UK HEP Forum 2022:
Neutrinos: What?

Where From?

Where to?

Solar & Reactor Neutrinos, and WATCHMAN

Matthew Malek

2022 November 22

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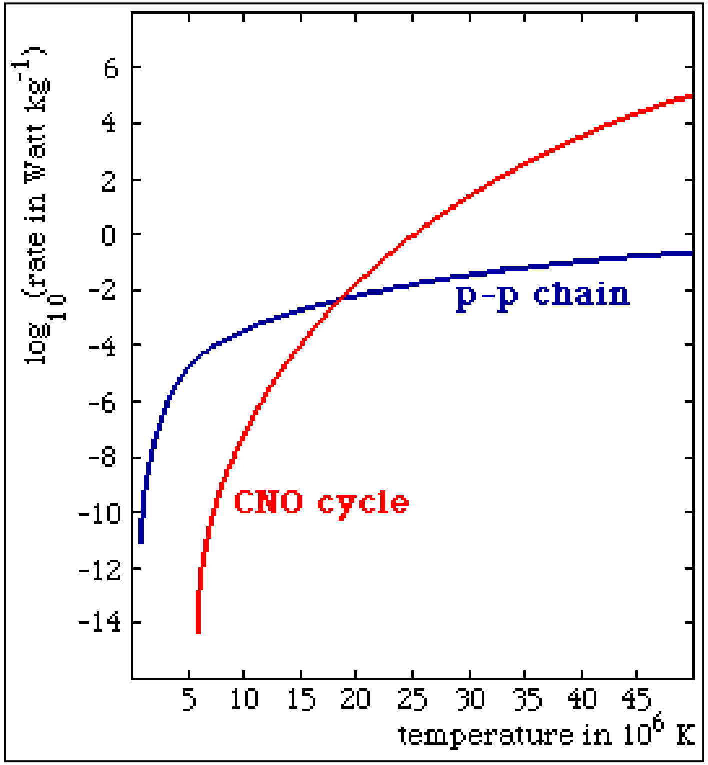
Where from? (Solar neutrinos)

- There are two major fusion processes in main sequence stars: the *pp chain* and the *CNO cycle*
- Both have the same net effect of converting hydrogen to helium:

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + \text{energy}$$

- Solar neutrinos are emitted from both processes
- The relative rates of the pp chain and the CNO cycle depend on the temperature of the star, esp. since the CNO cycle experiences higher Coloumb barriers
  - pp chain reactions start at about 4×10^6 K
  - The CNO cycle begins at about 1.3×10^7 K



The Proton-Proton Chain

- The chain has distinct branches; the main branch *ppI* is shown in the figure and has the following steps:

ppI:

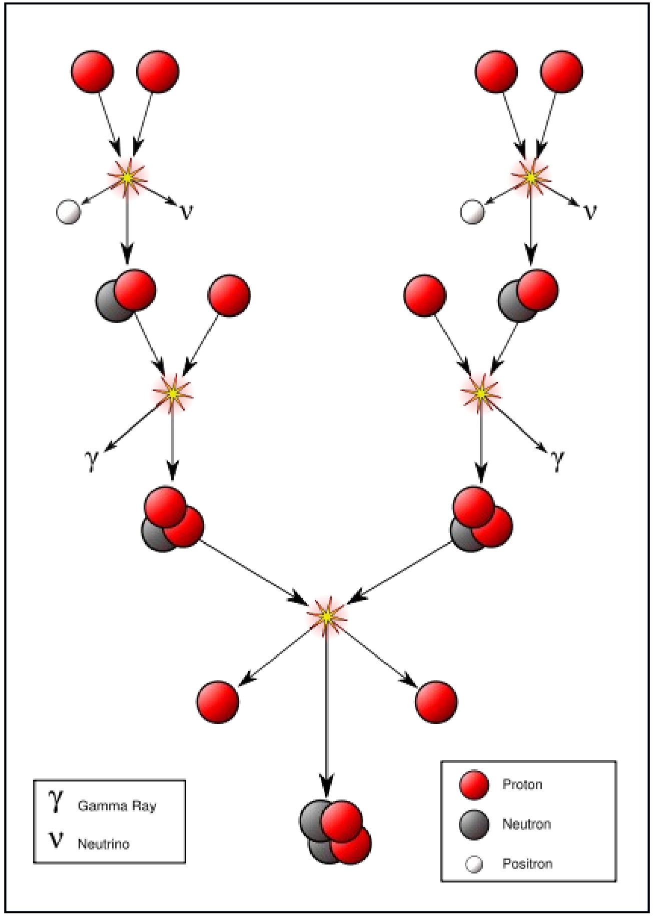
(i) $p + p \rightarrow {}^2H + e^+ + \nu_e$ (1.44 MeV) ['pp' neutrinos]

(ii) $p + {}^2H \rightarrow {}^3He + \gamma$ (5.49 MeV)

(iii) ${}^3He + {}^3He \rightarrow {}^4He + p + p$ (12.86 MeV)

Net result:

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.72\ \text{MeV}$$



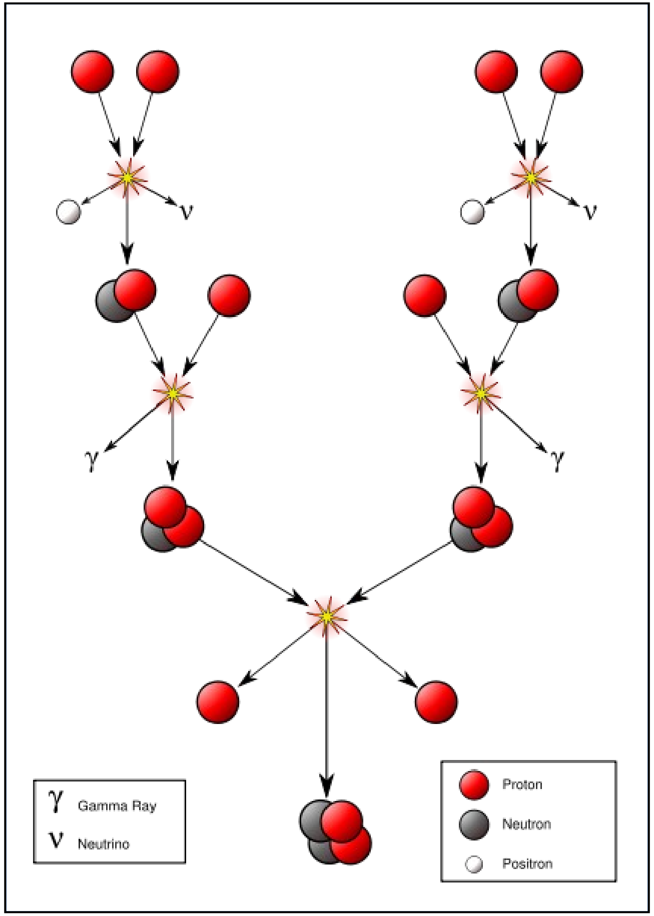
The Proton-Proton Chain

- The *ppII* branch diverges after step (ii), and the *ppIII* diverges further still after step (iv):

