Introduction to High-Energy Neutrino Astronomy

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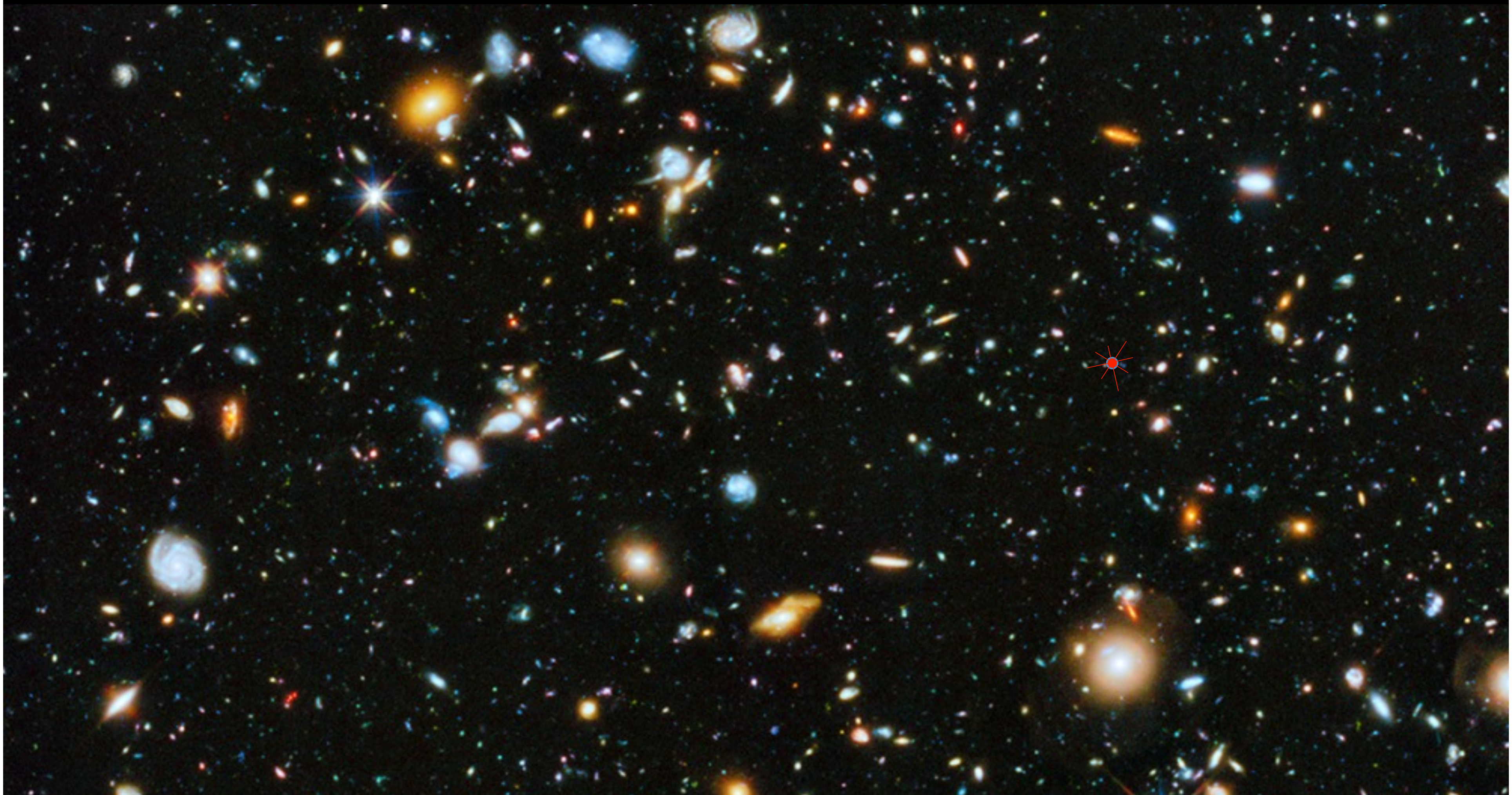
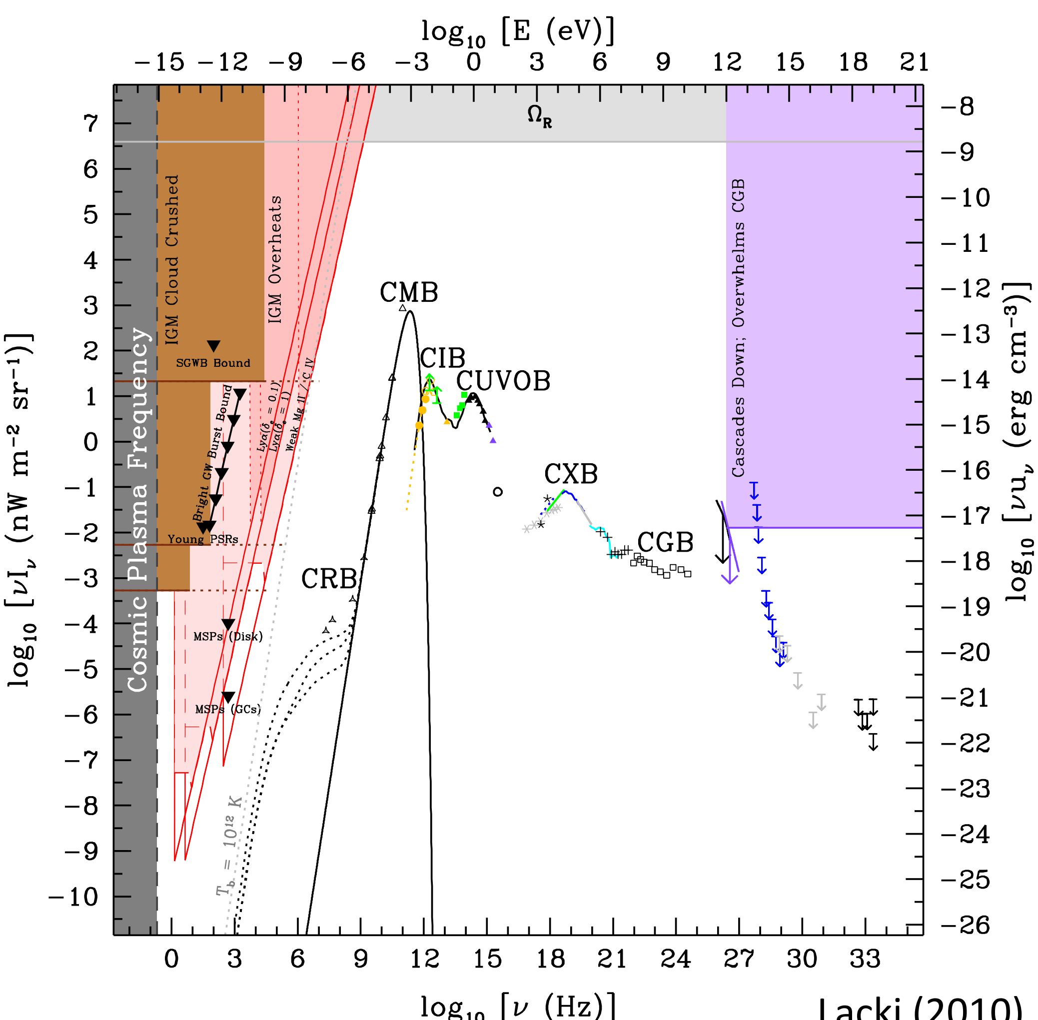


The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

Neutrino Cosmology and Astronomy

Photons



Lacki (2010)

Neutrinos

cosmo: Big Bang relics
“detected” by BBN, CMB

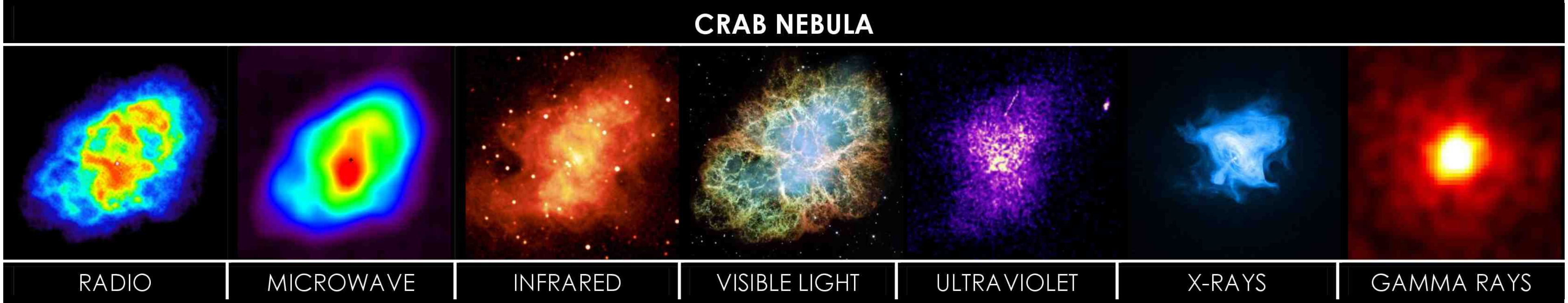
astro: stellar processes
Sun precisely measured
Supernova 1987A detected

astro: galactic processes
IceCube discovered what ???

