GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

The need for accurate nuclear cross sections for solar (and stellar) modeling

Marciana 2025 – Lepton Interactions with Nucleons & Nuclei

Marciana Marina – June 22nd-27th - 2025

A. Serenelli

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

The Sun as a cornerstone for astrophysics

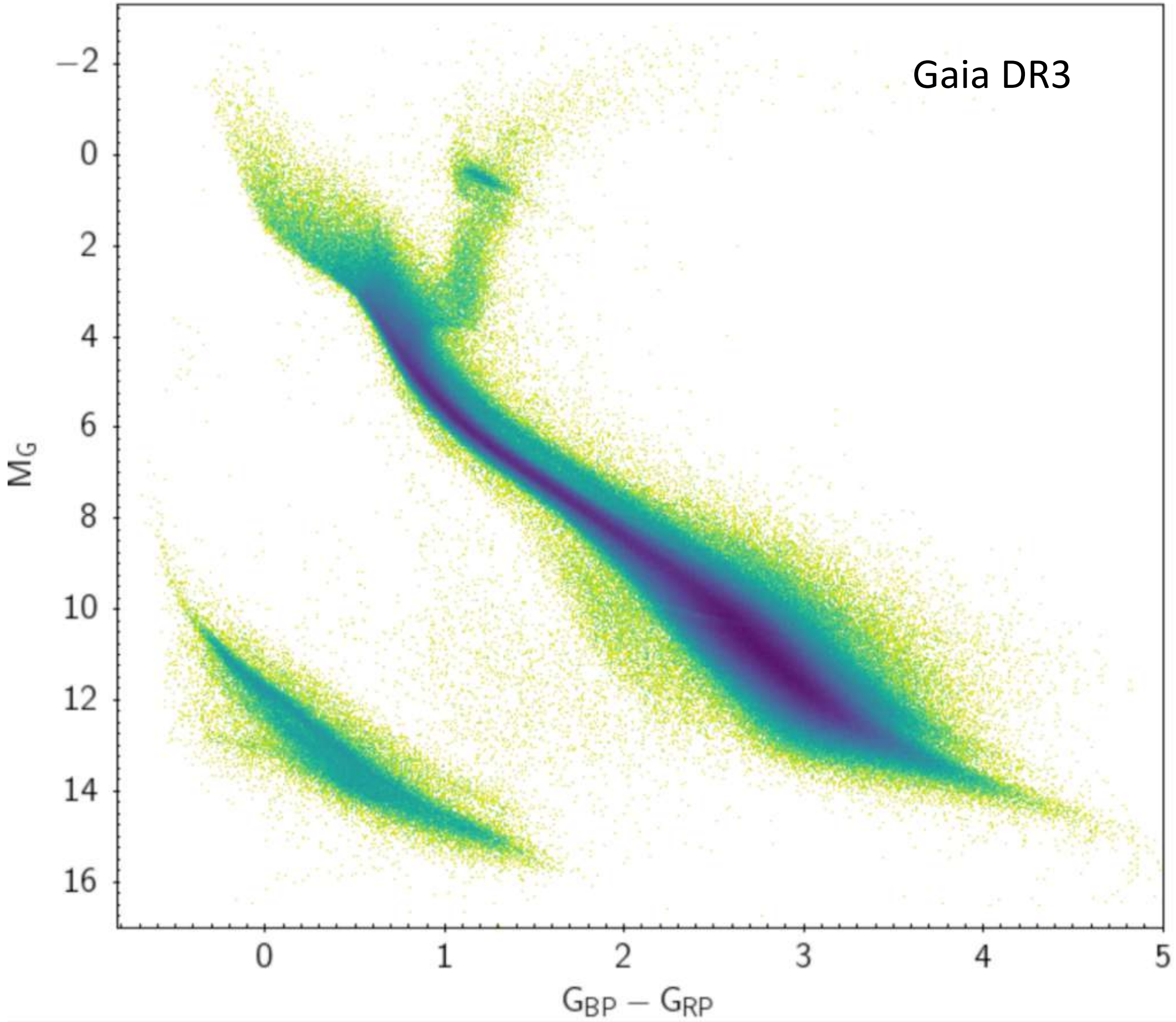
(Which?) Solar composition

- a view from helioseismology
- a view from solar neutrinos
- the need for accurate & precise nuclear cross sections

Solar-like stars

- convective cores in 1.1 – 1.5 $M_\odot$ stars in the context of asteroseismic missions (PLATO)
- the need for accurate & precise 14N+p cross section

Why the Sun? It is “foundation” science



~10^9 individual stars with measurements

colors, temperature, luminosity, (composition)

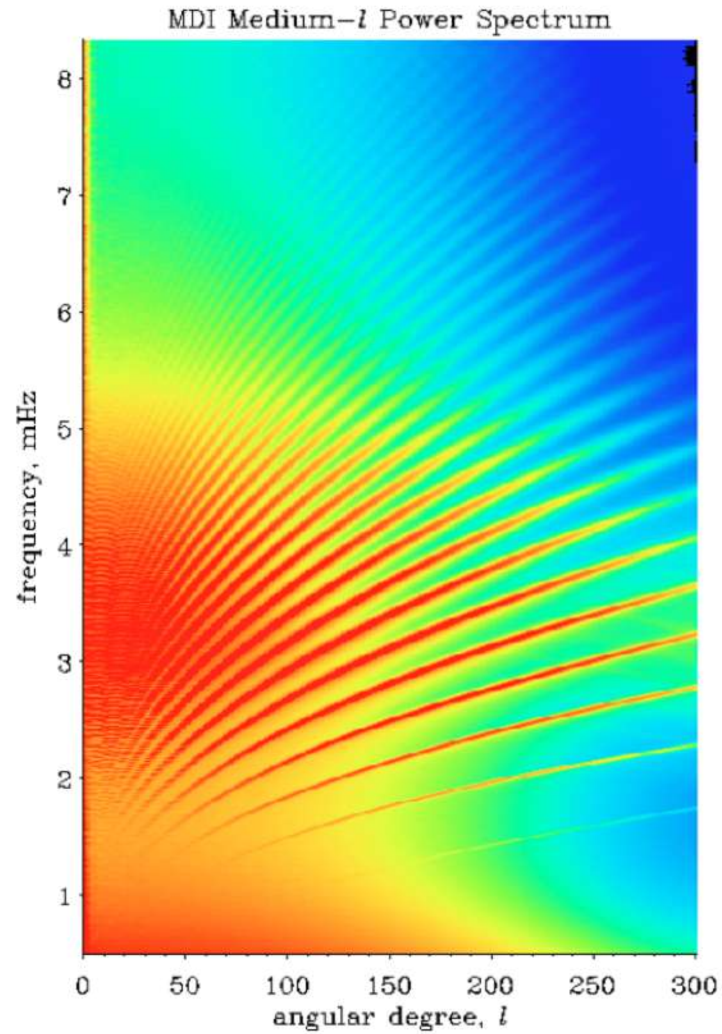
~ 10^3 with accurate, precise, (model) independent mass determinations

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



Helioseismology

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

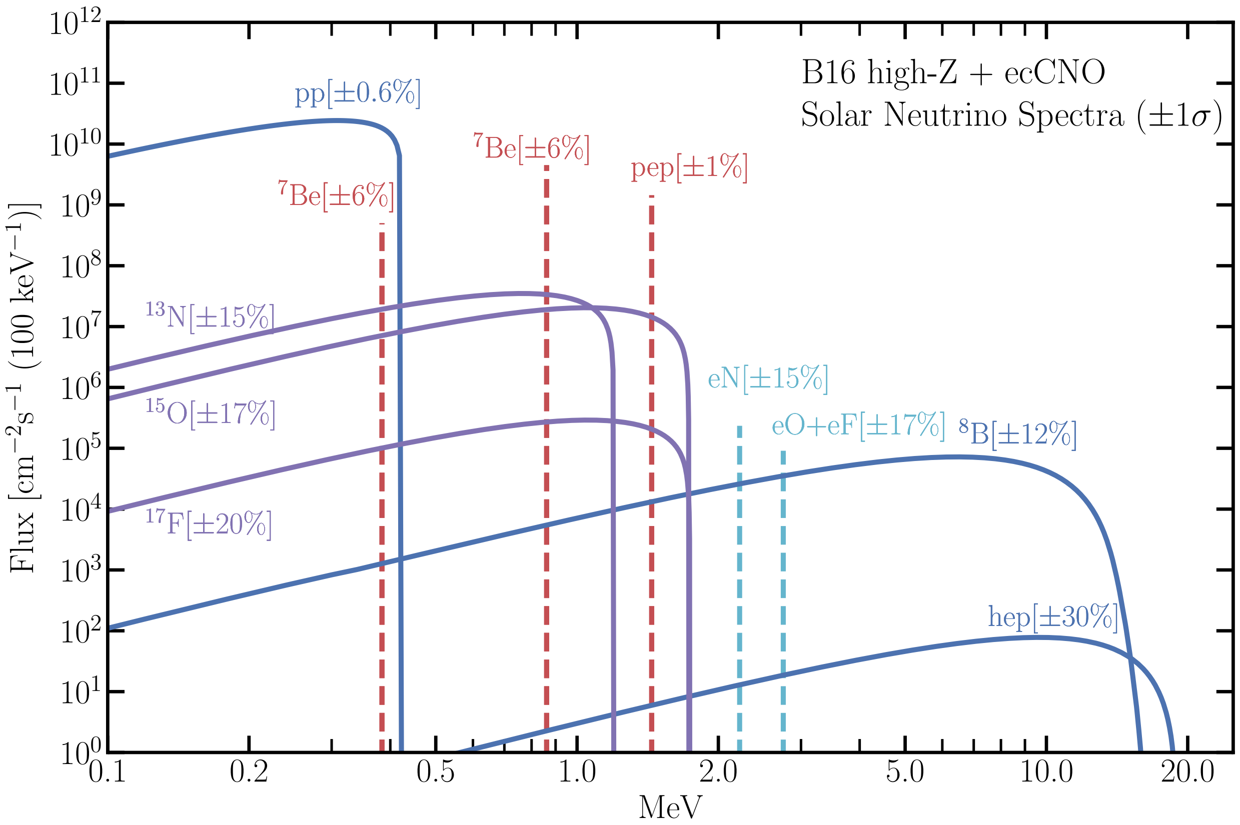
→ global quantities:
surface helium, depth of convective envelope

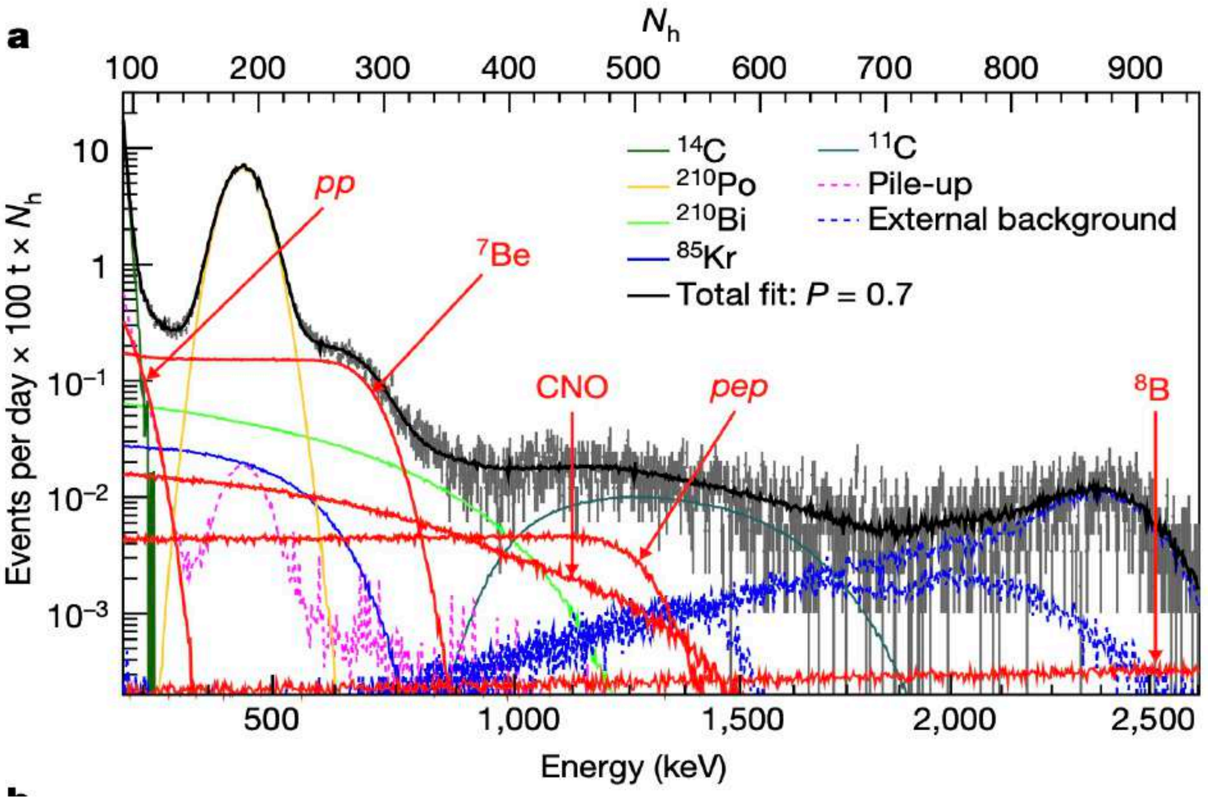
→ beyond standard solar models:
internal rotation profile (depth and latitude)

Allows testing theory of stellar evolution by looking at internal structure

Why the Sun? It is "foundation" science

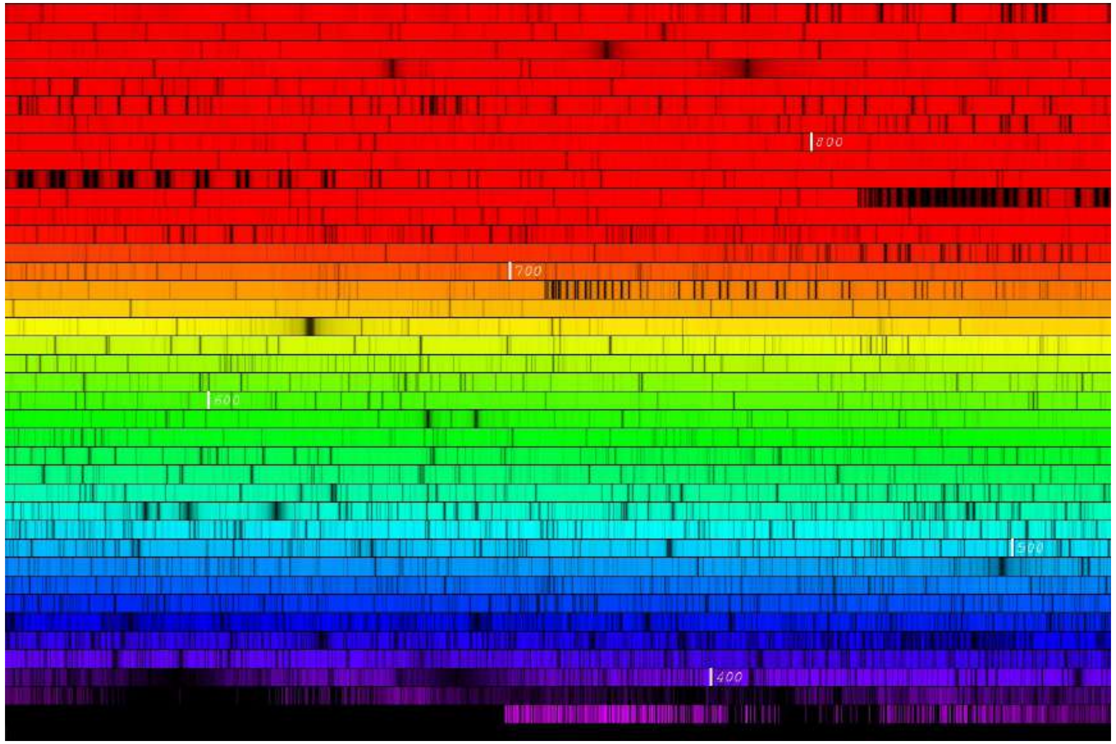
Solar neutrinos → information on solar core, nuclear physics

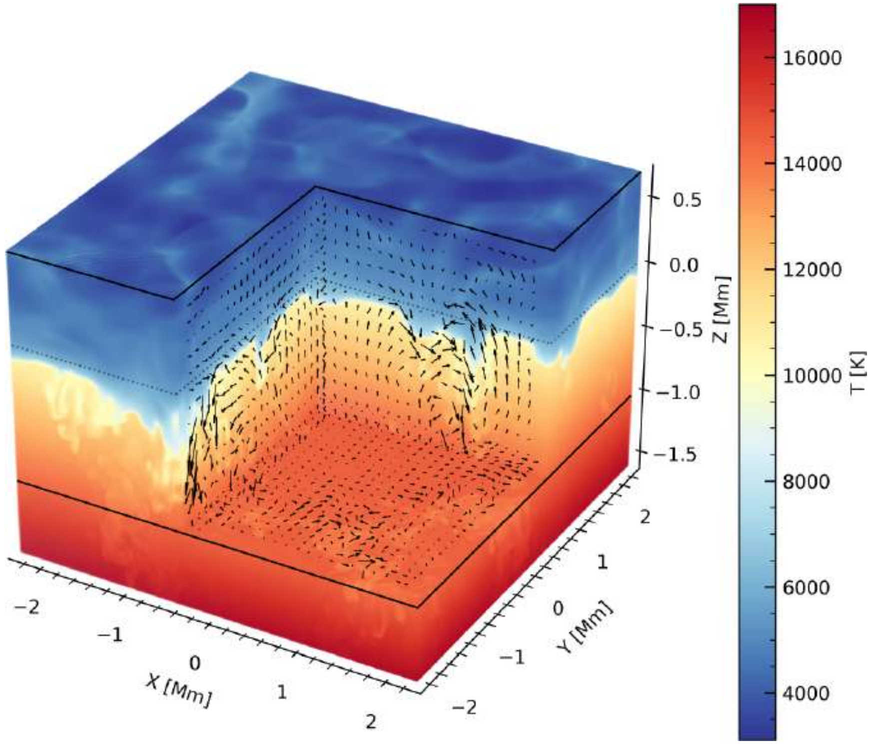




Borexino solar neutrino spectrum
and identified solar fluxes

Foundation science: Solar spectrum & abundances



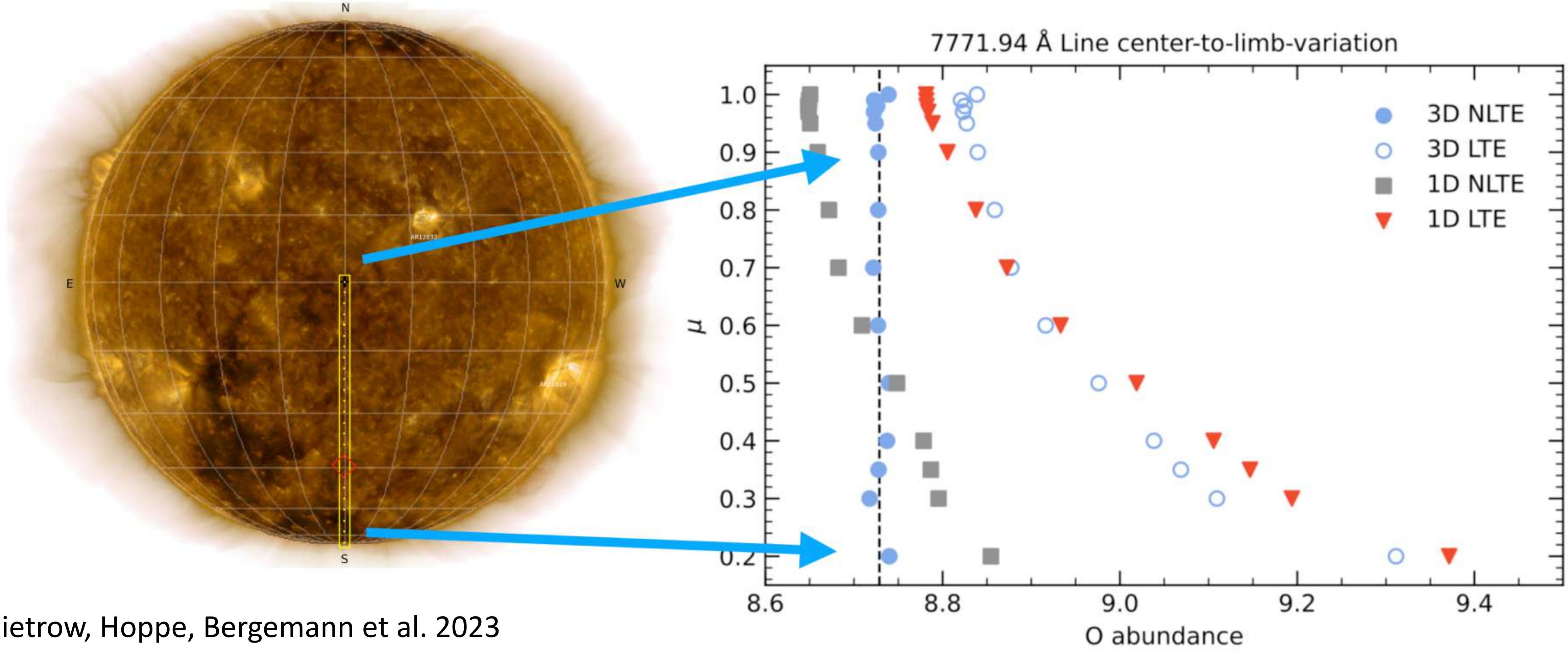


Solar envelope is convective
→ hydrodynamic models
→ 3D atmosphere model

Model atmosphere
→ detailed radiative transfer
→ synthetic spectrum to compare with observed one
→ determination of abundances

