Workshop on the Future of Dark Matter Astro-Particle Physics: Insights and Perspectives
Abdus Salam ICTP, Trieste, 8-11 October 2013

High Energy Neutrino Astrophysics

Soebur Razzaque
University of Johannesburg
South Africa

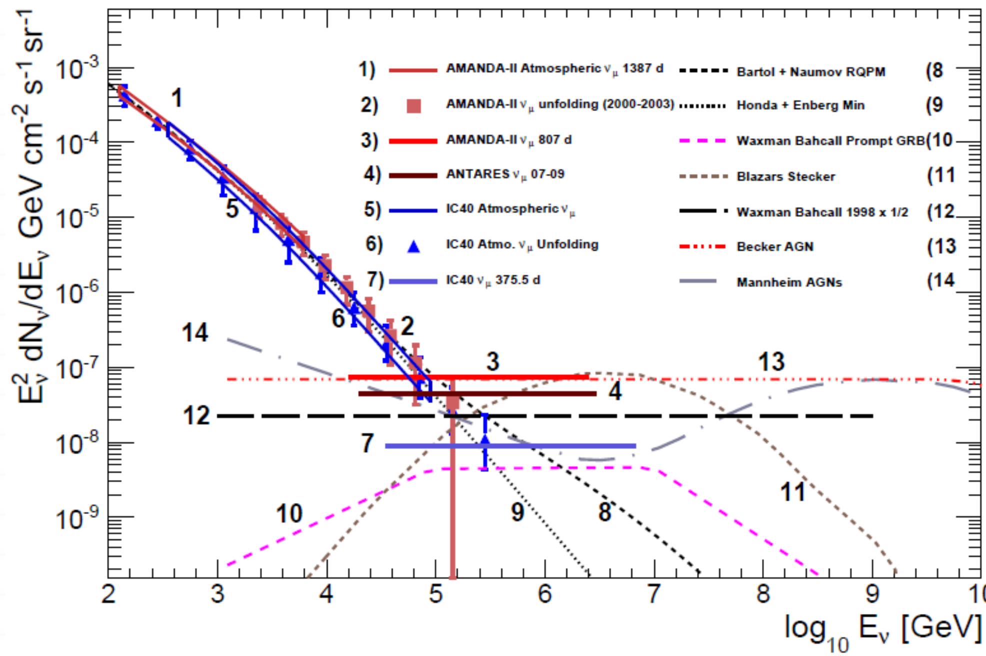
srazzaque@uj.ac.za

Neutrino Astrophysics

- High-energy (>1 GeV) neutrinos can open a new window to the universe
  - A new way to look at the sky beyond the curtains of cosmic radio-ultraviolet backgrounds, and intergalactic and Galactic magnetic field
  - Carry information from dense regions of astrophysical sources
  - Probe fundamental interactions at extremely high energies
  - Provide clues to Dark Matter particles and their interactions
- Astrophysical applications
  - Identify the sources of (ultra/very) high-energy cosmic rays
  - Learn about the sources: energetics, envirnonment
- Nature of neutrino sources
  - Transients or quasi steady state?
- hadronic interpretation of very high-energy gamma rays
  - Unambiguous?
  - A mix of inverse Compton (IC) and π^0 decay?

IceCube Limits on Diffuse ν fluxes and PeV ν Detection!

Diffuse neutrino flux limit from 40 string data



$$\phi_{\nu_\mu}(E)\, E^2 \le 8.9 \times 10^{-9}\ \frac{\mathrm{GeV}}{\mathrm{cm^2\, s\, sr}}$$

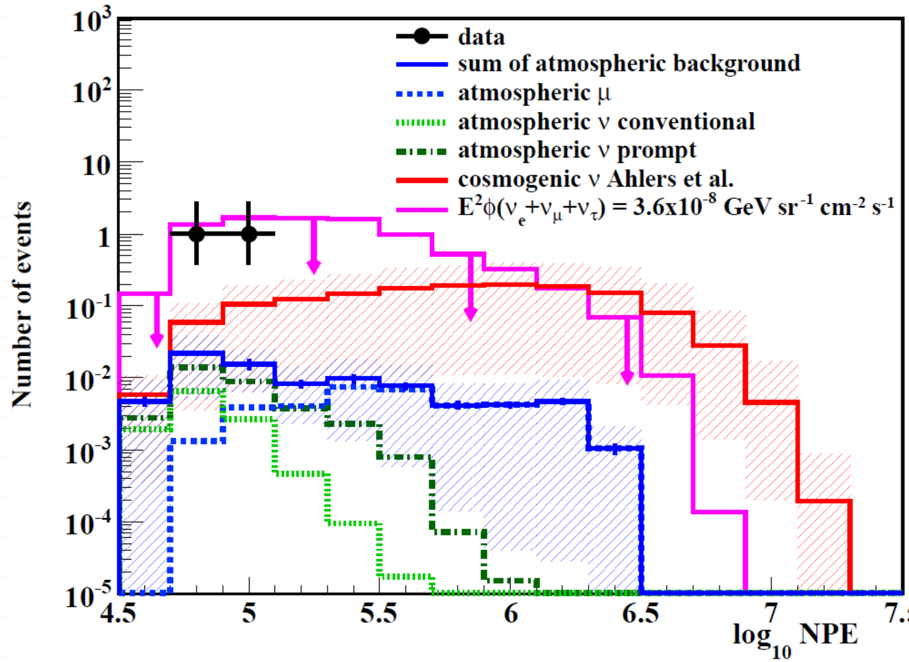
$$N_{\mu\uparrow} \simeq 2\pi\ [A\, t]\ \Phi_{\nu_\mu}(\ge 1\ \mathrm{TeV})\ \langle \varepsilon_{\nu\to\mu} \rangle$$

~3×10^{-6}

$$N_{\mu\uparrow} \simeq 50\ \frac{\mathrm{events}}{\mathrm{Km^2\ \ yr}}$$

Lipari 2011

Detection of 2 neutrinos o energy ~1 PeV each!

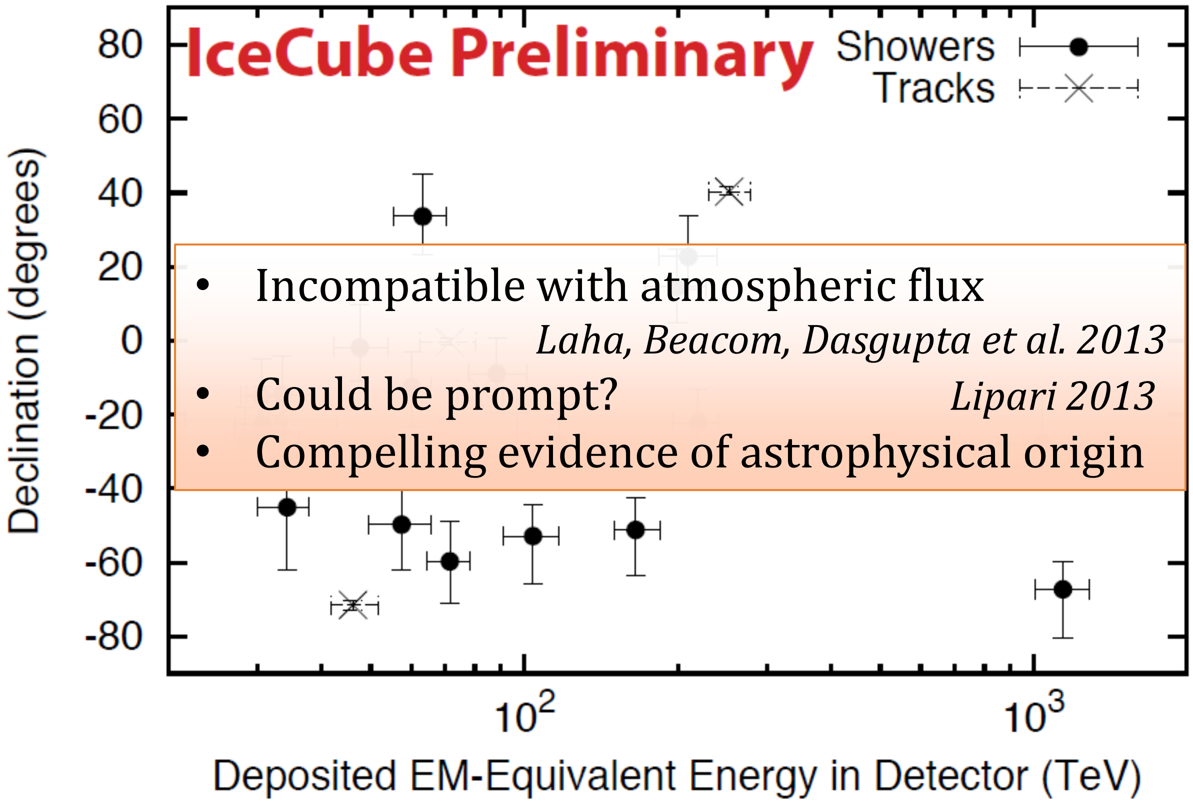


$$E^2\varphi(\ \ ) = 1.2 \times 10^{-8}\ \mathrm{GeV\ cm^{-2} s^{-1} sr^{-1}}$$

Required flux for the two events is similar to Waxman-Bahcall limit

More lower-energy events!

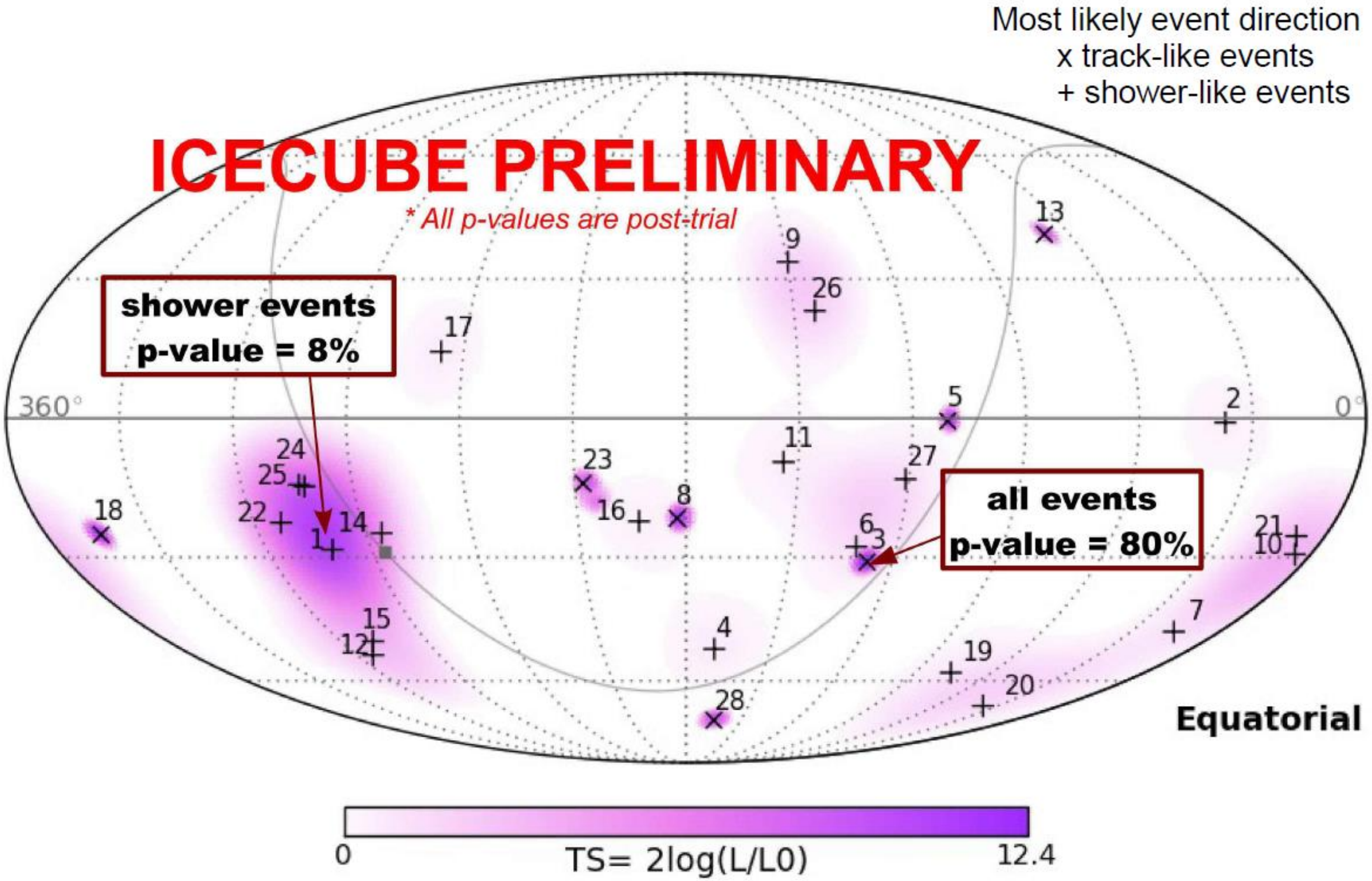
Results of Contained Vertex Event Search (4.3σ)



- Incompatible with atmospheric flux *Laha, Beacom, Dasgupta et al. 2013*
- Could be prompt? *Lipari 2013*
- Compelling evidence of astrophysical origin

28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

Resulting Test Statistic Map



Ingredients for HE Neutrino Astrophysics

- Particle physics of neutrino production is well understood

$$p + \gamma \to p/n + \pi^0 + \pi^+ \qquad \pi^0 \to \gamma + \gamma$$

$$p + p \to p/n + \pi^0 + \pi^+ + \pi^- \qquad \pi^+ \to \mu^+ + \bar{\nu}_\mu \to e^+ + \nu_e + \bar{\nu}_e + \nu_\mu$$

- Neutrino propagation/flavor oscillation physics is now known

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

In case of no "source oscillation"

$$\{\nu_e : \nu_\mu : \nu_\tau\} = \{1:2:0\}^{source} = \{1:1:1\}^{earth}$$

- Astrophysics of neutrino production is poorly understood at best

Question: How to predict neutrino flux from astrophysical sources?

One answer is to model >GeV gamma rays with hadronic model

Roughly, 1 hadronic gamma ray = 1 neutrino

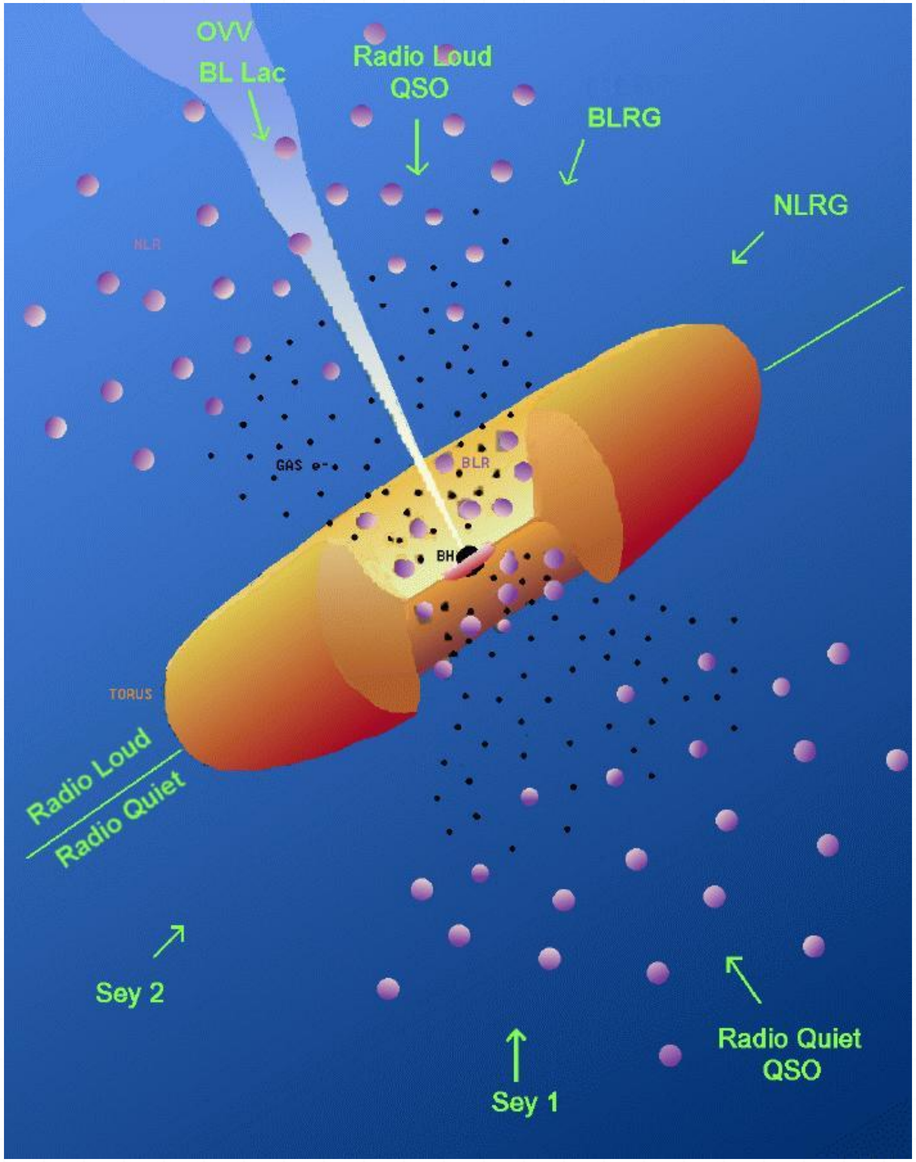
The other answer is to model source environment and energy balance

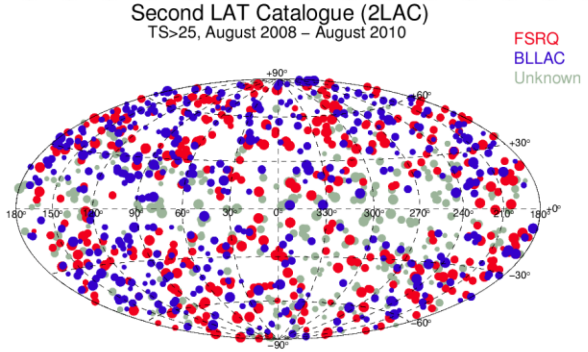
Do the most powerful sources make abundant neutrinos?

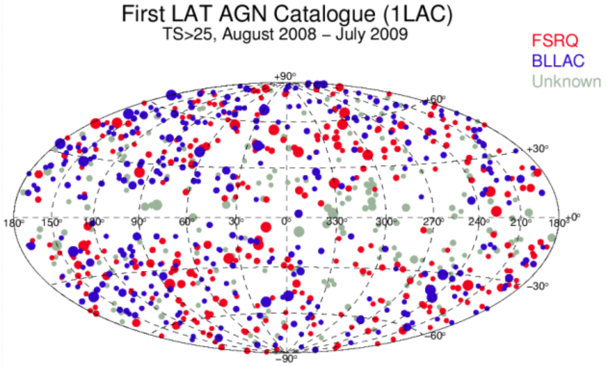
Extragalactic Sources:

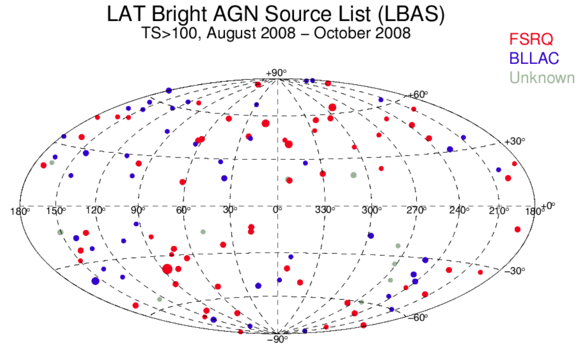
- Active Galactic Nuclei
- Gamma-Ray Bursts

Active Galactic Nuclei









High-energy neutrinos from AGNs

From Syefert galaxies:

Proton acceleration by shocks near the black hole, trapped by magnetic field, interact with UV photons from AGN disc

Stecker, Salamon, Drone & Sommers 1991

Flux at 1 PeV (large uncertainty)

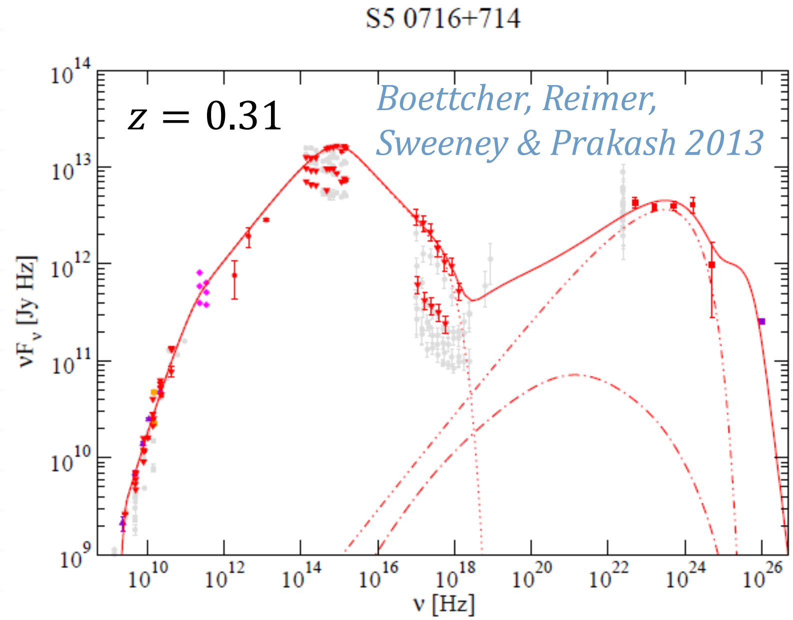
$$E^2\varphi(\ \ ) = 5.6 \times 10^{-8}\ \mathrm{GeV\ cm^{-2} s^{-1} sr^{-1}}$$

