Neutrino Astrophysics and Cosmology

John Beacom
The Ohio State University

Neutrino Astrophysics and Cosmology

Can neutrinos reveal hidden truths about the cosmos?

Only if neutrino interactions are understood

Only if astrophysical fluxes are large enough

Only if we have huge and sensitive detectors

For the first time, all of these are true

new probes of astrophysical processes
better tests of new physics with better astrophysics
surprising or exotic sources, including dark matter
novel tests of particle properties

Astrophysical Neutrino Sources

MeV: Thermal Sources

Qian

Milky Way supernova, ~ few per century
nearby supernovae, ~ 1 per year
Diffuse Supernova Neutrino Background, constant flux

TeV: Nonthermal Sources

this talk, Gerhardt

steady sources, e.g., Milky Way supernova remnants
varying sources, e.g., Active Galactic Nuclei
transient sources, e.g., gamma-ray bursts
possible sources from dark matter annihilation

EeV: Extreme Sources

Olinto

almost certain flux from UHE cosmic ray propagation
likely fluxes from those accelerators directly
possible sources from supermassive particle decays

Plan of the Talk

Cosmic Rays, Gamma Rays, and Neutrinos

Gamma Ray Detectors and Sources

Neutrino Detectors and Sources

Prospecting for New Physics

Concluding Perspectives

Cosmic Rays, Gamma Rays, and Neutrinos

Are there high energy processes in nature?

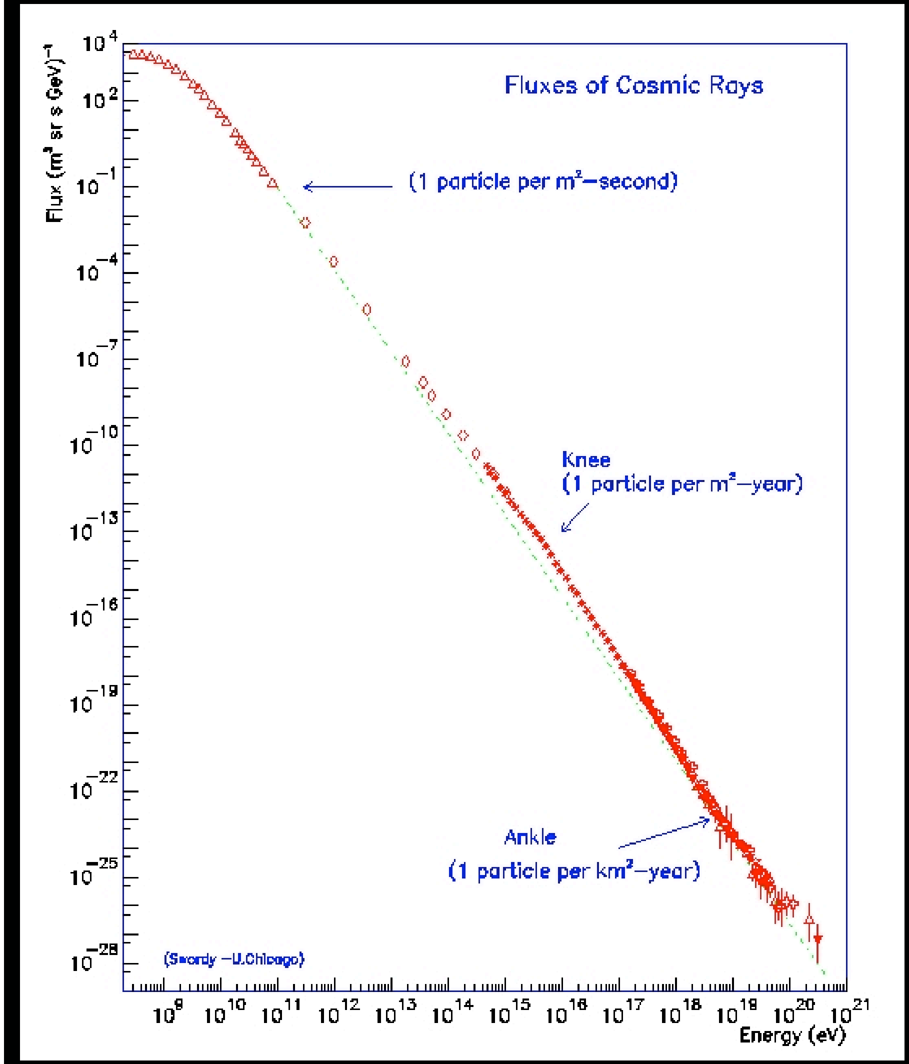
Do these produce gamma rays and neutrinos?

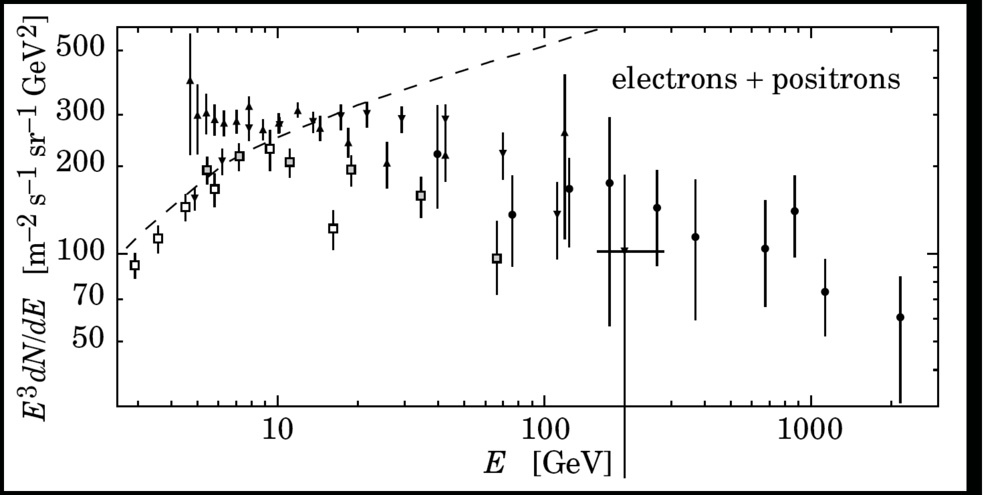
What's So Special About a TeV?

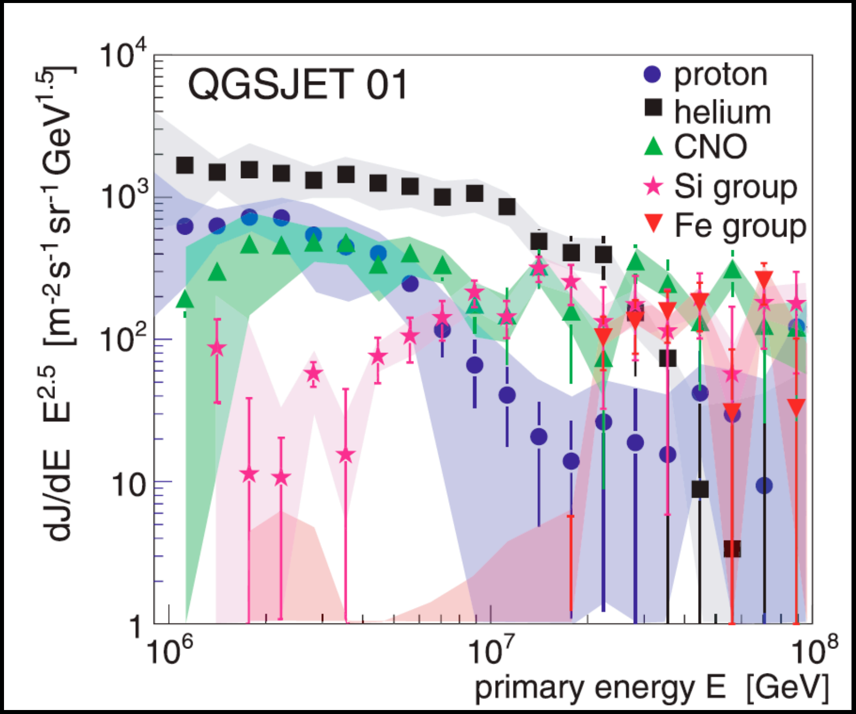
1 TeV = 10^{12} eV = 1.6 erg per particle

Far above atomic (eV) and nuclear (MeV) scales

Cosmic Ray Protons, Electrons, and Nuclei







Cosmic Rays Imply Gamma Rays and Neutrinos

- Hadronic mechanism

$$p + p \rightarrow p + p + \pi^0,\ p + n + \pi^+$$

$$\pi^0 \rightarrow \boxed{2\gamma},\ \pi^\pm \rightarrow e^\pm + \boxed{3\nu}$$

- Leptonic mechanism

$$e^- + \gamma \rightarrow \boxed{\gamma} + e^-$$

- Nuclear (A*) mechanism

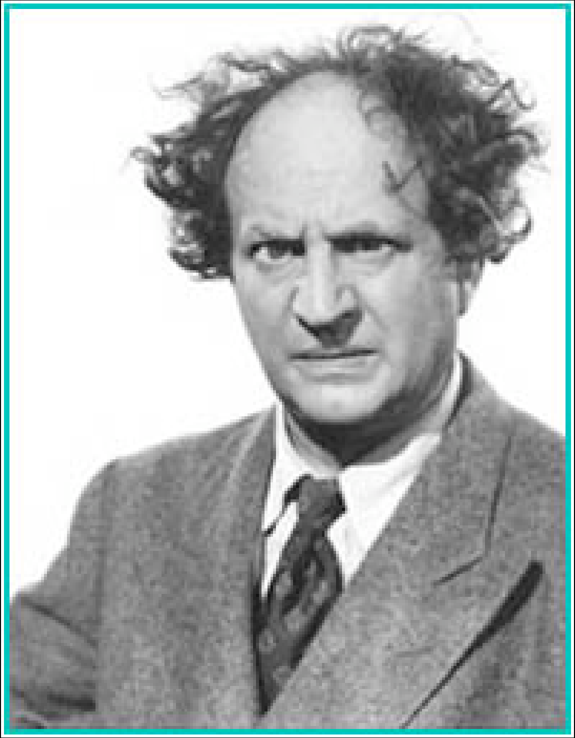
$$A' + \gamma \rightarrow A^* + X$$

$$A^* \rightarrow A + \boxed{\gamma}$$

Anchordoqui, Beacom, Goldberg, Palomares-Ruiz, Weiler, PRL 98, 121101 (2007)

Astronomy with New Messengers

cosmic rays	gamma rays	neutrinos
energetic	direct	revealing
divertable	stoppable	untrustworthy?



Gamma Ray Detectors and Sources

Do luminous high energy gamma ray sources exist?

