High Energy Neutrinos from Gamma Ray Bursts

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Outline

Definition of high energy:
~ **10^{11} eV** and above, which includes **ultra-high energies (UHE) 10^{17} eV and above**

- Introduction
- Fireball model and early theoretical predictions
- Overview of high energy neutrino experiments
- Experimental searches
- Prospects for future detection

$$1\ eV = 1.6 \times 10^{-19}\ J$$

Introduction

What are Gamma Ray Bursts (GRBs)?

- Most luminous explosions: Luminosity **~ 10^{52} erg s^{-1}** (entire galaxy: 10^{45} erg s^{-1})
- Brief: **0.1 s to several 100s s**
- Far: most occur at **~ 1 Gpc** from us
- Isotropically distributed in the sky
- Rare: ~ 0.3 Gpc^{-3} yr^{-1} (per volume per year)

$\mathbf{1\,erg = 10^{-7}\,J}$

pc = 3.26 light years

What are Gamma Ray Bursts (GRBs)?

- Two populations:
  - **Long** (t_{GRB} > 2 s, typically 20 s): associated with hypernovae (big supernovae, ≥ 10x more luminous)
  - **Short** (t_{GRB} < 2 s, typically 0.2 s): neutron star – neutron star (NS-NS) or neutron star – black hole (NS-BH) mergers
- Around 1000 GRBs per year, $^{2}/_{3}$ are Long

$L_{supernova} = 10^{41}\, erg\, s^{-1}$ $L_{sun} = 10^{33}\, erg\, s^{-1}$

Fireball model

&

Early theoretical predictions

Fireball model

Cataclysmic stellar event resulting in NS or BH

Sudden release of gravitational energy ($\sim M_{sun}$) in compact volume (10s of km)

<1% goes into fireball of $\boldsymbol{\gamma - rays, e^{\pm}, baryons}$

Kinetic energy of relativistically expanding fireball

hadronic model

shock accelerated electrons

shock accelerated protons

1. synchrotron
2. inverse-Compton

$\boldsymbol{\gamma - rays}$

$\mathbf{p}\boldsymbol{\gamma} \rightarrow \boldsymbol{\pi}^{+}, ..$

High energy neutrinos

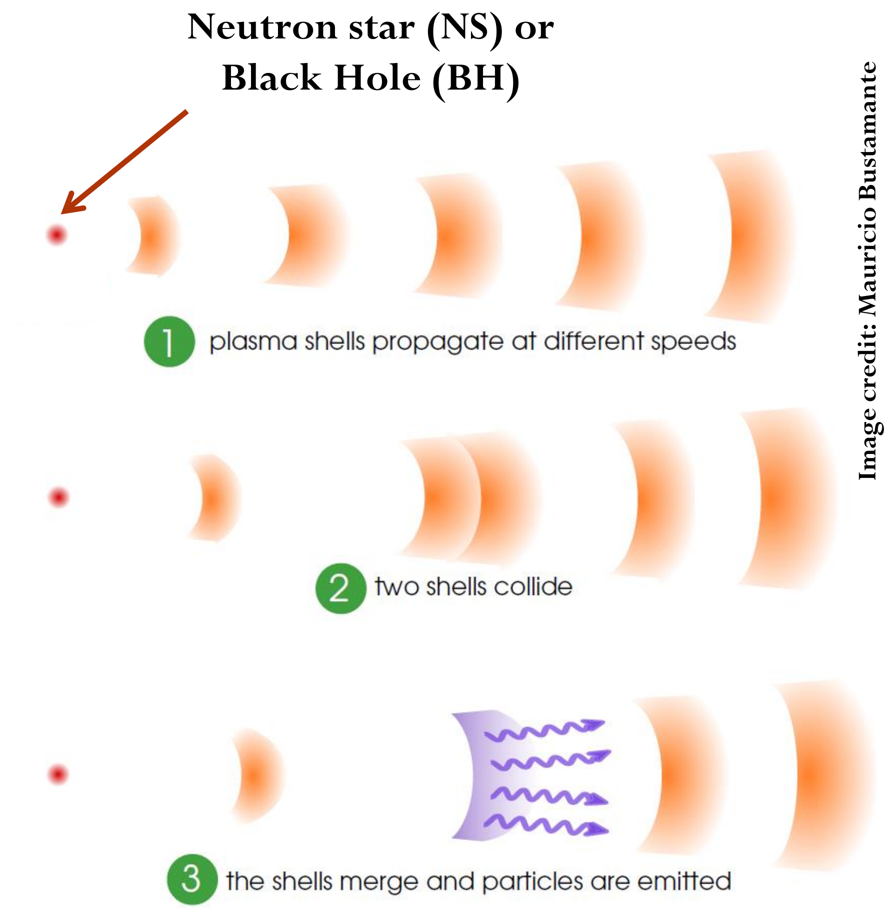


Image credit: Mauricio Bustamante

Theory: Photo-meson interaction that dominates neutrino production in GRBs

theorized cosmic rays from GRBs

$\mathbf{n \rightarrow p\, e^{-}\, \bar{\nu}_e}$

$$p + \gamma \longrightarrow \Delta^{+}\ (1232\ \mathrm{MeV/c^2}) \longrightarrow n + \pi^{+}\ \ \mathrm{OR}\ \ p + \pi^{0}$$

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

$$\pi^{0} \longrightarrow \gamma\gamma$$

theorized neutrinos produced by GRBs

WB Theory: Particle kinematics relation tells us expected GRB neutrino energies

$$\varepsilon_\gamma \varepsilon_p \cong 0.2\,\mathrm{GeV}^2\,\Gamma^2$$

Step 2

Solve for proton energy ε_p

Step 1a

Insert typical observed gamma-ray energy of 1 MeV (prompt emission) OR 100 eV (afterglow emission)

Step 1b

Insert Lorentz factor of 100

Step 3

$\varepsilon_\nu \sim 5\%\ \varepsilon_p$

Result

- **Prompt** emission: neutrino energy ~ **10^{14} eV**
- **Afterglow** emission: neutrino energy ~ **10^{18} eV**

Early (1997-2000) theoretical predictions by Waxman-Bahcall (WB)

- From cosmic ray observation WB set model-independent upper bound on high energy neutrino intensity:
  - $E_\nu^2 \Phi_\nu < 2 \times 10^{-8}\ GeV\ cm^{-2} s^{-1} sr^{-1}$