Stecker 2013

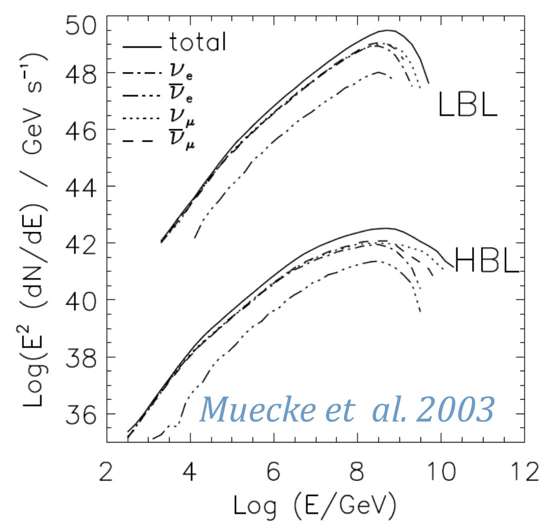
- Might explain detected PeV neutrinos
- Poorly constrained astrophysical model

Hadronic modeling of γ rays:

Proton acceleration and interactions in the blob inside jet. π^0 decay γ rays and synchrotron radiation by the primary protons and cascade particles



Example of predicted n flux from γ-ray modeling

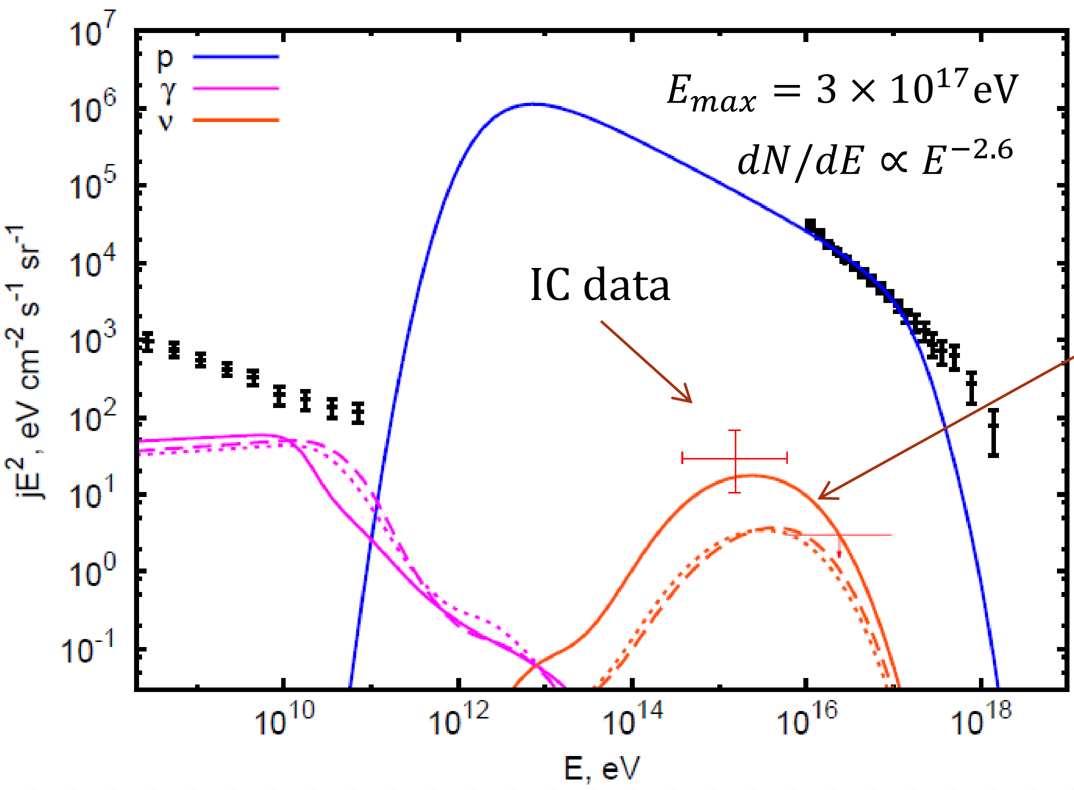


Usually too low!

High-energy neutrinos from AGNs

Diffuse ν flux from cosmic-ray interactions in the Extragalactic Background Light (EBL)

Kalashev, Kusenko & Essey 2013



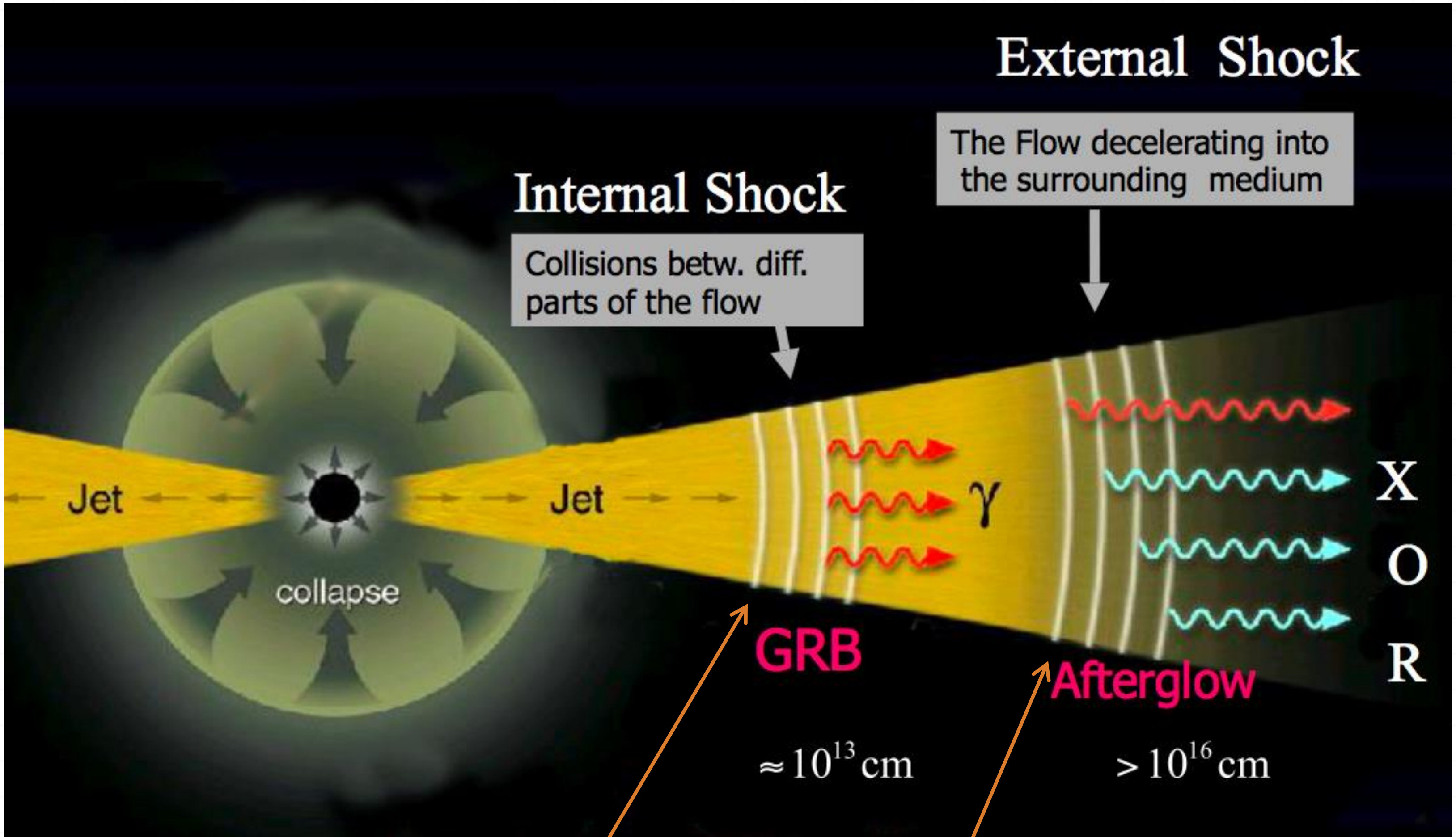
X-ray luminosity/AGN $L_x = 10^{45.5}$ erg/s

- Individual source detection is impossible
  - Low individual power
- May not be UHECR sources
  - Might over-predict diffuse γ-ray flux
- Highly dependent on EBL models
  - Stecker et al. 2006 model is ruled out by Fermi-LAT data
- Requires unrealistic source density evolution
  - $\propto (1+z)^{7.1}$
  - More reasonable is $\propto (1+z)^3$

unlikely scenario

High-energy neutrinos from GRBs

Fireball Shock Model *Meszaros, Rees, Piran, Sari, Narayn ...*



Waxman & Bahcall 1997
Dermer & Atoyan 2003
Murase & Nagataki 2006
Lipari et al. 2008

Burst ν's

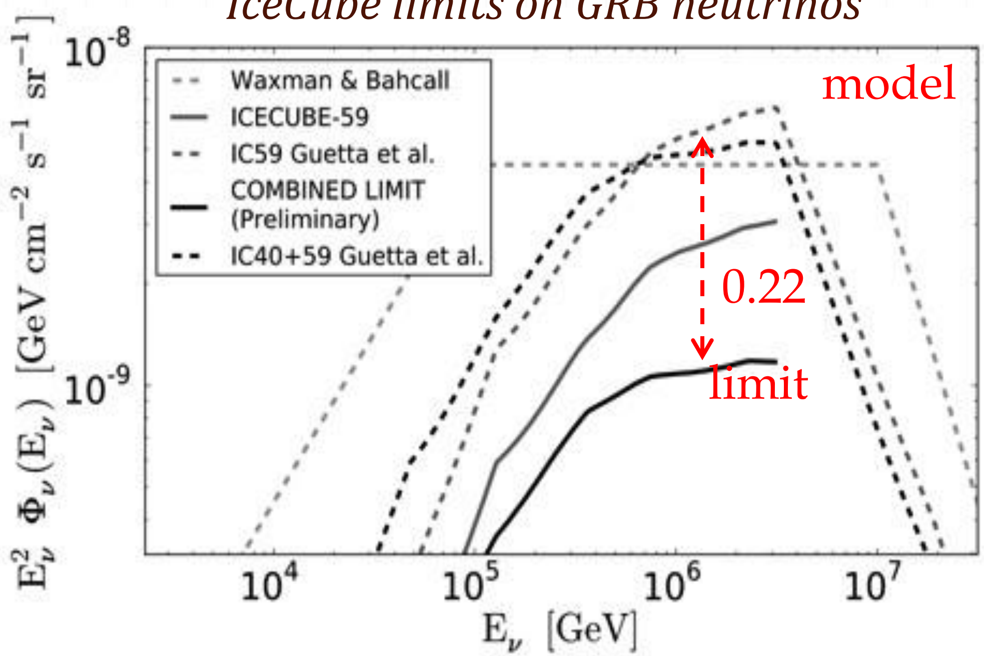
Afterglow ν's

Dai & Lu 2000
Waxman & Bahcall 2000
Murase 2007
Razzaque 2013

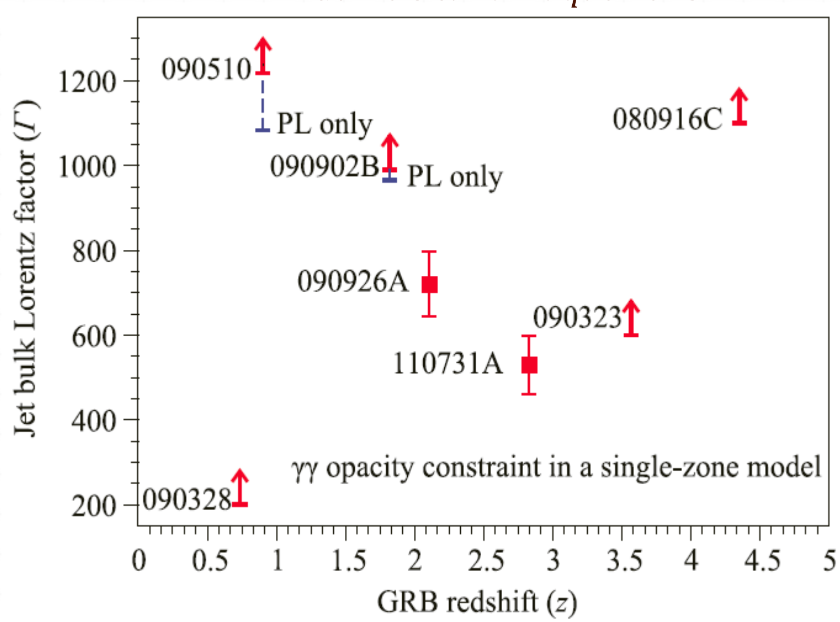
High-energy neutrinos from GRBs

- HE ν flux calculations were based on the possibility that GRBs are UHECR sources
  (Waxman 1995, Vietri 1995)
- ν flux calculations based on hadronic modeling of observed GeV γ flux are recent
  (Asano, Guiriec & Meszaros 2009, …)
- Hadronic modeling of GeV γ rays require large (100-1000 times) more jet energy
  (Wang+09, Asano+09, Razzaque+10, Eichler+Pohl10, Dermer+Razzaque10, …)
- Photopion production is quite an inefficient process $\sim 1/\Gamma^4$
  (Razzaque+08, Ackermann+11, Crumley+Kumar12, …)

IceCube limits on GRB neutrinos

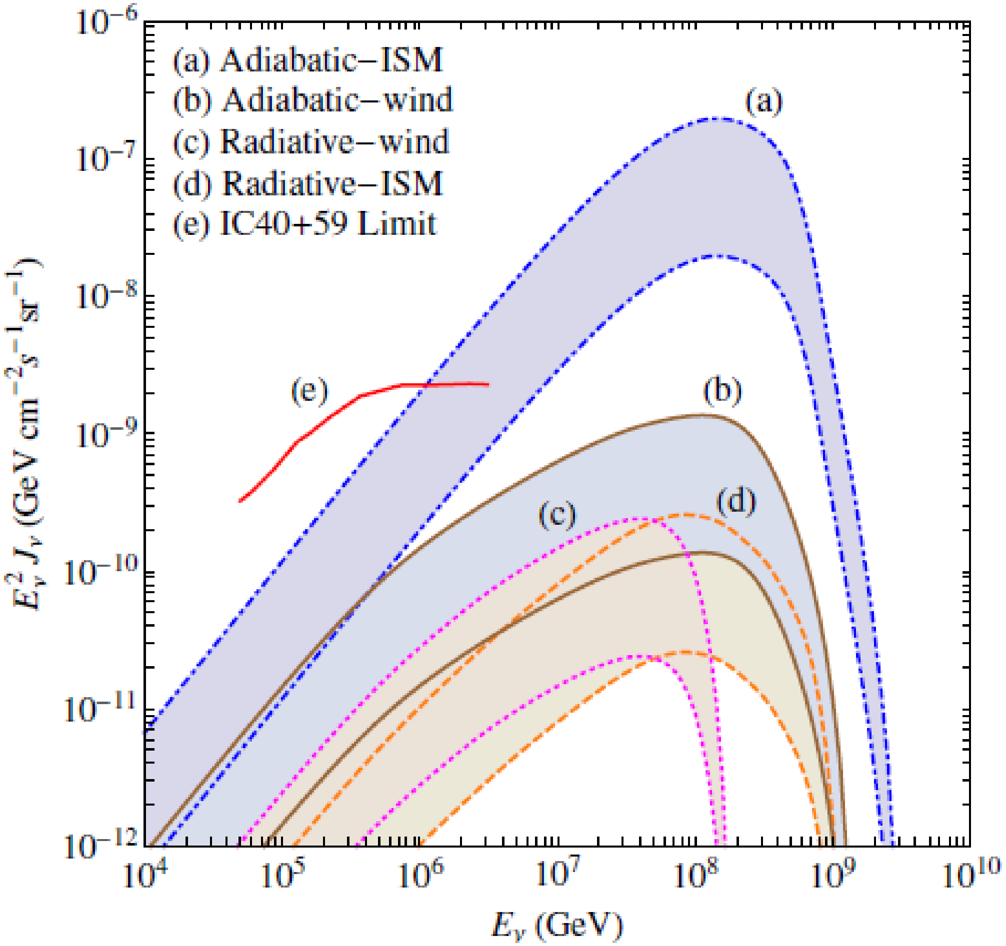


Gehrels & Razzaque 2013



GRB Afterglow neutrinos - Revisited

Diffuse muon neutrino and antineutrino fluxes in 4 different blastwave scenarios



Razzaque 2013

GRB Afterglow: X-ray to Radio synchrotron radiation by the electrons accelerated in the forward shock/blastwave

Evolution of blastwave depends on

- Nature (adiabatic/radiative)
- Environment (constant density/radial density profile)

Protons, accelerated to UHE in the GRB blastwave interact with afterglow photons to produce long-lived PeV-EeV neutrinos

Combined 3-ν flux (after oscillation) ~6×10^{-9} GeV cm^{-2} s^{-1} sr^{-1} @ 1 PeV

A factor ~6 smaller than IC detection

Powerful but Optically Thick Sources?

Extragalactic Sources:

- Chocked Gamma-Ray Bursts
- Jetted supernovae (Hypernovae)

Jet Propagation inside a Collapsar

Widely thought to be long GRB progenitor

Relativistic GRB-like jet inside star ➔ Successful or *choked* GRB

➔ Choked GRBs may be related to orphan afterglows

Shocks in the jet ➔ particle acceleration ➔ high-energy ν production

Zhang & Woosley

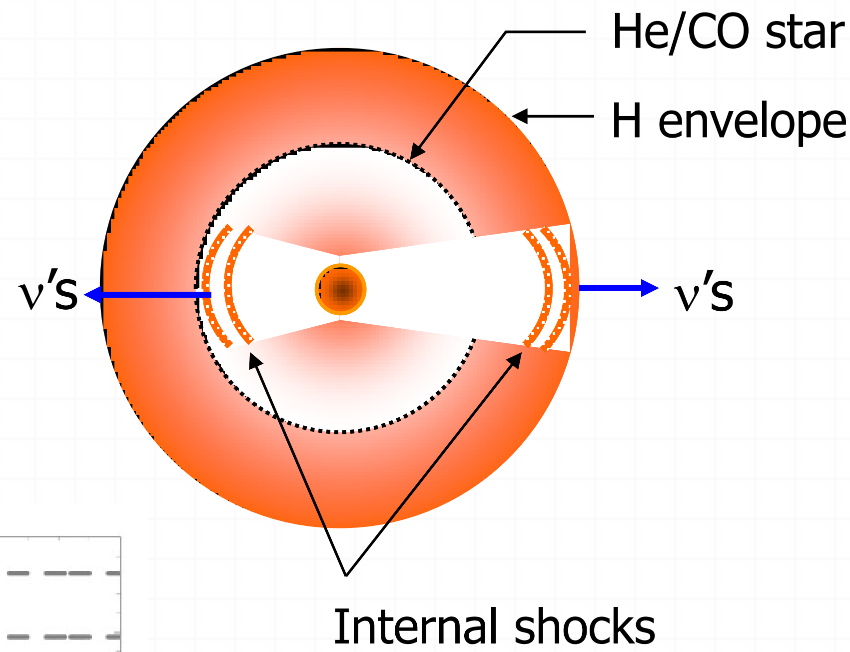
ν's precursor to GRB or Orphan Afterglow

Razzaque, Meszaros & Waxman 2003

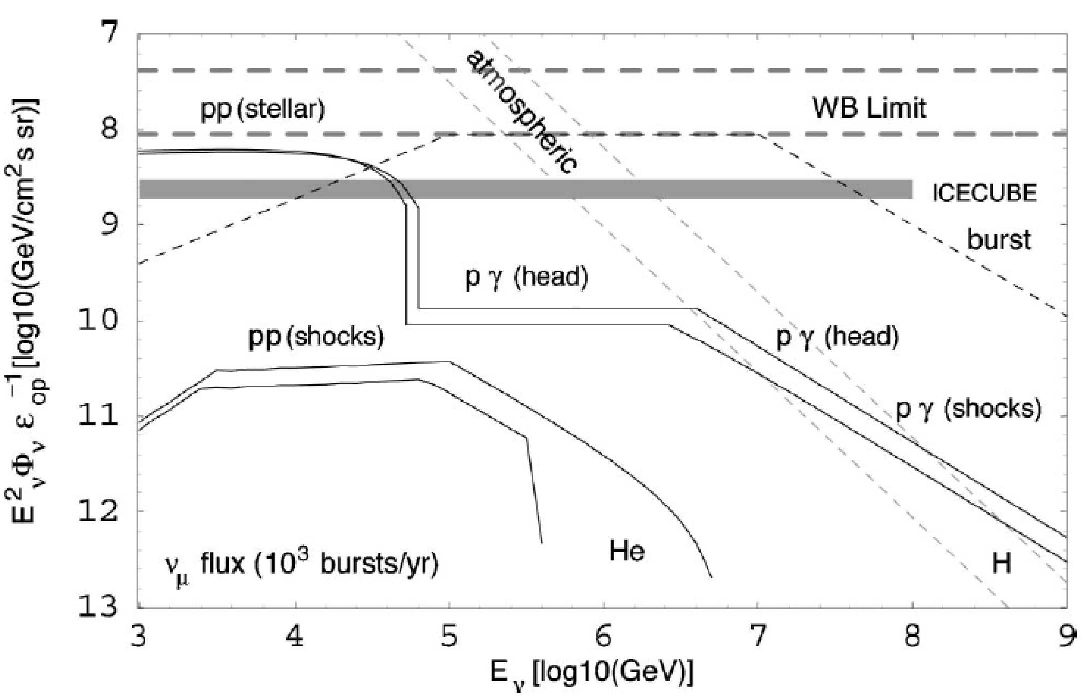
→ Optically thick shocks
→ High density of thermal γ-rays and target protons

$pp \rightarrow \nu' s$ Low energy

$p\gamma \rightarrow \nu' s$ High energy



$$R_i < R_\star \approx \begin{cases} 10^{11}\ cm\ (He) \\ 10^{12.5}\ cm\ (H) \end{cases}$$