astro: cosmogenic processes
GZK flux near detection

First Goal: New Astrophysics

What happens deep inside astrophysical systems?
Use knowledge of subatomic physics … *listen to theorists*



Example successes: solar and supernova neutrinos
Example searches: GRB neutrinos; CR sources in MW

Second Goal: New Particle Physics

What are the properties of familiar and of unmet particles?
Use knowledge of astrophysics … *listen to theorists*

Example successes: number of flavors; neutrino mass is small
Example searches: neutrino exotica; dark matter

Third Goal: New Surprises

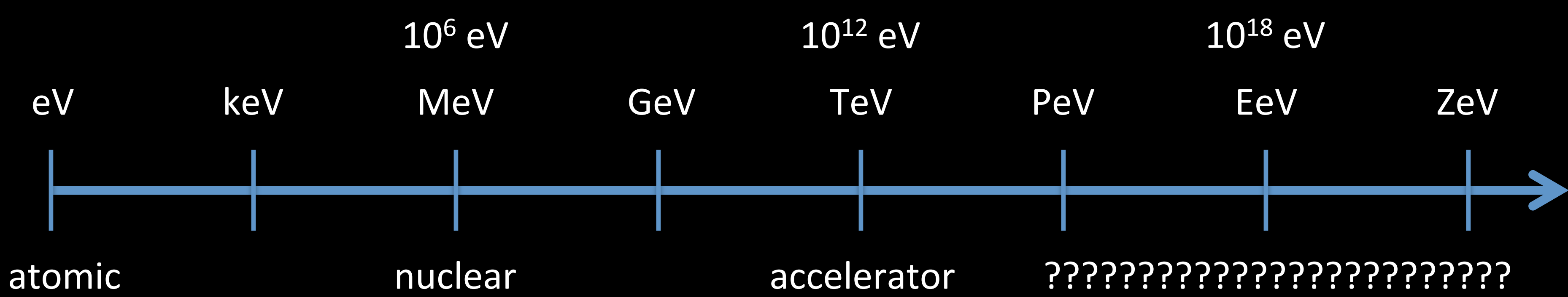
What haven't we thought of?
Develop flexible, powerful searches … *don't listen to theorists*

Example successes: neutrino mixing; cosmic ray anisotropies
Example searches: unknown unknowns!

Impossible? High-Energy Neutrino Astronomy

Requires: sources that reach high energies
sources that are luminous
sources of different types
particles that can reach us
particles that can point back
particles that can be detected
results that can be understood

Our part



Plan of the Talk

✔ Goals of neutrino cosmology and astronomy

High-energy astrophysical neutrinos must exist

They are detectable (theorists' verse)

They are detectable (experimentalists' verse)

Now what? (duet)

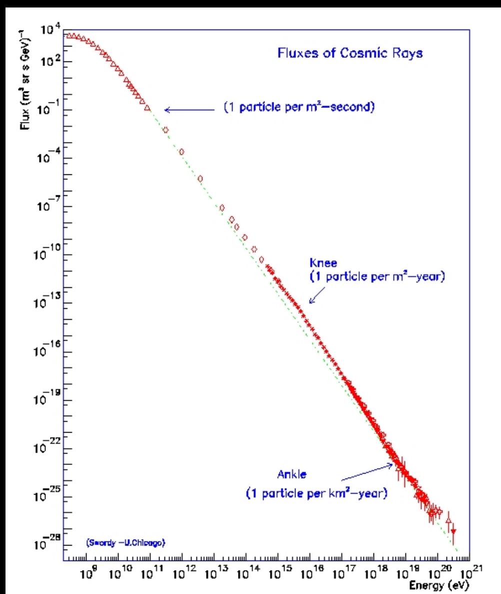
Neutrino astronomy is happening

HE astrophysical neutrinos must exist

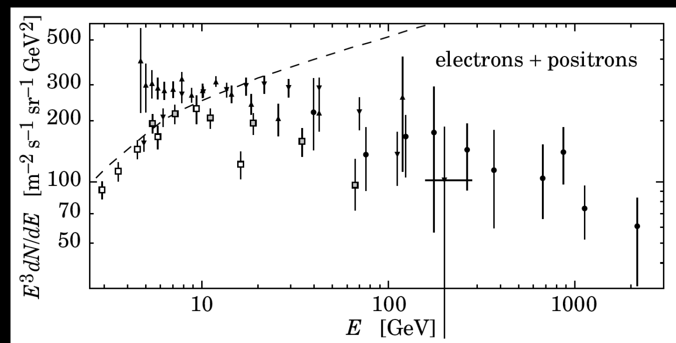
Energetic And Luminous CR Sources Exist

Charged cosmic rays first detected 100 years ago

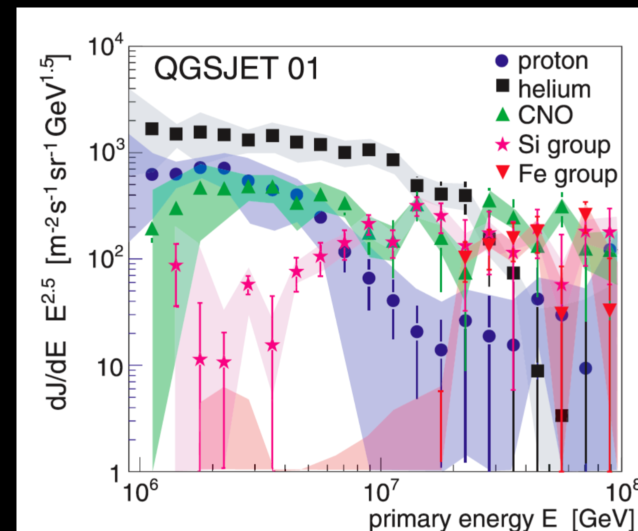
protons



electrons and positrons



nuclei



Cosmic rays produced with high energies (up to 10^{20} eV) and high densities ($U_{CR} \sim U_{starlight}$ in MW), but do not point back

Sources assumed astrophysical, but may also be exotic

Cosmic Rays Inevitably Make Secondaries

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

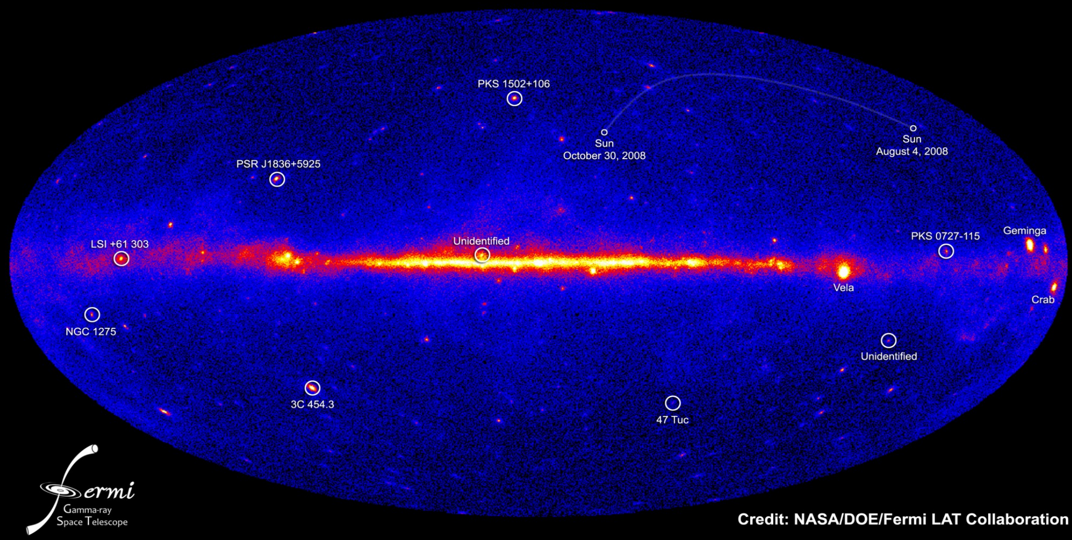
Nuclear (A*) mechanism $A' + \gamma \rightarrow A^* + X$

$A^* \rightarrow A + \boxed{\gamma}$ and some $\boxed{\nu}$

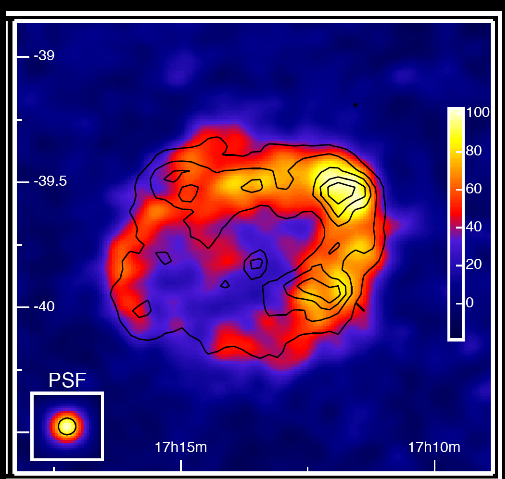
Exotic mechanisms unstable SM particle decays $\rightarrow \boxed{\gamma}, \; \boxed{\nu}$

