The Abdus Salam International Centre for Theoretical Physics

2246-25

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

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Prospects of detecting extragalactic sources of high energy neutrinos

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RUHR-UNIVERSITÄT BOCHUM

On the prospects of detecting extragalactic neutrino sources

Nusky 2011, Trieste

Julia K. Becker

FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV

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Conditions for a significant detection of extragalactic neutrinos

- **Identification of possible neutrino sources**
  - *Steady point sources* (starbursts, galaxy clusters, active galactic nuclei, …)
  - *Transient sources* (active galactic nuclei, gamma-ray bursts, supernovae, …)
  - *Diffuse flux*
- **Signal-background separation**
  - Improving *analysis techniques*
  - Good estimate of the *background*
- ***This talk:*** *discussion of neutrino flux* ***production sites and background*** *estimation*

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Hadronic interactions

- Proton-proton interactions (see e.g. Kelner et al, PRD **74** (2006)):

$$\Phi_\gamma(E_\gamma) \equiv \frac{dN_\gamma}{dE_\gamma\ dV\ dt} = n_H \int_{E_\gamma}^{\infty} \sigma_{\rm inel}(E_p) \cdot j_p(E_p) \cdot F_\gamma\left(\frac{E_\gamma}{E_p},\ E_p\right)\ \frac{dE_p}{E_p}$$

- Proton-gamma interactions (see e.g. Kelner et al, PRD **78** (2008)):

$$\frac{dN_\gamma}{dE_\gamma} = \int f_p(E_p)\, f_{\rm ph}(\epsilon)\ \Phi_\gamma(\eta,\, x)\, \frac{dE_p}{E_p}\, d\epsilon$$

- Uncertainties:
  - Cross sections (Particle Physics)
  - Primary spectrum (Plasma-Astrophysics)
  - Interaction target (Astrophysics)
  - Diffuse flux: source distribution (Cosmology)

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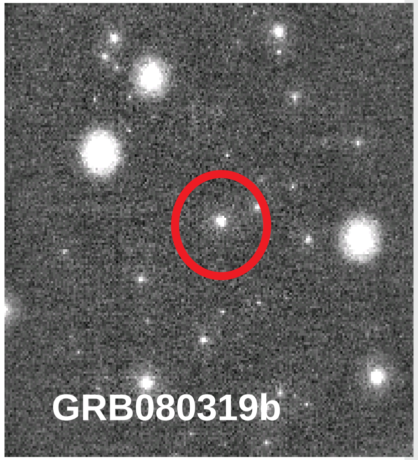
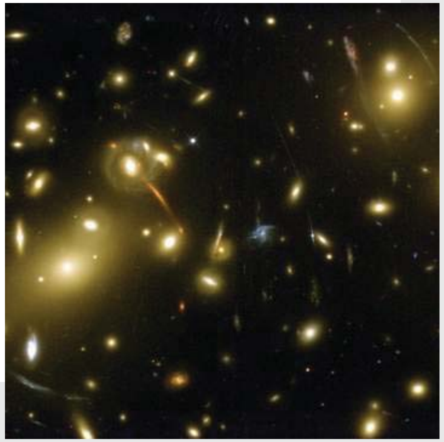
Contents

- Extragalactic neutrino source fluxes
- Investigation of atmospheric neutrino flux uncertainties
- Outlook: Possible cosmic ray (neutrino?) tracers

Extragalactic neutrino source candidates

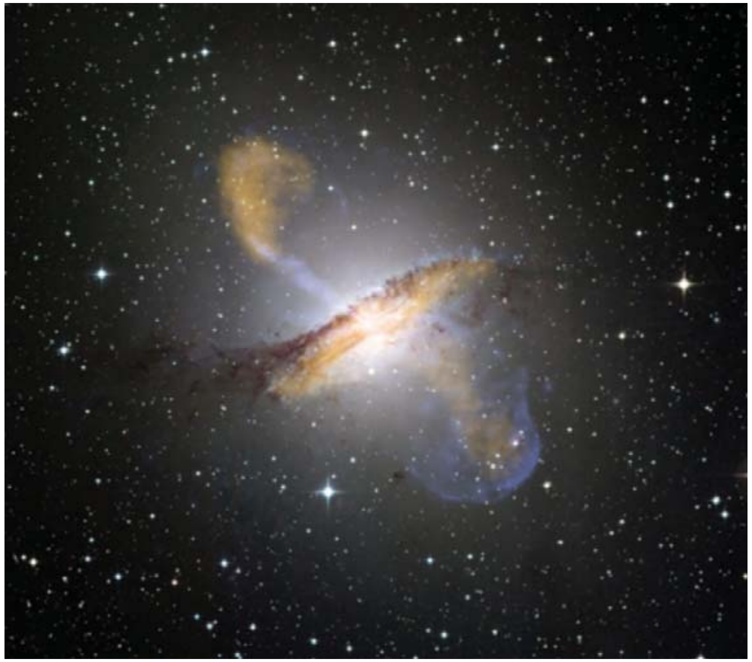
- Active galactic nuclei
- Gamma-ray bursts
- Starburst galaxies
- Galaxy clusters
- …





