Experimental Neutrino Physics I: Working with Neutrinos

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National Nuclear Physics Summer School, New Haven, CT

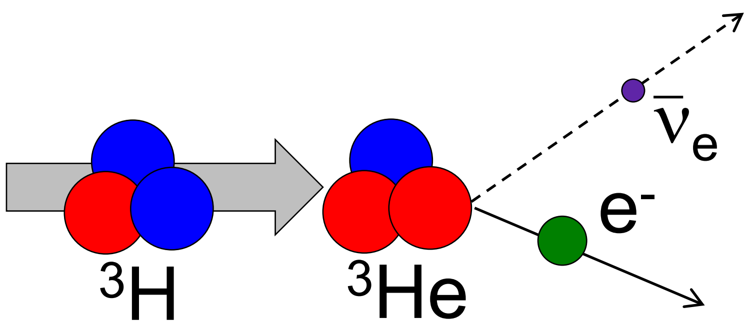
22 June 2018

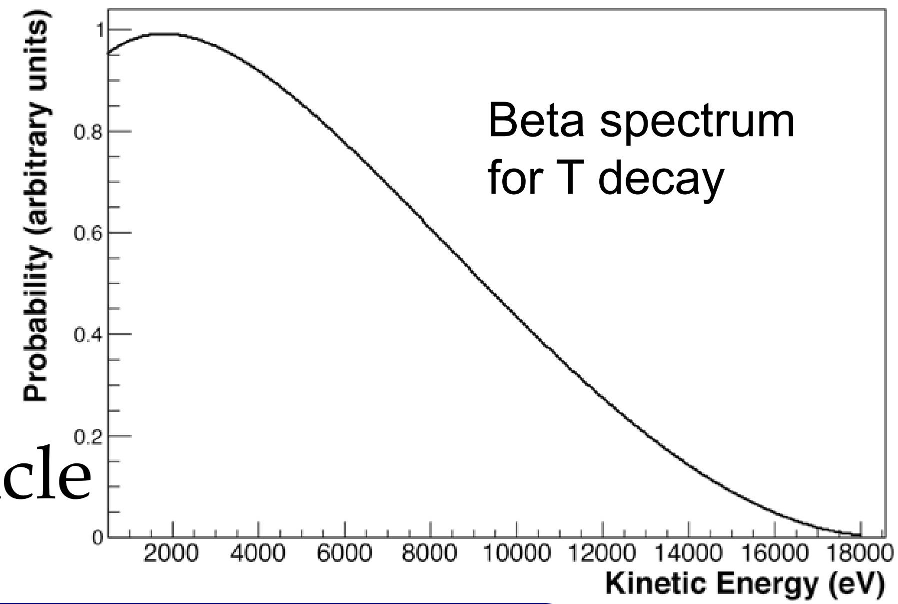
Lecture Plan

- **Lecture 1: Working with Neutrinos**
  - Sources
  - Detectors
  - Oscillations
- **Lecture 2: The Nature of Neutrinos**
  - Neutrino-mass scale
  - Searching for Majorana neutrinos
- **Lecture 3: Neutrinos as Tools**
  - Neutrinos for astrophysics
  - Neutrinos for geology
  - Neutrinos for nuclear physics
  - Neutrinos vs the Standard Model

The Neutrino: A “Desperate Remedy”

- 1930: Proposed by Pauli to explain beta spectrum





- Additional, unseen particle needed to save energy conservation

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

Neutrinos for Poets

Neutral

Leptons

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass...

-- John Updike, "Cosmic Gall" (1960)

Now we know better

Weak interactions

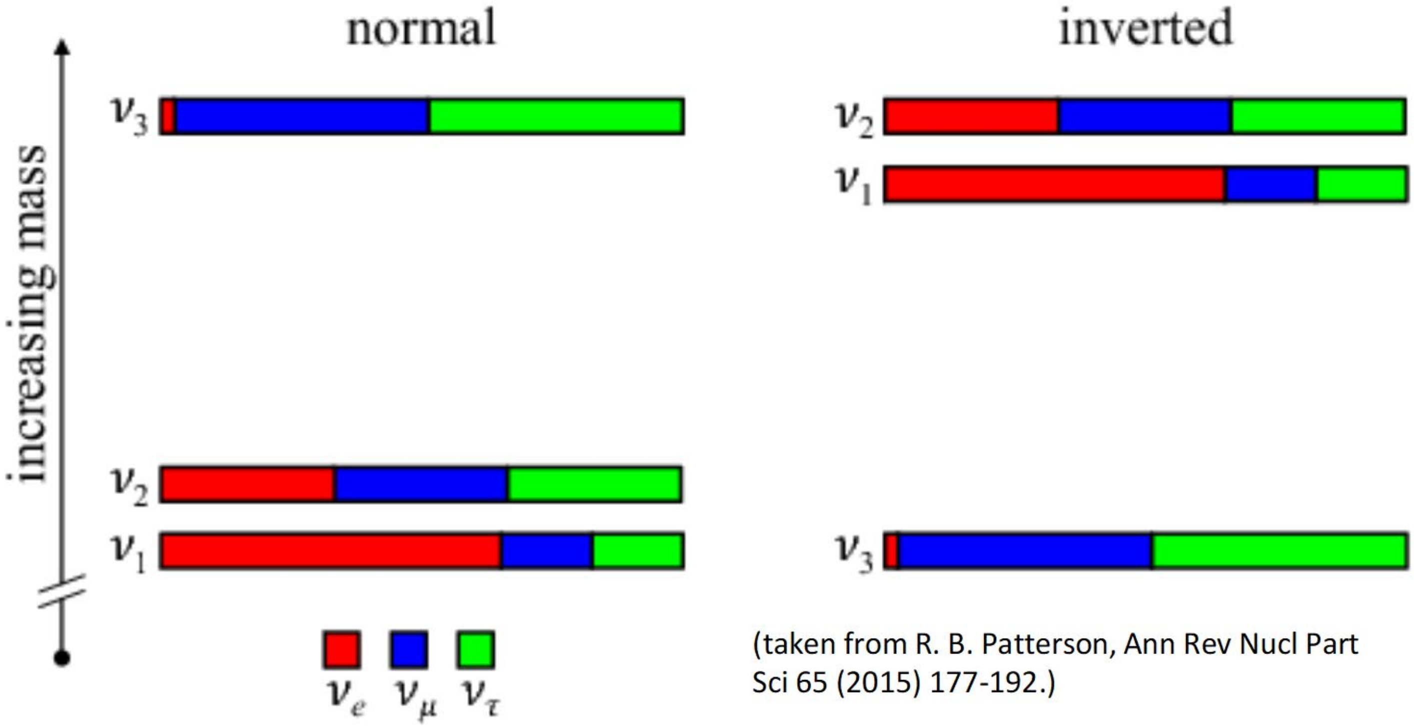
Correct

Outline

- Neutrino sources
  - Fission reactors
  - The Sun
  - Accelerators
  - The atmosphere
  - Outside the solar system
- Neutrino detectors
- Neutrino oscillations

What Kind of Neutrino?

- Two different neutrino bases: flavor and mass
  - Each flavor state is associated with a charged lepton (e, μ, τ) in charged-current interactions
  - Each mass state is a superposition of flavor states
- We'll consider neutrino sources based on **flavor** and **energy**

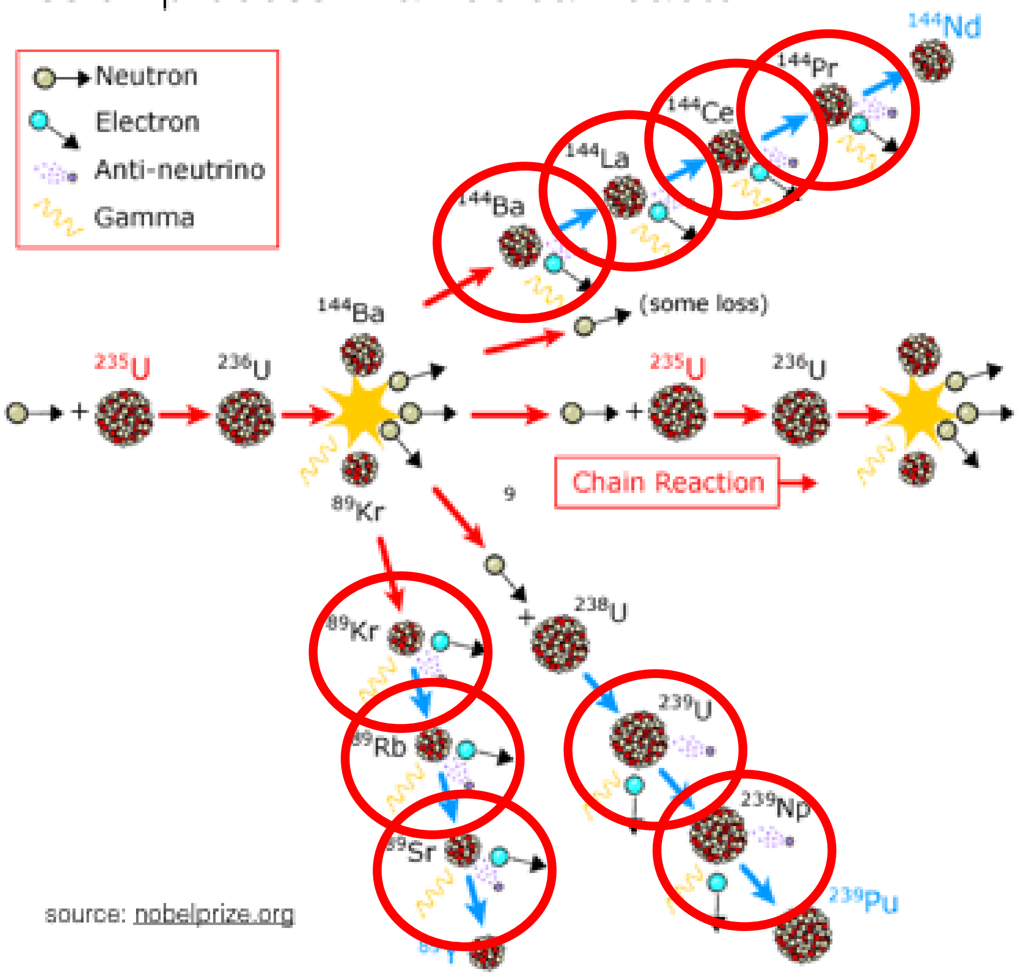


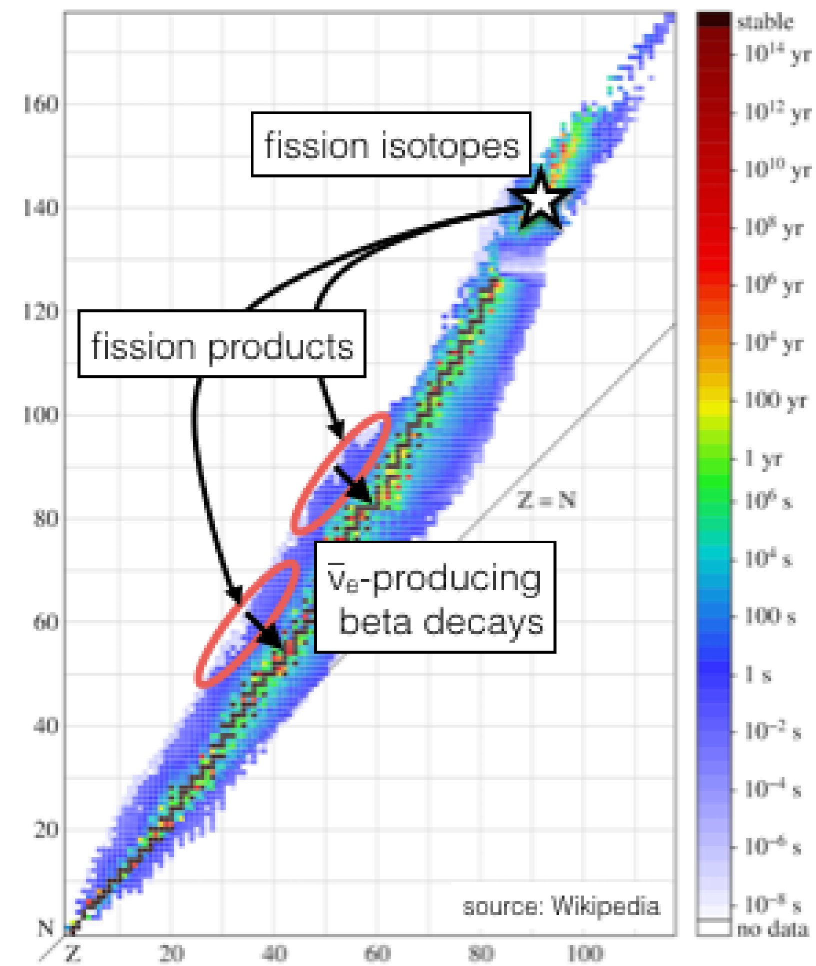
(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

Neutrinos from Nuclear Reactors

- Fission reactors produce electron antineutrinos at a few MeV

fission process in a nuclear reactor

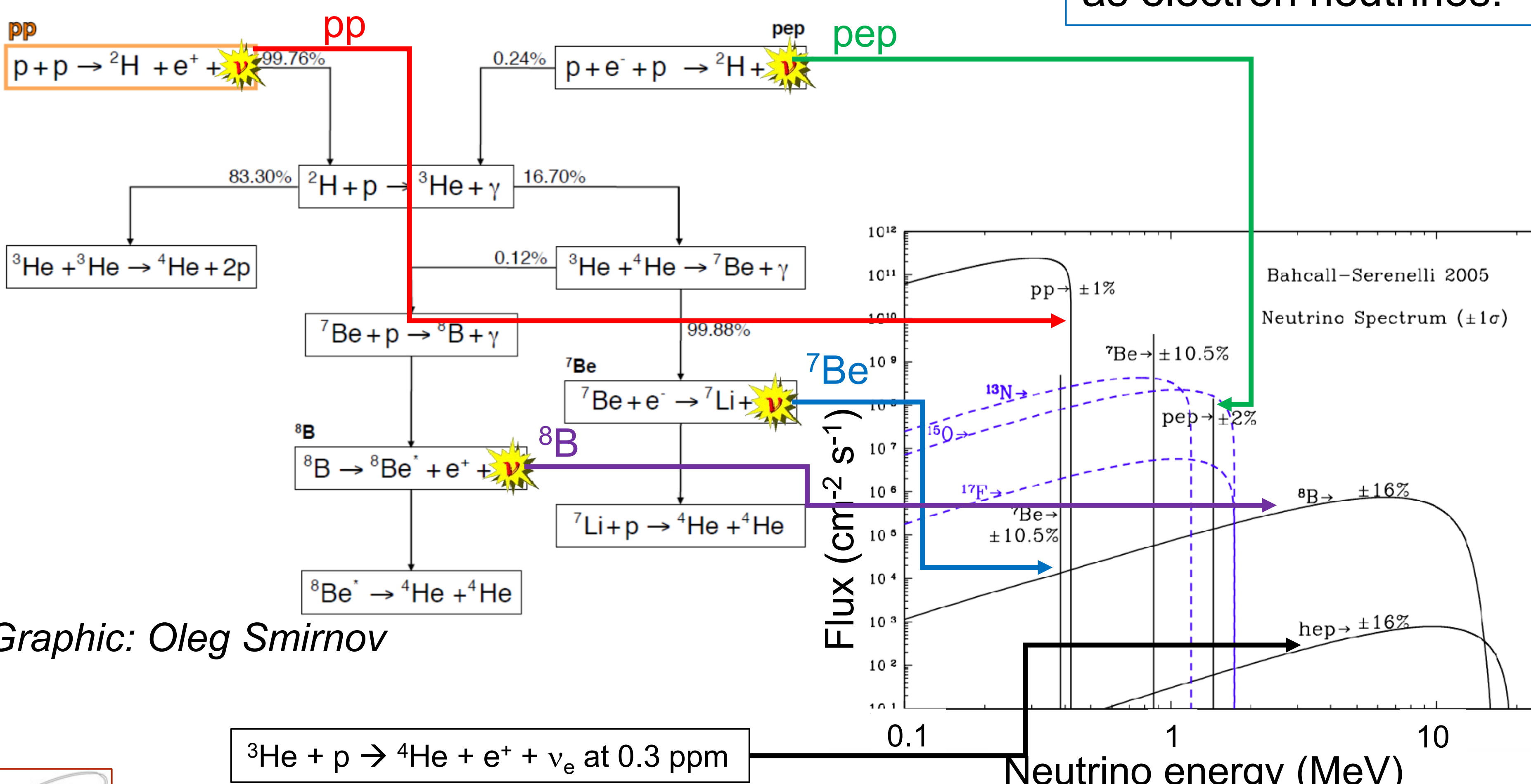




Neutrinos from the Sun

- At its core, the Sun is a fusion reactor ...

