Neutrino physics I: Neutrinos as a probe

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Here be dragons

- Postulating an impossibility:
  The neutrino is born
- The Solar Neutrino Problem
- Neutrinos to probe the Universe
- Experimental landscape

Solar Neutrinos come to Hollywood!

"2012"

"We were warned"

Solar Eruptions Cause Spikes in Neutrino Flux

"The count doubled after the last solar eruptions"

Postulating an Impossibility

1930

Wolfgang Pauli

- The continuous spectrum of β decay poses a problem...

Abschrift

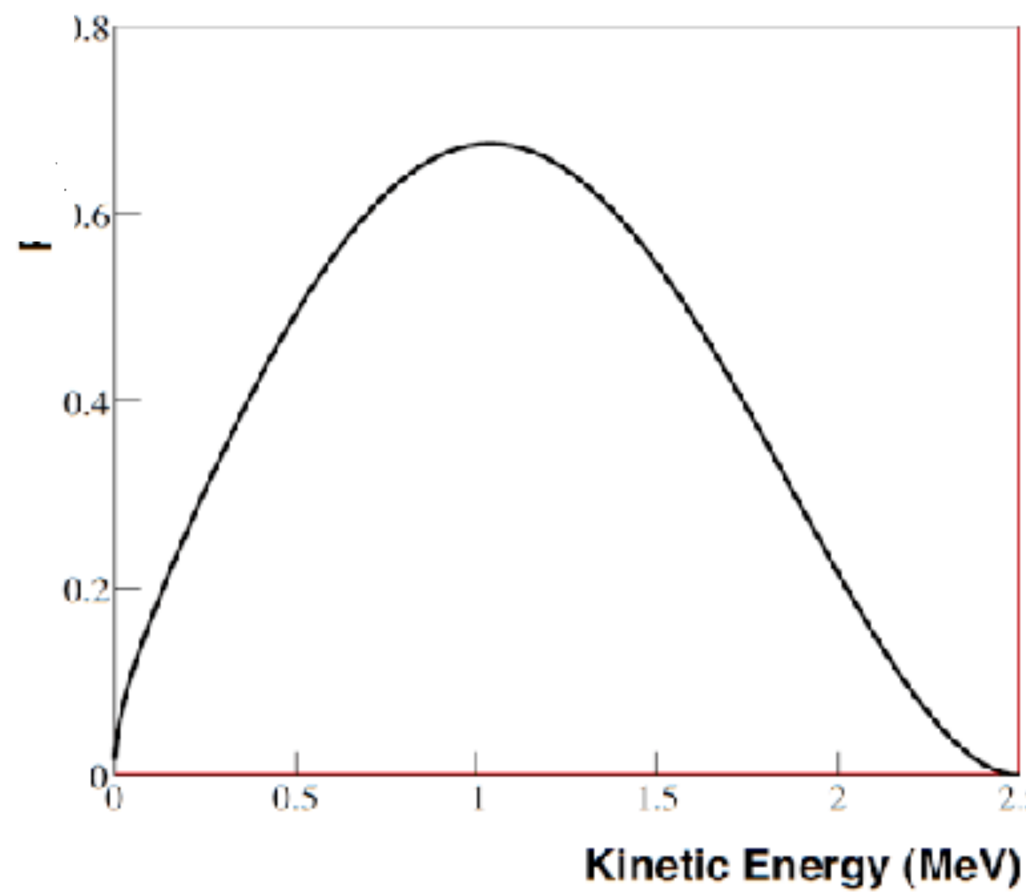
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetsen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

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



- 1930: Wolfgang Pauli proposes a new particle

"I have done a terrible thing. I have postulated a particle that cannot be detected"

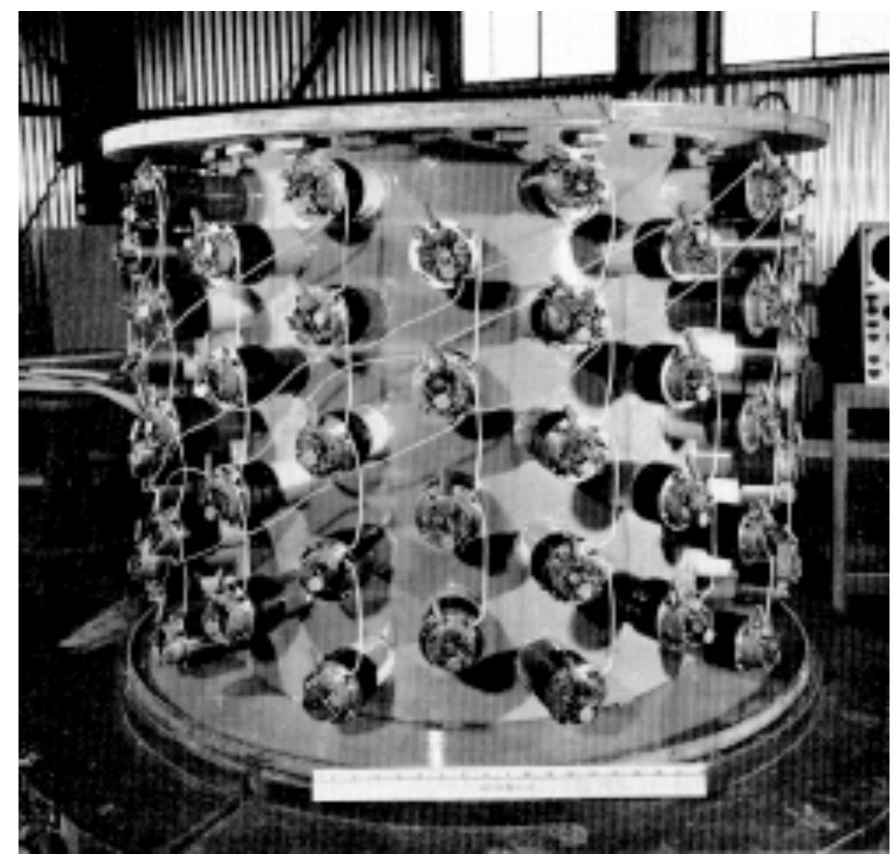
First Detection

1956

Fred Reines & Clyde Cowan

- 1956: Reines and Cowan

Anti-neutrinos detected
at Savannah River nuclear reactor



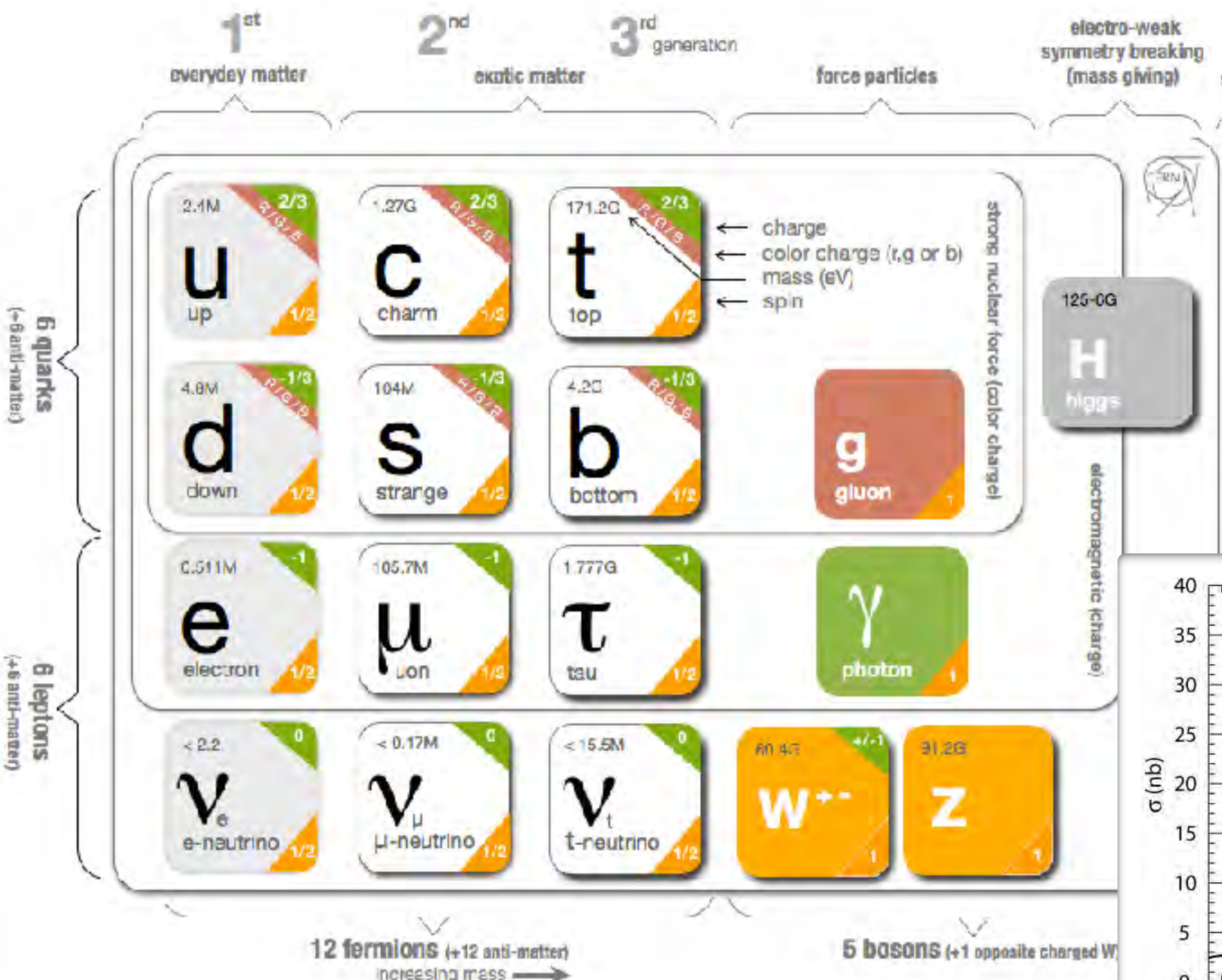
- Double coincidence signal

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

Prompt
annihilation
signal

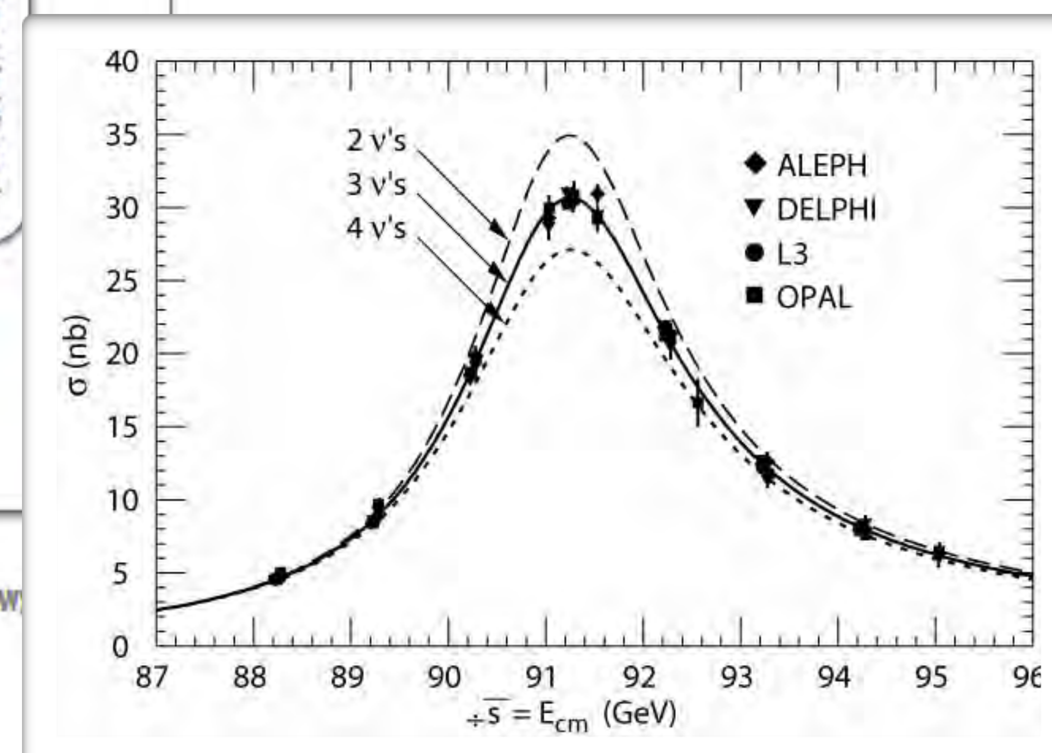
Delayed
neutron
capture

Standard Model Neutrinos

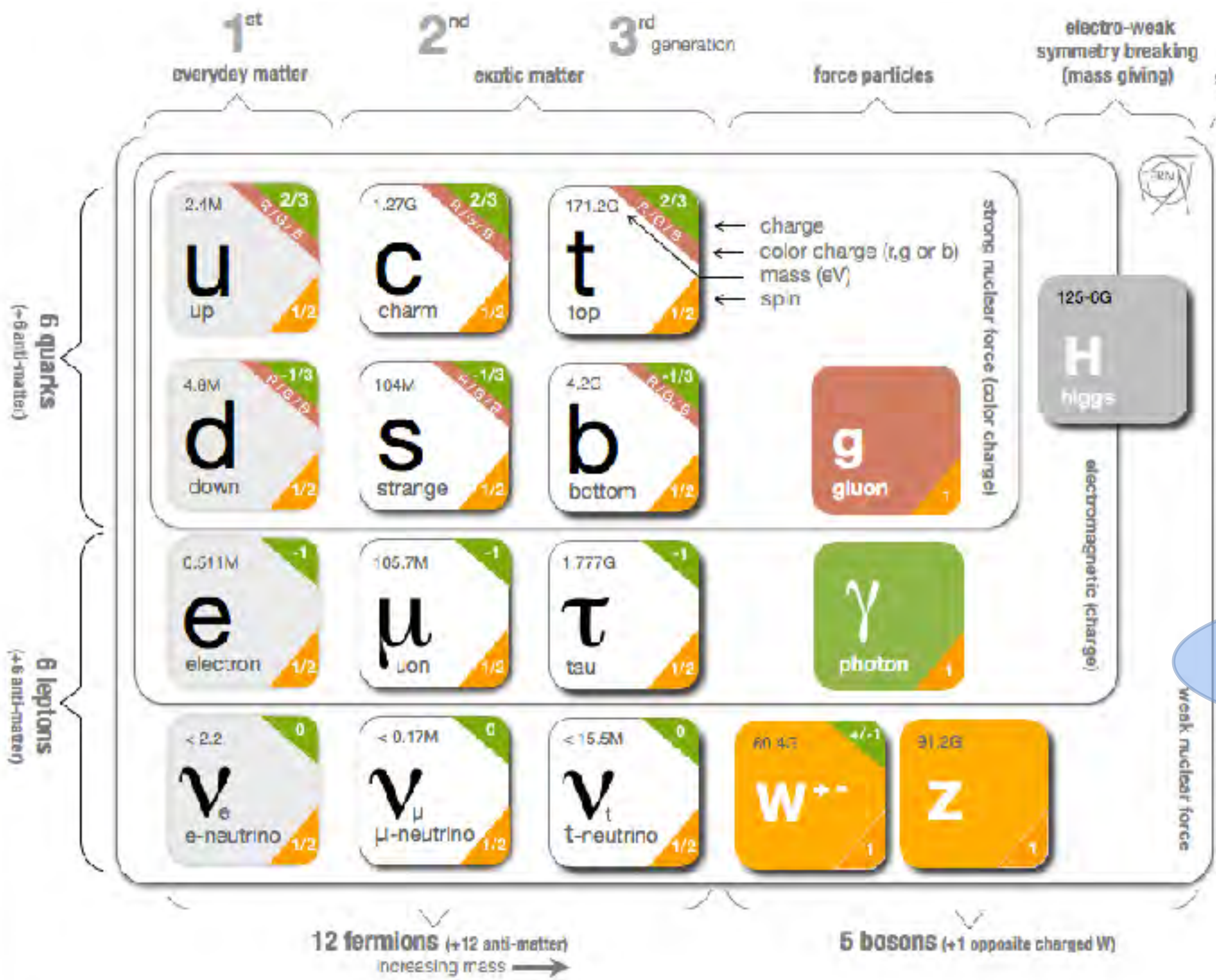


Neutrino properties:

1. Interact weakly
2. Very tiny masses
3. Three flavours



Standard Model Neutrinos



Neutrino properties:

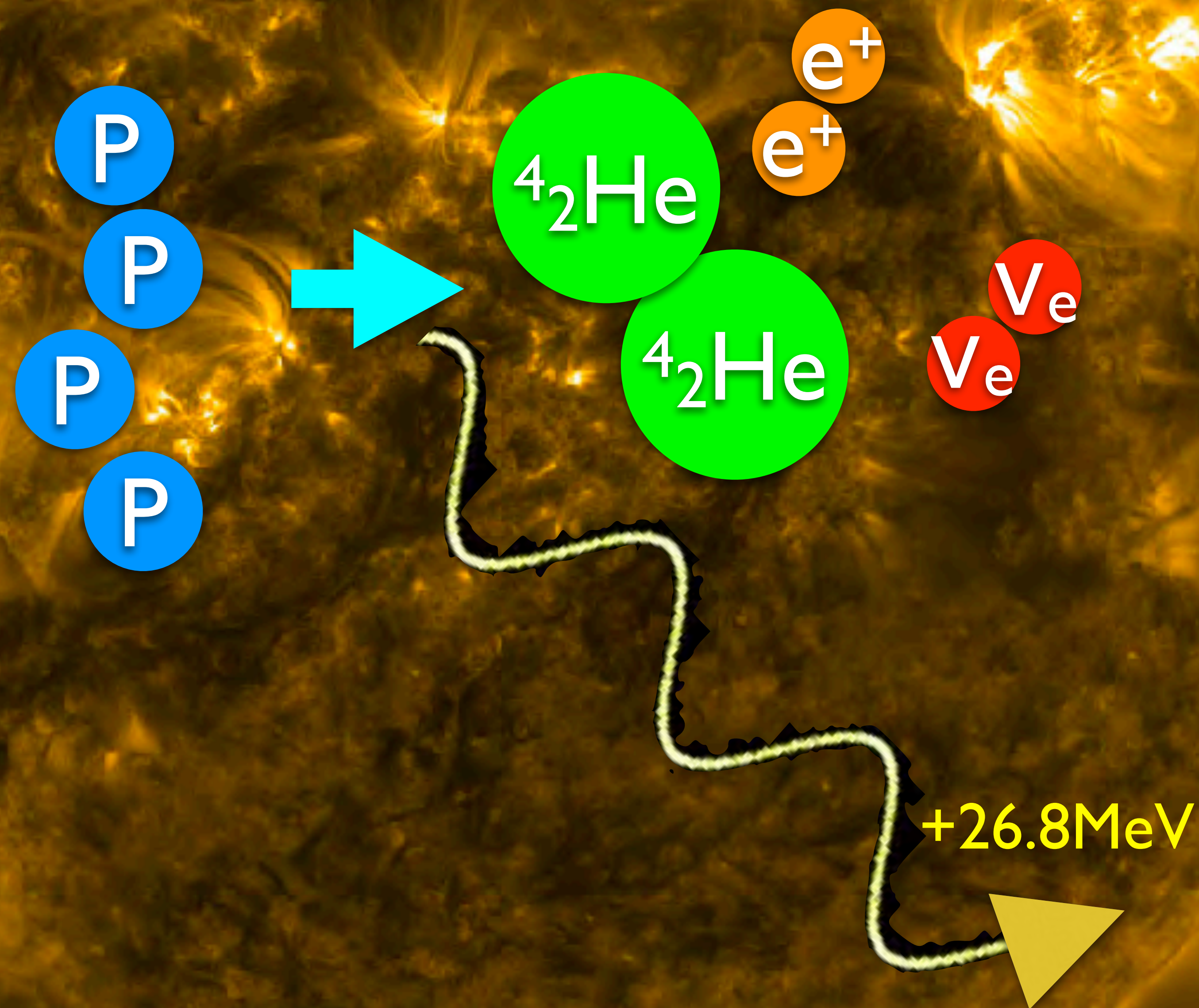
1. Interact weakly
2. Very tiny masses
3. Three flavours

ν_e - The Sun, nuclear reactors

ν_μ - Cosmic rays, man-made

ν_τ - Man-made beams
First observation in 2000

How Does the Sun Shine?



Nuclear fusion reactions in the core produce:

- Helium
- Energy (heat, light)
- Neutrinos

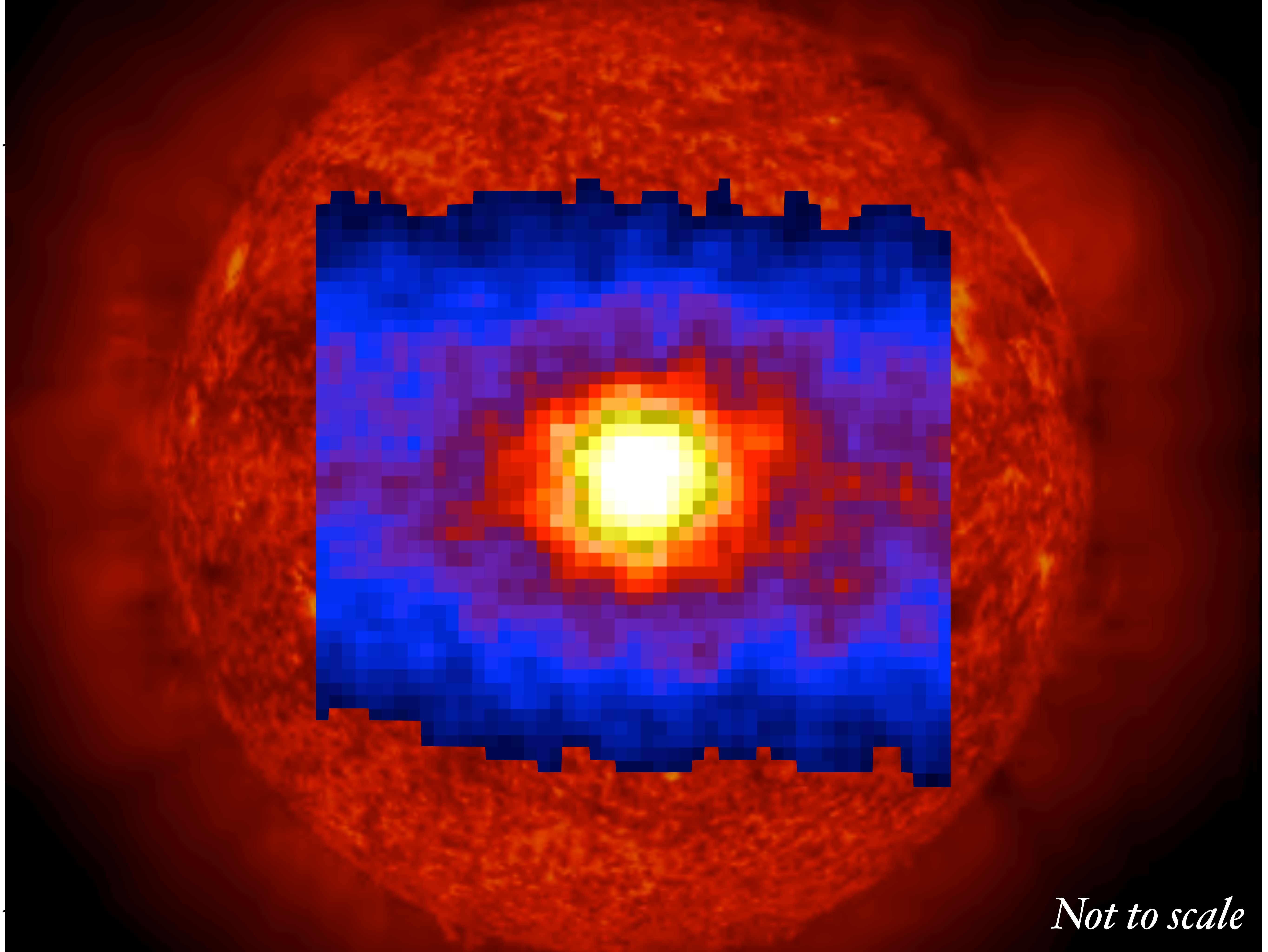
Neutrino facts

70 billion ν pass through your thumb nail every second

νs travel the Sun-Earth distance in 8 minutes

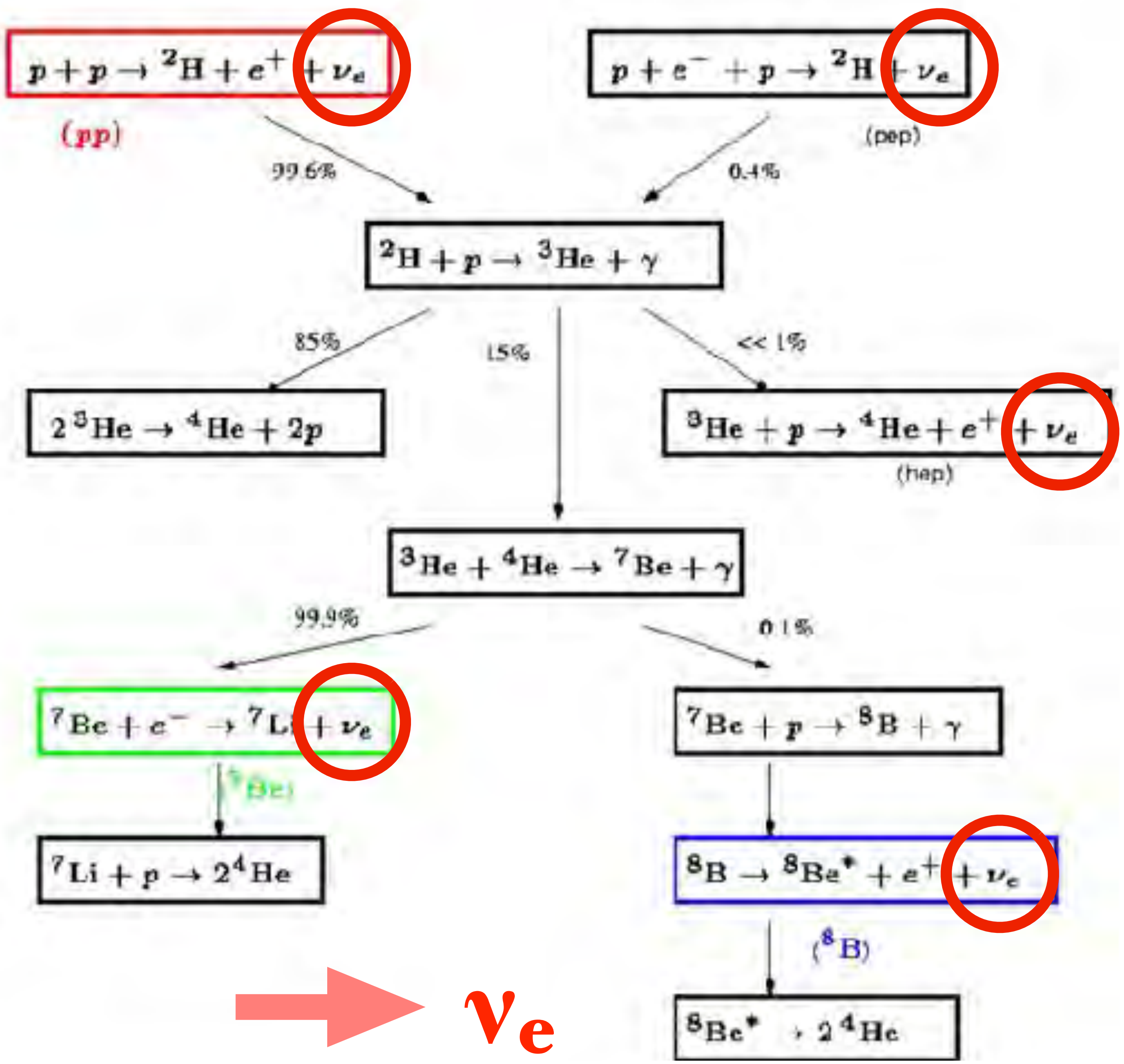
1 light year of lead would stops 50% of incident neutrinos

