Solar models and neutrinos
Where do we stand?

Aldo Serenelli

"NDM 2018"

Daejeon – 29.6.18-4.7.18

Coming full circle

How does the Sun shine?
What is the solar core temperature?

Radiochemical experiments
Kamiokande

Solar neutrino problem

Standard model(s) crises!

Helioseismic inference of
solar structure → agreement with solar models
→ Physics solution (circa 1996)

SuperK & SNO
ν oscillations

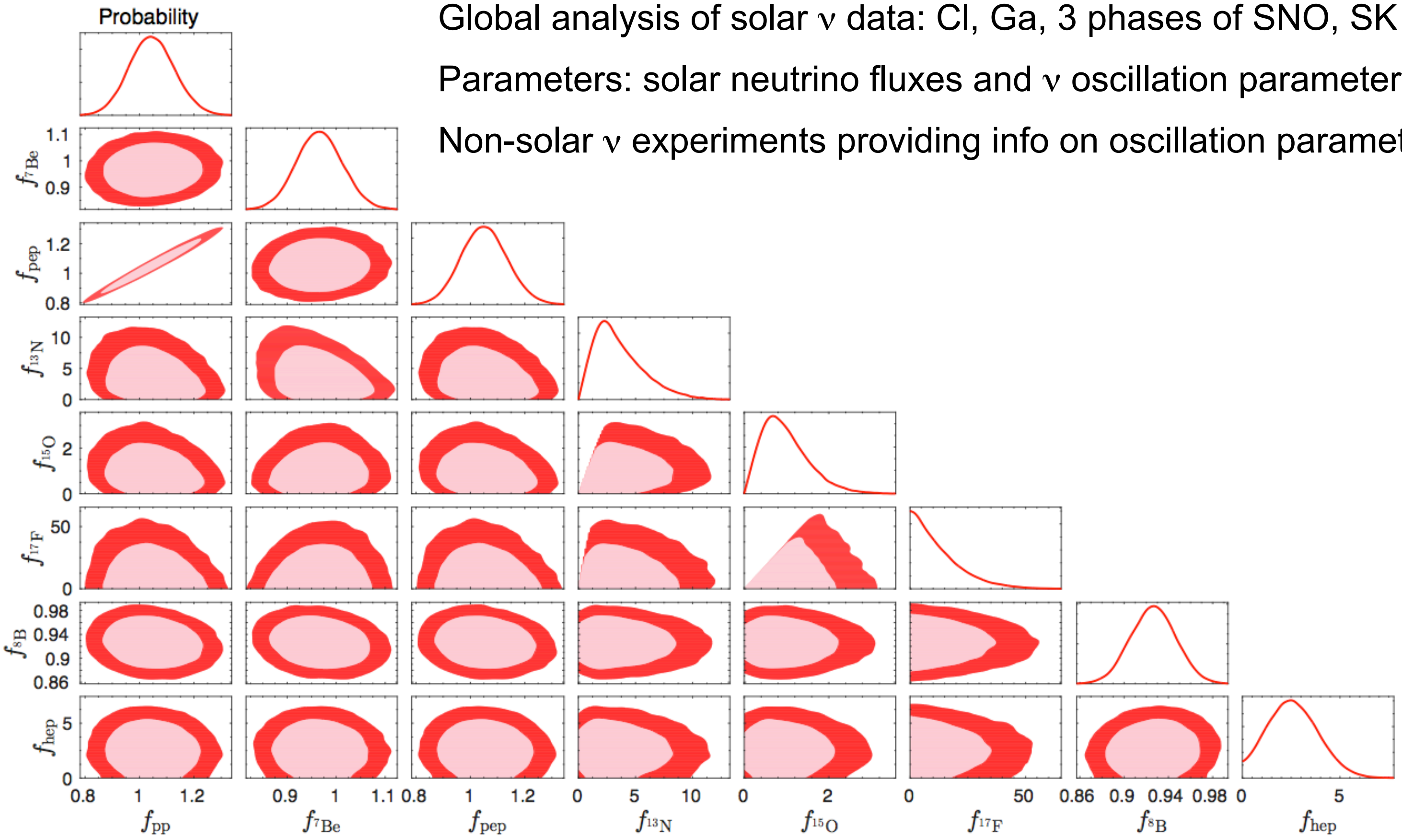
Solar νs as sensitive
probes of solar core

How does the Sun shine?

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



Bergstrom et al. 2016

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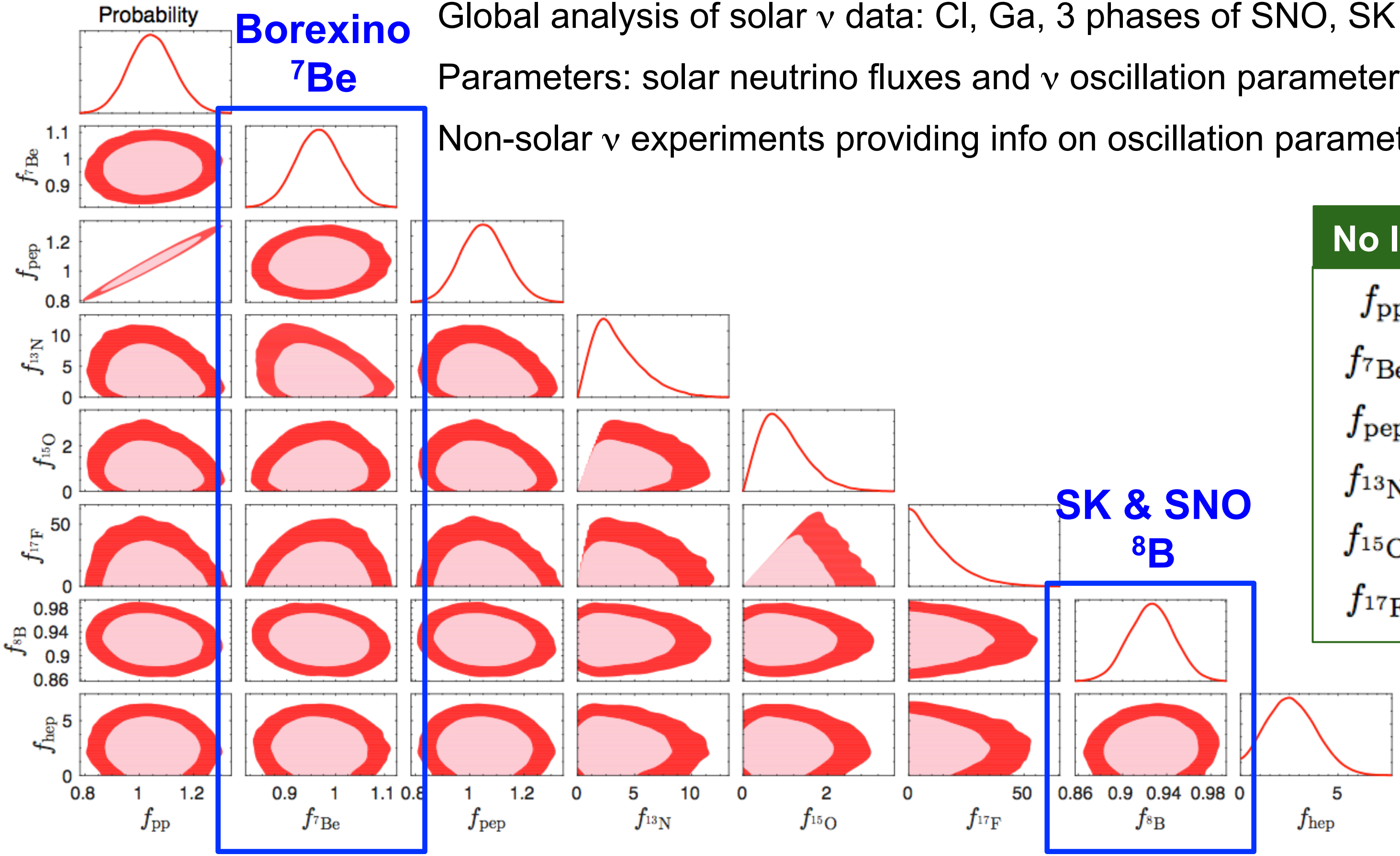

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Parameters: solar neutrino fluxes and ν oscillation parameters (Δm^2_{21}, θ_{12}, θ_{13})

Non-solar ν experiments providing info on oscillation parameters

No luminosity constraint

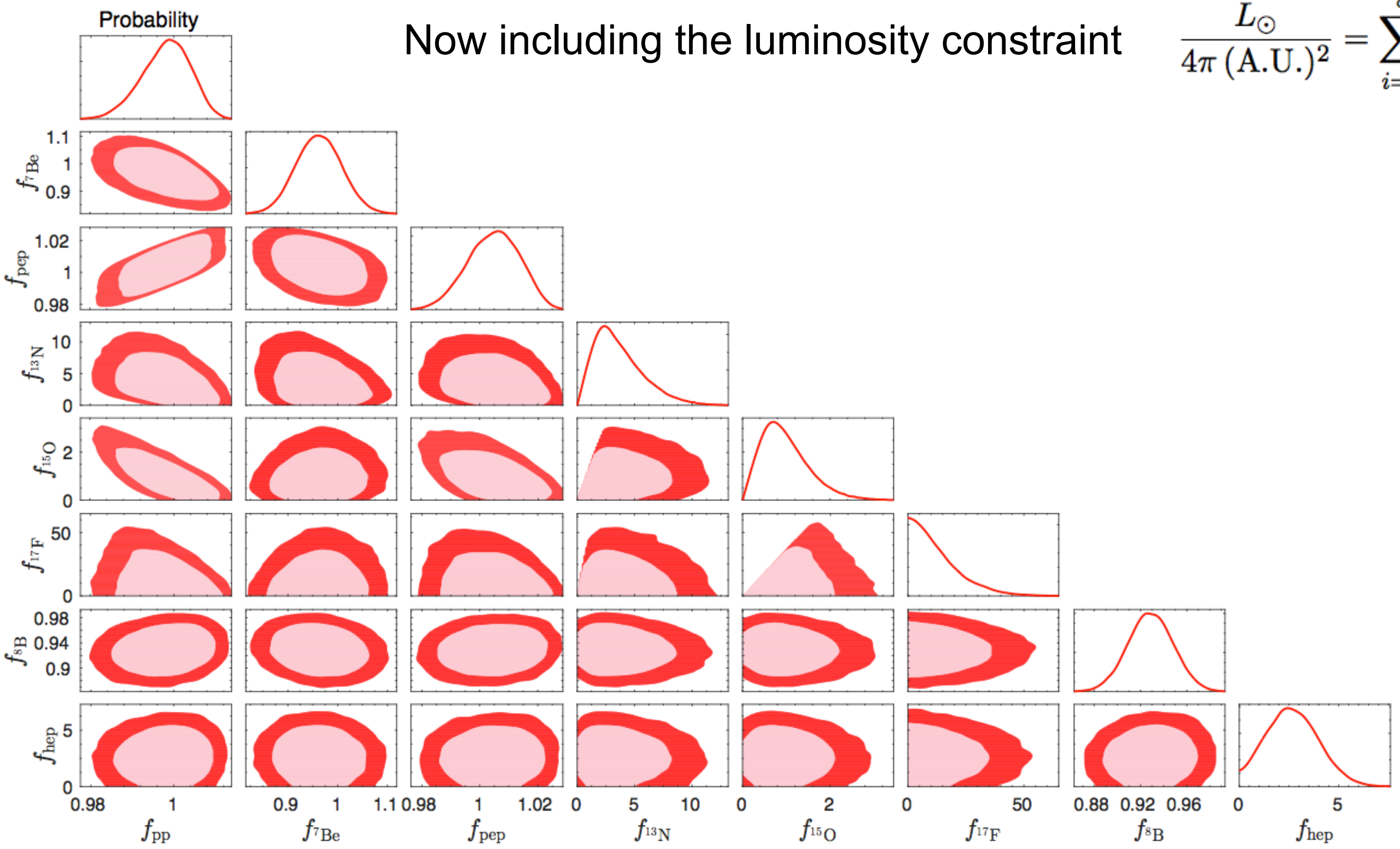
$$f_{pp} = 1.04 \pm 0.08 \left[{}^{+0.22}_{-0.20}\right],$$
$$f_{^7Be} = 0.97^{+0.04}_{-0.05} \left[\pm 0.12\right],$$
$$f_{pep} = 1.05 \pm 0.08 \left[{}^{+0.23}_{-0.20}\right],$$
$$f_{^{13}N} = 1.7^{+2.8}_{-1.0} \left[{}^{+8.4}_{-1.6}\right],$$
$$f_{^{15}O} = 0.6^{+0.7}_{-0.4} \left[\leq 2.6\right],$$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

Bergstrom et al. 2016

How does the Sun shine?

