Neutrino Physics

Nikolai Tolich, University of Washington

Nuclear astrophysics white paper open questions related to neutrinos

- 3.1: Origin of the elements
  - How can the observations of solar and supernova neutrinos be exploited toward a deeper understanding of stellar burning mechanisms?
  - What is the contribution of neutrino driven winds in core collapse supernovae to nucleosynthesis? And what role do neutrino properties play?
- 3.2: How stars work
  - What is the composition and low energy neutrino flux of the sun?
- 3.3: Explosions of core collapse supernova and long GRBs
  - What is the neutrino and gravitational wave signal from CC SNe?

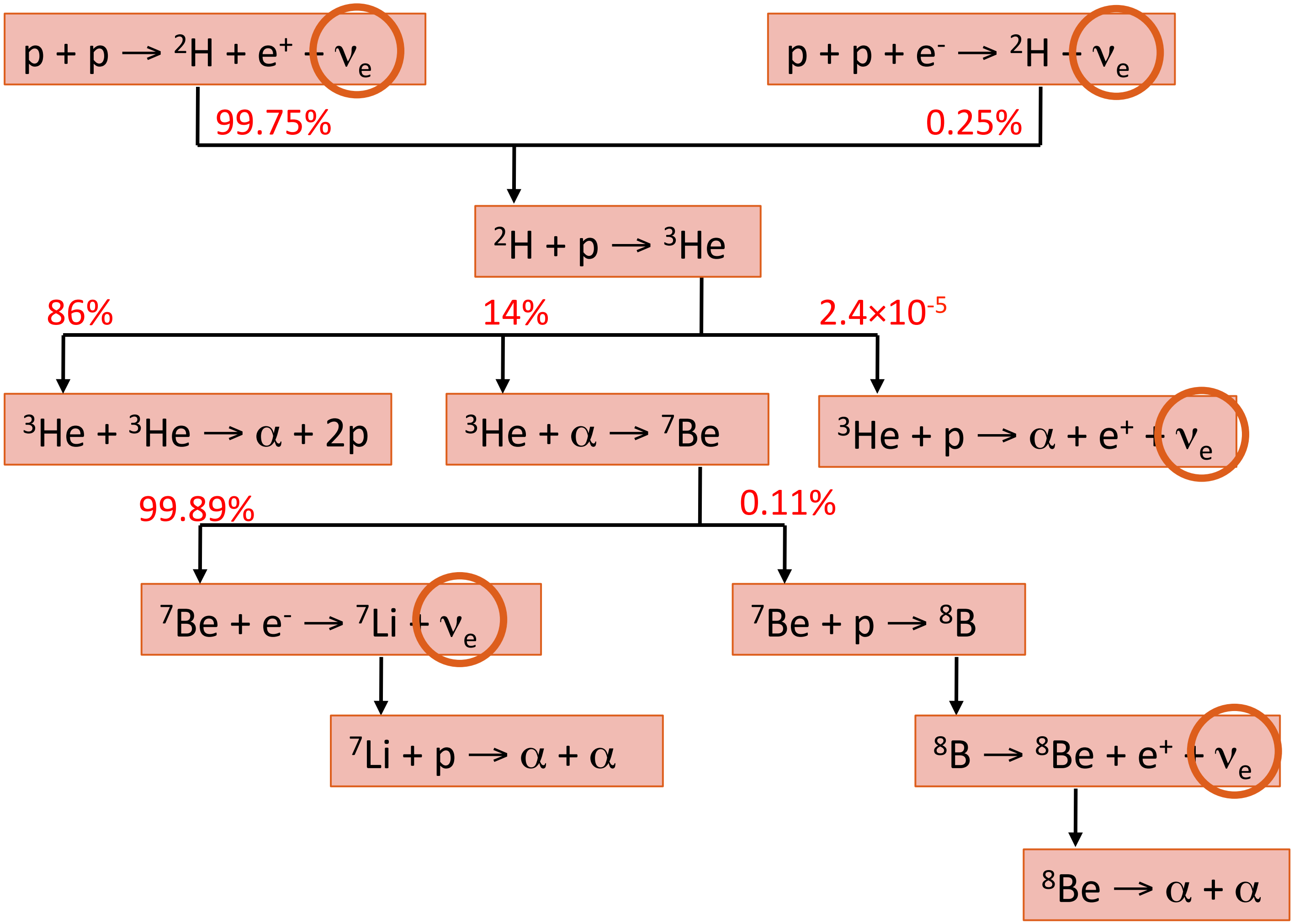
Nuclear astrophysics white paper open questions related to neutrinos

- 3.4: Compact object binary mergers and short GRBs
  - What is the nucleosynthesis output of neutron stars - neutron star and neutron star - black hole mergers and how is it affected by neutrino physics?
- 3.7: Big bang nucleosynthesis
  - Will the combination Big Bang nucleosynthesis studies with new precision measurements of anisotropies in the cosmic microwave background and improved nuclear reaction rates reveal new particle physics?

