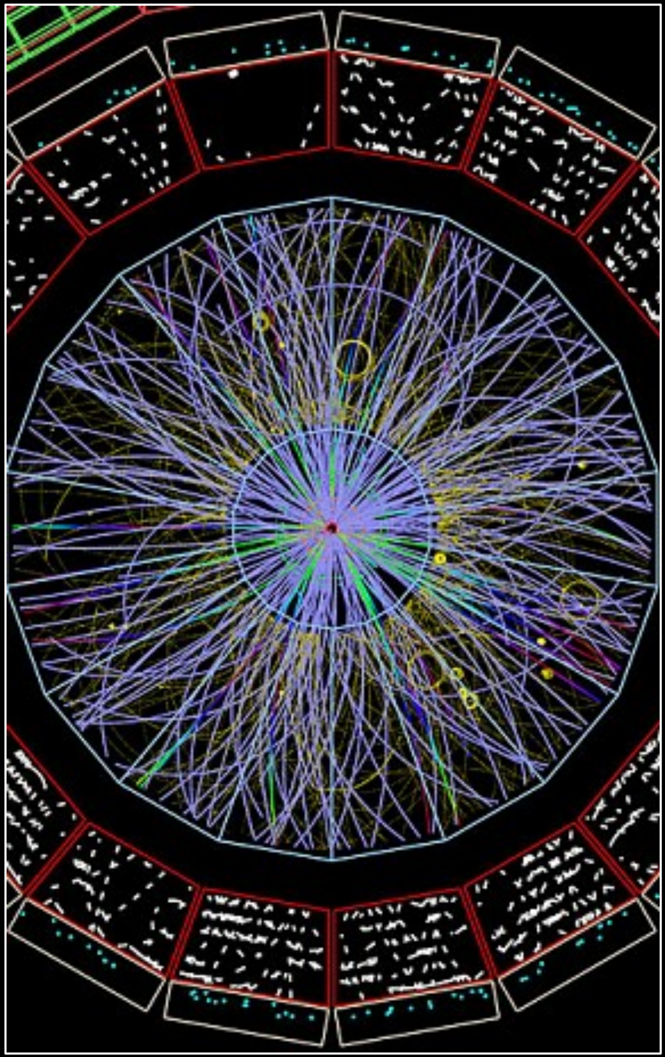
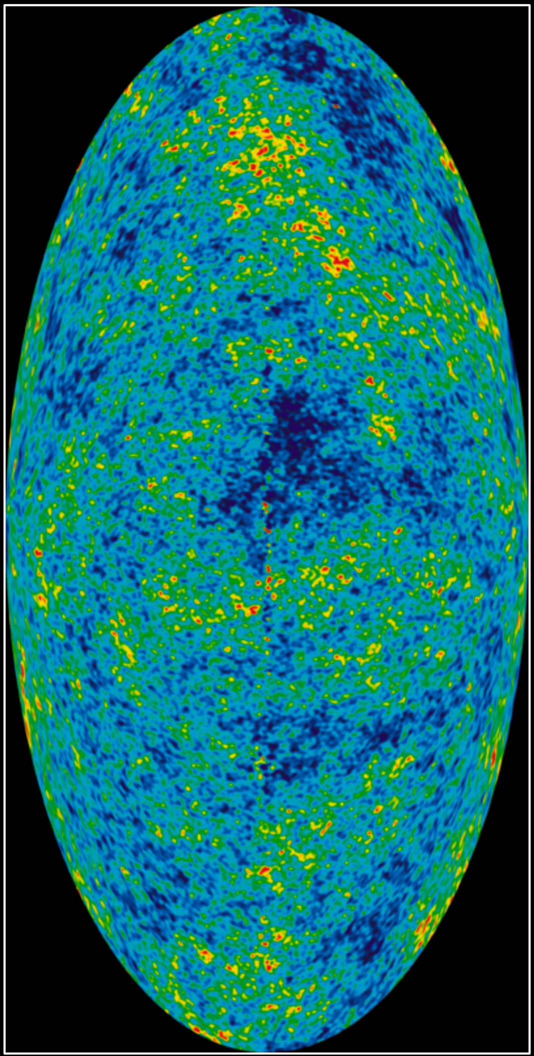
