Solar Neutrino Detection in SNO, SNO+, and Theia

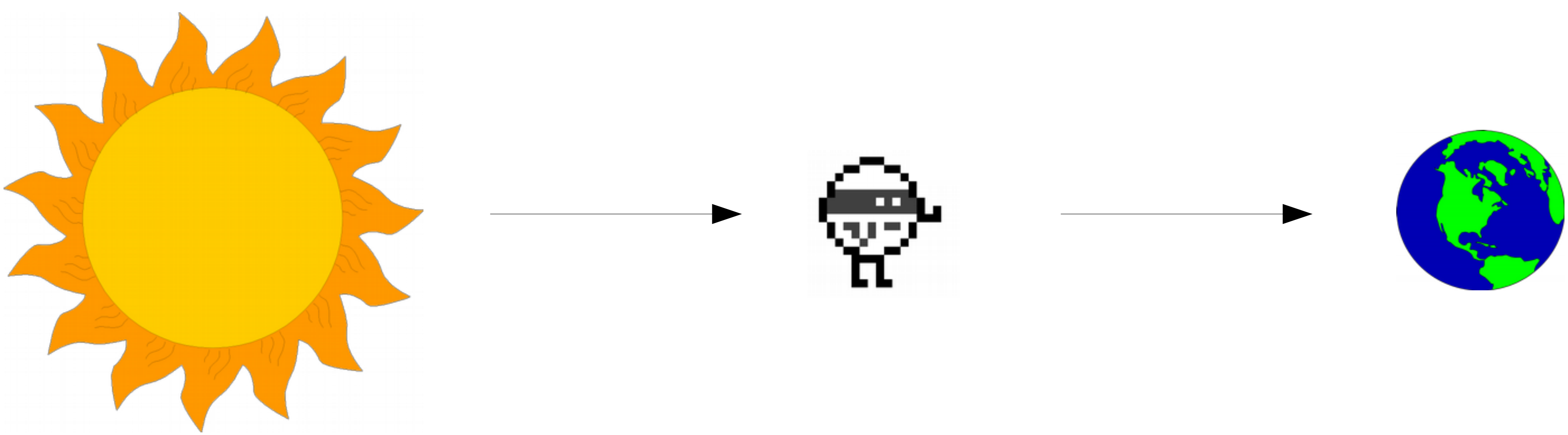
Benjamin Land
290E / Oct 19, 2016

Outline

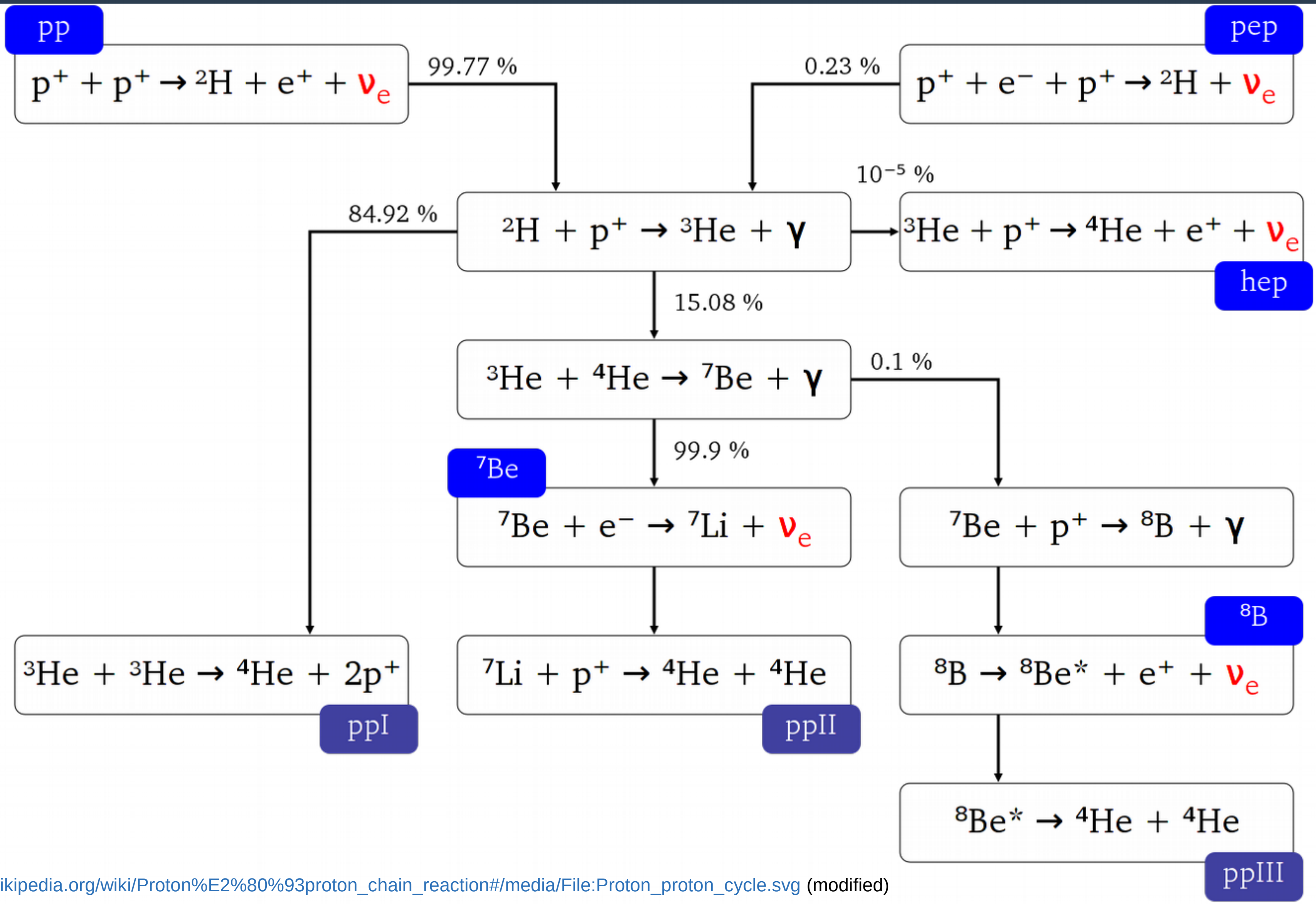
- **Solar neutrino introduction**
  - Where they come from
  - Standard solar models
- **The solar neutrino problem**
  - How it was identified and solved
  - Detection and analysis methods in SNO
  - Neutrino oscillations in vacuum and matter
- **Solar neutrino physics**
  - What physics can solar neutrinos probe
- **Current plans: SNO+**
- **Future Plans: THEIA**

Solar Neutrino Overview

- **Stars are powered by fusion reaction chains**
- **Fusion products are unstable, will decay**
  - β decays produce ν_e
- **Neutrinos escape the star largely* unhindered**
- **Eventually arrive at Earth to be studied**

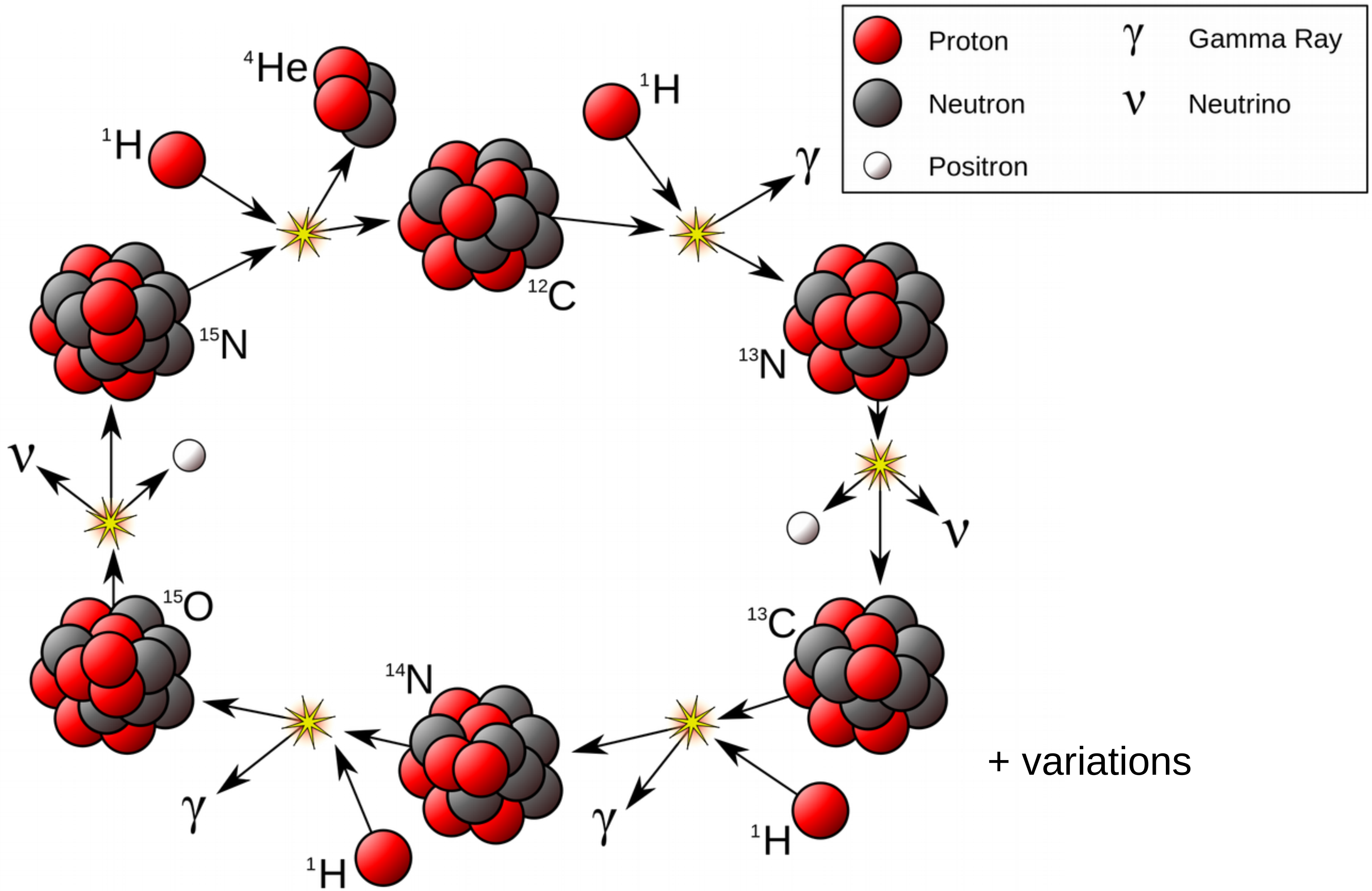


Proton-Proton Chain



https://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain_reaction#/media/File:Proton_proton_cycle.svg (modified)

