RUHR-UNIVERSITÄT BOCHUM

Constraints on the sources of extragalactic cosmic rays

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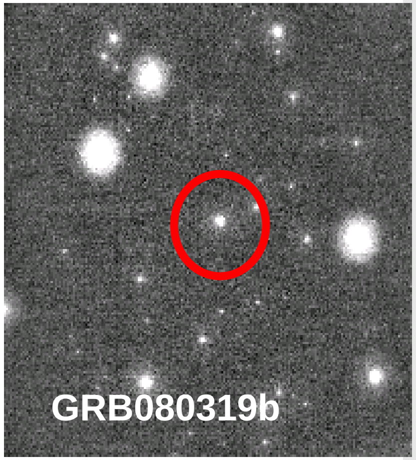
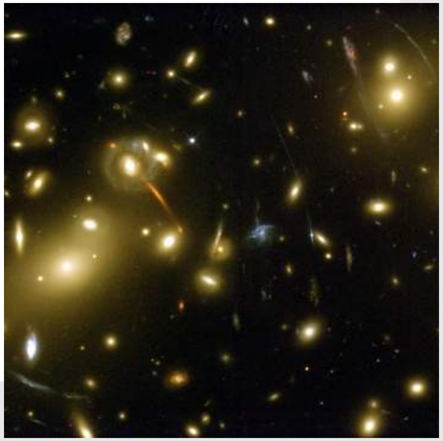
FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV

Extragalactic neutrino source candidates

- Active galactic nuclei
- Gamma-ray bursts
- (Starburst galaxies)
- (Galaxy clusters)
- …





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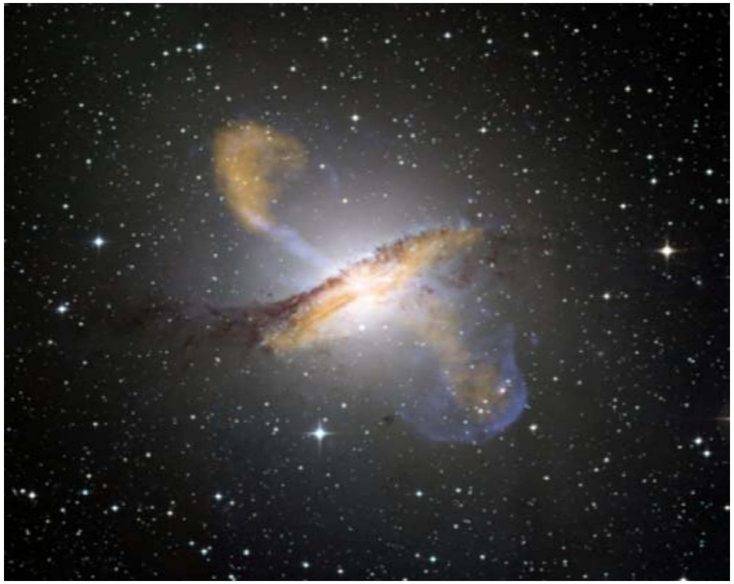
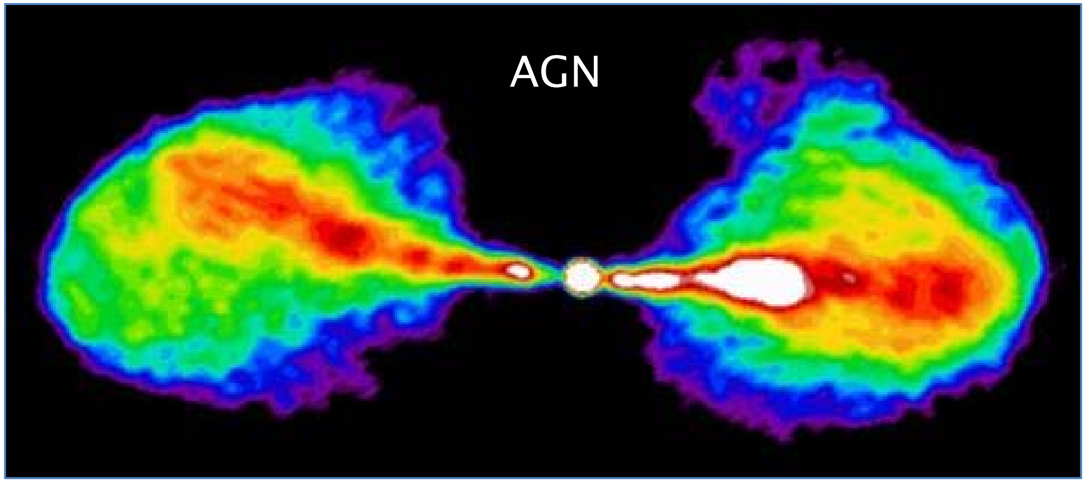


