A Vision for Neutrino Astronomy

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Three Ways of Looking at a Neutrino

Neutrino Laboratory

Neutrino Cosmology

Neutrino Astronomy

Neutrino Astronomy – Why Try?

Neutrinos reveal:

hot, dense matter; hadronic acceleration; dark matter annihilation

Can see:

- deep insides of sources, not the outsides
- initial energies, not reduced by scattering
- original timescales, not delayed by diffusion
- distant sources, not attenuated en route

The only thing is that neutrino signal detection is hard

Neutrino Astronomy – How Possible?

Factors we can't control

Nature provides sources: luminous, high-energy, numerous, varied

Factors we can control

We provide detectors: big, sensitive, low-background

Factors that require wisdom

We provide leverage: power of SM data, power of EM observations

Neutrino Astronomy – Unique Impact

To understand astrophysics,
only neutrinos can reveal these extreme conditions
(aka Multi-Messenger Astrophysics)

To understand neutrinos,
only these extreme conditions can reveal particle properties
(aka Beyond the Standard Model)

Talk Outline

Introductory Remarks

MeV—GeV Frontier

TeV—PeV Frontier

EeV—ZeV Frontier

Concluding Remarks

MeV—GeV Frontier

Sun, supernova
NS-NS mergers
flares from novae or supernovae
dark matter annihilation or decay
surprises

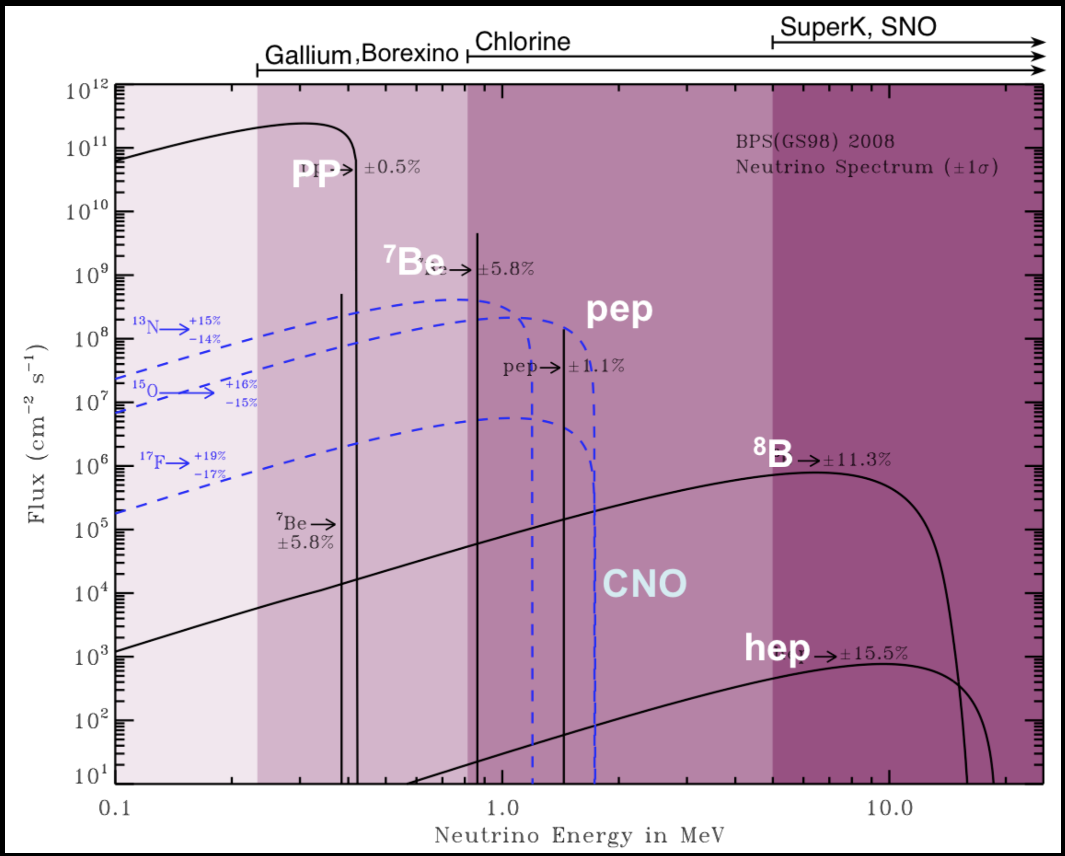
Solar: Motivations

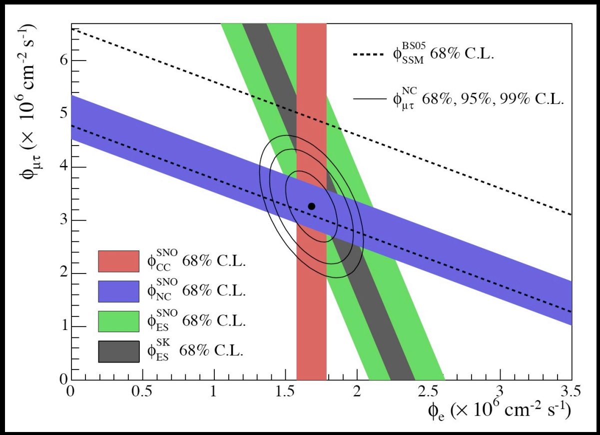
the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

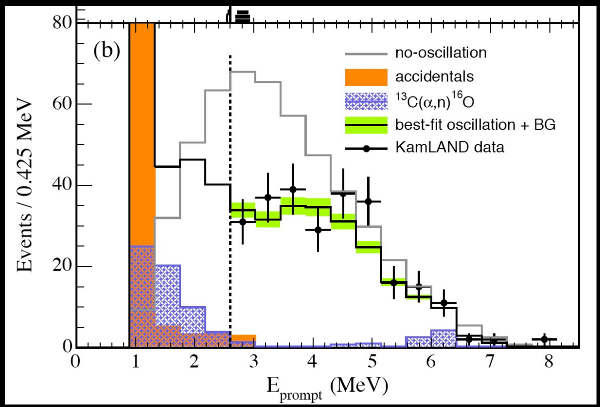
John Bahcall (1964)