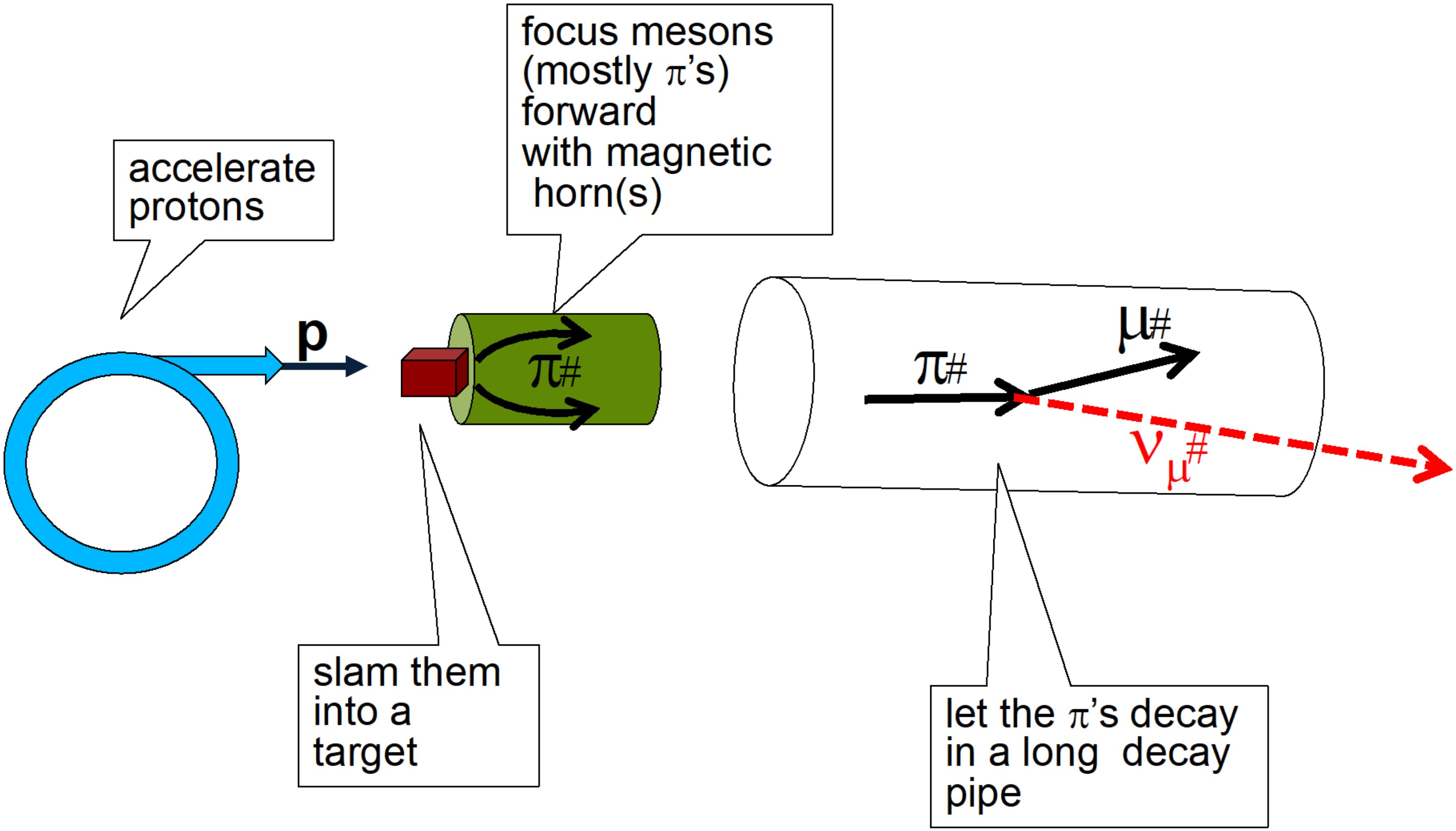
These are all created as electron neutrinos!



Graphic: Oleg Smirnov

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$ at 0.3 ppm

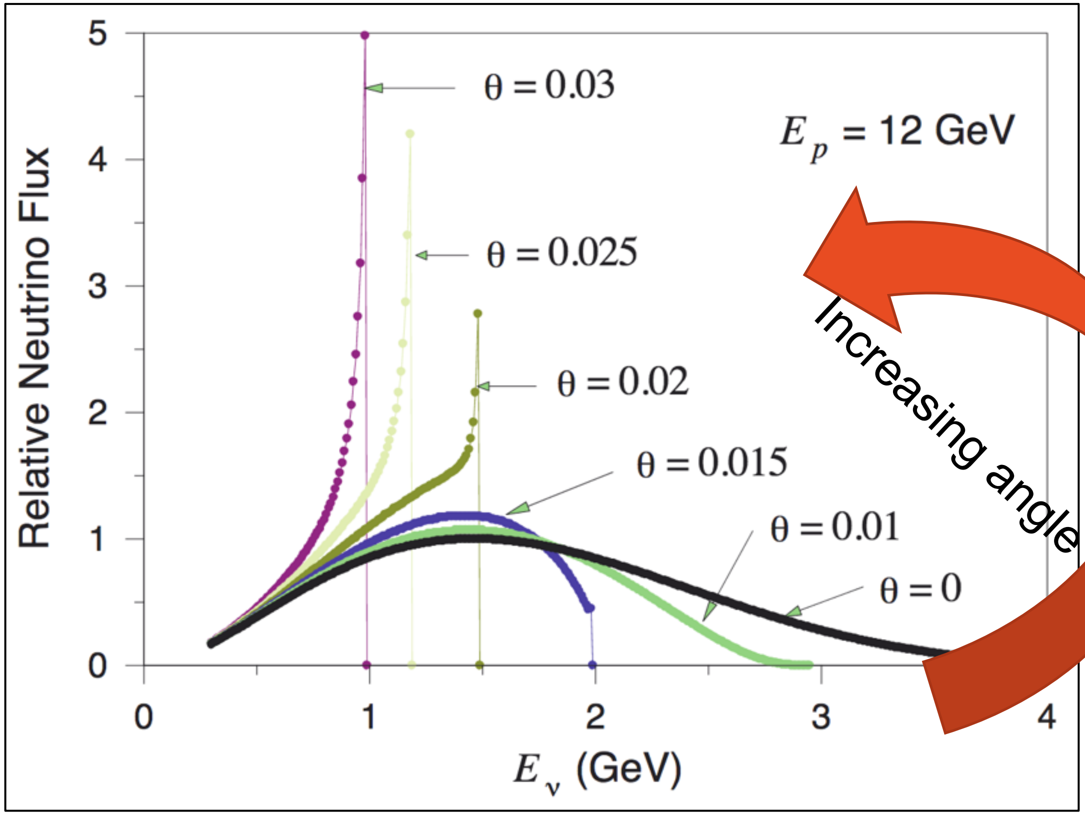
Neutrinos from Accelerators



Graphic: Kate Scholberg

Neutrinos from Accelerators

- Neutrinos are emitted from meson beam with a continuous distribution of energy and angle
- An off-axis detector sees a neutrino beam with a tighter energy spread

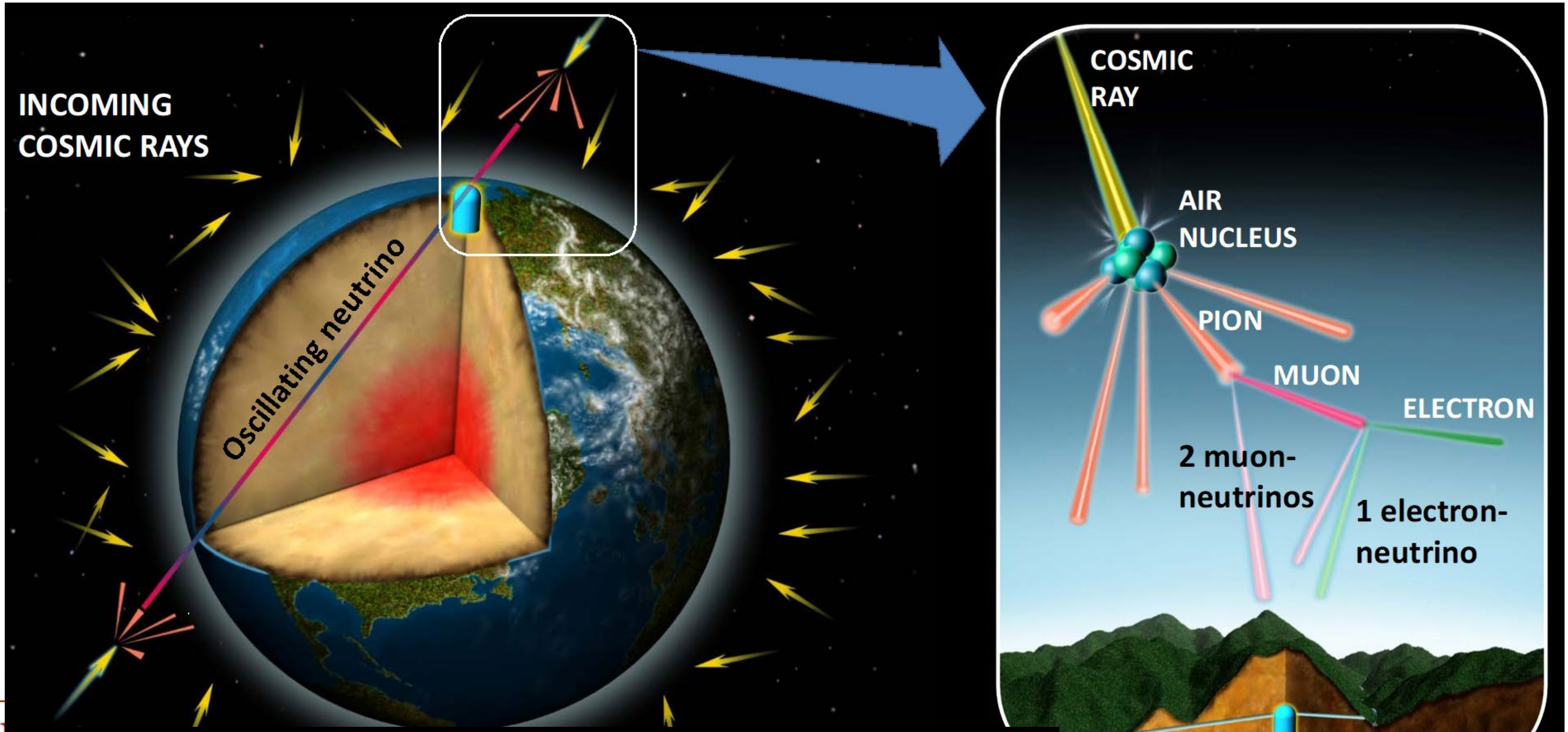


Plot: McDonald, arXiv: ज़ह्ह्ह्ज़ट्ट [hep-ex]

Preprint includes detailed derivation!

Neutrinos from the Atmosphere

- Cosmic rays interact in upper atmosphere, making muons
- Muons decay, producing neutrinos
- Use angular distribution to probe different path lengths



David Fierstein for Scientific American, August 1999

Neutrinos from Beyond ...

- Multi-messenger astronomy era – combination of data from photons, neutrinos, and gravitational waves – is beginning

Slide from Ignacio Taboada

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17
FROM: E

Claudio Ko
report on I

On 22 Sep,
probability
Extremely
normal on

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Y
K

Crede

Subjects: Gamma

Referred to by AT
10844, 10845, 10

Tweet | Rec

We searched for
neutrino event e
10787) with all-sk
ray Space Telesco
and also included
located inside the

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

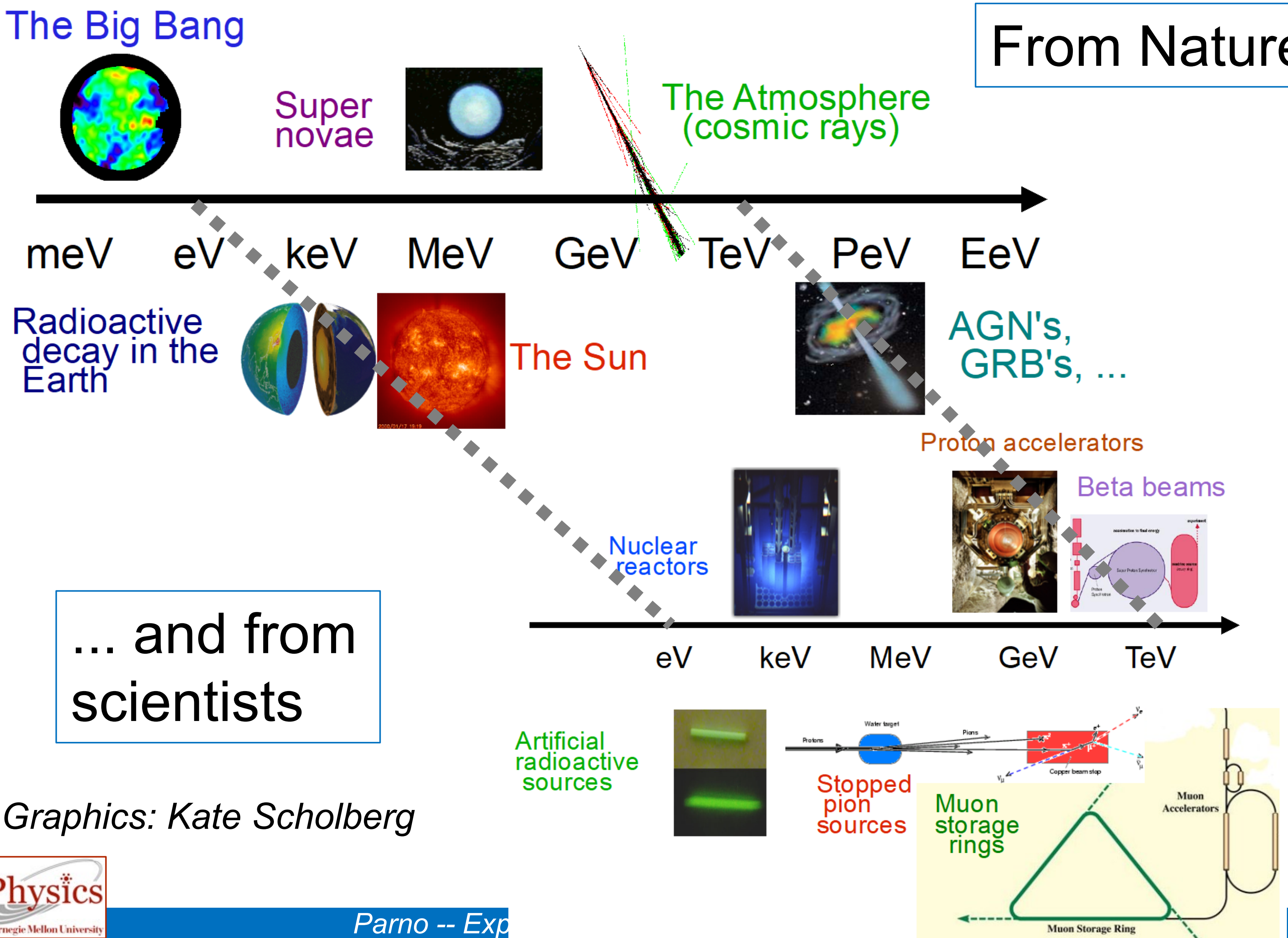
Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

