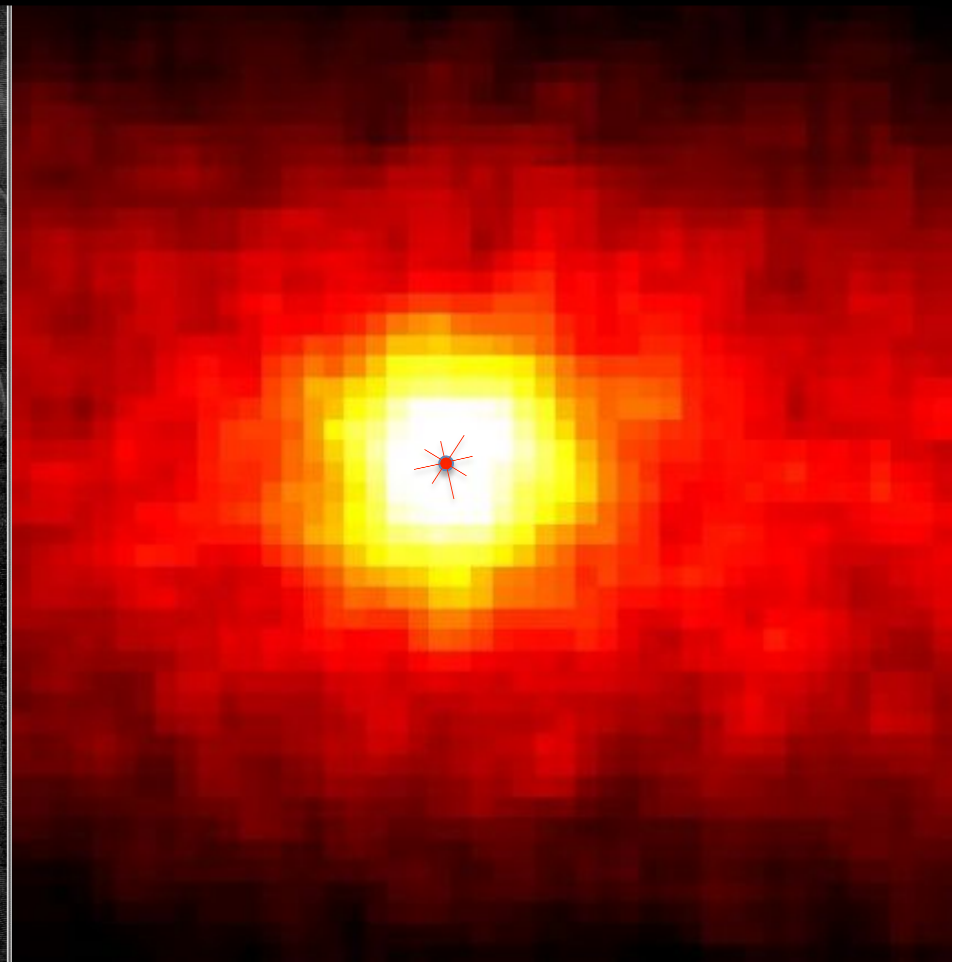
Neutrino Astronomy: No Longer a Dream

John Beacom, The Ohio State University



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

Topic: Impossible

~~High Energy Neutrino Astronomy~~

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

HE astrophysical neutrinos must exist

HE astrophysical neutrinos are detectable *(theorists' verse)*

HE astrophysical neutrinos are detectable *(experimentalists' verse)*

These detections probe astrophysics

These detections probe dark matter

These detections probe neutrinos

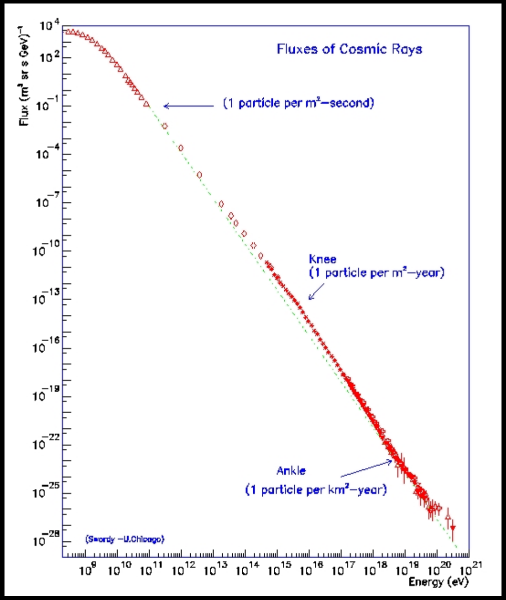
Neutrino astronomy is happening

HE astrophysical neutrinos must exist

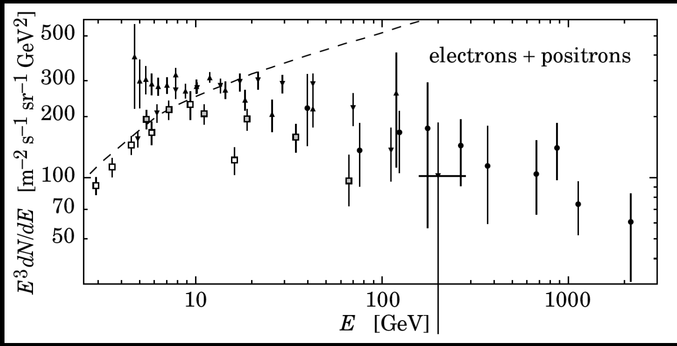
Energetic And Luminous CR Sources Exist

Charged cosmic rays first detected 100 years ago

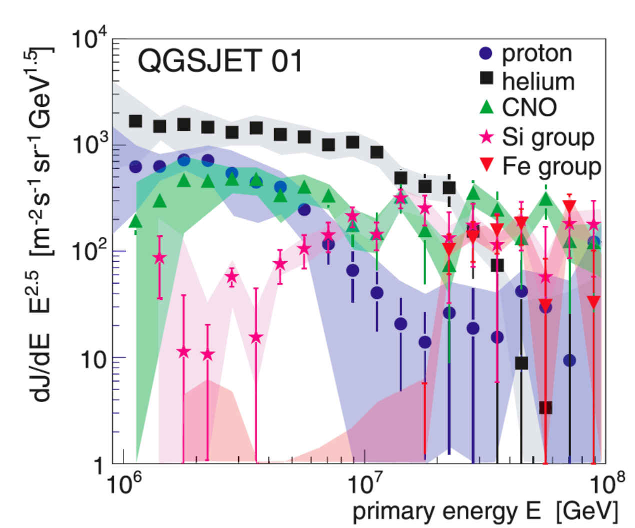
protons



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

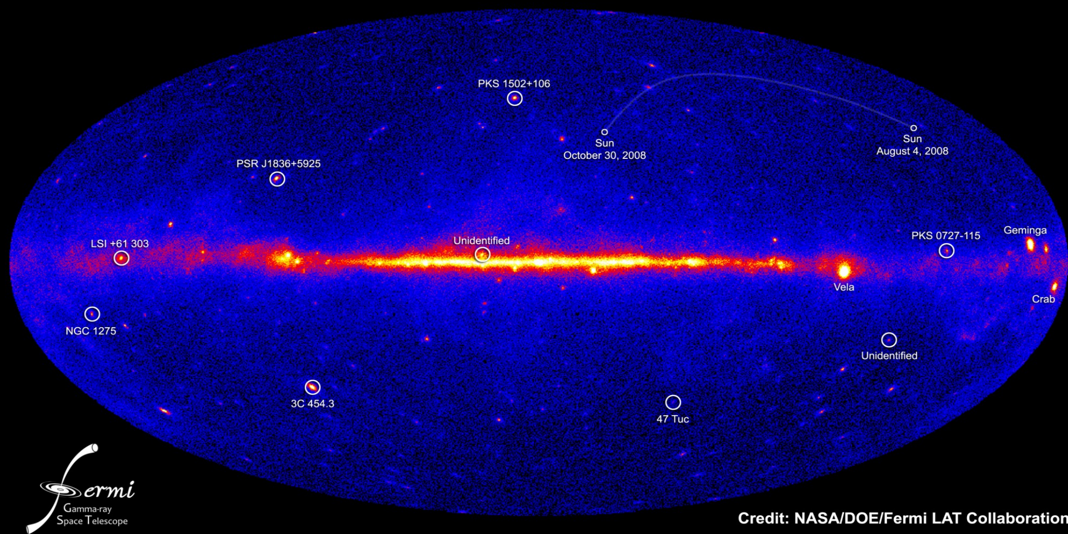
Nuclear (A*) mechanism $A' + \gamma \rightarrow A^* + X$

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

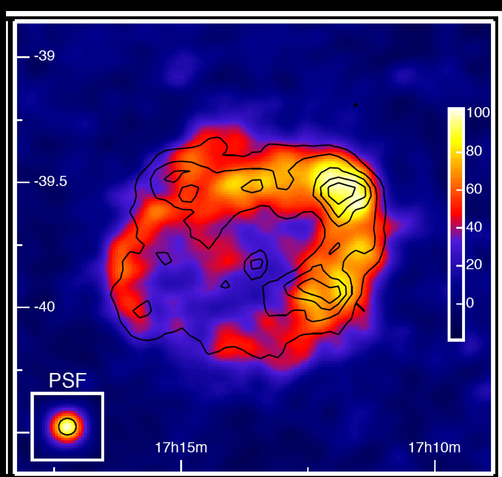
Exotic mechanisms unstable SM particle decays $\rightarrow \boxed{\gamma},\; \boxed{\nu}$

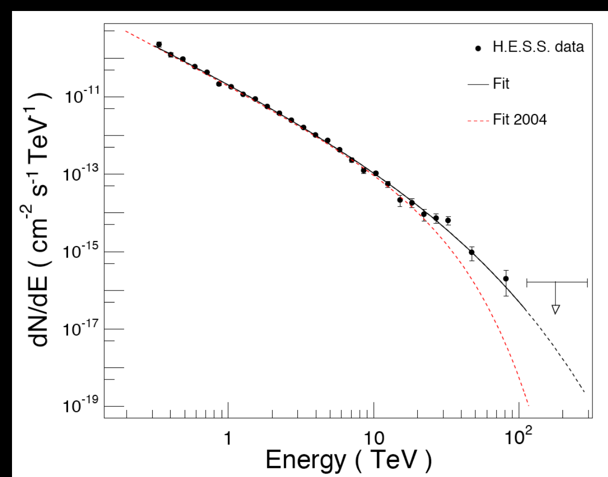
Production always makes a mess; propagation makes more

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.)

