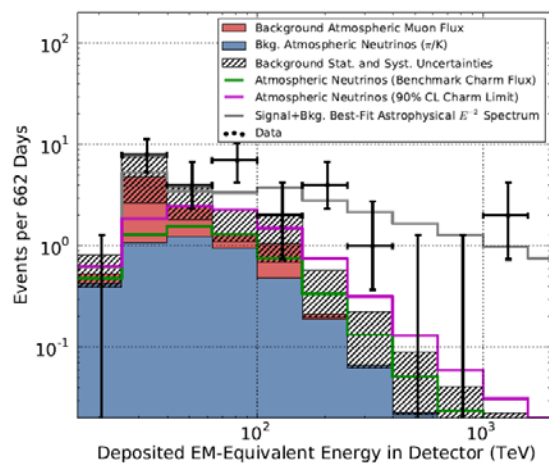
(no signals in IceTop)

Consequence

Number of atmospheric particles per year
reduced
from $1e11$ muons + $1e5$ neutrinos
to only **~10 atmospheric events**

First evidence: Extraterrestrial high energy vs

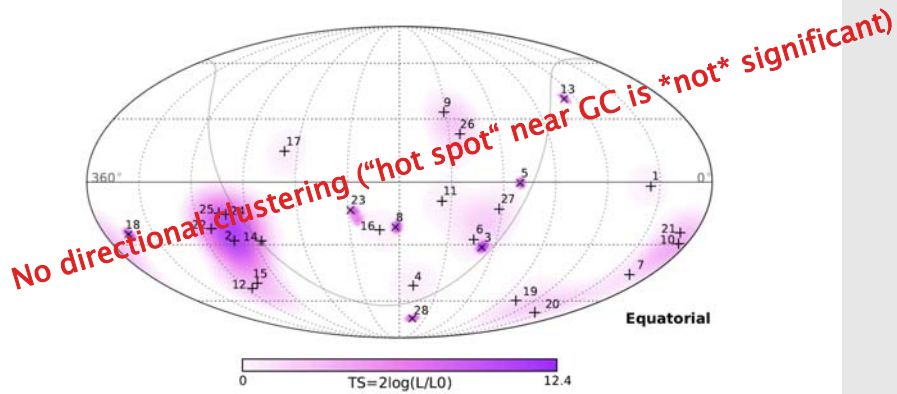
- 28 events
(expected ~ 10
atmospheric
events)
- Significance $\sim 4\sigma$



Aartsen et al (IceCube Coll), Science, Nov 2013

Directional information?

- Temporal evolution of a cascade can be used to get to resolutions of a few degrees:



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Aartsen et al (IceCube Coll), submitted, arXiv:1405.5303
Aartsen et al (IceCube Coll), Science, Nov 2013

WANTED

sources with such conditions

- Astrophysical signal of strength:
 $E^2 \cdot dN_\nu / dE_\nu \sim 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$
- Spectral behavior:
 - EITHER spectrum slightly steeper than E^{-2} ($\sim E^{-2.3}$)
 - OR cutoff @ PeV-energies
- Spatial Clustering?: So far isotropic distribution
- Temporal Clustering?: search for flares/gamma-ray bursts did not give a significant clustering result (yet)

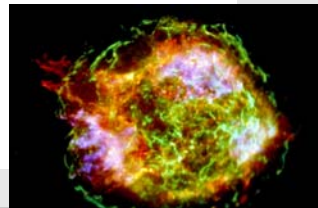
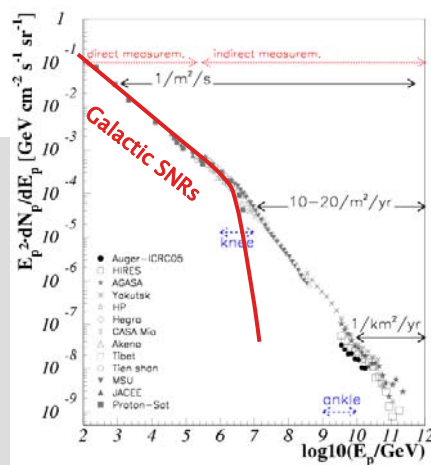
REWARD