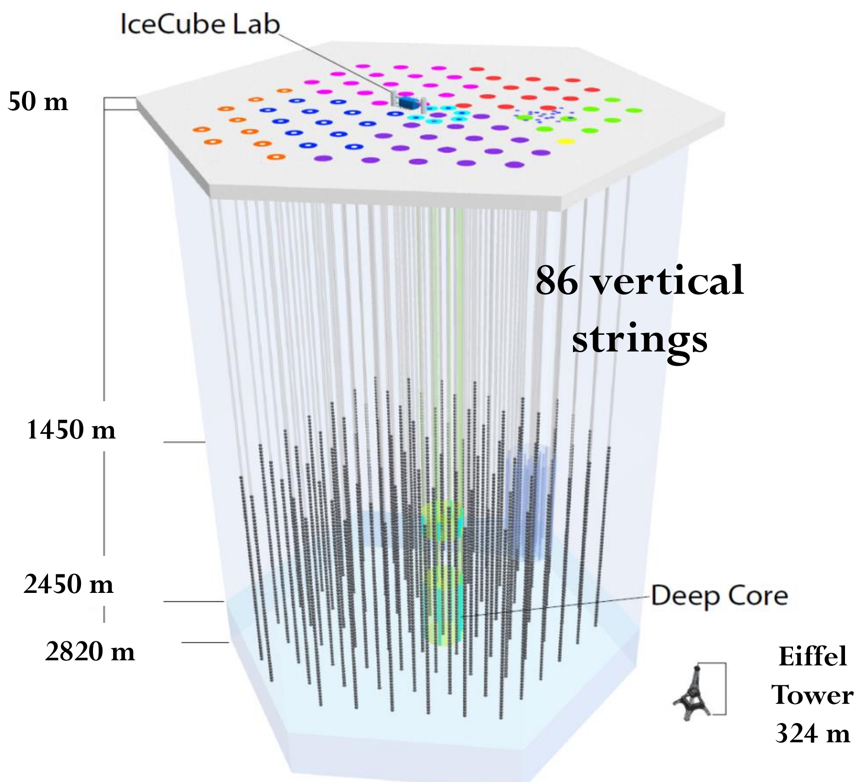
- $\sim$ 20 GRB muon neutrinos of energy **$\sim 10^{14}$ eV** per year over 4π steradian predicted for detection by km^2 neutrino detector

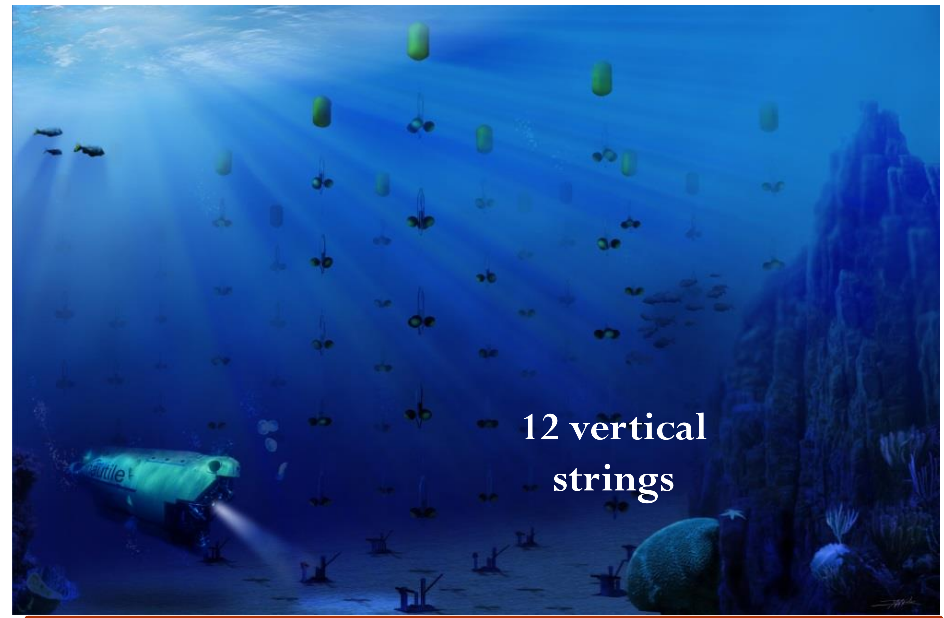
- $\sim$ **0.06** GRB muon neutrinos of energy **$10^{17} - 10^{19}$ eV** per year over 2π steradian predicted for detection by km^2 neutrino detector

Overview of high energy neutrino experiments

IceCube
ANTARES
ANITA
ARA

IceCube and ANTARES: Complementary optical Cherenkov neutrino observatories

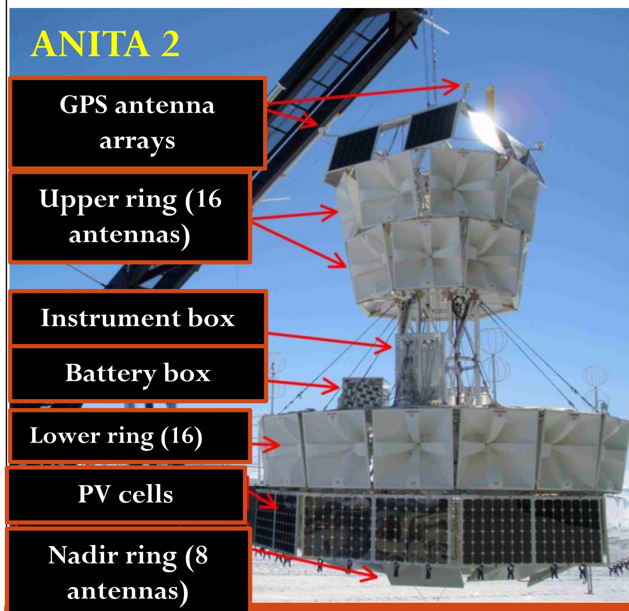


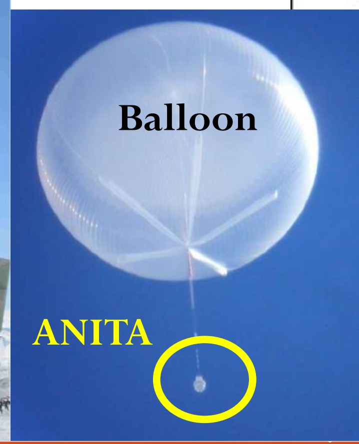


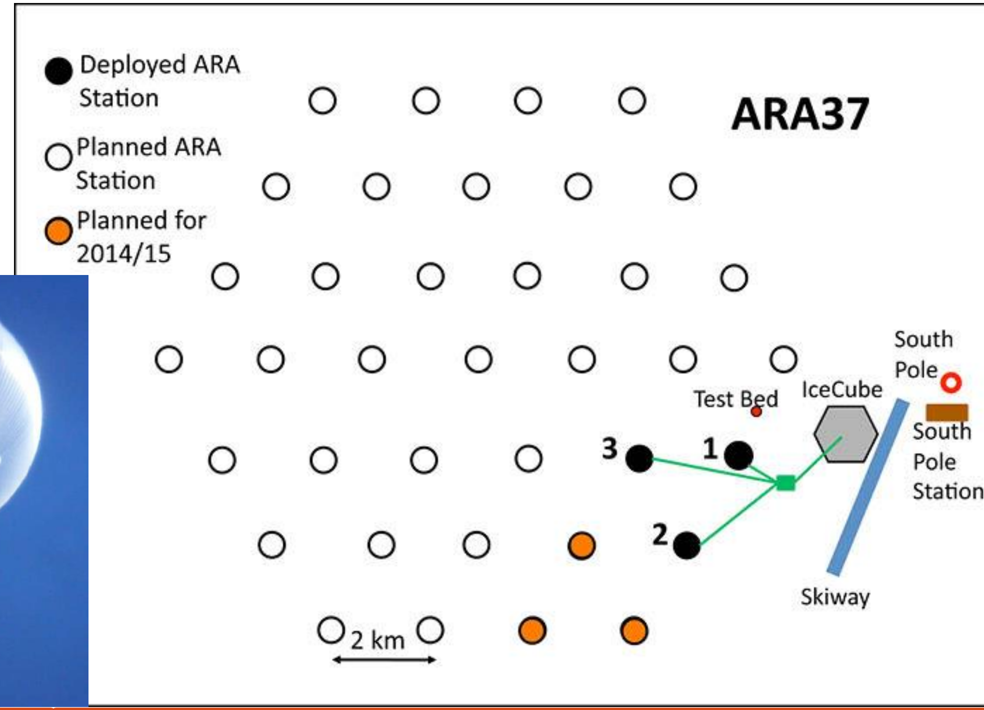
- IceCube located at the South Pole
- 5160 PMTs at depth 1450 – 2450 m
- Instrumented volume 1 km^3
- Was built to detect neutrinos of energy 100 GeV and higher

