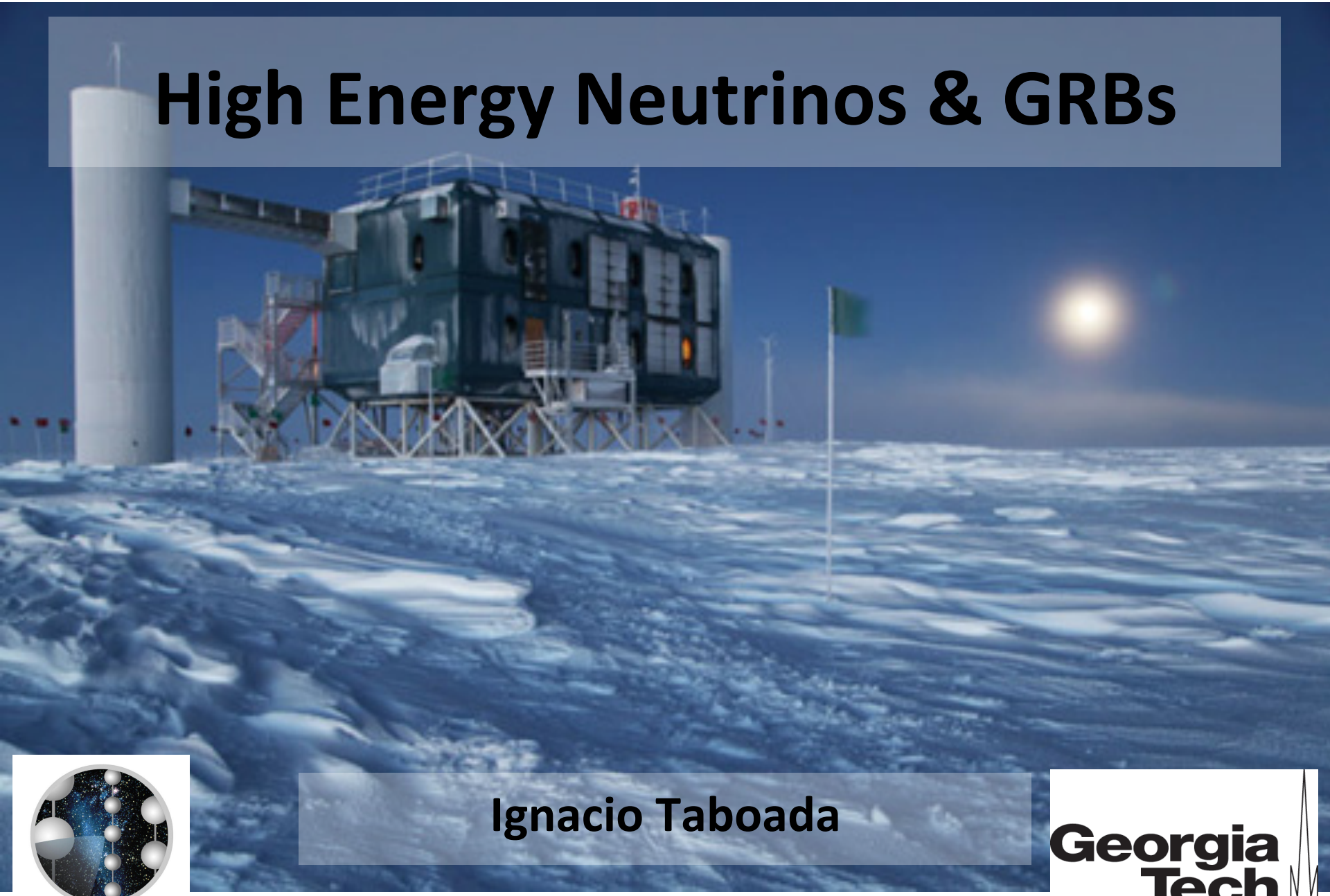
High Energy Neutrinos & GRBs

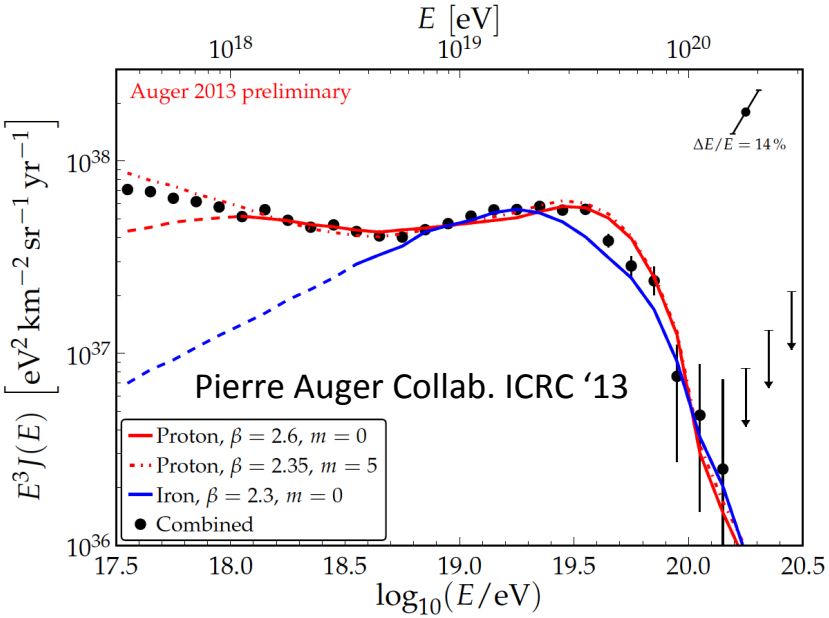


Ignacio Taboada

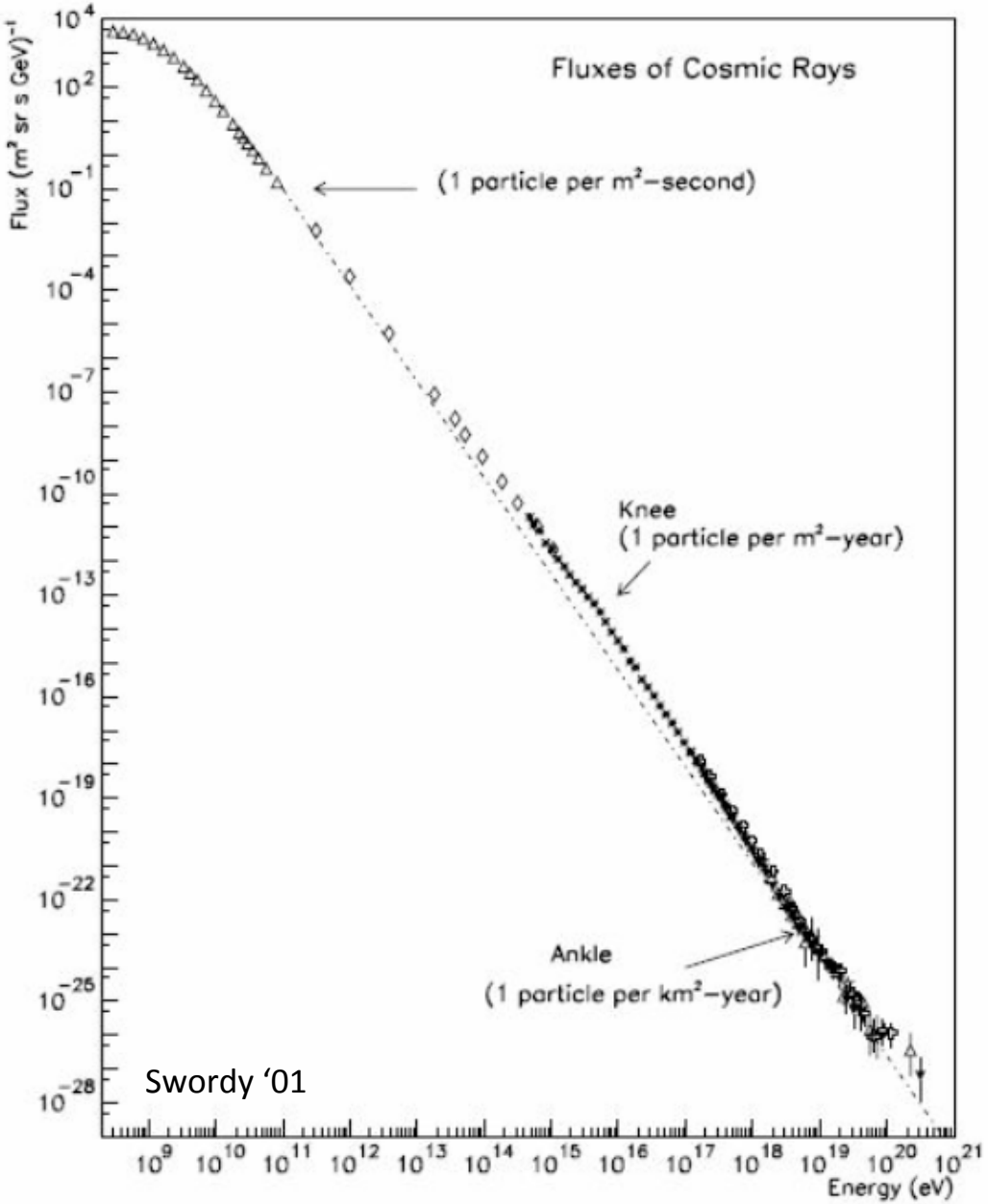
ICECUBE

Georgia Tech

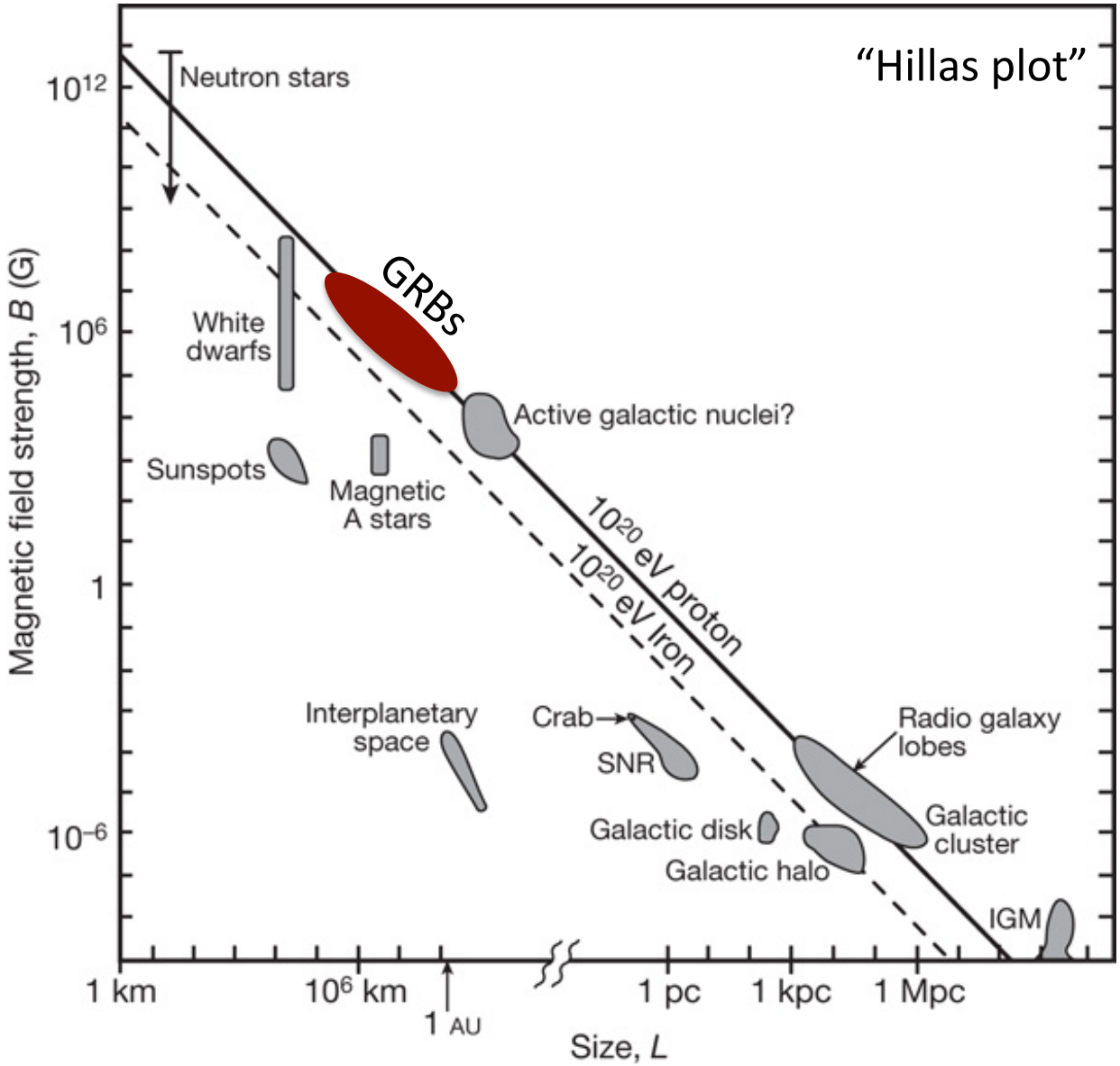
Cosmic Rays



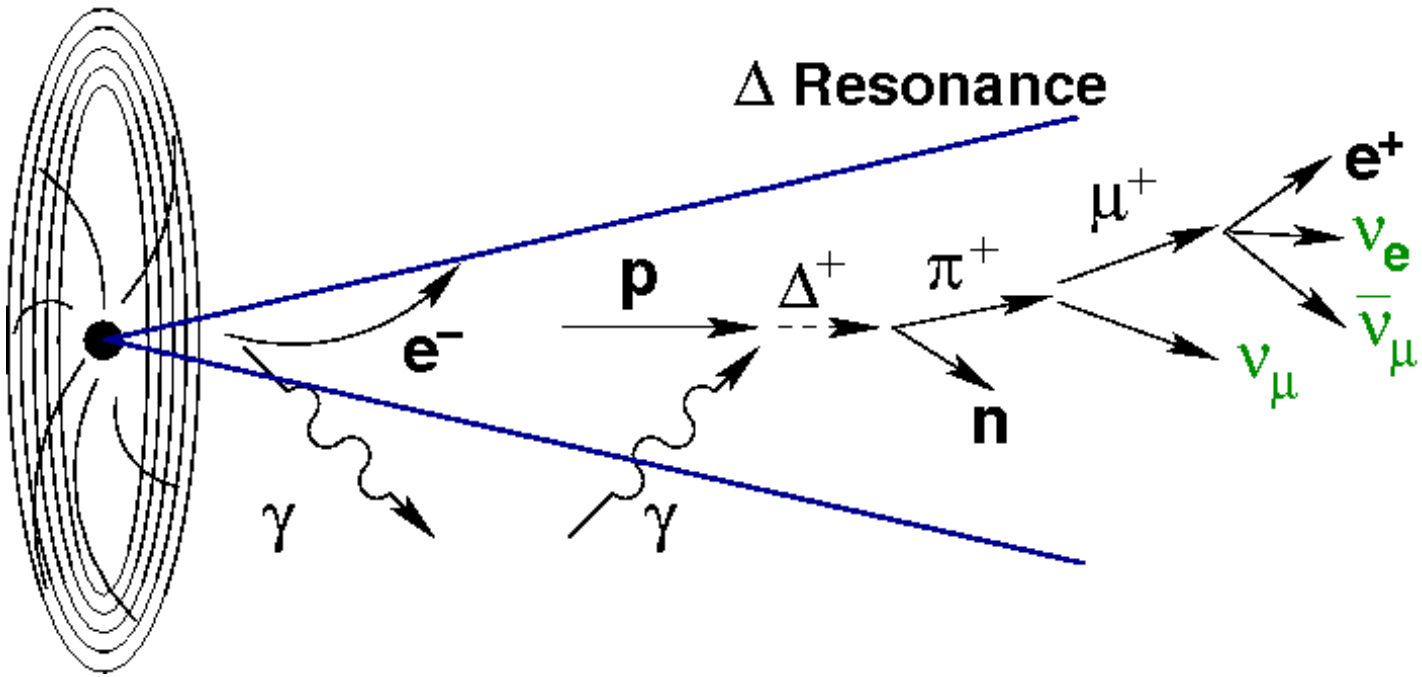