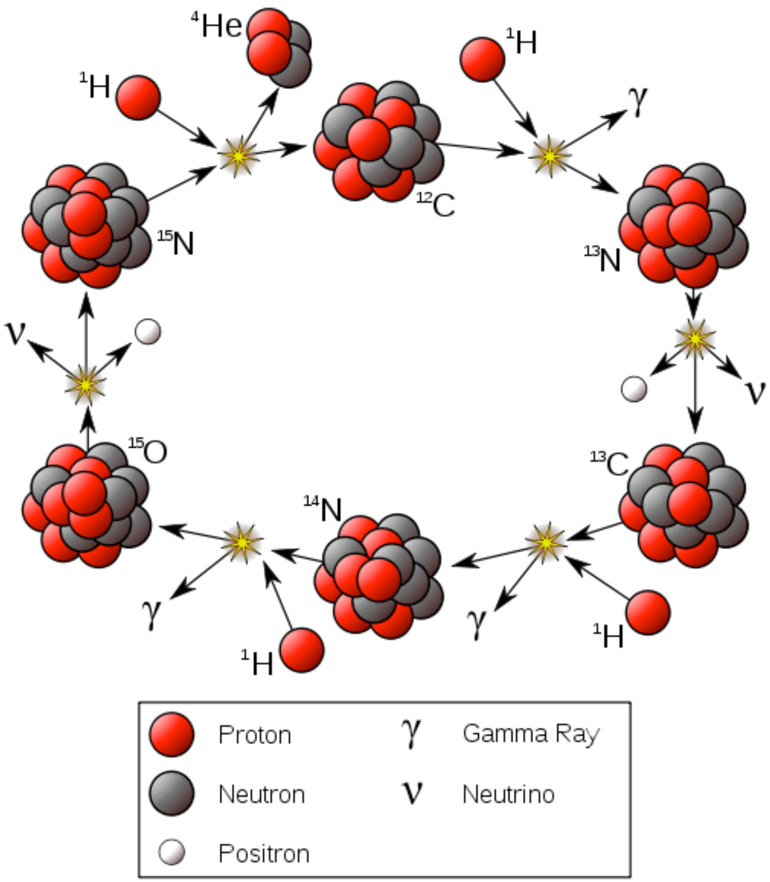
Solar neutrinos

Theory

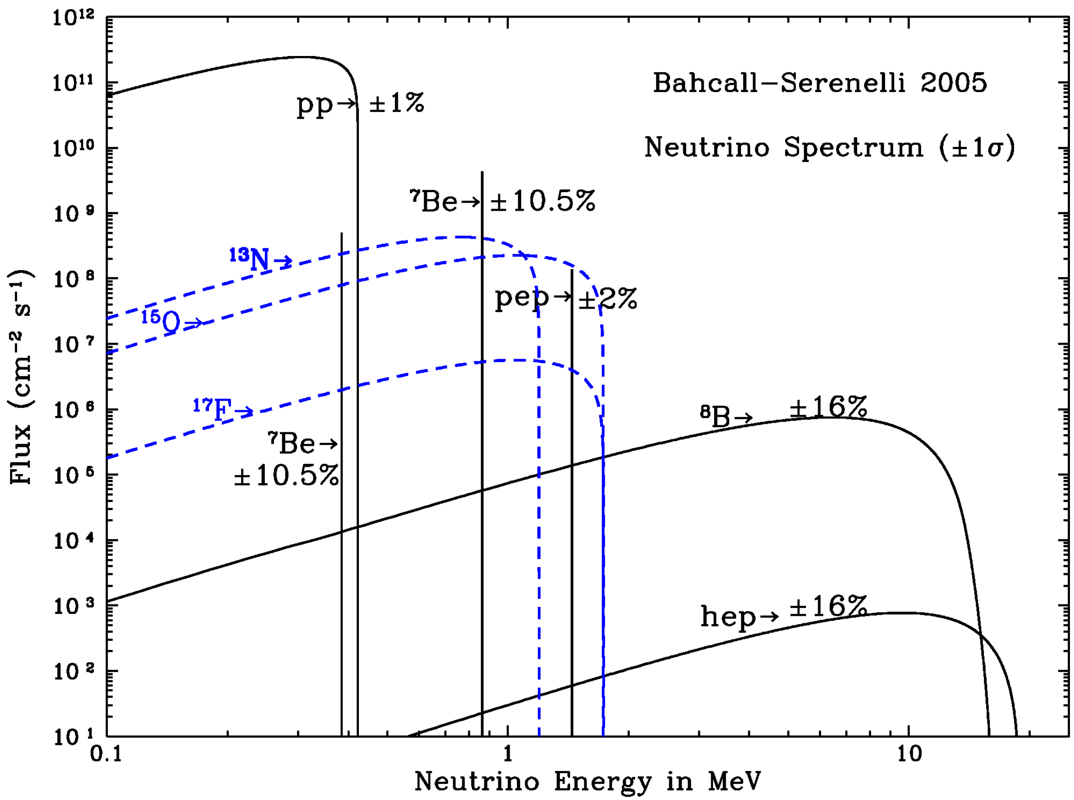
Solar pp chain reactions



Solar CNO chain reactions



Solar neutrino energy spectrum



Standard solar model predictions

Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1 {}^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1 {}^{+0.17}_{-0.16})$	$1.34(1 {}^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1 {}^{+0.19}_{-0.17})$	$3.25(1 {}^{+0.16}_{-0.15})$	44%
Cl	$8.46^{+0.87}_{-0.88}$	$6.86^{+0.69}_{-0.70}$	
Ga	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

