Snowmass Intensity Frontier Neutrino Subgroup Workshop

Low- and Medium-Energy Astrophysics with Large Underground LS Detectors

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SLAC

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Overview

- Experiments:
  - Current and future (near- and long-term)
- Physics Potential of LS detectors
- Experimental techniques:
  - The future of LS detectors

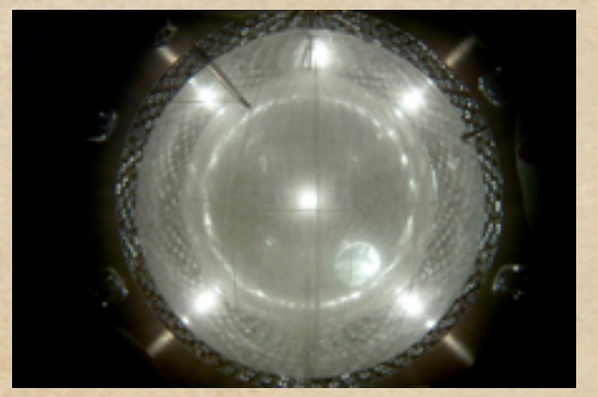
Current / Near-term Organic-Scintillator Experiments

ES detection of ν_x

High light yield

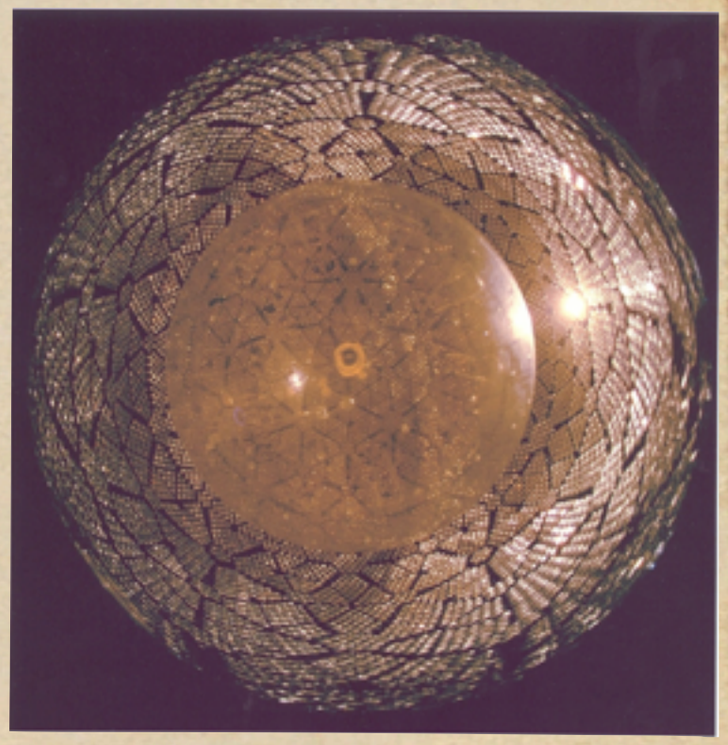
⇒ low E threshold

Borexino



KamLAND

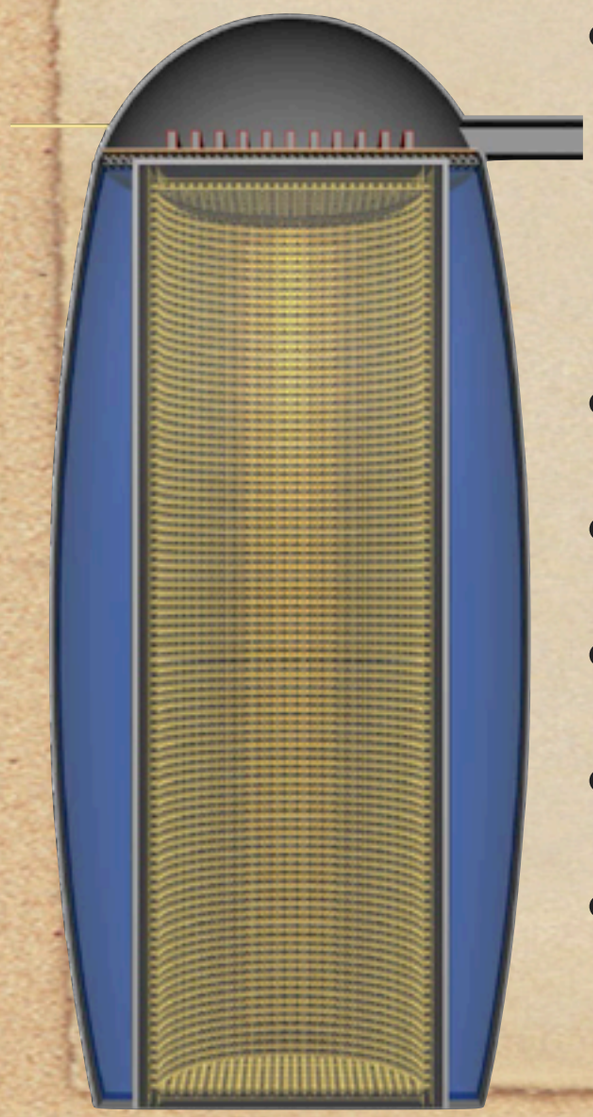
SNO+



Roughly to scale

Future / Proposed Organic-Scintillator Experiments

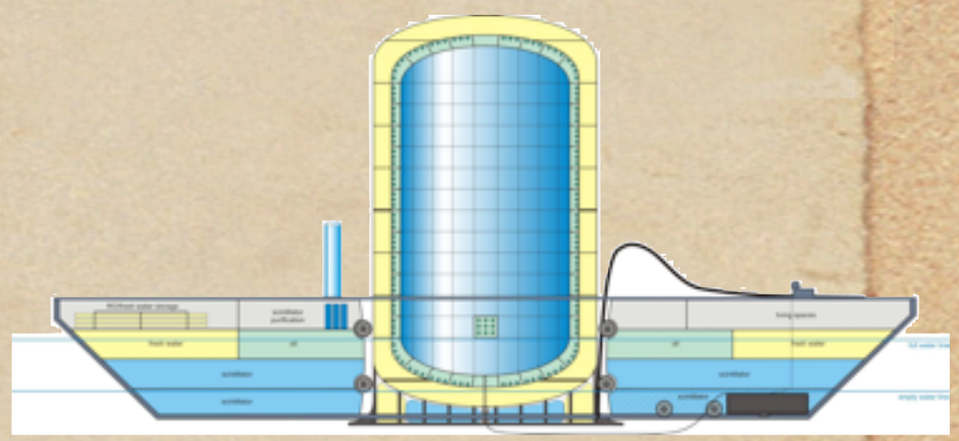
LENA



- 50kT
- 30,000 12" PMTs + concentrators
  - ➡ ~30% coverage
- Supernova neutrinos
- Geoneutrinos
- Solar Neutrinos
- Indirect dark matter
- Proton decay