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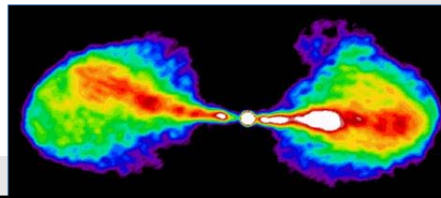
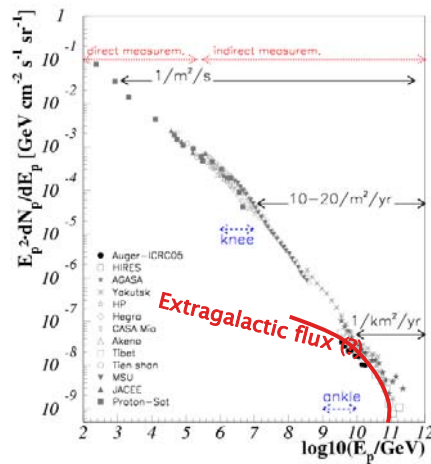
Galactic origin? Supernova remnants

- **Astrophysical signal of strength:**
 $E^2 \cdot dN_p/dE_p \sim 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$
 - **could work**
- **Spectral behavior:**
 - **cutoff @ PeV-energies**
 - **EXPECTED**
- **Spatial Clustering?: So far isotropic distribution**
 - **would expect clustering in the Galactic plane; does not seem to be the case**
- **Temporal Clustering?: no**
 - **not expected**



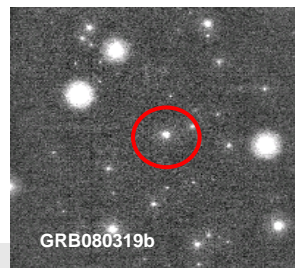
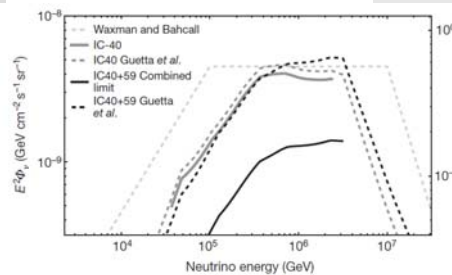
Extragalactic origin? Active Galactic Nuclei

- **Astrophysical signal of strength:**
 $E^2 \cdot dN_{\nu} / dE_{\nu} \sim 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$
 - **yes: for certain sub classes**
- **Spectral behavior:**
 - $E^{-2.3}$:
 - **yes: to be compatible with observed flux of UHECRs, it needs to be $E^{-2.3}$ or steeper**
- **Spatial Clustering?:** So far isotropic distribution
 - **would expect isotropic distribution from AGN source class**
- **Temporal Clustering?:** no
 - **not necessarily**



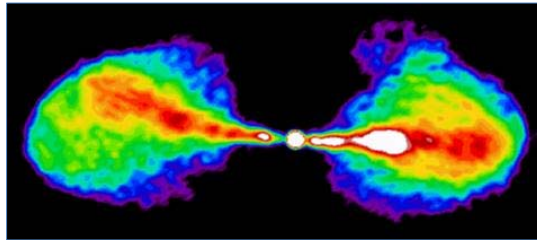
Extragalactic origin? Gamma-ray bursts

- **Astrophysical signal of strength:**
 $E^2 \cdot dN_{\nu} / dE_{\nu} \sim 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$
 - **too intense, not compatible with GRB limits**
- **Spectral behavior:**
 - $E^{-2.3}$:
 - **yes: to be compatible with observed flux of UHECRs, it needs to be $E^{-2.3}$ or steeper**
- **Spatial Clustering?:** So far isotropic distribution
 - **yes: would expect isotropic distribution from GRB source class**
- **Temporal Clustering?:** no
 - **yes (but not necessarily to be observed at this stage)**



Active Galactic Nuclei Neutrinos from proton-proton?

- Particle densities:
 - from $\sim 10^{10} \text{ cm}^{-3}$ (AGN jet/knots)
 - to $\ll 1 \text{ cm}^{-3}$ (termination shock intergalactic medium)



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Cross section Muon neutrino distribution function

$$\frac{dN_\nu}{dE_\nu dA} = N_H \cdot \int_0^1 \sigma_{pp} \left(\frac{E_\nu}{x} \right) \lambda_p \left(\frac{E_\nu}{x} \right) F \left(x, \frac{E_\nu}{x} \right) \frac{dx}{x} \quad \text{with } x = \frac{E_\nu}{E_p}$$

