Solar models and neutrinos (I)

Aldo Serenelli

"Recent Developments in Neutrino Physics and Astrophysics"

LNGS – September 2017

In collaboration with
N. Vinyoles, F. Villante
C. Gonzalez-Garcia, N. Song

SSM – a reminder

SSM assumes

Initially fully mixed composition due to convection in pre-MS
constant solar mass $M_\odot$ and known age 4.57 Gyr

"Standard physics" – tries to avoid ad-hoc and/or "over calibrated" physics
– minimizes number of adjustable parameters

3 free parameters

Convection parameter: α_{MLT}

Initial composition – helium and metal content Y_{ini} and Z_{ini}

to match 3 observables

solar radius $R_\odot$

solar luminosity $L_\odot$

metal-to-hydrogen abundance ratio $(Z/X)_\odot$

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

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

SSM – a reminder

Element	GS98	AGSS09+met
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

$\log(n_x/n_H)+12$

	$L_\odot$	$R_\odot$	$(Z/X)_\odot$
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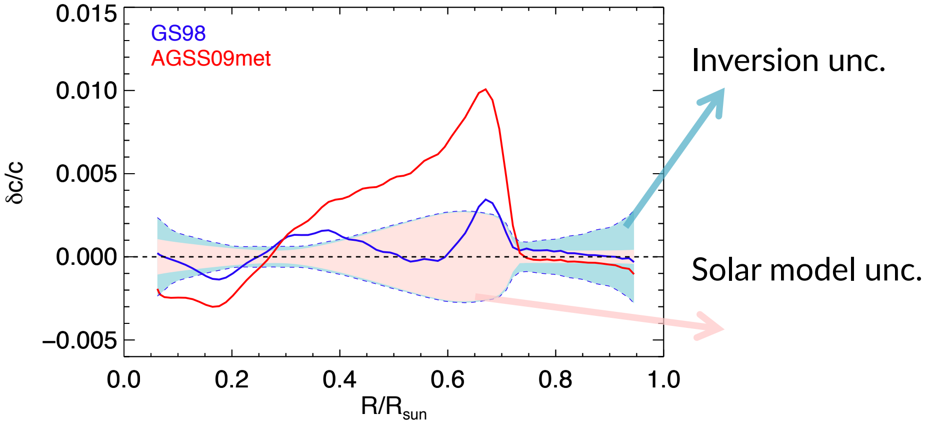
Z/X determines solar model composition
Z_{ini} & Y_{ini}

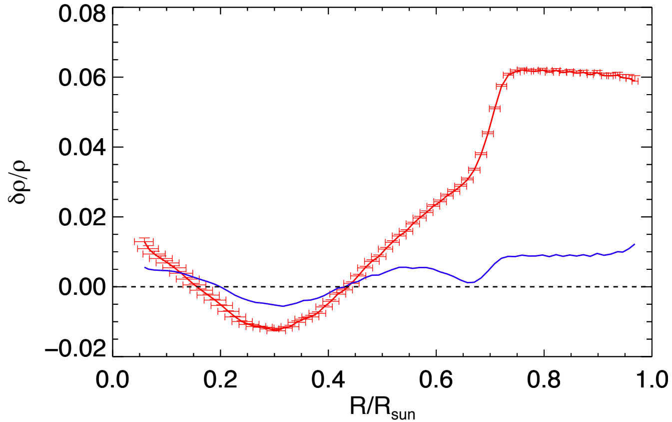
"Sub-solar" solar metallicity
Asplund et al. 2009, Scott et al. 2015

SSM – the problem

Sound speed relative difference



Density relative difference

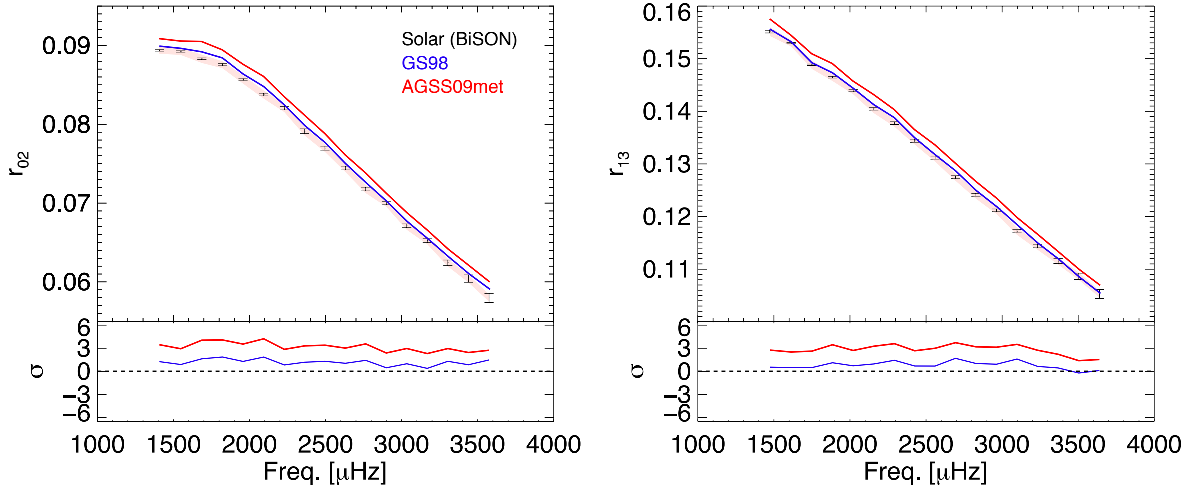


	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta\rho/\rho \rangle$	0.011	0.040	—

SSM – the problem

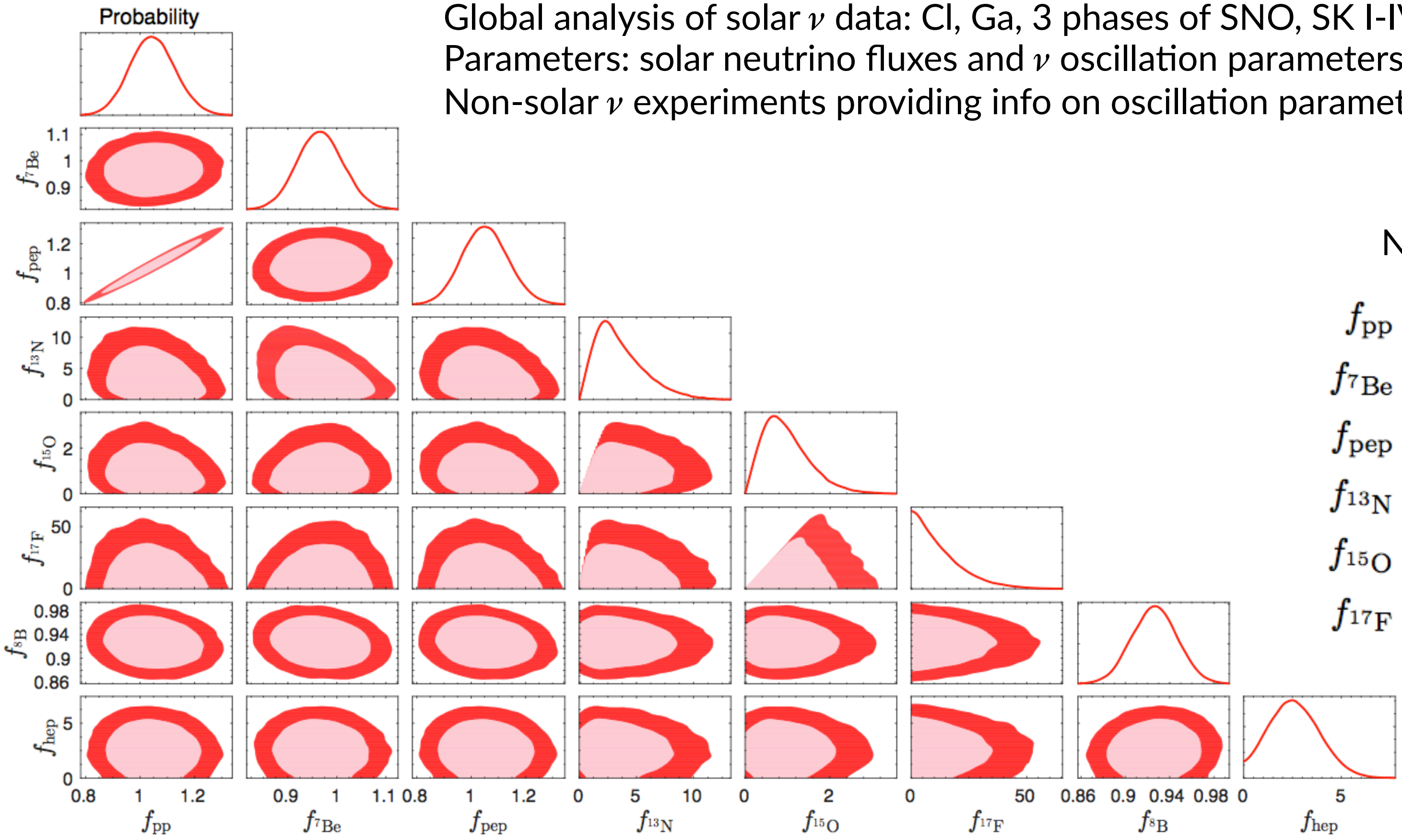
Core structure as seen by frequency separation ratios

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



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

SSM – neutrinos



Global analysis of solar ν data: Cl, Ga, 3 phases of SNO, SK I-IV, Borexino Phase 1&2
Parameters: solar neutrino fluxes and ν oscillation parameters (Δm^2_{21}, θ_{12}, θ_{13})
Non-solar ν 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

SSM – neutrinos

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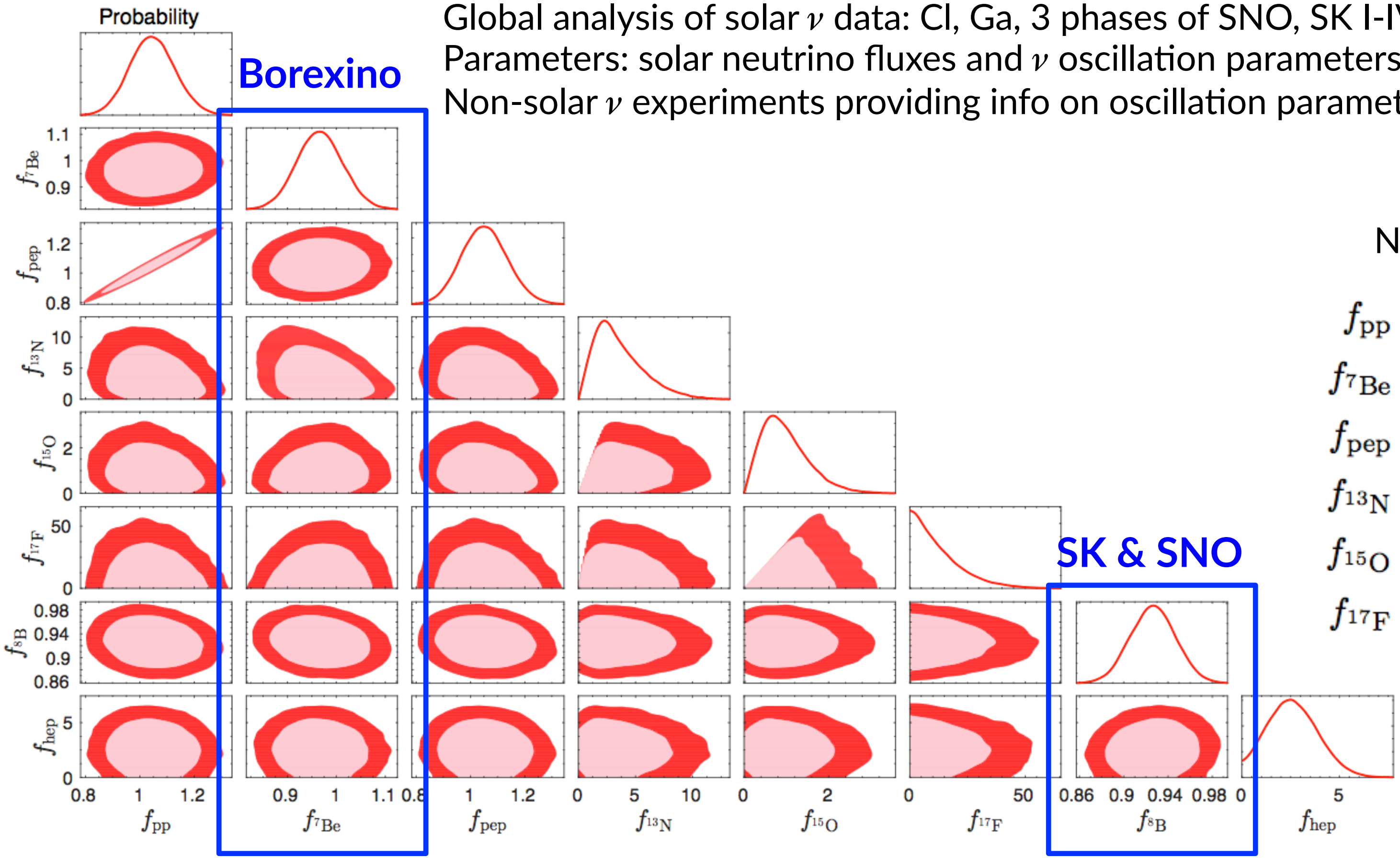