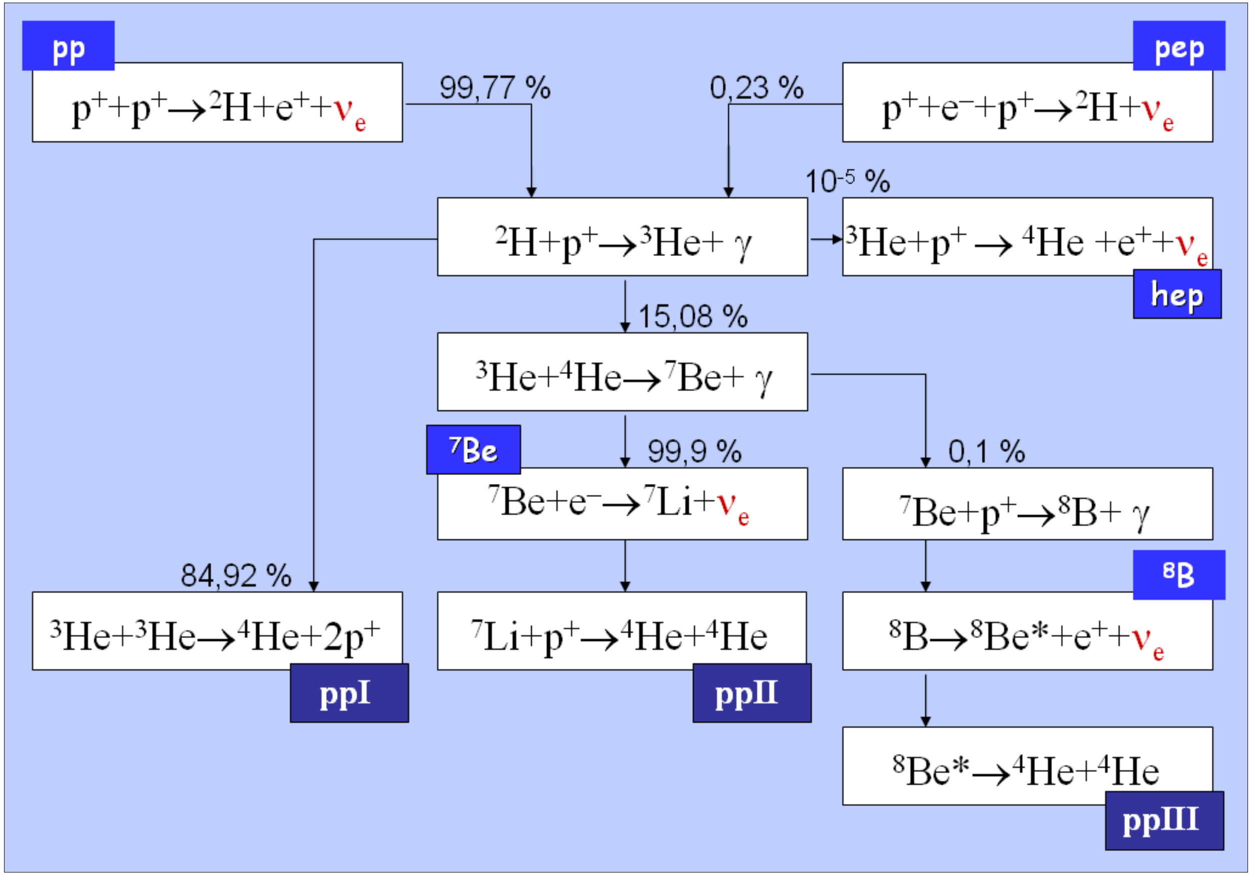
ppII: [After (i) and (ii)]
(iv) $^3He + {}^4He \rightarrow {}^7Be + \gamma$
(v) $^7Be + e^- \rightarrow {}^7Li + \nu_e$ ['^{7}Be' neutrinos]
(vi) $^7Li + p \rightarrow {}^8Be \rightarrow {}^4He + {}^4He$

ppIII: [After (i), (ii) and (iv)]
(vii) $^7Be + p \rightarrow {}^8B + \gamma$
(viii) $^8B \rightarrow {}^8Be + e^+ + \nu_e$ ['^{8}B' neutrinos]
(ix) $^8Be \rightarrow {}^4He + {}^4He$

- Others not shown here include '*pep neutrinos*' and '*hep neutrinos*' (see next slide).



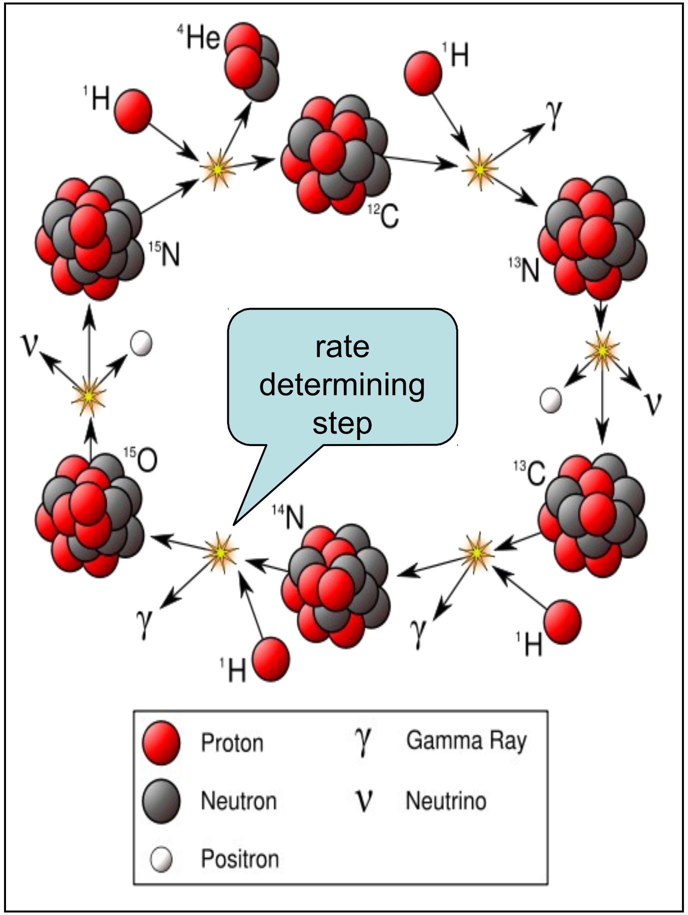
A Solar ν Summary



The CNO Cycle

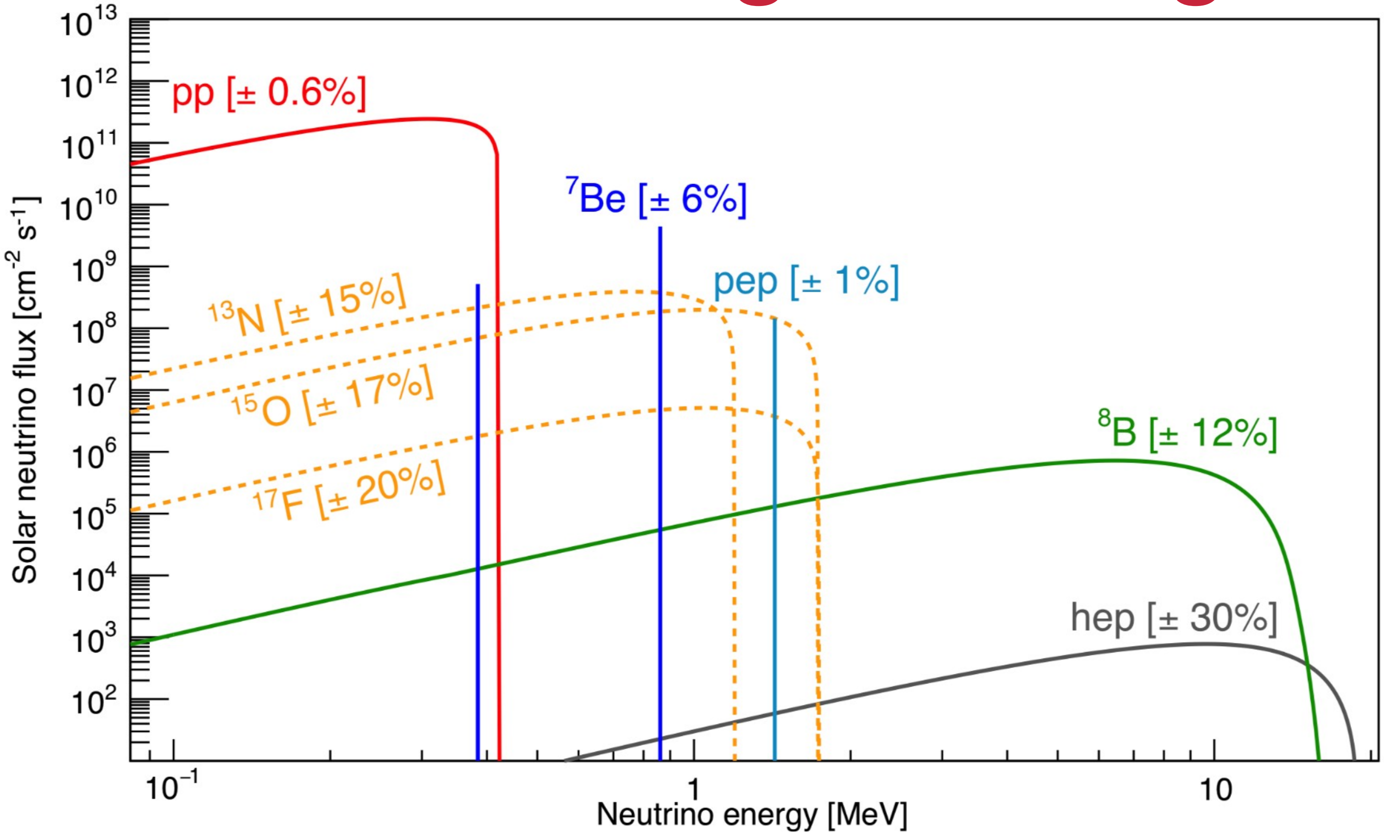
- The carbon-nitrogen-oxygen cycle achieves the same ends via rather different means:

$$p + \boxed{{}^{12}C} \rightarrow {}^{13}N + \gamma \quad (+\ 1.95\ \text{MeV})$$
$${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e \quad (+\ 2.22\ \text{MeV})$$
$$p + {}^{13}C \rightarrow {}^{14}N + \gamma \quad (+\ 7.54\ \text{MeV})$$
$$p + {}^{14}N \rightarrow {}^{15}O + \gamma \quad (+\ 7.35\ \text{MeV})\ **$$
$${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e \quad (+\ 2.75\ \text{MeV})$$
$$p + {}^{15}N \rightarrow \boxed{{}^{12}C} + {}^{4}He \quad (+\ 4.96\ \text{MeV})$$



- As with the pp chain, the CNO cycle has different branches (CNO-I is featured here)

Solar ν: Putting it all together



Flux	SFII-GS98 $\left[\mathrm{cm}^{-2}\mathrm{s}^{-1}\right]$
pp	5.98×10^{10}
pep	1.44×10^{8}
hep	8.04×10^{3}
^{7}Be	5.00×10^{9}
^{8}B	5.58×10^{6}
^{13}N	2.96×10^{8}
^{15}O	2.23×10^{8}
^{17}F	5.52×10^{6}

Solar ν: Radiochemical Expts

- First experiment started in 1960s by Ray Davis, using 615 tons of cleaning fluid (C_2Cl_4) to get the following reaction:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}^*$$

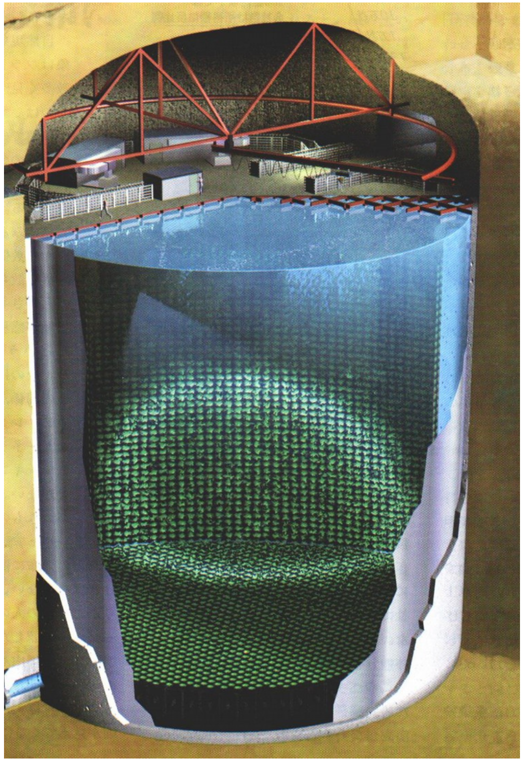
  - Mainly sensitive to ^{7}Be and ^{8}B neutrinos (plus some pp and CNO)
  - Led to Davis sharing the 2002 Nobel Prize 
  - Original intention was to probe solar models, though we know what happens to best laid schemes...

- Later radiochemical experiemtents – SAGE & GALLEX – used gallium for detection via:

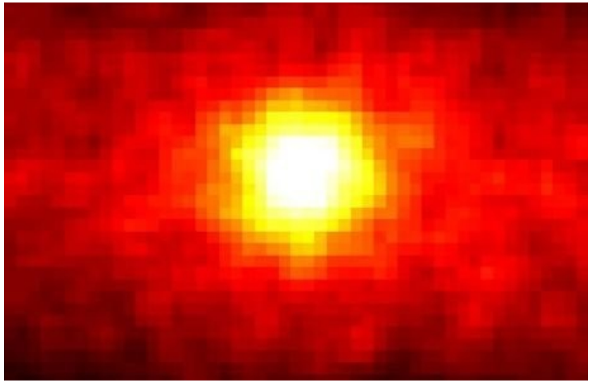
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$$

  - Much greater sensitivity to pp neutrinos, which are less model dependent.
  - Also still sensitive to ^{7}Be neutrinos (plus some ^{8}B and CNO)
  - Disparities led to ‘second solar neutrino problem’

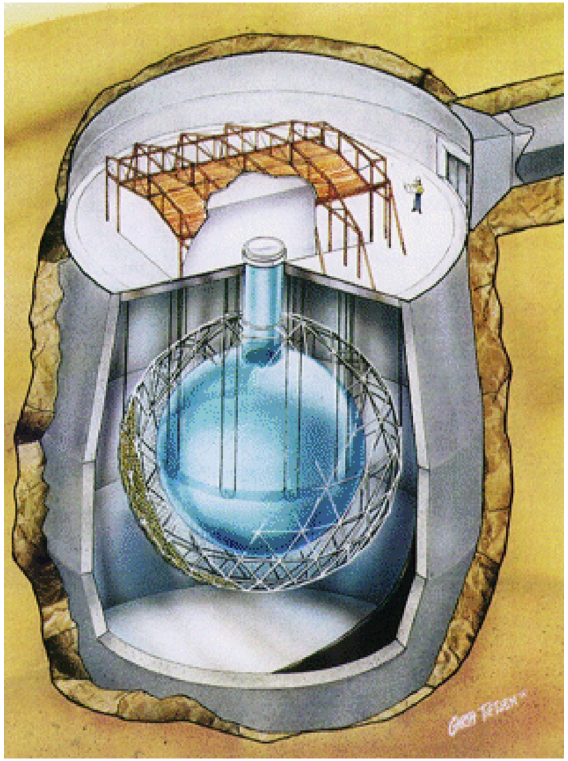
Solar ν: Water Cherenkov Expts



- Realtime observation of solar neutrinos began in the 1980s with Kamiokande, before kicking into high gear with the start of Super-Kamiokande in 1996 (left) and the Sudbury Neutrino Observatory (SNO) in 2000 (right).
  - Strong UK involvement in SNO from the start! 



