Cosmic Rays and Gamma Ray Bursts

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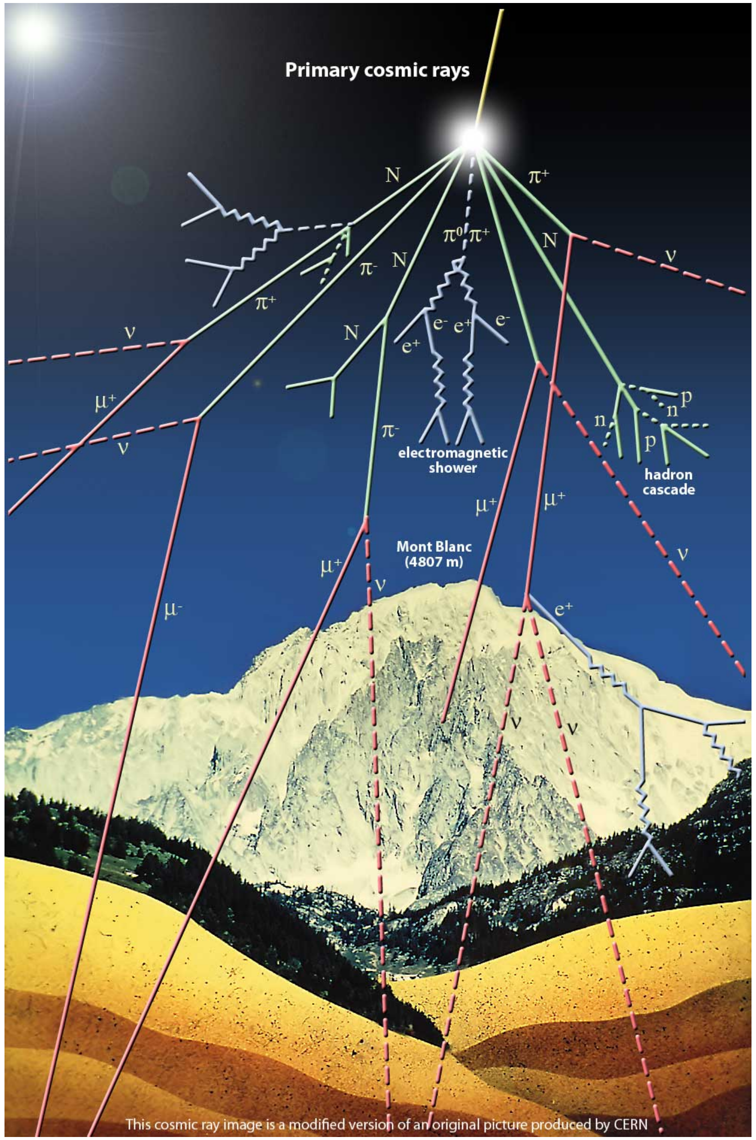


- Observations :

  Charge leaks slowly from capacitors

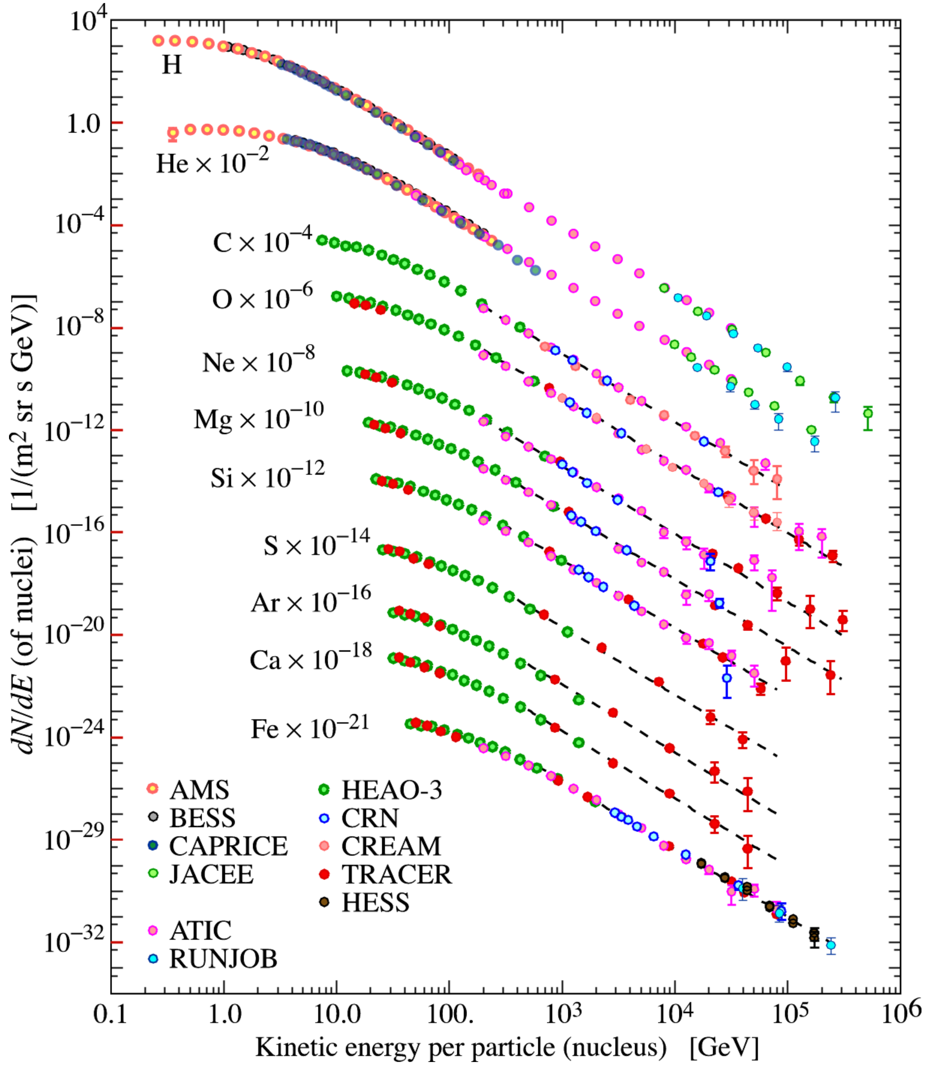
  Effect is smaller when shielded
- Idea :

  Air gets ionised by charged particles
- Where do these particles come from ?

  From outer space (Hess 1912)
- What sort of particles are these ?

  Cosmic ray experiments

Cosmic ray spectra



Below 1 GeV $\longrightarrow$ Solar modulation

At higher energies we observe

- Proportions of major components relatively constant with energy
- $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2.7}$
- Boron spectrum falls steeper

B is a spallation product of C and O

Secondary (e.g. spallation) nuclei steeper than primaries

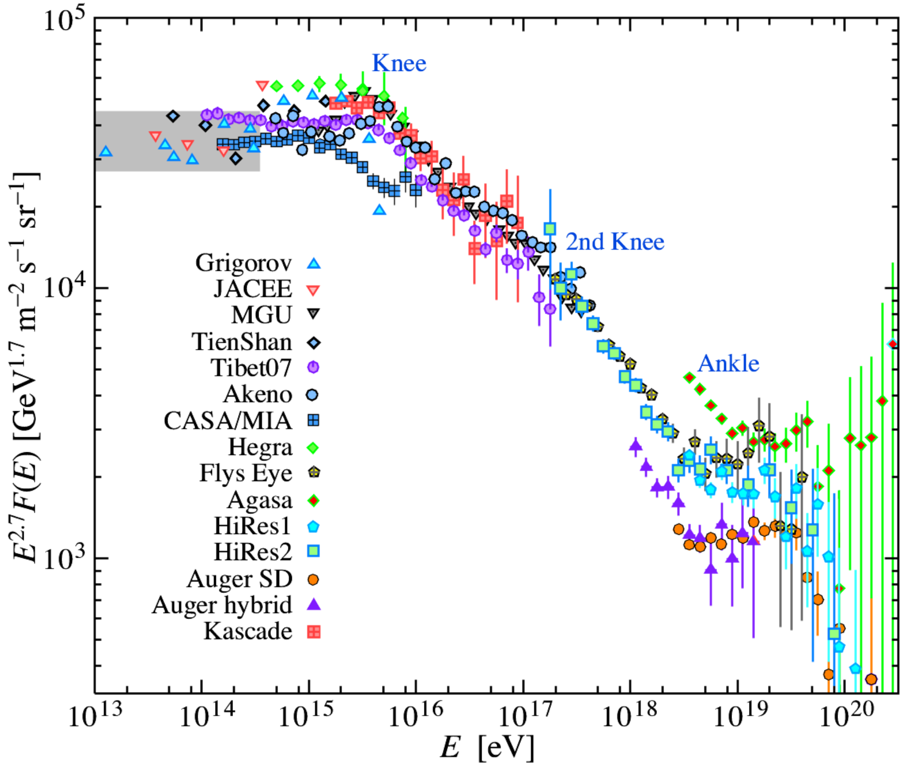
- sec./prim. decreases as energy increases

$\longrightarrow$ High E rays diffuse out of galaxy faster

What is the maximum energy ?

Cosmic rays

$E^{2.7}$ scaled flux



- Spectral features observed (knee, ankle)

  E limits of different cosmic accelerators ?

  What are these cosmic accelerator sites ?

- Rather large uncertainties in flux

  Due to different exp. and models
  (see later)

What is the cosmic acceleration mechanism ?

Shock wave acceleration

- Shock front due to an explosive event

  Thin matter sheet with $v > v_{sound}$

  $\longrightarrow$ bulk motion (Δv) after the shock

- Let a particle enter downstream of the shock and pass the front

  Energy gain $\Delta E = \alpha E \quad (\alpha \propto \Delta v/c)$

  May backscatter downstream again

  $\longrightarrow$ process may be repeated

- Multy-step particle acceleration

  Start energy E_0 and escape prob. P_{esc}

$*$ After n encounters : $E_n = E_0(1+\alpha)^n$

  $\longrightarrow n = \frac{\ln(E/E_0)}{\ln(1+\alpha)}$ to reach energy E

  and $P_{stay}(n) = P_{stay}^n = (1 - P_{esc})^n$

- Number of particles with energy above E

$$N(>E) \propto \sum_{k=n}^{\infty} P_{stay}^k = \frac{(1-P_{esc})^n}{P_{esc}}$$

Resulting in a spectrum

$$N(>E) \propto \frac{1}{P_{esc}} \left(\frac{E}{E_0}\right)^{-\beta}$$

where $\beta = \frac{-\ln(1-P_{esc})}{\ln(1+\alpha)} \approx \frac{P_{esc}}{\alpha}$

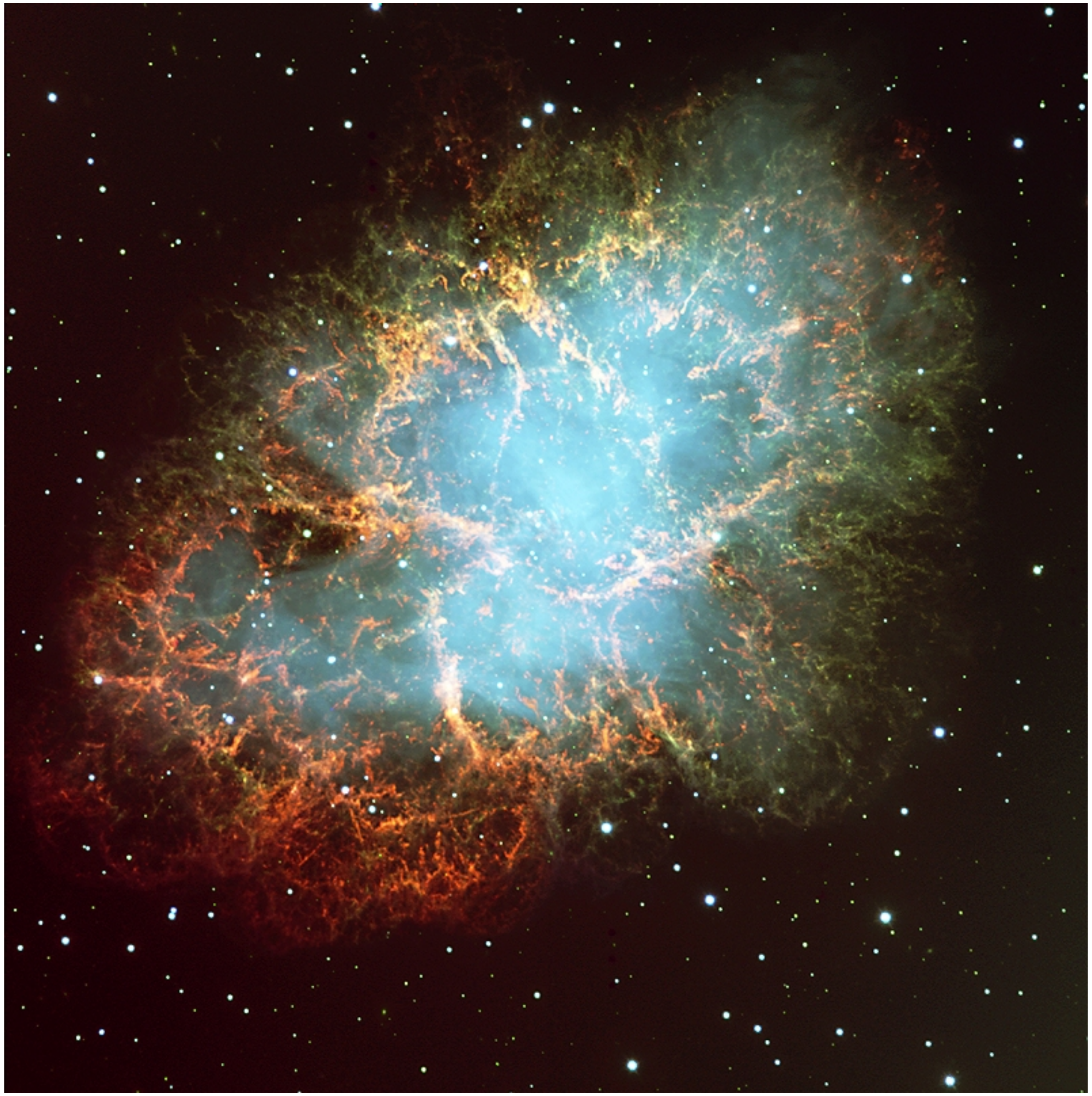
Indeed a powerlaw spectrum is obtained !

Note : P_{esc} is related to mean free path

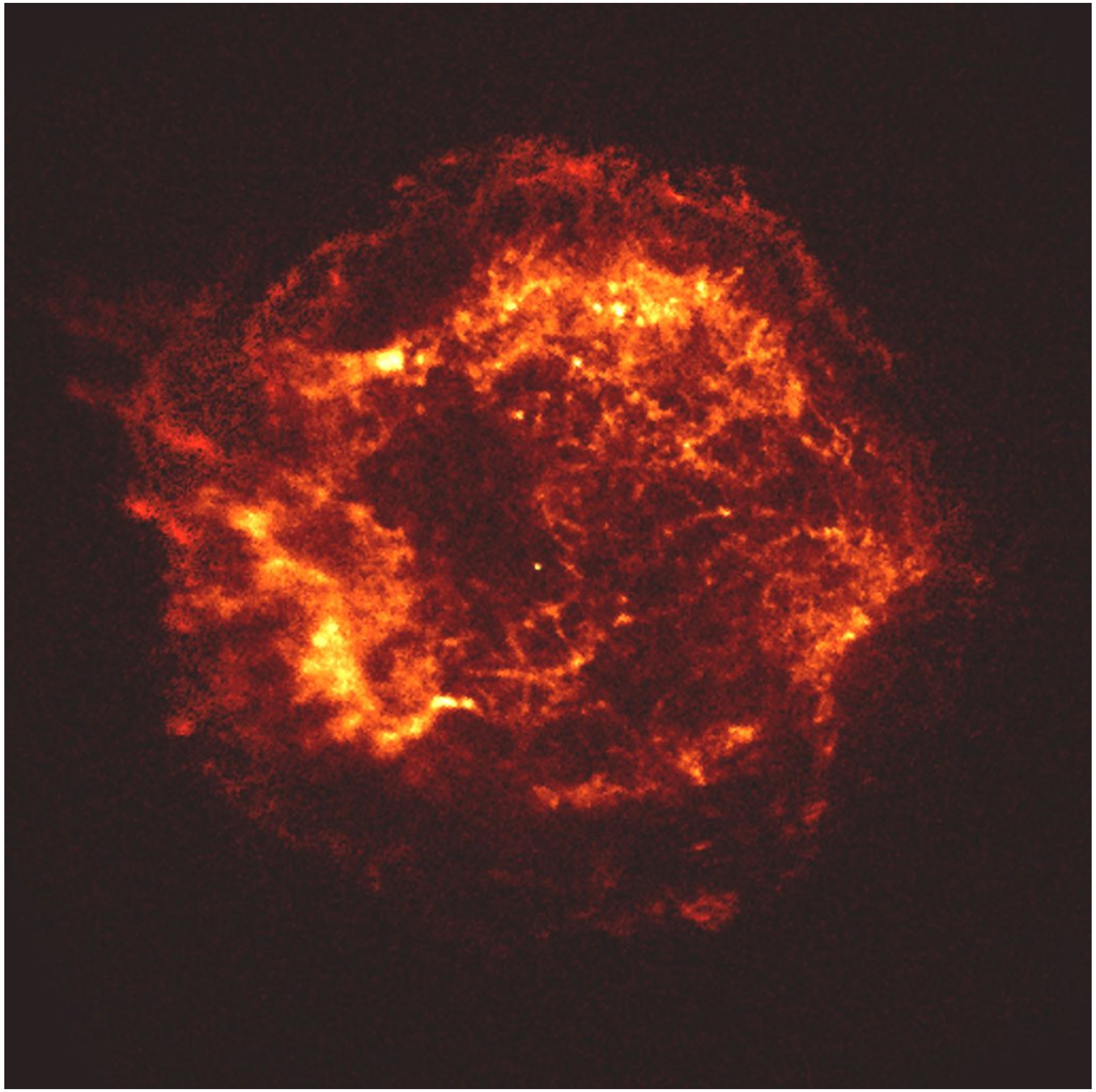
Spectral slope $\beta \propto (\sigma \cdot \text{density})^{-1}$

Where do we find shock waves ?

