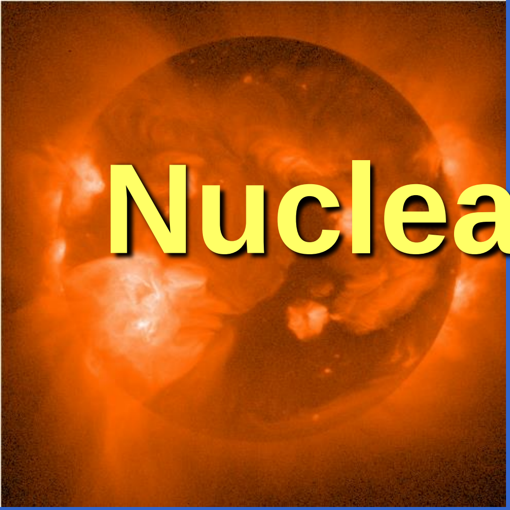
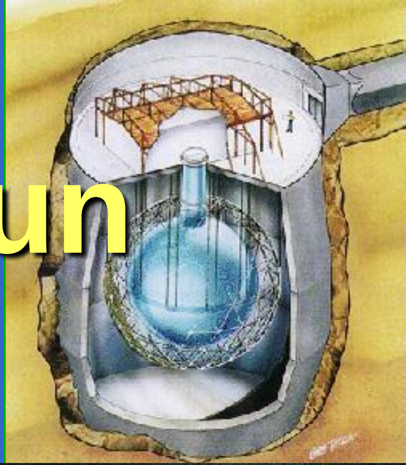
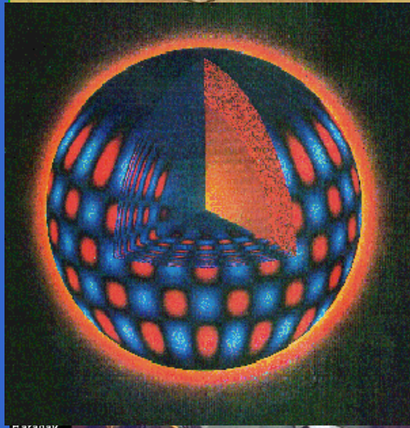
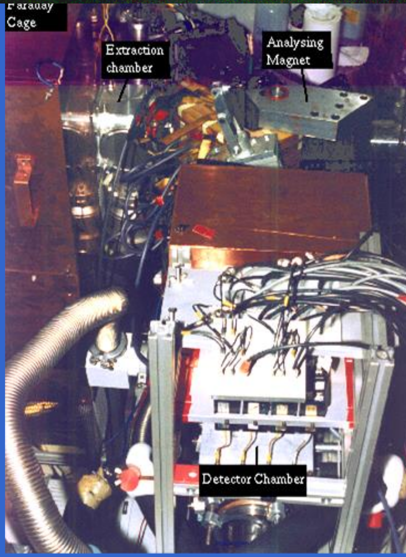


Nuclear fusion in the Sun







- The spies of solar interior:
  - neutrinos
  - helioseismology
- What can be learnt about the Sun?
- What can be learnt about nuclear reactions:
  - Energy source of the sun
  - Nuclear cross sections
  - Screening

The luminosity constraint

- The total neutrino flux can be immediately derived from the solar constant K if Sun is powered by transforming H into He.
- In the reaction:

$$4p + 2e^- \rightarrow {}^4He + Q + \; ?$$

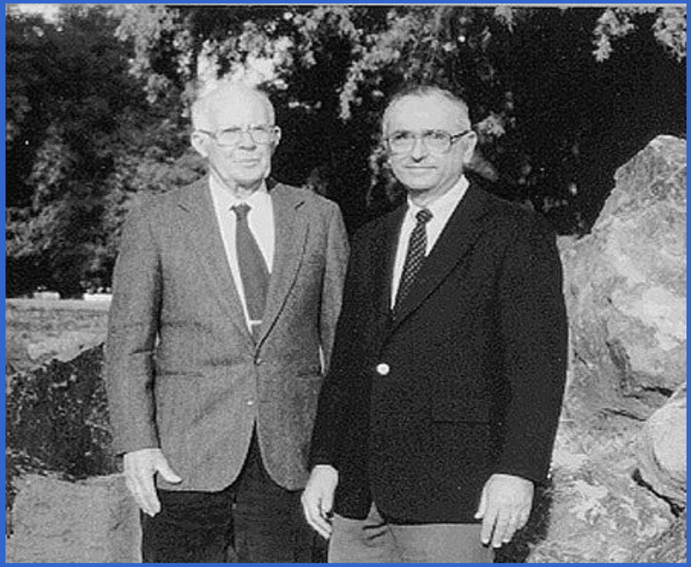
$$? = 2\nu \quad \text{if } L \text{ is conserved}$$

- Two neutrinos are produced for each Q = 26.7 MeV of radiated energy. The total produced flux is thus:

$$\Phi_{TOT} = \frac{K}{Q/2} = 6.4 \cdot 10^{10} \nu / cm^2 / s$$

- Neutrinos are the spy of nuclear fusion in the Sun

A 40 year long journey



•In 1963 J Bahcall and R Davis, based on ideas from Bruno Pontecorvo, started an exploration of the Sun by means of solar neutrinos.

•A trip with long detour: the “solar neutrino puzzle”:

•All experiments, performed at Homestake, Kamioka, Gran Sasso and Baksan, exploring different parts of the solar spectrum (B,pp+Be..) and sensitive to ν_e reported a neutrino deficit (disappearance) with respect to Standard Solar Model

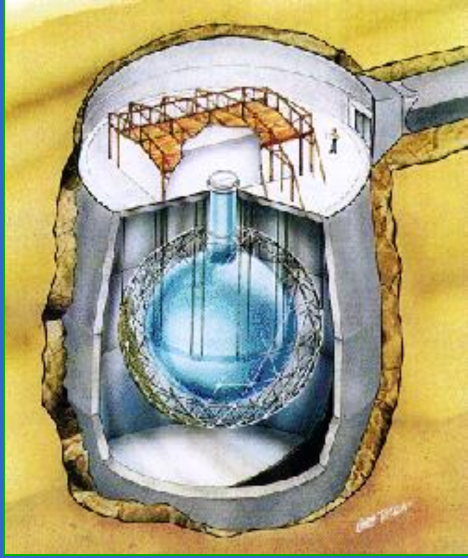
•Was the SSM wrong?

