Open questions in solar modeling
(and lessons for other stars)

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Outline

Some topics related to solar models

external constraints: solar composition
input physics: opacities

solar neutrinos

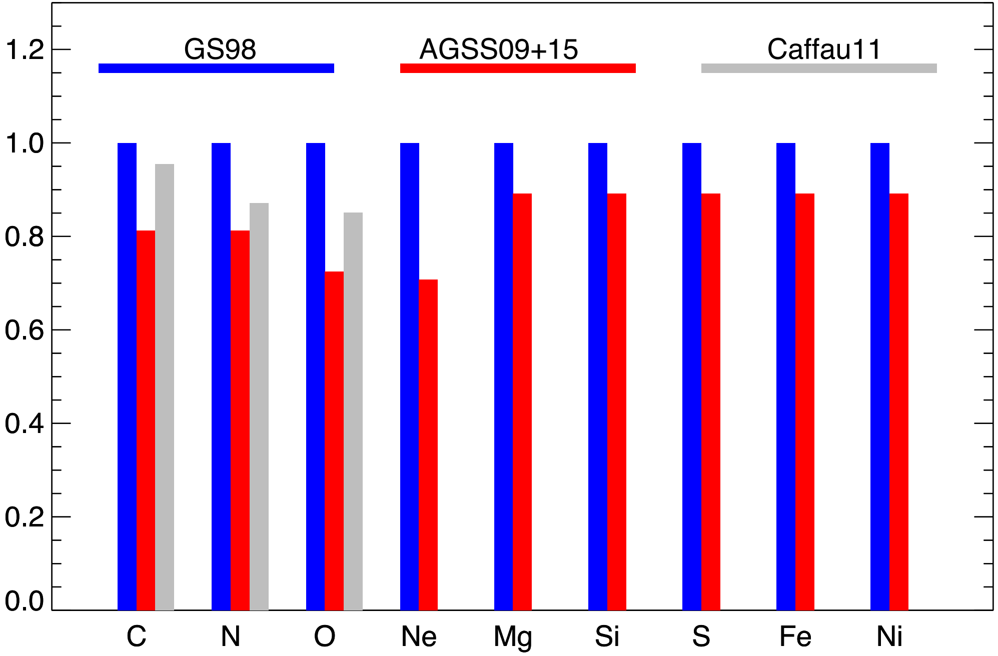
helio-(astero-)seismology with frequencies and frequency ratios

wishful thinking: accretion history during solar/stellar formation

(time allowing) a quick comment on solar g-modes

Not included: solar lithium, rotation, extra-mixing, etc.

Solar composition



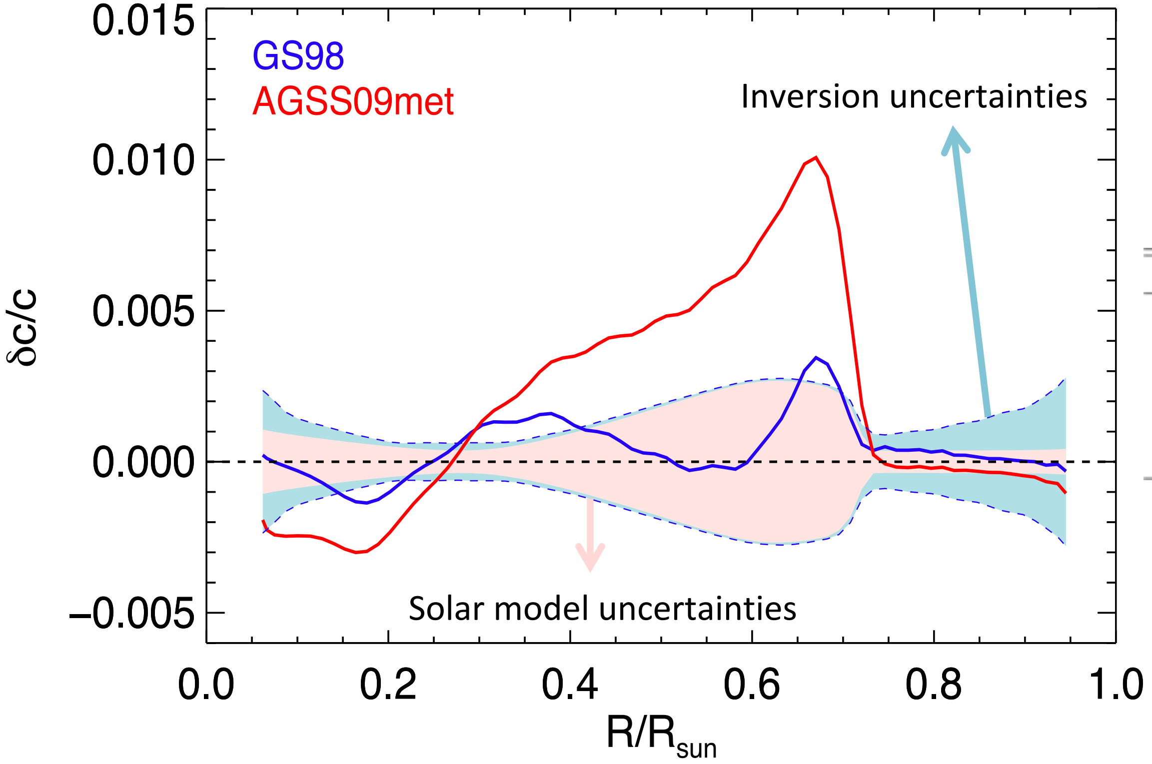
Large CNO reduction ~20-30%
Moderate refractories ~10%

~ half from 3D
~ half from atomic data, NLTE, blends

fundamental difference between 3D groups related to choice of lines (good atomic data, blends)

Impact on solar structure

Sound speed fractional difference from helioseismic inversions

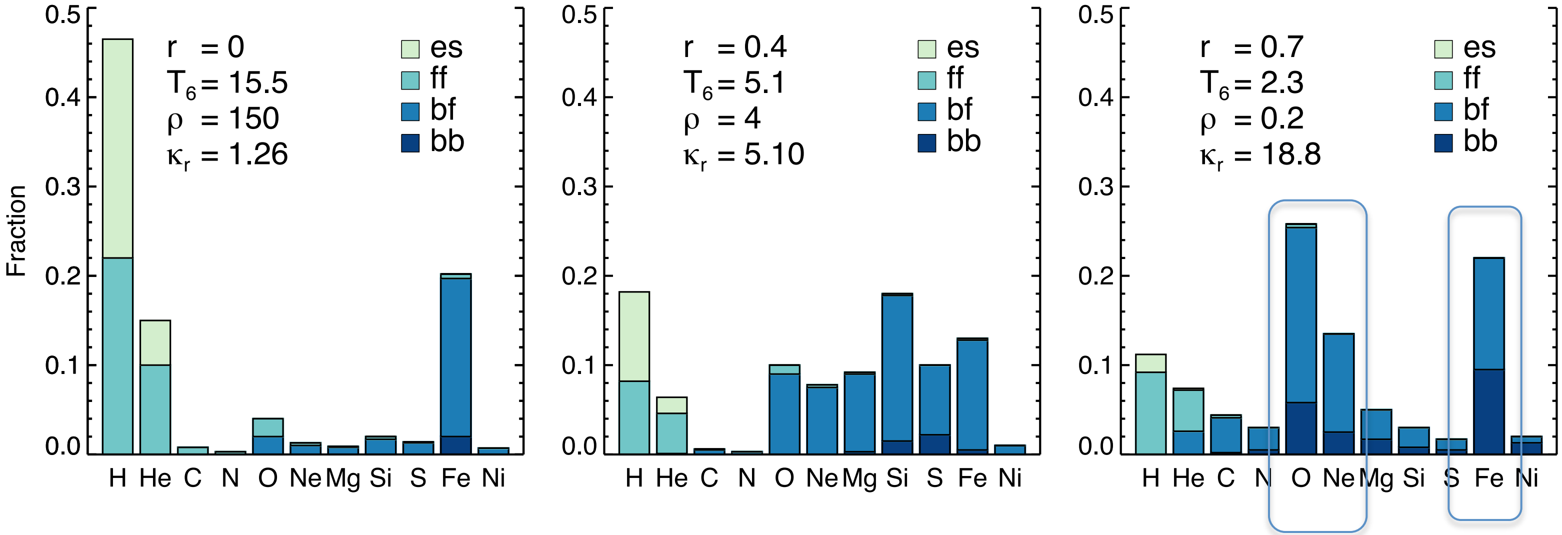


More results from helioseismology

	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	—

Metals & radiative opacity

Impact of metals through opacity in radiative interior $\nabla_{\rm rad} \propto \kappa$