Vast detectors required for observation

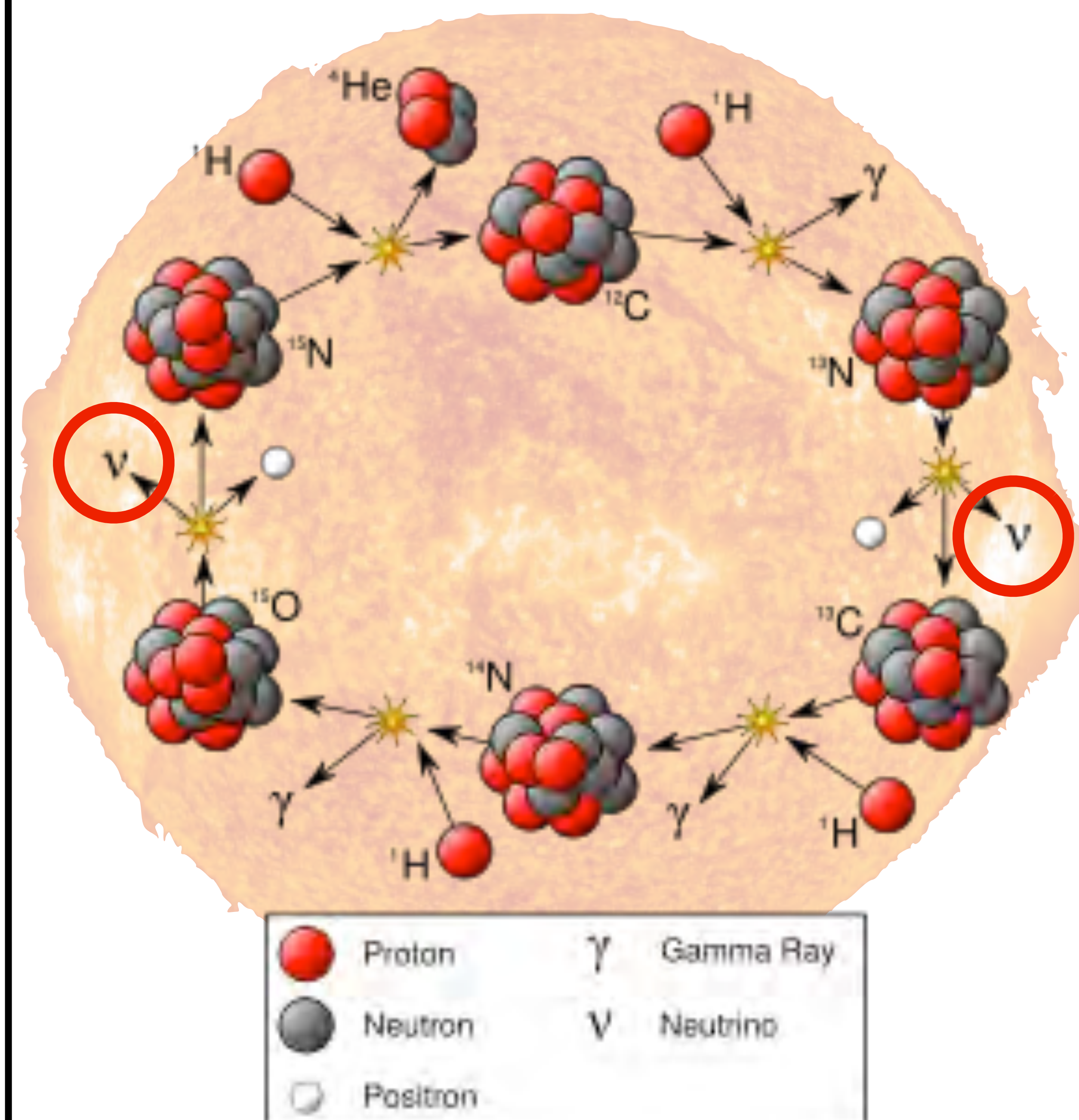

Not to scale

Solar Neutrinos

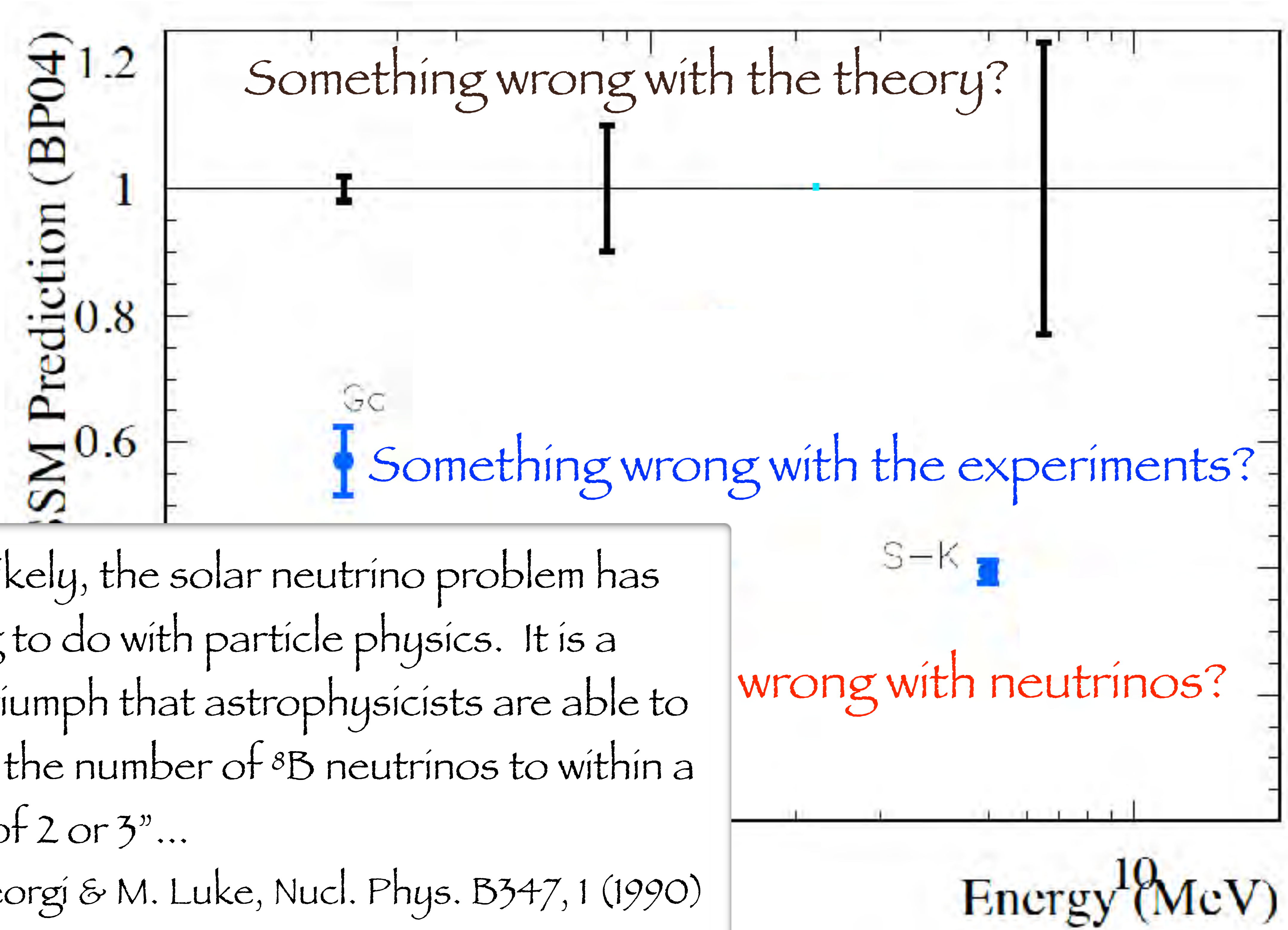
pp Chain



CNO Cycle
(contributes ~1% of solar energy)



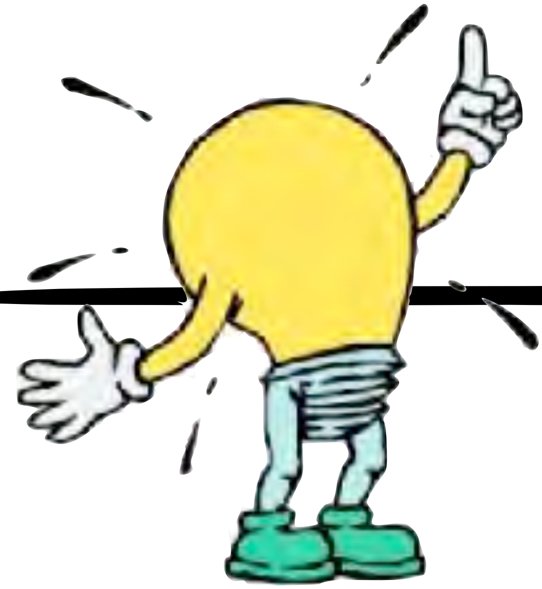
Solar Neutrino Problem



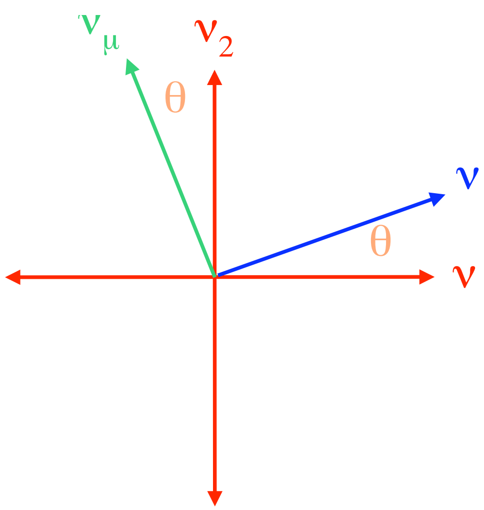
"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3"…

--H. Georgi & M. Luke, Nucl. Phys. B347, 1 (1990)

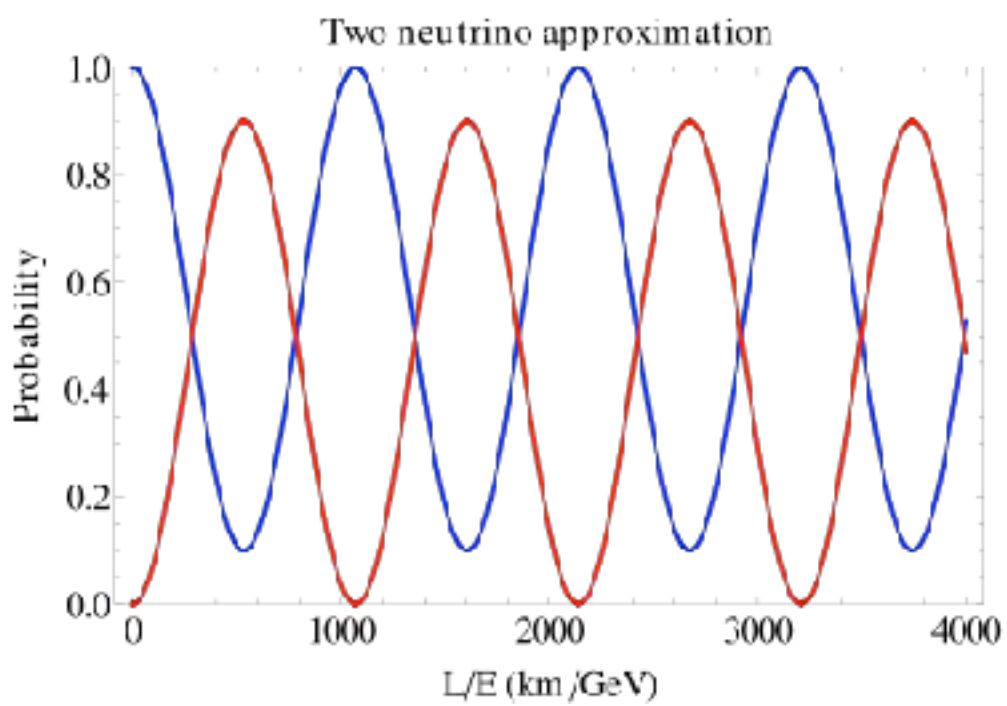
Neutrino Oscillations



Produced as weak (flavour) eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$
Propagate as physical (mass) eigenstates (ν_1, ν_2, ν_3)



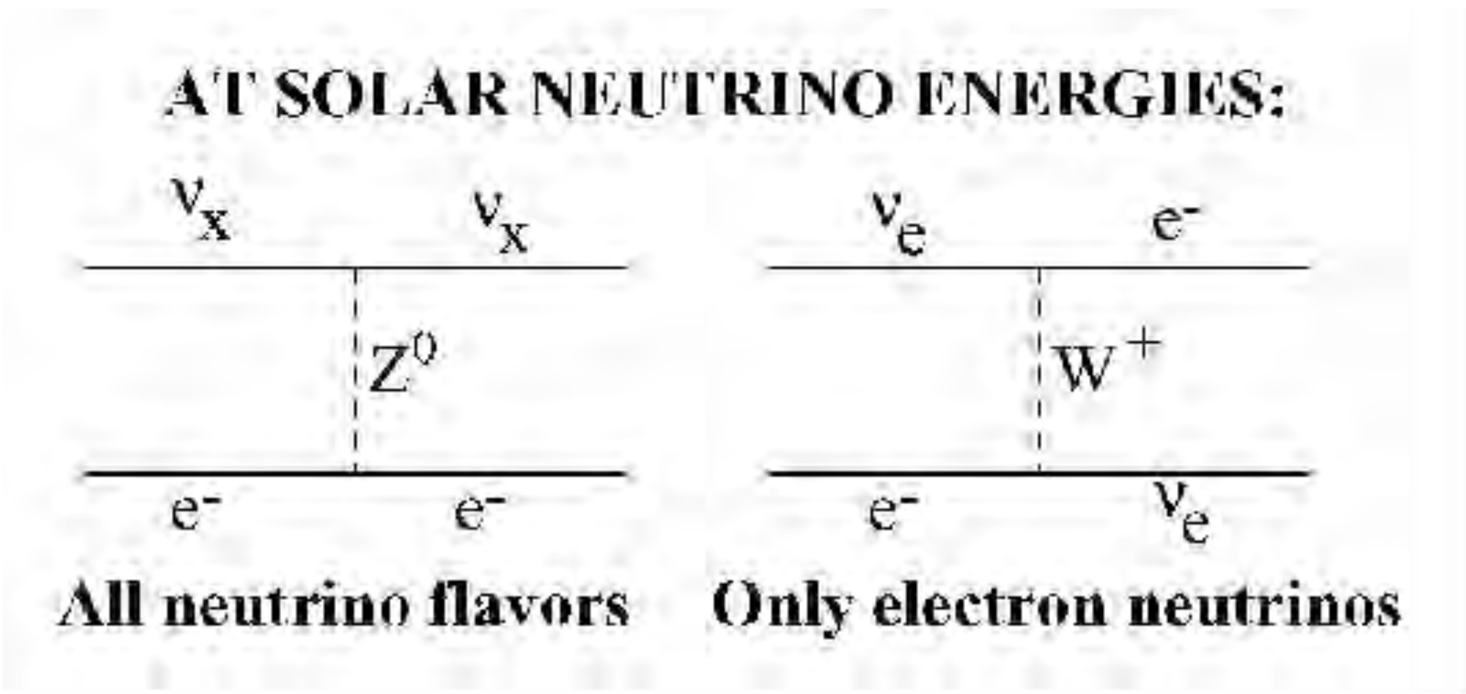
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \Rightarrow P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



Max suppression of 0.5 for vacuum oscillation over long baselines

The missing piece

Wolfenstein, Mikheyev & Smirnov: coherent forward scattering of ν_e in the Sun



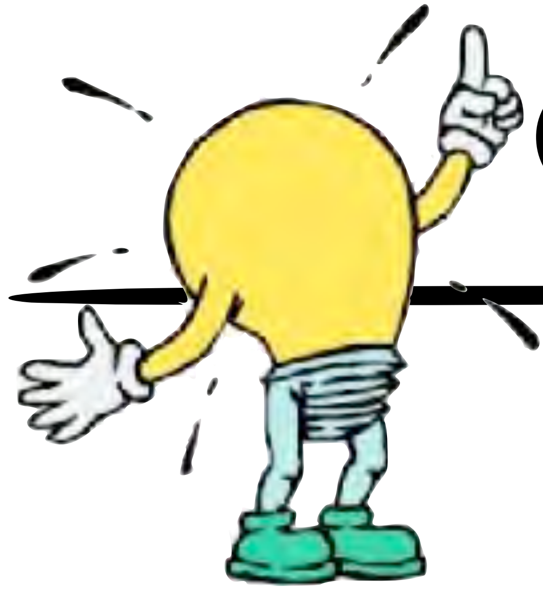
Increases effective mass of ν_e

Alters mixing angle in matter

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e}$$

Resonance when

$$\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e = 0$$



Can We Look For Appearance?

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Need:
1. 1kT heavy water
2. Deep underground
3. High PMT coverage

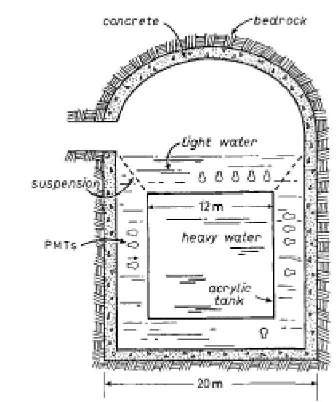
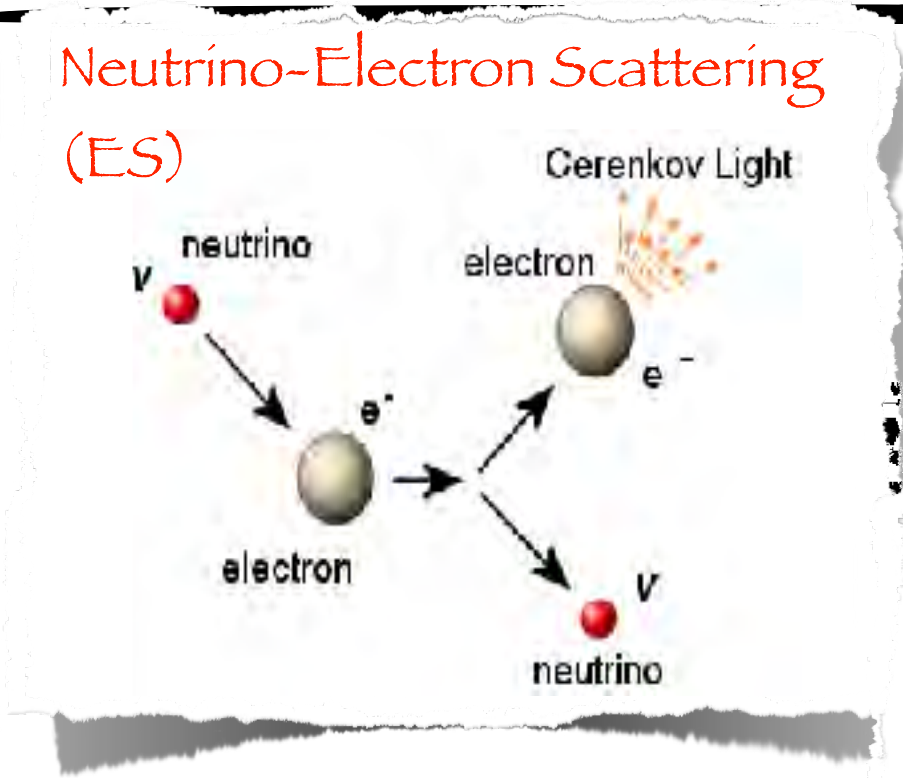


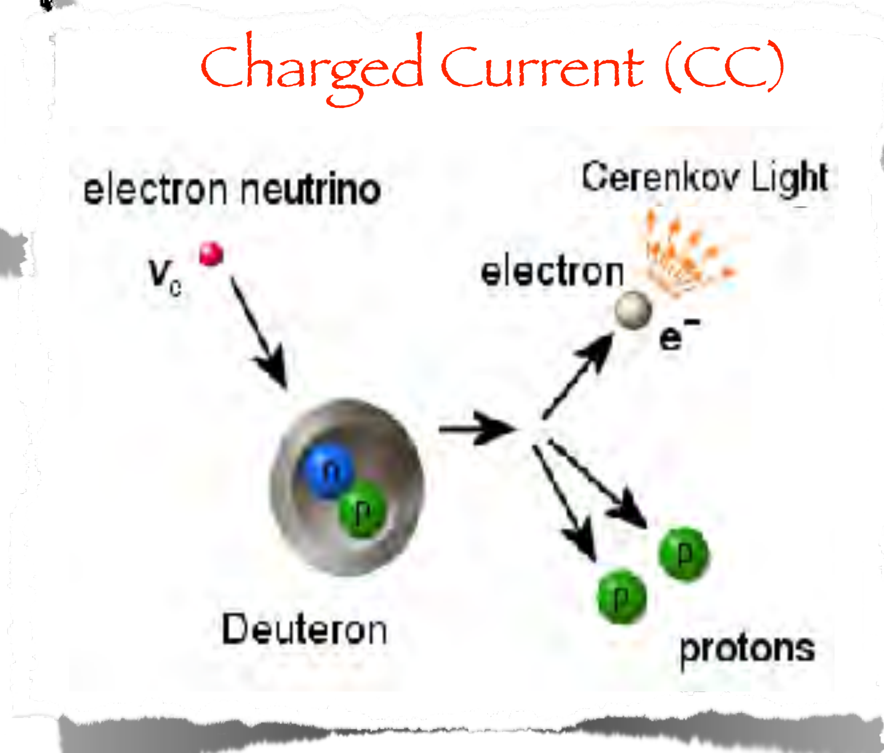
Fig. 5. – Conceptual design of the light/heavy-water detector. The heavy water is contained in an acrylic tank and is shielded from activity in the rock by low activity concrete and light water. The Čerenkov light produced in the water is detected by an array of 2400 50 cm diameter phototubes.

Review committee:
"Physics goals... are of outstanding value"
Funding agency award: $0

The Answer: Heavy Water

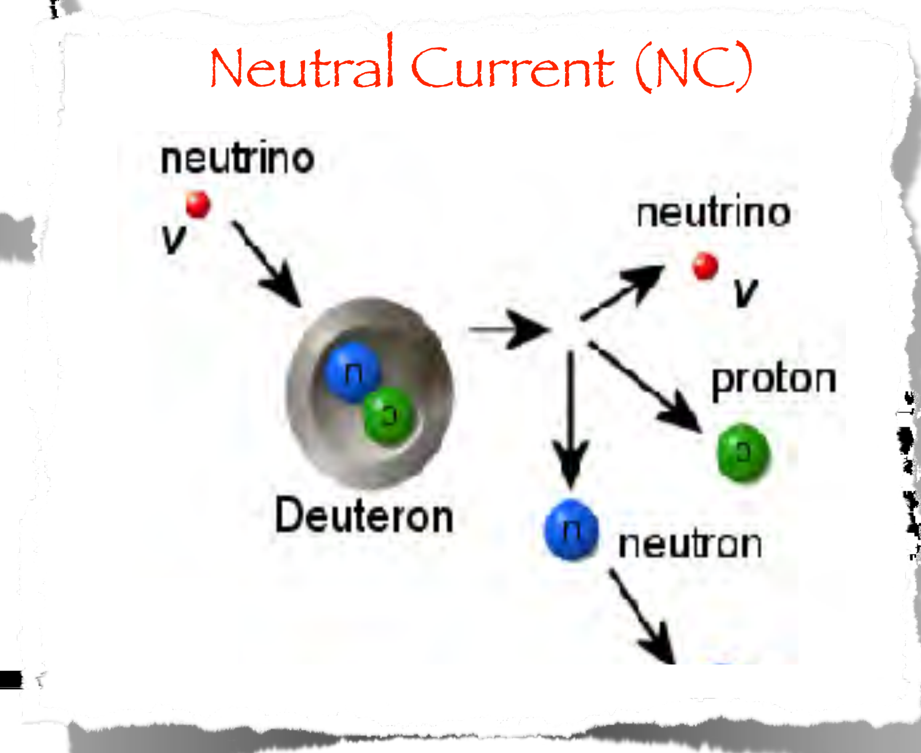


1. Elastic Scattering
Primarily sensitive to ν_e
Measures ν direction



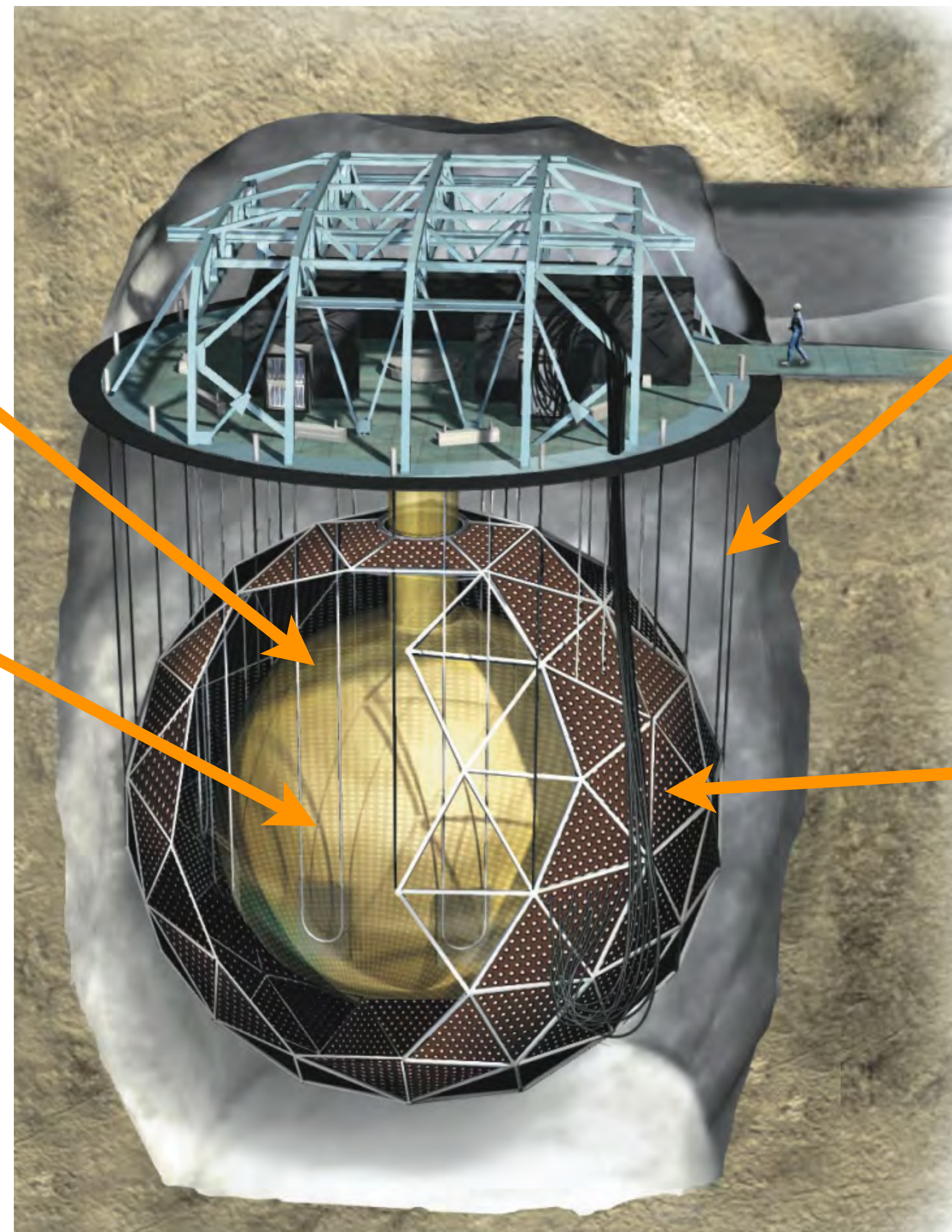
2. Charged Current
Sensitive only to ν_e
Measures ν energy

3. Neutral Current
Sensitive to all flavours
Measures total ^8B ν flux



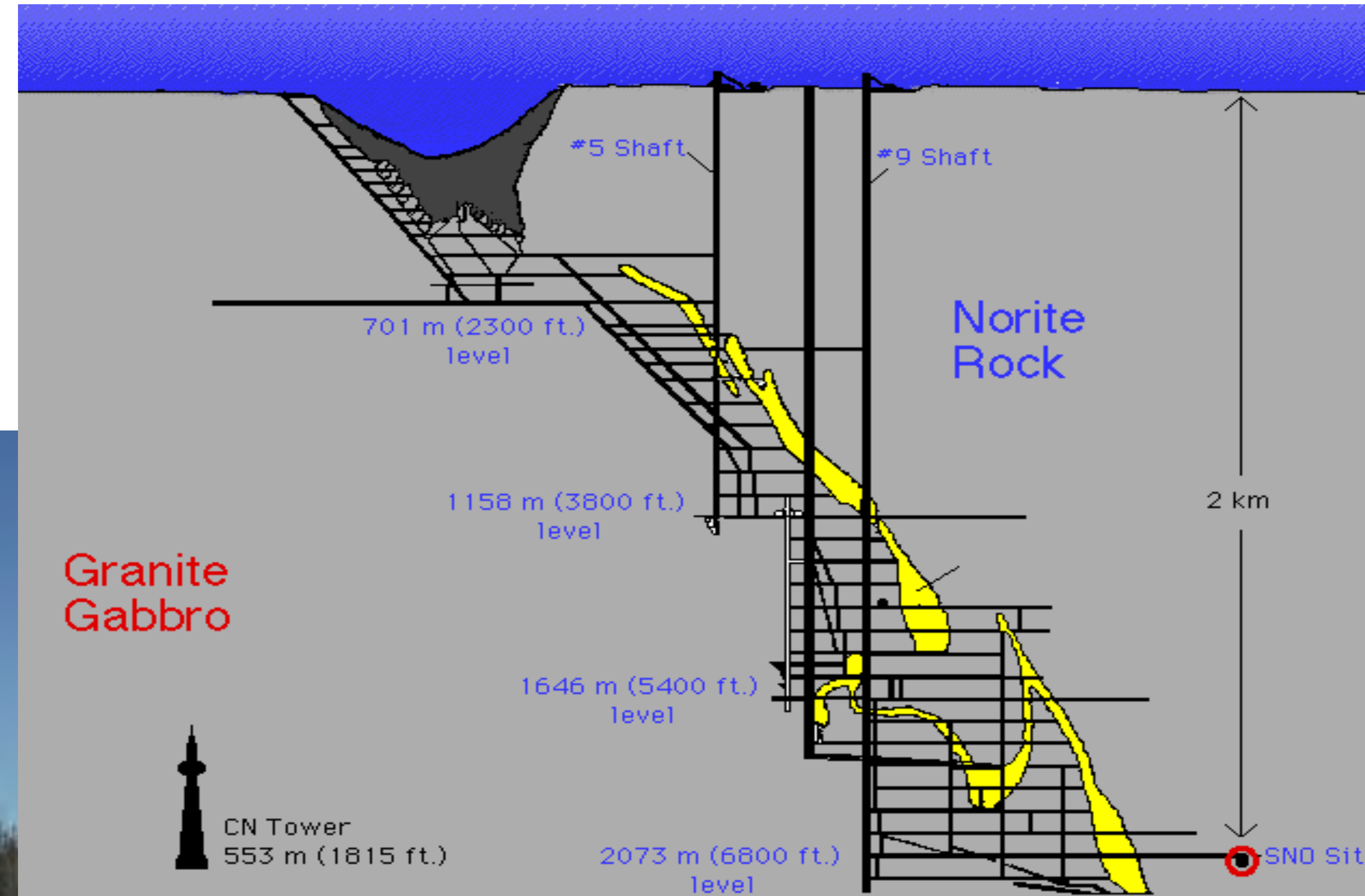
Sudbury Neutrino Observatory (SNO)

- 12m acrylic vessel
- 1kT D_2O
- 6800ft level
- 5890 m.w.e.



