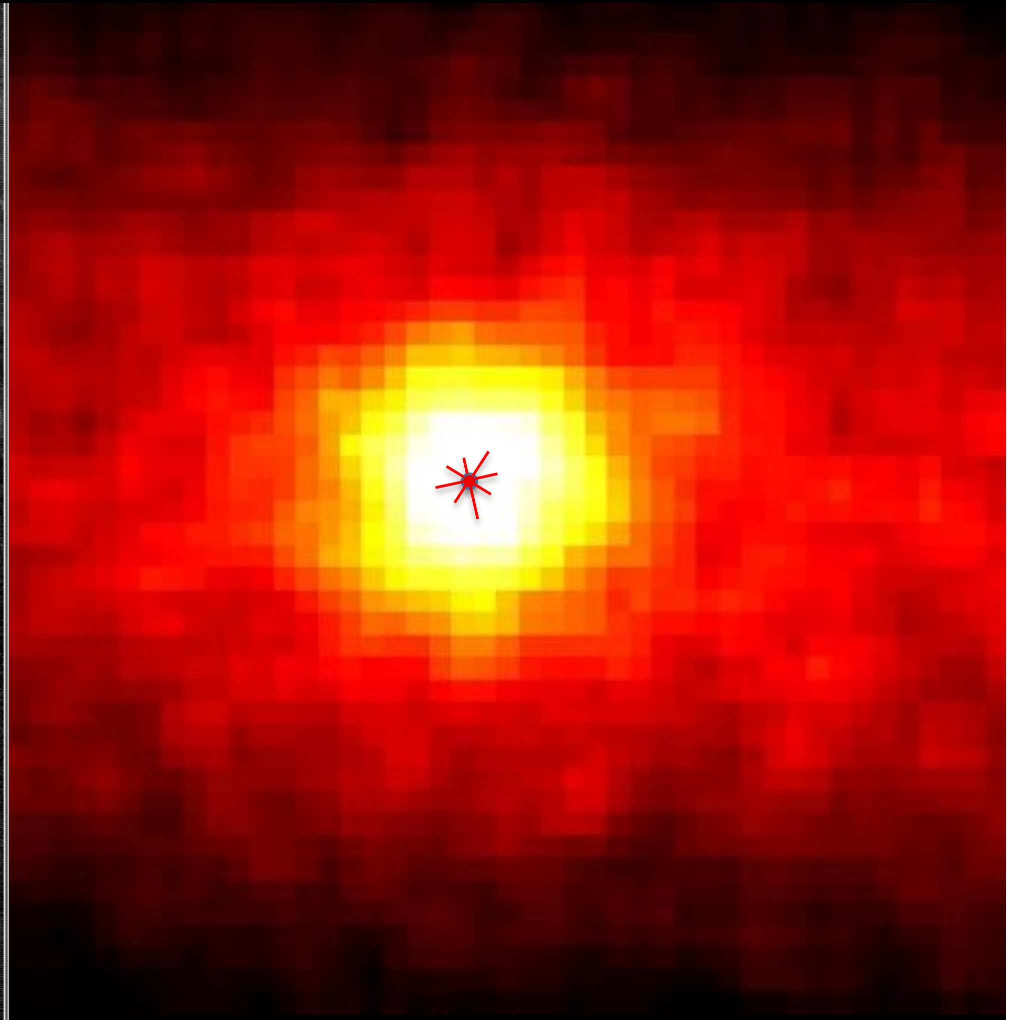
Neutrinos: The Long Game

John Beacom, The Ohio State University



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

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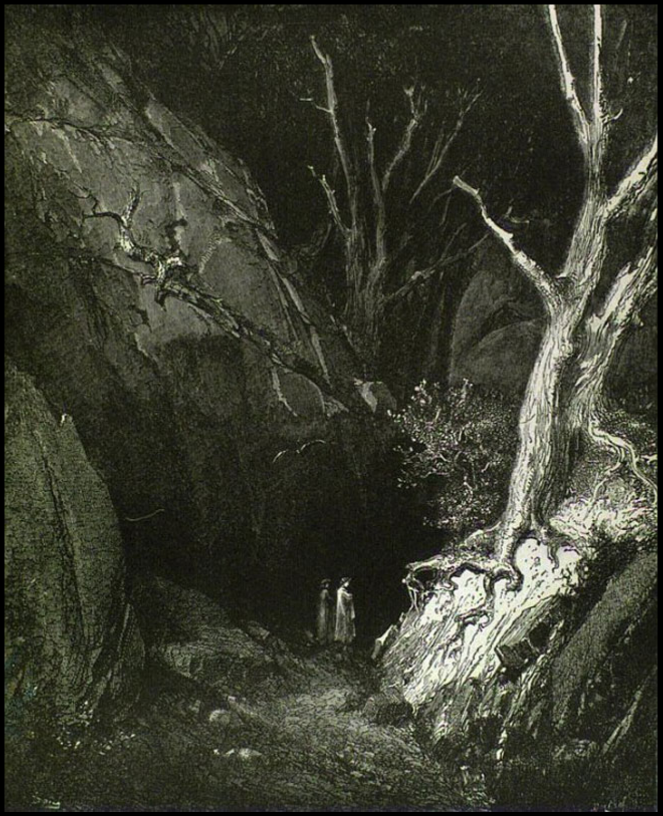
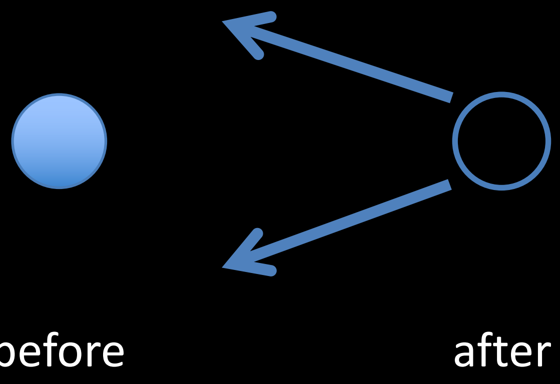


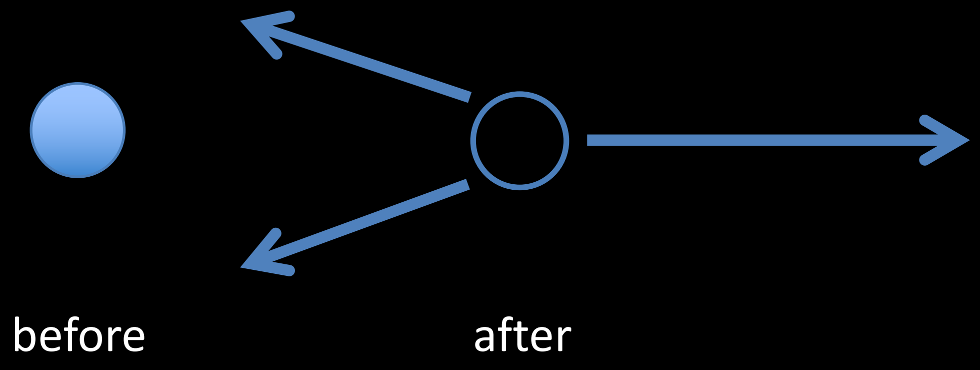
What Are Neutrinos?

Neutrinos – As Concepts

$$n \rightarrow p + e^-$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$





Violates conservation of momentum and energy

Respects conservation of momentum and energy

Pauli (1930): *I have done a terrible thing. I have postulated a particle that cannot be detected*

What About Other Unsolved Problems?

Other particle and nuclear decays?	*Neutrinos!*
Formation of chemical elements?	*Neutrinos!*
Cooling of white dwarfs and neutron stars?	*Neutrinos!*
Radiation energy density of universe?	*Neutrinos!*
What is the dark matter?	*Neutrinos!*
Where does lost computer data go?	*Neutrinos!*
Calculations don’t quite work?	*Neutrinos!*