Neutrino source candidates

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



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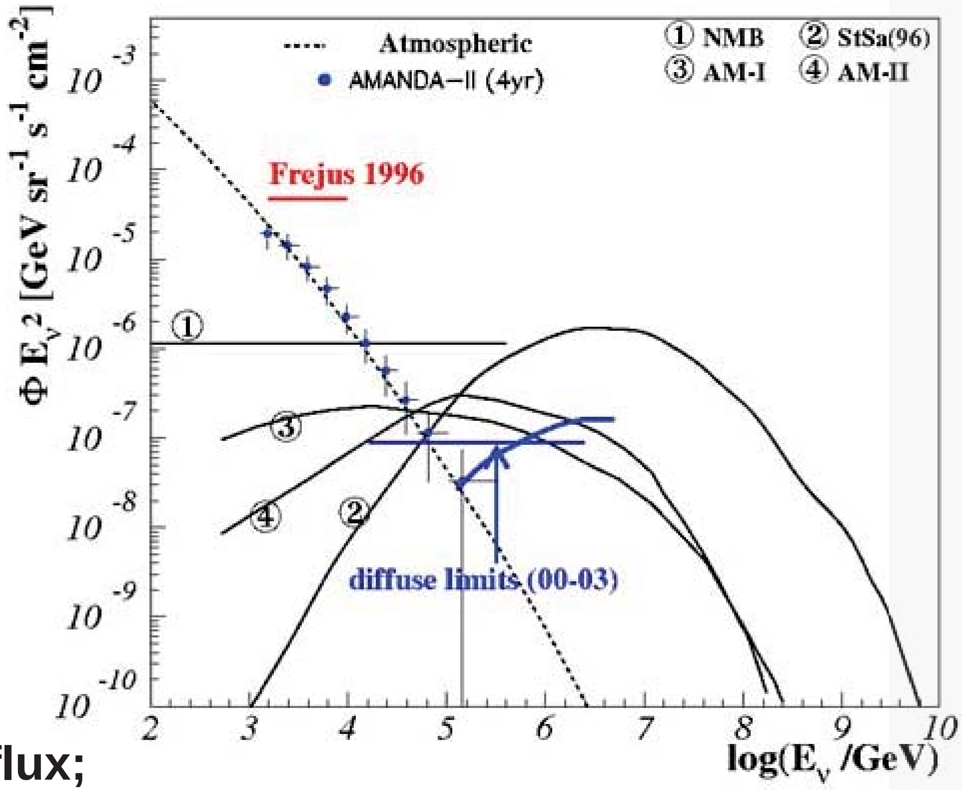
First constraints from neutrino limits

(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)

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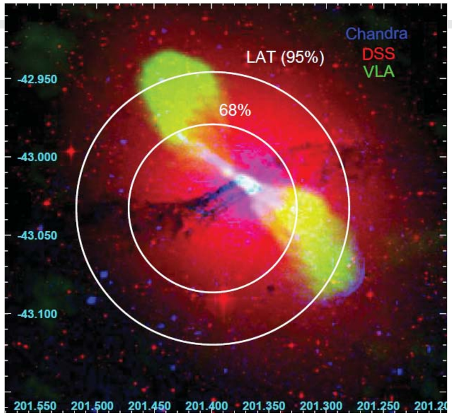
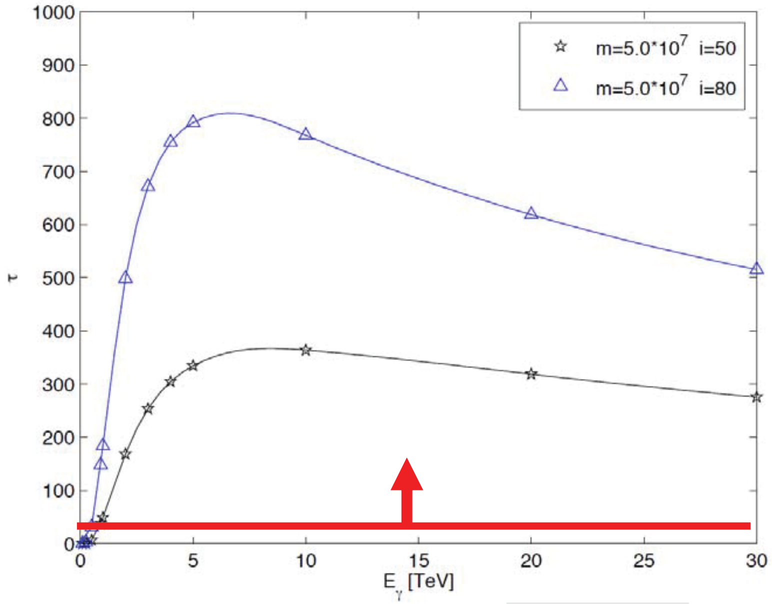
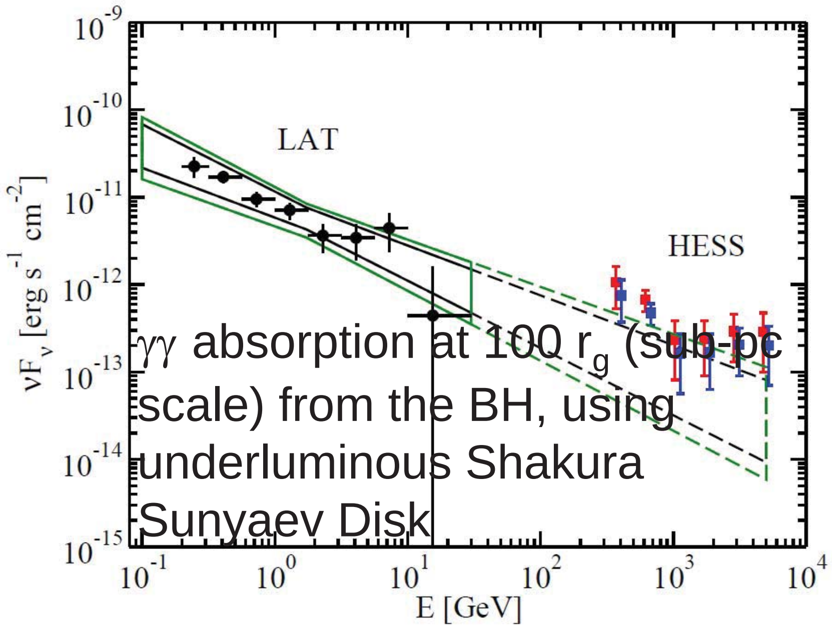
The case of CenA





- Core and jet models discussed
- Core: gamma-rays interact with photons from the disk
- Modeling shows: >TeV photons cannot escape the core region → observed TeV photons must come from further out
- < TeV photons and > TeV neutrinos might be detected from core region

H.E.S.S.: kpc scale, inner jet?