arXiv:0811.2424

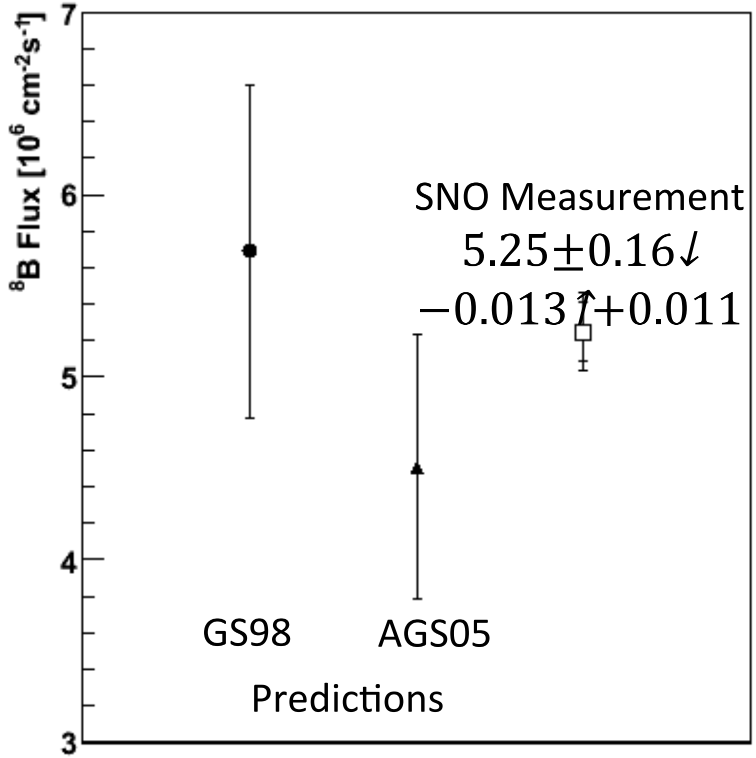
Main sources of uncertainty

- ^7Be
  - opacity (3.2%)
  - S_{34} (2.8%), S factor for $^3He + \alpha$
  - S_{33} (2.5%)
- ^8B
  - opacity (6.8%)
  - diffusion (4.2%)
  - S_{17} (3.8%)
- CNO (^{13}N, ^{15}O)
  - $S_{1,14}$ (6%, 8%)
  - diffusion (4%, 5%)
  - opacity (5%, 6%)