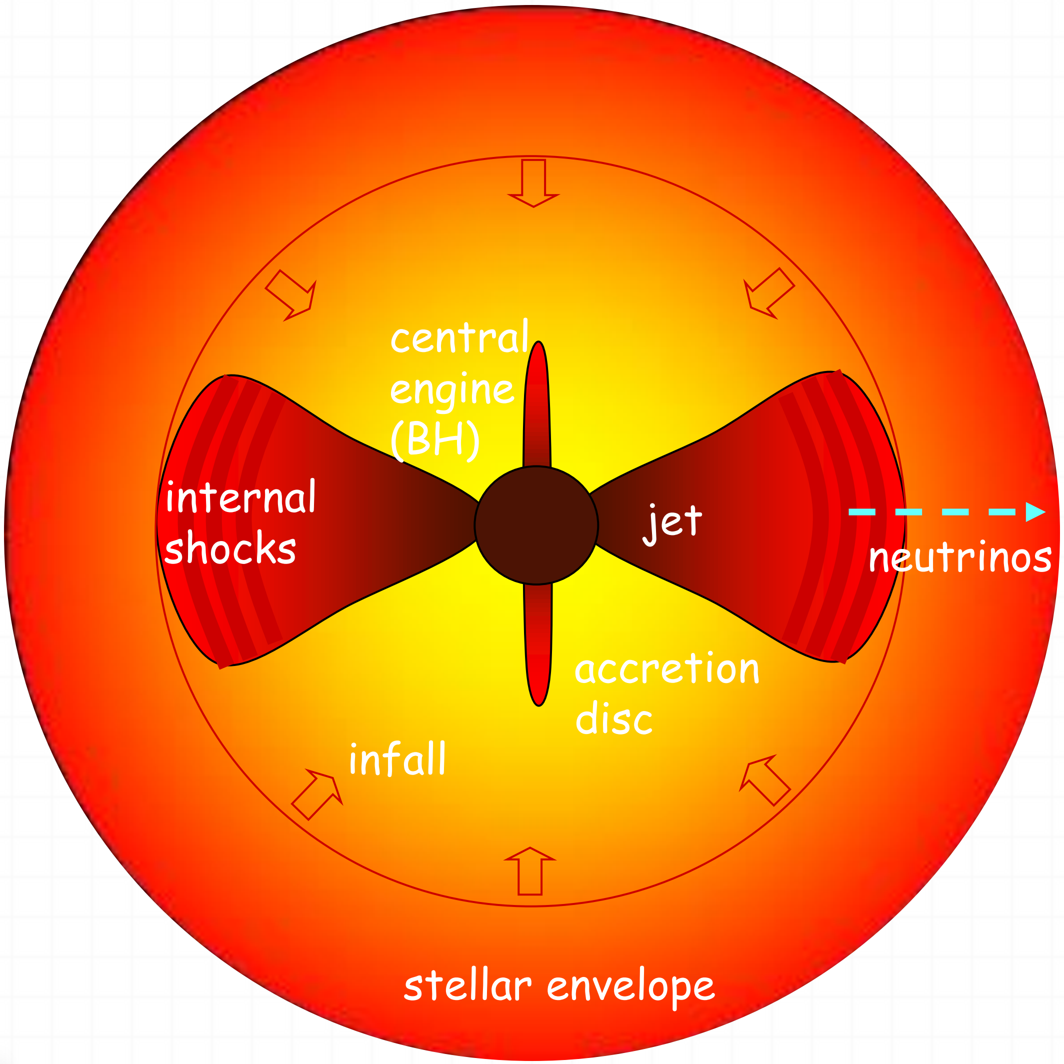


Diffuse flux

No. of choked jets can be Larger than the no. of GRBs

Jetted Supernova/Hypernova Model

Razzaque, Meszaros & Waxman 2004



- Core-collapse SNe (type Ib/c, II) forms a central engine, an accretion disc and launch bi-polar jets, as thought to be the case for long GRBs
- The jets, however, are much slower (Γ~ few) and broader (~1/Γ)than the GRB jets (Γ~100-1000)
- Intermitten accretion gives rise to inhomogeneity in the jet and collisions between them, analogous to internal shocks of GRBs
- Collisions produce shockwaves and protons in the jet can be accelerated to high energies by a Fermi mechanism
- Interactions of high-energy protons (pp) produce TeV-PeV ν's

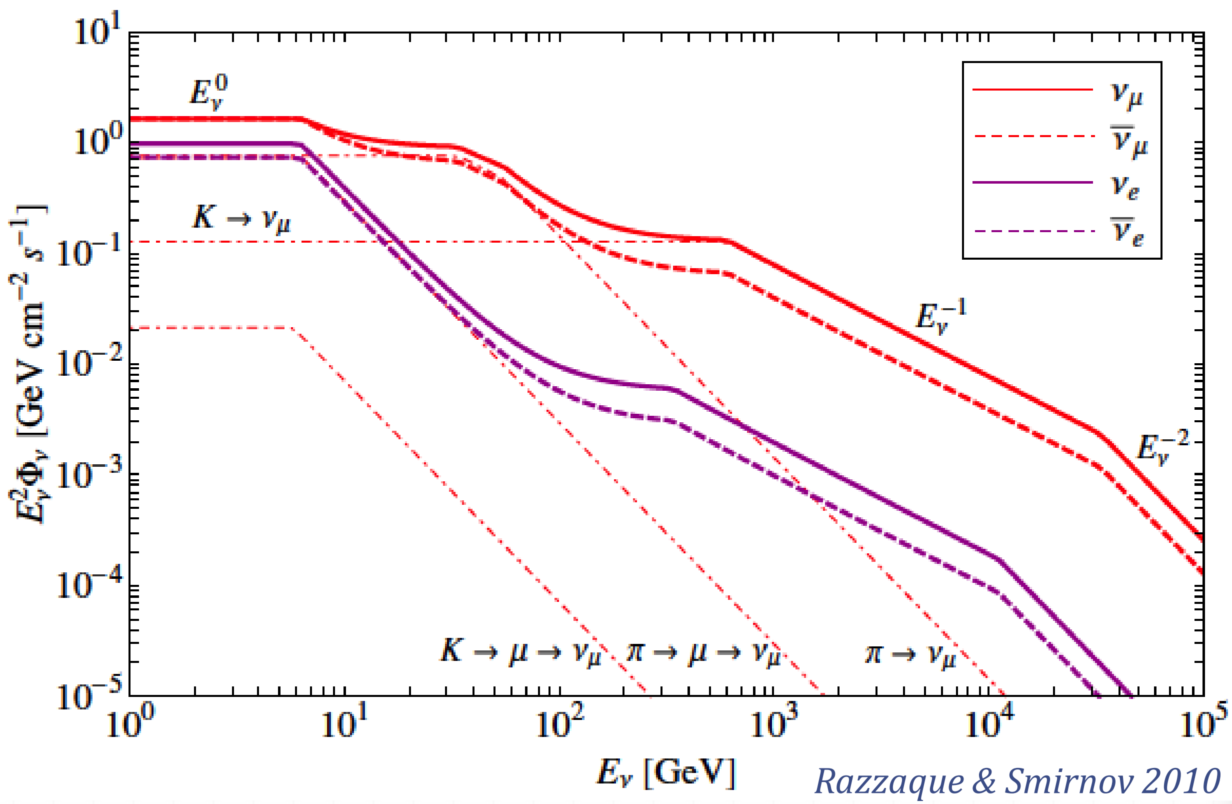
Neutrino Spectra from a Jetted Supernova

Razzaque, Meszaros & Waxman 2004, 2005
Ando & Beacom 2005
Mena, Mocioiu & Razzaque 2007
Enberg, Reno & Sarcevic 2009
Razzaque & Smirnov 2010

pp collisions dominantly produce charged π and K mesons, which decay to produce neutrinos

Fluxes from a hypothetical source at 10 Mpc

- Shape of the spectra are dominated by various energy losses by secondary mesons before decaying to ν's
- Charm mesons may contribute at very high-energies
- In-source neutrino oscillation (MSW effect) in addition to oscillation in vacuum can be important



Razzaque & Smirnov 2010

Jetted Core-Collapse Supernova Rate

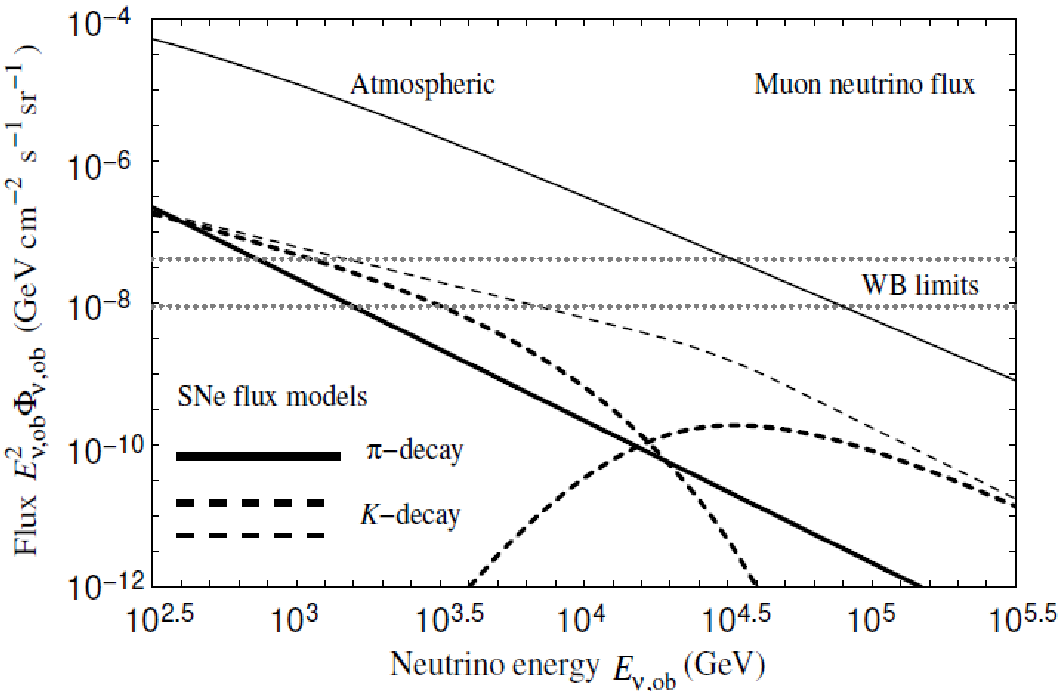
Diffuse neutrino flux from CC SNe assuming all have semi-relativistic jets

- hard to detect, much below atmospheric background
- Detection of individual bursts has better prospect of detection

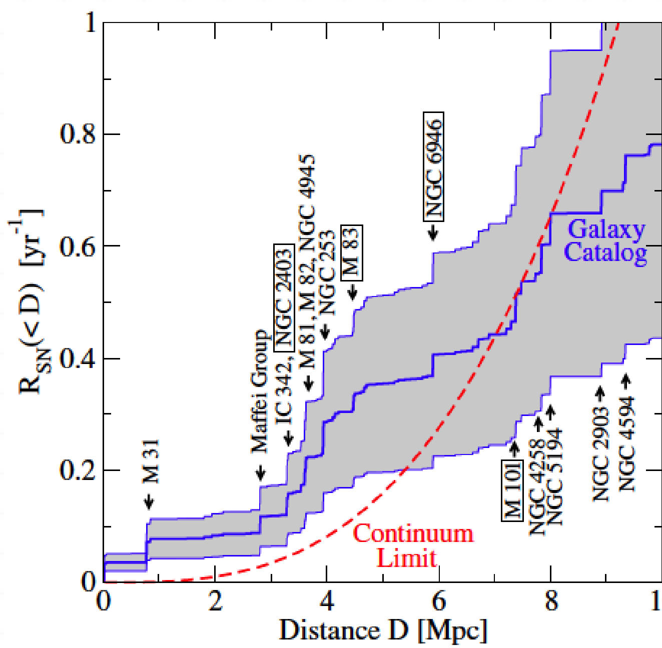
There are ~4000 galaxies known within 20 Mpc. With a combined rate of >1 SN/yr, IceCube is expected to detect >3 muon neutrino events per year if all core-collapse SNe have jets.

Cumulative SN rate vs. distance in the local universe

Razzaque, Meszaros & Waxman 2005



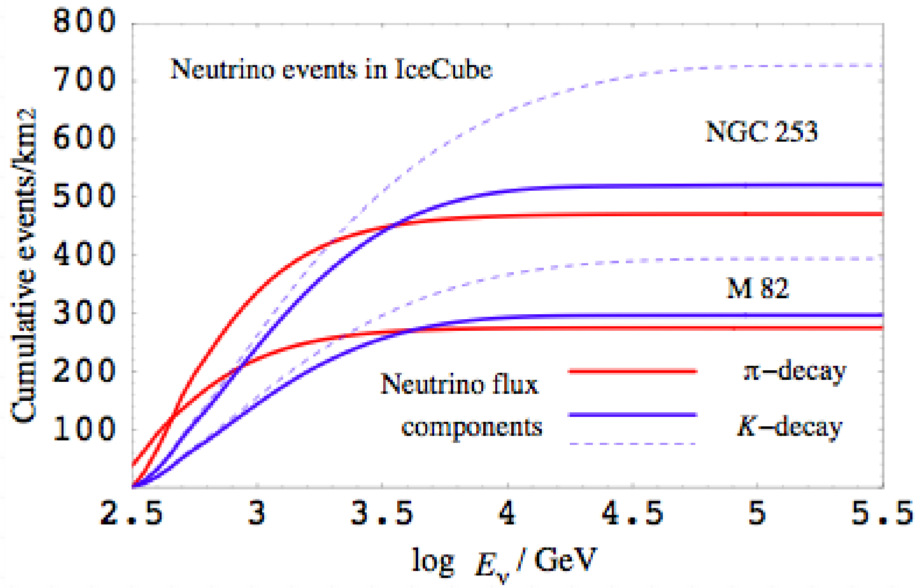
Ando, Beacom & Yuksel 2005



Detection Prospect

Detection of individual CC-SN event in nearby universe might be possible

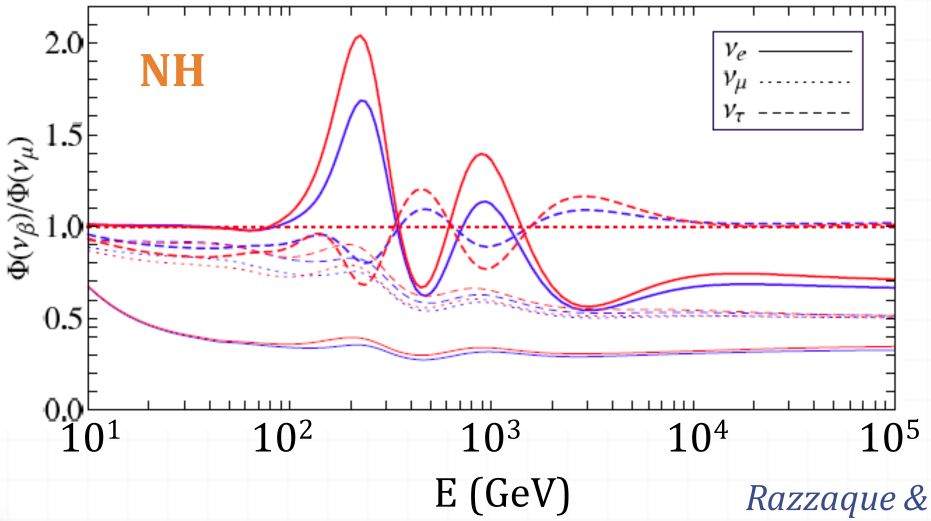
Detection in a nearby starburst galaxy can be very rewarding for fundamental neutrino physics too

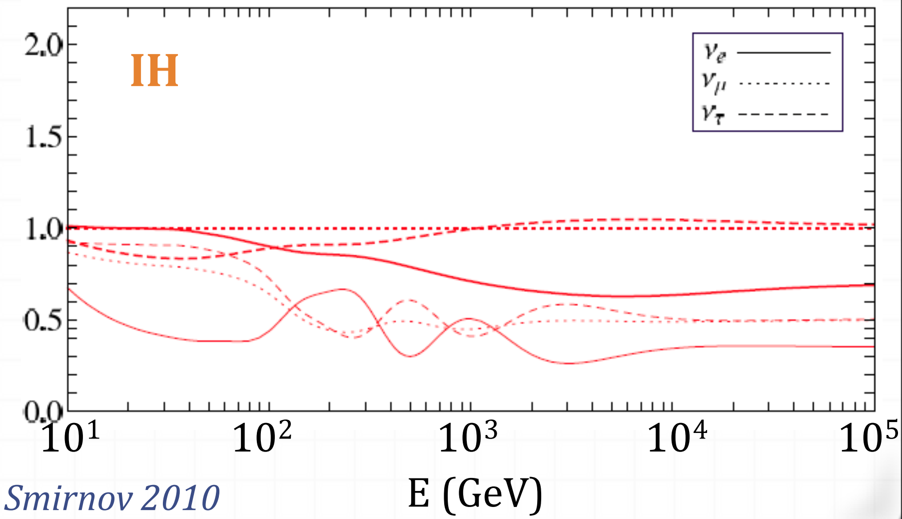


Ratio of cascade-to-track events for normal and inverted neutrino mass hierarchies

Mikheyev-Smirnov-Wolfenstein effect at high energies

Initial flavor ratio: ε:1:0

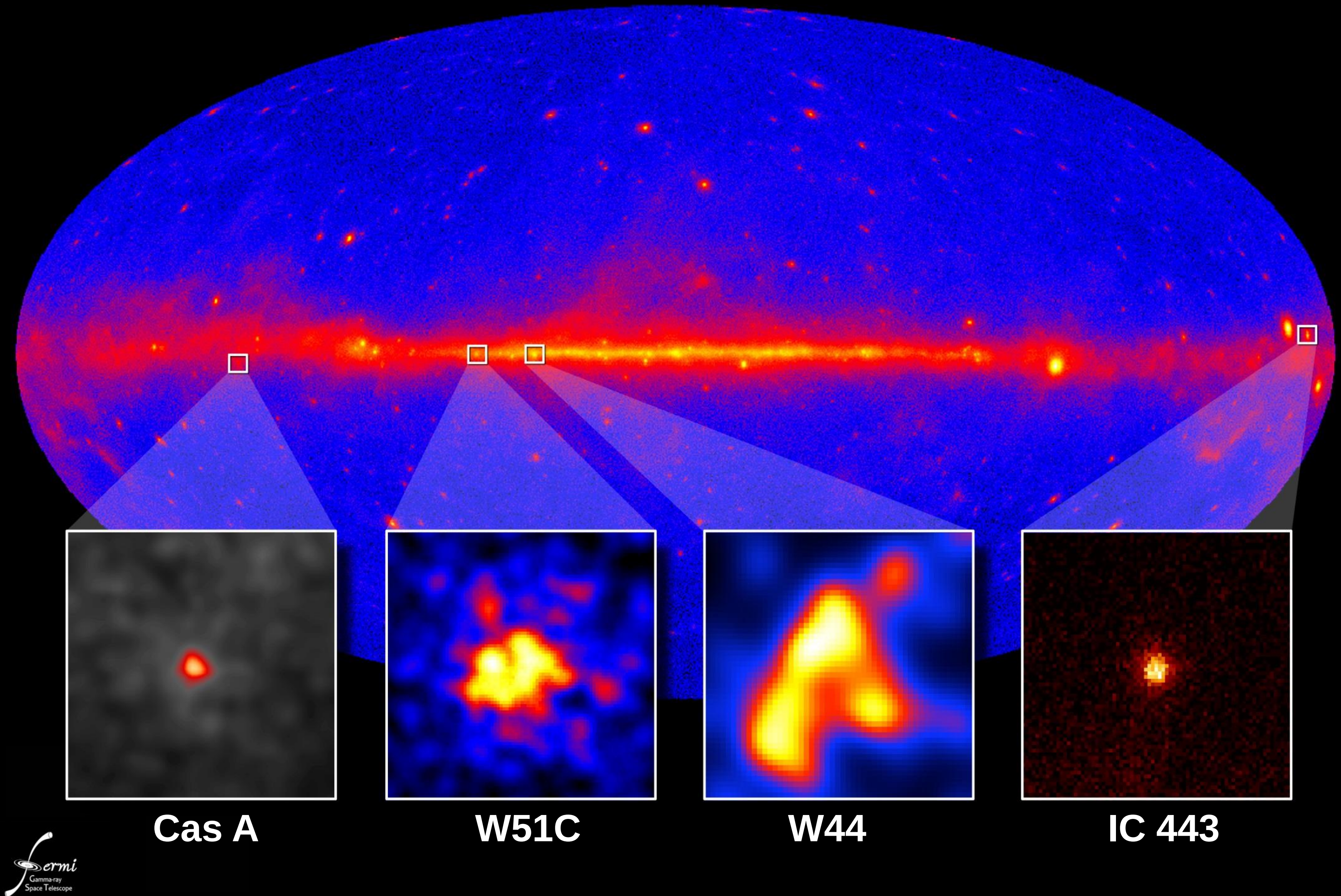




Razzaque & Smirnov 2010

Galactic Cosmic-Ray Sources?

Supernova Remnants



Supernova Remnant RX J1713.7-3946

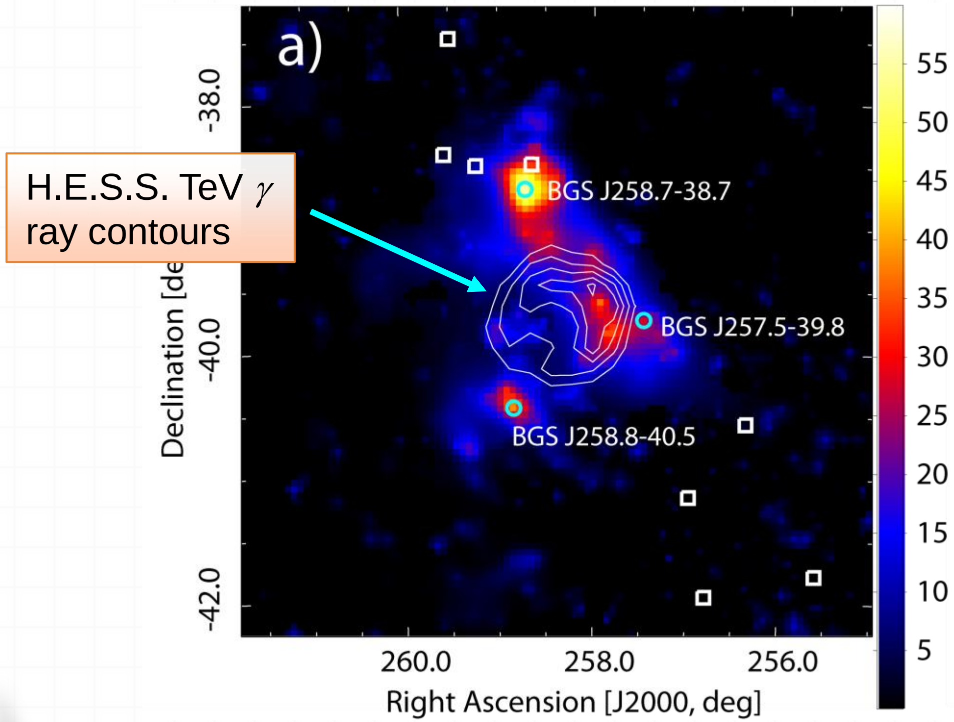
Young remnant, age: ~1600 yr
Distance: ~1 kpc

One of the brightest TeV γ-ray sources in the sky (H.E.S.S.)