Brodatzki, Pardy, JKB, Schlickeiser, accepted by ApJ; arXiv:1103.5552

The case of TeV-transparent AGN

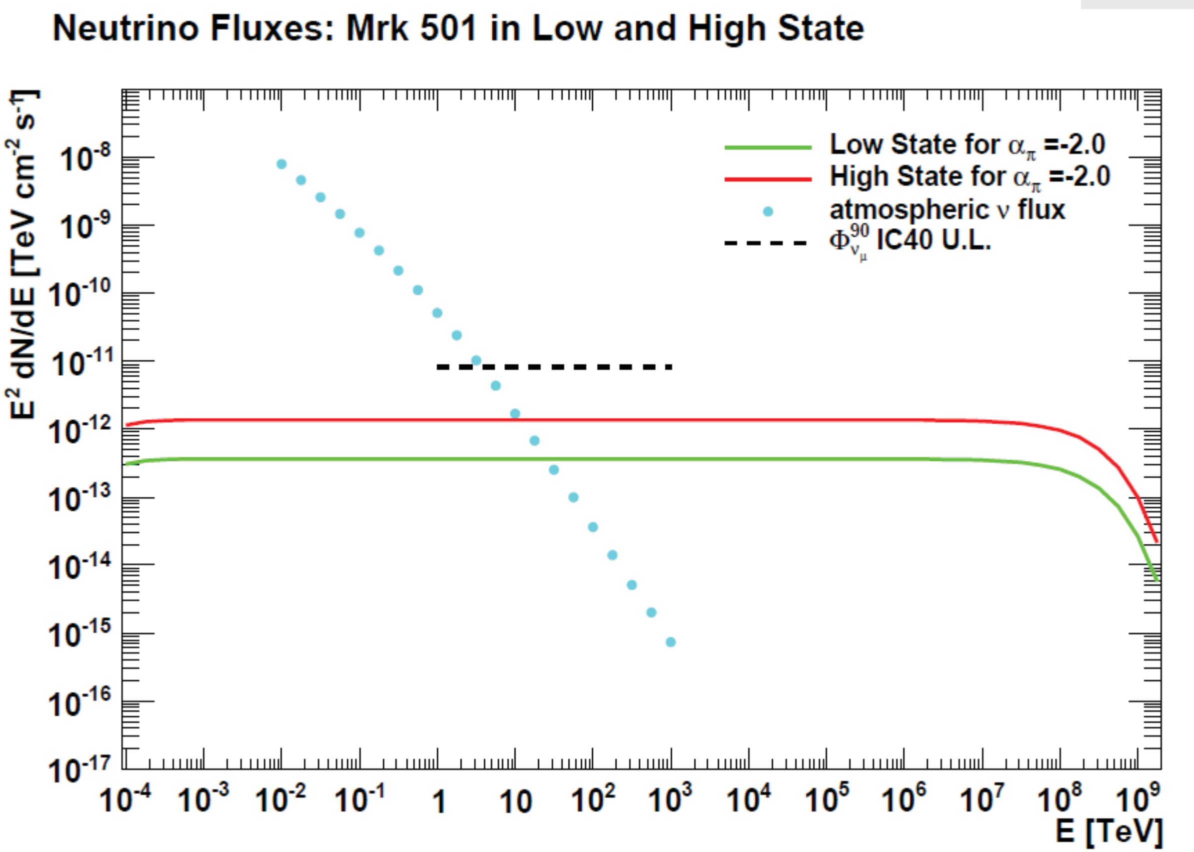
Test case: Mrk 501

- Bolometric method:

$$\int \frac{dN_\gamma}{dE_\gamma} E_\gamma dE_\gamma \propto \int \frac{dN_\nu}{dE_\nu} E_\nu dE_\nu$$

- Comparison low-state (green line) and high-state (red line)

- Average flux somewhere in between



Doert, Rhode, Halzen, JKB et al, in prep

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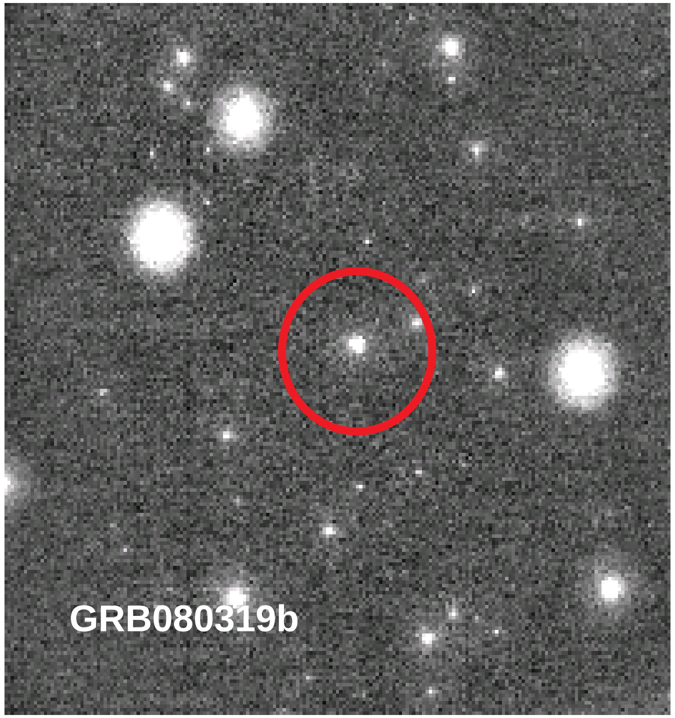
Prospects for AGN neutrino flux detection

- Point source (steady) – **probably difficult for TeV-transperant sources; good chances for TeV-thick sources**
- Point source (flaring) – **Yes!**
- Stacking – **Yes!**
- Diffuse flux – Possible, probably stacking and flares quicker

Neutrino source candidates

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



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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, ...)

