Cosmic Rays and Gamma Ray Bursts

Nick van Eijndhoven

nick@icecube.wisc.edu http://www.iihe.ac.be

Vrije Universiteit Brussel - IIHE(ULB-VUB)
Pleinlaan 2, B-1050 Brussel, Belgium

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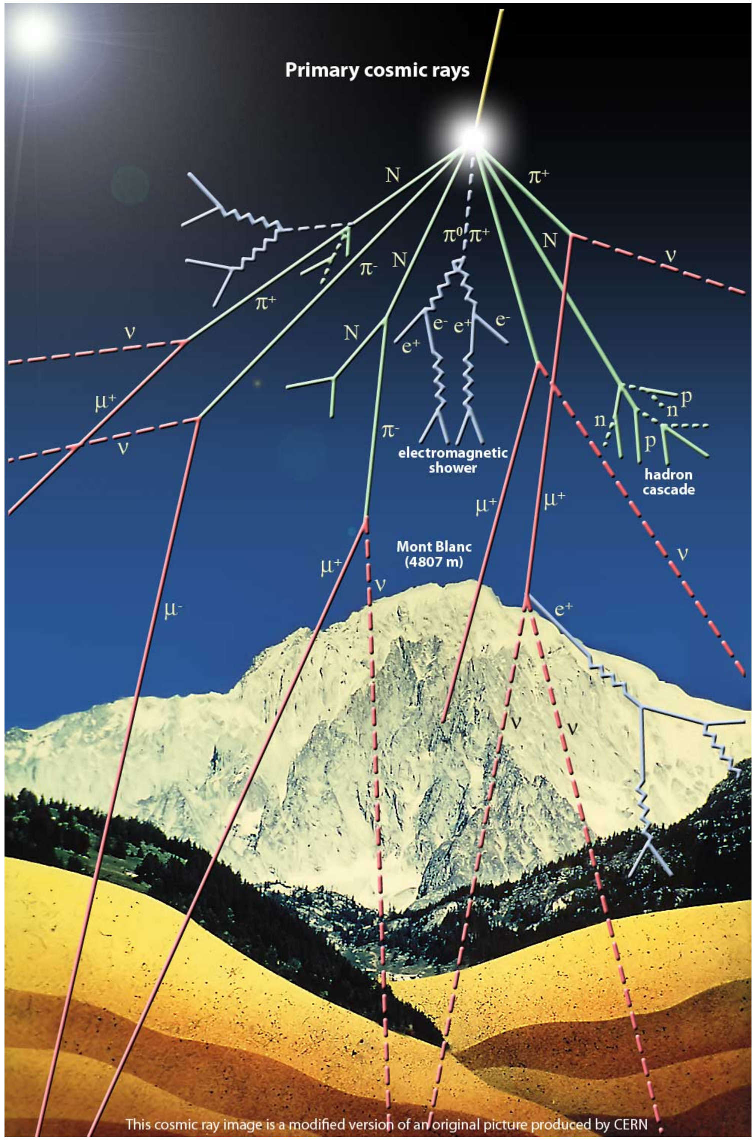
Cosmic rays



- Observations :

  Charge leaks slowly from capacitors

  Effect is smaller when shielded

- Idea :

  Air gets ionised by charged particles

- Where do these particles come from ?

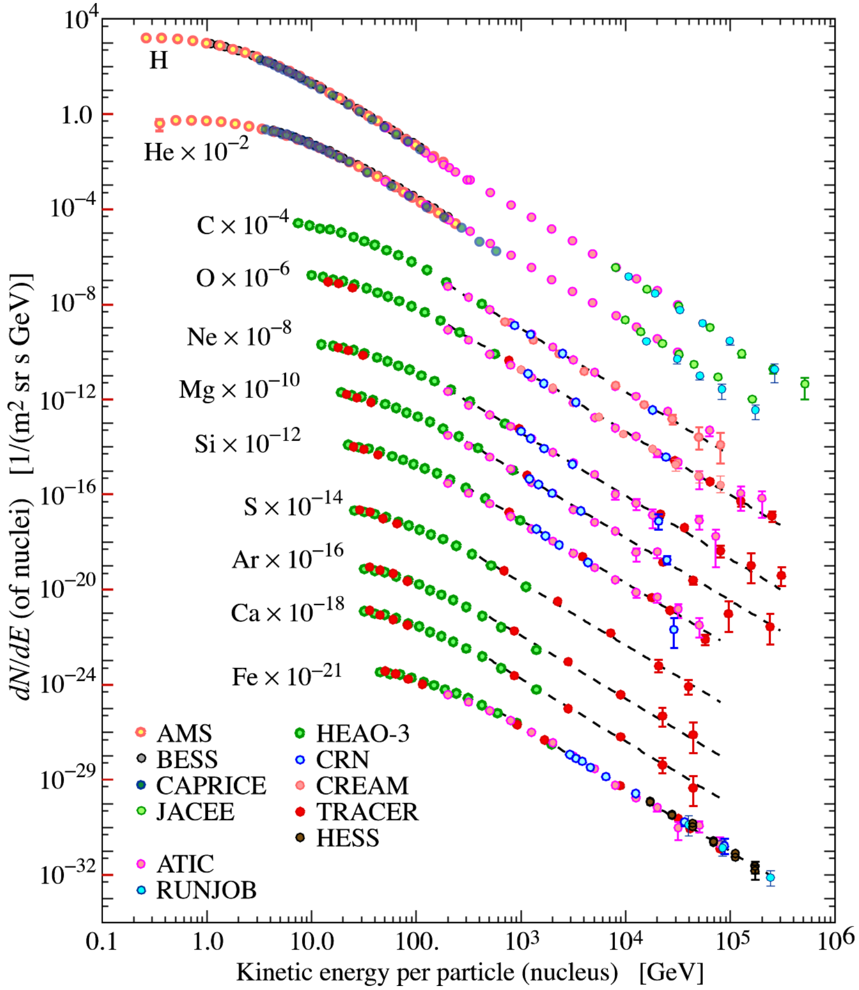
  From outer space (Hess 1912)

- What sort of particles are these ?

  Cosmic ray experiments

Cosmic rays

Cosmic ray spectra



Below 10 GeV $\rightarrow$ Solar modulation

At higher energies we observe

- Proportions of major components relatively constant with energy
- $\frac{dN}{dE} \propto E^{-2.6}$
- Boron spectrum falls steeper

  B is a spallation product of C and O

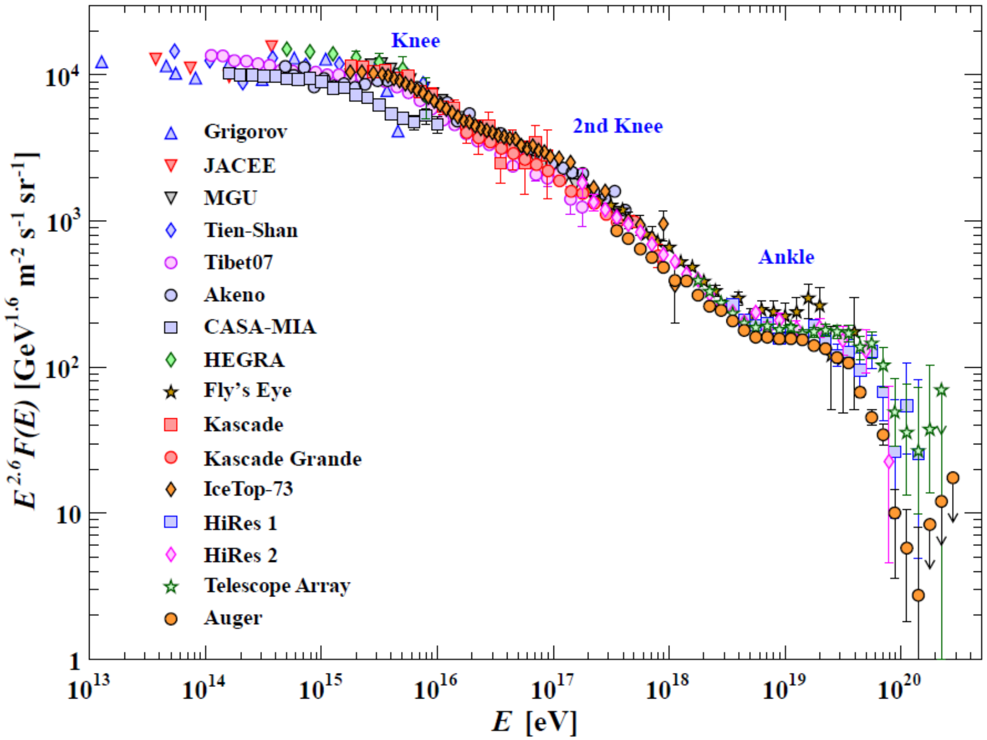
  Secondary (e.g. spallation) nuclei steeper than primaries
- sec./prim. decreases as energy increases

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

What is the maximum energy ?

Cosmic rays

$E^{2.6}$ 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 $v > v_{sound}$

  $\rightarrow$ 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

  $\rightarrow$ process may be repeated

- Multy-step particle acceleration

  Start energy E_0 and escape prob. P_{esc}

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

  $\rightarrow n = \frac{\ln(E/E_0)}{\ln(1+\alpha)}$ 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 $\beta = \frac{-\ln(1-P_{esc})}{\ln(1+\alpha)} \approx \frac{P_{esc}}{\alpha}$

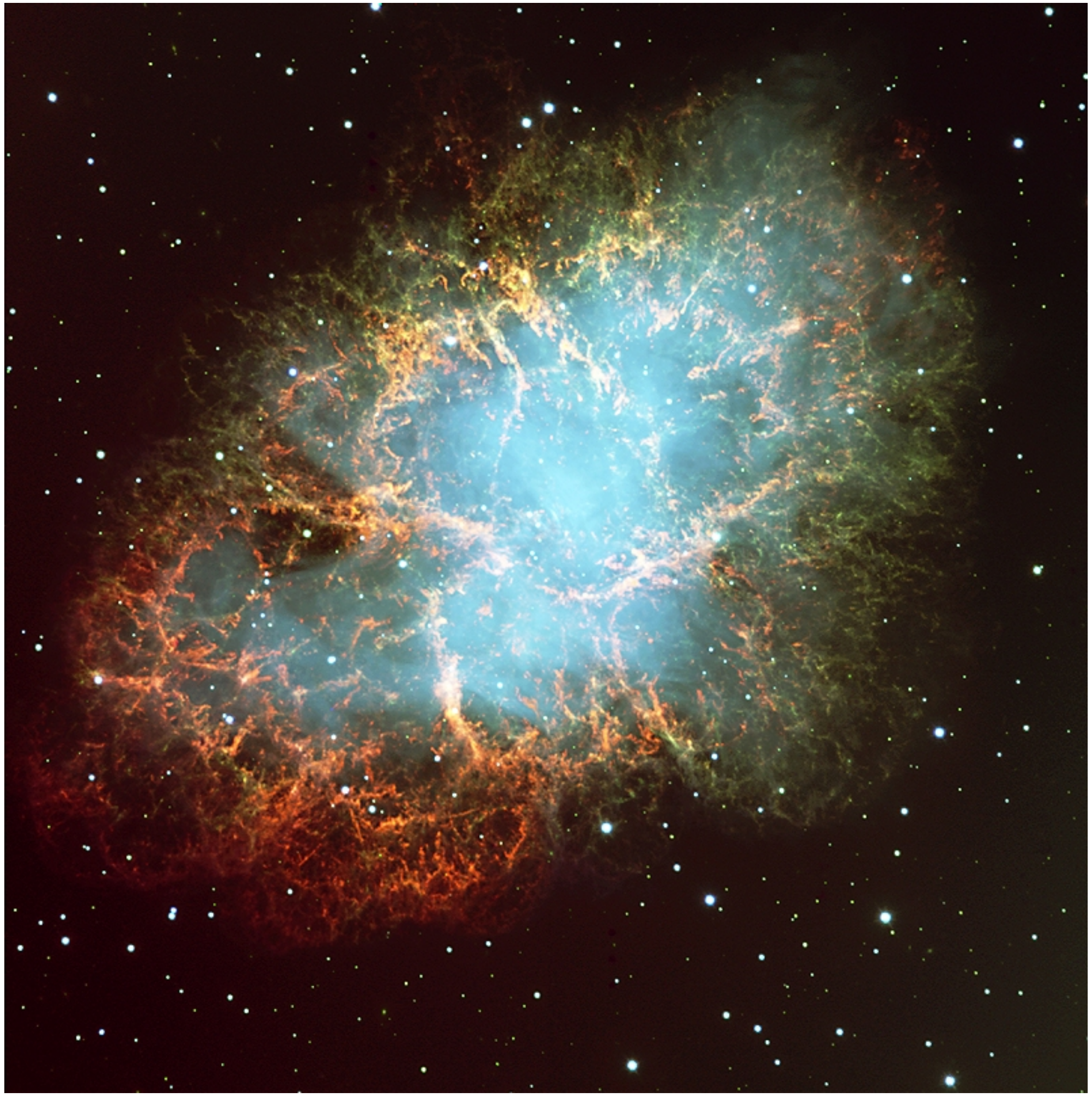
Indeed a powerlaw spectrum is obtained !

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

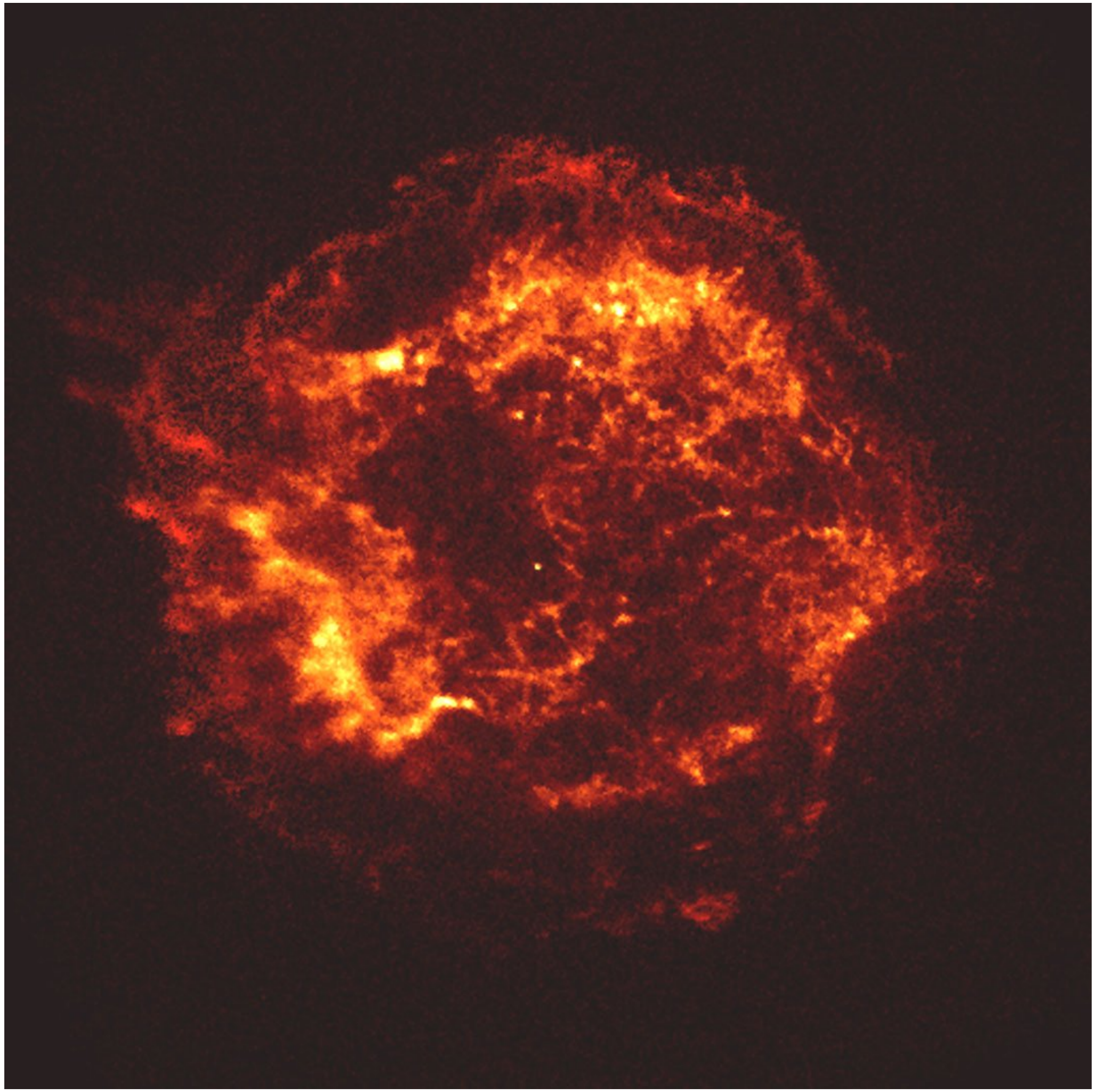
Spectral slope $\beta \propto (\sigma \cdot \text{density})^{-1}$

Where do we find shock waves ?

Cosmic rays



Cosmic rays



Cosmic rays

Origin of cosmic rays

- Supernova blast waves

  Moving charge in static mag. field

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

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

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

- Accelerator of size R

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

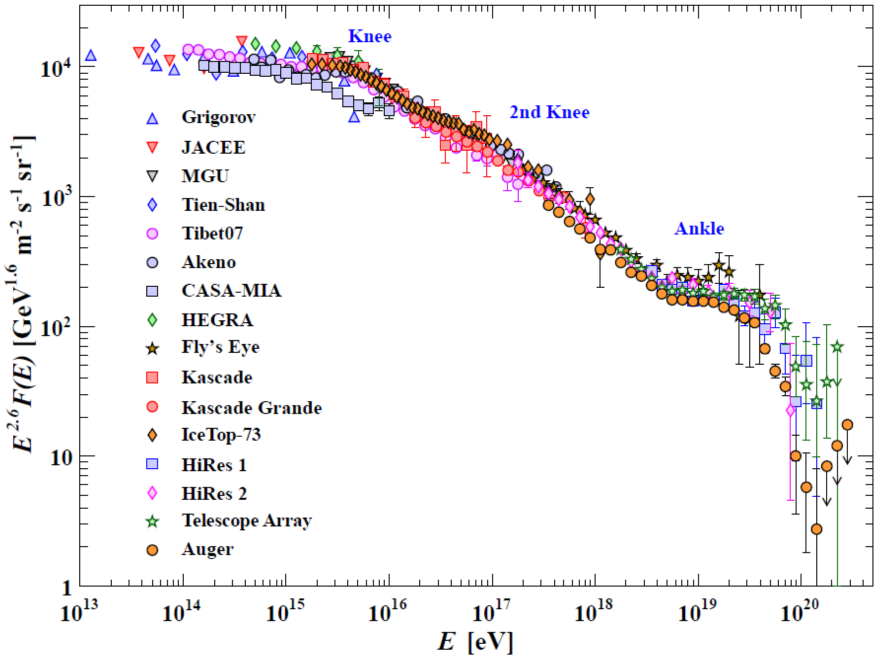
  Typical : $B \approx \mu$G $\quad R \approx 3 \cdot 10^{16}$ m

  $\rightarrow$ 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 ?

New cosmic sources ?

Do we see the GZK effect above 10^{19} eV ?

Cosmic rays

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 $\rightarrow \mu$, ν_μ
  4. Even later : μ decays $\rightarrow e$, ν_e, ν_μ

  With increasing primary E

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

  $\rightarrow N_e/N_\mu$ 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. $E \rightarrow N_\mu \propto A^\alpha \, N_e$

  - Heavy primaries $\rightarrow$ Muon rich showers
    Set scale limits by p and Fe
  - N_e/N_μ (and D_{max}) $\rightarrow A \rightarrow E$

  Quantitative analysis $\rightarrow$ MC needed

- Large discrepancies between various models

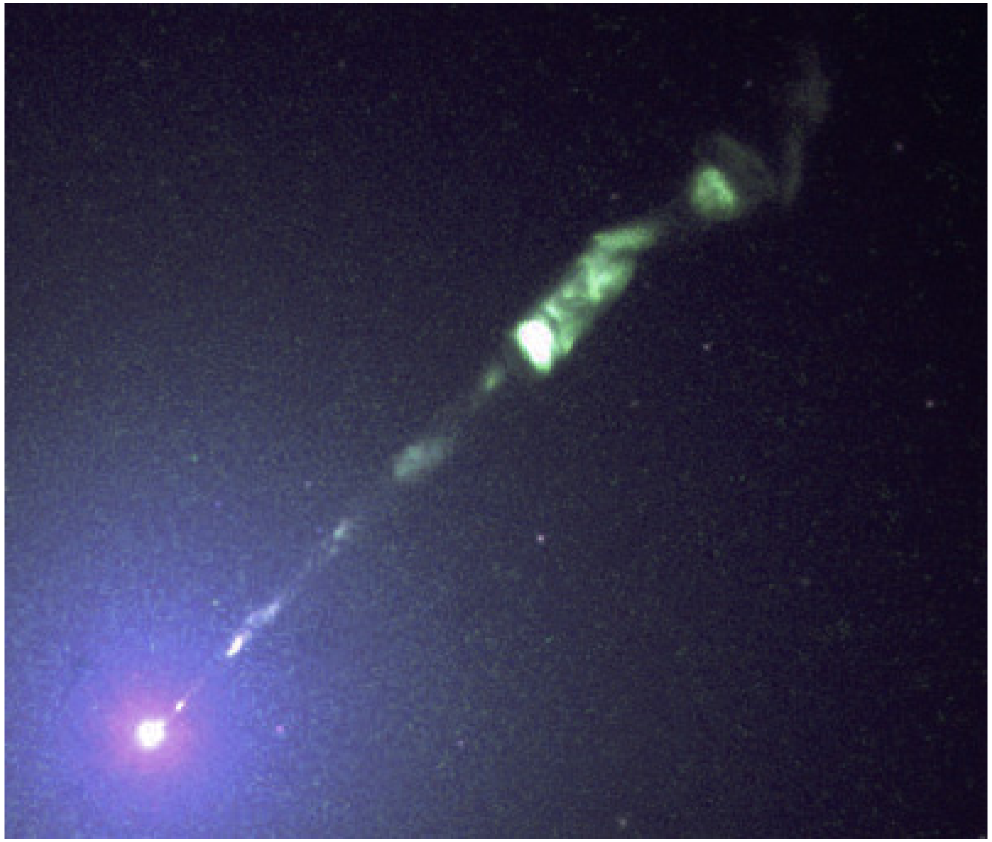
  Data needed to validate/tune models

  - CERN-LHC might provide insight here

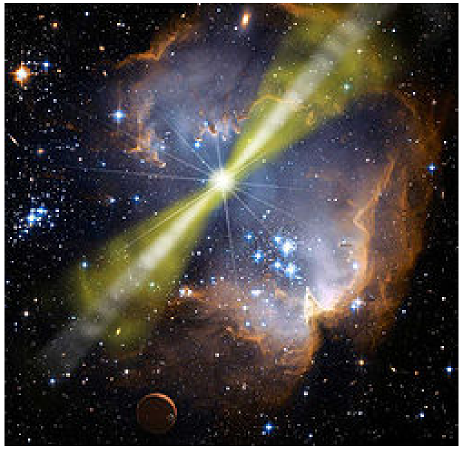
  Physics $E(Z)$ or cascade $E(A)$ effect ?

