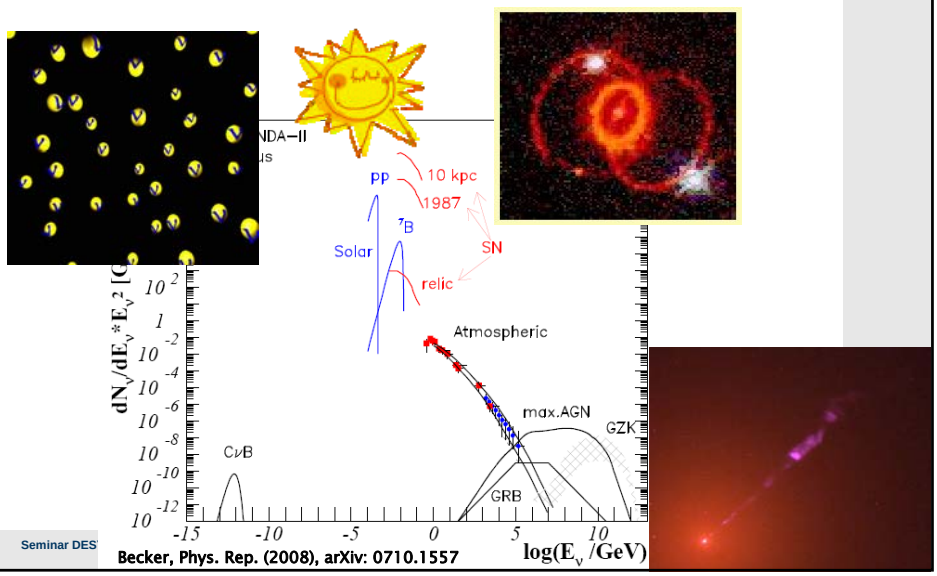
RUHR-UNIVERSITÄT BOCHUM

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

Julia Tjus (born: Becker)

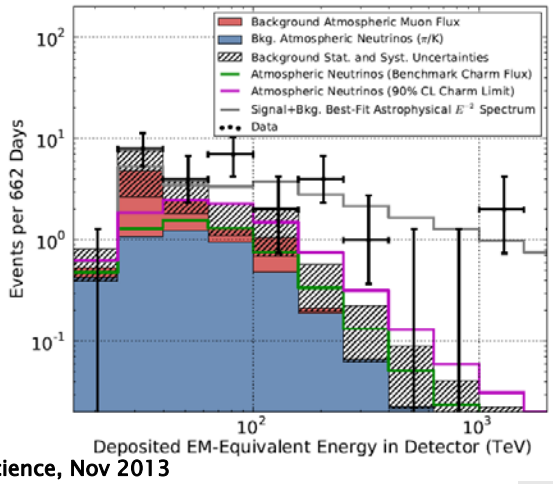
FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV: Plasma-Astroparticle Physics

Neutrinos in the Universe



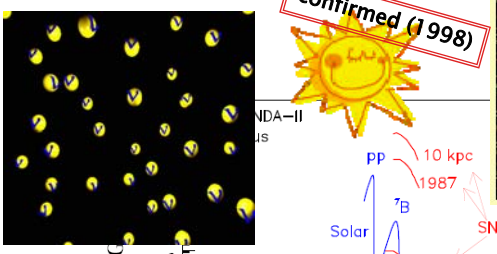
First evidence (2013): Extraterrestrial high energy νs

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

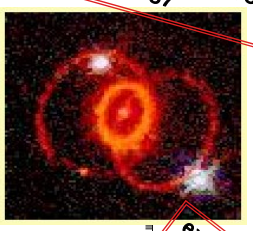


Aartsen et al (IceCube Coll), Science, Nov 2013

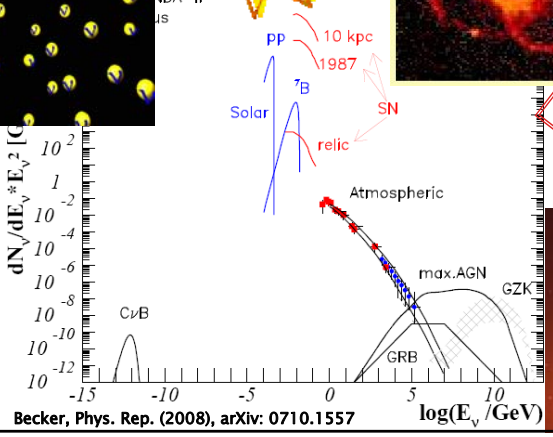
Neutrinos in the Universe



confirmed (1998)