Target column cm^{-2} Primary flux

Proton spectrum: $\lambda_p = A_p \cdot \left(\frac{E_\nu}{\text{TeV}} \right)^{-p} \cdot \exp \left(- \frac{E_p}{E_{\text{max}}} \right)$

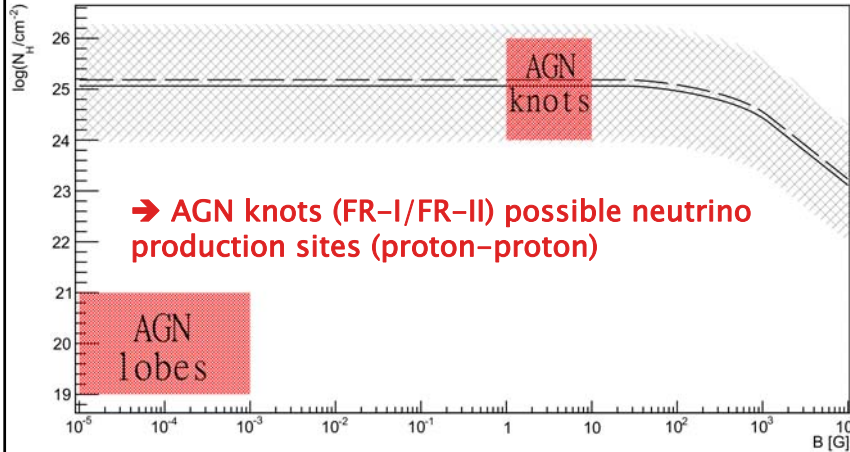
$L_{\text{radio}} \xrightarrow{\text{synch}} L_{\text{radio}} = \chi(B) \cdot L_e \xrightarrow{f_e \approx 0.1} L_e = f_e \cdot \chi(B) \cdot L_p$

→ Normalization via: $L_p = \frac{L_{\text{radio}}}{\chi(B) f_e}$

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→ $N_H - B$:

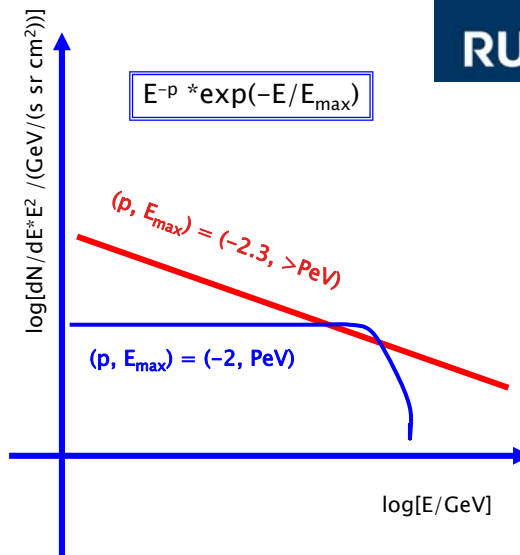
allowed Parameter space VS observed properties



Future tests

1. Spectral behavior:

- $E^{-2.3} \exp(-E/10^9 \text{ GeV})$: sources of UHECRs?
- $E^{-2.0} E^{-2.2} \exp(-E/10^6 \text{ GeV})$: sources of Galactic cosmic rays? starbursts?



Future tests

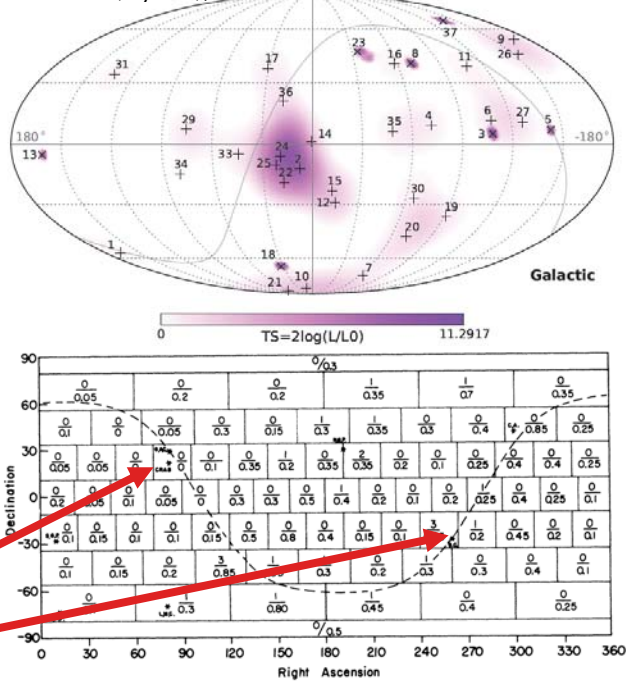
1. Spectral behavior
2. Directional information: when to expect the first point sources?