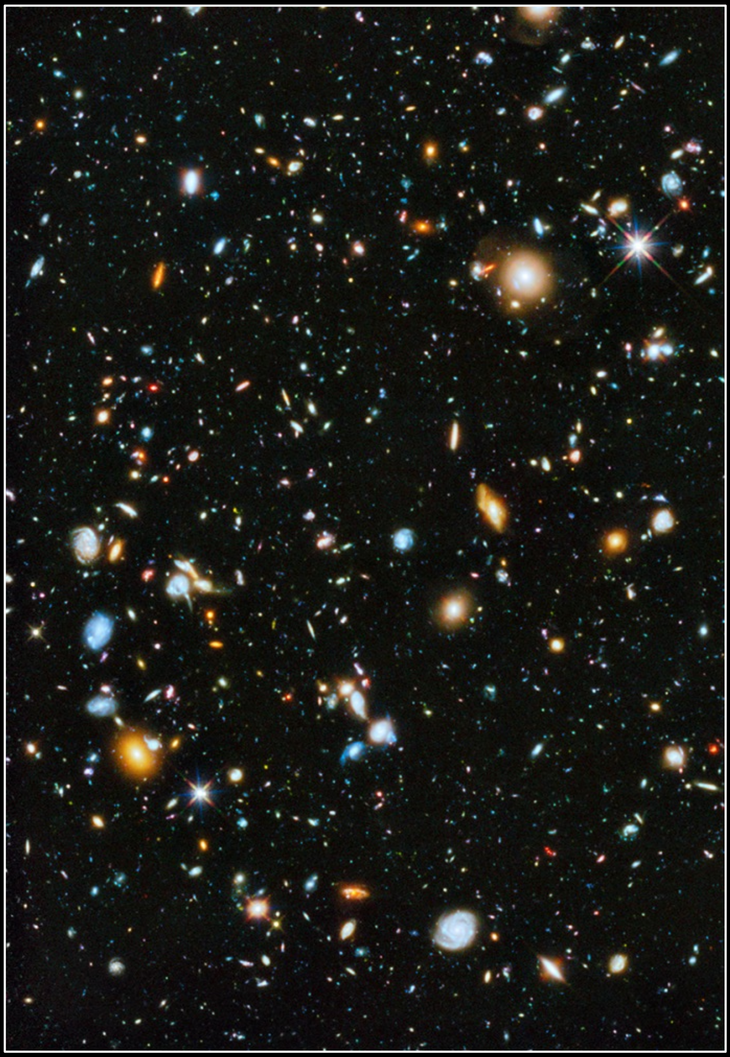
Discussion: Focus of Next-Generation Experiments

