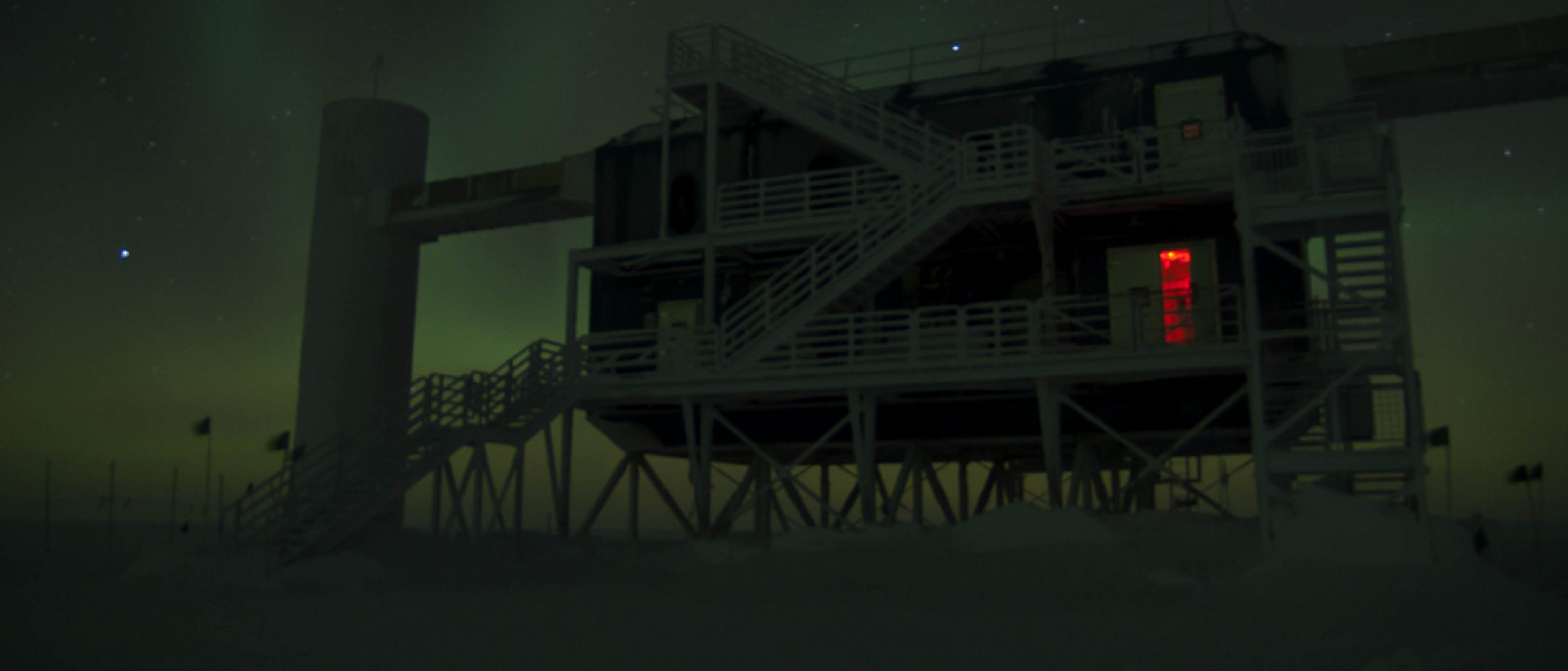
The flaring Universe: Neutrinos and Gamma Rays from Active Galaxies and Gamma Ray Bursts

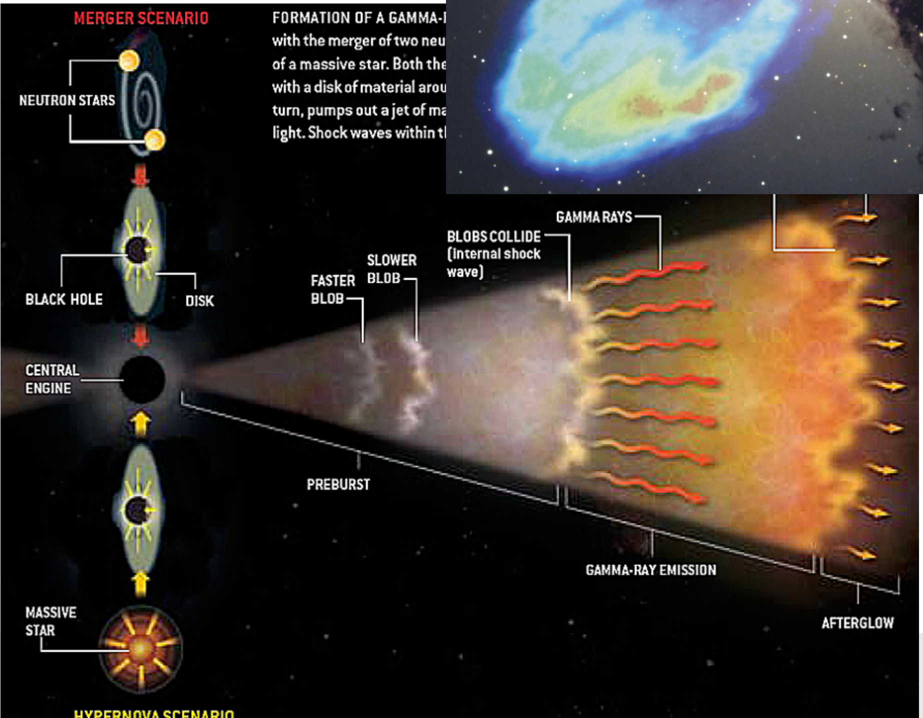
Julia Tjus

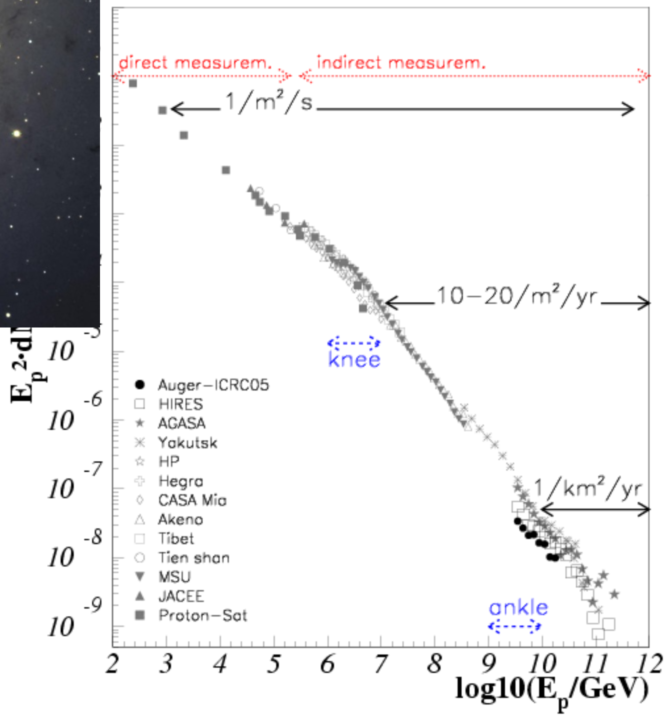
Ruhr-Universität Bochum



see also Physics Reports **458**, **ArXiv:0710.1557** (2008)

Where is the connection between these three images?





RUB

Flaring jet-sources as the origin of UHECRs

1. Introduction – Ultra-high energy cosmic rays (UHECRs) & their origin
2. Motivation – why AGN & GRBs?
3. Background – what are AGN & GRBs?
4. Non-thermal properties – what observables do we have?
5. Adding information from neutrinos: multimessenger modeling

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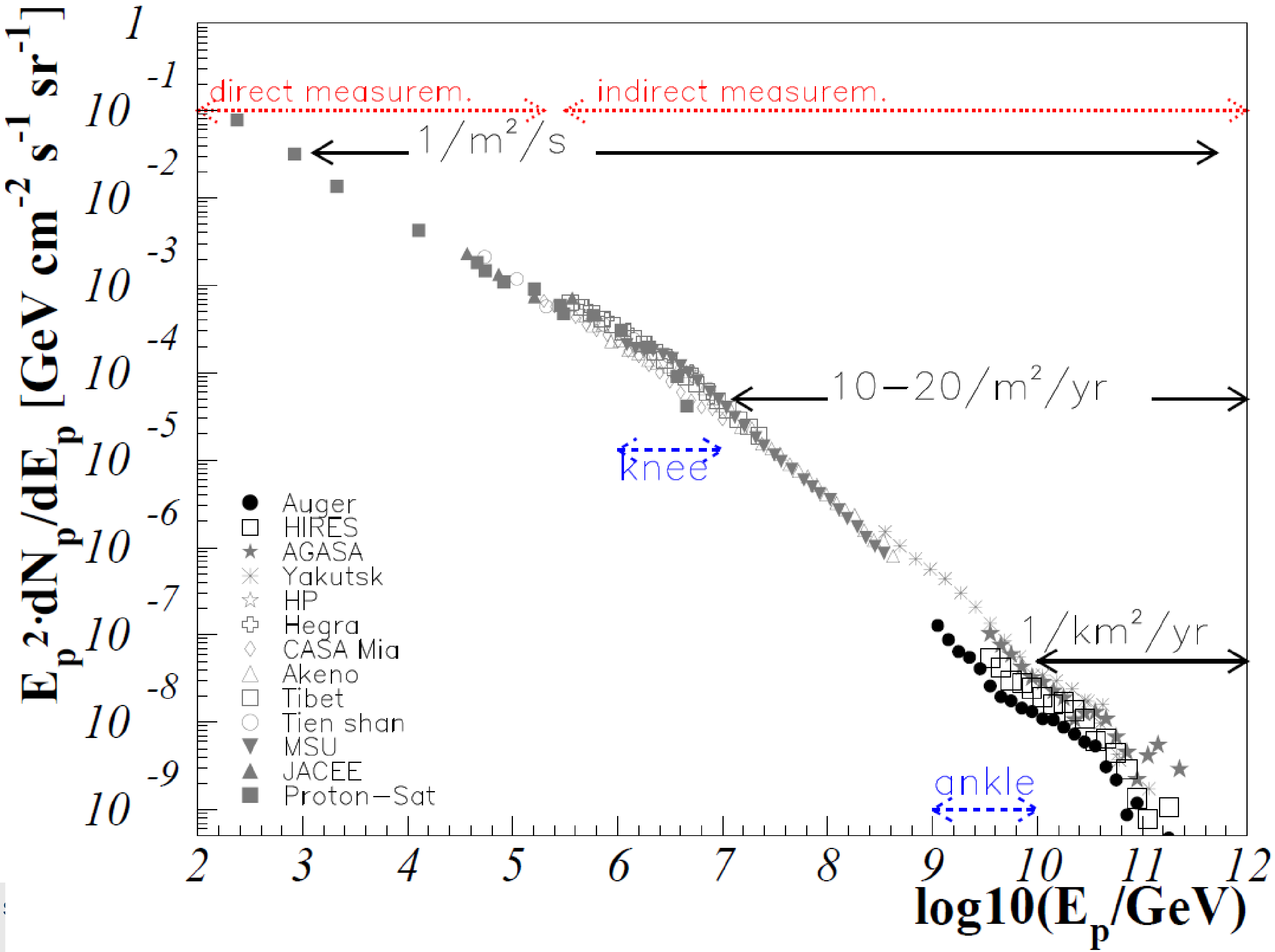
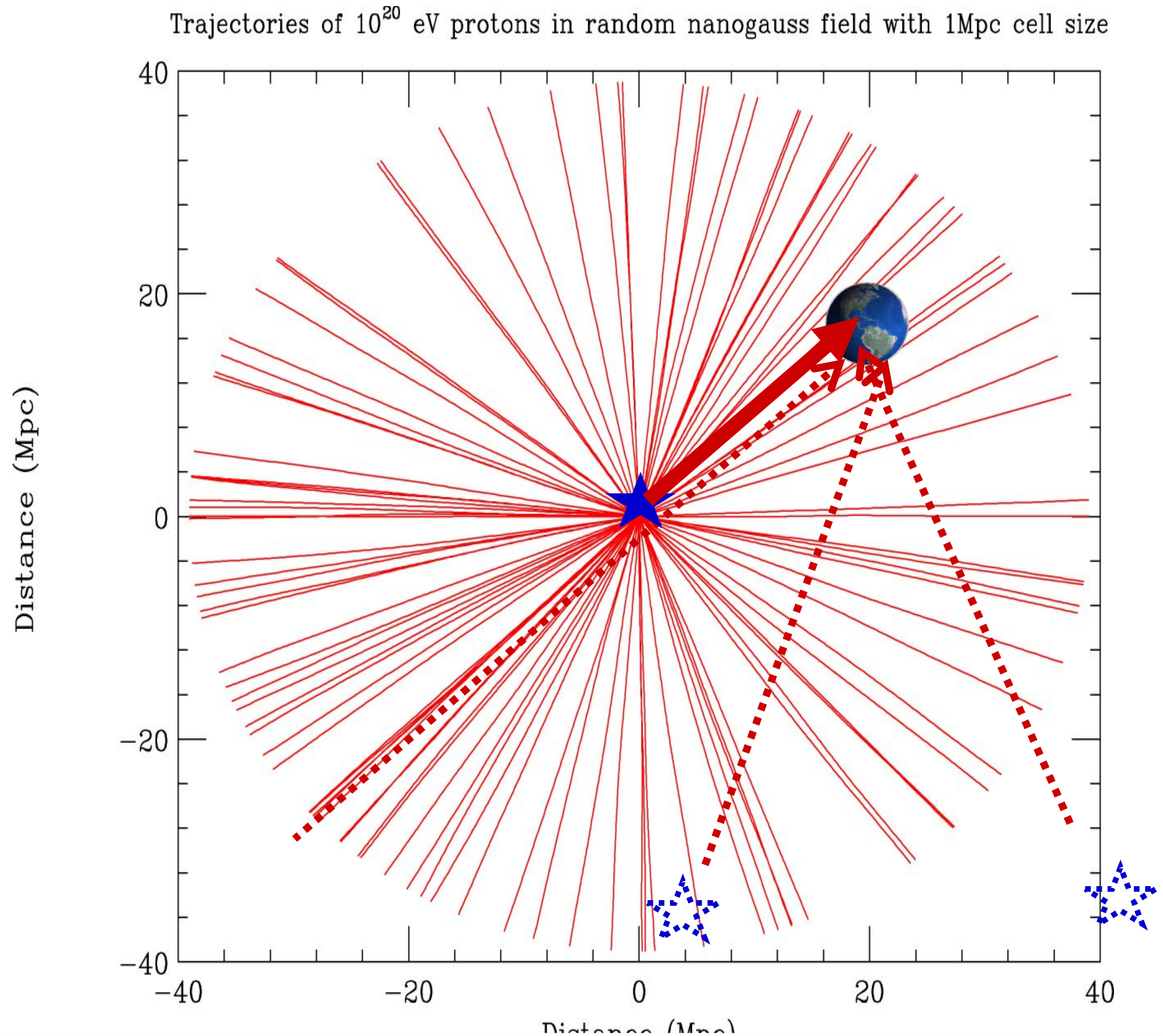
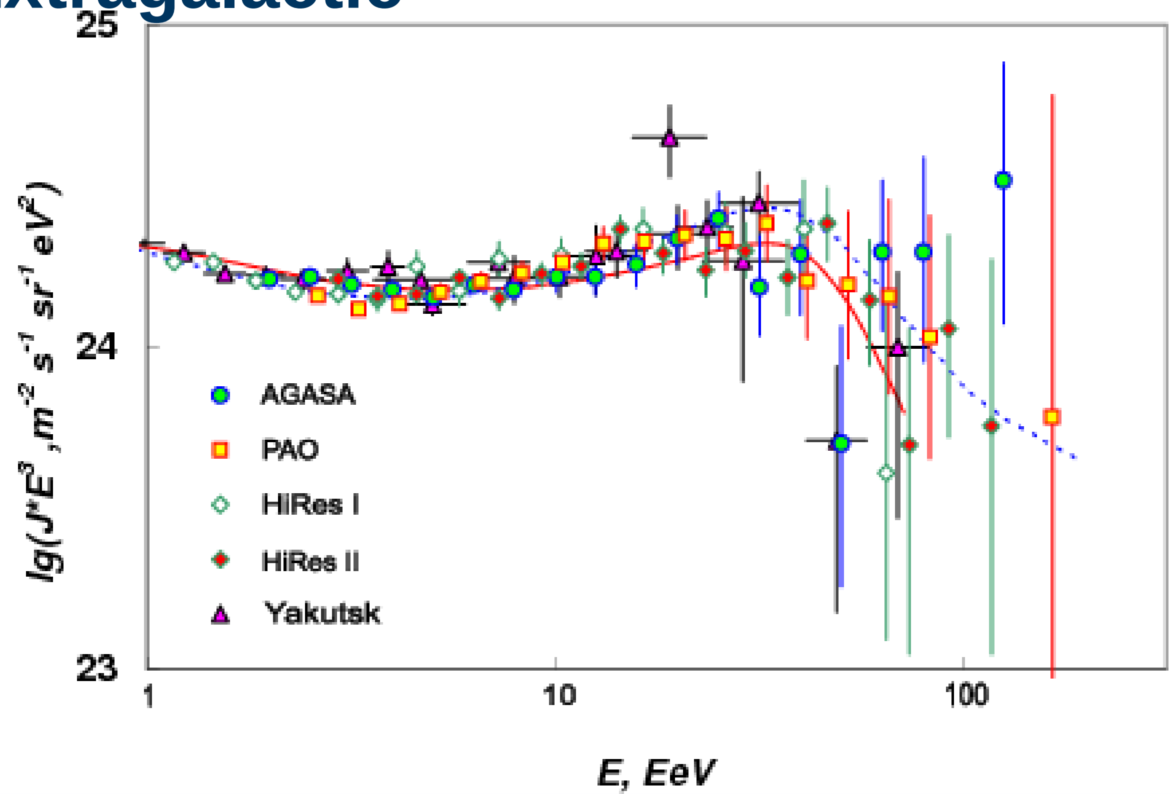
The observed Cosmic Ray spectrum





