Solar Neutrinos

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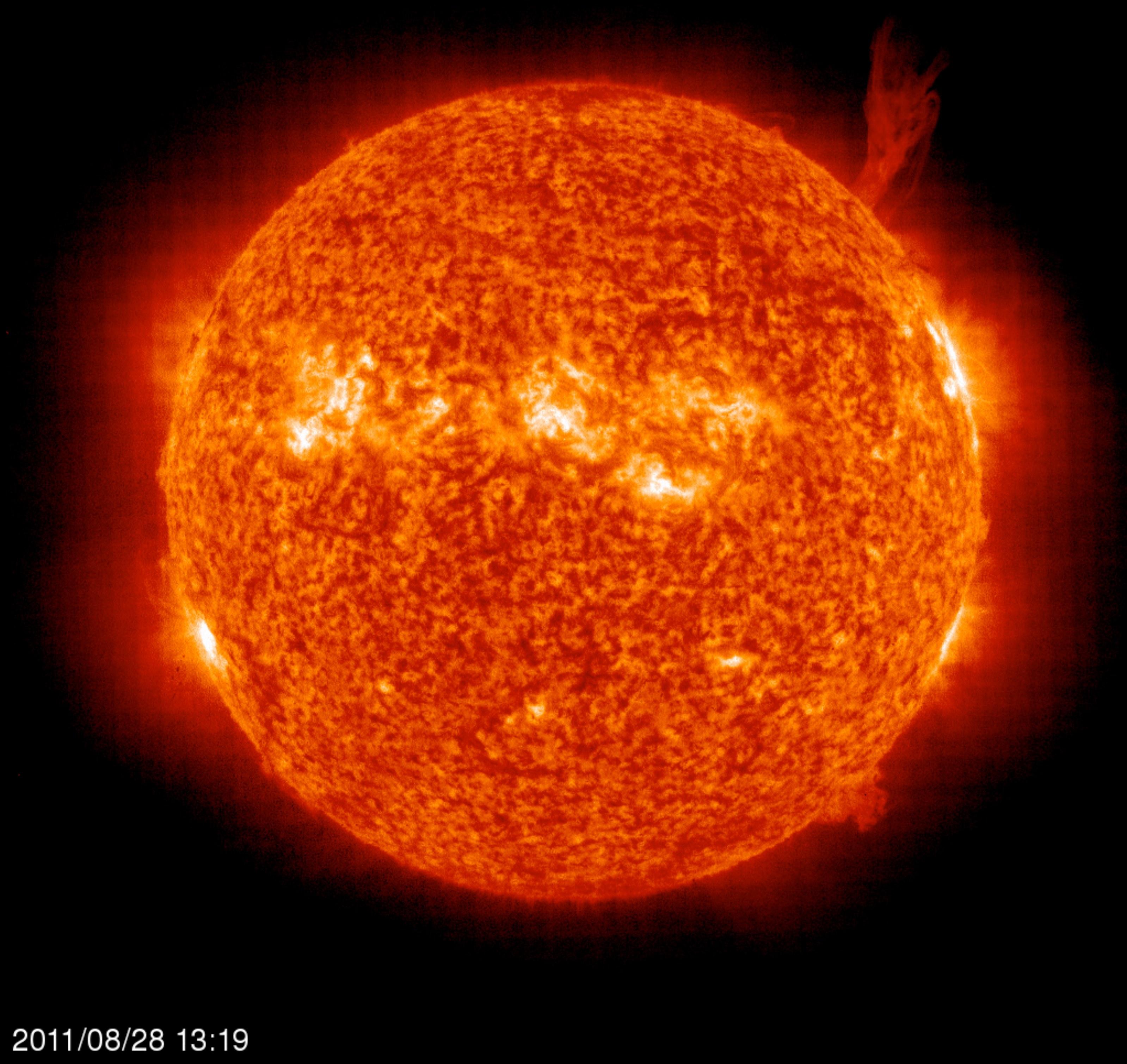
Borexino Collaboration

How does the Sun work?



http://sohowww.nascom.nasa.gov/data/realtime-update.html

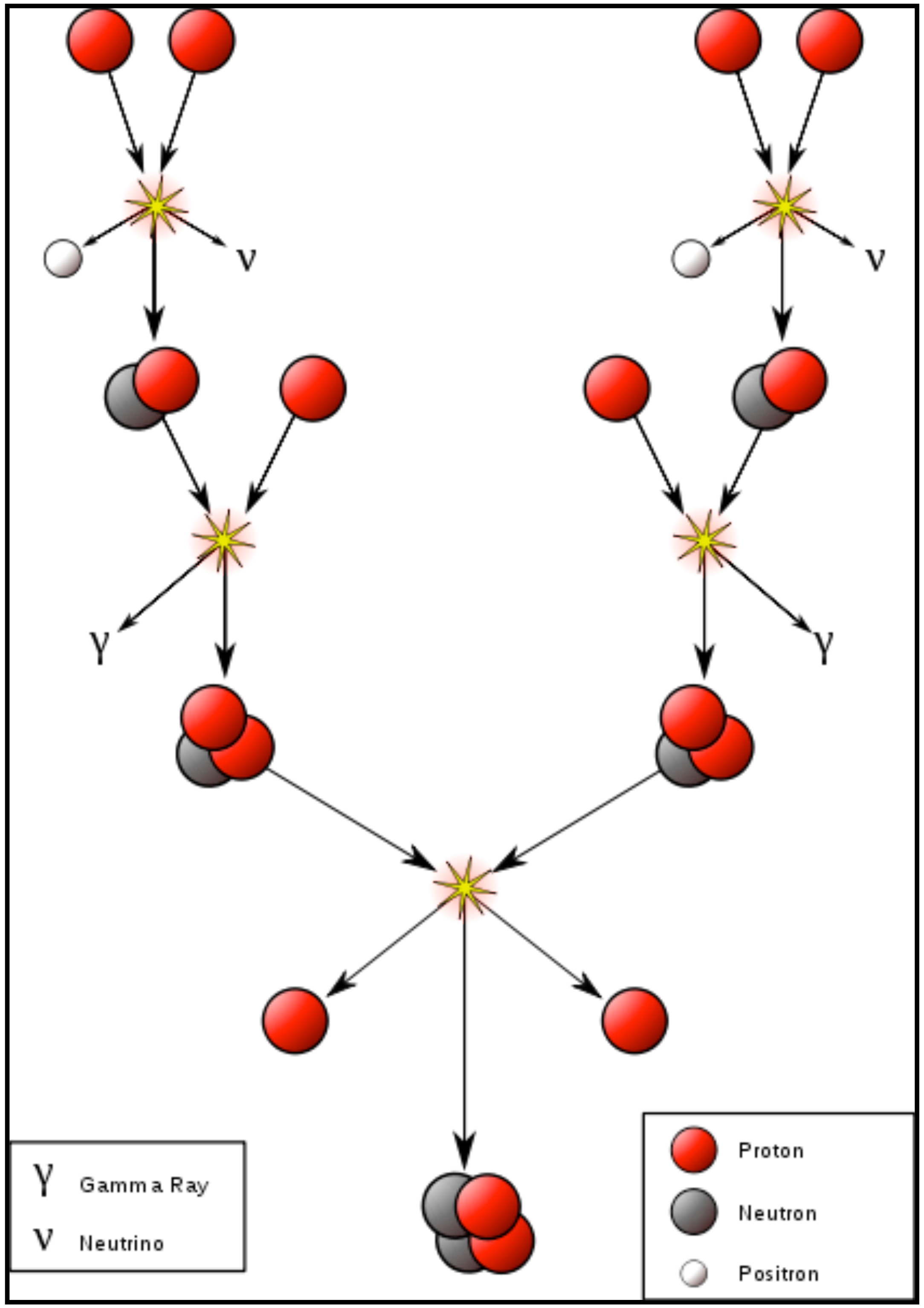
How does the Sun work?

The Sun is a god fueled by human sacrifice

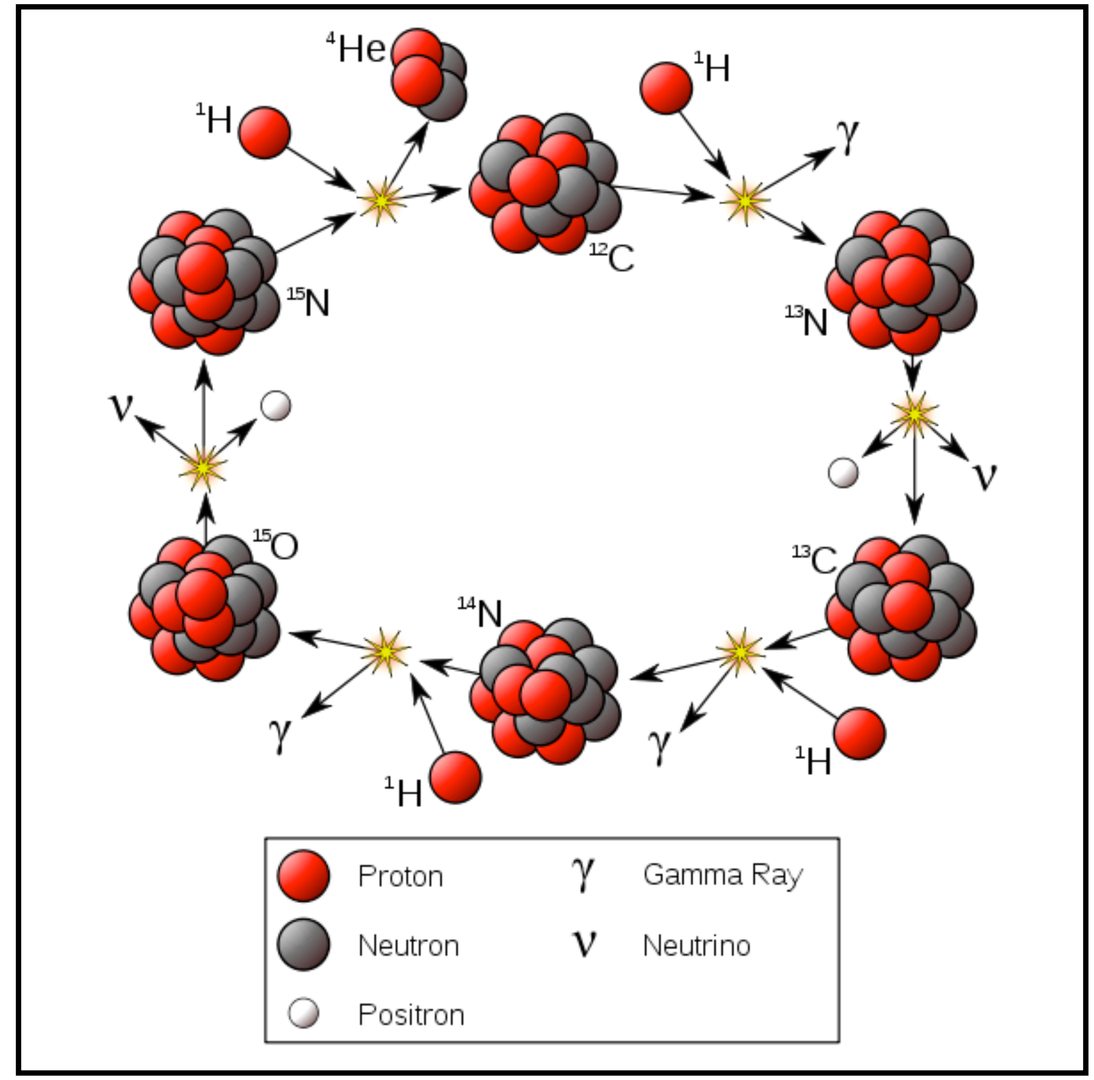
The harmless truth

- Since the 19th Century it was clear that the Sun could not be fueled by chemical reactions.
- **1904**: Rutherford suggests radioactive decay as a possible internal source of heat in the Sun.
- **1920**: Arthur Eddington proposes nuclear fusion of Hydrogen into Helium as the production mechanism of energy in the Sun.
- **1939**: Hans Bethe writes down the details of energy production in stars.

