Neutrino Oscillations

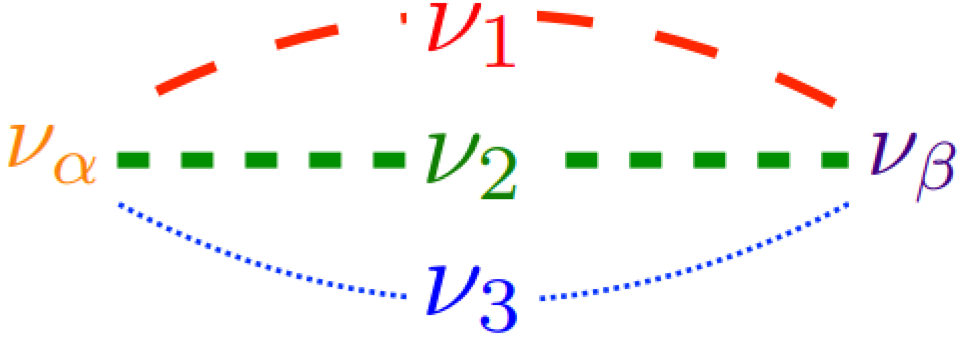
Dan Pershey (Florida State University) – Jul 18, 2024

Second school on neutrino and dark matter detection
South American Institute for Fundamental Research

Neutrino oscillations

Produced and detected in flavor basis but travel in mass basis

Interference of mass states → flavor transitions



Neutrino mixing encoded in PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Atmospheric   Reactor   Solar

Parameters to measure

		3 σ ranges
3 Euler angles	θ_{12}	32 – 38 deg
	θ_{13}	8.0 – 8.9 deg
	θ_{23}	42 – 51 deg
2 mass splittings	$\|\Delta^2_{12}\|$	(7.1 – 8.2) e-5 eV^2
	$\|\Delta^2_{32}\|$	(2.33 – 2.54) e-3 eV^2
CP violation	δ_{CP}	157 – 349 deg

For today: cover historical experiments that determined five known parameters

Solar, atmospheric, and reactor neutrinos

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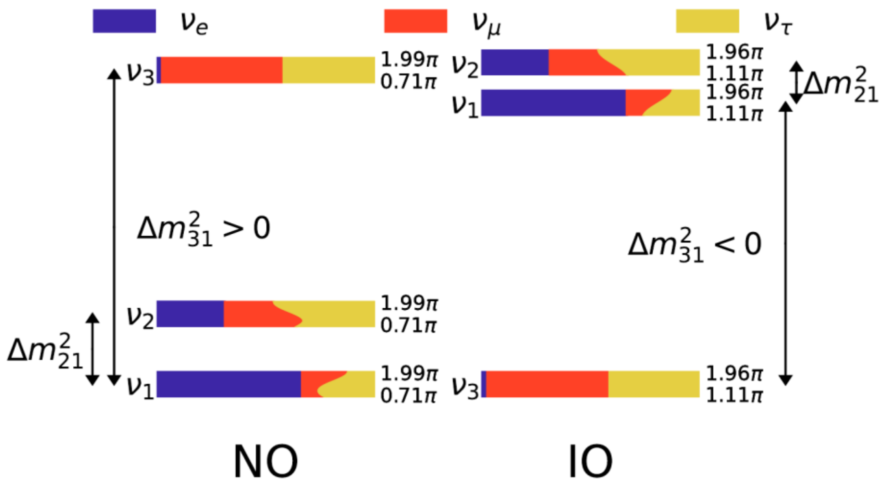
Tomorrow: efforts to answer remaining questions

Is CP conserved?

Is θ_{23} 45 deg? And if not, is it > or < 45 deg?

Is ν_2 or ν_3 the most massive state?



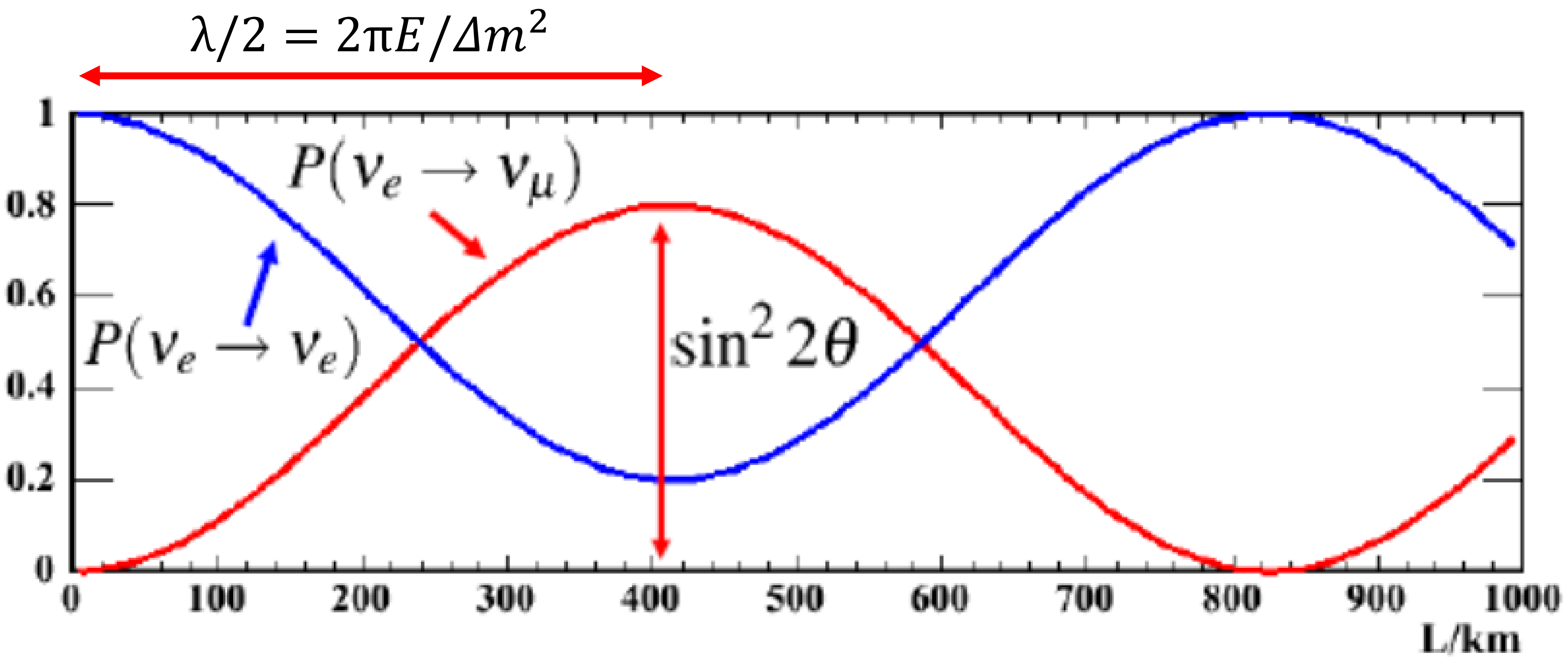
Two-flavor oscillations

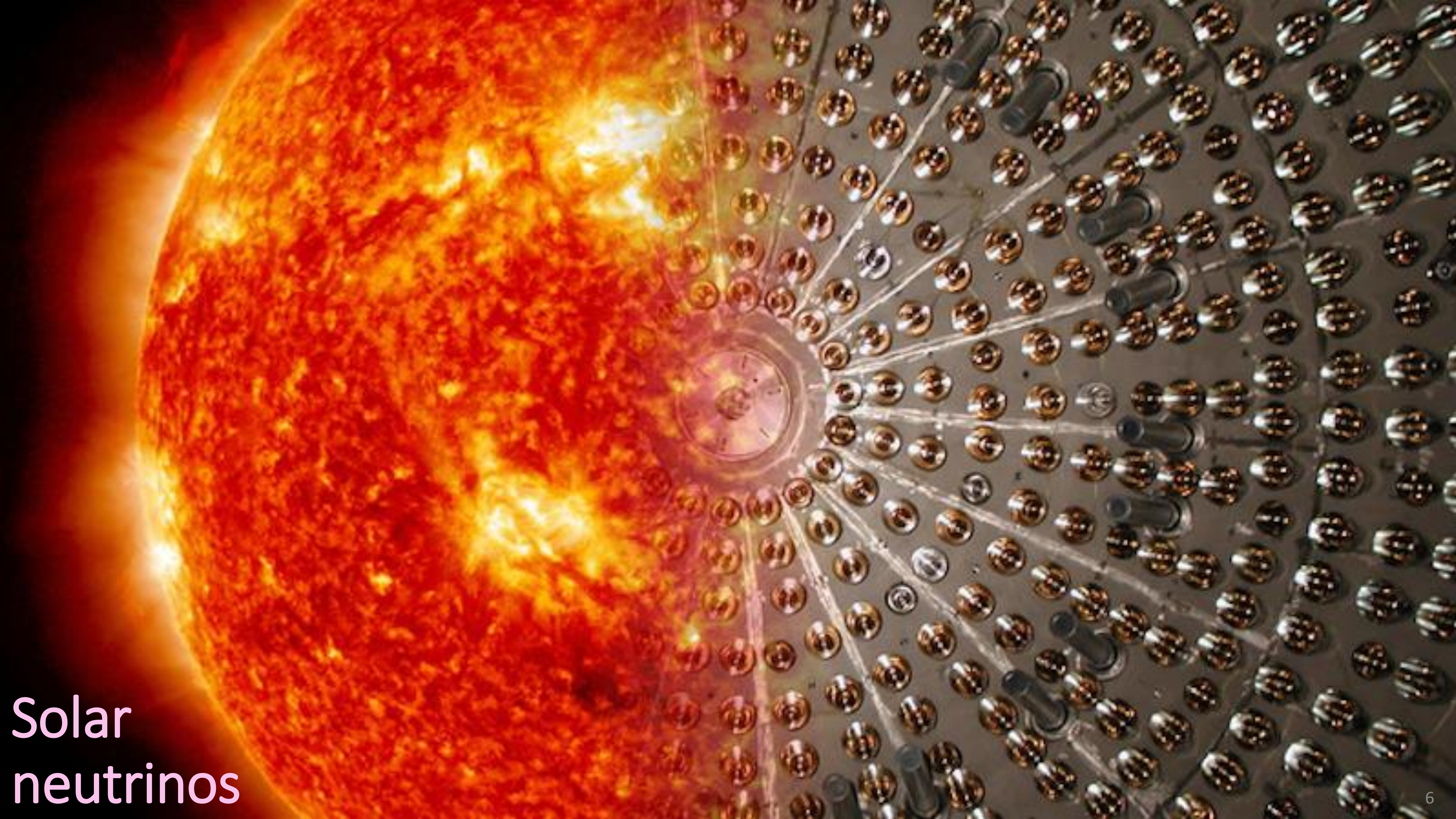
$$\frac{\Delta m^2_{32}}{\Delta m^2_{21}} \sim 30$$

Oscillations at different length scales – they factor

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta}$$

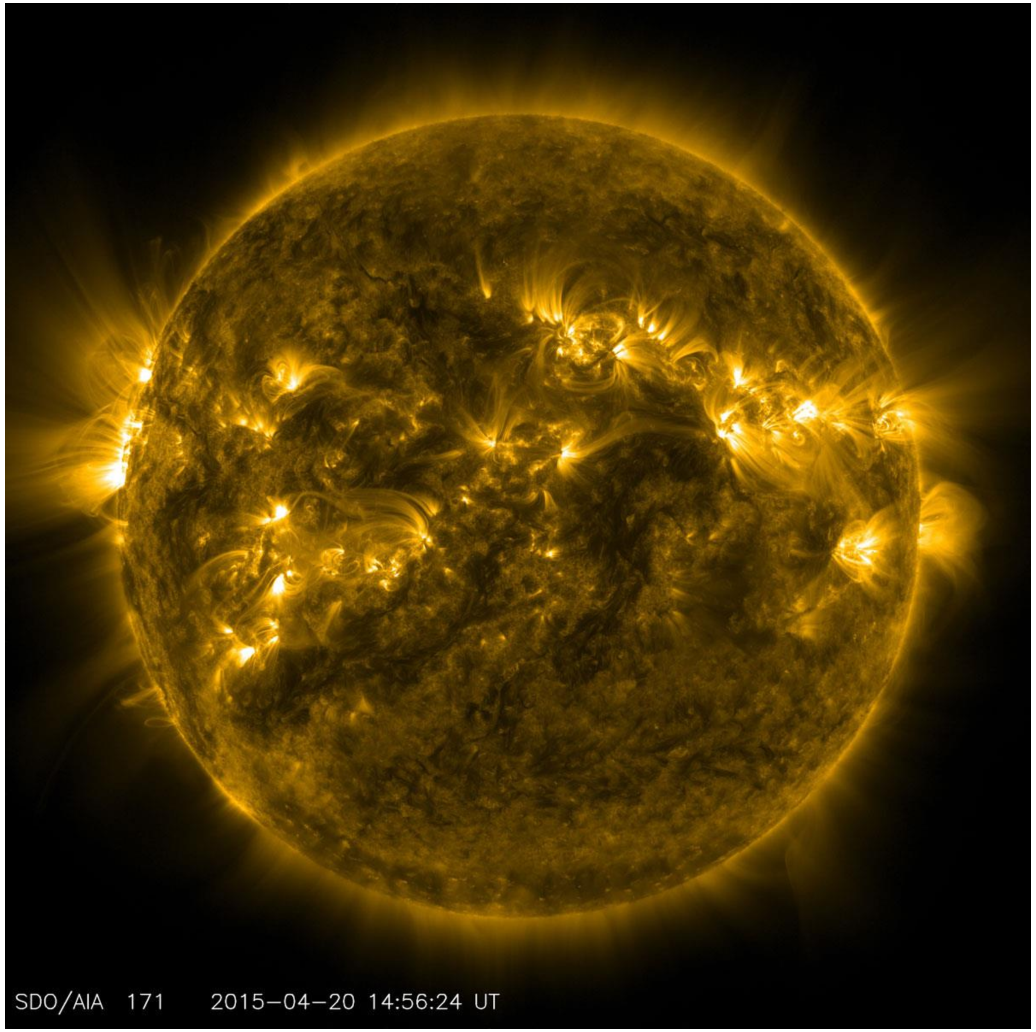


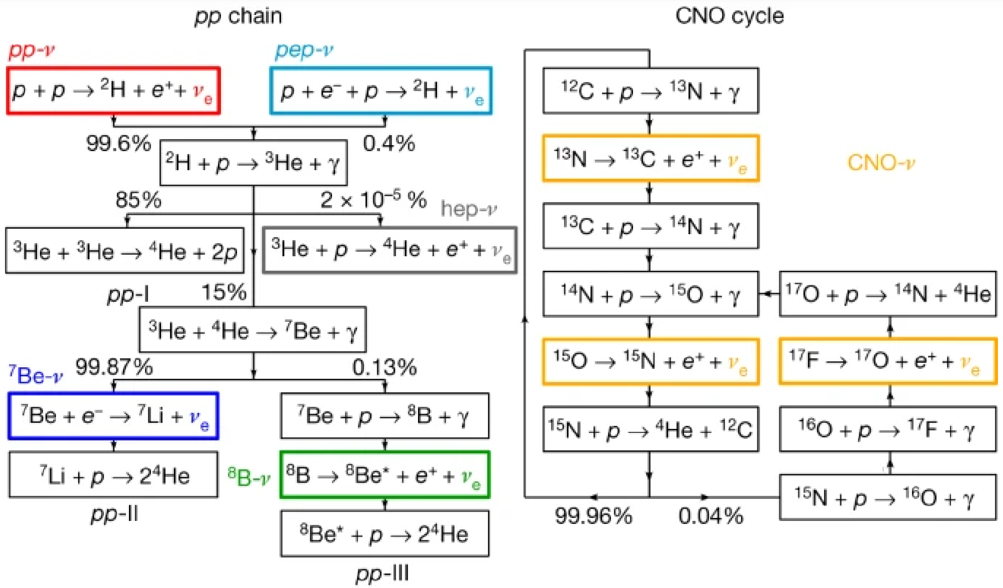


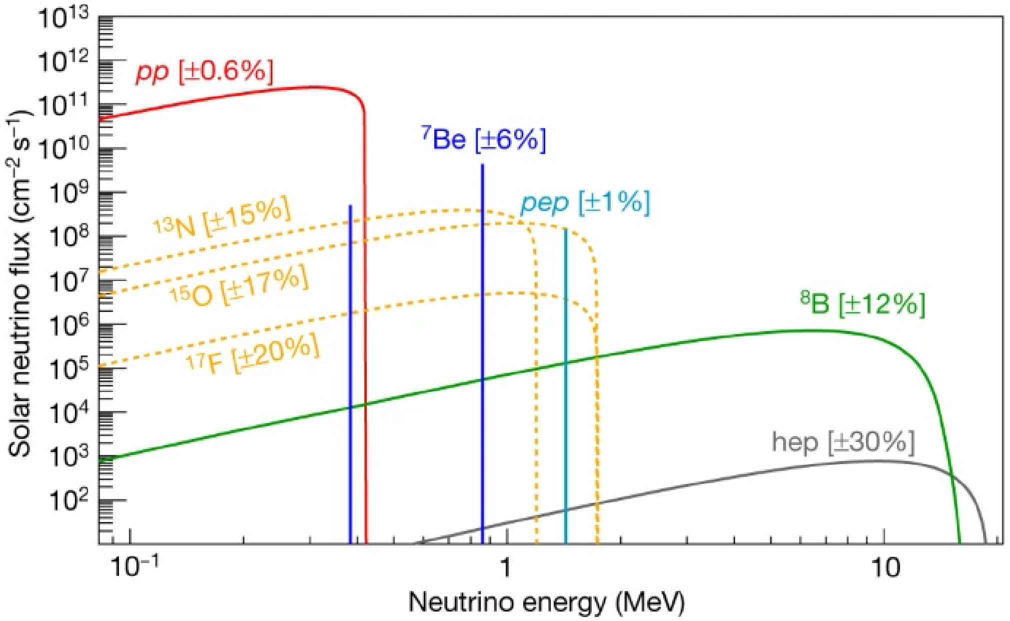
Solar neutrinos

Solar neutrinos

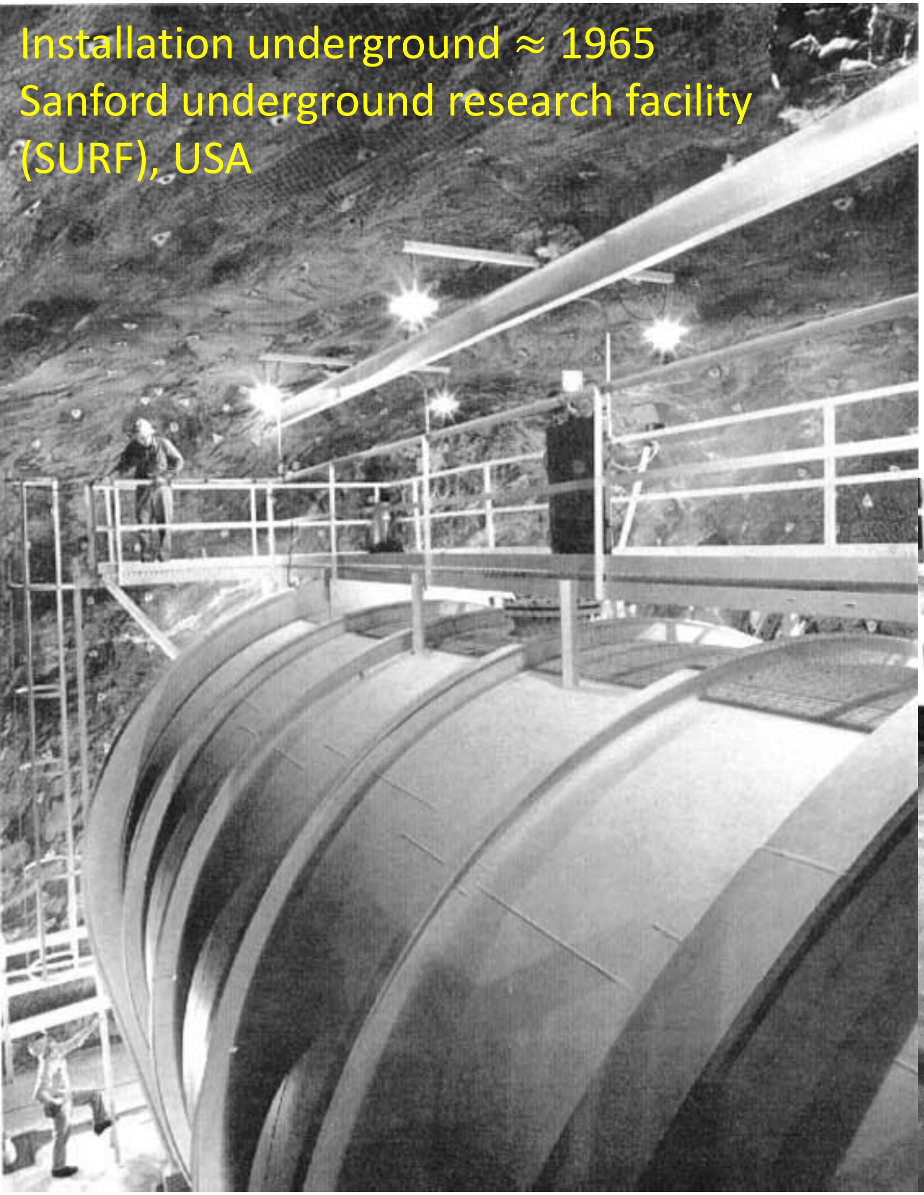
Nuclear processes that fuel the sun also produce neutrinos – huge flux physicists can study







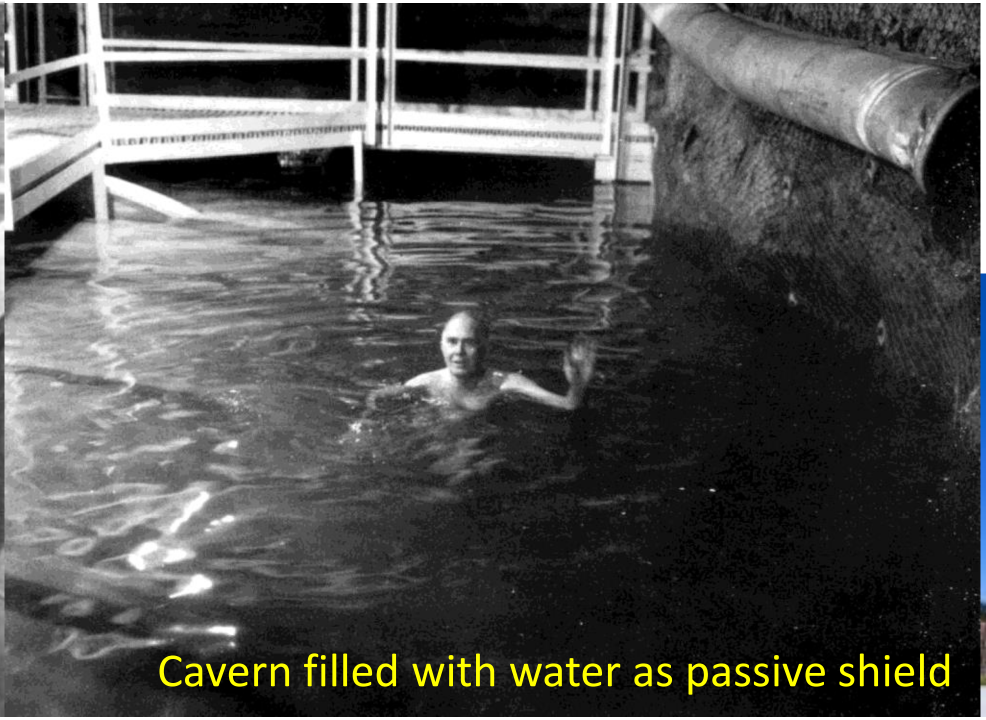
The Davis experiment



Ray Davis searched for solar neutrinos via:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} \quad E_\nu > 814\ \mathrm{keV}$$

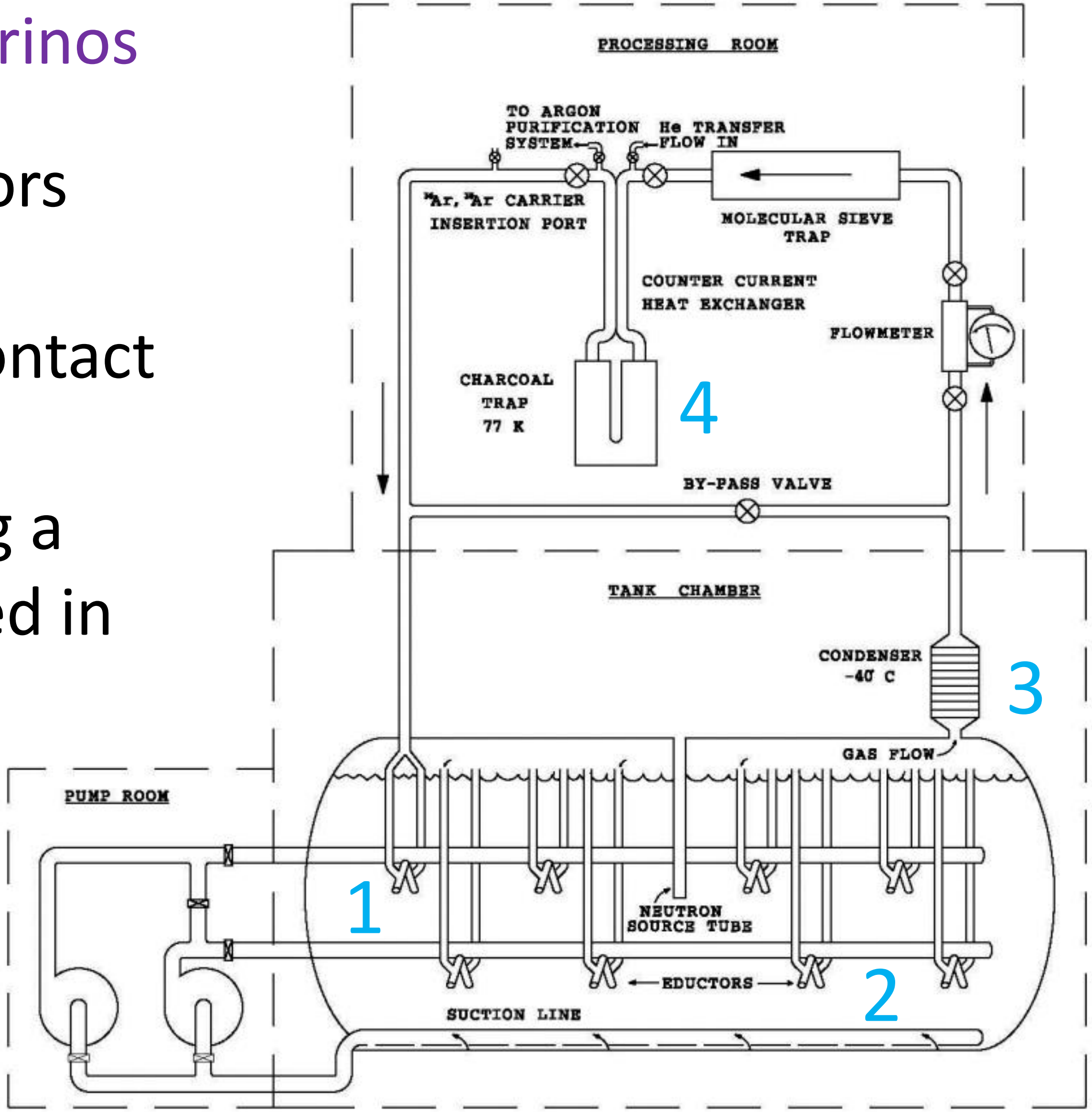
Built 620 ton tank of dry cleaning fluid (C_2Cl_4) and observed ≈ 15 interactions / month for 30 yrs



