GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

The 2024 state of the art of the Standard Solar Model

Inaugural Workshop on Nuclear Astrochemistry

27/2/24

A. Serenelli & Y. Herrera

ChETEC INFRA

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA).

Outline

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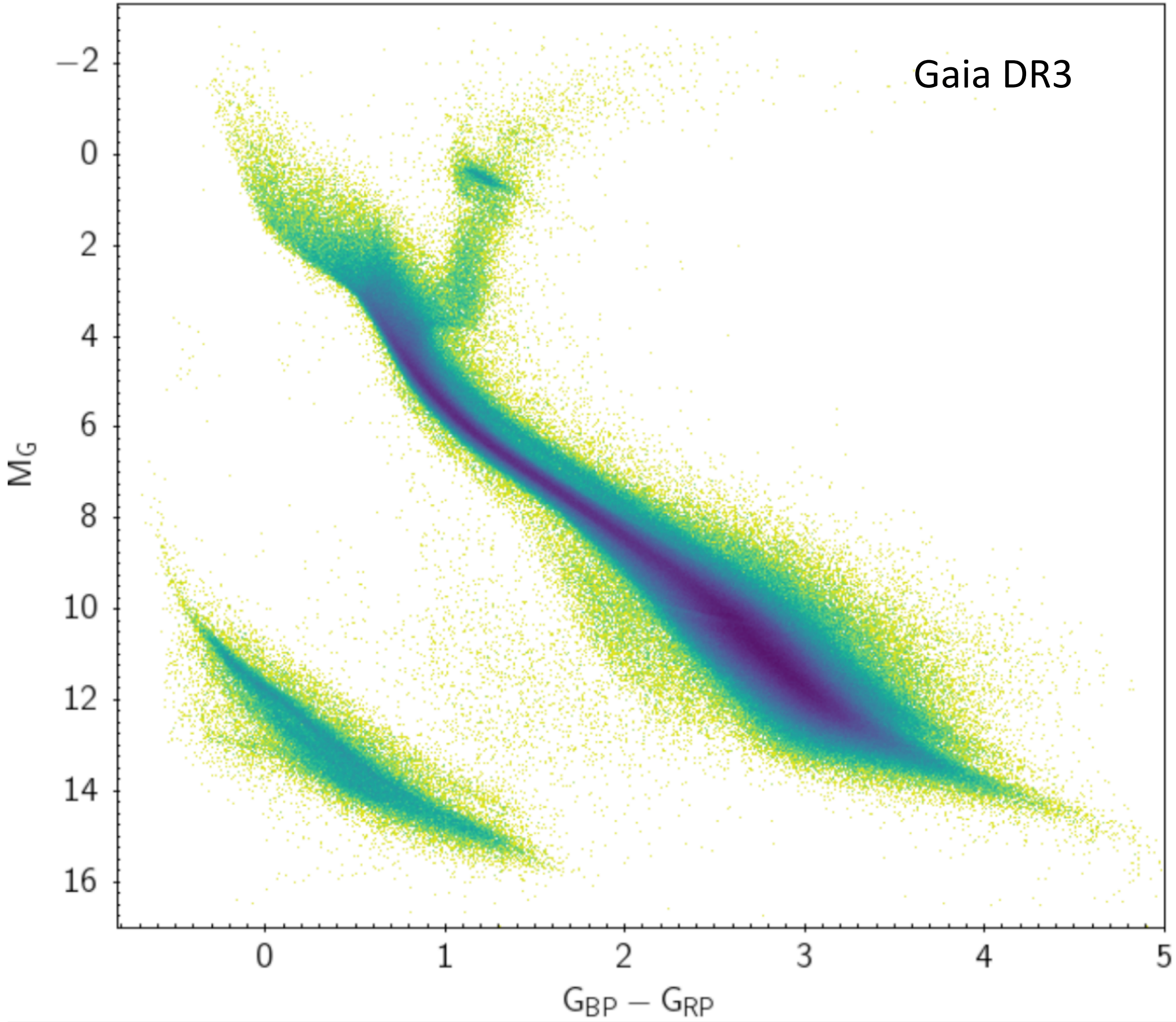
- Why should we continue to study the solar interior?
- Standard solar models in a nutshell
- The 2024 status of SSM: helioseismology and solar neutrinos
- SSMs in the context of precision stellar astrophysics

Why the Sun? It is “foundation” science



~10^9 individual stars with measurements

colors, temperature, luminosity, composition

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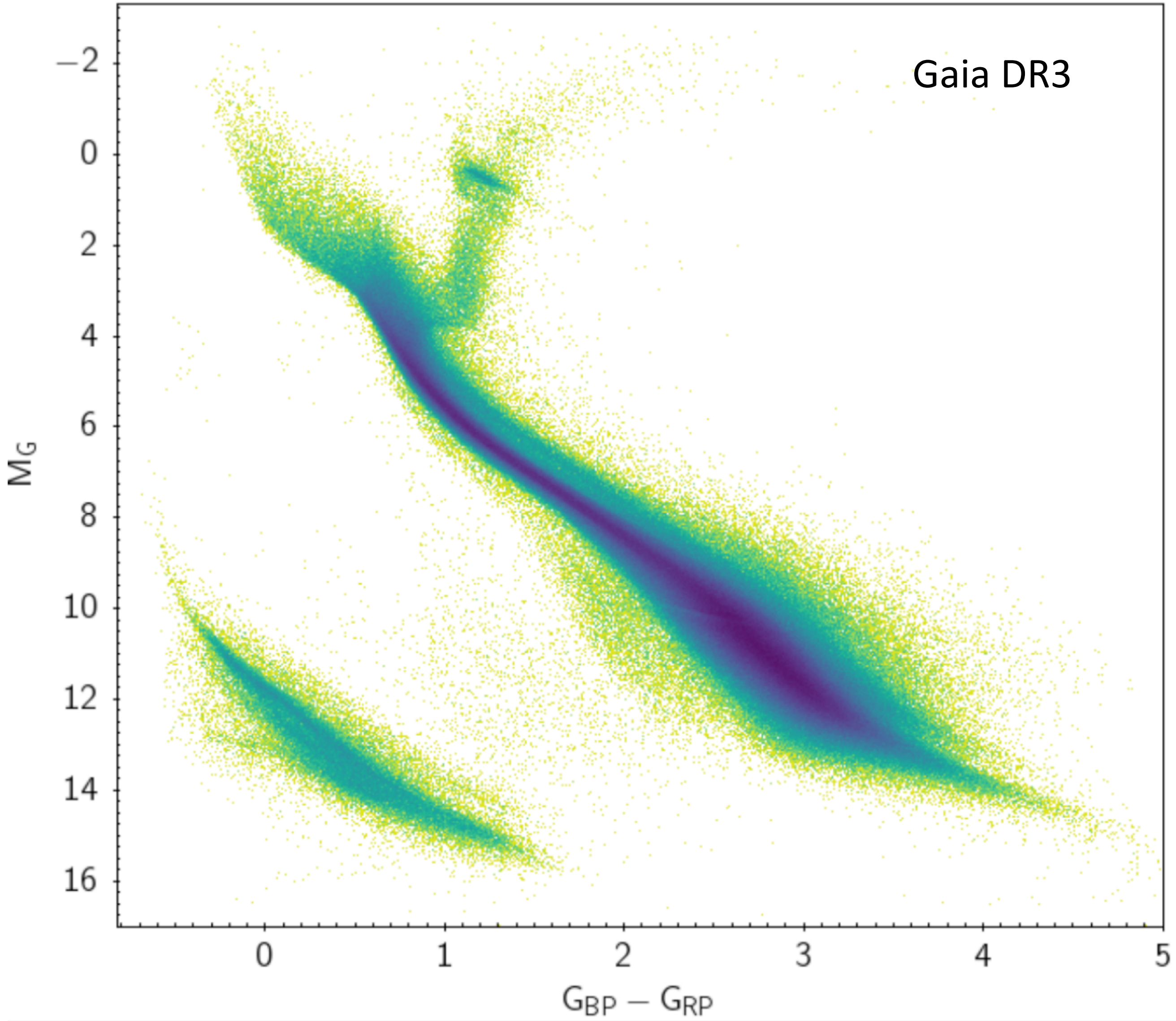

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~ 10^3 with accurate, precise, (model) independent mass determinations

selective club: eclipsing binaries

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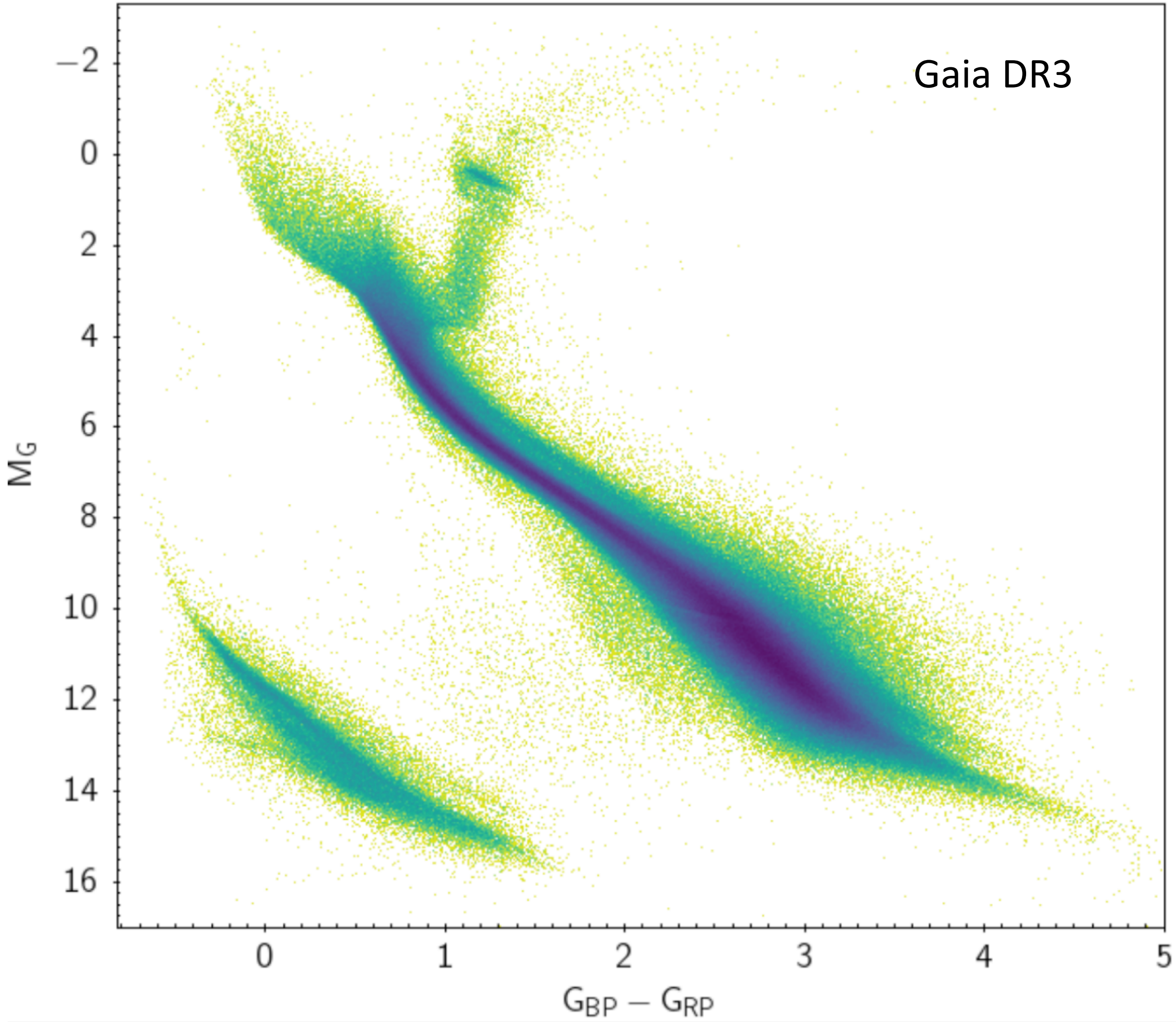

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meteoritic dating

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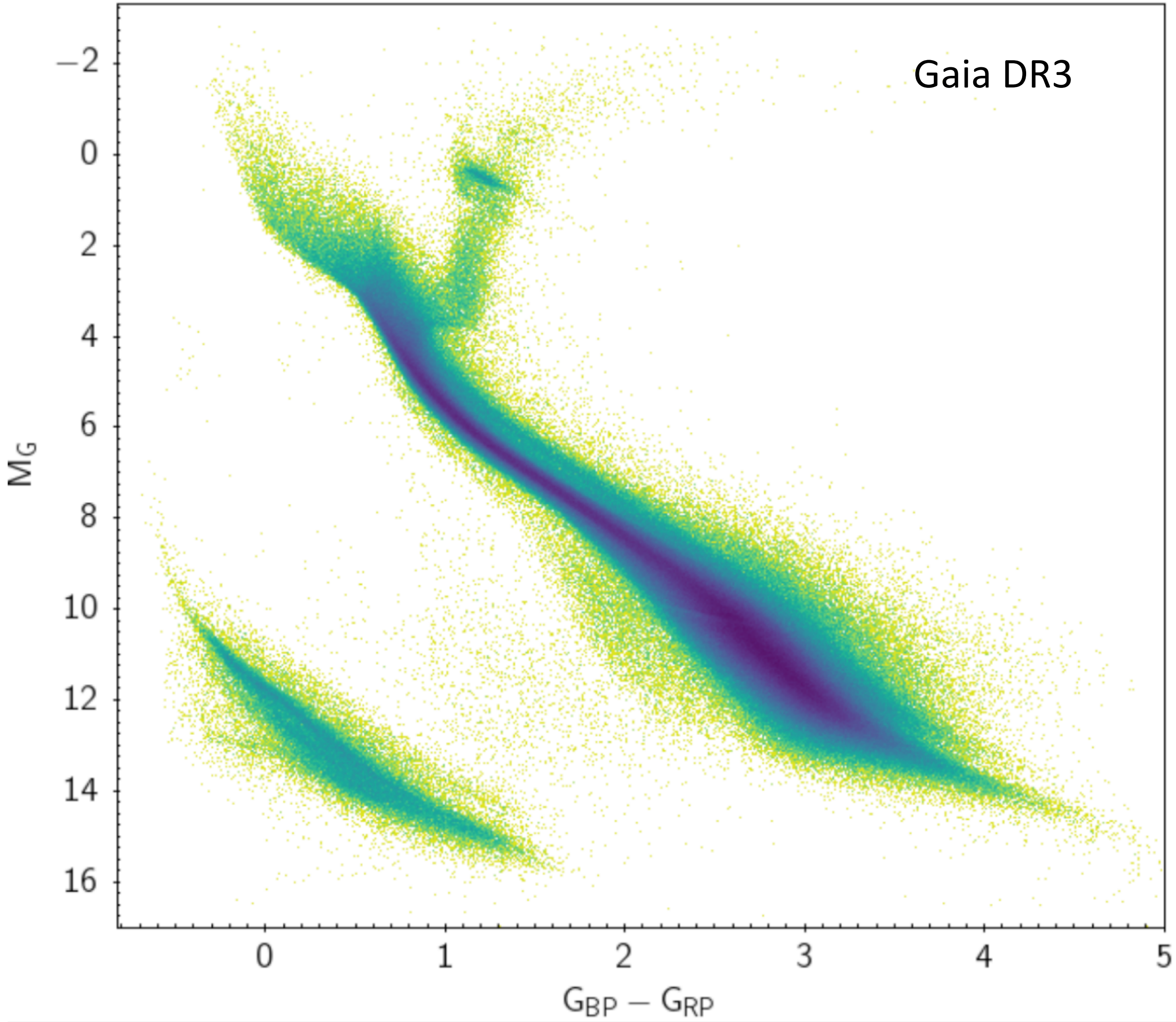


~10^9 individual stars with measurements

colors, temperature, luminosity, composition

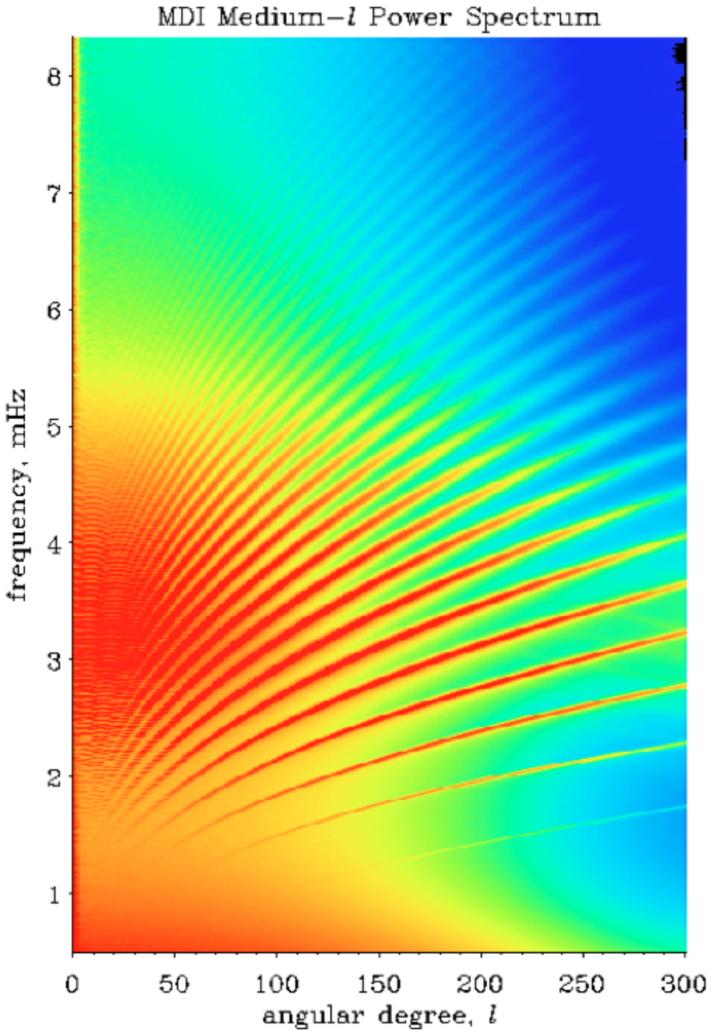
~ 10^3 with accurate, precise, (model) independent mass determinations

selective club: eclipsing binaries

1 star with accurate, precise, (model) independent age determination

meteoritic dating
+ highly accurate radius & mass

Why the Sun? It is “foundation” science



<u>Helioseismology</u>

>10^5 eigenmodes → inversion of internal structure:
sound speed, density, adiabatic index (EoS)