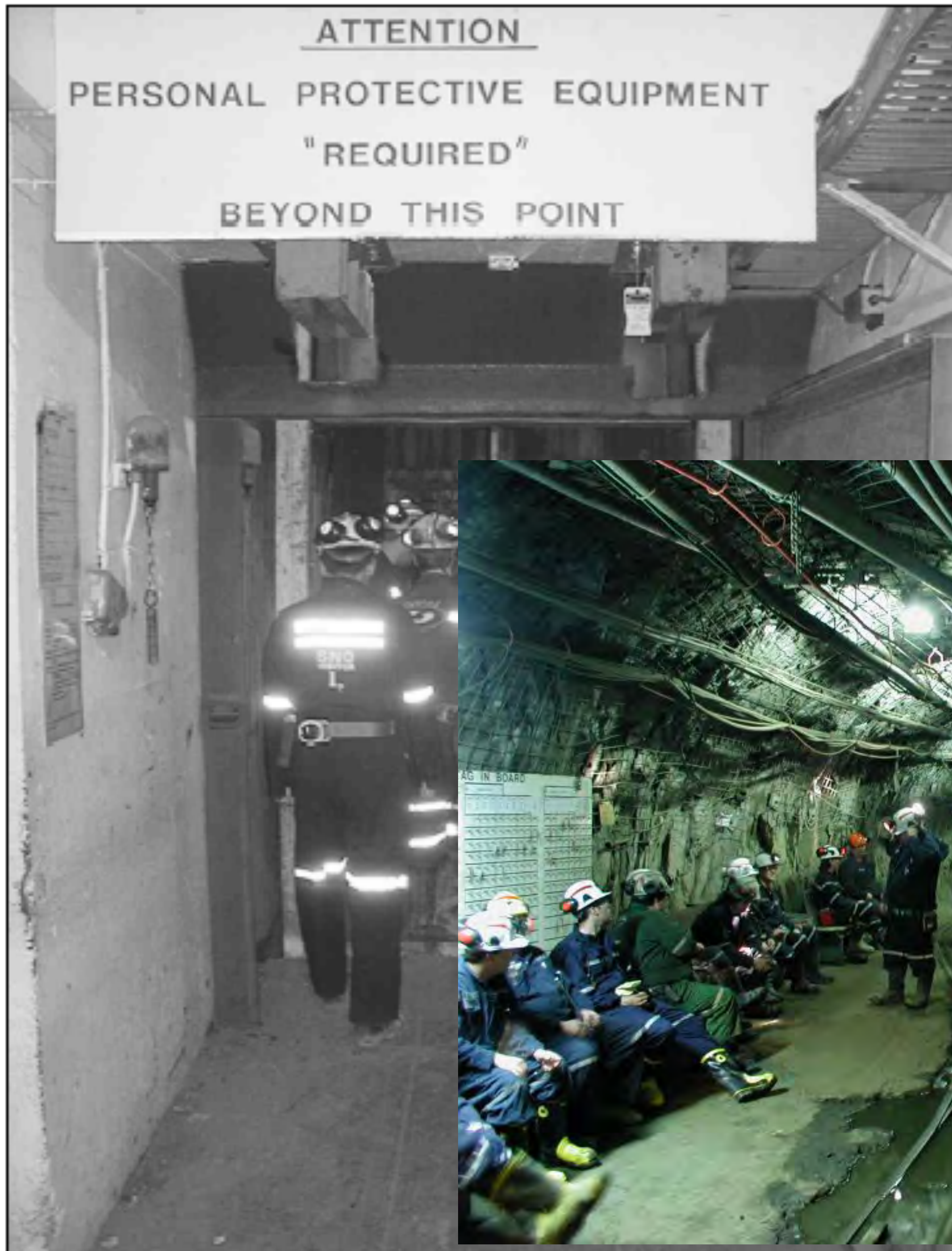
- 1.7kT + 5.3kT H_2O buffer
- 9500 PMTs 55% coverage

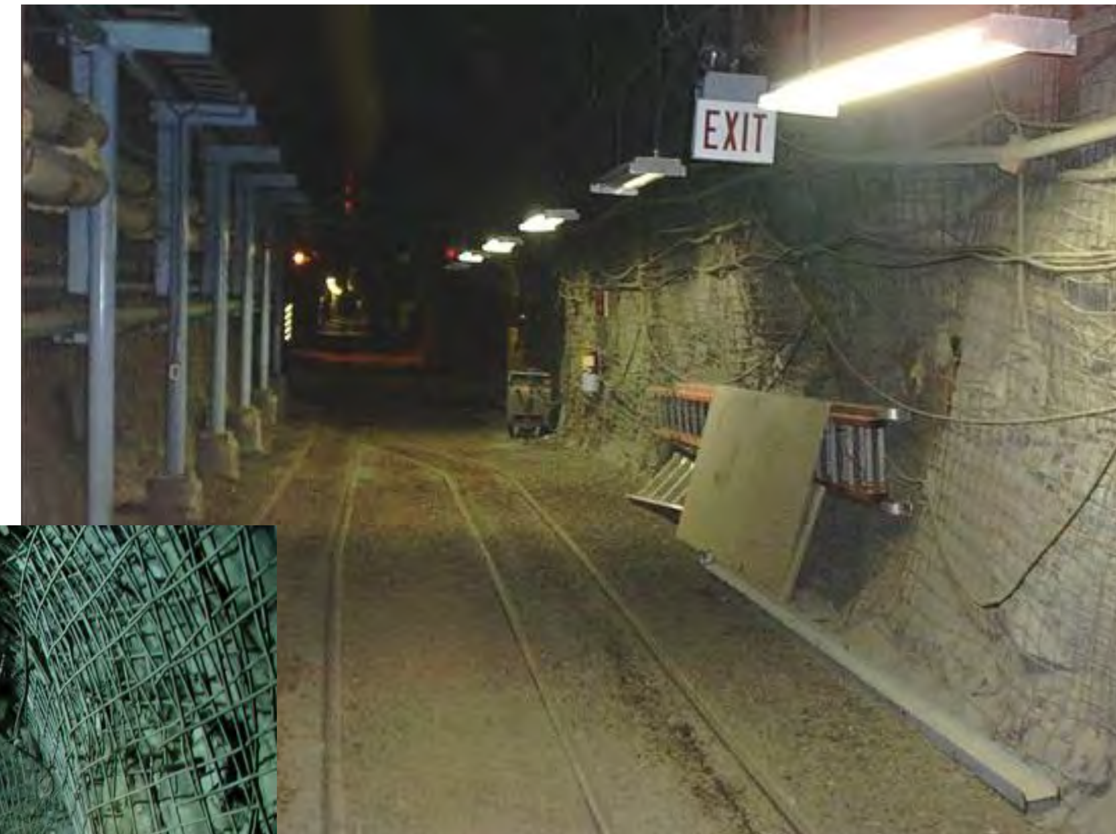
Creighton Mine



2km underground
Active nickel mine
Northern Ontario

Going Underground

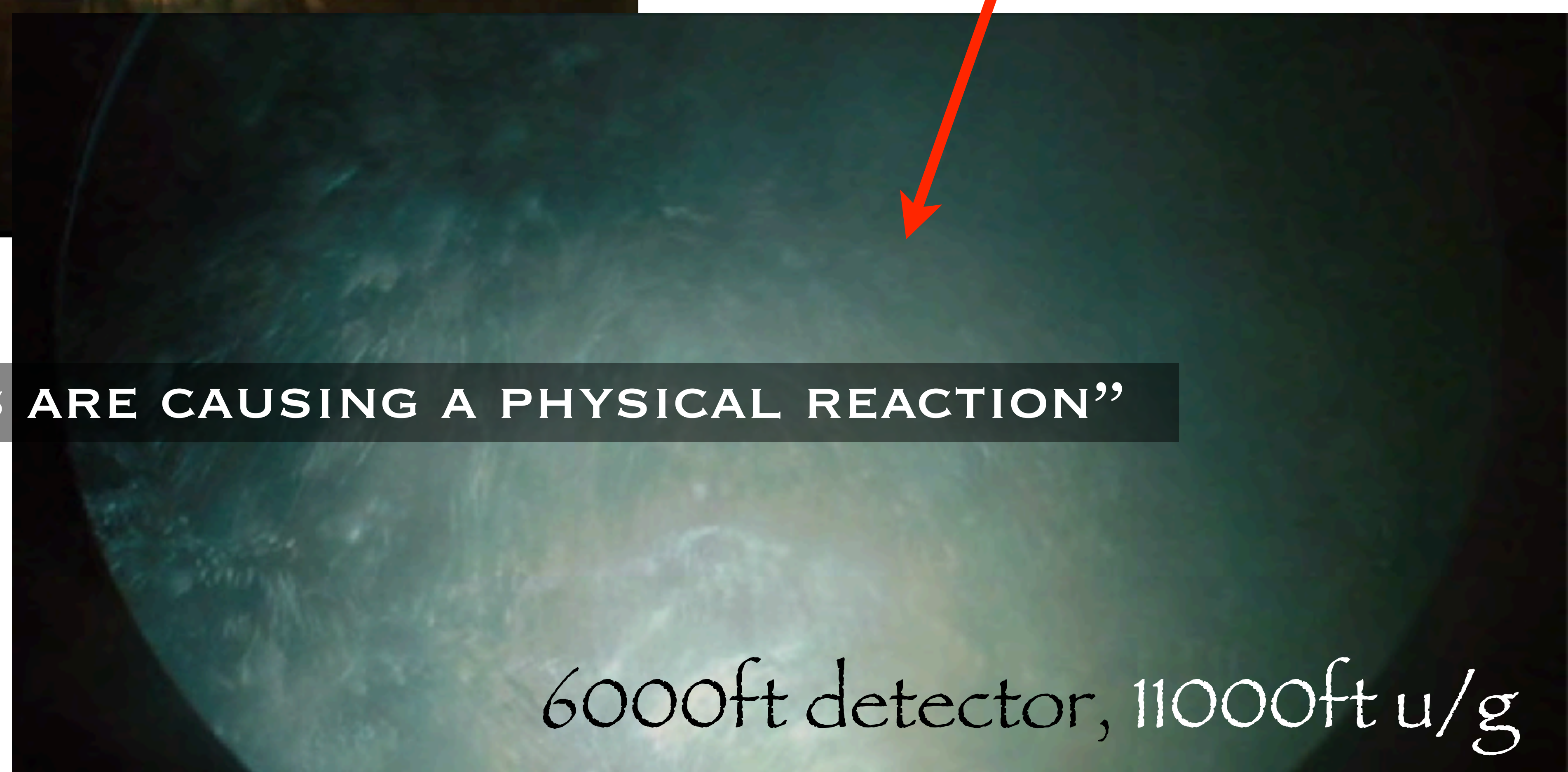




The End of the World...

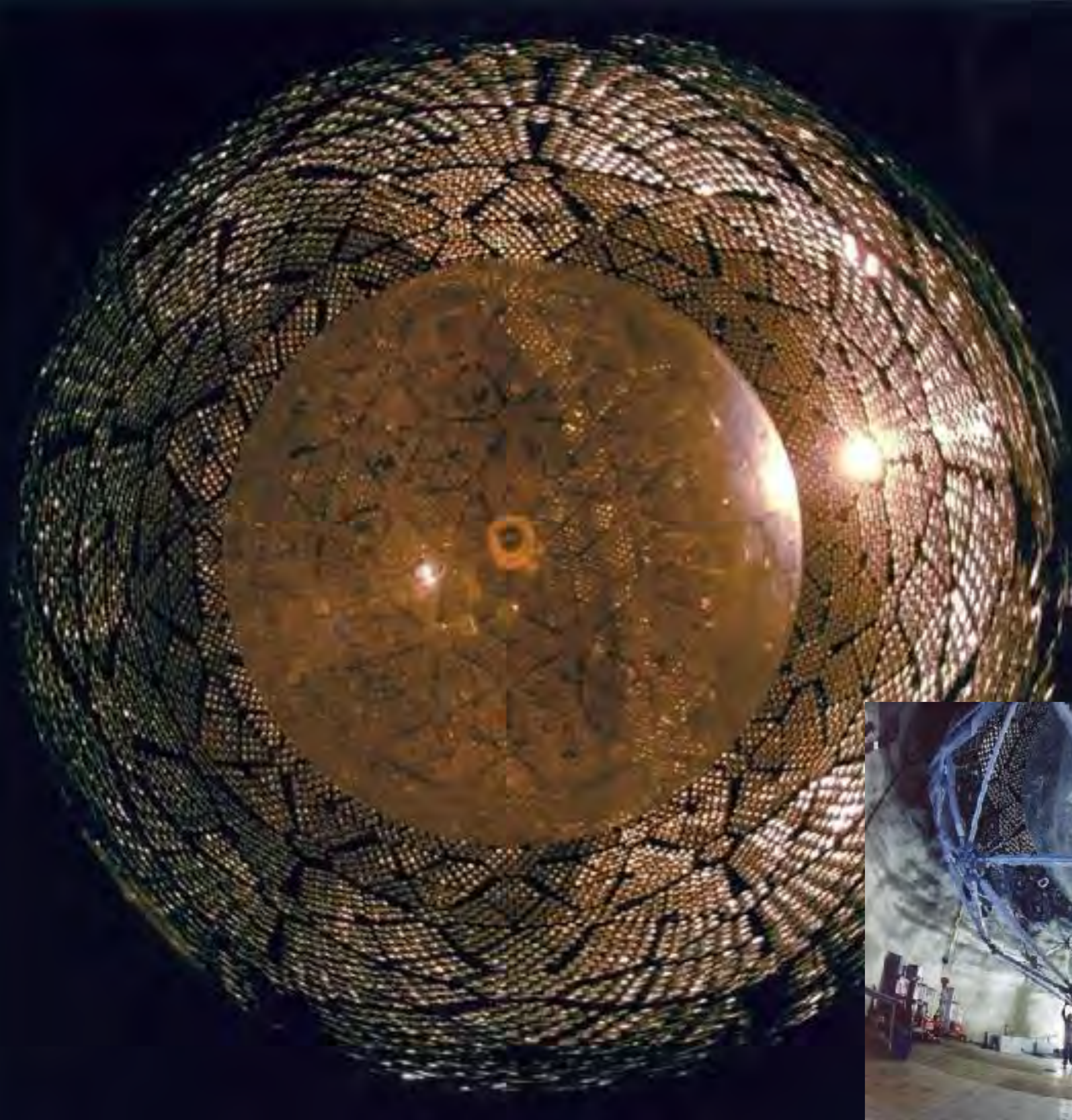
Incident vs cause water target to boil...

but only underground...

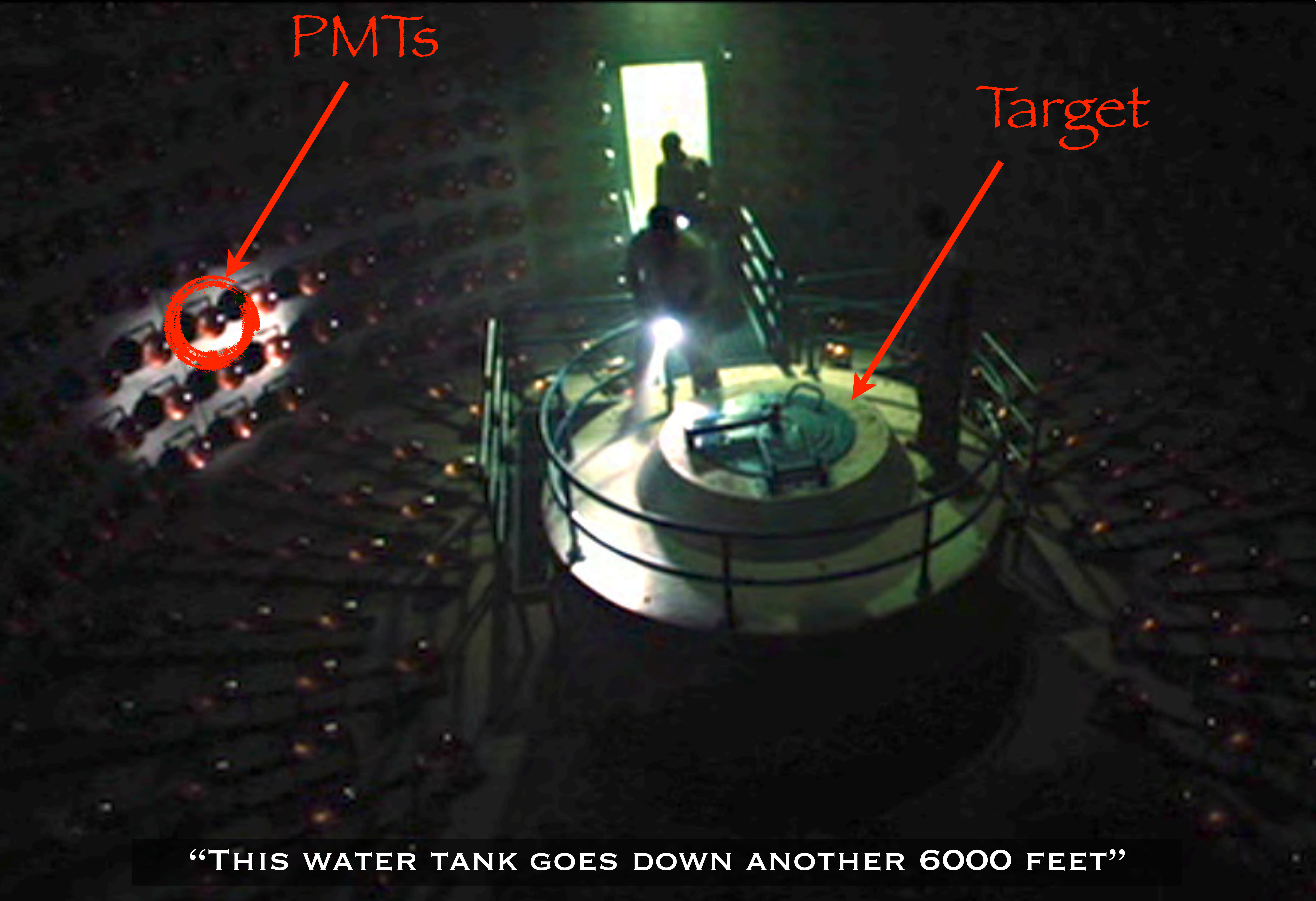


"...THE NEUTRINOS ARE CAUSING A PHYSICAL REACTION"

The SNO Detector

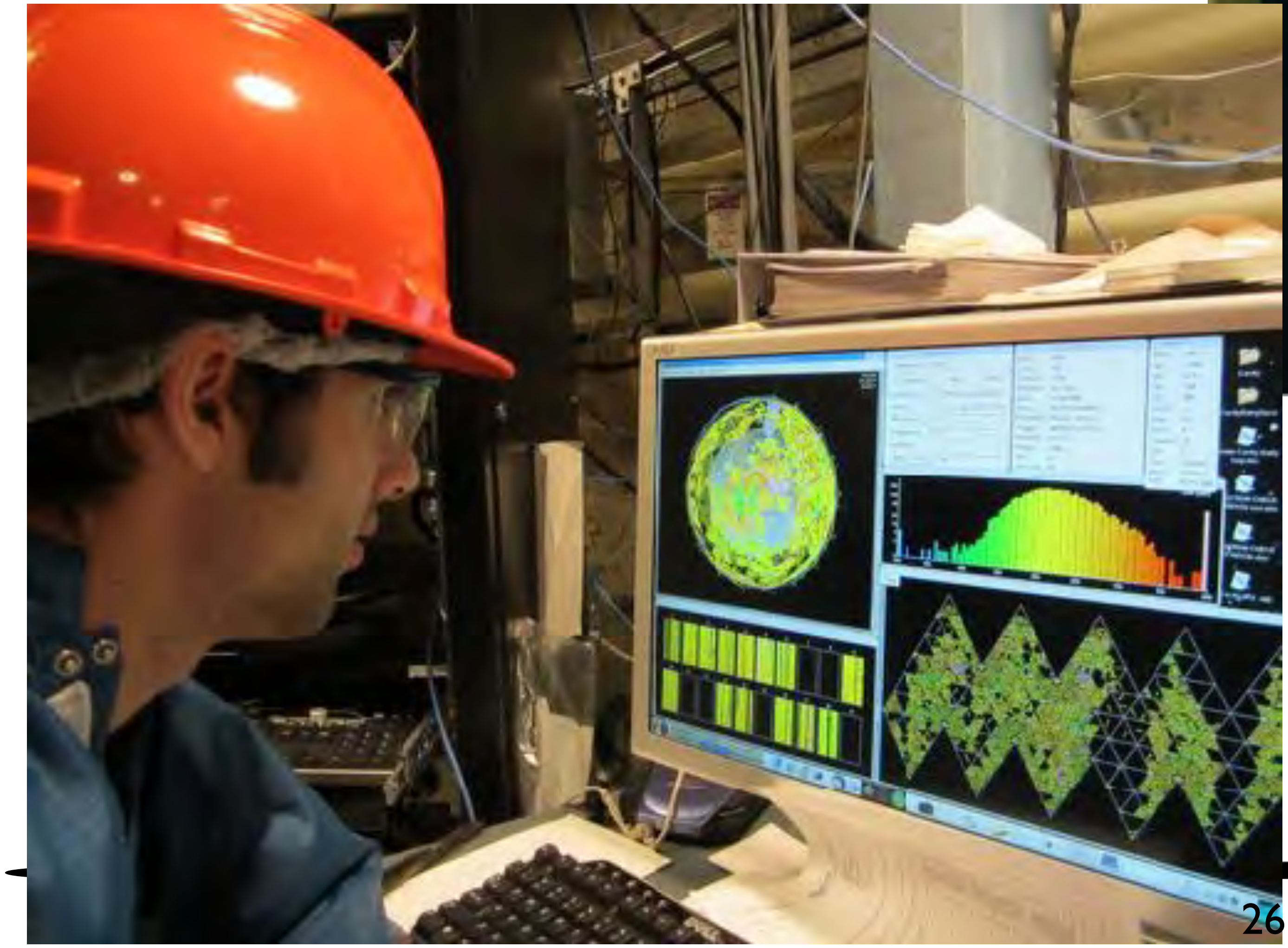


Hollywood's Take on Neutrino Detection



"This water tank goes down another 6000 feet"

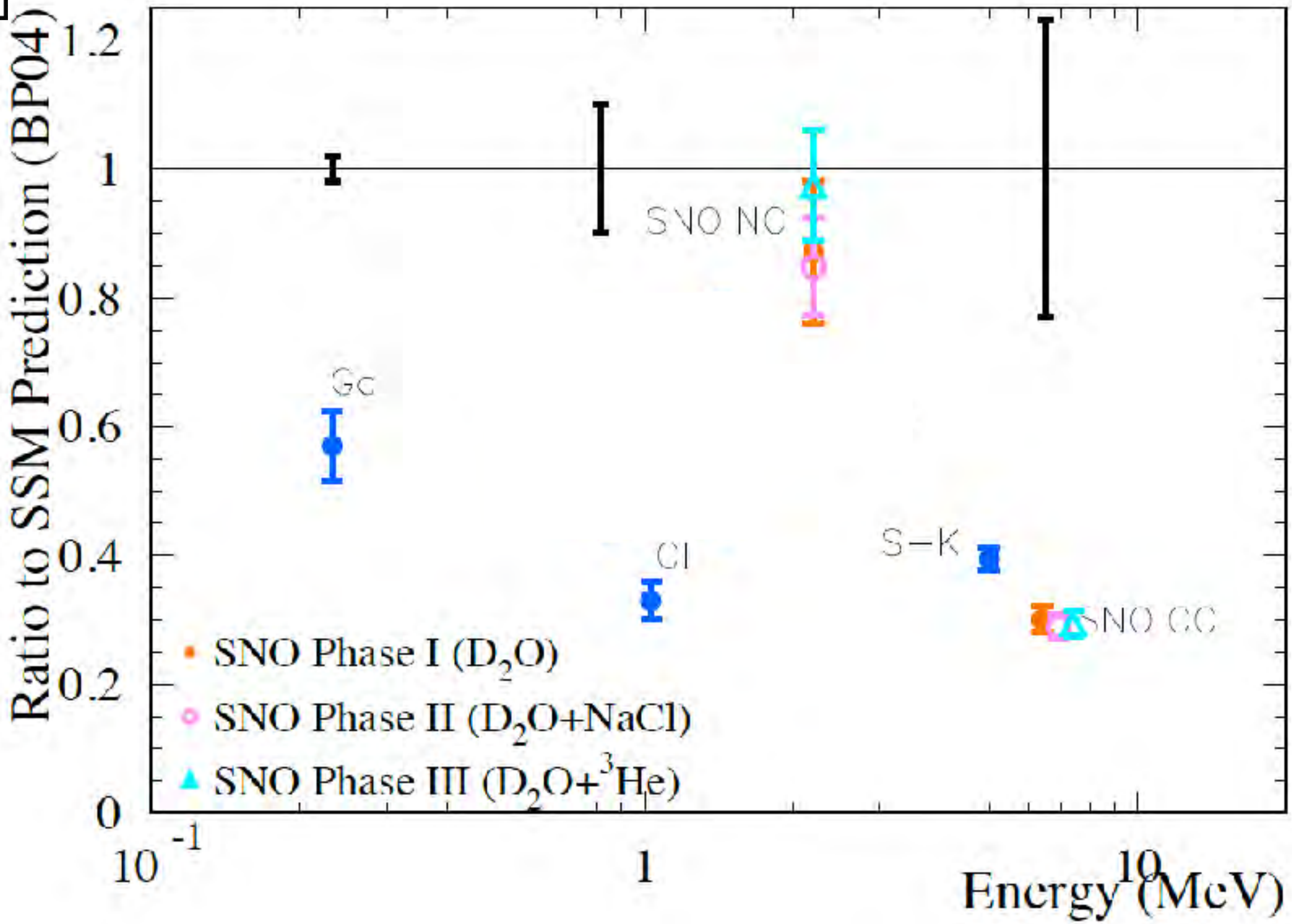
Hollywood's Take on - Event Display



Hollywood's Take on - Event Display

A Neutrino Track...

Solar Neutrino Problem Resolved



World News

Mellon Jazz
Festival: Penn's
Landing party,
John Swana,
more. Page 4.

ECTION F

The Philadelphia Inquirer

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NATIONAL NEWS

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BY VINO WONG—THE NIAGARA GAZETTE VIA ASSOCIATED PRESS

At Niagara Falls, New York Gov. George E. Pataki (R), at lectern, discusses plans to protect the Great Lakes by limiting volume of water sent inland.

guidelines approved today.

Five major diversions are in place, the largest of which is the 2.1 billion gallons that is taken each day from Lake Michigan at Chicago. Half the water is for drinking and the rest is used to reverse the flow of the Chicago Sanitary and Ship Canal. The diverted water winds up in the Mississippi River.

"Some might say this is not a serious problem because right now there are no serious [export] proposals in front of us. But if there's ever a serious drought elsewhere in the United States, you can be sure there will be serious proposals," said Michael J. Donahue, president of the Great Lakes Commission, a binational agency that promotes the protection of the Great Lakes.

Donahue said that Great Lakes conservationists have learned from past

Neutrino St
Puzzle and

By Guy Gugliotta
Washington Post Staff Writer

Every second of every day, tens of thous
ghostly subatomic particles called neutr
tiny offspring of nuclear fusion in the core
sun—harmlessly flash through a person's b
For 30 years physicists have know
thought they knew—how many neutrinos
to be reaching Earth, but every measuring
told the same story—there were many fe
rivals than expected. Either physicists h
wrong idea about solar fusion, or somethi
happening to the neutrinos en route.
Yesterday, an international team of phy
working in a lab sunk more than a mile d
Canadian nickel mine, presented the fi
crete evidence that the "solar neutrino de
curs because while three types of neutrin
the Earth, only one—until now—could re
counted.
"We have measured the total number o
nos coming from the sun, and [the measu
agrees with predictions made 30 years a
research physicist and team member
Klein of the University of Pennsylvania.
oldest, longest-lived puzzle in particle ph
The findings, reported in the journal
Review Letters by 180 authors from th
States, Canada and the United Kingdom,
portant implications for both the physi
very small and the physics of the very la
By showing that neutrinos toggle
forth on their journey to Earth amo
forms, or "flavors," the experiment prov
confirmation that neutrinos have mass.
agree that such "oscillation" can occu
substance has mass.
This concept has thrown a sizabl
wrench into the "Standard Model" o
which proposes a massless neutrino as

THE NEW YORK TIMES, TUESDAY, JUNE 19,

Sun's Missing Neutrinos: Hidden in Plain Si

By KENNETH CHANG

After three decades of searching, physicists have tracked down subatomic particles that have eluded them for 30 years. The particles, it turns out, were right there all the while but had hidden themselves as if by magic.

"We've solved a 30-year-old puzzle of the missing neutrinos of the Sun," said Dr. Arthur B. McDonald, director of the Sudbury Neutrino Observatory, near Sudbury, Ontario. In doing so, though, the researchers have answered questions about neutrino behavior and the fate of the universe.

Neutrinos are ghostly particles, one of the fundamental building blocks of the universe, like quarks, electrons and photons. Billions of them, produced by fusion reactions within the Sun, fly through every person every second. Minuscule and devoid of electric charge, though, they pass unnoticed. In fact, they are practically undetectable.

In 1968, Dr. John Bahcall, an astrophysicist at the Institute for Advanced Study at Princeton, N.J., calculated that the rate of neutrinos from the Sun passing through one square inch of area should be about 30 million a second.

Experiments beginning in the 1970's counted much lower rates; more than half of the expected neutrinos were never seen. Dr. Bahcall's predictions, refined over the years, remained unchanged.

Yesterday, scientists at the Sudbury Neutrino Observatory announced the first experimental evidence that provides a solution.

During the neutrinos' 93-million-mile journey from the Sun to the Earth, the researchers said, about two-thirds change into other varieties that are more difficult to detect.

The total number of neutrinos from the Sun, they conclude, is about 35 million per square inch per second. "The agreement is pretty good between the predictions and the measurement," said Dr. Joshua R. Klein, a professor of physics at the University of Pennsylvania who coordinated the analysis of the data.

Dr. Bahcall was ecstatic.

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty," Dr. Bahcall said. "For 33 years, people have called into question my calculations on the Sun."

The new finding "shows the calculations were correct," he said. "I feel like dancing," he added.

Less happy is Dr. David O. Caldwell, an emeritus professor of physics at the University of California at Santa Barbara. "My personal reaction is one of great disappointment," Dr. Caldwell said. "I was hoping for a rather different result." The data ran contrary to his hopes of finding a

Sudbury Neutrino Observatory

Lawrence Berkeley National Laboratory

At left, a drawing of the neutrino detector, built 1¼-miles underground and immersed in water within a cavity 110 feet deep. Above, the bottom of the detector.

trino Observatory consists of a 40-foot-wide acrylic sphere containing 1,000 tons of heavy water, in which the two hydrogen atoms of the water molecules have been replaced with deuterium atoms, a heavier version of hydrogen. The sphere is submerged within a 10-story cavity that was carved out of a nickel mine 1¼ miles underground and filled with 40,000 tons of ordinary water.

Occasionally, an electron neutrino will slam into one of the deuterium atoms in the heavy water, splitting it into a proton and a neutron. Detectors around the sphere of heavy water are able to spot the debris. The

other two types of neutrinos cannot break up deuterium. The scientists have seen 1,169 such collisions since the experiment began in 1999.

The researchers compared their results with earlier neutrino counts from the Super-Kamiokande neutrino experiment in Japan, which primarily detects collisions between electron neutrinos and electrons. But muon and tau neutrinos can also occasionally bounce off electrons.