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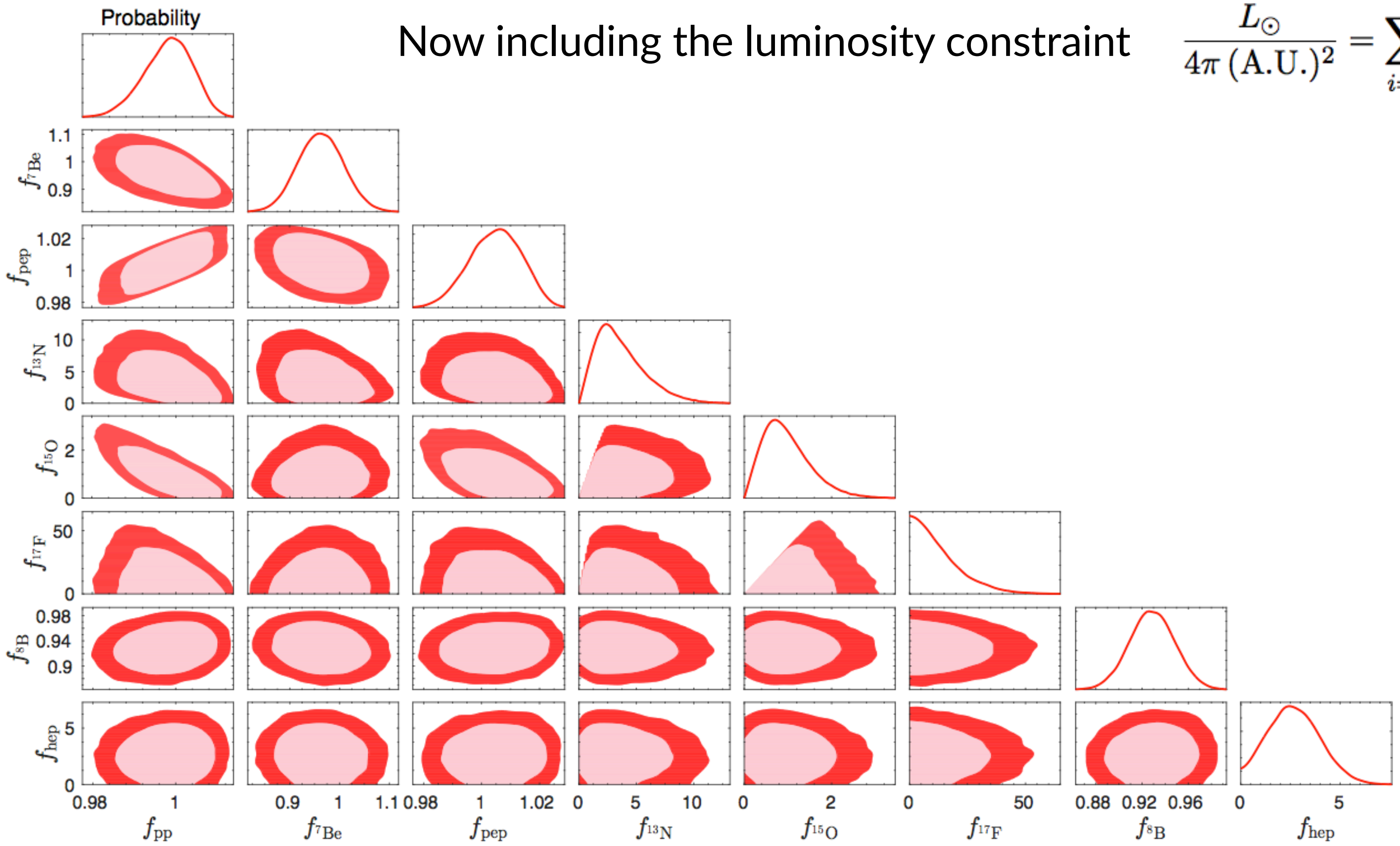
Bergstrom et al. 2016

SSM – neutrinos

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

$$f_{pp} = 0.999^{+0.006}_{-0.005}\,\left[^{+0.012}_{-0.016}\right],$$
$$f_{^7\mathrm{Be}} = 0.96^{+0.05}_{-0.04}\,\left[^{+0.12}_{-0.11}\right],$$
$$f_{pep} = 1.005 \pm 0.009\,\left[^{+0.019}_{-0.024}\right],$$
$$f_{^{13}\mathrm{N}} = 1.7^{+2.9}_{-1.0}\,\left[^{+8.4}_{-1.6}\right],$$
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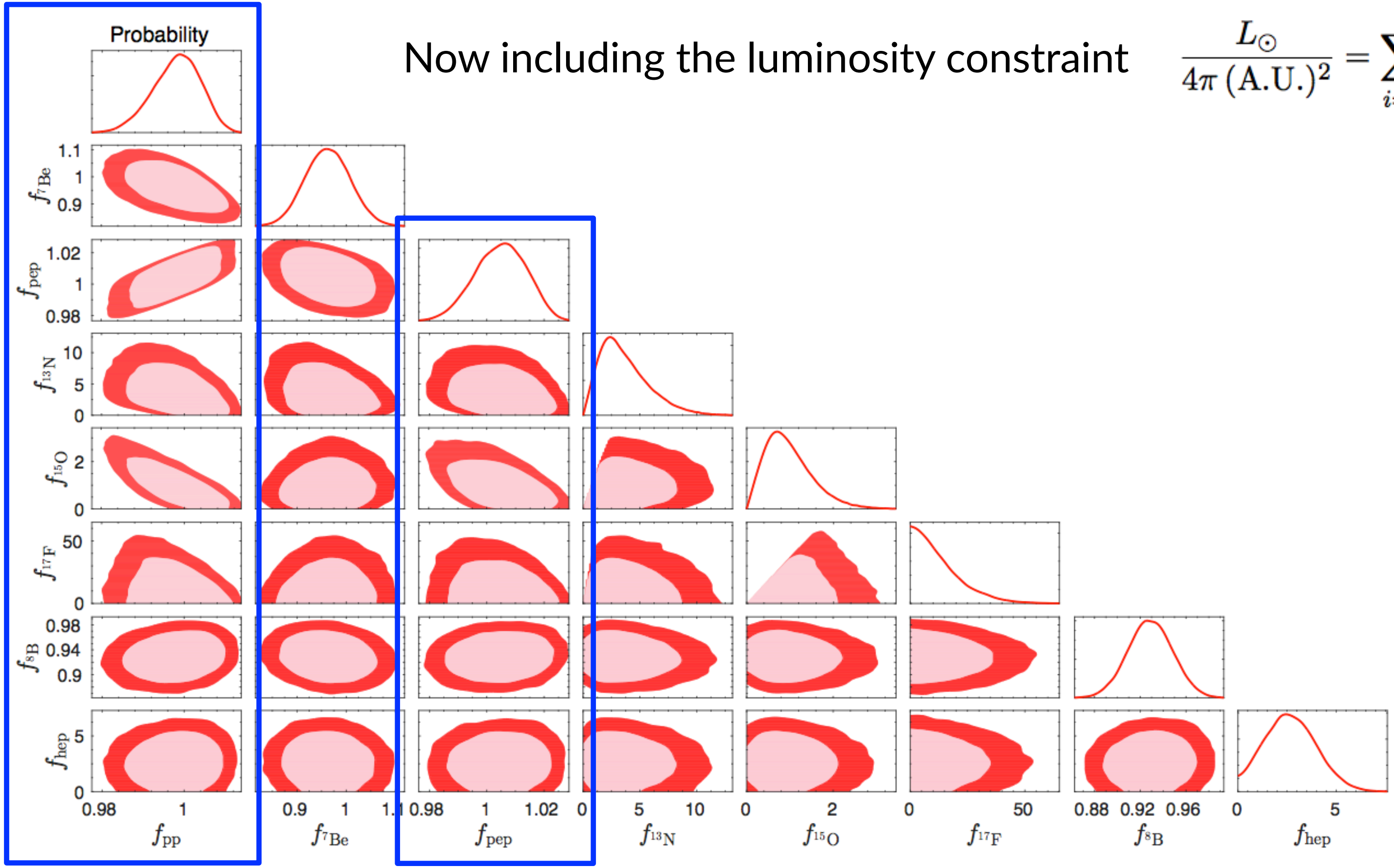
$$f_{^{17}\mathrm{F}} \leq 15\,[46],$$
$$f_{^8\mathrm{B}} = 0.92 \pm 0.02\,[\pm 0.05],$$
$$f_{hep} = 2.4^{+1.5}_{-1.2}\,[\leq 5.9],$$

Bergstrom et al. 2016

SSM – neutrinos



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Bergstrom et al. 2016

SSM – neutrinos

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

SSM – B16 models

Flux	B16-GS98	B16-AGSS09met	Solar[a]	Chg.
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$	0.0
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$	0.0
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$	-0.7
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$	-1.4
$\phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$	-2.2
$\phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7	-6.1
$\phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8	-8.1
$\phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85	-4.2

New SSMs - changes in some nuclear rates (Vinyoles et al. 2017)

	$S(0)$	Uncert. %	$\Delta S(0)/S(0)$
S_{11}	$4.03 \cdot 10^{-25}$	1	+0.5%
S_{17}	$2.13 \cdot 10^{-5}$	4.7	+2.4%
S_{114}	$1.59 \cdot 10^{-3}$	7.5	-4.2%

Small changes ^{7}Be-^{8}B (S_{11}-S_{17})

Larger for ^{13}N-^{15}O (S_{11}-S_{114})

SSM – B16 models

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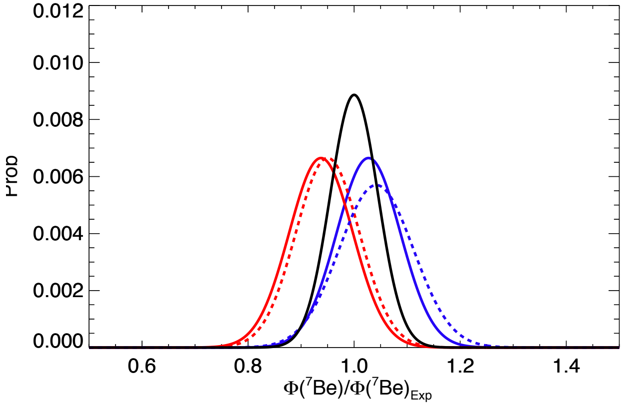


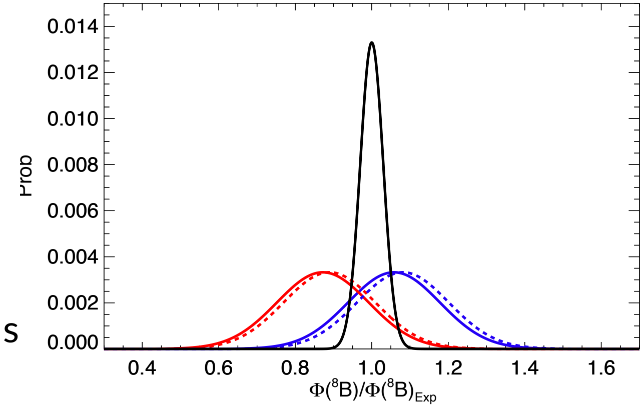
ν data fit

AGSS09

GS98

B16 models

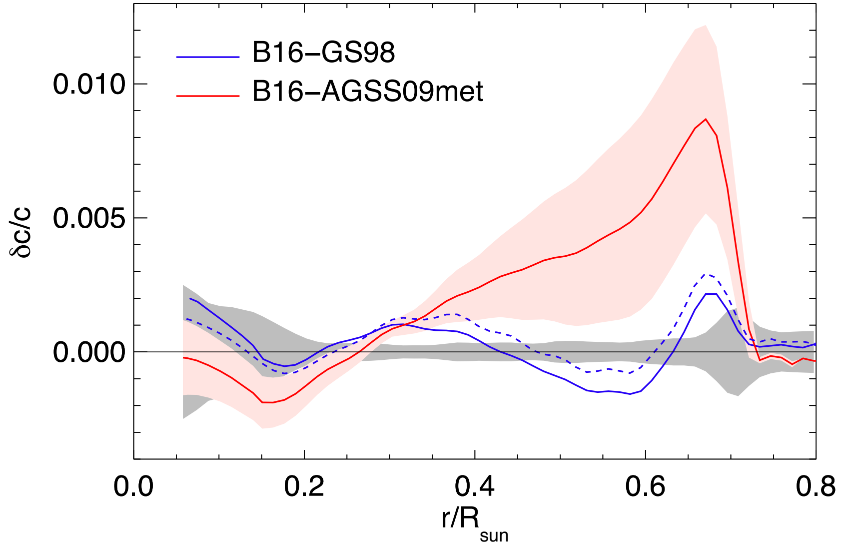
Older models



Revision of global analysis including new Borexino data needed

SSM – B16 models

Small changes in helioseismic probes



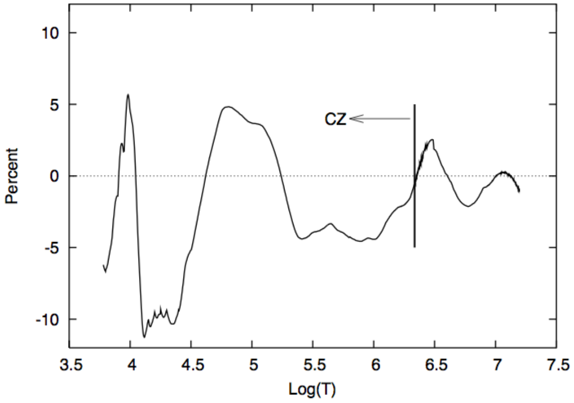
Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0005 ± 0.0004	0.0021 ± 0.001	—

