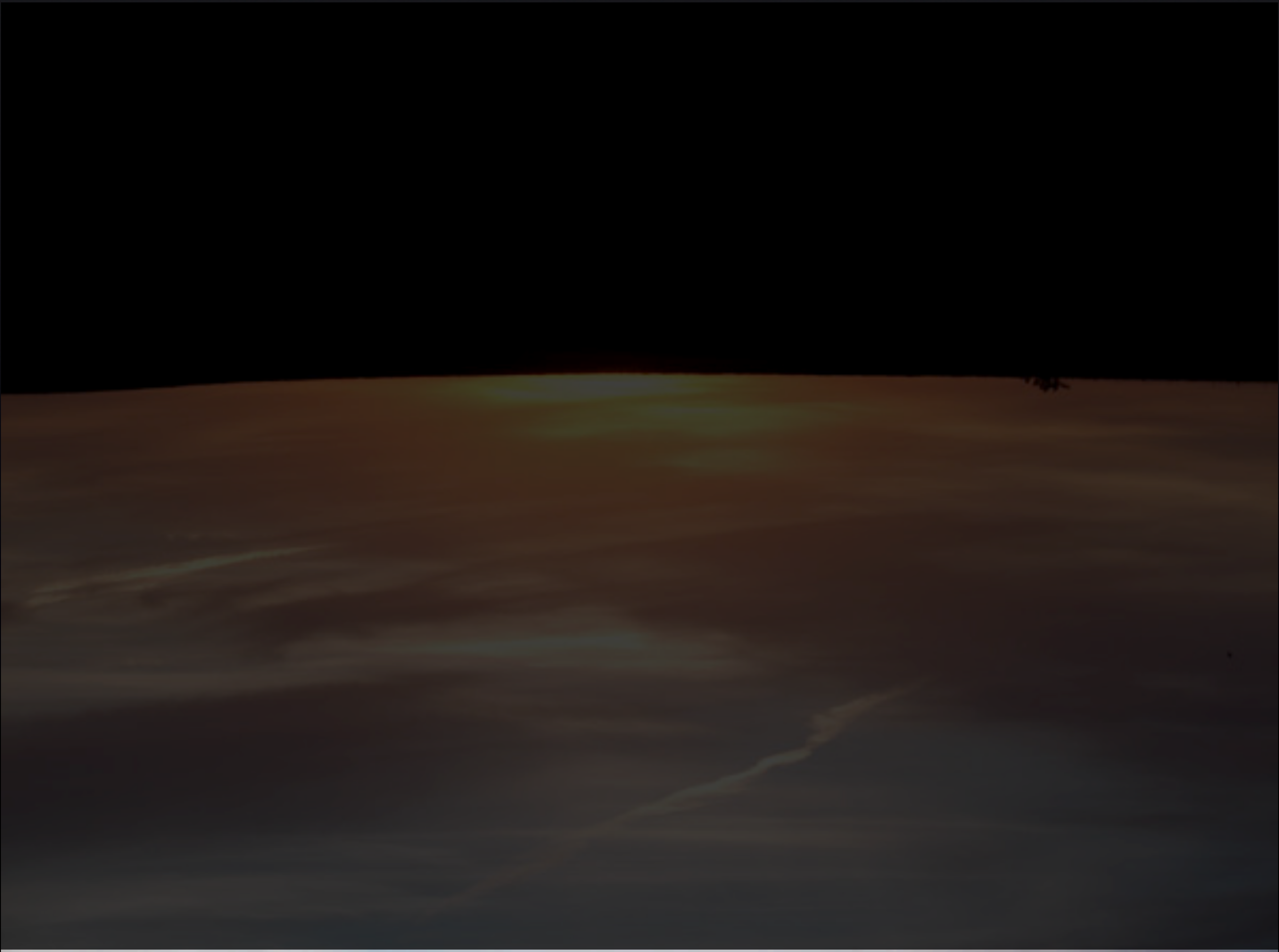
"If going underground, please remember the sunscreen...

J. A. Formaggio

MIT

October 16th, 2008



Outline of Talk:

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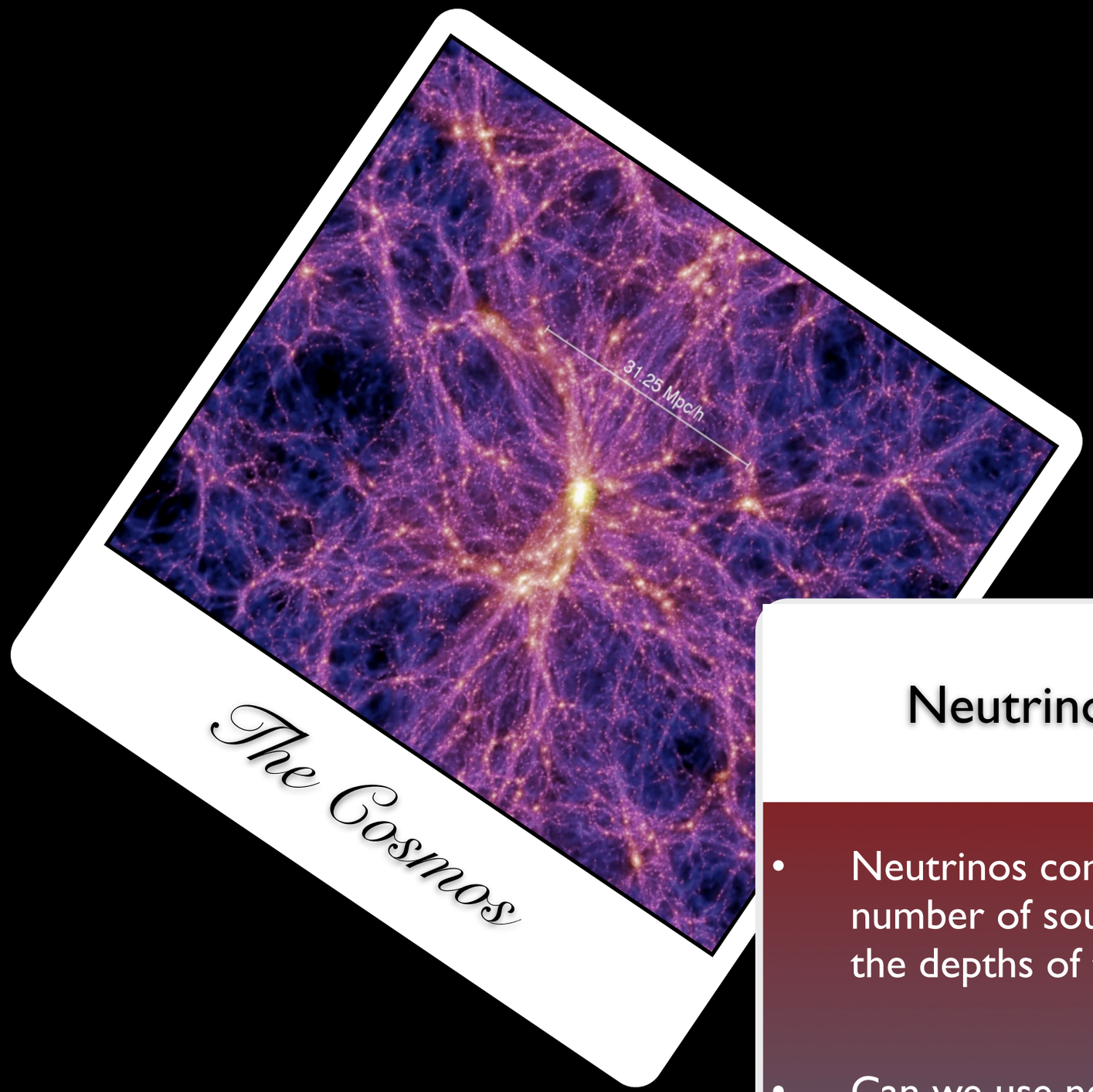
- Neutrinos, oscillations, and solar physics
- The specifics of SNO experiment
- The legacy of neutrino masses

Neutrinos as Probes

- Neutrinos come to us from a number of sources from the stars to the depths of the Earth.
- Can we use neutrinos to probe the interior of the sun?



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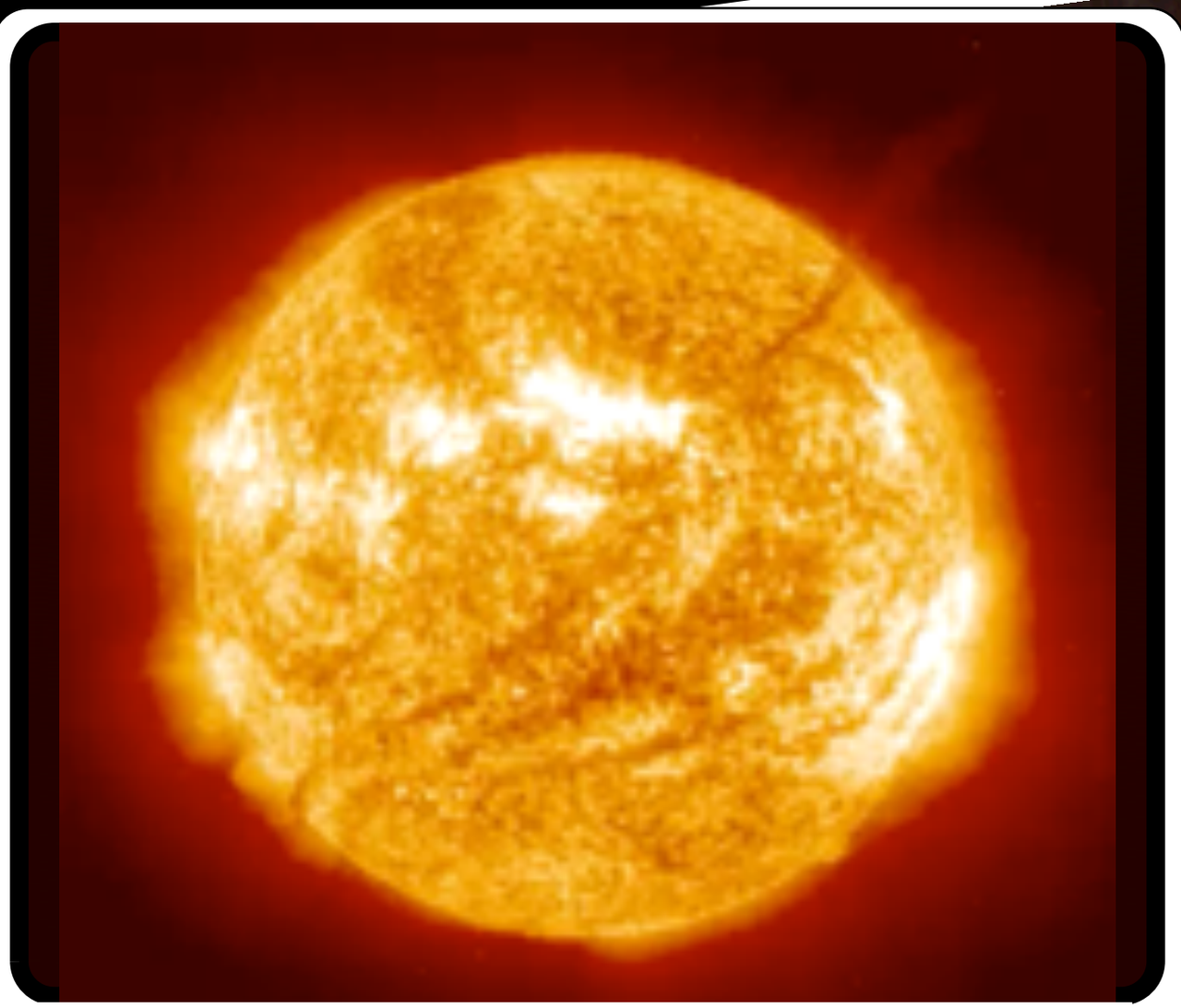
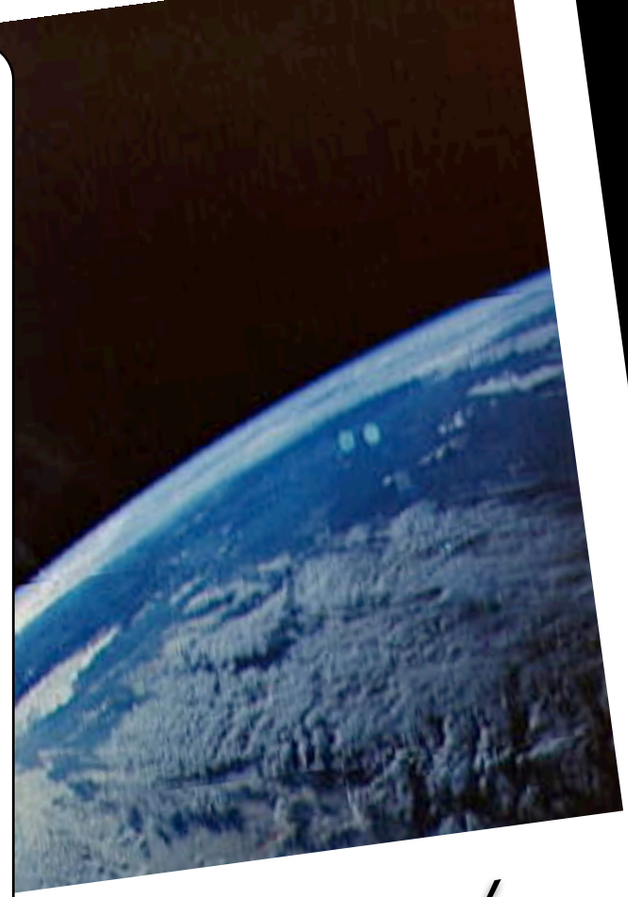


The Sun



th's Atmosphere

Cosmos

Neutrinos as Probes

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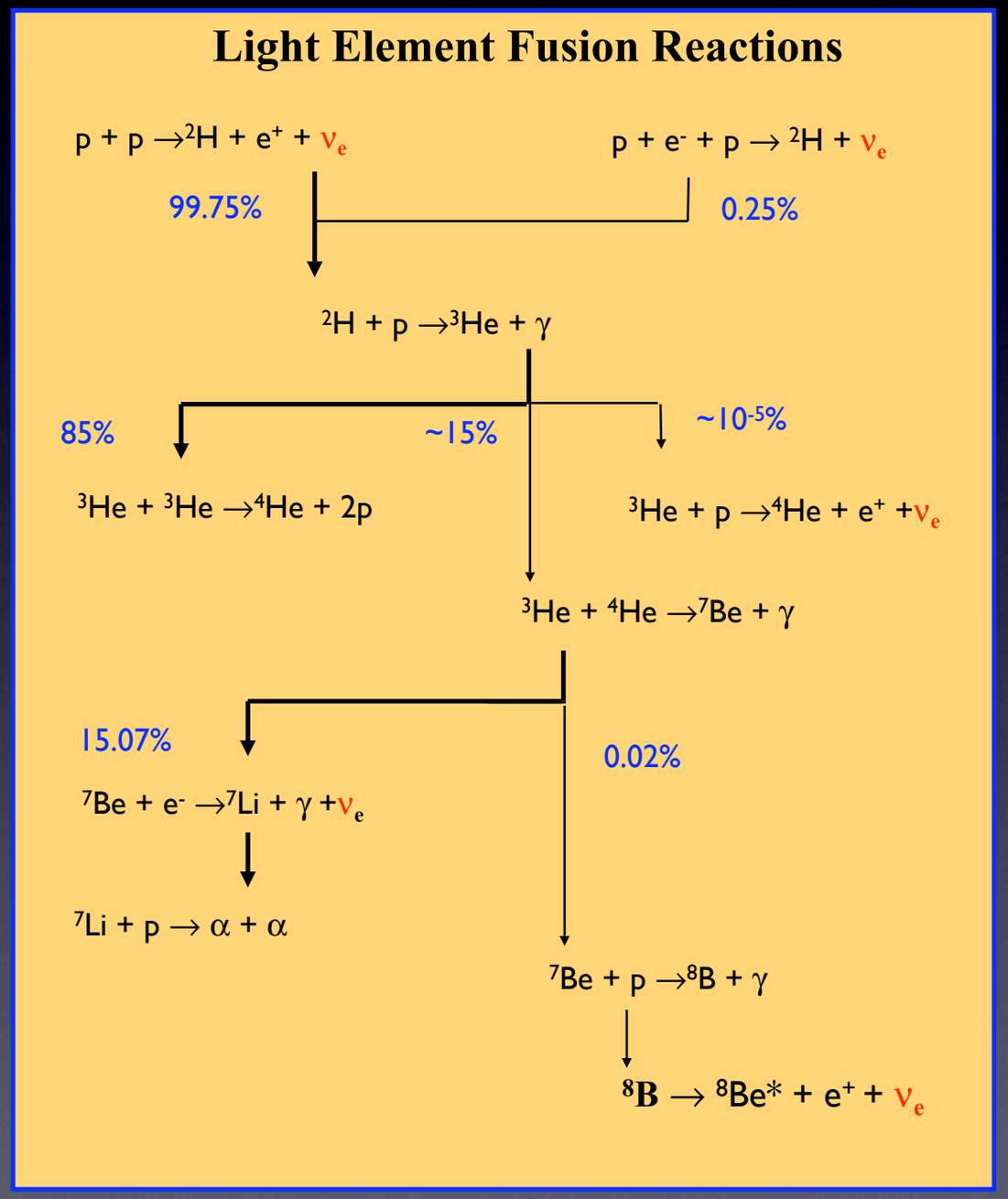
Window into the interior of the sun

- Neutrinos from the sun allow a direct window into the nuclear solar processes.
- Each process has unique neutrino energy spectrum
- Only electron neutrinos are produced at these energies.
- Different experiments sensitive to different aspects of the spectrum.



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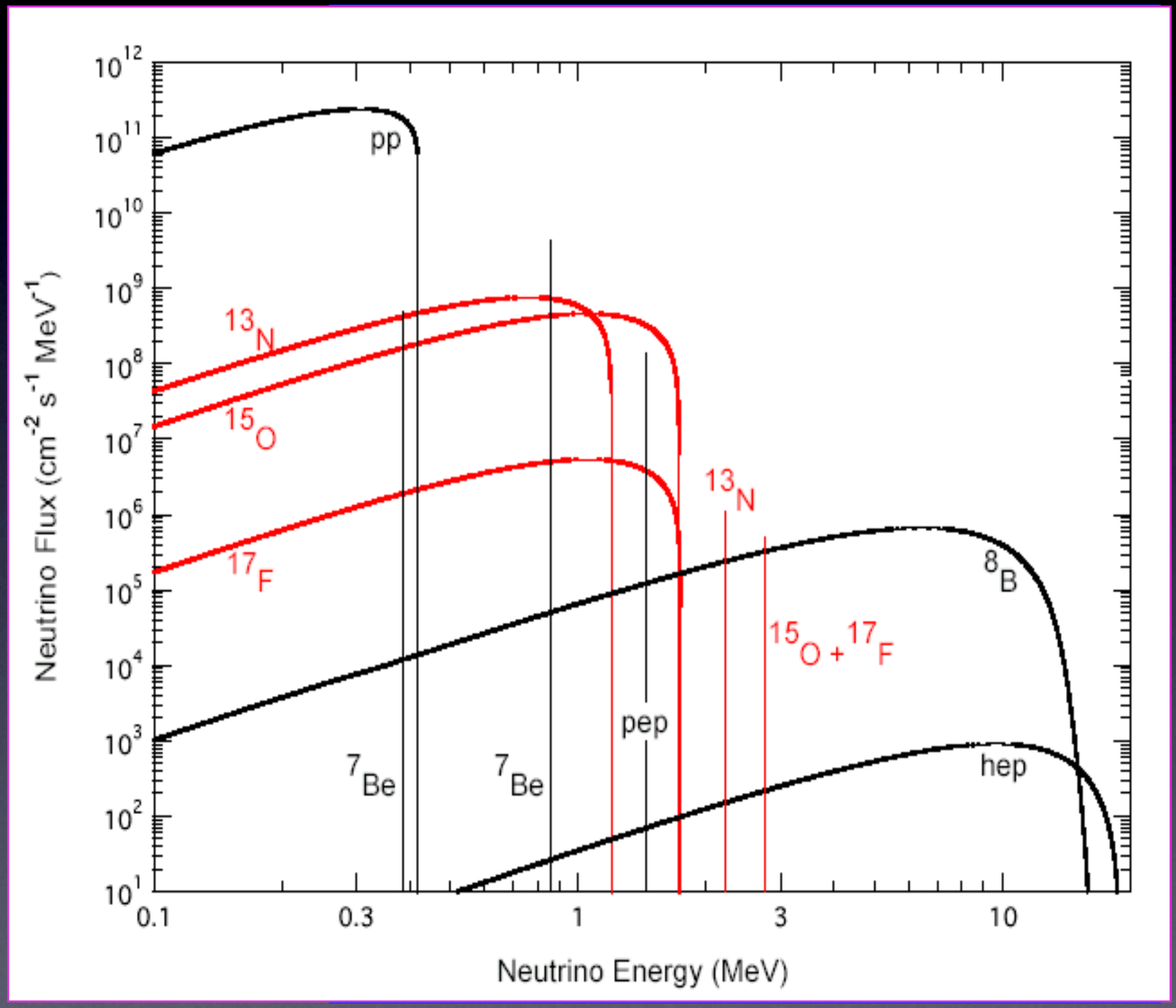

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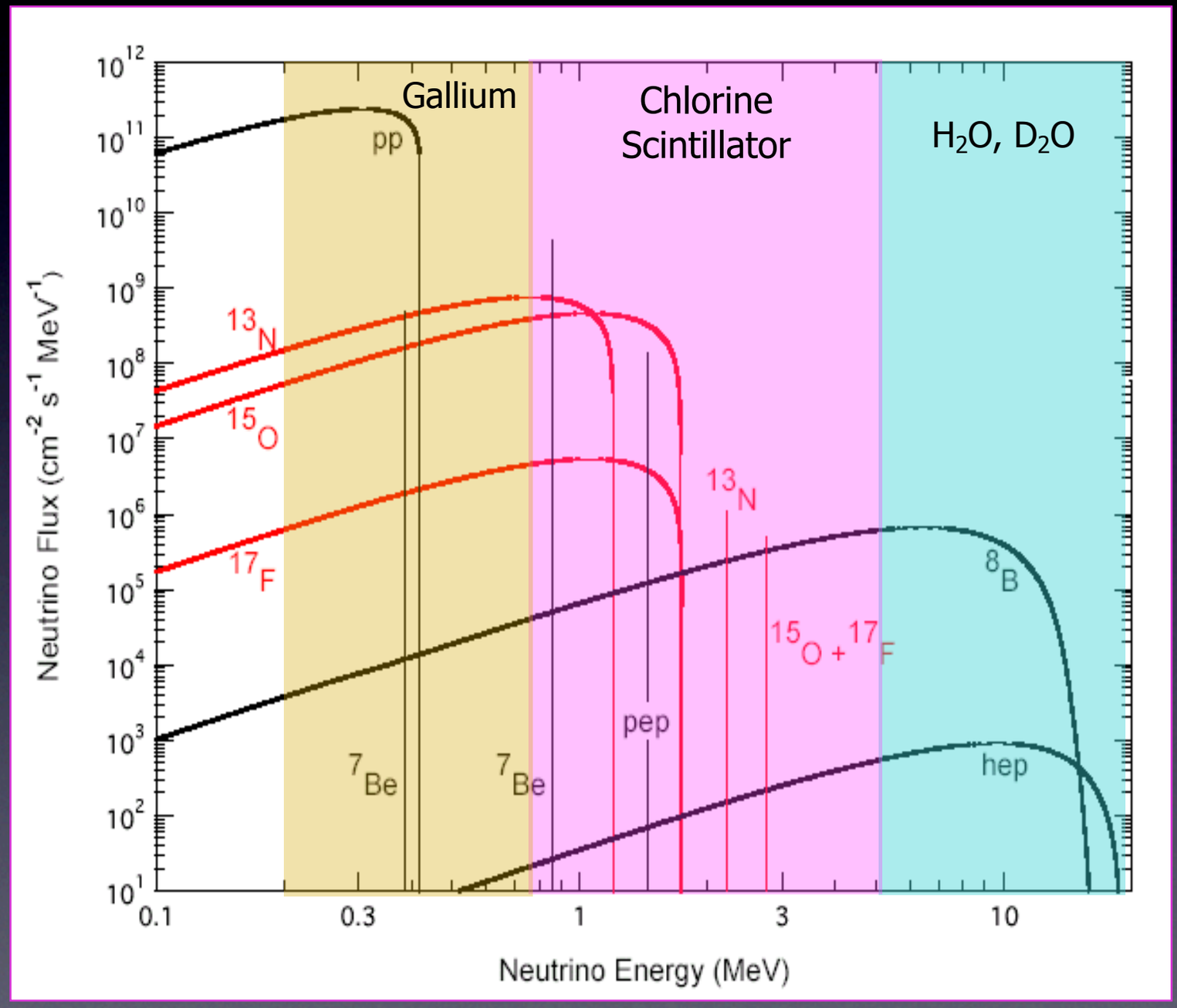
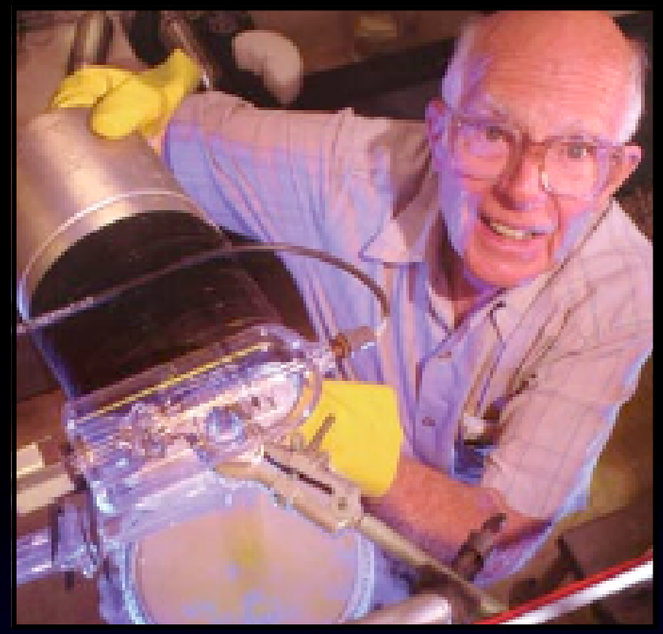


The Solar Puzzle Begins...



Raymond Davis, Jr.
Winner of 2002 Nobel Prize in Physics

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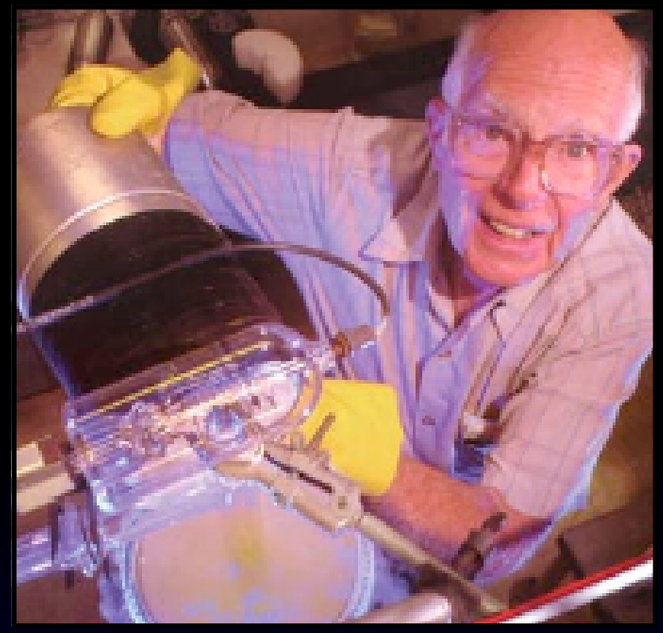

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60s

Ray Davis begins construction of Homestake

Bahcall provides solar flux predictions

70s

Solar puzzle begins

Homestake (^{37}Cl) measurements

MSW mechanism proposed

80s

SAGE (^{71}Ga) begins operations

Helioseismology models compared

90s

GALLEX (^{71}Ga) online

Super-K (H_2O) online

Solar puzzle SOLVED

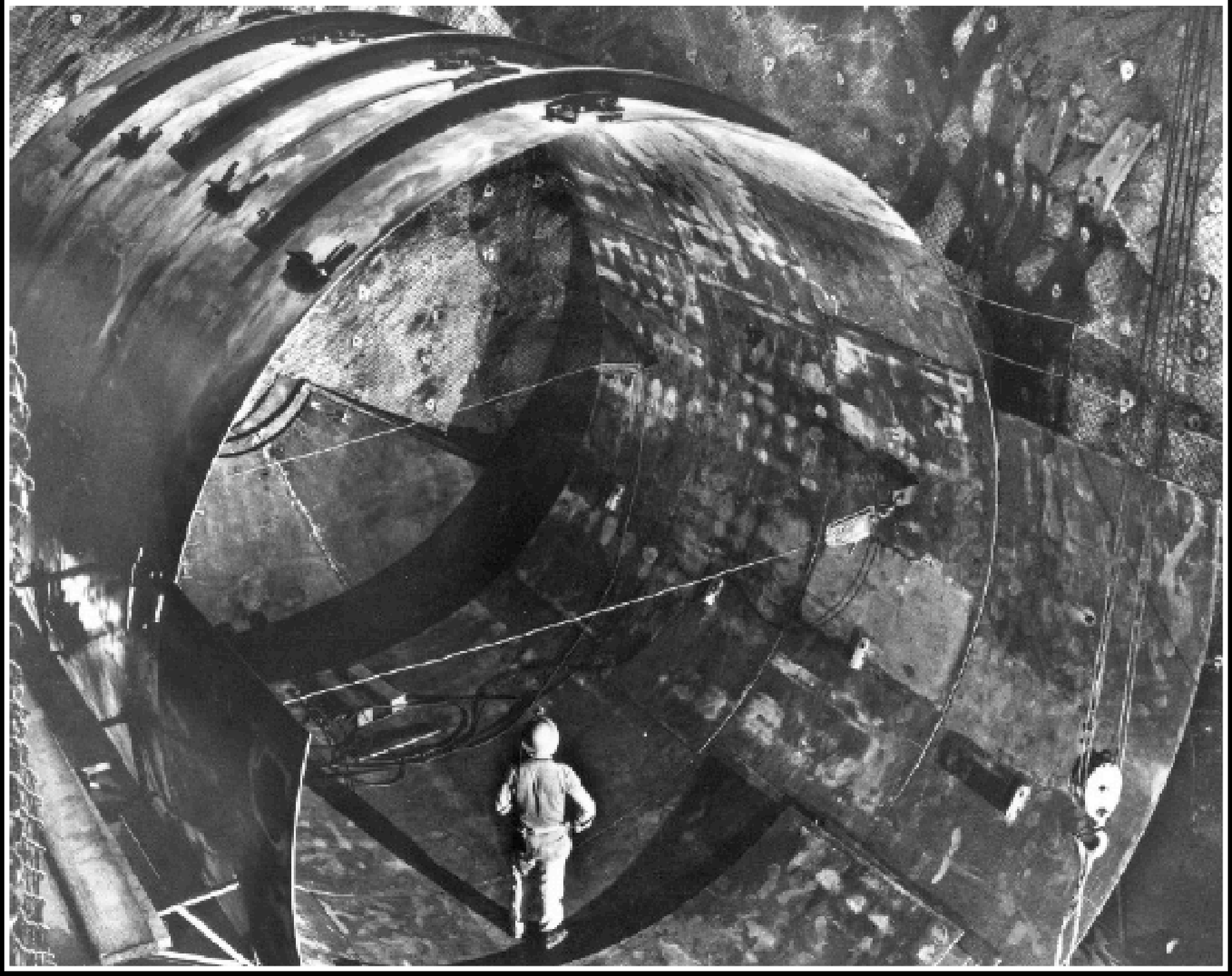
00s

GNO operational

SNO (D_2O) takes data

Borexino!

1st results from KAMLAND



Experimenting Underground

Ray Davis before the Homestake experiment...

Repeat as necessary...

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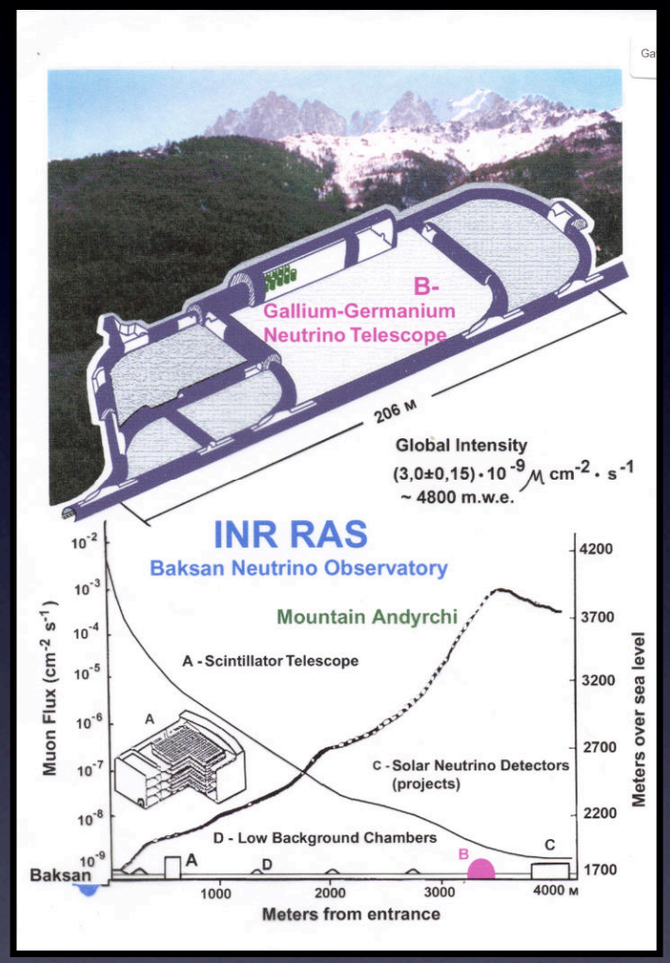
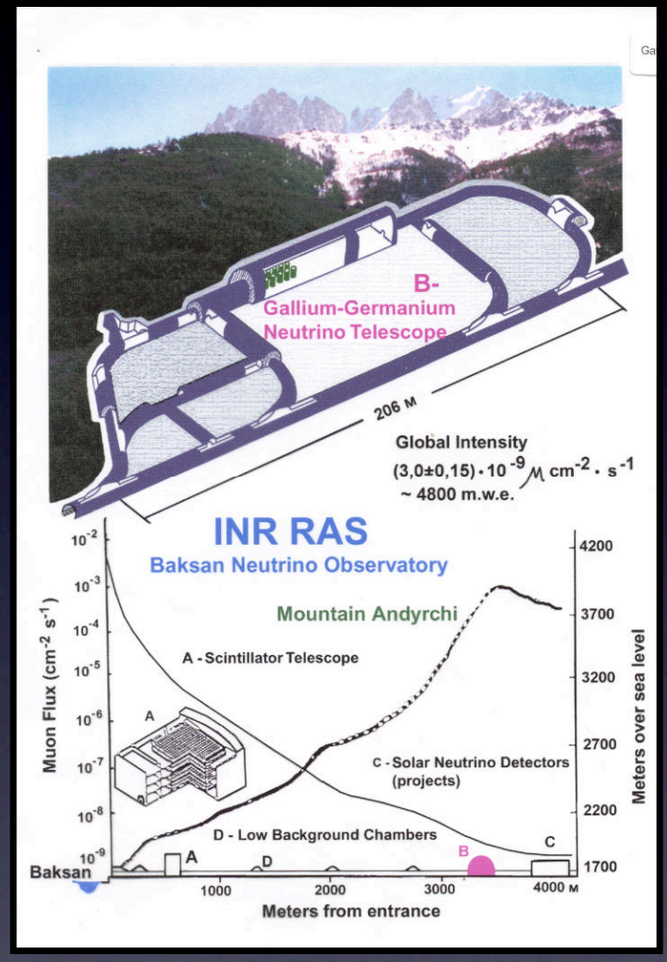


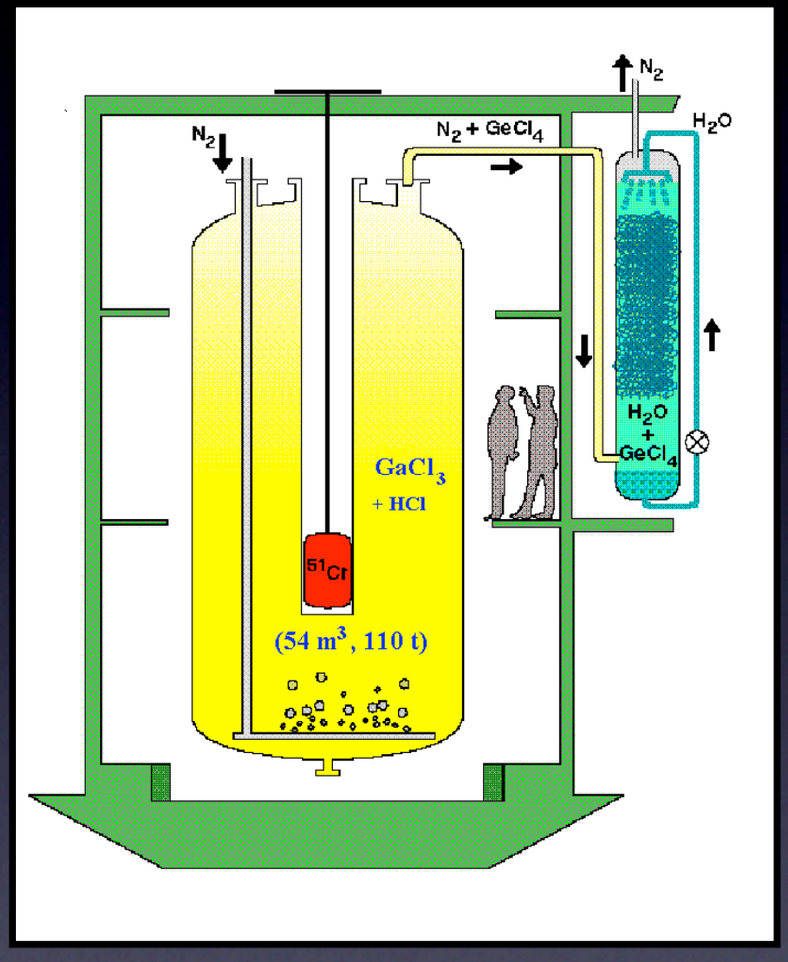
SAGE

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

Measures 1/2 of expected flux

Repeat as necessary...