If all the neutrinos reaching Earth from the Sun were of the electron variety, then the neutrino rates measured by Super-Kamiokande and Sudbury should match up. But Super-Kamiokande detected more. Since the Sun produces only electron neutrinos — the production of muon and tau neutrinos require higher-energy events, like matter falling into black holes or an exploding star — that means some of them must change

into muon or tau neutrin
"It's the first direct e
the changing of solar neu
electron type to another
Klein said. Most physicis
sidered neutrino morphi
most likely explanation f
ing neutrinos.
Dr. Caldwell's theory w
electron neutrinos were
into "sterile" neutrinos
interact with ordinary
looks like they've done a
ough job," he said. "It th
question if there is any
sterile neutrino. I don't
hope for it right now."
According to the equat
ticle physics, for this tran
of flavors to occur, at leas
neutrino types must poss
geon of mass. Coupled w
experimental results, th
ers conclude that each o
neutrino flavors weigh, at
60,000th as much as an el
But the universe is fille
neutrinos than any other
of particle, and some phys
wondered whether the
gravitation pull of neutri
strong enough to stop th
expansion of the universe
back into a big crunch.
At the upper limit, th
neutrinos may be subst
haps as much as the rest
matter, but far short of t
needed to collapse the un
Most of the mass of the
believed to be in "dark
still unknown form of ma
For particle physicists,
no data is one more piec
will need to incorporate in
unified theory of physic
scribes the behavior of al
and forces. The current
model does not predict the
neutrinos, but its equation
pler if neutrinos have no
Now scientists know th
of neutrinos is not simple.
are "very schizophrenic,
call said. Still unknown, fo
is whether the electron neu
changing into muon neutri
neutrinos or both.
"I expect to be up lat
trying to answer that ques
Bahcall said. "It's pointin
way — in the right way, we
make a better theory, a mo
passing theory."

2015 Nobel Prize in Physics

SuperK

Takaaki Kajita

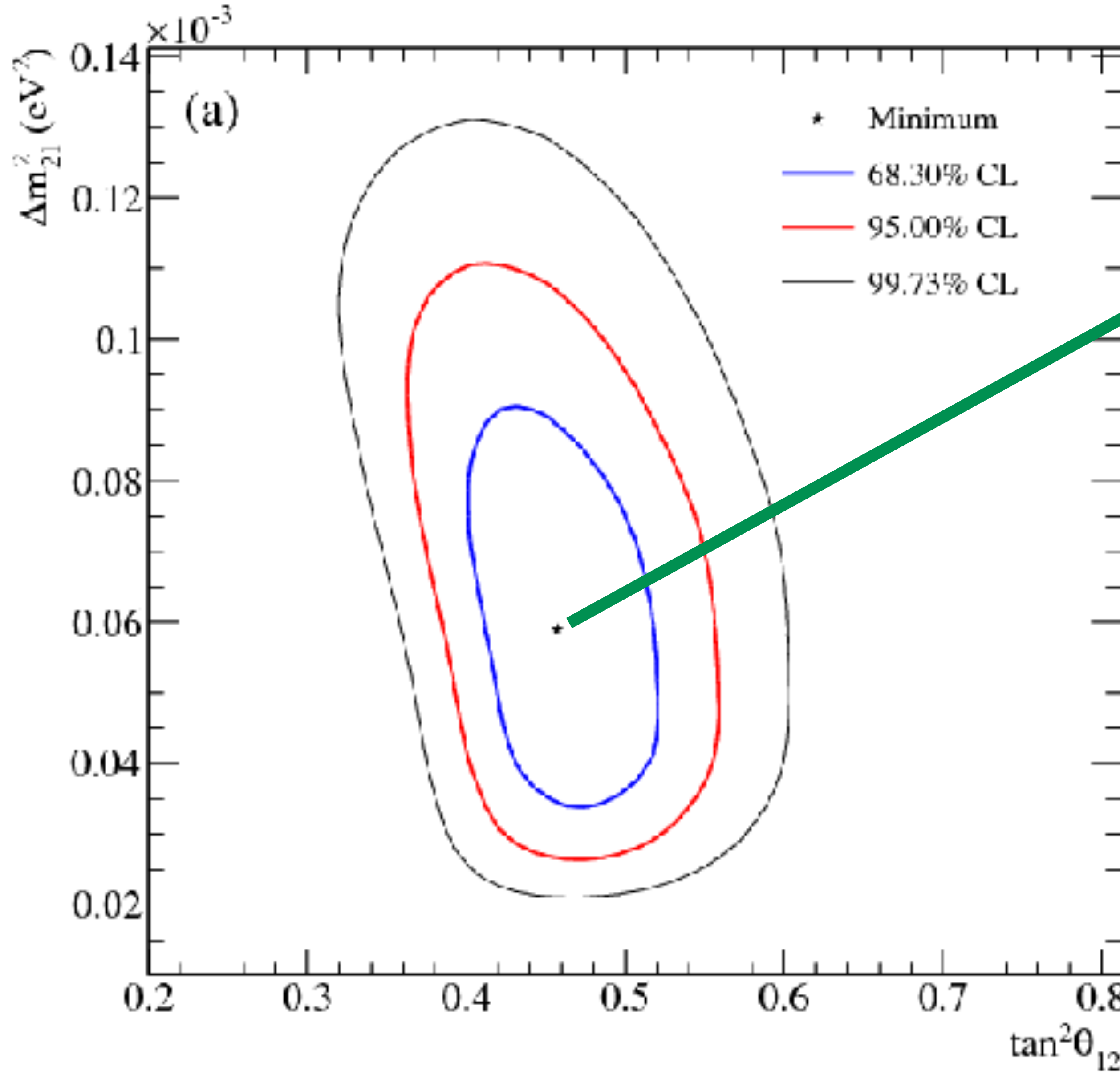
SNO

Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Fortuitous

Solar data:



Best-fit point of ***vacuum*** oscillation parameters under the hypothesis of MSW oscillations

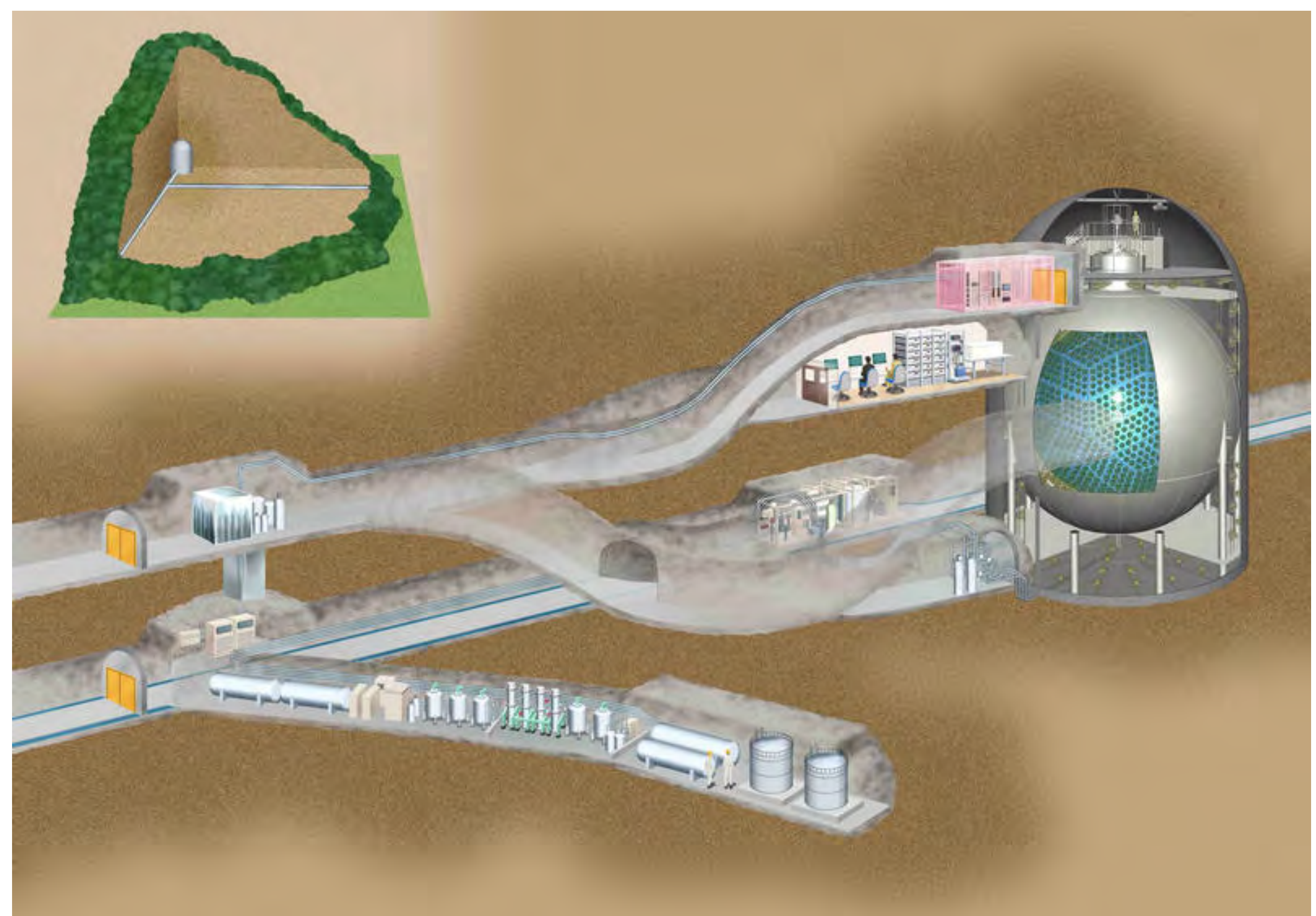
$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$

L ~ 70 km for E = 4 MeV

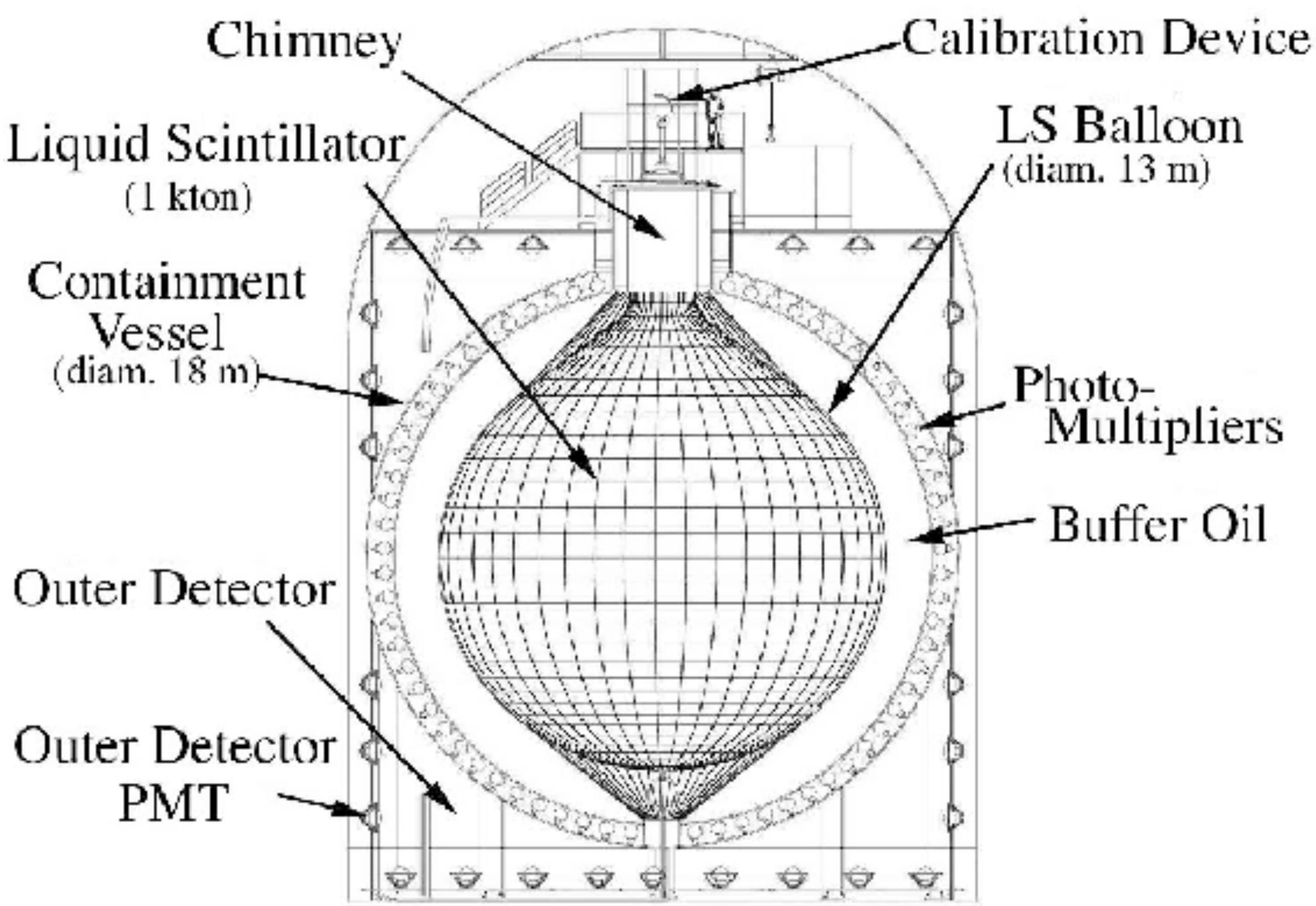
Can do this on Earth!

Even More Fortuitous

- KamLAND reactor experiment proposed before SNO began taking data
- Multiple reactors (60GW) in Japan at ~ right baseline
- L_{ave} = 180 km (flux-weighted average)
- E_ν ~ 2-4 MeV



KamLAND

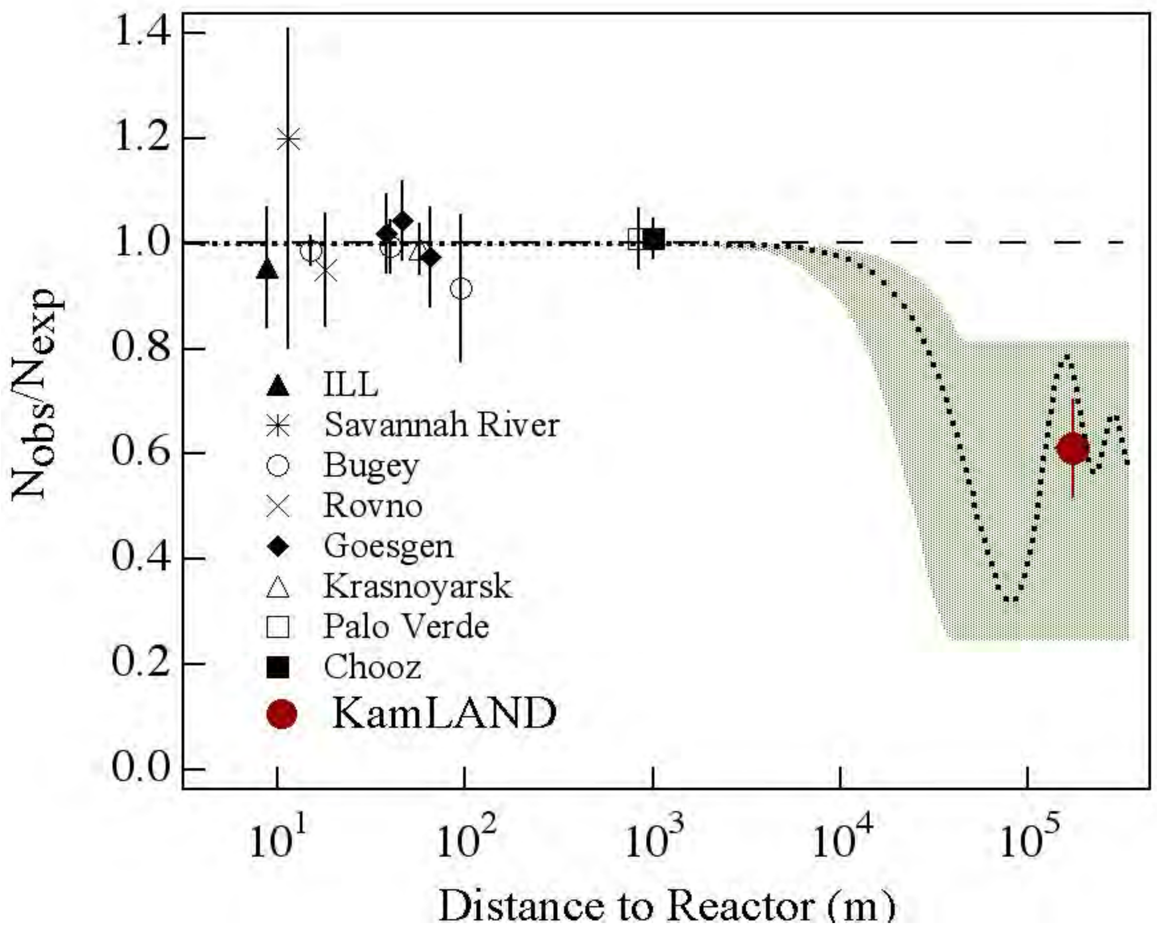


- 1 kT liquid scintillator
- 34% photocathode coverage
- H_2O veto
- Inverse beta decay:

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

Same as Reines/Cowan
No additive
n capture on H

Results



PRL, 2003
Most cited physics paper, 2003

+ oscillation pattern clearly observed

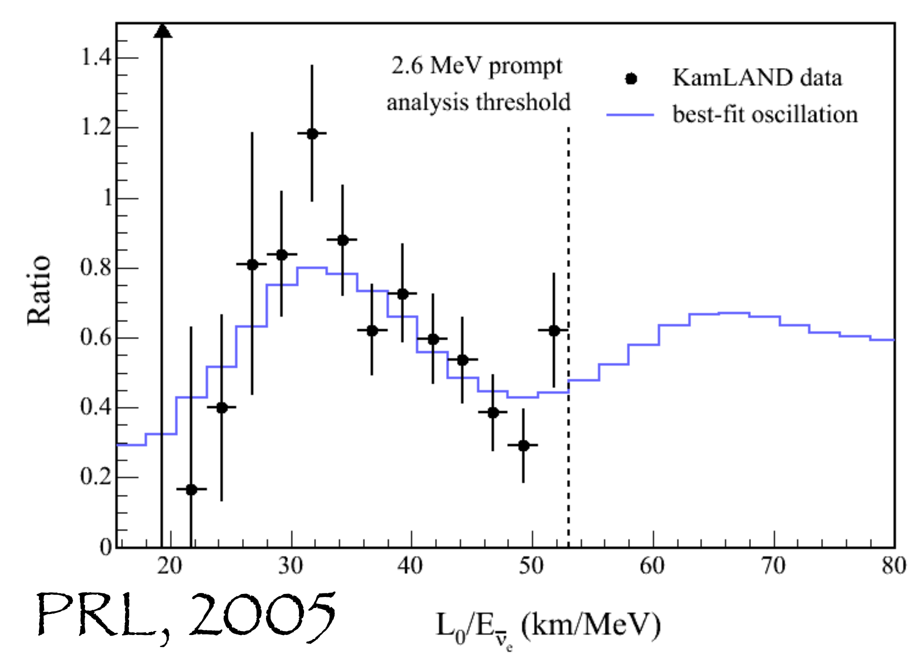
- Flux suppression:

  766 ton-yrs

  expect 365.2 + 17.8 bkg events

  observe 258

- Disappearance at 99.998% significance



PRL, 2005

Neutrinos for nonproliferation

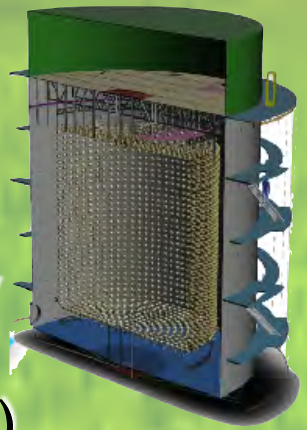
Near-field: ~100m
Inside a reactor facility
1—10 ton, LS
Surface possible (requires segmentation)

Increasing standoff, decreasing flux, wider field of view

Measure: reactor power, fissile core content, fuel burn up, maybe enrichment

Increasing depth required to reduce cosmic-ray induced bkg

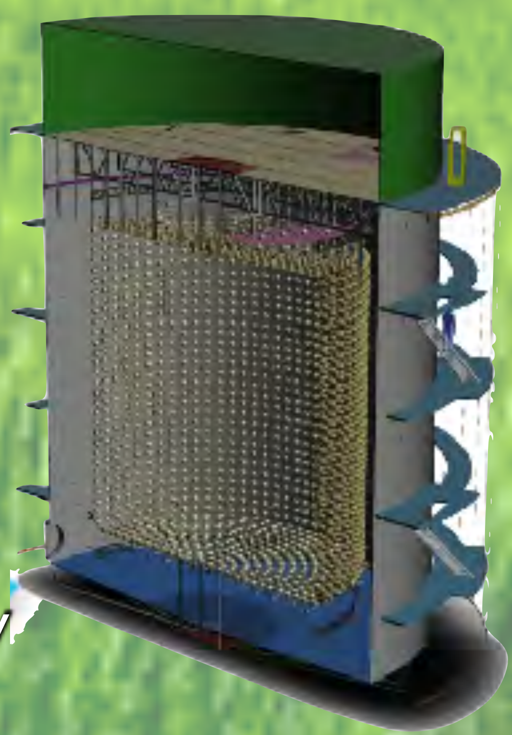
Mid-field: ~1km
Dedicated, but outside the facility
10–100 ton
Requires underground site (10s m)



Measure: reactor power, limit on Pu production, verify reactor shut down

Far-field: ~10km+
Monitor any facility within a region
100 ton — 1 kton
Deep underground site (100m-km)

Verify or exclude the presence of any reactor above a certain power level



Neutrinos for nonproliferation

Neutrino properties

Produced as a by-product of fission and fusion	↔	*Provide a unique signature of nuclear fission / fusion*
Weakly interacting	↔	*Signature can't be shielded*
Close to massless, travel ~c	↔	*Near-instantaneous detection*
Interaction products preserve incident direction	↔	*Can be used to "point" back to the source*

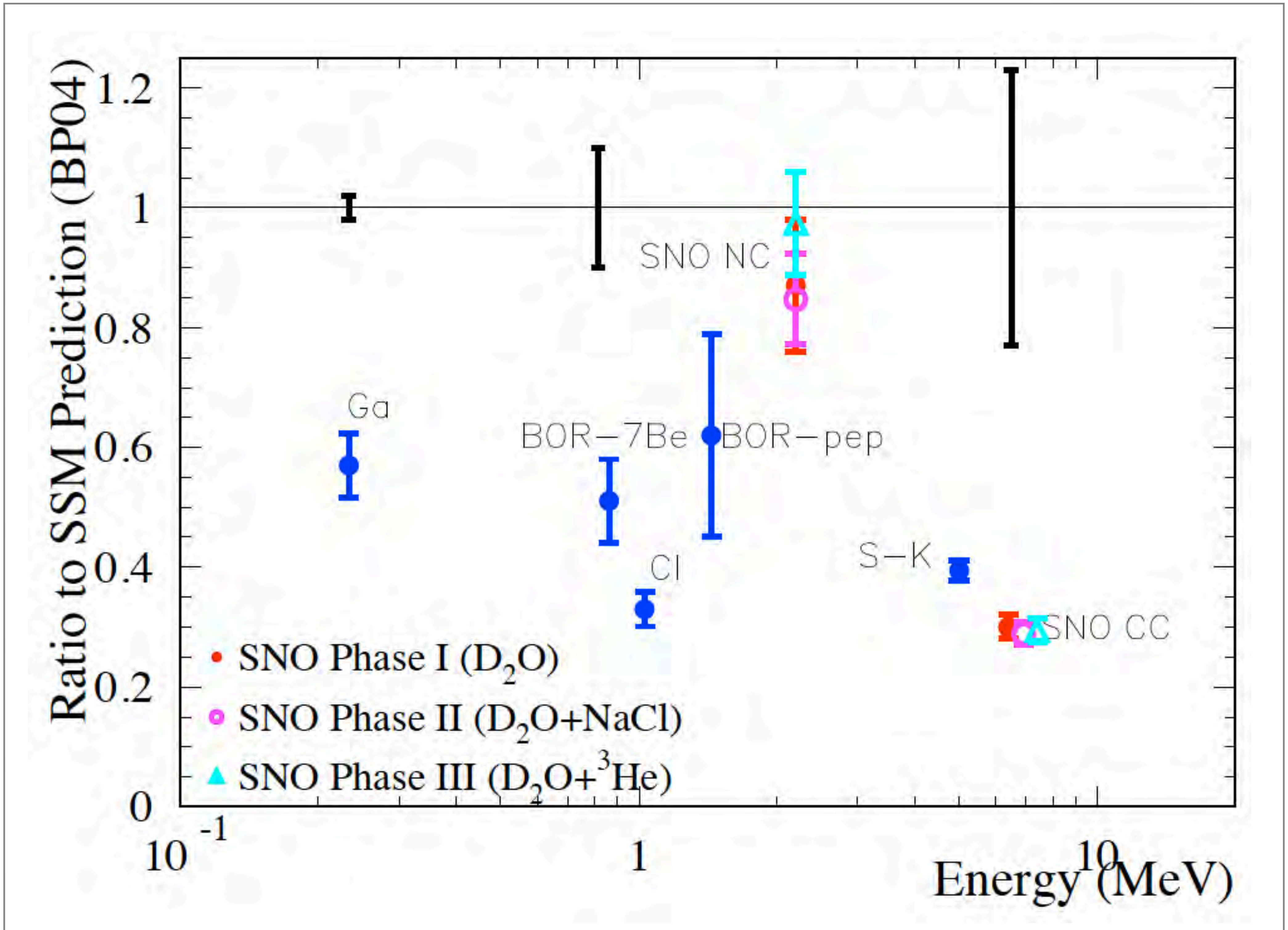
Test site transparency

Small modular reactors

Maritime sensing

- NuTools: 2021 study (DNN R&D) "exploring practical roles for neutrinos in nuclear energy and security"
- LBNL's focus is to advance the technology to enhance the capabilities of such a detector
  - Reduce the required scale, increase standoff, and provide additional synergies with Office of Science interests
- Close partnership with related efforts at BNL & LLNL

Solar Neutrino Oscillation



Solar Neutrinos

"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'

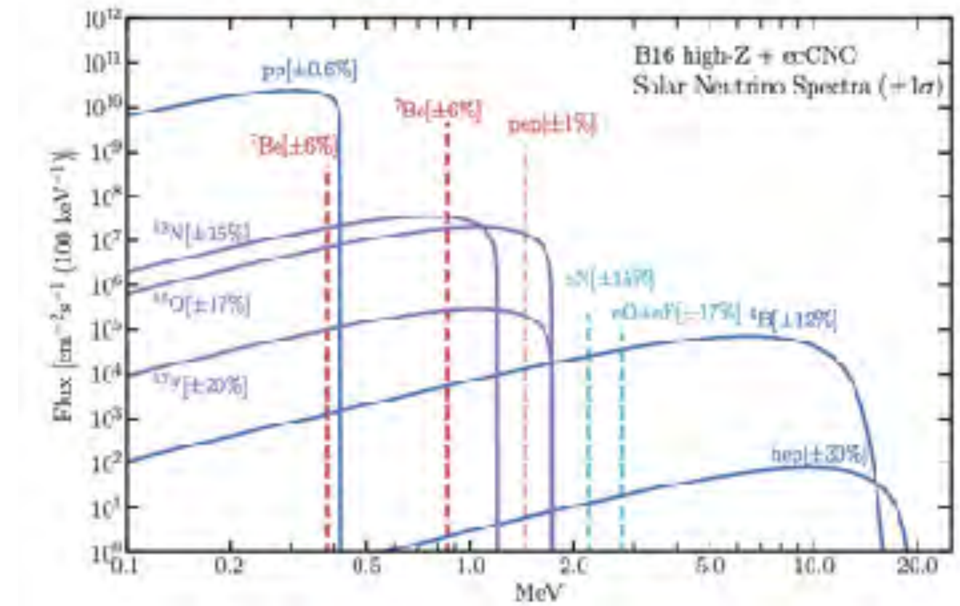
Then the SNO results came out.