• Was nuclear physics wrong?

• Were all experiments wrong?

• Or did something happen to neutrinos during their trip from Sun to Earth?

SNO: the appearance experiment



•A 1000 tons **heavy** water detector sensitive to Boron-neutrinos by means of:

- **CC:** ν_e+d -> p + p + e sensitive to ν_e only.
- **NC:** ν_x+d -> p + n + ν_x with equal cross section for all ν flavors, it measures the total ^{8}B flux from Sun.

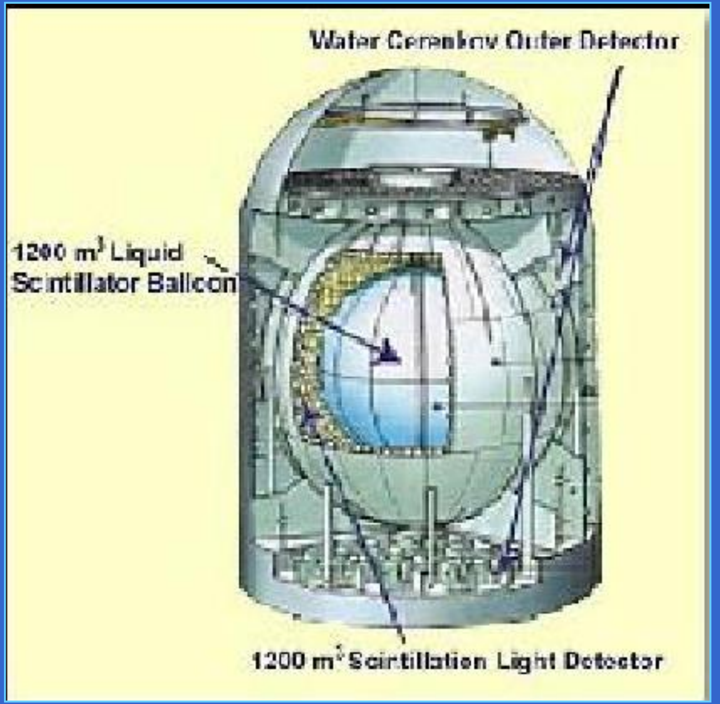
• SNO has determined both $\Phi_B(\nu_e)$ and $\Phi_B(\nu_e + \nu_\mu + \nu_\tau)$:

- The measured total B-neutrino flux agrees with the SSM prediction. → • SSM & N.P. are right

- Only 1/3 of the B-neutrinos survive as ν_e → • All experiments can be right

- 2/3 of the produced ν_e transform into ν_μ or ν_τ → • Neutrinos are wrong (L_e is not conserved)

From Sun to Earth: The KamLAND confirmation



•anti-ν_e from distant (≈100 km) nuclear reactors are detected in 1Kton liquid scintillator where:

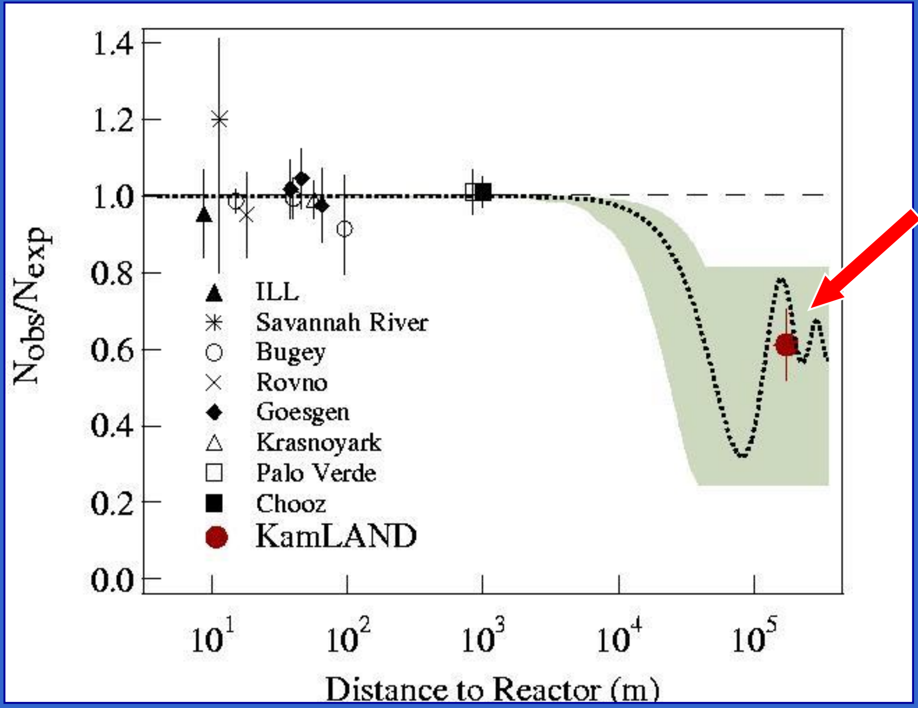
Anti–ν_e +p -> n + e^+

n + p -> d + γ

•Obs./Expected= 54/ (86+-5.5)