- In 2001, comparison of elastic scattering rates at Super-K with charged current rates at SNO solved solar neutrino problem via oscillation
  - Led to Art McDonald sharing 2015 Nobel Prize 
- Later neutral current measurements on heavy water in SNO were able to detect all the solar neutrinos (consistent w/ models)

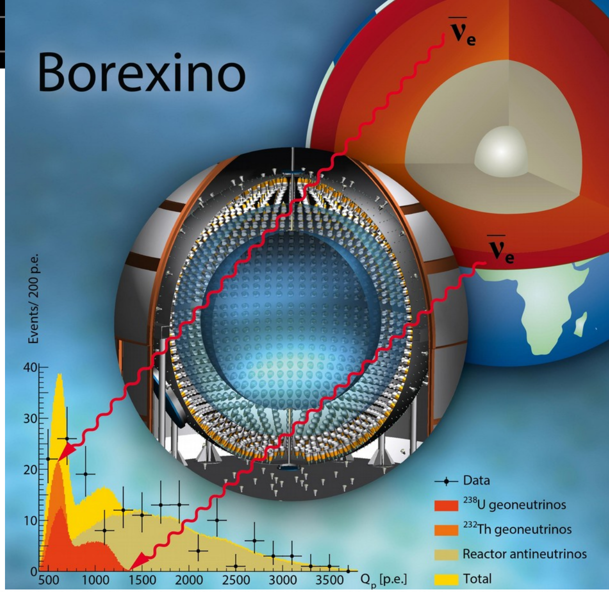


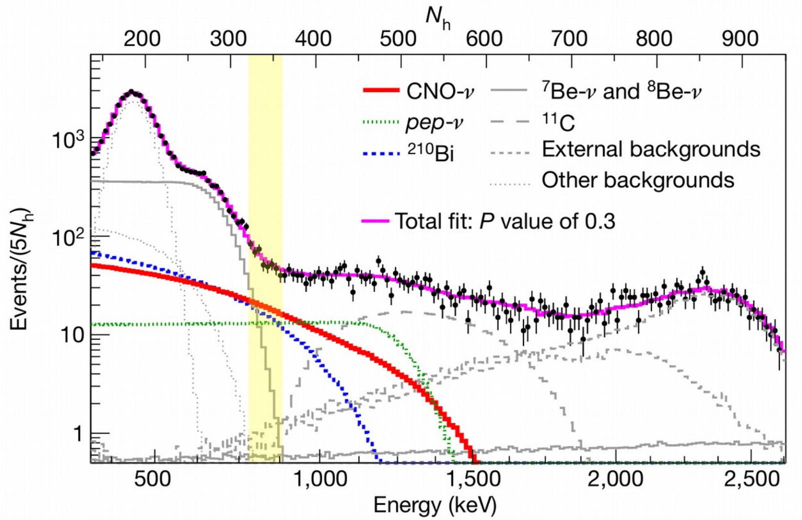
Where to? (Solar neutrinos)

- With the solar neutrino problem sorted, solar neutrinos return to being a probe of the solar interior.
- The Borexino detector at Gran Sasso used 280 tonnes of liquid scintillator as its active detection volume
  - Detection by elastic scattering: $\nu_x + e \rightarrow \nu_x + e$

- Impressive cleanliness and control of backgrounds (e.g. ^{210}Bi) enabled high precision measurements of neutrinos from pp chain, incl. *pep* neutrinos and ^{7}Be neutrinos.

- In 2020, Borexino made first observation (> 5σ) of neutrinos from the CNO cycle (*Nature* **587** 577-582).
- Future lies in improving statistics to distinguish between different solar models!

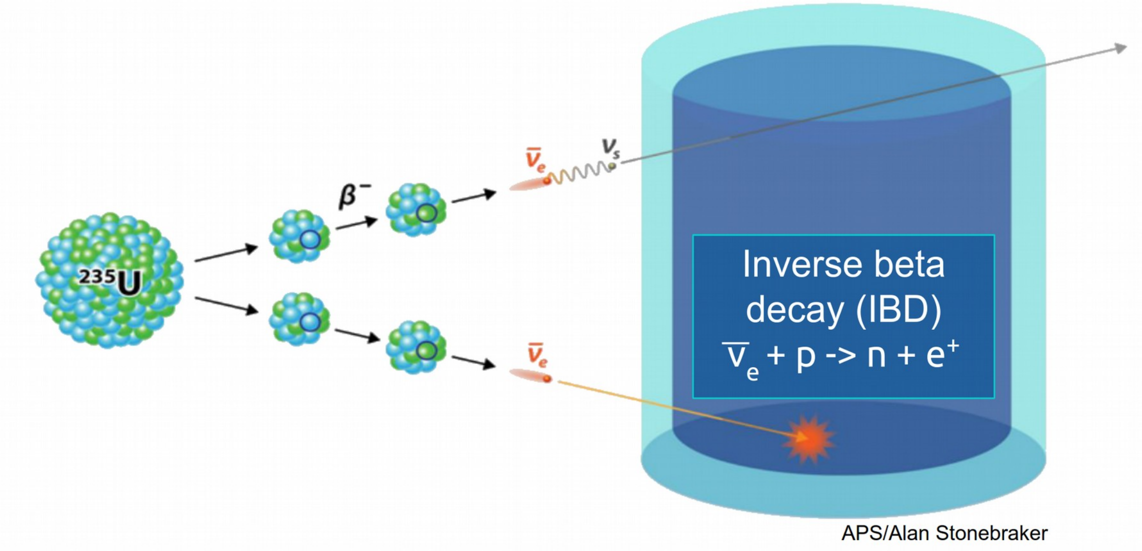




Where from? (Reactor neutrinos)

- Fission reactors split large nuclei like ^{235}U or ^{239}Pu

- The fission products are unstable and undergo radioactive decay, producing antineutrinos.
- On average, each fission in a reactor results in the emission of 6 antineutrinos.



- A typical 3 GW_{th} reactor emits $O(10^{22})$ antineutrinos per second.

Reactor ν: Early Expts

- Reactor antineutrino experiments go back even further than solar neutrino experiments.
- Although Cowan & Reines originally proposed detonating a nuclear weapon as a source of (anti)neutrinos...
  - See figure on top right
  - And this was somehow approved!!
- They eventually used the nuclear reactors at the Savannah River Site
  - This led to Fred Reines receiving the 1995 Nobel Prize 
- Other reactor experiments followed, including CHOOZ & Palo Verde

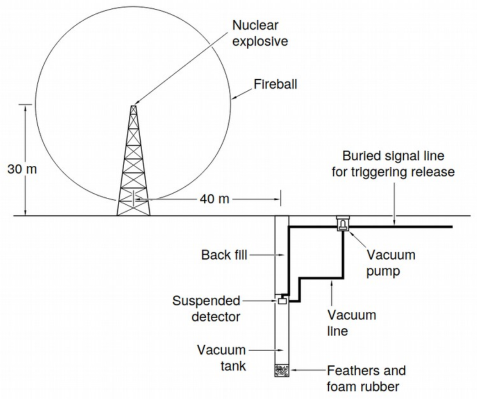
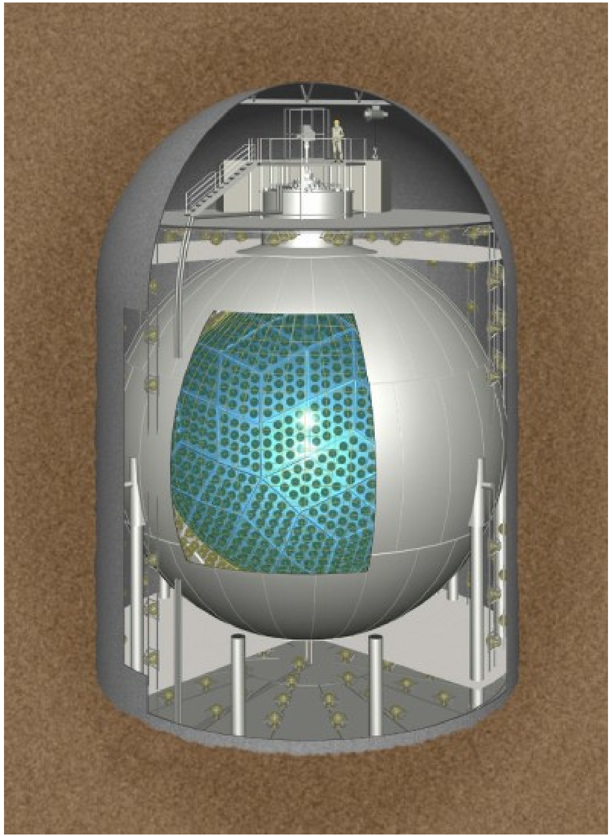
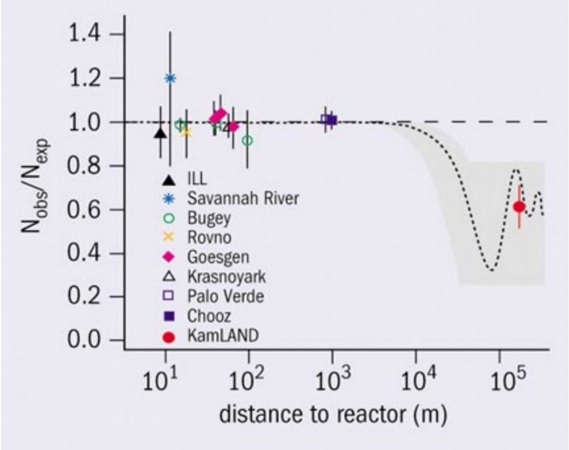


