Solar Neutrinos and the Solar Composition

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Neutrino Telescopes, Venice

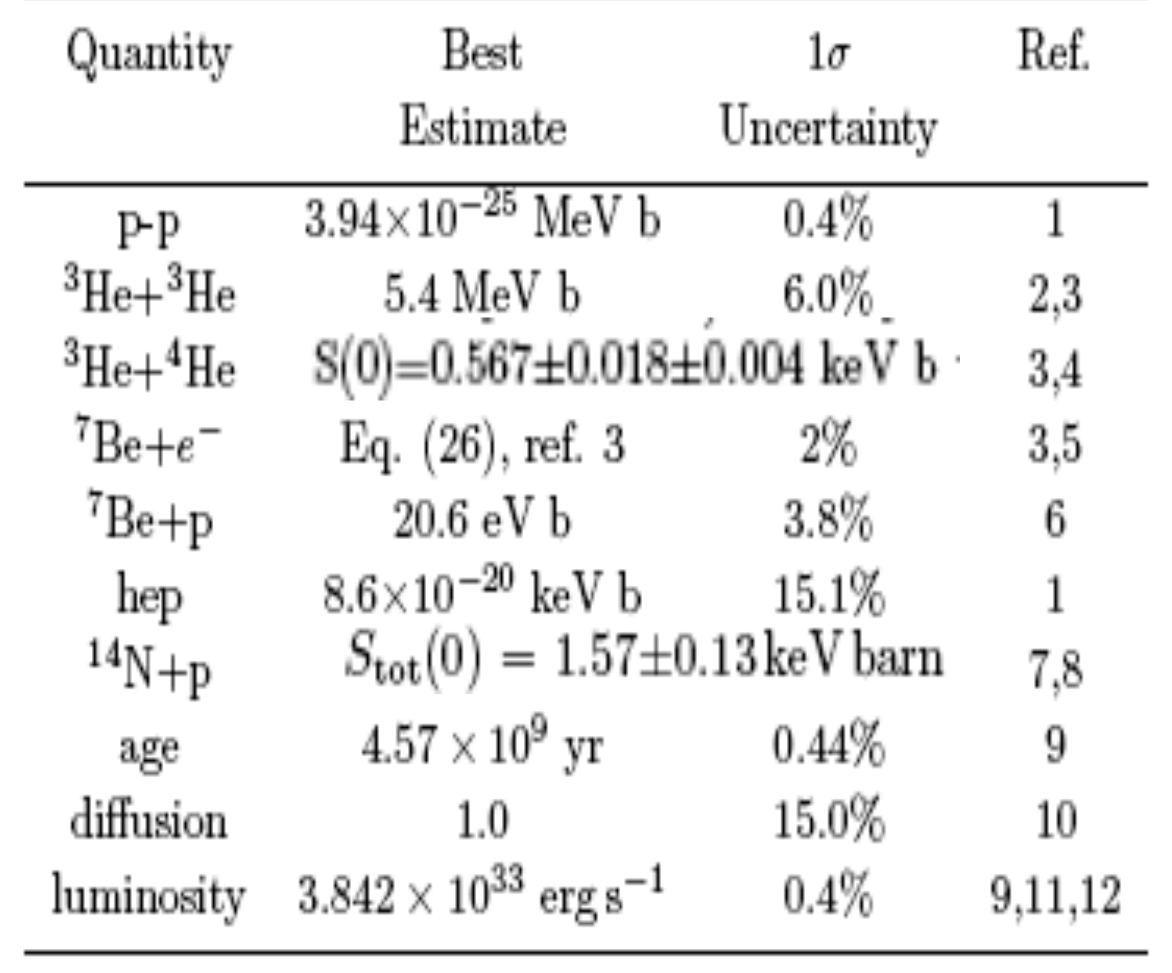
Solar Metallicity

“Un altro modo di guardare il cielo”

How do stars start?

Standard: Early Sun Chemically homogeneous (early fully convective Hayashi phase)

BPS08: Improved S_{34} & $S_{1,14}$ + GS98 Z_i/X

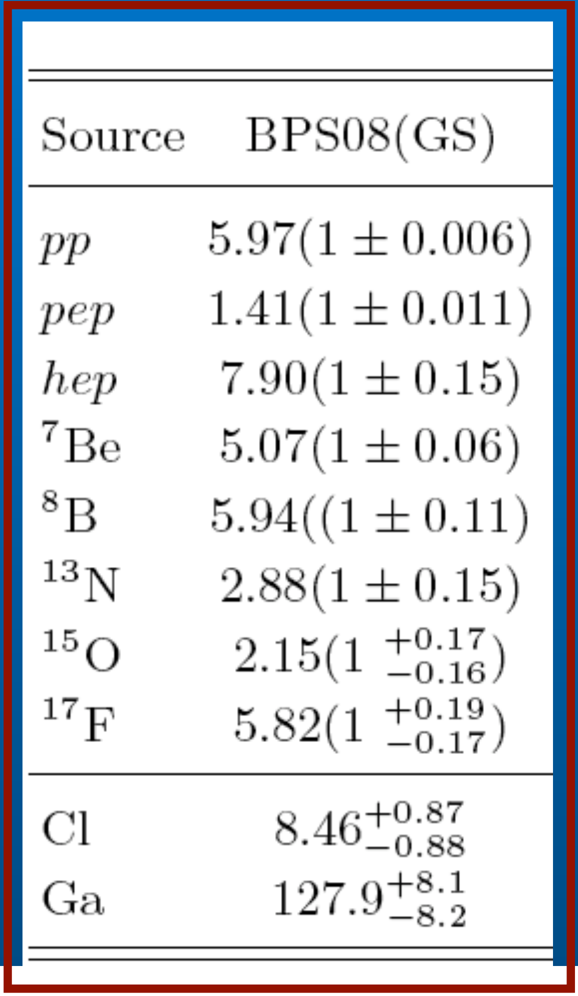


Quantity	Best Estimate	1σ Uncertainty	Ref.
p-p	3.94×10^{-25} MeV b	0.4%	1
^{3}He+^{3}He	5.4 MeV b	6.0%	2,3
^{3}He+^{4}He	S(0)=0.567±0.018±0.004 keV b		3,4
^{7}Be+e^-	Eq. (26), ref. 3	2%	3,5
^{7}Be+p	20.6 eV b	3.8%	6
hep	8.6×10^{-20} keV b	15.1%	1
^{14}N+p	$S_{\rm tot}(0) = 1.57\pm0.13$ keV barn		7,8
age	4.57×10^9 yr	0.44%	9
diffusion	1.0	15.0%	10
luminosity	3.842×10^{33} erg s^{-1}	0.4%	9,11,12

