Institute of
Space Sciences

Other inputs to stellar models: Nuclear rates, opacities, composition, EOS

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Institute of
Space Sciences

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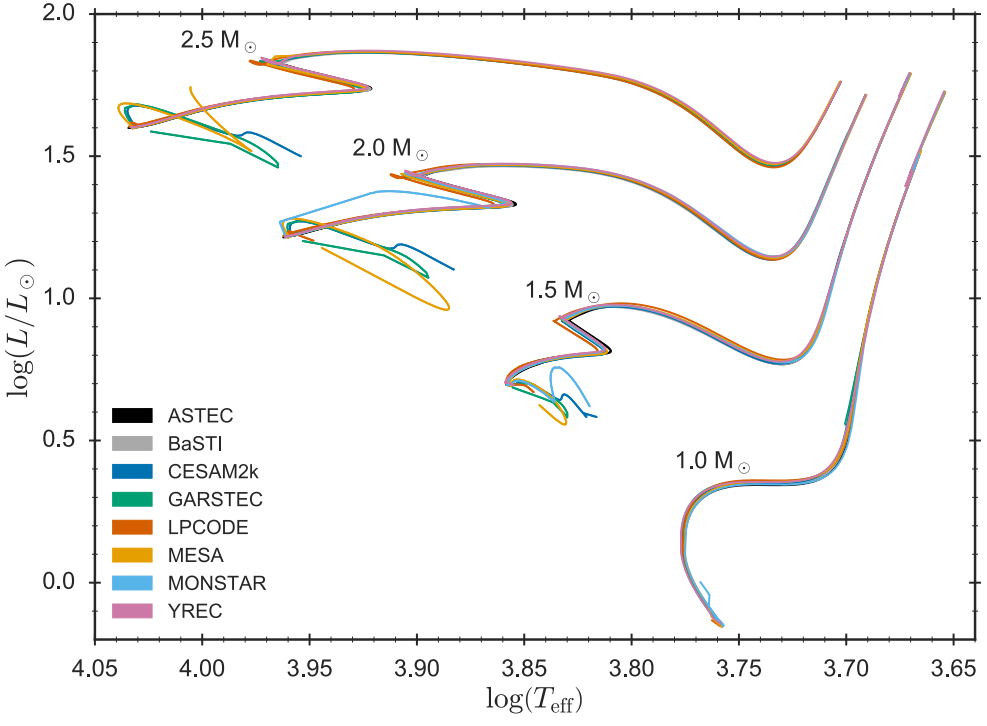
Outline

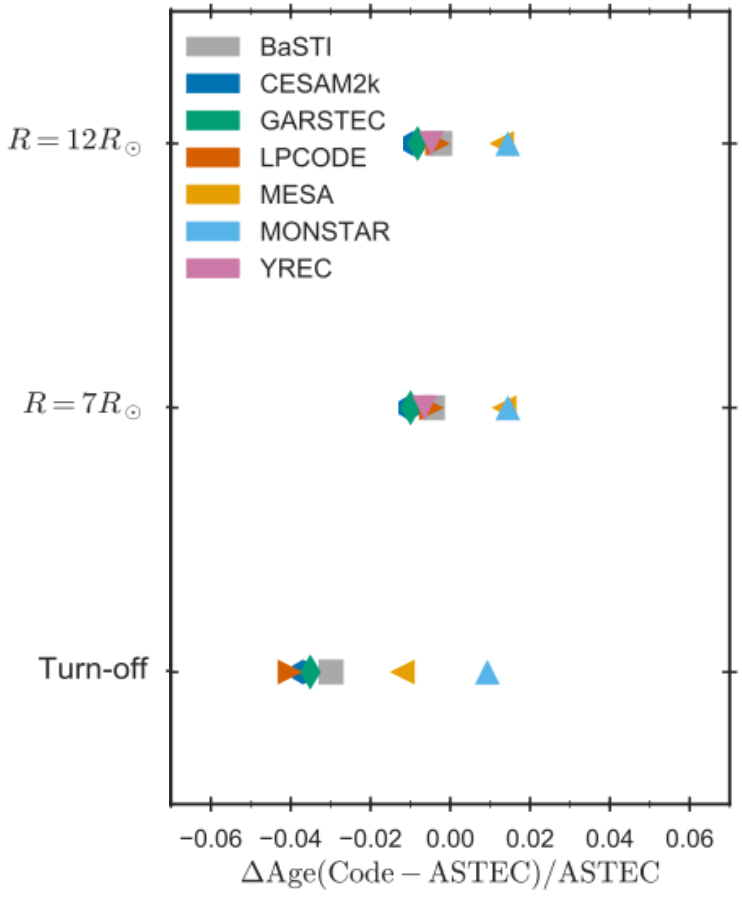
Inputs to stellar models

- nuclear reaction rates
- atomic radiative opacities
- detour on using frequency ratios
- composition – solar as reference
- equation of state

Stellar evolutionary tracks are NOT so different



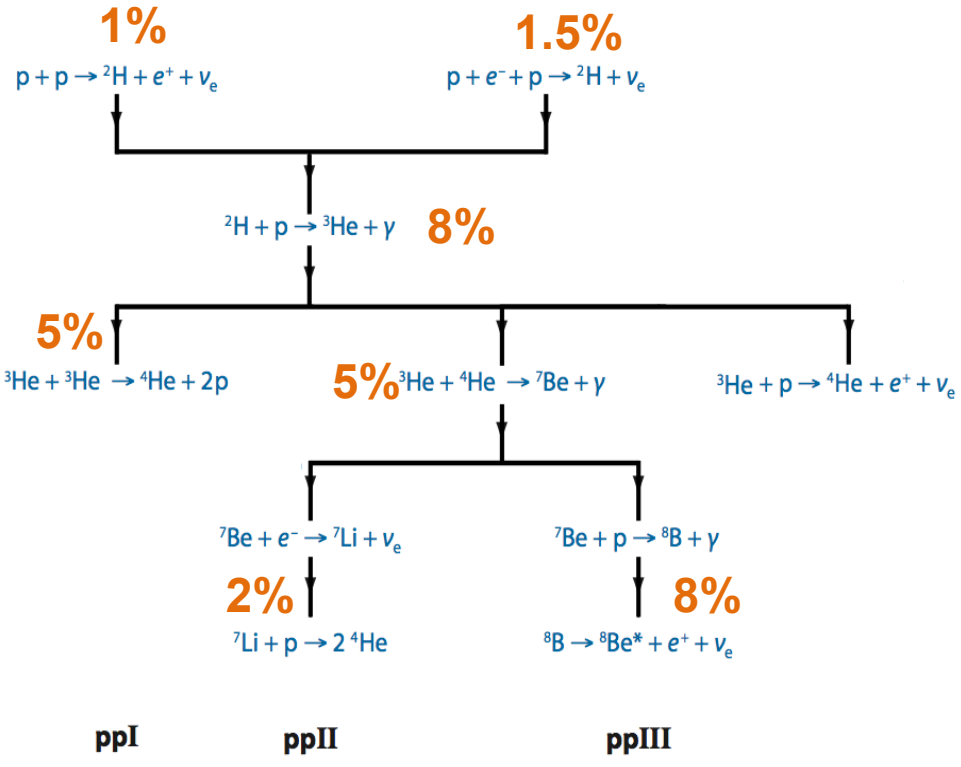
Age difference for 1.5M$_\odot$

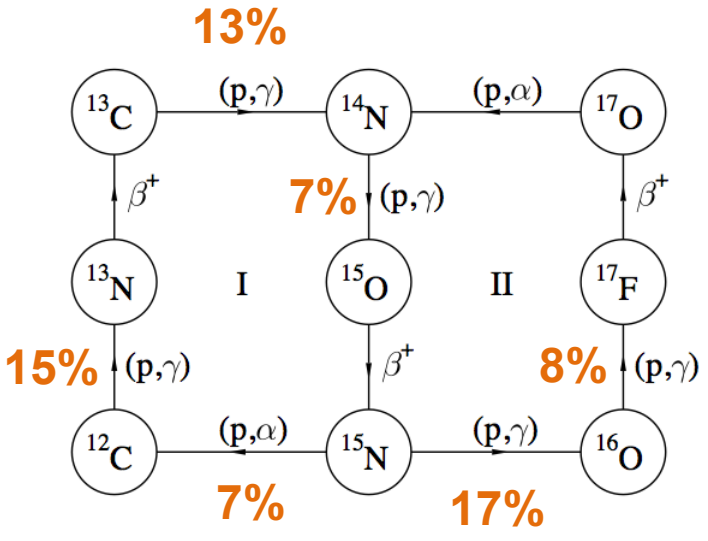


From the Aarhus Red Giants Modeling Workshops
Silva Aguirre et al. in prep

Nuclear reaction rates: H-burning

Looking at energetics (no detailed nucleosynthesis)
Most recent complete revision Adelberger et al.2011 (Solar Fusion II)





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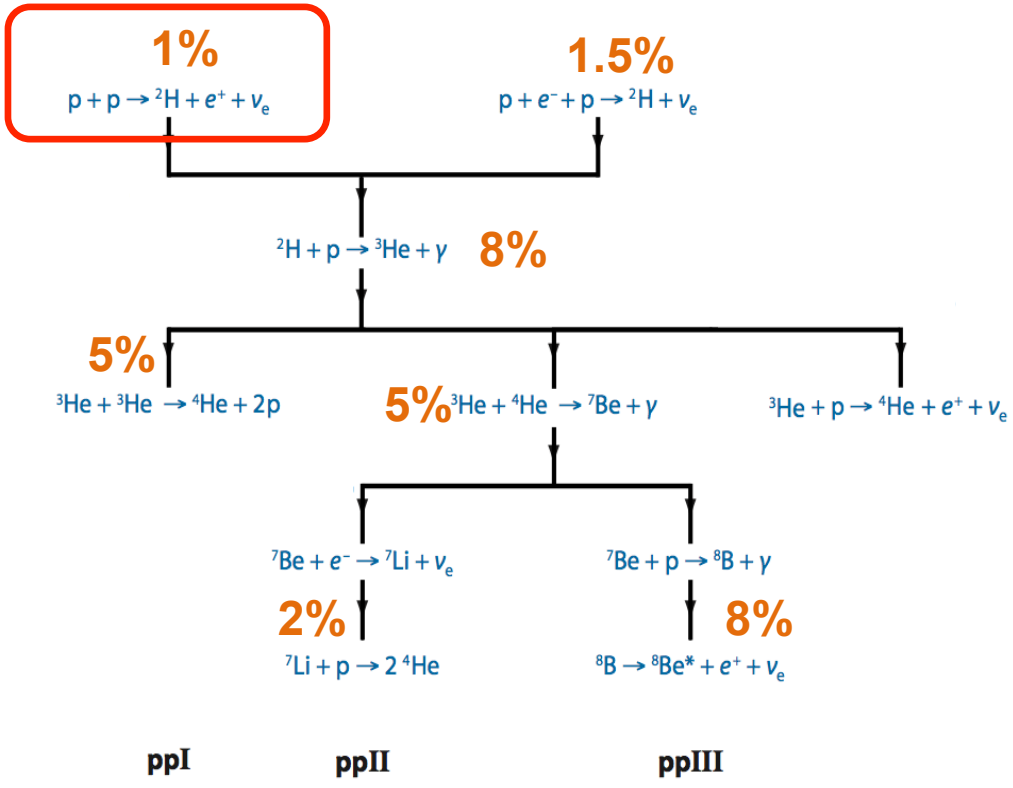