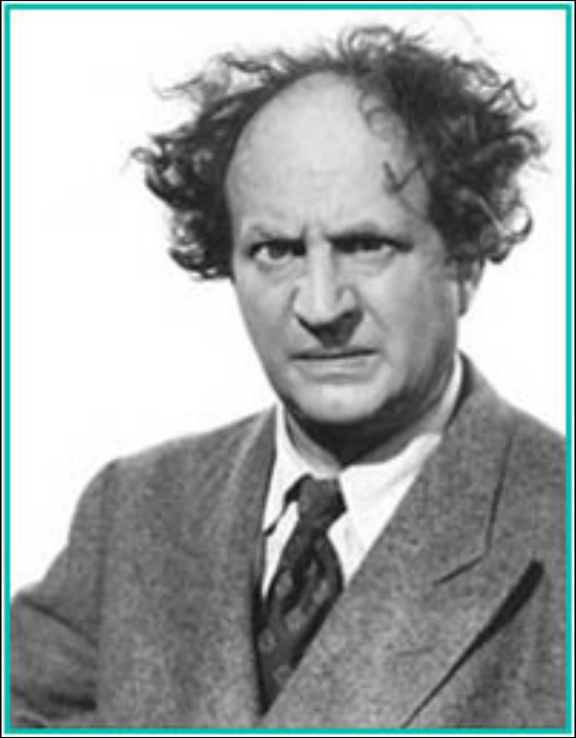
Now on a firm footing due to vastly better astrophysical data and decisive evidence from gamma-ray astronomy