Foundation science: Solar spectrum & abundances

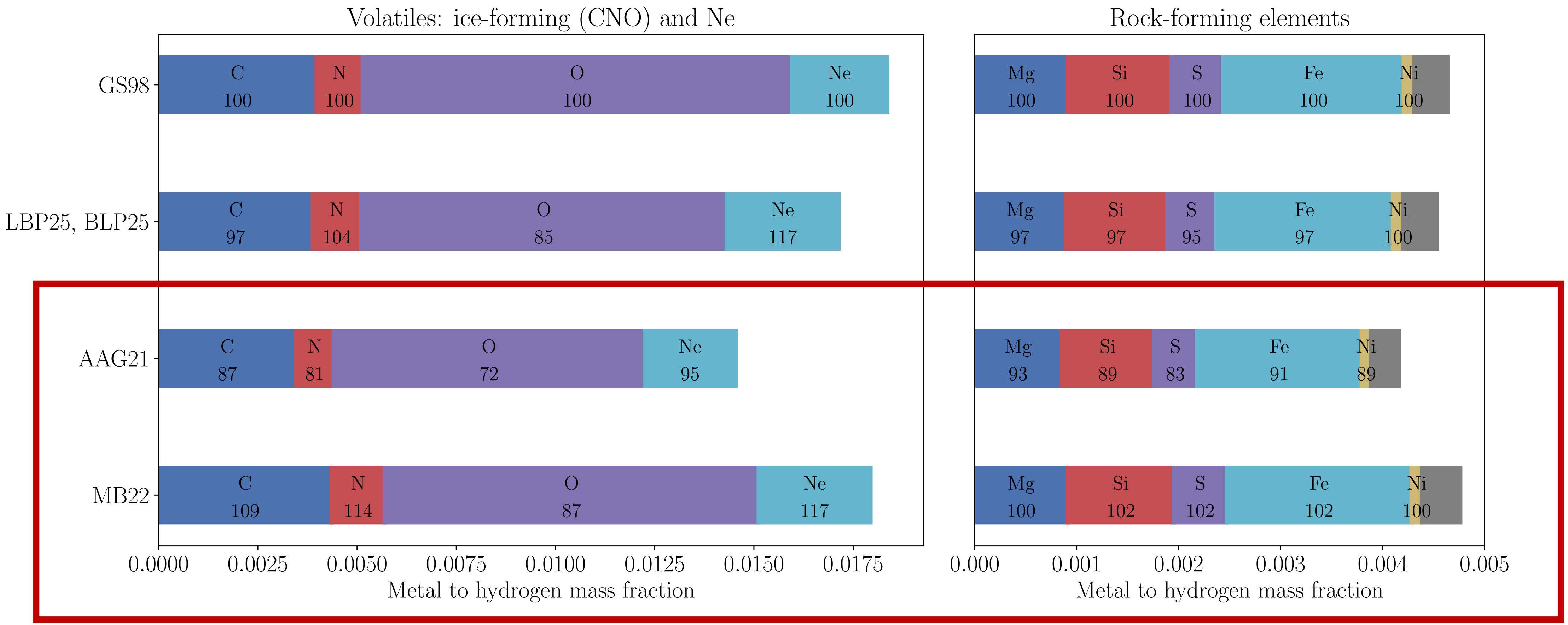
Only star that allows detailed tests, e.g. center-to-limb variations



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

(plots from M. Bergemann)

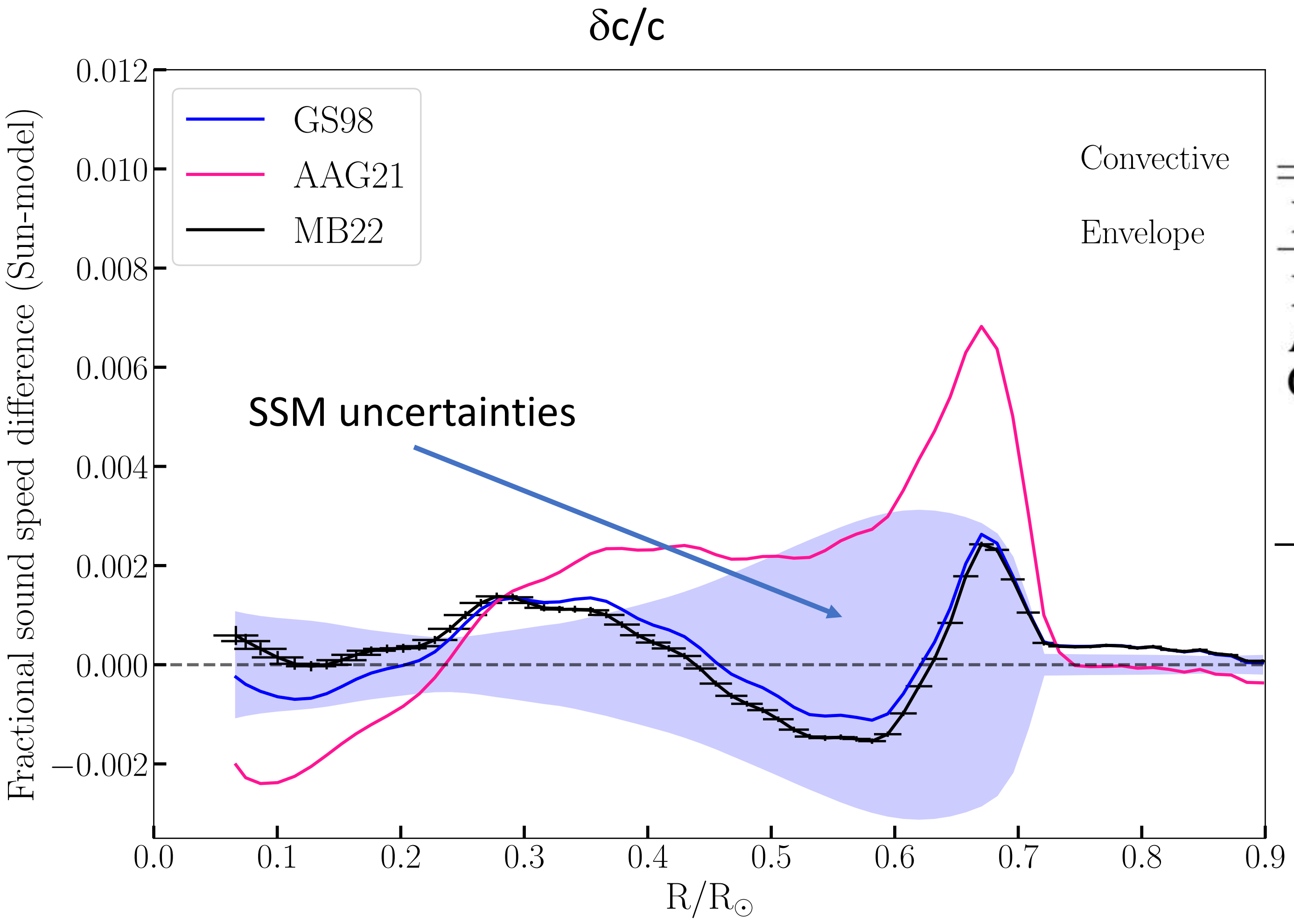
Which solar composition?



GS98: Grevesse & Sauval 1998
LBP25/BLP25: Lodders, Bergemann, Palme 2025
AAG21: Asplund et al. 2021,
MB22: Magg et al. 2022

Chemical abundances are a constraint, not a prediction, of (non-) standard solar models

What helioseismology tells us

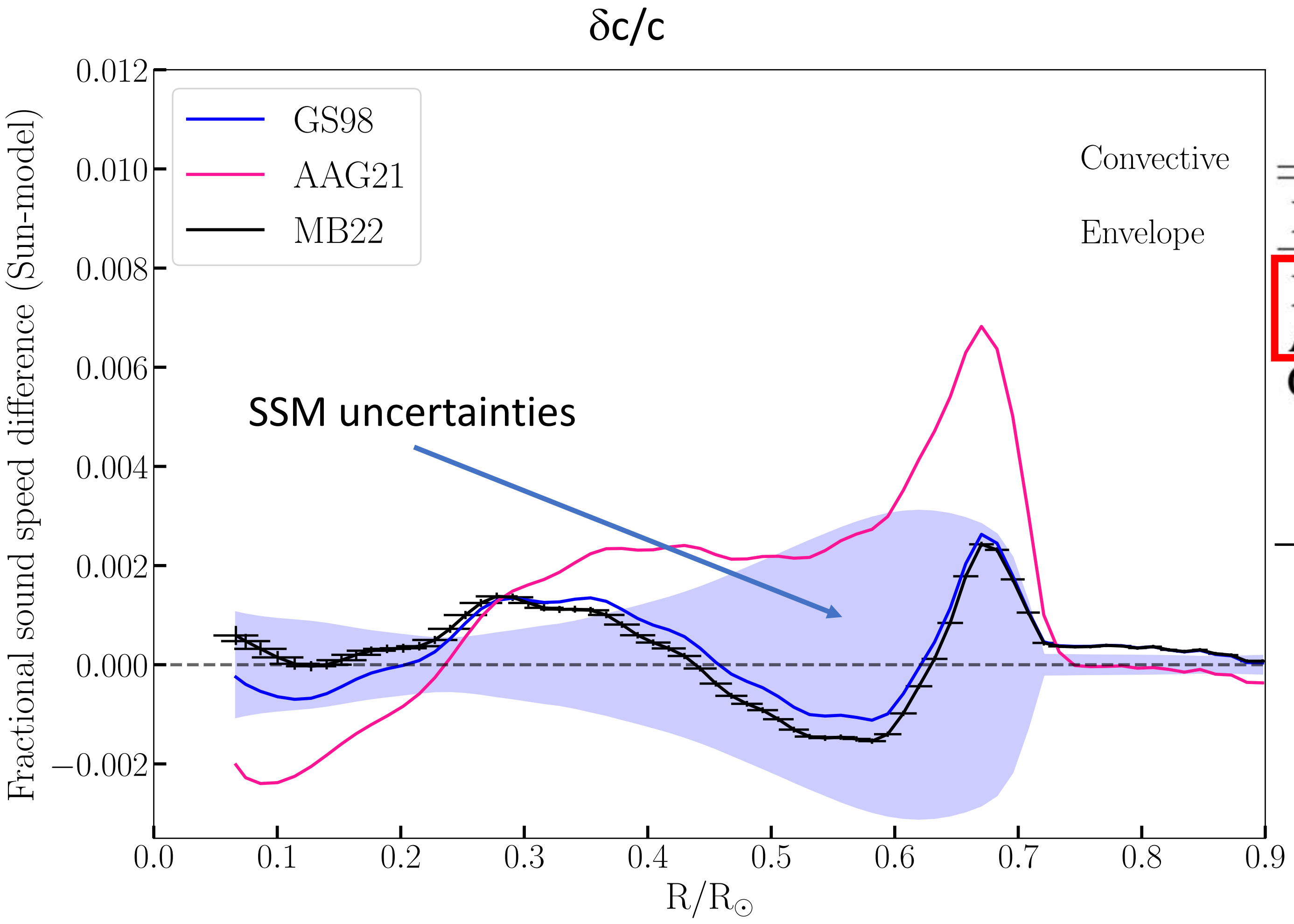


Model	$R_{CZ}/R_\odot$	Y_S	$\langle\delta c/c\rangle$	Y_{ini}	Z_{ini}
MB22	0.7123	0.2439	0.0010	0.2734	0.0176
AAG21	0.7197	0.2343	0.0027	0.2638	0.0155
GS98	0.7122	0.2425	0.0010	0.2718	0.0187
Solar	**0.713 ±0.001**	**0.2485 ±0.0035**			

What helioseismology tells us

Institute of Space Sciences

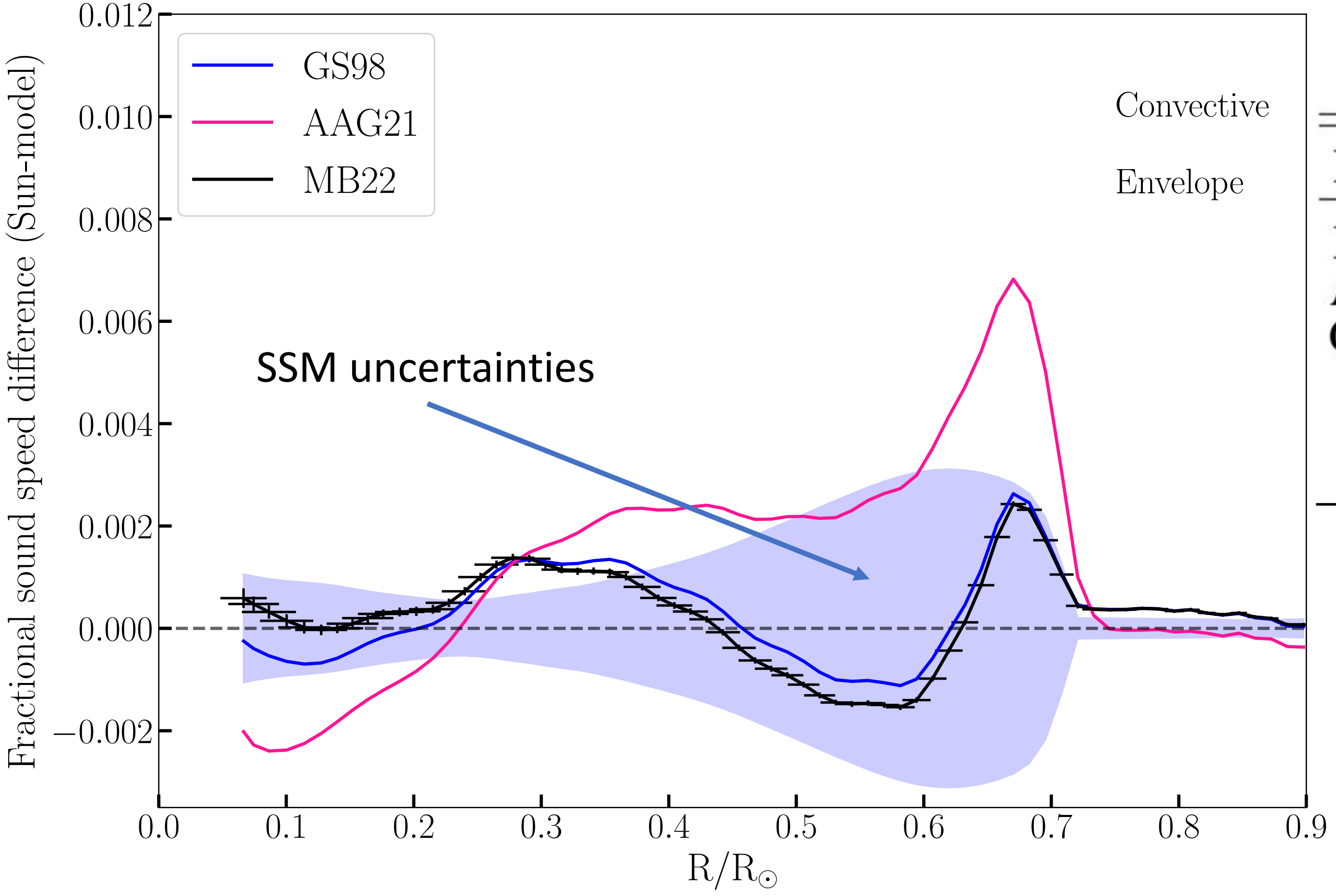
EXCELENCIA MARÍA DE MAEZTU



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

δc/c



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**			

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

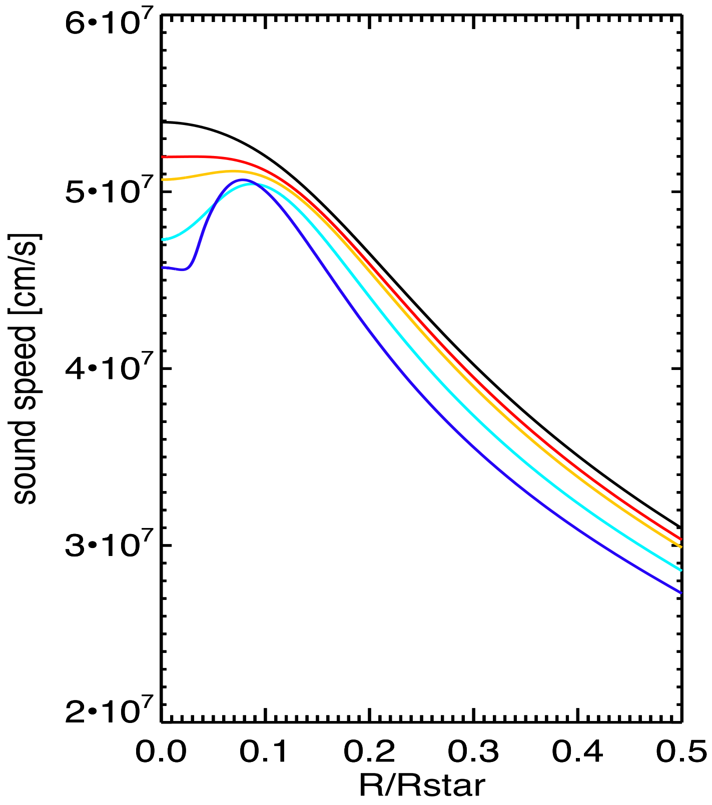
$$\nabla T^4 \propto \kappa \qquad c^2 \propto \frac{T}{\mu}$$