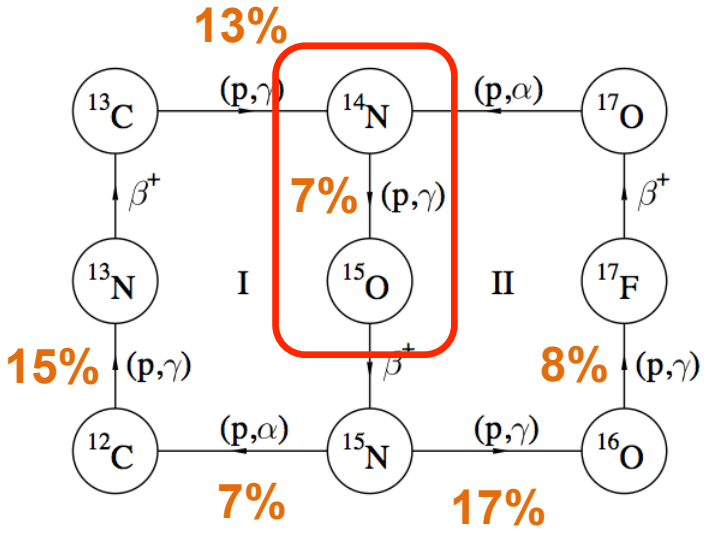

Only relevant for evolution: uncertainty in

$p+p \rightarrow d+e^+ + \nu_e$

$^{14}N+p \rightarrow {}^{15}O+\gamma$

Nuclear reaction rates: H-burning

p+p

No experimental data (rate too low)

SOURCE	S(0) [$\times 10^{-22}$keV b]	σ
NACRE (1999)	3.94	1%
Solar Fusion II (2011)	4.01	1%
Marcucci et al. (2013) - χEFT	4.033	0.07%
Acharya et al. (2016) - χEFT	4.047	0.7%

3% range in central values – smaller estimated uncertainties

Very small impact in tracks/isochrones (e.g. Valle et al. 2013)

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^{14}N+p

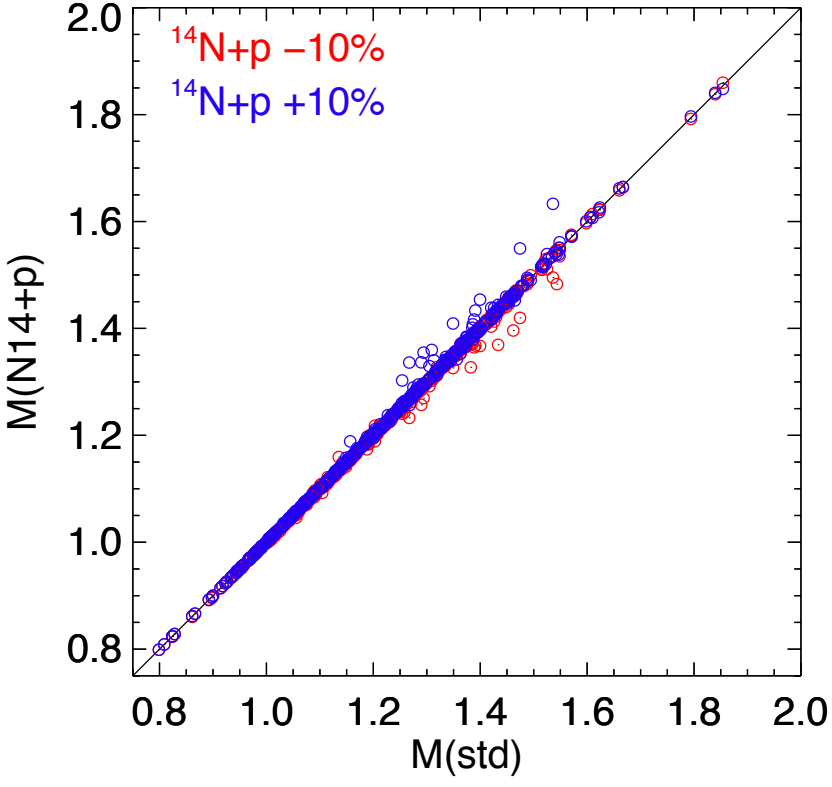
SOURCE	S(0) [keV b]	σ
Solar Fusion II (2011) - LUNA	1.66	7.2%
Marta et al. (2011) - LUNA	1.59	7.5%

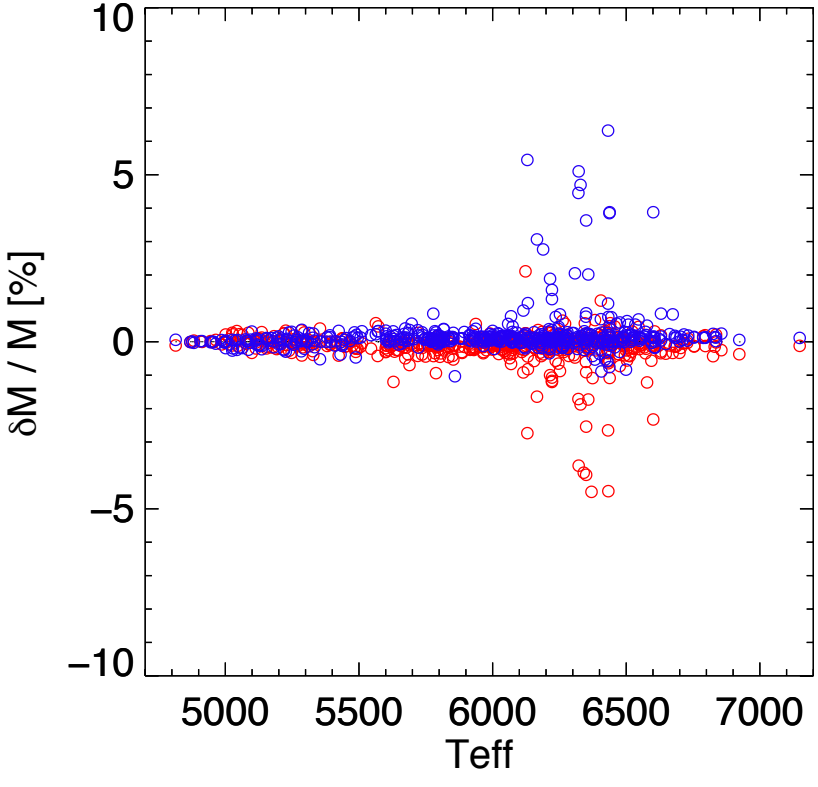
Assuming 10% uncertainty (Valle et al. 2013)
M=0.9$M_\odot$, Z=0.006 --> $\Delta \log L_{TO}$= -0.0028 dex – Δt_H= -0.05 Gyr (<0.5%)

Impact increases with Z, but remains small

^{14}N+p: seismic masses & age

From Chaplin et al. 2014 Kepler dwarfs catalogue (fiducial [Fe/H]=-0.2)
Using only $\Delta\nu$ and ν_{max}





