Solar opacities, neutrinos, and asymptotic period spacing

Aldo Serenelli
Institute of Space Sciences

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Institute of Space Sciences

CSIC
Consejo Superior de Investigaciones Científicas

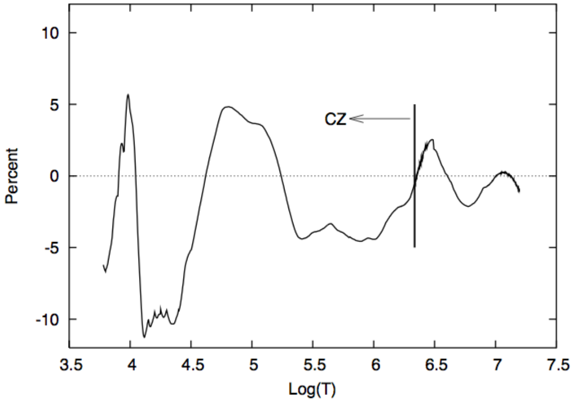
IEEC

Opacities

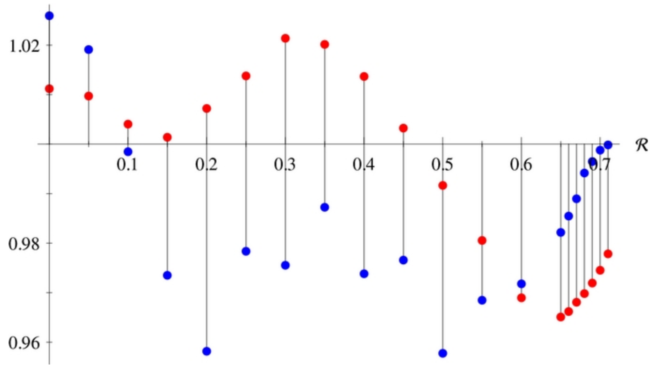
Helioseismic probes and pp ns depend on “effective” opacity profiles: opacity models + composition
details in F. Villante’s talk

Status of opacity models in 2014 @ “A special Borexino Event”

OP vs OPAL



OPAS vs OP (blue)

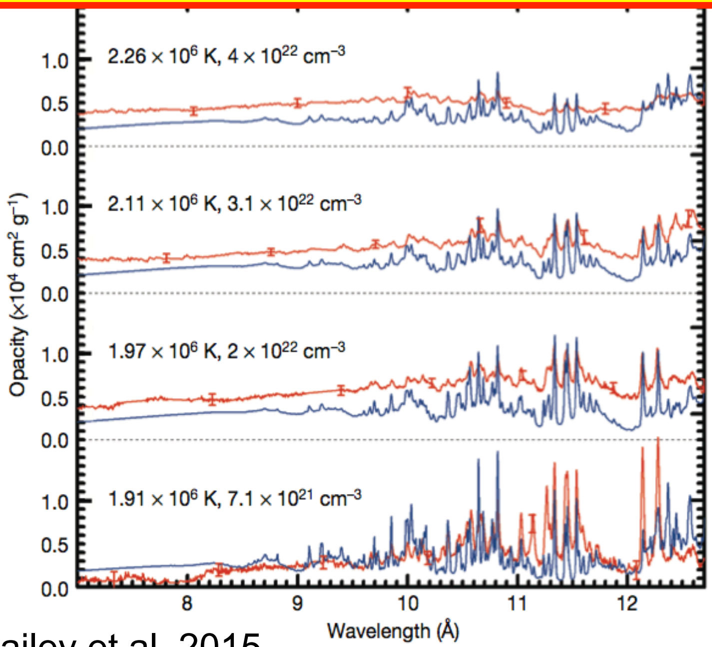


Few percent differences in solar interiors
Only theoretical calculations available

Opacities – Experimental result

First ever opacity measurement at conditions close to base of the solar convective envelope

Fe opacity @Sandia Lab -- > 7% increase of Rosseland mean opacity



$T \sim T_{CZ}$

$Ne \sim 1/4\ Ne_{CZ}$

Bailey et al. 2015

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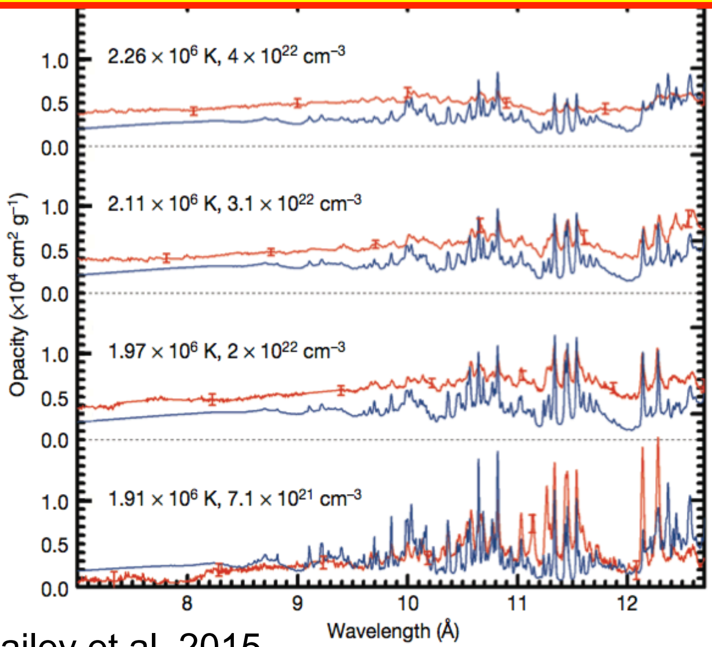
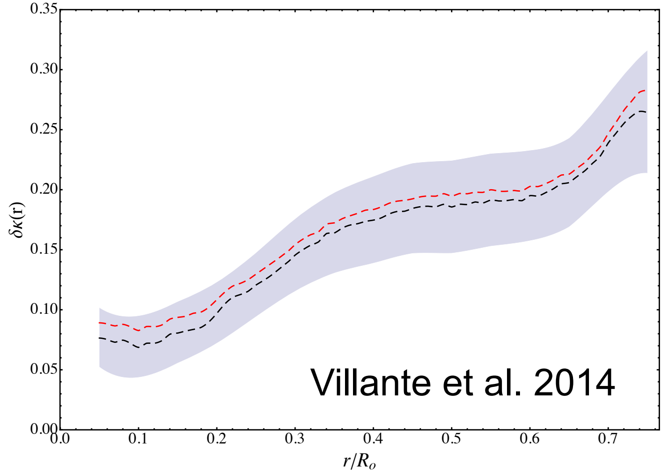


Bailey et al. 2015

$T \sim T_{CZ}$

$Ne \sim 1/4\ Ne_{CZ}$

Encouraging but insufficient: "missing opacity" at ~20%

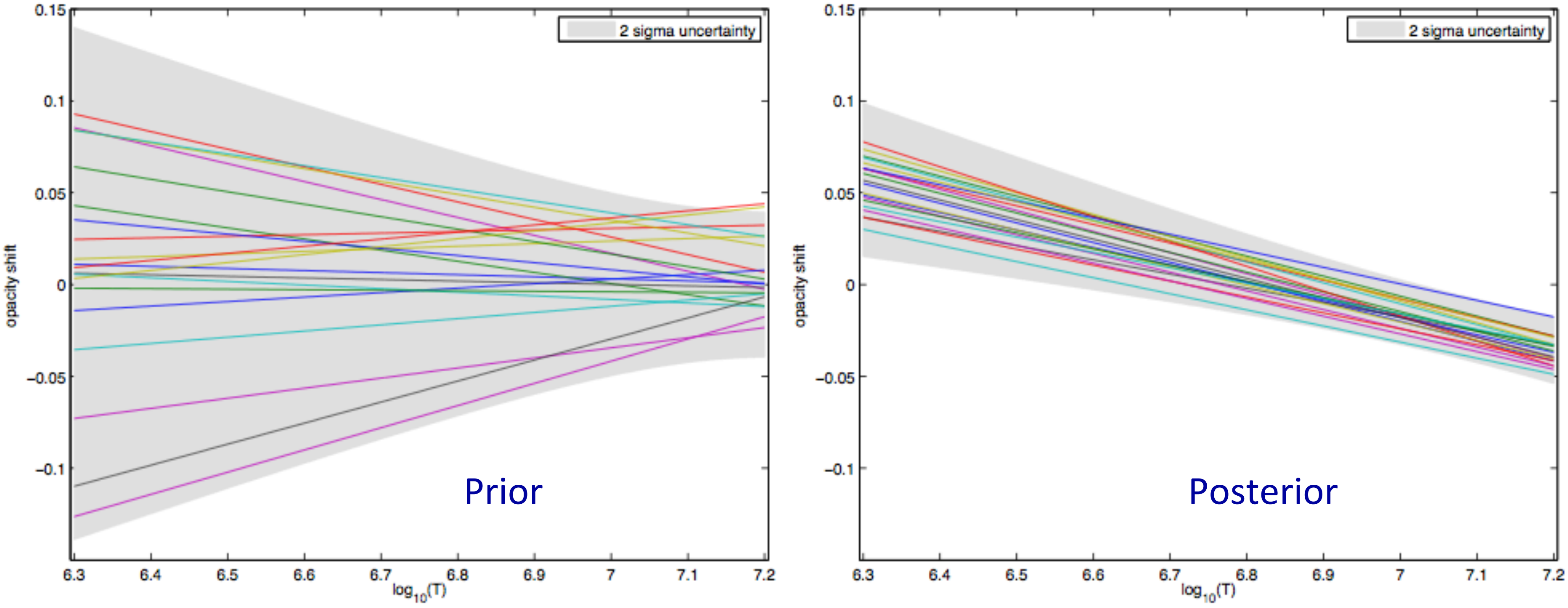


Villante et al. 2014

Solar opacities – intrinsic error

What is the true opacity error function? Linear, OP-OPAL, etc?

Linear model



Solar opacities – intrinsic error

$$f(x) \sim N(m(x), C(x,x'))$$

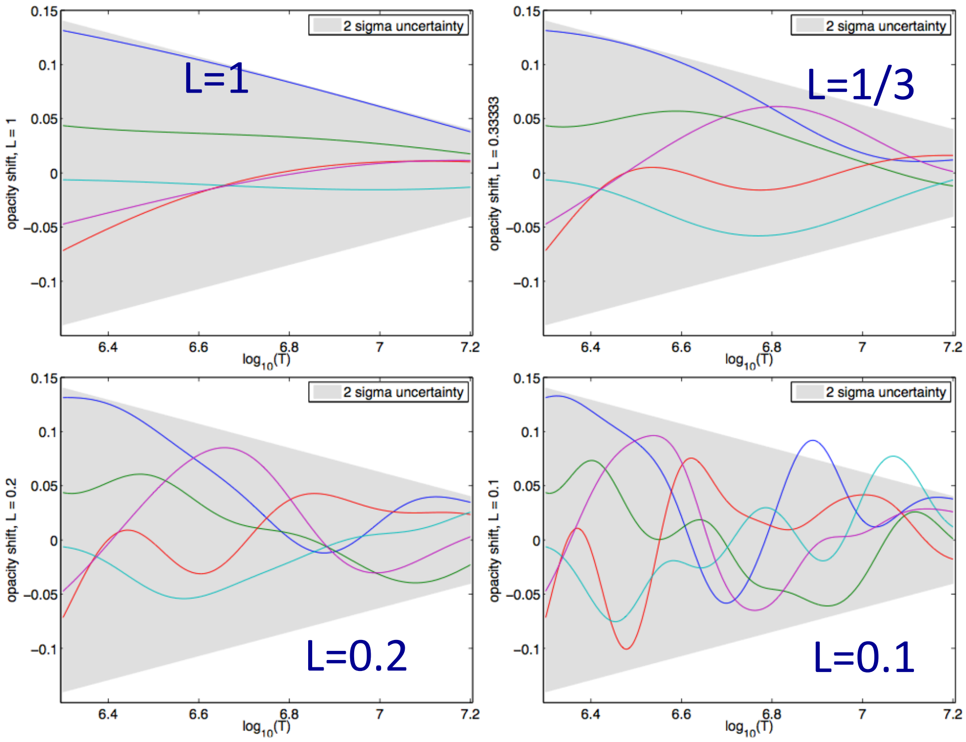
Locally a gaussian function of mean μ
e.g. 2% center or 7% at BCE

$$\rho(x,x') = e^{-|x-x'|^2/(2L^2)}$$

Correlation between two points
L correlation length

Define sensible priors for L
determine posterior from data

Use data to extract posteriors of all solar input parameters, including shape of opacity function



Song et al. 2018

Solar opacities – test the models

		Linear				Gaussian process			
		GS98		AGSS09met		GS98		AGSS09met	
$\vec{\mathcal{O}}$	n	$\mathscr{T}(\vec{\mathcal{O}})$	p-value (σ)	$\mathscr{T}(\vec{\mathcal{O}})$	p-value (σ)	$\mathscr{T}(\vec{\mathcal{O}})$	p-value (σ)	$\mathscr{T}(\vec{\mathcal{O}})$	p-value (σ)
$Y_S + R_{CZ}$	2	0.9	0.5	6.5	2.1	0.7	0.35	6.9	2.2
δc	30	58.0	3.2	76.1	4.5	35.6	1.2	40.2	1.6
all ν-fluxes	8	6.0	0.5	7.0	0.6	5.9	0.44	7.0	0.6
global	40	65.0	2.7	94.2	4.7	45.1	1.1	57.1	2.1