Center | Intermediate region | Base of convective envelope

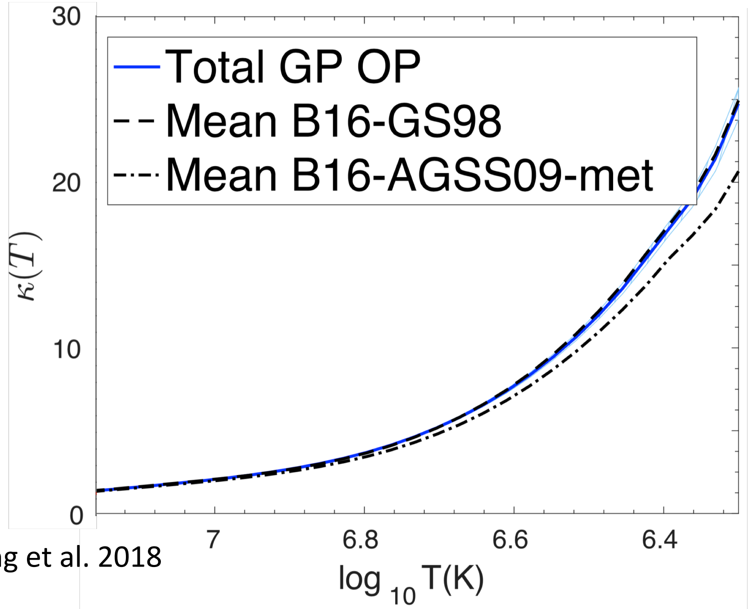
Low metals ←→ low opacity

Opacity profile from solar data

Helioseismic and solar neutrino data can be used to infer the effective solar opacity profile
What is the opacity profile that best reproduces the data?

$$\kappa_{\rm eff} = \kappa_{\rm ref} + \underbrace{\delta\kappa_{\rm comp}} + \underbrace{\delta\kappa_{\rm func}}$$

$\delta\kappa_{\rm func}$ modeled with a Gaussian Process – different composition priors used



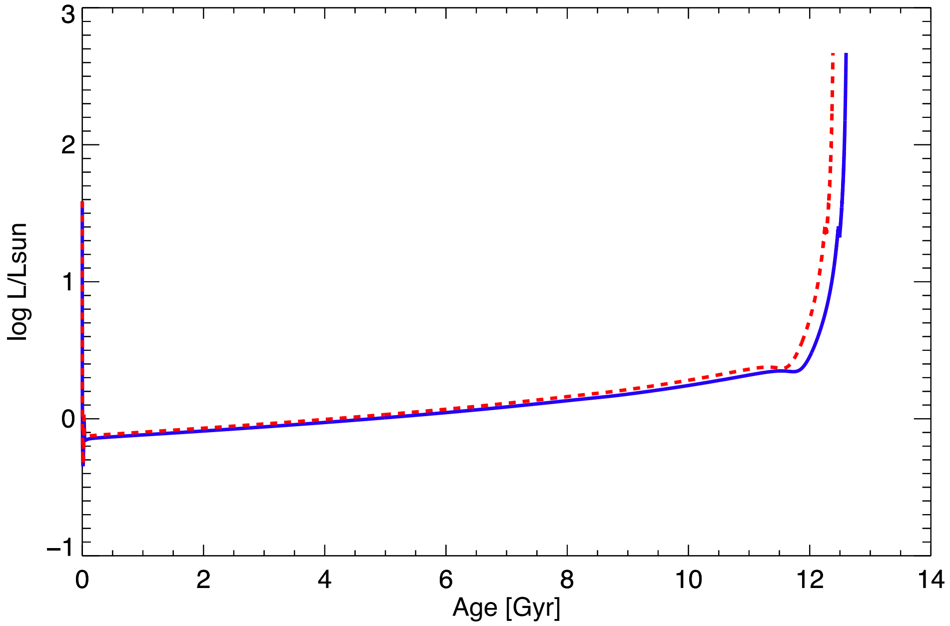
Song et al. 2018

Difference between best fit and AGSS09 model:

few % in core
18% base of conv. envelope

Age uncertainties: how well should we do?

Is there a missing opacity problem in solar (stellar) models? Should we care?
Consider evolutionary timescales for low mass stars



Canonical 1 $M_\odot$ model

Blue – calibrated composition GS98
Z_{GS98},Y_{GS98}

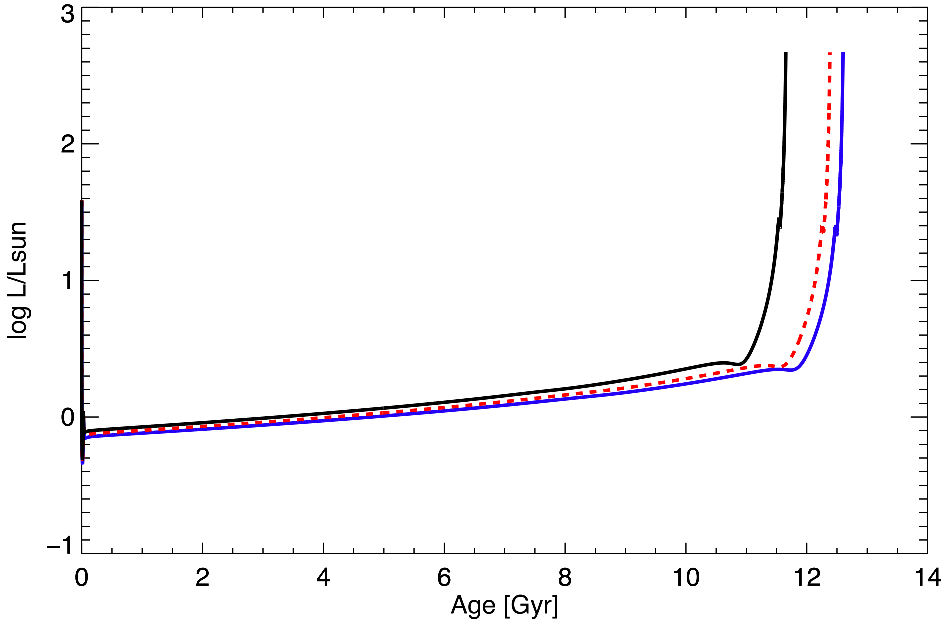
Red/dashed – calibrated comp. AGSS09
Z_{AGSS09},Y_{AGSS09}

There is some cheating here:

stellar Y does not depend on our ignorance about solar Z or opacities

Age uncertainties: how well should we do?

Is there a missing opacity problem in solar (stellar) models? Should we care?
Consider evolutionary timescales for low mass stars

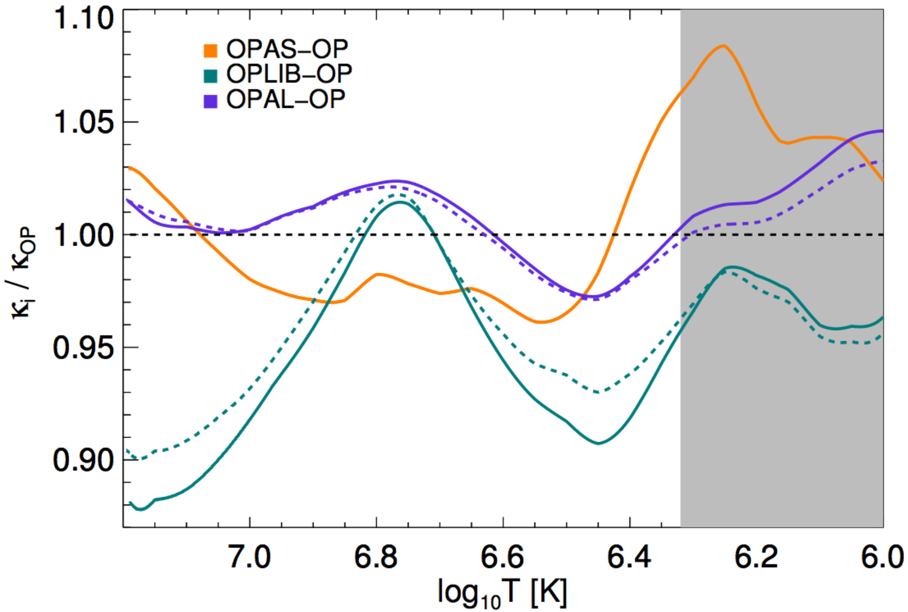


Canonical 1 $M_\odot$ model

If Y is fixed (black), age differences about 10% at turn-off and 8% in RGB

Current status of opacity calculations

Status of solar (stellar) opacities
Traditional calculations: OPAL (1996), Opacity Project (2005)
Renewed interest: OPAS (2012, 2015 – Blancard et al., Mundet et al.), Los Alamos (OPLIB; 2016 – Colgan et al.)