LENA: 4000 mwe, 50000 tons

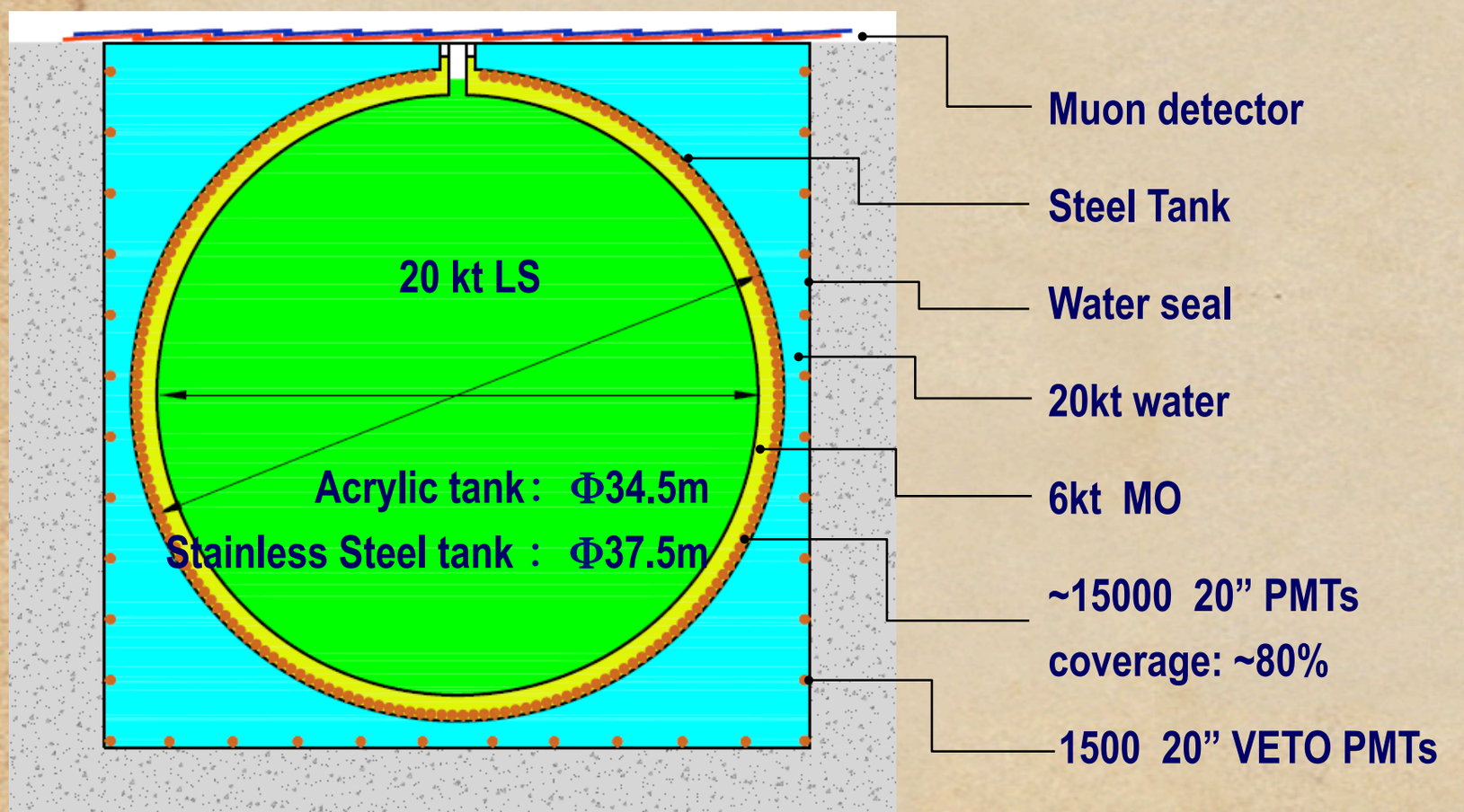
HanoHano



- 10kT movable detector
- Geoneutrinos
- Mass hierarchy

Future / Proposed Organic-Scintillator Experiments

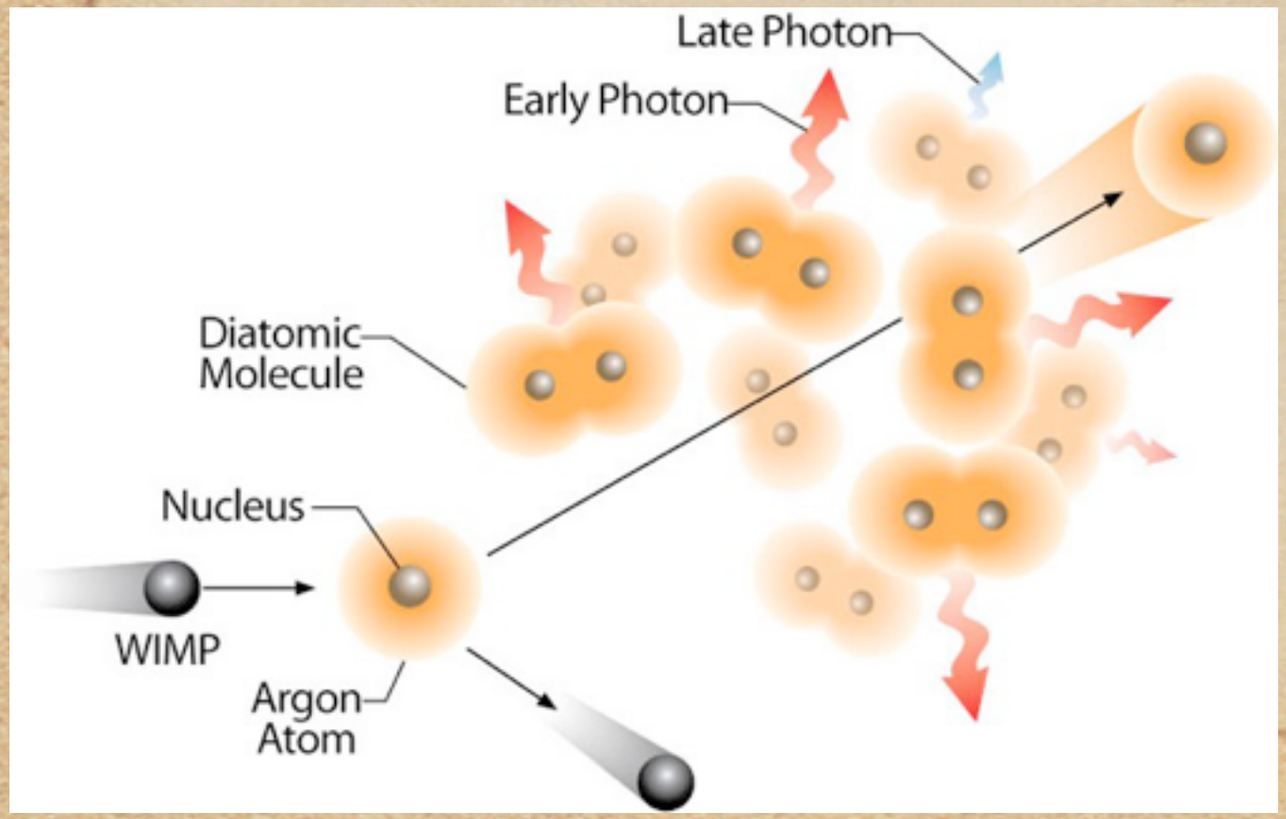
Daya Bay II



- 20kT
- ~80% coverage
- 3% resn:
  - ➡ 1200 pe/MeV
- Mass hierarchy
- Precision mixing parameter measts
- Supernova neutrinos
- Geoneutrinos

Inorganic LS Detectors

- Transparent to its own scintillation light
- High light yield (LAr ~ 40k γ /MeV) → low t/hs
- Energy dep produces singlet / triplet diatomic molecules with different decay times

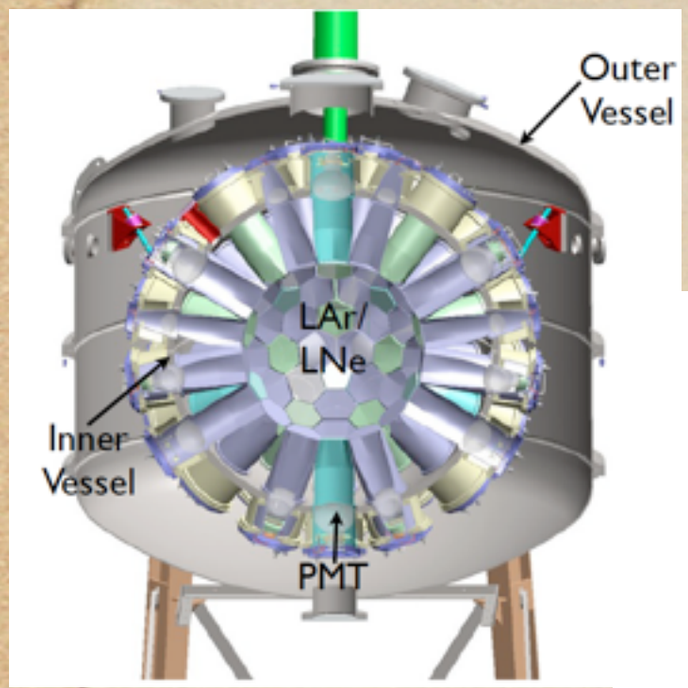


- Triplet state highly suppressed for nuclear recoils

➡ signal / bkg separation

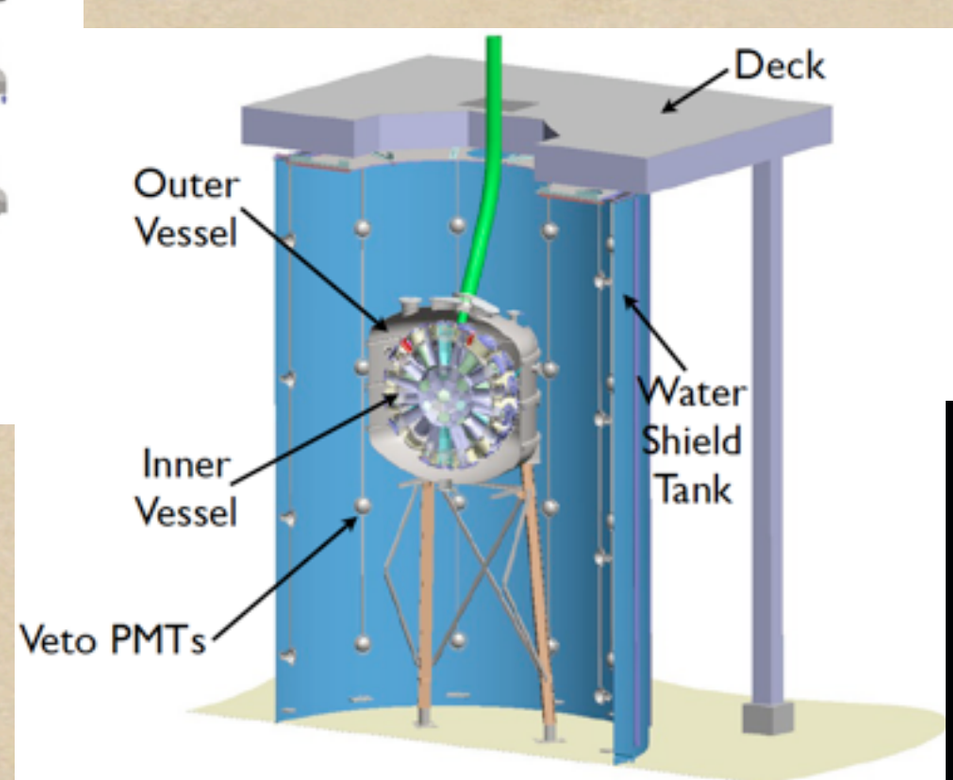
	Singlet	Triplet
He	~10ns	13 s
Ne	<18.2 ns	14.9 μs
Ar	7 ns	1.60 μs
Xe	4.3 ns	22 ns

