GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

The Sun as a cornerstone for (stellar) foundation science

European Nuclear Physics Conference 2025
Caen, France – September 22nd-26th - 2025

A. Serenelli

ChETEC INFRA

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Outline

- Fundamental science with the Sun

  solar atmosphere and theoretical spectroscopy

  a view from helioseismology

  a view from solar neutrinos – CN-νs, a unique opportunity

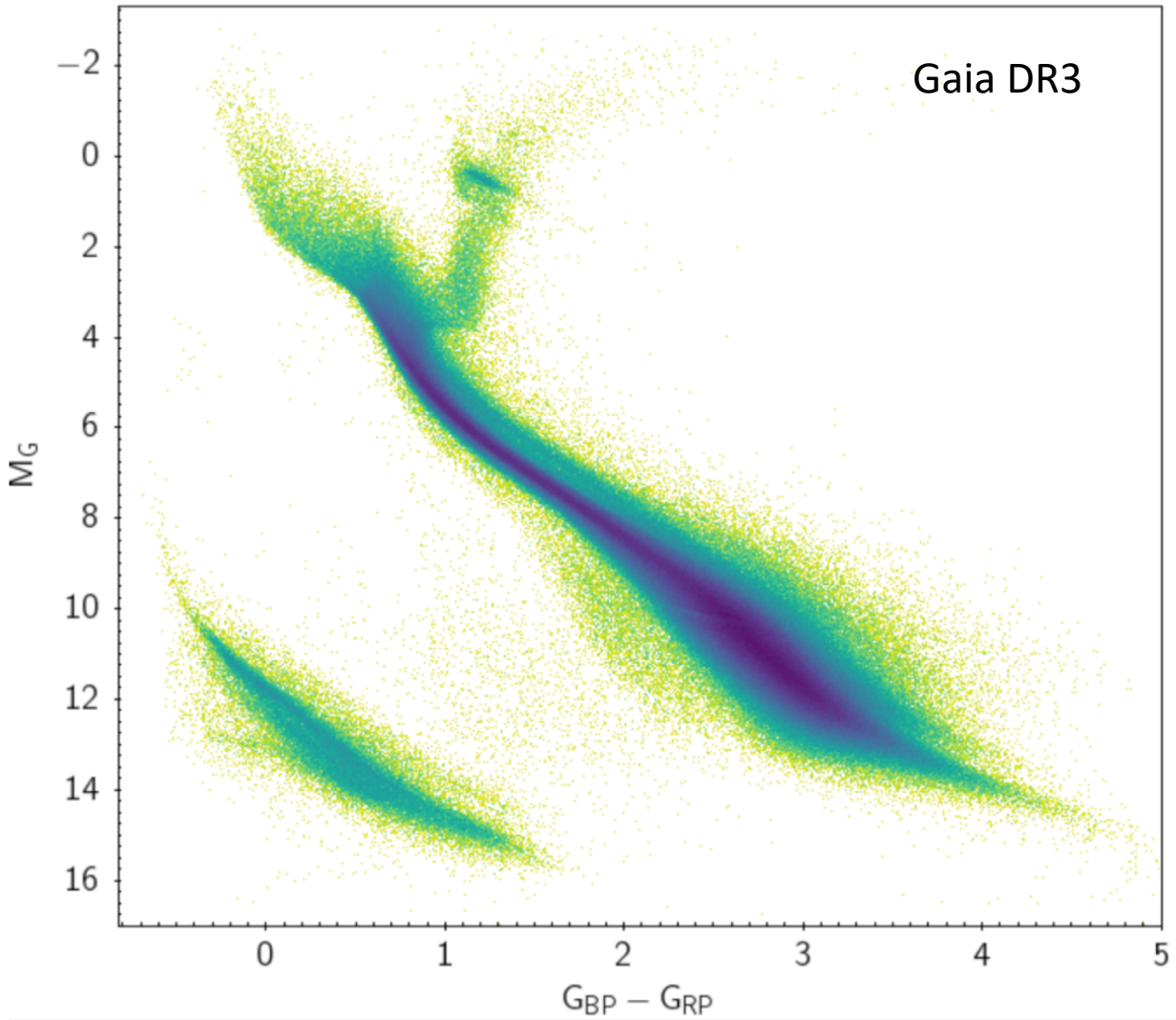
  Sun as a calibrator for stellar ages

- 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 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