confirmed (1987) SN1987



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

existance 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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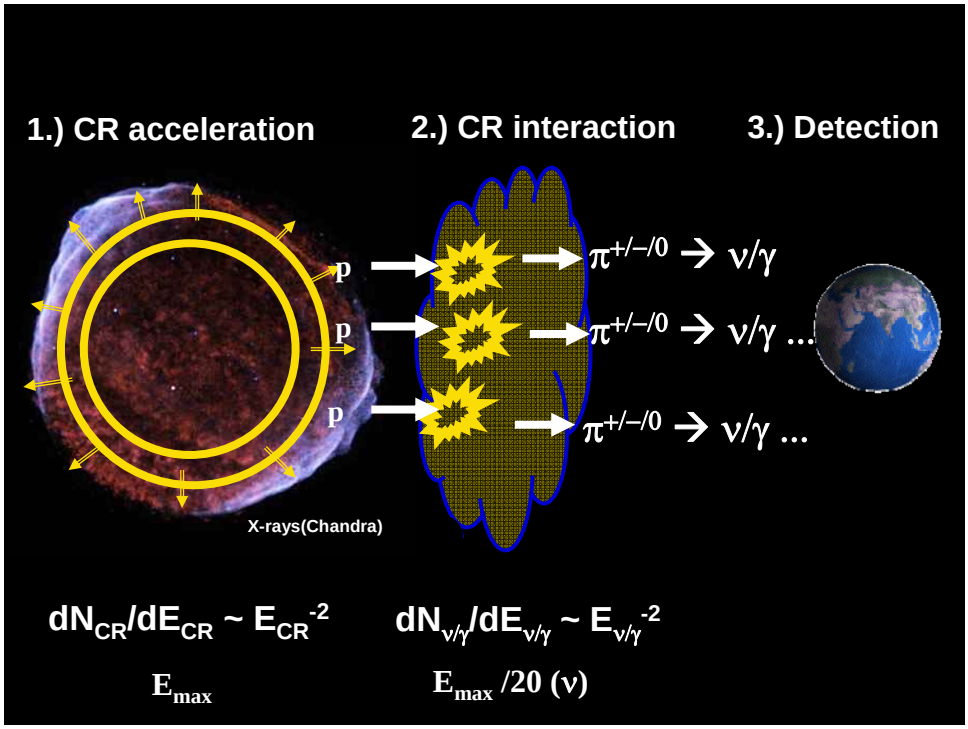
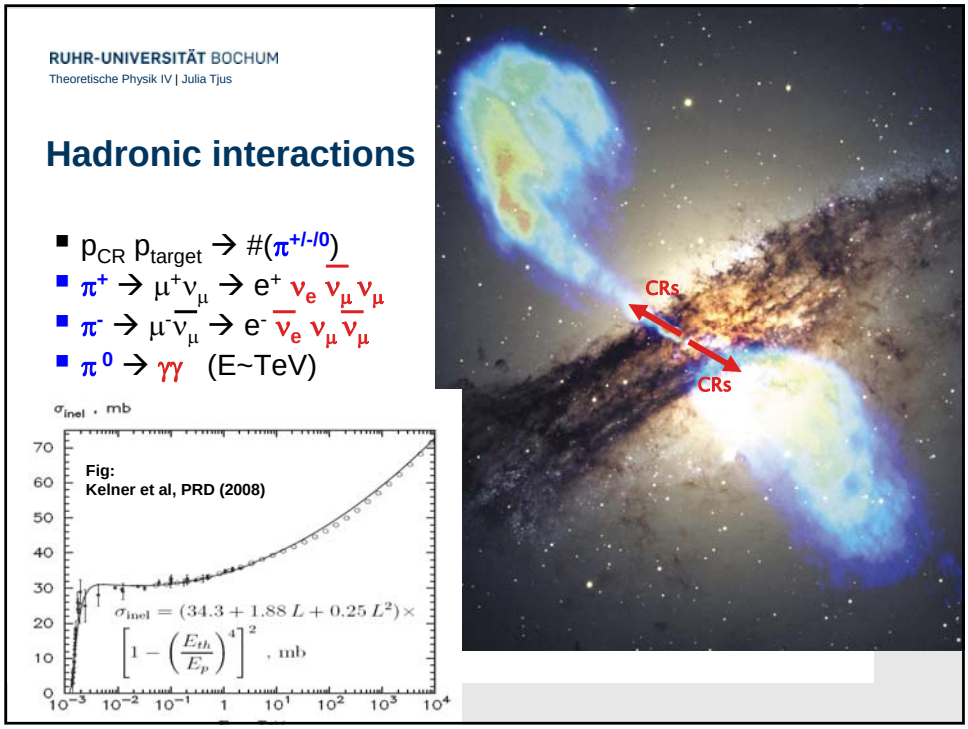

1.) CR acceleration
2.) CR interaction
3.) Detection
p
p
p
X-rays(Chandra)
$\pi^{+/-/0} \rightarrow \nu/\gamma$
$\pi^{+/-/0} \rightarrow \nu/\gamma$ ...
$\pi^{+/-/0} \rightarrow \nu/\gamma$ ...
$dN_{CR}/dE_{CR} \sim E_{CR}^{-2}$
E_{max}
$dN_{\nu/\gamma}/dE_{\nu/\gamma} \sim E_{\nu/\gamma}^{-2}$
E_{max} /20 (ν)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Hadronic interactions
$p_{CR}\ p_{target} \rightarrow \#(\pi^{+/-/0})$
$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\ \nu_e\ \nu_\mu\ \nu_\mu$
$\pi^- \rightarrow \mu^-\bar{\nu}_\mu \rightarrow e^-\ \bar{\nu}_e\ \nu_\mu\ \bar{\nu}_\mu$
$\pi^0 \rightarrow \gamma\gamma$ (E~TeV)
σ_{inel} , mb
Fig:
Kelner et al, PRD (2008)
$\sigma_{inel} = (34.3 + 1.88\,L + 0.25\,L^2) \times \left[1 - \left(\frac{E_{th}}{E_p}\right)^4\right]^2$, mb
CRs
CRs

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)

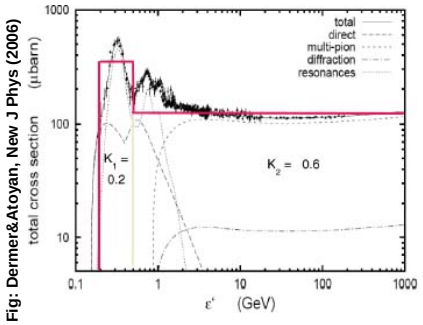
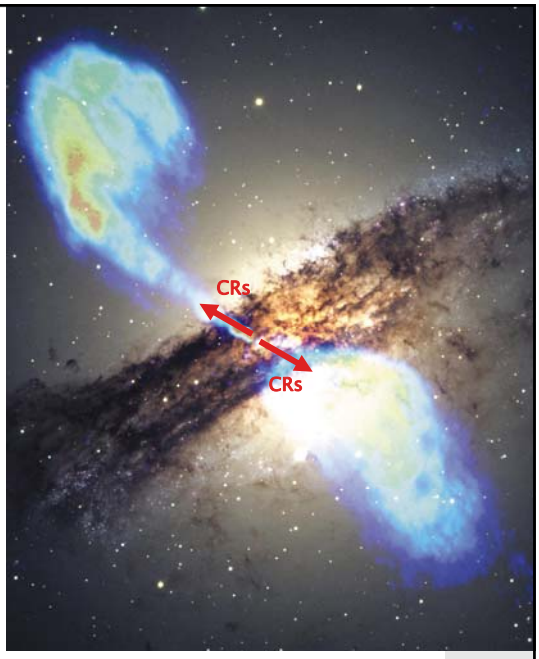


Fig: Dermer&Atoyan, New J Phys (2006)



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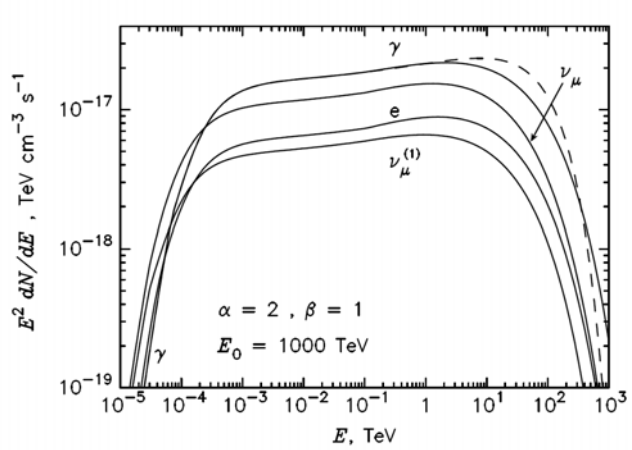
Neutrinos VS Gammas