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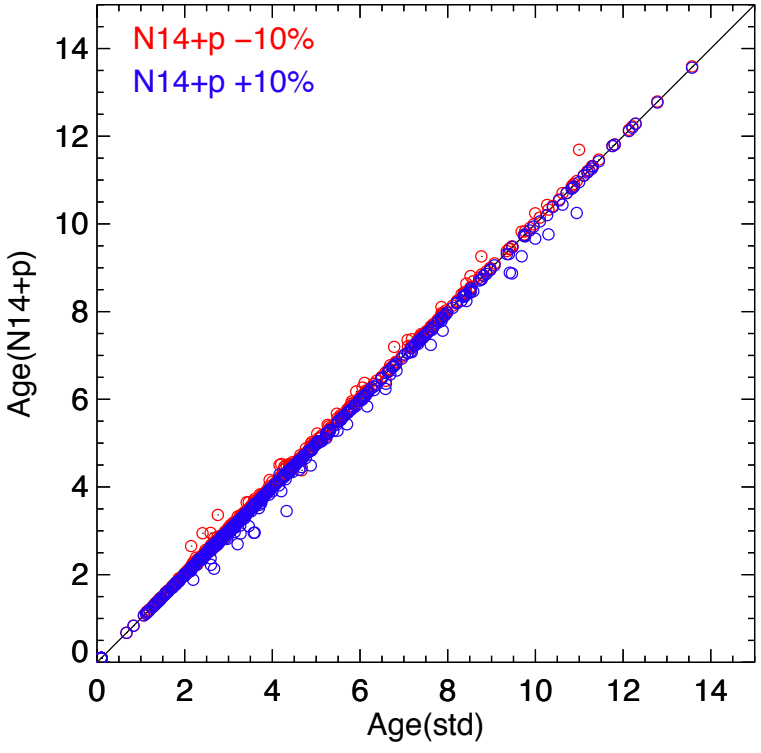
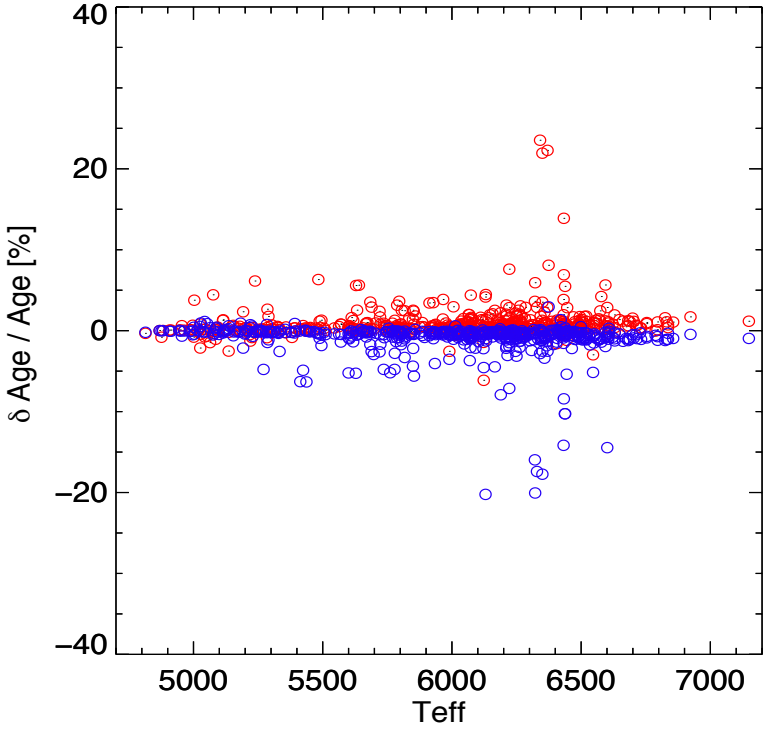
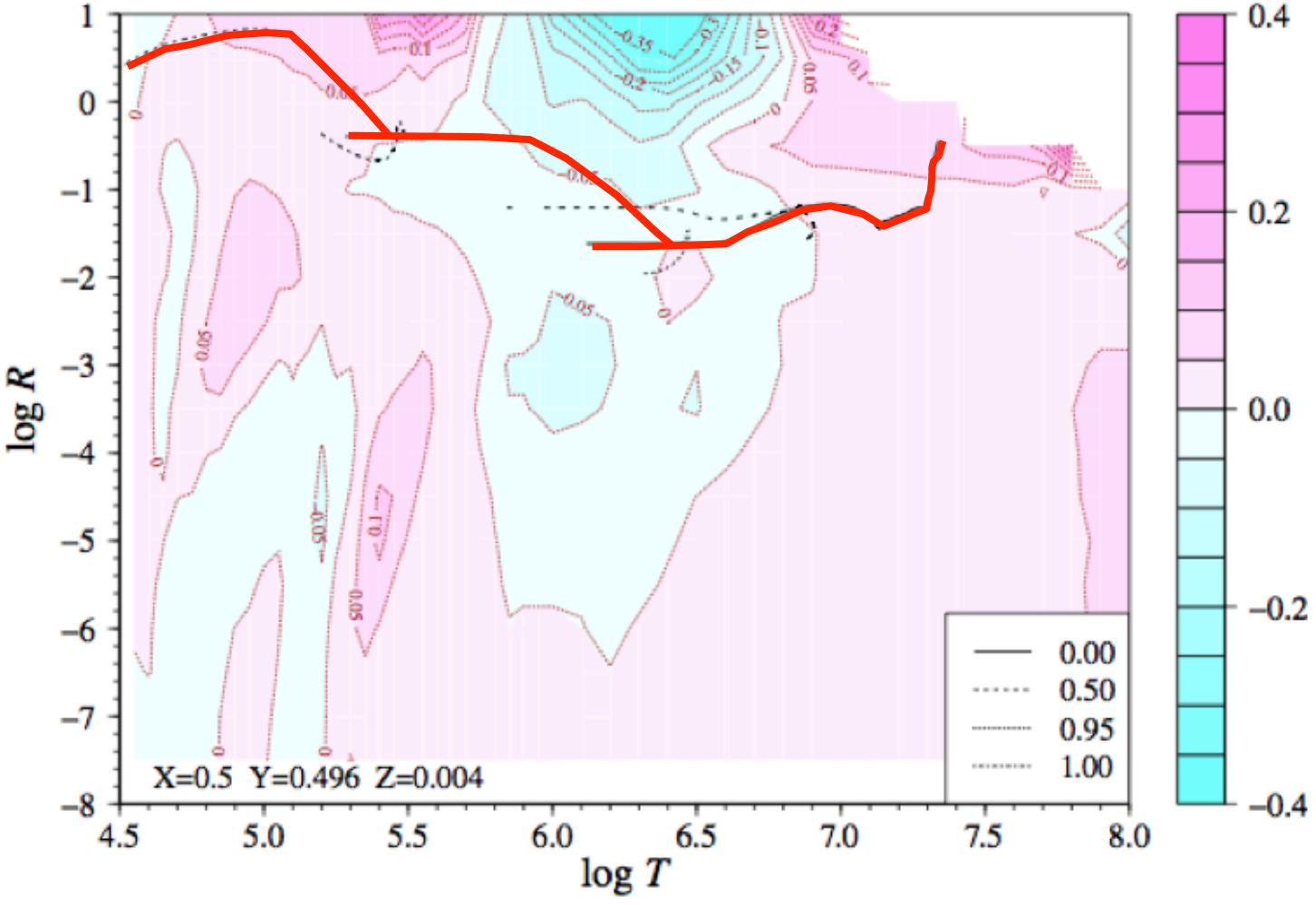




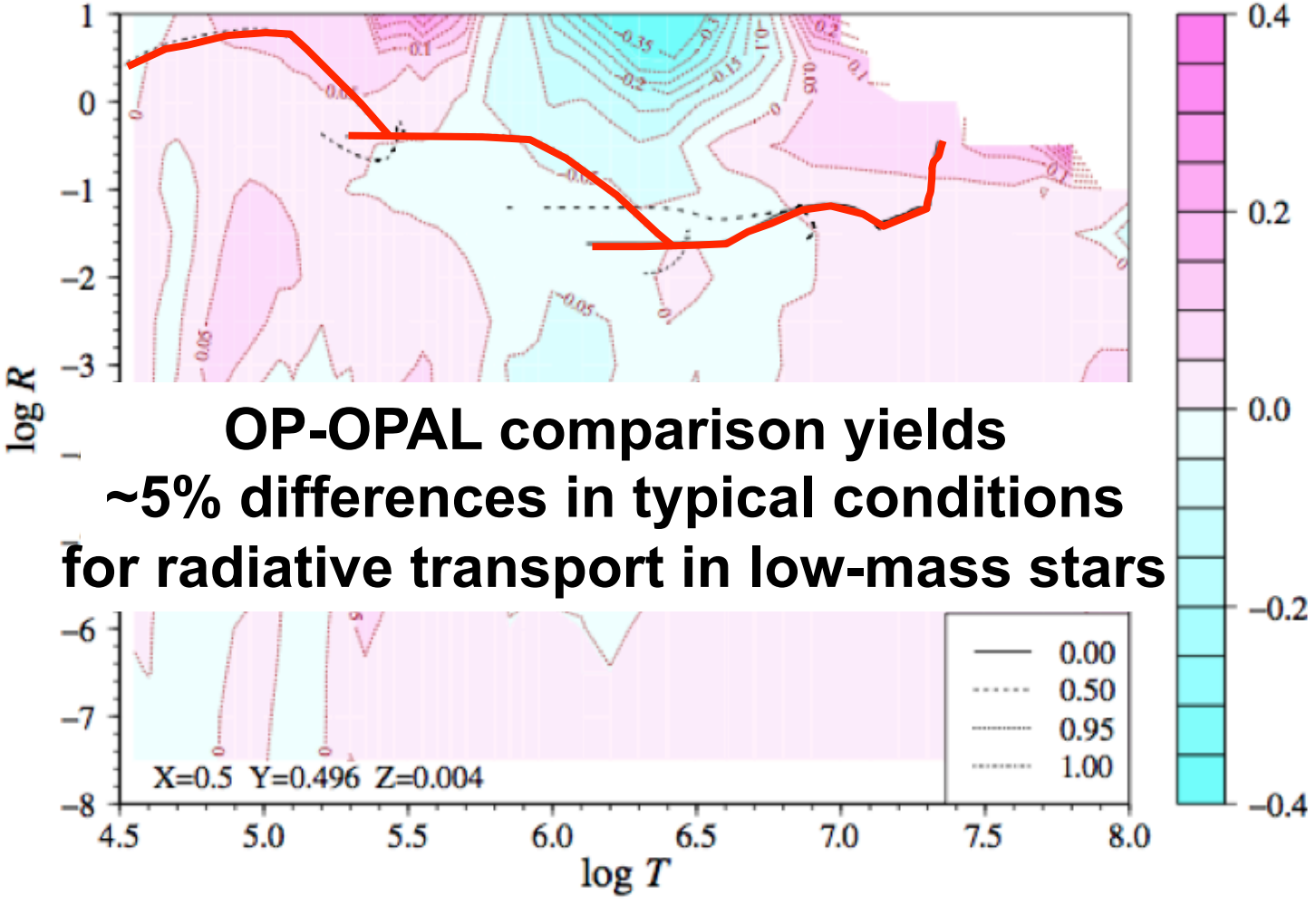
Nuclear rates probably not a problem – but tests are ongoing