-> Oscillation of reactor anti-ν_e proven

- > SNO is confirmed with man made (anti)neutrinos



The measured Boron flux

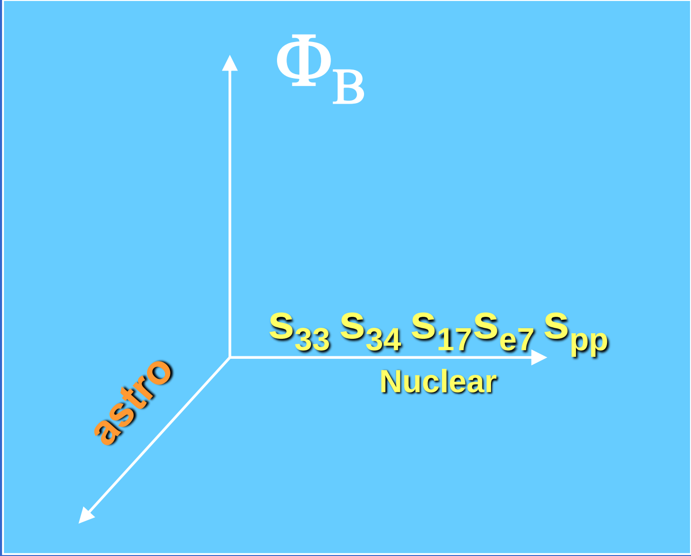
SSM	BP2000	FRANEC	GARSOM
Φ_B [$10^6 s^{-1} cm^{-2}$]	5.05	5.2	5.3

- The total active Boron flux $\Phi_B = \Phi(\nu_e + \nu_\mu + \nu_\tau)$ is now a measured quantity. By combining all observational data one has:

$$\Phi_B = (5.5 \pm 0.4)\ 10^6\ cm^{-2} s^{-1}.$$

- The result is in good agreement with the SSM calculations
- Note the **present** 1σ error is $\Delta\Phi_B/\Phi_B = 7\%$
- In the next few years one can expect : $\Delta\Phi_B/\Phi_B \approx 3\%$

The Boron Flux, Nuclear Physics and Astrophysics



- Φ_B depends on nuclear physics and astrophysics inputs.
- Scaling laws have been found numerically* and are physically understood:

$$\Phi_B = \Phi_B^{(SSM)} \cdot S_{33}^{-0.43} S_{34}^{0.84} S_{17}^{1} S_{e7}^{-1} S_{pp}^{-2.7} \cdot com^{1.4}\, opa^{2.6}\, dif^{0.34}\, lum^{7.2}$$

- These give flux variation with respect to the SSM calculation when the input X is changed by $x = X/X^{(SSM)}$.
- One can learn astrophysics if nuclear physics is known well enough.

*Scaling laws derived from FRANEC models including diffusion.

Uncertainties budget

- Nuclear physics uncertainties, particularly on S_{34} , dominate over the present observational accuracy $\Delta\Phi_B/\Phi_B$ =7%.
- The foreseeable accuracy $\Delta\Phi_B/\Phi_B$ =3% could illuminate about solar physics if a significant improvement on S_{34} is obtained.

**LUNA gift*

Source	$\Delta X/X$	$\Delta\Phi_B/\Phi_B$
S33	0.06*	0.03
S34	0.09	0.08
S17	0.05 ?	0.05 ?
Se7	0.02	0.02
Spp	0.02	0.05
Com	0.06	0.08
Opa	0.02	0.05
Dif	0.10	0.03
Lum	0.004	0.03

- The new measurement of S_{34} planned by LUNA at the underground Gran Sasso Lab. is thus important

Progress on S_{17}

- JNB and myself have long been using a conservative uncertainty, however recently high accuracy determinations of S_{17} have appeared.
- Average from low-energy (<425KeV) data of 5 recent determinations yields:

$S_{17}(0)= 21.4 \pm 0.5$ with χ^2/dof=1.2

- A theoretical error of ± 0.5 has to be added.
- However all other expts. give somehow smaller S17 than Junghans et al.

Results of direct capture expts.**

	$S_{17}(0)$ [eV b]	Ref.
Adel.-Review.	**19_{-2}^{+4}**	RMP 70,1265 (1998)
Nacre-Review	**21 ± 2**	NP 656A, 3 (1999)
Hammache et al	**18.8 ± 1.7**	PRL 86, 3985 (2001)
Strieder et al	**18.4 ± 1.6**	NPA 696, 219 (2001)
Hass et al	**20.3 ± 1.2**	PLB 462, 237 (1999).
Junghans et al.	**22.1 ± 0.6**	PRL 88, 041101 (2002)+ nucl exp 0308003
Baby et al.	**21.2 ± 0.7**	PRL. 90,022501 (2003)

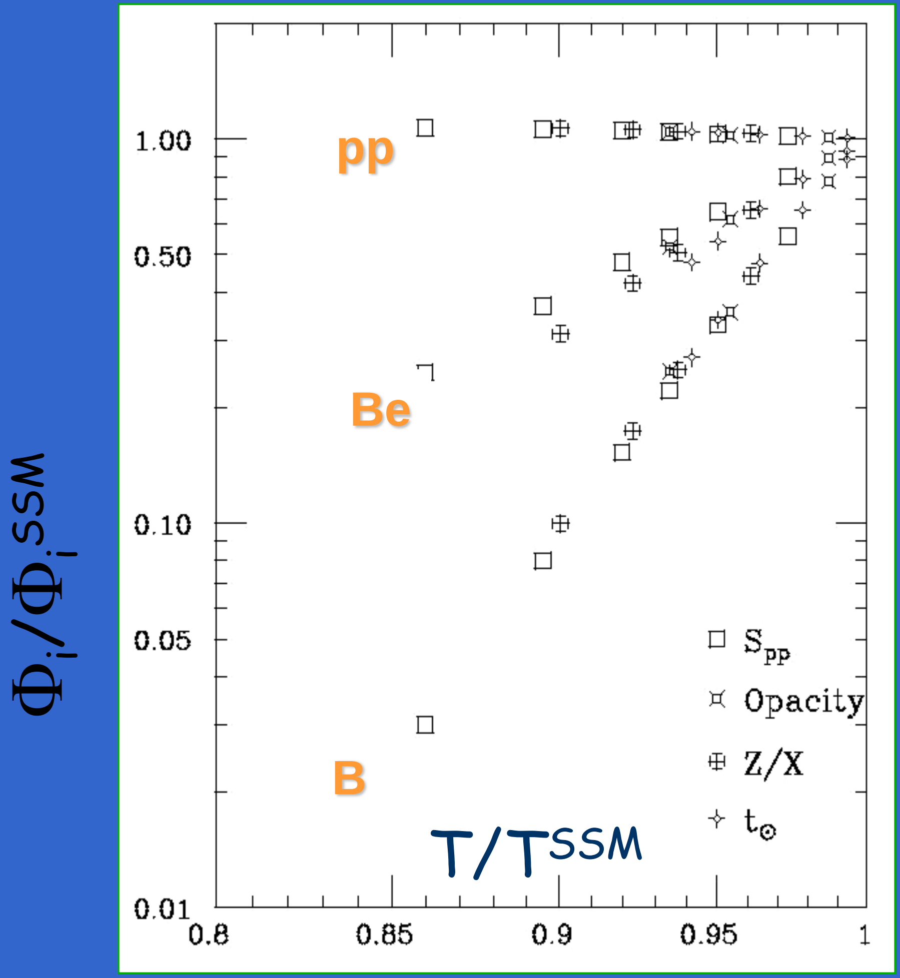
**See also Gialanella et al EPJ A7, 303 (2001)