- 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

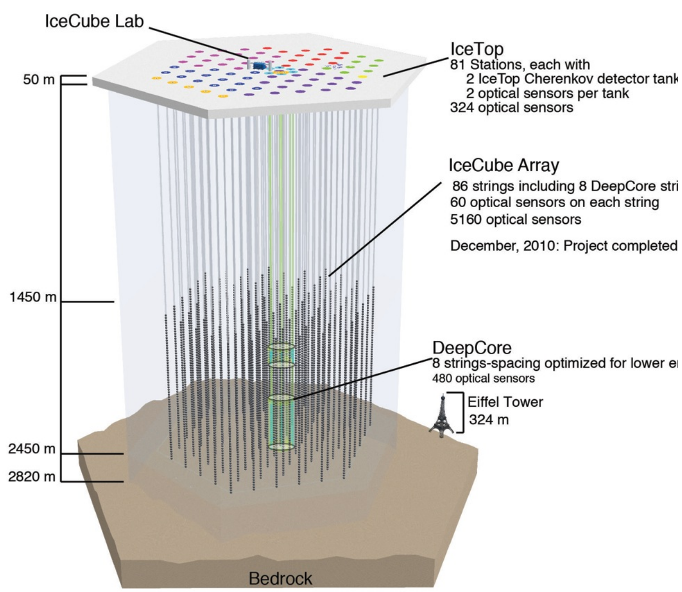
Time: excellent

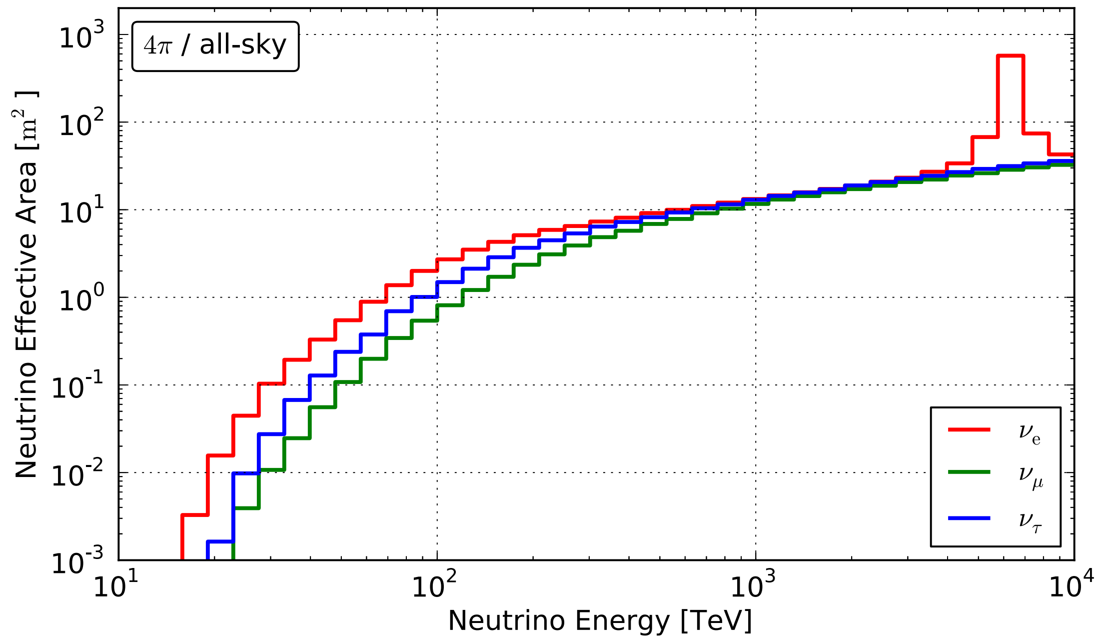
IceCube Is Big Enough To Succeed

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

Volume ~ 1 km^3

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



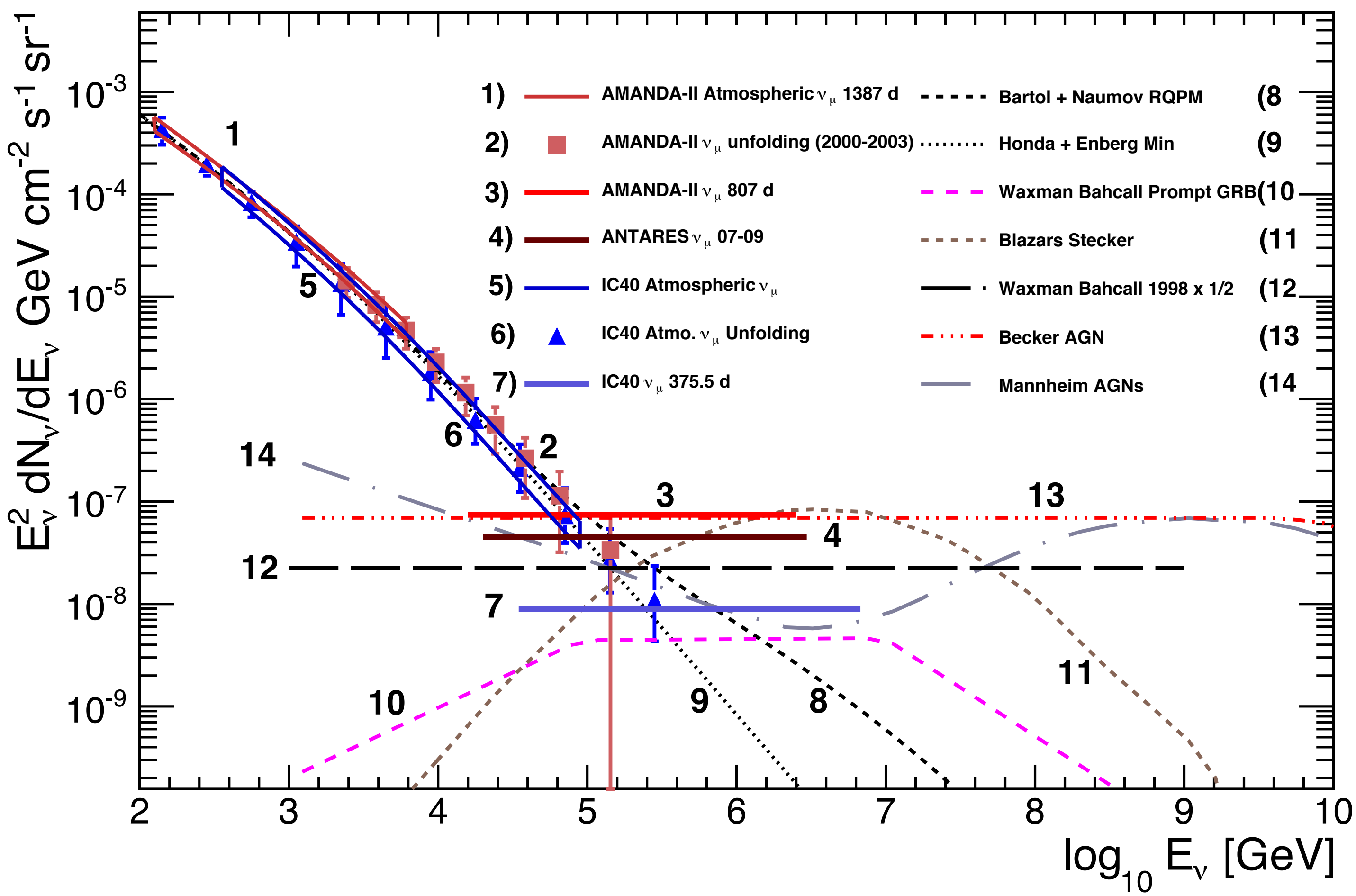


For many sources, ~ 1 km^3 is the minimum required

Second Difficulty: Rejecting Backgrounds

Atmospheric muons: enormous but greatly reducible *background*

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



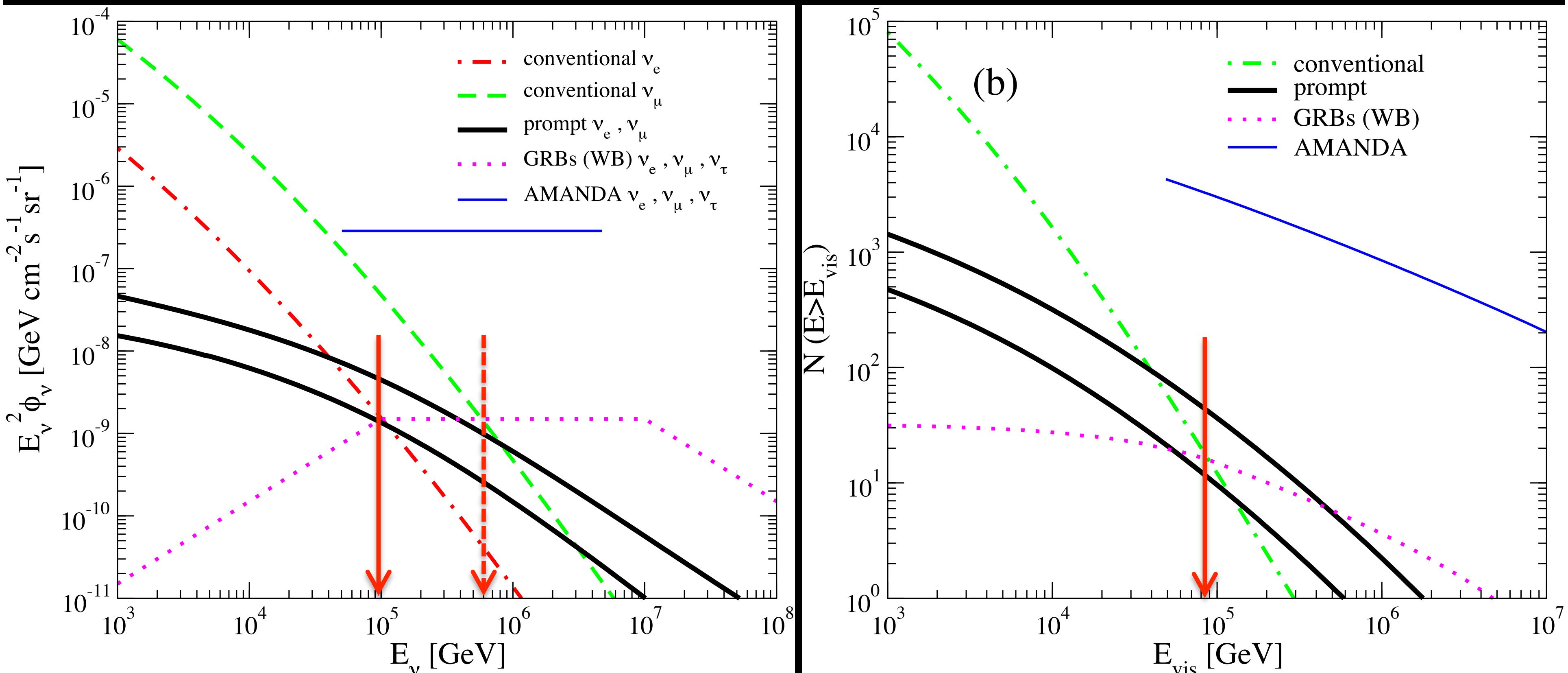
IceCube 2011:

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)

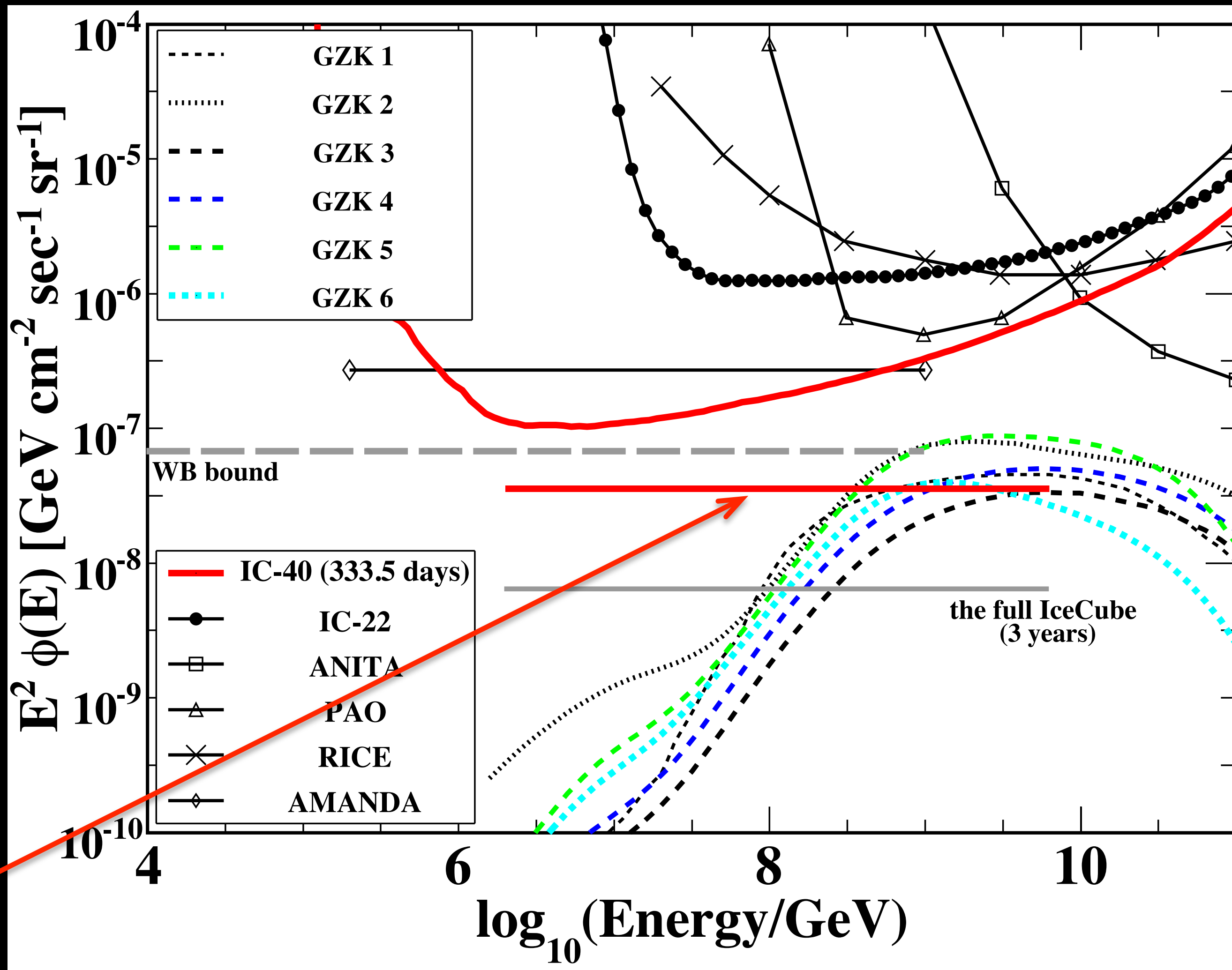
IceCube Search For UHE Neutrinos

Sensitivity to neutrinos from ultra-high-energy cosmic rays

Signal is very bright events induced by all neutrino flavors

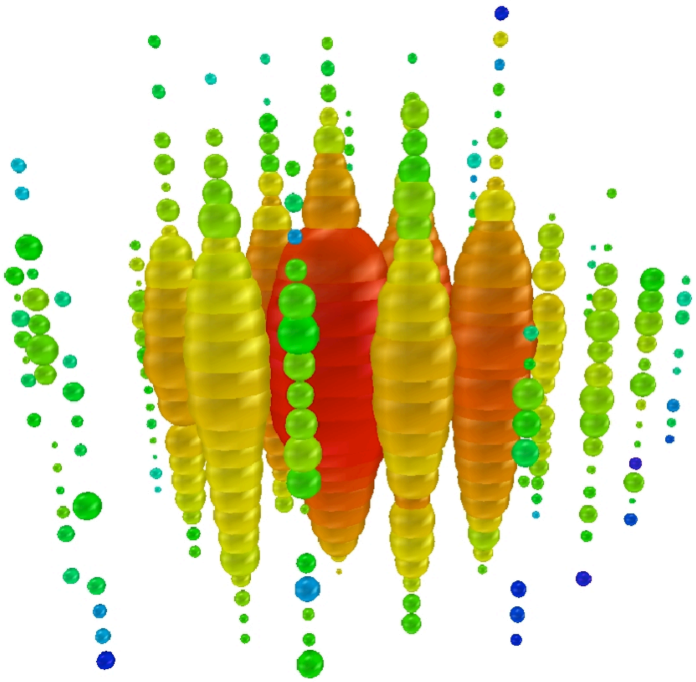
Backgrounds are due to muons and are low