- **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: ~ E^{-p} spectrum



- Kinematic threshold: **$E_{p,min}$ ~ 280MeV** (~ 100 MeV gamma energy)
- Above threshold: spectral behavior follows CR spectrum → ~ E^{-p}

Neutrinos ($p\gamma$)

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

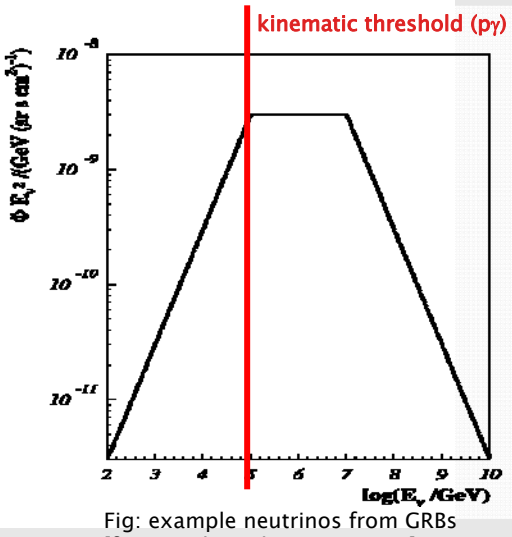


Fig: example neutrinos from GRBs [from Becker, Phys.Rep. 2008]

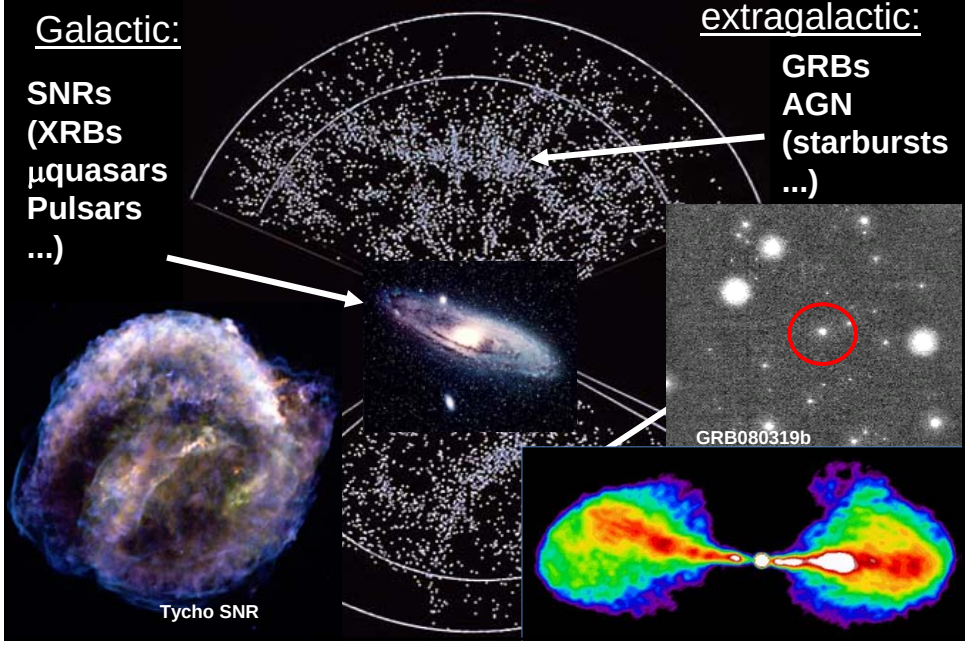
Potential neutrino sources = CR candidates

Galactic:

SNRs
(XRBs
μquasars
Pulsars
...)

extragalactic:

GRBs
AGN
(starbursts
...)



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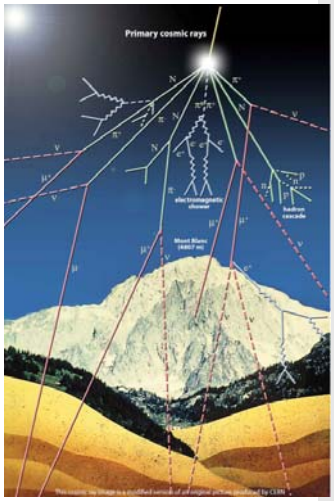
ν Background: Atmospheric ν

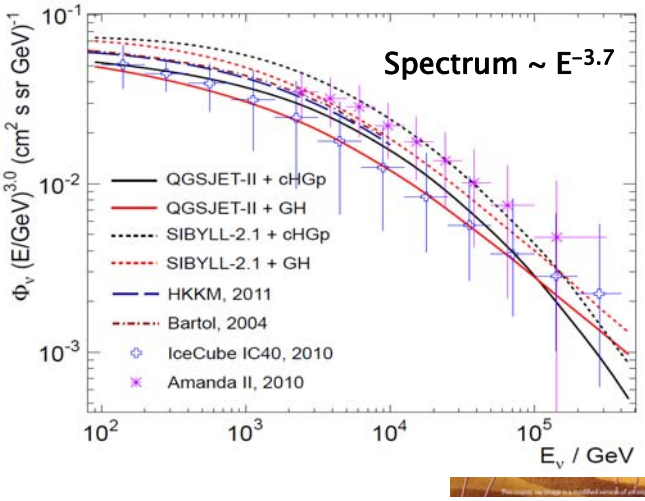
- proton-air collisions
- background estimate:
  - measurement plus simulation (CORSIKA)
- **ANFlux:** tool within IceCube for proper description of atmospheric background
  (Schöneberg, Becker Tjus, IceCube Coll.)