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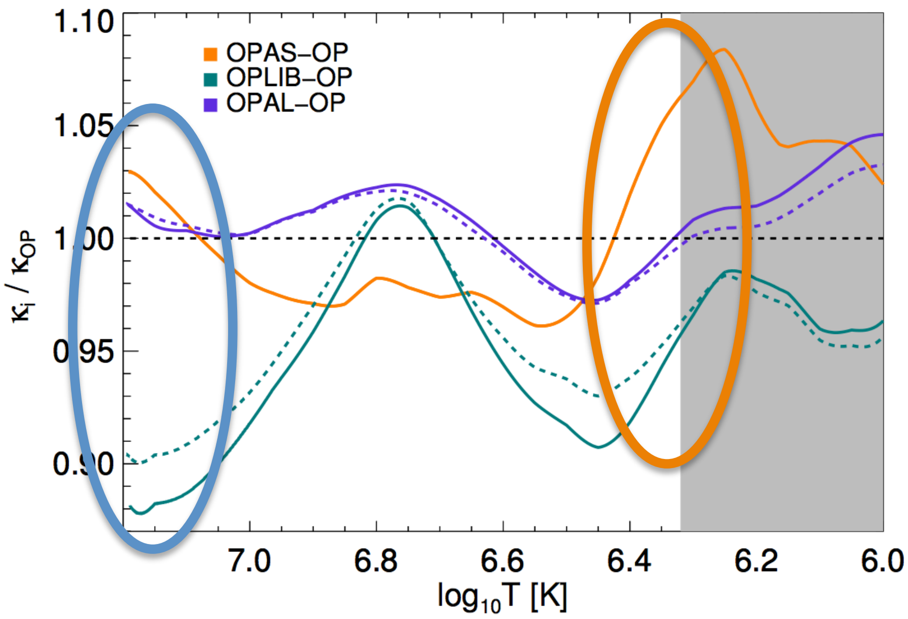


Fractional opacity differences
wrt Opacity Projects

Few % at base of convective envelope too low to compensate 15-18%

OPAS-OP-OPAL ok in center
OPLIB (Los Alamos) up to 15% lower
→ core temperature too low

Experimental result for Fe opacity in quasi solar conditions

Status of solar (stellar) opacities

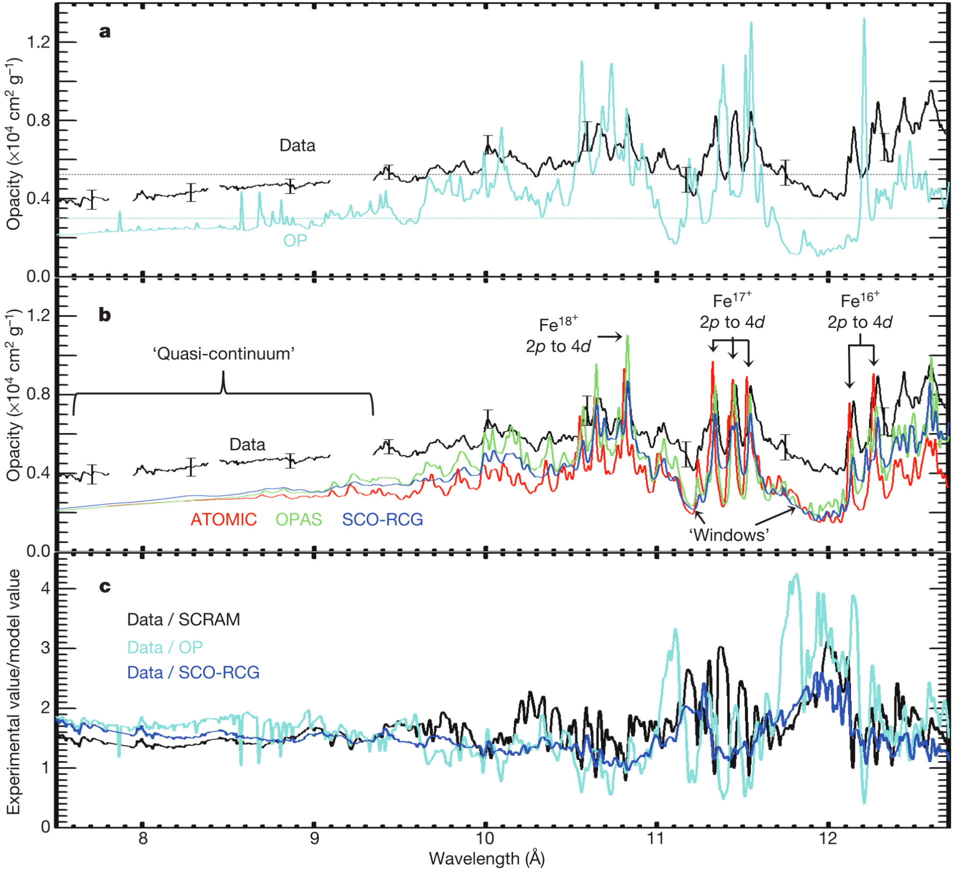
Fe-opacity from 1st ever experimental result close to solar conditions – base of CZ @ Sandia Lab (Bailey et al. 2015)