A chemist's neutrino experiment

Chemistry experiment discovered solar neutrinos

1: C_2Cl_4 pumped through system with eductors introducing bubbles of He into tank
2: Argon is a noble gas! Argon atoms that contact a He bubble get absorbed in gaseous state
3: Gaseous bubbles escape the tank entering a gaseous processing line. C_2Cl_4 vapor removed in -40 C condenser
4: Gas routed through liquid N_2 cooled charcoal trap. Argon freezes, He passes
5: Monthly, solate charcoal trap and heat, count ^{37}Ar decays in proportional counter



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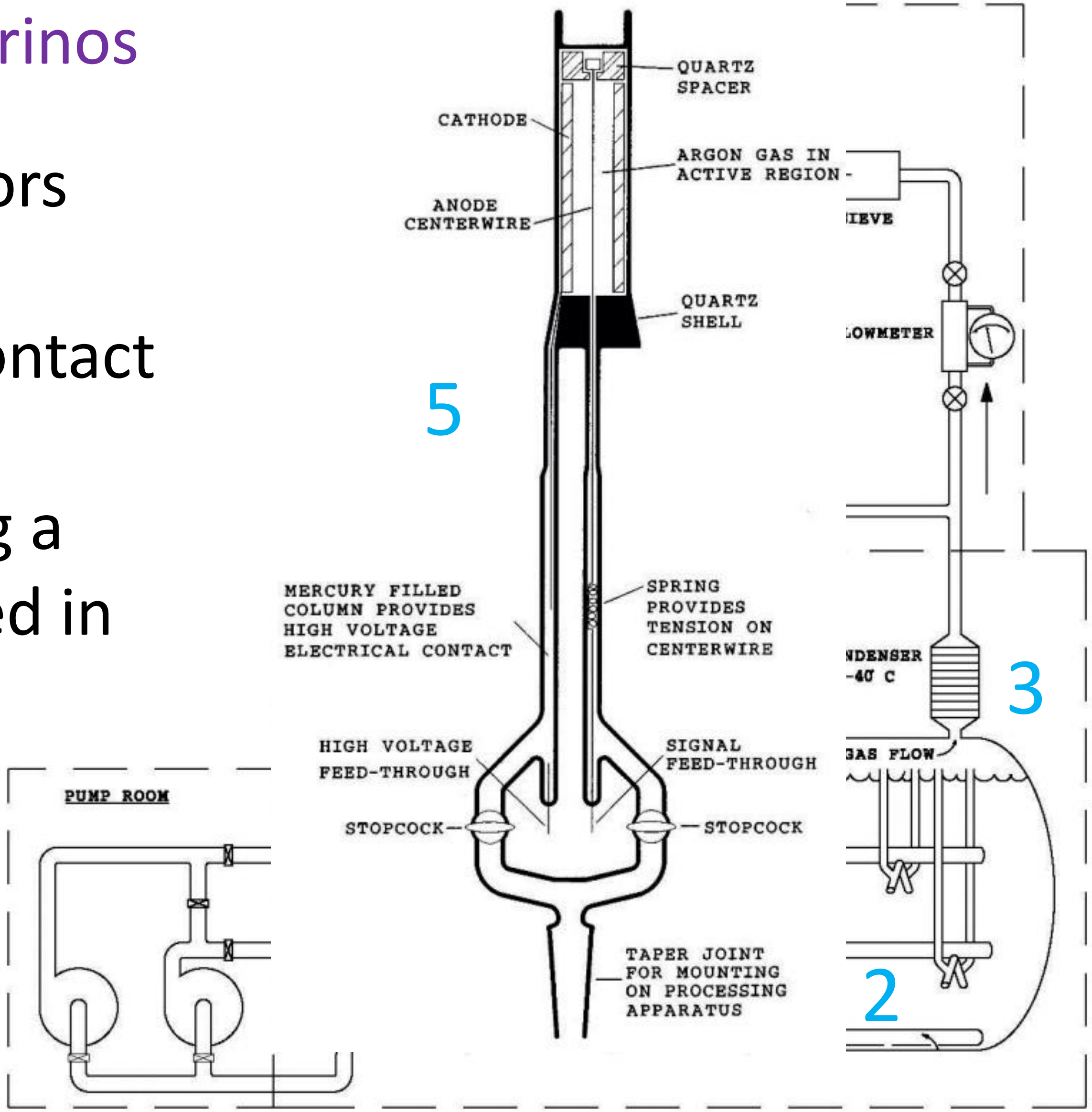
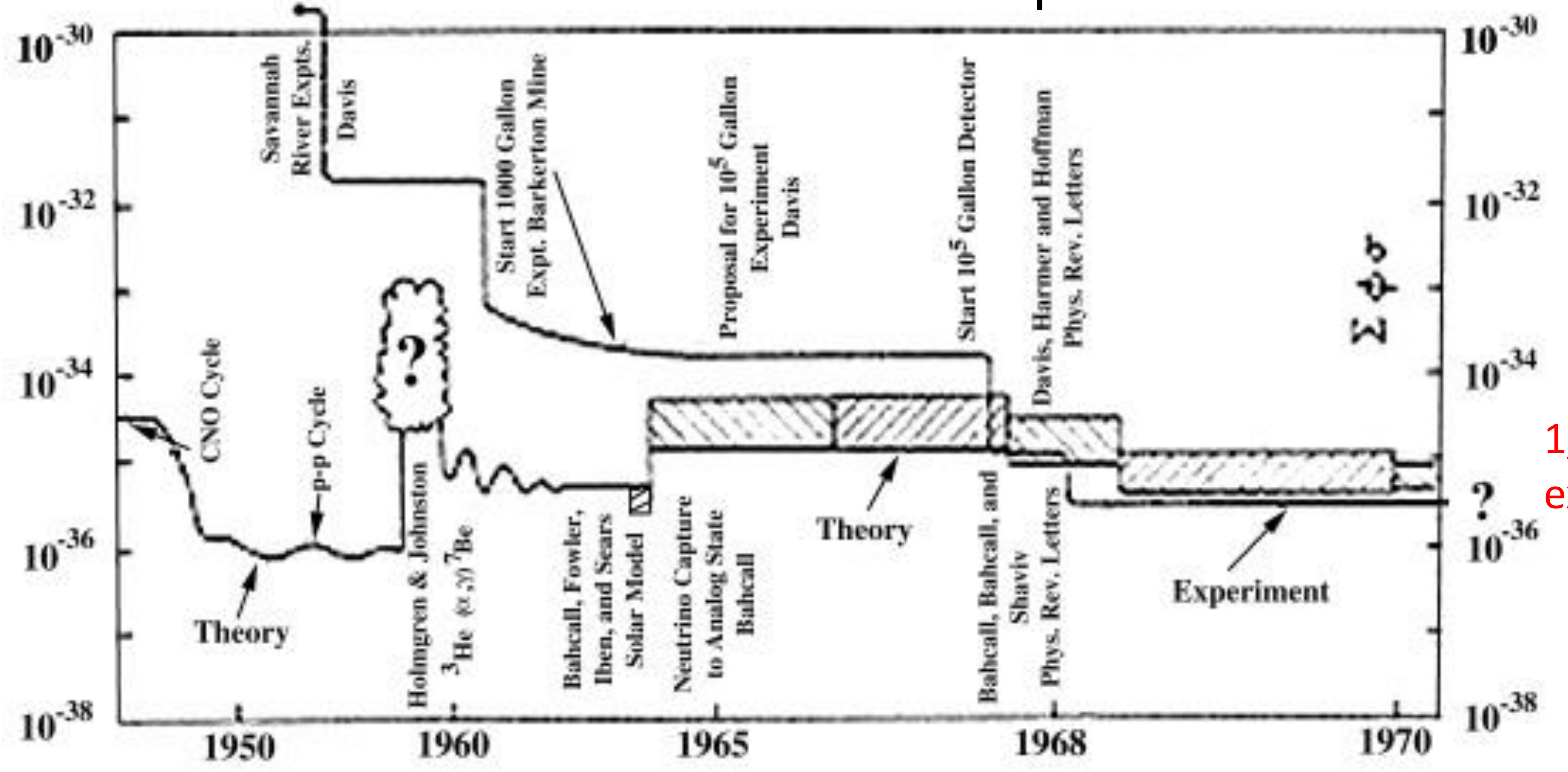


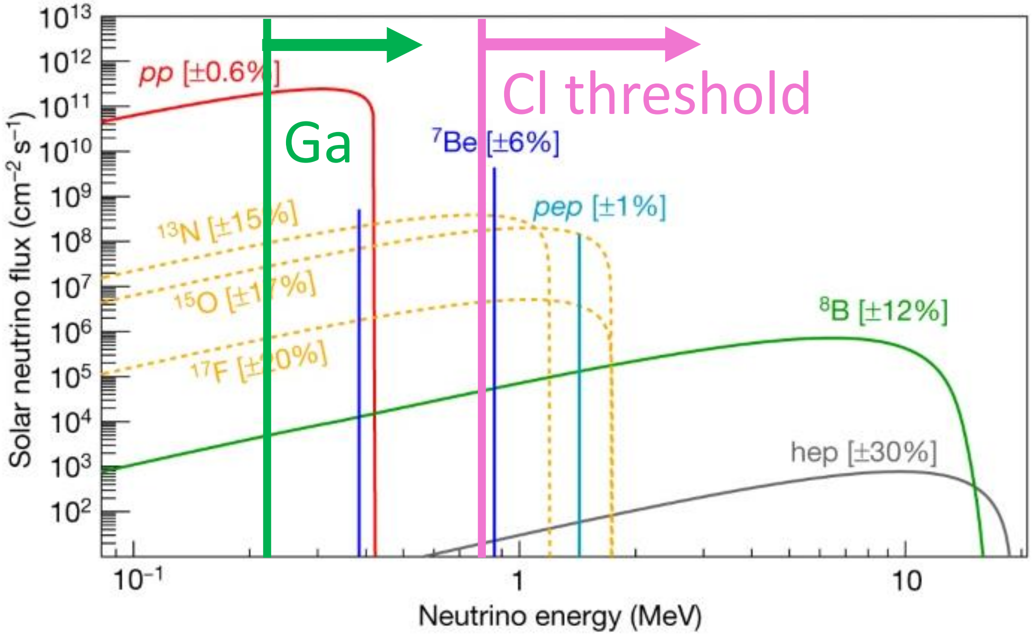
Discovering neutrinos – with a catch

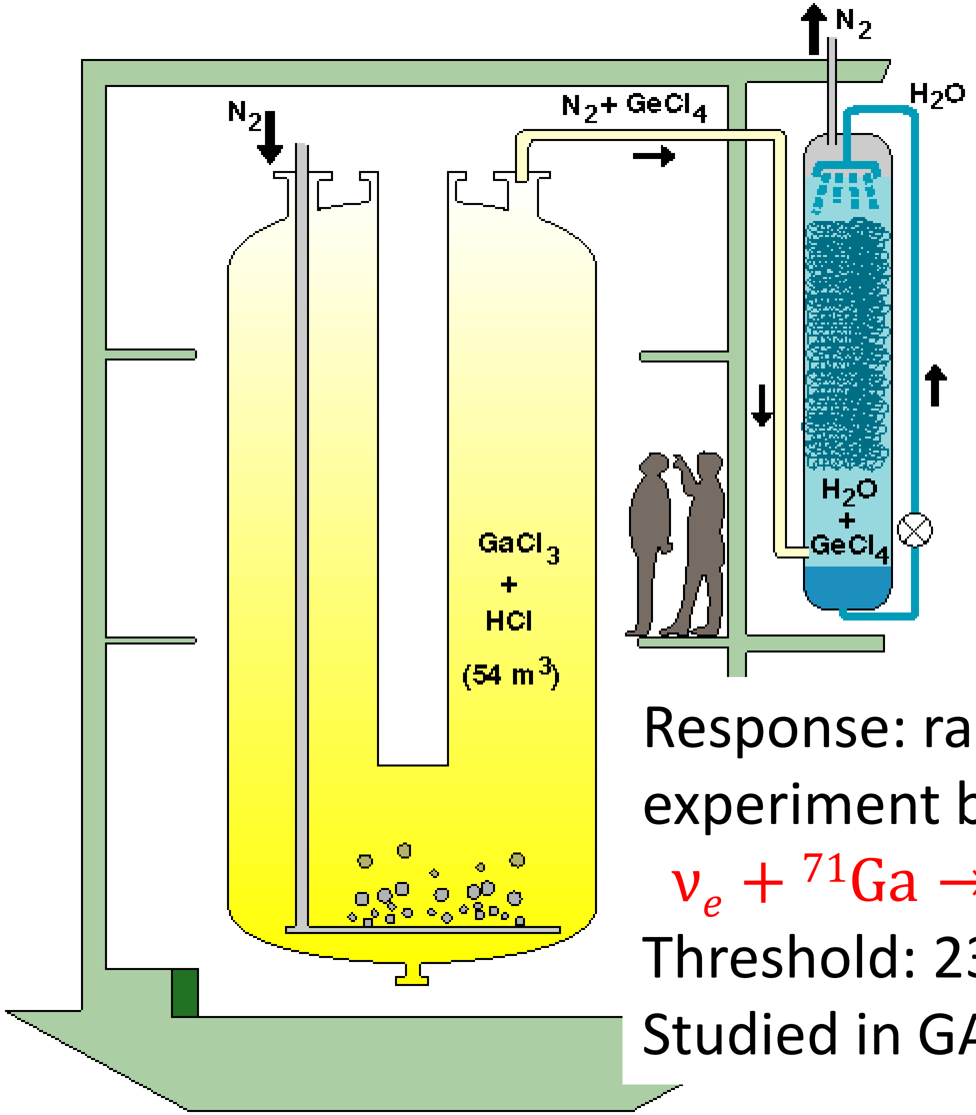
The solar neutrino problem



1/3 the rate expected!

Cross-checking with gallium experiments





– By 1980s, we – understood the Davis experiment was right

– 99% of solar neutrinos from p+p->d+e^++ν_e

– Maybe, the lower-flux, higher-energy processes mis-modeled due to theory uncertainties in the sun. Measure pp!

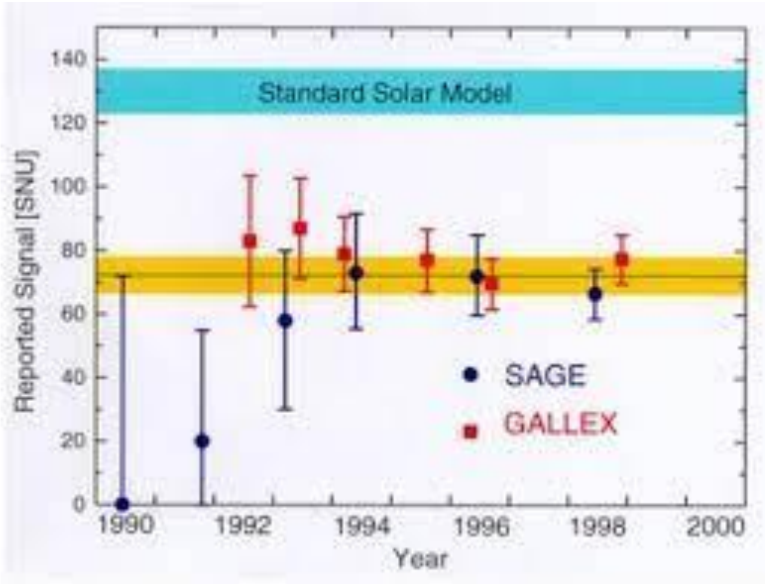
Response: radiochemical experiment based on Ga

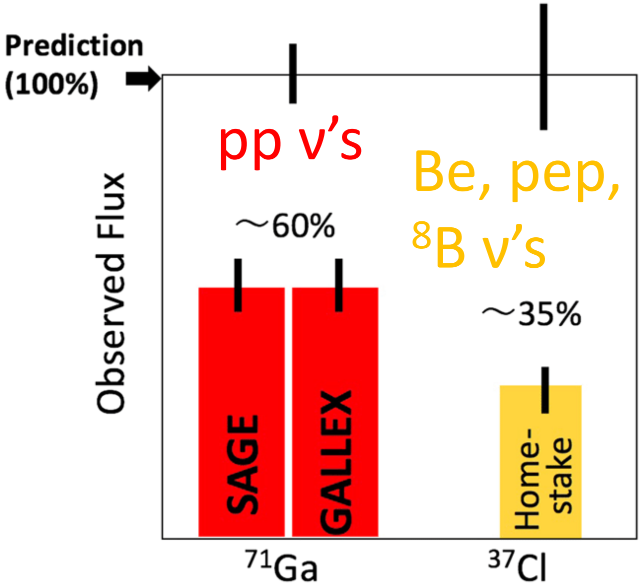
$$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$$

Threshold: 233 keV

Studied in GALLEX, SAGE

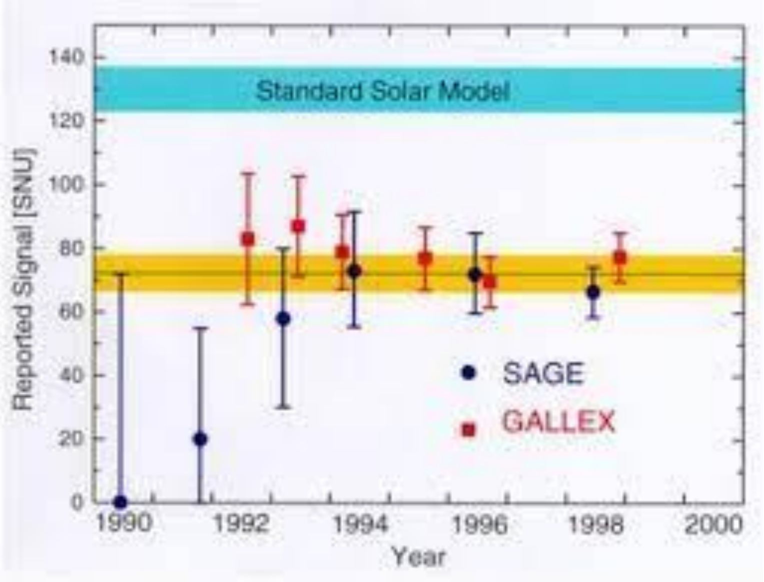
A decade of gallium data: the plot thickens

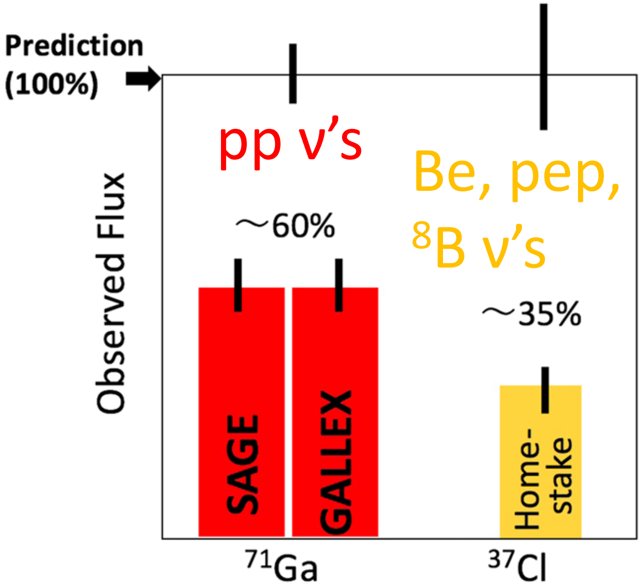




Gallium also sees a deficit! But it's different from Davis. Energy dependence?

A decade of gallium data: the plot thickens





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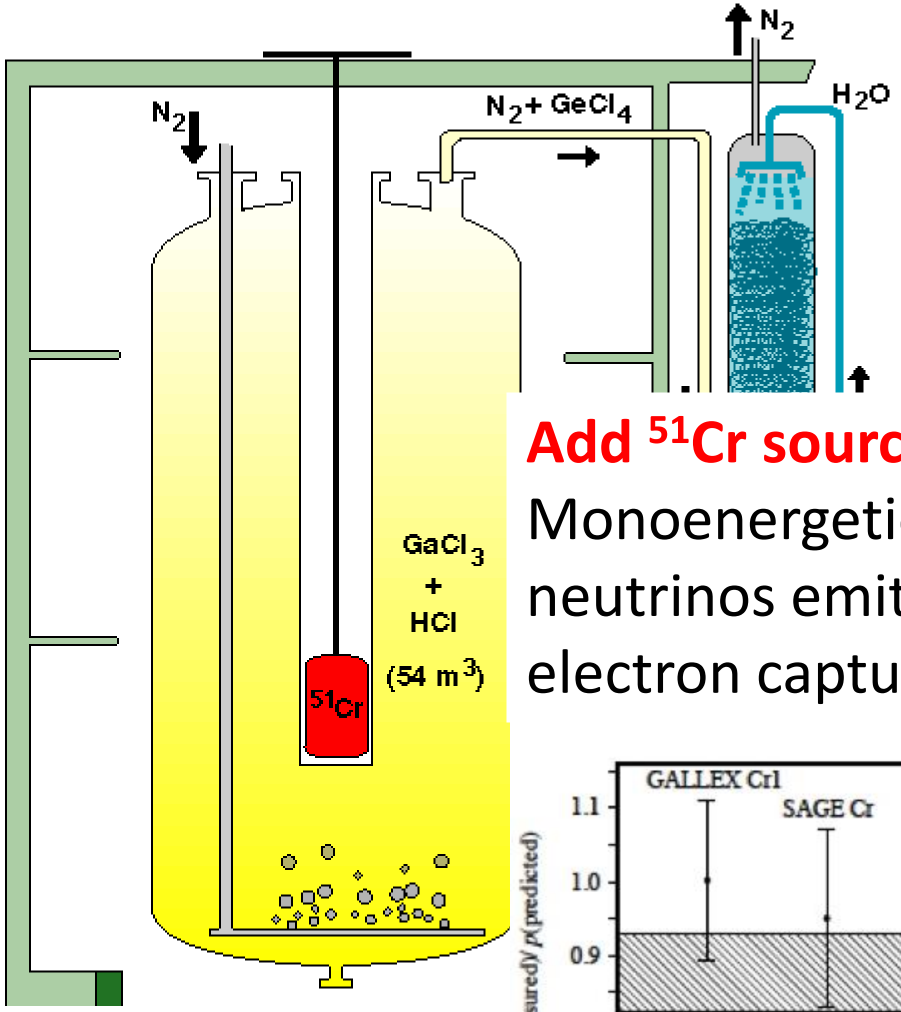
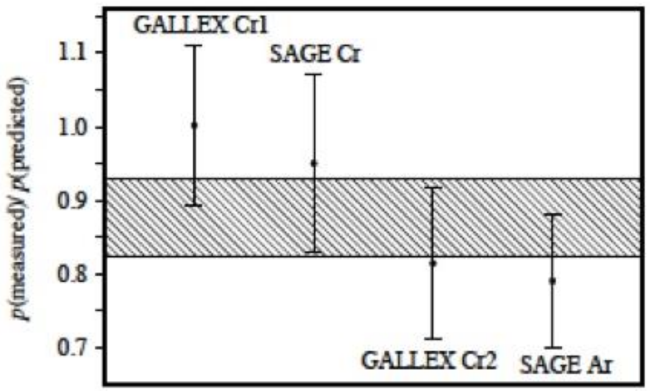
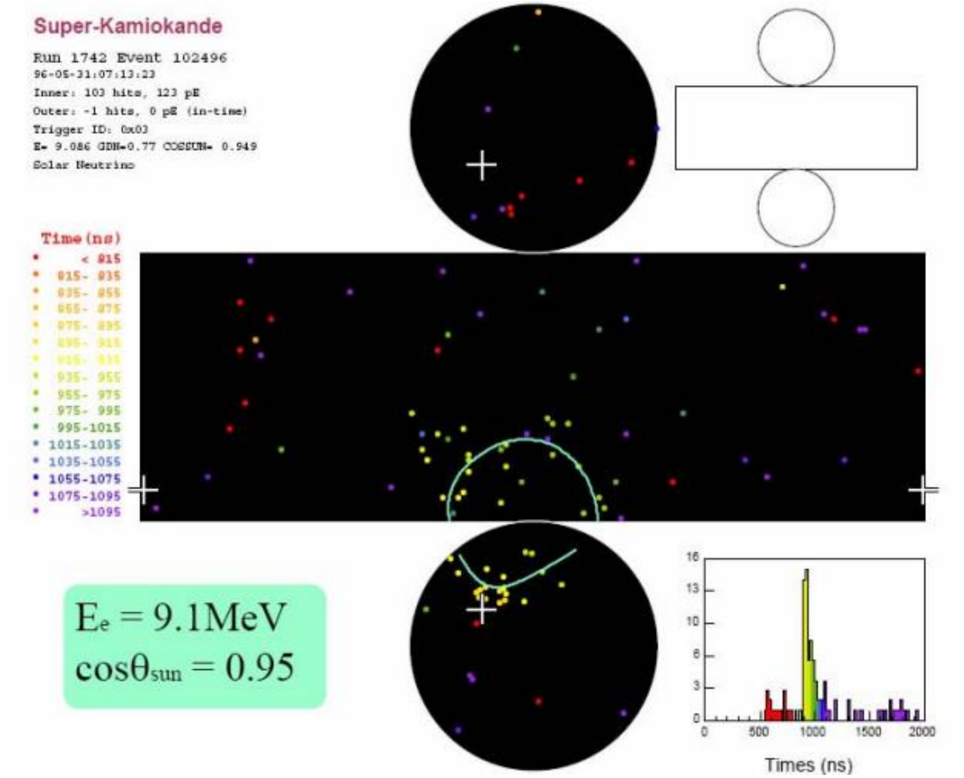


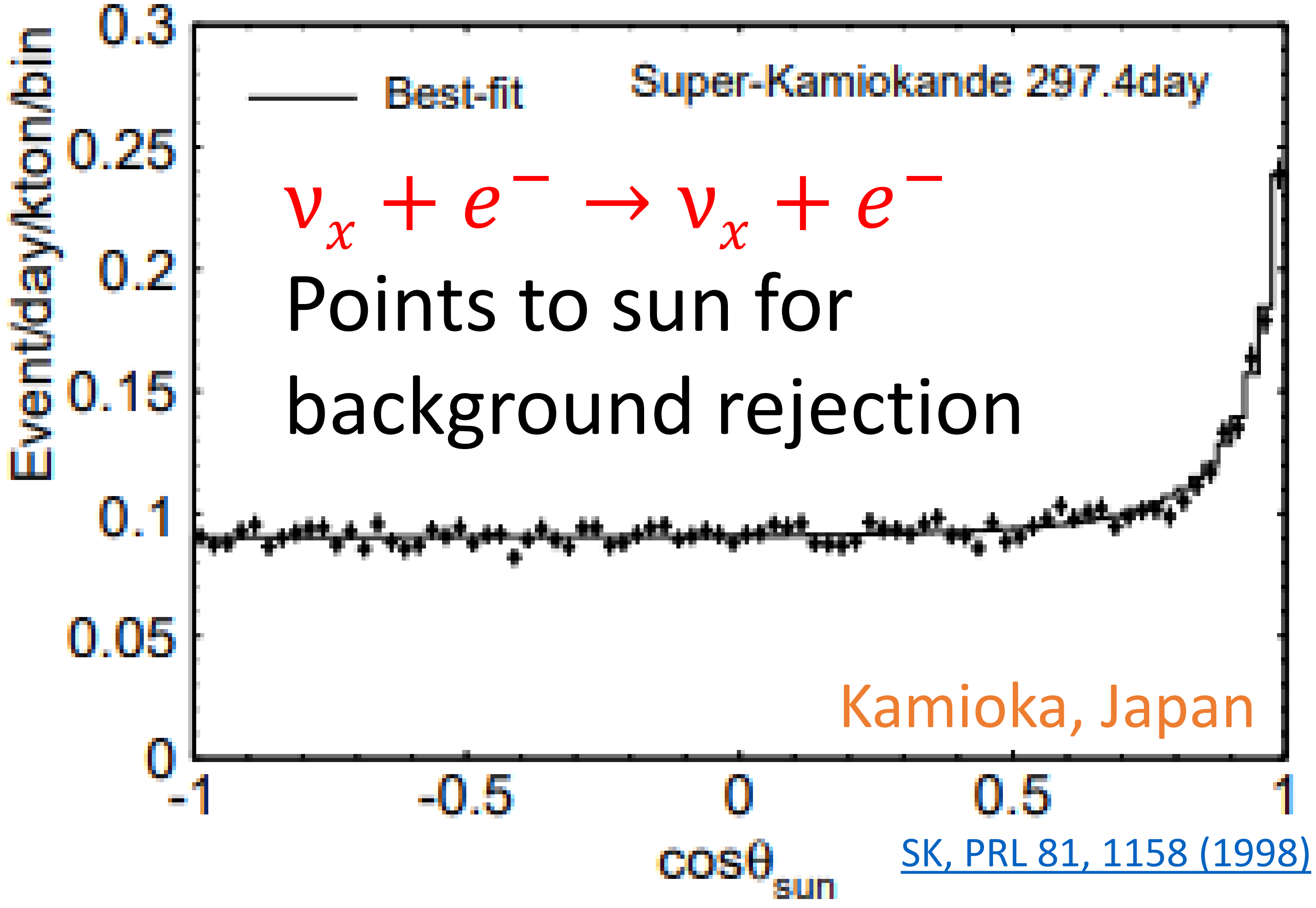
Add ^{51}Cr source
Monoenergetic 746 keV neutrinos emitted in electron capture.