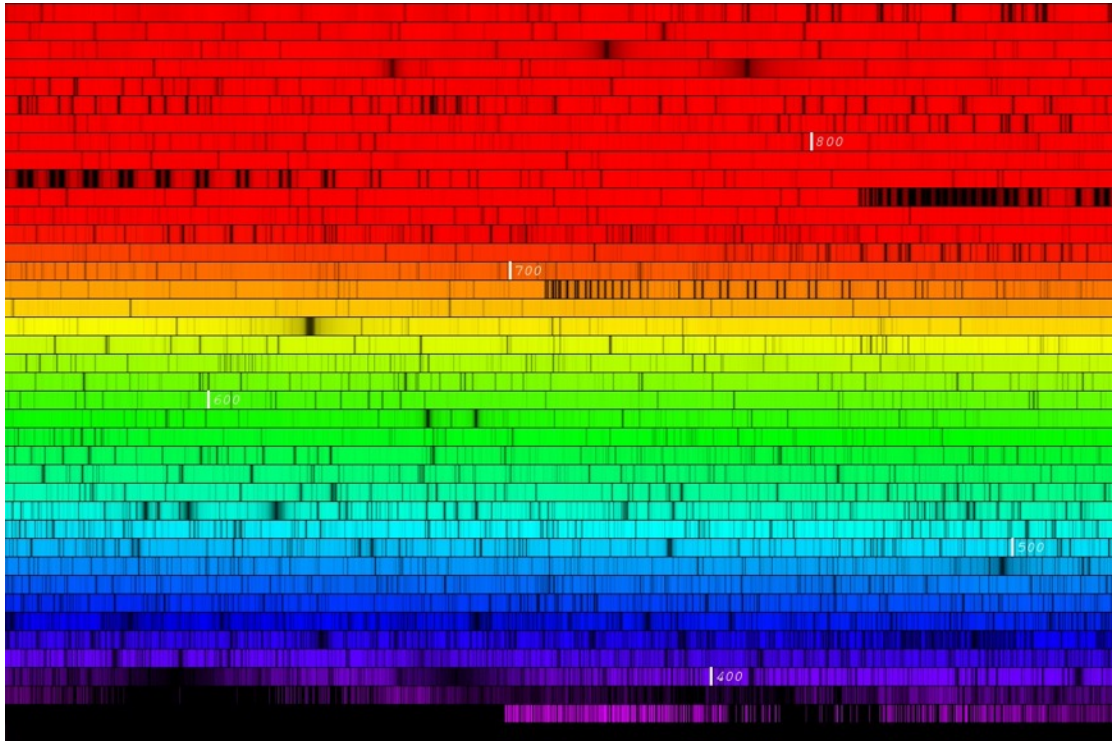
selective club: eclipsing binaries

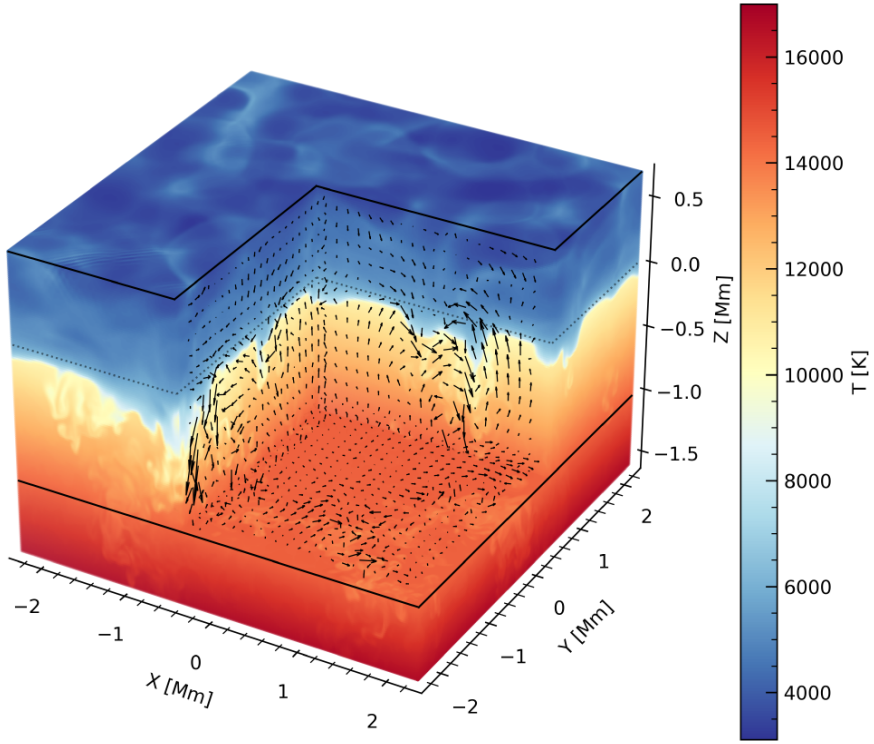
- **1 star with accurate, precise, (model) independent age determination**