Neutrinos – As Realities

$n \rightarrow p + e^- + \bar{\nu}_e$ Neutron decay happens

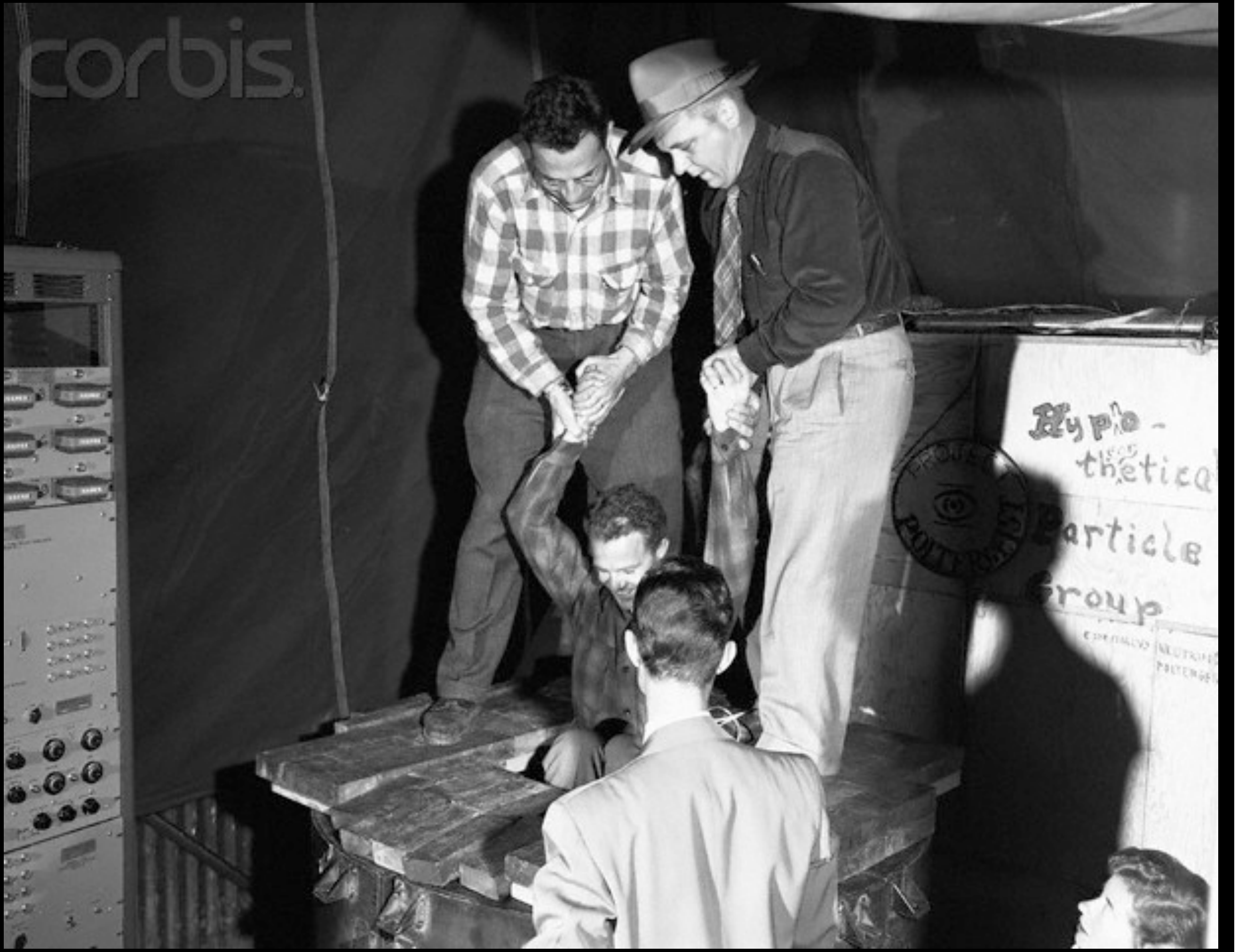
$p + e^- \rightarrow n + \nu_e$ Electron capture happens

$\bar{\nu}_e + p \rightarrow e^+ + n$ What about neutrino capture?

Required by time-reversal invariance of microscopic processes

> Bethe and Peierls (1934): *If [there are no new forces] one can conclude that there is no practically possible way of observing the neutrino*

What About Detection?



Reines and Cowan (1956): *Antineutrinos detected anyway!*

Neutrinos – As Messengers

Wherever conditions are hot and dense, or creating chemical elements, or accelerating particles, neutrinos are made

Neutrinos can reveal:

deep insides of sources, not the outsides

initial energies, not reduced by scattering

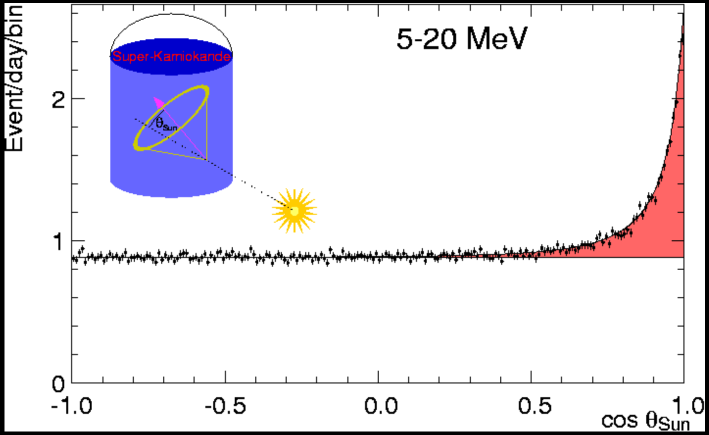
original timescales, not delayed by diffusion

distant sources, not attenuated en route

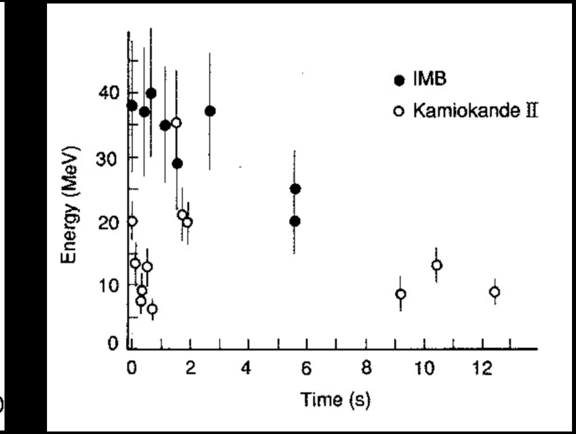
Many said: But non-lab neutrino signals are beyond reach

What About Practicality?

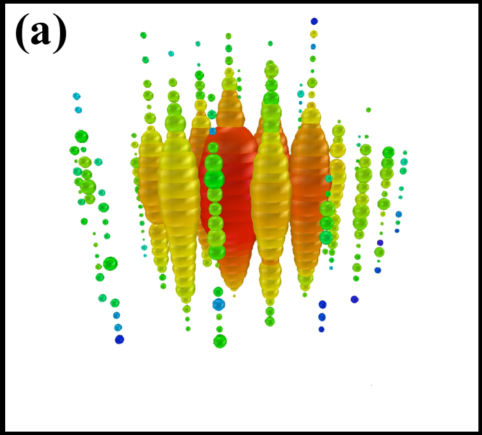
Astrophysics



Solar!

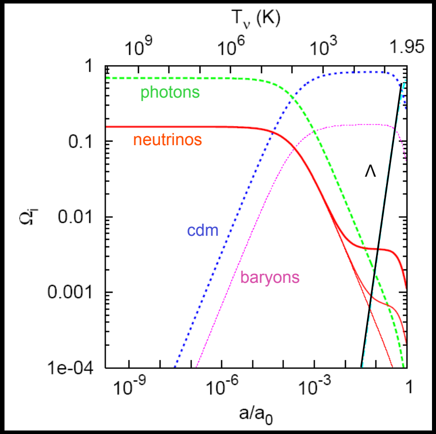


Supernova!

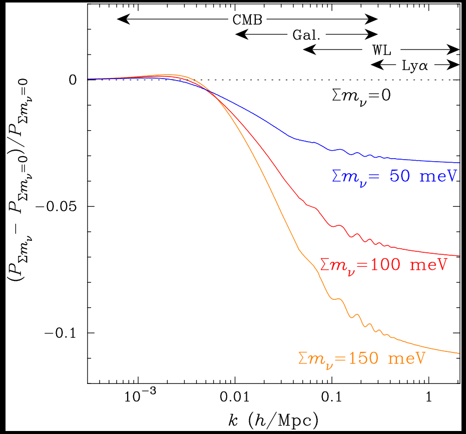


IceCube!

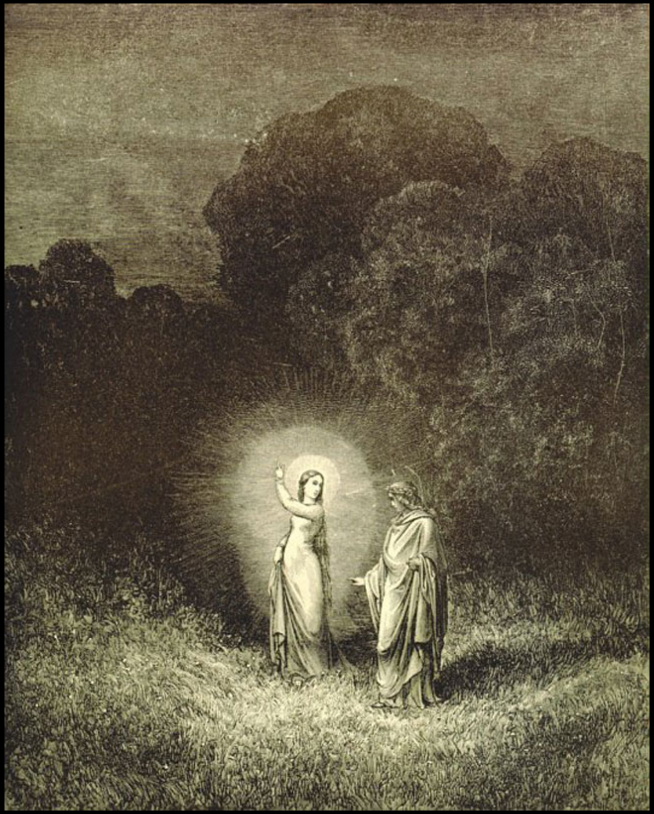
Cosmology



Dark Radiation!



Dark Matter!



What is Neutrino Science?

Three Strands of Neutrino Research

Laboratory Nu:	Cosmology Nu:	Astronomy Nu:
Goal: Particle nature of neutrinos	Goal: Constituents of universe	Goal: Mechanisms of sources
Superpower: Window to BSM	Superpower: Only known part of DM, DR	Superpower: Reveals deep interiors
Kryptonite: Requires precision tests	Kryptonite: Only measure bulk effects	Kryptonite: Need neutrino properties
Why now? FNAL, world program	Why now? Galaxy surveys, CMB, 21cm	Why now? IceCube, SK-Gd, GZK, etc.

Are There eV-Scale Sterile Neutrinos?