Active Galactic Nuclei



Radio-loud (10%)

Strong radio

Weak radio

Orientation

Radio quiet (90%)

Strong optical

Weak optical

Orientation

First constraints from neutrino limits

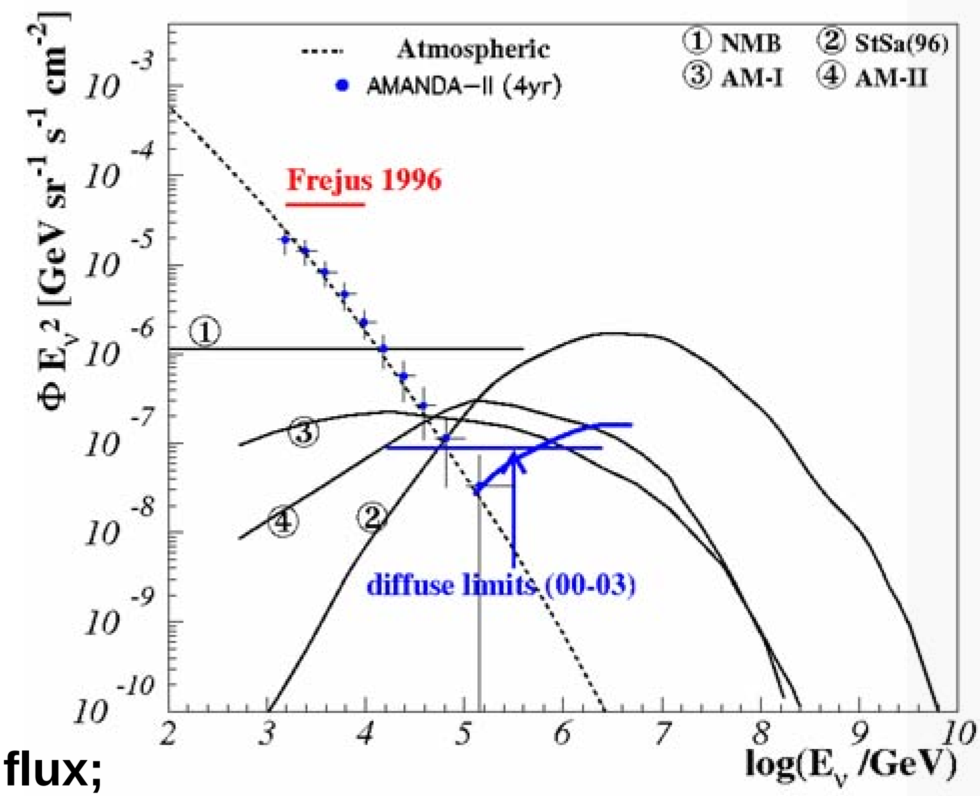
AMANDA

(1) *Nellen,Mannheim&Biermann* Phys.Rev.D (1993)

(2) *Stecker&Salamon* Space Science Rev. (1996)

(3/4) *Alvarez-Muñiz & Mészáros* PRD **70** (2004)