Inorganic LS Detectors



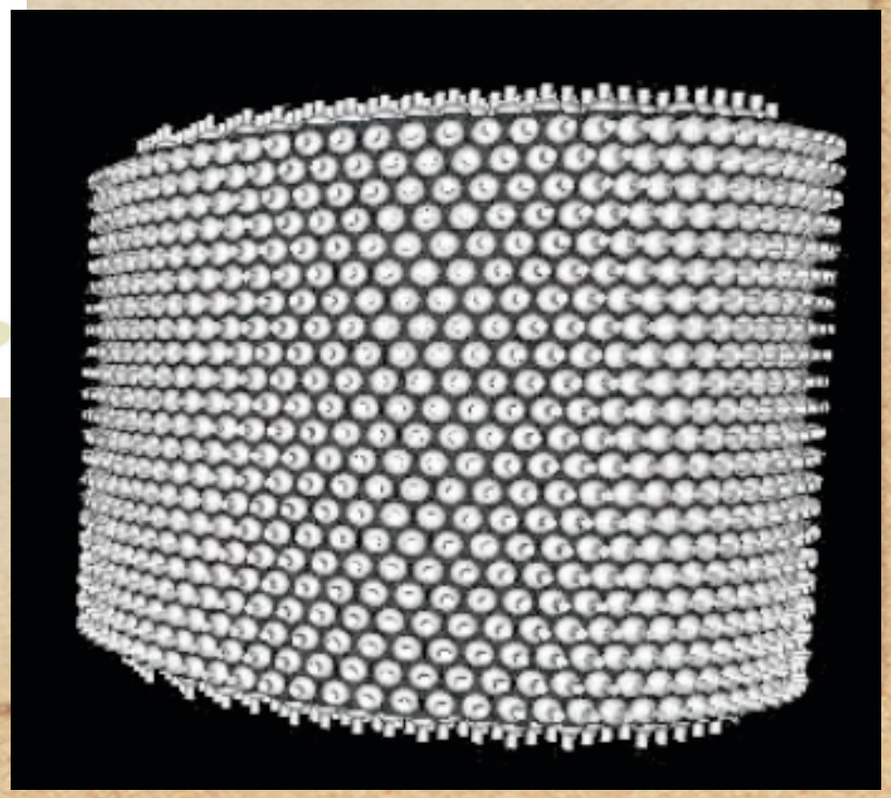
MiniCLEAN

& DEAP-3600



- Simple design
- Easily scalable
- (Relatively) inexpensive

CLEAN (40-140T)



- Direct dark matter detection

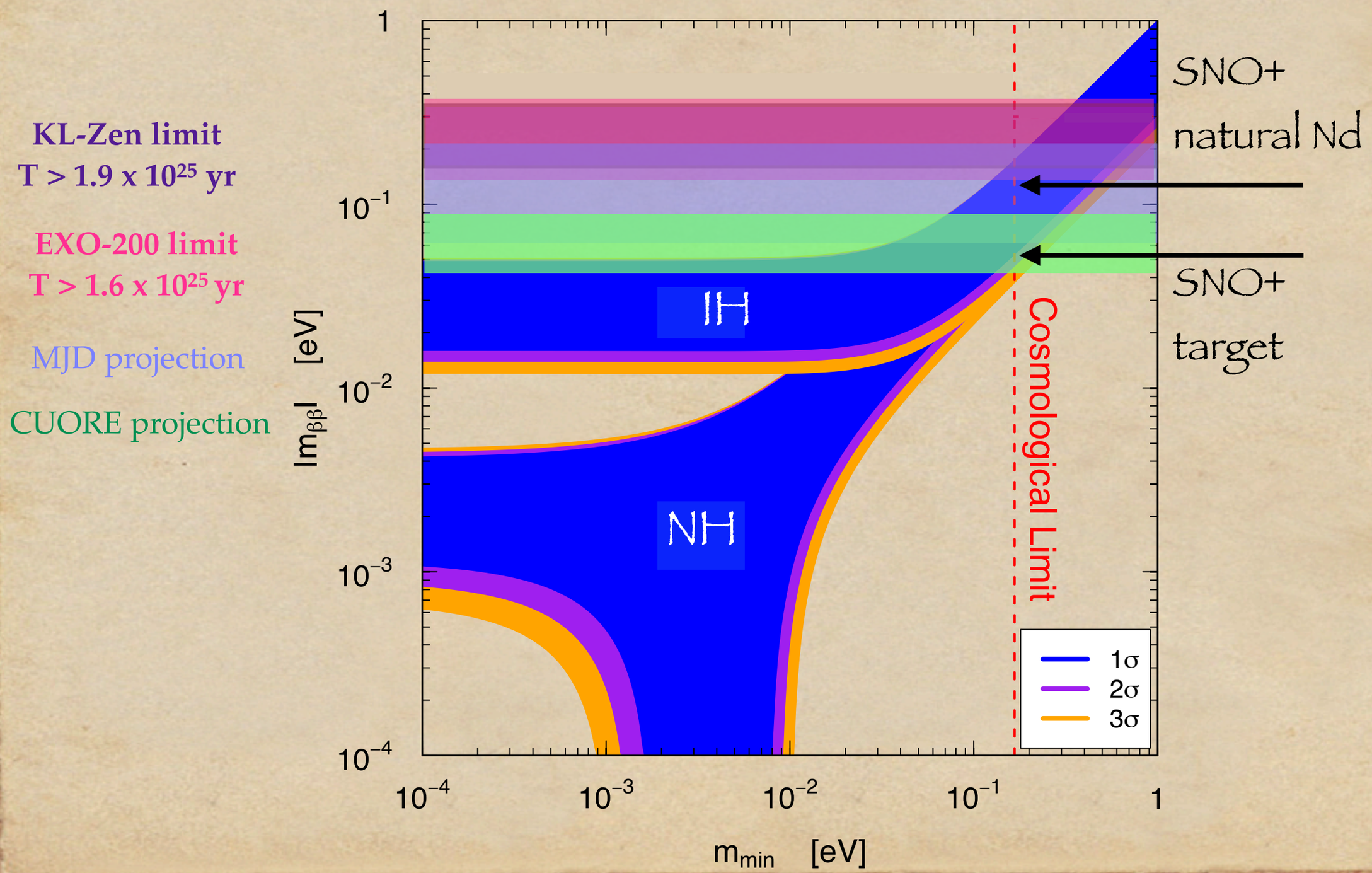
Features of LS Detectors

- High light yield (~ 10,000 γs / MeV)
  - ➡ Low energy threshold
  - ➡ Good energy resolution (rel to water Cherenkov)
  - ➡ Improved physics reach
- Particle-dependent decay time: α-β separation
- Isotropic light (no directional info)

Physics reach of LS Detectors

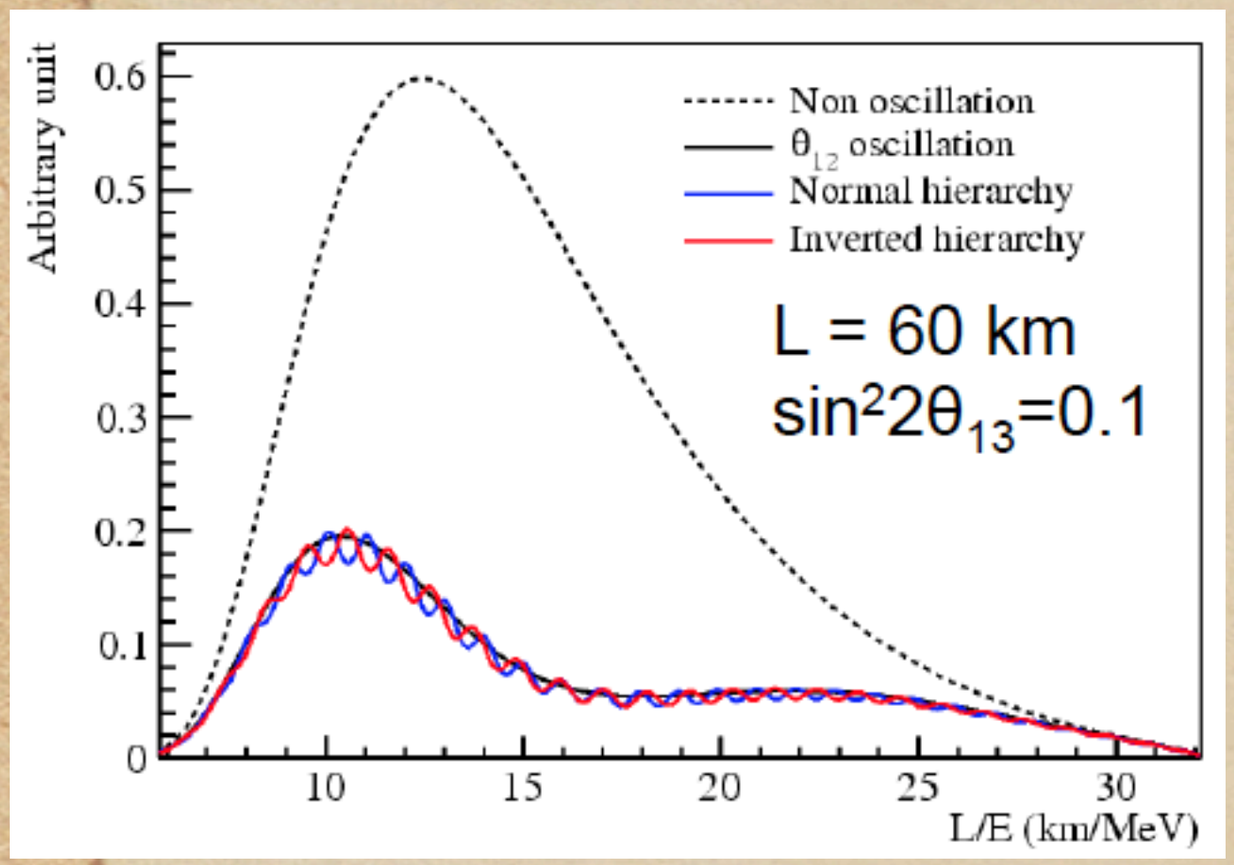
1. Neutrinoless DBD
2. Neutrino mass hierarchy
3. Solar neutrinos
4. Geoneutrinos
5. Supernova neutrinos
6. Dark matter
7. Proton Decay