Victor Hess



Cosmic Rays from Gamma Ray Bursts

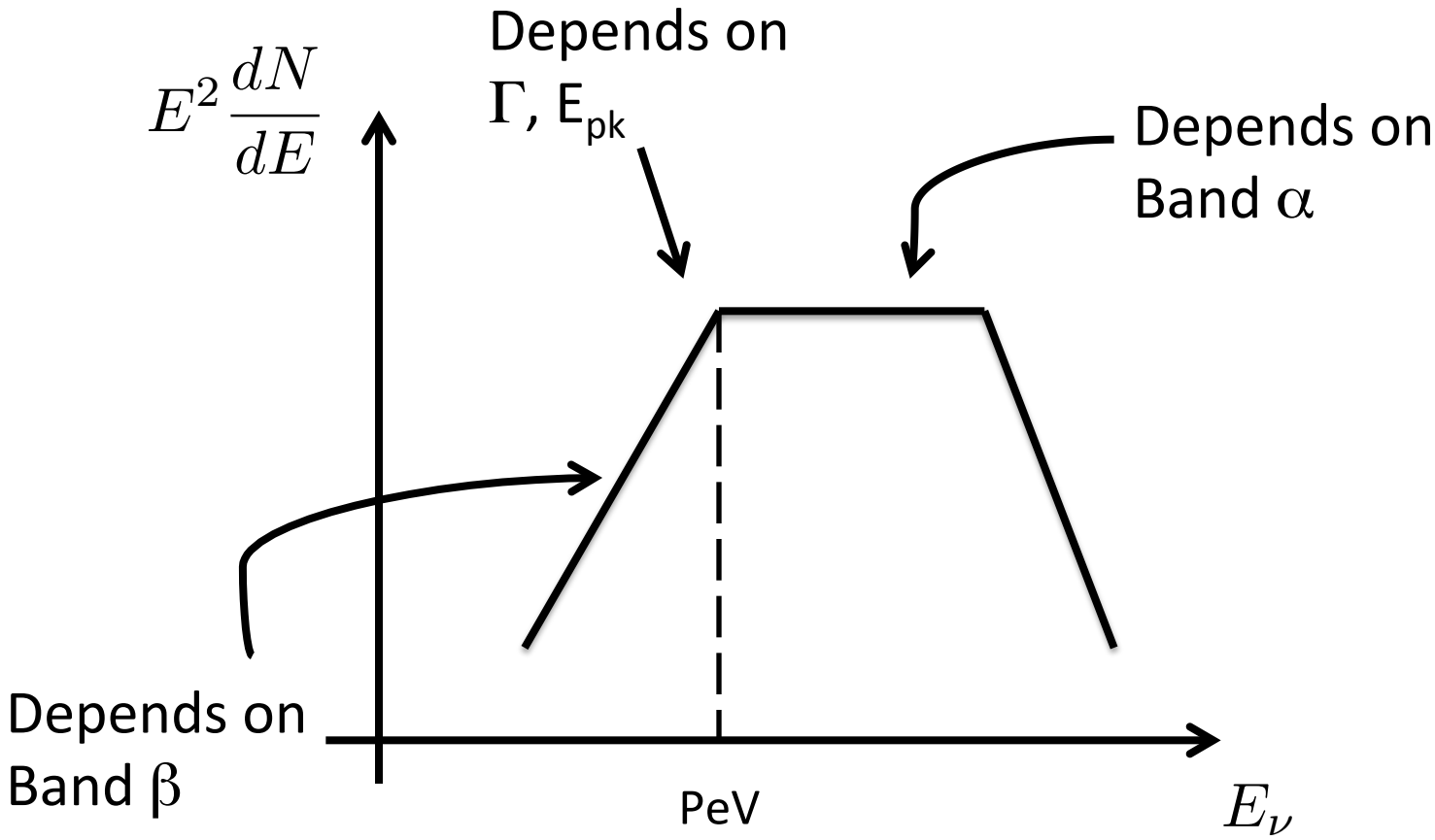


VHE Neutrinos from GRBs



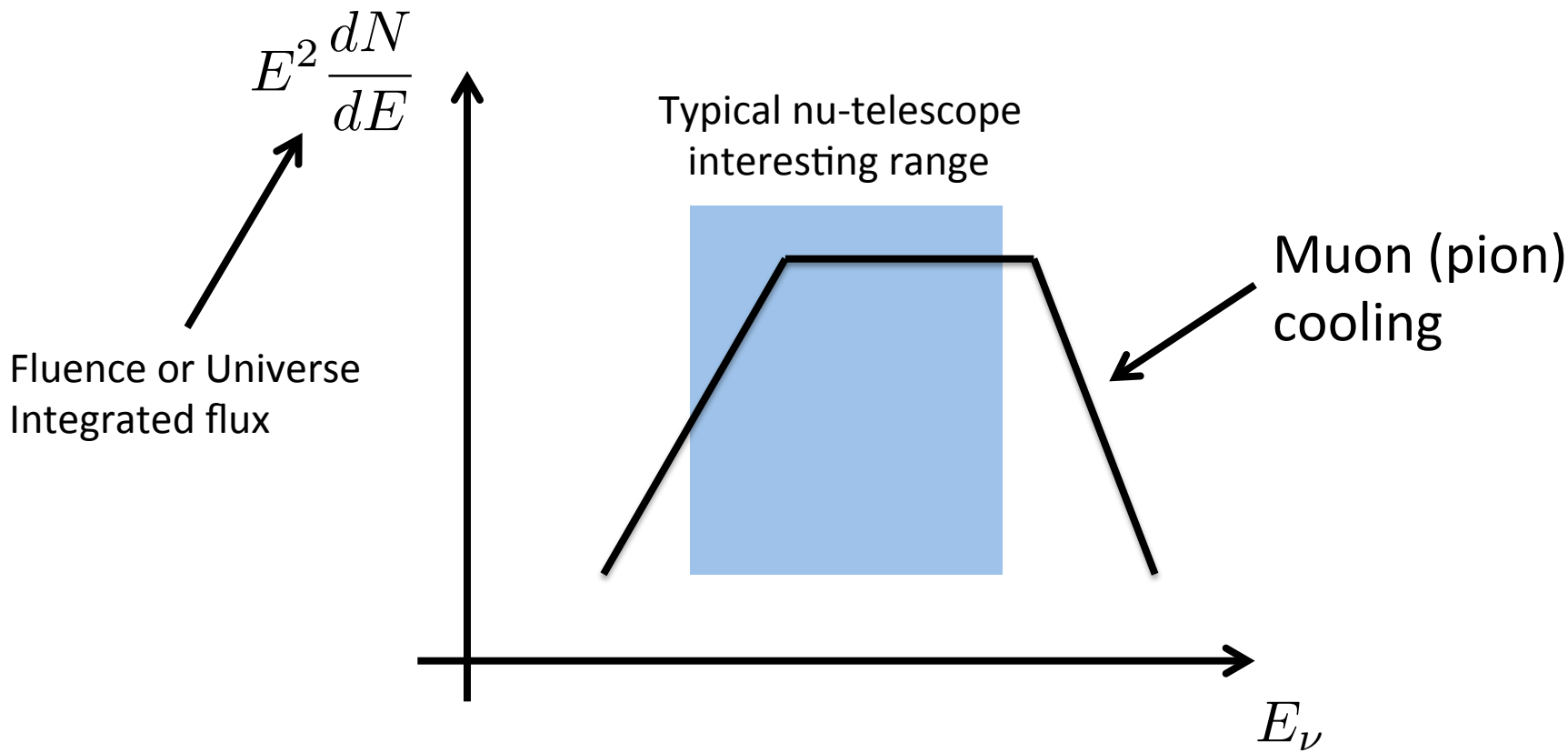
Precursor (or choked GRBs) neutrinos via p-p interactions
Burst (prompt) neutrinos
Afterglow neutrinos