Opacities

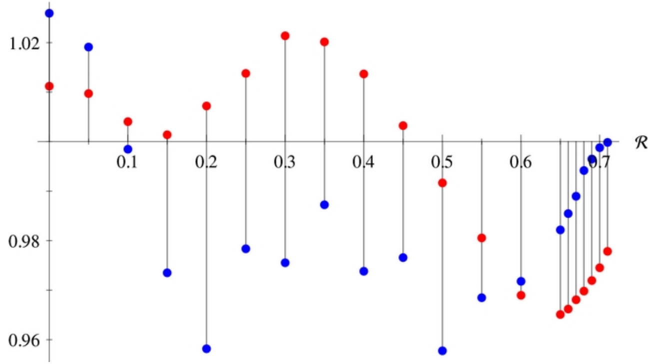
Helioseismic probes and pp νs depend on “effective” opacity profiles: opacity models + composition
details in F. Villante’s talk

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

OP vs OPAL



OPAS vs OP (blue)

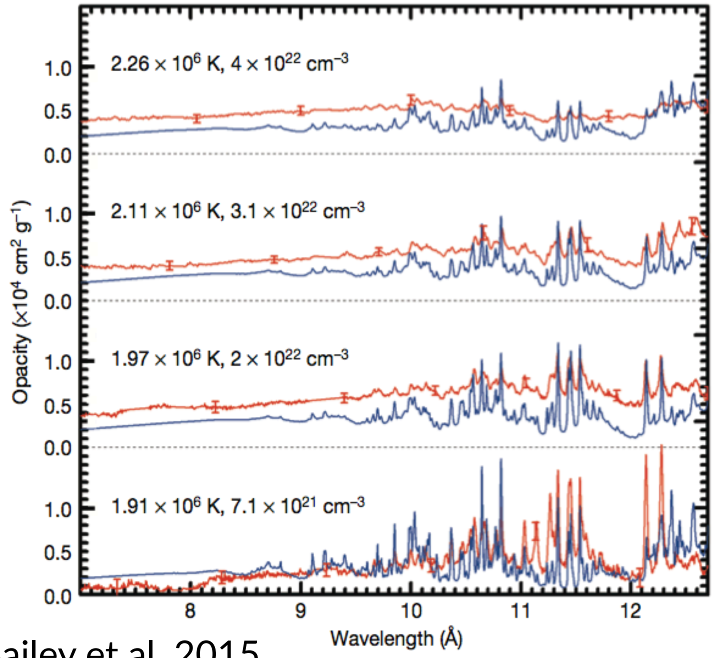


Few percent differences in solar interiors
Only theoretical calculations available

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



Bailey et al. 2015

$T \sim T_{CZ}$

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

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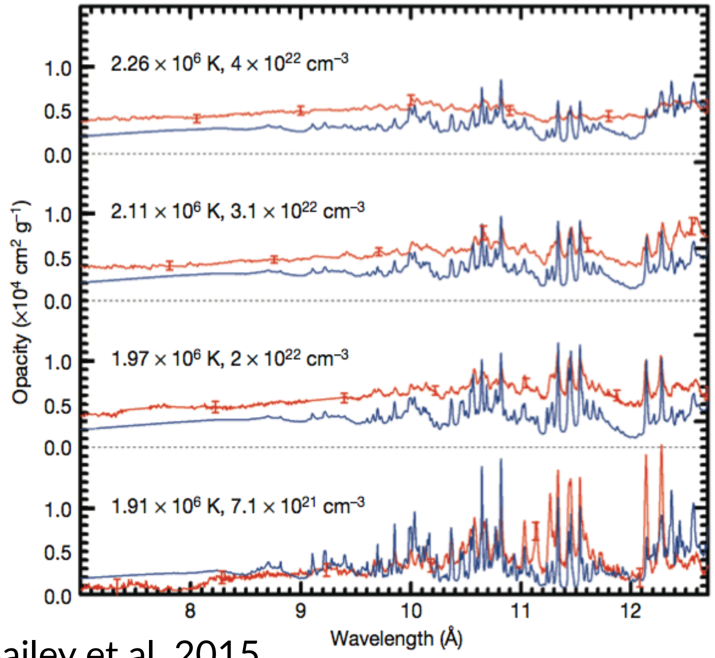
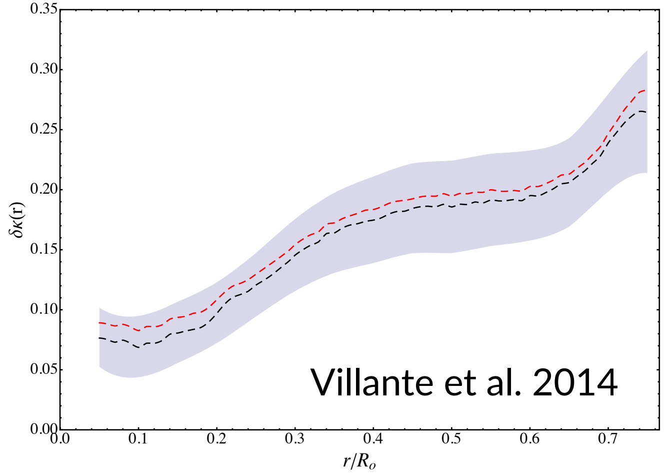


Bailey et al. 2015

$T \sim T_{CZ}$

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

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

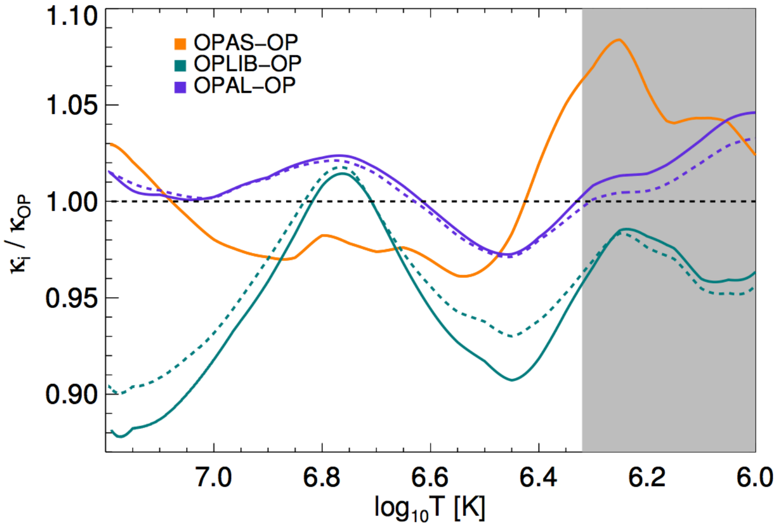


Villante et al. 2014

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

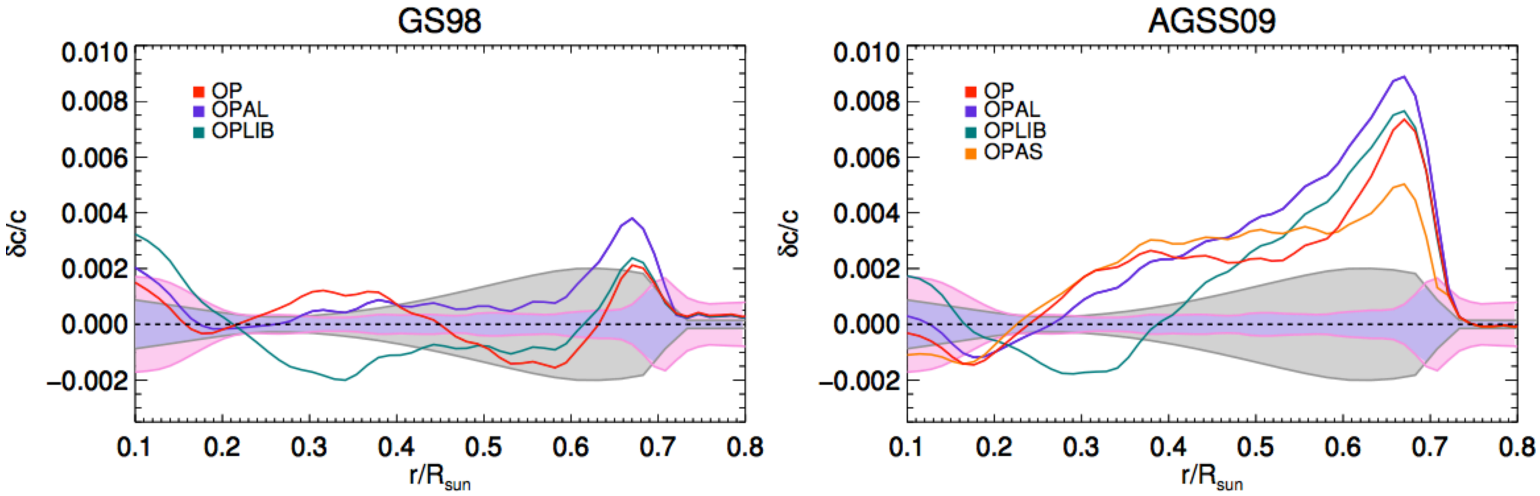


Solid – GS98

Dashed – AGSS09ph

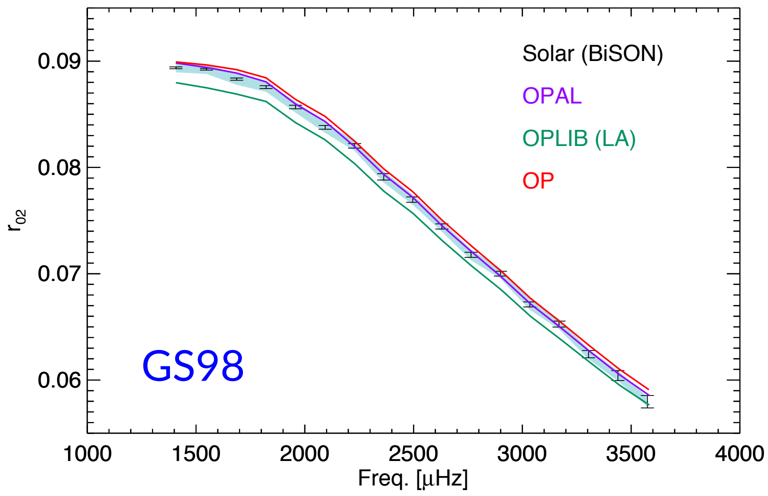
Not guaranteed that newer opacity models lead to higher opacity values