1. Neutrinoless DBD



S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

2. Neutrino Mass Hierarchy



Survival probability of electron antineutrinos depends on mass hierarchy:

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}),$$

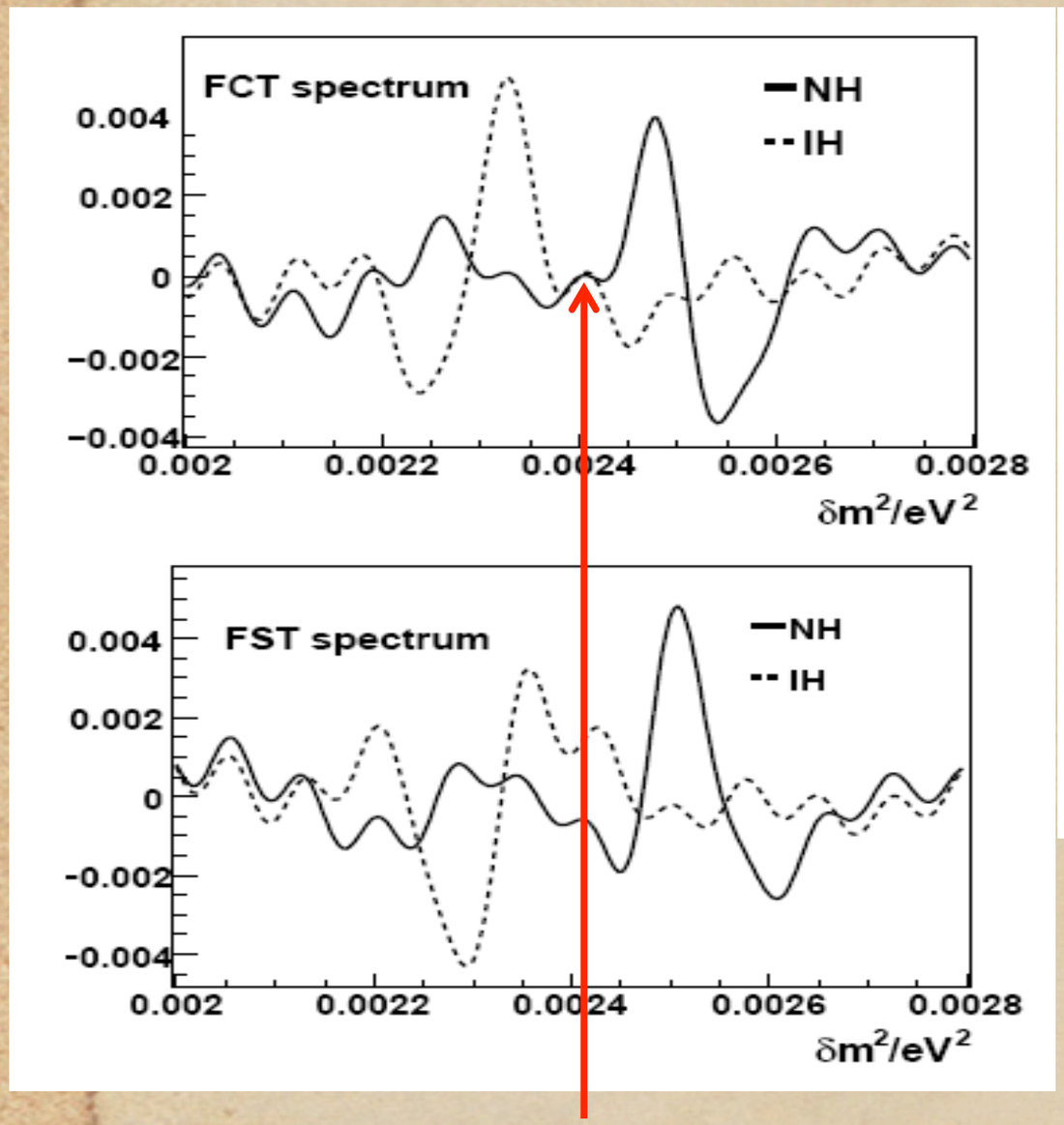
$$\Delta_{ij} = \frac{1.27\left|\Delta m^2_{ji}\right| L}{E}$$

Fourier analysis of observed spectrum can resolve the true mass hierarchy

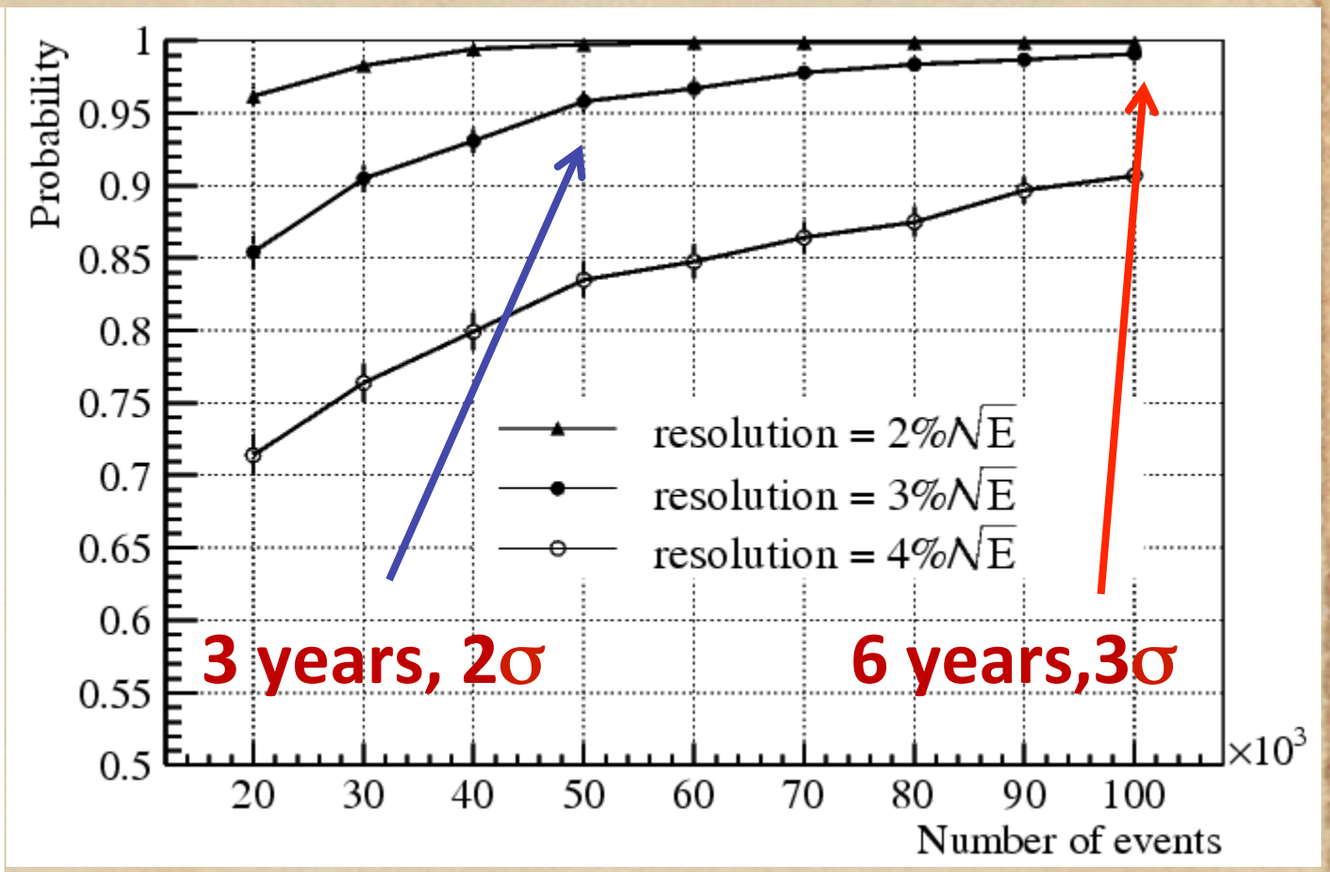
$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