  meteoritic dating
  + highly accurate radius & mass

- **Solar composition is the yardstick for all astronomical abundance determinations**

Foundation science: Solar spectrum & abundances





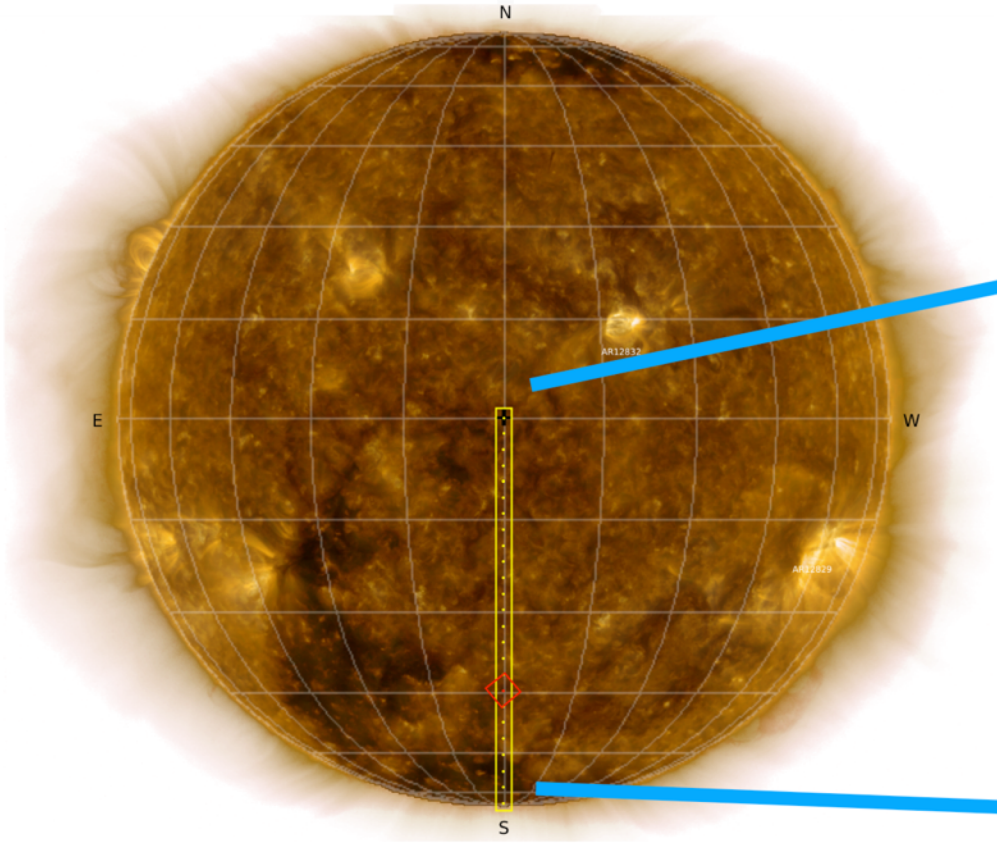
Solar envelope is convective
→ hydrodynamic models
→ 3D atmosphere model