… and how neutrinos work

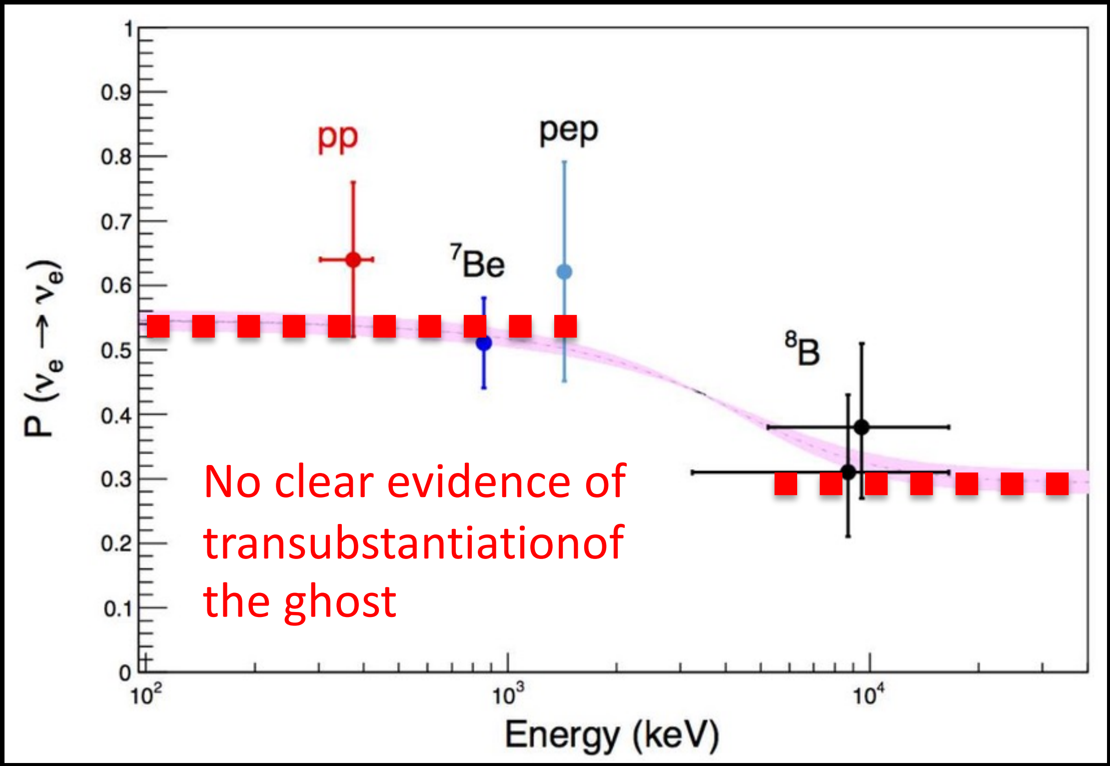
Solar: Accomplishments

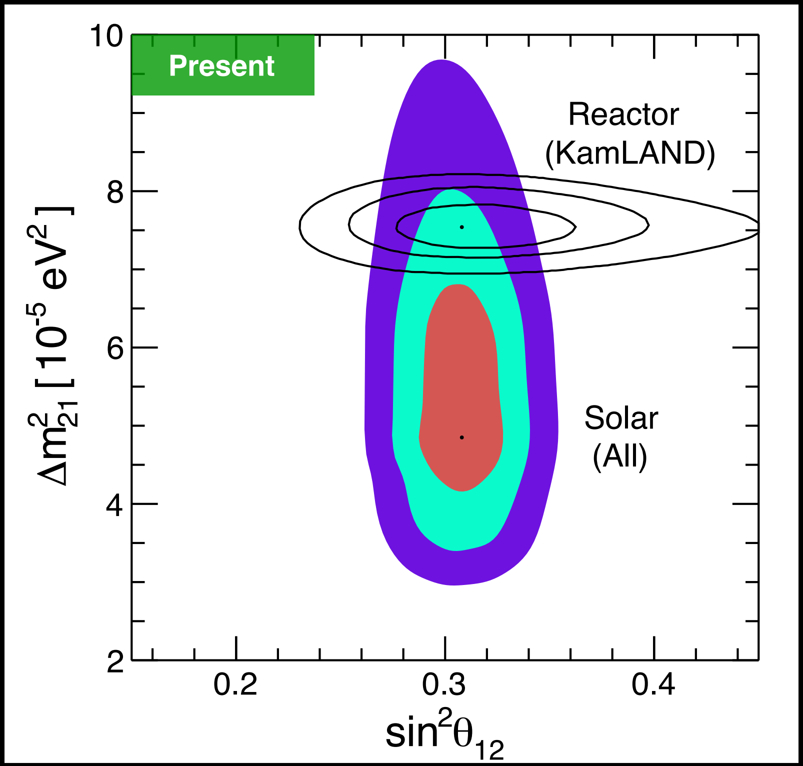






Solar: Unsolved





(tension in recent data is less)

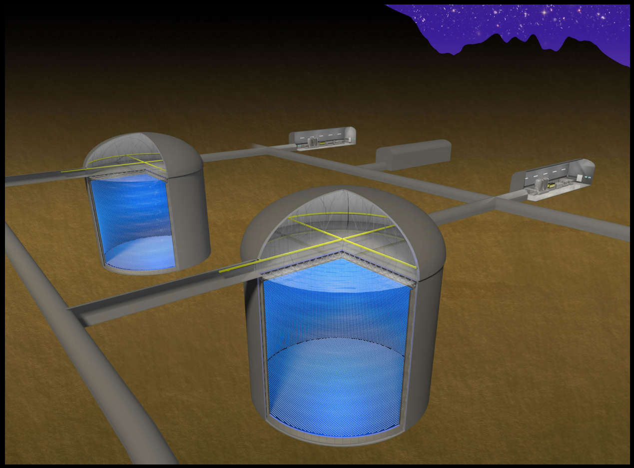
Solar: Hope

Low Energies

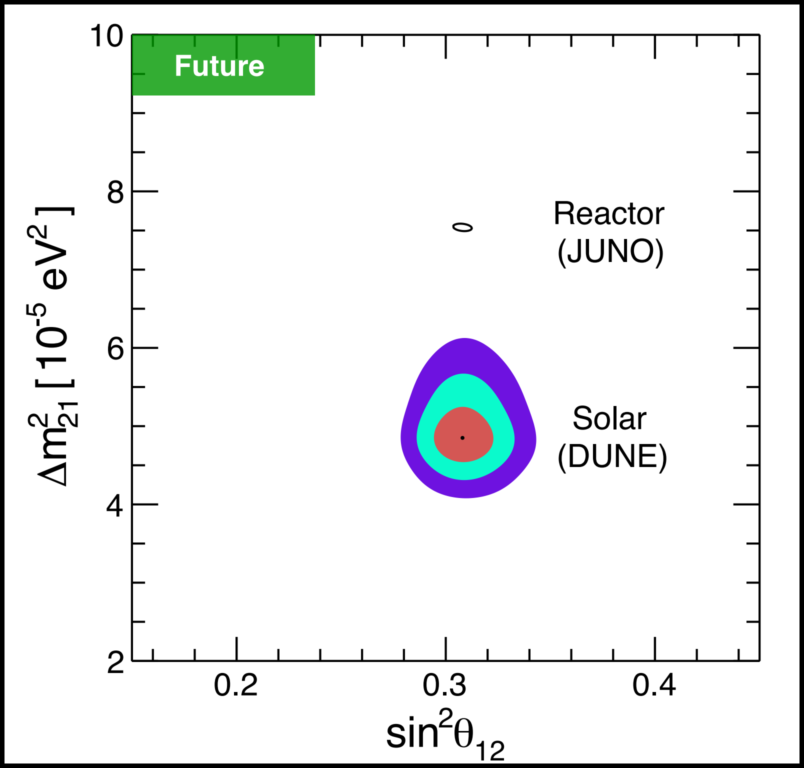
New detectors?

Liquid argon
DARWIN
SNO+

Hyper-K



DUNE Solar

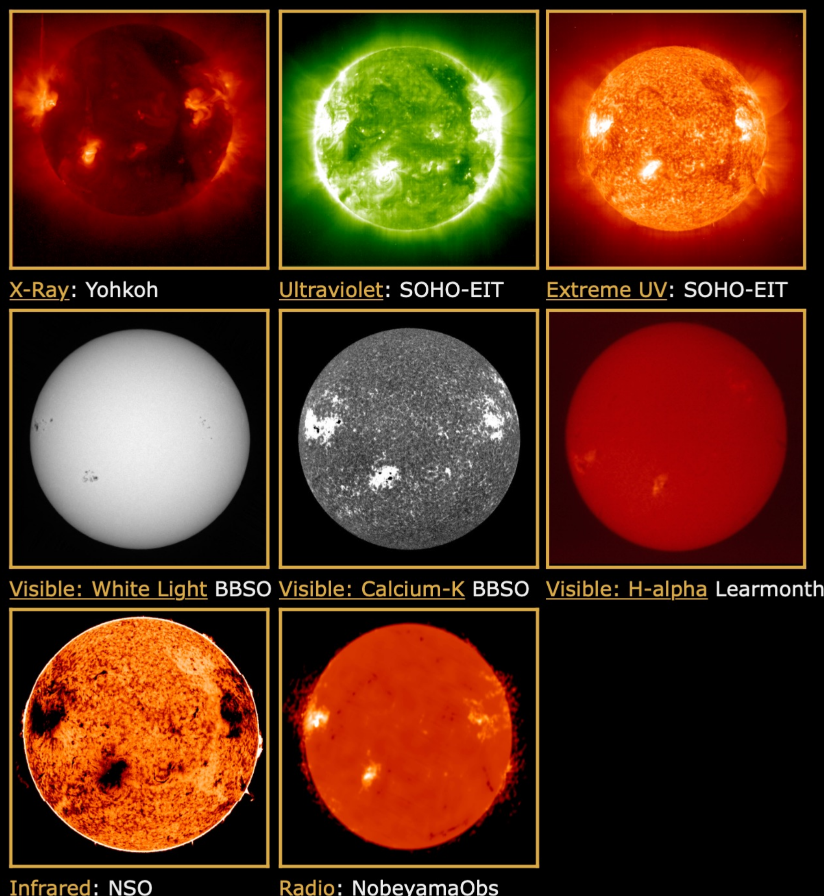


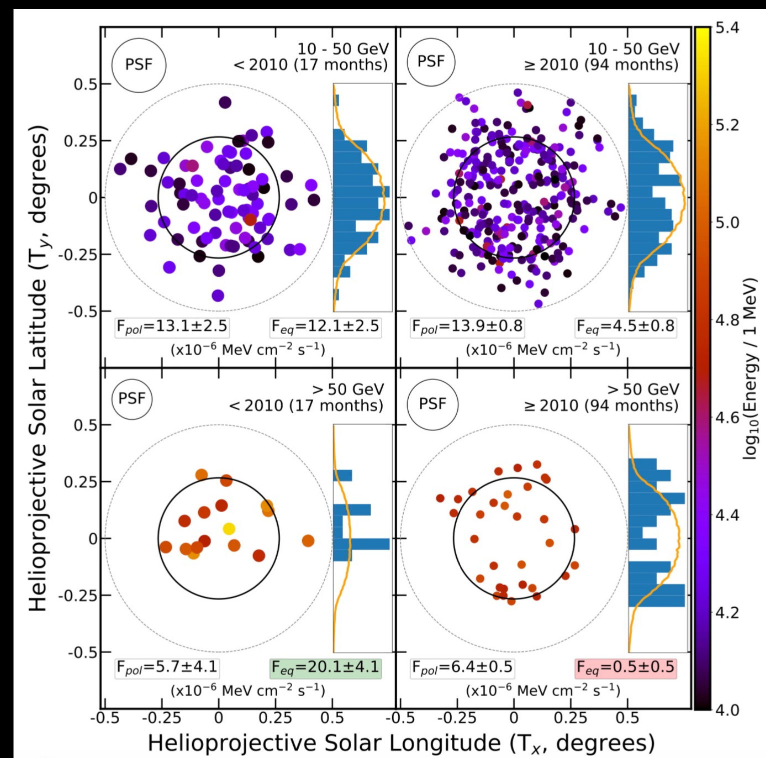
Capozzi, Li, Zhu, Beacom (2019)

Background Reduction

New techniques to cut spallation (Shirley Li)