Song et al. 2018

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Song et al. 2018

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$\vec{\mathscr{O}}$	n	Linear GS98 $\mathscr{T}(\vec{\mathscr{O}})$	Linear GS98 p-value (σ)	Linear AGSS09met $\mathscr{T}(\vec{\mathscr{O}})$	Linear AGSS09met p-value (σ)	Gaussian process GS98 $\mathscr{T}(\vec{\mathscr{O}})$	Gaussian process GS98 p-value (σ)	Gaussian process AGSS09met $\mathscr{T}(\vec{\mathscr{O}})$	Gaussian process AGSS09met p-value (σ)
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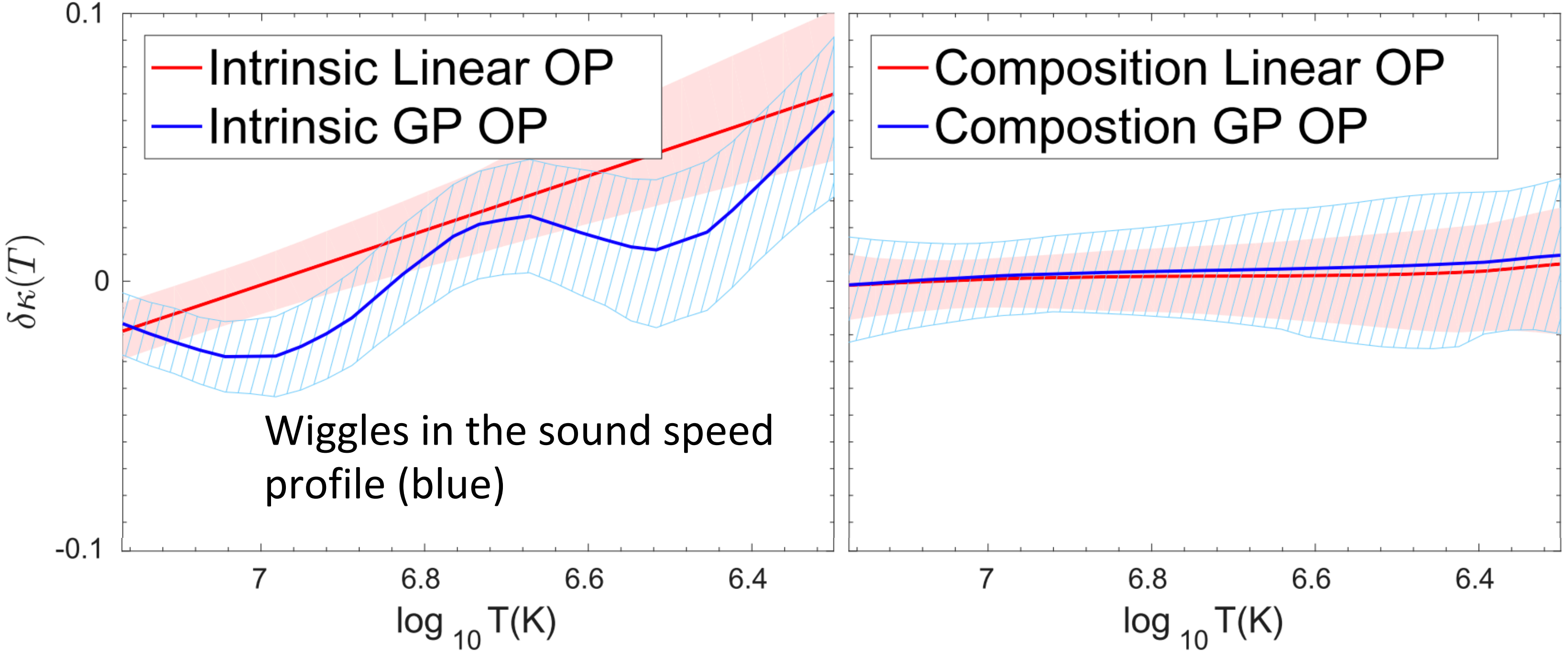
Data	B16-AGSS09met/B16-GS98 LIN-OP	B16-AGSS09met/B16-GS98 GP-OP
ν	-0.23	-0.27
$+Y_S+R_{CZ}$	-1.6	-2.2
+ sound speeds	-14.7	-4.1

Song et al. 2018

Solar opacities – what data tell us

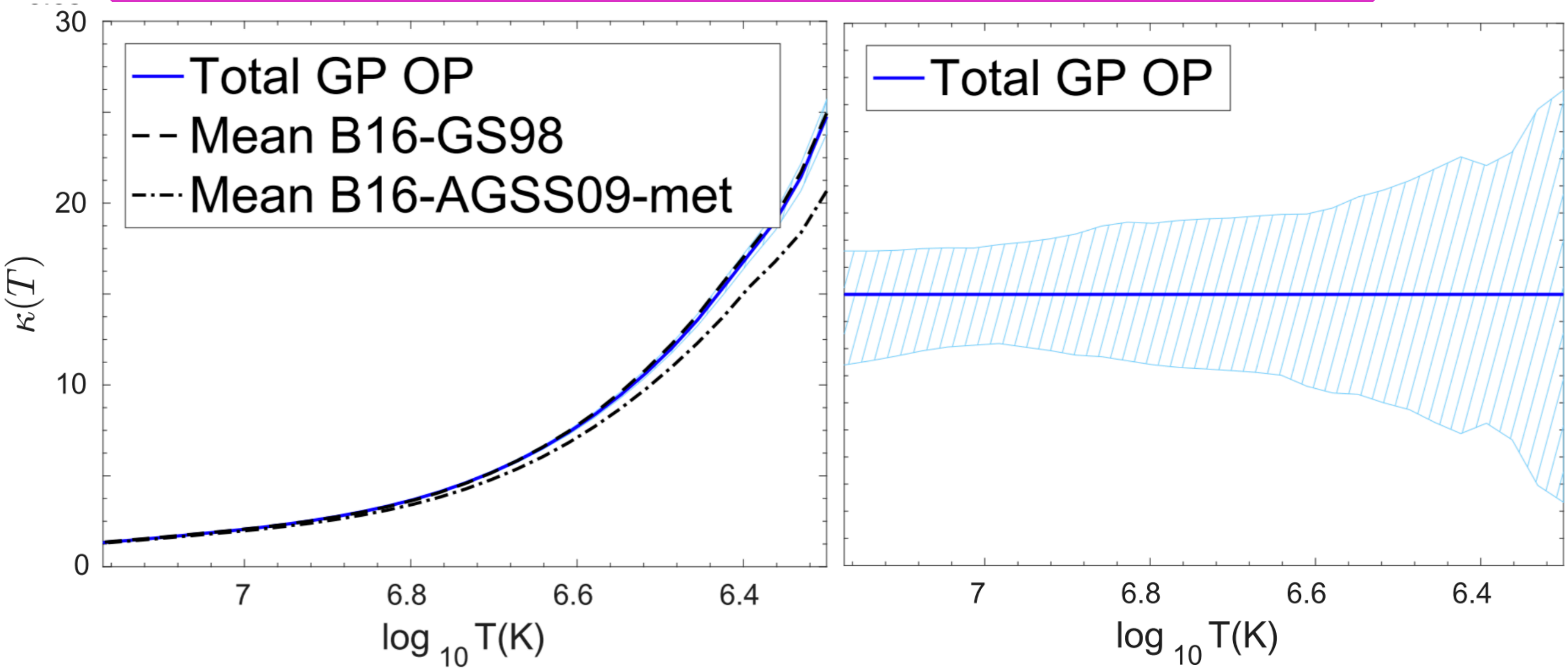
$$\delta\kappa(T) = \delta\kappa_I(T) + \delta\kappa_Z(T)$$

$$\delta\kappa_Z(T) \equiv \sum_i \frac{\partial \ln \kappa}{\partial \ln Z_i} \delta z_i$$



Solar opacities – what data tell us

Posteriors for all input parameters including opacity intrinsic changes



Total opacity uncertainty determined from solar data (& SSM physics): < 5%

SSM

$$m_{ij} = \frac{\partial \log c_i}{\partial \log p_j}$$

	$L_\odot$	$R_\odot$	$(Z/X)_\odot$
$\alpha_{\rm mlt}$	0.06	-0.19	0.06
$Y_{\rm ini}$	2.35	0.56	0.08
$Z_{\rm ini}$	-0.73	-0.14	1.11

constraints c_i

parameters p_j

SSM

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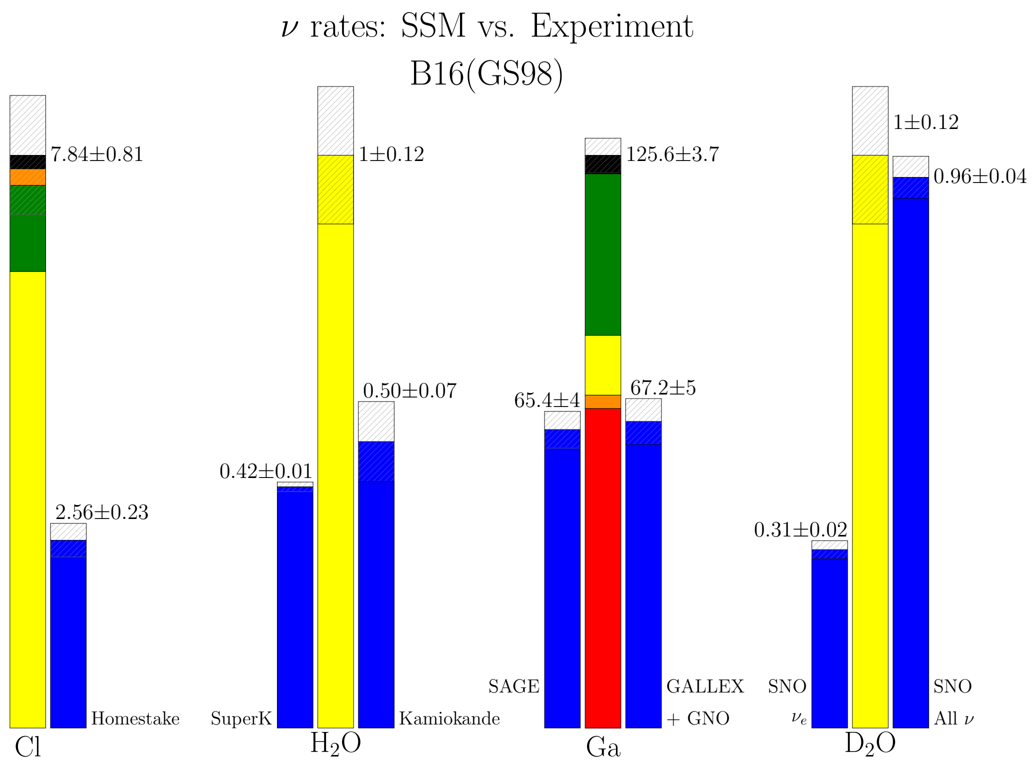
Z/X determines solar model composition
Z_{ini} & Y_{ini}
But it is in fact opacity (κ(Z) + Z)

Solar Neutrinos – experimental results



Solar Neutrinos – Borexino

^{8}B flux negligible for energetics (<0.01%)

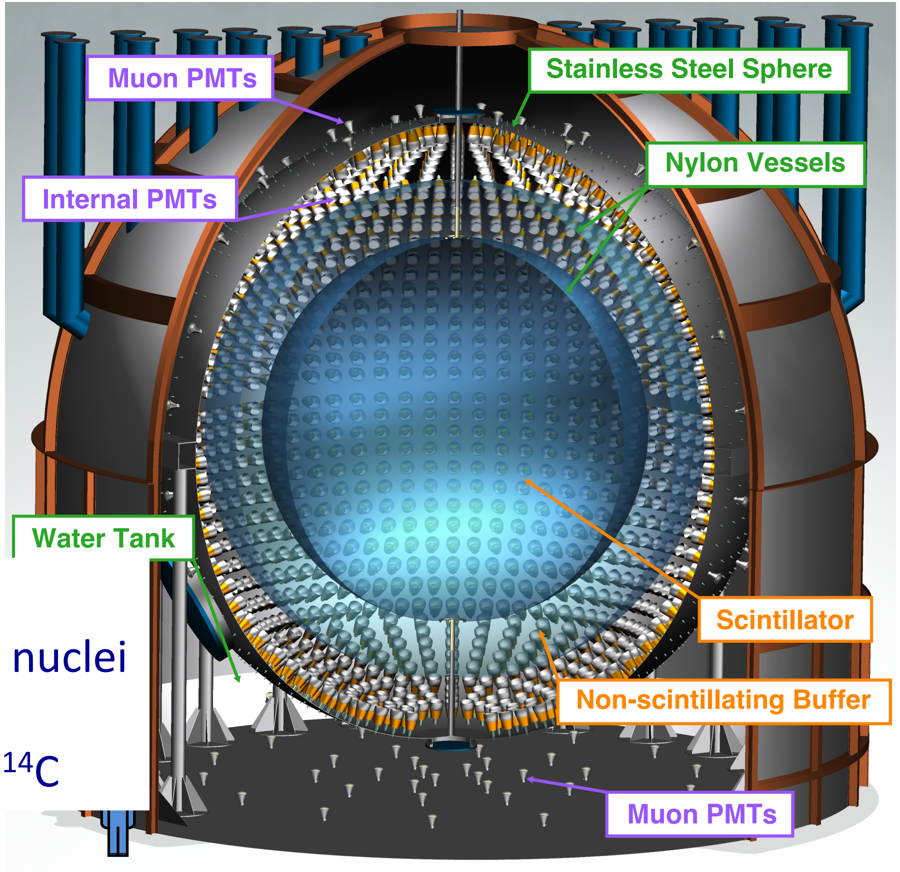
Other fluxes more relevant: ^{7}Be, pep, pp

Detector: organic liquid scintillator

high light output

very low energy threshold ~ 100keV

initial target: ^{7}Be



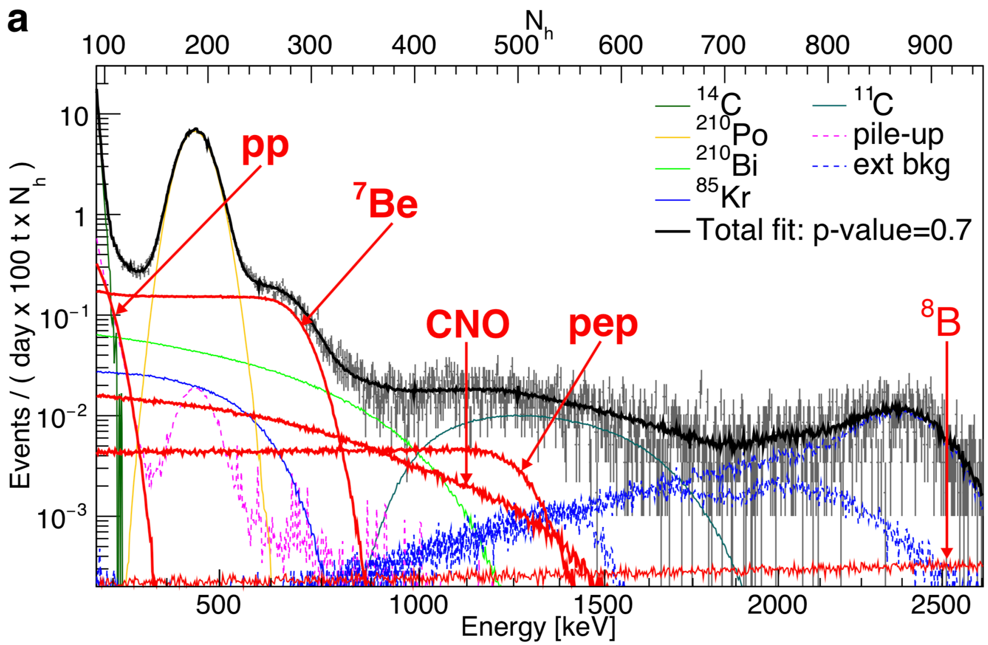
Extreme technical difficulty:

- many sources of background from radioactive nuclei
- high radiopurity needed
- scintillator produces its own background: ^{11}C, ^{14}C

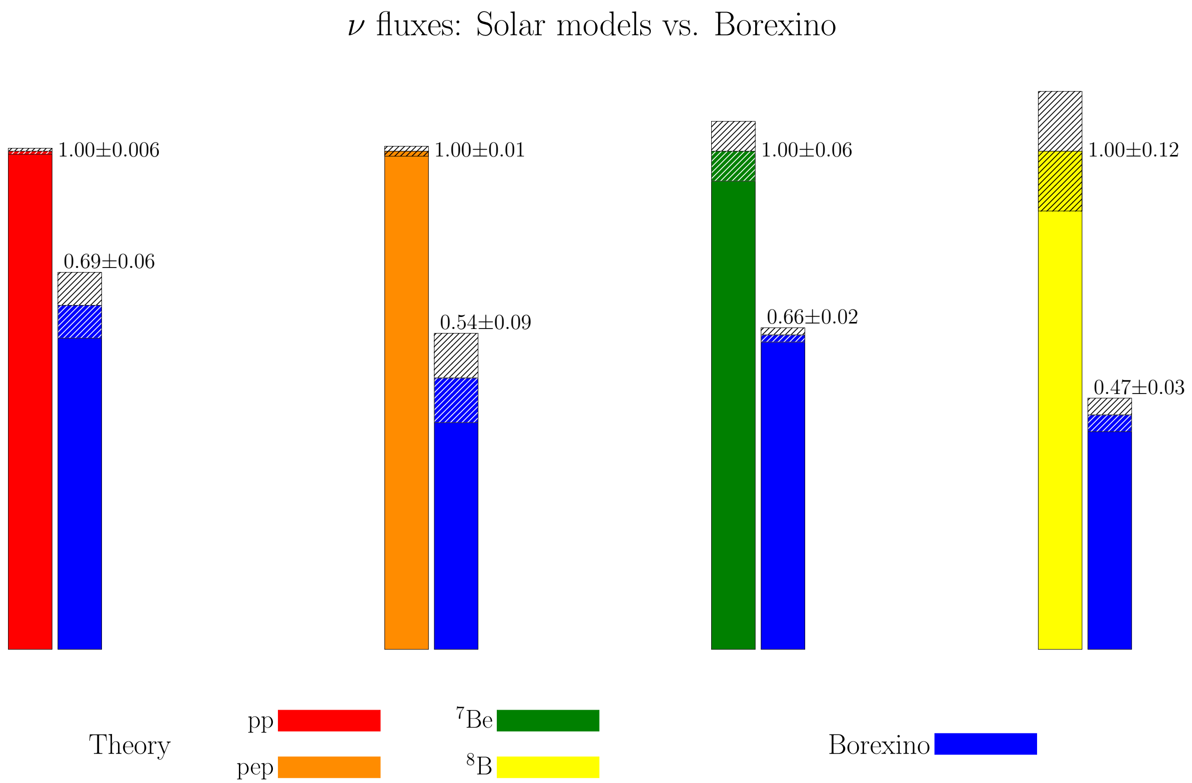
Solar Neutrinos – Borexino

Data taking for more than 10 years - Observed neutrino spectrum (published 2 weeks ago) – Caccinaga et al. 2018 (Borexino Collaboration)

Signal shown in red – measured spectrum in black



Solar Neutrinos – Borexino



No oscillations included – pure measurement

Solar Neutrinos – Borexino

Table 2 | Borexino experimental solar-neutrino results

Solar neutrino	Rate (counts per day per 100 t)	Flux (cm^{-2} s^{-1})	Flux–SSM predictions (cm^{-2} s^{-1})
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER-I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER-II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

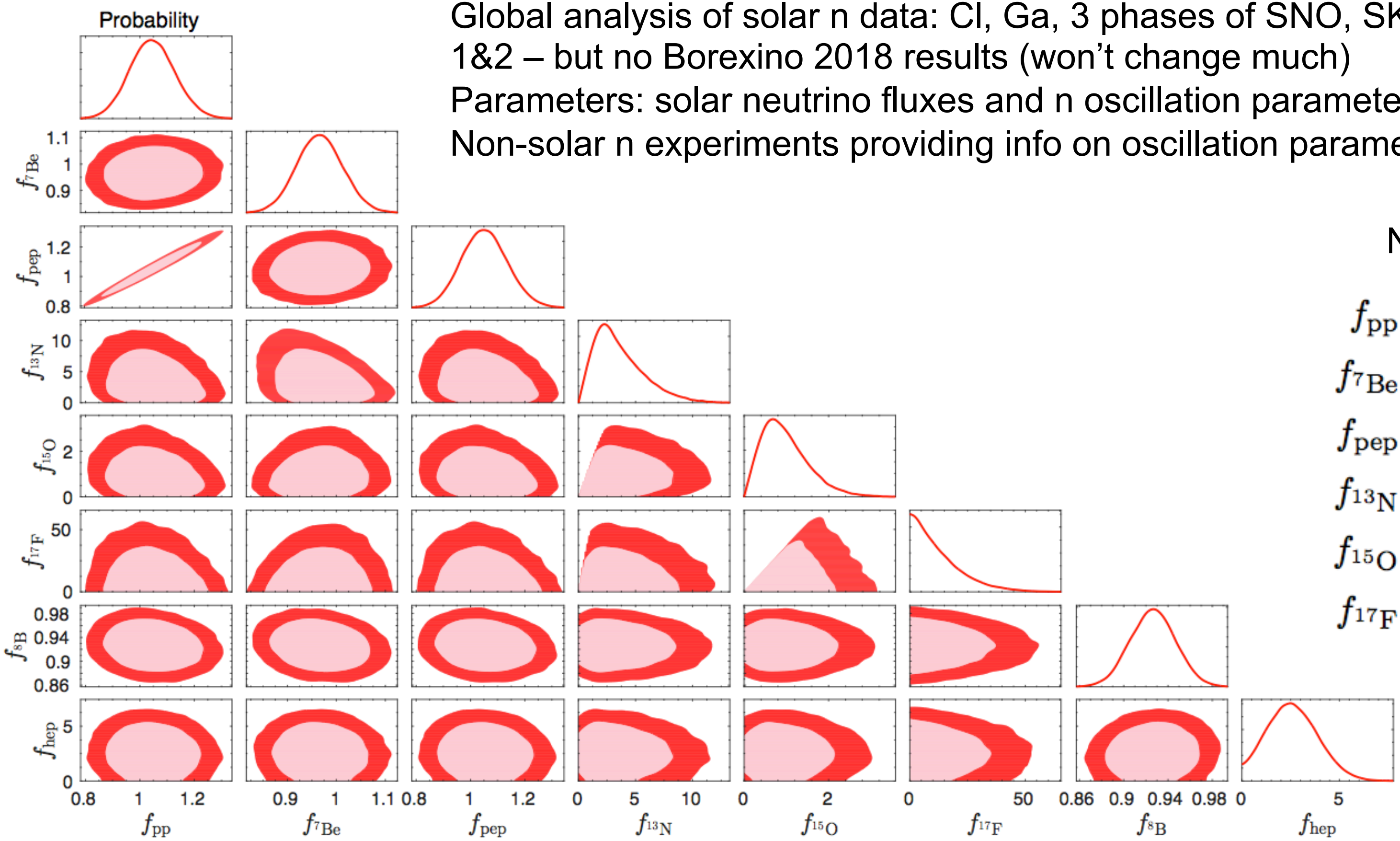
experimental fluxes after oscillations

Solar neutrinos – all experimental data

Global analysis of solar n data: Cl, Ga, 3 phases of SNO, SK I-IV, Borexino Phase 1&2 – but no Borexino 2018 results (won't change much)

Parameters: solar neutrino fluxes and n oscillation parameters (Δm^2_{21}, θ_{12}, θ_{13})

Non-solar n experiments providing info on oscillation parameters

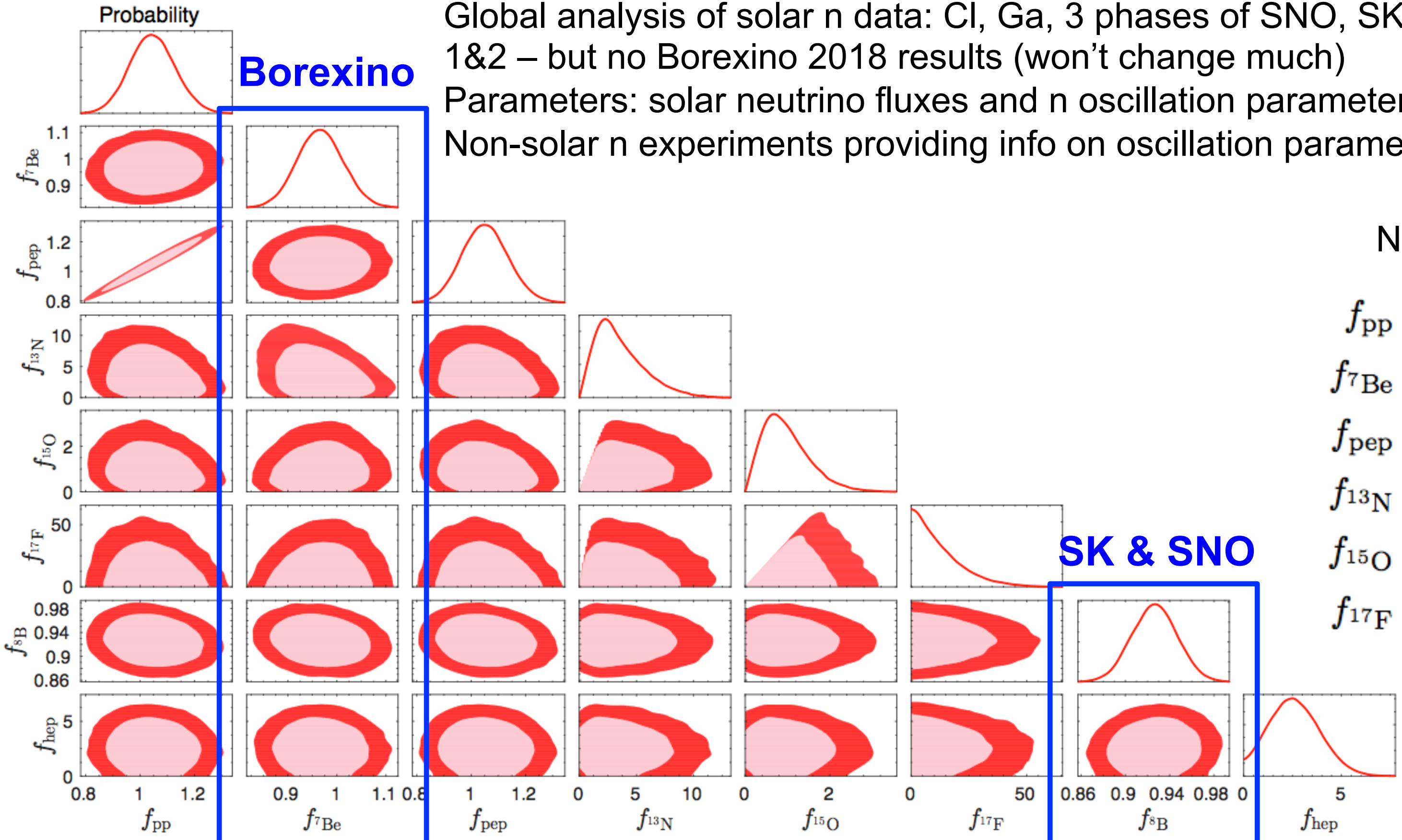


No lum. constraint

$$f_{pp} = 1.04 \pm 0.08 \, [^{+0.22}_{-0.20}] \, ,$$
$$f_{^7Be} = 0.97^{+0.04}_{-0.05} \, [\pm 0.12] \, ,$$
$$f_{pep} = 1.05 \pm 0.08 \, [^{+0.23}_{-0.20}] \, ,$$
$$f_{^{13}N} = 1.7^{+2.8}_{-1.0} \, [^{+8.4}_{-1.6}] \, ,$$
$$f_{^{15}O} = 0.6^{+0.7}_{-0.4} \, [\leq 2.6] \, ,$$
$$f_{^{17}F} \leq 15 \, [47] \, .$$