Laboratory

Could have large dm^2, large sin^2 sterile neutrino mixing

This would reveal new particle physics

BUT

Cosmology

Would violate neutrino number, mass constraints

Evading would require new early universe physics

BUT

Astrophysics

Could change supernova neutrino signals

This could provide new probes of astrophysics

These are not separable problems

Other Key Questions

Do neutrinos have non-standard interactions?

What are neutrino masses?

What were the dynamics of the early universe?

What powers astrophysical sources?

These are not separable problems either

How Can We Solve Our Problems?

We’re going to need a bigger boat

The Proper Pairing

To understand neutrinos
extreme conditions reveal neutrinos

To understand sources
neutrinos reveal extreme conditions

The Time for Neutrino Science is Now

Neutrino Science

Laboratory ν

Efforts:
Fermilab and more

Context:
Precision Physics,
BSM reach

Cosmology ν

Efforts:
CMB and more

Context:
Precision Cosmology,
BSM reach

Astronomy ν

Efforts:
IceCube and more

Context:
Transient Astronomy,
Multi-messenger

Progress depends on a unified approach

The Time for Neutrino Astronomy is Now

Astronomy ν

MeV—GeV ν

Efforts:
DUNE, HK, more

Targets:
Solar, SN, more
Surprises

TeV—PeV ν

Efforts:
IceCube and more

Targets:
GRBs, AGN, more
Surprises

EeV—ZeV ν

Efforts:
ANITA and more

Targets:
GZK process
Surprises

Neutrino astronomy must be broad

The Waiting Problem

Will we be ready to detect a supernova neutrino burst?

A Way We Could Fail – Supernova Neutrinos

Need all flavors to measure the total emitted energy

Need all flavors to fully test effects of neutrino mixing

$\bar{\nu}_e$ Precise (~ 10^4 events in Super-K)

$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ Inadequate (~ 10^2 events in oil)

ν_e Inadequate (~ 10^2 events in Super-K)

Super-K will shrink nuebar region to a point
But the comparison fails if we don't do others well too

The Timeline Problem

present and near future

large detectors
used to measure
neutrino mixing

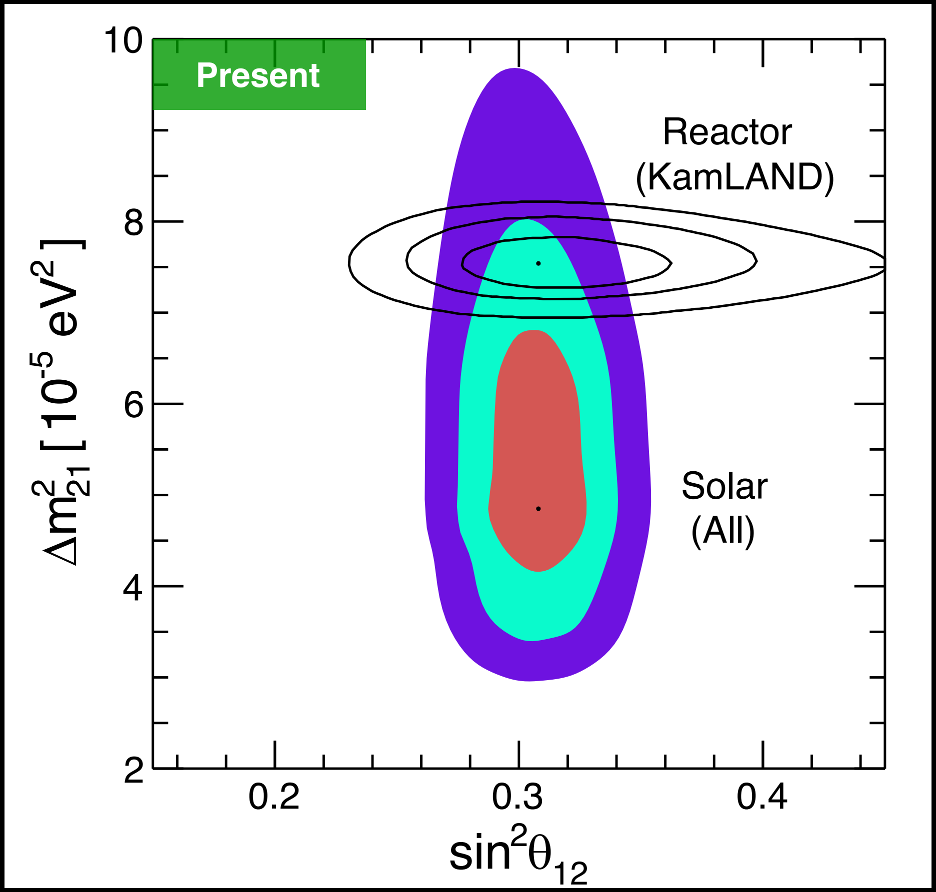
beyond that

maybe not
anymore

time

Who will build detectors for solar neutrinos?

A Way We Could Fail – Solar Neutrinos



JUNO will shrink reactor region to a point
But the comparison fails if we don't improve solar too

Revolutionizing MeV Neutrino Astronomy

Questions MeV Neutrinos Could Answer

- Stars: details of nuclear fusion reactions?

- Supernovae: how stars explode or make black holes?

- Neutron stars: mechanisms of late-time cooling?
  possible direct probe of mergers?

- Dark matter: new tests of scattering and annihilation?

- Neutrino properties: understand the messengers?

- Surprises: who knows?

Basic Features of MeV Neutrino Detection

Detectors must be massive:

Effectiveness depends on volume, not area

Example signals:

$$\nu + e^- \rightarrow \nu + e^-$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Detectors must be quiet:

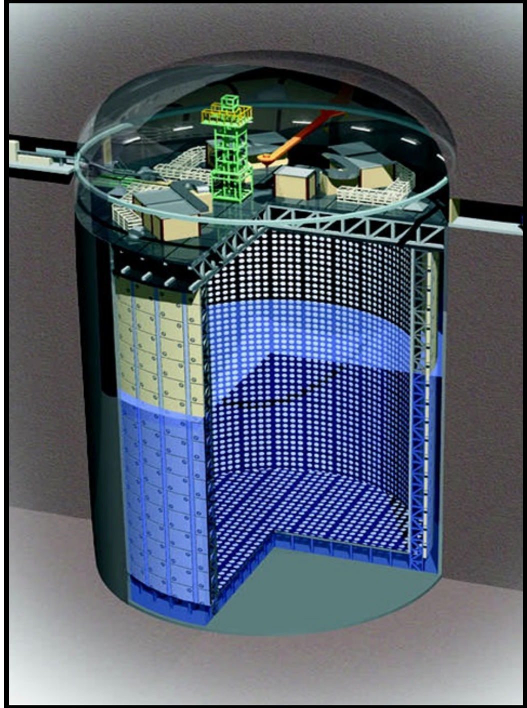
Need low natural and induced radioactivities

Example backgrounds (must also separate signals):

$$A(Z, N) \rightarrow A(Z+1, N-1) + e^- + \bar{\nu}_e$$

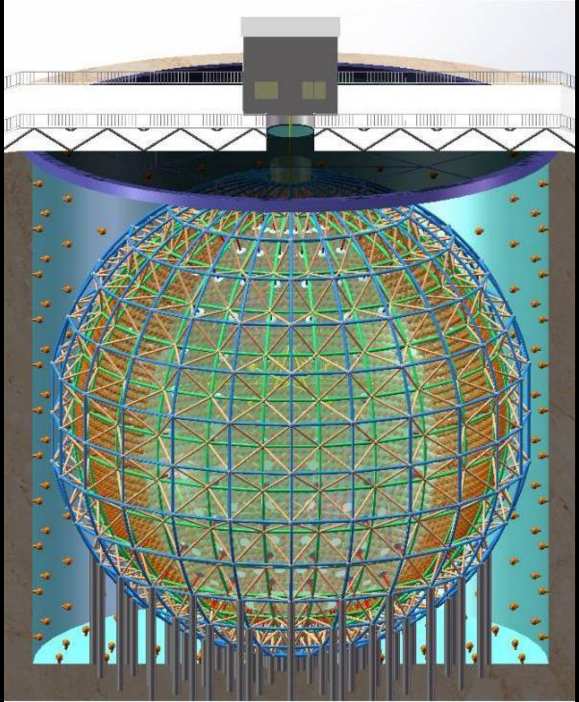
First: Exploit Planned Neutrino Detectors