Prompt neutrinos from GRBs: simplified



$$p + \gamma \rightarrow \Delta^+ \rightarrow ...$$

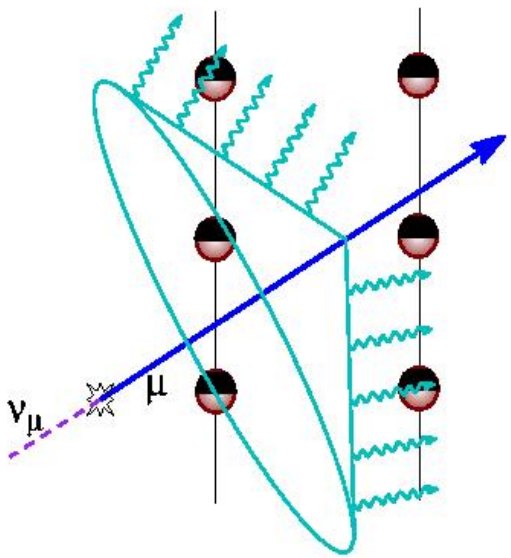
Prompt neutrinos from GRBs: simplified



GRBs as source of C.R. via neutron escape
GRBs as source of C.R. via proton escape
Fireball (internal shock) model
Photospheric model
Magnetic reconnection

High-energy neutrino detection

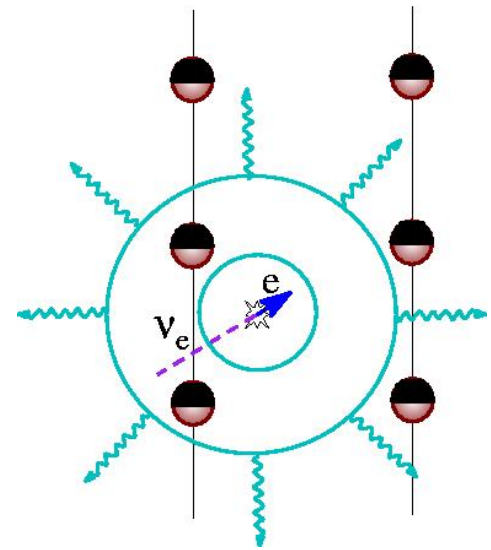
Tracks



O(km) muon tracks

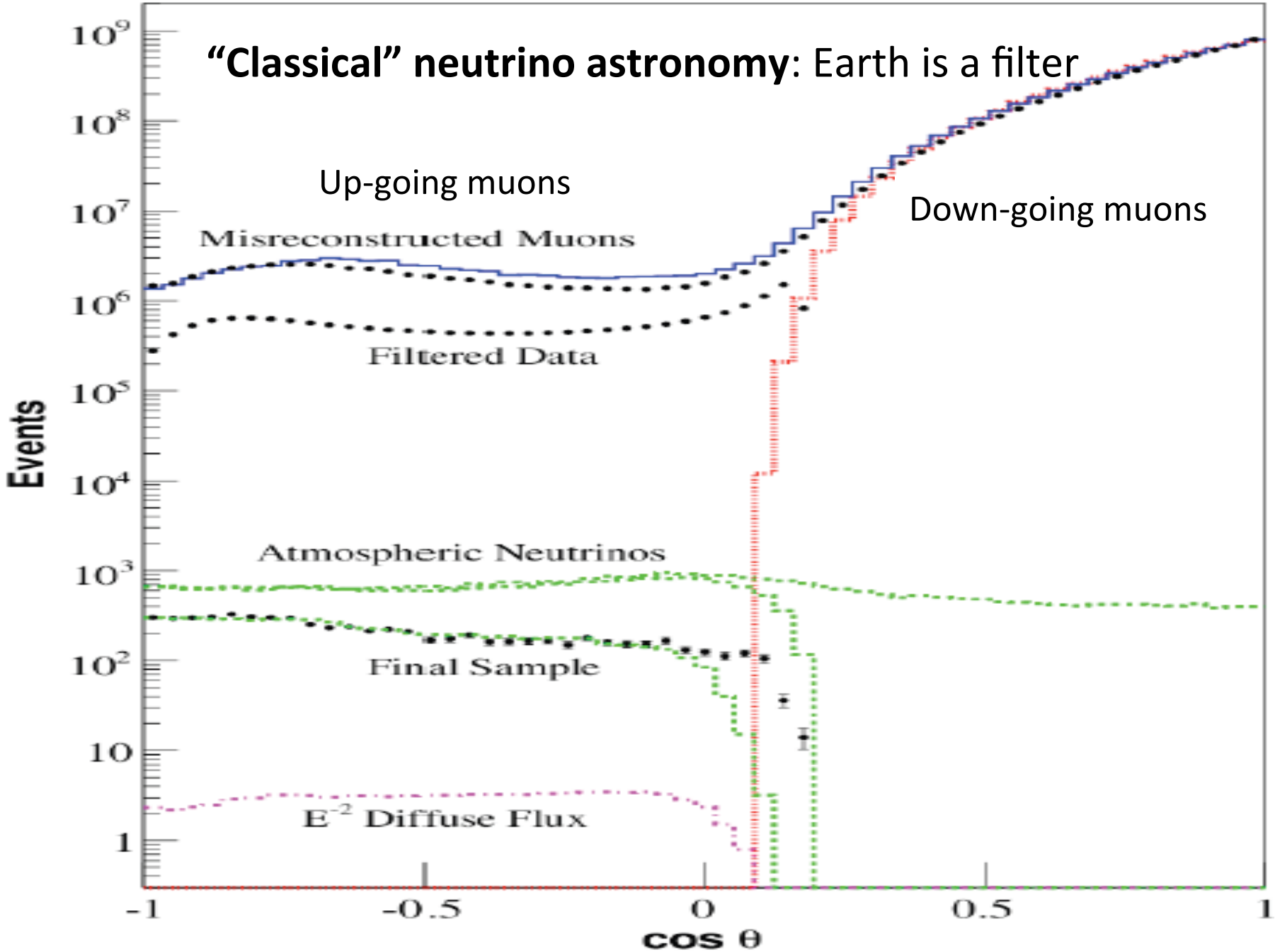
- ✓ PSF 1°
- ✓ ν_μ sensitivity

Cascades

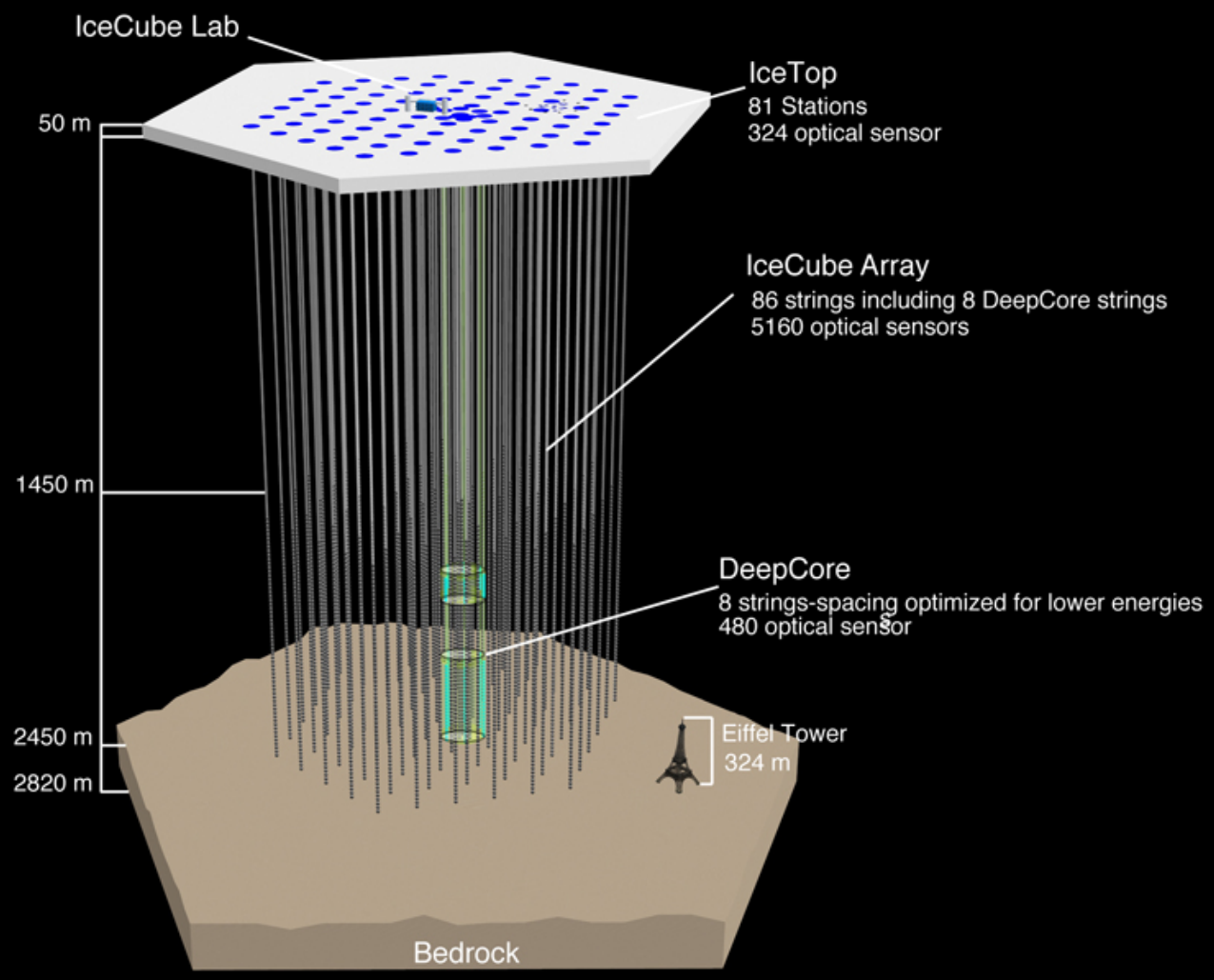


Light point sources

- ✓ 10% (vis.) energy resolution
- ✓ PSF: 10°-40°
- ✓ 4π sensitivity
- ✓ All flavor sensitivity


"Classical" neutrino astronomy: Earth is a filter
Up-going muons
Down-going muons
Misreconstructed Muons
Filtered Data
Atmospheric Neutrinos
Final Sample
E^-2 Diffuse Flux
Events
cos θ
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
-1
-0.5
0
0.5
1

IceCube



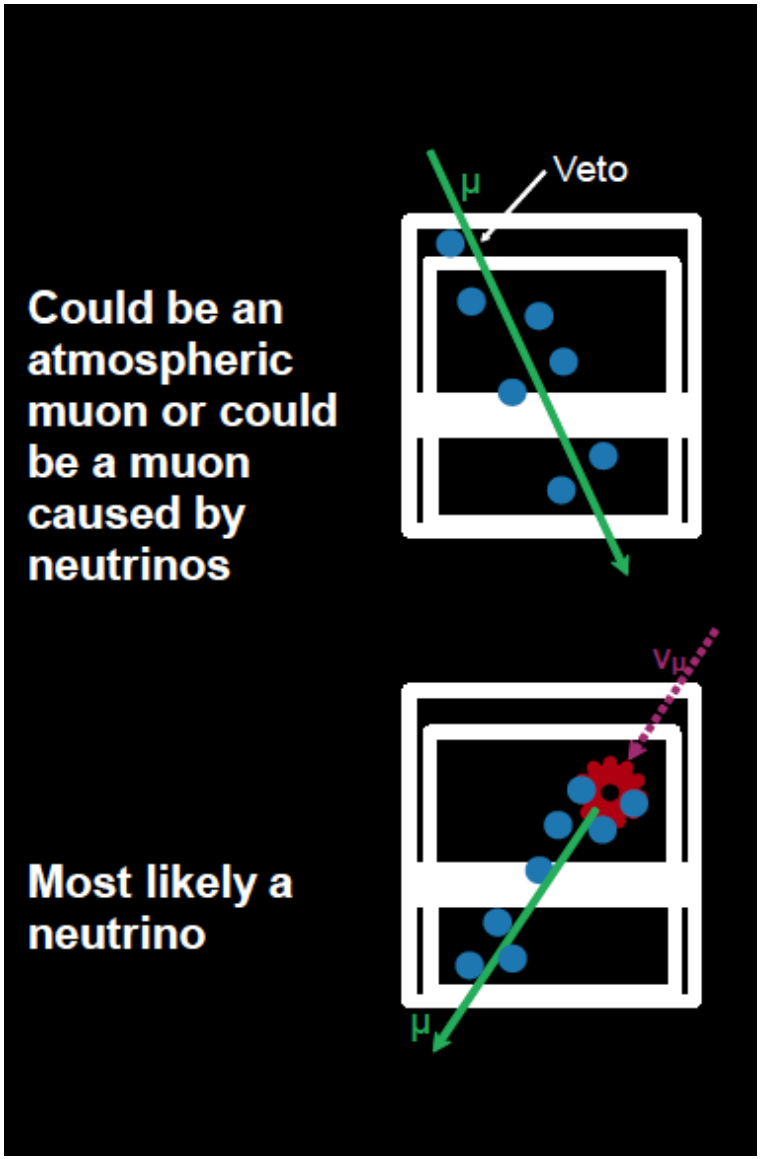
Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