Bergstrom et al. 2016

Solar neutrinos – all experimental data



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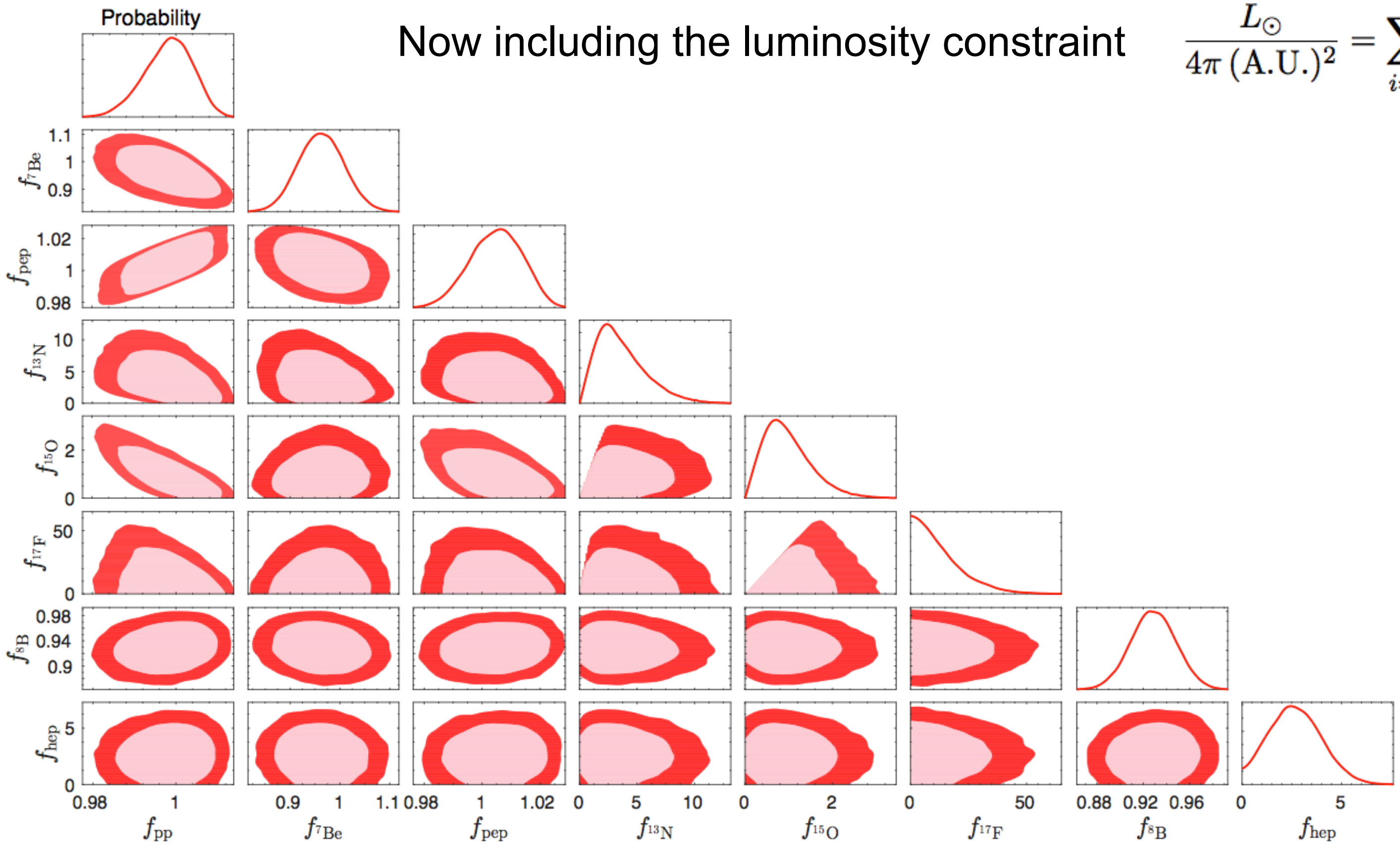
Solar neutrinos – all experimental data

Now including the luminosity constraint

$$\frac{L_\odot}{4\pi\,(\mathrm{A.U.})^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \,.$$



With lum. constraint

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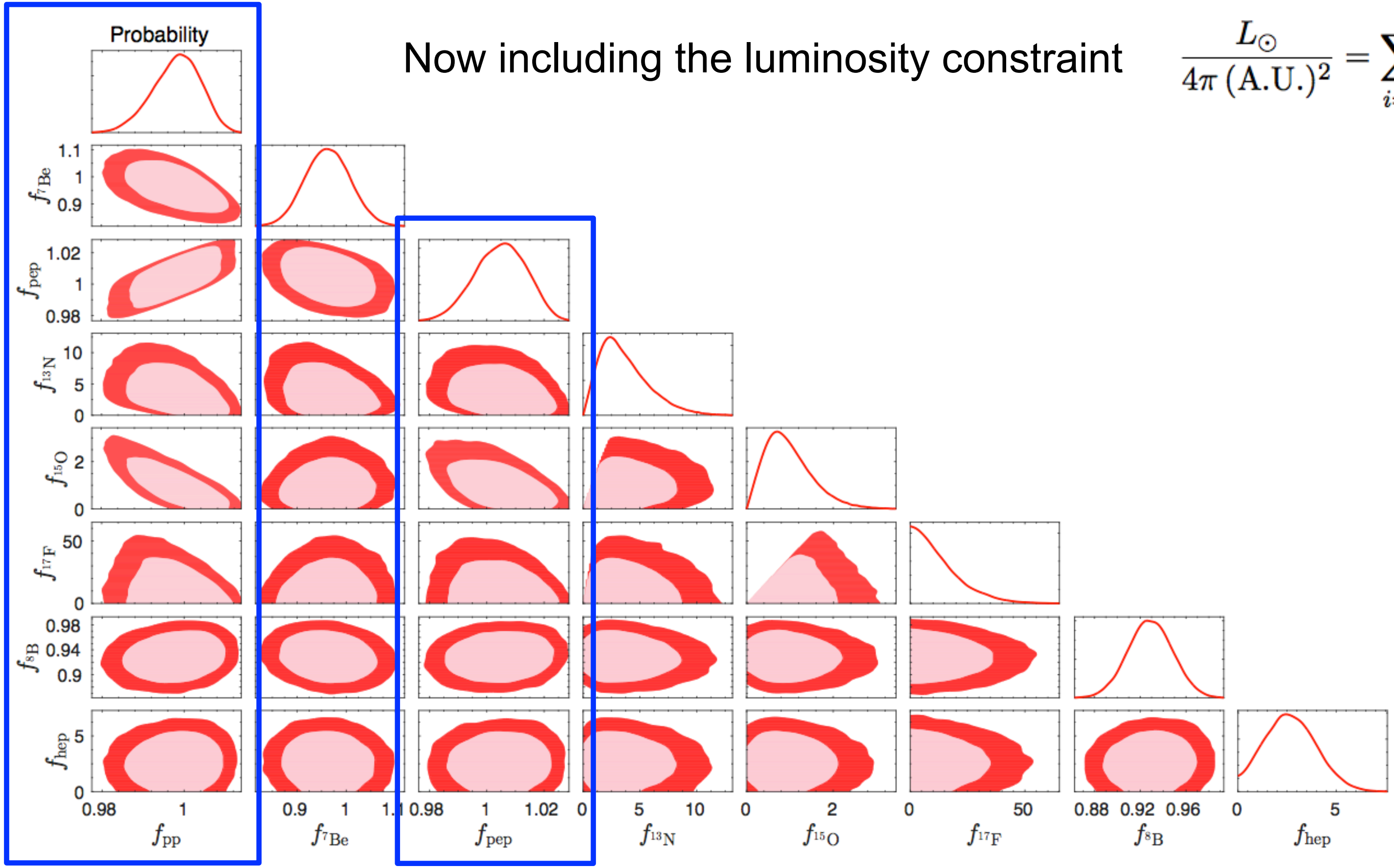
$$f_{^8B} = 0.92 \pm 0.02\,[\pm 0.05]\,,$$
$$f_{hep} = 2.4^{+1.5}_{-1.2}\,[\leq 5.9]\,,$$

Bergstrom et al. 2016

Solar neutrinos – all experimental data

Now including the luminosity constraint

$$\frac{L_\odot}{4\pi\,(\mathrm{A.U.})^2} = \sum_{i=1}^{8} \alpha_i \Phi_i\,.$$



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Bergstrom et al. 2016

Solar neutrinos – all experimental data

No luminosity constraint – purely experimental result

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 1.03^{+0.08}_{-0.07}\,\left[^{+0.21}_{-0.18}\right] \quad \text{and} \quad \frac{L_{\text{CNO}}}{L_\odot} = 0.008^{+0.005}_{-0.004}\,\left[^{+0.014}_{-0.007}\right].$$

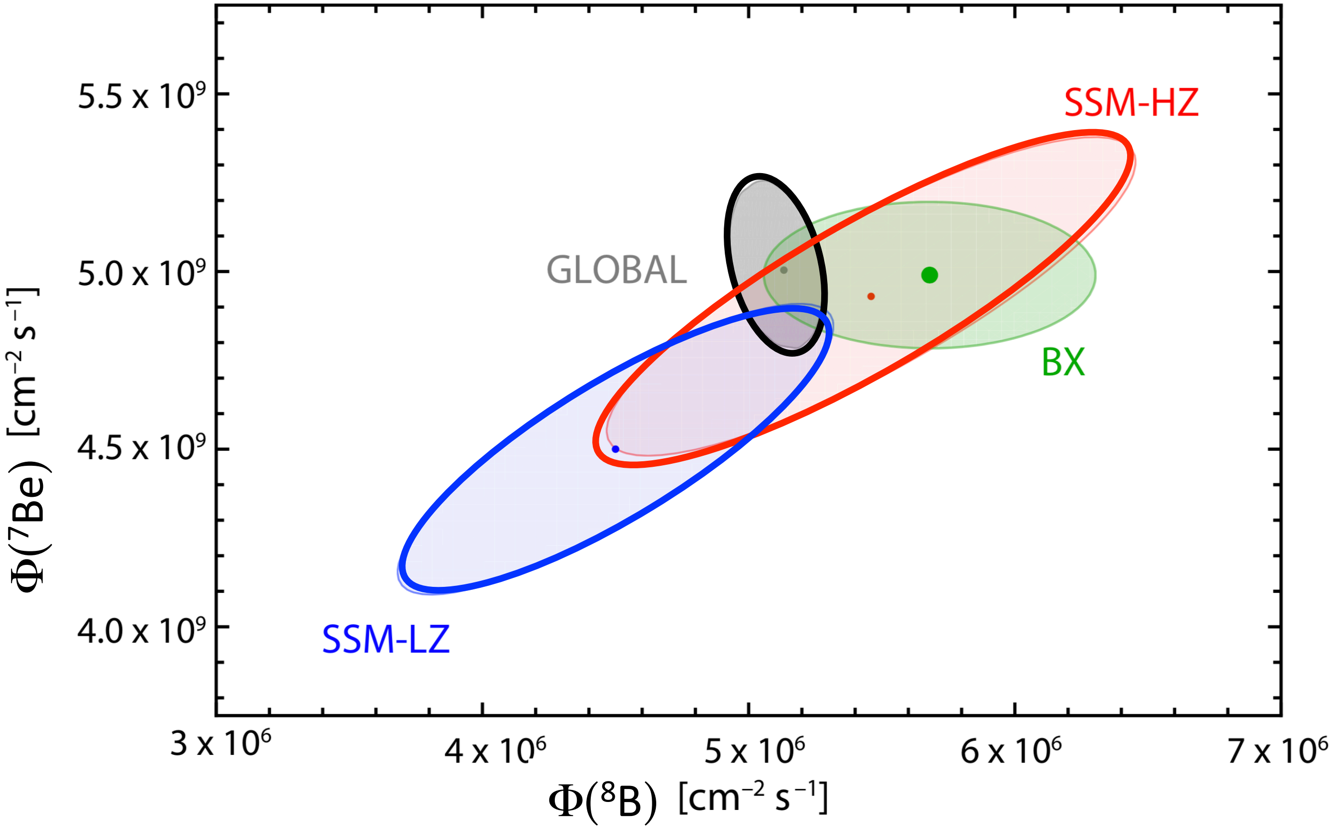
$$\frac{L_\odot(\text{neutrino-inferred})}{L_\odot} = 1.04\left[^{+0.07}_{-0.08}\right]\,\left[^{+0.20}_{-0.18}\right].$$

With luminosity constraint – $L_\odot = L_{nuc}$

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 0.991^{+0.005}_{-0.004}\,\left[^{+0.008}_{-0.013}\right] \iff \frac{L_{\text{CNO}}}{L_\odot} = 0.009^{+0.004}_{-0.005}\,\left[^{+0.013}_{-0.008}\right]$$

Bergstrom et al. 2016

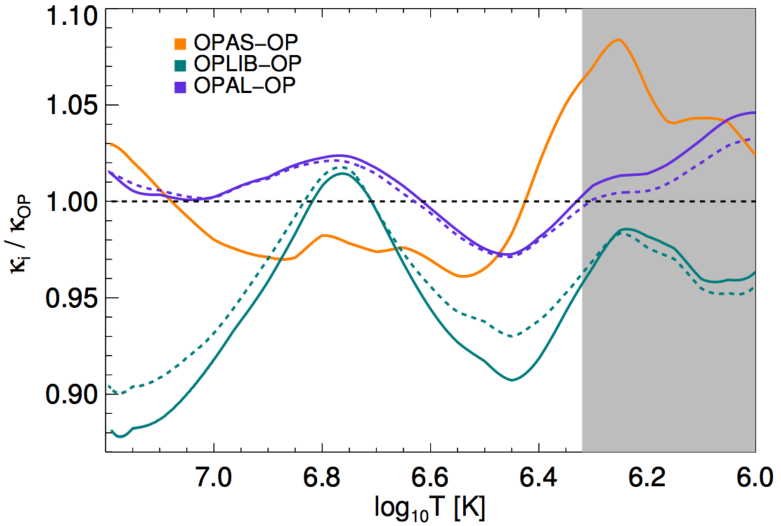
Solar neutrinos – all experimental data



Opacities – new calculations

Old generation
- OPAL – Iglesias et al. 1996
- Opacity Project (OP) – Badnell et al. 2005

New generation
- OPAS – Blancard et al. 2012 – now available Mondet et al. 2015 (only for AGSS09 composition)
- Los Alamos (OPLIB) – Colgan et al. 2016 – This is the most complete set from new generation