pp fusion chain



CNO cycle

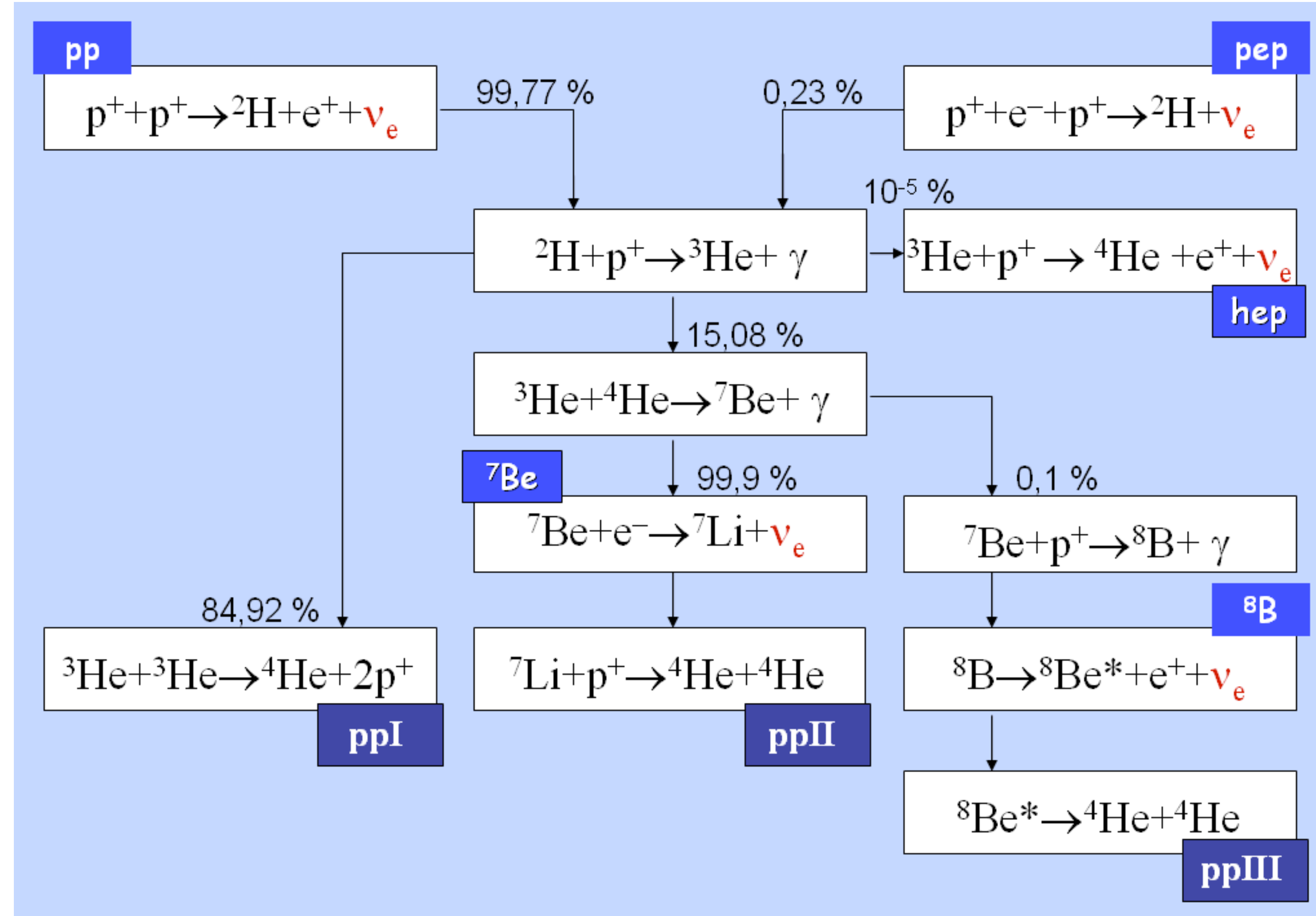


pp chain is main energy production mechanism for low-mass main sequence stars ($<1.5 M_\odot$).

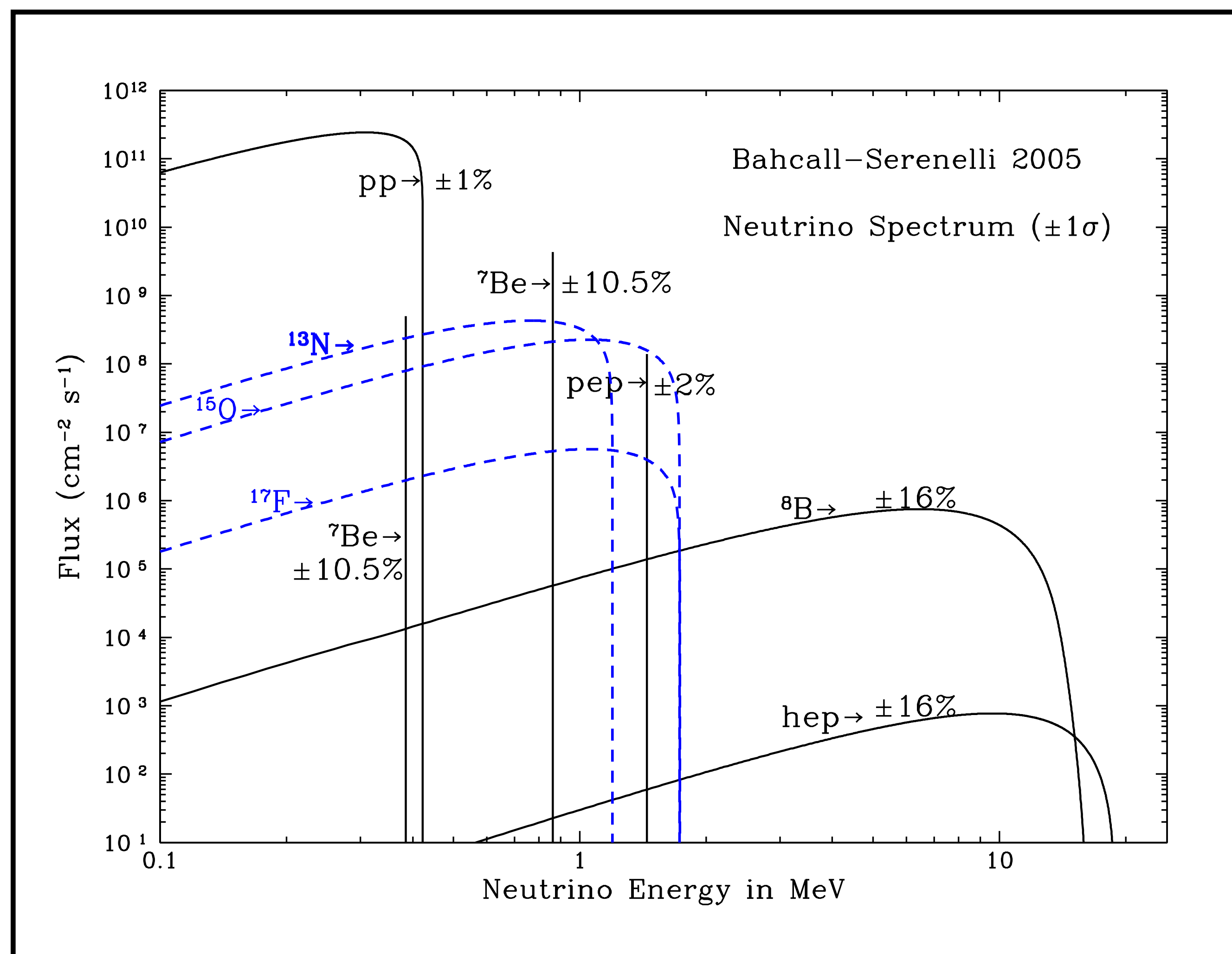
~99% of Sun's energy from pp chain.

pp Chain Details and Energy Spectra

Flux at Earth: $\sim 10^{11}\ cm^{-2}\ s^{-1}$



Very small interaction cross-sections: mean free path $\gg R_\odot$



Excellent probes for the interior of the Sun

Detecting Solar Neutrinos

- Low interaction rates ~0.1-1 events per ton of target.
- Low energy, mostly <10 MeV.
- Need detectors with low threshold and low background.
- Located at deep underground sites to shield from cosmic rays.

Radiochemical

Charged current interactions in target, producing isotopes with half-lives ~days that can be removed through chemical procedures