Sage: Russia
Gallex: Gran Sasso

First data from SuperKamiokande



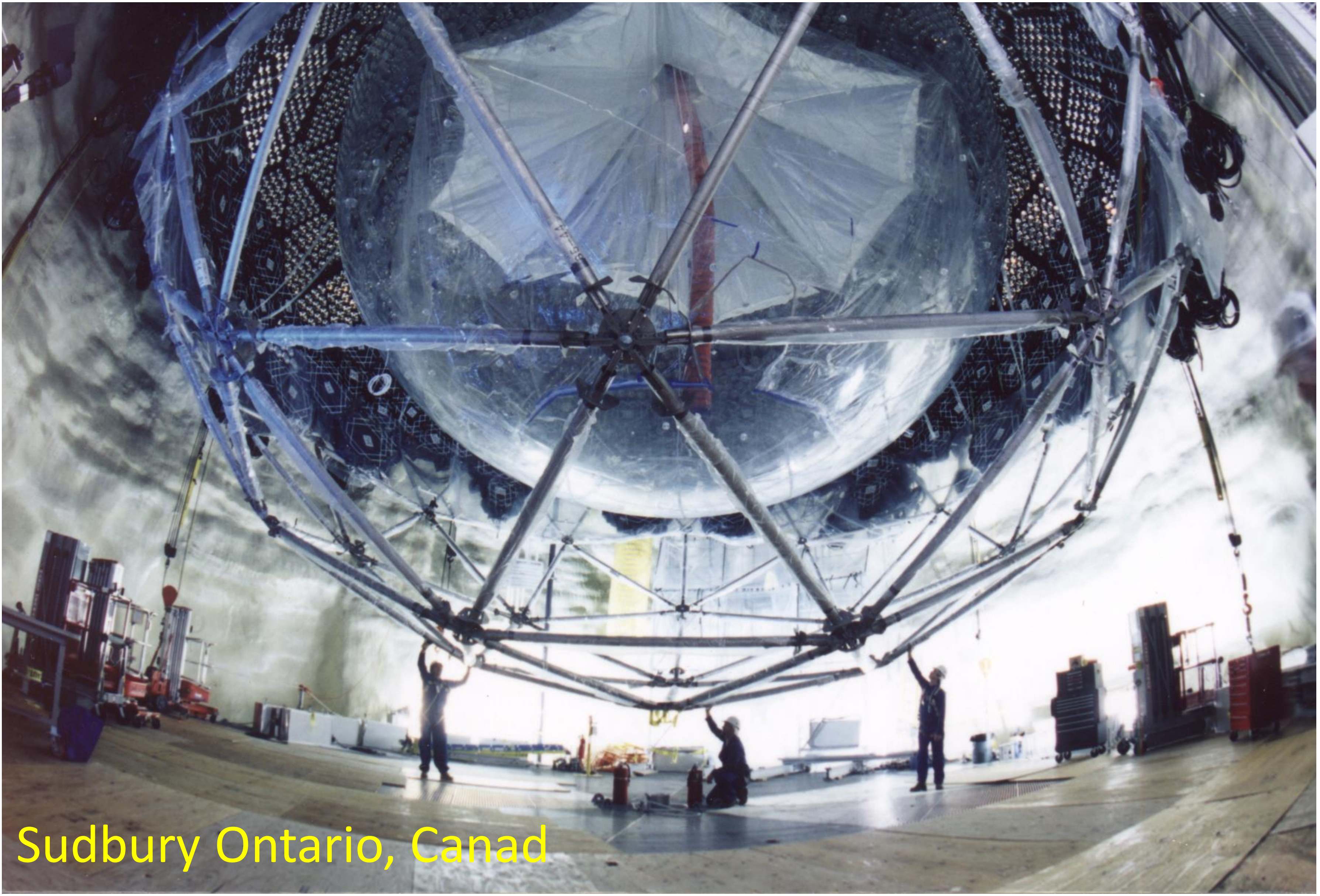


SK sensitive to neutrino-electron elastic scattering (ES) of ^{8}B neutrinos: $E_e > 6.5$ MeV

Also sees a deficit!

[SK, PRL 81, 1158 (1998)]

The SNO experiment



Heavy water Cherenkov

– 1 kt of d_2O held in 6-m radius acrylic vessel
– d_2O is sunk into 8.5-m radius H_2O tank providing shielding
– 9600 PMT's monitor the Cherenkov light from both regions
– vertex reconstruction allows fiducialization
– calorimetric information of solar neutrinos in d_2O

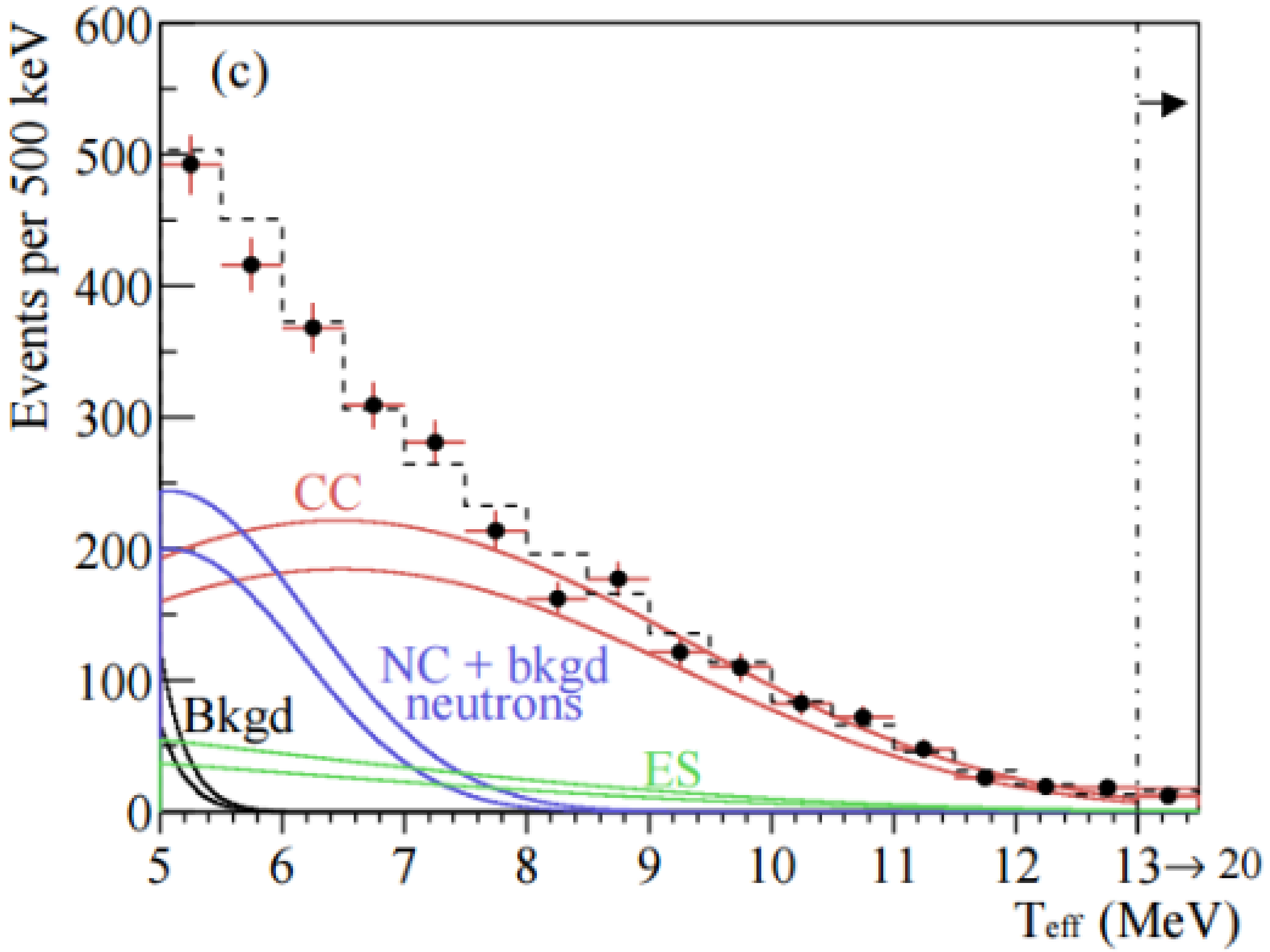
SNO discovers neutrino oscillations

Multiple interaction channels!

Neutral current (NC)
$\nu_e + d \rightarrow \nu_e + n + p$
doesn't oscillate

Charged current (CC)
$\nu_e + d \rightarrow e^- + p + p$
Oscillates

Electron scatter (ES)
$\nu_x + e \rightarrow \nu_x + e$
Mostly oscillates



SNO, PRL 87 071301 (2001)

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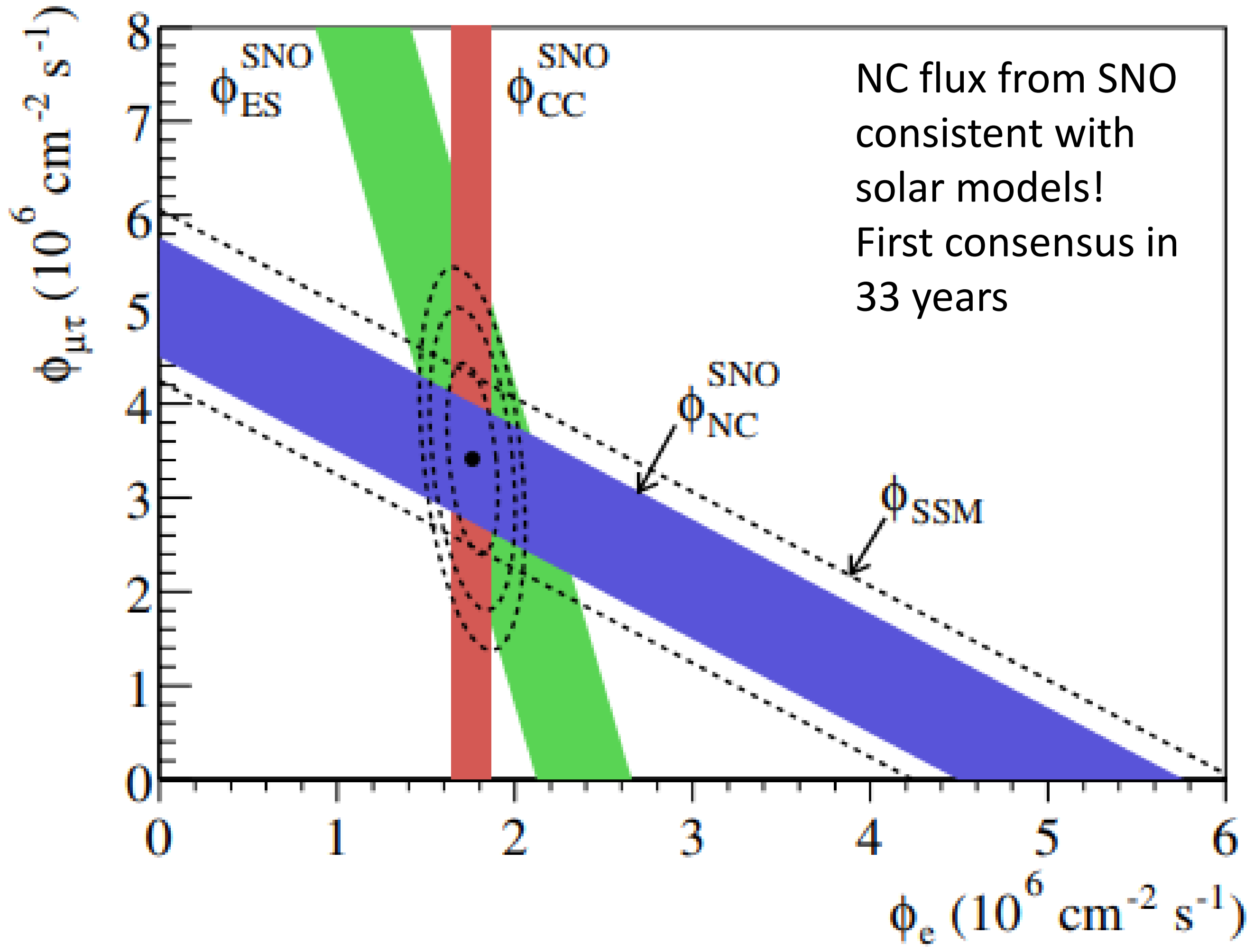


NC flux from SNO consistent with solar models!

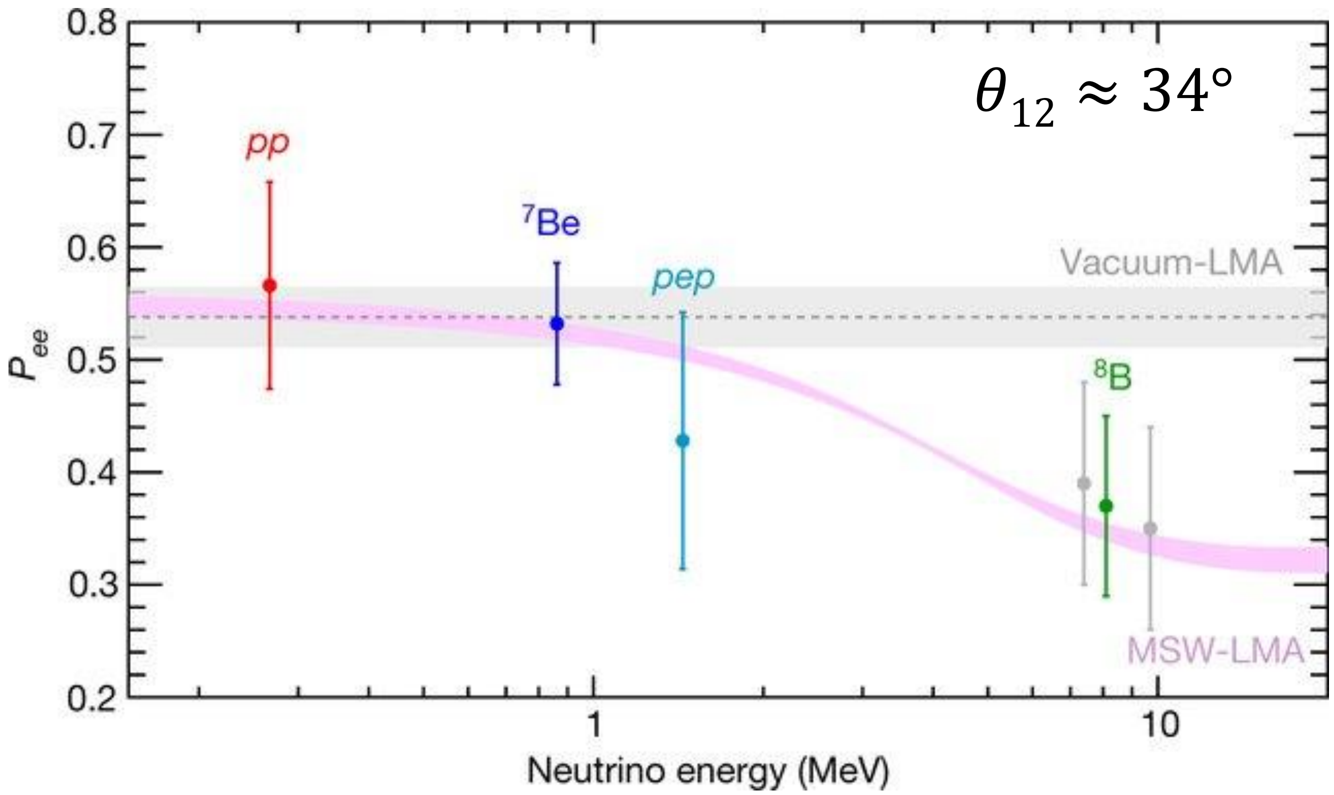
First consensus in 33 years

SNO, PRL 87 071301 (2001)

Analyzing the survival probability

$$H = \frac{1}{2E}\left[U \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2 \end{pmatrix} U^\dagger + \begin{pmatrix} \sqrt{8} G_F n_e E & 0 \\ 0 & 0 \end{pmatrix} \right]$$

Vacuum — Matter



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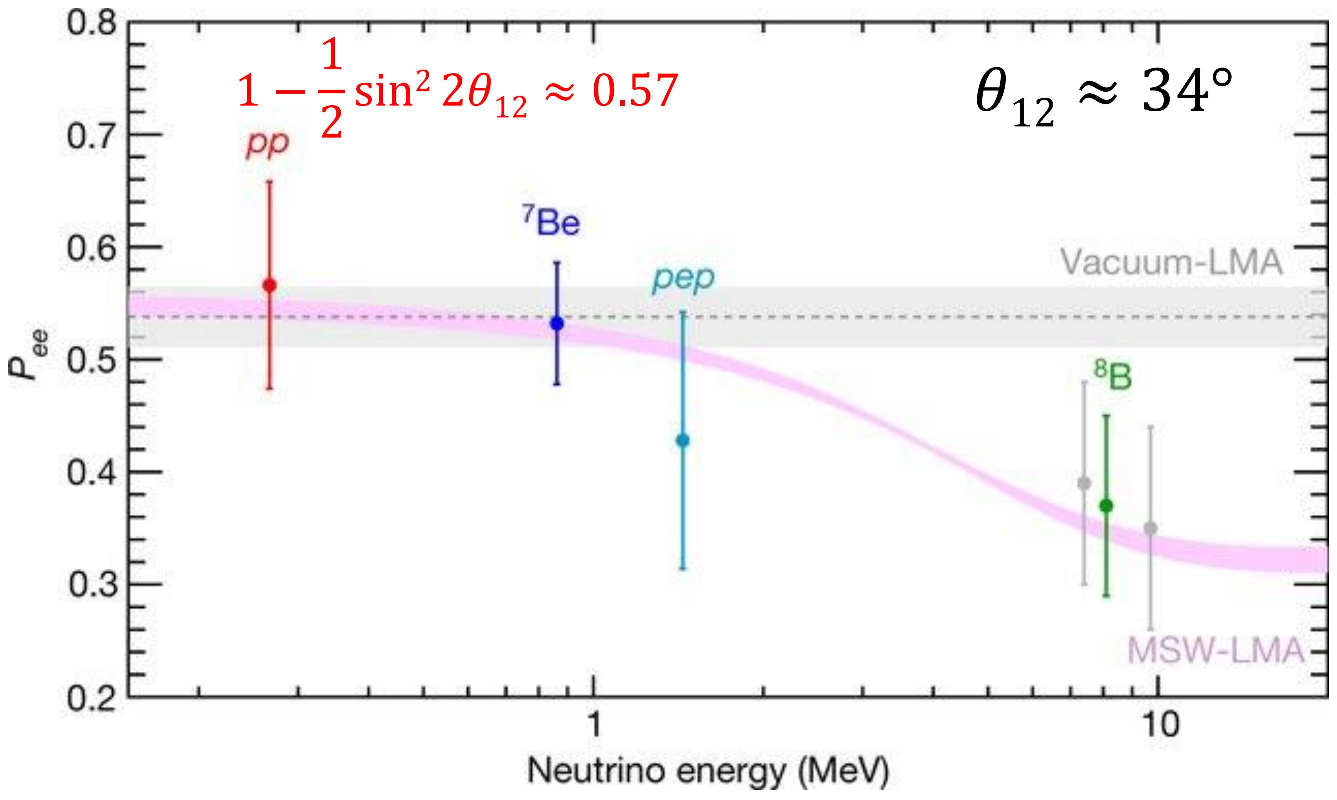
Vacuum Matter

Low-energy (E << $\Delta m^2/\sqrt{8} G_F n_e$):
Vacuum term dominates:

$$P_{ee} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2 L}{4E}$$

$$\langle P_{ee} \rangle = 1 - \frac{1}{2}\sin^2 2\theta_{12}$$



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Vacuum　　　　Matter

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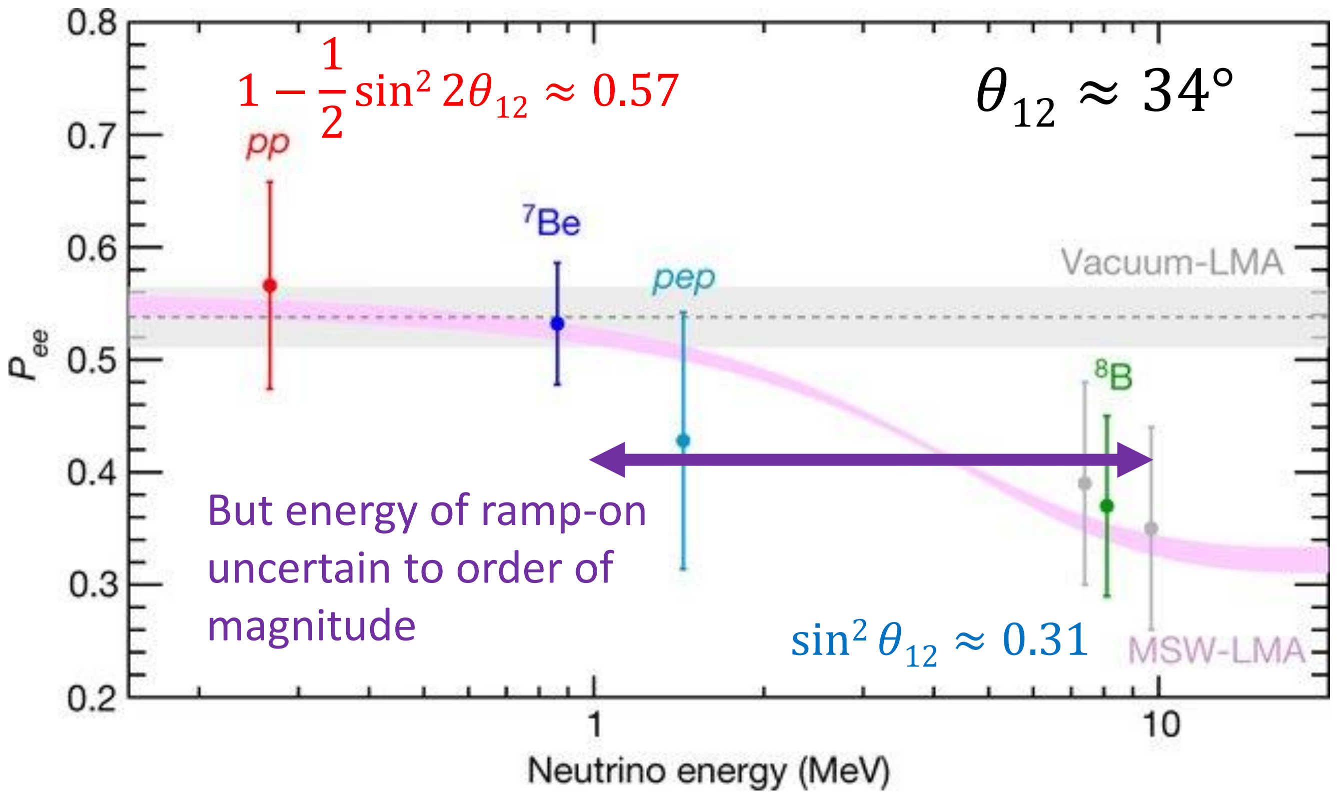
$$\langle P_{ee}\rangle = 1 - \frac{1}{2}\sin^2 2\theta_{12}$$