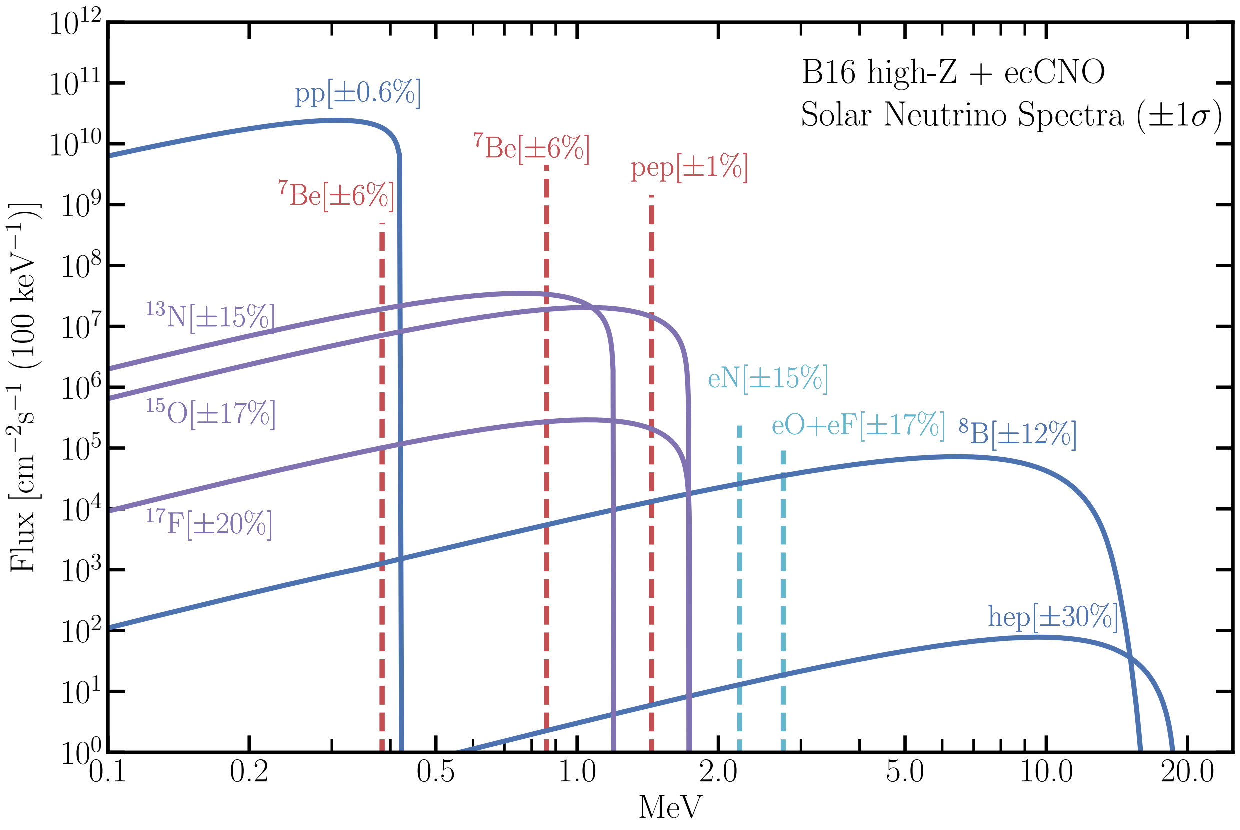
→ global quantities:
surface helium, depth of convective envelope

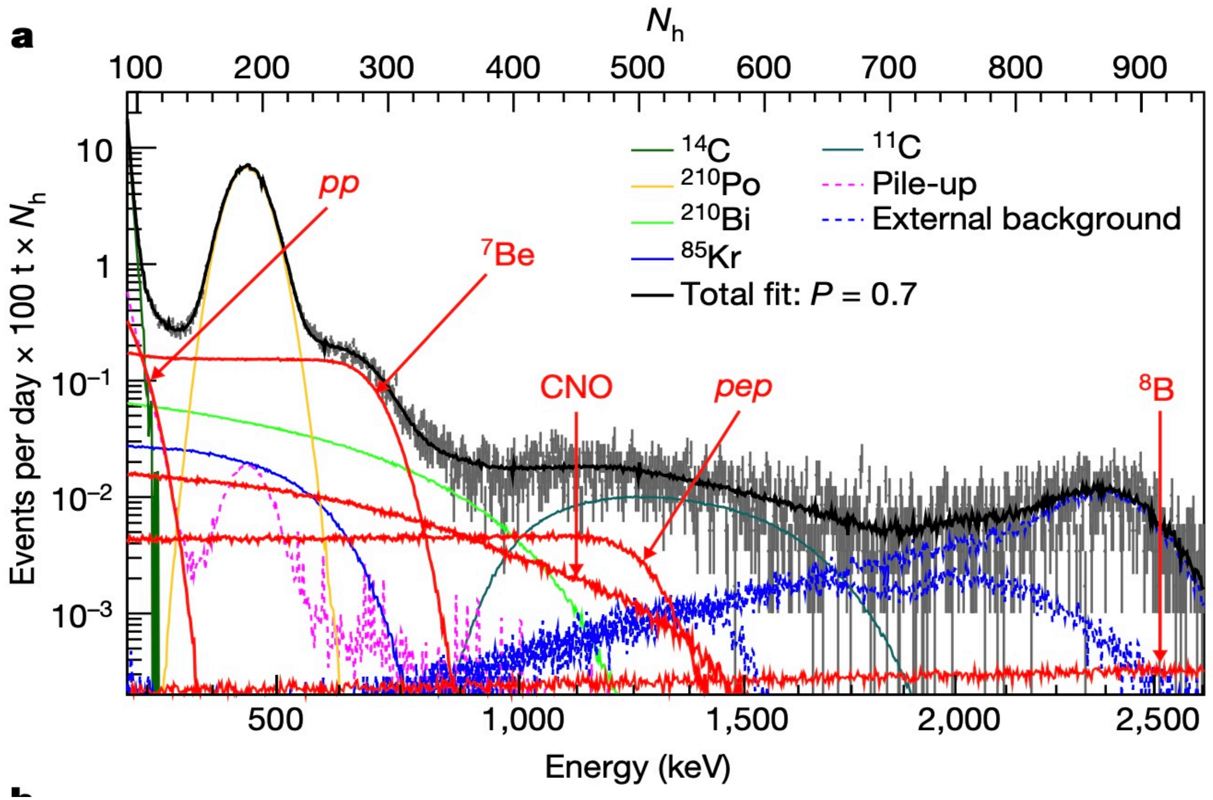
→ beyond standard solar models:
internal rotation profile (depth and latitude)

Allows testing theory of stellar evolution by looking at internal structure

Why the Sun? It is "foundation" science

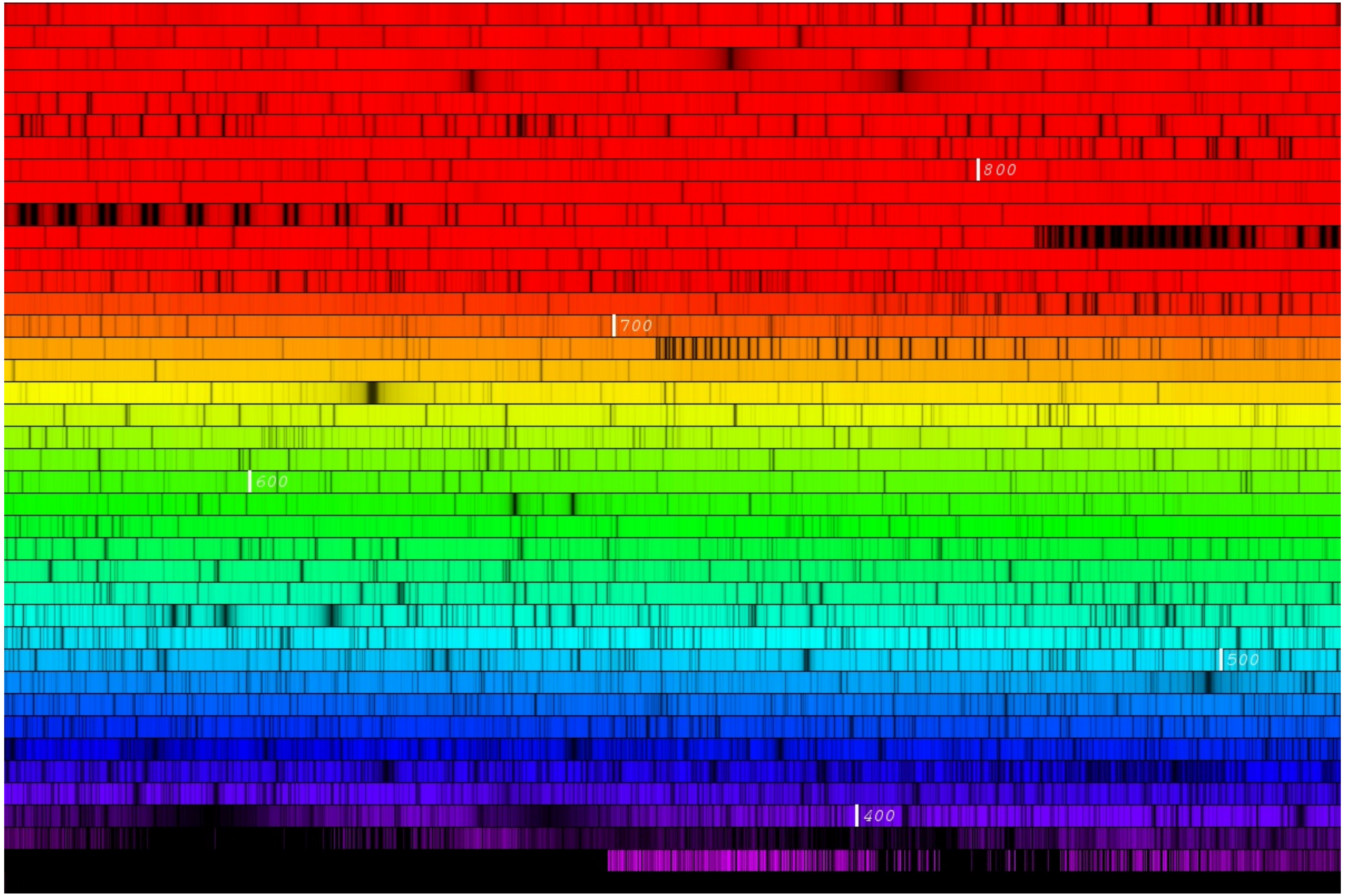
Solar neutrinos → information on solar core, nuclear physics





Borexino solar neutrino spectrum
and identified solar fluxes

Foundation science: Solar spectrum & abundances



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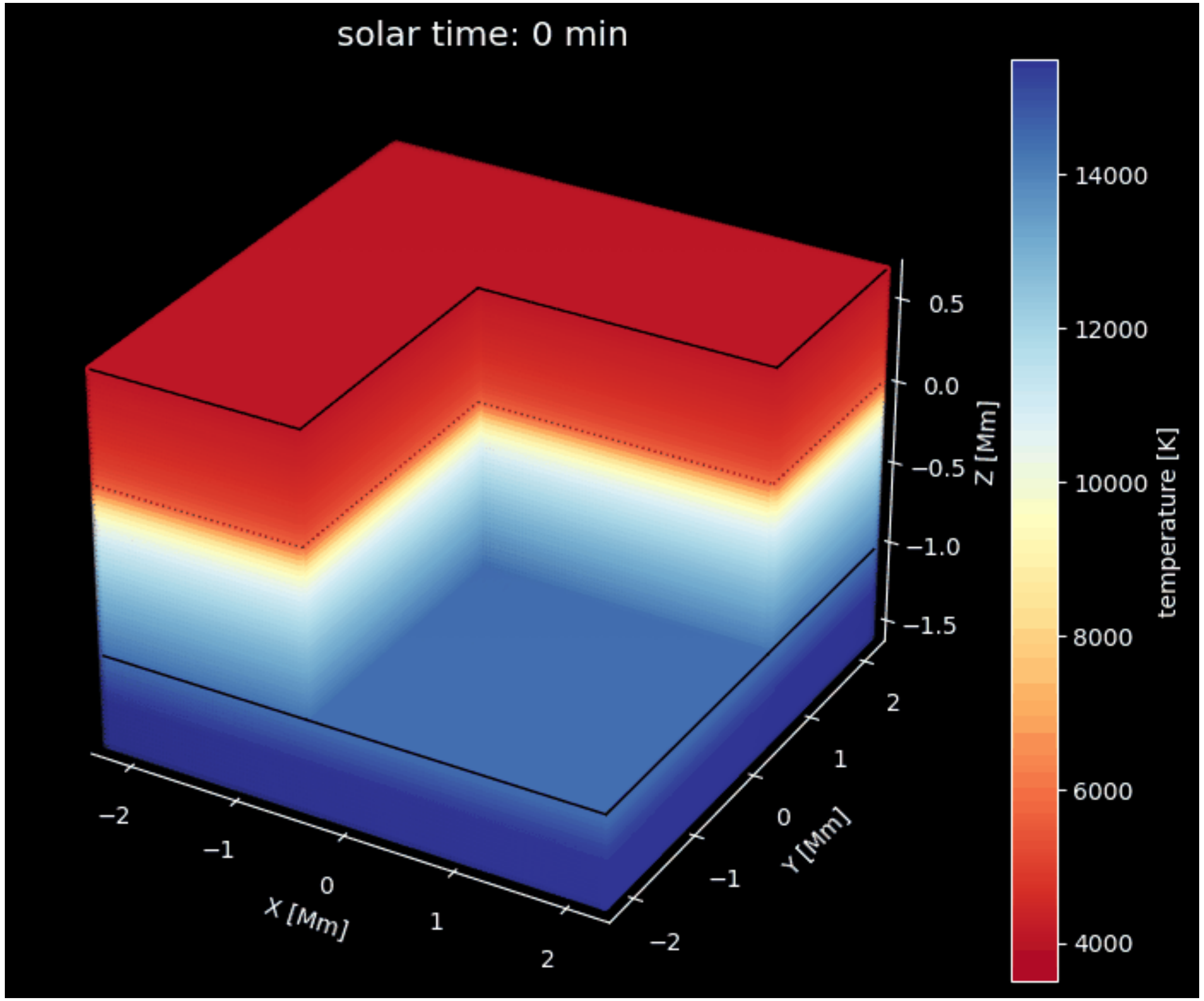


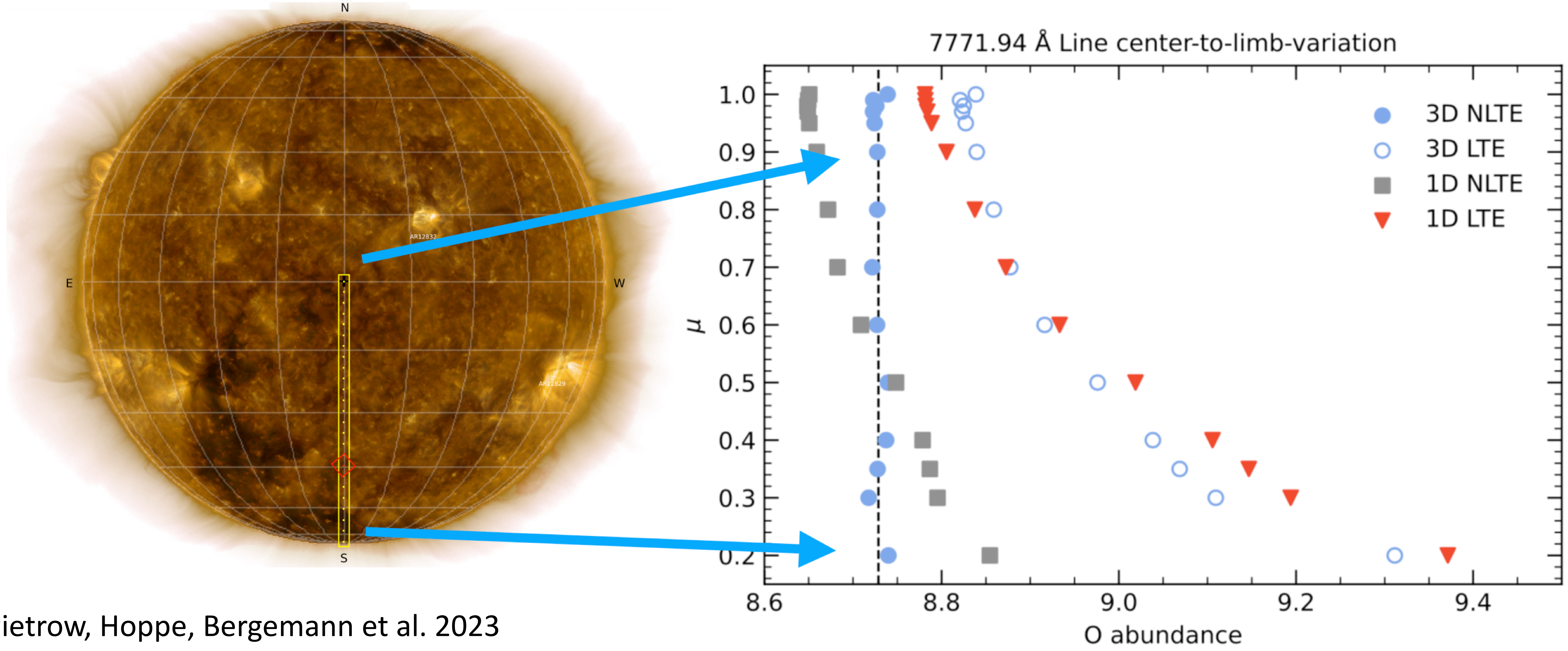
Eitner, Bergemann et al. in press

Solar envelope is convective
→ hydrodynamic models → 3D models

Structure of atmosphere used for detailed radiative transfer
→ synthetic spectrum
to compare with observed one