Work on-going

September 22, 2017: a neutrino alert issued by IceCube
Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
Very active multi-messenger follow-up from radio to γ-rays

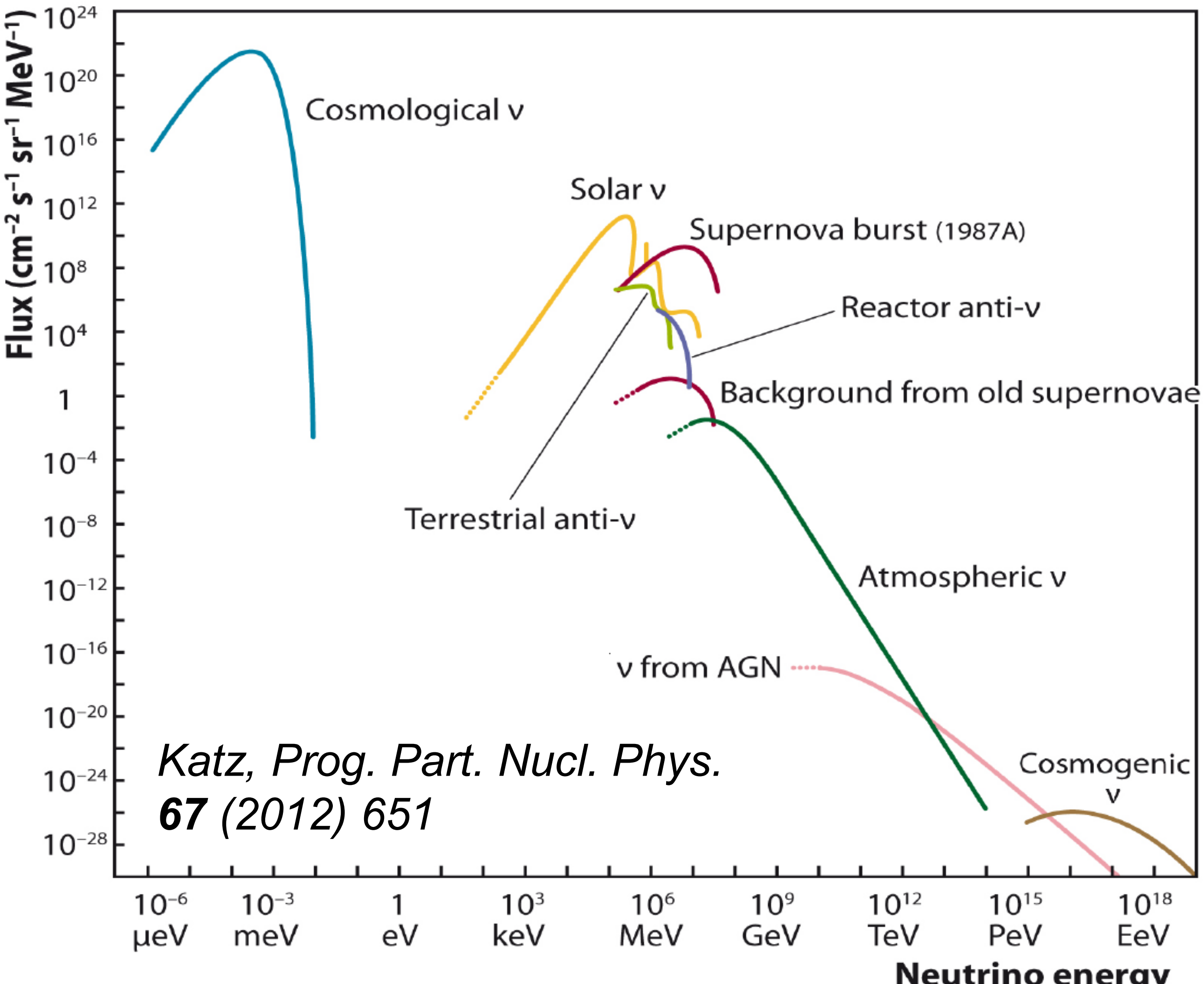
Neutrino Energy Scales



Graphics: Kate Scholberg

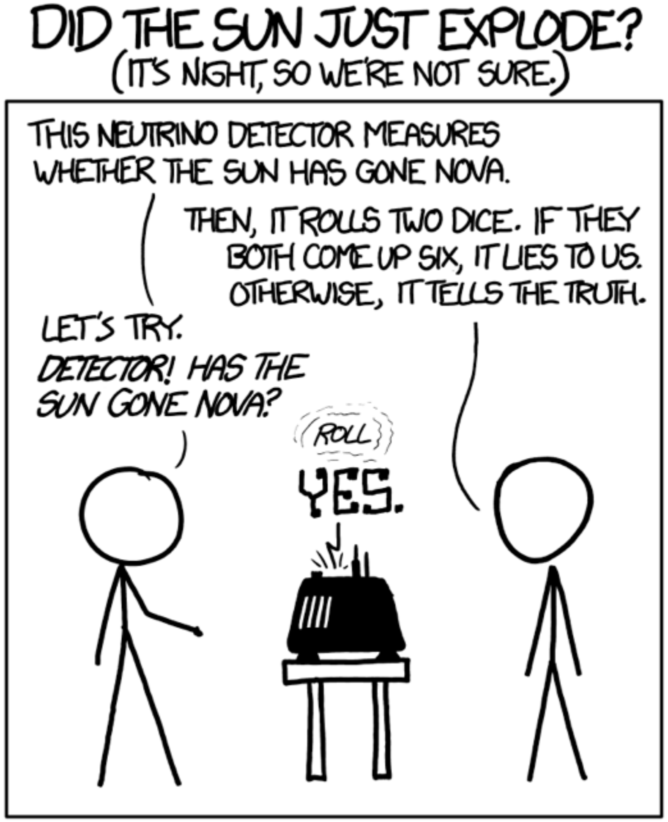
Neutrino Energy Scales

- Let's make that picture a little more quantitative ...



Outline

- Neutrino sources
- Neutrino detectors
  - Charged-current interactions
  - Neutral-current interactions
  - A few detector technologies
- Neutrino oscillations

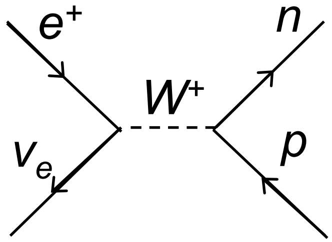


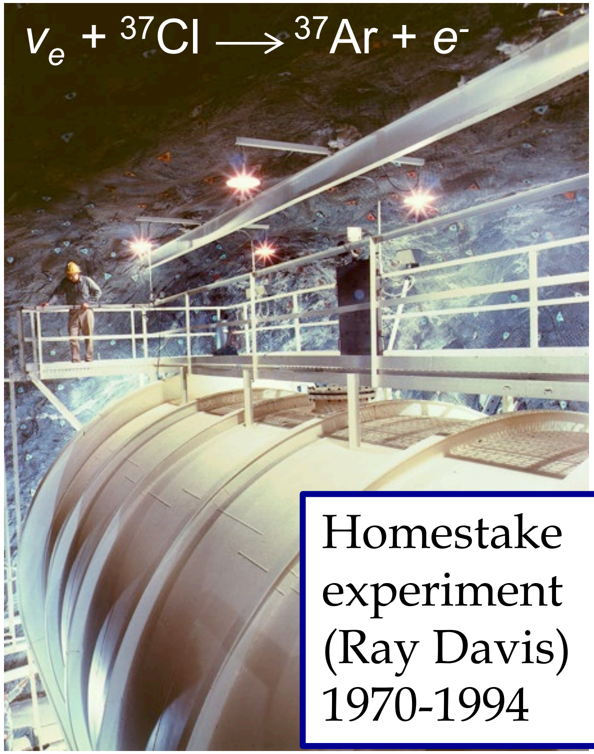
https://xkcd.com/1132/

Neutrino Detection I

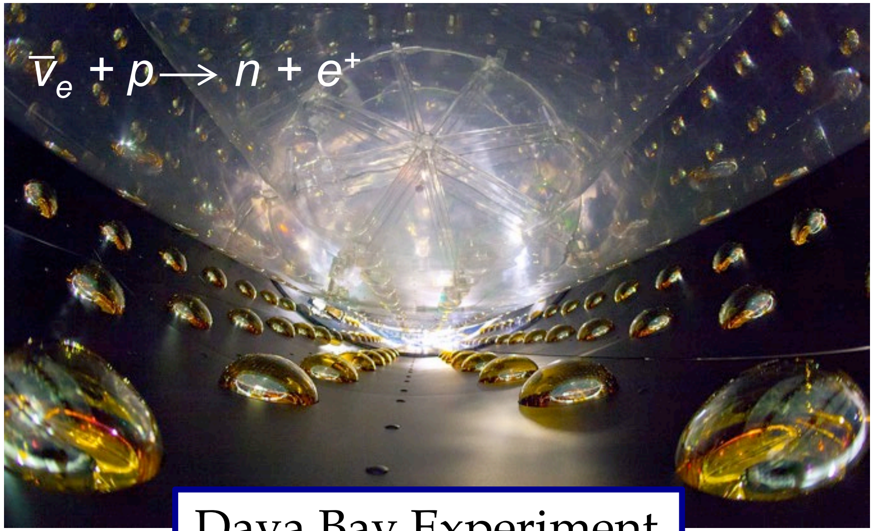
- Charged-current interactions
  - $W^{\pm}$ boson exchange
  - Initial neutrino $\longrightarrow$ final charged lepton

Example: inverse beta decay





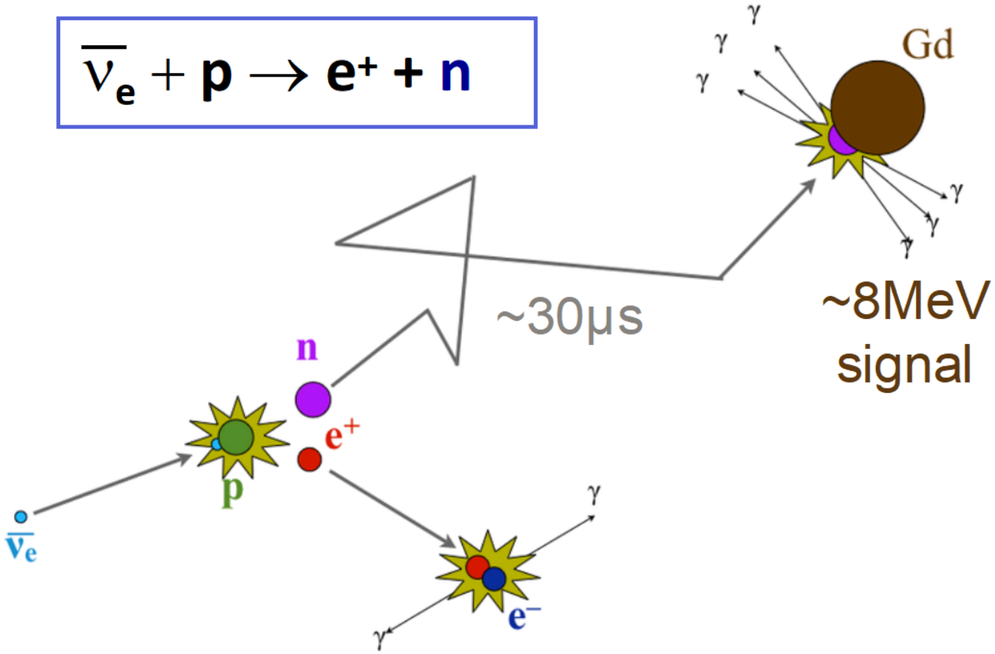
Homestake experiment (Ray Davis) 1970-1994