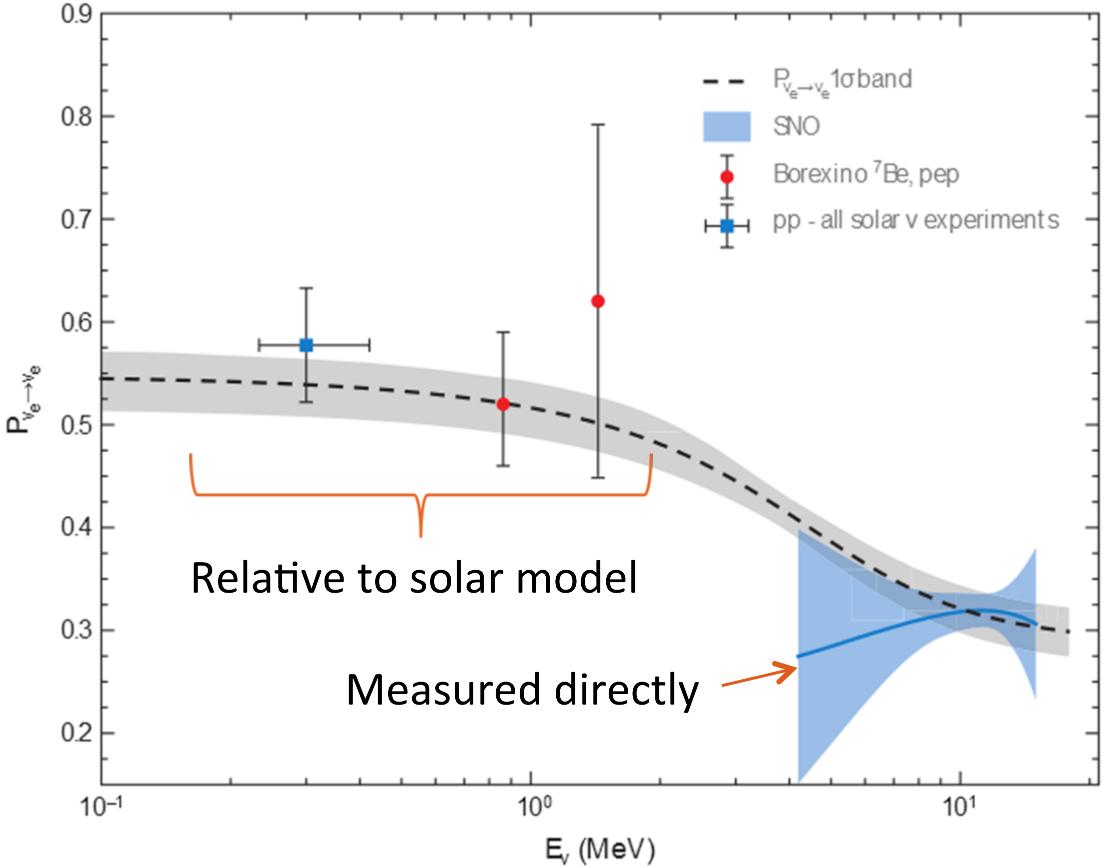
Solar neutrinos

Measurements

^{8}B solar neutrino flux

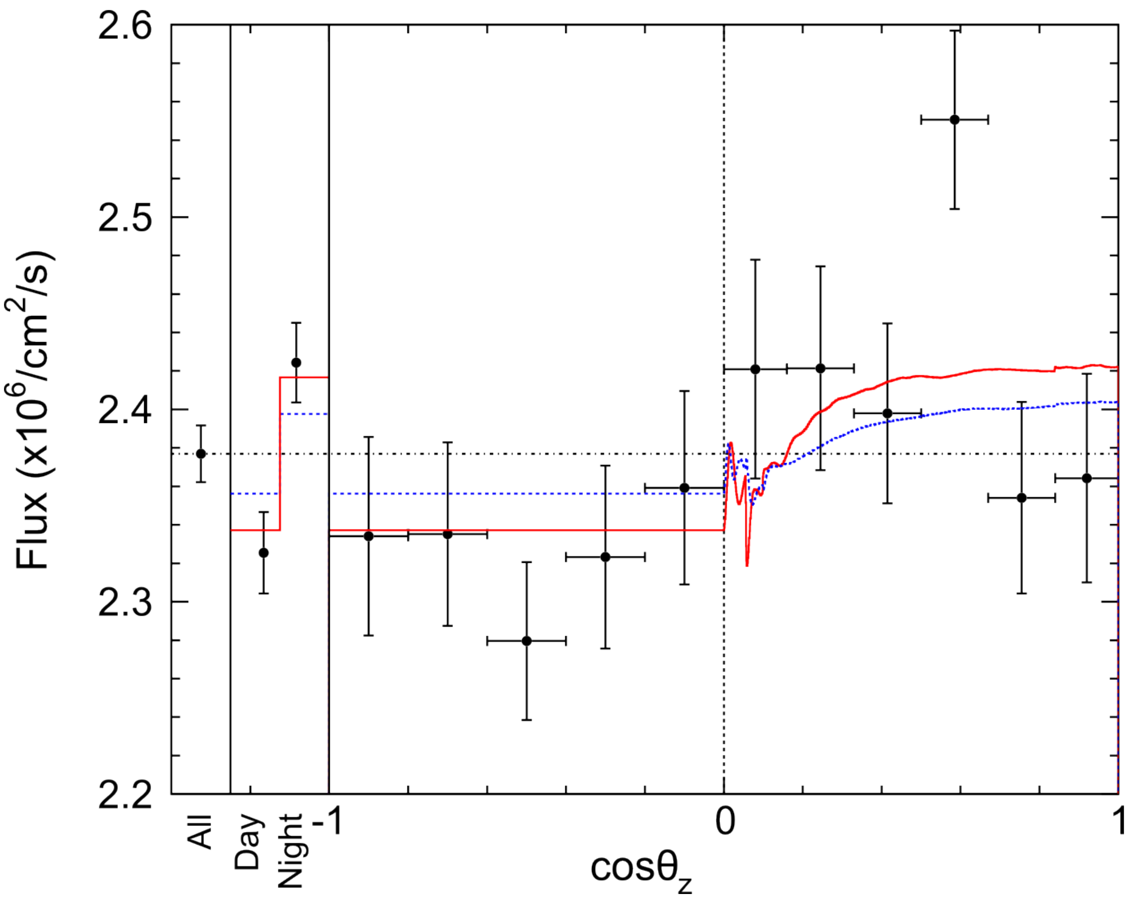


Solar neutrino oscillations



Haxton W. *et al.* Ann. Rev. Astron. Astrophys. (2013)

Evidence of matter effects



Super-K collaboration, PRL **112**, 091805 (2014)

Solar neutrinos

Outstanding questions

What is the solar core metallicity?

- Essentially this is the same question as what is the Sun's CNO neutrino flux?

  $$\phi(^{15}O)/\phi(^{15}O)^{SSM} = [\phi(^{8}B)/\phi(^{8}B)^{SSM}]^{0.729} x_{C+N}$$

  where x_{C+N} is the primordial core abundance of C + N

- Systematic uncertainties
  - 0.6%(solar model)
  - 2.7%(diffusion)
  - 9.9%(nuclear). Need factor 2 improvment in low energy extrapolation of the rate $^{7}Be(p,\gamma)$, $^{14}N(p, \gamma)$
  - 3.2%(θ_{12})

W.C. Haxton, R.G. Hamish Robertson, and Aldo M. Serenelli, Annu. Rev. Astron. Astrophys **51,** 21 (2013)

