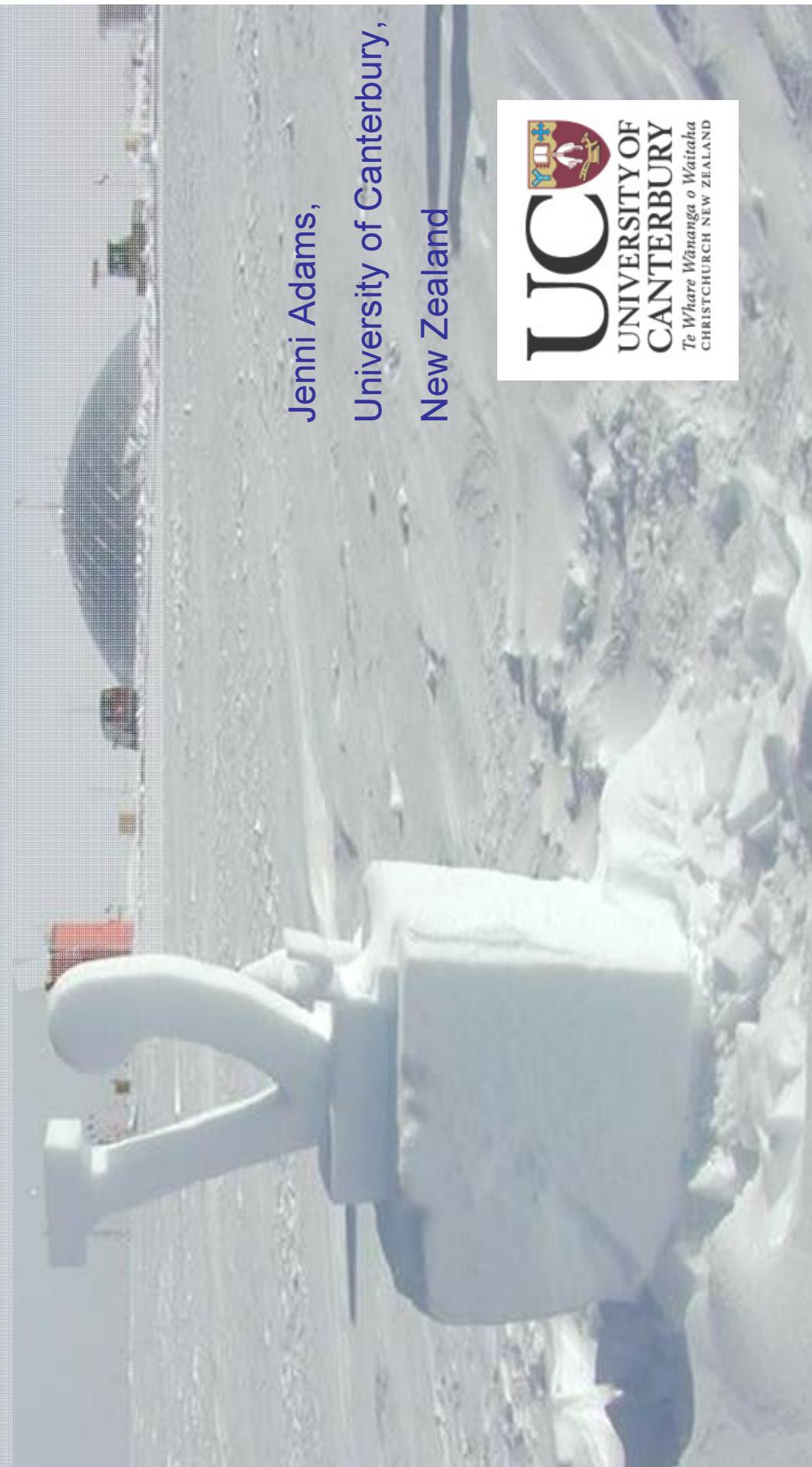
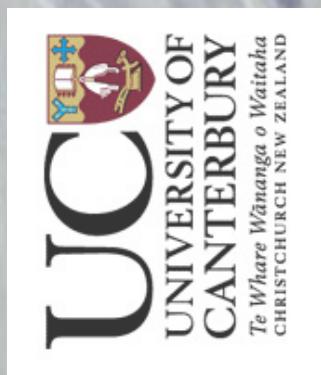


Neutrinos as probes of ultra-high energy astrophysical phenomena

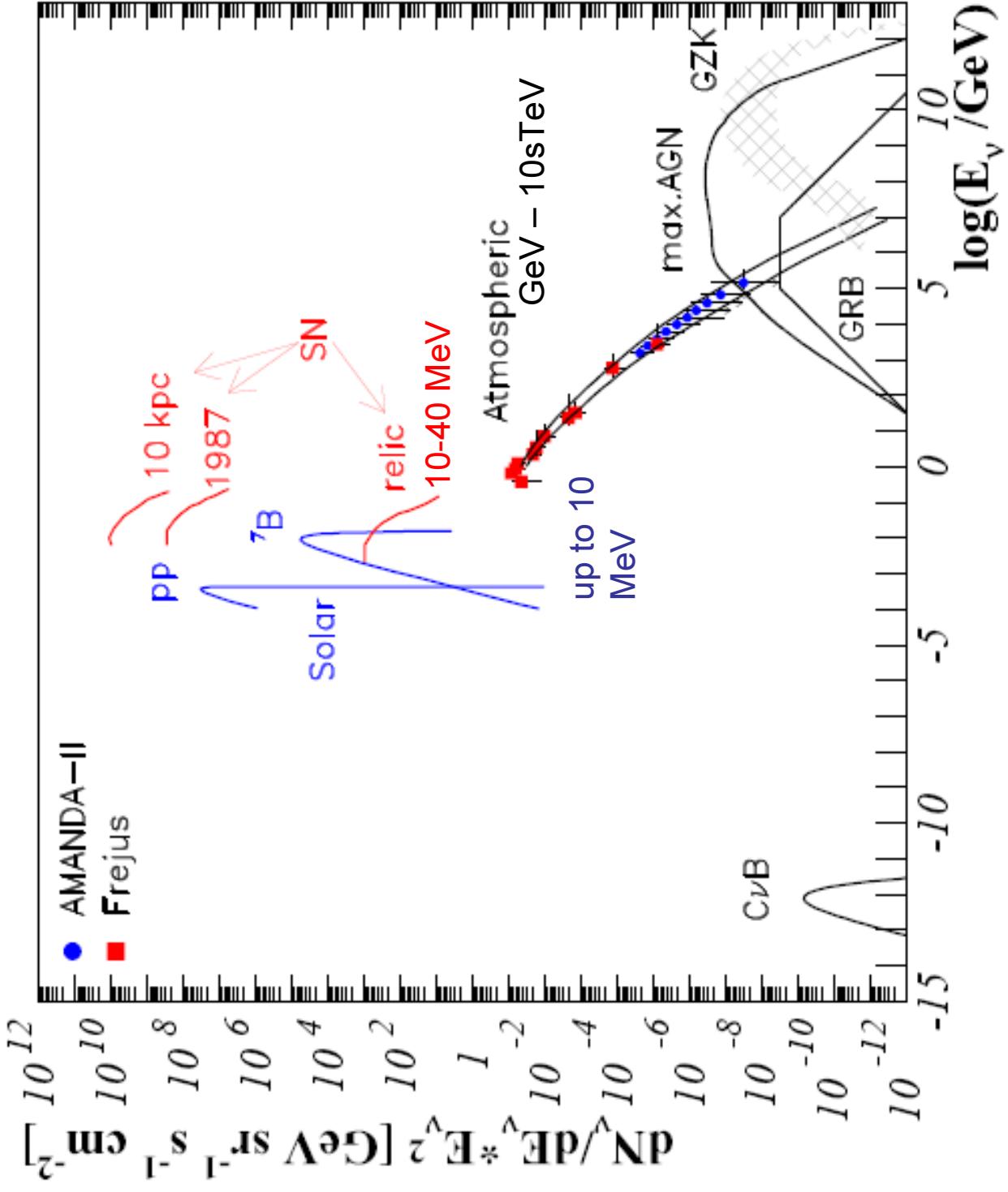


Jenni Adams,

University of Canterbury,
New Zealand



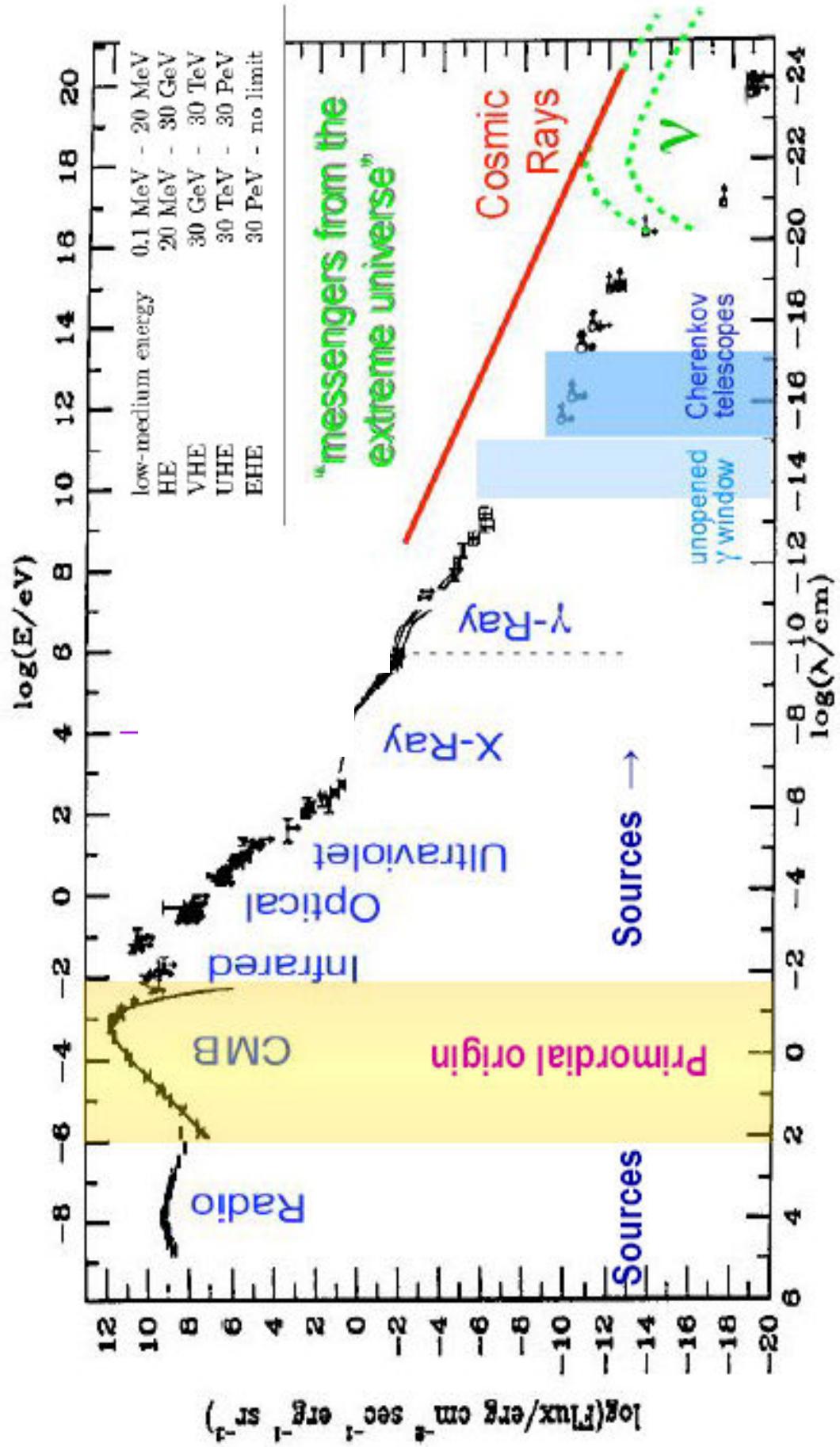
Neutrino sources



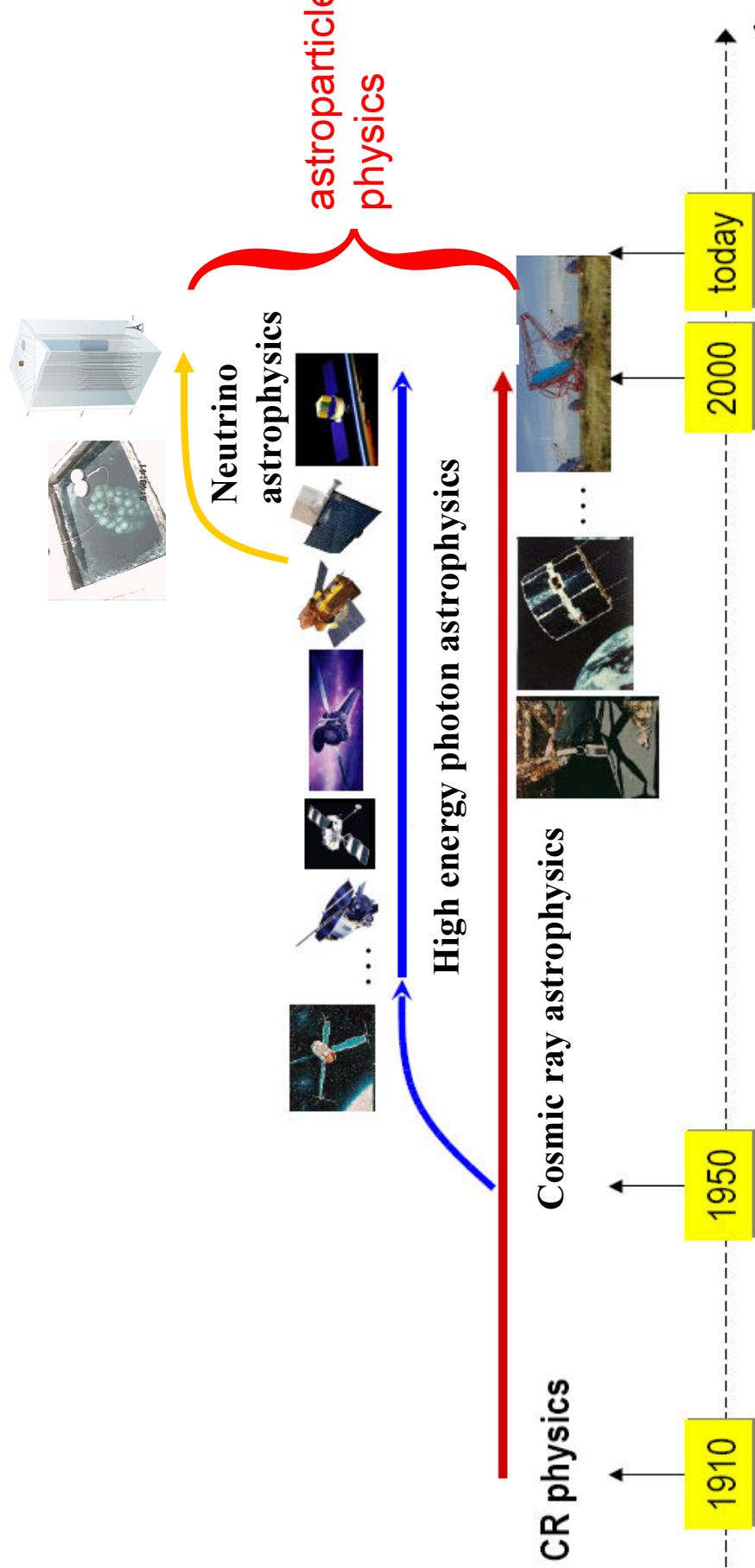
How do we know there are high energy astrophysical phenomena?