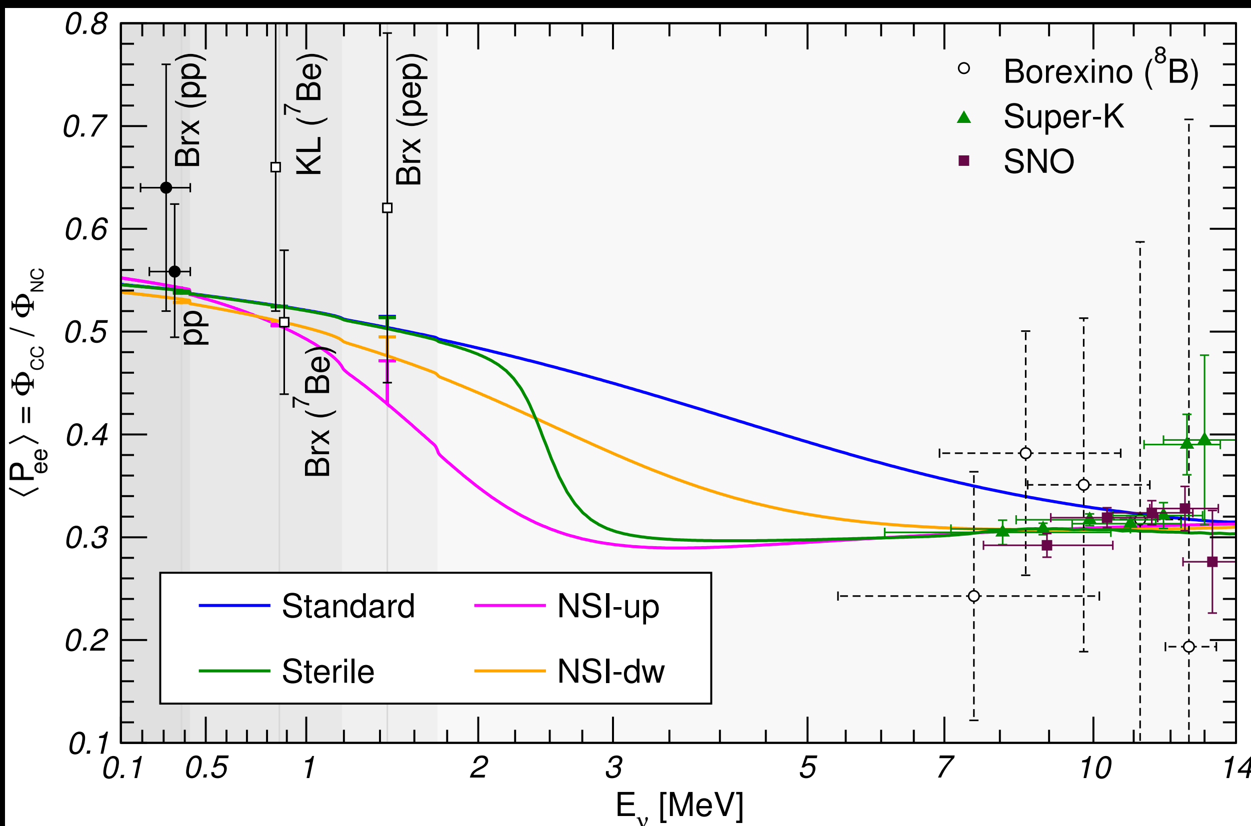
Solar: MMA





Linden et al. (2018) and related works for high-energy implications

Solar: BSM



Maltoni and Smirnov (2016)

Very sensitive to:

Sterile neutrinos
Non-standard interactions
Neutrino decay
and much more

Supernova: Motivations

NEUTRINOS VS. SUPERNOVAE

By Dr. G. GAMOW

PROFESSOR OF THEORETICAL PHYSICS, GEORGE WASHINGTON UNIVERSITY

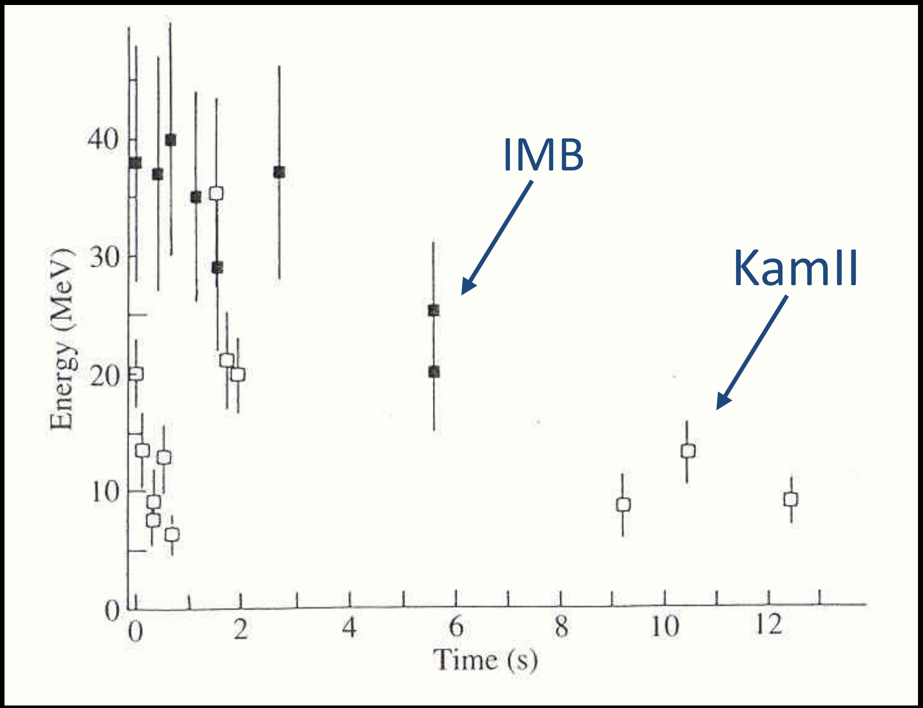
Thus we see that the beginning of the neutrino radiation from the hot central regions of contracting stars gives us the complete explanation of the causes of stellar collapses, and, since the neutrinos

George Gamow (1942)