IceCube 2011 upper limit



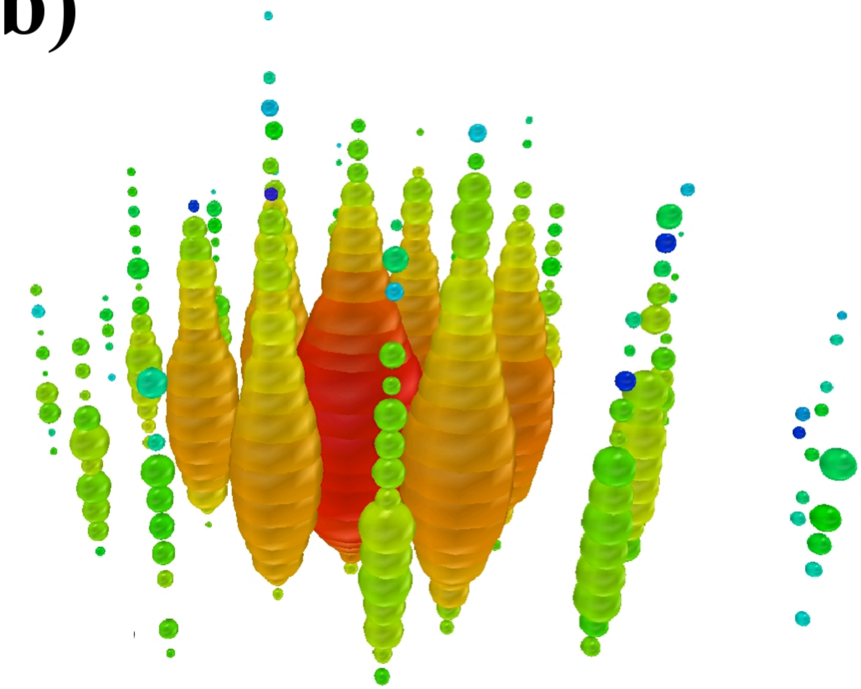
Who Ordered These?

(a)



2011: ~ 1 PeV cascade

(b)



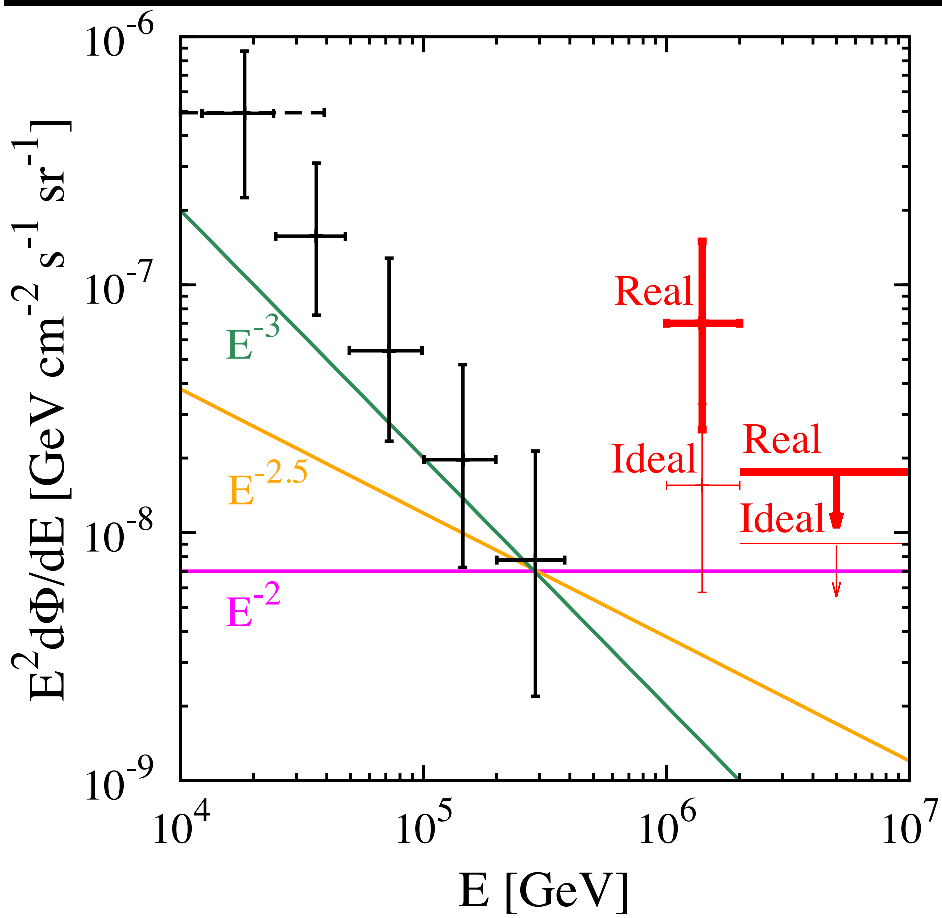
2012: ~ 1 PeV cascade

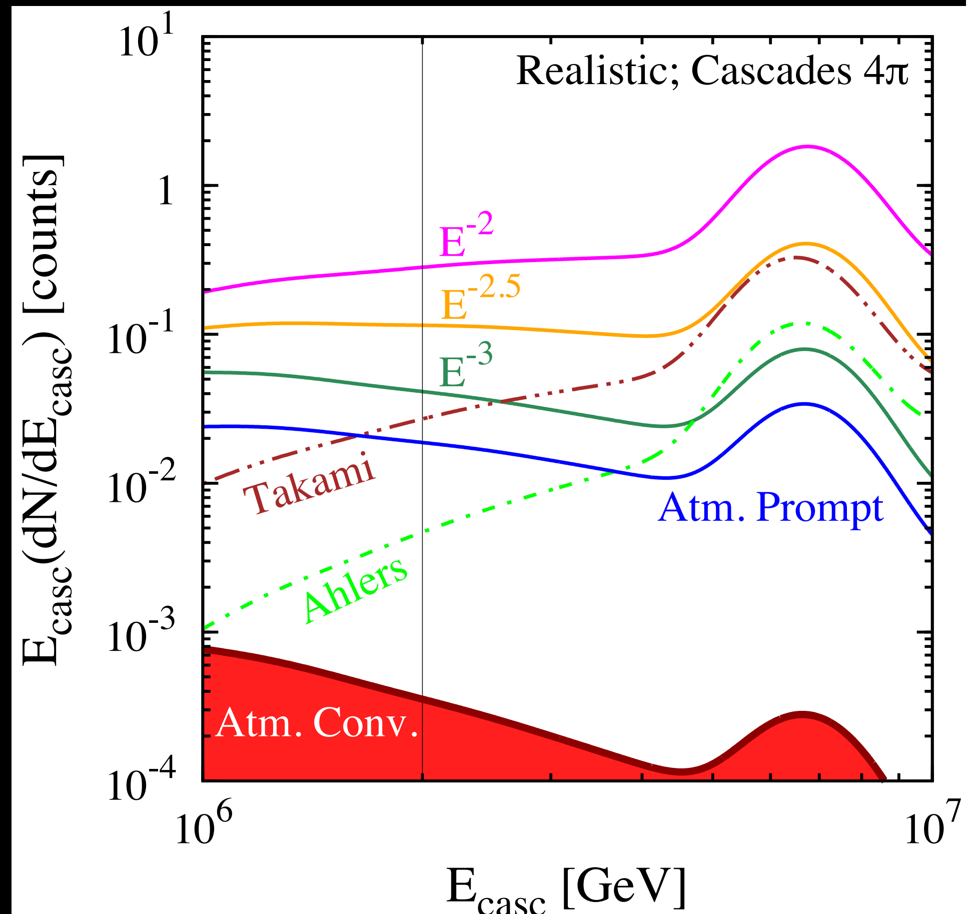
Great fortune in finding these events in this search (2013)