Courtesy of K.-B. Luk

MH at Daya Bay II



ΔM^2_{23}



Improved precision on ΔM^2_{23} (T2K/Nova):

1.5% → 4.5σ in 6 yrs

1.0% → 5.0σ in 6 yrs

Courtesy of Y. Wang

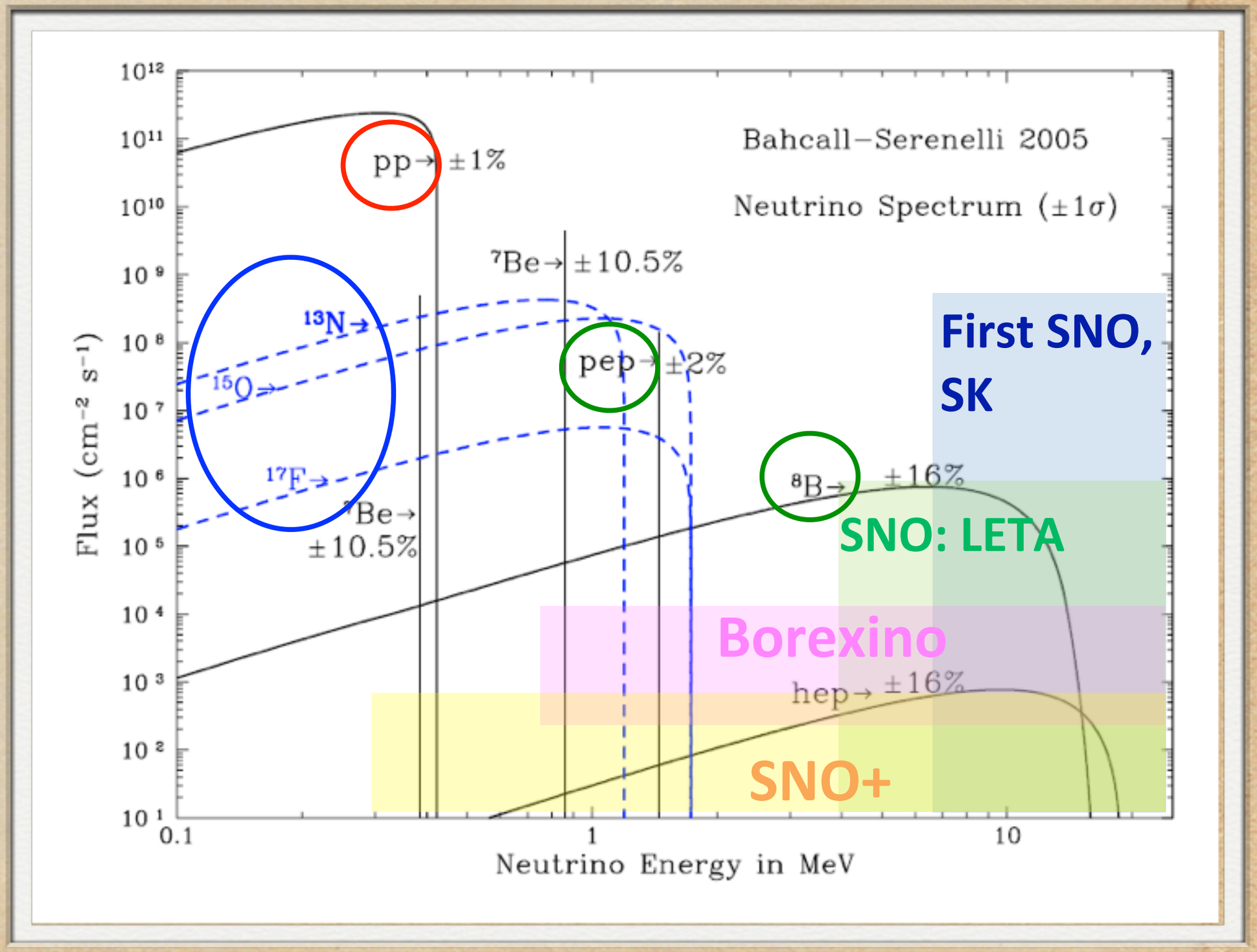
3. Solar Neutrinos

Luminosity constraint

Test MSW / new physics
Day-night

Solar metalicity

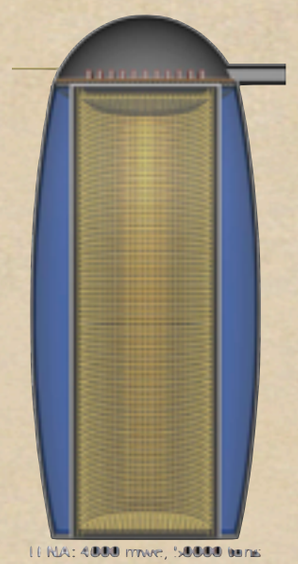
Precision oscillation parameters



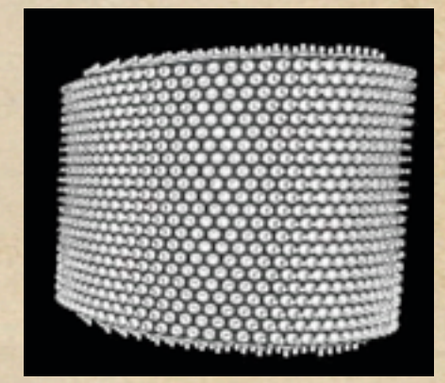
What is Left?

- Day/Night asymmetry
  - Needs statistics
- Ultra-low threshold detection
  - pp
- CC detection of solar neutrinos
  - Precision spectral measurement
  - CNO separation