Super-K



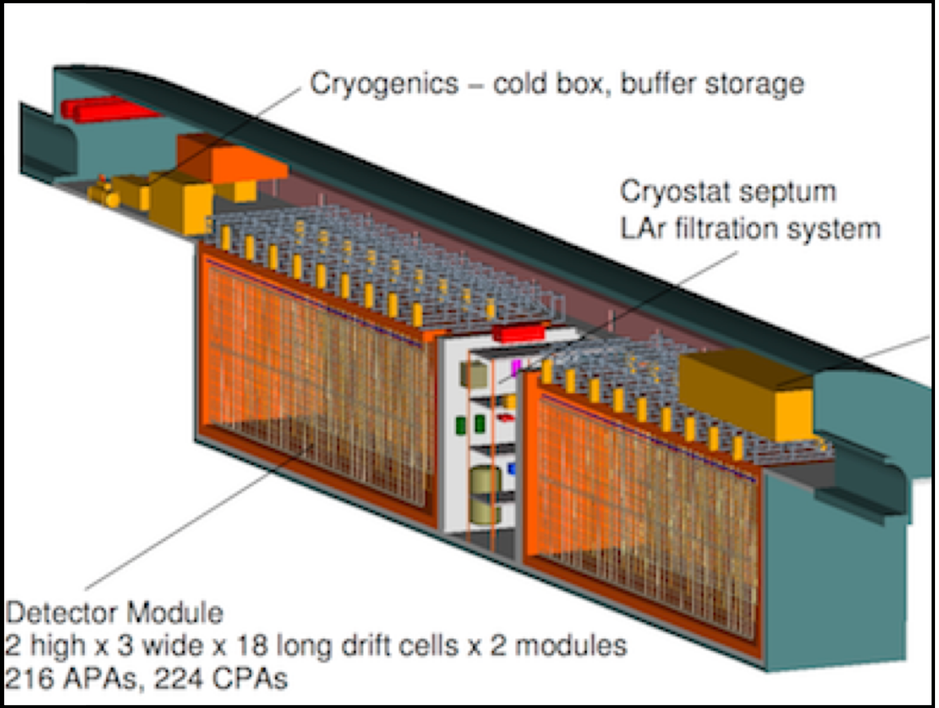
32 kton water
Japan
running

JUNO



20 kton oil
China
building

DUNE



34 kton liquid argon
United States
preparing

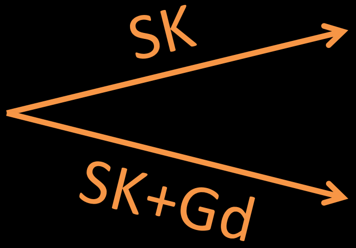
Excellent *potential* for MeV neutrino astronomy

Second: Enable Super-K Selection of Nuebar

Key signal reaction produces a neutron, but most backgrounds do not

Beacom and Vagins (2004):
First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



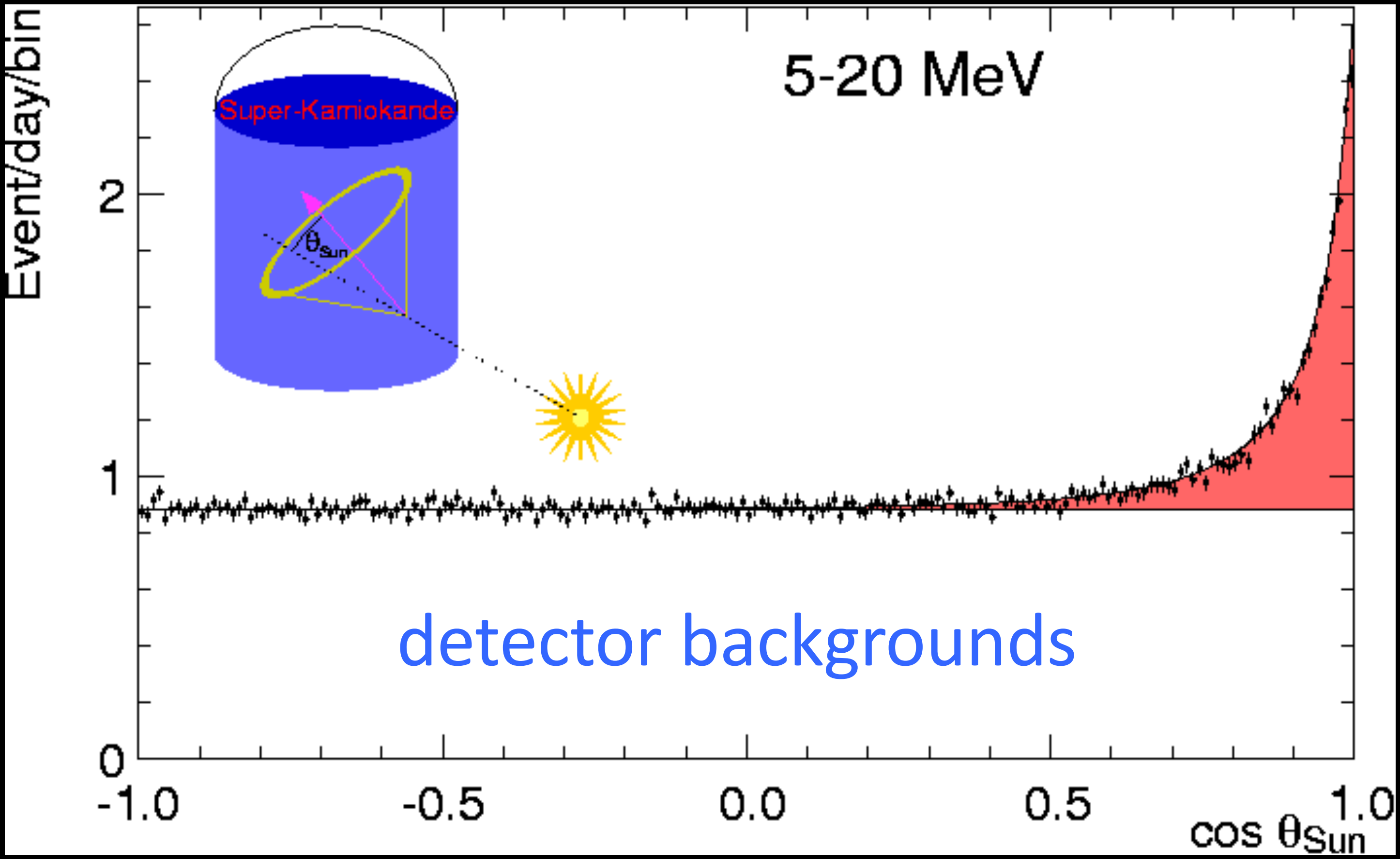
Neutron capture on protons
Gamma-ray energy 2.2 MeV
Hard to detect in SK

Neutron capture on gadolinium
Gamma-ray energy ~ 8 MeV
Easily detectable coincidence
separated by ~ 4 cm and ~ 20 μs

Super-K 2015: Yes

Third: Remove Detector Backgrounds

After strong cuts, still large detector backgrounds in Super-K



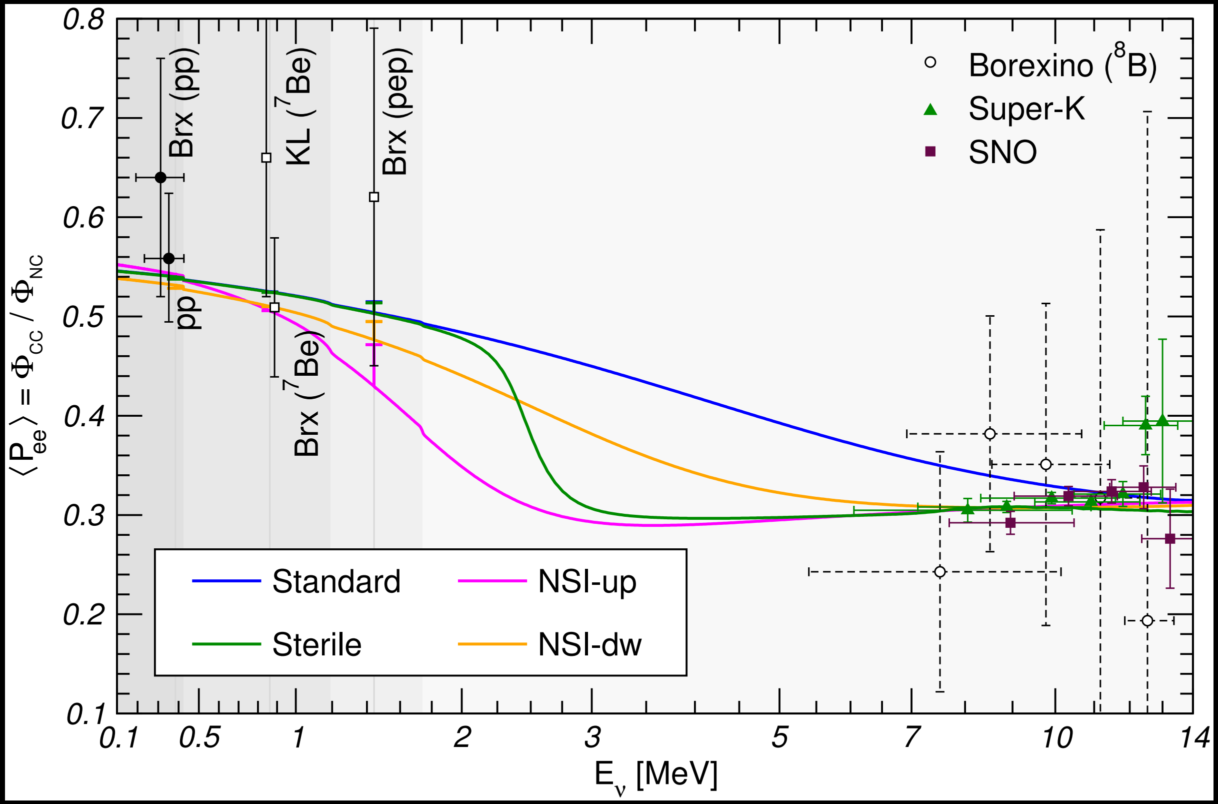
Signal is neutrino-electron scattering

Background is beta decays

Li and Beacom: can reduce spallation by factor ~ 10

Solar Neutrinos Redux

Discovery Potential: Particle Physics



Maltoni and Smirnov (2016)