CNO Cycle



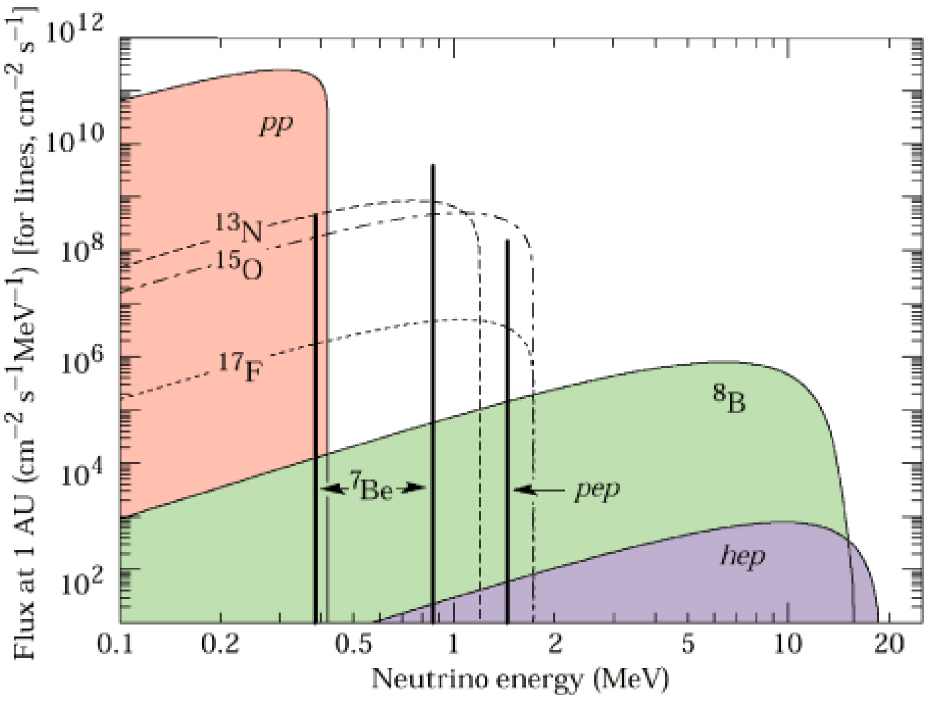
+ variations

https://en.wikipedia.org/wiki/CNO_cycle#/media/File:CNO_Cycle.svg (modified)

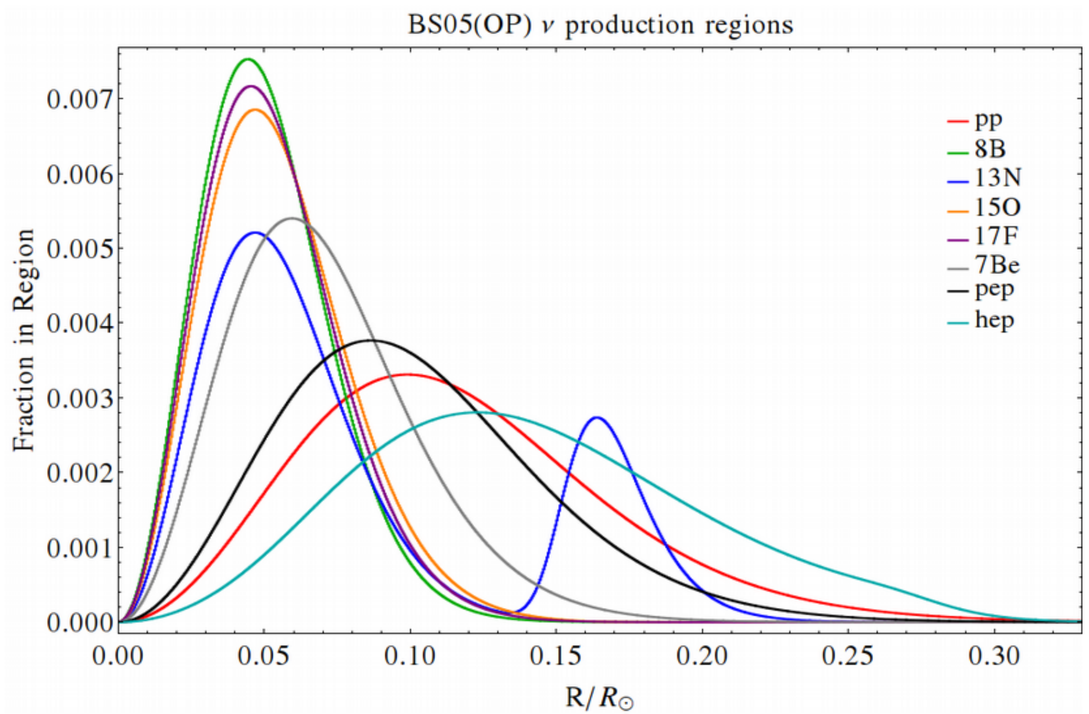
Standard Solar Models

- **SSM spearheaded by John Bahcall**
- **Goal: predict internal structure of the sun**
  - Radial profile of neutrino production
  - Rates of neutrino production (fusion reactions)
- **Utilizes best available information**
  - Helioseismology, metallicity measurements
  - Solar luminosity/mass/size
  - Theory predictions (cross sections)
- **Still, large theoretical uncertainties**
  - Neutrinos can probe directly for precision measurements

SSM Neutrino Fluxes



J. Bahcall et al. http://www.kip.uni-heidelberg.de/tt_detektoren/neutrinos.php?lang=en



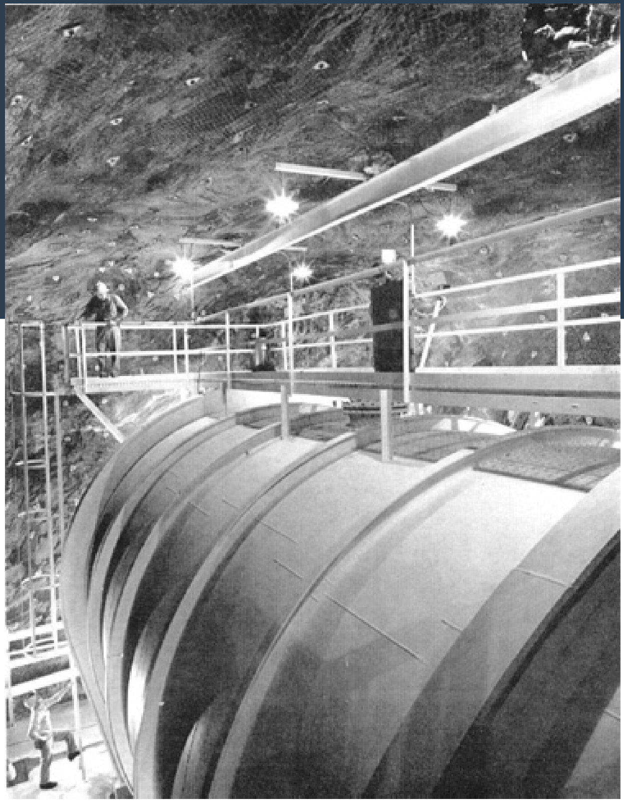
J. Bahcall et al. (plot by B. Land)

Early Measurements

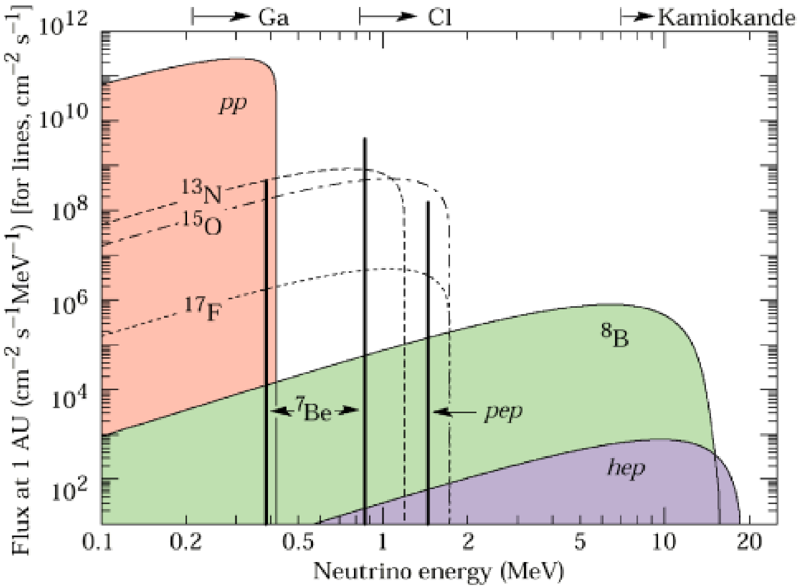
- **First measurement from Homestake experiment**
- **Large tank of tetrachloroethylene**
  - Neutrinos (ν_e specifically) capture on Cl