Many surprised by the details of the results

Demystifying The PeV Cascades

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

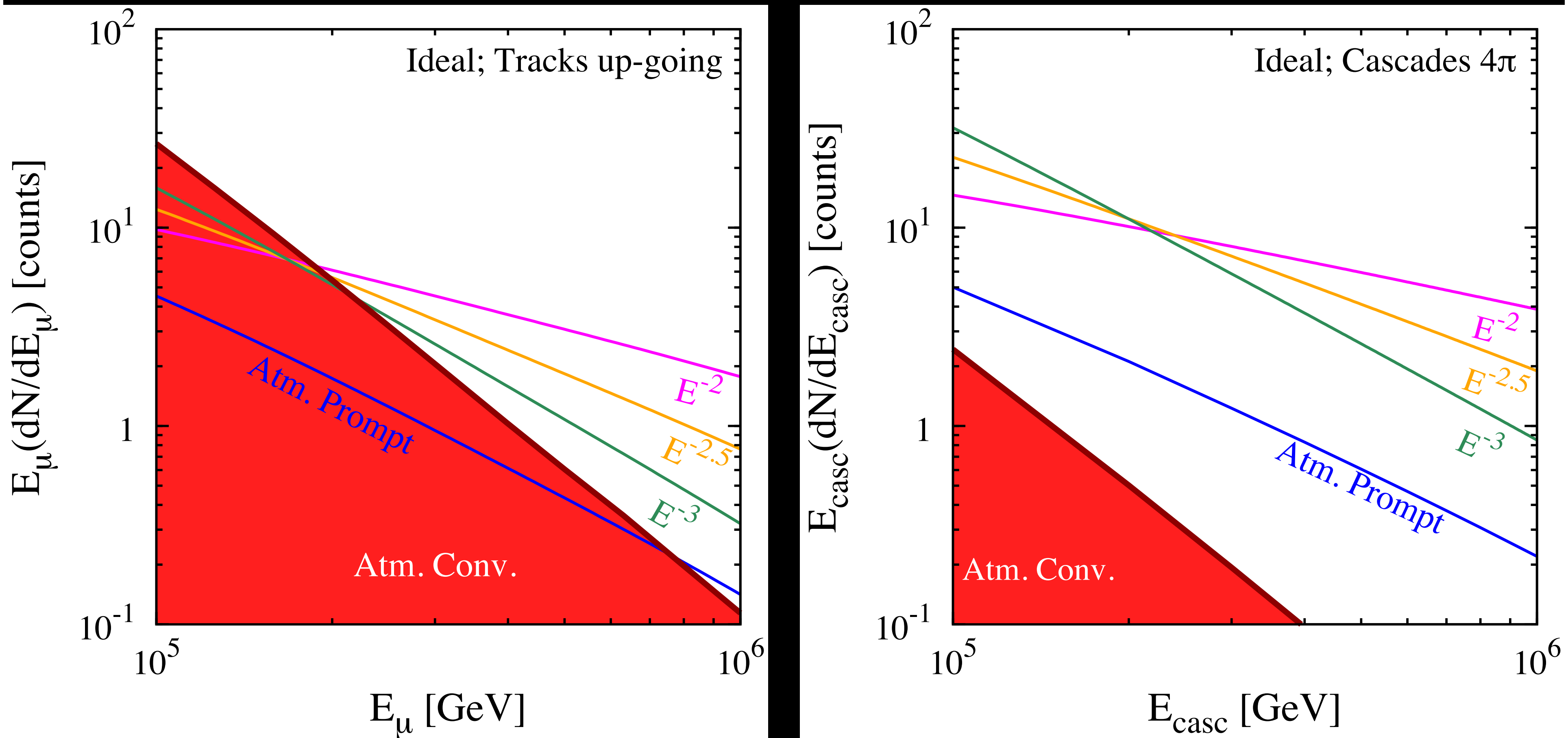




Mostly reasonable (IceCube has since changed inputs)

Less (Energy) Is More (Events)

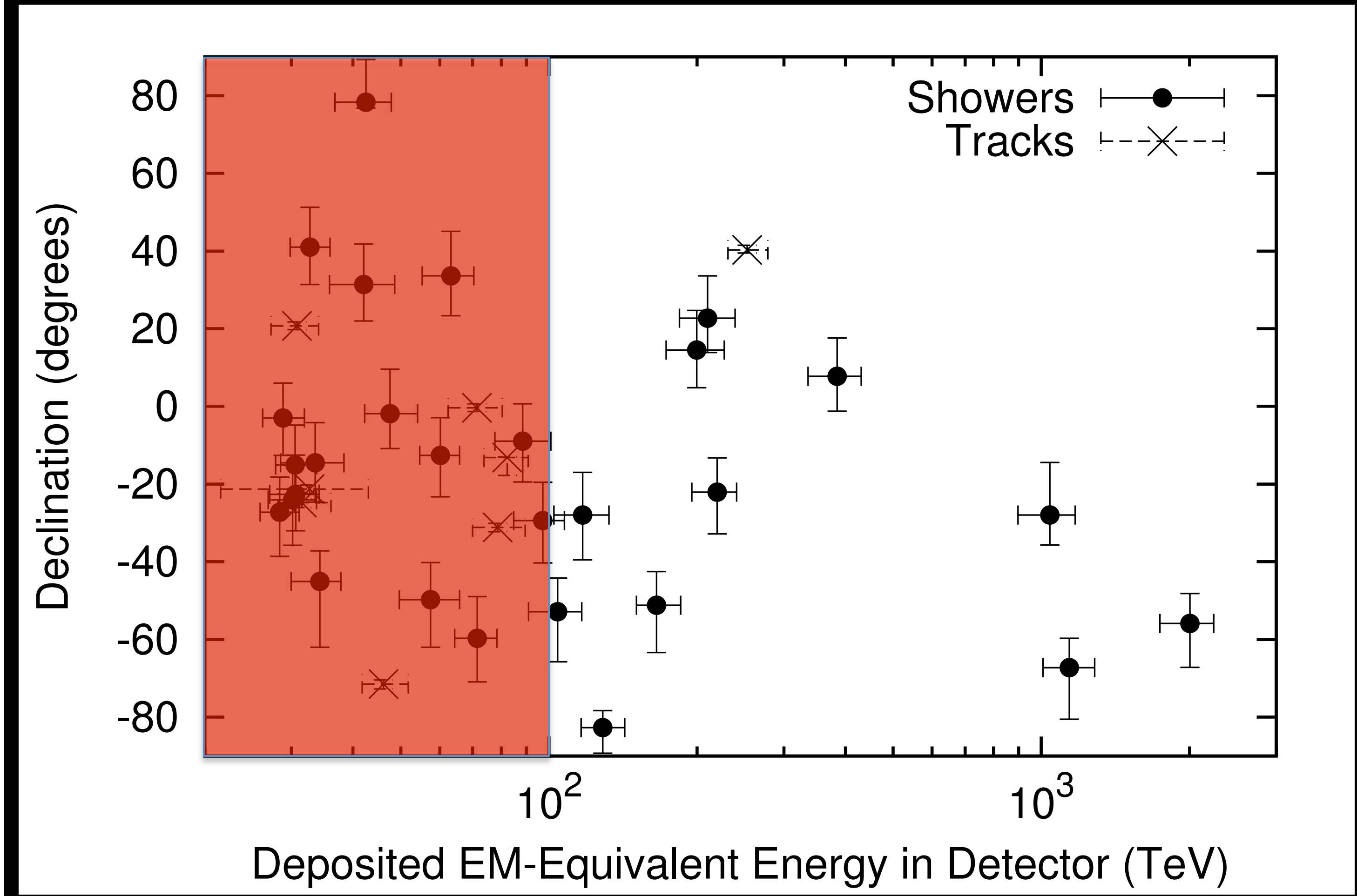
Quickest check of signal is at lower energies (Laha+ 2013)



Cascades have much lower backgrounds than muon tracks

Now Comes The Flood

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



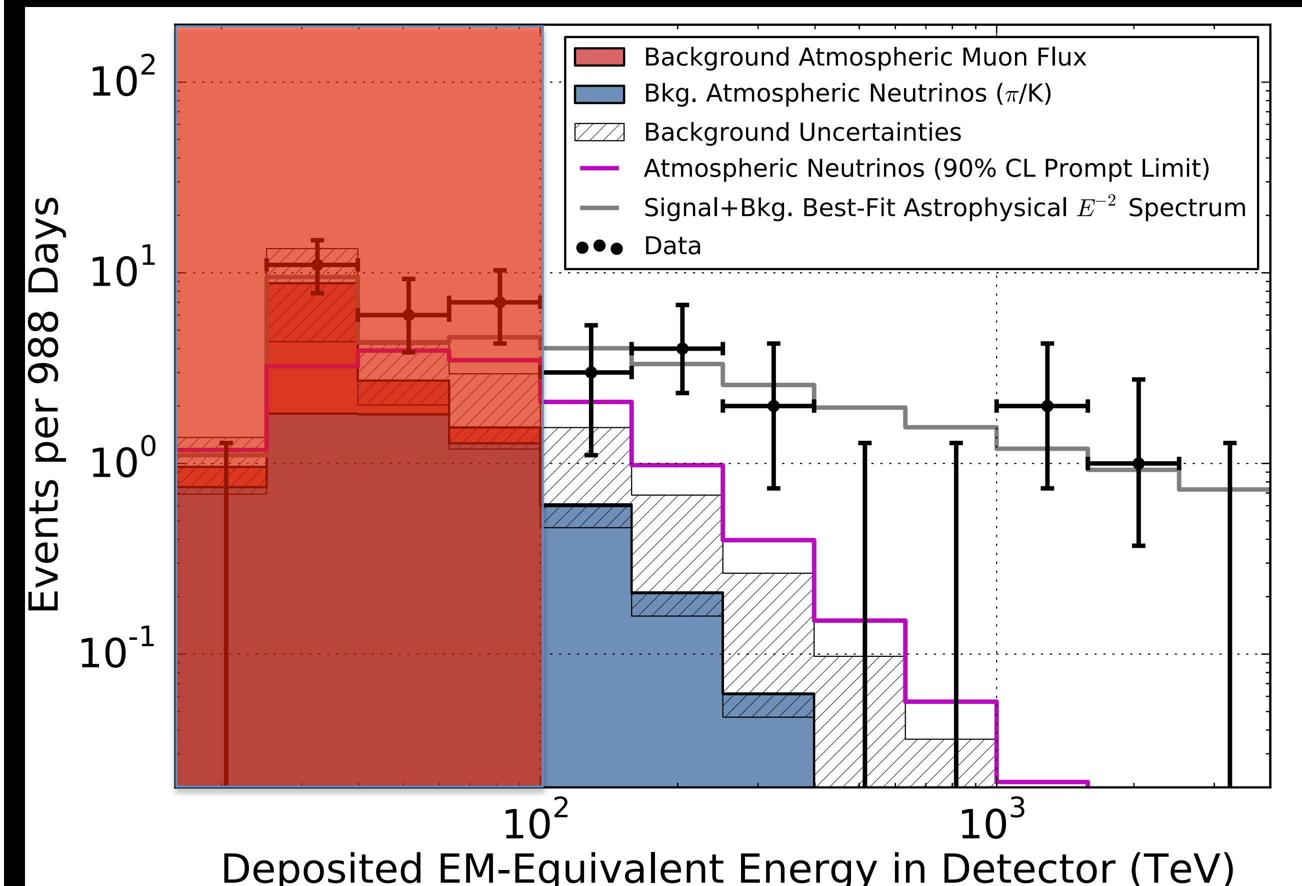
My opinion:
focus above 100 TeV on "Clean Dozen" events with negligible atmospheric backgrounds