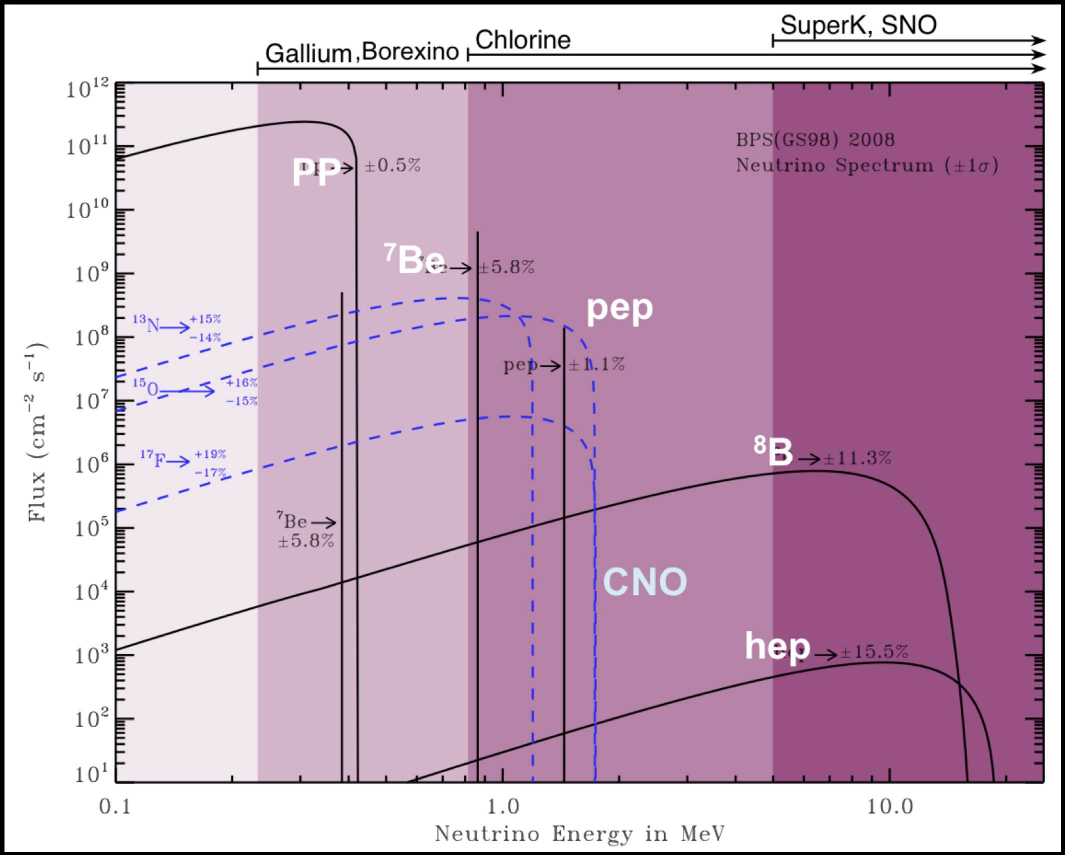
Directly measure energy dependence of MSW effect

Test solar-reactor dm^2 discrepancy

Many ways to search for new physics

Needs precise astrophysics to maximize potential

Discovery Potential: Astrophysics



Precisely measure 8B flux and hence core temperature

Discover *hep* flux and hence probe density profile

Discover CNO flux and hence probe metallicity puzzle

Needs precise particle physics to maximize potential

Two-Pronged Attack

Enu < few MeV

Fluxes high

Need new detectors at 1-kton scale

Improve on Borexino, etc. with mass

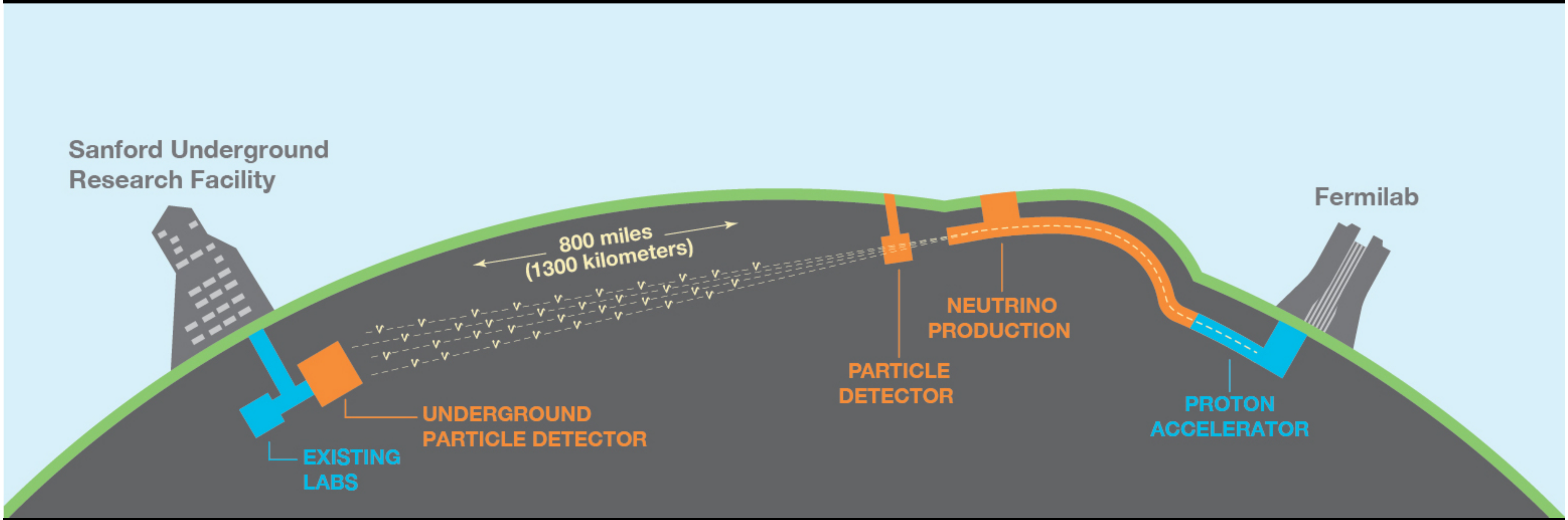
Enu > few MeV

Fluxes low

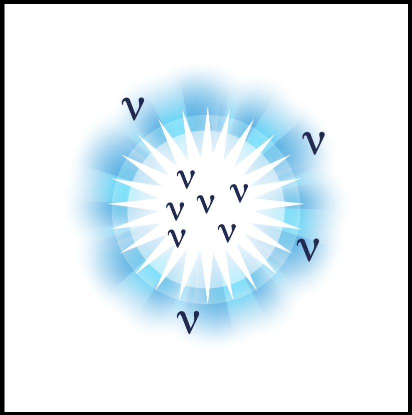
Need new detectors at 10-kton scale

Hard to improve on SK, SNO!

Behold DUNE



Origin of Matter

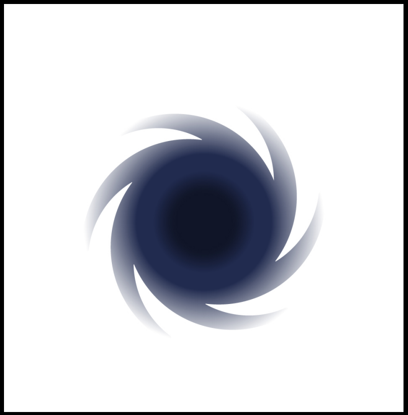


(Nu vs. Nu-bar)

Unification of Forces

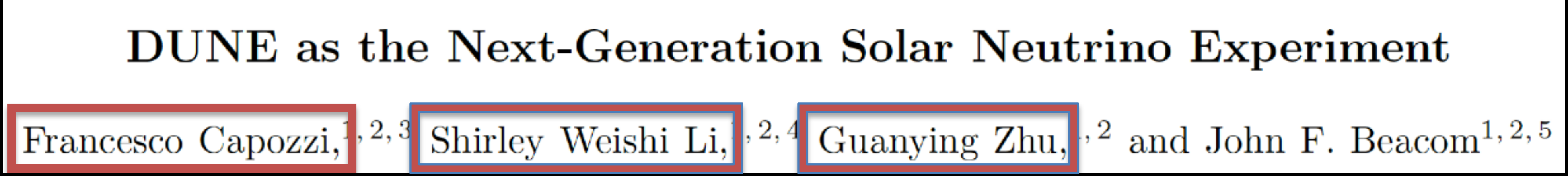
(Proton Decay)

Black Hole Formation



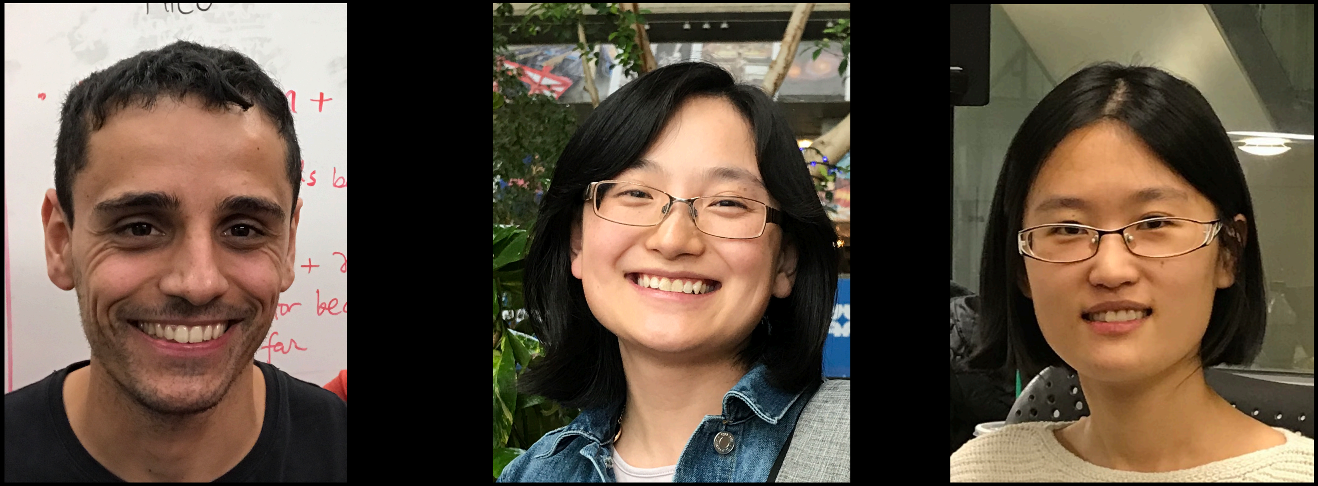
(Supernova Neutrinos)