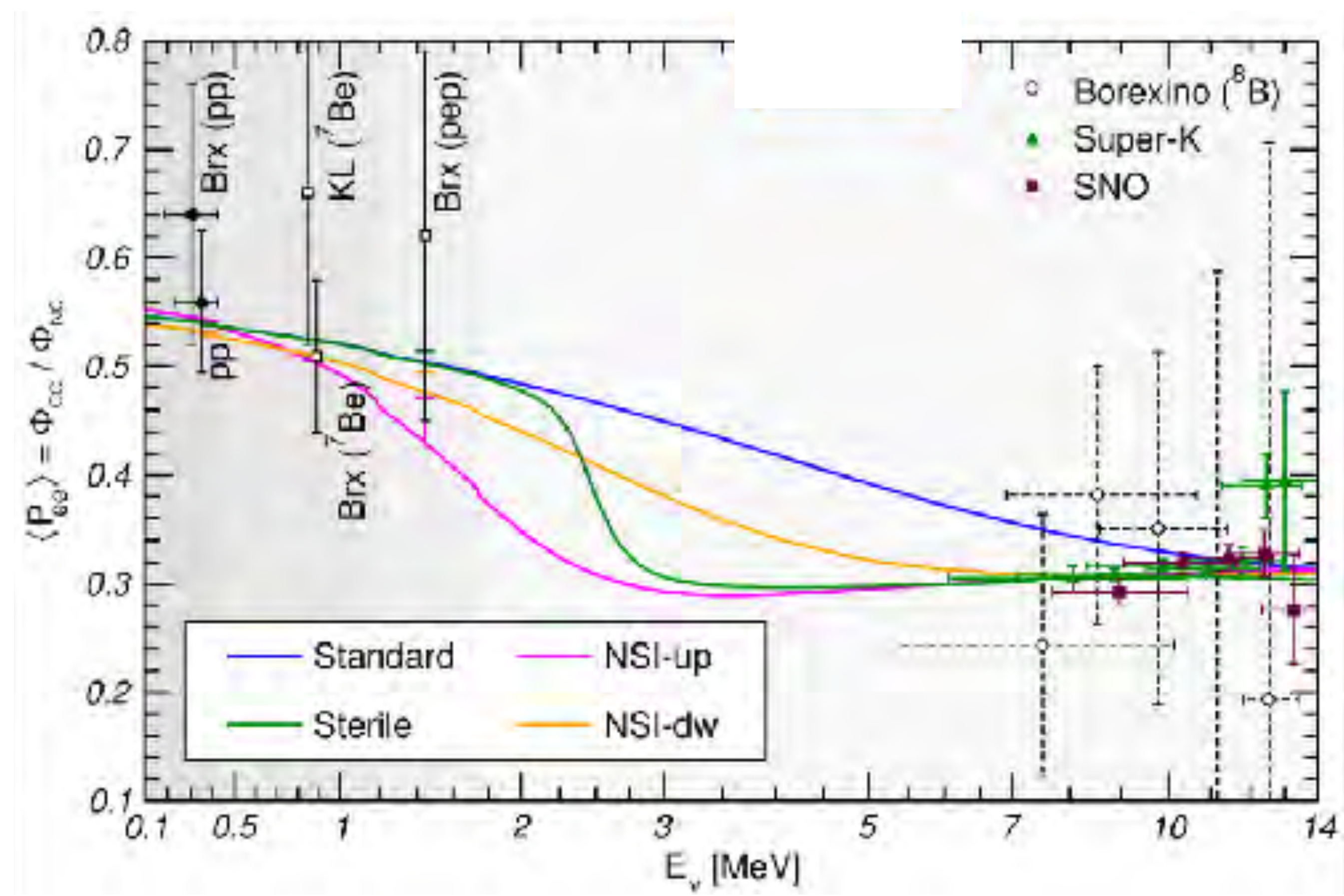
And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"

--- John Bahcall, 2003

Beyond the Solar Neutrino Problem

- Probing the Sun
    - hep: last unobserved flux
    - Precision CNO: Solar composition: high/low metallicity
    - 8B, 7Be: T, environmental factors
    - pp: luminosity constraint
- Solar neutrinos
    - Day/night effect
    - Δm^2_{12} (mild tension)
    - NSIs, sterile

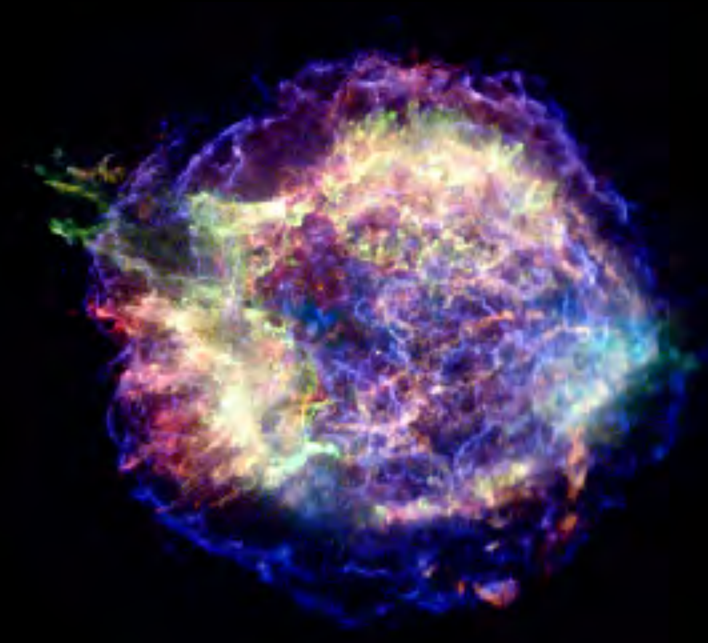




M. Maltoni et al., Eur. Phys. Jour. A 52 (2016) 87

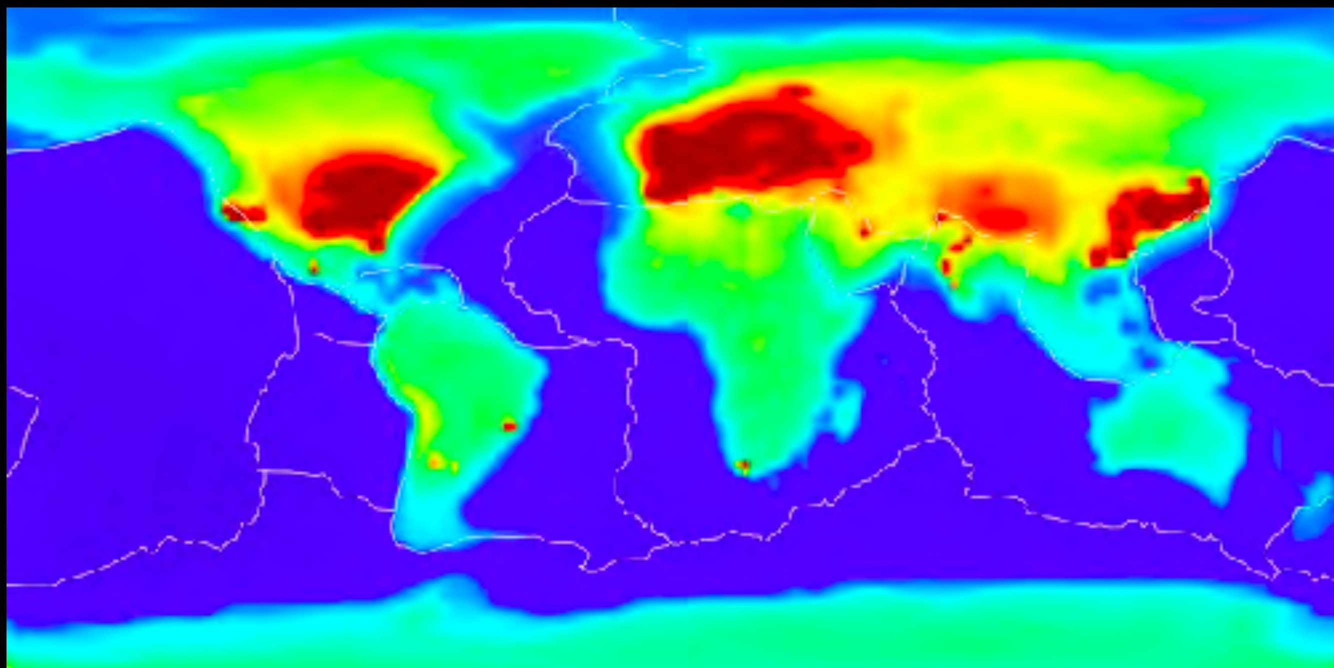
Neutrino (astro)physics

- Solar neutrinos ~few x 10^{-6} TeV
  - Study stellar astrophysics e.g. metallicity, T
  - Probe interaction of ν with matter
  - Search for new physics



- Supernova neutrinos ~few x10^{-5} TeV
  - Understand explosion mechanism
  - Probe neutrino flavour physics
  - Early warning for astronomers

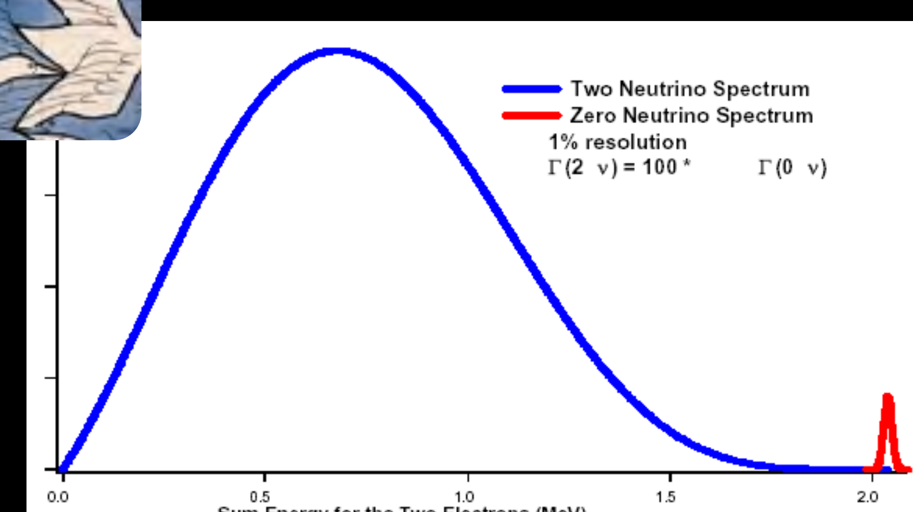
Nuclear / geo physics with neutrinos



- Geo neutrinos ~few x 10^{-6} TeV
  - Probe radiogenic heat production
  - Test model's of Earth's composition
  - Mantle contribution

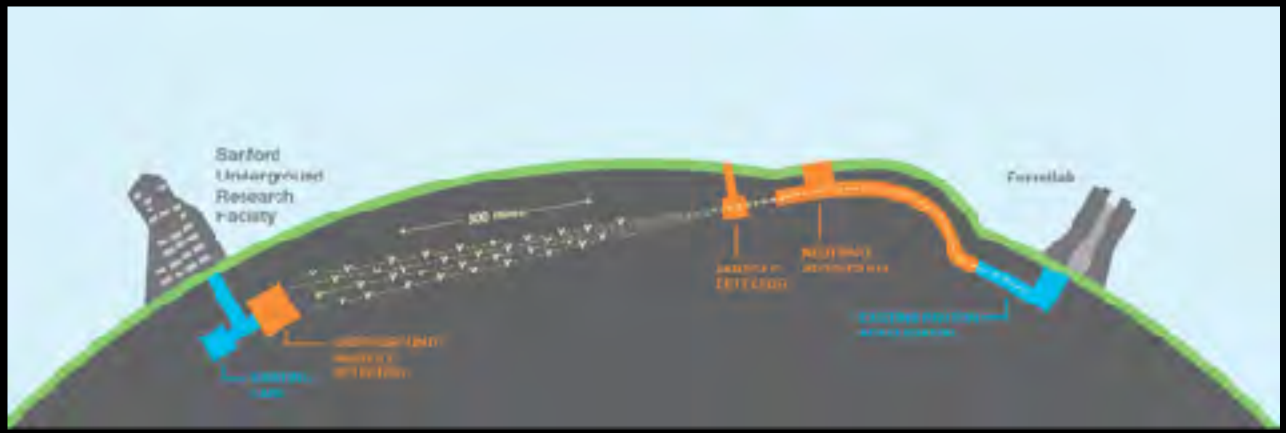
M.C. Escher

- Majorana neutrinos ~few x 10^{-6} TeV
  - Unique potential to be their own antiparticle
  - Demonstrate lepton no. violation
  - Explain matter/antimatter asymmetry



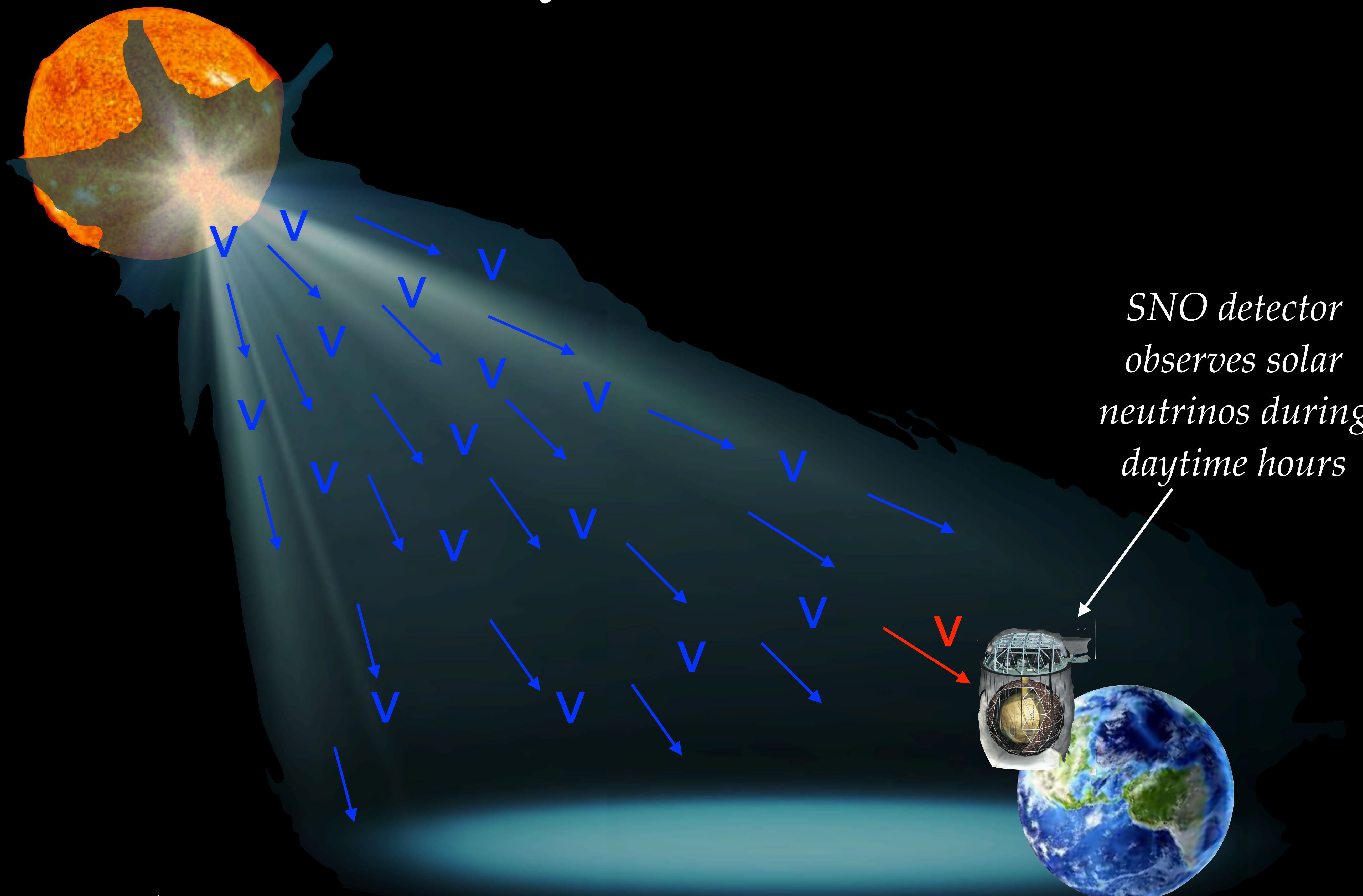
High energy physics with neutrinos

- Long baseline neutrinos
  - Neutrino mass ordering
  - Search for leptonic CP violation
  - Probe oscillation physics



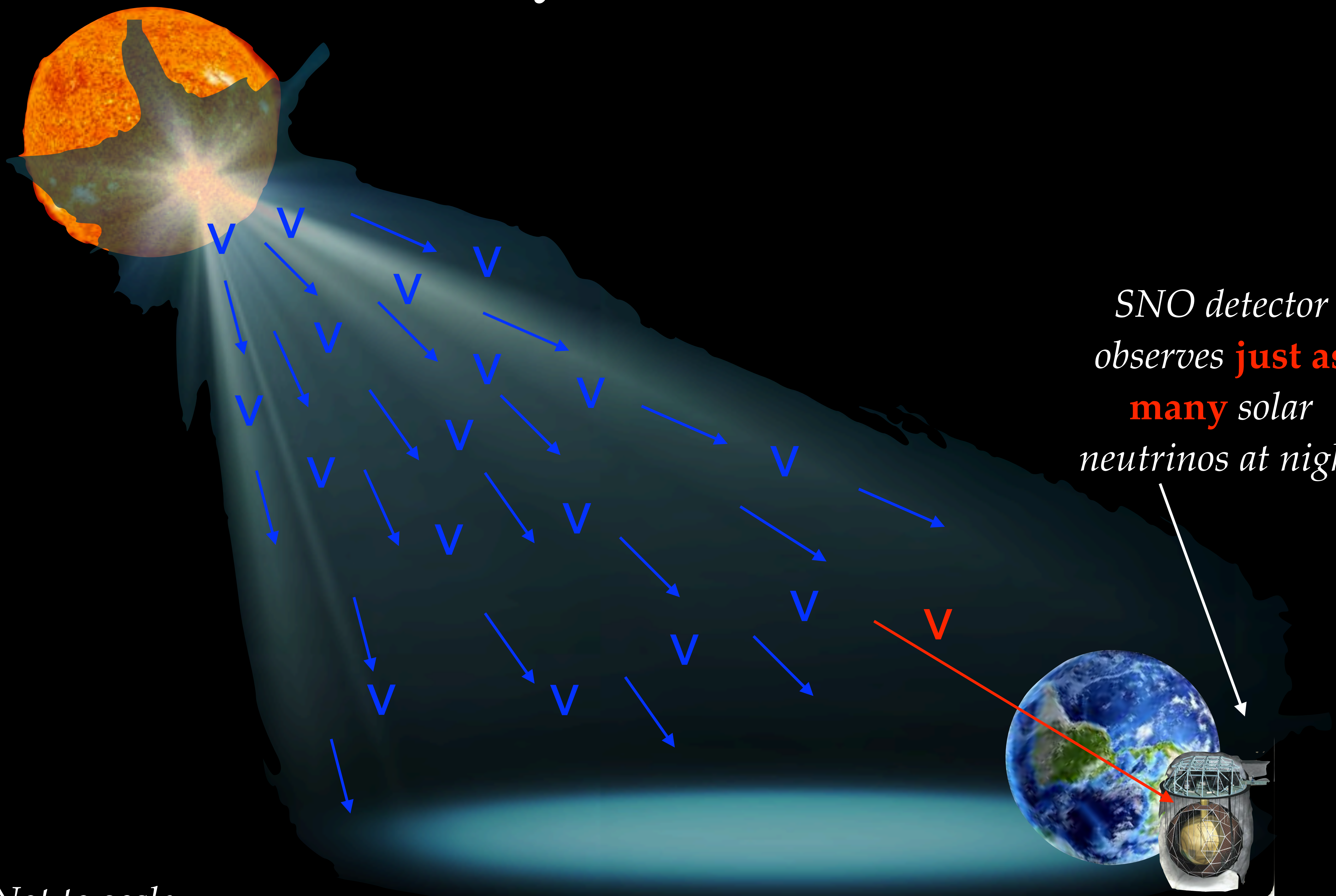
- Reactor neutrinos
  - Probe oscillations (Δm_{12}^2)
  - Sterile neutrinos
  - Coherent ν-N scattering
  - Nonproliferation applications

Why is it Hard?



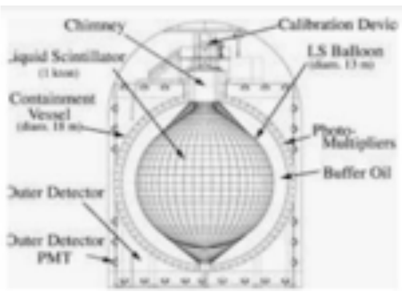
Not to scale

Why is it Hard?

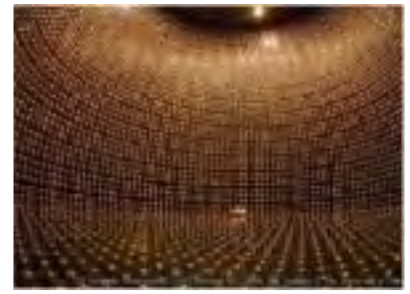


Not to scale

Experimental approaches



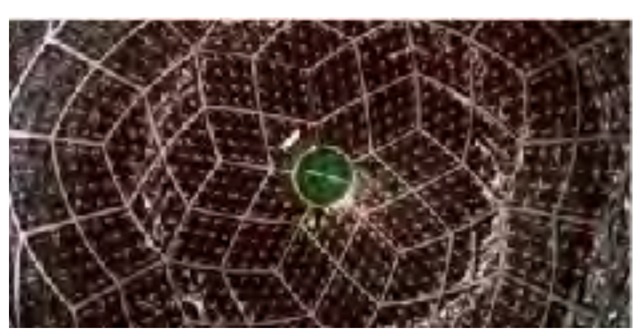
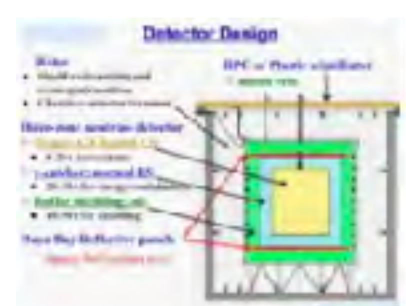


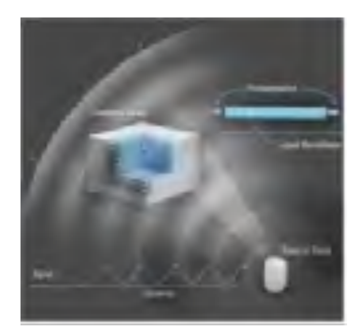




- Water Cherenkov detectors
- Liquid scintillator detectors
- "Hybrid" detection
- Noble liquid detectors — primarily for DM / LBL
- Solid state detectors — extremely good resolution
- *Disclaimer: will only discuss a few examples!*



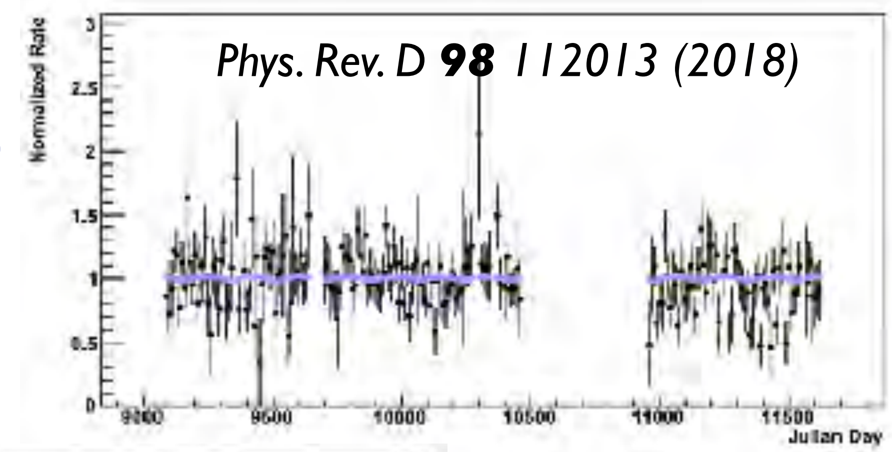





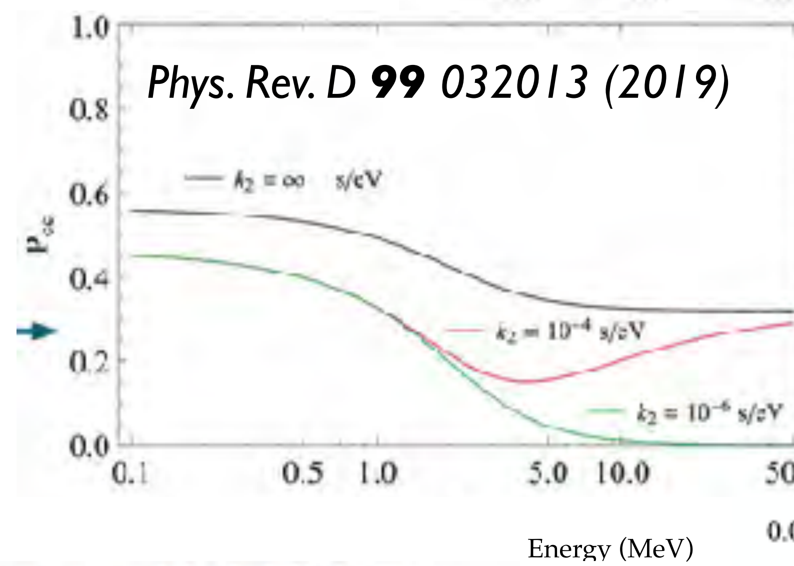
Experimental landscape

Sudbury Neutrino Observatory

- Search for Lorentz violating effects (preferred direction)
- New / improved constraints on 38 / 16 model parameters



- Search for neutrino decay
- Energy-dependent disappearance
- New limit on lifetime
  k_2 (= τ_2/m_2) > 1.92 x 10-3 s/eV (90% CL)



- Search for hep & DSNB neutrinos
- Final undetected solar ν flux
- Probe "glow" from past core-collapse SNe

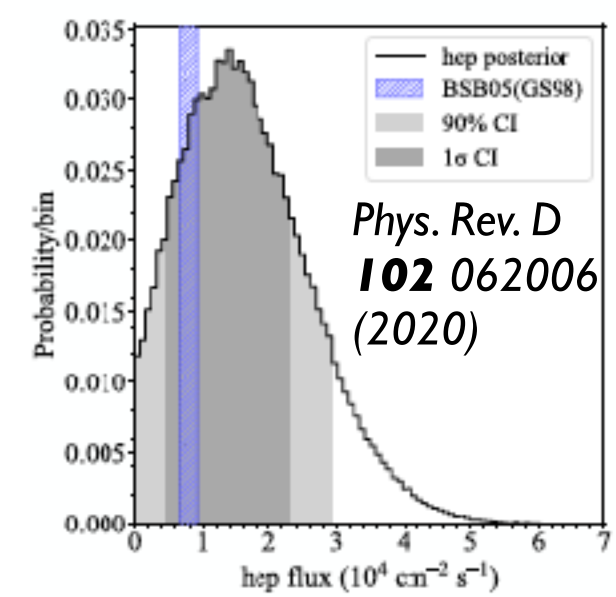
Bayesian one-sided 90% CI:

$\Phi_{DSNB}^{*} < 19$ cm^{-2} s^{-1} (22.9 < E_ν < 36.9 MeV)

(*sensitivity ~ 30 cm^{-2} s^{-1})

Bayesian 90% CI:

$\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1}

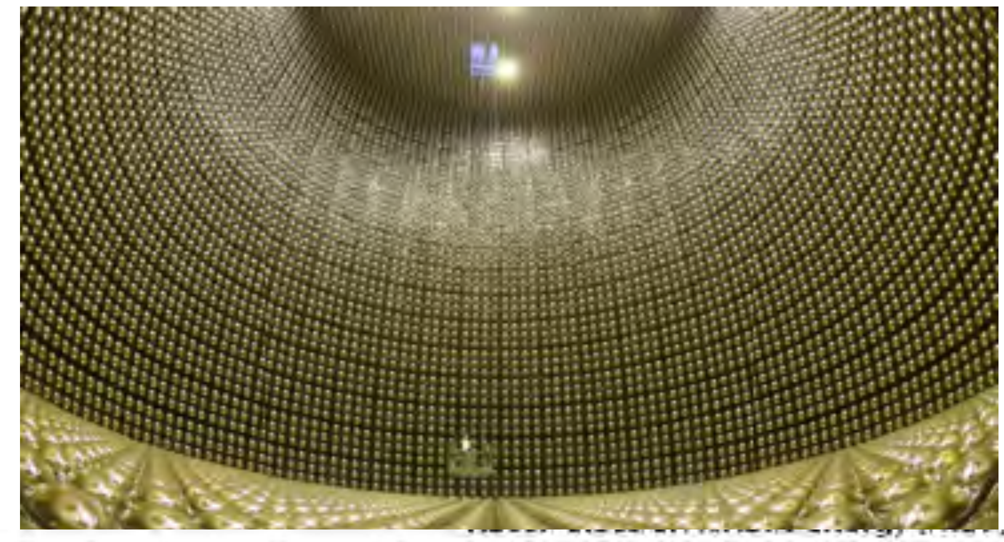


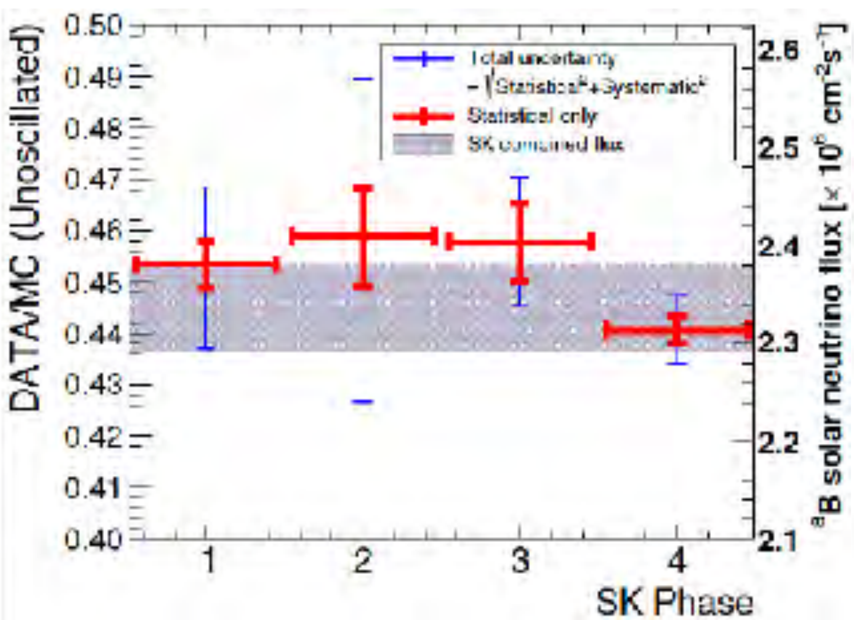
- Measurements of n production from μ and atm ν

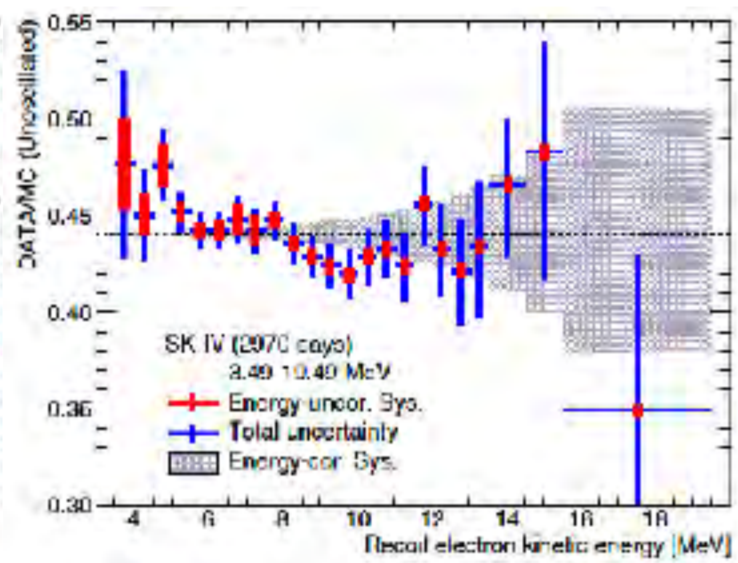
Phys. Rev. D **99** *112007 (2019), Phys. Rev. D* **100** *112005 (2019)*