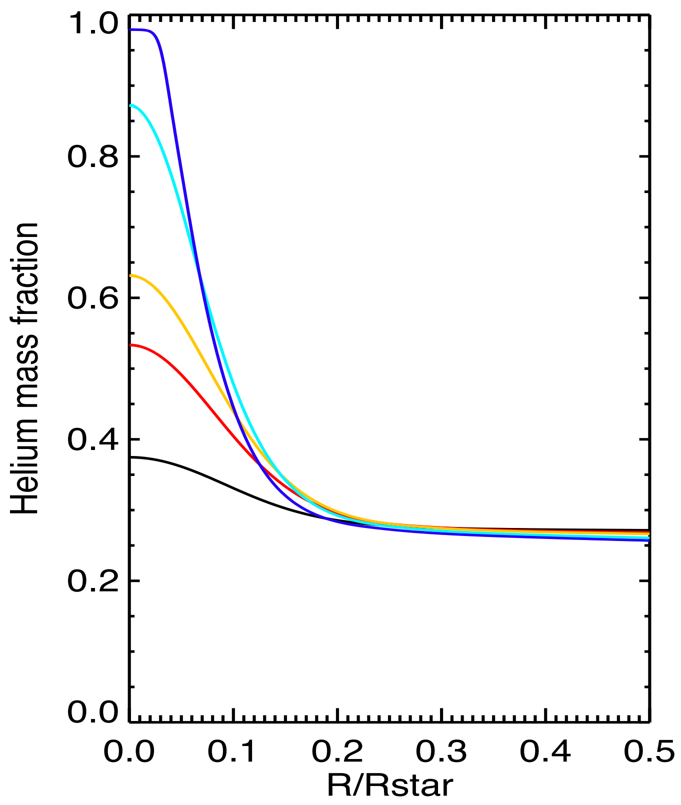
→ (composition + radiative opacities)

Dating the Sun "as a star"

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

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



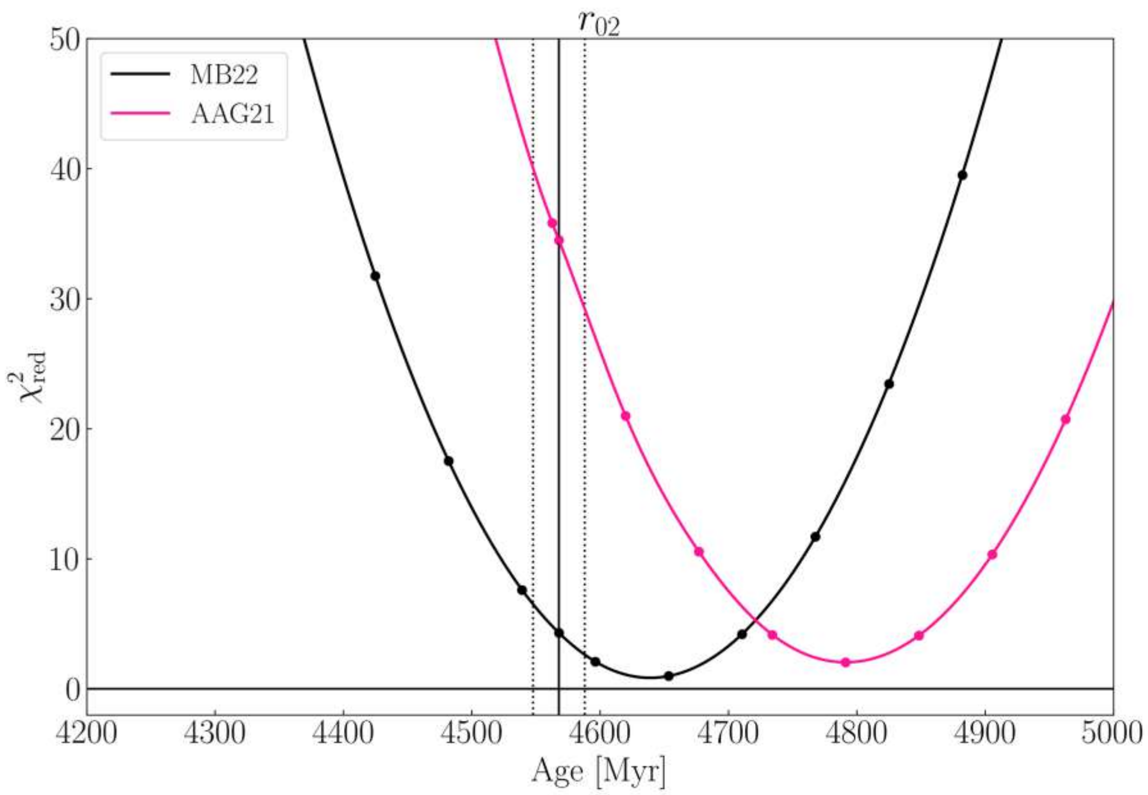


$$c^2 \propto \frac{T}{\mu}$$

The Sun from afar

No independent age for other stars

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



	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 of about to 250Myr (5%)

However,

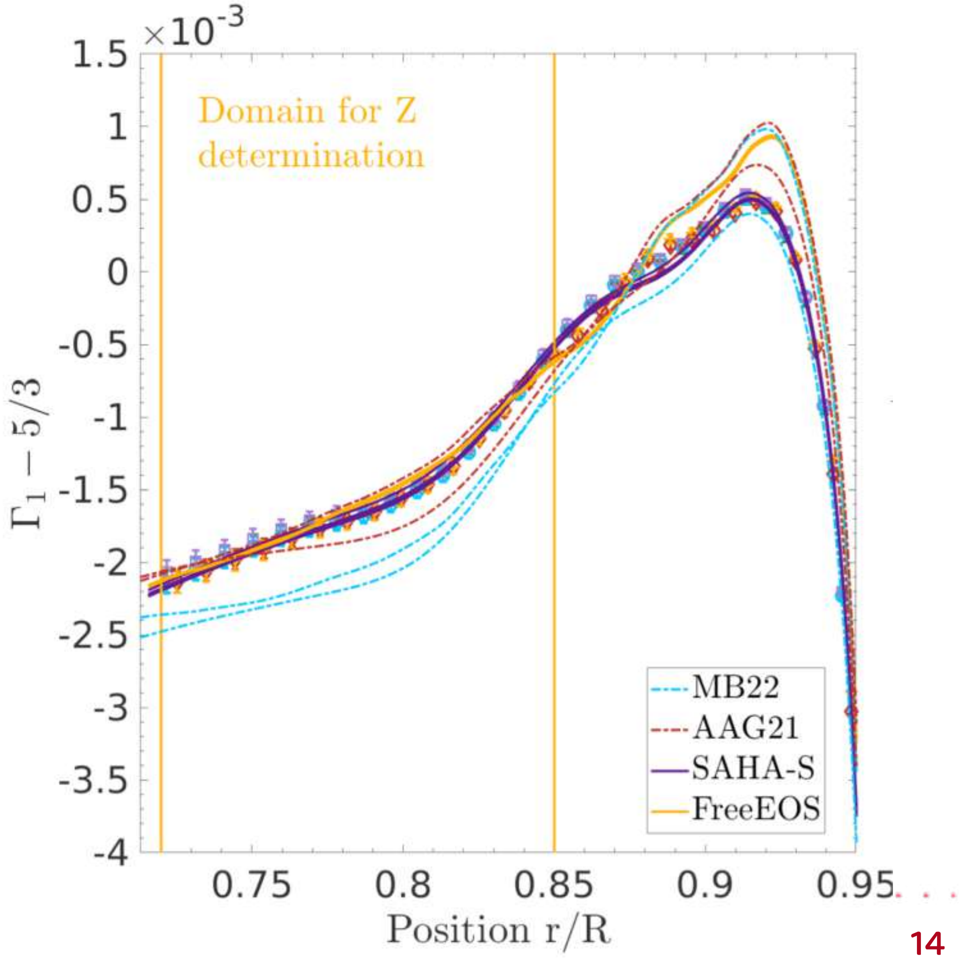
Propagation of sound waves carry information about composition through adiabatic index:

$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$

= 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 (low-Z) rather than MB2



Consensus (as of end of 2022) H-burning x-sections

INT WORKSHOP INT-22-82W

Solar Fusion Cross Sections III

July 26, 2022 - July 29, 2022

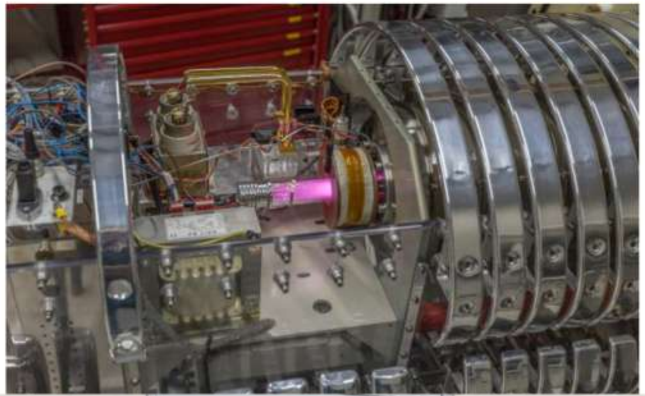
ORGANIZERS

Daniel Bemmerer
Helmholtz-Zentrum Dresden-Rossendorf
d.bemmerer@hzdr.de

Alessandra Guglielmetti
Universita degli Studi di Milano - INFN Milano
alessandra.guglielmetti@mi.infn.it

Wick Haxton
UC Berkeley
haxton@berkeley.edu

Aldo Serenelli
Institute of Space Sciences (ICE, CSIC)
aldos@ice.csic.es



Note to applicants: This wo
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.

B. Acharya

*Oak Ridge National Laboratory,
Oak Ridge, TN 37831,
USA*

M. Aliotta

*SUPA, School of Physics and Astronomy,
University of Edinburgh,
Edinburgh EH9 3FD,
United Kingdom*

A.B. Balantekin

*Department of Physics,
University of Wisconsin-Madison,
Madison WI 53706,
USA*

D. Bemmerer

*Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden,
Germany*

C.A. Bertulani

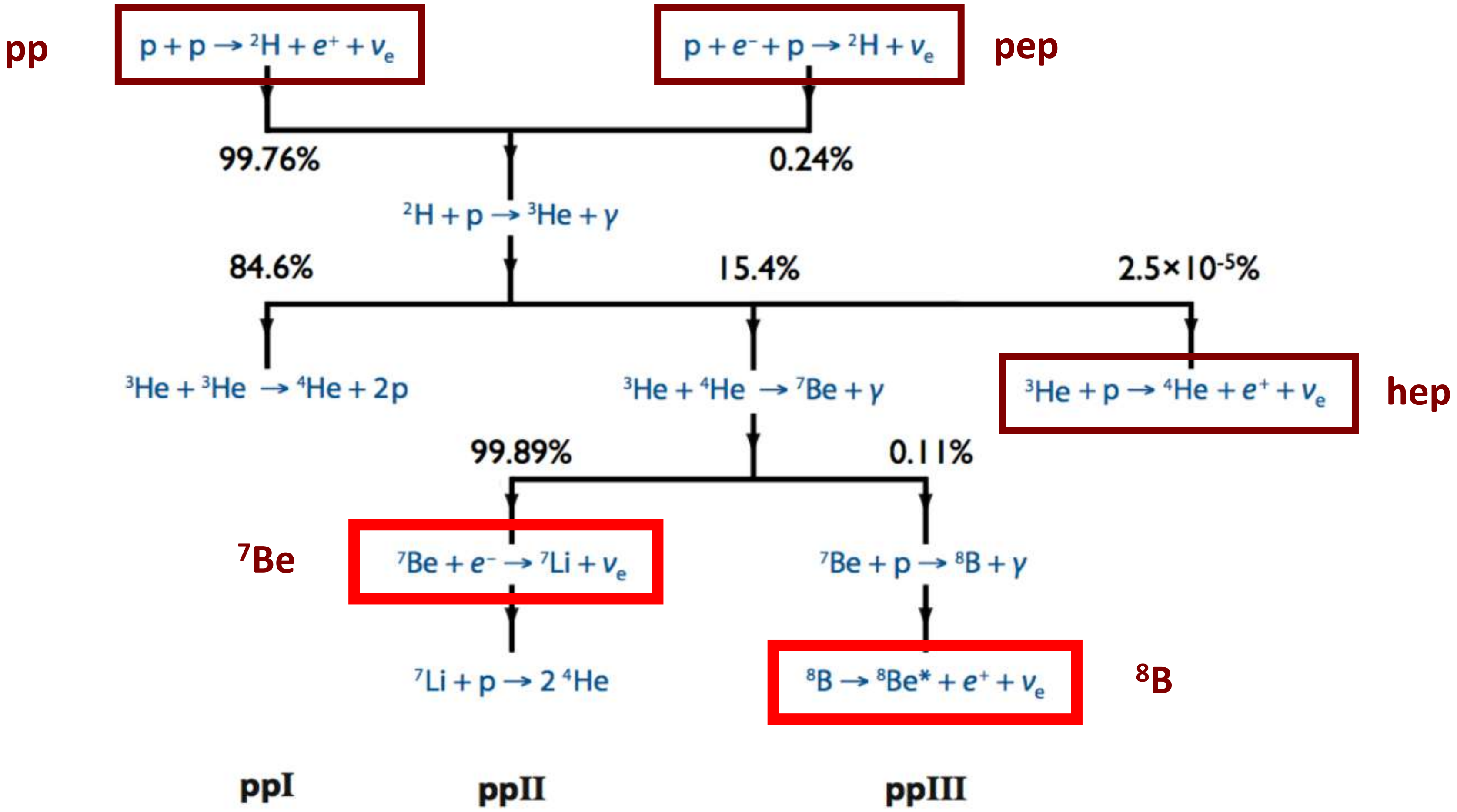
*Department of Physics and Astronomy,
Texas A&M University-Commerce,
Commerce, TX 75429-3011,
USA*

arXiv: 2405.06470
RMP coming (soon)

Consensus (as of end of 2022) H-burning x-sections

Reaction	1σ error (SFIII)	1σ error (SFII, 2010)	
p+p	1.5%	0.9%	GA/GV
^{3}He+^{3}He	6.6%	5.2%	uncert. in protons spectral shape
^{3}He+^{4}He	5.1%	5%	
^{7}Be+p	3.6%	7.5%	halo EFT & Fitting
^{14}N+p	8.4%	7.2%	R-matrix and data tension for ground state transition

What solar neutrinos from pp-chain tell us



What solar neutrinos from pp-chain 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%)
^{7}Be (10^{9})	4.52 (7.4%)	4.90 (7.6%)	4.93 (2%)
^{8}B (10^{6})	4.31 (12.6%)	5.13 (13.1%)	5.20 (1.9%)

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

Model uncertainties >> experimental ones

x-sections (S_{17}, S_{34},S11)

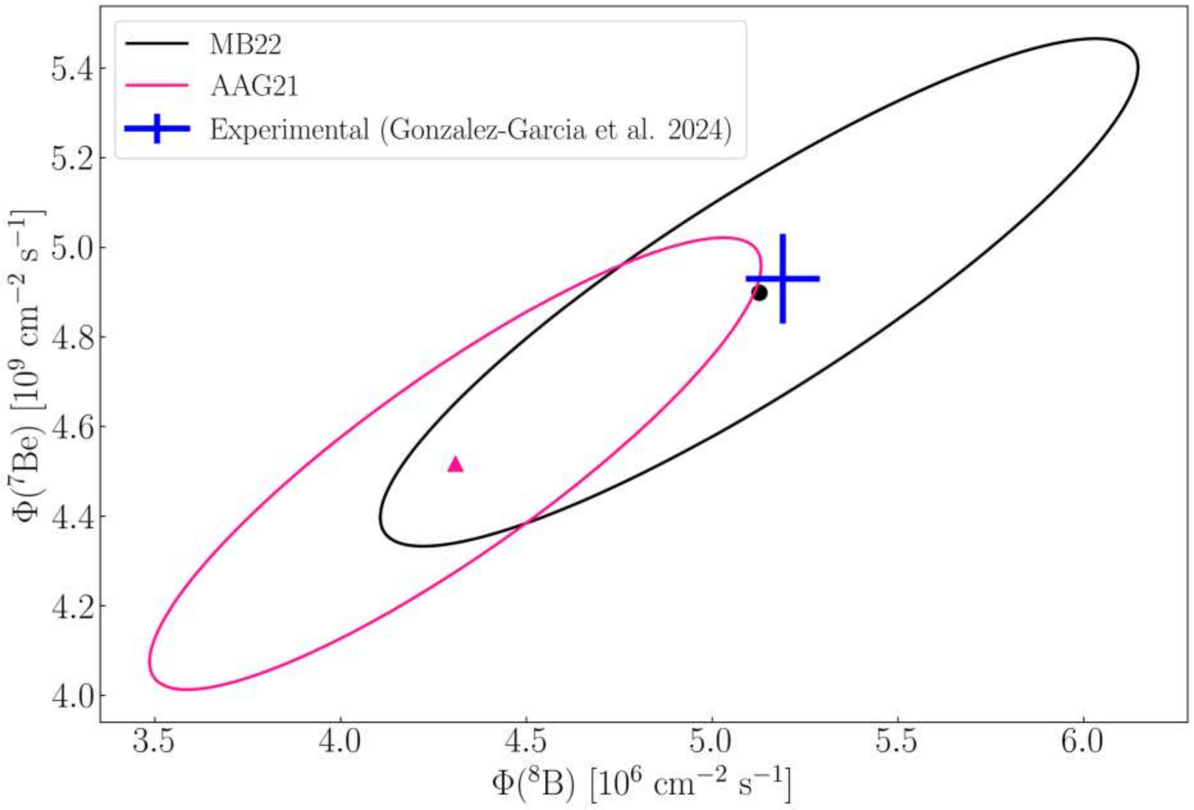
6% for ^{7}Be

8% for ^{8}B

radiative opacity

What solar neutrinos from pp-chain tell us

Mostly a temperature sequence with slope determined by nuclear reaction rates



$cm^{-2}s^{-1}$	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%)
^{7}Be (10^9)	4.52 (7.4%)	4.90 (7.6%)	4.93 (2%)
^{8}B (10^6)	4.31 (12.6%)	5.13 (13.1%)	5.20 (1.9%)

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

Model uncertainties >> experimental ones

x-sections (S_{17}, S_{34},S11)