- Note that indirect methods also give somehow smaller values

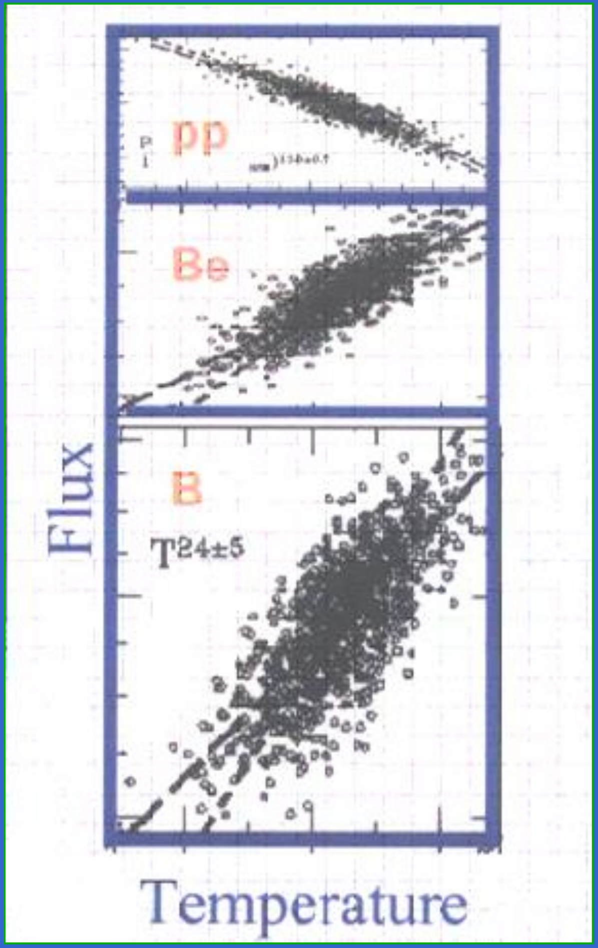
- **In conclusion, it looks that a 5% accuracy has been reached.**

Sensitivity to the central temperature

Castellani et al. '97



Bahcall and Ulmer. '96



- Boron neutrinos are mainly determined by the central temperature, almost independently on how we vary it.
- (The same holds for pp and Be neutrinos)

The central solar temperature

- Boron neutrinos are excellent solar thermometers due to their high (≈20) power dependence.

$$\Phi_B = \Phi_B^{(SSM)} \left[T / T_{(SSM)}\right]^{20} \cdot S_{33}^{-0.43}\, S_{34}^{0.84}\, S_{17}\, S_{e7}^{-1}$$

- From the measured Boron flux, by using nuclear cross sections measured in the lab. one deduces T with accuracy of 0.7%

$$T = (15.7 \pm 0.1)\ 10^6\ K$$

- Comparable uncertainties arise from measurement of flux and of S_{34} .

- New measurement of S_{34} is thus important

The Sun as a laboratory for astrophysics and fundamental physics

	BP-2000	FRANEC	GARSOM
T_6	15.696	15.69	15.7

- A measurement of the solar temperature near the center with accuracy of order 0.1% can be envisaged. It will be relevant for many purposes:
  - a new challenge to SSM calculations
  - a determination of the metal content in the solar interior, (important for the history of the solar system)
  - One can may constraints (surprises, or discoveries) on:
    - Axion emission from the Sun
    - The physics of extra dimensions

      (through Kaluza-Klein axion emission)
    - Dark matter

    (if trapped in the Sun it could change the solar temperature very near the center)
  - ...

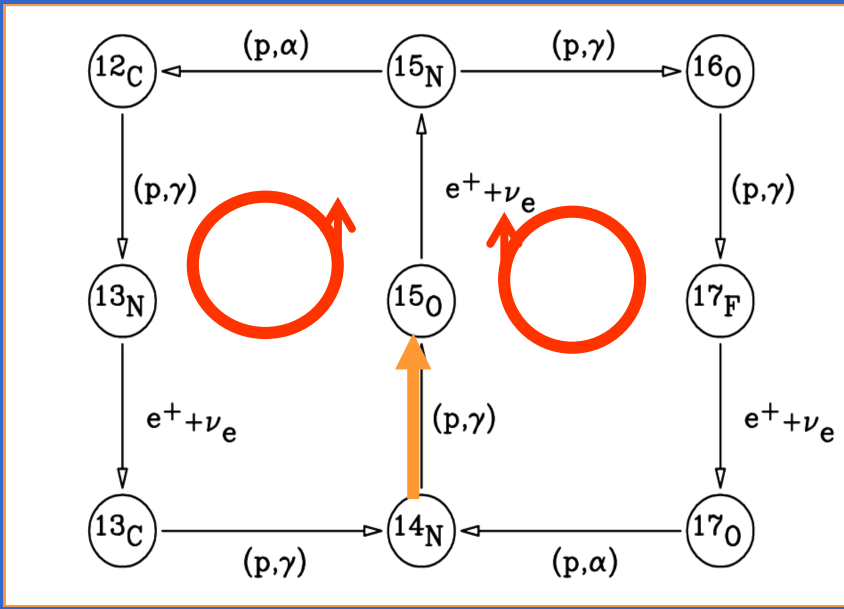
Is the Sun fully powered by nuclear reactions?