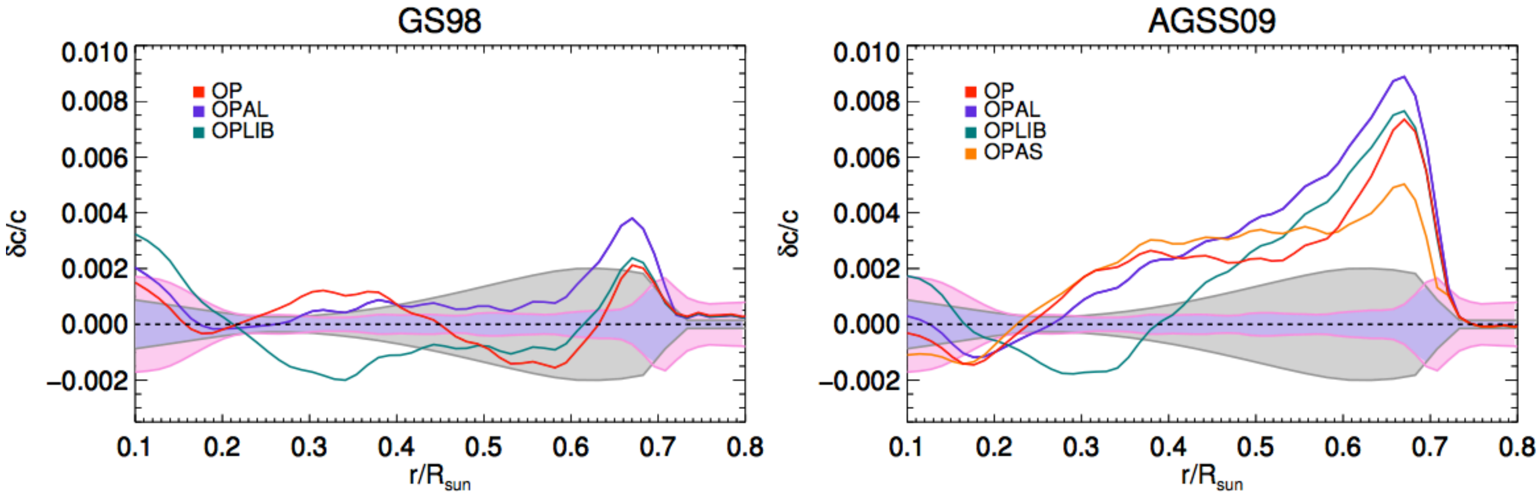


Solid – GS98

Dashed – AGSS09ph

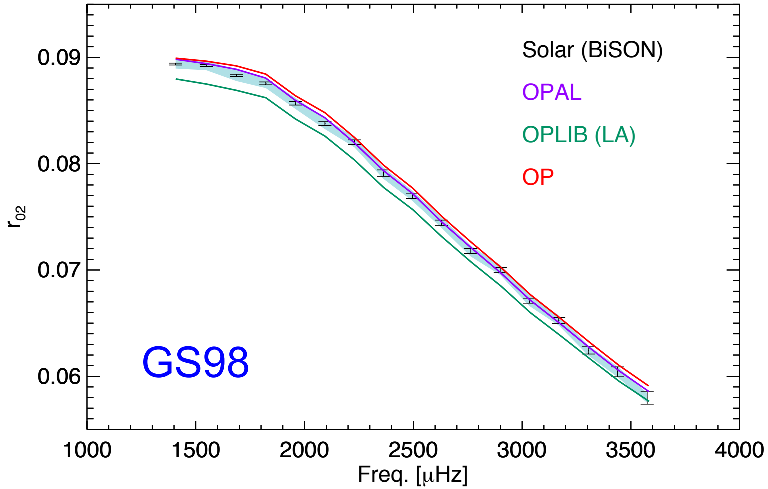
Not guaranteed that newer opacity models lead to higher opacity values

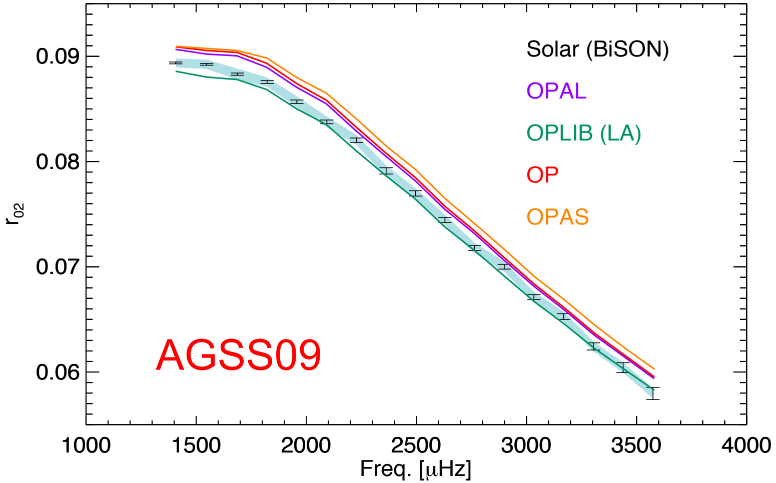
SSM with new opacities



New opacities lead to some variations in sound speed profiles but nothing too dramatic

SSM with new opacities

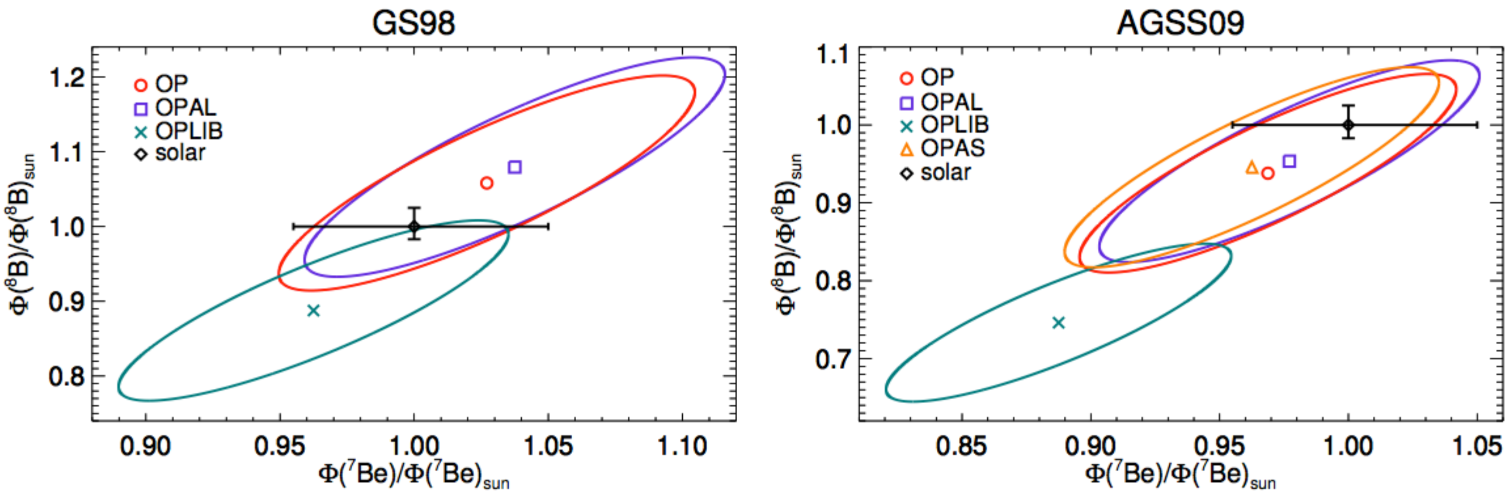




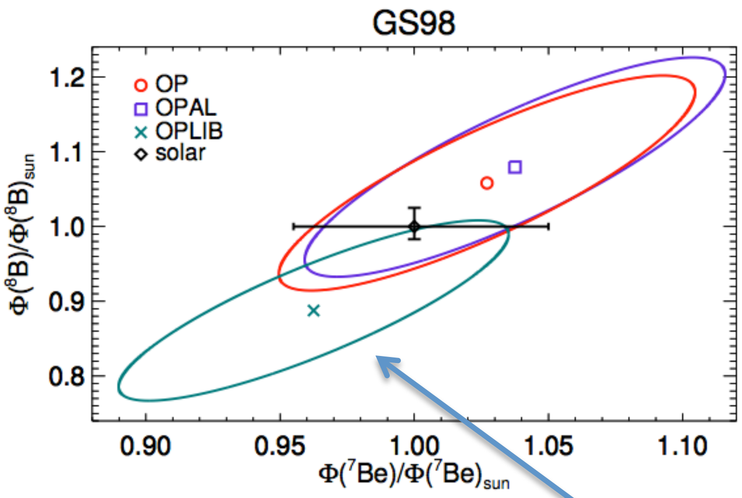
New OPLIB opacities lead to indecisive results for helioseismic probes

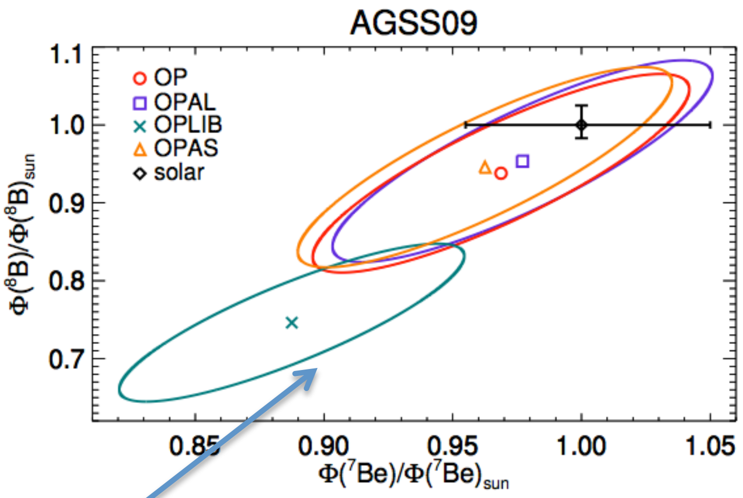
not all agree (disagree) with high(low) Z solar models

SSM with new opacities

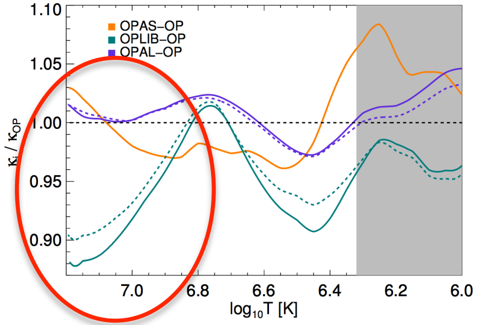


SSM with new opacities





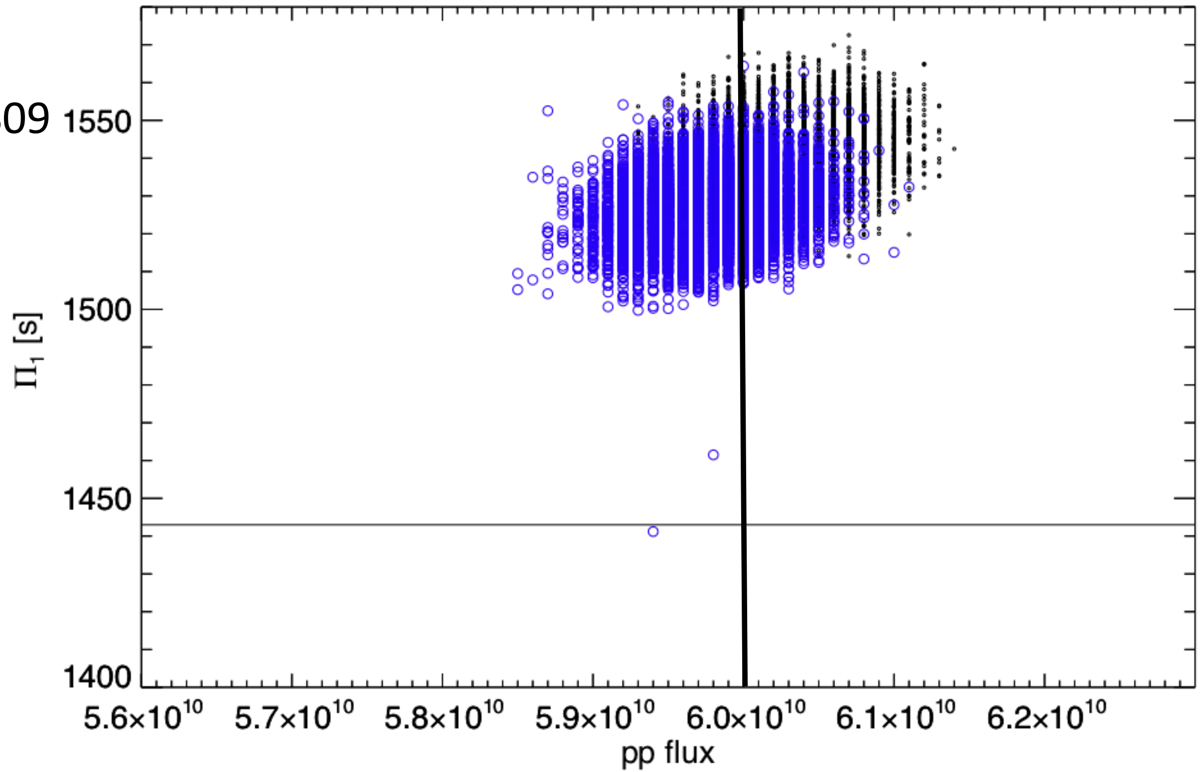
Solar νs strongly disfavor OPLIB opacities especially if low-Z accepted



pp-chain neutrinos and Π_1

Blue – GS98

Black – AGSS09



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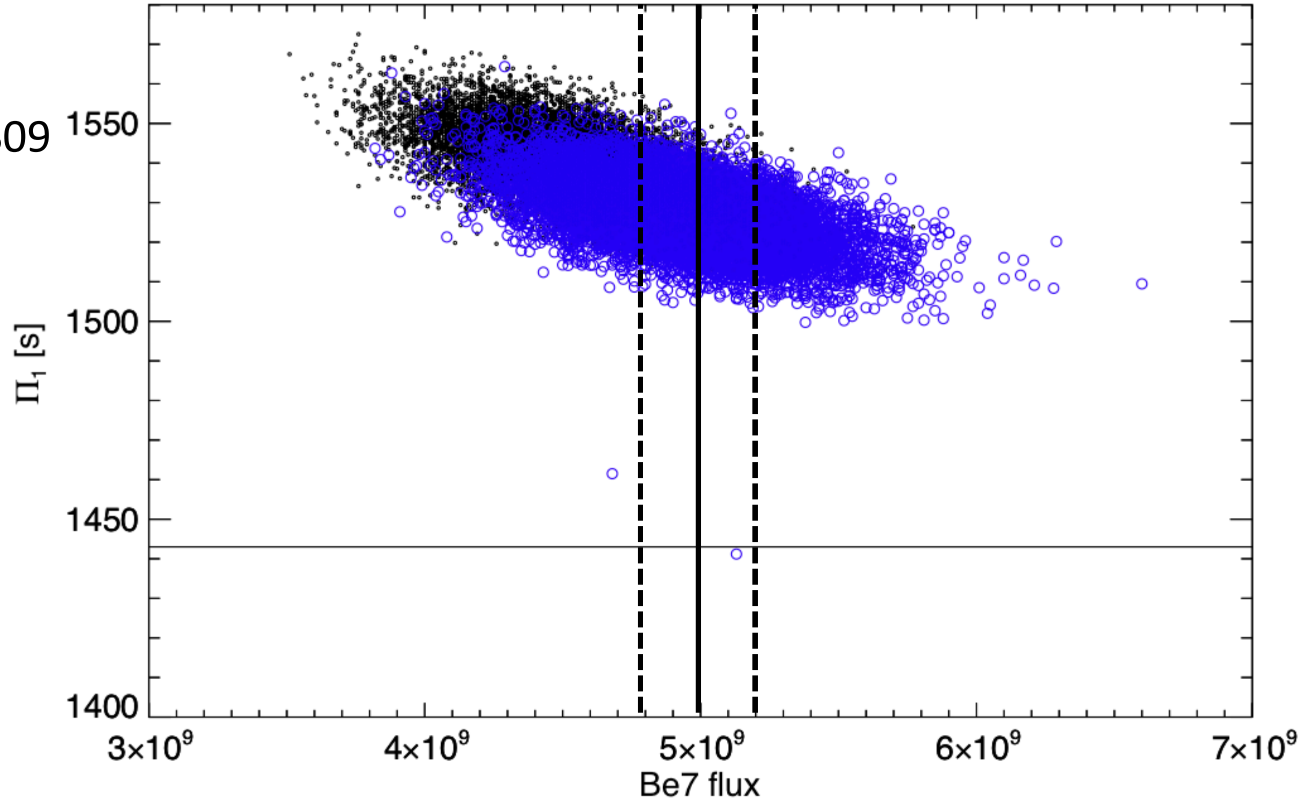