Possible high-energy sources

Active Galactic Nuclei (AGN)



Gamma Ray Bursts (GRBs)



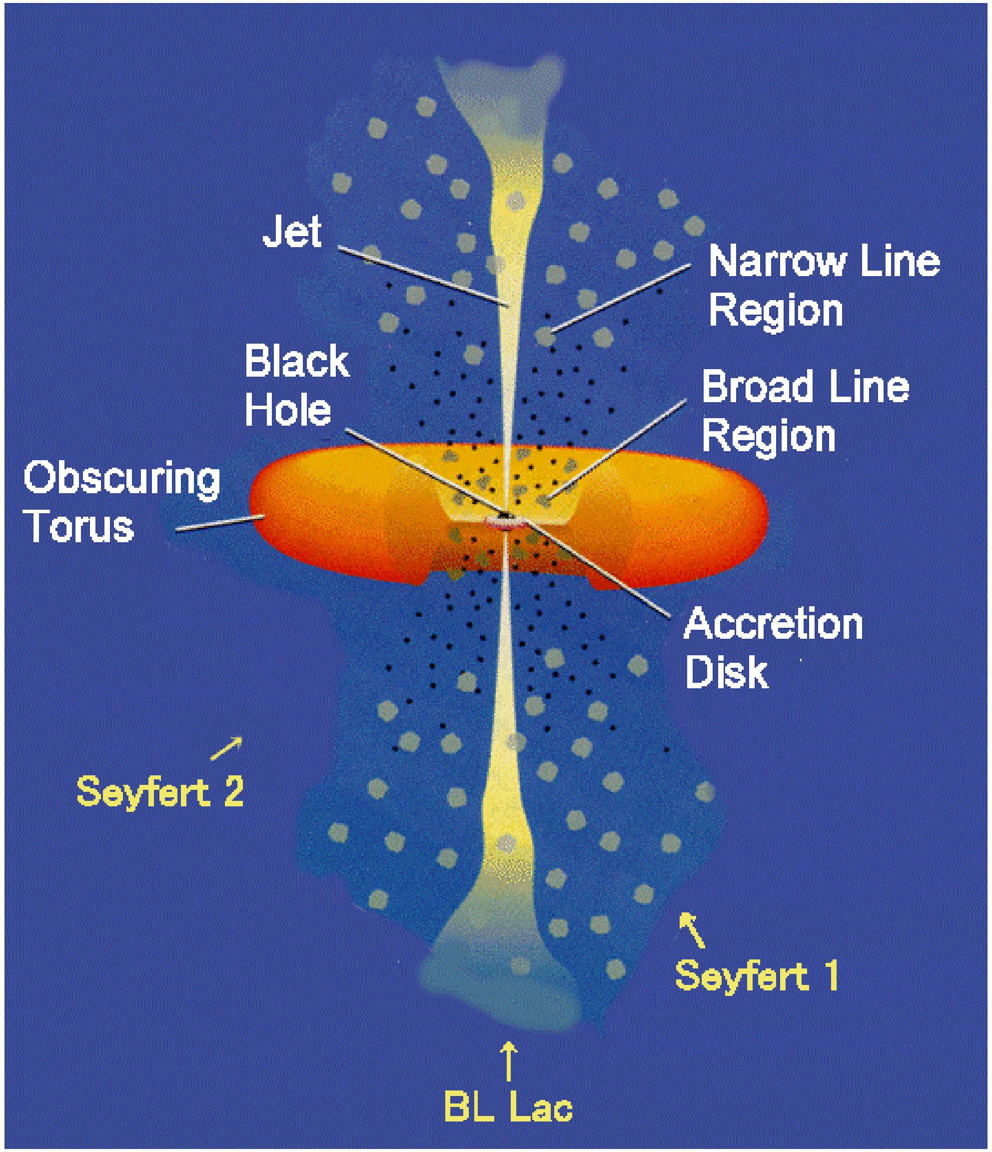
Possible high-energy sources

- ➤ 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

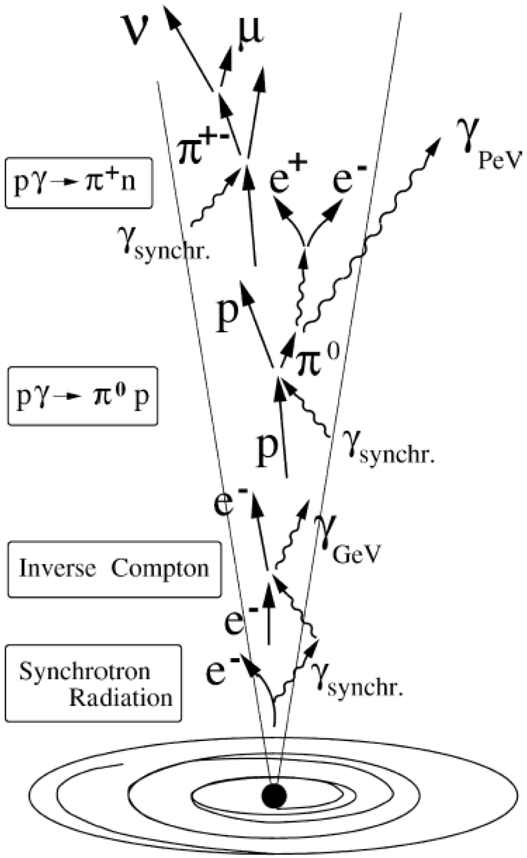
Can GRBs produce the flux at the ankle ?

Waxman&Bahcall PRL 78 (1997) 2292

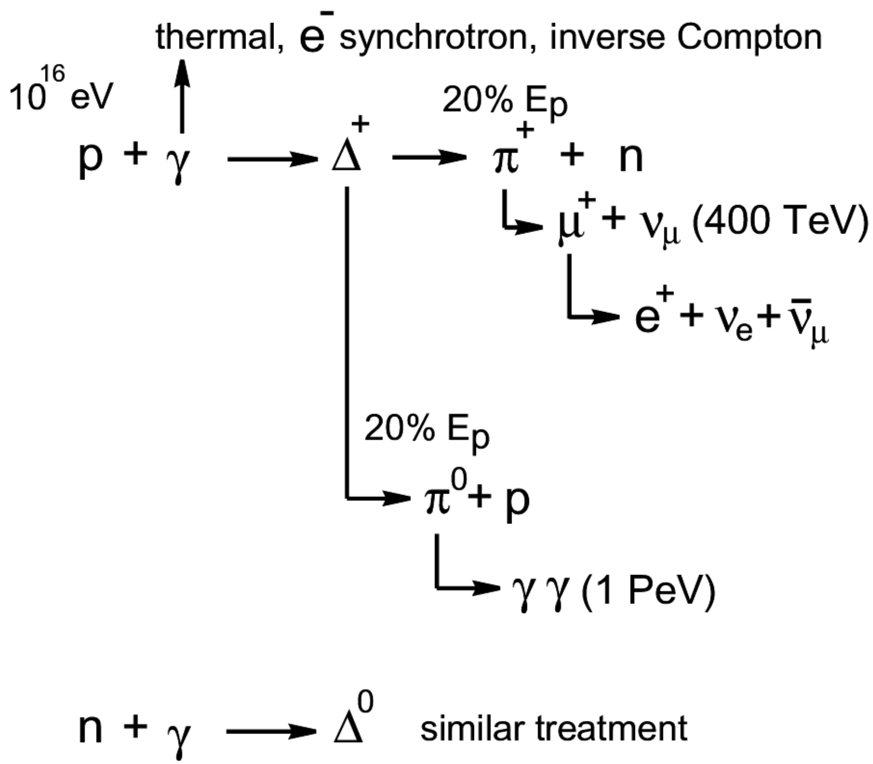


Possible high-energy sources

Processes in the jet



Neutrino production mechanism

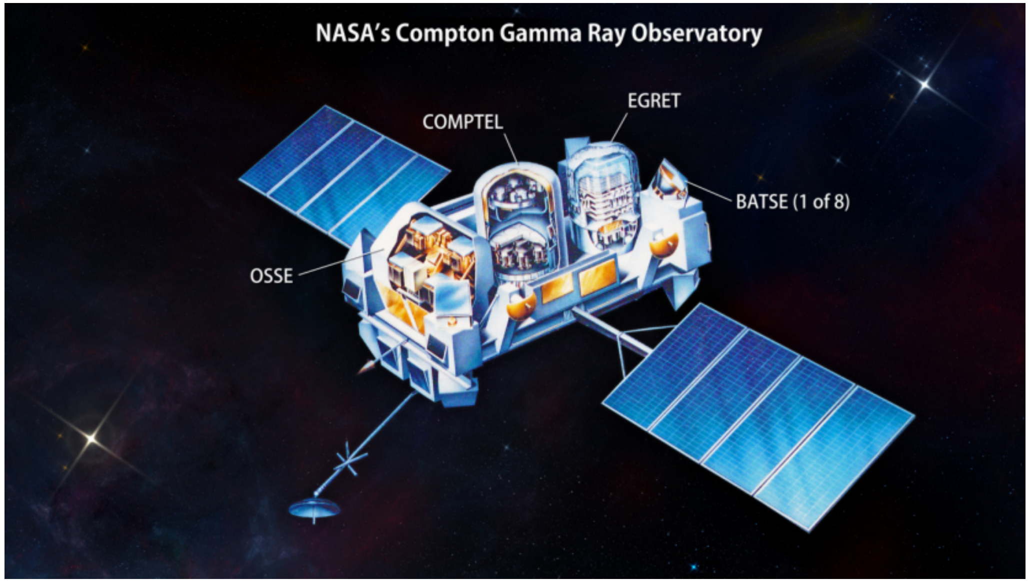


Can this GRB fireball model be probed ?

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 ?

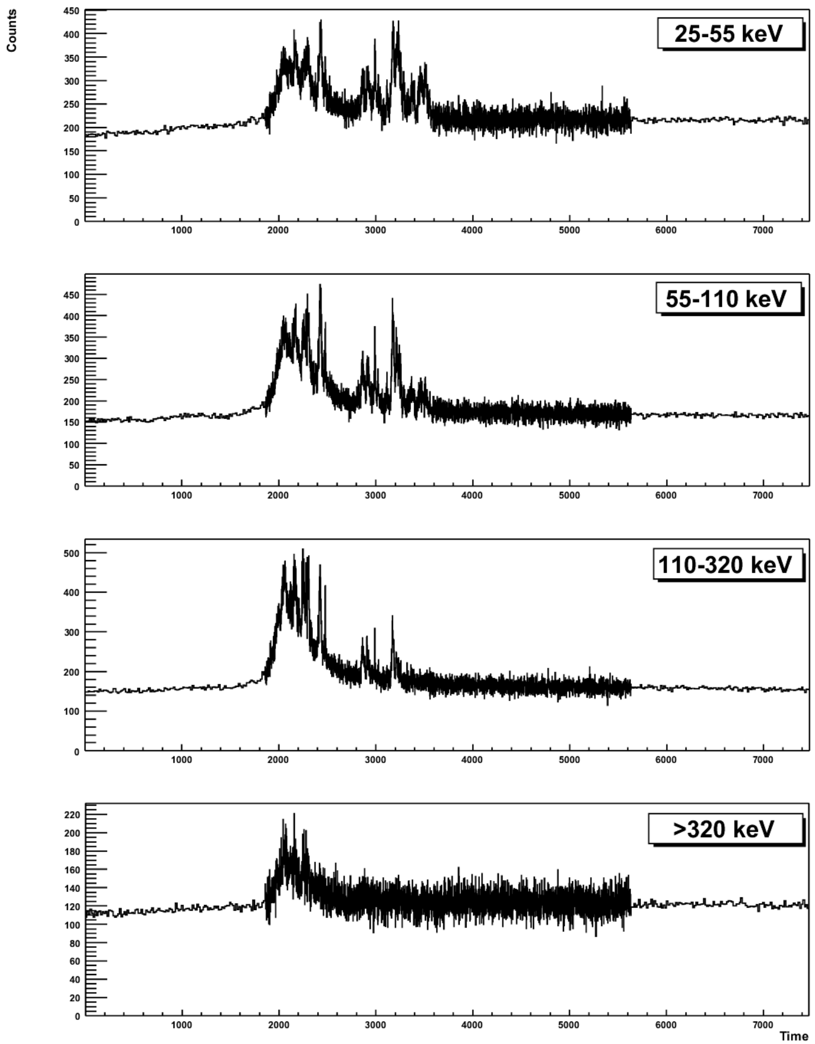
in other words :

Can we indicate hadronic processes in these objects ?

Even more violent transient phenomena are observed ...

Observation of high-energy photons

Batse GRB trigger 109



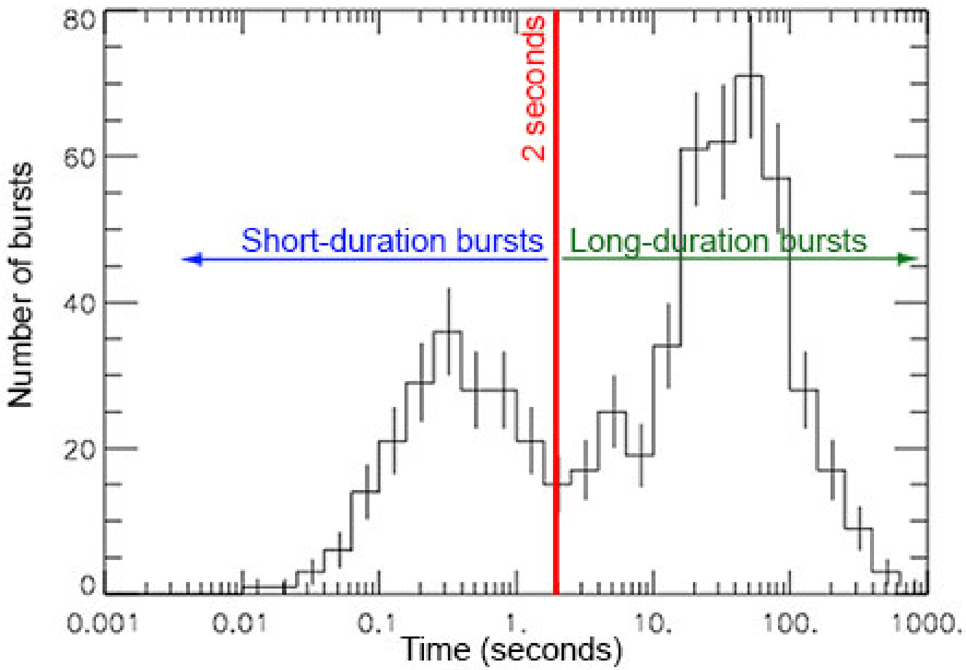
- Burst lasts ∼2 minutes
- Rich (energy dependent ?) structure
  - Rather compact source involved
  - Process might consist of several phases
    Various shock waves ?

What are these GRBs ?

- Common features ?
- Where are they located ?

Observation of high-energy photons

Burst duration analysis

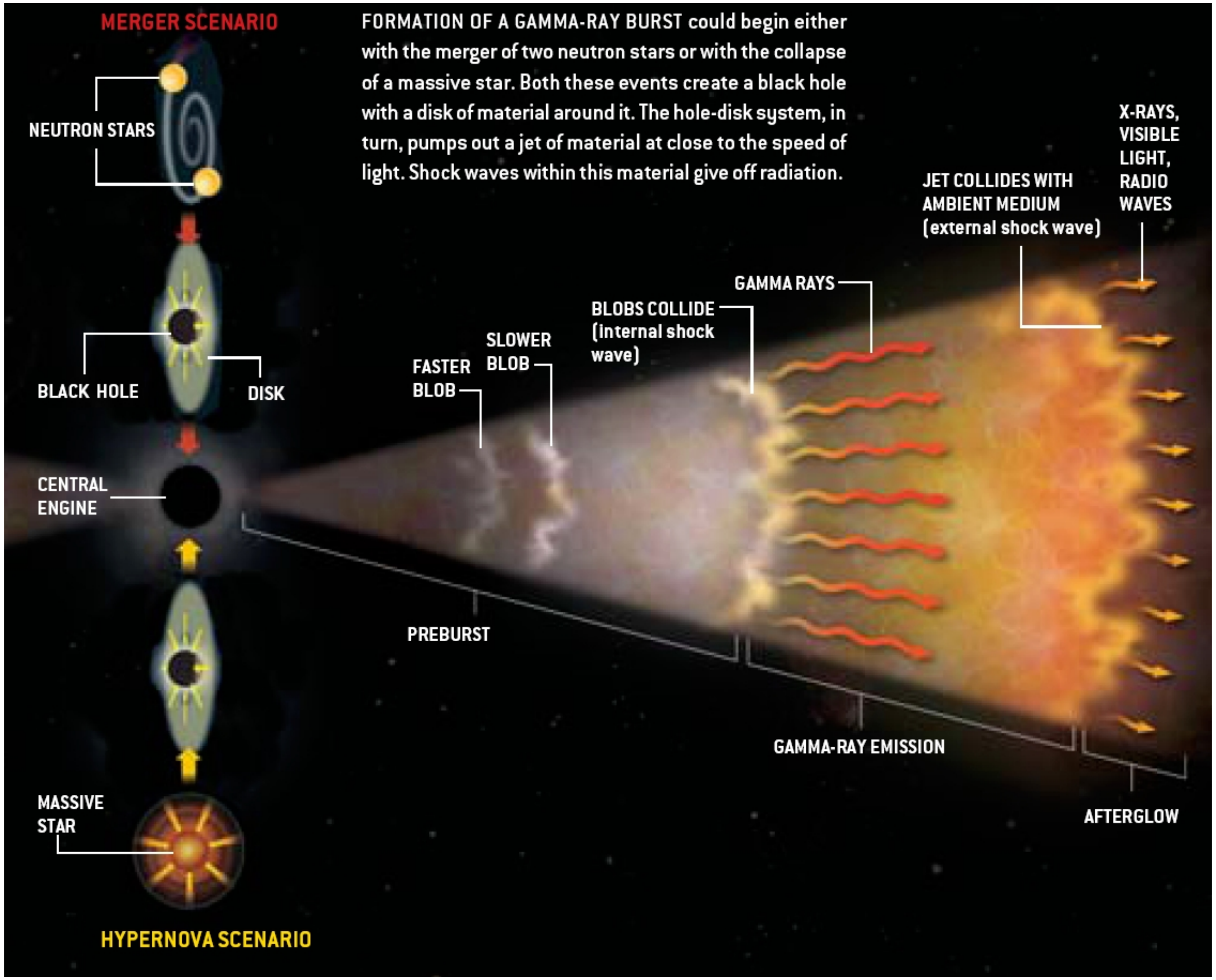


- t90 $\equiv \Delta t$ from 5% to 95% of fluence
- Two classes : short and long bursts ?
  - Long : dense medium (hypernovae ?)
  - Short : dilute medium (mergers ?)

Effect of (cosmological) time dilation ?

Observation of high-energy photons

Possible GRB scenarios



Multi-Messenger studies may provide insight in the various processes

Observation of high-energy photons

- GW170817: a NS-NS merger

  $M_1 \approx 1.2 M_\odot \quad M_2 \approx 1.5 M_\odot$

  $D \approx 40$ Mpc
- Weak, short GRB was observed

  Location coincidence

  GRB $\sim$1.7 sec. after the GW

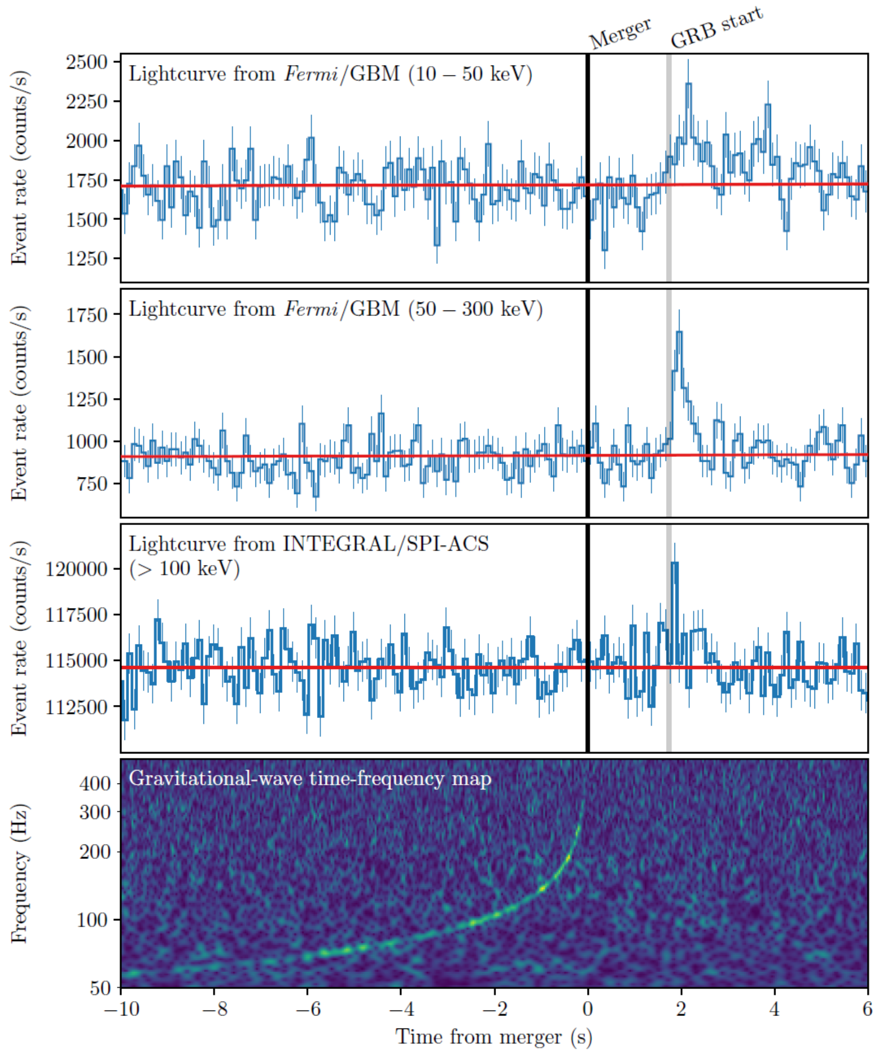
  Confirmed sGRB progenitor scenario
- GW provides a good T_{start}

  Nice for Multi-Messenger studies
- Observation of GW counterparts

  Exploration of source evolution

  Independent proof of GR ?

  Discover new phenomena ?