➔ cosmic rays at above the ankle must be of extragalactic origin

Possible sources for UHECRs?
→ Extragalactic



1. Power-law condition
2. Maximum energy necessary condition
3. Luminosity criterion

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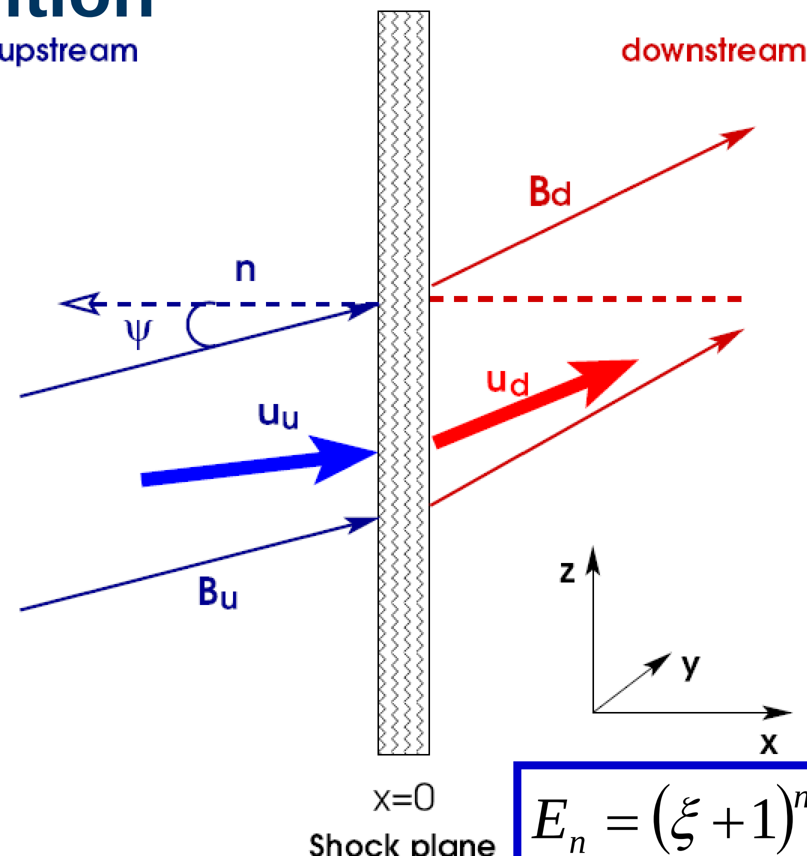
(1) Spectral behavior condition

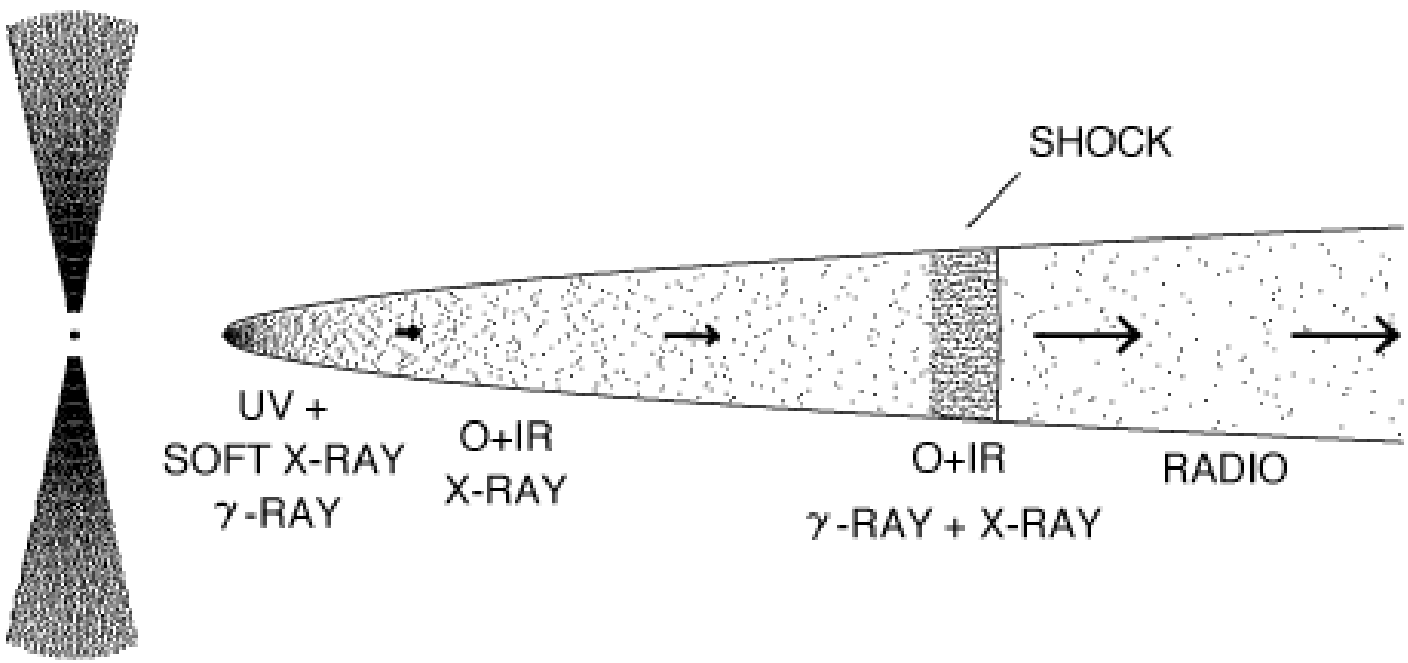
- **Leaky box model** (simplest version):
- $dN/dE \sim dQ/dE * \tau_{esc}$
- $dQ/dE \sim E^{-\alpha}$
- $\tau_{esc} \sim D^{-1} \sim E^{-\delta}$
- ➔ $dN/dE \sim E^{-\alpha-\delta} \sim E^{-2.7}$



$$E_n = (\xi + 1)^n \cdot E_0$$

$$N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\gamma}$$

Shock fronts in AGN/GRBs?



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(II) Maximum energy up to 10^{21} eV?

- 10^{21} eV ~ 100 Joule
  - E = γ*mc^2 with mc2 ~ 1 GeV ➔ g ~ 10^{12}
- Classical kinetic energy: E = m/2*v2 ➔
  Classical parameters for instance in tennis:
  - m ~57 g
  - v ~ 200 km/h
  - E = 1/2·m·v^2 ~ 100 Joule
- ➔ tiny cosmic ray reaches macroscopic energies!
- How do they do that?!

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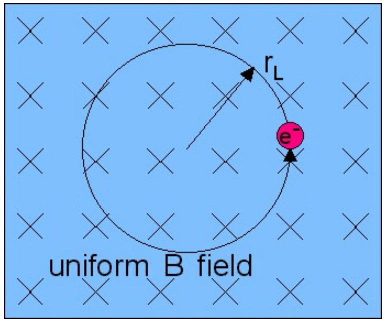
(II) Maximum energy condition

- For too high energies: particles get kicked out of accelerator



- $F_c = F_L$ ➔ integral: energy

$E_{max} \sim Z * e * B * R$

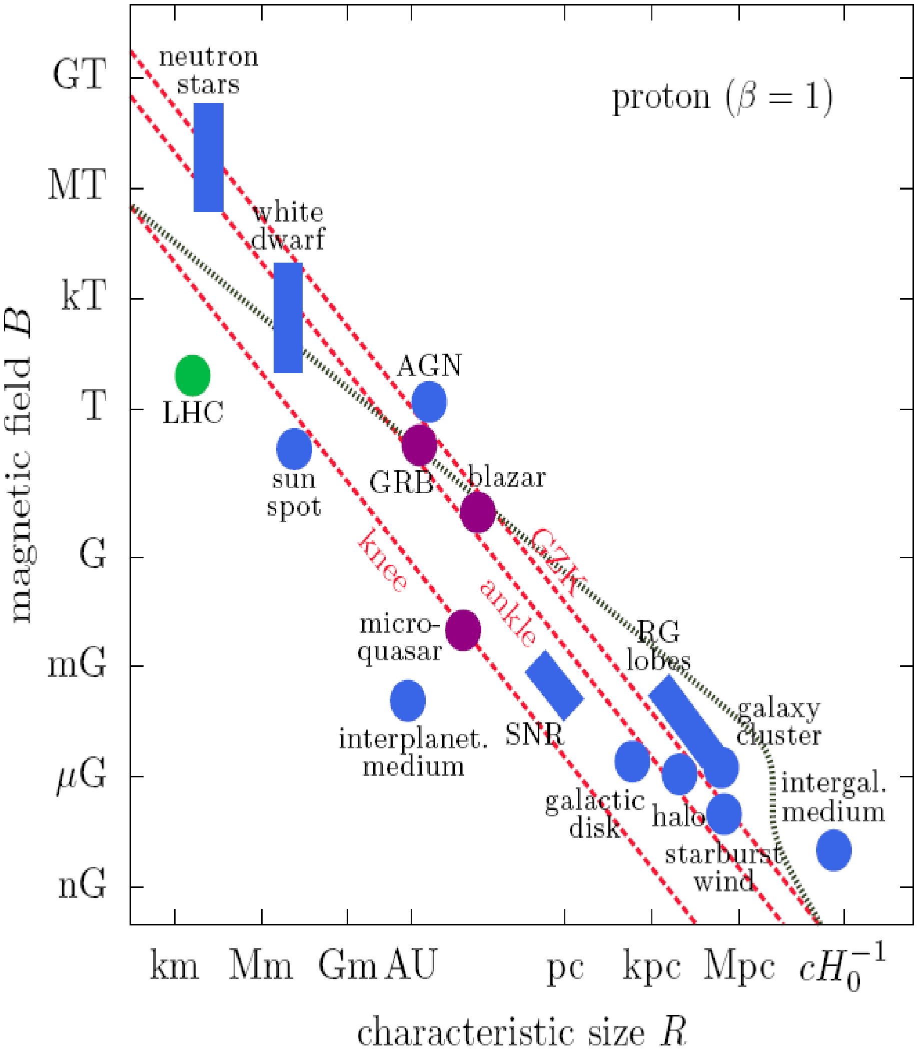


Figure: Ahlers et al, in Preparation

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(III) UHECR luminosity

$$L_{CR} = \dot{\rho}_{CR} \cdot V$$

volume

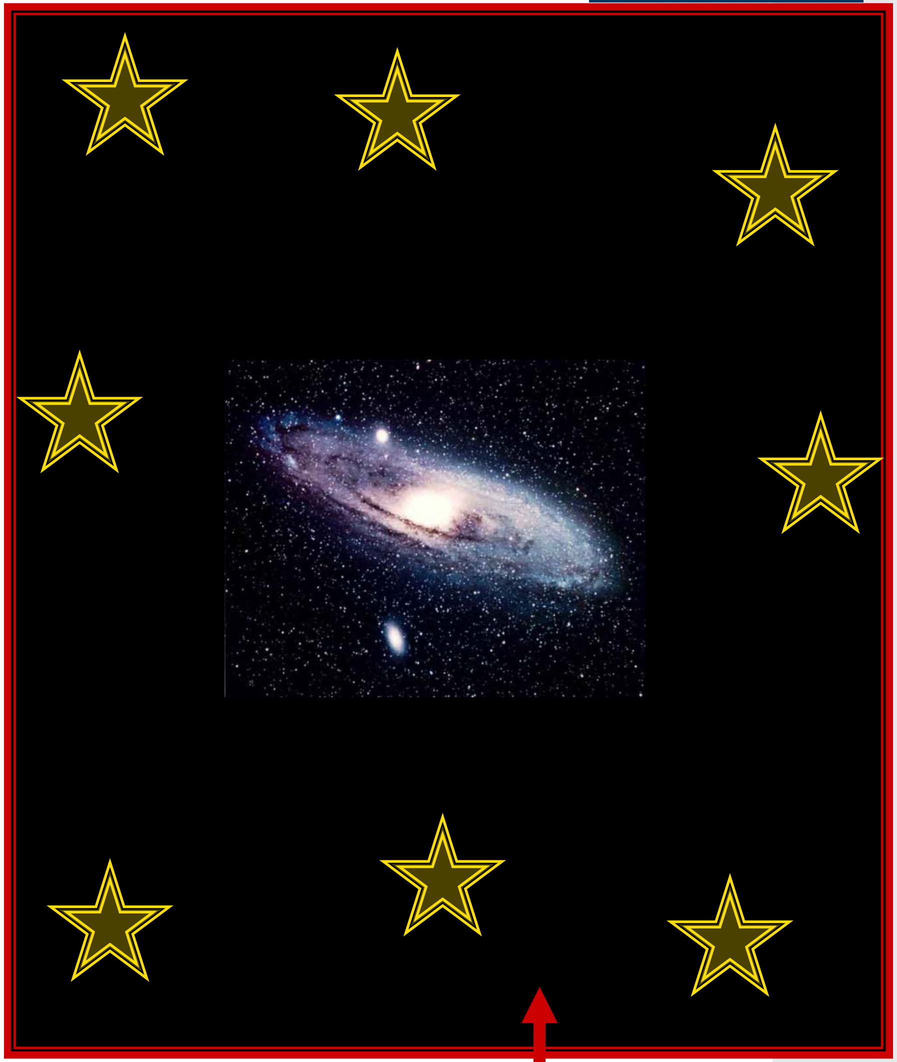
- Energy density rate:

$$\dot{\rho}_{CR} = \frac{4\pi}{\tau \cdot c} \cdot j_{CR}$$

- Energy flux:

$$j_{CR} = \int_{E_{\min}} \frac{dN}{dE} \cdot E \cdot dE$$

- Halflife of Cosmic Rays τ
  - ~Hubble time



Universe

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(III) UHECR luminosity criterion

$$\dot{\rho}_{CR} = \frac{4\pi}{\tau \cdot c} \cdot j_{CR}$$

- time ~ Hubble time:
  - **$\tau \sim 10^{10}$ yr**

$$j_{CR} = \int_{E_{\min}} \frac{dN}{dE} \cdot E \cdot dE$$

- E_{min} → above ankle ($E_{min} > 3 \cdot 10^{18}$ eV)

$$\dot{\rho}_{CR} = \frac{4\pi}{\tau \cdot c} \cdot j_{CR} \approx 10^{44}\, erg / Mpc^3 / yr$$

→ This energy density has to be matched by the potential sources!

see e.g. Halzen, ArXiv:0908.1874

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Energy density rate

- GRBs:

$$\dot{\rho}_{GRB} = \langle E_{GRB} \rangle \cdot \dot{n} \approx \left(10^{51} erg\right) \cdot \left(10 \cdot Gpc^{-3} \cdot yr^{-1}\right)$$

$$= 10^{43} erg / Mpc^{3} / yr$$

- AGN:

$$\dot{\rho}_{AGN} = \langle L_{AGN} \rangle \cdot n \approx \left(10^{44} erg / s\right) \cdot \left(10 \cdot Gpc^{-3}\right)$$

$$= 3 \cdot 10^{43} erg / Mpc^{3} / yr$$

Summary

- Spectral behavior condition: Magnetized shock fronts exist in GRBs/AGN
- Maximum energy condition: Hillas criterion fullfilled by GRBs/AGN
- Luminosity criterion: matched by GRBs & AGN

GRBs/AGN are basically the only objects that fulfill all three criteria

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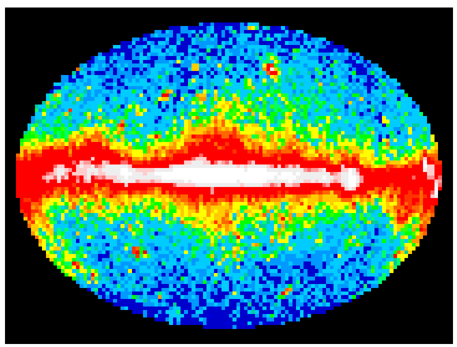
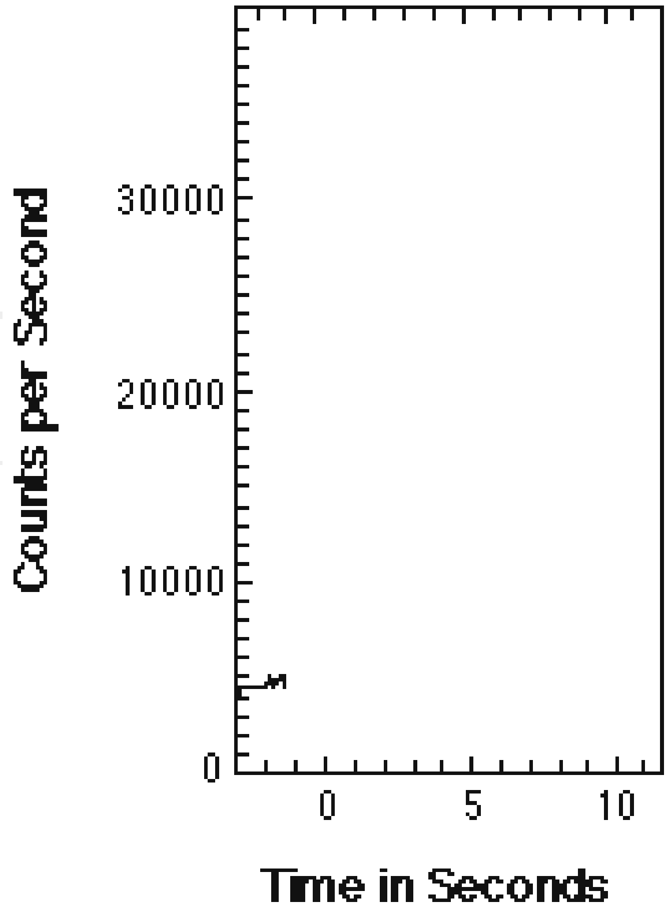
(I) Gamma-ray bursts