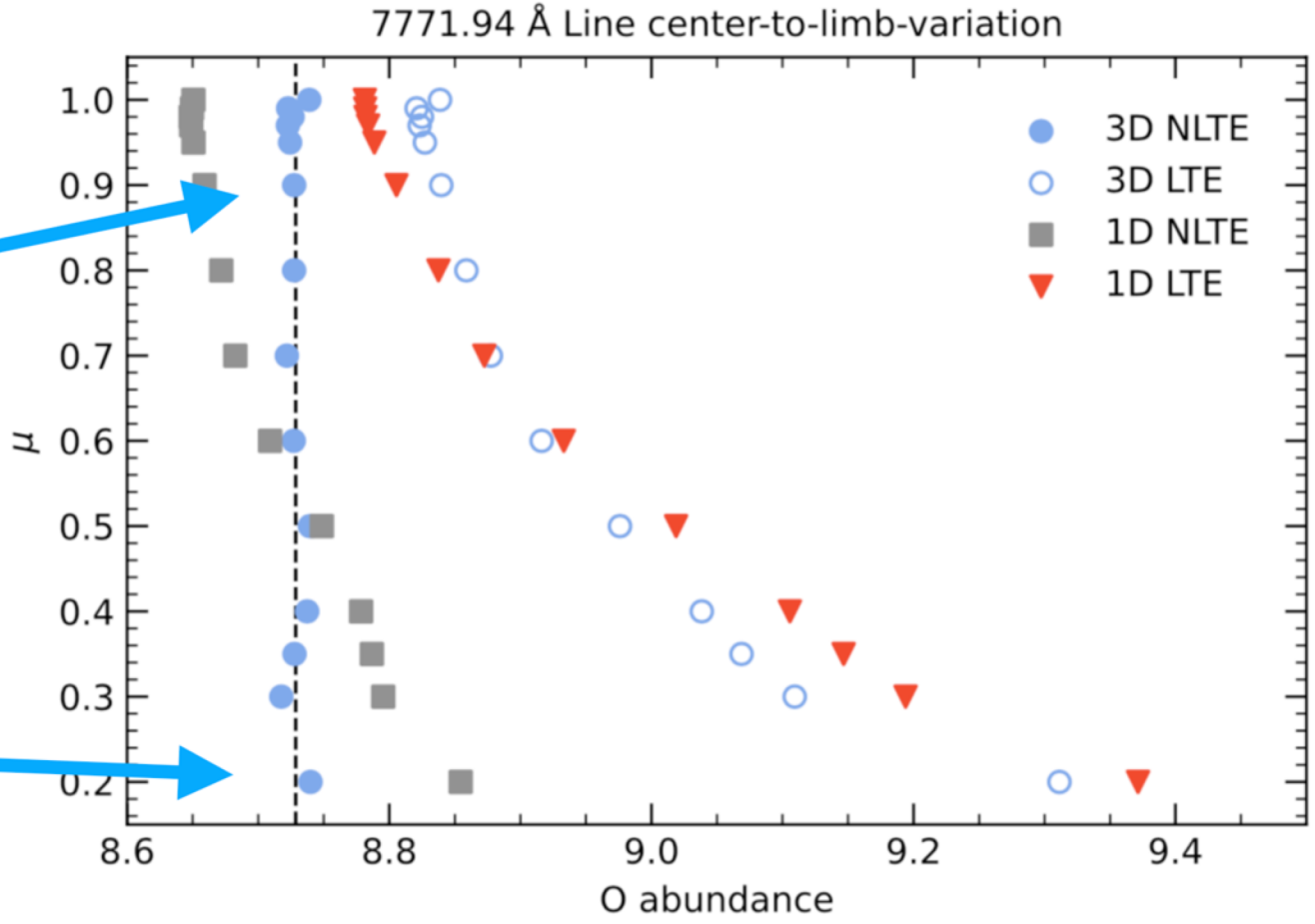
Model atmosphere
→ detailed radiative transfer
→ synthetic spectrum to compare with observed one
→ determination of abundances