Partial detectors analyzed:
IC22, IC40, IC59, IC79

Full detector:
IC86: 3 ½ years and counting …

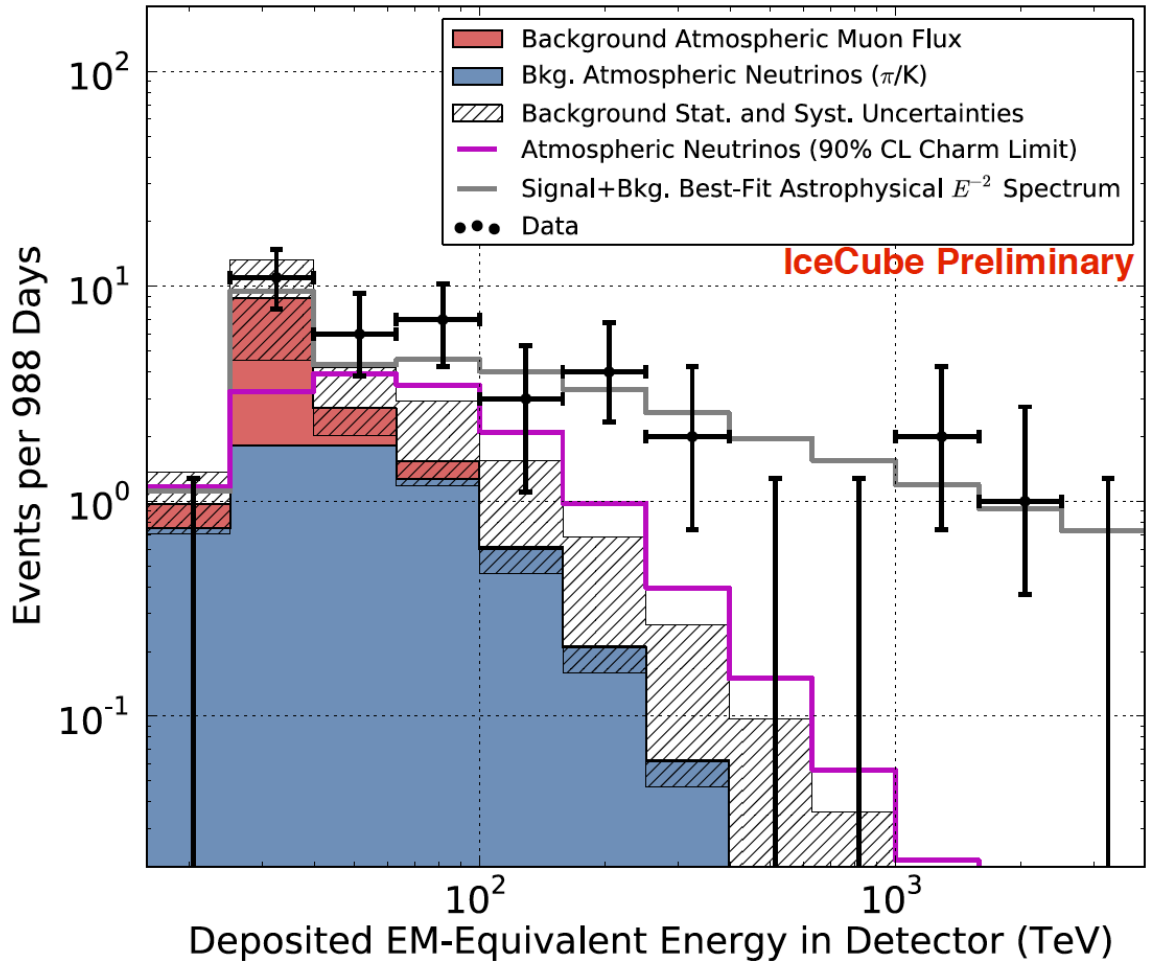
Astrophysical neutrinos: IceCube detection



Search for bright (high-energy) semi-contained events

- ✓ Sensitive to all flavors cascades and muon tracks
- ✓ Sensitive to 4 π sr
- ✓ Measure down-going muon bckg. with double veto layer
- ✓ Down-going atm. neutrinos vetoed

Astrophysical neutrinos: IceCube detection

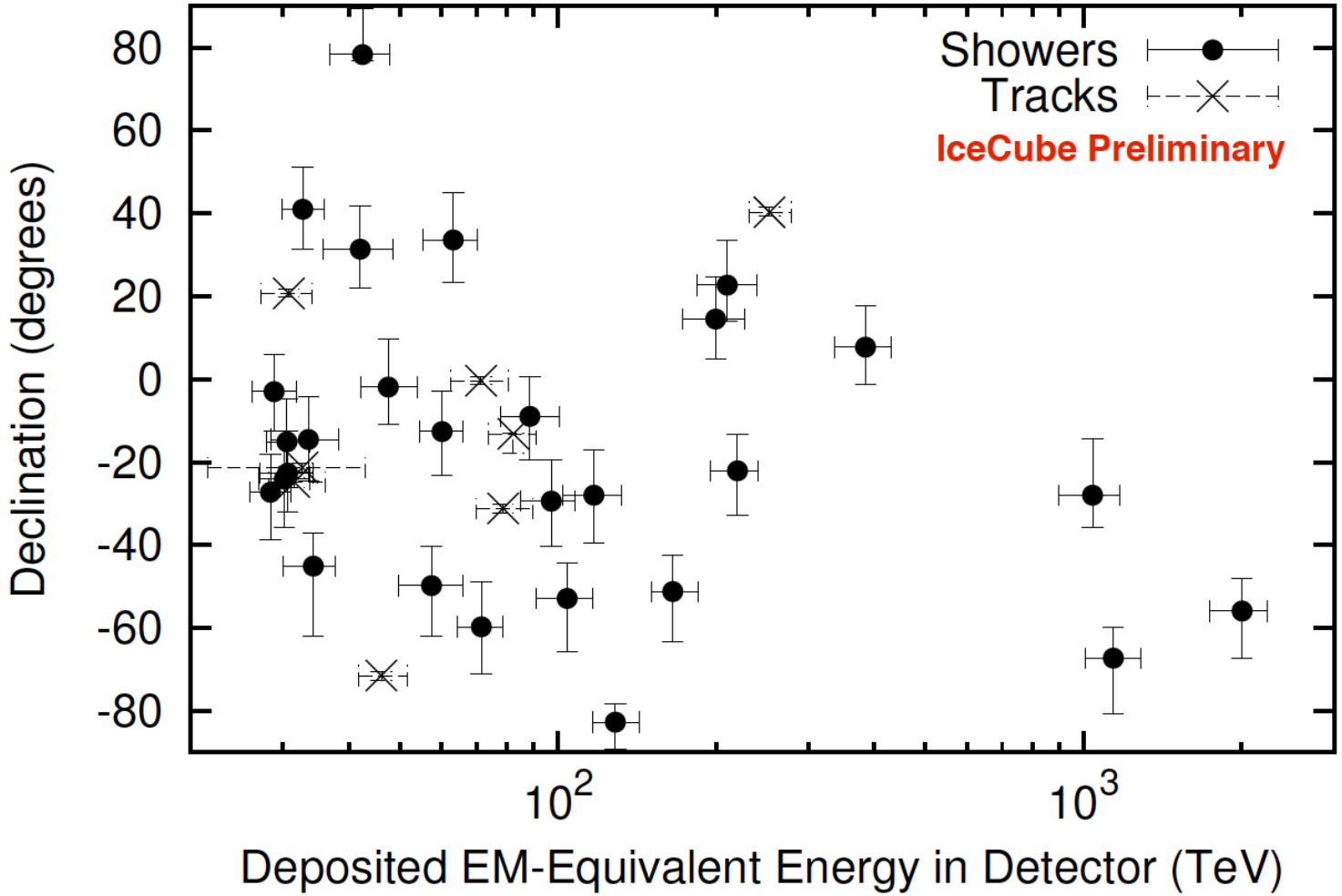


IceCube
Submitted to PRL

37 events found

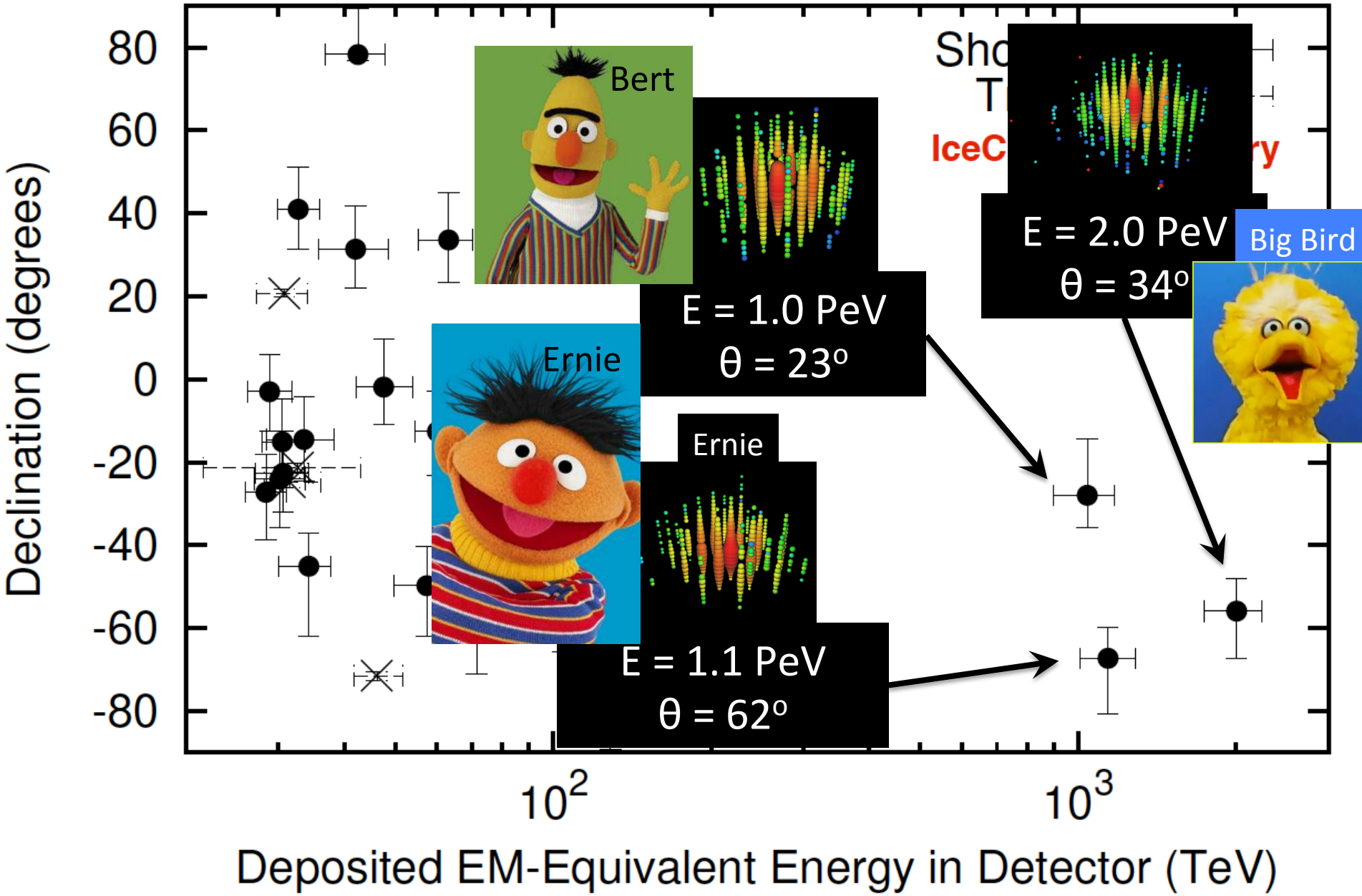
Bckg: 8.4 ± 4.2 (muons) + 6.6 $^{+5.9}_{-1.6}$ (atm ν)

Atmospheric only hypothesis rejected at 5.7 σ



Best fit for astrophysical spectrum (per flavor):

$$E^2\phi = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}}$$


Declination (degrees)
80
60
40
20
0
-20
-40
-60
-80
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)
Bert
Ernie
Ernie
Big Bird
E = 1.0 PeV
θ = 23°
E = 2.0 PeV
θ = 34°
E = 1.1 PeV
θ = 62°

GRB searches for neutrinos

I show results for three searches:
Muons, cascades, correlation with 35 events.