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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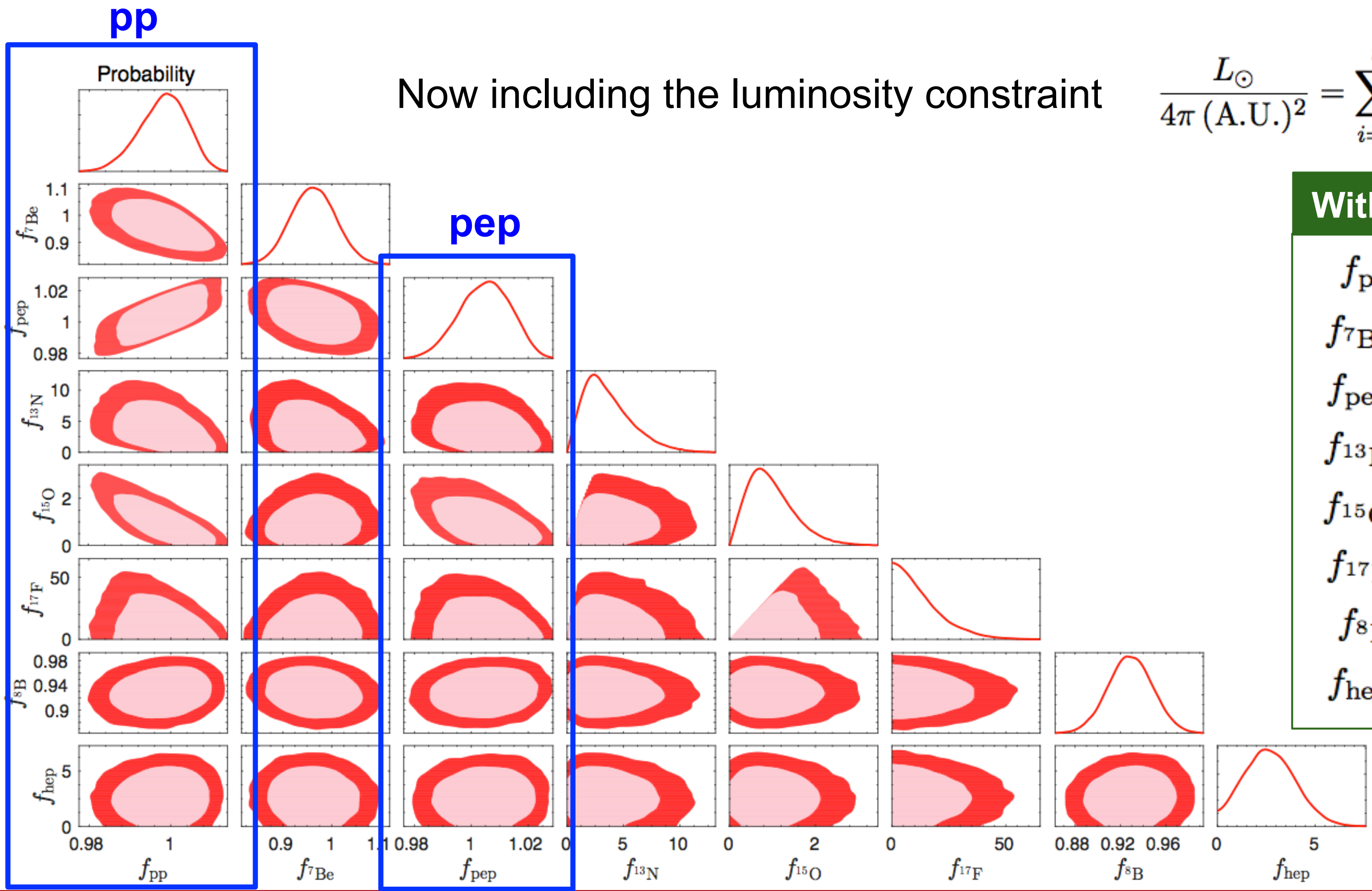

Now including the luminosity constraint

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

With luminosity constraint

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$$f_{^7Be} = 0.96^{+0.05}_{-0.04}\,[^{+0.12}_{-0.11}]\,,$$
$$f_{pep} = 1.005 \pm 0.009\,[^{+0.019}_{-0.024}]\,,$$
$$f_{^{13}N} = 1.7^{+2.9}_{-1.0}\,[^{+8.4}_{-1.6}]\,,$$
$$f_{^{15}O} = 0.6^{+0.6}_{-0.4}\,[^{+2.0}_{-0.6}]\,,$$
$$f_{^{17}F} \leq 15\,[46]\,,$$
$$f_{^8B} = 0.92 \pm 0.02\,[\pm 0.05]\,,$$
$$f_{hep} = 2.4^{+1.5}_{-1.2}\,[\leq 5.9]\,,$$

Bergstrom et al. 2016

SSM – neutrinos

No luminosity constraint – purely experimental result

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

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

Bergstrom et al. 2016

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With luminosity constraint – $L_\odot$ = Lnuc

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

Bergstrom et al. 2016

Global analysis with more recent data needed, e.g. Borexino – see Ianni's talk

Solar core temperature → solar models

Strong T dependence of ν-fluxes

$$\Phi(^8\mathrm{B}) \propto \mathrm{T}_\mathrm{c}^{25} \longrightarrow \mathrm{SuperK{+}SNO} \longrightarrow \delta\mathrm{T}_\mathrm{c}/\mathrm{T}_\mathrm{c} \approx 0.1\%$$

$$\Phi(^7\mathrm{Be}) \propto \mathrm{T}_\mathrm{c}^{10} \longrightarrow \mathrm{Borexino} \longrightarrow \delta\mathrm{T}_\mathrm{c}/\mathrm{T}_\mathrm{c} \approx 0.4\%$$

But this determines only precision – actual T_C determination requires solar models

Problems start here – models depend on inputs

- Solar composition
- Radiative opacities

- Nuclear reaction rates
- Chemical mixing (gravitational settling + other mixing processes)

- Equation of state

Solar composition

Change of paradigm in solar composition:

Grevesse & Sauval 1998 → Asplund et al. 2005, 2009, 2015 – Caffau et al. 2011

- 3D solar atmosphere models
- refined atomic data and line selection
- non-LTE treatment of line formation

Elem.	GS98	AGSS09met	Change
C	8.52 ± 0.06	8.52 ± 0.05	23%
N	7.92 ± 0.06	7.83 ± 0.05	23%
O	8.83 ± 0.06	8.69 ± 0.05	38%
Ne	8.08 ± 0.06	7.93 ± 0.10	41%
Mg	7.58 ± 0.01	7.53 ± 0.01	12%
Si	7.56 ± 0.01	7.51 ± 0.01	12%
S	7.20 ± 0.06	7.15 ± 0.02	12%
Fe	7.50 ± 0.06	7.45 ± 0.01	12%
$(Z/X)_\odot$	0.0229	0.0178	29%

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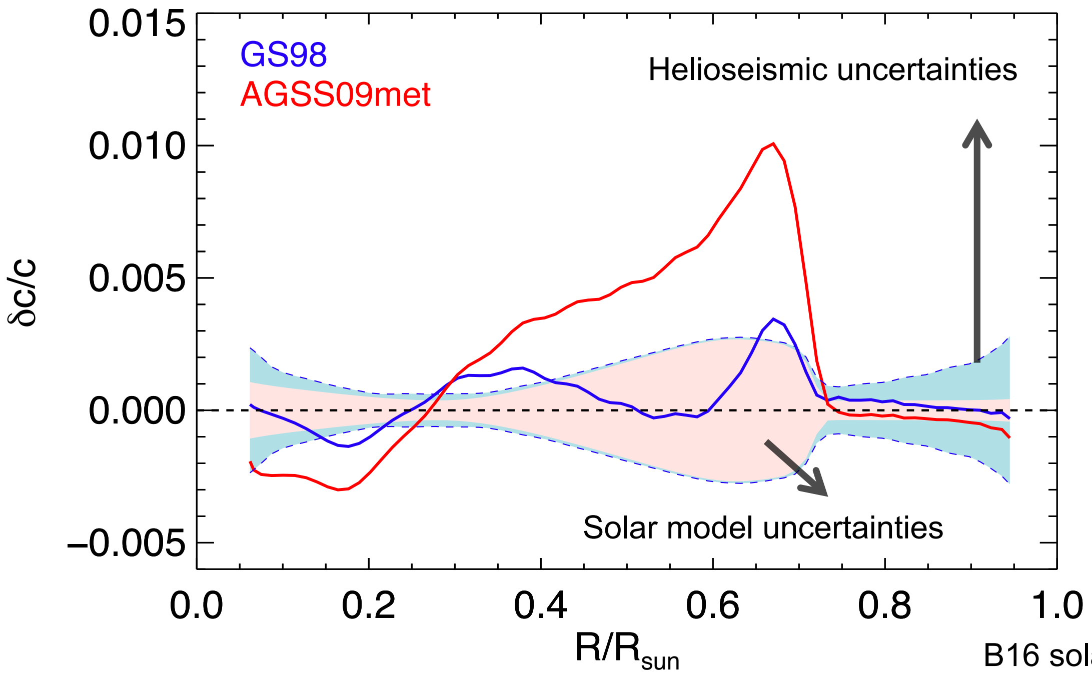
Impact of SSM calibration

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

Solar models - helioseismology



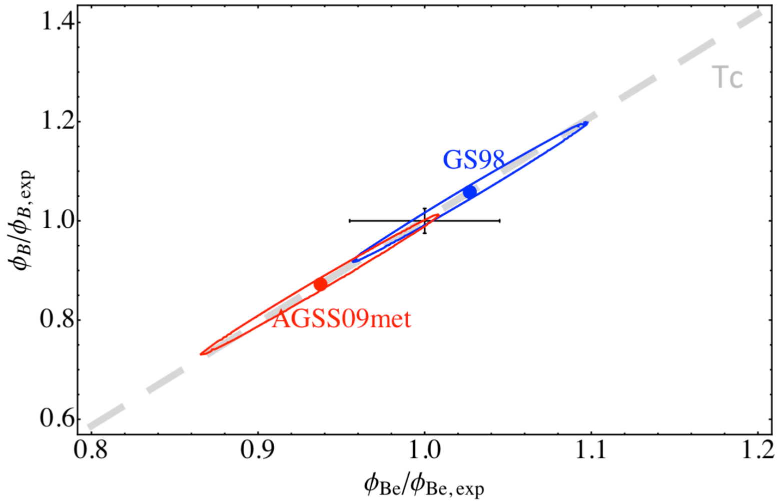
B16 solar models – Vinyoles et al. 2017

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
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0[a]