Foundation science: Solar spectrum & abundances

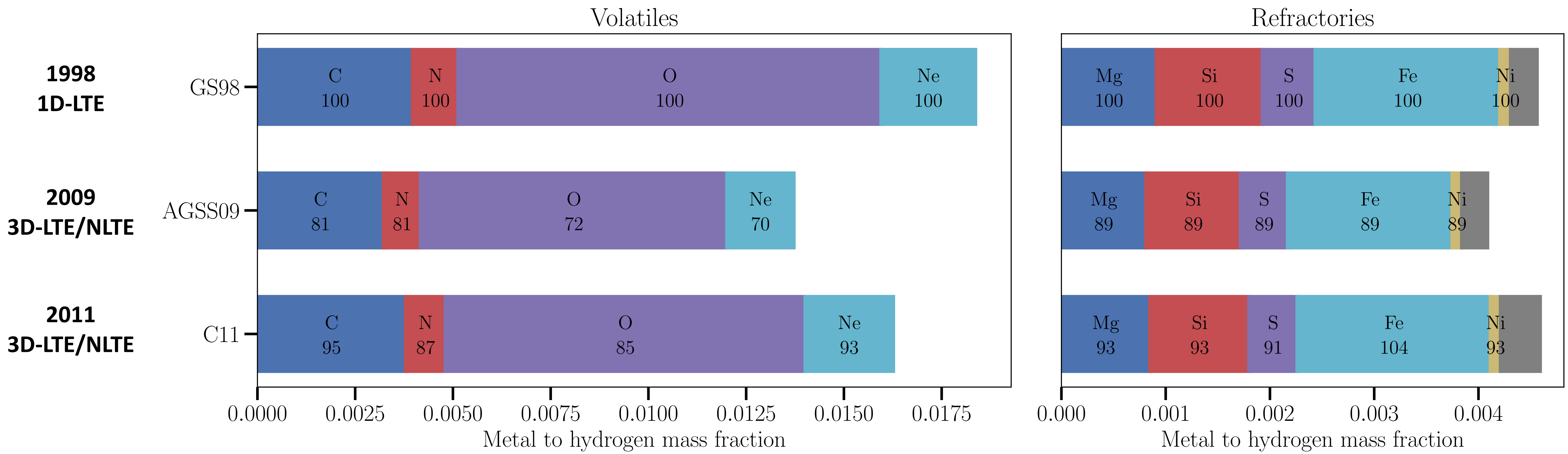
Spatially resolved spectroscopy → the need for accurate (NLTE) modeling



Pietrow, Hoppe, Bergemann et al. 2023
Bergemann, Hoppe, et al. 2021

(plots from M. Bergemann)

Which solar composition?



GS98: Grevesse & Sauval 1998, AGSS09: Asplund et al. 2009, C11: Caffau et al. 2011

Which solar composition?

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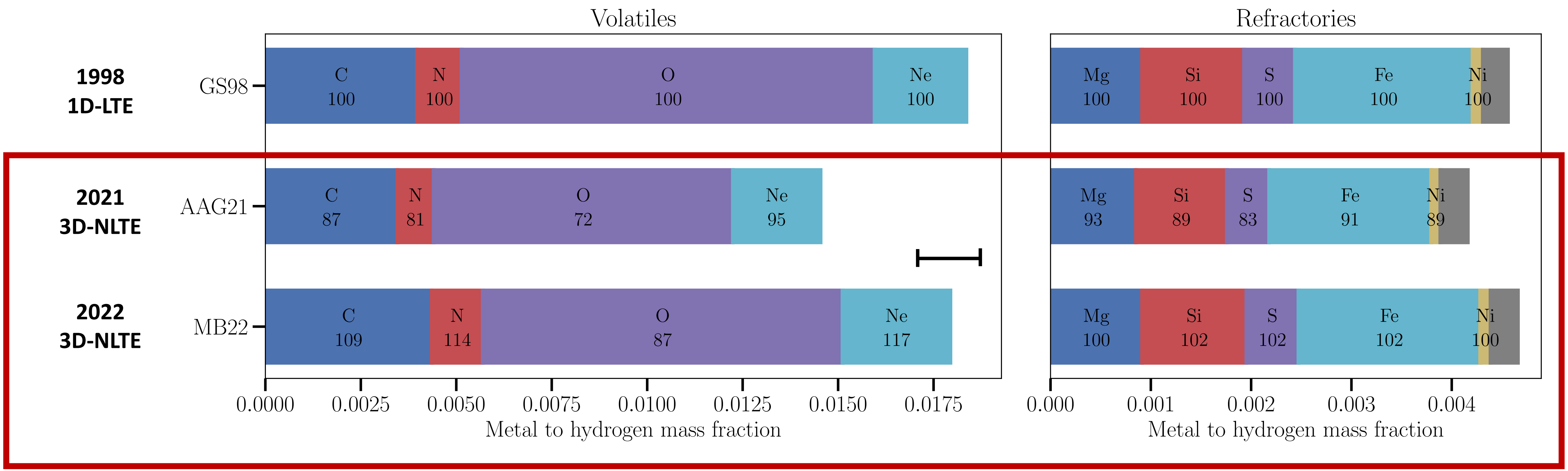

GS98: Grevesse & Sauval 1998, AAG21: Asplund et al. 2021, MB22: Magg et al. 2022

Building a standard solar model

Boundary conditions

Solar mass – $M_\odot$ – determined from $GM_\odot$ → limited by knowledge of G (~one part in 10^5)
Solar radius – $R_\odot$ – several methods: radio occultations, solar oscillations, Venus transit, (< one part in 10^3)
more loosely defined concept
Solar luminosity – $L_\odot$ – bolometric measurements (< one part in 10^3)
Solar (photospheric) composition (?) – solar spectrum, meteorites, (corona & wind)
AAG21, MB22
Solar age – $\tau_\odot$ – radioactive dating of meteorites (~one part in 10^3)

Input to standard solar models

solar mixture (relative abundances, no normalization)
radiative opacities, equation of state
nuclear reaction rates
mixing processes: convection, microscopic diffusion

Find the 3 free parameters: mixing length (convection), initial helium, initial metallicity that match observables at $\tau_\odot$

SSM framework IS NOT INTENDED to be a full description of the Sun (rotation, extramixing, magn. fields)

Direct contribution from the ChETEC community (and beyond)

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INT WORKSHOP INT-22-82W

Solar Fusion Cross Sections III

July 26, 2022 - July 29, 2022

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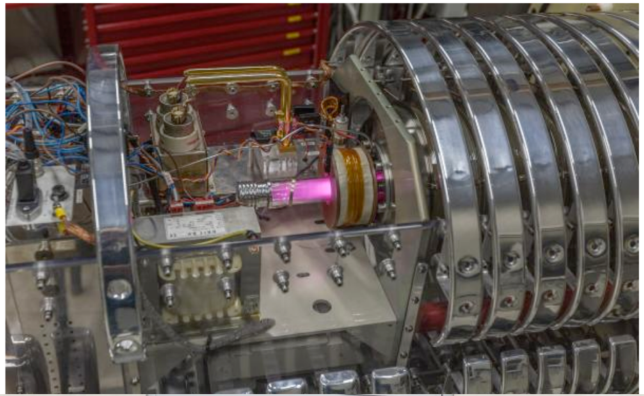

Note to applicants: This wc be held in the David Brow near the UC Berkeley c Berkeley, CA.

WORKING GROUP AI PRESENTATIONS WE

Draft, February 26, 2024.

Solar fusion III: New data and theory for hydrogen-burning stars.

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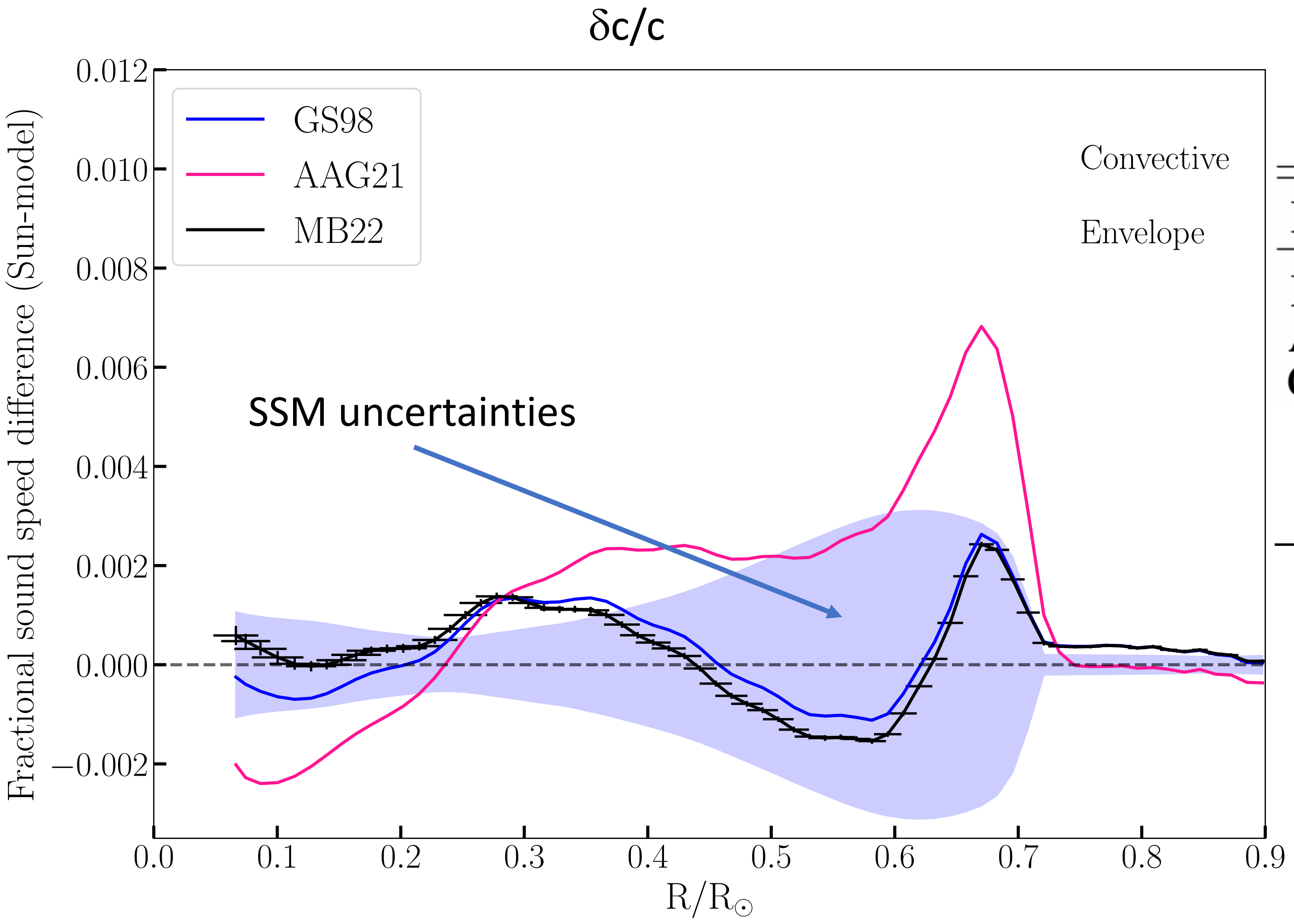
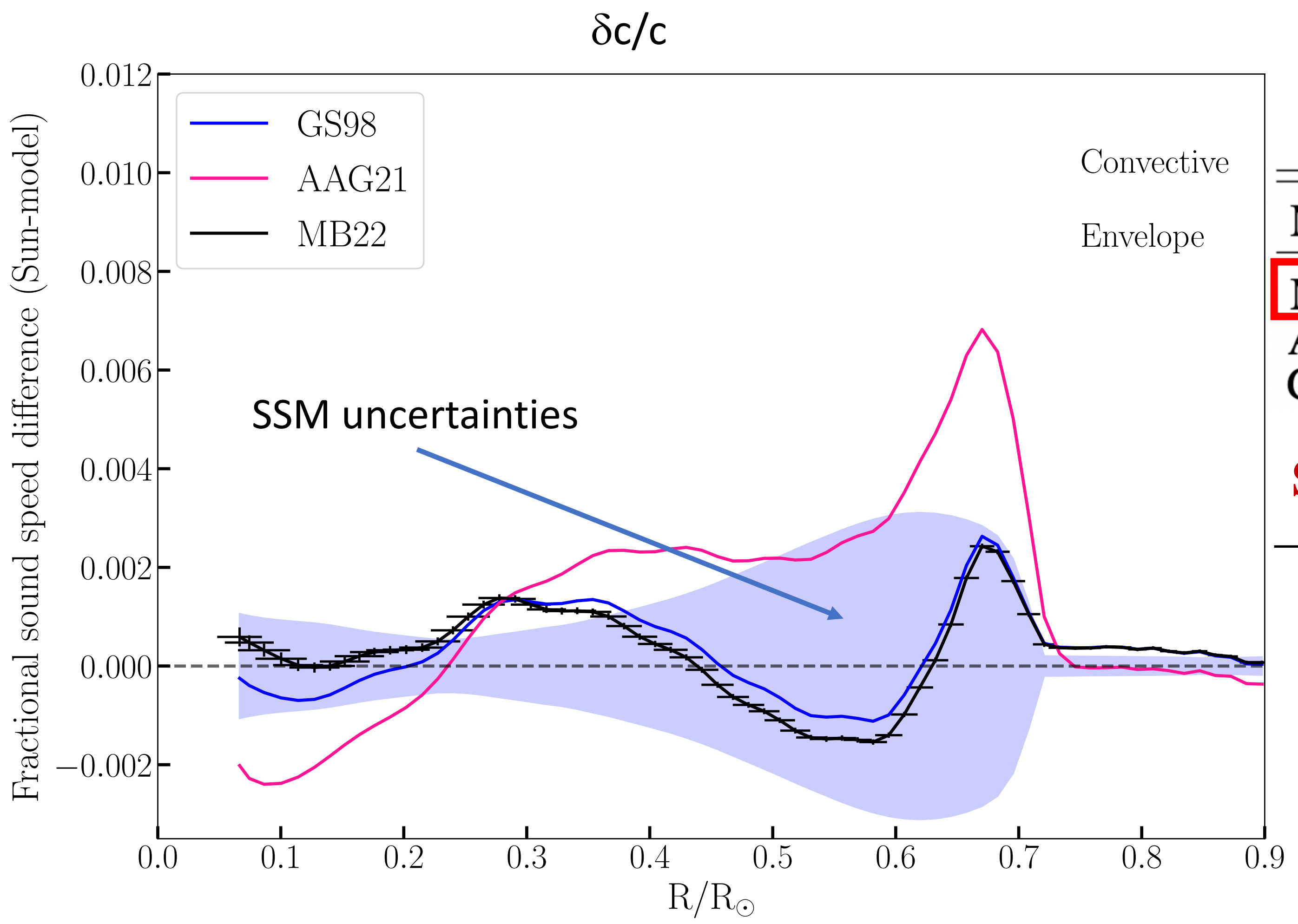
RMP coming (soon)

What helioseismology tells us



Model	$R_{CZ}/R_{\odot}$	Y_S	$\langle \delta c/c \rangle$	Y_{ini}	Z_{ini}
MB22	0.7123	0.2439	0.0010	0.2734	0.0176
AAG21	0.7197	0.2343	0.0027	0.2638	0.0155
GS98	0.7122	0.2425	0.0010	0.2718	0.0187
Solar	**0.713 ±0.001**	**0.2485 ±0.0035**			