High-energy (E >> $\Delta m^2/\sqrt{8}G_F n_e$):
Matter term dominates:

$$|\nu_1\rangle_m = |\nu_2\rangle$$

$$|\nu_2\rangle = \sin^2\theta_{12}|\nu_e\rangle + \cos^2\theta_{12}|\nu_\mu\rangle$$

$$P_{ee} = \langle\nu_e|\nu_2\rangle = \sin^2\theta_{12}$$

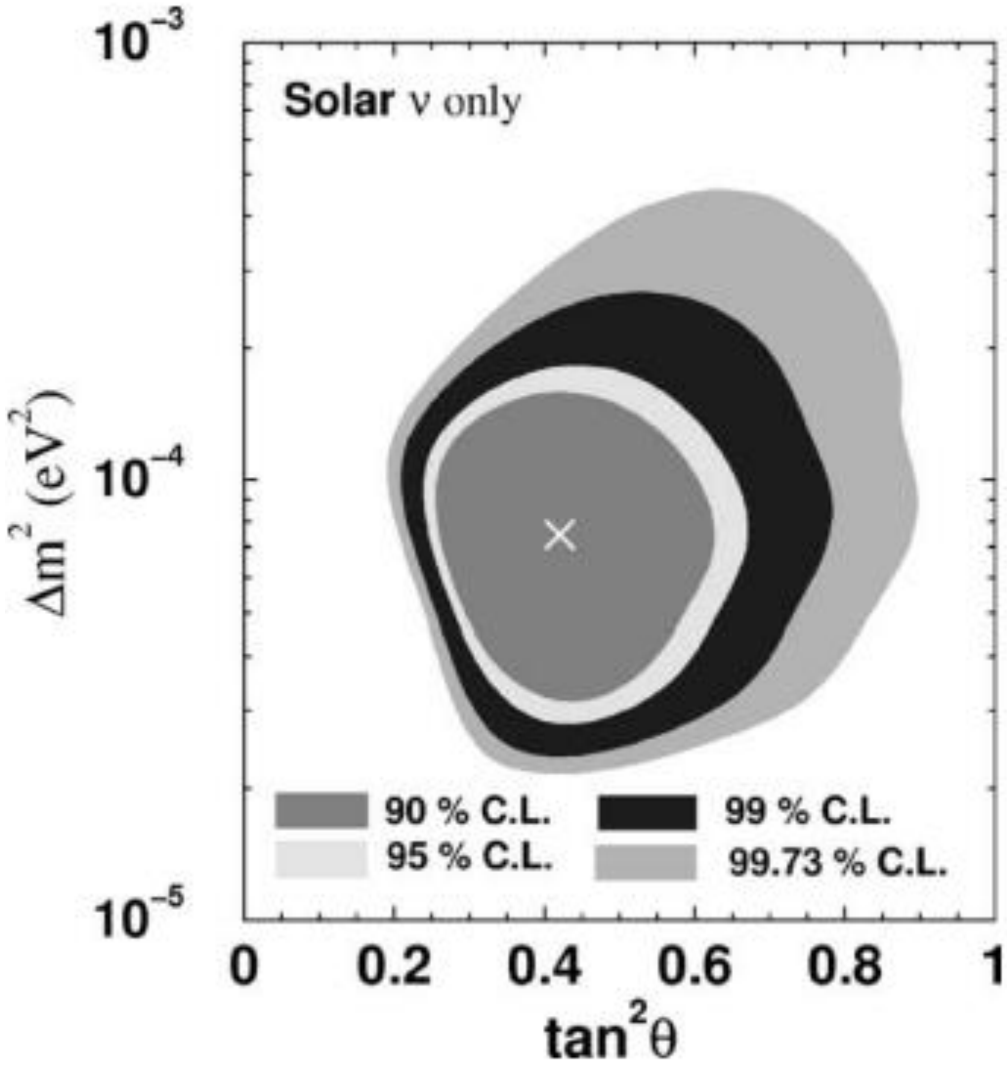


Estimating oscillation parameters

Taking Davis, Gallium, SK, and SNO data, a statistical log-likelihood fit can determine which oscillation parameters best fit solar data

With earliest data, ok determination of the mixing angle

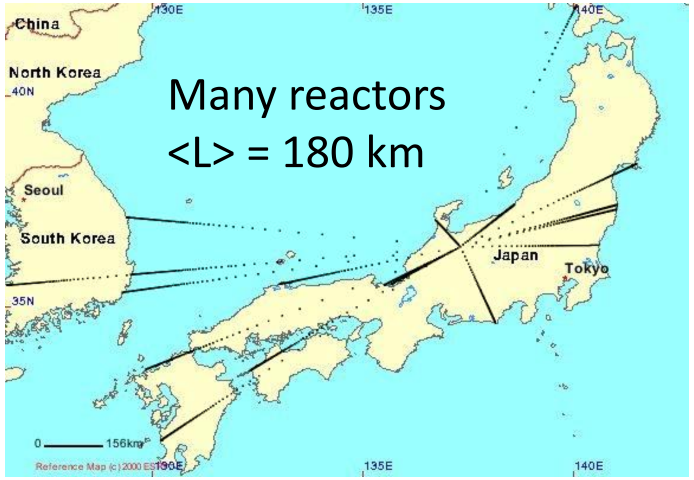
Uncertainty in the mass splitting was nearly an order of magnitude



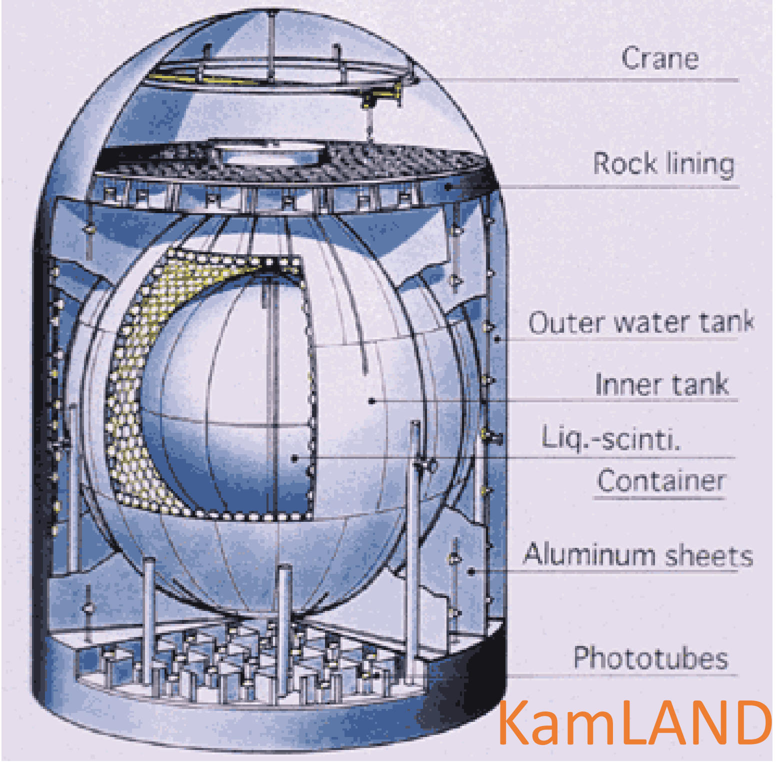
Nunokawa, Teves, and Funchal, *PLB* **562** 28 (2005)

Reactor measurement of Δm^2

1 kt of scintillator in balloon
Buffer volume of mineral oil
Outer water Cherenkov veto
1325 20” PMT’s



[KamLAND PRL 101 221803 (2008)]



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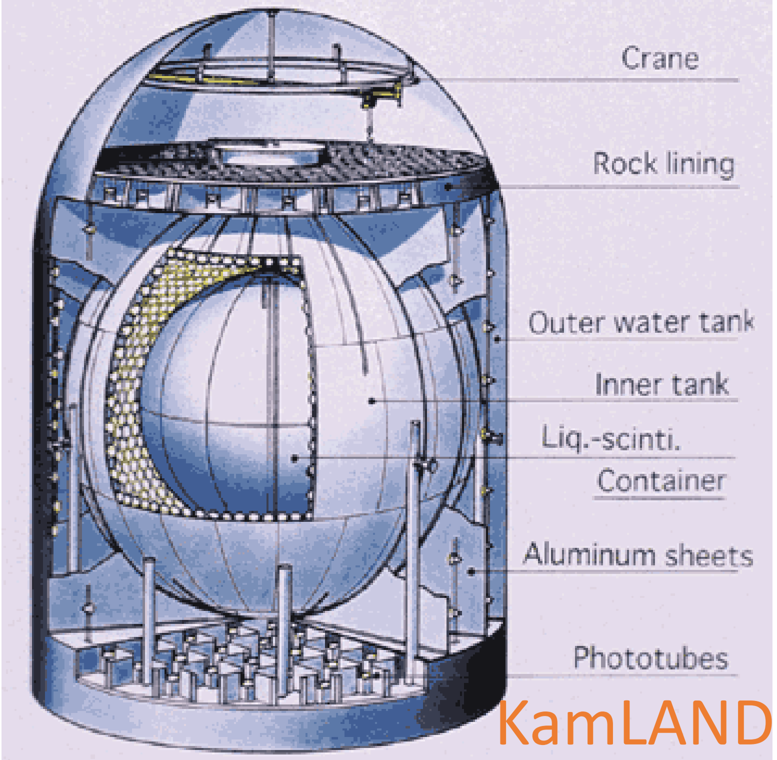
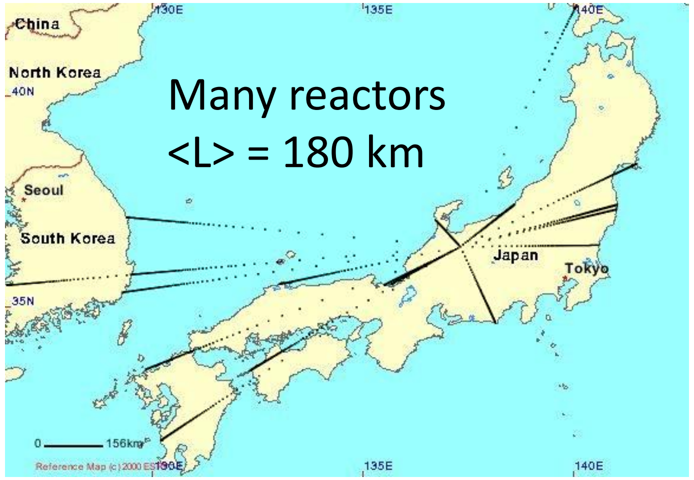
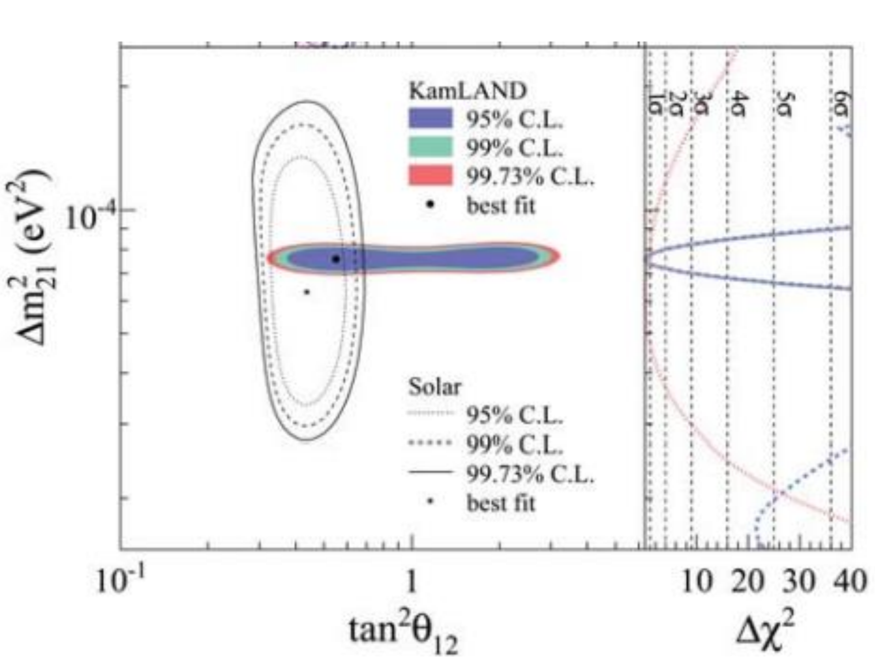
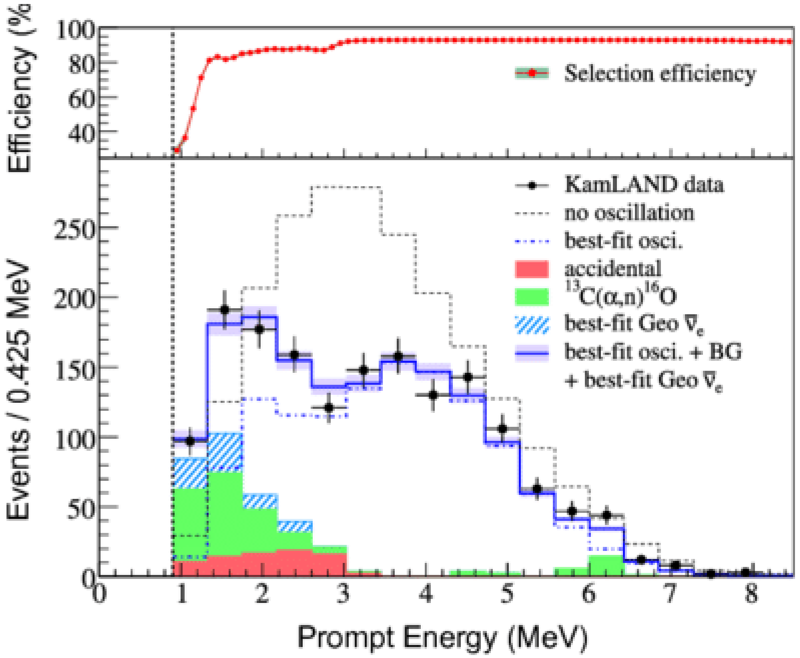
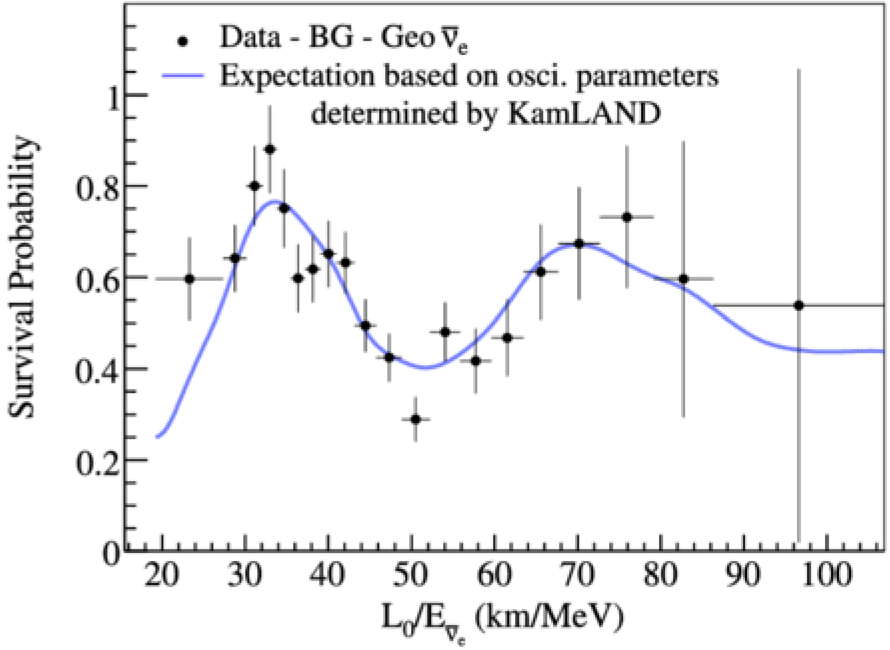










Precision measurements: the Borexino experiment

Onion-like scintillator

– Inner 321-t volume with organic scintillator and wavelength shifter. 8.5 m
– Inner veto volume with dimethylphthalate, a charge quencher. 8.5 to 11 m
– Outer veto volume with similar chemical composition. 11 to 13.7 m
– Stainless steel tank with 2212 mounted PMT's
– Surrounding water tank for additional passive shield

Flux measurements from Borexino

[Borexino, Nature 562 505-510 (2018)](#)

ES channel in scintillation detectors – must live with large, well-characterized background

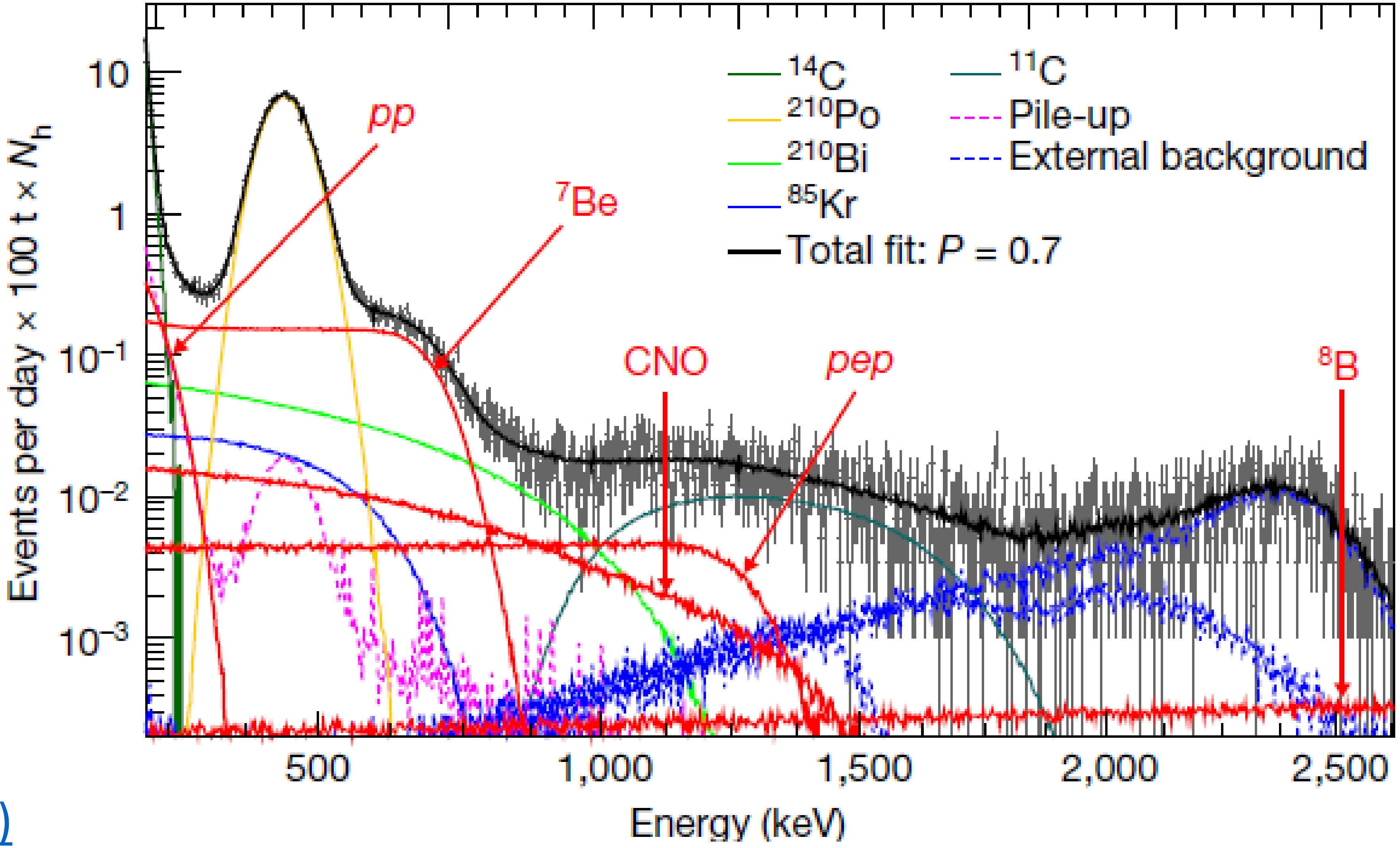
- Scintillator purification reduces $^{14}C/^{12}C$ ratio to 185e-18

pp chain spectroscopy

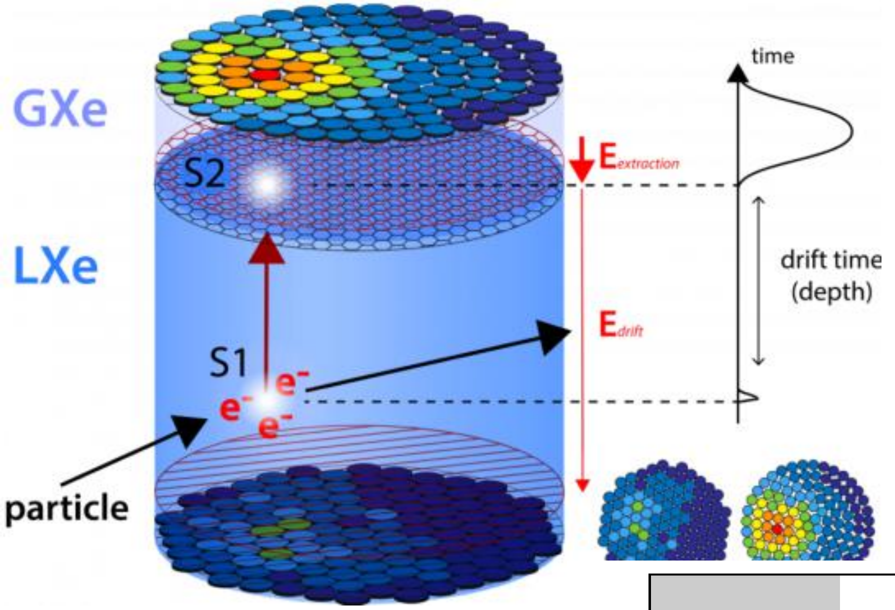
- :eading measurements of pp / ^{7}Be / pep

CNO chain discovery

- [Nature 587 577-582 (2022)](#)

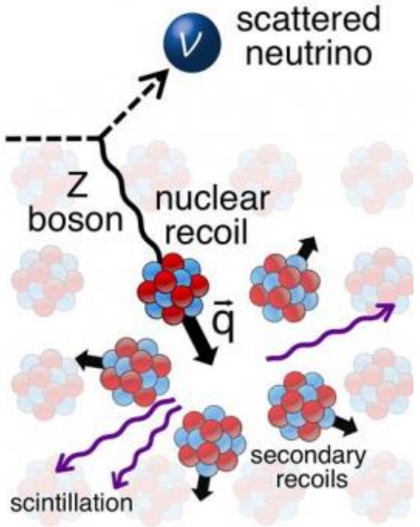


New detections from XENONnT + PandaX-4T

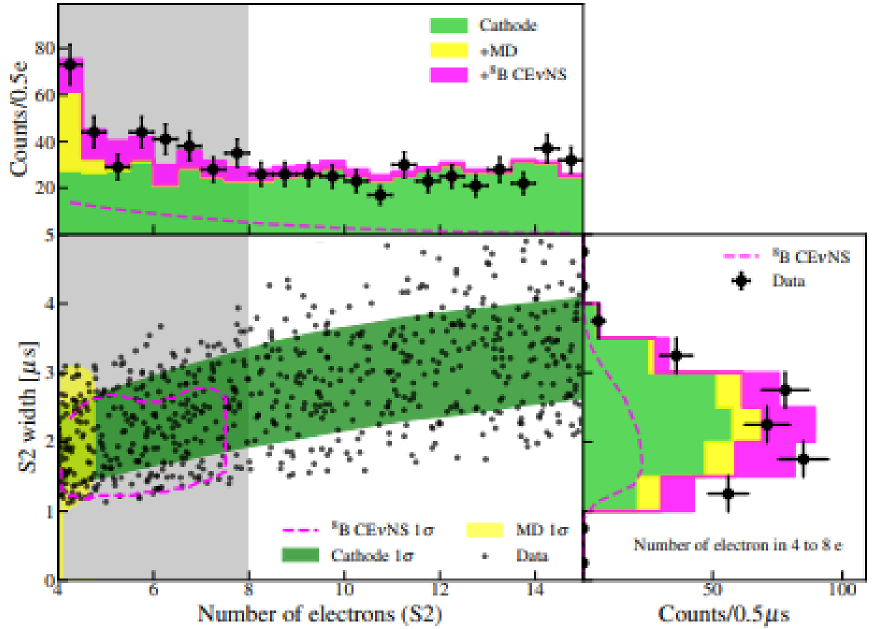


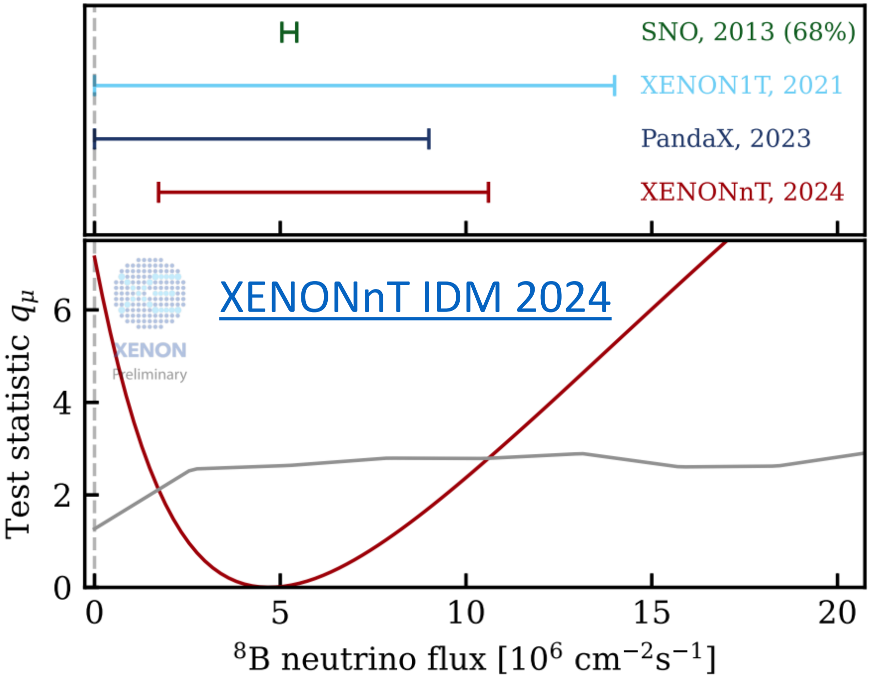
Liquid xenon time projection chambers searching for WIMP dark matter at Gran Sasso with 3.9-4.1 t (XENONnT) and Jinping with 2.5 t (PandaX-4T)

2.7σ detection of CEvNS in 3.51 t-yrs (XENONnT) and 2.6σ in 2.29 t-yrs (PandaX-4T)