Fermi LAT detection: Abdo et al. 2011

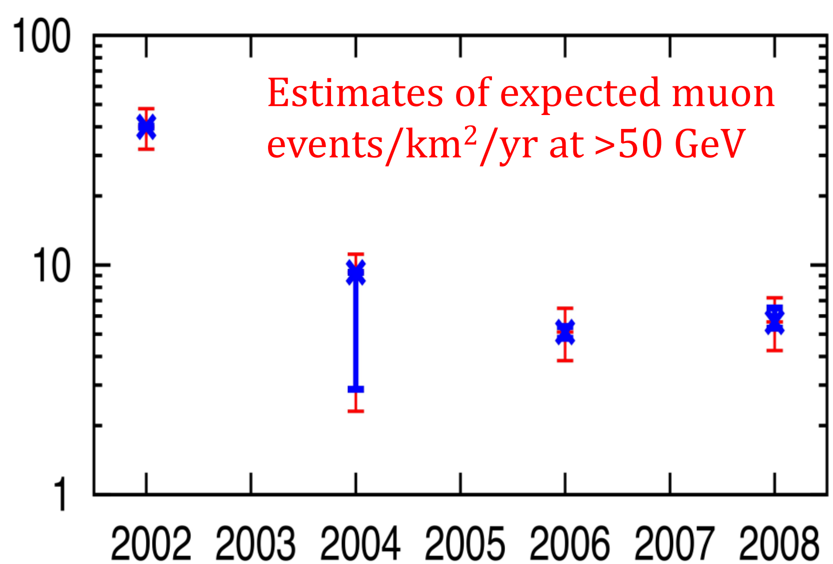
LAT TS map for > 0.5 GeV

ML fit for point sources around RX J1713



Widely thought to be a ν source, based on the modeling of TeV γ ray spectrum with a hadronic π^0 model

Alvarez-Muniz & Halzen 2002
Vissani & Costantini 2005

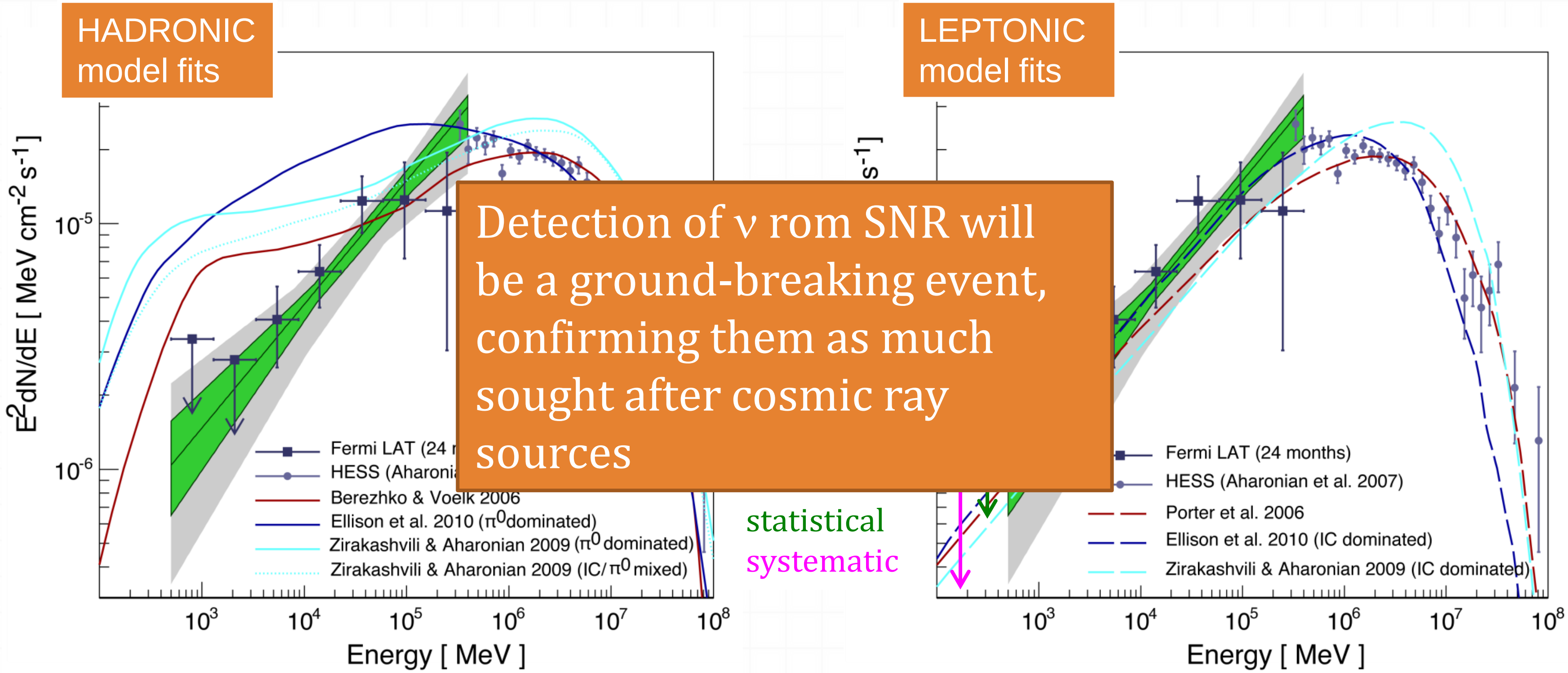


Vissani 2011

Supernova Remnant RX J1713.7-3946

Photon index in the LAT rage: $\Gamma_{LAT} = 1.5 \pm 0.1_{stat} \pm 0.1_{syst}$ *Very hard!!*

- Hadronic models (dominated by π^0 decay γ rays) fail to reproduce LAT spectrum
- Leptonic models (dominated by inverse Compton γ rays) fit data well
  - Required magnetic field, 0.01 mG, is lower than ~0.1-1 mG inferred from X-ray data modeled as synchrotron radiation *(Uchiyama et al. 2007)*



Detection of ν rom SNR will be a ground-breaking event, confirming them as much sought after cosmic ray sources

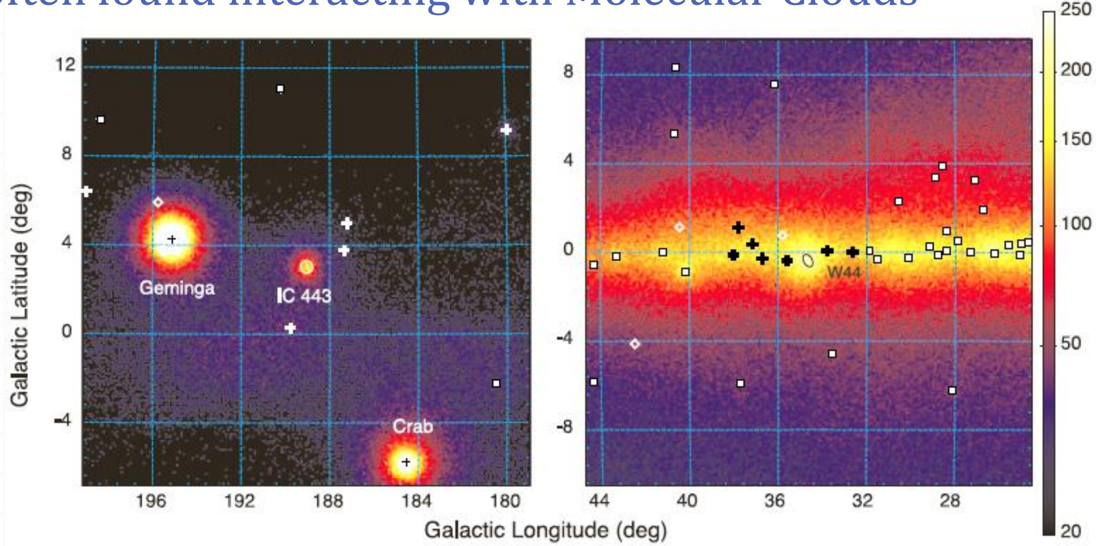
OLD SNRs: Confirmation of hadronic γ rays

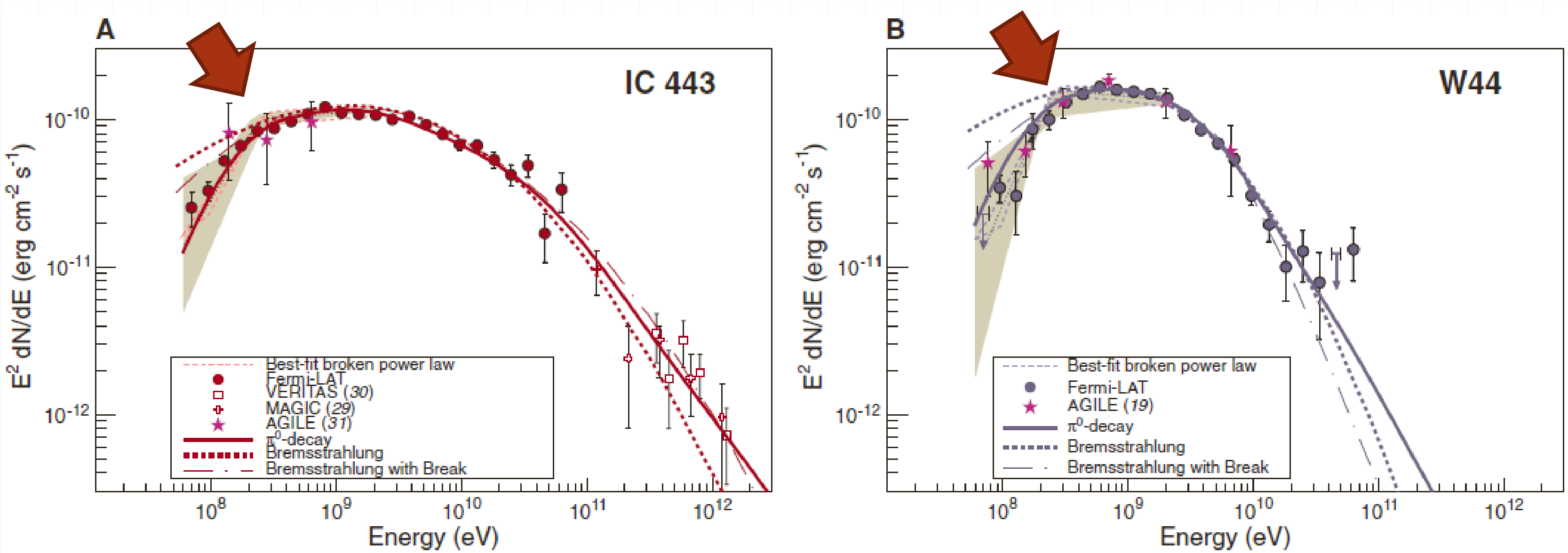
Typical age: ~10,000 yr, often found interacting with Molecular Clouds

Detection of characteristic pion-decay signature

[Fermi-LAT] Ackermann et al. 2013

- Bright GeV neutrino sources
- Faint TeV neutrino flux





A Little Cousin of Supernovae

Surprising discovery of the first γ-ray nova by *Fermi* LAT on March 10, 2010

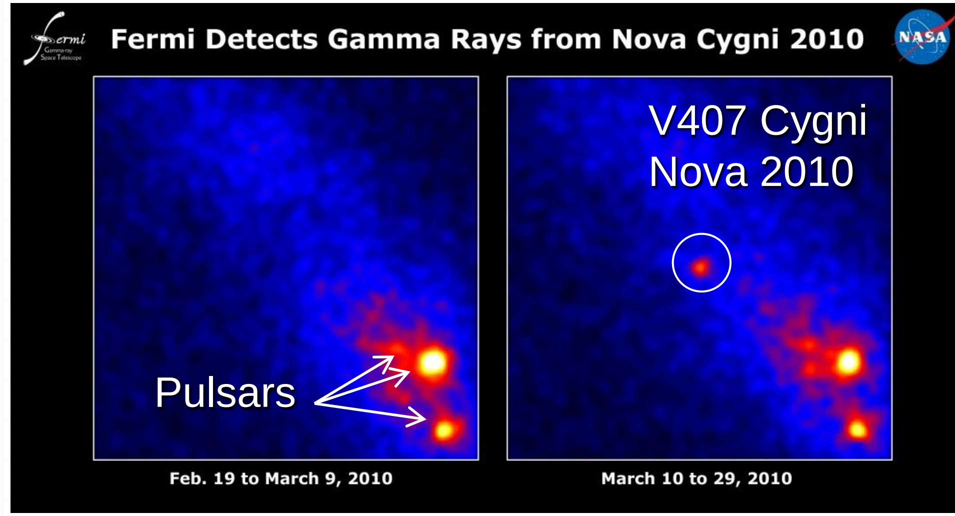
Announcement of optical detection by Nishiyama and Kabashima IAUC 2199 (2010) - Amateur astronomers

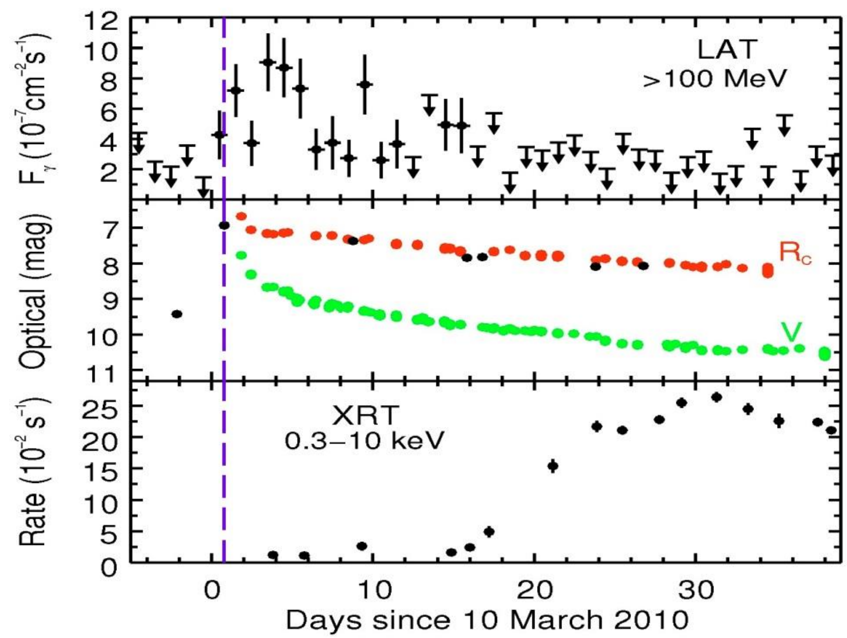
V407 Cygni Symbiotic binary system (2.7 kpc):
Mira-type pulsating star, most probably in its AGB phase
($M \sim$ few $M_{\odot}$, $R \sim 500\ R_{\odot}$)

Multi-wavelength light curves

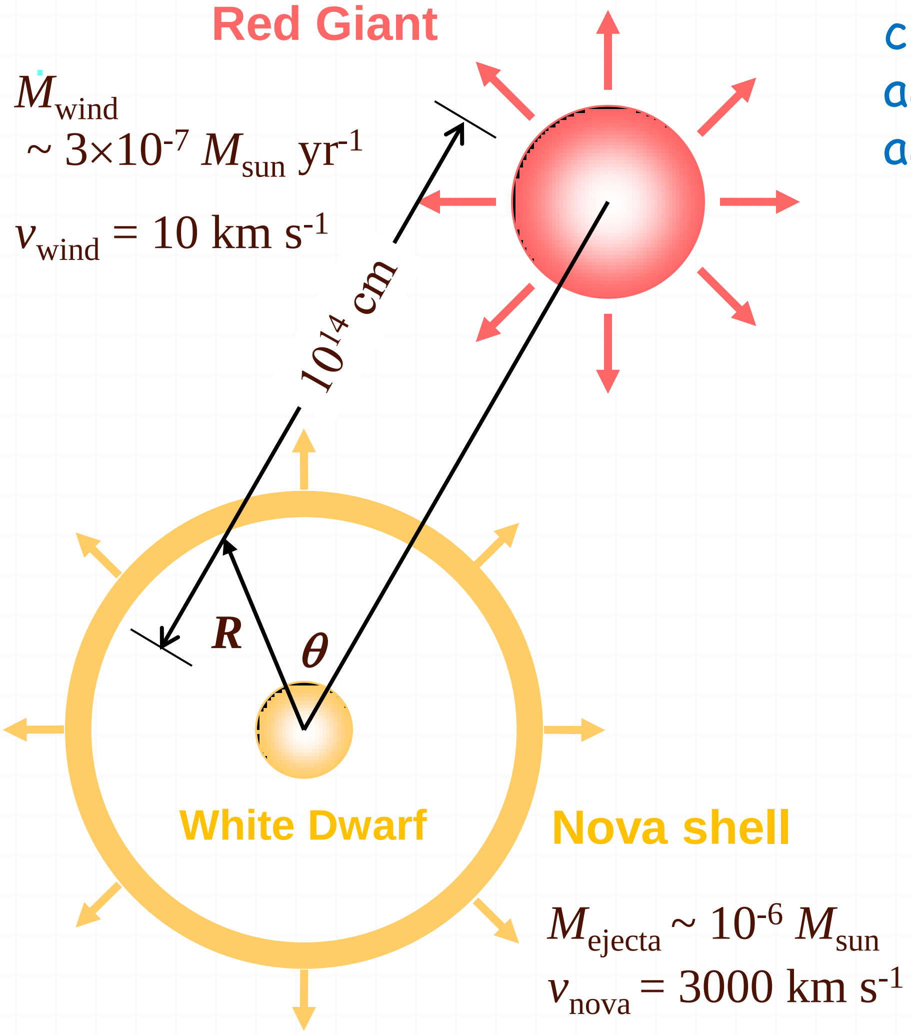
[Fermi Collab.] Abdo+2010

A Nova is a thermonuclear explosion on a white dwarf (WD) surface fueled by mass accreted from a companion star in a binary systems.

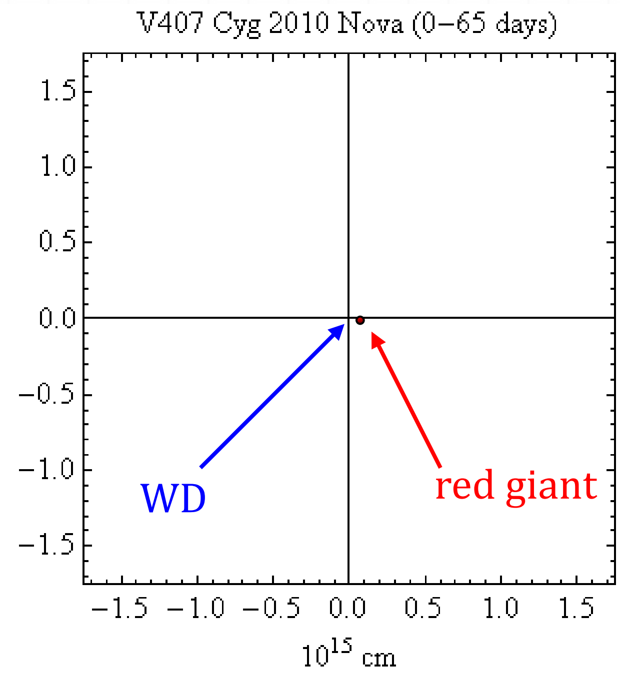




Gamma Ray Nova Model



Rapidly expanding nova shell in a dense circum-burst medium can produce shock and particles can accelerate in the shock, and interact to produce gamma rays

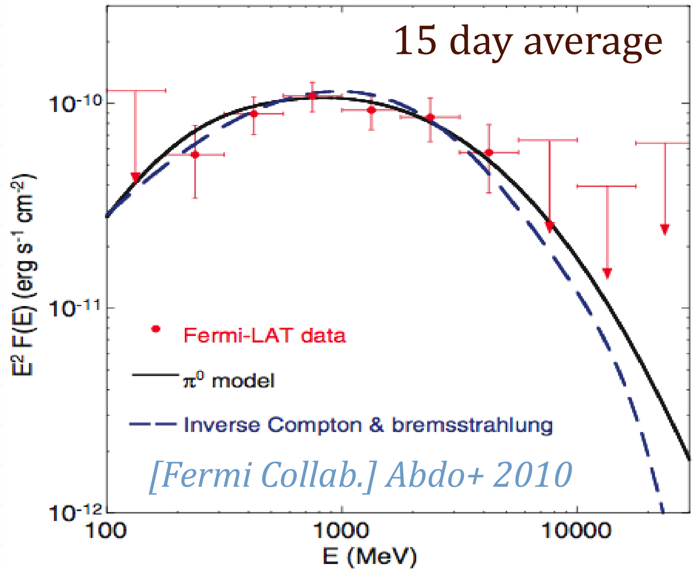


X-ray emission from the shell: Thermal bremsstrahlung in shock-heated gas

Gamma Ray Emission model (V407 Cyg)

Hadronic & leptonic models for *γ*-ray spectrum are statistically equivalent

- π^0 decay: accelerated p's collide with ambient wind material from the Red Giant
- Inverse Compton: accelerated electrons up-scattering infrared photons from the Red Giant

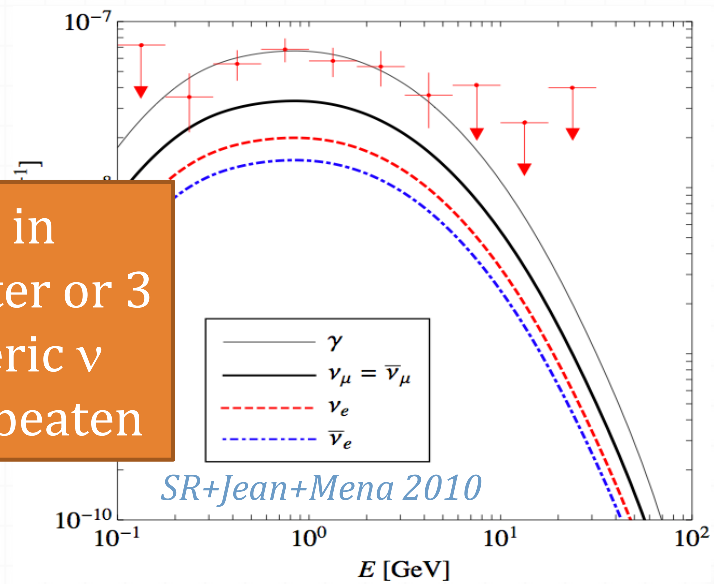


Kinetic energy of the nova shell ~10^{44} erg
Total energy in γ ray transient ~4×10^{41} erg
- Hadronic model ~9% of K.E.
- Leptonic model ~0.4% of K.E.