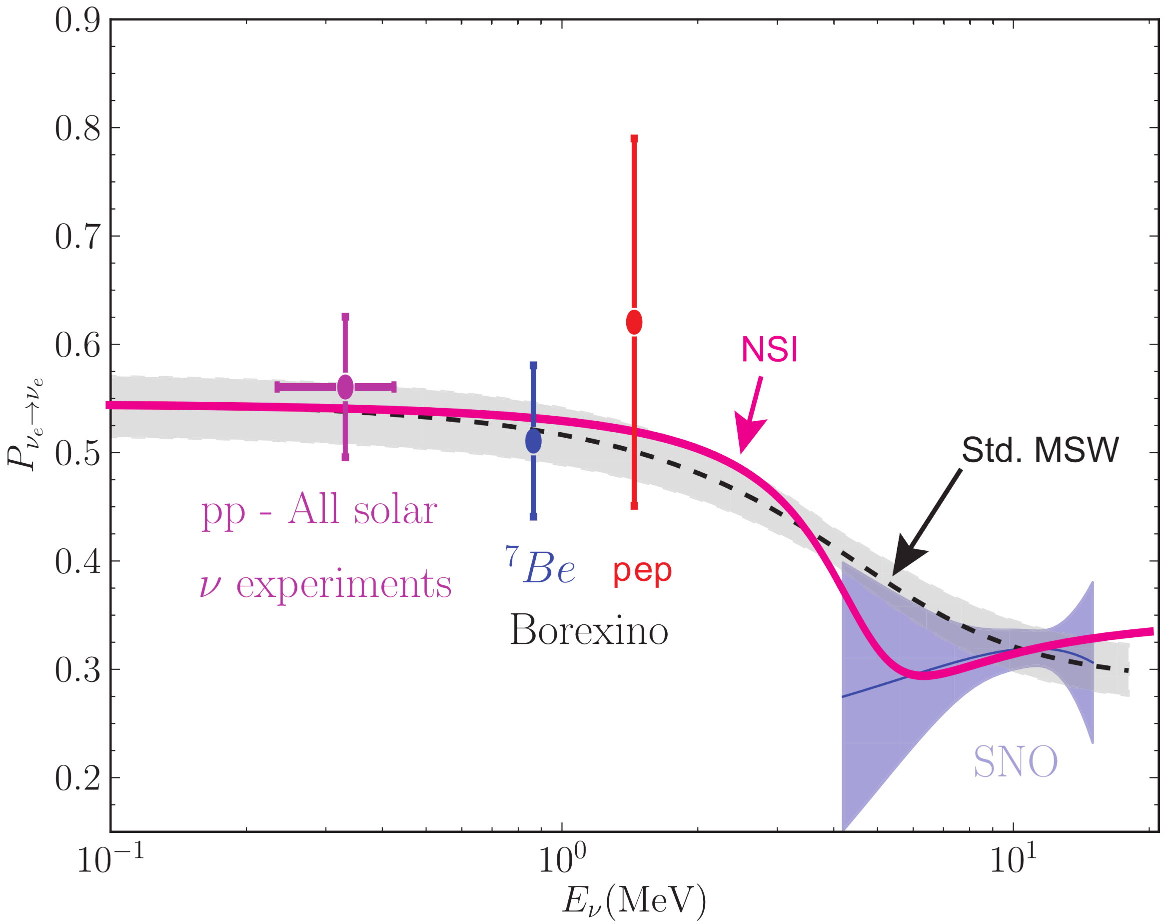
What is the solar core metallicity?

- This measurement is fundamental (from Wick Haxton)
  - probes the primordial gas from which our solar system formed
  - the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions
  - could help motivate "standard solar system models" that would link solar ν physics, solar system formation, planetary astrochemistry

What is the total solar luminosity measured with neutrinos?

- It would be significant to compare the Sun's photon luminosity (known to 0.01%) and ν luminosity, at the level set by nuclear physics uncertainties (1%)
- Measure *pp* or *pep* neutrinos to an accuracy of <1%

Are there non-standard neutrino interactions?

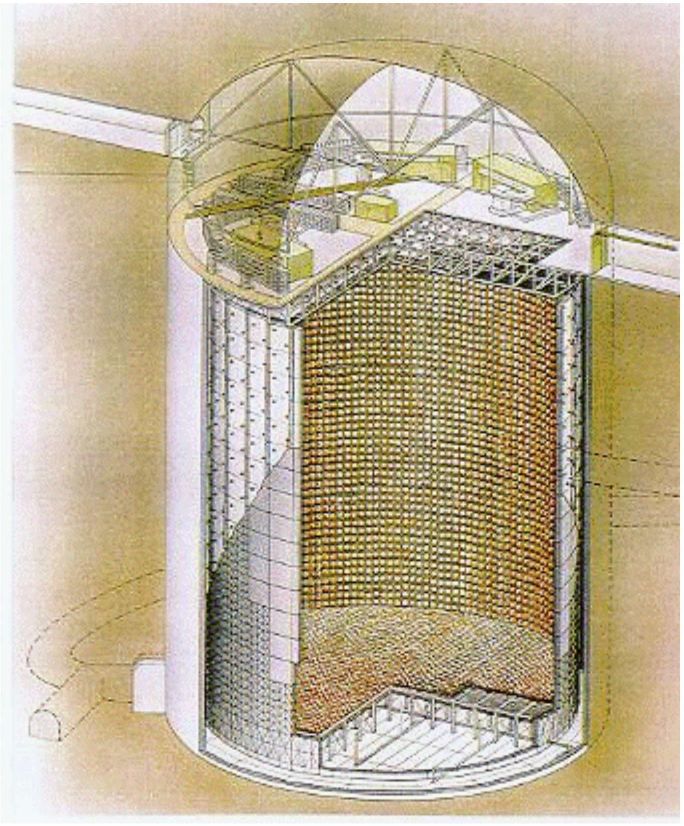


Friedland and Shoemaker, arXiv:1207.6642

Solar neutrinos

Future experiments

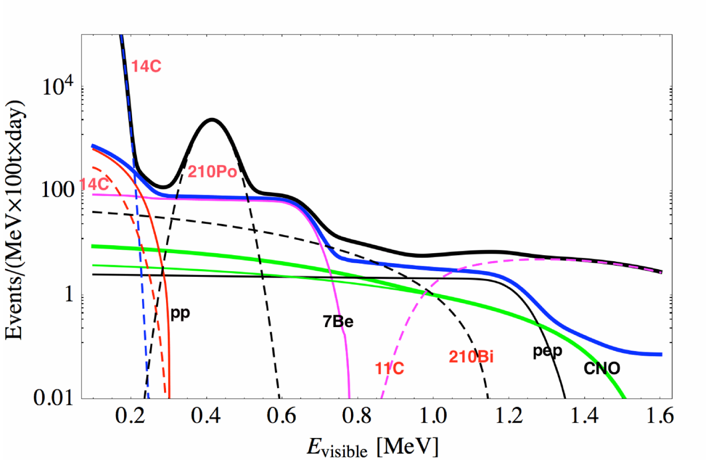
Super-K



- Currently operating
- Continues to measure ^{8}B solar neutrinos

Borexino

After re-purification 2012-2013 (with 11C cuts)