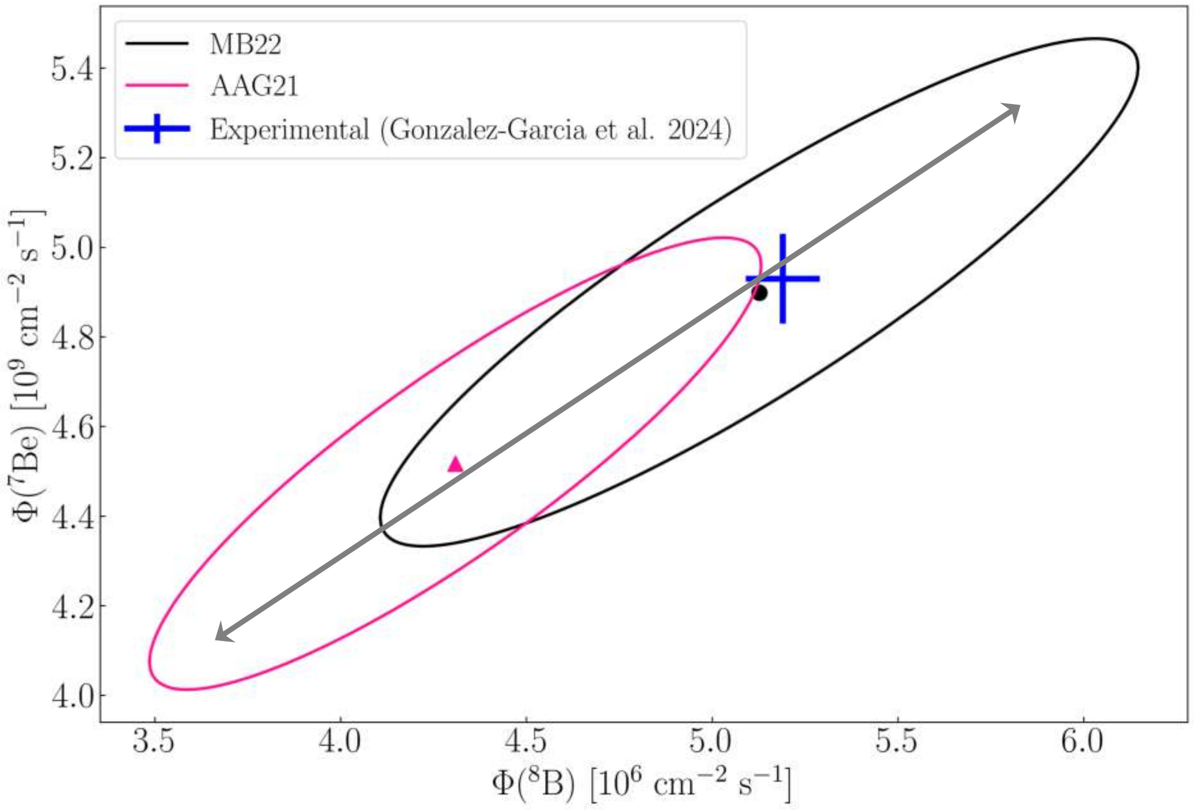
6% for ^{7}Be

8% for ^{8}B

radiative opacity

What solar neutrinos from pp-chain tell us

Mostly a temperature sequence with slope determined by nuclear reaction rates



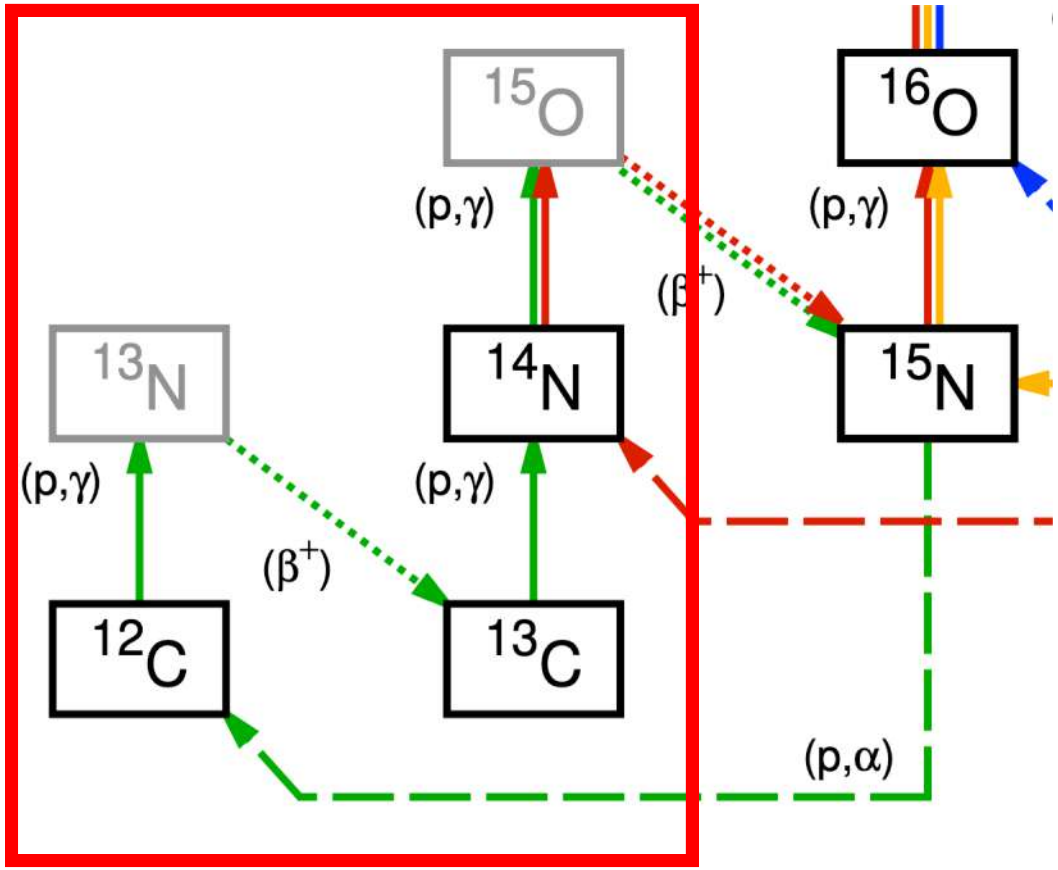
$cm^{-2}s^{-1}$	AAG21	MB22	Sun
pp (10^{10})	6.00 (0.6%)	5.95 (0.6%)	5.94 (0.4%)
pep (10^8)	1.45 (1.1%)	1.42 (1.1%)	1.42 (1.6%)
hep (10^3)	8.16 (30%)	7.92 (30%)	30 (33%)
^{7}Be (10^9)	4.52 (7.4%)	4.90 (7.6%)	4.93 (2%)
^{8}B (10^6)	4.31 (12.6%)	5.13 (13.1%)	5.20 (1.9%)

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

Combination of **composition + radiative opacities →**
→ core temperature consistent with higher opacity (Z?) models

CN-cycle is a trace contribution to solar structure

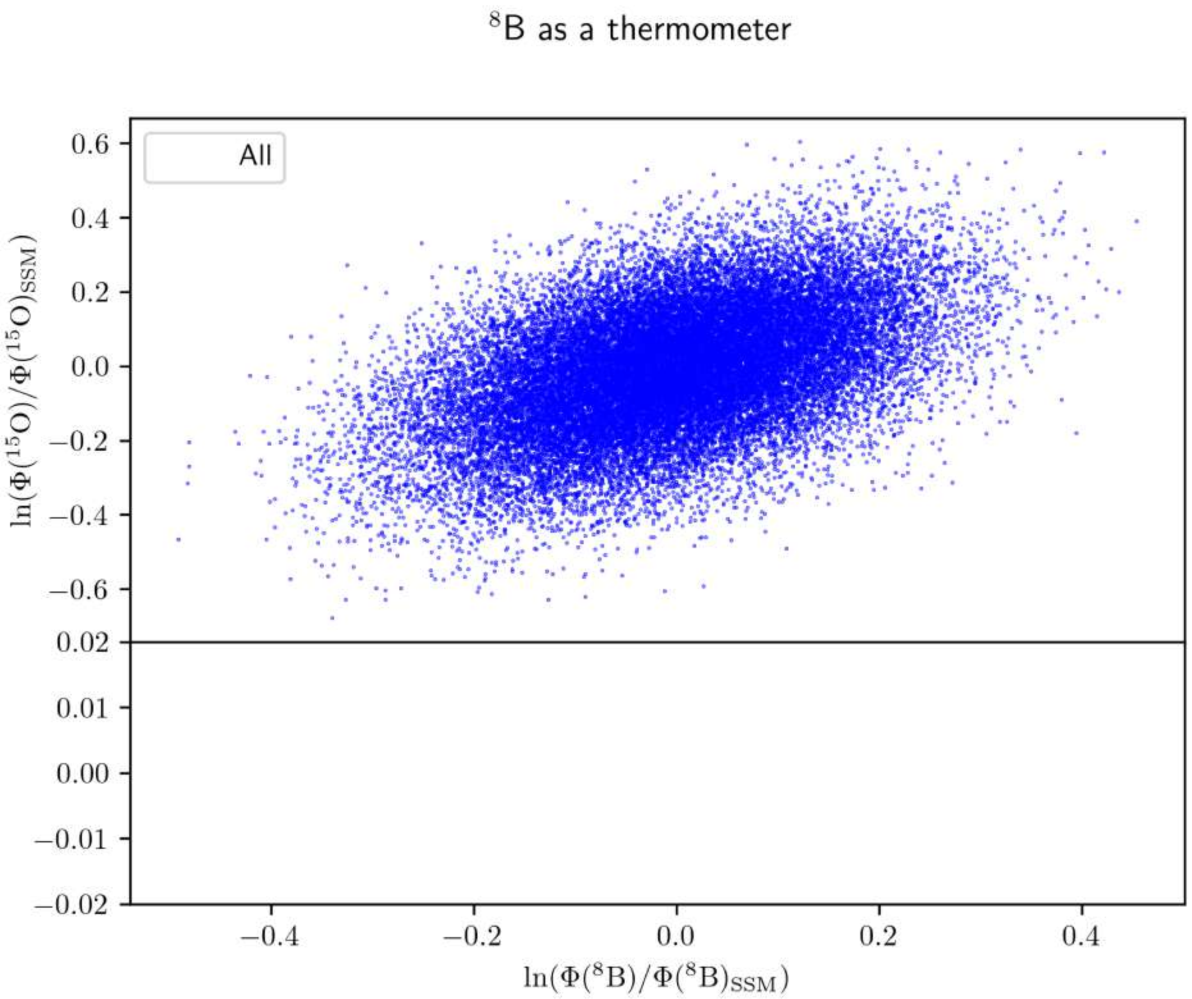
CN operates against a “fixed” structure determined by pp-chains



Changes in physics affecting CN do not change structure, **i.e. core temperature**,
→ retain explicit dependences:

- e.g. linear response to bottleneck nuclear reaction $^{14}N(p,\gamma)^{15}O$
- **linear dependence on abundance of catalyzers in solar core: C+N**
- **one-to-one relation between neutrino fluxes and CN abundance**

What CN solar neutrinos tell us



Neutrino fluxes depend on:

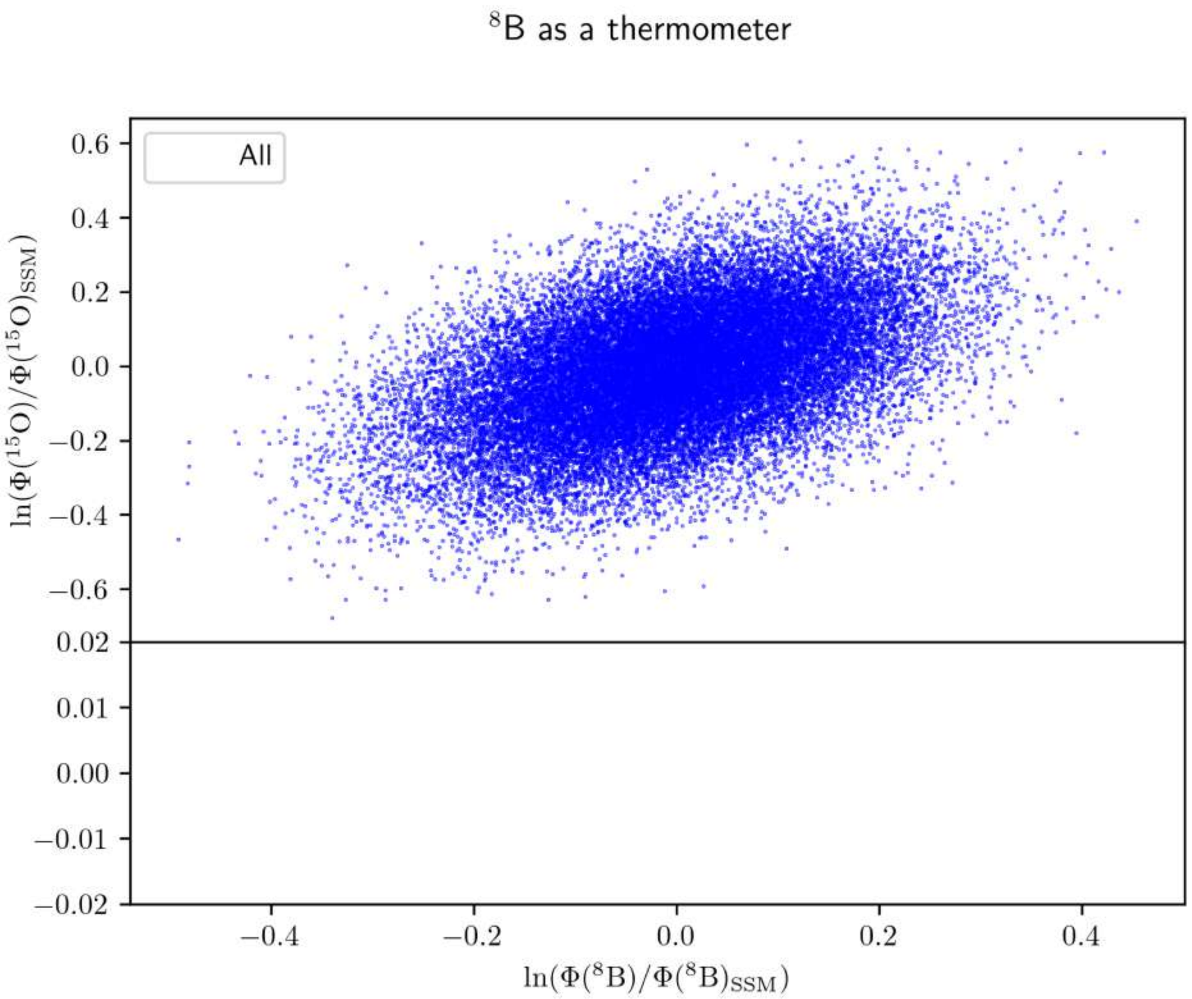
- **solar core temperature – environmental quantities**
  - opacity
  - heavy elements (Si, Mg, Fe)
  - luminosity, age

uncertainties in these quantities affect n-fluxes in a fully correlated way

- **nuclear reaction rates**
  - specific dependence for specific fluxes
  - (e.g. ^{14}N(p,g)^{15}O does not affect pp-chain)

- **catalyzing effect of abundances**
  - C & N abundance in the solar core → CN-cycle

What CN solar neutrinos tell us

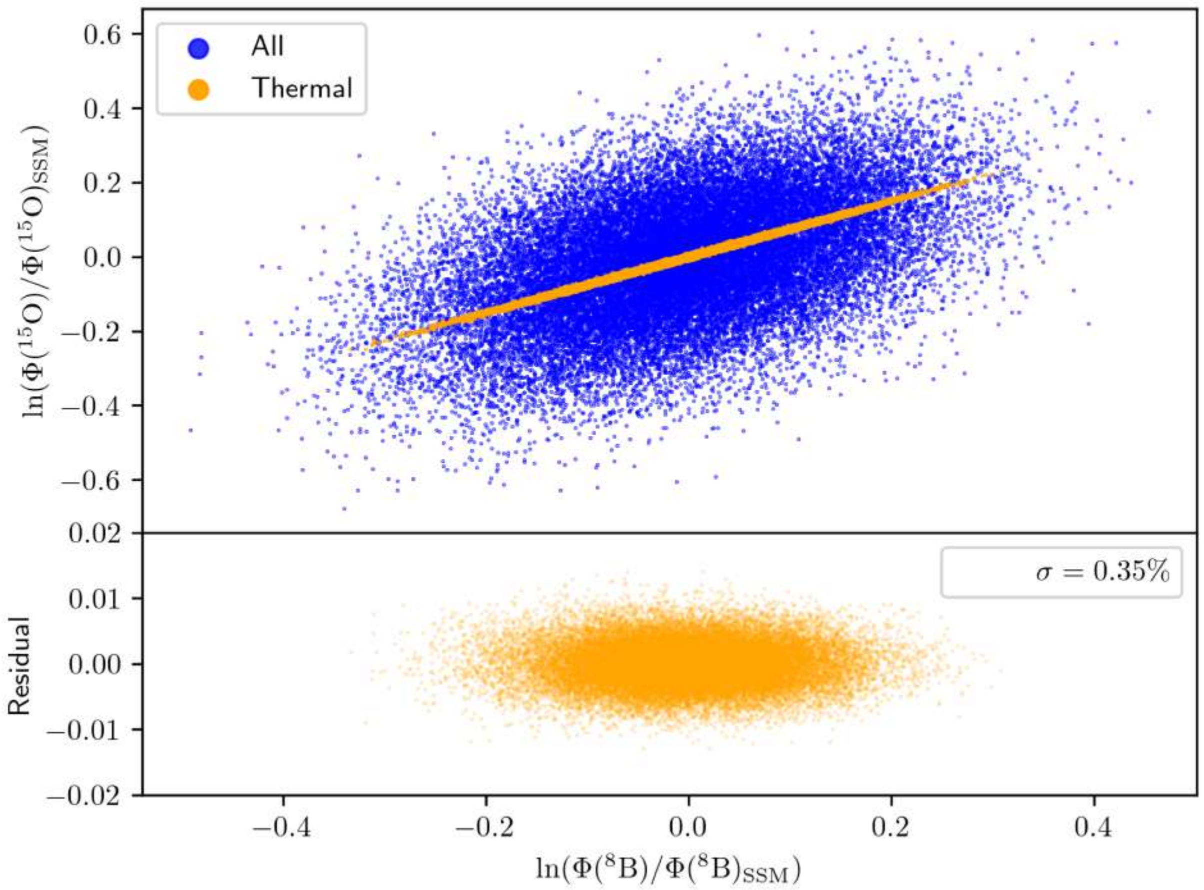


Neutrino fluxes as power-laws:

$$\frac{\phi(^{15}O)}{\phi(^{15}O)^{SSM}} = \left[L_\odot^{5.942} O^{2.034} A^{1.364} D^{0.382}\right] \times \left[S_{11}^{-2.912}\ S_{33}^{0.024}\ S_{34}^{-0.052}\ S_{17}^{0.0}\ S_{e7}^{0.0}\ S_{114}^{1.00}\right] \times \left[x_C^{0.815} x_N^{0.217} x_O^{0.112} x_{Ne}^{0.081} x_{Mg}^{0.069} x_{Si}^{0.150} x_S^{0.109} x_{Ar}^{0.028} x_{Fe}^{0.397}\right]$$

$$\frac{\phi(^8B)}{\phi(^8B)^{SSM}} = \left[L_\odot^{6.966} O^{2.734} A^{1.319} D^{0.278}\right] \times \left[S_{11}^{-2.665}\ S_{33}^{-0.419}\ S_{34}^{0.831}\ S_{17}^{1.028}\ S_{e7}^{-1}\ S_{114}^{0.00}\right] \times \left[x_C^{0.022} x_N^{0.007} x_O^{0.128} x_{Ne}^{0.102} x_{Mg}^{0.092} x_{Si}^{0.198} x_S^{0.138} x_{Ar}^{0.034} x_{Fe}^{0.498}\right]$$