LENA

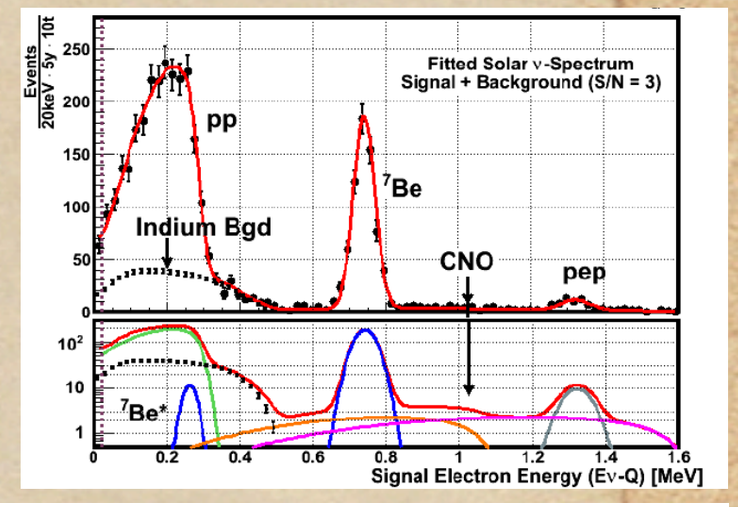


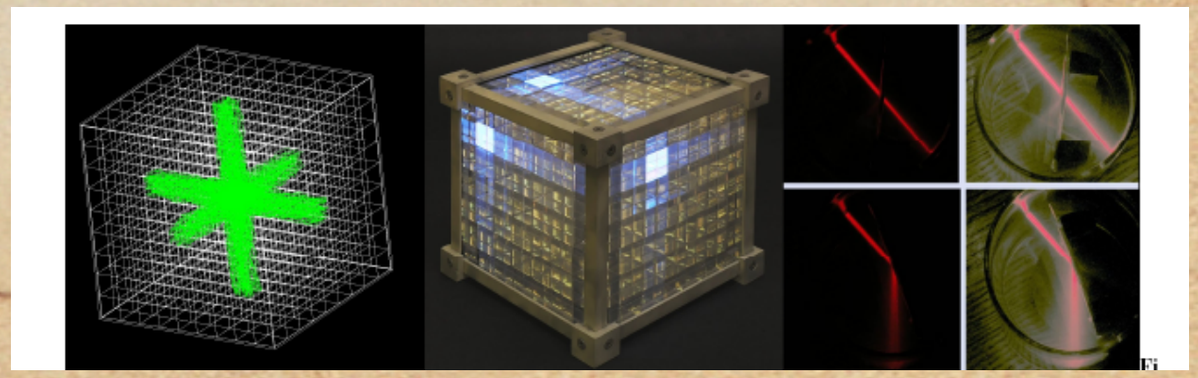
100T CLEAN



LENS

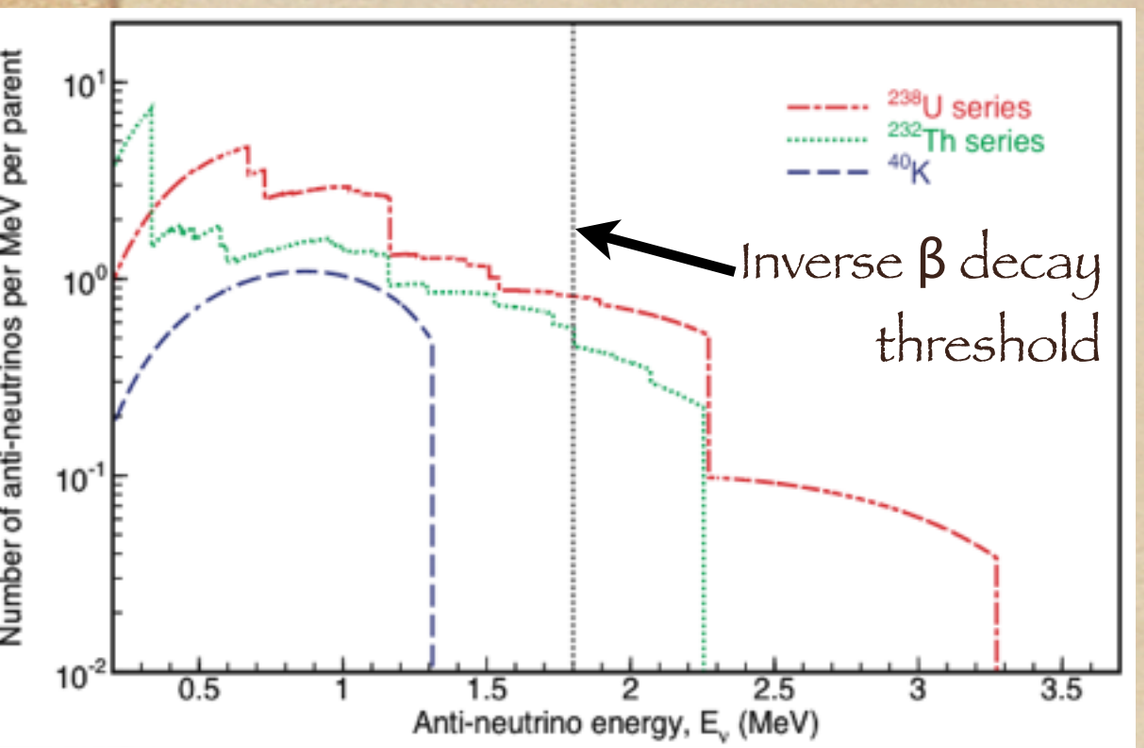
^{115}In-loaded LS





4. Geoneutrinos: To Date

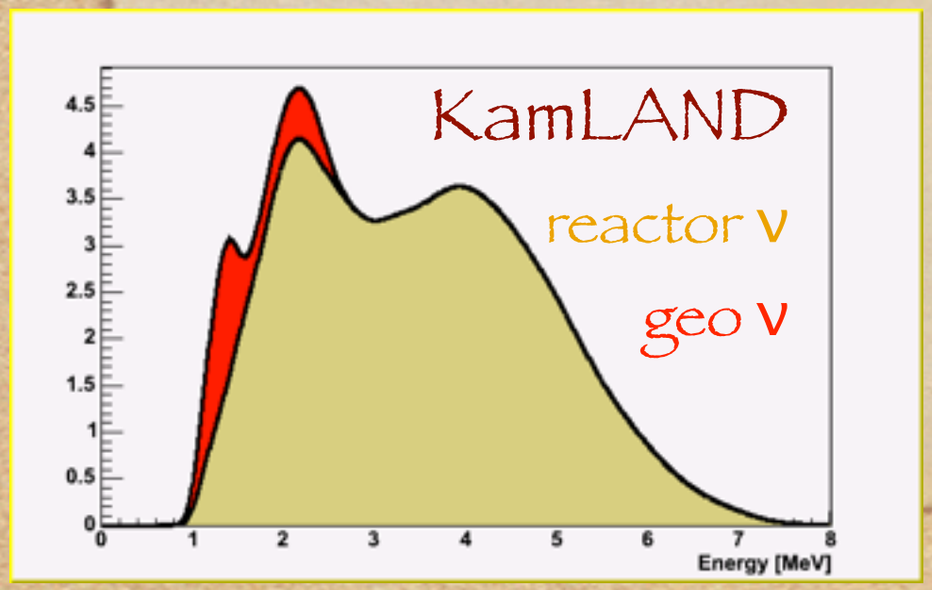
Electron antineutrinos from U, Th, K decay in the Earth



Assay the entire Earth by looking at the "antineutrino glow"

Fundamental info on terrestrial radiogenic heating

Important implications for the origin and thermal history of the Earth



KamLAND: 40.0 ± 10.5 ± 11.5 TNU

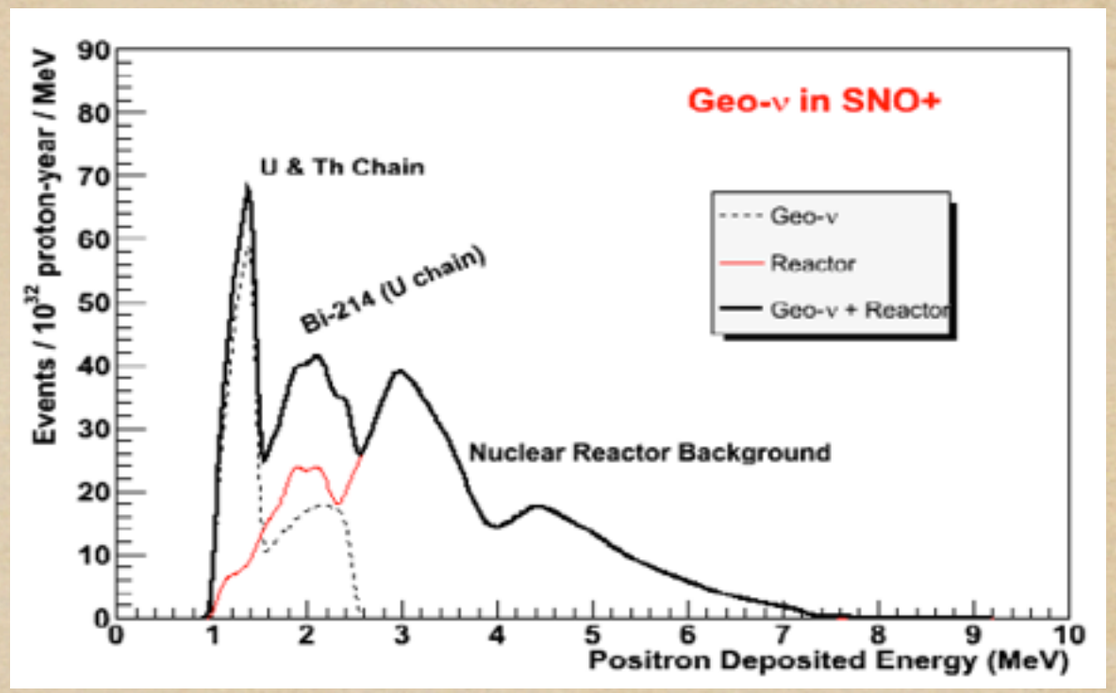
Borexino: 64 ± 25 ± 2 TNU

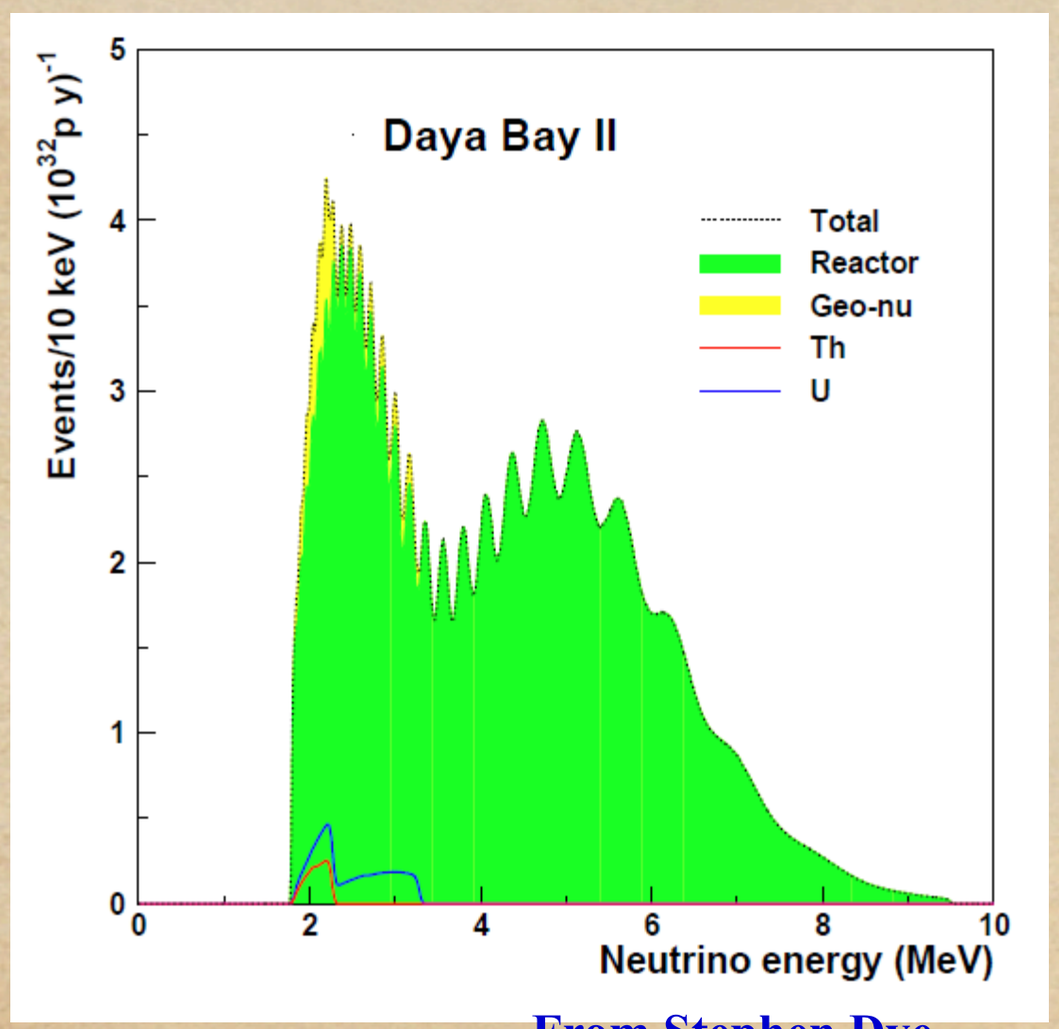
4. Geoneutrinos: Future

Low reactor bkg at SNO+

Rate: expect ~20 events /yr

(~20% mantle contribution)