Radiative Opacities: OP-OPAL comparison



Valle et al. 2013

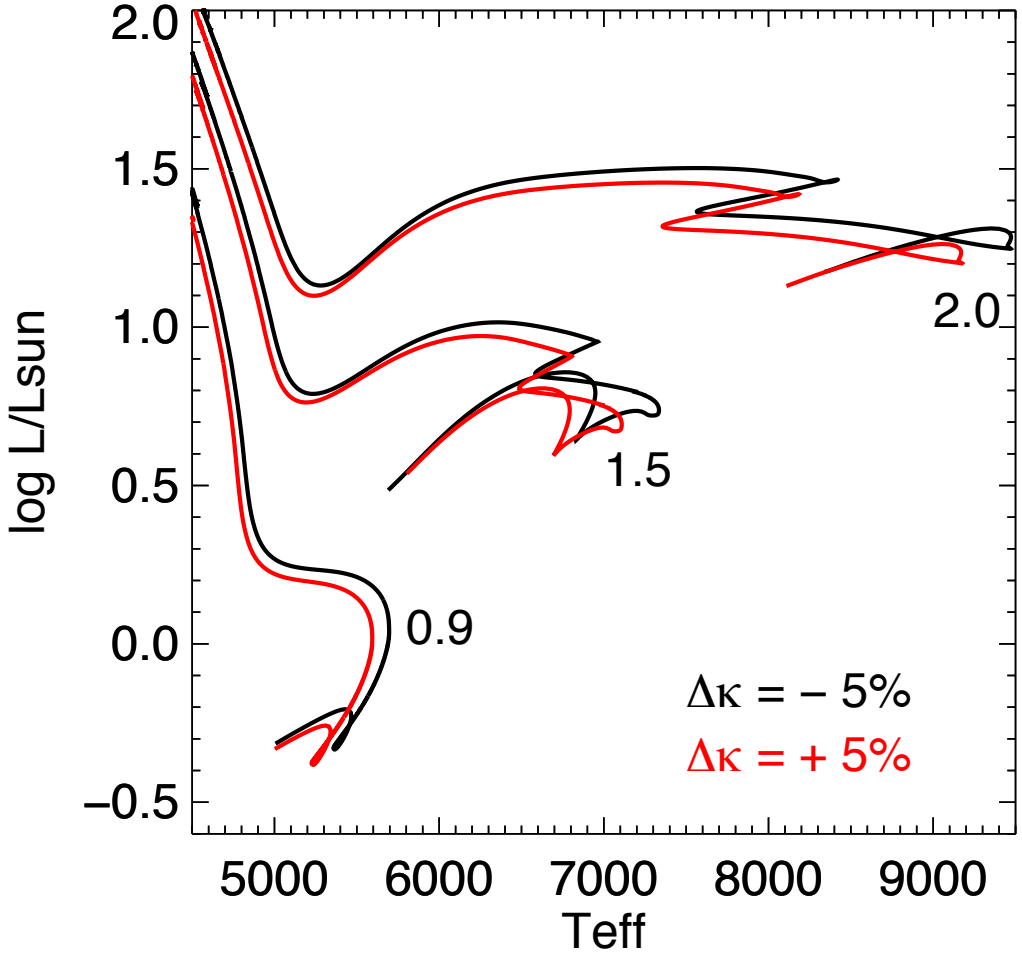
Radiative Opacities: OP-OPAL comparison

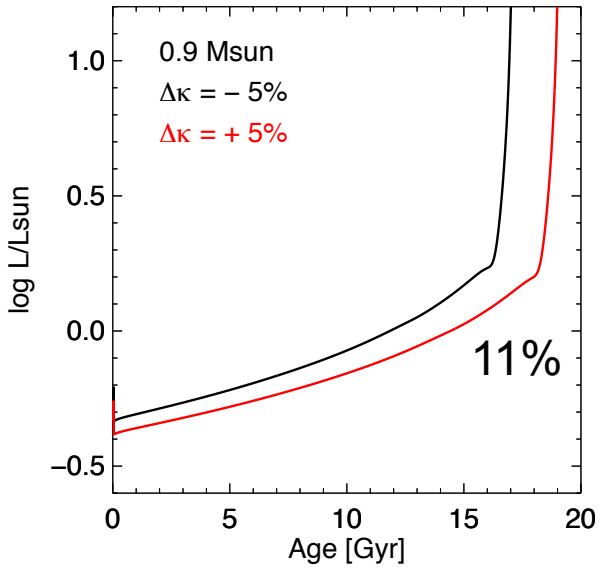


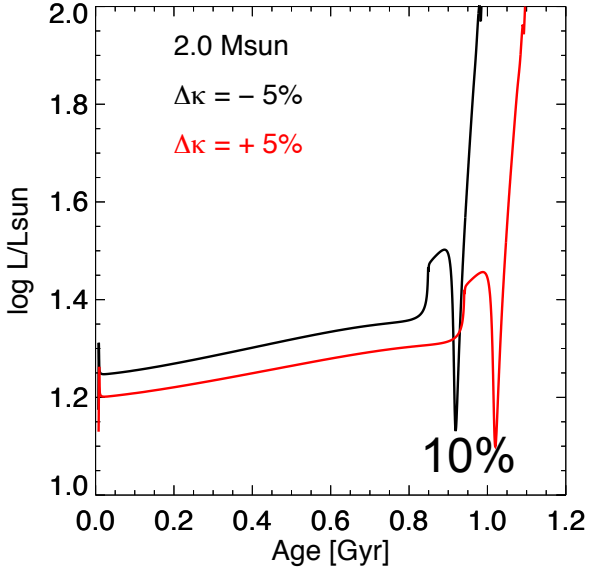
OP-OPAL comparison yields ~5% differences in typical conditions for radiative transport in low-mass stars

Valle et al. 2013

Opacity scaling ±5%







$$L \propto \frac{\mu^4 M^3}{\kappa}$$

~ linear effect on luminosity and evolutionary timescales

What is the actual uncertainty in opacities?

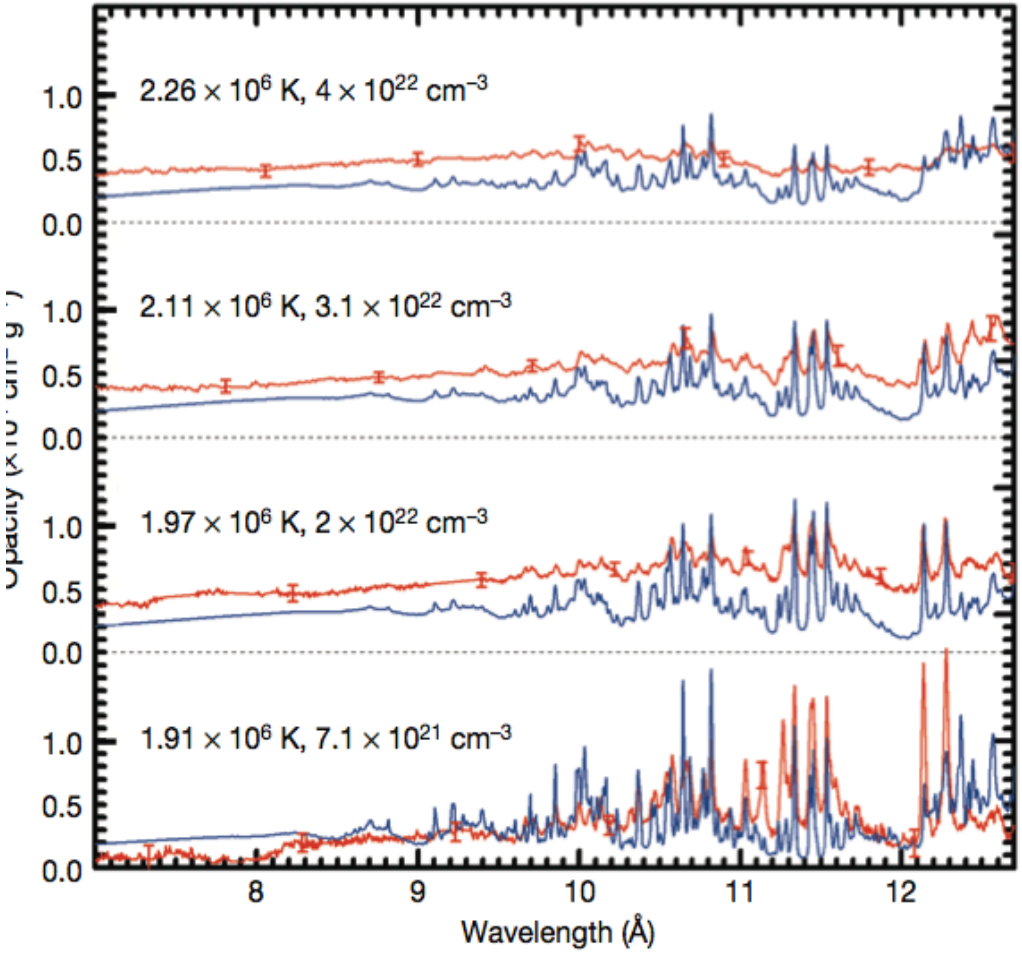
Short answer: we do not know

Sandia experiment
1st experiment in conditions close to solar

Monochromatic Fe opacity
30 – 400% larger than models

Fe opacity alone
-- > 7% increase of Rosseland mean
at solar base of CZ

Difference with models lies in the
Continuum – this is seen as problematic



What is the actual uncertainty in opacities?

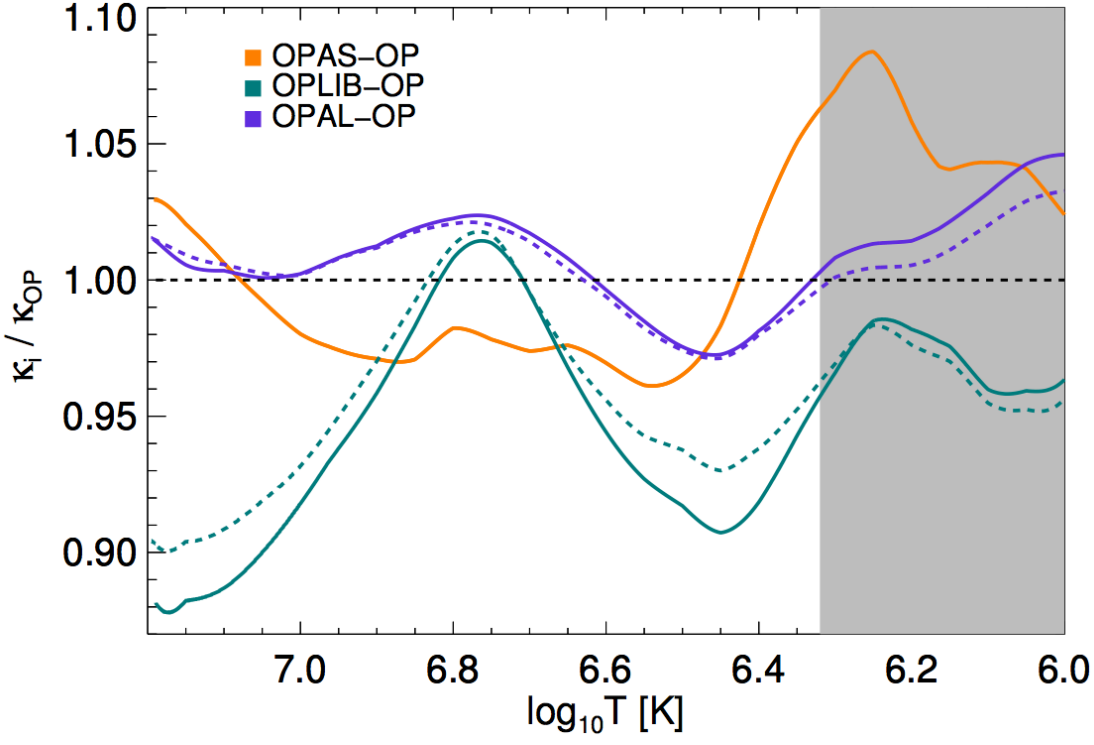
New theoretical calculations different by up to 15% differences in solar core
OPLIB – Los Alamos (Colgan et al. 2016)