LUNA, 0809.5269

LUNA, 0807.4919

SSM BPS08



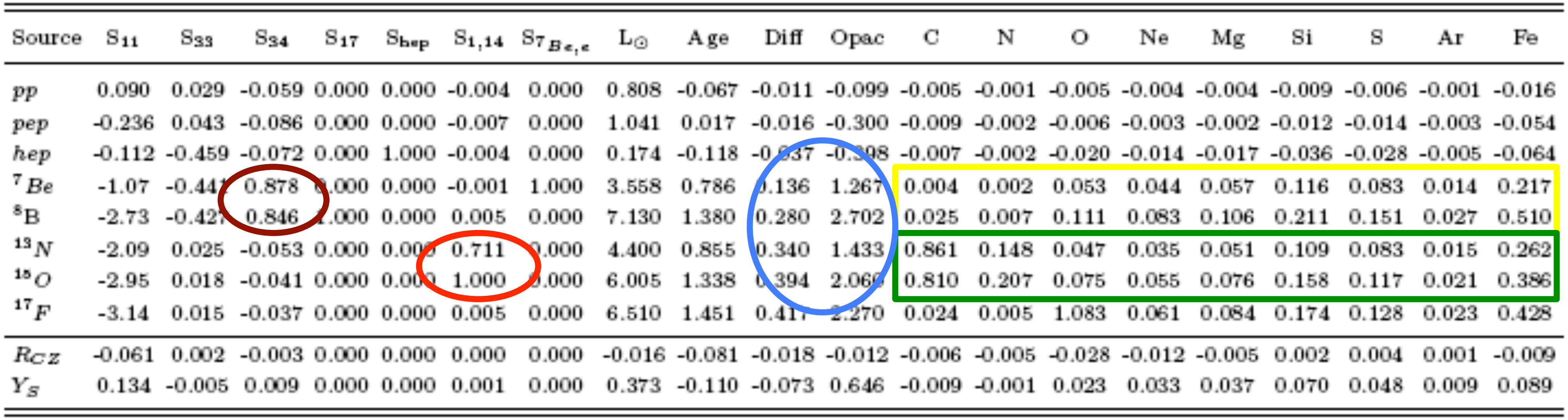
Source	BPS08(GS)
pp	$5.97(1 \pm 0.006)$
pep	$1.41(1 \pm 0.011)$
hep	$7.90(1 \pm 0.15)$
^{7}Be	$5.07(1 \pm 0.06)$
^{8}B	$5.94((1 \pm 0.11)$
^{13}N	$2.88(1 \pm 0.15)$
^{15}O	$2.15(1\ ^{+0.17}_{-0.16})$
^{17}F	$5.82(1\ ^{+0.19}_{-0.17})$
Cl	$8.46^{+0.87}_{-0.88}$
Ga	$127.9^{+8.1}_{-8.2}$

Precise fluxes: θ_{12}

Test matter effects

PG & Serenelli, arXiv: 0811.2424

Uncertainties: where to improve



Source	S_{11}	S_{33}	S_{34}	S_{17}	S_{hep}	$S_{1,14}$	$S_{7_{Be,e}}$	$L_\odot$	Age	Diff	Opac	C	N	O	Ne	Mg	Si	S	Ar	Fe
pp	0.090	0.029	-0.059	0.000	0.000	-0.004	0.000	0.808	-0.067	-0.011	-0.099	-0.005	-0.001	-0.005	-0.004	-0.004	-0.009	-0.006	-0.001	-0.016
pep	-0.236	0.043	-0.086	0.000	0.000	-0.007	0.000	1.041	0.017	-0.016	-0.300	-0.009	-0.002	-0.006	-0.003	-0.002	-0.012	-0.014	-0.003	-0.054
hep	-0.112	-0.459	-0.072	0.000	1.000	-0.004	0.000	0.174	-0.118	-0.037	-0.398	-0.007	-0.002	-0.020	-0.014	-0.017	-0.036	-0.028	-0.005	-0.064
^{7}Be	-1.07	-0.441	0.878	0.000	0.000	-0.001	1.000	3.558	0.786	0.136	1.267	0.004	0.002	0.053	0.044	0.057	0.116	0.083	0.014	0.217
^{8}B	-2.73	-0.427	0.846	1.000	0.000	0.005	0.000	7.130	1.380	0.280	2.702	0.025	0.007	0.111	0.083	0.106	0.211	0.151	0.027	0.510
^{13}N	-2.09	0.025	-0.053	0.000	0.000	0.711	0.000	4.400	0.855	0.340	1.433	0.861	0.148	0.047	0.035	0.051	0.109	0.083	0.015	0.262
^{15}O	-2.95	0.018	-0.041	0.000	0.000	1.000	0.000	6.005	1.338	0.394	2.060	0.810	0.207	0.075	0.055	0.076	0.158	0.117	0.021	0.386
^{17}F	-3.14	0.015	-0.037	0.000	0.000	0.005	0.000	6.510	1.451	0.417	2.270	0.024	0.005	1.083	0.061	0.084	0.174	0.128	0.023	0.428
R_{CZ}	-0.061	0.002	-0.003	0.000	0.000	0.000	0.000	-0.016	-0.081	-0.018	-0.012	-0.006	-0.005	-0.028	-0.012	-0.005	0.002	0.004	0.001	-0.009
Y_S	0.134	-0.005	0.009	0.000	0.000	0.001	0.000	0.373	-0.110	-0.073	0.646	-0.009	-0.001	0.023	0.033	0.037	0.070	0.048	0.009	0.089

Logarithmic partial derivatives of neutrino fluxes with respect to solar inputs times uncertainties show leading sources of uncertainty