- ANTARES located in Mediterranean Sea
- 885 PMTs over 350 m at depth 2.4 km
- Instrumented volume 0.02 km^3
- Sensitive to neutrino energy 10 GeV – 100 TeV

ANITA and ARA: Complementary radio Cherenkov neutrino observatories



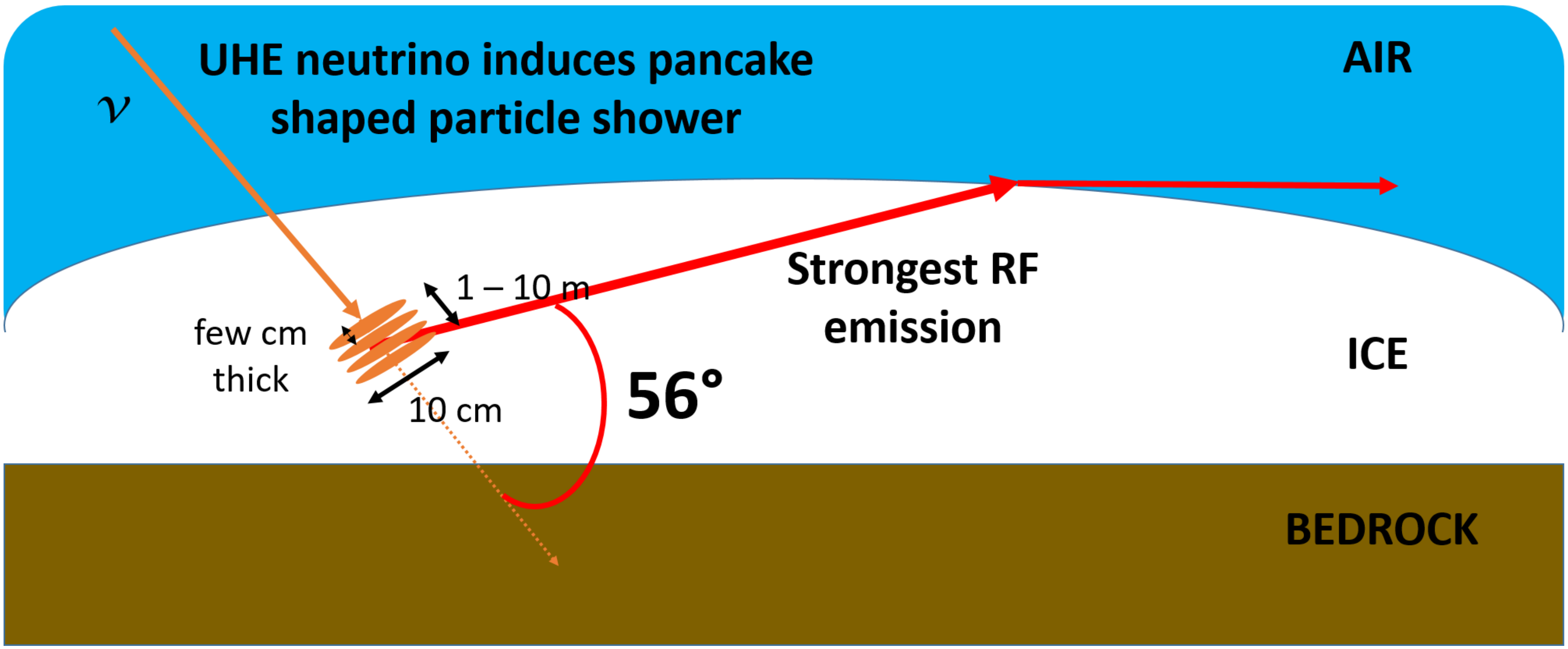




- Antarctic Impulsive Transient Antenna
- Balloon-borne, altitude 37 km
- Array of highly directional horn antennas
- Sensitive to frequency range 200 – 1200 MHz
- Completed 3 science flights
- ANITA 3 had 48 antennas, ANITA 2 had 40
- Covers ~ million km^2, sensitive to very rare neutrinos of energy 10^{18} eV and above

- Askaryan Radio Array
- Ground-based
- 37 deep stations at depth 200 m
- Each station ~ 16 embedded antennas in boreholes placed tens-of-meter apart
- Highly modular, each station standalone neutrino detector for surrounding ice
- Borehole antennas 150 MHz – 1 GHz
- Covers ~ 200 km^2, sensitive to 10^{16} – 10^{19} eV

Askaryan Effect: Coherent emission of Cherenkov radiation when wavelength larger than transverse size of particle shower