Expected *n* fluxes of differ… charged π and *K* decays ca… observed *γ*-ray flux

- ≥10 GeV *ν* fluence from…
- ≥100 MeV *γ* ray fluence…

Unless a γ-ray nova like in V407 is 10 times brighter or 3 times nearer, atmospheric ν background cannot be beaten



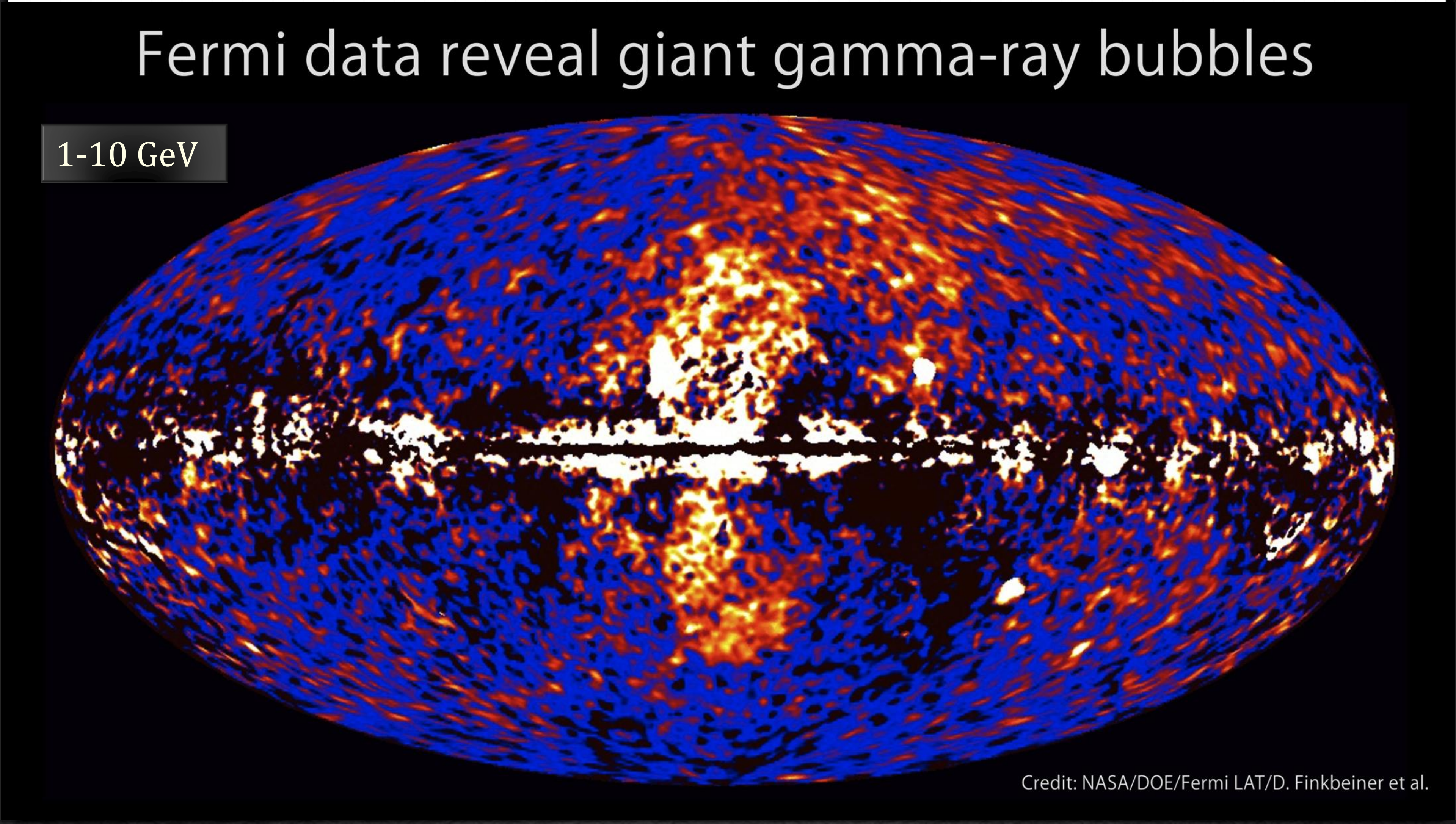
IceCube Deep Core Detector is sensitive at ~10 GeV

The center of Milky Way is the closest we can get to a black hole

Huge γ Ray Emitting Lobes at the Galactic Center

Fermi Bubbles

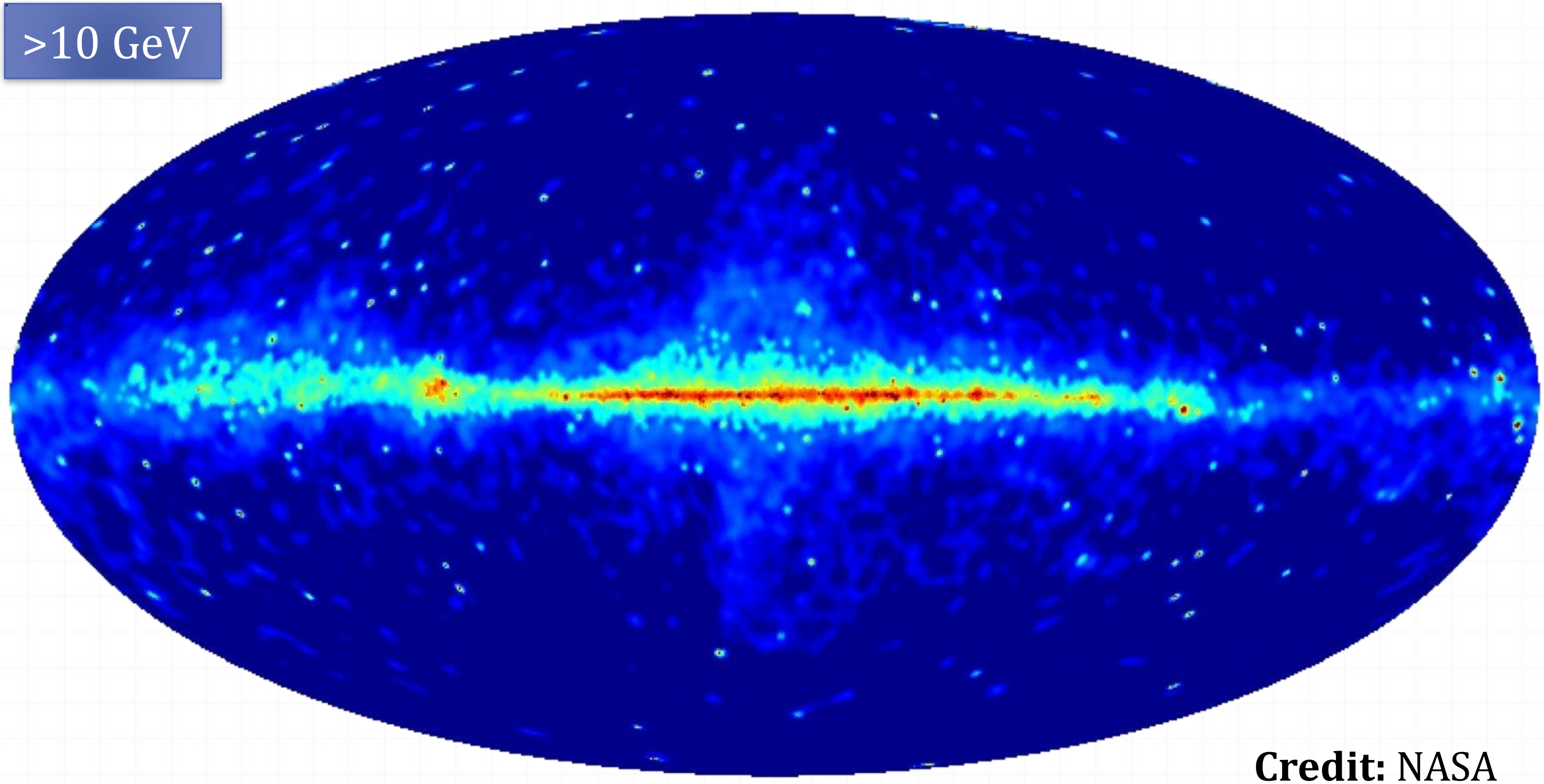
Discovered by Finkbeiner et al. (2010) in *Fermi* data



Fermi Bubbles at High Energies

- Fermi Bubbles are better visible at high energies ➔ Hard spectrum
- Seem to have well-defined boundary (sharp edges)
- Uniform projected intensity over the whole bubble surface

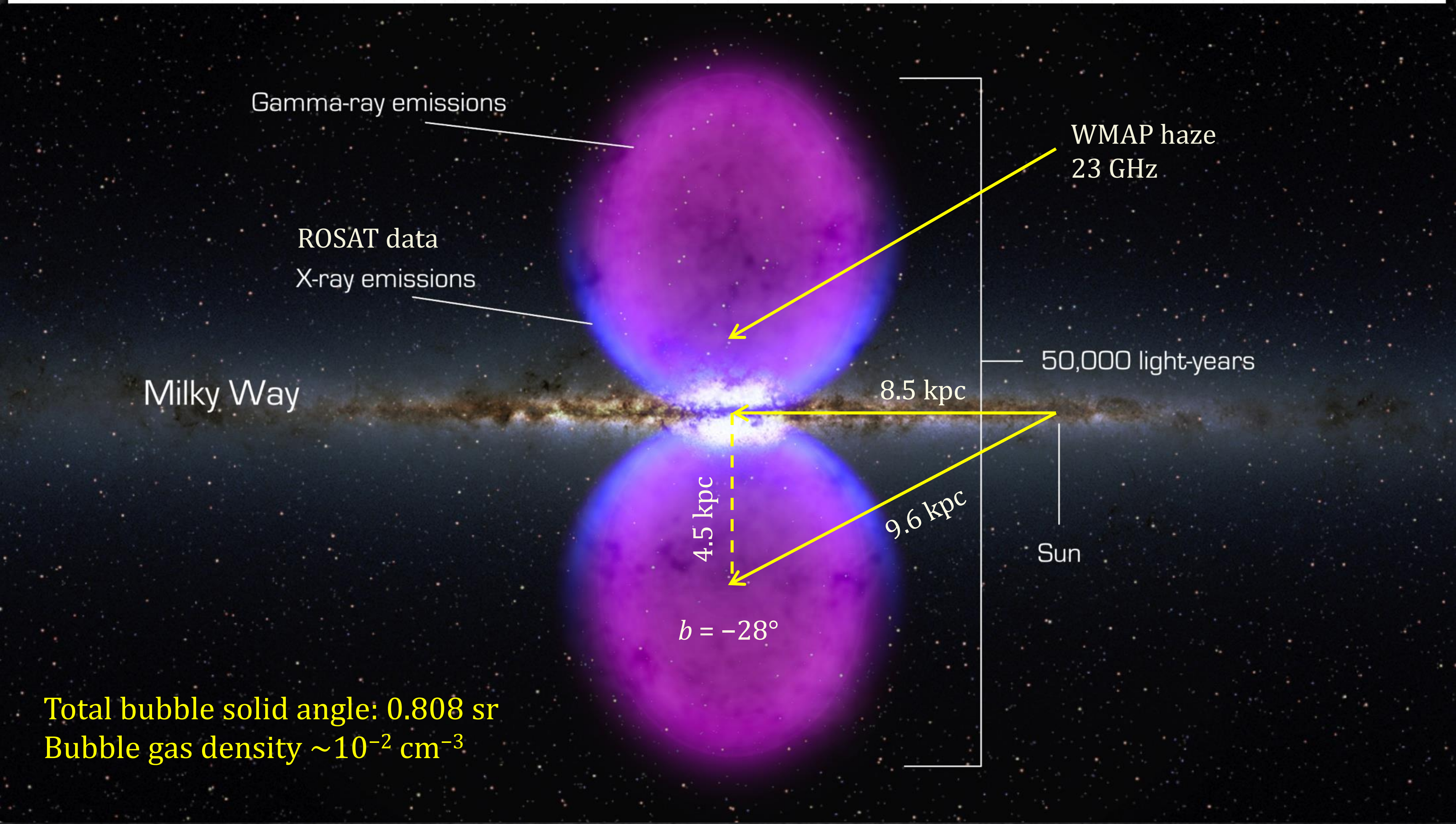
>10 GeV



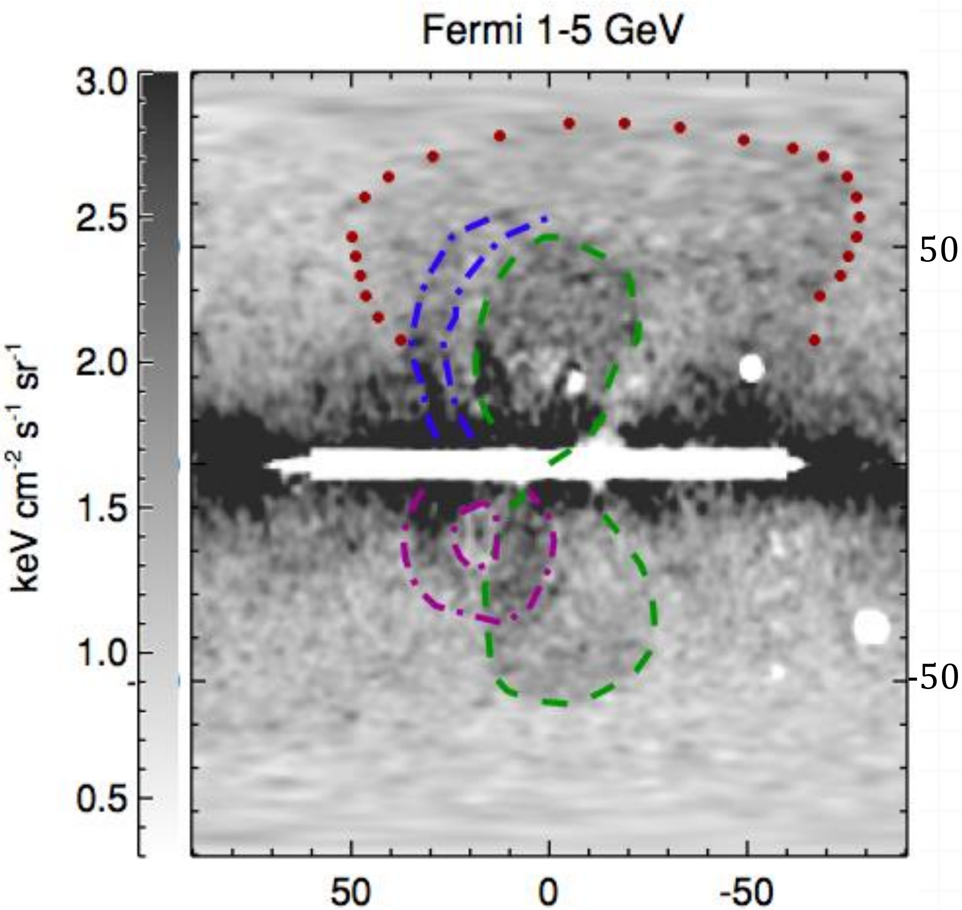
Credit: NASA

Bubble Geometry and Low Energy Observations

Credit: NASA Goddard Space Flight Center

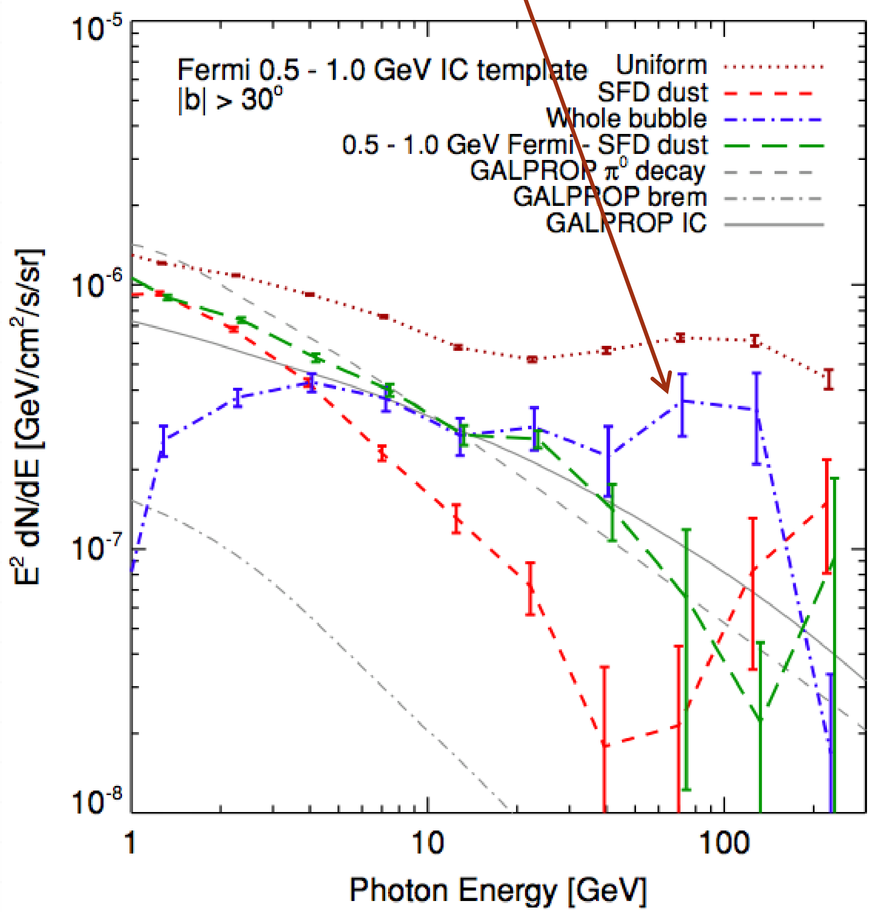


Bubble Morphology and Spectrum



Galactic Longitude

Very hard Bubble γ-ray spectrum



Su, Slatyer & Finkbeiner 2010

The Origin and Age of the Fermi Bubbles

- Leptonic origin of the gamma rays (inverse Compton)
  - Cooling time scale for up to 100 GeV gamma-ray producing electrons is a few million years – Age of the Bubbles
  - Possible origin –
    - Outflow from the Galactic center black hole Sgr A* (*Su et al. 2010, Mertsch & Sarkar 2011, Carretti et al. 2013*)
    - Capture of a star by Sgr A* (K.S. Cheng et al. 2011)
    - Localized star formation activity (K. Zubovas et al. 2011)
- Hadronic origin of the gamma rays (pion decay)
  - Cooling time scale for Cosmic-Ray protons $\sim 5\times10^{9}$ year!
    - Sets a lower limit on the bubble age
  - Possible origin –
    - Prolonged star formation activity at the Galactic Center (*Crocker & Aharonian 2011*)
- New Physics models
  - Dark matter annihilation *(Cholis 2011)*

FB from Galactic Center Starburst Activity

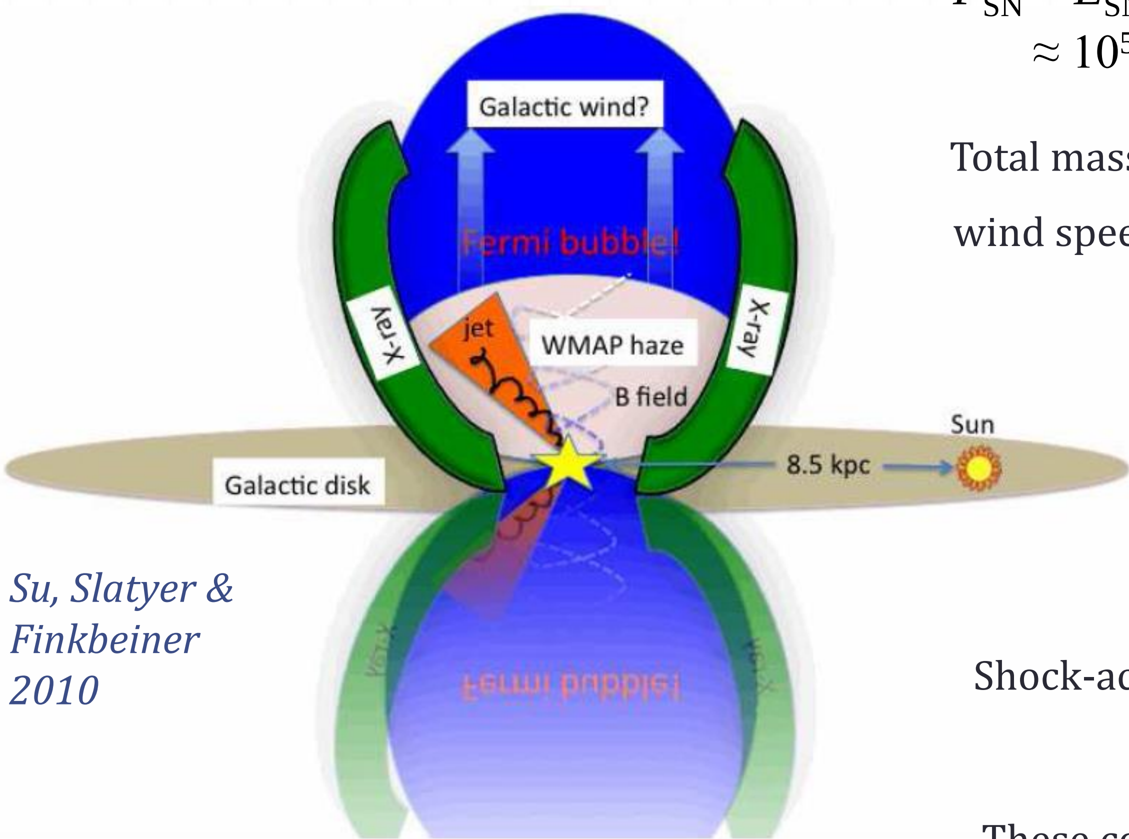
Total energy output rate (power) from SNe around the Galactic Center