Characterize correlations

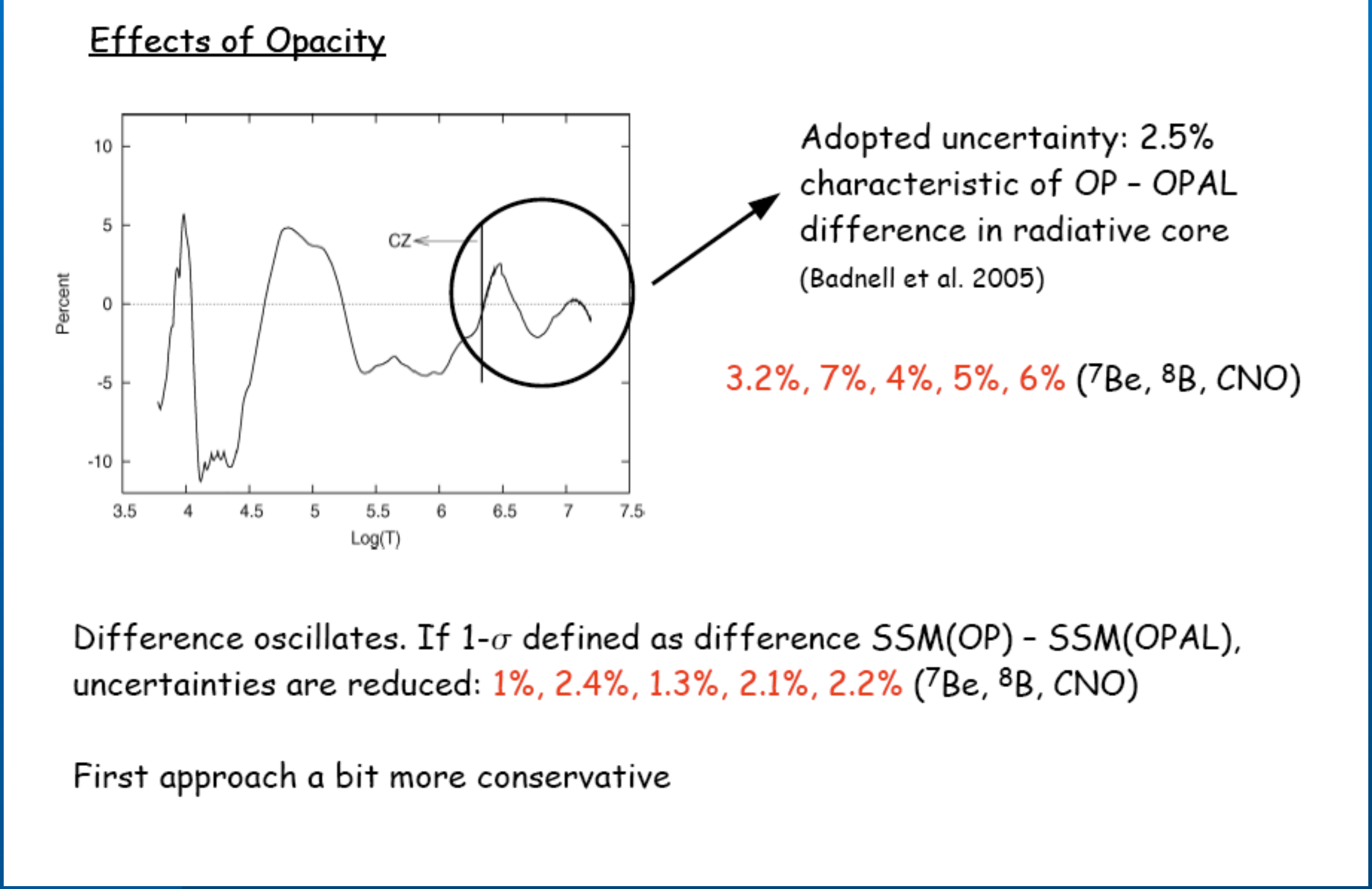
Uncertainties: Partial contributions

Source	No composition % (S_{33}, S_{34}, S_{17}, S_{114}, Op, Diff)	Composition %
^{7}Be	5 (2.5,2.8,0.0,0.0,3.2,2.0)	2
^{8}B	10 (2.6,2.7,3.8,0.0,6.8,4.2)	5
^{13}N	8 (0.2,0.2,0.0,6.0,3.6,5.1)	13
^{15}O	11 (0.2,0.2,0.0,8.3,5.2,5.9)	12

Recommendations:

- Reduce $S_{1,14}$ uncertainty to be below 5%
- Reduce uncertainty in Fe (to 0.02 dex)
- Reduce uncertaintiy in C (to 0.02 dex)

BPS08: Opacities



Effects of Opacity

Adopted uncertainty: 2.5% characteristic of OP – OPAL difference in radiative core

(Badnell et al. 2005)

3.2%, 7%, 4%, 5%, 6% (^{7}Be, ^{8}B, CNO)

Difference oscillates. If 1-σ defined as difference SSM(OP) - SSM(OPAL), uncertainties are reduced: 1%, 2.4%, 1.3%, 2.1%, 2.2% (^{7}Be, ^{8}B, CNO)

First approach a bit more conservative

Solar Neutrinos

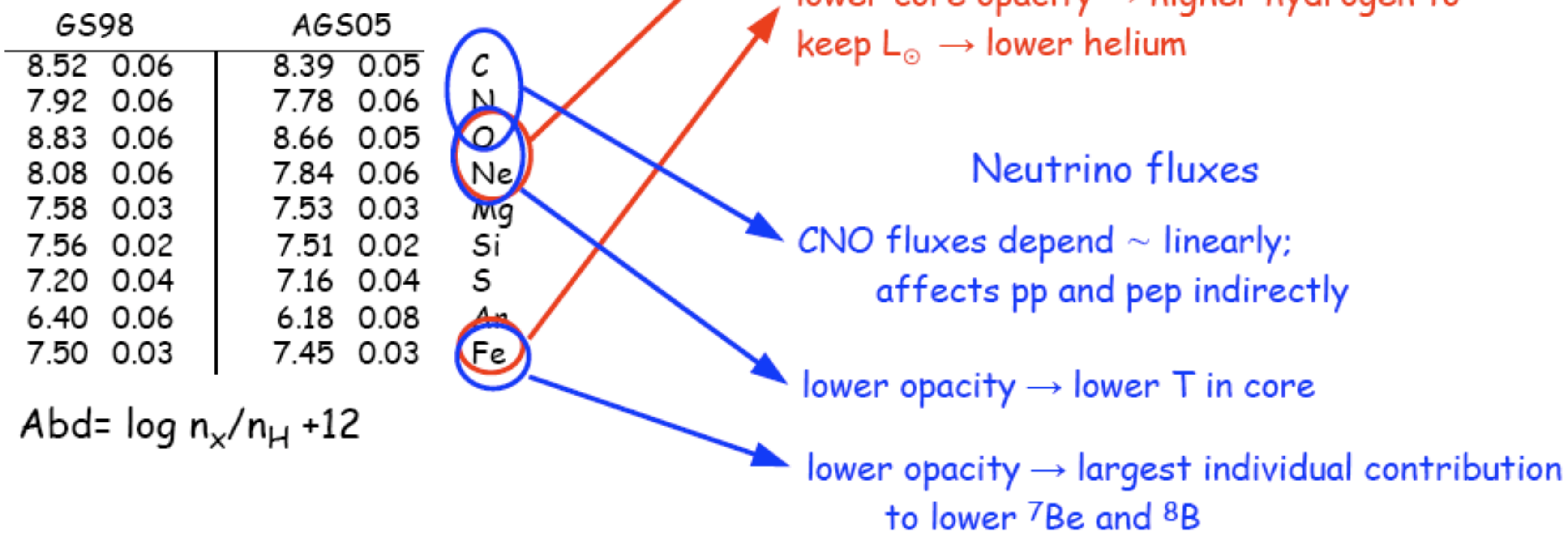
Rain on SSM's parade

Improved abundances: GS vs AGS

Different total metallicity

$Z/X = 0.0229$ (GS98)

$Z/X = 0.0165$ (AGS05)



GS98		AGS05		
8.52	0.06	8.39	0.05	C
7.92	0.06	7.78	0.06	N
8.83	0.06	8.66	0.05	O
8.08	0.06	7.84	0.06	Ne
7.58	0.03	7.53	0.03	Mg
7.56	0.02	7.51	0.02	Si
7.20	0.04	7.16	0.04	S
6.40	0.06	6.18	0.08	Ar
7.50	0.03	7.45	0.03	Fe