Fedynitch, Becker Tjus, Desiati, PRD (2012)

ν Background: Atmospheric ν

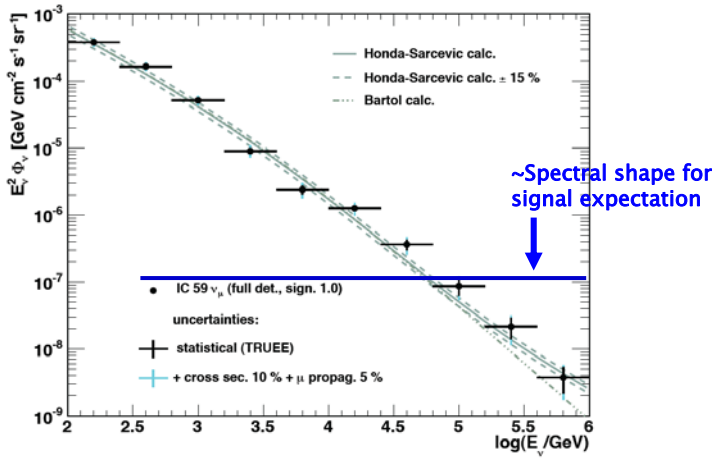
- pr
- ba
  -
- A
  pr
  ba
  (S
  Ic



Fedynitch, Becker Tjus, Desiati, PRD (2012)

Search for neutrinos

➔ Signal becomes visible toward high energies



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

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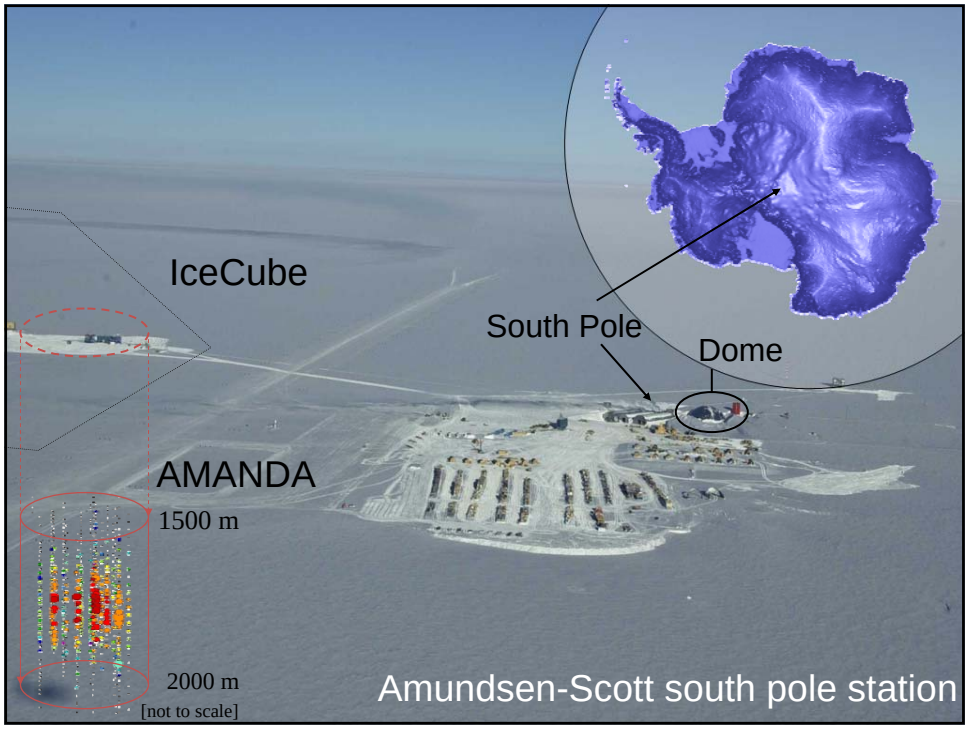

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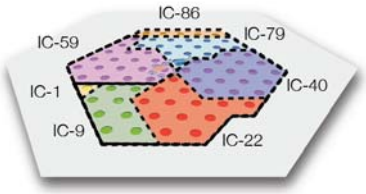
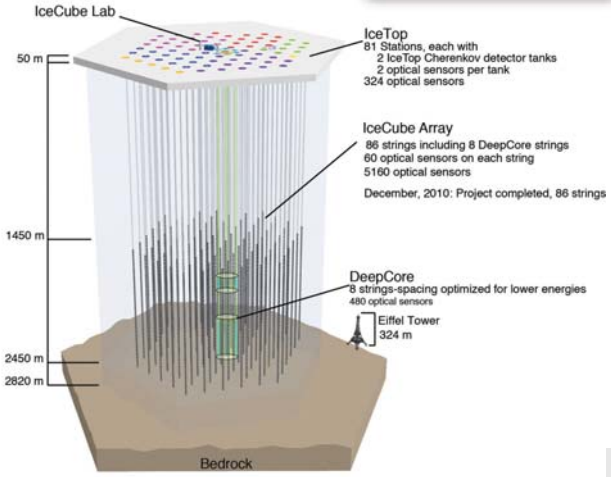
IceCube