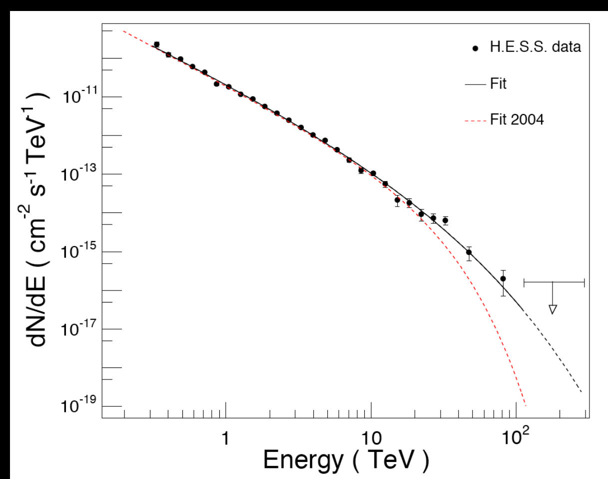
Production always makes a mess; propagation makes more

Energetic And Luminous Gamma Sources Exist



Wide variety of point and diffuse sources, high fluxes





Energies up to ~ 100 TeV

Gammas do point, but they do attenuate, don't reveal parents

Energetic And Luminous Neutrino Sources Exist

Speculation about high-energy neutrino astronomy since 1960s (Reines; Ruderman; Markov; Pontecorvo; Berezinsky; etc.)

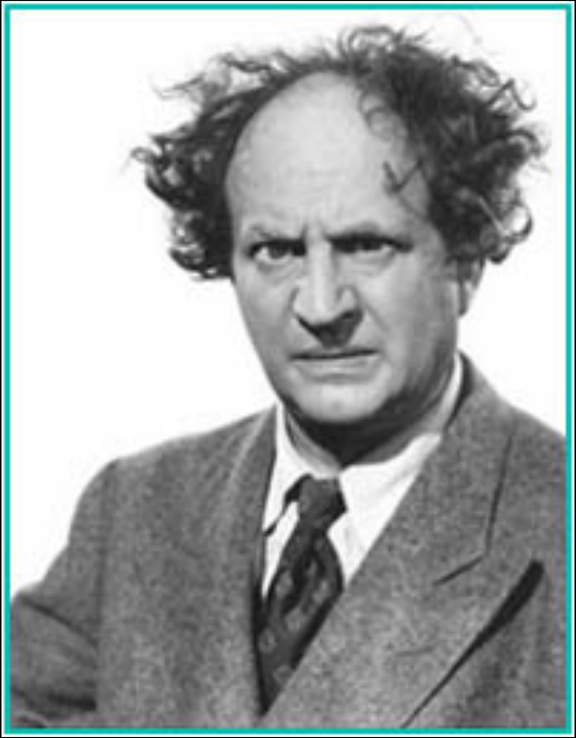
Now on a firm footing due to vastly better astrophysical data and decisive evidence from gamma-ray astronomy

- Leptonic sources: neutrino fluxes are zero
- Other sources: neutrino, gamma fluxes comparable

Large neutrino fluxes expected from a variety of diffuse, point, and transient sources in the Milky Way and cosmos ... and neutrino-bright surprises are possible

We Need All Three Messengers

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



But Neutrinos Are The Best

Neutrinos reveal:

- deep insides of sources, not the outsides
- initial energies, not reduced by thermalization
- original timescales, not delayed by diffusion
- distant sources, not attenuated en route
- source directions, not blurred by deflection

The only thing is that neutrino signal detection is hard

HE astrophysical neutrinos are detectable
(theorists' verse)

First Difficulty: Measuring Signals

$$\nu_e + n \rightarrow e^- + p$$ Electromagnetic showers

$$\nu_\mu + n \rightarrow \mu^- + p$$ Muon tracks (long!)

$$\nu_\tau + n \rightarrow \tau^- + p$$ Hadronic showers

Plus charge conjugates, plus neutral-current channels

Small cross section requires big detectors;
cost dictates sparse instrumentation

Energy: ~ 10% if contained

Direction: ~ 1° (muons), ~ 10° (showers)

Flavor: good

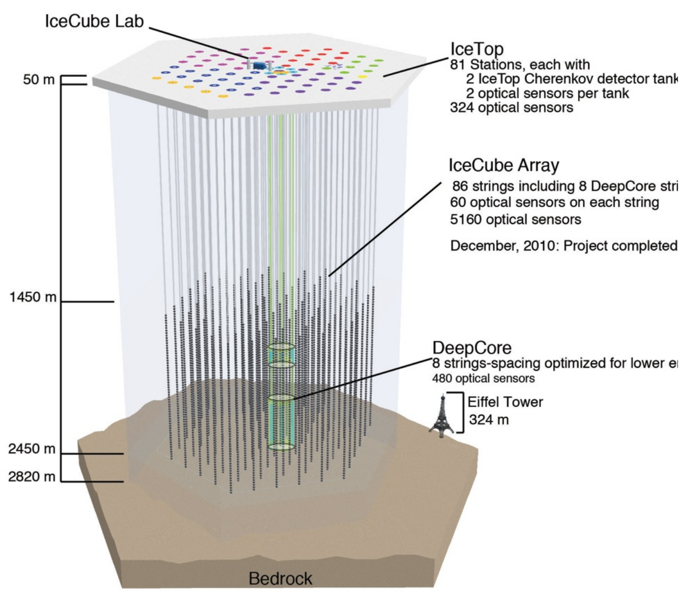
Time: excellent

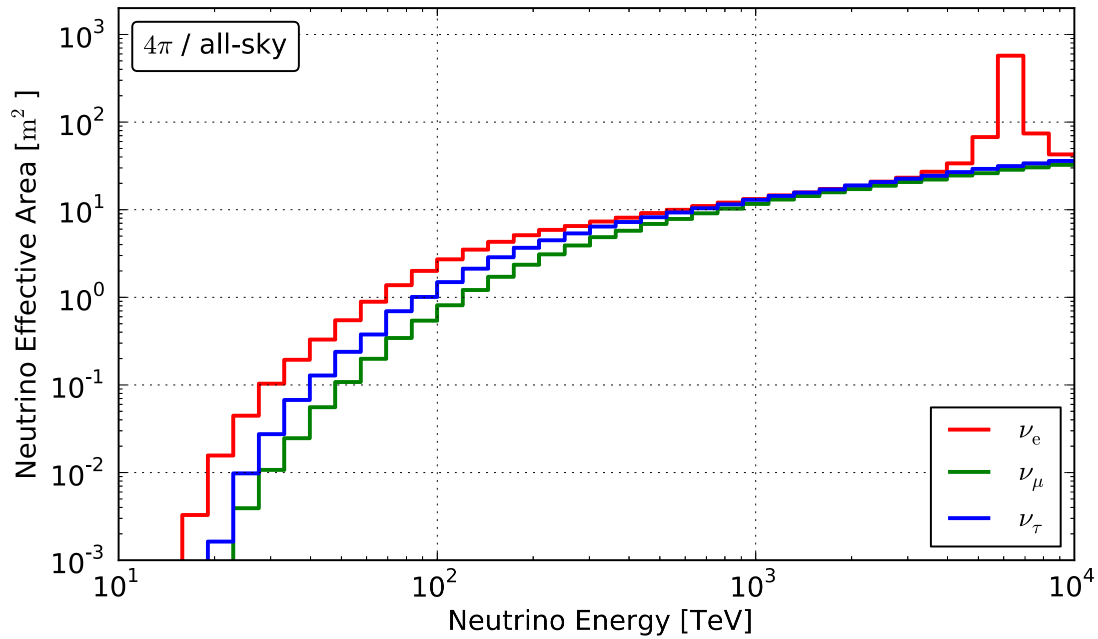
IceCube Is Big Enough To Succeed

$$N_{events} \sim 4\pi \,.\, N_{targets}\, \sigma \,.\, T \,.\, \Phi \sim 4\pi \,.\, A_{effective} \,.\, T \,.\, \Phi$$