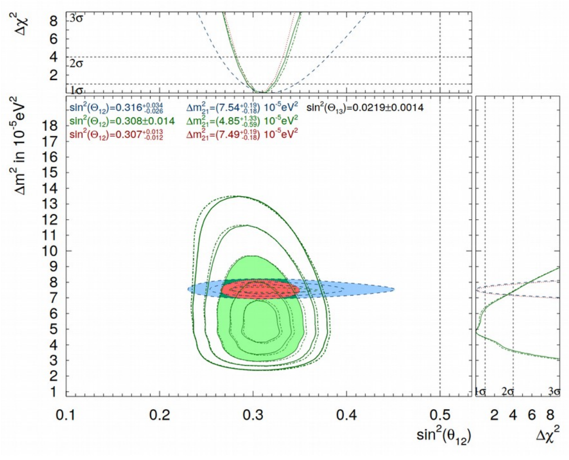
Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

Reactor ν: Modern Expts

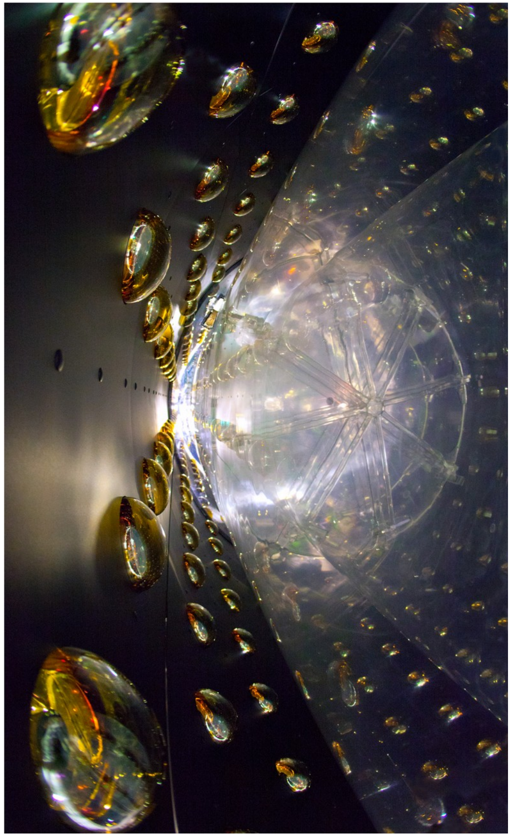


- KamLAND used 1000 tonnes of scintillator (mineral oil) to make a aggregated measurement of reactor antineutrinos from many reactors in Japan (and further afield).
  - Data taking started in 2002
  - Average baseline was 180 km
- This produced a much different point on the oscillation curve than previous measurements (see top right).
- Due to similarity of energies, global oscillation fits commonly compare solar neutrino data with KamLAND's reactor antineutrino data (see bottom right, using data from KamLAND, SNO, and Super-Kamiokande)

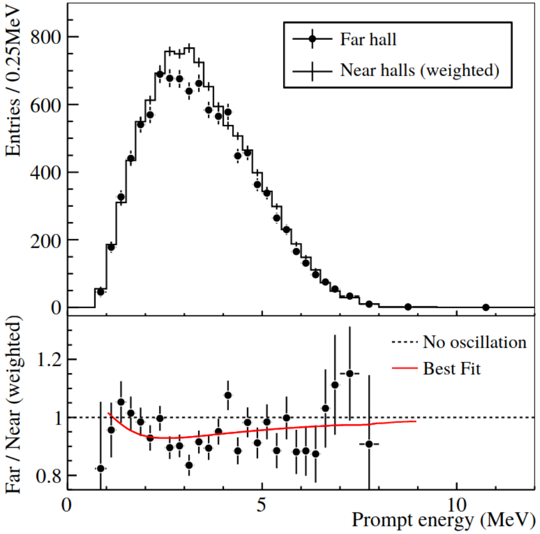


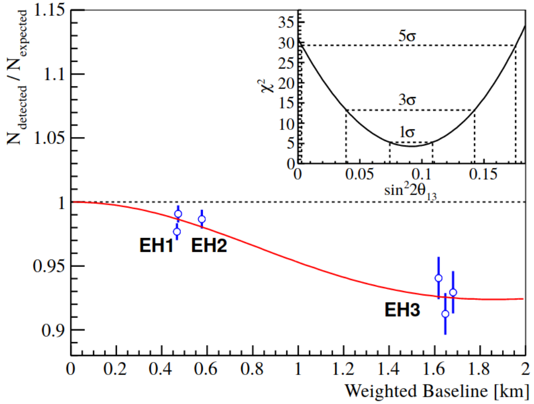


Reactor ν: Modern Expts



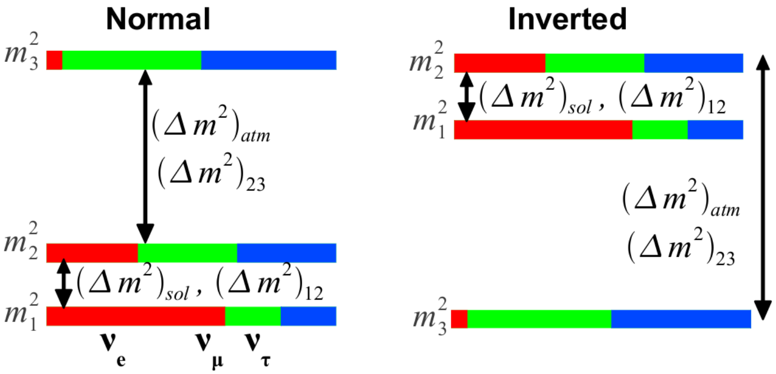
- In the 2010s, several short-baseline reactor neutrino experiments were able to measure the neutrino mixing angle θ_{13}.
- Daya Bay (China) came first, in 2012, followed soon after by RENO (S. Korea), and later by Double Chooz (France)
- Figures at left taken from *Phys. Rev. Lett.* **108**:171803 (2012)