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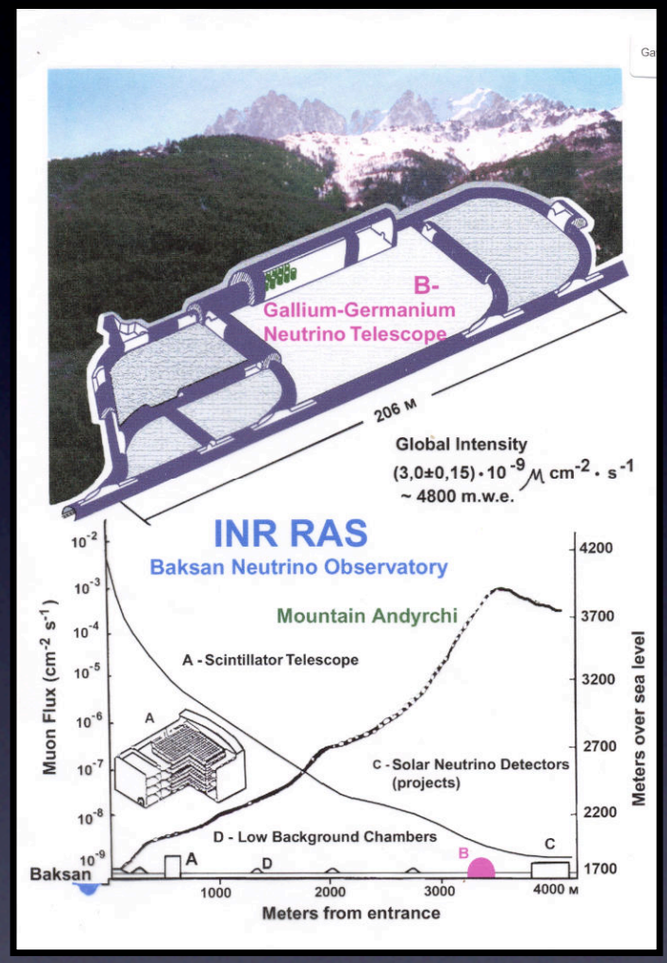

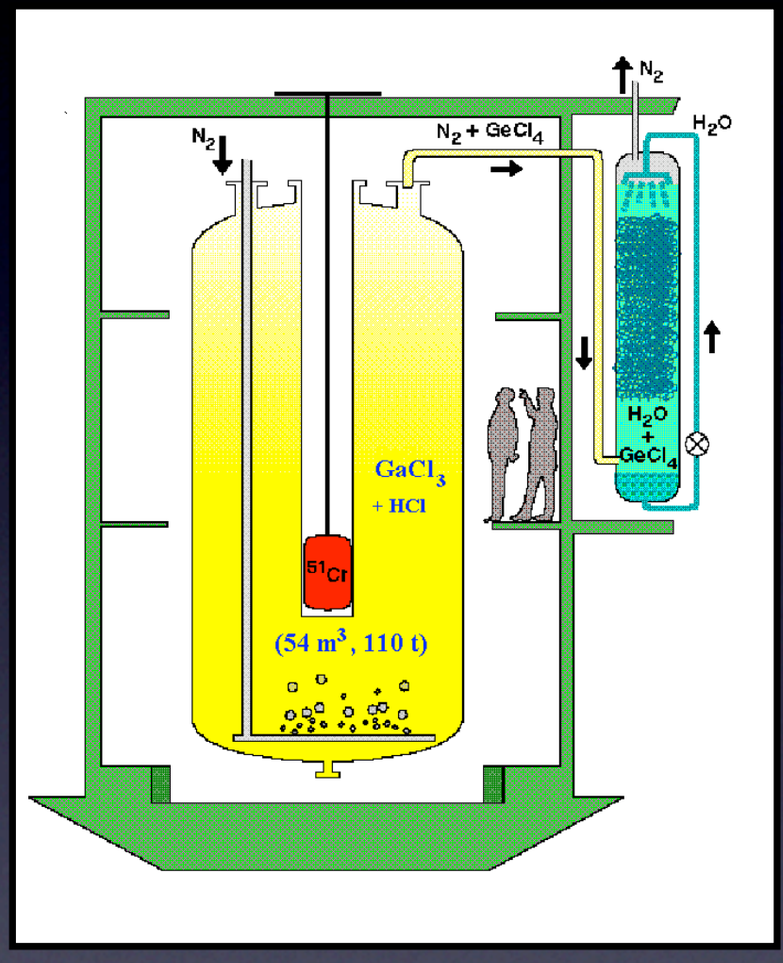

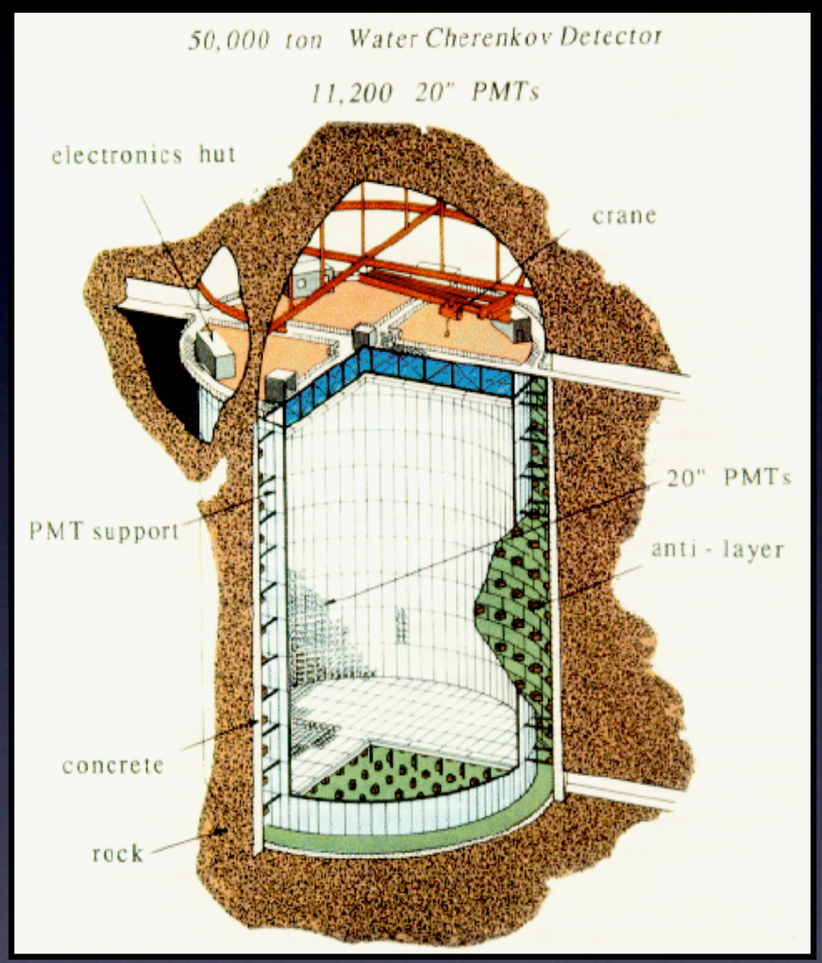

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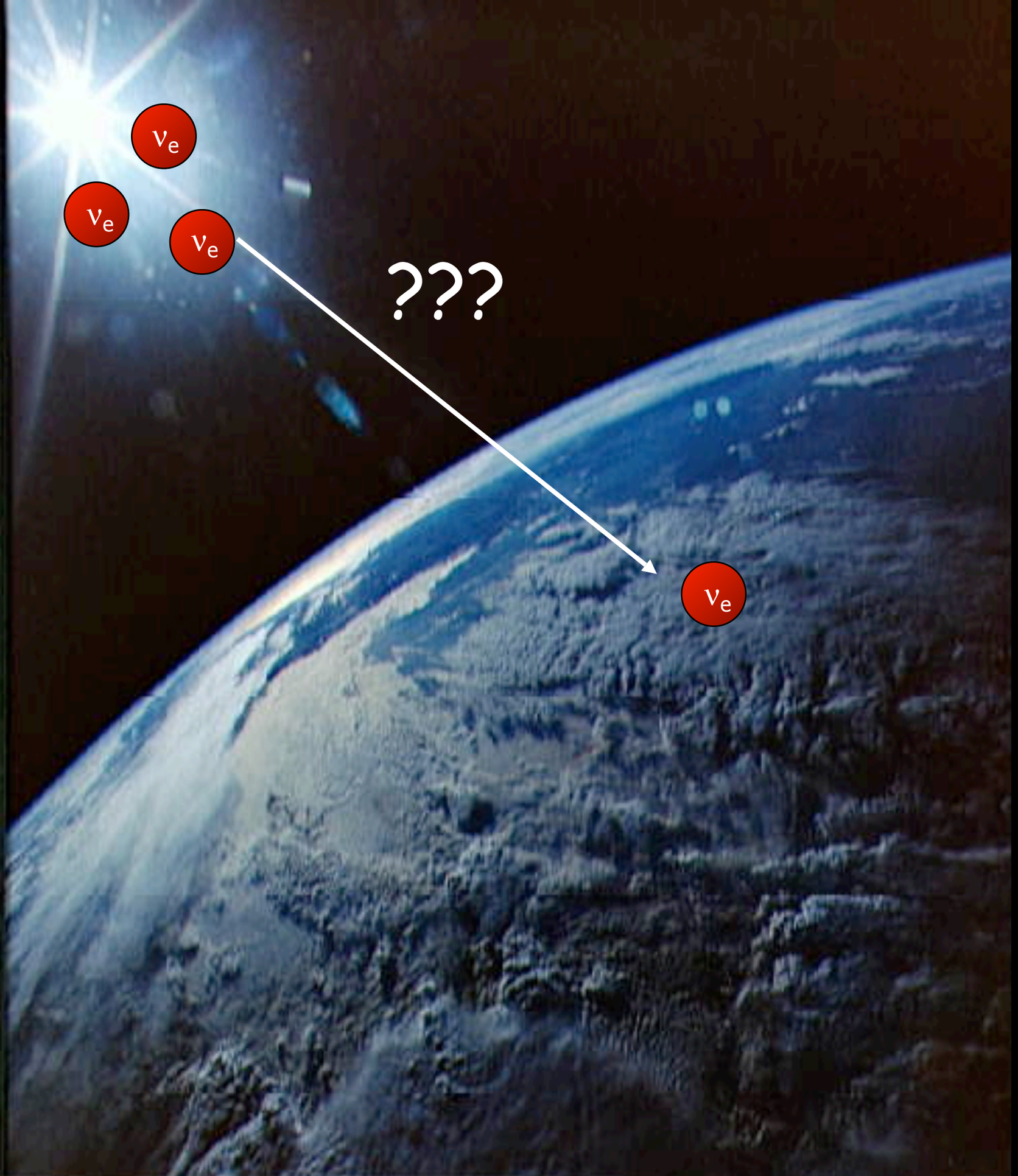
Super-Kamiokande

$e^- + \nu_e \rightarrow \nu_e + e^-$

Measures 40% of expected flux

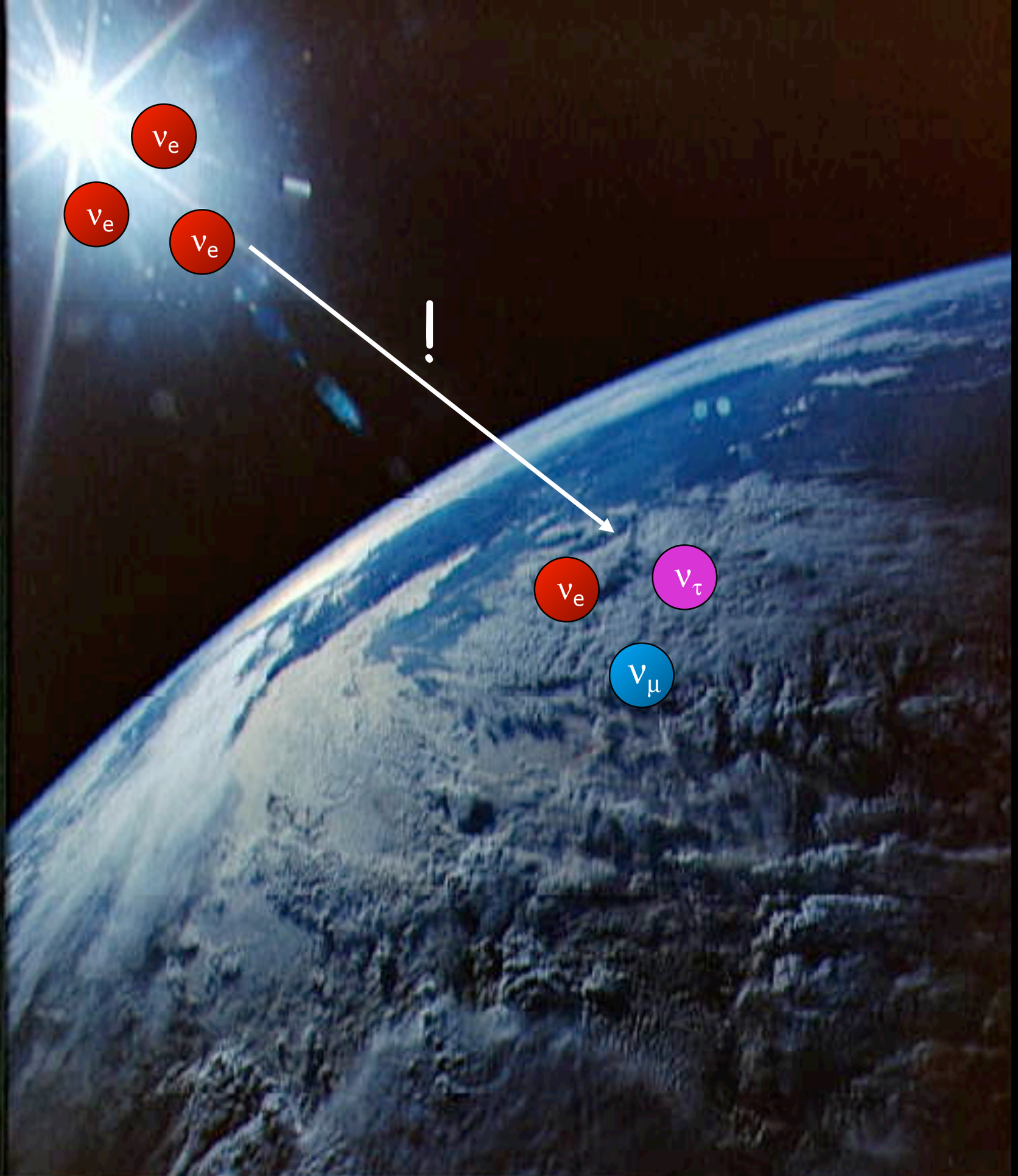


The sun only makes "electron-type" neutrinos

Detectors only detect electron-type neutrinos.

What if neutrinos are changing from one type to the other?

Need to measure ALL neutrino types, regardless of what kind (flavor) they are…



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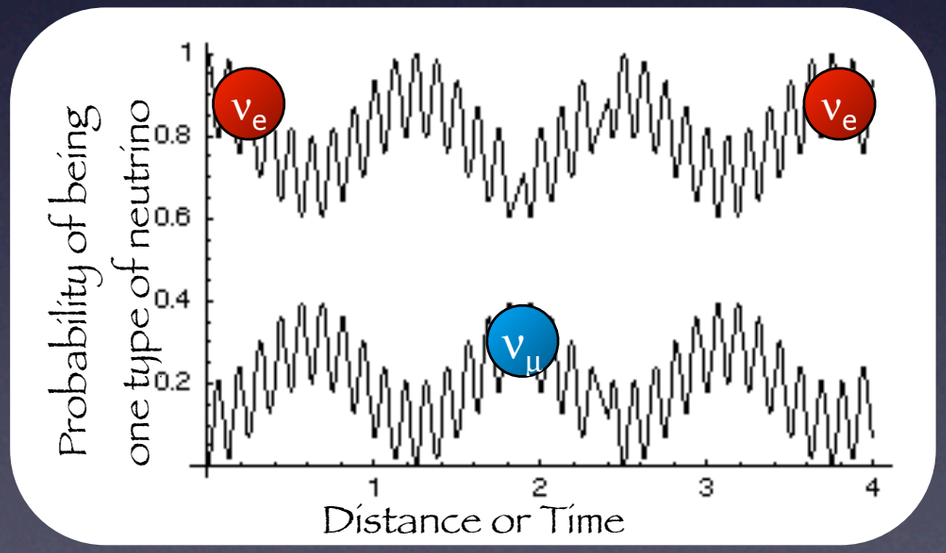
Neutrino Oscillations

- In general, we have a 3 x 3 matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

Bruno Pontecorvo

- However, the picture simplifies if one of the mixing angles is small...



- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4E_\nu} L)$$

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$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, long baseline}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

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$$\mathcal{P}_{\text{surv}} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E_\nu} L\right)$$

The SNO Collaboration

- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Louisiana State University
- Massachusetts Institute of Technology
- University of Pennsylvania
- University of Texas at Austin
- University of Washington
- University of British Columbia
- Carleton University
- University of Guelph
- Laurentian University
- Queen's University
- TRIUMF
- University of Oxford
- LIP, Lisbon, Portugal

The SNO Collaboration at MIT

Faculty (neutrinos)

Joseph Formaggio
Peter Fisher
Janet Conrad

Pappalardo Fellows & Post-docs:

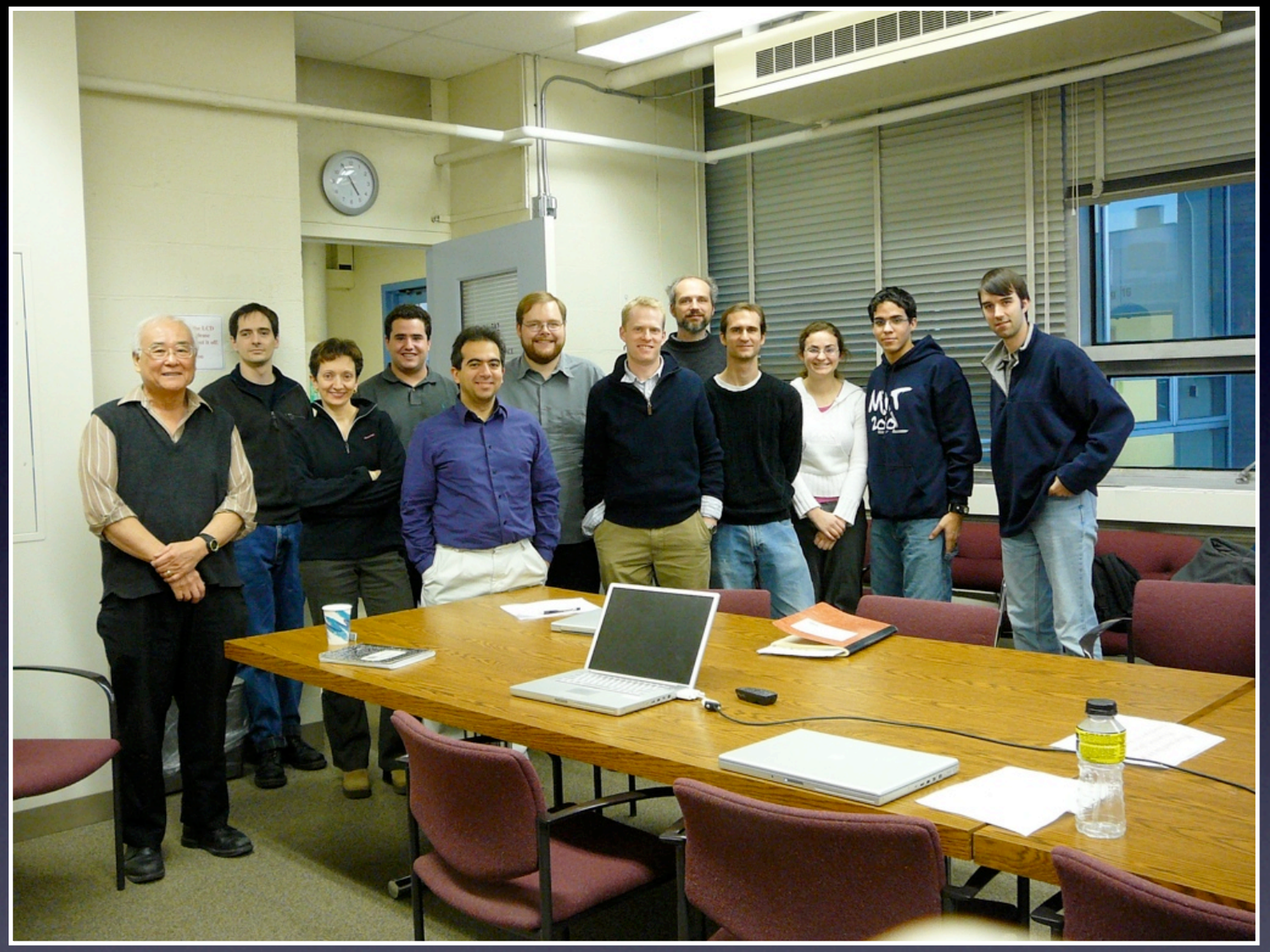
Michael Miller
Jocelyn Monroe
Benjamin Monreal

Graduate Students:

T. J. Corona
Daniel Furse
Asher Kaboth
Richard Ott
Thomas J. Walker
John Barrett

Undergraduate Students/UROPs:

Sara Trowbridge
Matt Heine
Sara Campell, Arthur Franke
Miriam Huntley
Renaldo Webb, Dennis Perepelitsa
Charles Sebens



Neutrino & Dark Matter Group at MIT circa 2007

The Sudbury Neutrino Observatory (surface view)

Neutrinos?

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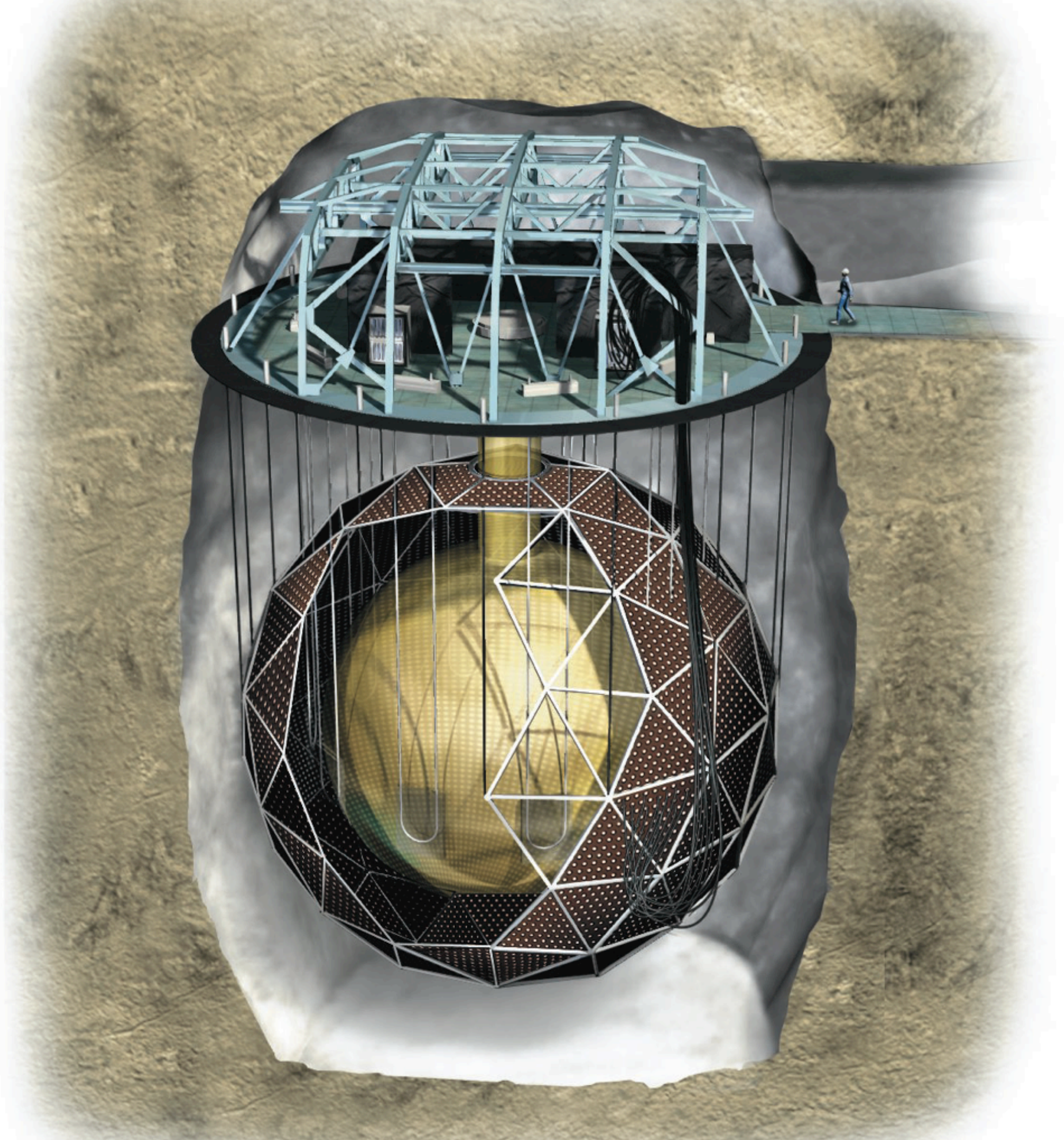
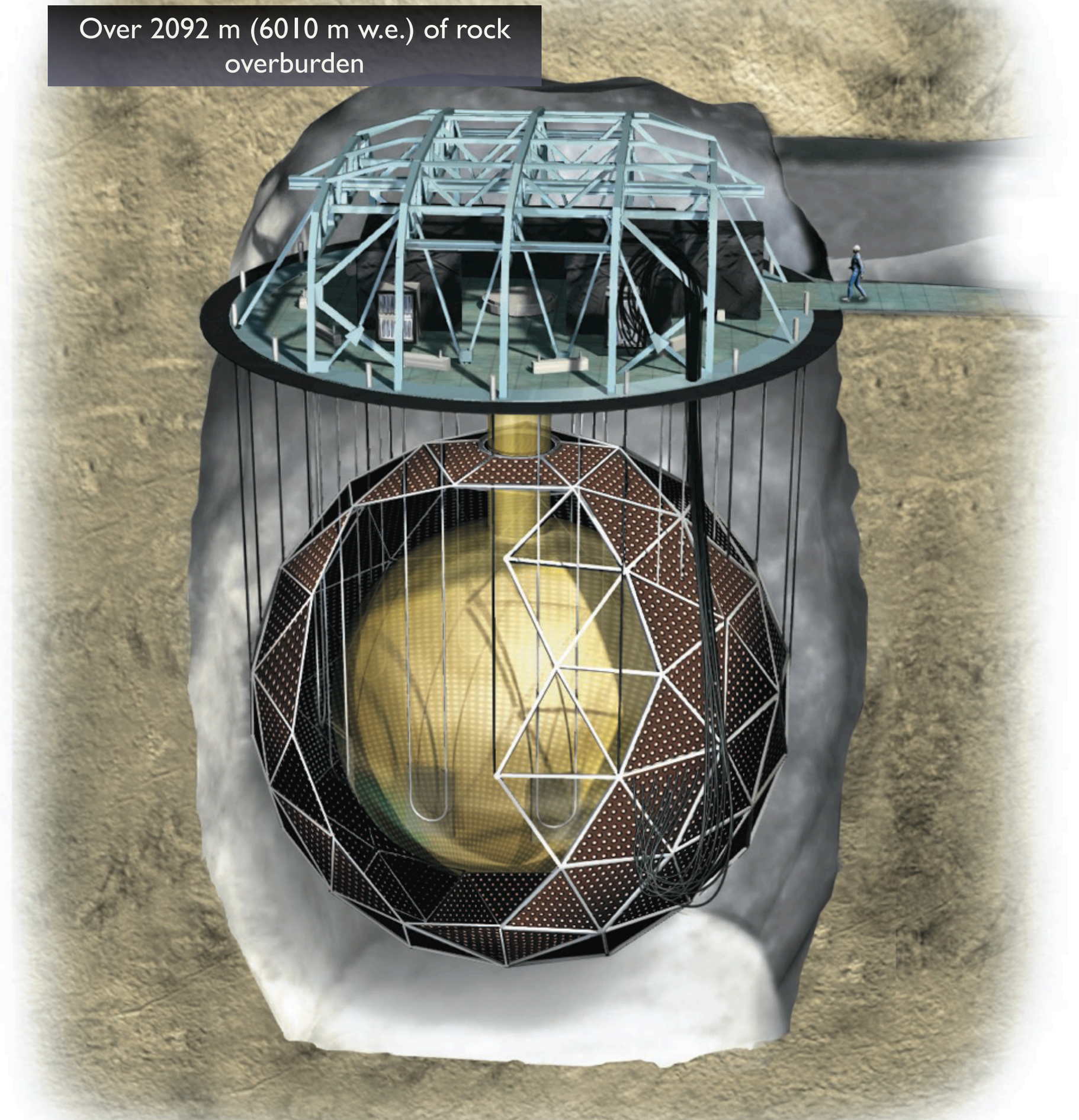


The Sudbury Neutrino Observatory



Over 2092 m (6010 m w.e.) of rock overburden

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

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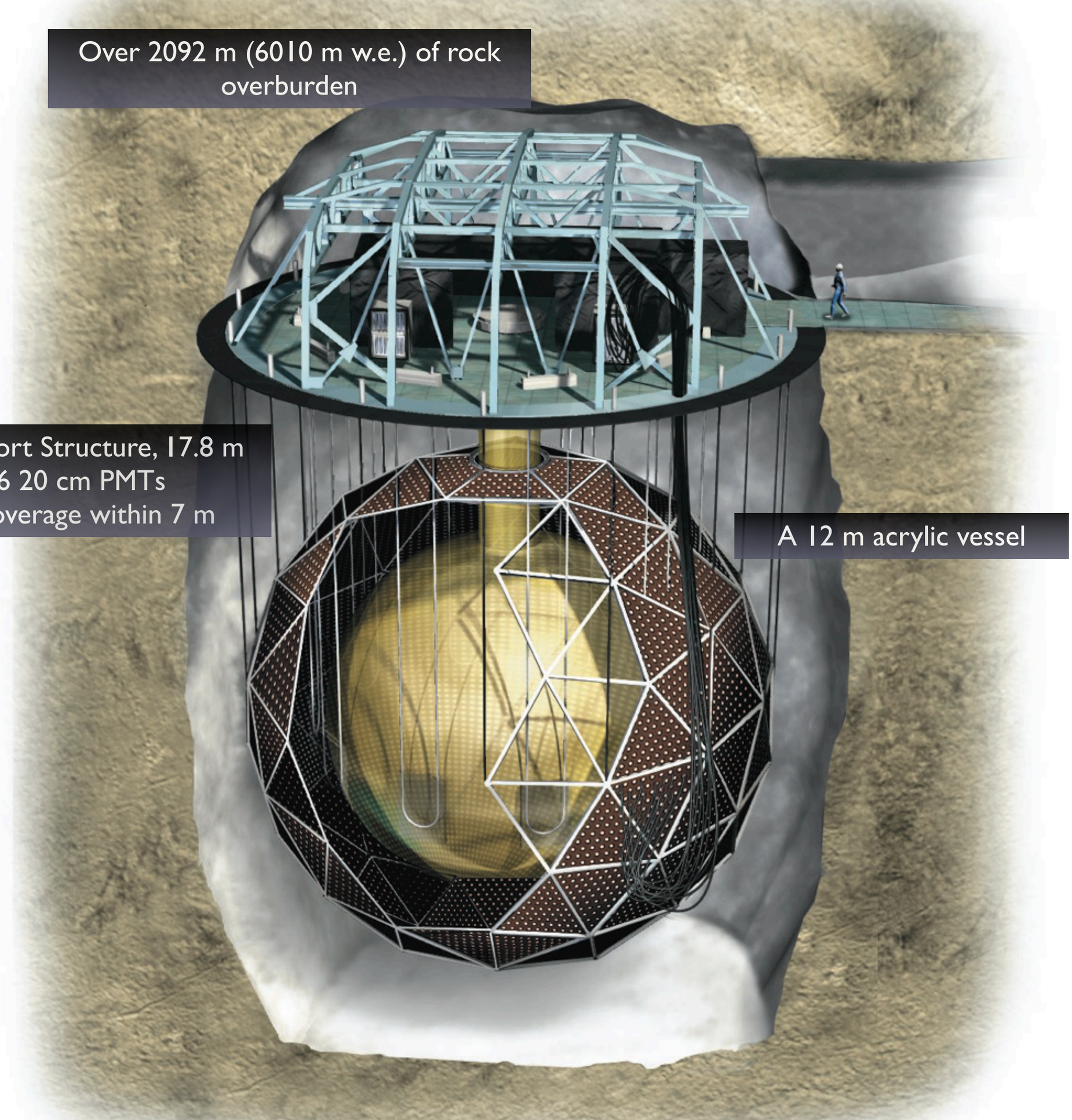

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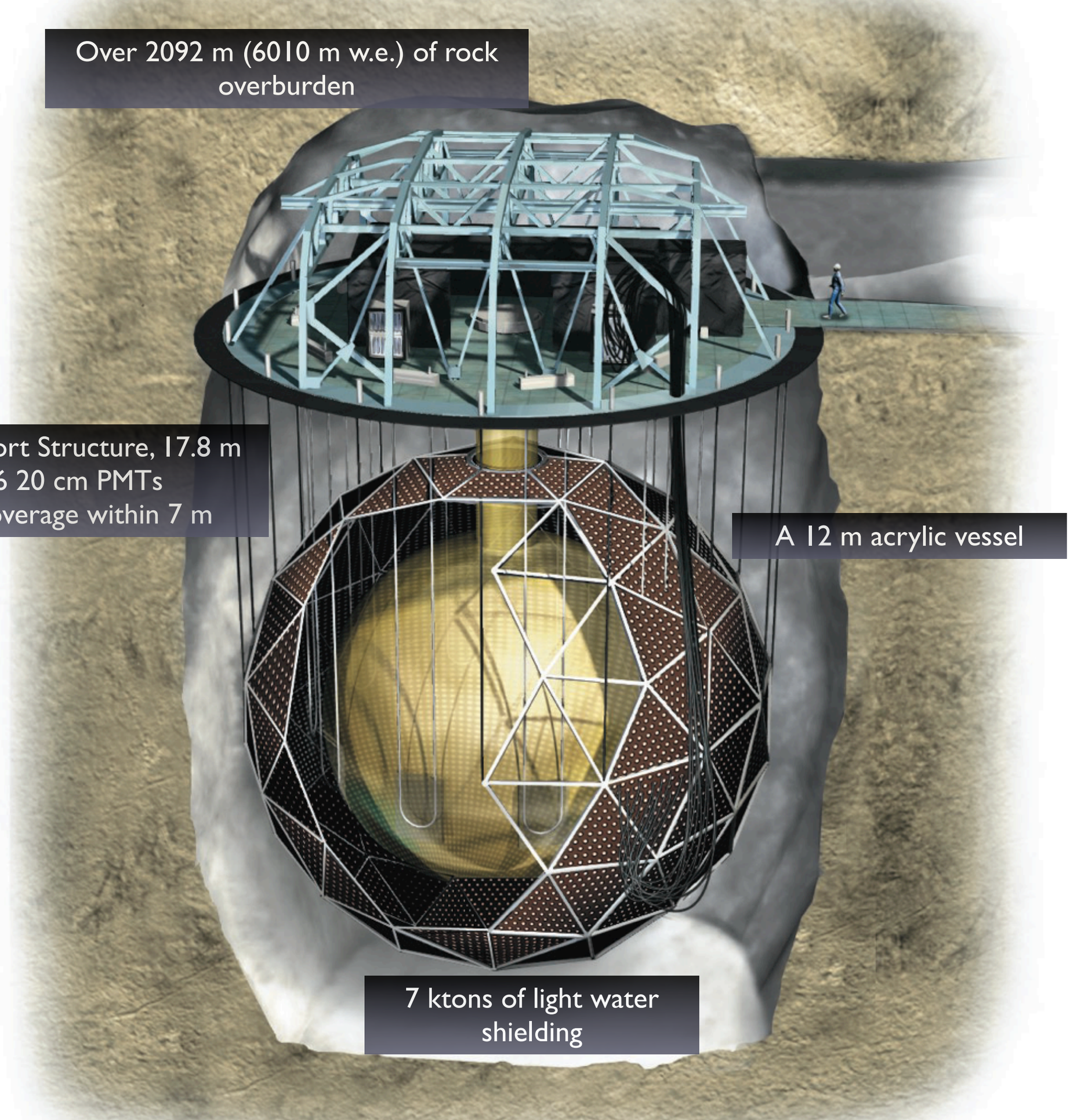

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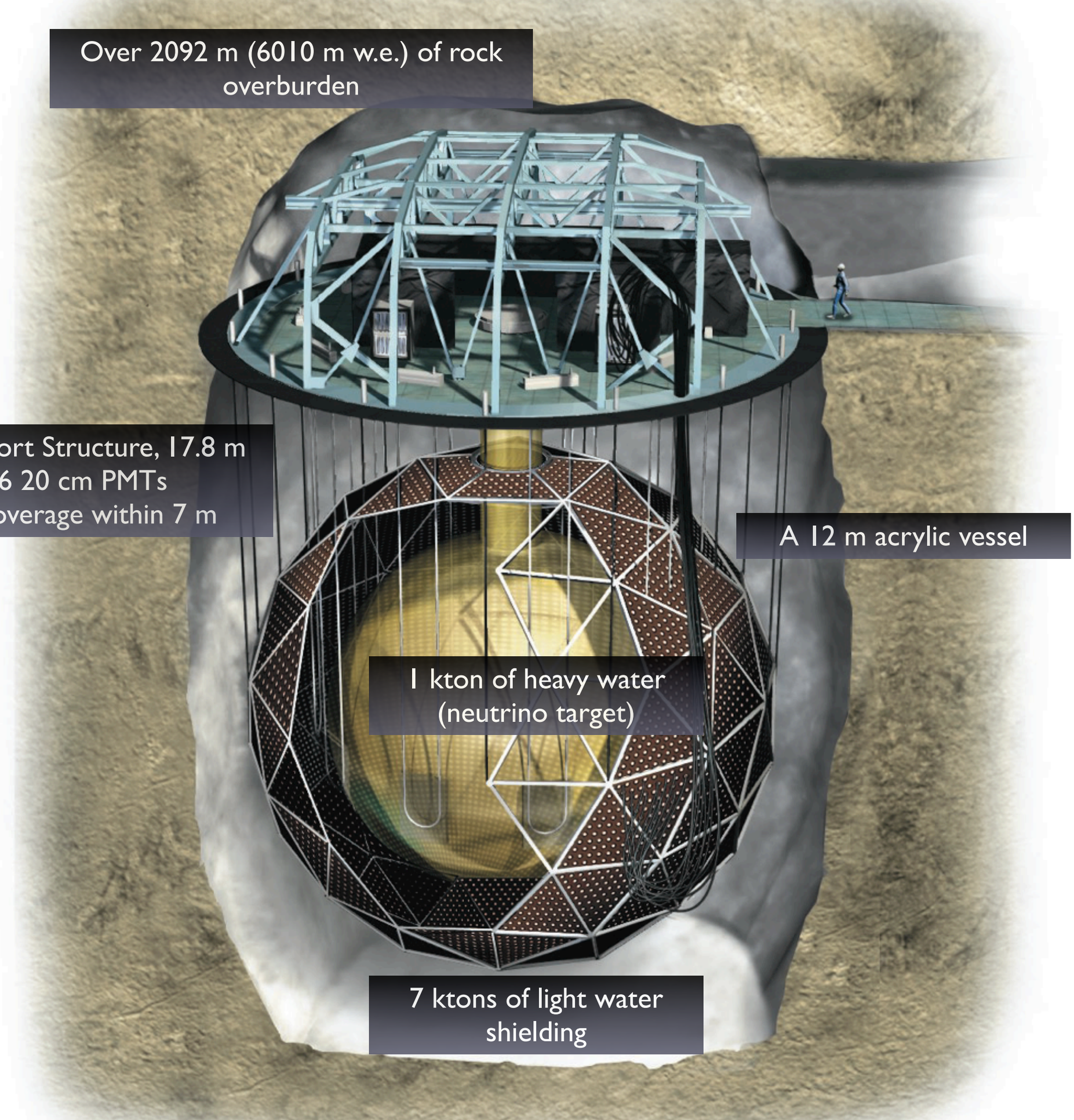