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

  - Count the Ar → determine the flux
- **Measured a flux about ⅓ of SSM predictions**
  - The solar neutrino problem
  - Confirmed by GALLEX, GNO, SAGE, (gallium); Kamiokande



J. Bahcall



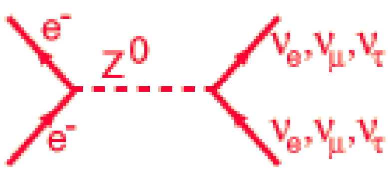
J. Bahcall et al. http://www.kip.uni-heidelberg.de/tt_detektoren/neutrinos.php?lang=en

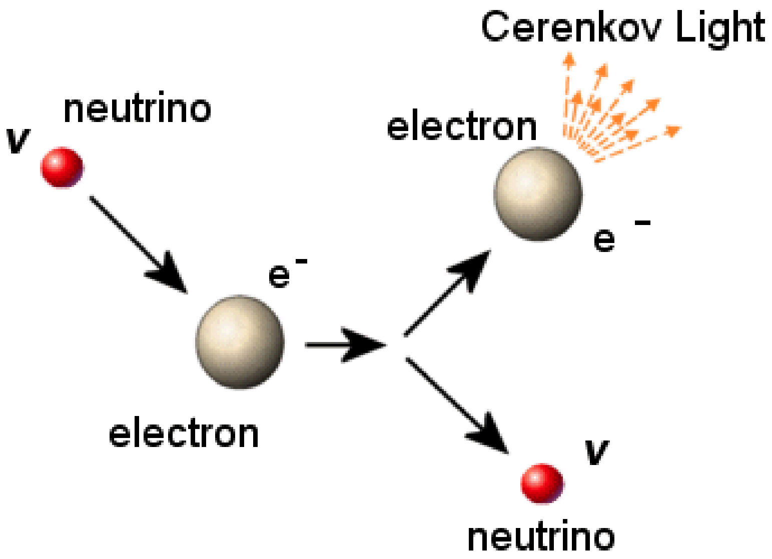
Missing Neutrinos?

- **Early experiments were only sensitive to ν_e**
  - Could a mechanism convert ν_e to ν_μ / ν_τ ?
- **Herb Chen proposed using a heavy water target**
  - Deuterium has a large neutral current (NC) cross section
  - Would be sensitive to all flavors of neutrinos

Interactions in Heavy Water

- **ν_e will undergo elastic scatter (ES) as usual**
  - Other flavors also ES but factor of ~6 less likely
  - Detect Cherenkov light from scattered electron

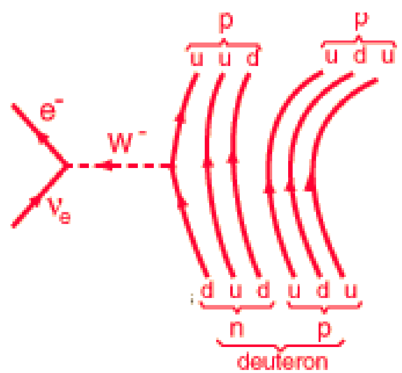


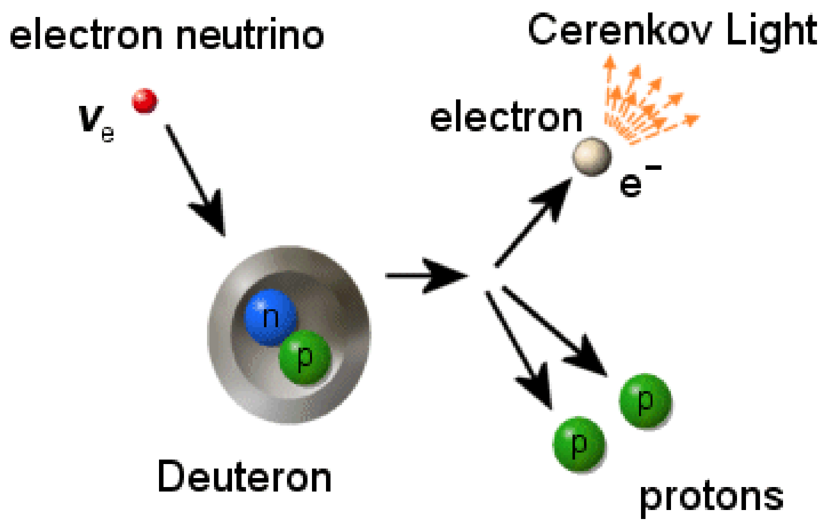


https://physics.carleton.ca/sno/about-sno-project/neutrino-reactions

Interactions in Heavy Water

- **ν_e will undergo and charged current (CC)**
  - Deuterium has a sufficiently large CC cross section
  - Detect Cherenkov light from scattered electron

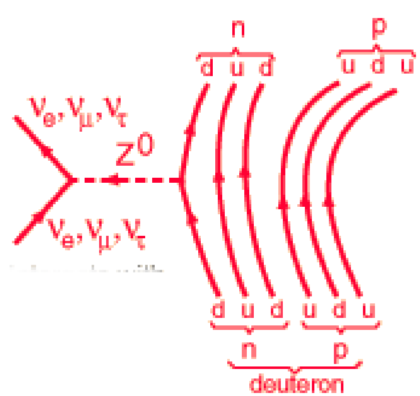


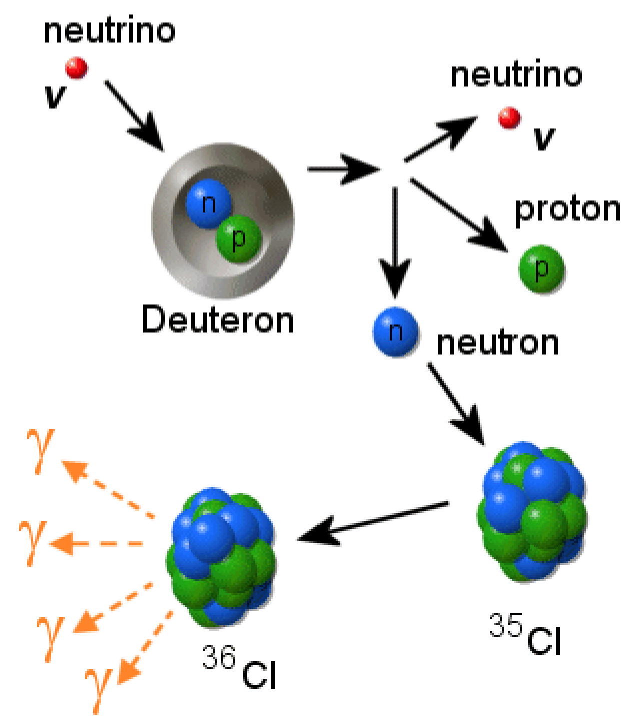


https://physics.carleton.ca/sno/about-sno-project/neutrino-reactions

Interactions in Heavy Water

- **All flavors undergo neutral current (NC) interactions**
  - Deuterium disassociated producing a free neutron
  - Neutron captures producing gamma(s)
    - Add a nucleus to capture neutrons
    - Chlorine (from salt) works well
  - Gamma(s) scatter producing energetic electrons
  - Detect Cherenkov light from scattered electrons