John Beacom, The Ohio State University







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

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Neutrinos — What's So Special?

Neutrinos – In the Laboratory

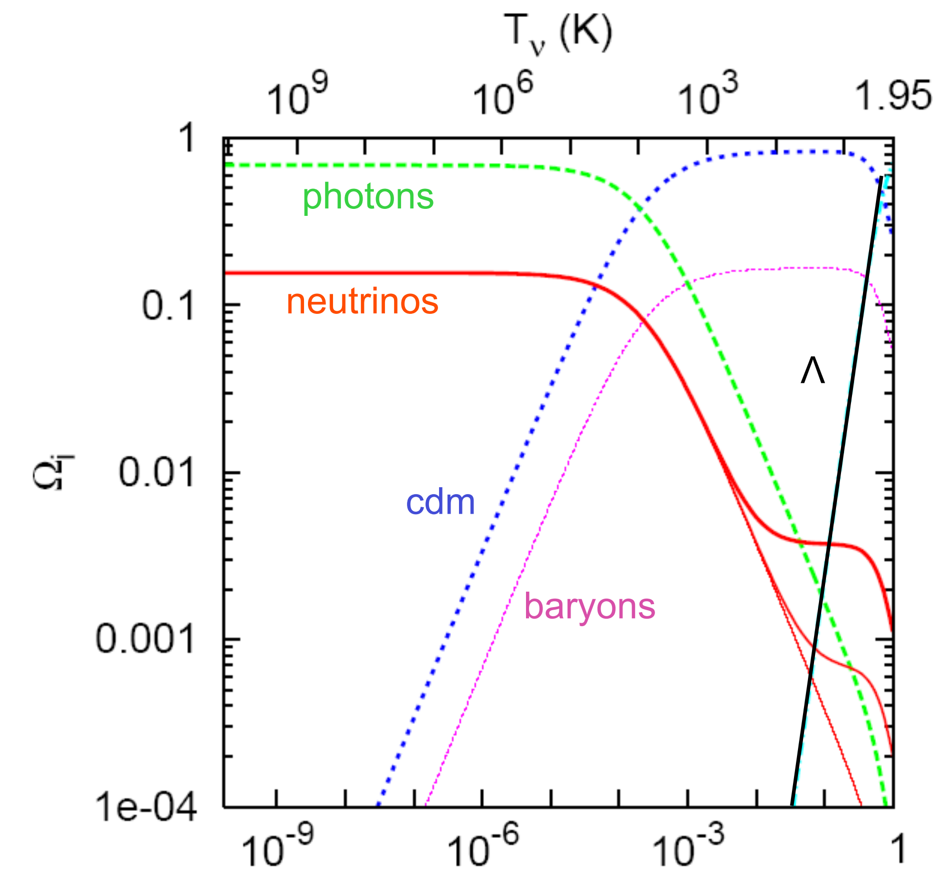
Interactions are feeble

Masses are infinitesimal

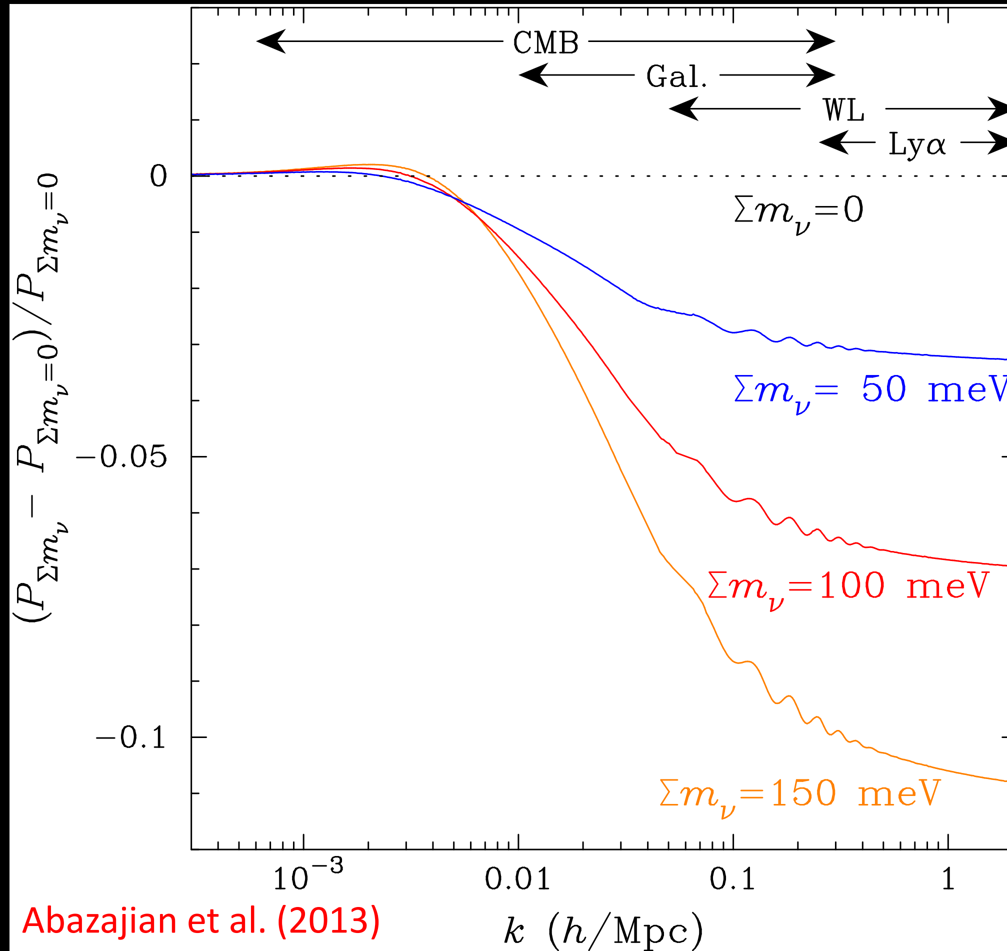
Decays are suppressed

Mixing is large

Neutrinos – In Cosmology



Lesgourges and Pastor (2012)



Abazajian et al. (2013)

Important part of radiation

Important part of dark matter

Neutrinos – In Astronomy

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

The Neutrino LCA-PCA Mixing Matrix

Methods \ Goals	Particle Physics	Cosmological Physics	Astro-Physics