- Are there additional energy sources beyond 4H->He?:
- Are there additional energy losses, beyond photons and neutrinos?
- Remind that every 4H->He fusion gives 26.7 MeV and 2 neutrinos
- One can determine the “nuclear luminosity” from measured neutrino fluxes (S-Kam. SNO, Cl Ga) $K_{nuc} = \Phi_{tot} Q/2$, and compare it with the observed photon luminosity K:

$$(K_{nuc}-K)/K= 0.40 \pm 0.35 \qquad (1\sigma)$$

- This means that - to within 35% - the Sun is actually powered by 4H->He fusion.

CNO neutrinos, LUNA and the solar interior



- Solar model predictions for CNO neutrino fluxes are not precise because the CNO fusion reactions are not as well studied as the pp reactions.

- For the key reaction $^{14}N(p,\gamma)^{15}O$ the NACRE recommended value:

$$S_{1,14}=(3.2\pm0.8)\text{keV b}$$

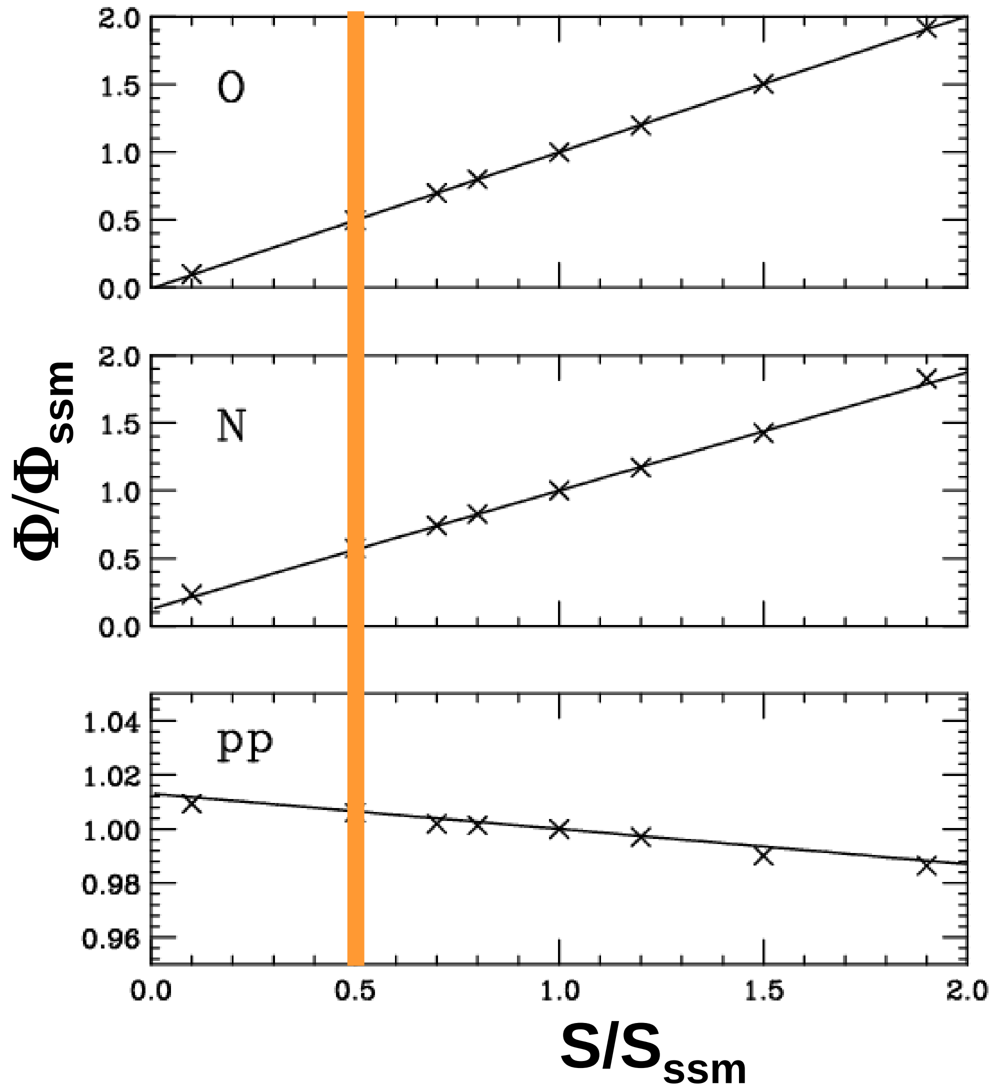
mainly based on Schroeder et al. data.