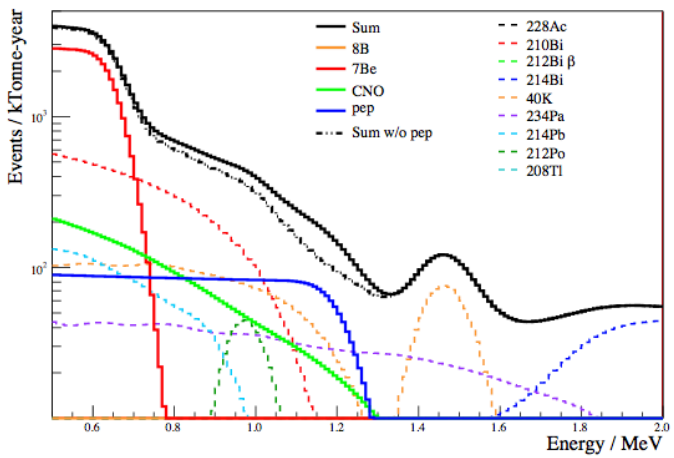


From F. Calaprice's talk at Solar Neutrinos at Jin Ping

- Currently operating
- Improved measurement of *pep* and ^{7}Be solar neutrinos
- Improve purity to go after CNO solar neutrinos

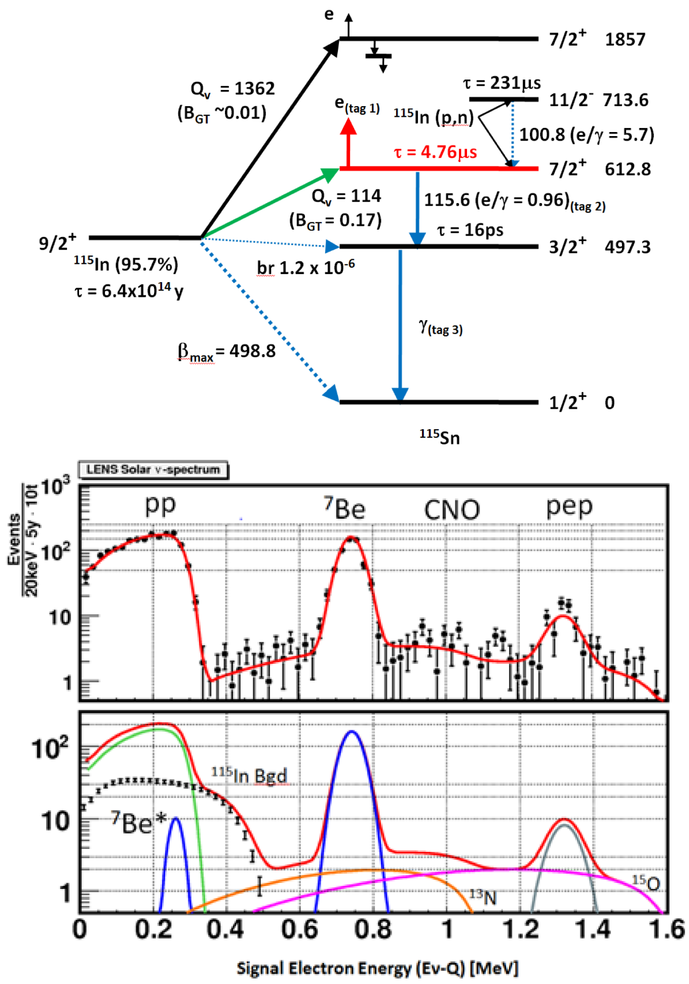
SNO+

Assuming initial Borexino-level backgrounds are reached



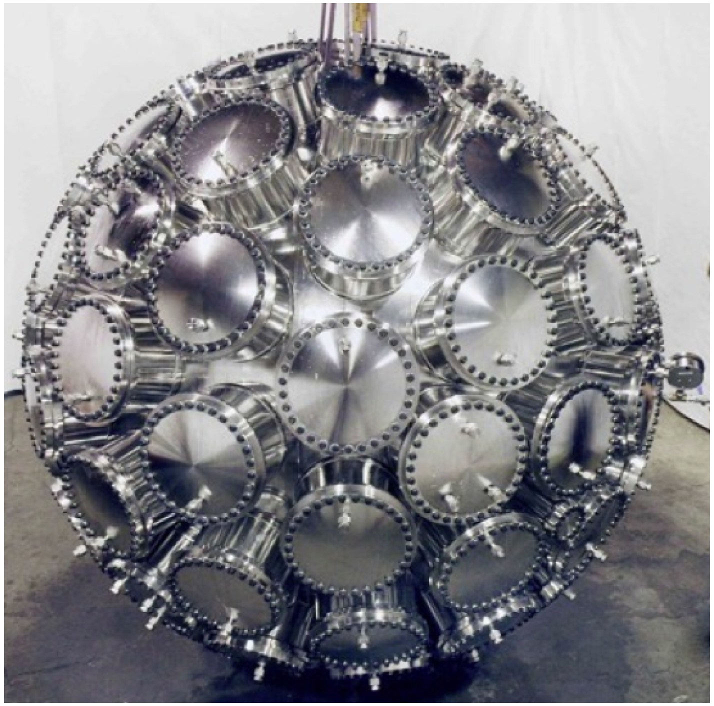
- Under construction
- Chosen to prioritize double beta decay
- Hopefully sensitive to *pep*, ^{7}Be, and CNO solar neutrinos
- Sensitivity at 2 years
  - *pep* 6.5%
  - ^{8}B 5.4%
  - ^{7}Be 2.8%
  - pp A few %?
  - CNO ~ 15%?