Fe-Rosseland mean +40%

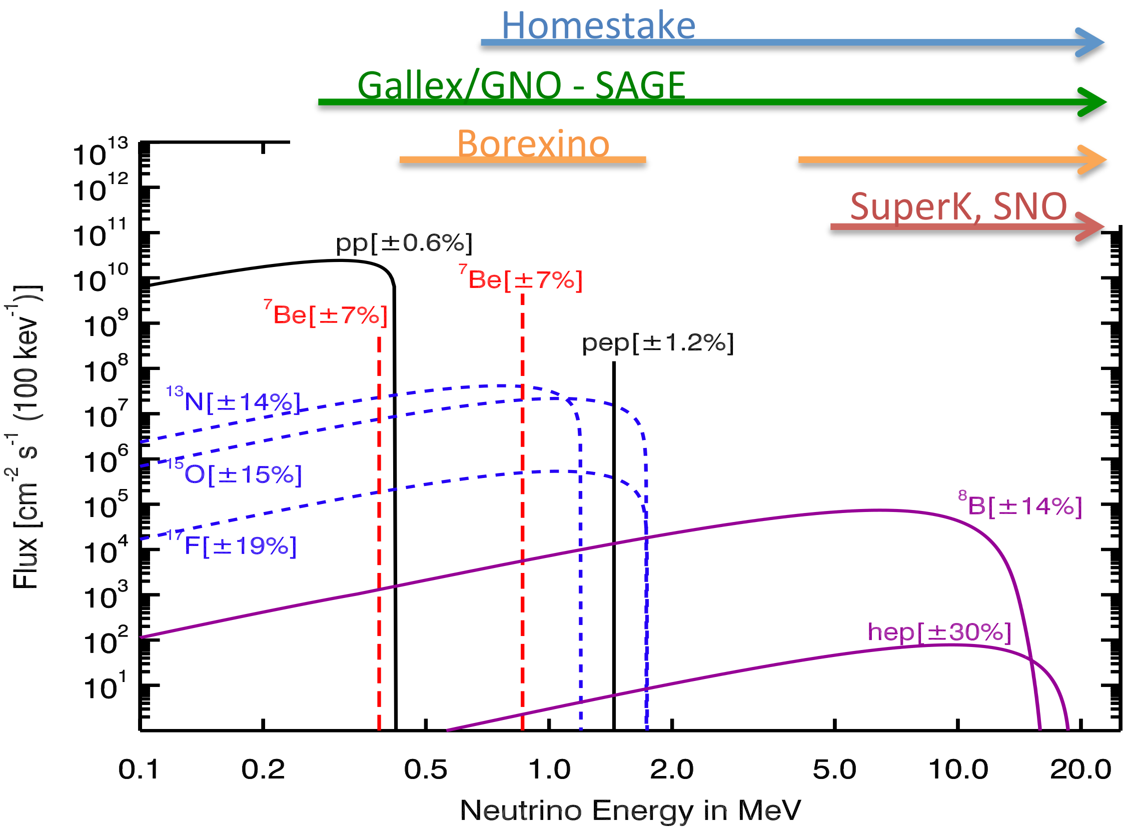
Total Rosseland mean +7±4%

Strong discrepancy in the continuum with all available models

Other elements in the queue (O most relevant)



What can we learn from solar neutrinos?



^{8}B measured @ 2% (SNO, SuperK)

^{7}Be measured @ 4% (Borexino)

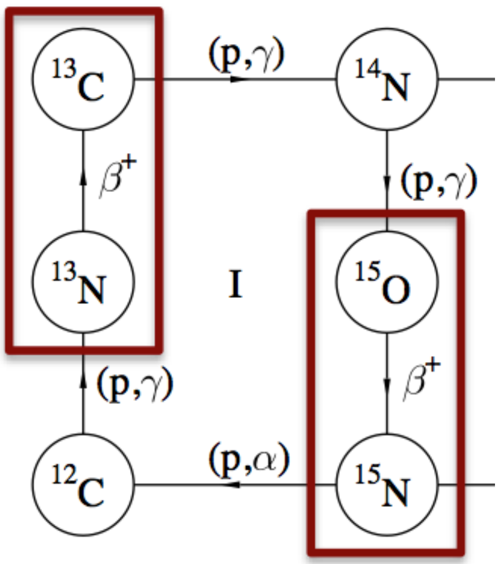
How does the Sun shine?
Purely experimental result

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

Bergstrom et al. 2016

What can we learn from solar neutrinos?

CN-cycle



In stars dominated by CNO

Increase CN abundace → increase energy release
→ lower temperature
→ CNO energy release self-regulated
(negative heat capacity, Scott's talk)

In stars the Sun, CNO << pp-chains

Increase CN abundace → increase CN energy release
→ total energy unchanged (pp)
→ linear relation between CN abundances & CN energy/neutrinos

What can we learn from solar neutrinos?

What determines CN ν-fluxes?

1) Solar core temperature – well determined through ^{8}B flux
2) Nuclear rates – ^{14}N+p
3) C+N abundance in the core

Using ^{8}B as thermometer, C+N core abundance can be extracted from CN-νs measurement to 10% plus experimental error

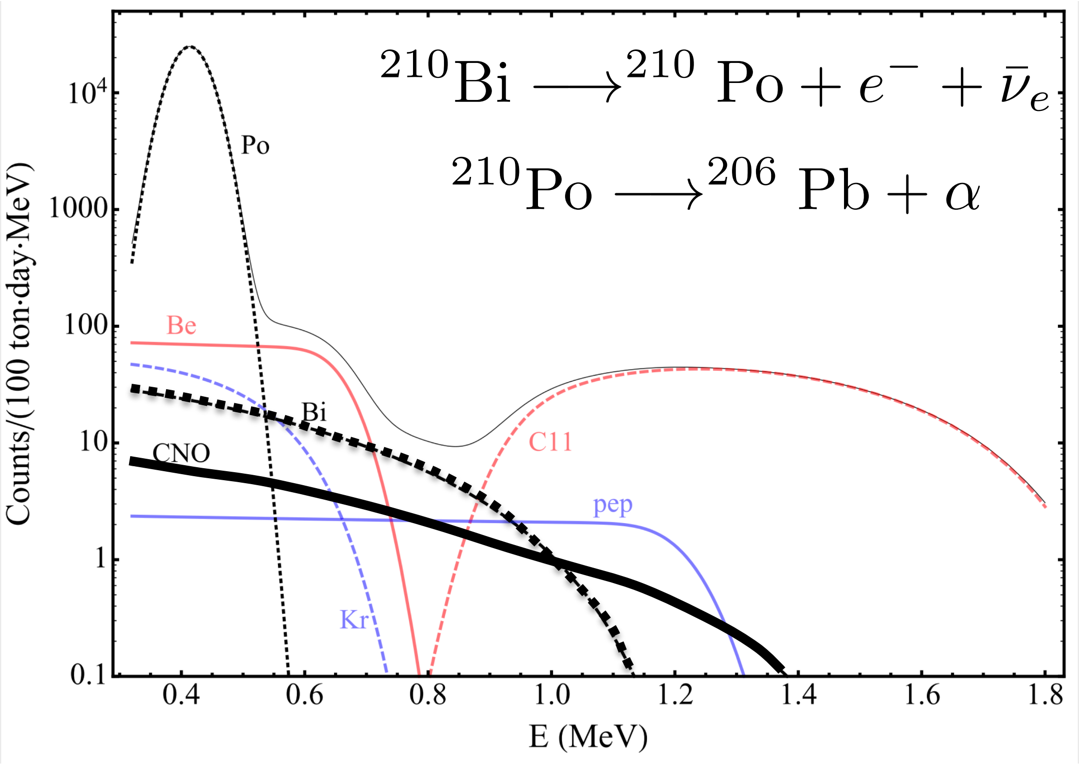
$$\frac{\Phi(^{15}\mathrm{O})}{\Phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} x_C^{0.749} x_N^{0.212}\,[1 \pm 0.003(\mathrm{env}) \pm 0.10(\mathrm{nucl})]$$

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

A 10% ν measurement → C+N core abundance to 15%!
Test of solar composition & eventually mixing processes in the Sun

What can we learn from solar neutrinos?

^{210}Bi background is the problem in measuring CN



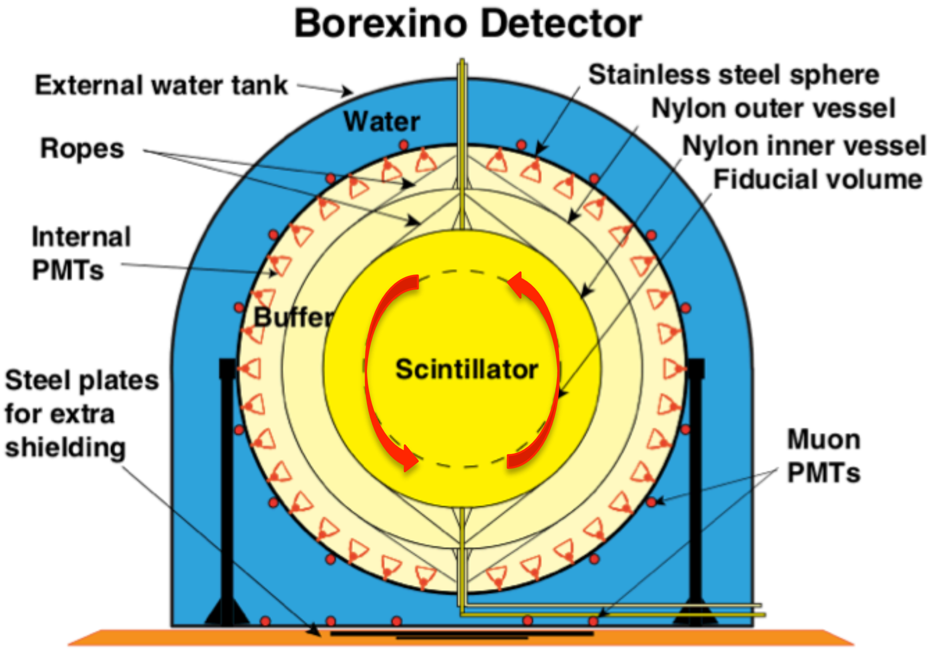
^{210}Po is an easy measurement

Deviation from exponential decay is signal of ^{210}Bi decay → extract background → determination of CN-ν flux

Requirement:

^{210}Po comes from ^{210}Bi in fiducial volume

What can we learn from solar neutrinos?