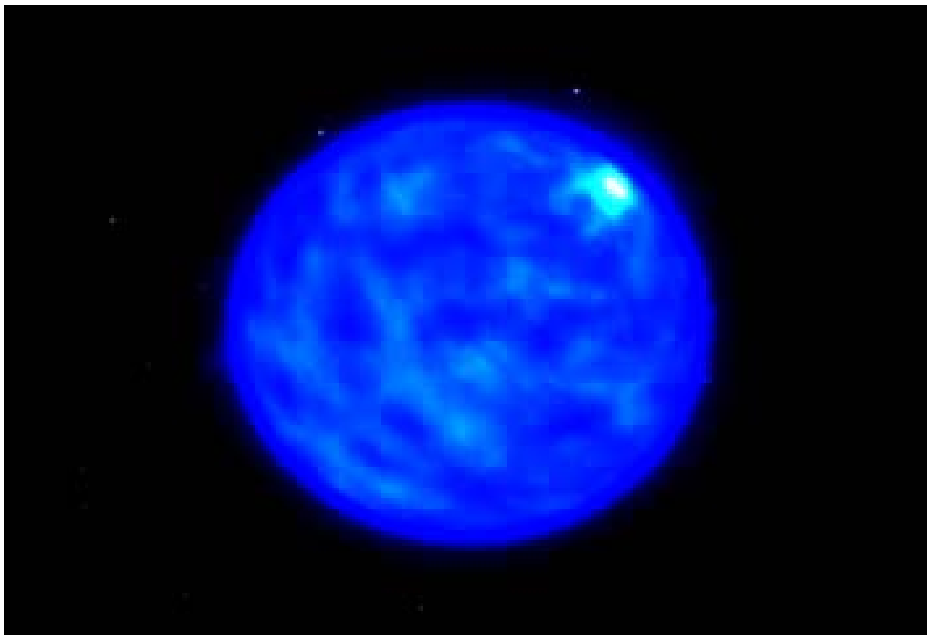


GRBs through time

- 1973: Announcement of **discovery**
- 1997: first **redshift** measurement (afterglow/Beppo Sax) → **extragalactic** origin
- 2003: **long GRBs** ←→ **supernova** explosions
- 2005: **short bursts** ←→ **binary mergers**

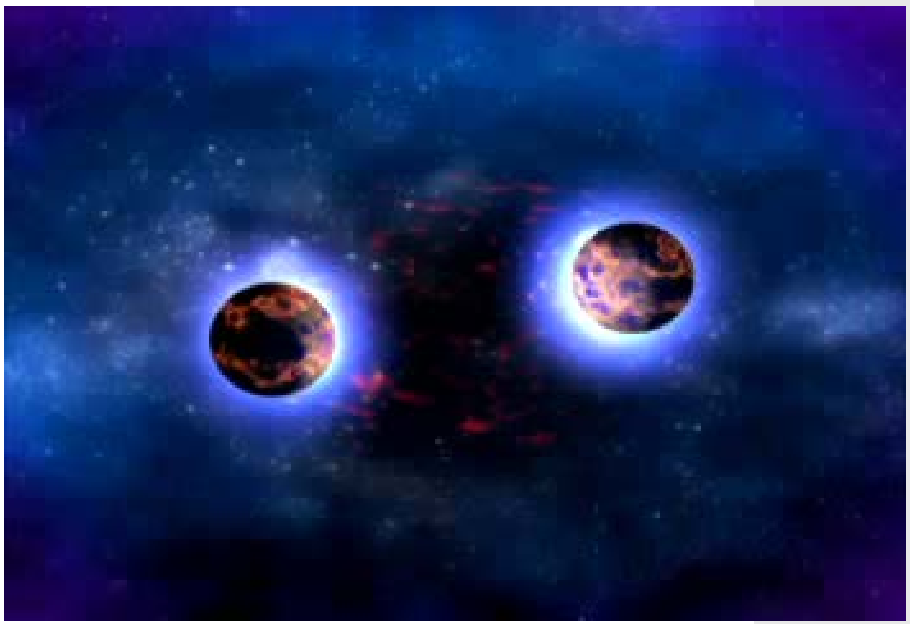
GRB progenitors?

Long GRBs ← Supernova Explosions



Duration > 2 s
typically ~ 40 s

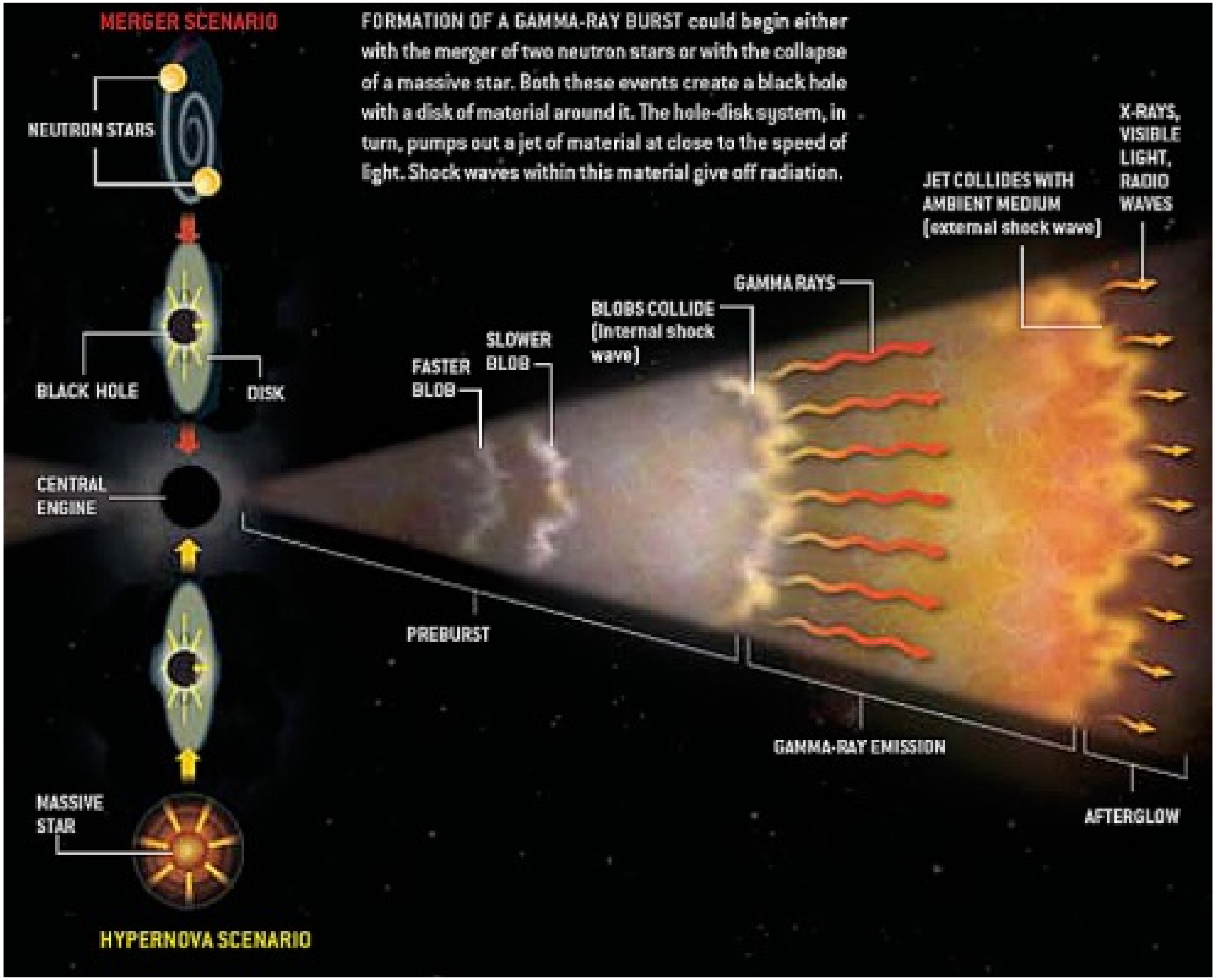
Short GRBs ← binary mergers



duration < 2 s
~ms - s

Credit: Nasa

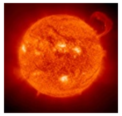
Emission model GRBs



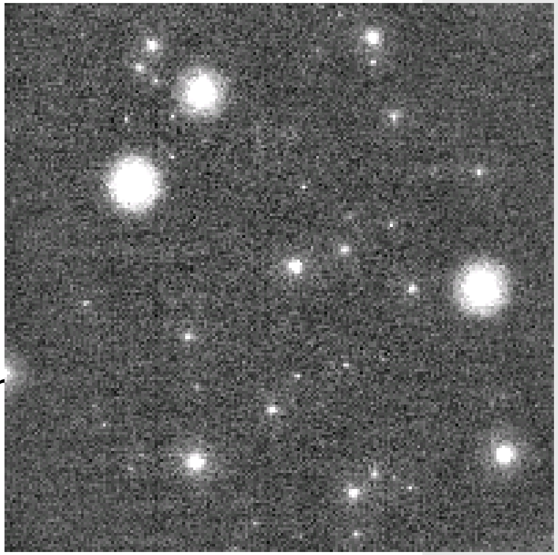
Credit: NASA

Highest power of in the Universe

- A GRB illuminates the sky for 10 Seconds with 10^{45} Watt:
  1000000000000000000000000000000000000000000000 Watt
- Comparison:
  - Light Bulb ~ 60 Watt
  - Total energy requirement human race ~ $1.5*10^{13}$ Watt
  - Solar power ~ 10^{26} Watt



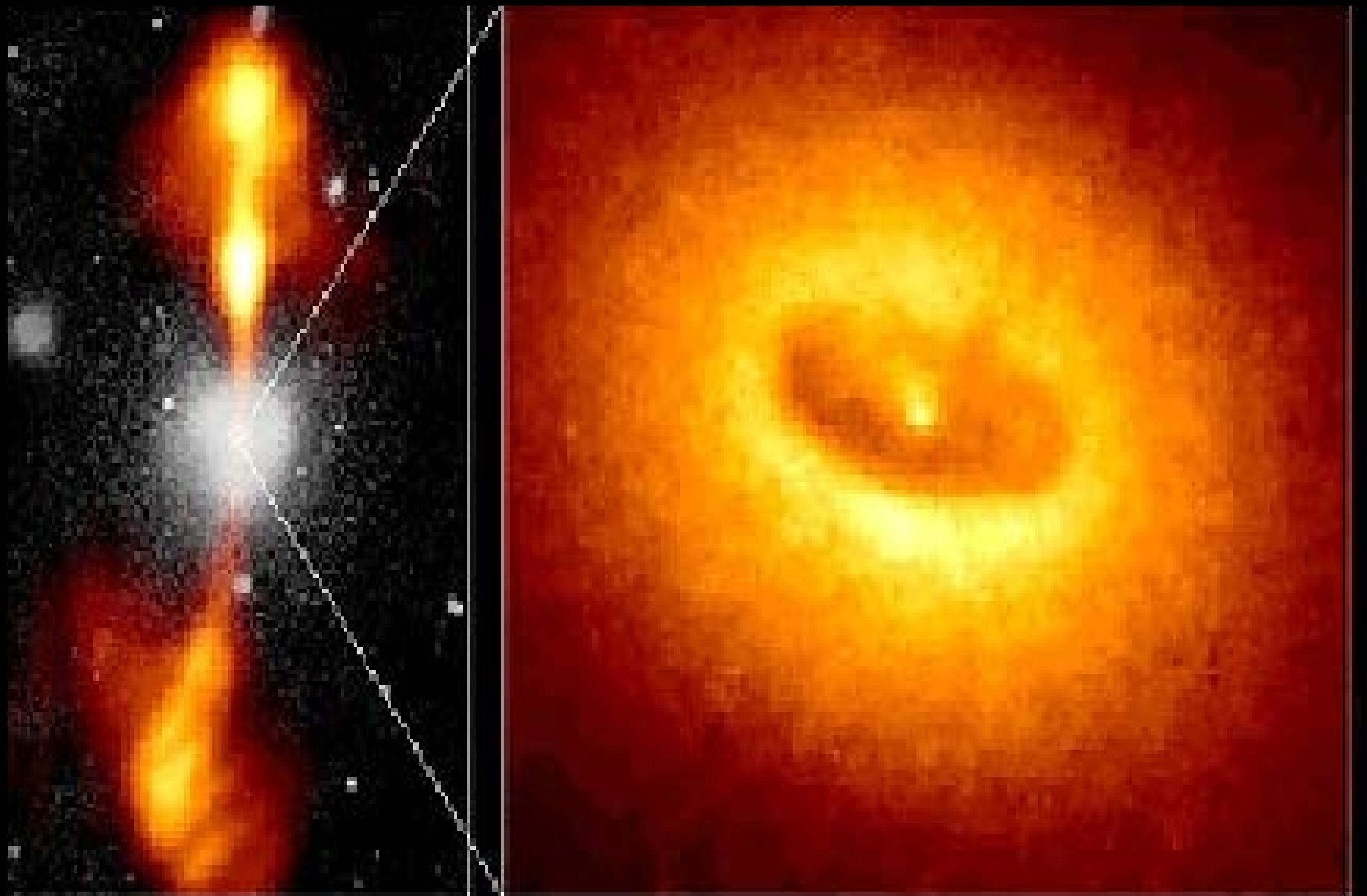
- High power: these phenomena can be detected even extremely far away. Record is z ~ 8, $1.3*10^{10}$ ly