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

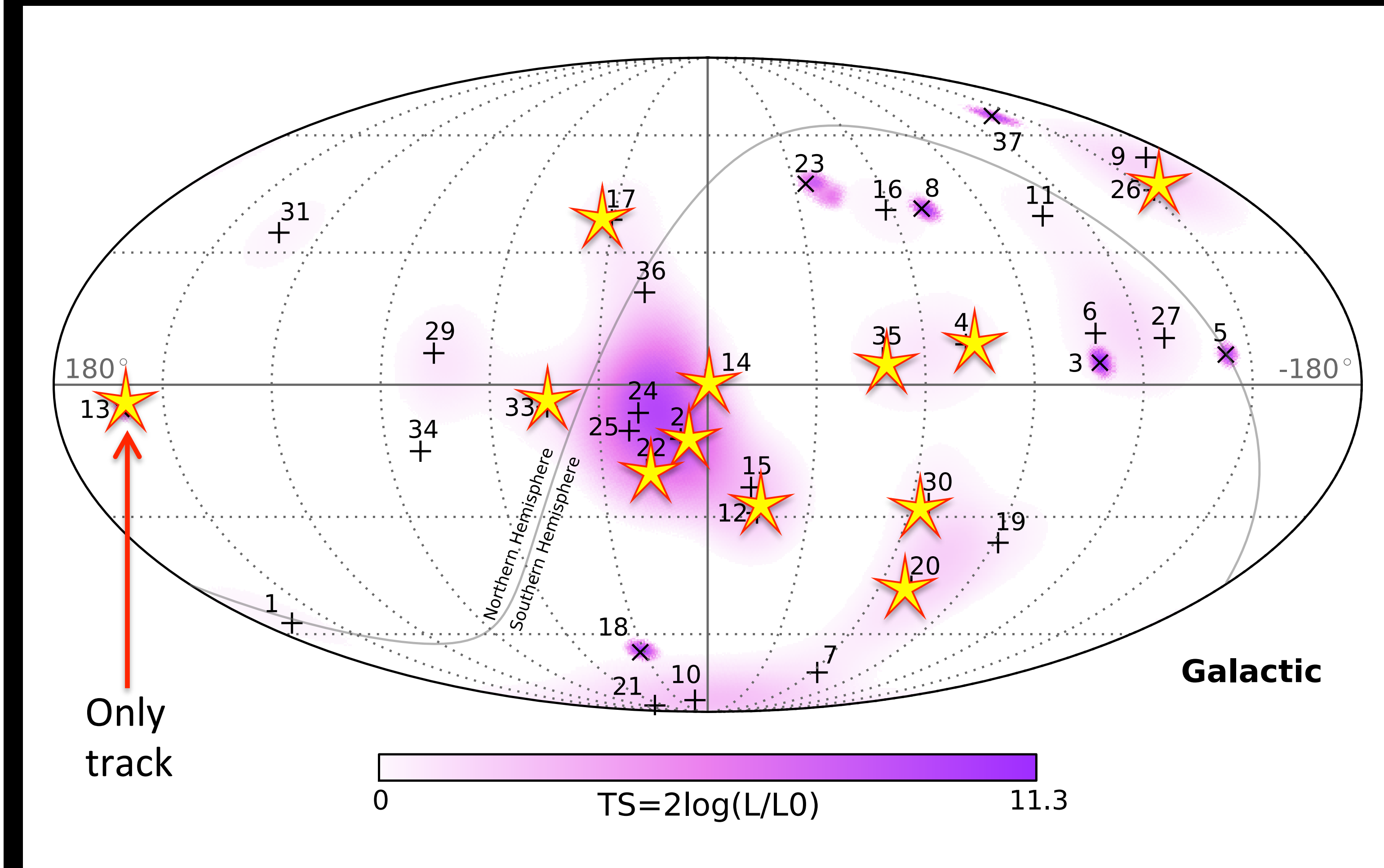


For "Clean Dozen" events, ignore the backgrounds shown because cascade channel dominates

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

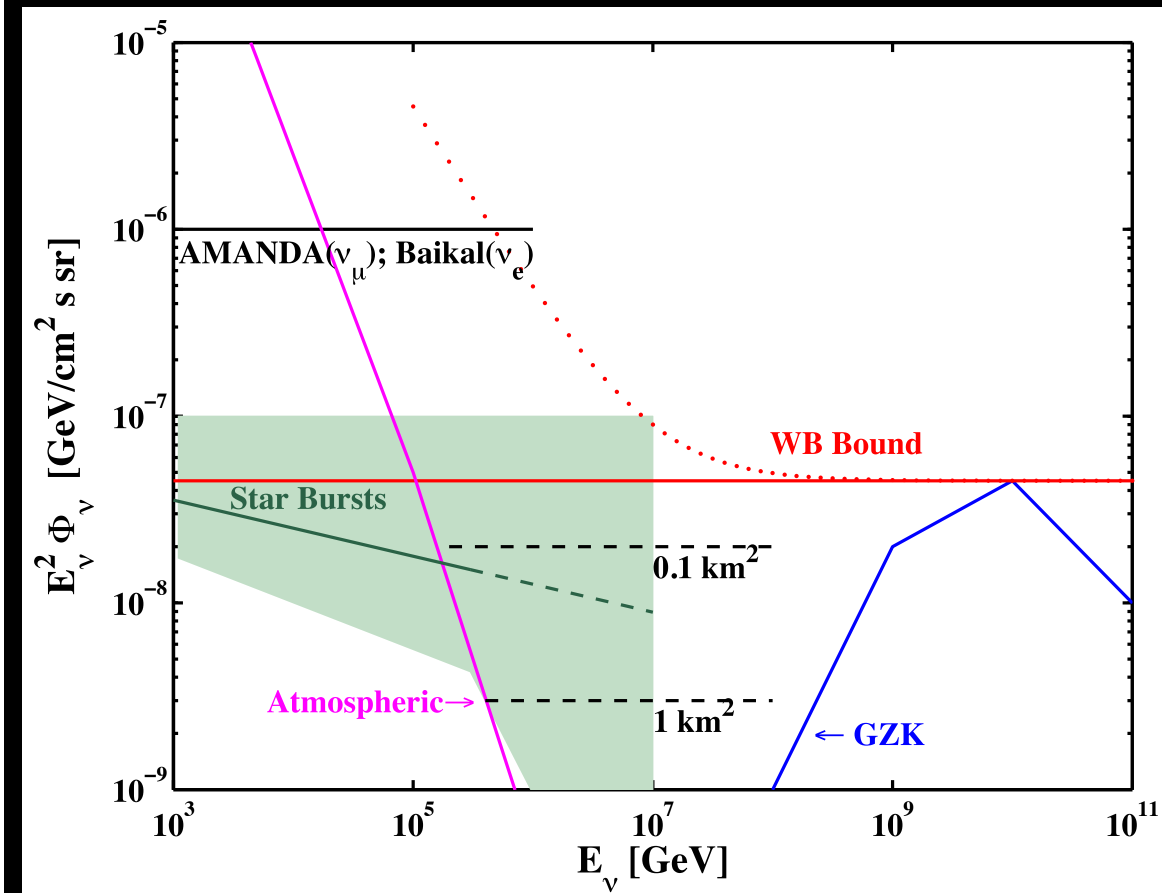
Flavor ratios: maybe consistent with 1:1:1, but a little weird
where are the muon tracks at high energy?

Time distribution: appears to be constant, not bursty

These detections probe astrophysics

What Sources Can Explain The Data?

Seemingly all models, especially with some post-data tweaks!



Loeb, Waxman 2006

One important example of a *predicted* model is starburst galaxies, which are likely to be a relevant component in any case

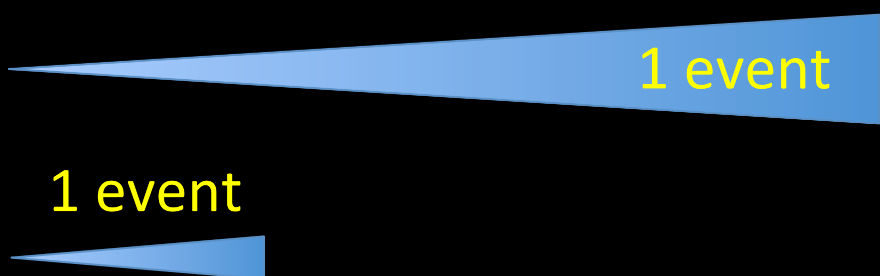
What key tests will distinguish between the many models?