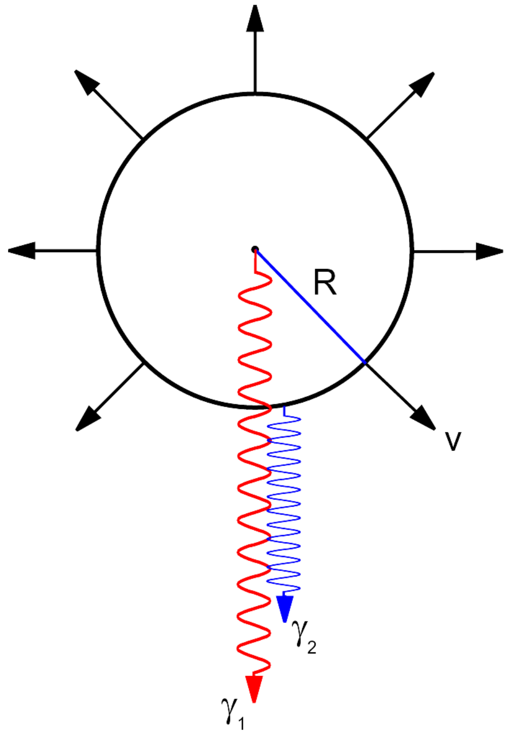


[ApJ Let. 848 (2017) L13]

Observation of high-energy photons

Time spectrum analysis

Possible source of time structure



- If distance r can be determined (see later)
  $\rightarrow$ (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

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

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

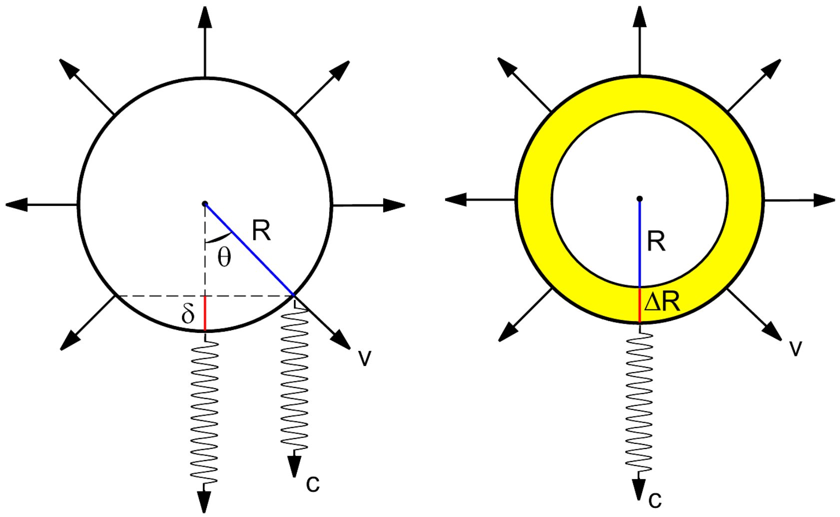
  Origin of the various spectral peaks ?

- Characteristic size R ?

  Would allow determination of γ factor

Observation of high-energy photons

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 ($\gamma \gg \Gamma$)

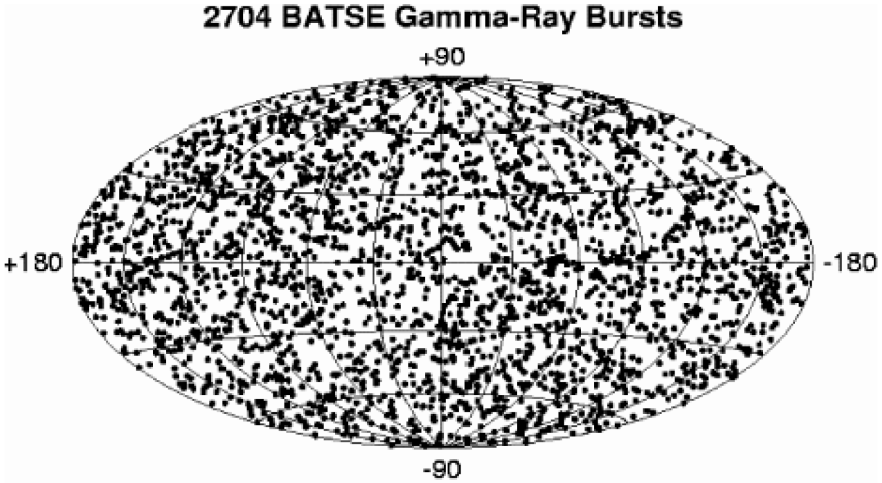
$$R^* = \Gamma R \qquad \Delta R^* = \gamma \Delta R$$

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

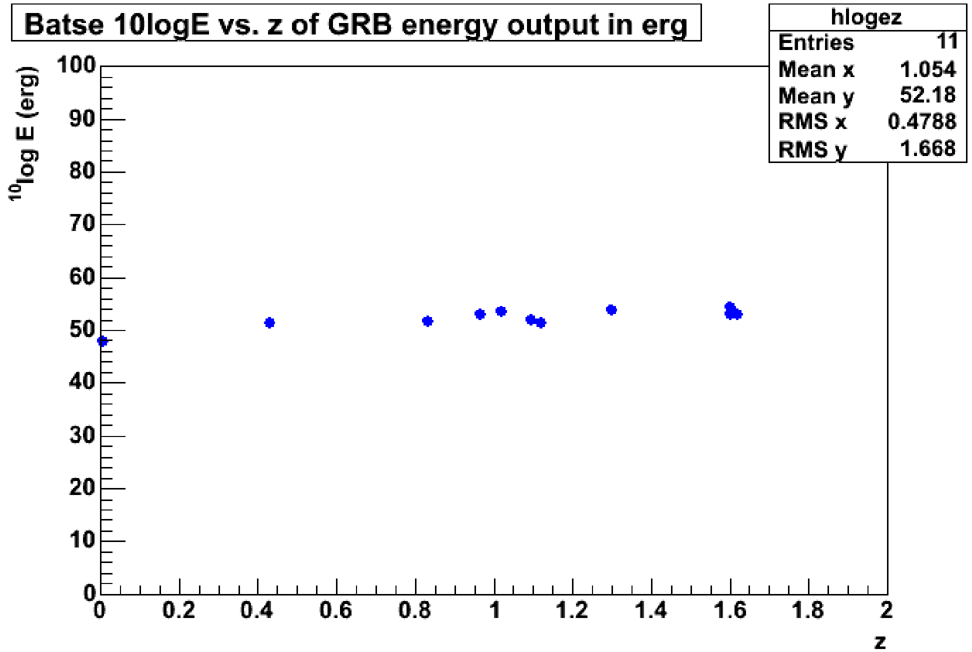
- Origin of the width of the peaks ?

Observation of high-energy photons

Burst location analysis



z and Batse fluence yield total E



- No concentration along galactic plane

  $\rightarrow$ Sources of cosmological origin

  Confirmed by afterglow (z values)

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

  $\rightarrow \beta = \frac{(1+z)^2-1}{(1+z)^2+1}$ 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

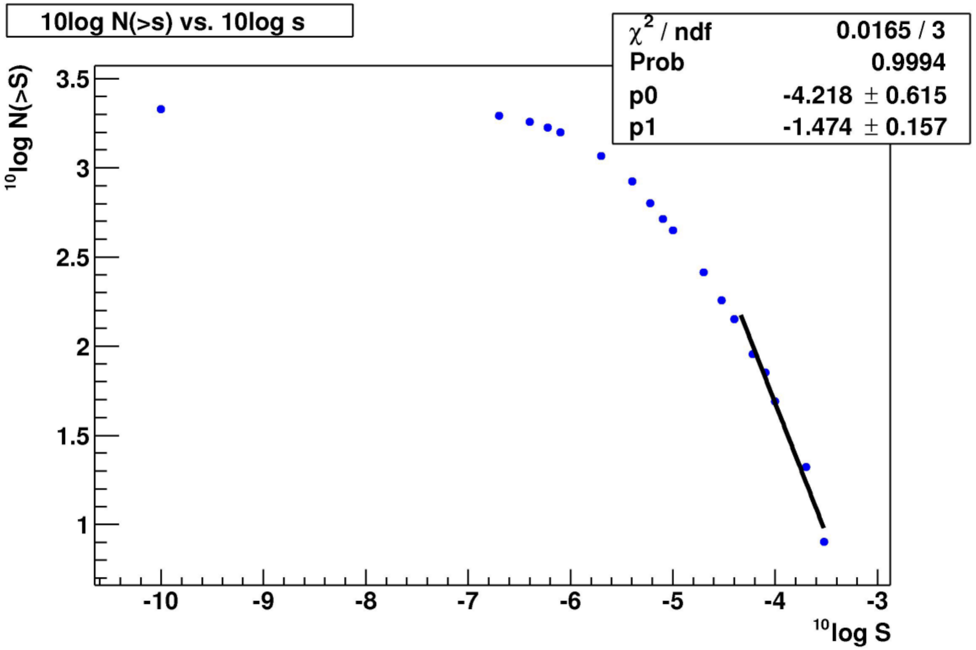
- $S = S_0$
  $\rightarrow$ specific distance $r_0 = \left(\frac{E_0}{4\pi S_0}\right)^{1/2}$

  Obviously $r < r_0 \rightarrow S > S_0$

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

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

  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 : $S_{obs} = \frac{E_0}{4\pi(r_{phys})^2(1+z)}$

- Flat Friedmann-Lemaître universe and Robertson-Walker metric

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

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

$\rightarrow$ Integral needs to be solved numerically

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

- $N(> S_0)$ 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 $\mathrm{d}r \rightarrow \mathrm{d}N = n \cdot 4\pi r_{phys}^2 \mathrm{d}r$ 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 : $F_{cr} = \displaystyle\int_{r=0}^{r_{max}} \frac{E_{cr} n\,\mathrm{d}r}{1+z}$
- Simplified model for $r_{phys}(z) \rightarrow F_{cr} = \displaystyle\int_0^{\infty} \frac{cE_{cr} n\,\mathrm{d}z}{H_0(1+z)^{3/2}} = \frac{2cE_{cr}n}{3H_0}$
- Taking $E_{cr} = 10^{52}$ erg $\quad n = 1.7 \cdot 10^{-10}$ Mpc^{-3} yr^{-1}

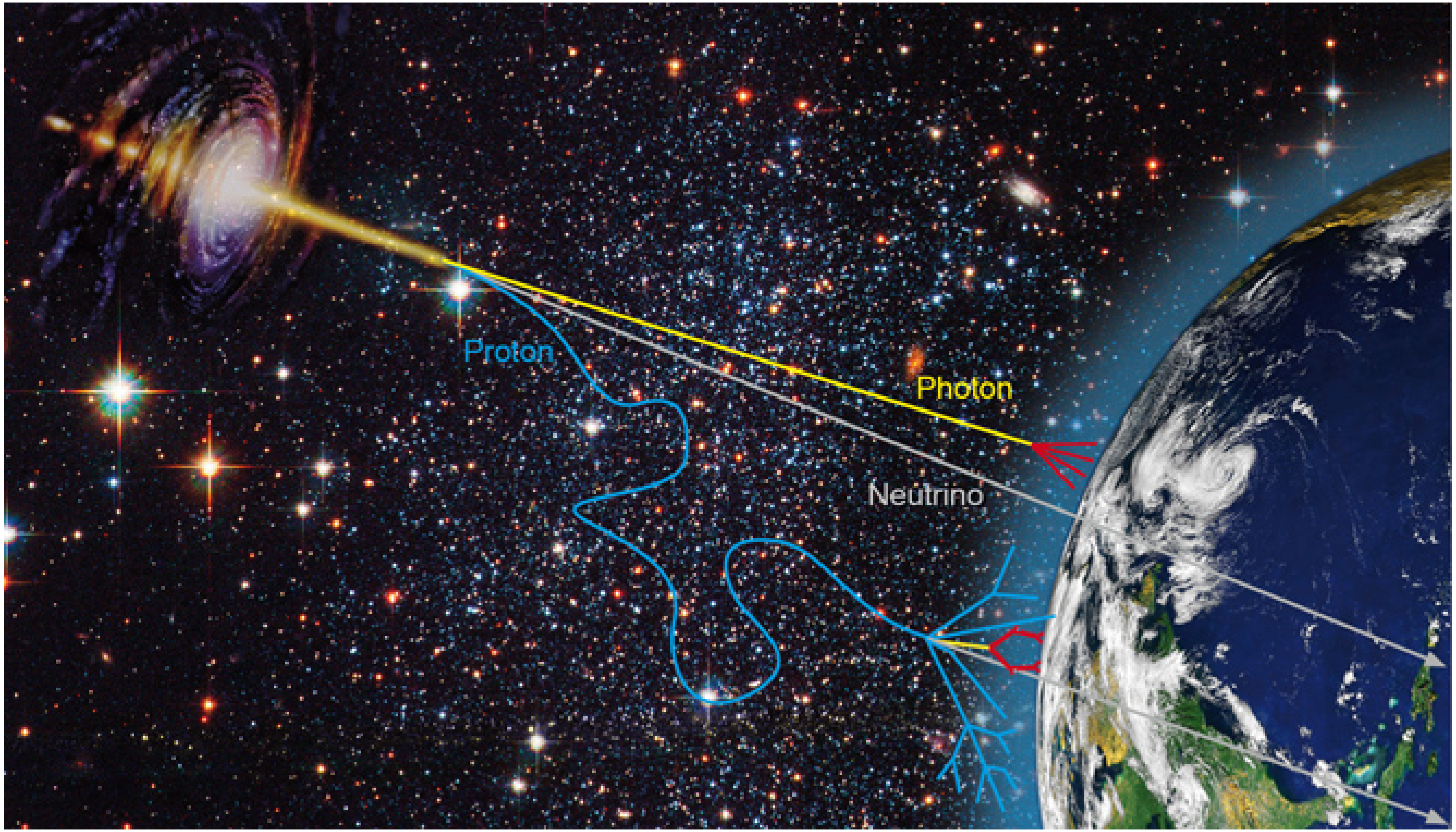
  $\rightarrow F_{cr} \approx 10^{-8}$ GeV cm^{-2} s^{-1} $\quad$ (observed $\approx 10^{-7}$ GeV cm^{-2} s^{-1})

  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

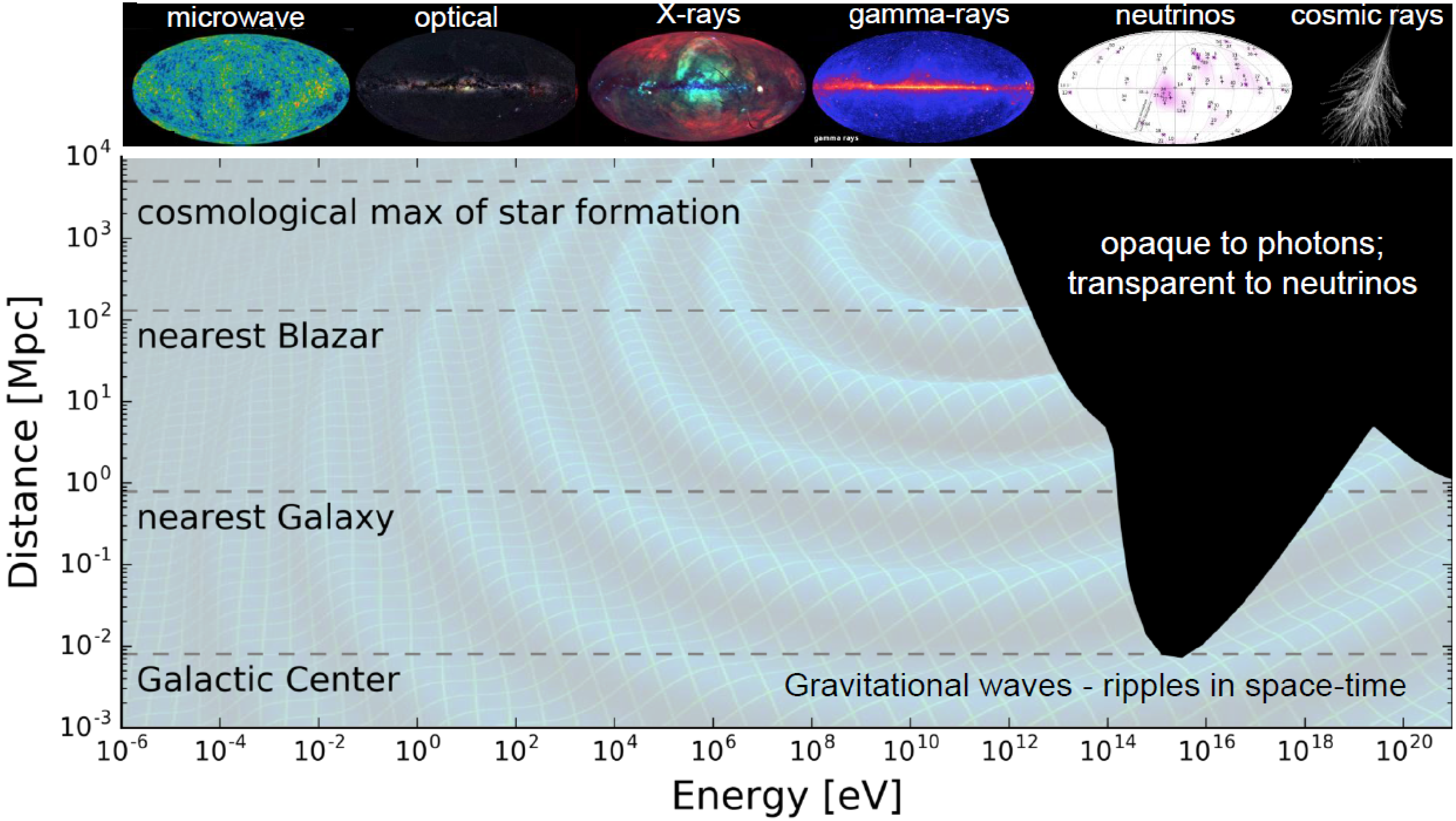
It's a long and difficult journey



Only photons and neutrinos point back to the source

Link with cosmic rays

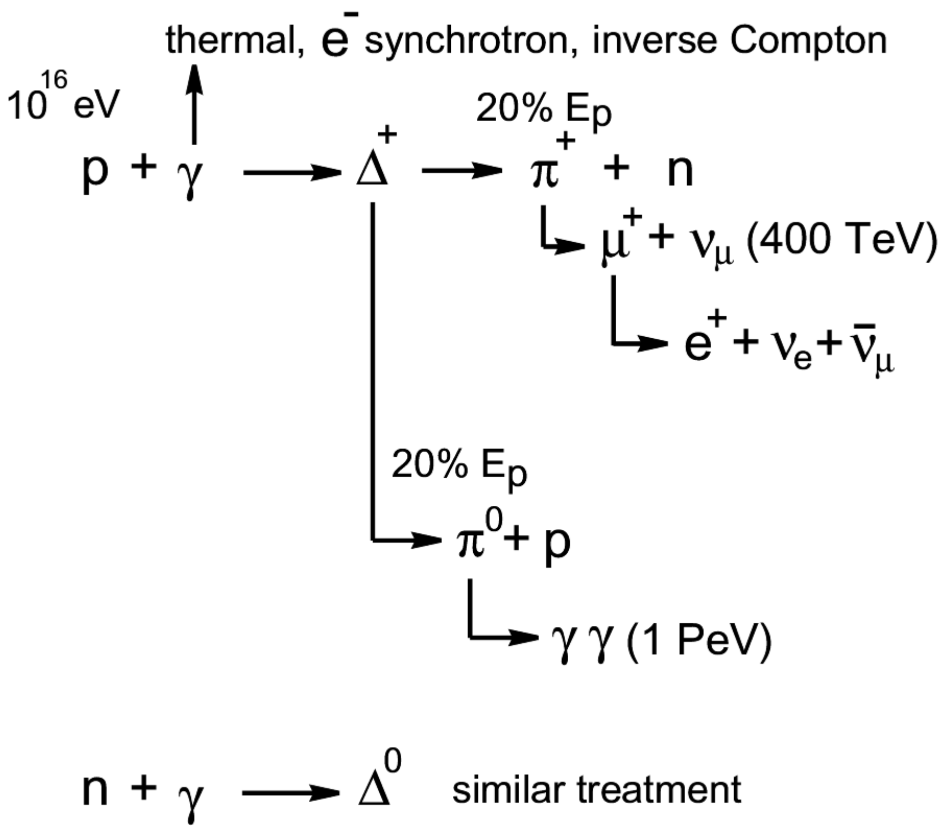
Beware of the observable Universe: $\gamma + \gamma_{EBL} \rightarrow e^{+}e^{-}$ $\quad N + \gamma_{CMB} \rightarrow \Delta$



[Credit Marek Kowalski]

Hunting for Cosmic Neutrino sources

Neutrino production mechanism



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

- **Waxmann-Bahcall** [PRL 78 (1997) 2292]

  High-E p diffuse out of the shocks

  Observed CR $\rightarrow$ lower limit on p flux

  Fraction of p used for ν production ?