Neutrinos – Laboratory	measure neutrino properties, interactions	predict neutrino cosmic constituents, clustering	predict effects on astro neutrino emission, propagation
Neutrino Cosmology	test for new particle properties, interactions, constituents	measure neutrino radiation, dark matter, clustering	predict expected sources, clustering of dark matter
Neutrino Astronomy	test for new particle properties, interactions	test for new sources, nature of dark matter	measure origins of cosmic rays, nature of gamma sources

Neutrino Astronomy — Why Try?

Impossibility of 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

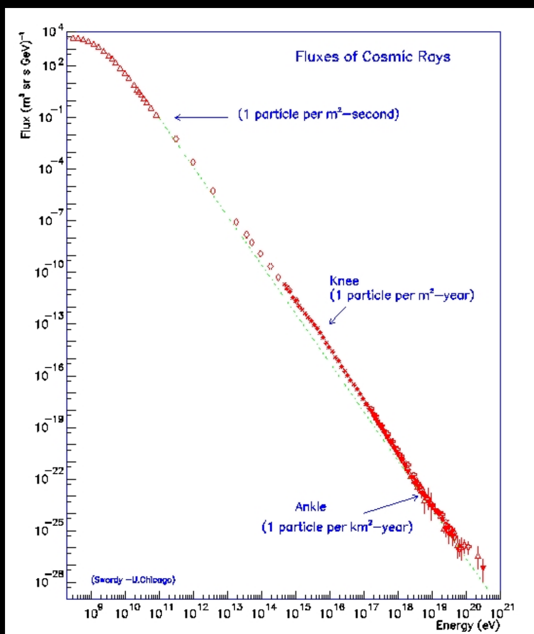
Our part

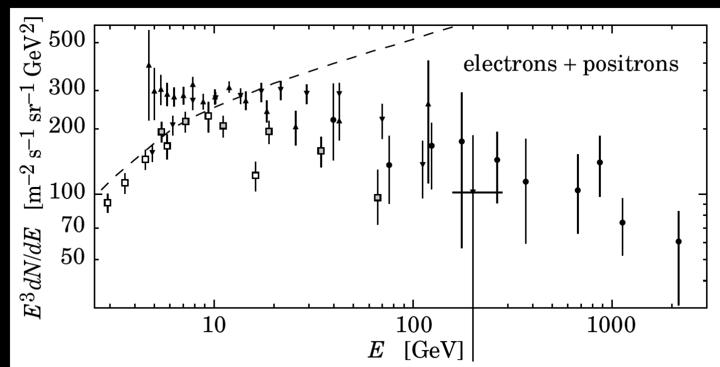
With neutrinos, we think we can do it all