- Observe high energy particles
- Observe radiation that is indicative of high energy processes
- There might be hidden sources...

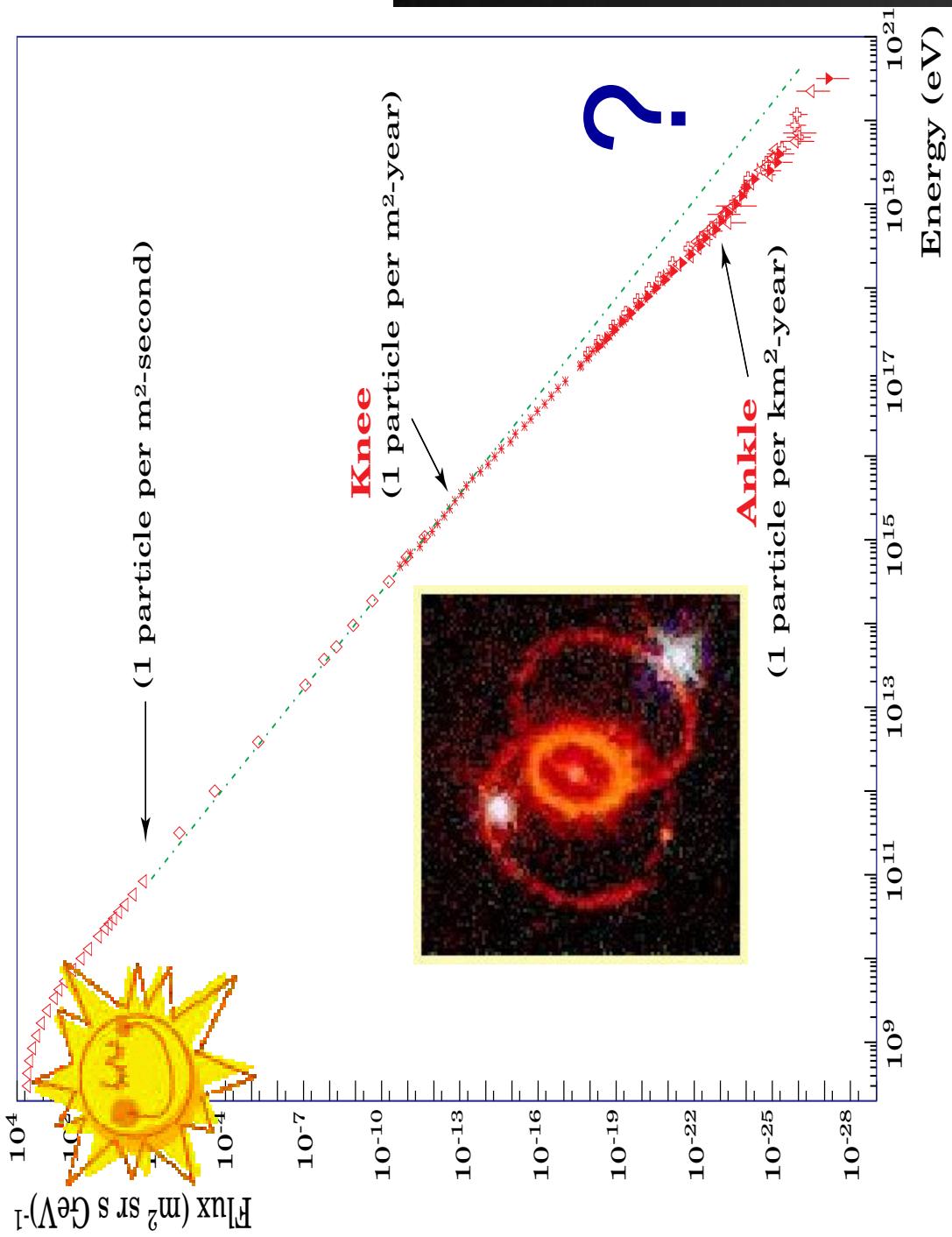
Cosmic messengers



Astroparticle physics



Origin of the ultra-high energy cosmic rays?



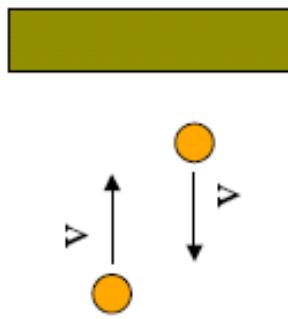
How do we accelerate a particle?

- Fermi Acceleration

How do we accelerate a tennis ball??

- Tennis ball bouncing off a wall

♦ No energy gain or loss



bounce = unchanged velocity

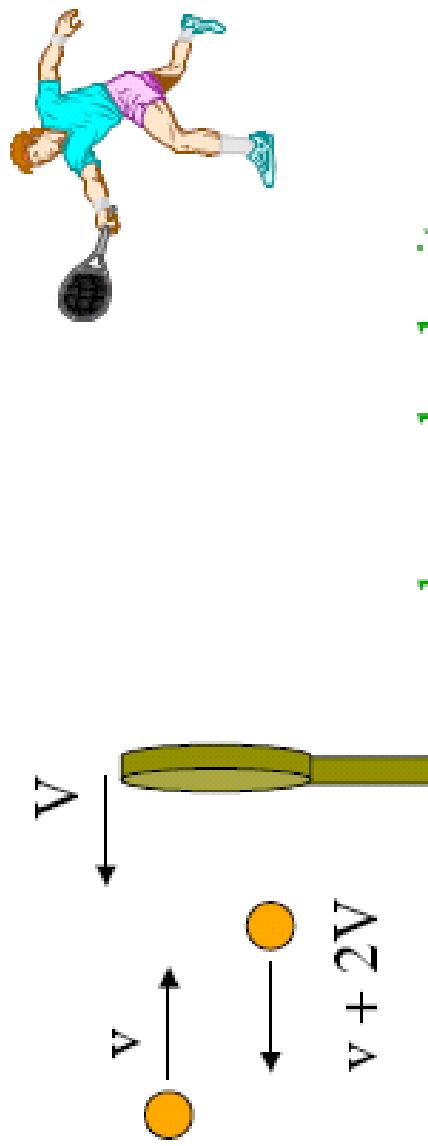


same for a steady racket...

- Not with a steady tennis racket!

Need a moving racket

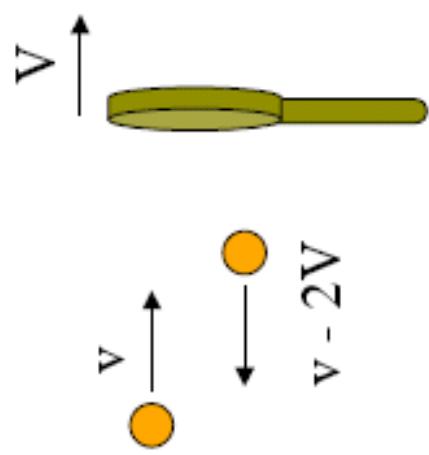
- ♦ No energy gain or loss... in the frame of the racket!



unchanged velocity
with respect to the
racket

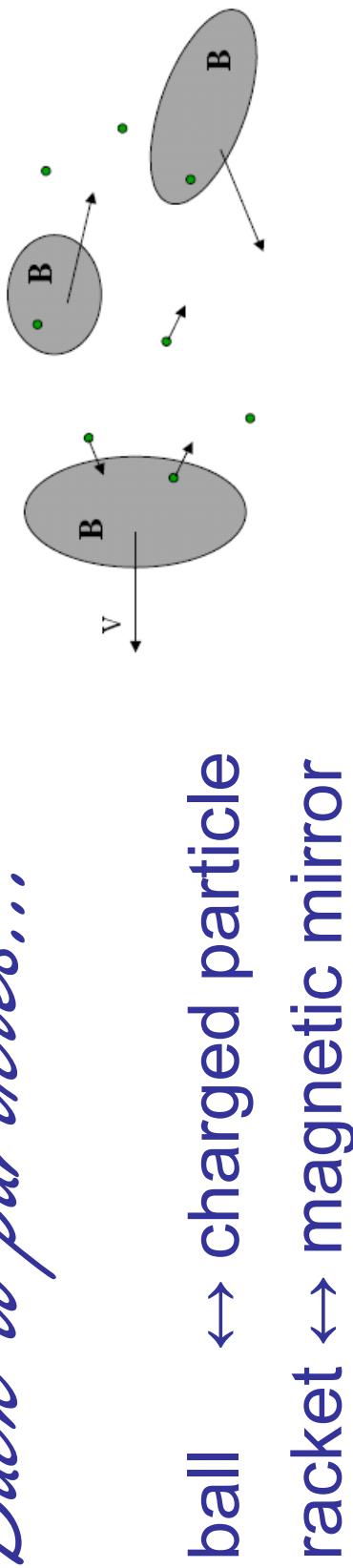
→ change-of-frame acceleration

- Drop shot



Particle deceleration

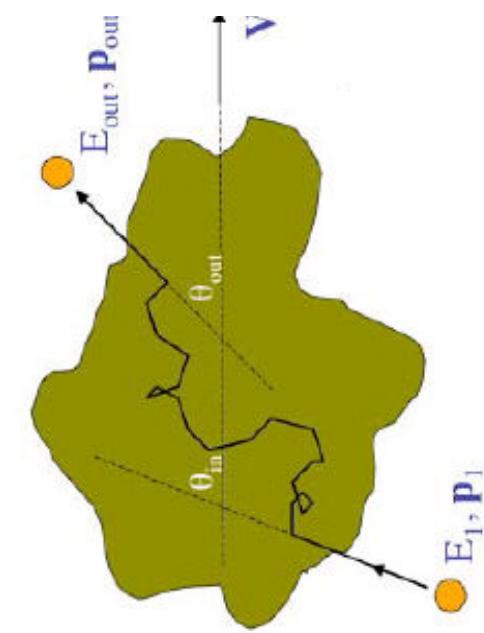
Back to particles...



- 1 When a particle is reflected off a magnetic mirror coming towards it, in a **head-on** collision, it **gains** energy
- 2 When a particle is reflected off a magnetic mirror going away from it, in an **overtaking** collision, it **loses** energy
- 3 head-on collisions are **more frequent** than overtaking collisions

\Rightarrow net energy gain, on average (stochastic process)