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

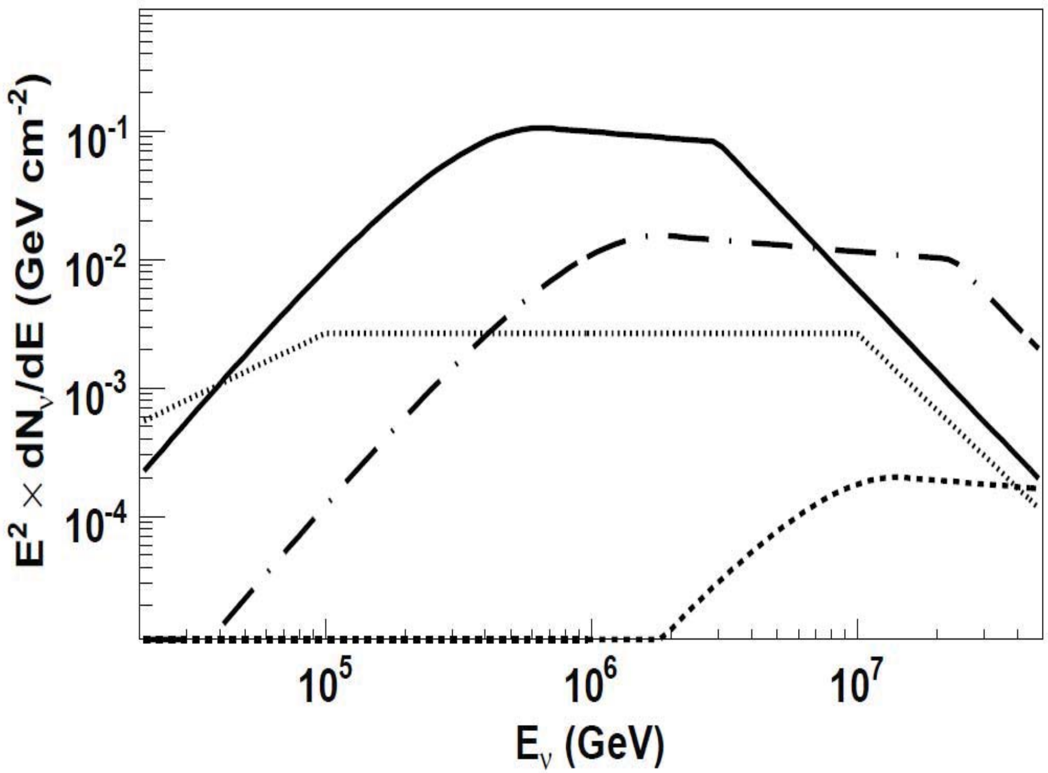
$$\epsilon_1 = 7.5 \times 10^5\,\text{GeV}\,\frac{1}{(1+z)^2}\left(\frac{\Gamma}{10^{2.5}}\right)^2\left(\frac{\text{MeV}}{\epsilon_\gamma}\right)$$

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

$$f_\nu \sim \frac{1}{8}\frac{\epsilon_p}{\epsilon_e}\left[1-(1-\langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right] \qquad \frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^B}{10^{52}\text{erg s}^{-1}}\right)\left(\frac{10\,\text{ms}}{\delta t}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{\text{MeV}}{\epsilon_\gamma}\right)$$

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)

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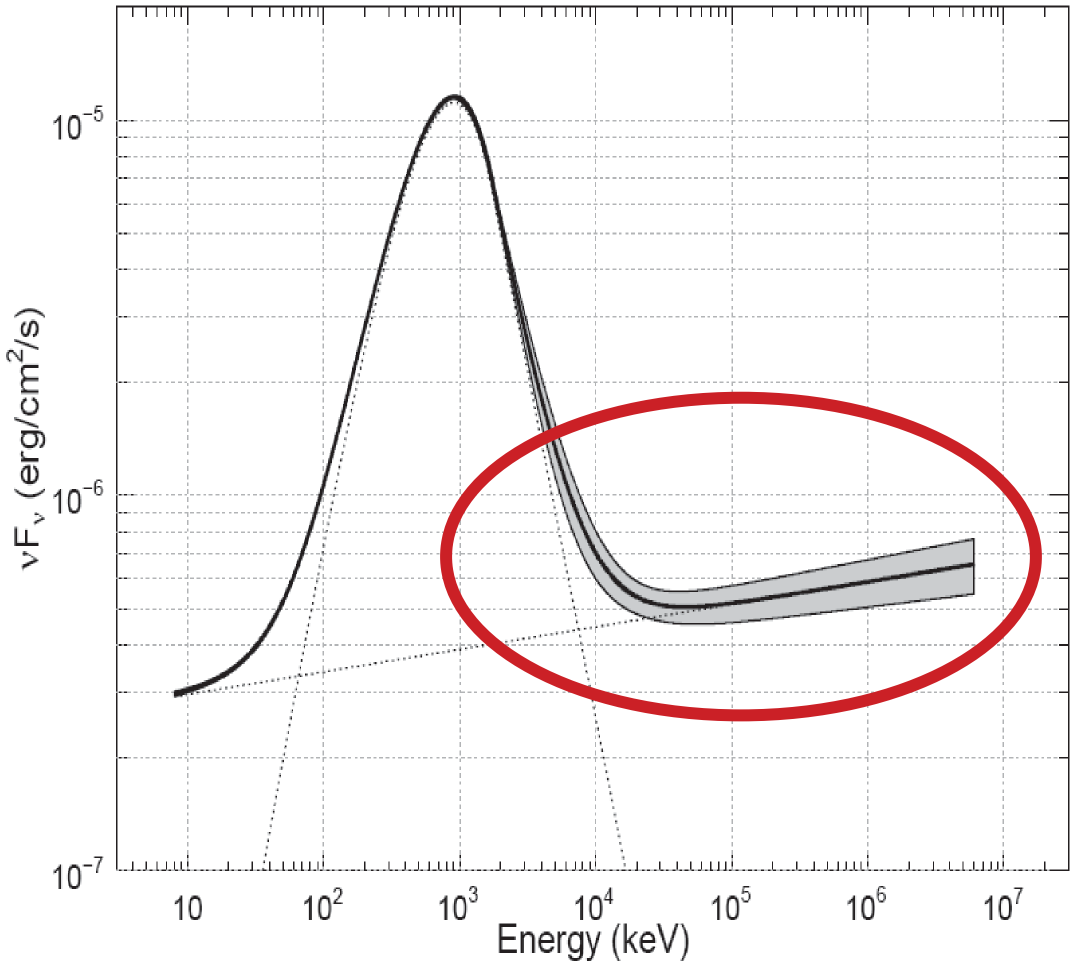
High-energy component GRBs:
Prospects for single bursts

- **GRB941017** – high-energy component (BATSE & EGRET) Gonzalez et al, Nature 2003
- **GRB090510 & GRB090902b** – high-energy component, most likely from π^0 decays (Ackermann et al, ApJ 716 (2010); Abdo et al, ApJL 706 (2009))