What CN solar neutrinos tell us

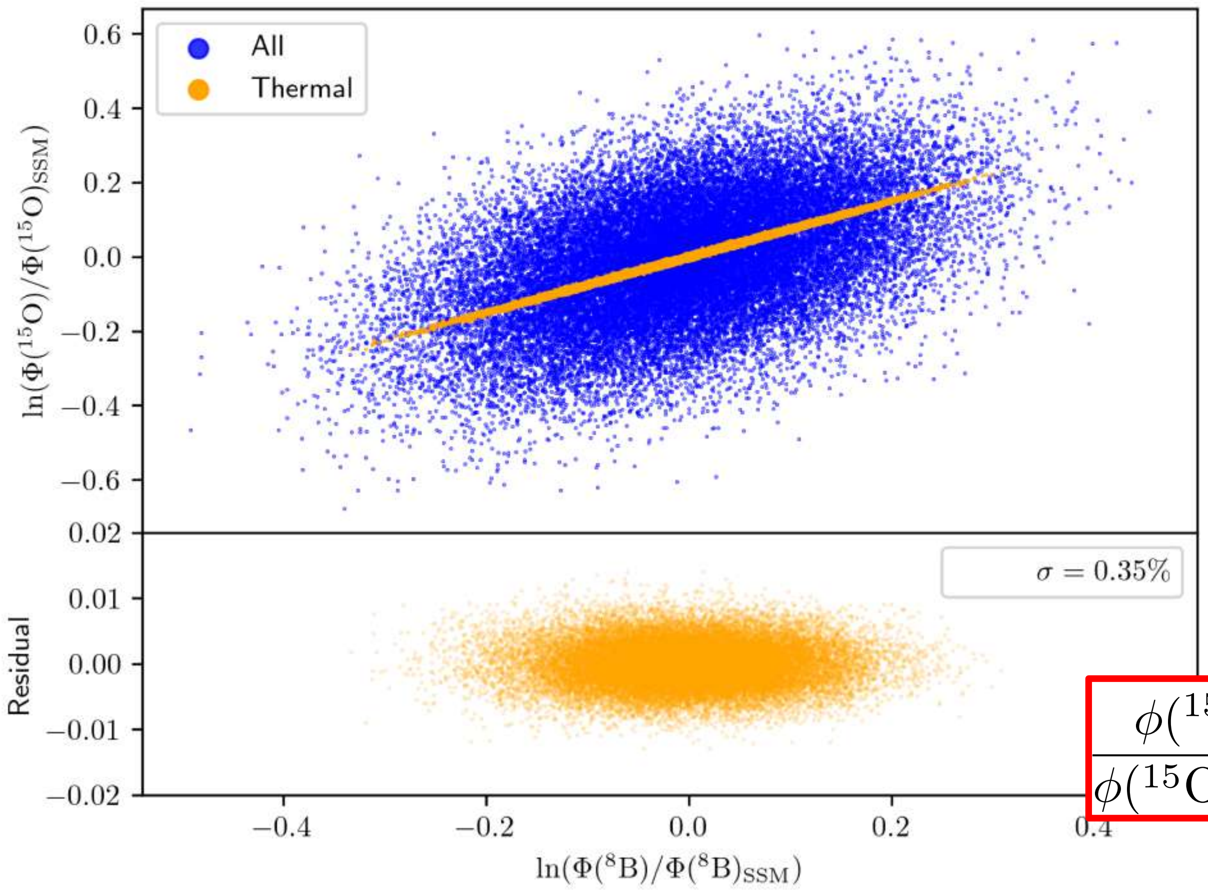


Thermal uncertainties are cancelled out, absorbed by a ^{8}B experimental measurement, down to 0.3%

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172} \times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right] \times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right] \times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$

What CN solar neutrinos tell us

^{8}B as a thermometer



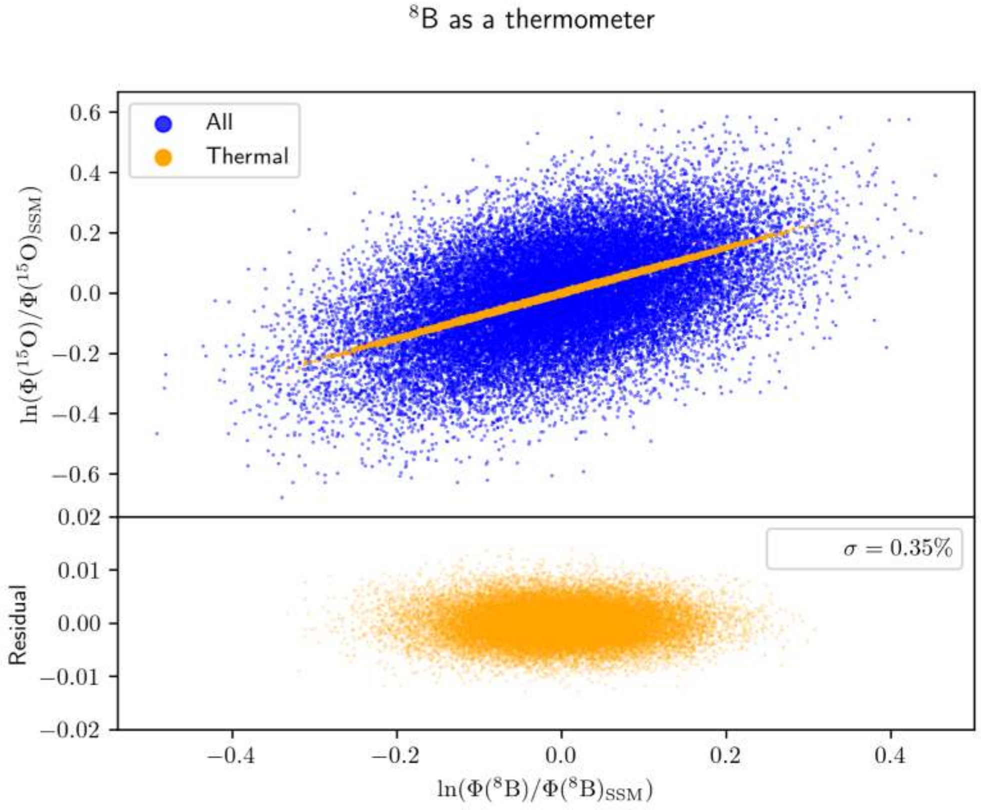
Linear dependence on C+N

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi^{\mathrm{SSM}}(^{8}\mathrm{B})}\right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172} \times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right] \times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right] \times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.\ldots} \ldots x_{\mathrm{Fe}}^{0.003}\right]$$

Nuclear reaction rates

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \simeq \left(\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.785} (x_{\mathrm{C+N}})[1 \pm 0.10(\mathrm{nuc}) + 0.03(\mathrm{D})]$$

What CN solar neutrinos tell us



SuperKamiokande, SNO, others → 2% measurement of ^{8}B flux

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \simeq \left(\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.785} (x_{\mathrm{C+N}})[1 \pm 0.10(\mathrm{nuc}) + 0.03(\mathrm{D})]$$

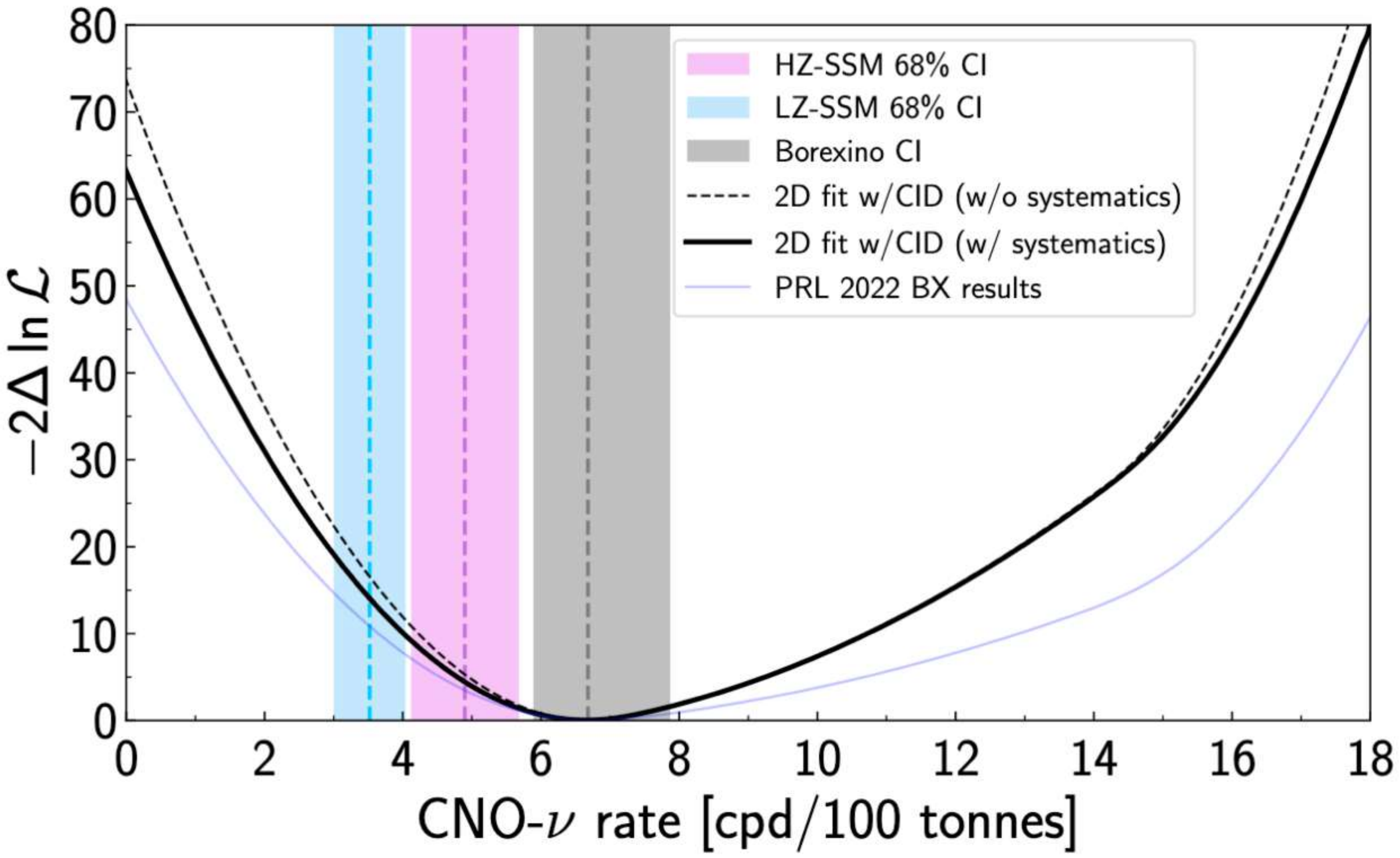
C+N abundance if ^{15}O flux is measured
(or any combination of ^{13}N & ^{15}O fluxes)

10% uncertainty (nuclear rates)
experimental uncertainty in CN-ν fluxes dominated by

- **^{14}N(p,γ)^{15}O (8.5%)**
- **^{3}He(^{4}He,γ)^{7}Be (5%)**

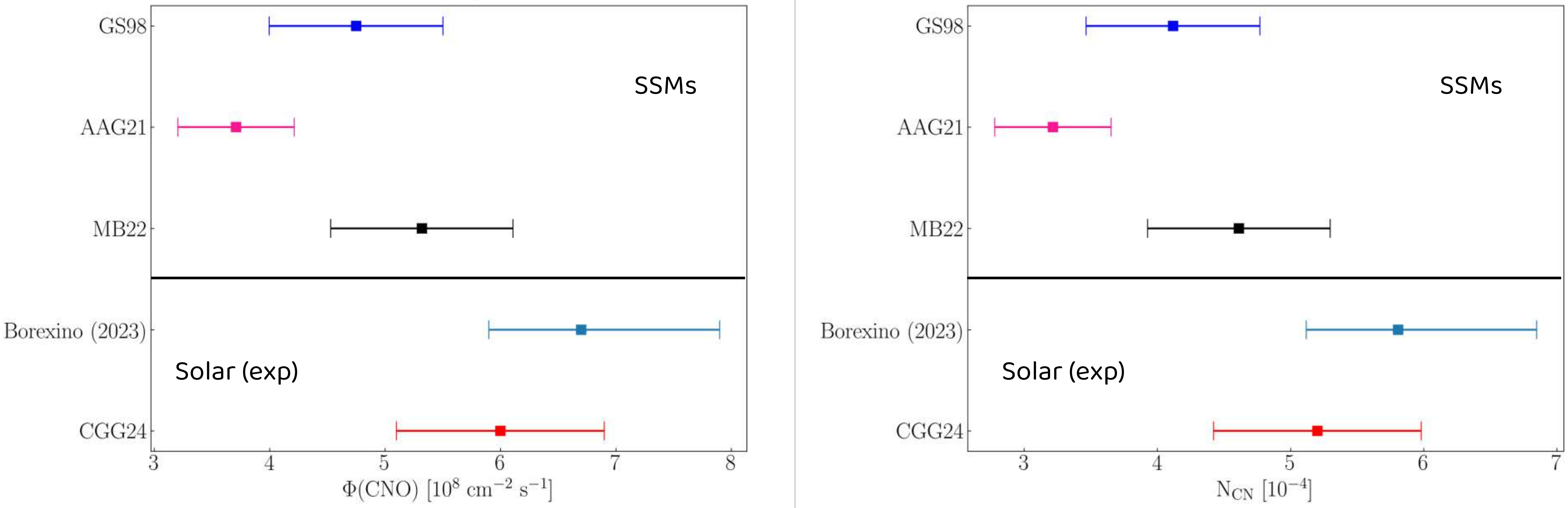
CN measurement by Borexino

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



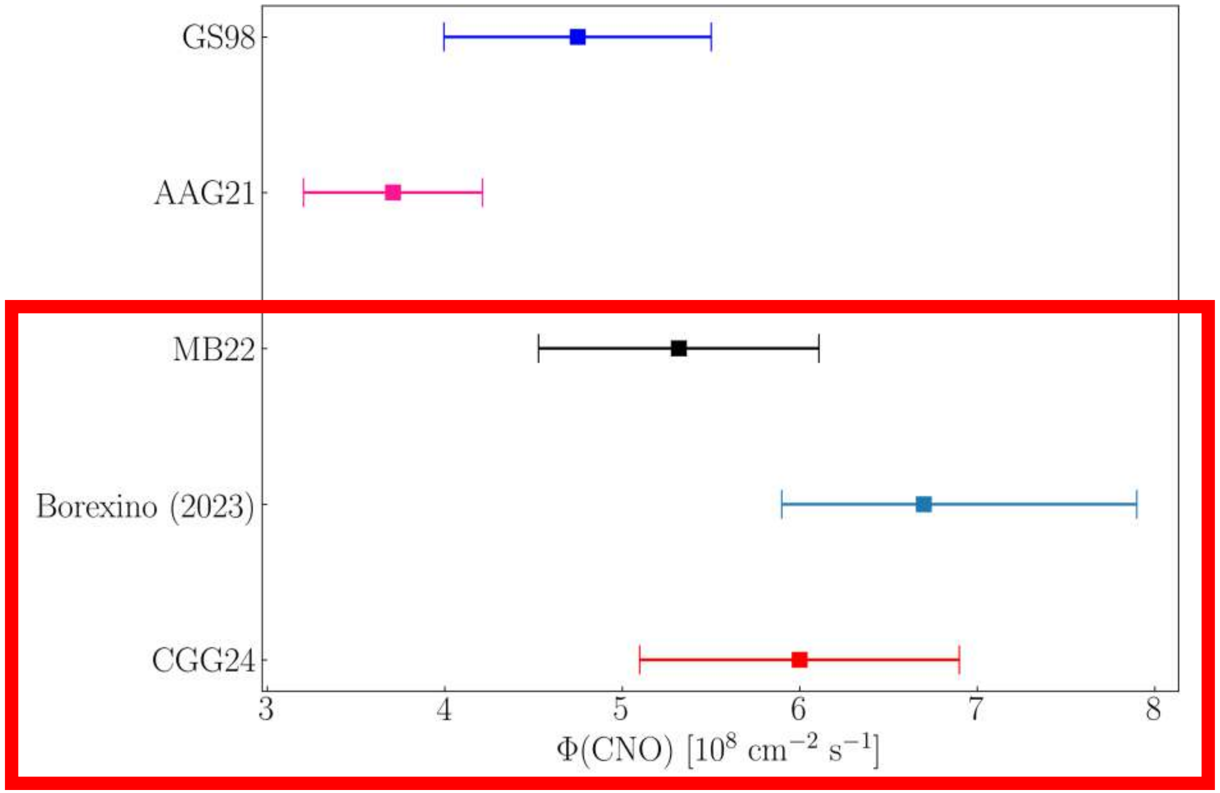
What CN solar neutrinos tell us

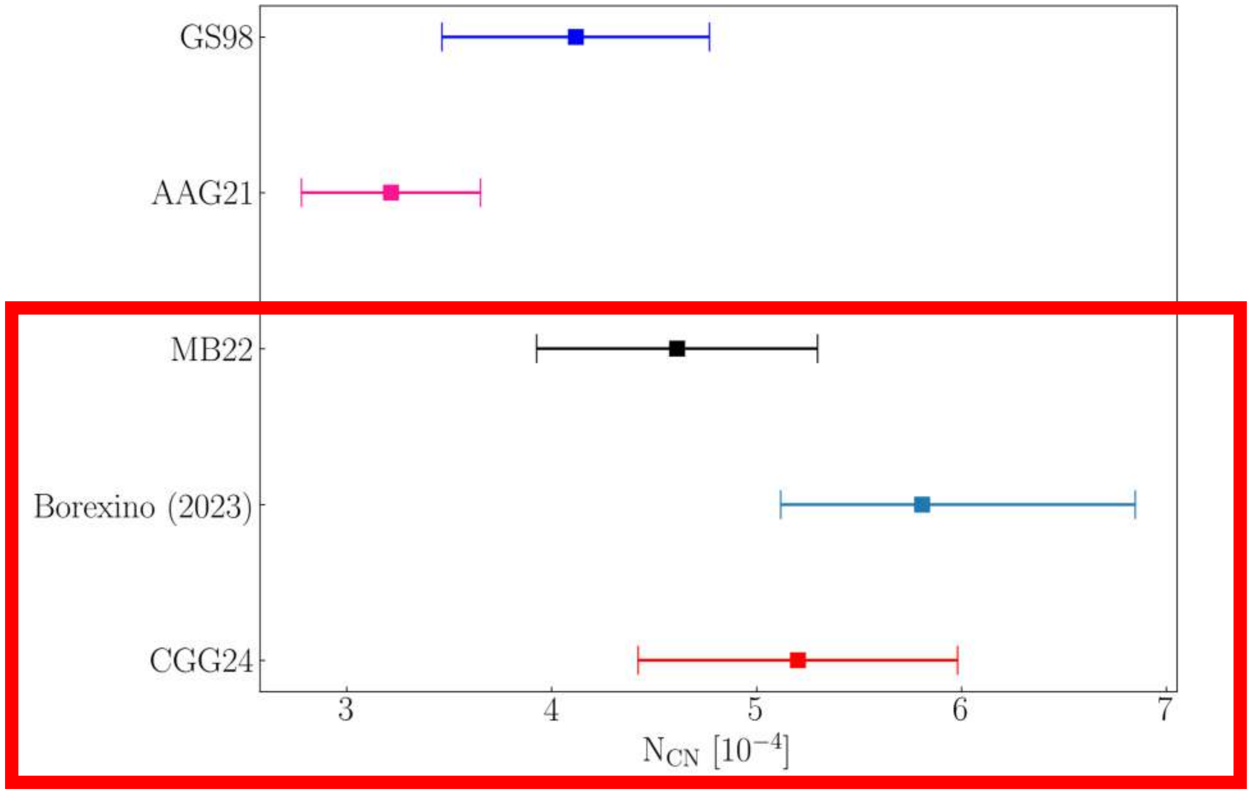
$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \simeq \left(\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.785} (x_{\mathrm{C+N}})[1 \pm 0.10(\mathrm{nuc}) + 0.03(\mathrm{D})]$$