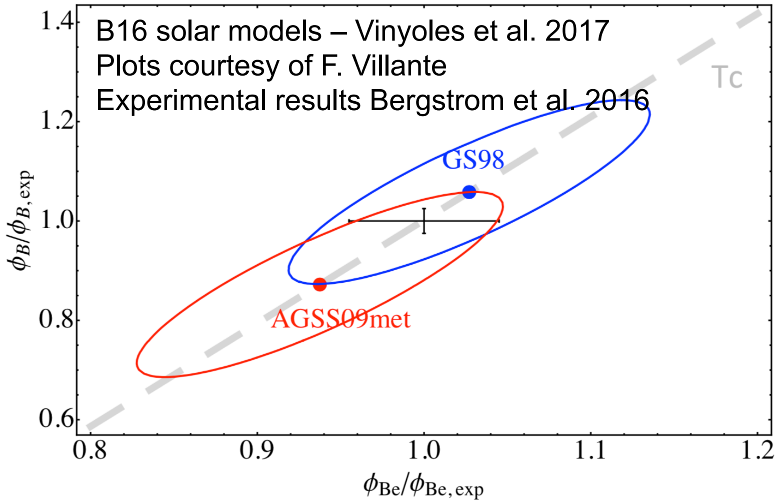
2-3 σ discrepancy for low Z

Solar models - neutrinos

Environmental (temperature) uncertainties
composition, opacity, age, luminosity, etc



+ nuclear rate uncertainties



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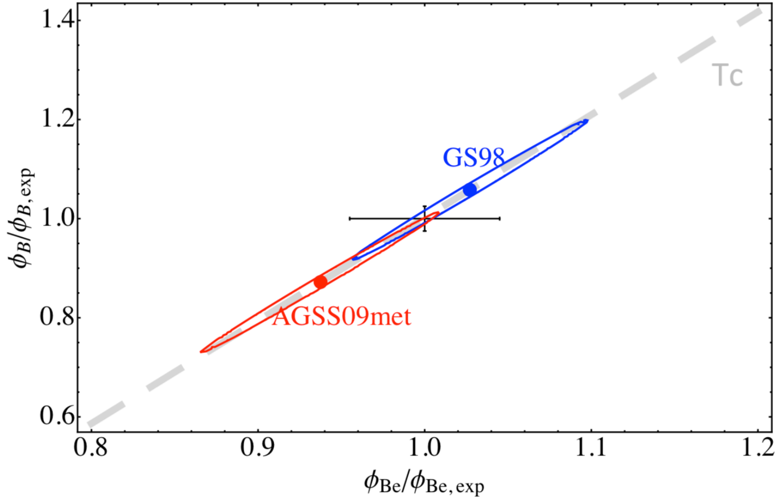
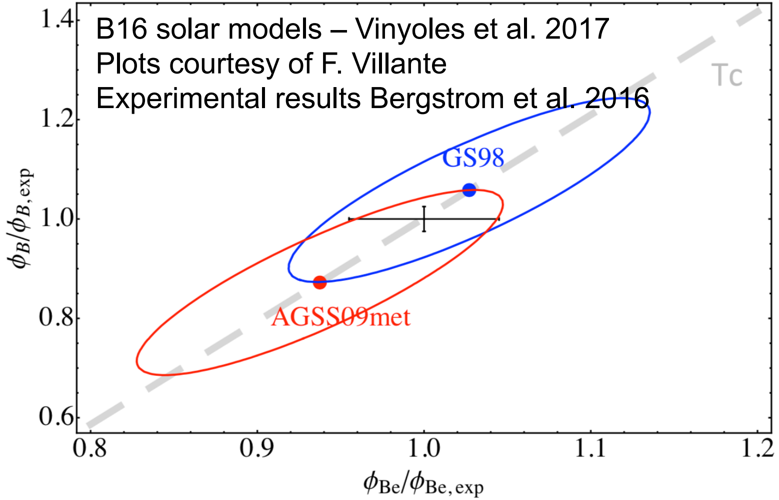




Composition → affects pp-chain fluxes through T_c change

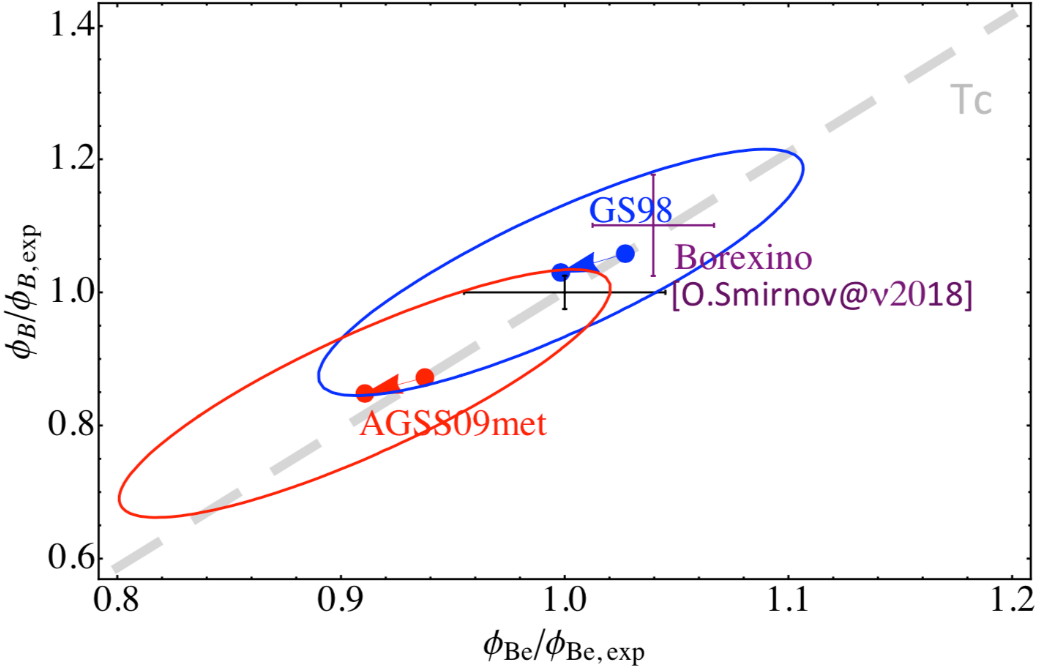
→ determines opacity

→ pp-fluxes sensitive to opacity (i.e. temperature, only indirectly to composition)

→ composition and atomic opacities are degenerate in pp-chain fluxes (and helioseismology)

Solar models – neutrinos

New Borexino ^{7}Be and ^{8}B – A. Ianni's talk today



Solar models – overall status

Case	dof	GS98 χ^2	GS98 p-value (σ)	AGSS09met χ^2	AGSS09met 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
$\Phi(^7\mathrm{Be}) + \Phi(^8\mathrm{B})$	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

High-Z models favored by helioseismology

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ν−fluxes comparably good agreement
(model uncertainties dominate)

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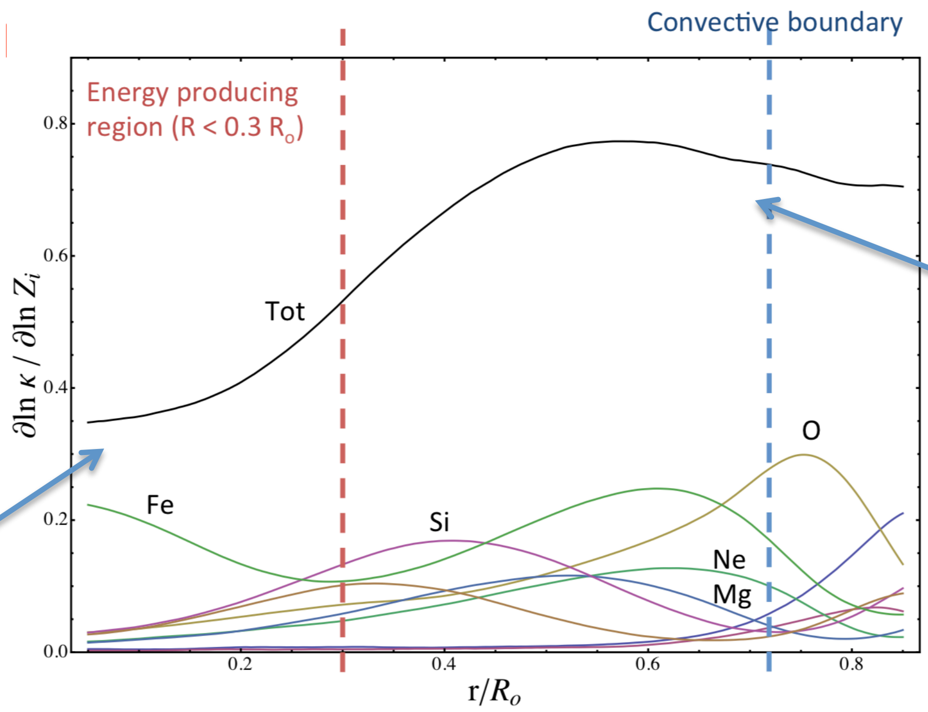
Global comparison favors high-Z models

i.e. models with (P, ρ) or (T, μ) profiles consistent with high-Z models

But interpretation in terms of solar composition is hampered by degeneracy between composition and opacity

Metals & Opacity



75% opacity from metals

35% opacity from metals

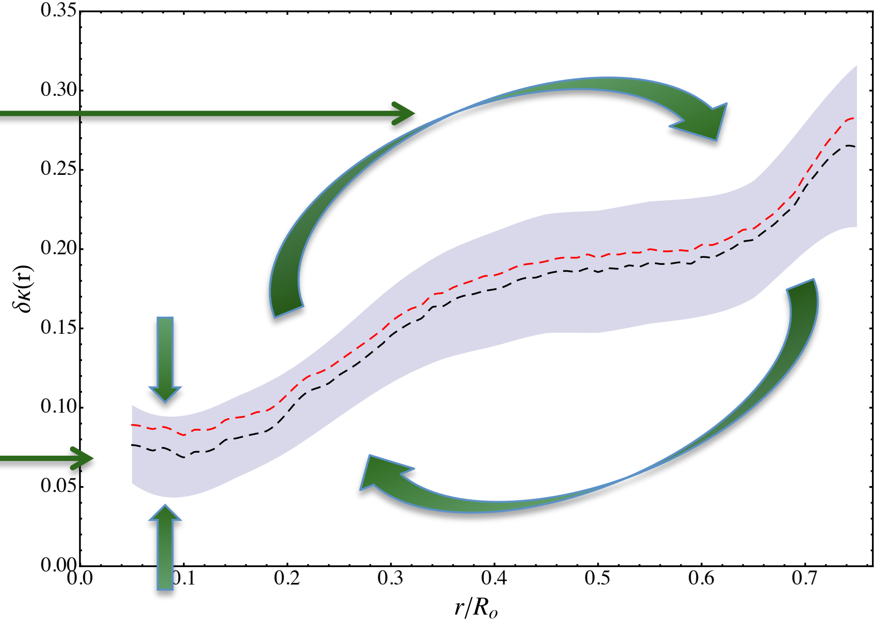
Intrinsic uncertainty + composition induced variation
(δ = fractional variation)

$$\delta\kappa = \delta\kappa_I + \sum \frac{\partial \log \kappa}{\partial \log z_i}\delta z_i$$

Solar opacity from νs and helioseismology

Helioseismology fixes the tilt

Solar neutrinos and Y_S the scaling (core)