What helioseismology tells us



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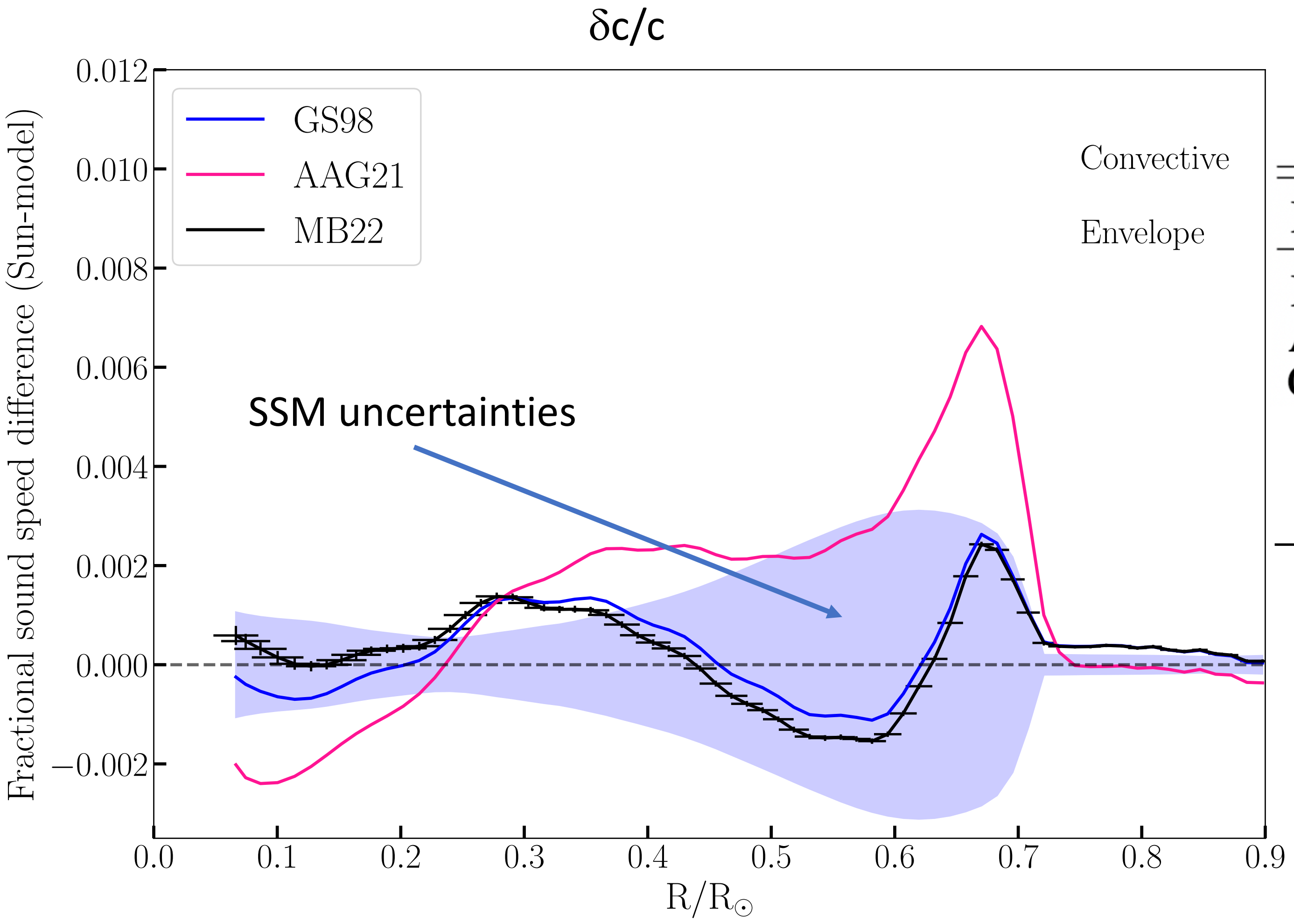

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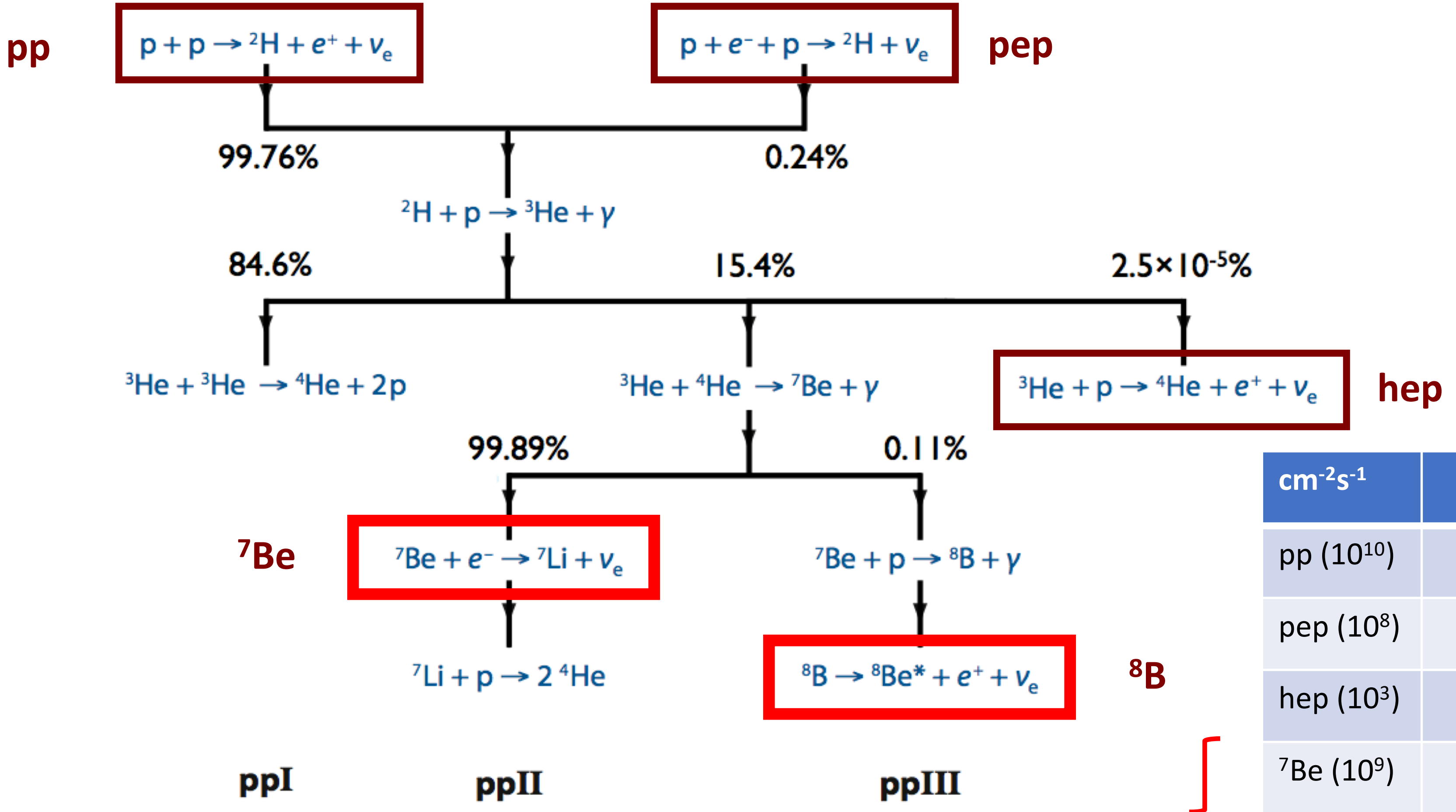
Results sensitive to thermal structure because sound speed scales with $T^{1/2}$

$$\nabla T^4 \propto \kappa$$

→ (composition + radiative opacities)

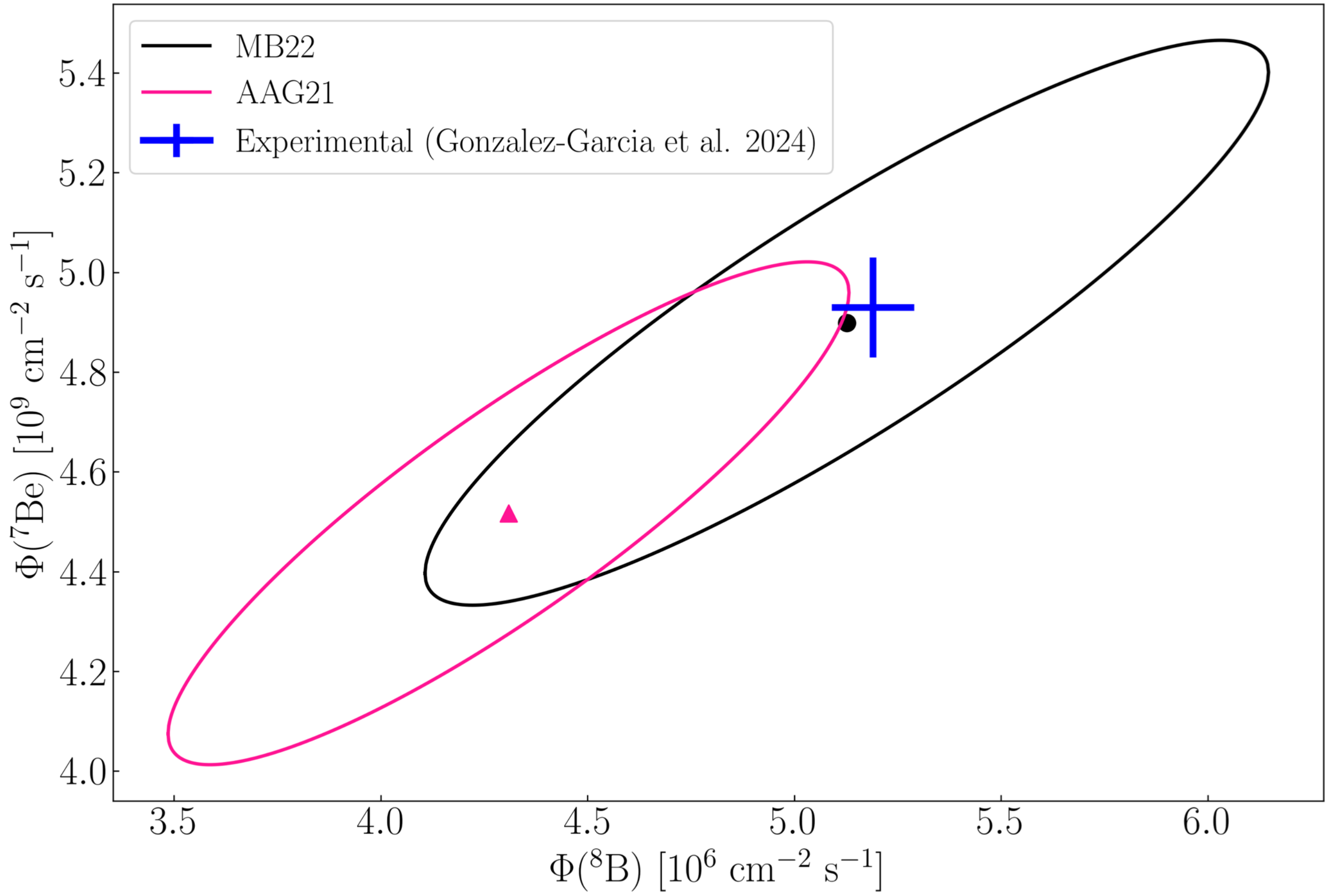
What solar neutrinos tell us



$cm^{-2}s^{-1}$	AAG21	MB22	Sun
pp (10^{10})	6.00 (0.6%)	5.95 (0.6%)	5.94 (0.4%)
pep (10^8)	1.45 (1.1%)	1.42 (1.1%)	1.42 (1.6%)
hep (10^3)	8.16 (30%)	7.92 (30%)	30 (33%)
${}^7Be$ (10^9)	4.52 (7.4%)	4.90 (7.6%)	4.93 (2%)
${}^8B$ (10^6)	4.31 (12.6%)	5.13 (13.1%)	5.20 (1.9%)

"Sun": experimental results from Gonzalez-Garcia et al. 2024

What solar neutrinos tell us



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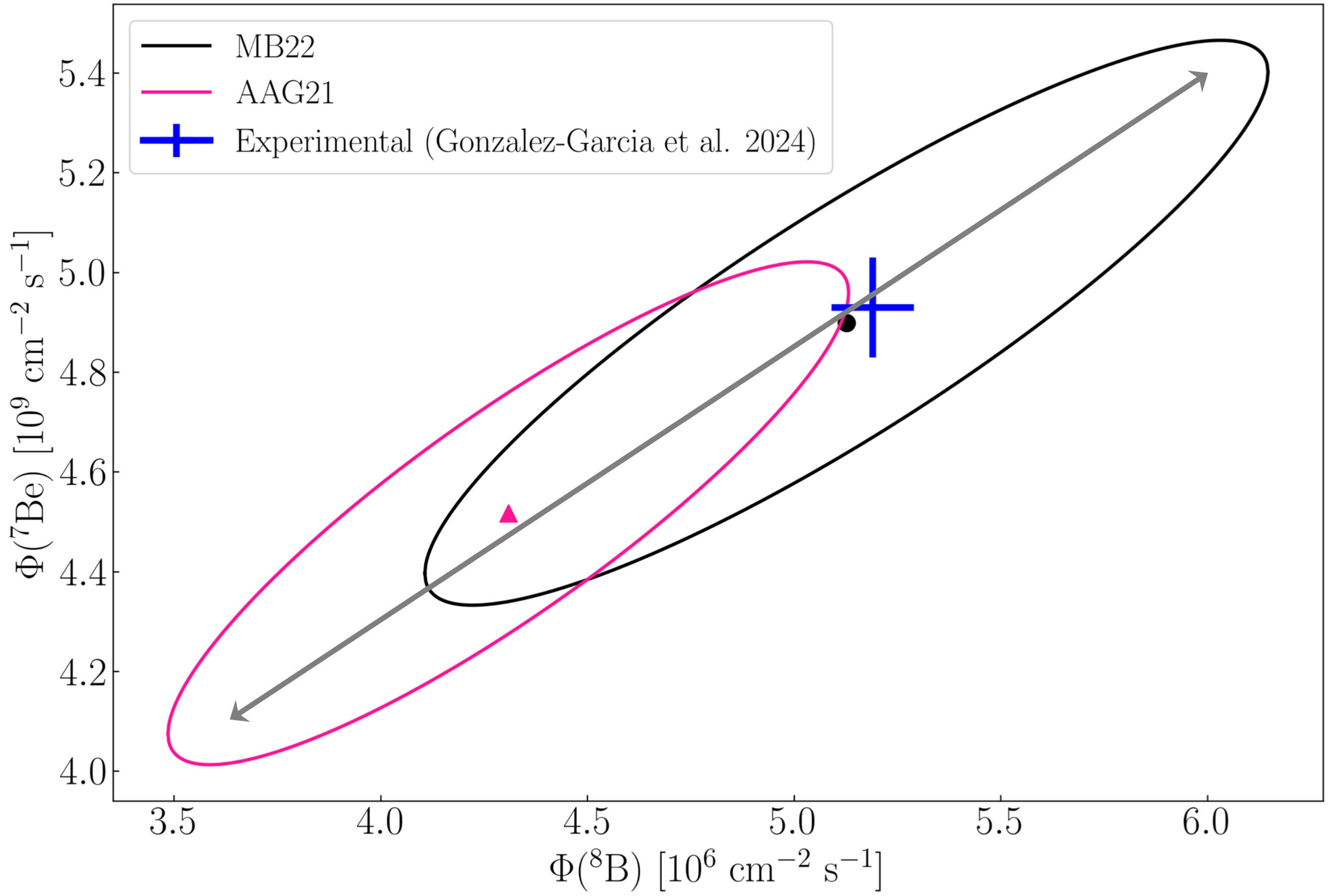
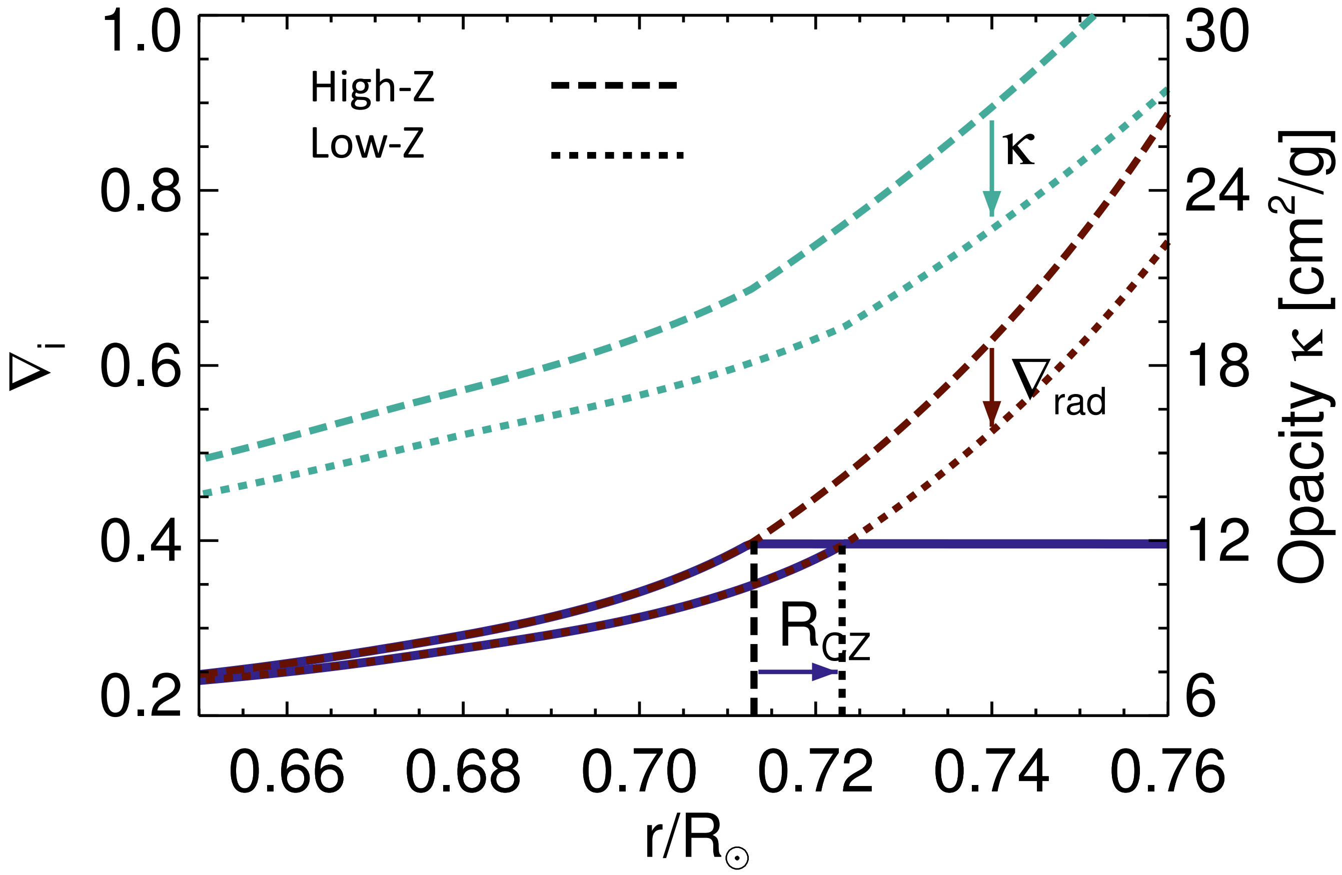
Mostly a temperature sequence with slope determined by nuclear reaction rates