Cosmic rays



Cosmic rays



Origin of cosmic rays

- Supernova blast waves

  Moving charge in static mag. field

  Gyroradius $r = \frac{p}{ZeB} \quad (\vec{p} \perp \vec{B})$

  $\rightarrow \left(\frac{p}{1 \text{ eV}}\right) = 0.03 \cdot Z \left(\frac{B}{1\ \mu\text{G}}\right) \left(\frac{r}{1 \text{ m}}\right)$

  Shock wave : extra factor $(\Gamma\beta)_{shock}$

- Accelerator of size R

  $r > R \rightarrow$ particles escape $\rightarrow E_{max}$

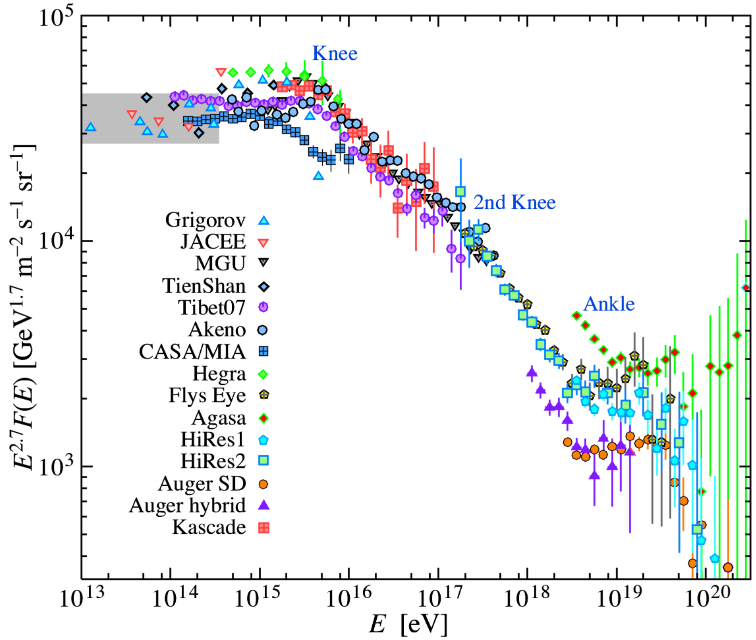
  Typical : $B \approx \mu$G $\quad R \approx$ pc

  $\rightarrow$ Protons : $E_{max} \approx 10^{15}$ eV

$*$ At a certain $r \rightarrow E_Z = ZE_{proton}$

$*$ $E > 10^{19}$ eV $\rightarrow r > R_{galaxy}$

$\Rightarrow$ Extra-galactic origin



What causes the slope change and 'ankle' ?

Change in composition ?

Incorrect energy determination ?

New cosmic sources ?

How can $E > 10^{20}$ eV exist ? (GZK)

Analysis of cosmic ray cascades

- Only sec. from atm. interactions observed
  - Properties of shower development
- Multidim. (N_e, N_μ) shower analysis
  1. At prim. vertex : π, K, Λ, Ξ, D, ...
  2. At shower maximum : large N_e
  3. After max. : meson decays $\longrightarrow \mu$, ν_μ
  4. Even later : μ decays $\longrightarrow e$, ν_e, ν_μ

  With increasing primary E
  - Maximum closer to detector (D_{max})
    D_{max} from e.g. fluorescence meas.
  - Larger sec. energies $\longrightarrow$ longer lifetimes

  $\longrightarrow N_e/N_\mu$ increases

  $N_e/N_\mu \propto (E/A)^\alpha \quad (\alpha > 0)$

- A dependence (composition)

  $N_\mu \propto (A/E)^\alpha N_e$

  Certain prim. $E \longrightarrow N_\mu \propto A^\alpha N_e$
  - Heavy primaries $\longrightarrow$ Muon rich showers
    Set scale limits by p and Fe
  - N_e/N_μ (and D_{max}) $\longrightarrow A \longrightarrow E$

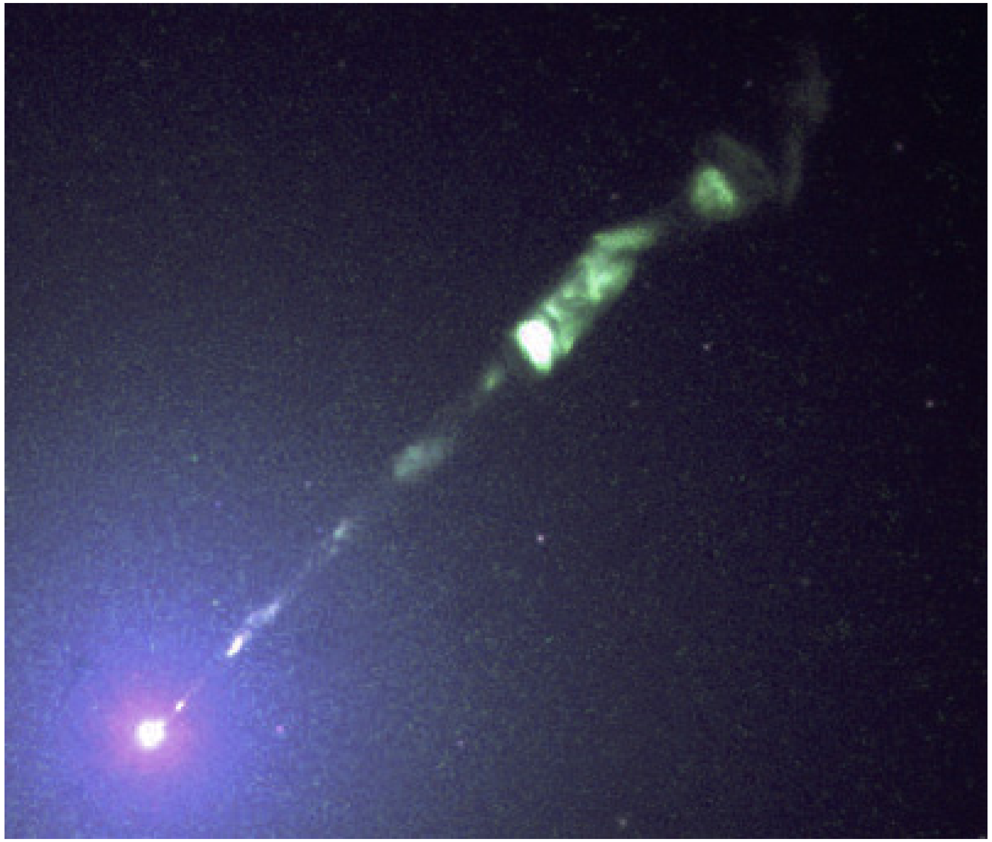
  Quantitative analysis $\longrightarrow$ MC needed
- Large discrepancies between various models

  Data needed to validate/tune models

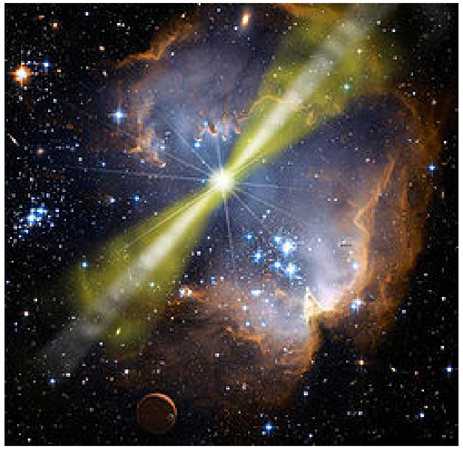
  - CERN-LHC might provide insight here
    Physics $E(Z)$ or cascade $E(A)$ effect ?

Possible high-energy sources

Active Galactic Nuclei (AGN)



Gamma Ray Bursts (GRBs)



Possible high-energy sources

➤ Engines which power AGN

- Acceleration via shock waves in the jets
- Jet directed to us $\longrightarrow$ Blazar
  Markarian 421 and 501

➤ Gamma Ray Bursts

- 'Hypernovae' $\longrightarrow$ Black hole
- NS+NS or NS+BH mergers
  Also shock wave acceleration

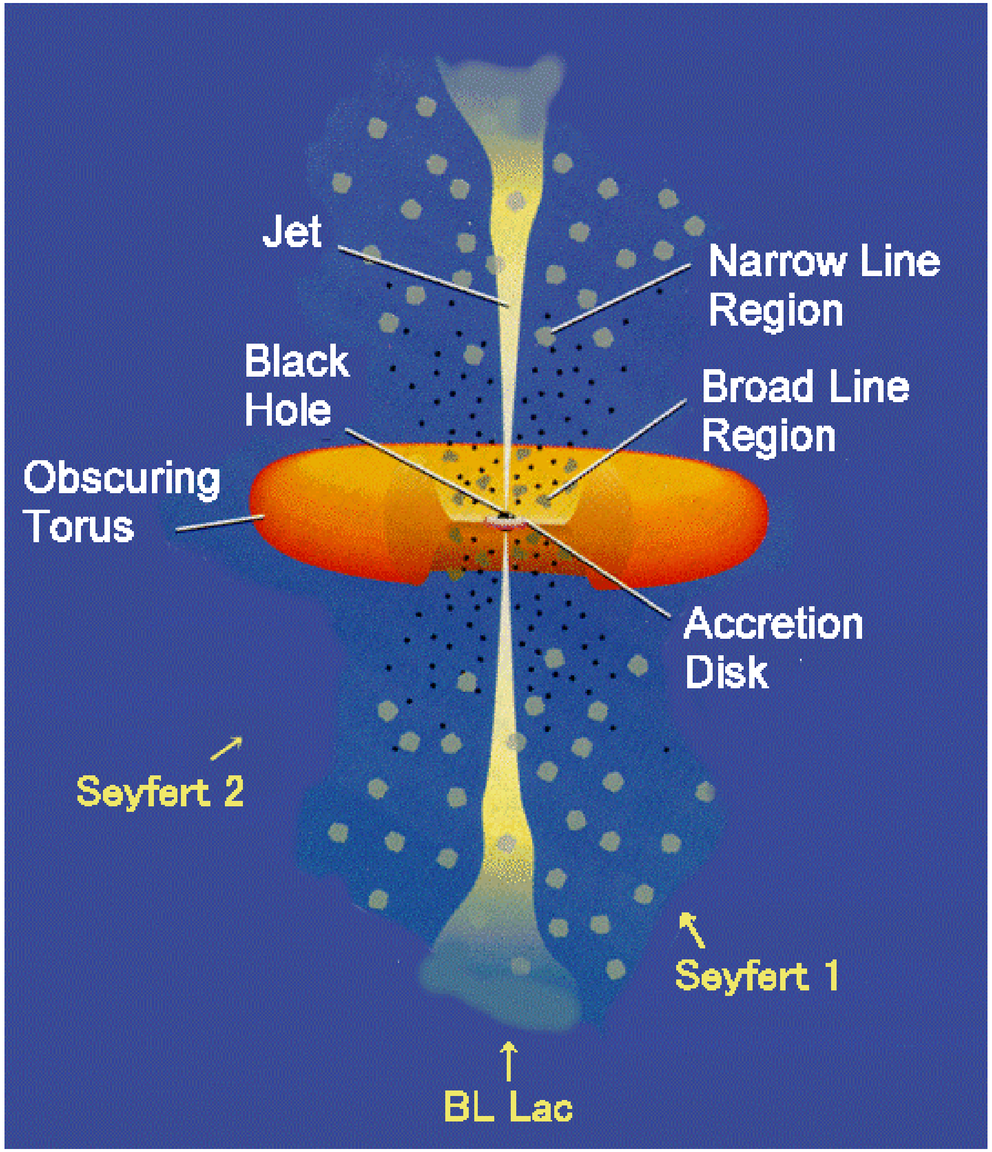
➤ Cold dark matter (WIMPs, SUSY particles)

- Annihilation $\longrightarrow$ High E neutrinos
  WIMPs at the center of Sun, Earth ?

∗ Most extreme events are GRBs

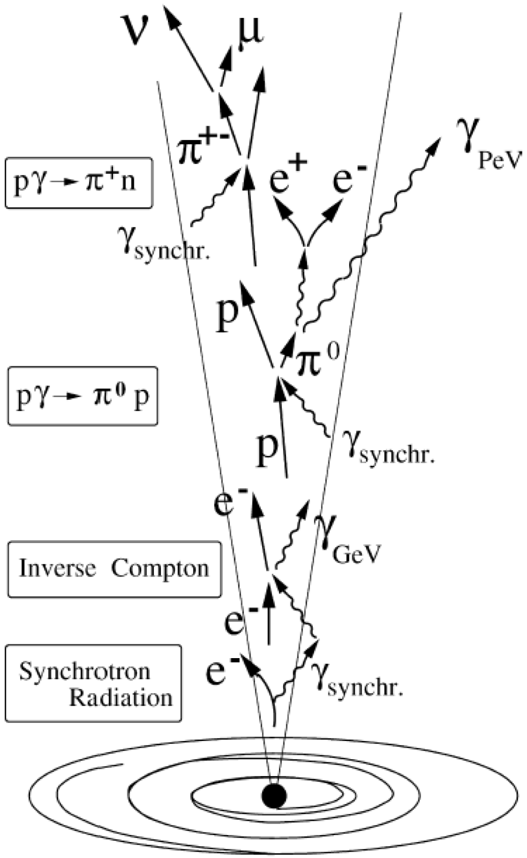
Can GRBs produce the flux at the ankle ?

Waxman&Bahcall PRL 78 (1997) 2292



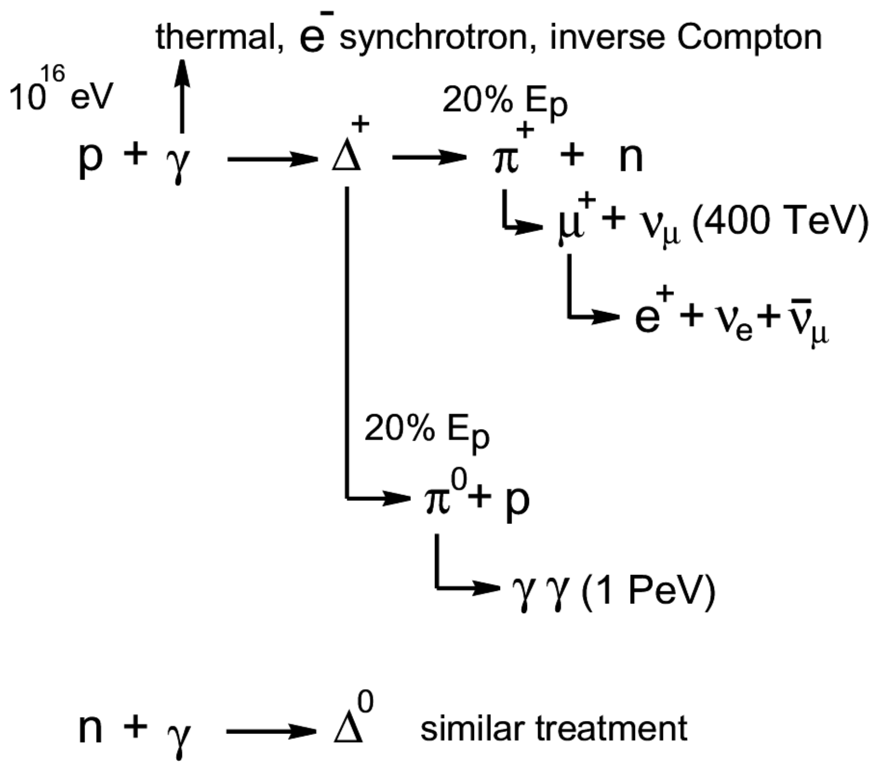
Possible high-energy sources

Processes in the jet



Can this GRB fireball model be probed ?

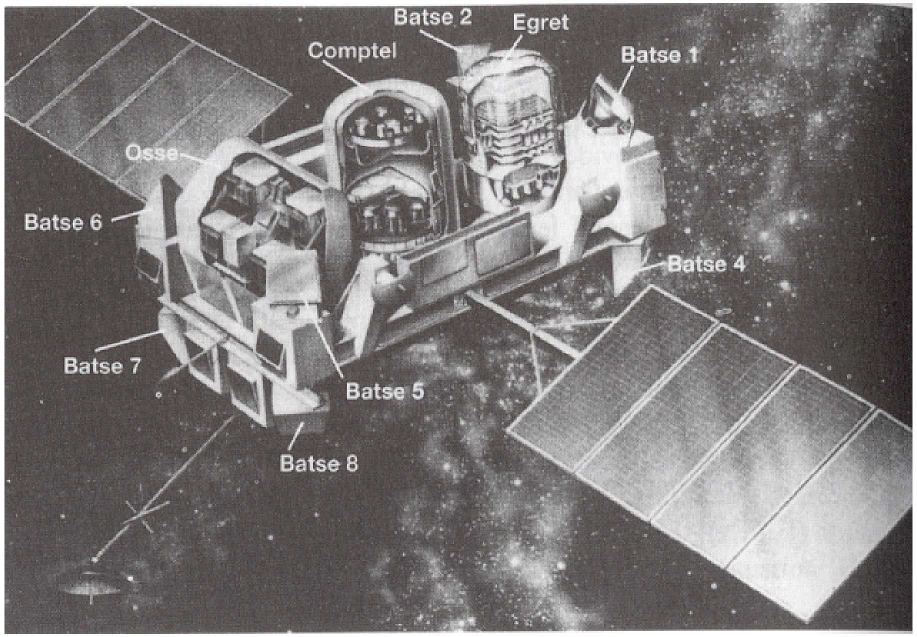
Neutrino production mechanism



Δ production threshold : $E_\gamma \geq 10$ eV (UV photons)

Observation of high-energy photons

Compton Gamma Ray Observatory



- COMPTEL (sky maps, spectroscopy)
  Compton Telescope
  Wide field 1-30 MeV
- EGRET (AGN, GRBs, Pulsars)
  Energetic Gamma Ray Exp. Telescope
  Wide field 20 MeV - 30 GeV
- OSSE (X-ray sources, QSO spectra, SNe)
  Oscillating Scintillation Spectrometer Exp.
  Narrow field ($4^0 \times 11^0$) 50 keV - 10 MeV
- BATSE (All sky monitor, GRBs)
  Burst and Transient Source Experiment
  Wide field (8 elements) 20 keV - 30 MeV

Observation of high-energy photons

The WHIPPLE gamma ray telescope

- Ground based (Arizona, USA)
  Reflective 10 meter diameter dish
- Cerenkov radiation from air showers
  Field of view : 3^0
  Shower energy 100 GeV - 10 TeV

Observation of high-energy photons

Observations of Markarian 421

- Markarian 421 : AGN at a distance of about 100 Mpc ($z = 0.031$).
- Discovered in 1991 by TeV gamma rays (Nature 160 (1992) 477).
- Observed by EGRET (1991-1993) and Whipple 1993-1994 : Flare at 14-15 may 1994. (ApJ 438 (1995) L59. ApJS 94 (1994) 551.)
- EGRET ($E_\gamma > 100$ MeV) : constant flux of $(1.7 \pm 0.3) \cdot 10^{-7}$ photons cm^{-2} s^{-1}
- Whipple ($E_\gamma > 250$ GeV) : average flux of $(2.3 \pm 0.3) \cdot 10^{-11}$ photons cm^{-2} s^{-1}

  Flux during 1994 flare : $(2.1 \pm 0.3) \cdot 10^{-10}$ photons cm^{-2} s^{-1}

Can the fireball model be probed ?