Gives an integrated count over an energy threshold

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

$$E_{th} = 814\ \mathrm{keV} \quad \tau_{1/2} = 35\ \mathrm{d}$$

Homestake

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

$$E_{th} = 232\ \mathrm{keV} \quad \tau_{1/2} = 11\ \mathrm{d}$$

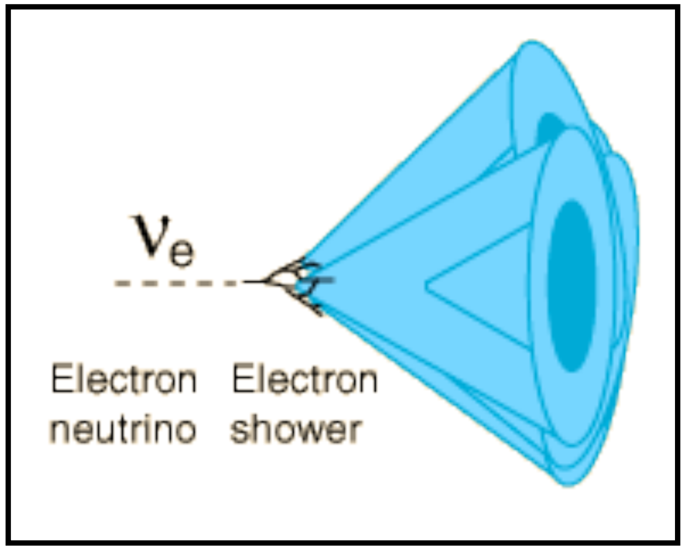
SAGE, GALLEX

Only sensitive to ν_e

Water Cherenkov

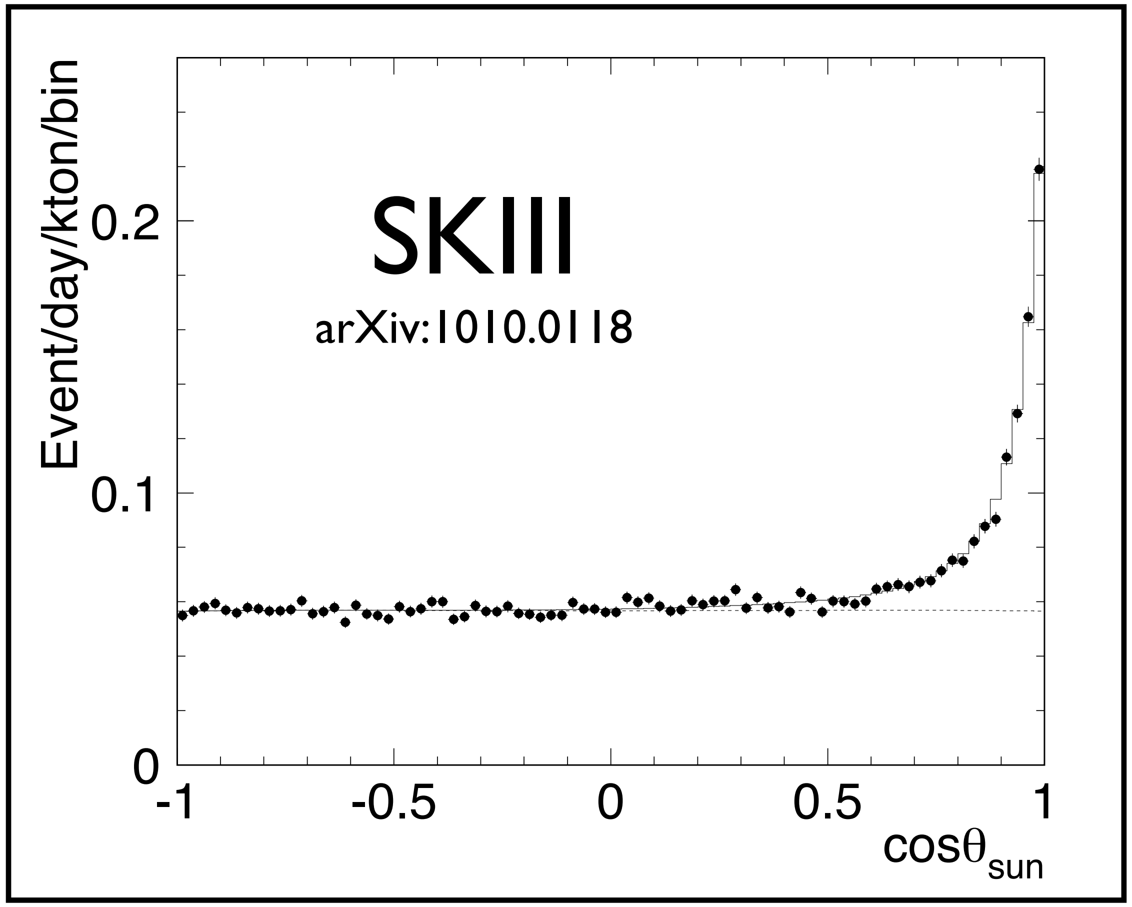
Detect charged particles from the emission of Cherenkov radiation

Energy of charged particle from number of Cherenkov photons produced.



Relatively low photon yield, effective threshold ~5 MeV

Can reconstruct position and direction of particle from orientation of Cherenkov cone



Water Cherenkov

$\nu_x + e^- \longrightarrow \nu_x + e^-$

Elastic scattering
Dominated by ν_e

If heavy water (D_2O)

$\nu_e + D \longrightarrow 2H + e^-$ Only sensitive to ν_e

$\nu_x + D \longrightarrow H + n + \nu_x$ Sensitive to all flavors

<u>Super-K</u>
50 kton H_2O

<u>SNO</u>
1 kton D_2O

Organic Liquid Scintillator

High light yield ~10^4 photons per MeV

Main limitation are radioactive backgrounds < 3 MeV

Well established purification techniques

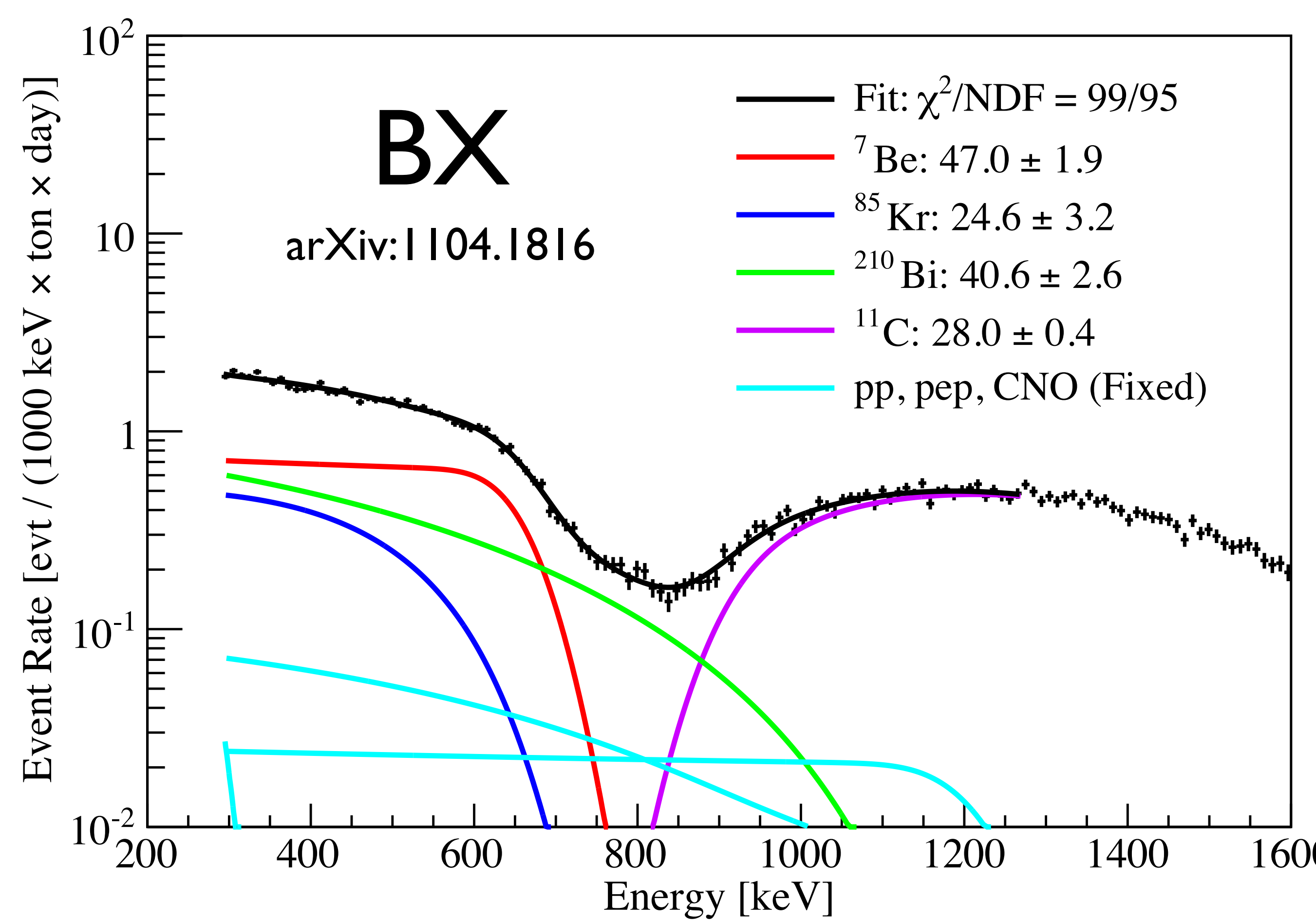
Light is isotropic, no directionality, spectroscopy

Position reconstruction

Pulse shape discrimination

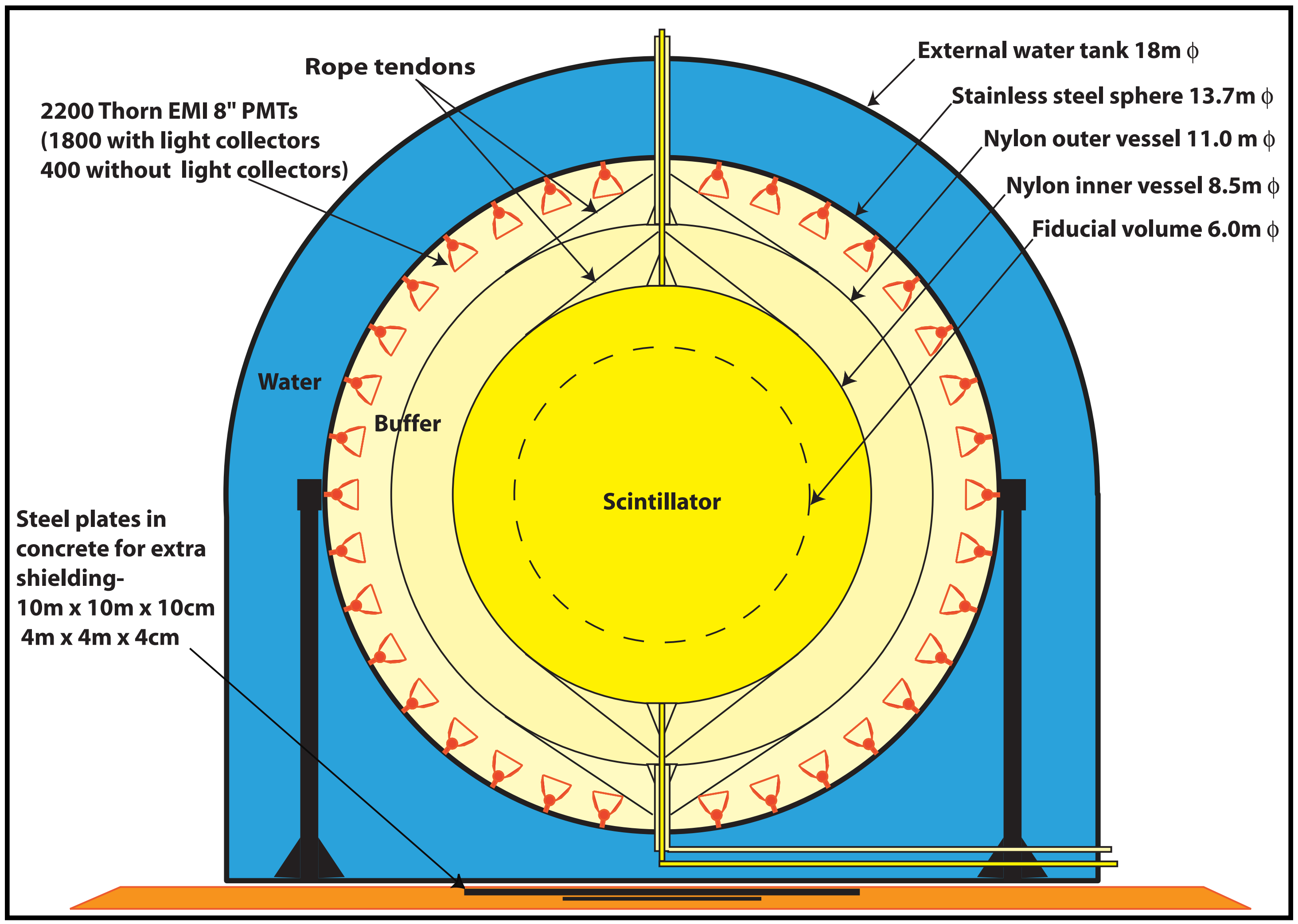
Only ES interaction:

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$



Organic Liquid Scintillator

Borexino



Exterior instrumented water tank
(Cherenkov detector)

898 tons of quenched scintillator as buffer

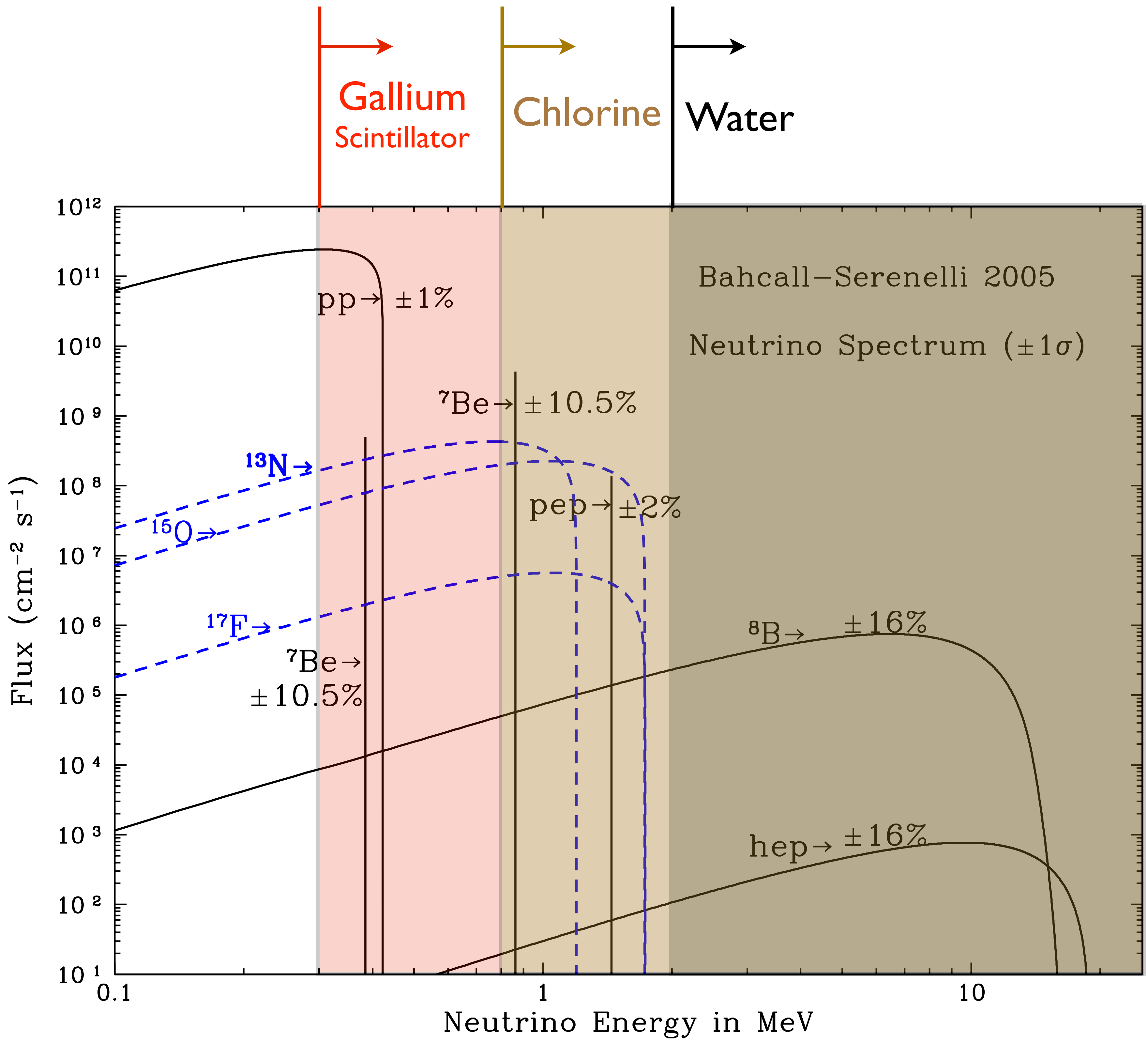
278 tons of active scintillator

Fiducial Mass ~ 75 tons

Count rate in FV above ^{14}C end point is 10^{-8} Bq kg^{-1}
10^{9} less radioactivity than natural water!

KamLAND and SNO+ are similar in design (~1 kton)

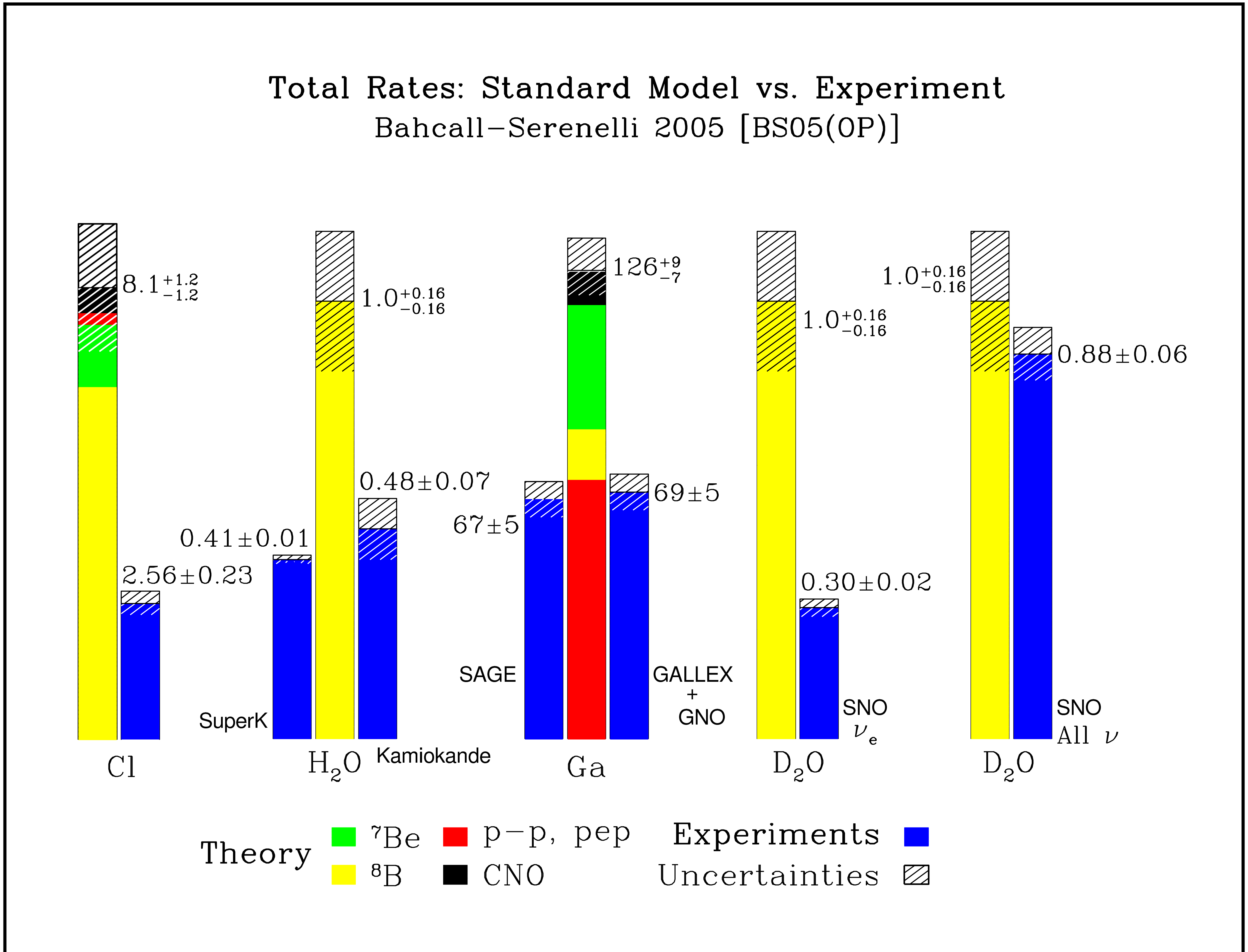
Detector Coverage



The Past

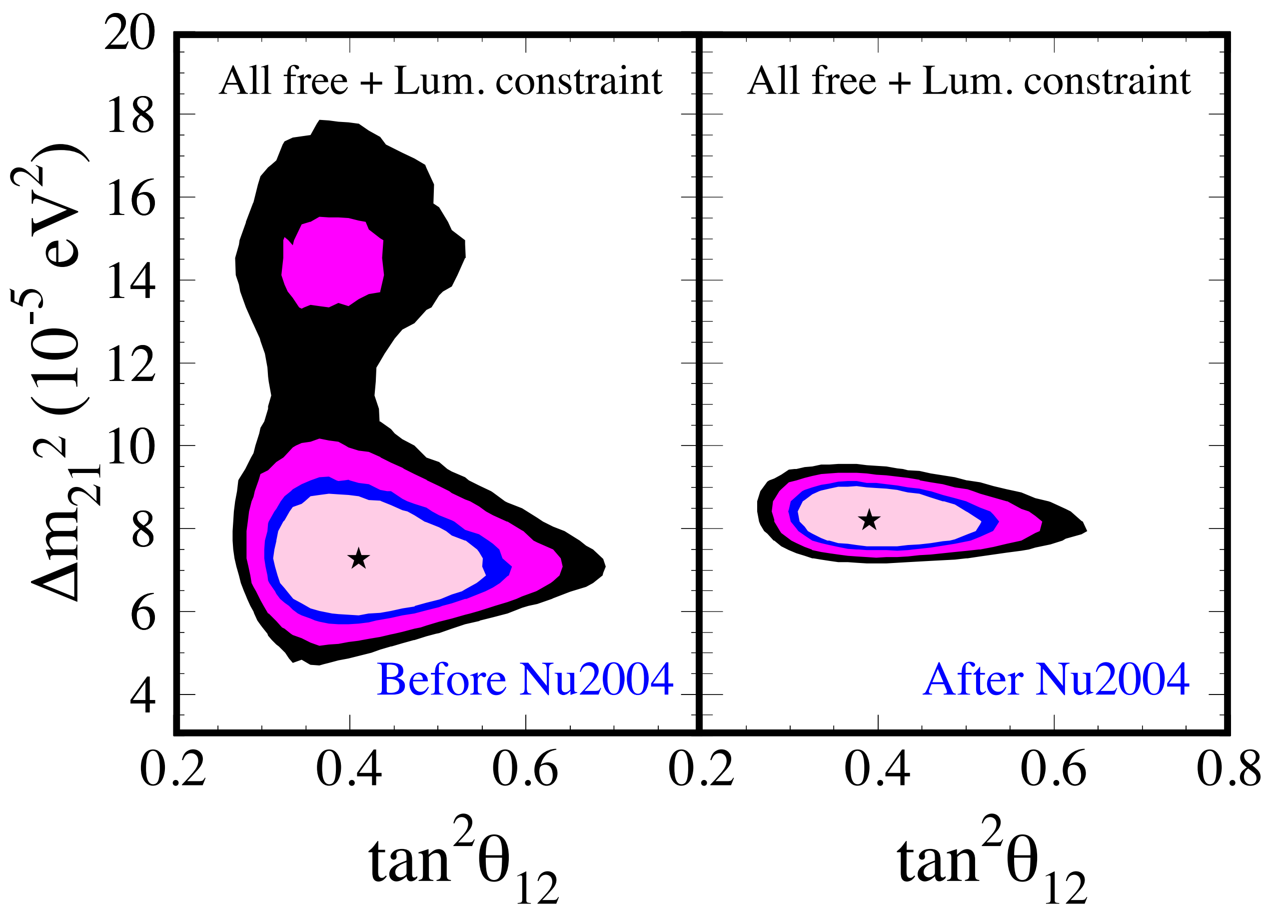
- Radiochemical experiments discovered Solar Neutrinos (1960s). The Sun is powered by nuclear fusion!
- Kamiokande measured solar ν_e ^8B neutrinos (1980s).
- **But** detected ν_e flux ~1/3 of expected: "The Solar Neutrino Problem"
- SNO measured (2000) the total ν_e and ν_x flux from ^8B neutrinos demonstrating neutrino oscillations.