Results sensitive to composition + radiative opacities

Impact of metallicity

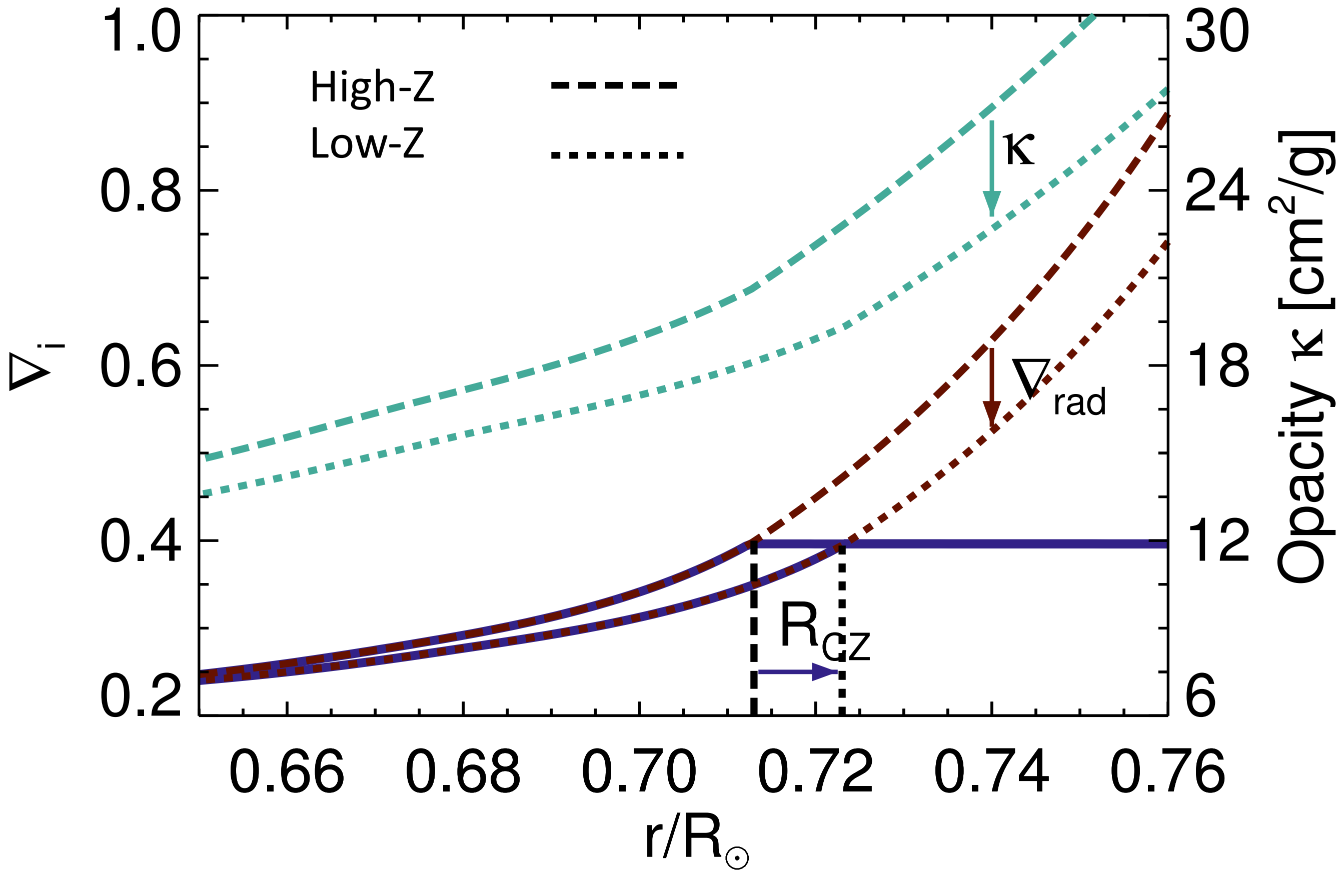


Solar model with low-Z has overall lower opacity

→ flatter temperature profile
→ slightly lower internal temperature

→ affects helioseismology
→ pp-chain neutrinos

Impact of metallicity



Solar model with low-Z has overall lower opacity

→ flatter temperature profile
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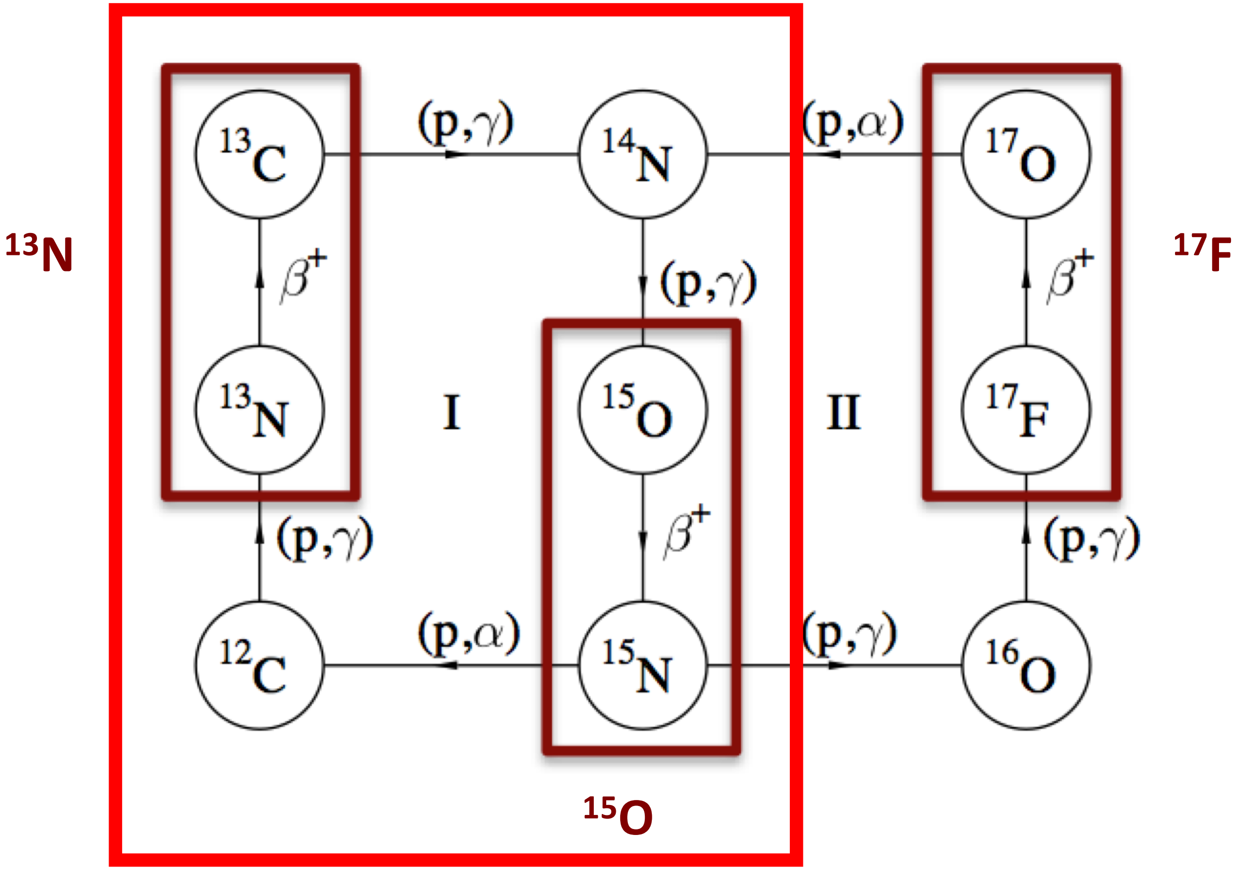
Degeneracy between metals and opacity very difficult to break

Opacities are the worst known fundamental piece of physics in solar/stellar modeling

What solar neutrinos tell us

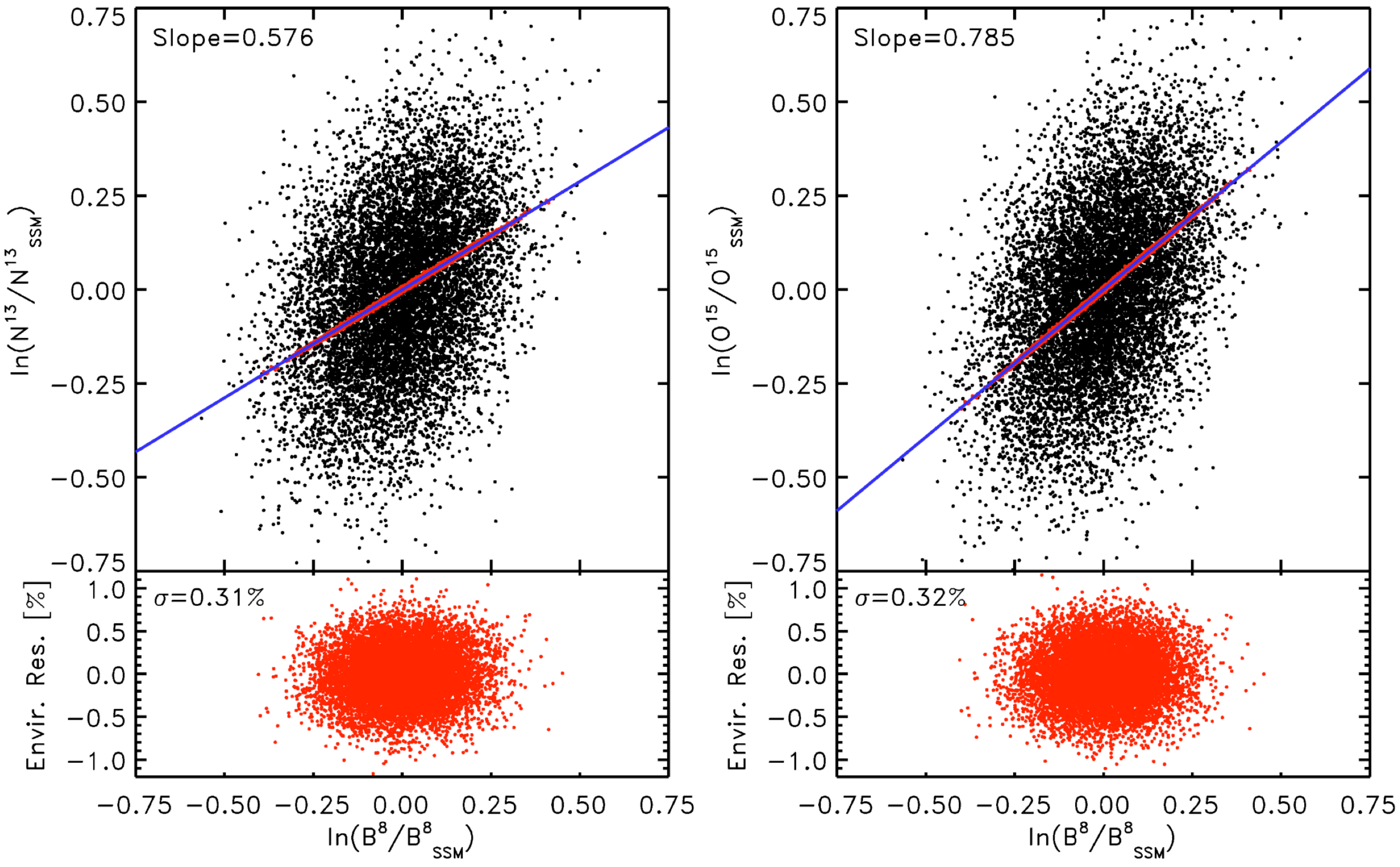


CN-cycle is marginal in the Sun: < 1% energy

This is good!! → sensitive to all changes
(nuclear rates, composition, core temp.)

C+N abundances catalyzes cycle
→ linear dependence on the rate

What solar neutrinos tell us

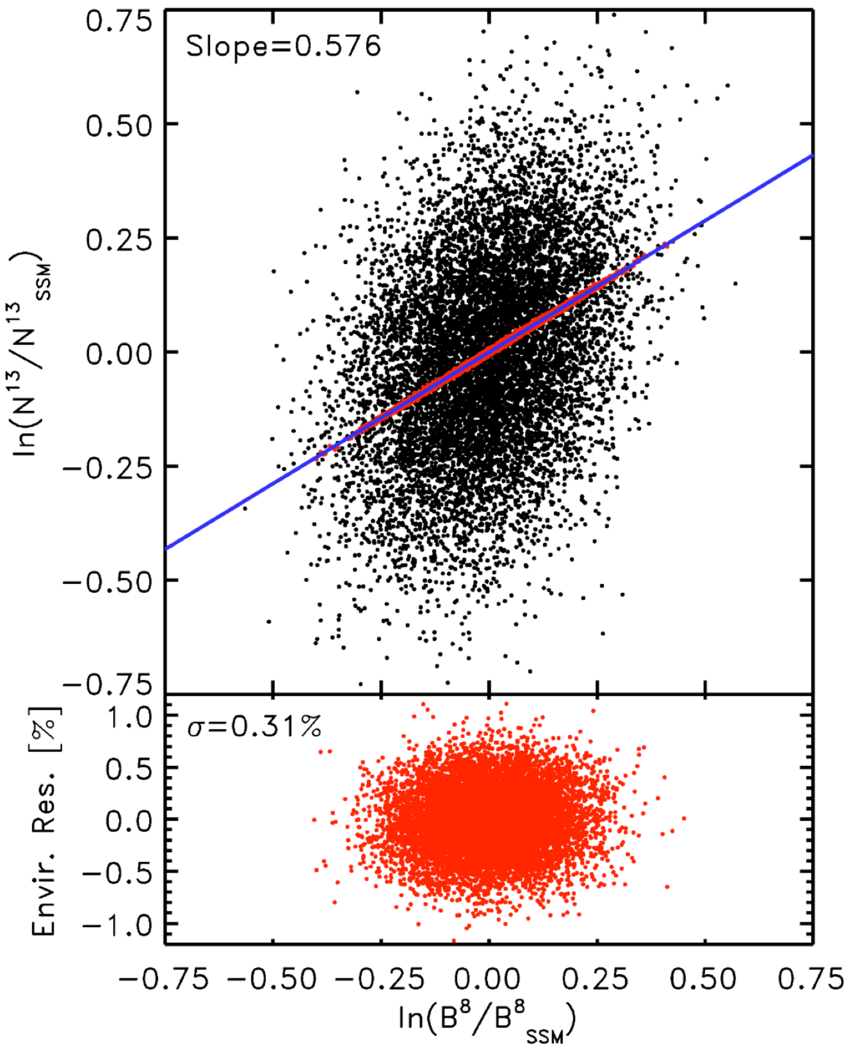


Black: all uncertainties

Red: environmental (core temp.) excluding CNO and nuclear reactions

Nice linear log-log relation between fluxes

What solar neutrinos tell us



Complete relation between ^{13}N and ^{8}B fluxes

$$\frac{\phi(^{13}\mathrm{N})}{\phi(^{13}\mathrm{N})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.576} = x_C^{0.840} x_N^{0.161} D^{0.183}$$

$$\times \left[L_\odot^{0.553} O^{-0.017} A^{0.157}\right]$$

$$\times \left[\mathrm{S}_{11}^{-0.639}\ \mathrm{S}_{33}^{0.264}\ \mathrm{S}_{34}^{-0.526}\ \mathrm{S}_{17}^{-0.576}\ \mathrm{S}_{e7}^{0.576}\ \mathrm{S}_{114}^{0.743}\right]$$

$$\times \left[x_{\mathrm{O}}^{0.002} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.004} x_{\mathrm{Si}}^{0.0} x_{\mathrm{S}}^{0.0} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.005}\right]$$