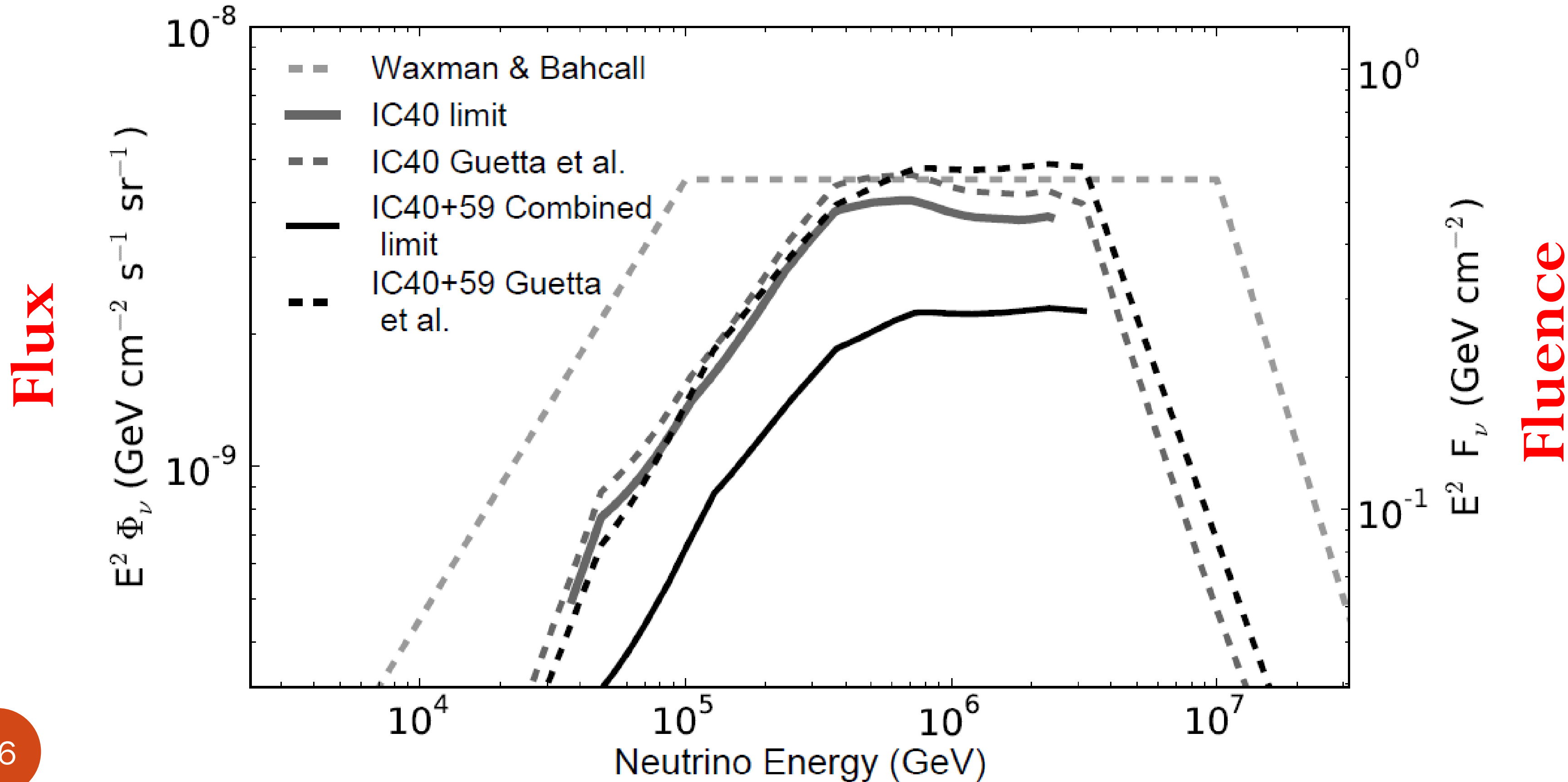


ANITA and ARA rely on the Askaryan Effect for detection of high energy neutrinos through impulsive radio signals

Experimental searches for high energy neutrinos from GRBs

Spoiler: None of the searches found a GRB neutrino yet (and that’s fine)

IceCube 2012: Experimental upper bounds *lower* than predictions by analytical model of Guetta *et al.* Concluded (rather hastily) GRB neutrino theories needed revision

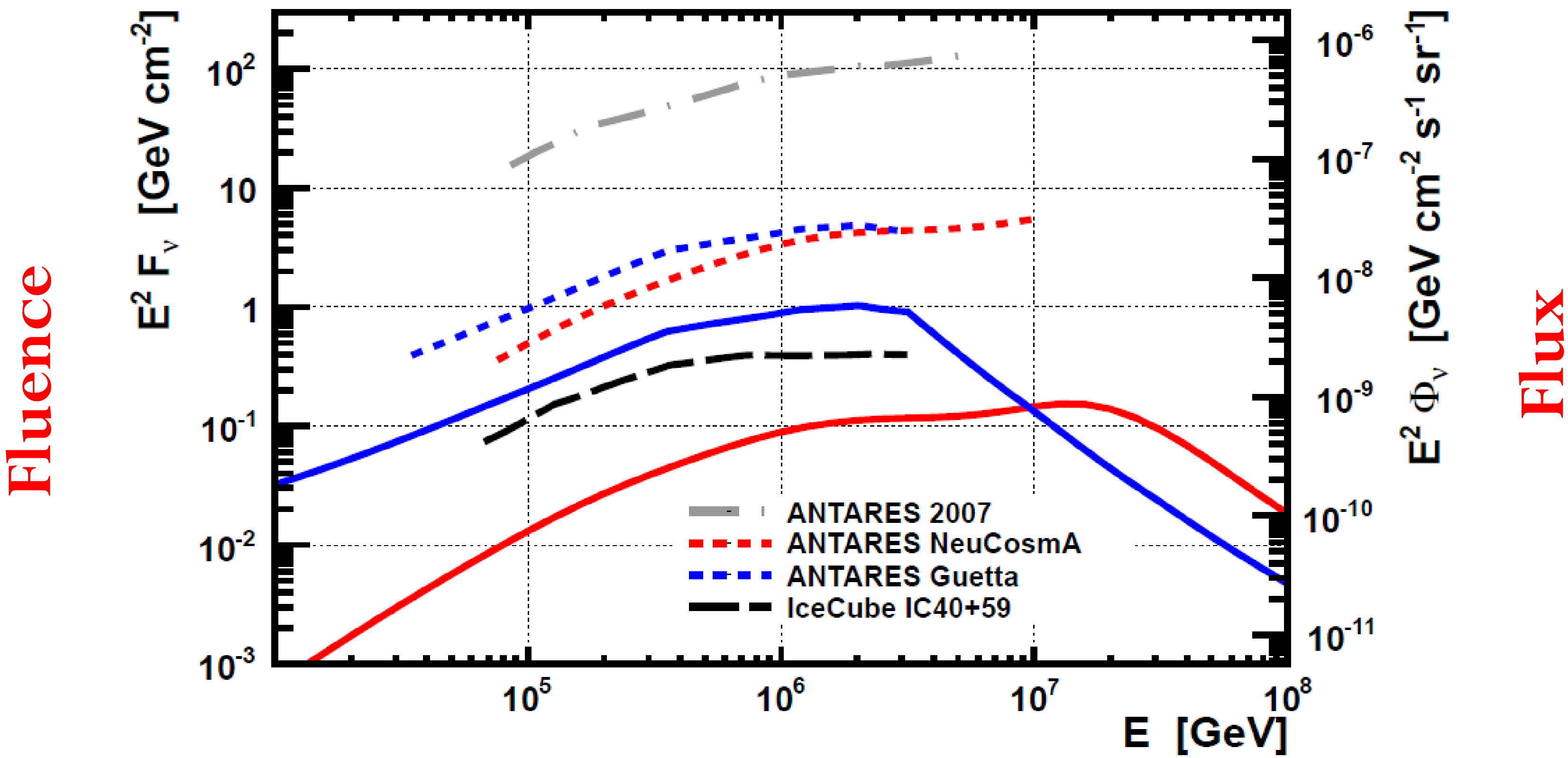


Theory update (2012): Following tension between theory and observation revision of GRB neutrino flux was conducted by Hummer *et al*.