Fermi Acceleration

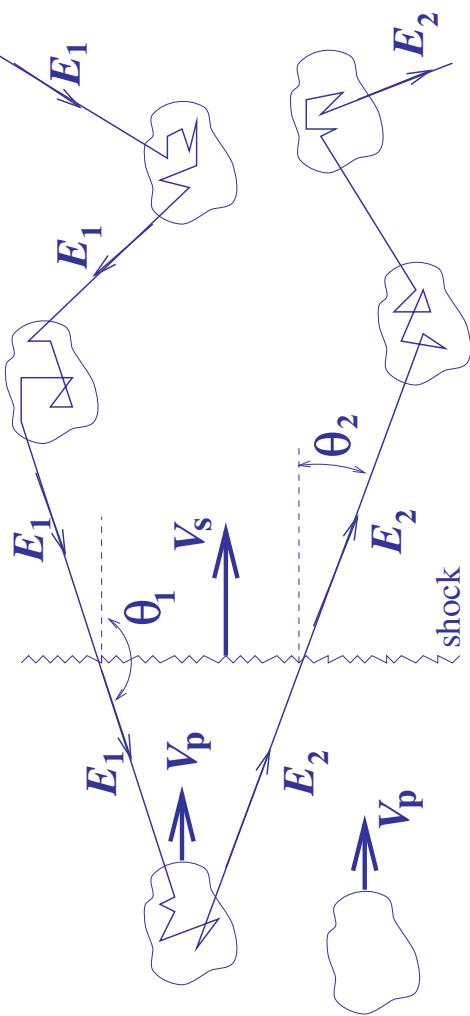


- 2nd Order:
randomly distributed magnetic mirrors

$$\frac{\Delta E}{E} \sim \beta^2 \quad \beta = \frac{v}{c} \leq 10^{-4}$$

slow and inefficient

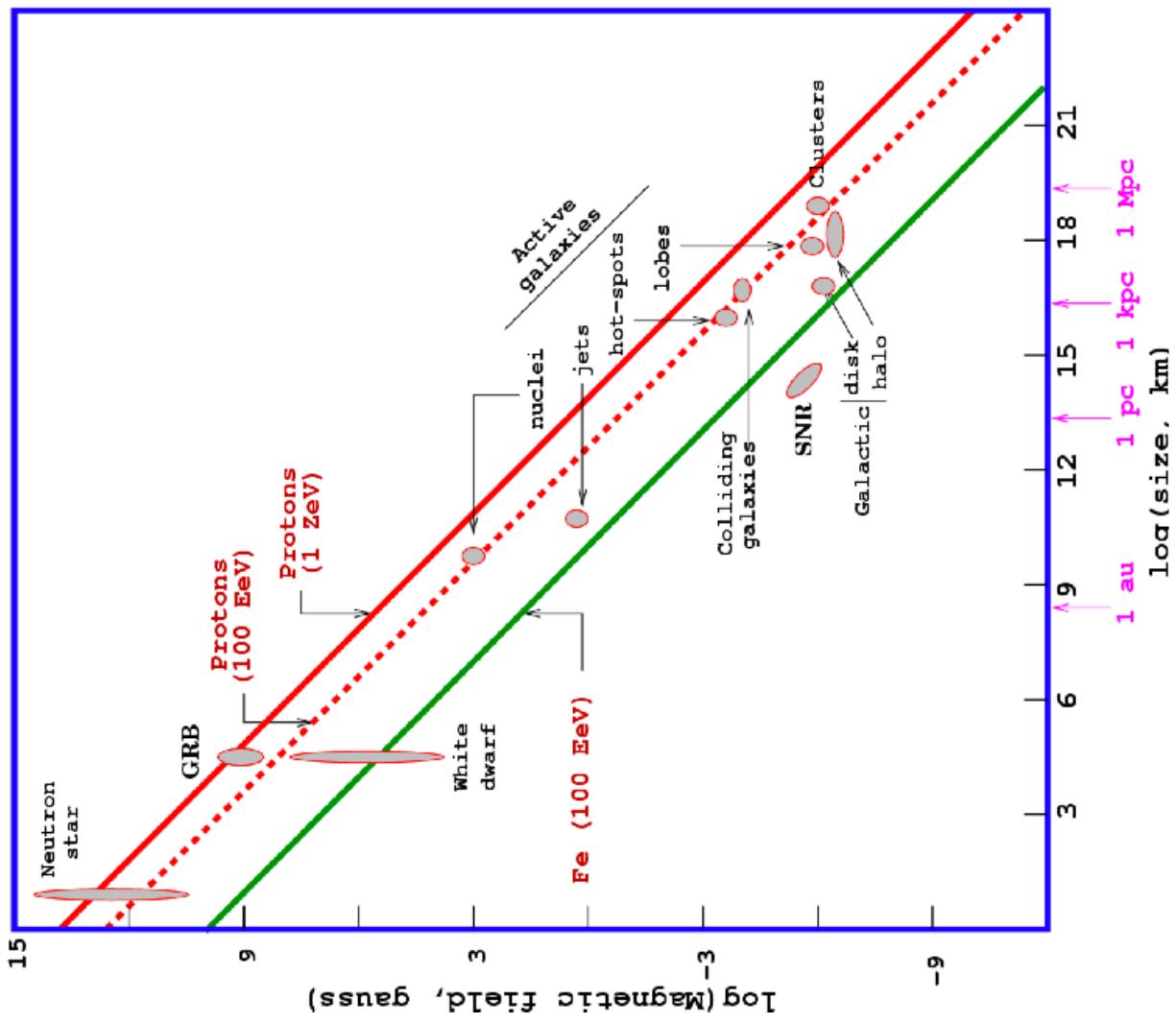
- 1st Order:
acceleration in strong shock waves



$$\frac{\Delta E}{E} \sim \beta \quad \beta = \frac{v}{c} \leq 10^{-1}$$

Hillas Plot

Hillas-plot (candidate sites for E=100 EeV and E=1 ZeV)



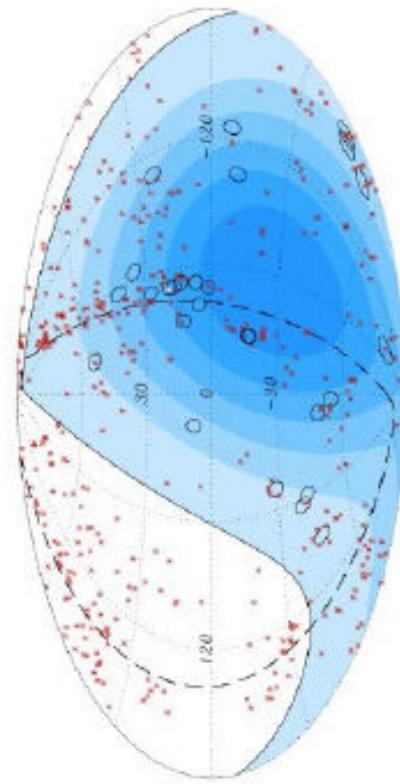
What condition is used to estimate the maximum energy which can be obtained from a given site?

The gyroradius is less than the linear size of the accelerator

$$E_{18}^{\max} = \beta_s ZBR$$

Auger sky map

- At energies $> 6 \times 10^{19}$ eV can get indications of origin (why not at lower energies?)



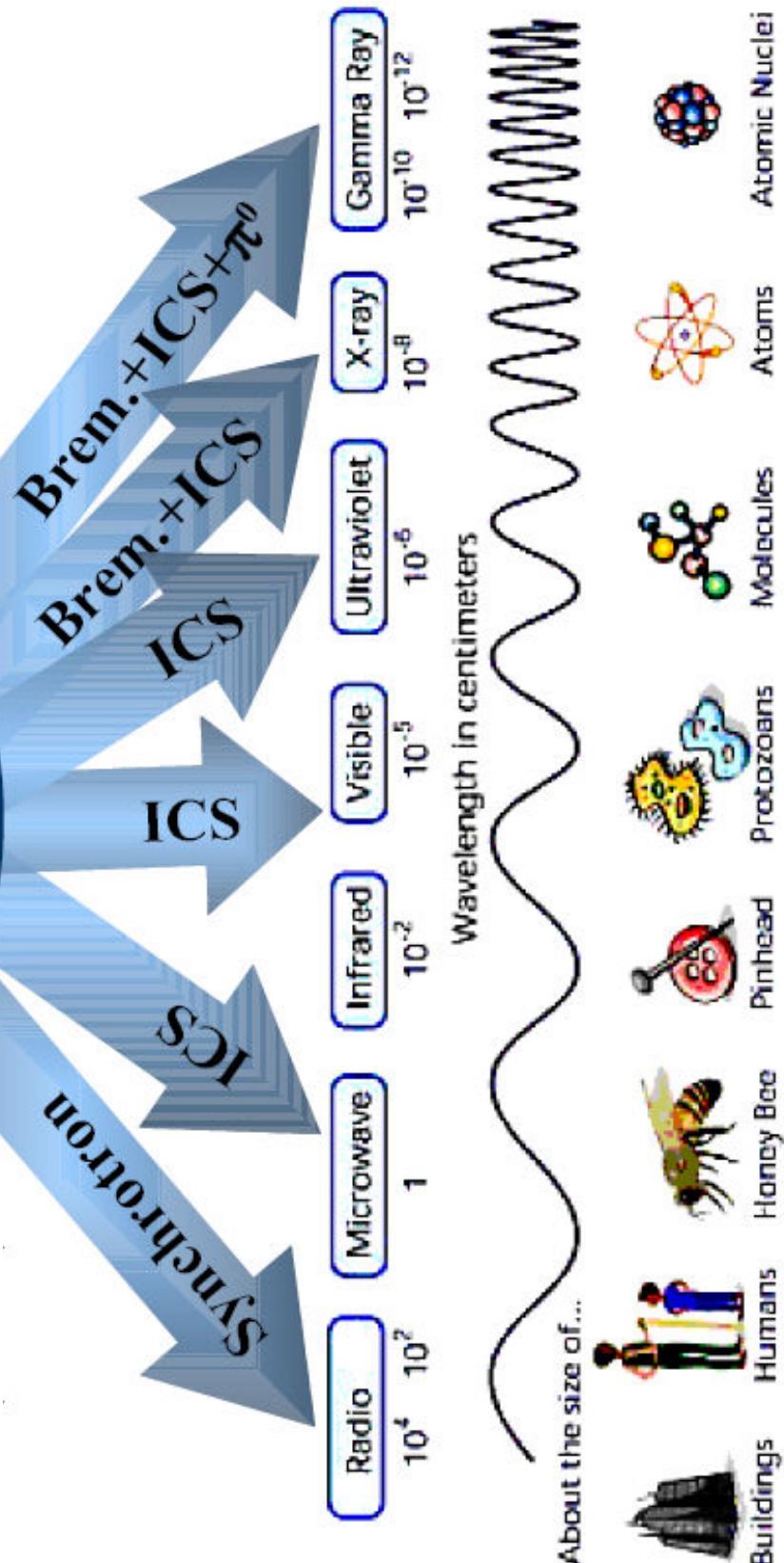
AUGER coll., astro-ph/0712.2843

- significance reduced in larger data set...?

How do we know there are high energy astrophysical phenomena?

- Observe high energy particles
- Observe radiation that is indicative of high energy processes
- There might be hidden sources...

*Non-thermal
radiation - what
do we mean by
non-thermal?*

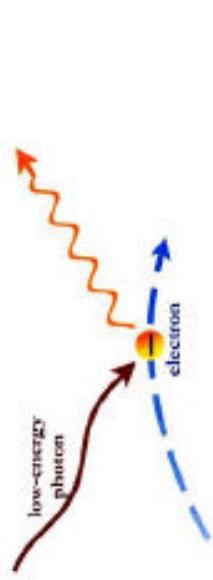


Leptons

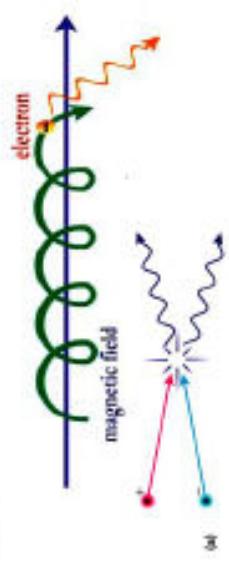
Bremsstrahlung



Inverse Compton



Synchrotron

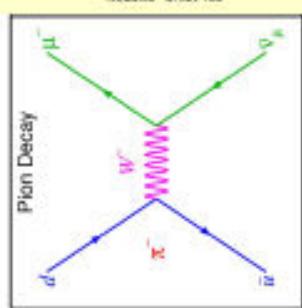


Pair production

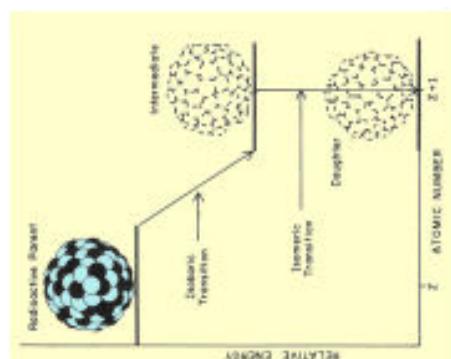
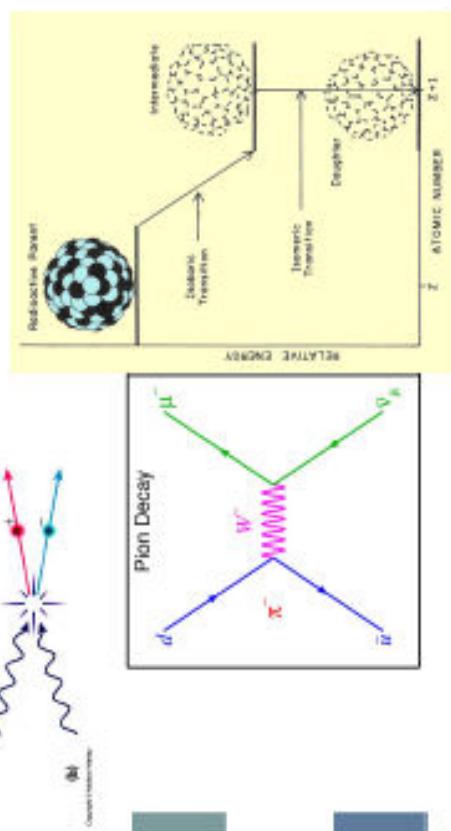


Hadrons

Pion decay



Nuclear transitions



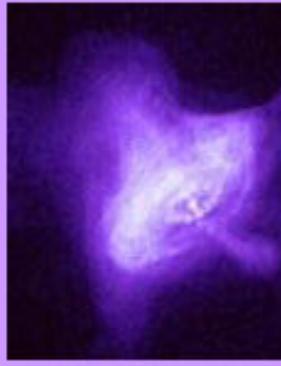
Nature's accelerators

Black Hole producing
relativistic jet of particles

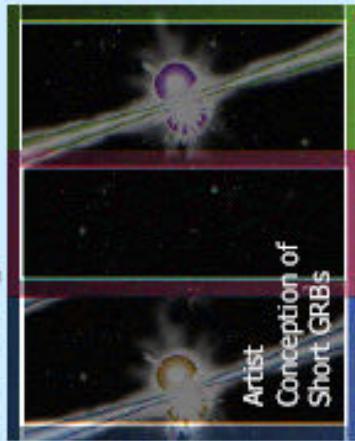
HST Image of M87 (1994)



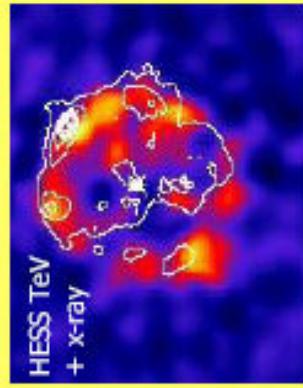
Spinning Neutron Star
powering a relativistic
wind



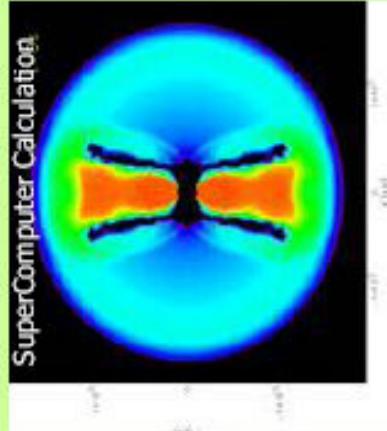
Binary Neutron Star
Coalescing



Tev image of Vela Jr.
Supernova Remnant



Massive Star Collapsing
into a Black Hole

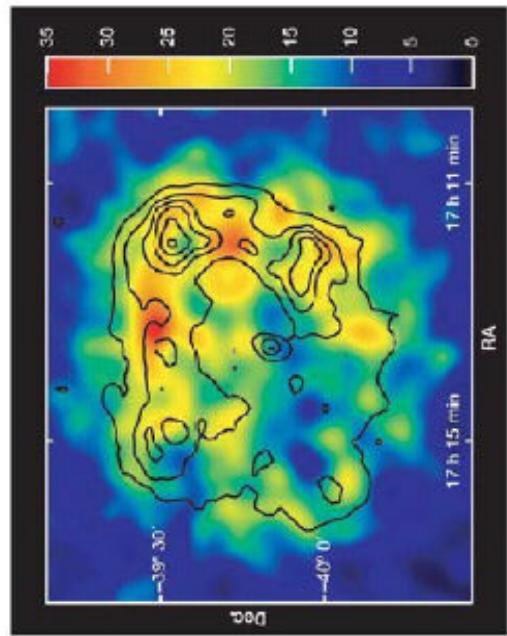


Mass image: Murray & Ostriker (1979)

Color image: Murray & Ostriker (1979)

Information from Gamma-Rays

- Lots of sources identified
- Morphology of galactic sources resolved
- but most sources can be described by leptonic models as well as hadronic



RXJ 1713-3946
(SNR seen by H.E.S.S.)