From Stephen Dye

Daya Bay II, LENA:

> x10 statistics

Challenging to get ~systematics

Would really like an oceanic meast

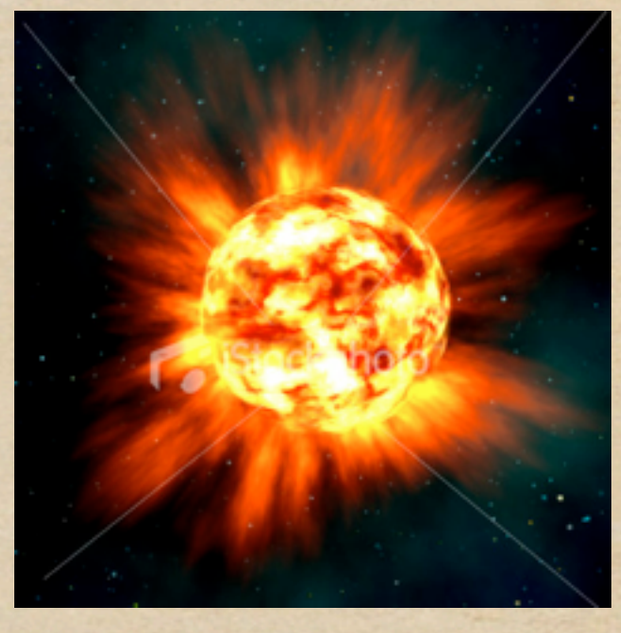
⇒ HanoHano

5. Supernova Neutrinos

Current generation (SNO+)

Anti neutrino reaction	Exp # events per 780T
$\nu_x + e^- \rightarrow \nu_x + e^-$	14 / 15
$\nu_x + p \rightarrow \nu_x + p$	494 / 318
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	2 / 2
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	6 / 3
$\nu_x + {}^{12}C \rightarrow {}^{12}C^*(15.11MeV) + \nu_x$	47 / 14
$\bar{\nu}_e + p \rightarrow n + e^+$	194 /121

M, Schumaker, using Beacom & Vogel / Burrows models
For supernova at 10kpc



A careful design of calibration hardware and operational procedures should allow a semi-automated response in the long run.

5. Supernova Neutrinos

Next generation: Daya Bay II

Anti neutrino reaction	Exp # events
$\nu_x + e^- \rightarrow \nu_x + e^-$	singles
$\nu_x + p \rightarrow \nu_x + p$	singles
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	10-100
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	10-100
$\nu_x + {}^{12}C \rightarrow {}^{12}C^*(15.11\text{MeV}) + \nu_x$	600
$\bar{\nu}_e + p \rightarrow n + e^+$	3000

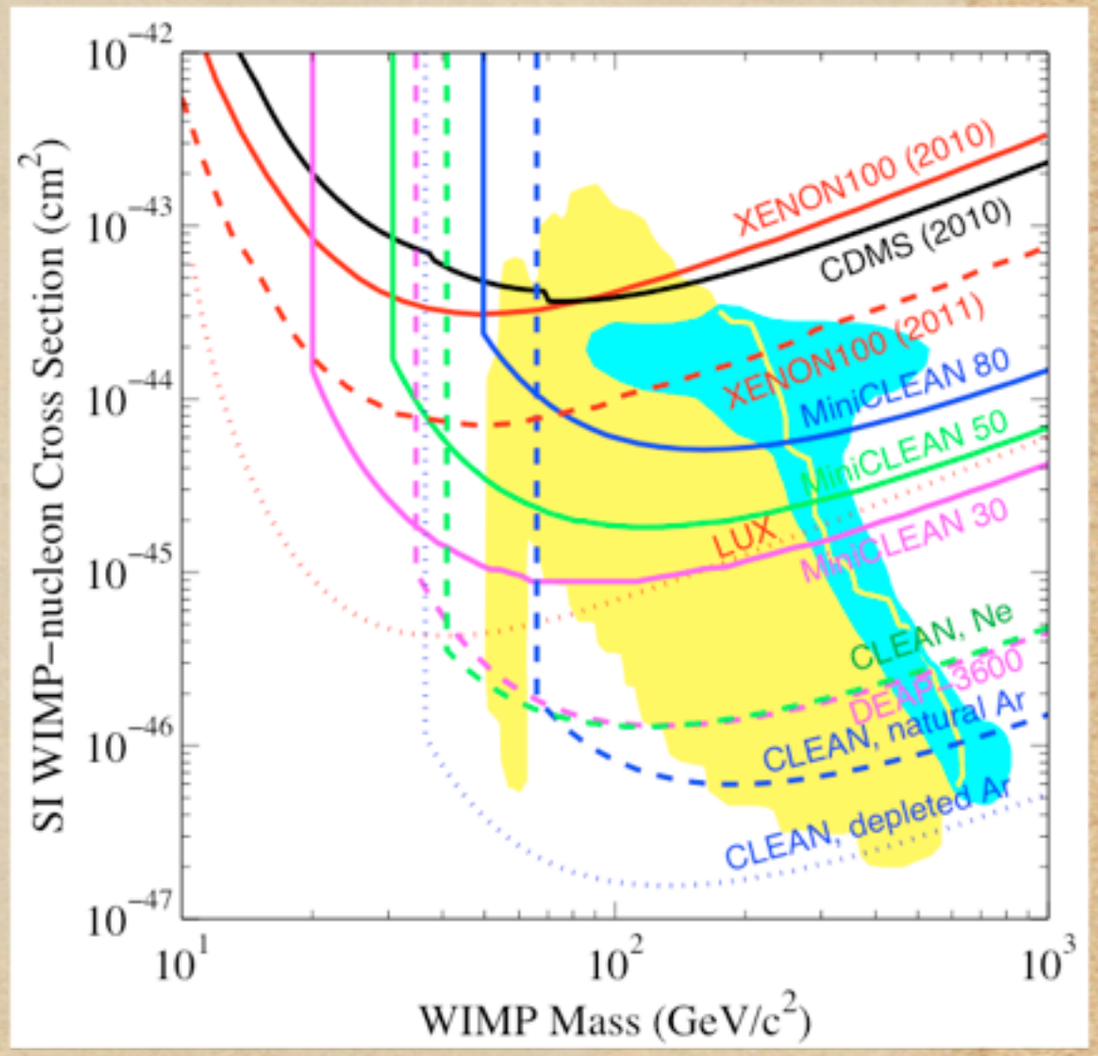
Correlated events, not seen by Cherenkov detectors

Courtesy of Y. Wang

Assume 10kpc, 3×10^{53} erg

6. Dark Matter

1. Direct detection with inorganic LS detectors
2. Indirect detection e.g. LENA
   - Antinu from DM annihilation / decay
   - Detect via IBD
   - Search for monoE peaks
   - Limits on $T_{1/2}$ or σ



7. Proton Decay

- Large-scale next-generation detectors:

  lots of protons!

- e.g. $p \rightarrow K^+ + \overline{\nu}$
- Current best limit: $\tau > 2.8 \times 10^{33}$ yr (90% CL) from SuperK (6.3-MeV γ tags p decay inside O nuclei)
- LS detector can directly detect the K^+ (& the μ from its decay)
- 10 yrs data in LENA $\Rightarrow \tau > 4 \times 10^{34}$ yr (90% CL)

Experimental Techniques

or "How to Scale Up?"