Total energy ~ GM^2/R ~ 10^{59} MeV
Average energy ~ 10 MeV

… and how neutrinos work

Supernova: Accomplishments

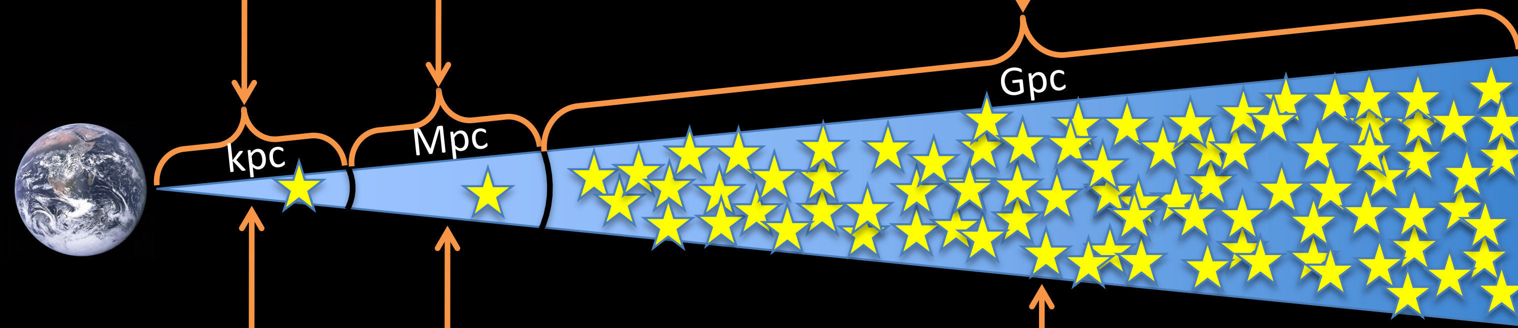


Supernova: Unsolved

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

high statistics,
all flavors

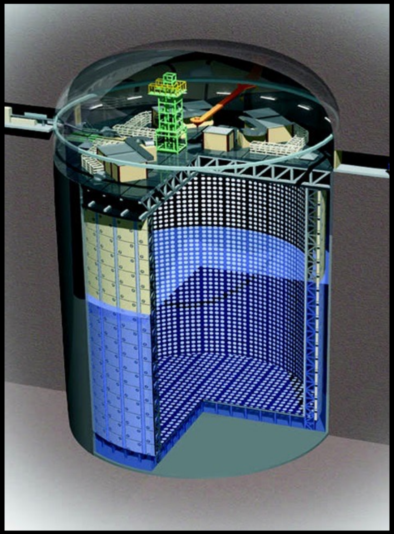
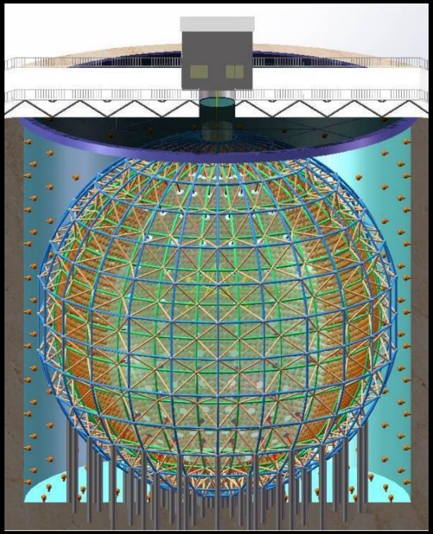
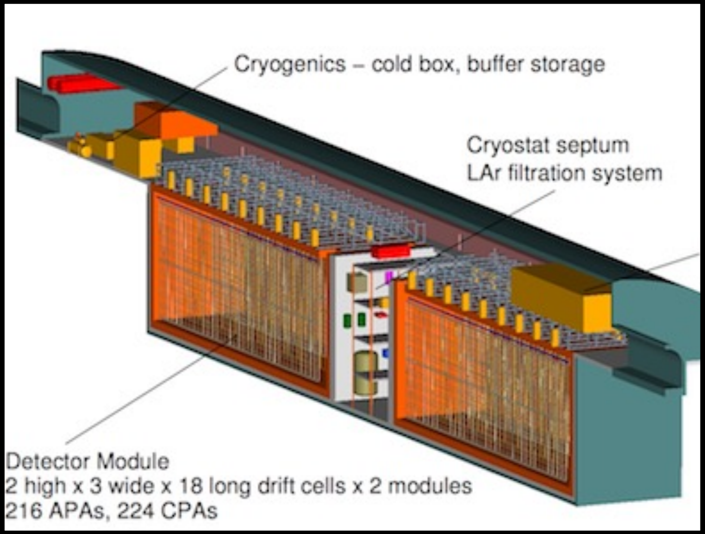
Rate ~ 1/yr

object identity,
burst variety

Rate ~ 10^8/yr

cosmic rate,
average emission

Supernova: Hope

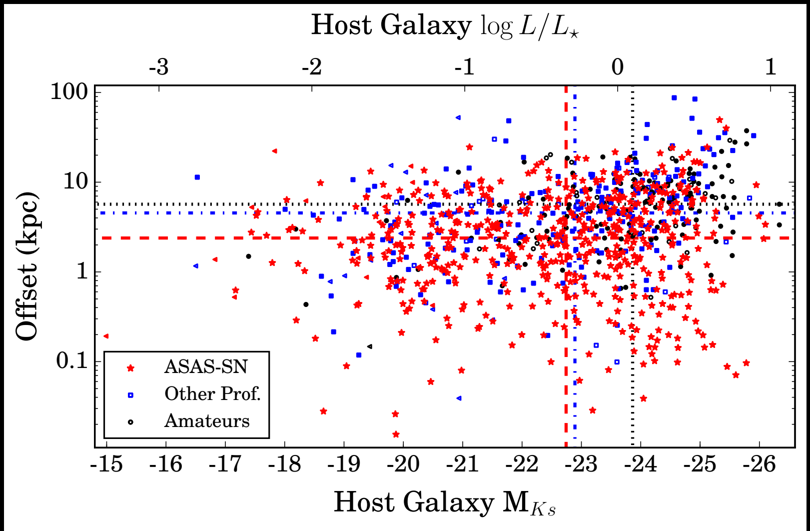
Super-K	JUNO	DUNE
		
32 kton water Japan *running*	20 kton oil China *building*	40 kton liquid argon United States *preparing*

Together, excellent potential for MeV neutrino astronomy

Supernova: MMA

Connection to astronomy crucial, but optical data were lacking

Enter OSU's "ASAS-SN" (All-Sky Automated Survey for SN)



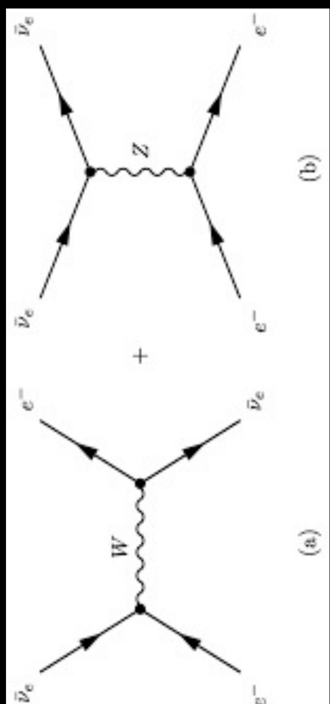
For MMA details:

Adams et al. (2013)
Nakamura et al. (2016)

Discovering and monitoring optical transients to 18th mag.

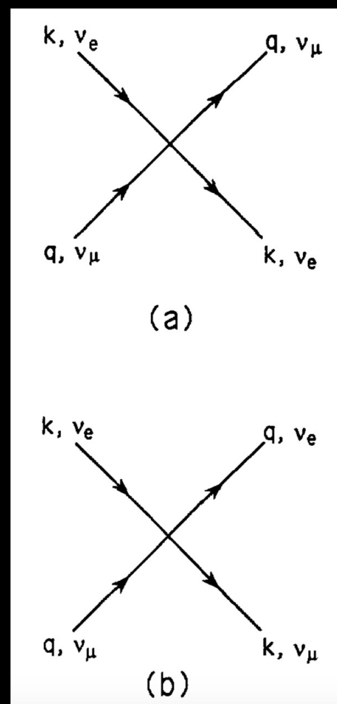
Supernova: BSM

Neutrino-Electron



MSW effect

Neutrino-Neutrino



Pantaleone (1992)

Very complex consequences for mixing and maybe for the supernova explosion!

Beyond reach of the lab

TeV—PeV Frontier

IceCube signals
SNRs, GRBs, AGN
cosmic-ray collisions with Sun
dark matter annihilation or decay
surprises

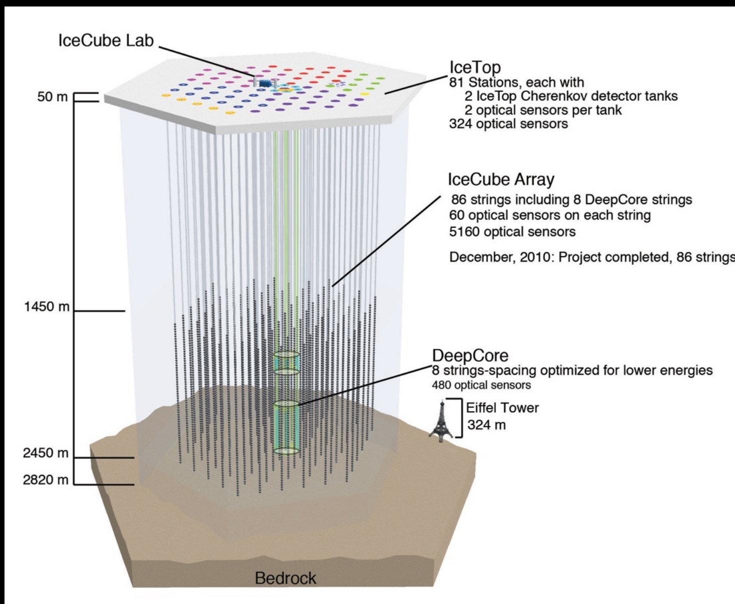
VHE Diffuse: Motivations

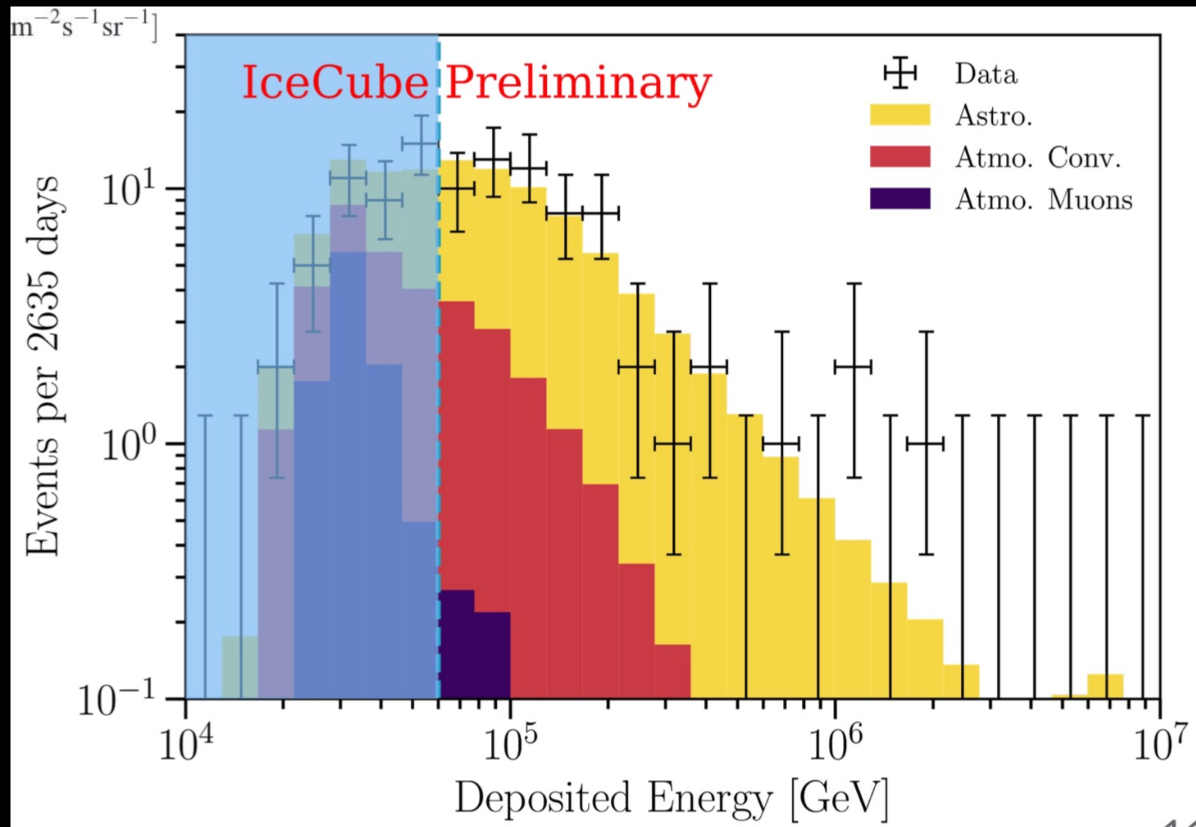
(*c*) The spectacular quasi-stellar radio sources, radio galaxies, and galactic optical synchrotron radiators such as the Crab nebula will be considered as possible candidates for detectable neutrino sources (as well as x ray, γ ray, etc.) as long as their origin remains uncertain. The observed synchrotron radiation suggests the