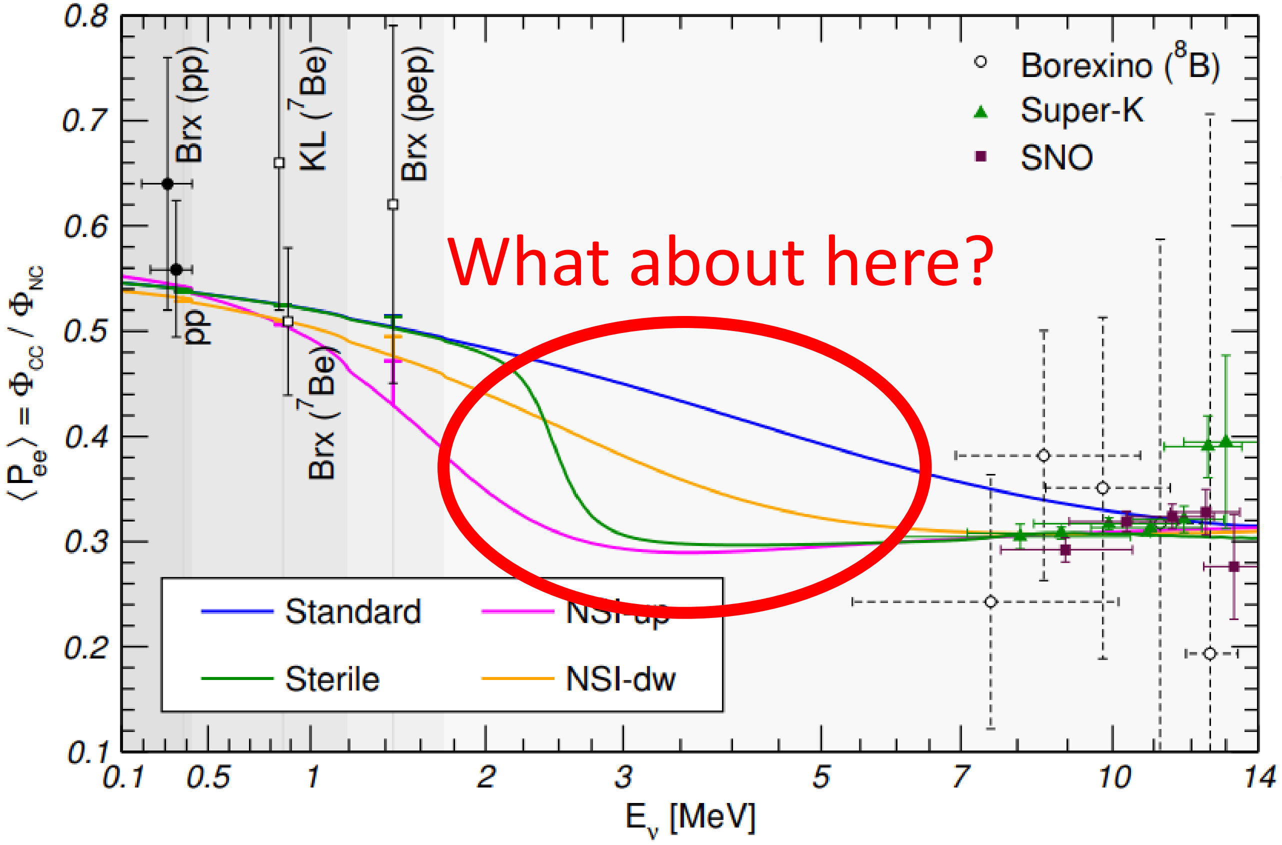


PandaX-4T arXiv:2407.10892



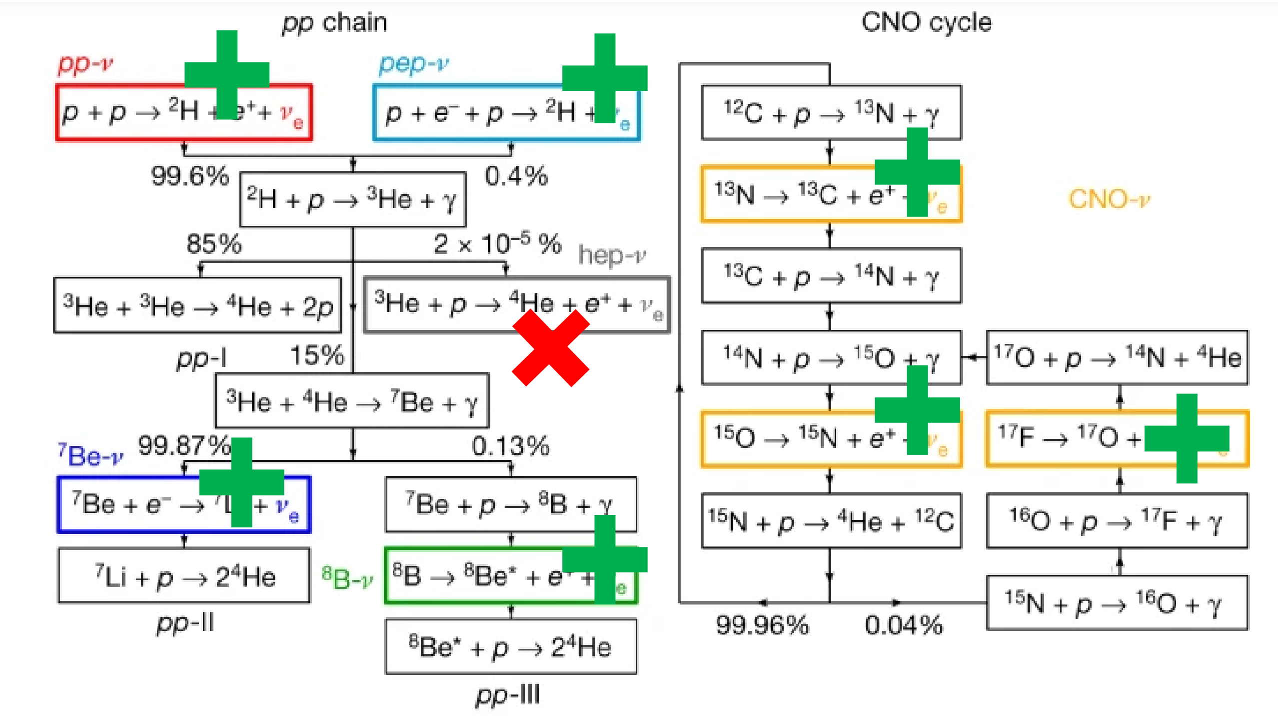


Future of solar neutrinos

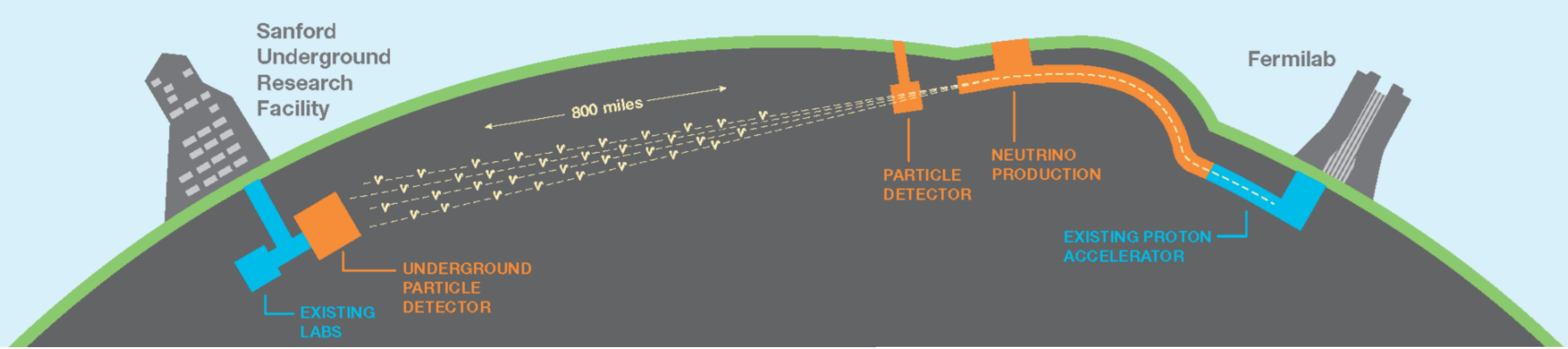


[Maltoni and Smirnov, *Eur. Phys. A* **52** 87 (2016)](#)

One remaining flux to measure



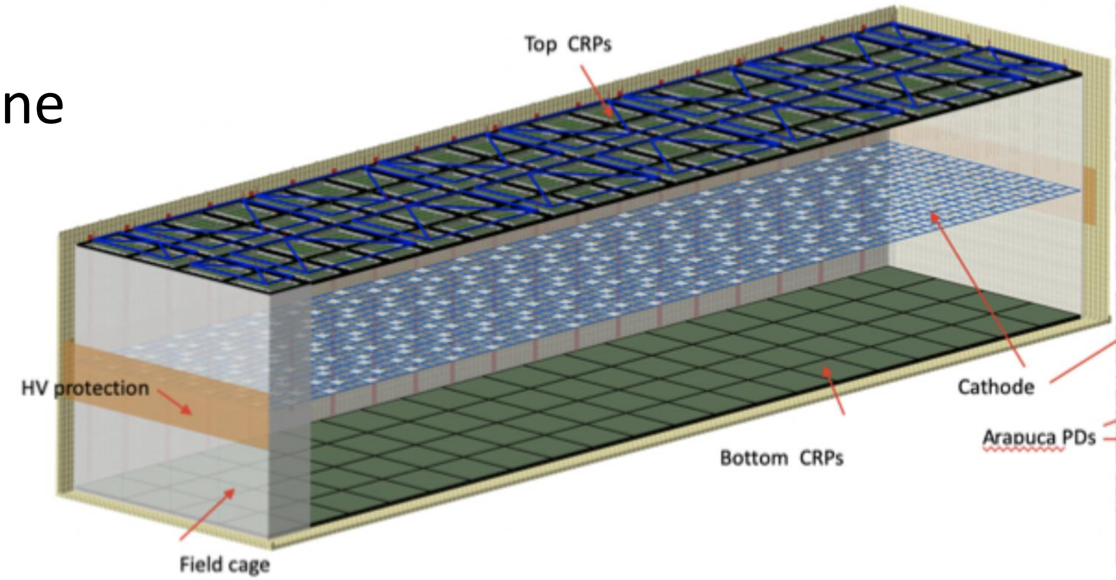
The DUNE experiment



– Upcoming neutrino experiment studying long-baseline oscillations, BSM searches, and **astro neutrinos**

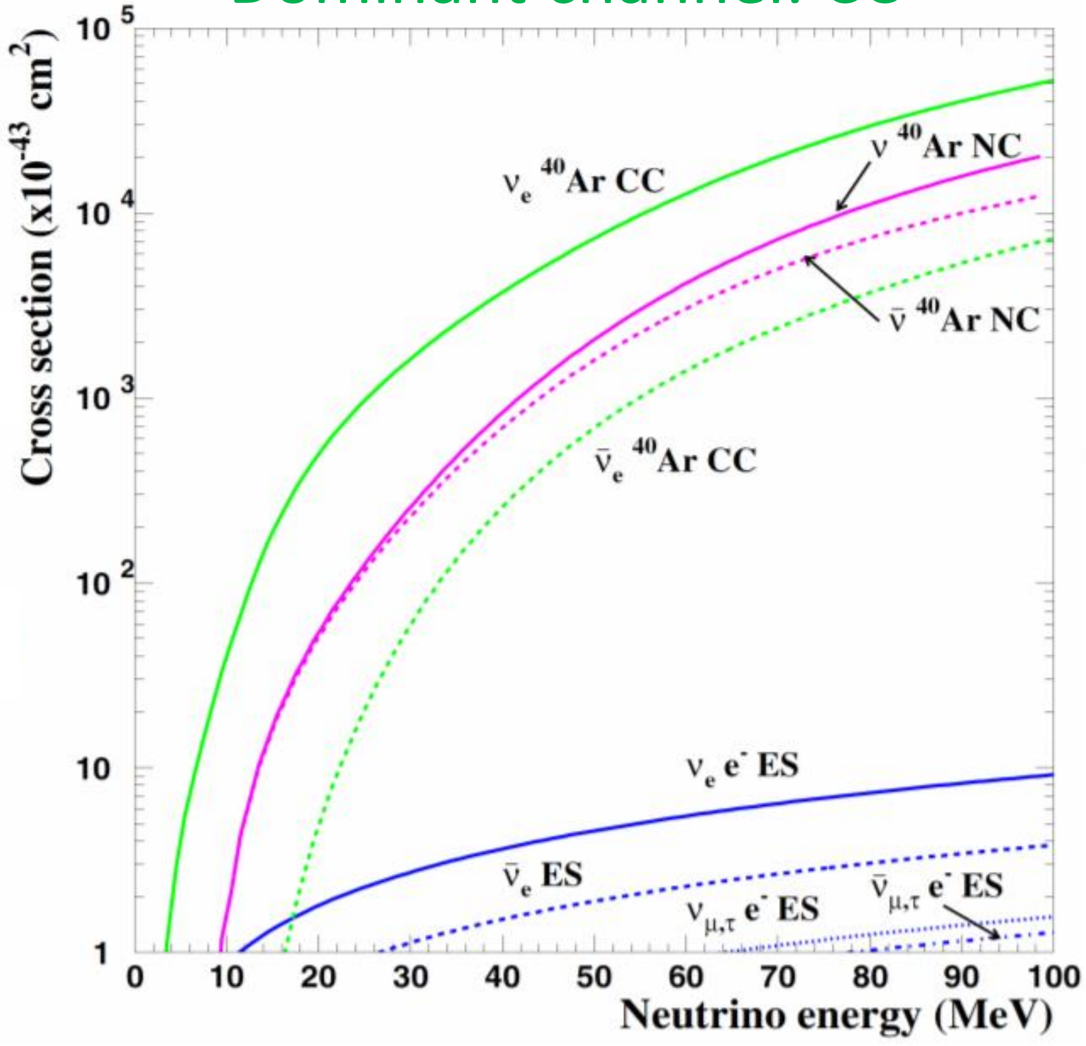
– 4 far detector (FD) modules are 17-kt LArTPC's 1300 m below ground in the SURF laboratory

– First FD data expected in 2028

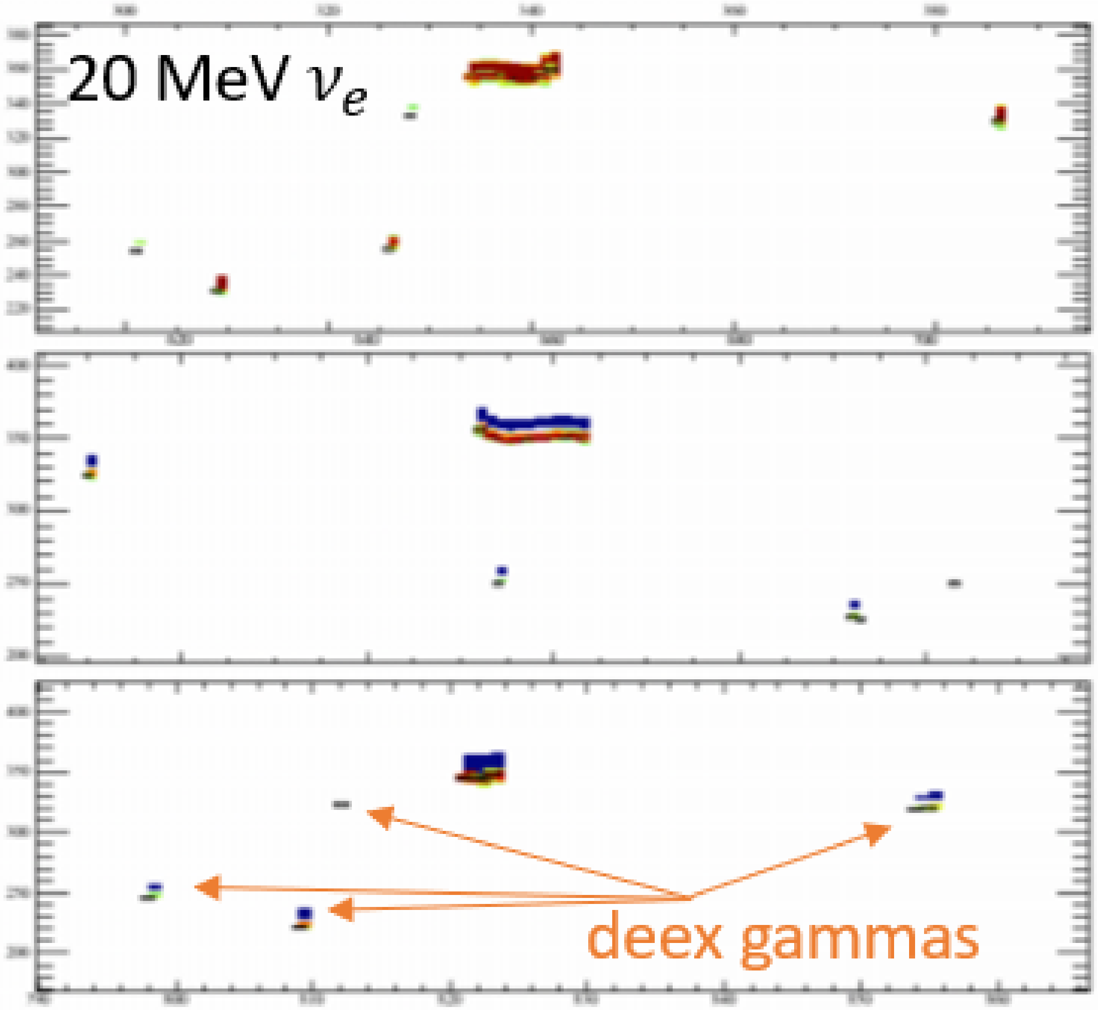


A new technology brings two critical strengths

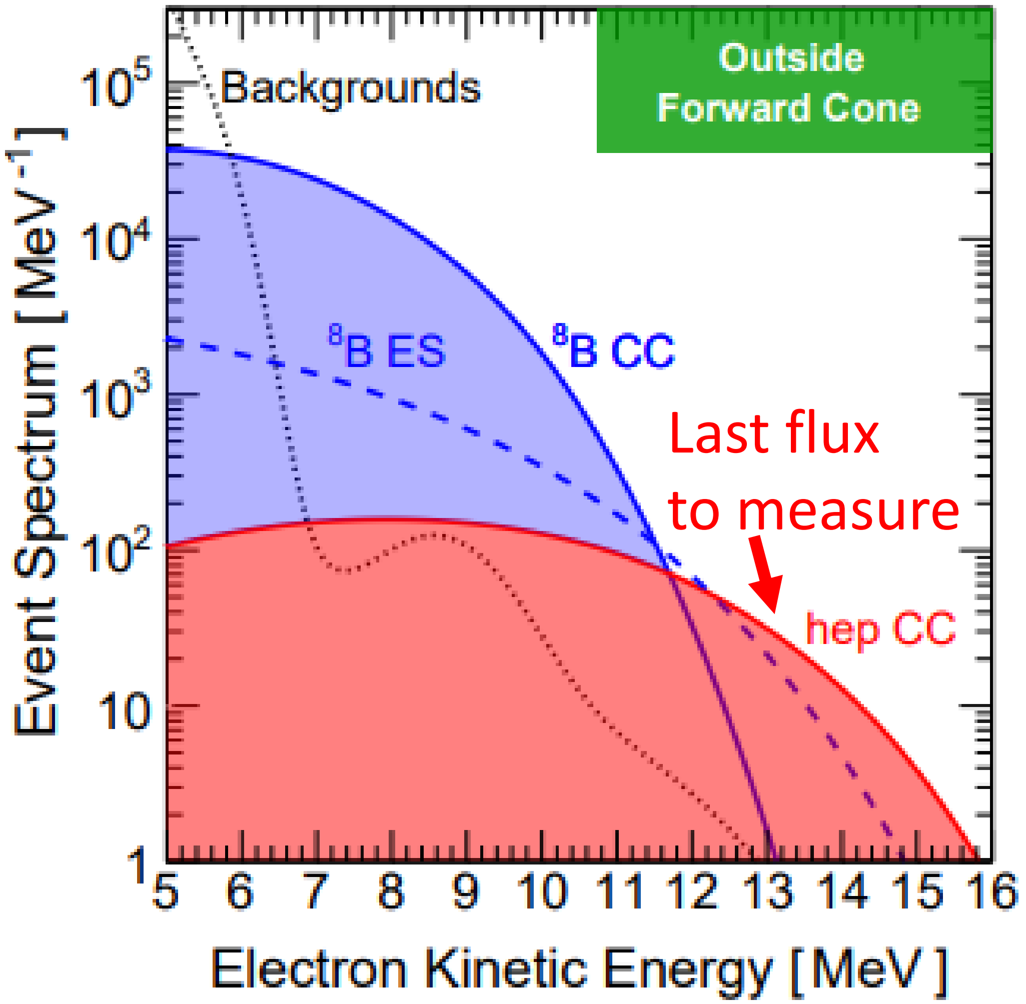
Dominant channel: CC



Sub-cm tracking, reconstruction and background rejection



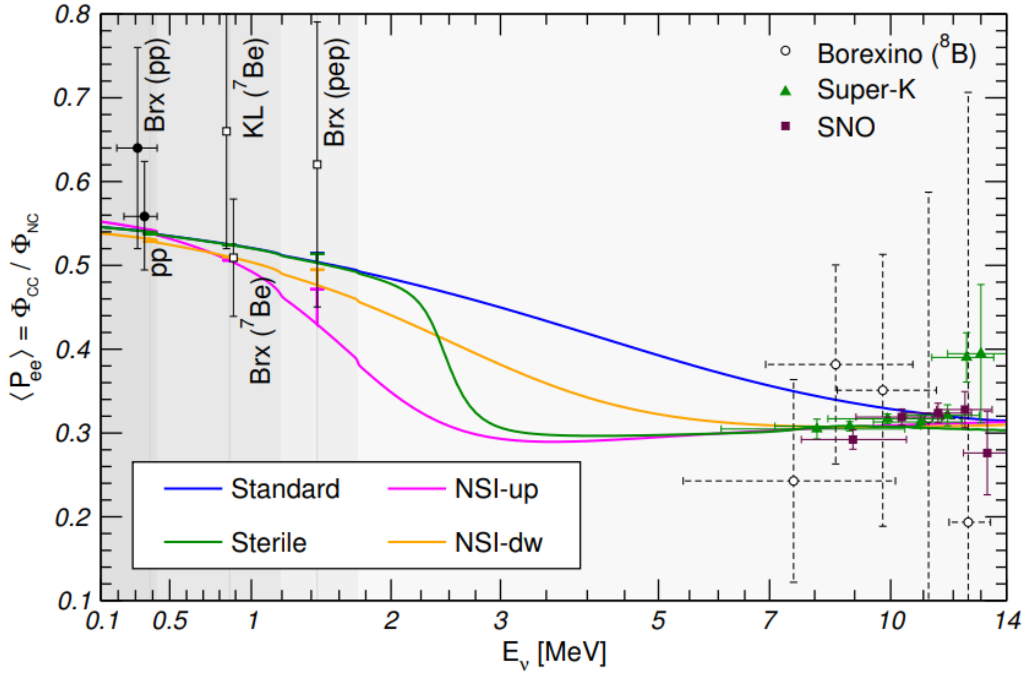
Future sensitivity to remaining questions



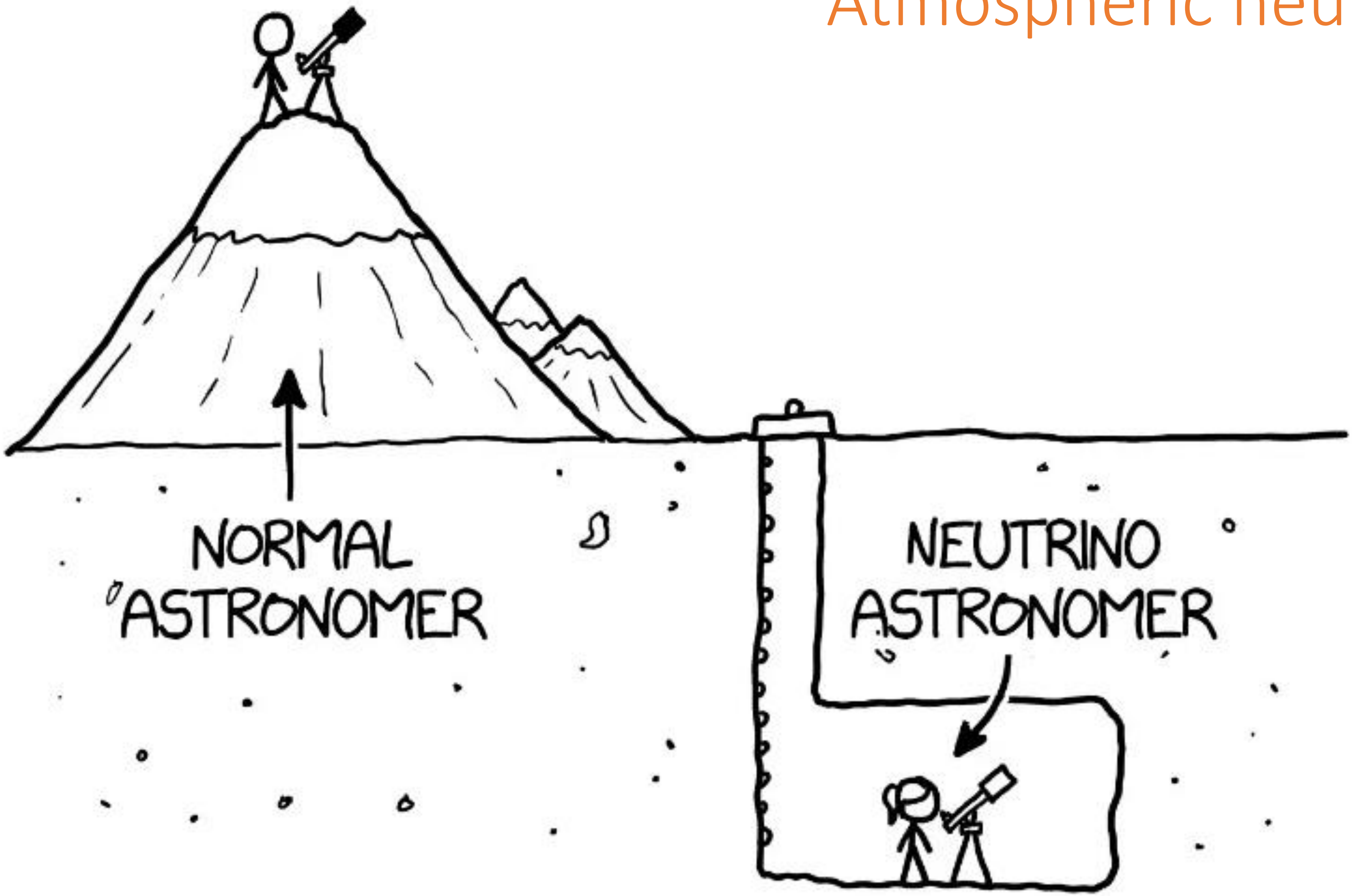
[Capozzi, Li, Zhu, Beacom, PRL 123 131803 (2019)]

Sensitivity to CC makes DUNE ideal for studying oscillation probability as a function of energy

Preliminary background estimates suggest 5 MeV threshold – can dig deeper into upturn of survival probability plot