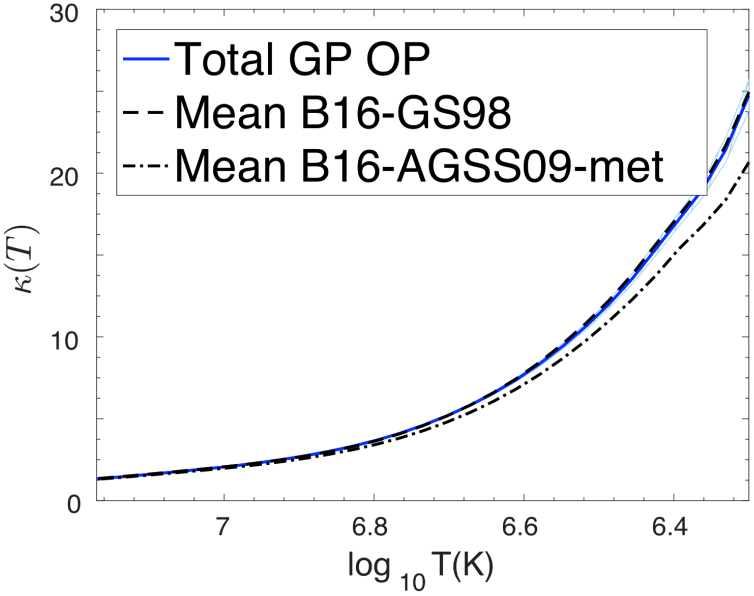


Villante et al. 2014

Solar opacity from νs and helioseismology

δκ$_I$ is an unknown function → Gaussian Process

$$\delta\kappa = \delta\kappa_I + \sum \frac{\partial \log \kappa}{\partial \log z_i}\delta z_i$$



Song et al. 2018

Bayesian analysis – composition free to vary

Opacity solar profile (posterior distrib)

Very close to that from GS98 model (unsurprisingly)

If AGSS09 composition → 20% increase at base of convective zone

Improvements wrt Villante et al. 2014:

- arbitrary δκ$_I$ function
- all relevant metals free to vary

Solar opacity from νs and helioseismology

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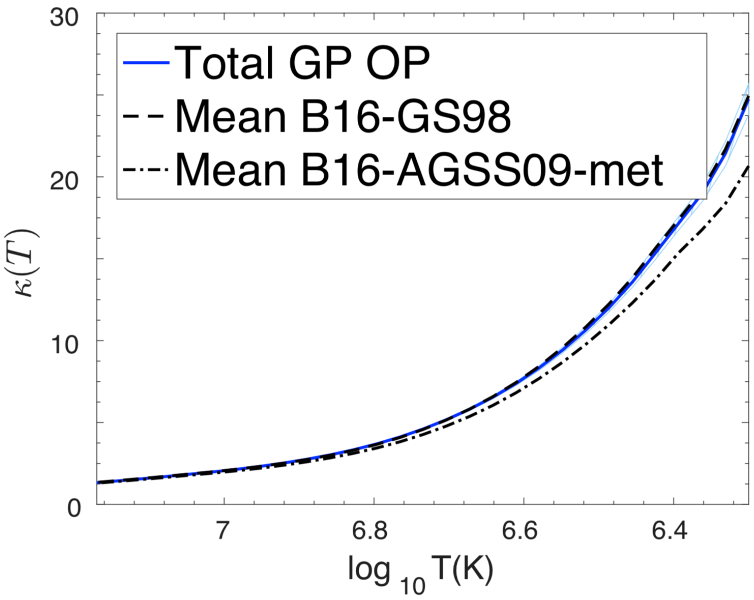
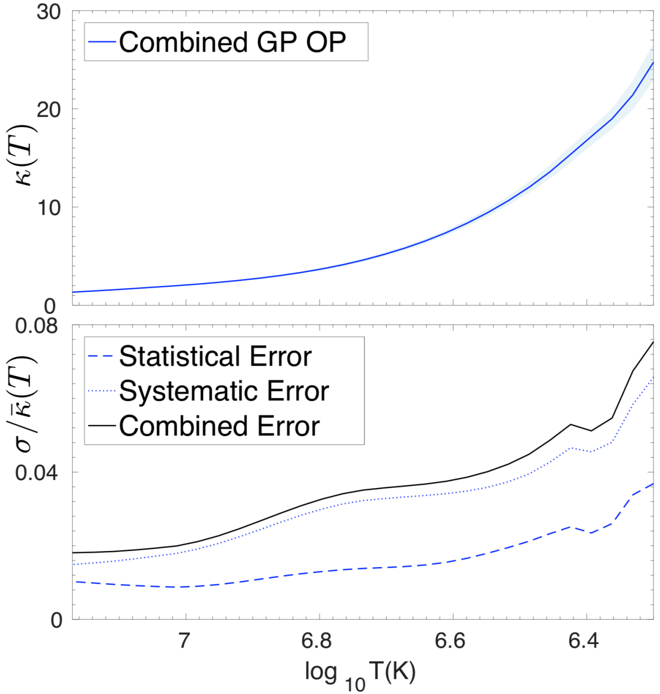


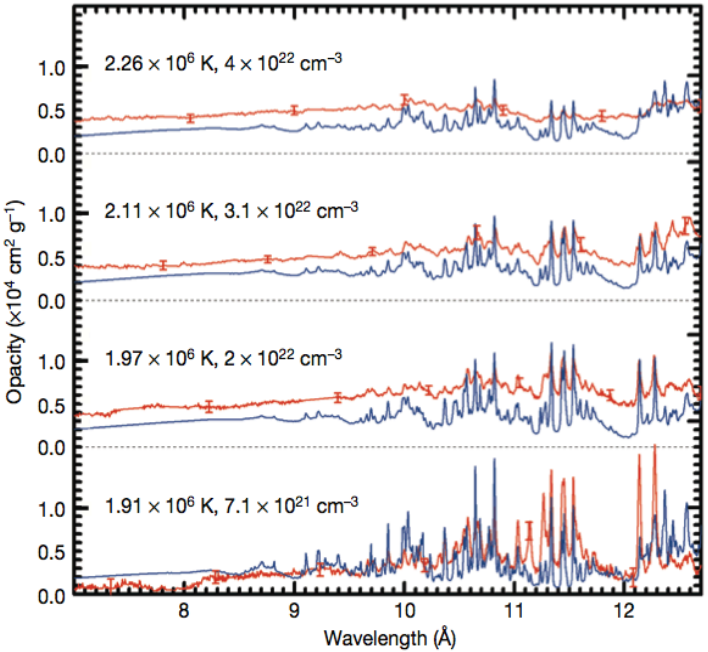


Song et al. 2018

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

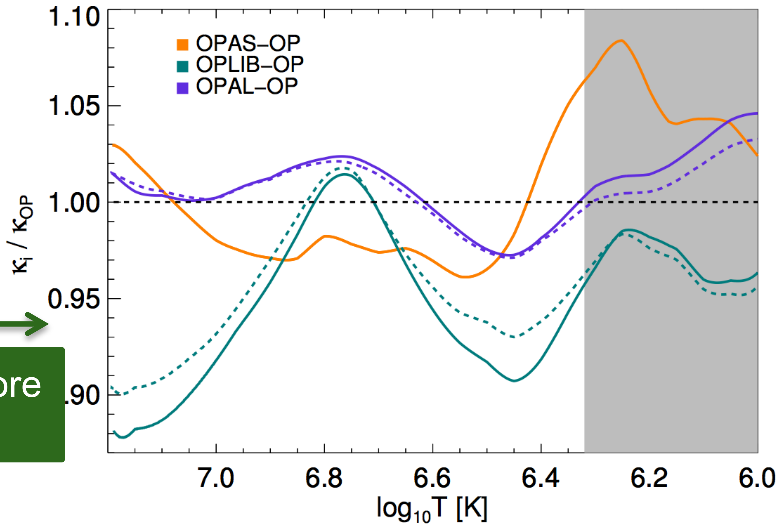
Opacities – new calculations

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 – Most complete set from new generation



Too low in solar core
Ruled out by νs

Solid – GS98

Dashed – AGSS09

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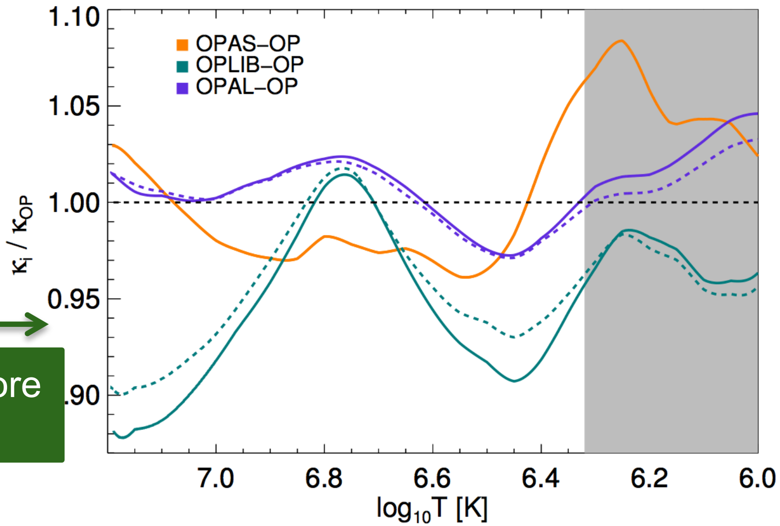