Core opacities too low

Core temperature too low

solar neutrinos in strong disagreement with experiments

Current OPLIB opacities should be disfavoured



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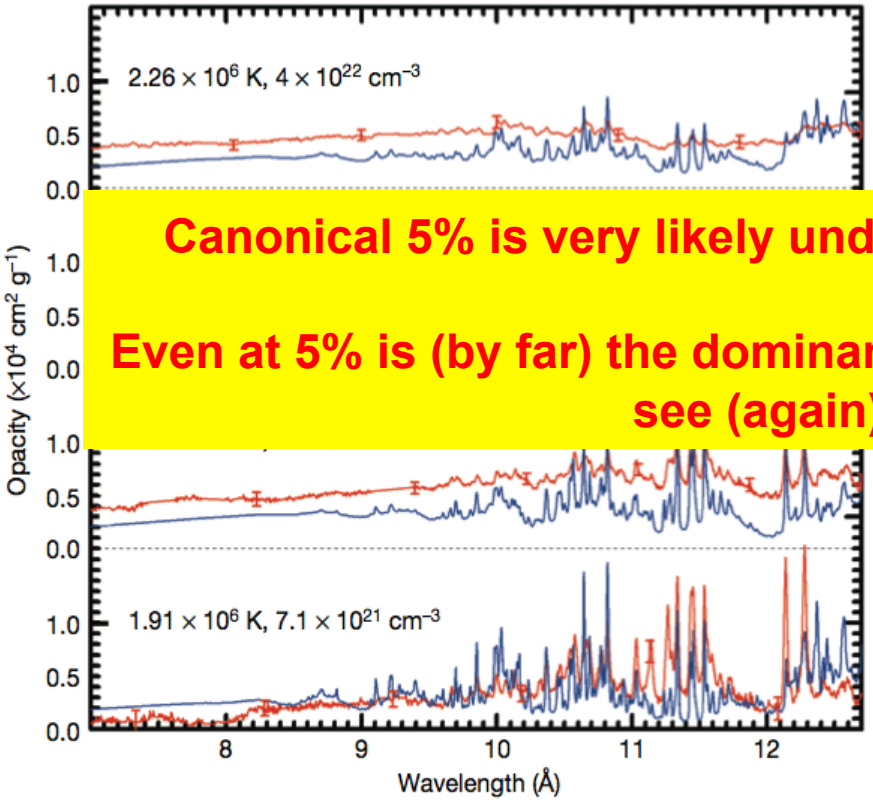
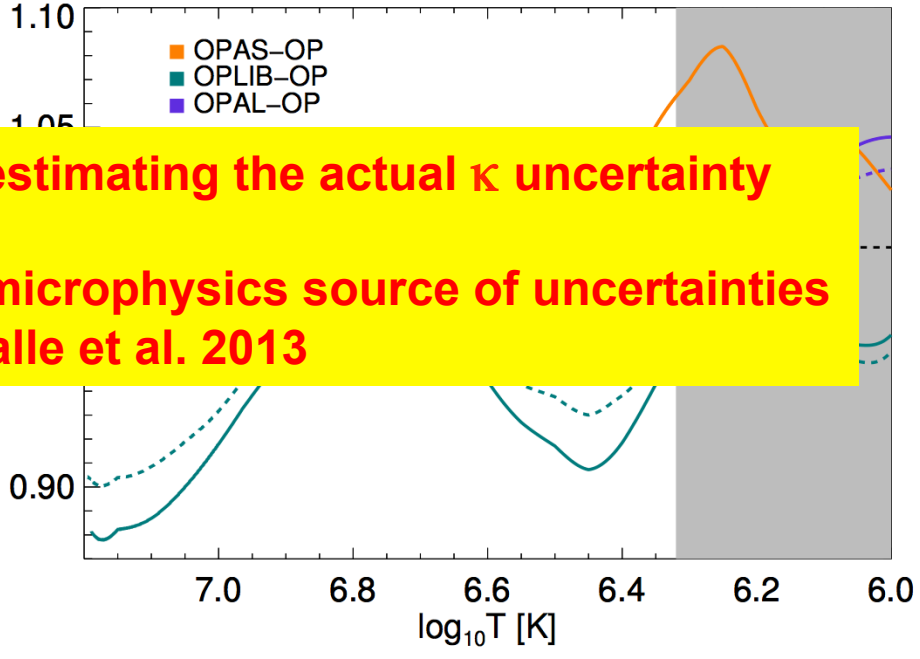


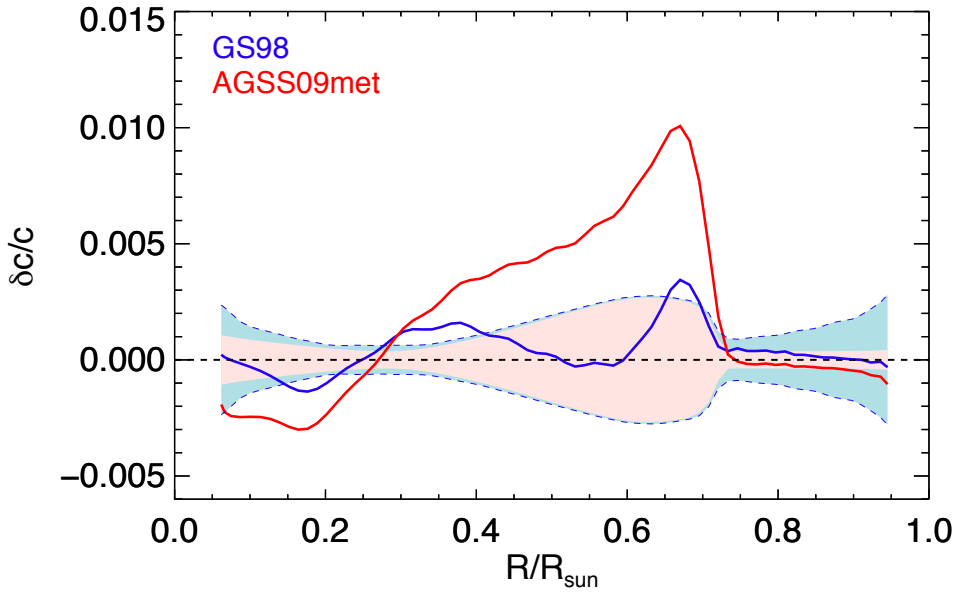


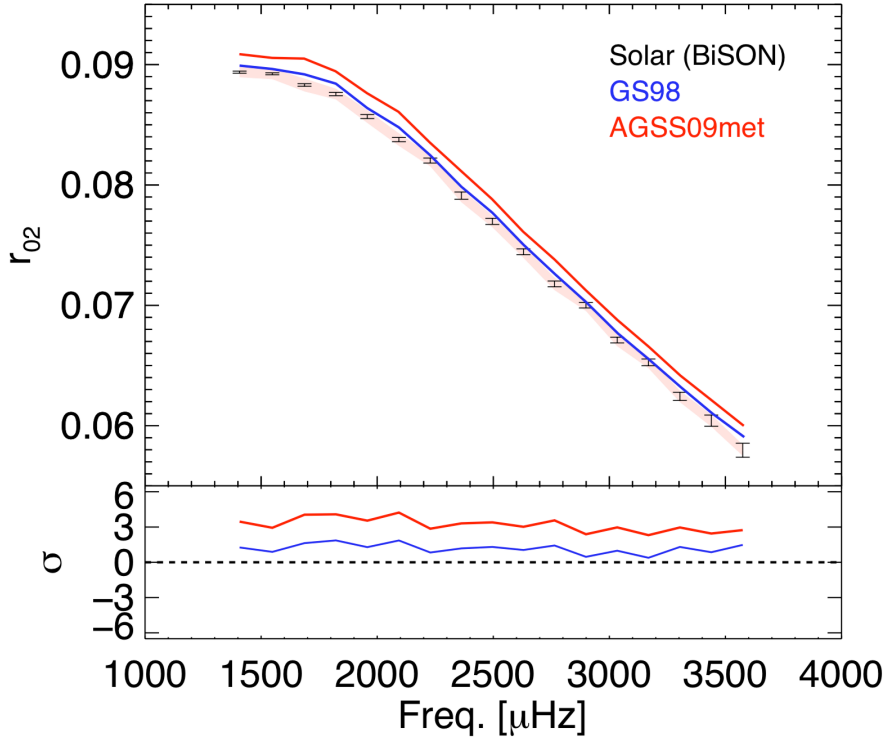
Canonical 5% is very likely underestimating the actual κ uncertainty

Even at 5% is (by far) the dominant microphysics source of uncertainties
see (again) Valle et al. 2013

Can using frequency ratios lead to biased results?

Good sound speed – good frequency ratios (GS98)
Bad sound speed – bad frequency ratios (AGSS09)



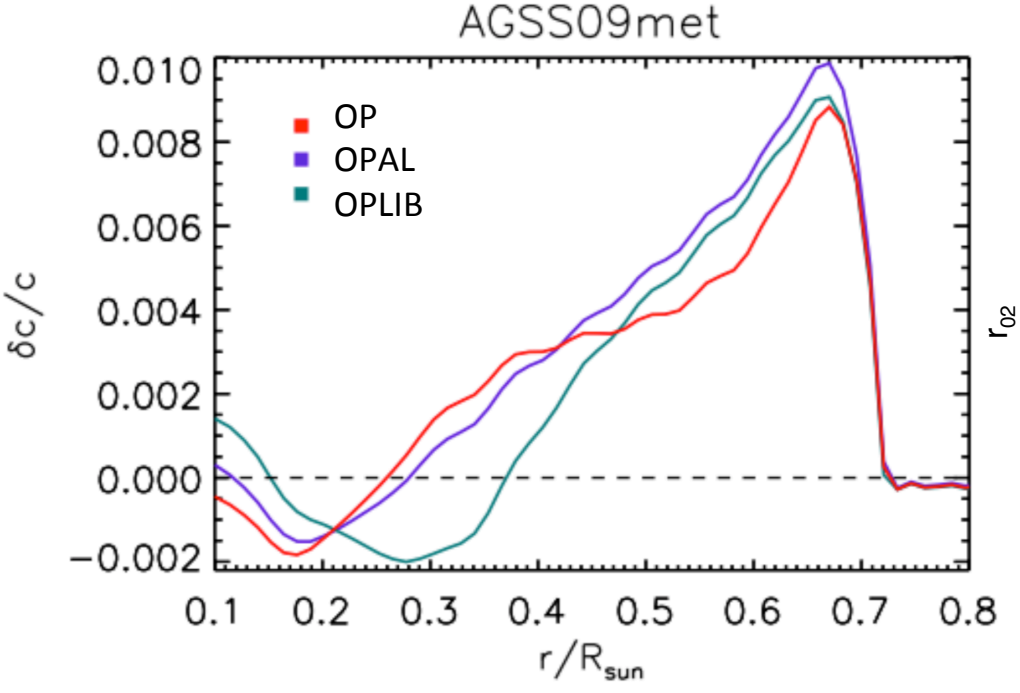


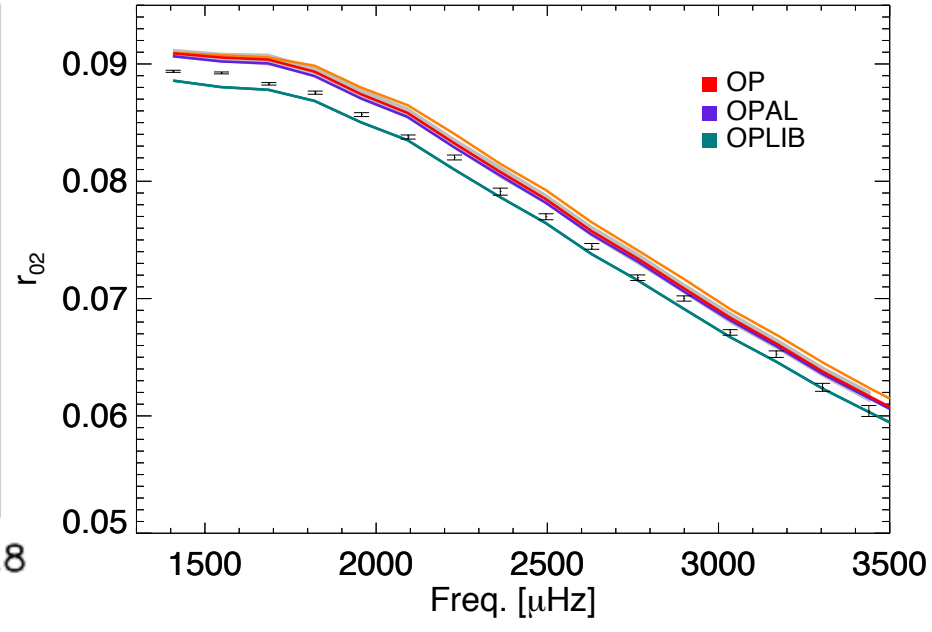
Can using frequency ratios lead to biased results?