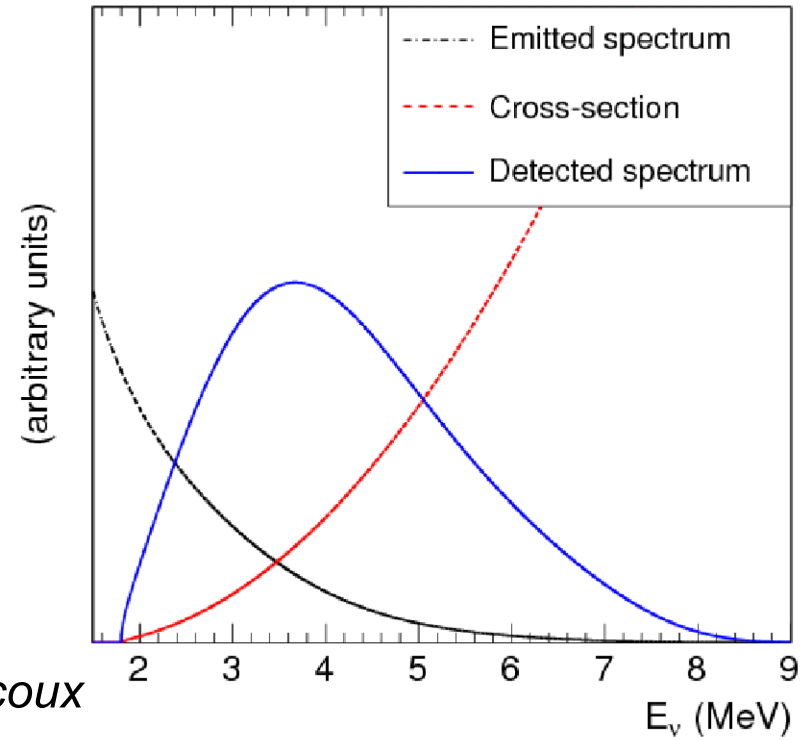
Daya Bay Experiment 2011 - Present

Detecting Inverse Beta Decay

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



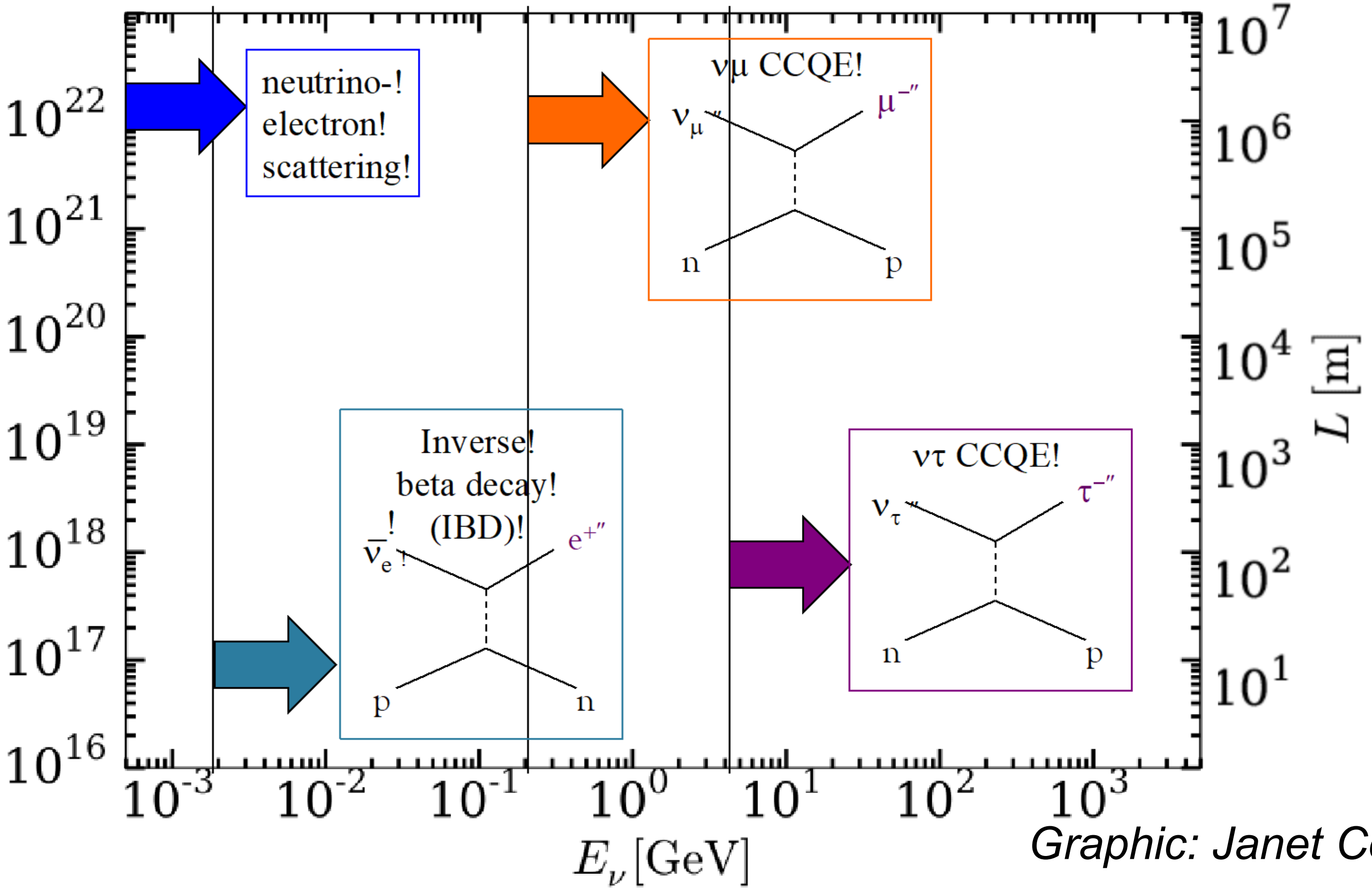
Graphic: J. Pedro Ochoa-Ricoux



- *Prompt* (= essentially no delay) observation of positron
  - Positron energy → incident antineutrino energy
- *Delayed* signal from neutron capture on Gd dopant
- Coincidence signal allows efficient background rejection

CC Detection Thresholds

- Charged-current interactions have flavor-dependent thresholds – you need enough energy to create the charged lepton!

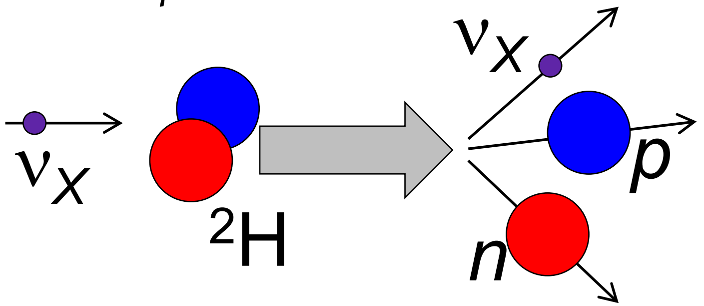


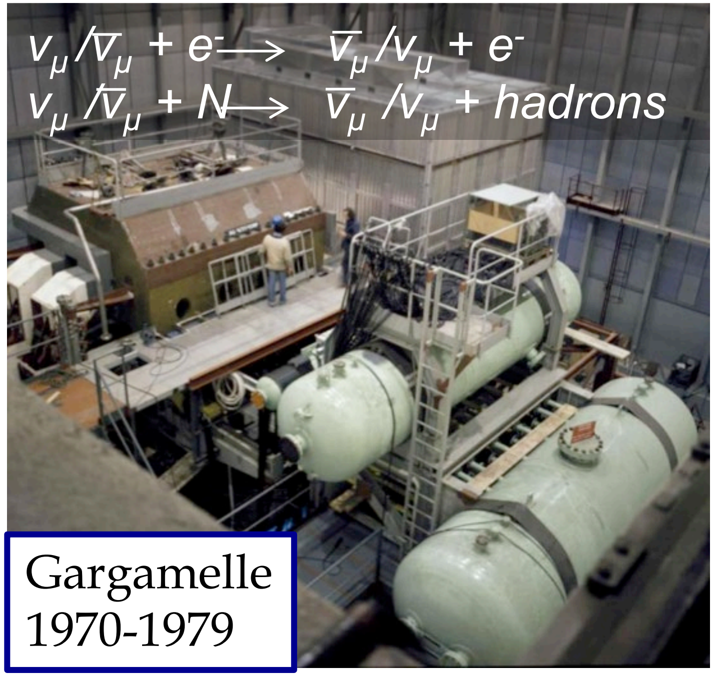
Graphic: Janet Conrad

Neutrino Detection II

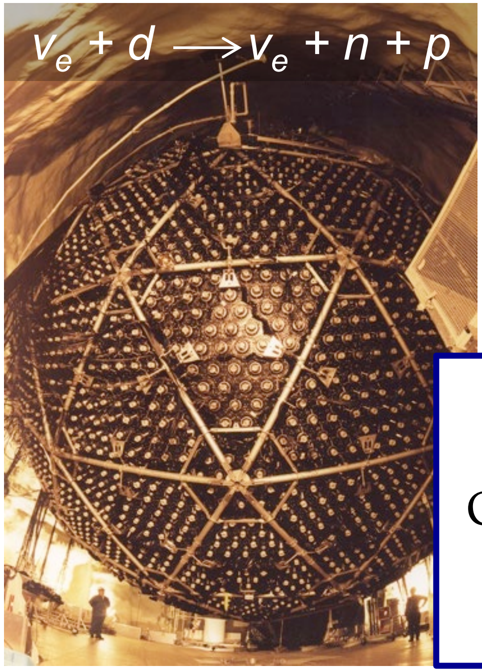
- Neutral-current interactions
  - Z boson exchange
  - Neutrino survives

Example: deuterium dissociation





Gargamelle
1970-1979



Sudbury Neutrino Observatory (SNO)
1999-2006

NC Event from Gargamelle

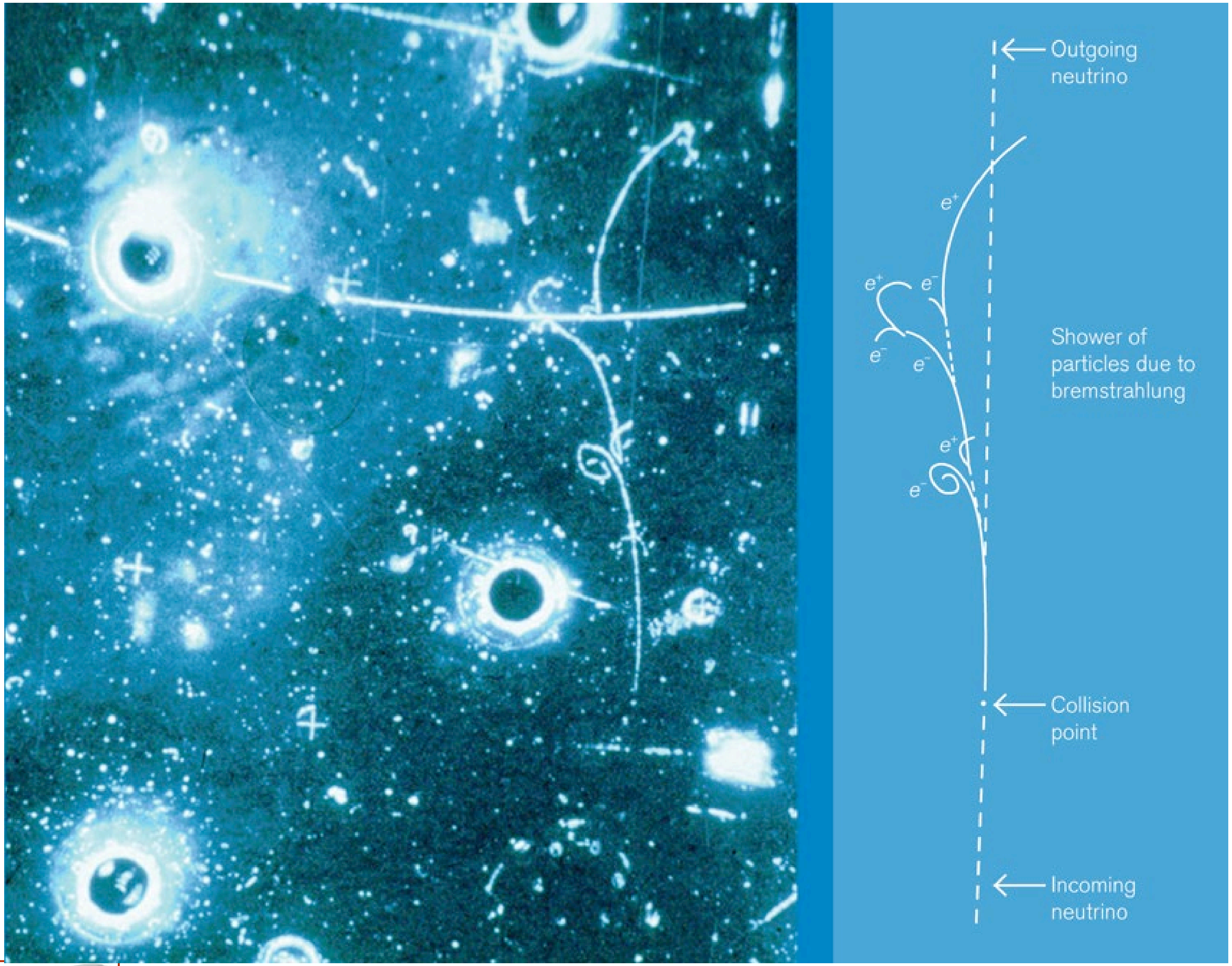
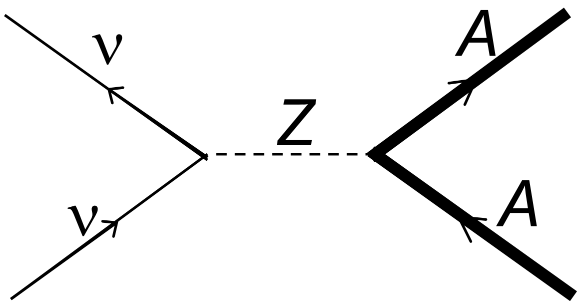


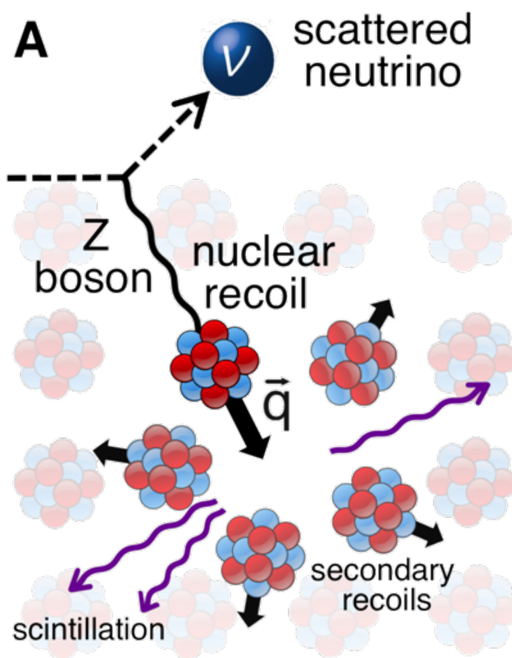
Image from CERN
Printed in *Symmetry*, August 2009

Coherent Elastic ν-N Scattering

- Enhanced cross section from coherent interaction with entire nucleus
- But – need E_ν < 50 MeV. Only signal is tiny nuclear recoil!



- COHERENT collaboration: First discovery, 2017!