Too low in solar core
Ruled out by νs

Solid – GS98

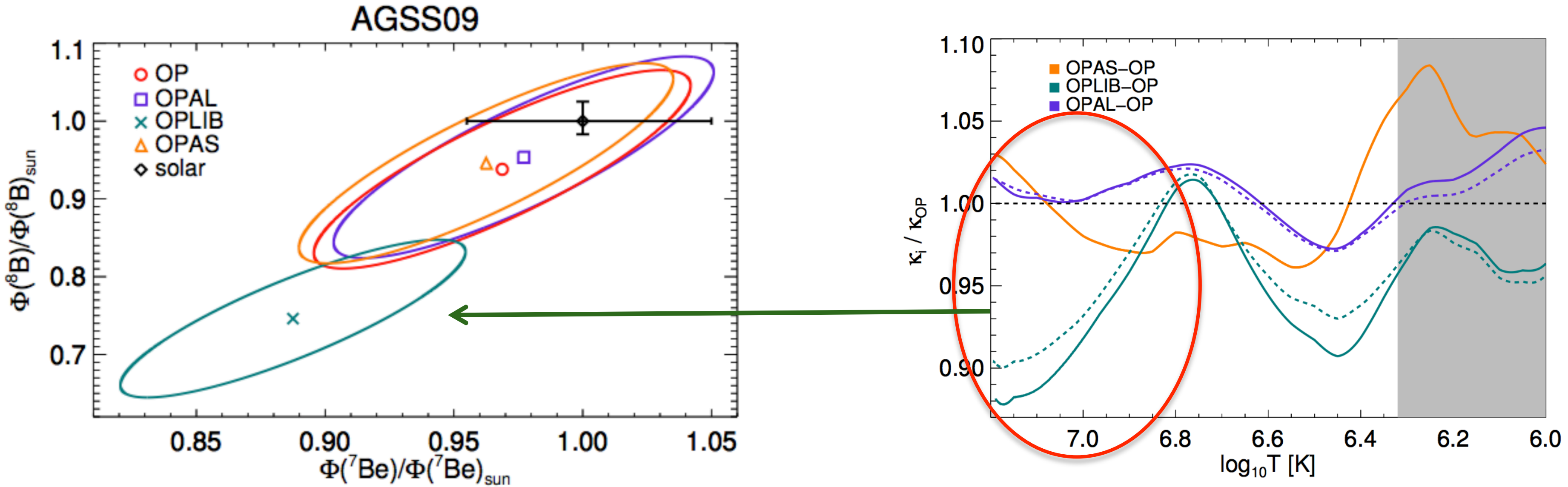
Dashed – AGSS09

Not guaranteed that newer opacity models lead to higher opacity values

± 5% variations

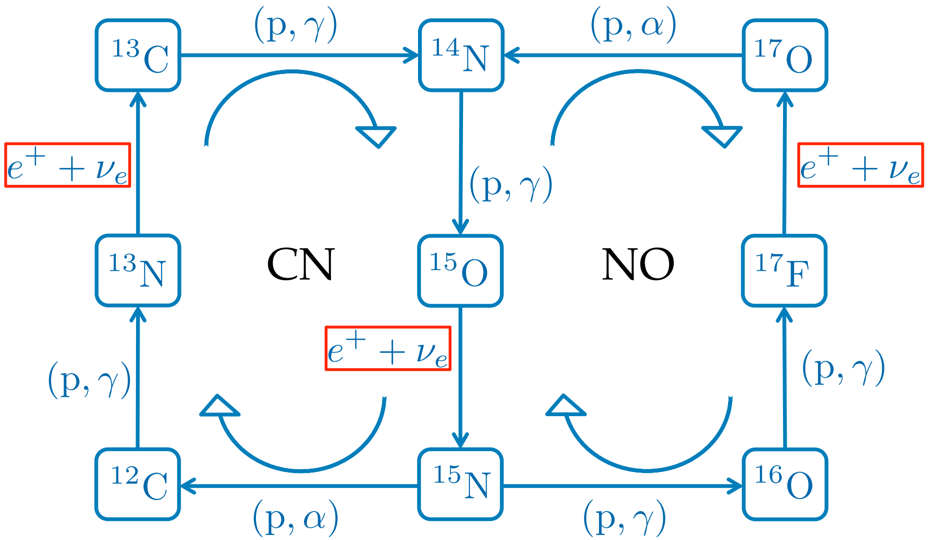
Current situation unclear

SSM with new opacities



Solar νs rule out OPLIB opacities for low Z models

CN-νs and solar composition



CN-cycle marginal in the Sun → intrinsic changes in its rate do not alter background state (e.g. T, ρ, X)

→ linear dependence on core C+N abundance and $S_{1,14}$ (for ^{15}O)

$$\boxed{\frac{\Phi(^{15}\mathrm{O})_{\mathrm{HZ}} - \Phi(^{15}\mathrm{O})_{\mathrm{LZ}}}{\Phi(^{15}\mathrm{O})_{\mathrm{LZ}}} \approx 40\%}$$

CN-νs and solar composition

Converting $\Phi(^{15}O)$ measurement into C+N core measurement – use $\Phi(^{8}B)$ as thermometer

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172}$$

$$\times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right]$$ → Temperature dependence

$$\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]$$ → Nuclear rates

$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$ → Temperature dependence

CN-νs and solar composition

Converting $\Phi(^{15}\mathrm{O})$ measurement into C+N core measurement – use $\Phi(^{8}\mathrm{B})$ as thermometer

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Temperature dependence

Nuclear rates

Temperature dependence

Reduces to

$$\boxed{\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} = \left[\frac{C+N}{C^{\mathrm{SSM}}+N^{\mathrm{SSM}}}\right] (1 \pm 0.4\%\,(\mathrm{env}) \pm 2.6\%\,(\mathrm{D}) \pm 10\%\,(\mathrm{nucl}))}$$

Nuclear uncertainty dominant: $\mathrm{S}_{1,14}$ (7%) & S_{17} (5%) – can be potentially reduced further

(Almost) direct measurement of C+N in solar core

Summary

- The Sun shines by pp burning : 1.03 ± 0.08 $L_\odot$
- adding luminosity constraint: CN < 1% at 3σ
- New theoretical opacities: OPLIB: excluded by ν measurements and surface helium
- Precise determination of solar opacity profile from νs (core opacity) and seismic data

Solar abundance/model problem remains: opacity ←→ composition degeneracy
Exporting abundance/opacity problem to other stars: systematic errors in ages by 10-15%

- CN fluxes remain necessary and only way to break degeneracy
- Whatever the result, very important measurement → core C+N abudance

  40% solar abundance problem, 15% chemical mixing processes in the Sun (surface/core difference)

First experimental opacity measurement @ solar conditions

→ hints of higher Fe opacity at right place : 7%
→ not enough : ~20 %

Opacity model calculations have differences ~10% → need improvements

Bonus (not included): Tentative discovery of g-modes – potential disagreement with SSM predictions?

Summary

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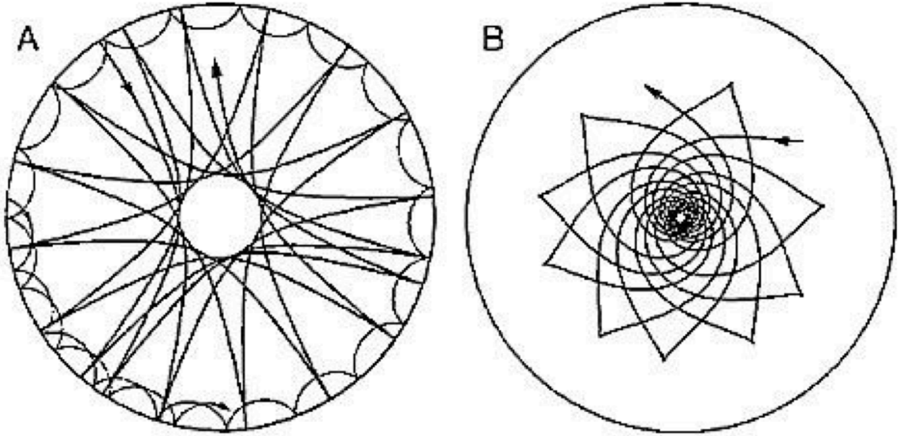
g-modes detection (finally?)

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 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

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

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
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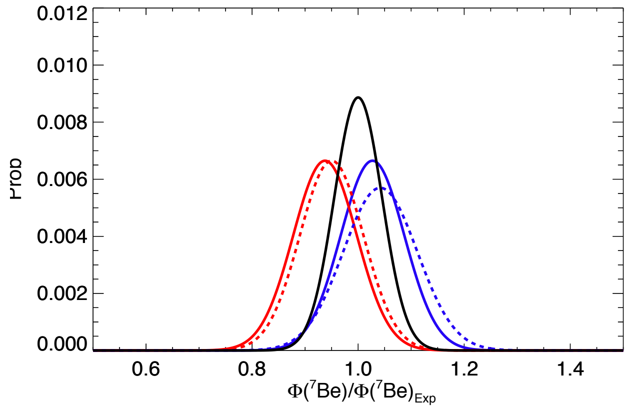
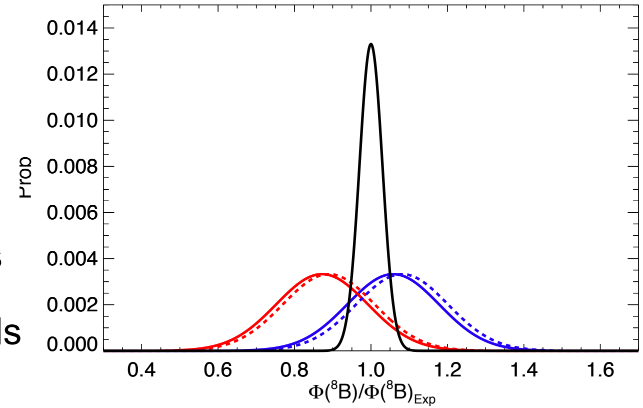


ν data fit
AGSS09
GS98

B16 models

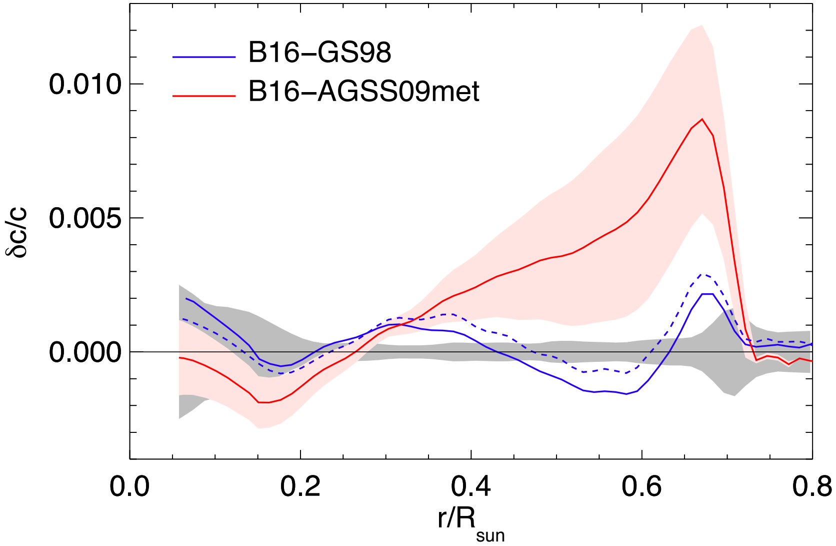
Older models



Revision of global analysis including new Borexino data needed

SSM – B16 models

Small changes in helioseismic probes



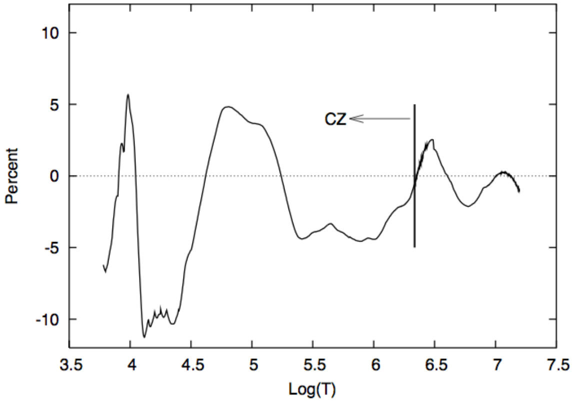
Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0005 ± 0.0004	0.0021 ± 0.001	—

Opacities

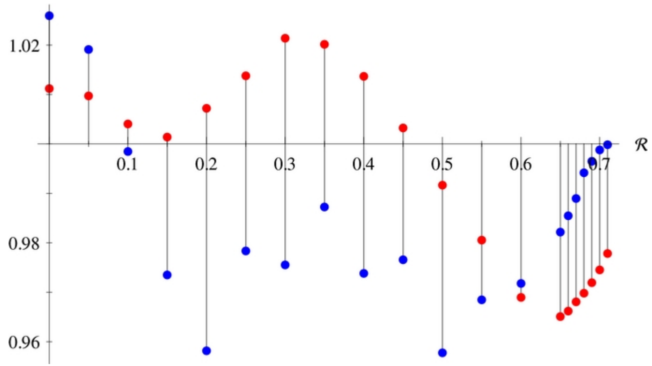
Helioseismic probes and pp νs depend on “effective” opacity profiles: opacity models + composition
details in F. Villante’s talk