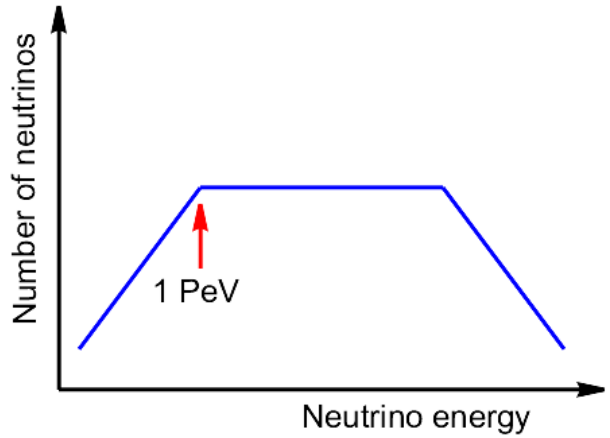
- **M. Ahlers et al.** [APP 35 (2011) 87]

  Protons trapped, neutrons escape

  CR observations provide the n flux

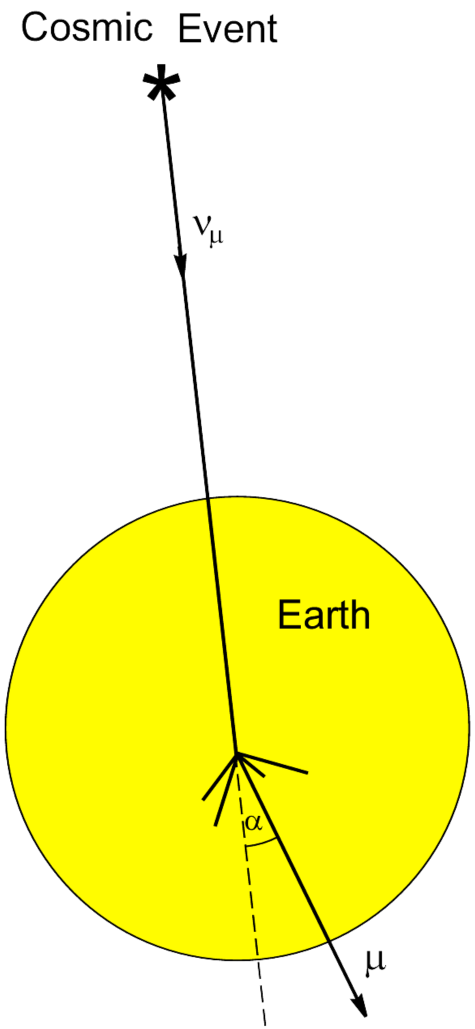
  Direct relation CR $\leftrightarrow$ ν flux

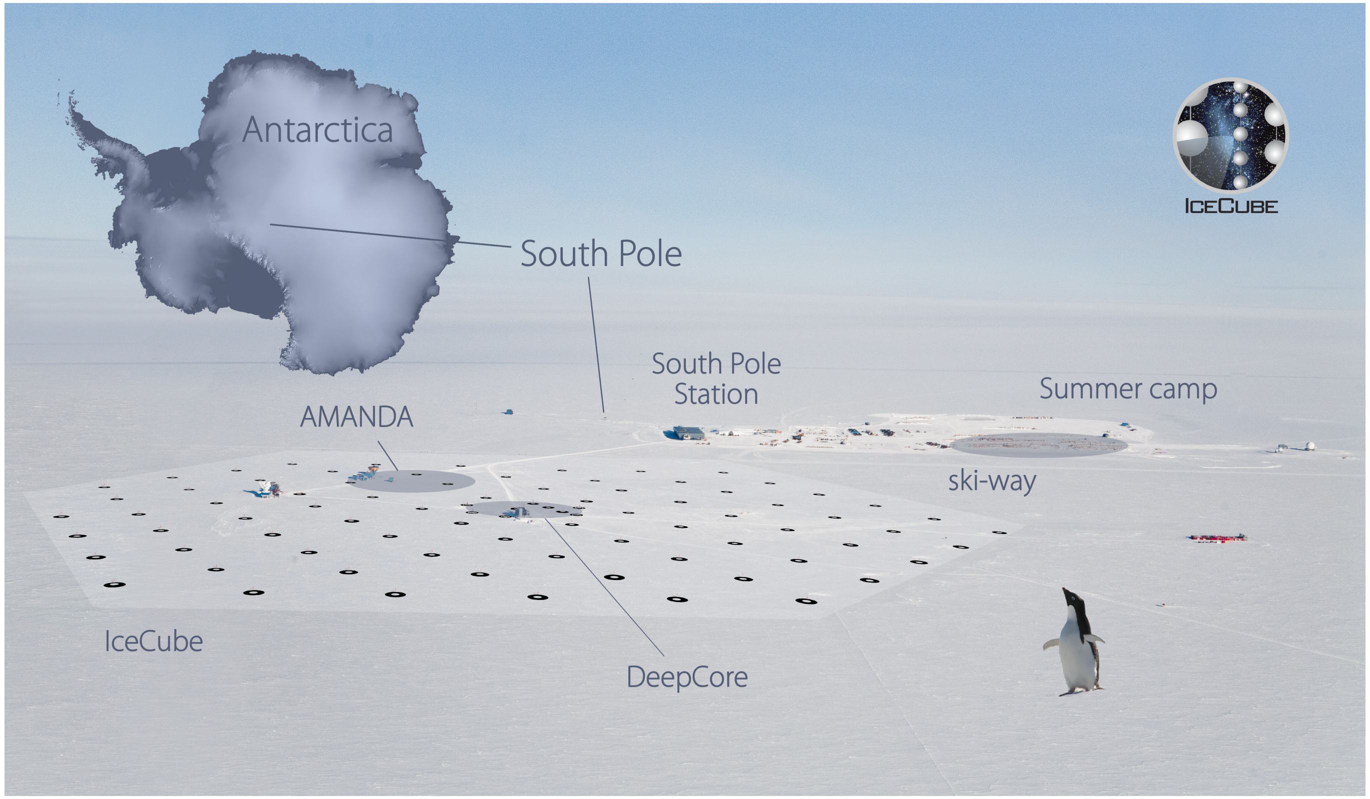
- **Generic ν spectrum** [JCAP 0903 (2009) 020]