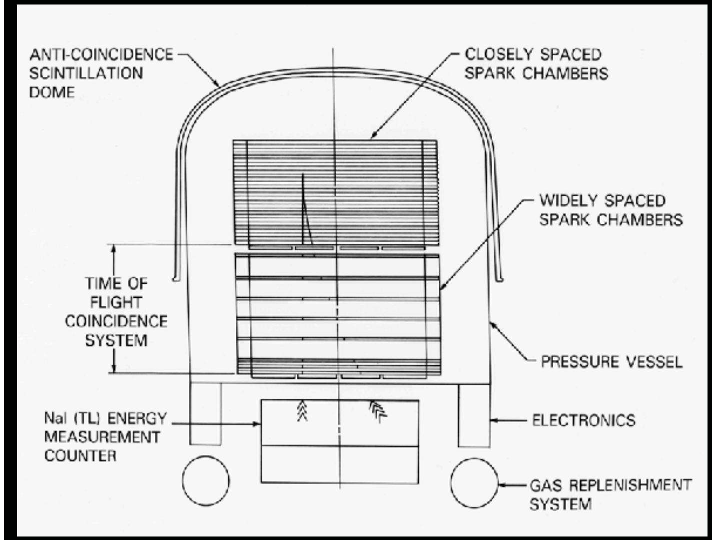
Can we find them and measure them?