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

OP vs OPAL

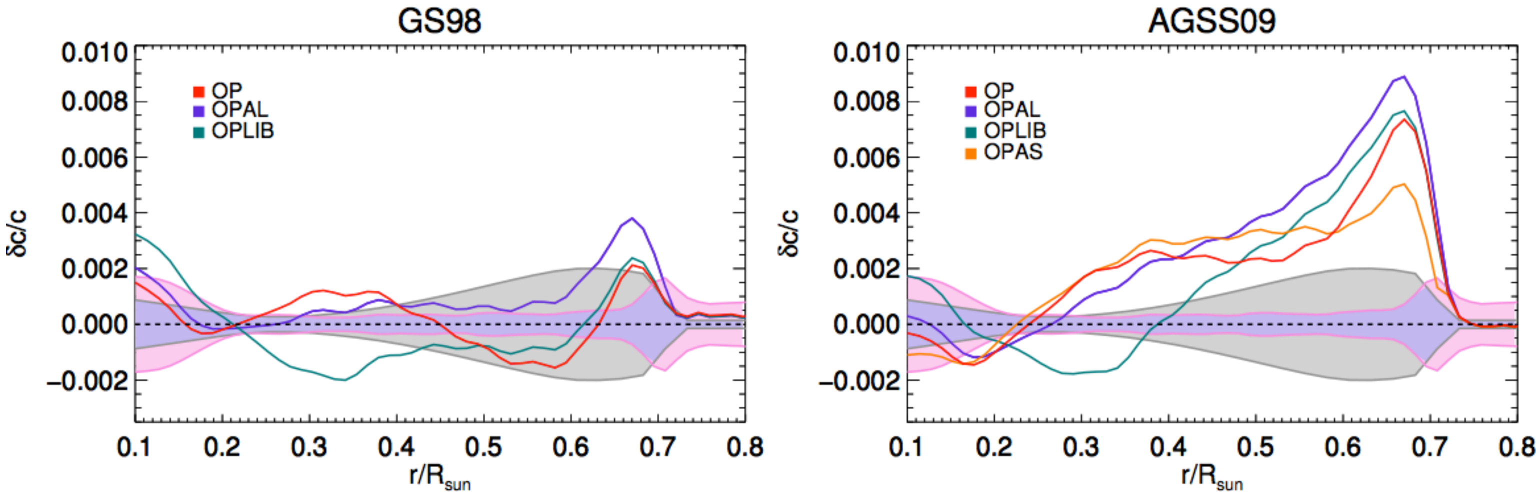


OPAS vs OP (blue)



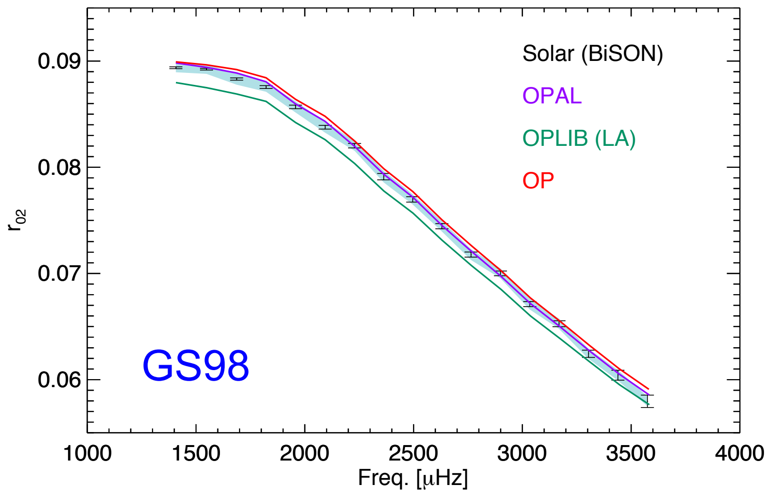
Few percent differences in solar interiors
Only theoretical calculations available

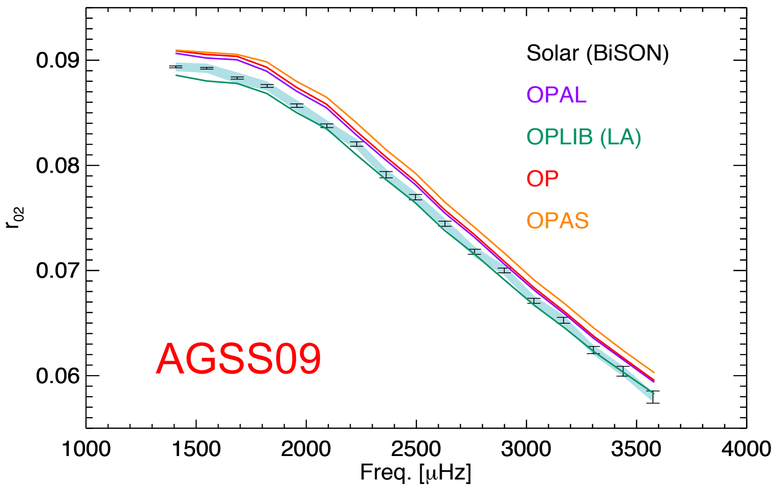
SSM with new opacities



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

SSM with new opacities

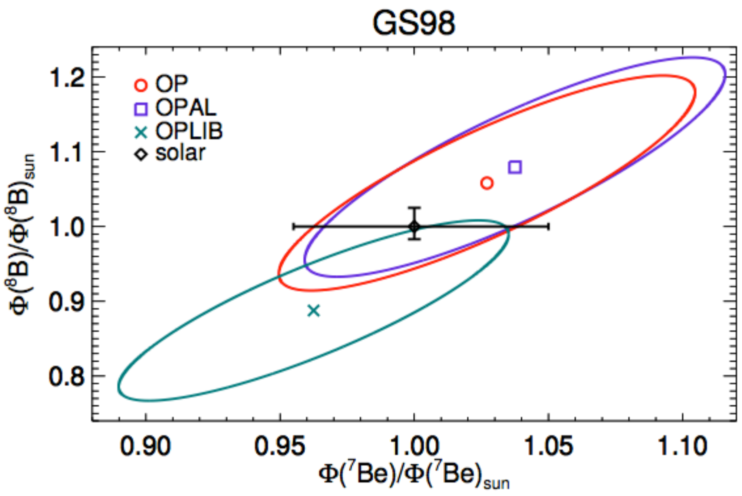


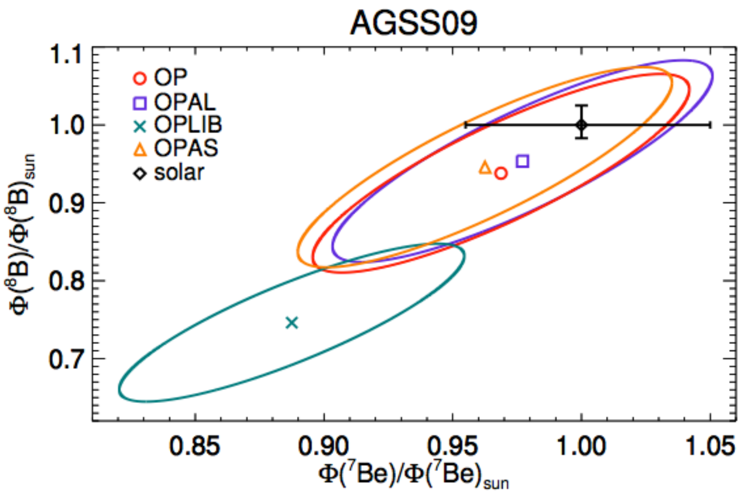


New OPLIB opacities lead to indecisive results for helioseismic probes

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

SSM with new opacities

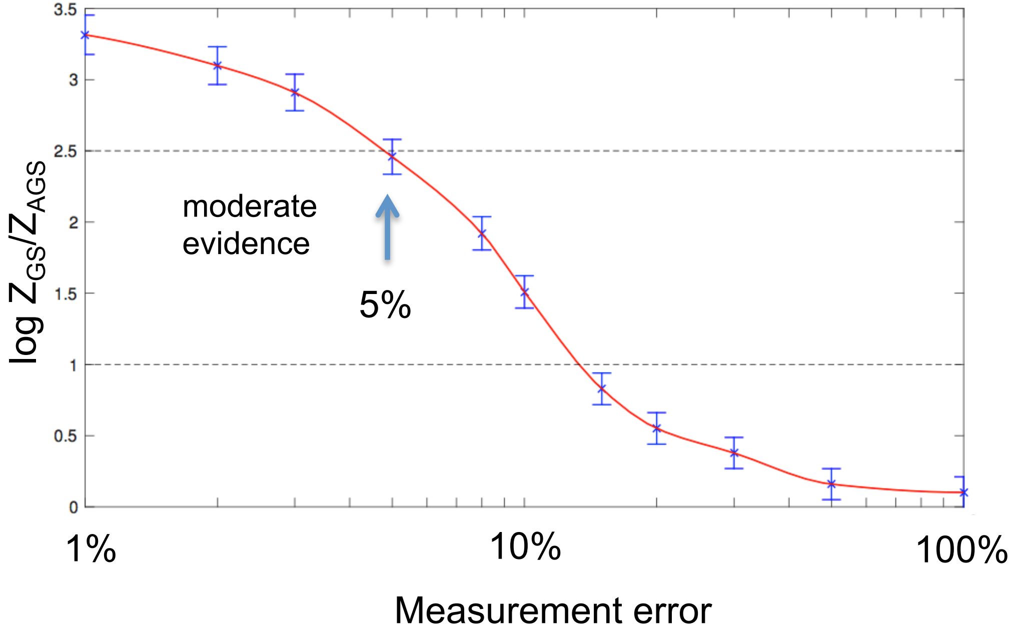




SSM: the need for CN(O)