SNO during Construction

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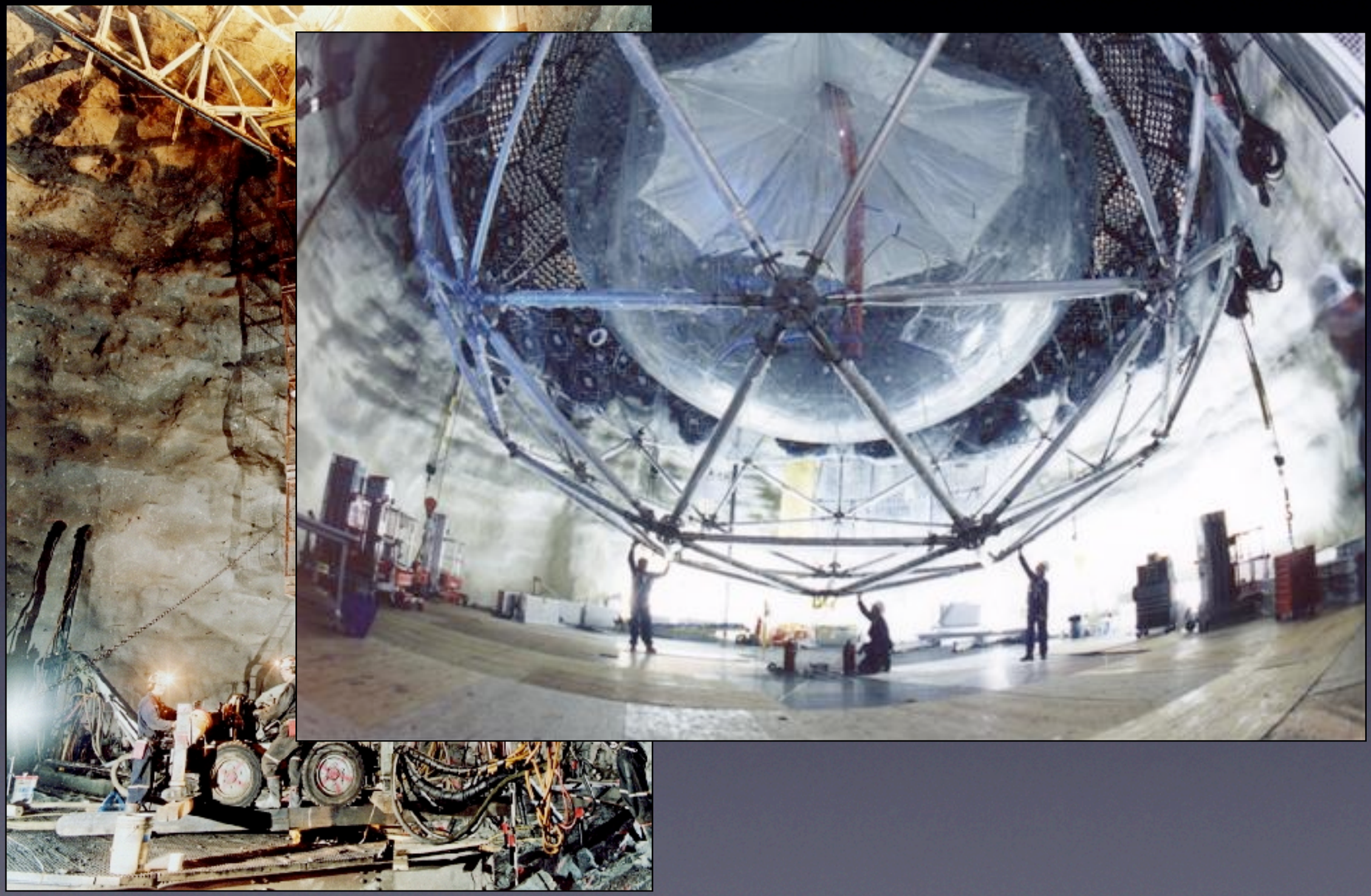

SNO during Construction

Different Channels
Same Experiment

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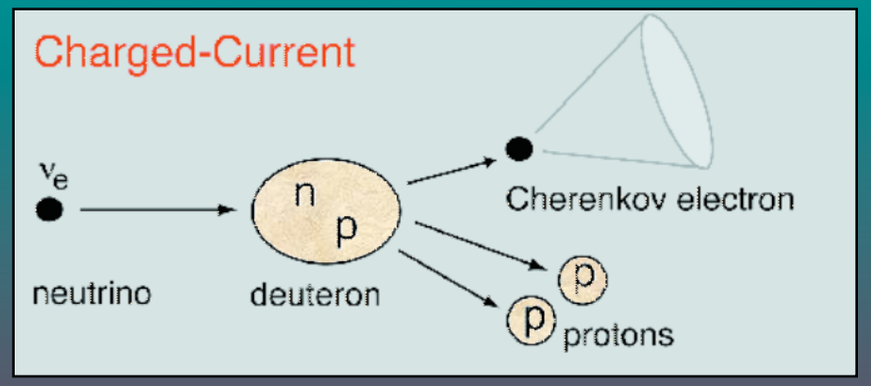
Same Experiment

The Charged Current (CC) Interaction:

Signature: Cerenkov ring from ejected electron

Sensitive to ν_e flux only.



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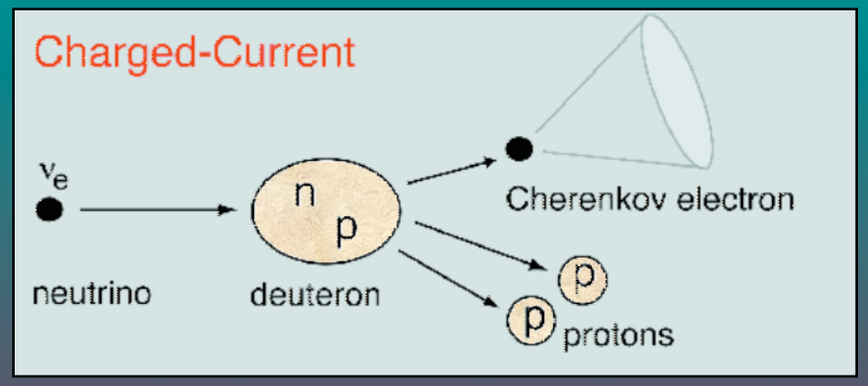
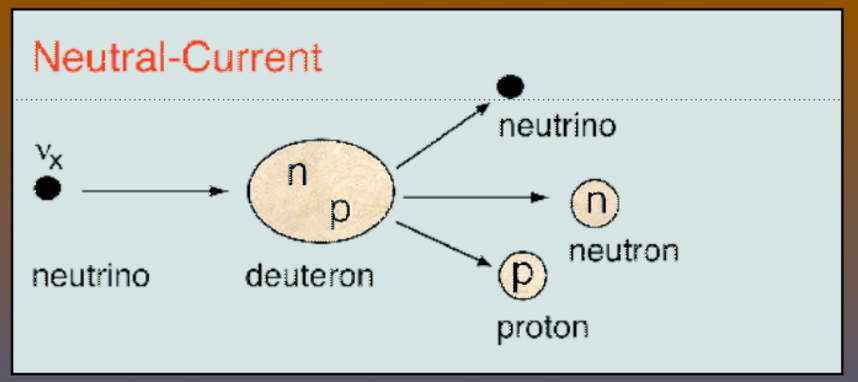


The Neutral Current (NC) Interaction:

Signature: Neutron emitted from deuterium break-up

Sensitive to ν_e,ν_μ, and ν_τ flux.



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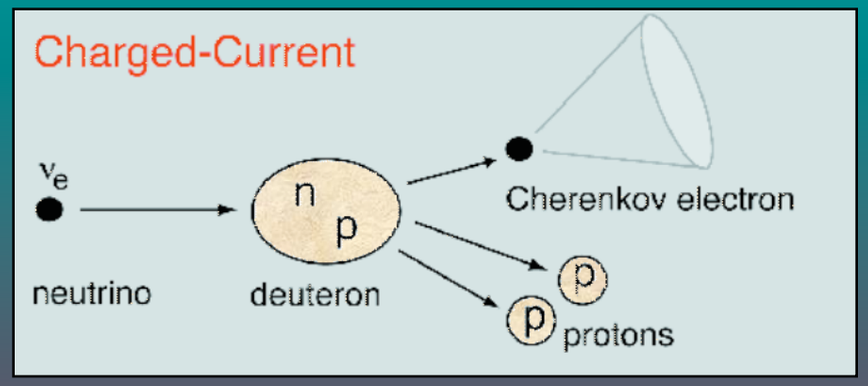

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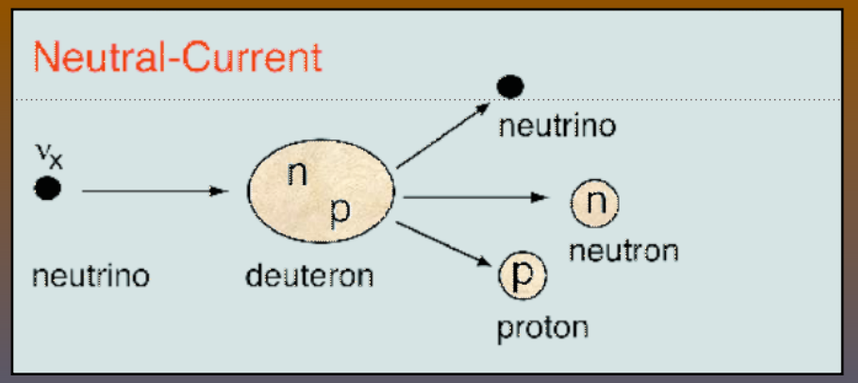
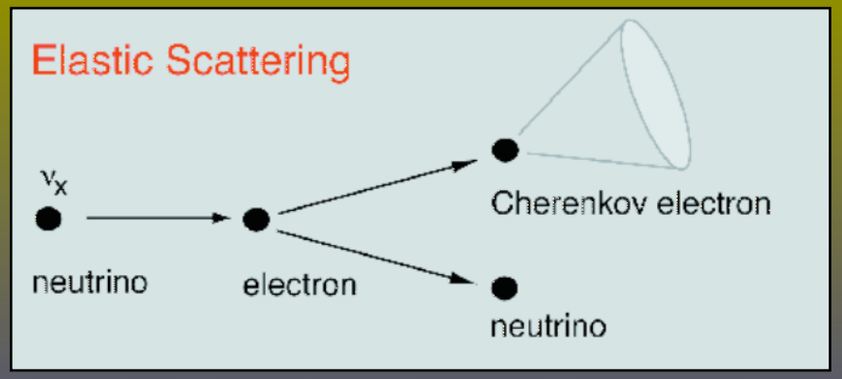


The Elastic Scattering (ES) Interaction:

Signature: Electron with high directional correlation to the sun

Sensitive mainly to ν_e . Some sensitivity to ν_μ, and ν_τ.



The Essence of the Measurement...

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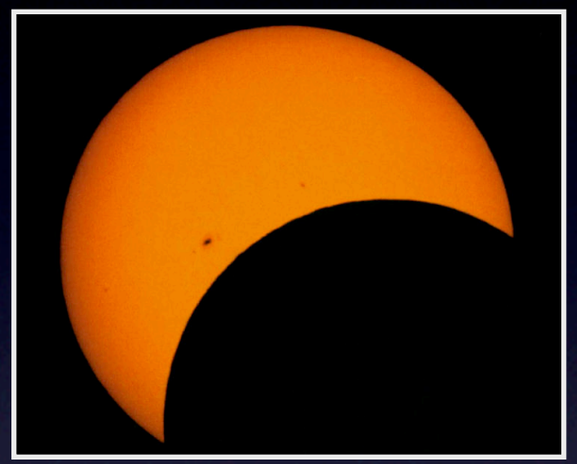

If one looks only
at electron neutrinos, only 1/3 are
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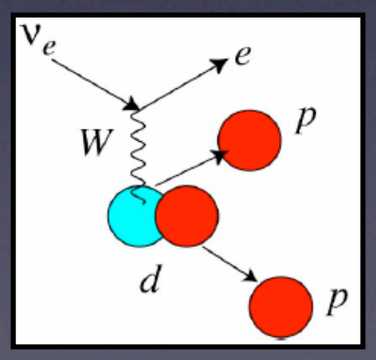
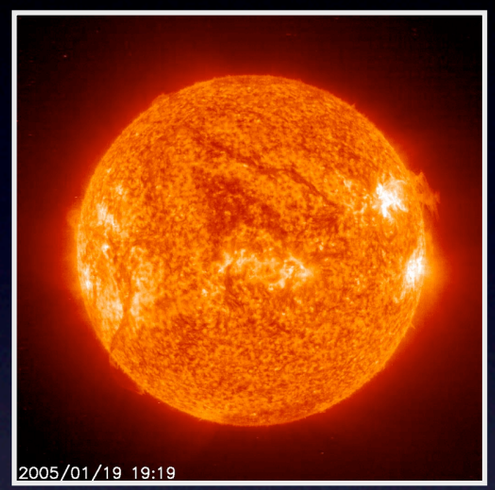


Charged Current

The Essence of the Measurement...



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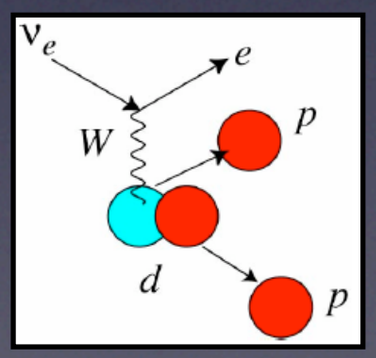
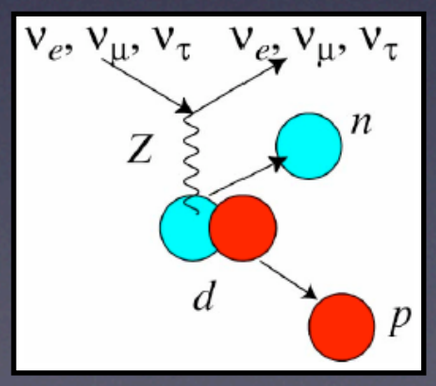


Charged Current

However, if one looks at all neutrino flavors, we see the number expected



Neutral Current

The Essence of the Measurement...

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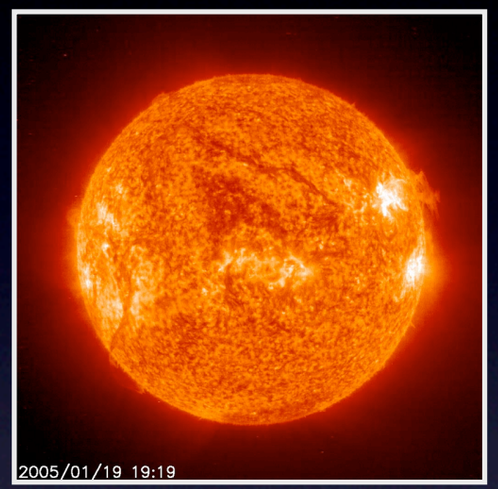

= Oscillations

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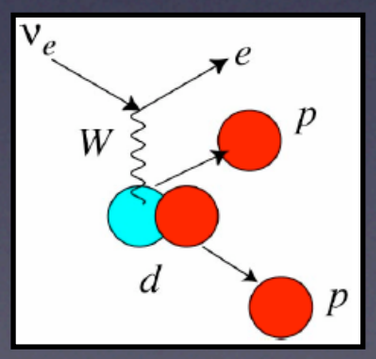

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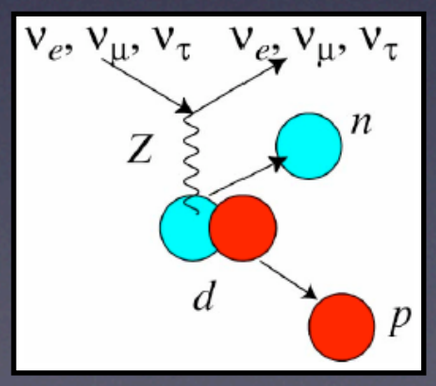

Neutral Current

The Three Phases of SNO...

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D_2O

NC sensitivity

Capture on deuterium
Run from 1999–2001
(304 live days)

$n + {}^2H \rightarrow {}^3H + \gamma$

Separate electron and neutron (photon) using energy, position, and direction.

The Three Phases of SNO...

D_2O

NC sensitivity

Capture on deuterium
Run from 1999–2001
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$n + {}^2H \rightarrow {}^3H + \gamma$

Separate electron and neutron (photon) using energy, position, and direction.

Salt

Enhanced
NC sensitivity

Capture on salt
Run from 2001–2003
(391 live days)

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$

Separate electron and neutron (photons) using ring topology.

The Three Phases of SNO...

D_2O

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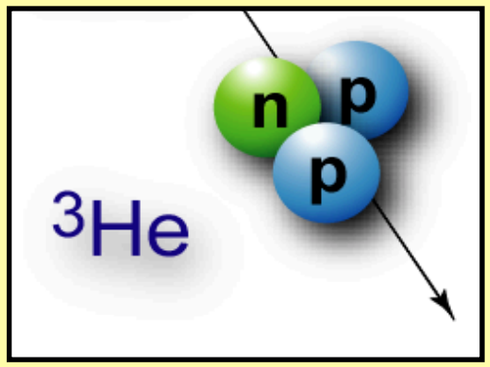
Separate electron and neutron (photons) using ring topology.

NCD

Neutral Current Detectors

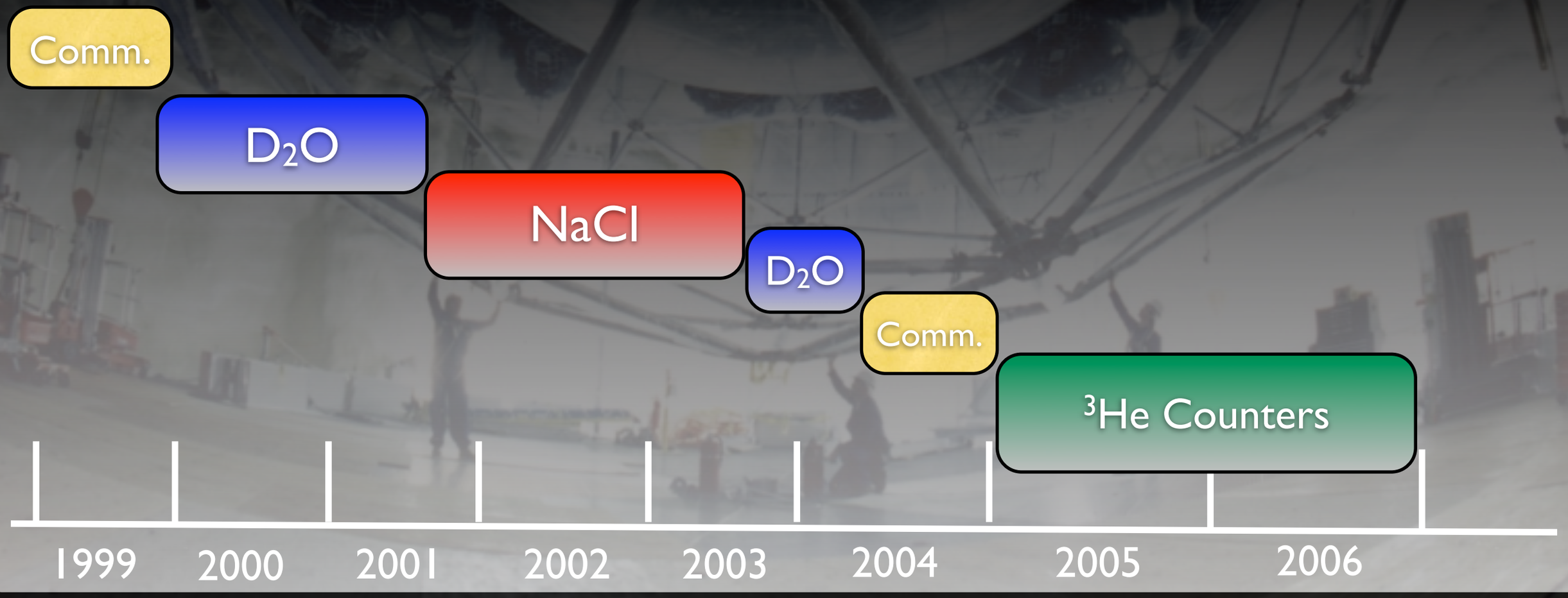
Capture on neutron counters
Run from 2004–2007
(385 live days)

$n + {}^3He \rightarrow {}^3H + p$



Measure NC rate with entirely *different* detection systems

The Three Phases of SNO...



The Why?...

The Why?...

It is natural to consider the
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The critics...

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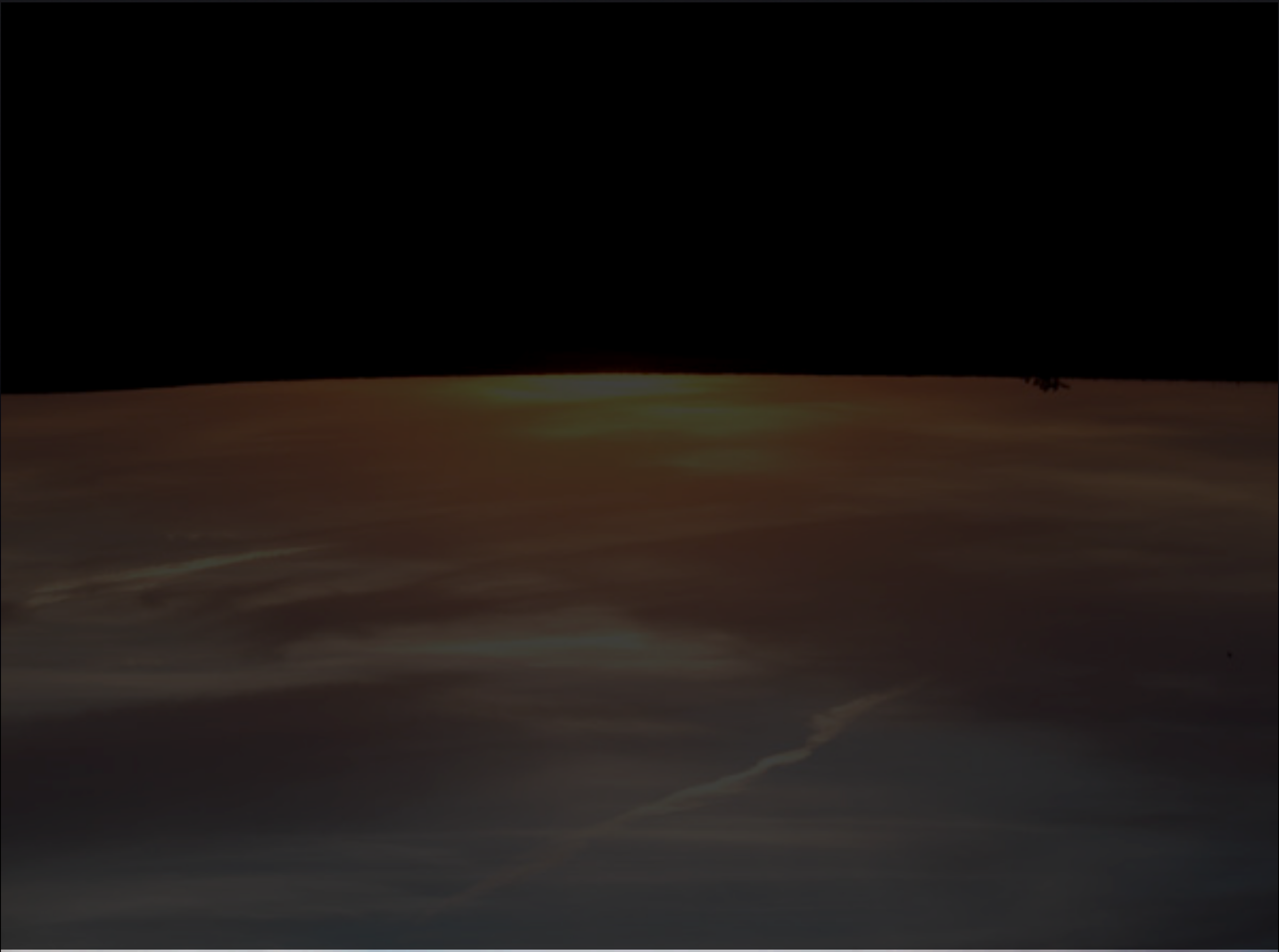
Bottom Line: We wanted to be as certain as possible



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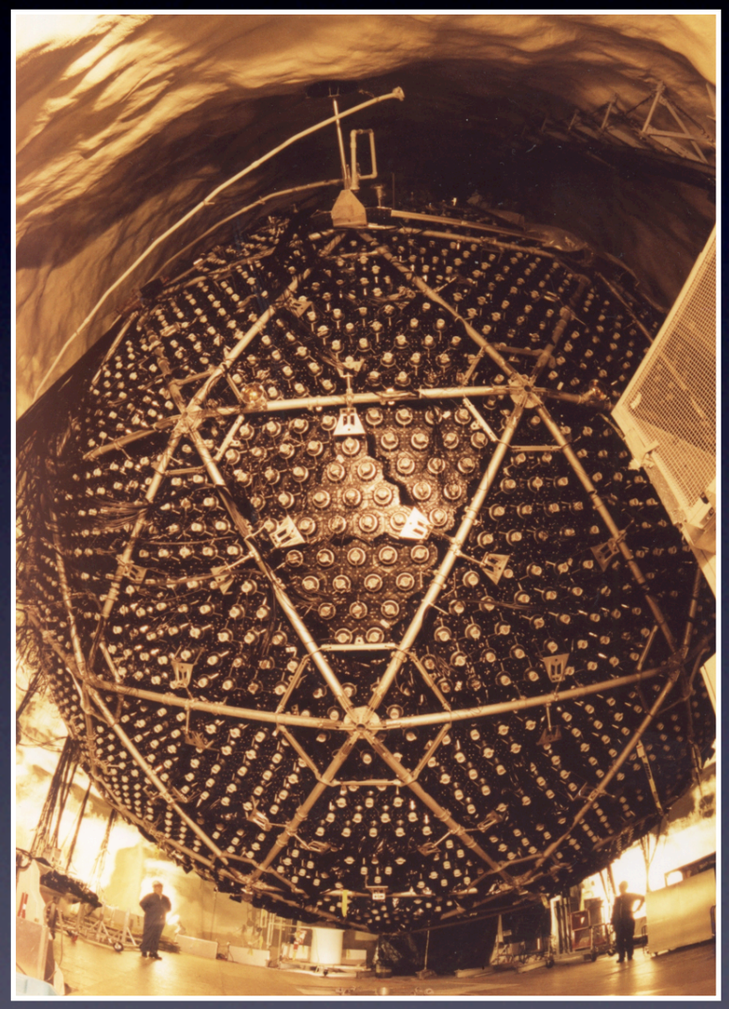
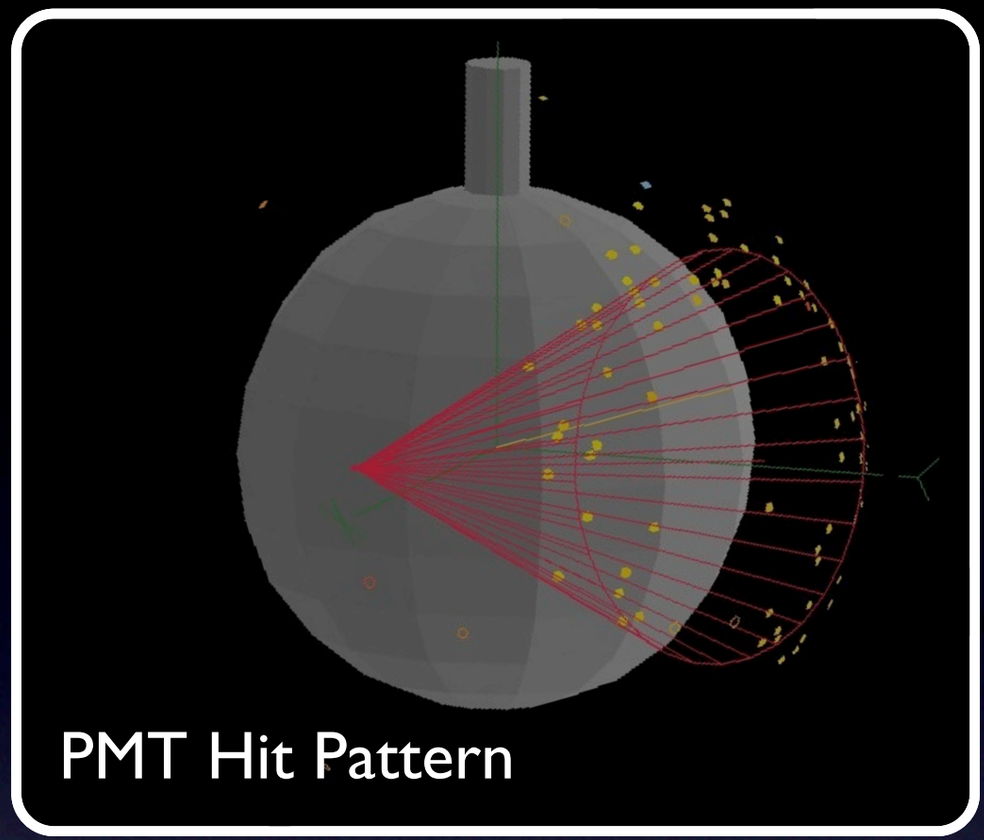
- You need to understand you background...
- You need to not fool yourself...

Understanding the detector

(the electron)



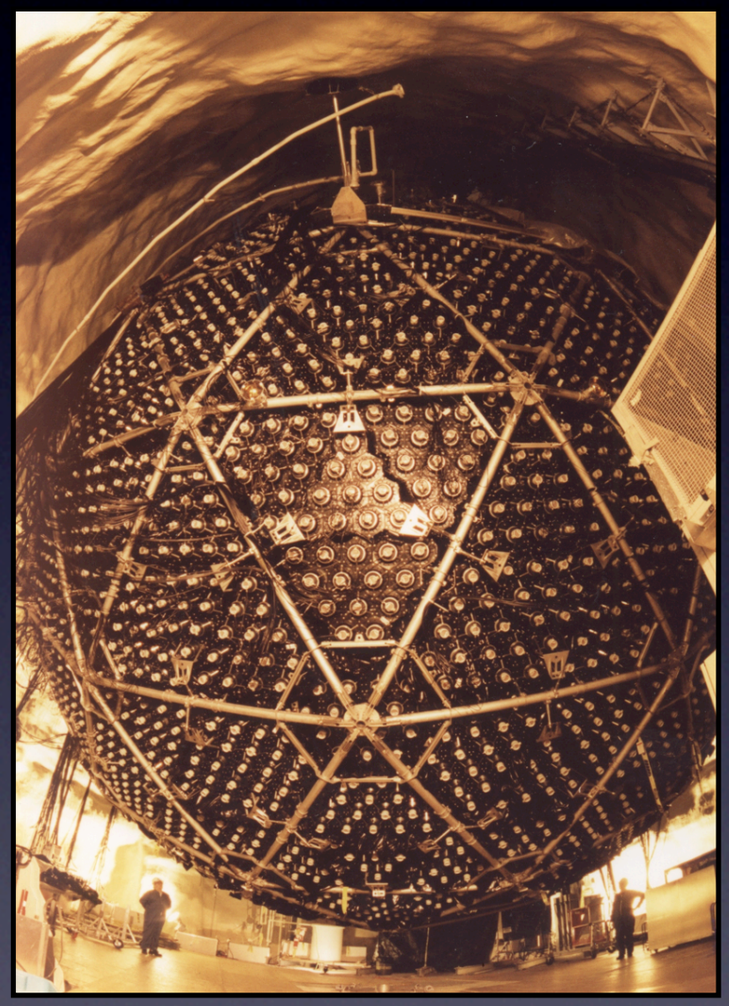
On the PMT side, reconstruction of electrons needed to extract charged current flux.



Electron Signature

- Cerenkov cone provides electron signature for charged current events.
- Light-collecting PMTs determine energy, direction and position of event.
- Light isotropy also used.

Reconstructing Events



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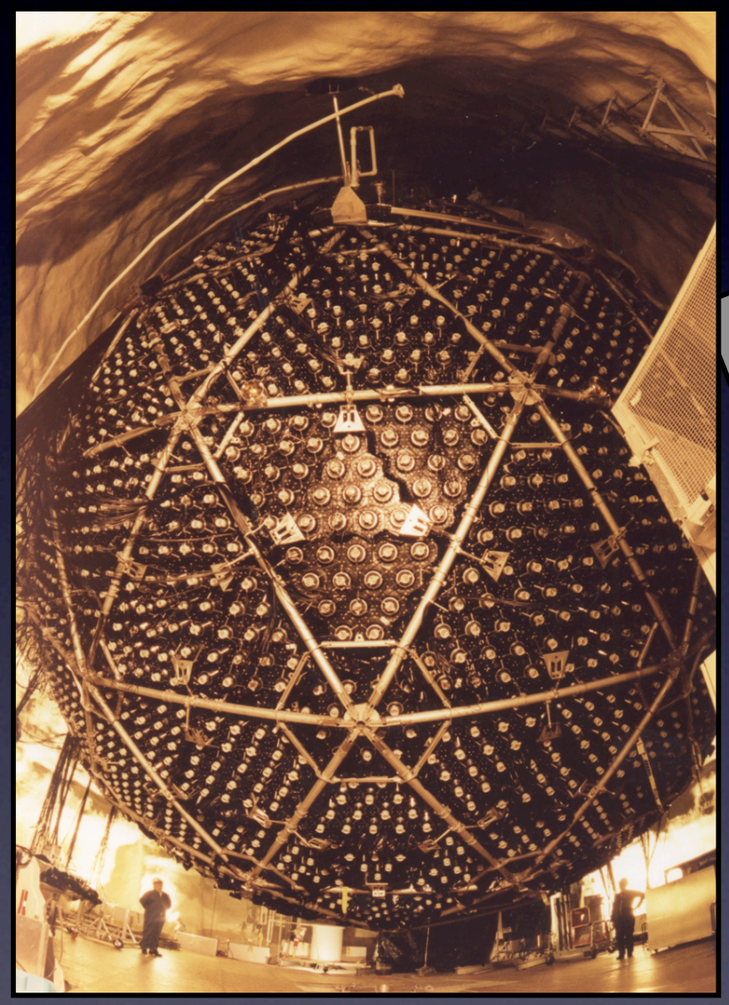

PMT hits, timing, & pattern

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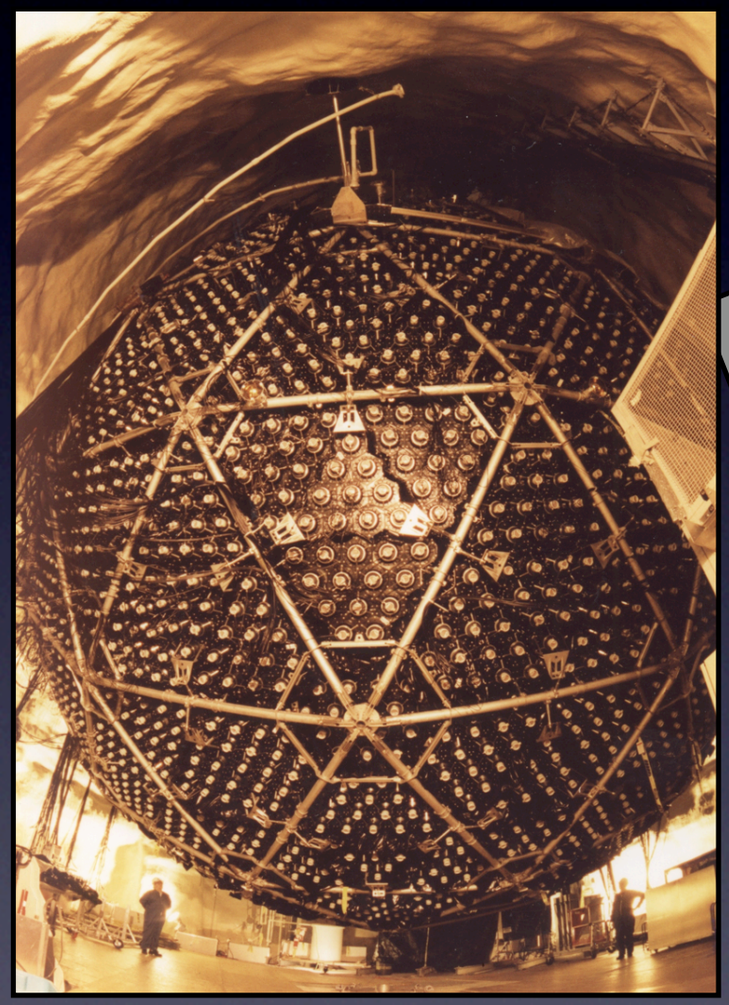
Reconstructing Events

Radius:

Flat for electron candidates, shaped for neutrons.