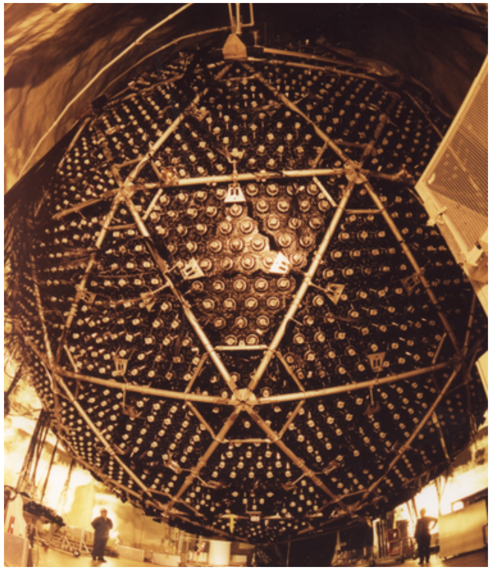


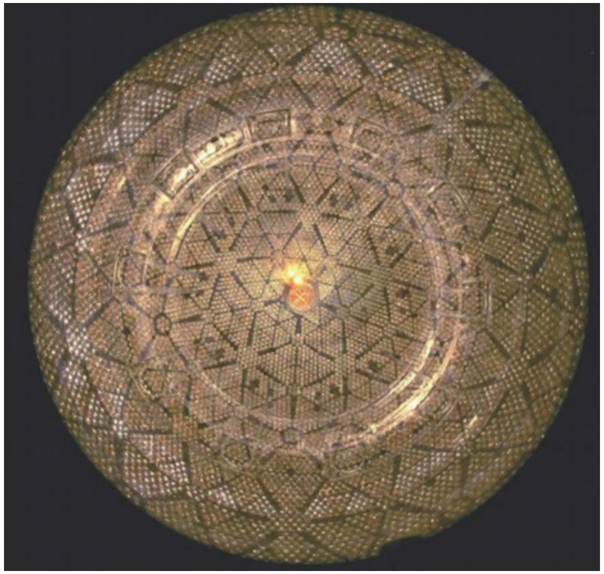


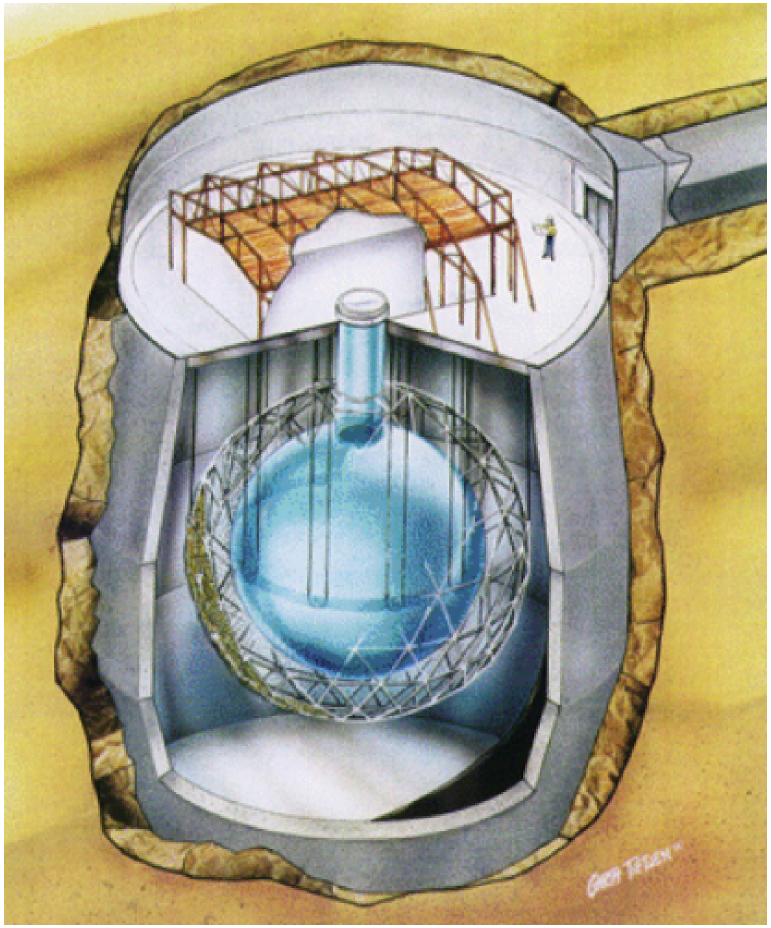
https://physics.carleton.ca/sno/about-sno-project/neutrino-reactions

The SNO Detector

- **SNO realized H. Chen's proposal**
  - 12m diameter acrylic vessel
  - 1kT of heavy water, ultrapure water buffer
  - Instrumented with ~9500 8" PMTs
  - 2km underground in Sudbury, CA
- **Primarily sensitive to ^{8}B neutrinos**



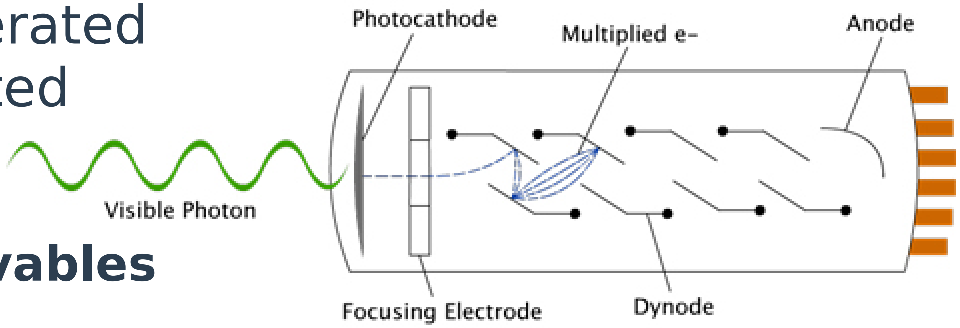




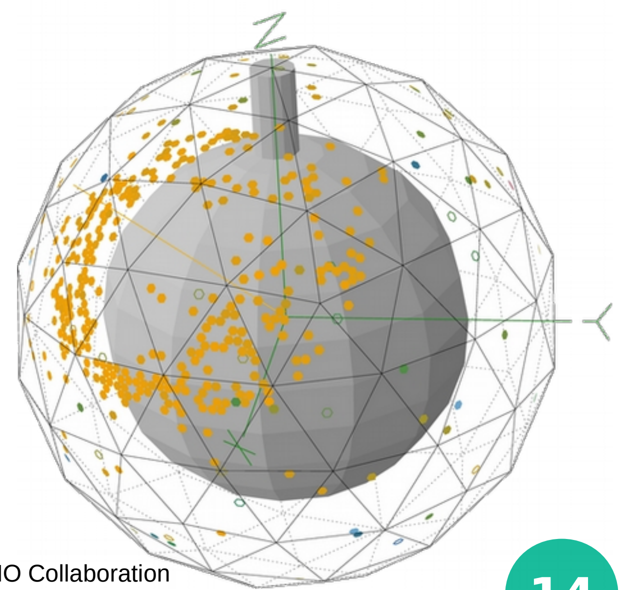
The SNO Collaboration

SNO Analysis

- **Raw data is from photomultiplier tubes (PMTs)**
  - Photon strikes photocathode, liberated electron amplified, charge collected
  - Hit **time**, integrated **charge**
- **Reconstruction algorithms fit observables from raw data event by event**
  - **Energy** from number of detected photons
  - Image cherenkov ring for **direction** of event
  - **Position** from minimizing hit time residuals
- **Used a statistical fit to disentangle signal and background with observables**
  - Also used a metric of **hit isotropy**



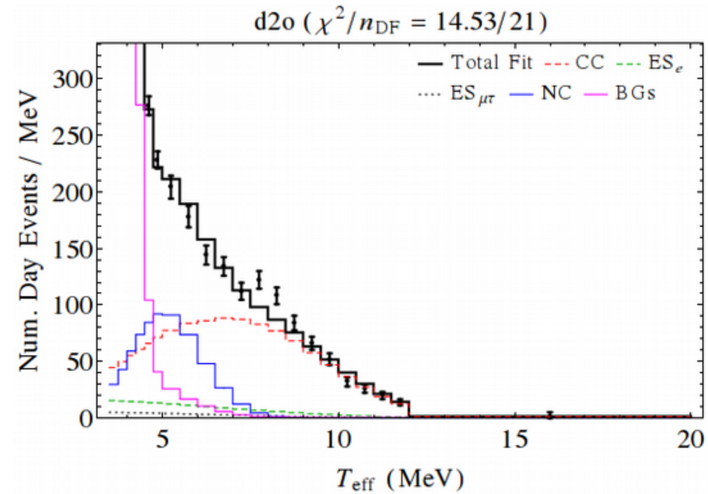
http://natefinney.com/images_large/figure1.jpg

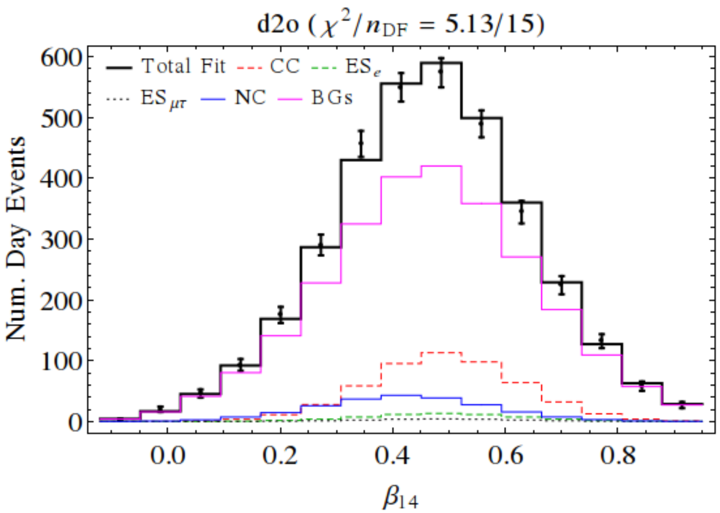


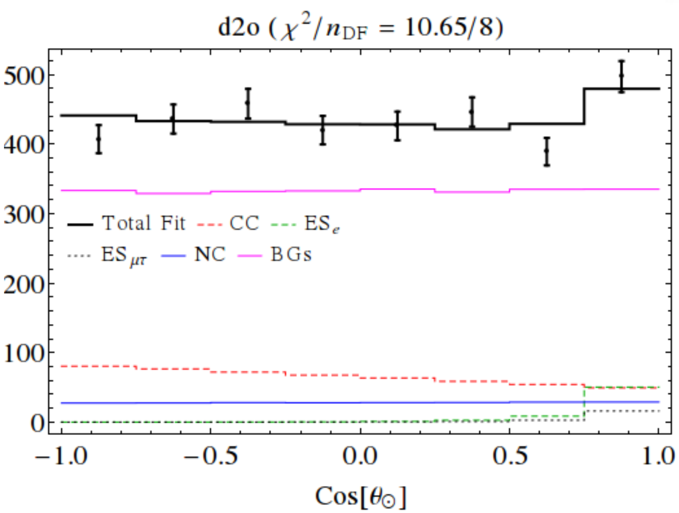
The SNO Collaboration

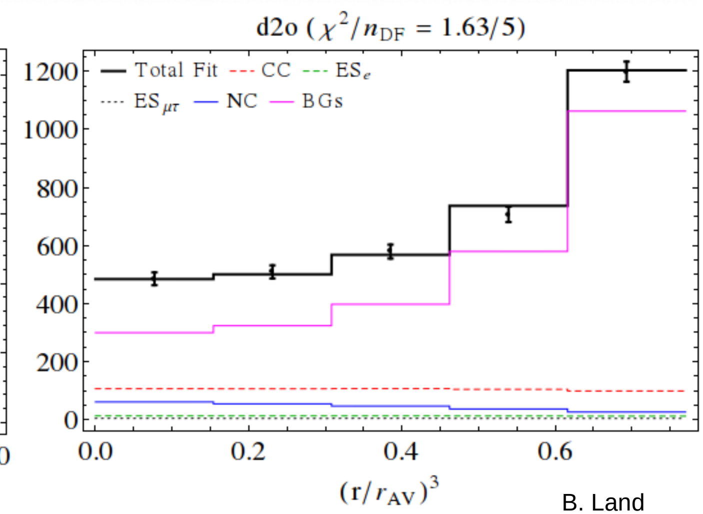
SNO Analysis

- **Monte-carlo predictions generated PDFs**
  - For signal and background classes
- **Fit out number of NC, CC, ES events**
  - Disentangle contributions from ν_e, ν_μ, ν_τ
  - Use livetime, cross sections to extract flux