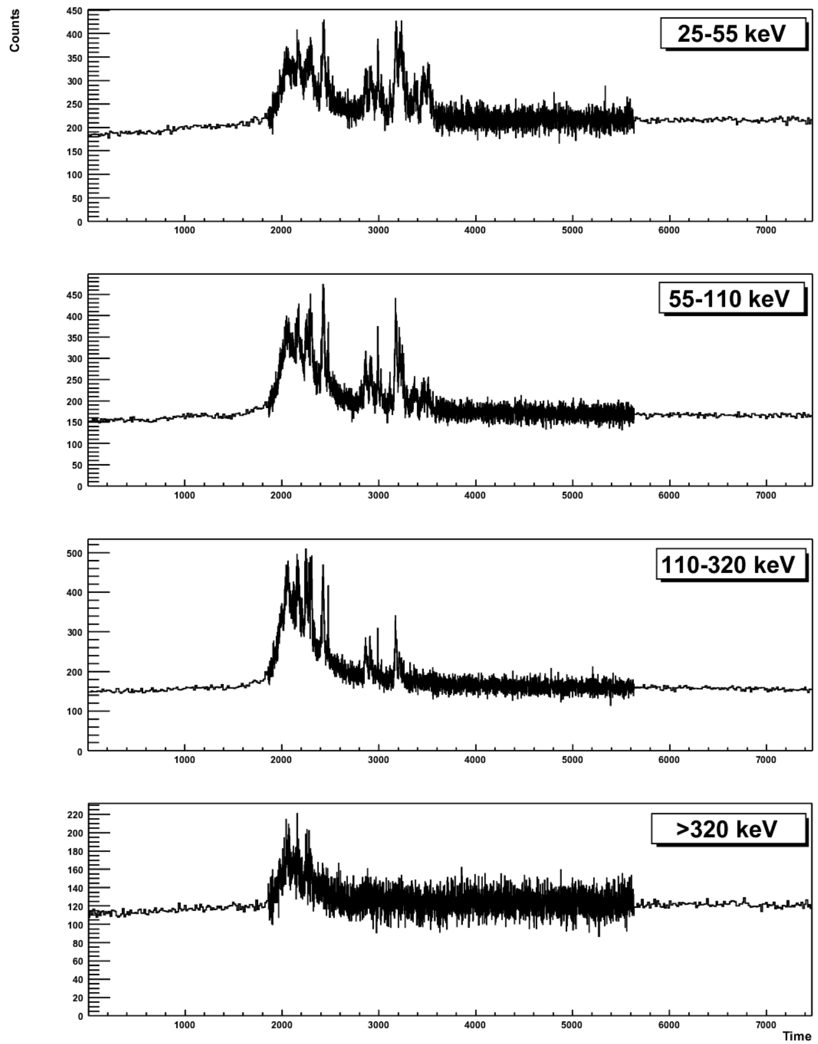
in other words :

Can we indicate hadronic processes in these objects ?

Even more violent transient phenomena are observed ...

Observation of high-energy photons

Batse GRB trigger 109



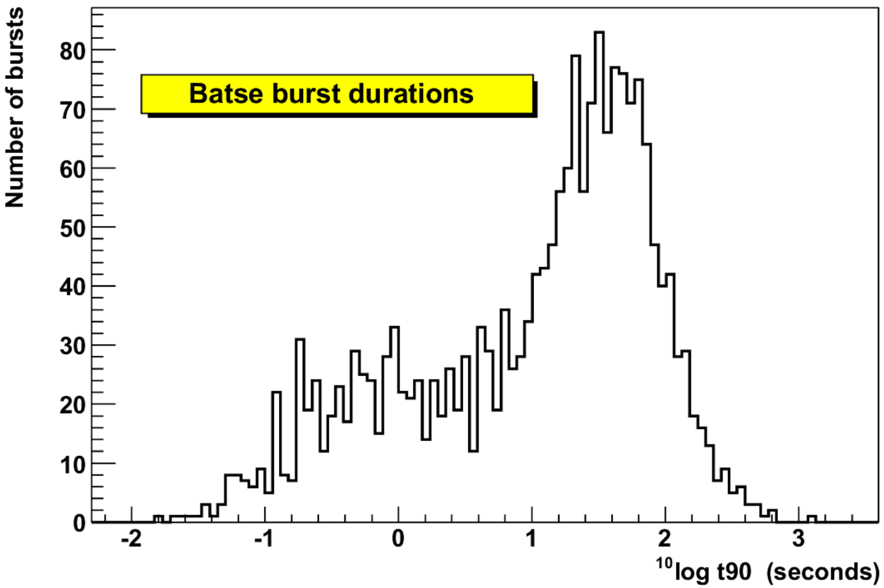
- Burst lasts ∼2 minutes
- Rich (energy dependent ?) structure
  - Rather compact source involved
  - Process might consist of several phases
    Various shock waves ?

What are these GRBs ?

- Common features ?
- Where are they located ?

Observation of high-energy photons

Burst duration analysis

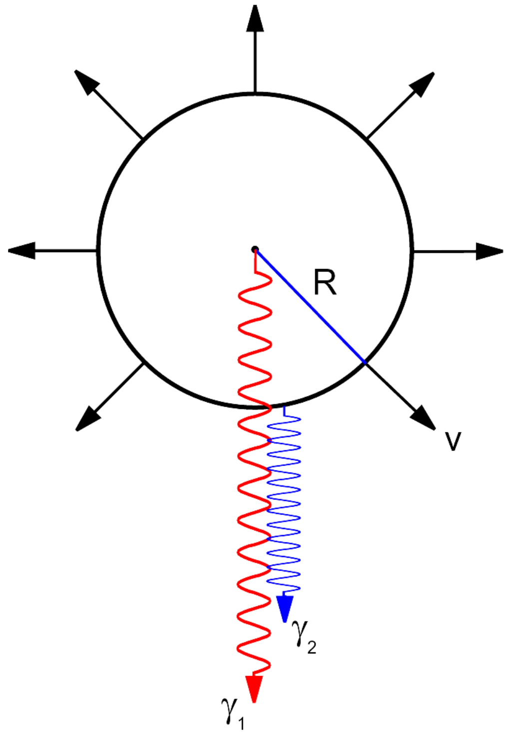


- t90 $\equiv \Delta t$ from 5% to 95% of fluence
- Two classes : short and long bursts ?
  - Long : dense medium (hypernovae ?)
  - Short : dilute medium (mergers ?)

Effect of (cosmological) time dilation ?

Time spectrum analysis

Possible source of time structure



- If distance r can be determined (see later)

  $\longrightarrow$ (Cosm.) time dilation correction known

- Consider center of GRB as origin at rest

  γ_1 produced at $t_1 = 0$

  γ_2 produced at $t_2 = t_1 + R/v$

  At some time $t > t_2$ we have

  $r_1 = ct$ and $r_2 = R + c(t - R/v)$

- γ_1 and γ_2 observed at the earth

  $$\Delta t = \frac{r_1 - r_2}{c} = \frac{R}{c}\left(\frac{1}{\beta} - 1\right)$$

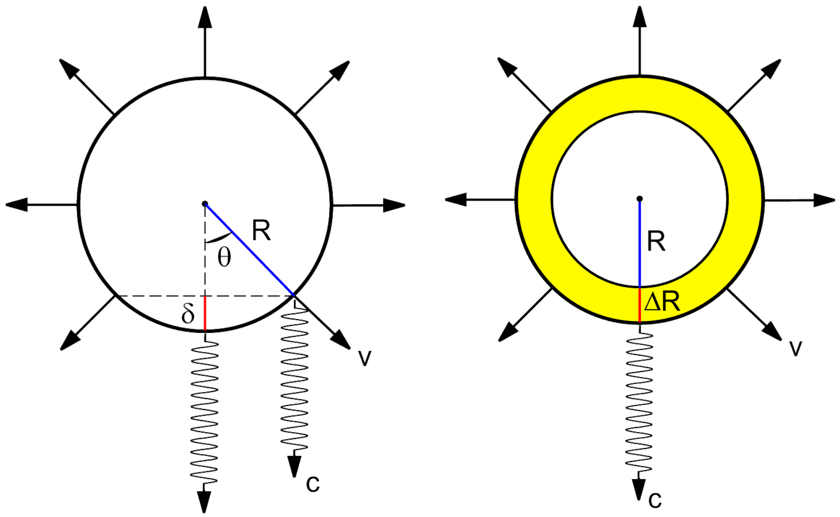
  $$\longrightarrow \Delta t = \frac{R}{v}(1 - \beta) \approx \frac{R}{v\gamma^2} \quad (\gamma \gg 1)$$

  Origin of the various spectral peaks ?

- Characteristic size R ?

  Would allow determination of γ factor

Another source of time structure



- Observed duration $\Delta t \rightarrow R$ and ΔR

$$\Delta t = \frac{\delta}{c} = \frac{R}{c}(1 - \cos\theta)$$

$\rightarrow R = c\Delta t$ Also : $\Delta R = c\Delta t$

- Quantities in CMS $(*)$ via inverse Lorentz transformation of observables

  Expanding shell $\rightarrow \gamma$

  Cosmic expansion $\rightarrow \Gamma$

- So we have $(\gamma \gg \Gamma)$

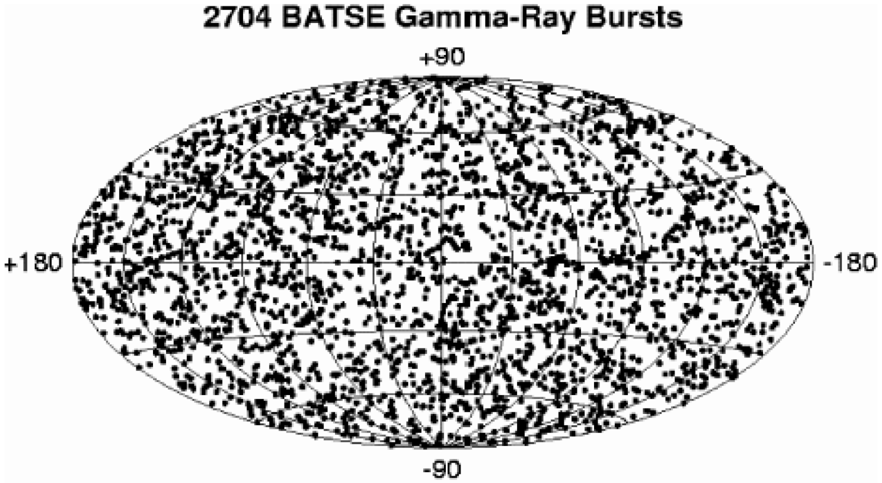
$$R^* = \Gamma R \qquad \Delta R^* = \gamma \Delta R$$

$$E^* = \gamma^{-1} E$$

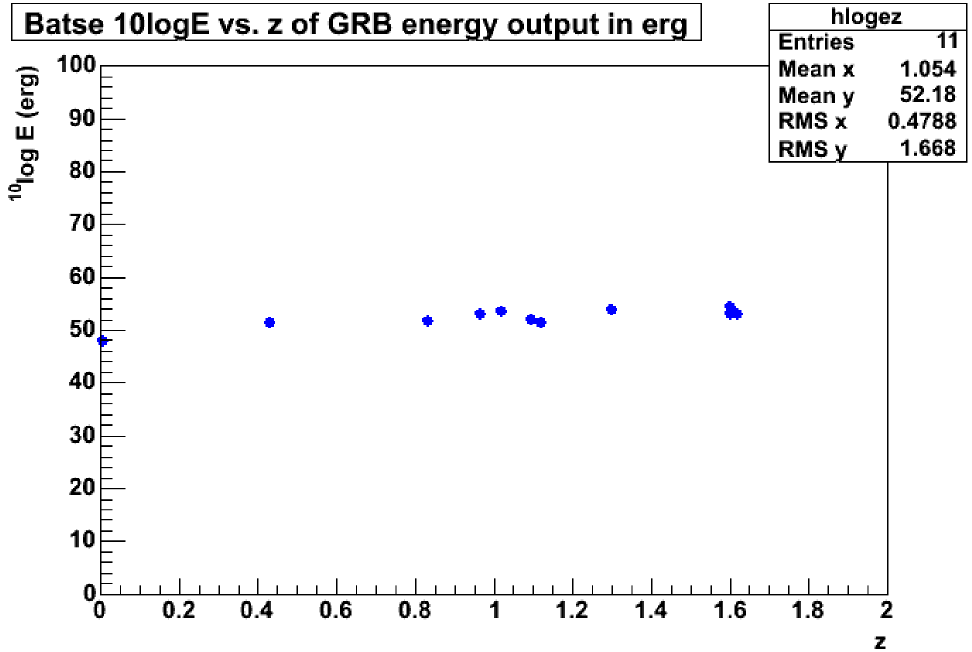
- Origin of the width of the peaks ?

Observation of high-energy photons

Burst location analysis



z and Batse fluence yield total E



- No concentration along galactic plane

  $\longrightarrow$ Sources of cosmological origin

  Confirmed by afterglow (z values)

- $(1+z) = \gamma(1+\beta)$ (small z)

  $\longrightarrow \beta = \frac{(1+z)^2-1}{(1+z)^2+1}$ and $v = H_0 r$

No beaming and $H_0 = 71$ km/s Mpc^{-1}

- Characteristic energy output

  In Batse energy window $E_0 \sim 10^{52}$ erg

  – Allows to investigate distance distr.

Observation of high-energy photons

- Batse observed fluence S
  and assume E_0 for all bursts

  $$E_0 = 4\pi r^2 S \rightarrow r = \left(\frac{E_0}{4\pi S}\right)^{1/2}$$

  Batse data provide distance distribution

- $S = S_0$

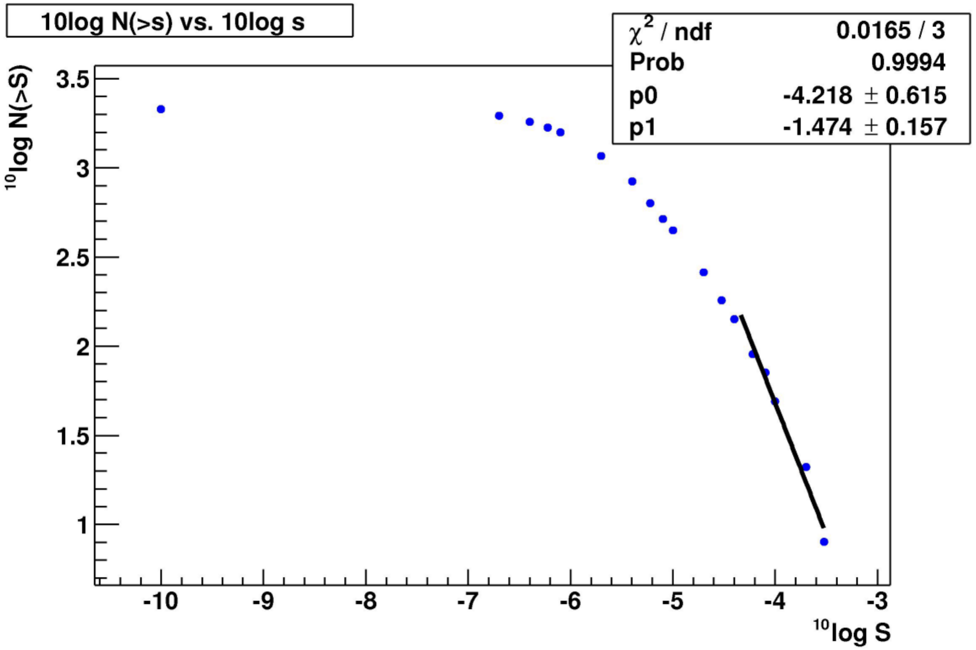
  $\longrightarrow$ specific distance $r_0 = \left(\frac{E_0}{4\pi S_0}\right)^{1/2}$

  Obviously $r < r_0 \longrightarrow S > S_0$

  Homogeneous burst density n Mpc^{-1} yr^{-1}

  $$\longrightarrow N(> S_0) = n\tfrac{4}{3}\pi r_0^3 \propto S_0^{-3/2}$$

  Batse data $N(> S_0)$ vs. S_0 probe n



∗ Was there a specific GRB epoch ?

∗ Match with cosmic-ray flux at the ankle ?