Gamma-Ray Detection Techniques

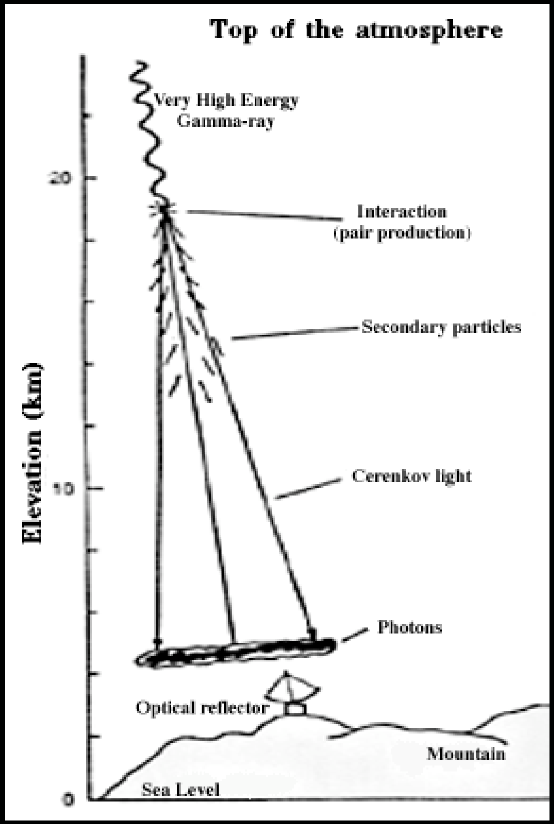
below ~ 0.3 TeV

~ 0.3-30 TeV

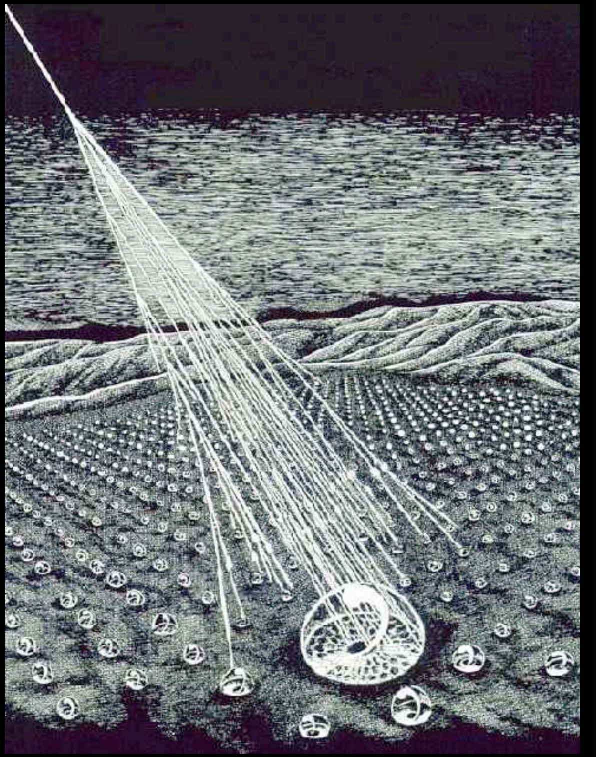
above ~ 3 TeV



primary gamma ray

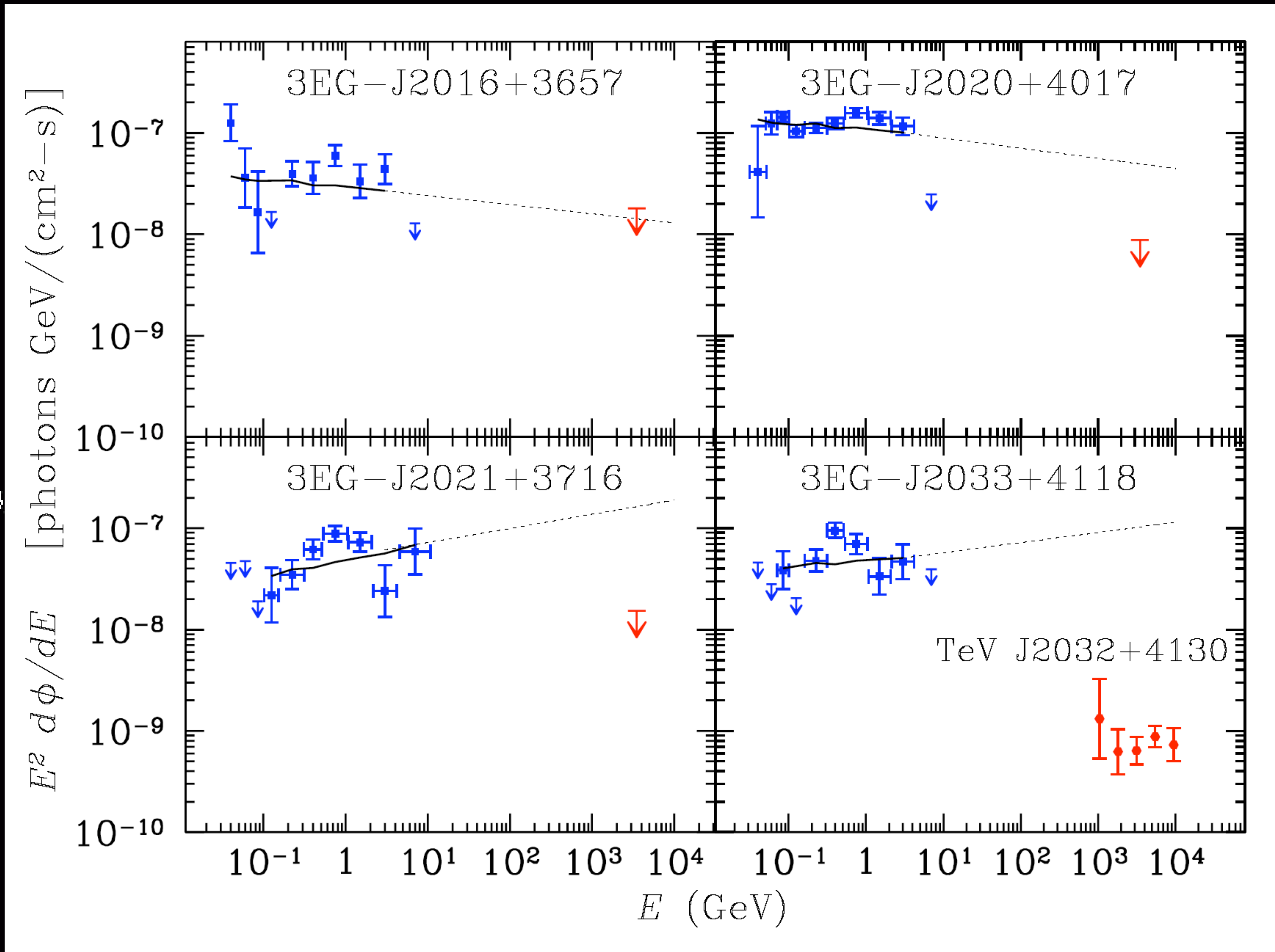


air Cerenkov from shower

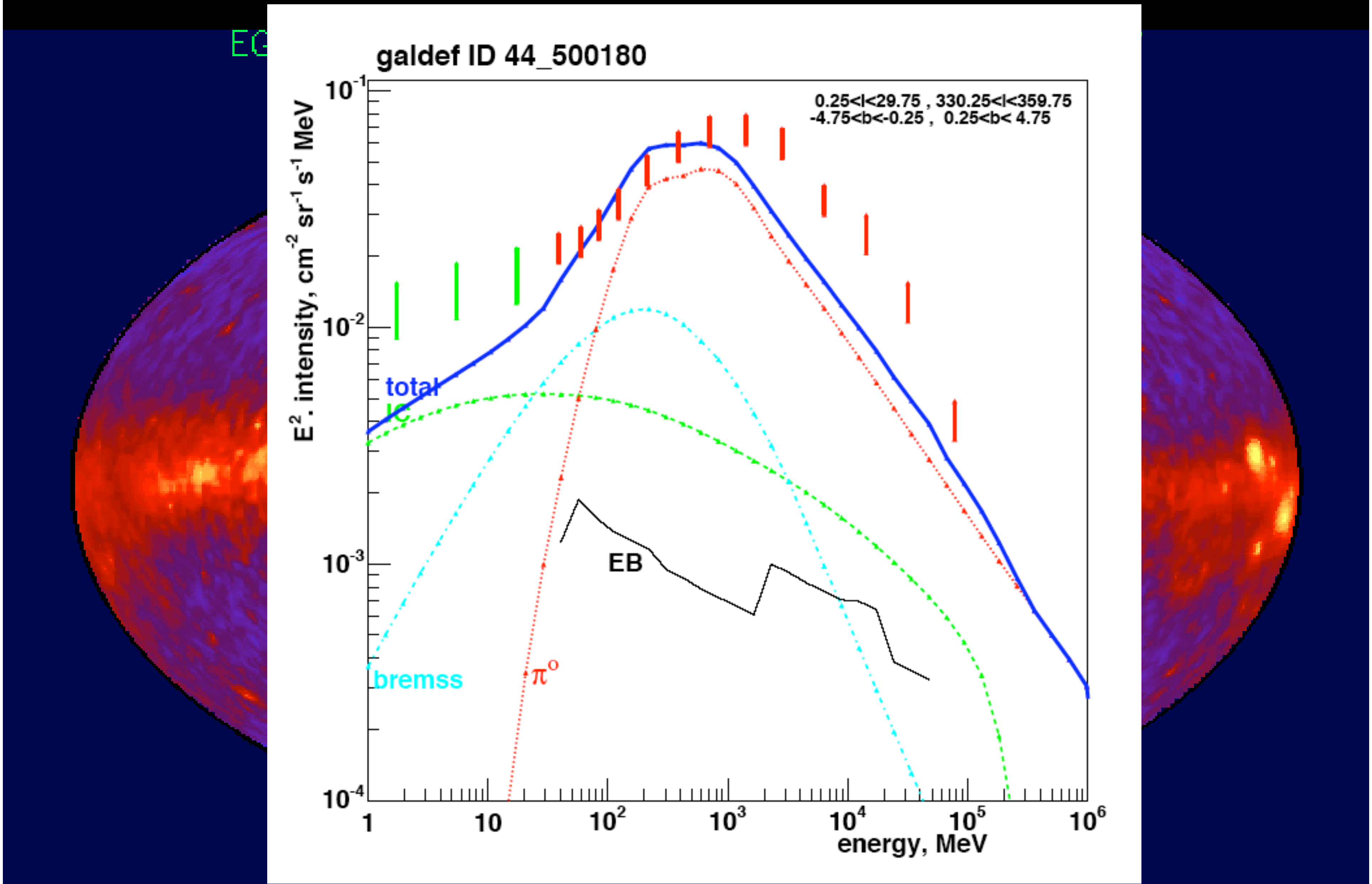


shower at ground

EGRET Source Results



EGRET Diffuse Results



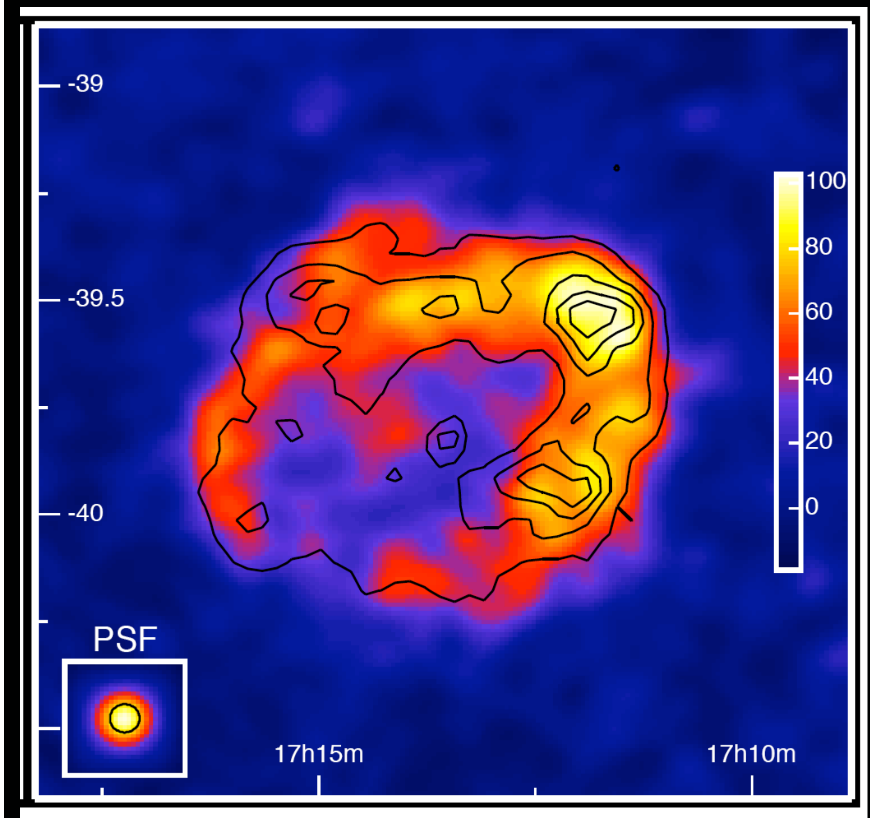
HESS Observatory

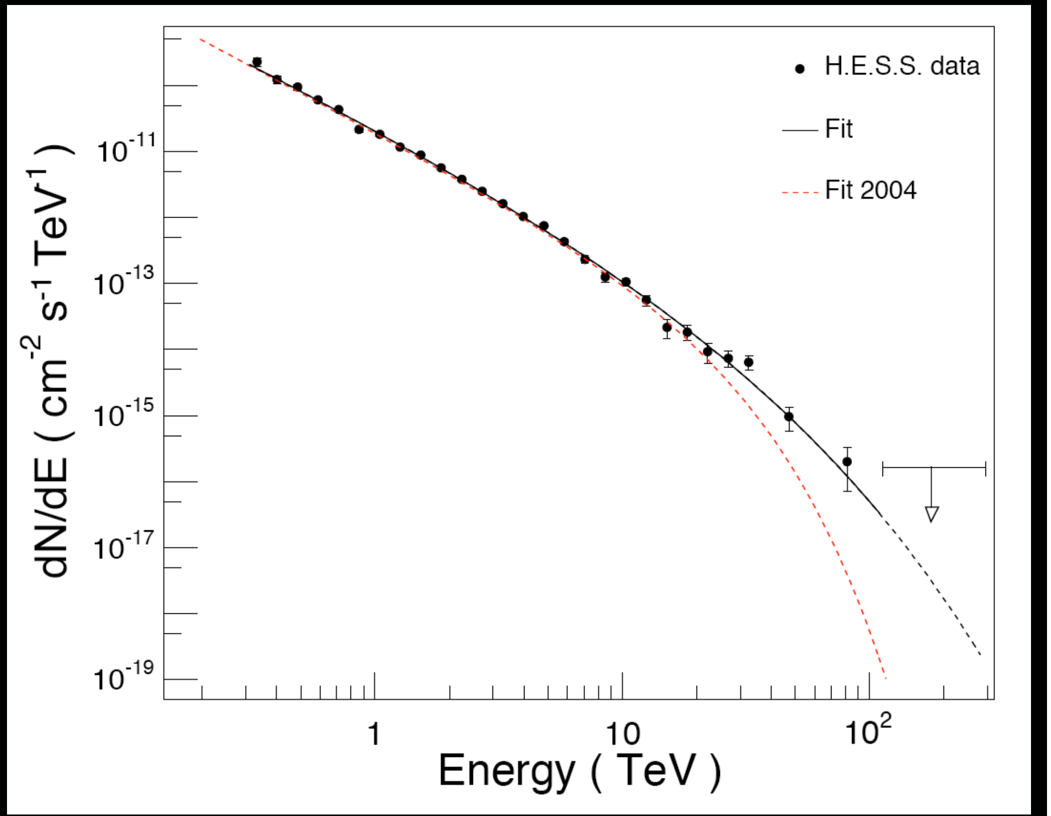
Four 13-m telescopes operated synchronously

In full operation in Namibia since 2004

Resolved Extended Sources

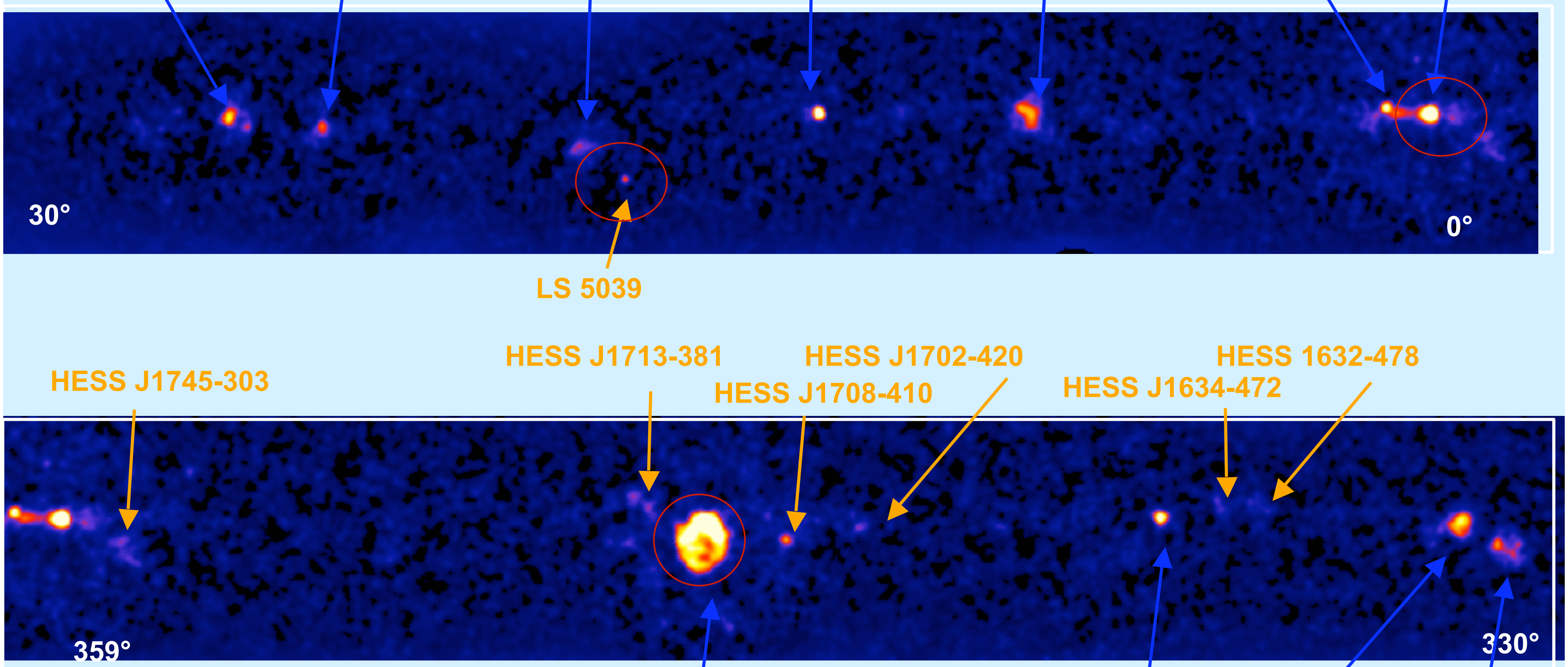
supernova remnant RX J1713.7-3946





HESS Collaboration (2006)

HESS Survey of the Inner Galaxy



Sources > 6 sigma (9 new, 11 total)
Sources > 4 sigma (7 new)