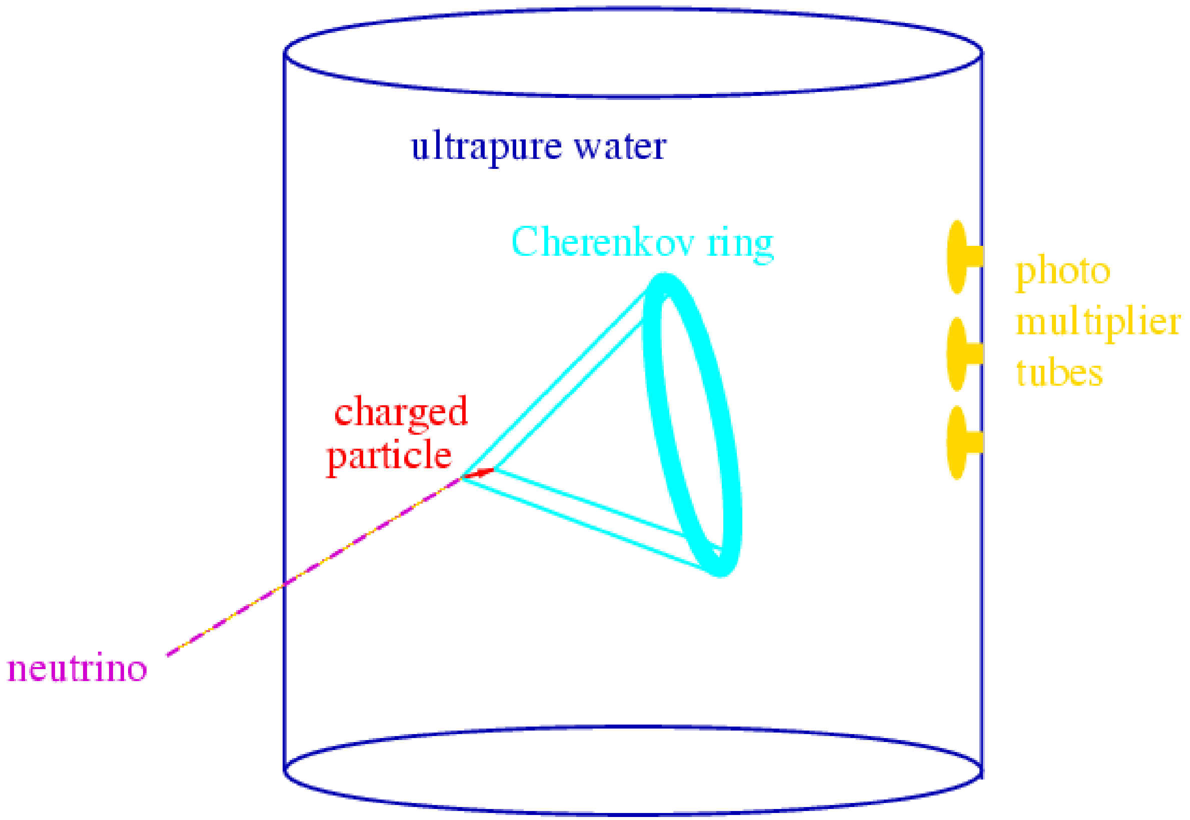


- CsI[Na] detector
- Pulsed neutrino beam from Spallation Neutron Source

*Akimov et al., Science **357**, 1123 (2017)*

Cerenkov Detectors

- If a charged particle in a medium has $\beta > 1/n$, it will emit Cerenkov radiation



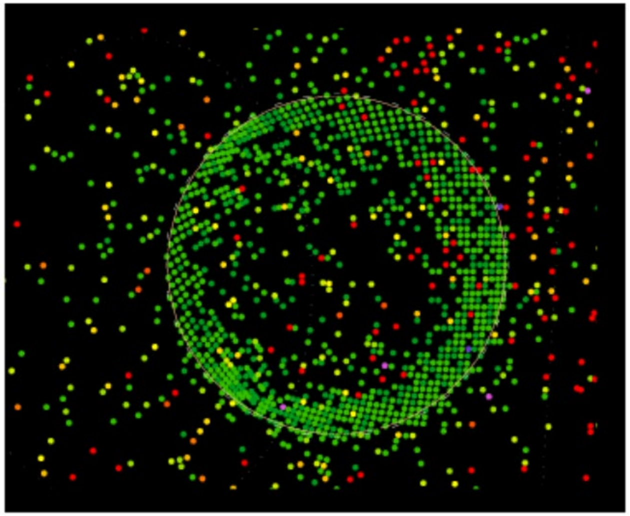
Graphics: Kate Scholberg

- # photons proportional to energy loss
- Cone gives directionality of incoming neutrino
- Now you just need enough phototube coverage to make a good measurement!

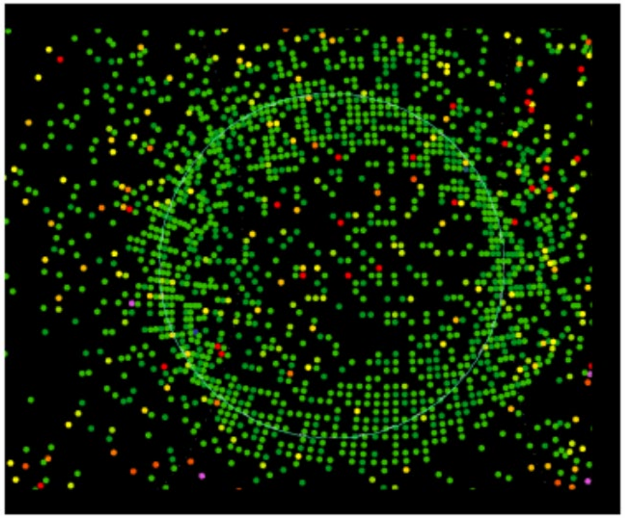
Particle ID with Cerenkov Light

- To measure in flavor basis, must distinguish muons from electrons
- Symmetry broken by interactions in medium
  - Muons (at these energies) are minimum-ionizing particles
  - Electrons produce showers
  - Light from showers blurs the conical surface

Sharp ring: Muon!

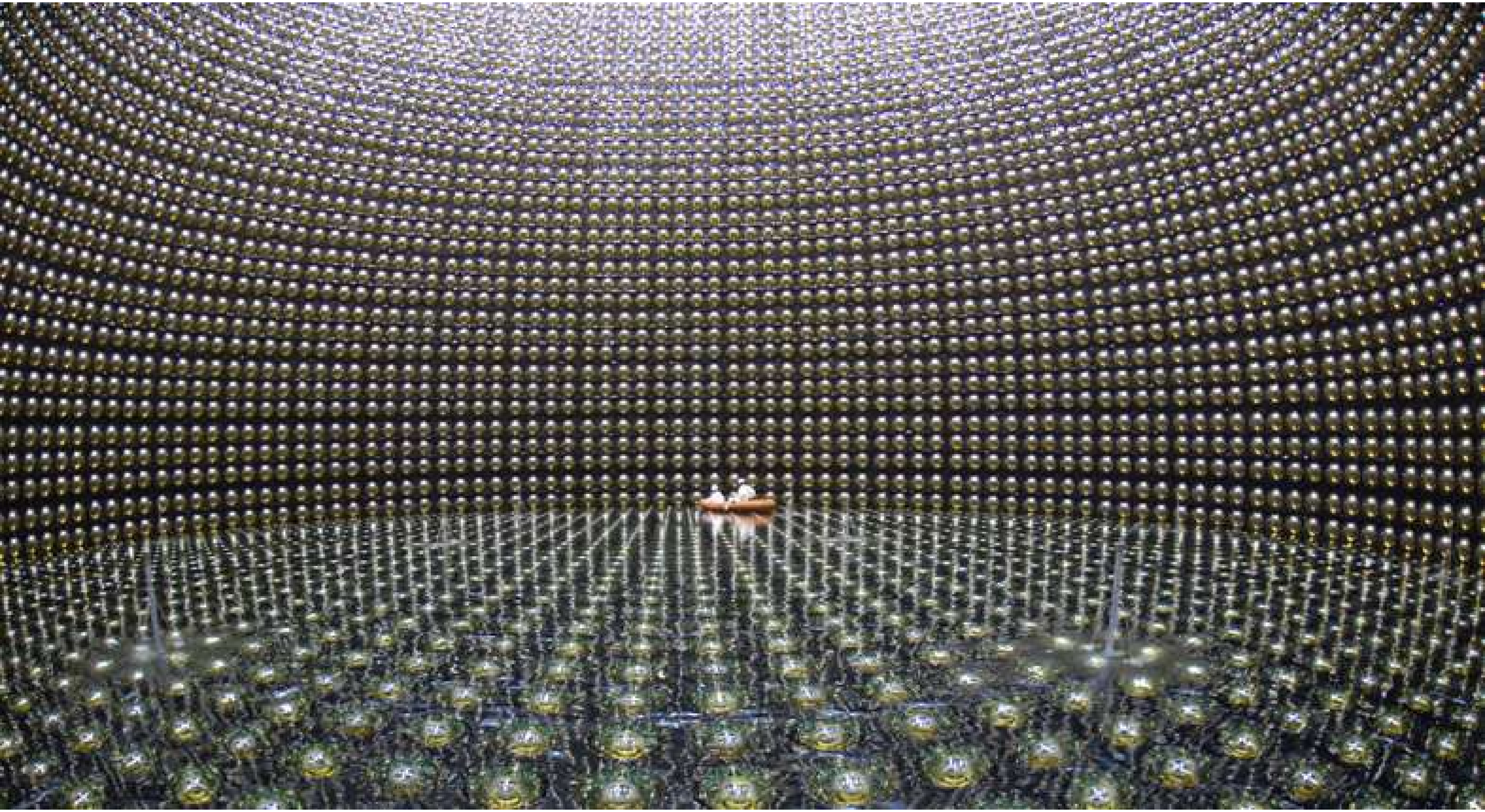


Fuzzy ring: Electron!



Graphics: SuperK

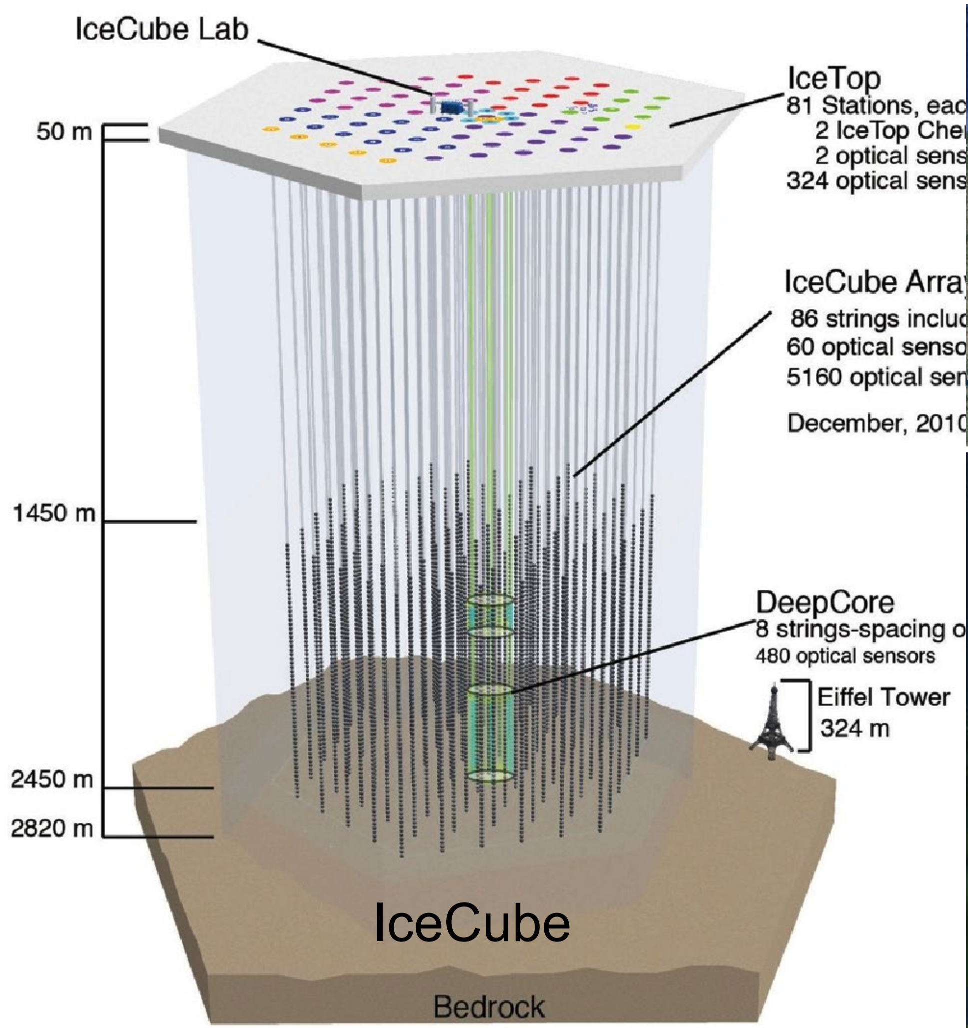
Build-Your-Own Tank



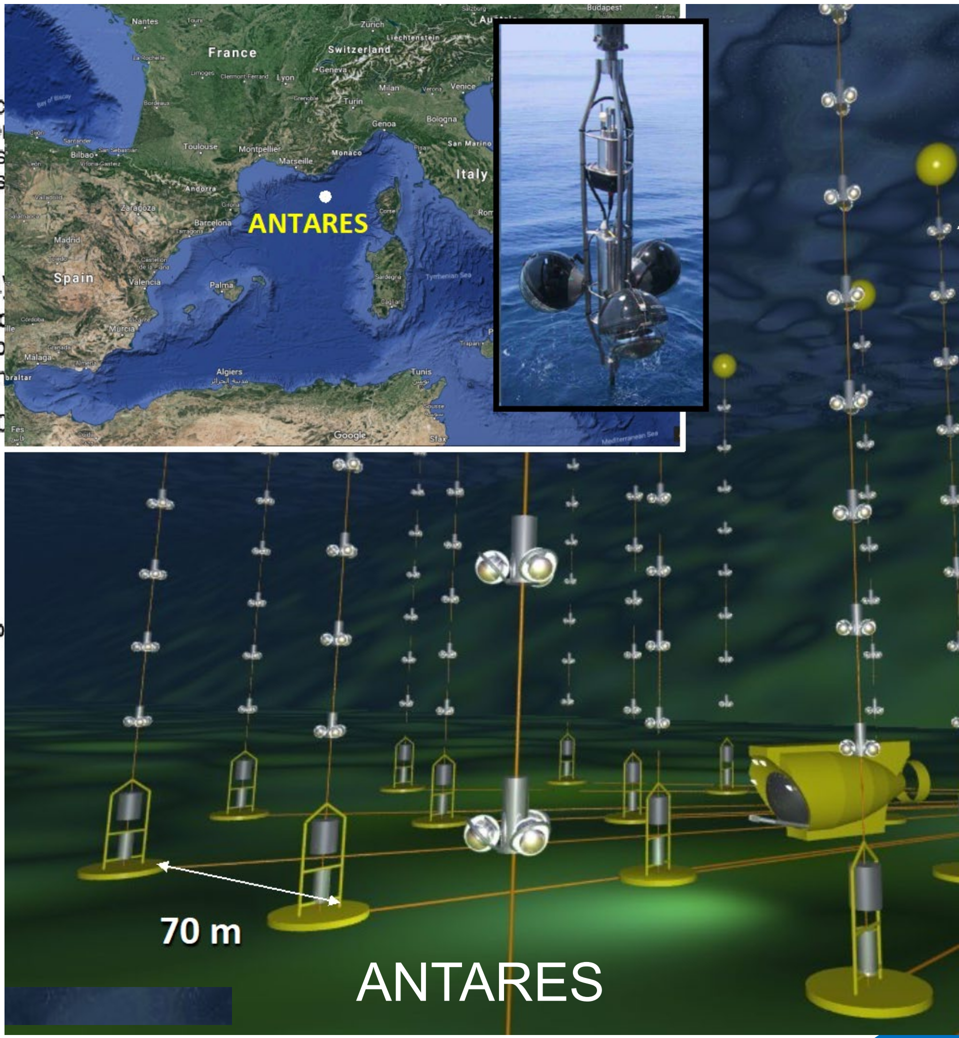
Super-Kamiokande: 32 kton ultrapure water; 11146 inner PMTs; 1 km underground

Neutrino Telescopes – Natural Tanks

- Instrument Antarctic ice?



- Or the Mediterranean?



Outline

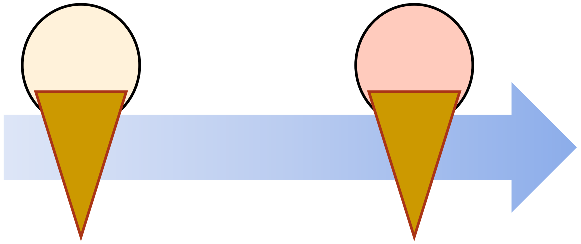
- Neutrino sources
- Neutrino detectors
- Neutrino oscillations
  - A very brief history of oscillation experiments
  - Snapshot of oscillation results
  - Goals for the next decade(s)

Design an Oscillation Experiment

- **Disappearance:**
  - Start with a known flavor.
  - Let it propagate.
  - Is it still there?

Not enough energy for charged-current interactions with new flavor

- **Appearance:**
  - Start with a known flavor.
  - Let it propagate.
  - Do you see a new flavor?