Why detect neutrinos?

Source of the highest energy cosmic rays

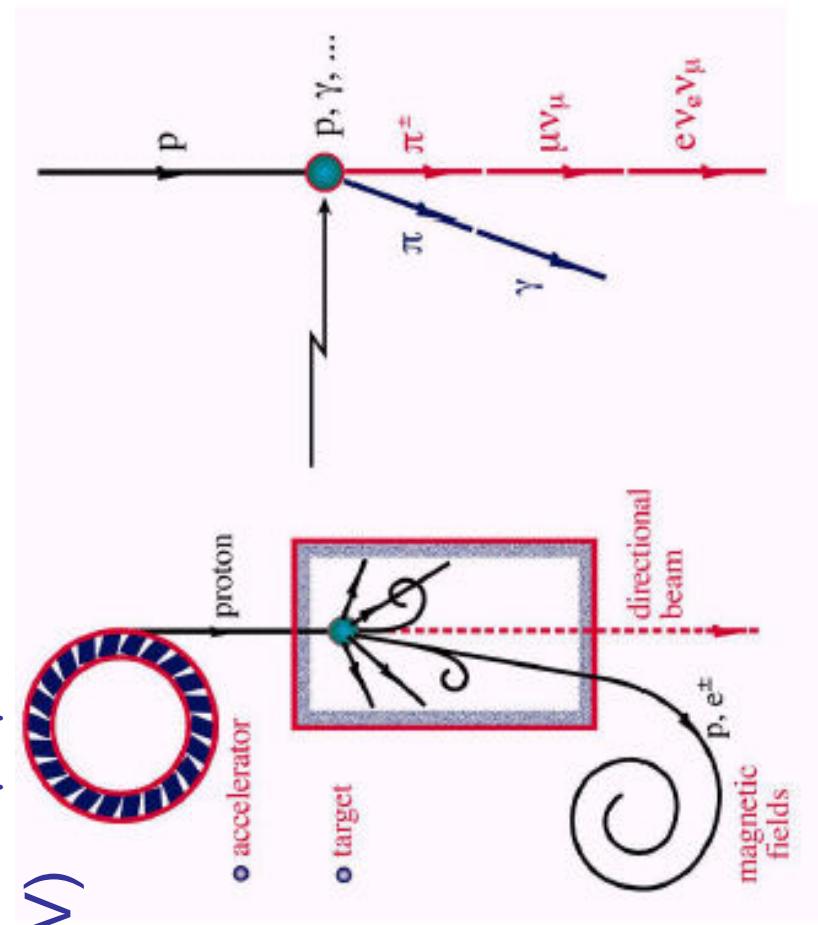
Neutrino production

Animation generated with povray

- **p + p or p + γ give pions which give neutrinos**

eg. $p\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n/\pi^0 p$

- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$
- $\pi^0 \rightarrow \gamma \gamma (E_\gamma \sim \text{TeV})$



Why detect neutrinos?

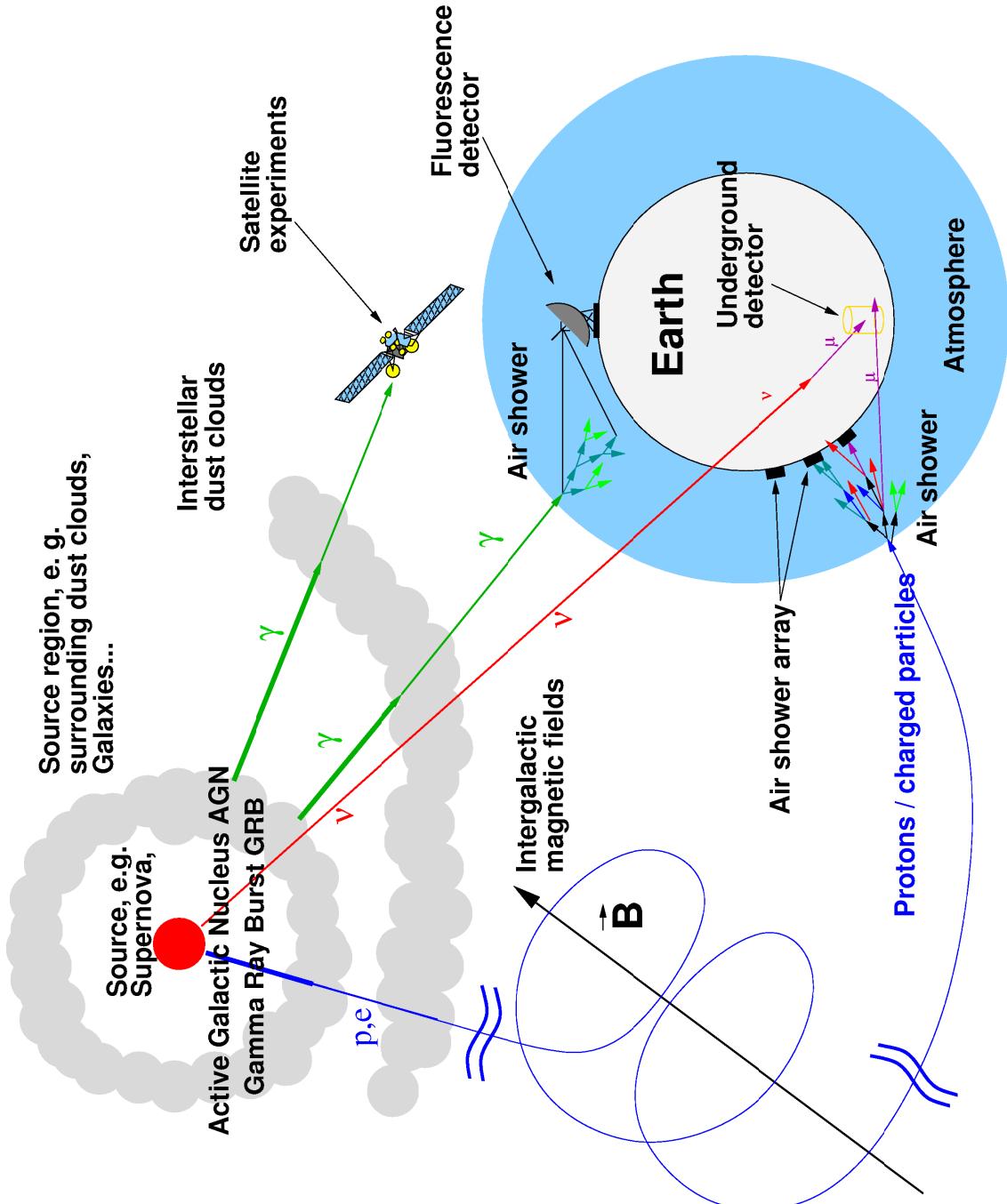


Figure: Wolfgang Wagner, PhD thesis

BL Lac Object

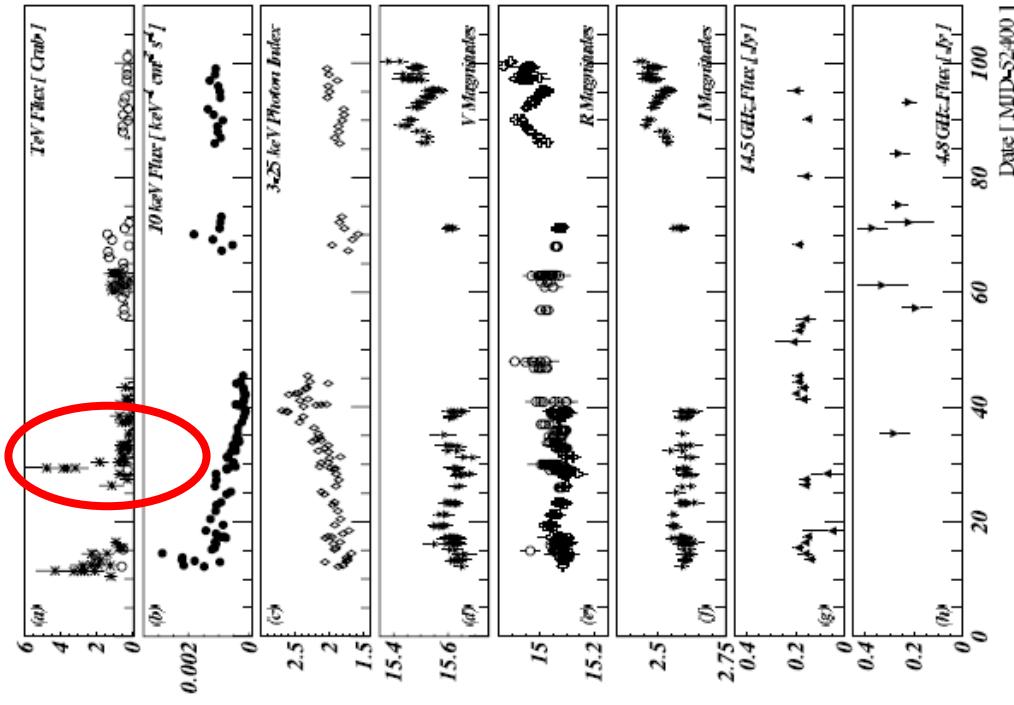
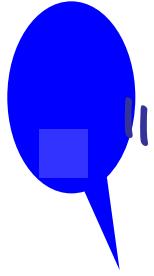


Fig. 2.—Results from the IES 1959+650 multiwavelength campaign (2002 May 16–August 14). (a) Whipple (stars) and HEGRA (circles) integral TeV γ -ray fluxes in Crab units above 600 GeV and 2 TeV, respectively; the Whipple data are binned in 20 minute bins and the HEGRA data in diurnal bins. (b) RXTE X-ray flux at 10 keV. (c) RXTE 3–25 keV X-ray photon index. (d) Absolute V magnitudes (Boltwood). (e) Absolute R magnitudes (crosses; Boltwood; circles; Abastumani). (f) Relative I magnitudes (Boltwood). (g) The 14.5 GHz flux density (UMRAO). (h) The 4.8 GHz flux density (UMRAO).

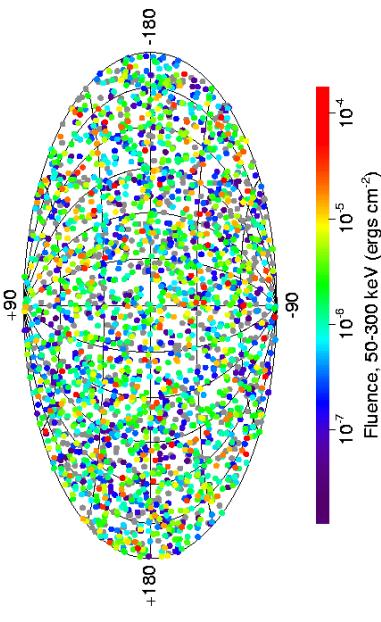
*Krawczynski et al.,
ApJ 601 (2004)*



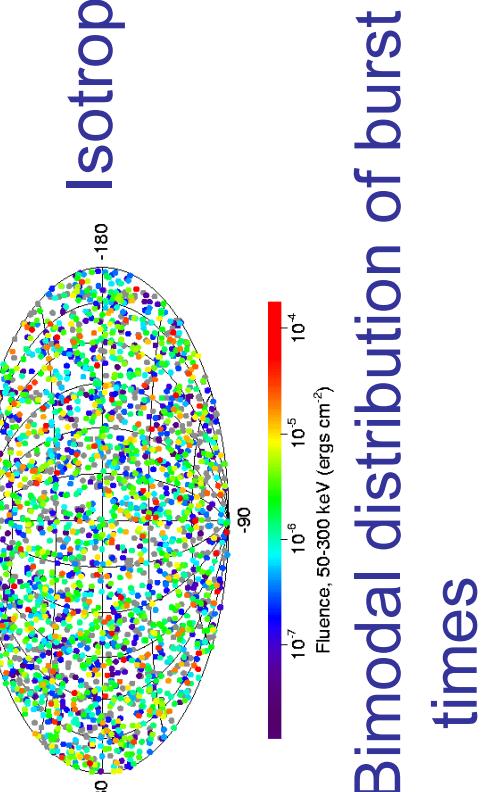
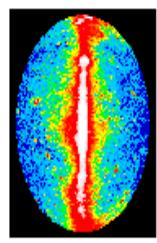
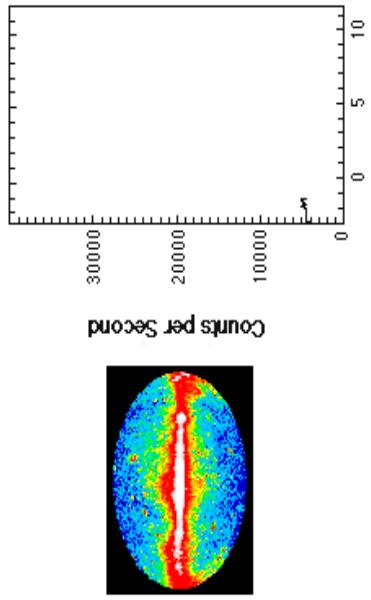
Accidentally discovered by the military
Vela satellites in the late 1960's

Short, intense, eruptions of high
energy photons, with afterglow
detected in X-ray to radio