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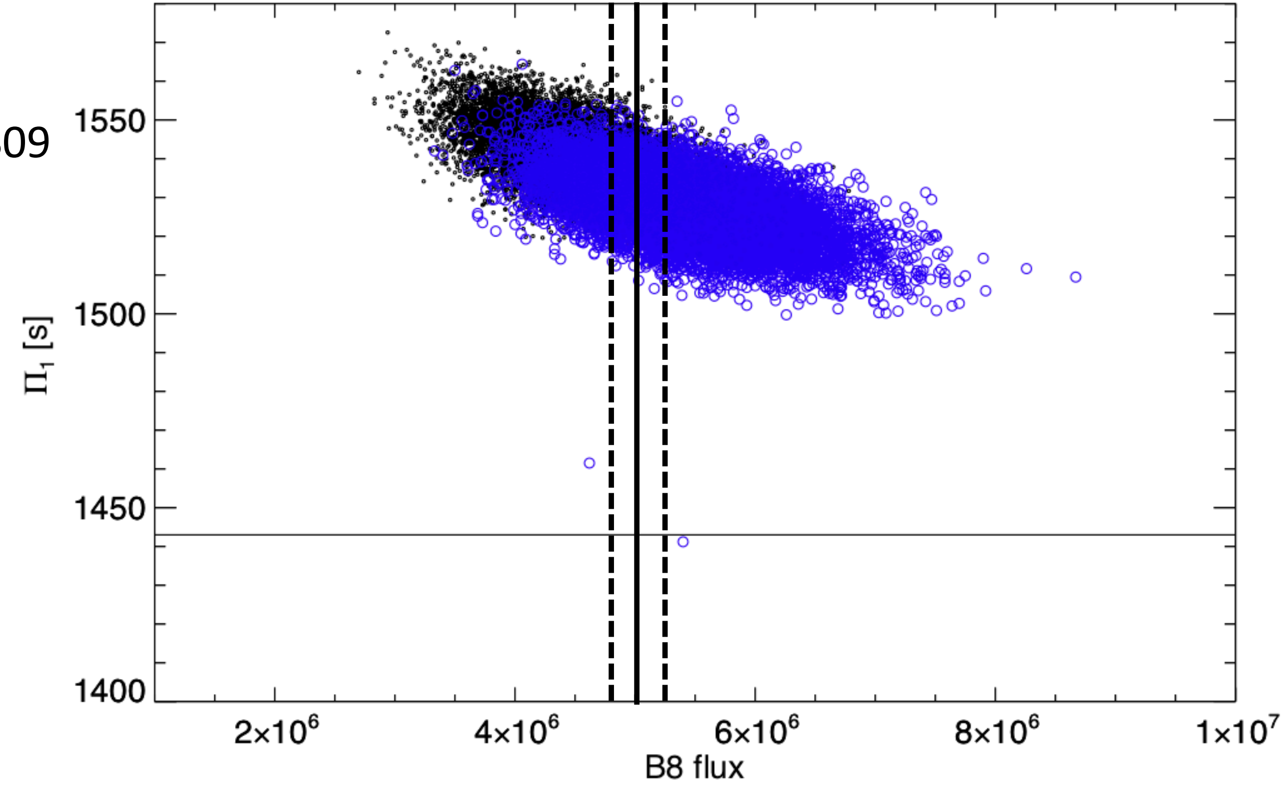
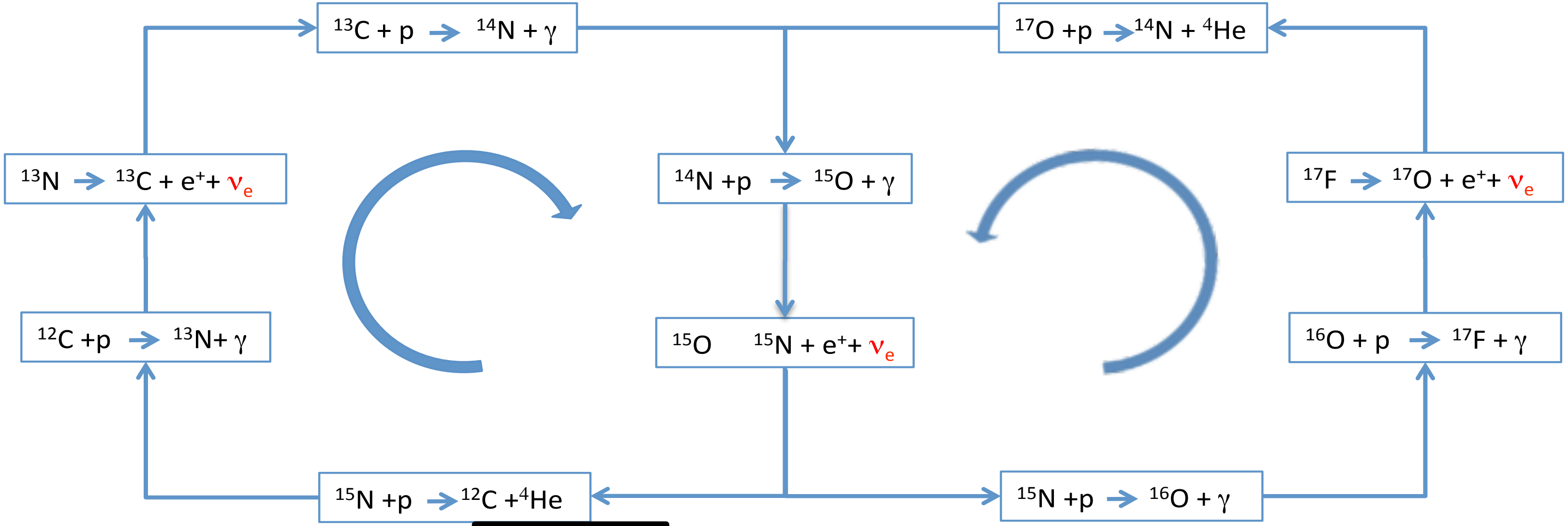


CNO fluxes

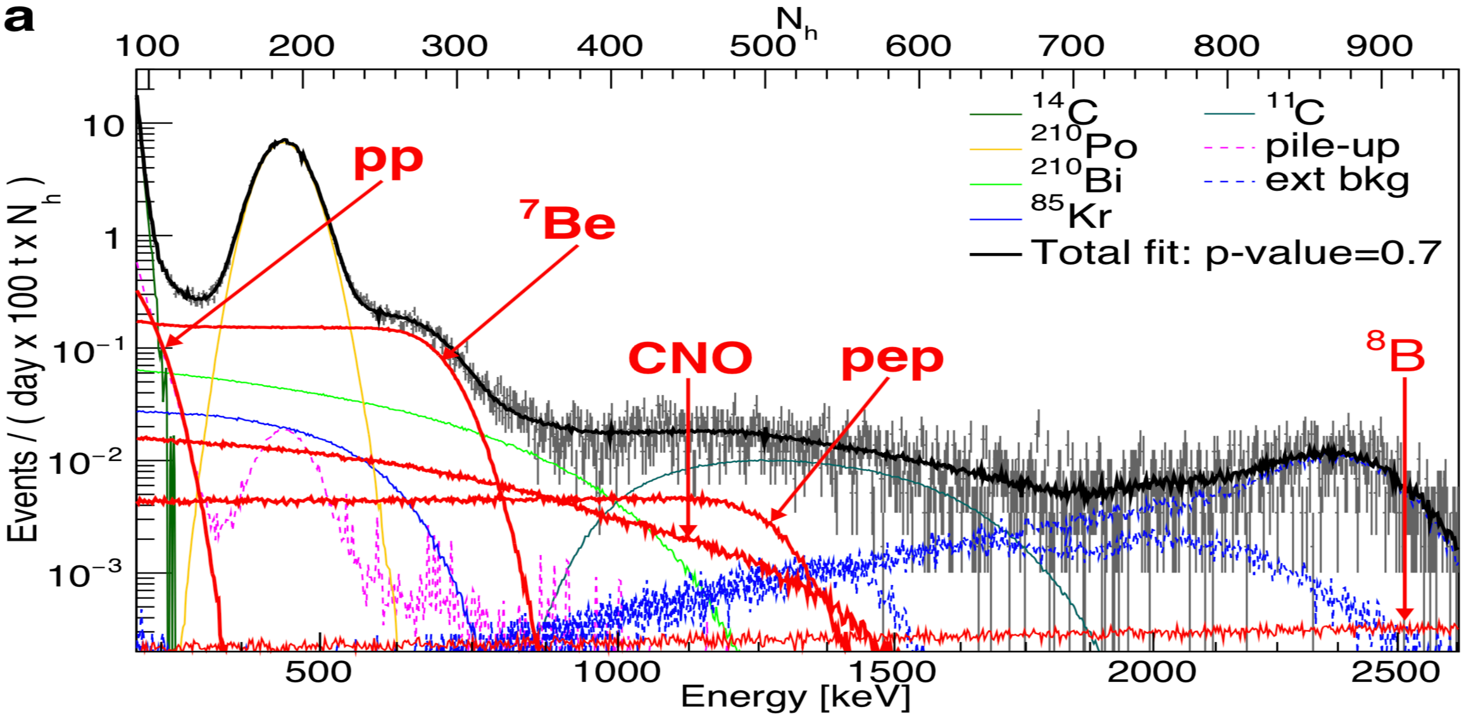


$$\epsilon_{\rm CNO} \approx 8.24 \times 10^{25} \rho X X_{\rm CNO} T_9^{-2/3} e^{-15.231/T_9^{1/3} - (T_9/0.8)^2} \ {\rm erg\ g^{-1} s^{-1}}$$

Core temperature fixed by 8B (very sensitive)

ε_{CNO} measured by neutrinos -- > determine X_{CNO}

CNO in Borexino

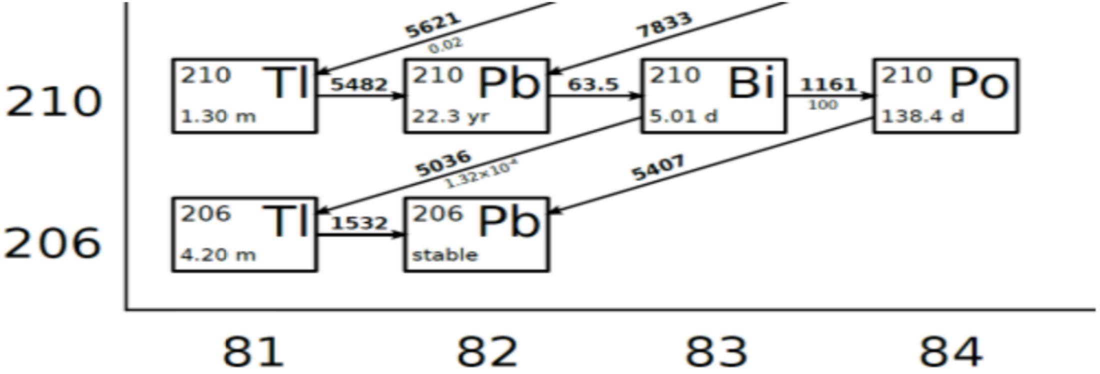


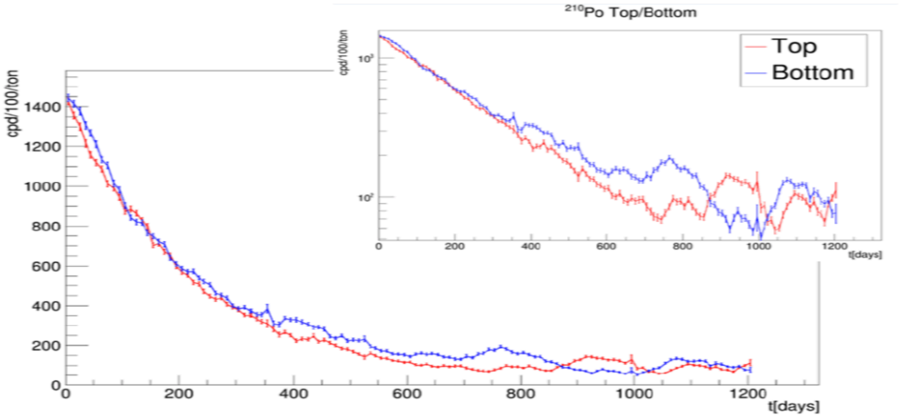
Difficulty: ^{210}Bi background

One way: determine ^{210}Bi by measuring ^{210}Po

Strategy towards CNO measurement

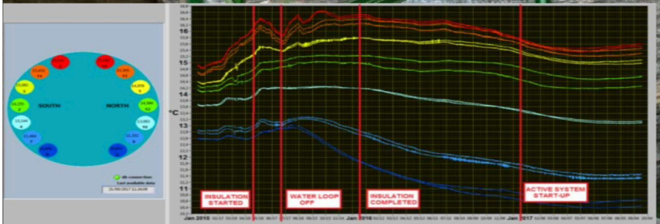
- Main route: using ^{210}Bi-^{210}Po temporal evolution to measure "support term" for ^{210}Po (secular equilibrium in ^{210}Pb sub-chain)
- Option: further purification of the LS by water extraction to reduce ^{210}Bi