Abdo et al, ApJL

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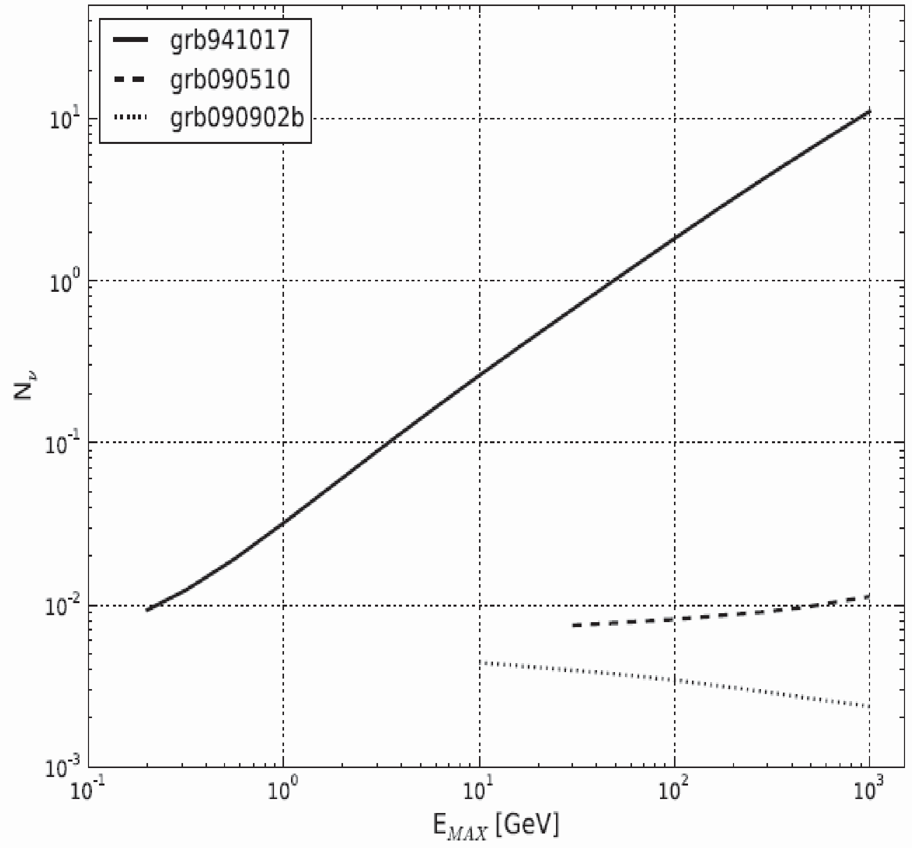
Neutrinos from high-energy compontent GRBs

- **GRB941017**: possibly event rates >10 → corresponds to clear detection in IceCube
- **GRB090510/GRB090902b** → average burst with ~ 1e-2 events ➔ only visible through stacking of sources
- **➔ stacking of GRBs or another big event will do the trick**

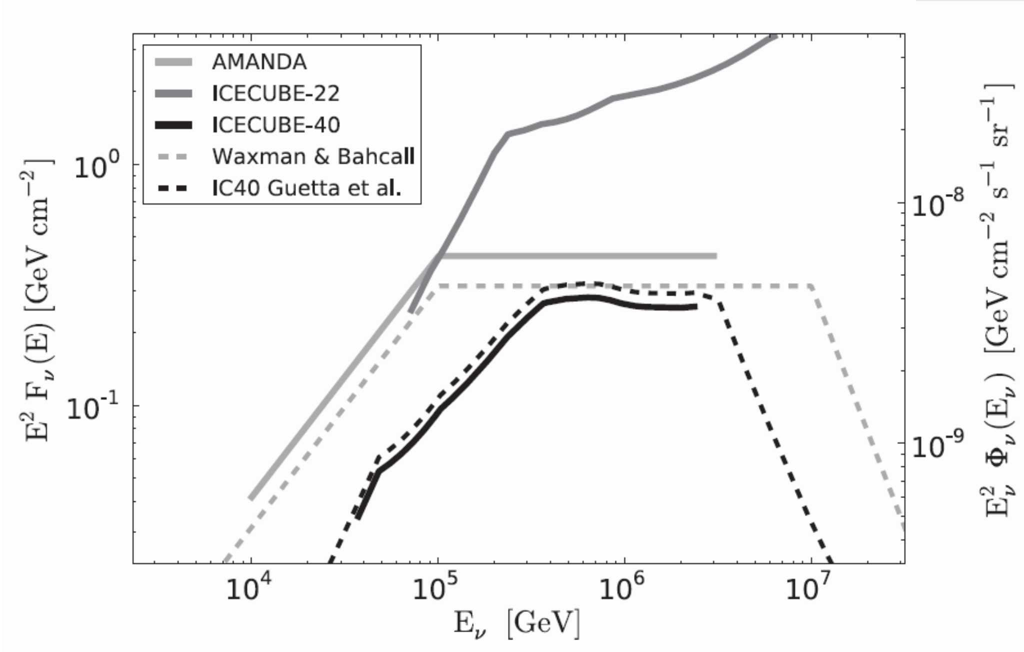


JKB, Halzen, O'Murchadha, Olivo, ApJ **721**:1891 (2010)

Stacking of satellite-observed bursts

Strong constraints on…

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



Prospects for GRB neutrino flux detection

- Single burst – **yes, for nearby and strong burst**
- Stacking – **yes! IceCube already starting to make severe constraints!**
- Diffuse Flux – **First two methods will be quicker (unless there are many choked bursts, not seen with satellites)**