Ankle : $E^2 \frac{\mathrm{d}N}{\mathrm{d}E} \approx 10^{-7}$ GeV cm^{-2} s^{-1}

- Correction for redshift needed
- Watch out for detector thresholds

Observation of high-energy photons

- Using redshift and physical distance : $S_{obs} = \dfrac{E_0}{4\pi(r_{phys})^2(1+z)}$

- Flat Friedmann-Lemaître universe and Robertson-Walker metric

$$r_{phys}(z_{obs}) = \frac{c}{H_0}\int_{z=0}^{z=z_{obs}} \frac{\mathrm{d}z}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

$*$ WMAP & Planck observations (2013) : $\Omega_M = 0.315 \pm 0.017 \quad \Omega_\Lambda = 0.685 \pm 0.017$

$\longrightarrow$ Integral needs to be solved numerically

$*$ Simplified model : $\Omega_M = 1 \quad \Omega_\Lambda = 0 \rightarrow r_{phys} = \dfrac{2c}{H_0}\left(1 - \dfrac{1}{\sqrt{1+z}}\right)$

- $N(> S_0)$ vs. S_0 analysis with simplified model yields : $n = 1.7 \cdot 10^{-10}$ Mpc^{-3} yr^{-1}

Link with cosmic rays

- Assume UHECR fluence originates from GRBs : $S_{obs} = \dfrac{E_{cr}}{4\pi (r_{phys})^2 (1+z)}$
- Spherical shell of thickness $\mathrm{d}r \longrightarrow \mathrm{d}N = n \cdot 4\pi r_{phys}^2 \mathrm{d}r$ GRBs per year
- CR flux observed on earth originating from this shell : $F_{shell}(r) = S\,dN = \dfrac{E_{cr} n\,\mathrm{d}r}{1+z}$
- Total CR flux observed on earth : $F_{cr} = \displaystyle\int_{r=0}^{r_{max}} \dfrac{E_{cr} n\,\mathrm{d}r}{1+z}$
- Simplified model for $r_{phys}(z) \longrightarrow F_{cr} = \displaystyle\int_0^{\infty} \dfrac{cE_{cr} n\,\mathrm{d}z}{H_0 (1+z)^{3/2}} = \dfrac{2cE_{cr} n}{3H_0}$
- Taking $E_{cr} = 10^{52}$ erg $\quad n = 1.7 \cdot 10^{-10}$ Mpc^{-3} yr^{-1}

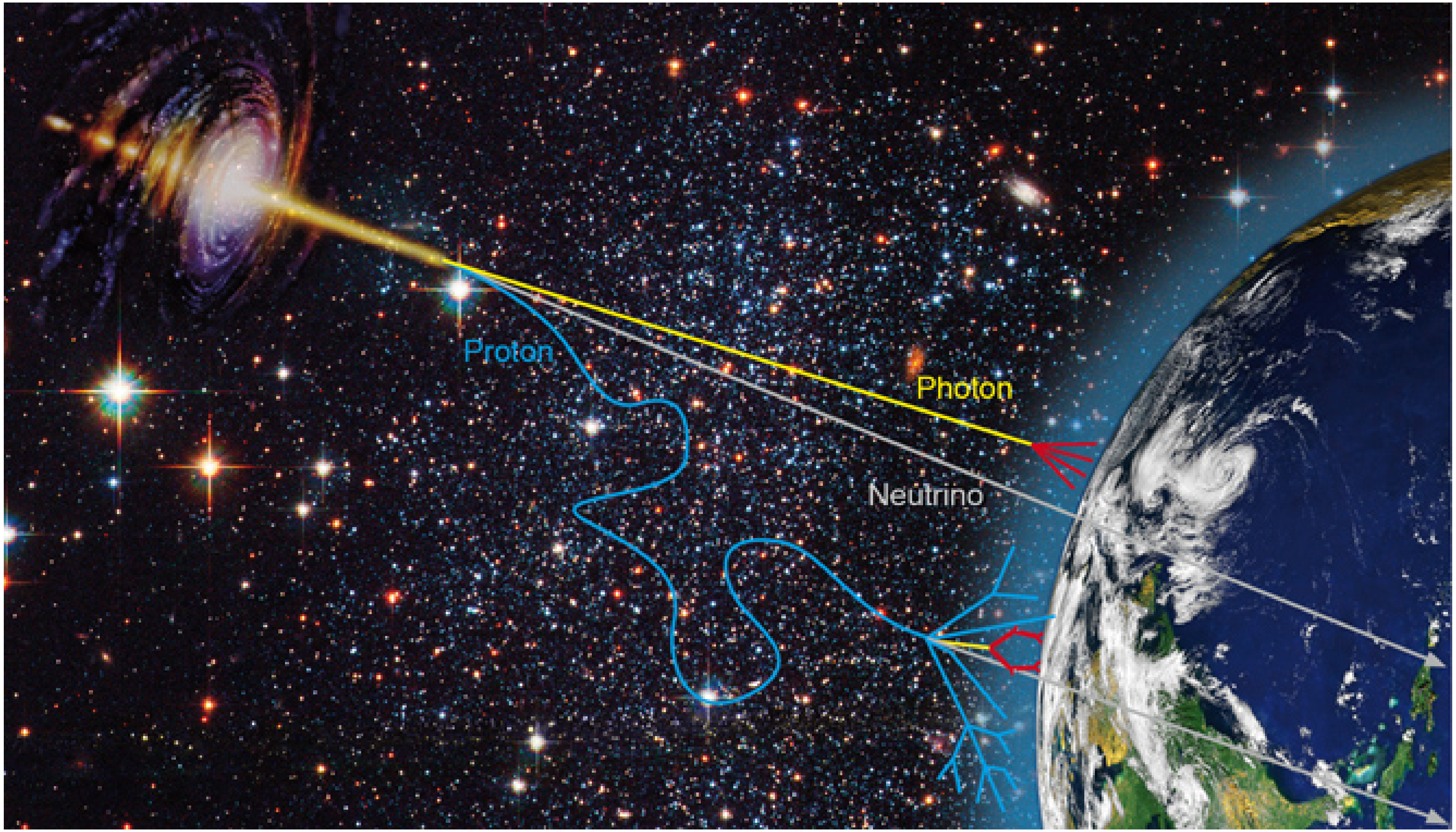
  $\longrightarrow F_{cr} \approx 10^{-8}$ GeV cm^{-2} s^{-1} (observed $\approx 10^{-7}$ GeV cm^{-2} s^{-1})

  Not a bad result for a simplified model !

What sort of particles could these be and where do they come from ?

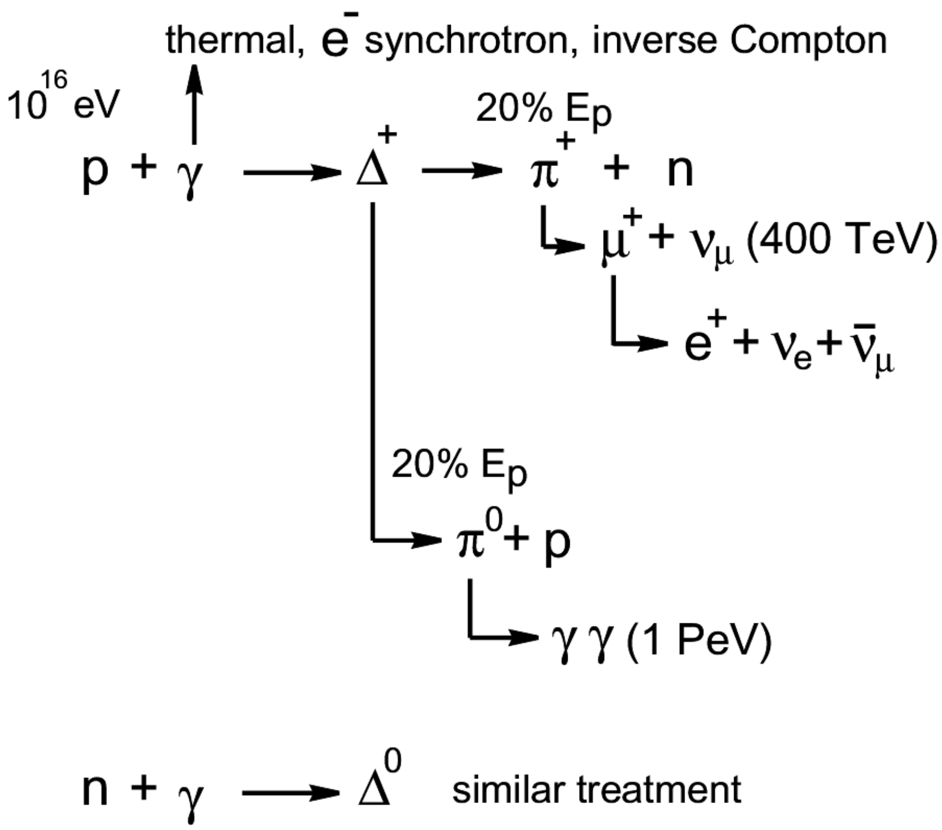
Link with cosmic rays

It's a long and difficult journey



Only photons and neutrinos point back to the source

Neutrino production mechanism



- Δ prod. threshold : $E_\gamma \geq 10$ eV (UV photons)

- Waxmann-Bahcall model

  High-E p diffuse out of the shocks

  Observed CR $\longrightarrow$ lower limit on p flux

  Fraction of p used for ν production ?

- Magn. confinement (Rachen, Ahlers)

  Protons trapped, neutrons escape

  CR observations provide the n flux

  Direct relation CR $\leftrightarrow$ ν flux

- Non-Cosmic Ray (Guetta, Hümmer)

  Fixed fraction of E_γ outflow as p

  Protons not necessarily escape

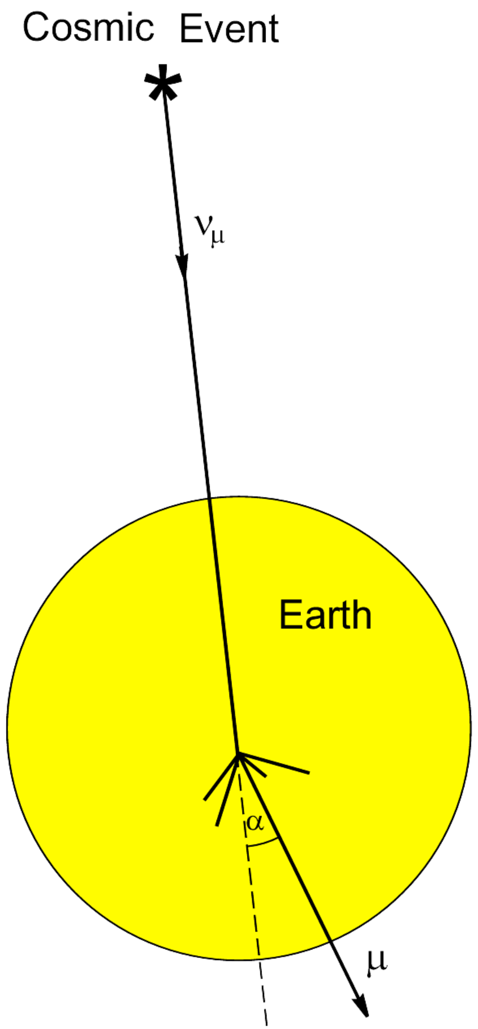
  Normalisation of proton fraction ?

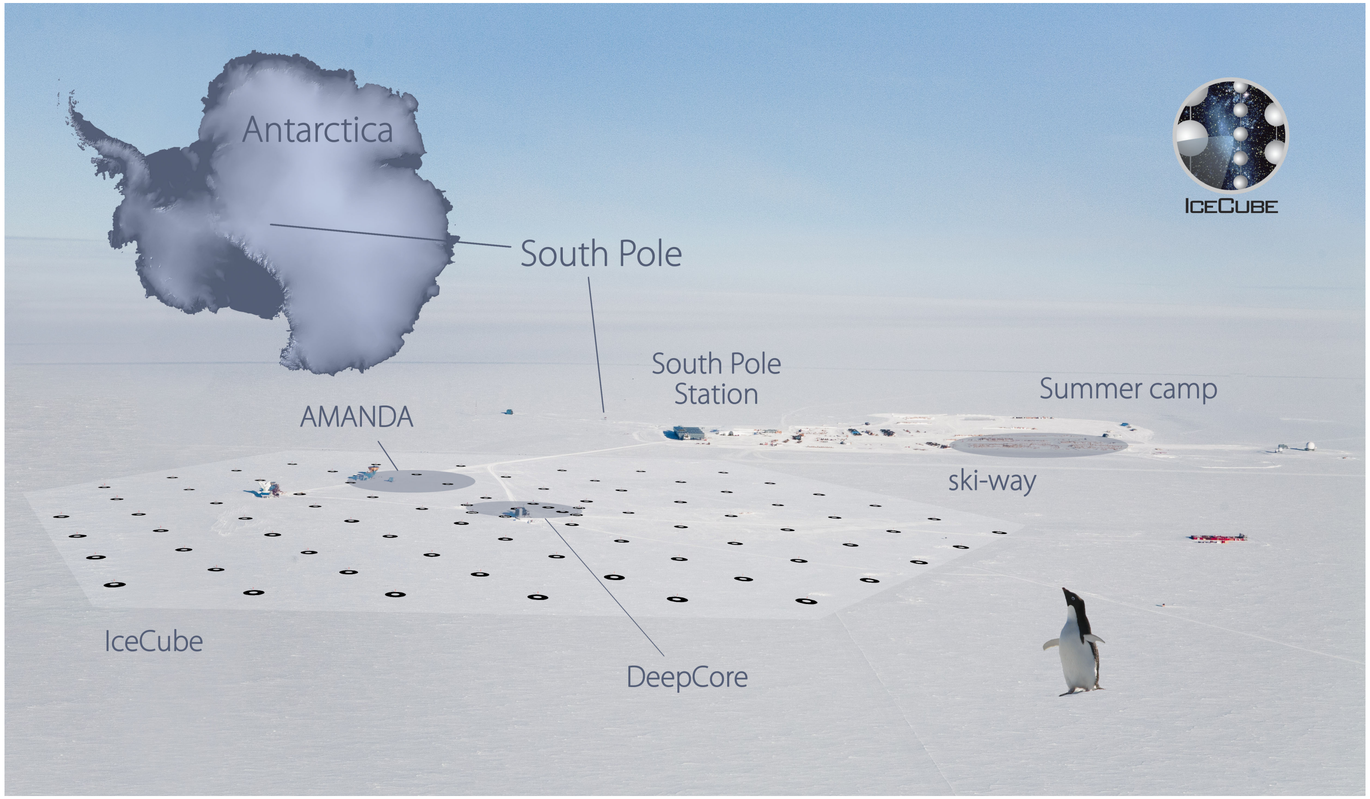
  Fraction of p used for ν production ?