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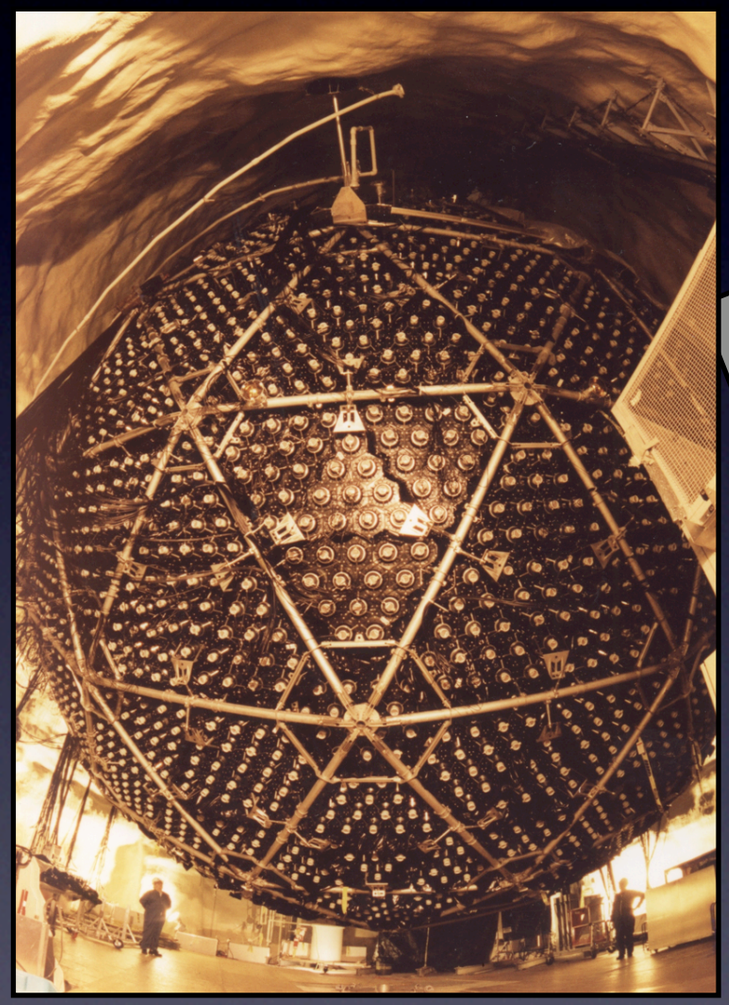

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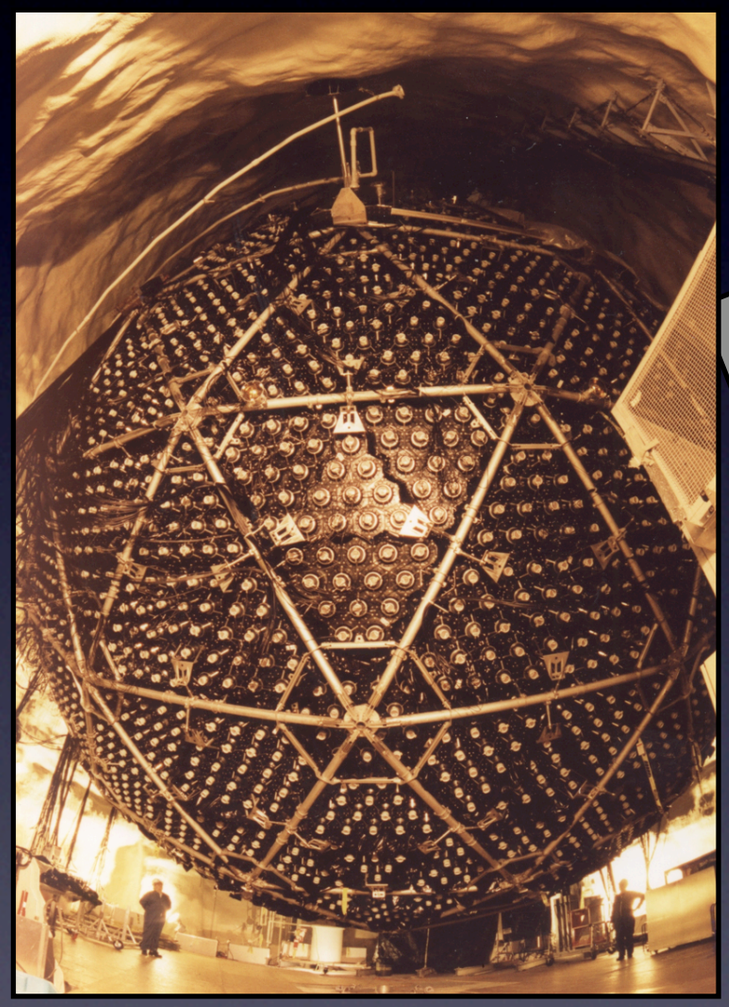

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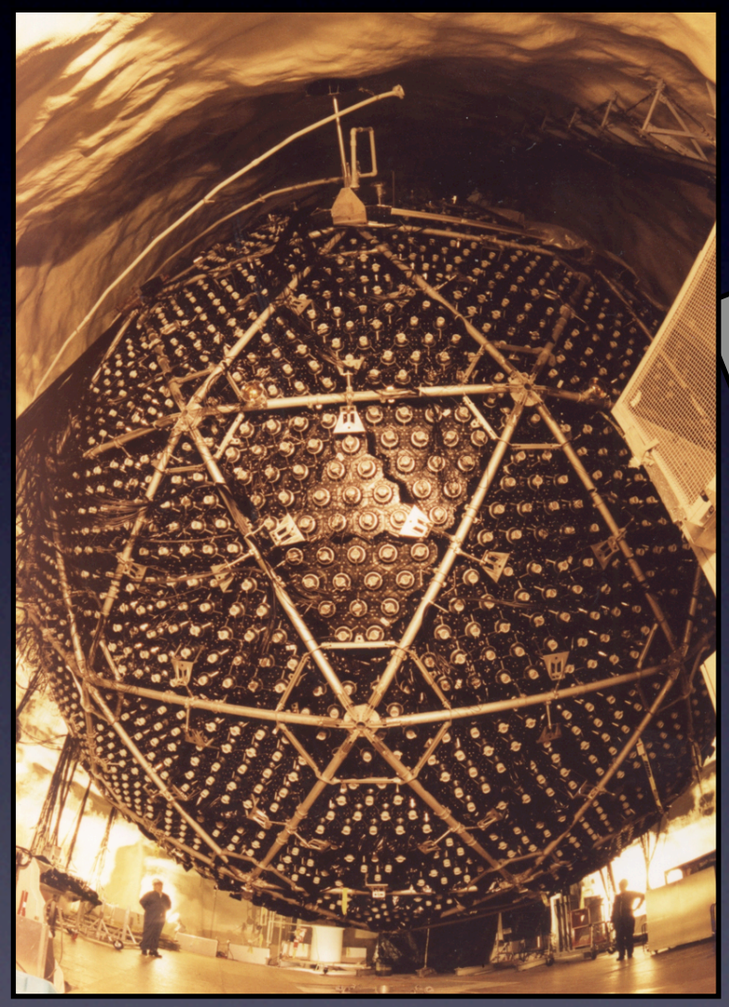

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also use...

Isotropy:

Helps separate signal from background

Understanding the detector

(the neutron)

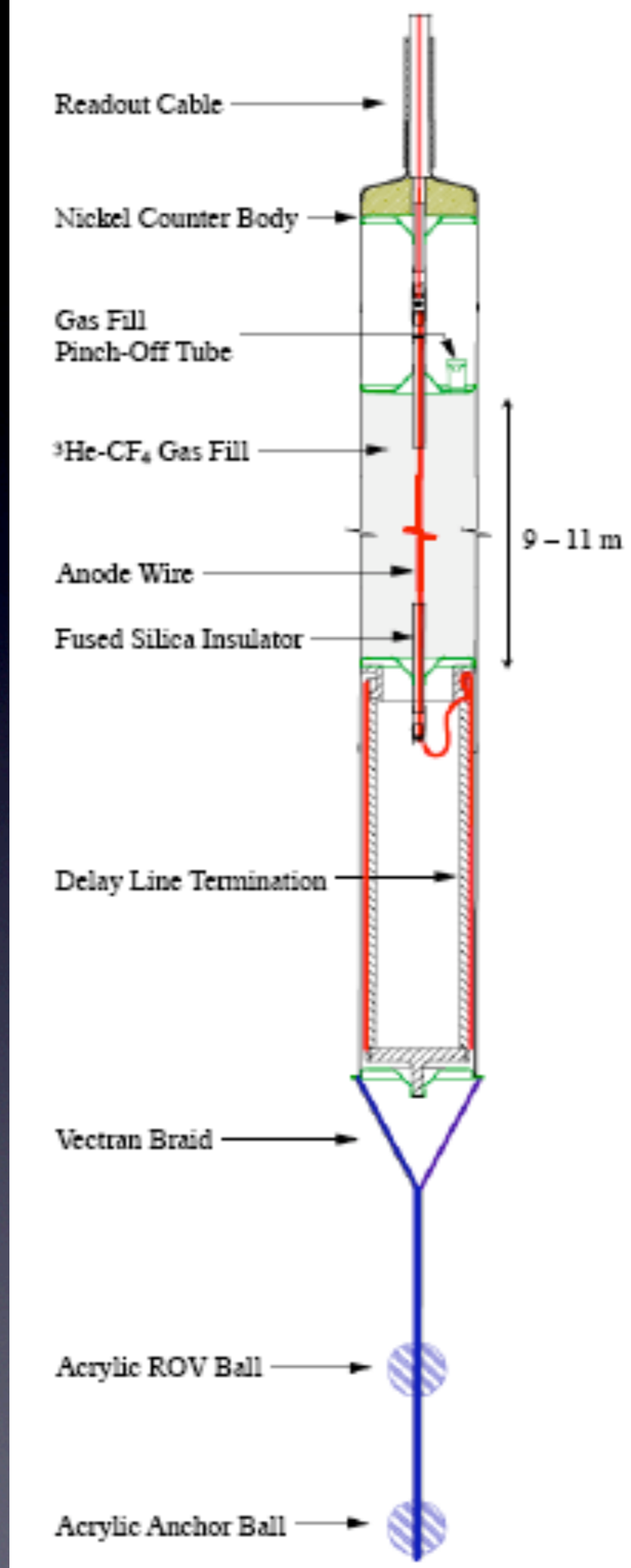
- Use ^{3}He proportional counters to capture and detect neutrons.

$$n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$$

- Nickel tubes filled with ^{3}He-CF_4 gas with single anode wire for signal detection.

- Record (part per trillion) cleanliness.

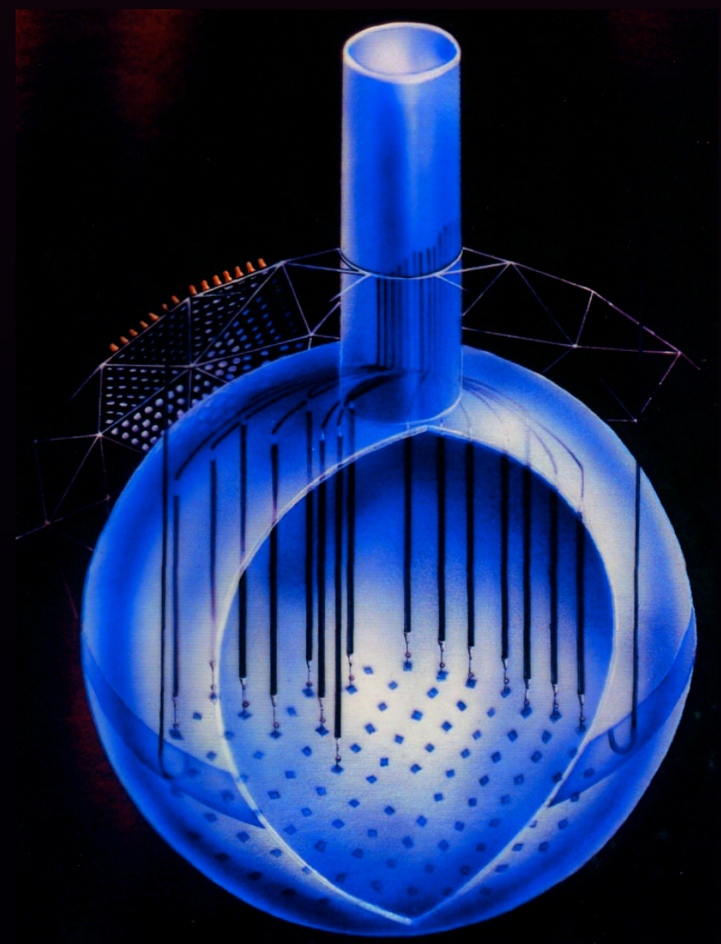
$$\mathrm{gTh/gNCD} = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$
$$\mathrm{gU/gNCD} = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$



Neutral Current String

The Array and its Deployment

Full array of 40 strings deployed in 2004 to measure neutron signal distinct from electron signal.



Array configuration

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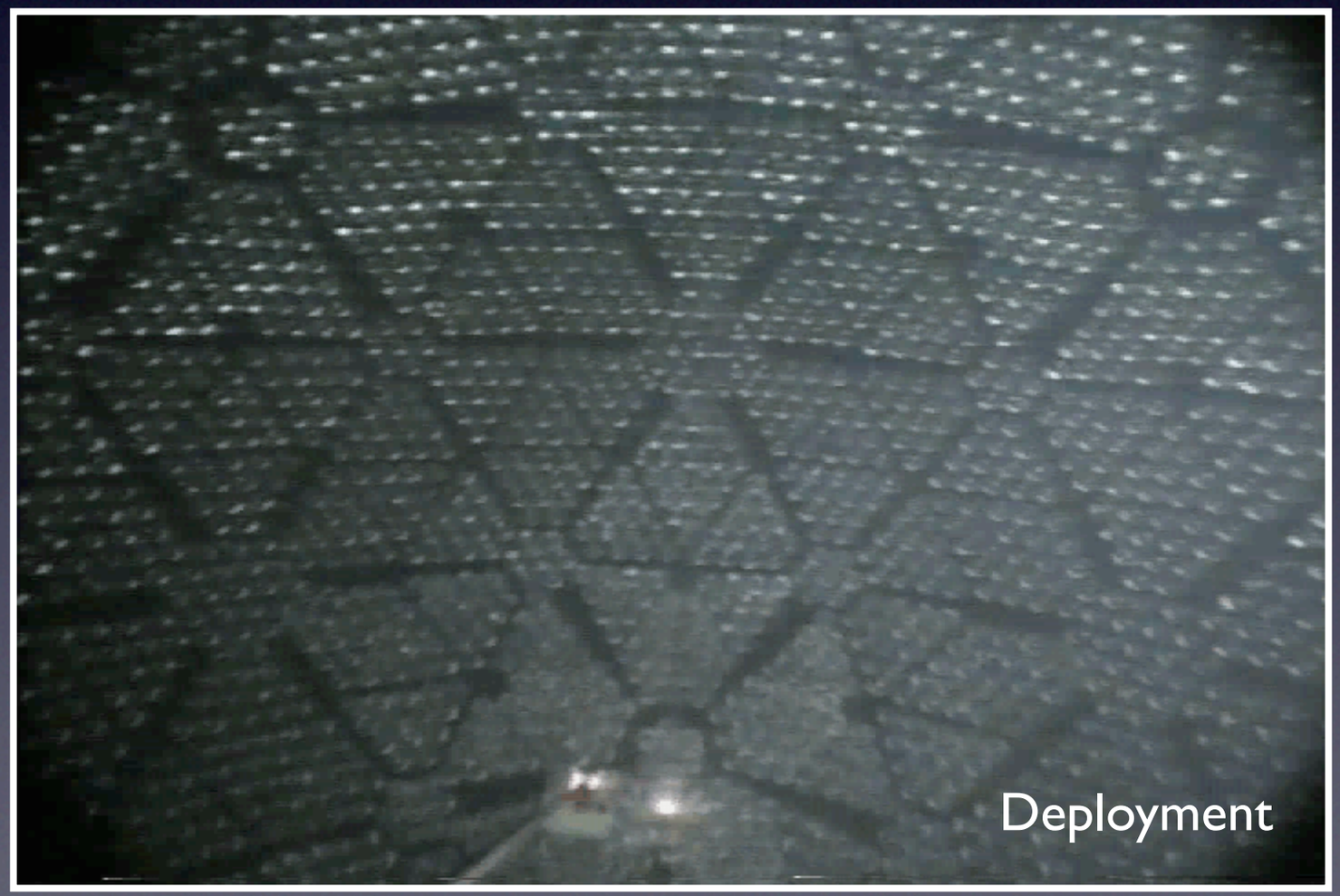

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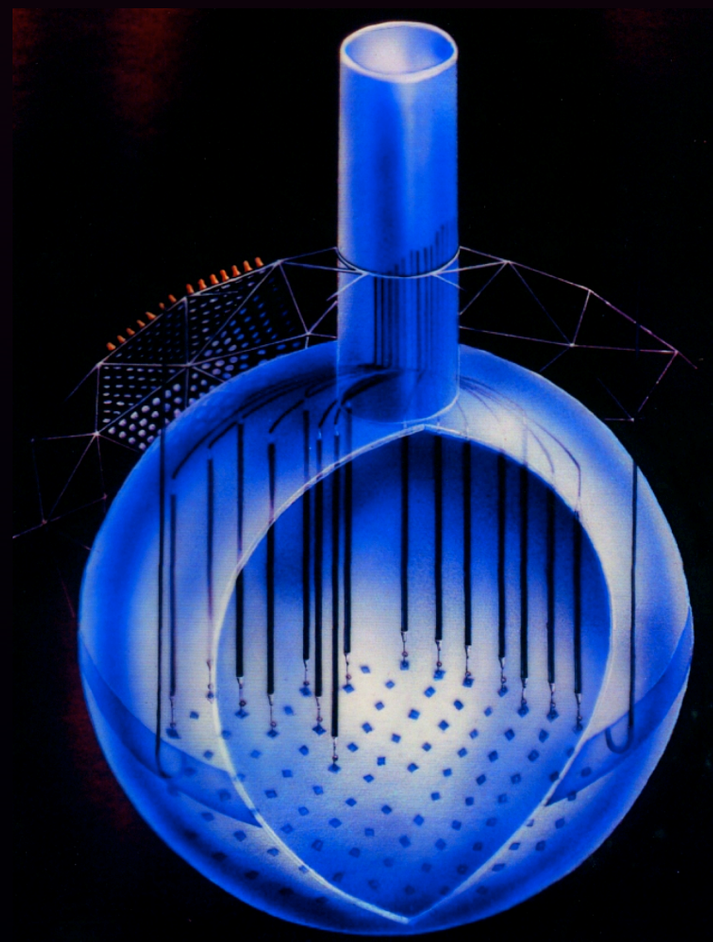

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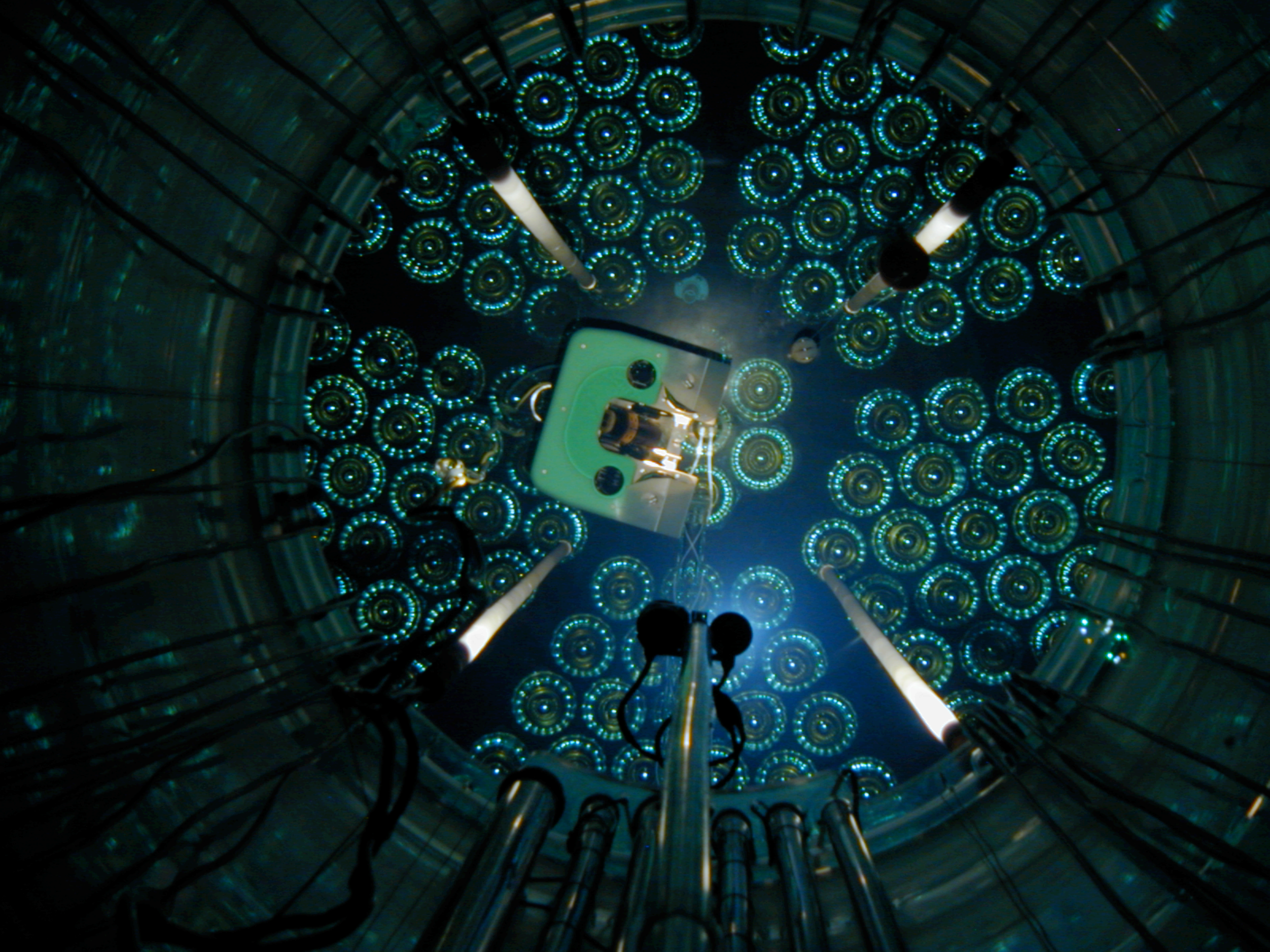


Understanding your signal...

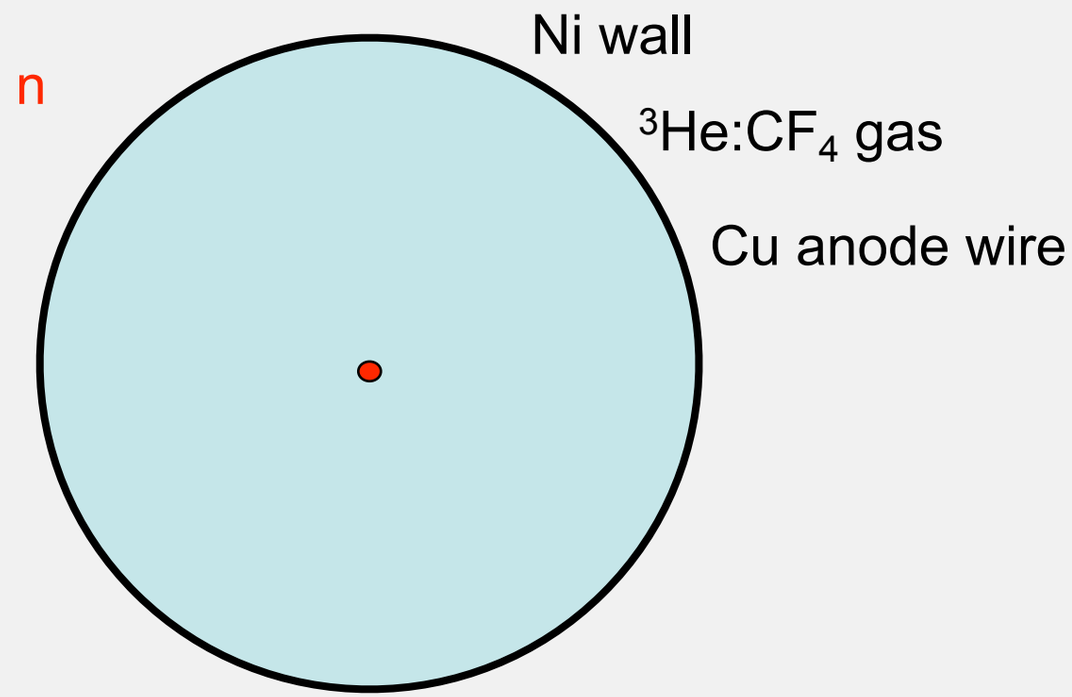
- Proportional counters look at neutron capture on helium for distinct signal.

$$n + {}^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H} + p$$

- Main peak stems from full energy deposition.

- Shoulders at 191 keV and 573 keV from triton or proton striking the nickel wall.

- Must also consider alpha energy deposition from walls, wire, and bulk (gas).



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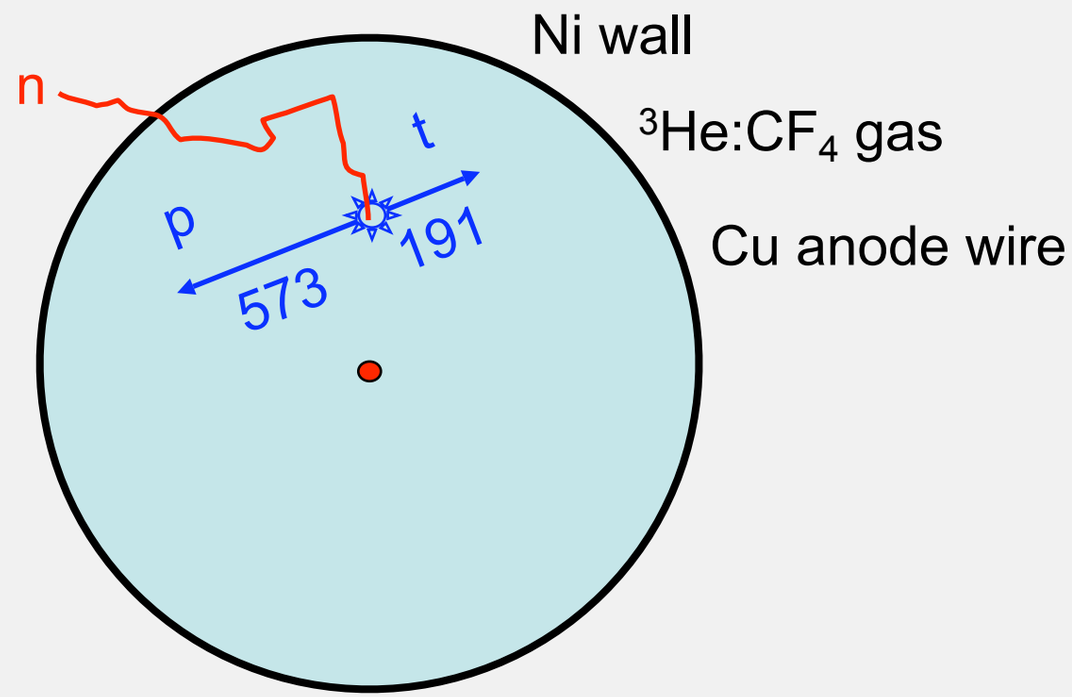

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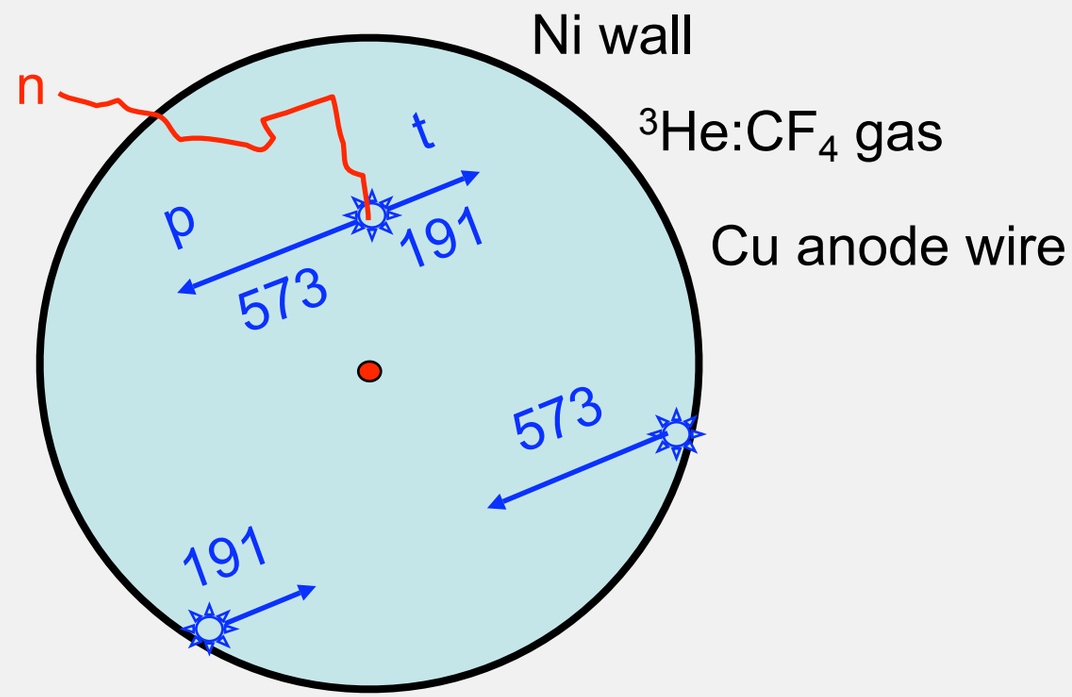

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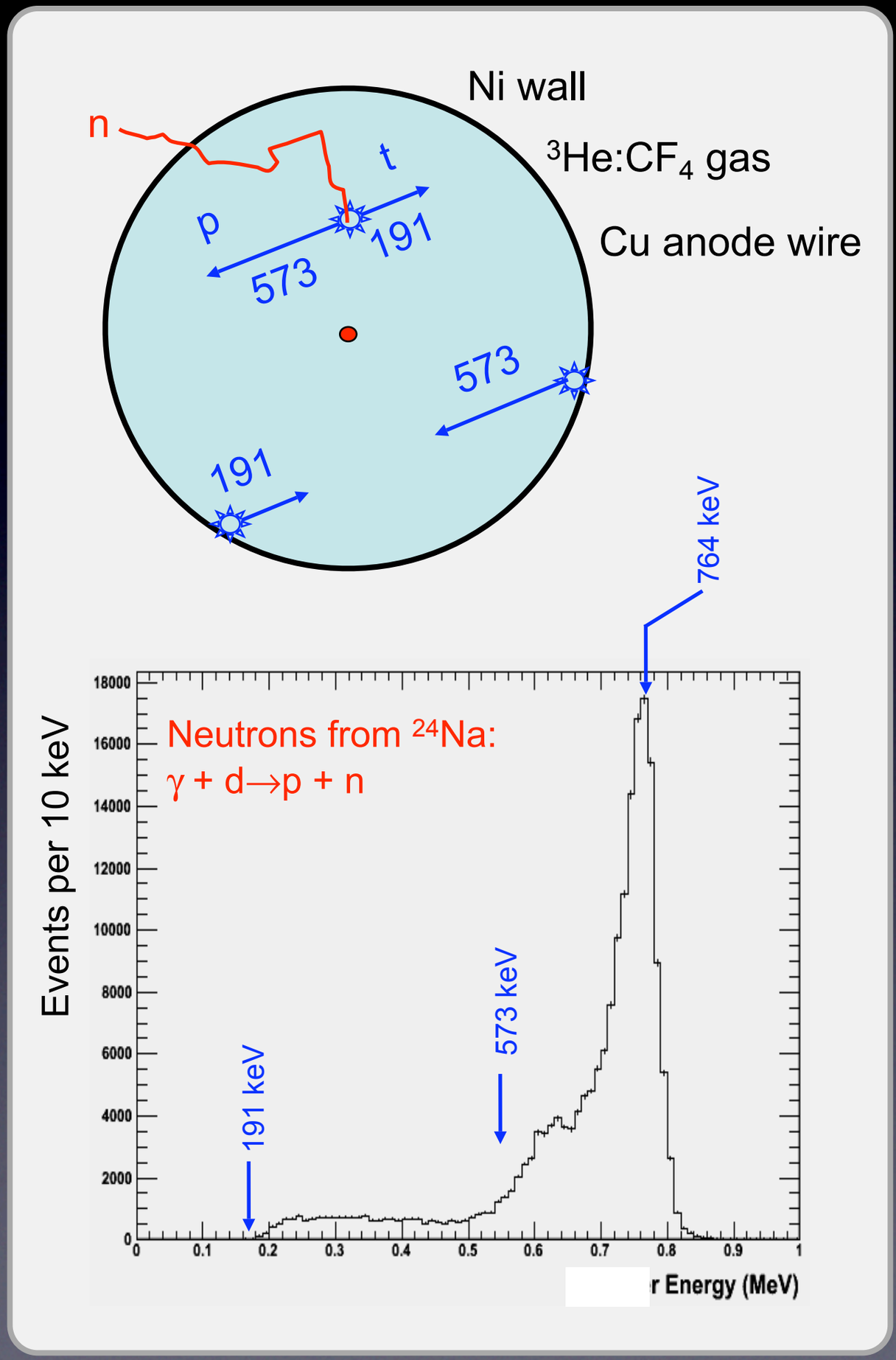
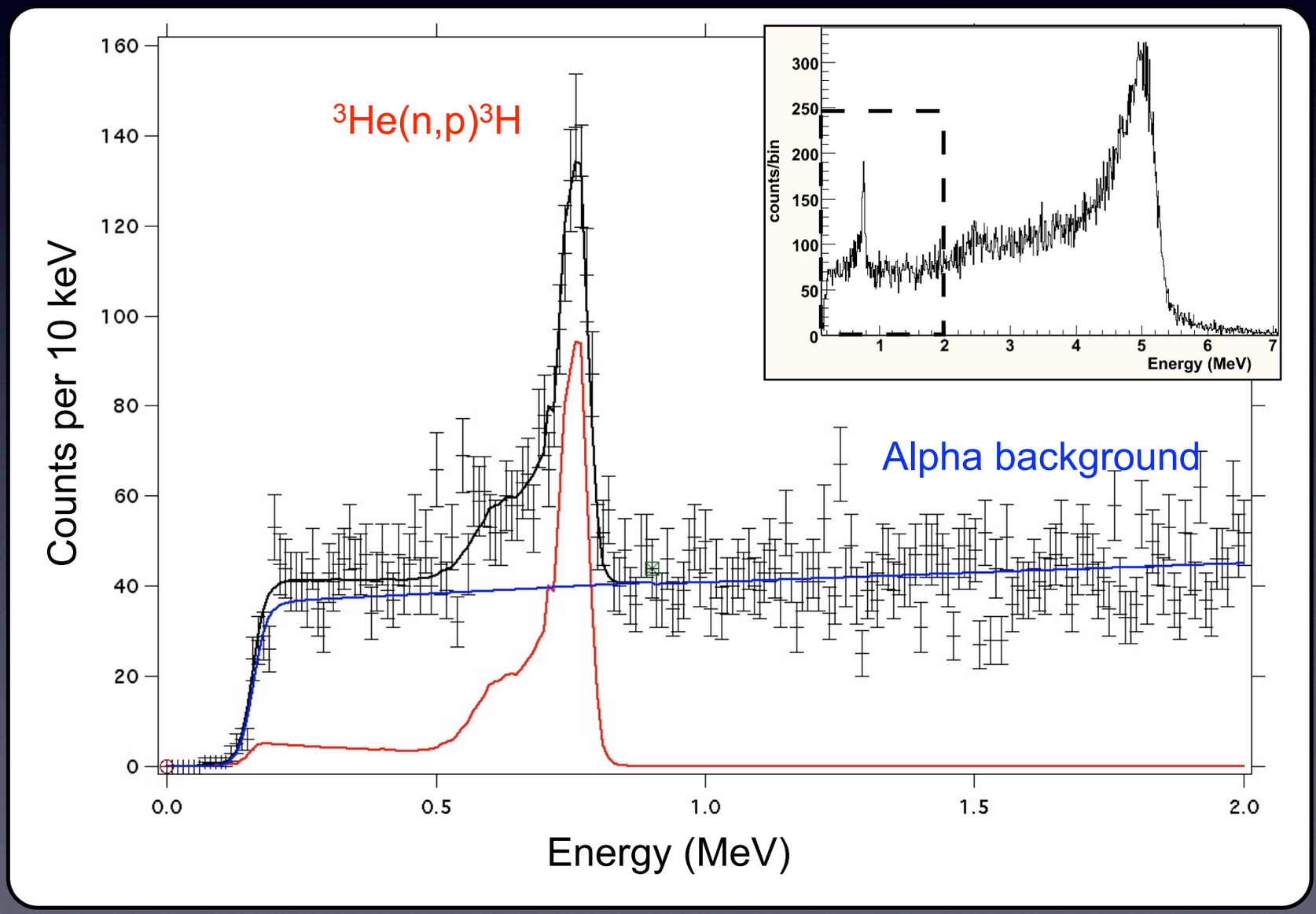


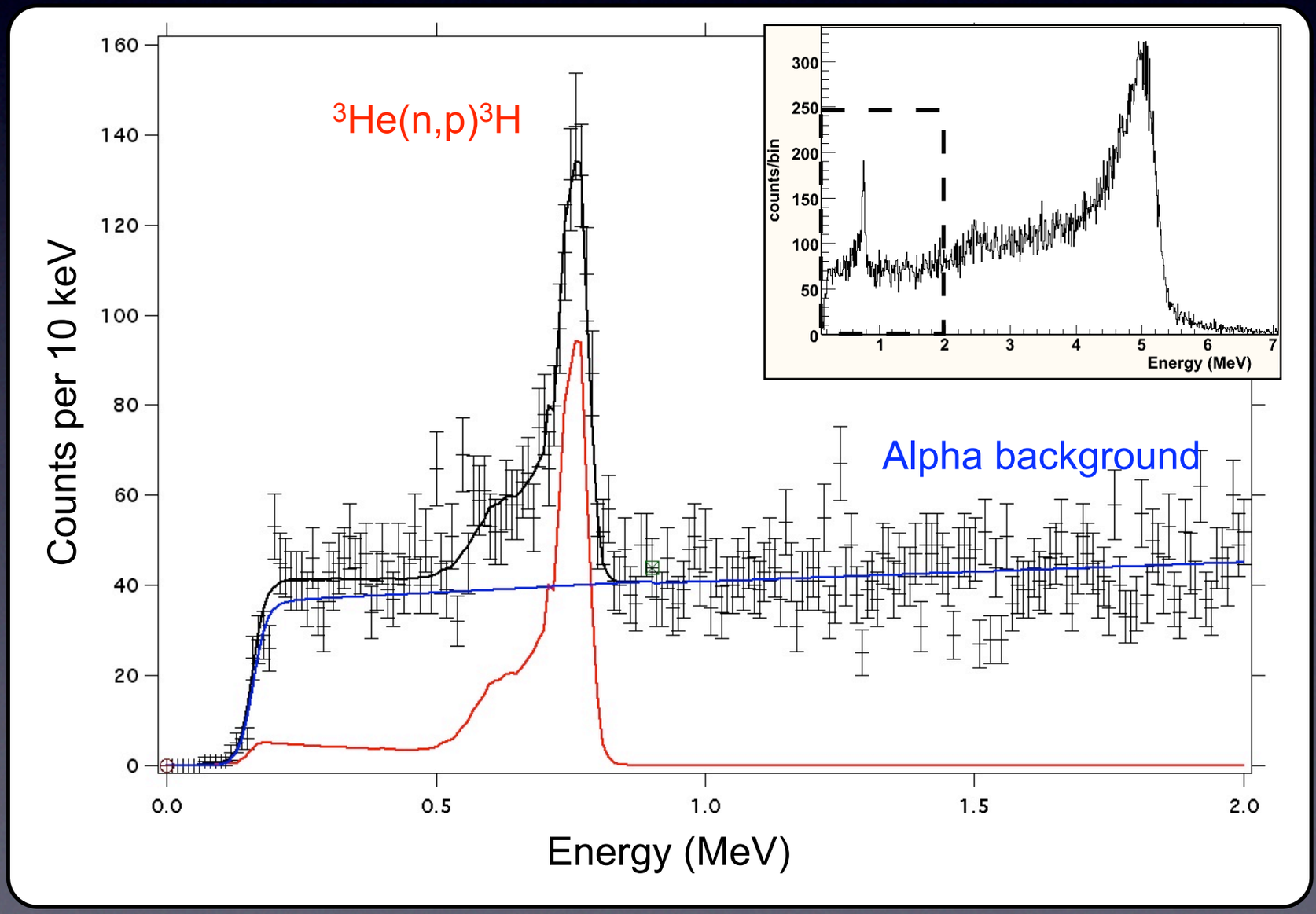
Neutrons & Alphas



Neutrons & Alphas

Neutron Signal:

- Use point and diffuse sources to extract absolute efficiency.
- Compare to Monte Carlo predictions.