Malvin Ruderman (1965)

… and how neutrinos work

VHE Diffuse: Accomplishments

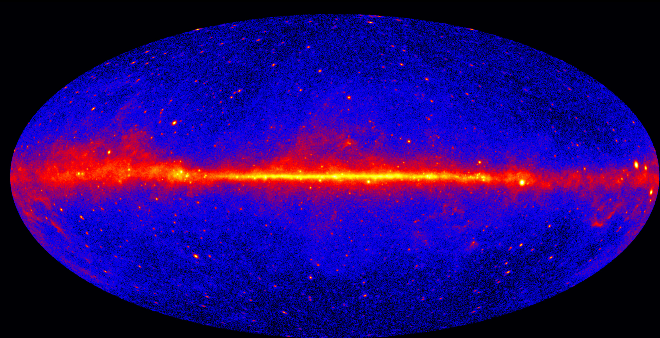


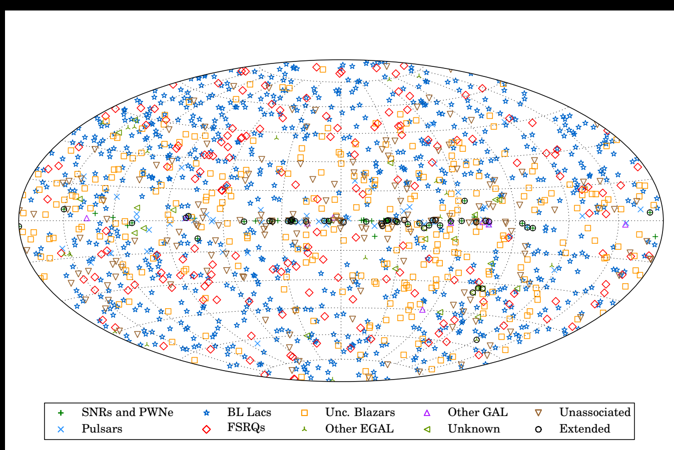


IceCube (2019)

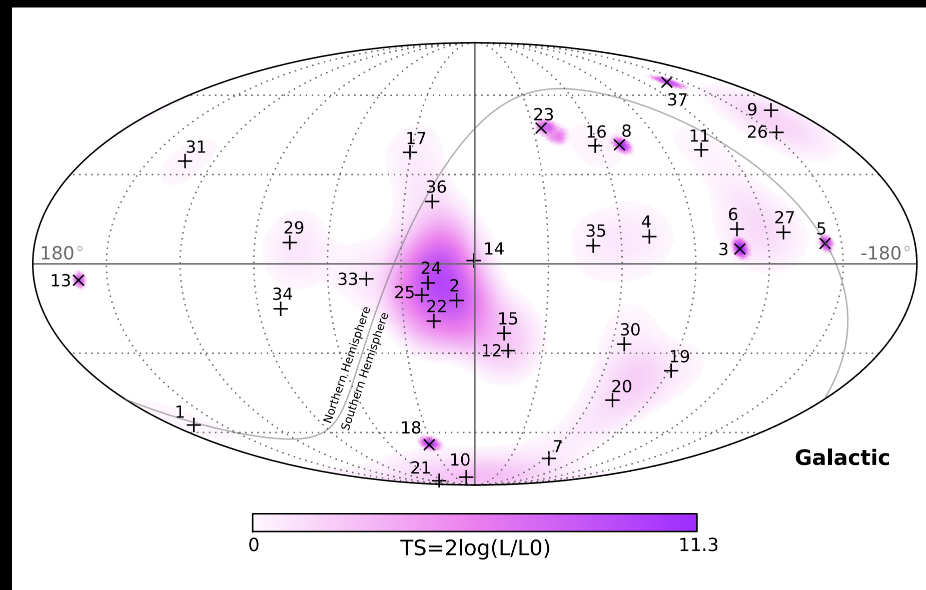
VHE Diffuse: Unsolved

Gamma Rays





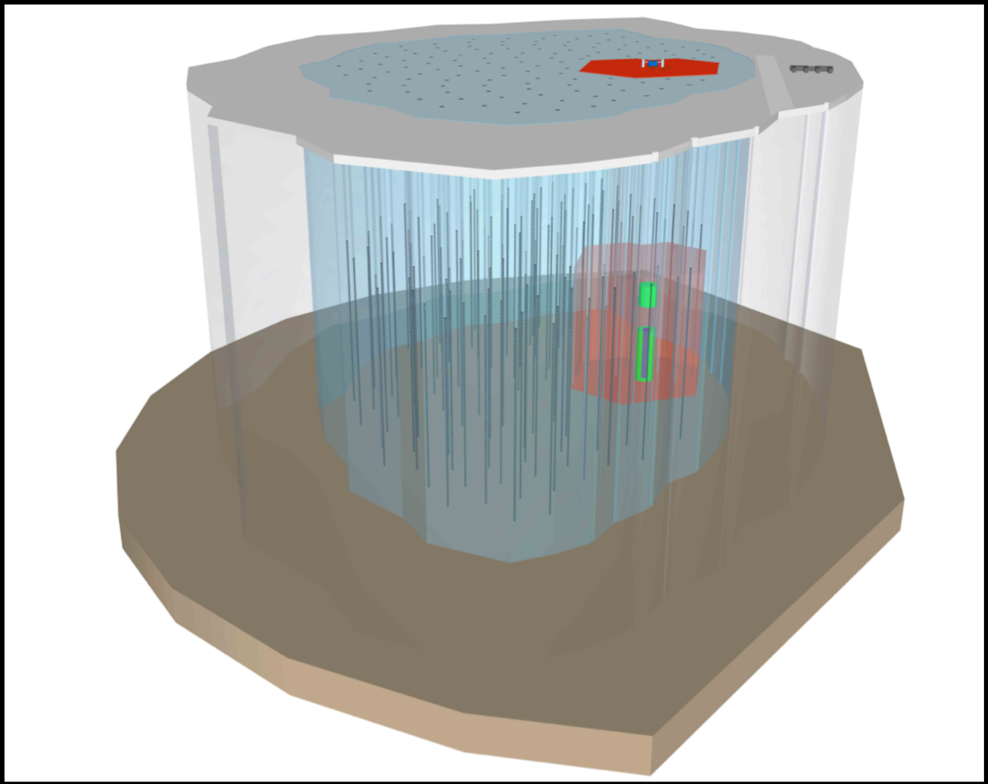
Neutrinos



(plot is a bit old; later data appear to be extragalactic, isotropic)