Our Proposal for “DUNE-Solar”



DUNE as the Next-Generation Solar Neutrino Experiment

Francesco Capozzi,^{1,2,3} Shirley Weishi Li,^{2,4} Guanying Zhu,^{2} and John F. Beacom^{1,2,5}



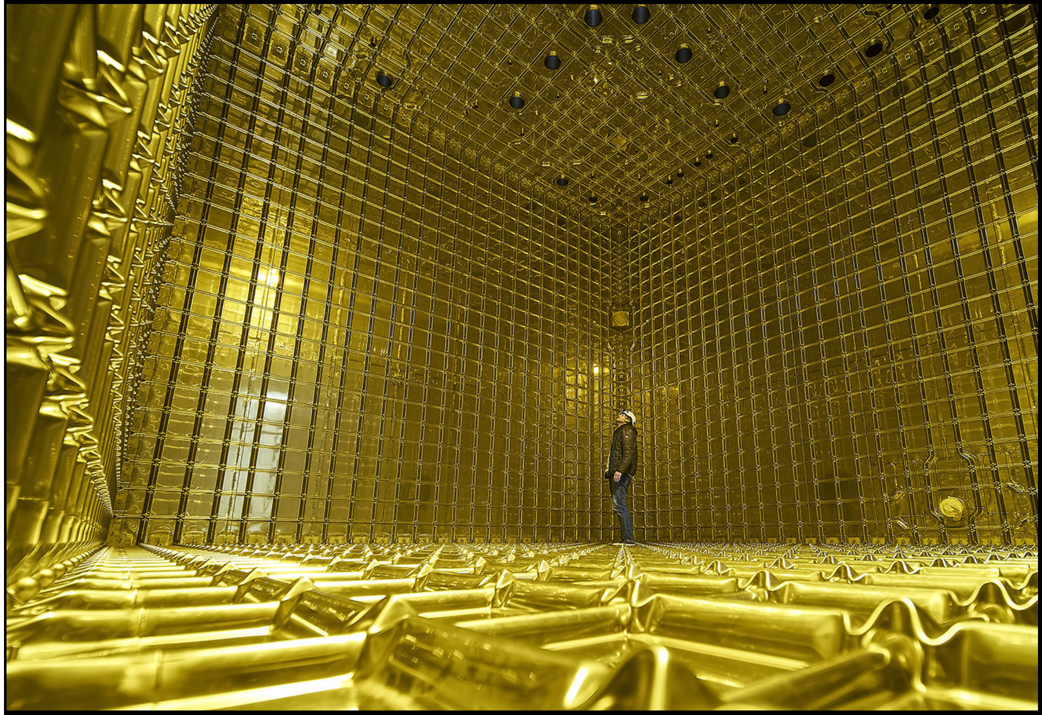
arXiv:1808.08232

Author Disclaimers:

We speak for ourselves as theorists, not on behalf of the DUNE Collaboration

This work is based on our ideas, our calculations, and publicly available information

DUNE Detector and Properties



Four modules, each 10 kton

Assume 100 kton-year
Triggering, processing, etc.
Read out as TPCs (charge)
Energy threshold 5 MeV
Energy resolution 7%
Angular resolution ~ 25 deg

We define physics goals and find the technical requirements
We find that they are challenging but feasible

Our Goals for DUNE-Solar

Particle Physics:

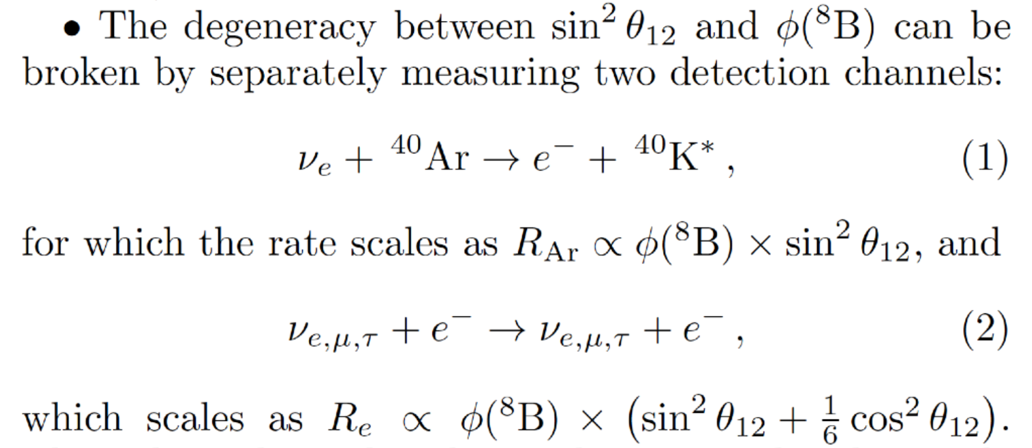
Best precision on sin^2
Best precision on dm^2
Powerful tests of new physics in comparison to JUNO reactor data

Astrophysics:

Best precision on 8B flux
Best precision on hep flux
Powerful tests of new astrophysics in comparison to other solar data

Must break essential degeneracies between the two

Our Strategy, Part 1



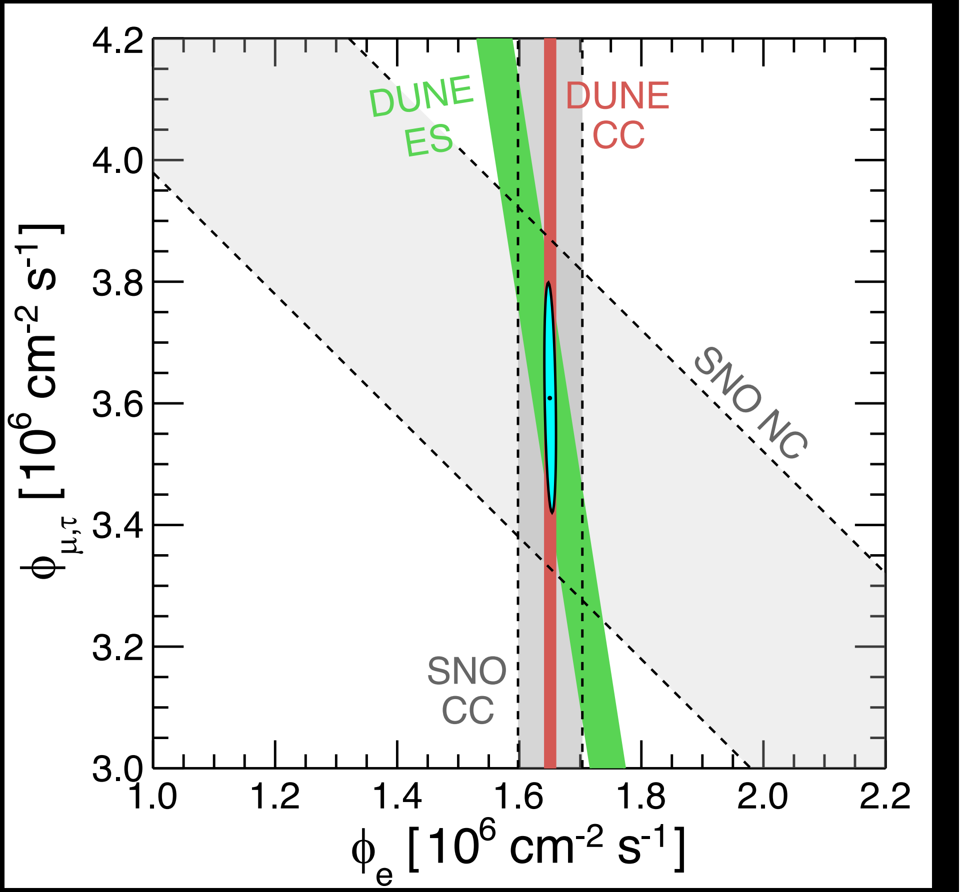
- The degeneracy between $\sin^2\theta_{12}$ and $\phi(^8\mathrm{B})$ can be broken by separately measuring two detection channels:

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^* \,, \qquad (1)$$

for which the rate scales as $R_{\mathrm{Ar}} \propto \phi(^8\mathrm{B}) \times \sin^2\theta_{12}$, and

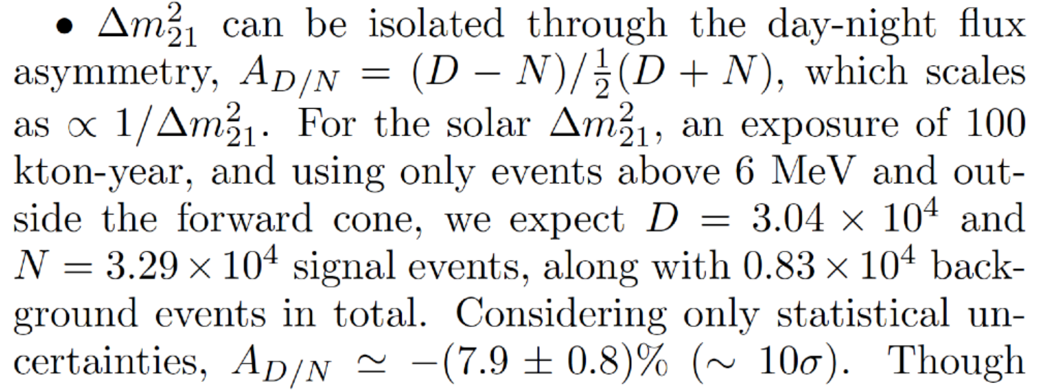
$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \,, \qquad (2)$$

which scales as $R_e \propto \phi(^8\mathrm{B}) \times \left(\sin^2\theta_{12} + \frac{1}{6}\cos^2\theta_{12}\right)$.