optical emission of a GRB from March 19, 2008

This high power is the reason that they serve as good UHECR candidates

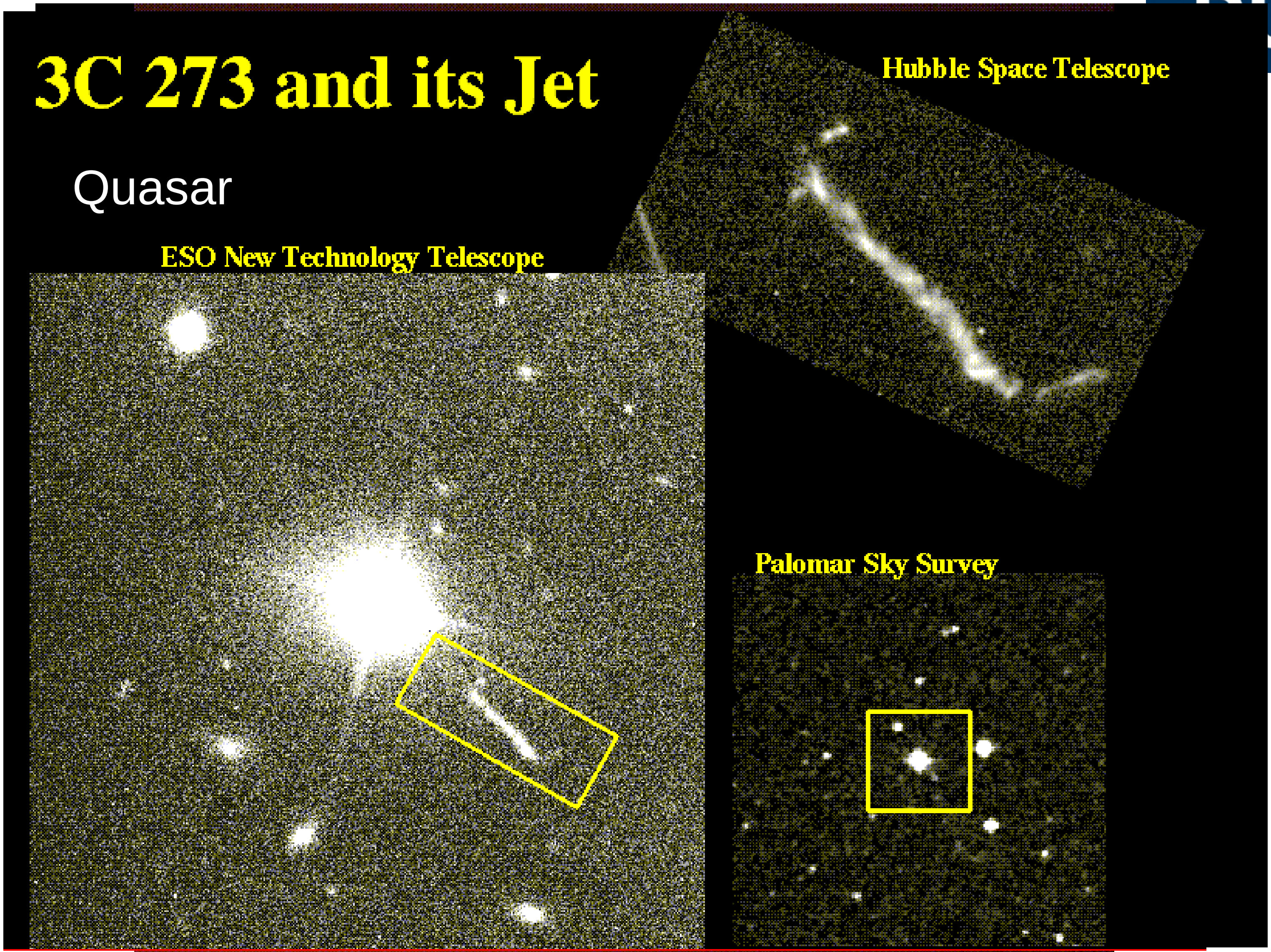
Active Galaxies



380 arcsec
88 000 ly

1.7 arcsec
400 ly

Different appearances



http://www.astr.ua.edu/keel/agn/

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Unified model

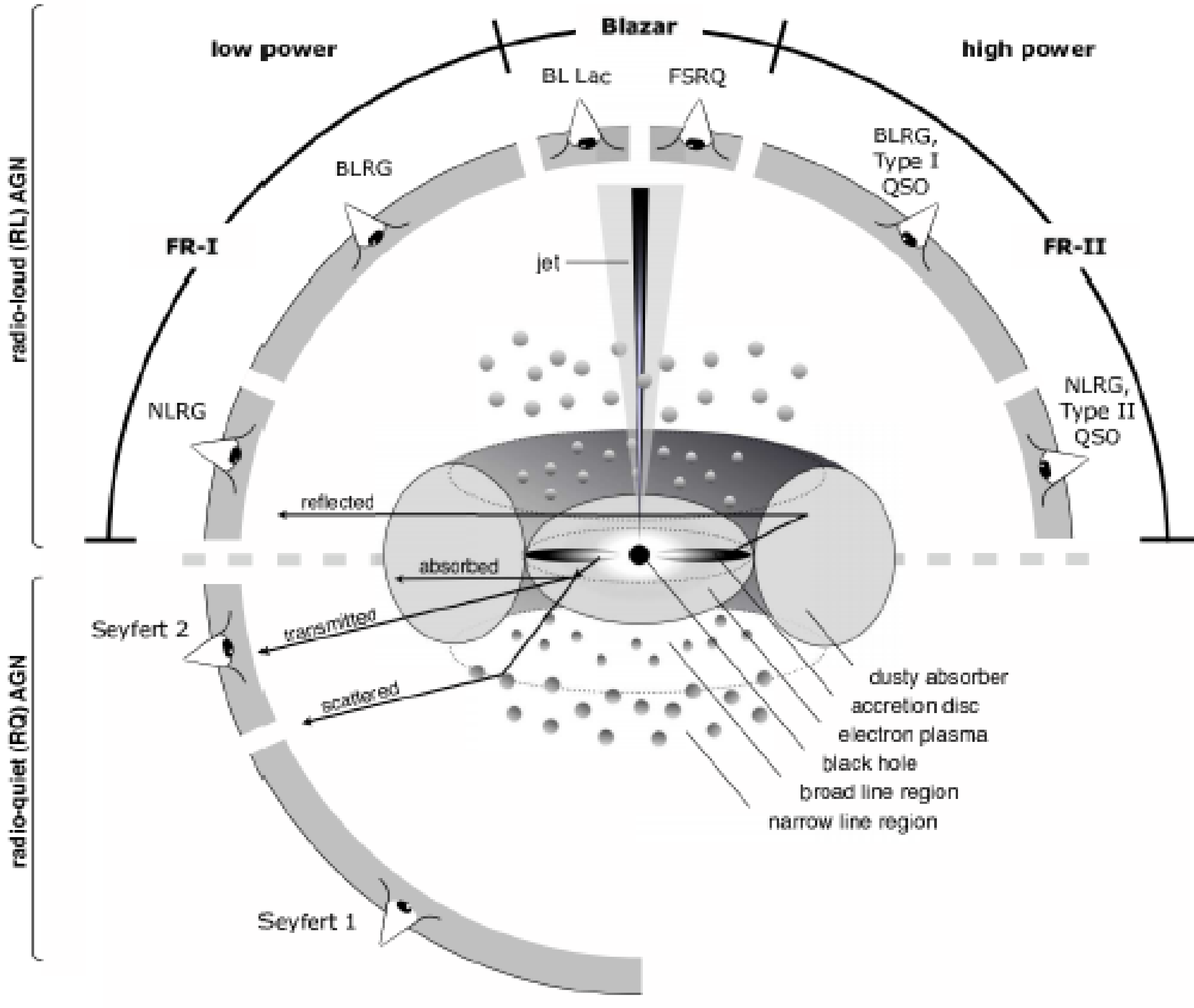
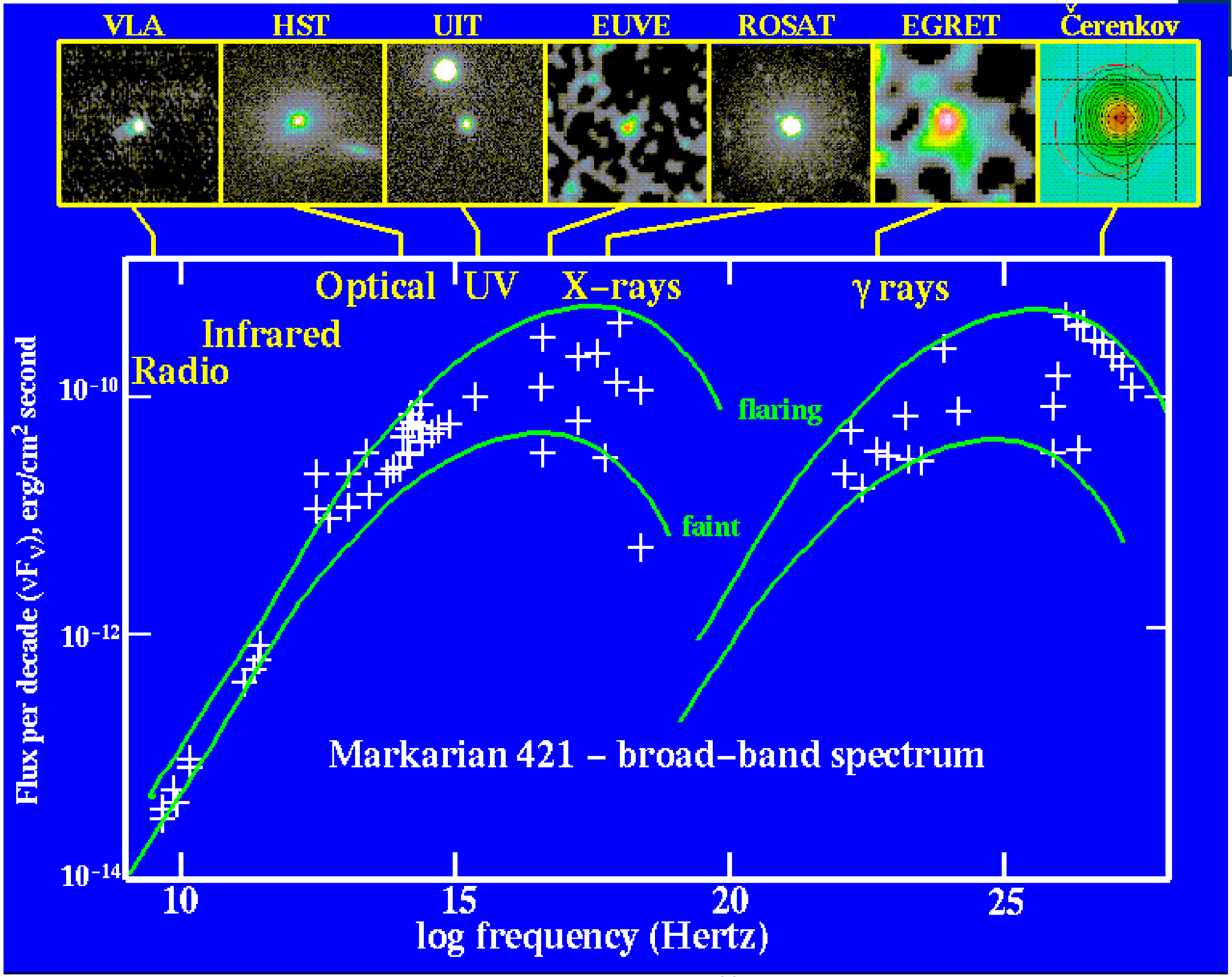


Figure 2.1: (Beckmann and Shrader 2012)

Example: Mkn 421



http://spiff.rit.edu/classes/phys230/lectures/bh/bh.html

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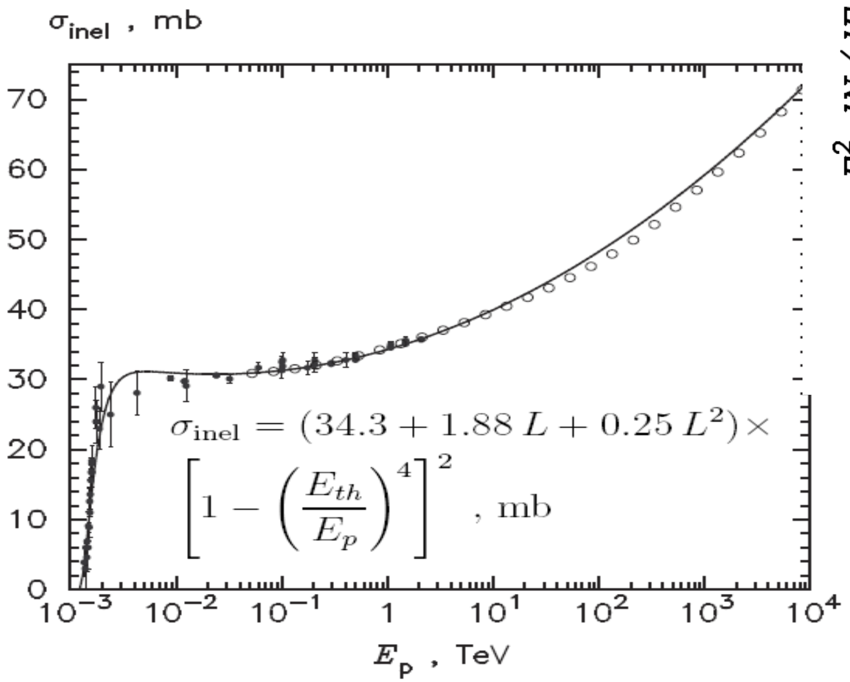
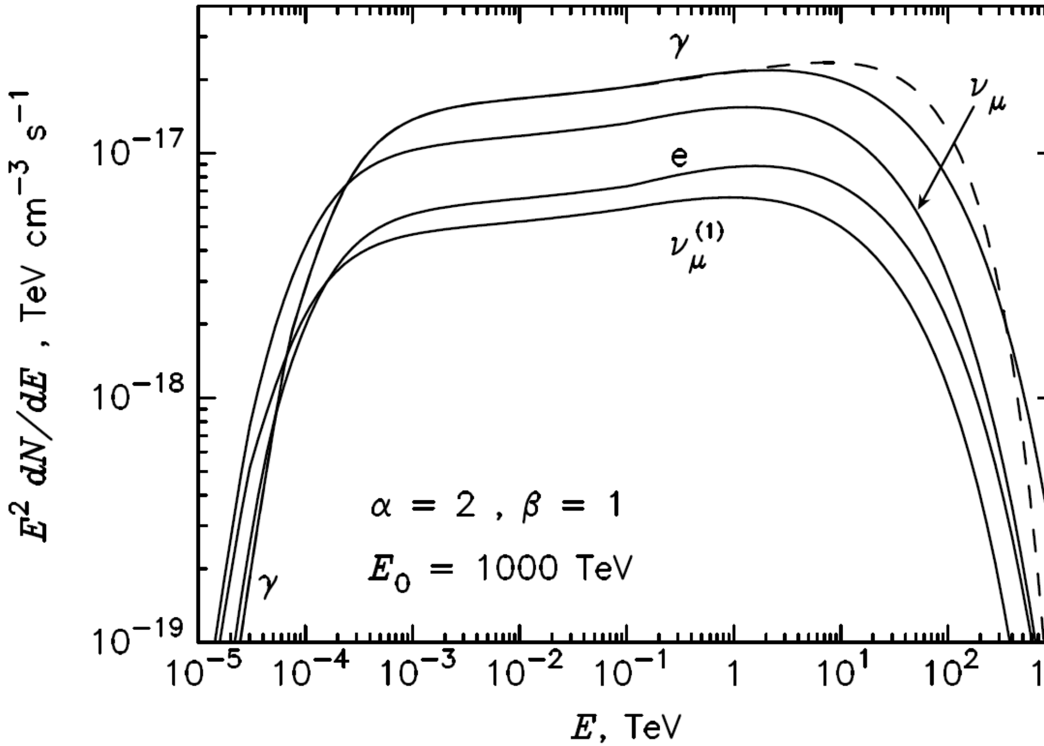
Hadronic interactions

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





Kinematic threshold: $E_{p,min}$ ~ 280MeV
Spectrum follows CR spectrum → ~ E^{-p}

Photohadronic interactions

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

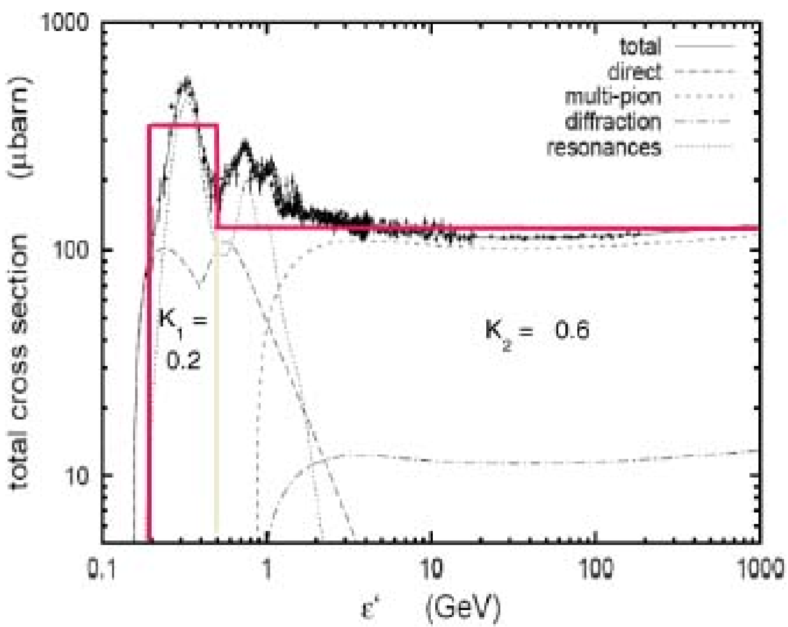
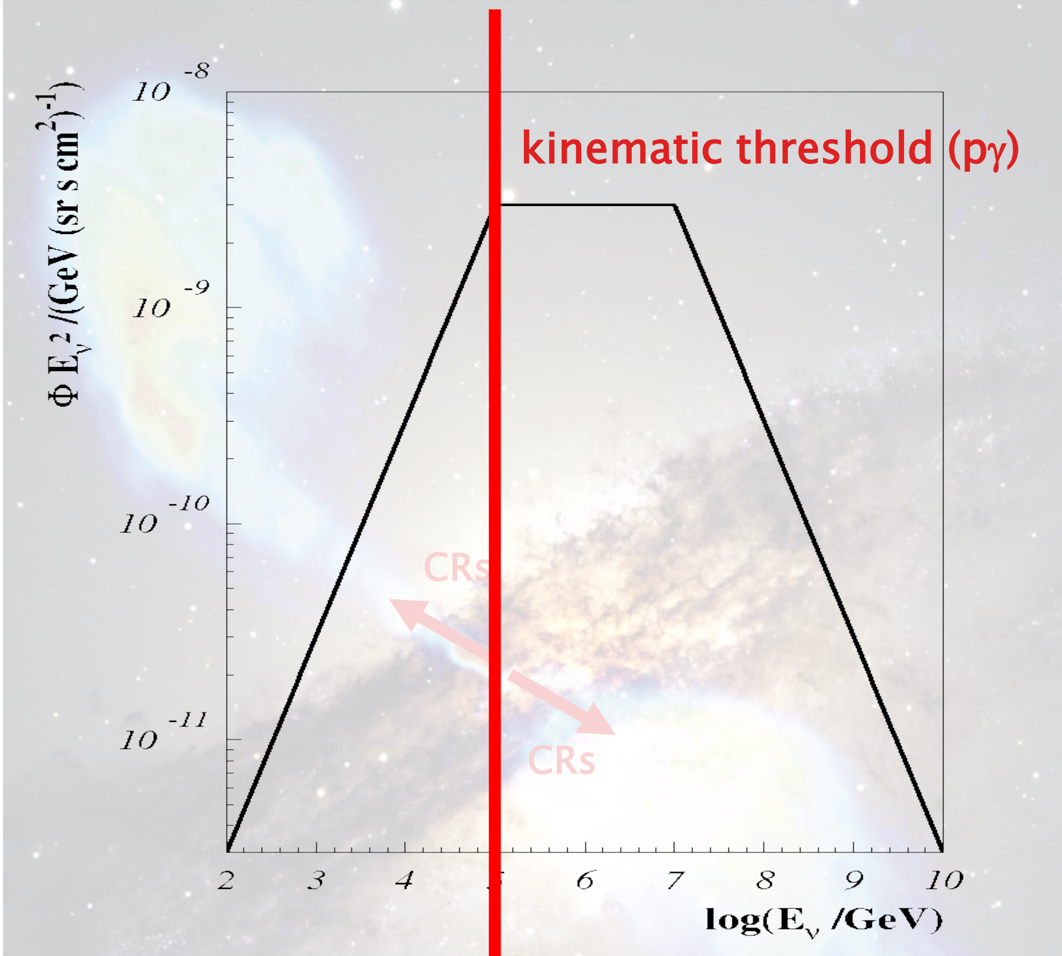


Fig: Dermer&Atoyan, New J Phys (2006)



Kinematic threshold for pion production

$$E_p * E_\gamma > (m_\Delta^2 - m_p^2)/4$$

Above threshold:

simple assumptions → **follows** $\mathbf{E^{-p}}$;

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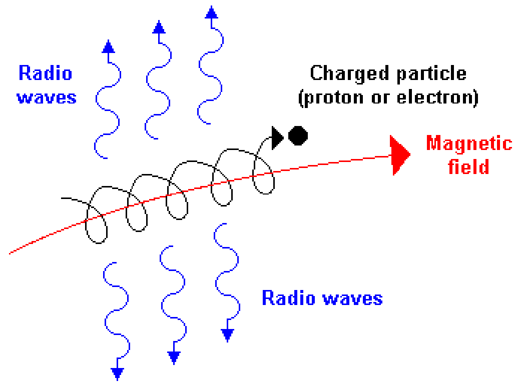
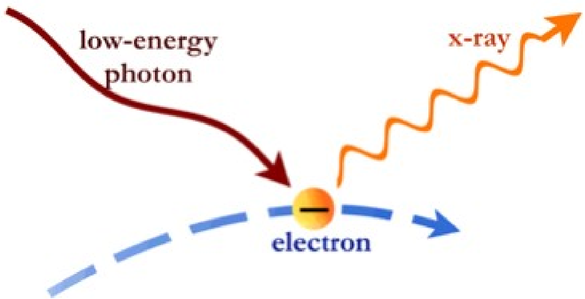
High-energy γ emission