Likelihood ratio analysis

$$\lambda = -n_s + \sum_{i=1}^{N} \log\left(\frac{n_s S_i}{\langle n_b \rangle B_i} + 1\right)$$

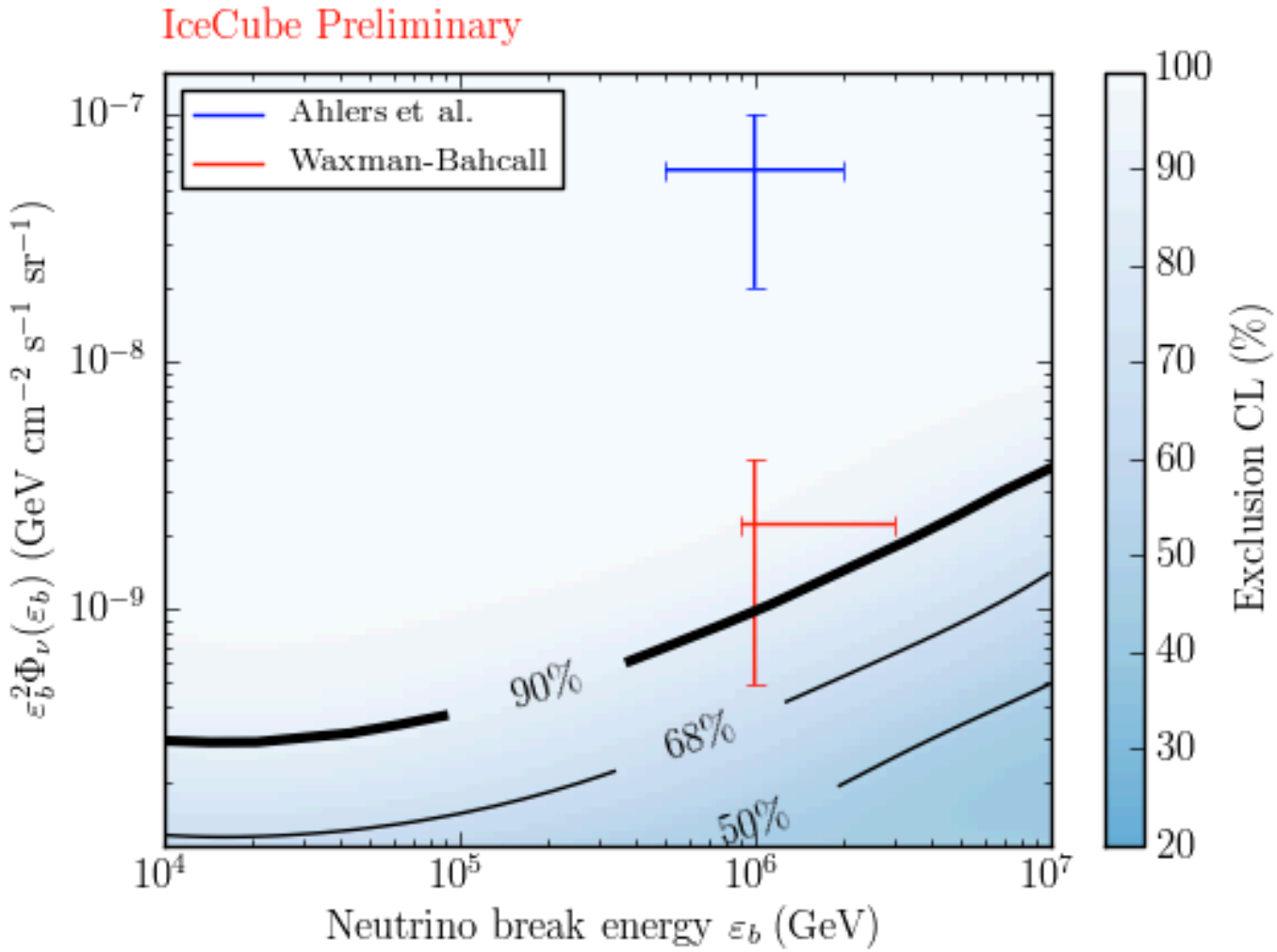
(likelihood for correlation with 35 events is similar but not identical)

Signal and background p.d.f. use <u>time</u> and <u>direction</u>. Sometimes also <u>energy</u>.

Event selection reduces event sample to neutrino-like events.

Off-time data used to measure background.

ν_μ limits: GRBs as C.R. sources

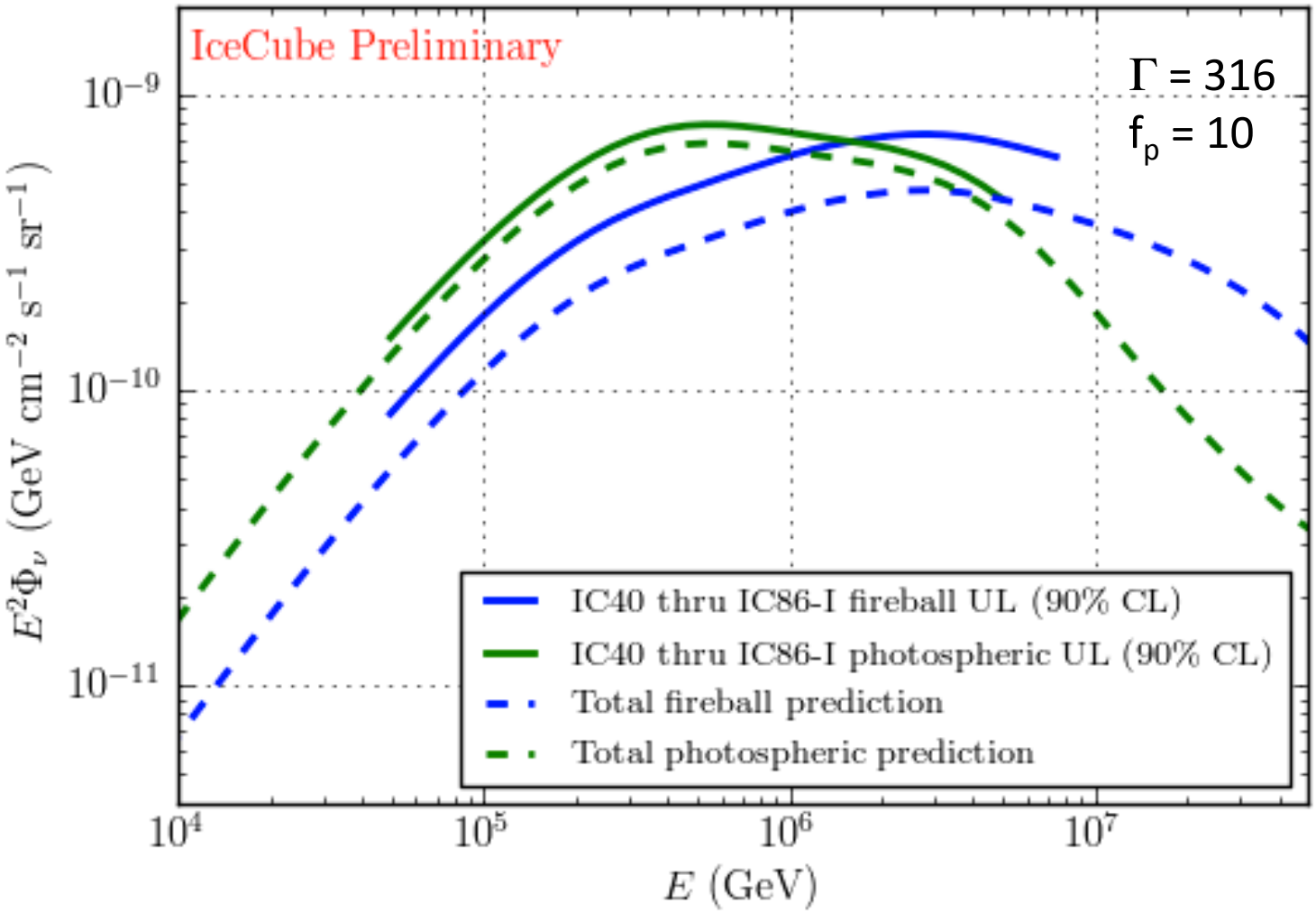


Update on Nature 484 (2012) 351

506 northern hemisphere GRBs IC-40 – IC-86-1 ("classical" ν astronomy)

Prompt phase

ν_μ limits: GRBs as neutrino sources

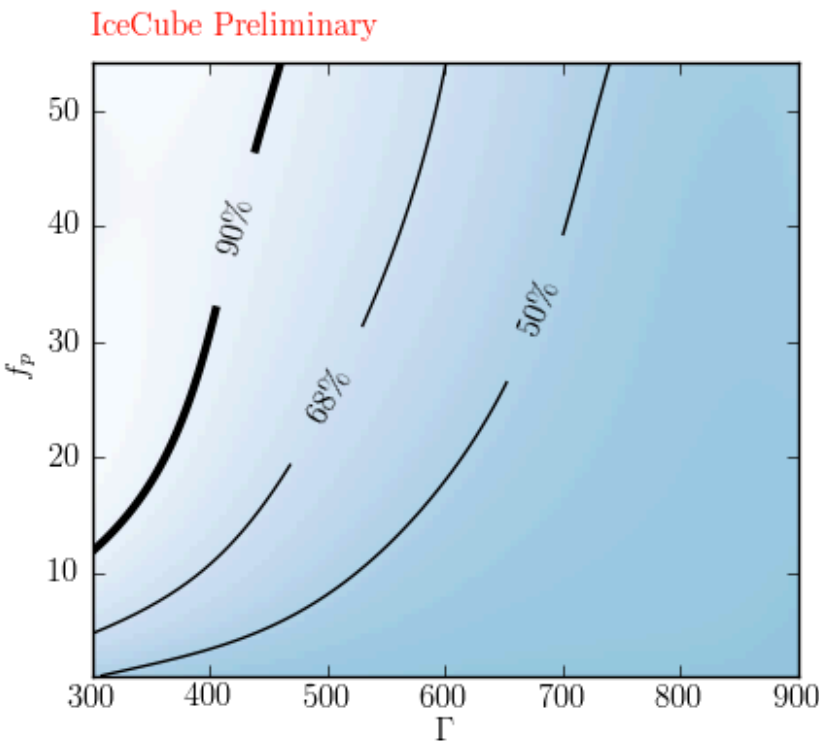


Observed flux is an order of magnitude above this figure …

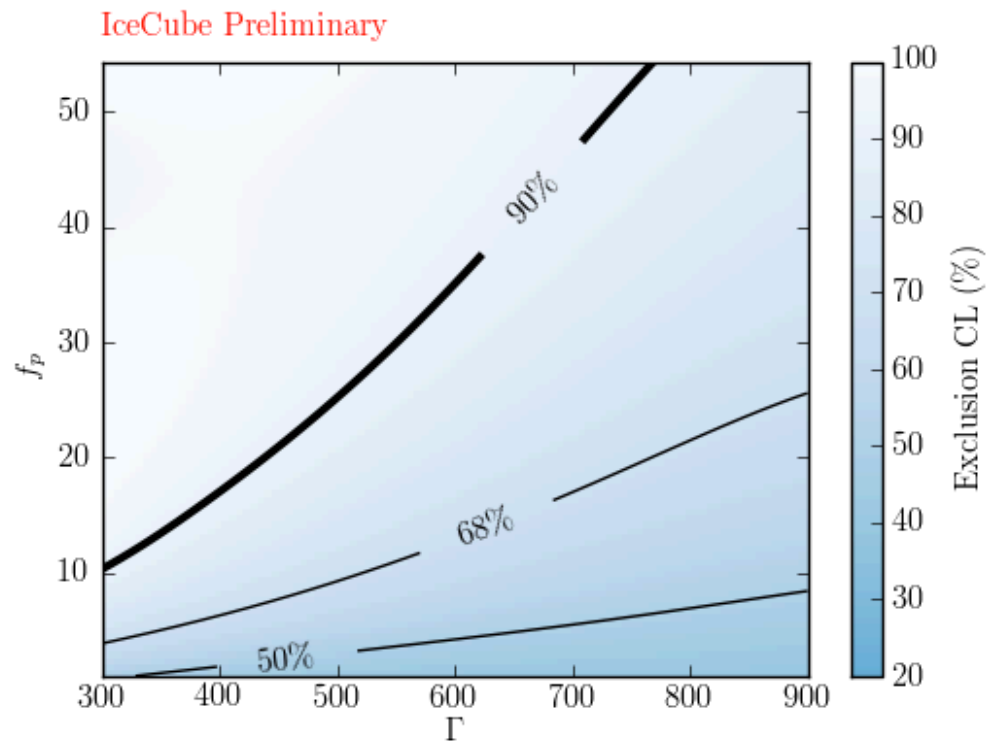
Difficult direct comparison, but ~x3 lower than IC40/59 limits.