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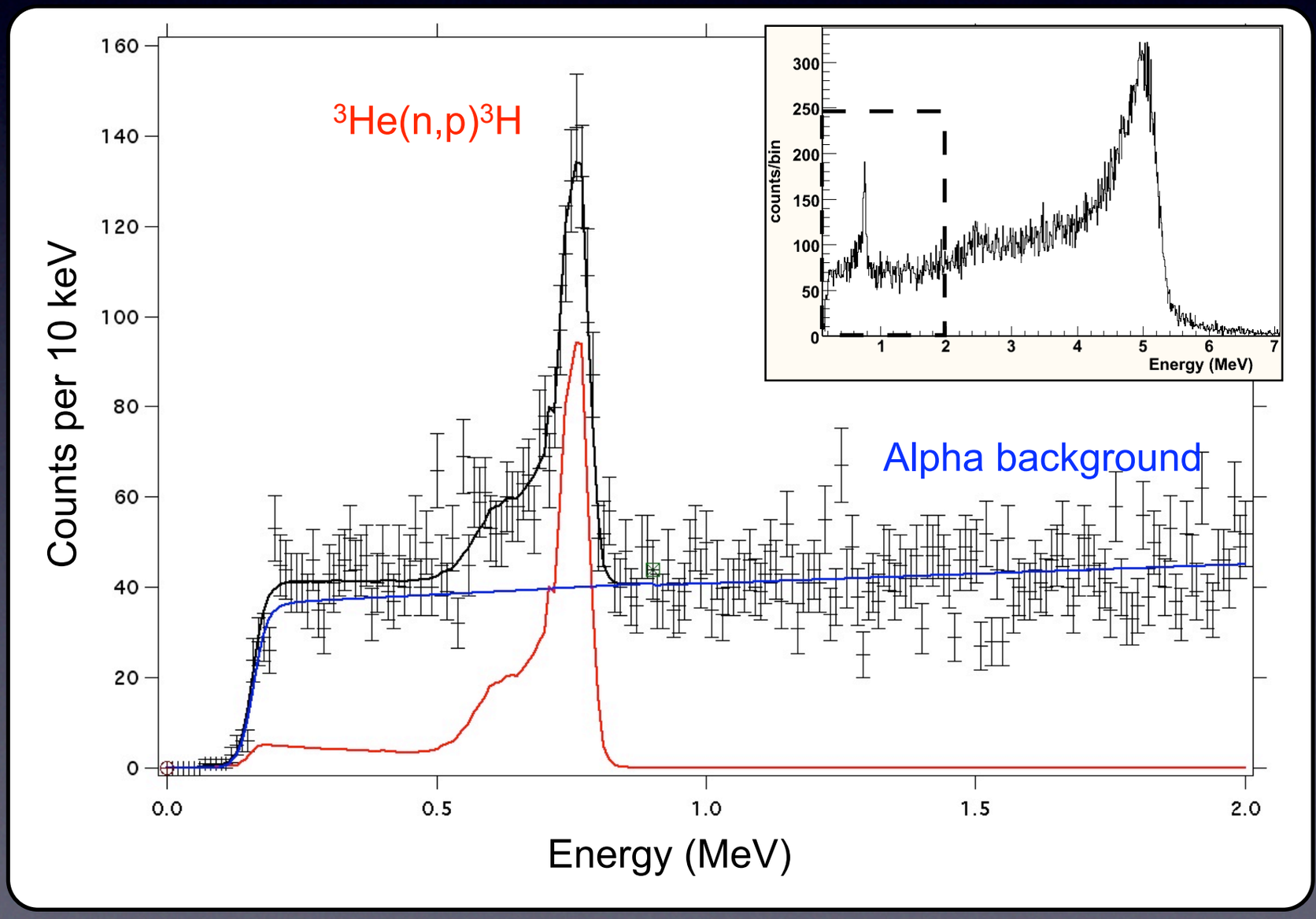
Alpha Contamination:

- Alphas from uranium and thorium chains provide a continuous background that contaminates the neutron energy window.
- Use Monte Carlo, pulse shape, and test counters to help constrain backgrounds.



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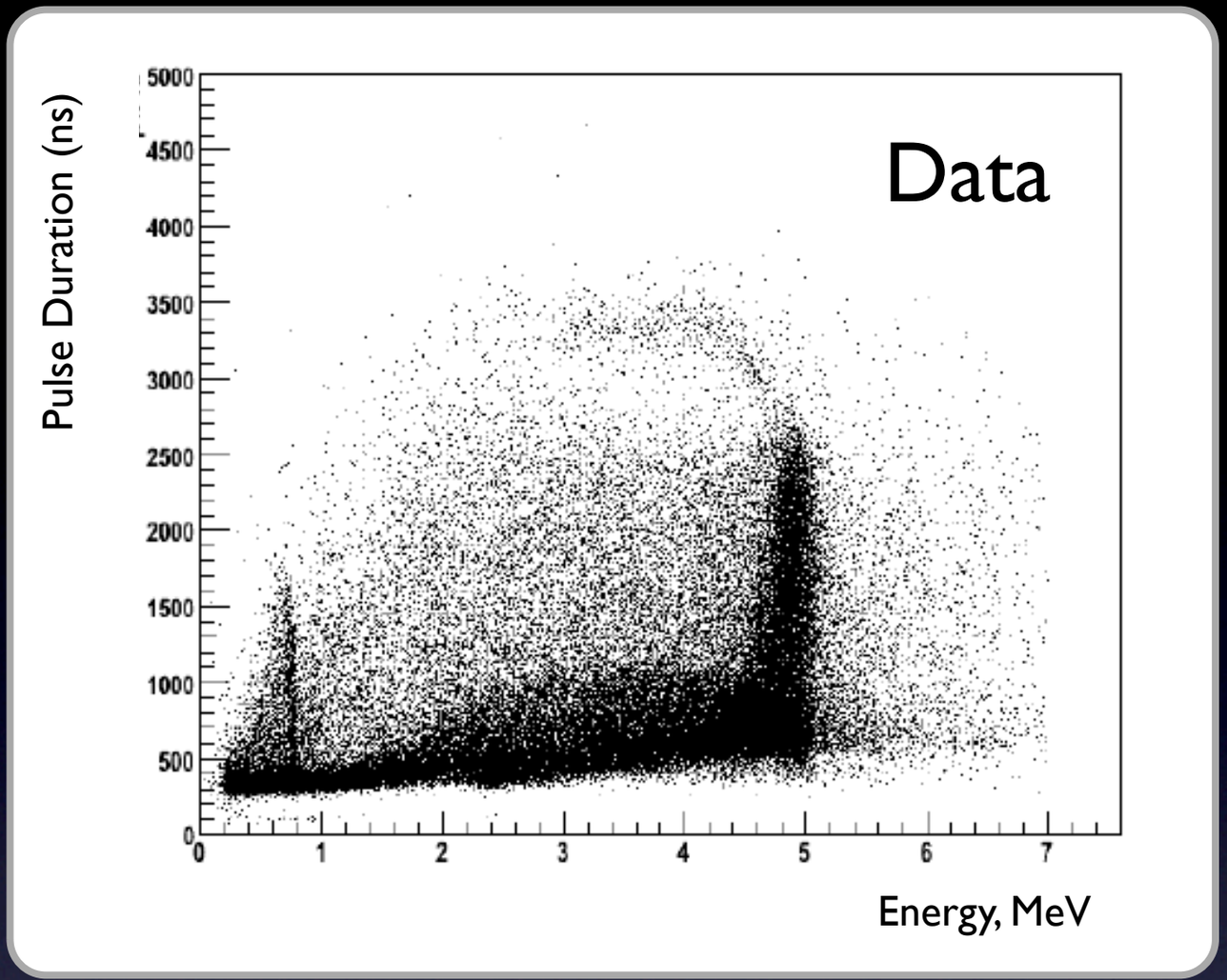

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neutron signal
surface polonium decay
bulk U and Th decay
wire polonium decay
wire bulk decay
insulator polonium decay
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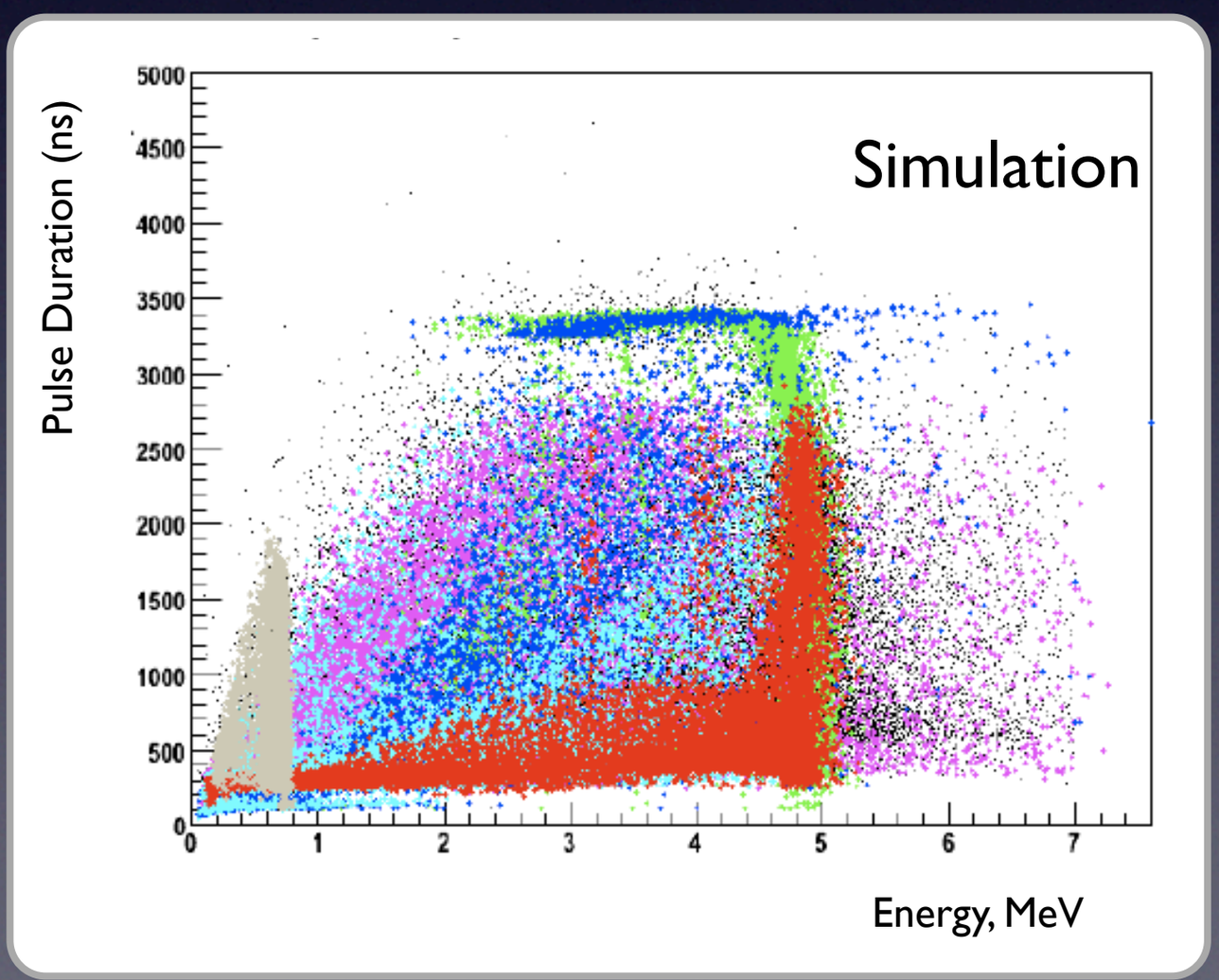

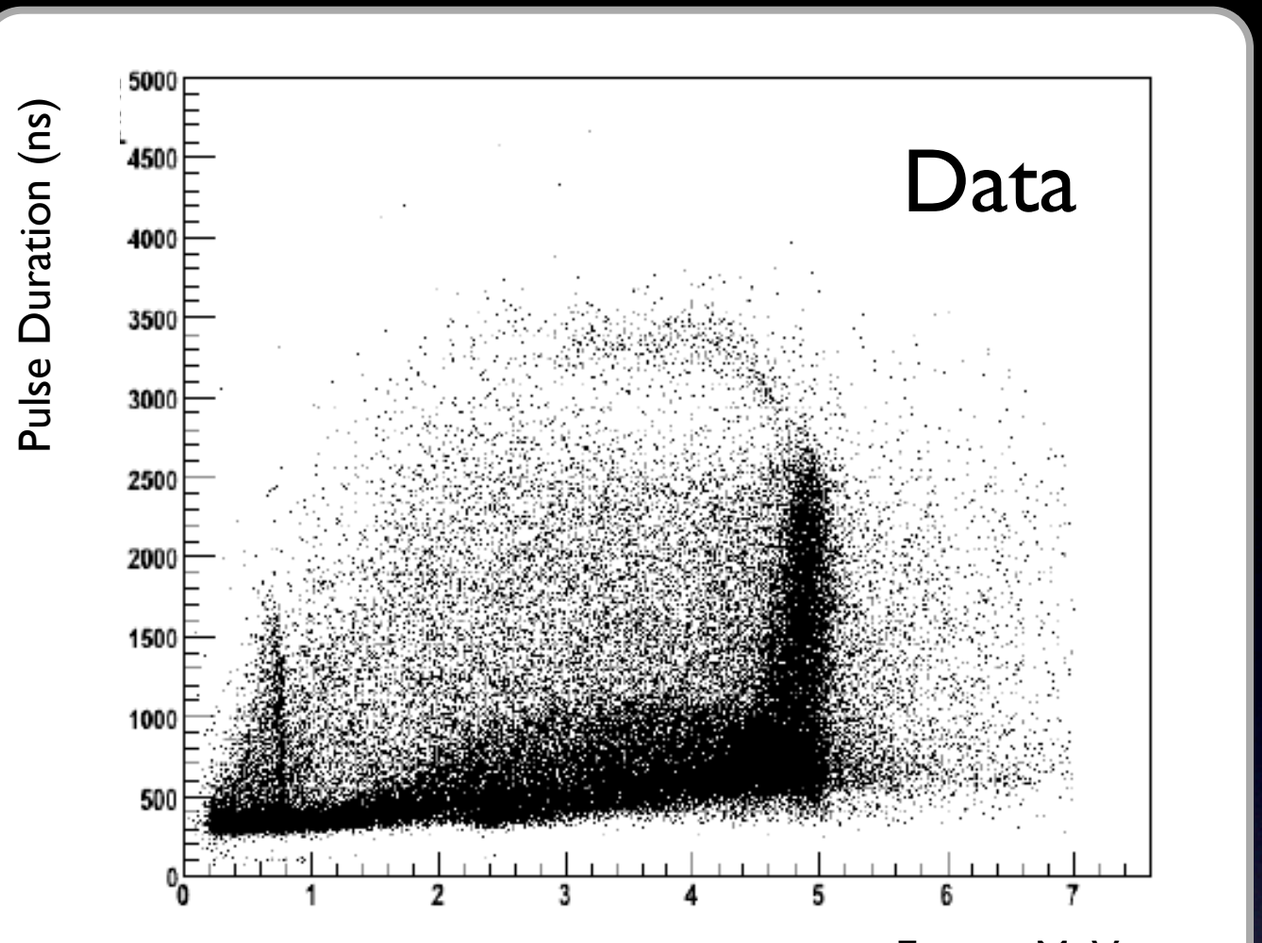

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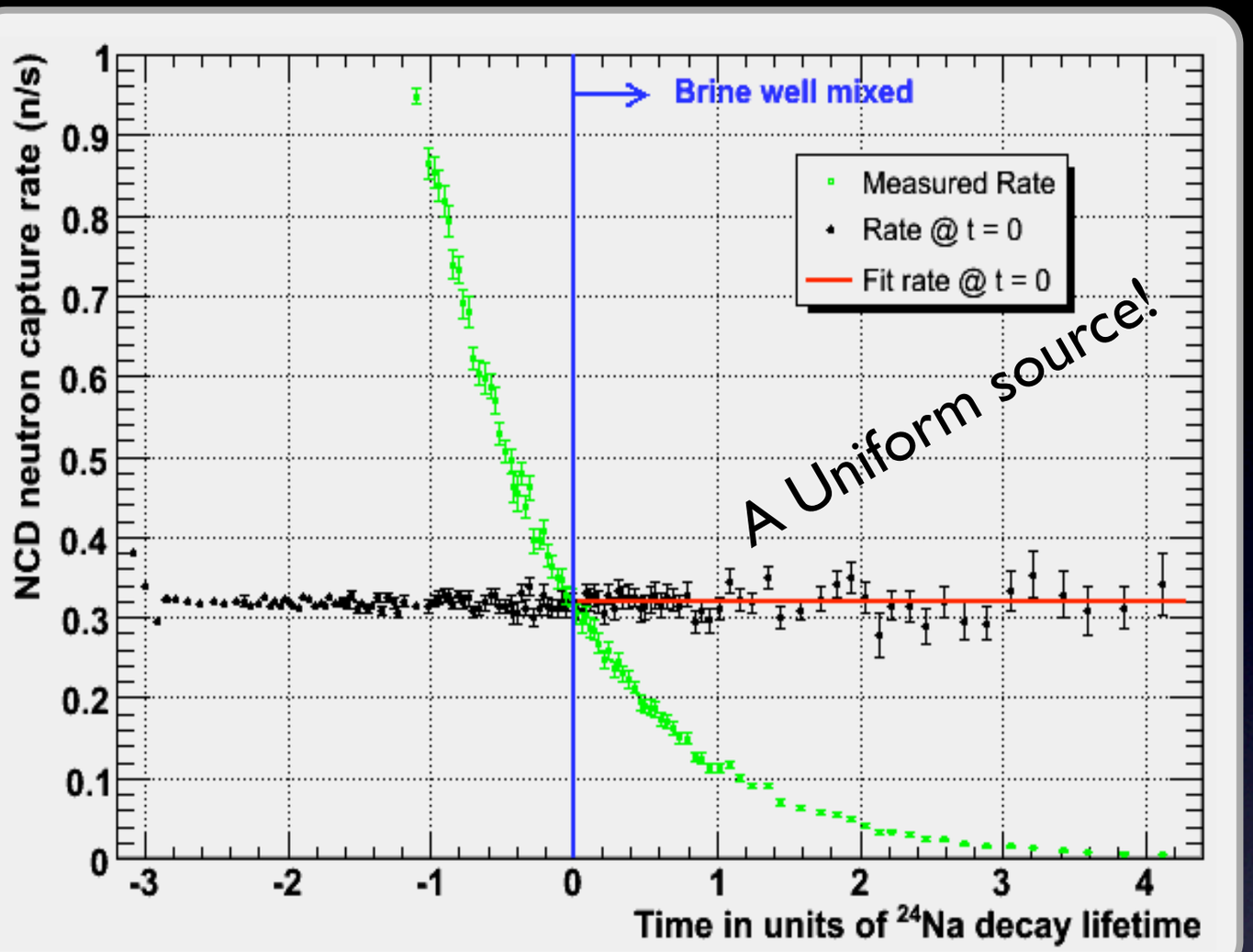
Uniform Neutron Source

- Ideal to also use a *uniform* neutron to determine absolute neutron efficiency.
- Use of two ^{24}Na spike injected via NaCl brine.
- Activated sodium allowed to mix; the 2.75-MeV photon break up deuteron, providing neutrons in D_2O volume.



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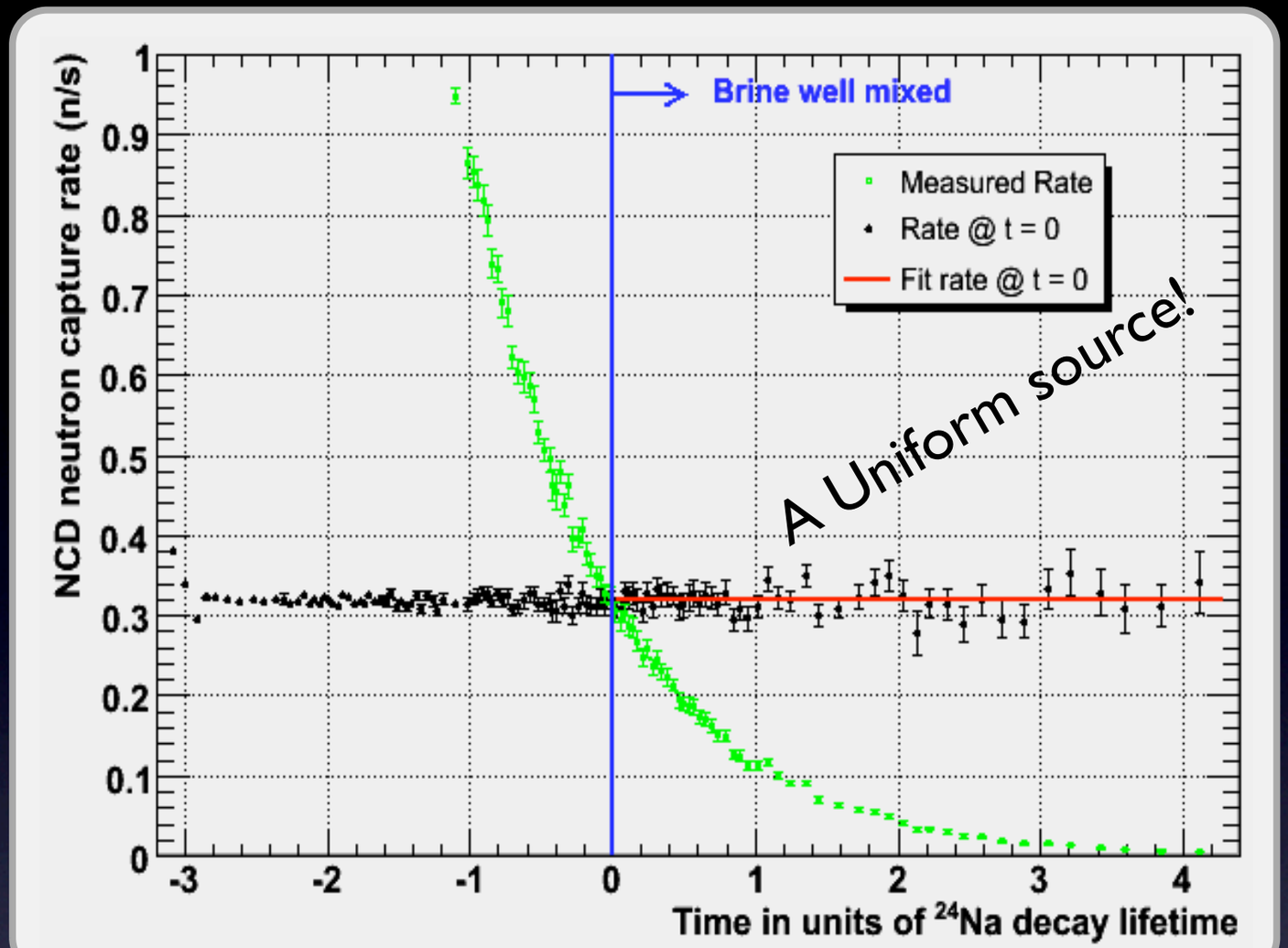
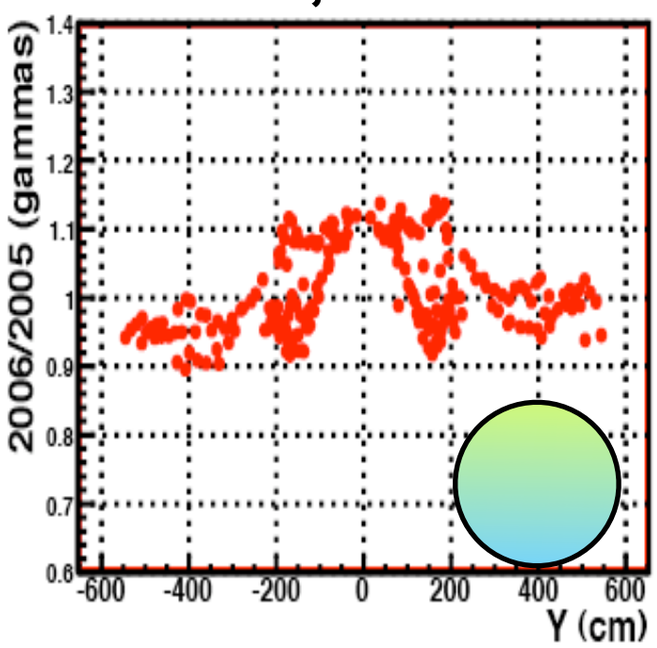


At Injection



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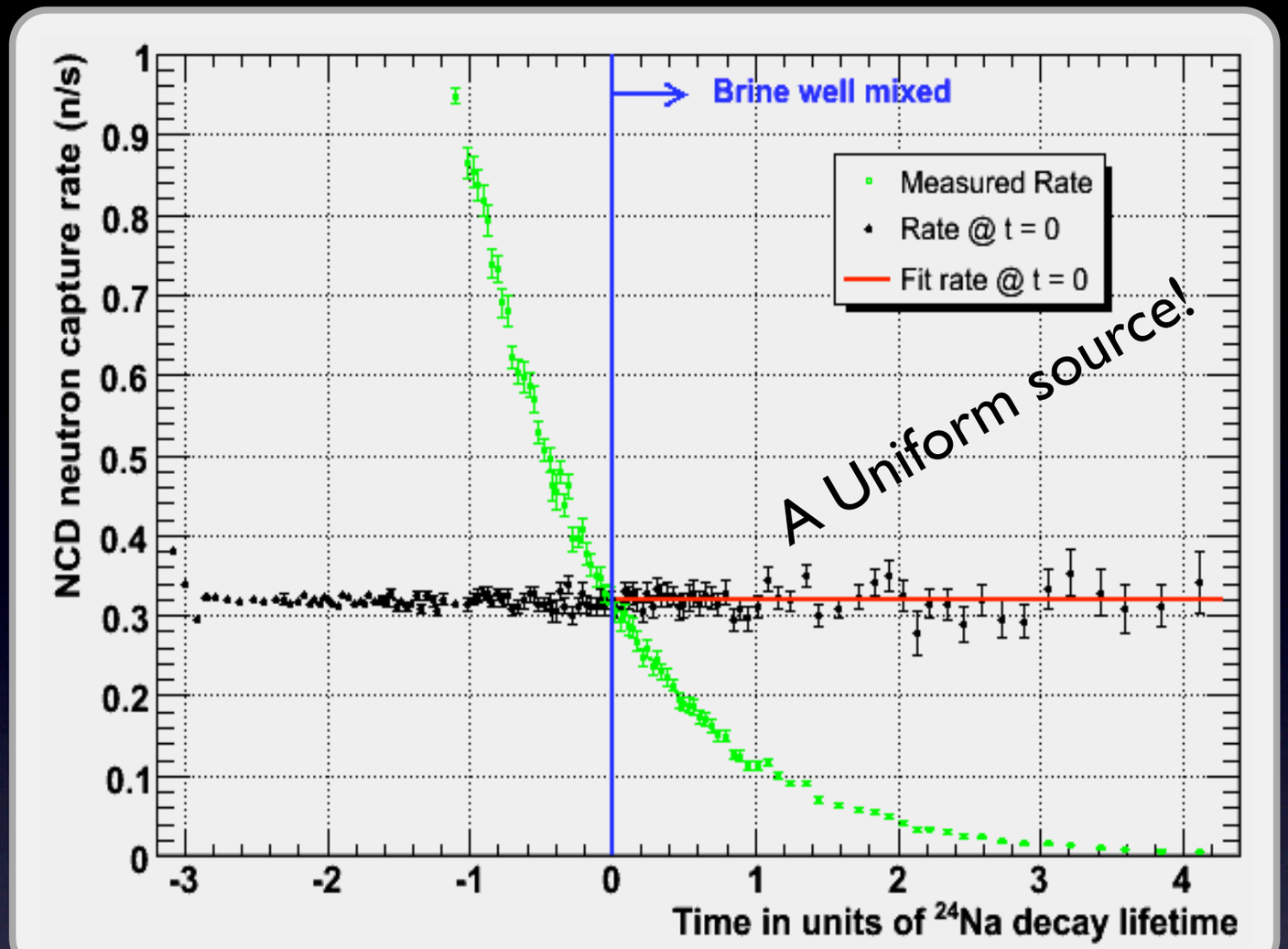

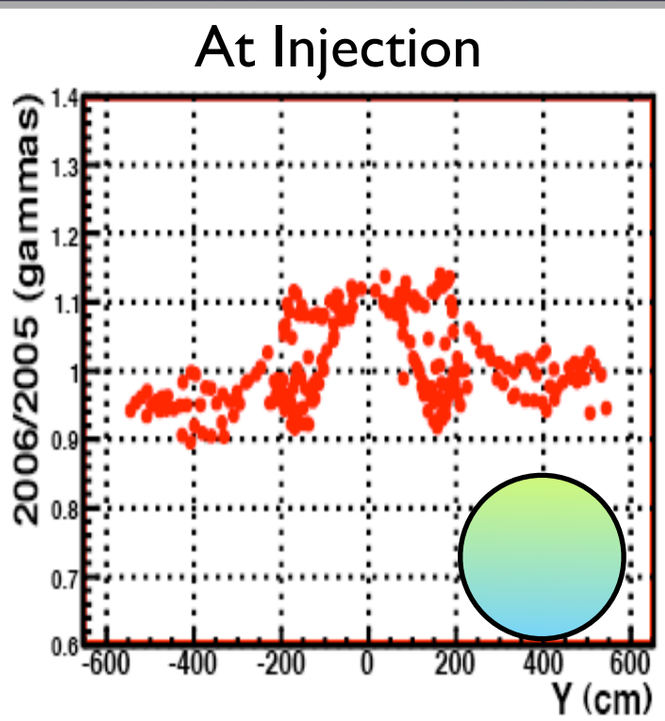

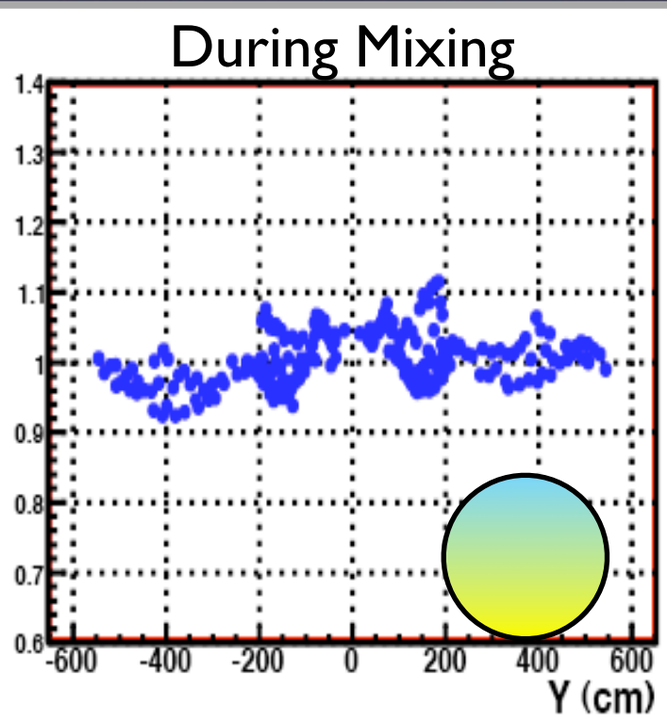

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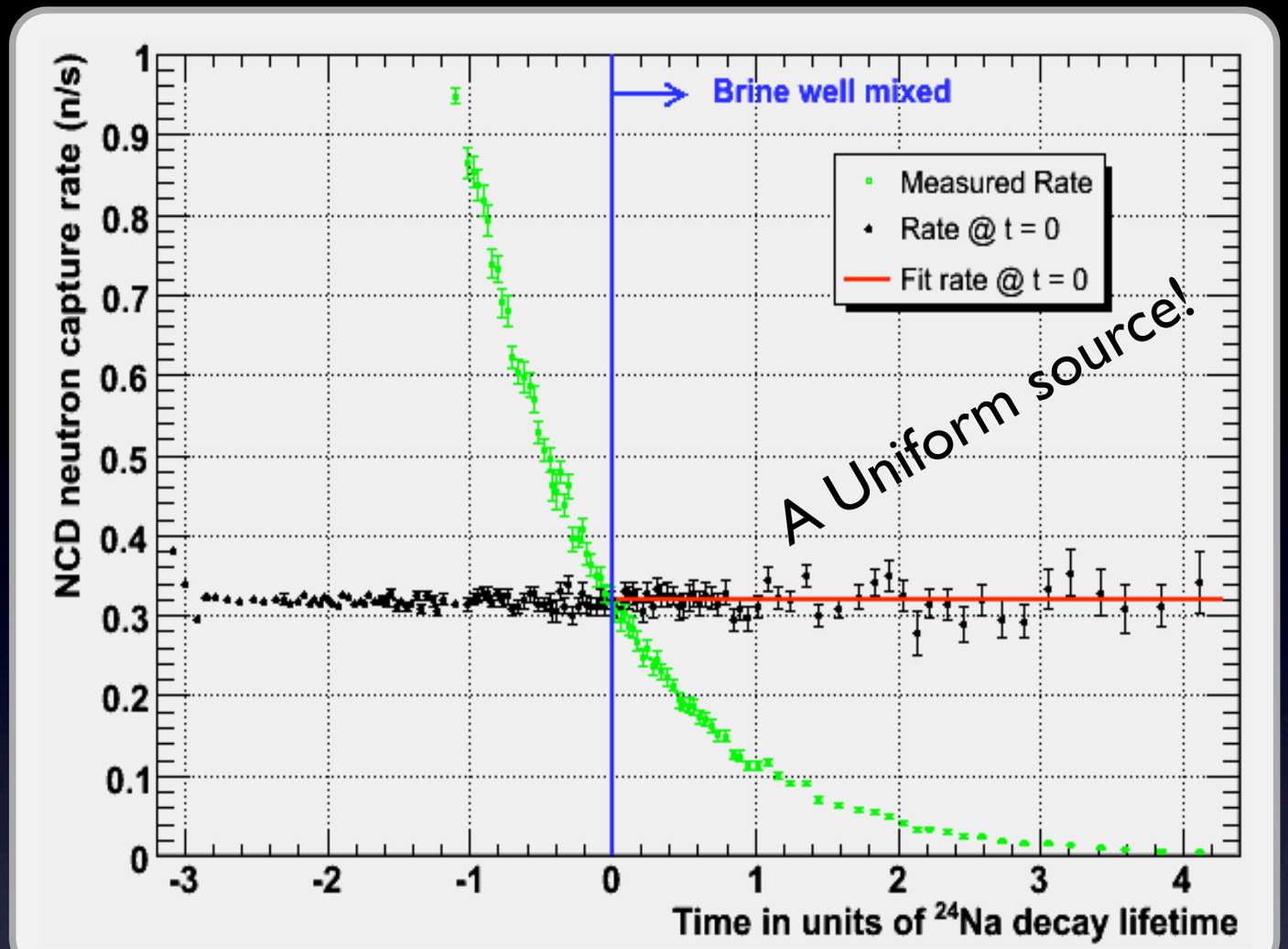

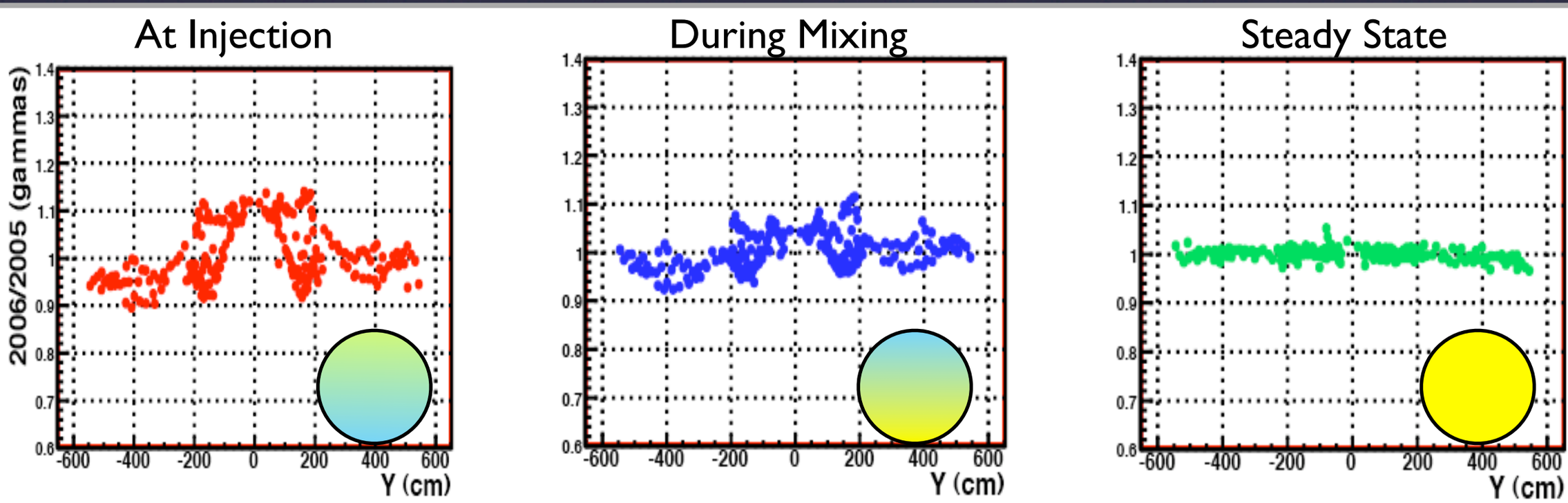

How to ruin our experiment...