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

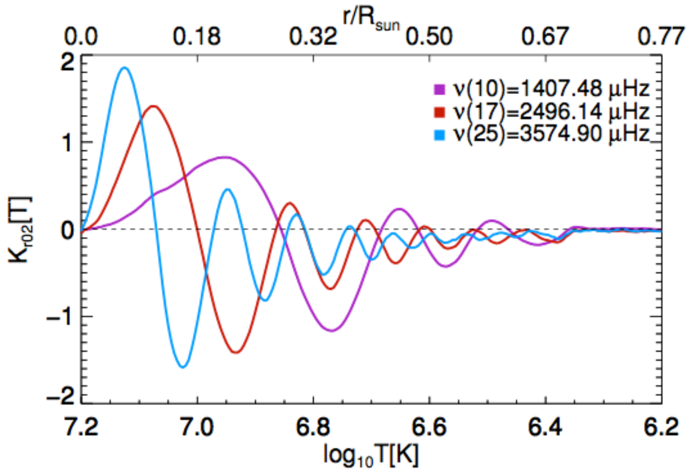


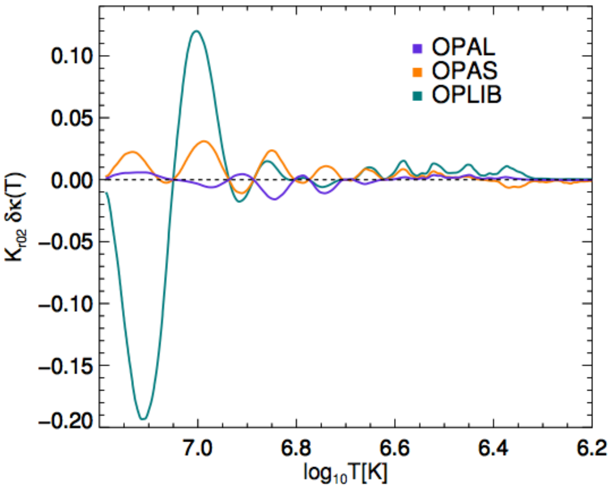
ν-experiments only

Bergstrom et al. 2016

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

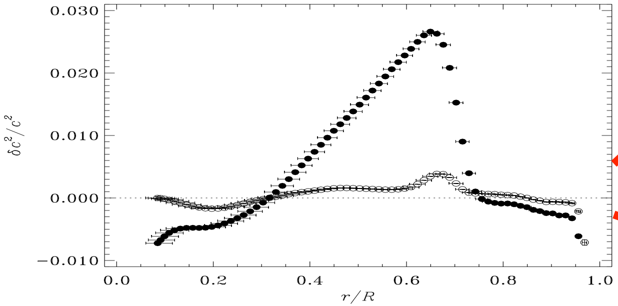
Extra slides



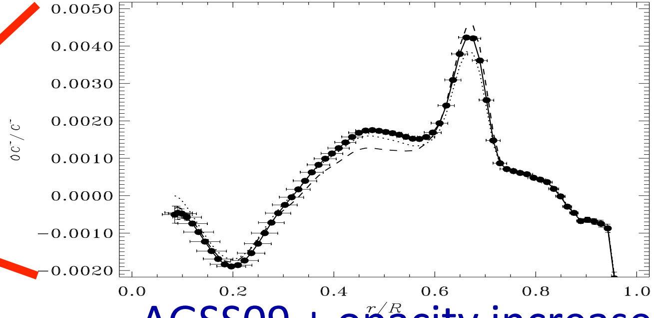


The role of radiative opacities

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



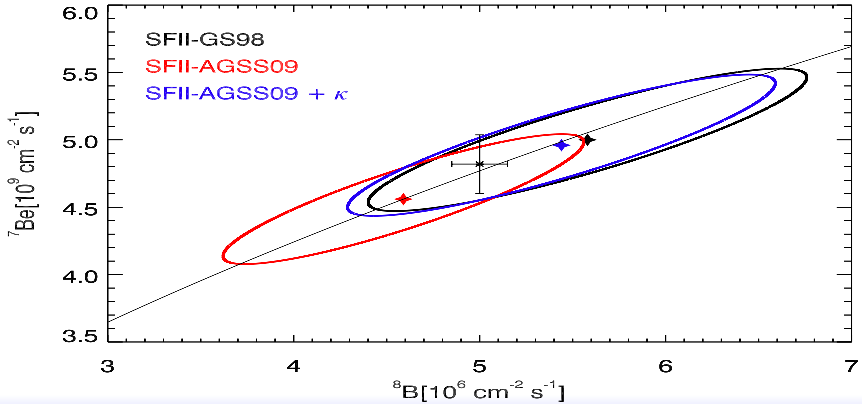
Christensen Dalsgaard et al 2009



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-m profile not to detailed composition

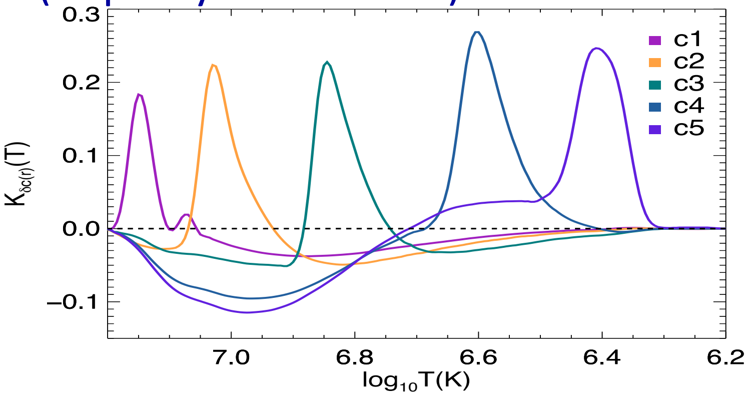
Opacity Kernels

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

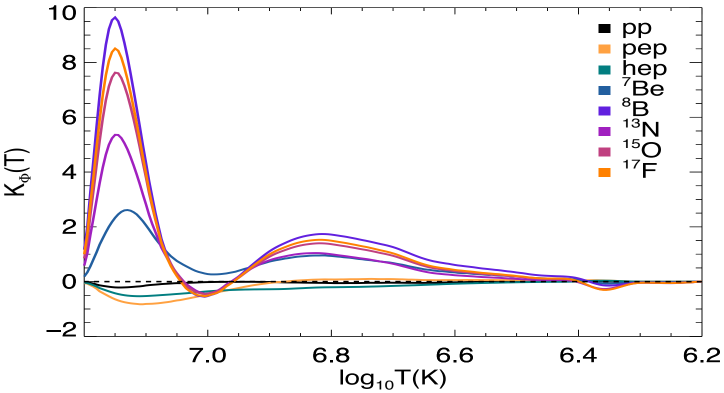
$$\delta Q = \int \frac{dT}{T} K_Q(T)\delta\kappa(T)$$

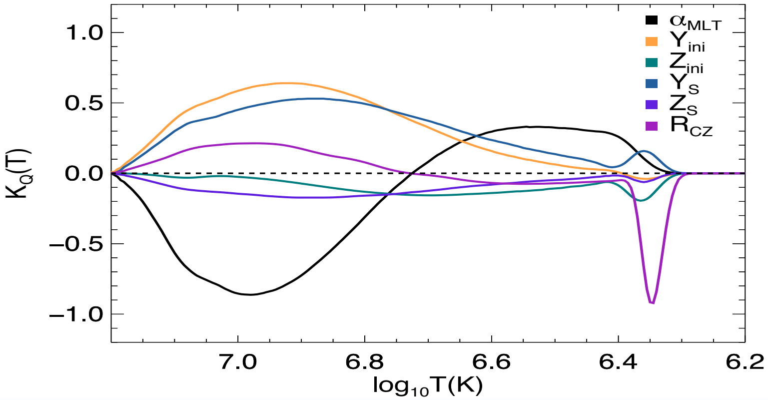
$$\delta\kappa(T) = C\delta(T - T_0)$$

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



Good as long as linear models have linear response

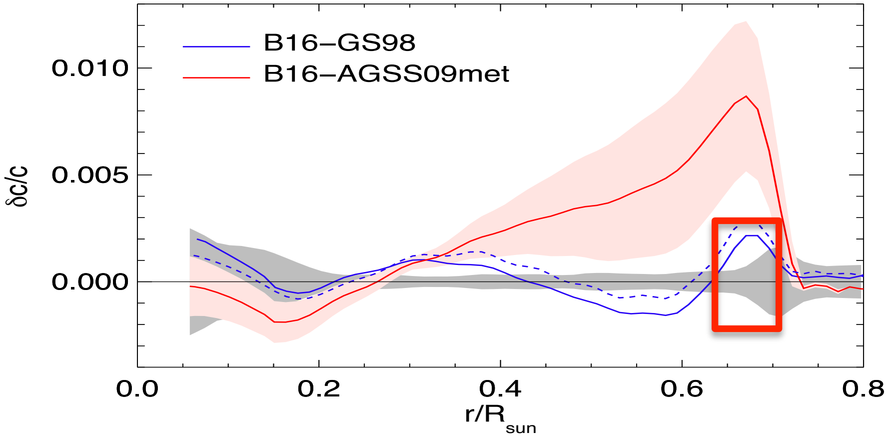




Solar models vs data

Including for correlations in models

		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



Looks can be deceiving – GS98 better but not excellent

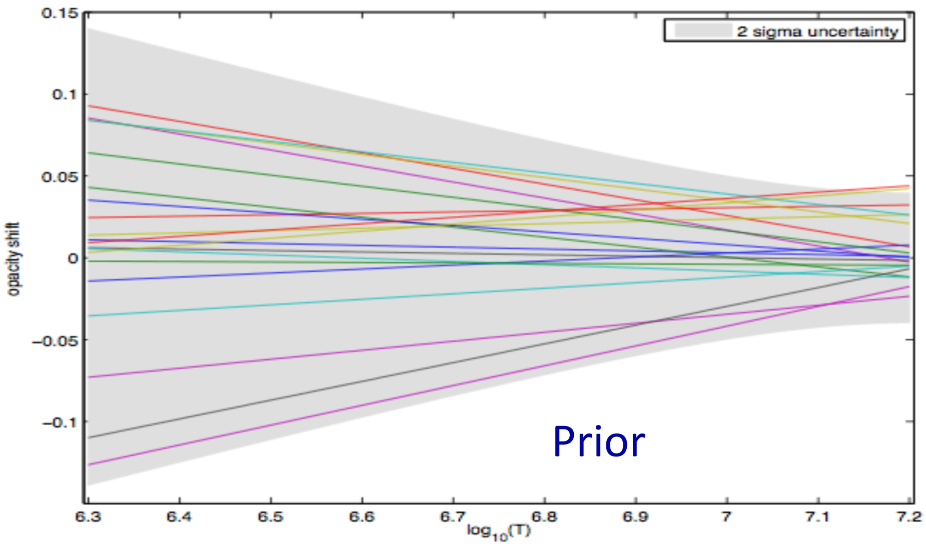
correlation in models very important

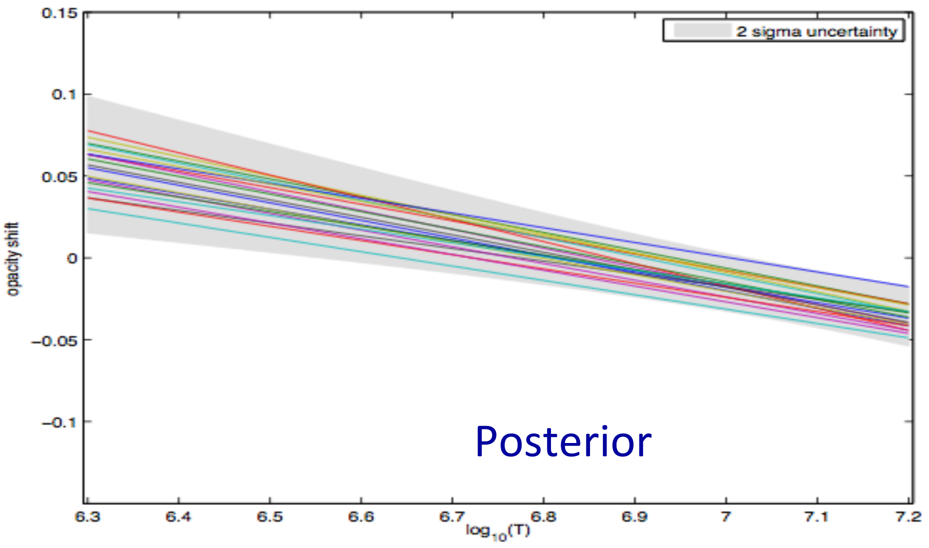
linear variation of opacity “too rigid”

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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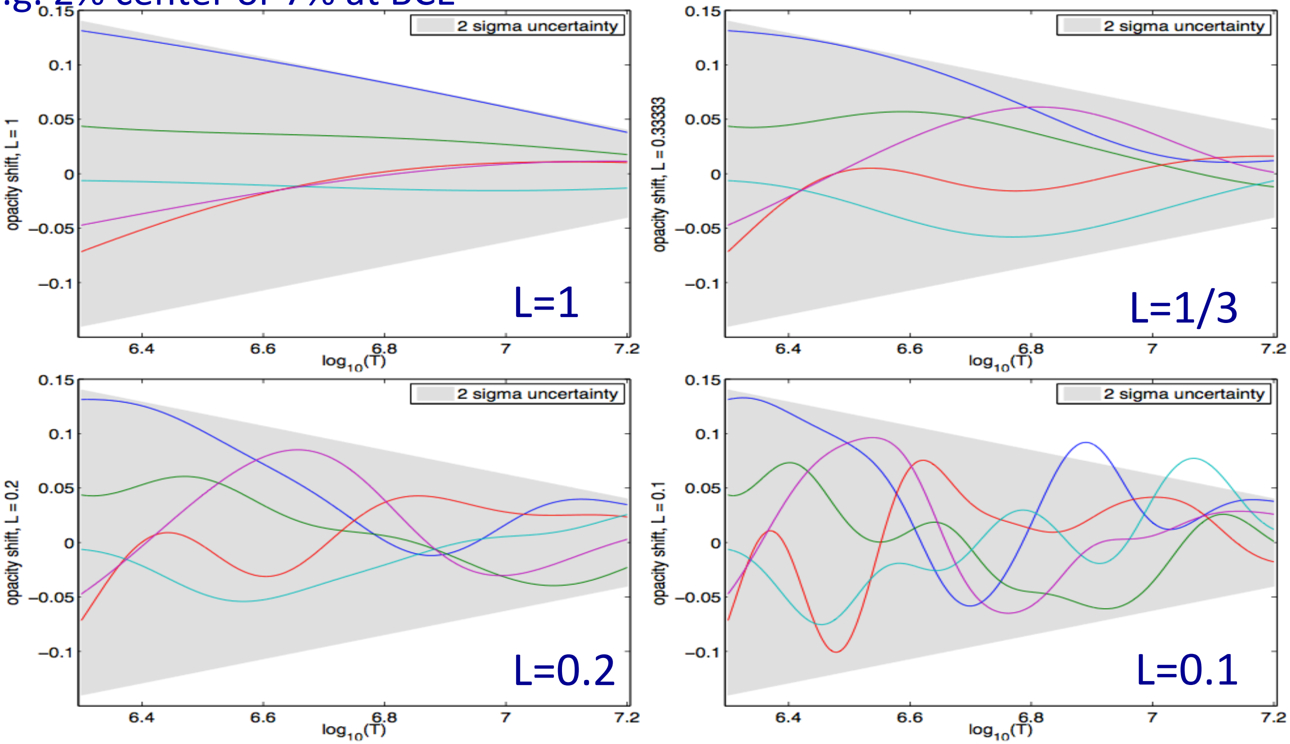
Correlation between two points