What CN solar neutrinos tell us

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \simeq \left(\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right)^{0.785} (x_{\mathrm{C+N}})[1 \pm 0.10(\mathrm{nuc}) + 0.03(\mathrm{D})]$$





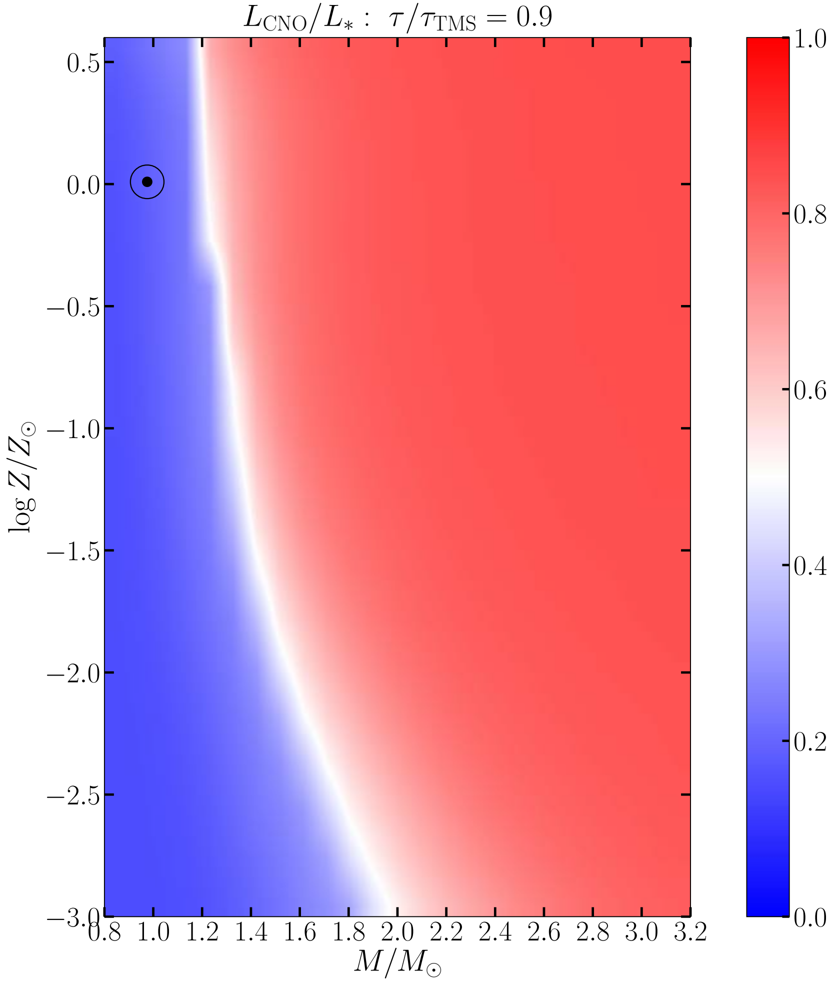
CN neutrinos break the degeneracy between composition and opacity

Favor large CN abundance

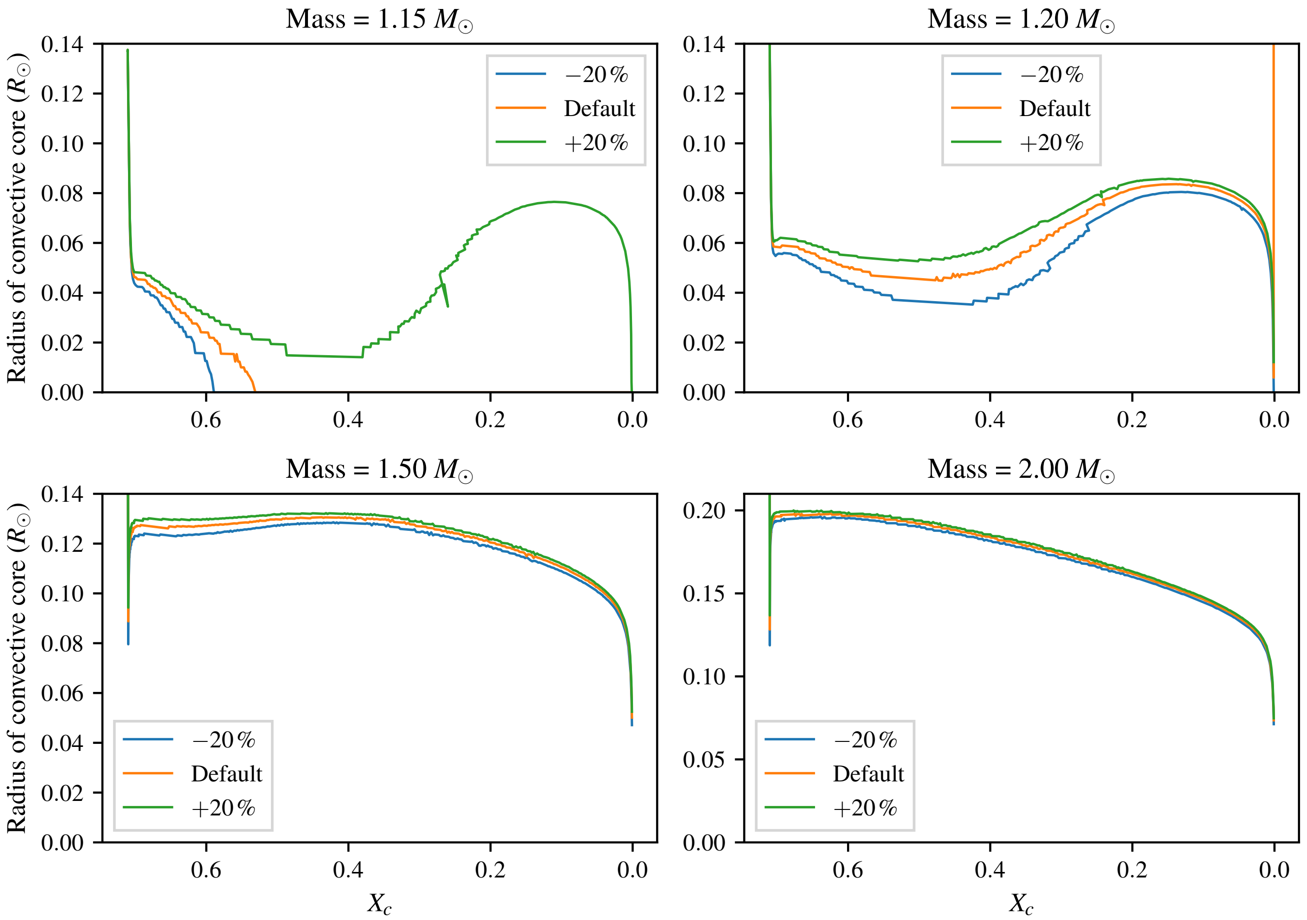
Nuclear rates largest source of uncertainty, but one we can control

CNO vs mass and metallicity

Stellar luminosity: CNO vs pp

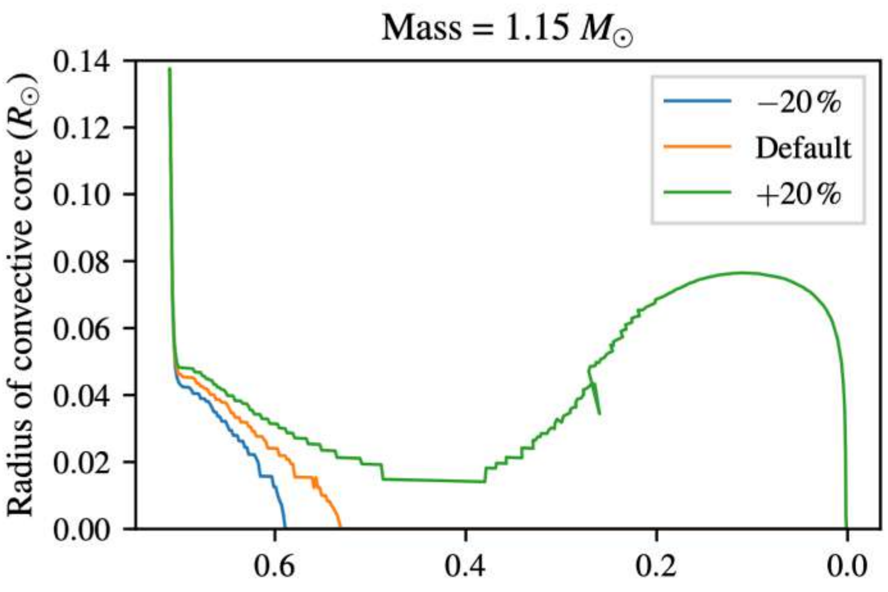


Dependence on 14N+p rate



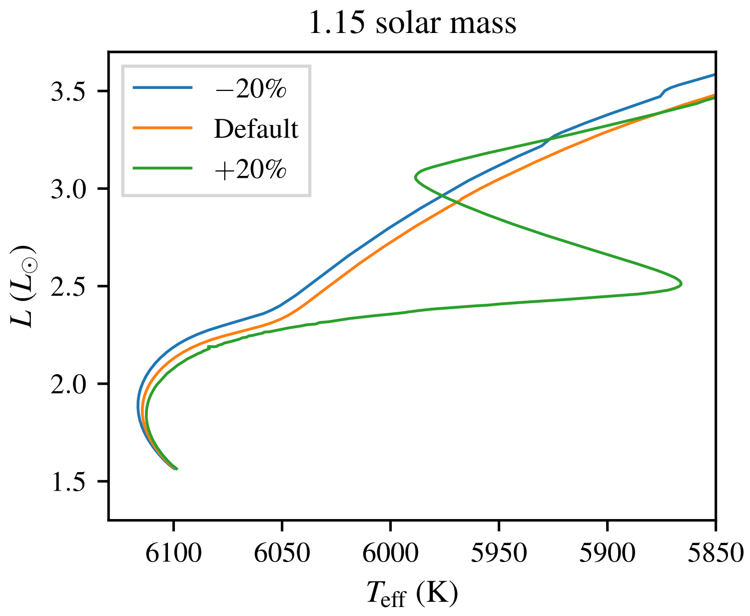
Convective core: to be or not to be

Size of convective core

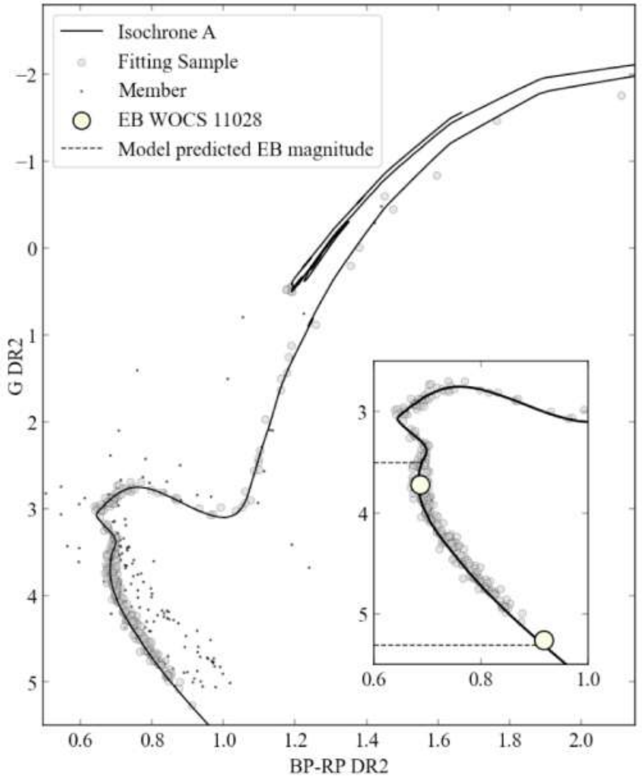


Central hydrogen

Hertzsprung-Russell Diagram



M67 Color-magnitude Diagram



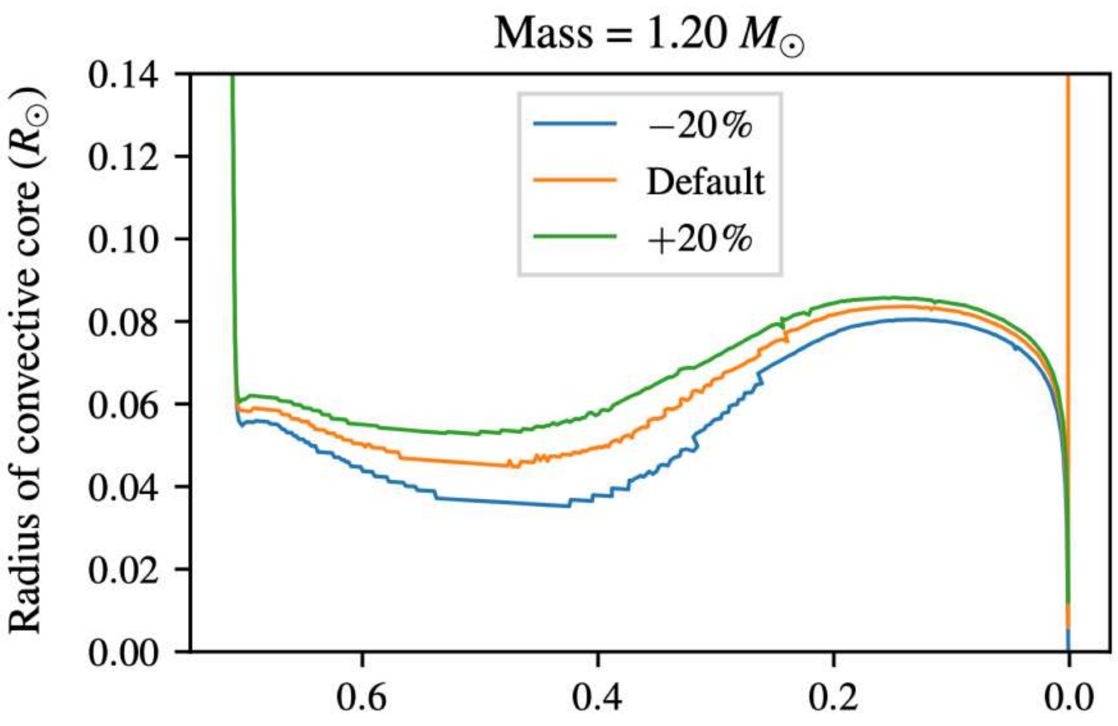
Reyes et al. 2024

Stellar mass @ which convective core develops depends on N14+p reaction rate

Qualitative change in HRD morphology

Size of mixed core: convective boundary + overshooting

Size of chemically homogenous (mixed) core is formed by
+ truly convective core
+ **overshooting region** (parametrized, α_{ov}, no 1st principles model)
It can be measured with astereoseismology



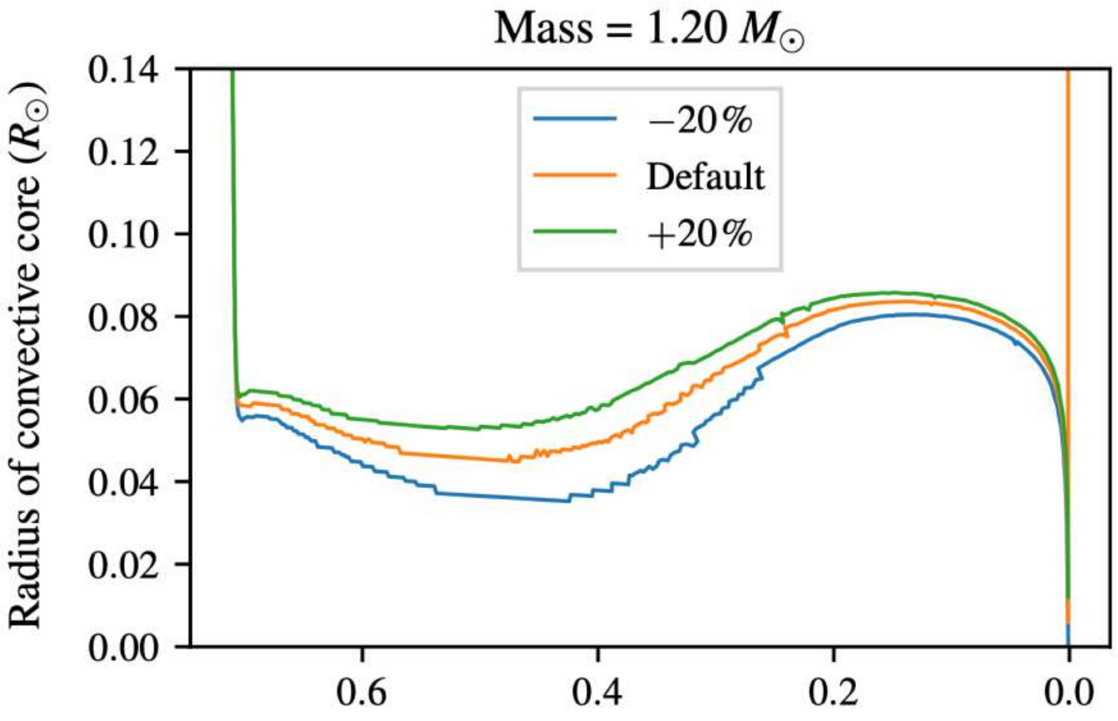
Central hydrogen

If 14N+p is not controlled, no way to separate the true CC boundary and the OV region