$\mathrm{Abd} = \log n_X/n_H + 12$

Helioseismology

lower opacity below CZ → R_{CZ} and c_s profile

lower core opacity → higher hydrogen to keep $L_\odot$ → lower helium

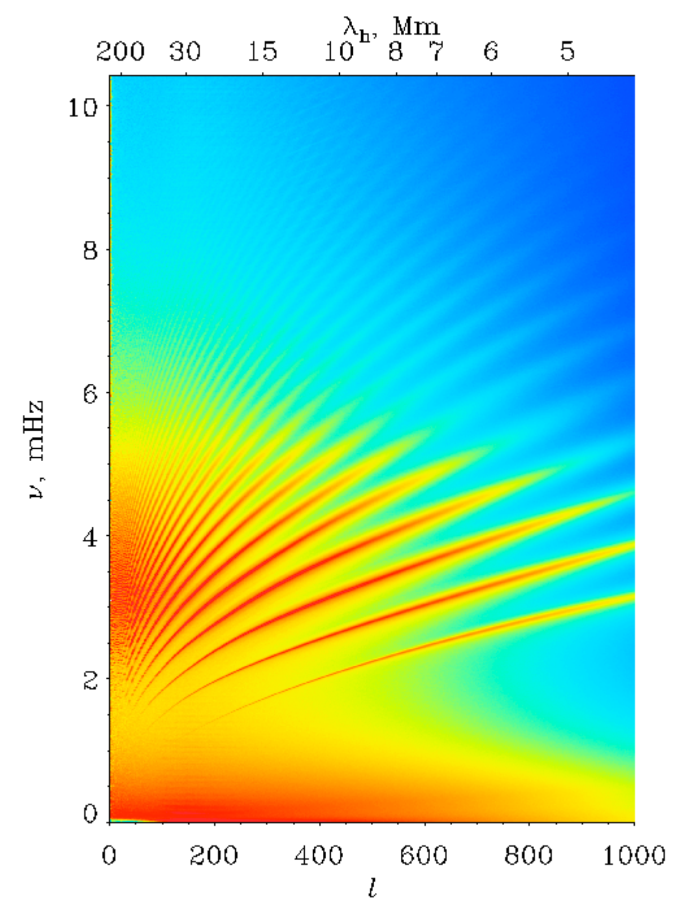
Neutrino fluxes

CNO fluxes depend ~ linearly; affects pp and pep indirectly

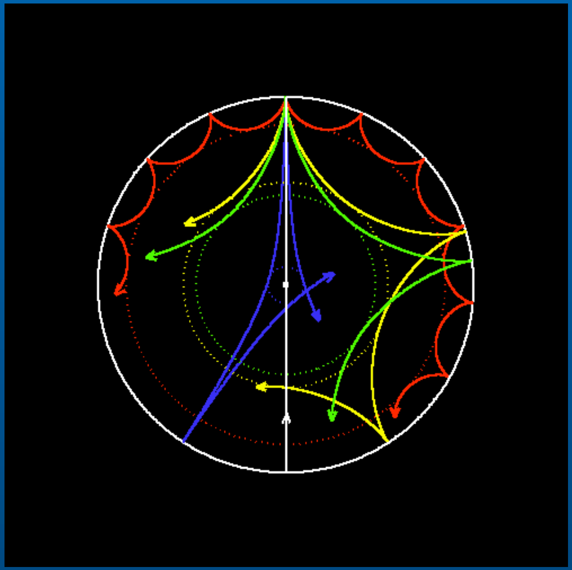
lower opacity → lower T in core

lower opacity → largest individual contribution to lower ^{7}Be and ^{8}B

The pulsating Sun: Helioseismology



Doppler observation of spectral lines:
- velocities ~ cm/s
- long observations needed
- Accuracy in frequencies ~10^{-5}



Physics: Acoustic waves, pressure-modes, stochastically excited by convection

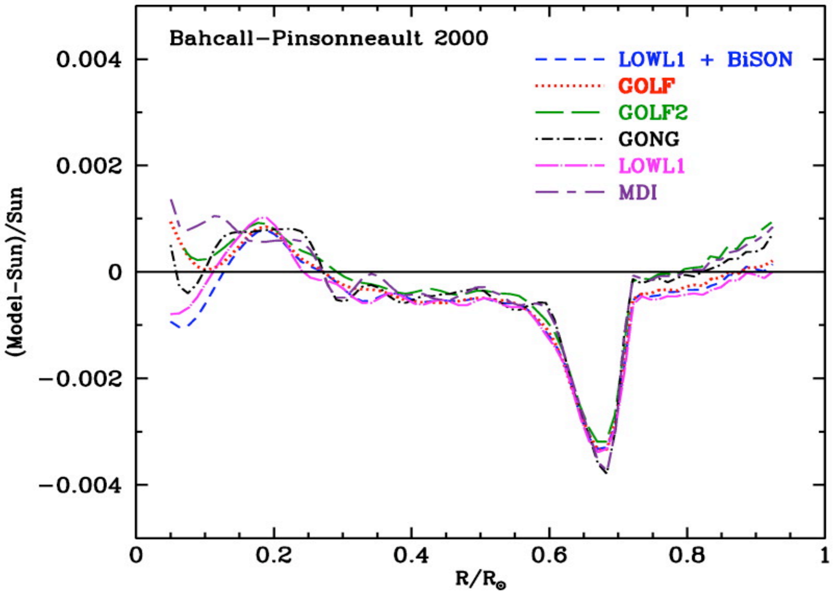
Helioseismology

- *Oscillation frequencies depend on ρ, P, g, c*
- *Inversion problem: use measured frequencies and a reference solar model to determine the solar structure*

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + F_{surf}(\omega_i)$$

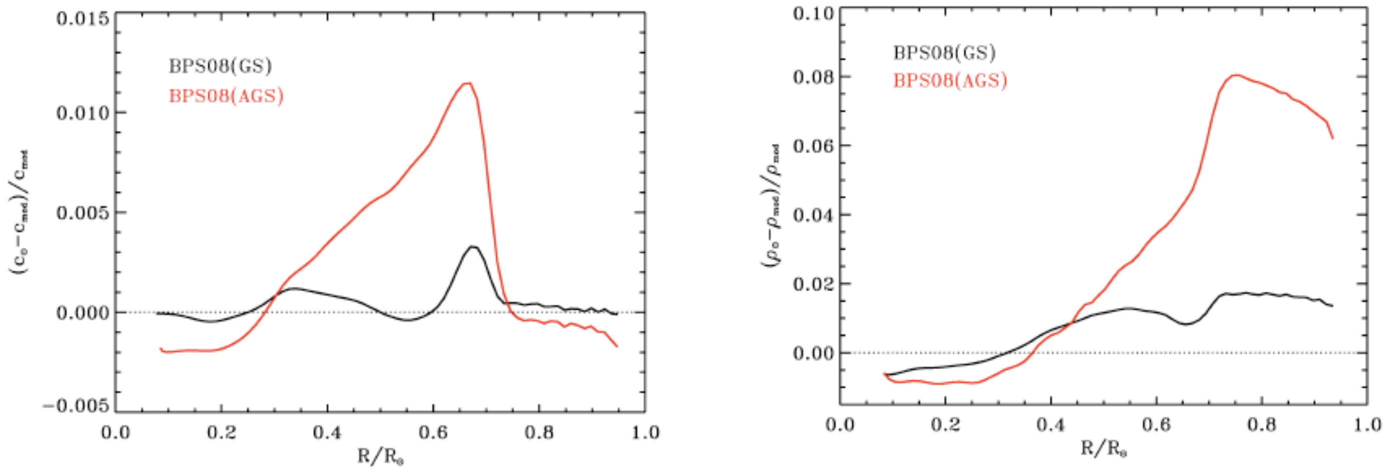
Output of inversion procedure: $\delta c^2(r)$, $\delta\rho(r)$, R_{CZ}, Y_{SURF}

Relative difference of c between Sun and BP00



BPS08 Helioseismology: GS vs AGS

Helioseismology: Sound speed and density profiles



	GS98	AGS05	Helioseism.
R_{CZ}	0.713	0.728	0.713±0.001
Y_S	0.243	0.229	0.248±0.035
$\langle\delta c\rangle$	0.010	0.053	---
$\langle\delta\rho\rangle$	0.005	0.047	---

Attemps to solve the discrepancy:
Increase opacity below CZ? Increase Ne abundance? Enhance diffusion?