LENS



- Currently running mini LENS (125 L)
- 50 ton.yr LENS could measure the *pp* solar neutrino flux to ~3%
- Need to be able to calibrate the reaction rate.

CLEAN

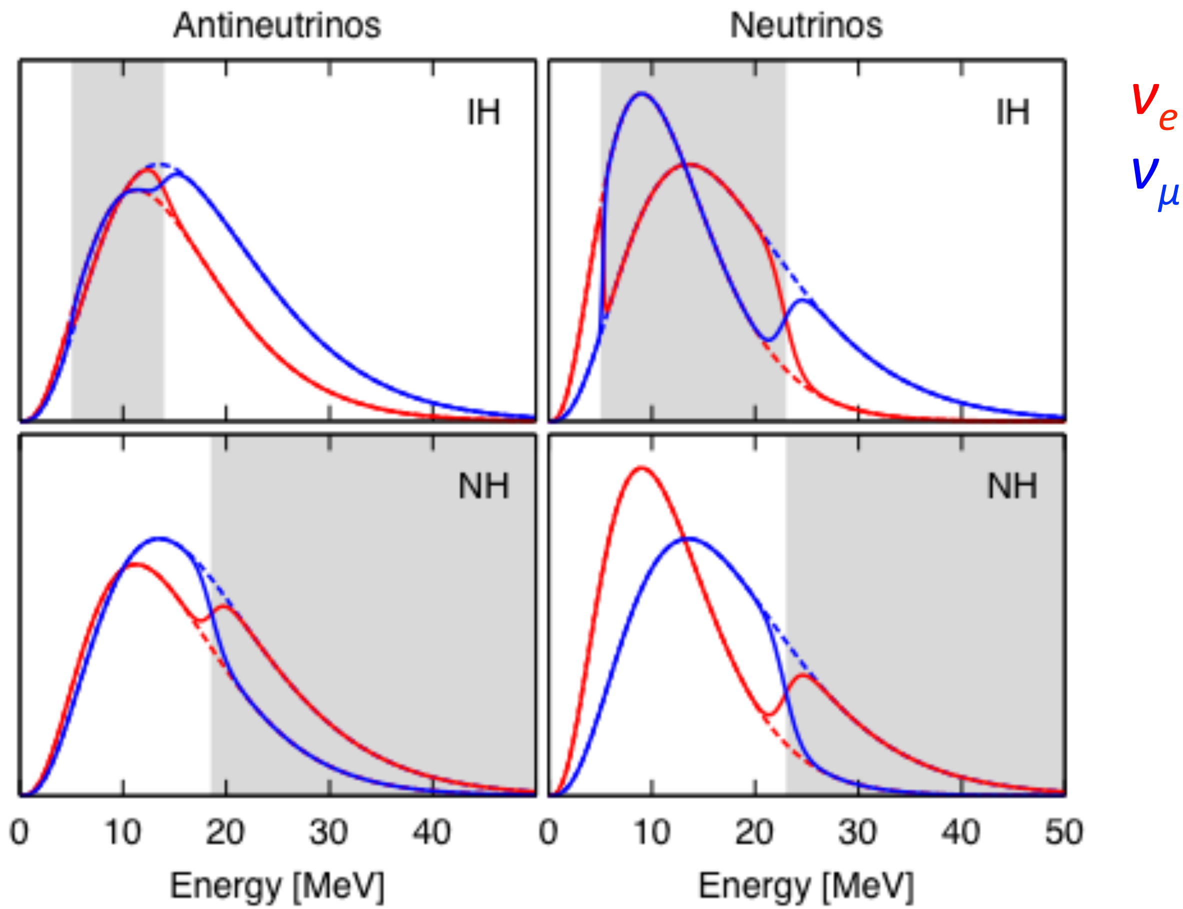


- Currently building miniCLEAN
- 40 ton fiducial liquid Ne detector could measure *pp* solar neutrino flux to ~2% with 5 years of running.