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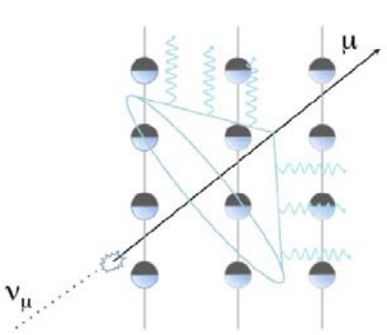
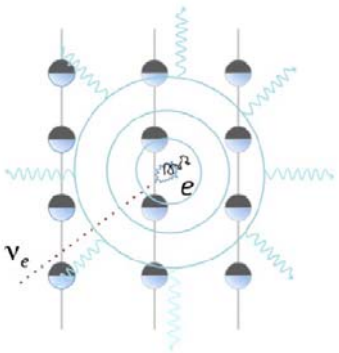
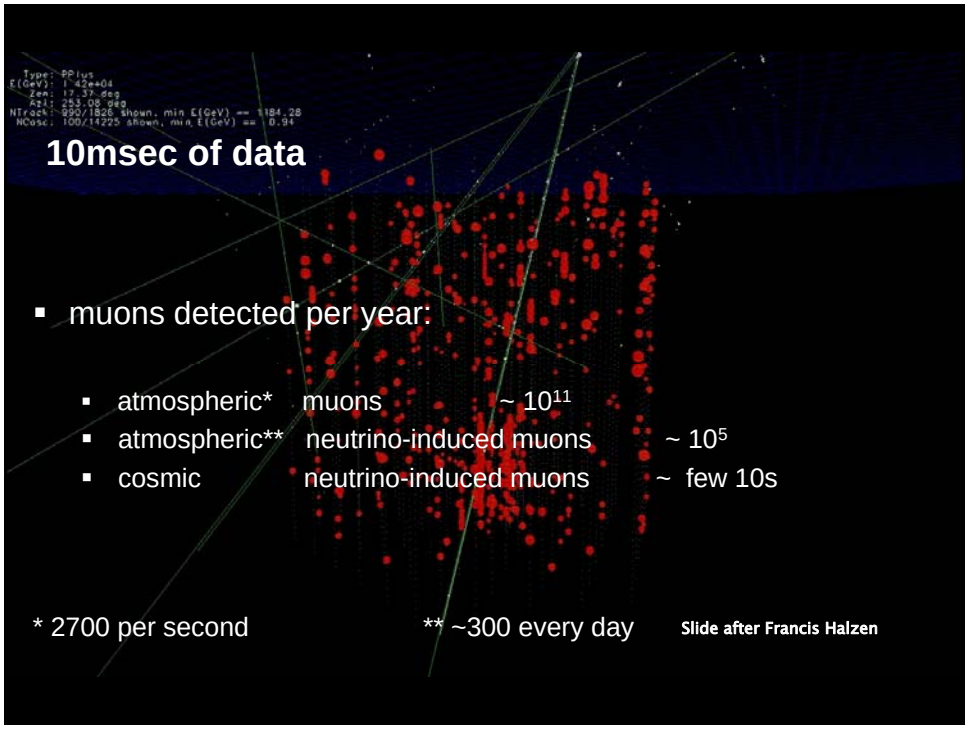
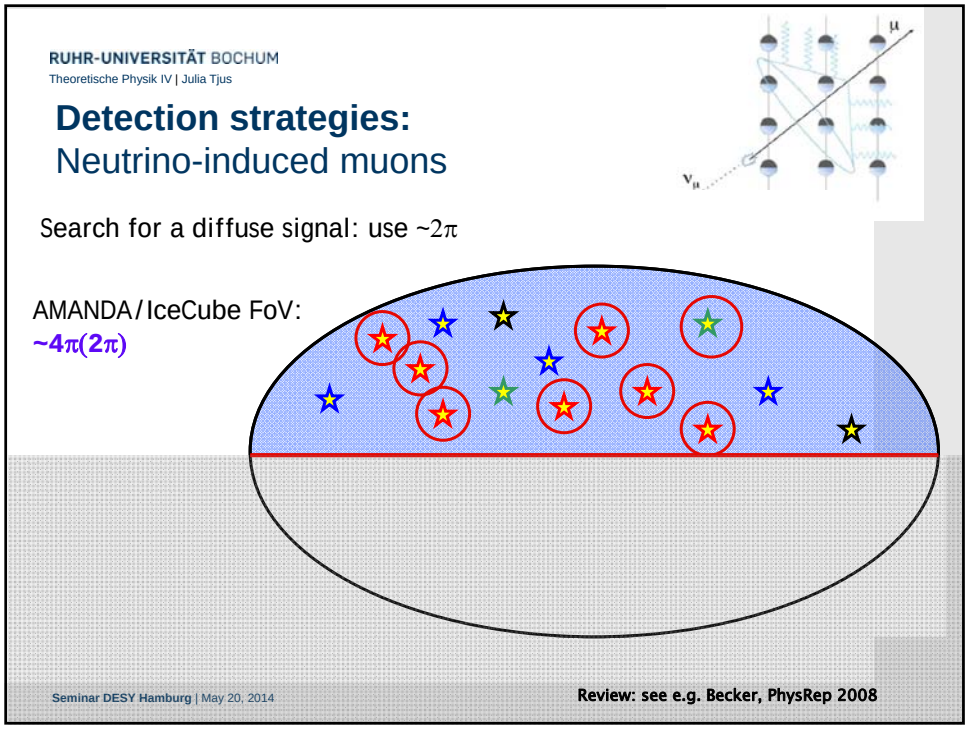
Detection method: Cherenkov light from charged particles

- ν_μ charged current interaction
- $(\nu_\mu)\nu_\varepsilon\ \nu_\tau$ charged current interaction
- $\nu_\mu\ \nu_\varepsilon\ \nu_\tau$ neutral current (ν N -> ν X)






10msec of data
muons detected per year:
atmospheric* muons ~ 10^11
atmospheric** neutrino-induced muons ~ 10^5
cosmic neutrino-induced muons ~ few 10s
* 2700 per second
** ~300 every day
Slide after Francis Halzen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Detection strategies:
Neutrino-induced muons
Search for a diffuse signal: use ~2π
AMANDA/IceCube FoV:
~4π(2π)
Seminar DESY Hamburg | May 20, 2014
Review: see e.g. Becker, PhysRep 2008

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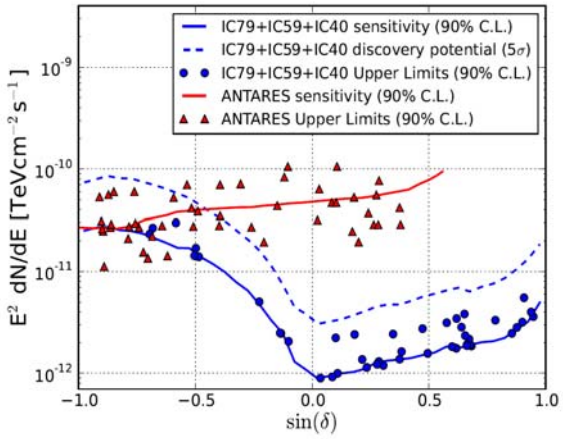
IceCube point source sensitivity



Aartsen et al (IceCube), arXiv:1307.6669

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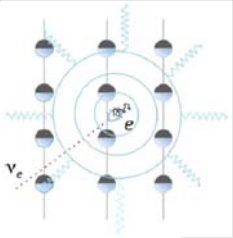
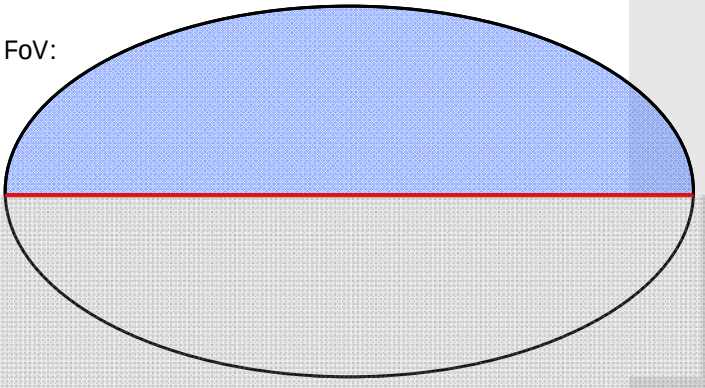


Detection strategies:
Neutrino-induced cascades

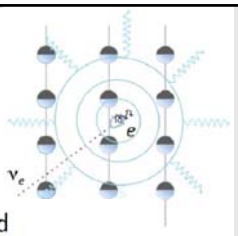
Search for a diffuse signal
Very little spatial information (nearly spherical event)