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(1) Take spoonful of dirt (mine dust will do nicely.

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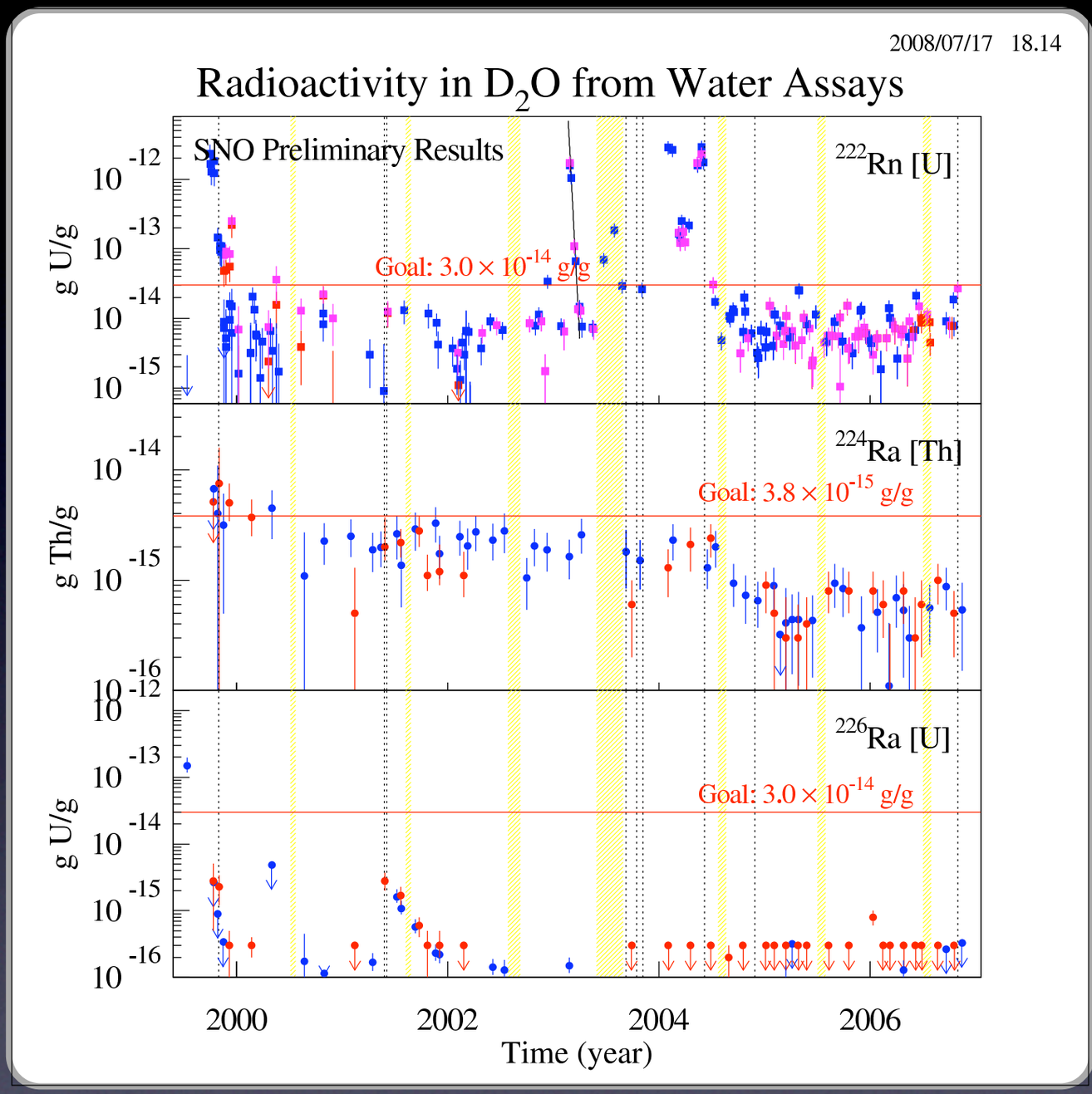
"(Come in under the shadow of this red rock),
And I will show you something different from either
Your shadow at morning striding behind you
Or your shadow at evening rising to meet you;
I will show you fear in a handful of dust."

--T.S. Eliot, The WasteLand

Understanding your backgrounds

- Uranium and thorium contamination needs to be known, since gamma disintegration can add neutrons to total detected rate.
- Employ:
  - Monitoring of water radon levels.
  - In-situ beta-gamma monitoring
  - Consistency & cross-checks



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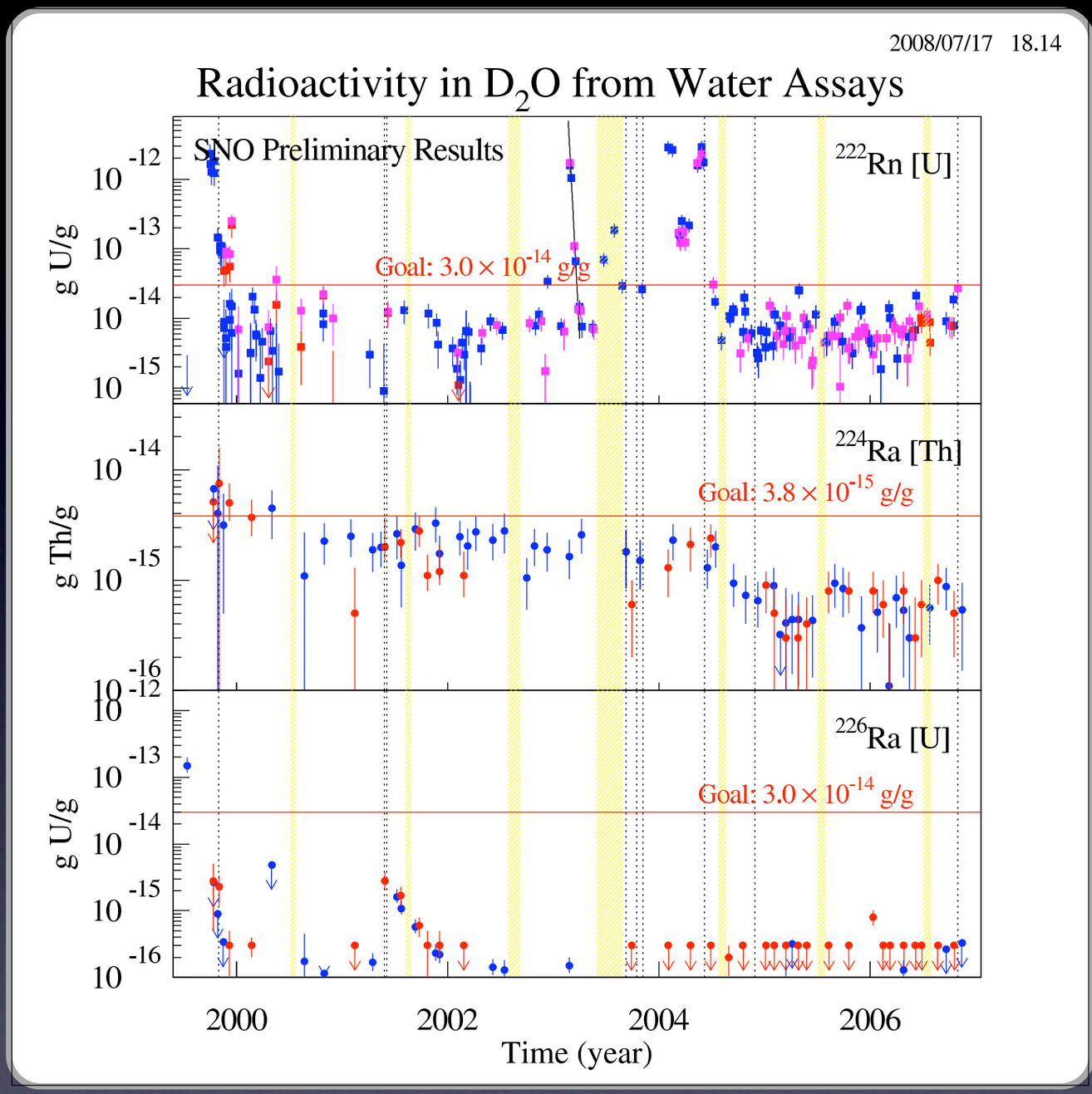

	Ex-Situ	In-Situ	Merged
fgTh/gD_2O	0.88 ± 0.27	0.58 ± 0.35	0.77 ± 0.21
fgU/gD2O	6.63 ± 1.22	5.10 ± 1.80	6.14 ± 1.01

picogram/gram purity of water volume!

Not fooling yourself...

SNO has consistently adopted a policy of a "blind" analysis, whereby the measurement is hidden from the observer.

To hide the answer, we:

(1) Keep a fraction of data closed

(2) Include hidden fraction of neutrons created from muon interactions.

(3) Omit a unknown fraction of candidate events.

Box opened only after detailed internal reviews have been completed.

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Pandora's Box

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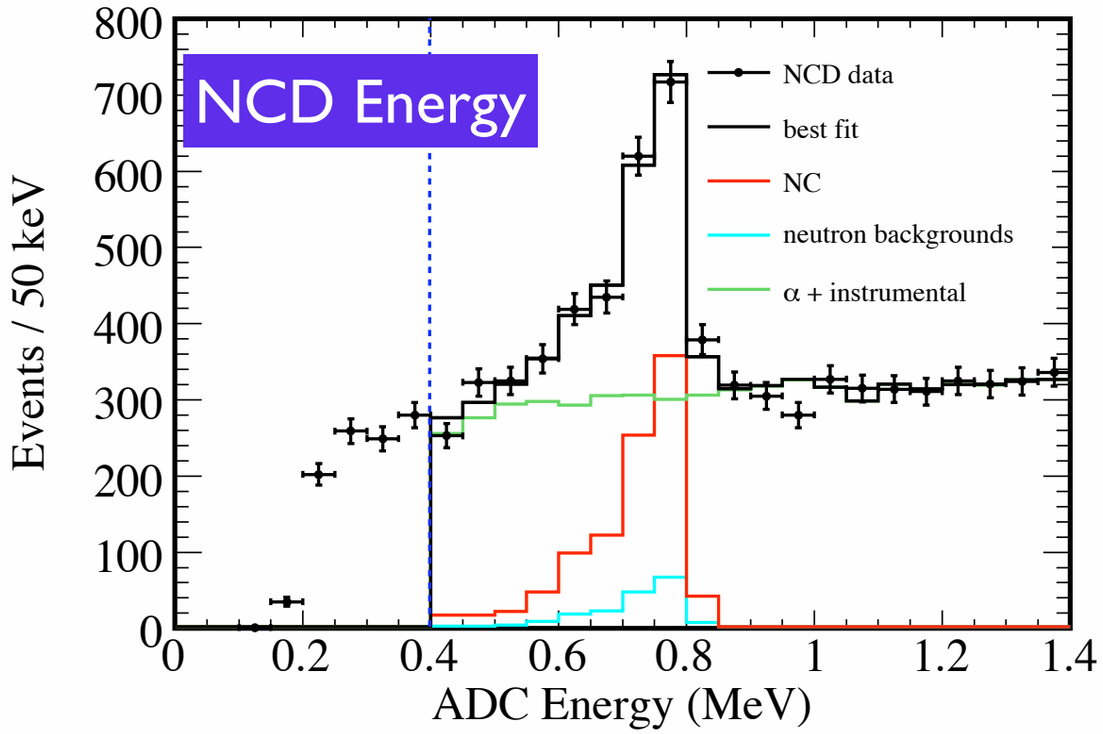
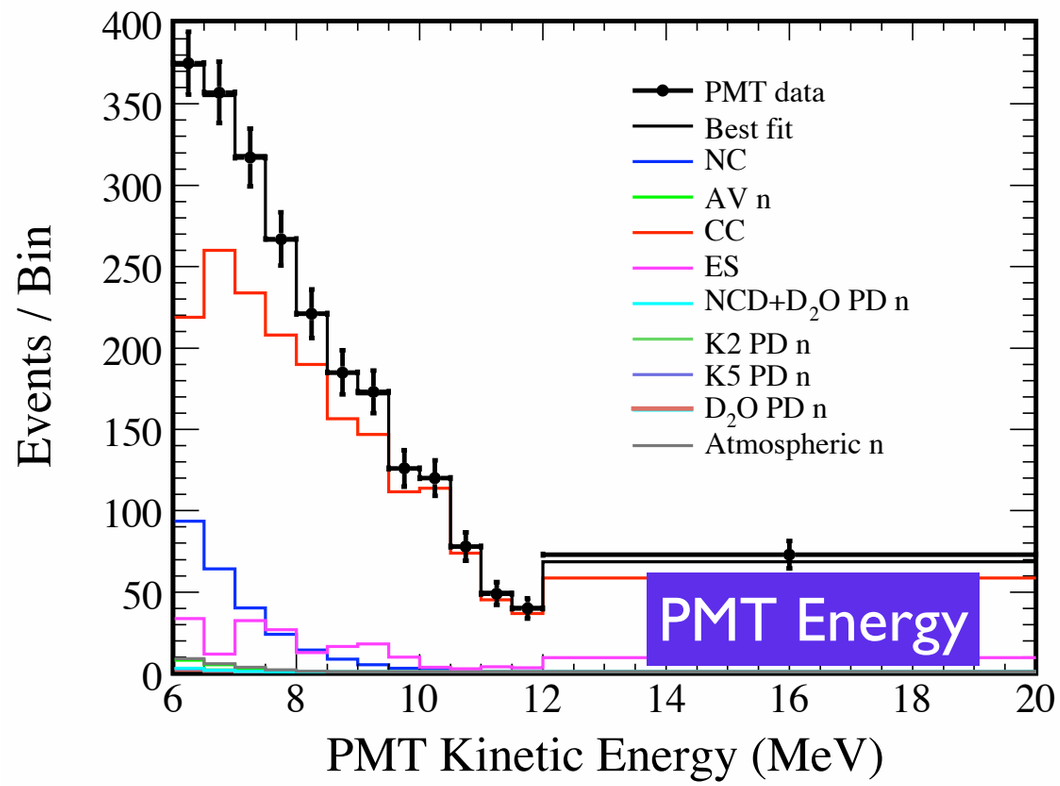
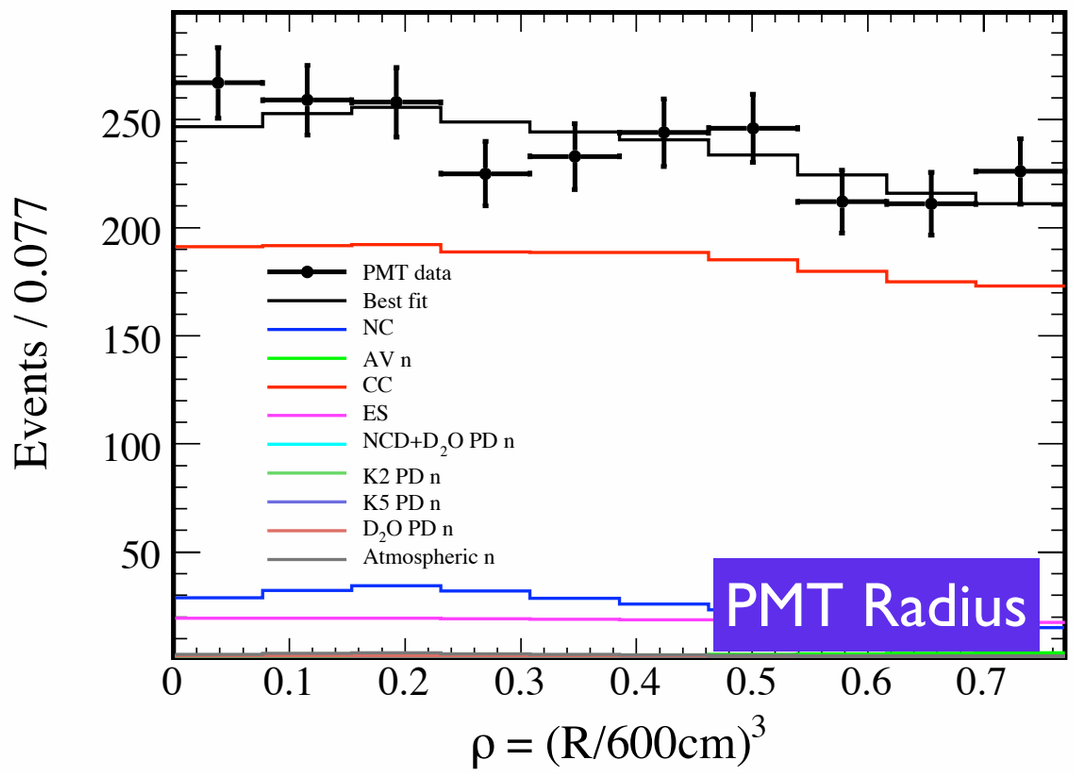
Other Painful boxes...

The process takes its toll,
but it does keep us honest.







Signal Extraction

Data from signal paths combined to determine neutrino fluxes.

Clean separation of charged and neutral current signals

Measured Fluxes

Reaction	Flux (x 10^6 cm^{-2} s^{-1})
Charged Current	$1.67^{+0.05}_{-0.04}\ (\mathrm{stat})^{+0.07}_{-0.08}\ (\mathrm{sys})$
Elastic Scattering	$1.77^{+0.24}_{-0.21}\ (\mathrm{stat})^{+0.09}_{-0.10}\ (\mathrm{sys})$
Neutral Current	$5.54^{+0.33}_{-0.31}\ (\mathrm{stat})^{+0.36}_{-0.34}\ (\mathrm{sys})$

NCD Phase

Perform combined fit of NCD neutrons and PMT observables to extract CC, NC, and ES fluxes.

Overall agreement across phases is good (p-value of 32.8%).

Across all phases

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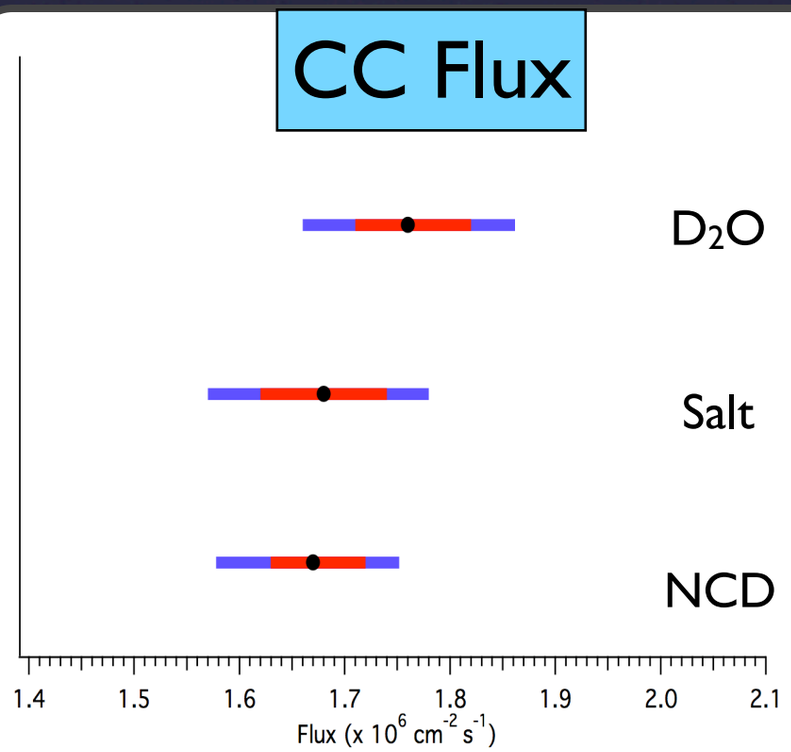

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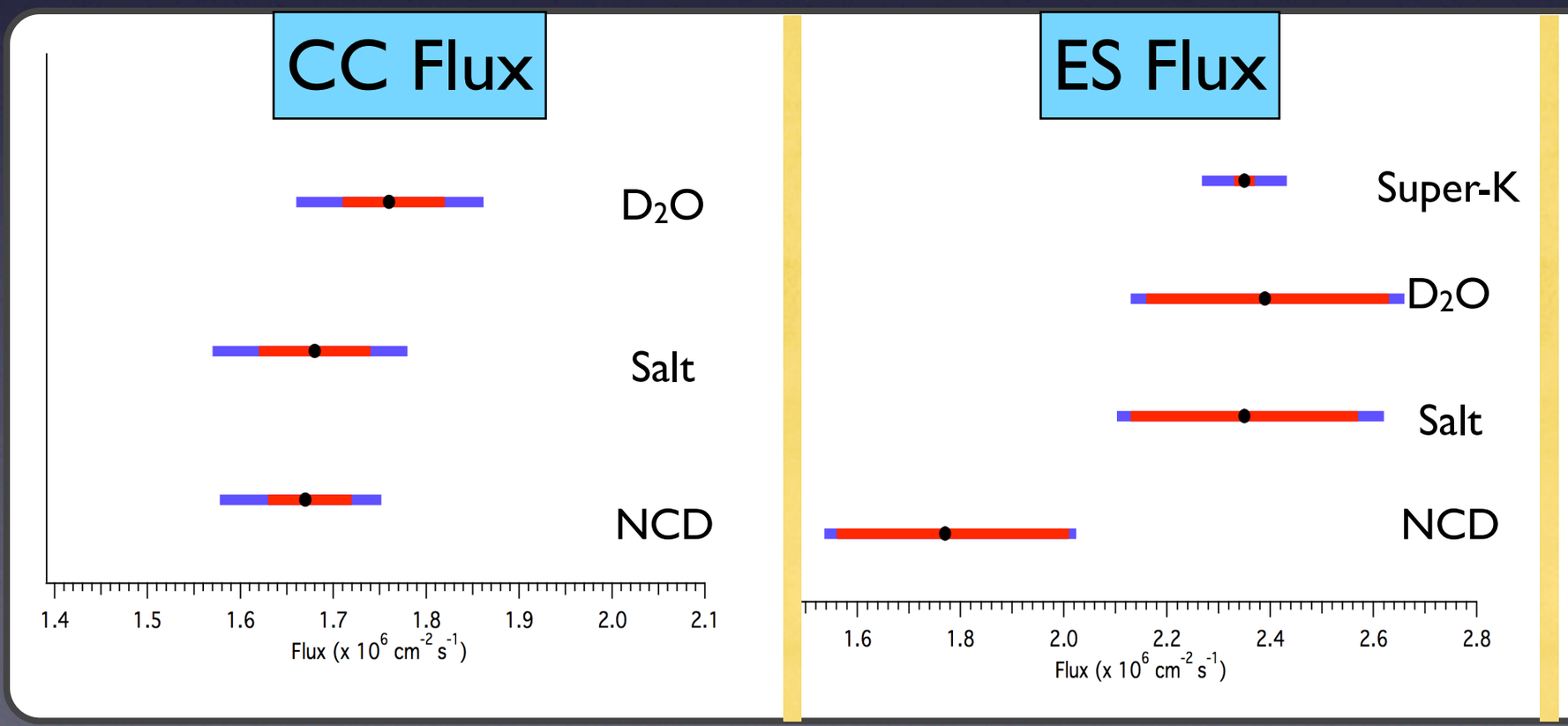

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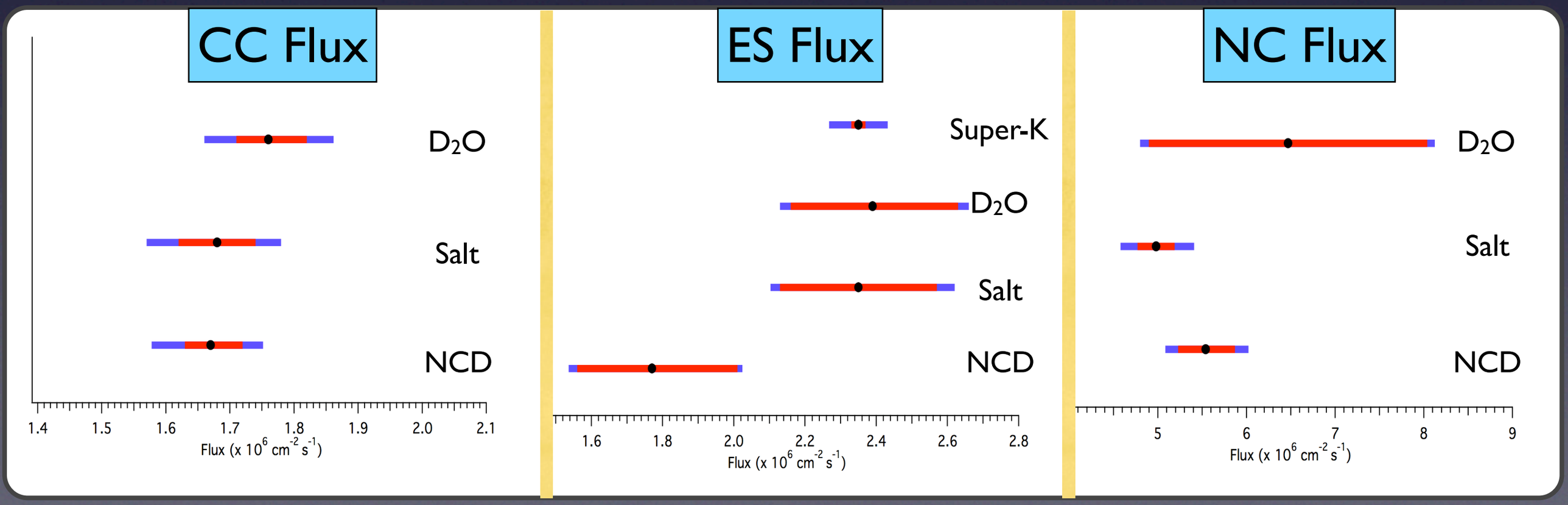
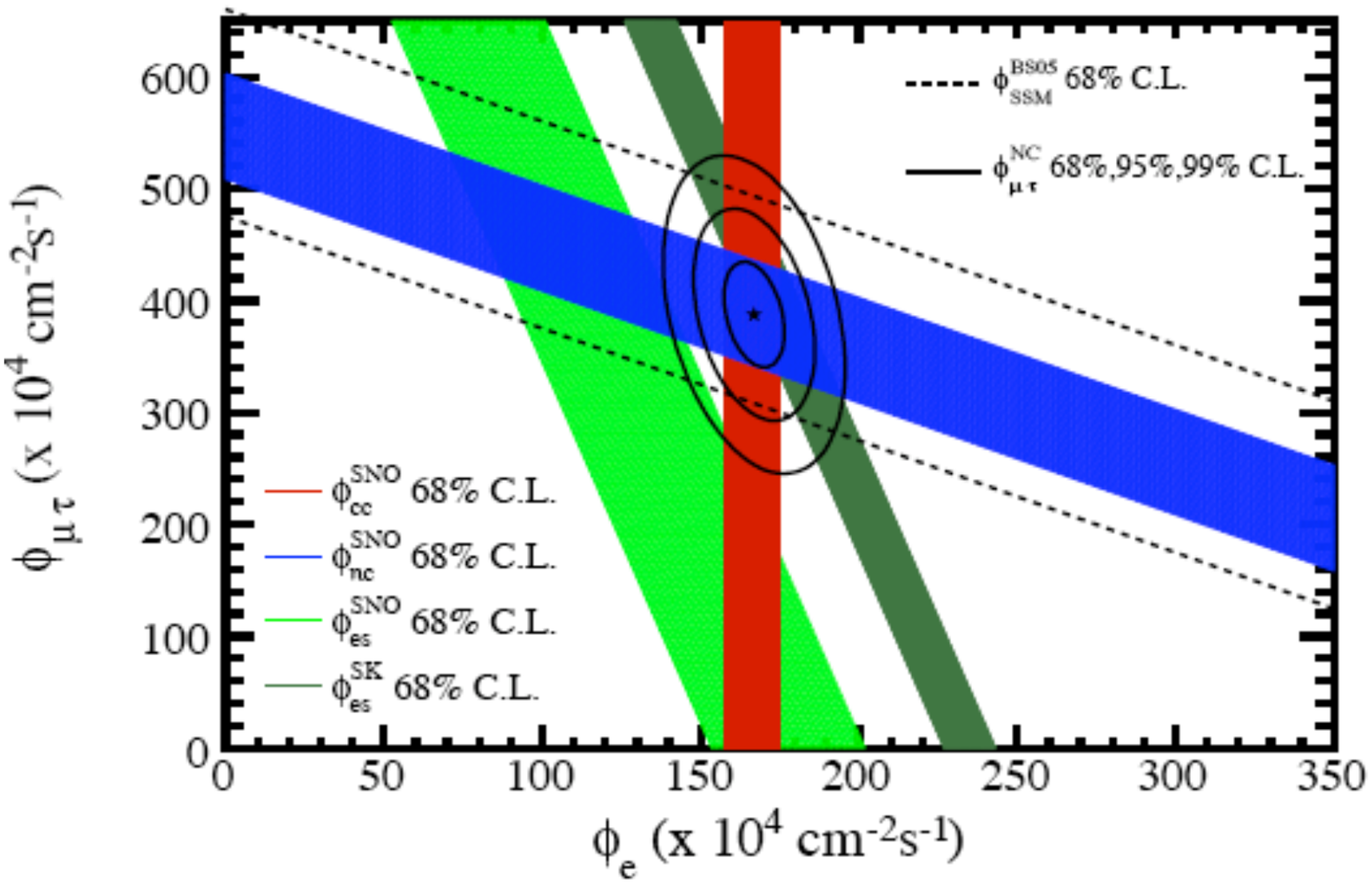


Results from the NCD Phase

$$\frac{\phi_{\mathrm{CC}}}{\phi_{\mathrm{NC}}} = 0.301 \pm 0.033 = \cos^4(\theta_{13}) \sin^2(\theta_{12})$$



SNO Collaboration, arXiv:0806.0989
Submitted to Physical Review Letters

Fluxes

(10^6 cm^{-2} s^{-1})

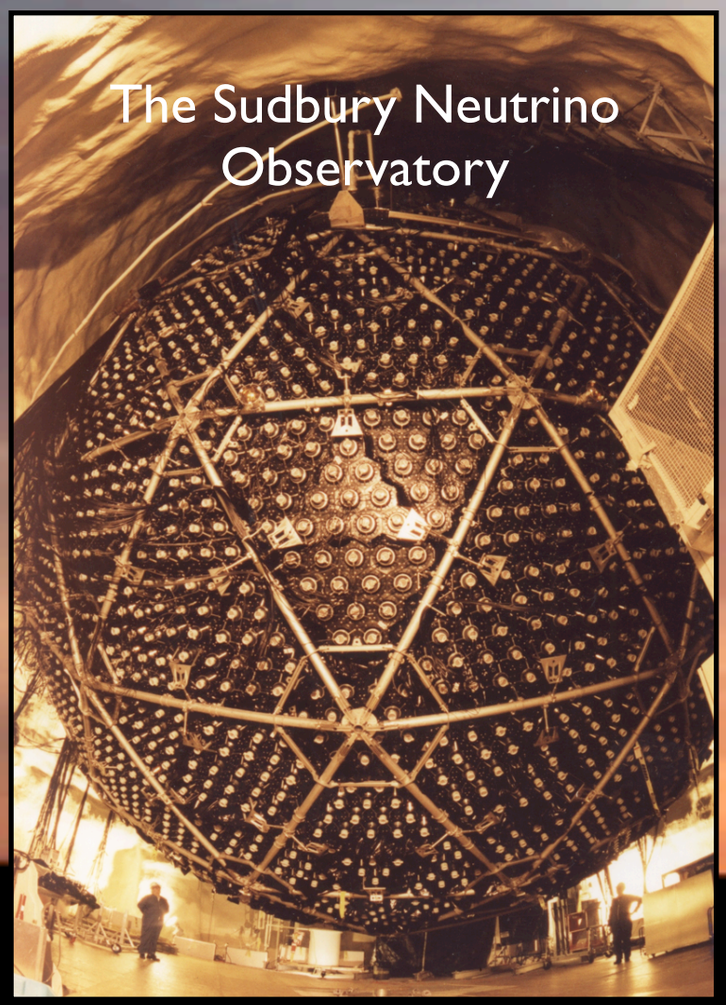
ν_e: 1.67 ± 0.09

ν_{ES}: 1.77 ± 0.26

ν_{total}: 5.54 ± 0.48

ν_{SSM05}: 5.69 ± 0.91

Neutrino Oscillations



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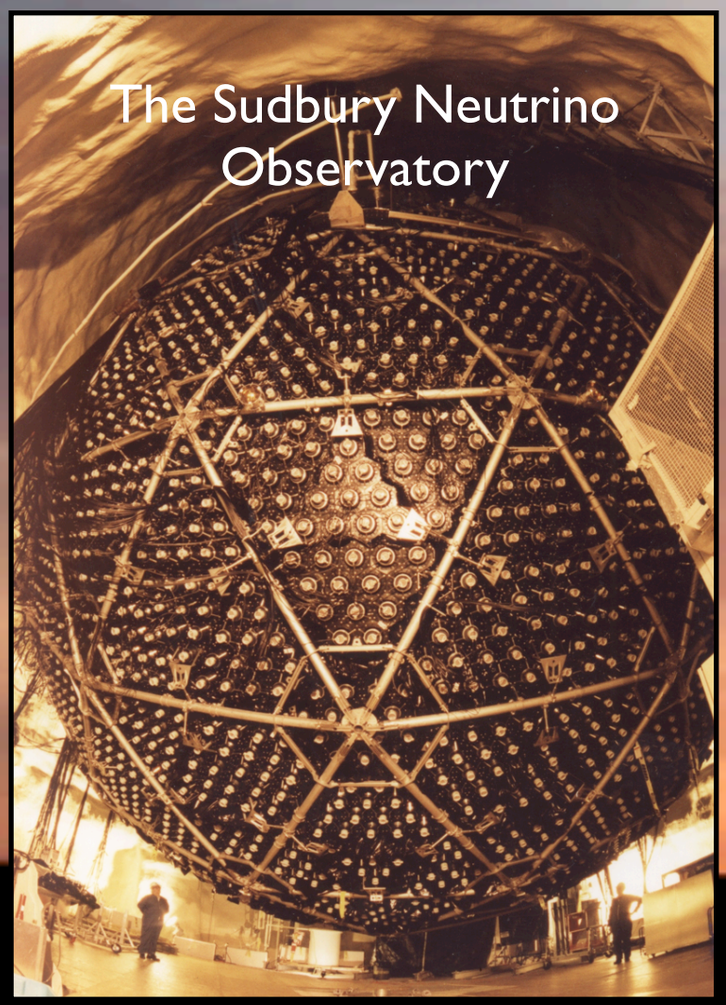
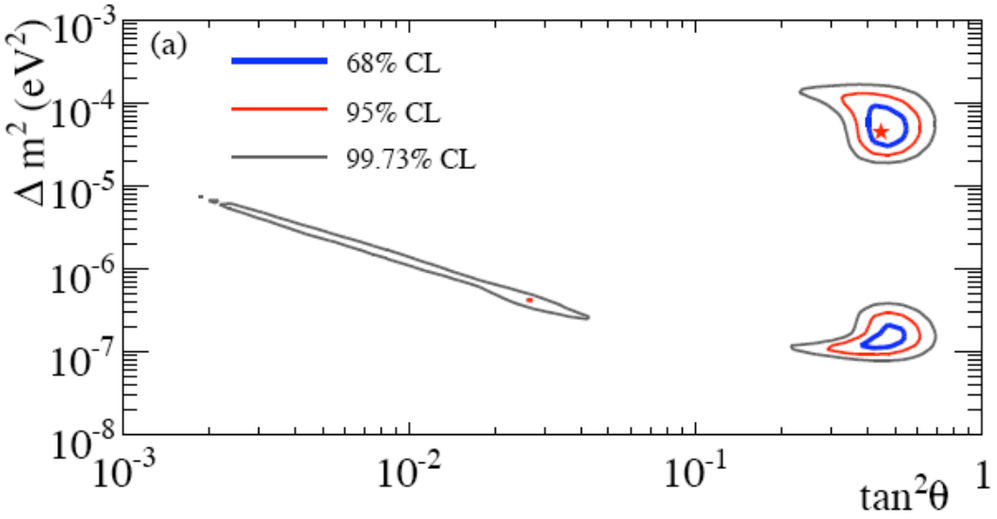