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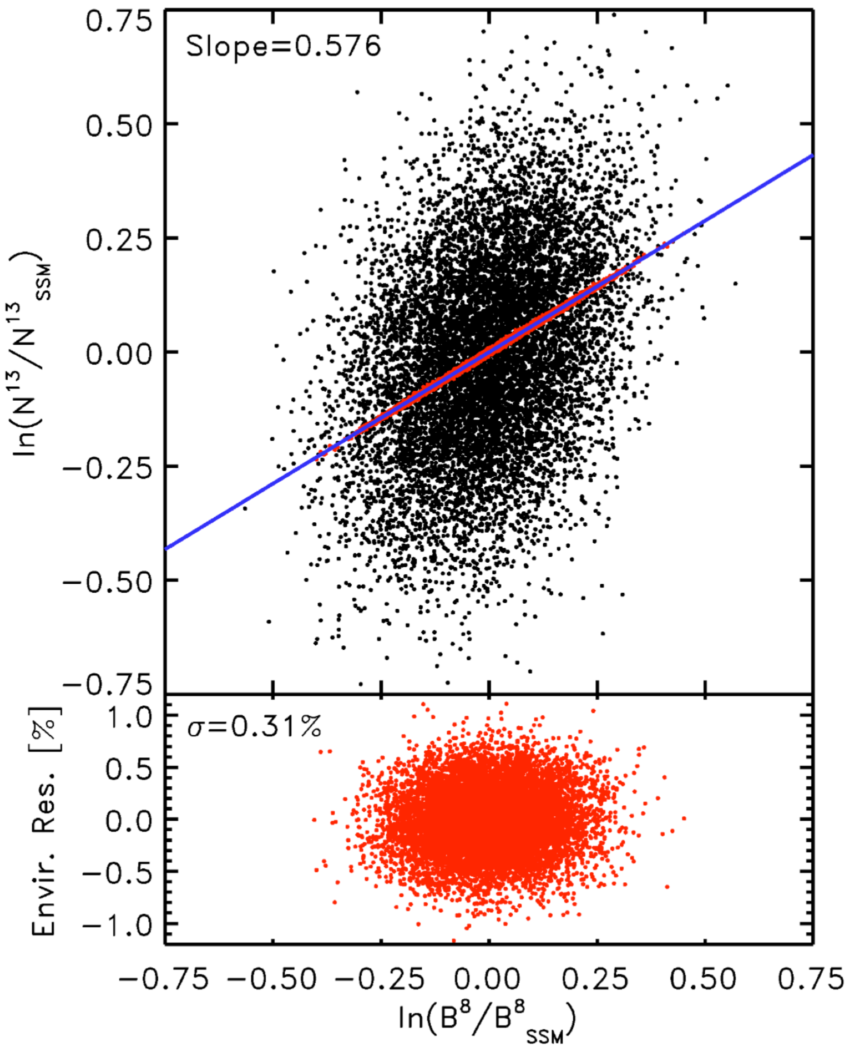

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What solar neutrinos tell us

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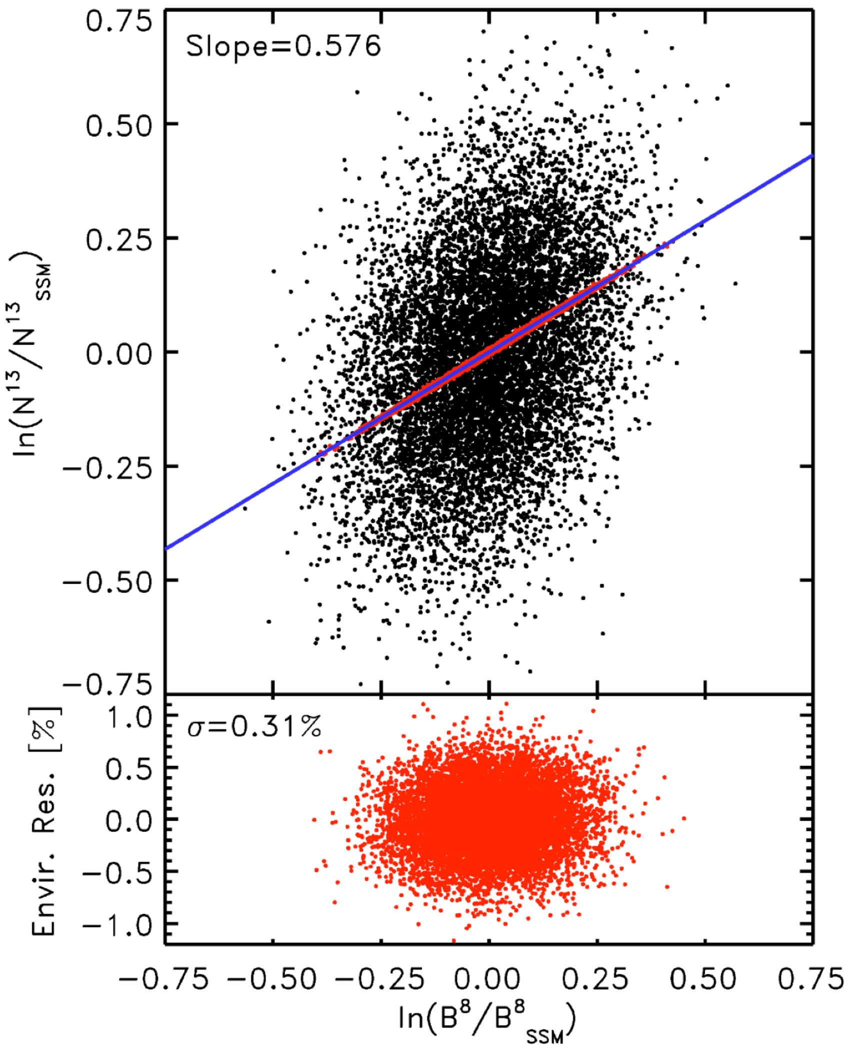

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$$\frac{\phi(^{13}N)}{\phi(^{13}N)^{\mathrm{SSM}}} \simeq \left(\frac{\phi(^{8}B)}{\phi(^{8}B)^{\mathrm{SSM}}}\right)^{0.576} (x_{C+N})\left[1 \pm 0.075(\mathrm{nuc}) \pm 0.03(\mathrm{D})\right]$$

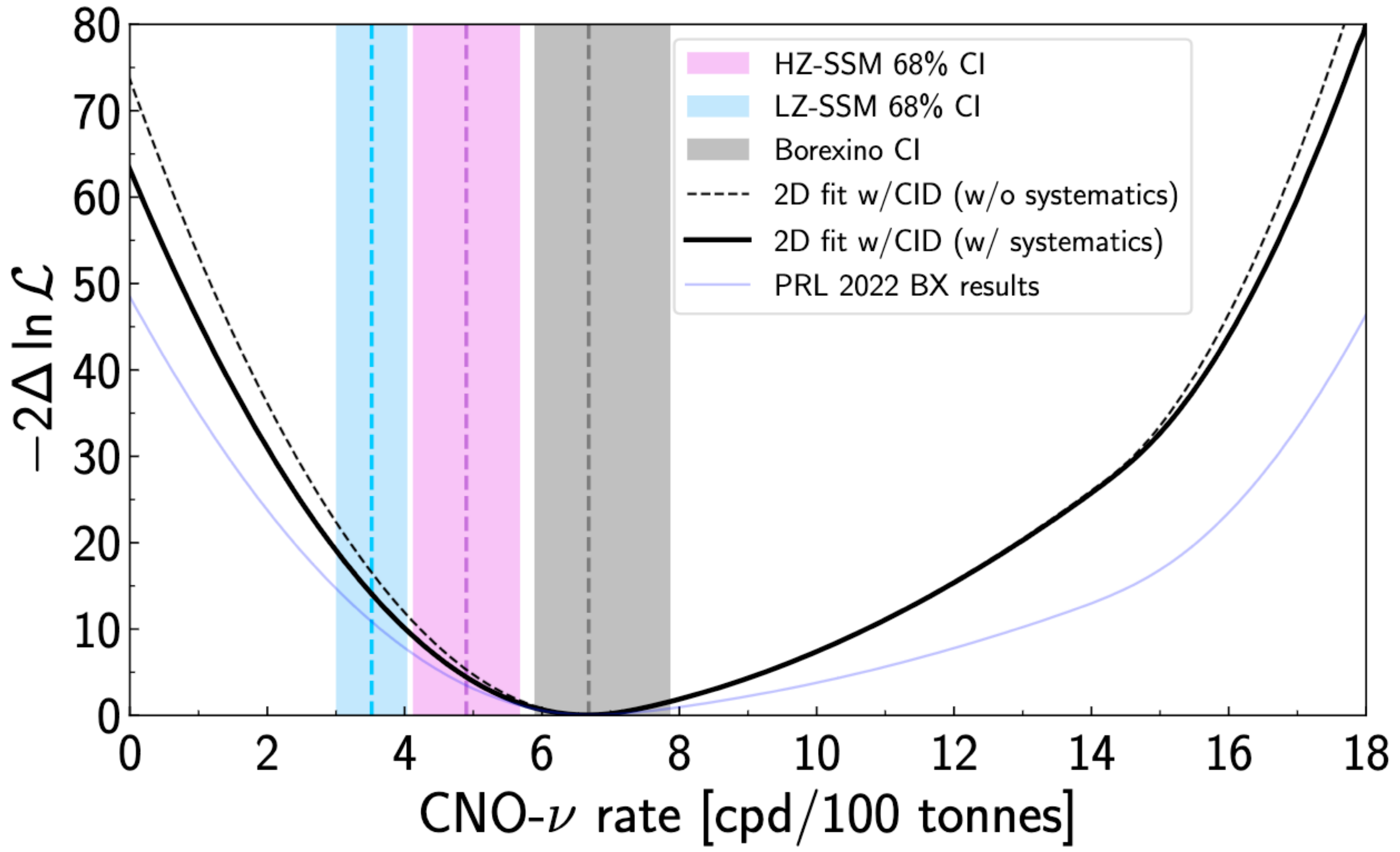
A measurement of CN fluxes leads to determination of solar core C+N

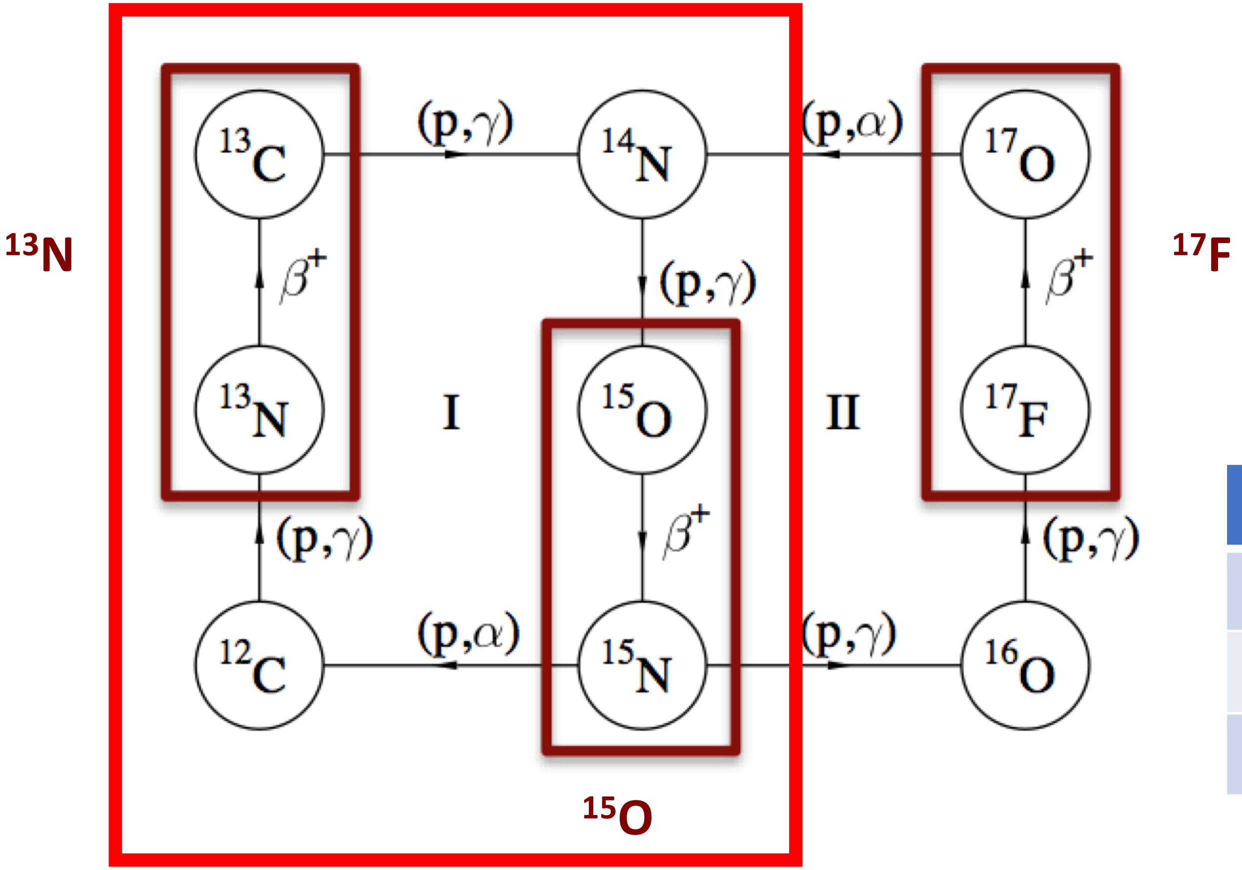
^{14}N(p,γ)^{15}O – 8.4% error → 6% contribution
^{3}He(^{4}He,γ)^{7}Be – 5% error → 3% contribution

after SFIII

What solar neutrinos tell us

Borexino measurement of $^{13}N+^{15}O$ fluxes (Borexino coll. 2022, 2023)





CN-cycle is marginal in the Sun: < 1% energy

This is good!! → sensitive to all changes
(nuclear rates, composition, core temp.)

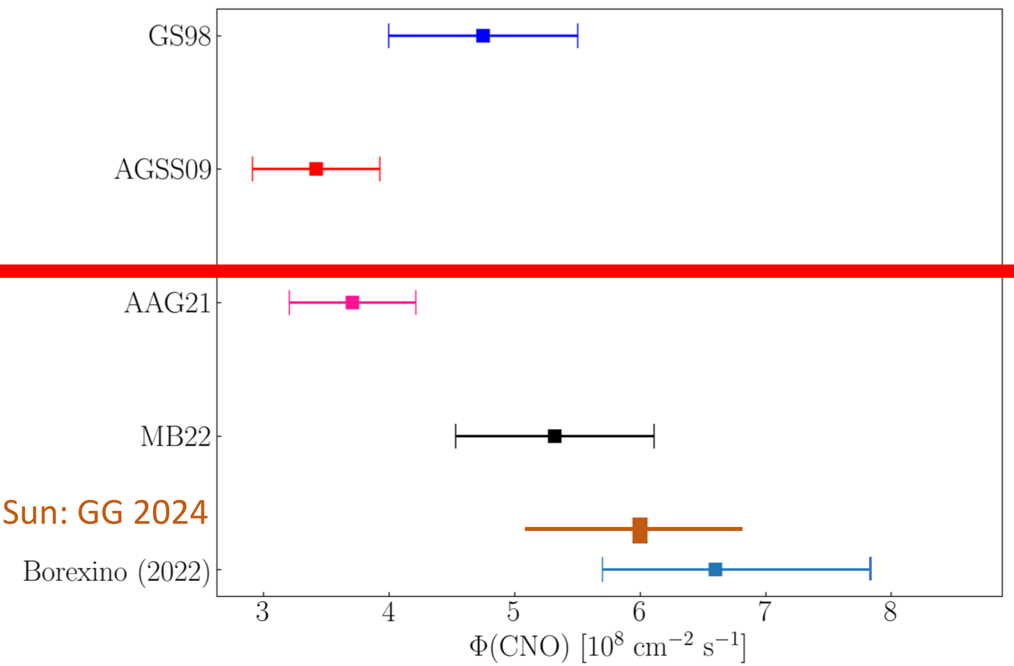
C+N abundances catalyzes cycle
→ linear dependence on the rate