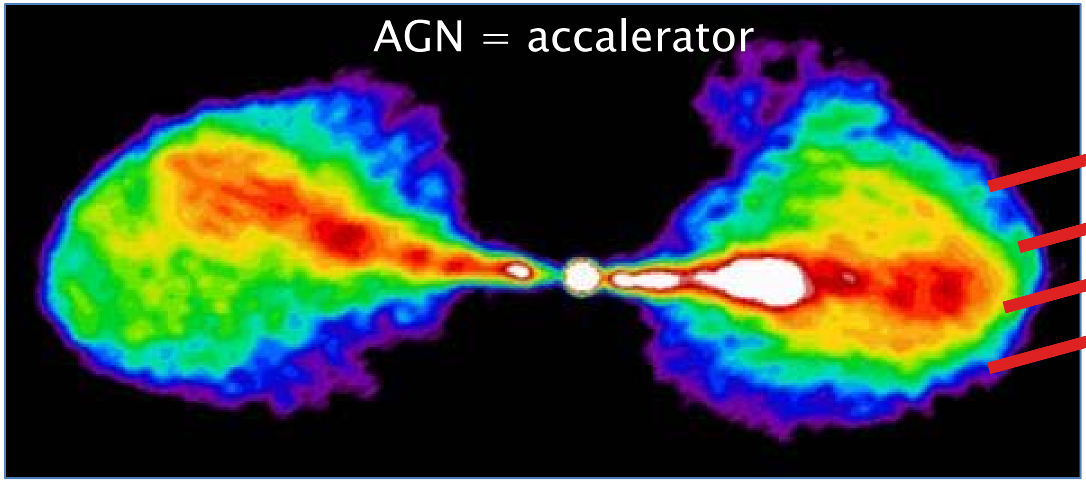
Data: *AMANDA (2000-2003)*
Spectrum: Münich et al., ICRC 2007
Limits: Achterberg et al, PRD **75** (2007)

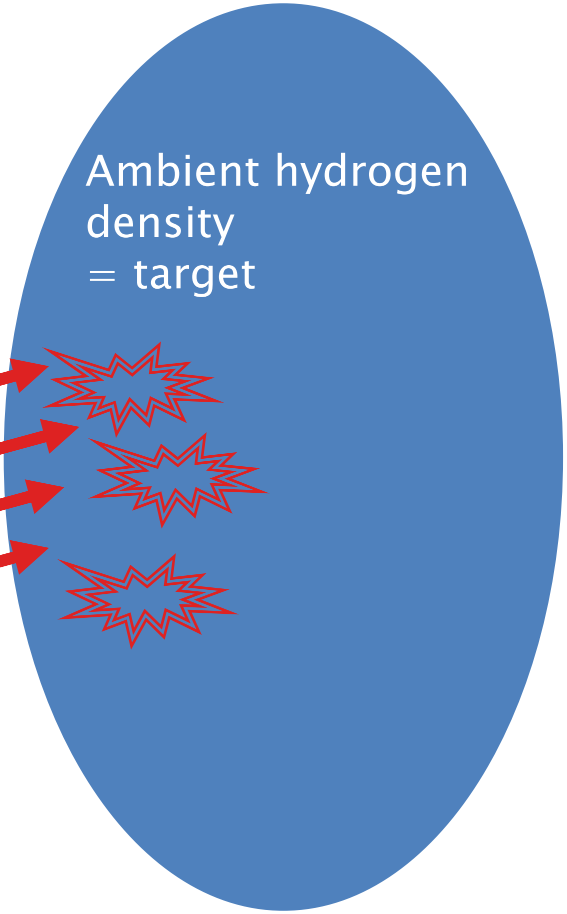


➔**No direct correlation with X-ray flux;**
➔compatible with astronomical findings that X-rays from AGN are dominantly of thermal origin

JKB et al, Astrop. Phys. **28**:98 (2007)

Proton-proton interactions





Proton flux: compare to radio flux
Target density: order 1 – 1000/cc

Work by Isaac Saba (Bochum)

RUB

Primary flux

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

- Powerlaw $1 < p < 3$
- $E_{max} \sim 10^{21}$ eV

- Normalization? → Use radio observation as measure of energy going into electrons with fixed ratio of electrons/protons f_e:

$$L_{radio} \xrightarrow{synch} L_{radio} = L_e \xrightarrow{f_e \approx 0.1} L_e = f_e \cdot L_p$$

$$\boxed{L_{radio} = f_e \cdot L_p}$$

Work by Isaac Saba (Bochum)