Foundation science: Solar spectrum & abundances

Institute of Space Sciences

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

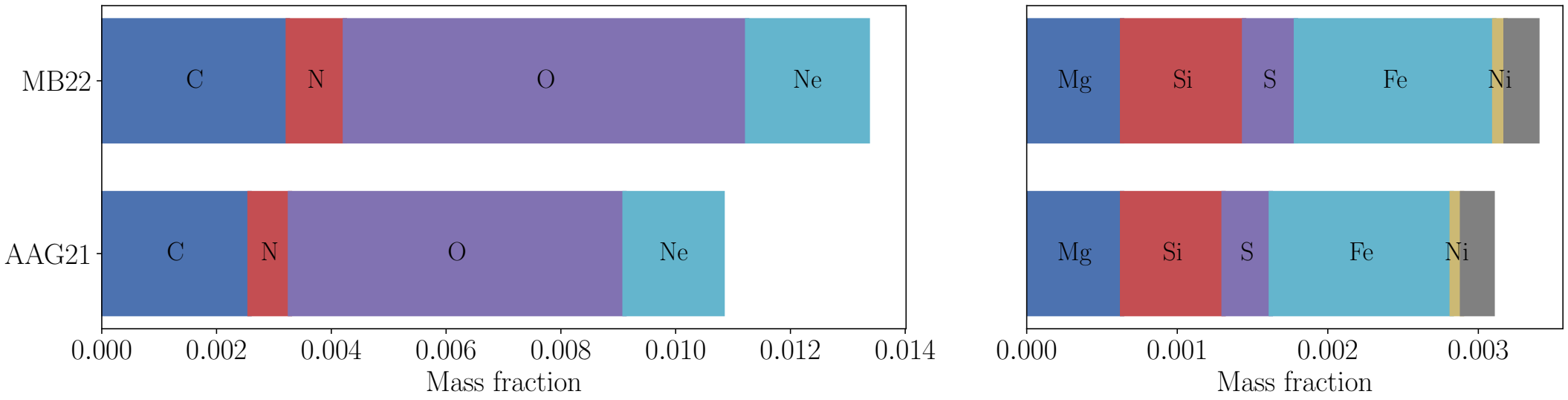




Pietrow, Hoppe, Bergemann et al. 2023
Bergemann, Hoppe, et al. 2021

(plots from M. Bergemann)

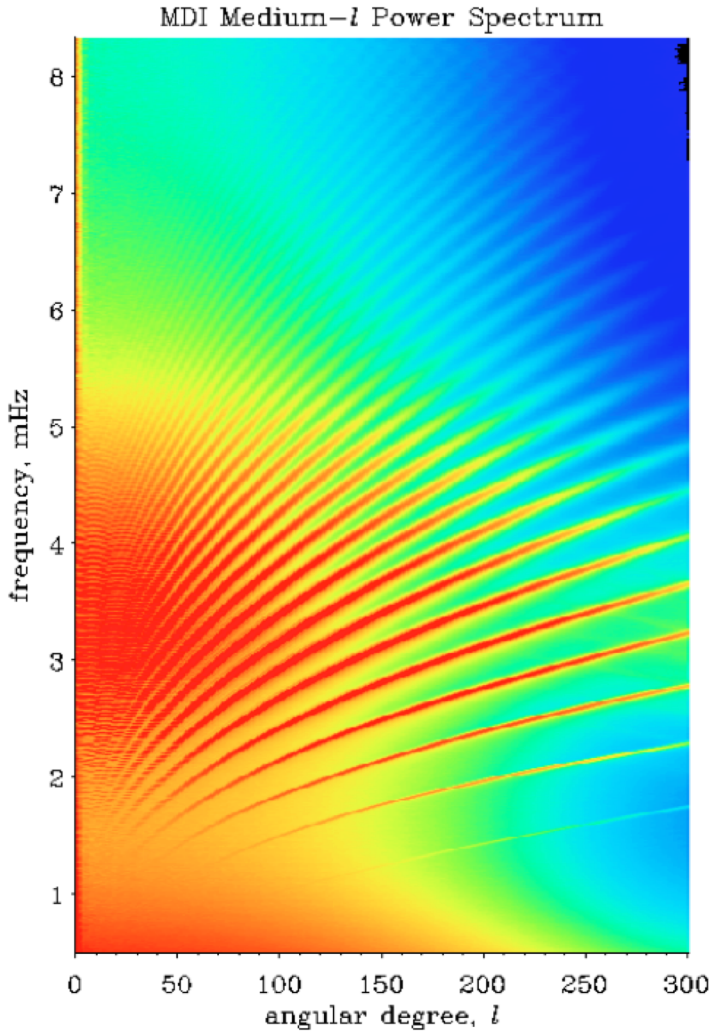
Which solar composition?