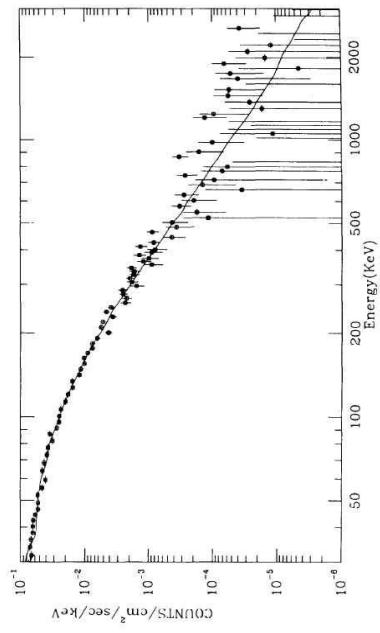
2704 BATSE Gamma-Ray Bursts



Isotropic distribution in the sky



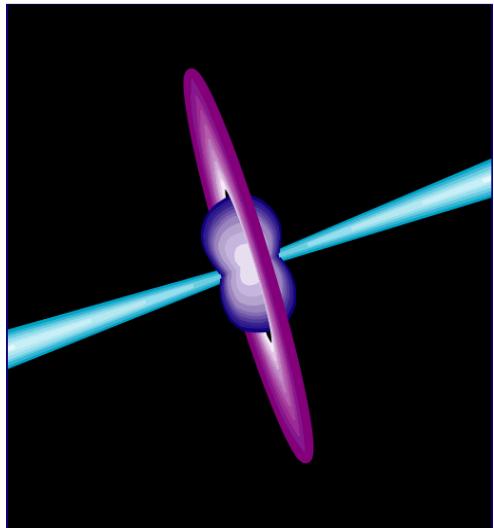
Bimodal distribution of burst times



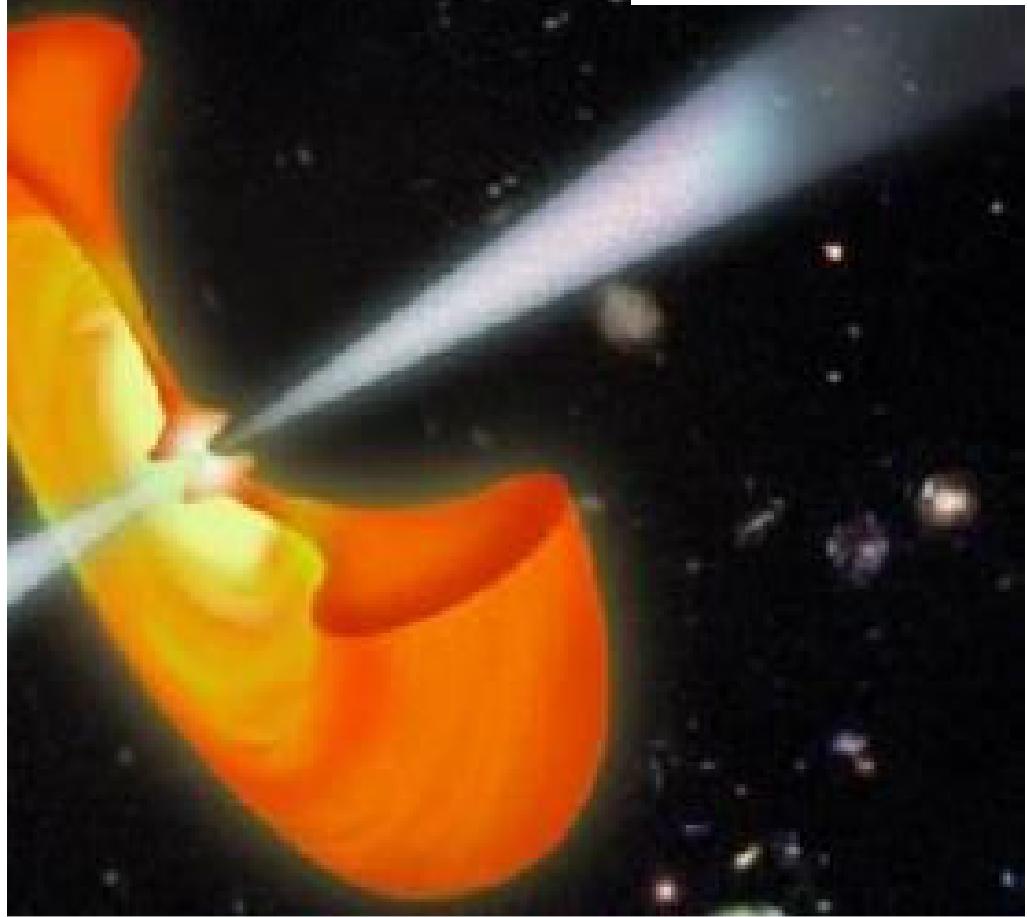
Non-thermal photon spectrum
Energy output of 10^{51} erg to
 10^{54} erg

Progenitors

- Long duration bursts result from collapse of massive star to black hole
 - GRB030329 observed by HETE II linked to type 1C Supernova
 - Long duration bursts in galaxies with young massive stars
- Short duration bursts result from collision of some combination of black holes and neutron stars
 - GRB050509B observed by Swift with limited afterglow
 - Appears to have occurred near a galaxy with old stars
- Theories may be rewritten by Swift observations
 - 050502B X-ray spike after burst, indications of multiple explosions

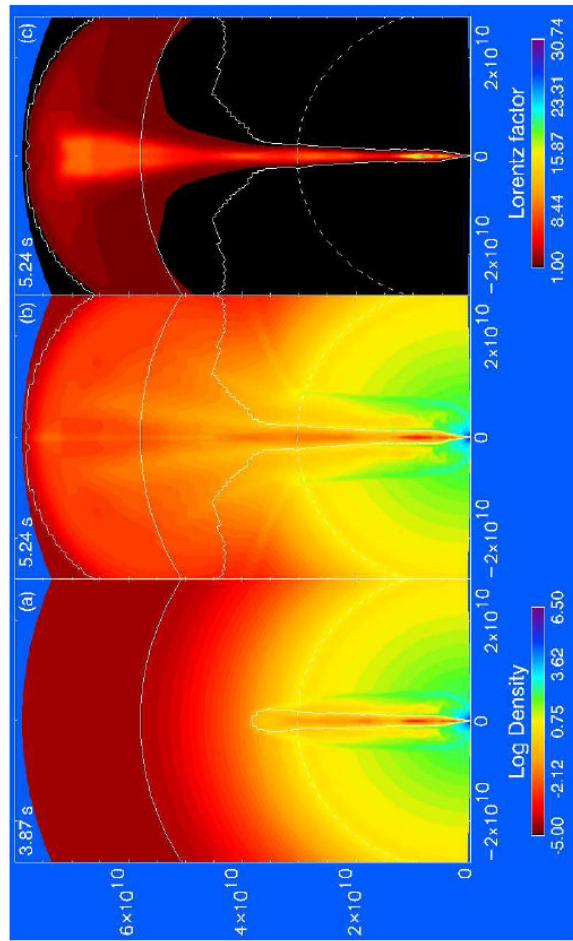


Fireball Model



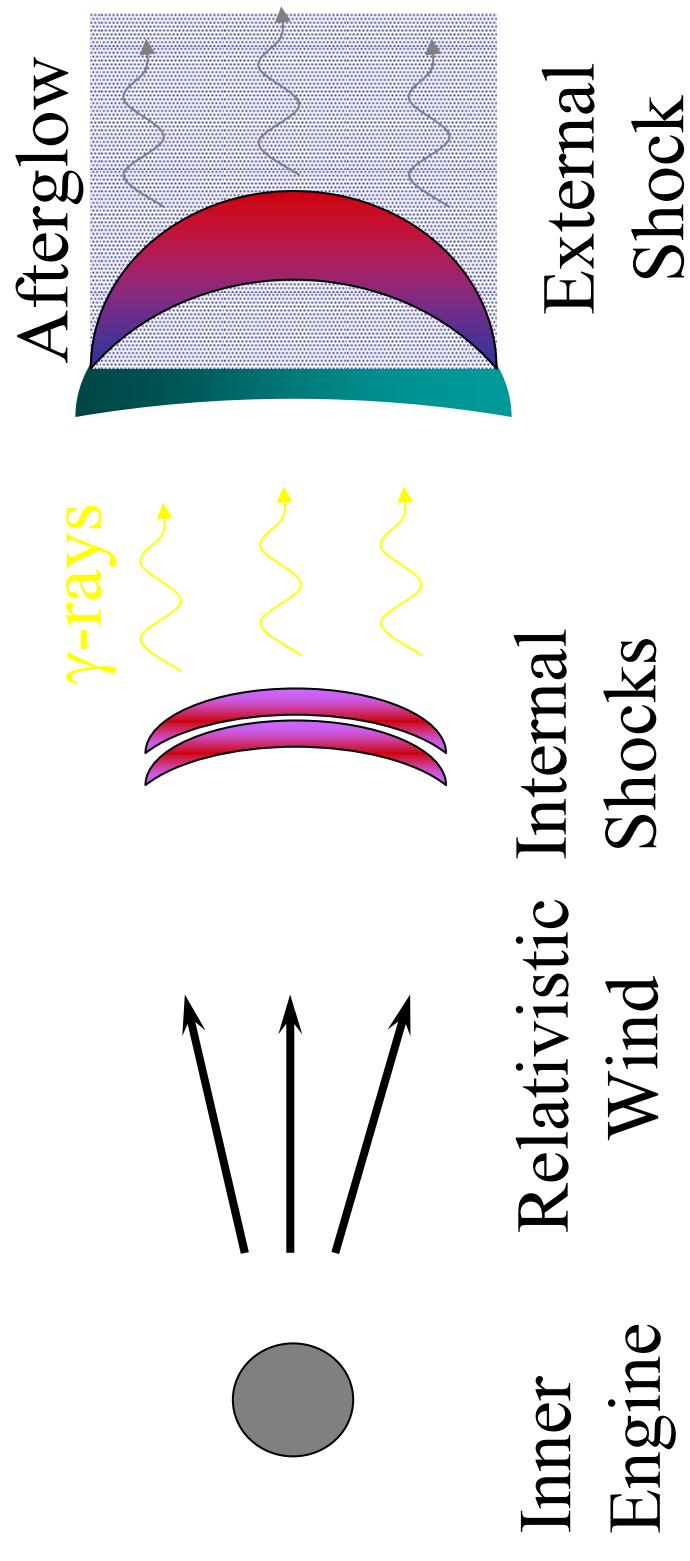
Radiation dominated soup of leptons
and photons implied by high optical
depth

Radiation pressure drives relativistic
expansion of material outward



M. Aloy et al. ApJL 2000

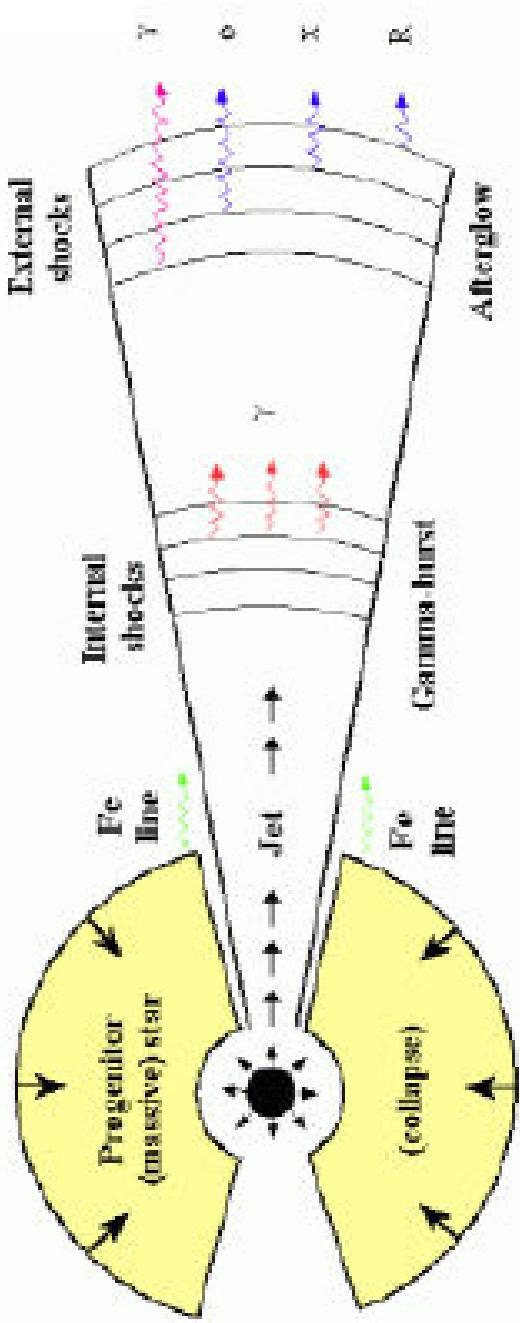
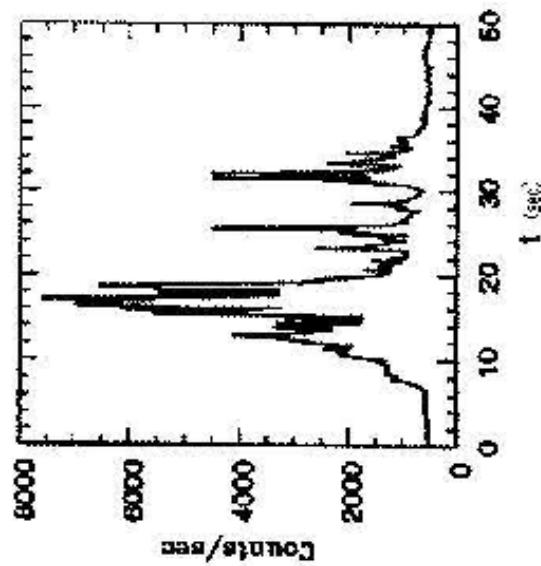
But observed spectrum is non-thermal and significant energy is expected to be transferred to the baryonic content in the wind