AMANDA/IceCube FoV:
~4π

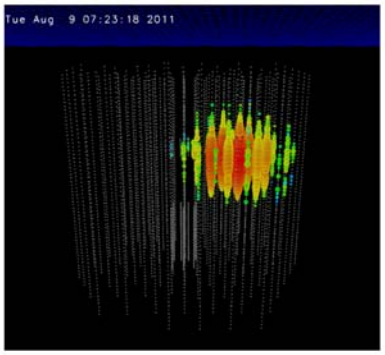


Review: see e.g. Becker, PhysRep 2008

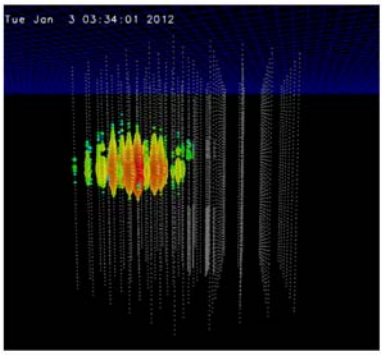
First detection of Neutrinos @ PeV energies: Cascade Channel



Appearance of ~ 1 PeV neutrinos at lower energy threshold



"Bert"
$\sim$ 1050 TeV



"Ernie"
$\sim$ 1150 TeV
arXiv:1304.5356

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

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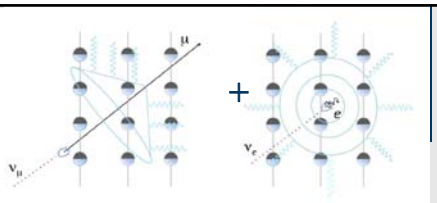
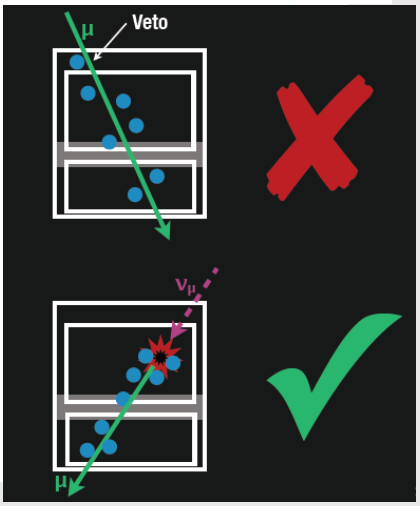
How can we exploit the detector even better to extract more possible signal?

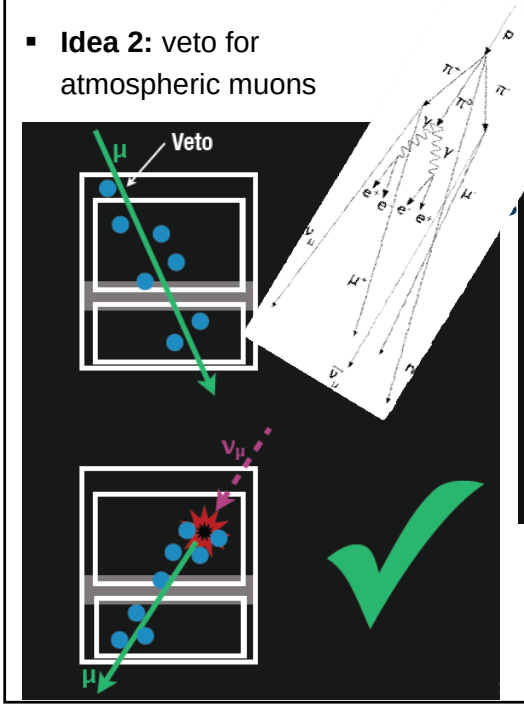


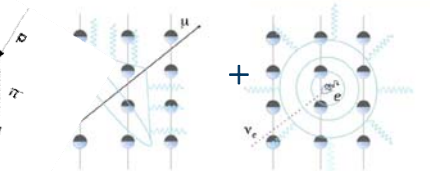
High-Energy Starting Events (HESE)

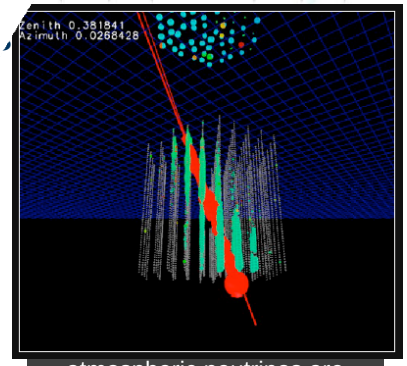
- **Idea 1:** only use contained events (veto: particles entering the detector)



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







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

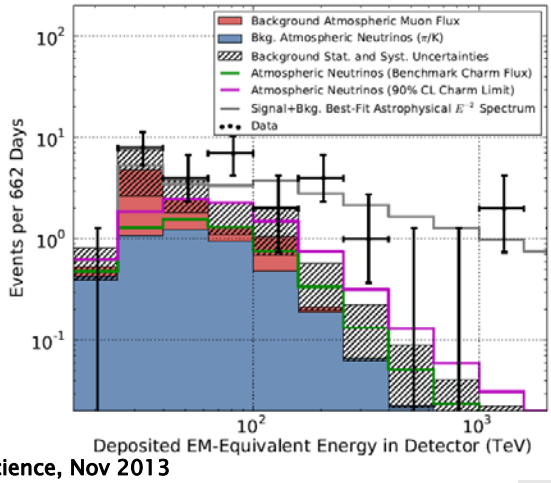
(no signals in IceTop)

Consequence

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

First evidence: Extraterrestrial high energy νs

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



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

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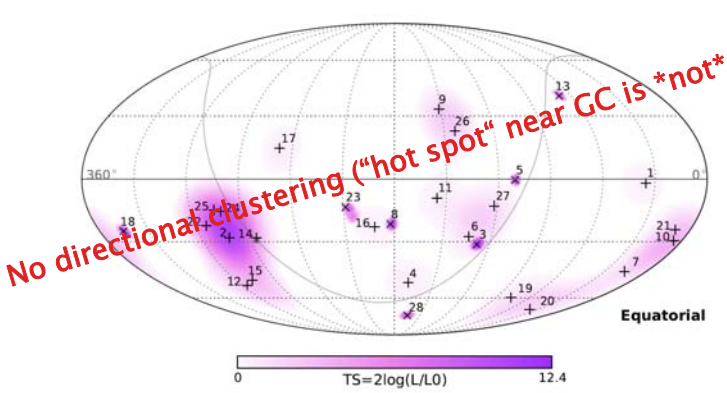
Directional information?