$*$ Let's search for high-E ν sources

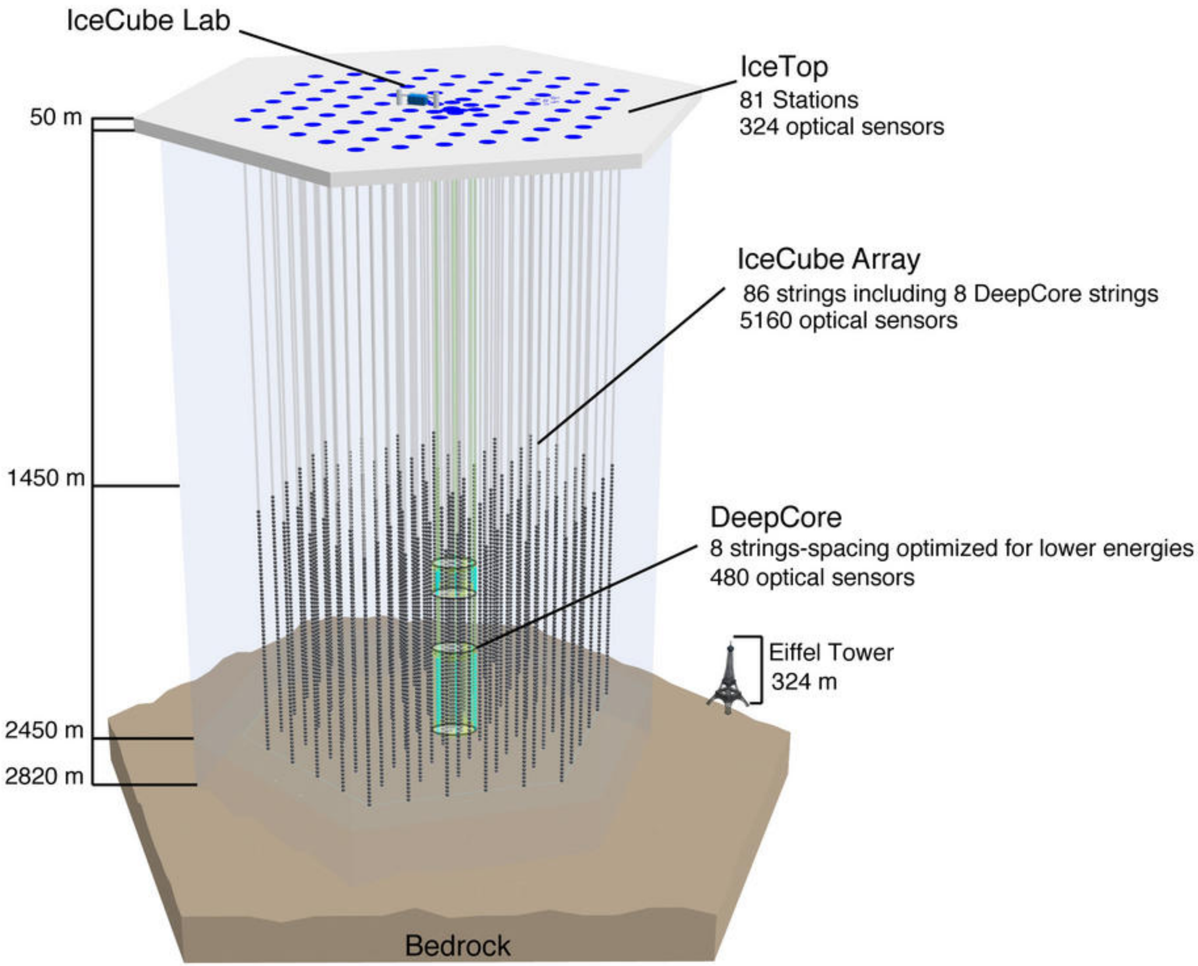
Hunting for Cosmic Neutrino sources

Hunting for Cosmic Neutrino sources

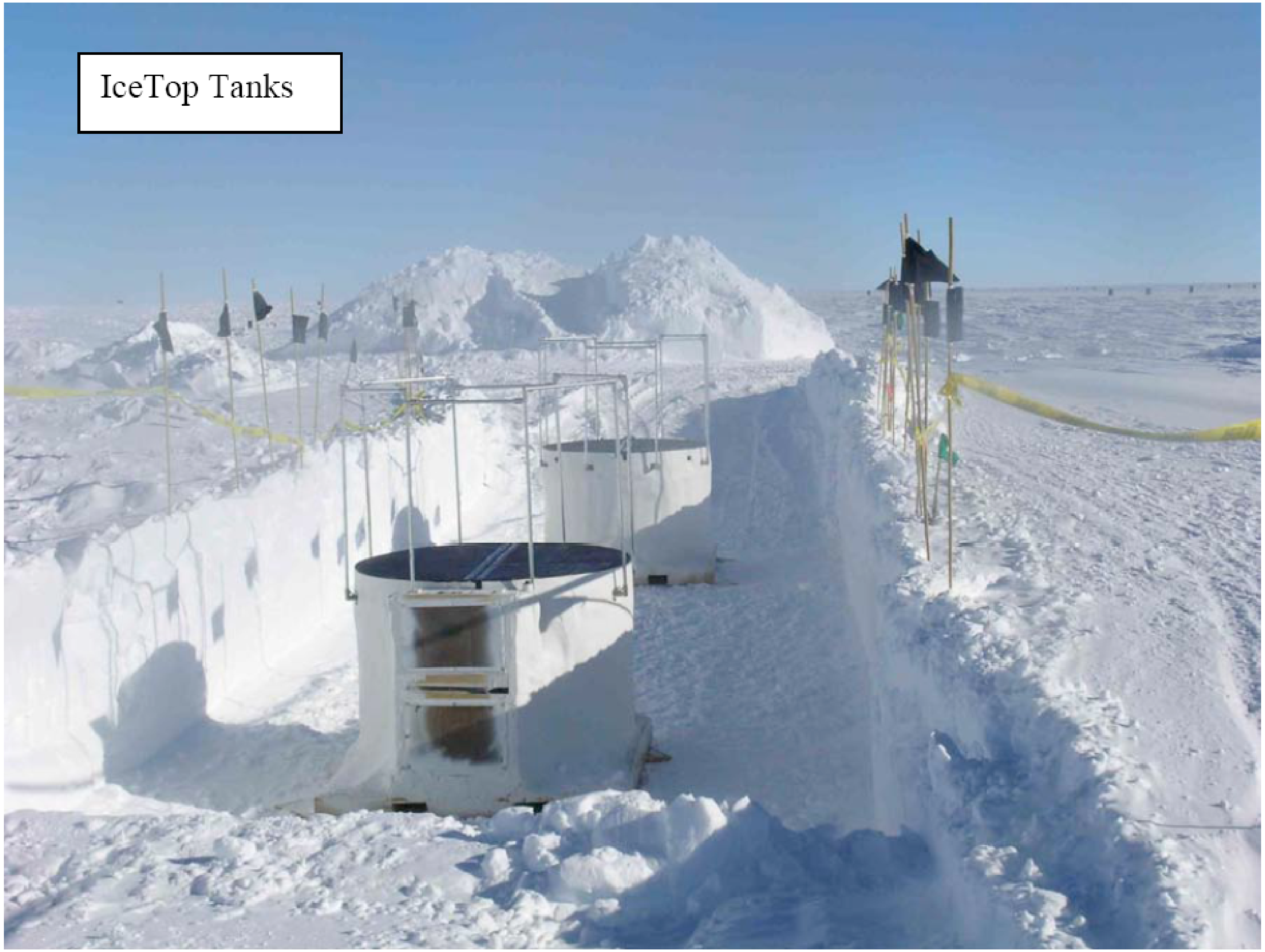




The IceCube neutrino observatory

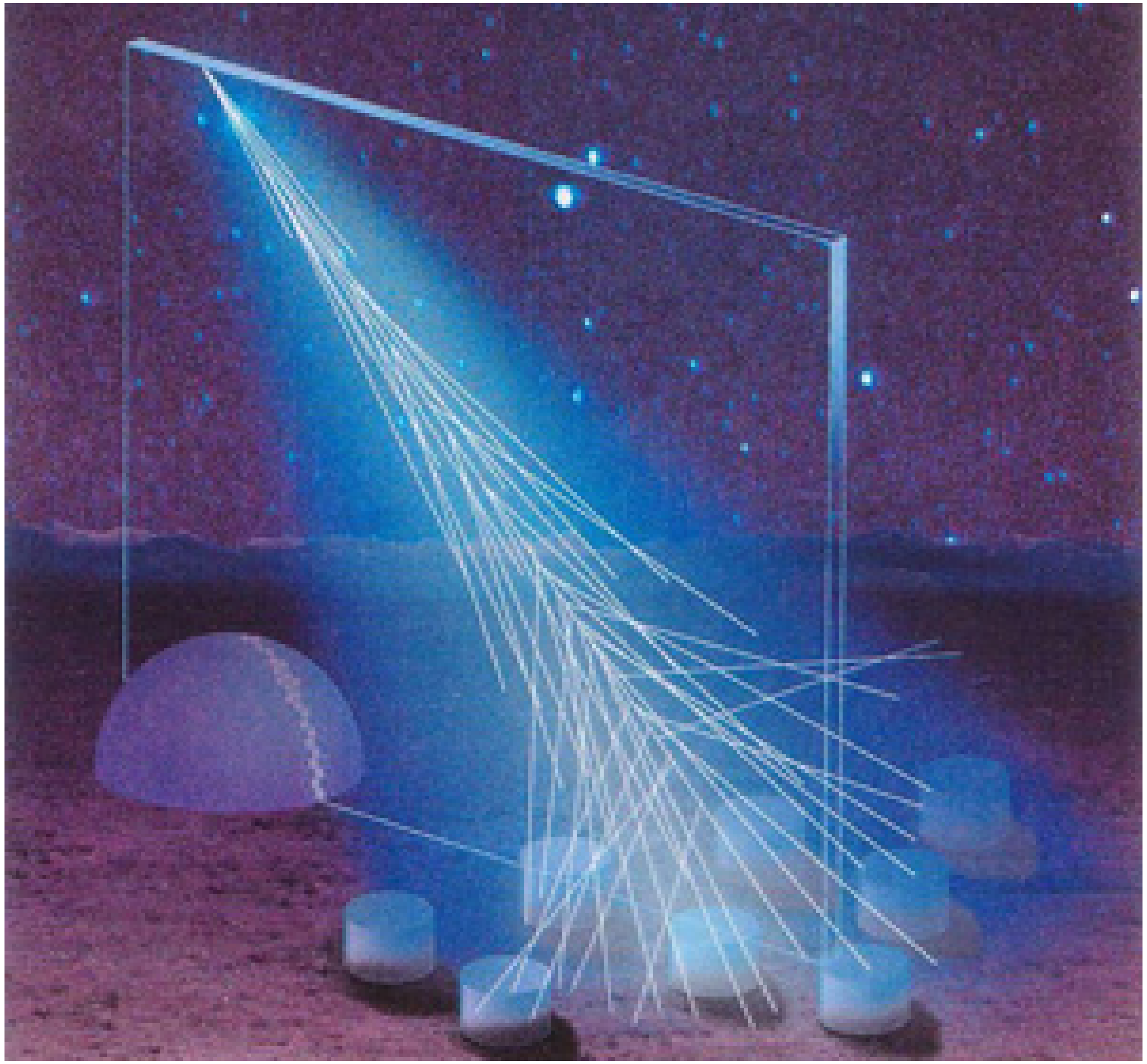


Hunting for Cosmic Neutrino sources



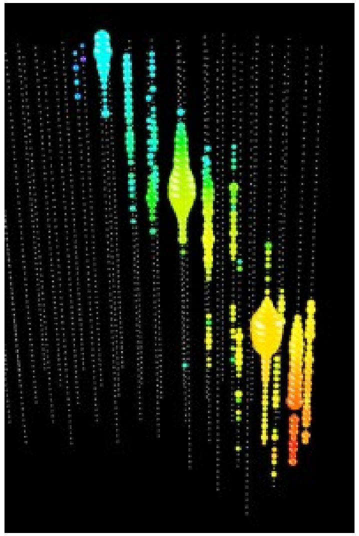
Hunting for Cosmic Neutrino sources

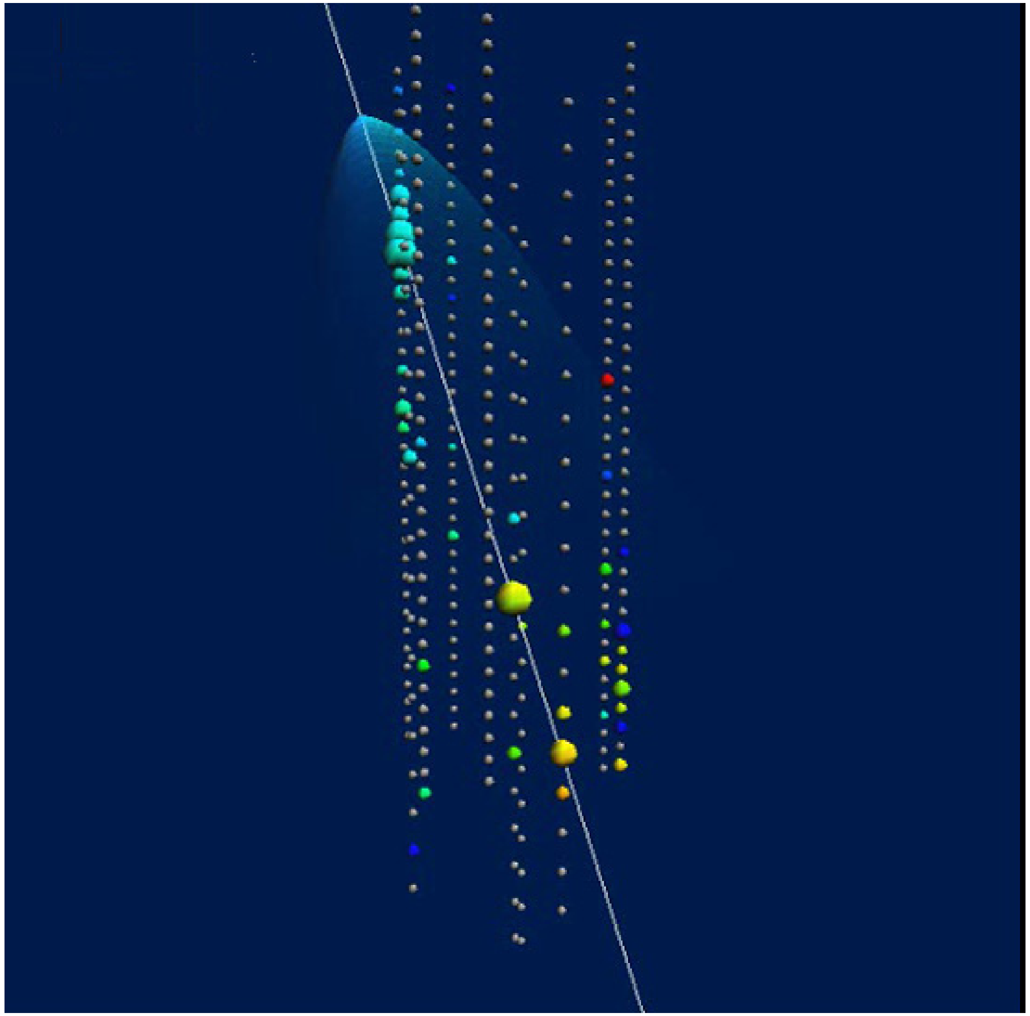
The IceTop detection principle



Hunting for Cosmic Neutrino sources

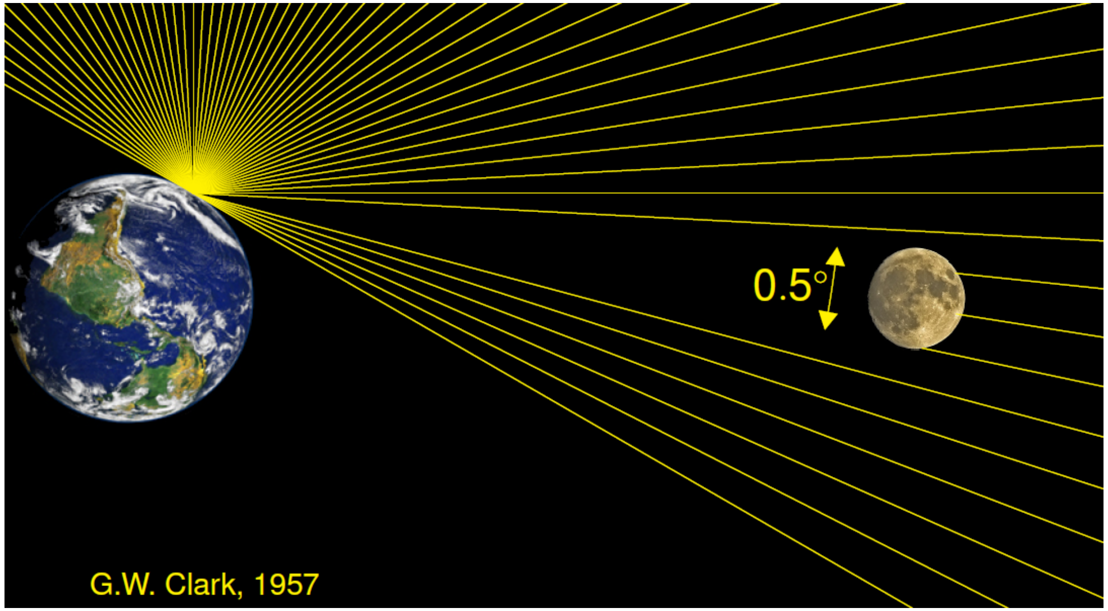
The InIce detection principle

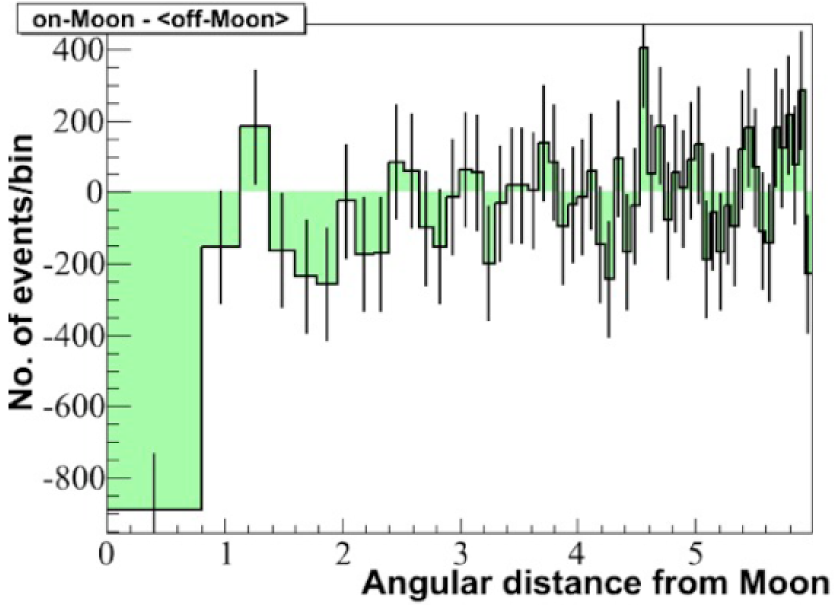




Muons from atmospheric interactions

The shadow of the Moon

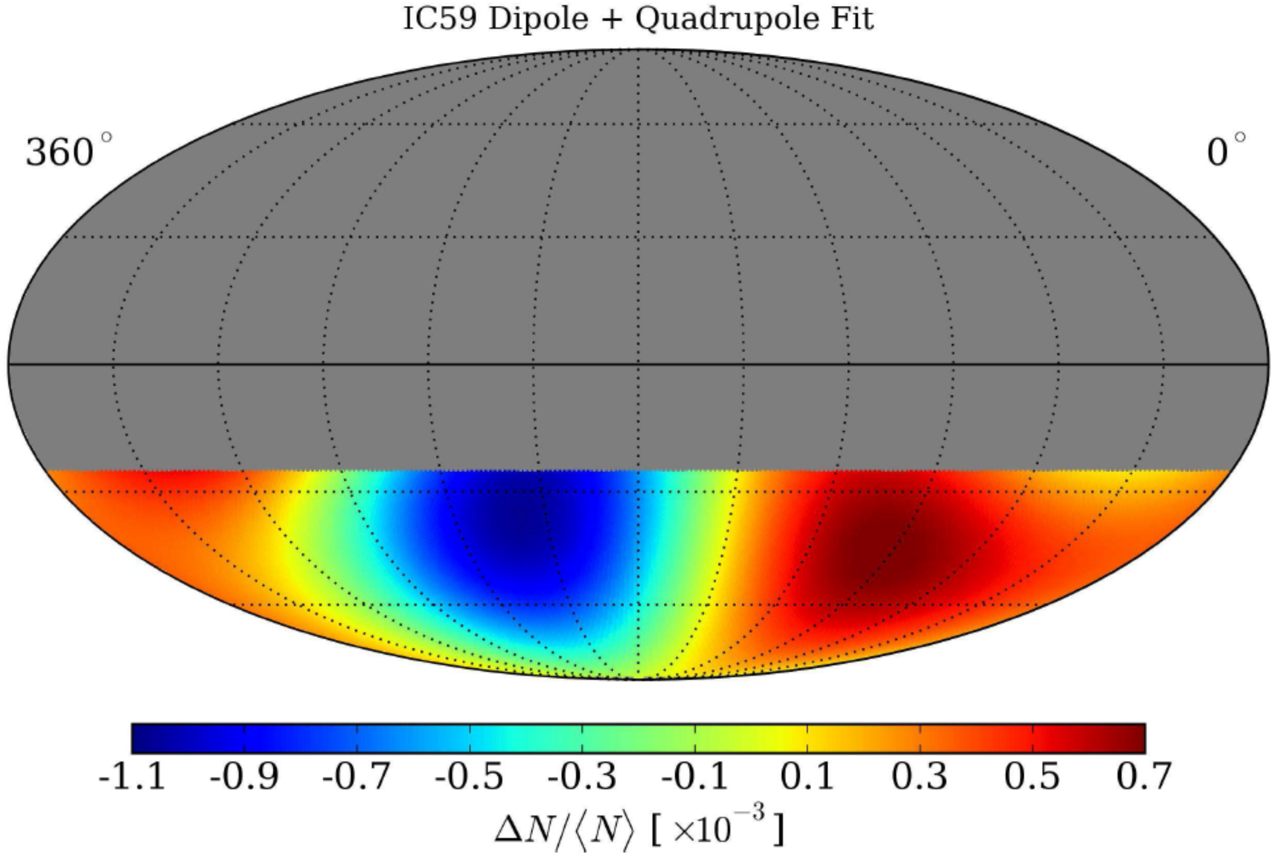




Angular resolution : $\sim 0.8^\circ$

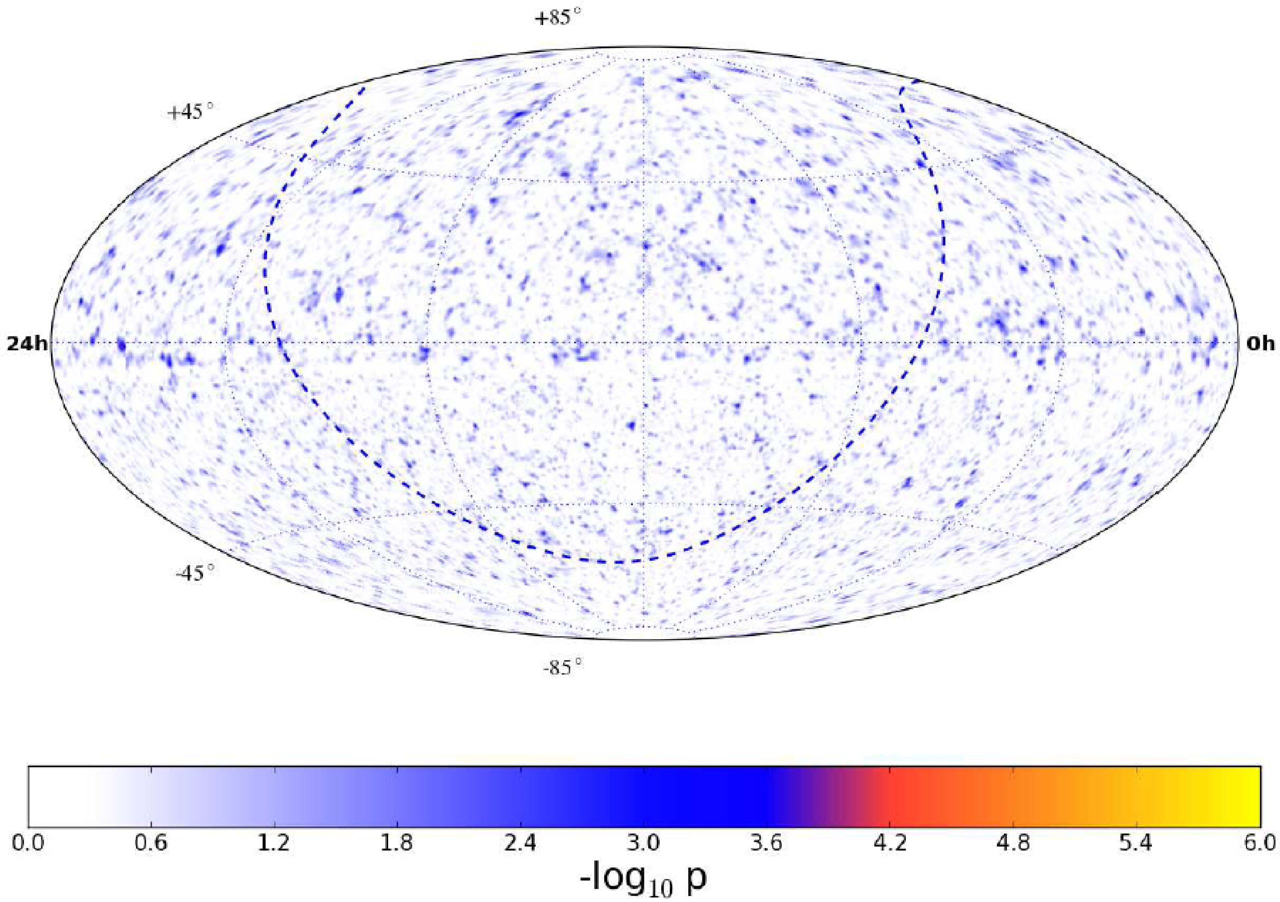
Muons from atmospheric interactions

Cosmic ray anisotropy



Hunting for Cosmic Neutrino sources

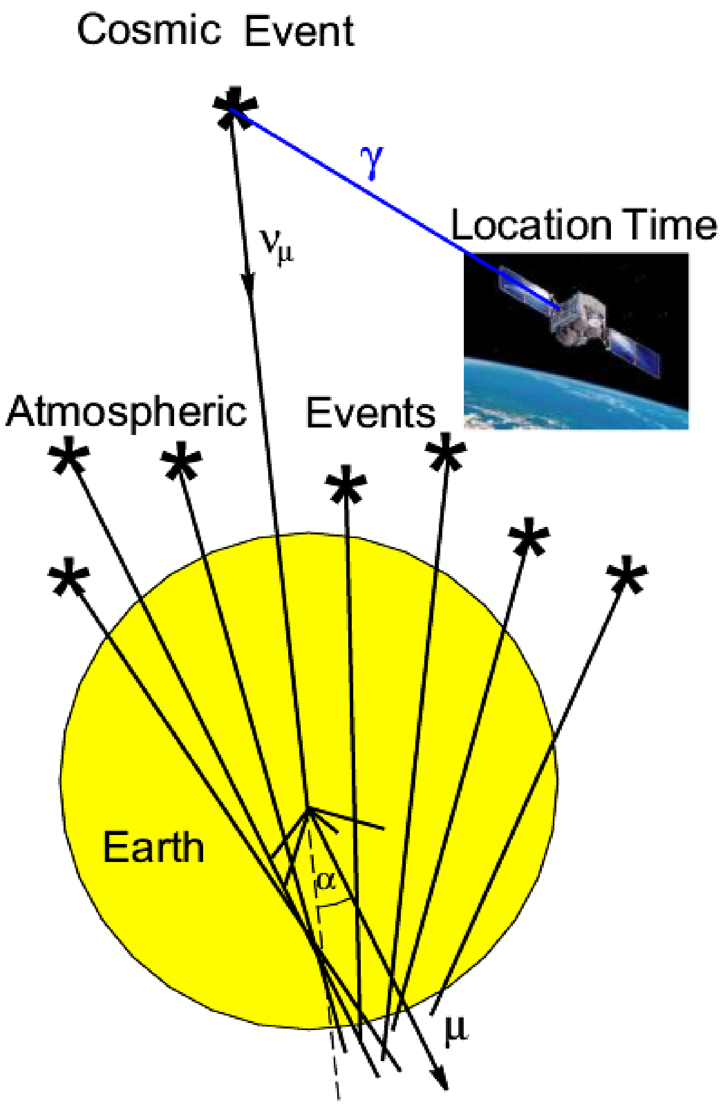
IceCube neutrino equatorial skymap (ApJ 779 (2013) 132)



Most significant excess : $\alpha = $ 2h 17m 0s $\quad \delta = 2.75^\circ \quad$ P-value $= 1.96 \cdot 10^{-5}$

Randomised α data sets $\longrightarrow$ post-trial : P-value=0.57

Transient cosmic sources