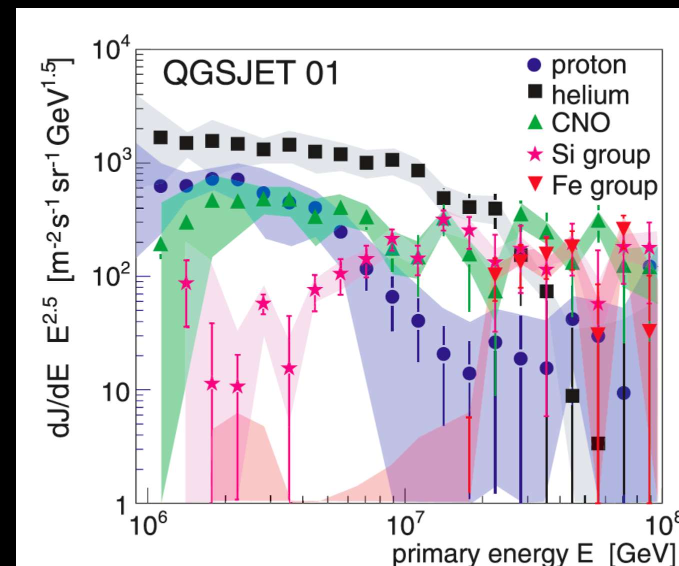
Energetic and Luminous CR Sources Exist

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

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

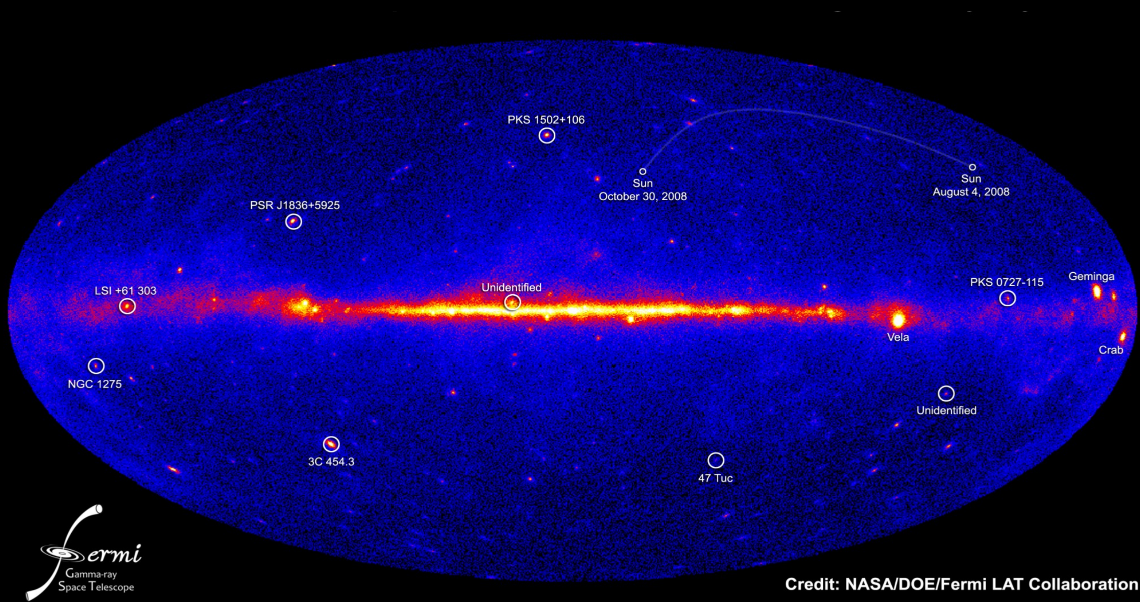
$$A^* \rightarrow A + \boxed{\gamma}$$ and some $\boxed{\nu}$