Diffuse Versus Point Sources

Can there be associations with specific extragalactic sources?

For source types that do exist in the Milky Way, *No.*
Why? Because the Milky Way would far outshine the sky.

For source types that do not exist in the Milky Way, *Likely No.*
Why? Because of two effects:



versus all other directions

versus larger radii in cone

With such a small diffuse flux, any detectable point sources must be extremely luminous and rare, and hence not nearby

Many Promising Searches Ongoing

Milky Way gamma-ray sources

UHE cosmic ray sources

Active Galactic Nuclei

Gamma-Ray Bursts

Galaxy clusters

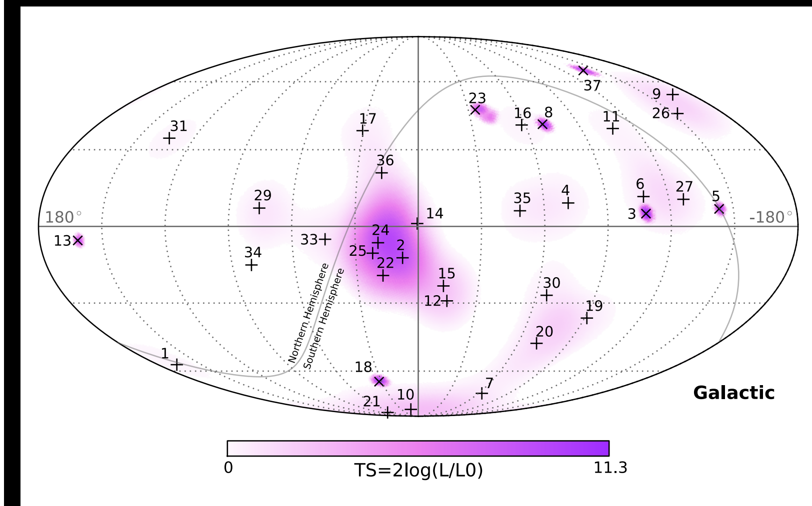
Dark matter

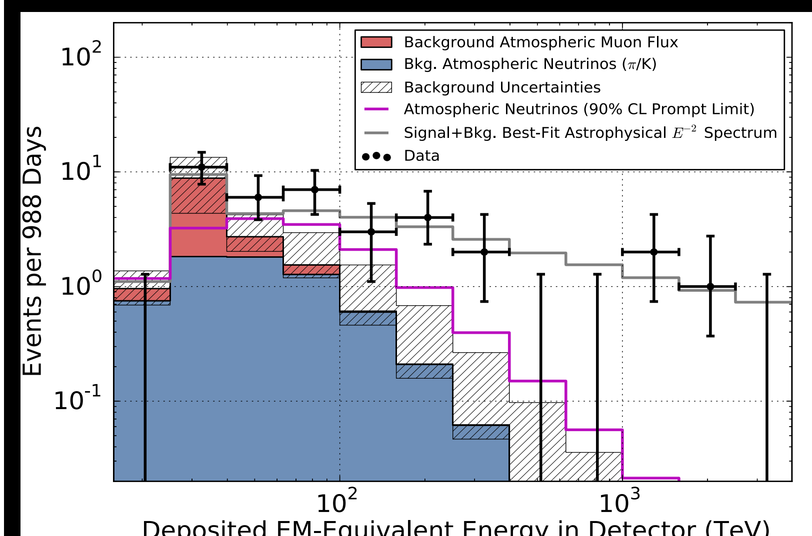
?

These detections probe dark matter

Dark Matter Decay

DM may decay (slowly), but there is no predicted lifetime





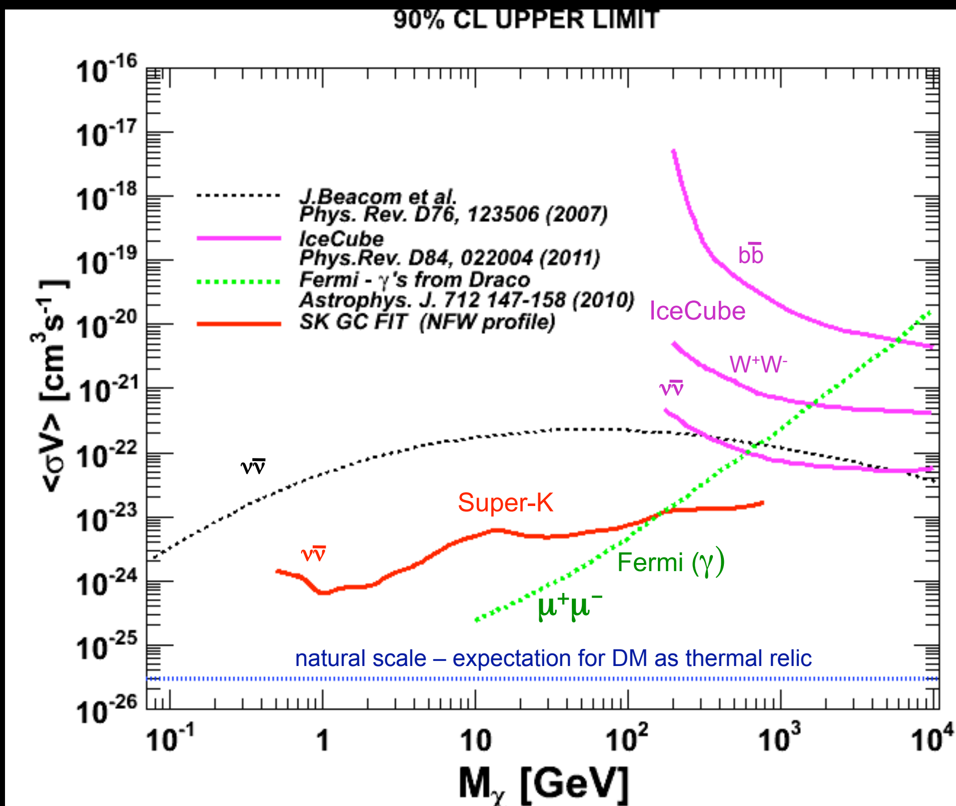
Excitement that DM decay may explain Galactic Center peak and spectrum dip (Feldstein+ 2013; Esmaili+ 2013; Bai+ 2013; Ema+ 2014; Bhattacharya+ 2014)

Re-examination is needed using new IceCube data, care with other neutrino, gamma-ray cascade limits (Murase, Beacom 2012; Ibarra+ 2013)