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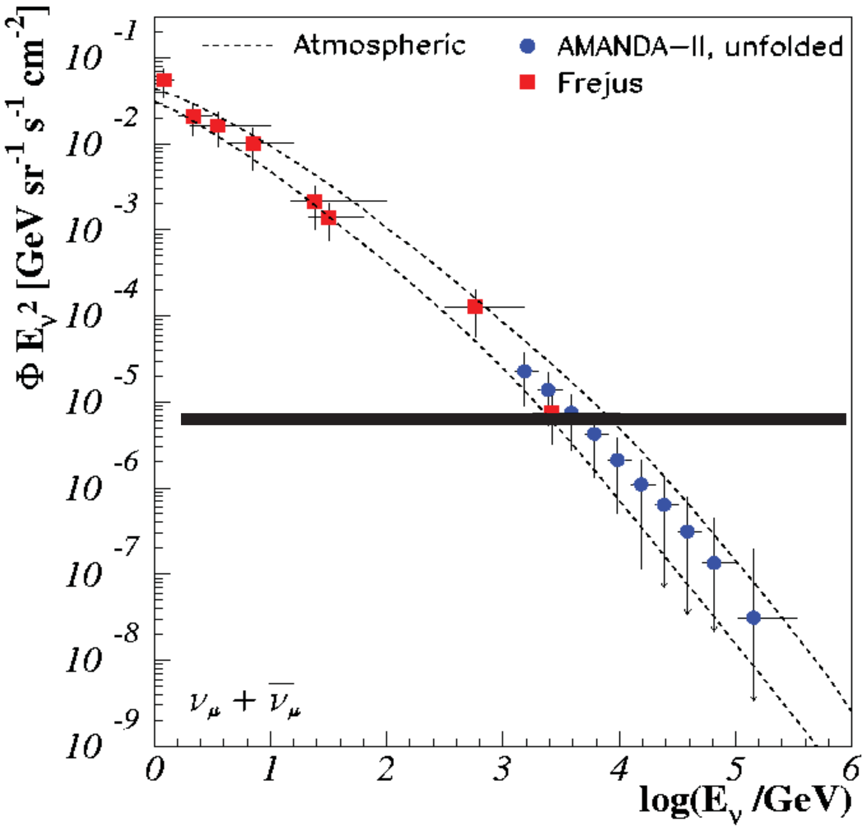
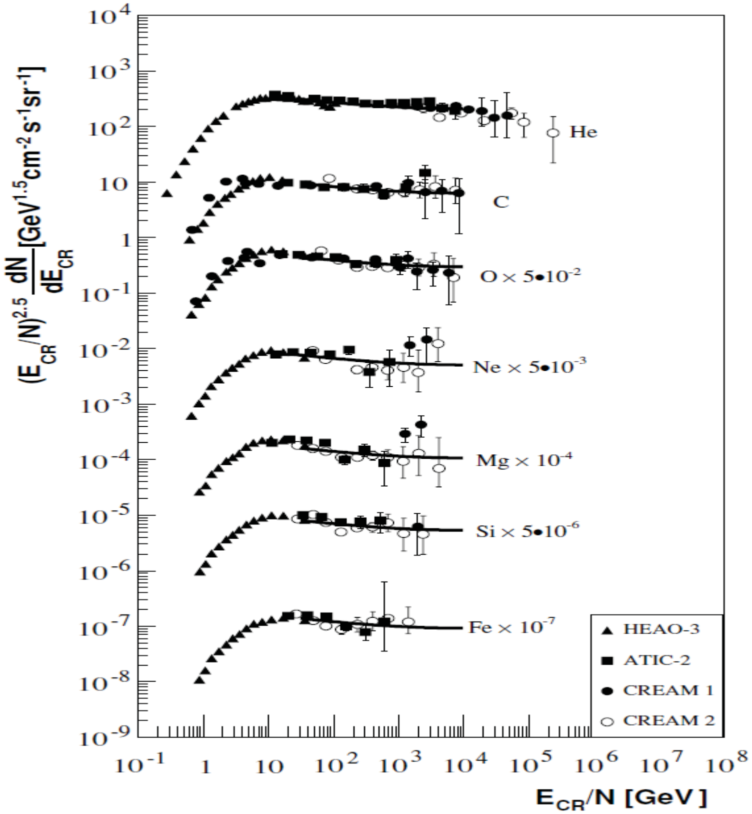
Atmospheric Background

- 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



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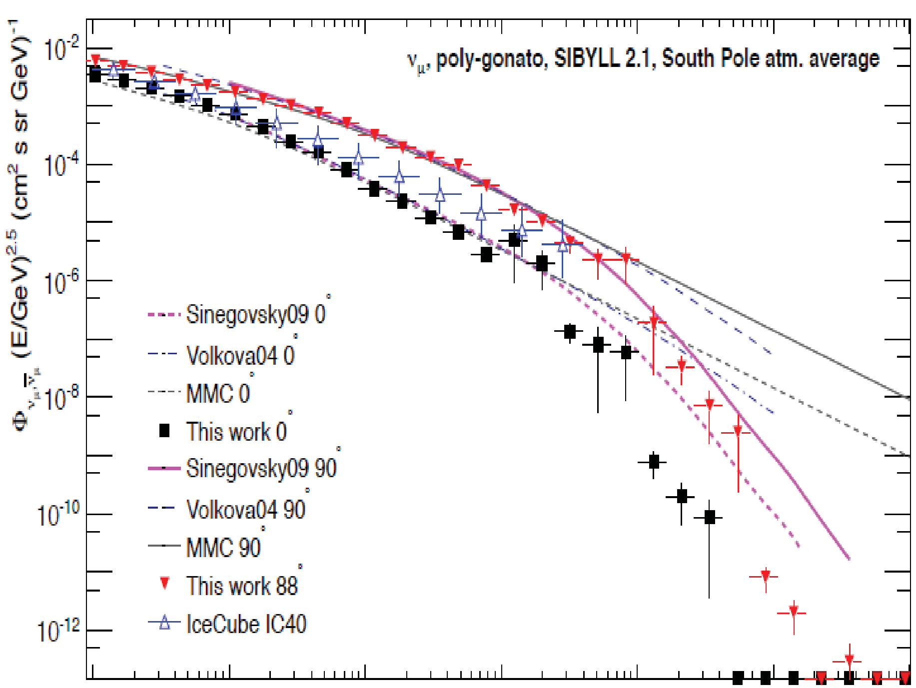
Corsika Simulations