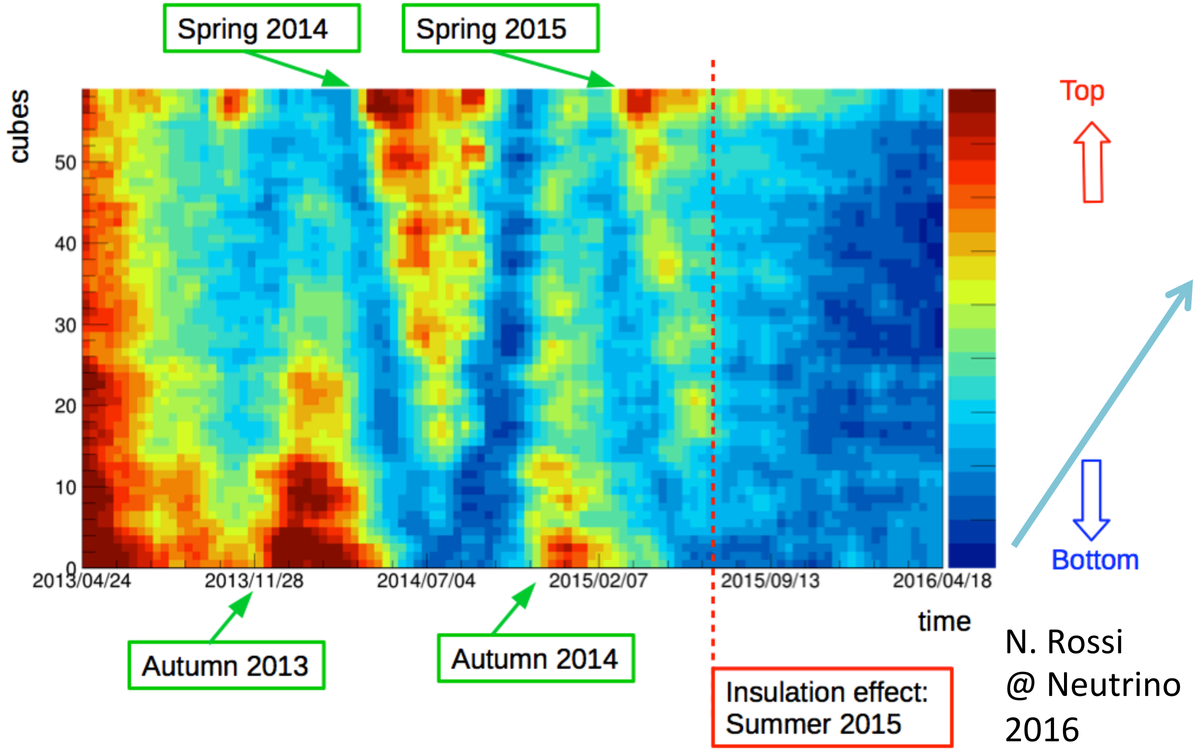


Slow convection of liquid scintillator outside fiducial volume prevents measurement

Thermal insulation used to inhibit convection

What can we learn from solar neutrinos?

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



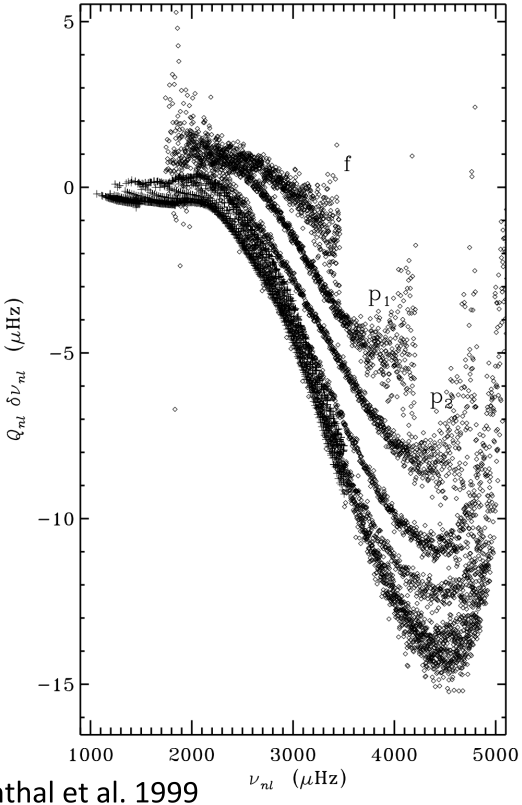
N. Rossi @ Neutrino 2016

Asymptotic concentration → ^{210}Bi

Currently measuring ^{210}Bi levels

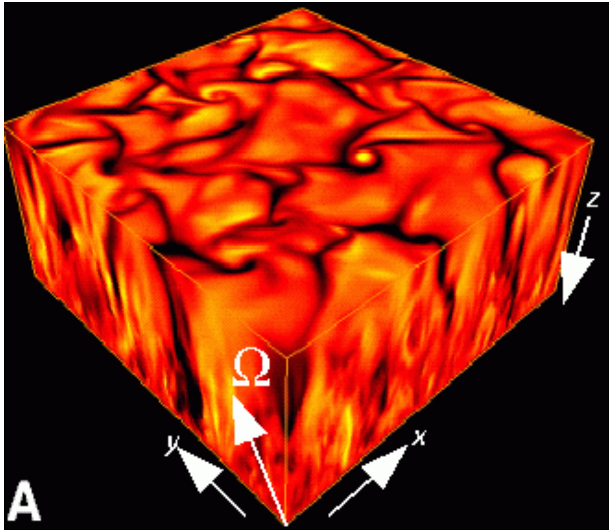
Expected 2-3s (maybe better) CN measurement by end 2018!

Helio-(astero-)seismology from frequencies: surface effects



Rosenthal et al. 1999

Systematic difference between in data – model due to poor modeling of near-surface convection: e.g. upflows, downflows, turbulent pressure