Volume ~ 1 km^3

$A_{effective}$ ~ 1 m^2 at 100 TeV



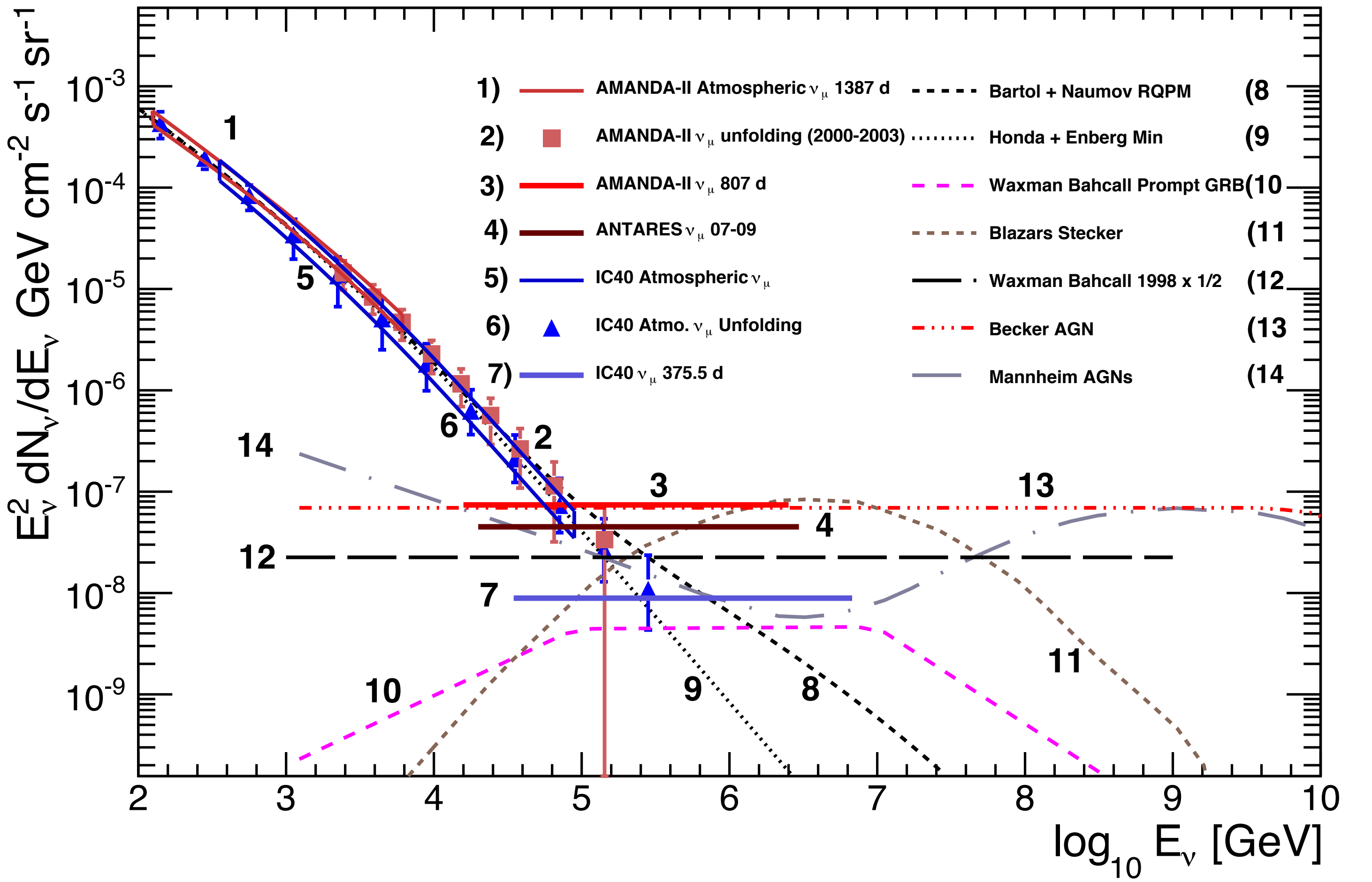


For many sources, ~ 1 km^3 is the minimum required

Second Difficulty: Rejecting Backgrounds

Atmospheric muons: enormous but greatly reducible *background*

Atmospheric neutrinos: big but reducible (Schonert+ 2008) *foreground*



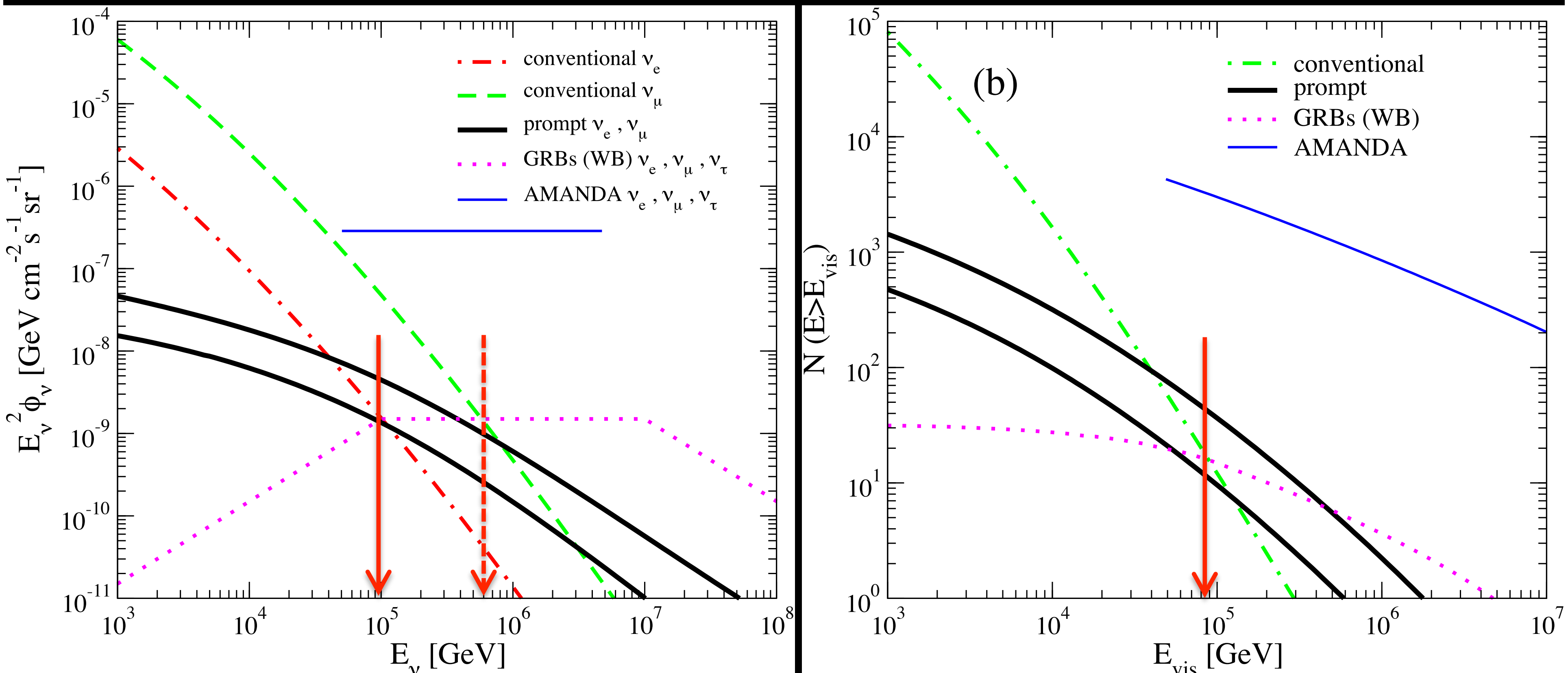
IceCube 2011:

Atm. nu measured up to ~ 200 TeV

Astro. nu strong limits at higher energies

Cascades Predicted To Suppress Backgrounds

Beacom+Candia, "Shower Power" (2004): First to show; largely ignored



Key point is using measurable energy instead of neutrino energy

Cascade signal emerges at energy ~ 10 times lower than track signal

HE astrophysical neutrinos are detectable
(experimentalists' verse)