Must clearly distinguish between reactions with multiple flavors

The First Clue: Homestake

Potential for radiochemical solar neutrino detection:

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^- . \qquad \text{(Threshold: 0.8 MeV)}$$

Concept:

Step 1:
Fill a tank with 100,000 gallons of cleaning fluid (Chlorine).

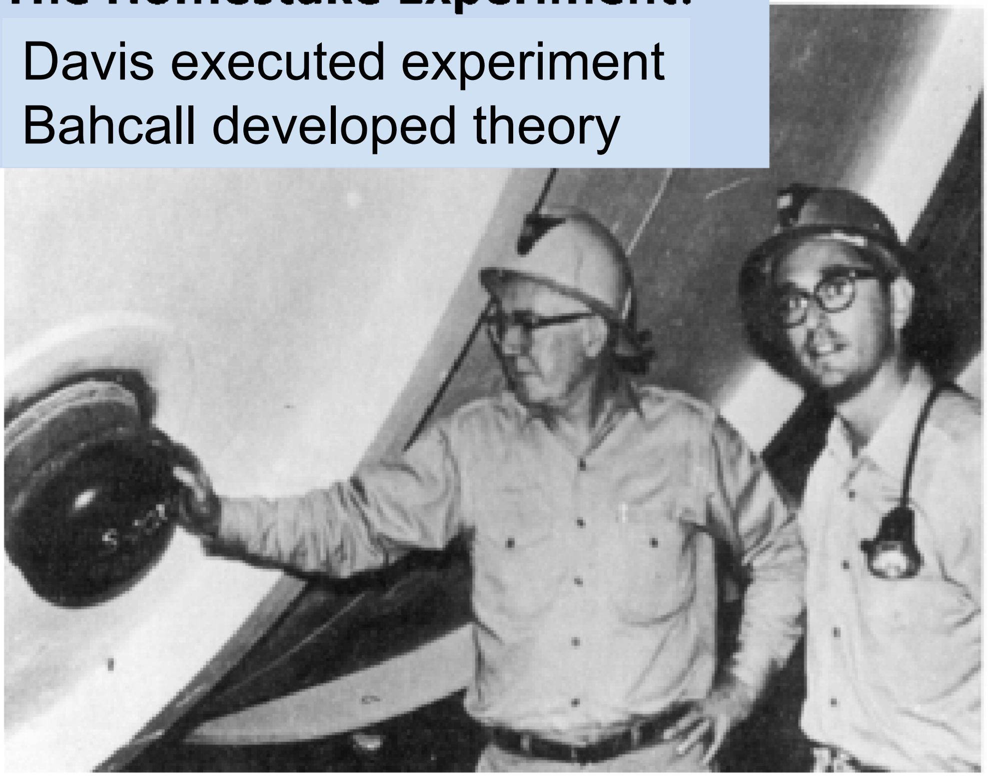
Step 2:
Put it ~1 mile underground.

Step 3:
Wait for solar neutrinos to convert a few Cl atoms to Ar.

Step 4:
Take Argon atoms out of tank and count them.

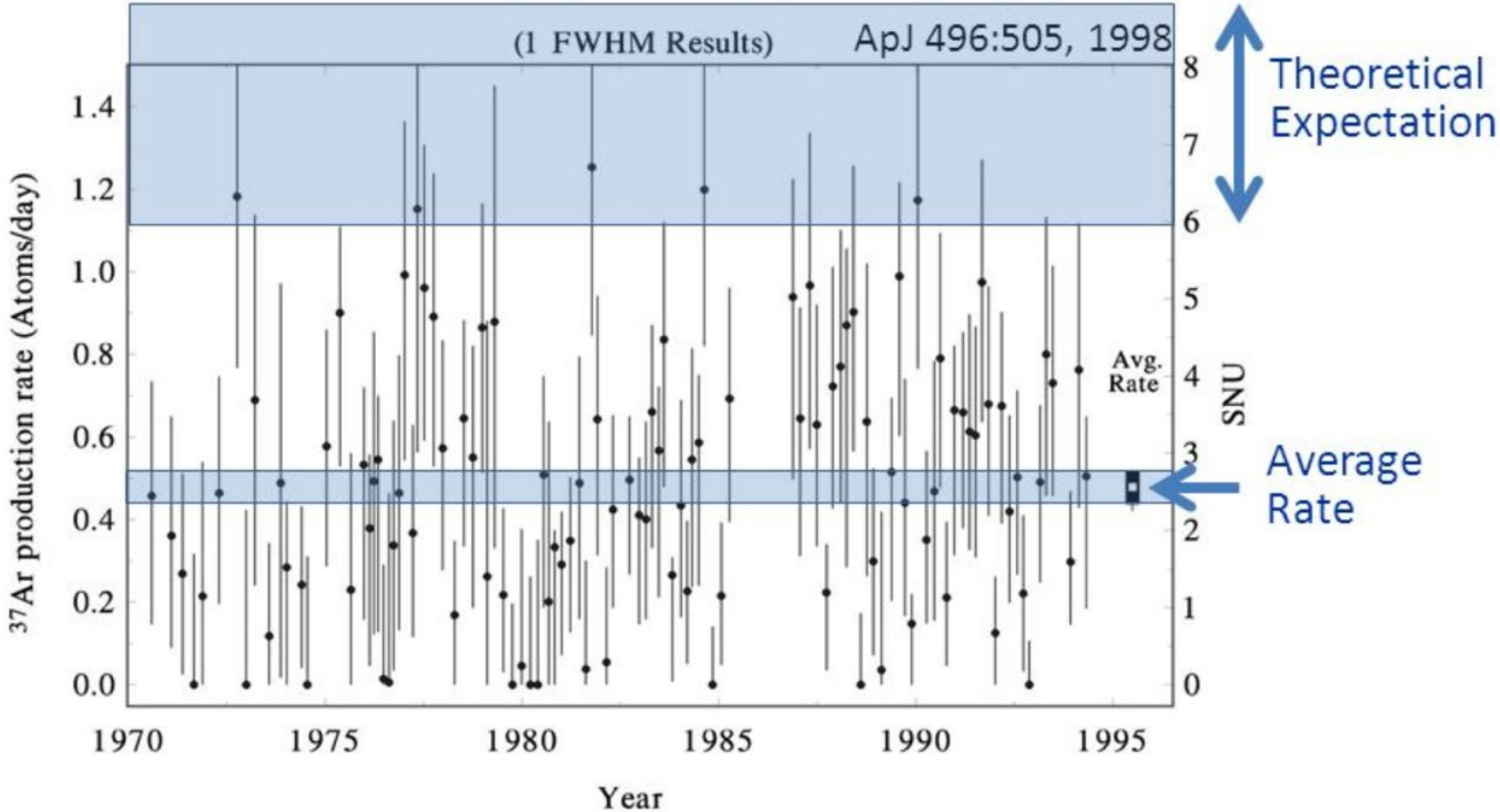
The Homestake Experiment:

Davis executed experiment
Bahcall developed theory



Slide: Dan Dwyer

The First Clue: Homestake



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

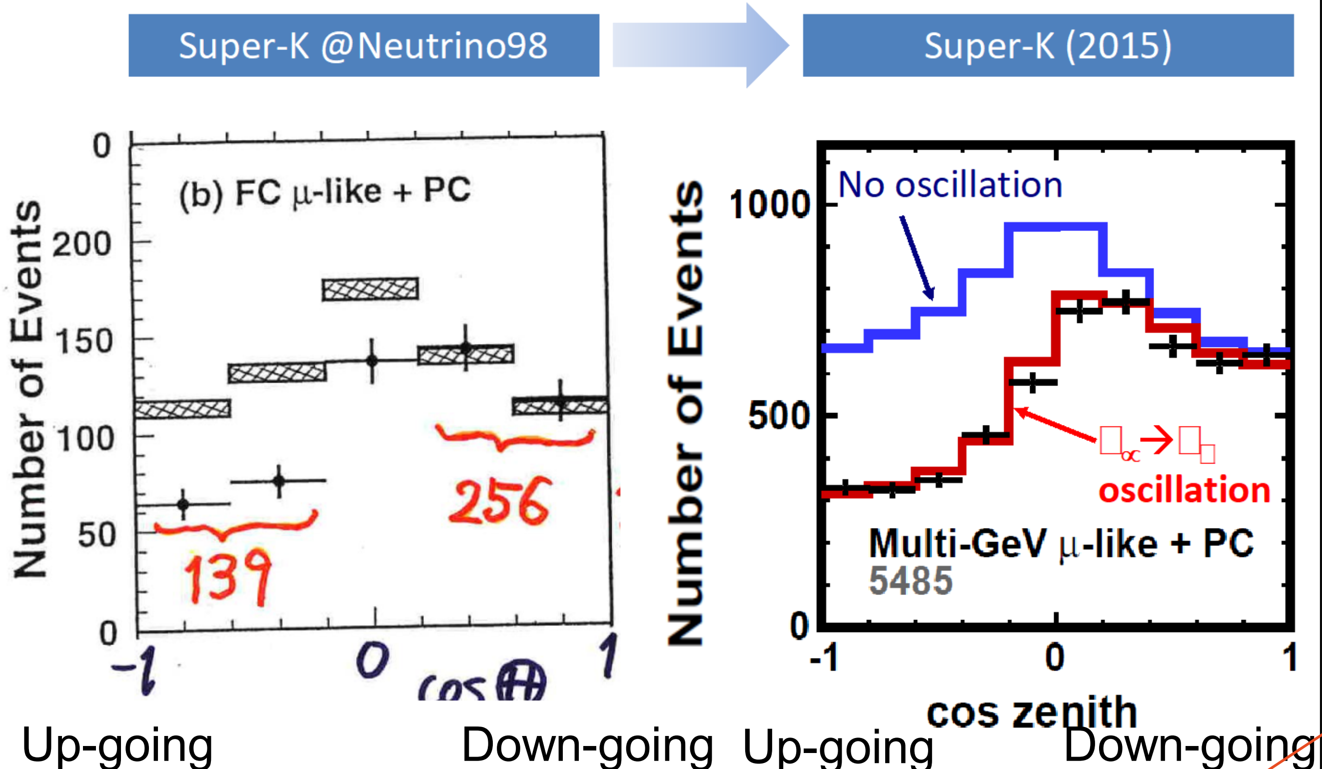
Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Slide: Georg Raffelt

Clear Signature: Super-K

- Measure “up/down” asymmetry in atmospheric nm
- Up-going neutrinos pass through Earth – longer path length for oscillation



Number of events plotted:

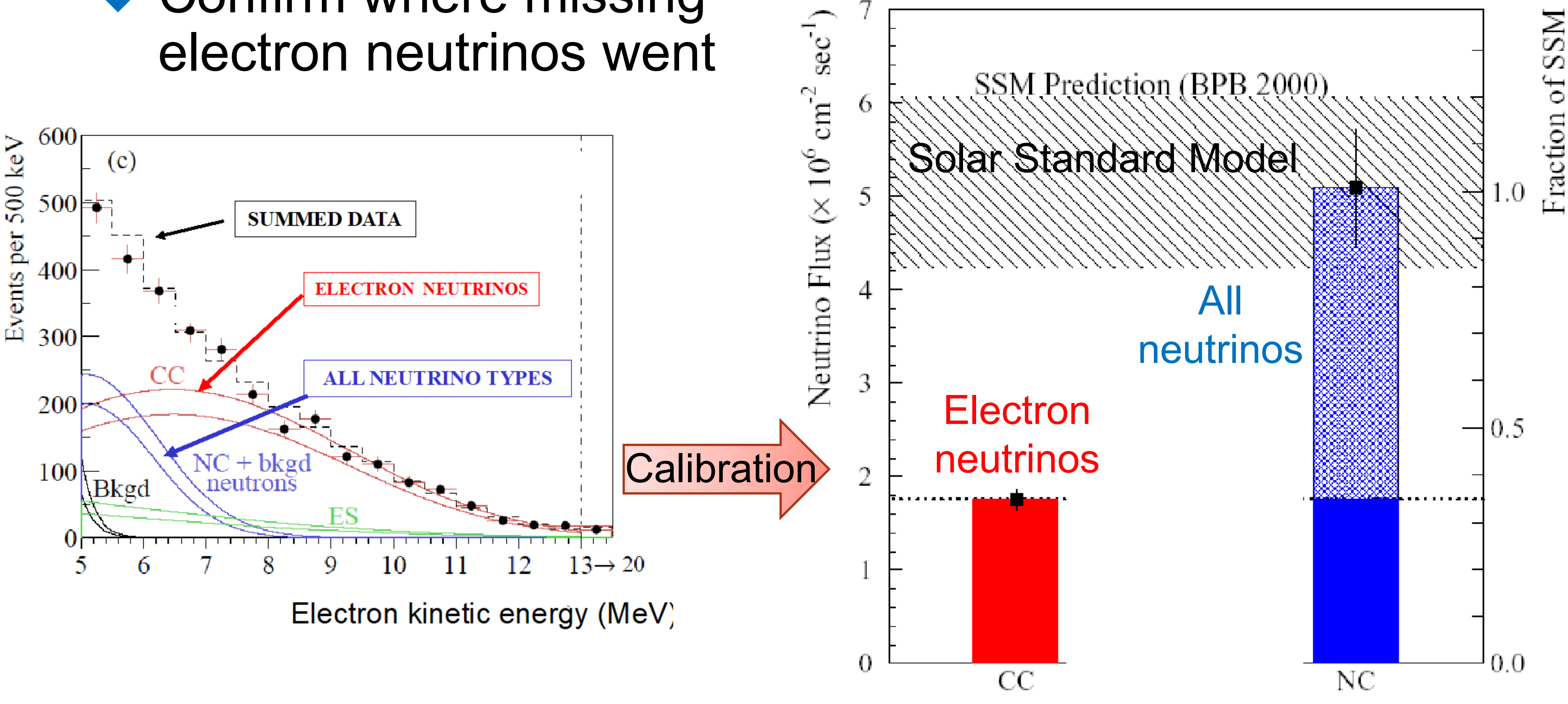
531 events → 5485 events

Takaaki Kajita, Nobel Prize Lecture, 2015

<5500 events in 19 years of running – neutrino experiments catch ghosts

Confirmation: SNO

- Sudbury Neutrino Observatory: combine CC, NC sensitivity
  - Measure both ν_e disappearance AND total ν_X flux
  - Confirm where missing electron neutrinos went



Plots from Art McDonald, Nobel Prize Lecture, 2015

The PMNS Matrix

- Governs mixing between ν **flavor** and **mass** states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