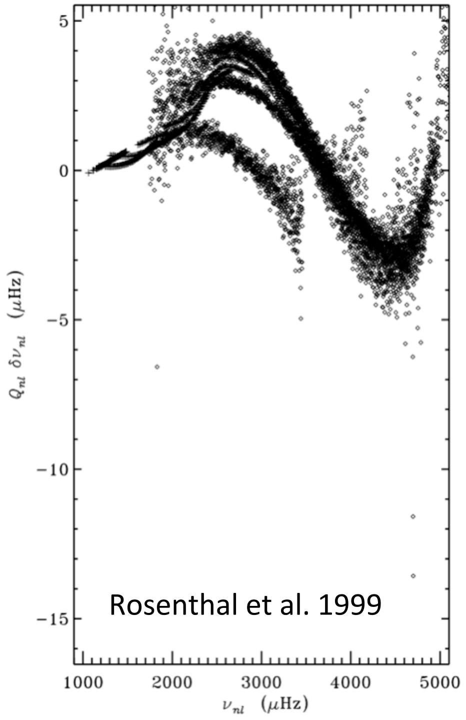


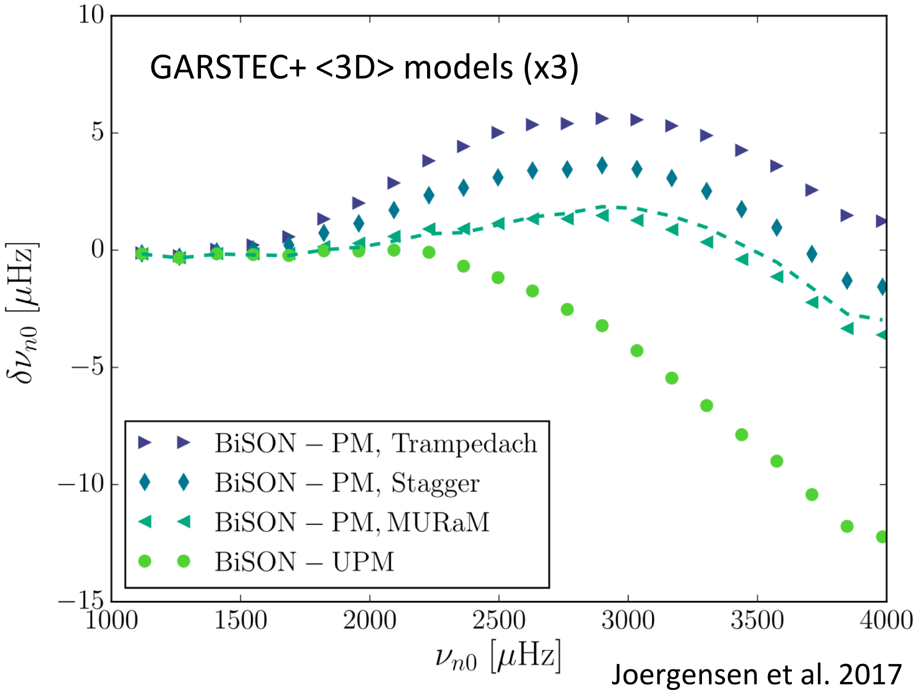
Credit: N. Brummell

Surface effects x100-500 that frequency uncertainties for Sun x20-50 for best Kepler dwarfs (Legacy sample, Lund et al. 2017)

Helio-(astero-)seismology from frequencies: surface effects

Coupling solar models and <3D> atmospheres: reduction of systematic uncertainties





Joergensen et al. 2017

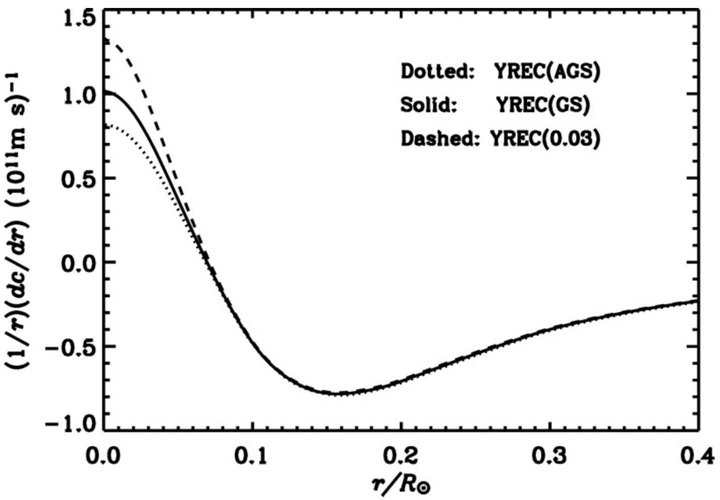
The Sun offers best possible test because M and R are known and frequencies scale as $(R^3/M)^{1/2}$

Frequency ratios: a way around using individual frequencies?

Specific frequency combinations that are immune to surface effects

$$\left.\begin{aligned} r_{02}(n) &= \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}} \\ r_{13}(n) &= \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}} \end{aligned}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$

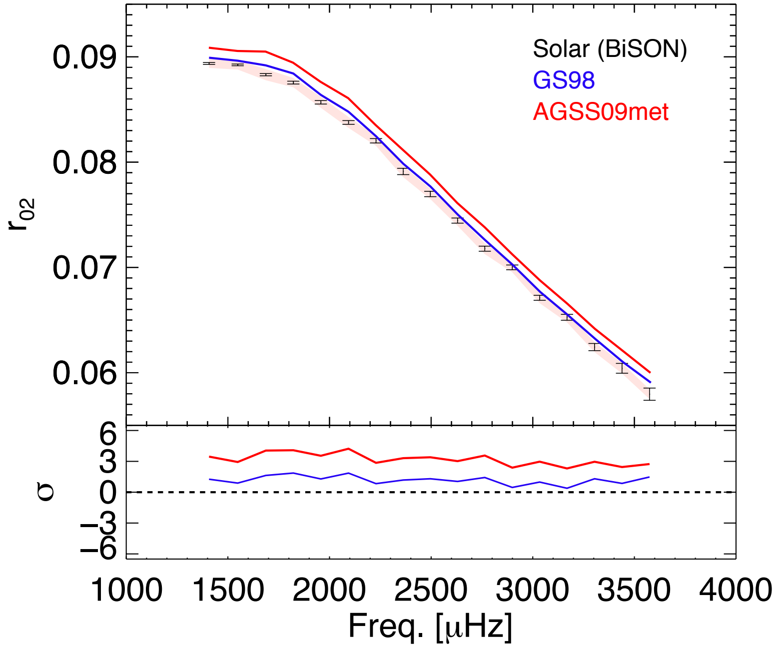
Roxburgh & Vorontsov 2003
Basu et al. 2007

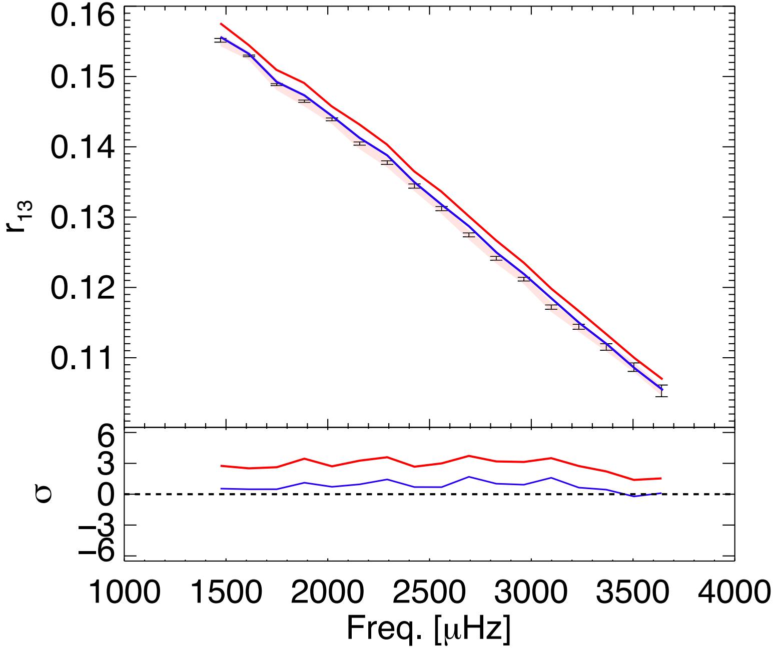


Frequency ratios: a way around using individual frequencies?

Results from frequency ratios consistent with all other helioseismic probes:

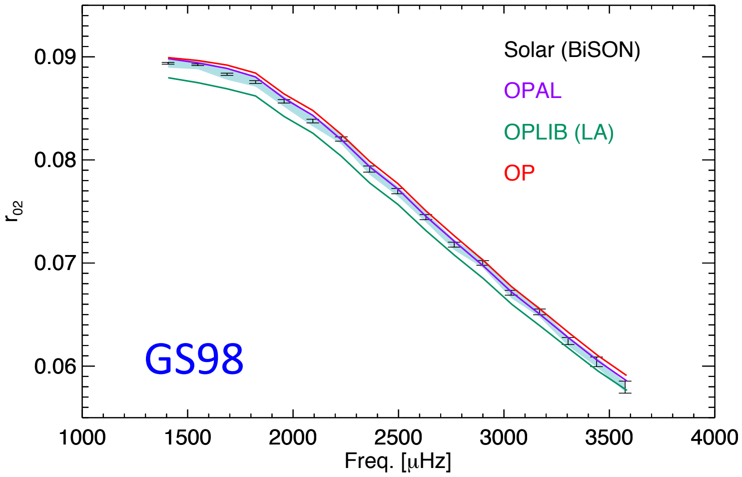
good for high-Z/opacity – bad for lowZ/opacity