Model with OPLIB

Equally bad sound speed – good frequency ratios (same for r01, r13, etc)

(see also Buldgen et al. 2017)



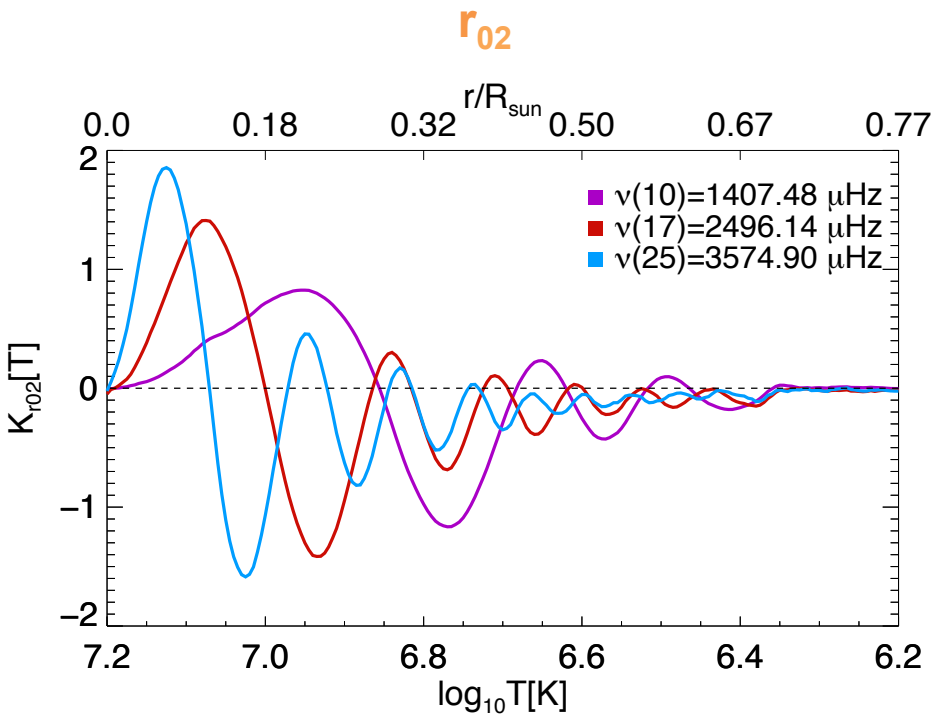


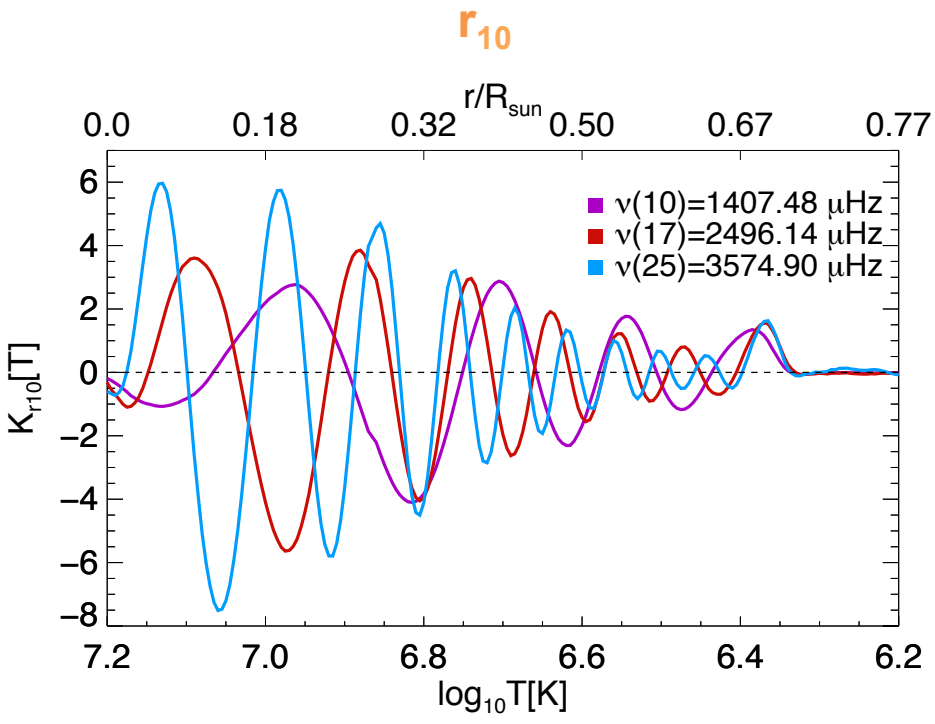
Guided by ratios, we would believe the model is OK – but we know it is not

Differences in ratios between models larger than GS98 – AGSS09 problem

Can using frequency ratios lead to biased results?

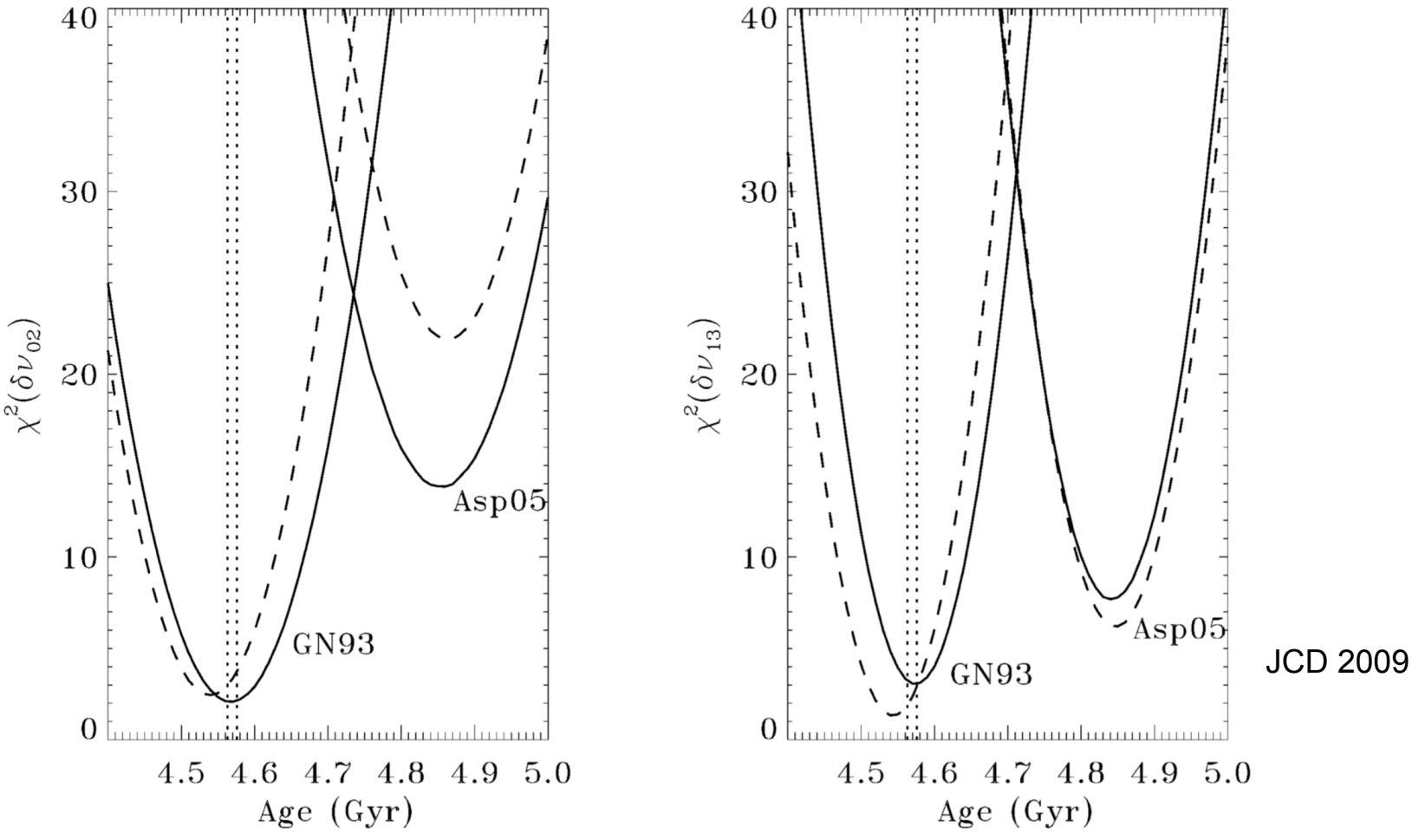
Opacity kernels





Oscillatory nature of kernels → ratios are sensitive to detailed opacity changes

Can using frequency ratios lead to biased results?