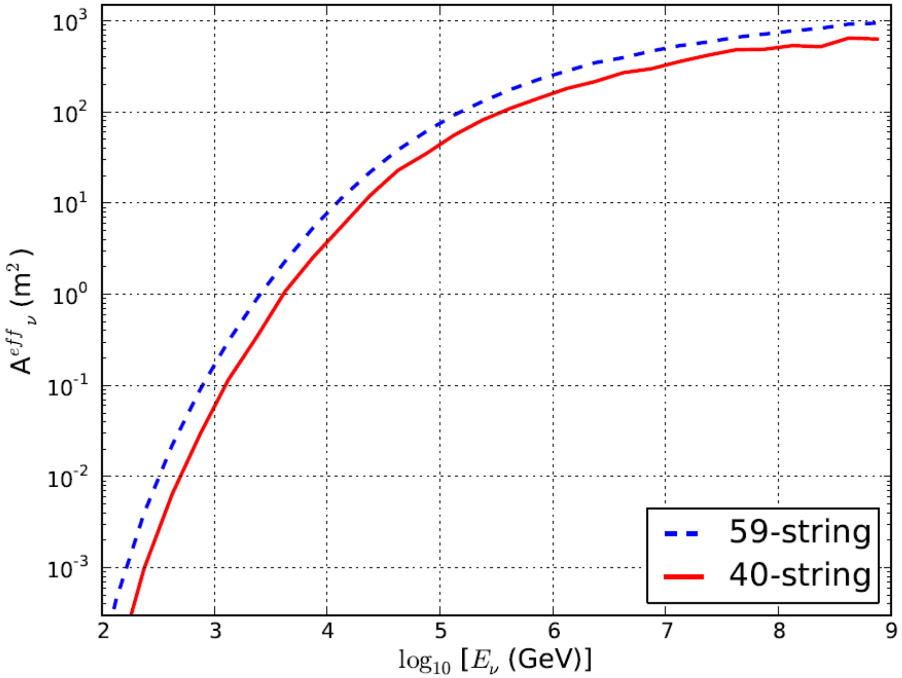


- No signal $\longrightarrow$ Give flux upper limit
- Link observations and flux via Effective area

  $A_{eff} \equiv$ obs. event rate / incoming flux

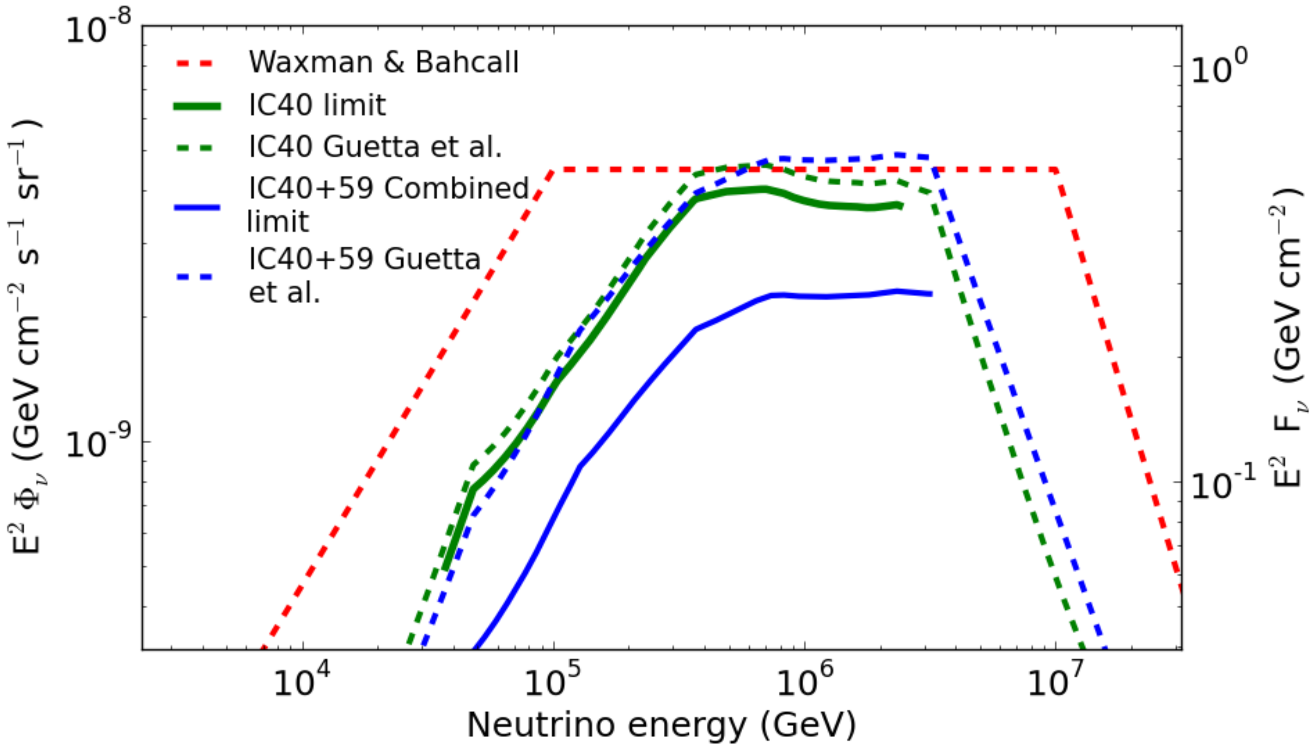
  $\longrightarrow$ Flux limit = max. event rate / A_{eff}

$\nu_\mu + \bar{\nu}_\mu$ Effective area (solid angle averaged)



Transient cosmic sources

IceCube limit (Nature 484 (2012) 351)



- GRBs are not (the only) UHECR sources $\longrightarrow$ AGN ?

  Or : Efficiency of ν production lower than expected
- Models with standard parameters excluded by observations

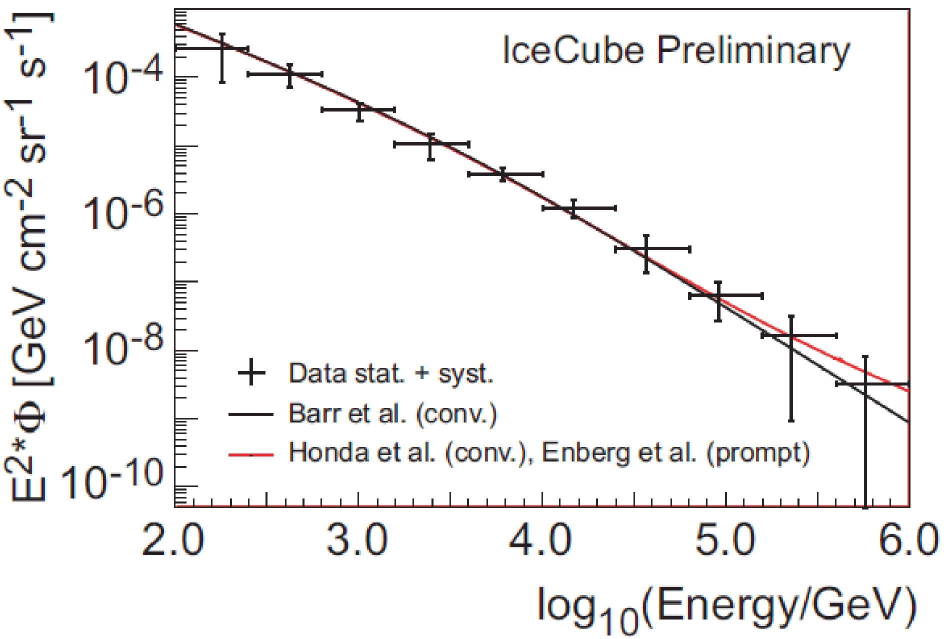
Search for a diffuse cosmic ν flux

- Many point sources : diffuse ν flux
  Expected flux $\sim E^{-2}$
  (Fermi shock acceleration)
  Observed in TeV photons
- CR primaries : flux $\sim E^{-2.7}$
  $\longrightarrow$ Calculate atm. ν E-spectrum
- IceCube observed atm. ν spectrum
  Validate calculated spectrum

$*$ PDF for atm. ν E-spectrum

- Energy determination is essential
  Require contained events

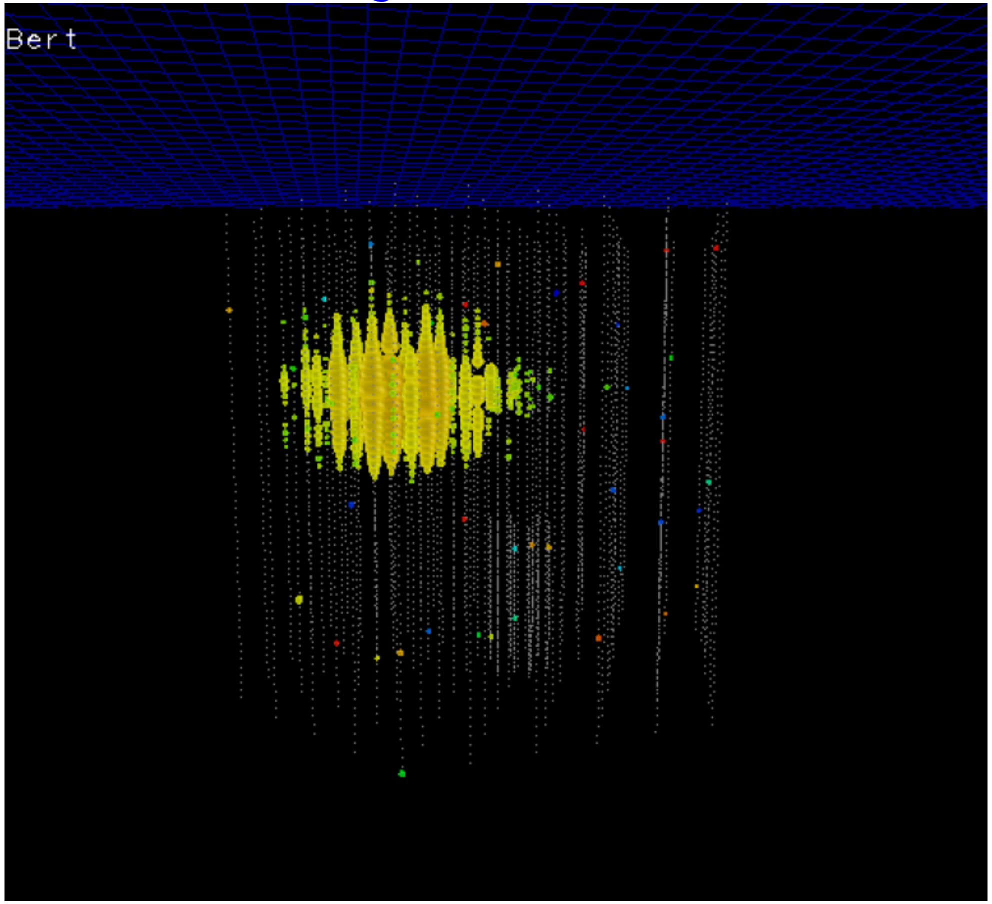
The atmospheric neutrino spectrum
(ICRC2013)



- Very high E : Nearly atm. bkg free
  0.1 atm. ν per year at 1 PeV
  EHE events might prove cosmic ν