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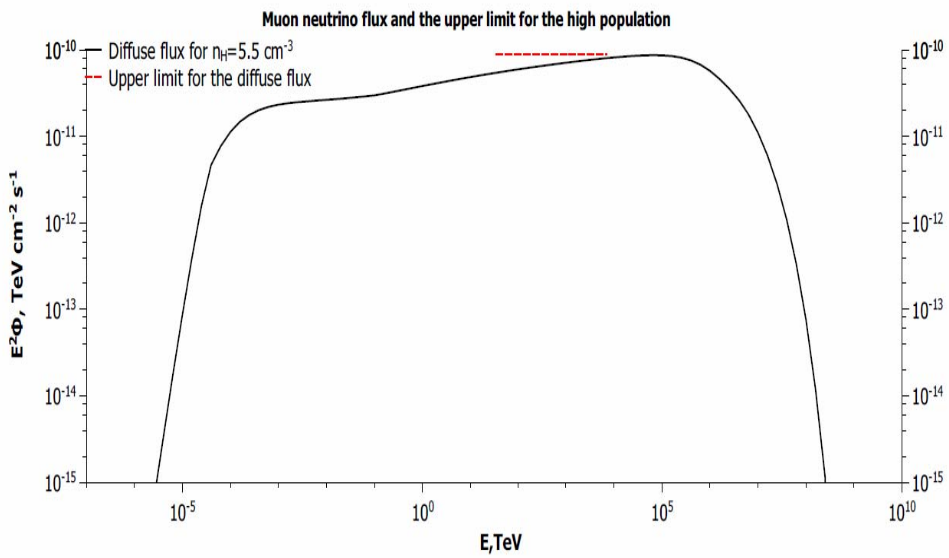
e.g. diffuse flux from FR – II galaxies

- Theory:

$$A_\nu \propto f_e^{-1} \cdot n_H$$

- IceCube:
- A_ν < 8.9e-11/TeV/s/sr/cm^2
- ➔ n_H < 5.5 cm^{-3} *(f_e/0.1)



- If protons are accelerated in **FR – II** jets:
  - **Average target density must be smaller than a few particles/cc**
  - Realistic, but at the boundary (smaller than 1/cc seems rather unlikely)

Work by Isaac Saba (Bochum)

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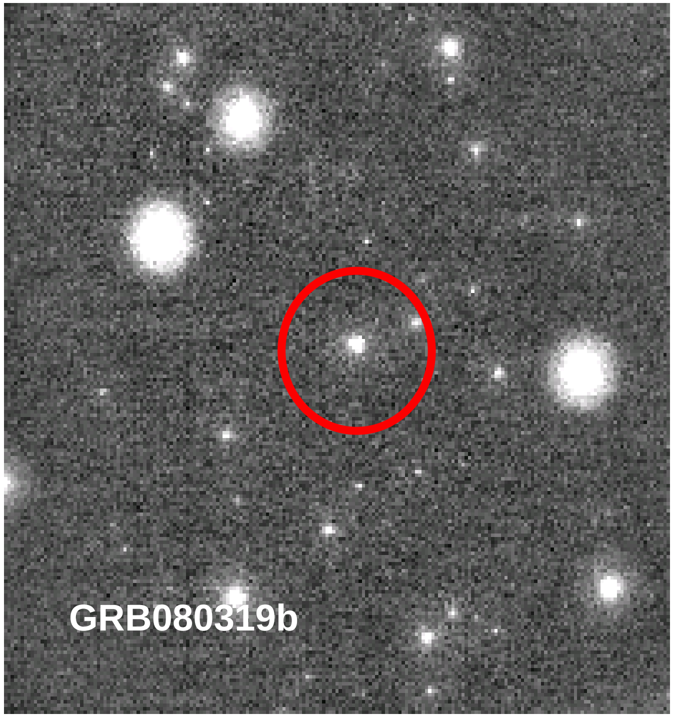
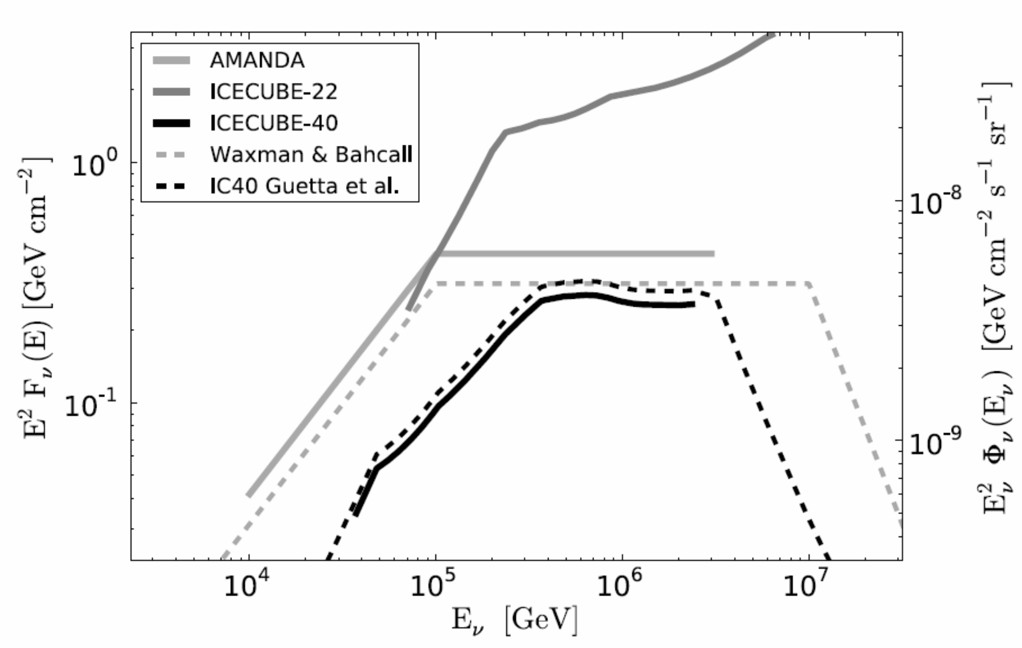