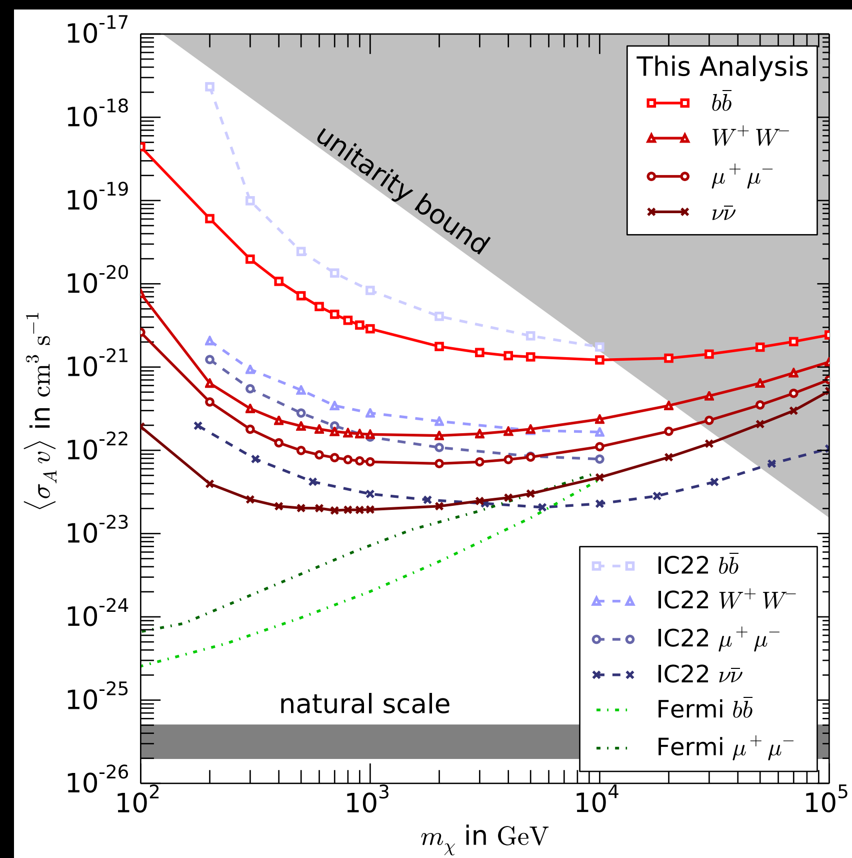
Dark Matter Annihilation

DM likely should annihilate with a predicted cross section

First use of neutrinos to probe halo DM by Beacom+ 2006



P. Mijakowski, Super-K preliminary 2012



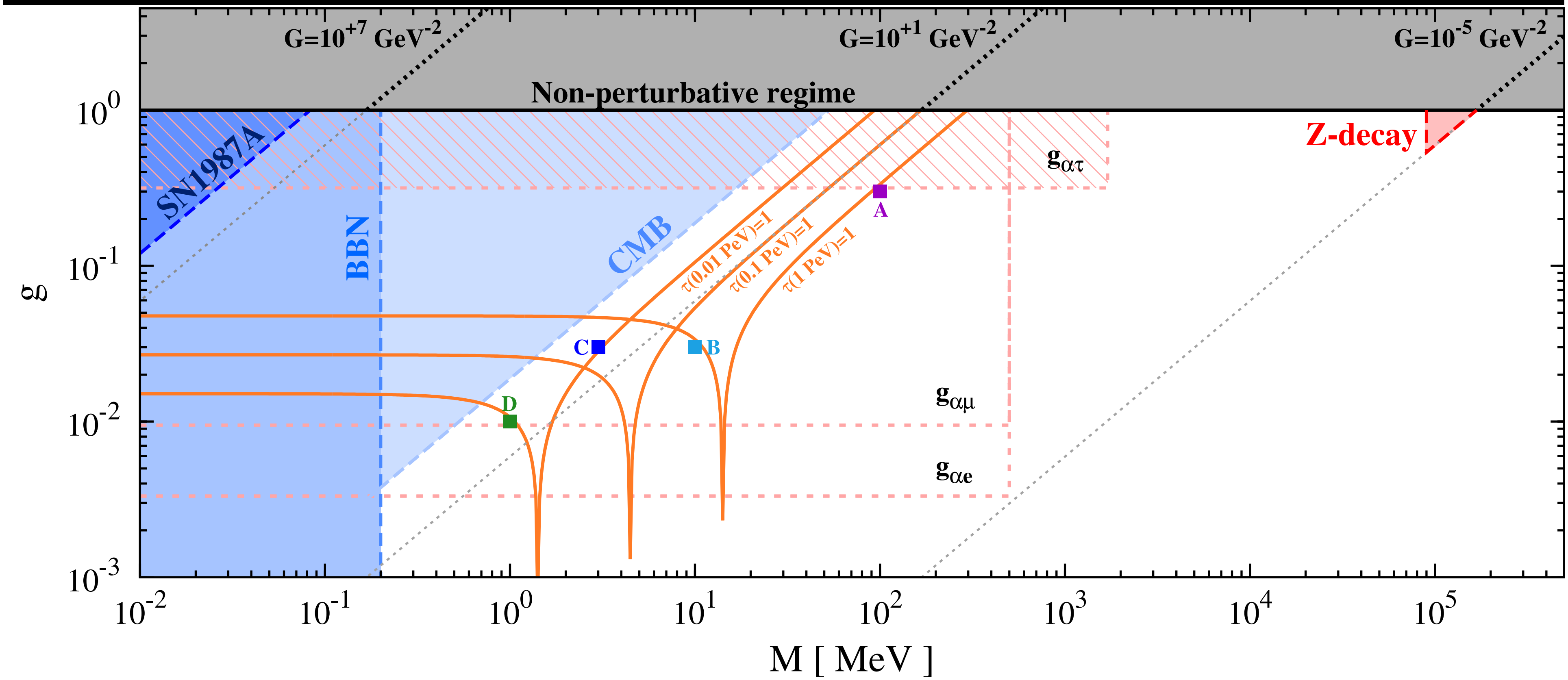
IceCube 2014

These detections probe neutrinos

Neutrino Properties Beyond Laboratory Reach

New extremes of distance, energy, environment powerfully test neutrino mixing, decay, LIV, interactions, etc.

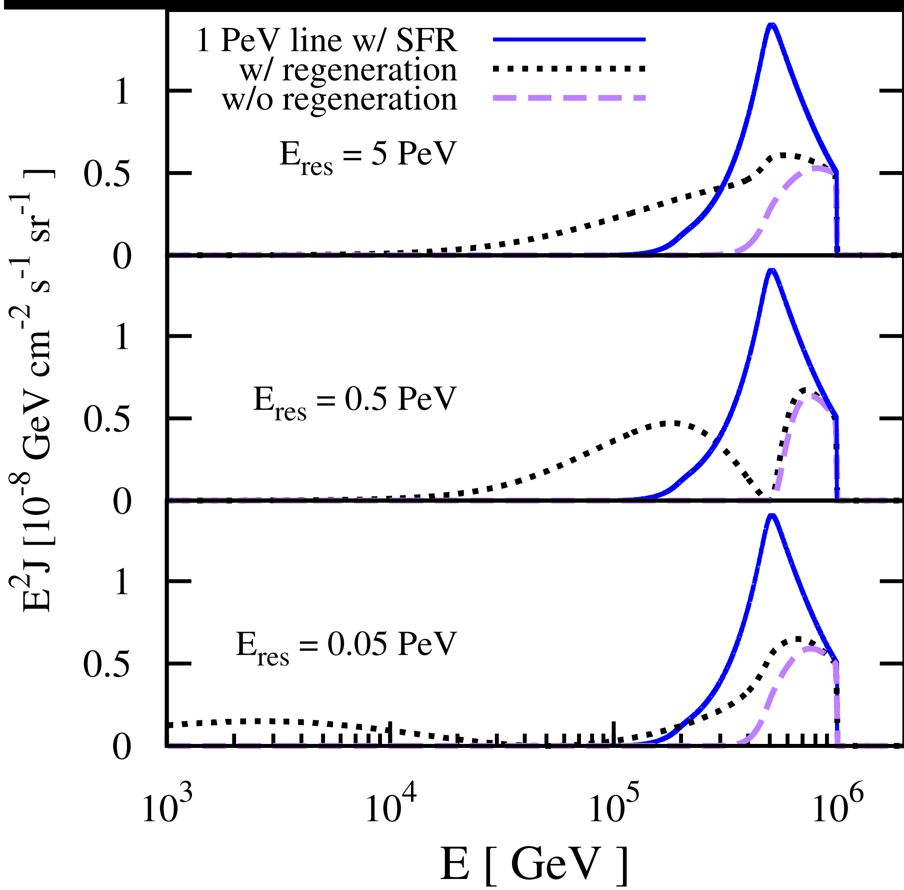
What about $\nu+\nu \rightarrow \nu+\nu$? (Ng, Beacom 2014; Ioka, Murase 2014)



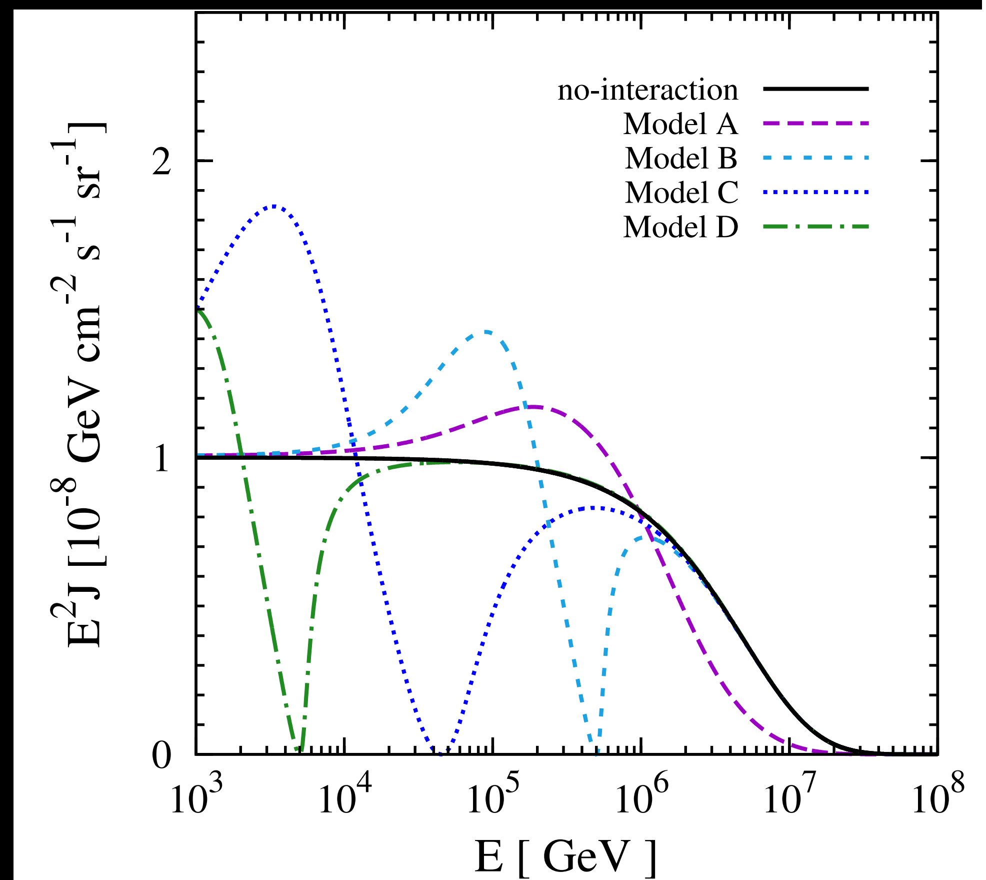
Effects Of Neutrino Secret Interactions

Must include attenuation, regeneration, multiple scattering

Line spectrum injection



Continuum spectrum injection



Variety of distortions possible; cascades are best channel

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 Astronomy Must Be Broad

MeV: Thermal Sources

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

TeV: Non-thermal Sources

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

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

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: *this year alone, 12 CCAPP alumni got permanent-track jobs*

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Recent faculty hires: Linda Carpenter, Chris Hirata, Annika Peter
Incoming faculty hires: Adam Leroy, Laura Lopez
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CCAPP Postdoctoral Fellowship applications welcomed in Fall