VERITAS Observatory

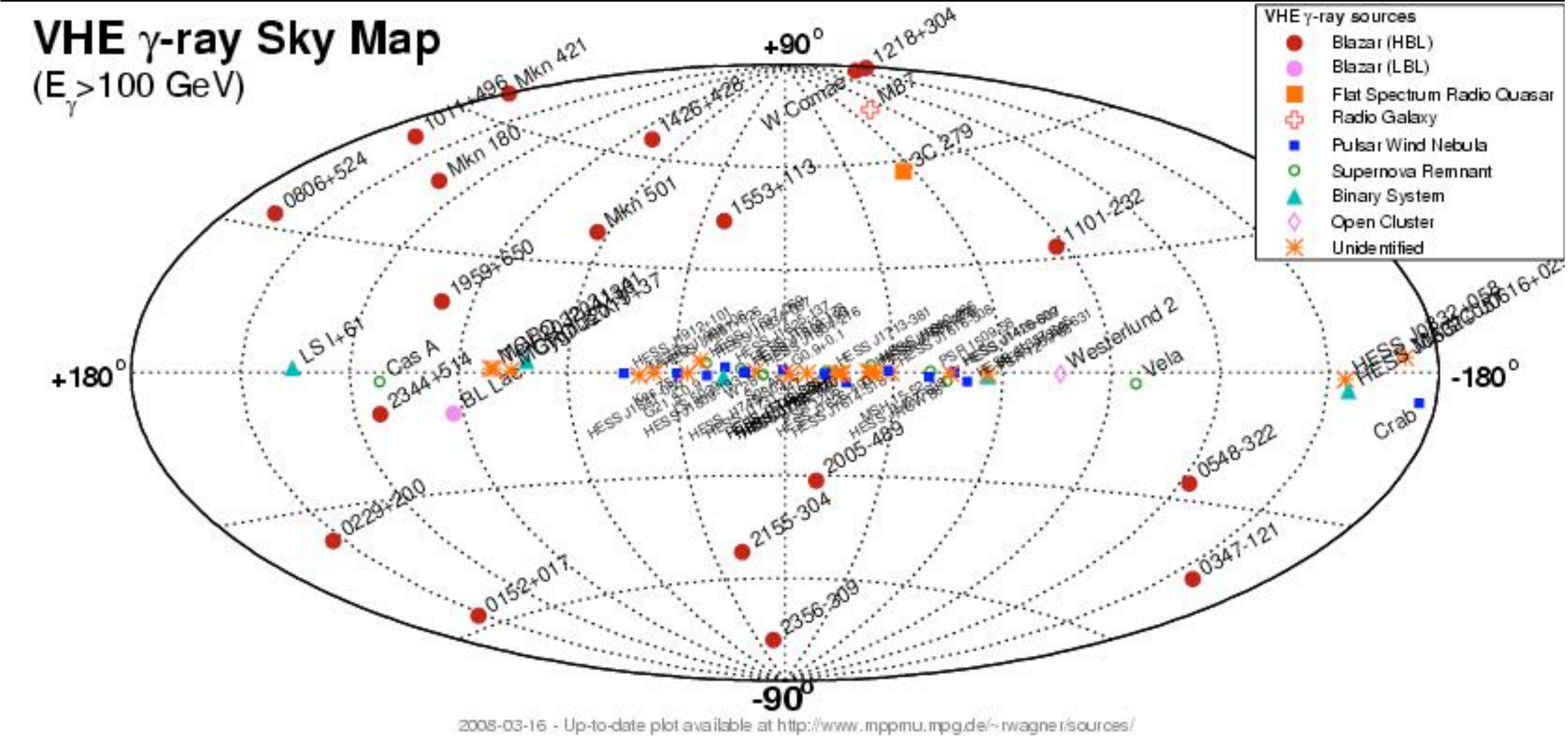
Instrument:

- Four 12-m telescopes
- 500-pixel cameras (3.5° FoV)
- FLWO, Mt. Hopkins, AZ (1268 m)
- Completed Spring 2007

Specifications:

- Energy threshold ~ 150 GeV
- Source location < 0.05°
- Energy resolution ~ 10-20 %

Skymap of VHE Gamma-Ray Sources

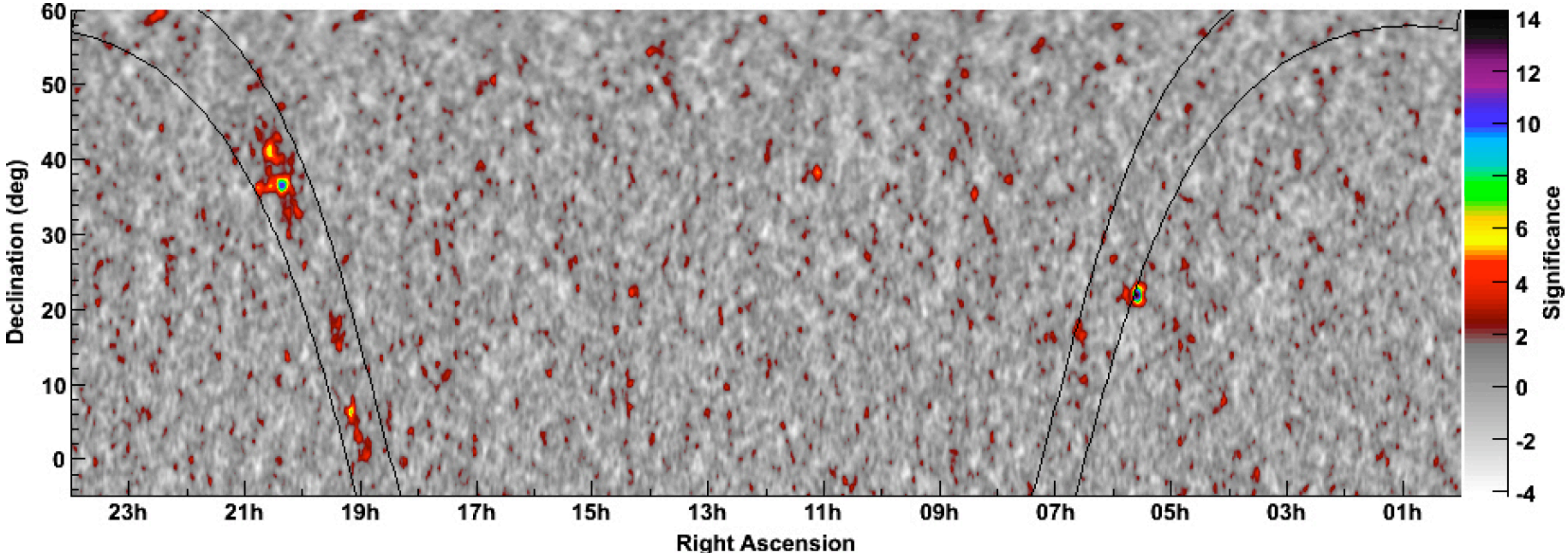


Milagro Experiment

- Water Cherenkov Detector
- 2600m asl
- 898 detectors
  - 450(t)/273(b) in pond
  - 175 water tanks
- 4000 m^2 / $4.0x10^4$ m^2
- 2-20 TeV median energy
- 1700 Hz trigger rate
- 0.4^o-1.0^o resolution
- 95% background rejection

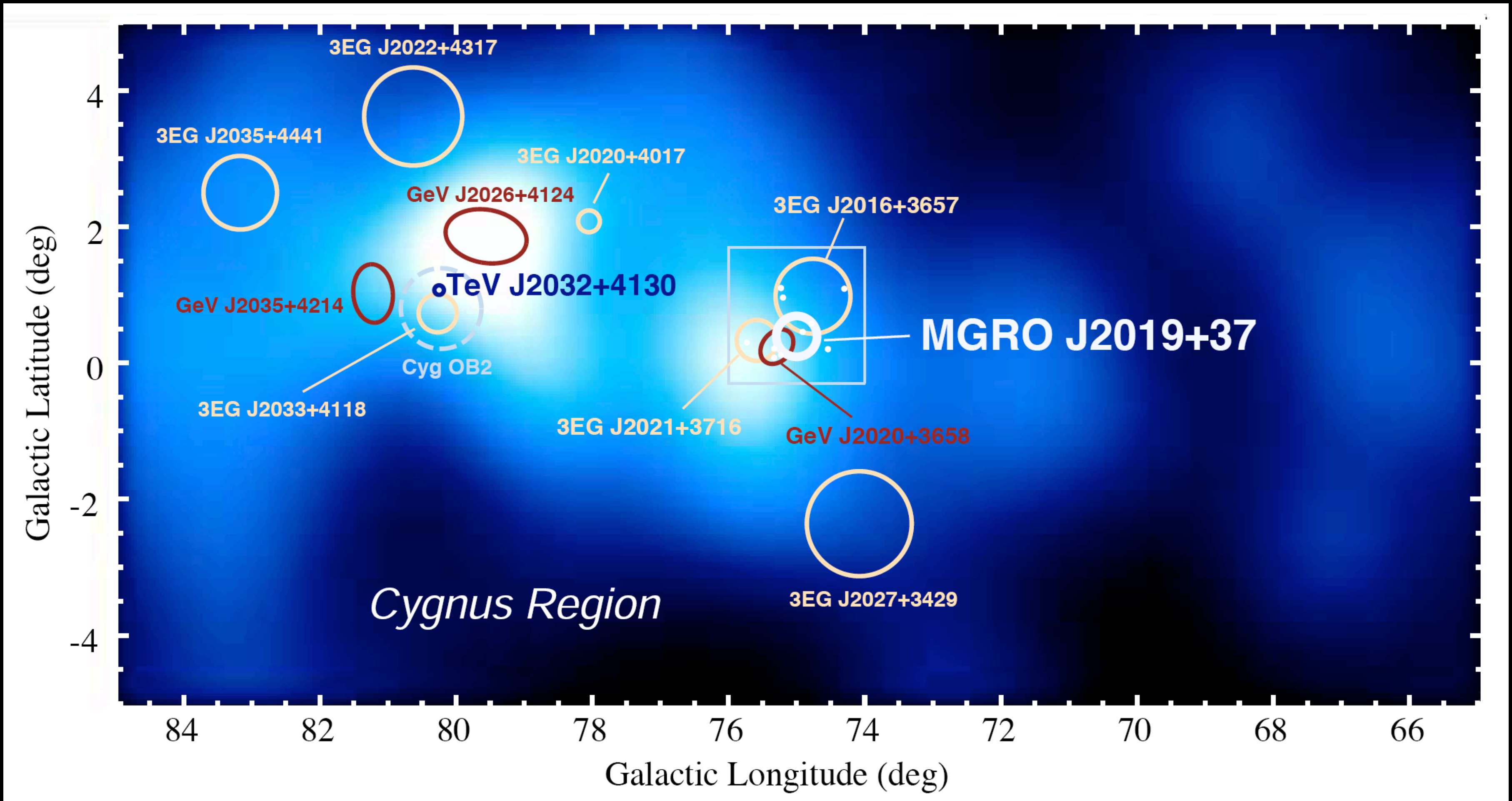
Milagro 12 TeV Diffuse

First partial preview of the Northern neutrino sky?