Low abundances: non-local solution needed

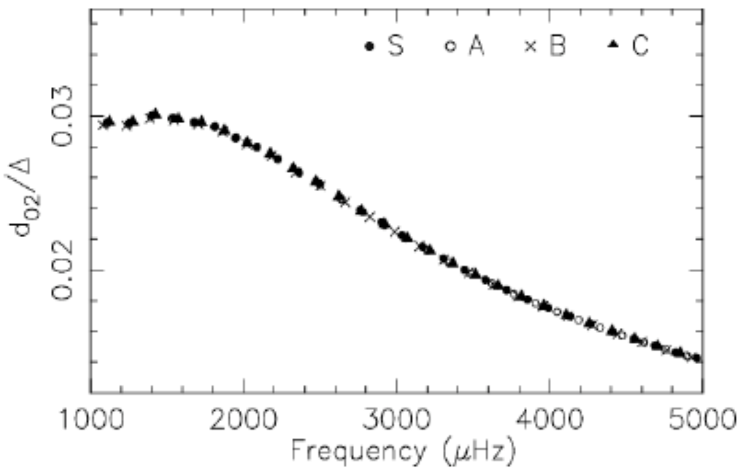
Solar core: Helioseismology with low-l modes

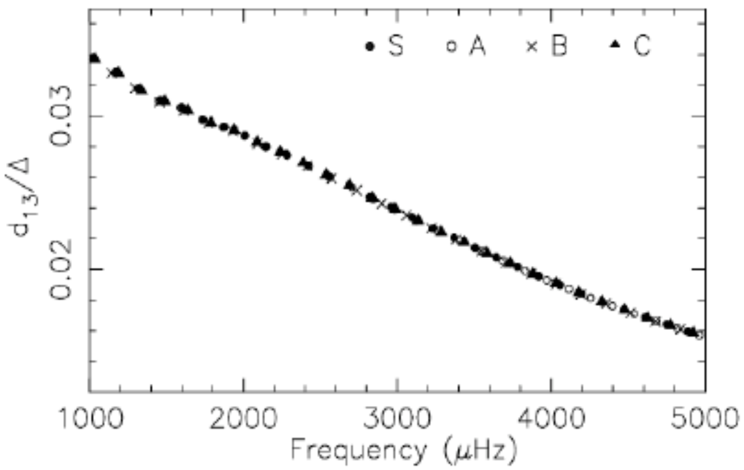
Roxburgh & Vorontsov (2003): ratio of small to large separation ratios depend only on interior structure

Separation ratios: r_{02} - r_{13}

$$r_{02}(n)=\frac{d_{02}(n)}{\Delta_1(n+1)}=\frac{\nu_{n,0}-\nu_{n-1,2}}{\nu_{n,1}-\nu_{n-1,1}}$$

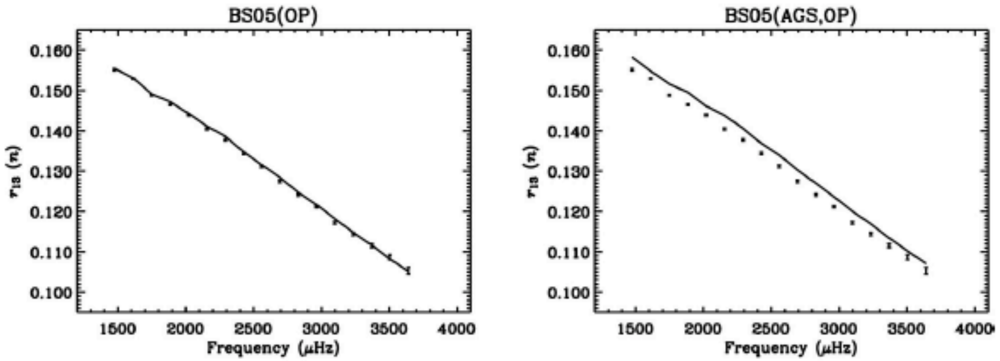
$$r_{13}(n)=\frac{d_{13}(n)}{\Delta_0(n+1)}=\frac{\nu_{n,1}-\nu_{n-1,3}}{\nu_{n,0}-\nu_{n-1,0}}$$





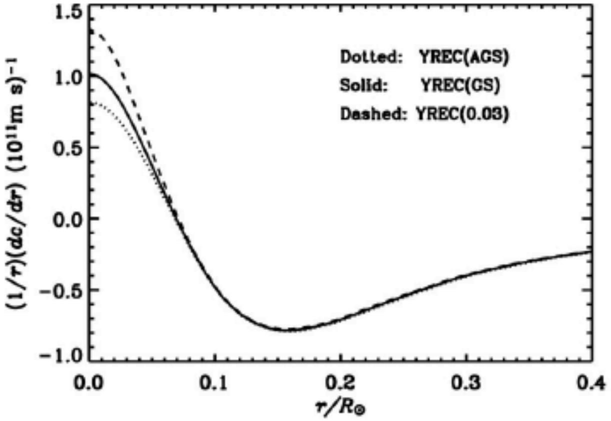
Low abundances: non-local solution needed

Solar core: Helioseismology with low-l modes



Effect of metalicity arise in the core

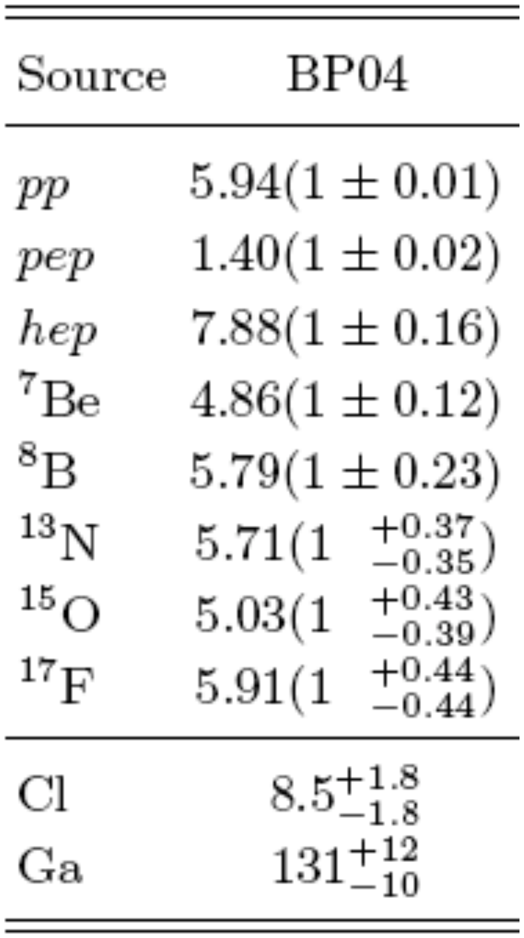
$$\delta_{nl} \equiv \nu_{nl} - \nu_{n-1\,l+2} \simeq -(4l+6)\frac{\Delta\nu}{4\pi^2\nu_{nl}}\int_0^R \frac{dc}{dr}\frac{dr}{r}$$