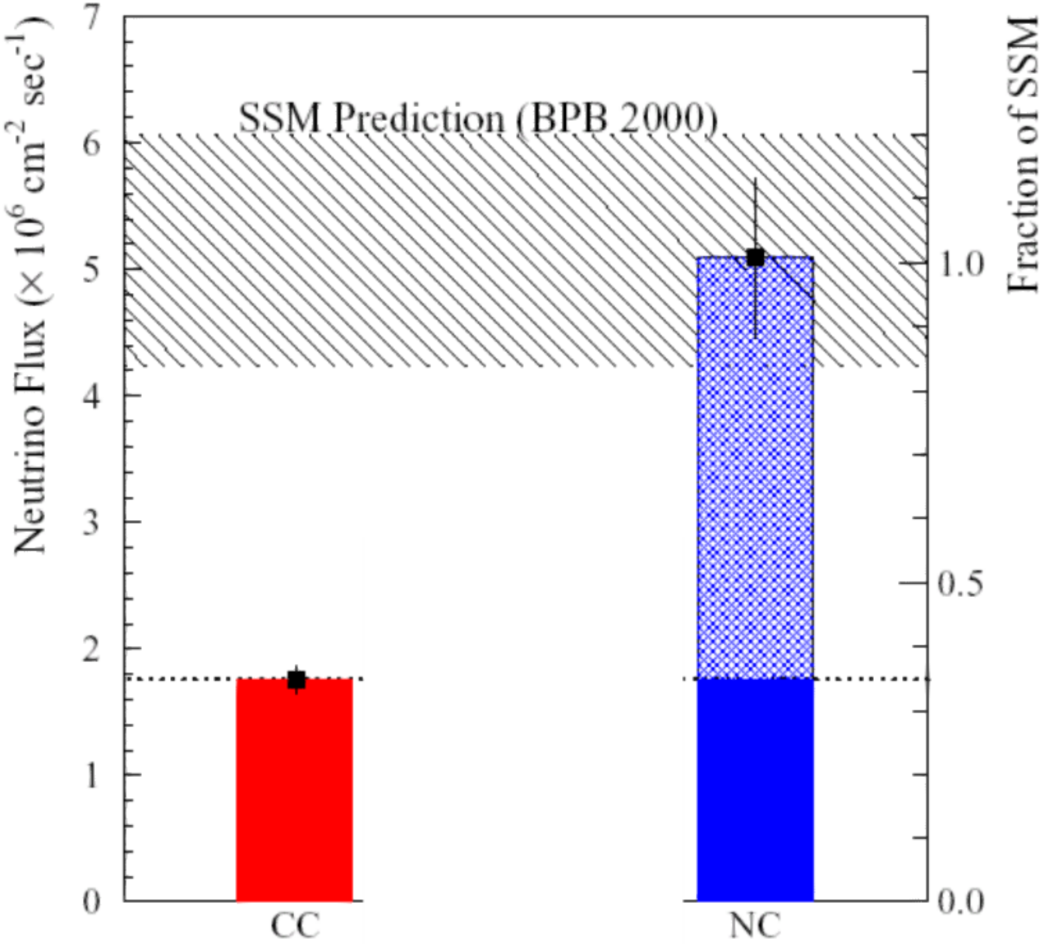




B. Land

SNO Results

- **Sum agreed well with SSM predictions!**
  - Confirms that neutrinos do change forms
- **Relative proportions require more explanation**



The SNO Collaboration

Neutrino (Vacuum) Oscillation

- **Proposed method to explain neutrino mutation**
- **Mass basis rotated relative to flavor basis**

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle$$

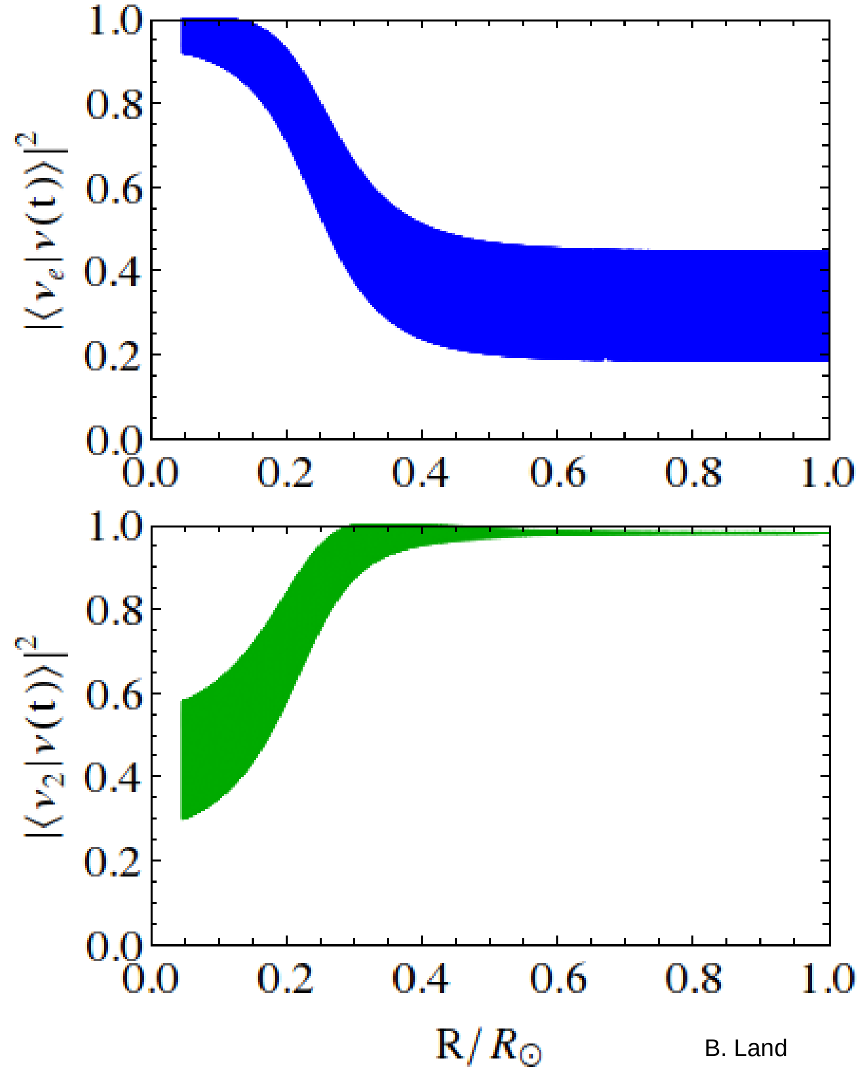
  - Requires that neutrinos have mass
- **The solar core is large relative to oscillation lengths**
  - Oscillations would be averaged out
  - Easy to compute electron neutrino “survival probability”

$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

- **Vacuum oscillations are not the whole story!**

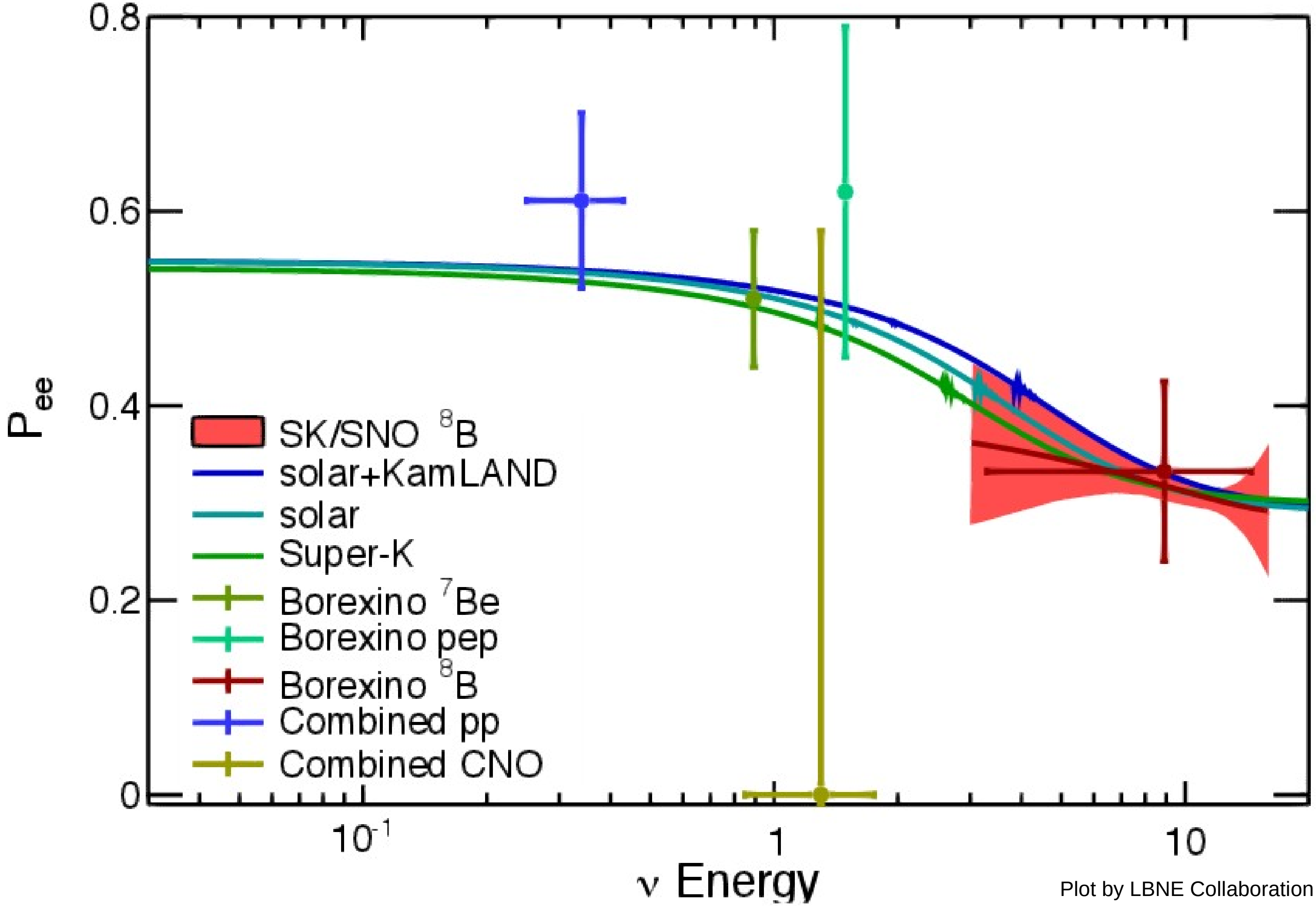
The Mikheyev–Smirnov–Wolfenstein (MSW) Effect