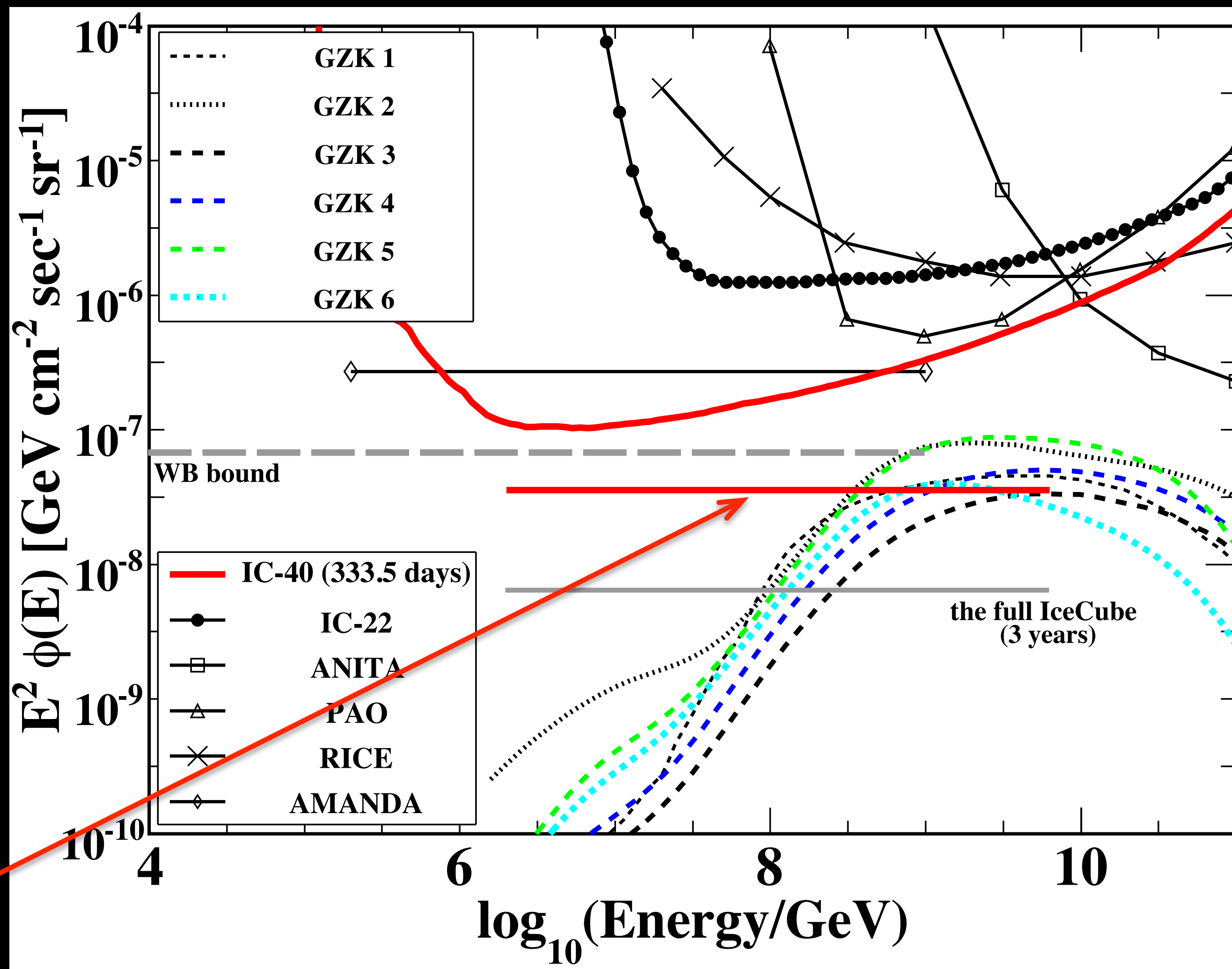
IceCube Search For UHE Neutrinos

Sensitivity to neutrinos from ultra-high-energy cosmic rays

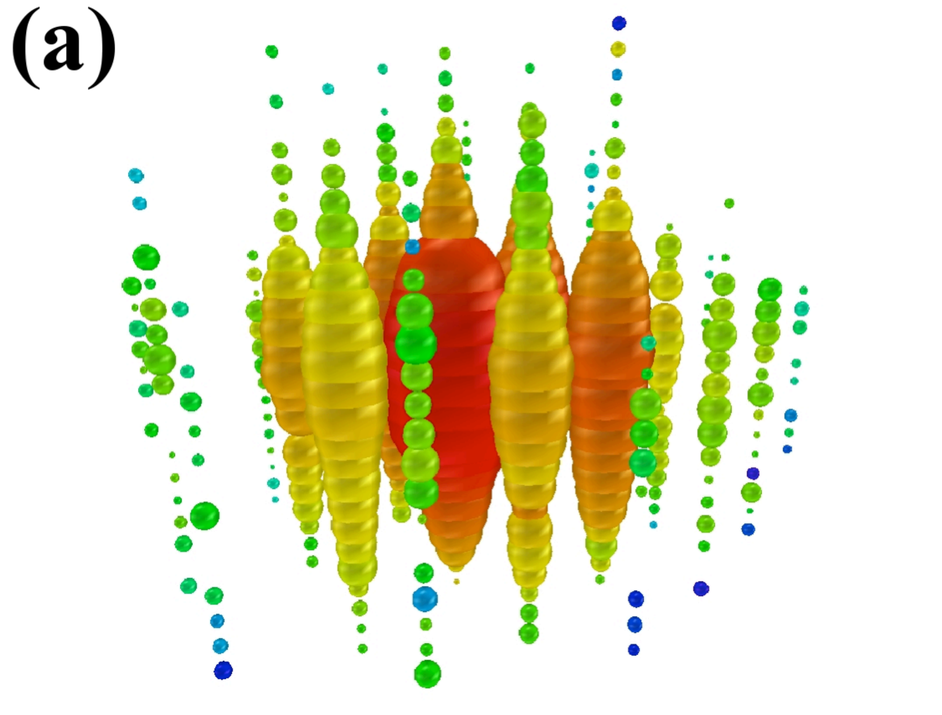
Signal is very bright events induced by all neutrino flavors

Backgrounds are due to muons and are low

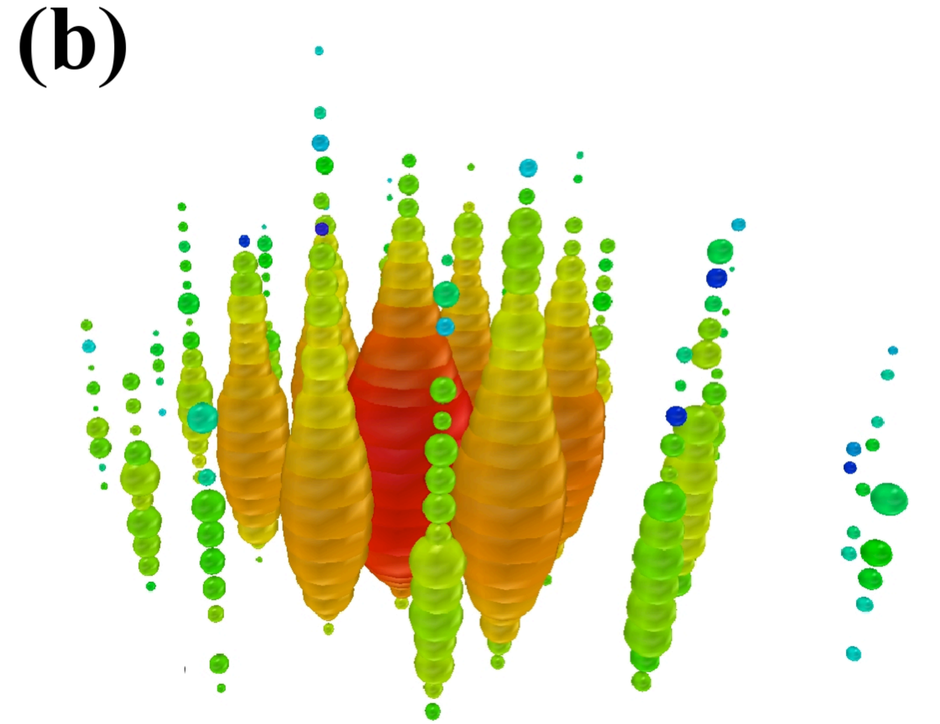
IceCube 2011 upper limit



Who Ordered These?



2011: ~ 1 PeV cascade



2012: ~ 1 PeV cascade

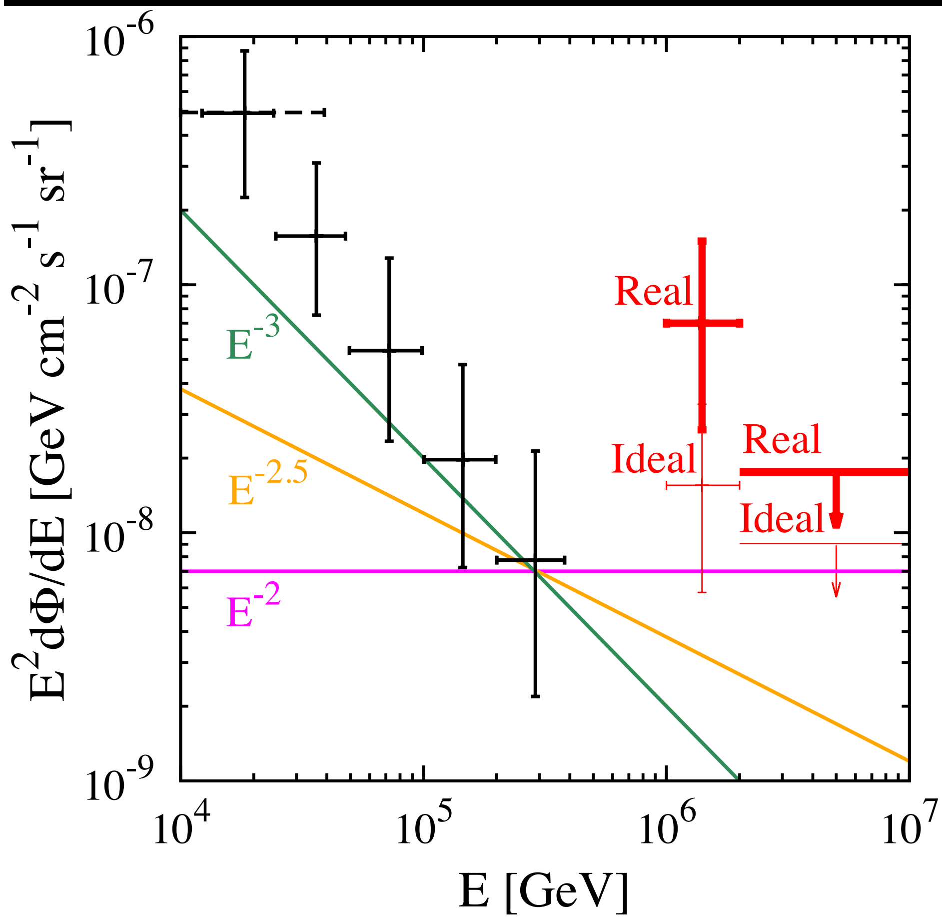
Great fortune in finding these events in this search (2013)