Shock fronts

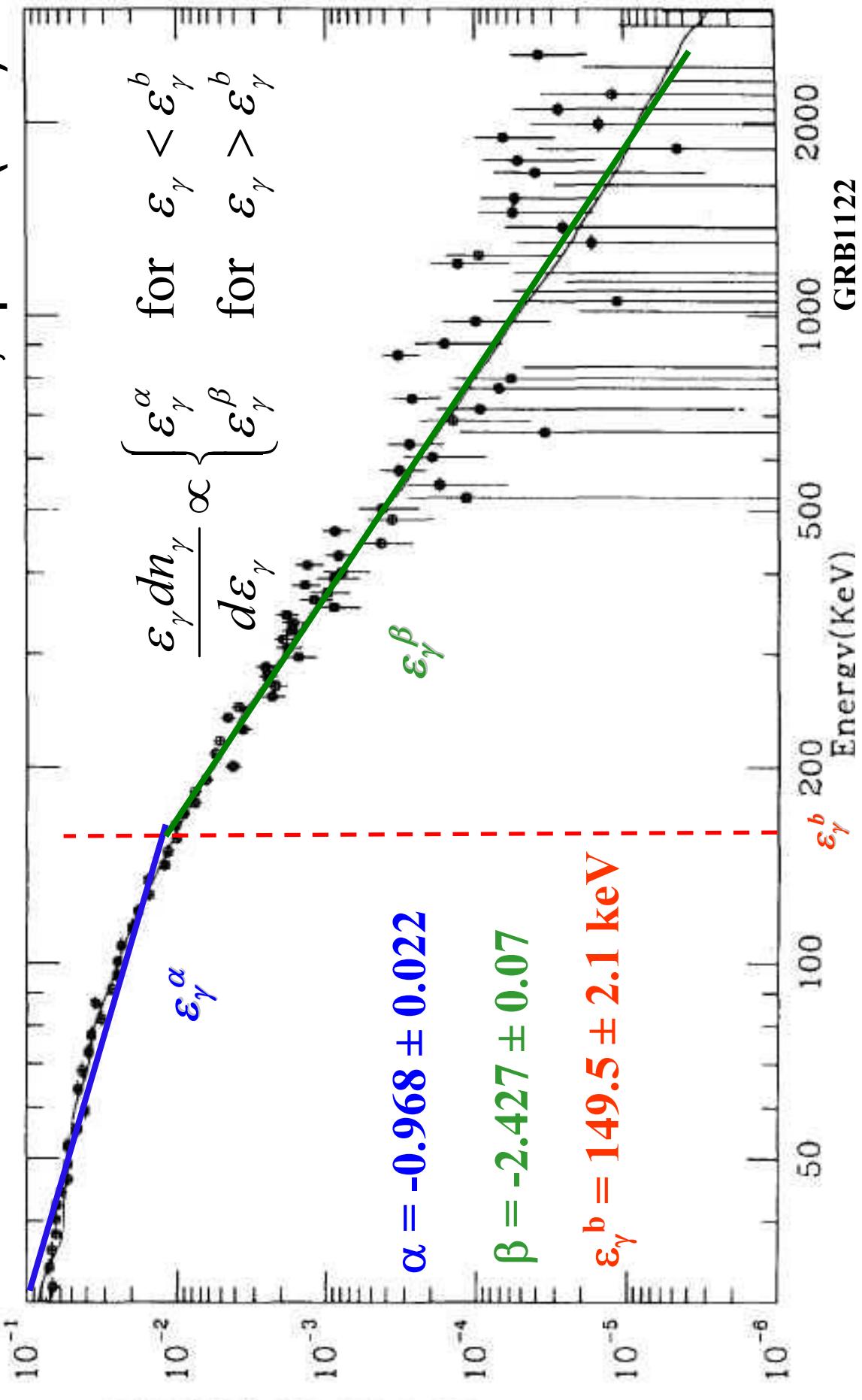
Prompt γ -ray emission produced by dissipation of fireball kinetic energy in internal shocks - supported by microstructure

Afterglow produced in external shocks – softened spectrum due to decreasing Lorentz factor



Burst spectrum

Band et al., ApJ 413 (1993)



Burst spectrum

$$\frac{\epsilon_\gamma dn_\gamma}{d\epsilon_\gamma} \propto \begin{cases} \epsilon_\gamma^\alpha & \text{for } \epsilon_\gamma < \epsilon_\gamma^b \\ \epsilon_\gamma^\beta & \text{for } \epsilon_\gamma > \epsilon_\gamma^b \end{cases}$$

Inverse Compton scattering or cooling of electrons at high energies

$$\epsilon_\gamma^\alpha$$

Synchrotron radiation from accelerated electrons

$$\alpha \sim -1$$

$$\beta \sim -2$$

$$\epsilon_\gamma^b = 100 - 300 \text{ keV}$$

$$\epsilon_\gamma^b$$

$$\epsilon_\gamma^\beta$$

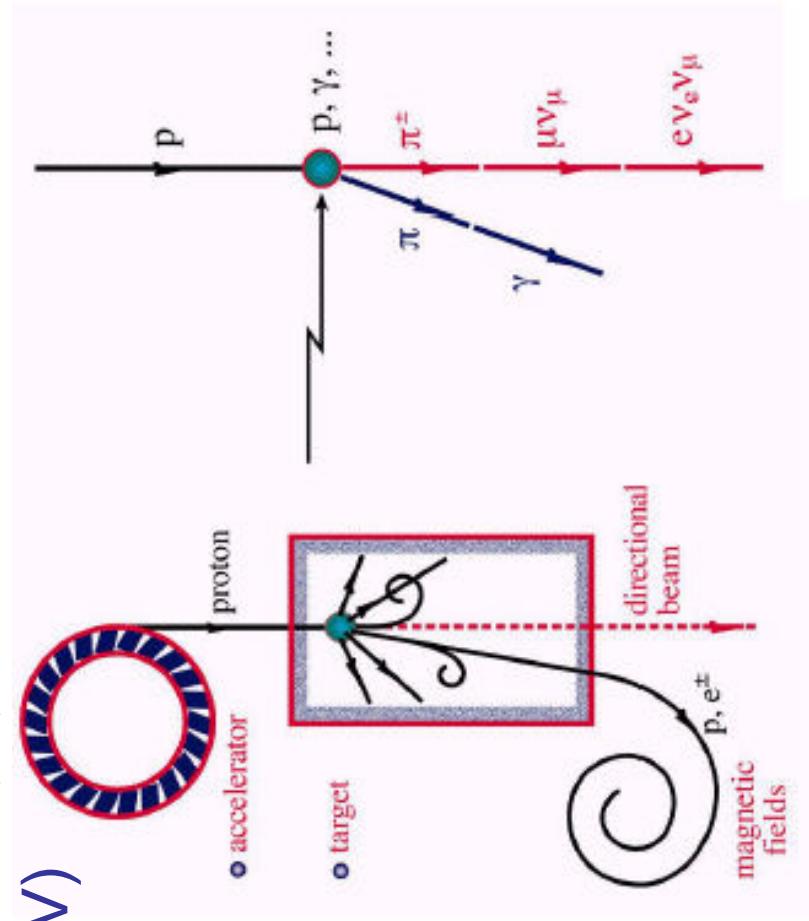
*Example of neutrino spectrum for high energy
astrophysical object - GRB ν Spectrum*

Neutrino production

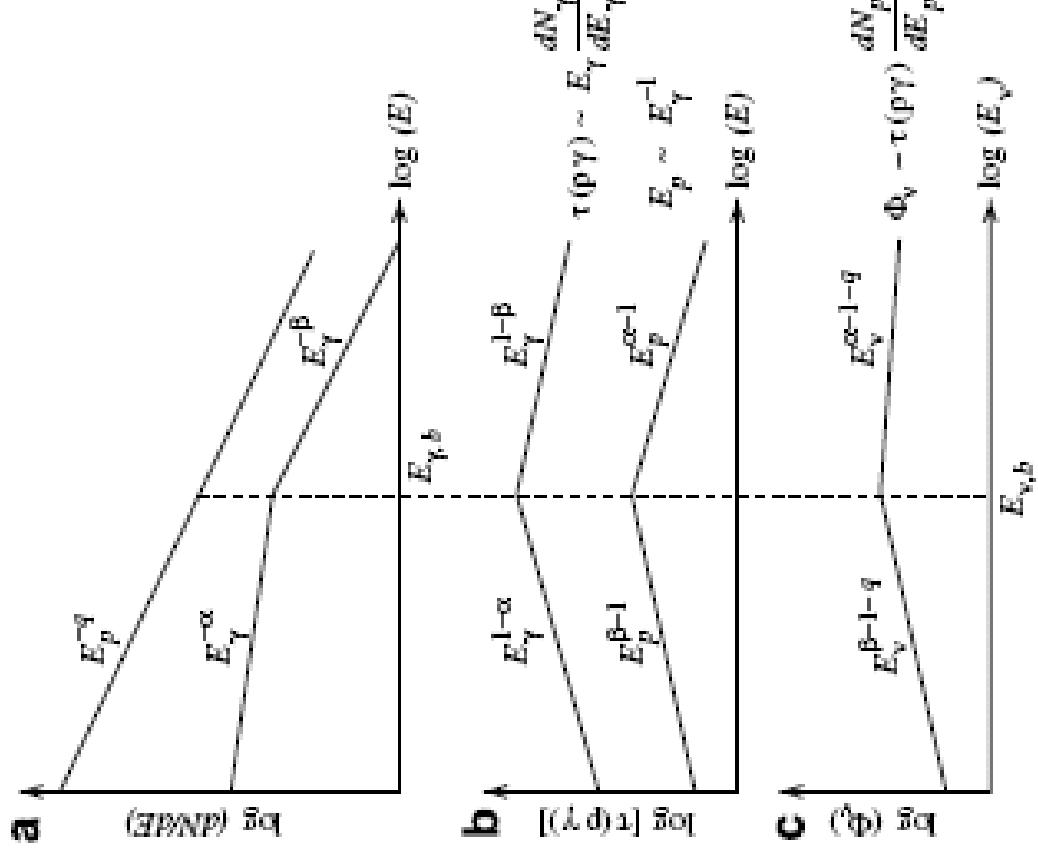
- $p + p$ or $p + \gamma$ give pions which give neutrinos

eg. $p\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n/\pi^0 p$

- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$
- $\pi^0 \rightarrow \gamma \gamma (E_\gamma \sim \text{TeV})$



Example of neutrino spectrum



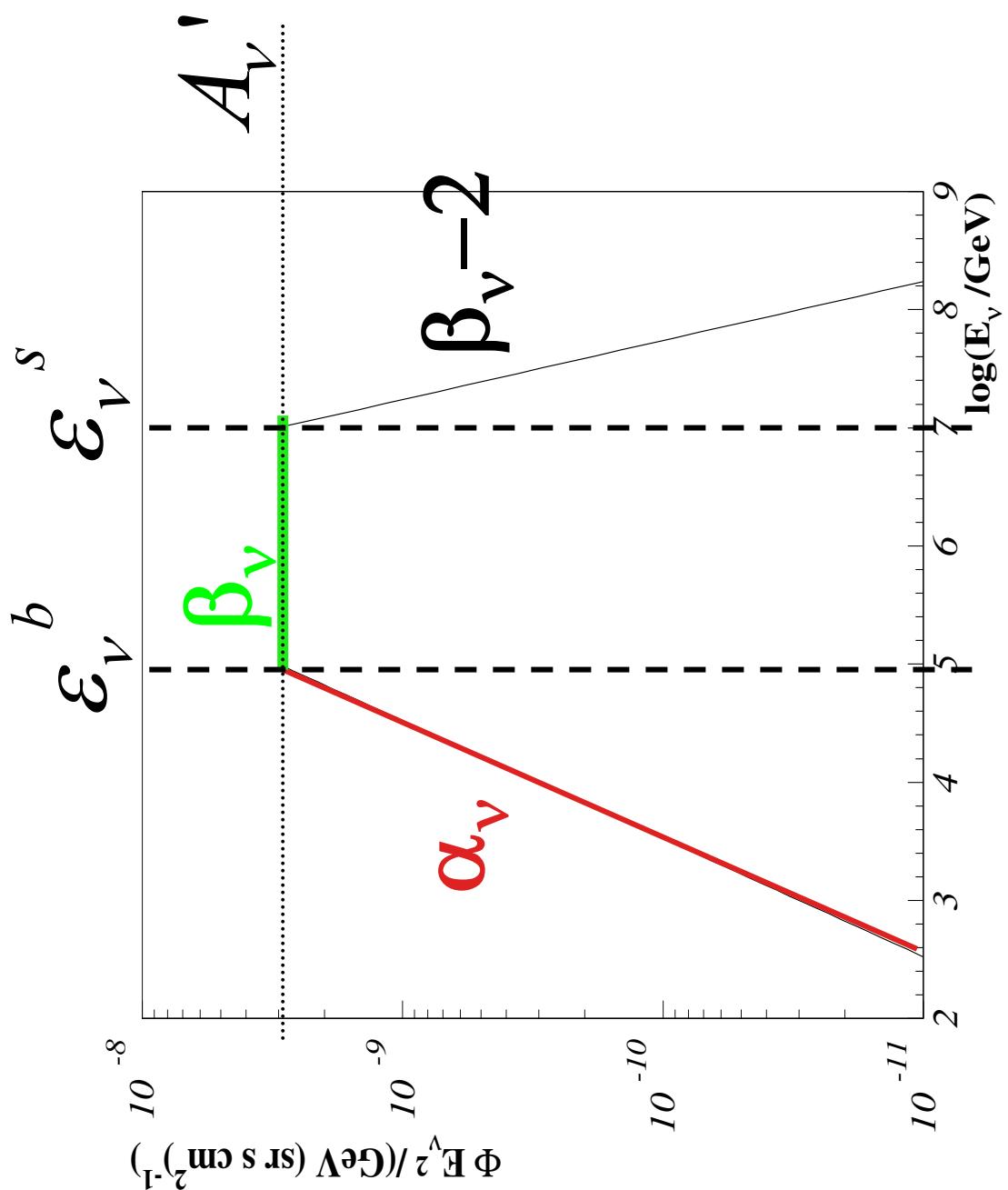
$$\varepsilon'_p \geq \frac{m_\Delta^2 - m_p^2}{4\varepsilon'_\gamma}$$

$$E_p E_\gamma \propto E_\nu E_\gamma \sim const \Rightarrow E_\gamma \propto E_\nu^{-1}$$

$$\frac{E_\nu^2 dN_\nu}{dE_\nu} \propto \begin{cases} E_\nu^{-\beta-1} & \text{for } E_\nu < \mathcal{E}_\nu^b \\ E_\nu^{-\alpha-1} & \text{for } E_\nu > \mathcal{E}_\nu^b \end{cases}$$

GRB ν Spectrum (//)

- Highest energy pions lose energy via synchrotron emission before decaying reducing the energy of the decay neutrinos
- Effect becomes important when the pion lifetime is comparable to the synchrotron loss time
- Neutrino spectrum steepens by a power of two after this second break energy