Hunting for Cosmic Neutrino sources

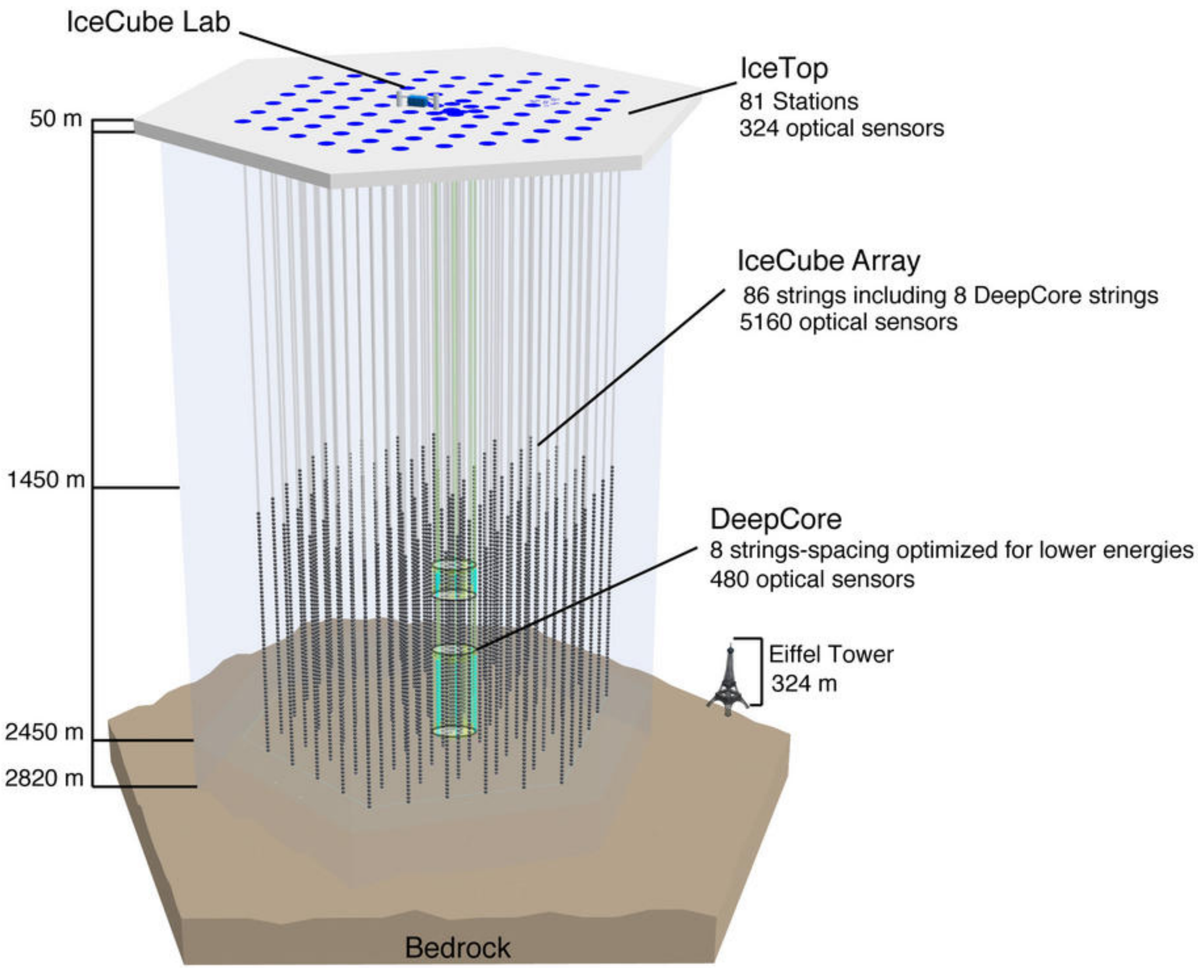
Hunting for Cosmic Neutrino sources





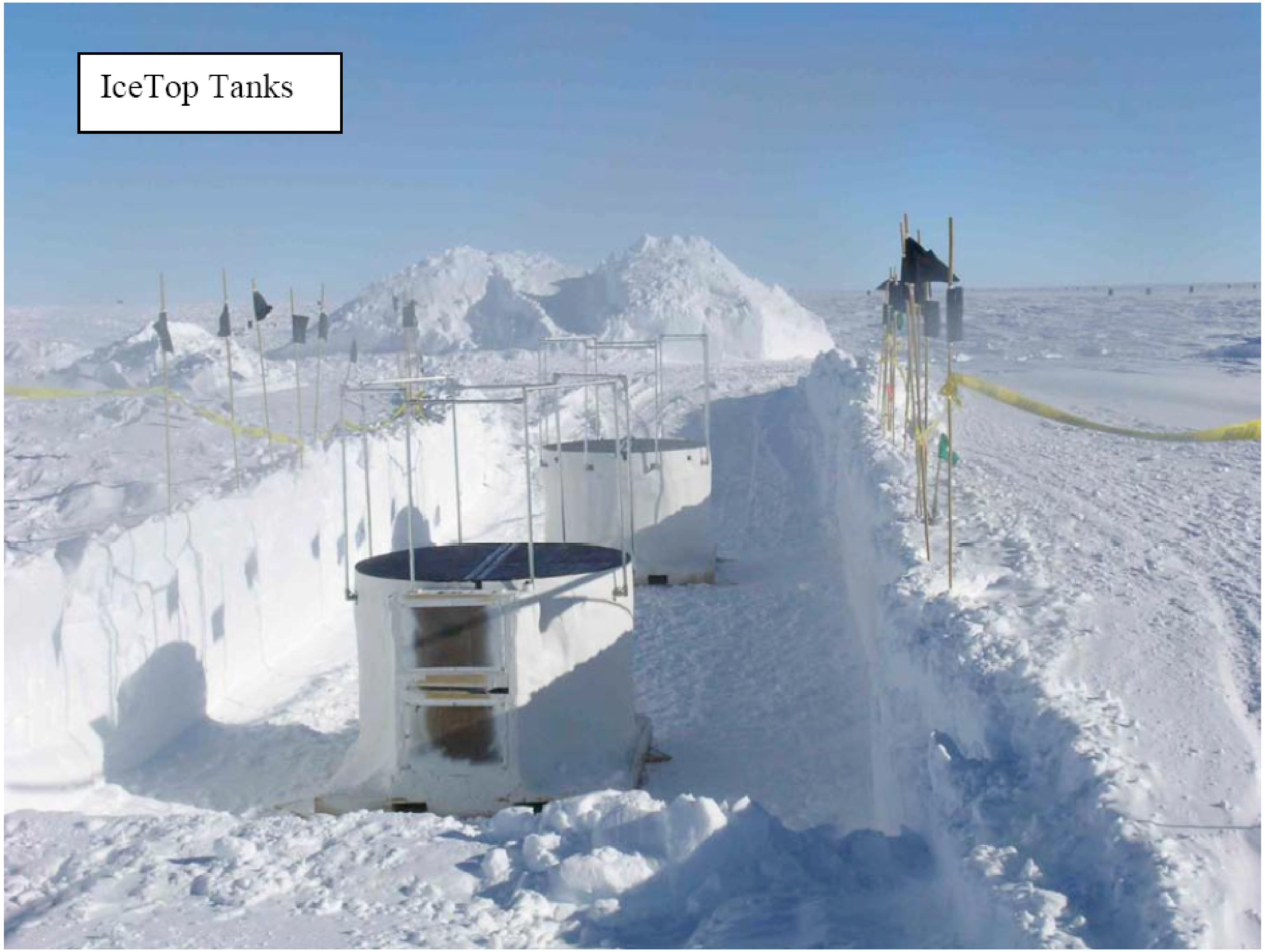
Hunting for Cosmic Neutrino sources

The IceCube Neutrino Observatory at the South Pole

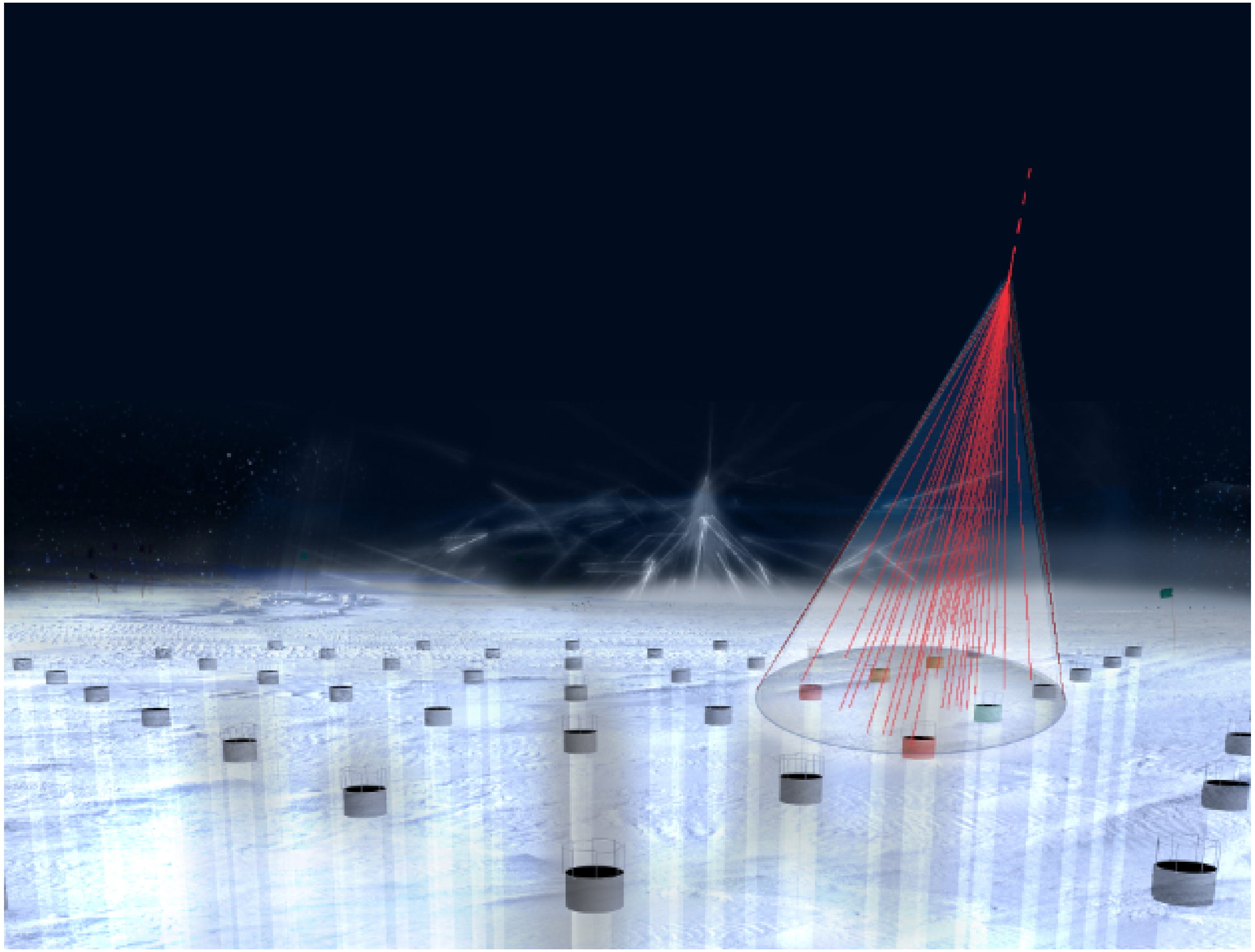


86 strings, 5160 optical sensors, instrumented volume $\sim 1\ \mathrm{km}^3$

Hunting for Cosmic Neutrino sources

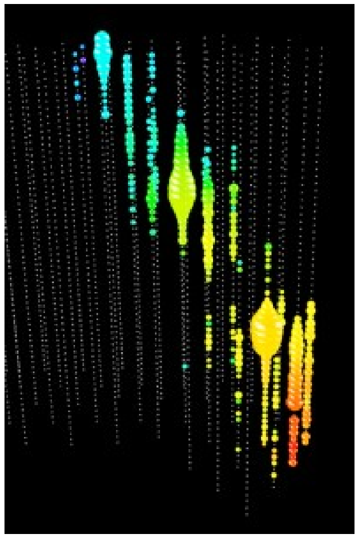


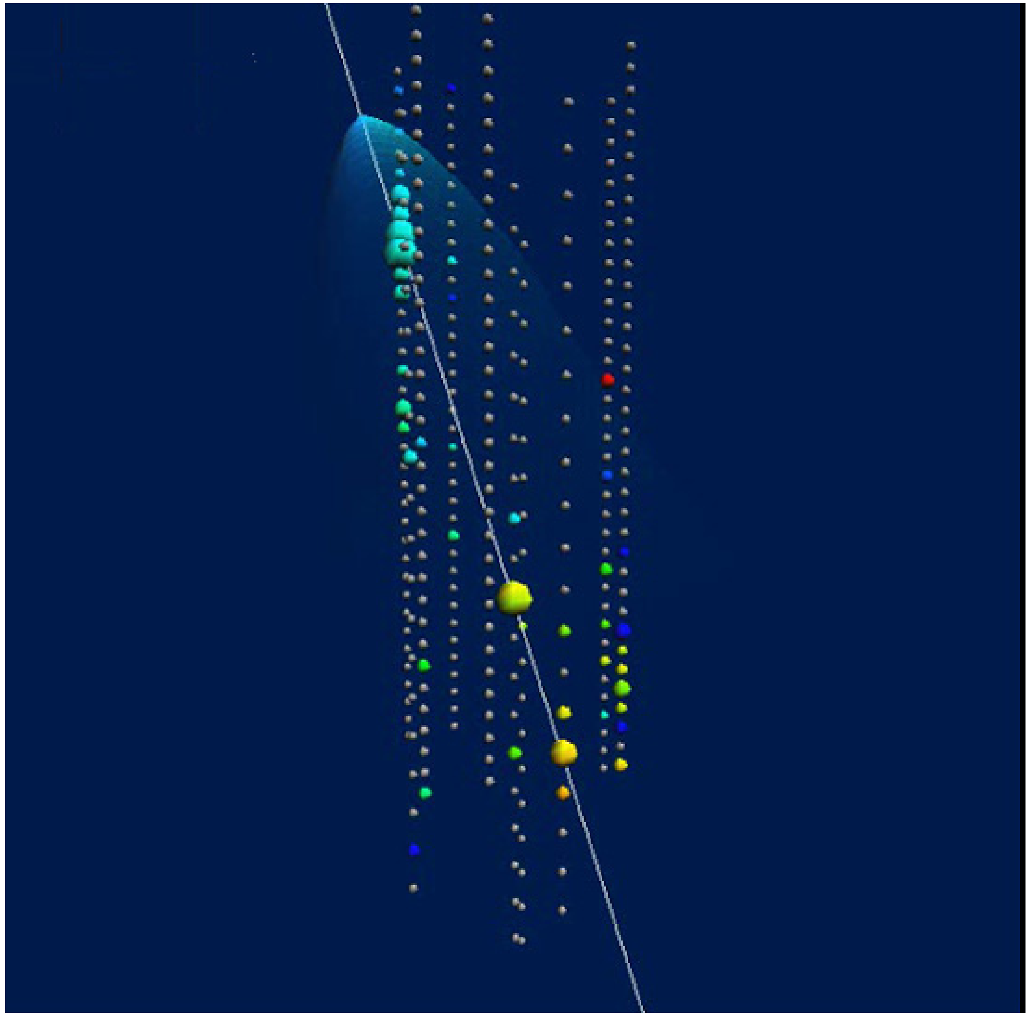
The IceTop detection principle



Hunting for Cosmic Neutrino sources

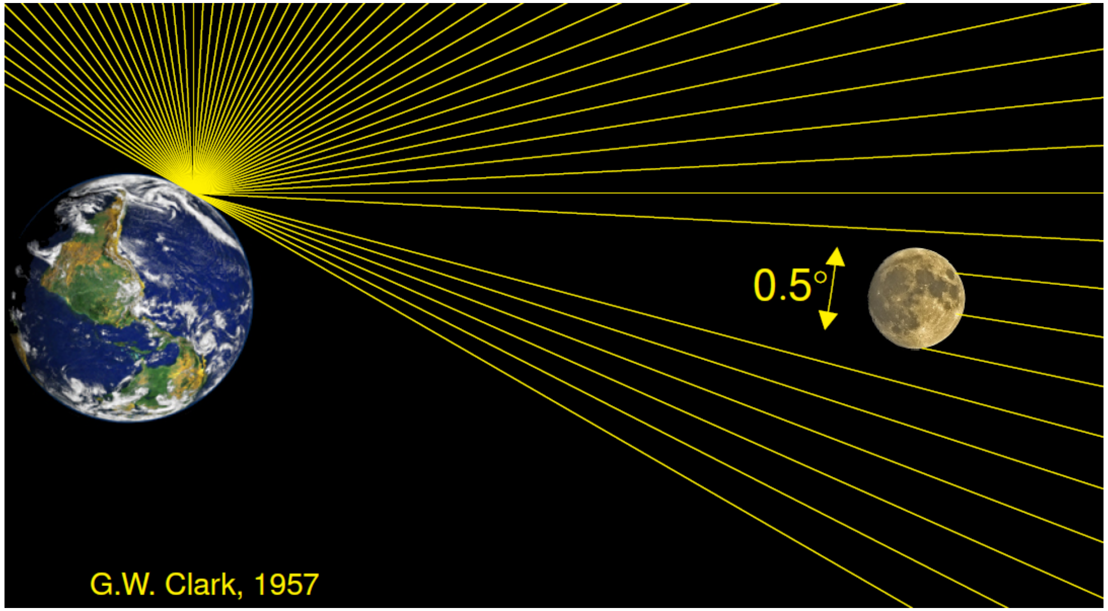
The InIce detection principle

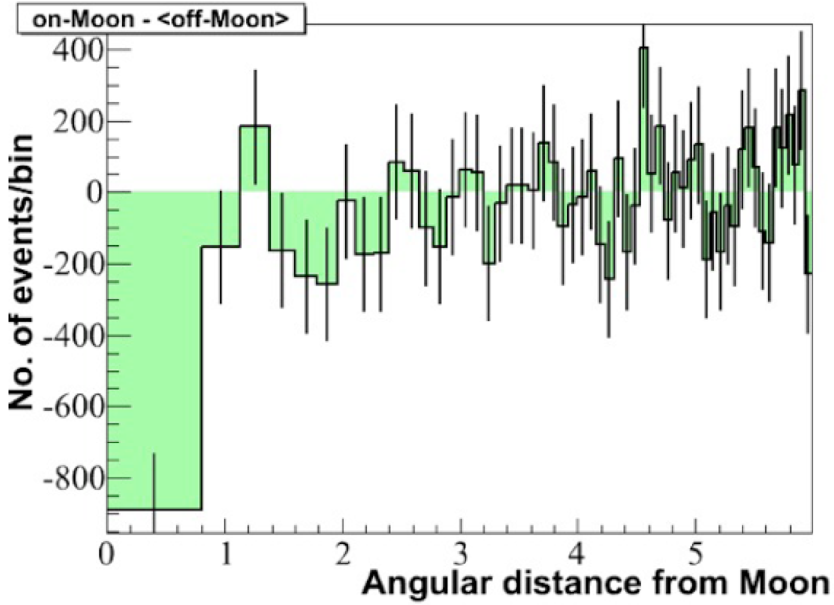




Muons from atmospheric interactions

The shadow of the Moon

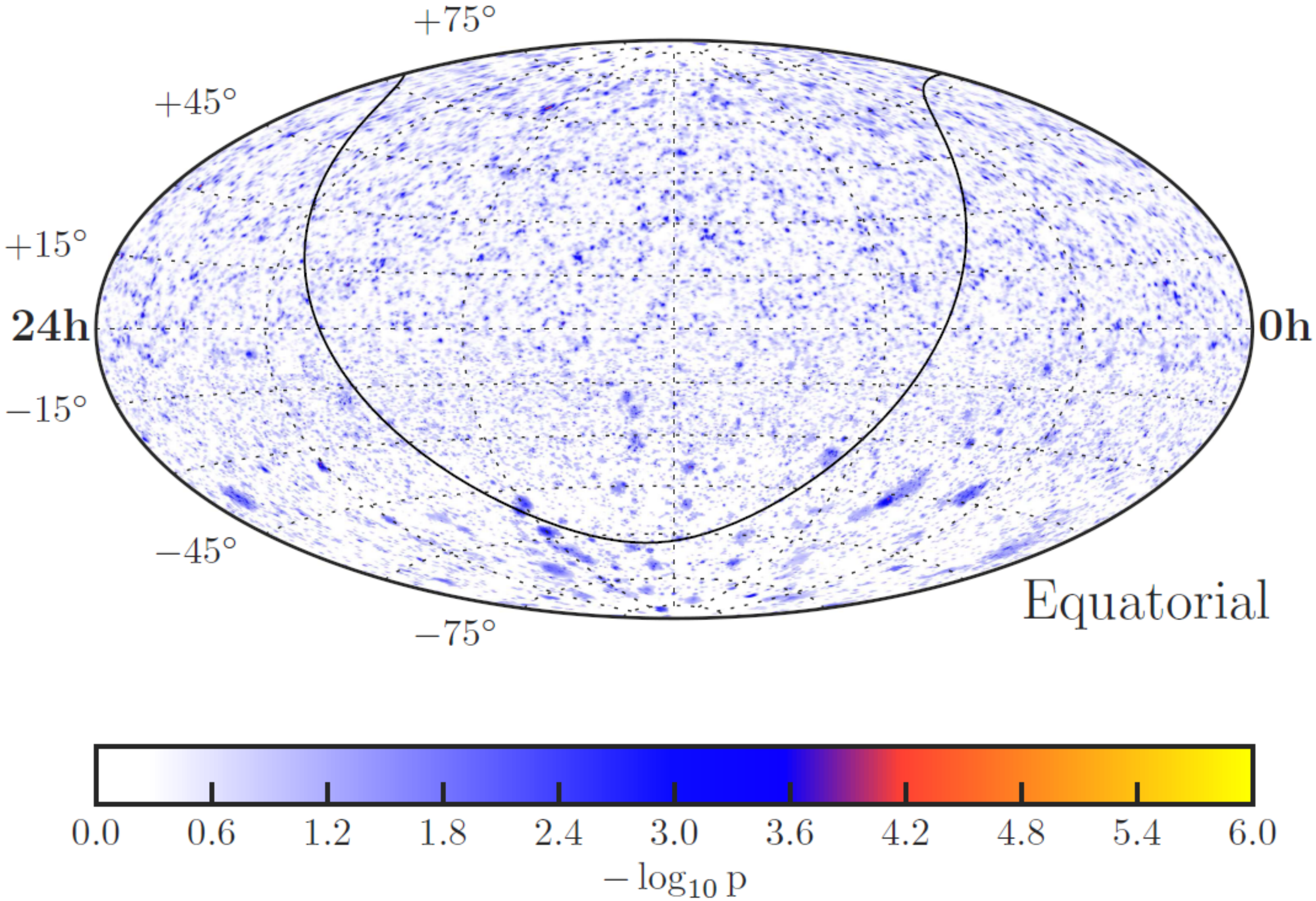




Angular resolution : $\sim 0.8^{\circ}$

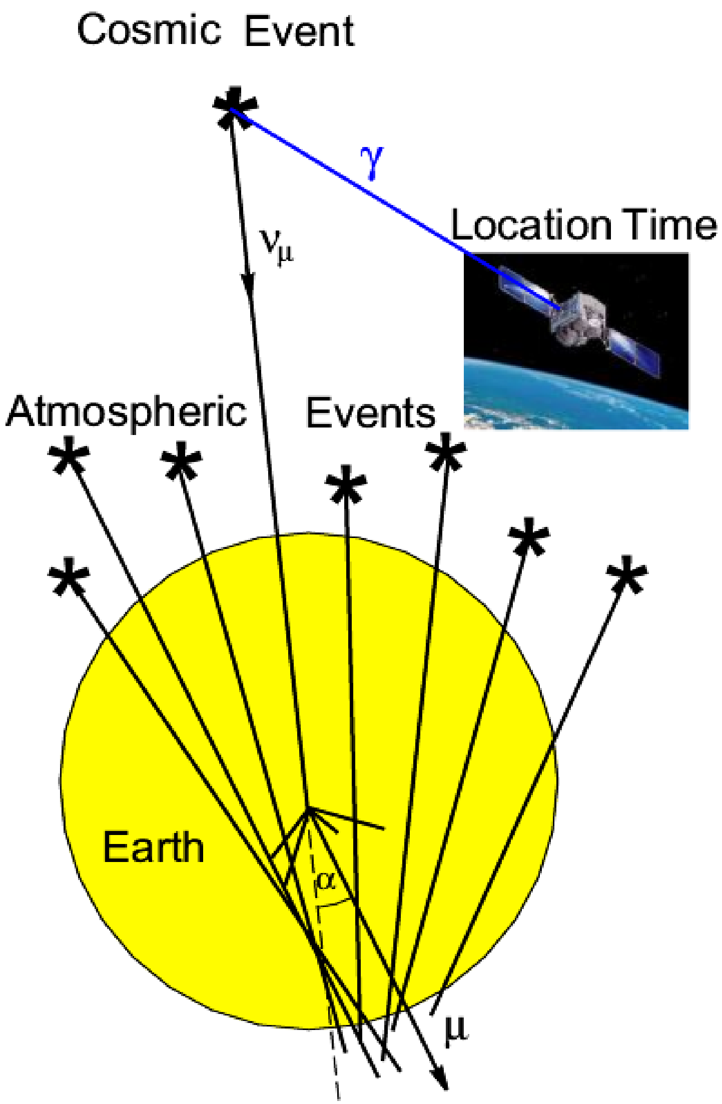
Hunting for Cosmic Neutrino sources

IceCube 7-years skymap (~700'000 events) [ApJ 835 (2017) 151]



No evidence for point sources (yet)

Transient cosmic sources

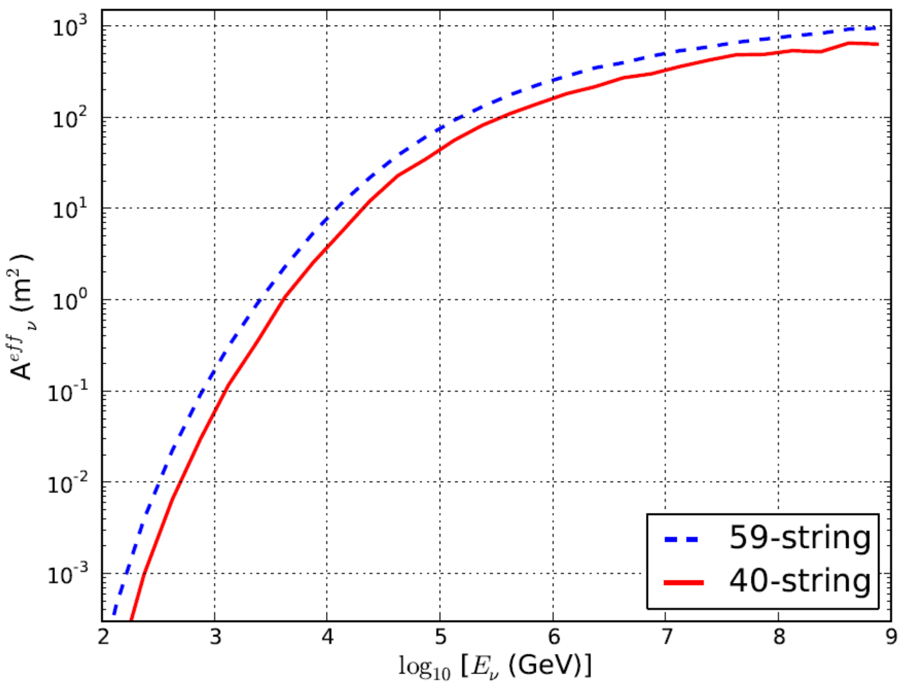


- No signal $\longrightarrow$ Give flux upper limit
- Link observations and flux via Effective area

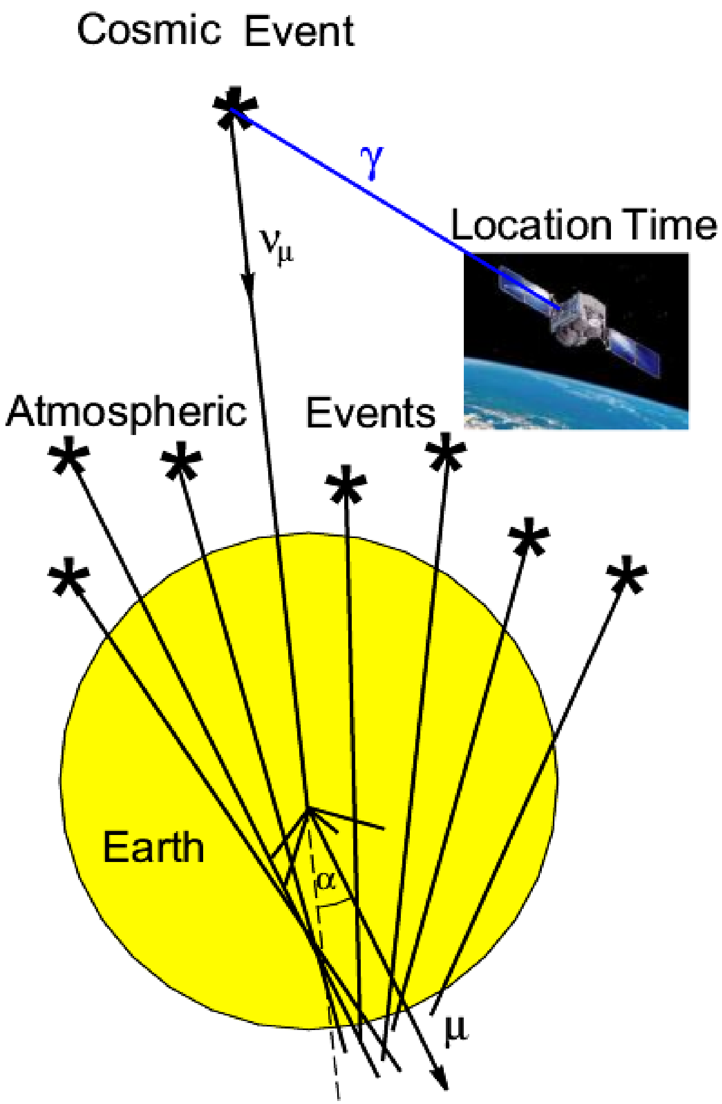
$A_{eff} \equiv$ obs. event rate / incoming flux

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

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

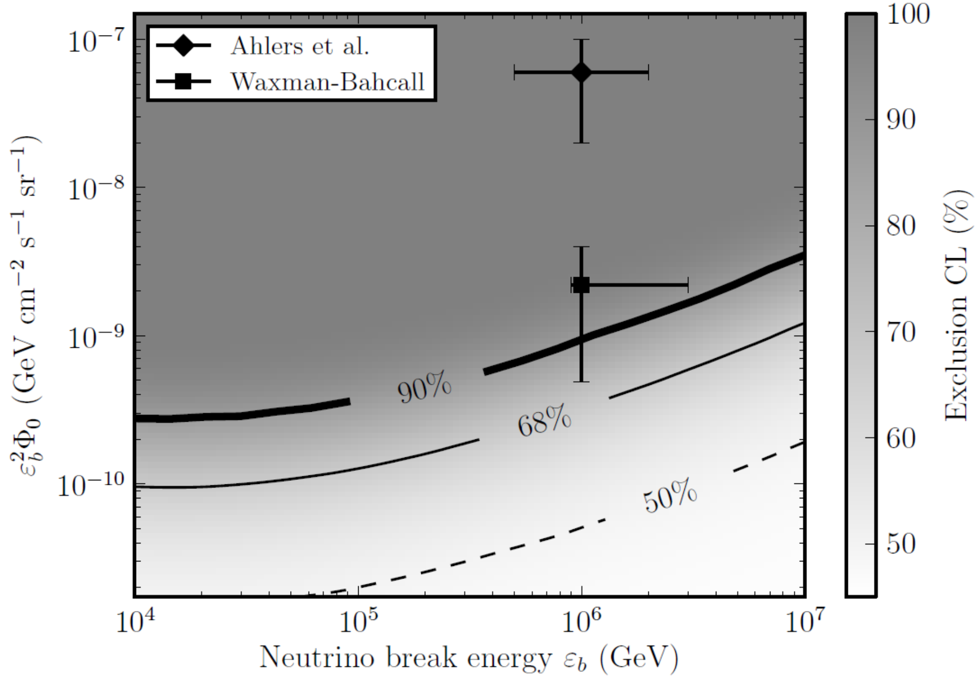


Transient cosmic sources



IceCube GRB prompt ν flux limit

[ApJ Let. 805 (2015) L5]



GRBs not the (only) UHECR sources

Or : ν prod. lower than expected

Or : ν prod. outside prompt phase

Search for a diffuse cosmic ν flux

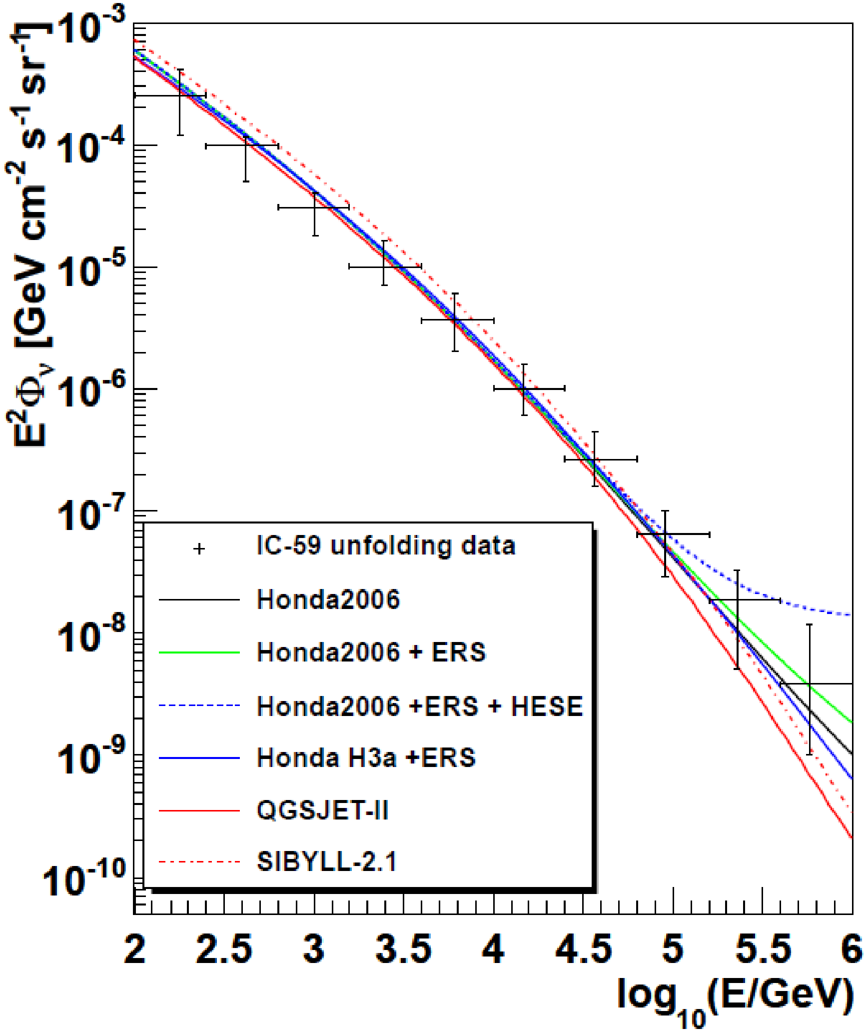
- Many point sources : diffuse ν flux
  Expected flux $\sim E^{-2}$
  (Fermi shock acceleration)
  Observed in TeV photons
- CR primaries : flux $\sim E^{-2.7}$
  $\rightarrow$ Calculate atm. ν E-spectrum
- ν det. observe atm. ν spectrum
  Validate calculated spectrum

$*$ PDF for atm. ν E-spectrum

- Very high E : Nearly atm. bkg free
  0.1 atm. ν km^{-3} year^{-1} at 1 PeV
  VHE events might prove cosmic ν

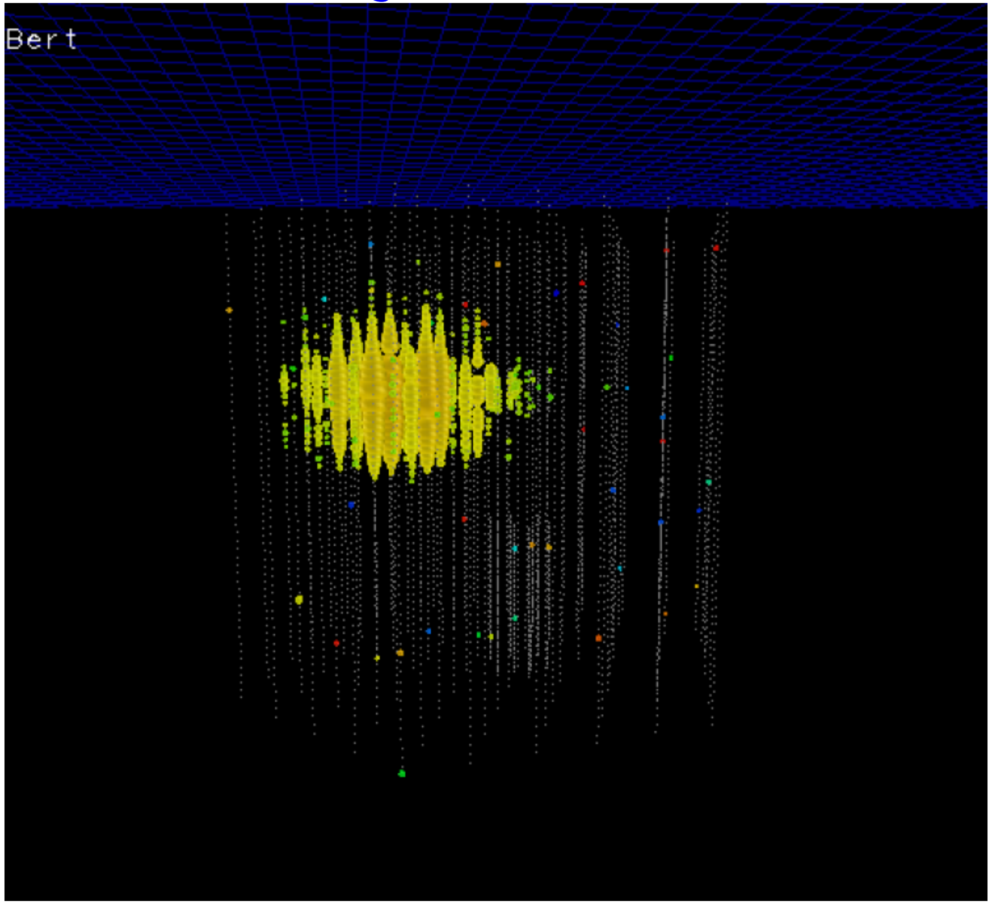
IceCube atmospheric ν spectrum

[Eur. Phys. J. C75 (2015) 116]