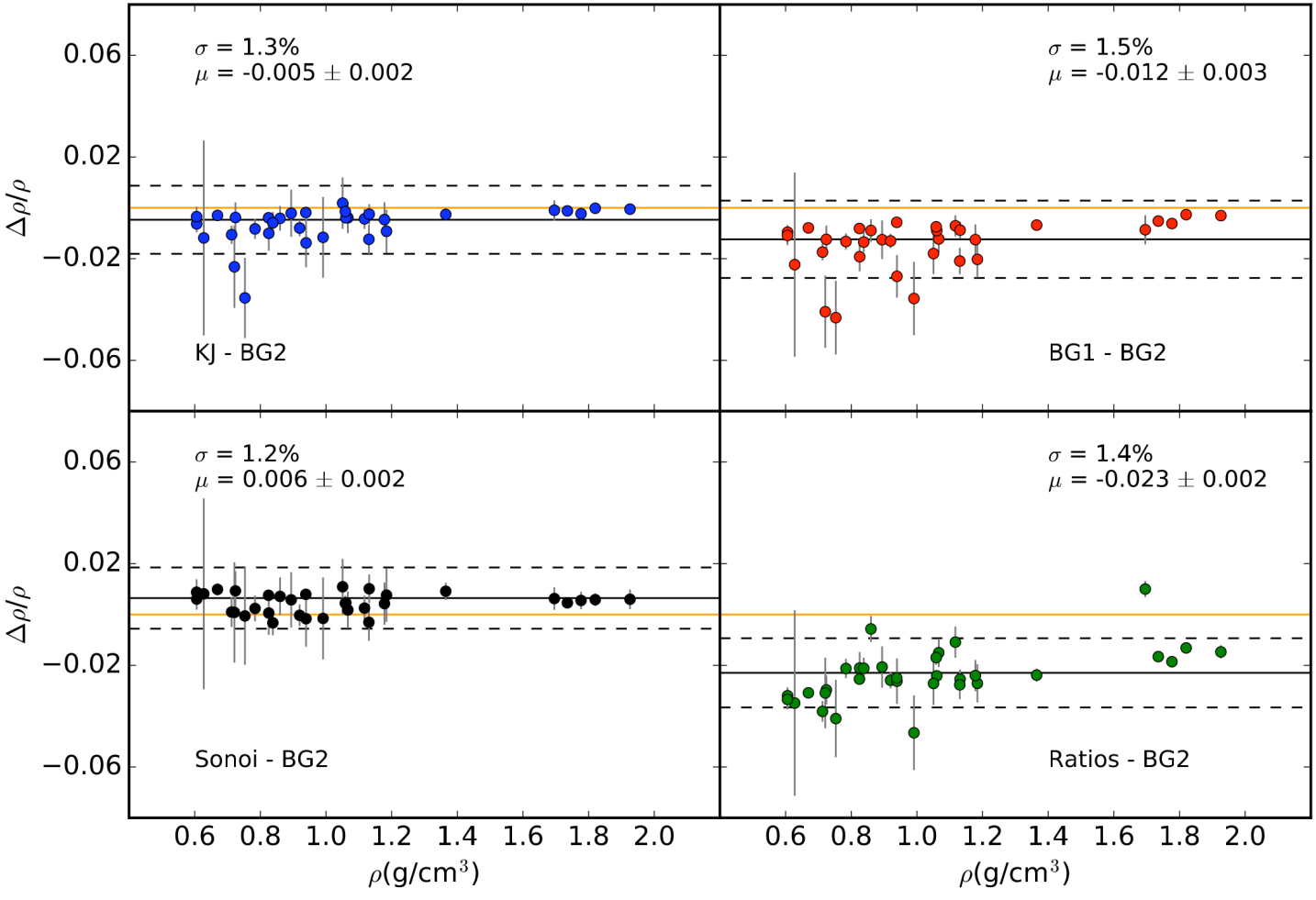
JCD 2009

Such difference in ratios matter
For reference 8-10% age difference for high-Z / low-Z models

Should this be addressed more systematically (synthetic stars – avoid surf. effect)?

Can using frequency ratios lead to biased results?

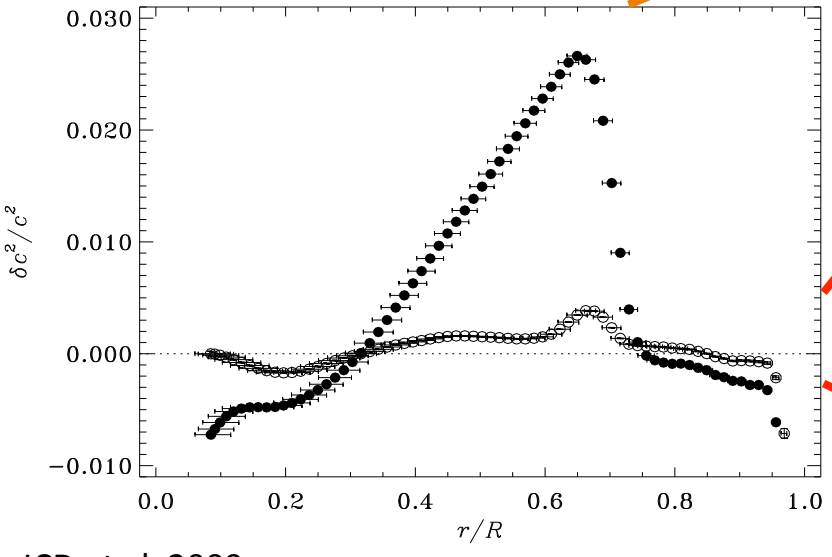
Ratios used as reference for testing surface corrections

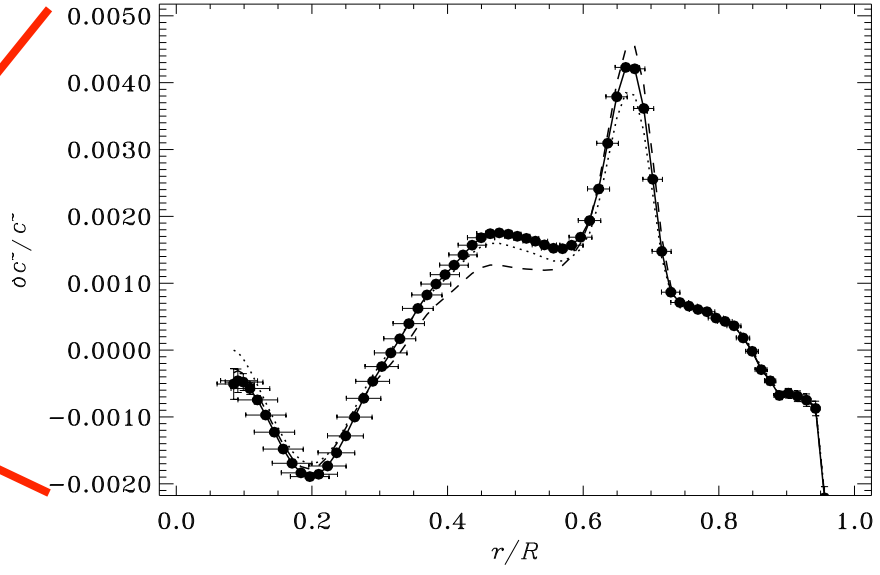


Solar composition & opacities

(Helio)seismic probes: degeneracy between opacity profile and composition

Increase κ (20% BCE, few percent in core) – keep Z low





JCD et al. 2009

Solar composition & opacities

Solar composition – with current generation of opacities

- 3D-RHD based composition (AGSS09) – seismically off solar model
- 1D-based solar composition (GS98, GN93) – seismically correct solar model
- King Solomon's approach: split difference in half (CO^5BOLD) composition (as done in new BaSTI)

A pragmatic choice is needed – at least now

Solar composition & opacities

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<u>What possibilities of determining Z independently of opacities?</u>

Helioseismic attempts at solar composition – now degeneracy composition-EOS

Helium: in the range 0.240 – 0.255 (different techniques, different EOS)

Metals: Lin & Basu (2007) – Z consistent with high-Z solar comp.
Houdek & Gough (2011) – Z consistent with low-Z solar comp.
Vorontsov et al. (2013, 2014) – Z (much) lower than low-Z solar comp.

Different methods – different EOS → let's talk about EOS

Equation of state

Equation of state enters at two different levels

- stellar evolution: structural changes, evolutionary timescales

  ‘Modern’ EOS: OPAL, MHD, FreeEOS are likely to be OK (stress likely, TBD)

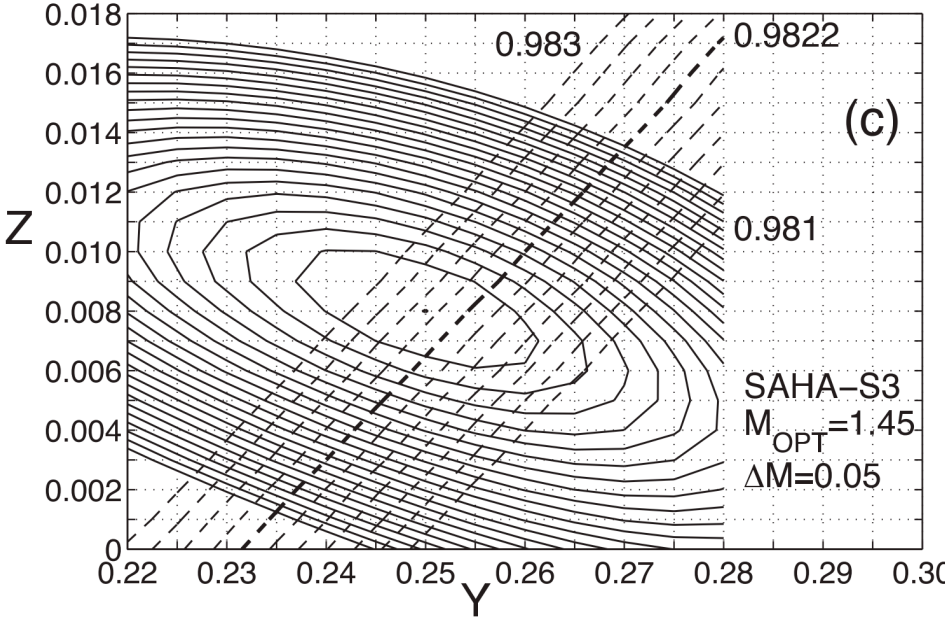
- extracting information from glitches might be more sensitive

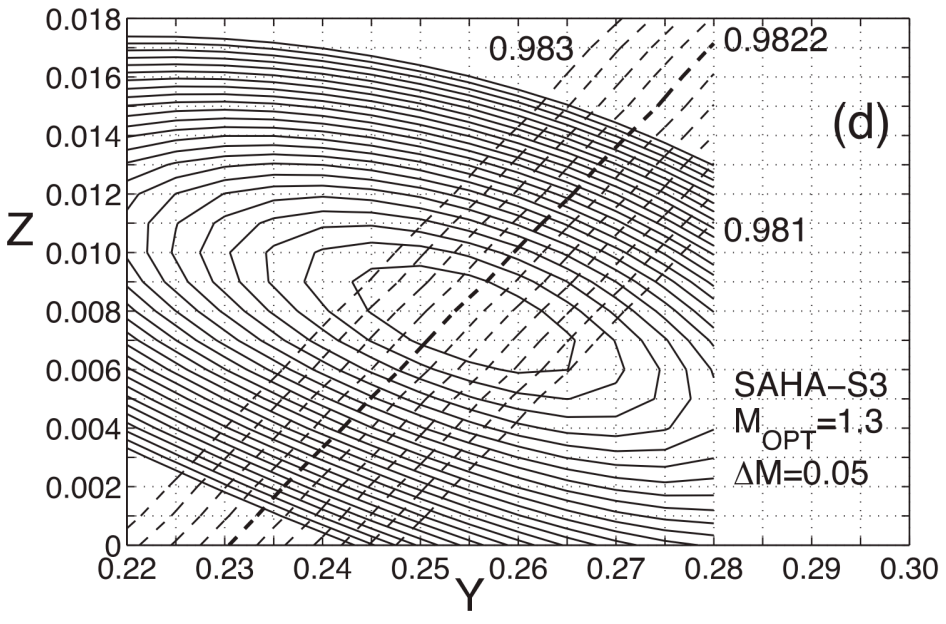
  (but maybe data quality dominates)

Equation of state

SAHA-S3 presented a few years ago with application to solar Y-Z determination
(Vorontsov et al. 2013, 2014)