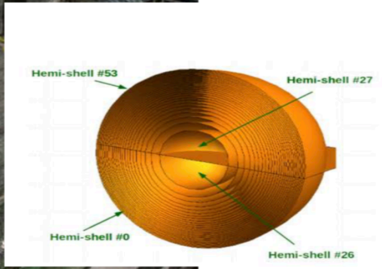


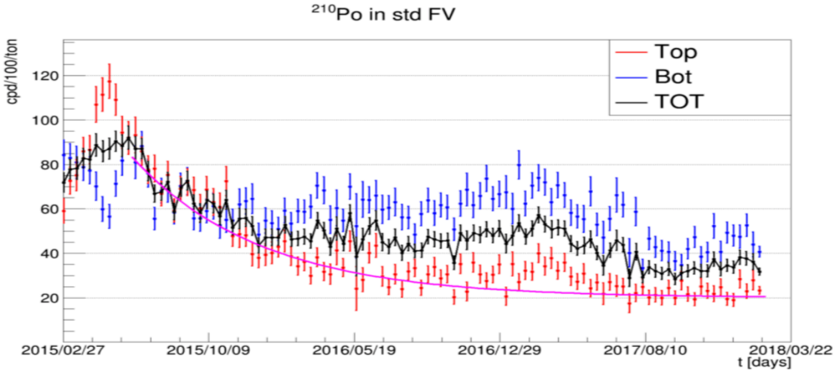


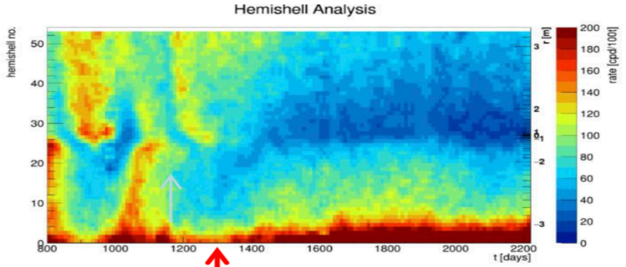
Instabilities observed in the temporal evolution of the ^{210}Po (making impossible precision evaluation of the ^{210}Bi) were found to be the result of the temperature instabilities of the surrounding

Hardware solution for thermal stabilization : thermal insulation of the external tank



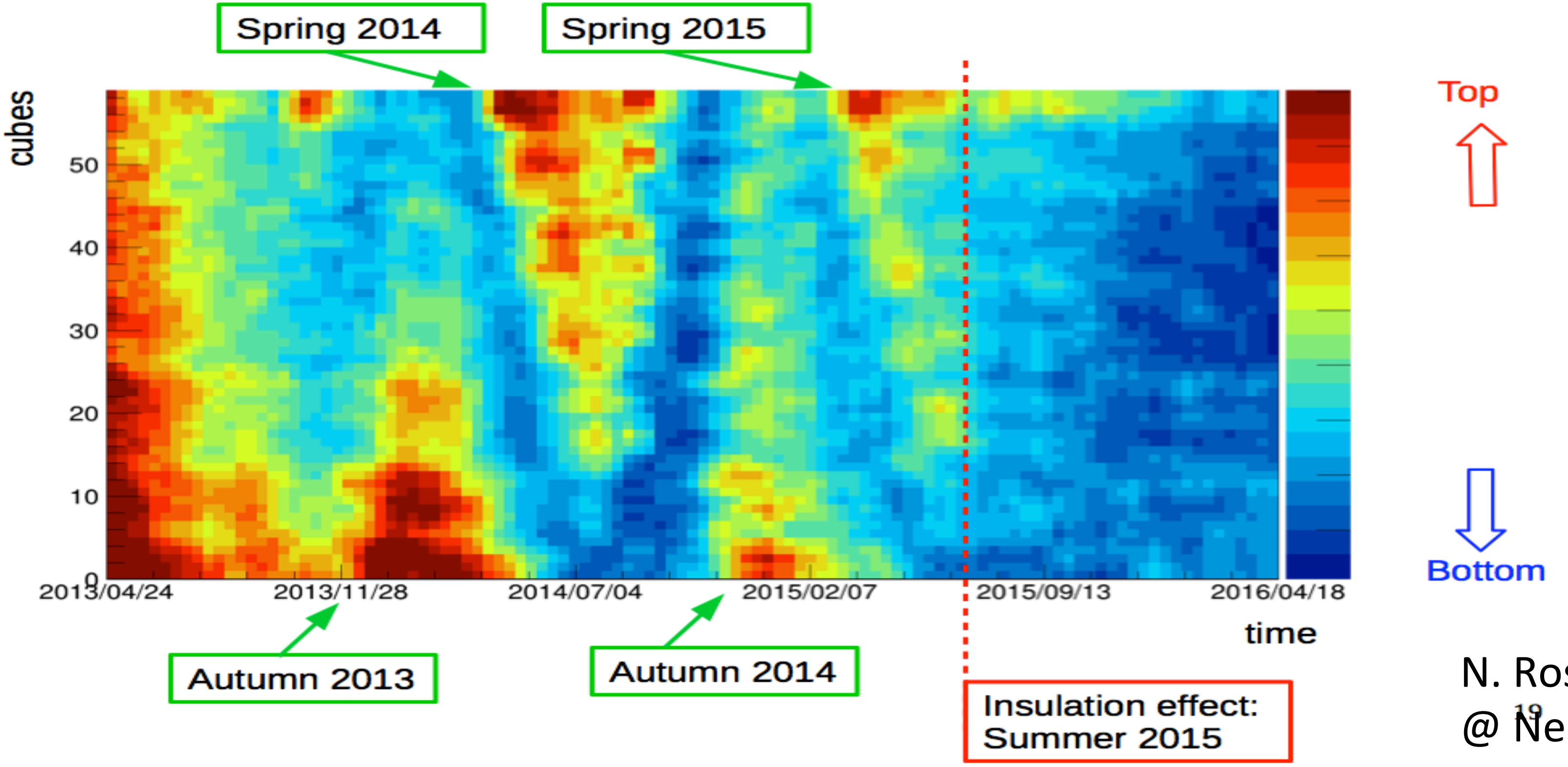






day 1300: insulation (summer 2015)

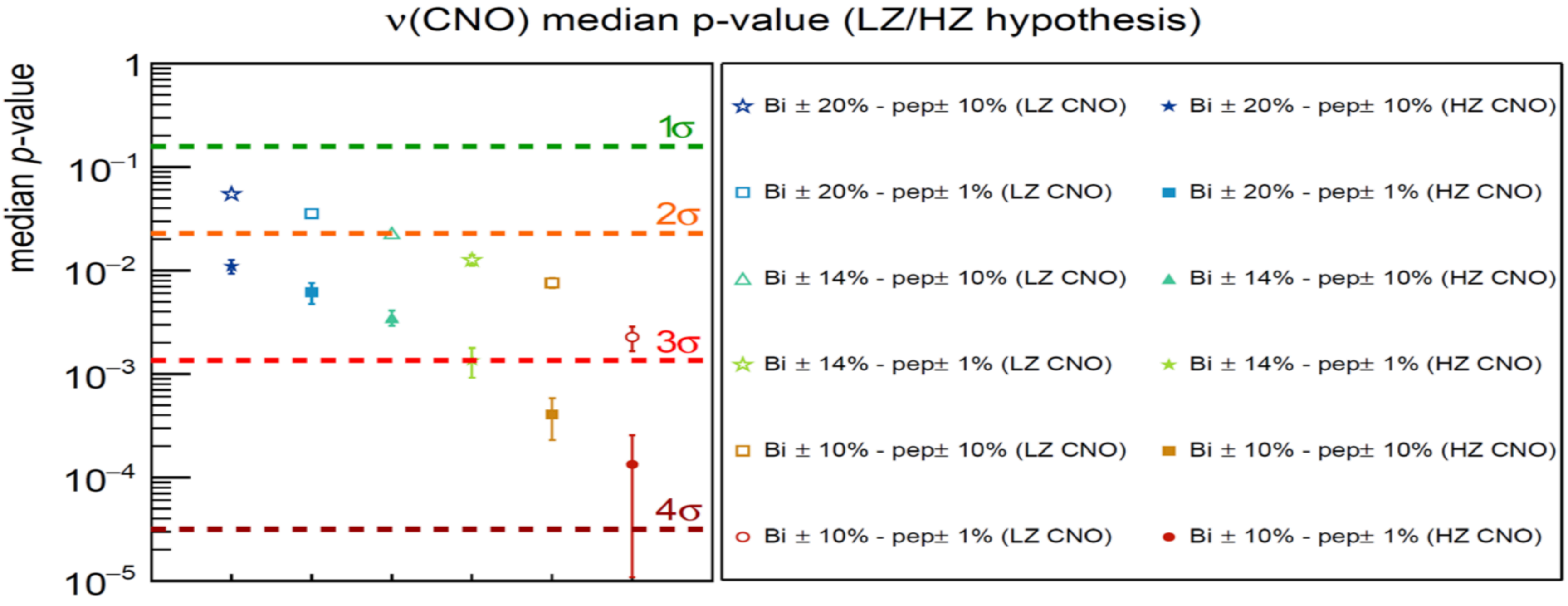
^{210}Po in 60 cubes (r < 3 m)



N. Rossi
@ Neutrino 2016

CNO sensitivity

Depends on both ^{210}Bi and pep-neutrino rates. We assume that ^{210}Bi will be measured (10-20%) and pep-rate can be constrained by constraining pp/pep ratio in the fit.



Power-law dependences

#	S11	S33	S34	Se7	S17	Shep	S114	S116
pp	0.101	0.034	−0.066	0.000	0.000	0.000	−0.006	−0.000
pep	−0.222	0.049	−0.095	0.000	0.000	0.000	−0.010	0.000
hep	−0.104	−0.463	−0.081	0.000	0.000	1.000	−0.006	−0.000
Be7	−1.035	−0.440	0.874	0.002	−0.001	0.000	−0.001	0.000
B8	−2.665	−0.419	0.831	−0.998	1.028	0.000	0.007	0.000
N13	−2.114	0.030	−0.061	0.001	0.000	0.000	0.762	0.001
O15	−2.916	0.023	−0.050	0.001	0.000	0.000	1.051	0.001
F17	−3.072	0.021	−0.046	0.001	0.000	0.000	0.007	1.158
Ys	0.131	−0.005	0.010	0.000	0.000	0.000	0.001	0.000
RCZ	−0.059	0.002	−0.004	0.000	0.000	0.000	−0.000	−0.000

Power-law dependences

age	diff	lumi	opacA	opacB
−0.085	−0.013	0.773	−0.084	−0.019
−0.003	−0.018	0.999	−0.270	−0.001
−0.125	−0.039	0.149	−0.395	−0.107
0.753	0.132	3.466	1.332	0.380
1.319	0.278	6.966	2.863	0.658
0.863	0.345	4.446	1.592	0.314
1.328	0.395	5.960	2.220	0.456
1.424	0.418	6.401	2.427	0.503
−0.195	−0.077	0.351	0.608	0.255
−0.081	−0.018	−0.016	0.008	−0.079

Power-law dependences

C	N	O	Ne	Mg	Si	S	Ar	Fe	
-0.007	-0.001	-0.005	-0.005	-0.003	-0.009	-0.006	-0.001	-0.019	pp
-0.014	-0.002	-0.011	-0.005	-0.003	-0.012	-0.013	-0.004	-0.060	pep
-0.008	-0.002	-0.024	-0.018	-0.016	-0.036	-0.027	-0.006	-0.066	hep
-0.000	0.002	0.057	0.053	0.052	0.106	0.075	0.018	0.209	be7
0.022	0.007	0.128	0.102	0.092	0.198	0.138	0.034	0.498	b8
0.864	0.154	0.073	0.051	0.047	0.110	0.078	0.020	0.272	n13
0.819	0.209	0.104	0.075	0.068	0.153	0.107	0.027	0.388	o15
0.026	0.007	1.112	0.082	0.074	0.167	0.116	0.029	0.424	f17
-0.008	-0.001	0.019	0.032	0.032	0.062	0.042	0.010	0.084	ys
-0.003	-0.003	-0.024	-0.012	-0.004	0.003	0.005	0.001	-0.008	rcz

Solar Neutrinos – Borexino

Table 2 | Borexino experimental solar-neutrino results

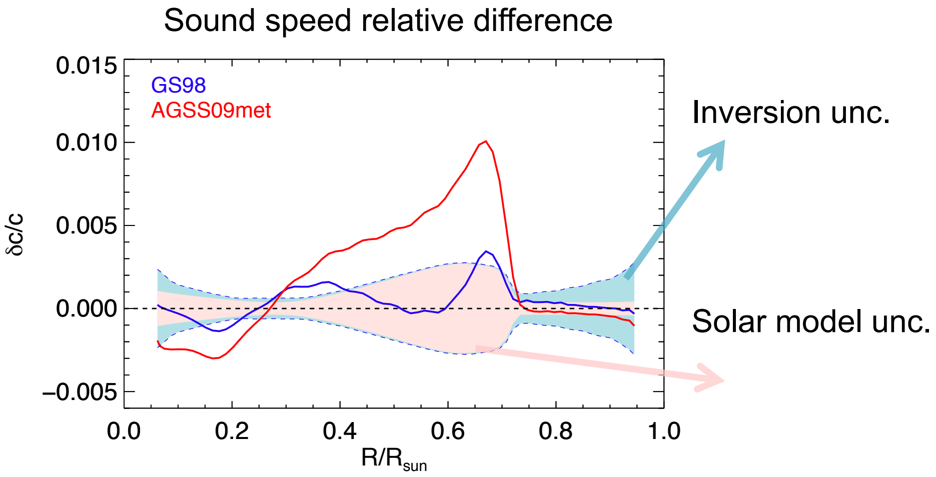
Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2}\,s^{-1}$)	Flux–SSM predictions ($cm^{-2}\,s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER\text{-}II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