- ***Solar core densities are high enough to matter**
- **ν_e selectively experience CC**
  - Many e, virtually no τ or μ
  - Gives a potential energy to ν_e
    - Coherent forward scatter
    - c.f. refractive index of light
- **Short version: initial ν_e exits as ν_2**
  - For high energy neutrinos (^{8}B)
  - MSW prediction matches SNO data well
  - Agrees with many other measurements



B. Land

The Mikheyev–Smirnov–Wolfenstein (MSW) Effect



Plot by LBNE Collaboration

Solar Neutrino Problem

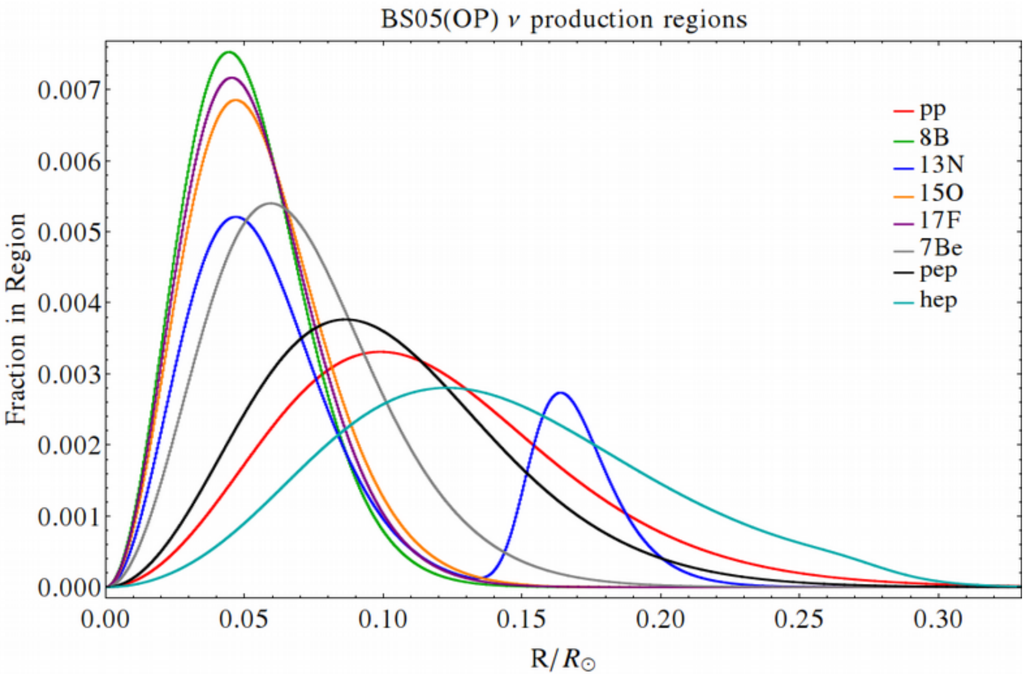
==

Solved!

What else can we do?

Solar Neutrino Physics

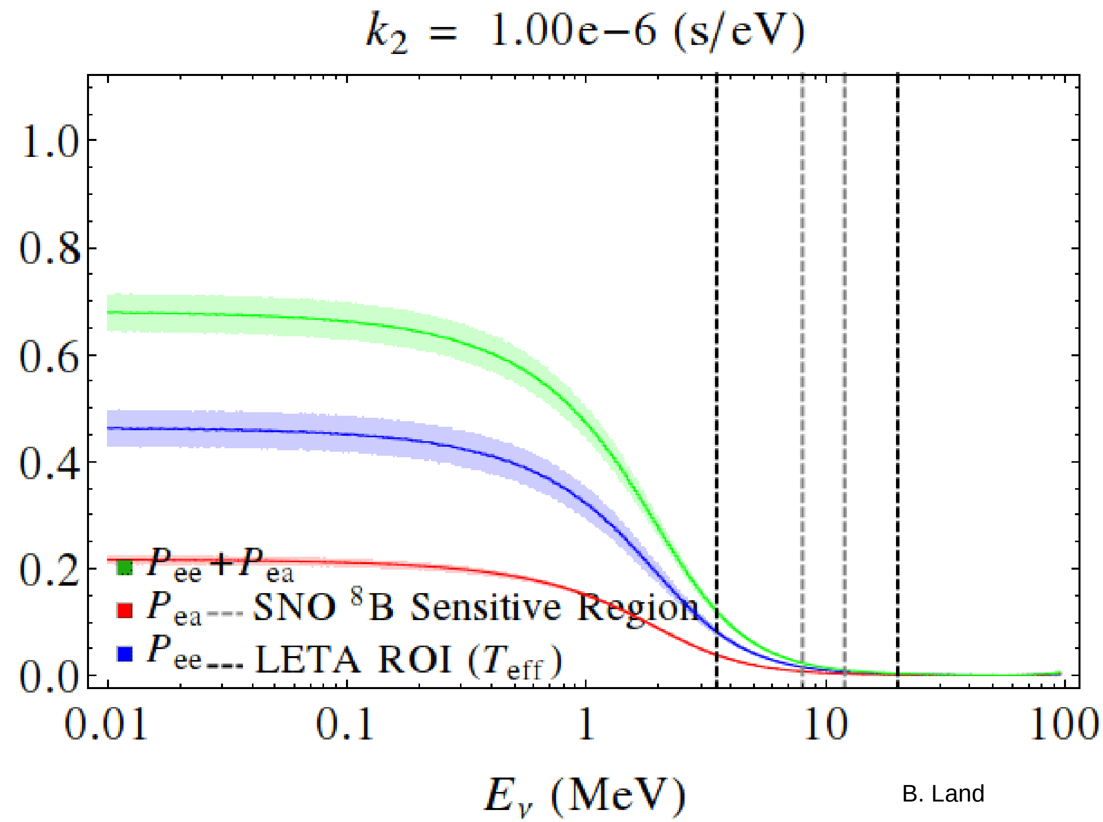
- **Studying the solar core**
  - Neutrino rates are direct measure of fusion rates
  - Different neutrinos produced in different regions
  - Highly dependent on properties of the core
  - Directly related to metalicity, resolve tensions in other measurement
- **Constrain mixing angles, squared mass differences**
  - Primarily θ_{12} and Δm^2_{12}



J. Bahcall et al. (plot by B. Land)

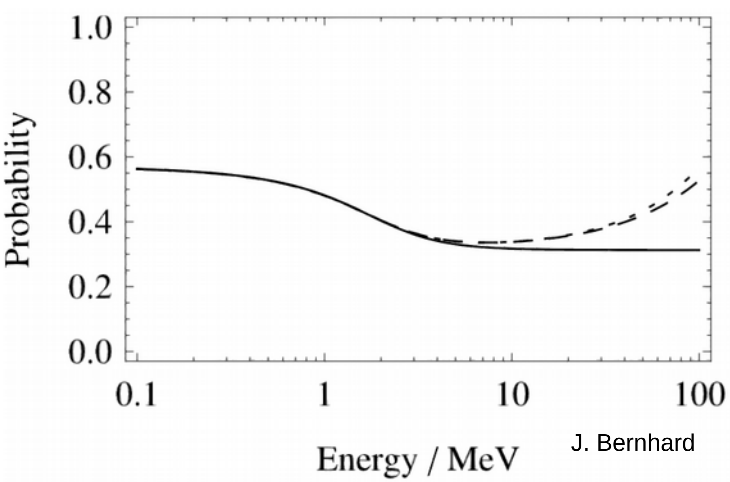
Solar Neutrino Physics

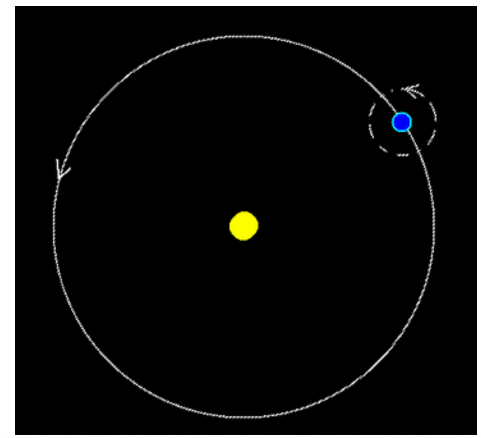
- **Neutrino lifetime**
  - Neutinos have mass, could decay
  - Solar provides *long* baseline, constrained initial flux
  - Probes beyond standard model physics
- **Sterile neutrinos**
  - Would lack potential present for other flavors
  - Solar densities uniquely sensitive to MSW-like resonances