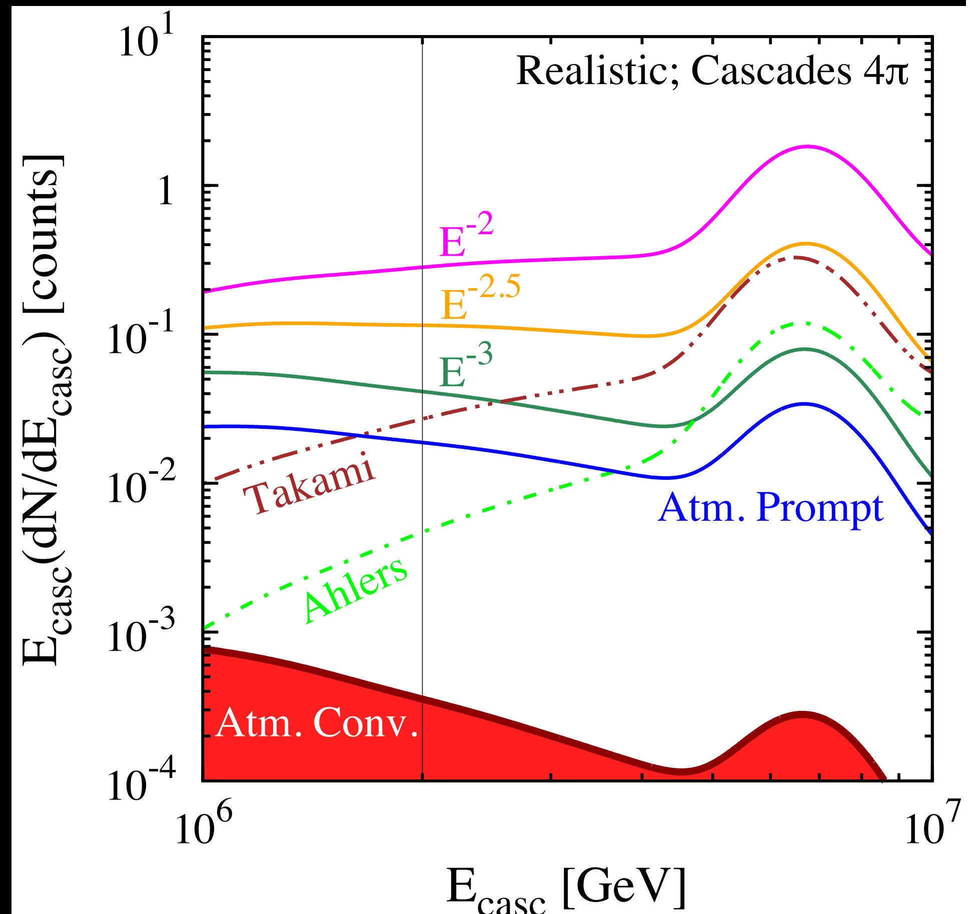
Many surprised by the details of the results

Now what? (duet)

Demystifying The PeV Cascades

What can you learn from two events? A lot. (Laha+ 2013)

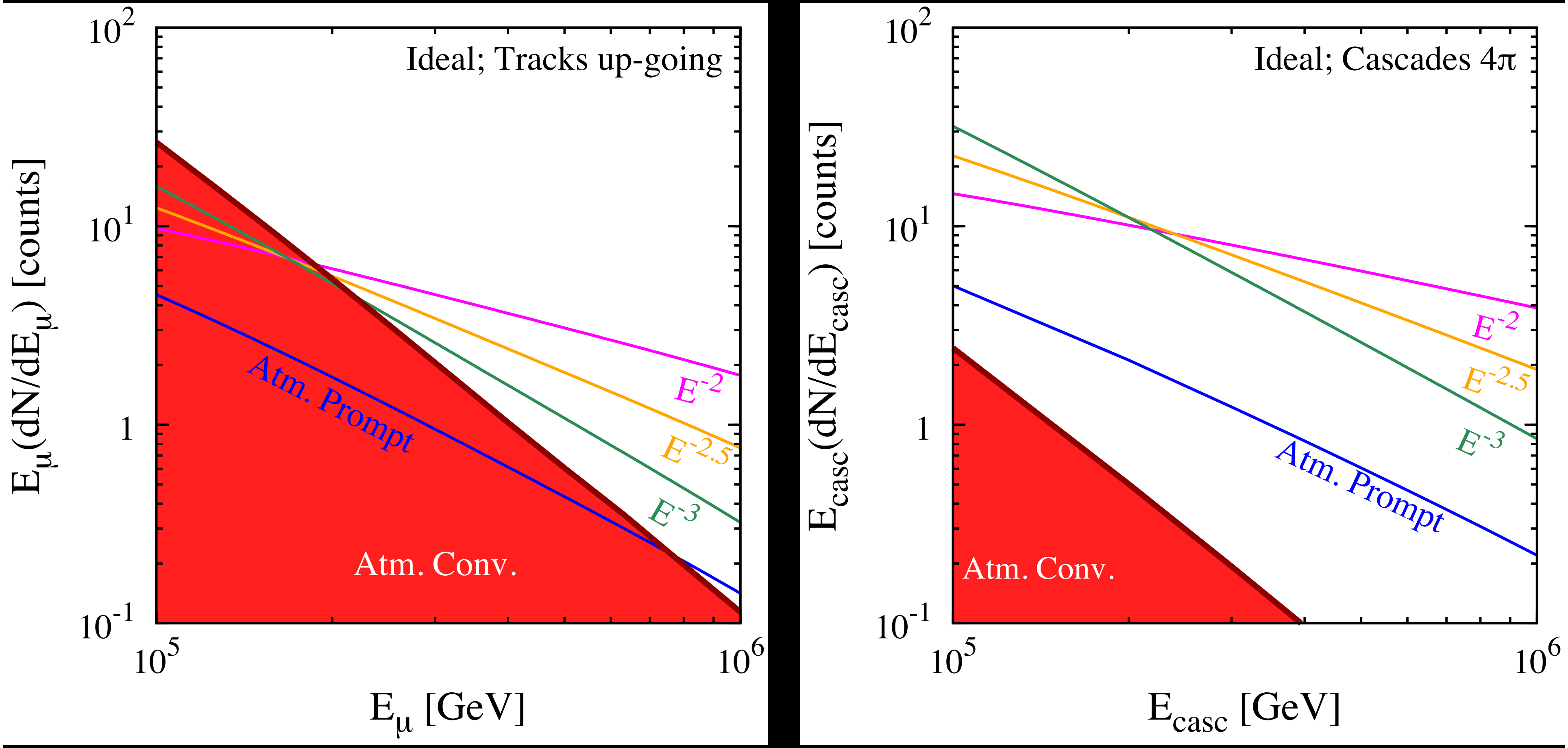




Mostly reasonable (IceCube has since changed inputs)

Less (Energy) Is More (Events)