Stacking of satellite-observed bursts

Strong constraints on…

- Strong contraints on…
  - Proton-to-electron energy fraction
  - Variability time
  - Boost factor
- … from neutrino observations



Abbasi et al (2011)

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Gamma-ray bursts

- Proton-gamma interactions result in the following neutrino flux description
- (**original idea: Waxman & Bahcall 1999**; follow-up papers: Guetta et al 2004, JKB et al 2005/2010, Baerwald et al 2011, ...)

$$\frac{dN_\nu}{dE_\nu} = f_\nu \cdot \begin{cases} \epsilon_1^{\alpha_\nu - \beta_\nu} \mathrm{E}_\nu^{-\alpha_\nu} & \text{if } \mathrm{E}_\nu < \epsilon_1 \\ \mathrm{E}_\nu^{-\beta_\nu}, & \text{if } \epsilon_1 < \mathrm{E}_\nu < \epsilon_2 \\ \epsilon_2^{\gamma_\nu - \beta_\nu} \mathrm{E}_\nu^{-\gamma_\nu} & \text{if } \mathrm{E}_\nu > \epsilon_2 \end{cases}$$

$$\epsilon_1 = 7.5 \times 10^5 \,\mathrm{GeV} \frac{1}{(1+z)^2} \left(\frac{\Gamma}{10^{2.5}}\right)^2 \left(\frac{\mathrm{MeV}}{\epsilon_\gamma}\right)$$