Supernova neutrinos

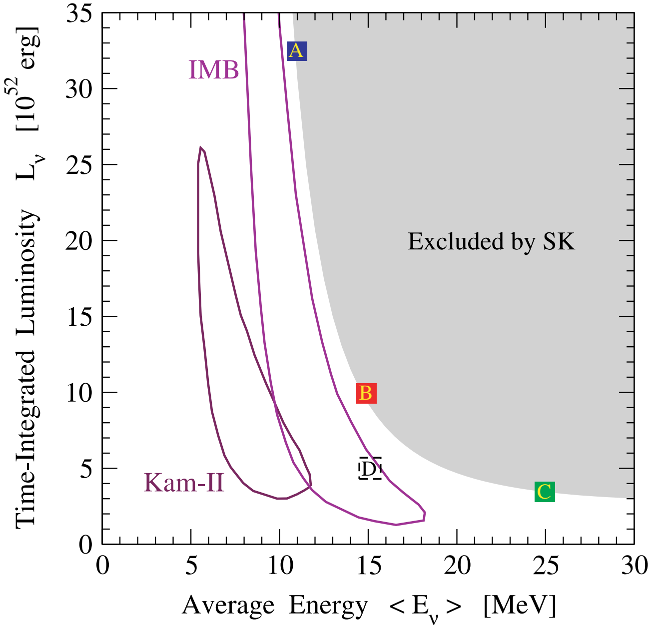
Introduction

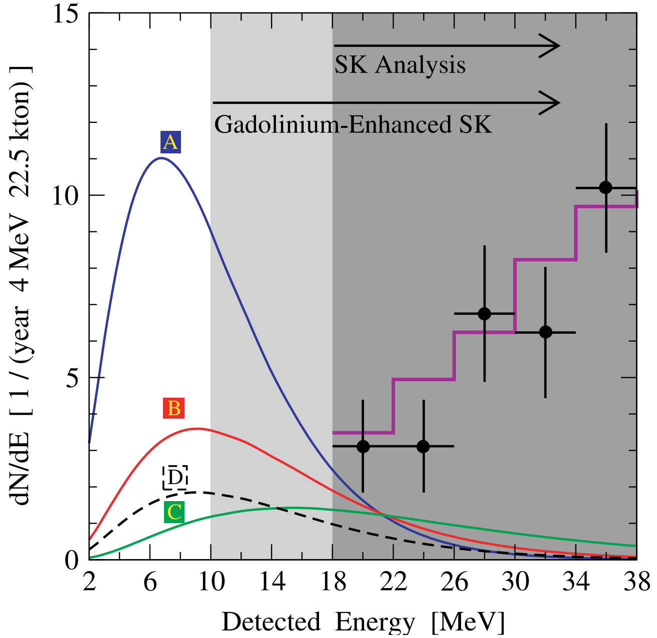
SN neutrinos



B. Dasgupta *et al.* PRL **103**, 051105, 2009

Relic SN neutrinos





Yüksel, Ando, Beacom PRC **74**, 015803, 2006

Outstanding SN neutrino questions

- What is the temperature and luminosity for νe, $\nu\ e$, and νx?
- Can we see evidence of collective oscillations?
- Can we determine the neutrino mass hierarchy?
- Can we see evidence of neutronization?

Supernova neutrinos

Experiments

Water Cerenkov

- Sensitive to
  - $\nu\ e$ spec. and flux through neutron inverse beta decay
  - νe spec. and flux from electron scattering
- Super-K is currently operating and should see 1000's of neutrinos from a typical galactic SN
- Hyper-K is under consideration
- Gadzooks will add Gd to Super-K allowing sensitivity to neutrons and therefore relic neutrinos

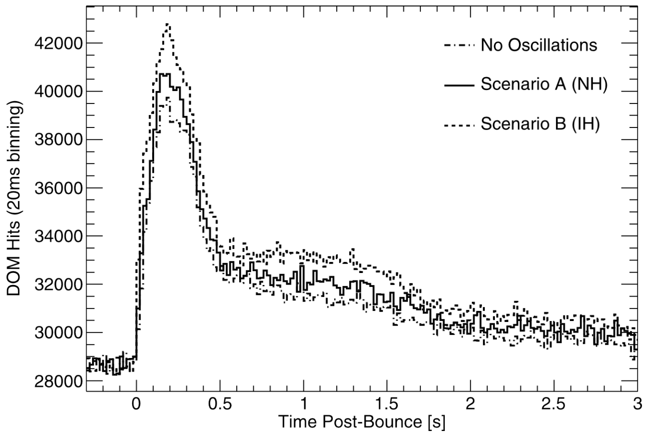
Liquid scintillator

- Sensitive to
  - νe spec. and flux through neutron inverse beta decay
  - νx spec. and flux from proton scattering
- KamLAND is currently operating should see 100's of neutrinos from a typical galactic SN
- Borexino is currently operating should see ~100 neutrinos from a typical galactic SN
- SNO+ is under construction should see 100's of neutrinos from a typical galactic SN
- Idea for a very large water based liquid scintillator detector (WbLS)

Liquid Ar

- Sensitive to
  - νe spec. and flux
- LBNE has CD1 but final detector configuration is still uncertain

IceCube



IceCube collaboration,
A&A **535**, A109 (2011)

- Sensitive to time spectrum mostly of νe

Summary

- Neutrino experiments have confirmed our basic model of solar fusion.
- To measure metalicity of solar core we should measure the solar neutrino flux from CNO cycle to 5% accuracy.
- To measuring solar luminosity using neutrinos we should measure the solar neutrino flux from the *pp* or *pep* reactions to an accuracy of 1%.
- Solar neutrino experiments have also allowed us to understand neutrino oscillations. They could be a sensitive test of non-standard interactions.
- Given the long time between galactic SN, SN burst detectors normally have another primary purpose. We should have many detectors sensitive to different reactions to not only learn about SN physics, but also neutrino physics.