506 northern hemisphere GRBs IC-40 – IC-86-1 ("classical" ν astronomy)
Prompt phase

ν_μ limits: GRBs as neutrino sources

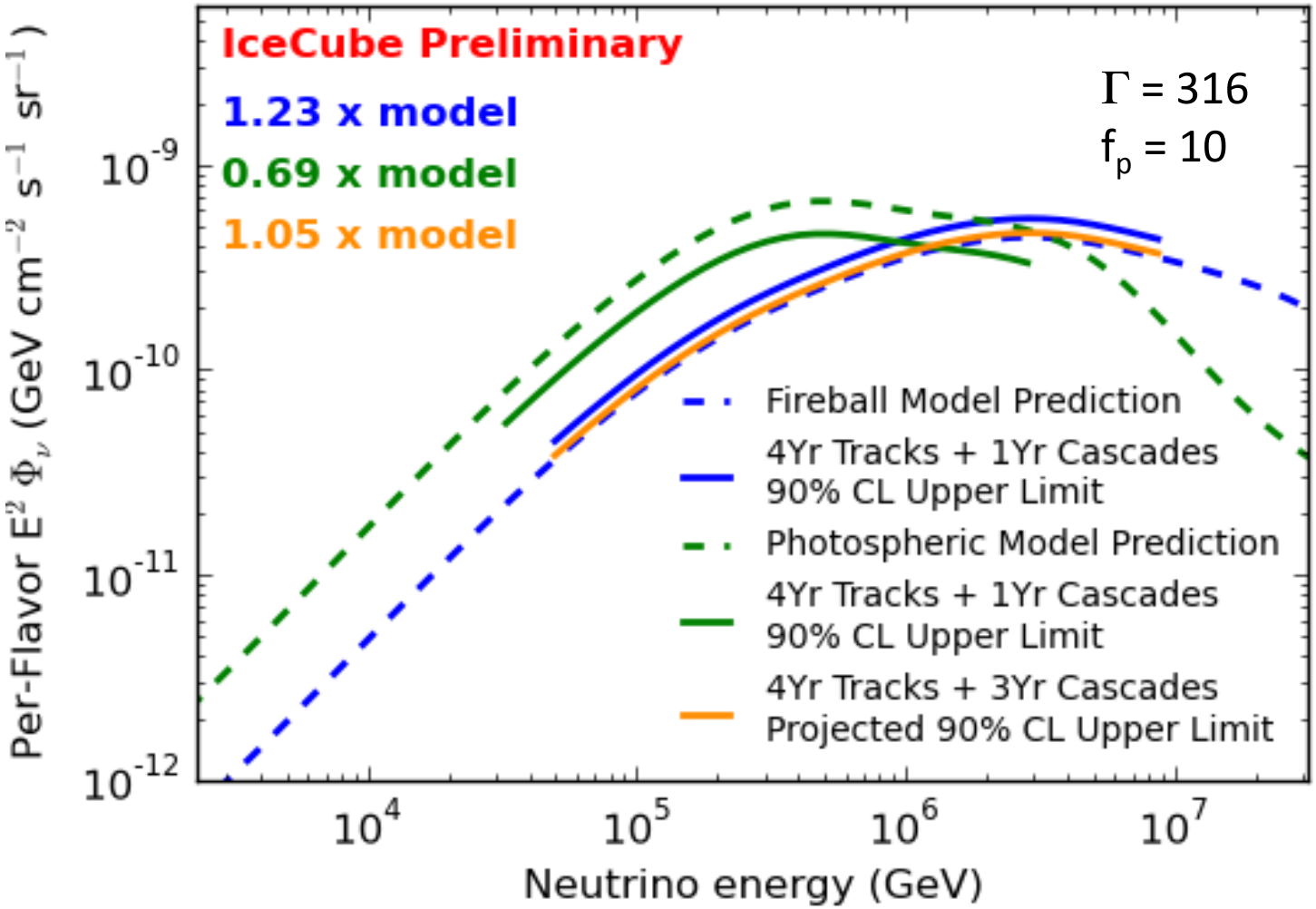


Standard fireball



Photospheric model

Cascade limits: GRBs as neutrino sources



257 northern hemisphere GRBs IC-79. 4 π sr.
prompt phase

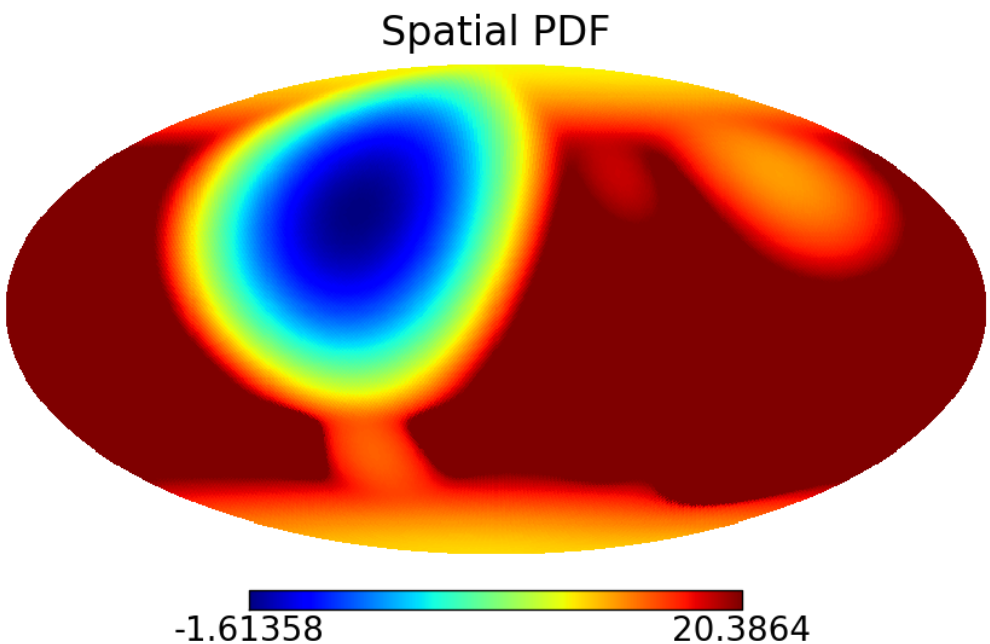
Are GRBs responsible for the IceCube flux?

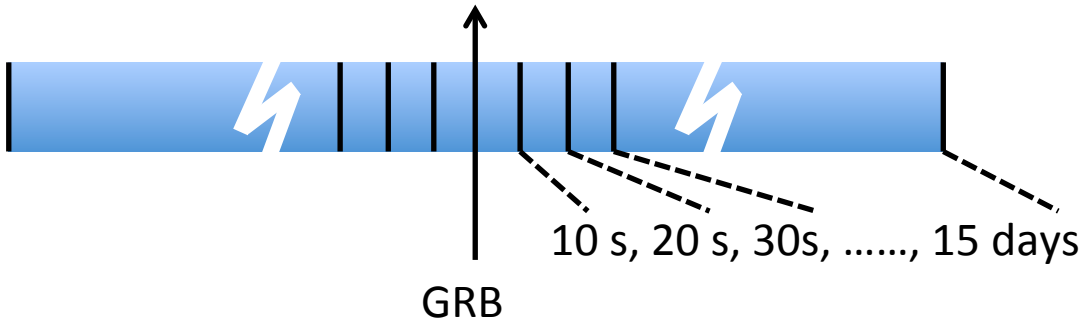
35 events (ignore 2)

568 GRBs

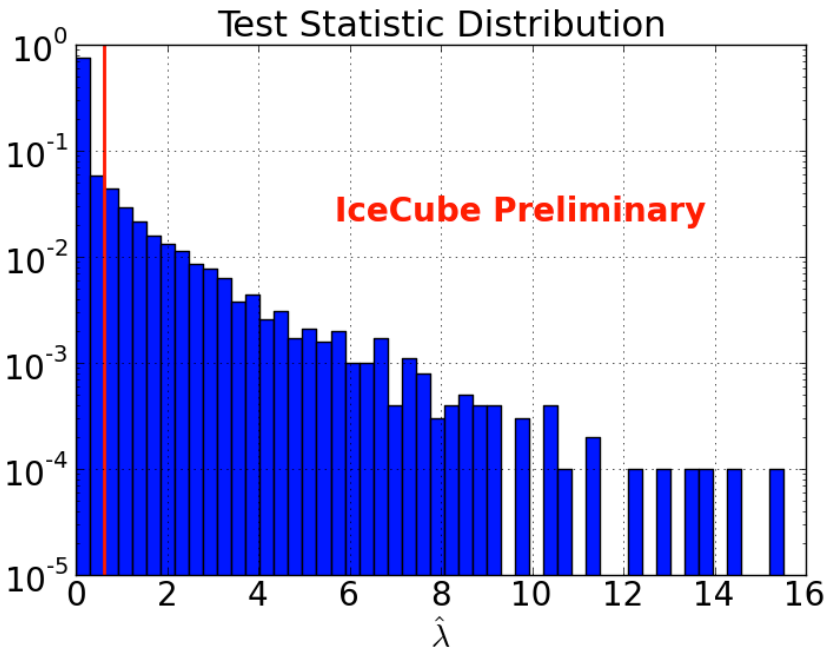
4π sr

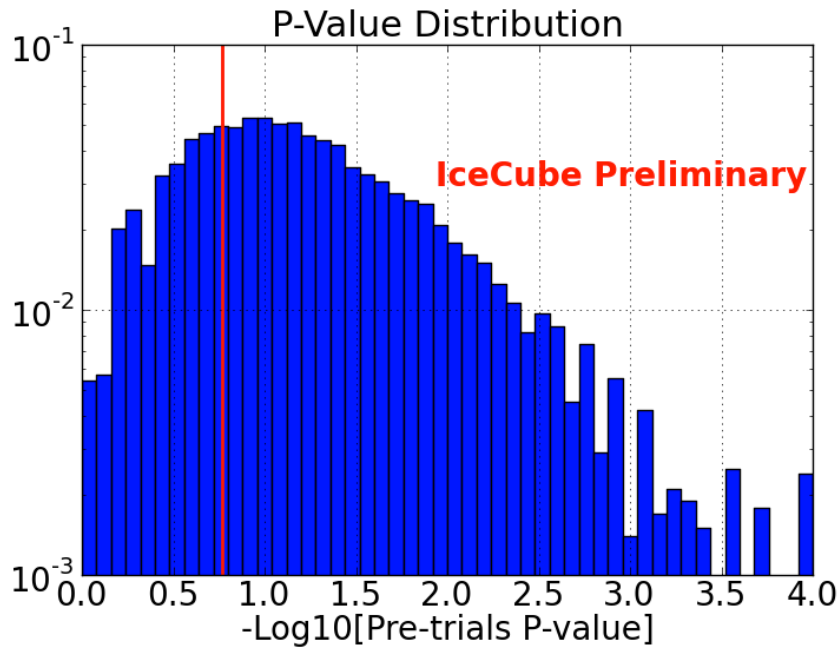
Likelihood ratio for ±10 s to ±15 days





Gamma Ray Bursts & the IceCube flux





Most significant time window: 4.9 days

Pre-trial p-value for this time window: 18.8%

Post-trial p-value: 76.8 %

Known GRBs are not the source of the IceCube flux even over very large time scales.