B. Pontecorvo

$$U_{3\times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

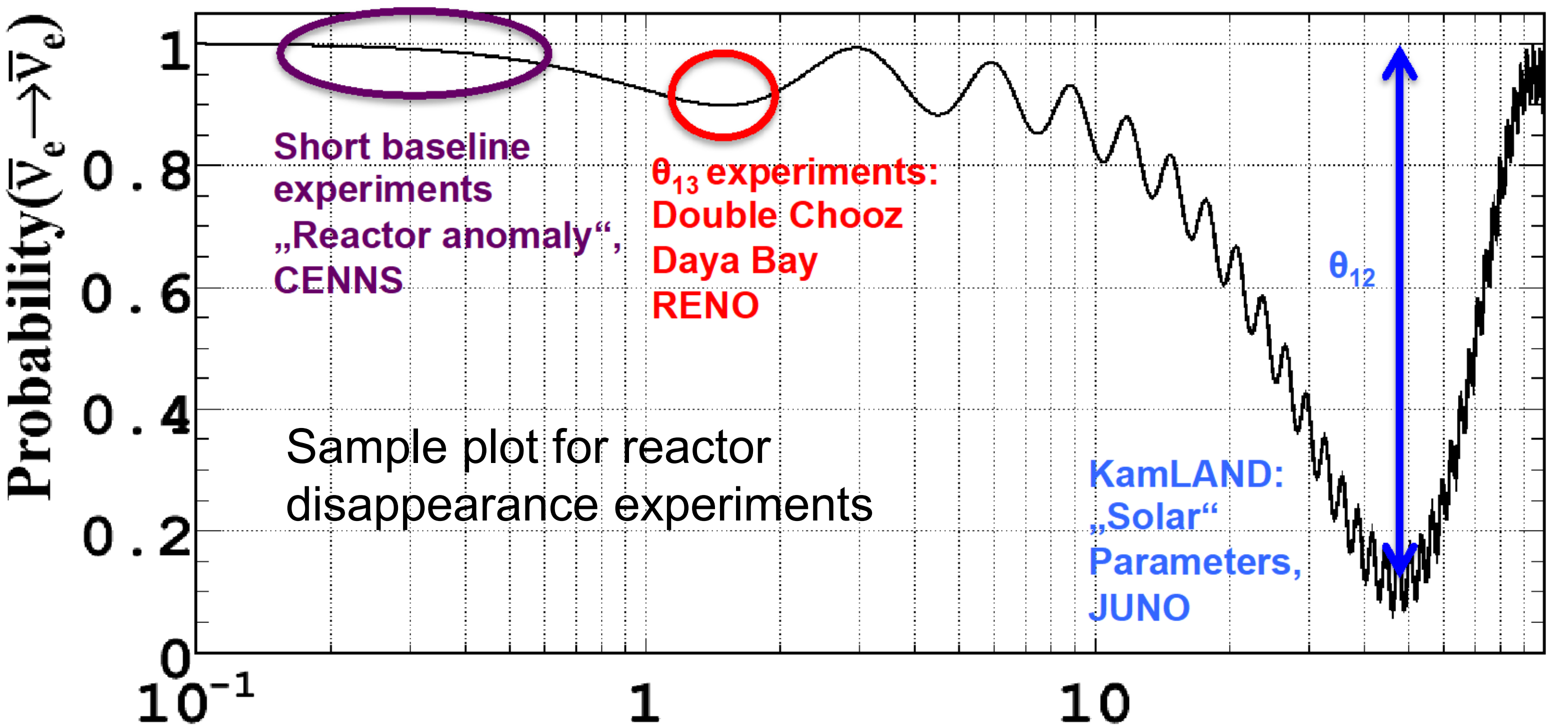
- Simplified 2-flavor neutrino oscillation:

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta_{ij})\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

More details from Michael Ramsey-Musolf on Monday

Picking a Baseline

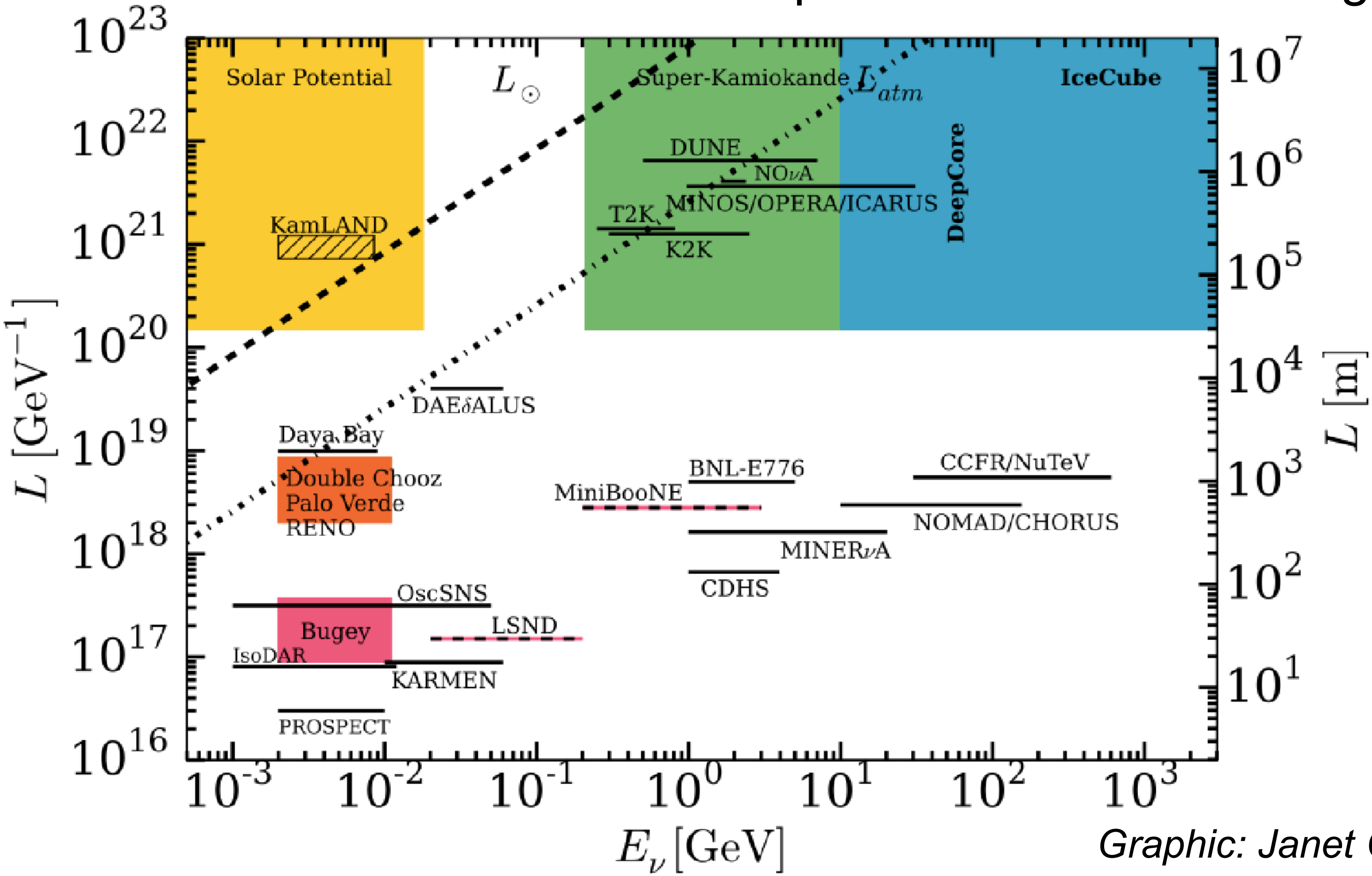
- Oscillation wavelength proportional to L/E_ν
- Tune source energy – or baseline – to optimize sensitivity to selected oscillation parameters



Plot: Christian Buck

Experimental Landscape

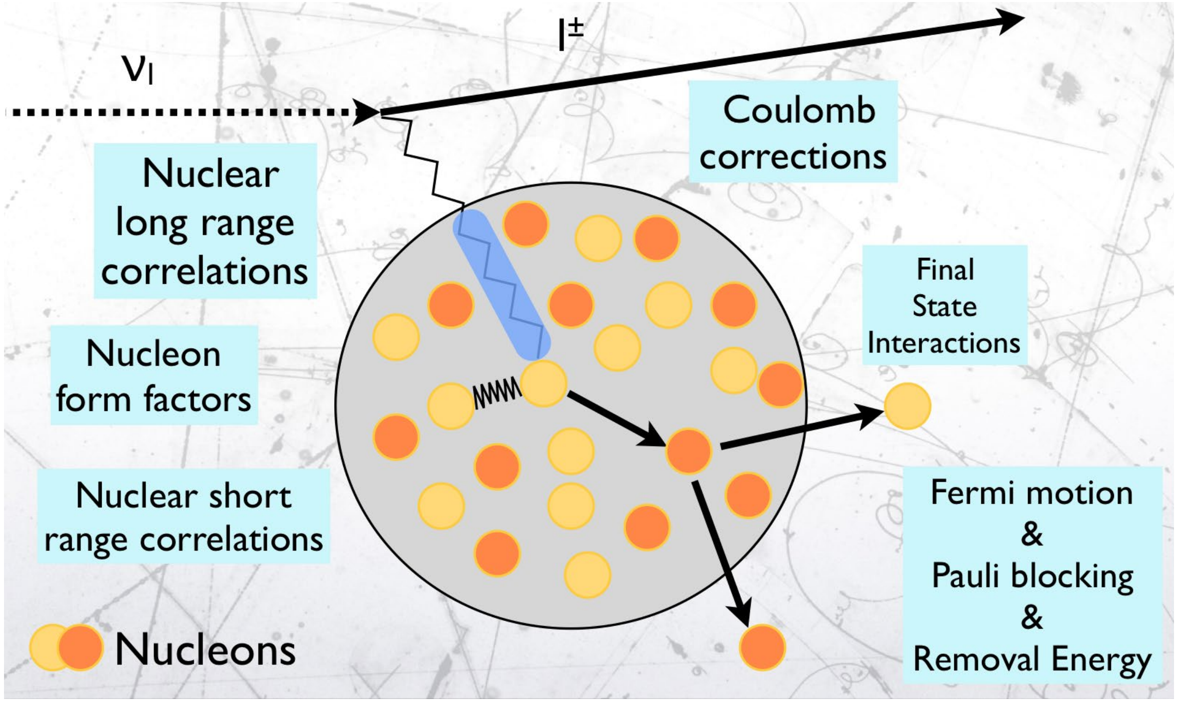
- Terrestrial-source oscillation experiments cover lots of ground



Graphic: Janet Conrad

Caveat: Energy Reconstruction

- “Measured” neutrino energy is reconstructed from final-state leptons and hadrons
  - We don’t know the nuclear physics that well!



Graphic: *Federico Sánchez*

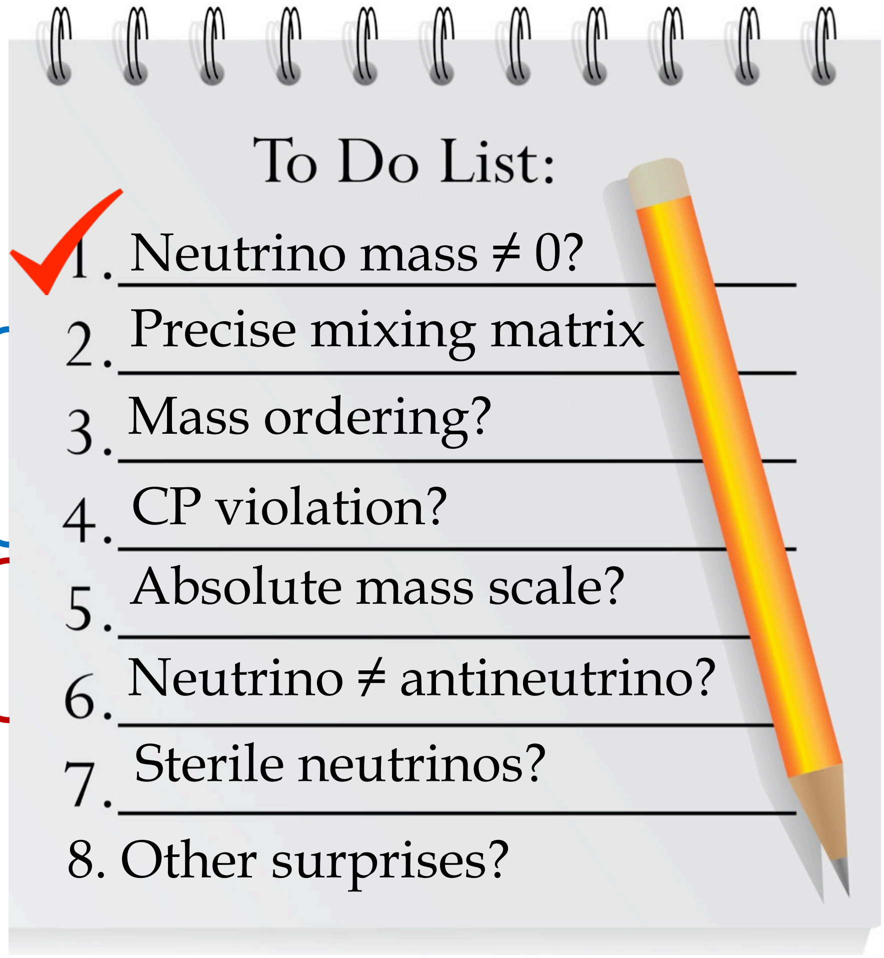
- Dedicated nuclear cross-section measurements
- Identical Near/Far detectors help cancel systematics
  - Also aid in flux normalization

Remaining Questions

Oscillation experiments

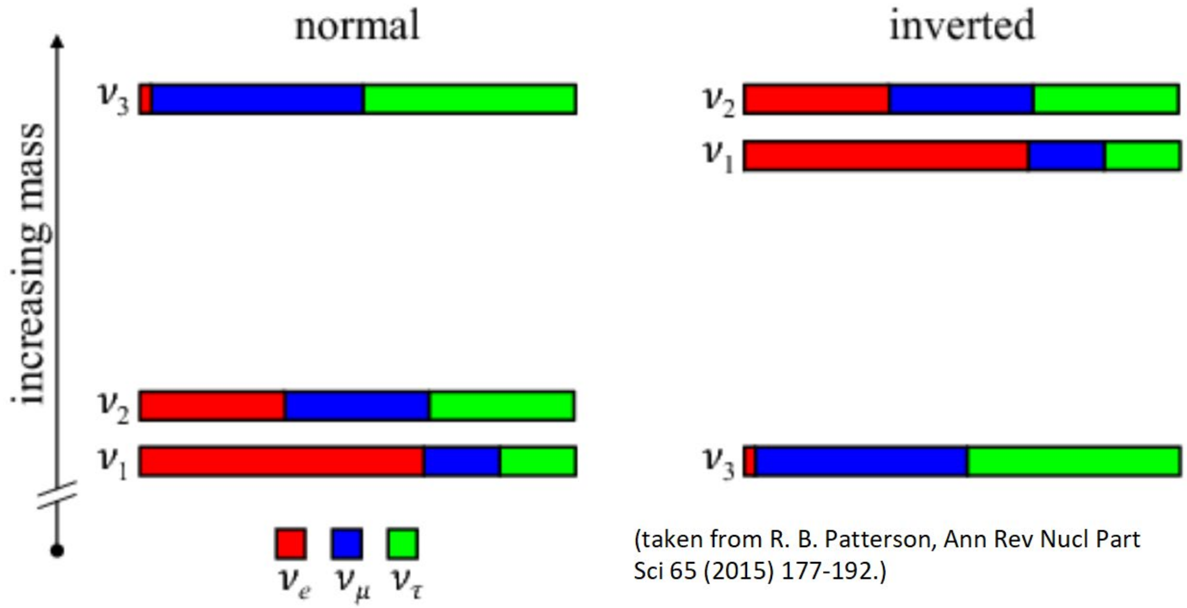
Next lecture

Next Friday



Mass Ordering and CP Violation

- Is ν_3 – the mass state that couples most to ν_τ – the heaviest or the lightest of the neutrino masses?