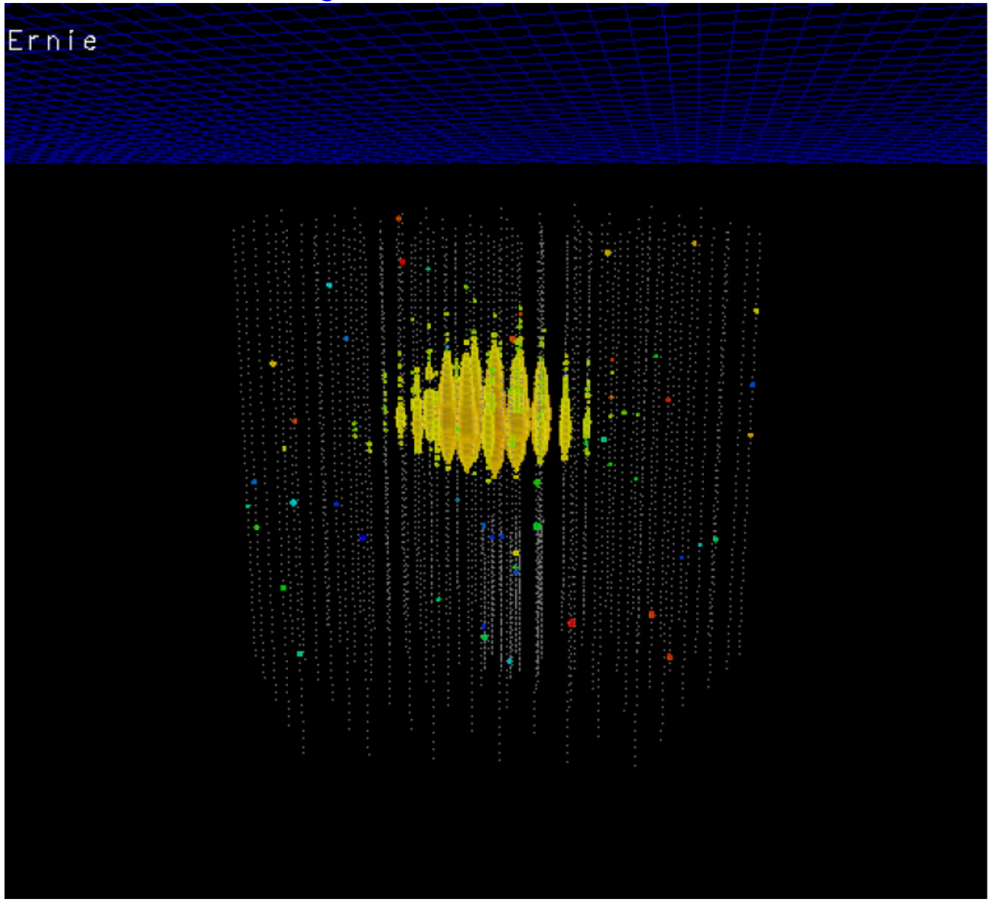
Search for a diffuse cosmic ν flux

Tue 09-aug-2011 07:23:18 UTC



1.04 ± 0.14 PeV

Tue 03-jan-2012 03:34:01 UTC



1.14 ± 0.14 PeV

Atmospheric ν background ?

P-value : $2.9 \cdot 10^{-3} \quad (2.8\sigma)$

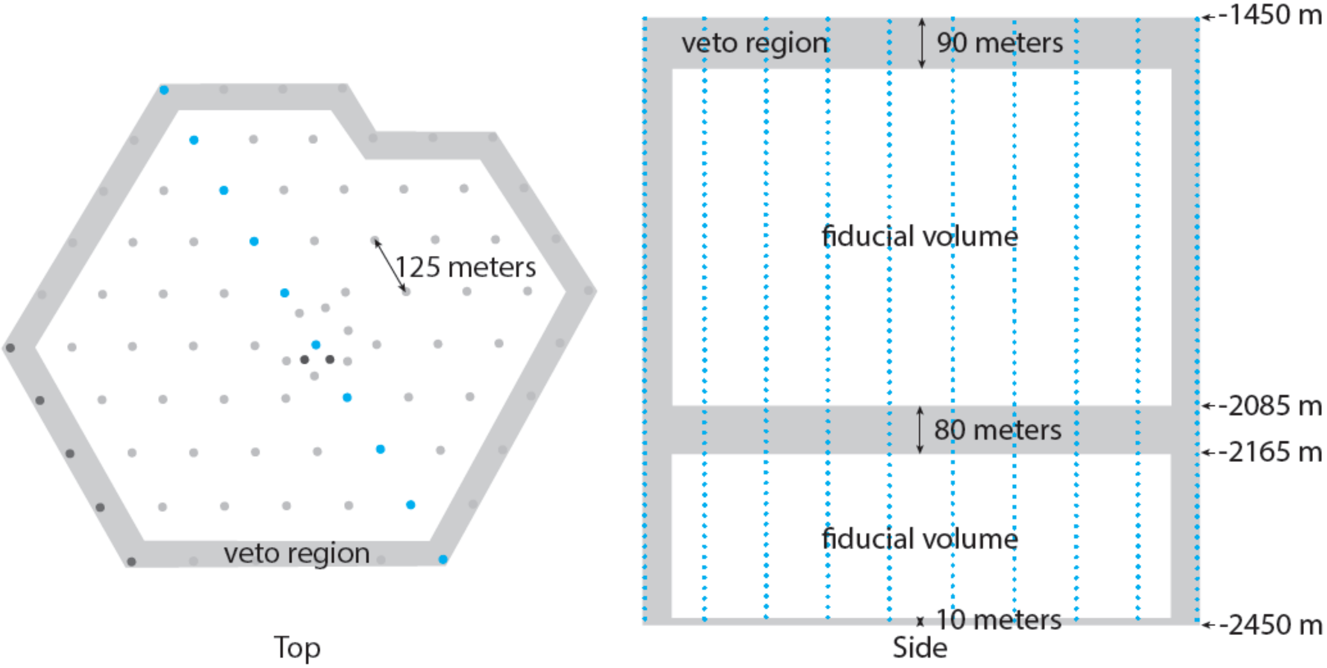
Search for a diffuse cosmic ν flux

Try to get more "Muppets in the basket"

- Perform a High-Energy Starting Event analysis (may 2010 — may 2013)

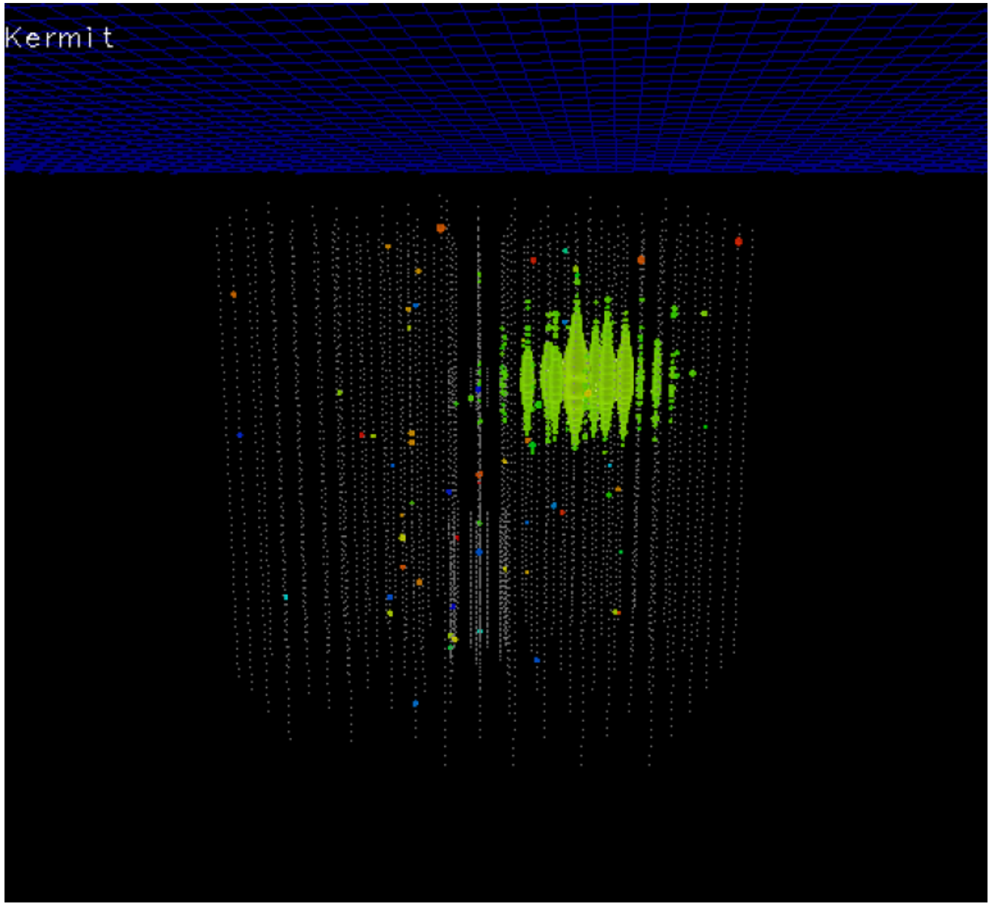
  Use event start veto criteria $\longrightarrow$ remove atm. bkg μ and ν (showers)

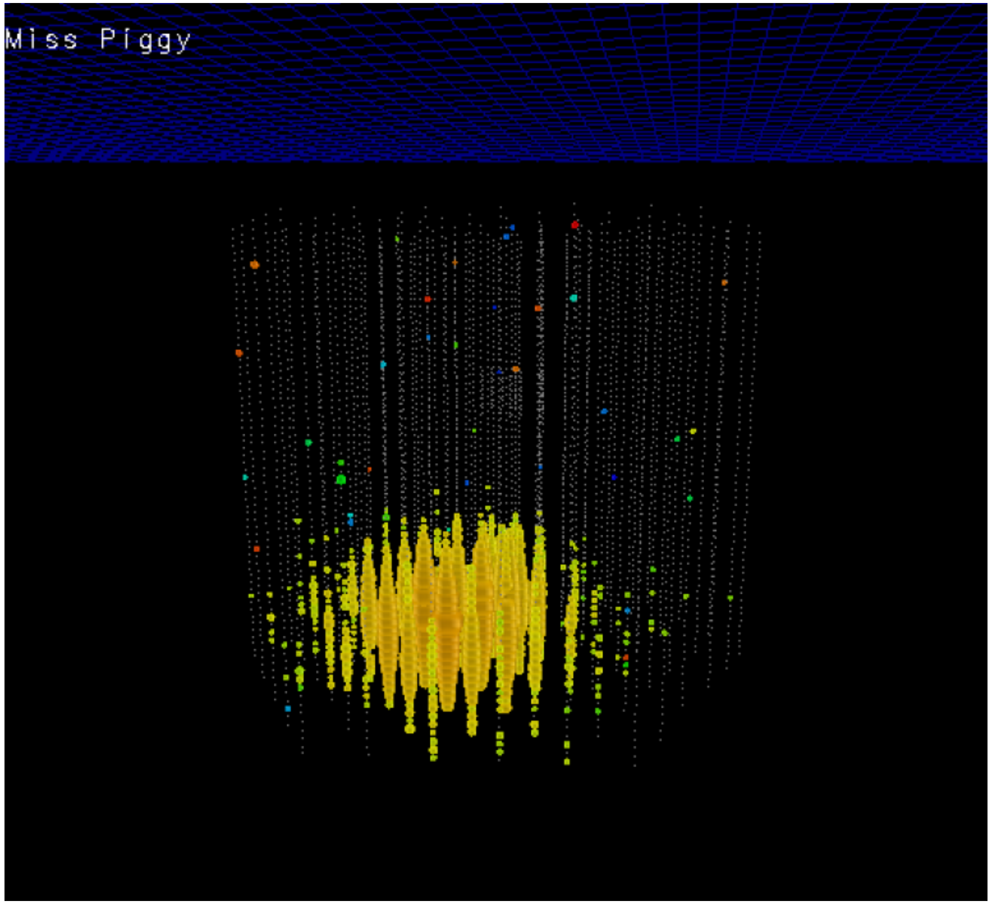
  Guarantees (contained) ν events and allows lower E cut $\longrightarrow 4\pi$