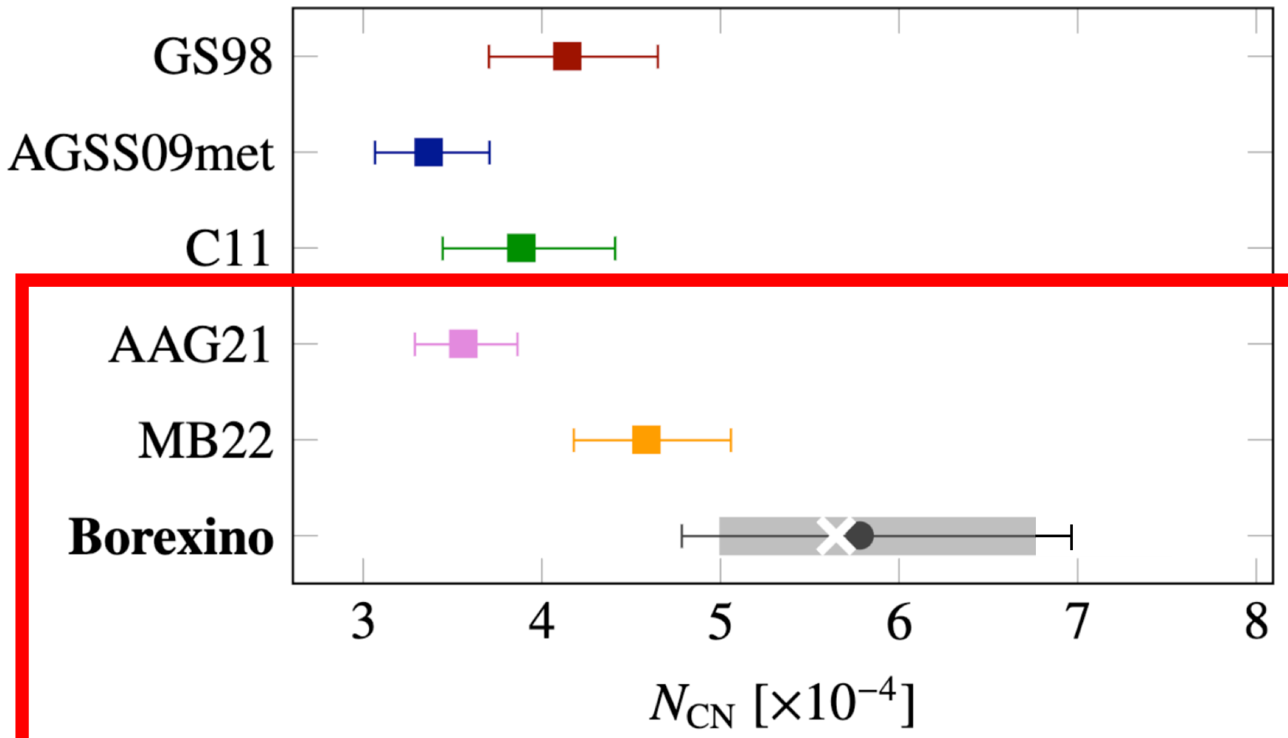
$cm^{-2}s^{-1}$	AAG21	MB22	Sun
^{13}N (10^8)	2.21 (13%)	3.12 (15%)	3.48 (14%)
^{15}O (10^8)	1.58 (16%)	2.32 (17%)	2.53 (14%)
^{17}F (10^6)	3.40 (16%)	4.74 (16%)	----

"Sun": Gonzalez-Garcia et al. 2024

What solar neutrinos tell us

Borexino measurement C+N abundance in the solar core (Borexino coll. 2022, 2023)





CN neutrinos break the degeneracy between composition and opacity

Favor large CN abundance

However, back to helioseismology

Propagation of sound waves carry information about composition through adiabatic index:

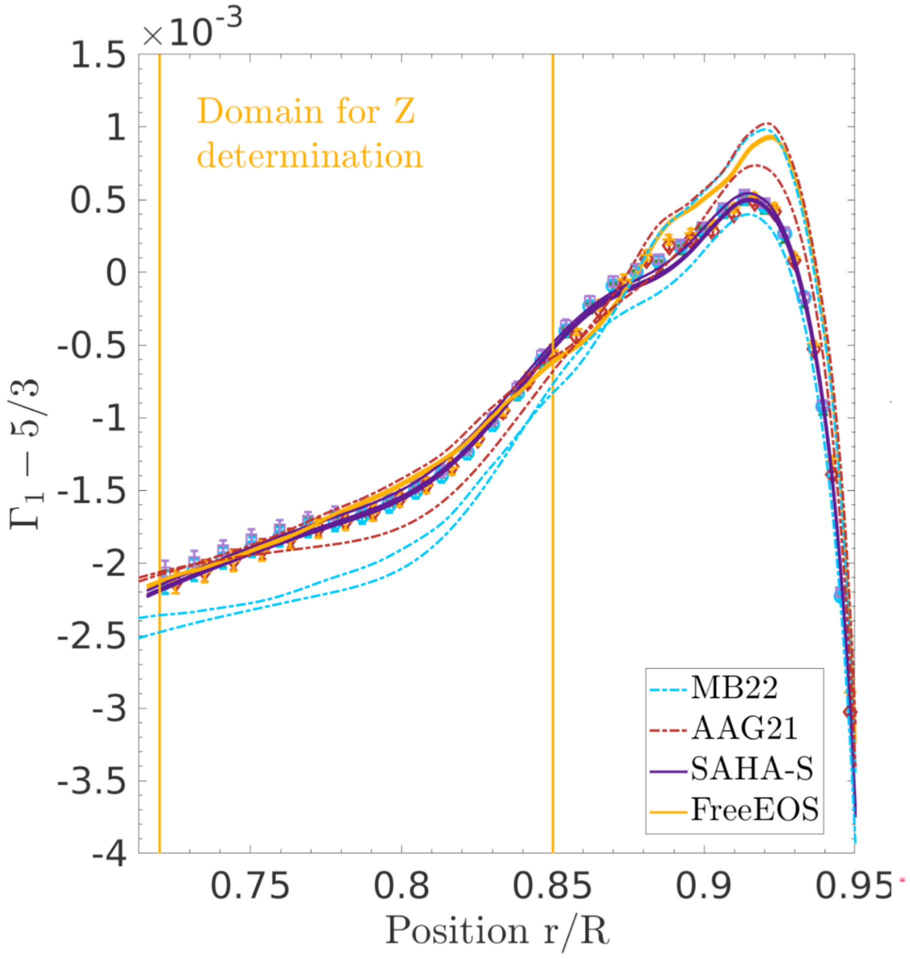
$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$ = 5/3 (for fully ionized gas) < 5/3 in partial ionization regions

It can be determined through inversion of solar oscillations and compared to solar models.

Only sensitive to total Z (not individual elements)

Results are degenerate with equation of state

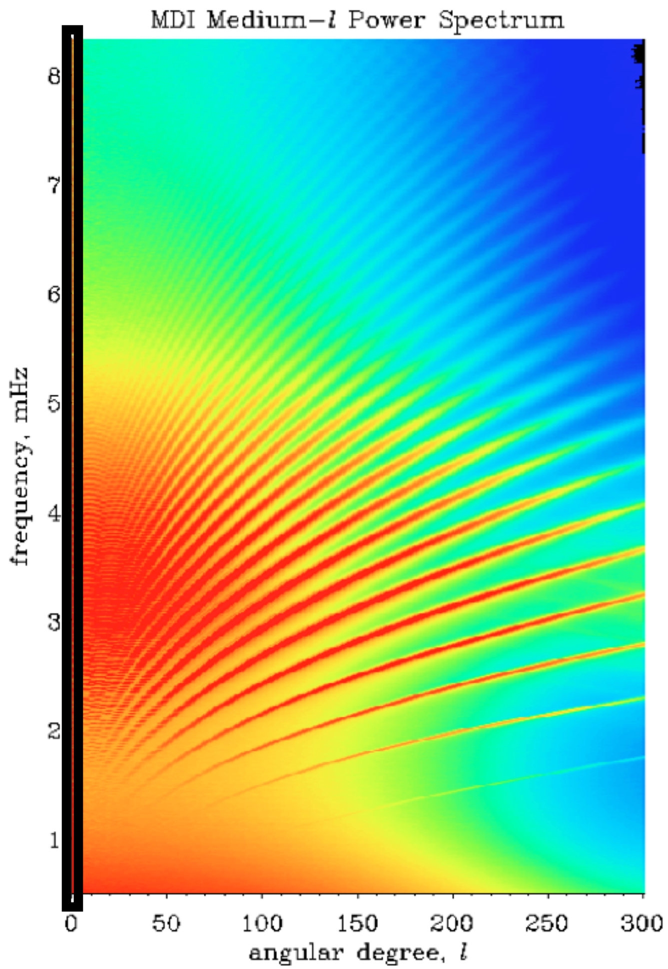
Results indicate agreement with AAG21 rather than MB22

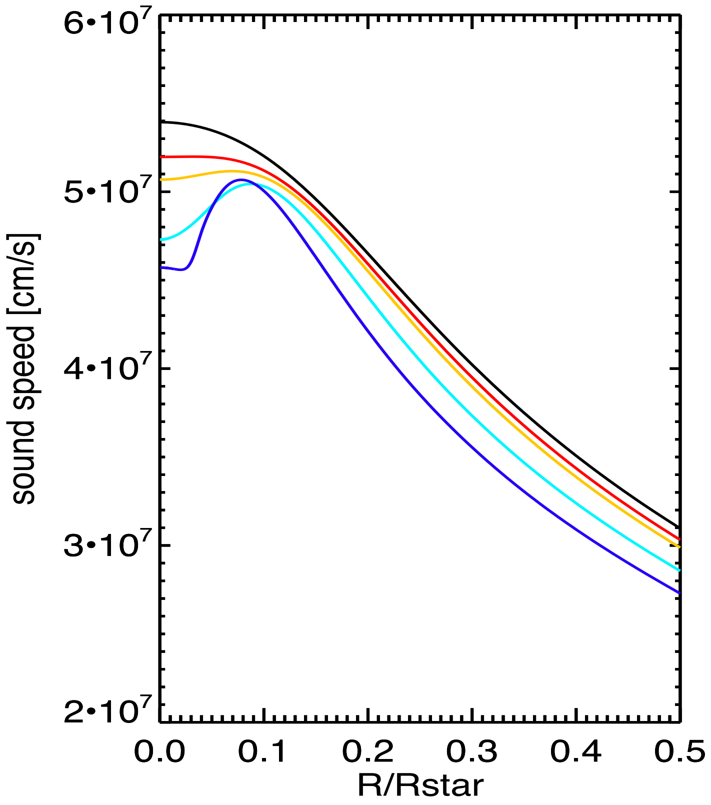


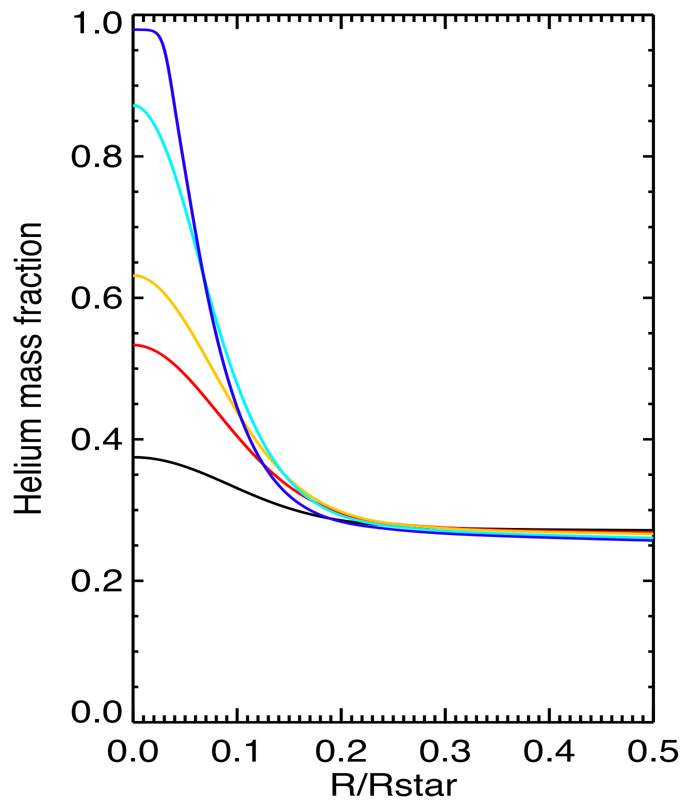
Cancellation effects limit modes to l=0, 1, 2, (3) for other stars (e.g. Kepler, TESS, PLATO)

$$\nu_{n,\ell} - \nu_{n-1,\ell+2} \propto \frac{1}{4\pi\nu_{n,\ell}} \int_0^R \frac{dc}{dr}\frac{dr}{r}$$

→ age diagnostics



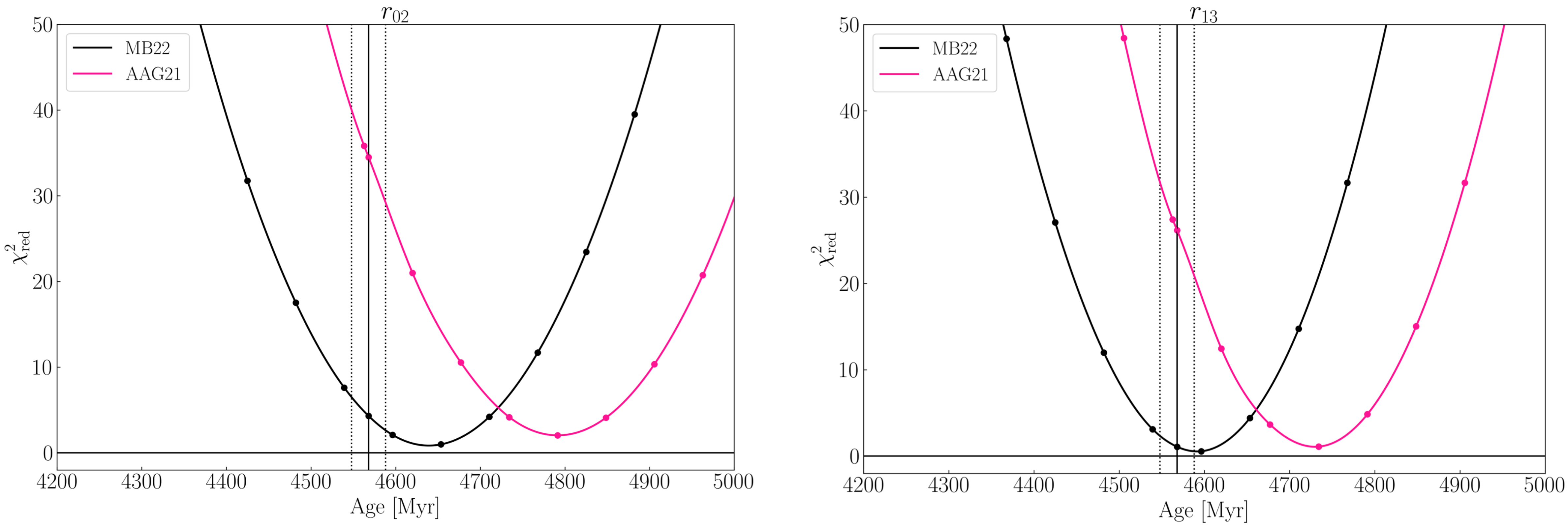




The Sun from afar

No independent age for other stars

$$\nu_{n,\ell} - \nu_{n-1,\ell+2} \propto \frac{1}{4\pi\nu_{n,\ell}} \int_0^R \frac{dc}{dr}\frac{dr}{r}$$



Composition introduces a systematic effect on age determination (assuming solar mass is perfectly known) up to 250Myr (5%)

The Sun from afar

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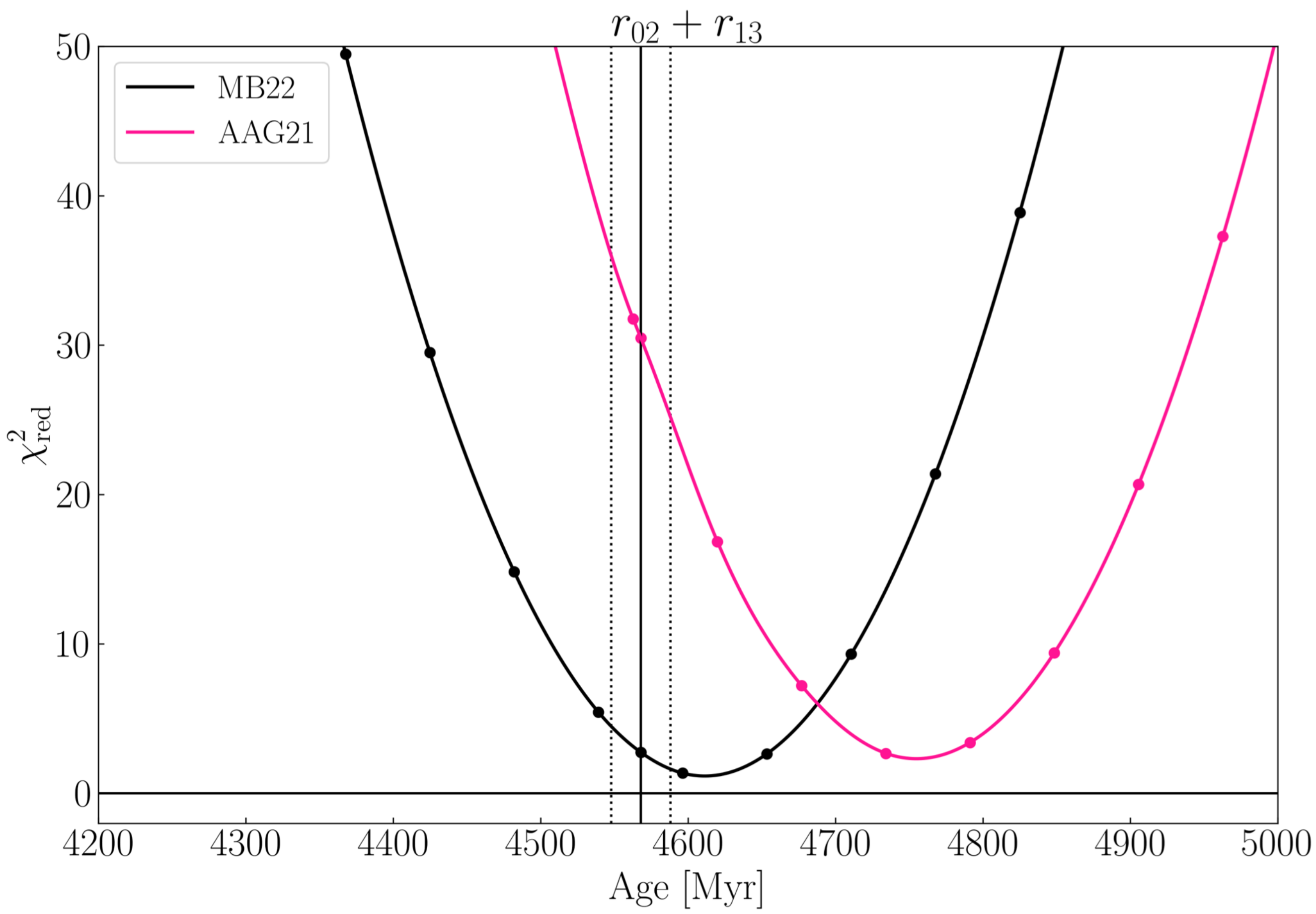