OV is the largest uncertain in stellar modeling

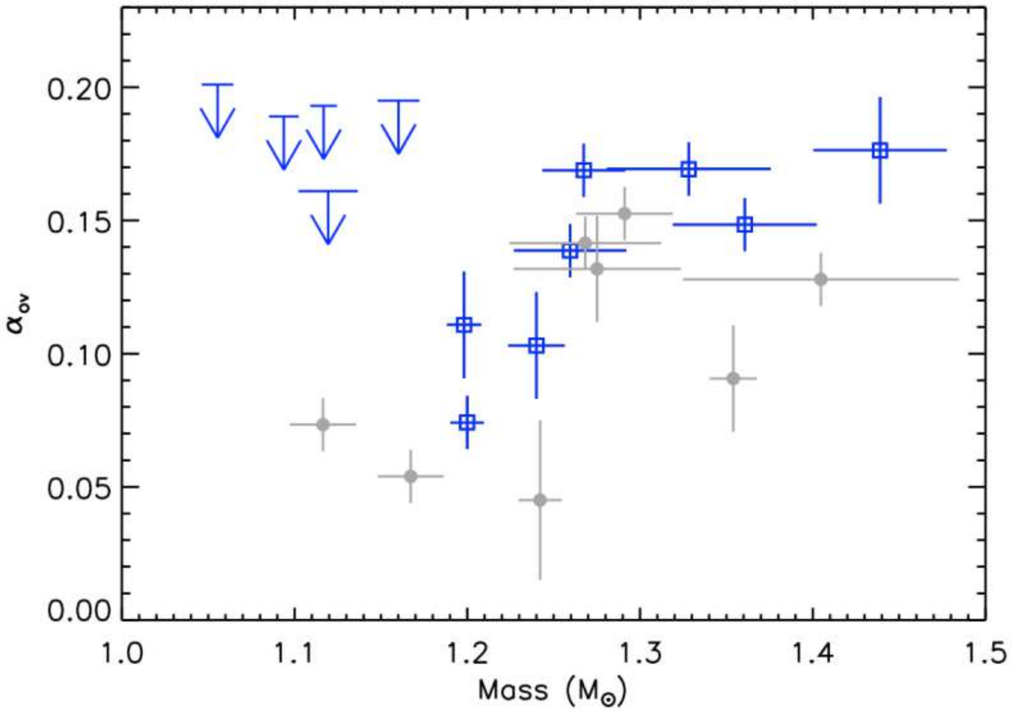
Size of mixed core: convective boundary + overshooting

Size of chemically homogenous (mixed) core is formed by
+ truly convective core
+ **overshooting region** (parametrized, α_{ov}, no 1st principles model)
It can be measured with astereoseismology



Central hydrogen

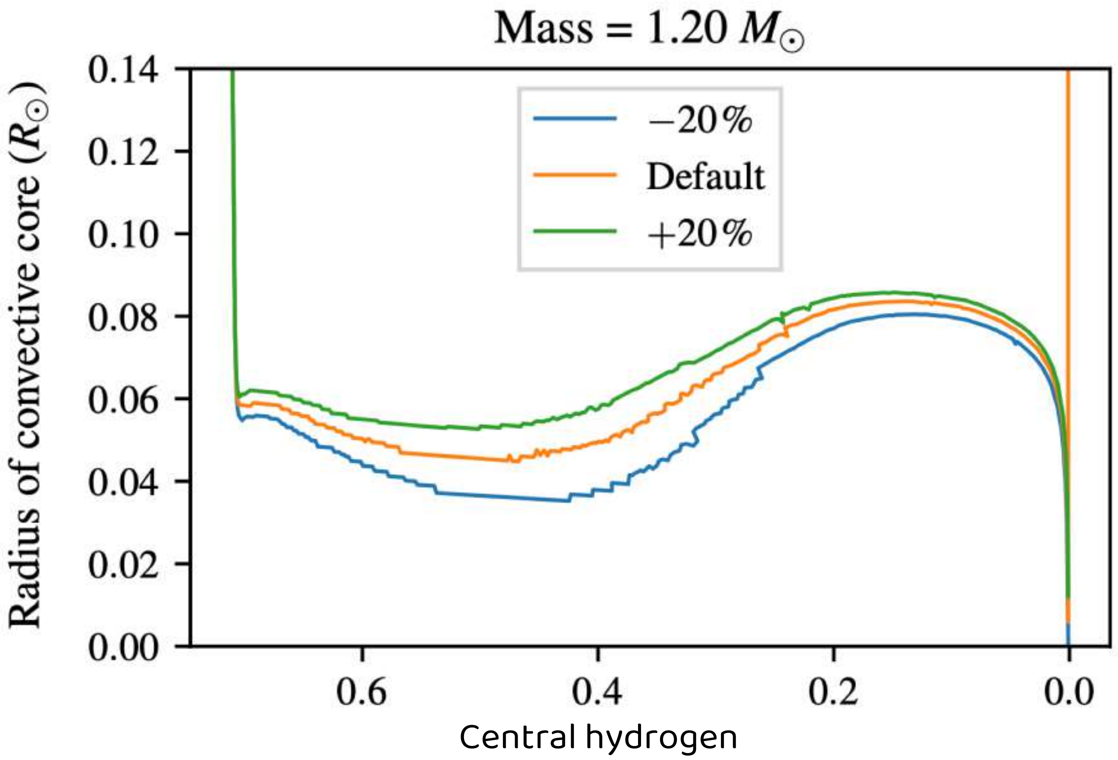
Calibrating OV in stars
Only if N14+p well known



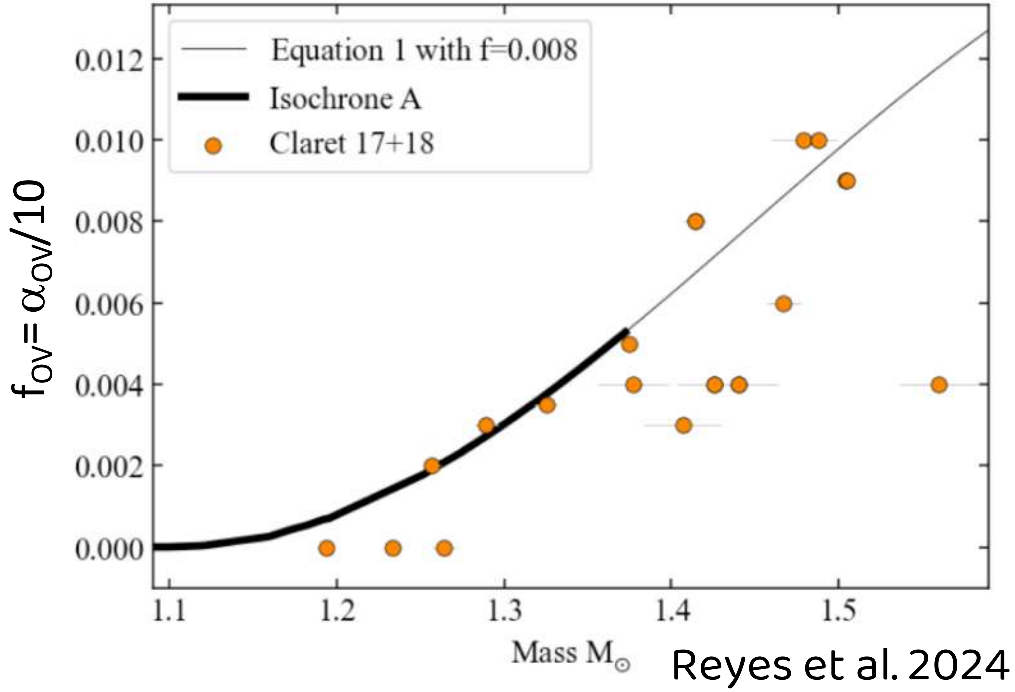
Deheuvels et al. 2016

Size of mixed core: convective boundary + overshooting

Size of chemically homogenous (mixed) core is formed by
+ truly convective core
+ **overshooting region** (parametrized, α_{ov}, no 1st principles model)
It can be measured with astereoseismology



Calibrating OV in M67
Only if N14+p well known

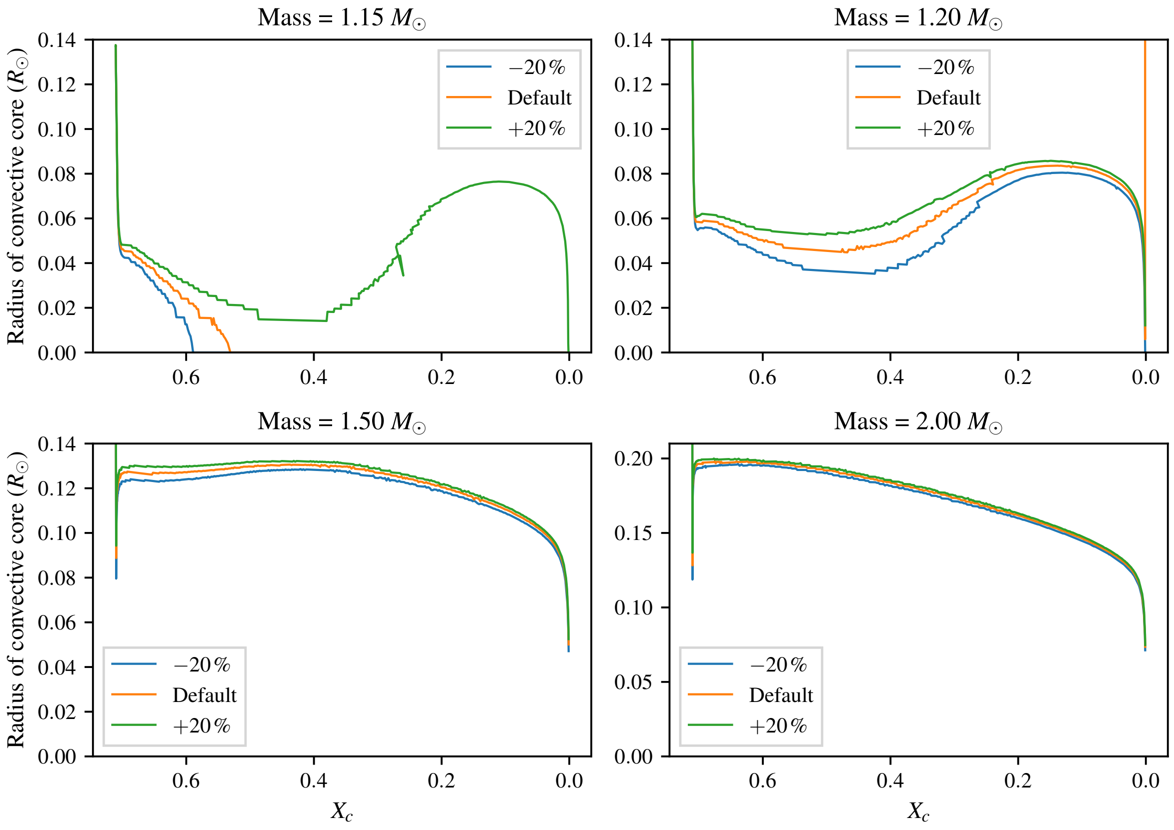


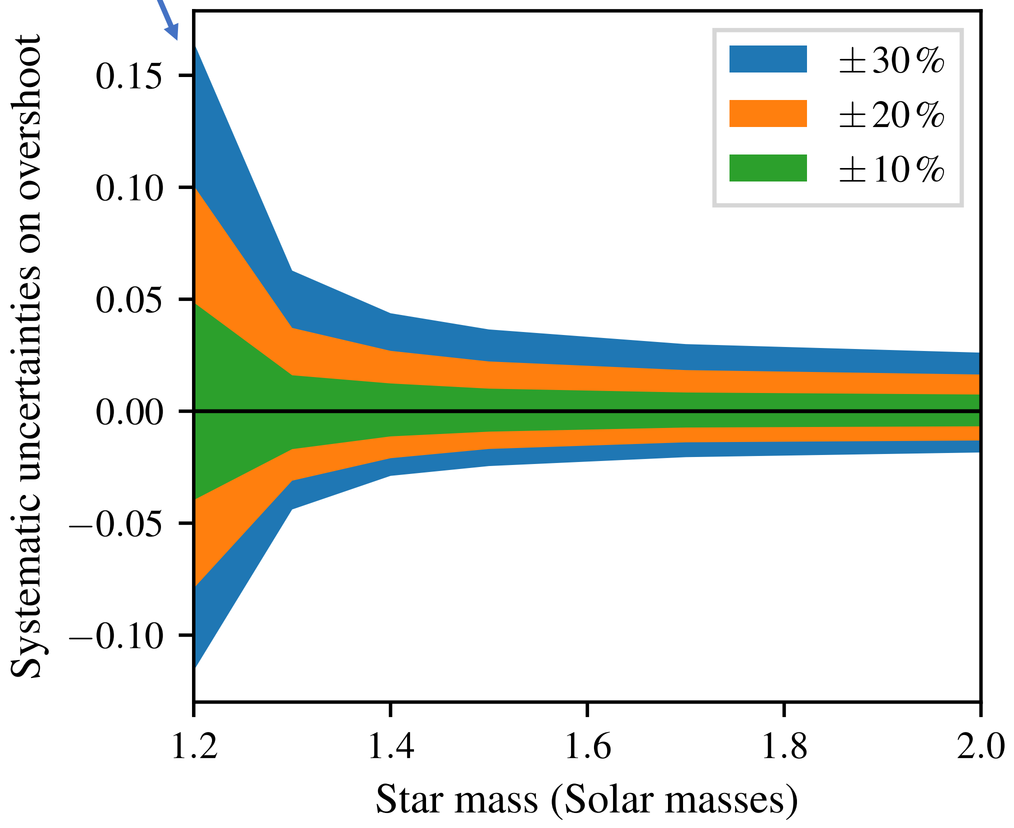
Reyes et al. 2024

Size of mixed core: convective boundary + overshooting

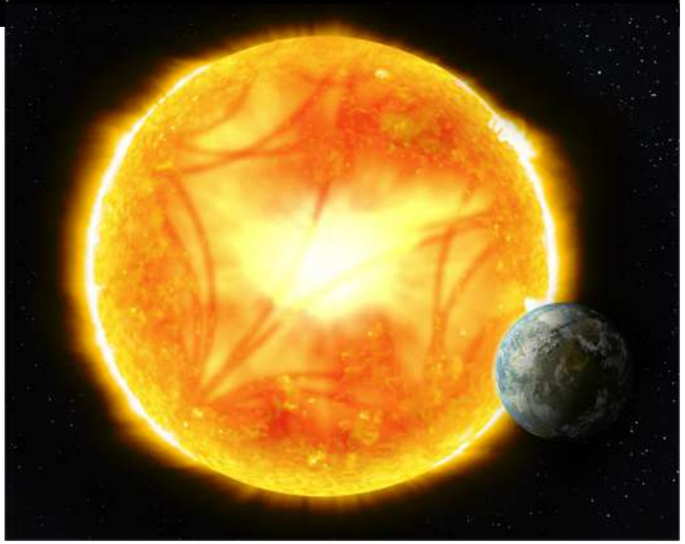
Parametrization of overshooting for stars in the 1.1-1.4 $M_\odot$ range requires improved 14N+p

Typical OV values are 0.2-0.25 → at low masses, uncertainty is very large

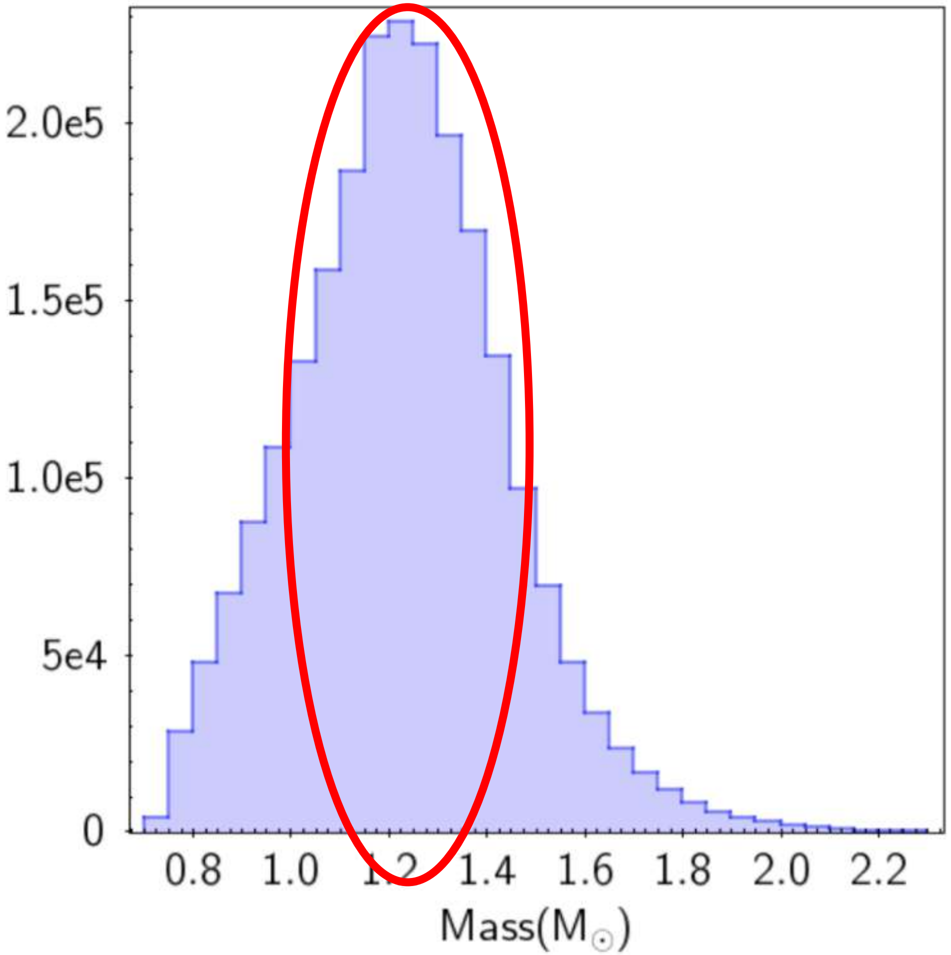




Critical for PLATO science, ESA's planet hunter & asteroseismology mission (launch December 2026)