From infrared luminosity

$$P_{\rm SN} = E_{\rm SN} \times {\rm rate}_{\rm SN}$$
$$\approx 10^{51}\ {\rm erg} \times 0.04/100\ {\rm yr} \approx 1.3\times 10^{40}\ {\rm erg/s}$$

Total mass loss rate in wind: $\dot{M}_{\rm w} \sim 0.03\ M_{\rm sun}/{\rm yr}$

wind speed: $v_{\rm w} \approx (2P_{\rm SN}/\dot{M}_{\rm w})^{1/2} \sim 1200$ km/s



Su, Slatyer & Finkbeiner 2010

Minimum bubble formation time scale

$$T_{\rm bbl} > n_{\rm gas} V_{\rm bbl}/\varepsilon \dot{M}_{\rm w} \sim 3\times 10^{9} \varepsilon^{-1}\ {\rm yr}$$

~0.01/cc, 2 blobs of r = 3.5 kpc

Shock-accelerated cosmic-ray power in wind

$$P_{\rm CR} \sim 0.1 P_{\rm SN} \sim 10^{39}\ {\rm erg/s}$$

These cosmic-rays interact with bubble gas to produce π^0 decay γ's on a time scale

Hadronic model by *Crocker & Aharonian 2011* ➔

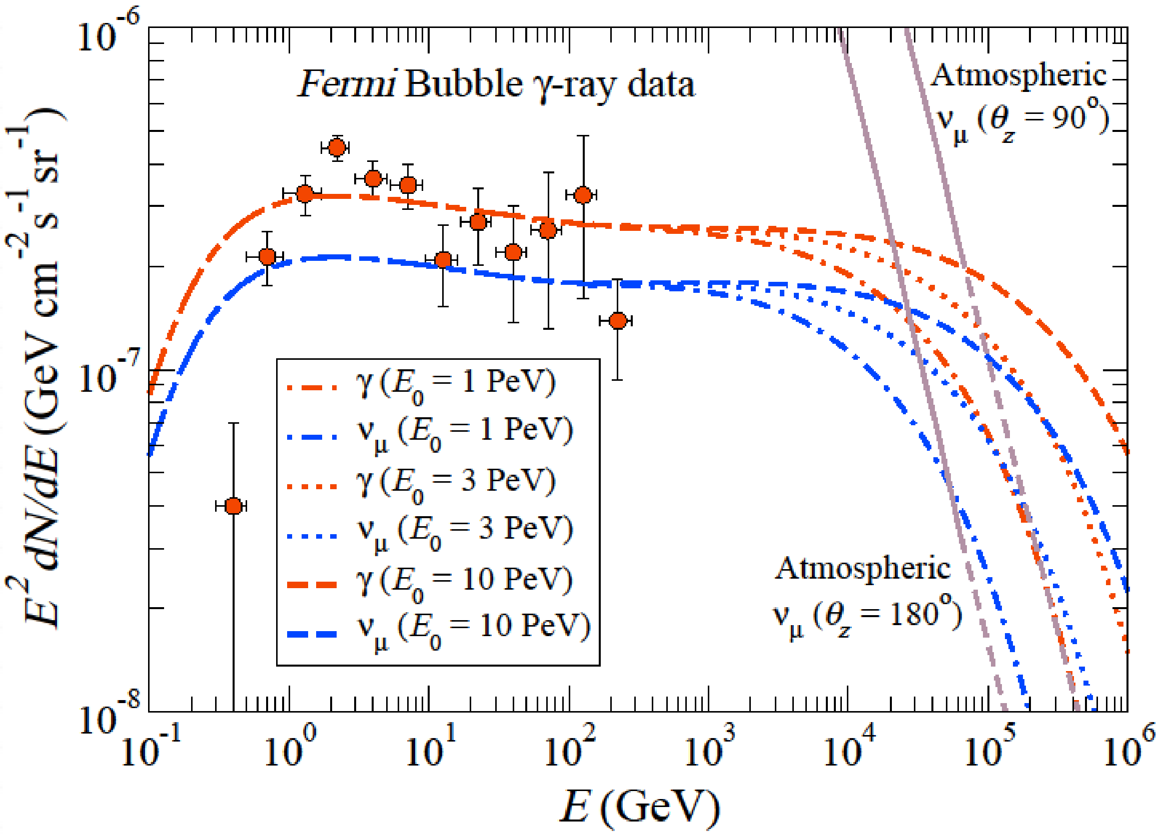
$$t_{\rm pp} \approx (n_{\rm gas}\sigma_{\rm pp}\kappa_{\rm pp} c)^{-1} \sim 5\times 10^{9}\ {\rm yr}$$

Bubble Gamma Ray Spectrum and ν Flux Models

Primary Cosmic Ray spectrum: $\sim E^{-2.1} \exp(-E/E_0)$; $E_0 = (1 \div 10) \times 10^{15}$ eV

Cutoff energy is motivated by the "knee" of the CR spectrum

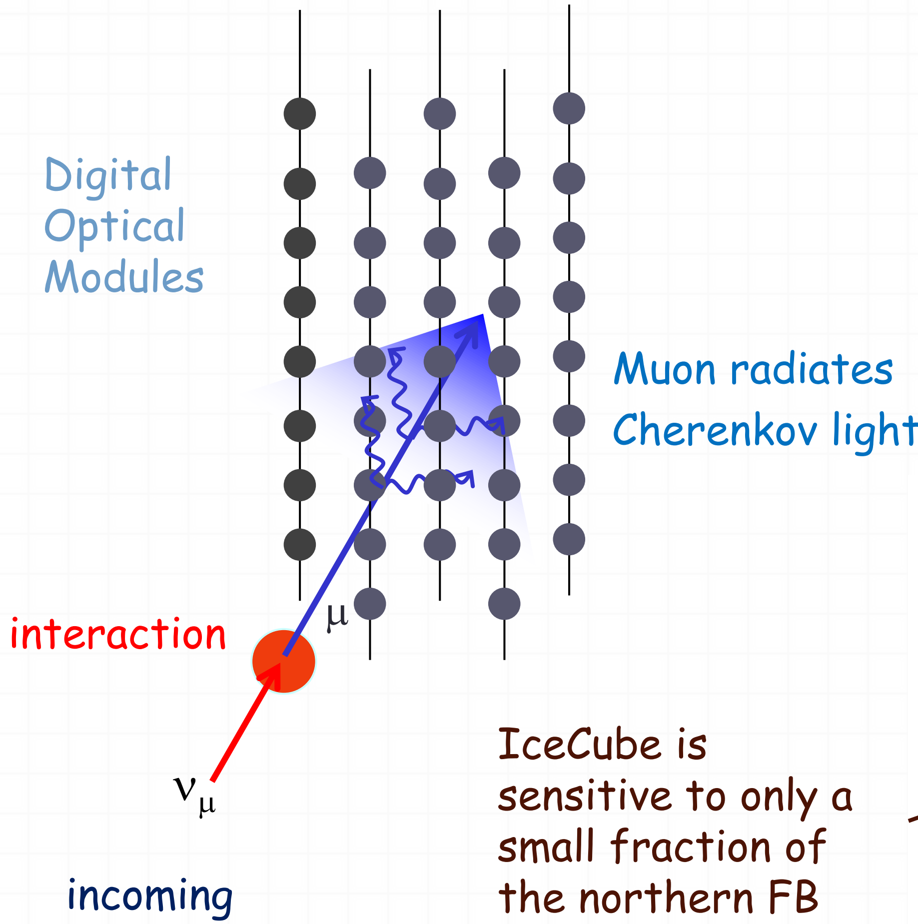
Lunardini & Razzaque 2012

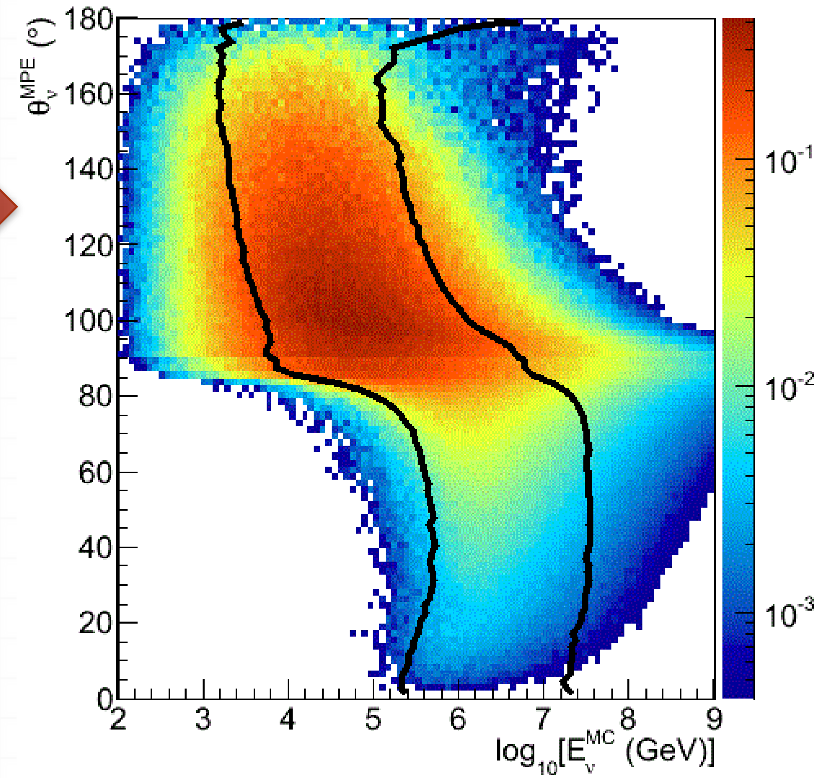


- Gamma and neutrino fluxes (>10 GeV) from parameterization of pp interactions from QGSJET hadronic model
- Low energy fluxes from delta-function approx
- Neutrino flux follows gamma-ray flux in spatial coordinates
- Knowing position of the bubbles helps greatly to reduce the atmospheric neutrino background

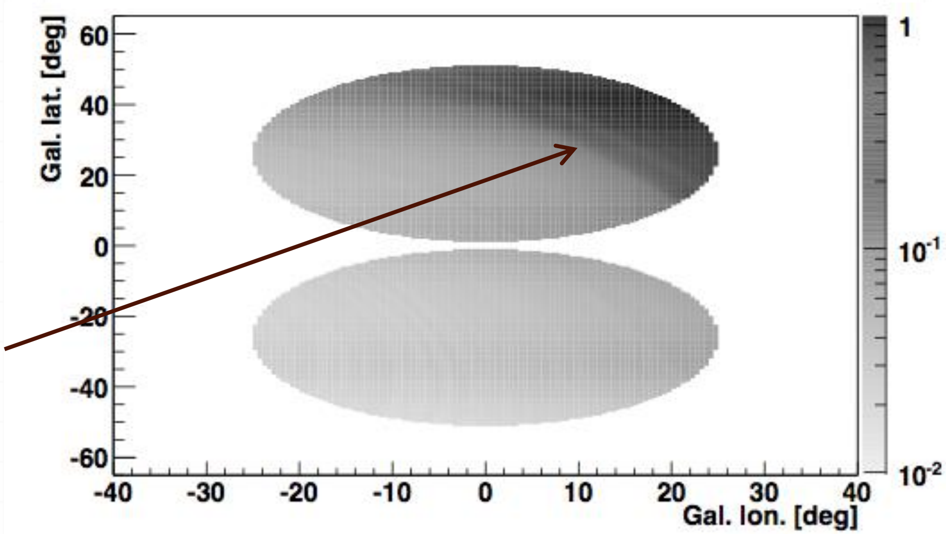
Sensitivity of IceCube

ν Telescopes are mostly sensitive to the sky below the horizon





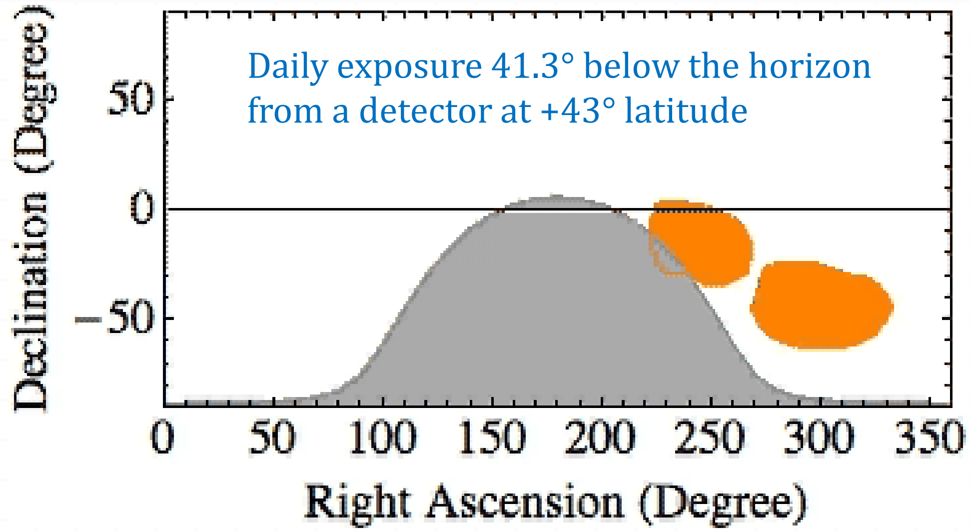
IceCube is sensitive to only a small fraction of the northern FB



N. Kurahashi 2011

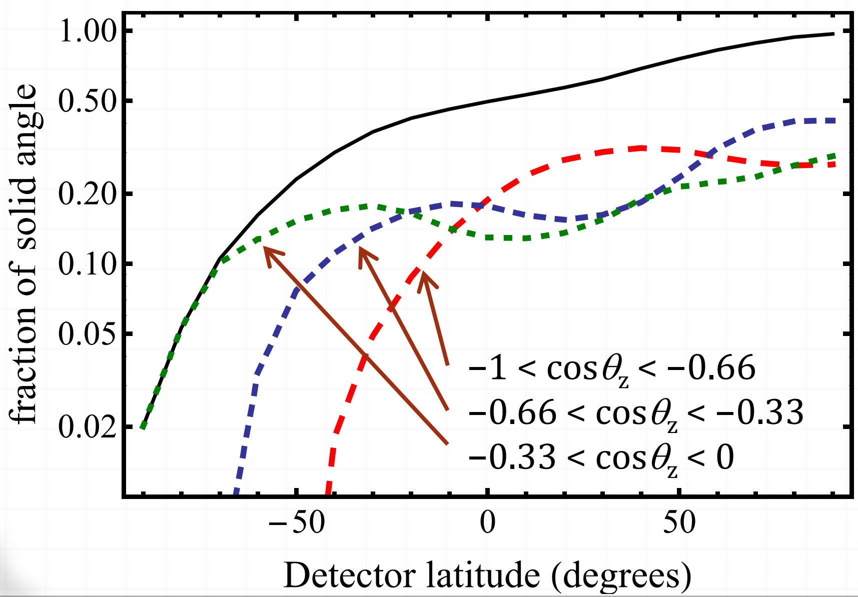
Choice of location for a ν Telescope sensitive to FB

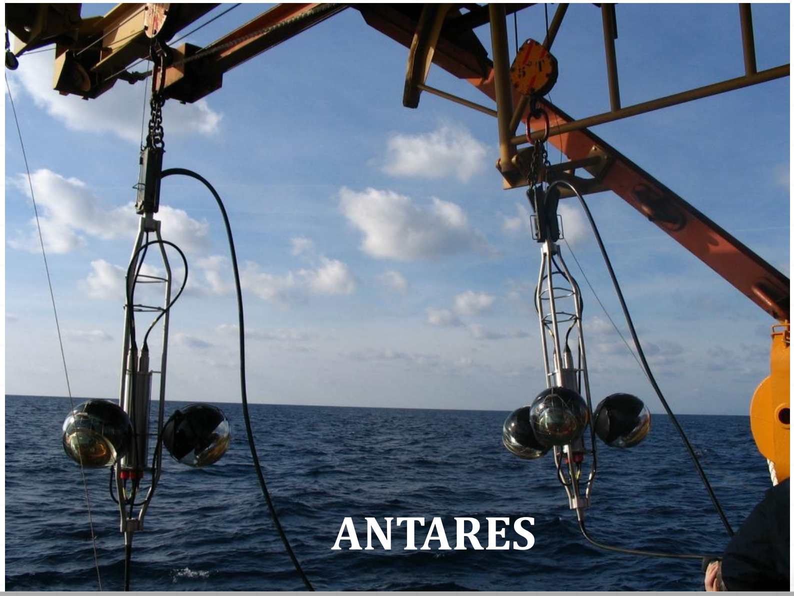
Exposure to the bubbles vary daily due to rotation of the Earth



For maximum sensitivity to the FB, telescope needs to be at high latitude in the northern hemisphere

→ **planned KM3NeT in the Mediterranean**

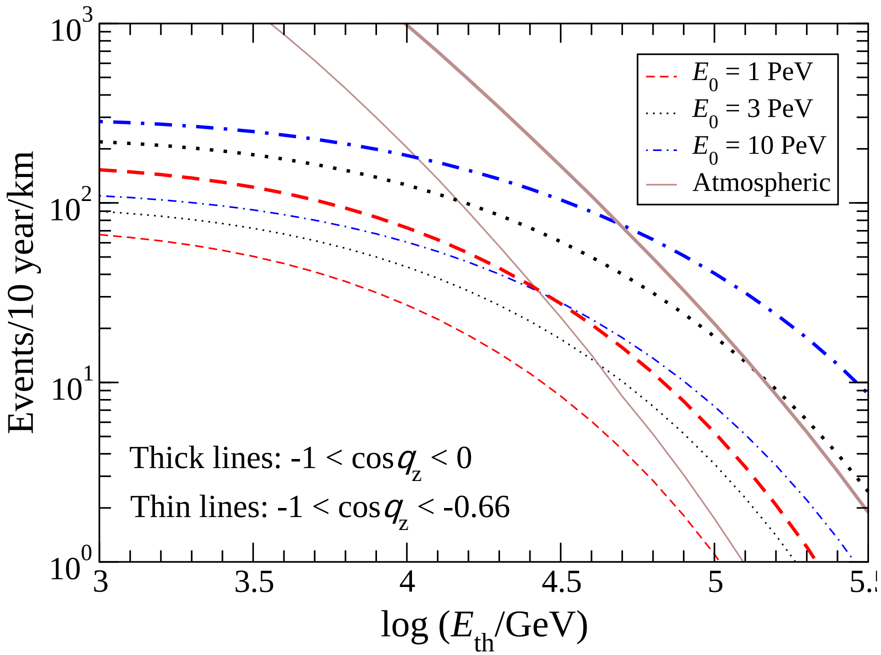


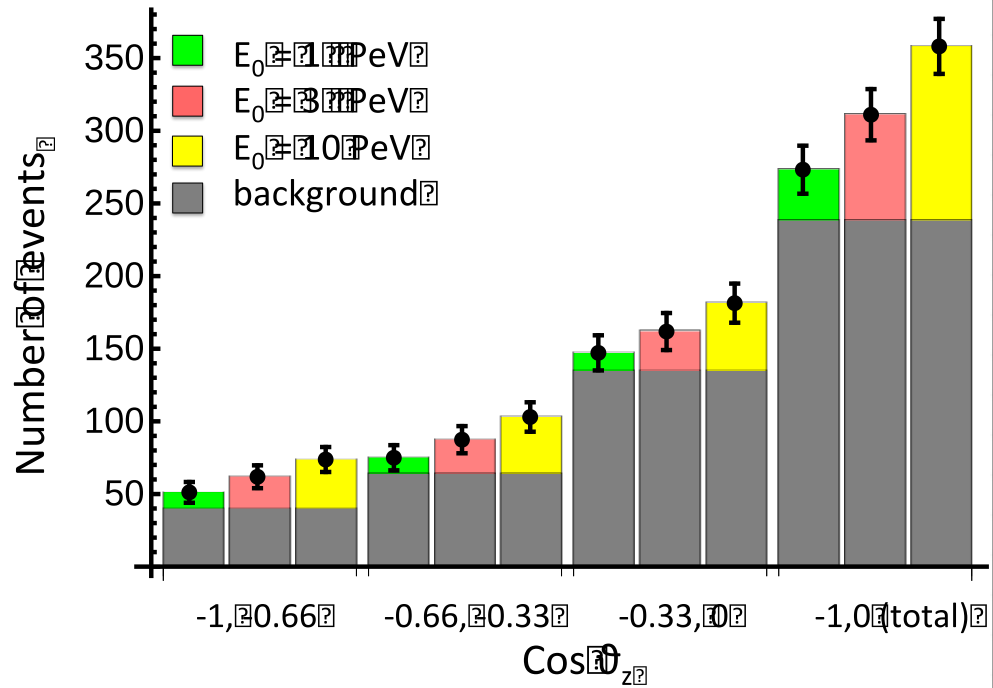


ν Event rates for the Fermi Bubbles

Upcoming Muon neutrino event rates for a km scale detector in the Mediterranean (δ=+43°) for different threshold energies