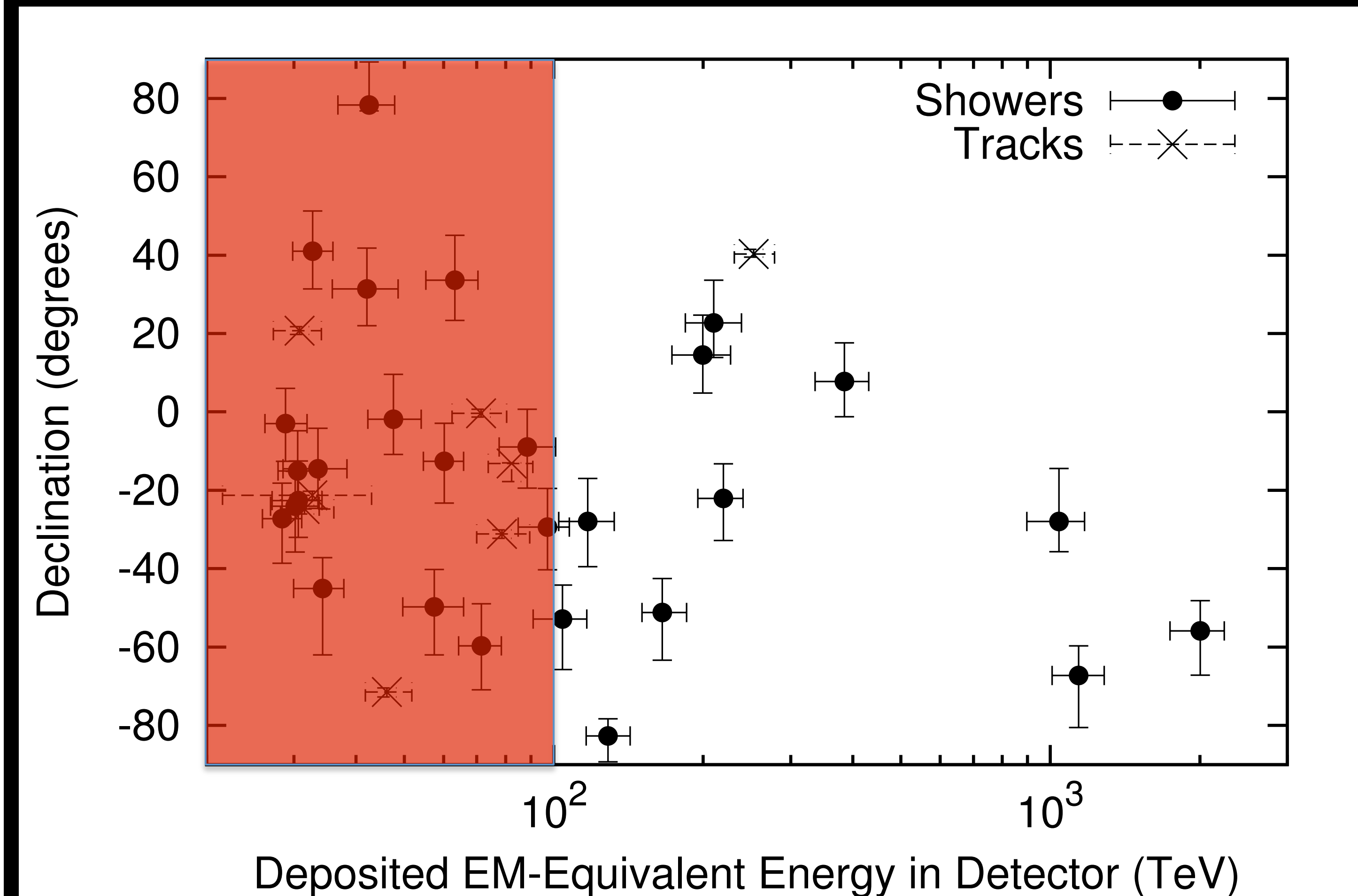
Quickest check of signal is at lower energies (Laha+ 2013)



Cascades have much lower backgrounds than muon tracks

Now Comes The Flood

New (2014) IceCube TeV-PeV search, using 2010—2013 data



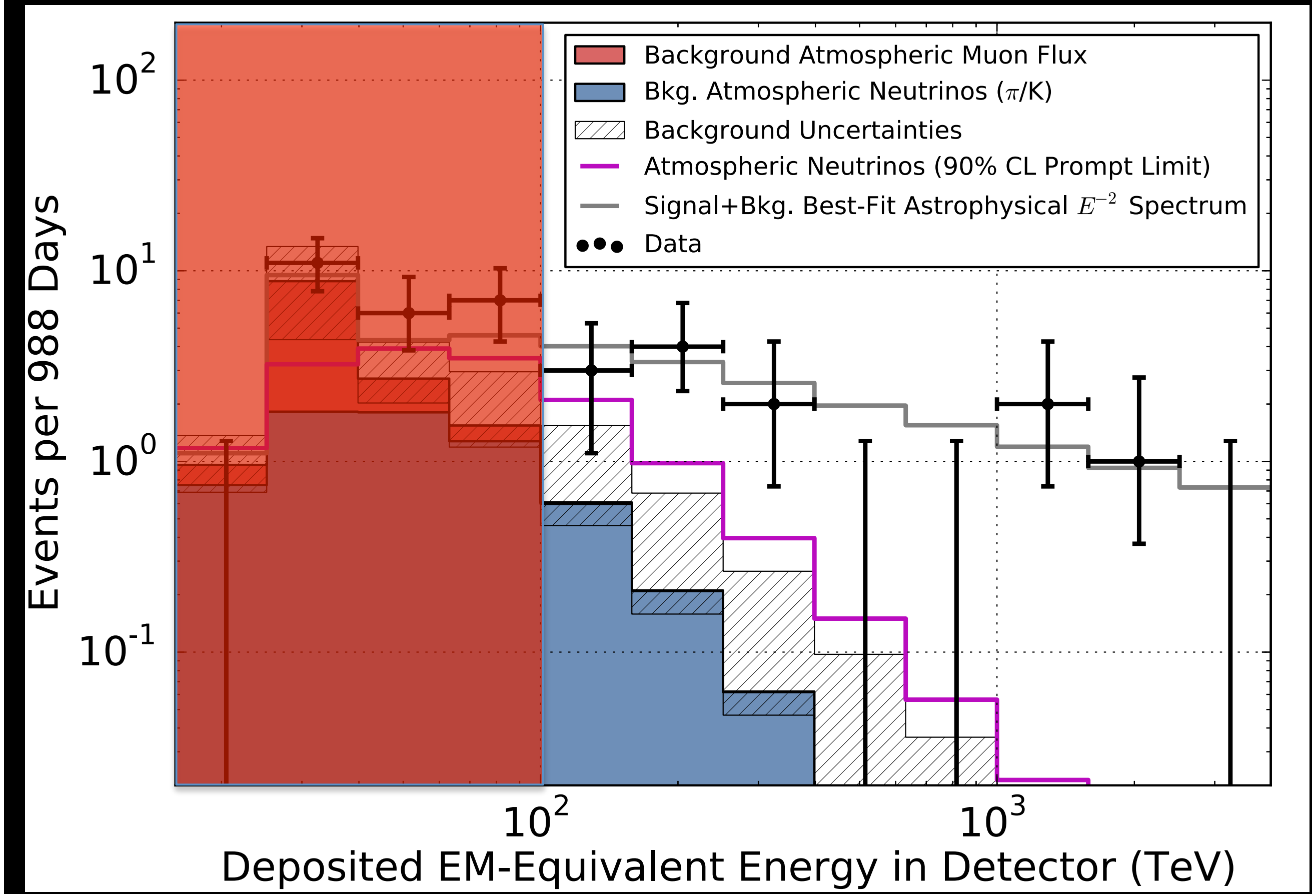
My opinion:
focus above 100 TeV on "Clean Dozen" events with negligible atmospheric backgrounds

Conservative analysis: 37 candidates, ~ 15 background, 5.7σ

What Does The Energy Spectrum Tell Us?