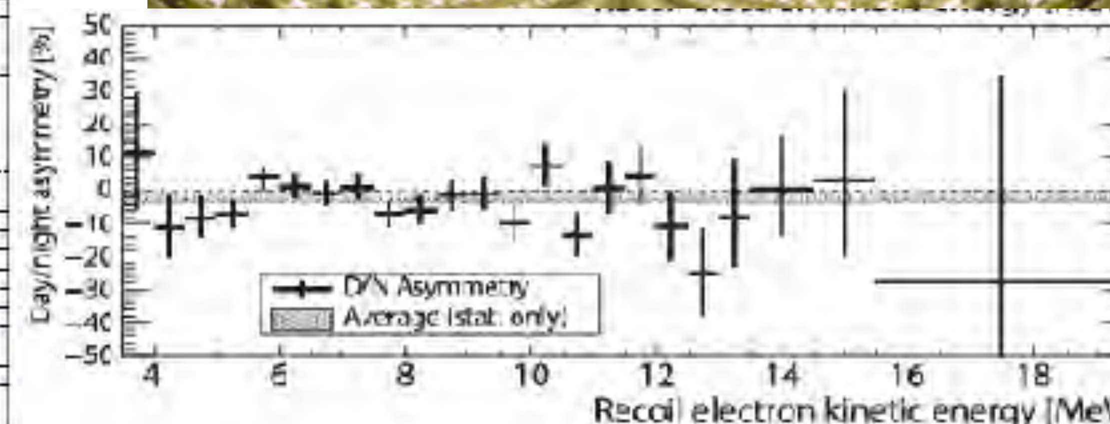
Super-Kamiokande (+Gd)

- Largest solar neutrino detector: 22.5kton (fiducial)
- Four phases of operation, 20+ years of data!
- High-precision rate, hint of day/night (~2σ)
- Spectral measurements

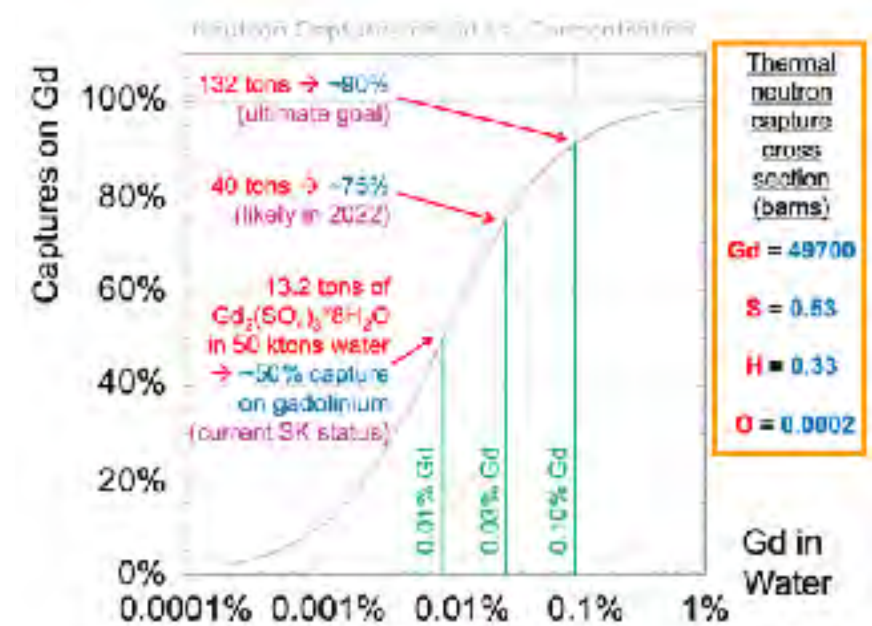






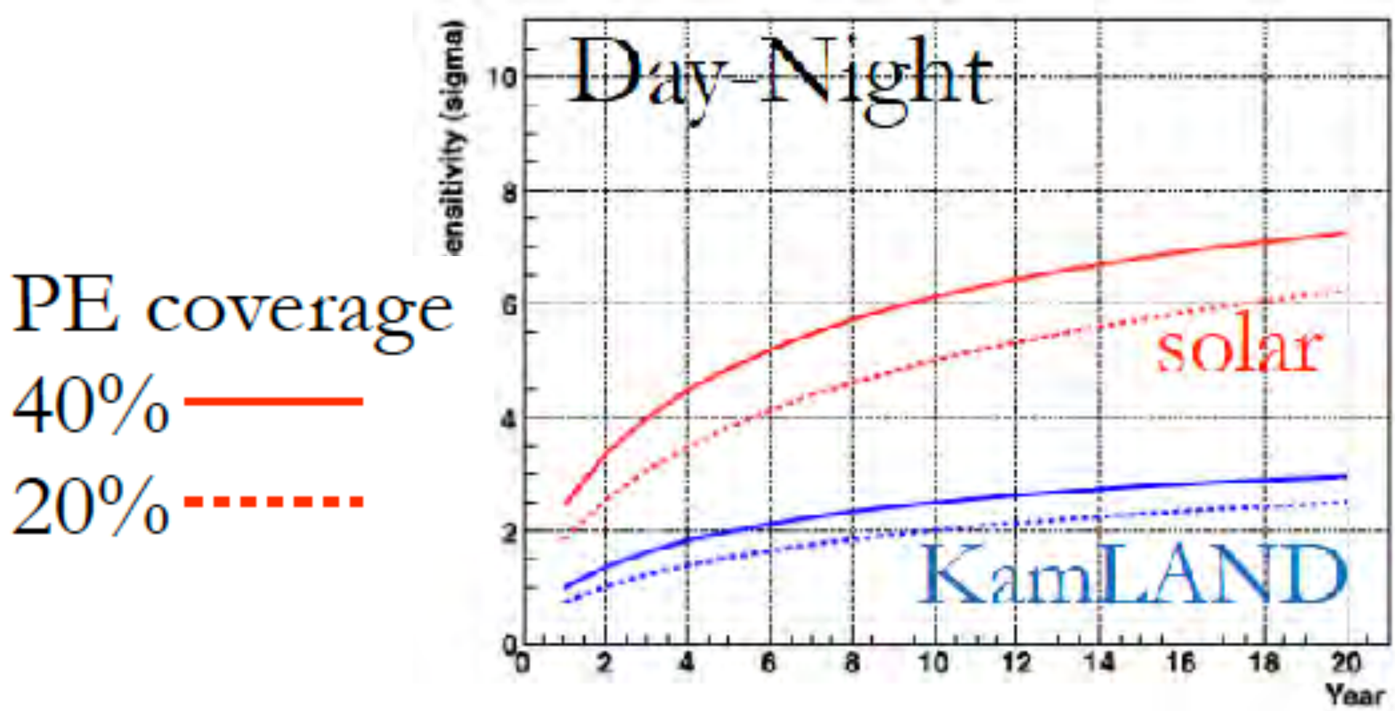


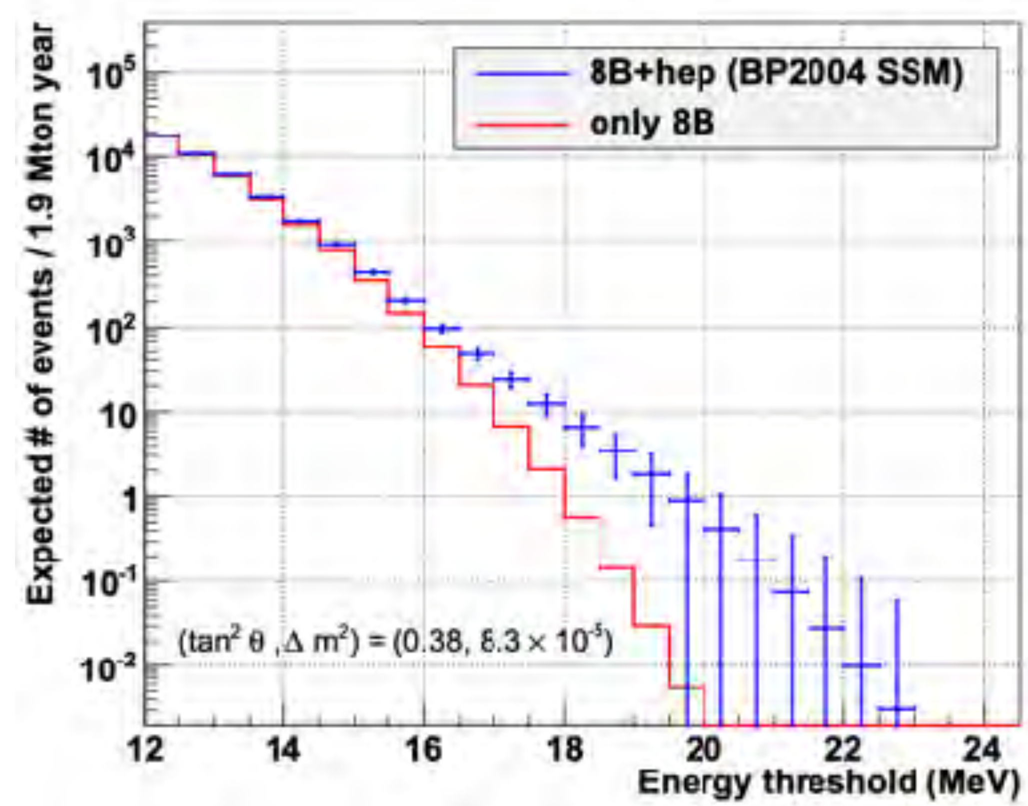
- First large detector ever to be filled with Gd-H2O (0.021% $Gd_2(SO_4)_3$ ~0.01% Gd)
- Enhance neutron capture efficiency
- Transparency observed to be as good as H2O phase
- 0.03%Gd should allow first detection of DSNB



Hyper-Kamiokande

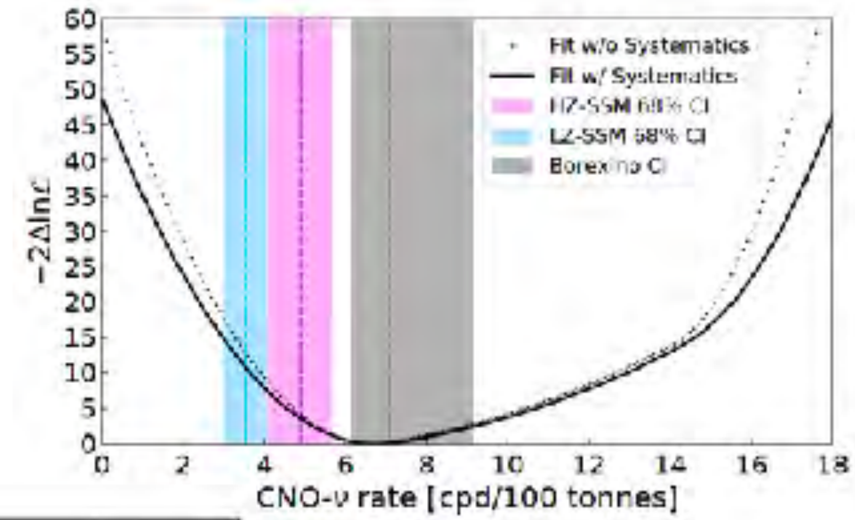
- Largest ever neutrino detector, starting 2027
- Less deep than SK: higher cosmogenic backgrounds; several methods to tag showers
- Huge statistics: ~5 8B ν/hour
- If oscillation parameters are that of solar best fit, can reach 5σ precision on day-night effect and low energy upturn (less if reactor)
- 2-3 σ measurement of hep νs
- >200 kton, 40% coverage

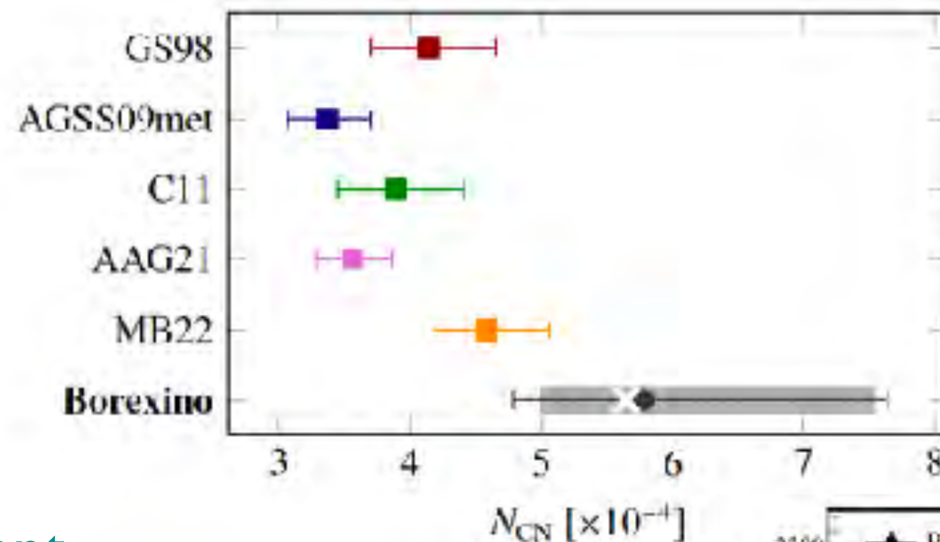




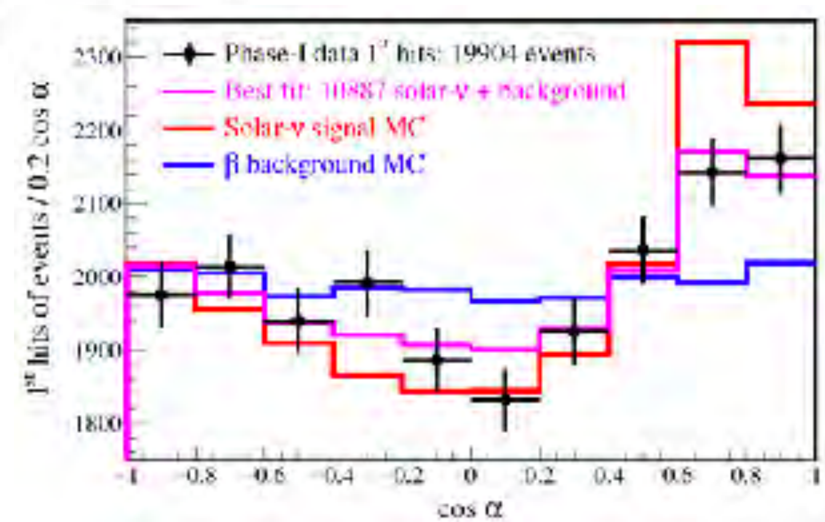
Borexino

- First measurement of CNO ν flux!
  - ^{232}Th and ^{238}U ~ 10^{-19}g/g; ^{210}Bi events ≤11.5 ± 1.3 cpd/100t
  - CNO flux: 6.6 $^{+2}_{-0.9}$ x10^{8} cm^{-2}s^{-1} (7σ)
  - First evaluation of C, N solar abundance using ν
  - 2σ tension with low-metallicity measurements
  - Global fit (8B, 7Be) allows to disfavour B16-AGSS09met (vs B16-GS98) at 3.1σ





- Integrated directionality at Borexino:
  - consider earliest photons in the event
  - take angle between early photons and solar direction
  - 6σ angular excess caused by Cherenkov photons
- Measurement of primarily 7Be ν demonstrates first directional detection of sub-MeV neutrinos



Nature 587, pages 577–582 (2020), Phys.Rev.Lett. 128 (2022) 9, 091803, Phys.Rev.D 105 (2022) 5, 052002; PRD 105.052002, PRL 128 (2022) 9, 091803

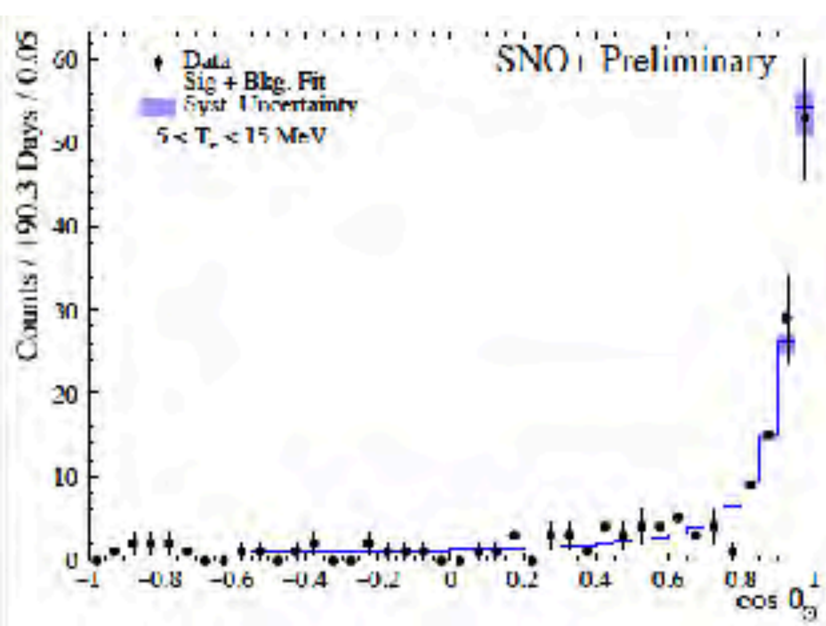
SNO ⇛ SNO+

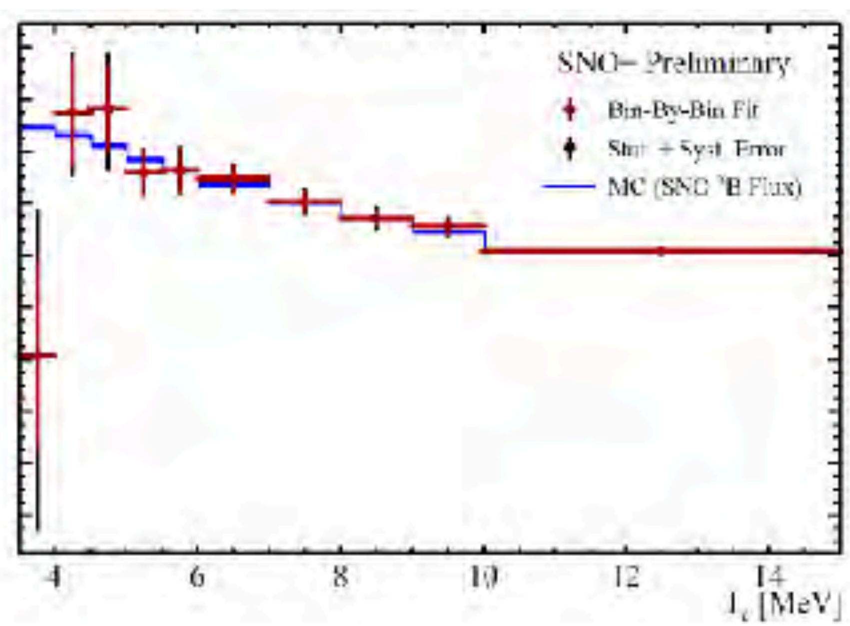
- Completed data taking with water
- LS fill complete, end of March, 2021 (780kg LAB+PPO)
- PPO fill complete: 2.2 g/L
- Largest, deepest operating LS detector
- Ultra-low background
- NLDBD target backgrounds achieved!
- Broad ongoing physics program

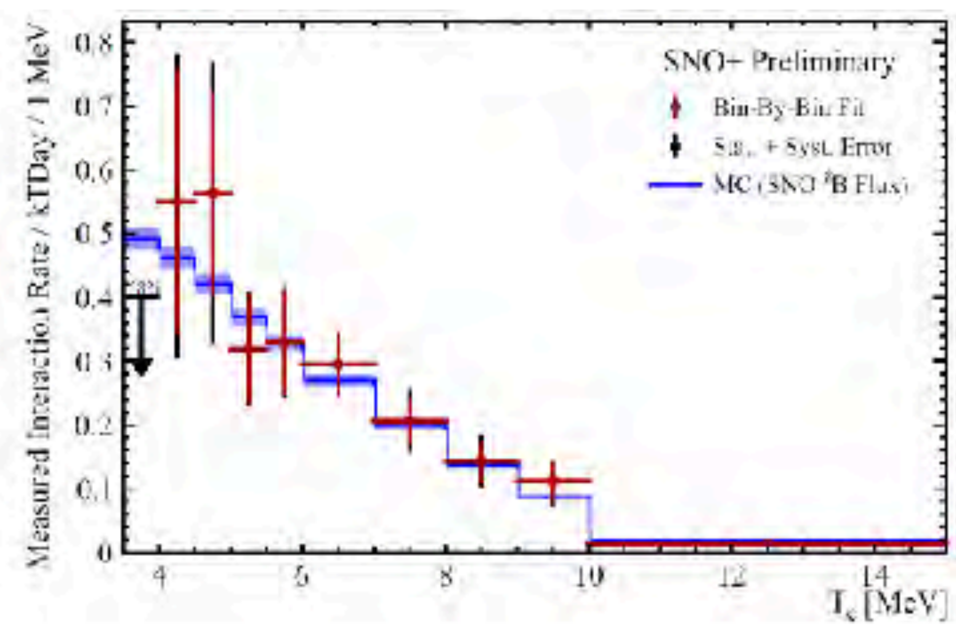
Related work:
Phys. Rev. D 105, 112012 (2022)
JINST 16 P10021 (2021)
JINST 16 P08059 (2021)
JINST 16 P05009 (2021)
Phys. Rev. C 102, 014002 (2020)
Phys. Rev. D 99, 032008 (2019)
Phys. Rev. D 99, 012012 (2019)

SNO+ water phase

- New analysis of 126.6 kt-days, including 190.3 days of low background data
- Radon in water ~6 × 10−15 gU/g
- Lowest background for water Cherenkov detectors > 5 MeV: 0.32 ± 0.07 ev./kt-days
- 3.5 MeV threshold (large uncertainties in lowest bins)
- Best-fit flux consistent (inc. oscillations) with other experiments, and HZ and LZ solar models

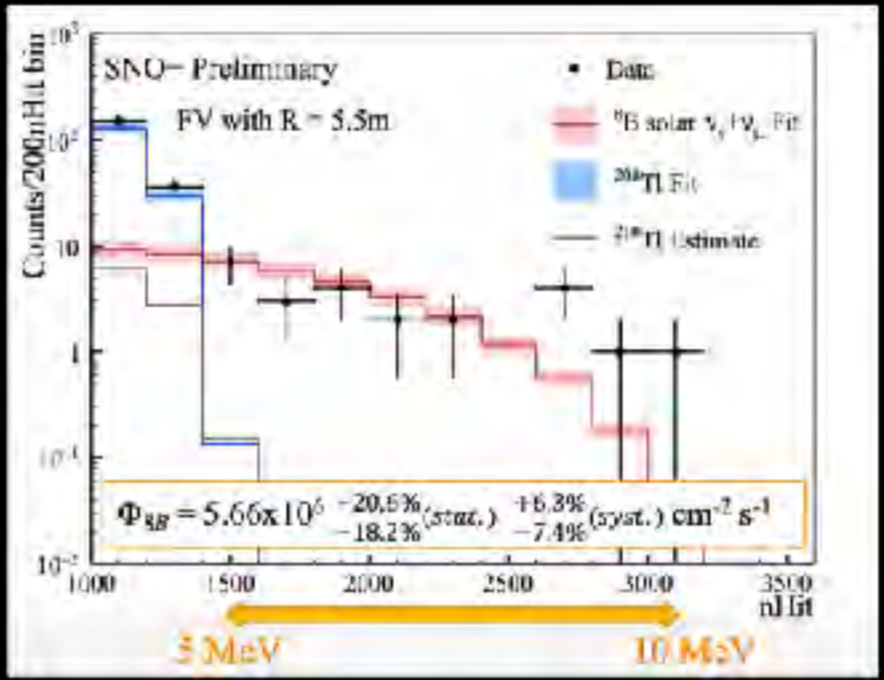






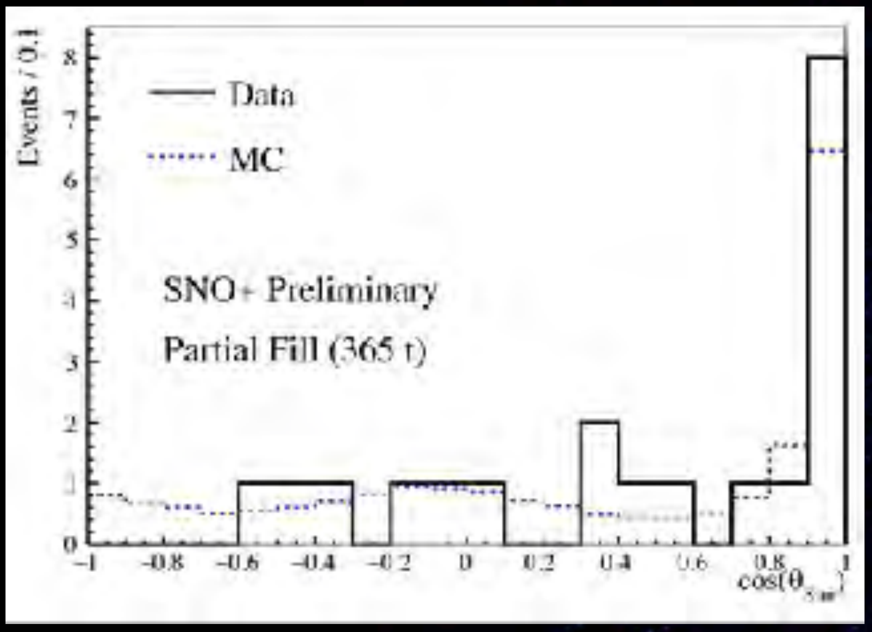
“Partial fill” / LS physics

- ~ 7 months data with 365t LAB + 0.5 g/L PPO
- Threshold lowered from 1MeV to 40keV
- Measure internal backgrounds, detector response with LS
- New physics opportunities



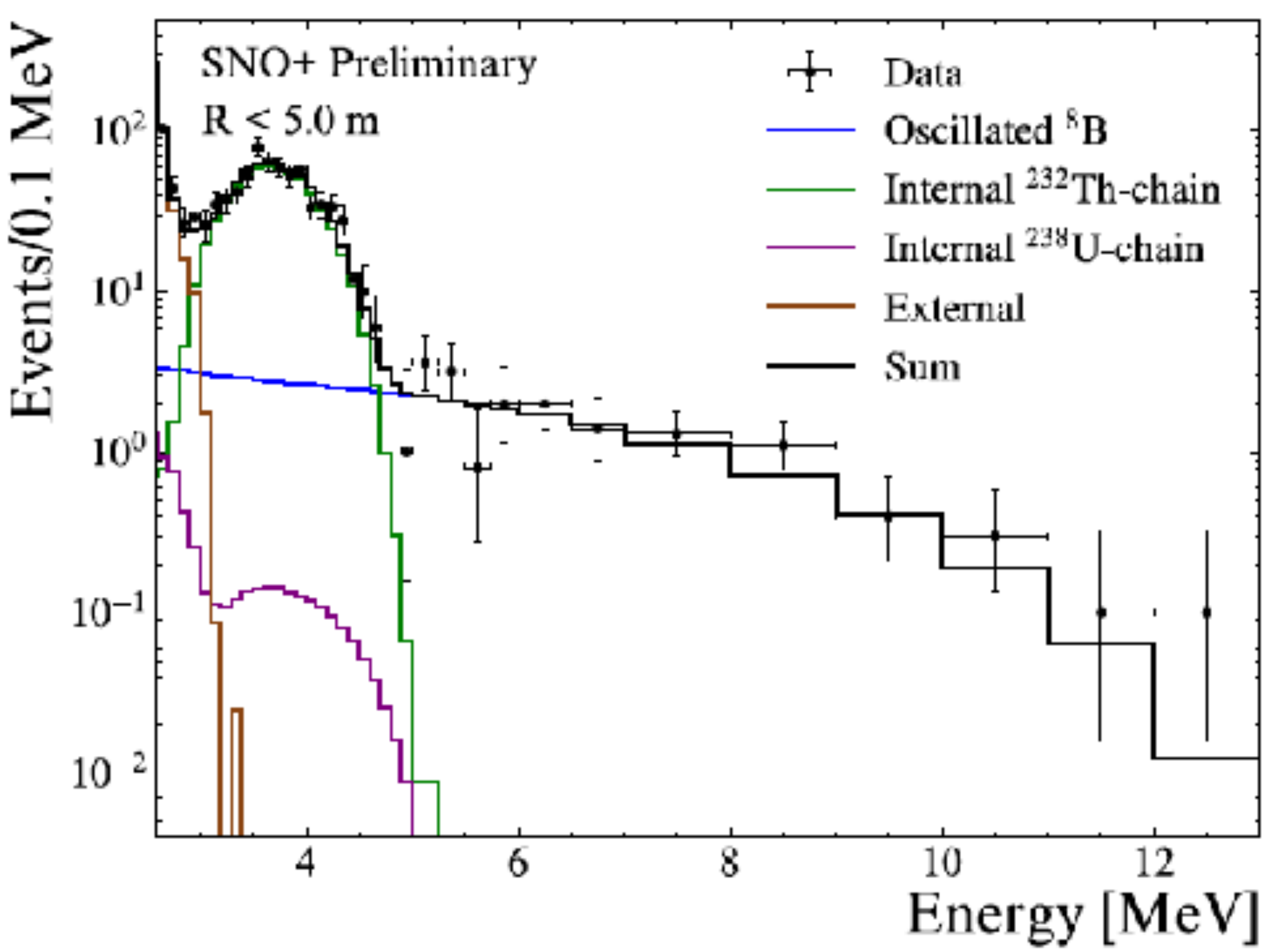
Preliminary ^{8}B solar ν + Bkg. Fit to the PF data,

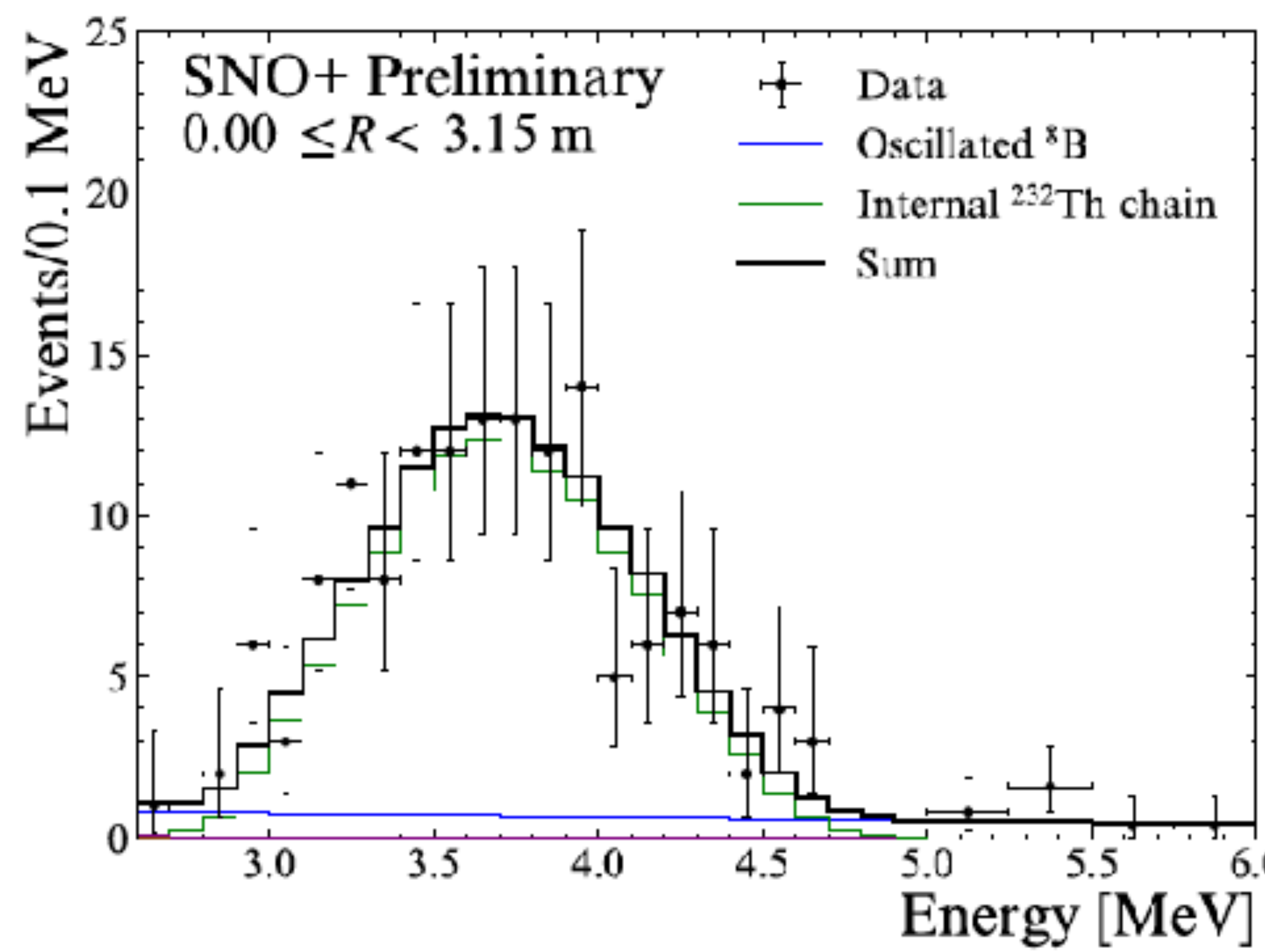
First event-level directionality in LS!