Milagro Collaboration (2007)

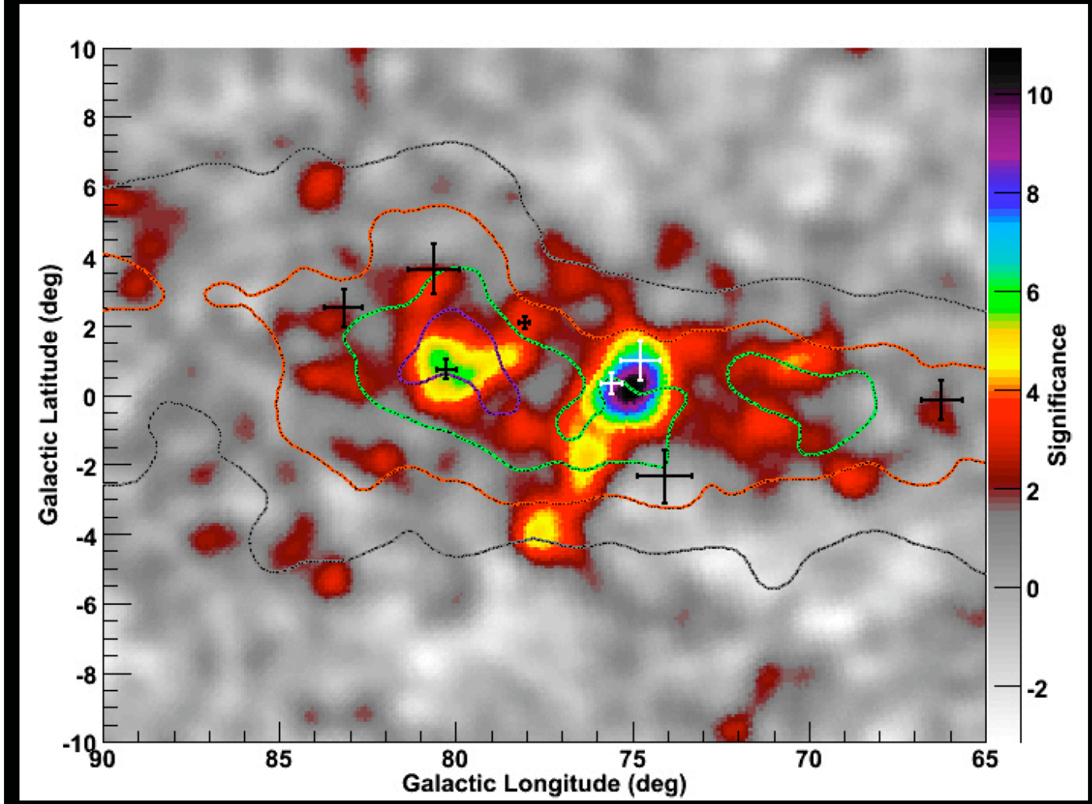
Cygnus Region

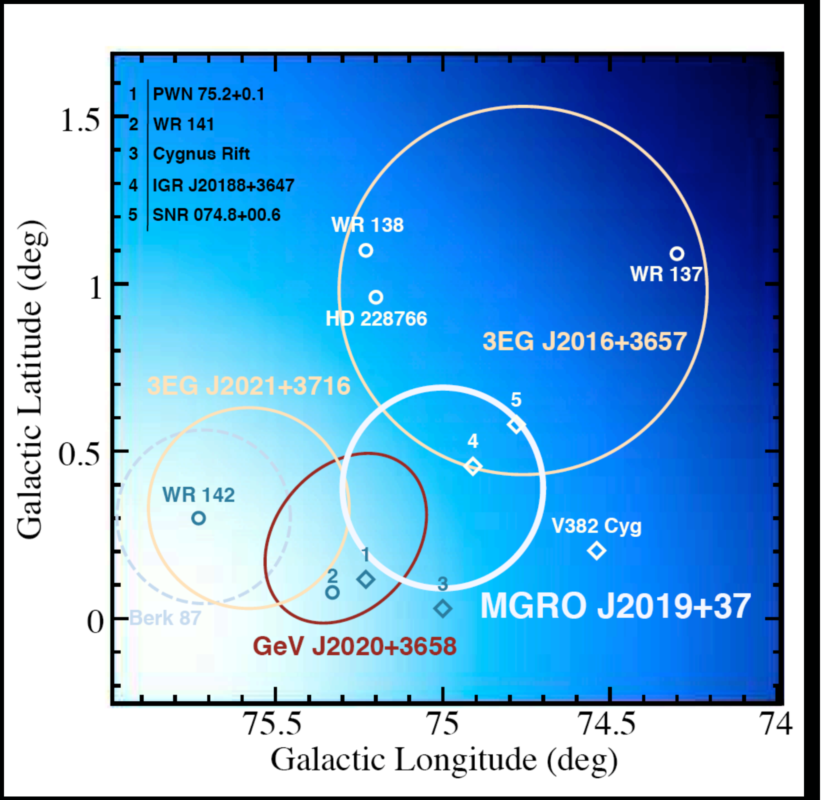


Beacom, Kistler (2007)

Milagro J2019+37 Region

MGRO J2019+37 in Cygnus





Milagro Collaboration (2007)

Beacom, Kistler (2007)

Gamma-Ray Scorecard

- Up to ~ 0.1 TeV
  - EGRET saw ~ 10^2 sources in the full sky
  - EGRET saw full-sky diffuse emission

- Around 1 TeV
  - Whipple, HESS, etc saw tens of sources
  - No data on diffuse emission

- Around 10 TeV
  - Milagro saw a few sources *in survey mode*
  - Milagro saw diffuse emission in part of sky

Neutrino Detectors and Sources

Do luminous high energy neutrino sources exist?

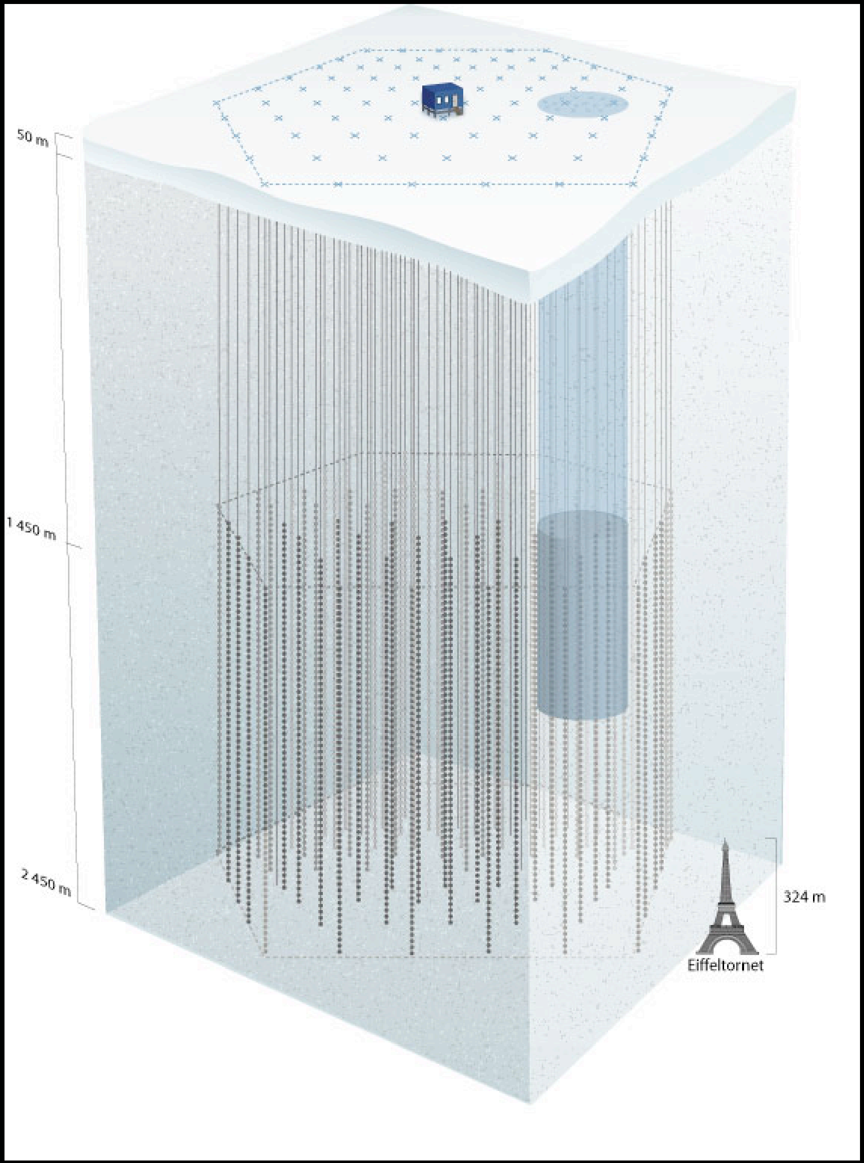
Can we find them and measure them?

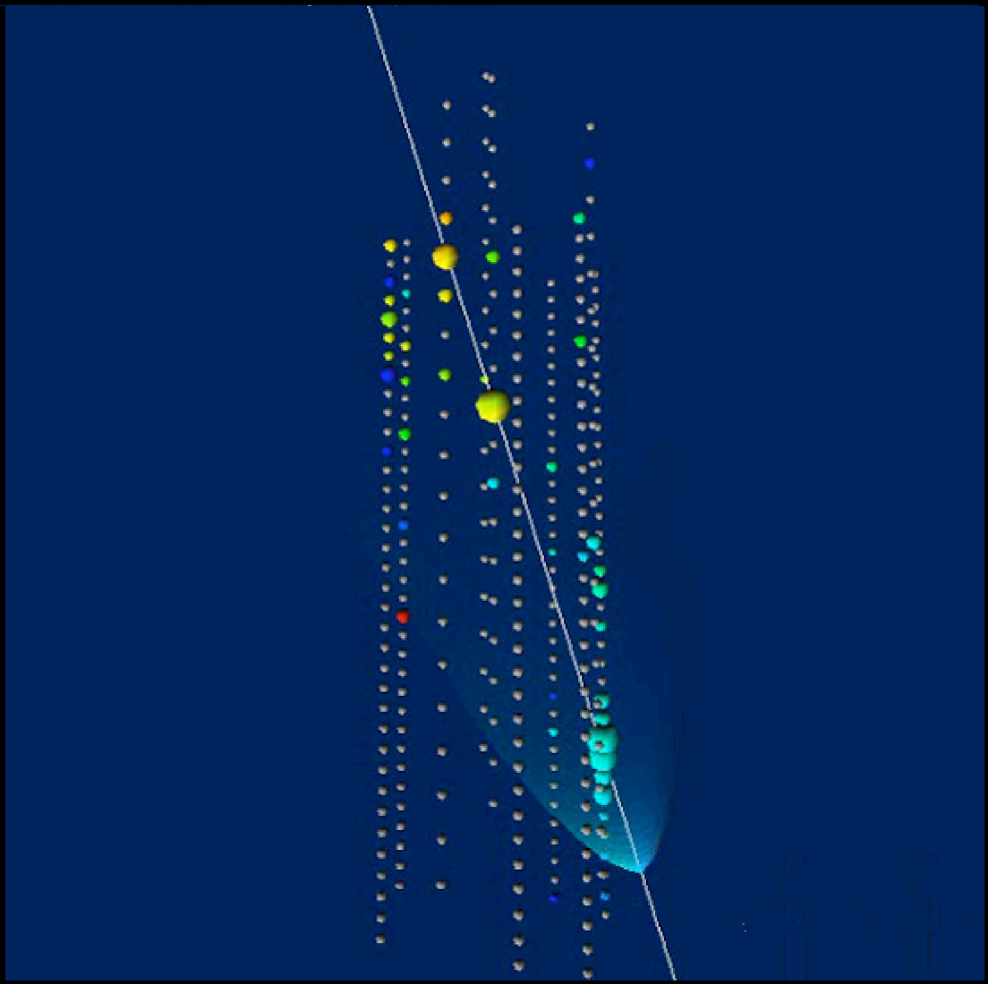
Muon-Induced Neutrinos

- For hadronic sources, $\phi_\nu \sim \phi_\gamma$
- Detection reaction is $\nu_\mu + n \rightarrow \mu^- + p$
- Muon range is ~ 1-10 km
- Near 1 TeV, $P(\nu \rightarrow \mu) \sim n\sigma L \sim 10^{-6}$