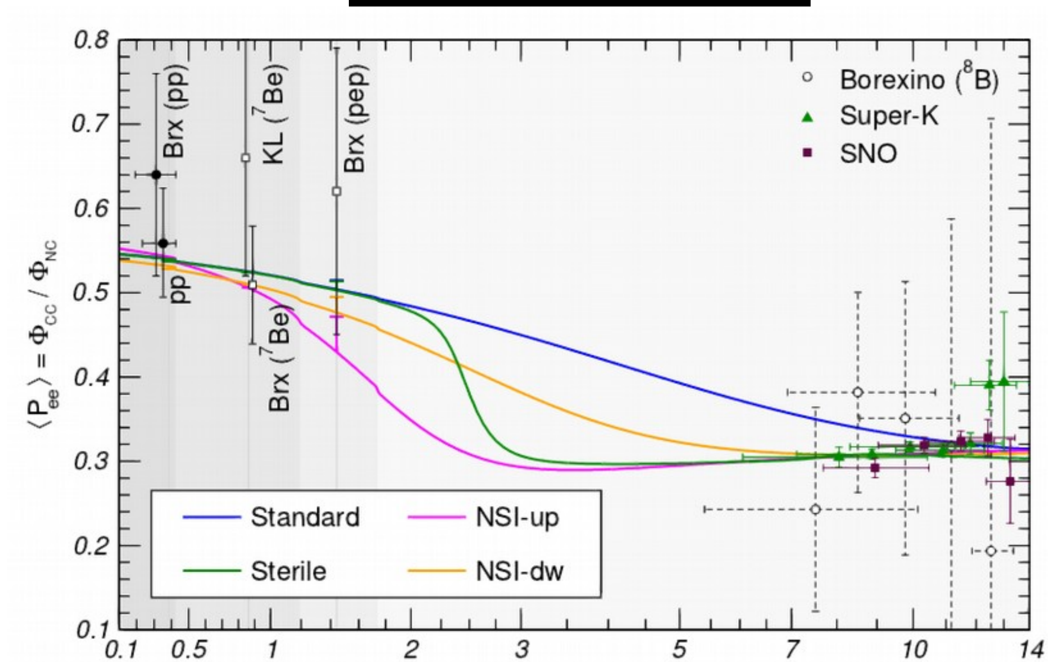
Solar Neutrino Physics

- **Fundamental symmetry violation**
  - *Long* baseline that rotates yearly (earth orbit)
  - Perfect for looking for Lorentz violations





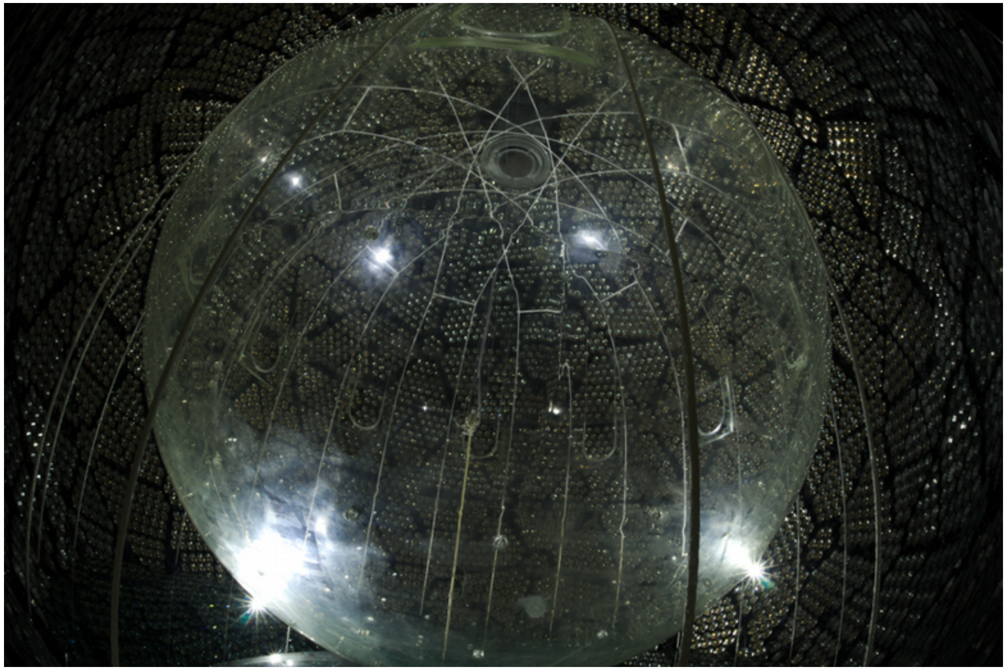
- **Other beyond standard model effects**
  - Look for distortions in energy spectrums



M. Maltoni and A. Smirnov

Moving Forward: SNO+

- **Upgrade of the SNO detector**
- **Replaces heavy water with liquid scintillator**
  - Linear alkylbenzene(LAB)+PPO
  - Loses sensitivity to NC, CC
  - Otherwise similar detection methods as SNO, just with isotropic scintillation
- **Primarily a $0\nu\beta\beta$ experiment**



SNO+ Collaboration

  - Starting with a water commissioning phase (filling now!)
  - Followed by pure scintillator phase
    - Potentially great for solar neutrinos (demonstrated by Borexino), other physics
  - Finally loading ^{130}Te into the scintillator for $0\nu\beta\beta$

Scintillator Detection

Pros

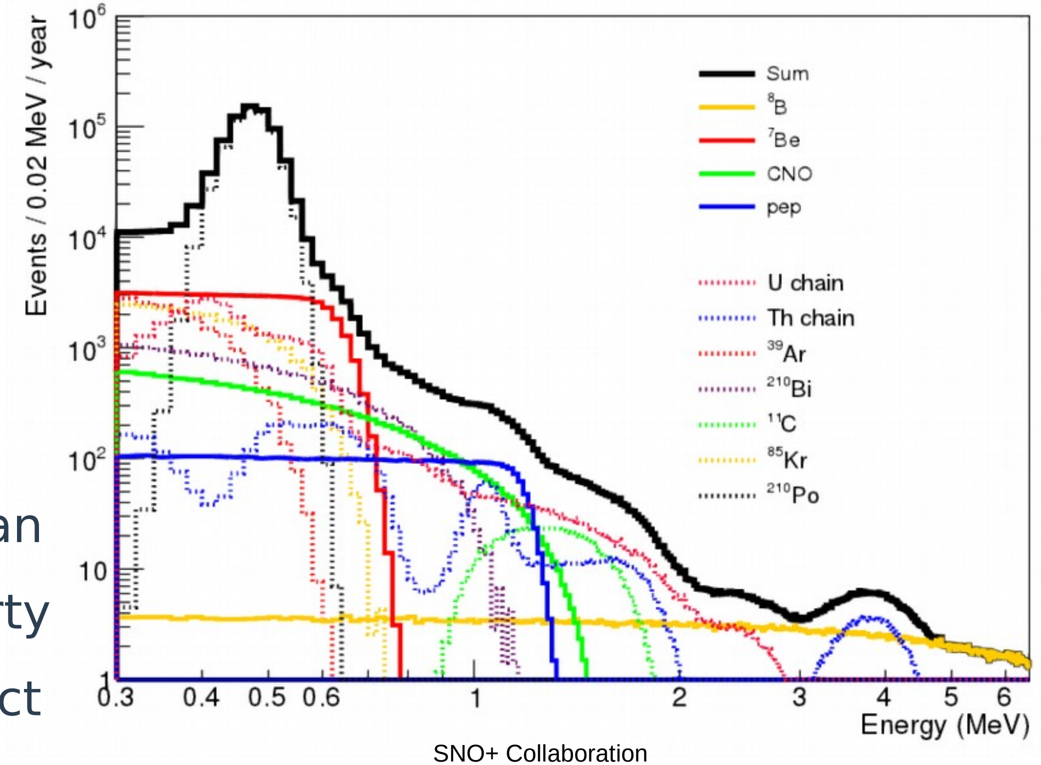
- **Greater light yield**
  - ~500 hits/MeV vs ~10 hits/MeV
  - Improved energy resolution
  - Lower thresholds
  - No cutoff for light production
- **Demonstrated by Borexino**

Cons

- **Loses directionality**
  - Scintillation is inherently isotropic, no ring or similar directionality
  - Cherenkov intensity lost in scintillation fluctuations
- **Shorter scattering lengths**
  - Modifies hit time residuals, hinders reconstruction

SNO+ Solar Neutrinos

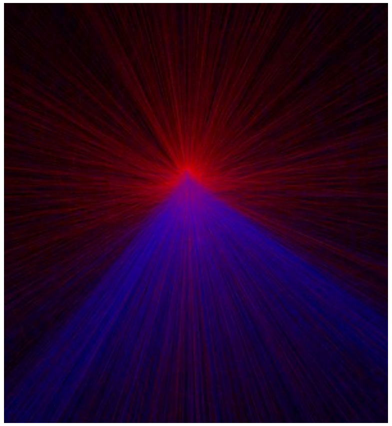
- **Monte-carlo predictions**
  - Similar analysis to SNO, without directionality
  - Sensitivity to 8B, 7Be, pep, CNO
- **Backgrounds are an issue**
  - Scintillator can be made ultra clean
  - Acrylic vessel is comparatively dirty
  - Effort underway to estimate impact
- **Directionality would help**
  - Backgrounds should not change with solar direction
  - Far easier to fit out solar neutrinos