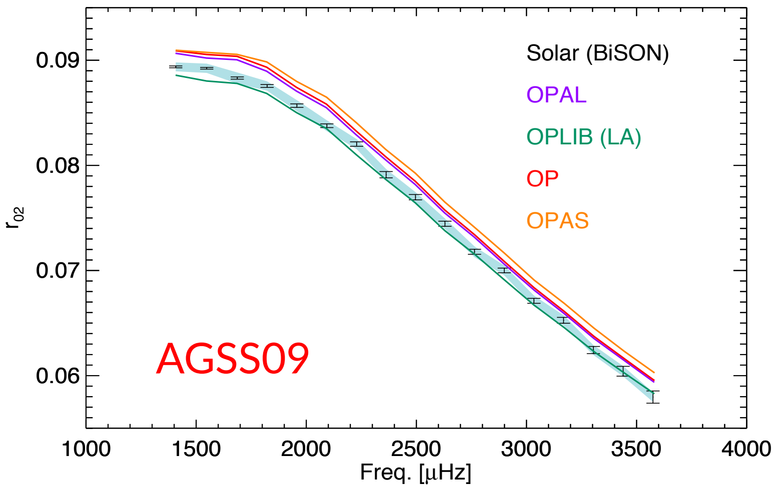
SSM with new opacities



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

SSM with new opacities

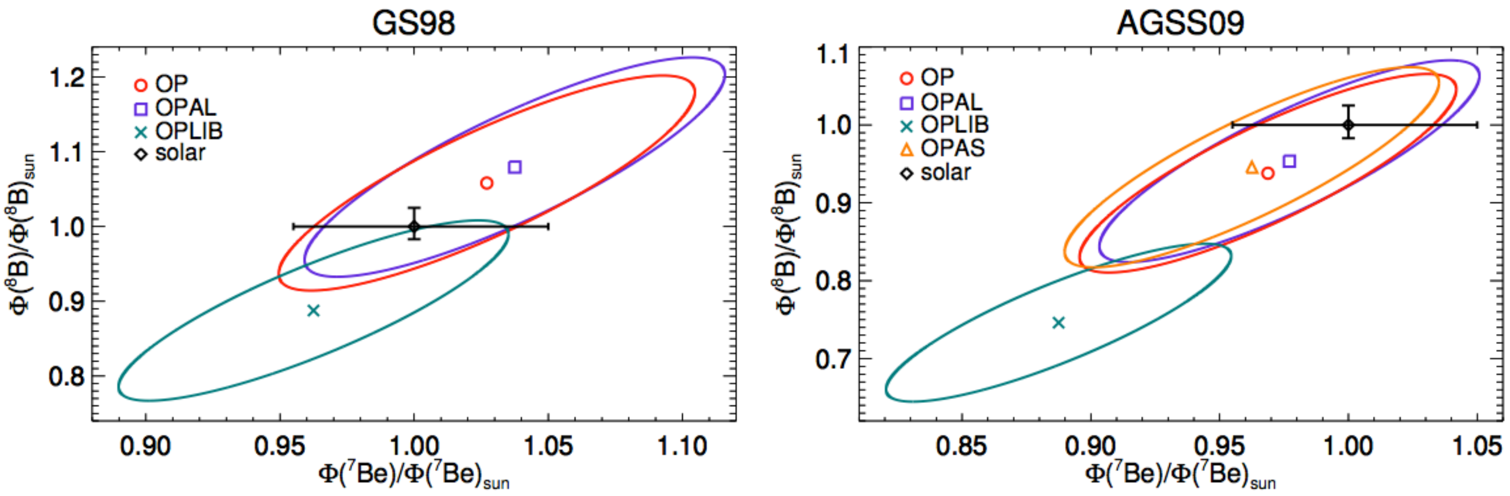




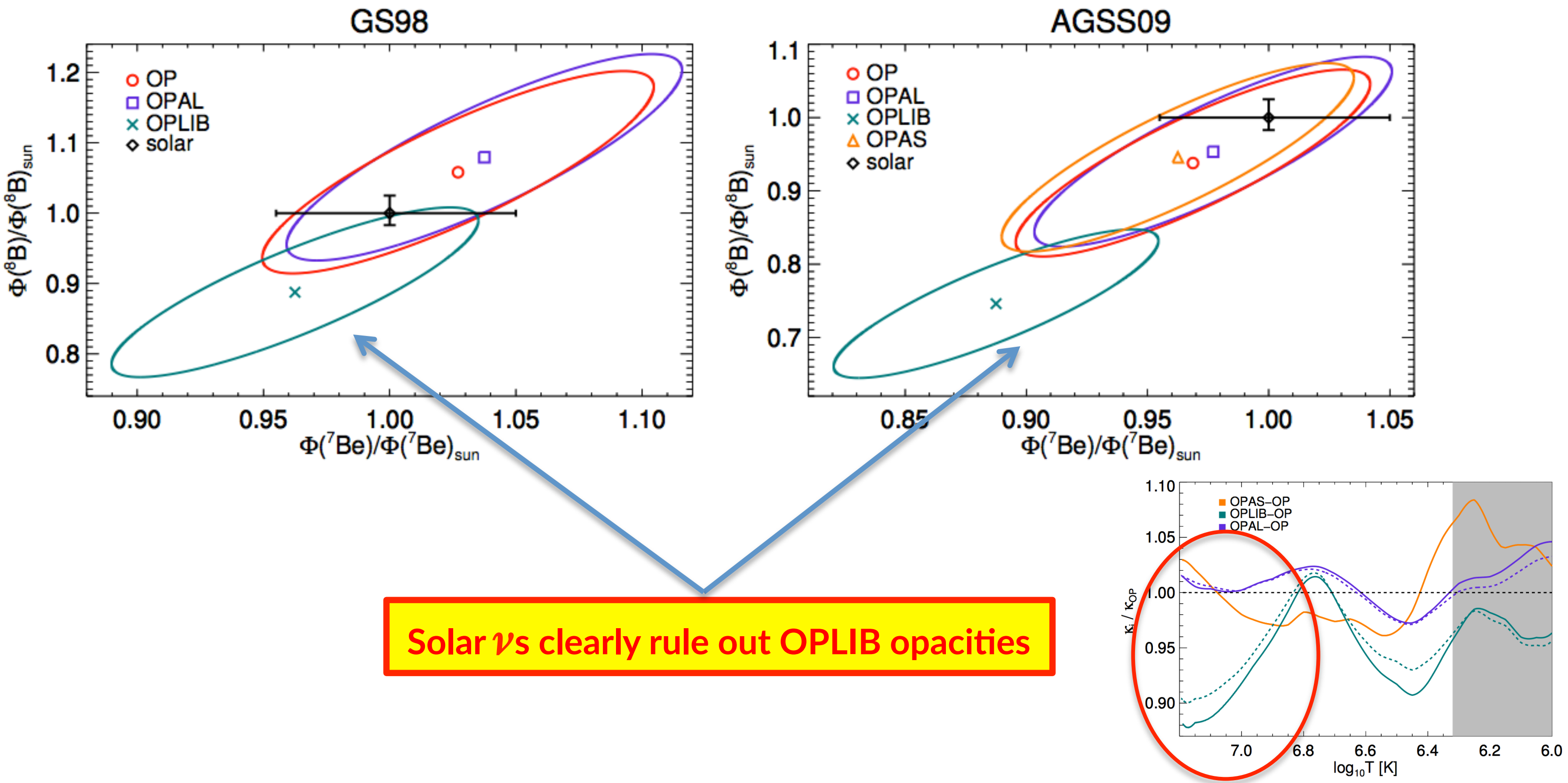
New OPLIB opacities lead to indecisive results for helioseismic probes

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

SSM with new opacities



SSM with new opacities

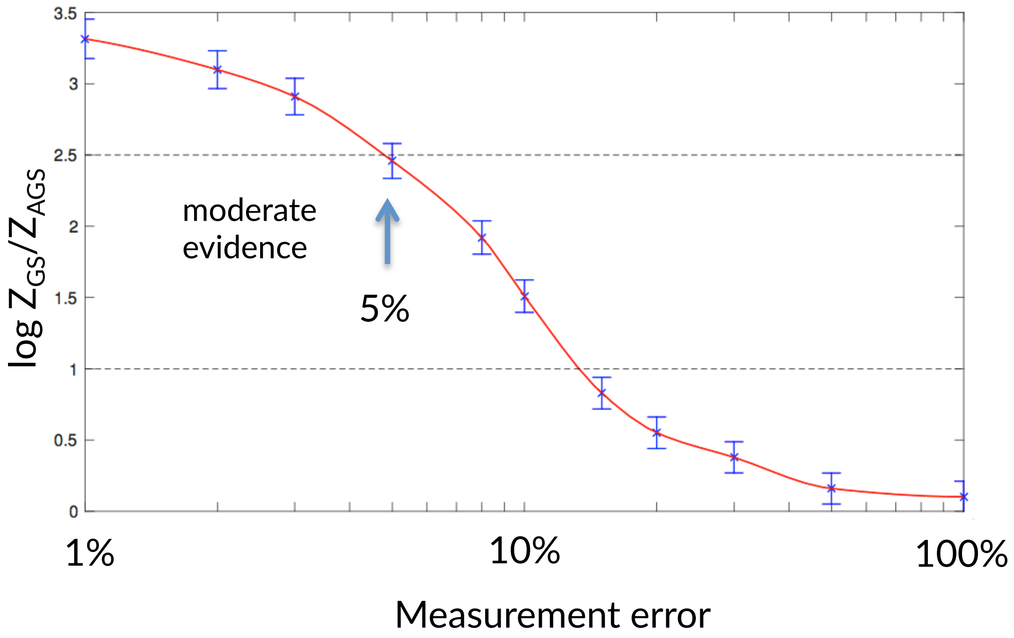


Solar νs clearly rule out OPLIB opacities

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 νs



ν-experiments only

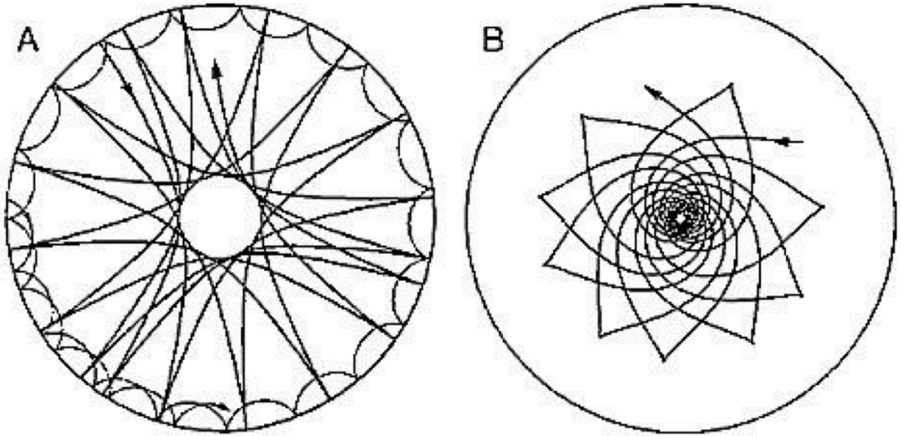
Bergstrom et al. 2016

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. Π_1 = 1443.1 ± 0.5s - Π_2 = 832.8 ± 0.7s

GS98 SSMs: Π_1 = 1525 – 1540 s - Π_2 = 880 – 890 s

AGSS09 SSMs: Π_1 = 1535 – 1560 s - Π_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 ν-fluxes

g-modes detection (finally?)

Two important claims in Fossat et al. 2017

1) Asymptotic period spacings for l= 1 , 2

From Appourchaux et al. 2010 review

and data-analysis perspectives – to give unambiguous detections of individual g modes. The review ends by concluding that, at the time of writing, there is indeed a consensus amongst the authors that *there is currently no undisputed detection of solar g modes.*

2)

Maybe some impact for chemical mixing in the core – but in direction of lowering ν-fluxes

Summary

B16 - Some updates in nuclear rates -- > small changes in 7Be and 8B fluxes
larger for CN fluxes (lower expectation values)

The Sun shines by pp burning : 1.03 ± 0.08 $L_\odot$

With luminosity constraint: CN < 1% at 3σ

Solar abundance/model problem remains unchanged

First experimental opacity measurement @ solar conditions
--> hints of higher opacity at right place : 7%
--> not enough : ~20 % (F. Villante's talk)

New theoretical opacities: OPAS not a game changer – some improvements, some old problems
OPLIB: excluded by ν measurements and surface helium
but frequency ratios are good for AGSS09
sound speed profile, R_{CZ} not much changed

CN fluxes remain necessary and only way to break degeneracy (F. Villante's talk)

Tentative discovery of g-modes – potential disagreement with SSM predictions

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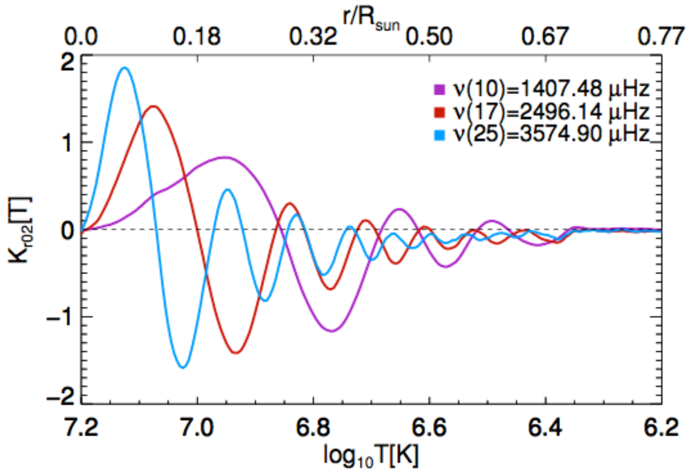
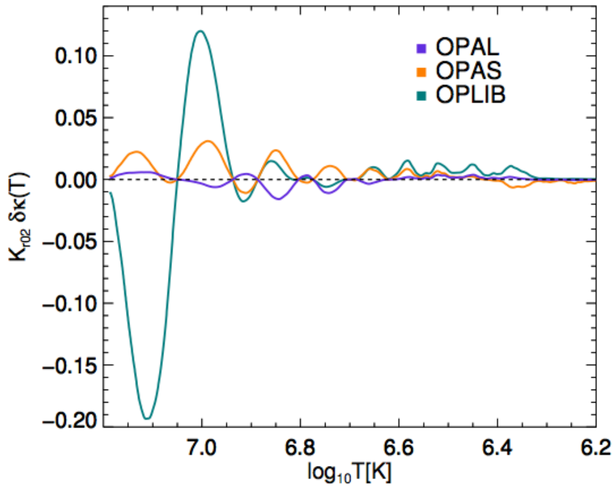
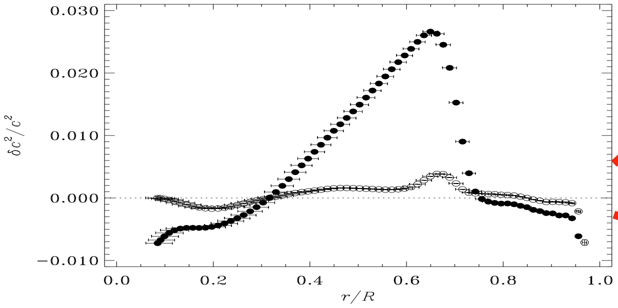
Extra slides