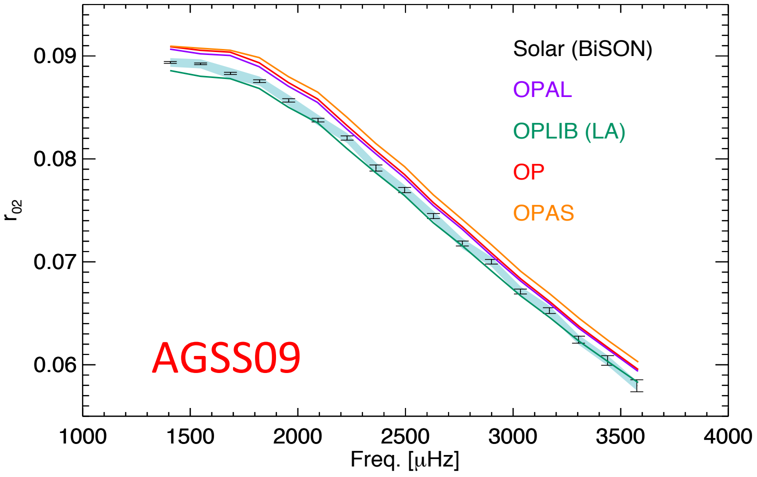




But… solar models with new Los Alamos (OPLIB)

Solar models with the new OPLIB have WRONG freq. ratios for high-Z/opacity
and GOOD freq. ratios for low-Z/opacity





	GS98	AGSS09
Ratios	✗	✓
Sound speed	✓	✗
Surface helium	✓	✗
Depth conv.env.	✓	✗

Fitting the frequency ratios might lead to not optimal models

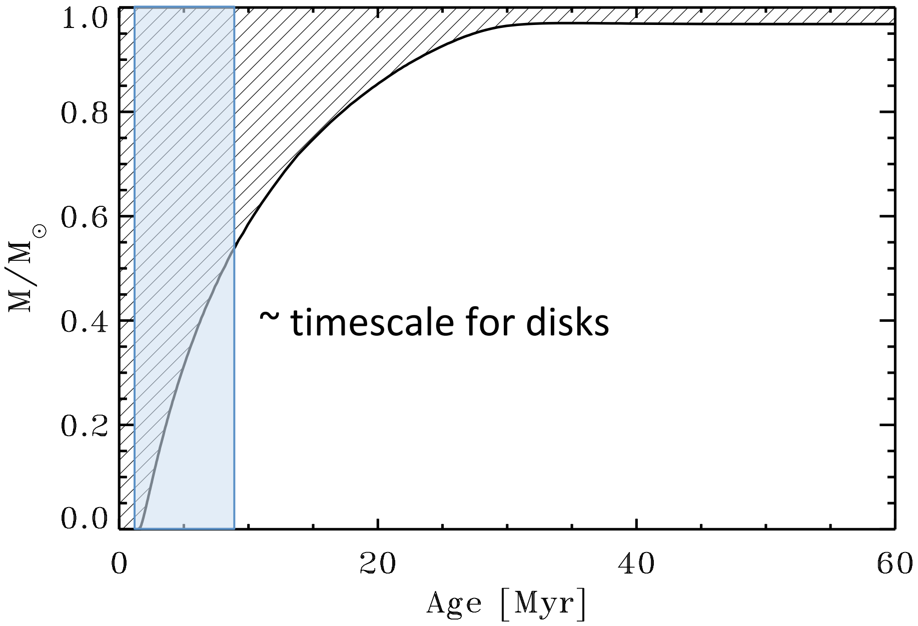
Modeling based on individual frequencies required for asteroseismology (eventually)

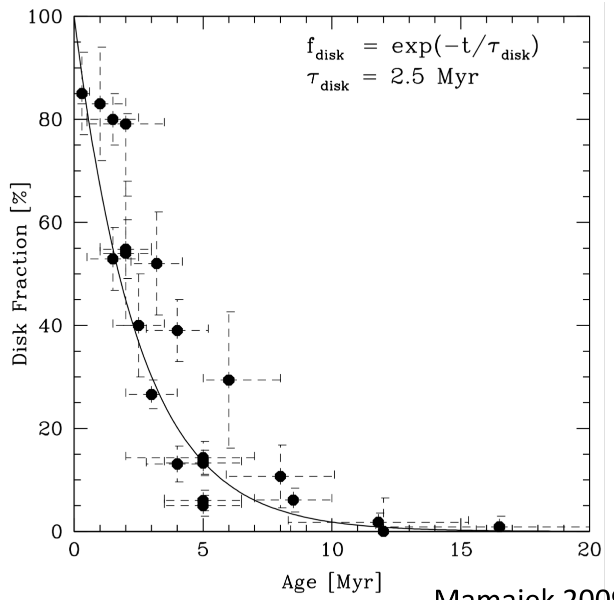
Was the initial Sun well mixed?

Basic paradigm in stellar evolution:

stars fully convective after mass assembly is over → initially homoegenous

Convective envelope in young Sun



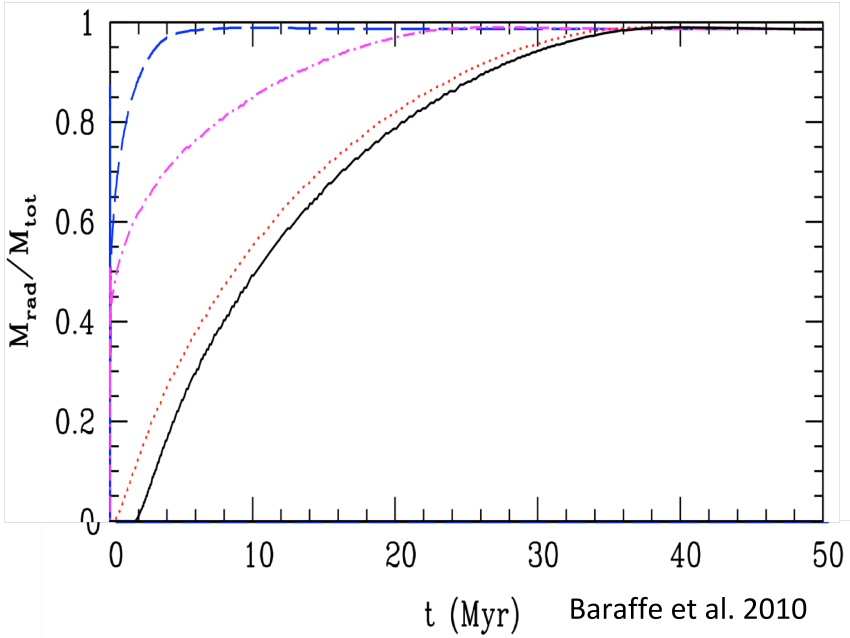


Mamajek 2009

Was the initial Sun well mixed?

Evolution of convective envelope depends strongly on accretion history

Timescales can then be shorter ~1Myr – fully convective phase might be absent altogether (Wuchterl & Klessen 2001)



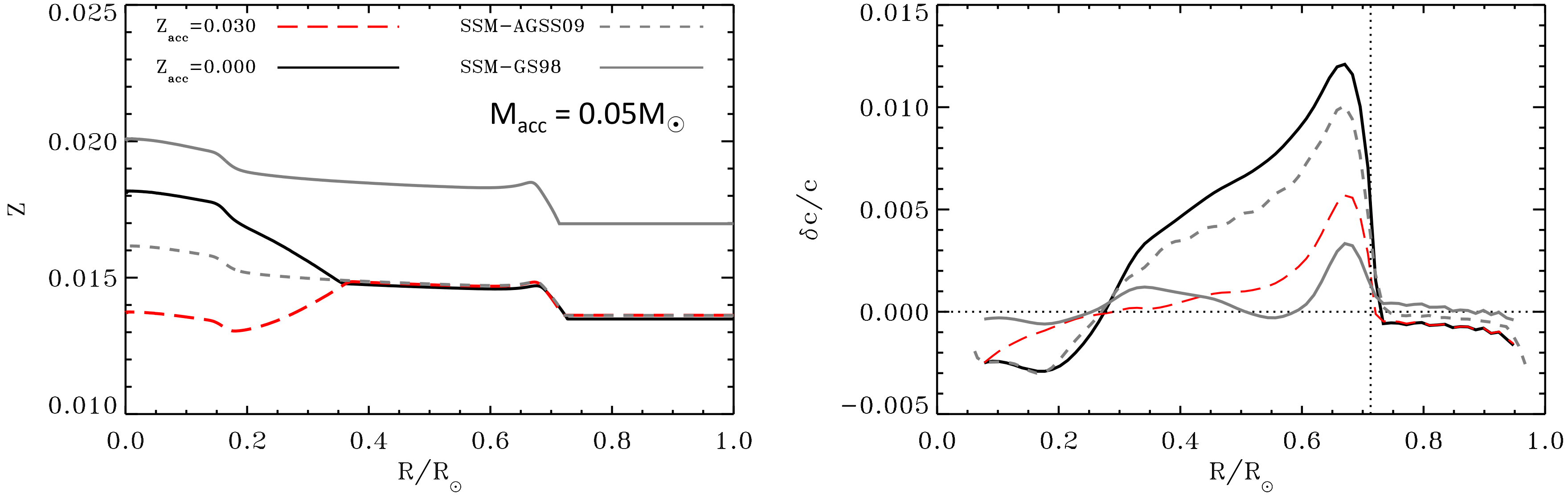
Baraffe et al. 2010

Was the initial Sun well mixed?