Low l-modes BiSON data
Chaplin et al (2007)

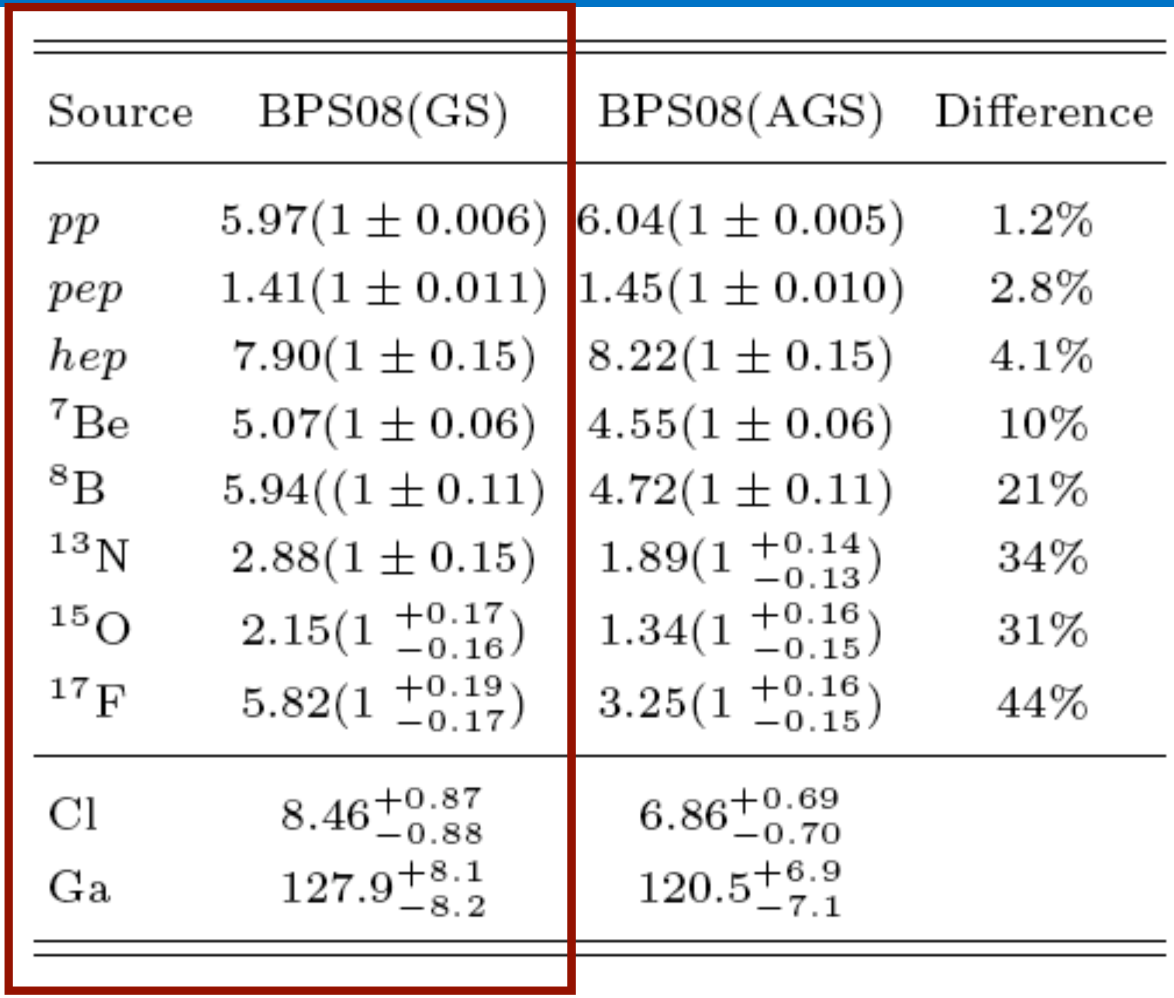
- Low-Z models not compatible with low-l frequencies
- Conservative abundances: too conservative → assume smaller uncertainties for SSM

BPS08: GS vs AGS solutions



Source	BP04
pp	$5.94(1 \pm 0.01)$
pep	$1.40(1 \pm 0.02)$
hep	$7.88(1 \pm 0.16)$
^{7}Be	$4.86(1 \pm 0.12)$
^{8}B	$5.79(1 \pm 0.23)$
^{13}N	$5.71(1 \,^{+0.37}_{-0.35})$
^{15}O	$5.03(1 \,^{+0.43}_{-0.39})$
^{17}F	$5.91(1 \,^{+0.44}_{-0.44})$
Cl	$8.5^{+1.8}_{-1.8}$
Ga	131^{+12}_{-10}

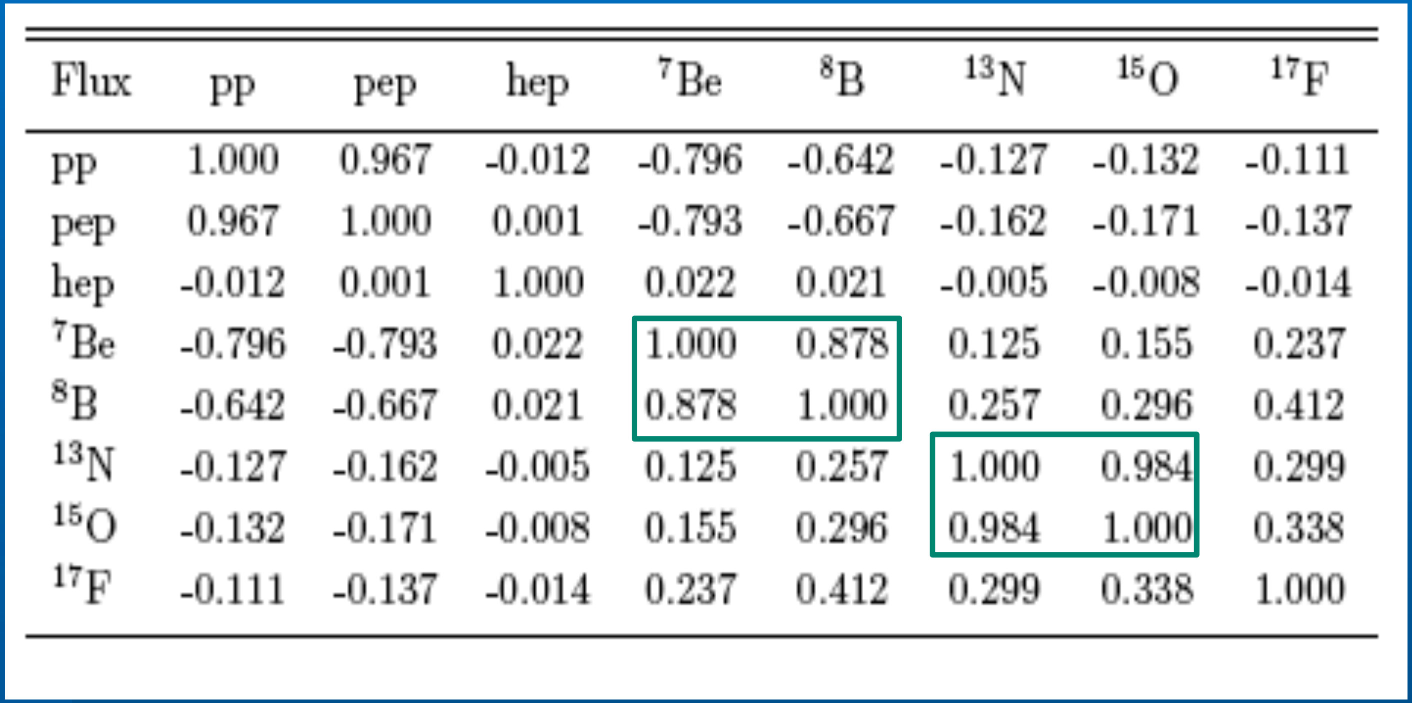
Bahcall & Pinnsoneault
PRL92,121301 (2004)