SNO Only



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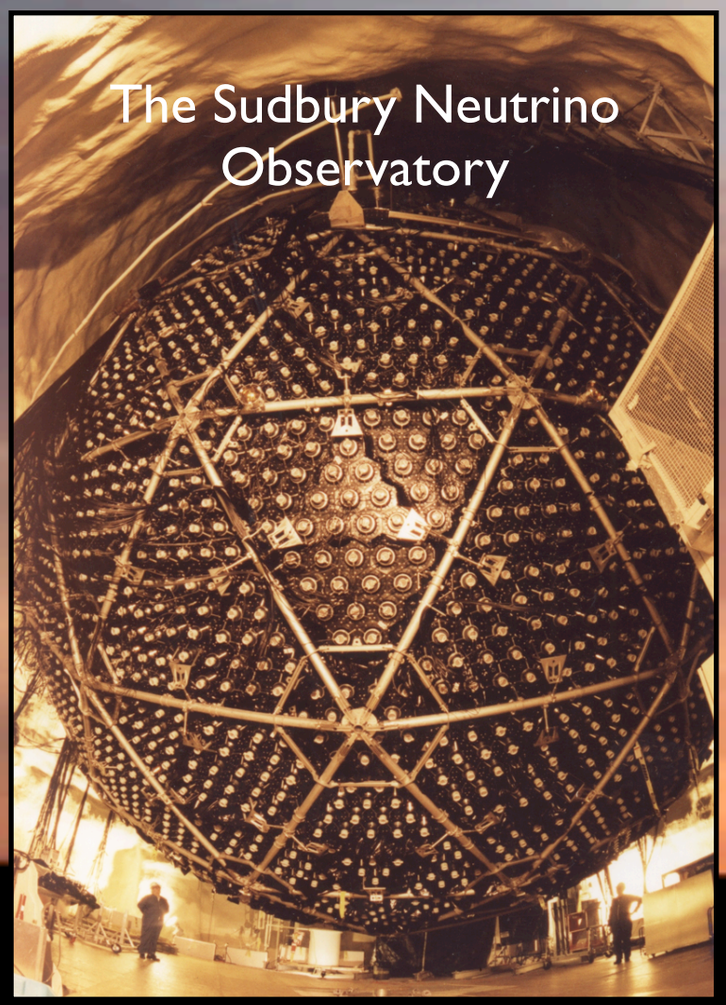
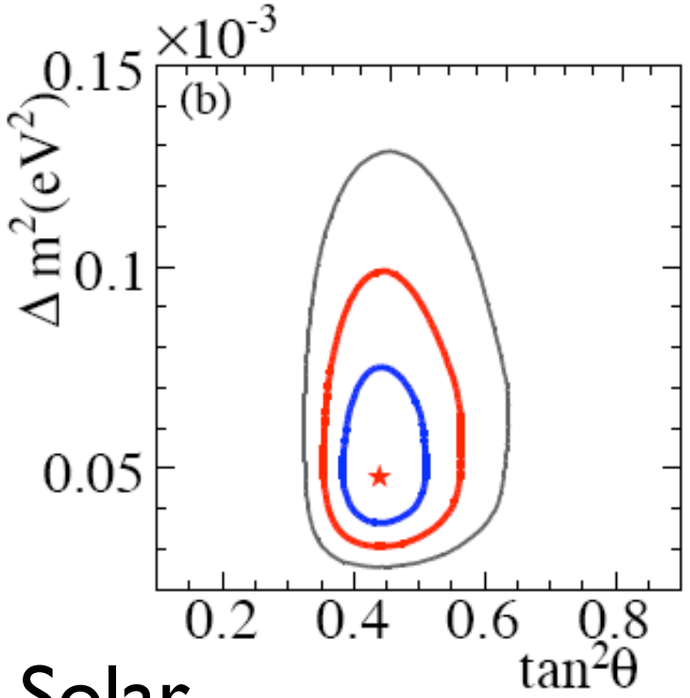
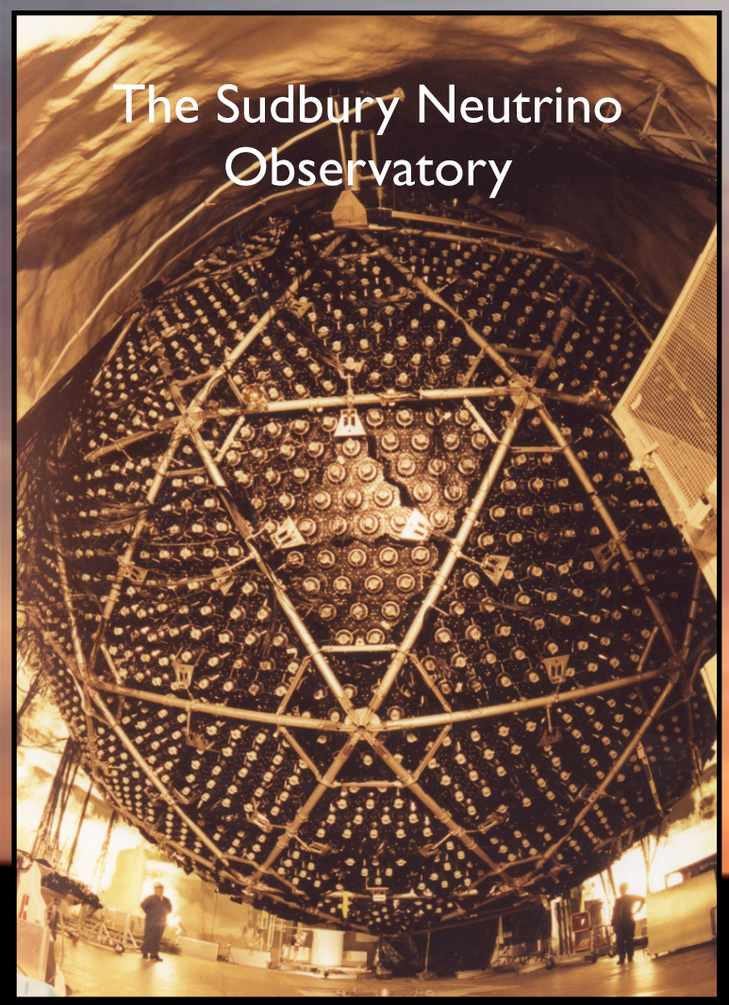
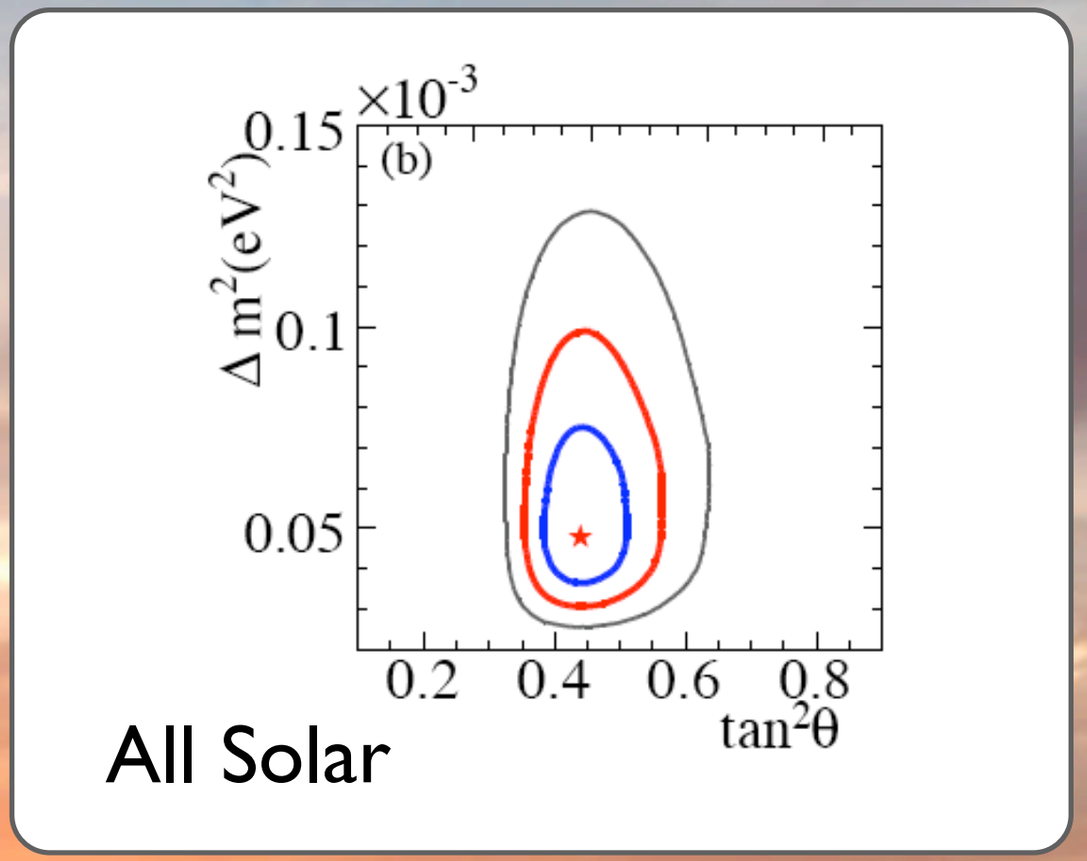




All Solar

Neutrino Oscillations





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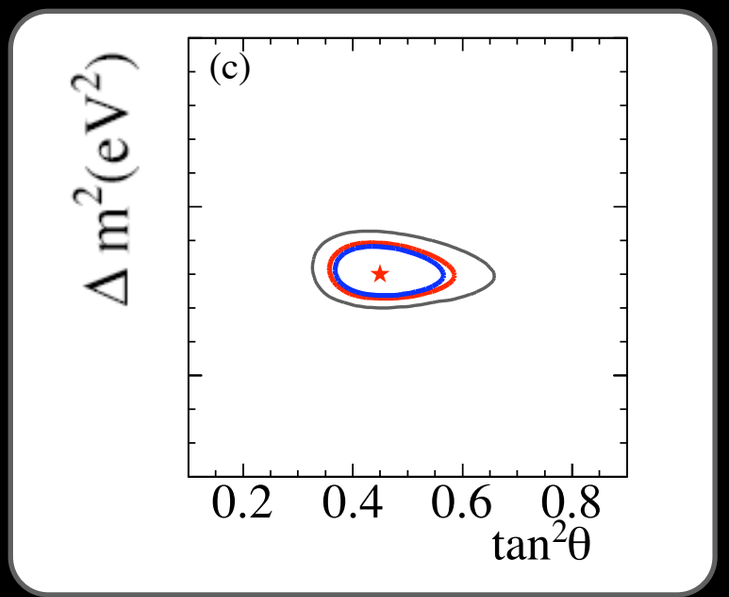

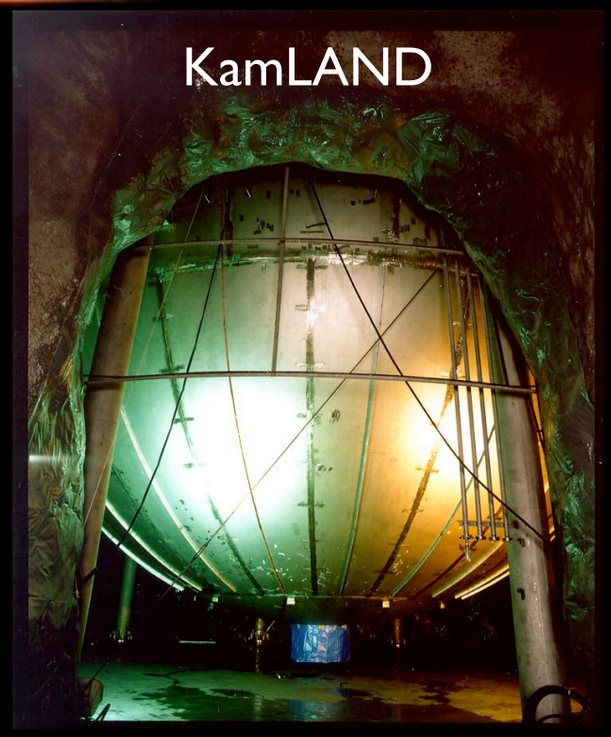

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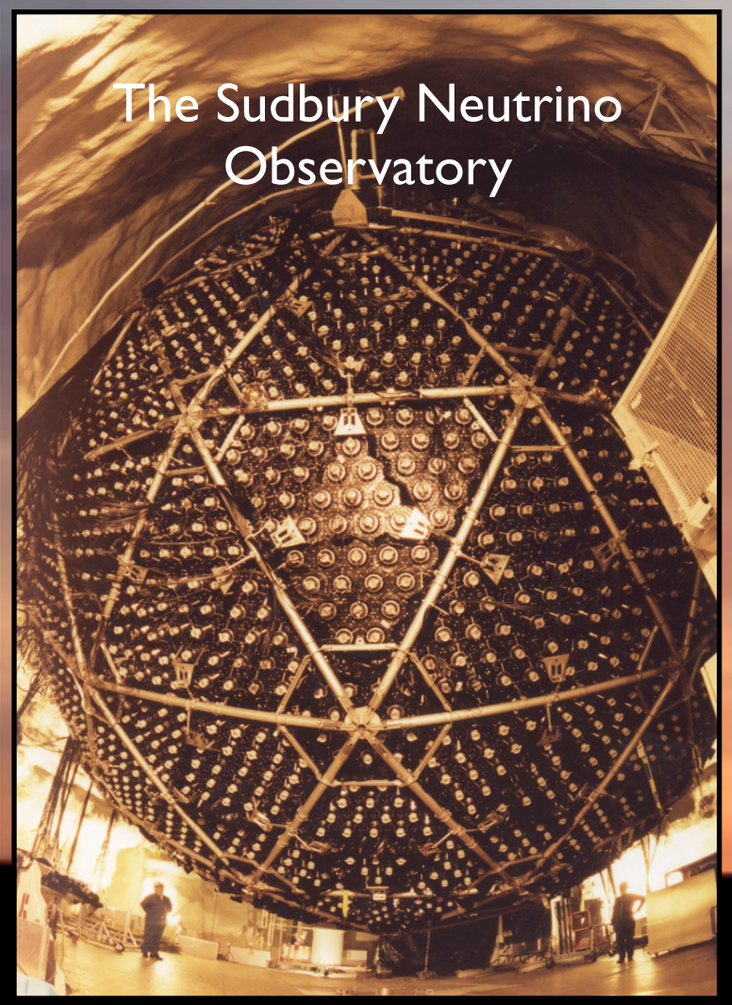

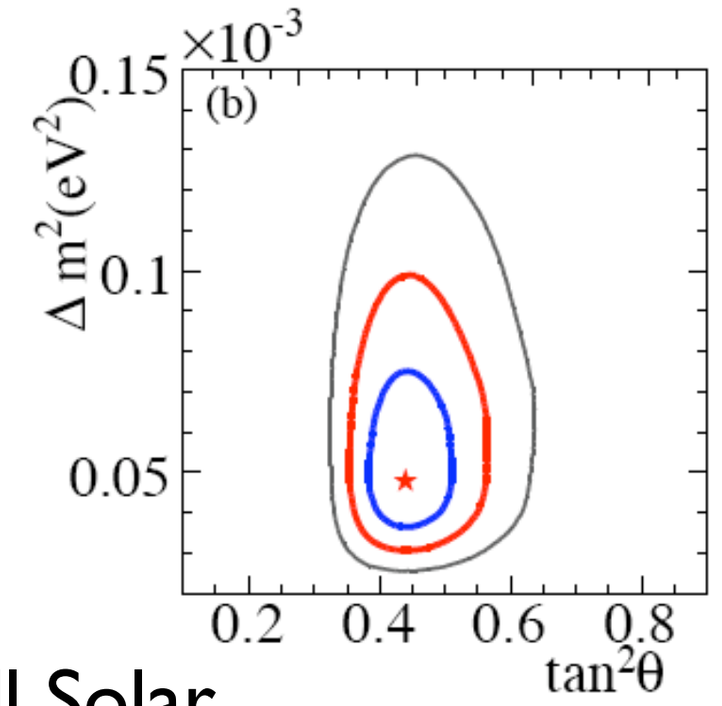

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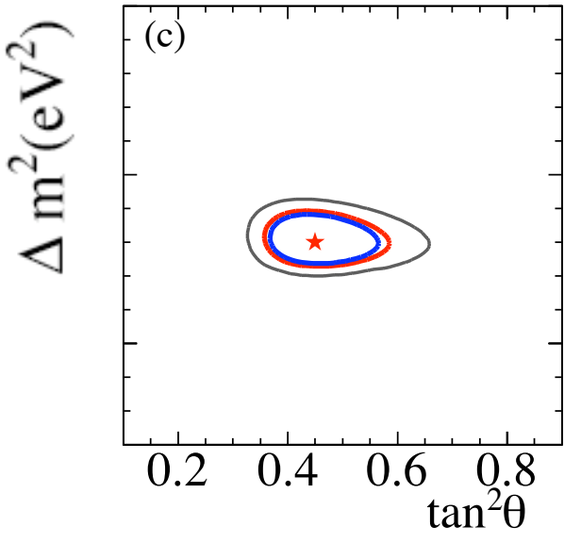
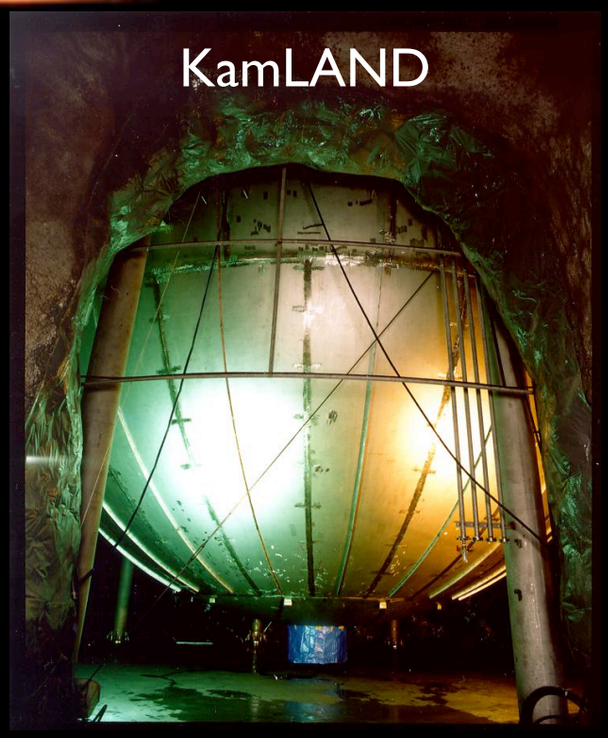


Best-fit
Neutrino Parameters

Δm^2: $7.94\ ^{+0.42}_{-0.26} \times 10^{-5}\ eV^2$

θ_{12}: $33.8\ ^{+1.4}_{-1.3}$ degrees

f_{8B}: 0.873



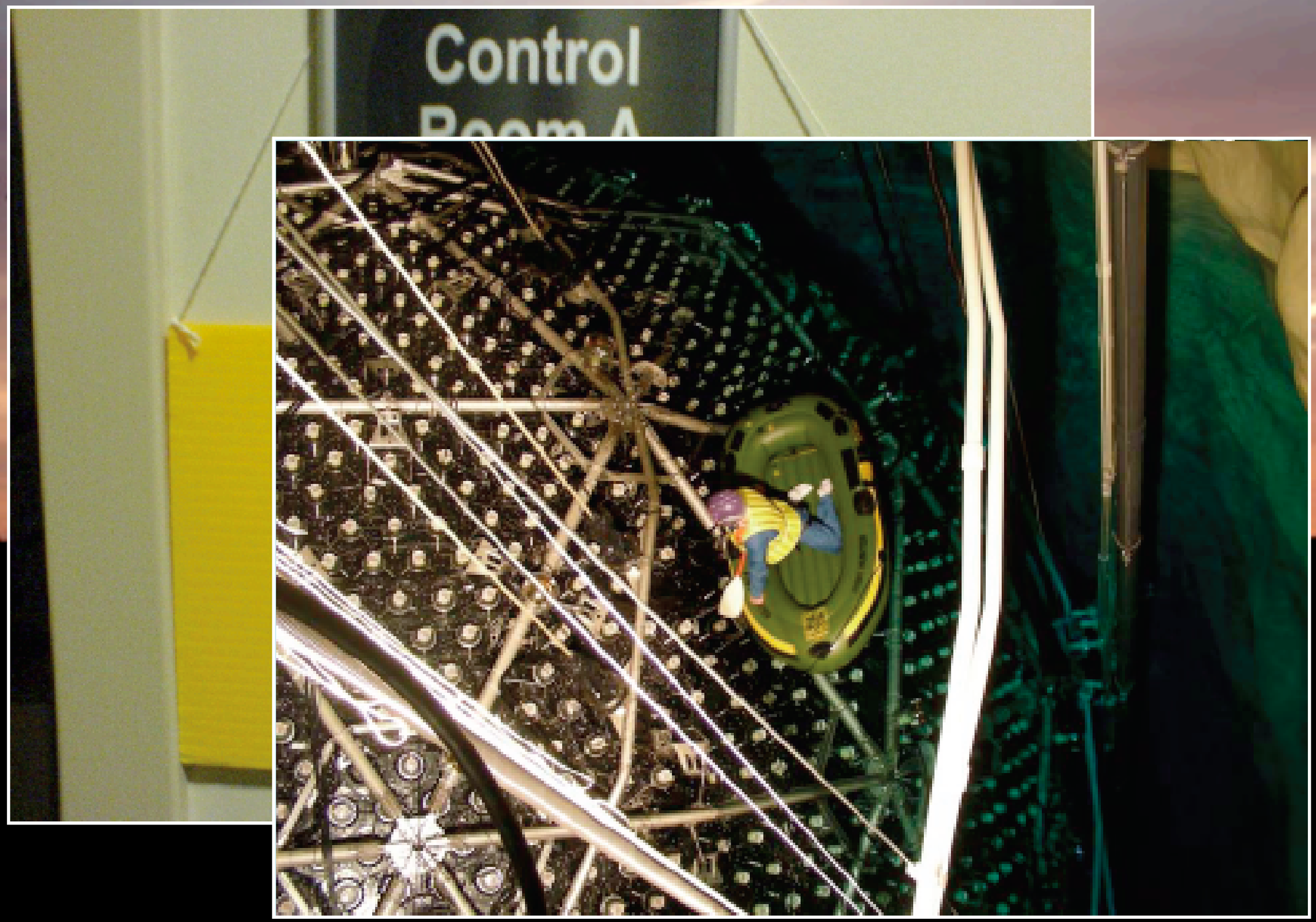
...so?

Is it over?

All good things...

All good things...

All good things...



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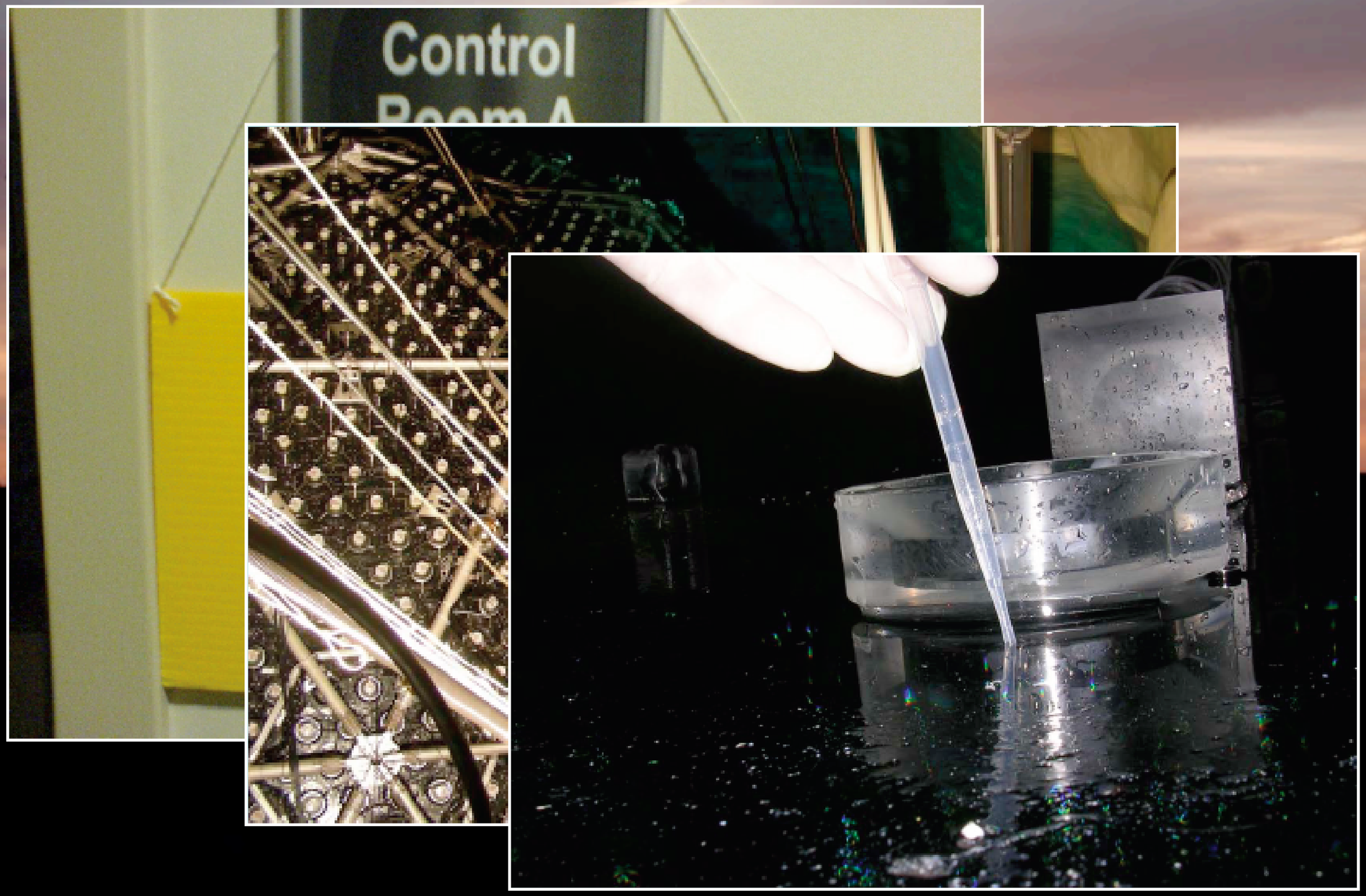
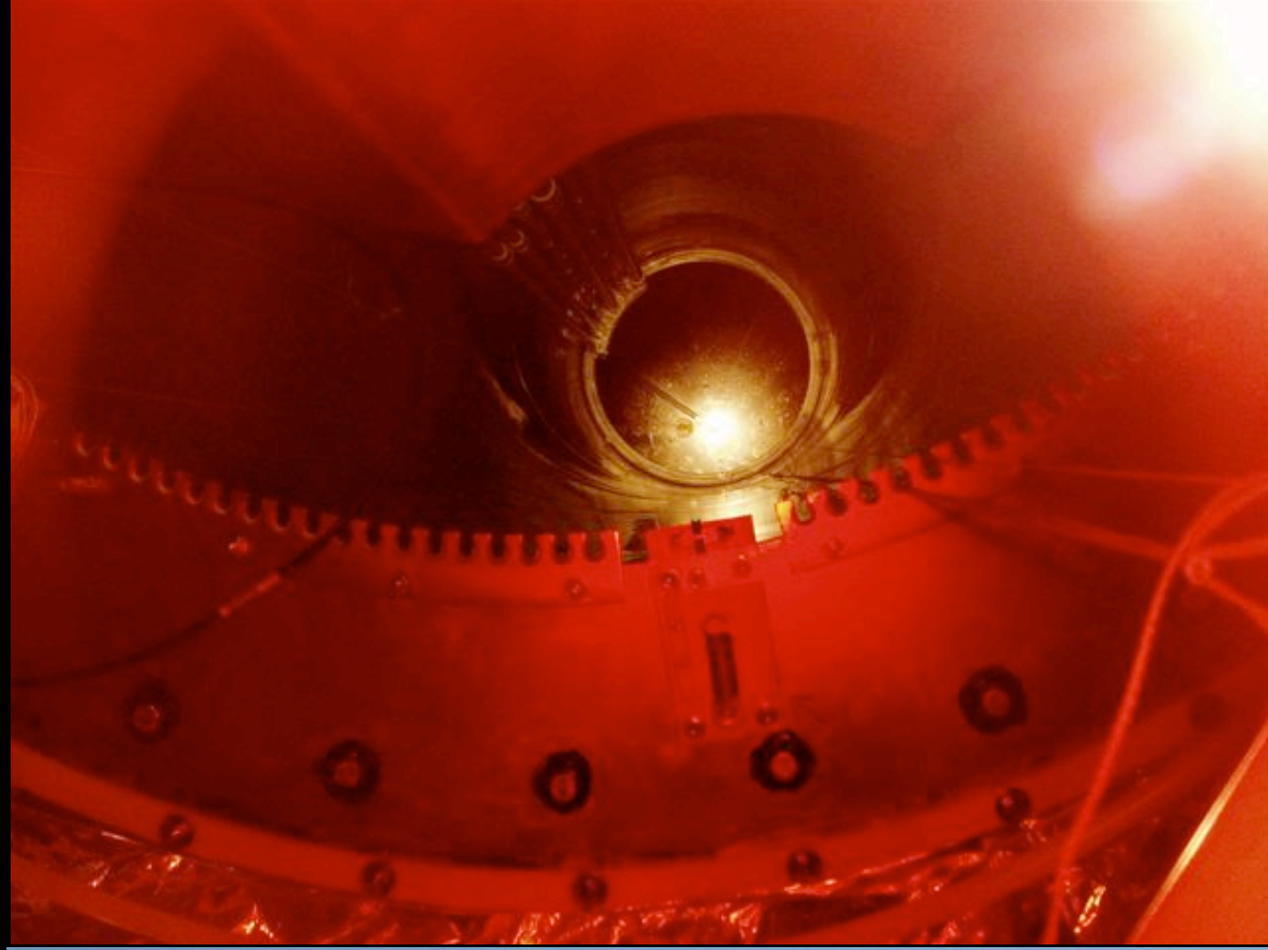


SNOLAB

MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE



The First Crack of the Standard Model

- Neutrino oscillation experiments carried out over the last forty years have revealed that neutrinos do possess a small and finite mass, providing the first contradiction in the Standard Model.

- Questions remain: what can we learn from neutrino oscillations and from neutrino masses?

The Full Context of Neutrino Oscillations

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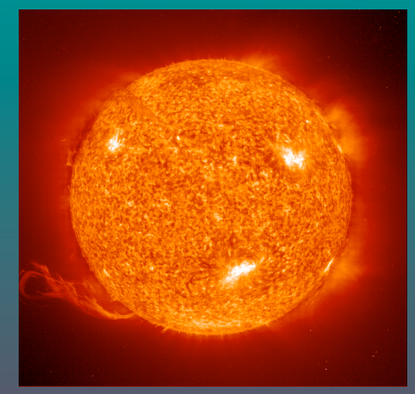
Solar/reactor neutrino experiments:
(SNO, KamLAND, Super-K, GNO, etc)

$\theta_{12} = 33.8^{o} \pm 1.4^{o}$

Limit solar mixing parameters:

$\Delta m^2_{12} = 7.94 \pm 0.42 \times 10^{-5}\ eV^2$



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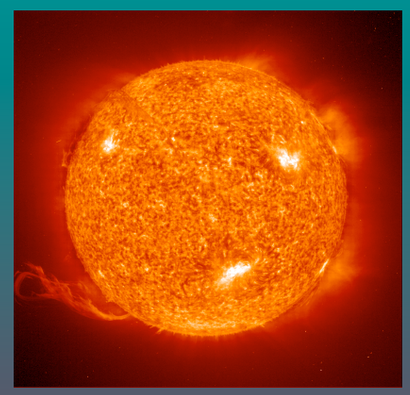

Atmospheric neutrino experiments:
Super-K, Soudan, Kamiodande, new MINOS results)

$\theta_{23} = 42^{o} \pm 4^{o}$

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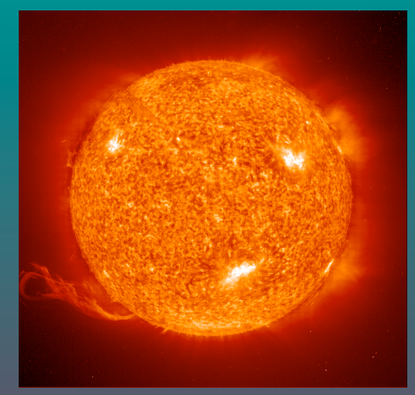

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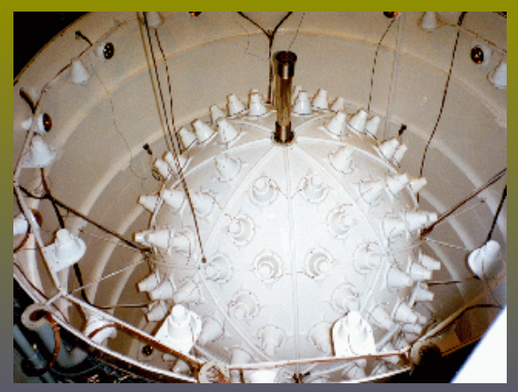
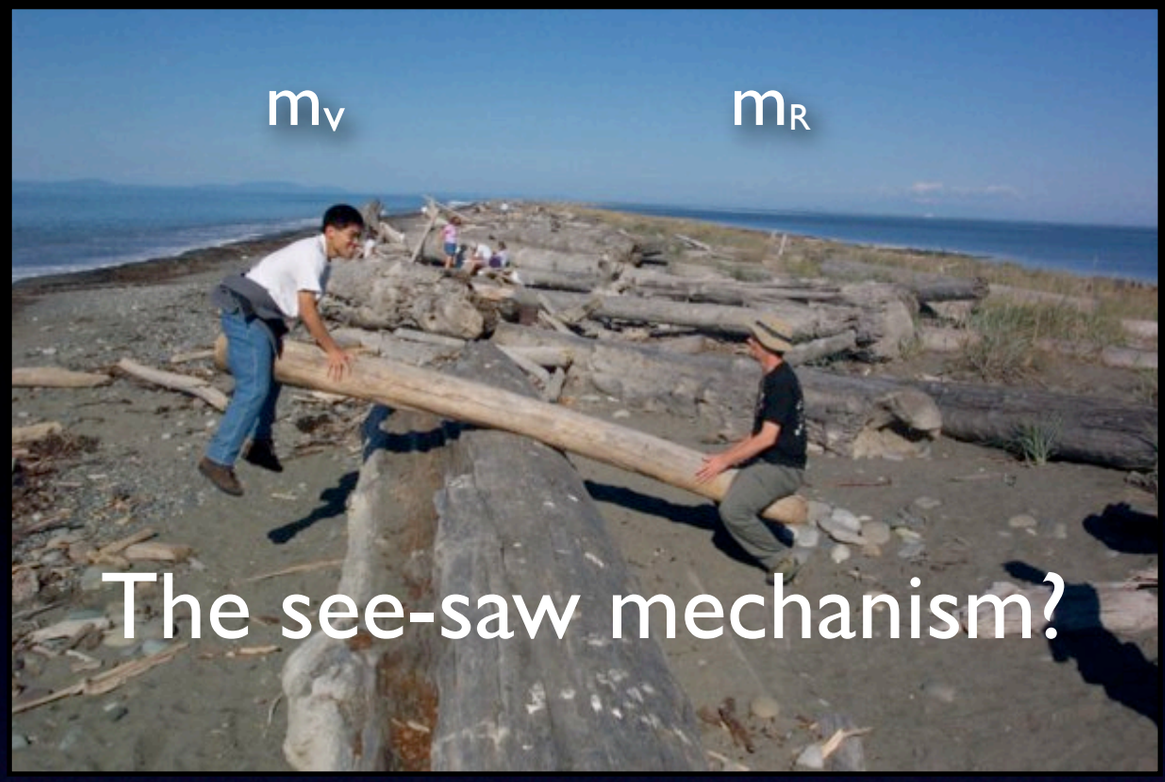
Short baseline & reactors experiments:
(LSND, CHOOZ, Palo Verde, etc…)

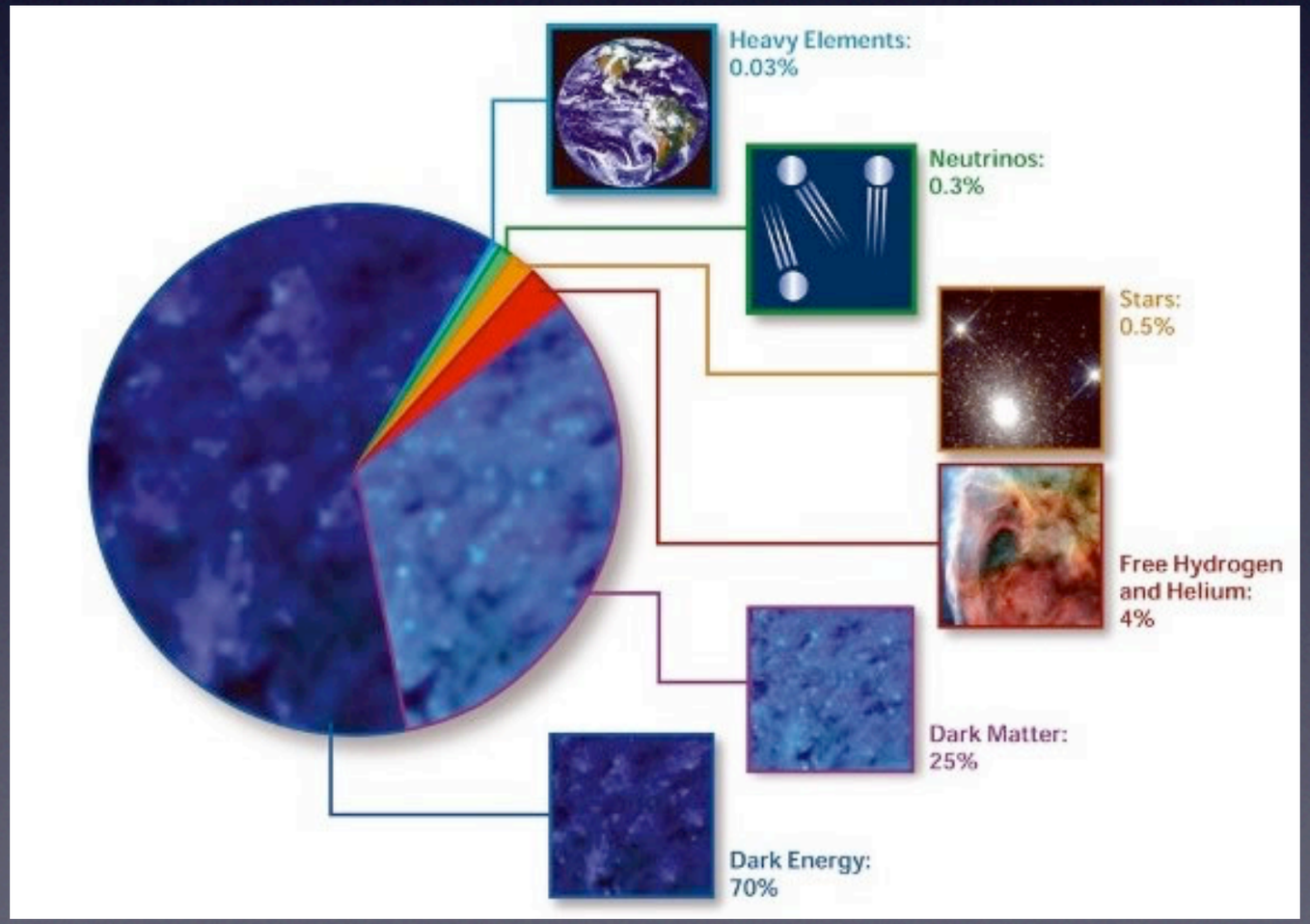
$\theta_{13} < 10^{o}$ (95% C.L.)

Limits on last mixing angle.



The Role of Neutrino Mass





- Does neutrino mass have a role in understanding physics at the GUT scale?
- What is the nature of neutrino mass? Are they Dirac or Majorana particles?
- What is the scale of neutrino masses? Can they have an impact on cosmological observations at the level of detection?