GRB ν Spectrum (//)

$$E_{tot}[\gamma, \sim keV] \propto E_{tot}[\nu]$$

$$\int_{E_{\min}}^{E_{\max}} \frac{dn_{\nu}}{dE_{\nu}} E_{\nu} dE_{\nu} = \chi \cdot F_{\gamma}$$

$$\chi = f_{\pi} / f_e \cdot \frac{1}{2} \cdot \frac{1}{4}$$

50% charged pions,
25% per particle

fe: fraction of electron
to proton total energy

f_π: fraction of proton energy going into pions

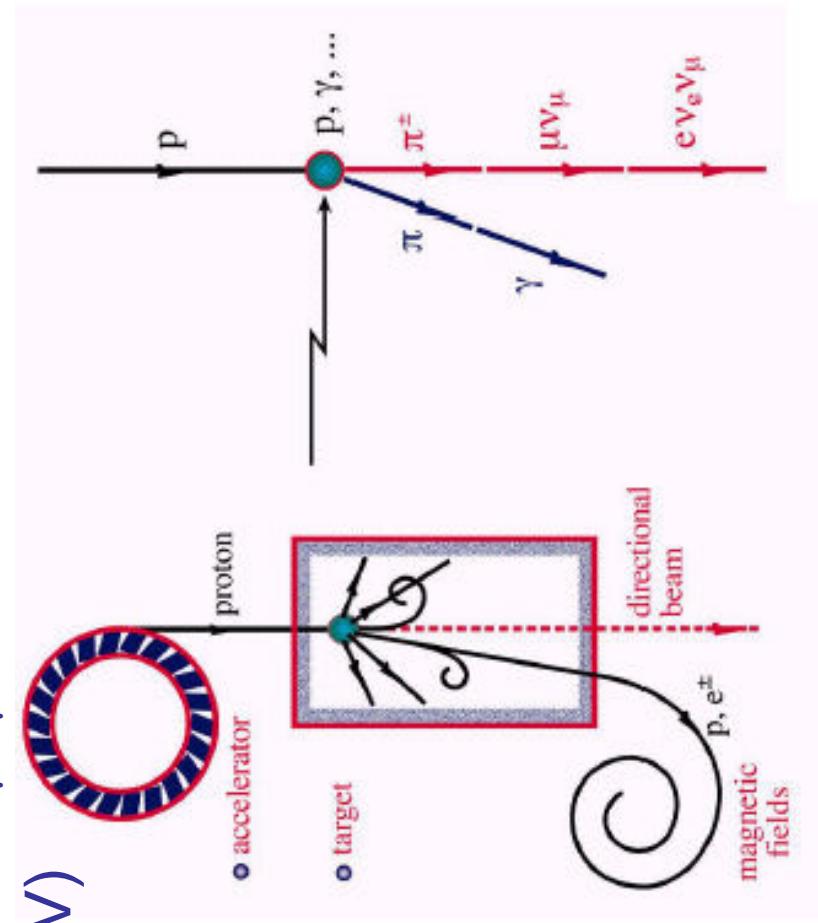
Neutrino production

Animation generated with povray

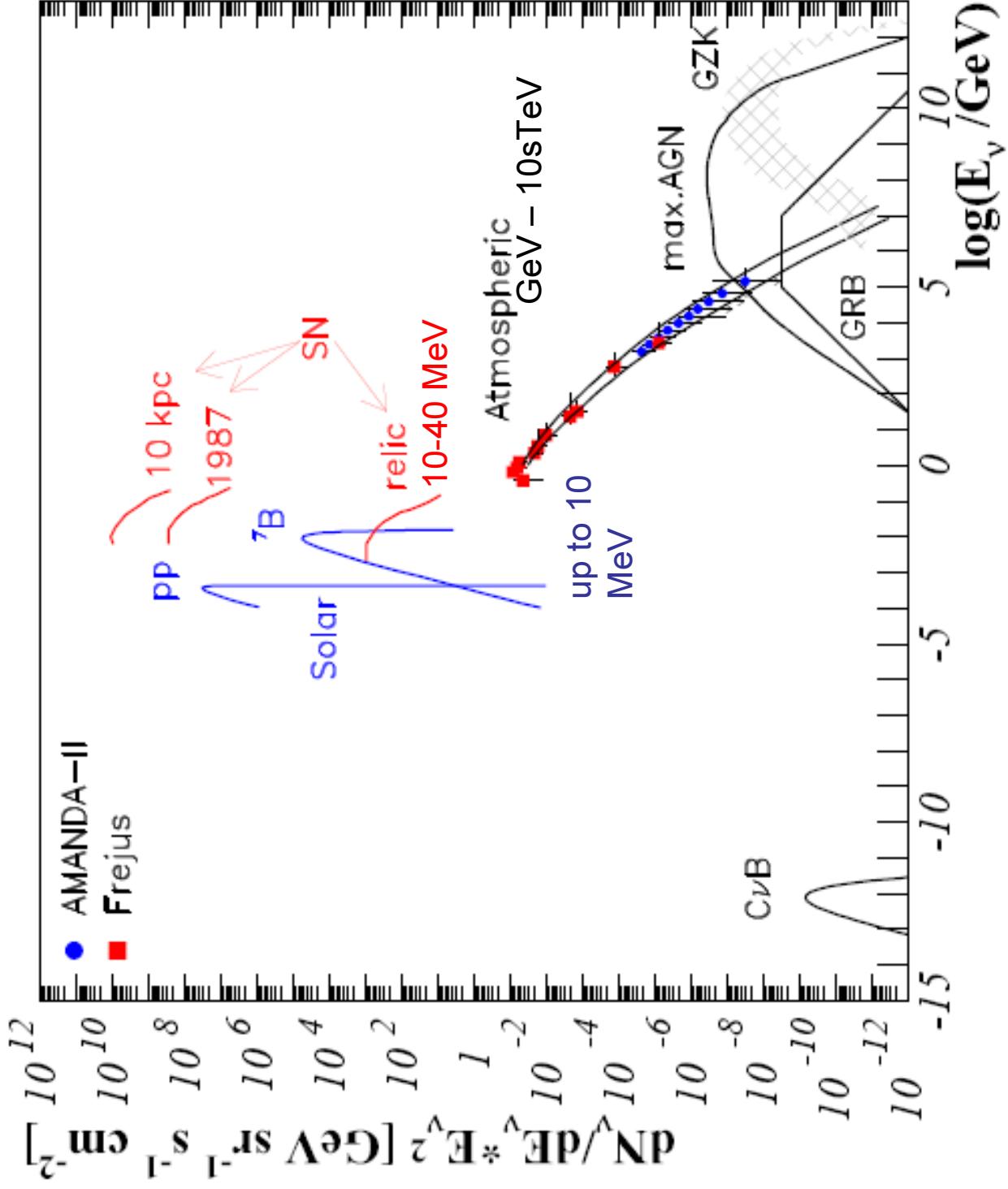
- **p + p or p + γ give pions which give neutrinos**

$$\text{eg. } \mathbf{p}\gamma \rightarrow \Delta^+ \rightarrow \pi^+ \mathbf{n}/\pi^0 \mathbf{p}$$

- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$
- $\pi^0 \rightarrow \gamma \gamma (E_\gamma \sim \text{TeV})$



Neutrino sources



HE Neutrino probes of fundamental physics

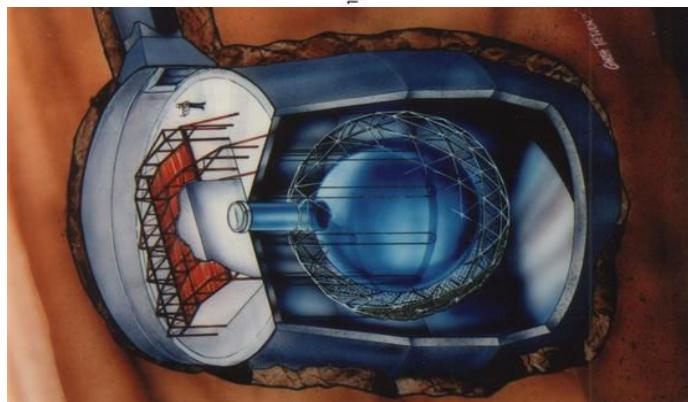
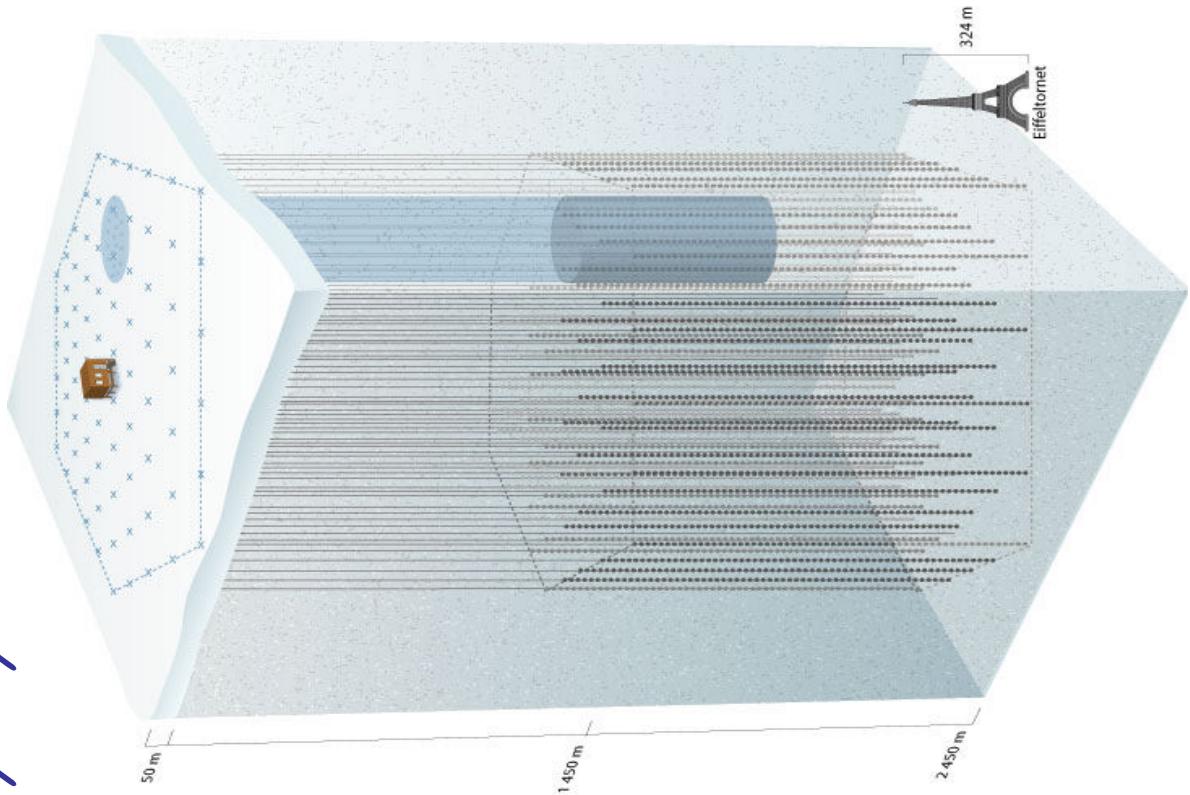
- New ν or source properties distort expected 1:1:1 neutrino flavor ratio

Source Flavor Ratio	Neutrino Physics	Detected Flavor Ratio	Assumption s/Comments	References
1:2:0	Standard vacuum oscillations	1:1:1		
0:1:0	Standard vacuum oscillations	4:7:7	Muon damped sources	Rachen & Meszaros astro-ph/9802280; Kashti & Waxman arXiv:astro-ph/0507599v4
1:2:0	ν decay (normal hierarchy)	6:1:1	$U_{e3}=0$; Complete decay.	
1:2:0	ν decay (inverted hierarchy)	0:1:1	Current limits on ν decay are weak. No initial flavor ratio can give either 6:1:1 or 0:1:1.	Beacom et al. arXiv:hep-ph/0211305
pure $\overline{\nu}_e$	Standard vacuum oscillations	5:2:2	Neutron accelerator	Anchordoqui et al., arXiv:astro-ph/0311002v3
1:2:0 and 0:1:0	CP violation		Θ_{13} not too small; $\Delta\Theta_{12}$ and $\Delta\Theta_{23}$ reduced; 10% error on flux. Optimistic...	Blum, Nir and Waxman arXiv:0706.2070v1

Incomplete list!

Incomplete list!