Search for a diffuse cosmic ν flux

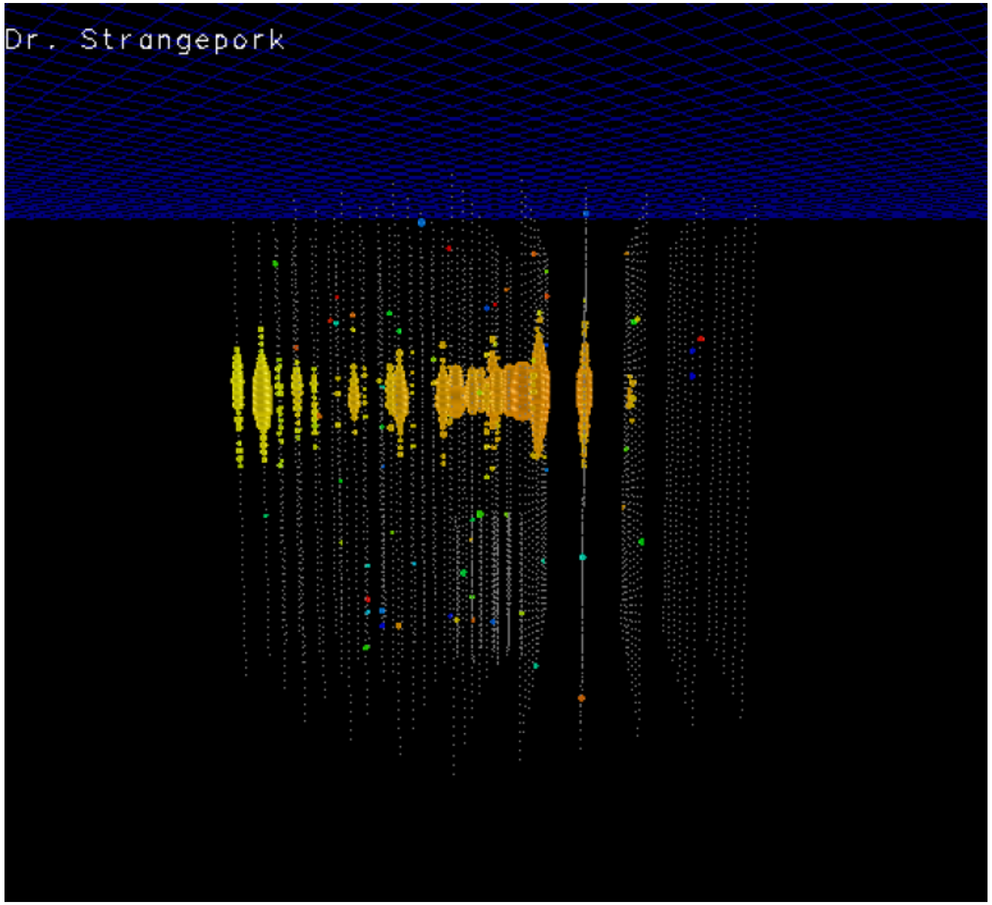
35 additional events were found

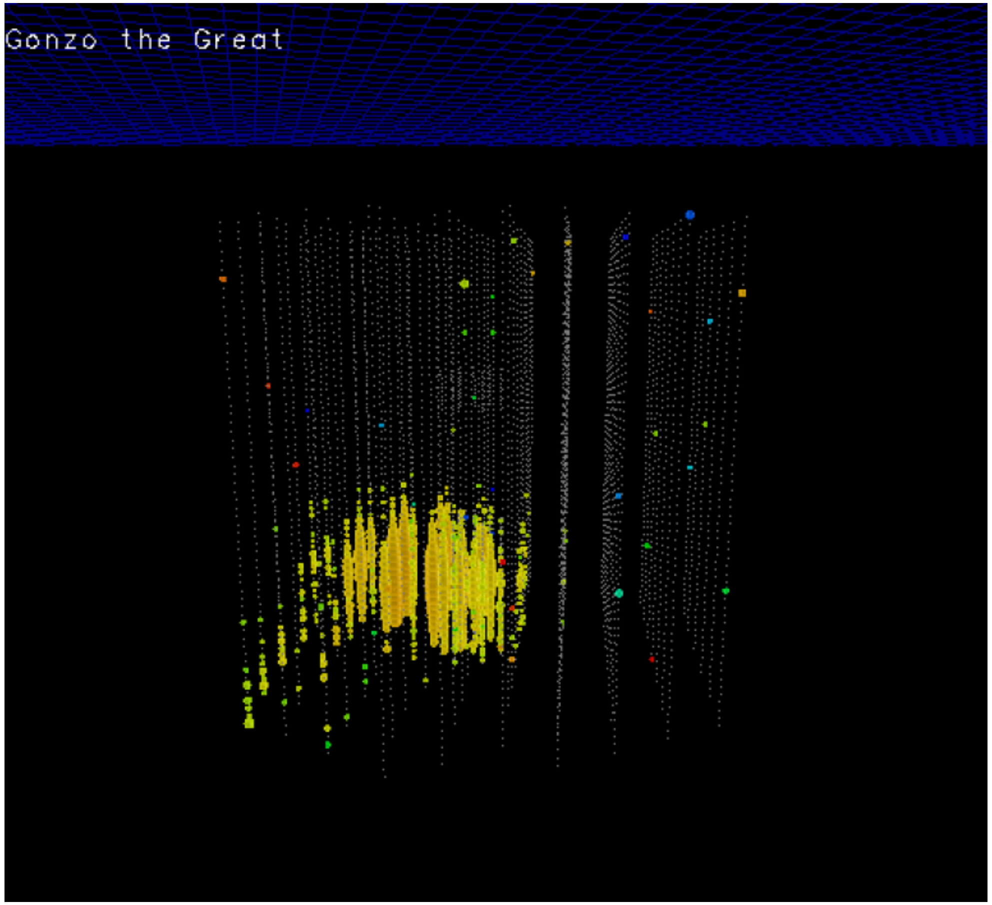




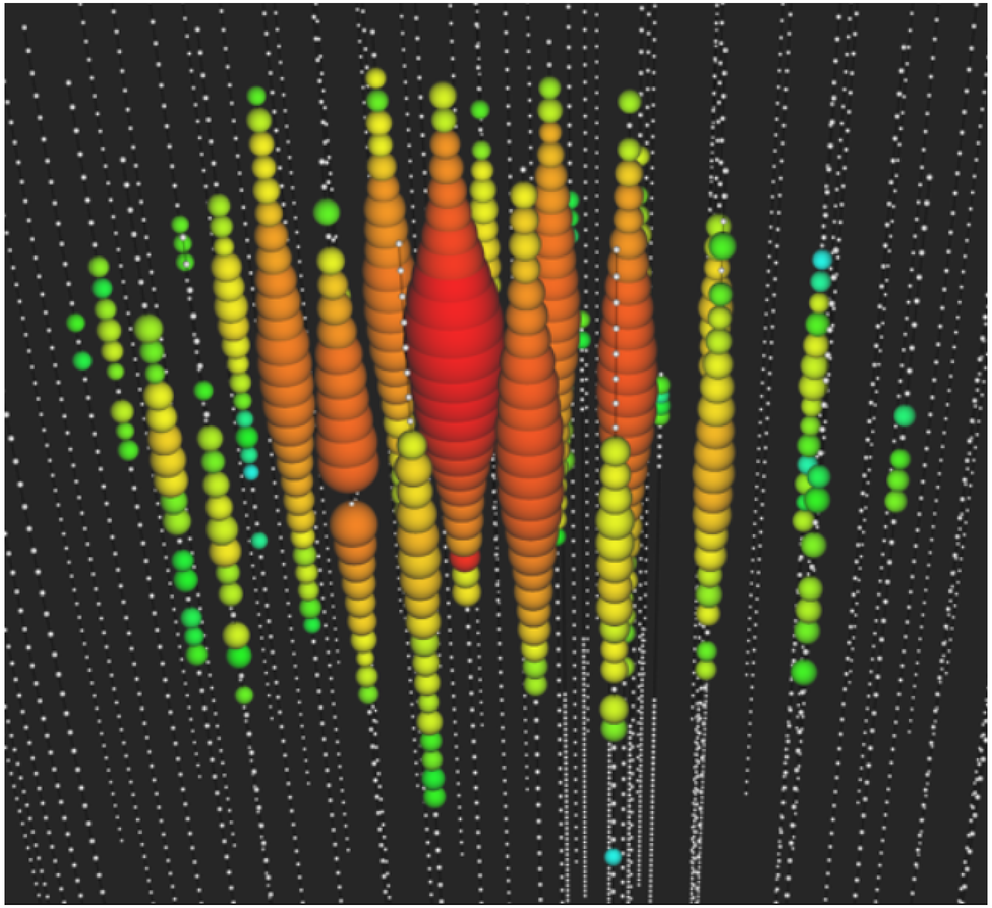
Search for a diffuse cosmic ν flux

Also some μ track signatures





Our current champion

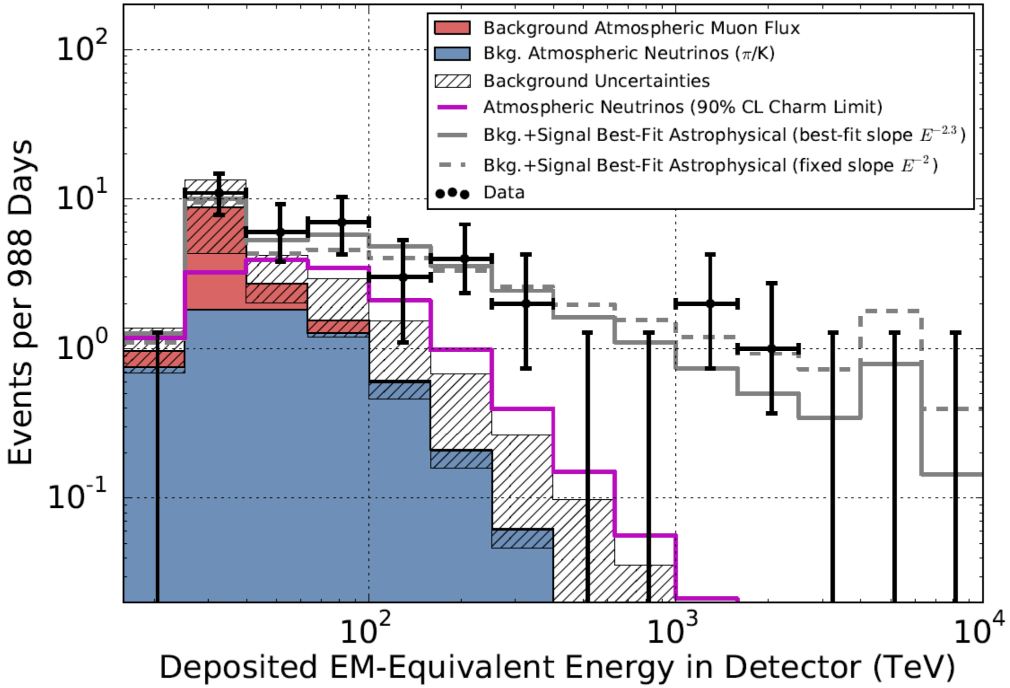


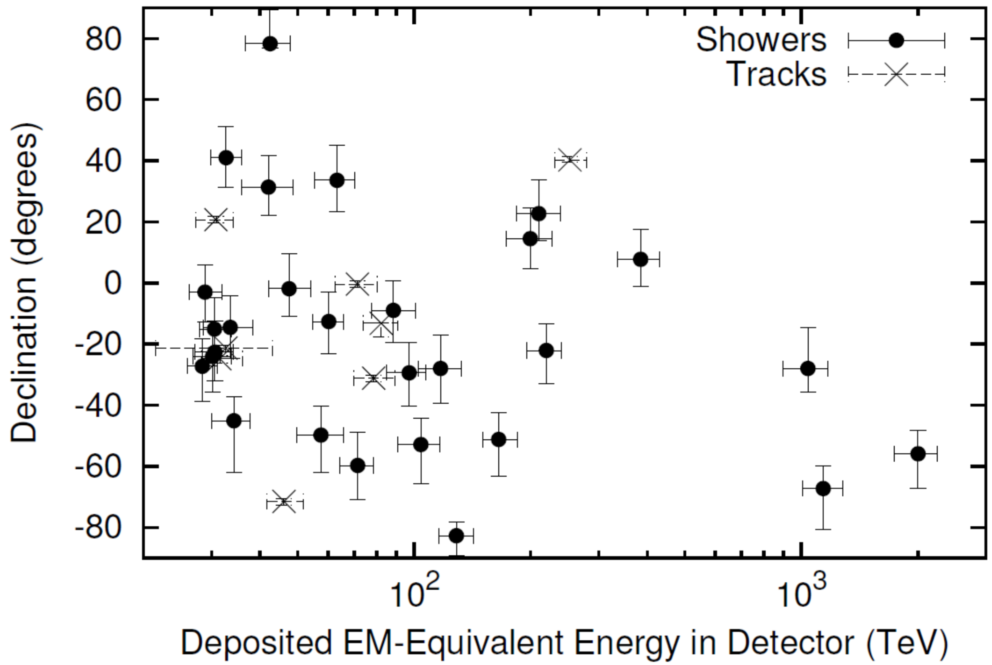
2.00 ± 0.25 PeV

Big Bird

Search for a diffuse cosmic ν flux

Energy distribution of the 37 events





Evidence for cosmic high-energy neutrinos

Search for a diffuse cosmic ν flux

physicsworld
BREAKTHROUGH OF THE YEAR 2013

Physics World Breakthrough of the Year 2013

The *Physics World* Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

This is to certify that the *Physics World* Breakthrough of the Year has been given to

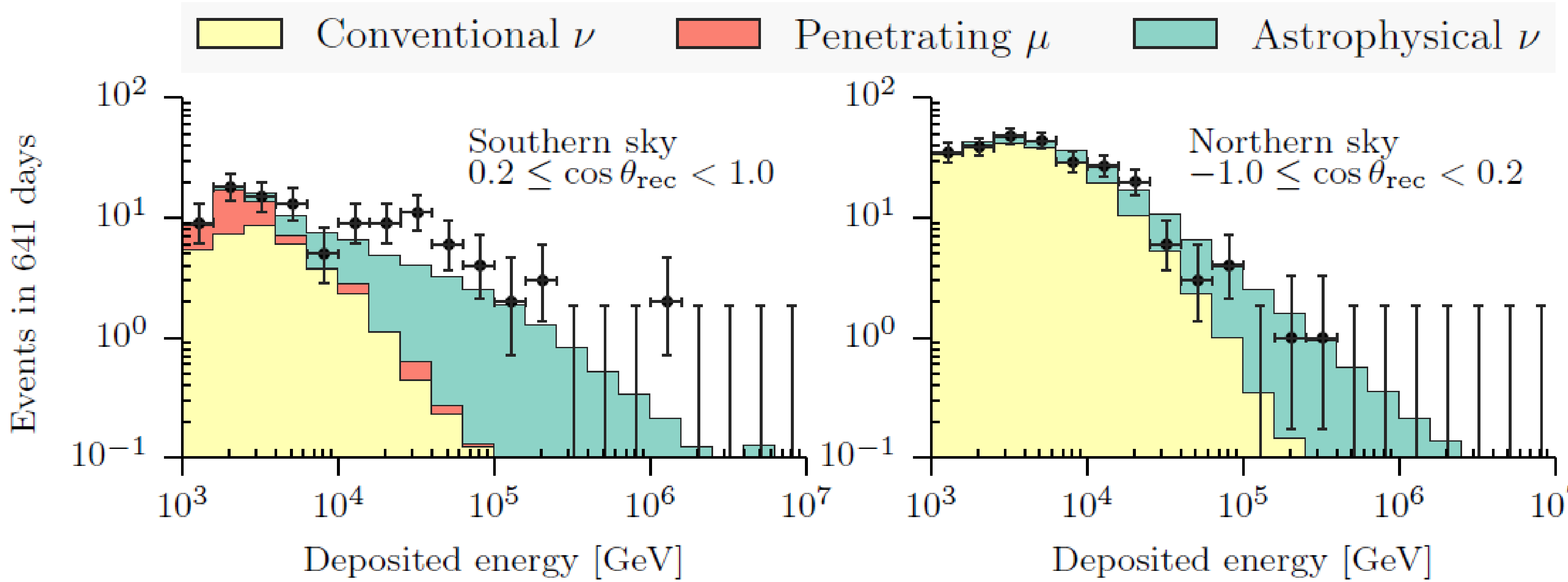
The IceCube South Pole Neutrino Observatory

for making the first observations of high-energy cosmic neutrinos

Search for a diffuse cosmic ν flux

Cosmic origin confirmed at lower energies

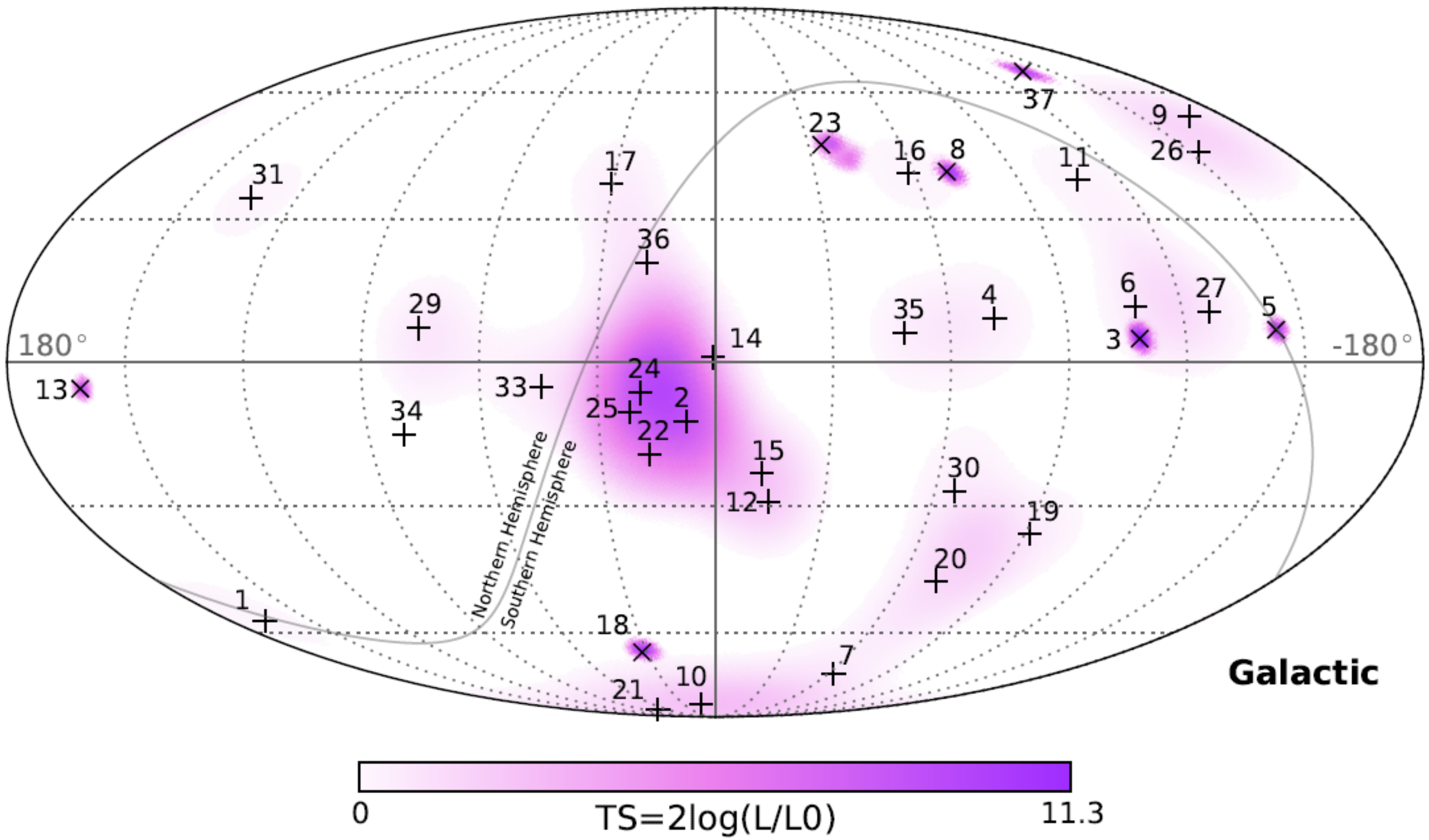
IceCube Preliminary



IceCube has raised the curtain for Neutrino Astronomy

Search for a diffuse cosmic ν flux

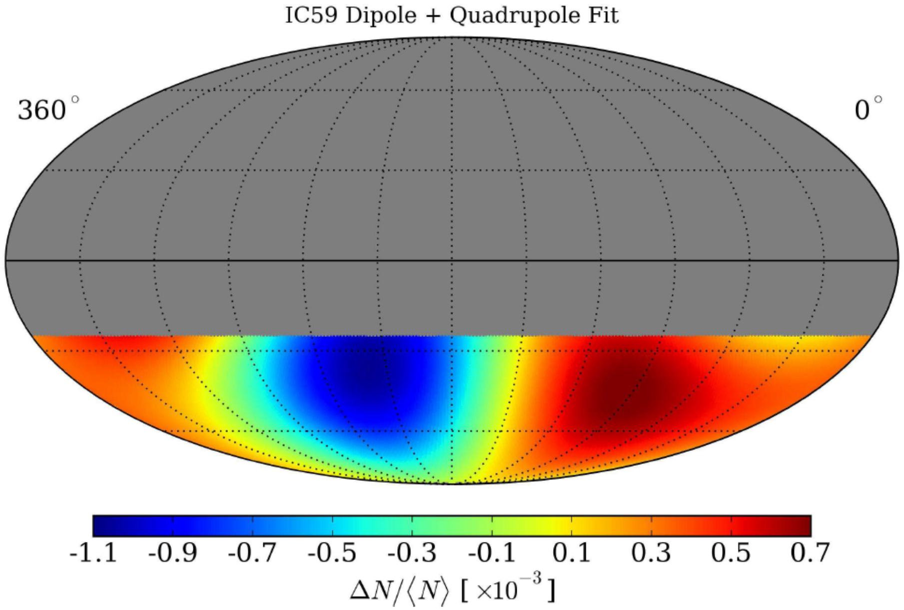
Source directions of the 37 events



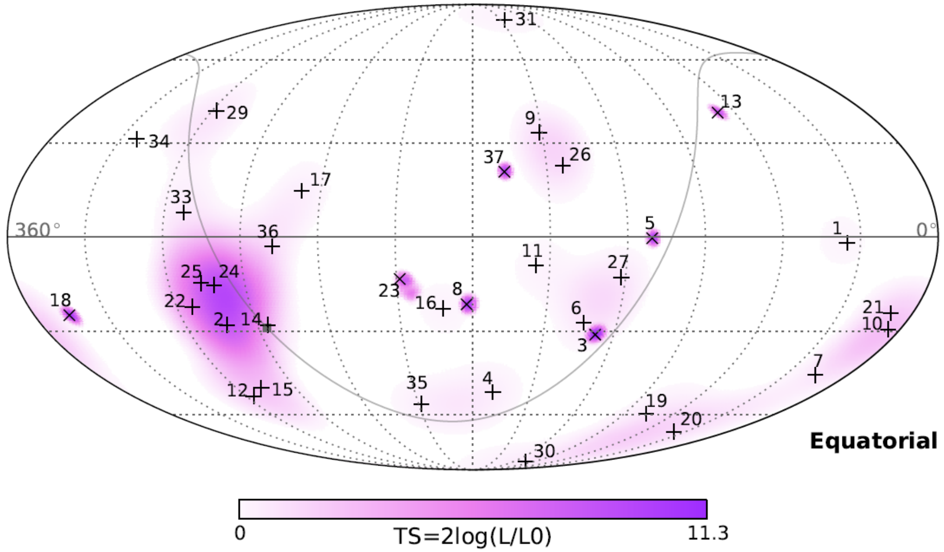
No evidence for point source(s)

Search for a diffuse cosmic ν flux

The IceCube observed CR anisotropy (ApJ 740 (2011) 16)



The skymap of our 37 events



Investigating correlations might become interesting

Outlook for Astroparticle Physics

The curtain has been raised for Neutrino Astronomy

Let the show begin !