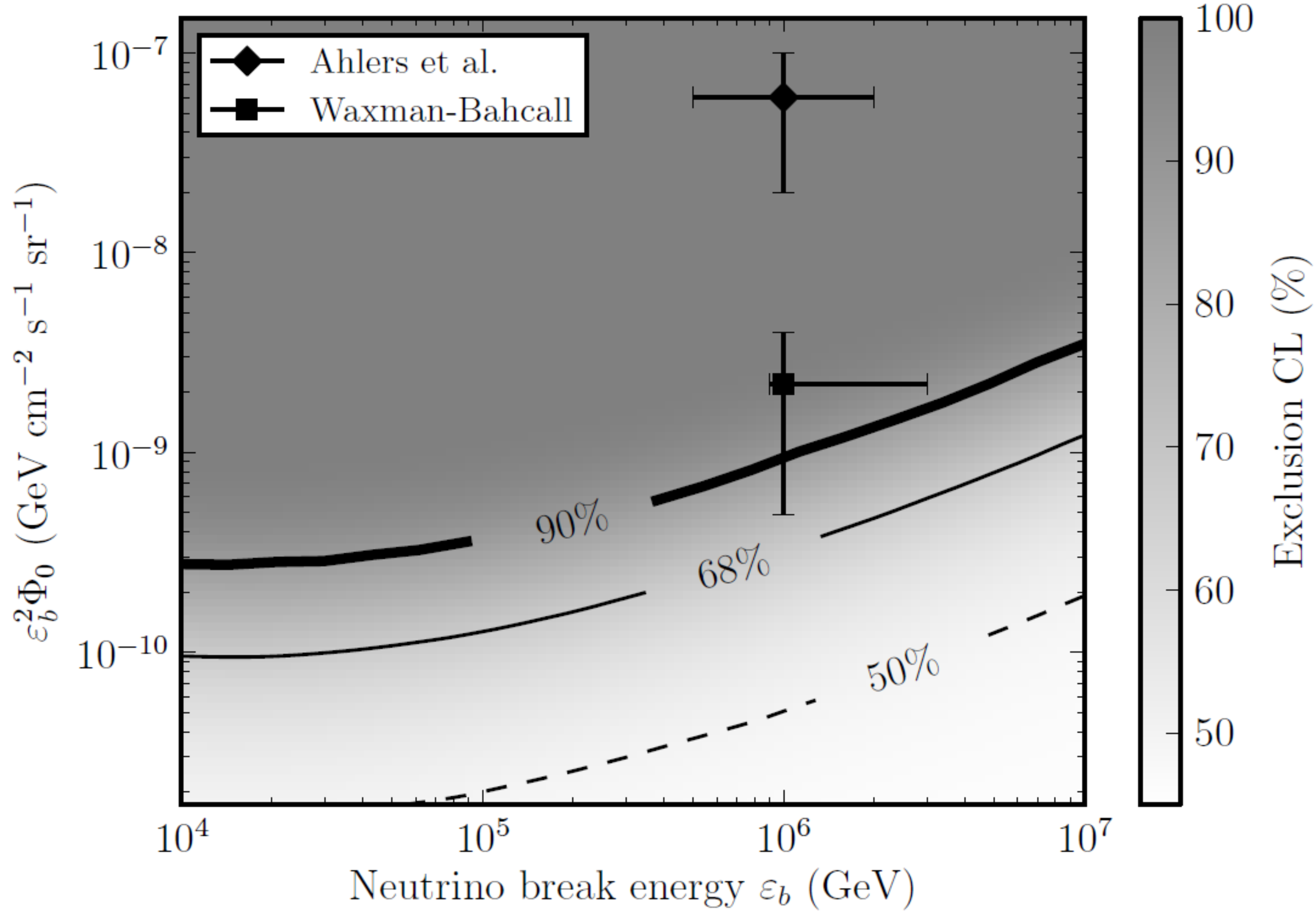
- Neutrino flux recalculated by **numerical** methods via NeuCosmA
- $p\gamma \rightarrow \Delta^{+}(1232\ \mathrm{MeV}/c^2) \rightarrow \pi^{+}, \pi^{0}, \ldots$
- Kaon production modes
- Synchrotron losses of secondaries
- Full photon spectrum
- Neutrino flavor transitions

Using same GRB source catalog as IceCube 2012 numerical method yielded neutrino flux prediction that was still order of magnitude below IceCube's sensitivity → fireball paradigm not yet probed

ANTARES 2013: First search with up-to-date numerical simulations showed expected fluxes are order of magnitude lower than prediction by Guetta analytical model → fireball paradigm *not yet probed*

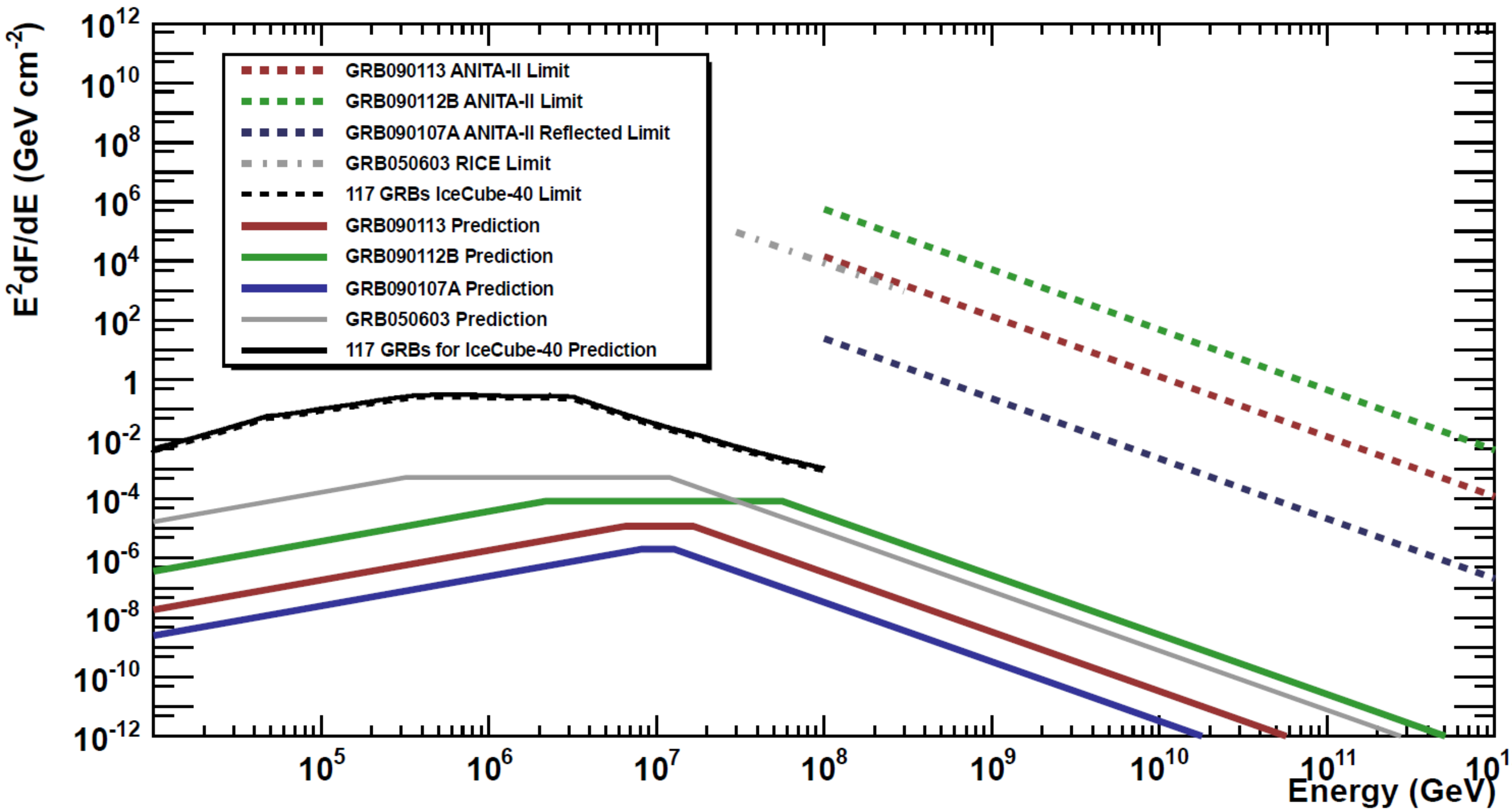


IceCube 2015: Neutron model by Ahlers *et al*. (only neutrons allowed to escape fireball as cosmic rays) finally ruled out but WB fireball model (protons escape too) stills holds