- Angulo et al. reanalysed data by Schroeder et al. within an R-matrix model, finding:

$$S_{1,14} \rightarrow \tfrac{1}{2}\ S_{1,14}$$

- **The new measurement by LUNA is obviously welcome (Imbriani)**

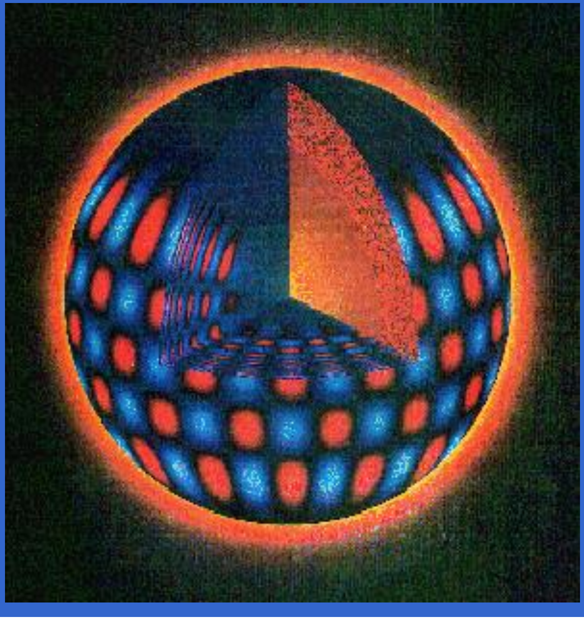
What if $S_{1,14}$->1/2 $S_{1,14}$?

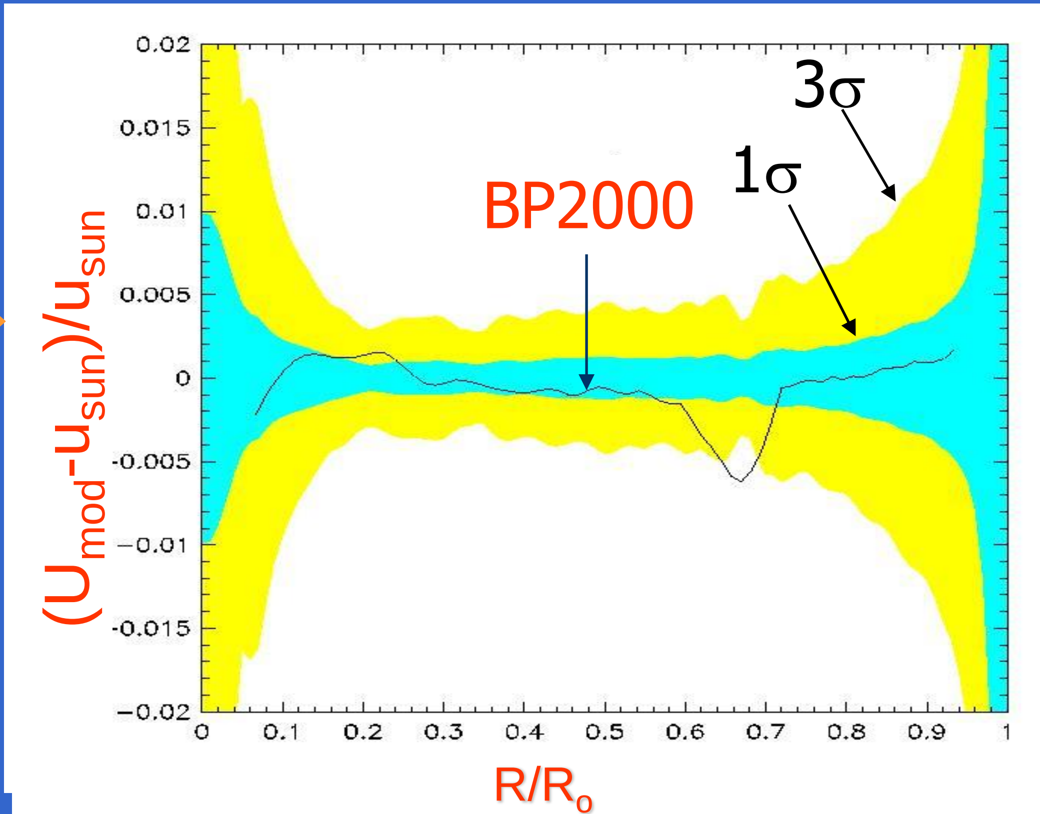


- Neutrino fluxes from N and O are halved
- pp-neutrinos increase, so as to keep total fusion rate constant
- The SSM+LMA signal for Ga and Cl expts decrease by 2.1 and 0.12 SNU.
- It alleviates the (slight) tension between th. and expt. for Chlorine.
- It also affects globular clusters evolution near turn off (Brocato et al 96) changing the relationship between Turnoff Luminosity and Age

Helioseismology

- From the measured oscillation frequencies of the solar surface one reconstructs sound speed in the solar interior ($\sqrt{u}$)
- Complementary to neutrinos, sensitive to Temperature
- Excellent agreement with Standard Solar Model
- Provides tests of solar models when some input (e.g. cross section, screening) is varied.





Heliosesimology and p+p -> d + e^+ + ν

- The astrophysical factor S_{pp} is the result of (sound) theoretical calculations, but it has not been measured in the laboratory. What if $S_{pp} \neq S_{pp}(SSM)$?
- The observed solar luminosity determines the rate of hydrogen burning in the sun. In order to keep it fixed, if the astrophysical factor S_{pp} is (say) larger than S_{pp}(SSM), temperature in the core has to be smaller than in the SSM.
- On the other hand, chemical composition is essentially fixed by Sun history so that the "molecular weight" μ is fixed.
- Sound speed $\approx (kT/\mu)^{1/2}$ has thus to be smaller than in SSM
- Thus helioseismology can provide information on S_{pp}