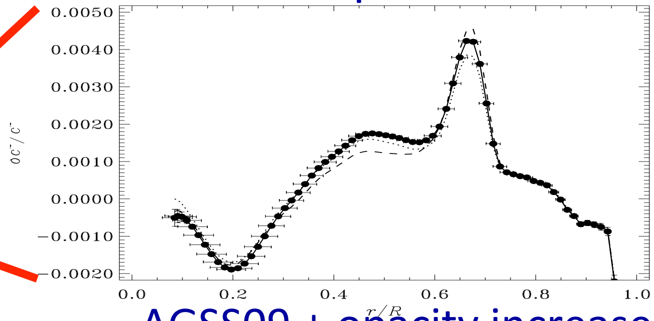


The role of radiative opacities

Helioseimic probes and νs from pp-chains not directly sensitive to Z, but to radiative opacity -- > degeneracy exists between composition and κ



Christensen Dalsgaard et al 2009

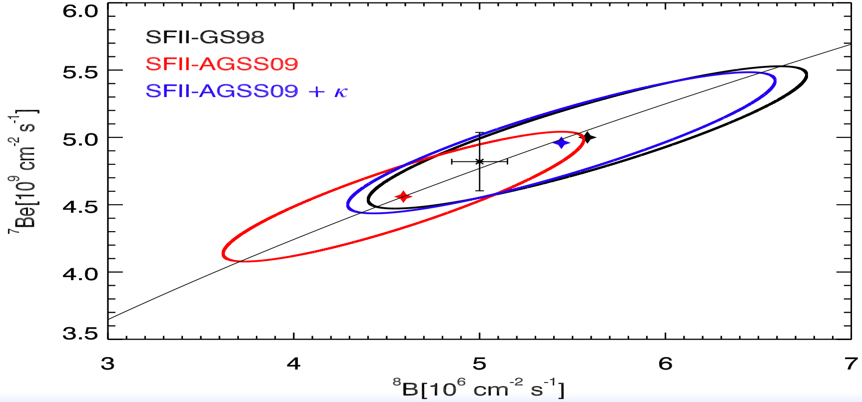


AGSS09 + opacity increase (15 to 20%)

Also frequency ratios r_{02}, r_{13}

Sound speed and pp-chain neutrinos

-- > recover GS98 “like” values



All probes sensitive to temperature-μ profile not to detailed composition

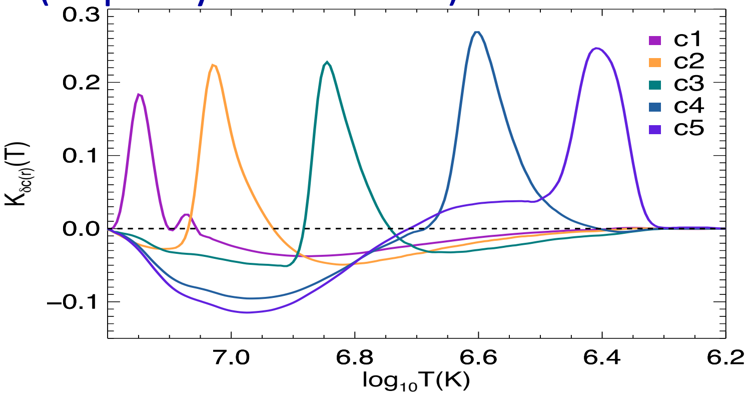
Opacity Kernels

Treatment of opacity uncertainties – opacity Kernels (Tripathy & JCD 1998)

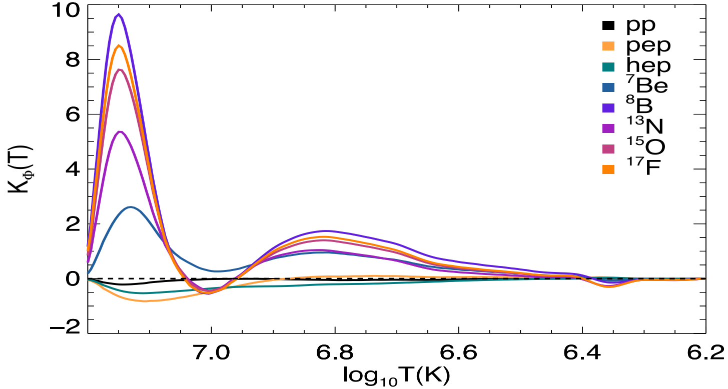
$$\delta Q = \int \frac{dT}{T} K_Q(T)\delta\kappa(T)$$

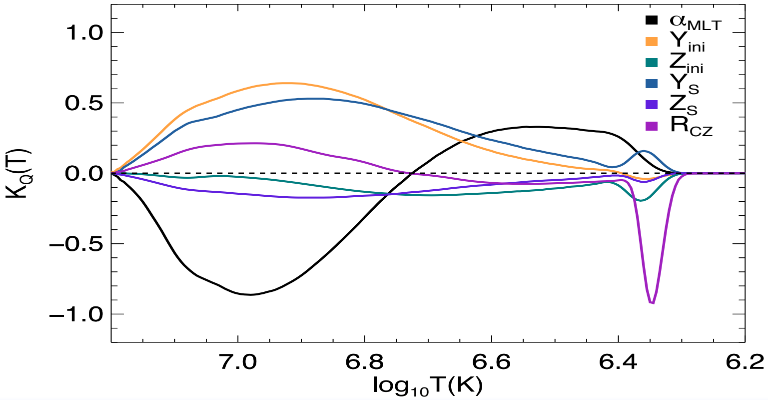
$$\delta\kappa(T) = C\delta(T - T_0)$$

$$K_Q(T_0) = \frac{\delta Q}{C}$$



Good as long as linear models have linear response





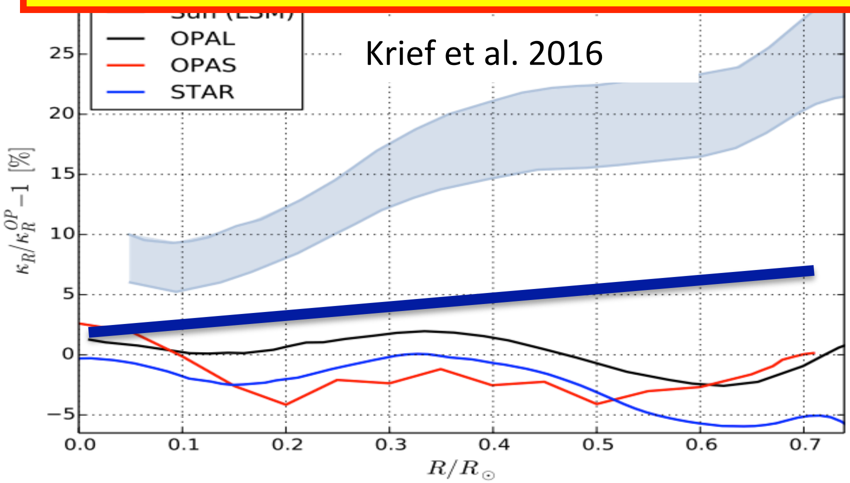
Opacity uncertainties

Linear increase of opacity uncertainty from the center outwards

$\sigma(\kappa,\text{center})$= 2% up to $\sigma(\kappa,\text{bce})$= 7% - **TILT** of the κ profile necessary for seismic probes

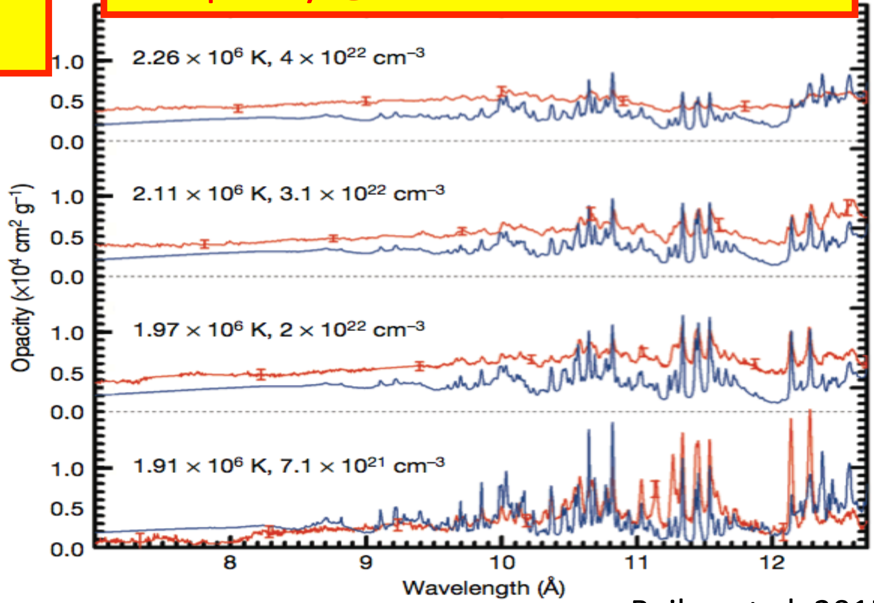
Supported by

Theoretical calculations show larger variations at the BCE



Krief et al. 2016

Fe opacity @Sandia Lab 7% increase



Bailey et al. 2015

Solar models vs data

Including for correlations in models –

AGSS09met is bad

GS98 better. but not excellent

		GS98		AGSS09met	
Case	dof	χ^2	p-value (σ)	χ^2	p-value (σ)
$Y_S + R_{CZ}$ only	2	0.9	0.5	6.5	2.1
$\delta c/c$ only	30	58.0	3.2	76.1	4.5
$\delta c/c$ no-peak	28	34.7	1.4	50.0	2.7
$\Phi(^7\text{Be}) + \Phi(^8\text{B})$	2	0.2	0.3	1.5	0.6
all ν-fluxes	8	6.0	0.5	7.0	0.6
global	40	65.0	2.7	94.2	4.7
global no-peak	38	40.5	0.9	67.2	3.0

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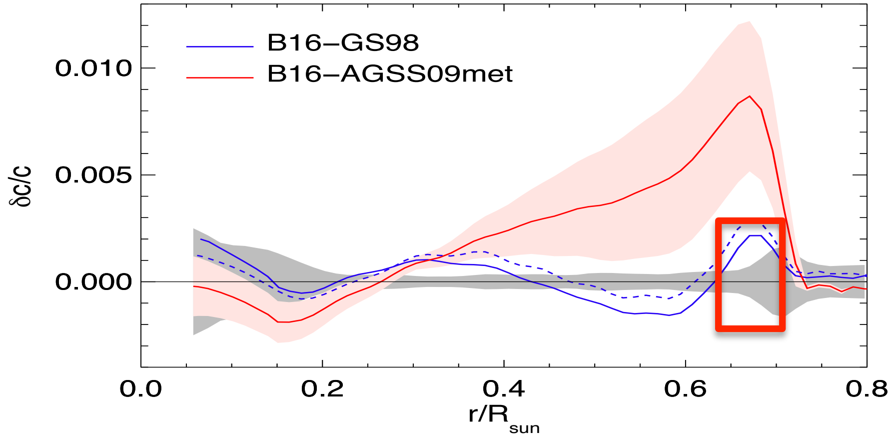

Looks can be deceiving – GS98 better but not excellent
correlation in models very important
linear variation of opacity "too rigid"