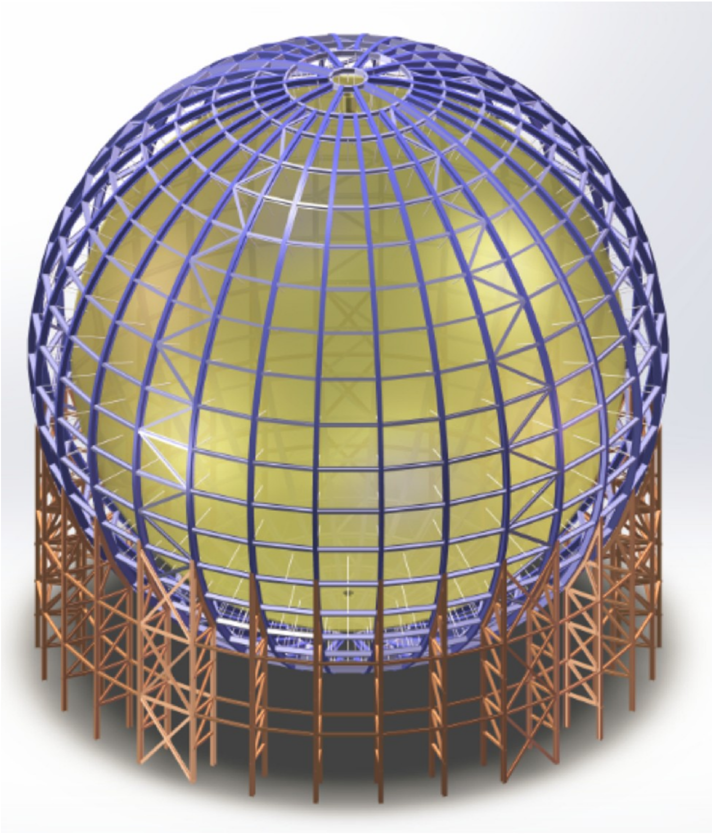


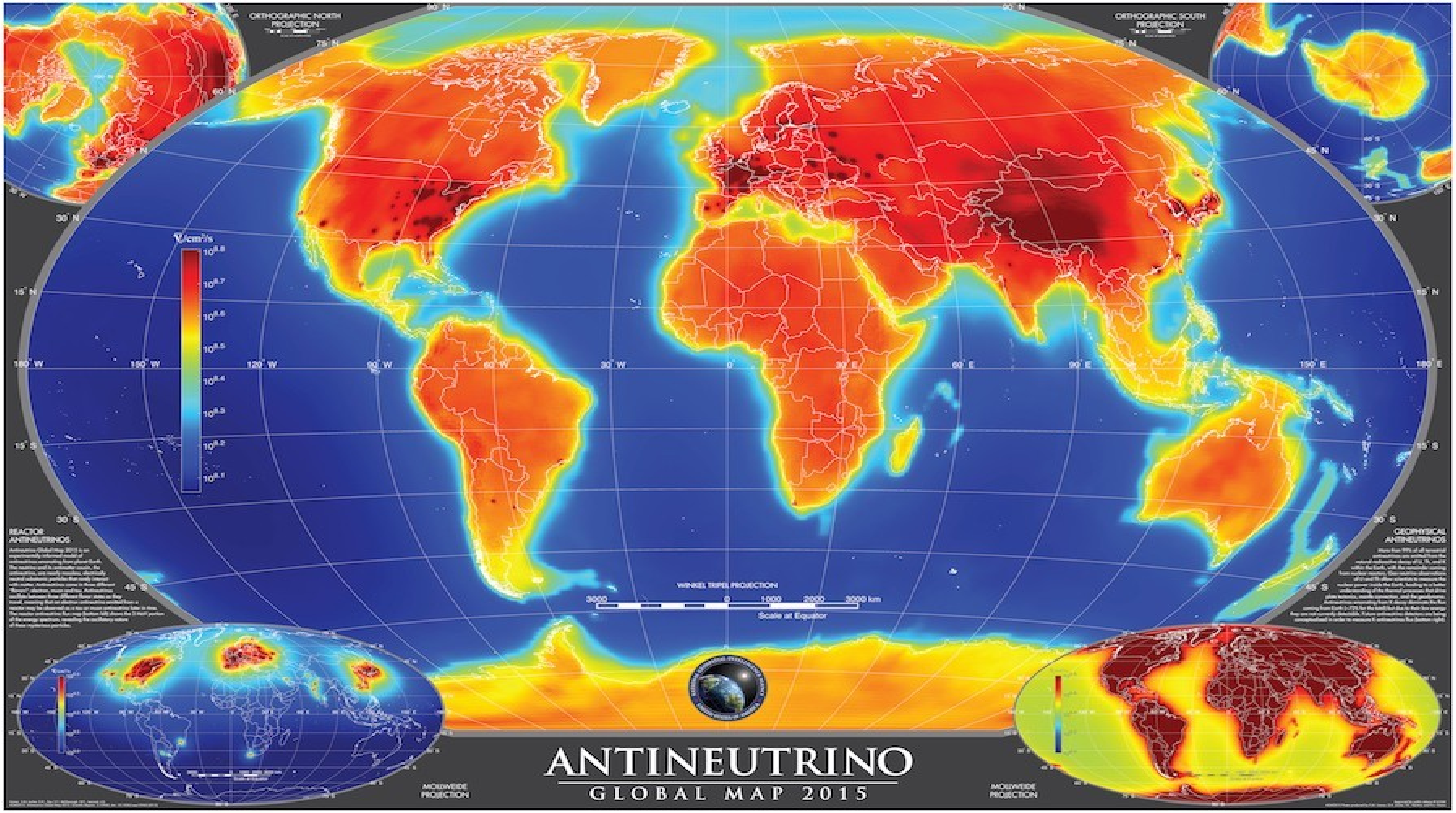


Where to? (Reactor neutrinos)

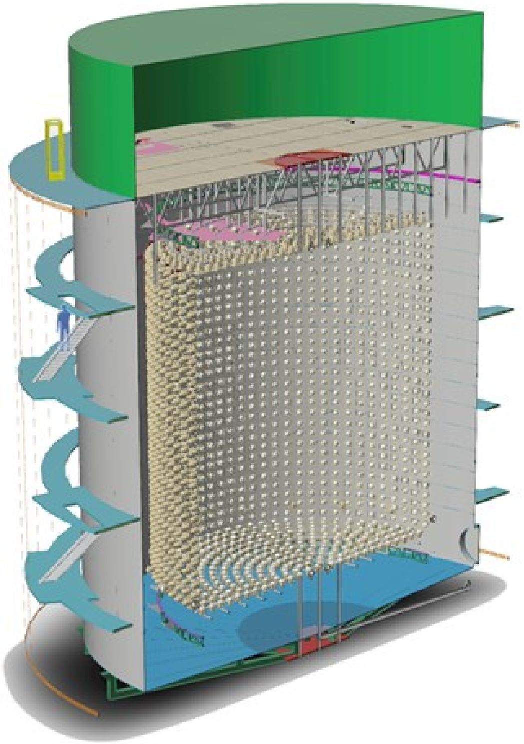
- The Jiangmen Underground Neutrino Observatory (JUNO) is the successor to the Daya Bay neutrino experiment
- JUNO is in construction phase
  - Will contain 20,000 tonnes of liquid scintillator (LAB w/ 2.5 g/L PPO + 3 mg / L bis-MSB)
  - 18,000 large PMTs (20” diameter) + 25,600 small PMTs (3” diameter)
- Primary physics goal is using reactor antineutrinos to determine the neutrino mass ordering
  - Requires impressive energy resolution (3% @ 1 MeV) to distinguish Δm^2_{12} from Δm^2_{23} and determine which is larger.
- UK involvement from Warwick (Xianguo Lu) & Durham (Jessica Turner, Jack Franklin, and Yuber Perez-Gonzalez)