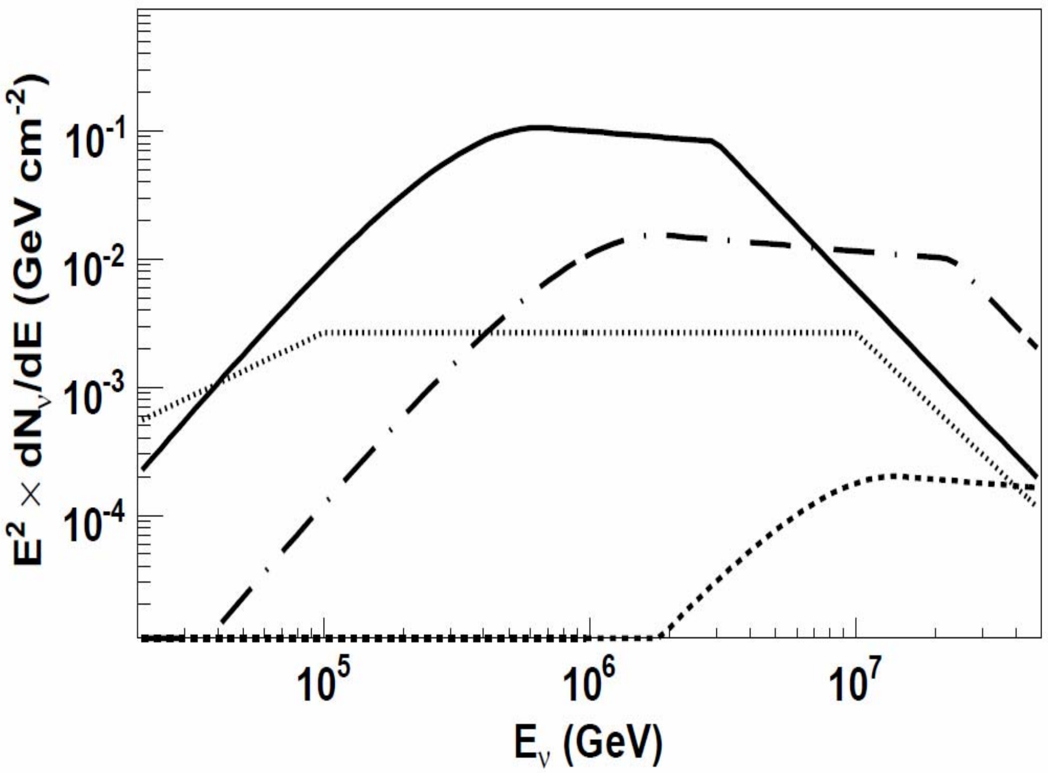
$$\epsilon_2 = 10^7 \,\mathrm{GeV} \frac{1}{1+z} \sqrt{\frac{\epsilon_e}{\epsilon_B}} \left(\frac{\Gamma}{10^{2.5}}\right)^4 \left(\frac{\delta t}{10\,\mathrm{ms}}\right) \sqrt{\frac{10^{52}\,\mathrm{ergs\ s^{-1}}}{L_\gamma^{\mathrm{B}}}}$$

$$f_\nu \sim \frac{1}{8} \frac{\epsilon_p}{\epsilon_e} \left[1 - (1 - \langle x_{p\to\pi} \rangle)^{\Delta R/\lambda_{p\gamma}}\right]$$

$$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\mathrm{B}}}{10^{52}\mathrm{erg\ s^{-1}}}\right) \left(\frac{10\,\mathrm{ms}}{\delta t}\right) \left(\frac{10^{2.5}}{\Gamma}\right)^4 \left(\frac{\mathrm{MeV}}{\epsilon_\gamma}\right)$$

Parameter space of observables

- Boost factor
- Variability time
- Ratio of energies between protons and electrons