Explorer XI, 22 γ -events
(> 50 MeV),
Kraushaar & Clark, PRL 1962

generally compatible with isotropy

Crab: 0 events
Galactic center: 2 events
(Kraushaar et al, ApJ 141 (1965)
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IceCube (3 years), 37 events



Future tests

1. Spectral behavior
2. Directional information: when to expect the first point sources?
3. Flavor ratio (ν_μ, ν_e, ν_τ)

Typical π -decay ratio incl. oscillations:

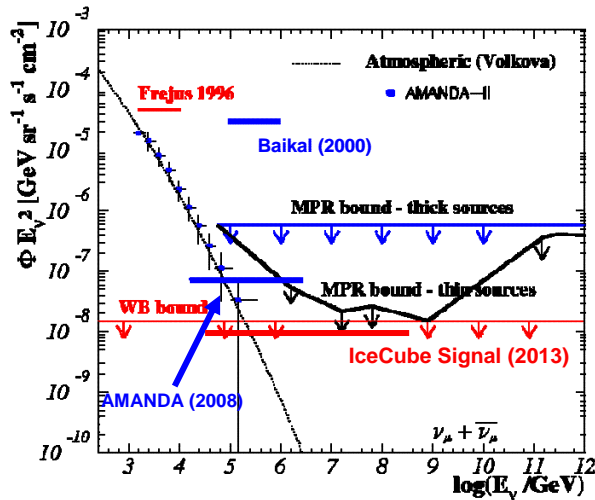
$(\nu_\mu, \nu_e, \nu_\tau) \sim (1:1:1)$

x: Myon (CC ν_μ)
+: cascade (CC $\nu_e + (\nu_\mu) + \nu_\tau$, NC $\nu_e + \nu_\mu + \nu_\tau$)
 $\sigma_{CC} \sim 2 * \sigma_{NC}$

→ (X:+) $_{(1:1:1)}$ -prediction $\sim (1:4.0-4.5)$

Measurement: 7 muon tracks, 30 cascades:
→ (X:+) $_{measured} \sim (1:4.3)$ [ok so far]

Summary (I)



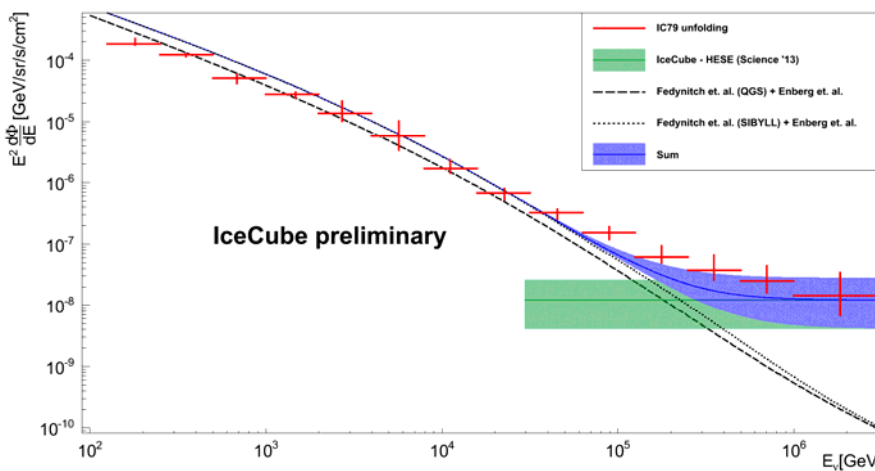
Waxman&Bahcall, PRD 59:23002 (1999)

Mannheim et al., PRD 63:23003 (2001)

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update of Becker, Neutrino 2008; ArXiv:0811.0696

Outlook (I)



IceCube Analysis, ν -induced muons, TU Dortmund (Martin Schmitz, Wolfgang Rhode++)

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Outlook (2)

- Statistics with IceCube: several 10s of neutrinos per year;
- Life time of IceCube > 10 years
- → for detailed statistics, a larger detector is needed:
 - KM3NeT (mediterranean);
 - IceCube high-energy extension
- → Detectors need to be a factor of a few larger than IceCube