Γ_1 inversions (but tested other techniques) – different datasets



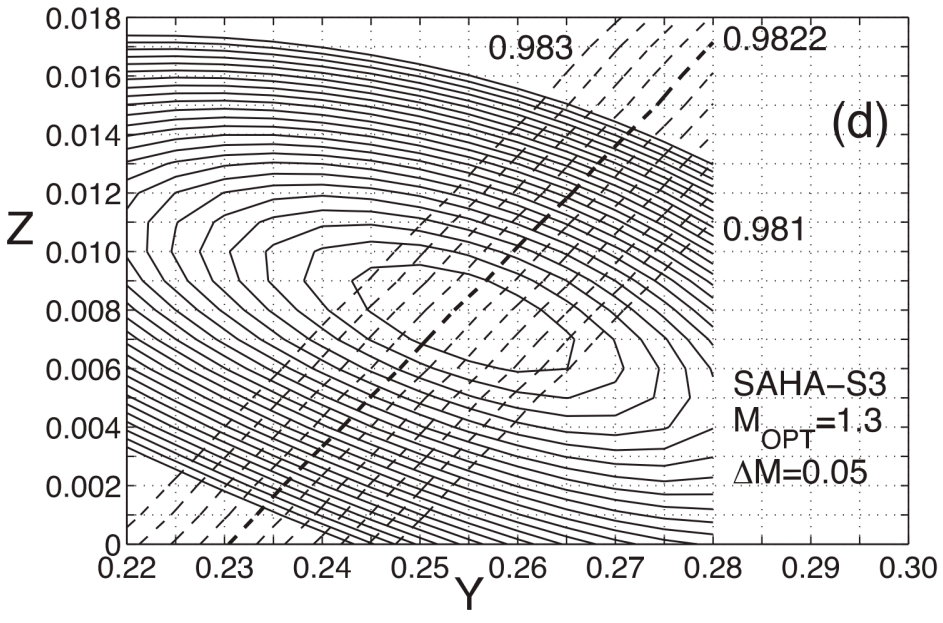


Y inference in line with previous ones : 0.245 – 0.255

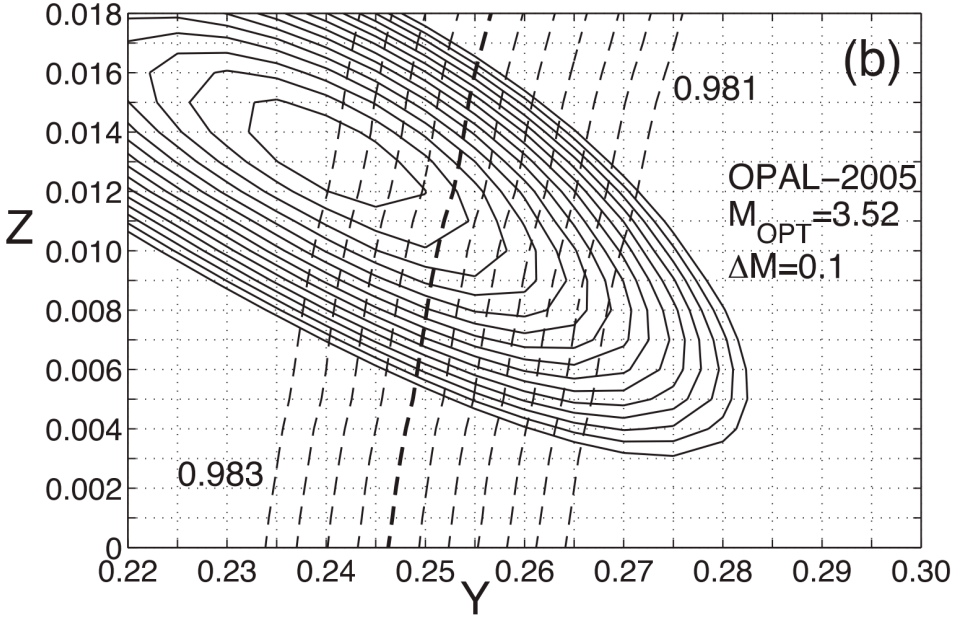
Z = 0.008 (best result) – complete range 0.008 – 0.013 (mean 0.0105)

Equation of state

SAHA-S3



OPAL-2005



SAHA-S3	0.008 (best)
SAHA-S3	0.0105 (average)
OPAL	0.013
AGSS09	0.0134
CO5BOLD	0.0153
GS98	0.0169

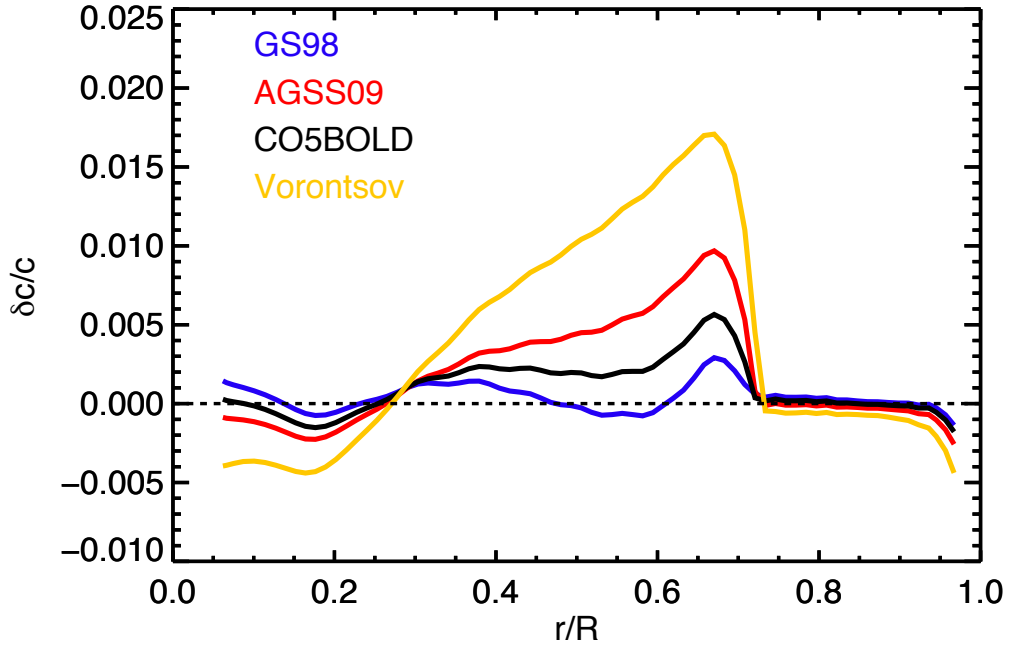
SAHA-S3 inferred mean Z = 0.0105

Part might be to technique – but much is due to EOS – is it trustworthy?

Equation of state

SAHA-S3 inferred mean Z = 0.0105

→ 40% increase of opacity at base of CZ to have good seismic solar model



For inferred values Z_S = 0.0105 – Y_S = 0.250

It is not possible to construct a solar model satisfying those results

Problem is very fundamental: with our understanding of stellar physics the Z_S-Y_S combination cannot reproduce the solar luminosity!

At fixed physics, models require much lower initial Y (below SBBN) → Y_S = 0.21

Summary

- Nuclear rates under control – detailed quantification undergoing

- Opacities – more problematic : OP-OPAL might underestimate true uncertainty
  5% might be OK for stellar cores

  but outer layers might be larger
  - experimental result
  - solar abundance problem
  - newer opacity calculations (might be) flawed
  - developments to be expected in few years time

- Solar composition – choice linked to opacities
  at least if we want to guarantee seismically good solar model

  pragmatic choice? Which?

- EOS – available EOS probably OK for evolution (timescales, etc.)
  for extracting information from glitches might not be so clear

- Helioseismic inferences not always consistent (freq. ratios vs sound speed)
  a systematic study ratios vs frequencies might be interesting

Summary

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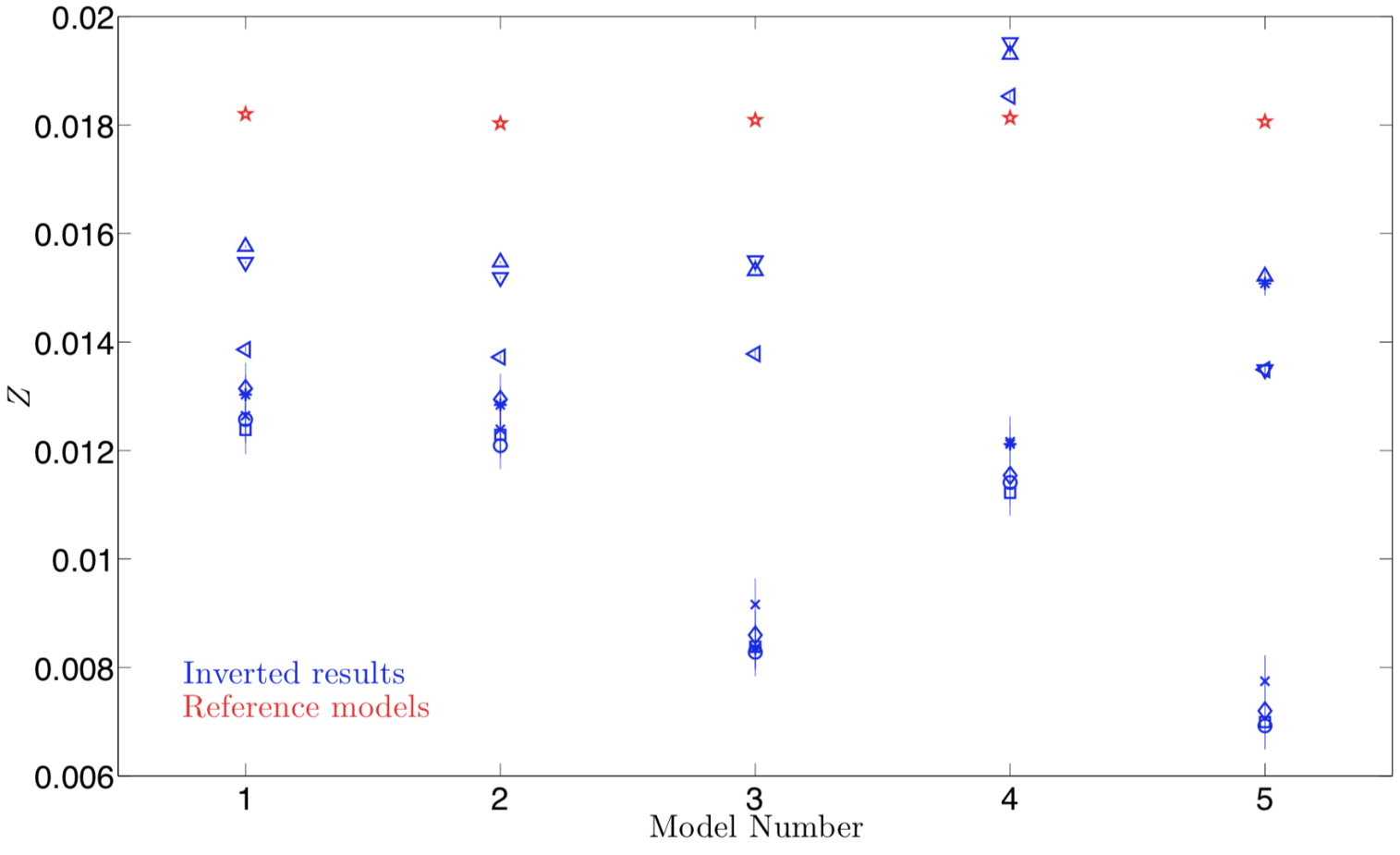
Equation of state



Buldgen et al. 2017