10 year event rate for a fixed threshold energy of 25 TeV



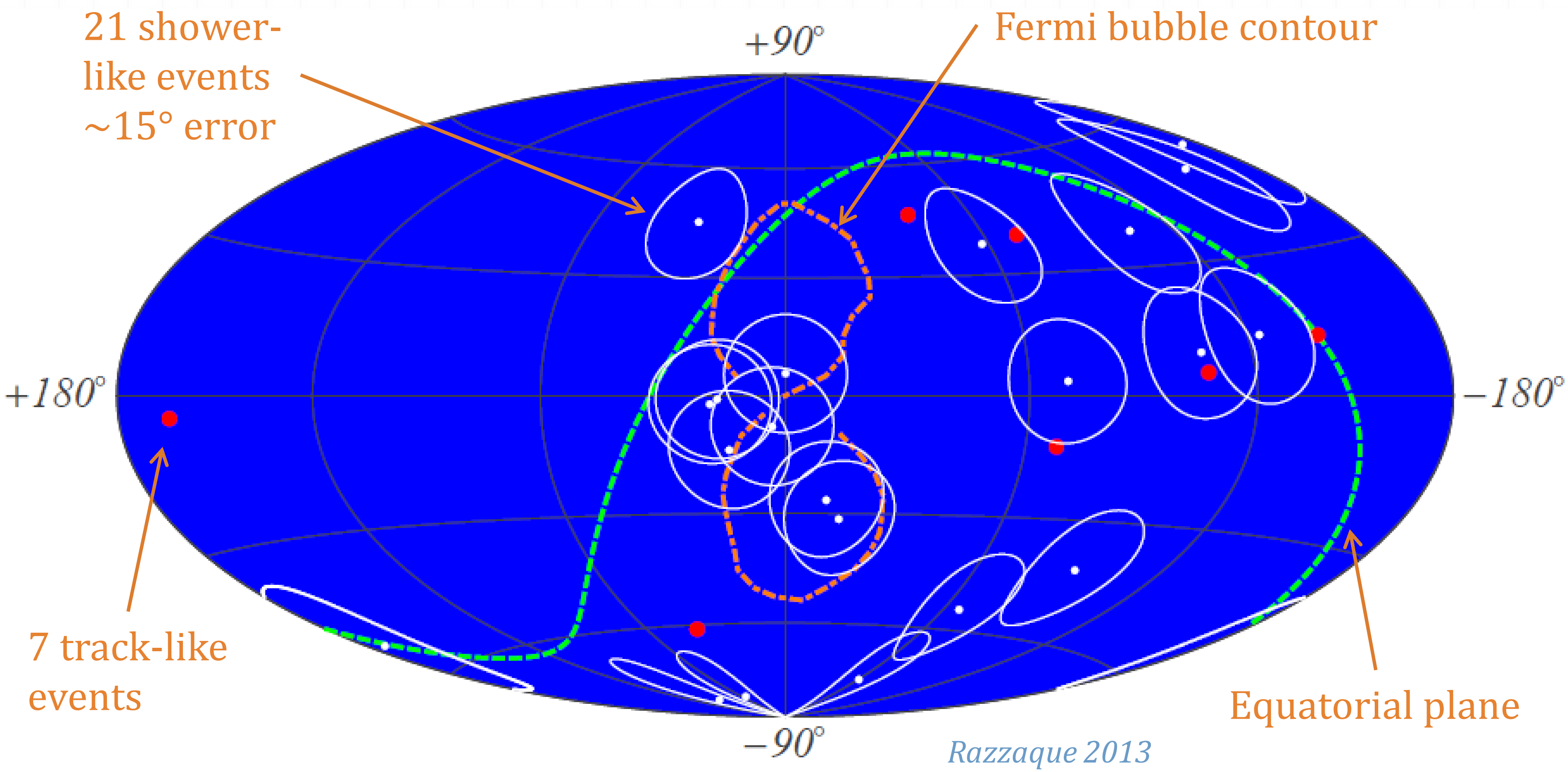


The final scale of KM3NeT could reach 6 km^2 (R. Coniglione 2011)

➔ Higher event rates, faster detection of the bubbles

➔ Fermi Bubbles can be detected within few years!

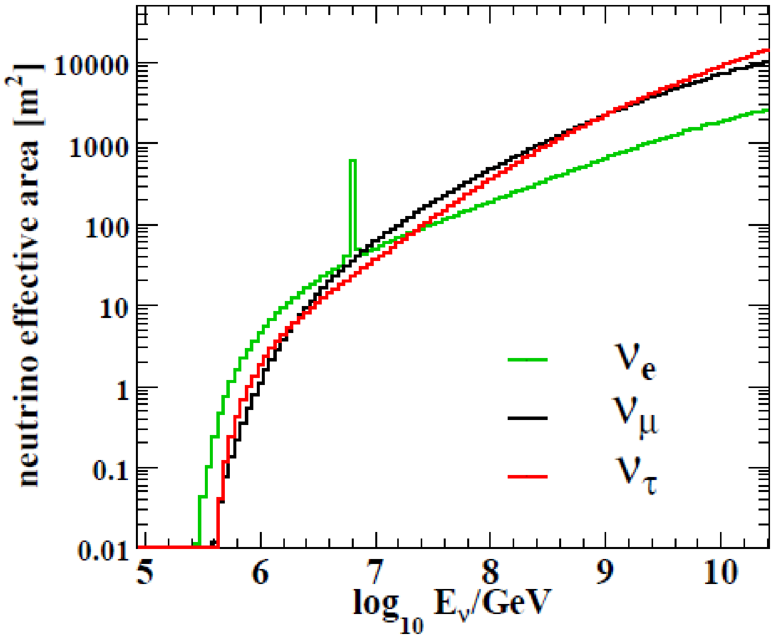
A Subset of IceCube events from GC region



- 5 shower-like events are concentrated at the Galactic Center region
- 3 shower-like events are correlated with Fermi bubbles at high latitudes

A Subset of IceCube events from GC region

Average effective area



[IceCube Collab.] Aartsen et al. 2013

- Incompatible with Atmospheric flux

$$E^2\Phi(\nu_\mu) = 5.0 \times 10^{-11}\,(E/\mathrm{PeV})^{-1.6}\ \mathrm{GeV\ cm^{-2}\ s^{-1}}$$

- Inferred flavor ratio is compatible with 1:1:1

Galactic Center region:
8° around the center, $\Omega_{GC} = 0.06$ sr

- 4 Shower-like events at 100 TeV
- 1 shower-like event at 1 PeV

Flux of ν from GC region: Hard $\propto E^{-\alpha}$; $\alpha \sim 2$

$$E^2\Phi(\nu_e + \nu_\mu + \nu_\tau) \sim \begin{cases} 1.3 \times 10^{-9}\ \mathrm{GeV\ cm^{-2}\ s^{-1}}\ ;\ (100\ \mathrm{TeV}) \\ 1.1 \times 10^{-9}\ \mathrm{GeV\ cm^{-2}\ s^{-1}}\ ;\ (1\ \mathrm{PeV}), \end{cases}$$

- Compatible with extrapolation of γ-ray flux from inner Galaxy ($|l| \leq 80°, |b| \leq 8°$) detected by Fermi-LAT

π^0 decay γ-ray flux component at 1 PeV within $\Omega_{GC} = 0.06$ sr and $\propto E^{-2.3}$

$$\sim 3.8 \times 10^{-9}\ \mathrm{GeV\ cm^{-2}\ s^{-1}}$$

A common origin for both γ and ν

A Subset of IceCube events from GC region

Is supernova activity at the Galactic Center region responsible for ν events?

- Bolometric ν luminosity from $\Omega_{GC} = 0.06$ sr: $\sim 4.1 \times 10^{34}$ erg/s
- Cosmic-ray power from supernova activity is $\sim 1.3 \times 10^{39}$ erg/s

Crocker & Aharonian 2011

Cooling time scale of cosmic rays within 1 kpc of the GC

$t_{pp} = (\sigma_{pp}$ … $^{-3})^{-1}$ year

8 shower-like events may originate from the supernova activity at the GC region

$\sim 6 \times 10^{6}\, M_{sun}$ in gas

Cosmic-ray escape time scale from GC region

$$t_{esc} = \frac{3}{2}\frac{m_p^2}{E_p}\frac{B_G}{B_{cr}}R^2 \sim 5.4 \times 10^6 \left(\frac{E_p}{10\,\mathrm{PeV}}\right)^{-1}\left(\frac{B_G}{12\ \mu\mathrm{G}}\right)\left(\frac{R}{\mathrm{kpc}}\right)^2 \ \mathrm{year}$$

A hard cosmic-ray spectrum follows from : $t_{acc} < t_{pp} \leq t_{esc}$

Fermi-bubble ν events from high-latitudes

Lunardini & Razzaque 2012

$N_{FB/2} \sim E\Phi(\nu_e + \nu_\tau)\Omega_{FB/2}(A_e + A_\tau)t_{live} \sim 1.1$ ~2-3x higher possible

A New Window to the Universe

Information known prior to 1940

It took more than 330 years to go beyond Optical Telescopes

- Radio Astronomy (1930's)
- Infrared Astronomy (1950's)
- X-ray Astronomy (1960's)
- γ-ray Astronomy (1960's)

Neutrino Astronomy is still in infancy

Future may hold surprises too!!!

ν's from Sun and SN 1987A
IceCube events(?)

Nature of the sources are unknown, only hints from
→ photon astronomy
→ Cosmic ray observations

Summary

- High-energy astrophysical neutrinos can open a new window to the extreme and unseen universe
  - Detection of 28 events by IceCube is very welcome!
- Methods to model neutrino fluxes from astrophysical sources are not well-understood
  - Many candidates but no definitive sources
- IceCube Limit on GRB prompt neutrino flux is consistent with radiation from large radii or large bulk Lorentz factor
  - UHE ($\geq$1 PeV) neutrinos from GRBs and TeV-PeV neutrinos from optically thick sources are yet to be constrained
- Galactic center region and Fermi bubbles are interesting targets for neutrino telescopes (both for astrophysical sources and dark matter signals)
  - A subset of the 28 IceCube events could originate from GC activity

More events are and theoretical study are needed!

Backup Slides

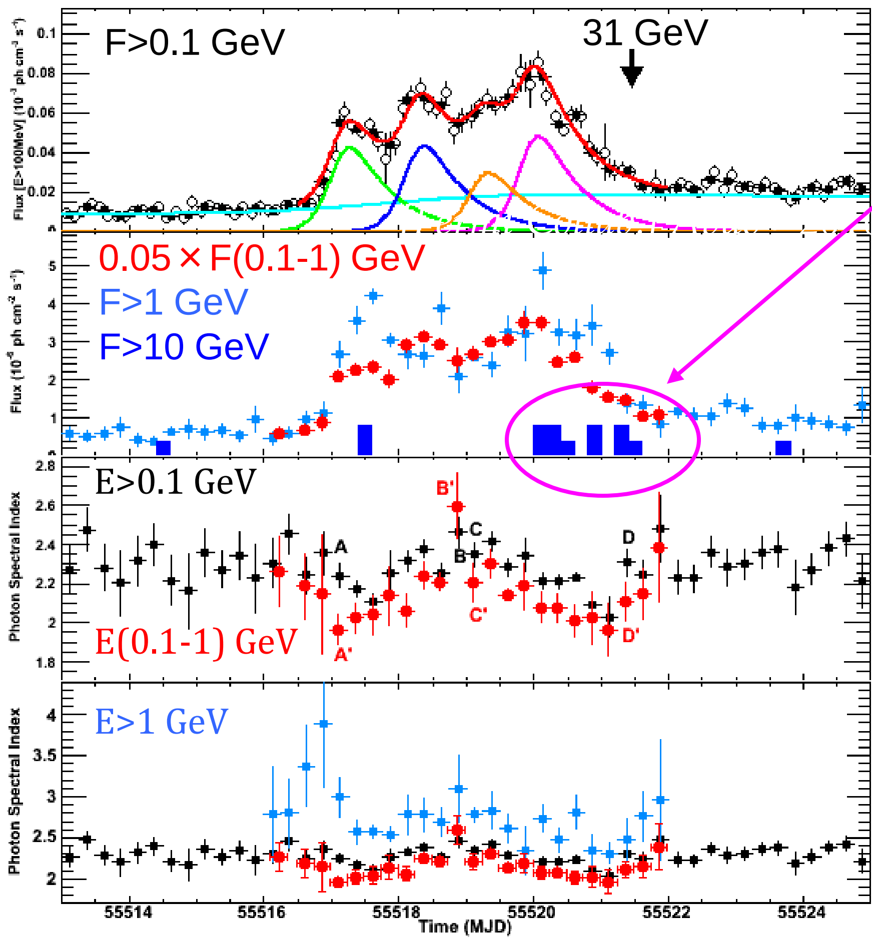
Nov ‘10 Giant Flare of 3C 454.3

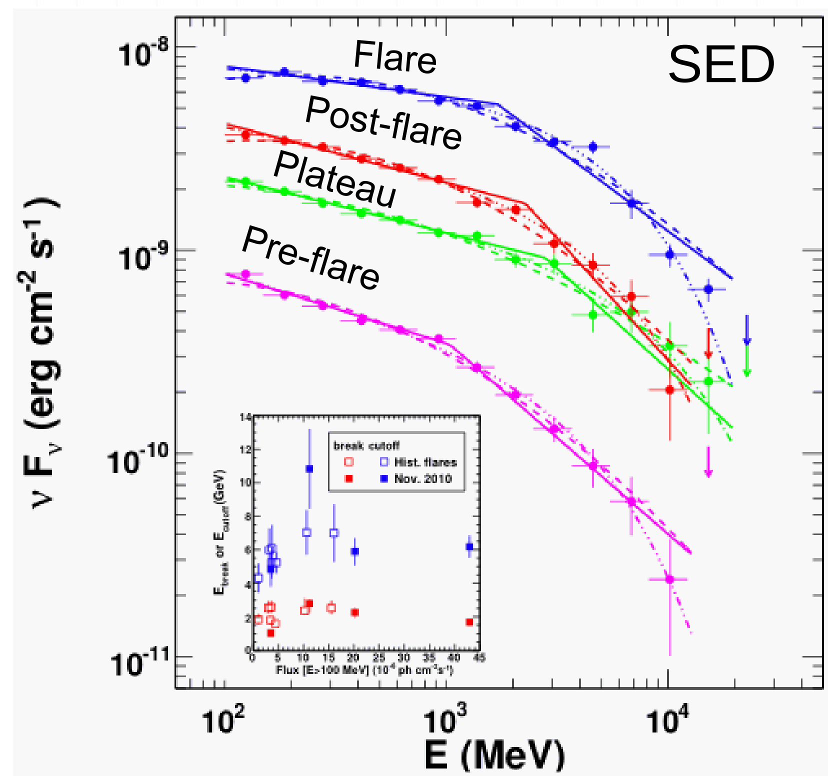
5 times brighter than the Vela pulsar, the brightest γ-ray source

Light Curves of 5 day outburst

Apparent-isotropic γ-ray luminosity: $(2.1\pm0.2)\times10^{50}$ erg/s !!

UHECR acceleration?





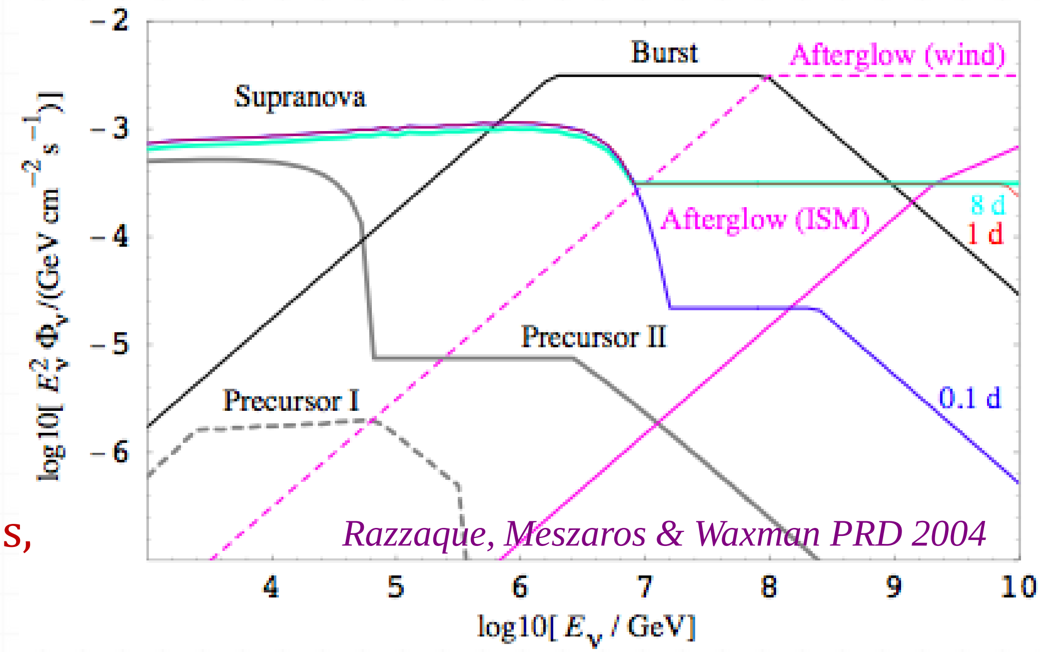
High Energy GRB ν Detection Prospects

Projected ν events for IceCube

Flux model	ν_μ	ν_e
Precursor I (He)	-	-
Precursor II (H)	4.1	1.1
Burst/prompt	3.2	0.3
Afterglow (ISM)	-	-
Afterglow (wind)	0.1	-
Supranova (>0.1 d)	13	2.4

E_ν > TeV, no oscillation

GRB 030329/SN 2003dh
Typical long duration GRB with bright SN
~10^{51} ergs/s luminosity at redshift z = 0.17



- Expected prompt muon neutrinos, after oscillation ~1.6
- Current non-detection of neutrinos from GRB 130427A (z=0.34) is consistent with prediction

Neutrino flux models:
Dai & Lu 2000 (afterglow wind)
Razzaque, Meszaros & Waxman, PRL 2003 (supranova)
Razzaque, Meszaros & Waxman, PRD 2003 (precursor)
Waxman & Bahcall 2000 (afterglow ISM)
Waxman & Bahcall 1997 (burst/prompt)

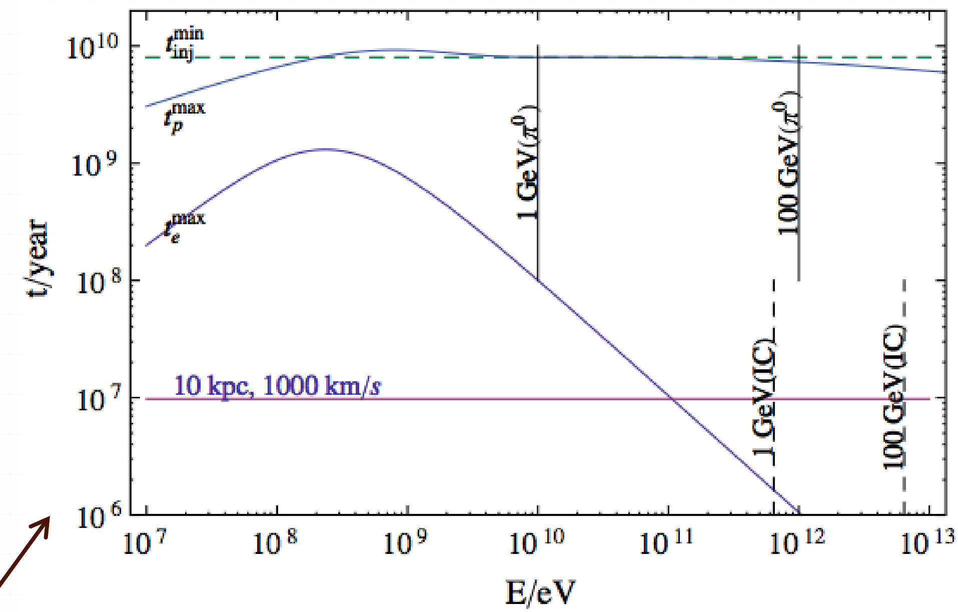
FB Origin in Leptonic Scenario

Brief (few Million yr) activity of the Galactic Center Black Hole (Sgr A*) can supply the necessary power to inflate the bubbles – with enough accreting material

$$L_{\text{Edd}} \sim 10^{44}\ \text{erg/s}$$

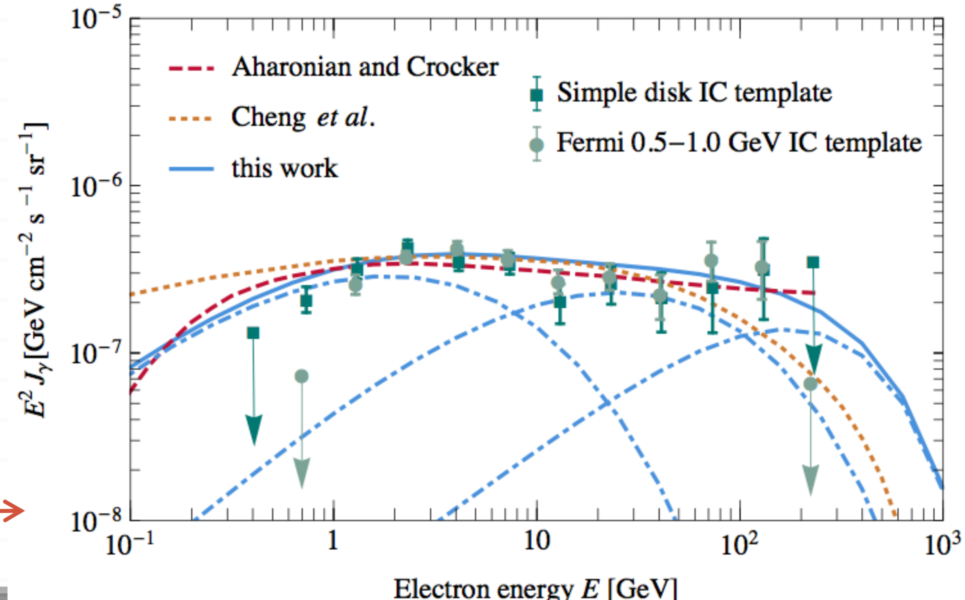
Problem – Relativistic electrons cool rapidly in the bubbles