Sum of cascade (all flavors), starting track (muon) channels

True significance is *much higher* than reported

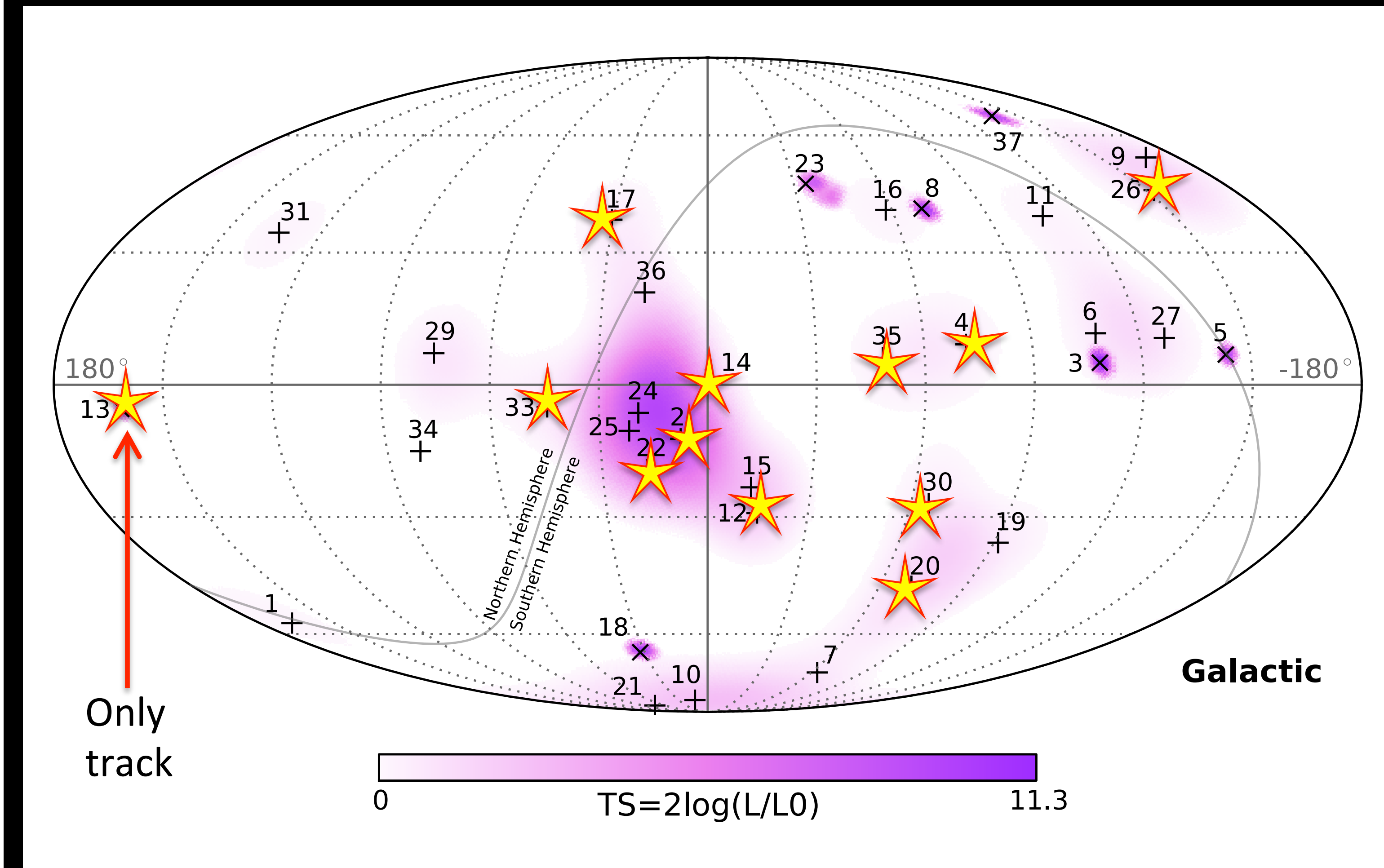


For "Clean Dozen" events, ignore the backgrounds shown because cascade channel dominates

Easy to see (!): astrophysical neutrinos with spectrum ~ E^{-2}

What Does The Angular Distribution Tell Us?

First HE neutrino skymap; some caveats for interpretation



Isolating "Clean Dozen" changes picture

Easy to see (!): sources mostly isotropic, extragalactic

Certainties, Probabilities, Mysteries

Signal origin: definitely observed extraterrestrial neutrinos
likely no UHE, Galactic, or exotic sources

Energy spectrum: $E^2 \Phi \sim$ 10^-8 GeV cm^{-2} s^{-1} sr^{-1}
shape E^-2 with cutoff or a bit steeper

Angular distribution: likely isotropic with Earth attenuation
no obvious clustering or correlations

Flavor ratios: maybe consistent with 1:1:1, but a little weird
where are the muon tracks at high energy?

Time distribution: appears to be constant, not bursty

What's Next?

IceCube unblinded the fourth year of data

Will soon update previous analyses with more exposure
A handful of events at very high energies could be decisive

Look for new analyses that separate cascades and tracks

Cascades have much better signal-to-background than tracks
Beacom and Candia (2004); Laha, Beacom, et al. (2014)

Look for new analyses to probe Milky Way point sources

Combined with gamma-ray data, one event could mean detection
Kistler and Beacom (2006); Beacom and Kistler (2007)

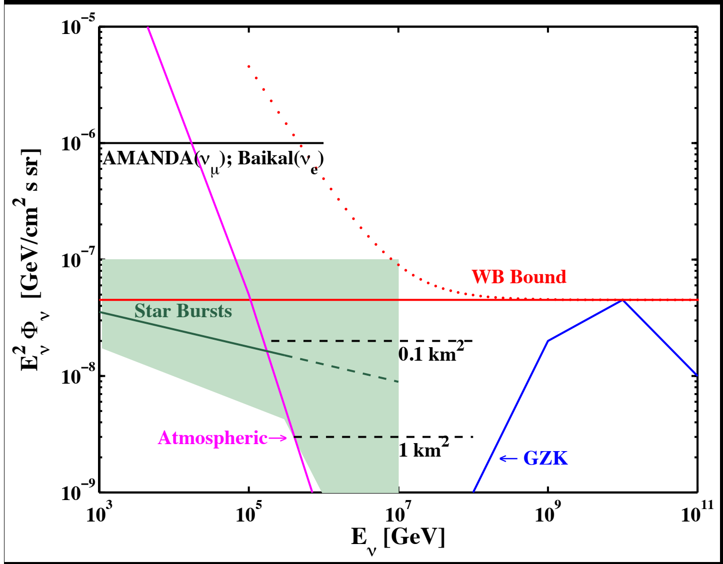
Look for leverage from new HAWC gamma-ray results

First powerful synoptic survey for very high energy gamma rays
Sees mostly Northern hemisphere, well-matched to IceCube

The Promise of Patience

Astrophysics:
Hadronic luminosity?

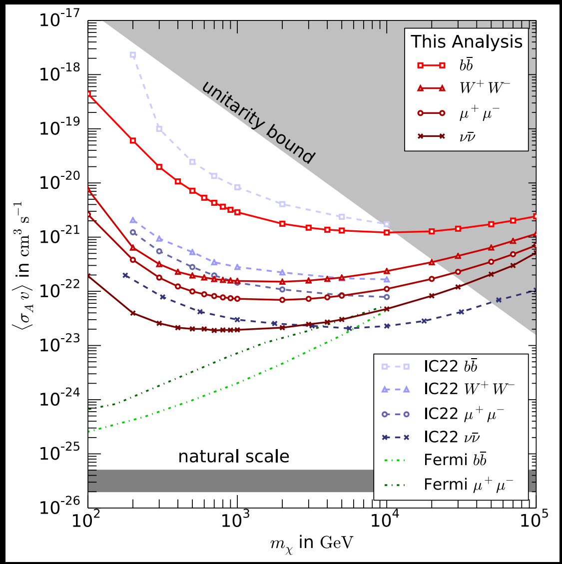
Ex.: Star Formation History



Loeb, Waxman 2006
countless others

Dark Matter:
Coupling to SM?

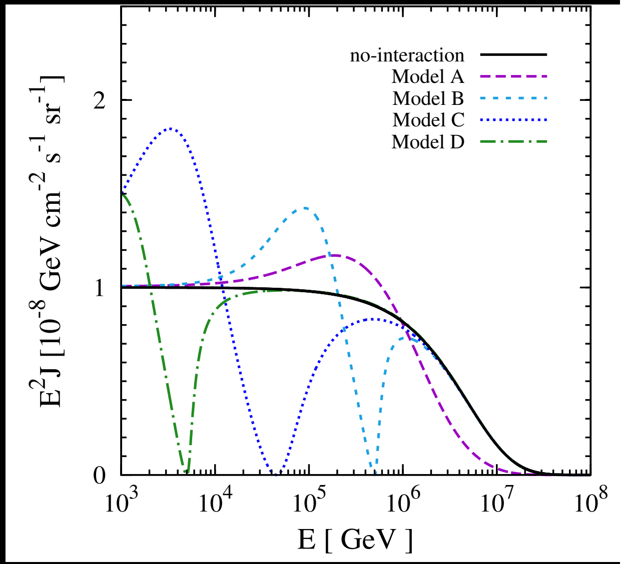
Ex.: DM Annihilation



Beacom, Bell, Mack 2006
IceCube 2014

Neutrinos:
New nu properties

Ex.: nu+nu scattering



Ng, Beacom 2014
Ioka, Murase 2014
Cherry, Friedland, Shoemaker 2014

Neutrino astronomy is happening

Summary: High-Energy Neutrino Astronomy

Great unsolved mysteries in high-energy astronomy:

Origin of cosmic rays, nature of gamma ray sources, particle properties of dark matter and neutrinos, etc.

Cannot give decisive answers without neutrinos:

Microscopic processes and energies, fast timescales and extreme interiors of sources, possible surprises, etc.

IceCube has pioneered the high-energy neutrino sky:

First discovery already sheds new light on astrophysics, dark matter, neutrino properties, etc.

Exciting prospects to continue and make new discoveries:

Besides running IceCube longer, crucial role for KM3NeT, IceCube extensions, and experiments like HAWC, etc.

Neutrino Astrophysics Must Be Broad

MeV: Nuclear-Physics Sources

Transient sources, e.g., supernova bursts
Steady sources, e.g., backgrounds from supernovae
Possible sources from dark matter decay or annihilation

TeV: Particle-Physics Sources

Transient sources, e.g., AGN and GRBs
Steady sources, e.g., Milky Way sources, SB galaxies
Promising sources from dark matter annihilation or decay

EeV: Extreme-Physics Sources

Certain fluxes from UHECR and propagation products
Likely fluxes directly from their accelerators
Possible sources from supermassive particle decays

Must connect γ, ν, CR to each other, physics, and astronomy

Center for Cosmology and AstroParticle Physics

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

CCAPP

Columbus, Ohio: 1 million people (city), 2 million people (city+metro)
Ohio State University: 56,000 students
Physics: 55 faculty, Astronomy: 20 faculty
CCAPP: 20 faculty, 10 postdocs from both departments
Placements: *In 2014 alone, 12 CCAPP alumni got permanent-track jobs*

ccapp.osu.edu

Recent faculty hires: Linda Carpenter, Chris Hirata, Annika Peter
Incoming faculty hires: Adam Leroy, Laura Lopez
Recent PD hires: M. Bustamante, A. Nierenberg, A. Ross, A. Zolotov
Incoming PD hires: K. Auchettl, J. Hanson, T. Linden

CCAPP Postdoctoral Fellowship applications welcomed in Fall