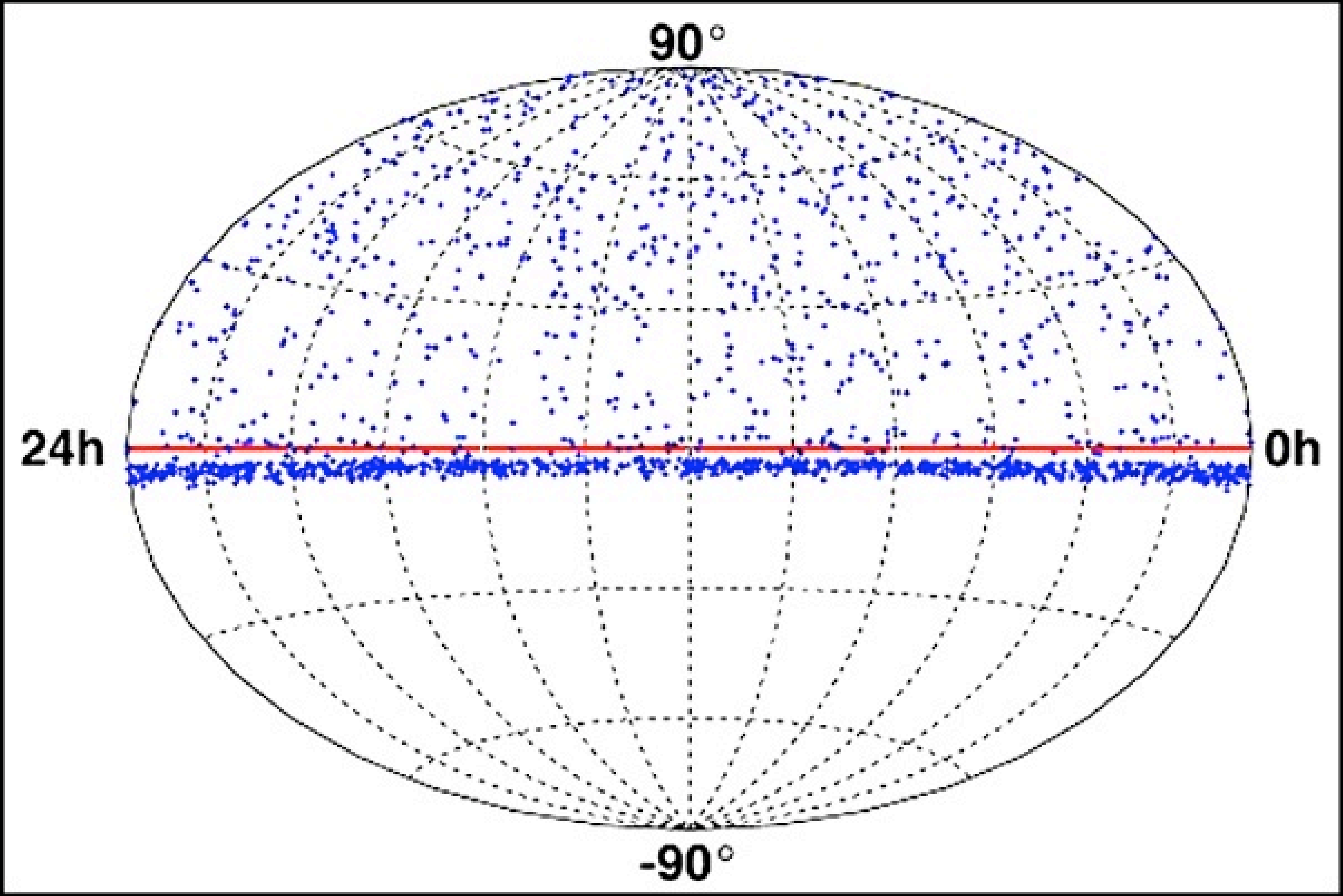
Gaisser, Halzen, Stanev (1995)

IceCube



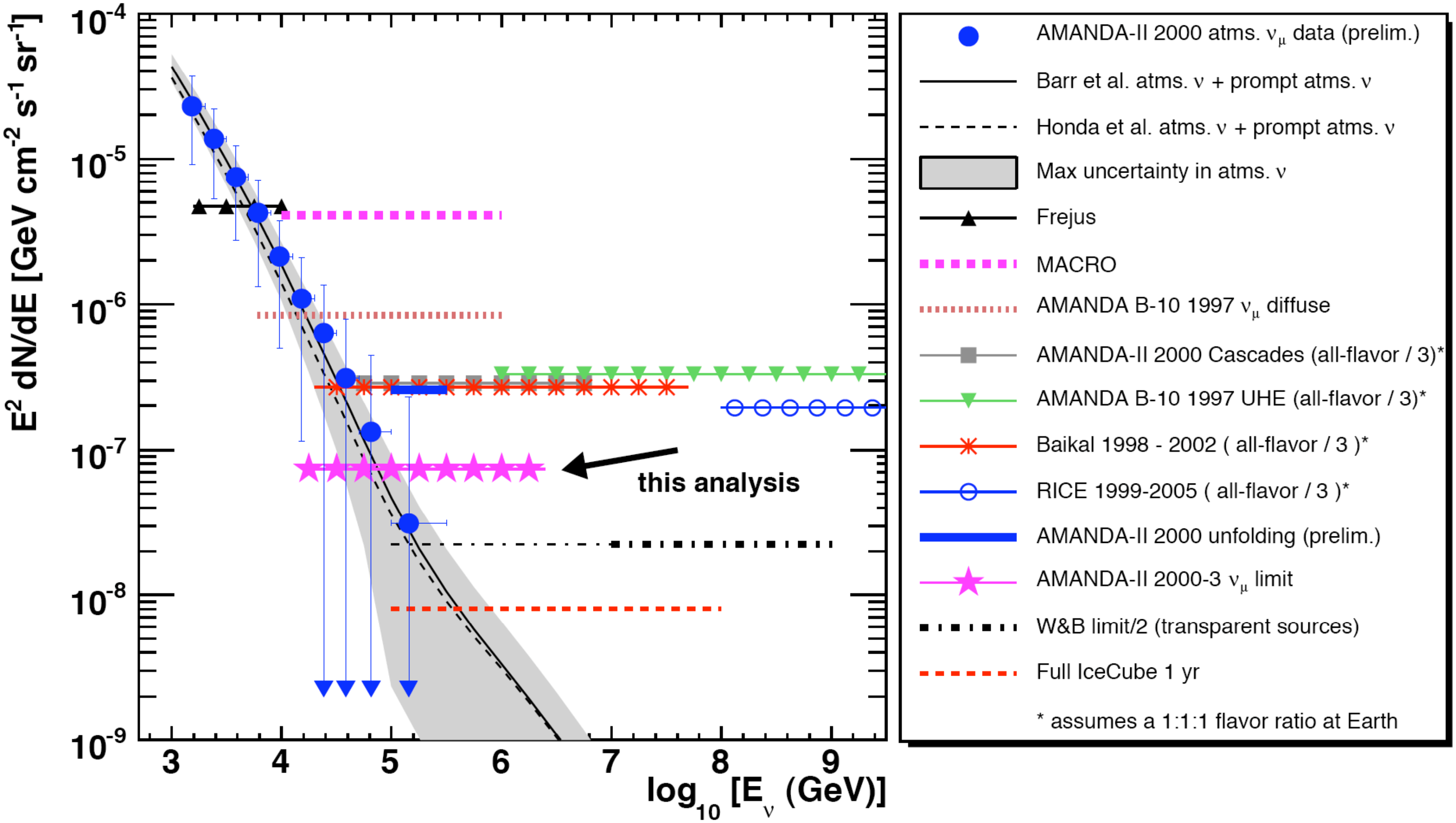


Neutrino Skymap?



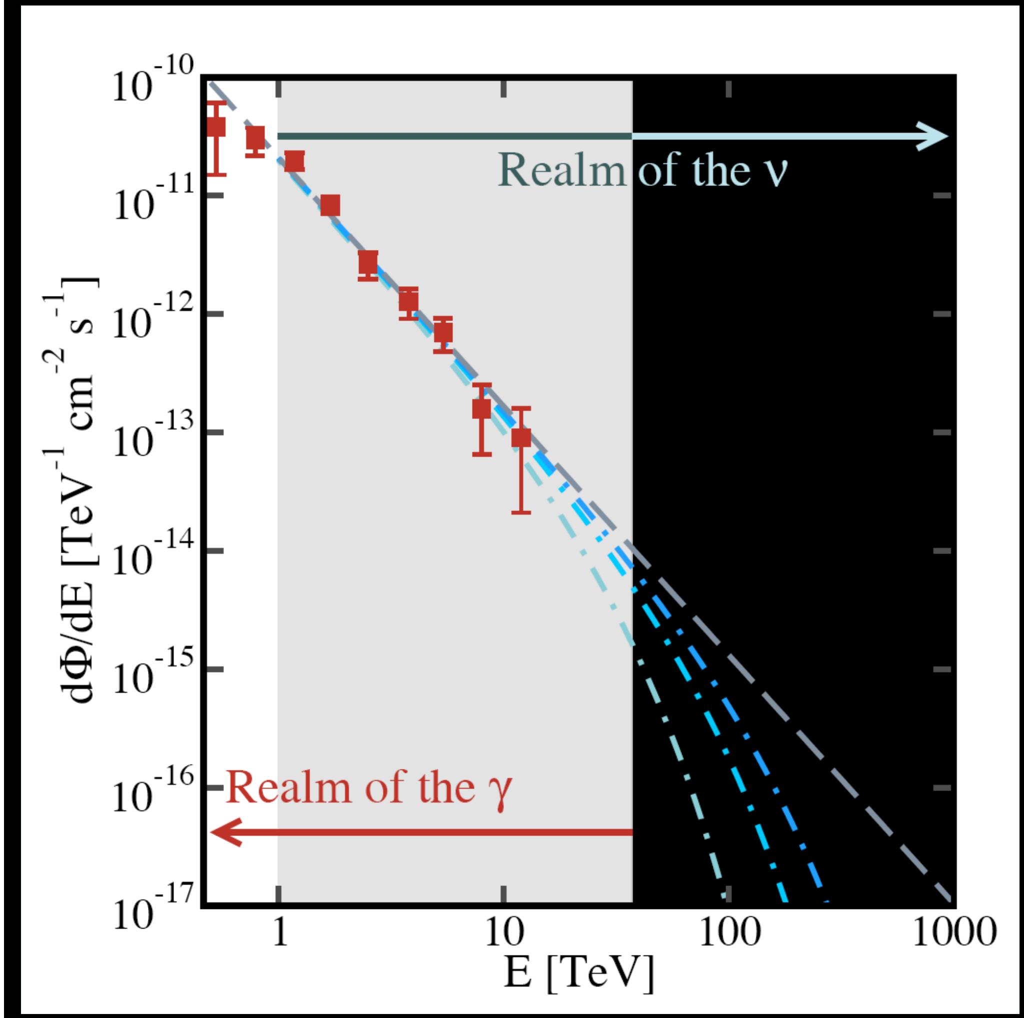
AMANDA Collaboration (2003)