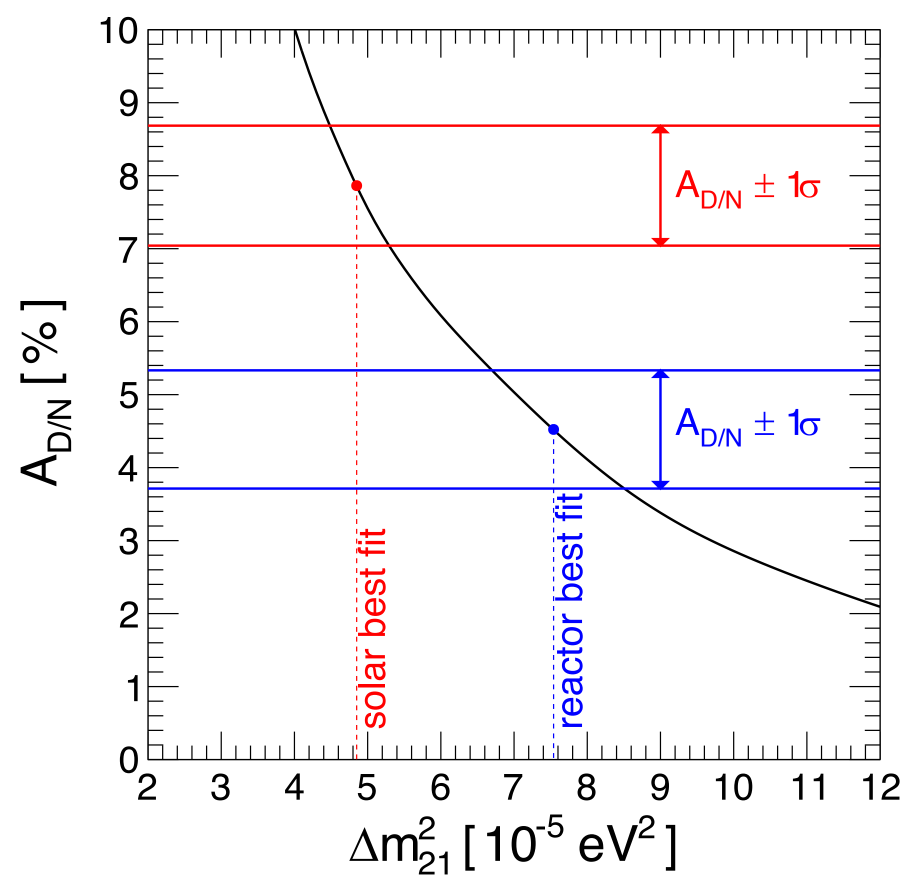


Isolate sin^2, 8B flux with crossing (and huge statistics)

Our Strategy, Part 2

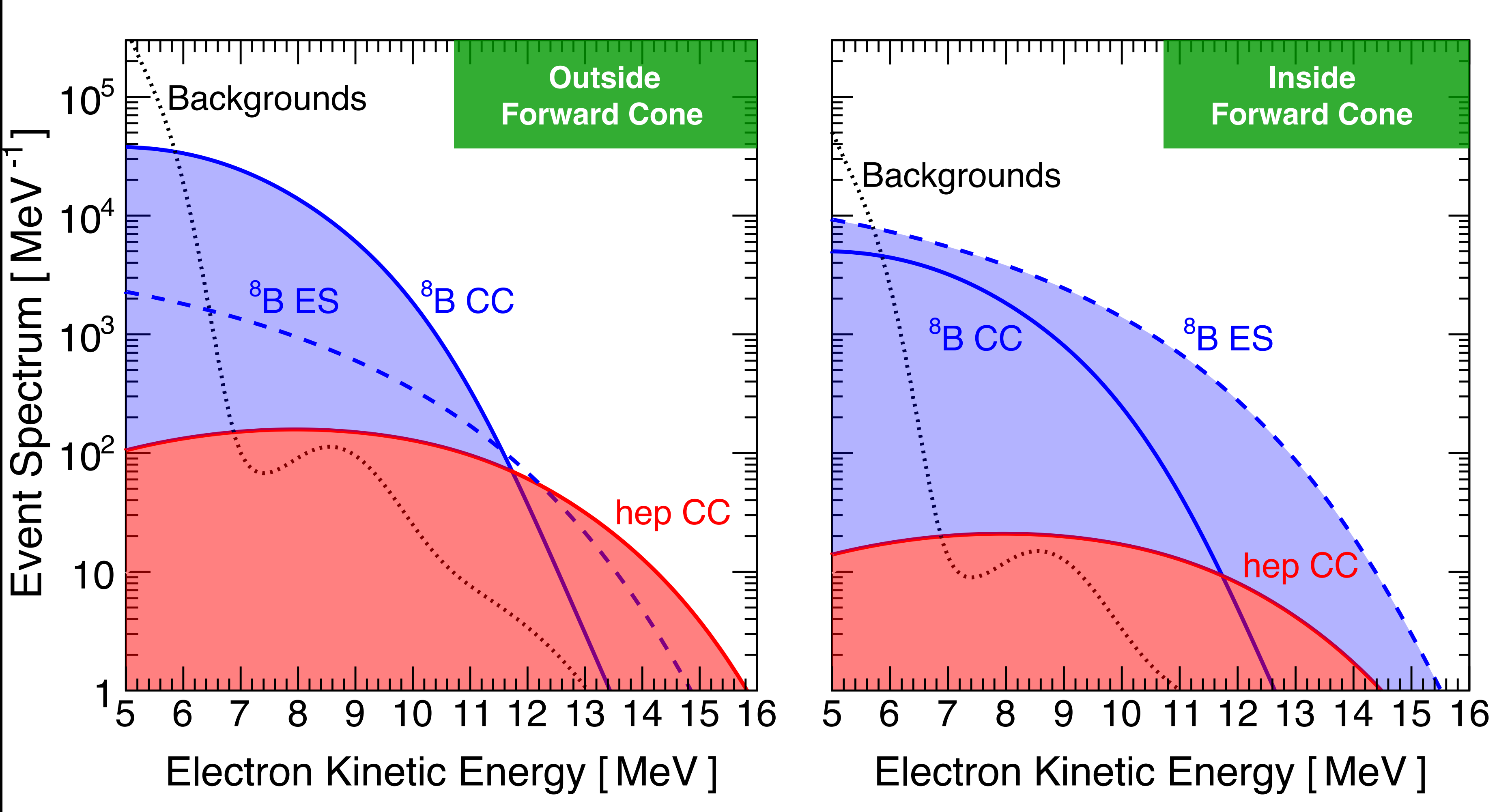


- Δm^2_{21} can be isolated through the day-night flux asymmetry, $A_{D/N} = (D - N)/\frac{1}{2}(D + N)$, which scales as $\propto 1/\Delta m^2_{21}$. For the solar Δm^2_{21}, an exposure of 100 kton-year, and using only events above 6 MeV and outside the forward cone, we expect $D = 3.04 \times 10^4$ and $N = 3.29 \times 10^4$ signal events, along with 0.83×10^4 background events in total. Considering only statistical uncertainties, $A_{D/N} \simeq -(7.9 \pm 0.8)\%$ ($\sim 10\sigma$). Though