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



No directional clustering ("hot spot" near GC is *not* significant)

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

WANTED

sources with such conditions

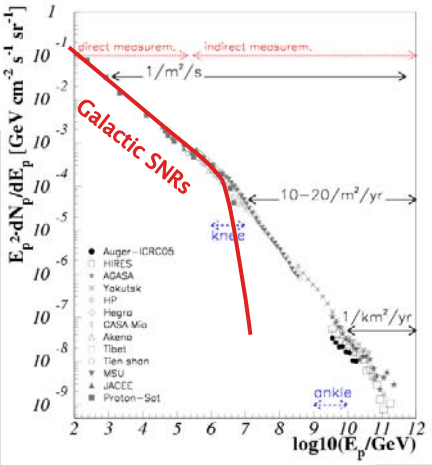
- **Astrophysical signal of strength:**
  $E^2 * dN_\nu/dE_\nu \sim 10^{-8}$ GeV s^{-1} cm^{-2} sr^{-1}
- **Spectral behavior:**
  - *EITHER* spectrum slightly steeper than E^{-2} ($\sim E^{-2.3}$)
  - *OR* cutoff @ PeV-energies
- **Spatial Clustering?:** So far isotropic distribution
- **Temporal Clustering?:**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

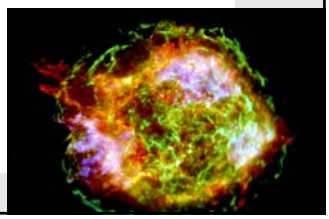
REWARD

Contents

Galactic origin?
Supernova remnants

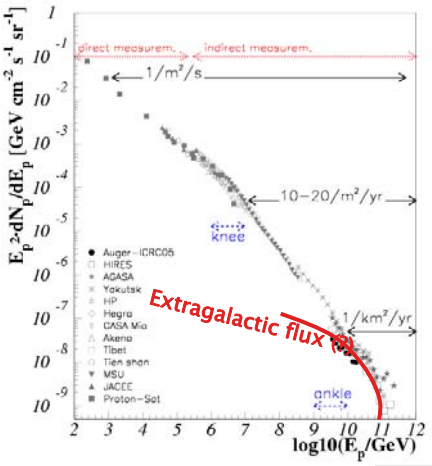
- **Astrophysical signal of strength:** $E^2 * dN_\nu/dE_\nu \sim 10^{-8}$ GeV s^{-1} cm^{-2} sr^{-1}
  - **could work**
- **Spectral behavior:**
  - **cutoff @ PeV-energies**
  - **EXPECTED**
- **Spatial Clustering?: So far isotropic distribution**
  - **would expect clustering in the Galactic plane;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

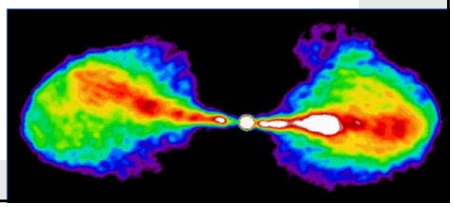




Extragalactic origin?
Active Galactic Nuclei

- **Astrophysical signal of strength:** $E^2 * dN_\nu/dE_\nu \sim 10^{-8}$ GeV s^{-1} cm^{-2} 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





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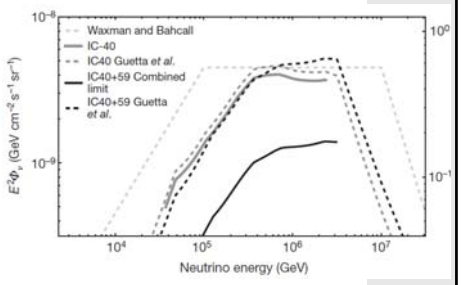
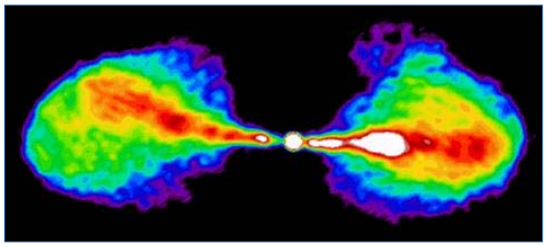
Extragalactic origin? Gamma-ray bursts

- **Astrophysical signal of strength:** $E^2 * dN_\nu/dE_\nu \sim 10^{-8}$ GeV s^{-1} cm^{-2} 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 ~10^{10} cm^{-3} (AGN jet/knots)
  - to << 1 cm^{-3} (termination shock intergalactic medium)



Becker Tjus, Eichmann, Halzen, Saba, accepted in PRD, arXiv:1406.0506

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Cross section

Muon neutrino distribution function

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

Target column cm^{-2}

Primary flux

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

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

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

Seminar DESY Hamburg | May 20, 2014

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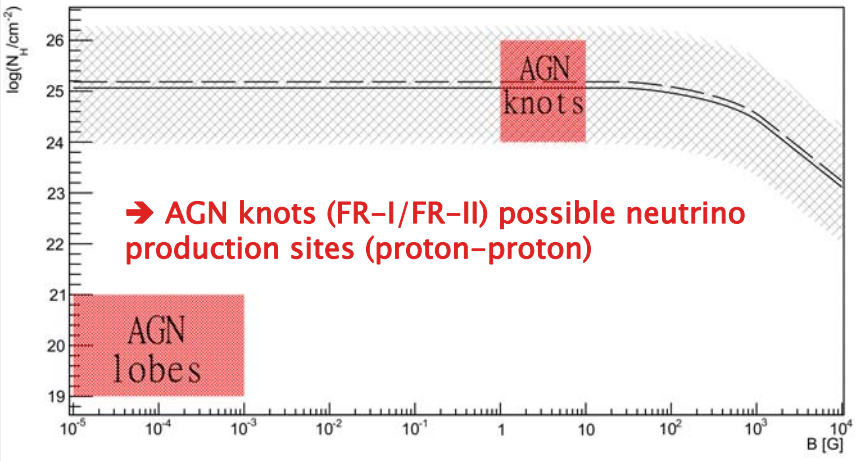
➔ N_H – B:
allowed Parameter space VS observed properties



➔ AGN knots (FR-I/FR-II) possible neutrino production sites (proton-proton)