AMANDA Results



AMANDA Collaboration (2007)

Probing Sources With Neutrinos



Kistler, Beacom (2006)

Definitive sign of hadronic mechanism

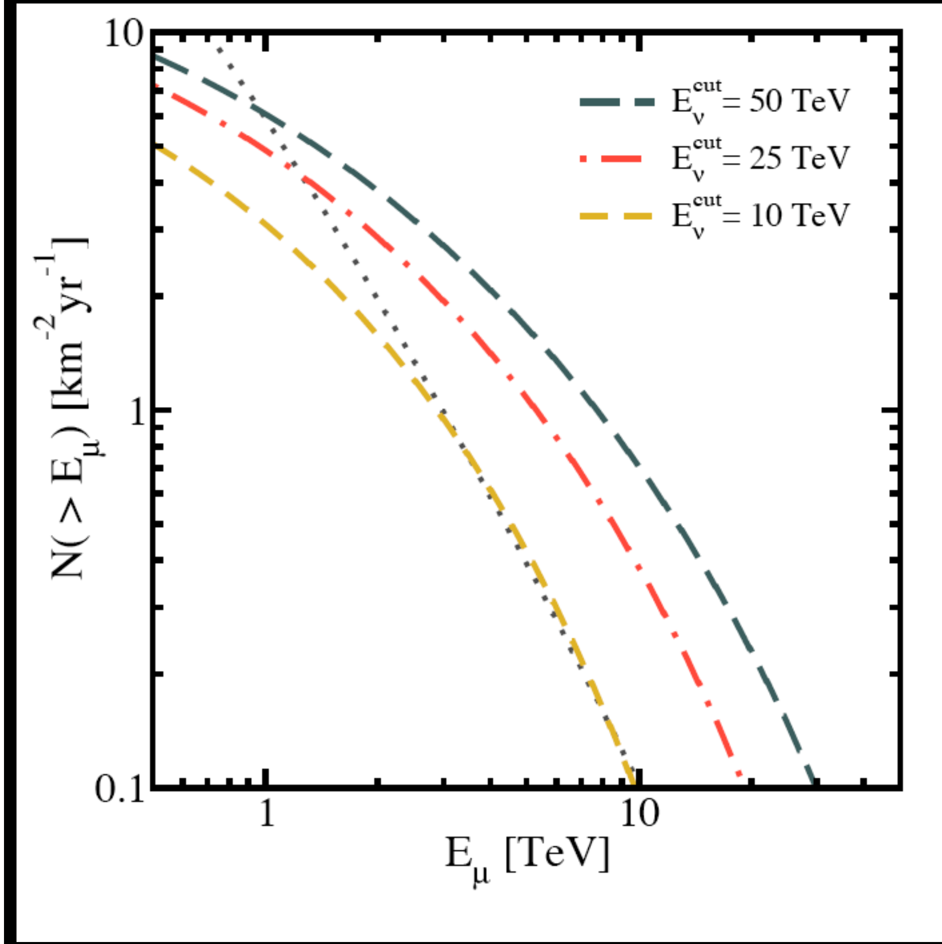
km^3 detectors are big enough

Advantages at large energies

Neutrino-only sources?

Galactic Neutrino Sources

Vela Jr. supernova remnant



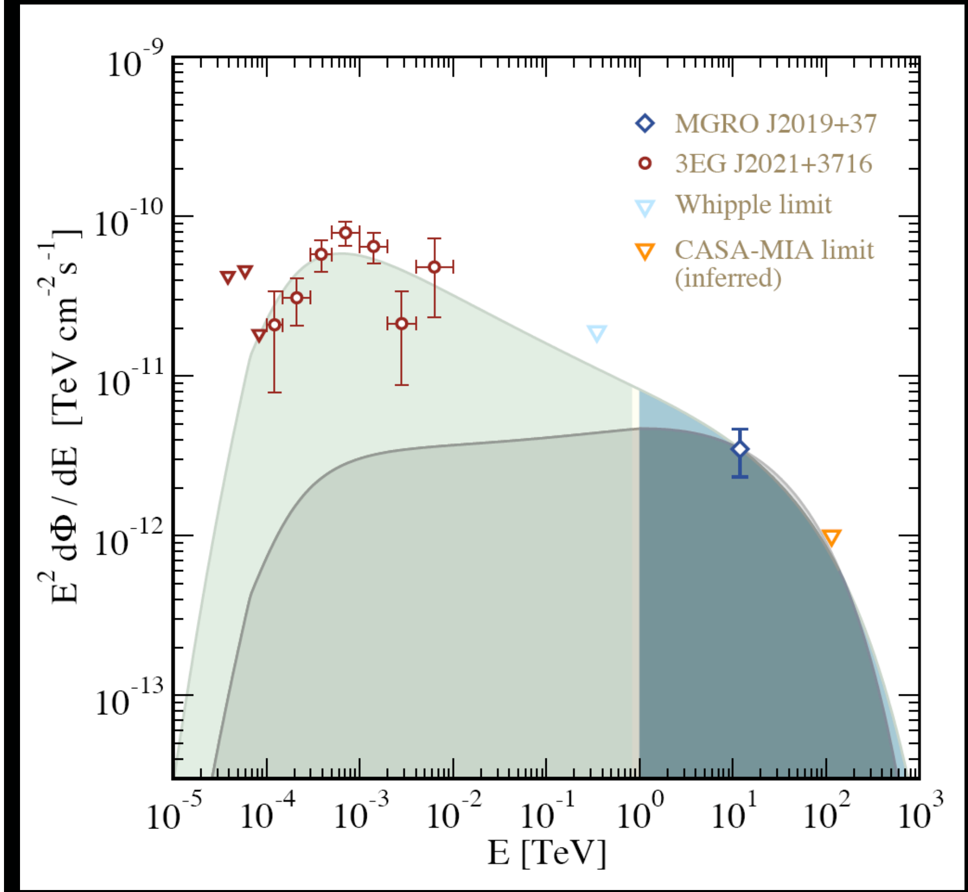
(and many more)

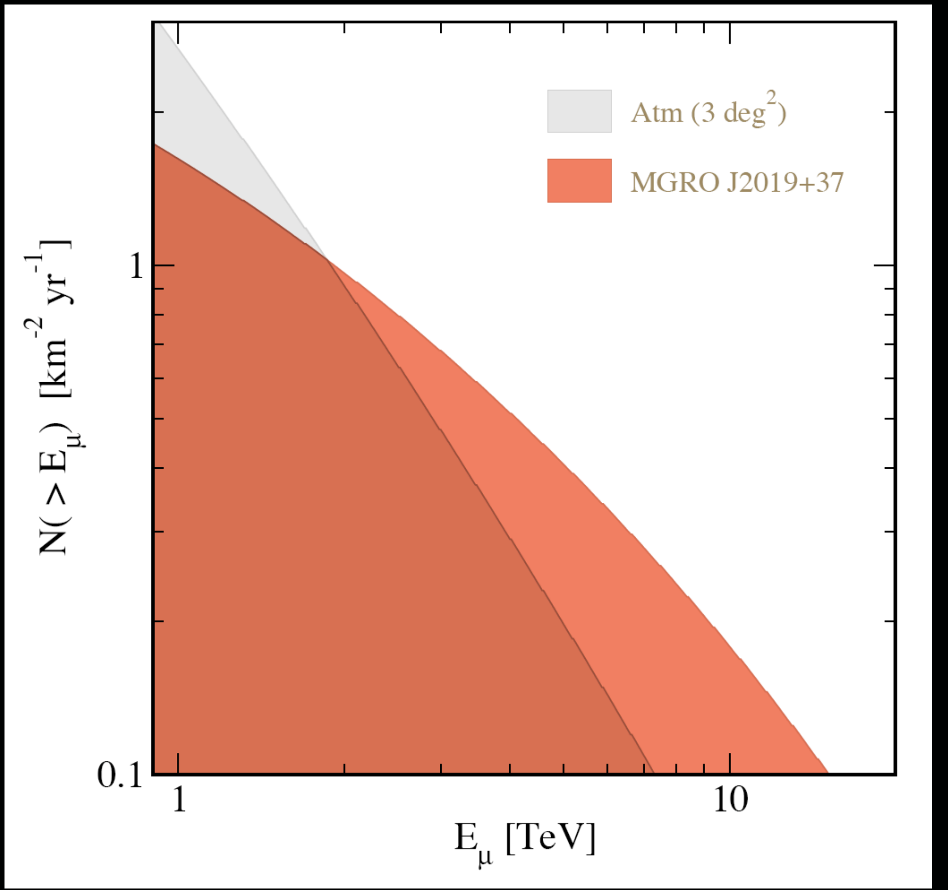
Source	ϕ_γ	Γ	E_ν^{cut} (TeV)	$N_\mu(>1$ TeV)
Vela Jr.	21.0	2.1	10	3.1
(RX J0852.0–4622)			25	4.9
			50	6.1
GC Diffuse	5.2	2.29	20	0.5
			50	0.7
(+ GC Source)			20	0.8
			50	1.0
RX J1713.7–3946	15.0	2.19	50	2.8
	20.4	1.98	6	2.2
Vela X	9.0	1.45	7	4.5
Crab (IceCube)	33.0	2.57	50	2.7
HESS J1514–591	5.7	2.27	25	0.9
			50	1.1
HESS J1616–508	6.0	2.35	10	0.5
			50	0.9
HESS J1632–478	5.5	2.12	10	0.8
			50	1.5

Kistler, Beacom (2006)

Neutrinos from the Milagro Source

MGRO J2019+37 in Cygnus





Beacom, Kistler (2007)

Neutrino Scorecard

- Up to ~ 1 TeV
  Super-Kamiokande, other experiments saw only atmospheric neutrinos

- Above 1 TeV
  AMANDA saw only atmospheric neutrinos
  Excellent prospects for IceCube

- At much higher energies
  From several experiments, only upper limits on fluxes

Prospecting for New Physics

Do neutrinos or dark matter have new properties?

Are there dark matter annihilation signals?

What surprises are out there?