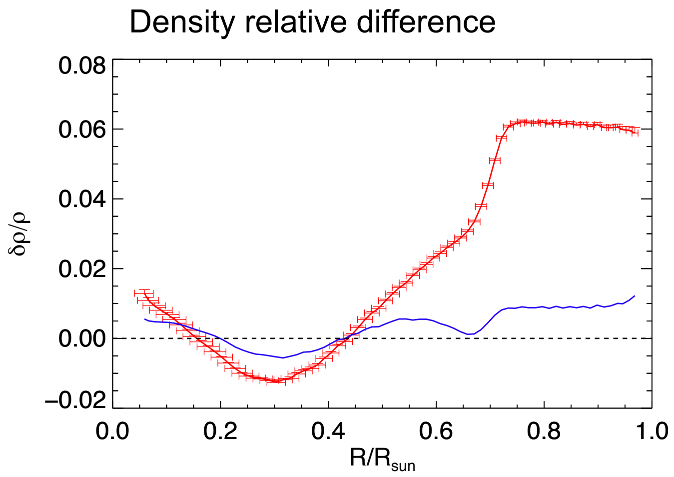
	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$

experimental fluxes for oscillations

Esteban et al. 2017

SSM – the problem



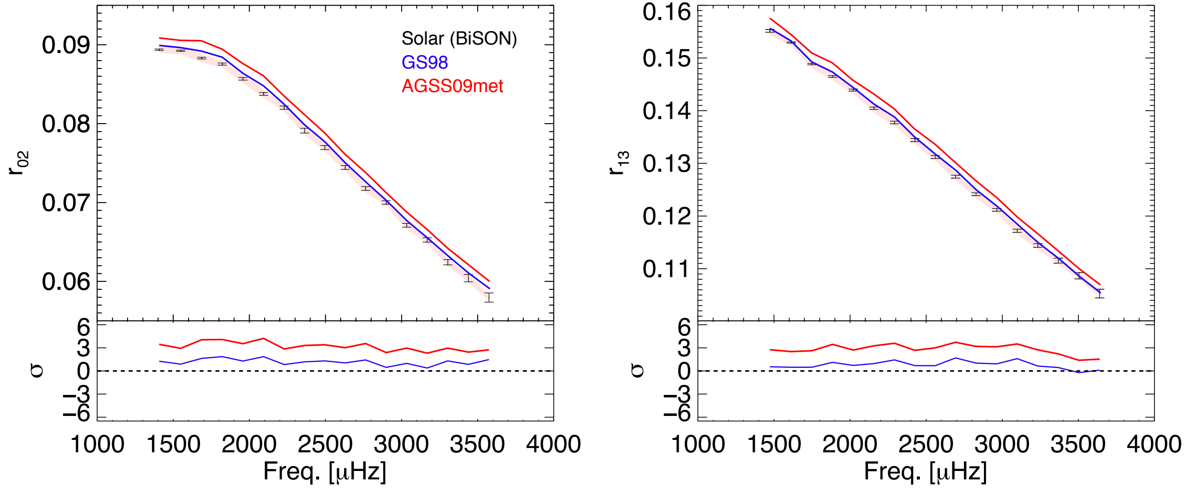


	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

SSM – the problem

Core structure as seen by frequency separation ratios

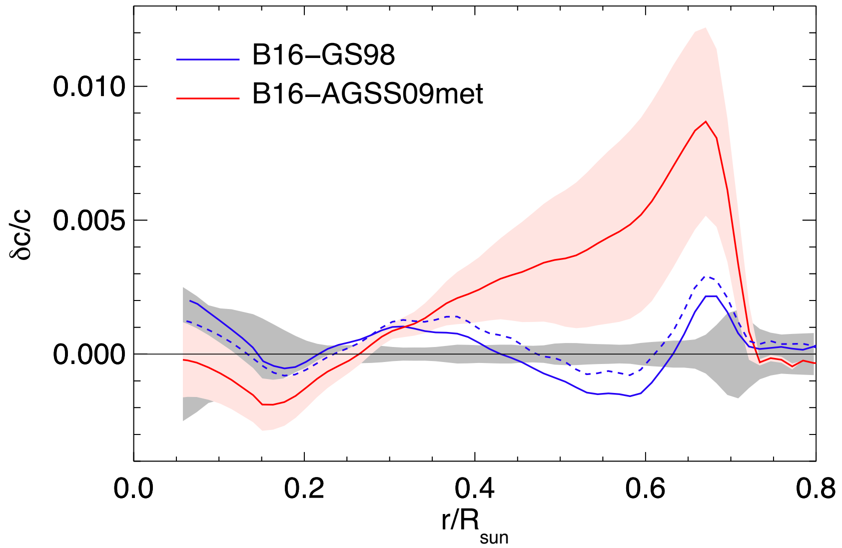
$$\delta\nu_{n,l} \simeq -(4\ell+6)\frac{\Delta\nu}{4\pi^2\nu_{n,l}}\int_0^R \frac{dc}{dr}\frac{dr}{r}$$



All helioseismic probes show consistent results:
Given current input physics, low-Z models are disfavored

SSM – B16 models

Small changes in helioseismic probes

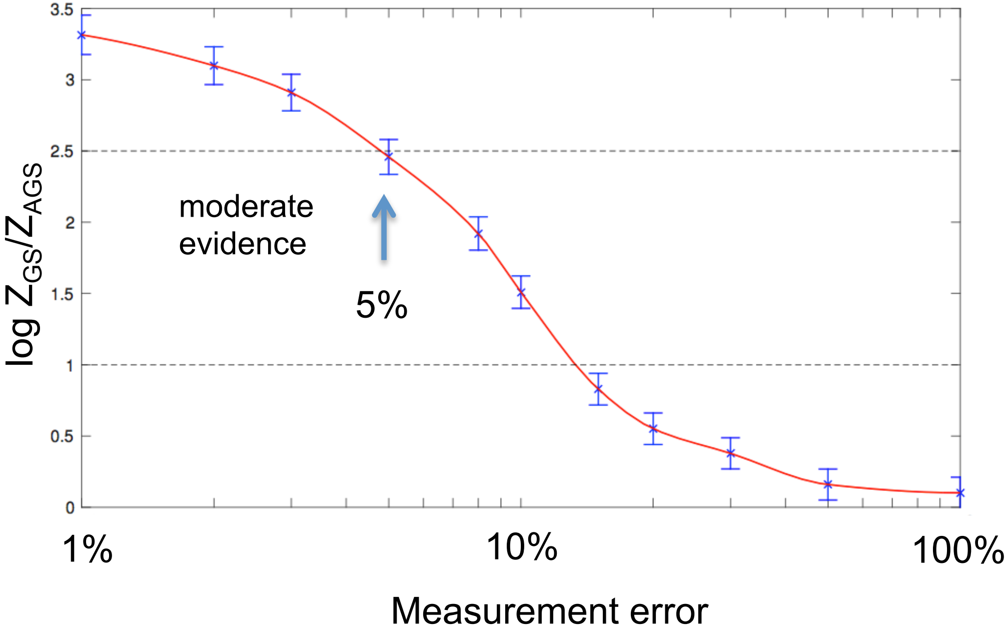


Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{\rm CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0005 ± 0.0004	0.0021 ± 0.001	—

SSM: the need for CN(O)

New opacity calculations do not alter state-of-the-art or complicate matters more

Most robust way to break the opacity < -- > composition degeneracy is through CNO ns



n-experiments only

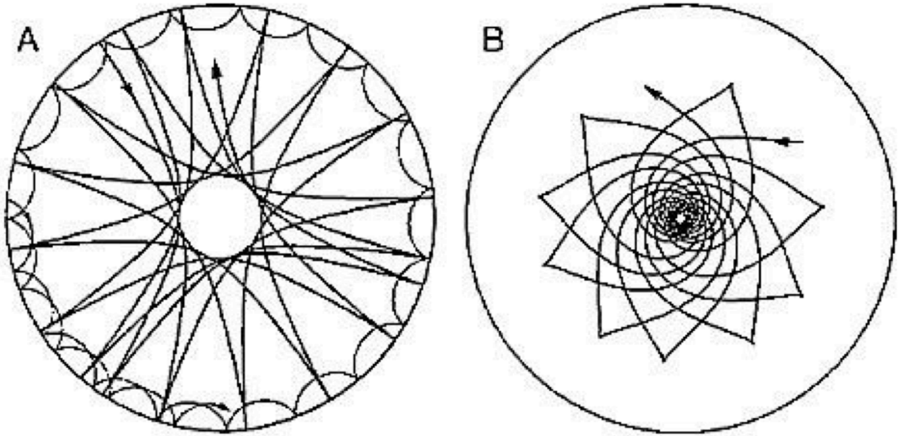
Bergstrom et al. 2016

Discriminating power can improve if model information is added (Haxton et al. 2008)

Next talk by F. Villante

g-modes detection (finally?)

g-modes probe inner regions – but strongly damped in the surface – tiny amplitudes & high background



direct searches for g-modes have failed (despite claims in Garcia et al. 2007)

Fossat et al. 2017 use new method: long term modulations in p-mode spectrum

Claim detections of more than 200 g-modes of angular degree l = 1 , 2

g-modes detection (finally?)

Two important claims in Fossat et al. 2017

1) Asymptotic period spacings for l= 1 , 2

$$\Pi_\ell = \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left[\int_0^{R_{CZ}} N \frac{dr}{r} \right]^{-1} \qquad N = g\left(\frac{1}{\Gamma_1} \frac{d\log p}{dr} - \frac{d\log\rho}{dr} \right)$$

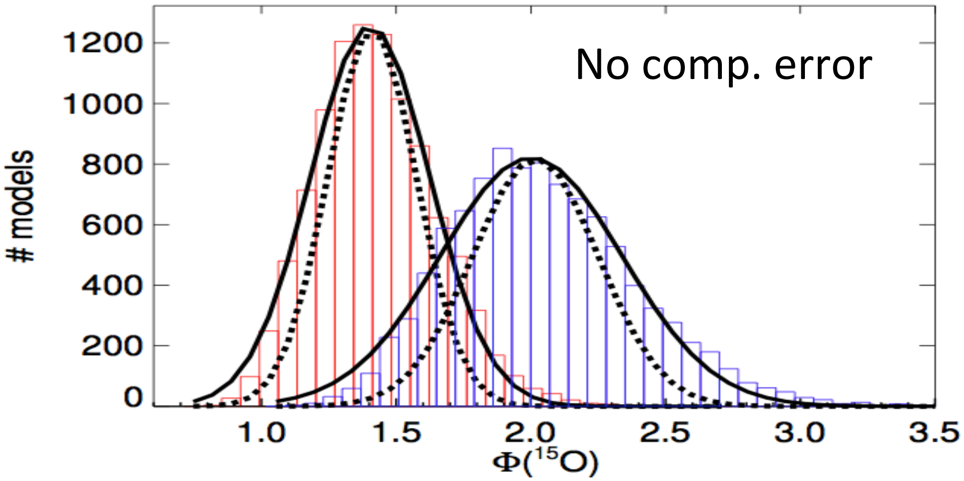
Fossat et al. P_1 = 1443.1 ± 0.5s - P_2 = 832.8 ± 0.7s

GS98 SSMs: P_1 = 1525 – 1540 s - P_2 = 880 – 890 s

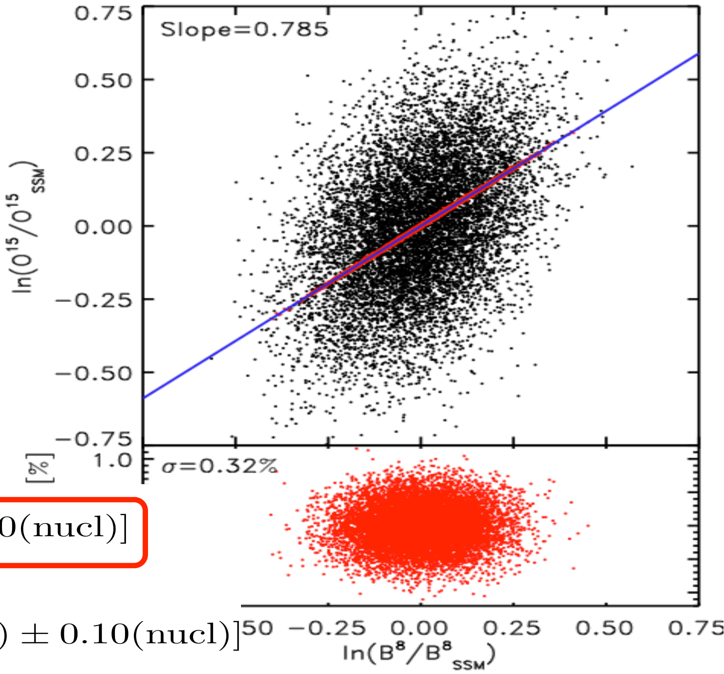
AGSS09 SSMs: P_1 = 1535 – 1560 s - P_2 = 886 – 900 s

2) Rotational splitting -- > solar core rotation ~ x3 faster than intermediate regions
Maybe some impact for chemical mixing in the core – but in direction of lowering n-fluxes

CN n fluxes



Temperature dependences can be cancelled out using ^8B



$$\frac{\Phi(^{15}\mathrm{O})}{\Phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} x_C^{0.749} x_N^{0.212} \, [1 \pm 0.003(\mathrm{env}) \pm 0.10(\mathrm{nucl})]$$

$$\approx \left[\frac{\Phi(^{8}B)}{\Phi(^{8}B)^{\mathrm{SSM}}}\right]^{0.785} \left[\frac{N_{\mathrm{C}} + N_{\mathrm{N}}}{N_{\mathrm{C}}^{\mathrm{SSM}} + N_{\mathrm{N}}^{\mathrm{SSM}}}\right] [1 \pm 0.003(\mathrm{env}) \pm 0.10(\mathrm{nucl})]$$

Discriminates compositions to better than ~ 3-s before adding CN experimental error