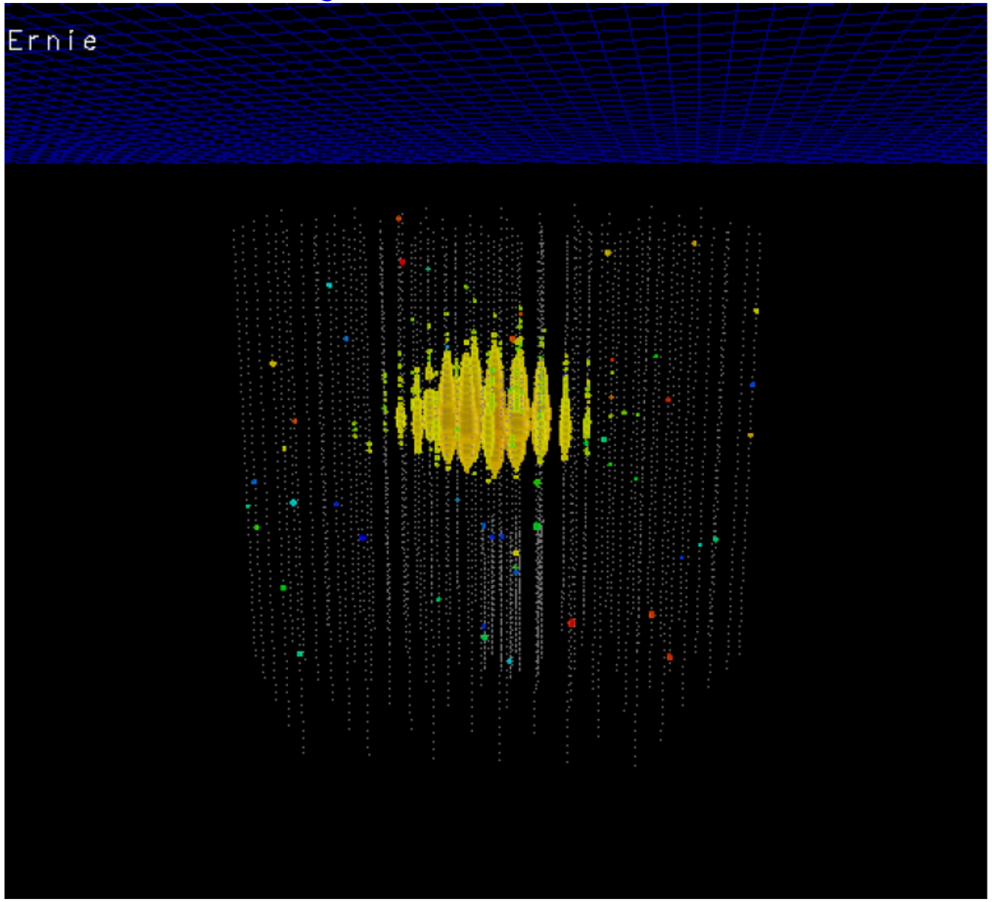
Search for a diffuse cosmic ν flux

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

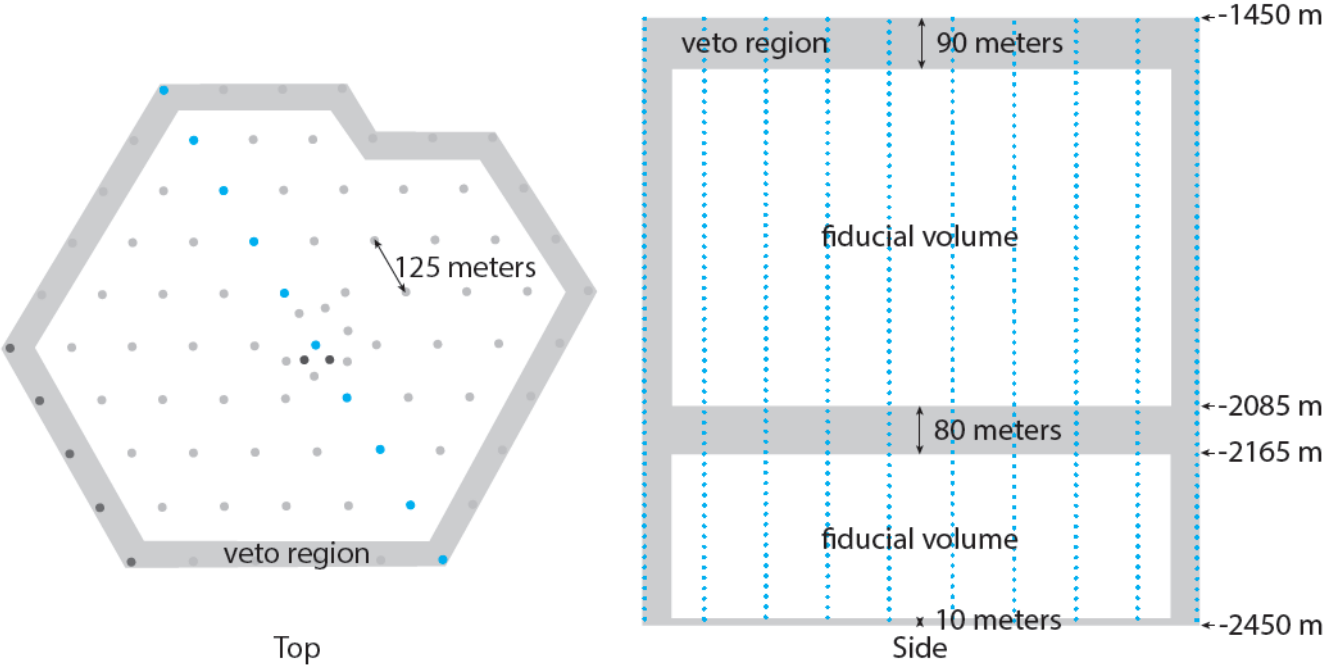
Search for a diffuse cosmic ν flux

Try to get more "Muppets in the basket"

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

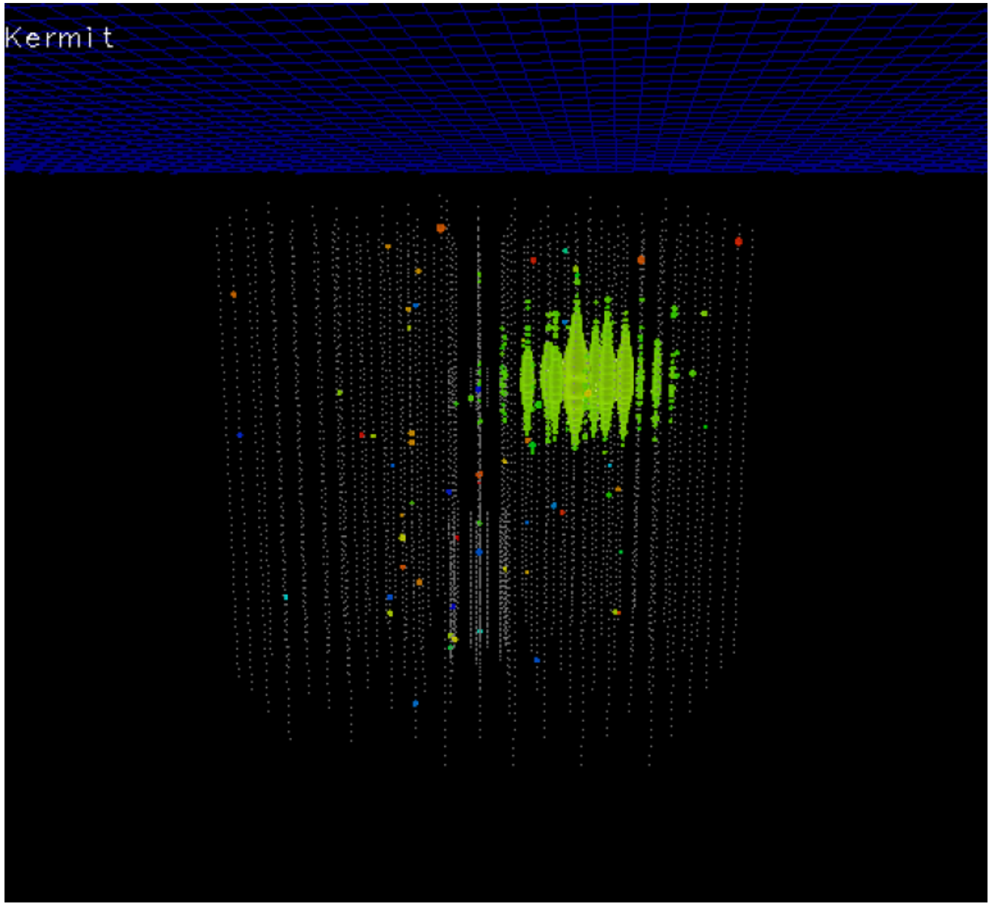
  Use event start veto criteria $\rightarrow$ remove atm. bkg μ and ν (showers)

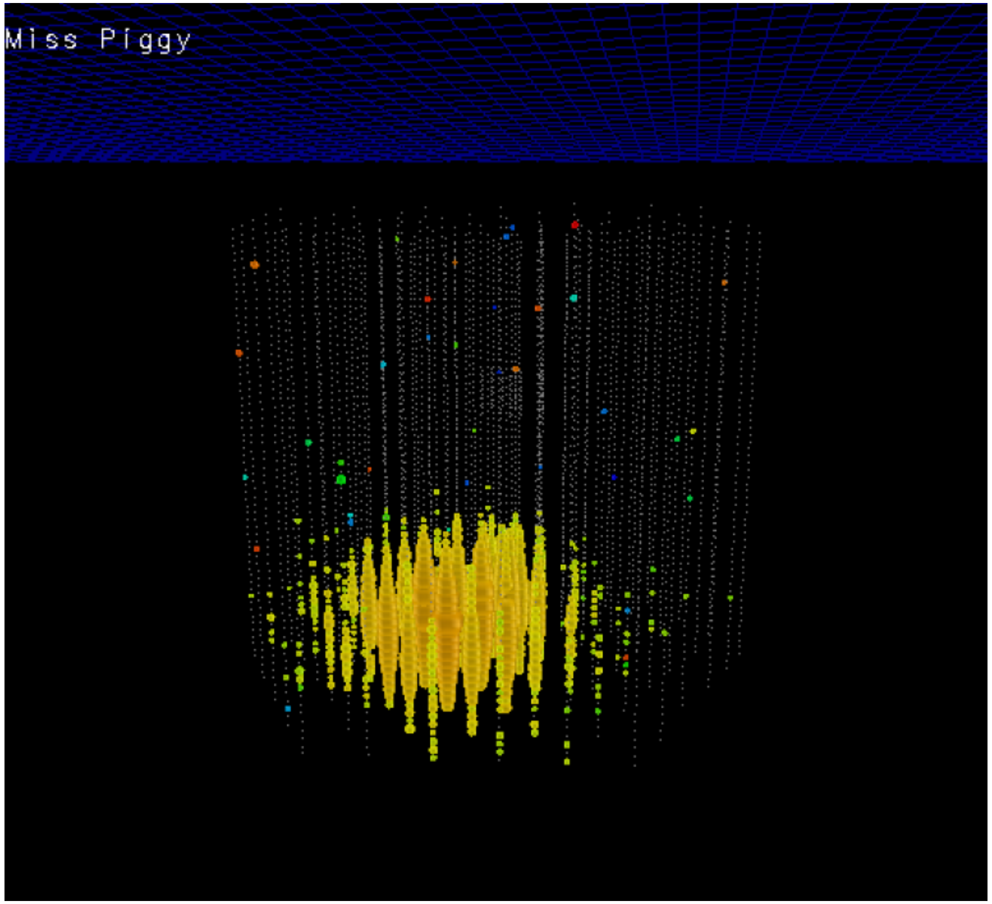
  Guarantees (contained) ν events and allows lower E cut $\rightarrow 4\pi$



Search for a diffuse cosmic ν flux

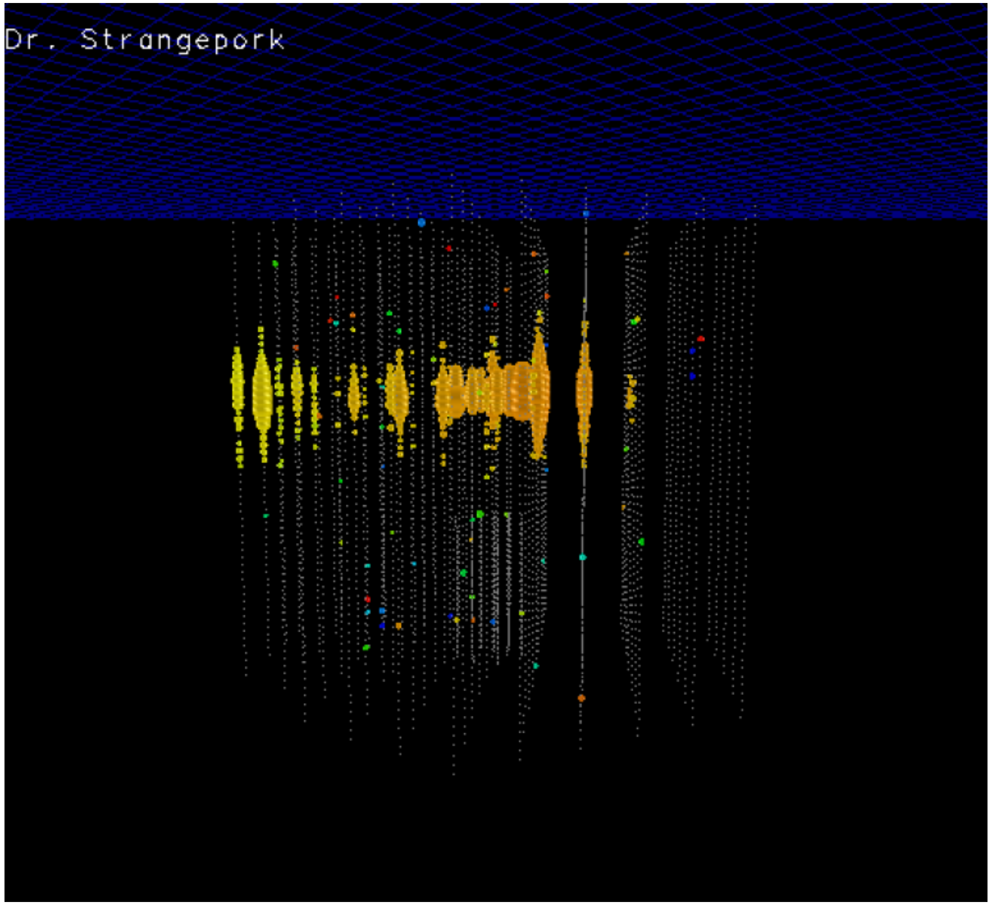
Several additional events were found

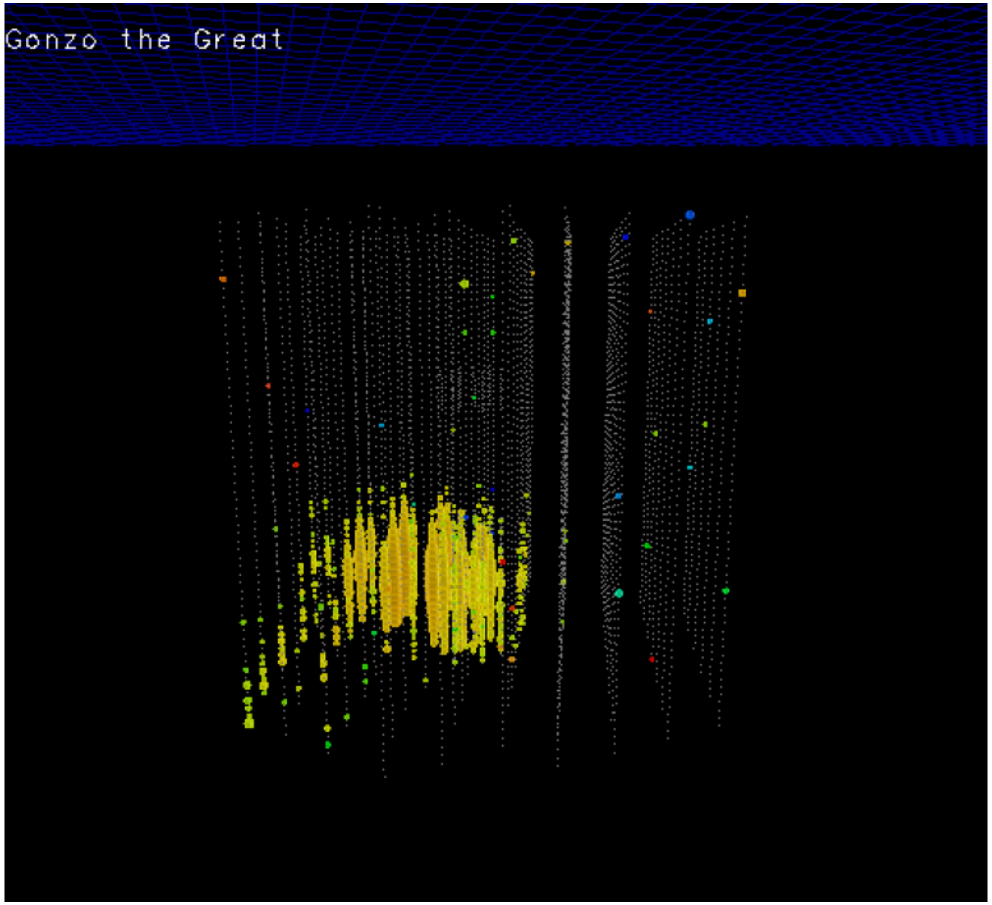




Search for a diffuse cosmic ν flux

Also some μ track signatures





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

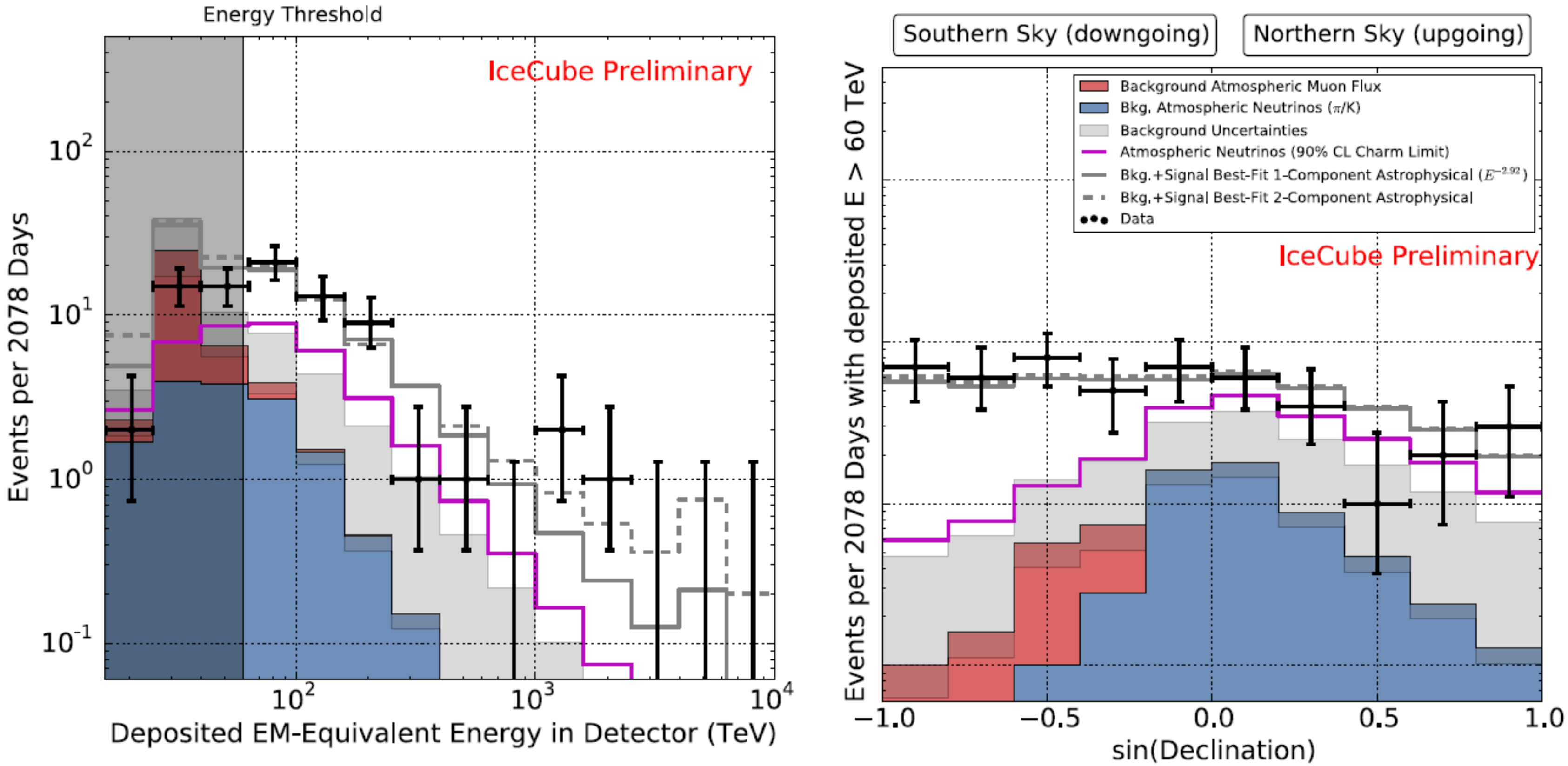
This is to certify that the *Physics World* Breakthrough of the Year has been given to

The IceCube South Pole Neutrino Observatory

for making the first observations of high-energy cosmic neutrinos

Search for a diffuse cosmic ν flux

82 observed Icecube High-Energy Starting Events (HESE) [C. Kopper, ICRC2017]



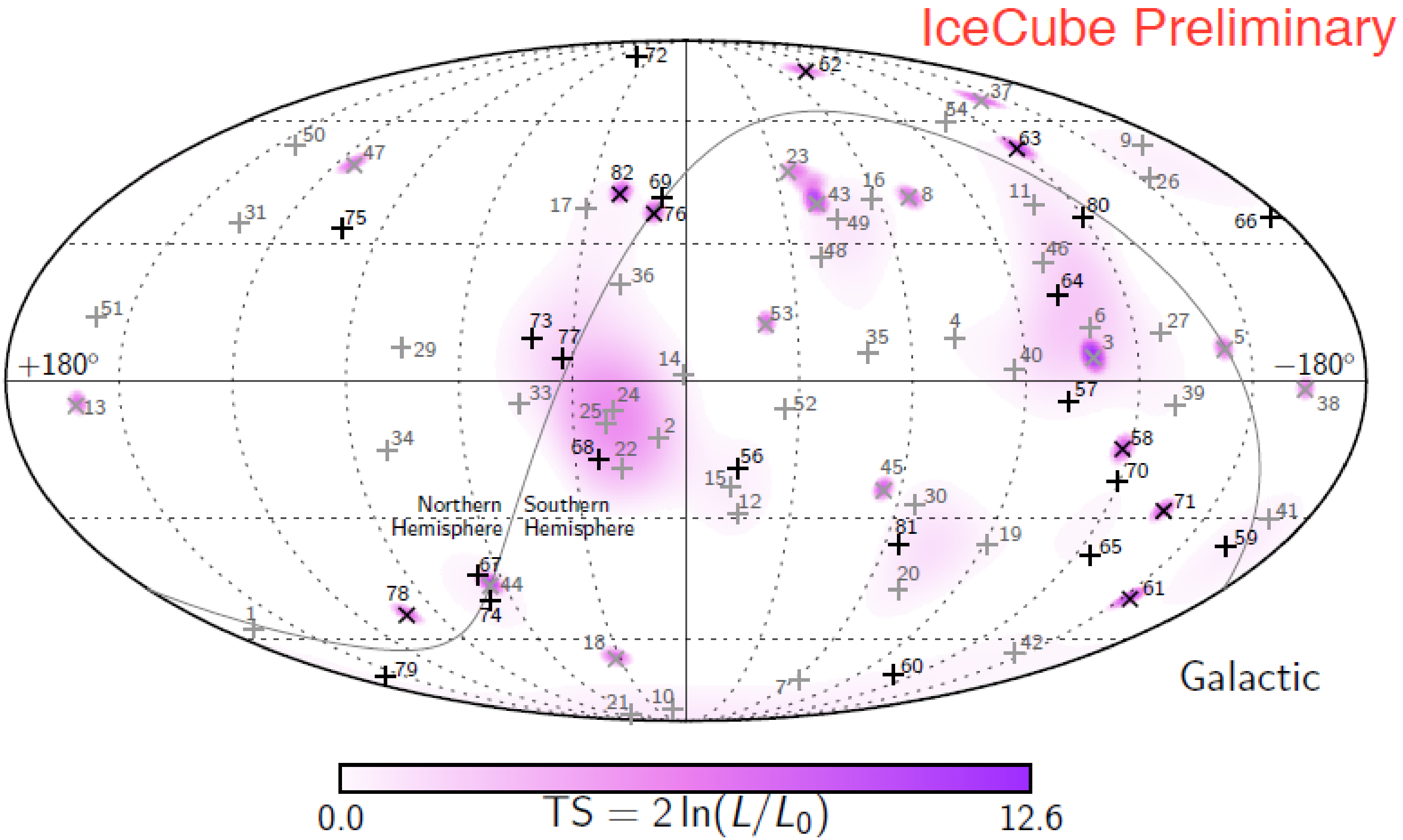
Evidence ($> 7\sigma$) for cosmic high-energy neutrinos

What are the sources ?

Where are the multi-PeV events ?