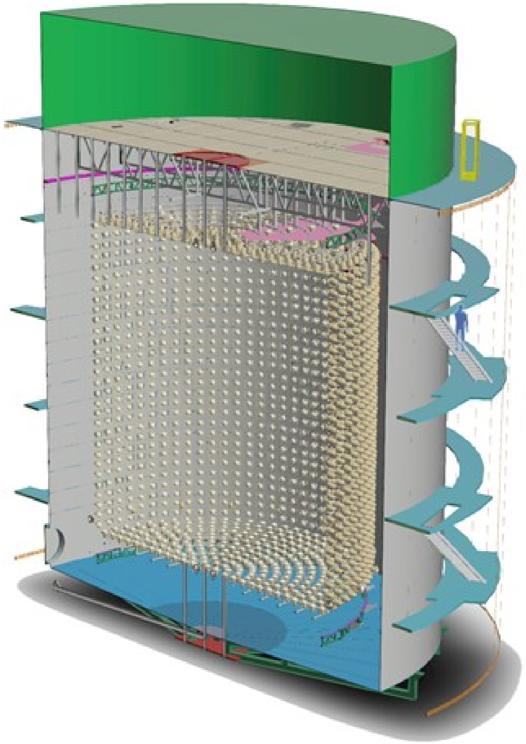



ORTHOGRAPHIC NORTH PROJECTION
ORTHOGRAPHIC SOUTH PROJECTION
90° N
75° N
60° N
45° N
30° N
15° N
15° S
30° S
45° S
180° W
150° W
120° W
90° W
60° W
30° W
0
30° E
60° E
90° E
150° E
180° E
ν/cm²/s
$10^{6.8}$
$10^{6.7}$
$10^{6.6}$
$10^{6.5}$
$10^{6.4}$
$10^{6.3}$
$10^{6.2}$
$10^{6.1}$
WINKEL TRIPEL PROJECTION
3000 0 1000 2000 3000 km
Scale at Equator
REACTOR ANTINEUTRINOS
GEOPHYSICAL ANTINEUTRINOS
MOLLWEIDE PROJECTION
MOLLWEIDE PROJECTION
ANTINEUTRINO
GLOBAL MAP 2015

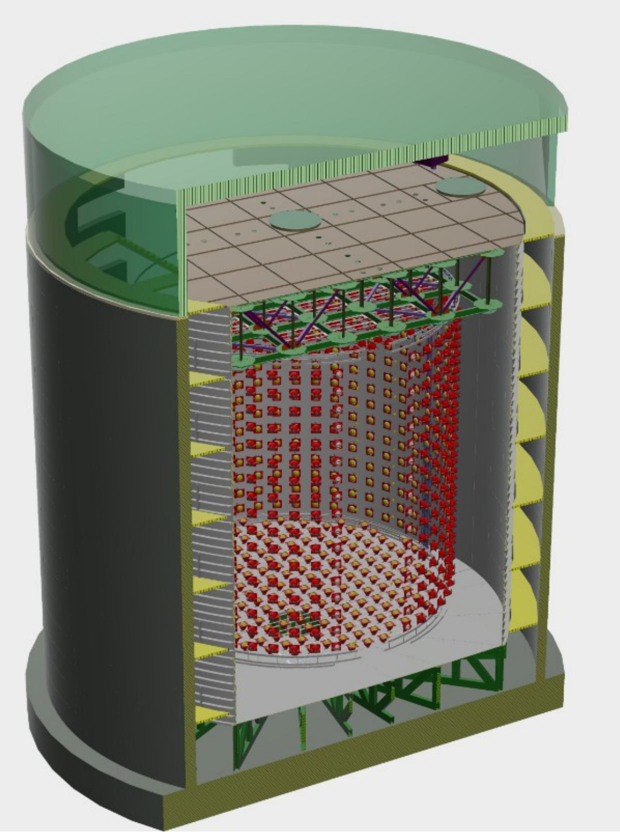
Applied Antineutrino Physics: The WATCHMAN Concept



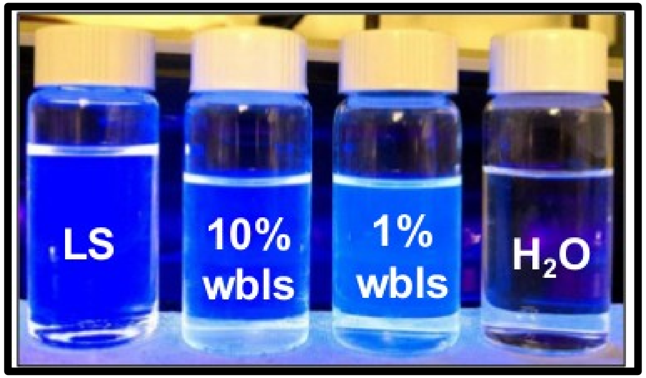
- In addition to enabling fundamental science, reactor antineutrinos provide an unshieldable signal that could be harnessed for nuclear non-proliferation.
- Objectives include:
  - Detection of a clandestine reactor
  - Determining the direction to that reactor
  - Determining the distance to that reactor

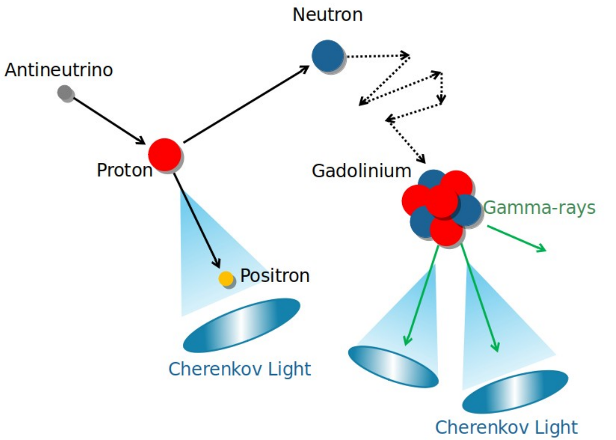


The WATCHMAN Detector



- Similar to basic water Cherenkov detector, but loaded with gadolinium and water-based liquid scintillator (WbLS).
- Gadolinium reduced background by enabling the tagging of antineutrinos via coincidence between positron and neutrino from inverse beta decay
- WbLS enables lower energy thresholds and better energy resolution at a lower cost than a pure liquid scintillator detector → vital for applications!





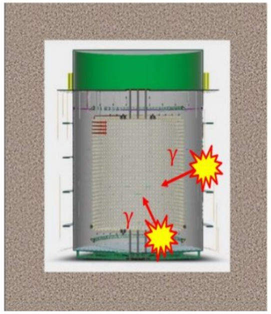
	H_2O	H_2O + 0.1% Gd
Thermal capture cross section (σ)	~ 0.3 barns	~49,000 barns
Capture time (τ)	~220 μsec	~30 μsec
Energy released	2.2 MeV (single γ)	~8 MeV (γ cascade)

WATCHMAN @ Boulby

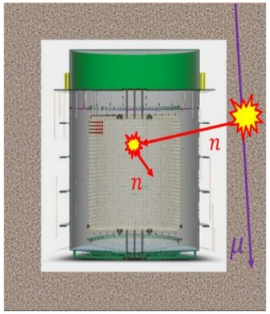
- A WATCHMAN-type detector was proposed for the STFC Boulby Underground Laboratory in 2017; the main source of reactor antineutrinos would be the EDF Hartlepool dual AGR cores
- Signal and backgrounds are:

Uncorrelated: Accidental coincidences

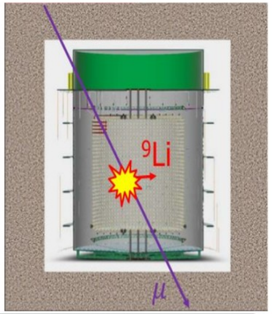
Correlated: Interaction due to cosmogenic muons in the rock and detector