Searches not covered in this presentation

Neutrino multiplets ≥2 ν_μ (>TeV) within 100 s and 3.5^o

Optical (PTF, ROTSE) / X-ray (Swift) follow up (>TeV)

DeepCore transient search (50 – 200 GeV)

Transient point source search (>TeV)

Joint LIGO / IceCube all sky search. (>TeV)

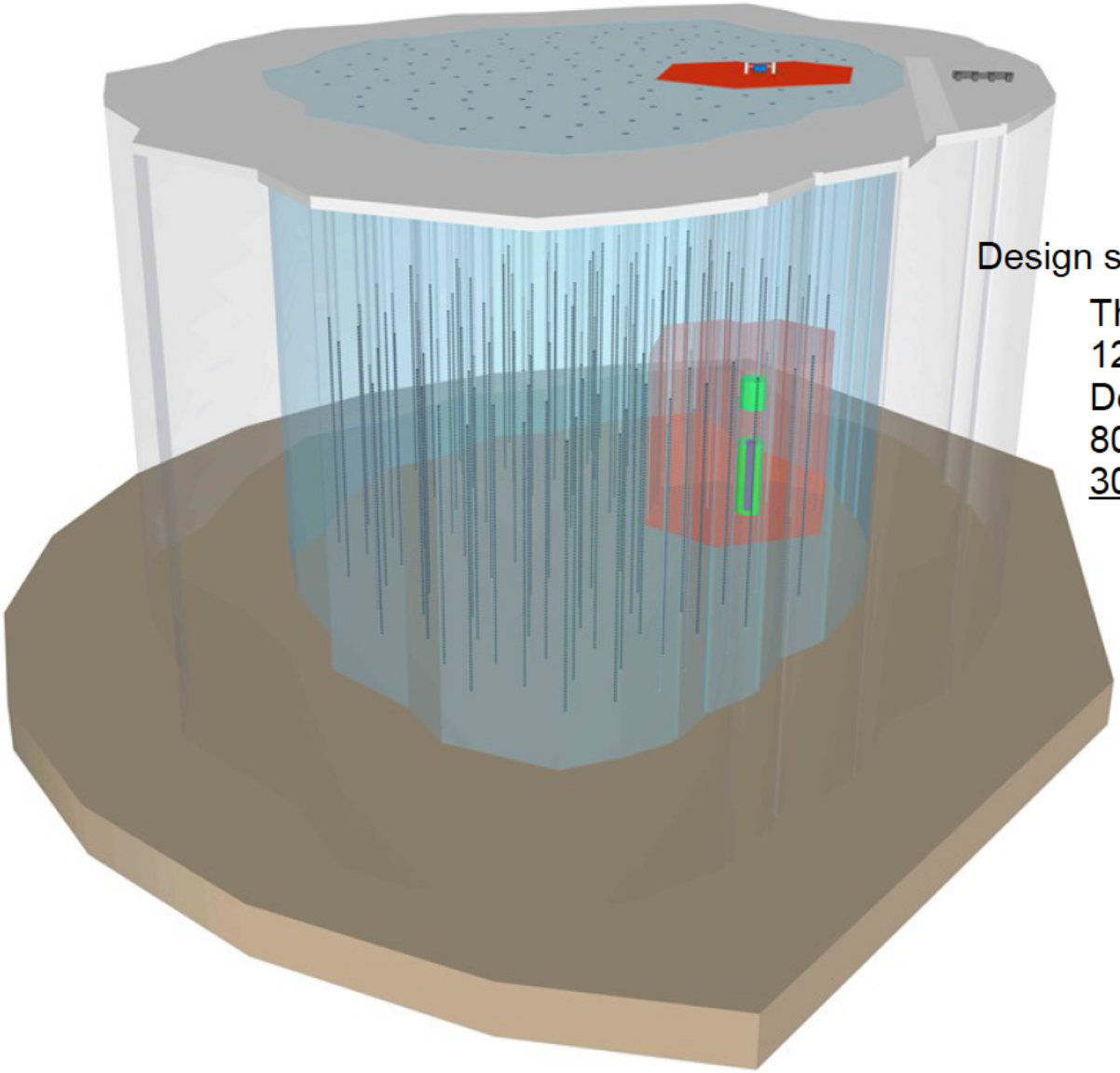
Neutrinos from GRB 130427A (>TeV)

… and more …

Next generation IceCube

Focus on higher statistics and ν_μ (pointing)

Also possible: surface veto



Design studies under way!

This figure:
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

Larger spacing probes higher energies

The IceCube Collaboration
University of Alberta
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls
Chiba University
University of Oxford
Université Libre de Bruxelles
Université de Mons
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Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Conclusions

(known) GRBs are not a main contributor to the recently discovered astrophysical flux

Neutron escape models for GRBs have been ruled out by IceCube

GRBs are unlikely to be the dominant source of cosmic rays (a la Waxman-Bahcall) – but there's a small amount of parameter space that remains unexplored

GRBs may still produce high-energy neutrinos, while being a subdominant source of cosmic rays. IceCube will continue to search for neutrinos from GRBs

Magnetic reconnection models untested by IceCube – we should fix this!

HAWC shoutout

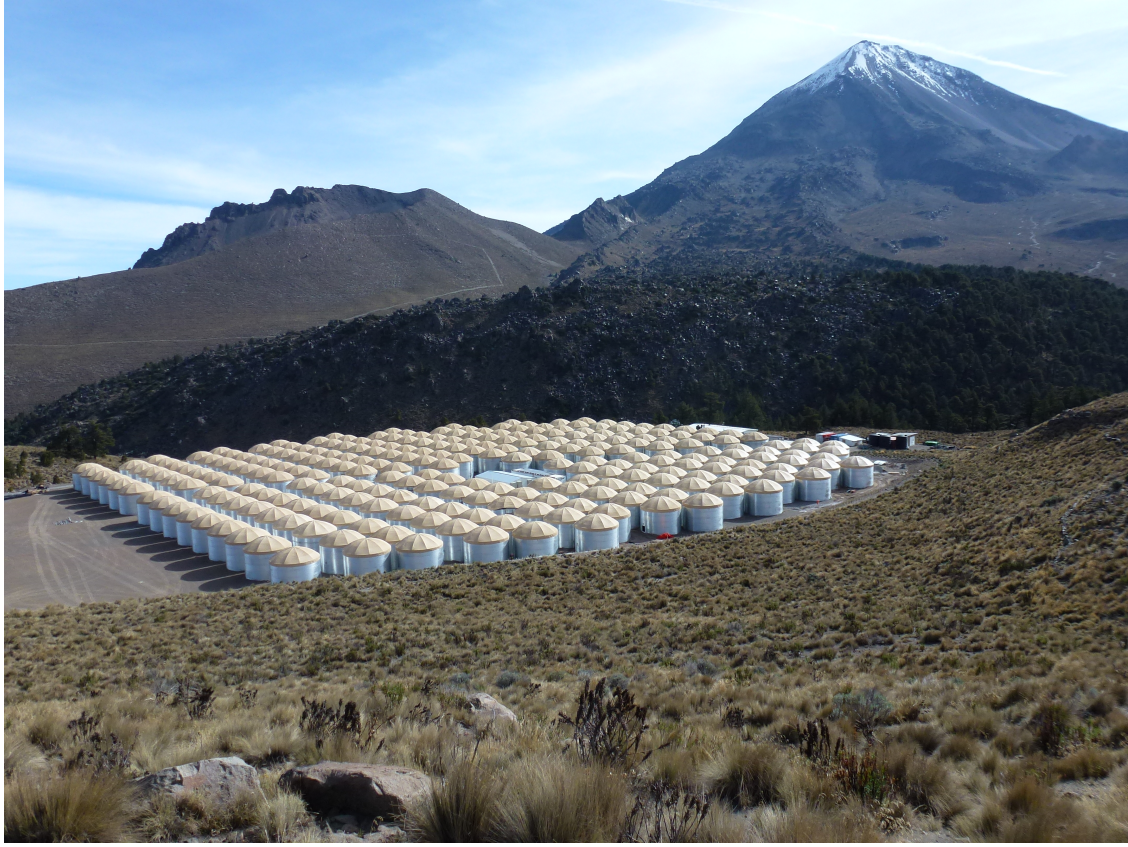
1/3 of the detector operating for 1 year

Full operation by end of year

2 sr F.o.V. >95% duty cycle

Sensitive to historical bright GRBs:

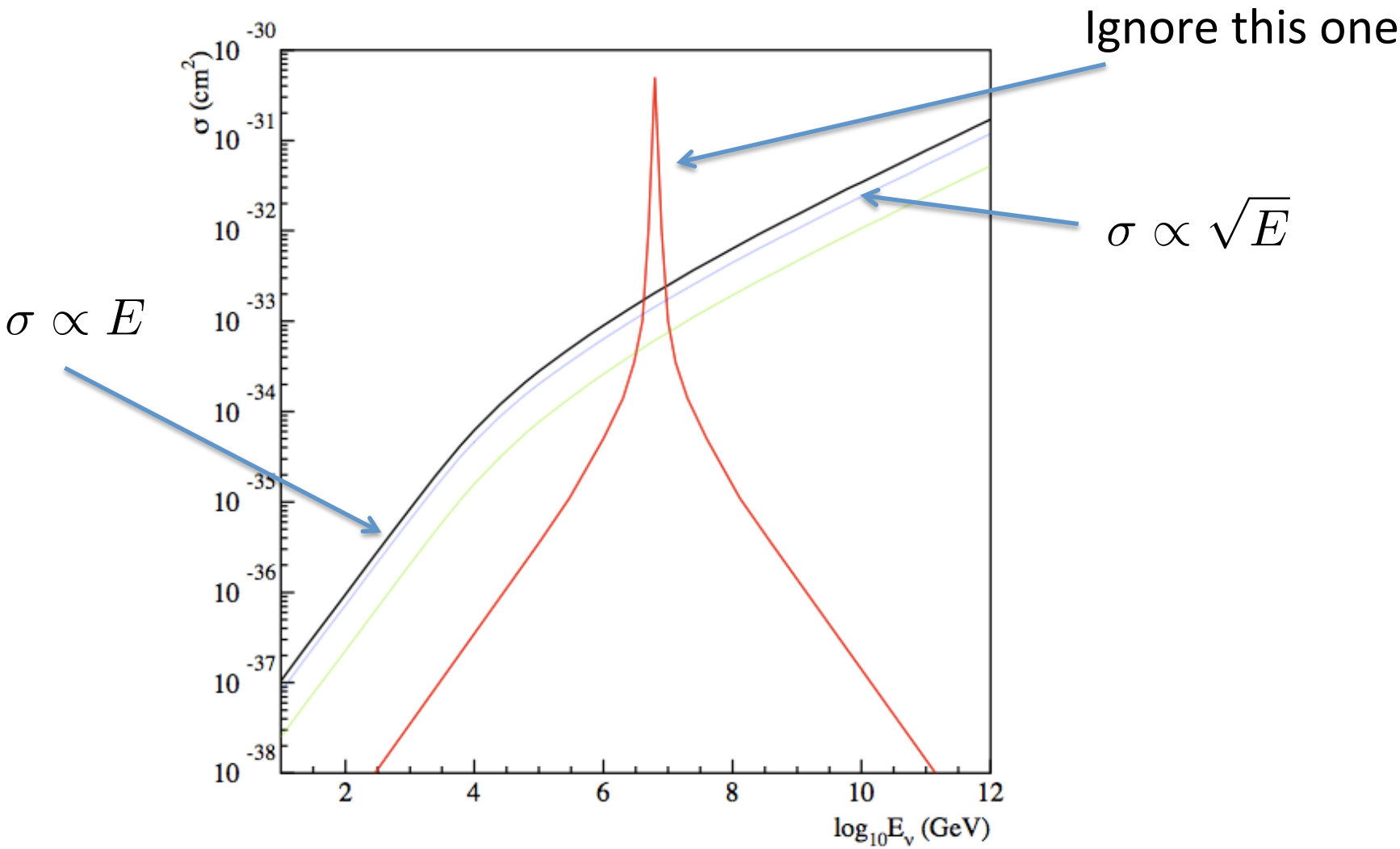
080916C, 090510, 090902B, 130427A



Picture: May 16, 2014

Abeysekara et al. – HAWC – (2012)
Taboada & Gilmore (2013)

Detecting neutrinos at cosmological distances



@ MeV the cross section is 14 orders of magnitude below that of PeV scale

Vacuum oscillations for astrophysical neutrinos

For astrophysical neutrinos (baseline tends to ∞):

$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

So for astrophysical baselines, oscillations are independent of Δm^2. With the current knowledge of mixing angles:

	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

$U_{\alpha i}$: element of PMNS matrix

Waxman-Bahcall bound on diffuse neutrinos

Cosmic rays provide an upper limit on the flux of neutrinos.
Waxman & Bahcall, PRD 59, 023002 (1998)

Assume that C.R. above 3×10^{18} (the ankle) are extraterrestrial and assume that they are protons. Assuming $dN_{\rm CR}/dE_{\rm CR} \propto E^{-2}$, then the power density in cosmic rays from 10^{19} to 10^{21} eV is:

$$\int_{10^{19}\ \rm eV}^{10^{21}\ \rm eV} E_{\rm CR}\frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}dE_{\rm CR} = 5\times10^{44}{\rm erg}\cdot{\rm Mpc}^{-3}\cdot{\rm yr}^{-1}$$

It is assumed that neutrino production is via p-γ interactions. This is expected at both AGNs and GRBs. It is also assumed that a fraction of the protons escape. If the source is very opaque to protons, i.e. $\tau_{p\gamma} >> 1$, the the source may produce neutrinos but it can't produce cosmic rays.