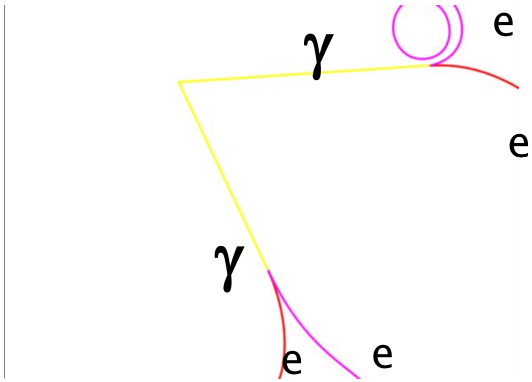
nrumiano

- **Synchrotron radiation (radio-Xray)**
  - Electrons are accelerated and emit synchrotron radiation



http://www.astro.wisc.edu/~bank/img/inversecompton.jpg

- **Inverse Compton scattering (MeV-TeV):**
  - electrons give energy to synchrotron photons
- **Bremsstrahlung**
  - Interaction of e- with ionized medium
- **π^0-decay (MeV-TeV)**
  - proton-photon interactions yield pions → TeV photons



http://teachers.web.cern.ch/

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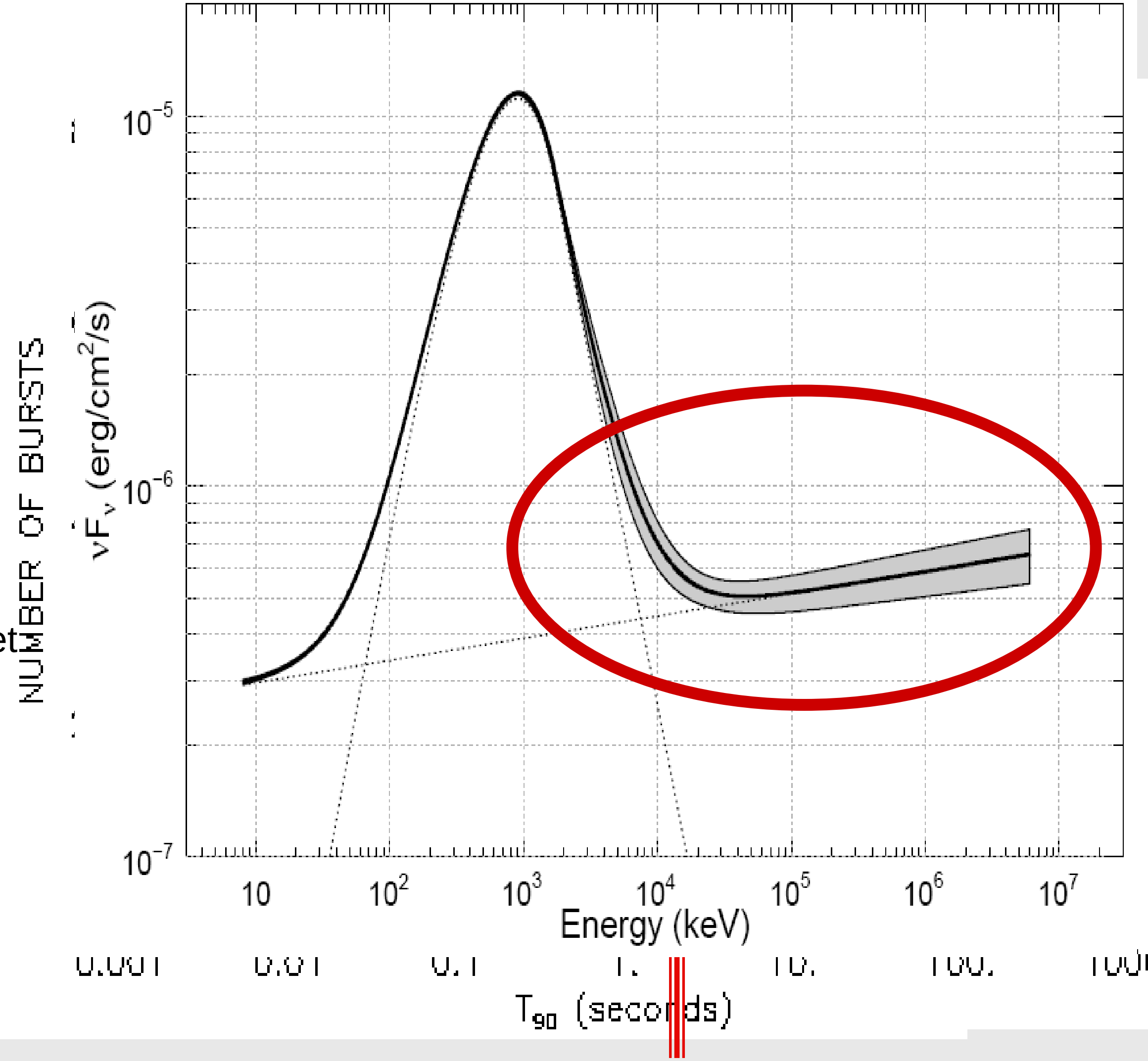
Gamma-ray burst SED & time scale

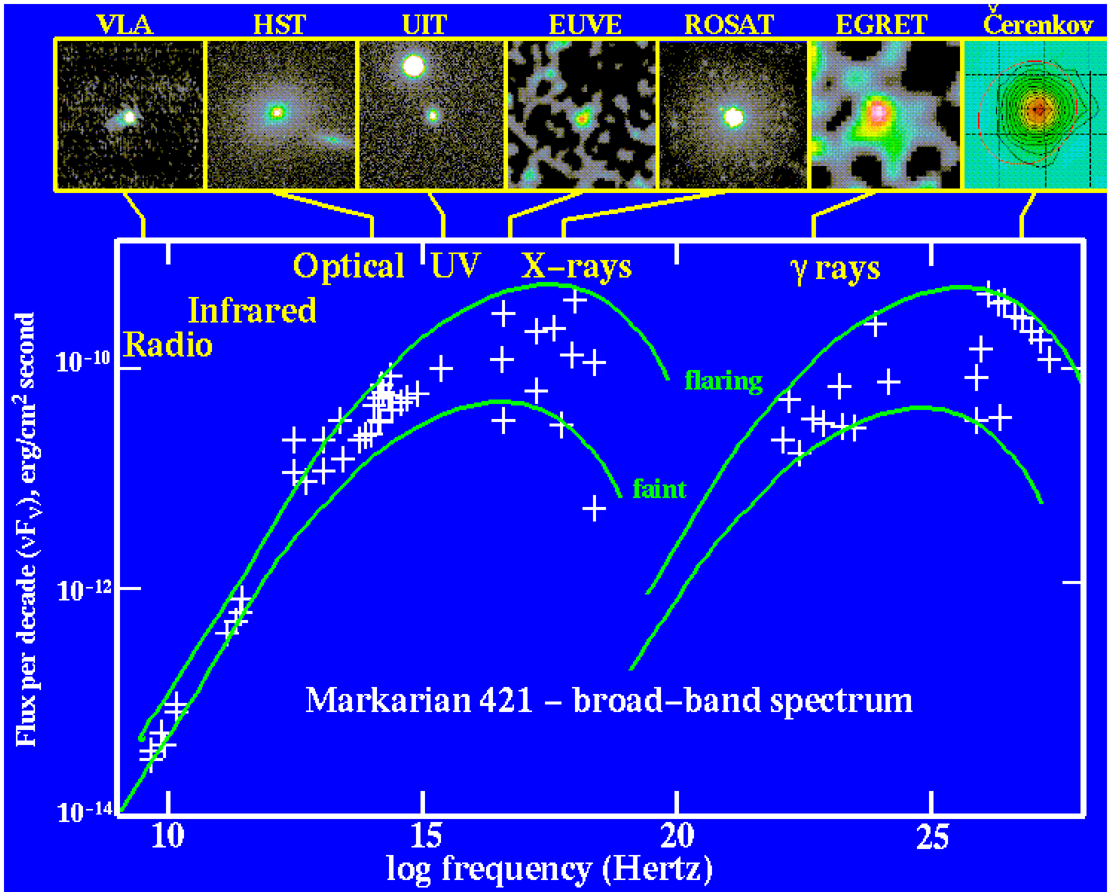
- **GRB941017** – high-energy component (BATSE & EGRET) Gonzalez et al, Nature 2003

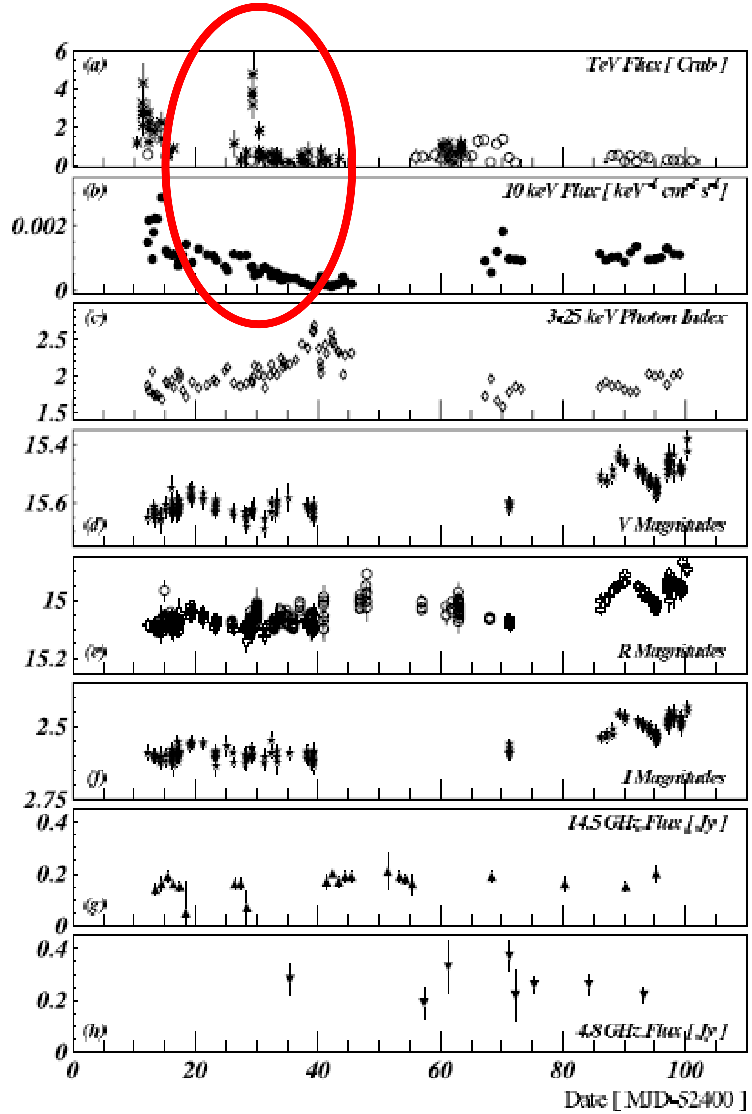
- **GRB090510 & GRB090902b** – high-energy component, most likely from π^0 decays (Ackermann et al, ApJ 716 (2010); Abdo et al, ApJL 706 (2009))



Abdo et al, ApJL

AGN: highly time-dependent emission





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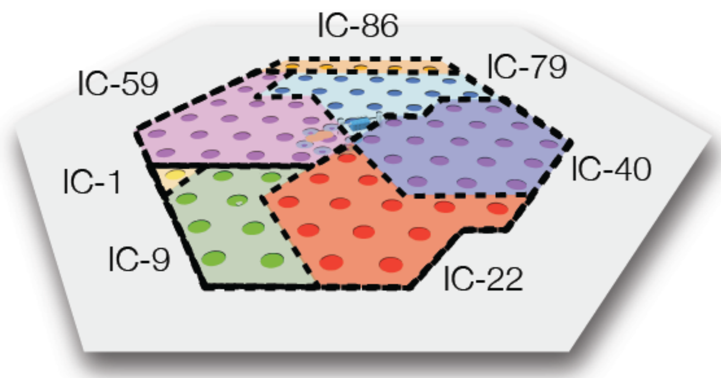
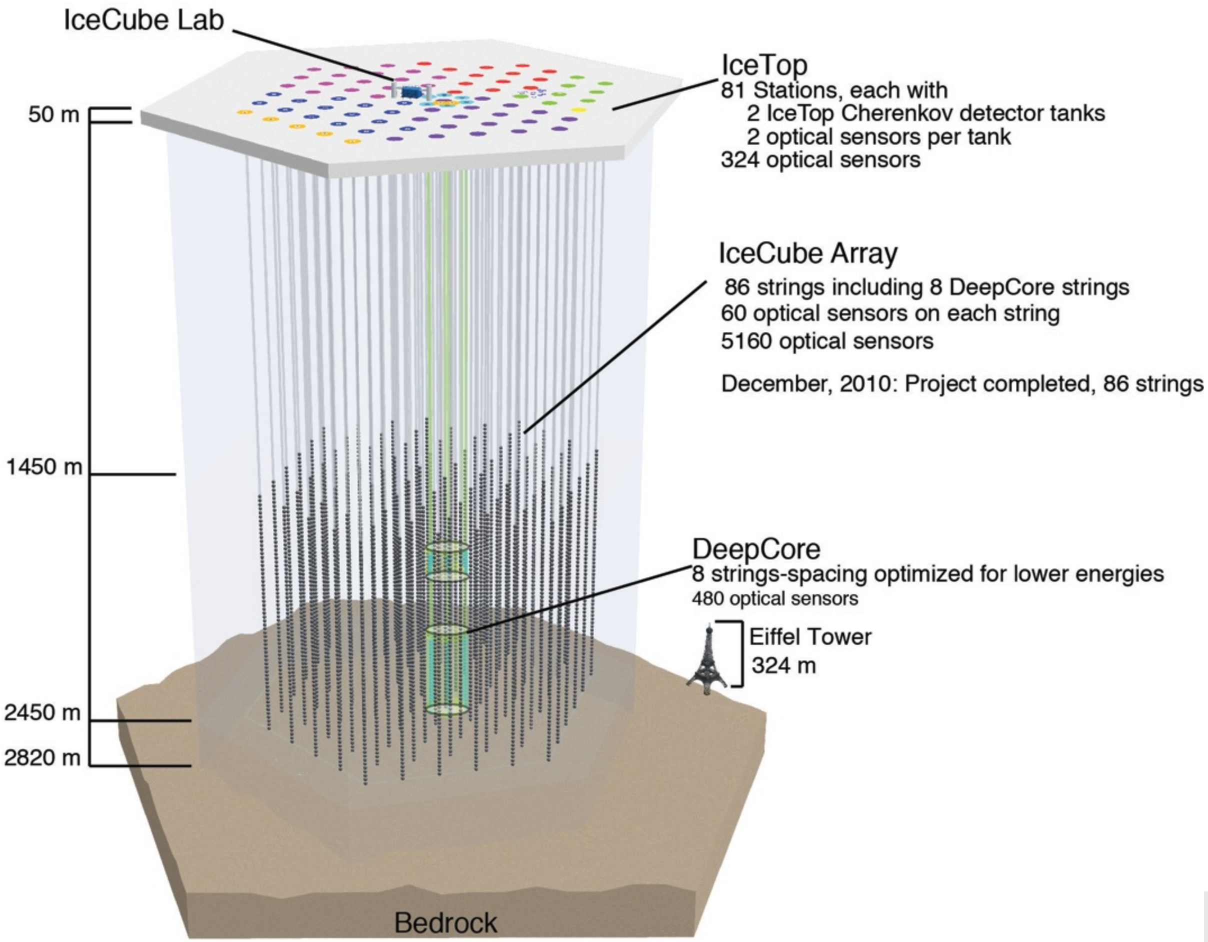
Neutrinos as new messengers: IceCube