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	$127.9^{+8.1}_{-8.2}$	$120.5^{+6.9}_{-7.1}$	

PG & Serenelli, arXiv: 0811.2424

Neutrino fluxes: correlations



Flux	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
pp	1.000	0.967	-0.012	-0.796	-0.642	-0.127	-0.132	-0.111
pep	0.967	1.000	0.001	-0.793	-0.667	-0.162	-0.171	-0.137
hep	-0.012	0.001	1.000	0.022	0.021	-0.005	-0.008	-0.014
^{7}Be	-0.796	-0.793	0.022	1.000	0.878	0.125	0.155	0.237
^{8}B	-0.642	-0.667	0.021	0.878	1.000	0.257	0.296	0.412
^{13}N	-0.127	-0.162	-0.005	0.125	0.257	1.000	0.984	0.299
^{15}O	-0.132	-0.171	-0.008	0.155	0.296	0.984	1.000	0.338
^{17}F	-0.111	-0.137	-0.014	0.237	0.412	0.299	0.338	1.000

Large correlation of fluxes (^{8}B - ^{7}Be, ^{13}N - ^{15}O) may help to discriminate predicted fluxes

Global Analysis (+ lum. constraint)

$$\chi^2_{\text{global}} = \chi^2_{\text{solar}}(\Delta m^2, \theta_{12}, \{\xi, f_{\text{B}}, f_{\text{Be}}, f_{p-p}, f_{\text{CNO}}\}) + \chi^2_{\text{KamLAND}}(\Delta m^2, \theta_{12}, \theta_{13}) + \chi^2_{\text{CHOOZ+ATM}}(\theta_{13}) .$$

+K2K+MINOS

$$\begin{aligned}
\Delta m^2_{21} &= (7.7 \pm 0.2) \times 10^{-5} \text{eV}^2 \\
\tan^2\theta_{12} &= 0.46^{+0.04}_{-0.05} \quad ; \quad \sin^2\theta_{13} = 0.014^{+0.011}_{-0.009} \\
f_{\text{B}} &= 0.91 \pm 0.03 \quad ; \quad f_{\text{B}e} = 1.02 \pm 0.10 \\
f_{\text{pp}} &= 1.00^{+0.01}_{-0.02} \quad ; \quad L_{CNO} = 0.0^{+2.9}_{-0.0}\%
\end{aligned}$$

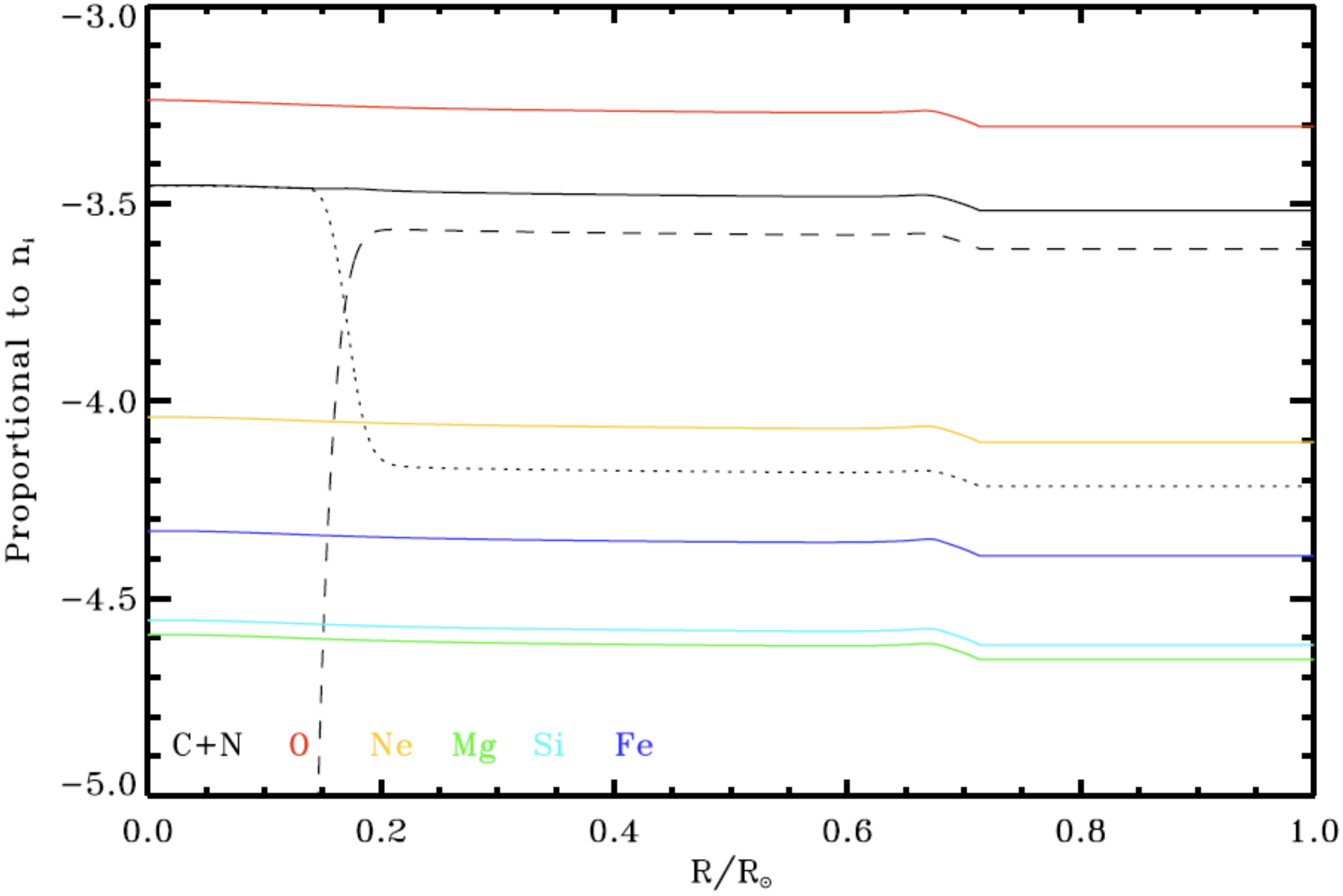
$$\text{R}=\langle {}^3\text{He}+{}^4\text{He}\rangle / \langle {}^3\text{He}+{}^3\text{He}\rangle = 0.19 \pm 0.02$$