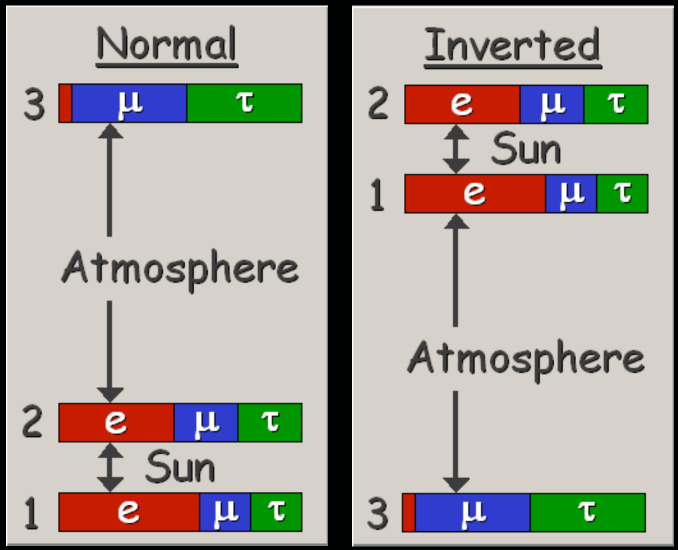
Neutrino Flavor Ratios

$$\pi \to \mu + \nu_\mu \to e + \nu_e + 2\nu_\mu \qquad \phi_e : \phi_\mu : \phi_\tau \sim 1:2:0$$

$$\nu_\mu \leftrightarrow \nu_\tau \qquad \phi_e : \phi_\mu : \phi_\tau \sim 1:1:1$$

Neutrino invisible decays are not ruled out, and would greatly alter the ratios

Other new physics can lead to different ratios



~ 5:1:1 ~ 0:1:1

Beacom, Bell, Hooper, Pakvasa, Weiler, PRL 90, 181301 (2003);
Beacom, Bell, Hooper, Pakvasa, Weiler, PRD 69, 017303 (2004)

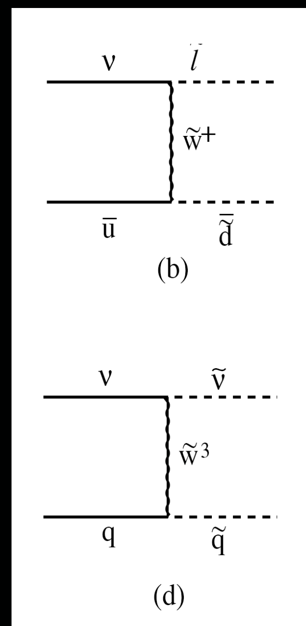
Dark Matter Properties

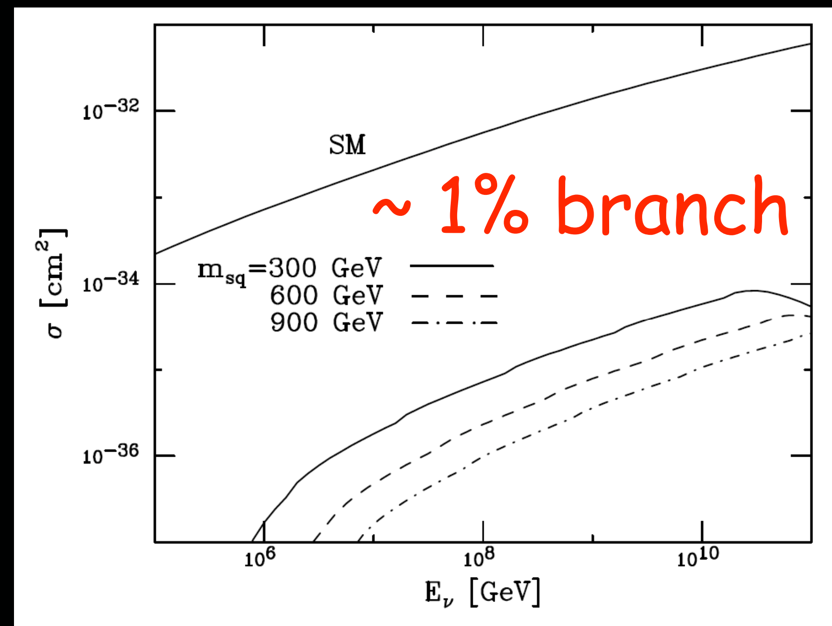
Su

Albuquerque, Burdman, Chacko, PRL 92, 221802 (2004)

NLSP is charged and short-lived

Astro neutrinos make NSLP pairs in Earth





Energetic NLSP pairs make a new signal in IceCube

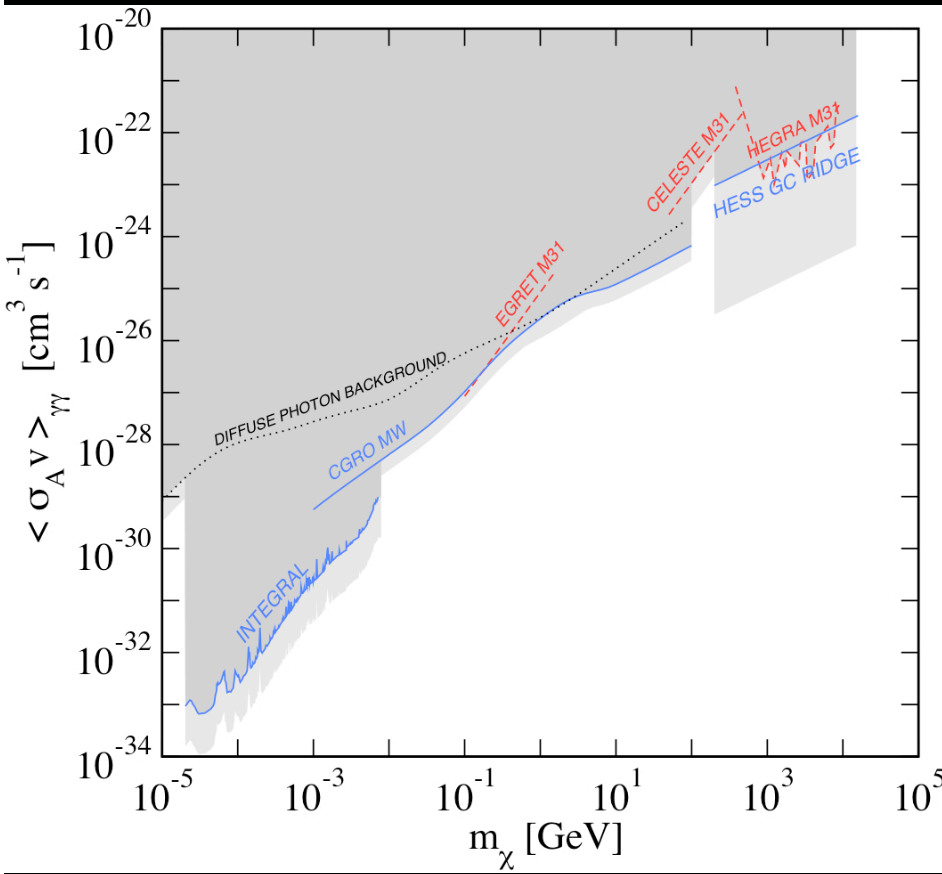
Better if prompt atmospheric neutrino flux is large

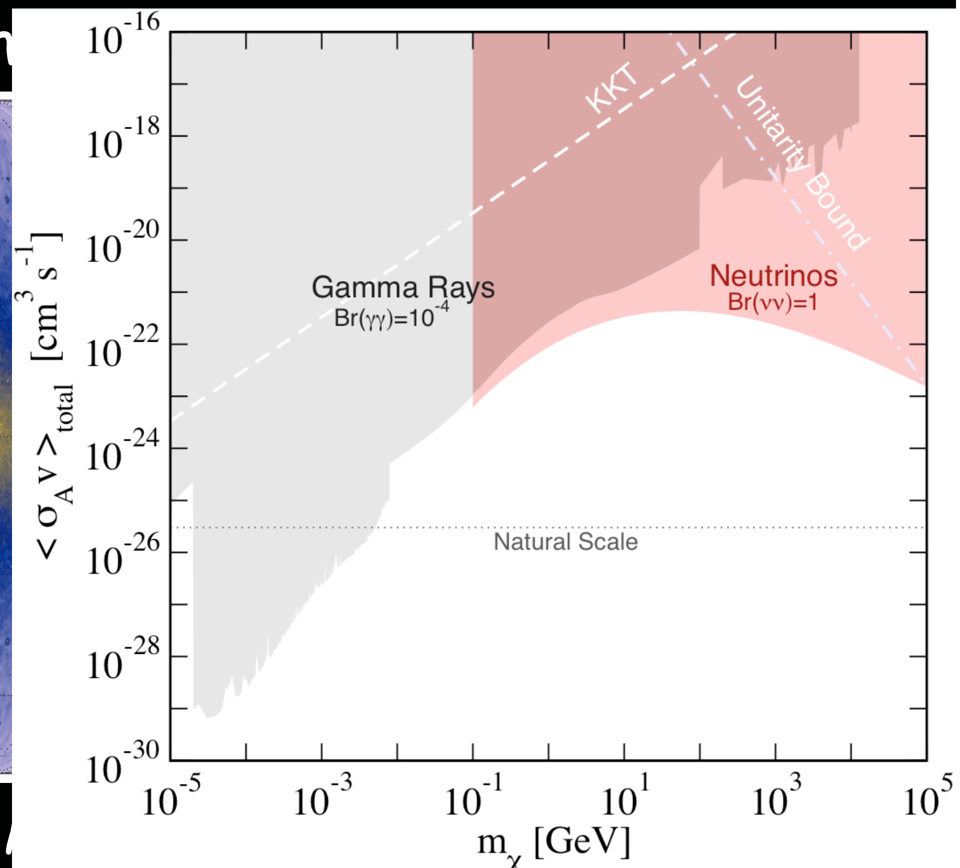
Ando, Beacom, Profumo, Rainwater, JCAP04 (2008) 029

Dark Matter Annihilation

Hooper

Annihilation products: gamma rays and *neutrinos*





upper limit on $\langle \sigma_A v \rangle_{\gamma\gamma}$ upper limit on $\langle \sigma_A v \rangle_{total}$

Mack, Jacques, Beacom, Bell, Yuksel (2008)

Concluding Perspectives

Conclusions

Luminous TeV gamma-ray sources exist:
Most have uncertain astronomical associations
Fundamental question of production mechanism

Better gamma-ray observations are essential:
Increase energy range to test spectra
Refine angular resolution to make identifications
Cover the full sky to study populations and diffuse

Neutrino observations can be decisive:
IceCube and other detectors coming online
Novel probe of the cosmos and new particle physics

Great future with lots of complementary data

CCAPP at Ohio State

The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

Center for Cosmology and AstroParticle Physics

Mission: To house world-leading efforts in studies of dark energy, dark matter, the origin of cosmic structure, and the highest energy particles in the universe, surrounded by a highly visible Postdoc/Visitor/Workshop Program.

ccapp.osu.edu

Postdoctoral Fellowship applications welcomed in Fall