Search for a diffuse cosmic ν flux

Source directions of the HESE events

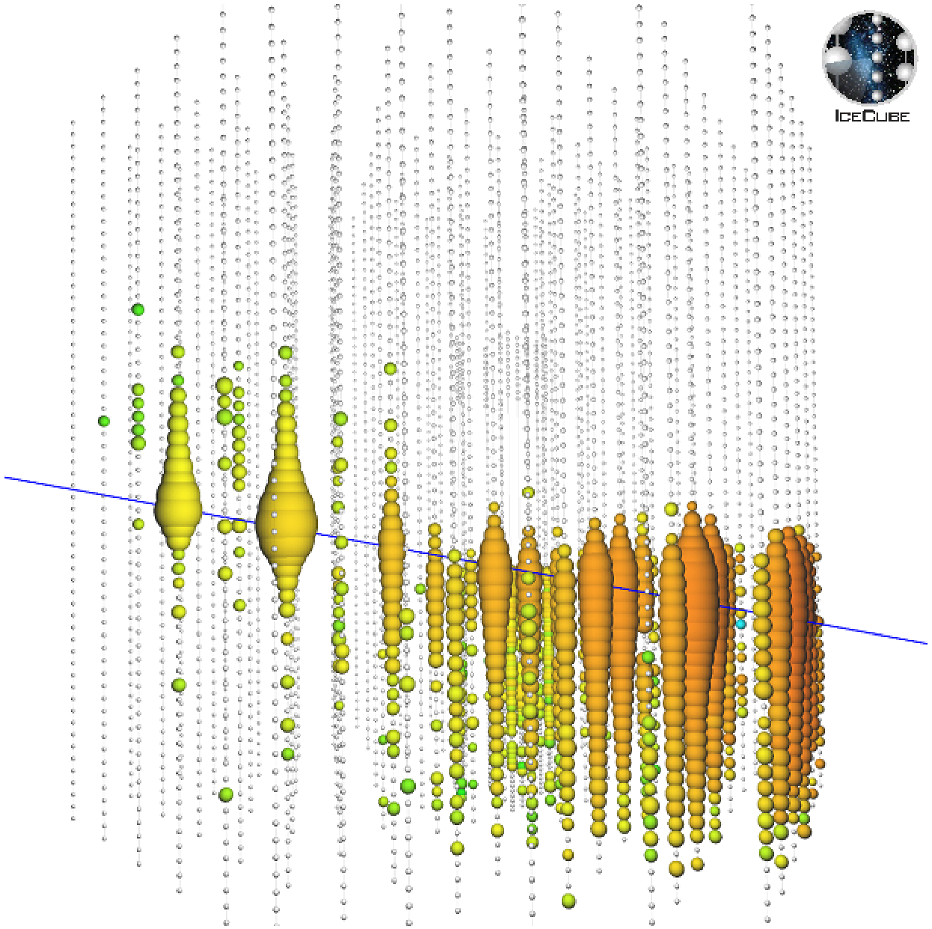


No evidence for point sources (yet)

Search for a diffuse cosmic ν flux

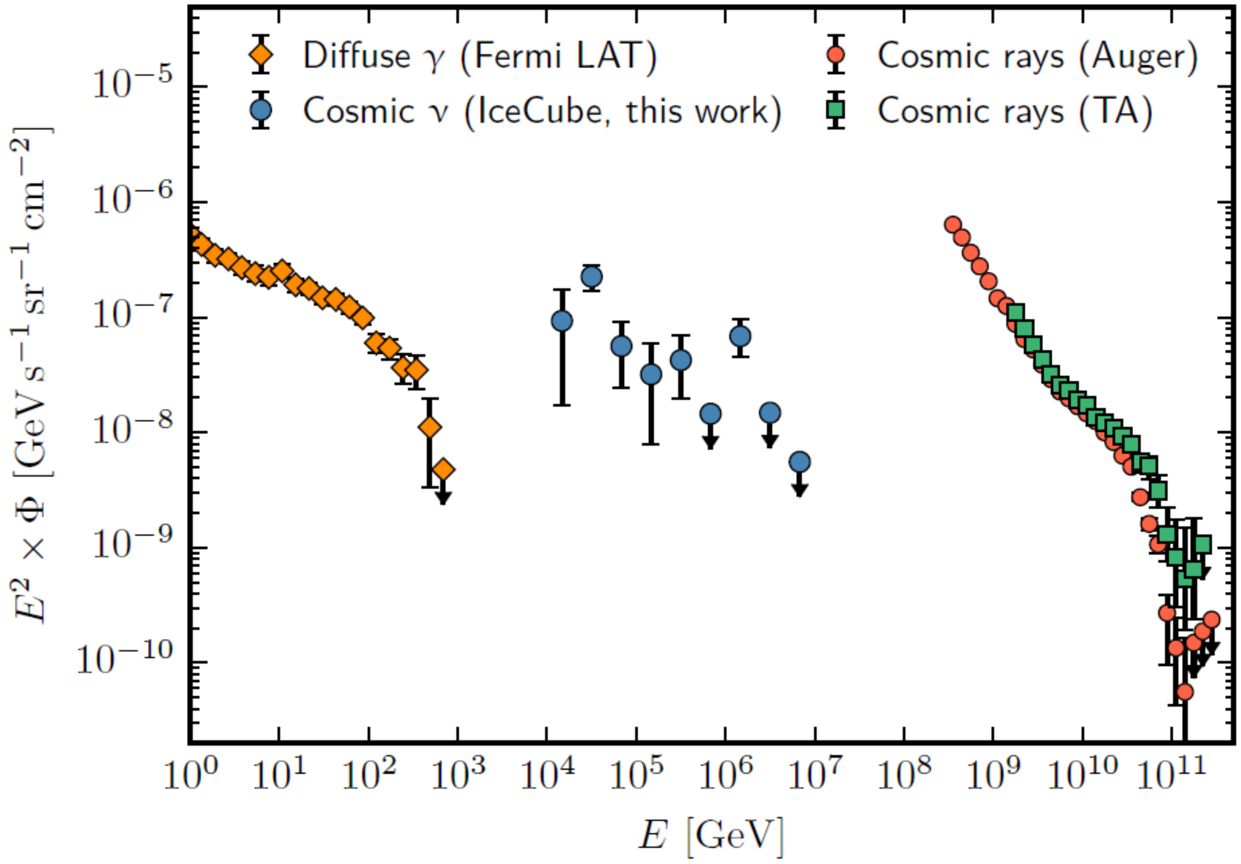
IceCube observation (11-jun-2014) of a very energetic through-going muon

α : 7h 21m 22s $\quad \delta$: 11.5° [ApJ 833 (2016) 3]



Deposited energy 2.6 ± 0.3 PeV $\rightarrow E_\mu = 4 - 5$ PeV $\rightarrow E_\nu > 5$ PeV

The Neutrino-Gamma connection



[Lars Mohrmann, PhD 2015, Humboldt University Berlin]

Common astrophysical sources ?

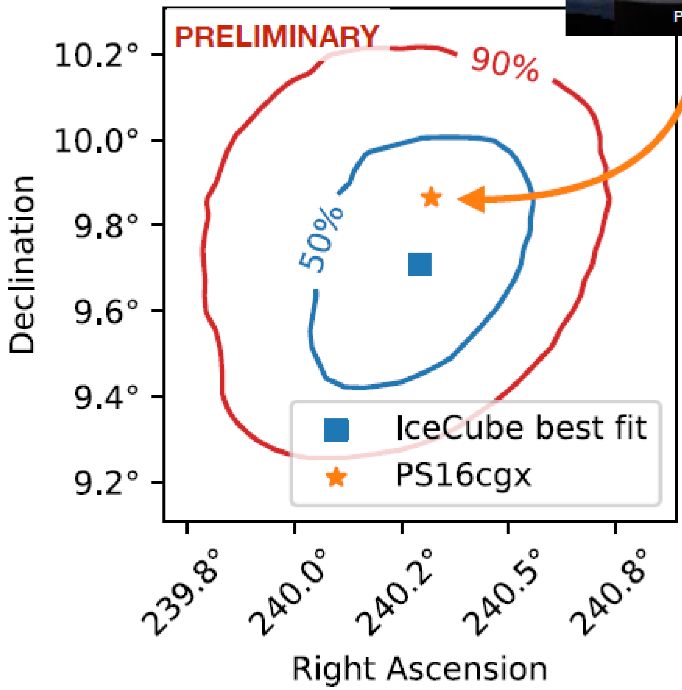
$N + \gamma \rightarrow \Delta \rightarrow \pi + N$ **(CR)** $\quad \pi^0 \rightarrow \gamma\gamma$ **(Fermi)** $\quad \pi^\pm \rightarrow \nu, \bar{\nu}$ **(IceCube)**

The Neutrino-Gamma connection

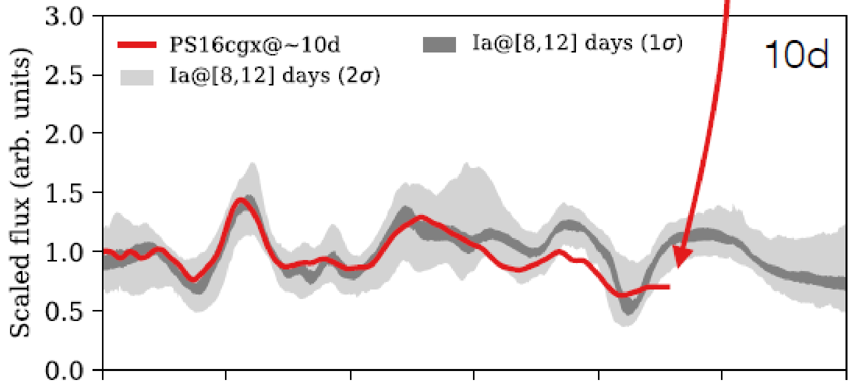
Follow up for transients on neutrino alerts

PanStarrs follow up of IceCube alert on 2016-04-27 and found a young supernova at z=0.3:

Light curve consistent with explosion days before neutrino alert



Optical spectroscopy 10, 20 days post-peak



Features atypical for SNIa, but not sufficient to exclude

Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

[Credit M. Kowalski SuGAR2018]

The Neutrino-Gamma connection

nature physics

ARTICLES

PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1*], F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]

individual objects are too low to make an unambiguous source association. Here, we report that a major outburst of the blazar PKS B1424-418 occurred in temporal and positional coincidence with a third petaelectronvolt-energy neutrino event (HESE-35) detected by IceCube. On the basis of an analysis of the full sample of γ-ray blazars in the HESE-35 field, we

There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ~5% for a chance coincidence. Our model reproduces the

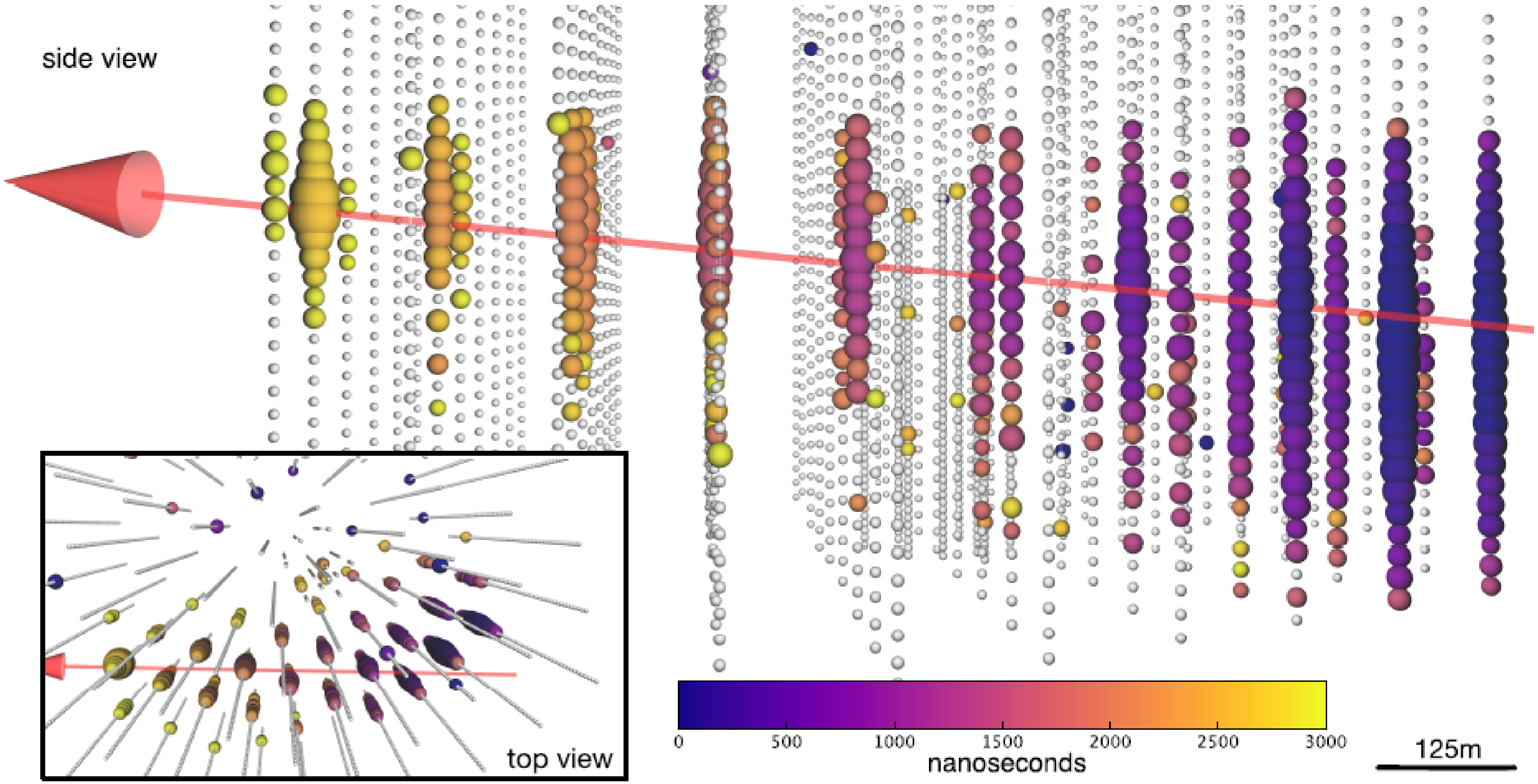
[Credit M. Ahlers SuGAR2018]

The Neutrino-Gamma connection

Multi-messenger studies look promising !

The Neutrino-Gamma connection

IceCube: Track with $E_{dep} \sim 24$ TeV observed at 22-sep-2017 20:54:30.43 UTC
$\rightarrow$ EHE alert (IC170922A) issued (~ 4 per year)



IC170922A track parameters: $\alpha = 77.4^\circ \quad \delta = 5.7^\circ \quad E_\nu = 290$ TeV

The Neutrino-Gamma connection

IC170922A track parameters: $\alpha = 77.43^{\circ}{}^{+0.95}_{-0.65}$ $\delta = 5.72^{\circ}{}^{+0.50}_{-0.30}$ $E_{\nu} = 290$ TeV

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

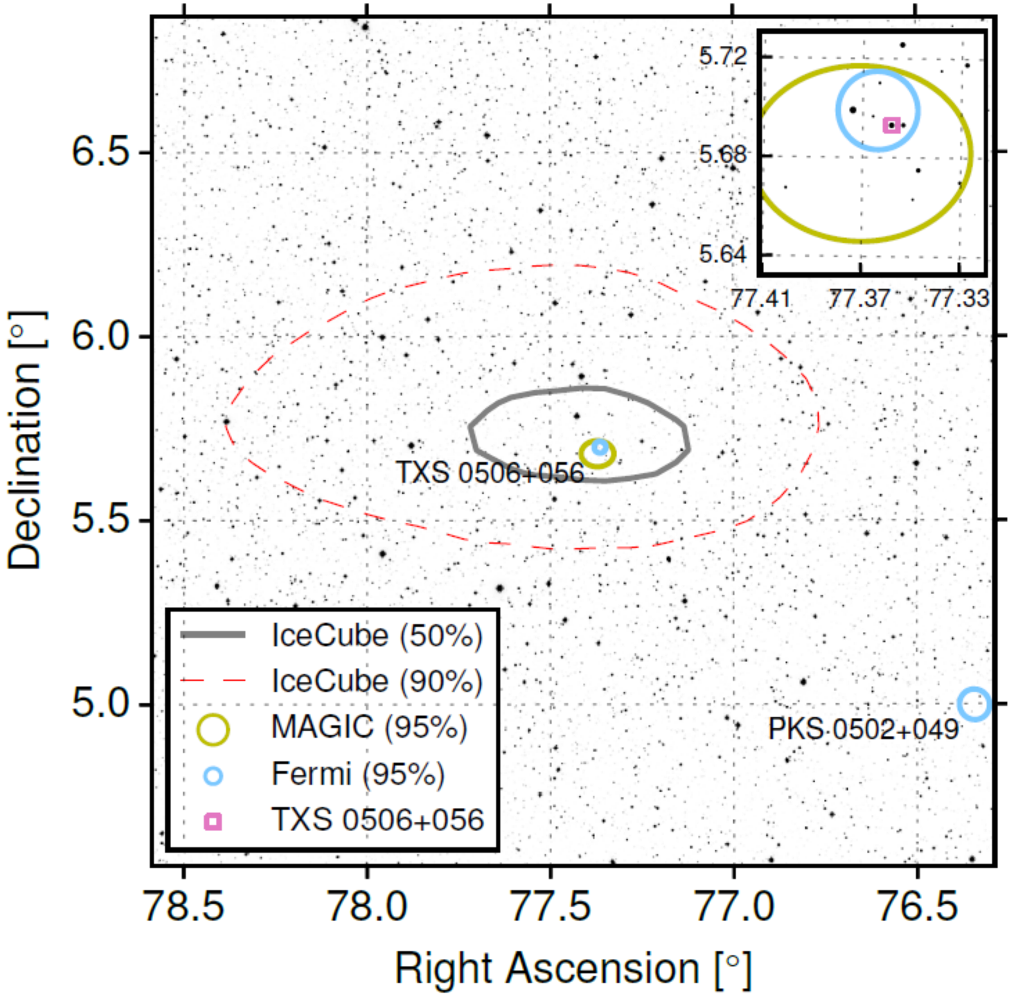
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

The IC170922A area



- Many radio and X-ray sources

  Most lack the needed energetics
- Only 2 candidates remain

  [Padovani et al. MNRAS 12-jul-2018]

$*$ TXS 0506+056 (BL Lac $z = 0.3365$)

$D_{phys} = 1.37$Gpc (∼4.5 Gly)

$*$ PKS 0502+049 (FSRQ $z = 0.954$)

$D_{phys} = 3.29$Gpc (∼11 Gly)

- Only TXS satisfies ν constraints (spatial, temporal and energetic)

  PKS is 1.22° away from TXS

The Neutrino-Gamma connection

Addressing a random flaring Blazar coincidence with IC170922A

• Consider the 90% uncertainty patch around IC170922A and "Play darts"

$\rightarrow p(r) \sim 0.001/4\pi$ to randomly obtain a Blazar from an isotropic population

• The Fermi 3LAC catalogue: 660 BL Lac and 440 FSRQ $\rightarrow$ Total: 1144 Blazars

$\sim 3\%$ of Blazars similar to TXS are found to be flaring

$\rightarrow p(r) \sim 3 \cdot 10^{-3}$ to randomly obtain a flaring Blazar from the sample

• Using the temporal correlation with the flare

∗ Needs detailed information the TXS lightcurve $\rightarrow$ Likelihood analysis

Flaring activity observed on timescales of 40-180 days

• IceCube observed 24 EHE neutrinos in 7 years $\rightarrow$ rate ~ 0.01 per day

Random EHE ν within flare period $\rightarrow$ Poisson distr. with mean $0.4 \leq \mu \leq 1.8$

Probability to find at least 1 EHE ν in flare period: $0.33 \leq p(n \geq 1|\mu) \leq 0.83$

• Probability for a random coincidence: $10^{-3} \leq p(r) \leq 2.5 \cdot 10^{-3}$ $(\leq 3\sigma)$

The Neutrino-Gamma connection

The IceCube 9.5 years archival dataset

Sample	Start	End
IC40	2008 Apr 5	2009 May 20
IC59	2009 May 20	2010 May 31
IC79	2010 May 31	2011 May 13
IC86a	2011 May 13	2012 May 16
IC86b	2012 May 16	2015 May 18
IC86c	2015 May 18	2017 Oct 31

Note : IC170922A happened in the data period IC86c

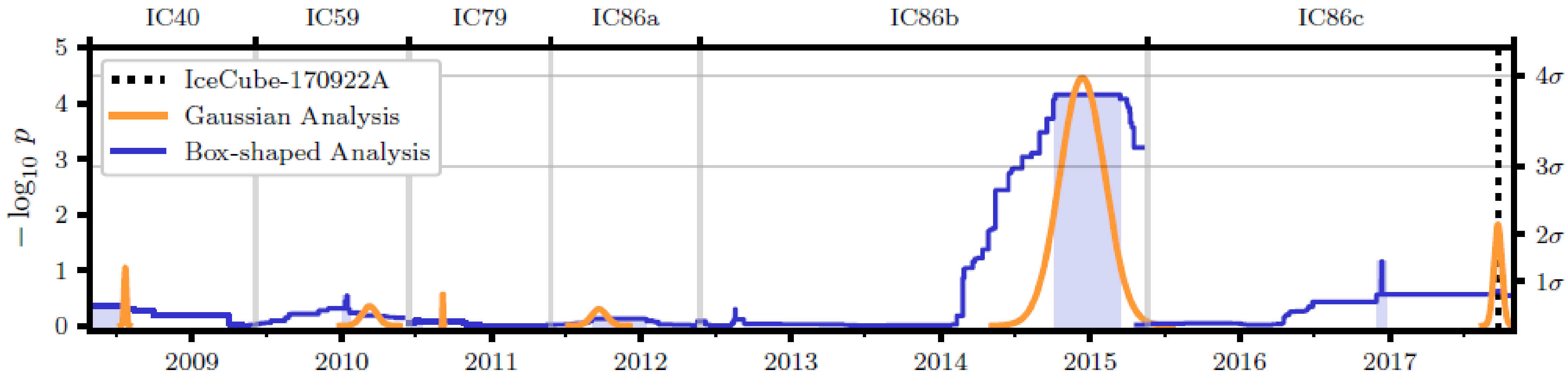
The Neutrino-Gamma connection

The IceCube archival analysis result

- Use the TXS 0506+056 location for evaluation
- Use unbinned likelihood with a Gaussian spatial pdf and $\Phi \cdot E^{-\gamma}$ energy pdf
- Use a Gauss c.q. Box time window T_W around a central time T_0