Physics summary:

- Neutrino oscillations
- CNO luminosity & pp termination chain by data

How do stars start? (I)

Metal difusion



Testing BPS08(GS) & BPS08(AGS) with ν data

^{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%

$$\chi^2 = \sum_{ij} (f_i^{th} - f_i)\sigma_{ij}^{-2}(f_j^{th} - f_j)$$

$$\sigma_{ij}^2 = \sigma_{exp,i}\sigma_{exp,j}\rho_{ij}^{exp} + \sigma_{\mathrm{th},i}\sigma_{\mathrm{th},j}\rho_{ij}^{\mathrm{th}}$$

$$\chi^2_{\mathrm{B}PS08(GS)} = 0.9\ (63\%) \quad \text{and} \quad \chi^2_{\mathrm{B}PS08(AGS)} = 1.5(47\%)$$

Now: Both models acceptable.
Soon (SNO/SK + Borexino):
- increase power of this test,
- within reach $\Delta\chi^2$(AGS-GS) = 6.2 (2.5 σ)

Roadmap: CNO fluxes

$^{13}\mathrm{N}$	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
$^{15}\mathrm{O}$	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%

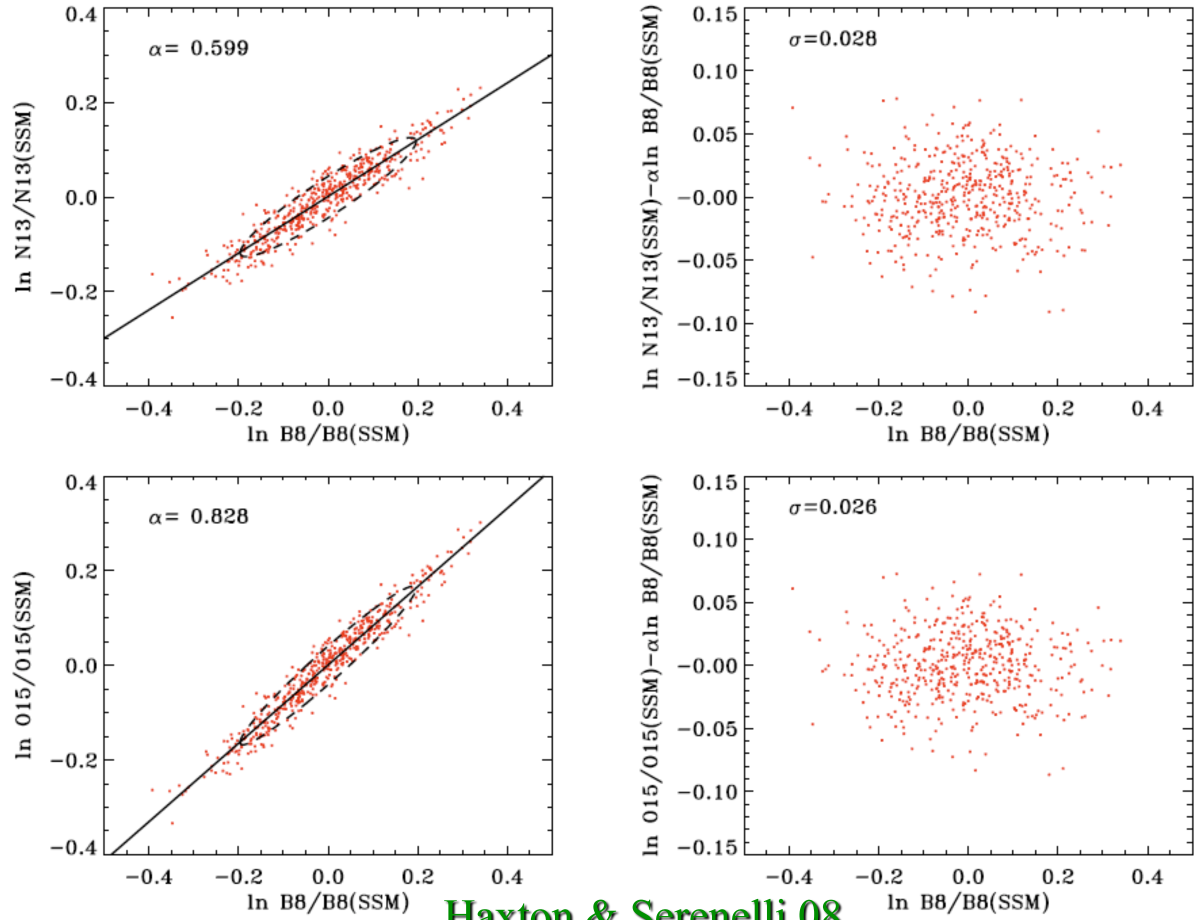
Precision required ~ 15%

Direct evidence of how stars (heavier or older than the Sun) bright.

Contribution to further test BPS08(GS) and BPS08(AGS). Strong correlation may improve power of solar composition test

How do stars start? (II)

How to extract core metallicities



Haxton & Serenelli 08

$$\frac{\phi(^{13}\mathrm{N})}{\phi^{SSM}(^{13}\mathrm{N})} = \left[\frac{\phi^{SNO}(^{8}\mathrm{B})}{\phi^{SSM}(^{8}\mathrm{B})}\right]^{0.599} [1 \pm 2.8\%(\text{resid. environ.}) \pm 5.0\%)(\text{nuclear})] \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.858} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.141}.$$

$$\frac{\phi(^{15}\mathrm{O})}{\phi^{SSM}(^{15}\mathrm{O})} = \left[\frac{\phi^{SNO}(^{8}\mathrm{B})}{\phi^{SSM}(^{8}\mathrm{B})}\right]^{0.828} [1 \pm 2.6\%(\text{resid. environ.}) \pm 7.1\%(\text{nuclear})] \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.805} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.199}$$

Conclusions

Solar neutrinos: Best θ_{12} (10% in $\tan^2\theta_{12}$) and test MSW
Neutrino fluxes determined (pp/pep, ^{7}Be, ^{8}B) and CNO luminosity constrain

BPS08 neutrino fluxes: more precise, dominant sources identified ($S_{1,14}$, Op, Diff, Z_i/X) and being further studied

Improvements in solar surface composition lead to wrong beating Sun in all regions.

Ongoing and future neutrino experiments will probe the solar composition:
- test BPS08(GS) & BPS08(AGS) solutions
- test core CN abundances