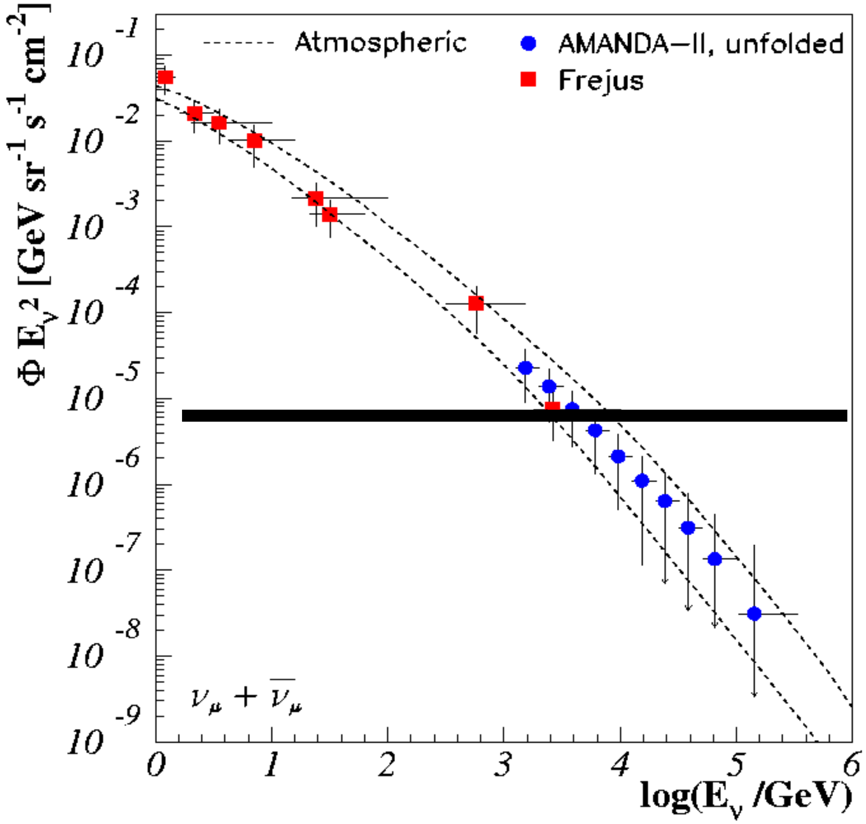


Example: "Naked-eye burst (V~5)" GRB080319B, **Γ = 300, 500, 1400**

Abbasi et al (IceCube Coll), ApJ 701 (2009)

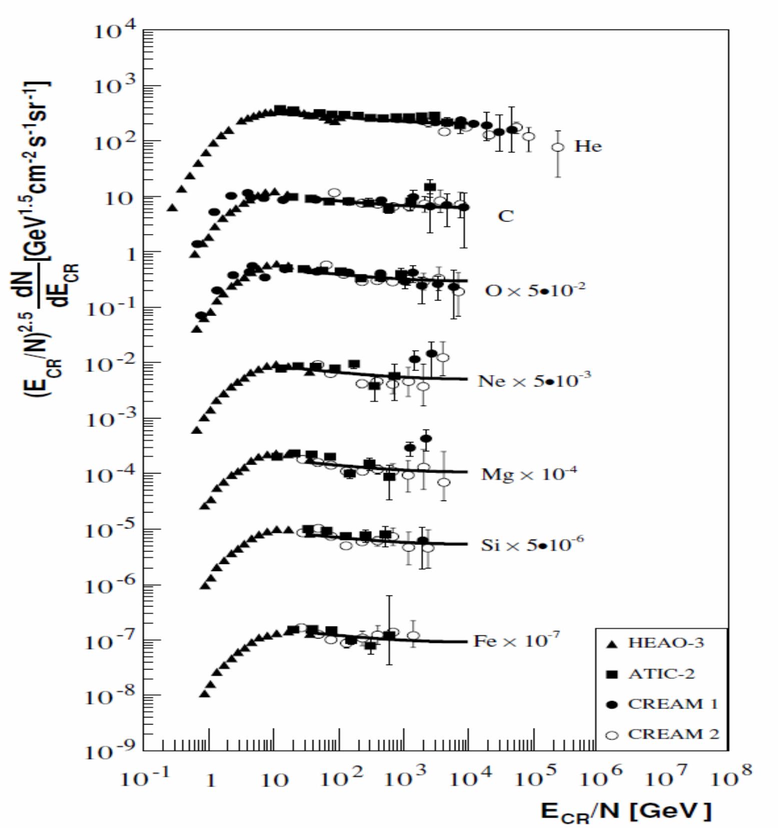
Atmospheric Background

- Search for enhanced signal above atmospheric background
- ➔ important to know and reduce possible systematic uncertainties