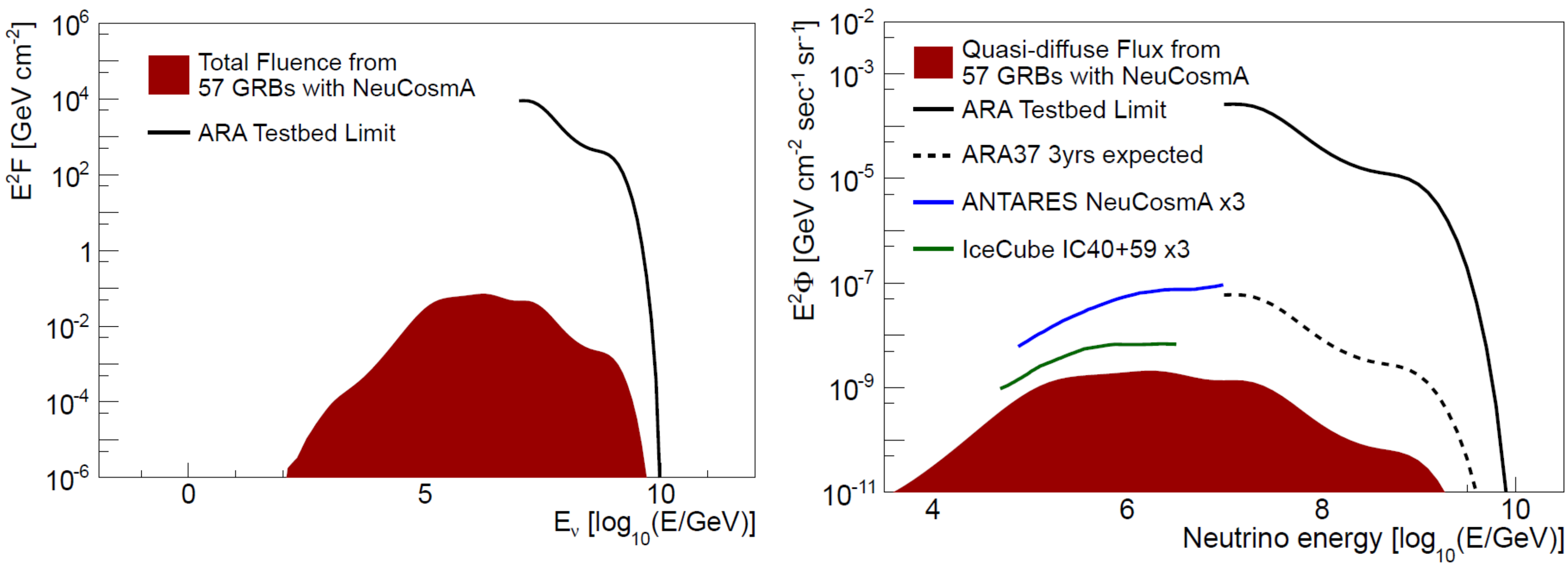


ANITA 2011: First limits on UHE GRB neutrino fluence at energies greater than 10^{18} eV

Fluence



ARA 2015: UHE GRB neutrino fluence limit and first limit on the UHE GRB quasi-diffuse neutrino flux for energies 10^{16} – 10^{19} eV using data collected by ARA Testbed



Prospects for future detection

Future searches will reveal more about GRB physics with results in different energy regimes

- **Prospects for GRB prompt neutrino detection:**
  - IceCube saw 2 PeV neutrino, getting increasingly sensitive
  - Next gen optical Cherenkov telescope KM3NeT under construction

- **Prospects for GRB afterglow neutrino detection:**
  - Room for factor of 5 improvement with ANITA 3 if GRB occurs with good geometry relative to payload
  - ANITA 4 will be launched in 2016
  - ARA preparing to deploy 3 more deep stations in 2017
  - ARA should have at least factor 6 improvement in sensitivity compared to analysis with ARA Testbed

Thank you!

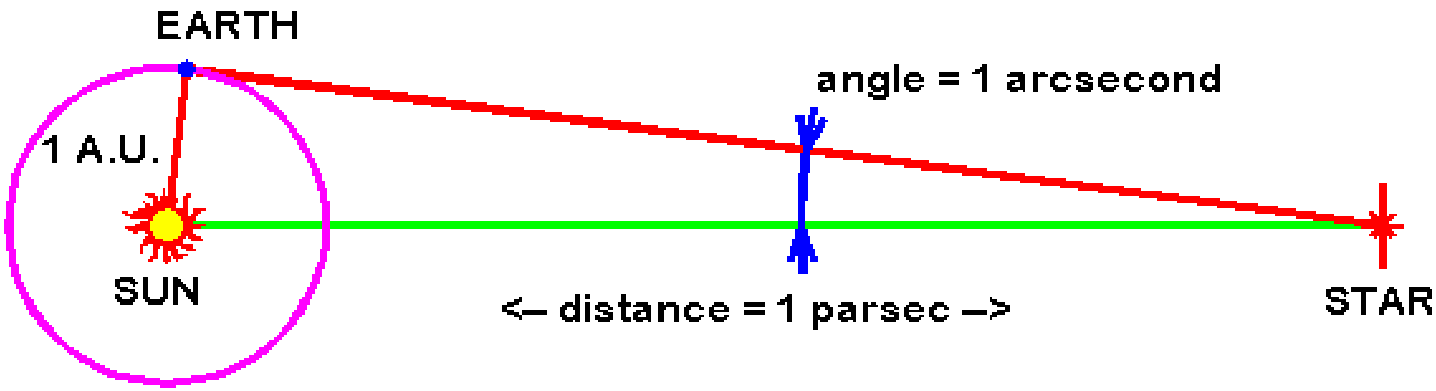
Back up slides

Fireball FAQs

- Expands – why?
  - Observed photon luminosity ≫ Eddington luminosity = **1.3 x 10^{38} (M/M_{sun}) erg s^{-1}**
  - Above which radiation pressure exceeds self-gravity, so the fireball will expand

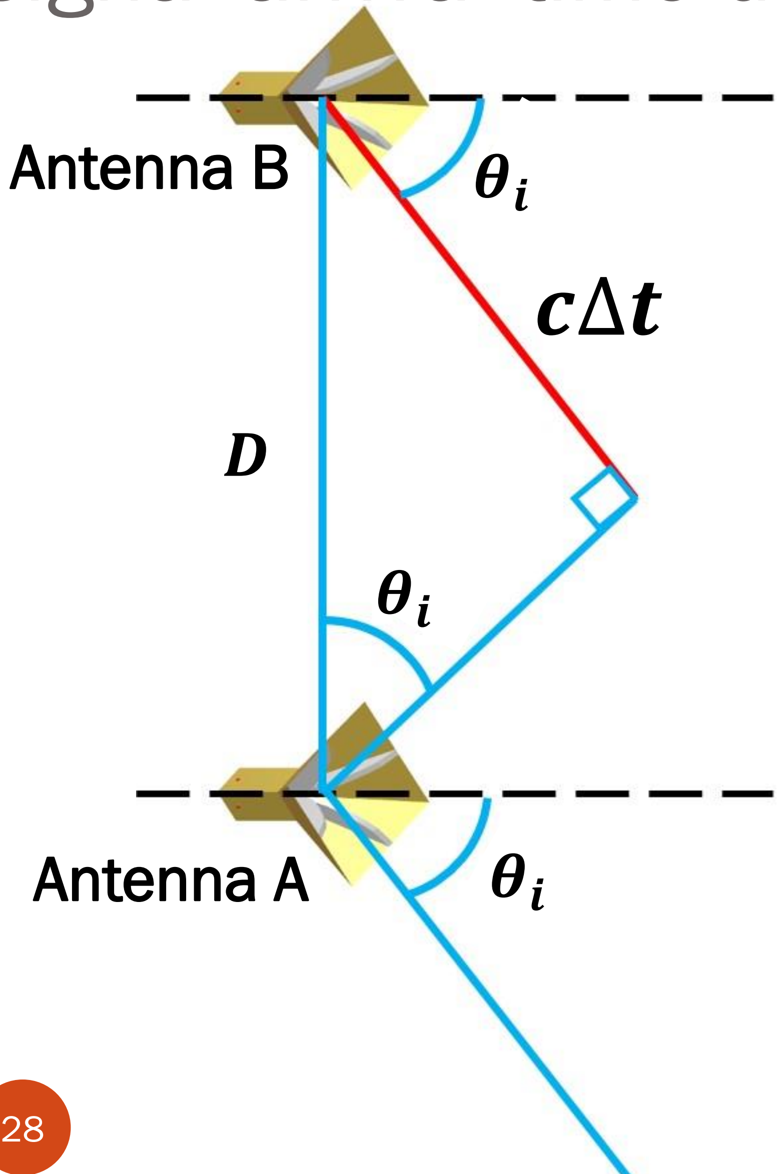
- Highly relativistic – why?
  - Mean free path of $\gamma\gamma \rightarrow e^{\pm}$ in isotropic plasma (if sub-relativistically expanding fireball) would be very short
  - But many bursts show spectra extending above 1 GeV so flow must be able to avoid degrading these via $\gamma\gamma$ interactions
  - Flow must be expanding with Lorentz factor $\Gamma \geq 100$