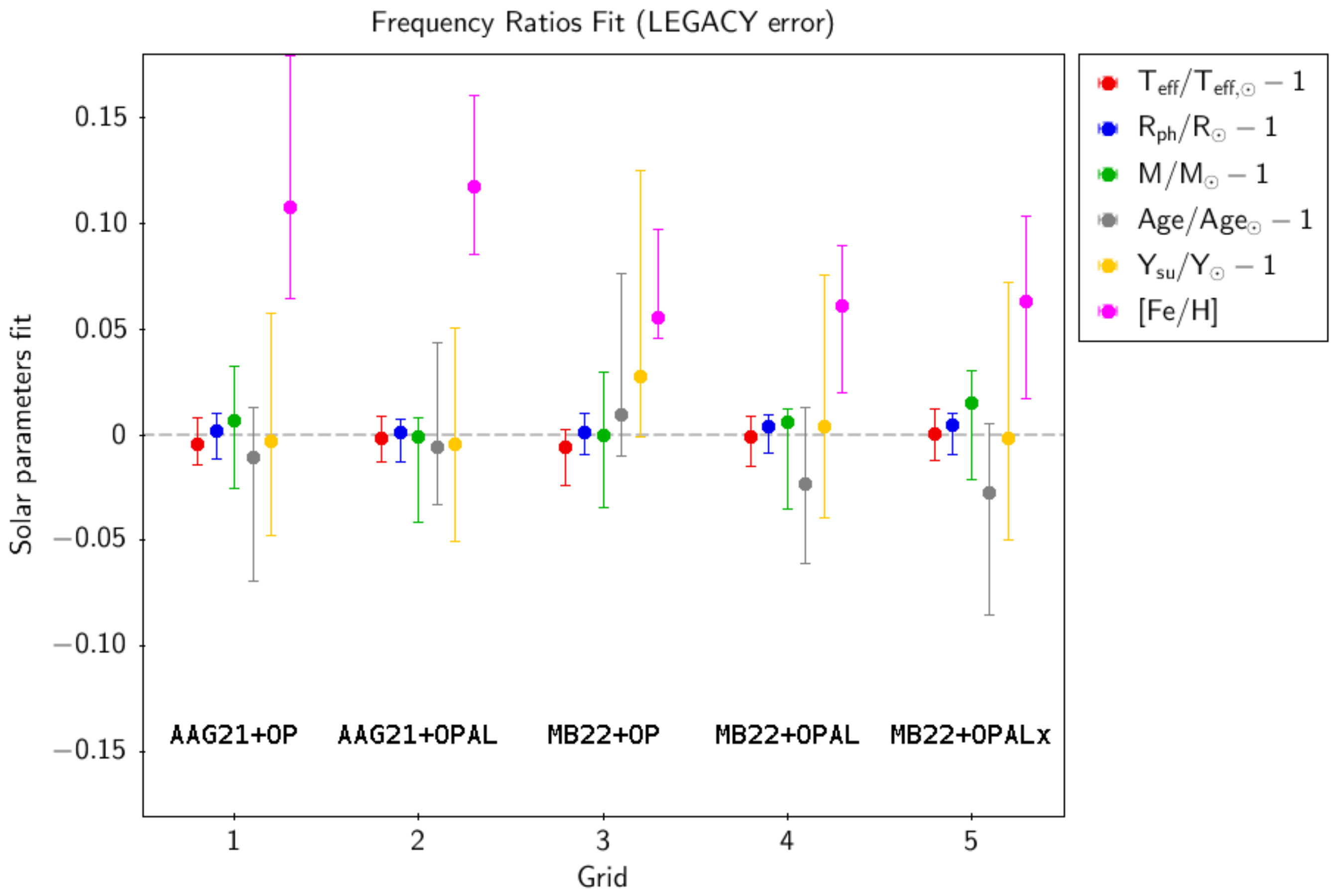
	Solar age (Gyr)	χ^2 (33 dofs)
Sun	**4.568 ± 0.020**	---
AAG21	4.755 ± 0.034	76.6
MB22	4.611 ± 0.032	38.4

Composition introduces a systematic effect on age determination (assuming solar mass is perfectly known) up to 250Myr (5%)

The Sun as a star

No independent mass, radius, or age. Typical spectroscopic errors for temperature and metallicity [Fe/H]

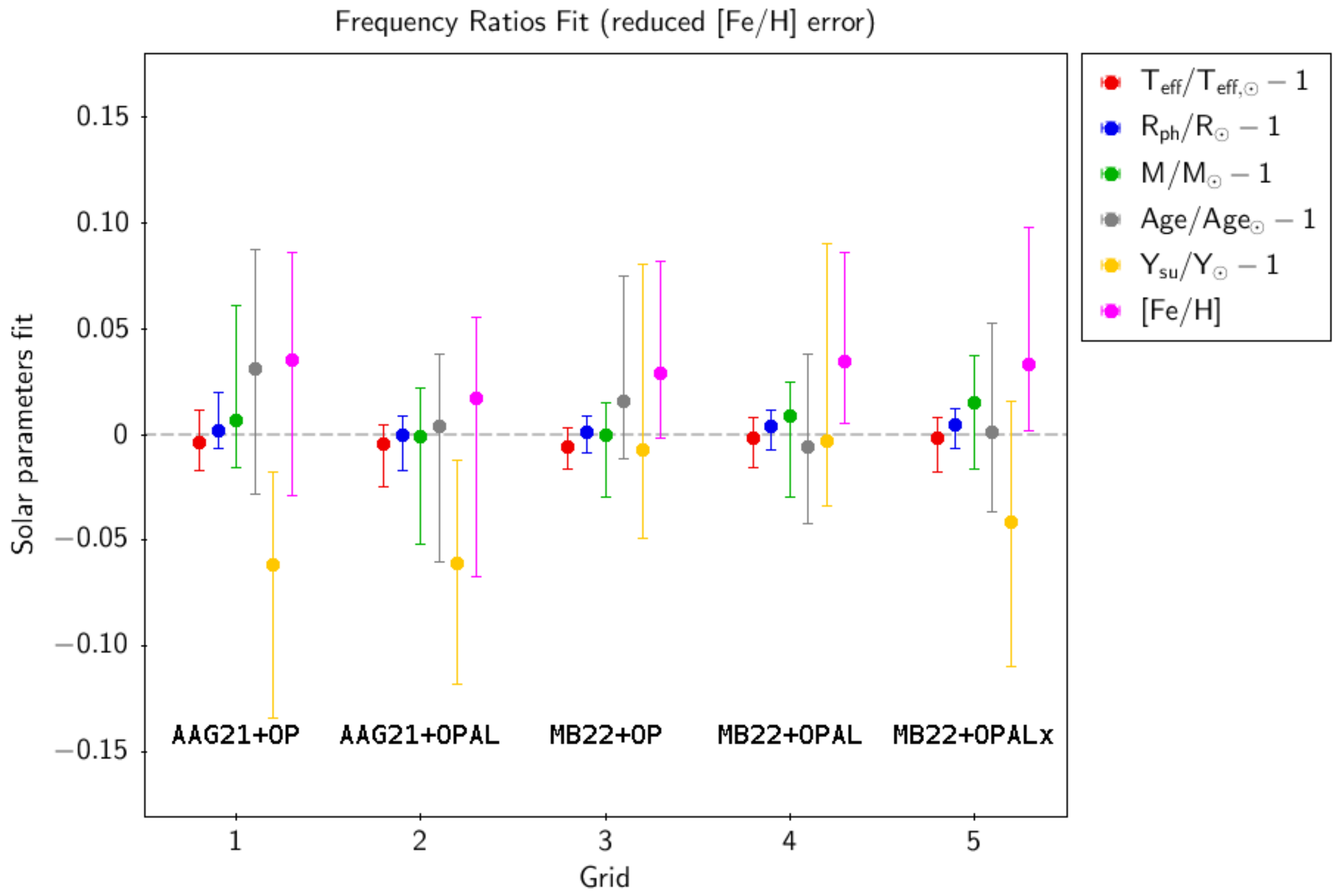
Asteroseismology favors higher metallicity, seen here as a “non-solar” solar abundance



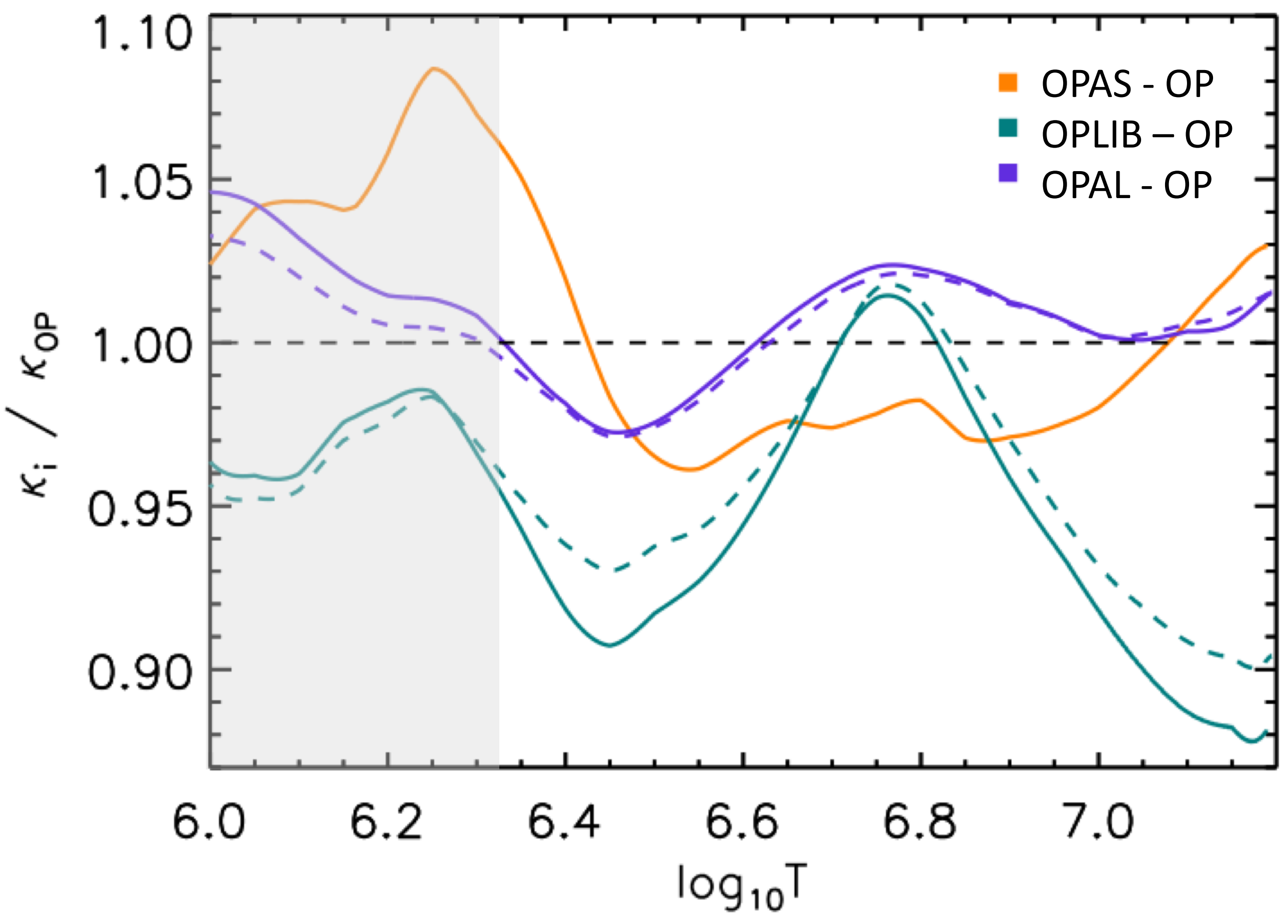
The Sun as a star

No independent mass, radius, or age. Typical spectroscopic errors for temperature and metallicity [Fe/H]

Forcing [Fe/H] to match by reducing its uncertainty, problems start to appear in helium, age



Solar (stellar) radiative opacities



Dashed – GS98

Solid – AGSS09

Solar (stellar) opacities

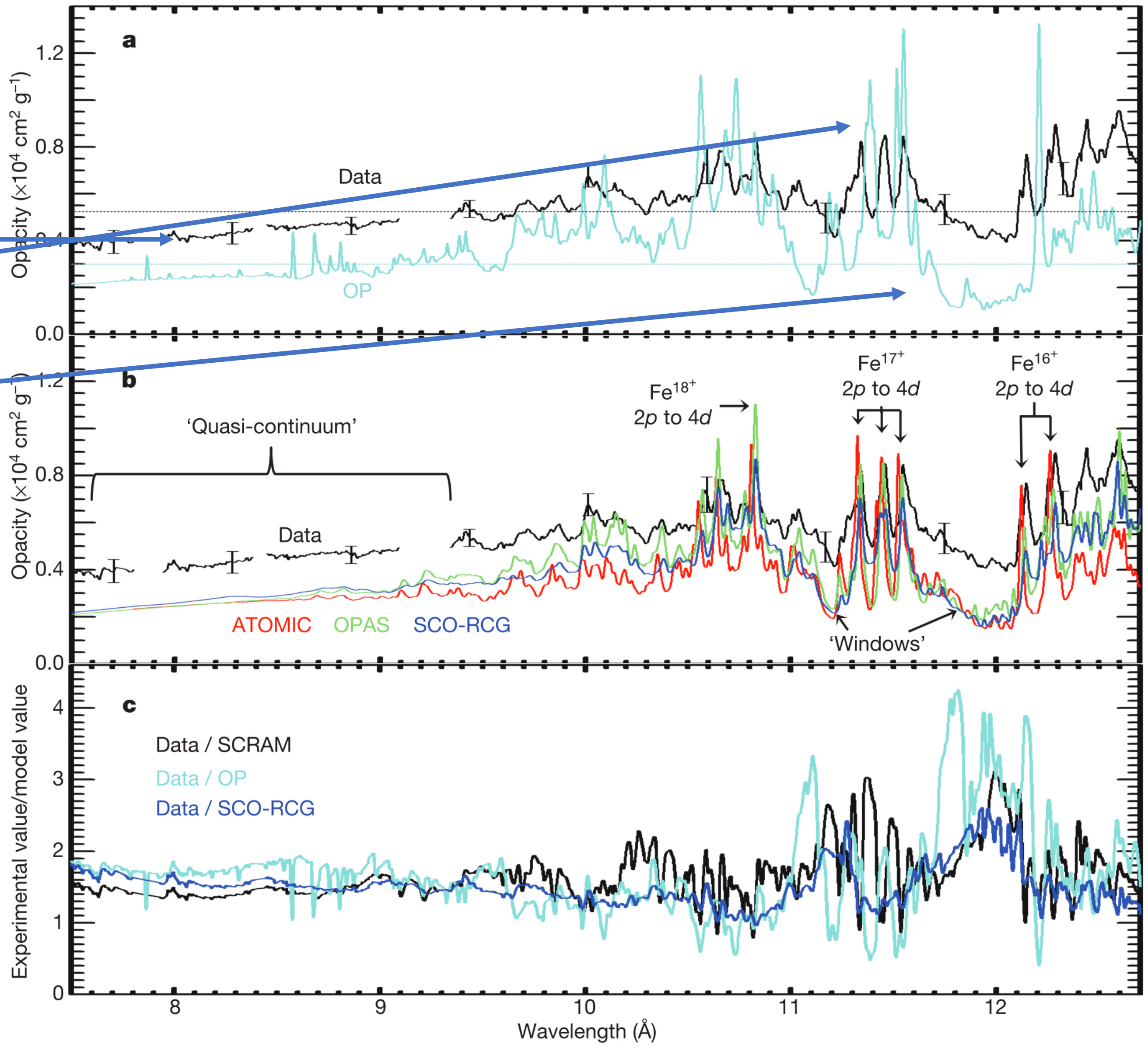
Bailey et al. 2015

Calculations have:

1) Lower quasicontinuum

2) Narrower lines

3) Deeper opacity windows



Experimental hint of higher opacity than theoretical calculations predict
but situation unclear because of large differences in continuum

Summary, so far

Constraints to compute solar models – composition is the big uncertainty:

- High solar metallicity is favored by (degenerate with opacity):
  - sound speed, surface helium, depth of convective envelope
  - pp-chain solar neutrinos
- by CNO neutrinos (independent of opacity)
- but lower solar metallicity is favored by (degenerate with equation of state):
  - adiabatic index

Dominant uncertainties in models:

- radiative opacities
- nuclear reactions (esp. ^{14}N+p, then ^{3}He+^{4}He)
- equation of state

Foundation science – only possible in the Sun

For solar-like stars:

- solar metallicity is reference value (see Camilla's talk)
- systematic offsets in age (5%) and other parameters (not too large but PLATO aims at < 10% age error)
- radiative opacities