Becker Tjus, Eichmann, Halzen, Saba, accepted in PRD, arXiv:1406.0506

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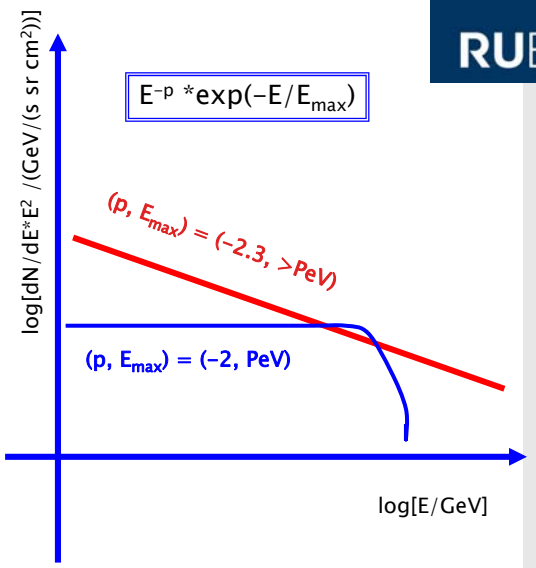
Future tests

1. Spectral behavior:

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



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Future tests

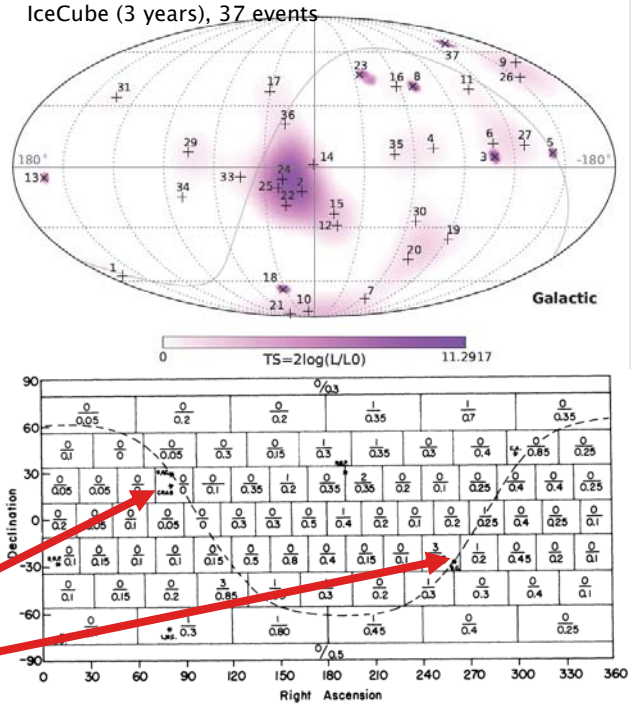
1. Spectral behavior
2. Directional information: when to expect the first point sources?

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)

IceCube (3 years), 37 events



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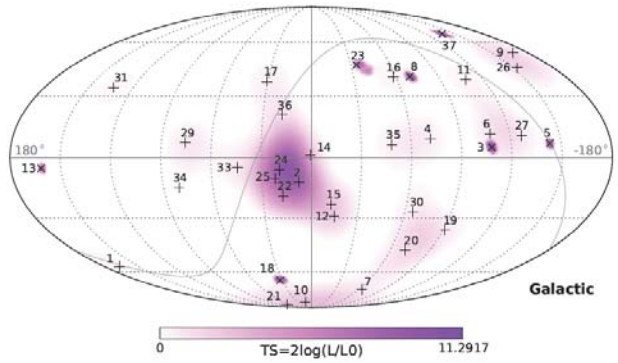
Future tests

1. Spectral behavior
2. Directional information: when to expect the first point sources?
3. Flavor ratio $(\nu_\mu, \nu_e, \nu_\tau)$

Typical π-decay ratio incl. oscillations:
$(\nu_\mu, \nu_e, \nu_\tau)$ ~ (1:1:1)

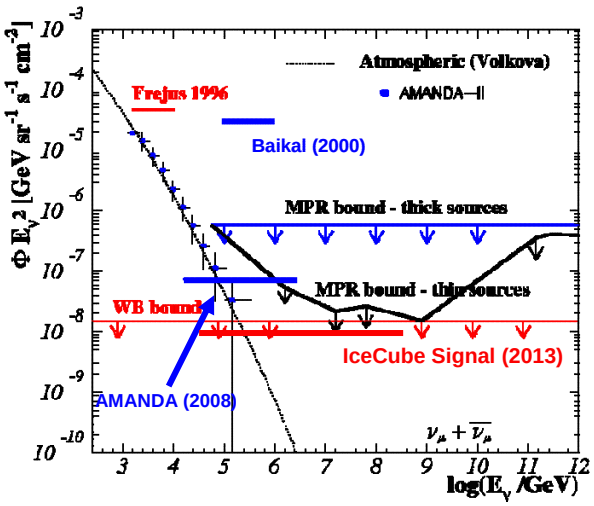


x: Myon (CC ν_μ)
+: cascade (CC $\nu_e+(\nu_\mu)+\nu_\tau$, NC $\nu_e+\nu_\mu+\nu_\tau$)
$\sigma_{CC} \sim 2*\sigma_{NC}$

➔ $(x{:}+)_{(1:1:1)\text{-prediction}} \sim (1{:}4.0\text{-}4.5)$

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)

update of Becker, Neutrino 2008; ArXiv:0811.0696

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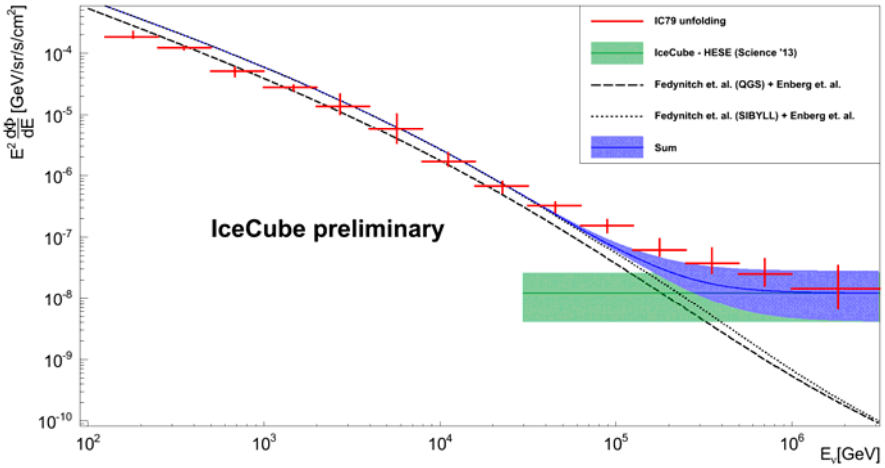
Outlook (I)



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

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 (mediterrenean);
  - IceCube high-energy extension
- ➔ Detectors need to be a factor of a few larger than IceCube