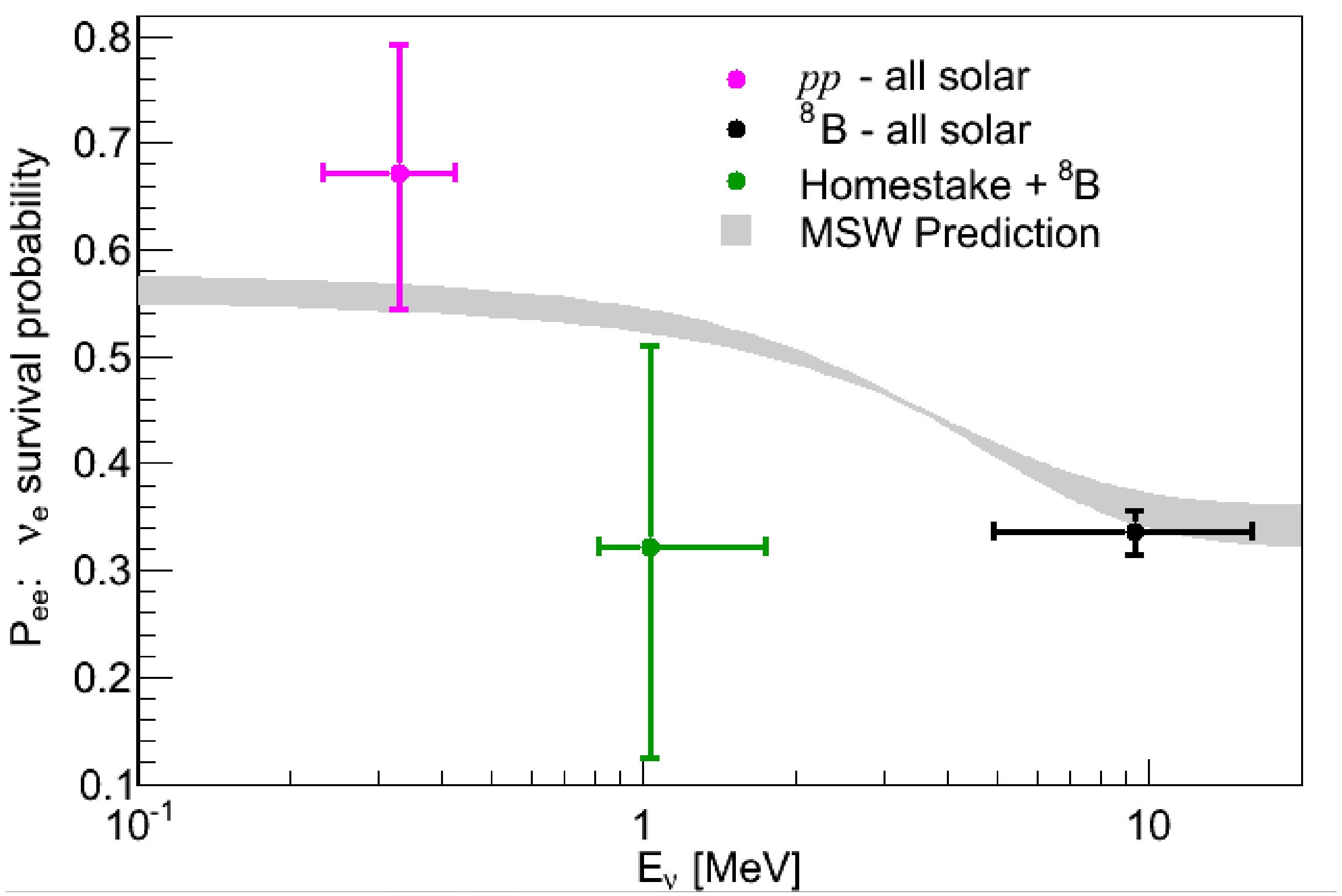
The Past



Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]
$8.1^{+1.2}_{-1.2}$
2.56±0.23
Cl
$1.0^{+0.16}_{-0.16}$
0.48±0.07
0.41±0.01
SuperK
H_2O
Kamiokande
126^{+9}_{-7}
67±5
69±5
SAGE
GALLEX
+
GNO
Ga
$1.0^{+0.16}_{-0.16}$
0.30±0.02
SNO
ν_e
D_2O
$1.0^{+0.16}_{-0.16}$
0.88±0.06
SNO
All ν
D_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

The Past





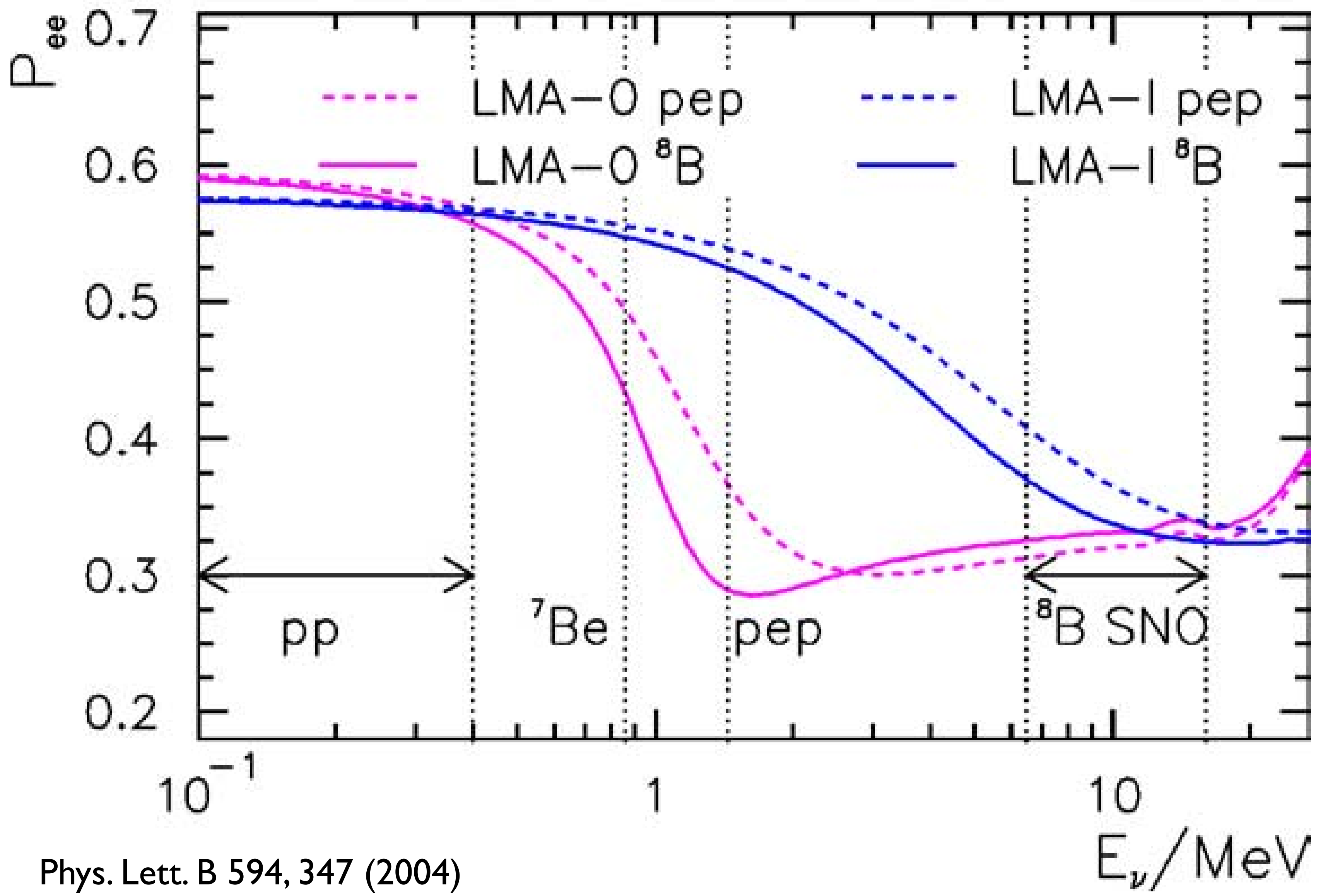
MSW-LMA solution

Oscillations parameters Δm^2 and $\tan^2\theta$ constrained from solar + KamLAND reactor data

The Present 2009-2011

- Is MSW-LMA correct? How well can we test the model?
- Physics beyond the Standard Model can affect the features of the P_{ee} dependence on neutrino energy.
- Probe the P_{ee} transition region.
- How well are solar neutrino fluxes predicted by the SSM? Two competing models High and Low Metallicity.

Other possible scenarios



Phys. Lett. B 594, 347 (2004)

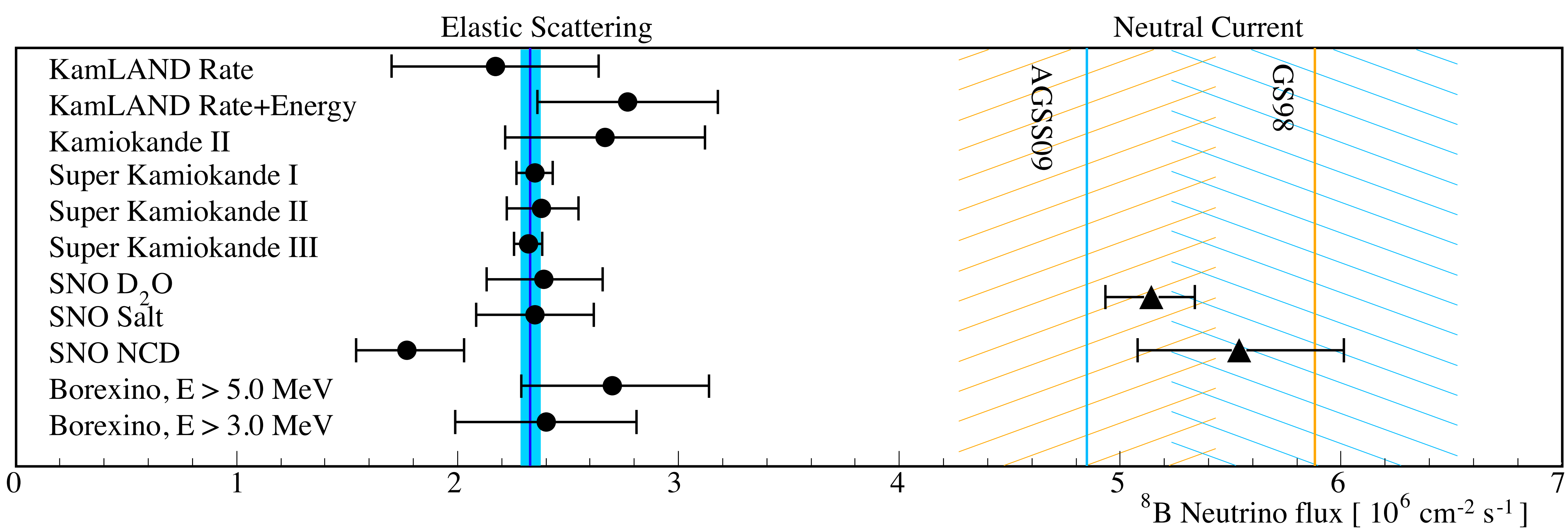
Non-standard interactions can give P_{ee} curves dramatically different from standard scenario.