Chemically differentiated accreted matter can leave its imprint in interior structure

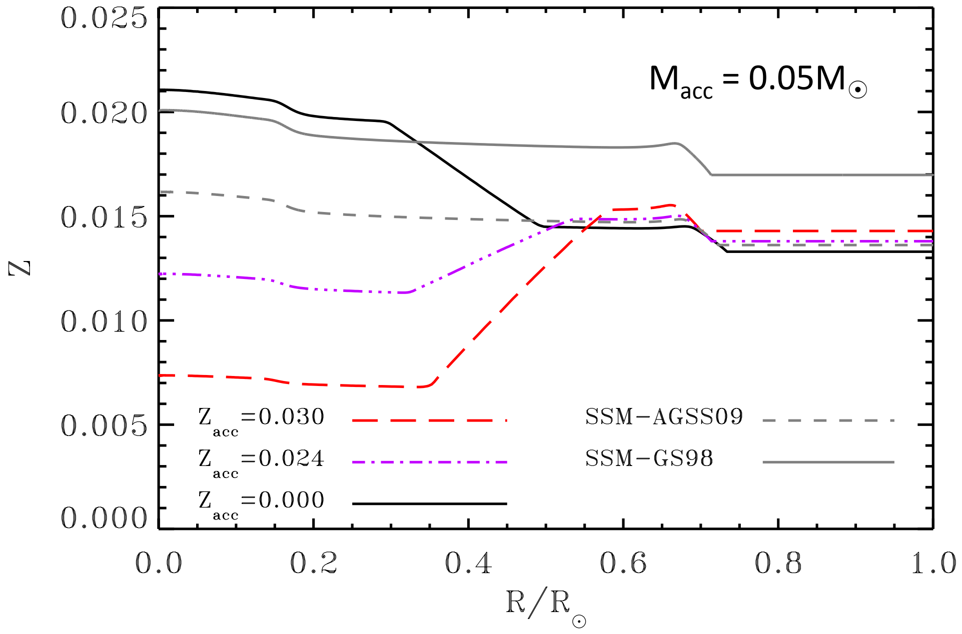
Assume fixed surface $(Z/X)_\odot$ (or [Fe/H] for other stars)

Z profile in solar models today



Was the initial Sun well mixed?

Later differentiated accretion – larger metallicity contrasts produced

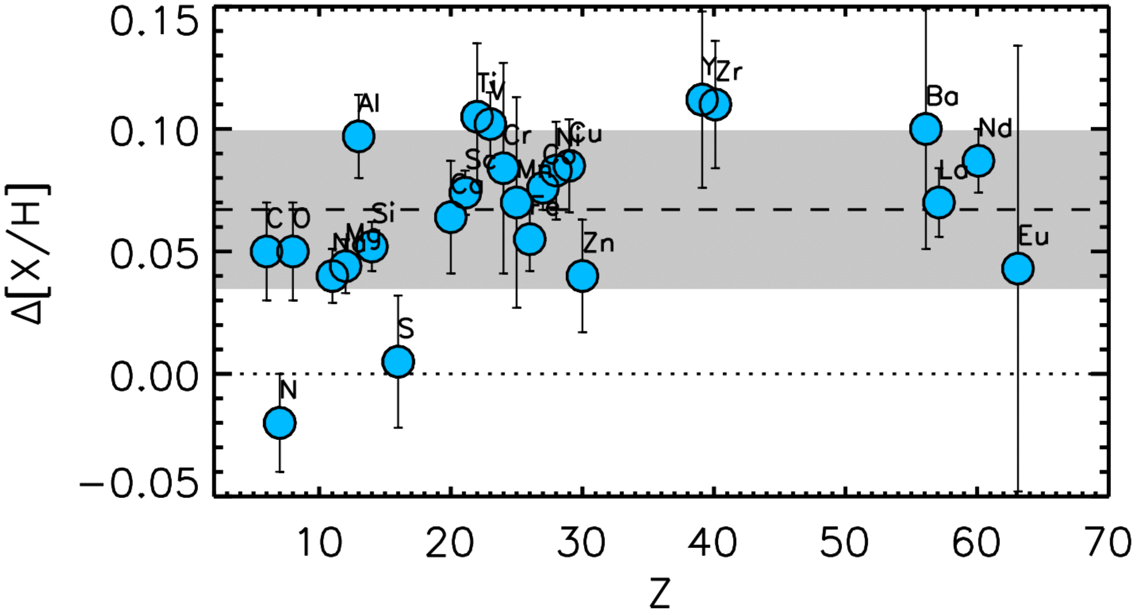


Accretion might shorten or even prevent fully convective phase

If differentiated composition then structural differences in structure to be expected

Example: Abundance differences in XO-2

XO-2 S: M sini = $0.26M_J$ – P = 18d & Msini = $1.37M_J$ – P = 121d
XO-2 N: M = $0.60M_J$ – P = 2.62 d



0.08 dex difference for refractories

0.025 dex for volatiles

Relation to planets?

What is the accretion history and internal (composition) structure of such stars?

Summary

Solar opacity profile determined from current data with few % precision

Current opacity calculations not compatible with low-Z solar composition
Experimental result in right direction
Theoretical calculations have problems

Solar neutrinos (CN) could provide a determination of core C+N in near future:
composition, mixing

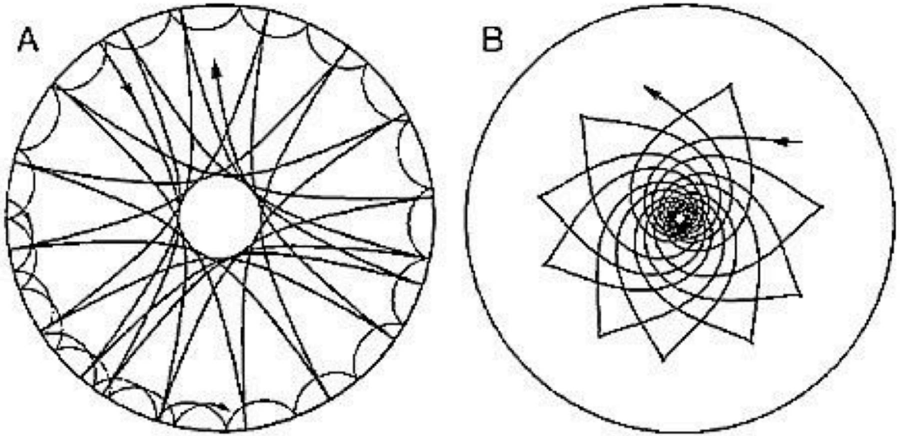
Helio/asteroseismology: individual frequencies require large and uncertain surface corrections
frequency ratios might be deceiving (not consistent helioseismic results)

Early phases of formation/pre-MS evolution seem to challenge fully convective picture
accretion history – rates and composition – would be great to have

TESS LAUNCH TODAY!!

Bonus: solar g-modes

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

Bonus: solar g-modes

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

3% - 6% difference with solar models

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

Bonus: solar g-modes

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

The End