Atmospheric neutrinos



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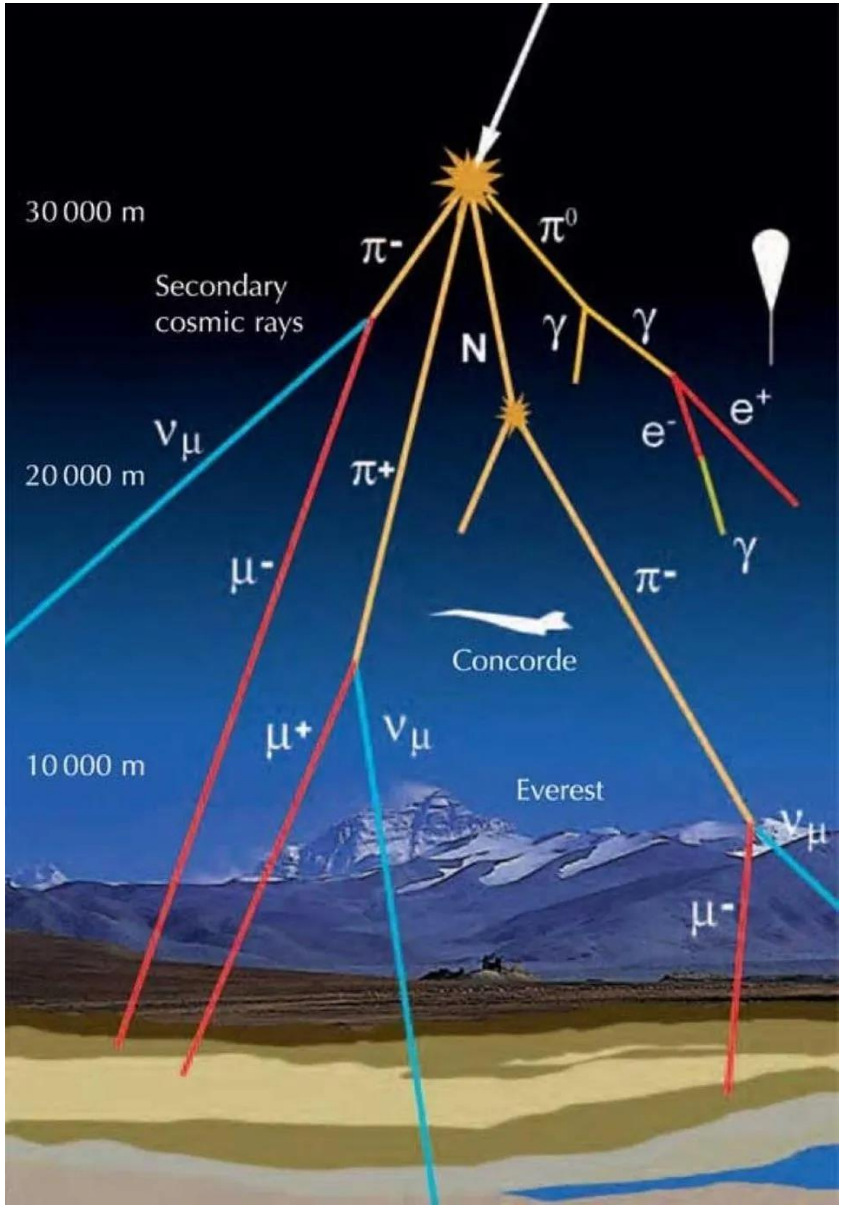
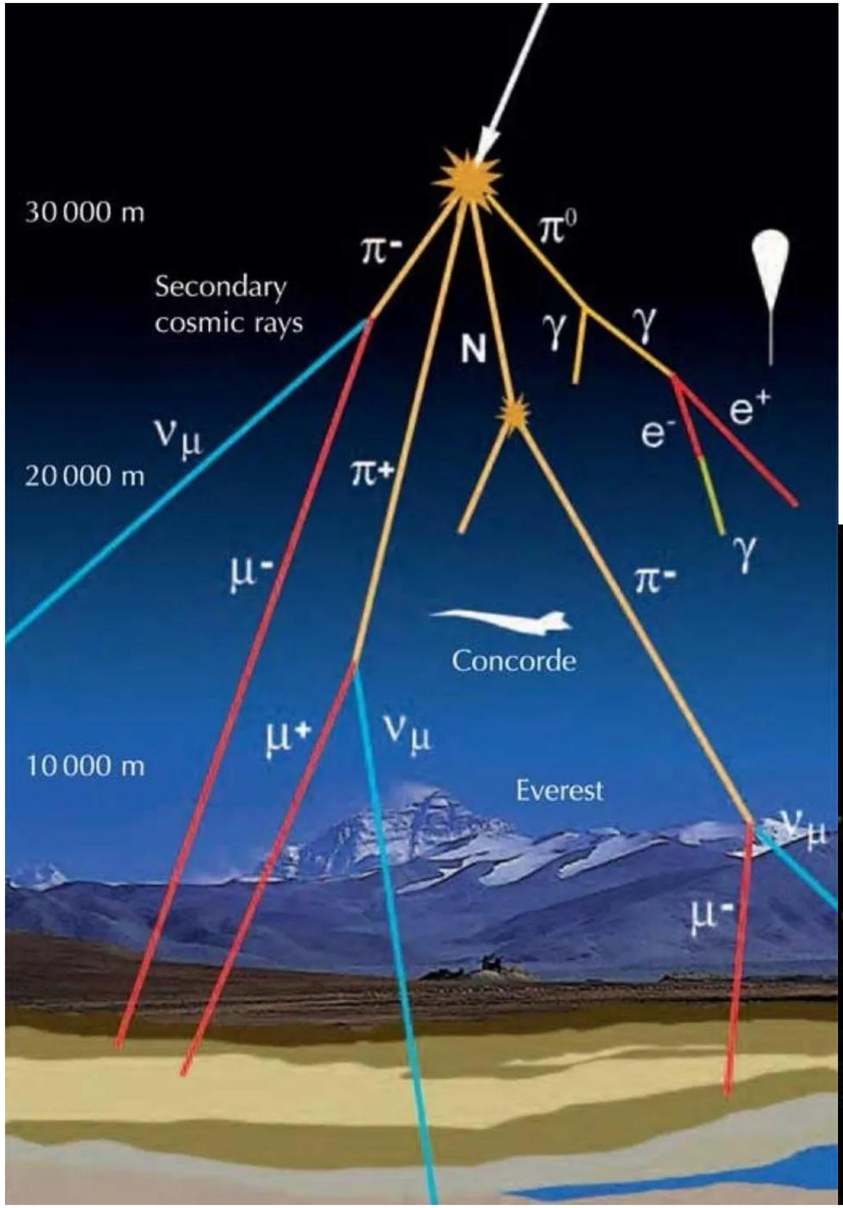


Atmospheric neutrinos produced when cosmic ray protons interact with nuclei in the upper atmosphere producing mesons

With solar neutrinos, atmospheric neutrinos definitively proved that neutrinos oscillate and have mass

Atmospheric neutrinos



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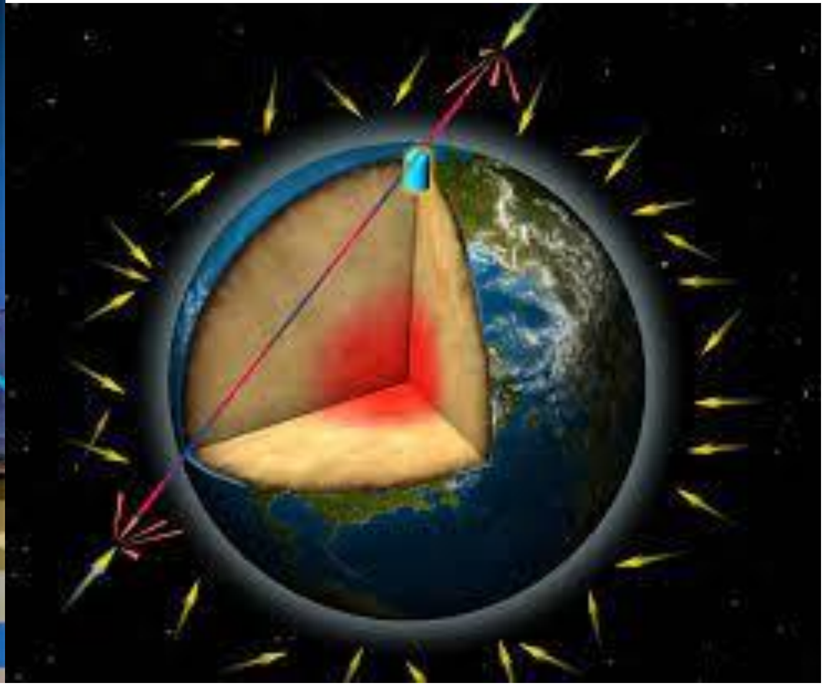
– Arrive in detector from multiple baselines



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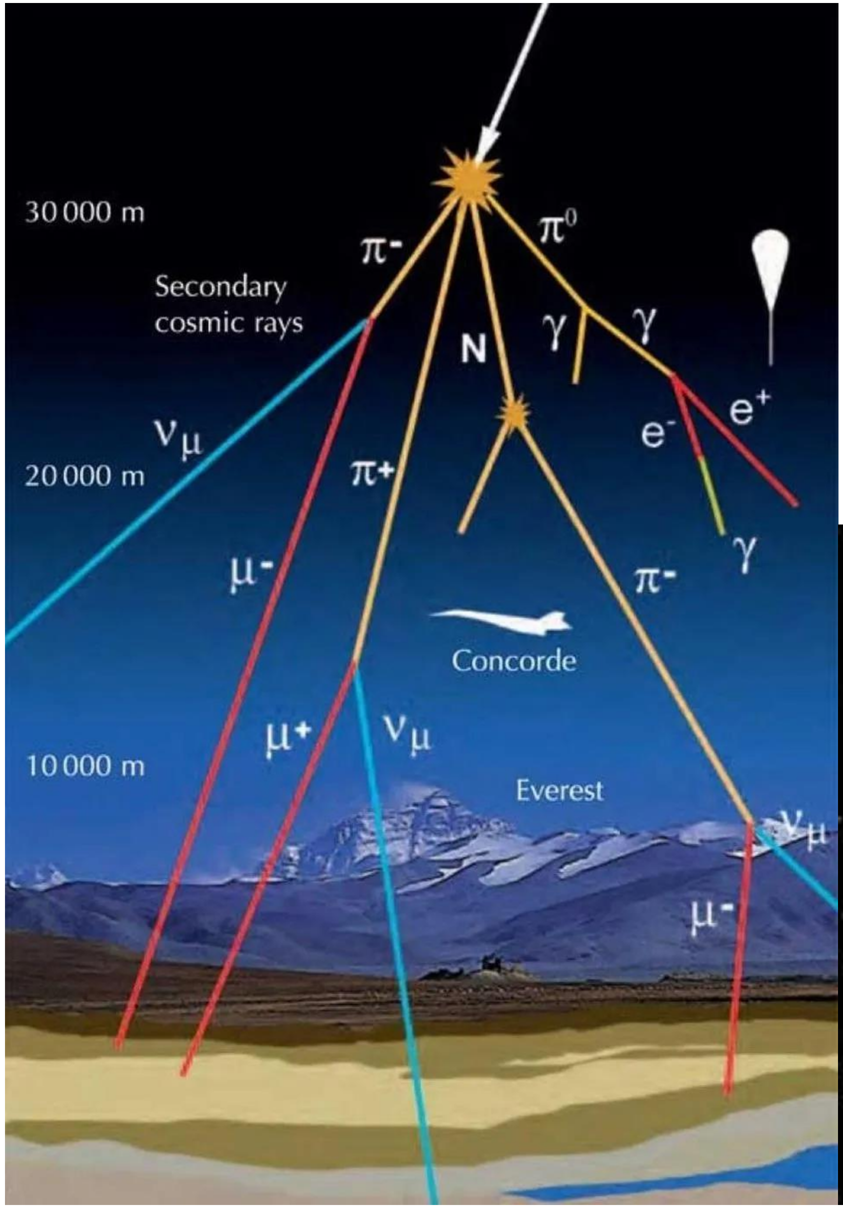
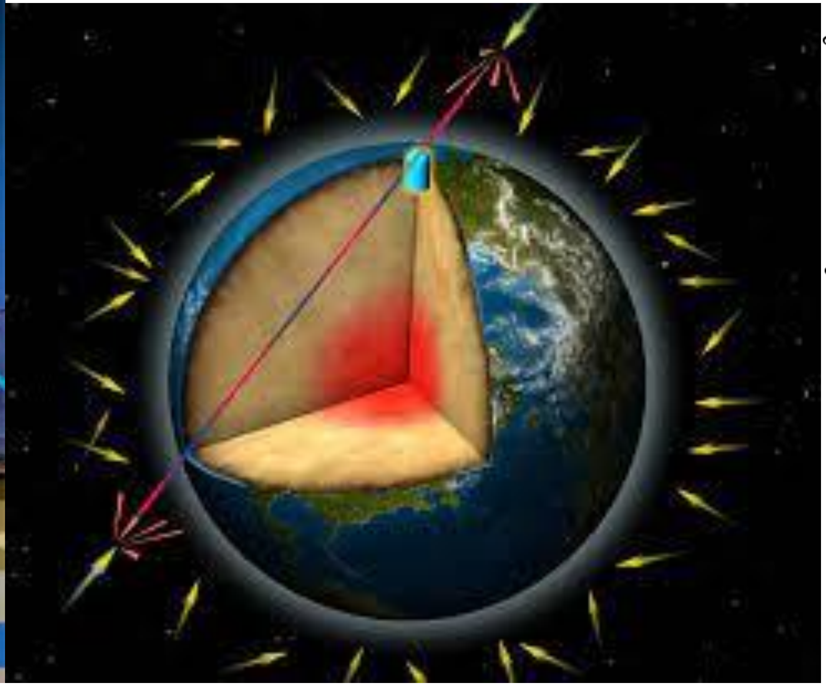


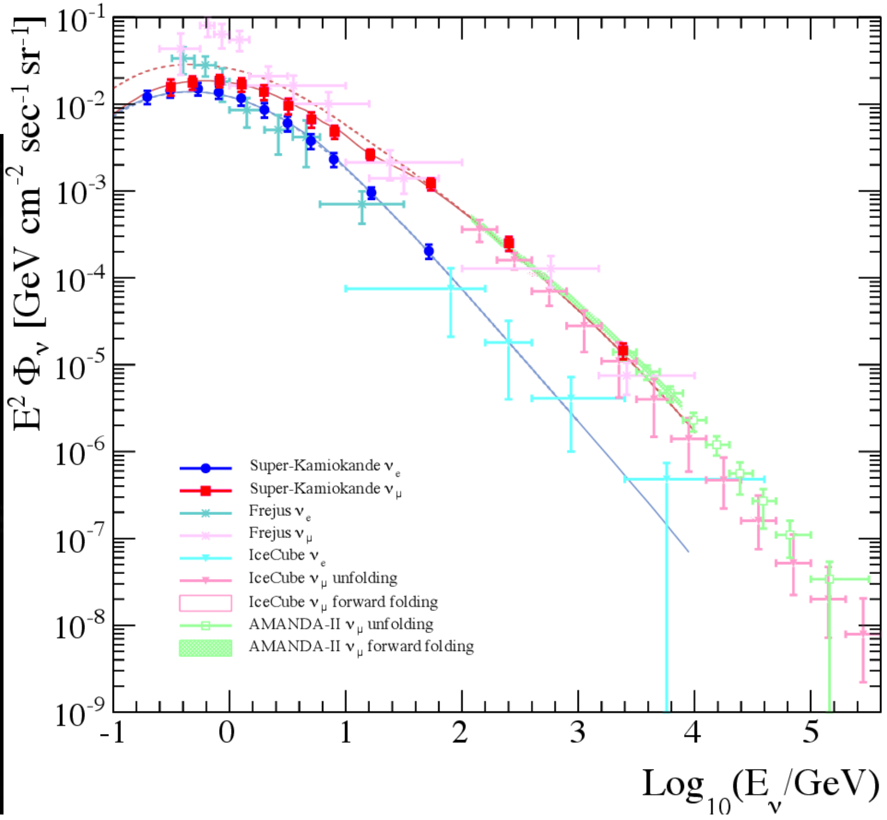
Atmospheric neutrinos produced when cosmic ray protons interact with nuclei in the upper atmosphere producing mesons

With solar neutrinos, atmospheric neutrinos definitively proved that neutrinos oscillate and have mass

– Arrive in detector from multiple baselines

– 100s of MeV to multi-GeV

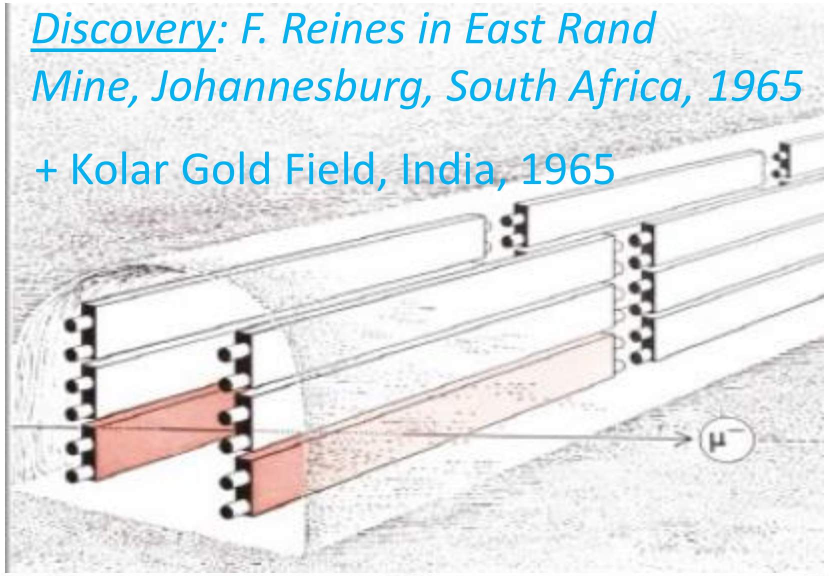




Early history of atmospheric neutrinos

Discovery: F. Reines in East Rand Mine, Johannesburg, South Africa, 1965

+ Kolar Gold Field, India, 1965



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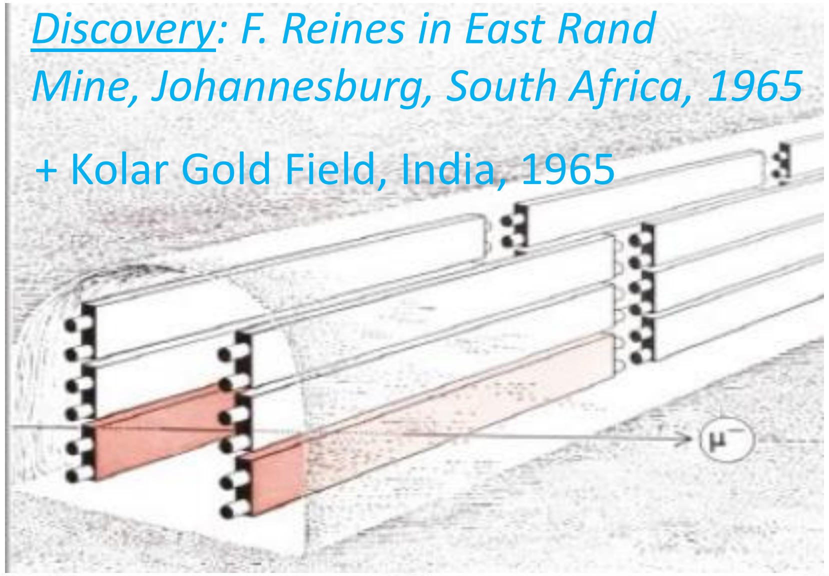
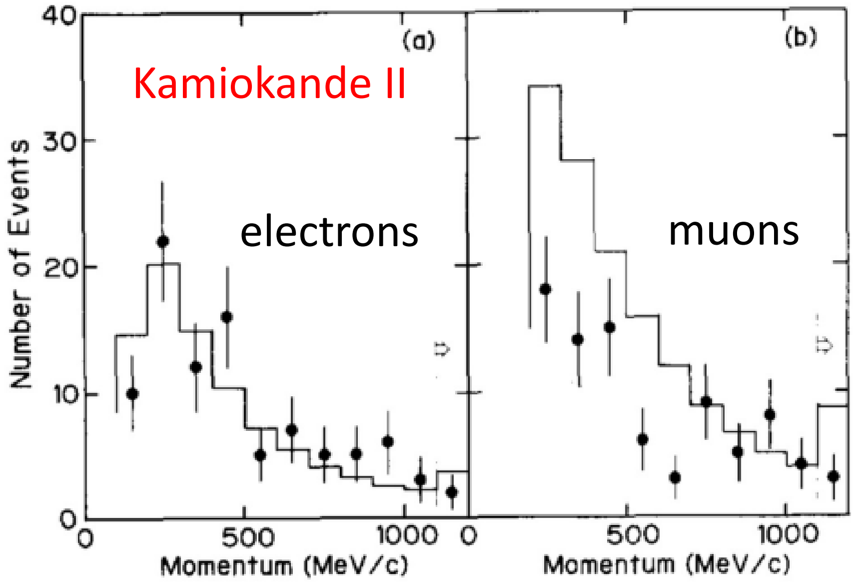
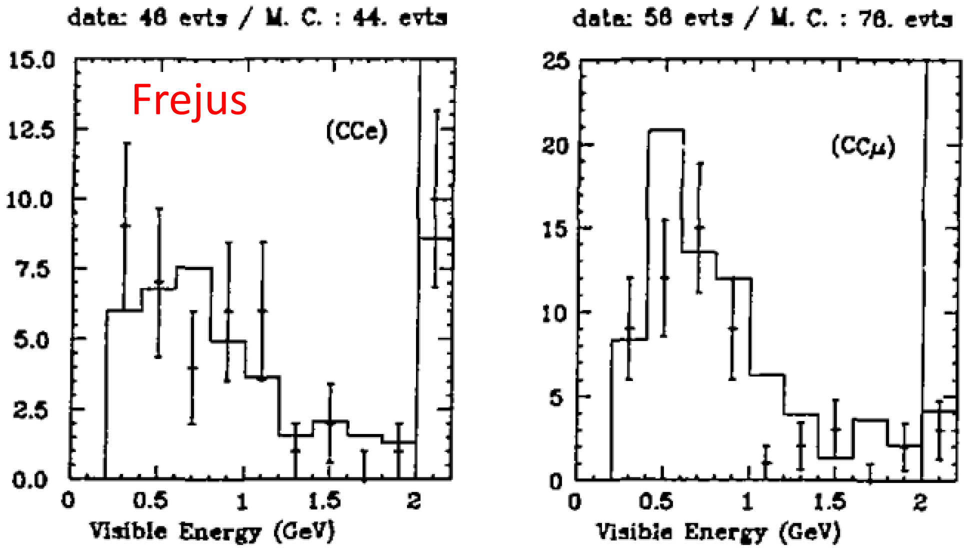


1980s: dedicated study from proton decay experiments

Oscillations there, but need more convincing sample



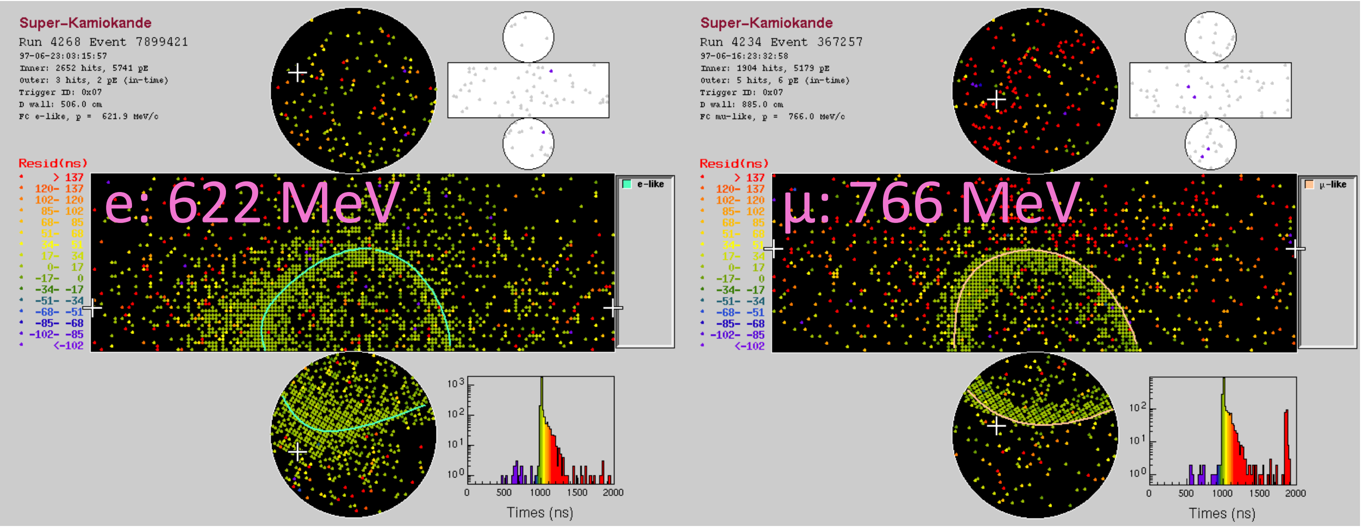


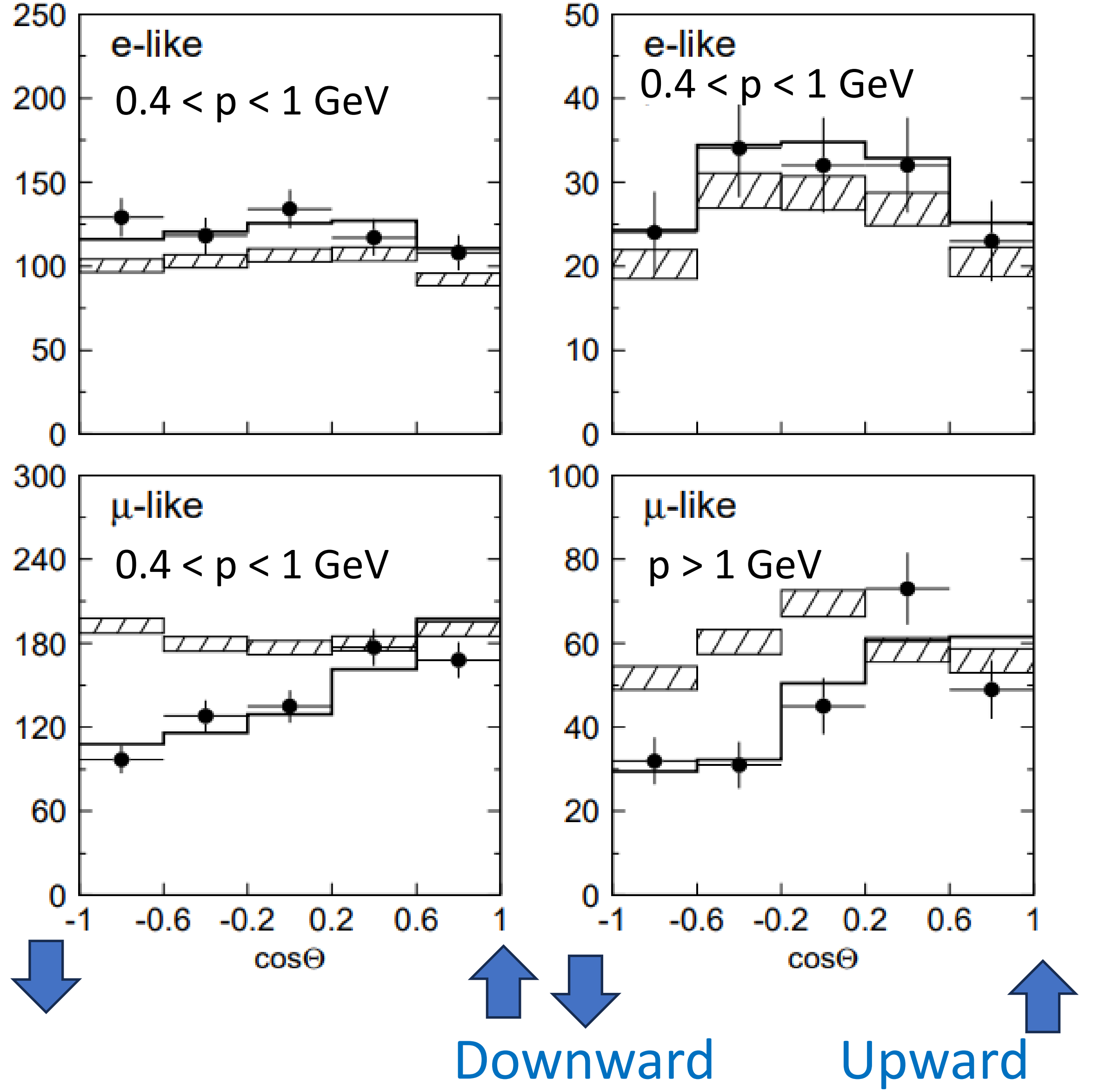
First data from Super-Kamiokande

SK, *PRL* **81** 1562 (1998)