Estimated mass distribution for FGK PLATO Sample



Summary

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

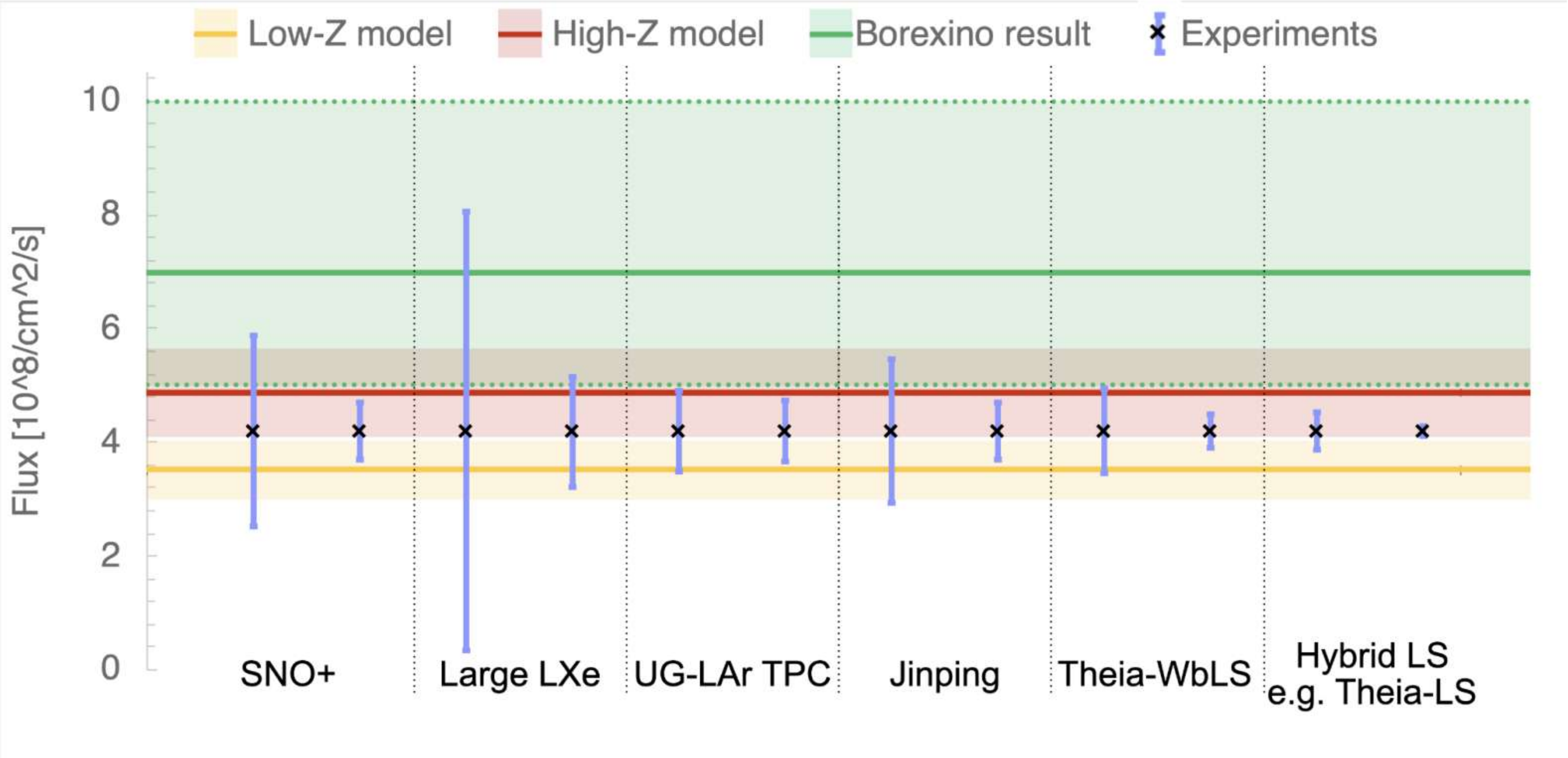
- High solar metallicity is favored by (degenerate with opacity):
  - sound speed, surface helium, depth of convective envelope
  - pp-chain solar neutrinos
- but lower solar metallicity is favored by (degenerate with equation of state):
  - adiabatic index
- CNO neutrino break degeneracy with opacity → nuclear reactions main (and controllable) uncertainty
- Uncertainty in composition can be tamed by better CN neutrinos (models and experiments)

Science – only possible in the Sun

For solar-like oscillators:

- main target of PLATO missions – finding an Earth analog around solar-like stars
- 14N+p is fundamental to model evolution of stars in range 1.1 to 1.5 $M_{\odot}$
- empirical determinations of overshooting – the largest uncertainty in stellar modeling – are contigent to our knowledge of 14N+p rate

Future



Orebi-Gann et al. 2021

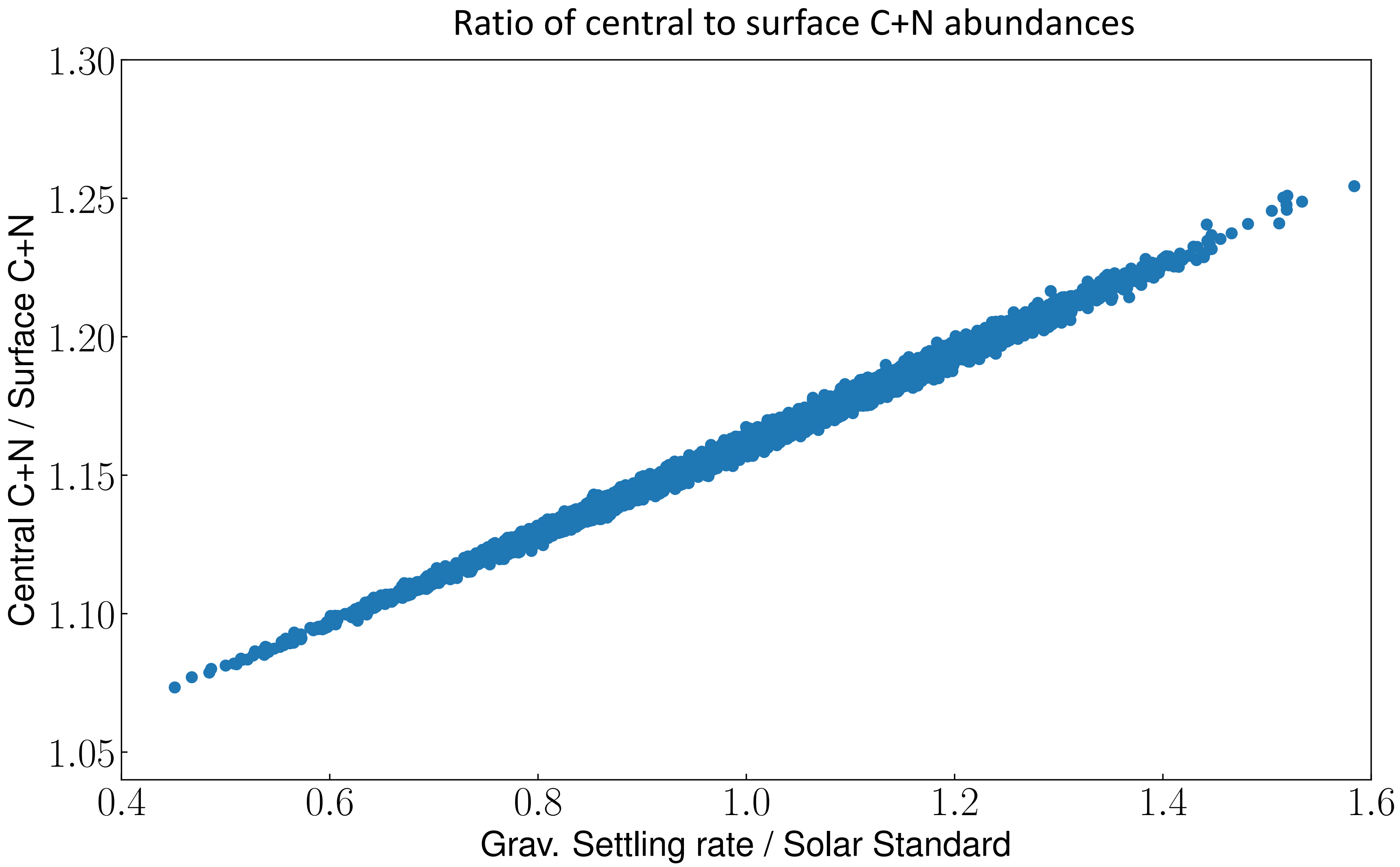
Future: measurement of diffusive processes in the Sun?

Current errors too large

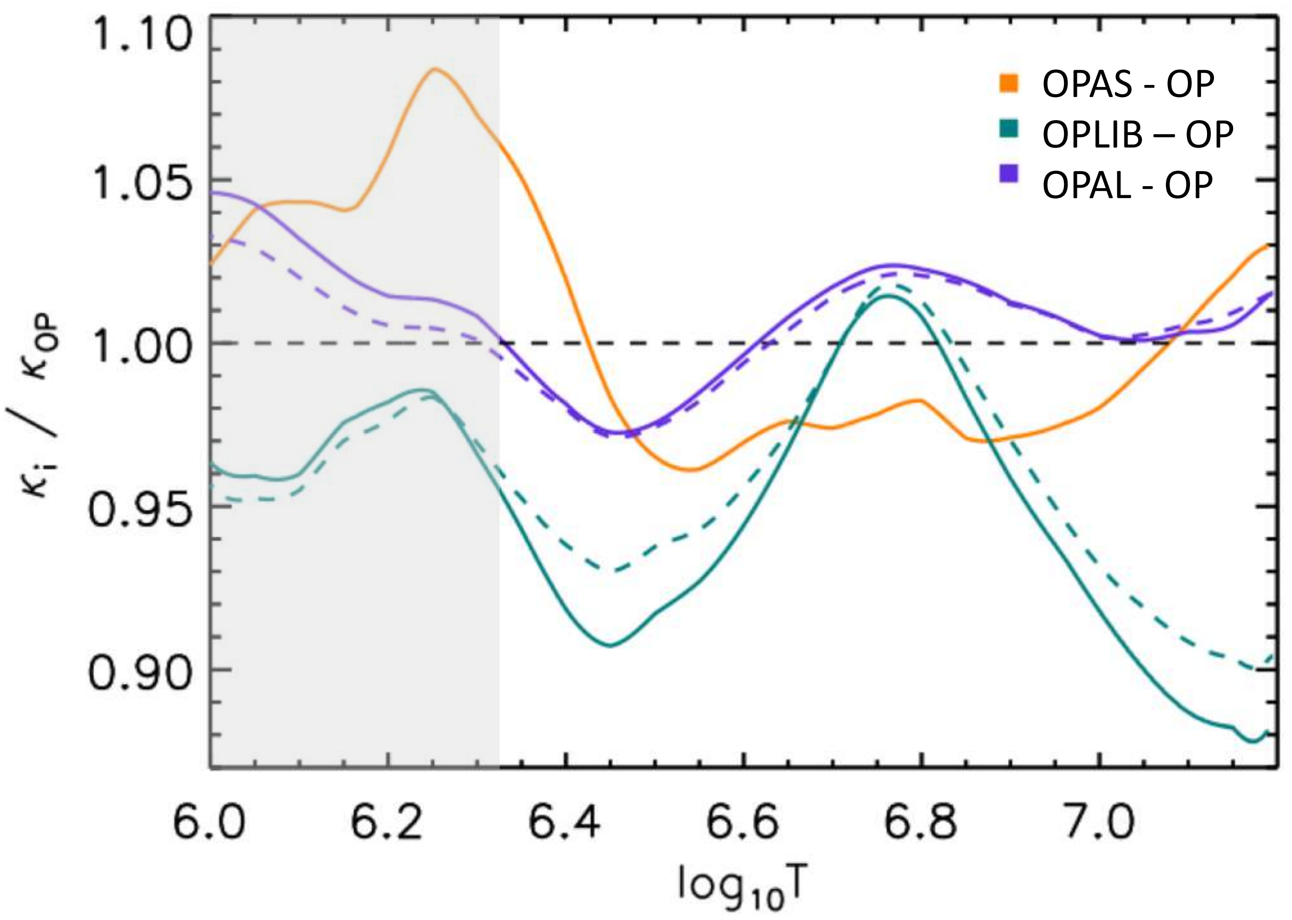
- 10-15% spectroscopy
- 20% neutrinos

Errors of a few % would be needed

Possible in the (distant?) future



Solar (stellar) radiative opacities



Dashed – GS98

Solid – AGSS09

Solar (stellar) opacities

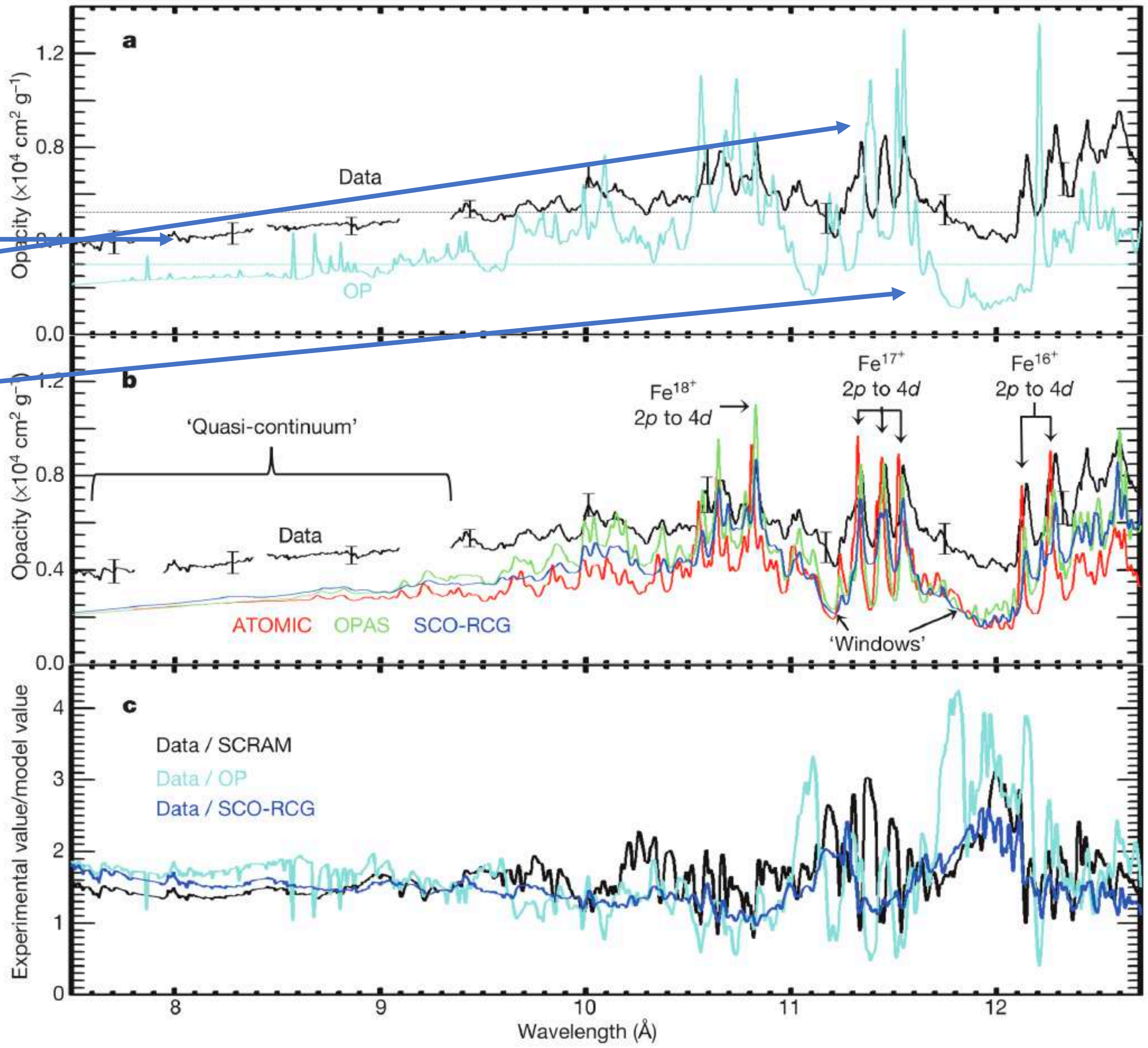
Bailey et al. 2015

Calculations have:

1) Lower quasicontinuum

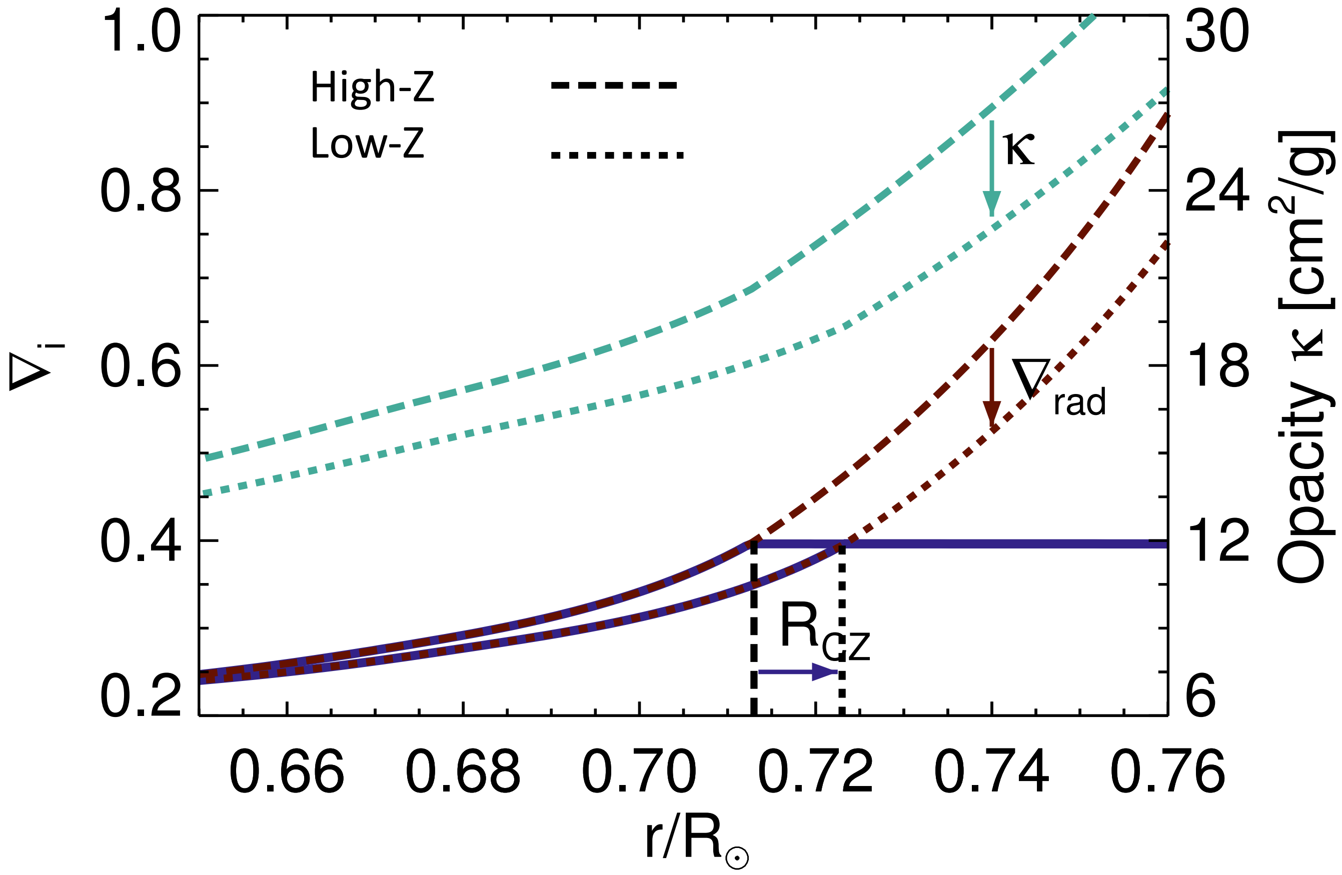
2) Narrower lines

3) Deeper opacity windows



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

Impact of metallicity



Solar model with low-Z has overall lower opacity

→ flatter temperature profile
→ slightly lower internal temperature

→ affects helioseismology
→ pp-chain neutrinos

Degeneracy between metals and opacity very difficult to break

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