- Increase photocathode coverage
  - HQE PMTs + light concentrators
  - LAPPD (Large Area PS Photo Detector)
- Increase light yield
  - Reduce attenuation
  - Additive e.g. quantum dots (*)
- Increase information
  - Directionality from Cherenkov component

(*) "Next Generation Liquid Scintillator Based Detectors: Quantums Dots and Picosecond Timing" L. Windlow

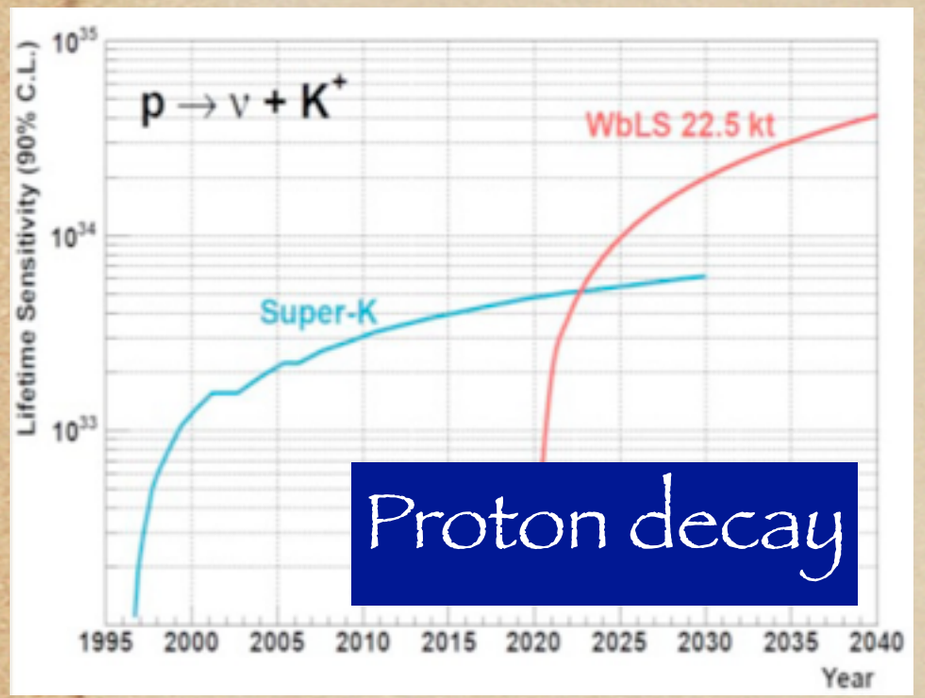
Water-Based LS Target

Dissolution of LS into ultra-pure water

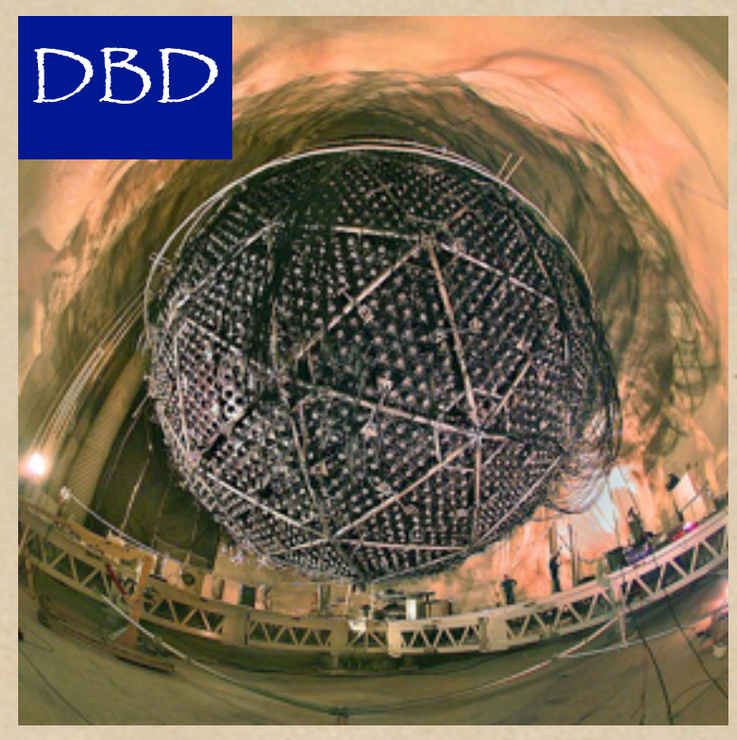
- ✳ High light yield of LS
  - ➡ Low energy threshold
  - ➡ Good energy resolution
- ✳ Directional info from Cherenkov in H_2O
- ✳ Long attenuation of water
- ✳ Increased metal loading (hydrophilic ions)

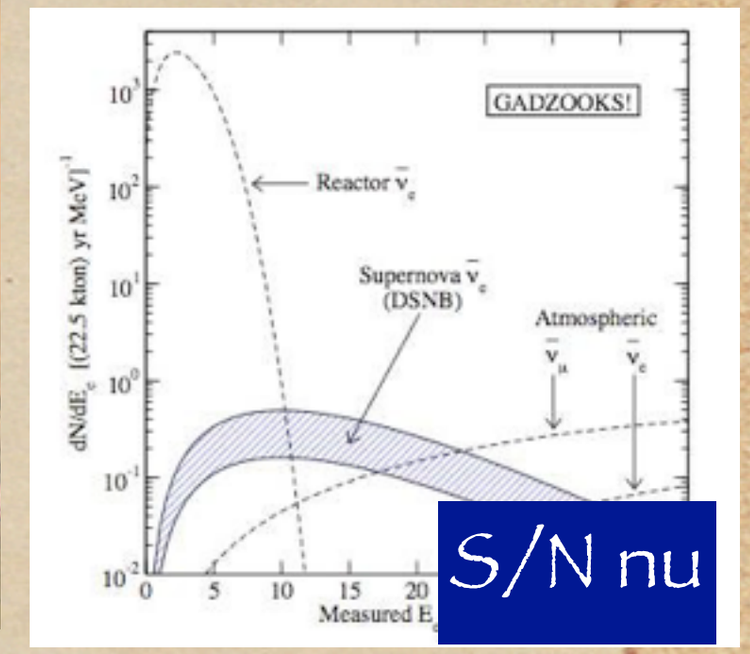
M. Yeh et al., BNL

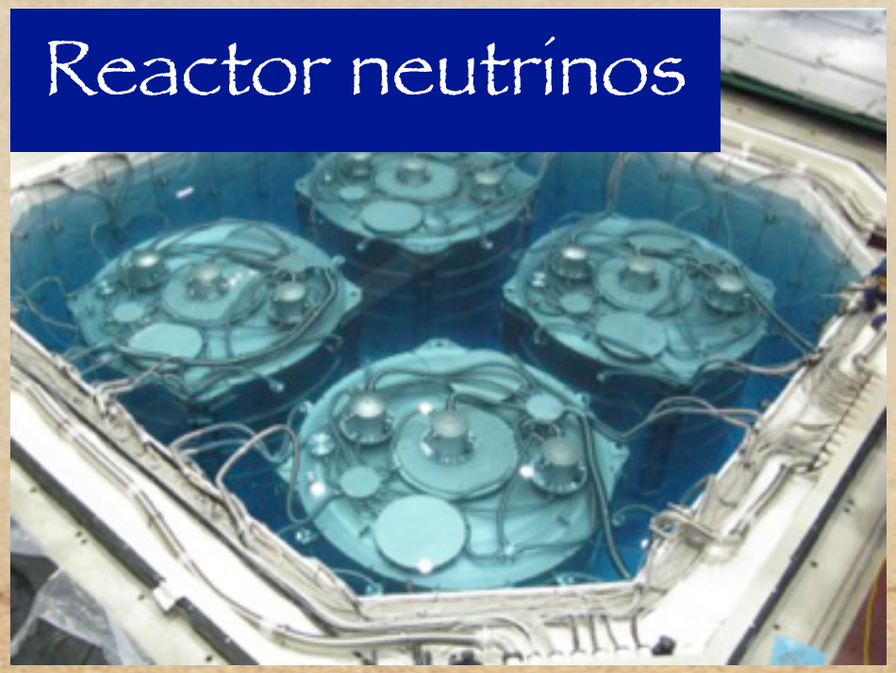
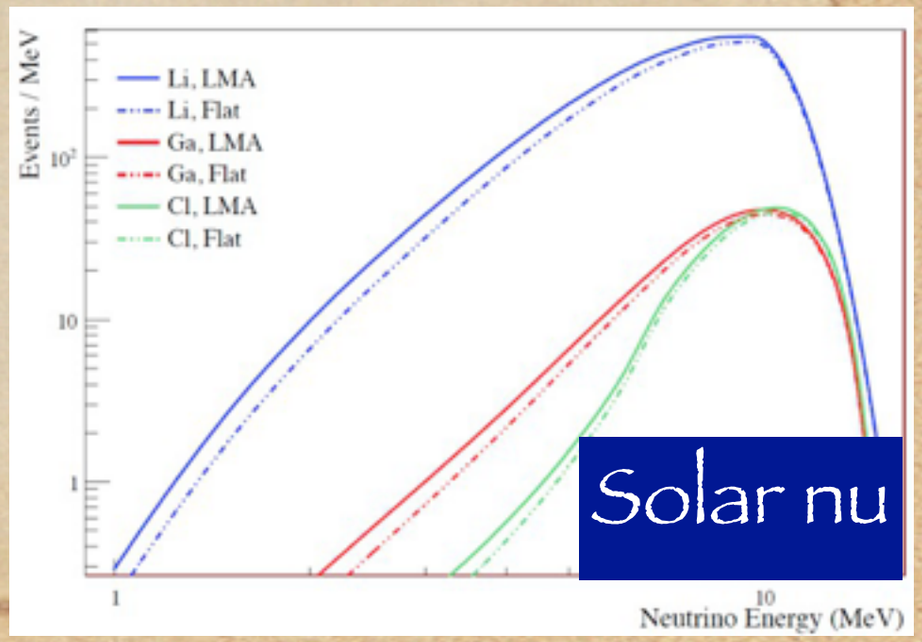
Physics Reach of WbLS



10 yrs: $\tau > 4 \times 10^{34}$ yr (90% CL)







"A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay p→K+ν & Other Physics" D. Beznosko et al.