Exotic mechanisms

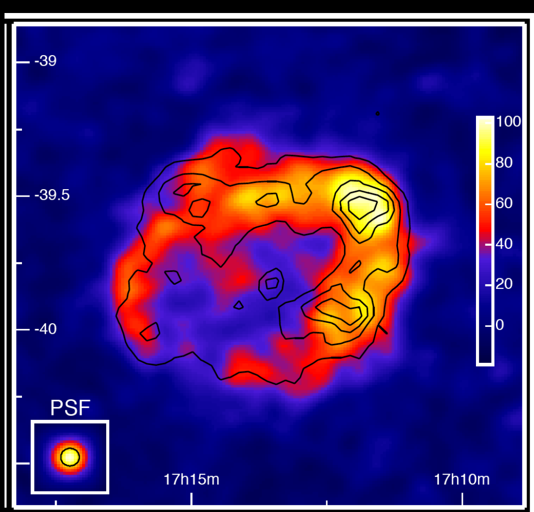
unstable SM particle decays $\rightarrow \boxed{\gamma}, \boxed{\nu}$

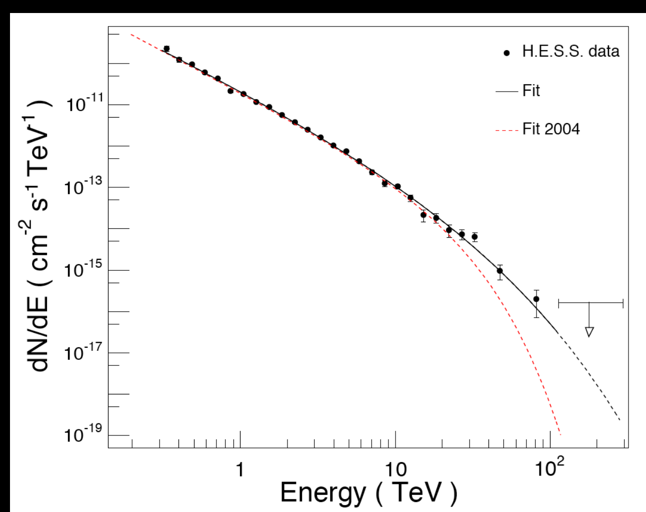
Production always makes a mess; propagation makes more

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 greatly strengthened and directed by gamma-ray data

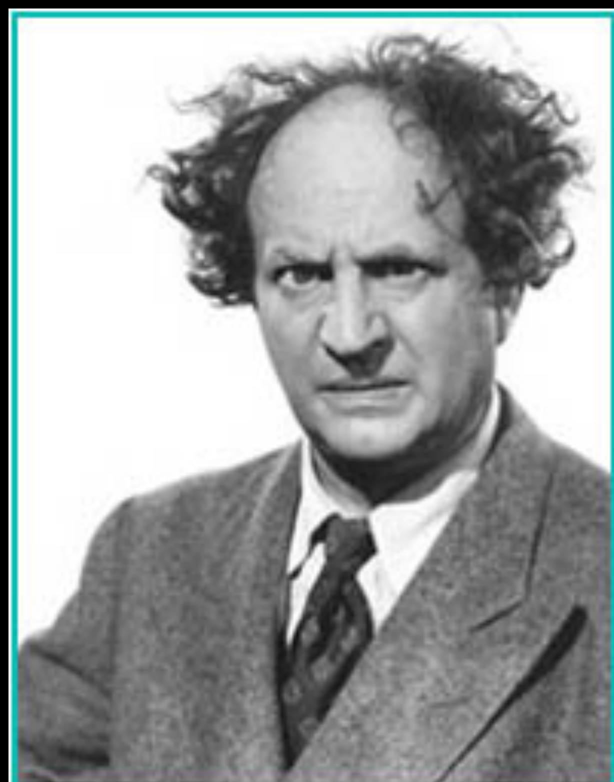
Leptonic sources: versus Hadronic sources:

$$\Phi_\nu \sim 0 \qquad\qquad \Phi_\nu \sim \Phi_\gamma$$

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

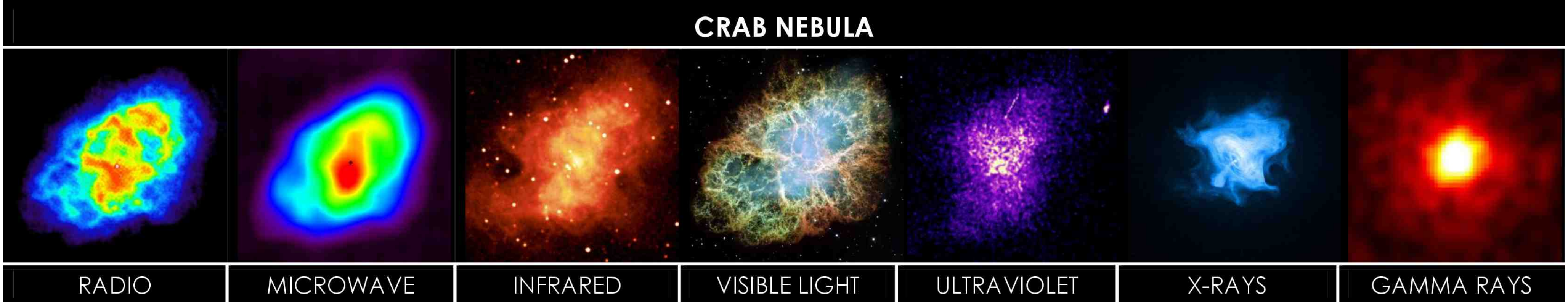
cosmic rays	gamma rays	neutrinos
energetic	direct	revealing
divertable	stoppable	untrustworthy?



Neutrino Astronomy — How To Try?

First Goal: New Astrophysics

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



Example successes: solar and SN neutrinos; IceCube 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*

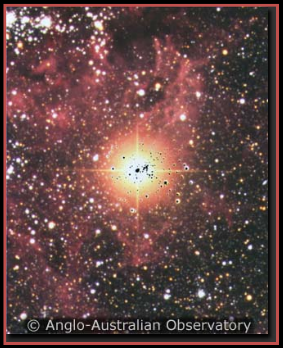
Example successes: neutrino mixing; confirm weak interations
Example searches: neutrino exotica; dark matter

Third Goal: New Surprises

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

Example successes: supernova trigger; CR anisotropies
Example searches: unknown unknowns!

Neutrino Astronomy Must Be Broad



MeV: Nuclear-Physics Sources

GADZOOKS!

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

What We Know and Don't Know

What We Know: Fundamental Points

Experiment: We have the technology, working in many forms

Observation: We have clear detections up to PeV energies

Auxiliary: We have precise supporting data

Theory: We have reachable goals, appropriate uncertainties

The situation is incredibly different now than earlier

What We Know: Specifics

Energy Range: VHE but not UHE

Distance: Extragalactic, maybe Galactic

Classes: At least one, but unknown what

Variability: Steady, no transients

Solutions: Nothing yet

This is not yet neutrino astronomy

What We Want To Know (Dream Version)

Energy Range: From MeV to TeV to ZeV

Distance: Galactic to galactic to cosmic

Classes: 17

Variability: Steady, fluctuating, explosive

Solutions: Cosmic rays, gamma rays, dark matter, surprises

Success will make it neutrino astronomy

Focusing Our Goals

Concept: Proposed Charge

Make neutrino astronomy a rich and broad-based, of leading importance to several fields of physics and astronomy

Concept: Take Better Actions

Barwick-Beacom work on APS Neutrino Study (2004)

A.6 Executive Summary of the Neutrino Astrophysics and Cosmology Working Group

PARTICIPANTS: *B. Balantekin, S. Barwick, J. Beacom, N. Bell, G. Bertone, D. Boyd, L. Chatterjee, M.-C. Chen, V. Cianciolo, S. Dodelson, M. Dragowsky, J.L. Feng, G. Fuller, E. Henley, M. Kaplinghat, A. Karle, T. Kattori, P. Langacker, J. Learned, J. LoSecco, C. Lunardini, D. McKay, M. Medvedev, P. Mészáros, A. Mezzacappa, I. Mocioiu, H. Murayama, P. Nienaber, K. Olive, S. Palomares-Ruiz, S. Pascoli, R. Plunkett, G. Raffelt, T. Stanev, T. Takeuchi, J. Thaler, M. Vagins, T. Walker, N. Weiner, B.-L. Young*