(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

- Is CP symmetry – invariance under charge conjugation + mirror inversion – conserved in the neutrino sector?

Oscillation Parameters

- Worldwide program working toward precision parameters

https:/ / globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	[illegible]	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.47 [illegible]	[illegible]	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

Fits change based on mass ordering

Is this mixing angle maximal?

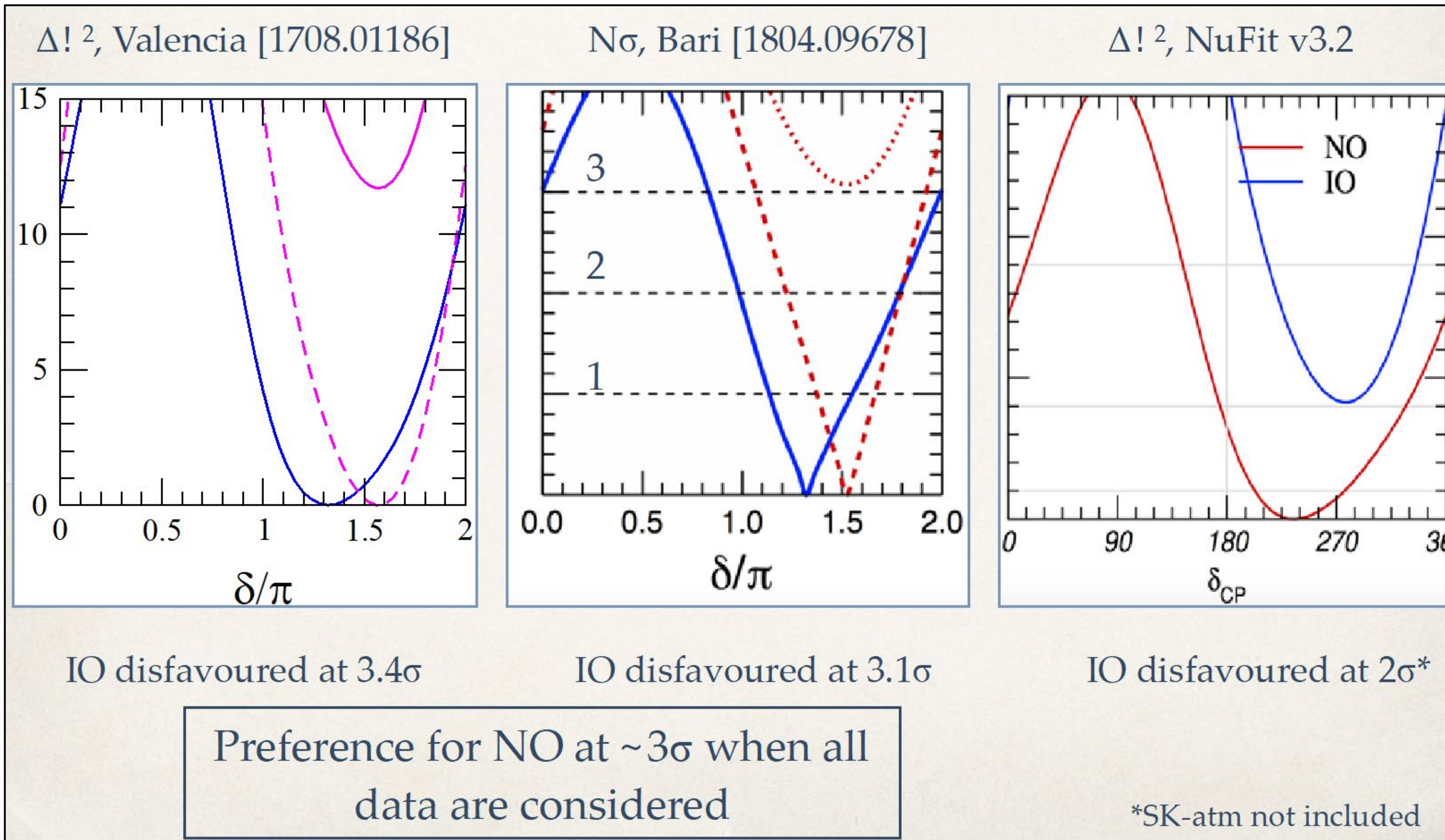
deSalas et al, 1708.01186 (May 2018)

Slide: Mariam Tórtola

Physics
Carnegie Mellon University

Early Hints

- Several experiments favor normal ordering – but not by much
- Careful joint analyses are beginning

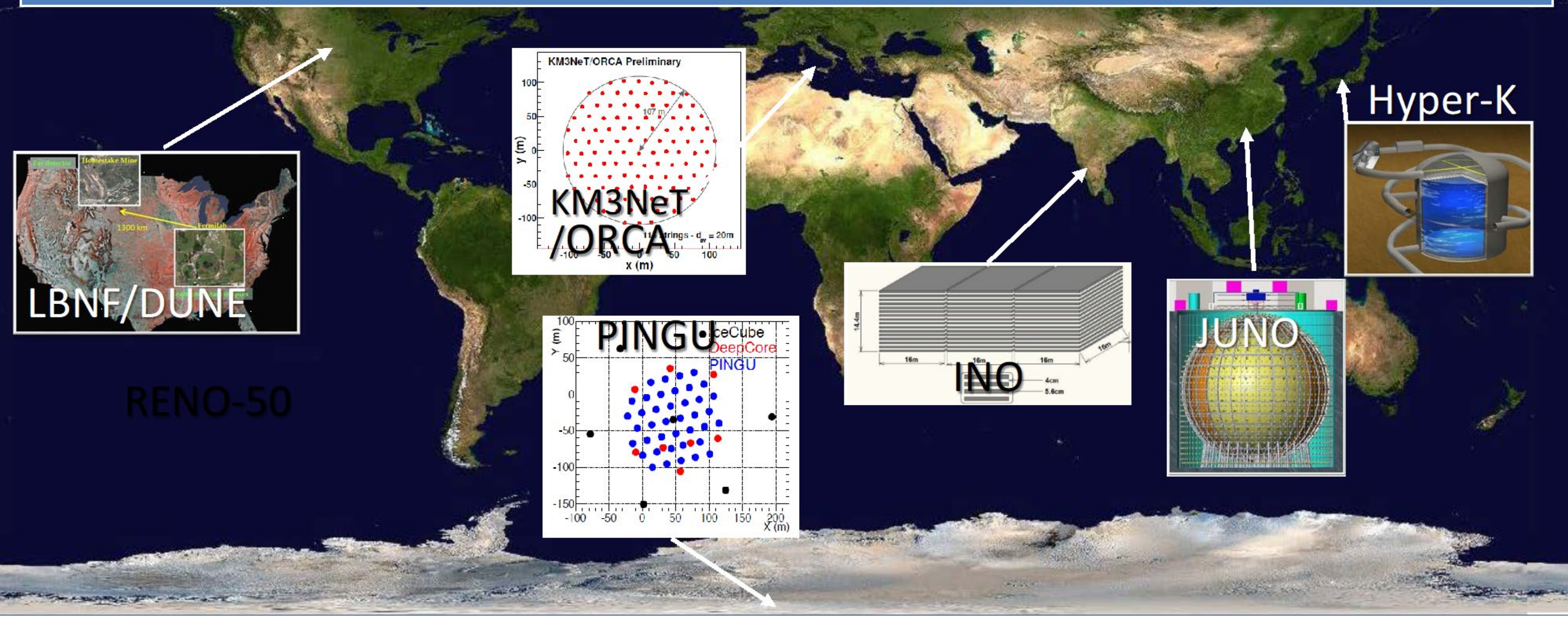


Slide: Mariam Tórtola

Closing in on the Mass Ordering

Future experiments that will tell us the neutrino masses hierarchy

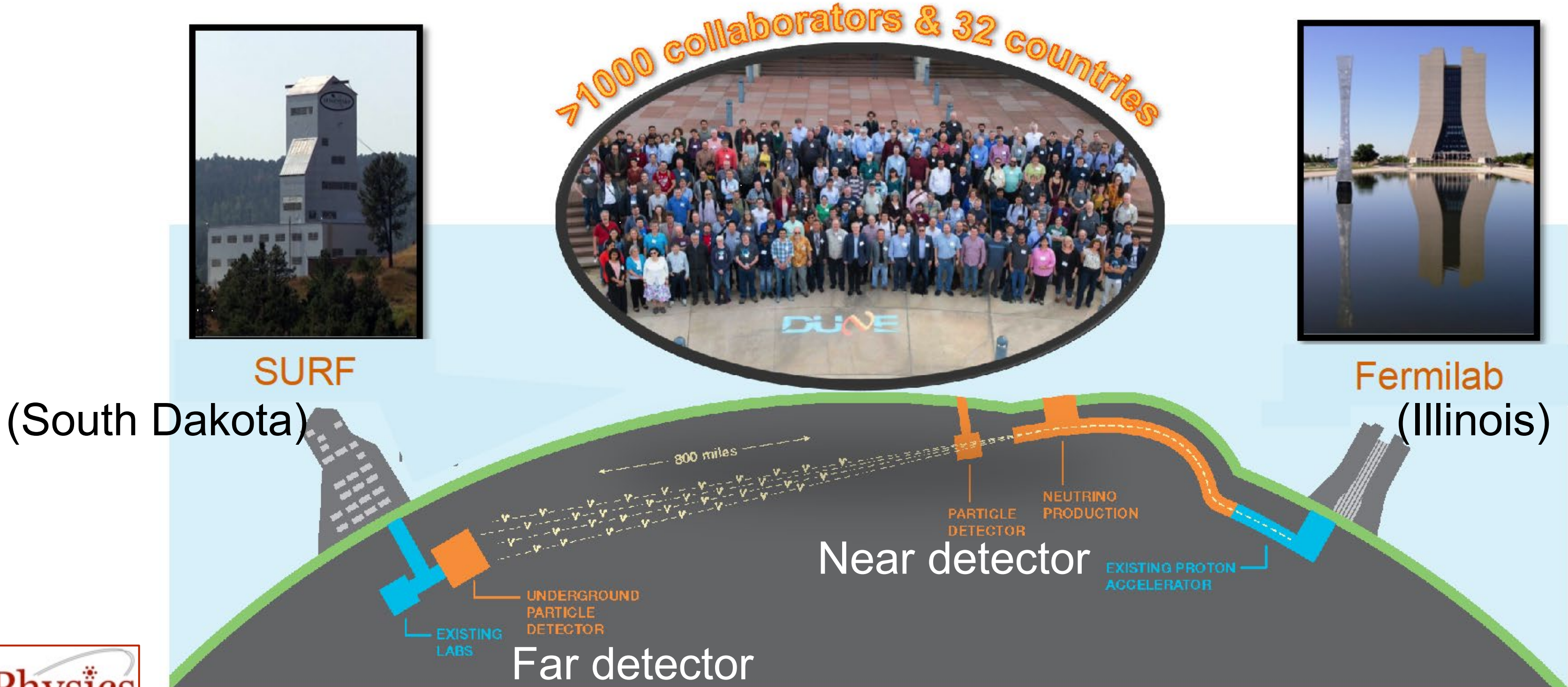
We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with > 3 □ CL from each exp.



Slide from Takaaki Kajita, Neutrino 2018

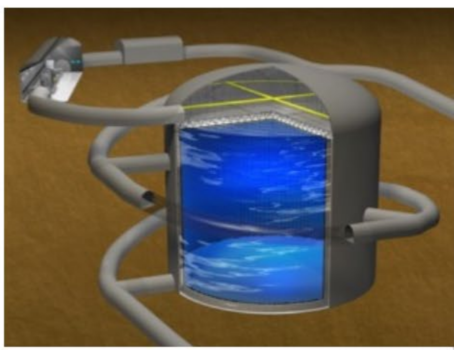
Next Generation: DUNE

- 40-kton LAr time-projection chamber to measure ν_μ disappearance and ν_e appearance
- Start investigating mass ordering, CP violation when beam comes on in 2026
  - Head start on physics with solar, atmospheric νs



Next Generation: Hyper-K

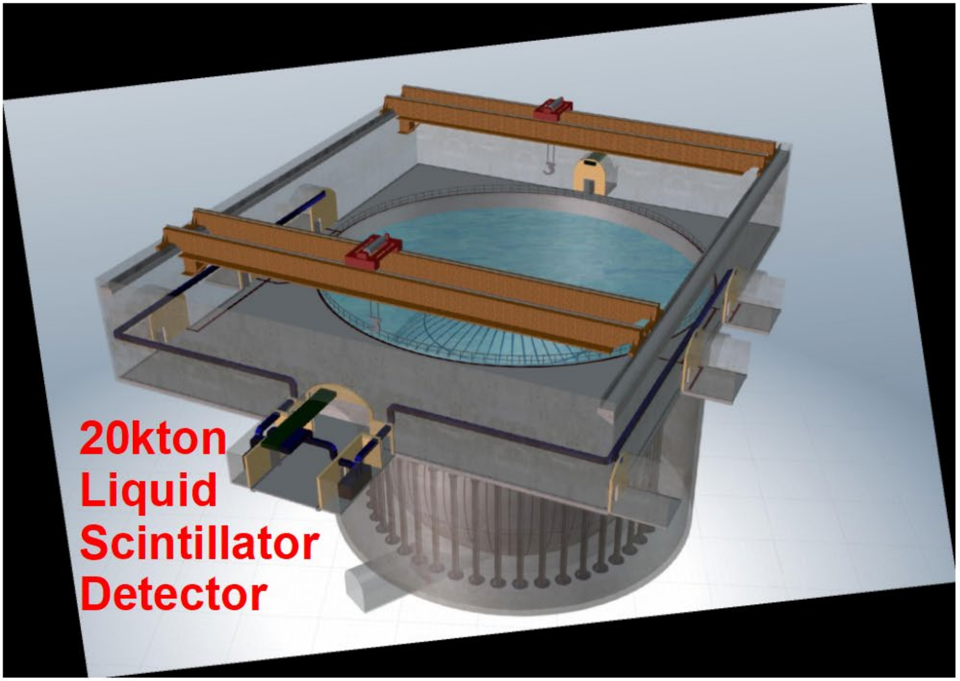
- 186-kton water Cerenkov detector
  - Also sensitive to proton decay among other physics
- Beam + detector online 2026
  - Non-beam studies before that



Plus (maybe) a very far detector in South Korea?

Next Generation: JUNO

- JUNO will use reactor neutrinos (not accelerator)
  - Complementary neutrino source (and detection method)
- Data-taking targeted to 2021



Graphics: Björn Wonsack

High power nuclear power plants (26.6 GW total power)

What About Sterile Neutrinos?

- Not all oscillation results are entirely consistent with the standard 3-neutrino picture
  - Why don't measured reactor fluxes match predictions?
  - What is the measured bump in reactor antineutrino spectrum at 5 MeV?
  - Why does MiniBooNE see too many electron neutrinos?
    - arXiv:1805.12028 [hep-ex]
- One possible explanation: ***sterile*** neutrinos with no weak charge, that mix with the active (e,μ,τ) flavors

Michelle Dolinski
Seminar next Friday

Comprehensive (but slightly out of date) review at arXiv:1204.5379 [hep-ph]

A Shameless Advertisement

- My group is hiring a postdoc to work on:
  - KATRIN
    - Direct measurement of neutrino mass – see lecture after lunch
  - COHERENT
    - CEvNS measurements on multiple nuclei
- Apply on Interfolio by July 17 for full consideration:
  - https://apply.interfolio.com/5143

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