Degl'Innocenti,GF and Ricci Phys Lett 416B(1998)365

Helioseismic determination of S_{pp}

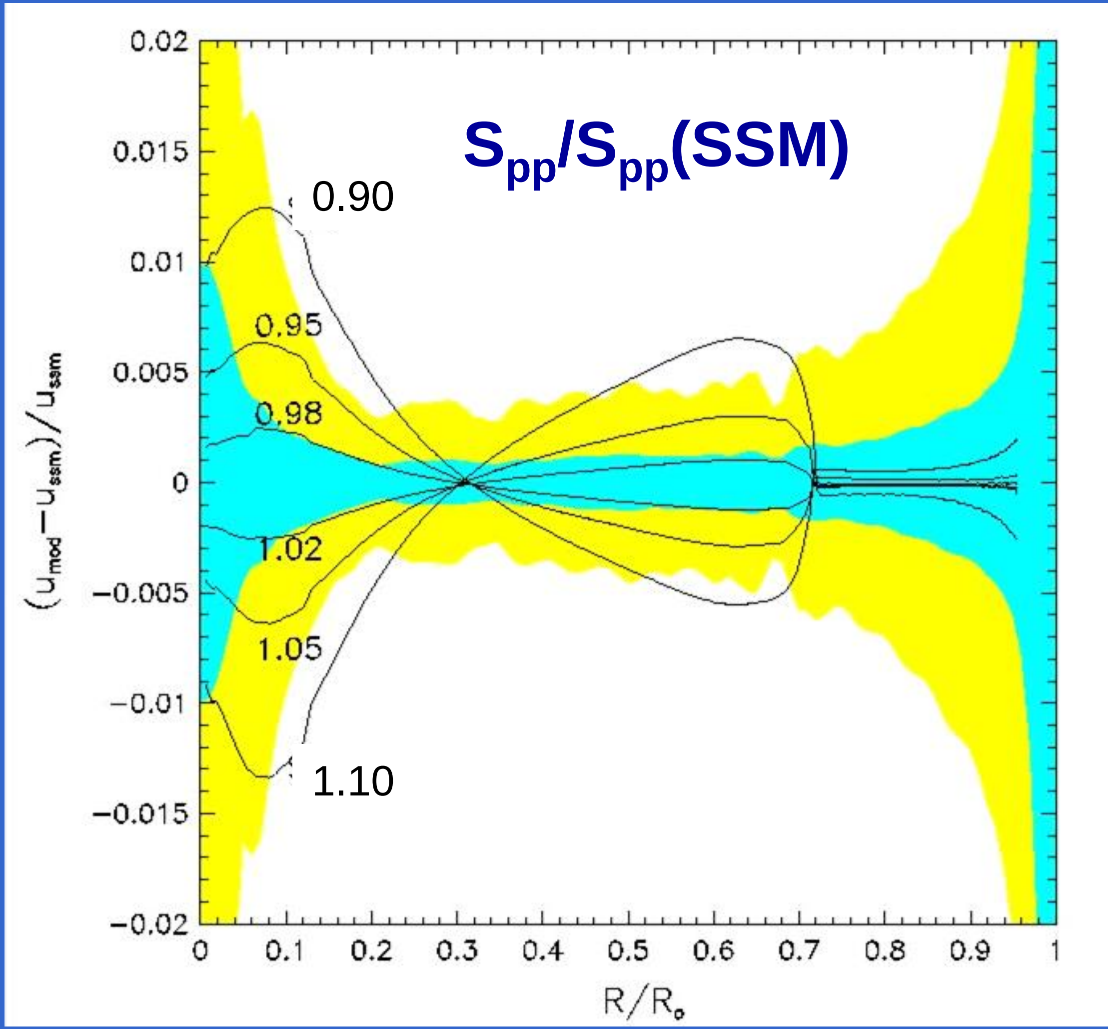
- Consistency with helioseismology requires:

$S_{pp}=S_{pp}(SSM)(1 \pm 2\%)$

- This accuracy is comparable to the theoretical uncertainty:

$S_{pp}(SSM)=4(1 \pm 2\%)$

X 10^{-22}KeVb

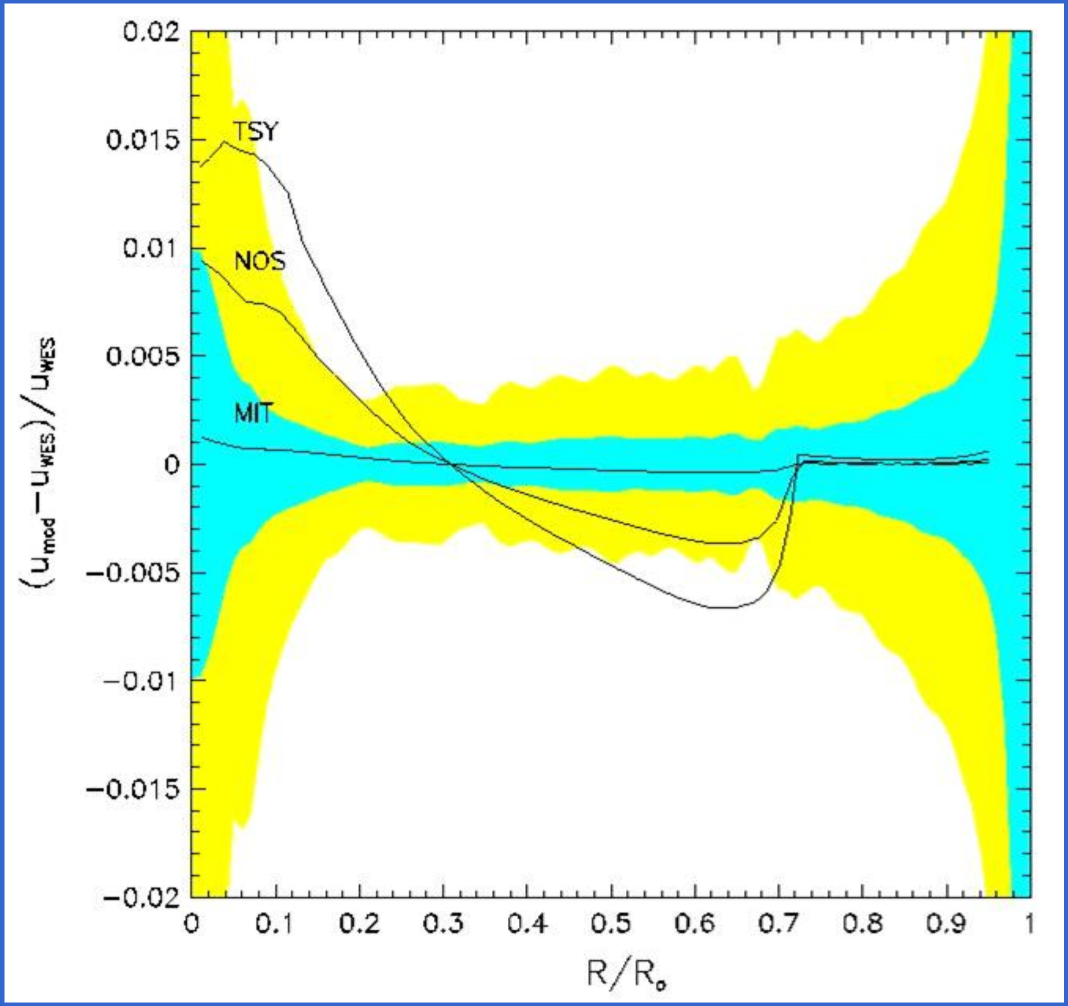


Screening of nuclear reactions

- Screening modifies nuclear reactions rates

$S_{pp} \to S_{pp} f_{pp}$

- Thus it can be tested by means of helioseismology
- NO Screening is excluded.
- Agreement of SSM with helioseismology shows that (weak) screening does exist.
- TSYtovitch anti-screening is excluded at more than 3σ



GF, Ricci and Villante, astro-ph 0011130, PLB

Helioseismology and CNO

- Helioseismology unsensitive to $S_{1,14} < S_{1,14}(SSM)$
- Helioseismology excludes $S_{1,14} > 5\, S_{1,14}(SSM)$

i.e. one has an upper bound for CNO contribution to solar luminosity $L_{CNO} < 7.5\% L_o$

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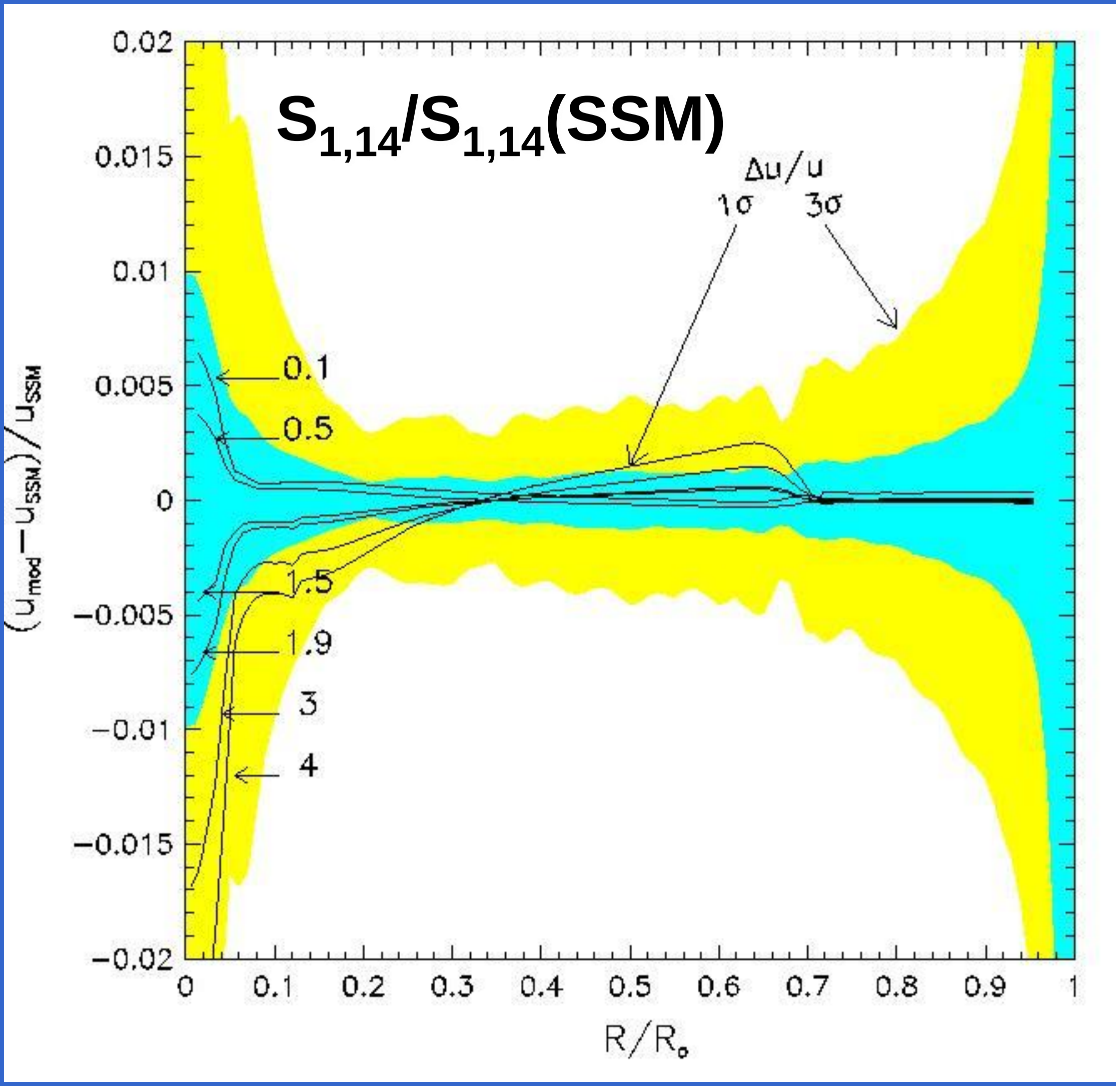

Summary

- Solar neutrinos are becoming an important tool for studying the solar interior and fundamental physics.
- Better determinations of S_{34} and $S_{1,14}$ are needed for fully exploiting the physics potential of solar neutrinos.
- All this brings towards answering fundamental questions:
  - Is the Sun fully powered by nuclear reactions?
  - Is the Sun emitting something else, beyond photons and neutrinos?