Parsec



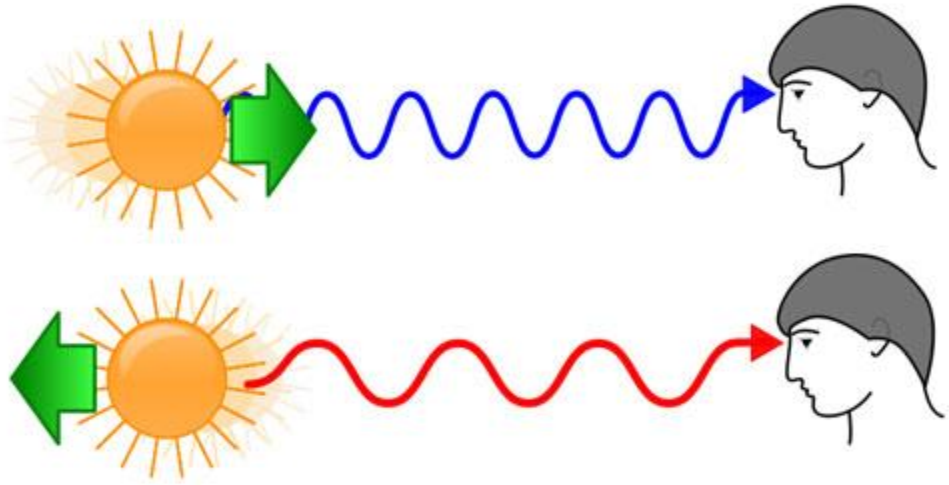
- A **parsec** (symbol: pc) is a unit of length used to measure large distances to objects outside the Solar System.
- One **parsec** is the distance at which one astronomical unit subtends an angle of one arcsecond.
- A **parsec** is equal to about 3.26 light-years (31 trillion kilometers or 19 trillion miles) in length.

ANITA and ARA: Angular reconstruction from signal arrival time delay



- θ_i = incident angle
- D = distance between antennas
- Δt = time delay between received signals
- $c\Delta t$ = extra length signal needed to travel to reach antenna B
- $\sin\theta_i = \dfrac{c\Delta t}{D}$