Solar models vs data

Including for correlations in models

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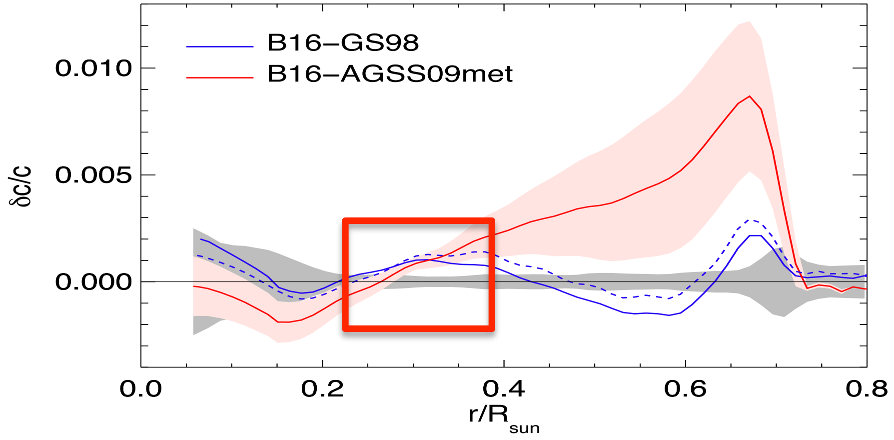
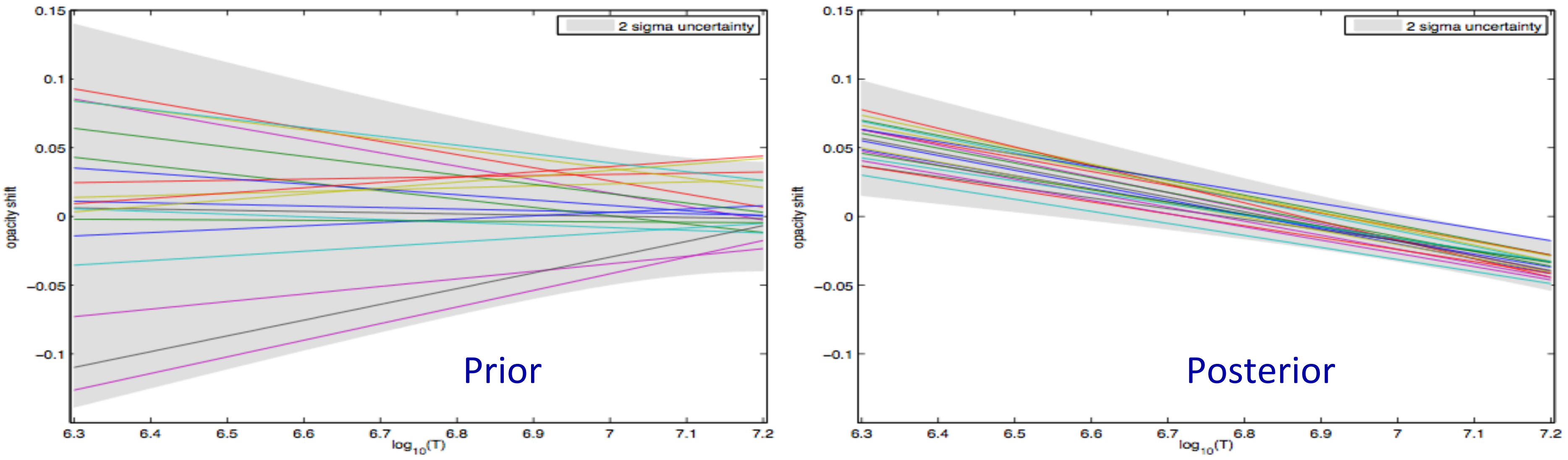


Removing the δc/c peak – AGSS09met has irreducible discrepancy
GS98 now much better
but linear variation of opacity "too rigid" even for GS98 (wiggles)

A more general approach to error function: gaussian process

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

Linear model



A more general approach to error function: gaussian process

Let the data decide. Well… as much as possible

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

Locally a gaussian function of mean m
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

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Correlation between two points
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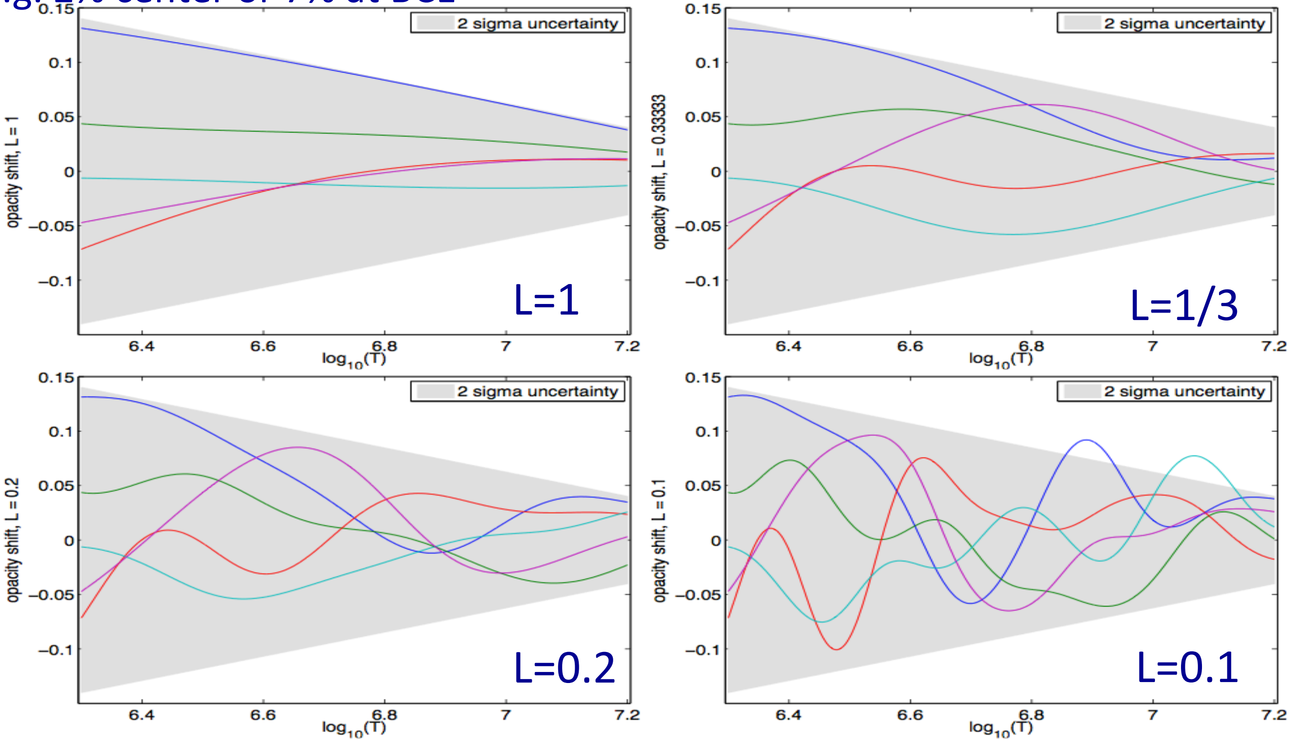
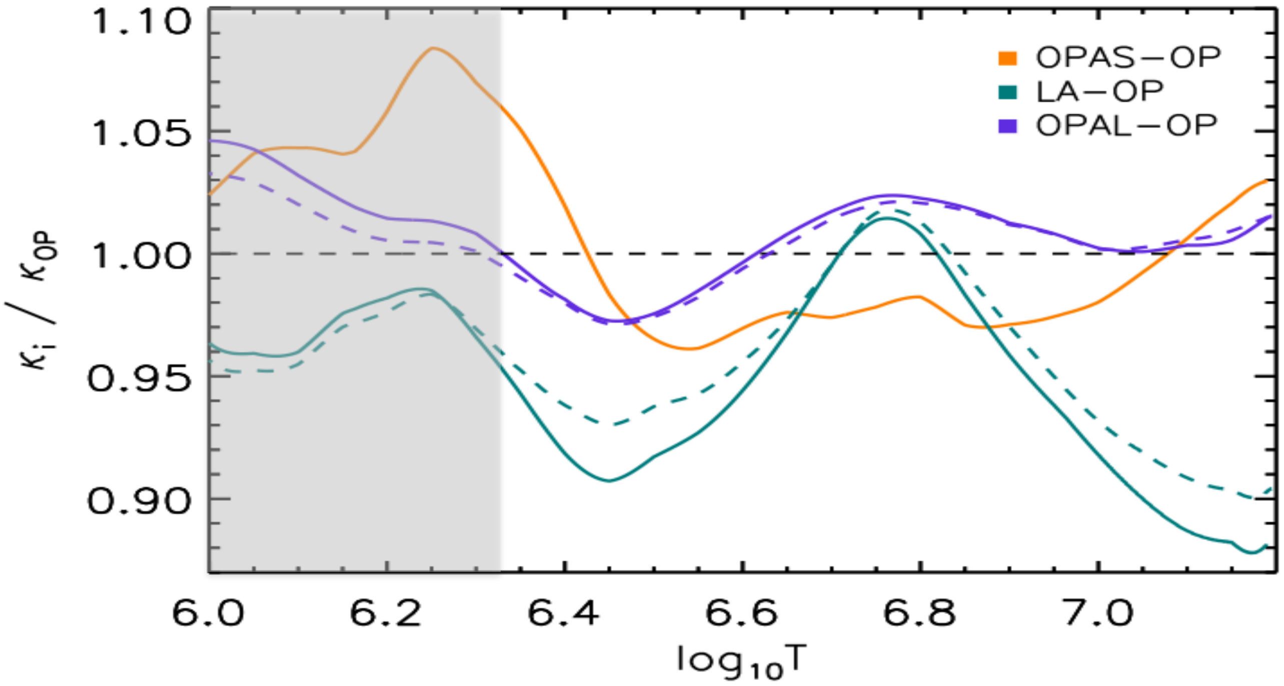
Define sensible priors for L
determine posterior from data

Obtain “best” opacity fit



Song et al. in preparation

New opacity calculations: impact on SSMs

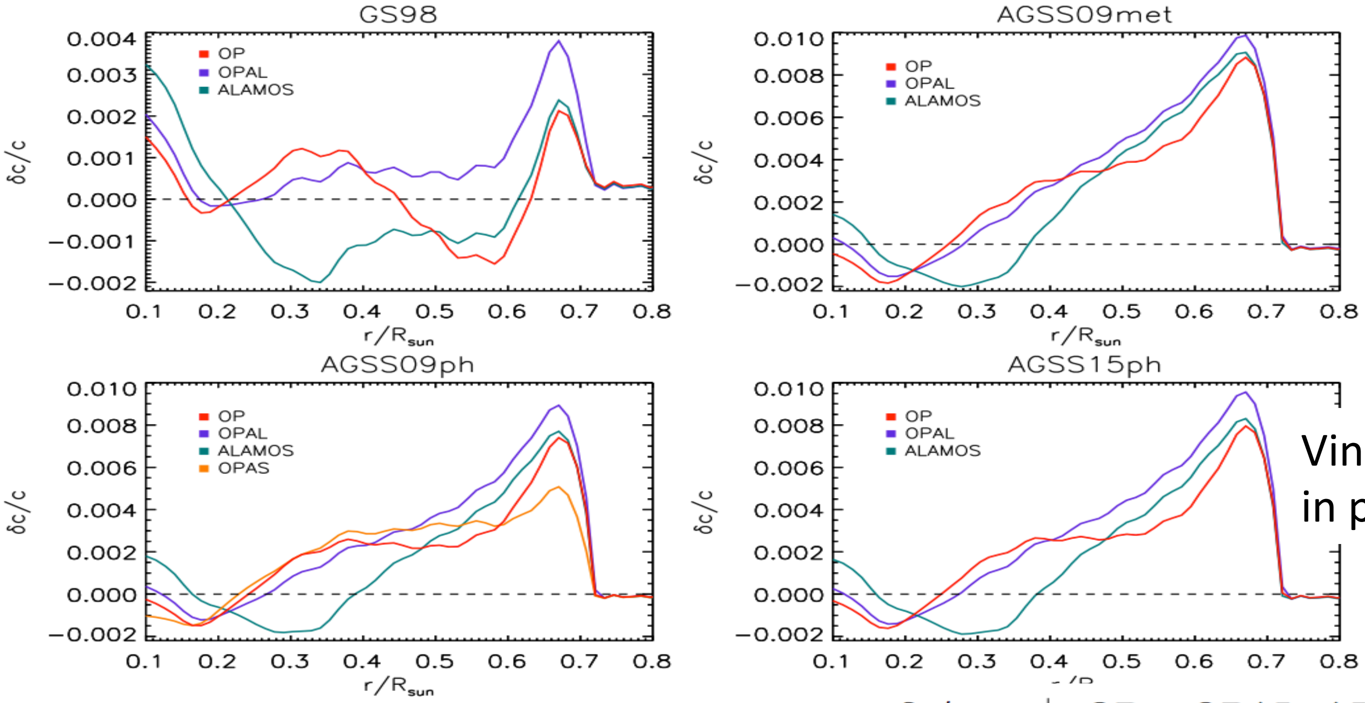


Solid – GS98

Dashed – AGSS09ph

Not guaranteed that newer opacity models lead to higher opacity values

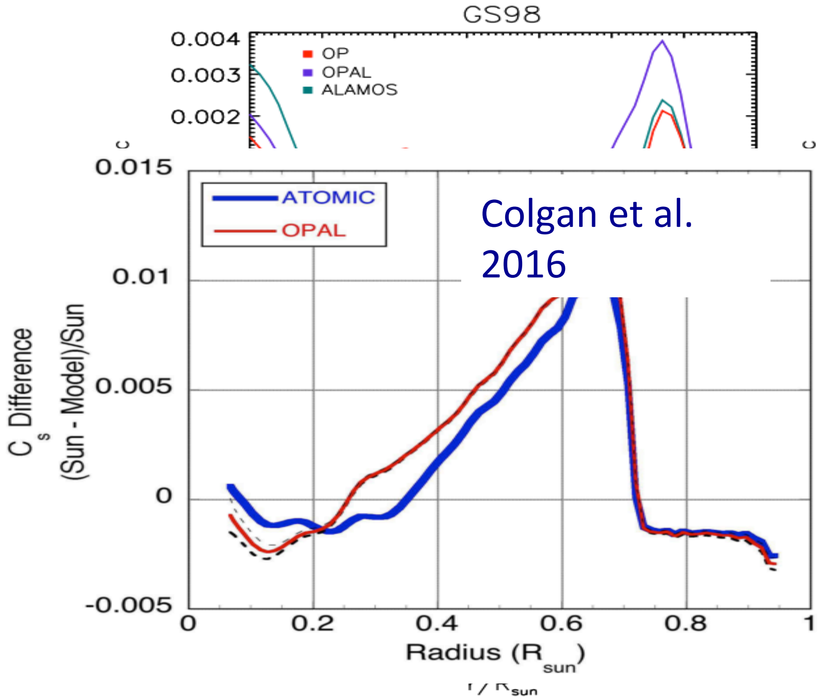
New opacity calculations: impact on SSMs