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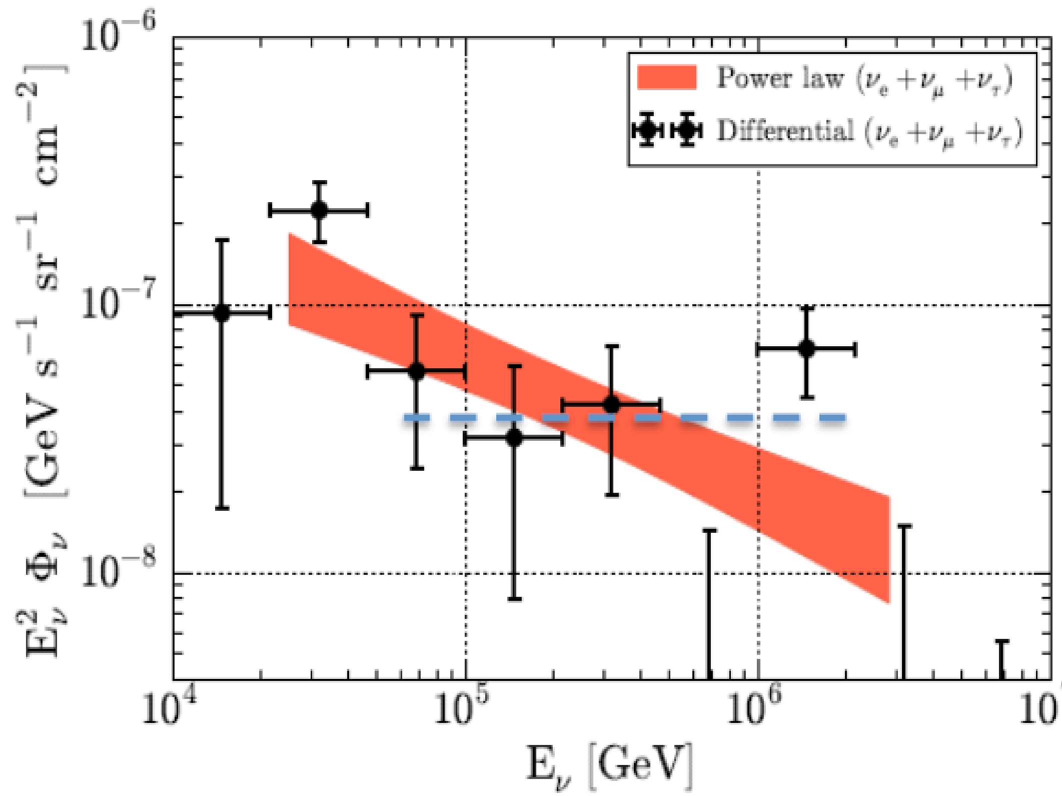
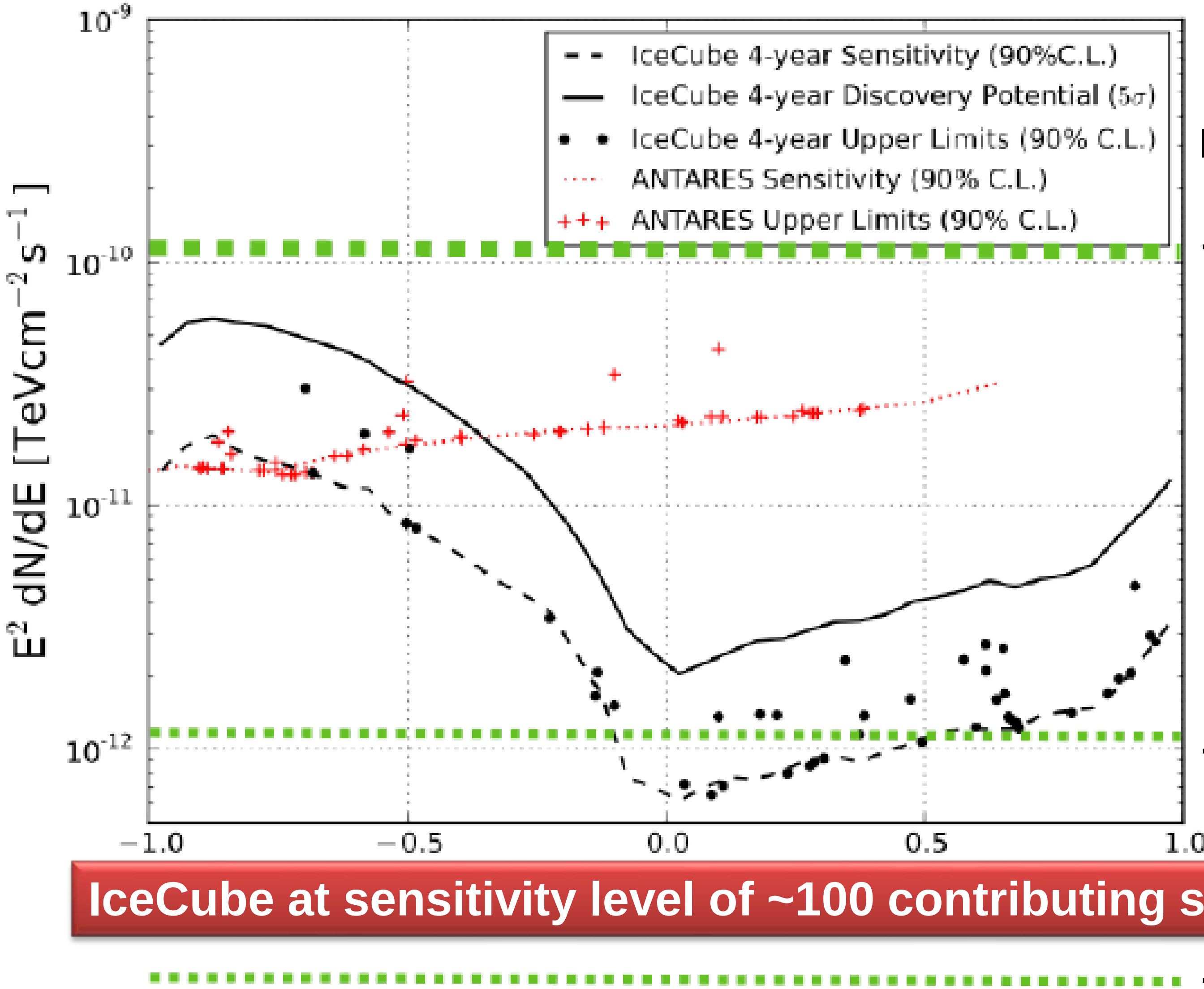
Spectral behavior: information from 6 different data samples

- Different strategies to suppress the atm. μ background
- Large samples: track-like and cascade-like events
- Power-law without cutoff between 25 TeV and 2.8 PeV
- Spectral index? E^{-2} disfavored with 3.8 σ; steeper than E^{-2}



IceCube, ApJ (2015)

Point source limits and diffuse measurement



Diffuse flux =

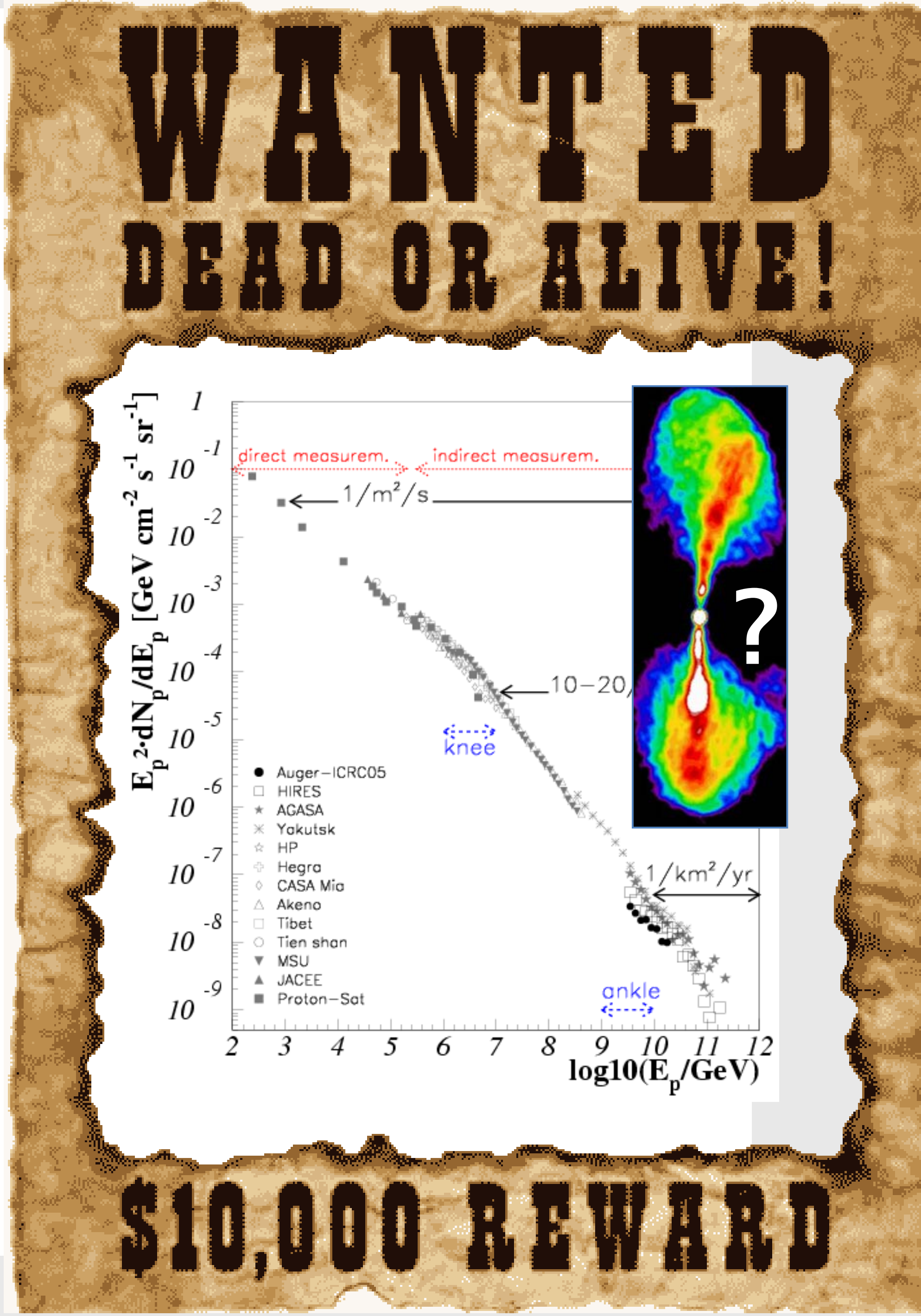
… one point source

… 100 sources

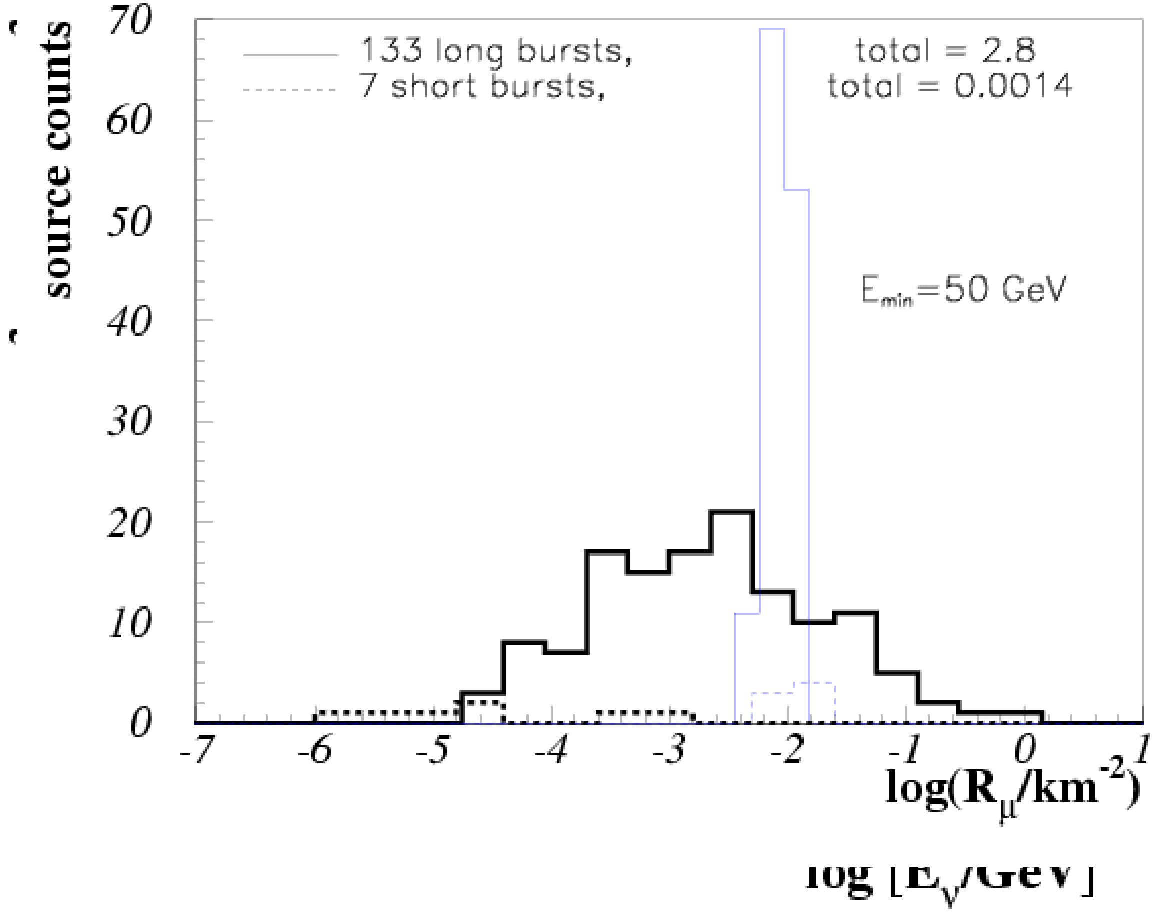
IceCube at sensitivity level of ~100 contributing sources

… 1000 sources

- **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 – must be >100 sources contributing
- **Temporal Clustering?:** no flares identified yet



Individual GRB rates in km3-detector



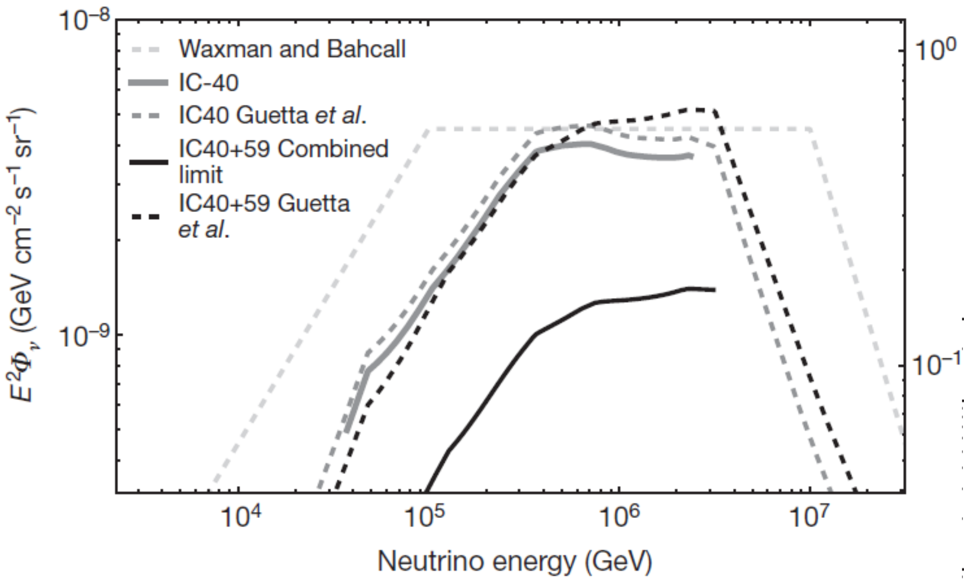
JK Becker et al, Astrop.Phys. (2006); astro-ph/0511785

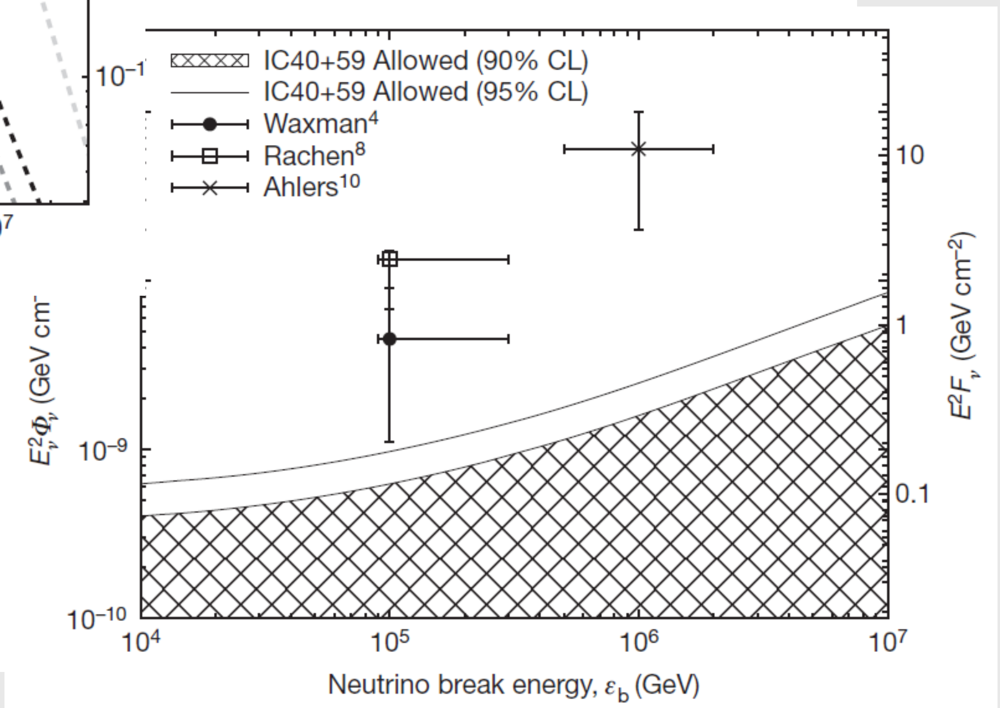
Stacking method in IceCube

Neutrino flares:
(1) temporal and spatial selection reduces background to ZERO
(2) multiwavelength-coincidenes of flares enhances significance

astro-ph/0609534

GRB/Nature

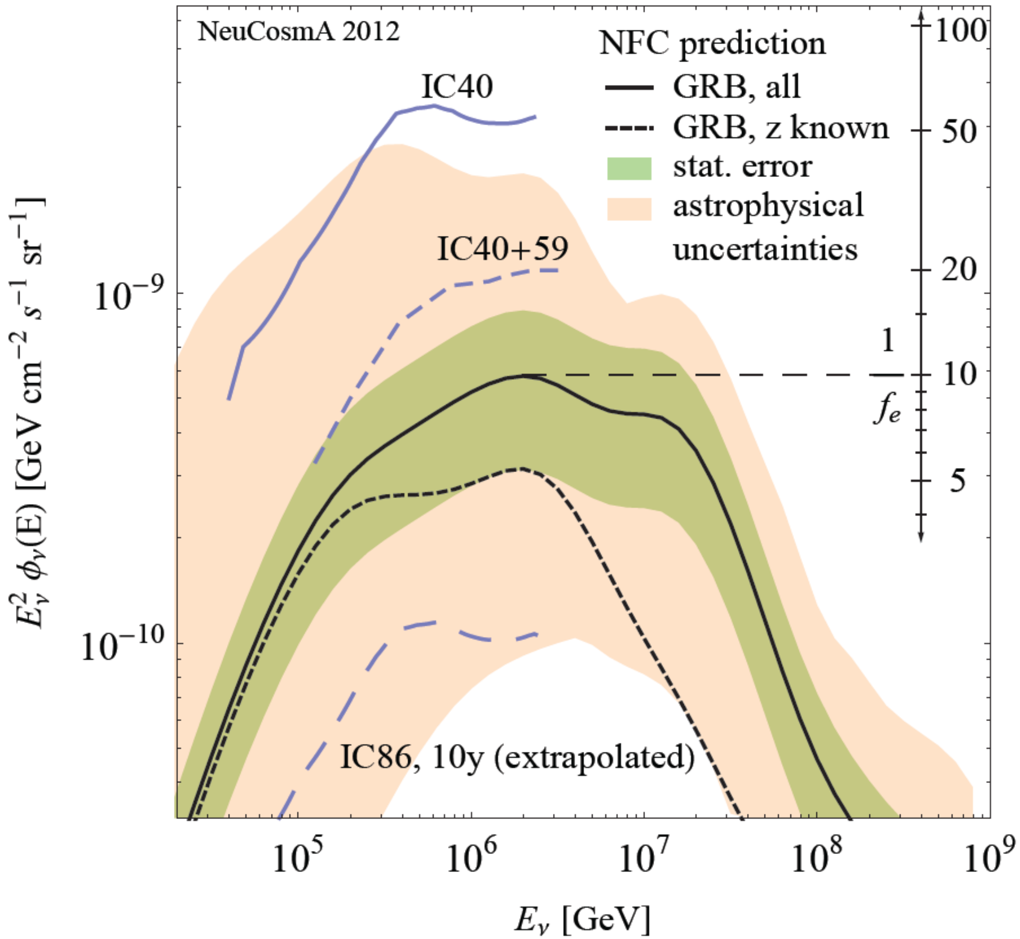

Waxman and Bahcall
IC-40
IC40 Guetta et al.
IC40+59 Combined limit
IC40+59 Guetta et al.
Neutrino energy (GeV)