- 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

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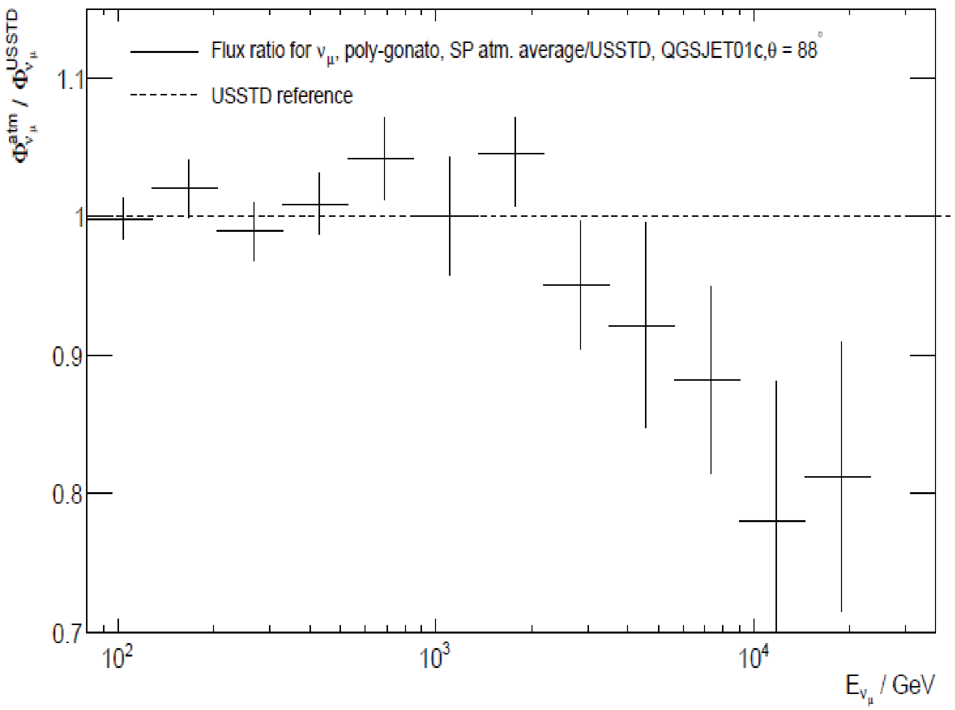
Atmospheric uncertainties

- Large deviations from standard atmosphere possible (>10%)
- Those systematic errors can be removed: detailed atmospheric data available from MSIS (work in progress)



Fedynitch, Desiati, Becker, in preparation

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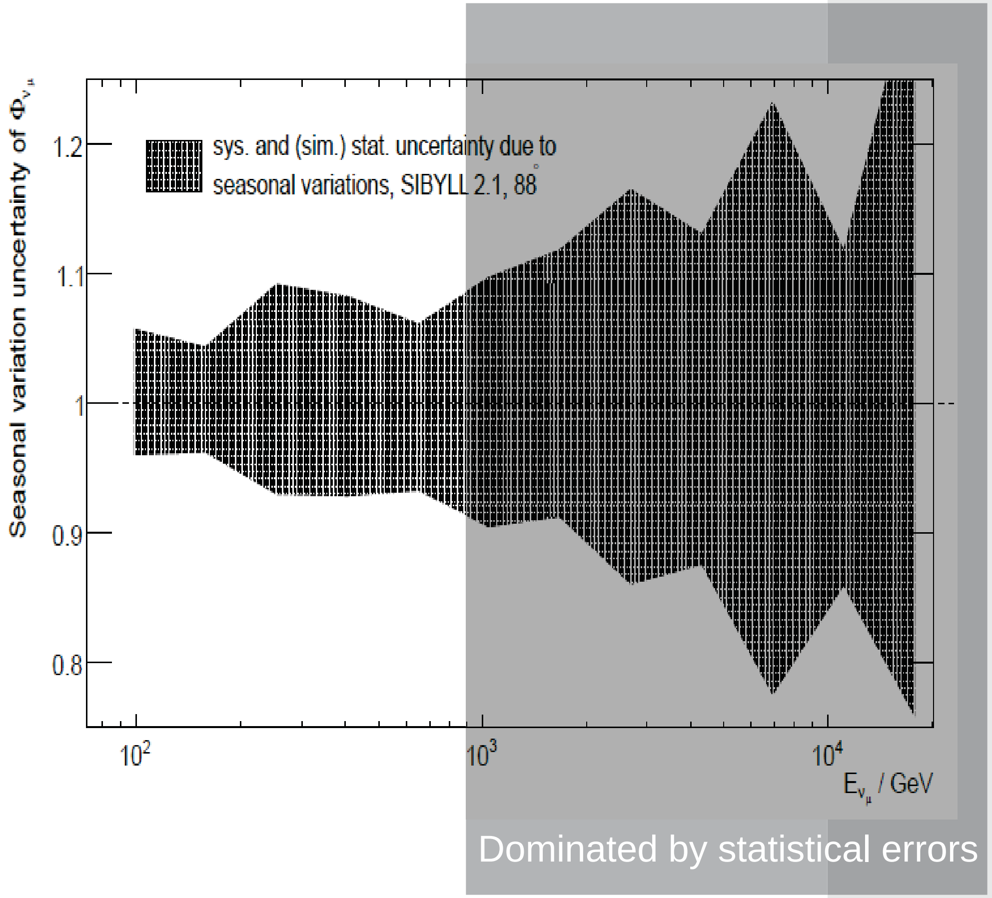
Uncertainties from primary composition

- Uncertainties can be determined up to ~1 TeV
- For different models, up to 10% systematic uncertainties
- Can be minimized with new data from CREAM/PAMELA below TeV energies
- Above TeV, some uncertainties remain (composition not well-known); will be quantified in future work



Fedynitch, Desiati, Becker, in preparation

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Interaction processes

- High-energy (GeV – EeV)
  - $p\,\gamma \rightarrow \Delta^+ \rightarrow \pi\,N$
  - $p\,p \rightarrow \#(\pi^{+/-/0})$
    - $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\,\nu_e\,\nu_\mu\,\overline{\nu_\mu}$
    - $\pi^0 \rightarrow \gamma\gamma$ (E~TeV)
- Low-energy (keV – GeV)
  - $CR + H_2 \rightarrow H_2^+ + e^- + CR'$
    - $H_2^+ + H_2^+ \rightarrow H_3^+ + H$
      - …