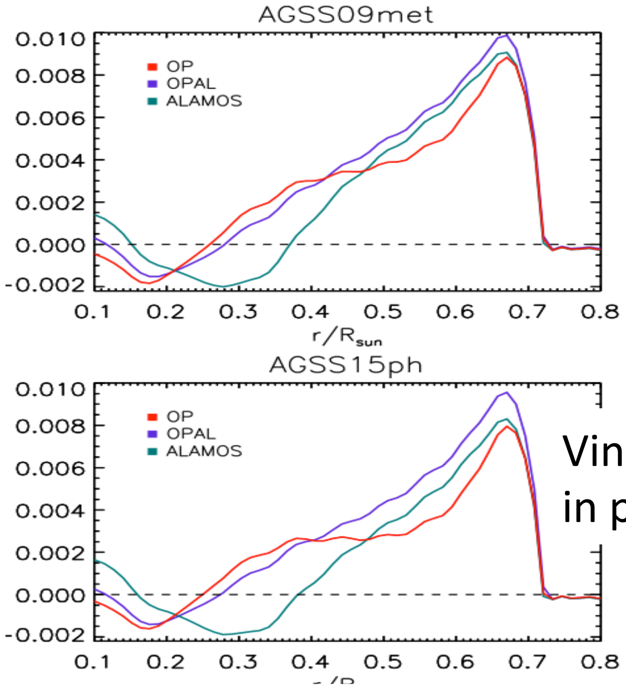
Vinyoles 2017
in preparation

$<\delta c/c>$	OP	OPAL	ALAMOS	OPAS
GS98	0.0005	0.0008	0.0010	-
AGSS09met	0.0021	0.0024	0.0023	-
AGSS09ph	0.0016	0.0020	0.0017	0.0017
AGSS15ph	0.0018	0.0022	0.0020	-

New opacity calculations: impact on SSMs



Colgan et al. 2016

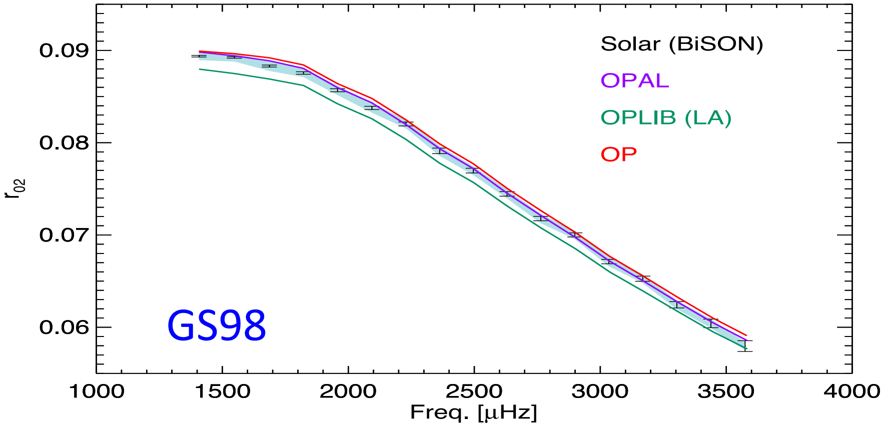


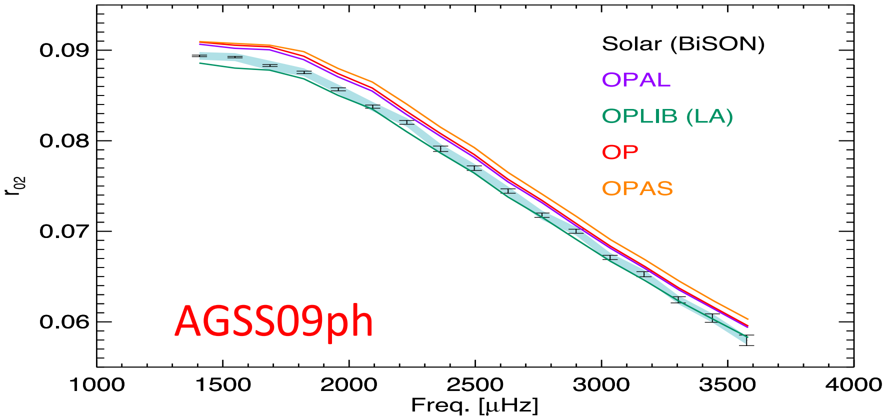
Vinyoles 2017 in preparation

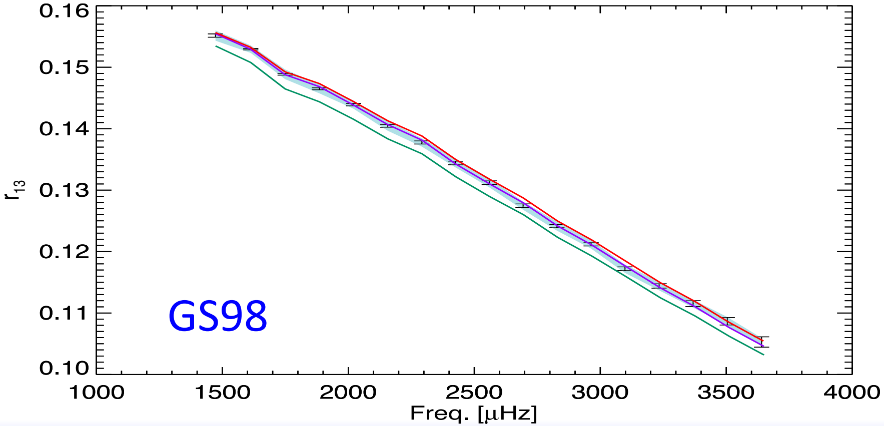
$< \delta c/c >$	OP	OPAL	ALAMOS	OPAS
GS98	0.0005	0.0008	0.0010	-
09met	0.0021	0.0024	0.0023	-
S09ph	0.0016	0.0020	0.0017	0.0017
S15ph	0.0018	0.0022	0.0020	-

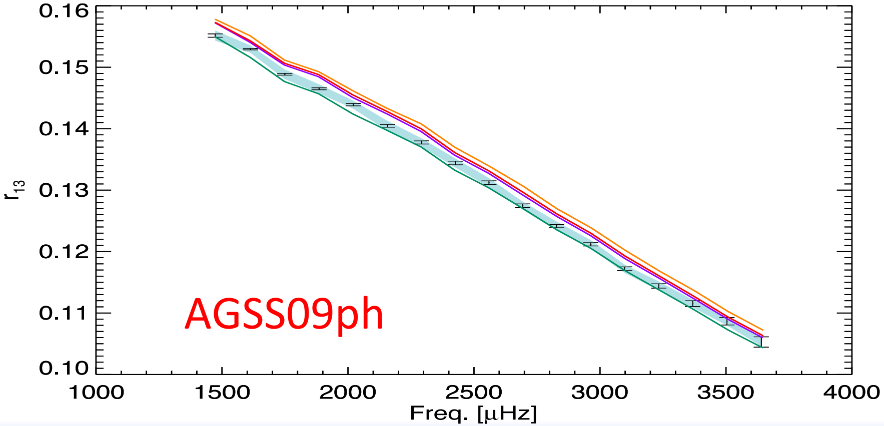
New opacities – OPAS & Los Alamos (ATOMIC/OPLIB)
Marginal improvement in δc/c