IC40+59 Allowed (90% CL)
IC40+59 Allowed (95% CL)
Waxman4
Rachen8
Ahlers10
Neutrino break energy, εb (GeV)

Discussion

- Uncertainties of astrophysical parameters:
  - B-field
  - Boost factor
  - redshift
  - variability time

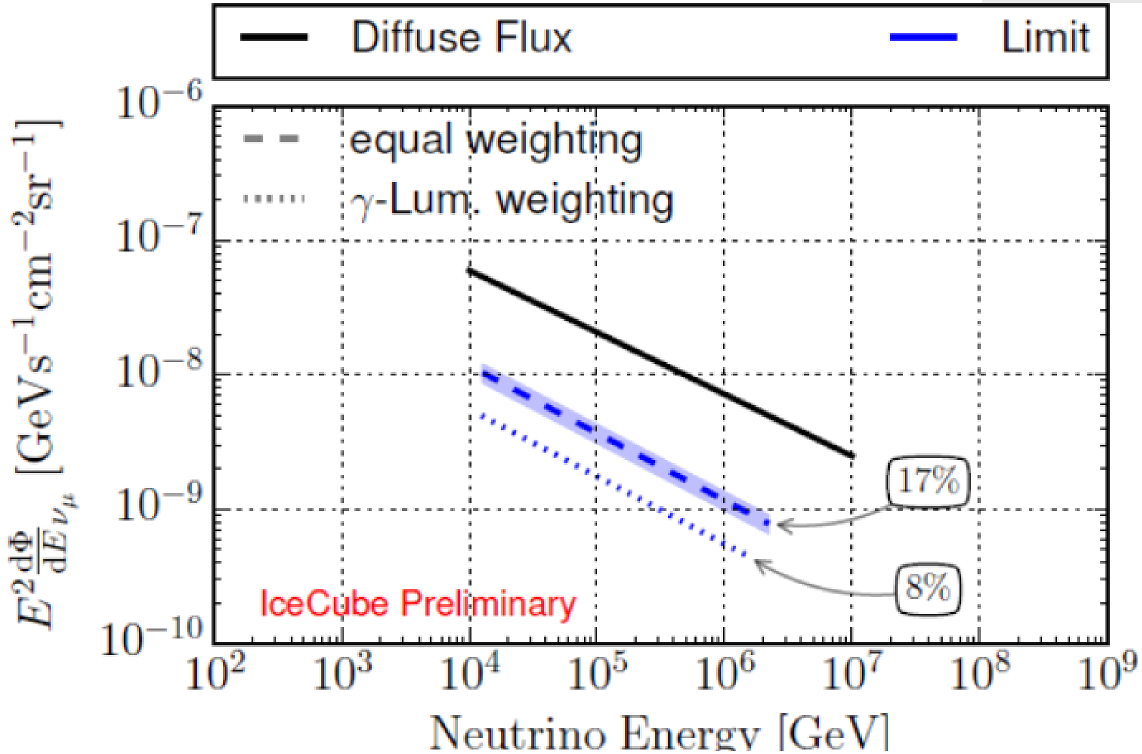
- IceCube analysis now at a level to start to seriously constrain GRBs as UHECRs



Hümmer et al, PRL (2012)

Fermi Blazars Stacking

- Tracks, 2009 – 2011
- 862 blazars from the 2nd Fermi AGN catalog
- ➔ < 30% of diffuse ν flux from Fermi blazars

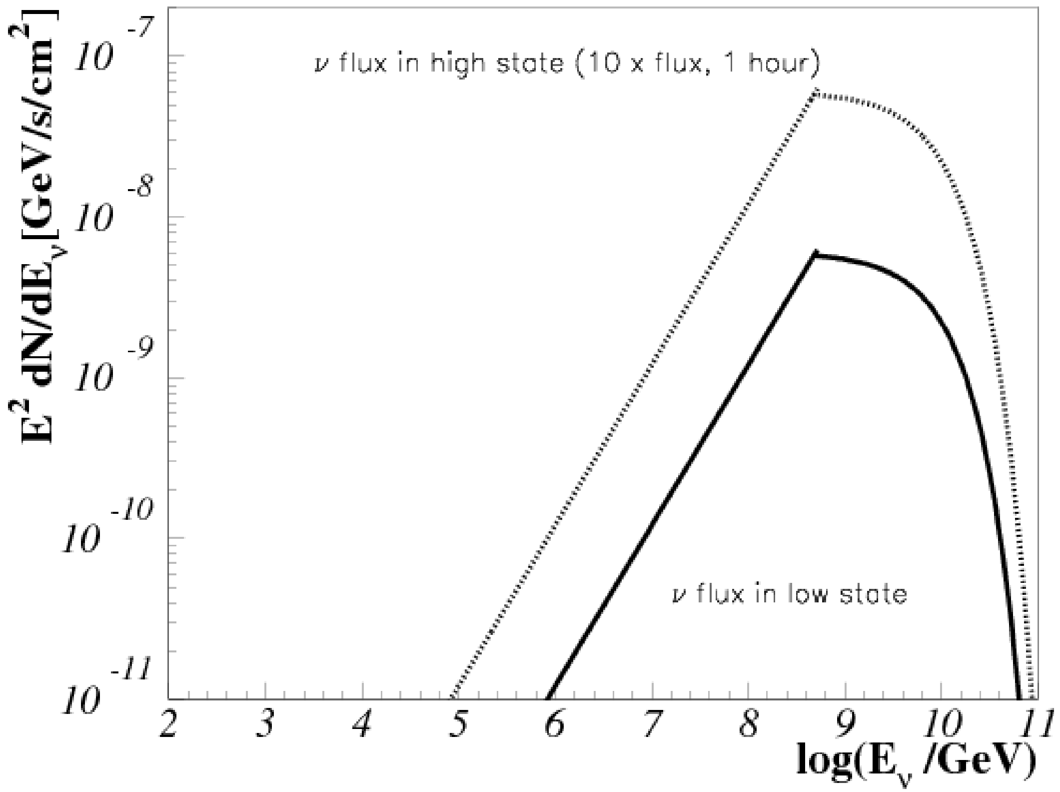


[T. Glüsenkamp, RICAP 2014, arXiv:1502.03104]

Blazar flares: enhancement for short time

Pks2155-304

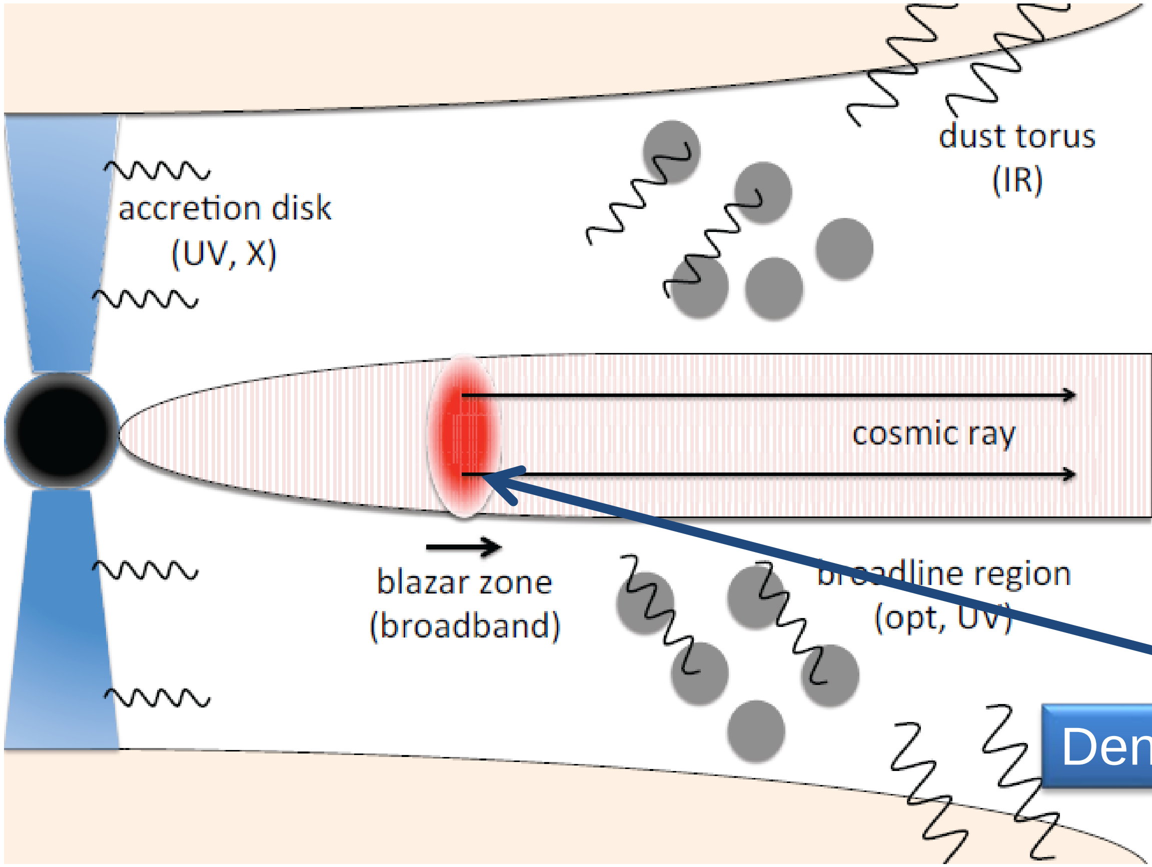
- Short time flares ~ day-timescales
- Enhancement of TeV flux by factor 10 (example Pks2155-304)
- Might be too weak to see in Fermi ➔ more than 800 sources would contribute in that case



Becker, Meli & Biermann, ICRC2009

Neutrino production in AGN?

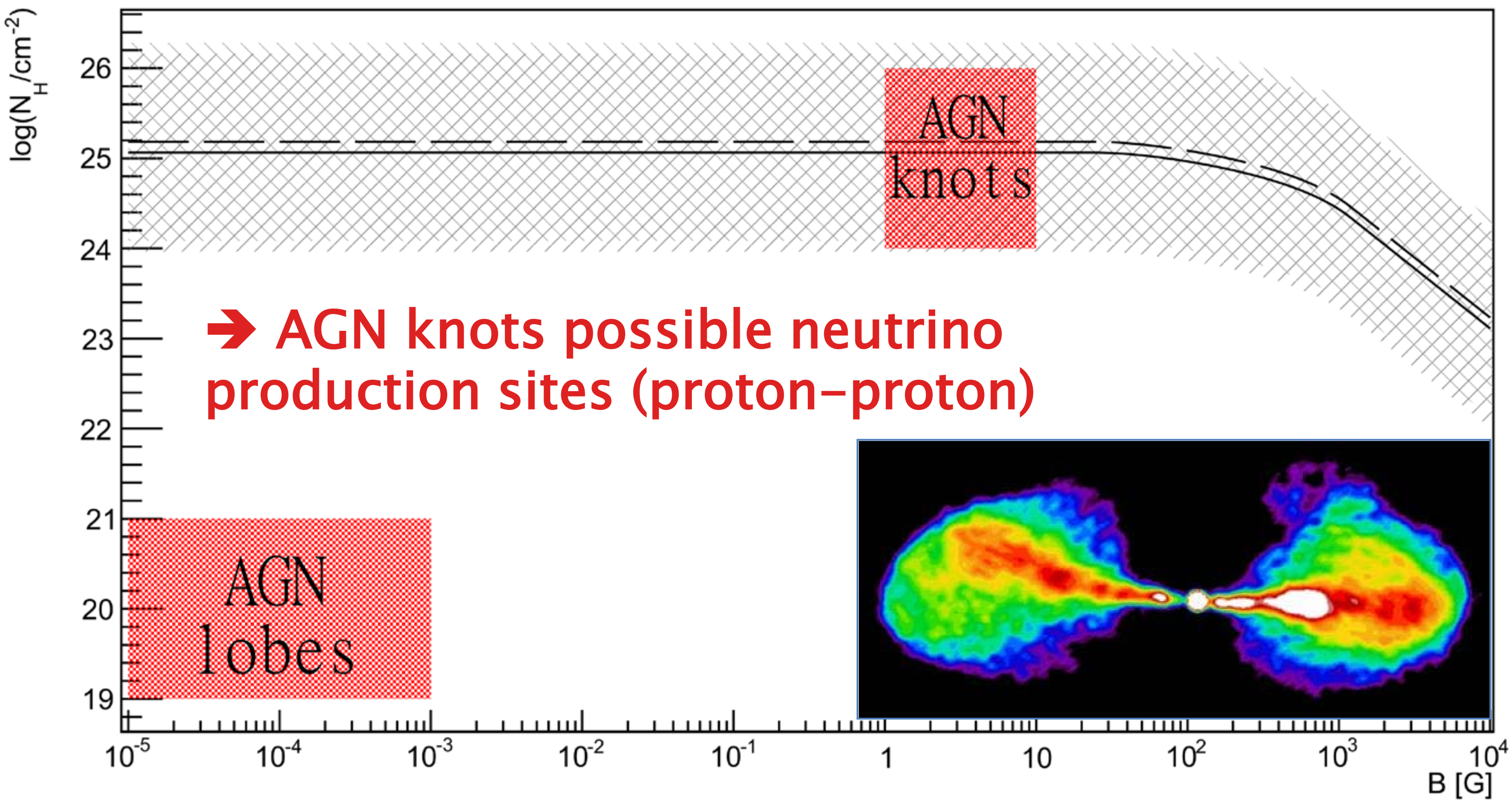
Different photon target fields



Densities up to 10^{10}cm^{-3}

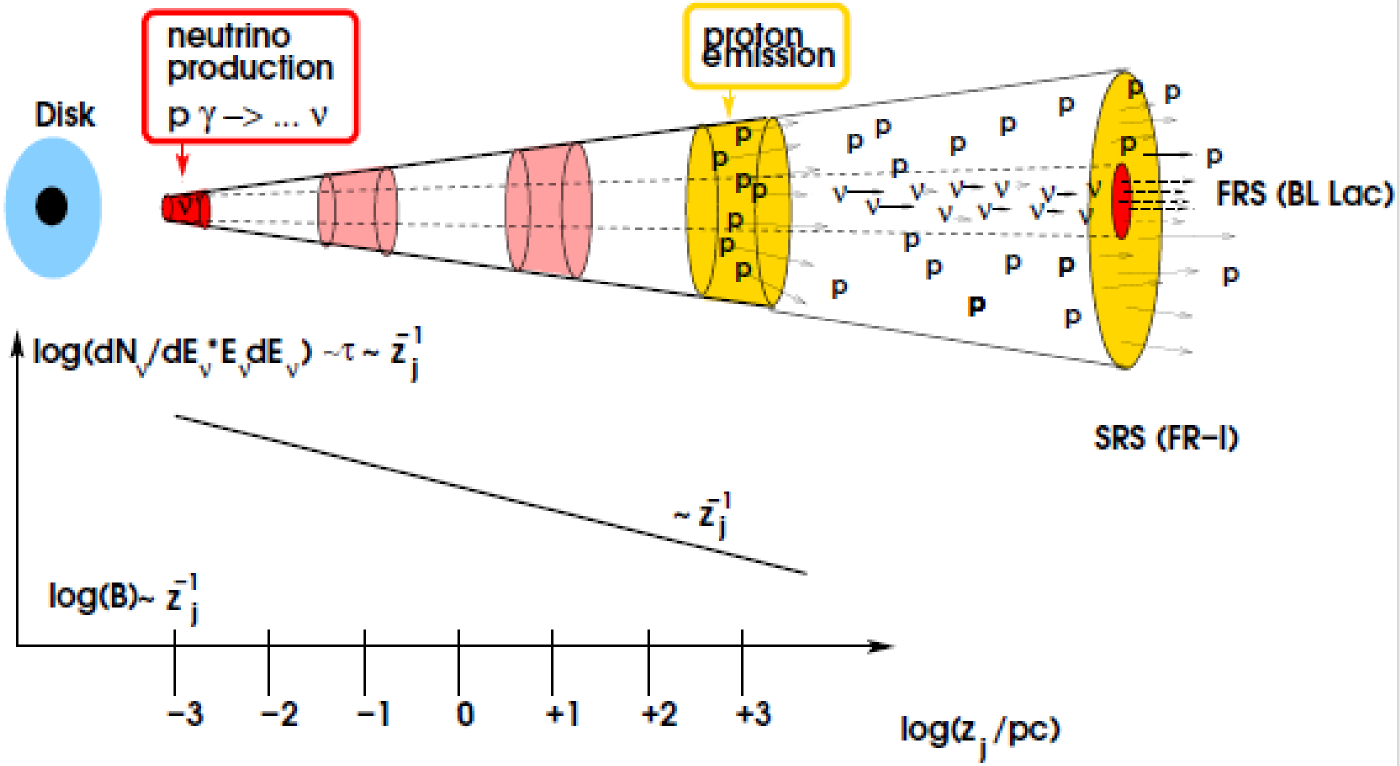
➔ N_H – B:
allowed Parameter space VS observed properties