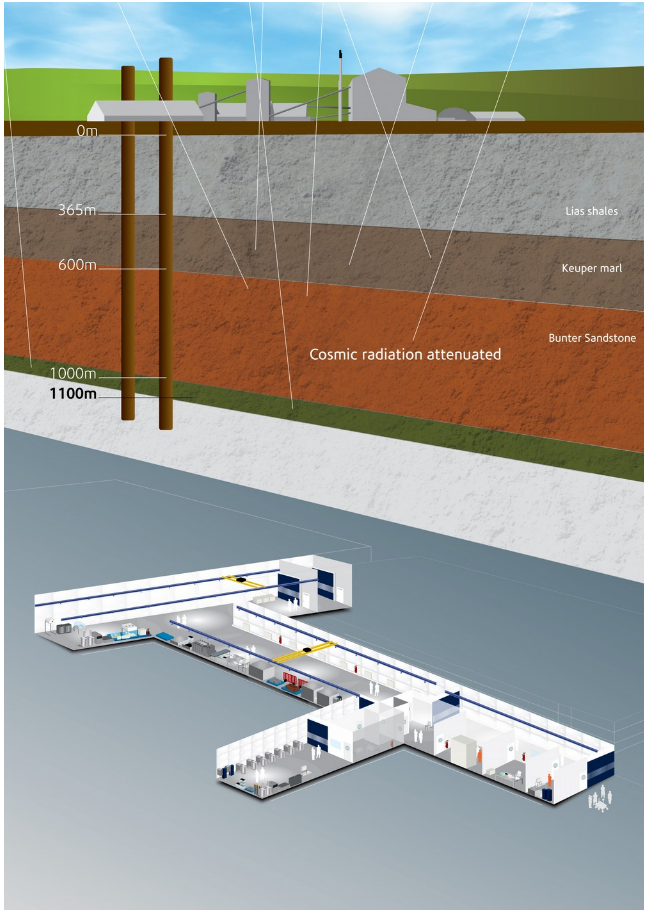
Gammas from radioactivity in detector components & environs



Fast neutron pairs from cosmic muons interacting in the rock around the detector



Long-lived radio-nuclides from cosmic muon interations in the detector (spallation).



Sensitivity to distant reactors 🇬🇧

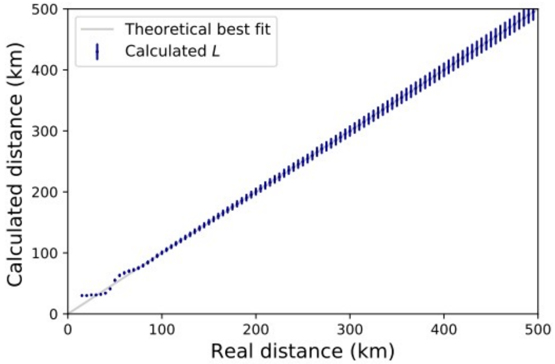
- Aggregate detection of the world's reactor antineutrino flux was detected by the SNO+ collaboration (arXiv:2210:14154) during water phase
- For non-proliferation purposes, detection of a single site is required
  - Ongoing effort at Super-Kamiokande, exploiting Gd loading
- Sensitivity studies were conducted for a proposed Gd+WbLS detector sited at the STFC Boulby Underground Laboratory location
  - Reactor complexes considered are shown in the map (right)
- Results in table below are taken from a recent paper at arXiv:2210.11224 (submitted to *Phys. Rev. Applied*)

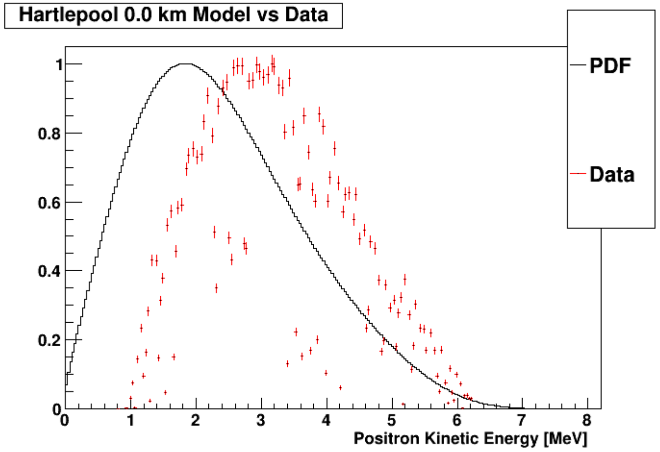
TABLE VI: Cobraa results summary for anomaly detection - dwell time in days for rejection of the background-only hypothesis to 3σ significance assuming normal reactor operation.

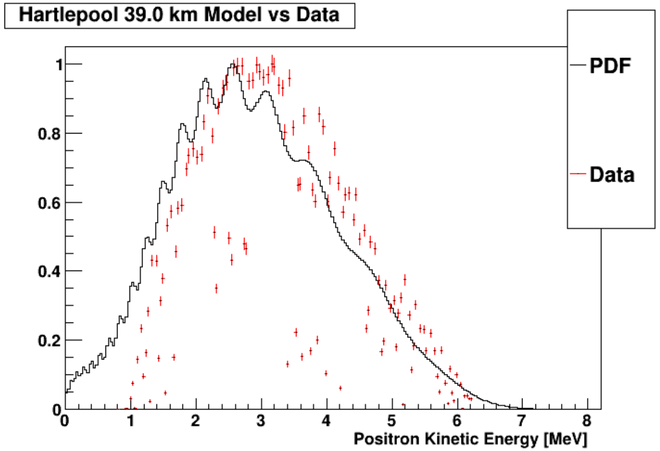
Detector	Hartlepool 1 & 2	Hartlepool 1	Heysham 1 & 2	Heysham 2 + Torness	Heysham 2
16 m Gd-H_2O	12	61	2327	3488	8739
16 m Gd-WbLS	7	35	738	1022	3008
22 m Gd-H_2O	3	11	241	232	985
22 m Gd-WbLS	2	8	152	192	647

Reactor ranging

- Reactor ranging relies on the fact that neutrinos carry information about their distance travelled, in the form of oscillation probabilities
- Two ranging analyses were attempted – minimum χ^2 and Fourier analysis
- In general, the χ^2 method worked well for nearby reactors (< 50 km), but could not handle low signal-to-noise ratios at greater distances
- In contrast, the Fourier analysis is more robust at greater distances, but cannot resolve the wiggles for nearby reactors (see below)
- WbLS is not the ideal medium for such analysis; pure liquid scintillator would be better suited to reactor ranging.





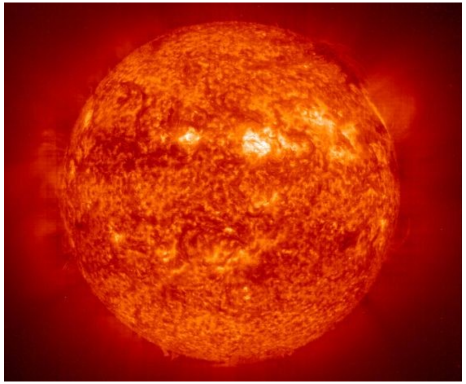


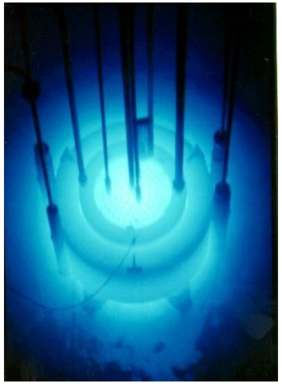
Where to? (Reactor monitoring)

- EDF Energy put an end to the possibility of a WATCHMAN-like detector based in the UK when they announced at all existing AGR reactors will be decommissioned between now and the end of March 2028.
- Alternative sites are being investigated, such as the Fairport mine in the United States (previously home to the IMB experiment), which is 13 km away from the Perry nuclear reactor.
- In parallel, a R&D programme is continuing in the UK, jointly sponsored by STFC and the US National Nuclear Security Administration. This is the Boulby Underground Technology Testbed Observing Neutrinos (BUTTON), currently in construction phase.
- In addition to ‘far-field’ monitoring there is a strong interest in ‘near-field’ monitoring techniques that could be used cooperatively for treaty verification. One such technology is opaque liquid scintillator (‘LiquidO’), which Jeff Hartnell will be speaking about tomorrow.

Summary

- Solar neutrinos and reactor antineutrinos are the yin and yang of low energy neutrino physics.
- Together, they have provide us with eight decades of insight to the nature of the universe, with no end in sight.
- One more player on the field of low energy neutrino physics is supernova neutrinos, which encompasses both neutrinos <u>and</u> antineutrinos
  - See tomorrow's talk by Yuber Perez-Gonzalez for more...





Thank you for listening!

BACK UP SLIDES

(Here be dragons...)

The Solar ν Problem: Summary