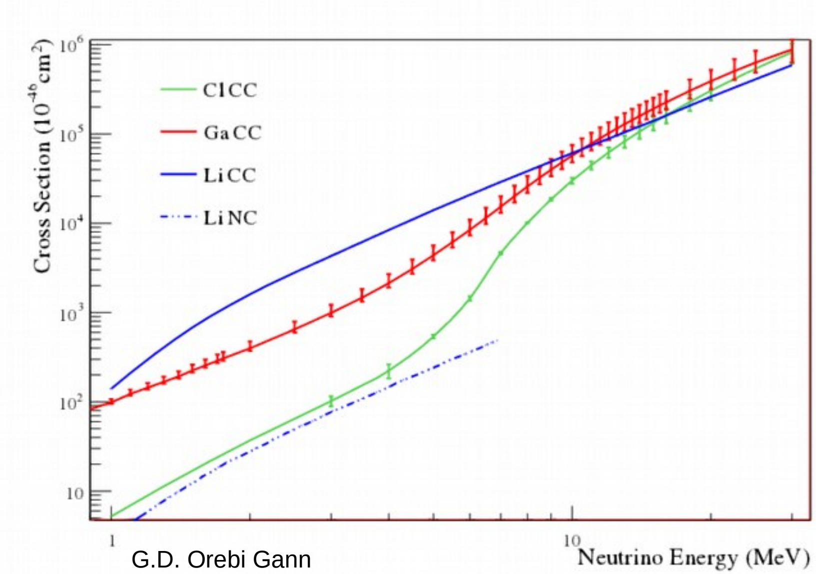
SNO+ Collaboration

The Future: Cherenkov+Scintillation

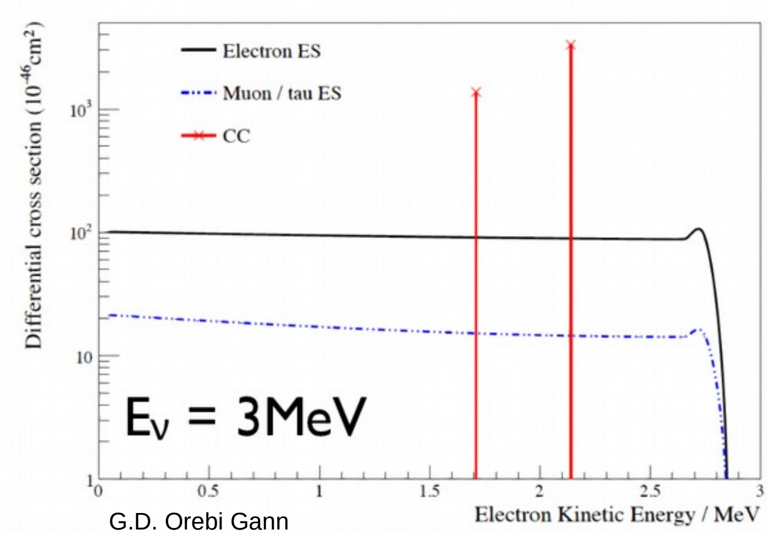
- **Combination potentially has the best of both worlds**
  - Directional rejection of backgrounds
  - High light yield → better energy resolution
- **Make it BIG**
  - More interactions
  - Better self-shielding of backgrounds
- **Load it with something**
  - e.g. ^{7}Li has a large CC cross section, sharply peaked response
  - Very precise spectral measurement possible



B. Land



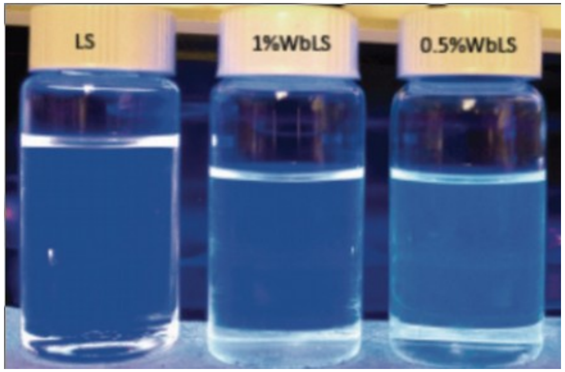
G.D. Orebi Gann



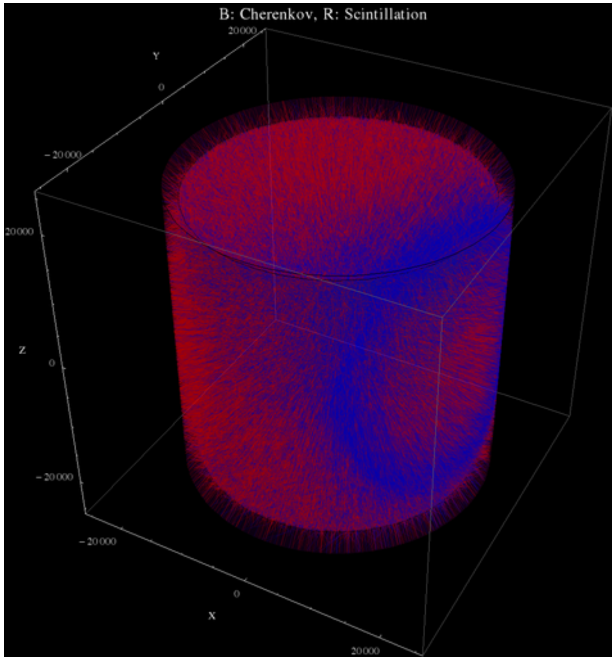
G.D. Orebi Gann

The Future: THEIA

- **Proposed experiment to realize combined Cherenkov and Scintillation detection**
- **Uses water based liquid scintillator (WbLS)**



  - Developed by Minfang Yeh
  - Scintillator suspended water
  - Tune loading fraction of scintillator to tune scintillation light yield



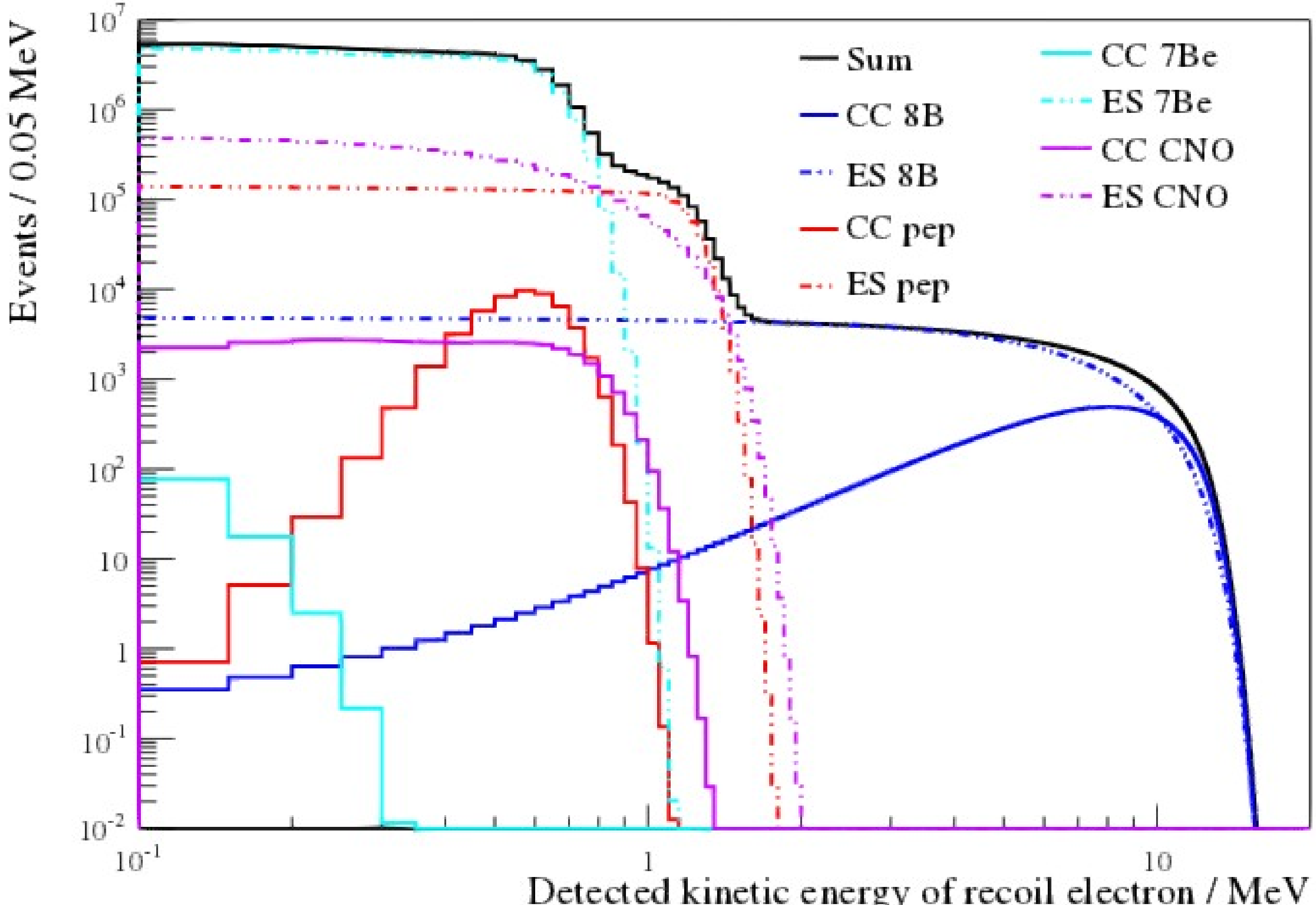
B. Land

B. Land

- **Broad physics program, and great for solar**

THEIA MC Predictions

30-kT WbLS THEIA detector loaded with 1% ^{7}Li



THEIA Interest Group

Questions?

References

- J. Bahcall Scientific American, Volume 221, Number 1, July 1969, pp. 28-37
- J. Bahcall ApJ, **621**, L85 (2005), astro-ph/0412440
- B.T. Cleveland, et al. Astrophys.J. 496 (1998) 505-526
- The SNO Collaboration, Phys. Rev. C **88**, 025501 (2013)
- G.D. Orebi Gann, arXiv:1504.02154v2 [nucl-ex]
- J.R. Alonso, et al., arXiv:1409.5864v3 [physics.ins-det]
- Theia Interest Group arXiv:1504.08284v1 [physics.ins-det]
- M. Yeh, et al., Nucl. Inst. & Meth. A **660** 51 (2011)
- M. Maltoni and A. Smirnov, arXiv:1507.05287v3 [hep-ph]
- J. Bernhard, arXiv:1009.4717 [hep-ph]