Other neutrino detectors in proportion

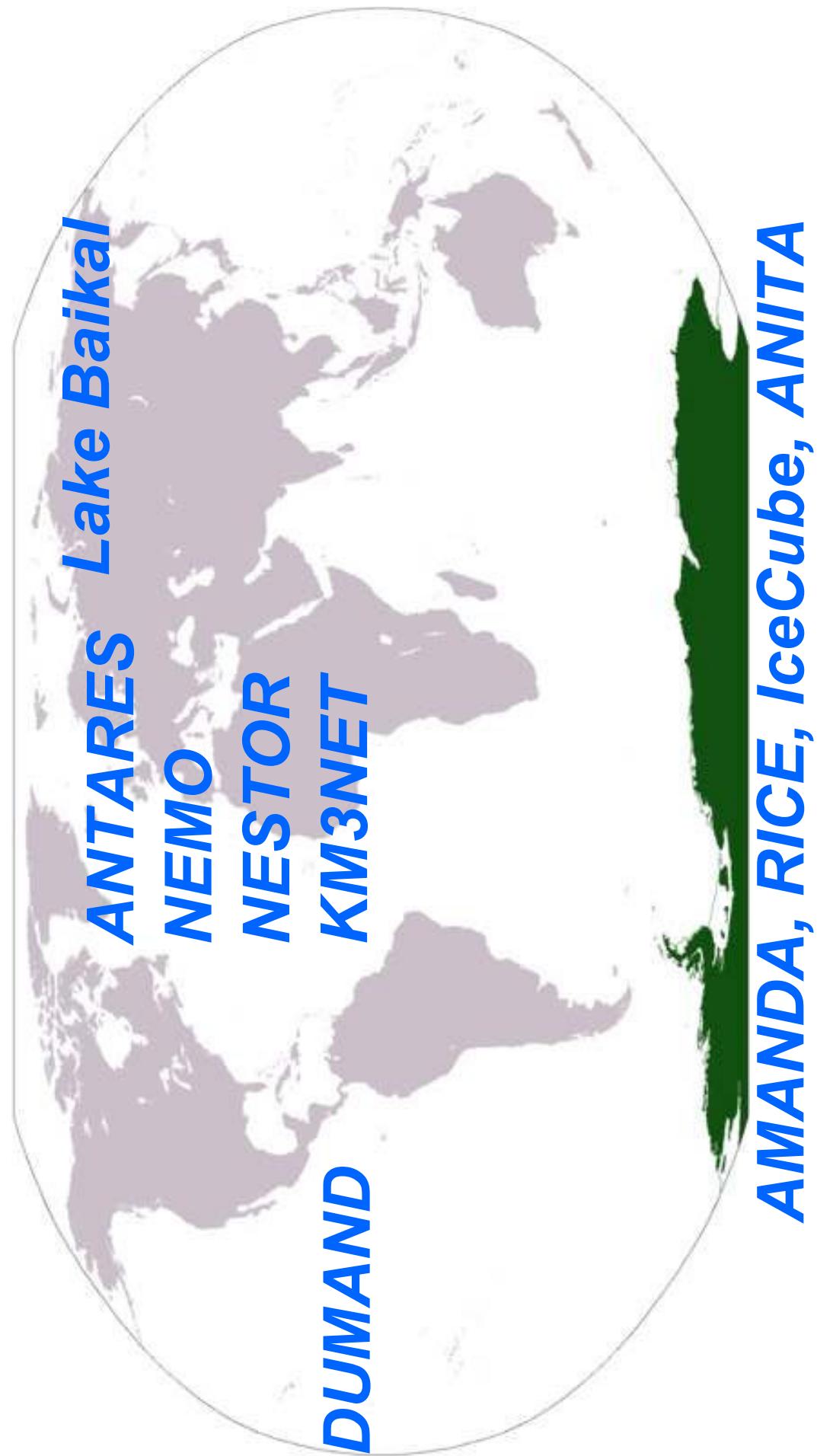


SNO



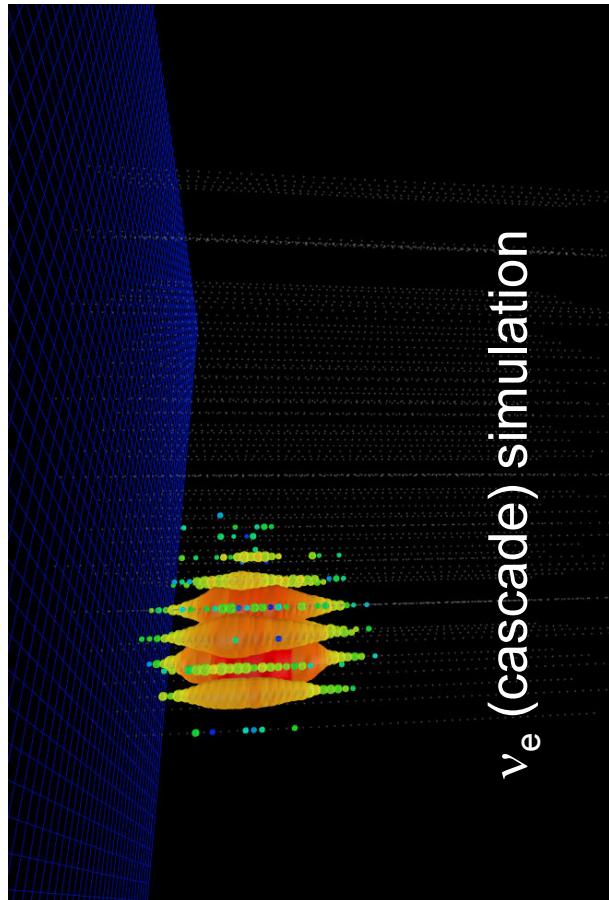
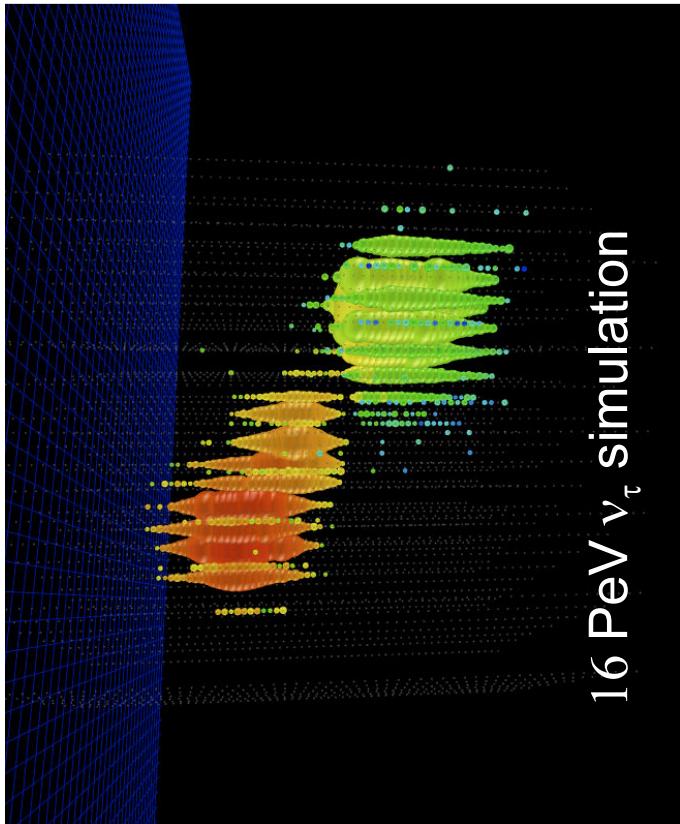
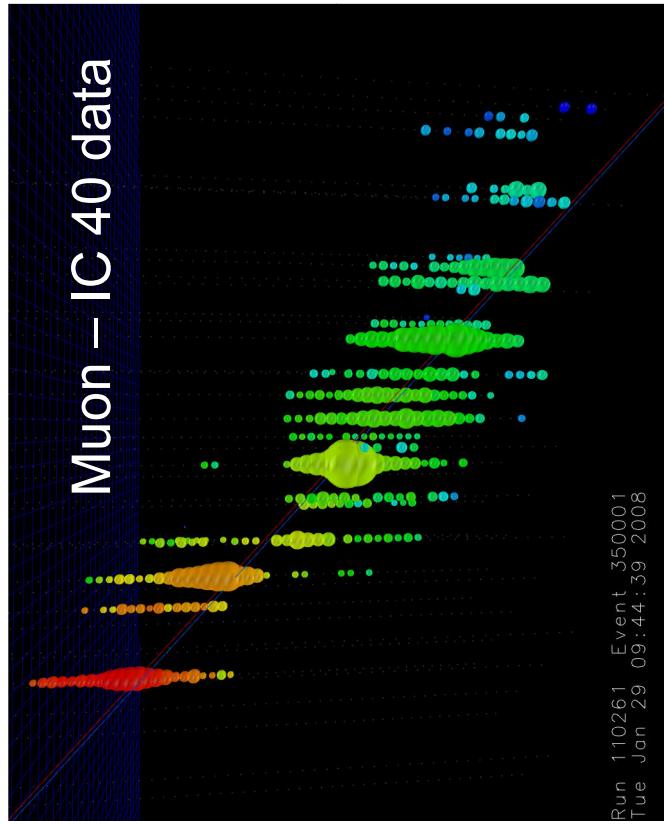
Super Kamiokande

Neutrino telescopes around the globe

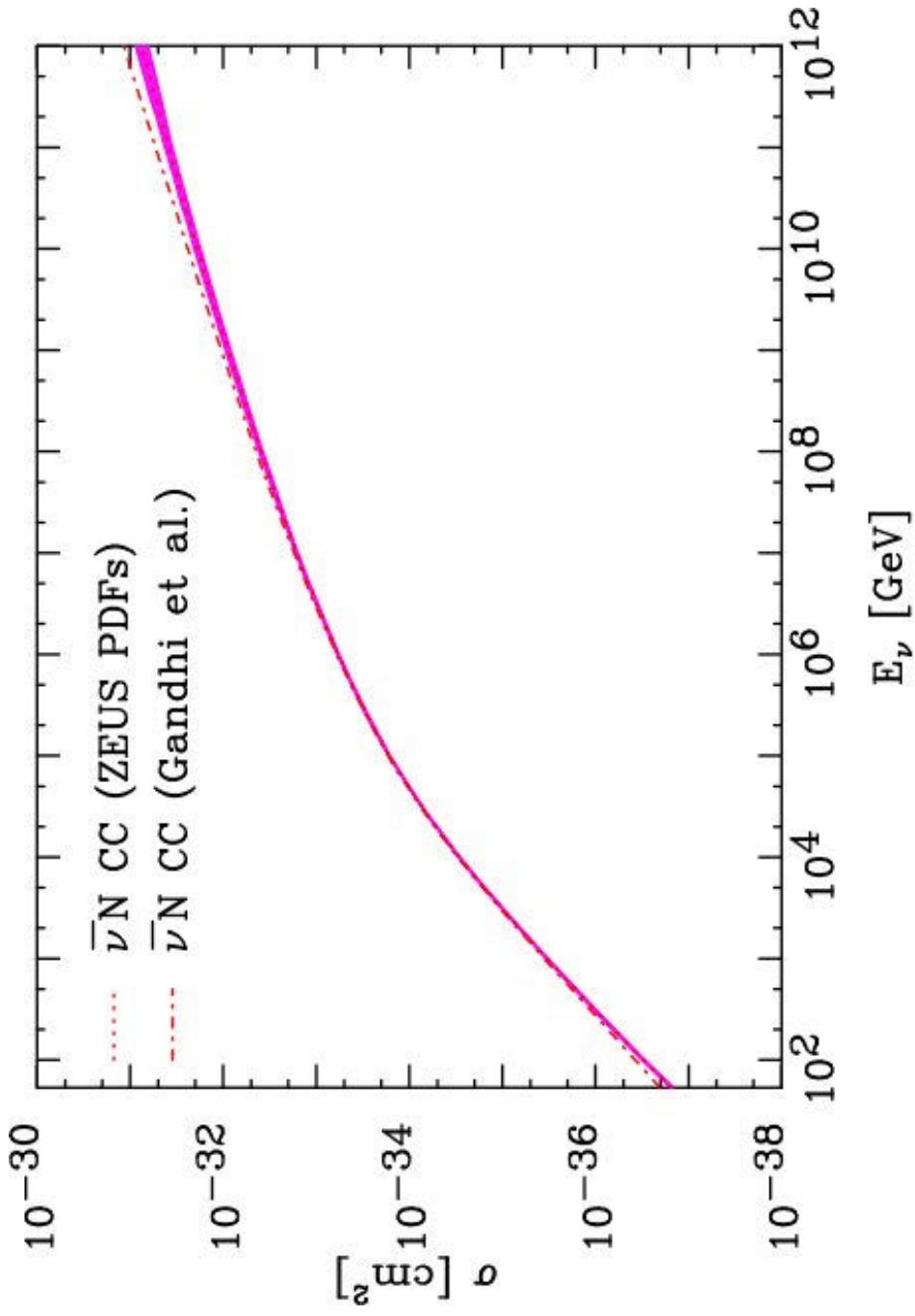


Topological Flavour Identification

- ν_μ produce long μ tracks
- Angular resolution $\sim 1^\circ$
- ν_e CC, ν_x NC cause showers
 - \sim point sources ->'cascades'
 - Good energy resolution
- ν_τ 'double bang' events
 - Other ν_τ topologies under study

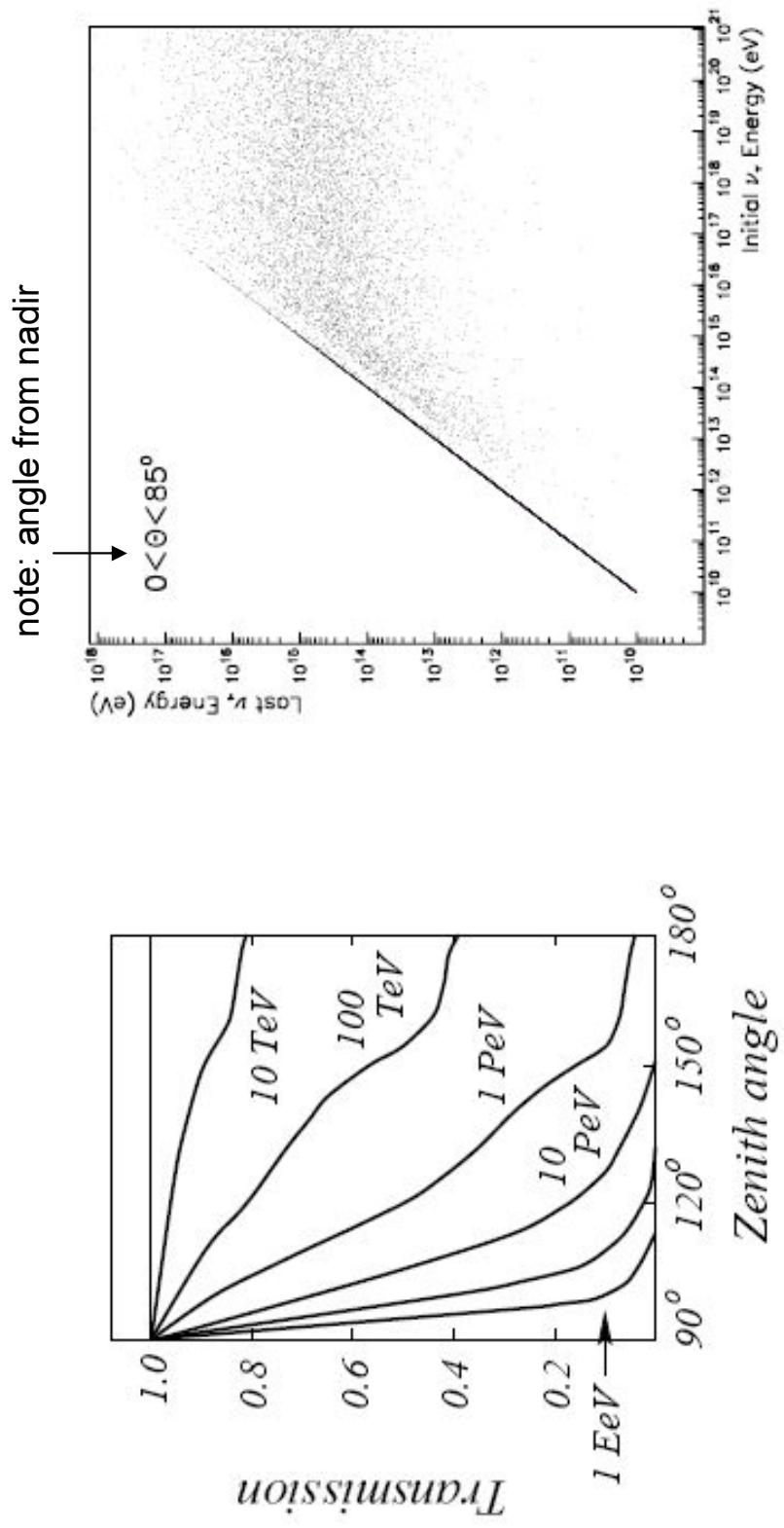


Neutrino-nucleon cross-section



Cooper-Sarkar & Sarkar [arXiv:0710.5505]

Earth becomes opaque for ν_e and ν_μ



*Coming to a cinema (conference, journal)
near you soon...*