535 days of SK data shows strong preference for disappearance of atmospheric νμ

Downward going (short baselines) agree well – sounds like oscillations





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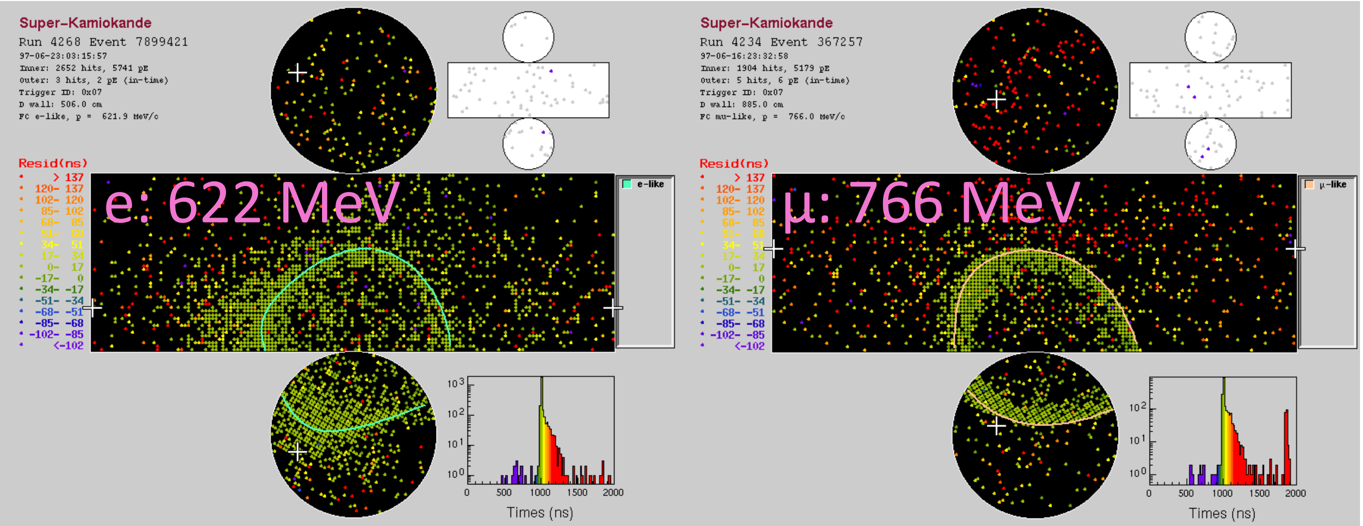
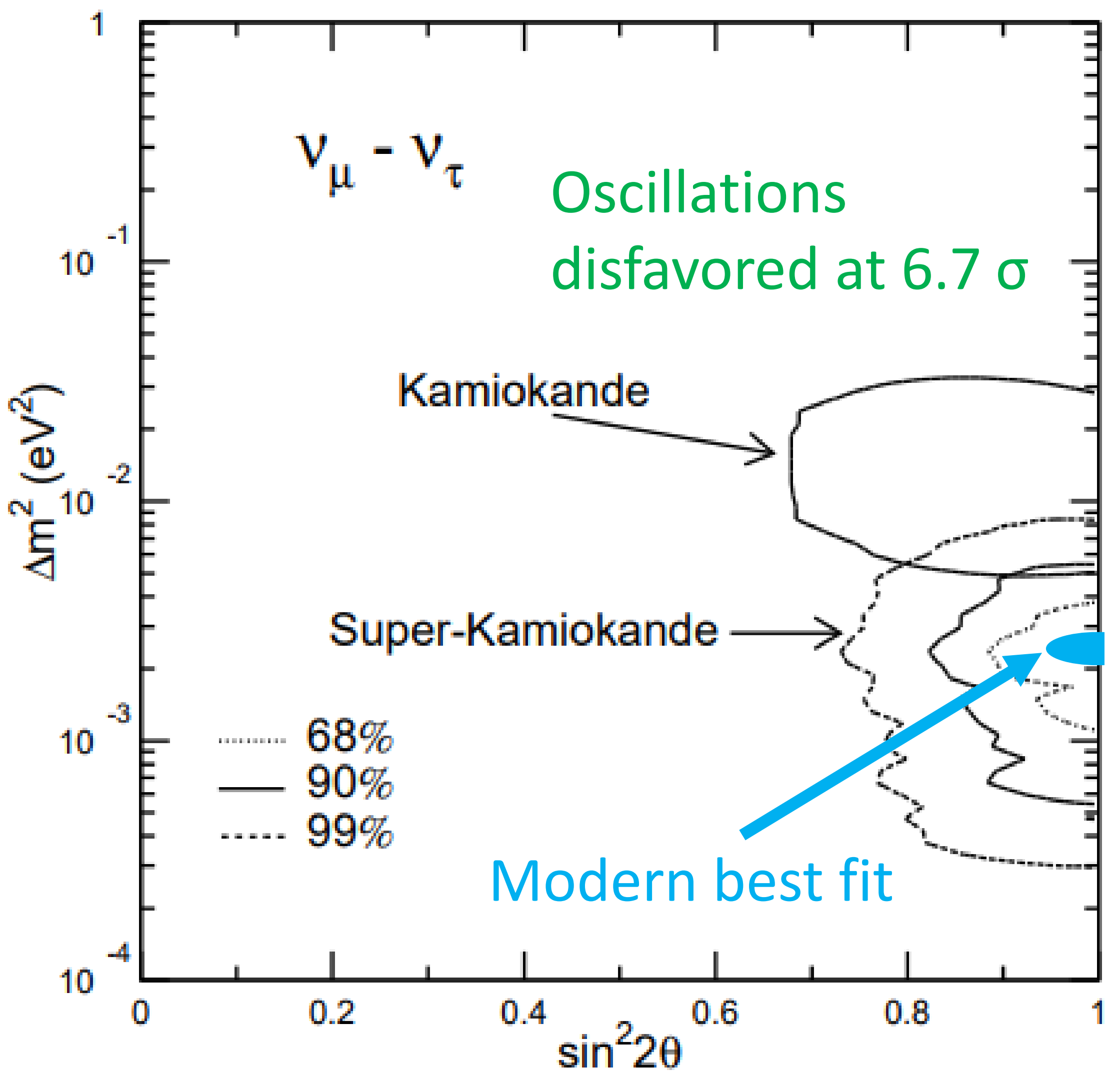
Maximal ν_μ/ν_τ mixing with a mass splitting $\Delta m^2_{32} \approx 2.4\text{e-}3\ \text{eV}^2$ (about 30x solar, 7.5e-5 eV^2)





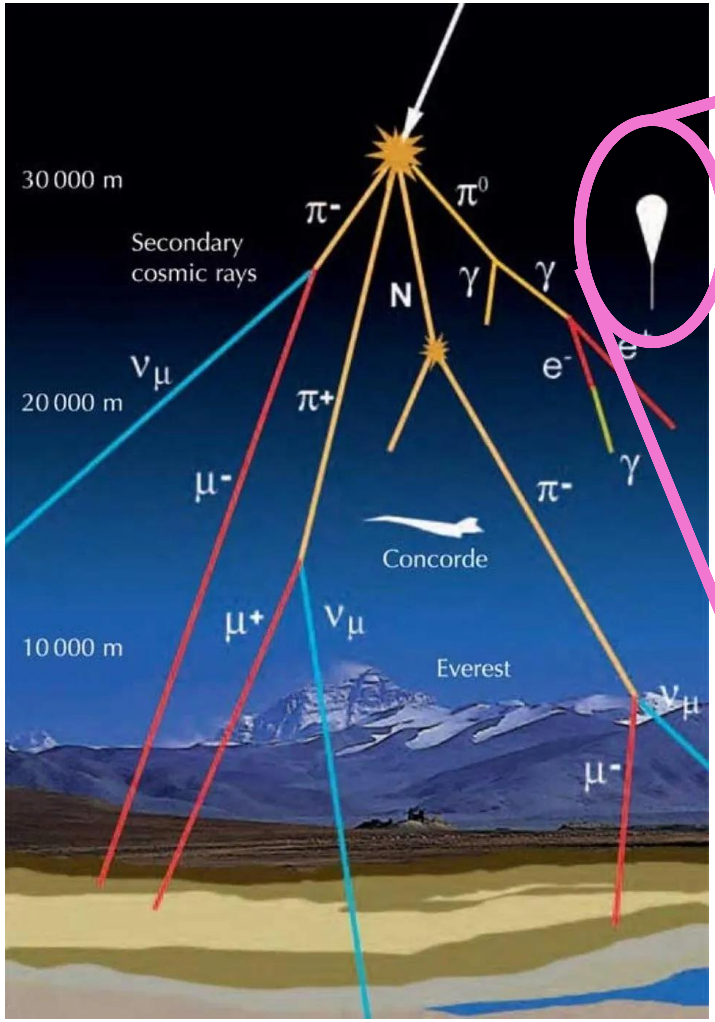
Possible uncertainties on event rates

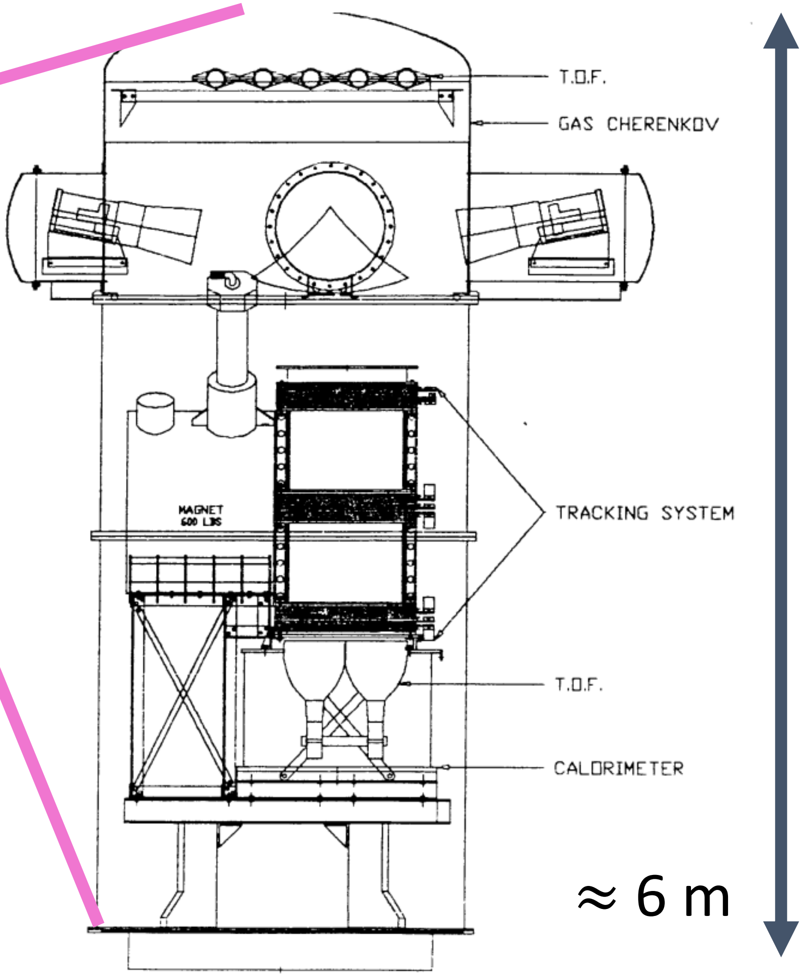
$$N_{\mathrm{evt}}(E) = N_{\mathrm{tar}} \times \varphi(E) \times \sigma(E)$$

Flux and cross section more uncertain than in solar neutrino case!

Possible uncertainties on event rates – neutrino flux

$$N_{evt}(E) = N_{tar} \times \varphi(E) \times \sigma(E)$$





– Mass balloon flew in 1991
– Time-of-flight + magnetic tracker for v + p reco
→ particle identification!
– Max altitude: 36 km
– Measures primary proton flux for input into atmospheric neutrino calculation

Bellotti et al., PRD 60 052002 (1999)

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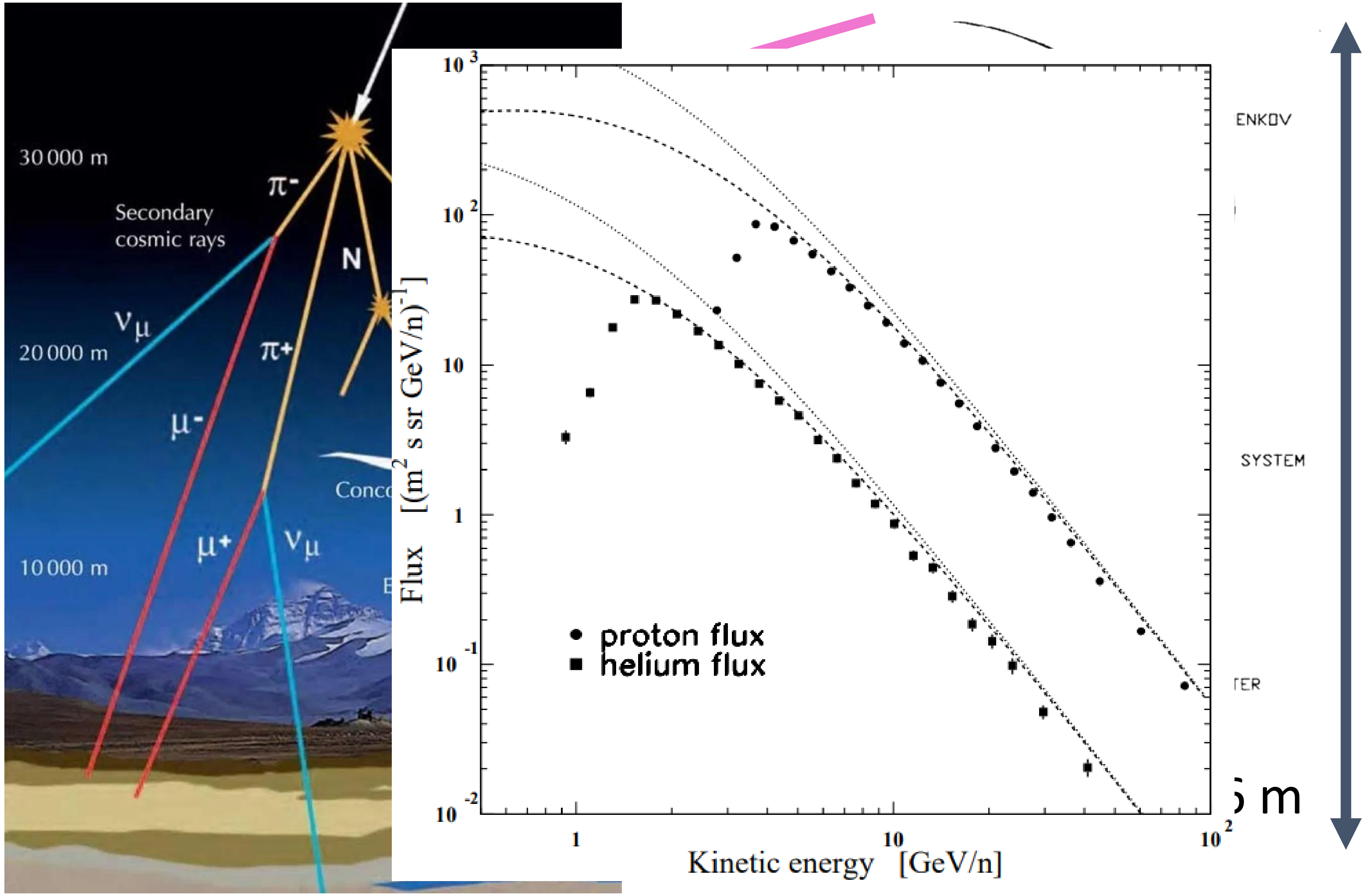

– Mass balloon flew in 1991
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→ particle identification!
– Max altitude: 36 km
– Measures primary proton flux for input into atmospheric neutrino calculation

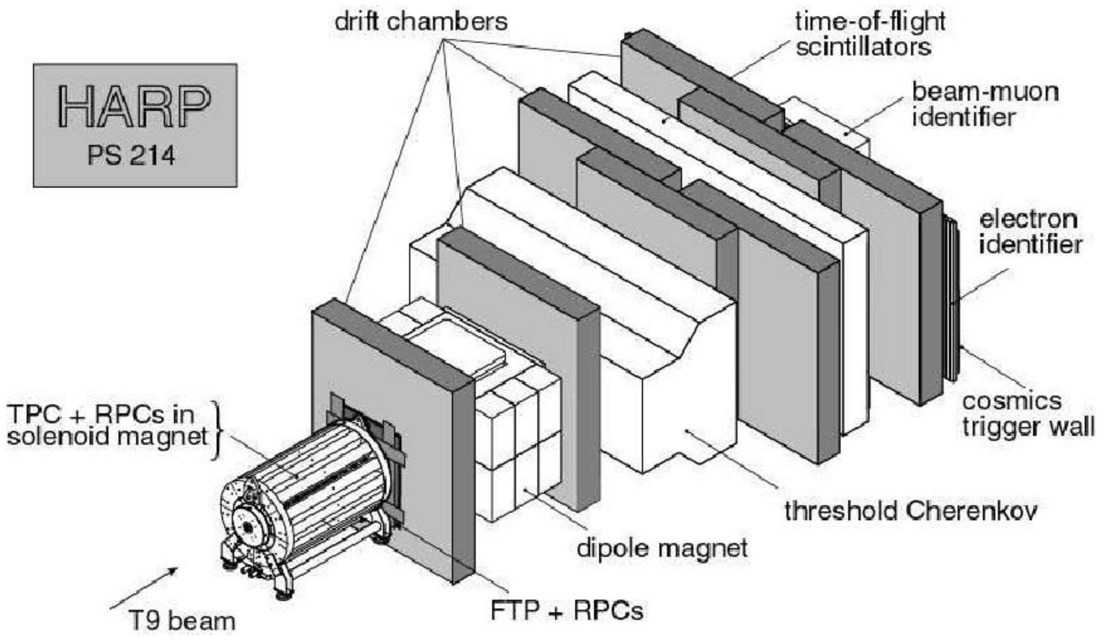
Data agrees with expectations!

Bellotti et al., *PRD* **60** 052002 (1999)

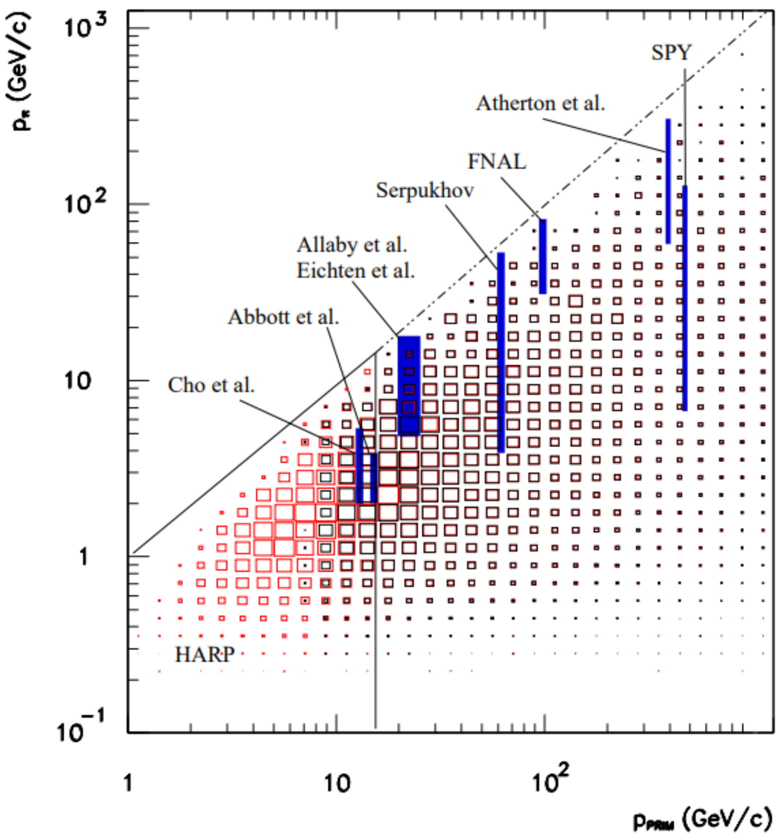
Possible uncertainties on event rates – neutrino flux

$$N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E)$$

HARP, *Nucl Phys A* **821** 118-192 (2009)



HARP experiment at CERN studied meson production from p-nucleus collisions on multiple nuclei providing final-state kinematics



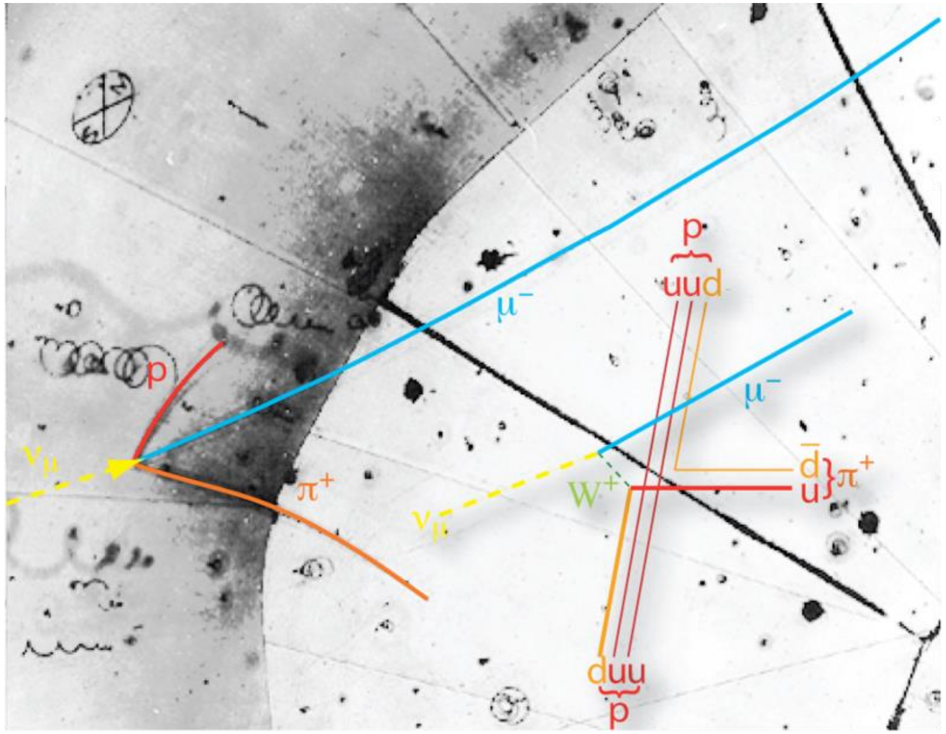
Barr, Robbins, Gaisser, Stanev, *PRD* **74** 094009 (2006)

Solution to flux uncertainties:
Data-driven model using primary data from balloons and meson production from HARP

EMPHATIC + SHINE experiments still using these methods for beam oscillations

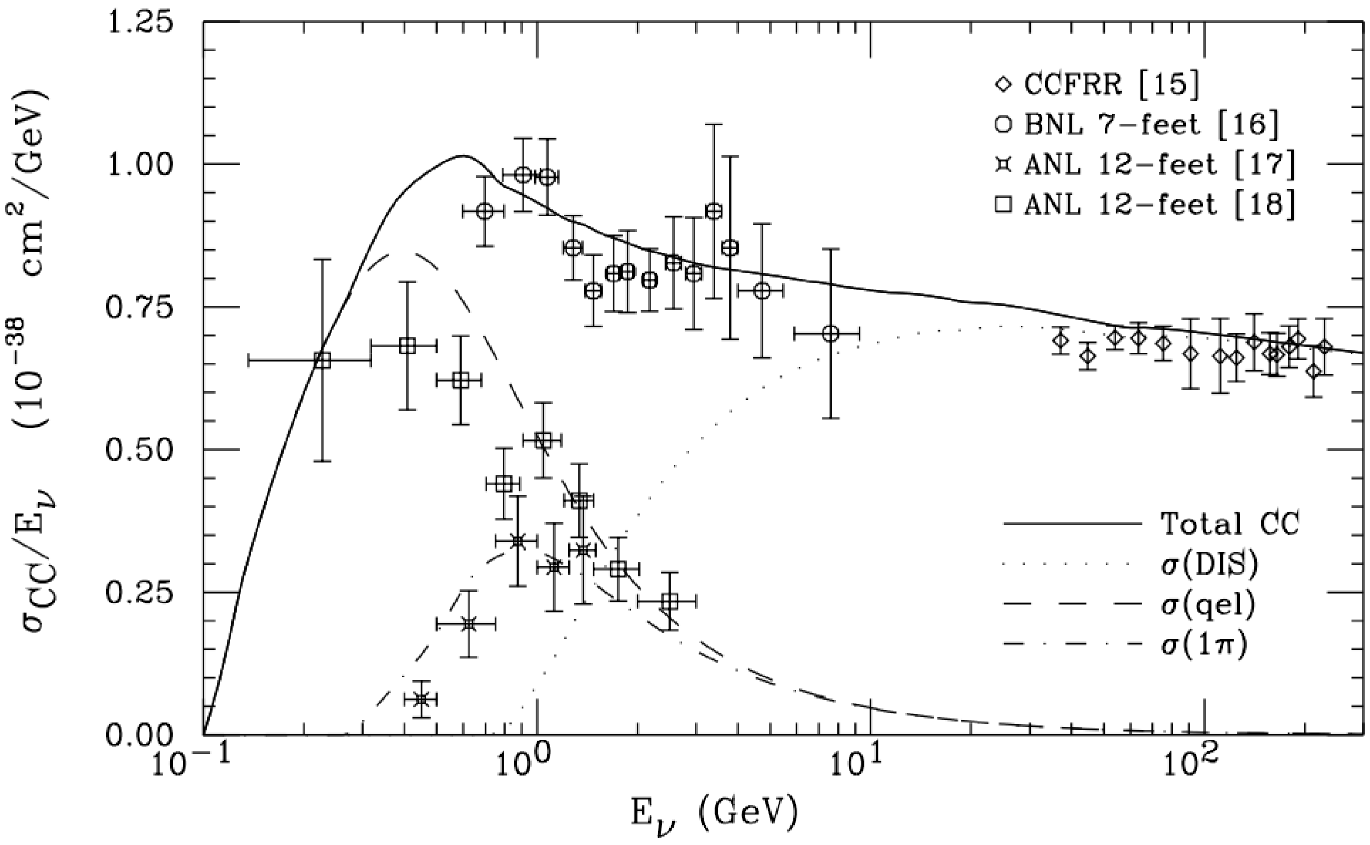
Possible uncertainties on event rates – cross section

$$N_{\text{evt}}(E) = N_{\text{tar}} \times \varphi(E) \times \sigma(E)$$



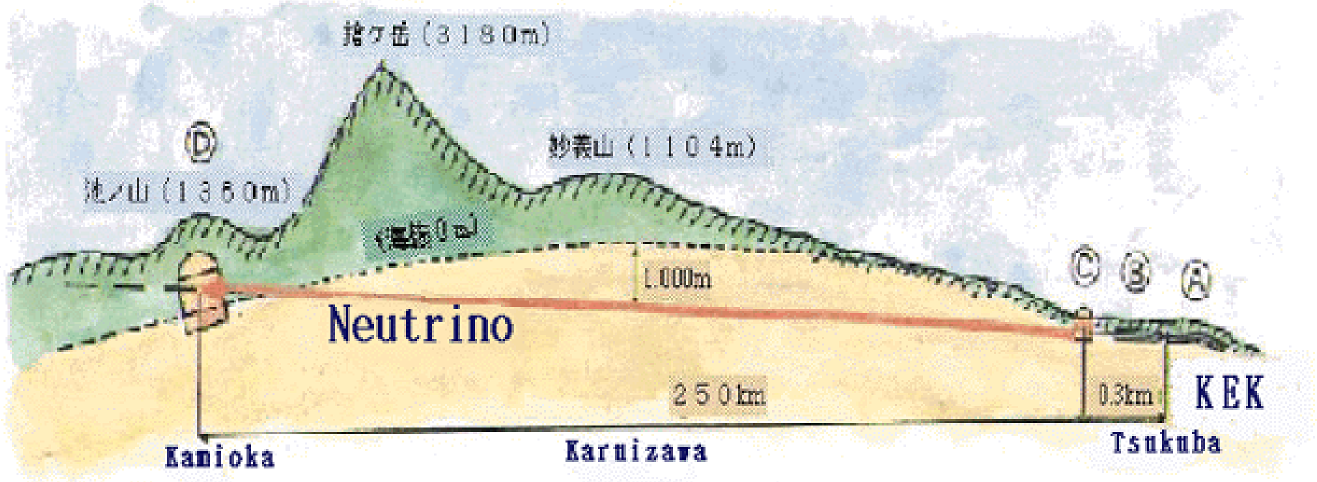
Bubble chamber data from 1980s
Effort to re-analyze in context of cross sections for atmospheric neutrinos