Atmospheric neutrino flux: Central uncertainties

- Primary composition
- Atmospheric variations
- Interaction model



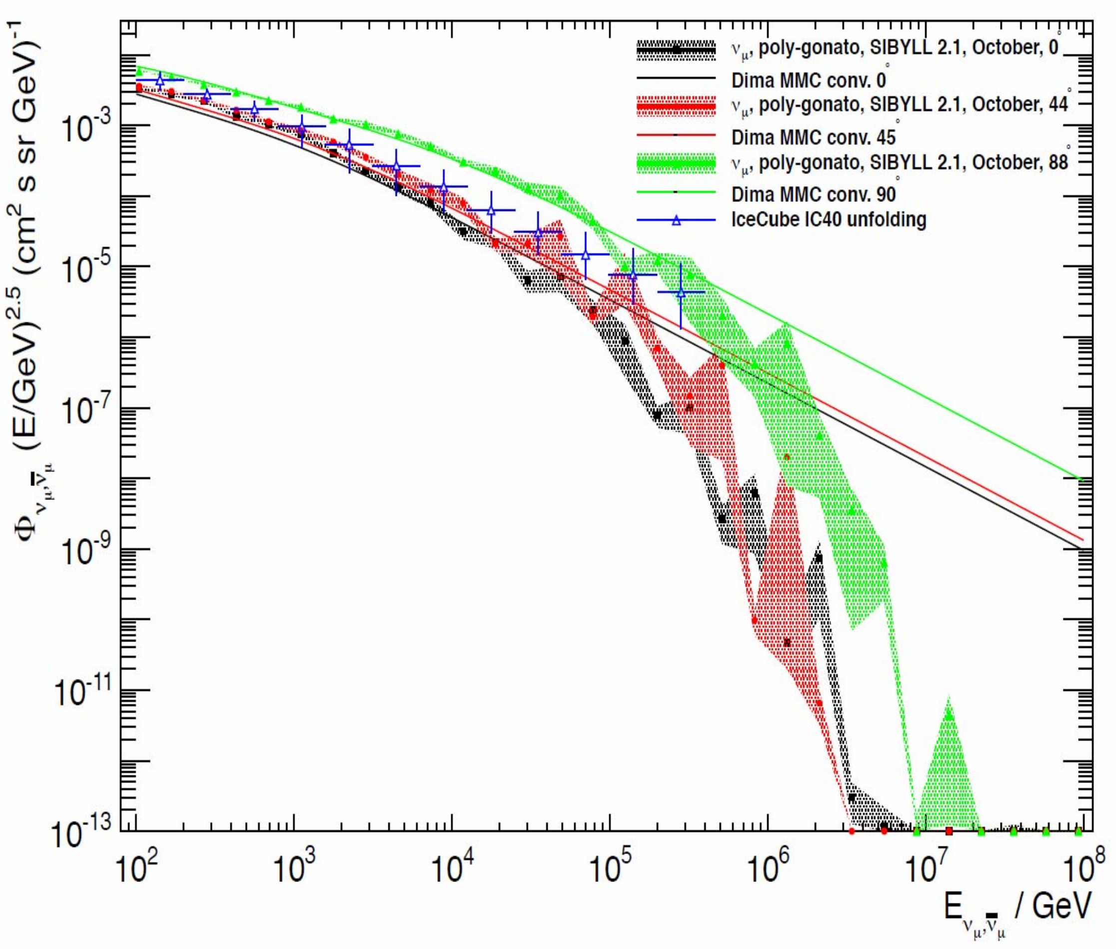
Corsika Simulations

- Primary energy: 100 GeV - 10^{10} GeV (not per nucleon), 5 bins/decade
- Primary composition: H, He, CNO, MgAlSi, Fe
- Zenith angles: 0, 44, 88 degrees
- Secondary particles: muon neutrinos, electron neutrinos, muons
- Interaction models: SIBYLL 2.1, QGSJET01c
- Geographic location: South pole
- Atmospheric profiles: 4 seasons at the south pole
- Altitude: surface above IceCube (2834 m)
- Observed secondary energy range 80 - 10^8 GeV
- Statistics: 50000 showers at 100 GeV, 1000 showers at 10^{10} GeV, $E^{-1.2}$ spectrum, results in more than 10^8 individual shower simulations

Fedynitch, Desiati, Becker, in preparation

Atmospheric neutrino spectra

- Standard simulations in IceCube do not include the knee in the primary spectrum
- **Overestimation of atmospheric background without including the knee**
- Including knee reduces atmospheric background and enhances detection possibility



Fedynitch, Desiati, Becker, in preparation

Summary

- Neutrino limits now starting to put serious constraints on:
  - Gamma-ray bursts as UHECR sources (proton-gamma)
  - Proton-proton interactions in active galactic nuclei
- The conclusions from the limits are not straight-foward, but need to be reviewed carefully in the context of the physics parameters!