New opacity calculations: impact on SSMs

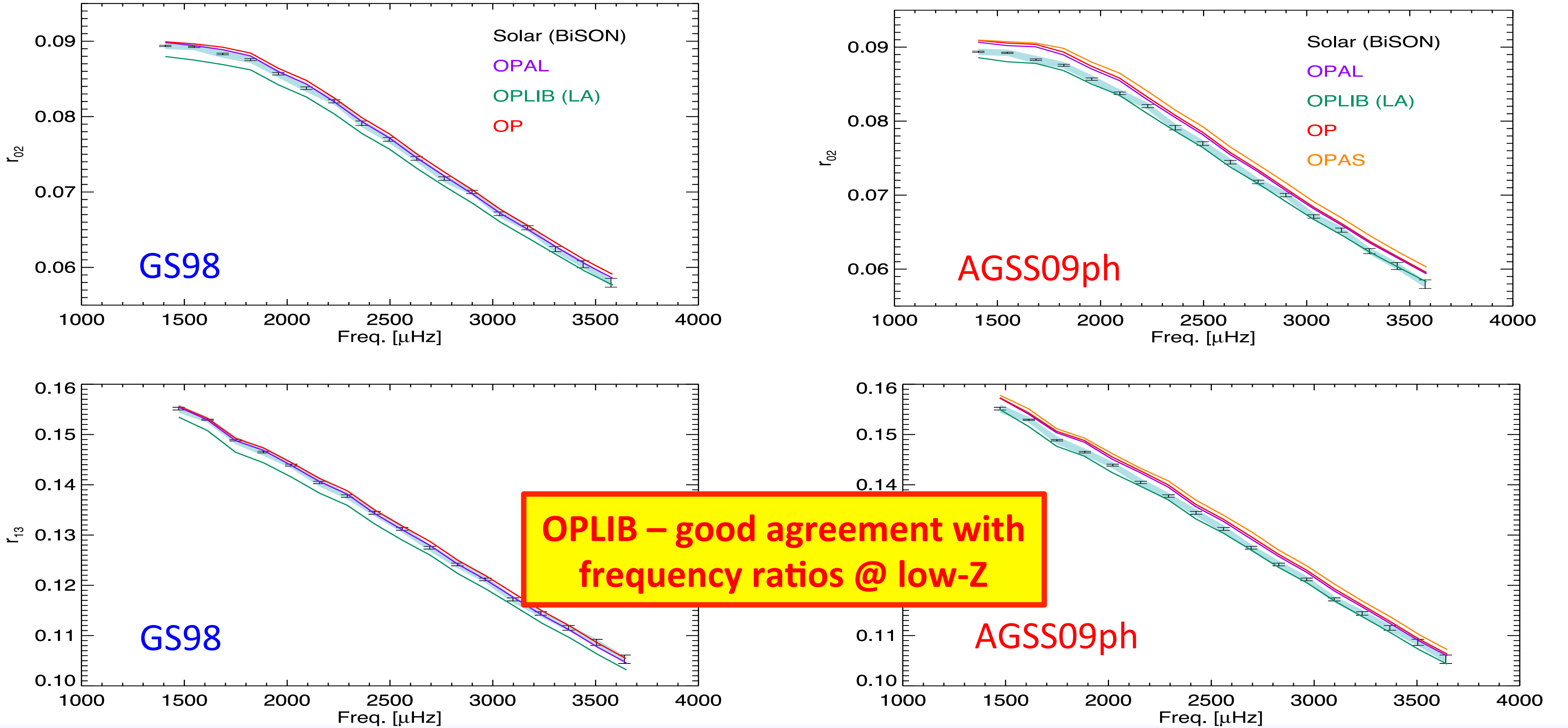






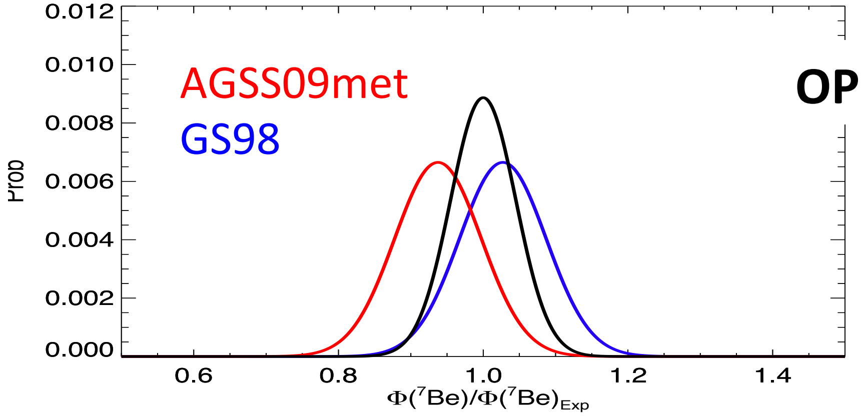


New opacity calculations: impact on SSMs

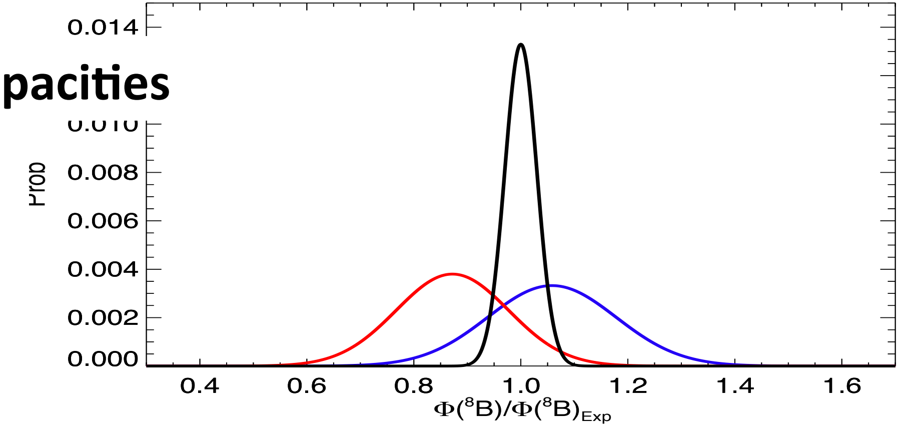


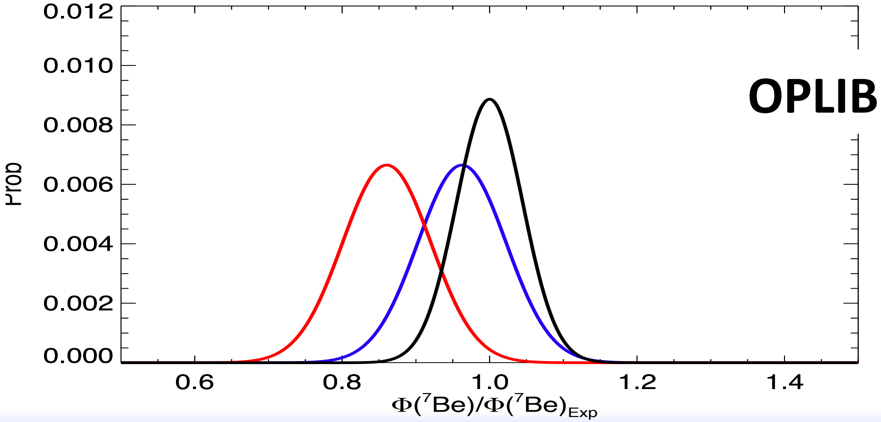
OPLIB – good agreement with frequency ratios @ low-Z

New opacity calculations: impact on SSMs

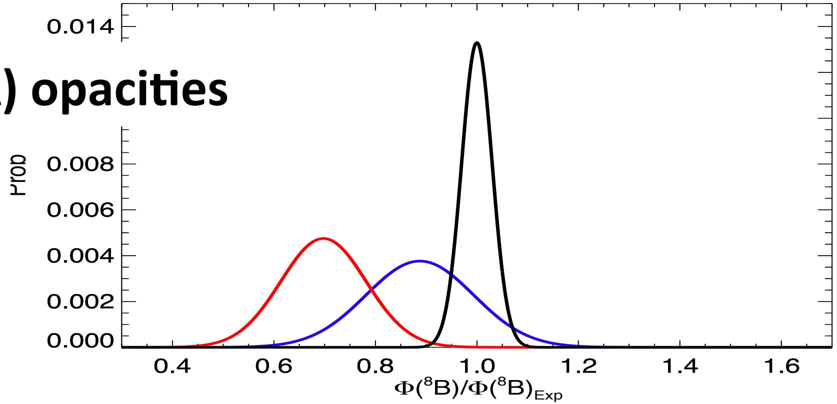


OP opacities

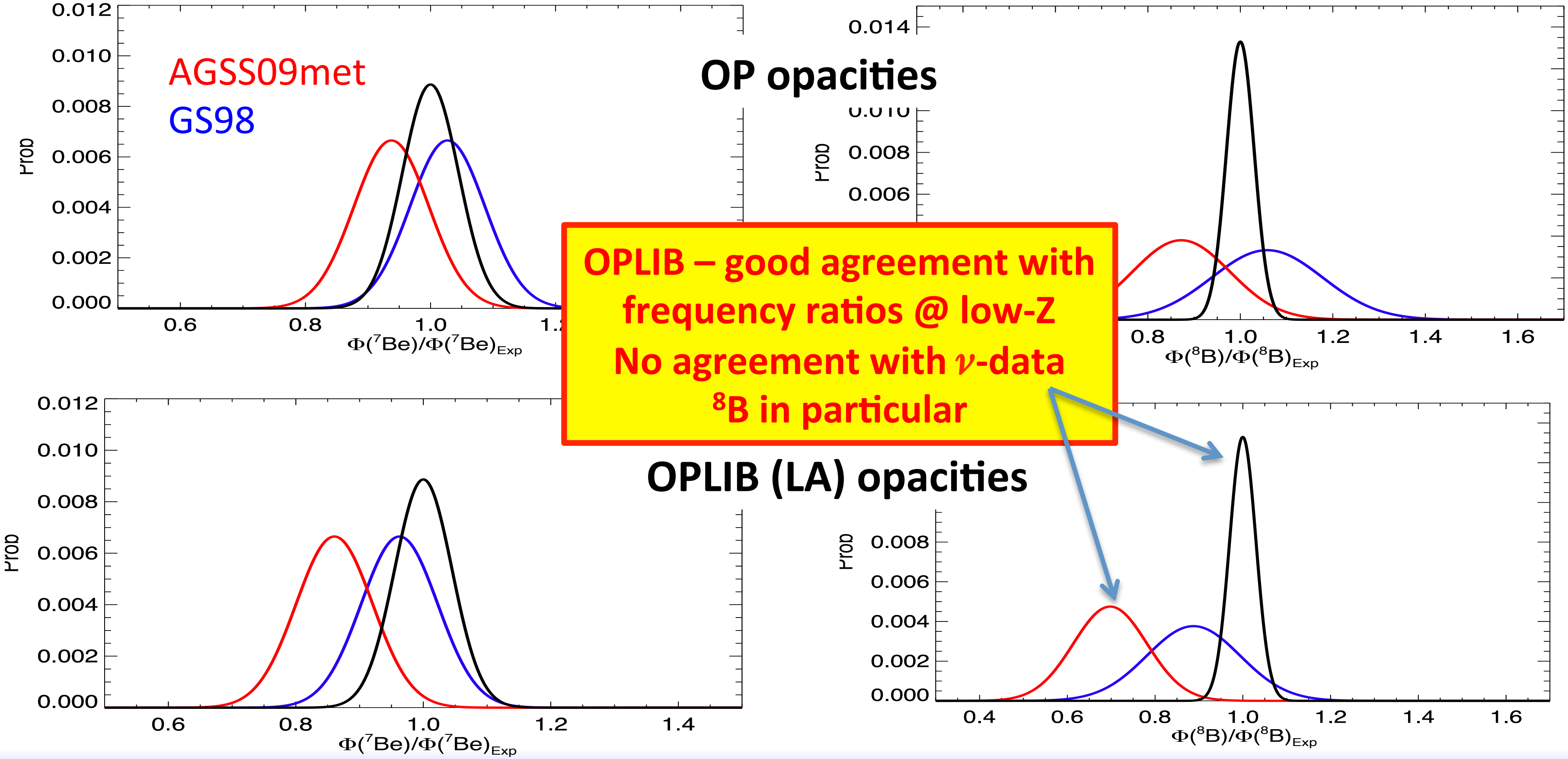




OPLIB (LA) opacities



New opacity calculations: impact on SSMs



New opacity calculations: impact on SSMs

Opac.	Qnt.	GS98	AGSS09met	Solar
OP	Y_S	0.2426	0.2317	0.2485 ± 0.0035
OPLIB	Y_S	0.2368	0.2241	0.2485 ± 0.0035
OPAS (photo)	Y_S	—	0.2324	0.2485 ± 0.0035
OP	$R_{CZ}/R_\odot$	0.7116	0.7223	0.713 ± 0.001
OPLIB	$R_{CZ}/R_\odot$	0.7115	0.7214	0.713 ± 0.001
OPAS (photo)	$R_{CZ}/R_\odot$	—	0.7164	0.713 ± 0.001

New opacities

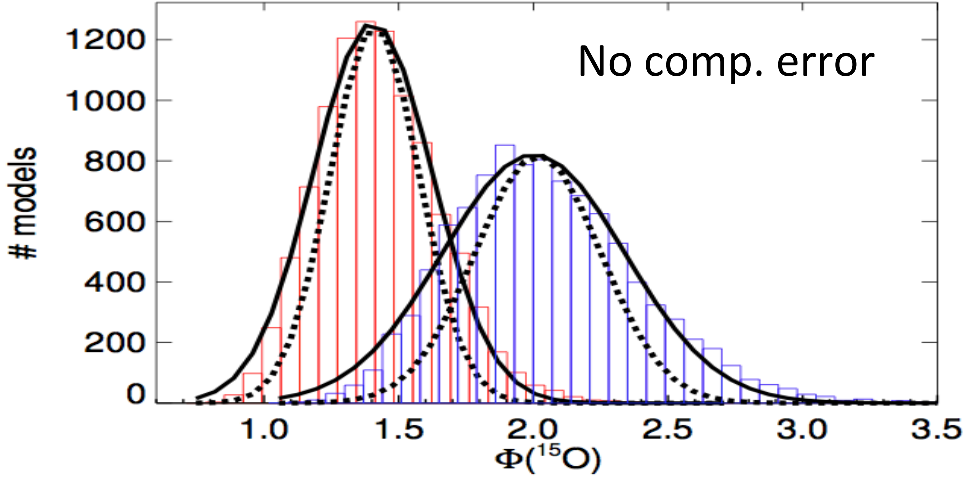
OPAS (partially useful – limited application) – Do not change the overall picture

OPLIB – substantially lower in the core – increase TILT between core and envelope

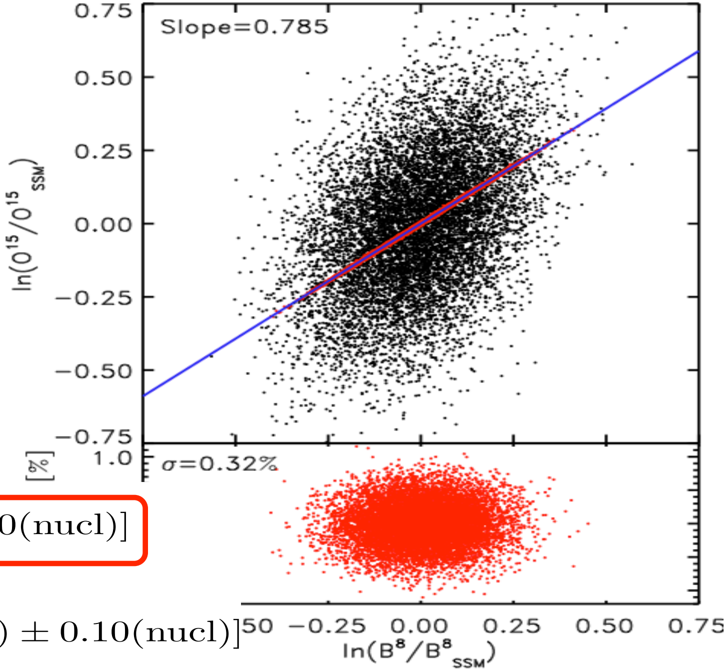
- **partial reduction of $\delta c/c$ peak**
- **agreement for frequency ratios**
- **too low surface Y – too low core opacity**
- **bad results for solar neutrinos – too low core opacity**

Seismic and solar neutrinos view of solar core is different

CN ν fluxes



Temperature dependences can be cancelled out using ^{8}B



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

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

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