L correlation length

Define sensible priors for L

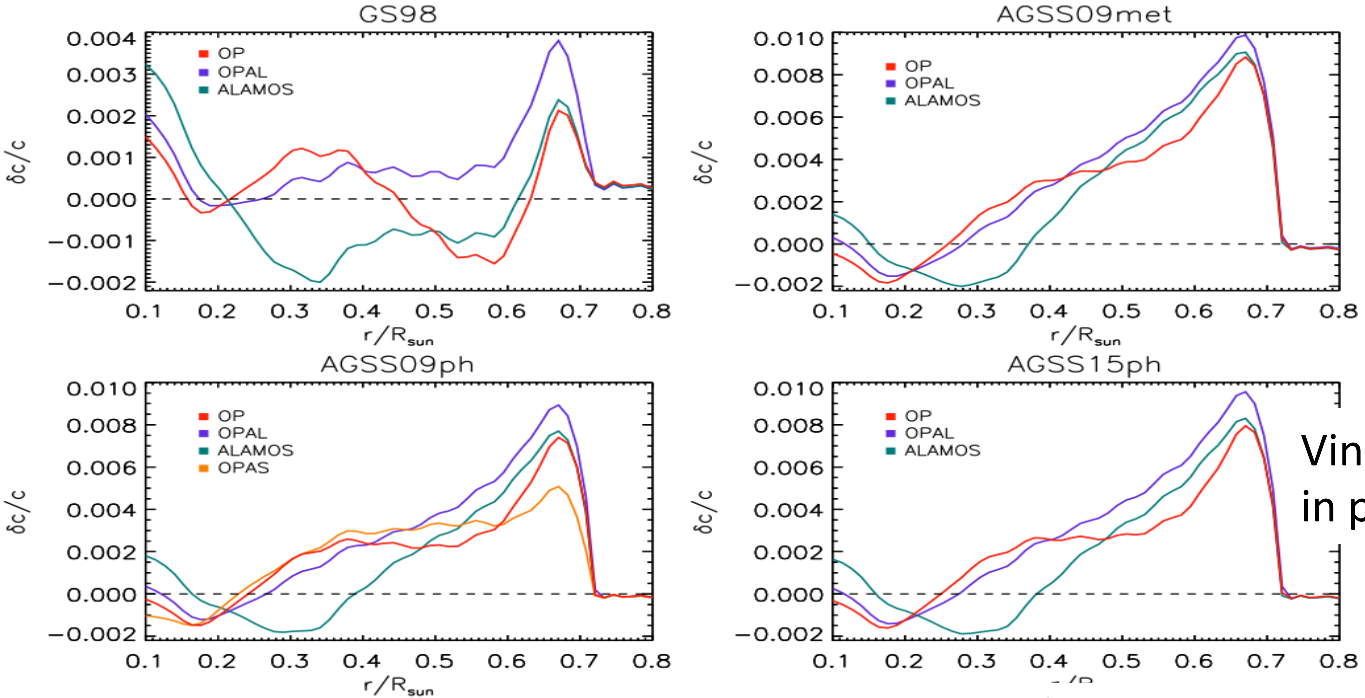
determine posterior from data

Obtain “best” opacity fit



Song et al. in preparation

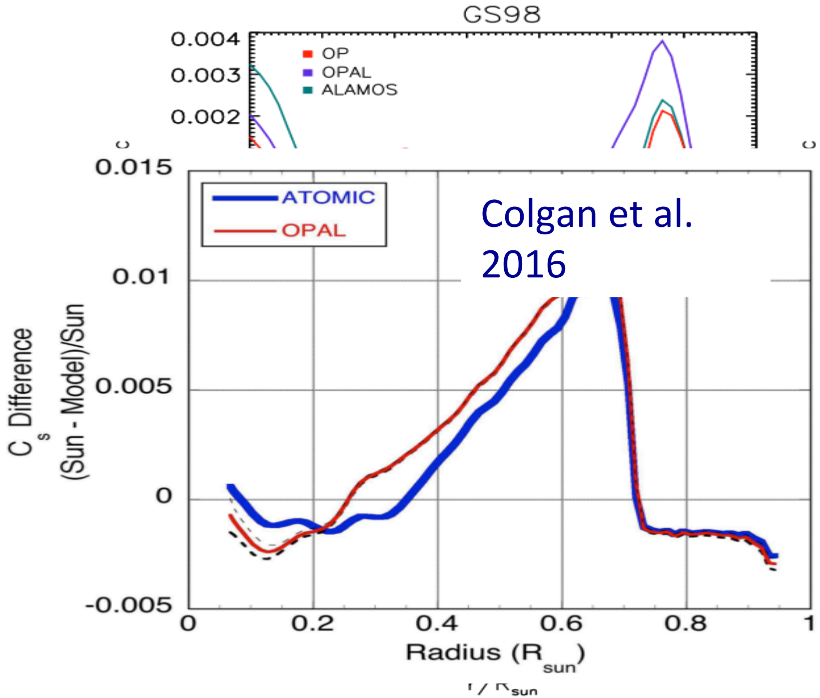
New opacity calculations: impact on SSMs



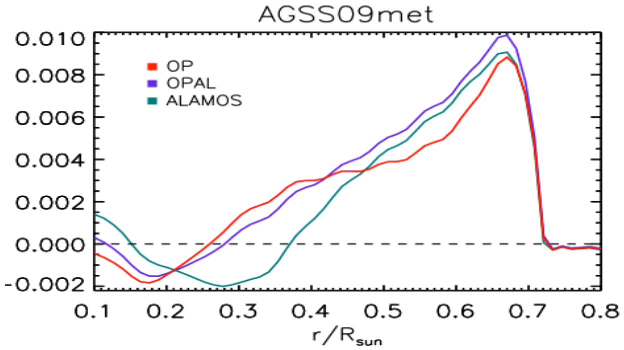
Vinyoles 2017
in preparation

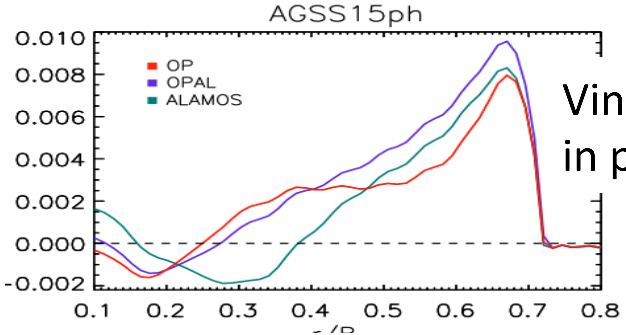
$< \delta c/c >$	OP	OPAL	ALAMOS	OPAS
GS98	0.0005	0.0008	0.0010	-
AGSS09met	0.0021	0.0024	0.0023	-
AGSS09ph	0.0016	0.0020	0.0017	0.0017
AGSS15ph	0.0018	0.0022	0.0020	-

New opacity calculations: impact on SSMs



Colgan et al. 2016





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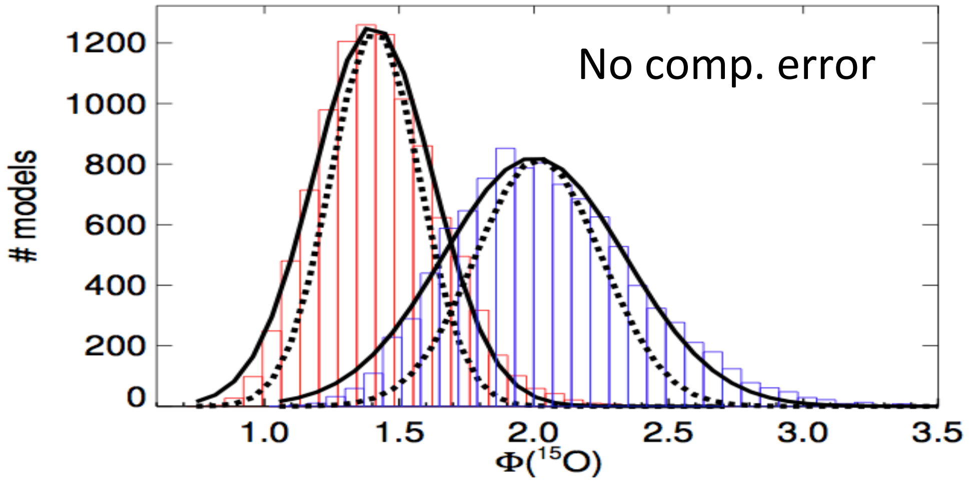
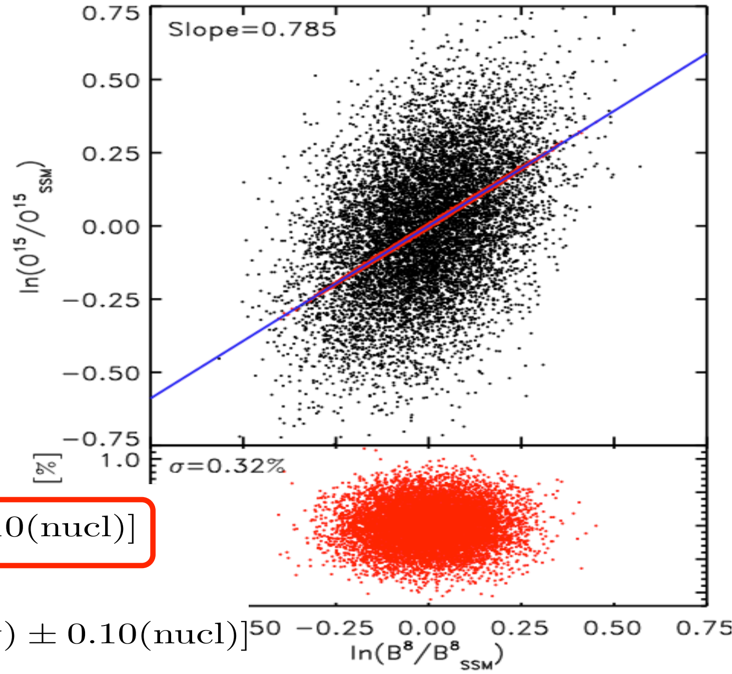
New opacities – OPAS & Los Alamos (ATOMIC/OPLIB)
Marginal improvement in dc/c

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