^8B neutrinos

Lowering energy threshold to see increase in P_{ee} at lower energies.

2010: SNO (3.5 MeV, Phase I and II), Borexino (3 MeV)
2011: KamLAND (5.5 MeV), SNO (Phase III), SKIII (5 MeV)

All current observations consistent with expectations:

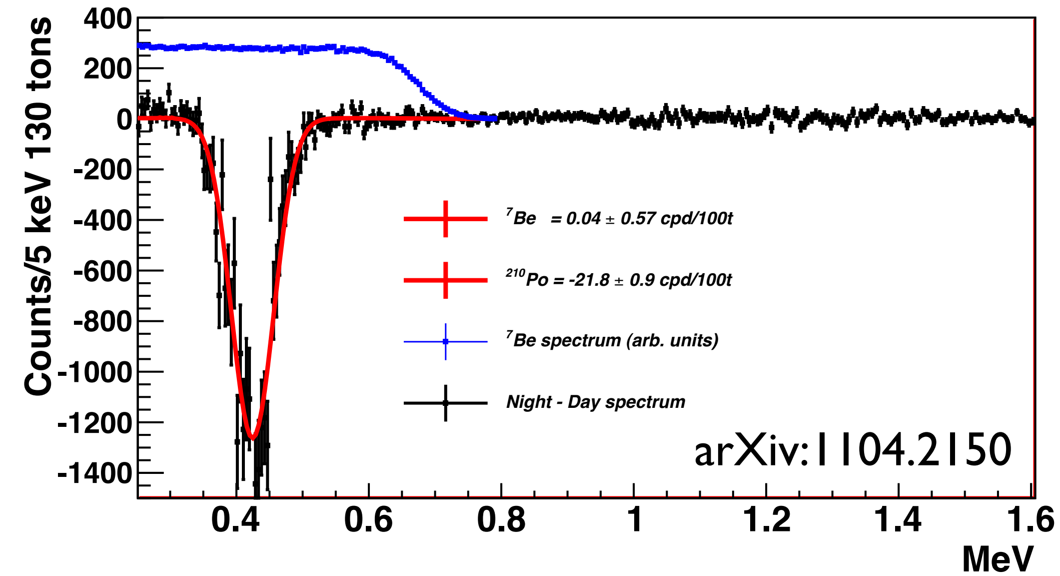


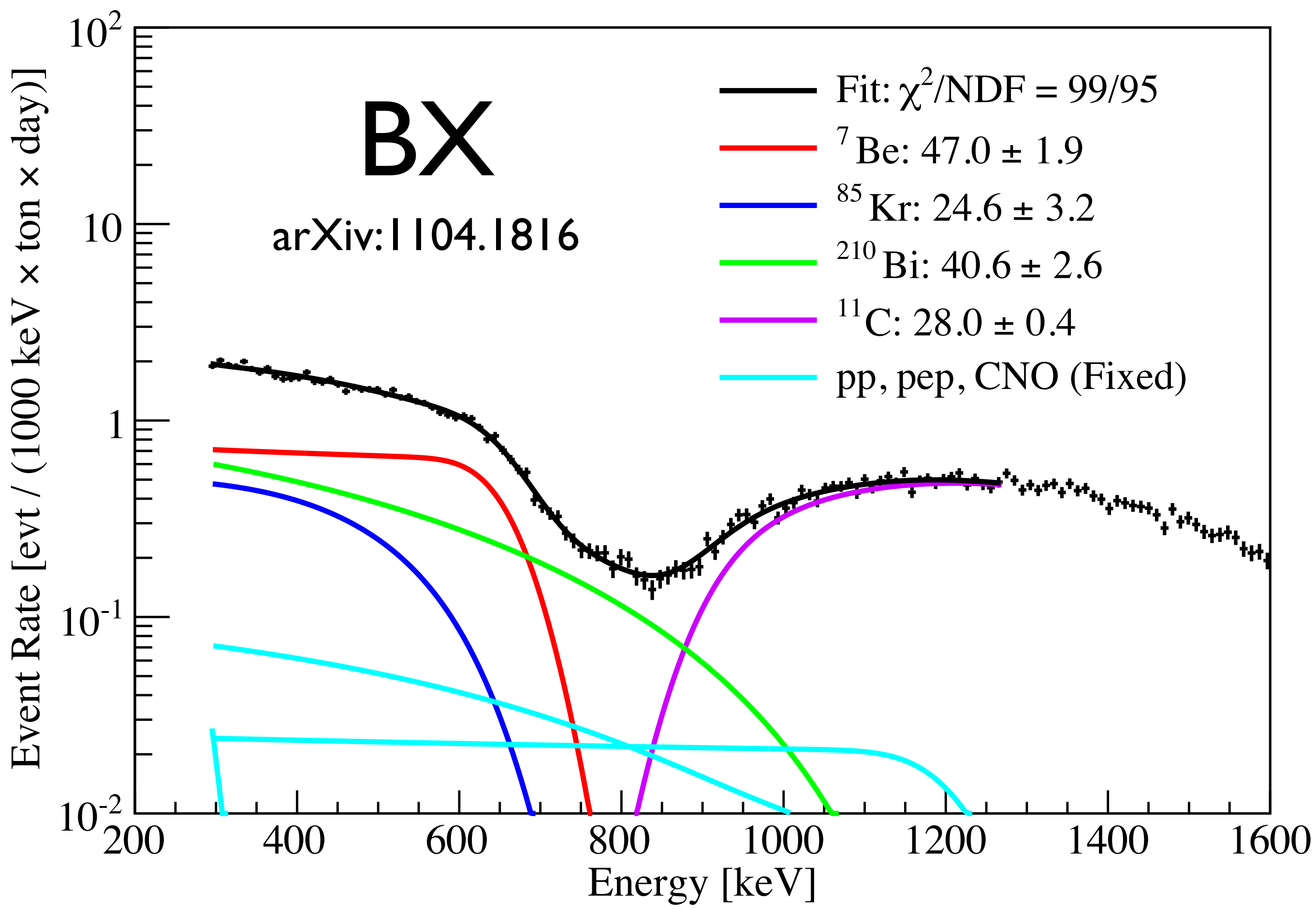
arXiv:1106.0861v3

^{7}Be neutrinos

- Large flux: 100 times larger than ^{8}B.
- Flux predicted with 7% uncertainty.
- Mono-energetic E = 862 keV.

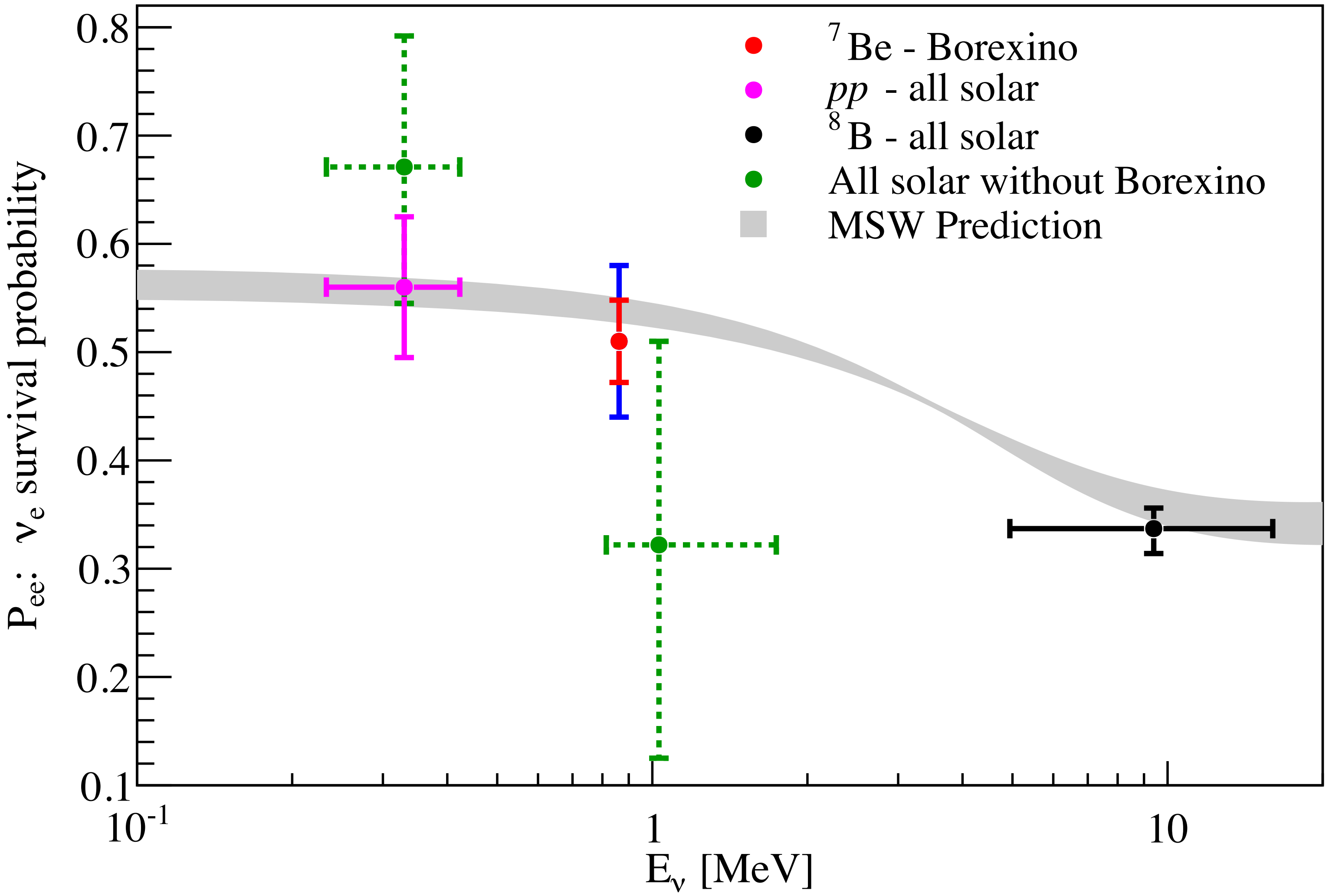
<u>Day/Night Asymmetry</u>





$$2\frac{\Phi_n-\Phi_d}{\Phi_n+\Phi_d} = 0.001 \pm 0.014$$

^{7}Be ν_e flux:
$(3.10 \pm 0.15) \times 10^9\ \mathrm{cm}^2\mathrm{s}^{-1}$



+ Global solar analysis
Total fluxes

pp flux:
$(6.06^{+0.02}_{-0.06})\times10^{10}$ cm^{-2}s^{-1}

CNO flux:
$<1.3\times10^{9}$ cm^{-2}s^{-1}

Result consistent with MSW-LMA. 5σ from no oscillation

Measured rate uncertainty smaller than flux uncertainty

Absence of Day/Night asymmetry supports MSW-LMA and strongest constraint on matter effects on ~1 MeV neutrinos