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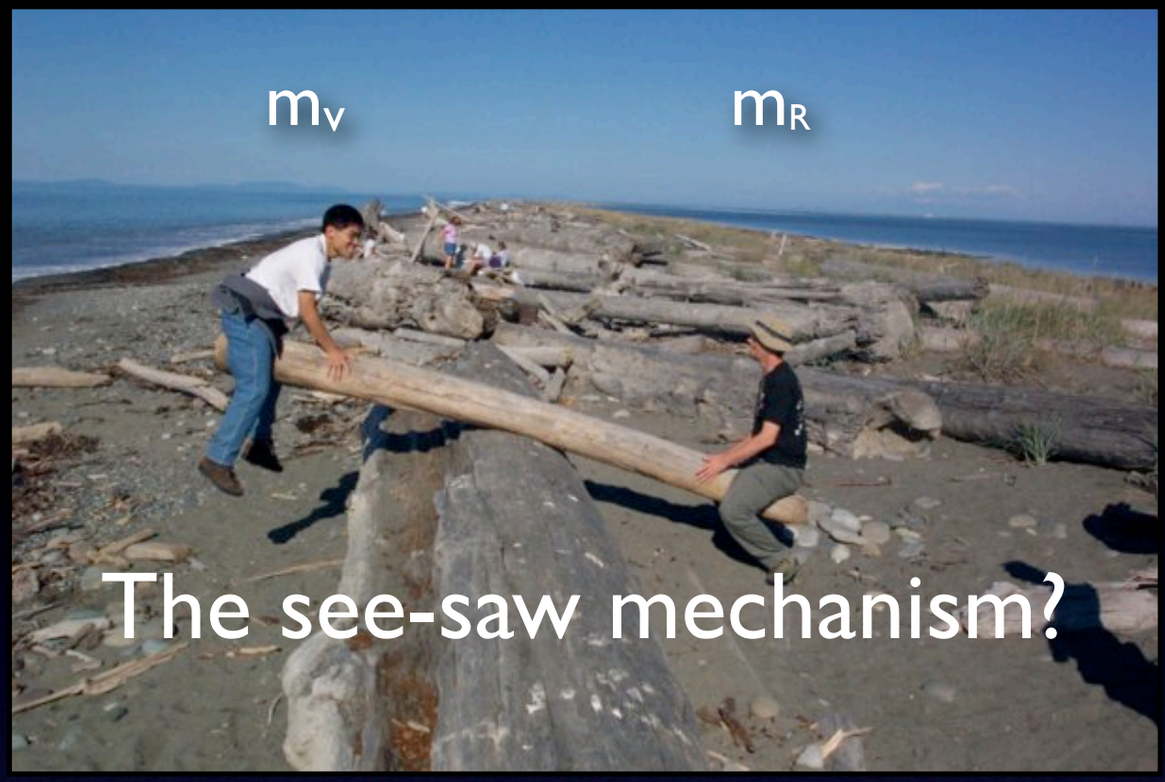

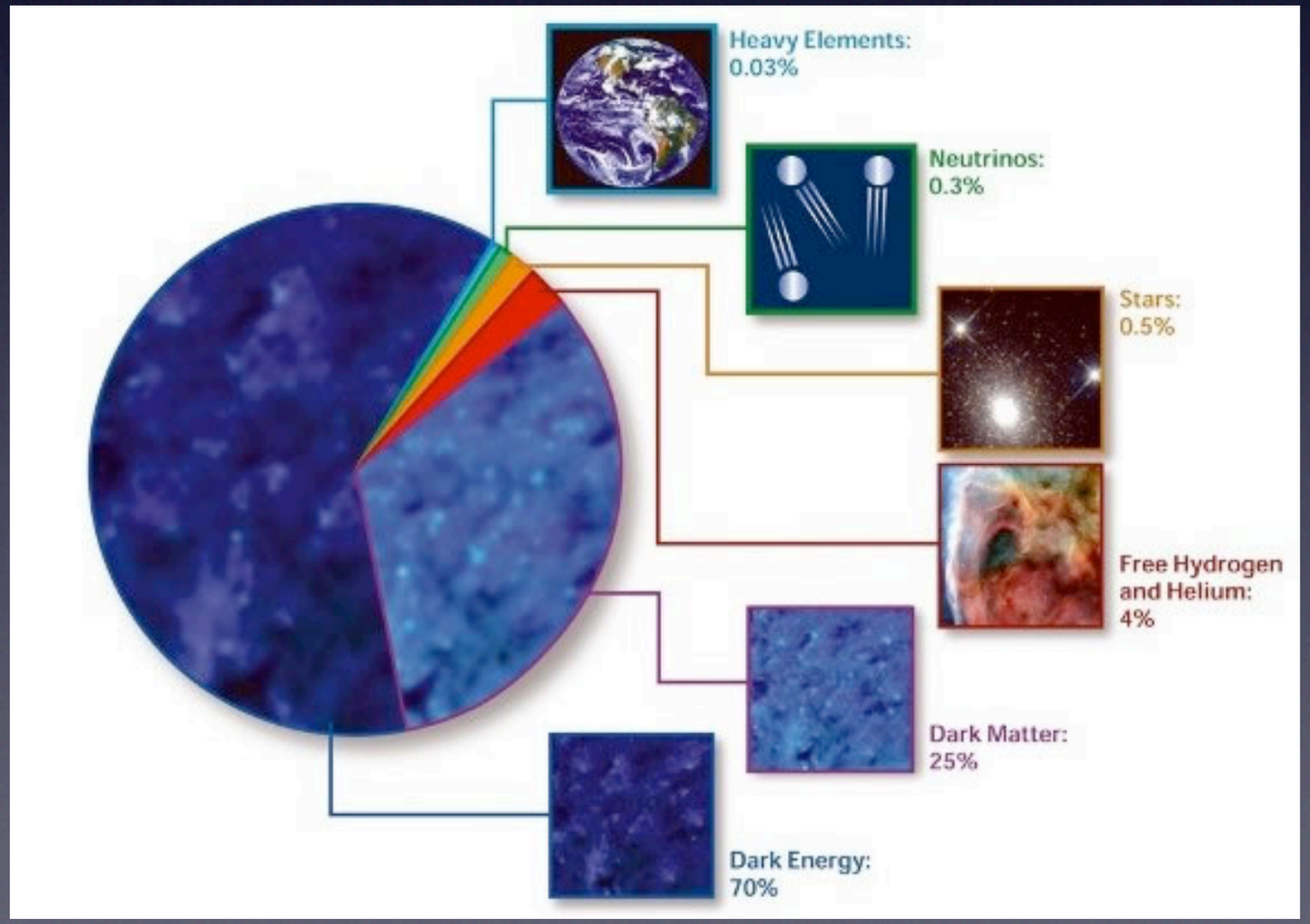

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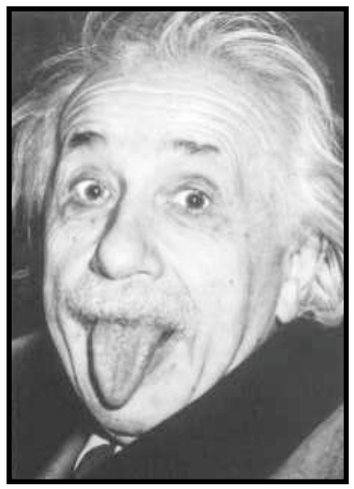
Model-Independent Measurement

Tritium β-decay allows precise measurement of the absolute neutrino mass scale.

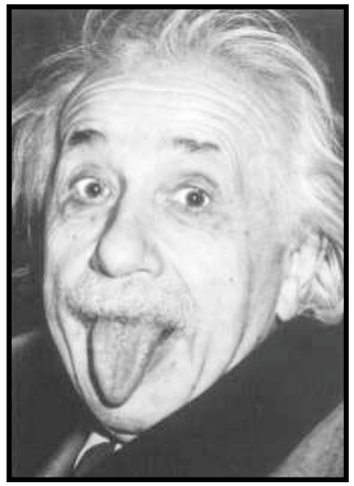
Model-Independent Measurement



From $E= mc^2$

Tritium β-decay allows precise measurement of the absolute neutrino mass scale.

Model-Independent Measurement



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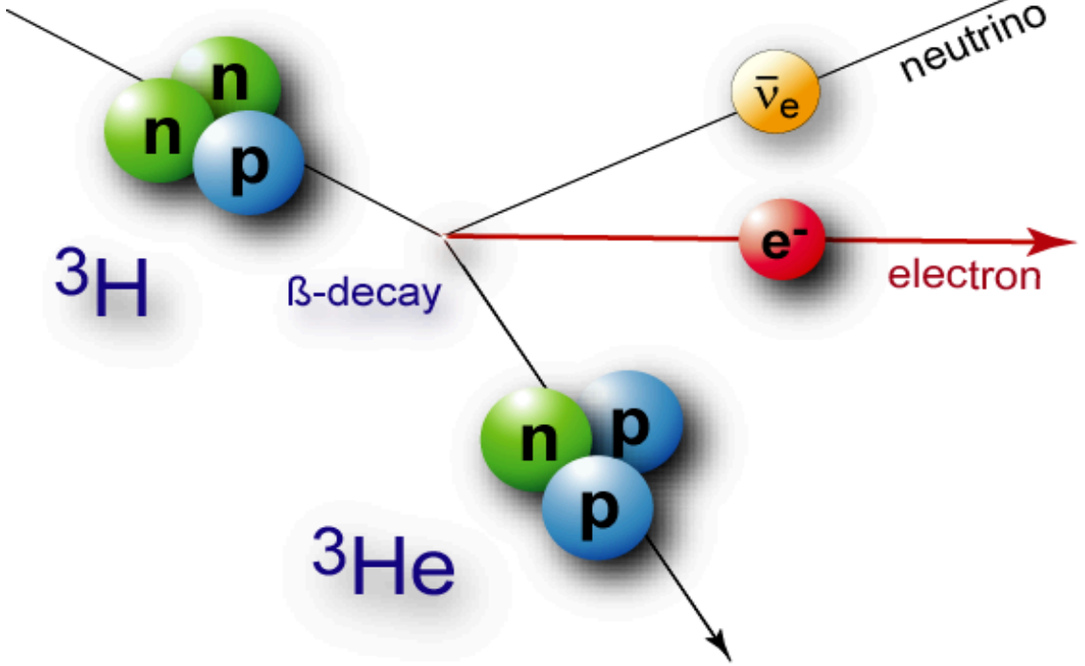
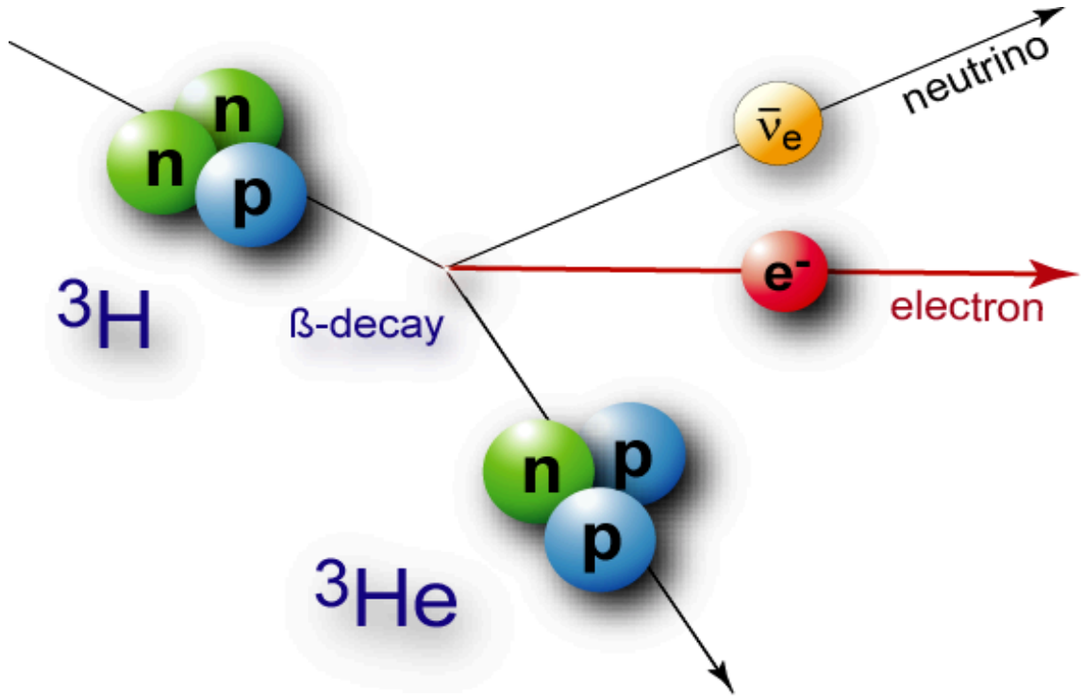


If massive, the neutrino takes away some energy...

...from the electron (which we detect)

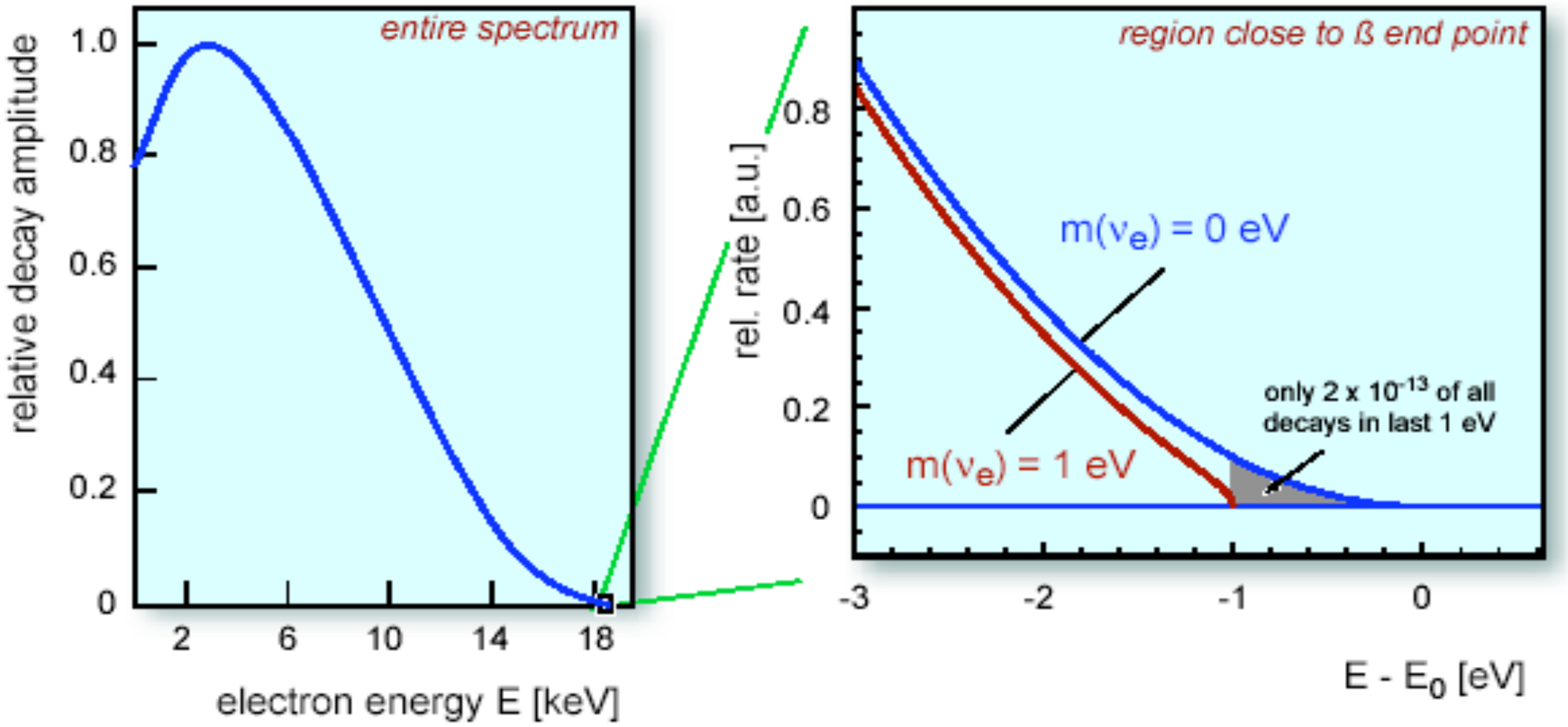
Tritium β-decay allows precise measurement of the absolute neutrino mass scale.

Measuring the Endpoint *Spectrum*



- Tritium beta decay allows for a model-independent measurement of neutrino mass.
- Search for distortion near endpoint of the beta spectrum.

Measuring the Endpoint *Spectrum*



$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

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The KArlsruhe TRItium Neutrino Experiment

(KATRIN)

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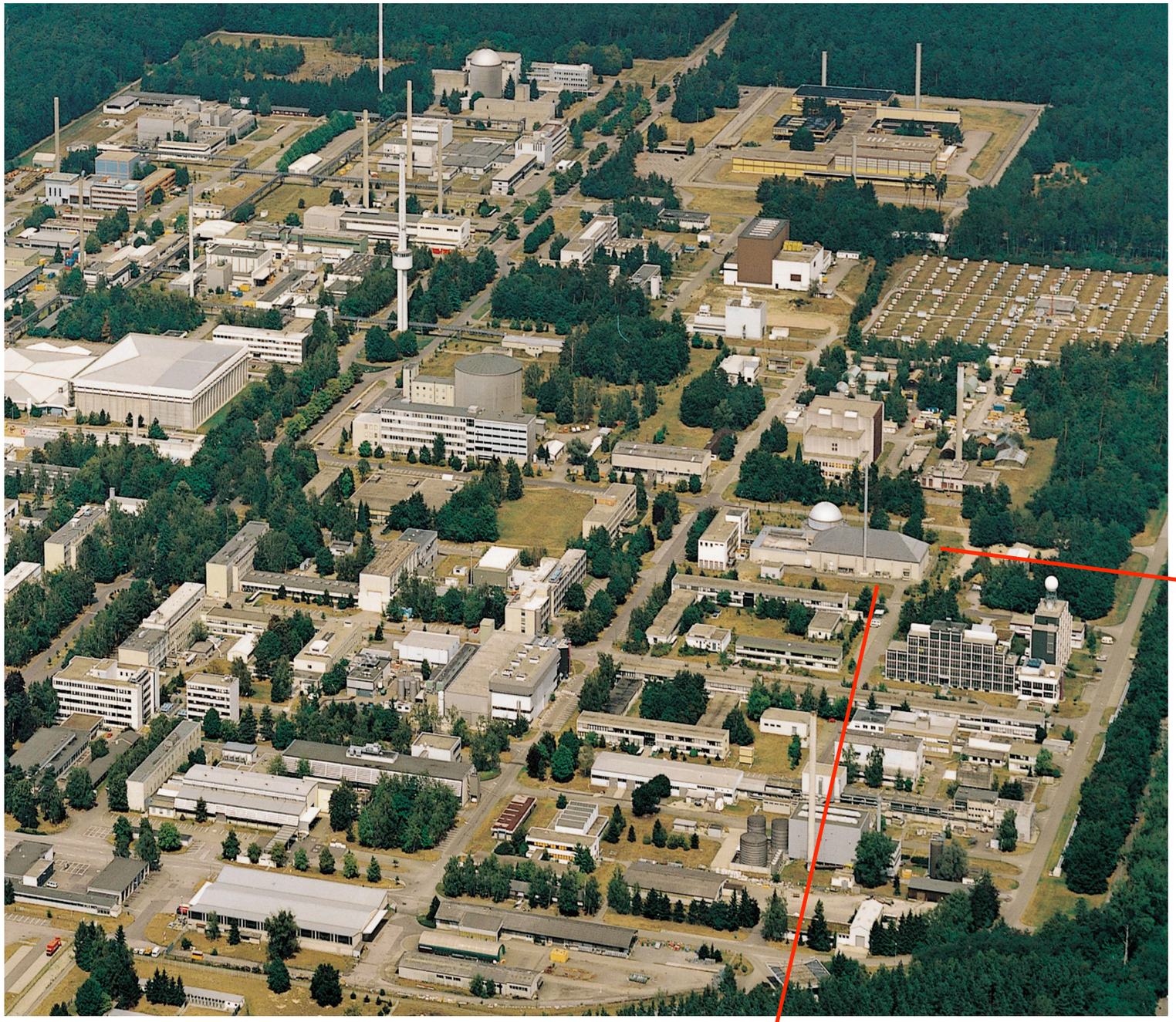
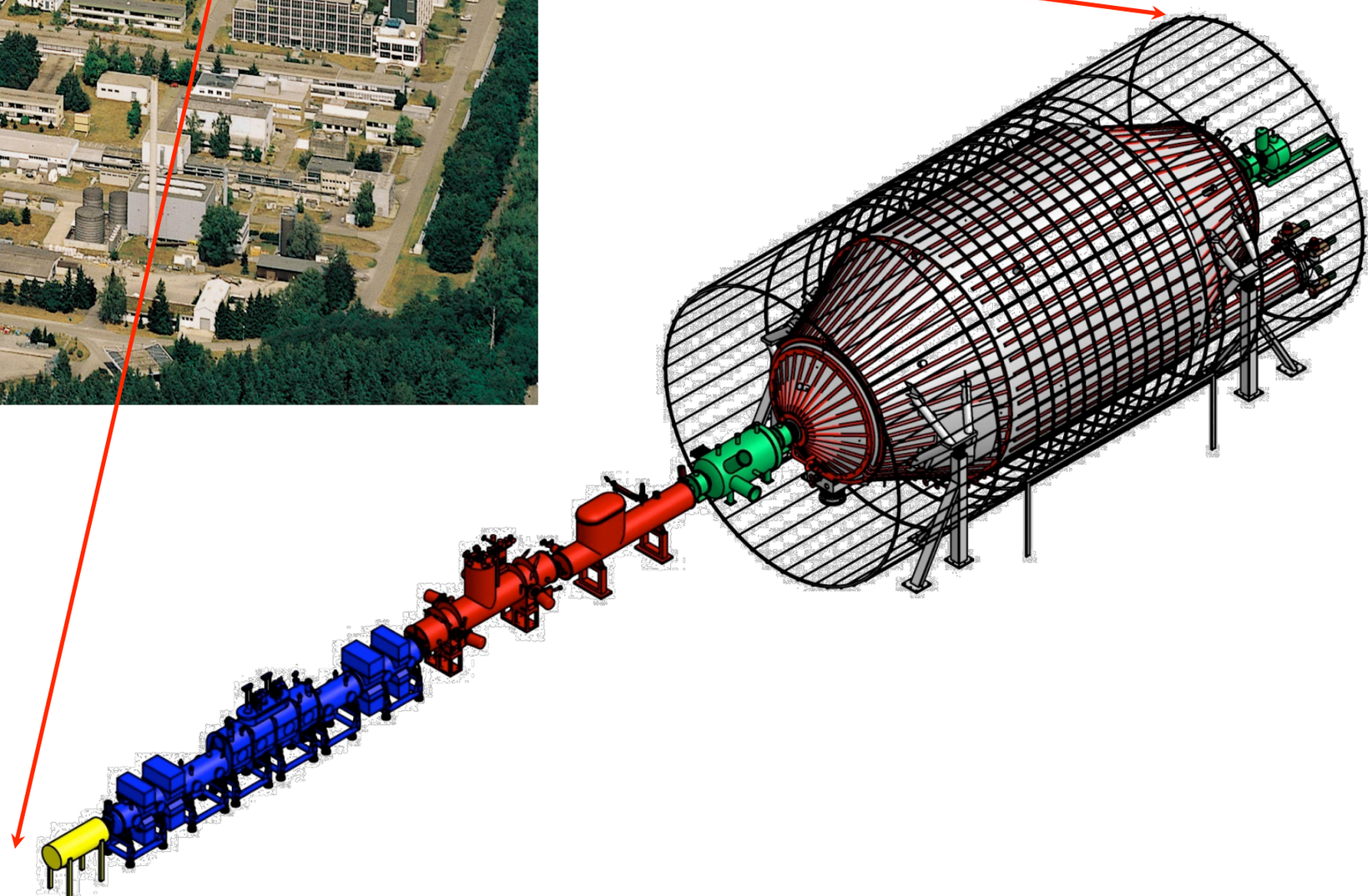
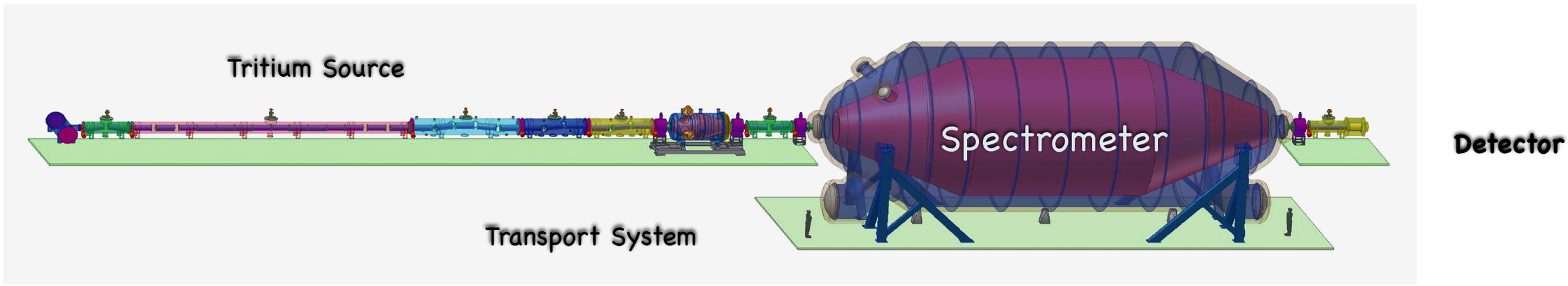
(KATRIN)





QuickTime™ and a
decompressor
are needed to see this picture.



The long journey....

Scale 1: 19,500,000

Lambert Conformal Conic Projection, standard parallels 40°N and 56°N

0 300 Kilometers

0 20 300 Miles

journey....

Scale 1: 19,500,000
Lambert Conformal Conic Projection,
standard parallels 40°N and 56°N
0 300 Kilometers
0 300 Miles
20

The long journey....

Ocean
Belfast
UNITED
Sea
DENMARK
Copenhagen
Malmö
Oland
Kaliningrad
RUSSIA
Vilnius
LITHUANIA
Minsk
Mahilyow
Dnepro
Isle of Man (U.K.)
Irish Sea
Dublin
IRELAND
Leeds
Manchester
Liverpool
KINGDOM
Bornholm
Gdańsk
Hrodna
BELARUS
Homyel'
Hamburg
Bremen
Berlin
Warsaw
Brest
Poznań
POLAND
Kiev
Cardiff
Birmingham
Amsterdam
NETH.
Rotterdam
Oder
Łódź
Rivne
Celtic Sea
London
Essen
Cologne
Leipzig
Elbe
Wrocław
Vistula
Dnipro
Brussels
Lille
BEL.
Bonn
GERMANY
Prague
Kraków
L'viv
UKRAINE
Guernsey (U.K.)
Jersey (U.K.)
Frankfurt am Main
CZECH REPUBLIC
Brno
SLOVAKIA
CARPATHIANS
Chernivtsi
Mykolayiv
Luxembourg
LUX.
Paris
Seine
Stuttgart
Bratislava
Chișinau
Strasbourg
Rhine
Munich
Danube
Vienna
Budapest
Cluj-Napoca
Iași
MOLDOVA
Nantes
Loire
LIECH.
AUSTRIA
Zürich
Bern
Vaduz
HUNGARY
ROMANIA
Bay of Biscay
SWITZ.
Geneva
FRANCE
Ljubljana
Zagreb
Bucharest
SLOVENIA
MASSIF CENTRAL
Lyon
Milan
Venice
Turin
Po
Bordeaux
BOSNIA AND HERZEGOVINA
Belgrade
Varna
Genoa
SAN MARINO
CROATIA
Sarajevo
Serbia
BULGARIA
Sofia
Bilbao
Toulouse
MONACO
Ligurian Sea
Florence
Marseille
Adriatic Sea
Istanbul
Porto
Andorra la Vella
PYRENEES
ANDORRA
Zaragoza
Corsica
ITALY
Rome
Podgorica
Skopje
F.Y.R.O.M.
Bursa
VATICAN CITY
Tirana
ALB.
Thessaloniki
Naples
TURKE
Sardinia
Tyrrhenian Sea
Aegean Sea
Izmir
GREECE
Athens
Cagliari
Ionian Sea
Palermo
Rhodes
Sicily
Crete
Tunis
Valletta
MALTA
TUNISIA
MOROCCO
ALGERIA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
0 300 Kilometers
0 300 Miles
20

The long

Ocean
Sea
UNITED
KINGDOM
Belfast
Isle of Man (U.K.)
Irish Sea
Dublin
IRELAND
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
NETH.
Amsterdam
Rotterdam
Brussels
Lille
BEL.
Bonn
Essen
Cologne
Leipzig
GERMANY
Guernsey (U.K.)
Jersey (U.K.)
Paris
Luxembourg
LUX.
Frankfurt am Main
Stuttgart
Strasbourg
Munich
Nantes
Loire
Rhine
Elbe
Hamburg
Bremen
Berlin
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
RUSSIA
Gdańsk
Poznań
Oder
POLAND
Warsaw
Łódź
Wrocław
Vistula
Brest
Hrodna
BELARUS
Minsk
Mahilyow
Homyel'
Dnepro
Kiev
Rivne
L'viv
UKRAINE
Kraków
Prague
CZECH REPUBLIC
Brno
SLOVAKIA
Bratislava
Vienna
AUSTRIA
Danube
Budapest
HUNGARY
CARPATHIAN MTS.
Chernivtsi
Cluj-Napoca
Iaşi
MOLDOVA
Chişinau
Mykolayiv
ROMANIA
Bucharest
Varna
Black Sea
Ljubljana
SLOVENIA
Zagreb
BOSNIA AND HERZEGOVINA
Belgrade
CROATIA
SAN MARINO
Sarajevo
Serbia
BULGARIA
Sofia
Montenegro
Podgorica
Skopje
F.Y.R.O.M.
Tirana
ALB.
Thessaloniki
Istanbul
Bursa
İzmir
Aegean Sea
GREECE
Athens
Rhodes
Crete
ITALY
Adriatic Sea
Rome
Naples
Tyrrhenian Sea
Ionian Sea
Palermo
Sicily
Valletta
MALTA
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Melilla (SPAIN)
Oran
Algiers
Tunis
Rabat
Casablanca
MOROCCO
ALGERIA
TUNISIA
Scale 1: 19,500,000
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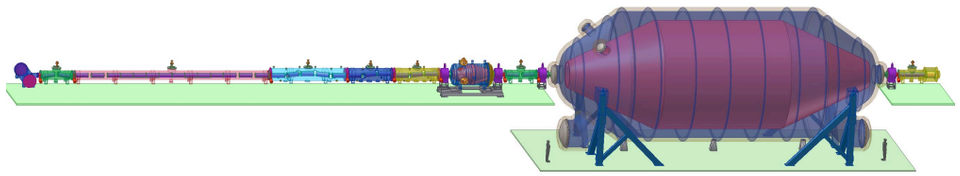
20

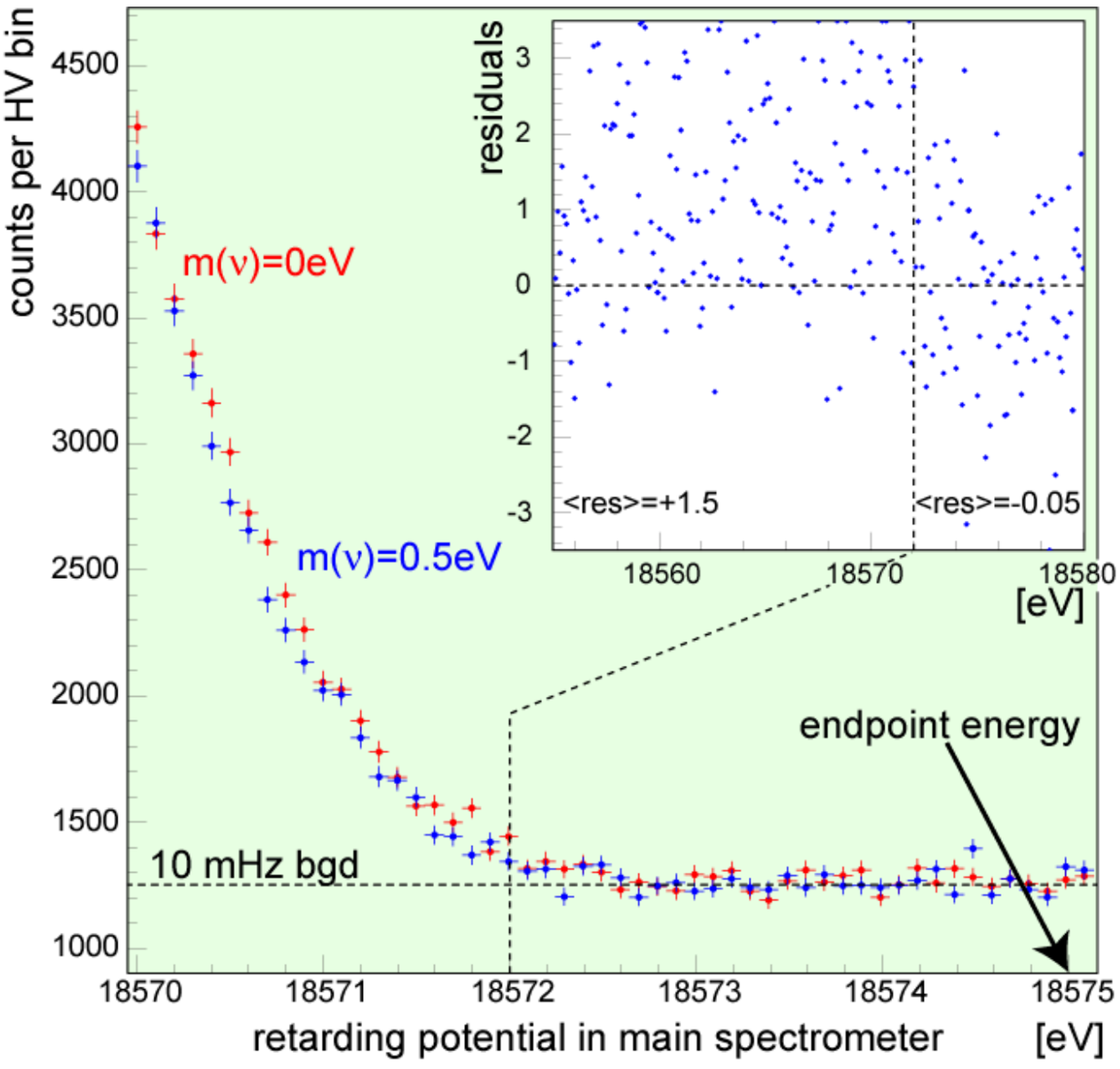

PHOTO
DRIVE

KATRIN Lands!

KATRIN Lands!



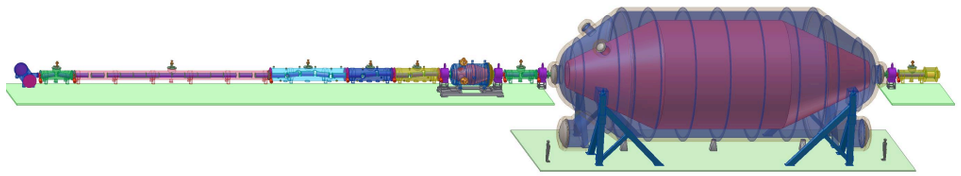
Final Sensitivities



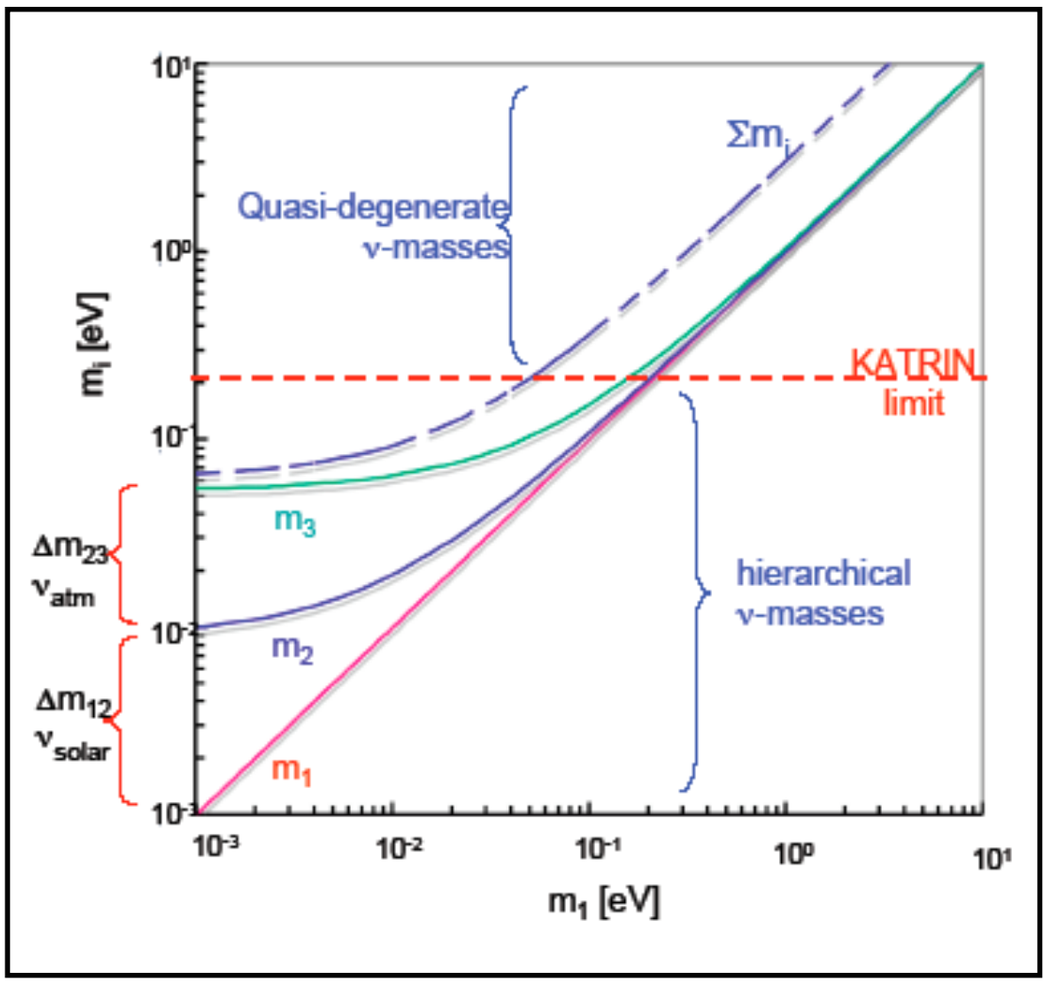
Final Sensitivities:

- Concentrating on last 10 eV of spectrum allows control of most theoretical uncertainties.

- Statistical & systematic uncertainties equalize after 3 years of data.



Final Sensitivities



Final Sensitivities:

- Concentrating on last 10 eV of spectrum allows control of most theoretical uncertainties.

- Statistical & systematic uncertainties equalize after 3 years of data.

Sensitivity

$m_\nu < 200$ meV (90% C.L.)

$m_\nu < 350$ meV (5σ level)

Twilight, again...

- SNO has completed its three-phase program, providing an accurate measurement on the mixing parameters of the solar sector.

- We are now beginning a new chapter in the question of neutrino masses, as we transition from asking "Do neutrinos have mass?" to "What does this all mean?"

- More answers to be sought as a new day begins...

Fin