Waxman-Bahcall bound on diffuse neutrinos

If the cosmic rays loose a fraction of their energy ε in neutrino production then the present day neutrino density is

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx 0.25 t_H \epsilon E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Here t_H is the Hubble time.

For energy independent ε, the neutrino spectrum is E^{-2}_ν and each neutrino carries, on average, 5% of the proton energy. The factor of 0.25 arises, because approximately half the pions produced in $p\gamma$ interactions (sic – this is not what we found for delta resonance) are neutral and because the energy carried by each nm is ¼ of the charged pion energy.

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

Waxman-Bahcall Bound on diffuse neutrinos

The maximum neutrino flux that is consistent with a CR source is obtained for ε=1.

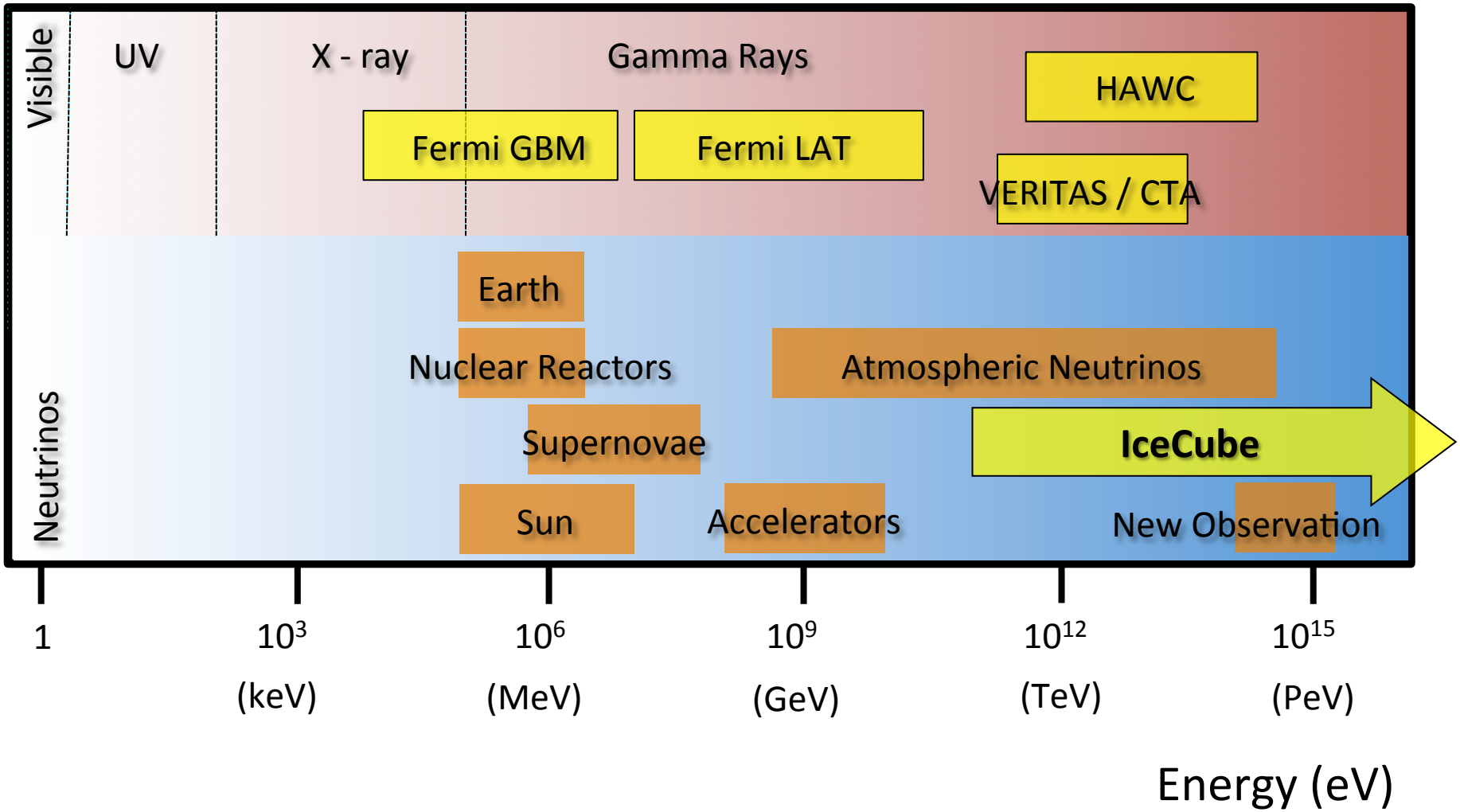
$$E_{\nu_\mu}^2 \phi_{\nu_\mu} \lesssim 0.25 \xi_Z t_H \frac{c}{4\pi} E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$
$$\approx 1.5 \times 10^{-8} \xi_Z {\rm GeV} \cdot {\rm cm}^{-2} \cdot {\rm s}^{-1} \cdot {\rm sr}^{-1}$$

The factor ξ_Z is order unity and describes the potential redshift evolution of cosmic ray sources.

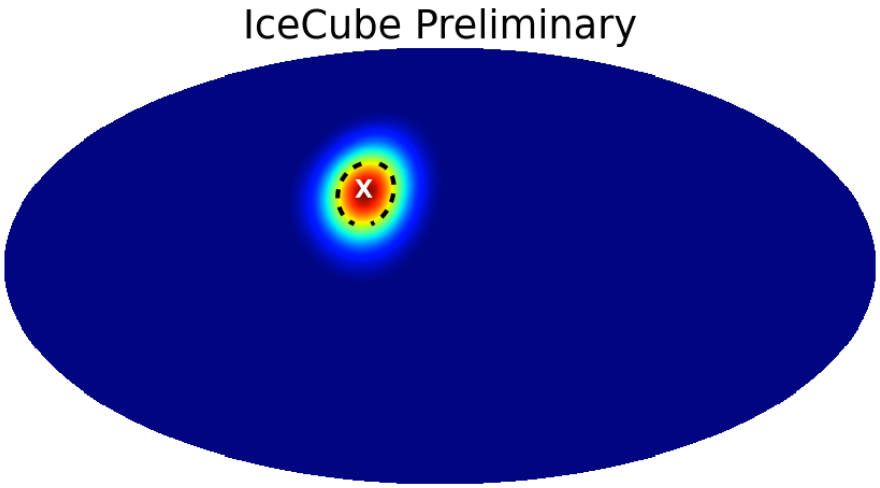
Caveats:

- This calculation doesn't include neutrino oscillations (easy to fix 1:2:0 -> 1:1:1)
- This calculation applies to protons, which contradicts Pierre Auger
- Cosmic Ray "Dark" sources that exceed this limit are possible.

Energy scales



Gamma Ray Bursts & the IceCube flux



Most significant event:

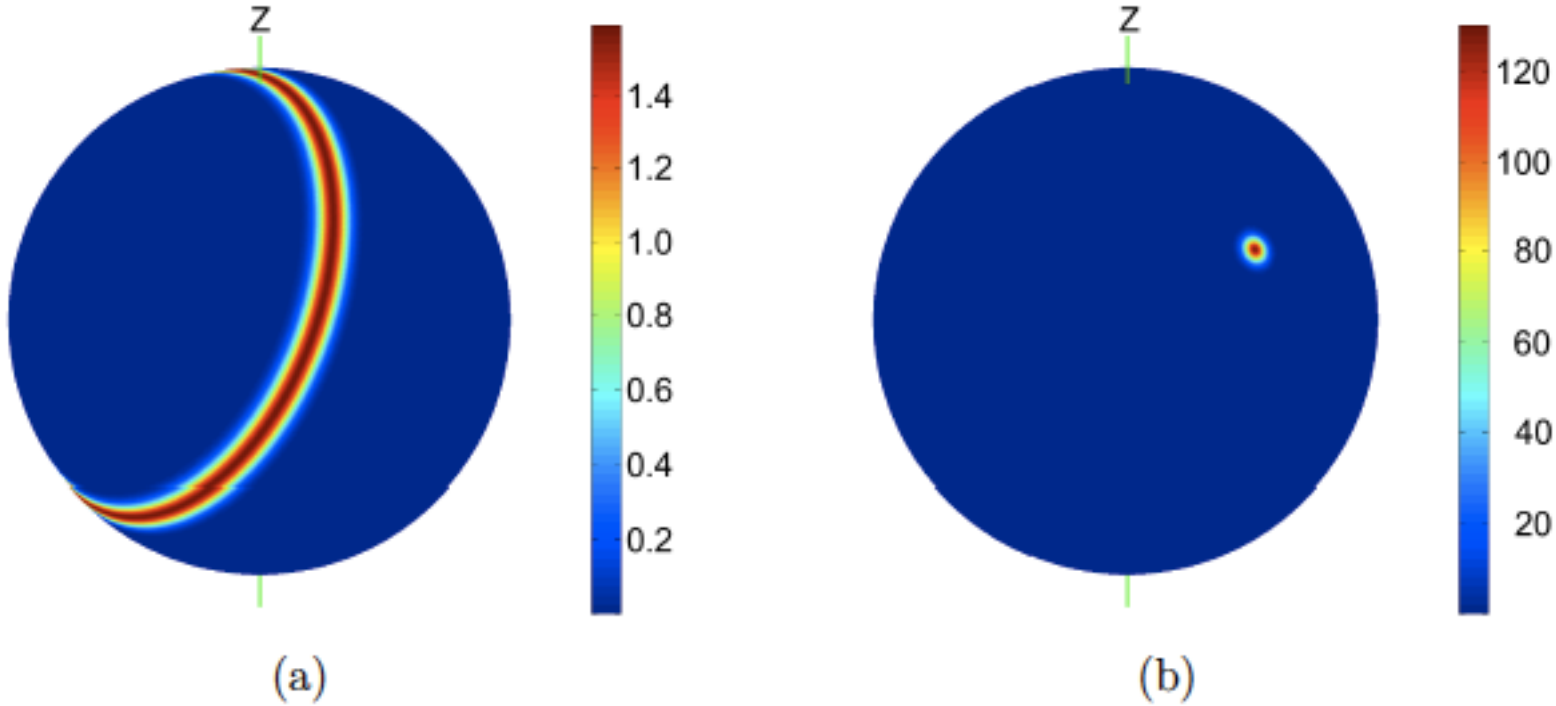
track-like, 33 TeV

4.9 days before the GRB

GRB detected by GBM only (Jan 2, 2012), 11° uncertainty

(This is not significant!)

Joint LIGO - IceCube search



Spatial PDF for LIGO (a) and IceCube (b)

Search will proceed on archival data for LIGO science run 5 in coincidence with IceCube

Publication in preparation