SNO+ pure LS phase

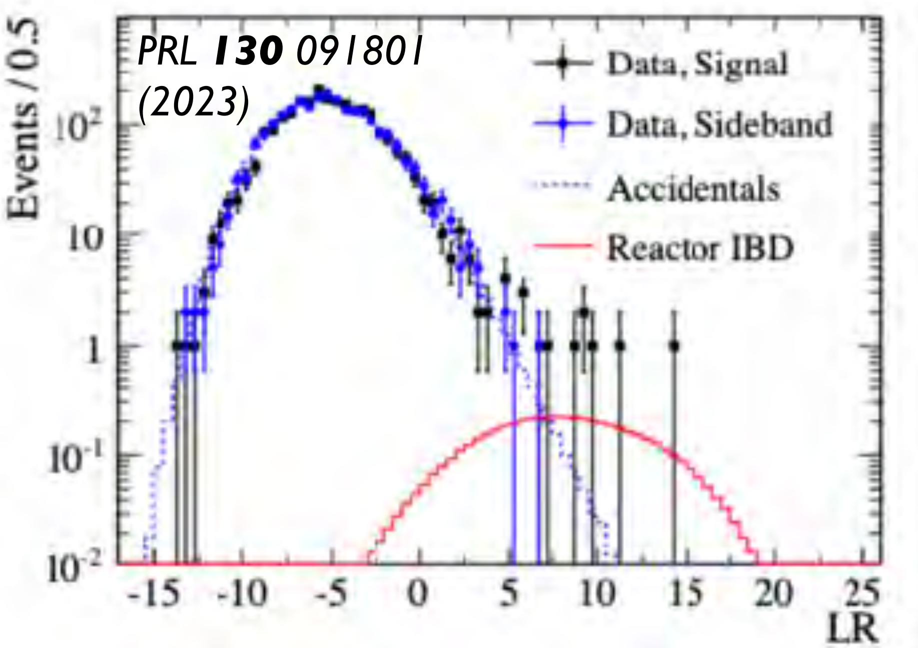
- Analysis of 8B ES interactions in 138.9 live days of scint. data
- Fitted oscillation parameters compatible with global fits
- Strict fiducial volume cut opens prospects for future sensitivity < 3 MeV
- 232Th still dominates 3-5 MeV regions; multi-site discriminant will help



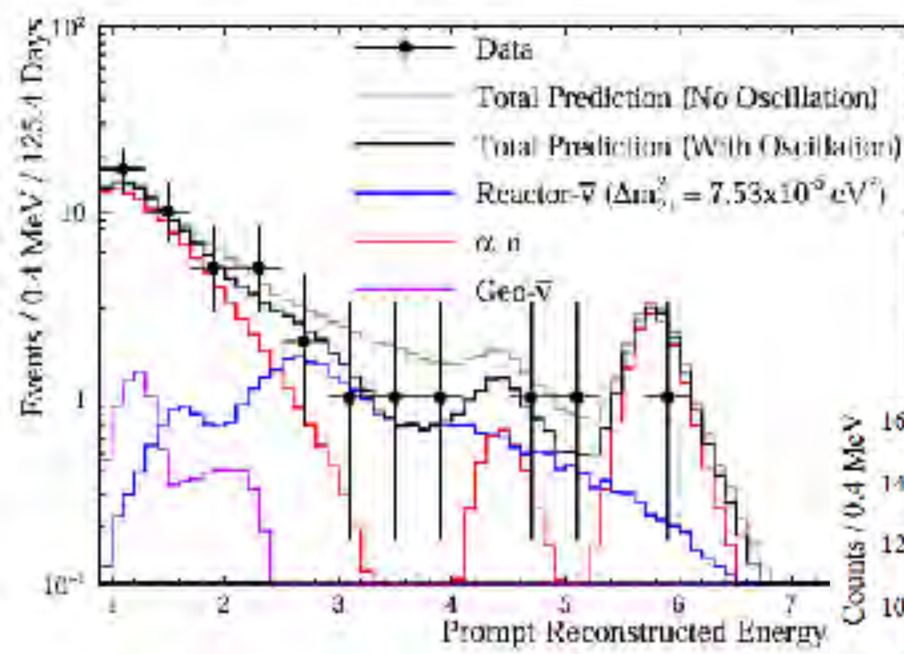


Antineutrino detection

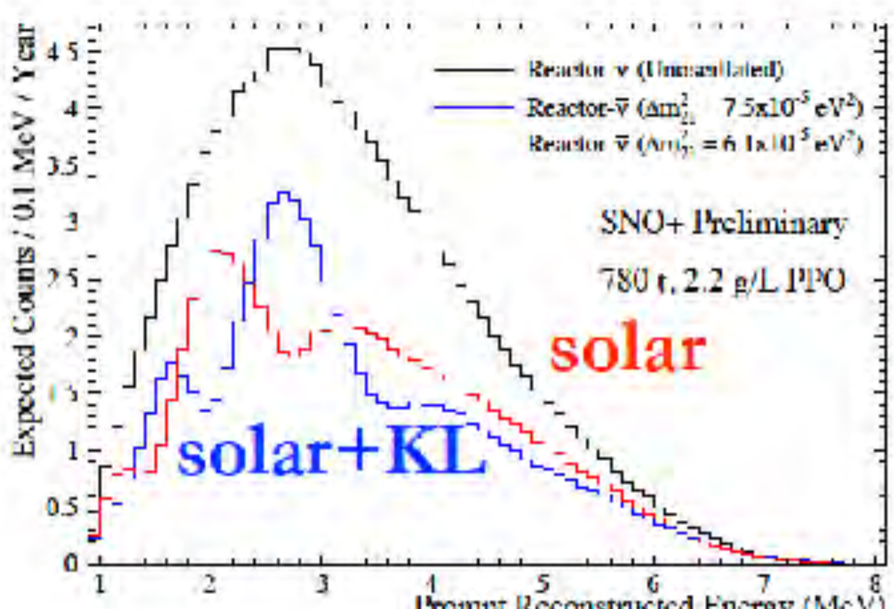
- Evidence of antineutrinos from distant reactors using pure water at SNO+

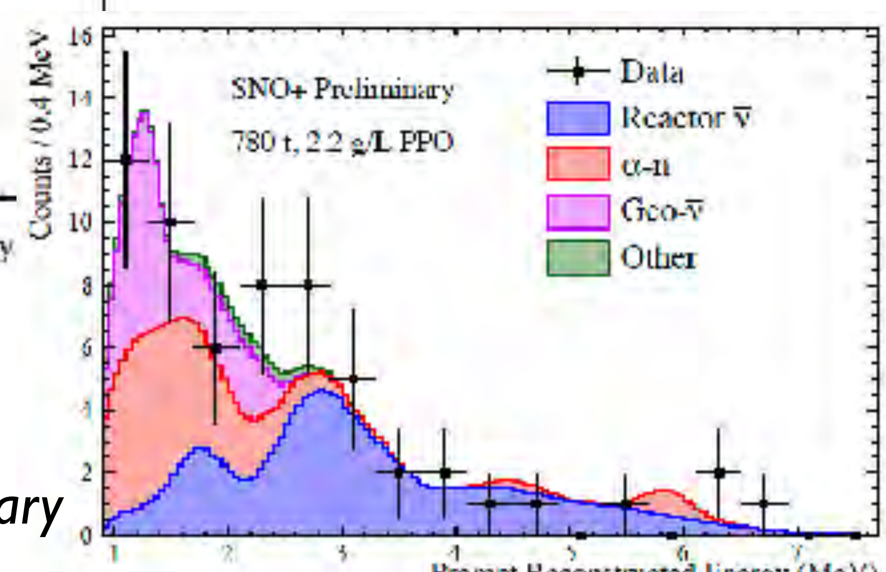


- Following first detection in a water Cherenkov detector, new results from partial and scint phases
- Main background: (α,n) reactions on 13C; αs from high rate 210Po decays
- Partial fill: 114 t.y exposure, 85 Hz of 210Po Stats and background-limited
- Pure LS: lower bkg, expect reactor + geo sensitivity



Partial fill

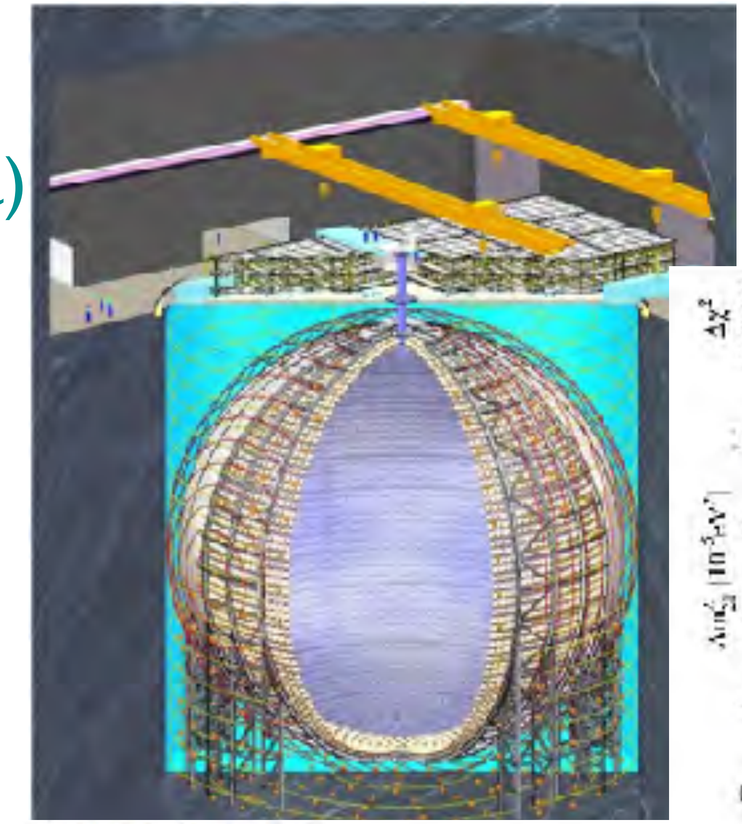




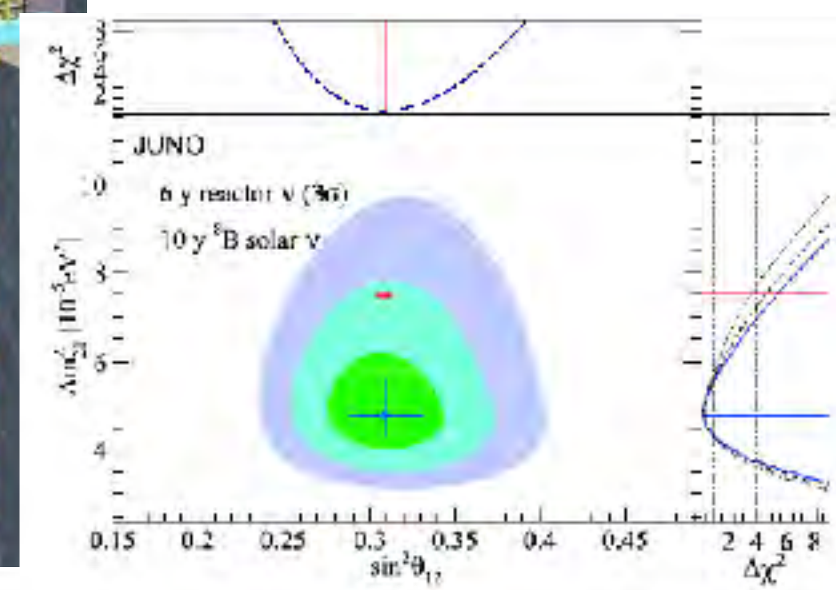
Pure LS, preliminary

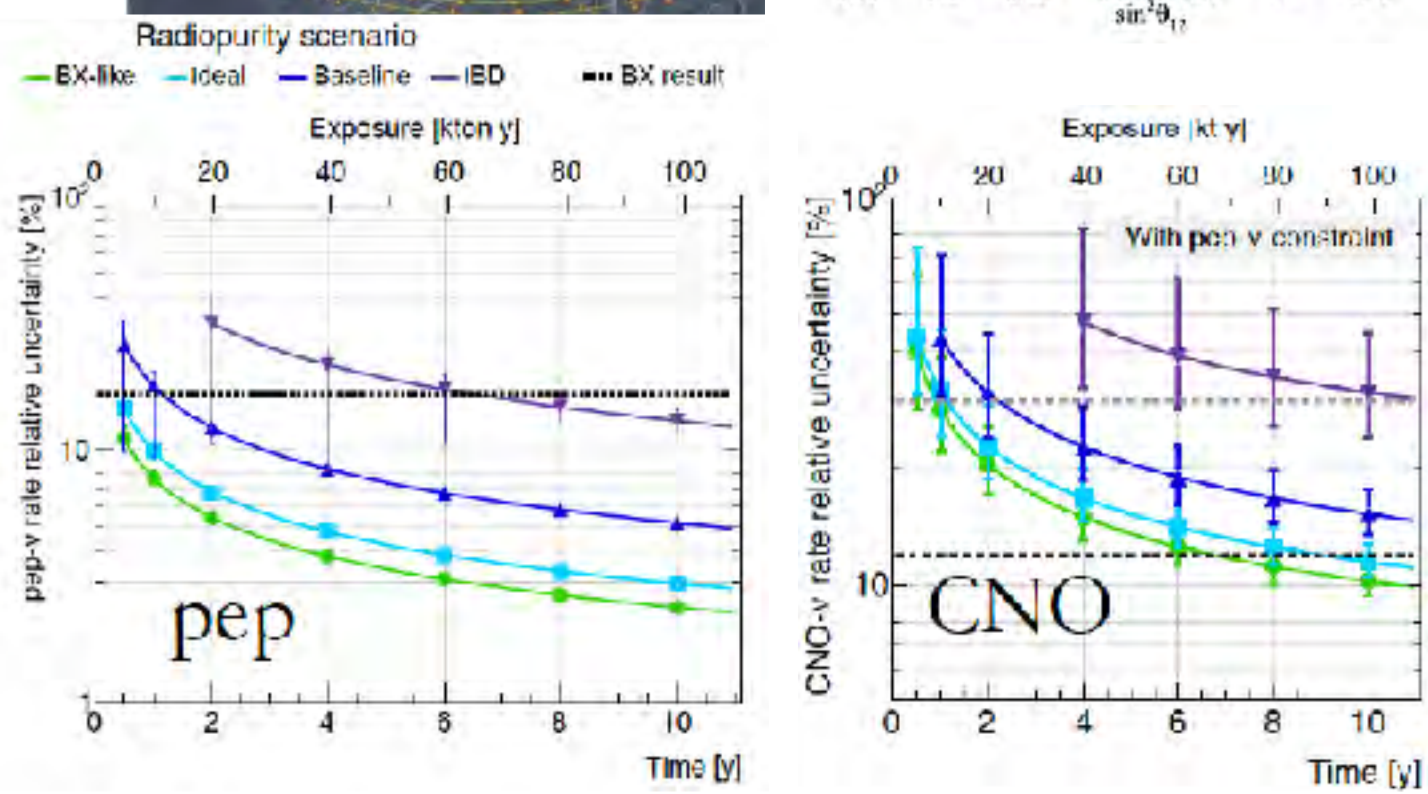
JUNO

- 20 kton, 3% / MeV resolution
- 0.7 km overburden (Guangdong, China)
- Data taking starts this year!
- Largest LS to-date, with world-leading sensitivity to several oscillation parameters and physics searches
- 2-MeV t/h:
  sensitivity to probe transition region via low-energy ^{8}B ν
- 2-3σ sensitivity to day/night
- 7Be rate < 1%
- Pep rate < 10%
- CNO rate ~ Bx
- Precision measurement of ΔM^2_{21}

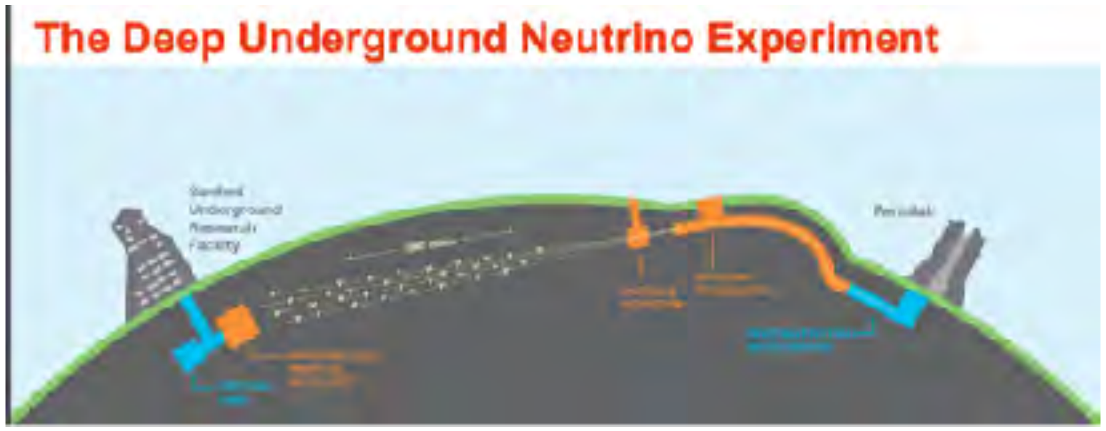


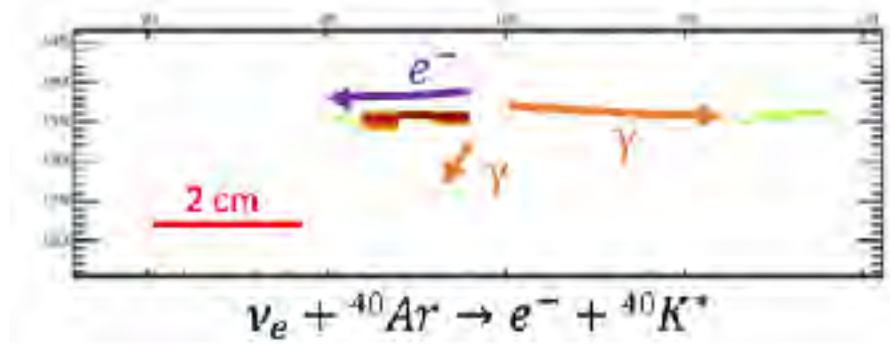
The Astrophysical Journal, 965:122 (13pp), 2024 April 20





LAr: DUNE

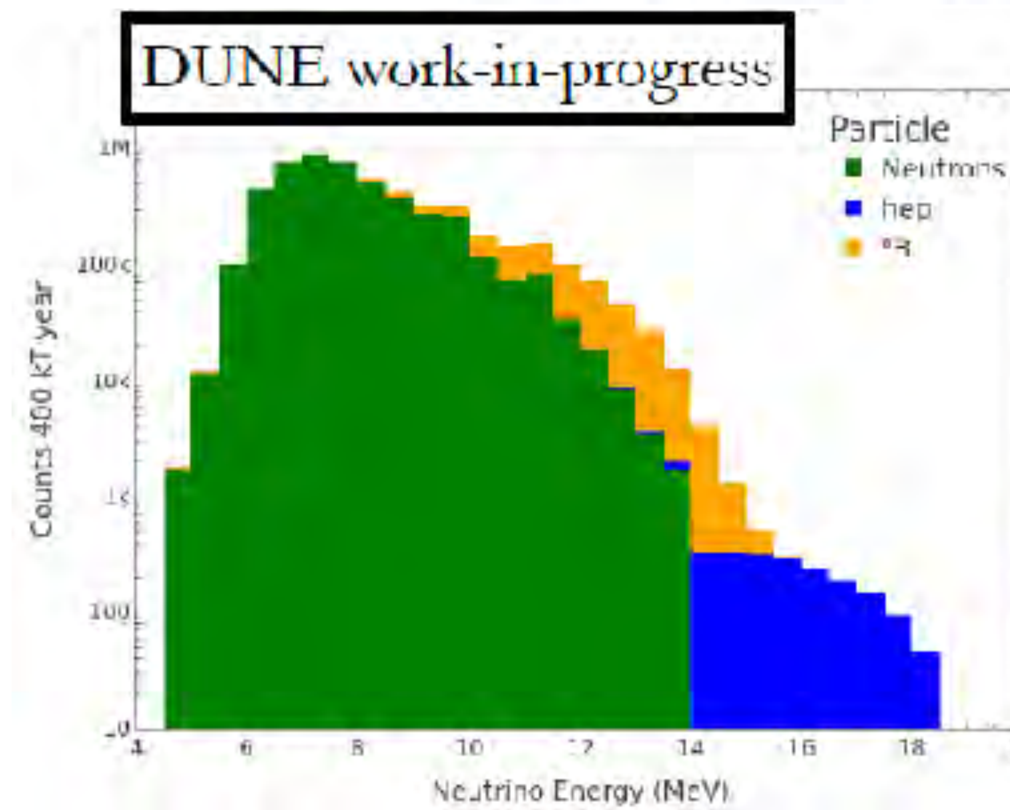




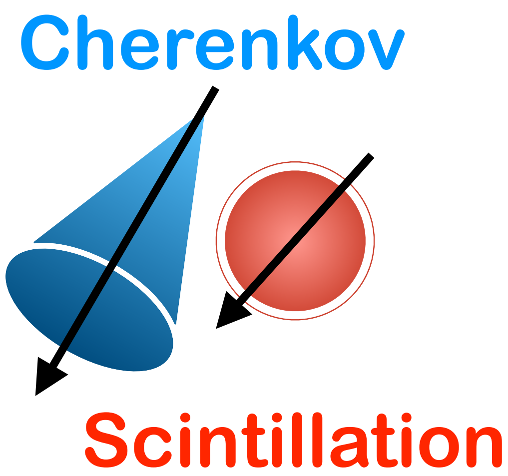
CC dominates signal
~10MeV e + γ cascade

Bkg	Rate
^{40}Ar(n,γ)	44 / t-yr
^{36}Ar(n,γ)	0.62 / t-yr
^{40}Ar(α,γ)	0.051 / t-yr

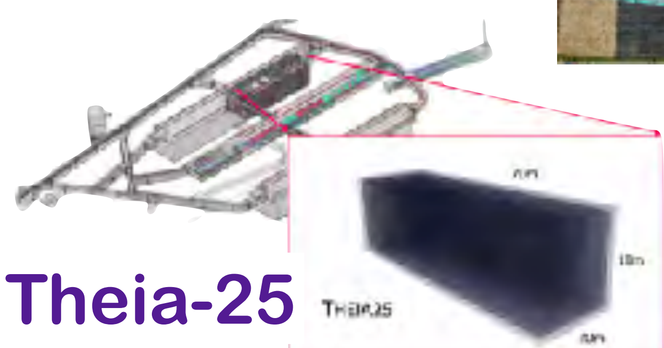
- Offers CC on Ar, good for precision spectral measurement (day/night);
- Limited by threshold and background
- Novel ideas to leverage phase II upgrades
  - UG-Ar,
  - pixelated detectors,
  - novel readout,
  - Xe doping
  - Hybrid detection (Theia-25)



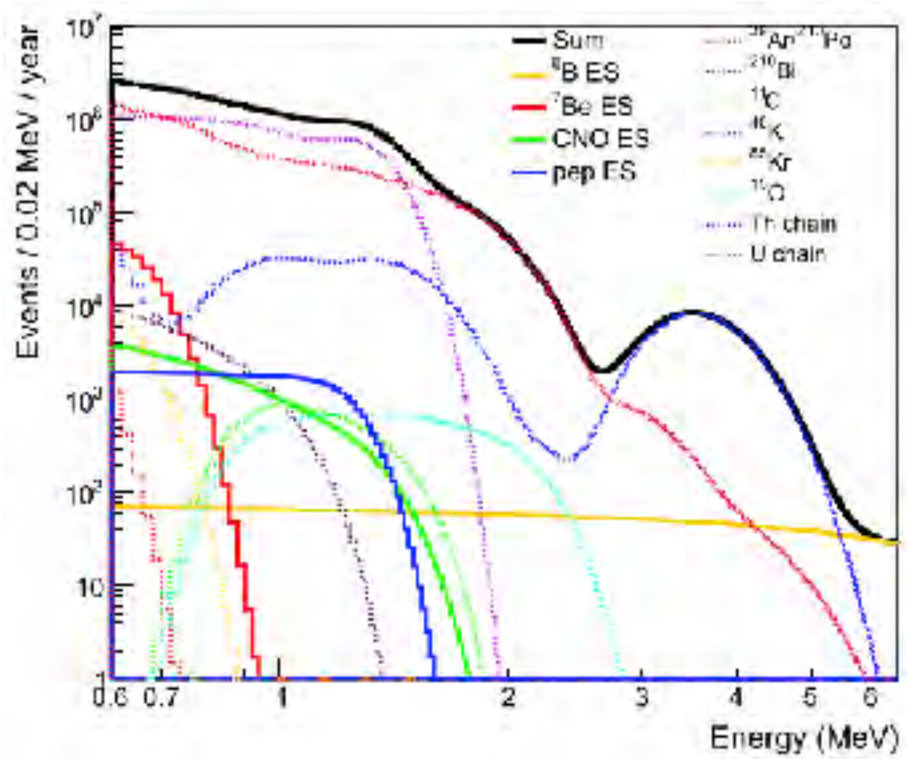
Hybrid detection: THEIA

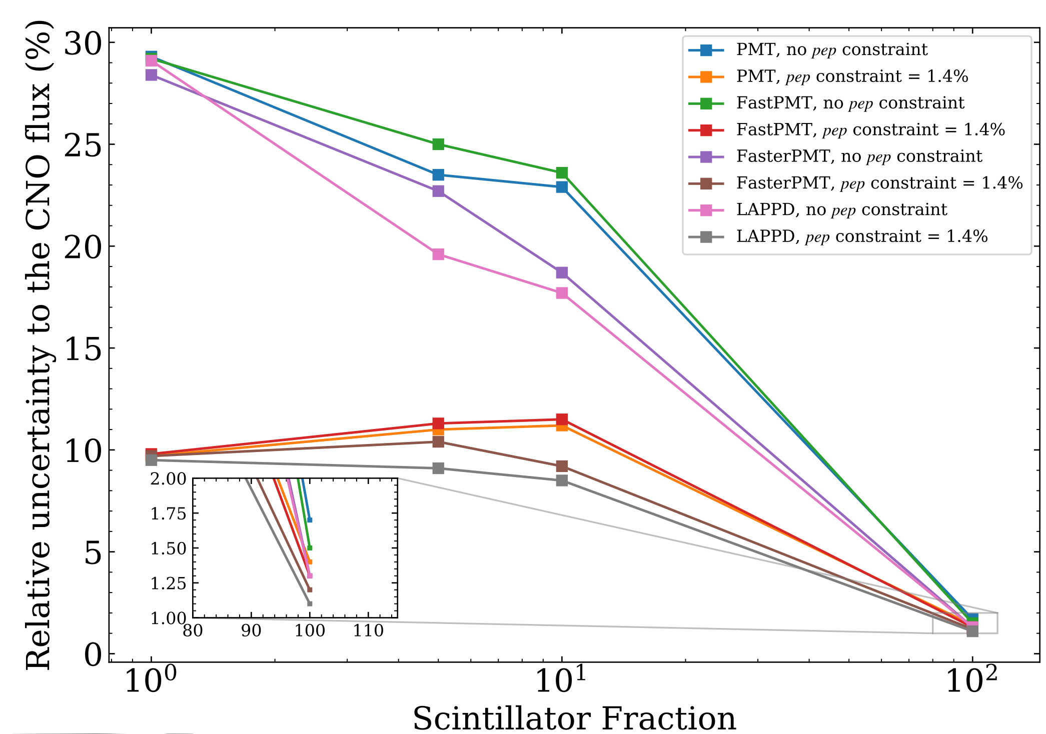


- Dominant background to CNO ν: ^{210}Bi
- Unique low-threshold, directional detection
- Particle and event ID from LS time profile, quenching, Ch/S ratio
- Few-% level sensitivity to CNO ν, 8B spectral shape



Eur. Phys. J. C 80, 416 (2020);
Eur. Phys. J. C (2018) 78: 435;
Phys. Rev. D 103, 052004 (2021)