Crocker & Aharonian 2011



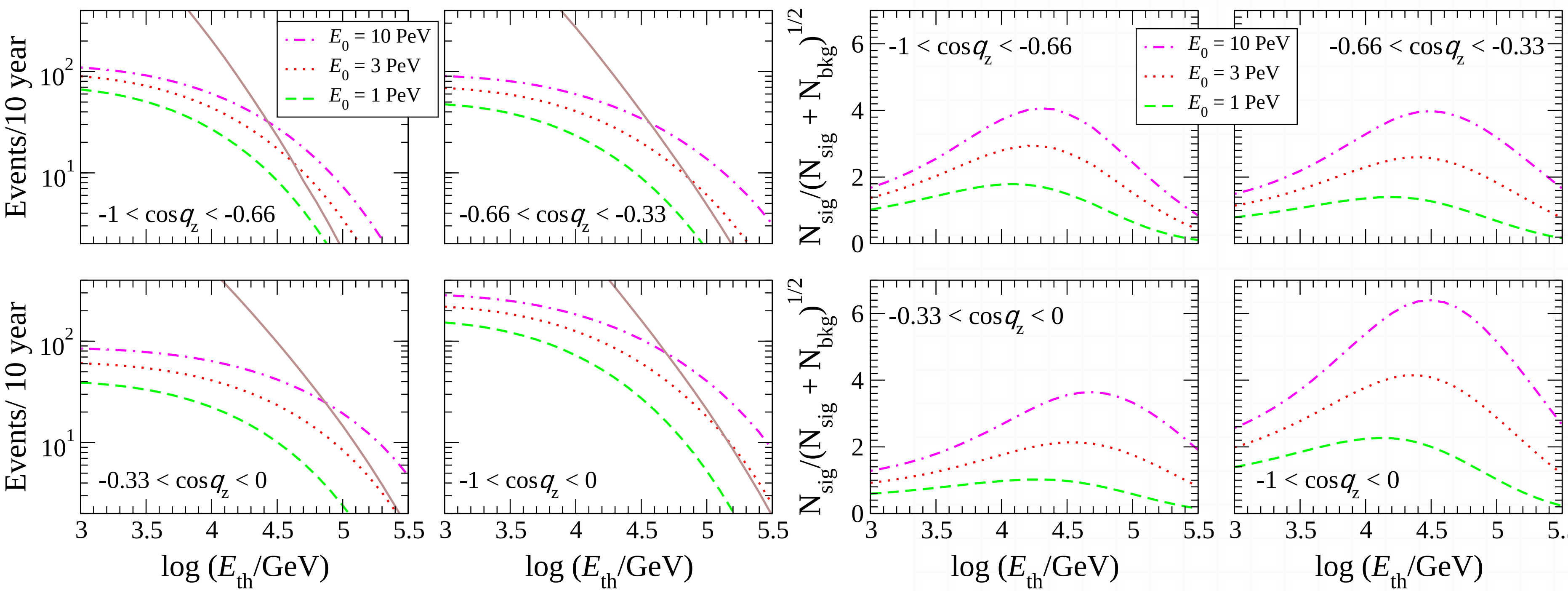
A re-acceleration mechanism (e.g. plasma turbulence) is certainly needed to energize electrons that fill the bubble volume

Martsch & Sarkar 2011

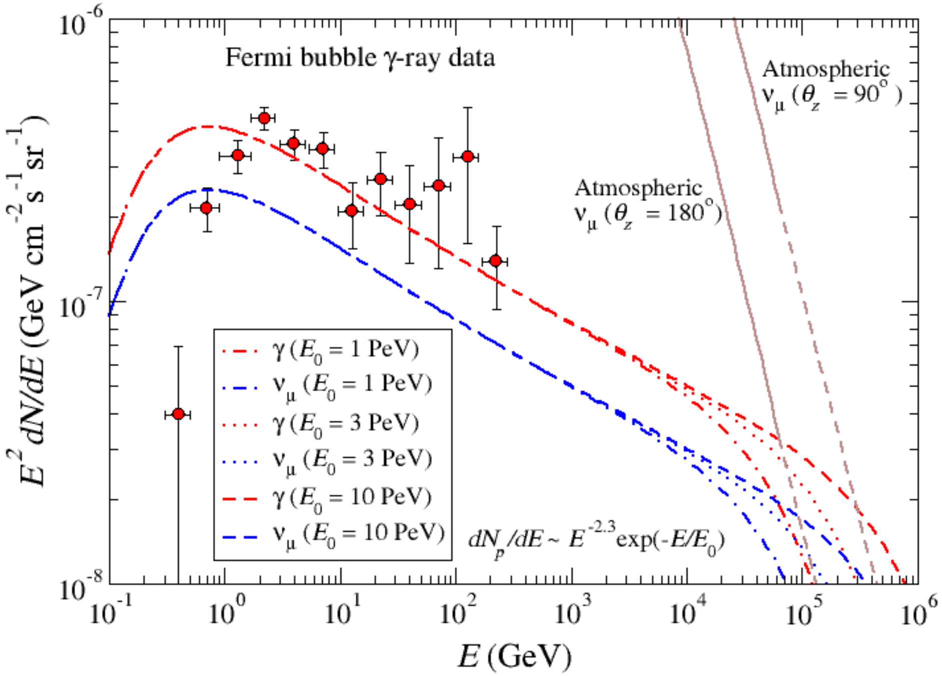


Neutrino Events and Detection Significance in Different Zenith Angle Bins

- Events are calculated for a km scale Mediterranean detector (KM3NeT)
- Daily modulation (visibility of the bubble fraction at different hours of the day) are taken into account for each zenith angle bins

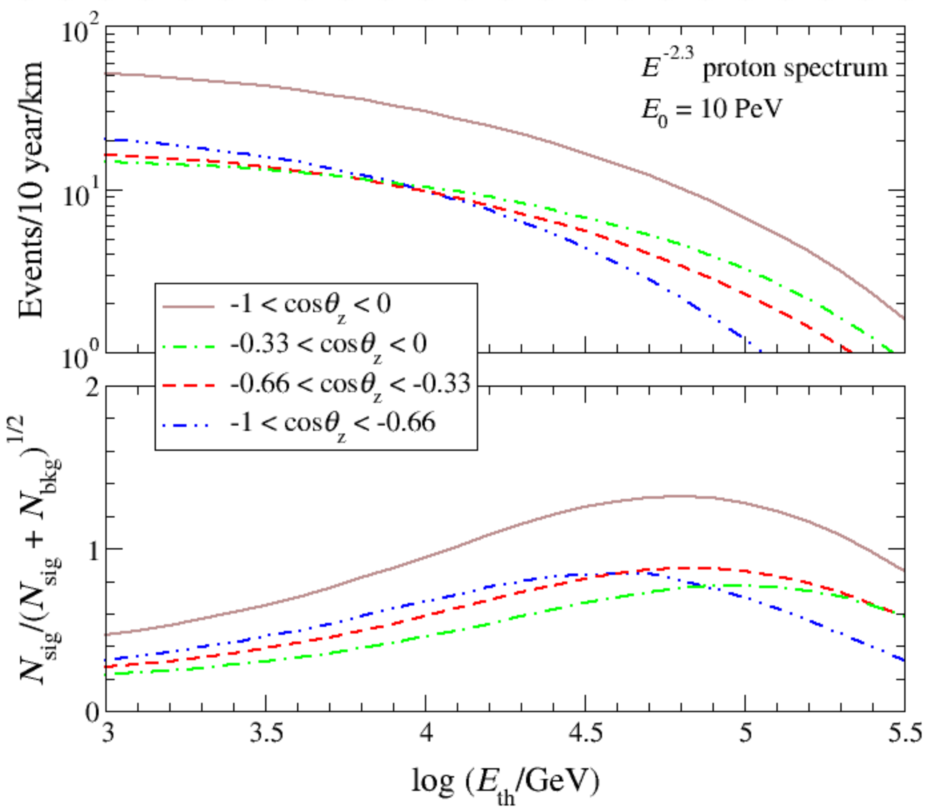


A Steeply Falling Gamma-Ray Flux Model for the Fermi Bubbles and Neutrino Detection Prospects



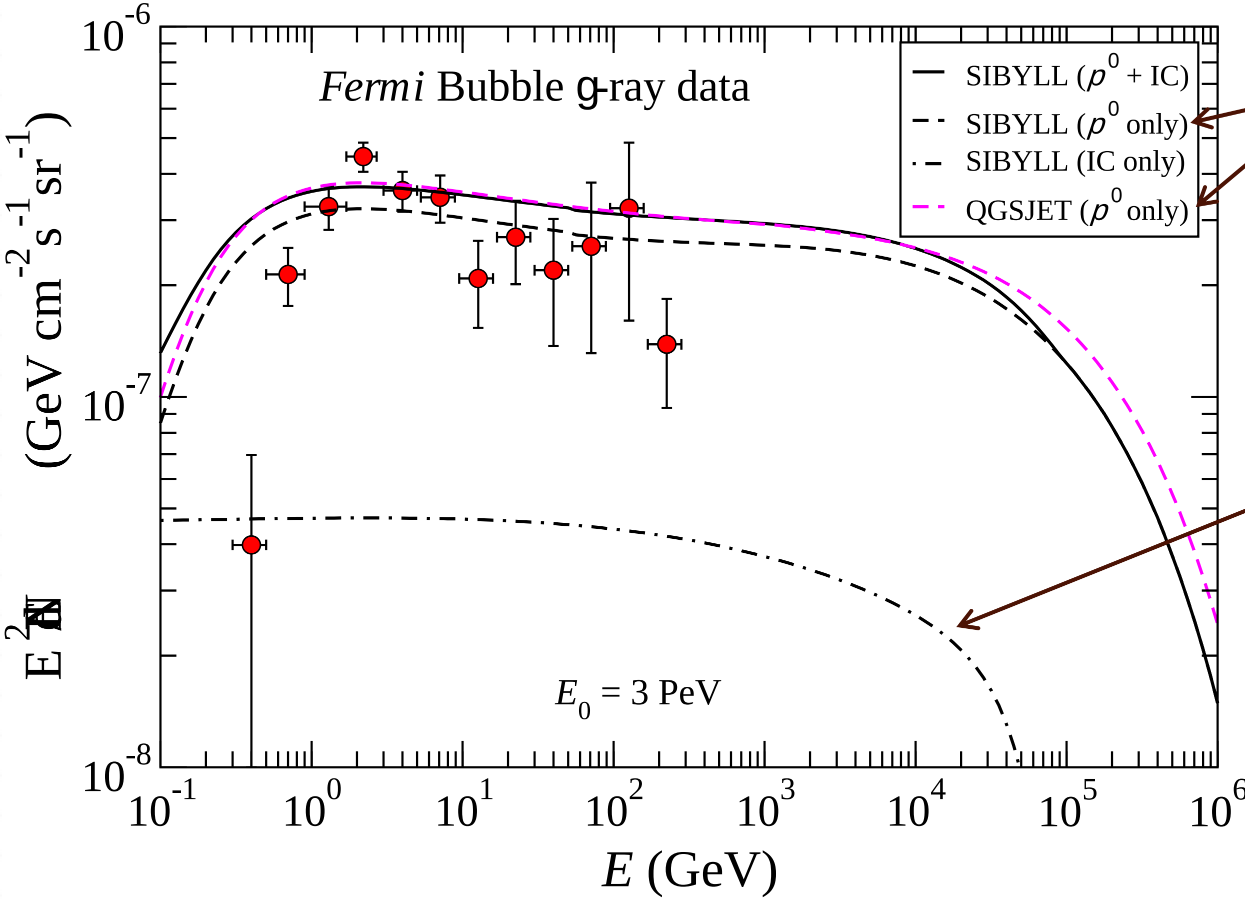
Future gamma-ray data will constrain spectrum better

Neutrino detection prospect is low



Other Processes Contributing to Gamma Ray Flux and Uncertainties in Hadronic Models

Of the order of 10% uncertainties



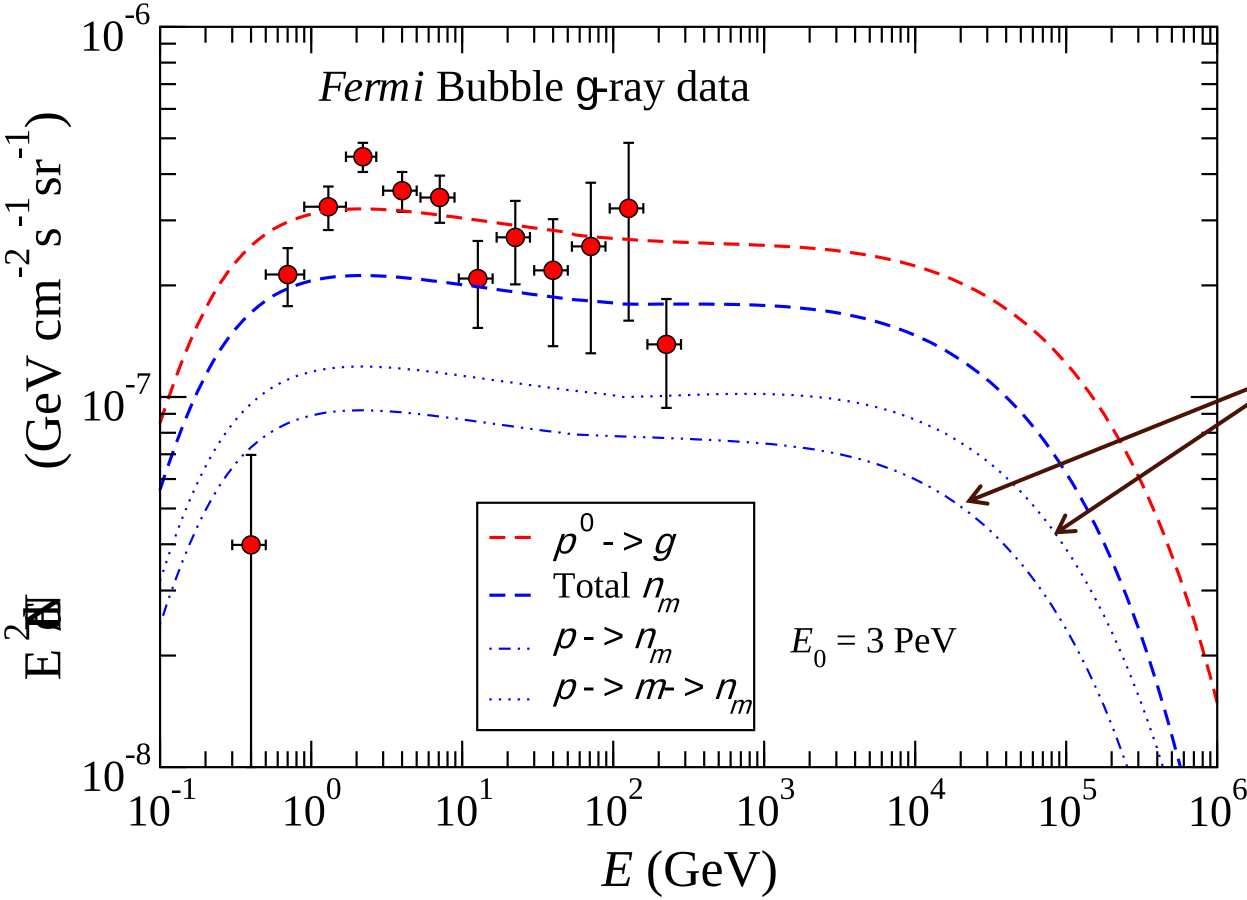
Two different hadronic models of gamma-ray production

Inverse Compton scattering off the CMB photons by pion-muon chain-decay electrons

Bubble magnetic field is not known

Flavor Composition of the Fermi Bubble Neutrino Flux and Flux at the Detector

Source flux is composed of ν_μ and ν_e at a ratio 2:1



Neutrino telescopes cannot distinguish between neutrinos and antineutrinos. All fluxes are sum of the two

Decomposition of source ν_μ flux

ν_μ flux at the detector is ½ of the source flux after ν-flavor oscillation

Gamma Ray Bursts and Supernovae

Gamma-Ray Bursts are likely very rare events when core-collapse SNe form a highly-relativistic jet with a bulk Lorentz factor

$$\Gamma = [1-(v/c)^2]^{-1/2} \sim 100\text{-}1000$$

- The observed GRB rate is ~ 1 $Gpc^{-3}\ yr^{-1}$ as compared to ~10^4 - 10^5 $Gpc^{-3}\ yr^{-1}$ core-collapse SN rate
- A class of weak GRBs, referred to as low-luminosity GRBs show very bright SN and their occurrence rate can be very high, 10^3 $Gpc^{-3}\ yr^{-1}$
- Numerical simulations (Woosley et al.) show that a weak jet with low Γ forms after CC much more frequently than GRB-type high Γ jet

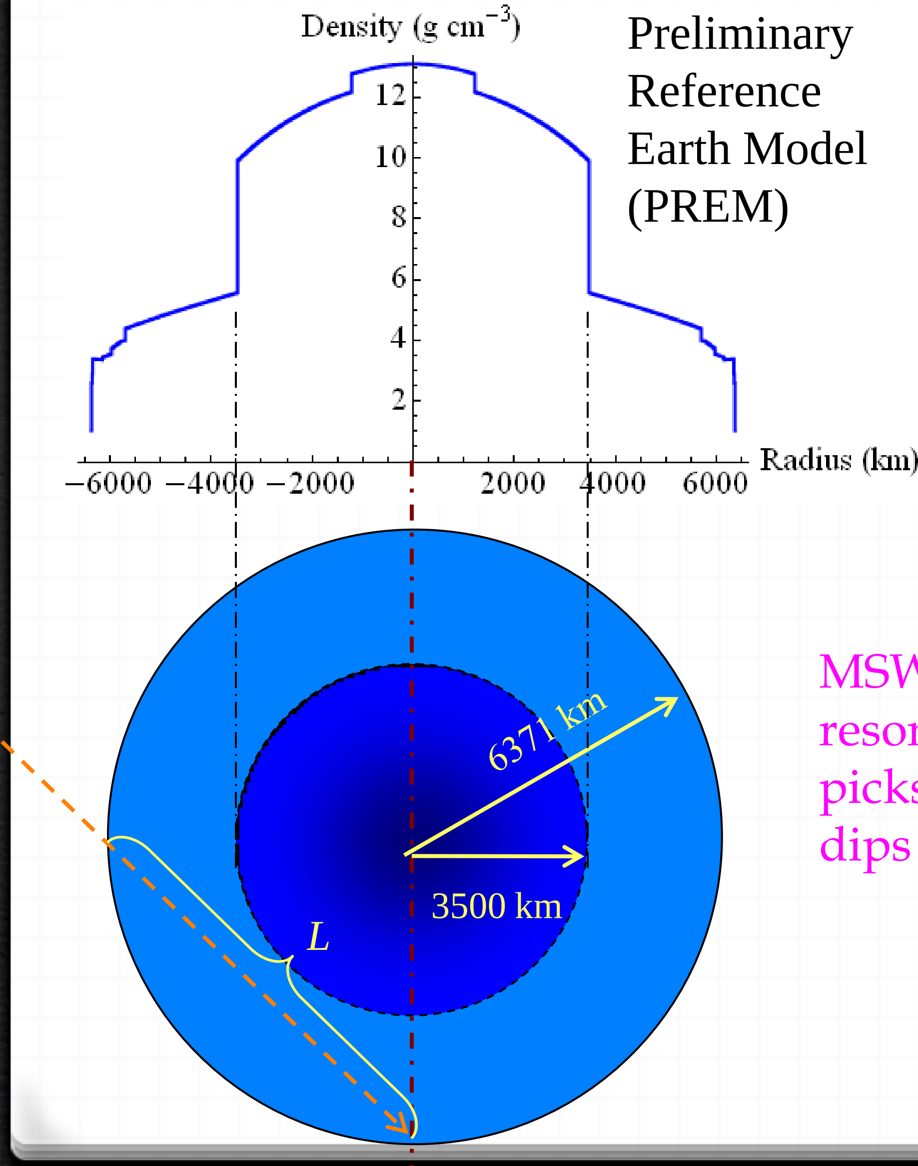
Other observations also suggest presence of a weak jet formed after the core collapse

- High velocity (30-40 x 1000 km/s) first observed in SN 1998bw.
- Radio afterglow not associated with gamma-ray emission.
- Asymmetric explosion geometry of SN type Ib/c.

Jetted Supernova Model Details

- The pre-supernova star, after losing its outermost envelope, is typically a Wolf-Rayet star of radius ~10^{11} cm in the case of a type Ib or larger in the case of a type II supernova
- We model the mildly relativistic SN jet inside the pre-supernova star with a bulk Lorentz factor Γ~3 and a total jet kinetic energy ~3×10^{51} ergs which is ~1% of the total energy released in the SN explosion
- Because of its relativistic motion, the jet is beamed with an opening half angle ~$1/\Gamma$ ~20 deg. which is much wider compared to a GRB jet
- The jet duration is ~10 s, typical of a long-duration GRB
- The jet may choke inside the collapsar or break-out the envelope
- Optical SN event follows afterward

Neutrino Propagation through Earth

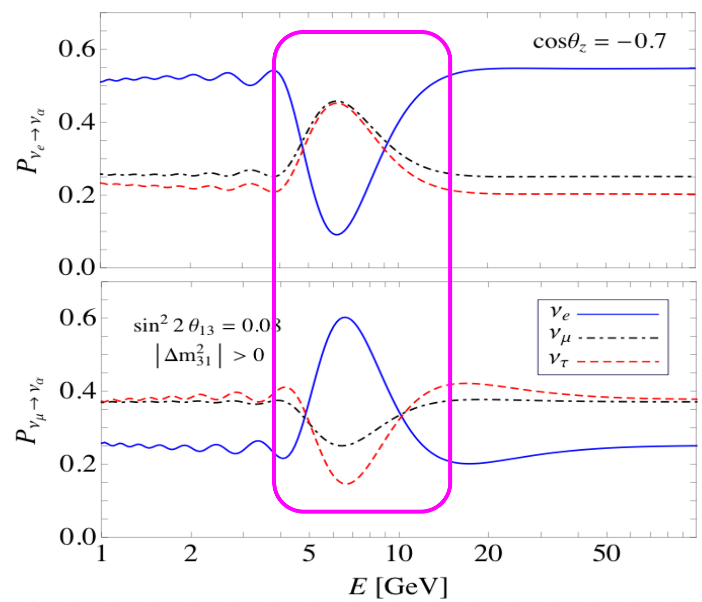


Preliminary Reference Earth Model (PREM)

← Earth's density profile

ν arriving at the detector at different zenith angle θ_z go through different densities (~8.4 g/cc for core-crossing, ~5 g/cc for mantle-crossing)

Standard 3ν probabilities for a given θ_z



MSW resonance picks and dips