- *What can neutrinos disclose about the deep interior of astrophysical objects, and about the mysterious sources of very high energy cosmic rays?*

A.6.2 RECOMMENDATIONS

Our principal recommendations are:

- *We strongly recommend the development of experimental techniques that focus on the detection of astrophysical neutrinos, especially in the energy range above 10^{15} eV.*

  We estimate that the appropriate cost is less than $10 million to enhance radio-based technologies or develop new technologies for high energy neutrino detection. The technical goal of the next generation detector should be to increase the sensitivity by factor of 10, which may be adequate to measure the energy spectrum of the expected GZK (Greisen-Zatsepin-Kuzmin) neutrinos, produced by the interactions of ultra-high energy cosmic ray protons with the cosmic microwave background (Fig. 11). The research and development phase for these experiments is likely to require 3-5 years.

What succeeded? What failed?

Concept: Define Our Pitch

Fundamental goals: Astrophysics of sources, exploration

Focal point: Goals that can only be met with neutrinos

Approach: Goals before methods, long- before short-term, speak coherently across the neutrino community

Broad appeal: Essential element of multi-messenger astro needed to undertand the most extreme sources

Connections: Many aspects of particle, nuclear, gravitational physics, astronomy, cosmology

Concept: Define Landscape

	VHE	UHE	Joining
Science	sources	cosmogenic	maybe common
Technology	optical	radio	must connect
Community	one	another	must connect
Location / Infrastructure	one	another	maybe connect

Concept: Define Stages

Conventional approach:

Define exposure needed to detect N ~ 1 event

Appropriate for motivating experiments to prove existence of flux, *but inadequate to do science we want*

“Red-line” approach (Beacom-Karle-Waxman):

Define exposure needed to require new physics/astrophysics if zero events detected

This likely gives enough events in the actual cases

Seems crazy, but it is not that far away

We can propose less, but we should note where this is

Proposed Strategy

Proposed Strategy: VHE

Overarching goals:

To use neutrinos to discover and probe in detail nature's most powerful high-energy sources, which ubiquitously shape galaxies through their cosmic rays and other consequences, isolating those that accelerate protons and nuclei. To use these data to develop a robust new multi-messenger astronomy, connecting to observations with gamma rays and gravitational waves.

Supporting evidence:

Cosmic rays; gamma rays; neutrinos; powerful sources

Requirements:

Reach ~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} sensitivity with IC-Gen2 (red line 10^{-10}…)
Complete KM3NeT

Proposed Strategy: UHE

Overarching goals:

To use neutrinos to discover and probe in detail nature's highest-energy sources, which reveal the most extreme physical conditions. To explore the high-energy, high-distance reaches of the cosmos, which can only be probed with neutrinos, and perhaps to develop directional astronomy with ultra-high-energy cosmic rays.

Supporting evidence:

Cosmic rays; powerful sources

Requirements:

Reach ~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} sensitivity with radio-based detectors (red line 10^{-10} …)

Proposed Strategy: Joining VHE and UHE

Overarching goals:

To use neutrinos to develop a broad-based astronomy that spans observations over many orders of magnitude in energy and a variety of types of sources. To discover new classes of sources and to test the physical connections between them.

Supporting evidence:

Gamma-ray/neutrino/cosmic-ray connection; powerful sources

Requirements:

Join optical- and radio-based sensitivities near 10—100 PeV, for complete coverage from TeV to ZeV

Conclusions

The physics potential of neutrino astronomy is first-rate

The goals are technologically reachable

Key questions cannot be answered any other way

With the right strategy, we can convince others

We will make it neutrino astronomy