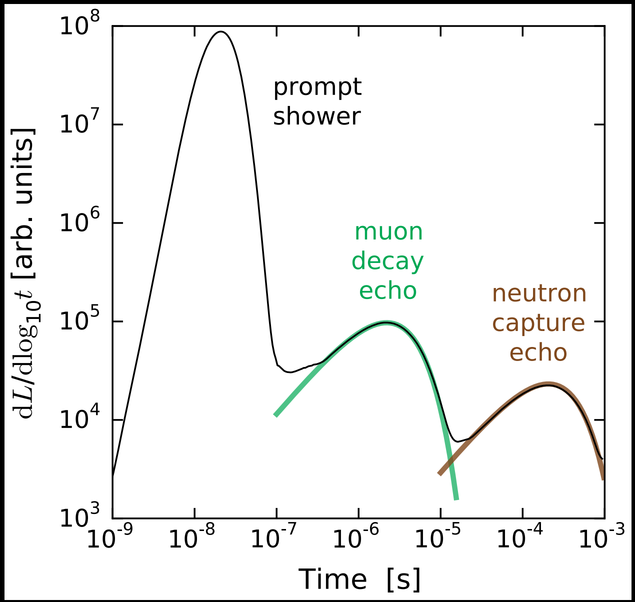
VHE Diffuse: Hope

IceCube-Gen2



Echoes

Separates ν_e from ν_τ

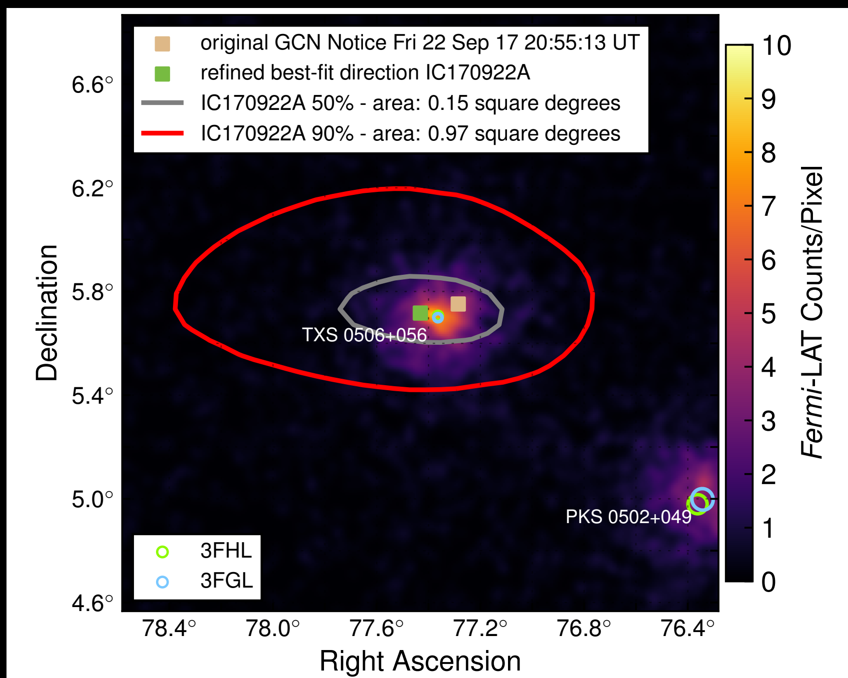


Li, Bustamante, Beacom (2019)

VHE Diffuse: MMA

TXS event

IceCube-170922A and TXS 0506+056



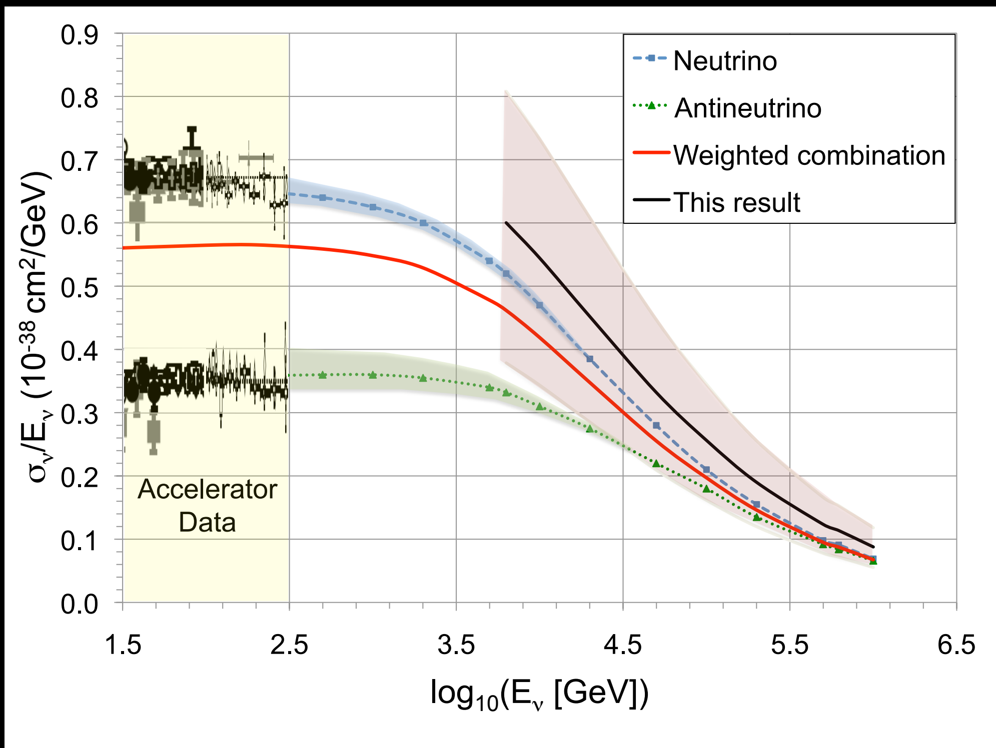
IceCube, Fermi-LAT, everyone (2017)

Gamma Rays

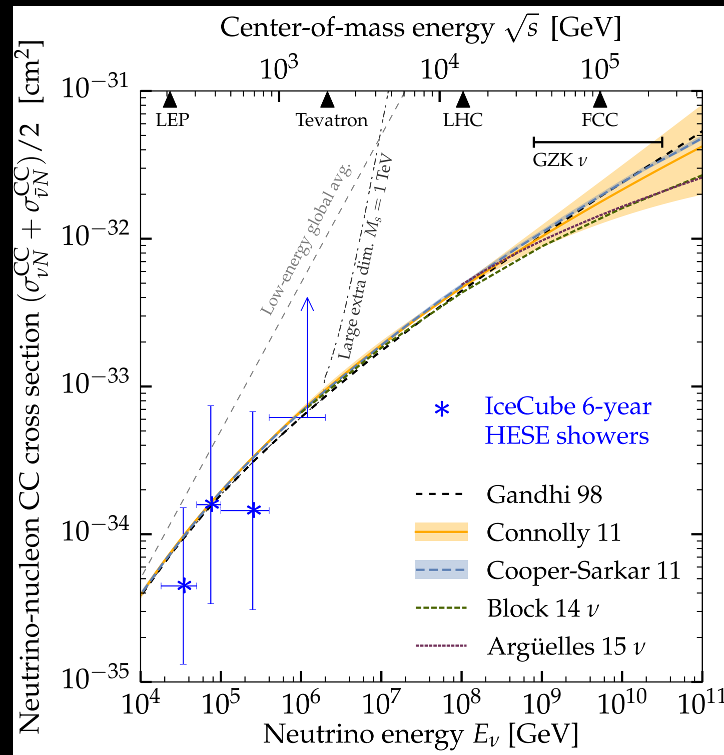
Huge advances with

HAWC
LHAASO
CTA

VHE Diffuse: BSM



IceCube (2017)



Bustamante and Connolly (2017)

EeV—ZeV Frontier

no detections, only limits
sources of UHE cosmic rays
supermassive dark matter decay
surprises