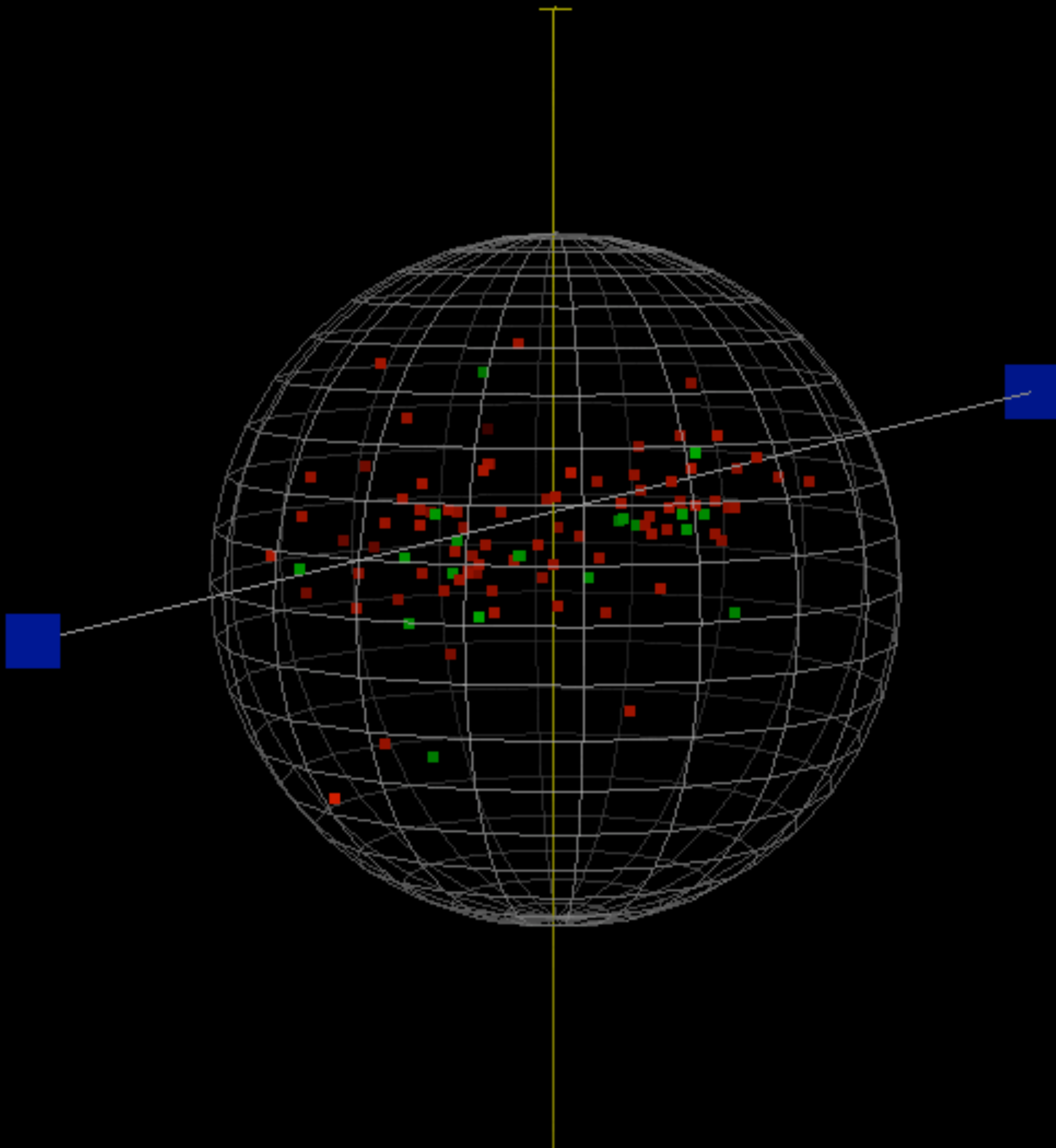
<1% uncertainty in pp flux

CNO flux limit 2.5 times High Z prediction

pep and CNO neutrinos

- Tests of MSW-LMA with ^{7}Be limited due to uncertainty in solar flux.
- pep flux predicted with higher precision, 1.2% uncertainty. Allows for more stringent tests of oscillation models. Also mono-energetic.
- CNO fluxes directly related to Solar Metallicity. Allows to discern between High Z and Low Z models.
- Fluxes 10 times smaller than ^{7}Be. End points 1-2 MeV. ^{11}C is the dominant background in Borexino.

Cosmogenic ^{11}C



$$\boxed{\mu + {}^{12}C \longrightarrow n + {}^{11}C}$$

Track of the parent μ.

Neutrons within
1.6 ms after μ.

^{11}C candidates within
2 h after μ.

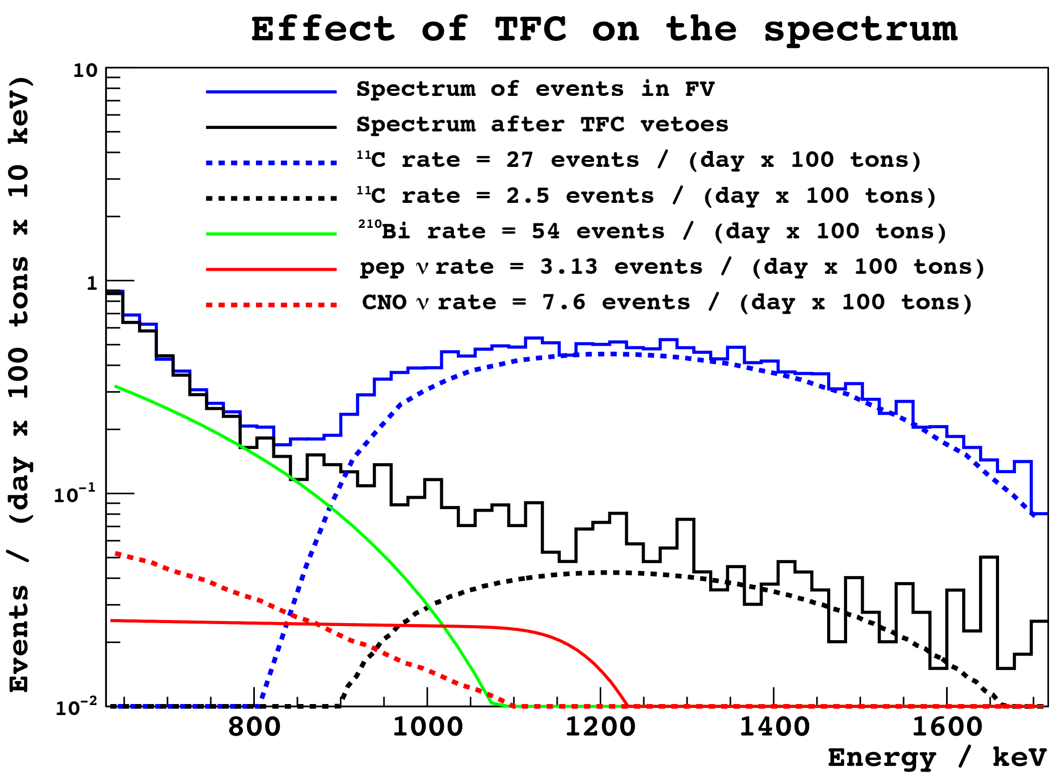
Reconstructed μ entry/exit points

Reconstructed position of neutron

Reconstructed position of ^{11}C

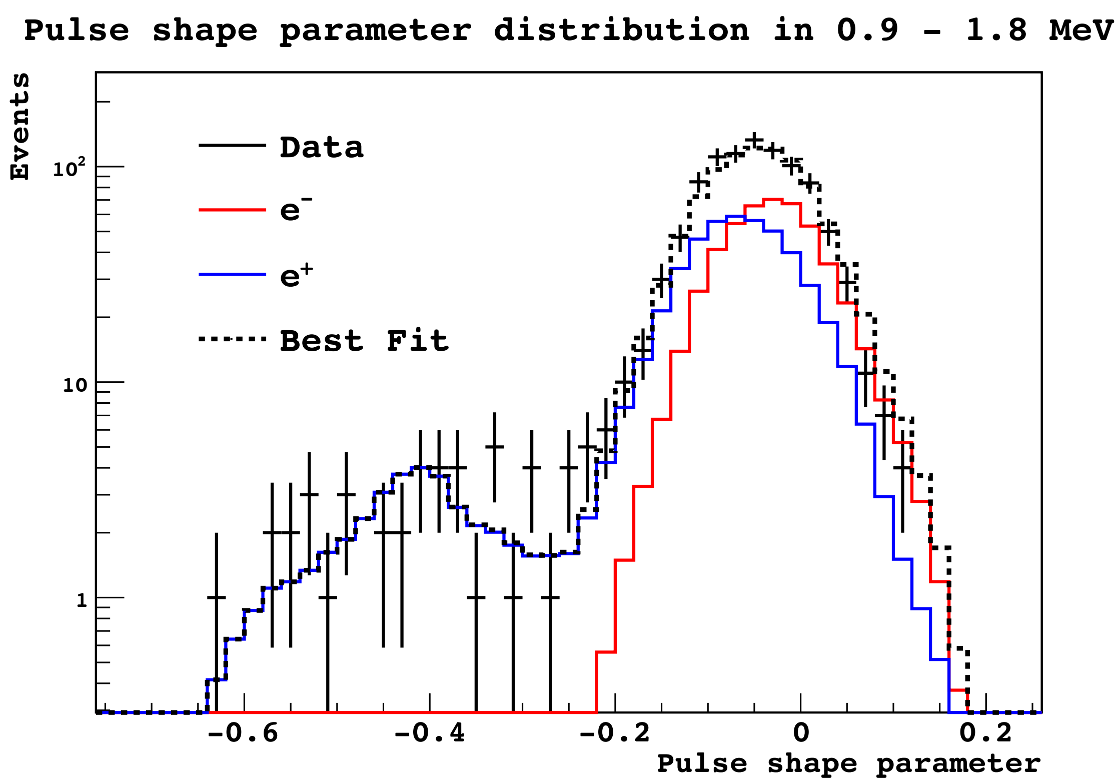
Can use space + time correlation with μ + n to veto regions of the detector with higher ^{11}C background: Three-fold coincidence (TFC) technique