Redshift



REDSHIFT

denoted by z

$$1 + z = \frac{observed\ wavelength}{emitted\ wavelength}$$

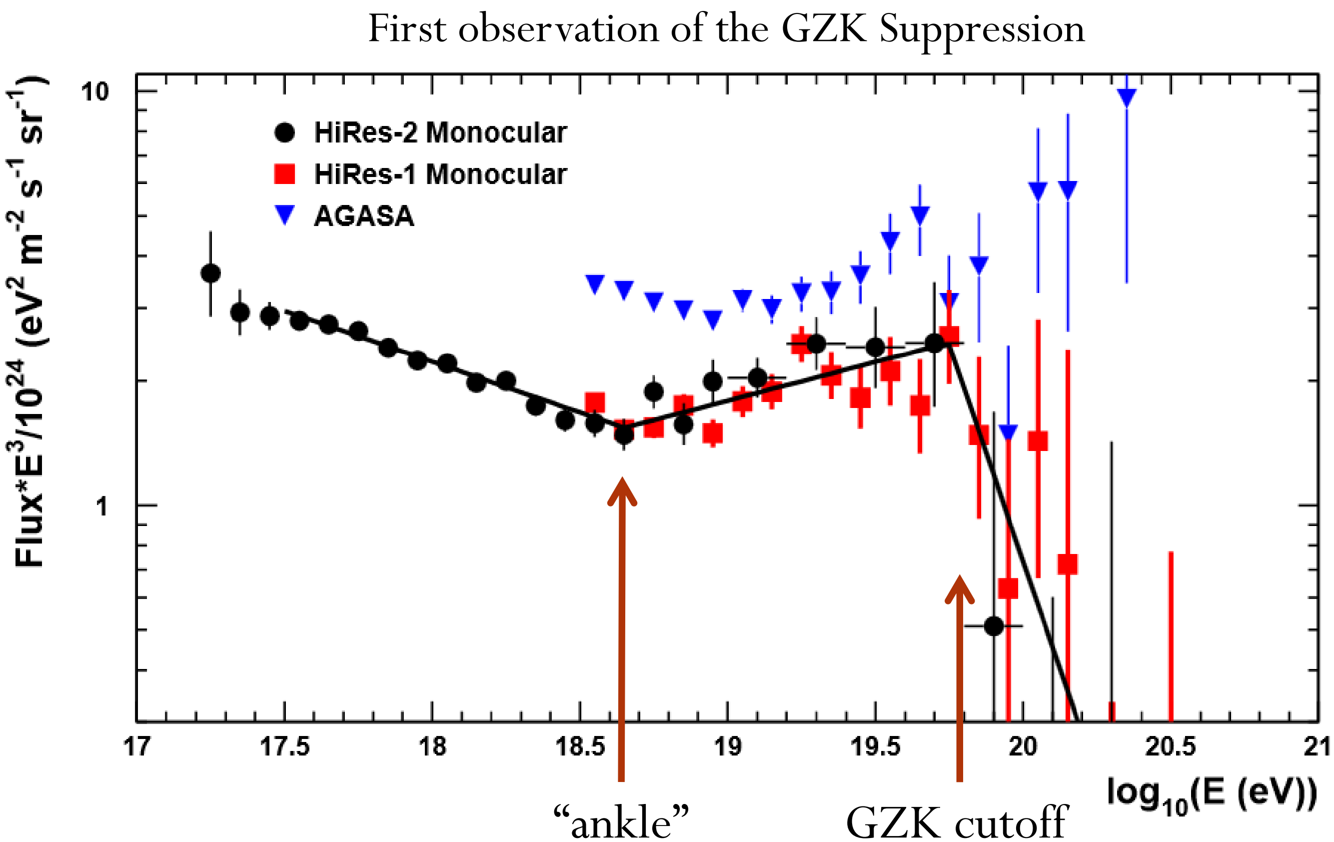
Break energy

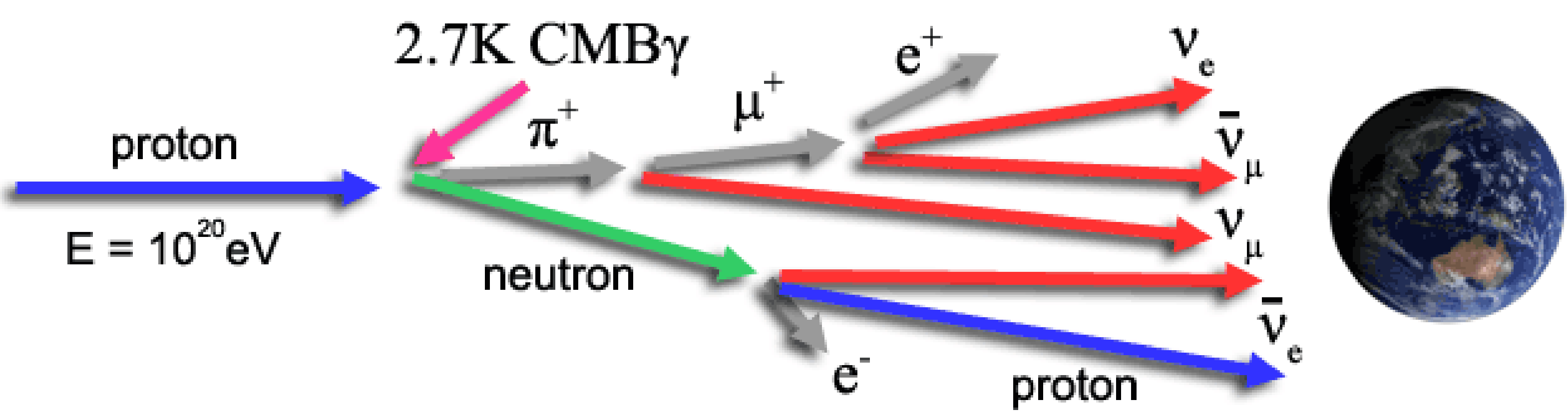
- Theory → GRB neutrino flux follows broken power law given by ϵ_{ν}^{-b} where b = 2 for prompt emission and b = 4 for afterglow. Break energy is the energy at which b changes.

GZK cutoff

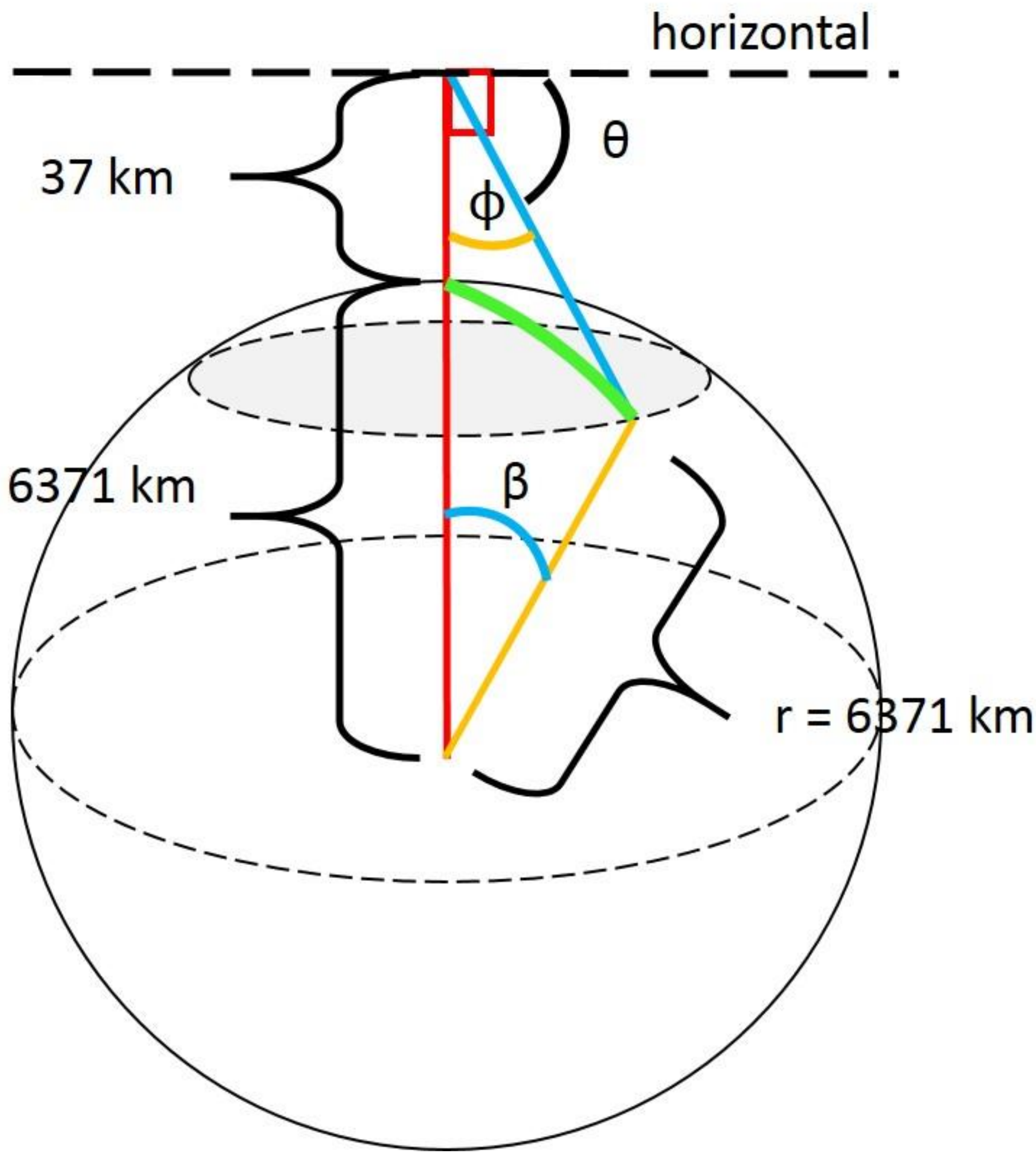
Limit on cosmic proton energy: **~ $10^{19.5}$ eV**

Limit on cosmic proton propagation distance: ~ **50 Mpc**





ANITA coordinates



How big is ANITA?

Waxman review: Optical depth (< 1) is a function of Lorentz factor → Γ ≥ 100

$$\tau_{\gamma\gamma} = \frac{1}{128\pi} \frac{\sigma_T L_\gamma \epsilon_t}{c^2 (m_e c^2)^2 \Gamma^6 \Delta t}$$

- $\boldsymbol{\tau_{\gamma\gamma}}$: optical depth to pair creation
- $\boldsymbol{\sigma_T}$: Thomson scattering cross section $= \mathbf{6.65 \times 10^{-29}}\ \boldsymbol{m^2}$
- $\boldsymbol{L_\gamma}$: GRB Luminosity ~ 10^{52} erg s^{-1}
- $\boldsymbol{\epsilon_t}$: photon energy
- $\boldsymbol{\Gamma}$: Lorentz factor = $\sqrt{{}^{1}/_{1 - v^2/c^2}} \geq 100$
- $\boldsymbol{\Delta t}$: time scale over which variability (light curve) in GRB is observed