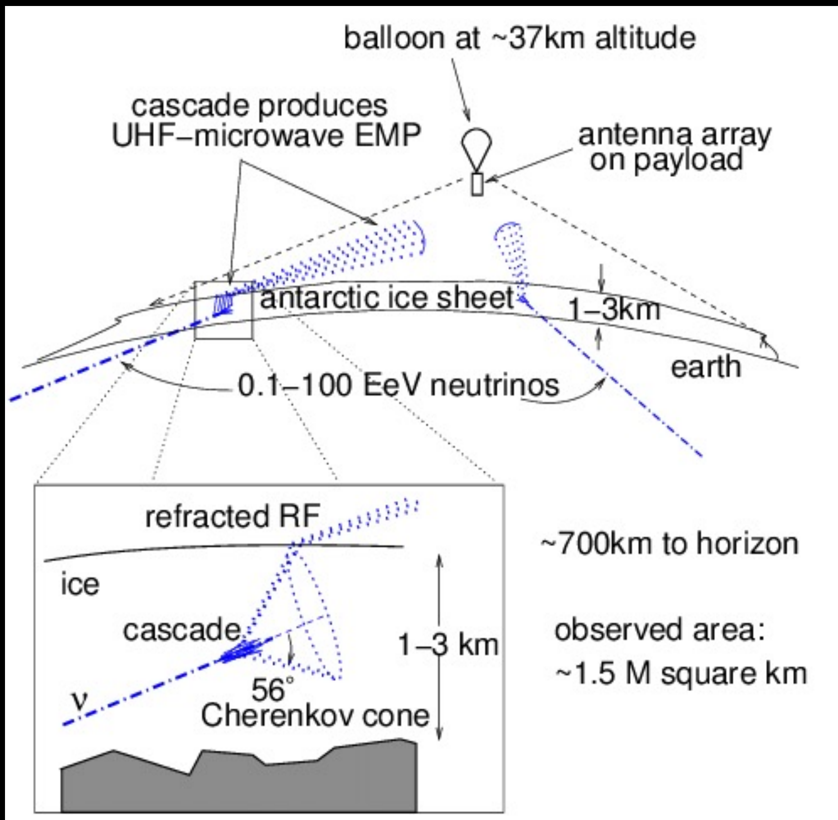
UHE Fluxes: Motivations

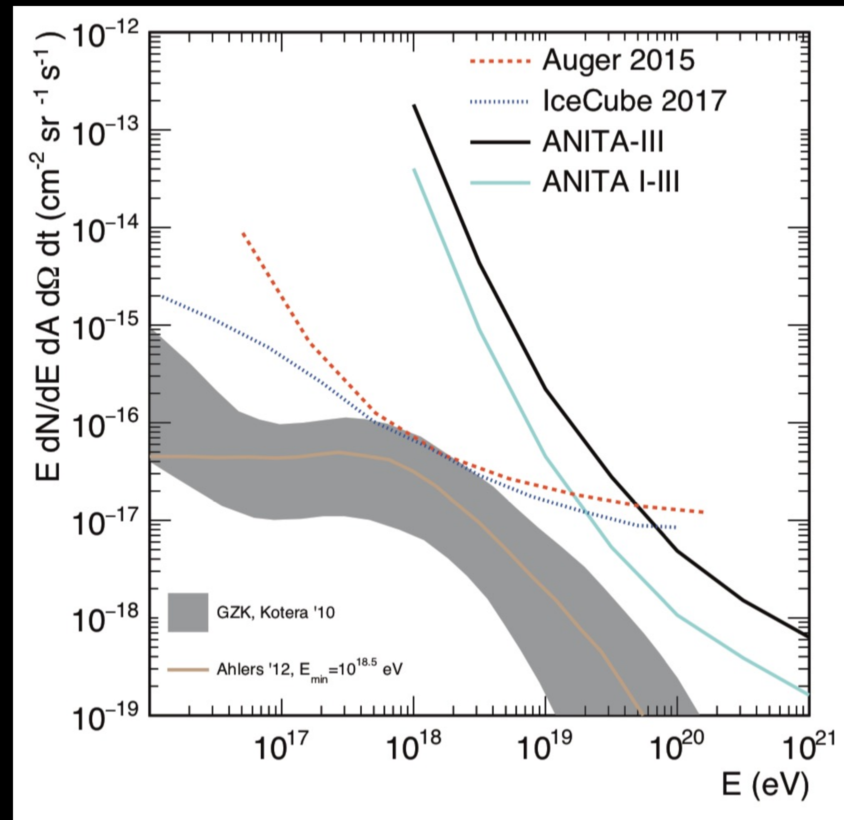
The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Venya Beresinsky and Georgiy Zatsepin (1969)

… and how neutrinos work

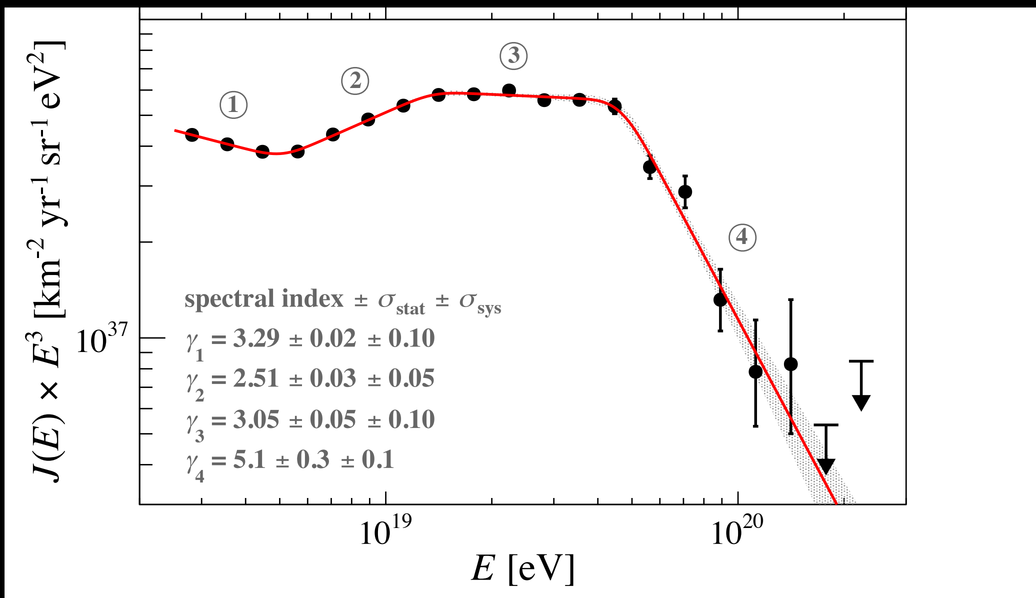
UHE Fluxes: Accomplishments



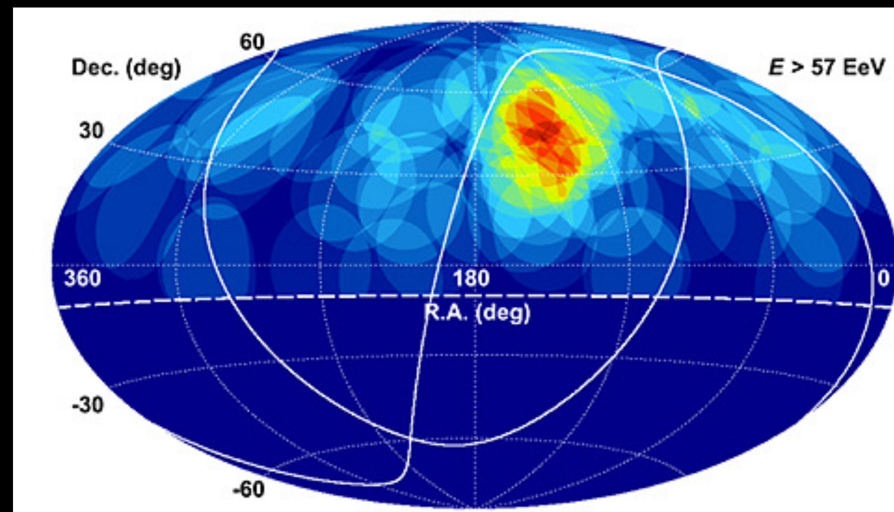


ANITA (2019)

UHE Fluxes: Unsolved



Auger (2020)



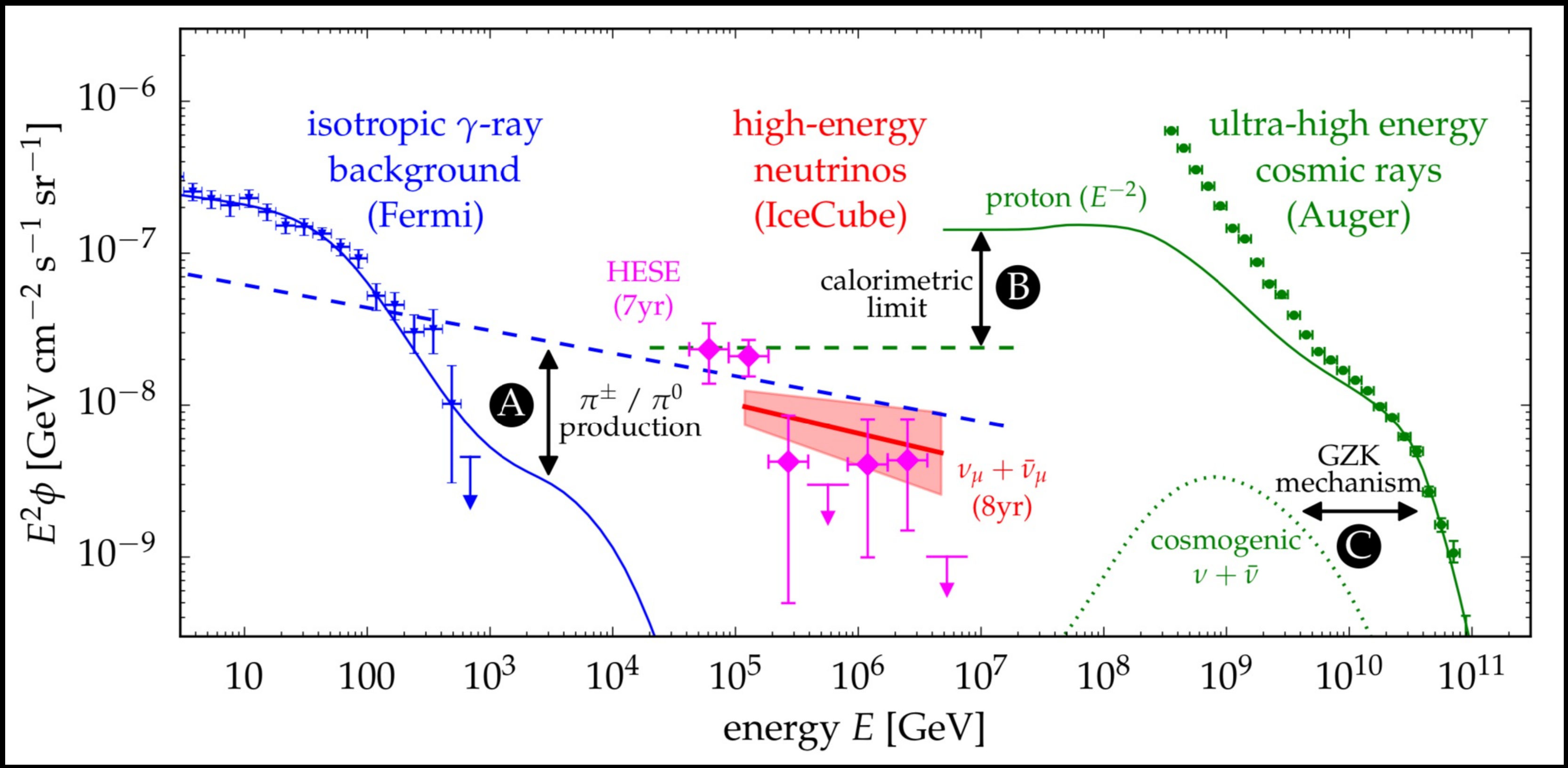
Telescope Array (2019)