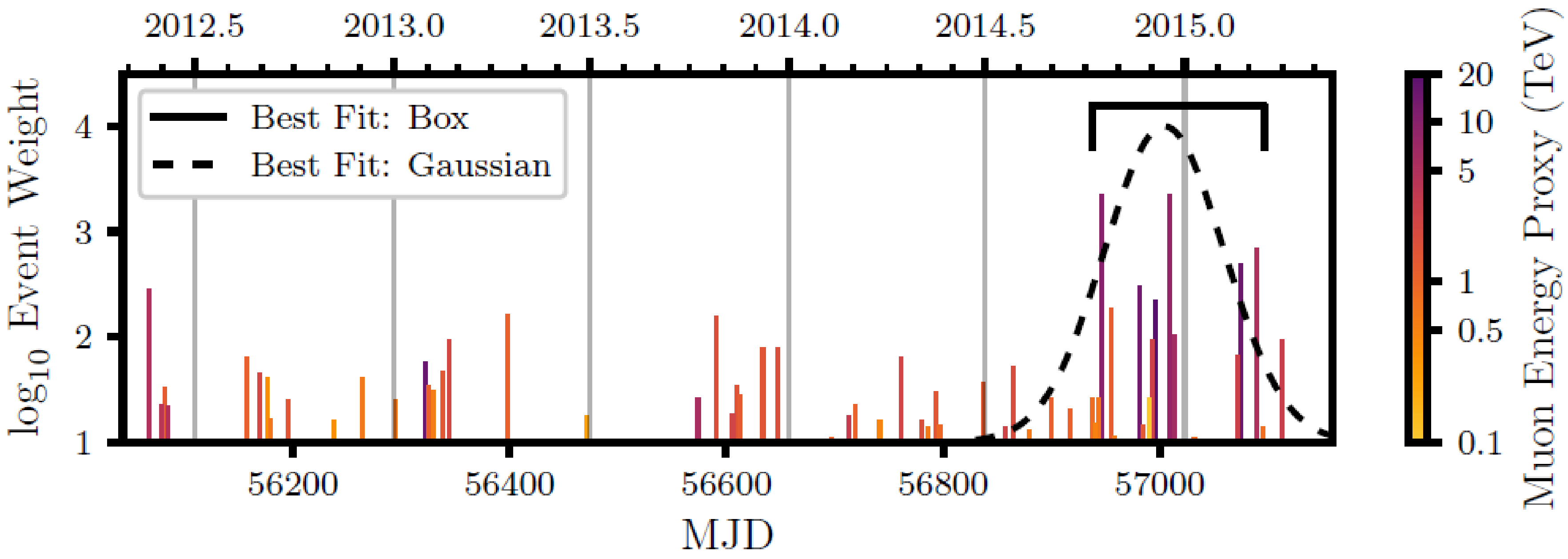
  $\rightarrow$ Search for event clustering with Spatial*Energy*Time weights
- Use randomized data to represent background and determine the significance

  $\rightarrow$ Find (Φ, γ, T_0, T_W) that maximizes the likelihood ratio



The Neutrino-Gamma connection

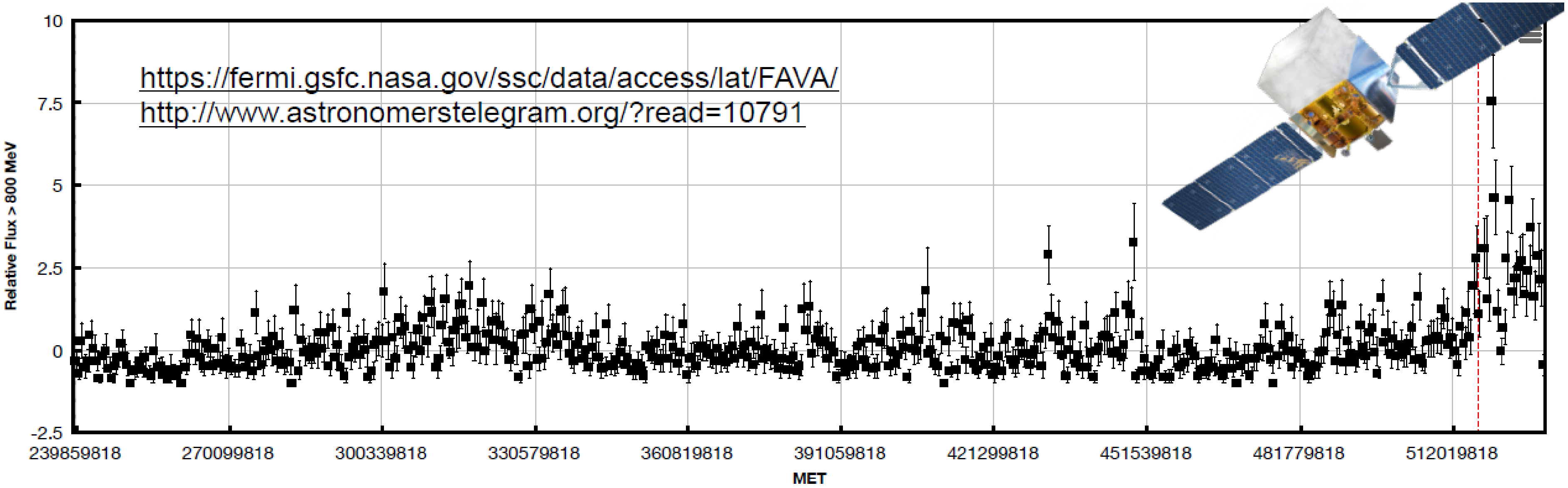
Spatial*Energy weights for the IceCube archival IC86b data



- Gaussian time window: T_0 =13-dec-2014 $\pm$ 21 days $T_W = 110^{+35}_{-24}$days
- Excess of 13 ± 5 events above atmospheric background
- Best spectral fits: $\int \Phi dt = 2.1^{+0.9}_{-0.7} \cdot 10^{-4}$ TeV cm^{-2} at 100 TeV $\quad \gamma = 2.1 \pm 0.2$
- Box time window: T_0 =26-dec-2014 T_W =158 days and similar spectrum

The Neutrino-Gamma connection

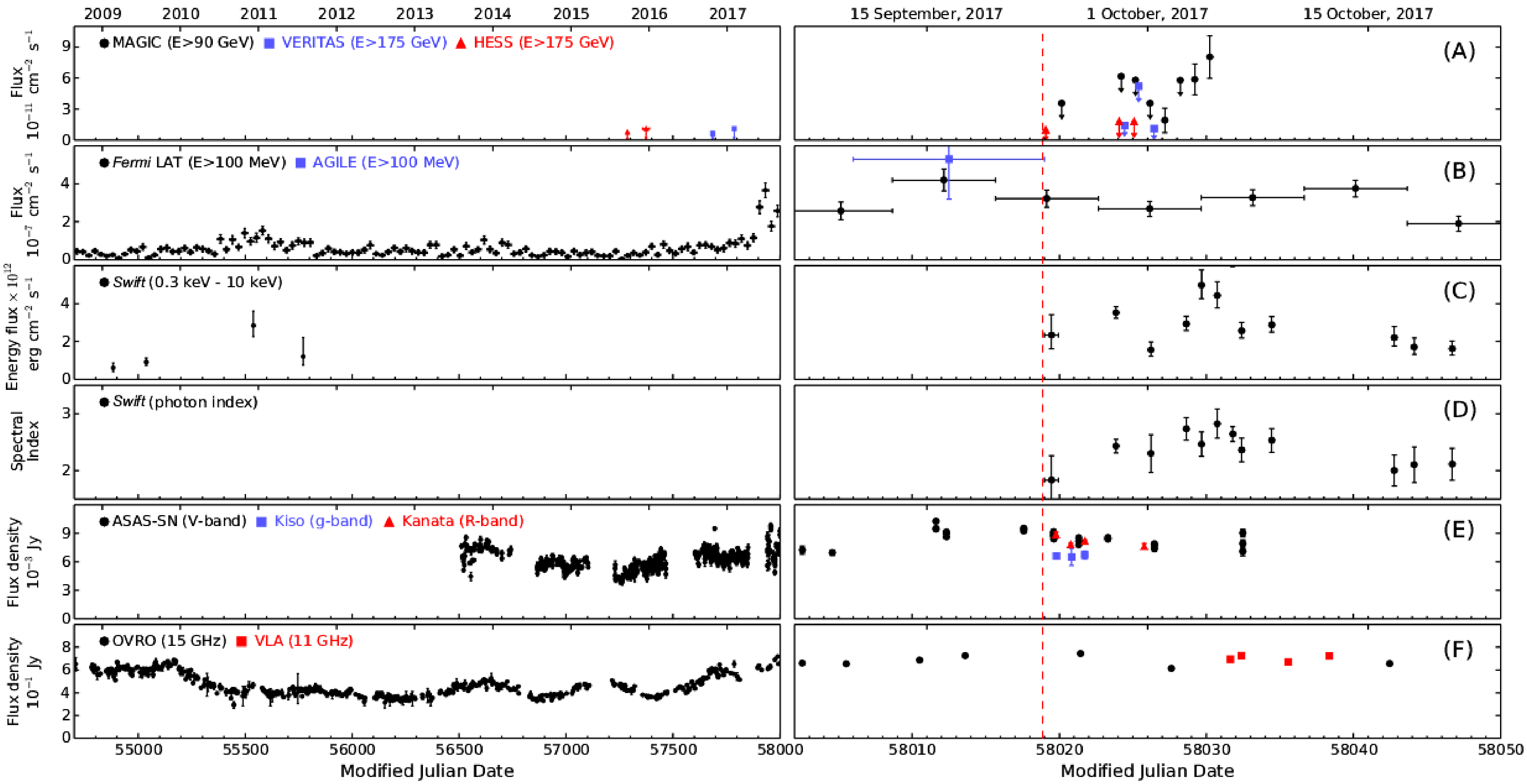
Fermi lightcurve for IC170922A



[Credit M. Kowalski SuGAR2018]

The Neutrino-Gamma connection

The TXS 0506+056 Multi-wavelength lightcurves



The Neutrino-Gamma connection

- Fermi EGB observations

  $\sim$85% of diffuse γ's from Blazars
- IceCube observations [ApJ 835 (2017) 45]

  Cosmic ν's NOT from Fermi Blazars
- Take EGB NON-Blazar component

  $\longrightarrow$ Prediction for ν flux

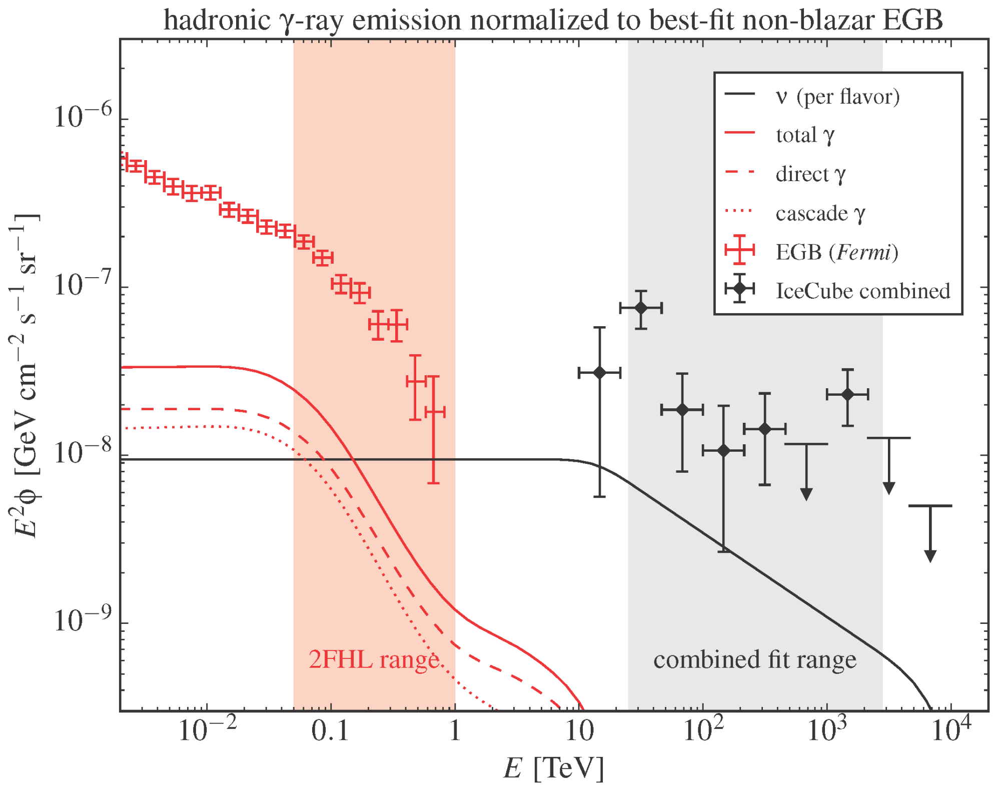
$*$ ν flux underestimated

Fermi and IceCube data tension

- Cosmic ν's from obscured sources ?

  [PRD 94 (2016) 103007]
- Dust may provide a "CR beam dump"

  $\longrightarrow$ Neutrino factory



[arXiv:1511.00688]

(2FHL: 2nd Fermi Hard Source List)

The Neutrino-Gamma connection

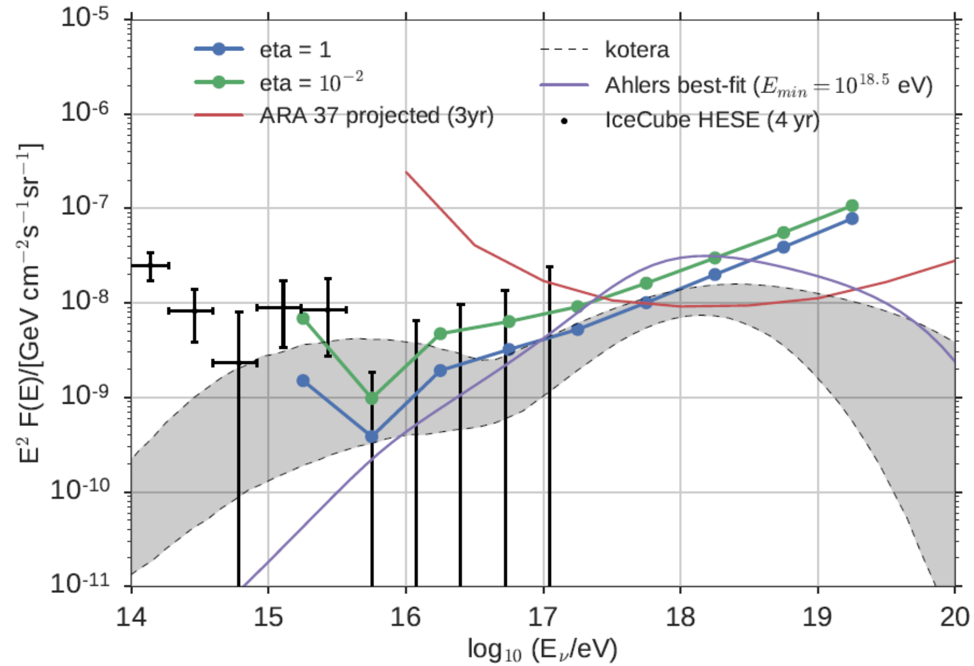
More neutrino data needed at multi-PeV energies

Radio signals of ν showers

- Long (km-scale) attenuation length
  Cover large ($\sim$200 km^2) area
- Detect events $> 10^{17}$ eV
- GZK ν : Proof of GZK effect
  or : Insight in UHECR composition
- $p + \gamma \to \Delta \to \nu \quad (E_\nu \approx 4\% \ E_p)$
  $p + \gamma_{EBL}$: Low-E bump
  $p + \gamma_{CMB}$: High-E bump
- Iron: lower E/A and dissociation
  $\to$ Higher E threshold and lower flux
- IceCube-Radio energy gap
  Currently not covered

The multi-PeV neutrino landscape

[arXiv:1802.05543]

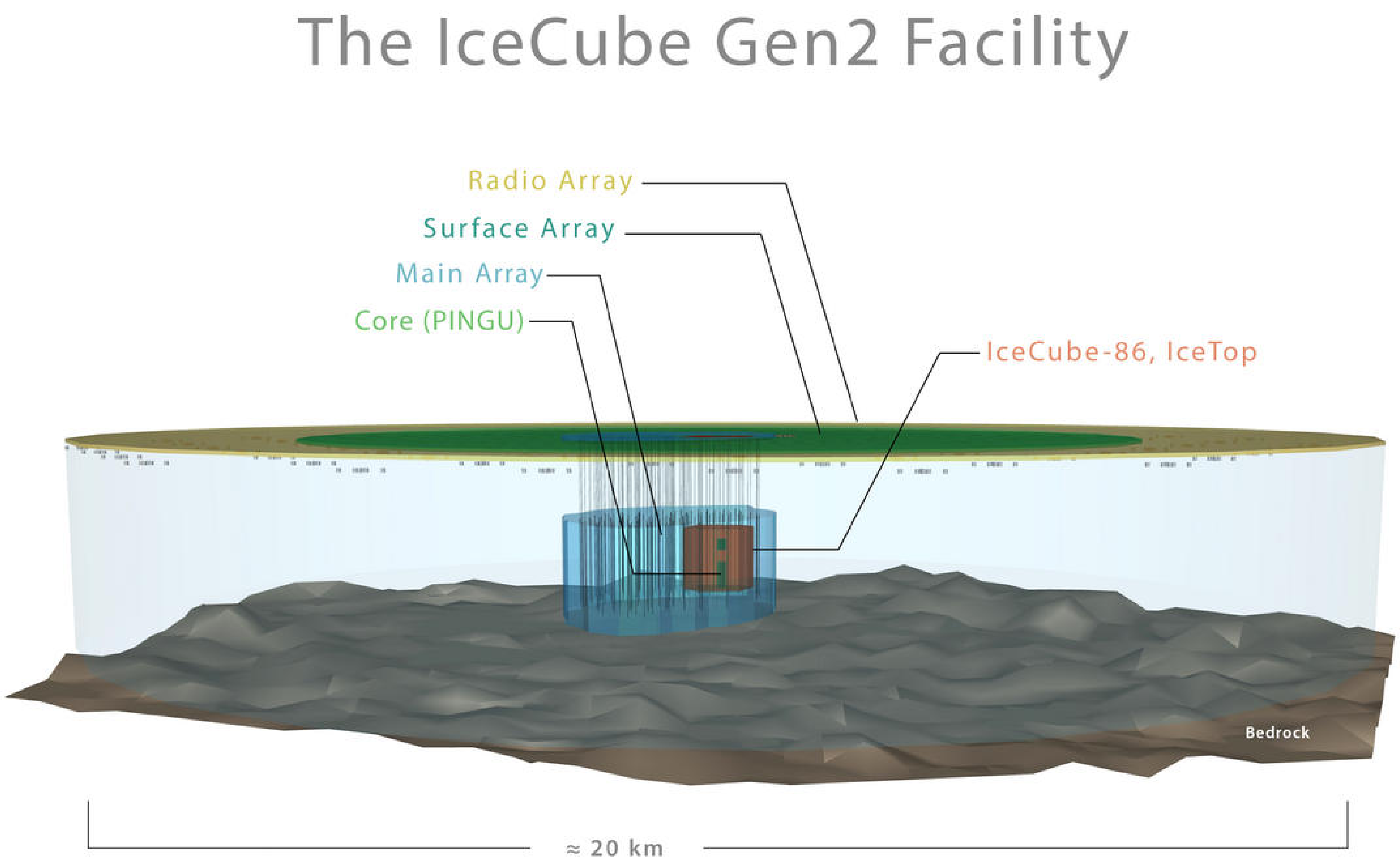


Radar reflections from shower plasma

New idea (VUB) for $E < 10^{17}$ eV

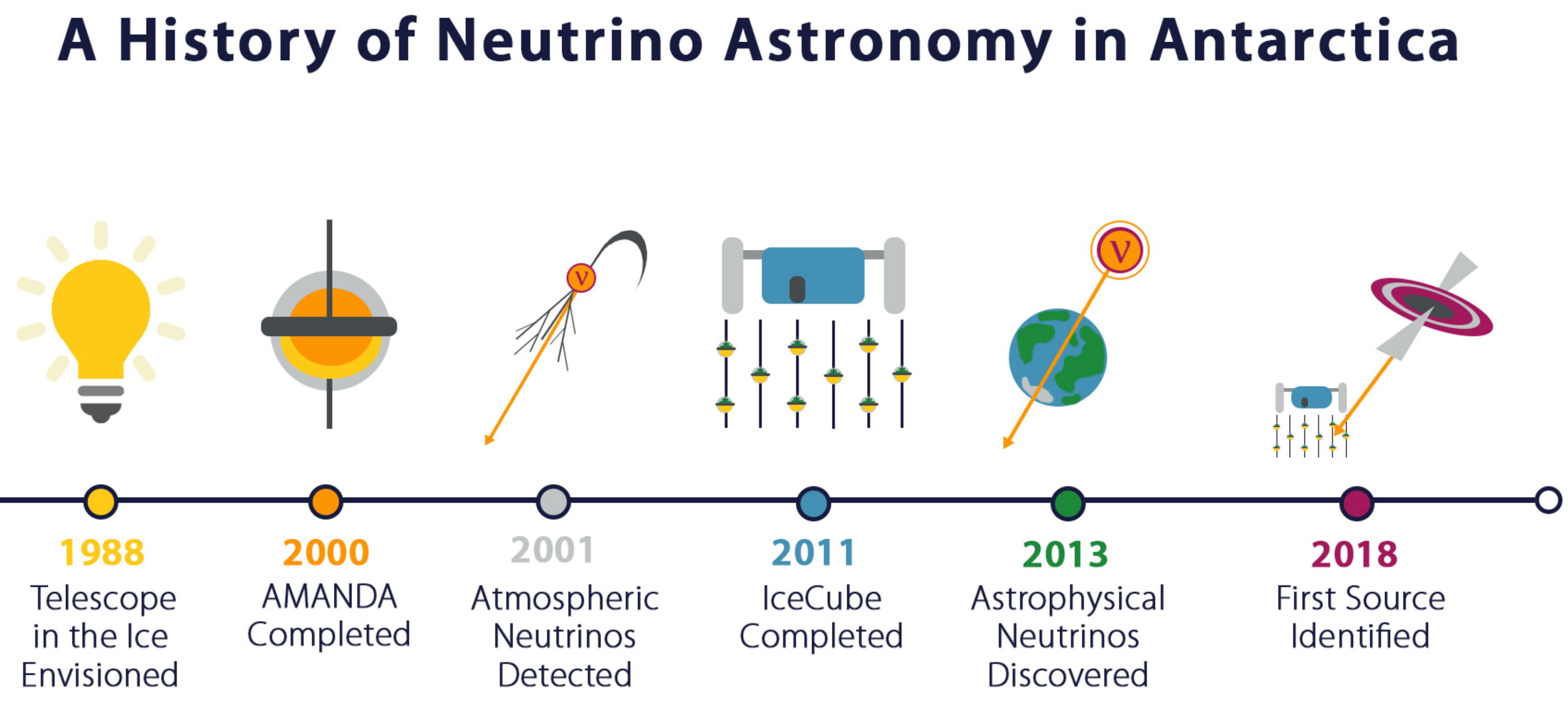
Fill IceCube-Radio E gap

The Neutrino-Gamma connection



The Neutrino-Gamma connection

IceCube has now really opened the area of Neutrino Astronomy !



The Neutrino-Gamma connection

The curtain has been raised.......

Let the show begin !