Supernova Detection

- ~90% events are IBD

  Highly complementary to ν_e LAr signal

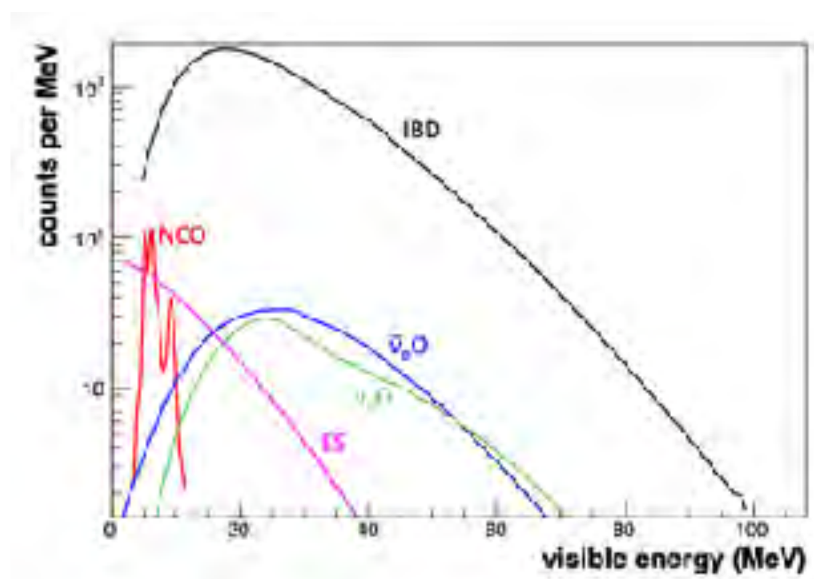
  Fast, can act as trigger for DUNE
- ES ⇒ pointing accuracy < 1°
- CC & monoE γ from NC ⇒

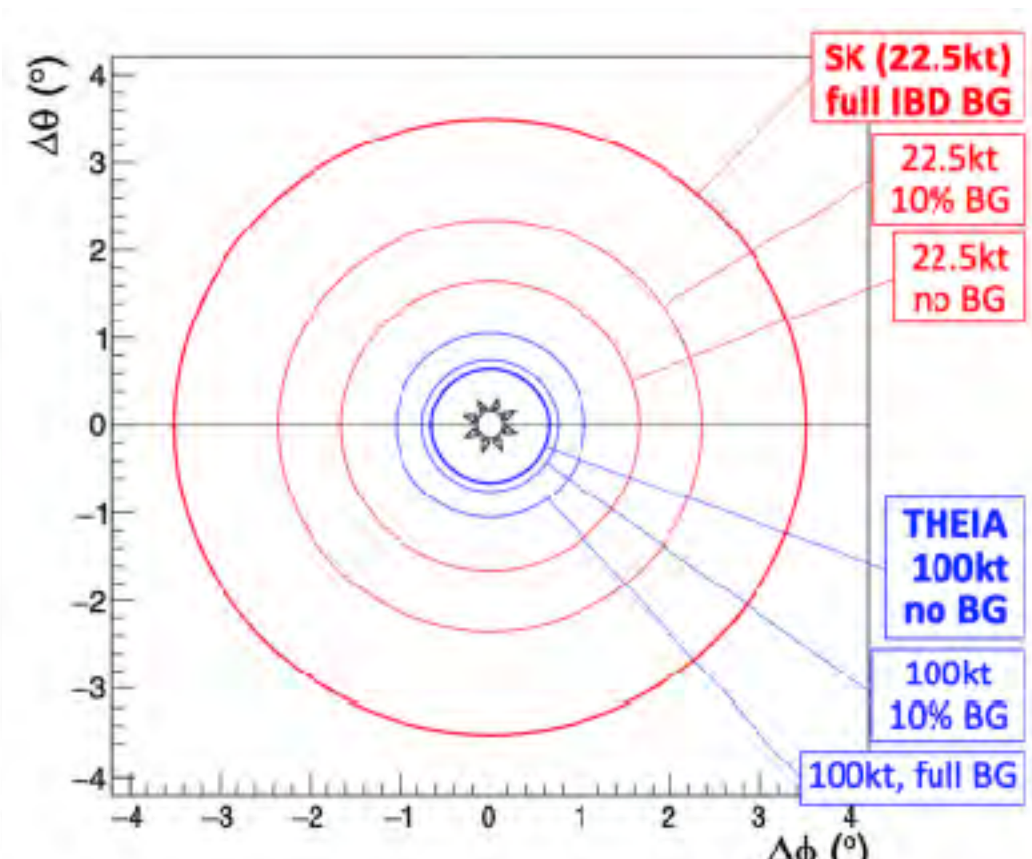
  burst T & subsequent mixing
- Flavour-resolved neutrino spectra
- High-stats, low-threshold signal with good resolution
- Pre-supernova

  ν sensitivity

Event rate in 100-kt WbLS, SN at 10 kpc

Reaction		*Rate*
(IBD)	$\bar{\nu}_e + p \to n + e^+$	19,800
(ES)	$\nu + e \to e + \nu$	960
(ν_eO)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1100





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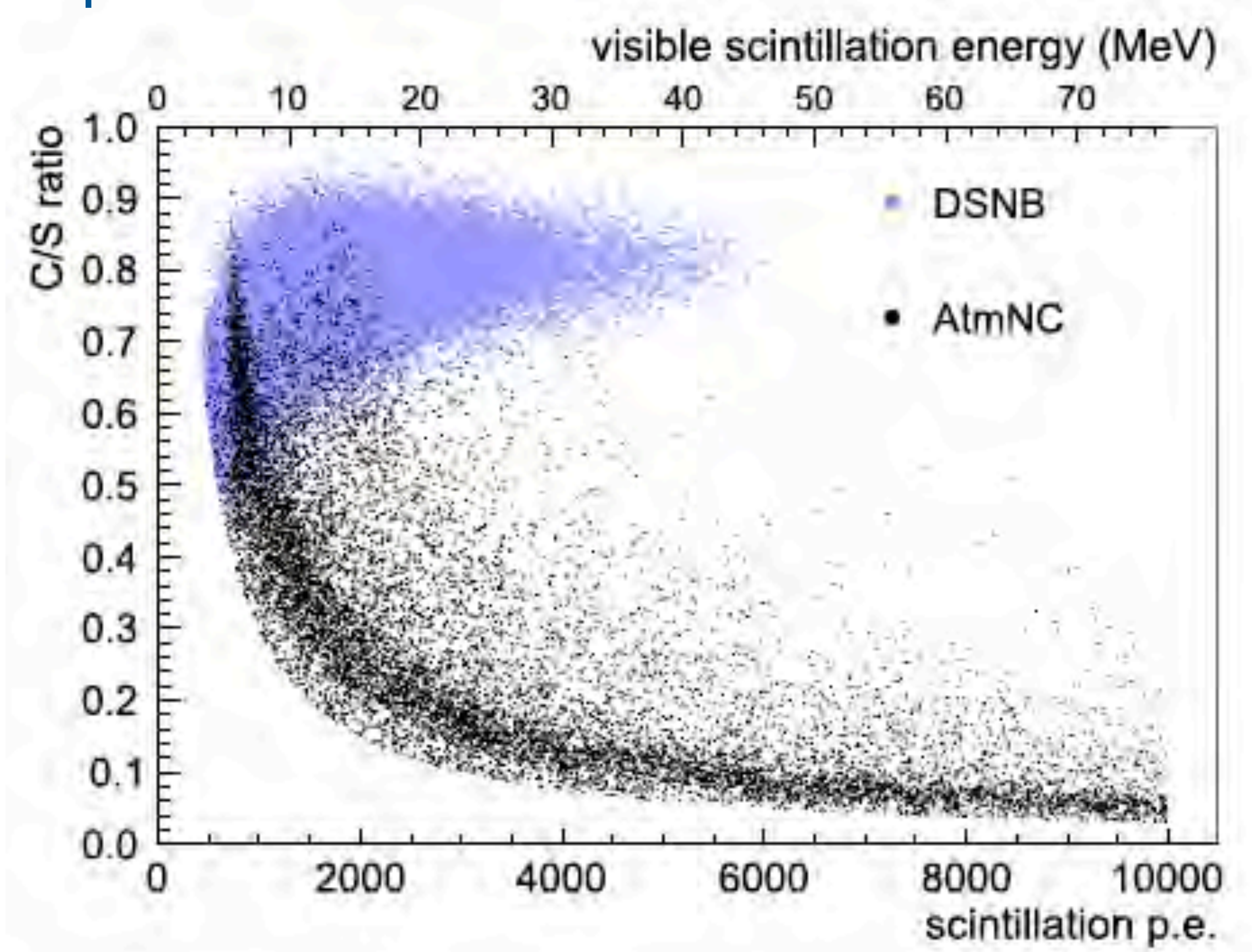
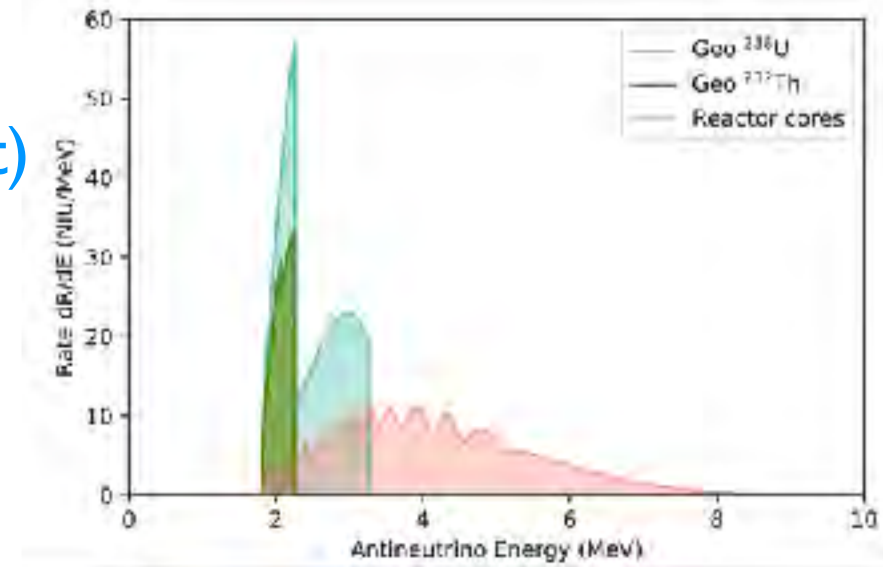
Diffuse Supernova ν Background

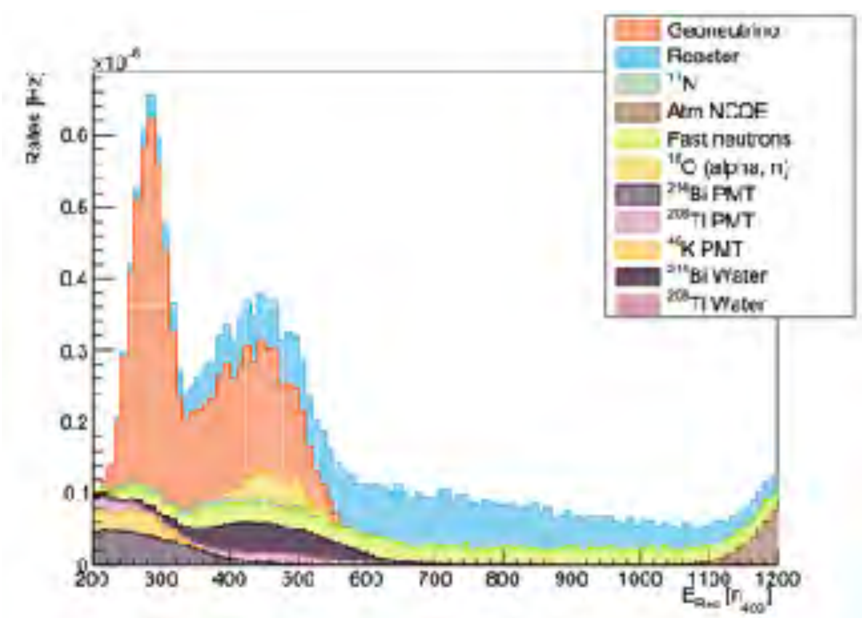
- Diffuse ν "glow" from past core-collapse supernovae
- Astrophysics of SNe
- Signature: IBD detection of antineutrino signal
  - Prompt e+ and delayed n-capture signal
- Main background: NC interaction of atmospheric ν
  - ν hits C nucleus, causing recoil
  - n captures
  - Can mimic signal
- Cherenkov/scintillation ratio provides a powerful handle for background discrimination
- 5σ in 125 kton-yrs

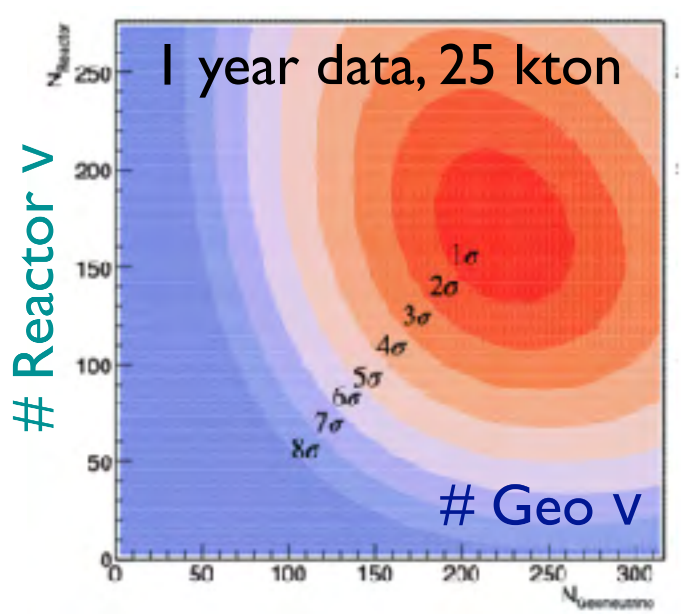


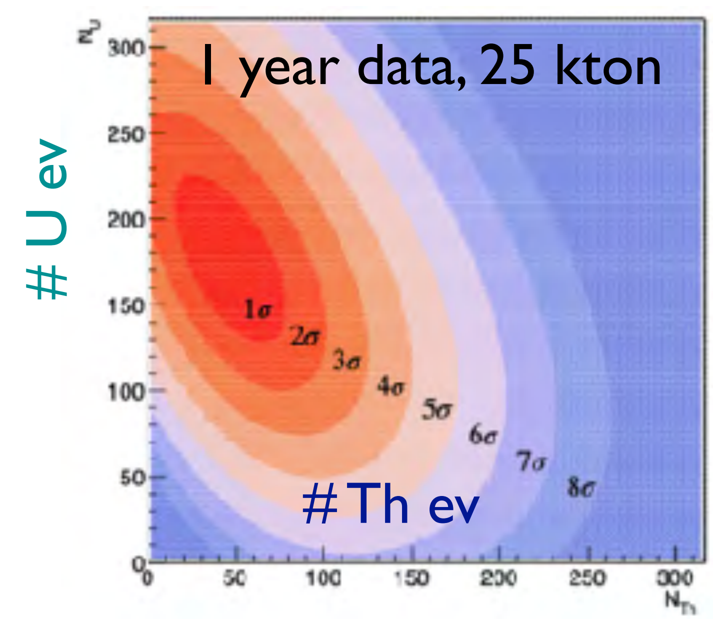
Anti-ν Detection

- **Geo-ν** observation by KL, Borexino (< 220 ev)
- **THEIA**: large statistics, complementary site: 218 ev/yr (25 kt)
- Full spectral analysis with BDT for bkg rejection
- Future improvements: PID (p/e+, e-/e+)
- Could offer first evidence for surface variation
- U/Th ratio to 15% precision in 10 years
- **Reactor ν** prospects: ~ 20 reactor ev/kt-yr
- Demonstrate techniques for remote reactor monitoring
- Range & direction at >1000km standoff







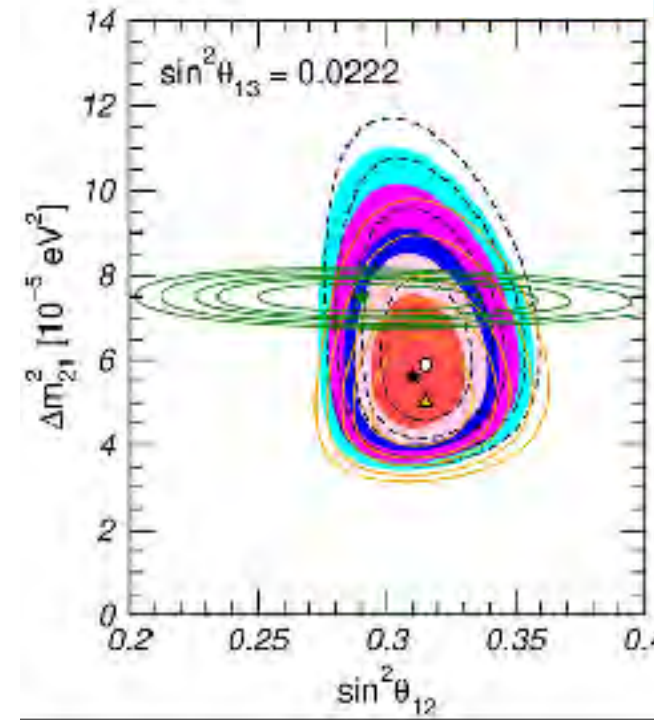


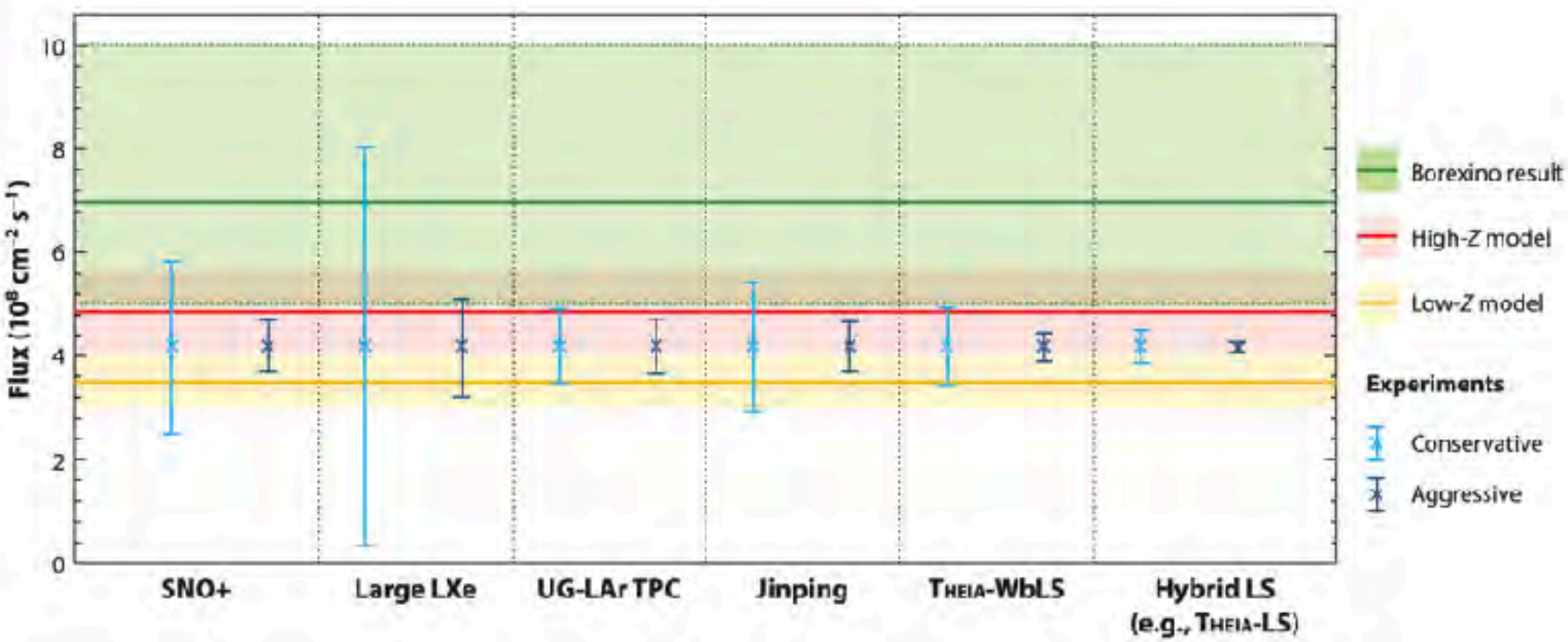
Eur. Phys. J. C 80, 416 (2020); arXiv:2204.12278

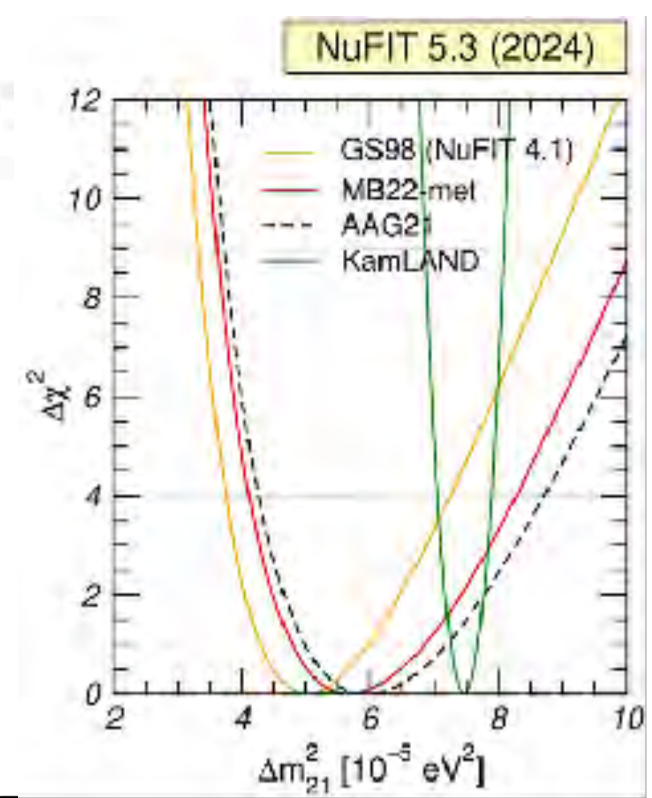
Prospects

- First hep observation: within reach at future large WCD
- Day/night effect: within reach at future large WCD / LS / LAr
- Δm^2_{12} within reach (WCD / LS / LAr)
- Large LXe offers good prospects for luminosity / lowest energy (high flux) signals
- Precision CNO for probe of metallicity may require new technology

Esteban et al, J High En Phys 2020 178 (2020)

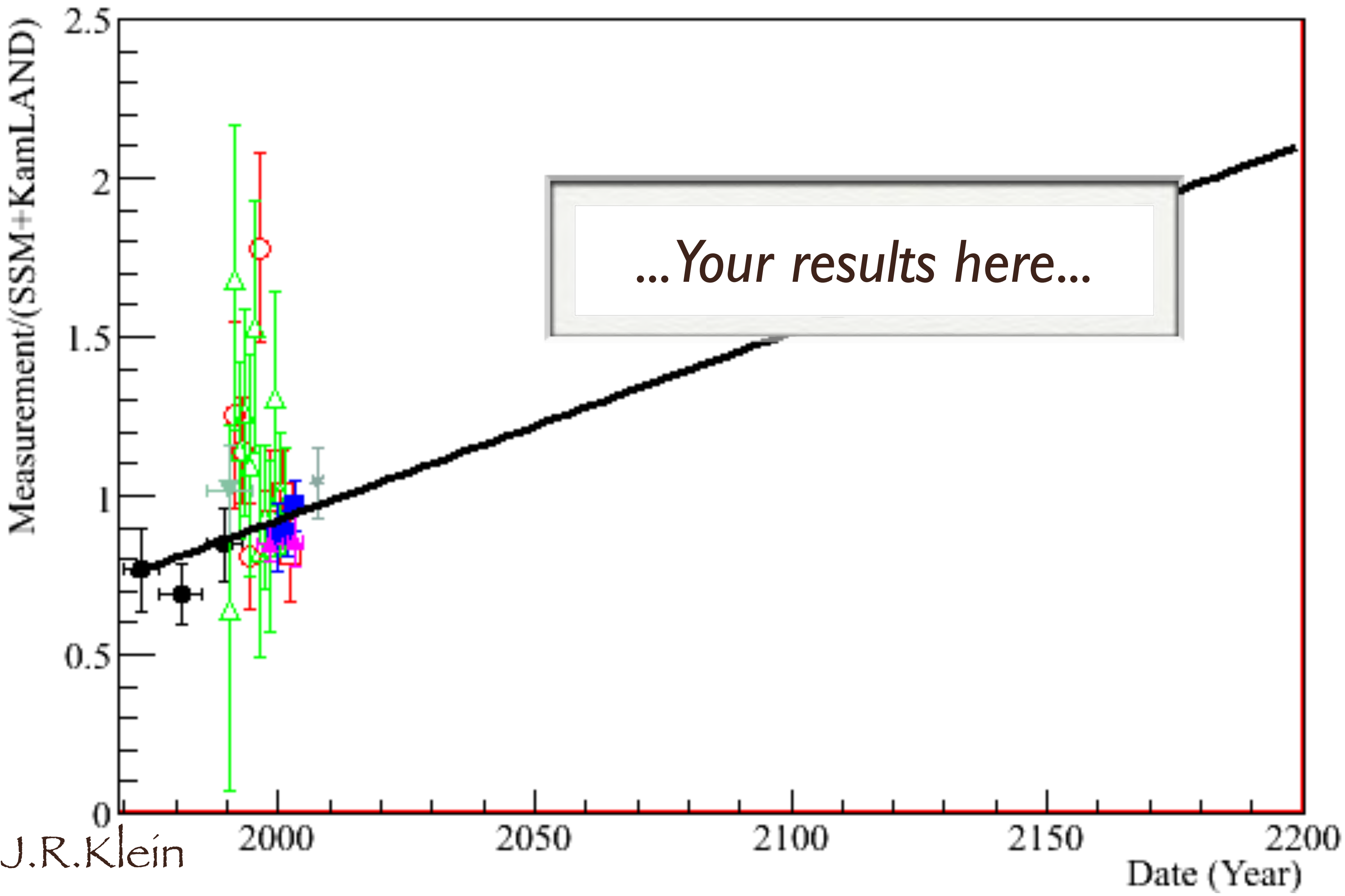






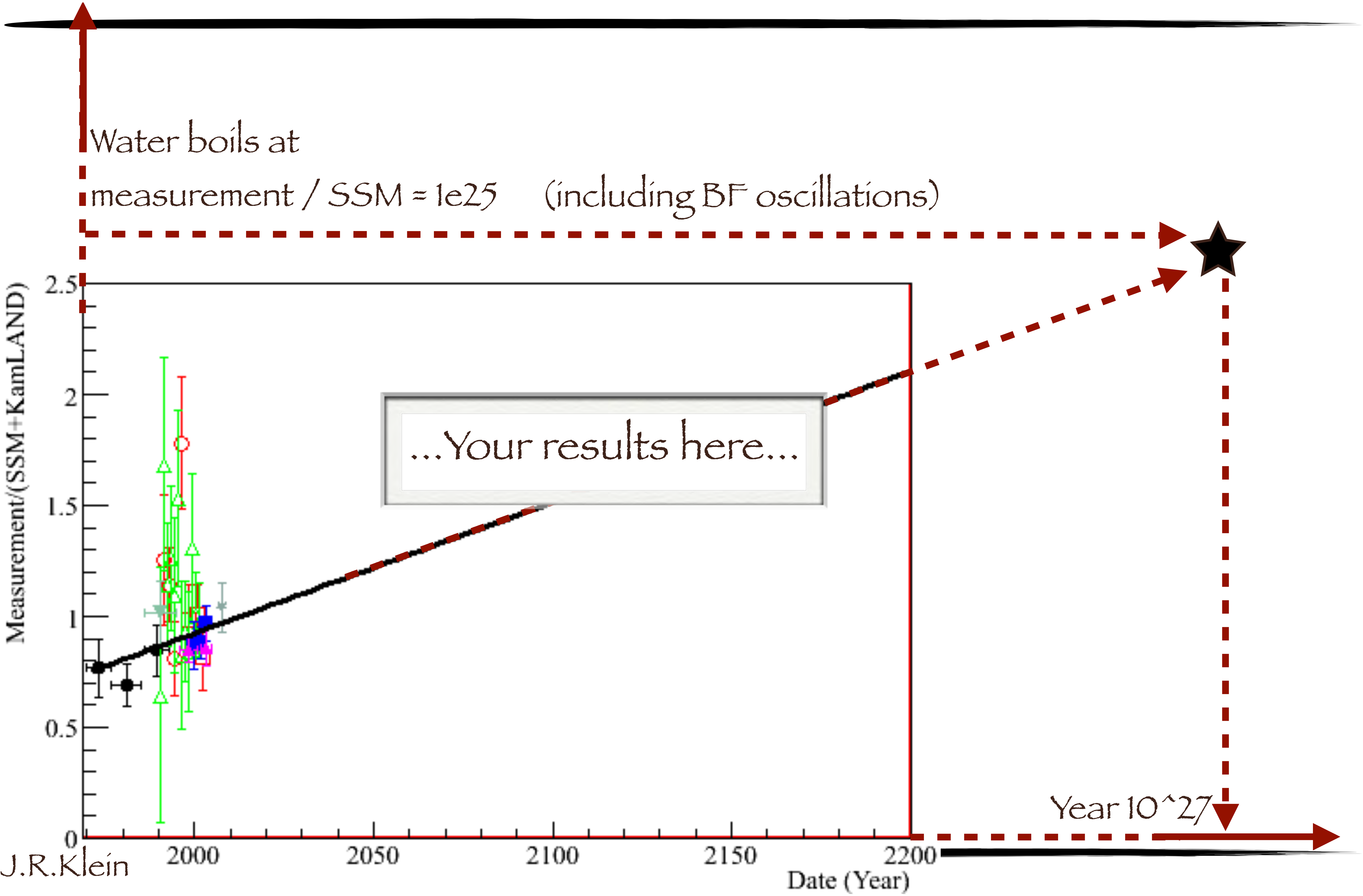
https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-011921-061243

The Future



Measurement/(SSM+KamLAND)
2.5
2
1.5
1
0.5
0
2000
2050
2100
2150
2200
Date (Year)
...Your results here...

The Future



J.R.Klein

Summary

Introduction to the neutrino

SNO: Solving the Solar Neutrino Problem

SNO+: a multi-purpose neutrino experiment

⇒The search for the nature of the neutrino

⇒Understanding the Earth & the Sun

⇒Hollywood's scare

mongering!


Thank you
for your
attention