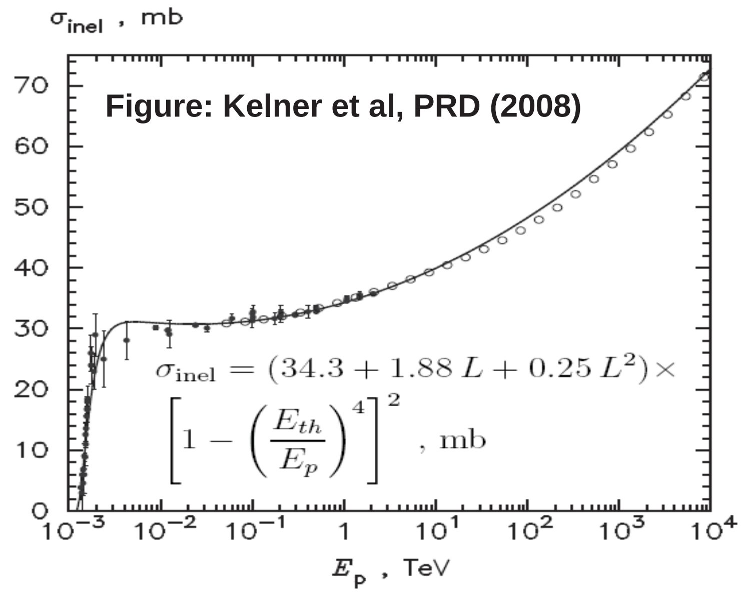


Figure: Kelner et al, PRD (2008)

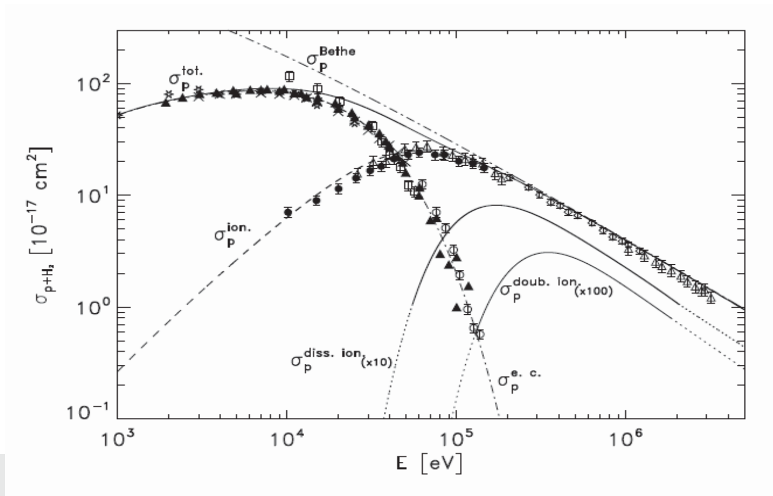
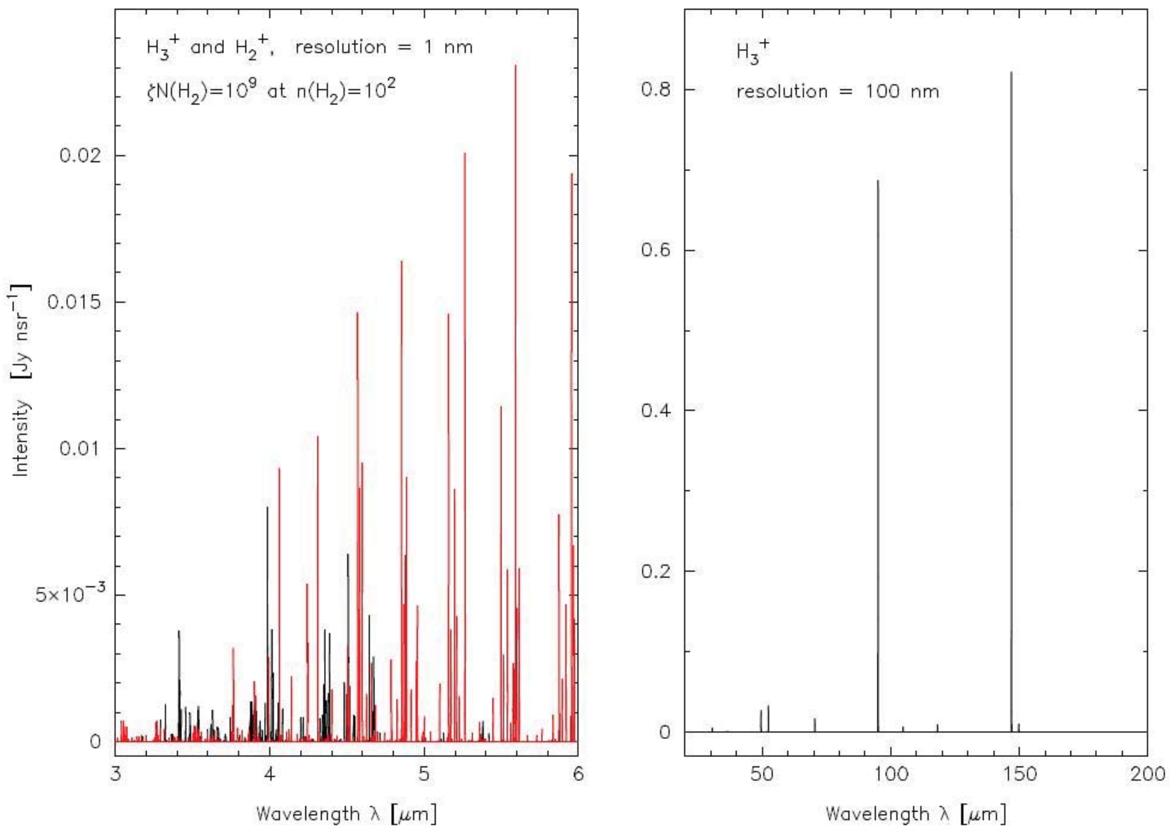


Figure: Padovani et al, A&A (2009)

Molecule spectra at high combination of flux and density: H_2^+ and H_3^+



First prediction of an observable H_2^+ spectrum

 JKB, Black, Safarzadeh, Schuppan, to be submitted (2011)