Uncertainty too small to explain oscillation effect



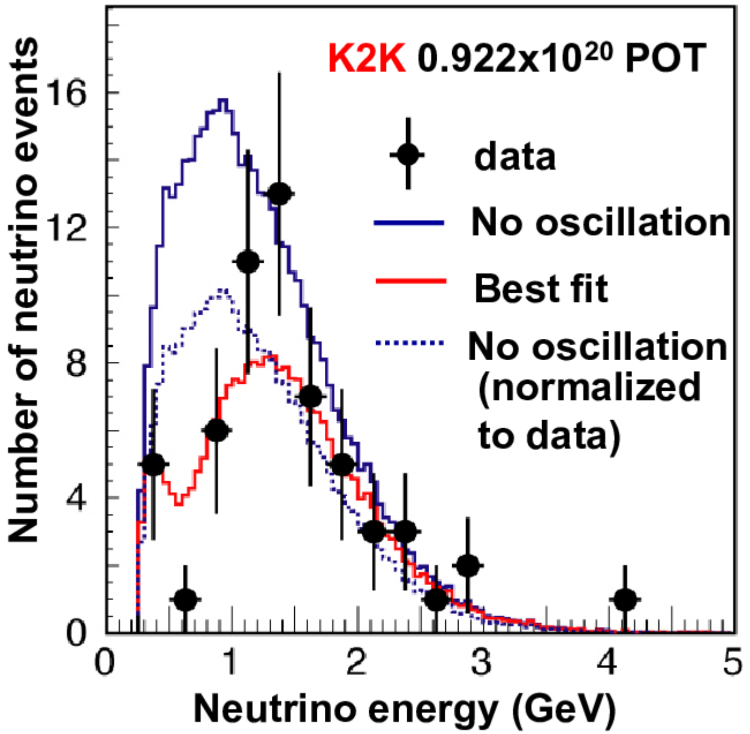
Lipari, Lusignoli, Sartogo, PRL 74 4384 (1995)

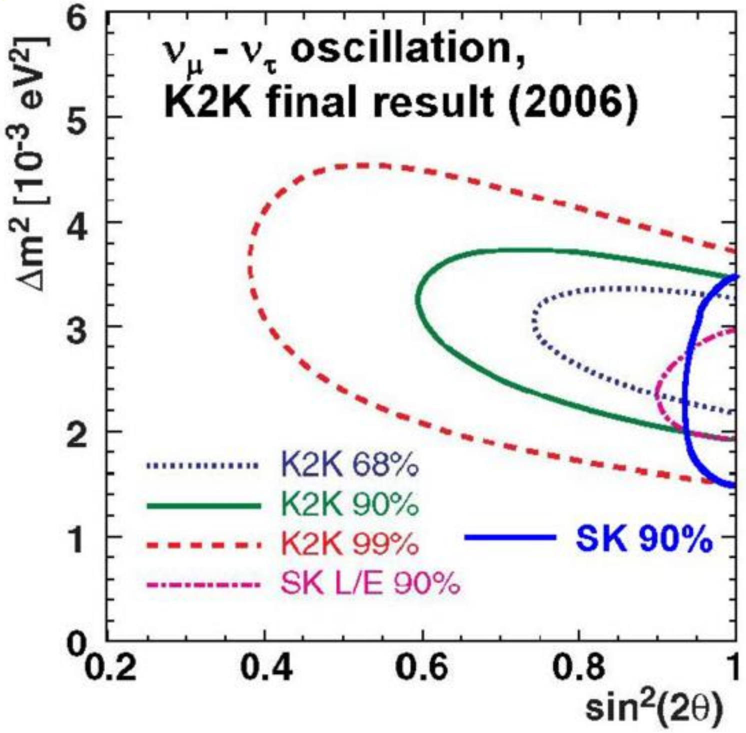
Final cross check: K2K



Want a laboratory test using a human-made neutrino source

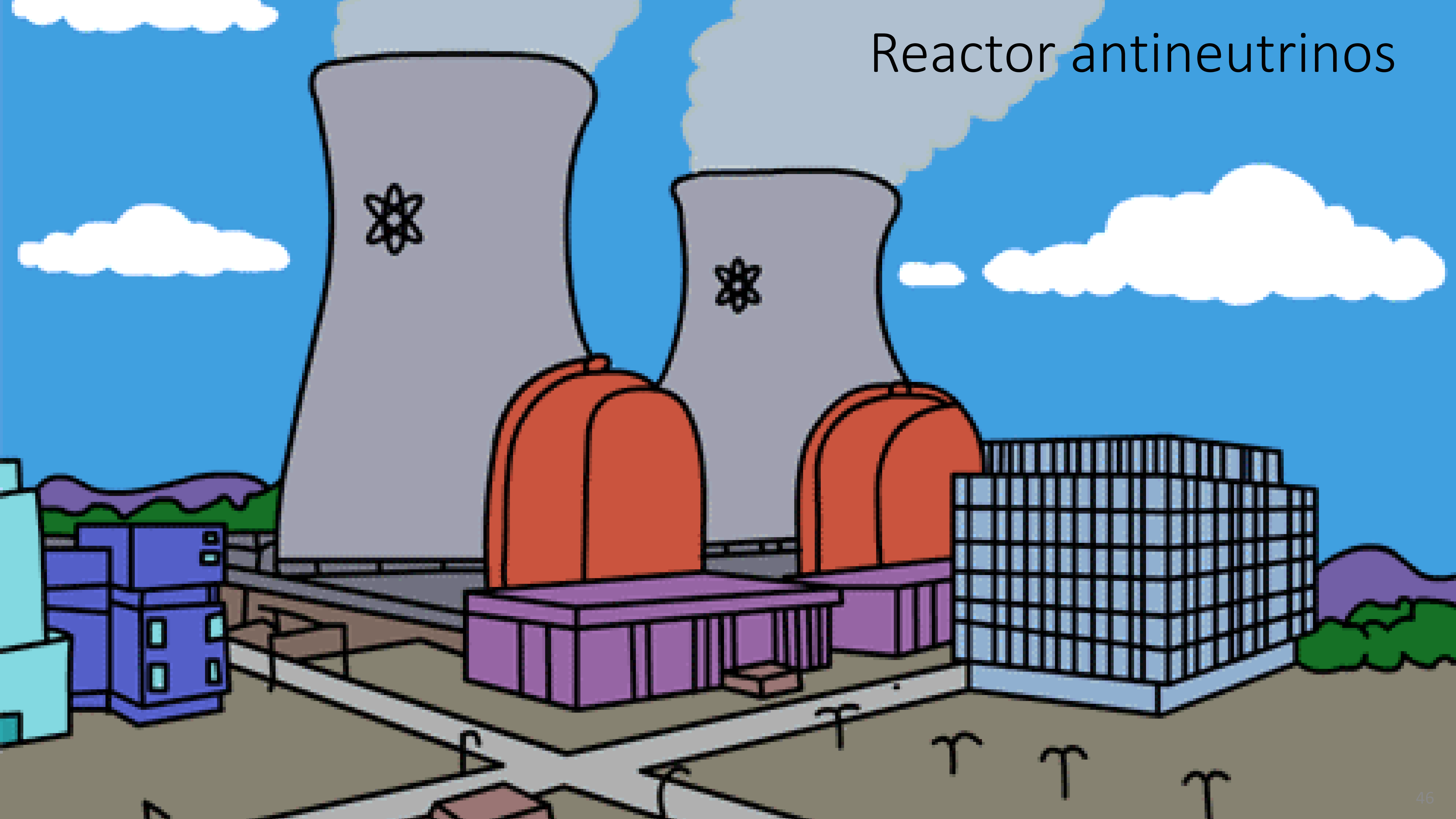
– KEK: 12 GeV proton synchrotron produces a beam of νμ
– 1 km downstream: a 1-kt water Cherenkov near detector for uncertainties
– 250 km downstream: SK measures oscillated spectrum





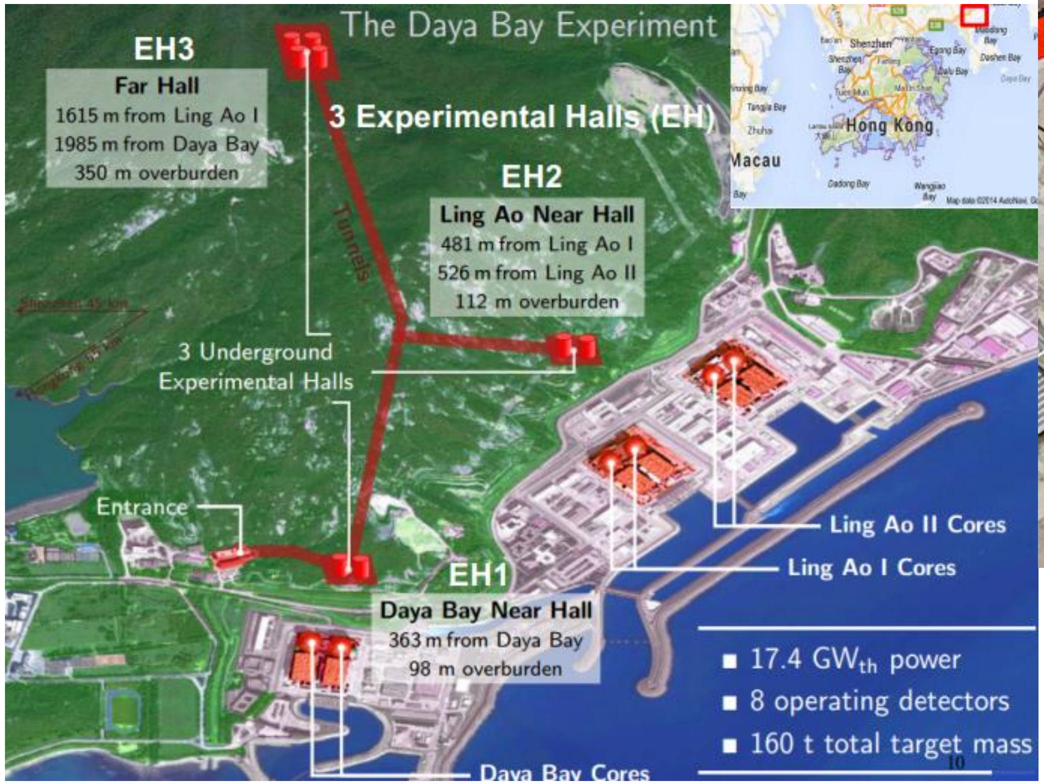
[K2K, *PRL* **90** 041801 (2002)](#)

Reactor antineutrinos

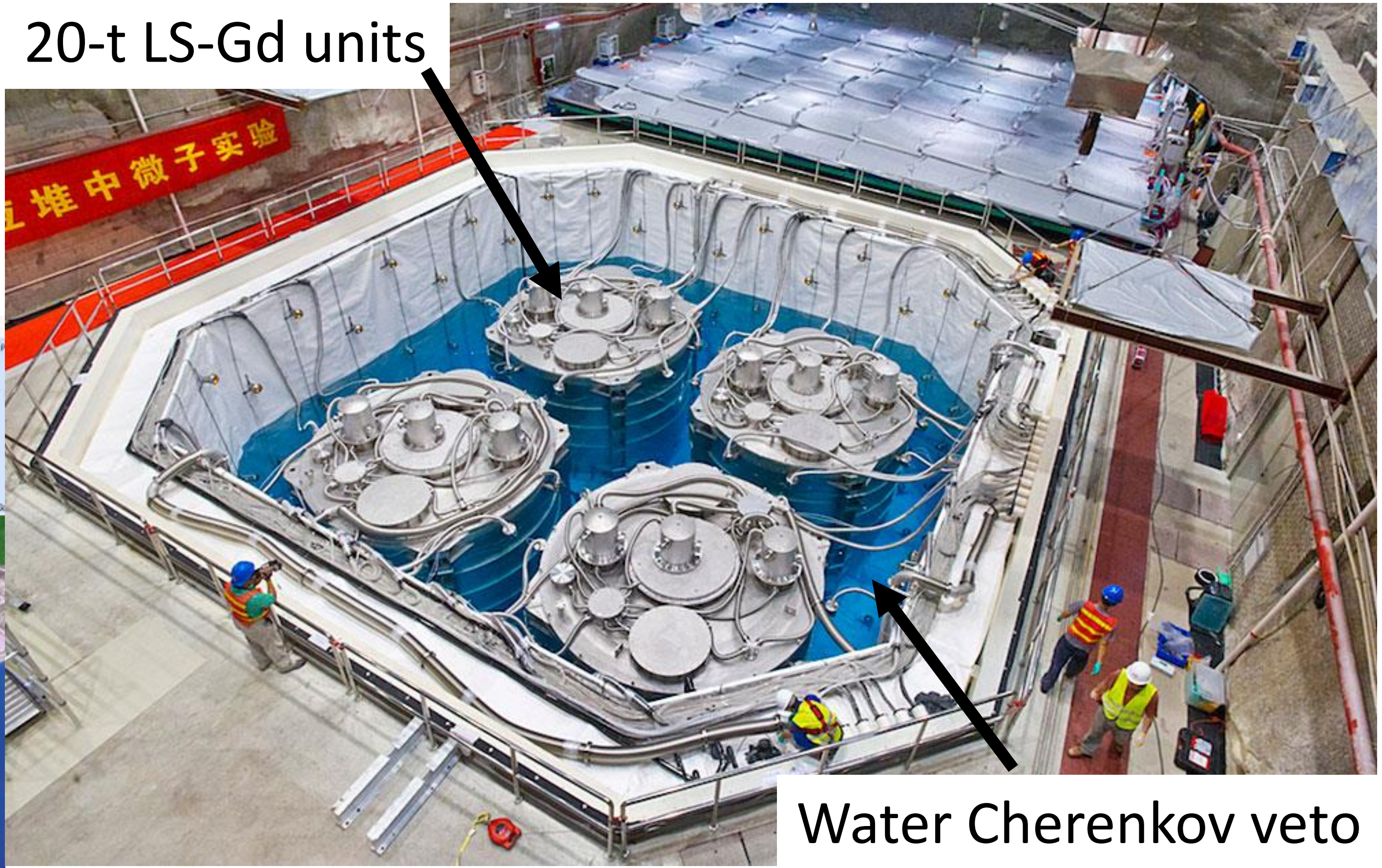


The Daya Bay experiment

Look for disappearance of reactor $\bar{\nu}_e$
Identical near/far detectors
  Each 4 x 20 ton LS-Gd detectors
IBD with prompt-capture coincidence

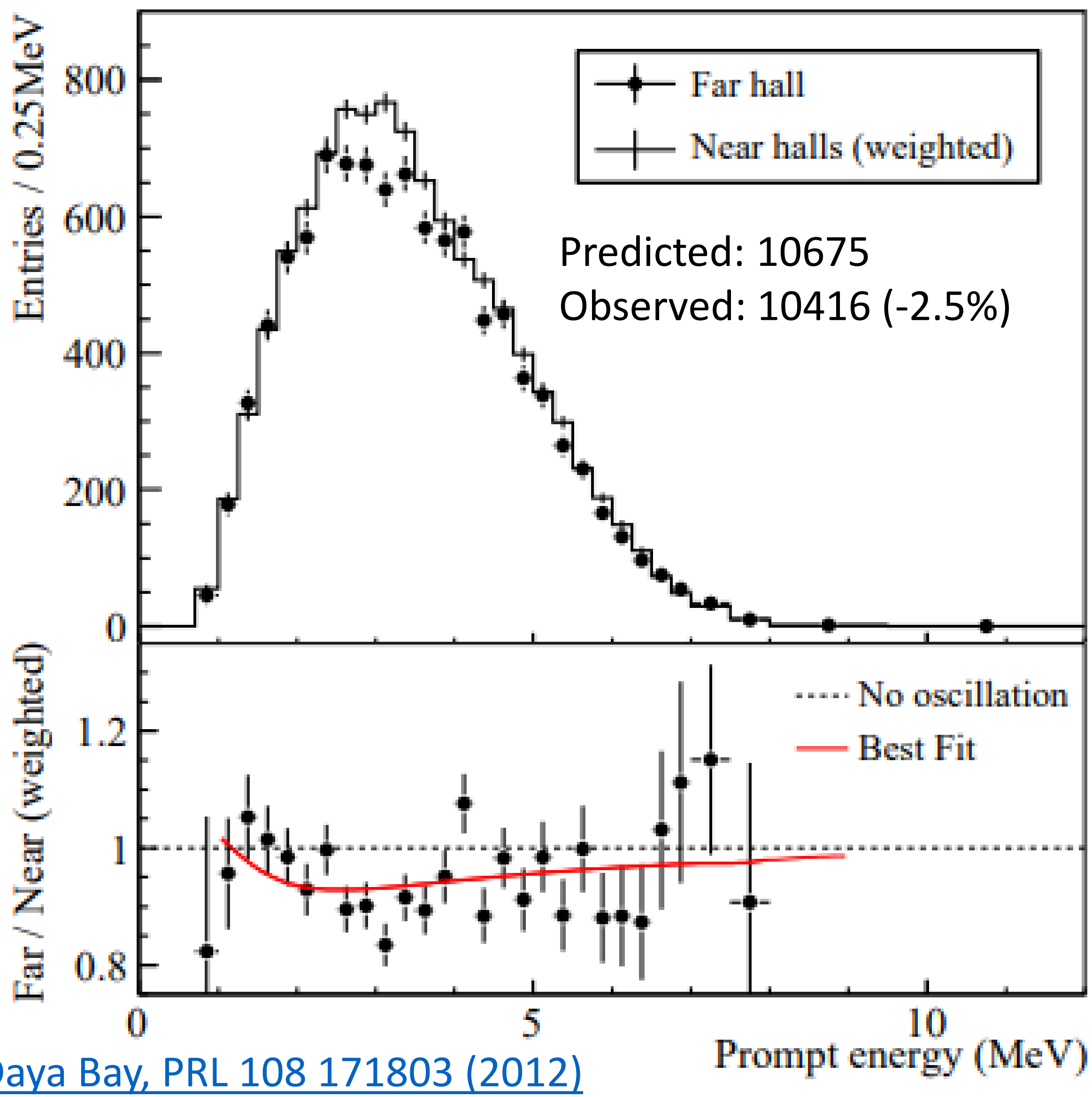


20-t LS-Gd units

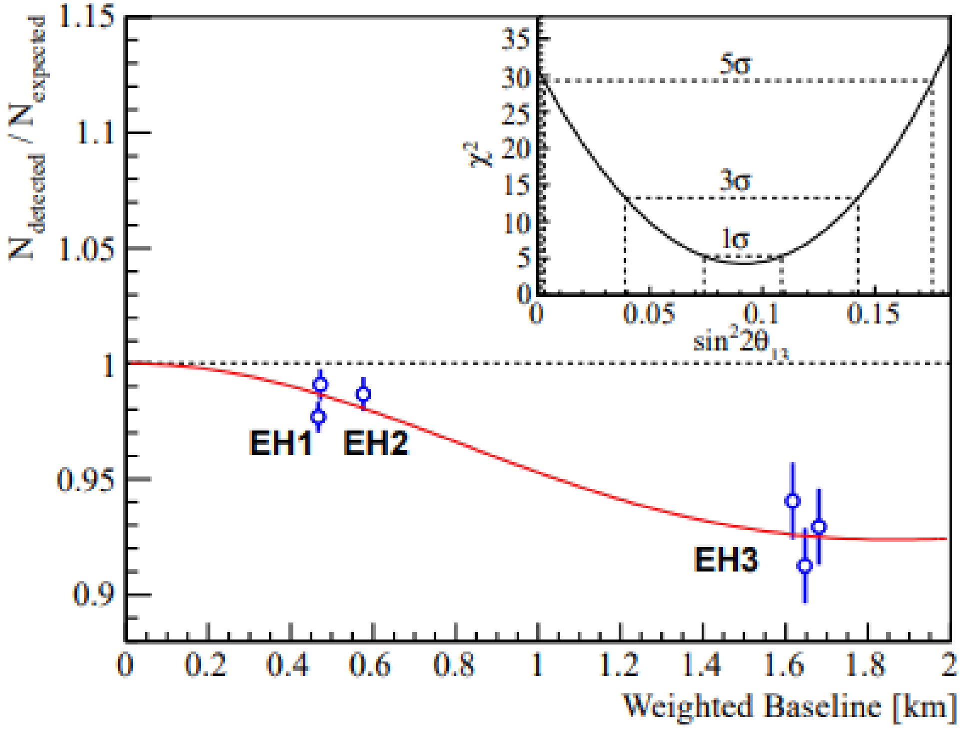


Water Cherenkov veto

First results – discovery of $\bar{\nu}_e$ disappearance



Daya Bay, PRL 108 171803 (2012)



> 95% pure IBD sample

Small, 2.5% effect, but observed at 5.2 σ with first result

Near/Far ratio fits well to oscillation model

Implication: $\nu_\mu \rightarrow \nu_e$ common enough for accelerator CP violation searches

Summary

– Natural sources of neutrinos – solar and atmospheric – dominate the history of neutrino oscillation discoveries

– SNO / SK data definitively demonstrate oscillations with solar / atmospheric neutrinos which were both cross-checked by 2000-2005

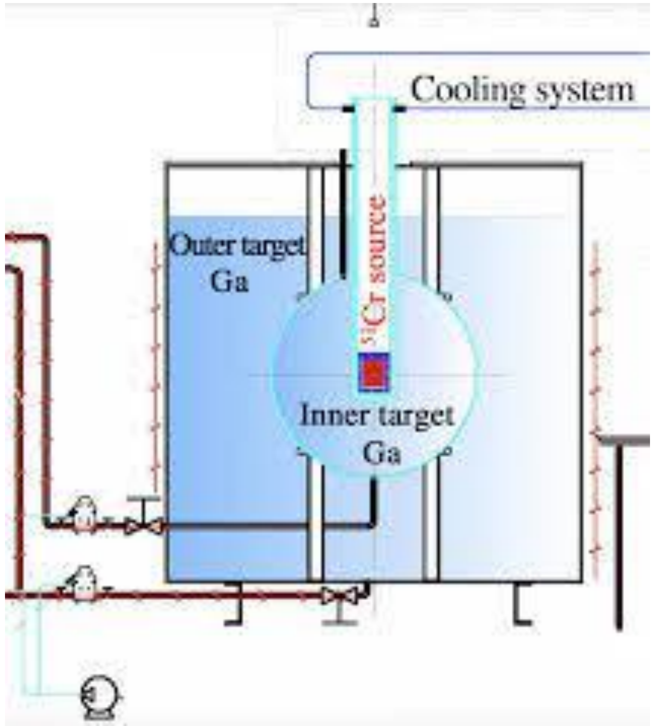
– Reactor data measured last mixing angle θ_{12} in 2012

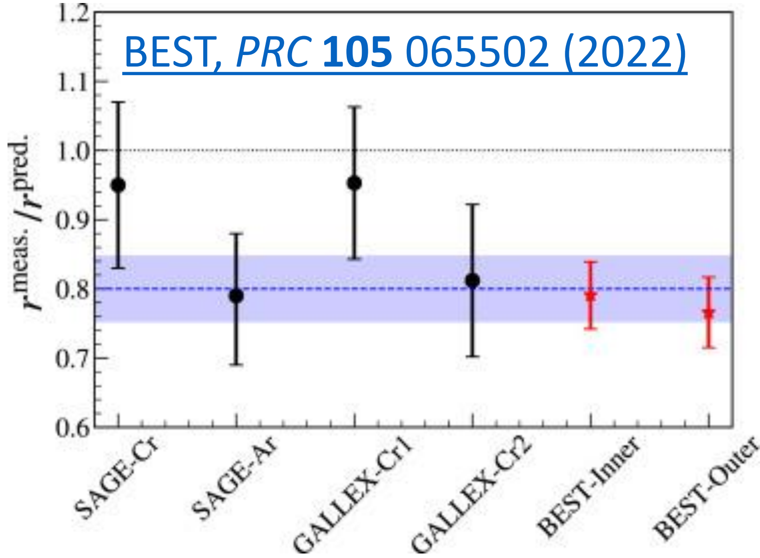
Aside

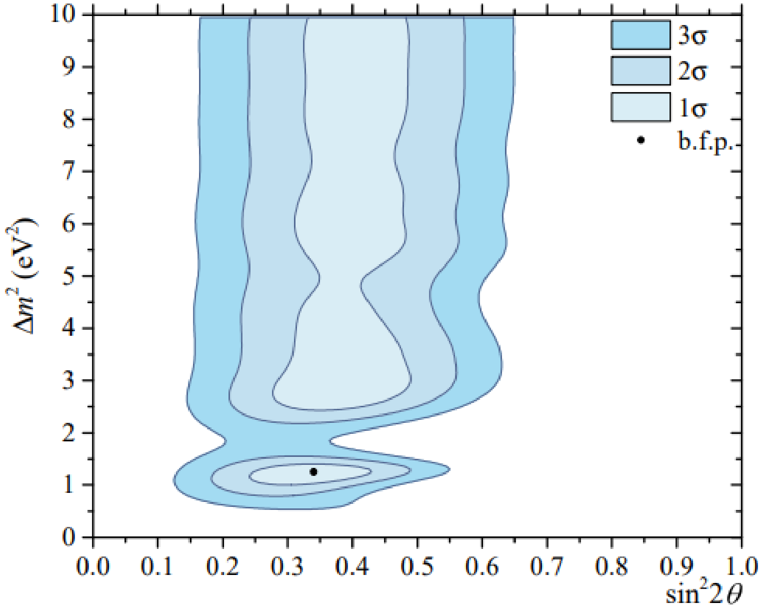
Gallium: solar neutrino problem 2 – electric boogaloo

Gallium calibration: lower event rate than expected, but not low enough to explain solar deficit

Maybe new physics?







BEST experiment released results in 2022 with much improved systematic uncertainties

> 5σ deficit

Could be sterile neutrino? Unknown uncertainty?

Back to solar neutrinos