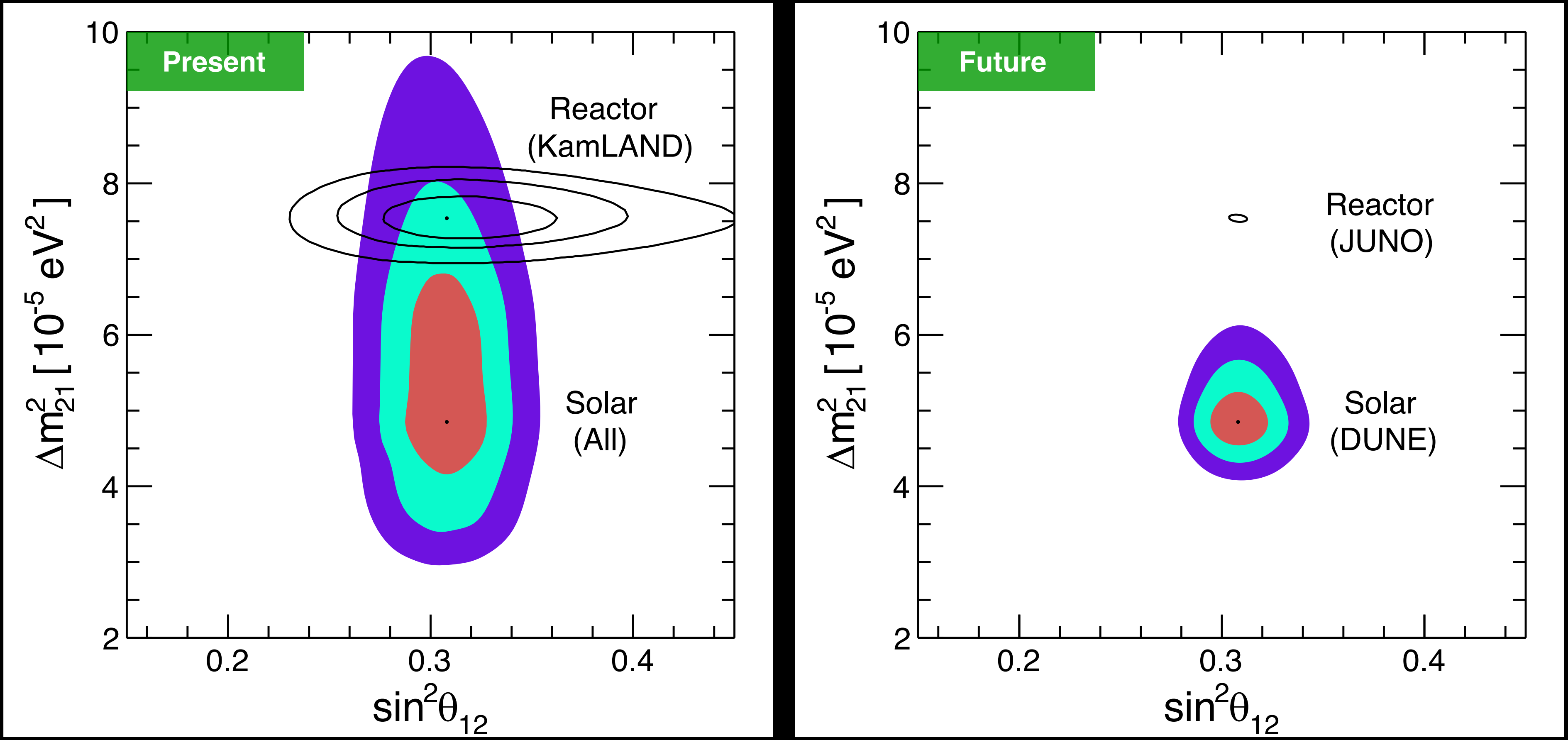
Isolate dm^2 with day-night effect (and huge statistics)

Calculated Spectra



In each panel, we assume only statistical separation

Calculated Sensitivity



In addition, 8B flux measured to ~ 2.5%, hep flux to ~ 11%

Prospects for Solar Neutrinos

- Solar neutrinos: great open questions, need new experiments
- This is the first study to consider the solar-neutrino prospects in DUNE in a comprehensive, detailed, realistic way
- DUNE would open substantial discovery space in particle physics and astrophysics that cannot be fully matched

This could greatly expand the return of DUNE
And, without it, we might not finish solar neutrinos

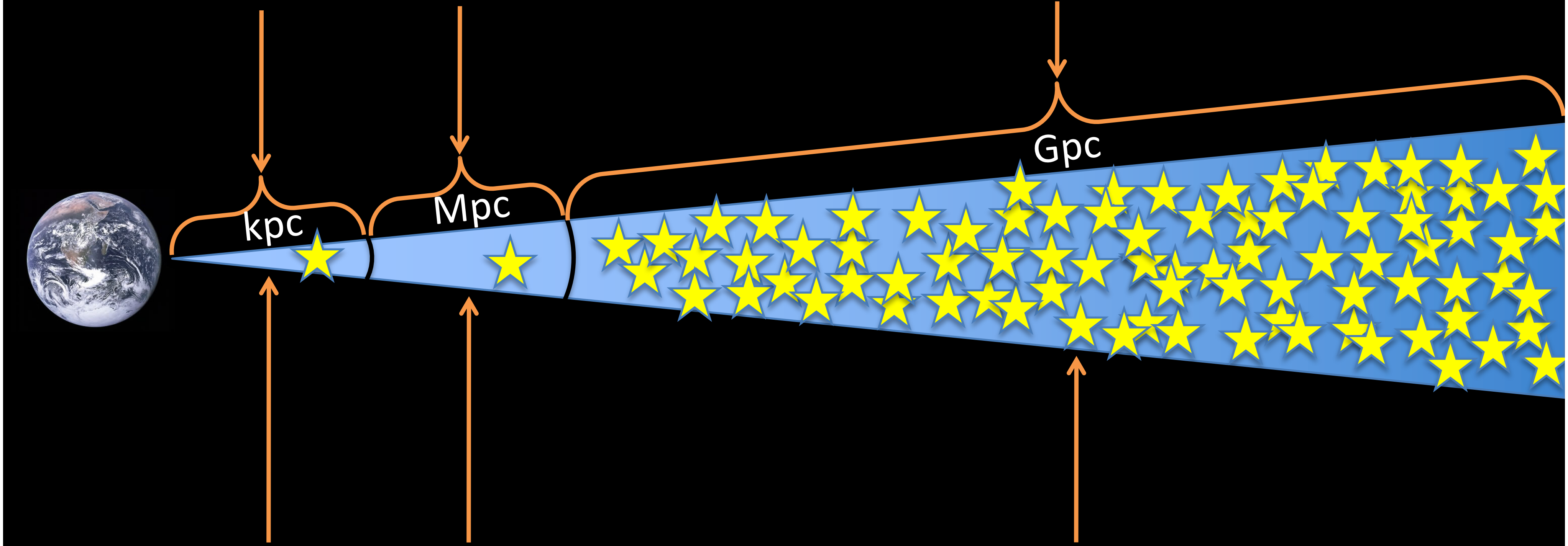
Supernova Neutrinos Redo

Distance Scales and Detection Strategies

$N \gg 1$: Burst

$N \sim 1$: Mini-Burst

$N \ll 1$: DSNB



Rate ~ 0.01/yr

Rate ~ 1/yr

Rate ~ 10^8/yr

high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

What May Be Missing

Milky Way Burst:

DUNE to collect full nu_e spectrum, know cross sections
JUNO to collect full nu_x spectrum
Localization of SN with neutrinos and ASAS-SN, etc.

Nearby galaxies Mini-Bursts:

A large enough neutrino detector

Diffuse Supernova Neutrino Background:

HK with added Gd

Need all three detections to understand core collapses

Fulfilling the Prophecy

The Long Game

Neutrino Science

Laboratory ν

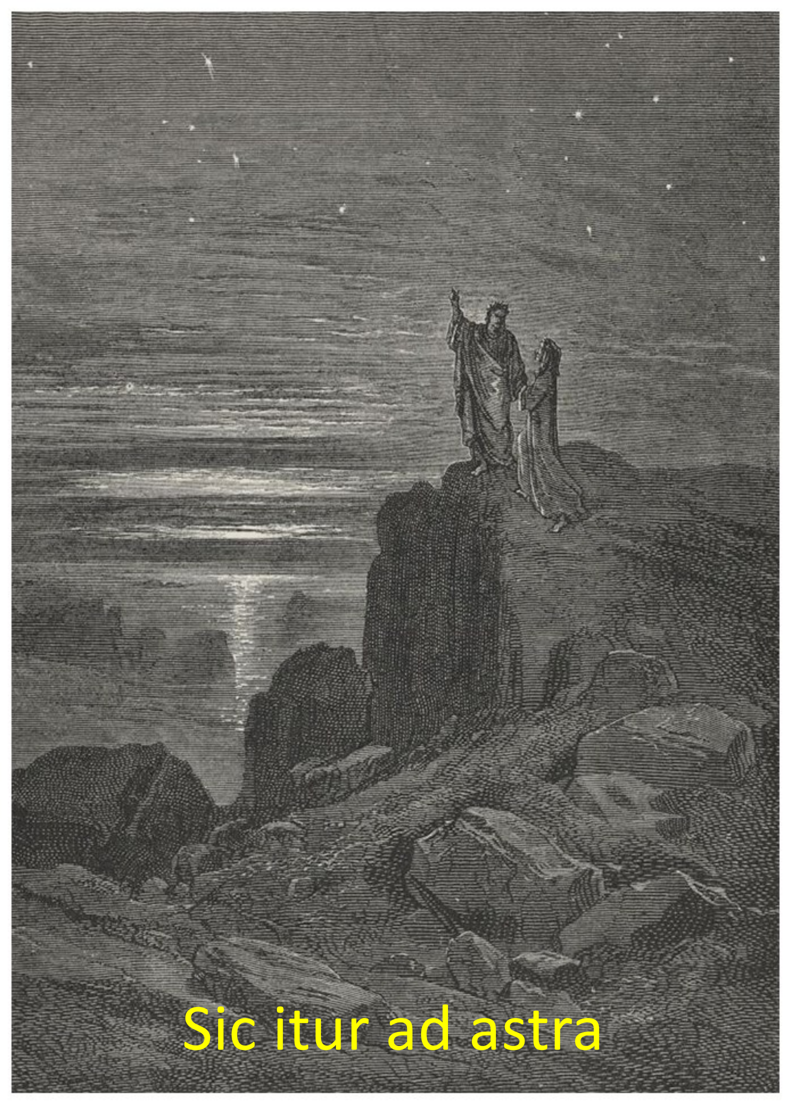
Cosmology ν

Astronomy ν

By combining these approaches, we will open rich discovery space to learn – simultaneously – about:

Neutrino properties
Cosmic history
Astrophysical sources

DUNE at MeV energies is critical



Thanks!

I am honored to visit the “House of Bari,” a legendary neutrino group