➔ AGN knots possible neutrino production sites (proton–proton)



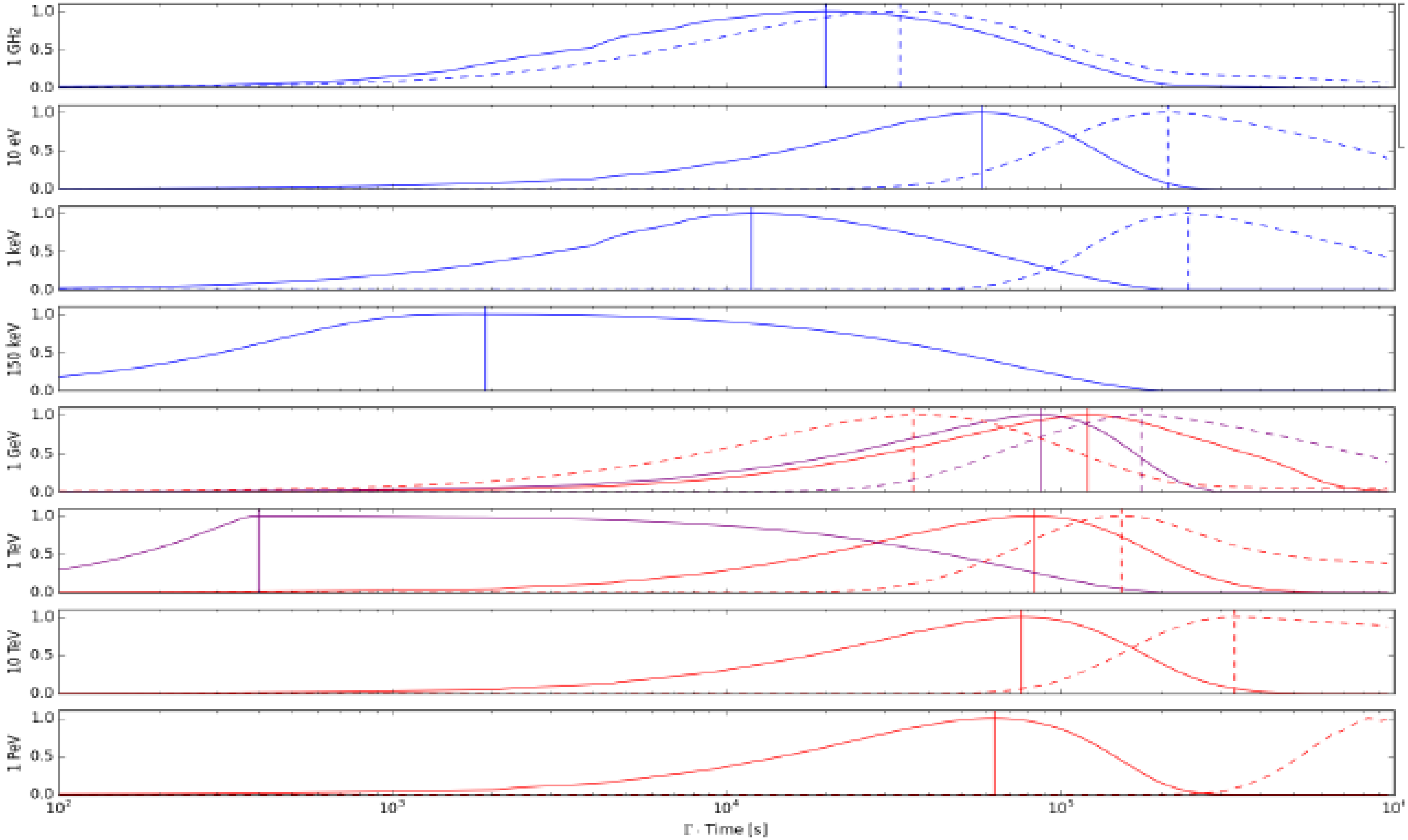
Becker Tjus, Eichmann, Halzen, Saba, PRD 2014

Neutrino and CR emission model



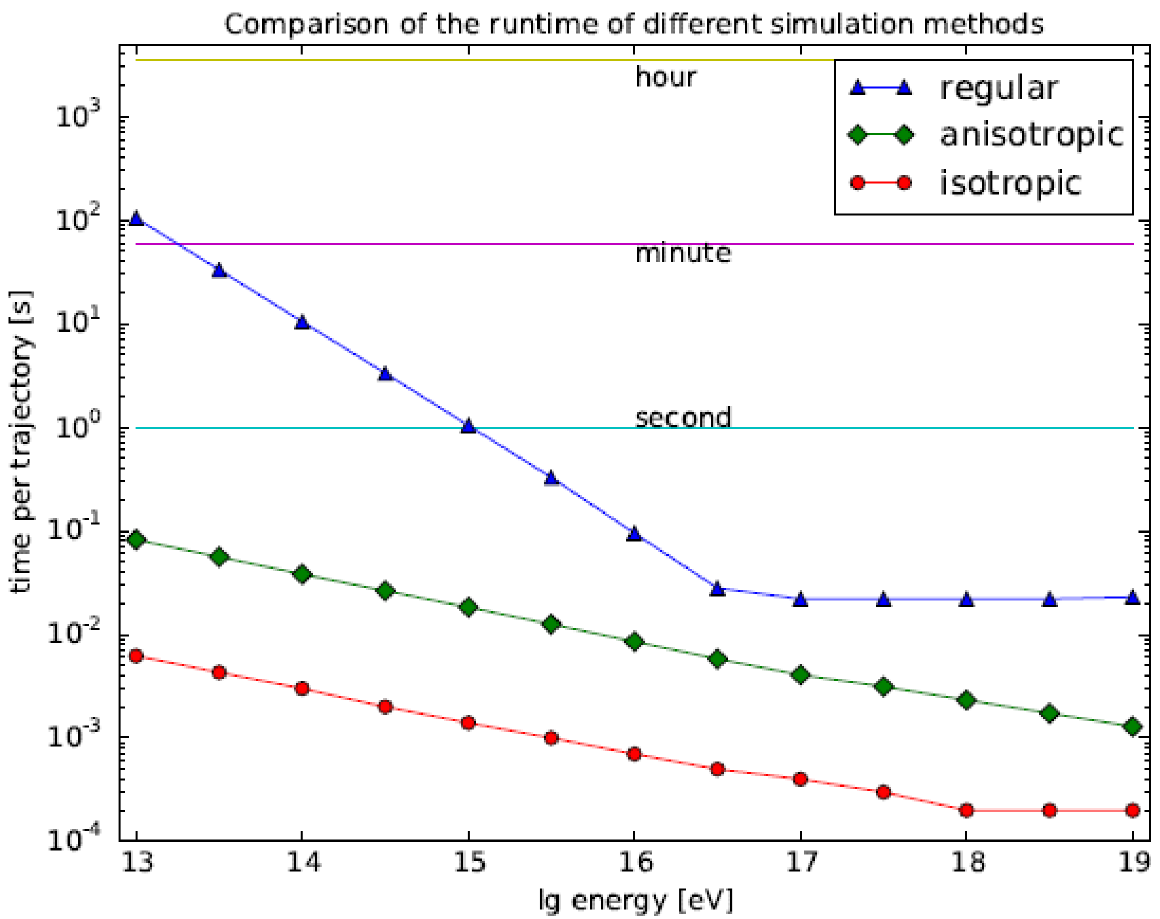
Becker & Biermann, Astro.Phys 2009

Outlook: modeling time lags in AGN



M. Mandelartz, PhD thesis, Bochum

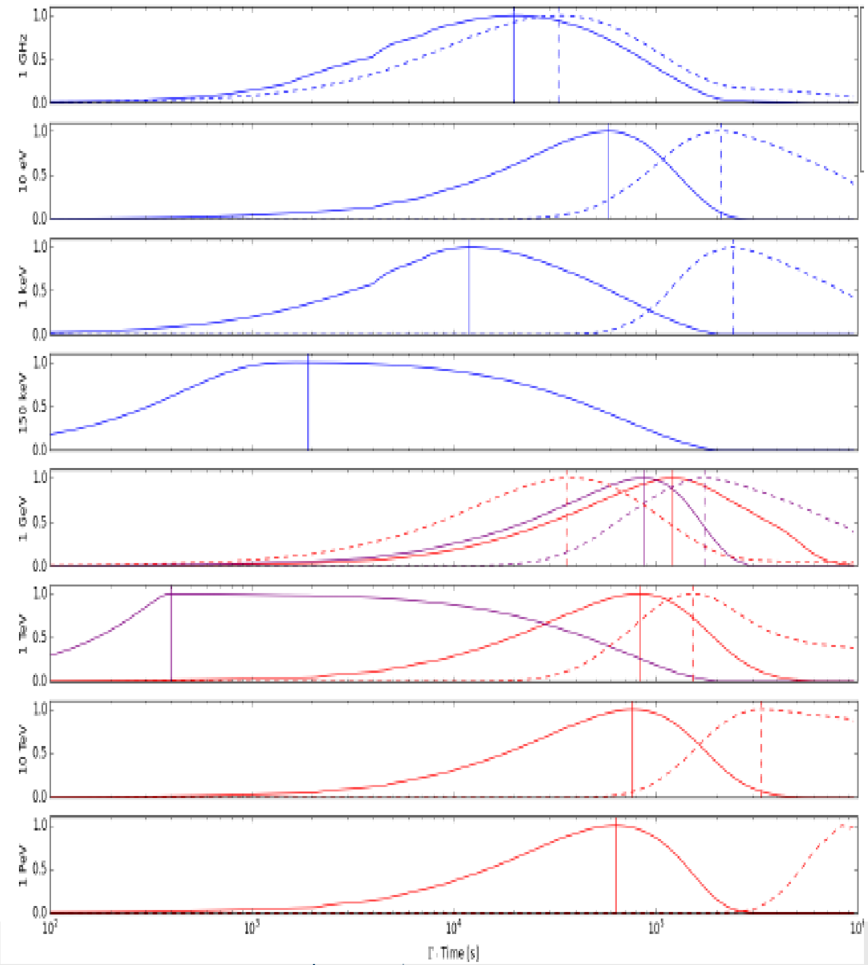
Performance improvement
SDE VS EoM

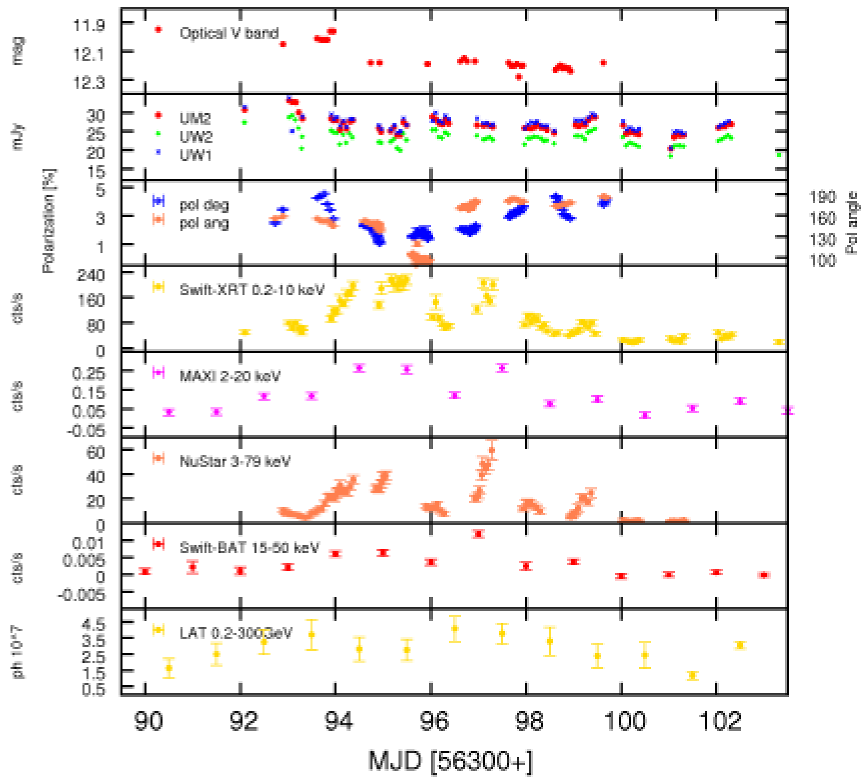


Merten et al, CRPropa Galactic Extension, in prep.
Merten, PhD thesis, Bochum

Outlook: modeling time lags in AGN

$$\frac{\partial f_a}{\partial t} = \nabla \cdot (D \nabla f_a) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(D_p p^2 \frac{\partial f_a}{\partial p} + \dot{p}_a f_a\right) + S_a \delta(t)$$





M. Mandelartz, PhD thesis, Bochum

Outlook (2)

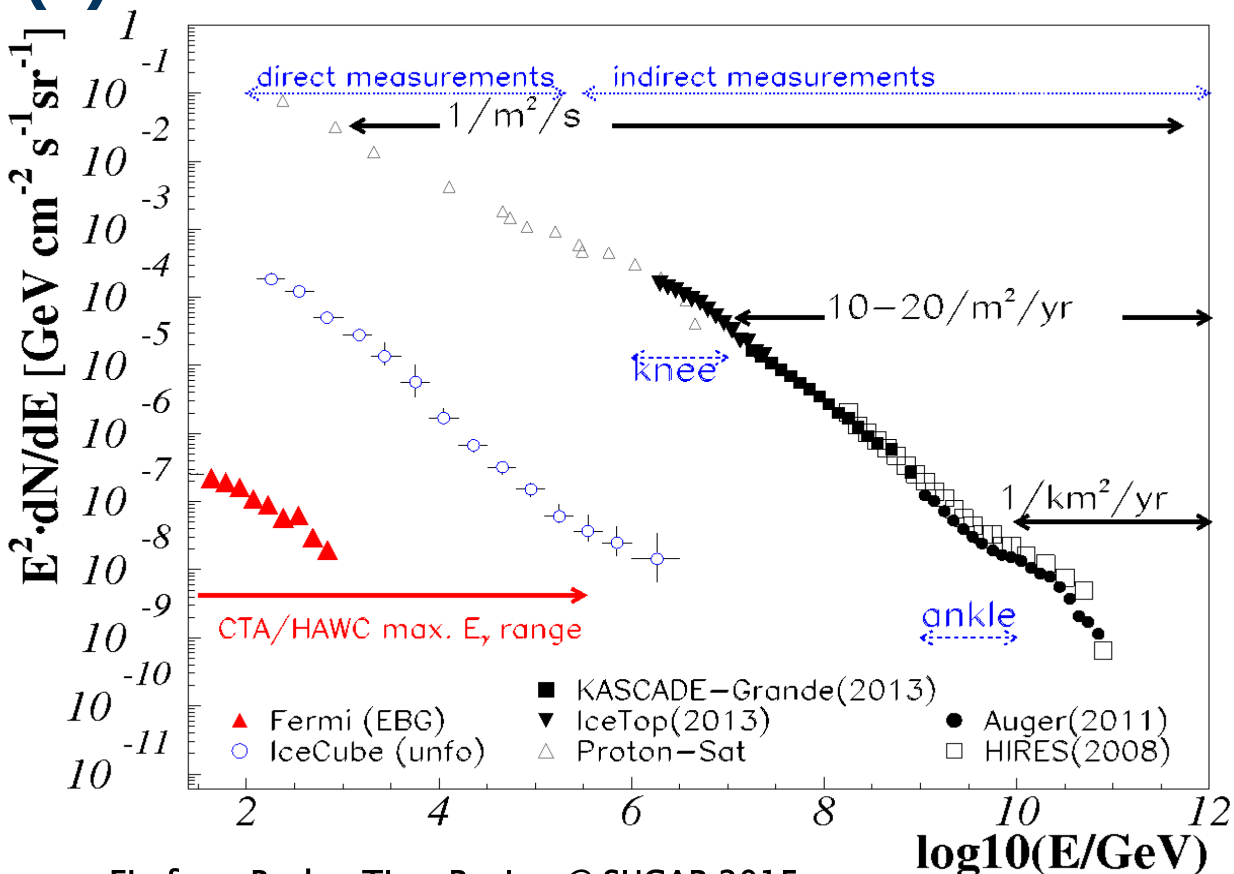


Fig from Becker Tjus, Review @ SUGAR 2015

Neutrinos from the knee region and above
➔ disentangling Galactic and extragalactic cosmic rays

RUB

Thank you!

Questions?