UHE Fluxes: Hope

Many proposed experiments:

ARA
ARIANNA
BEACON
GRAND
IceCube radio extension
JPL
POEMMA
RNO
Trinity
RADAR Echo Telescope (2104.00459)
…

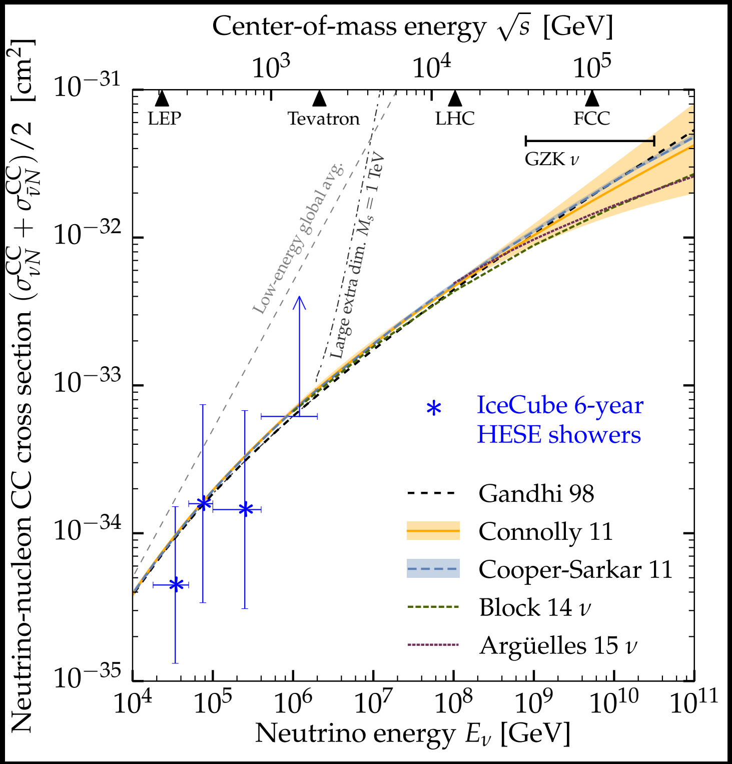
UHE Fluxes: MMA



Ahlers (2018)

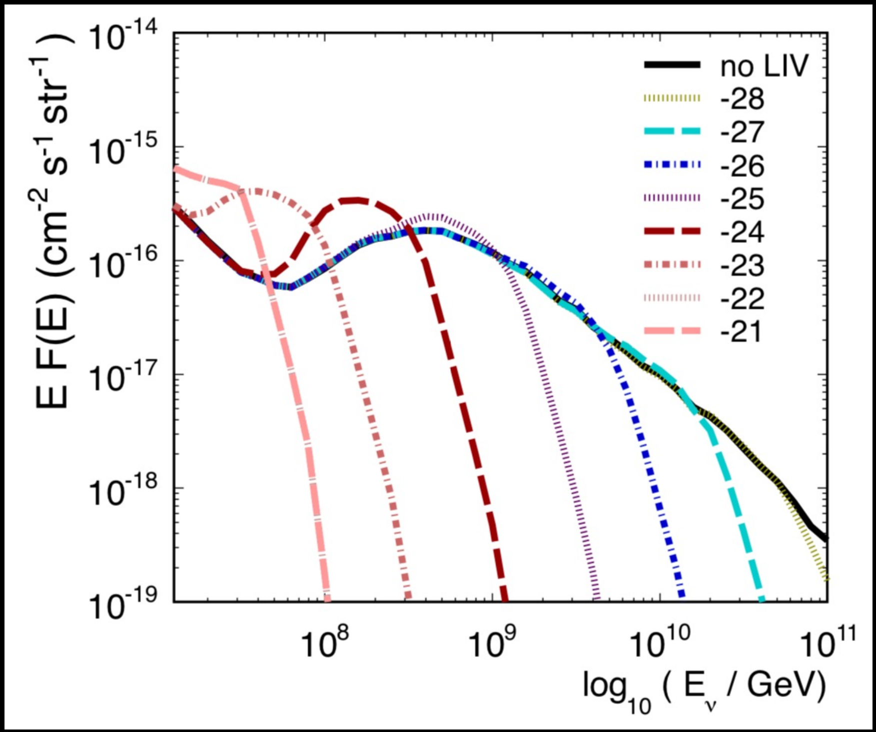
UHE Fluxes: BSM

Cross Section



Bustamante and Connolly (2017)

Lorentz Violation



Gorham et al. (2012)

Concluding Remarks

How to Advance our Goals?

We're going to need a bigger boat

The Time for Neutrino Astronomy is Now

Neutrino Astronomy

MeV—GeV ν	TeV—PeV ν	EeV—ZeV ν
Efforts: SK, HK and more	Efforts: IceCube and more	Efforts: ANITA and more
Targets: Solar, SN, more Surprises	Targets: GRBs, AGN, more Surprises	Targets: GZK process Surprises

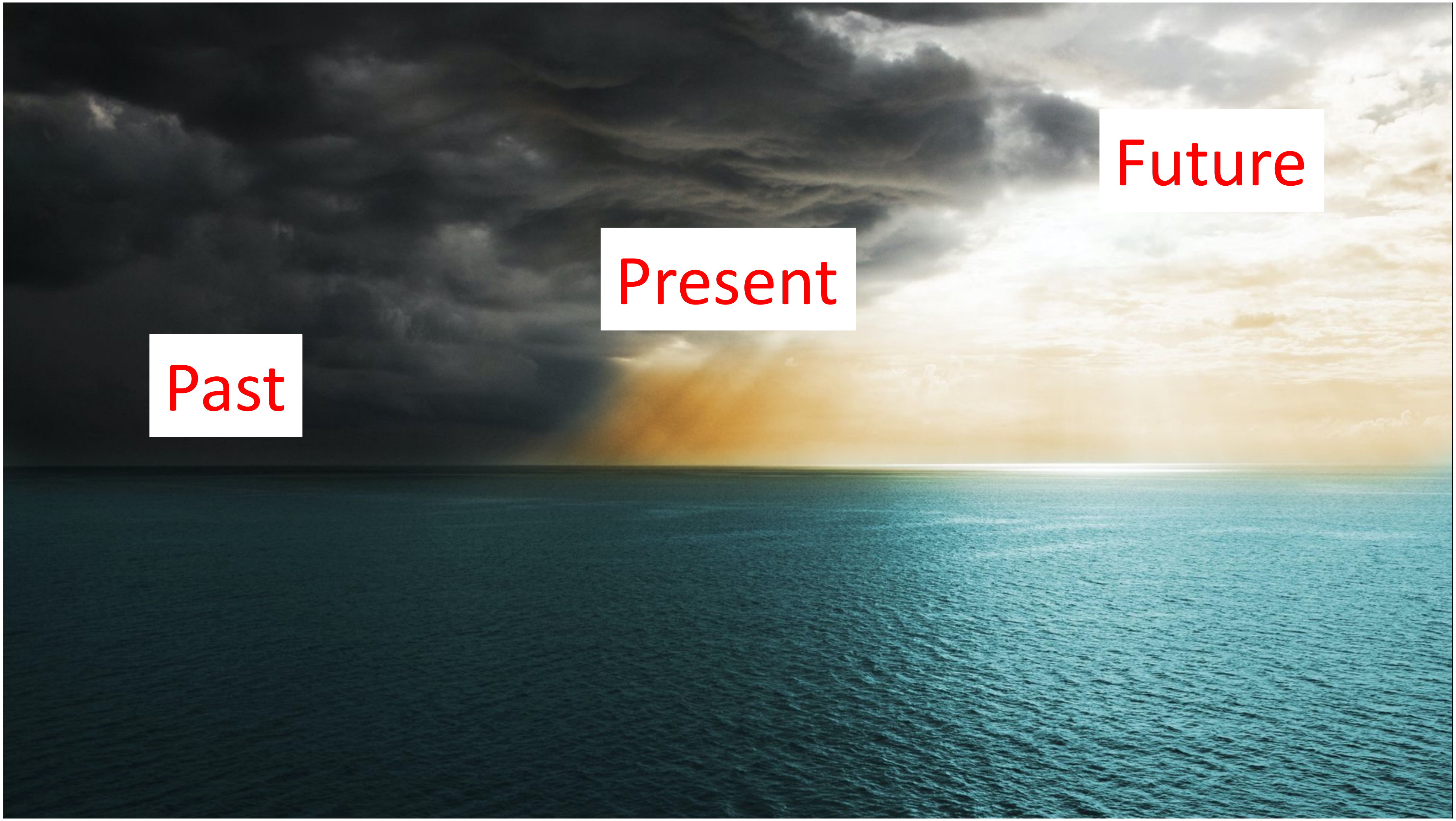
Neutrino astronomy must be broad

The Time for Neutrino Science is Now

Neutrino Science

Laboratory ν	Cosmology ν	Astronomy ν
Efforts: Fermilab and more	Efforts: CMB and more	Efforts: IceCube and more
Context: Precision Physics, BSM reach	Context: Precision Cosmology, BSM reach	Context: Transient Astronomy, Multi-messenger

Neutrinos are multi-frontier science


Future
Present
Past