^{11}C suppression in Borexino



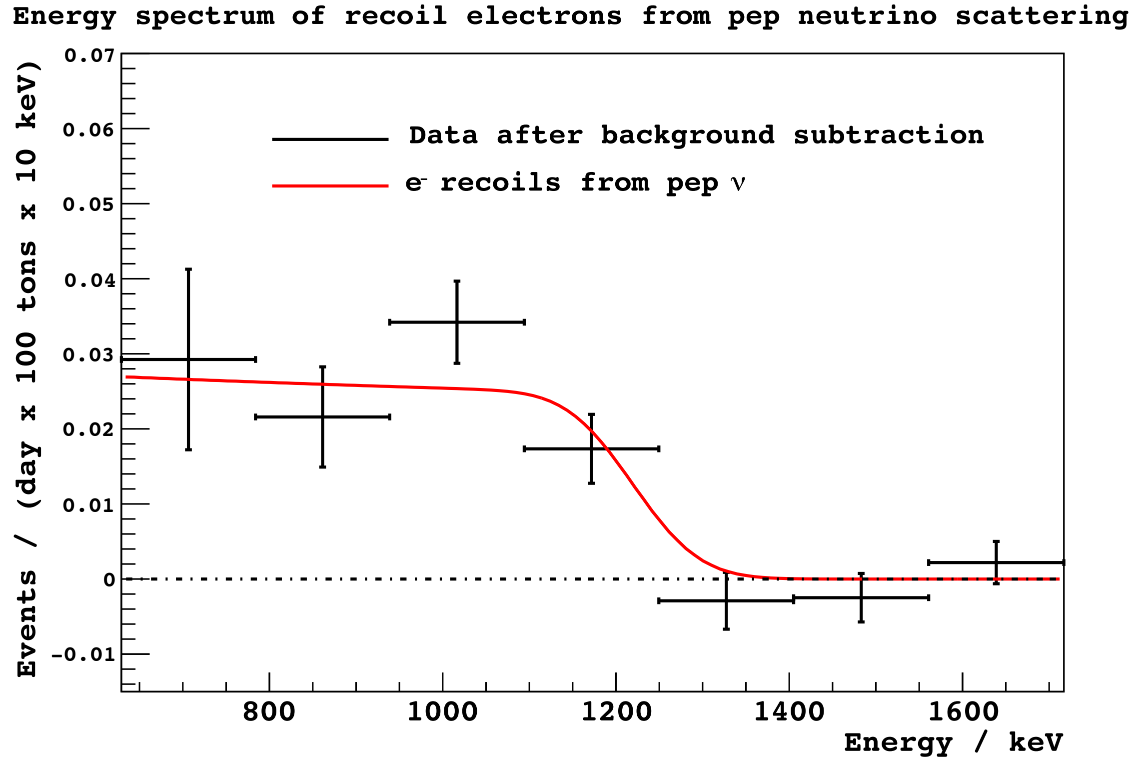
TFC decreases ^{11}C rate to ~10% of its original value with ~50% loss of exposure.

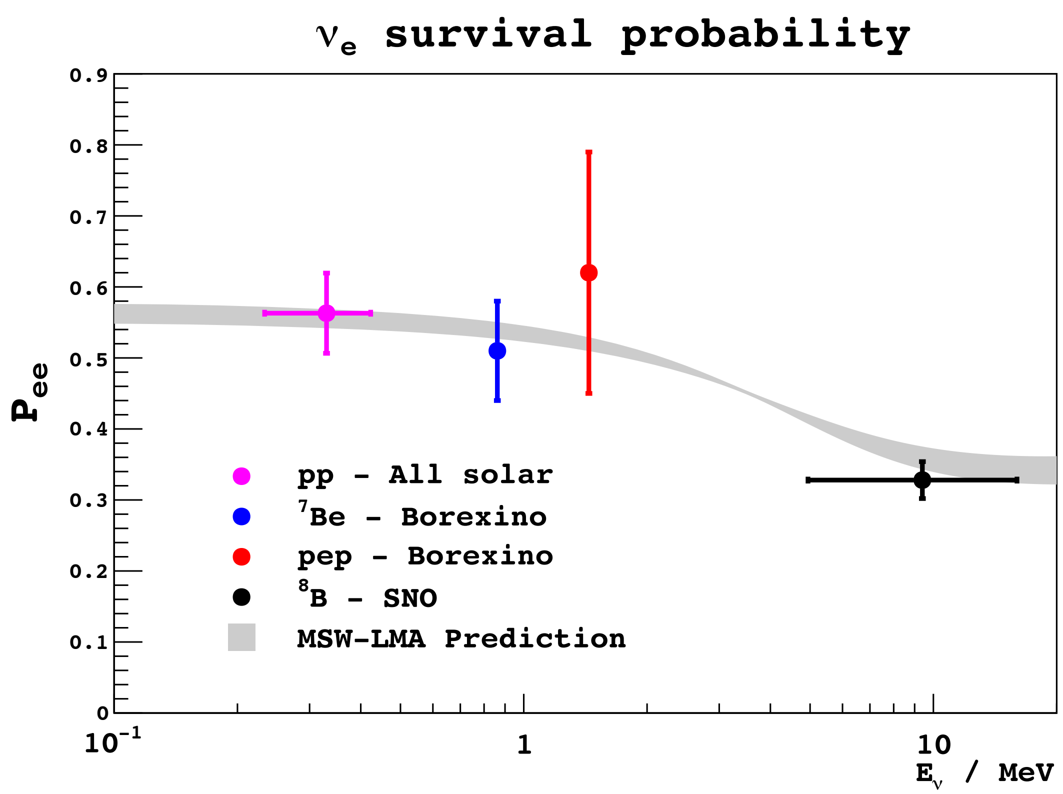
Limiting background is now internal ^{210}Bi.



<u>β-/β+ Pulse Shape discrimination</u>

Formation of positronium and multiple energy deposits from annihilation γ's lead to different reconstructed emission time profiles.





Statistical significance of pep measurement 97% C.L.

Total fluxes from direct measurement

pep flux: $(1.6 \pm 0.3) \times 10^8$ cm^{-2}s^{-1}

CNO flux: $<7.4 \times 10^8$ cm^{-2}s^{-1}

No oscillation hypothesis disfavored at 96% C.L.

CNO flux limit 1.4 times High Z prediction

Results consistent with MSW-LMA and SSM

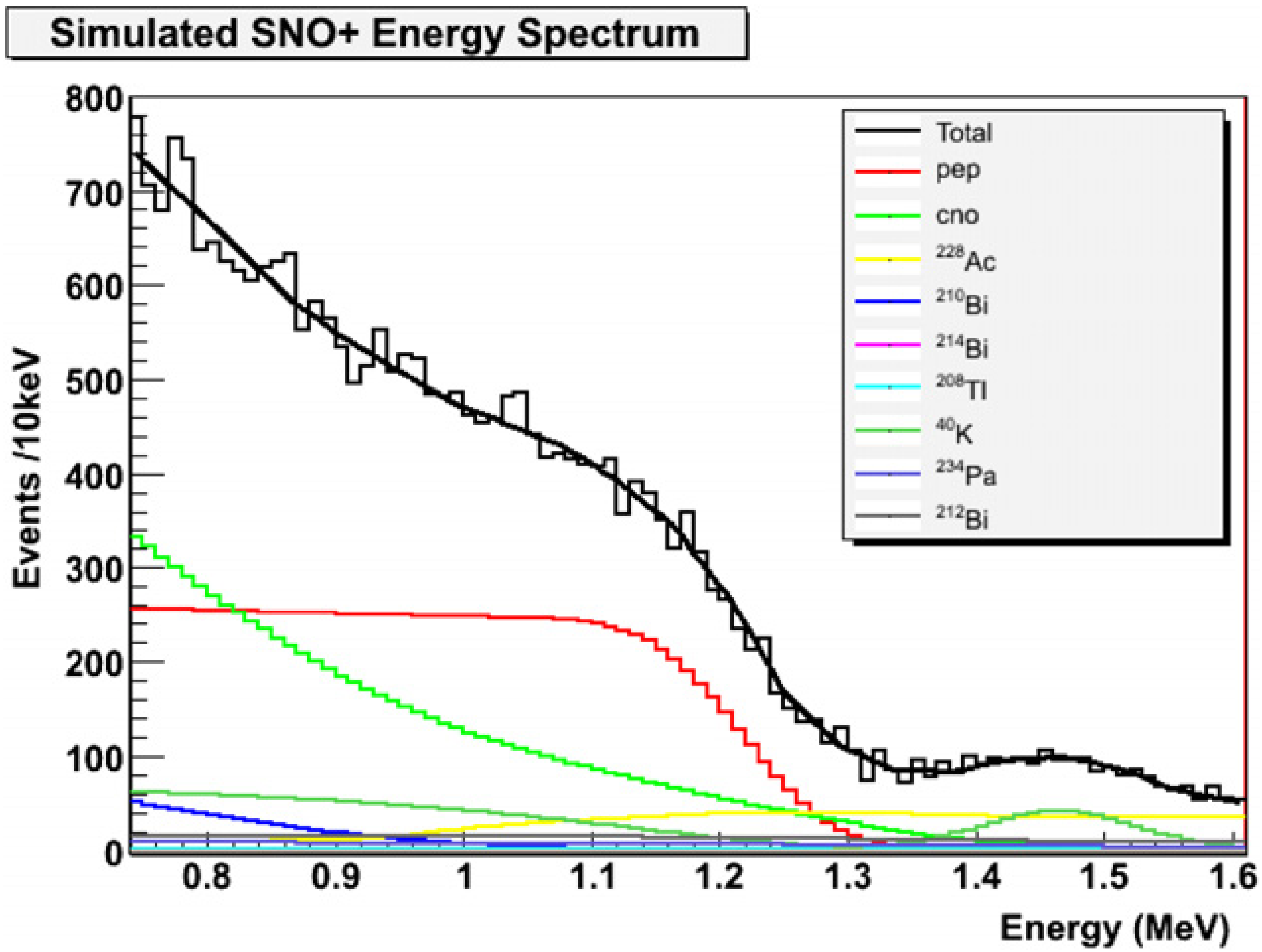
The Future

- Borexino's first evidence for pep strengthens the prospects for organic liquid scintillator detectors.
- For a precise measurement of pep and a measurement of CNO flux, lower backgrounds are necessary.
- In deeper sites ^{11}C production will be suppressed due to lower cosmic ray flux.
- ^{210}(Pb)Bi background can only be reduced through purification.

Borexino Phase II

- Since July, 2010 we have undertaken a series of purification campaigns to decrease radioactive backgrounds.
- Nitrogen stripping has been successful at removing ^{85}Kr. No evidence since January.
- Moderate success at removing ^{210}Pb(Bi) by Water Extraction.
- Operations on-going and hope to decrease ^{210}Bi significantly and possibly ^{210}Po.
- Decrease of ^{210}Po may be necessary to obtain an independent estimate of ^{210}Bi contamination and a more precise measurement of CNO ν rate [arXiv:1104.1335v1].

SNO+



>3 times larger than Borexino

At SNOLAB, ~2x deeper than Gran Sasso, no ^{11}C

Can the ^{210}Bi background be lower than Borexino?

If successful will make the first precision measurement of the pep neutrino flux (~5%)

Will also measure CNO neutrinos

pp neutrinos

- Predicted by SSM with smallest uncertainty <1%
- High rate >1 event per day per ton, lowest energy.
- Highest precision test to the standard SSM + LMA-MSW.
- Very hard to detect in organic liquid scintillator detectors due to irreducible ^{14}C background.
- LENS: Indium-loaded LS has a delayed tag.
- XMASS, CLEAN: noble liquids, high light yield, no intrinsic natural radioactivity.

Conclusion

- 40 years of Science with Solar Neutrinos.
- ^{8}B neutrino results published by 4 collaborations in last two years.
- Latest ^{7}Be measurement by Borexino in agreement with MSW-LMA. High-precision test.
- First evidence of pep neutrinos by Borexino opens the door for future tests.
- Borexino Phase II could measure the CNO flux and solve The Solar Metallicity Problem.
- SNO+ could measure the pep flux precisely, stringent test on MSW-LMA.