AAG21: Asplund et al. 2021
MB22: Magg et al. 2022

Chemical abundances are a boundary condition imposed to, not a prediction of, (non-) standard solar models

A unique view into the Sun: helioseismology



Helioseismology

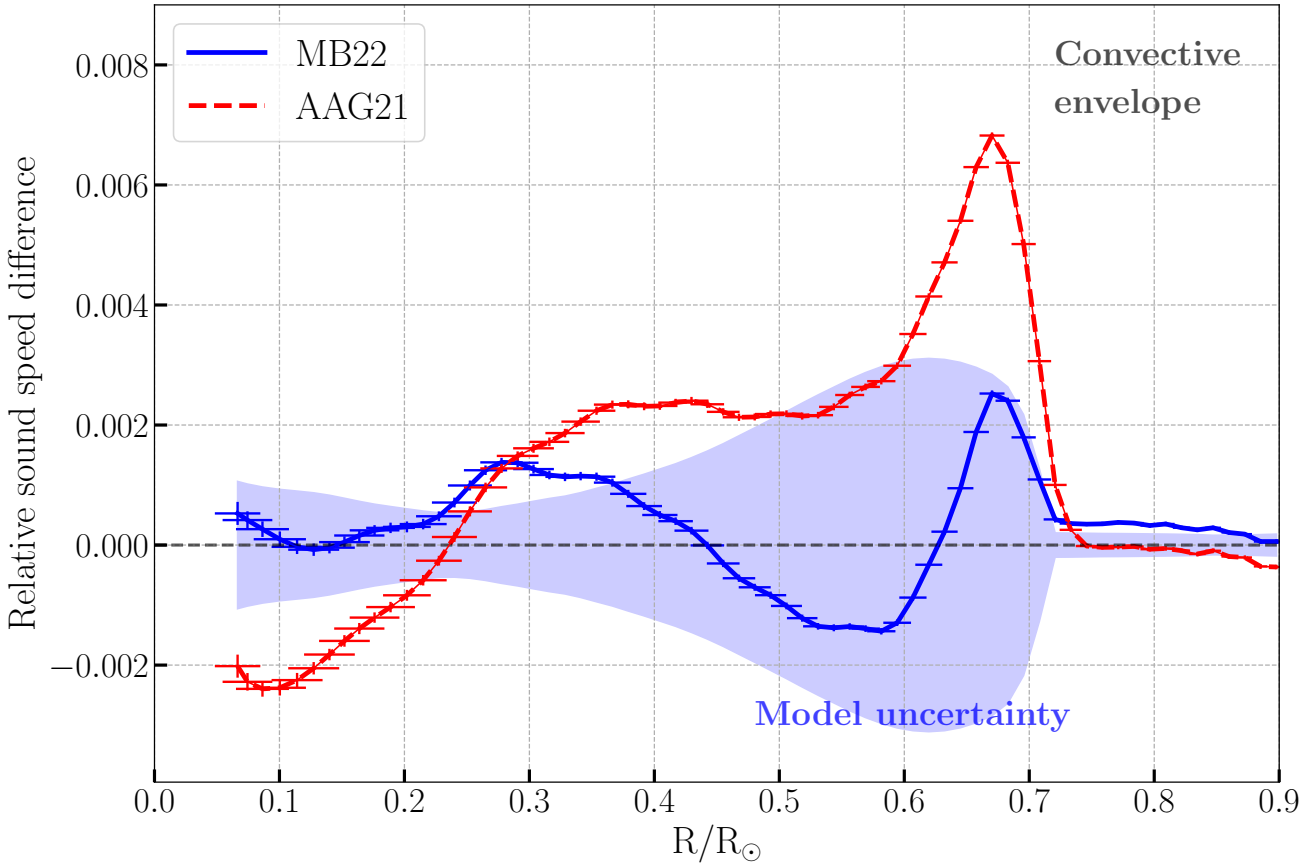
>10^5 eigenmodes → inversion of internal structure:
sound speed, density, adiabatic index (EoS)

→ global quantities:
surface helium, depth of convective envelope

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

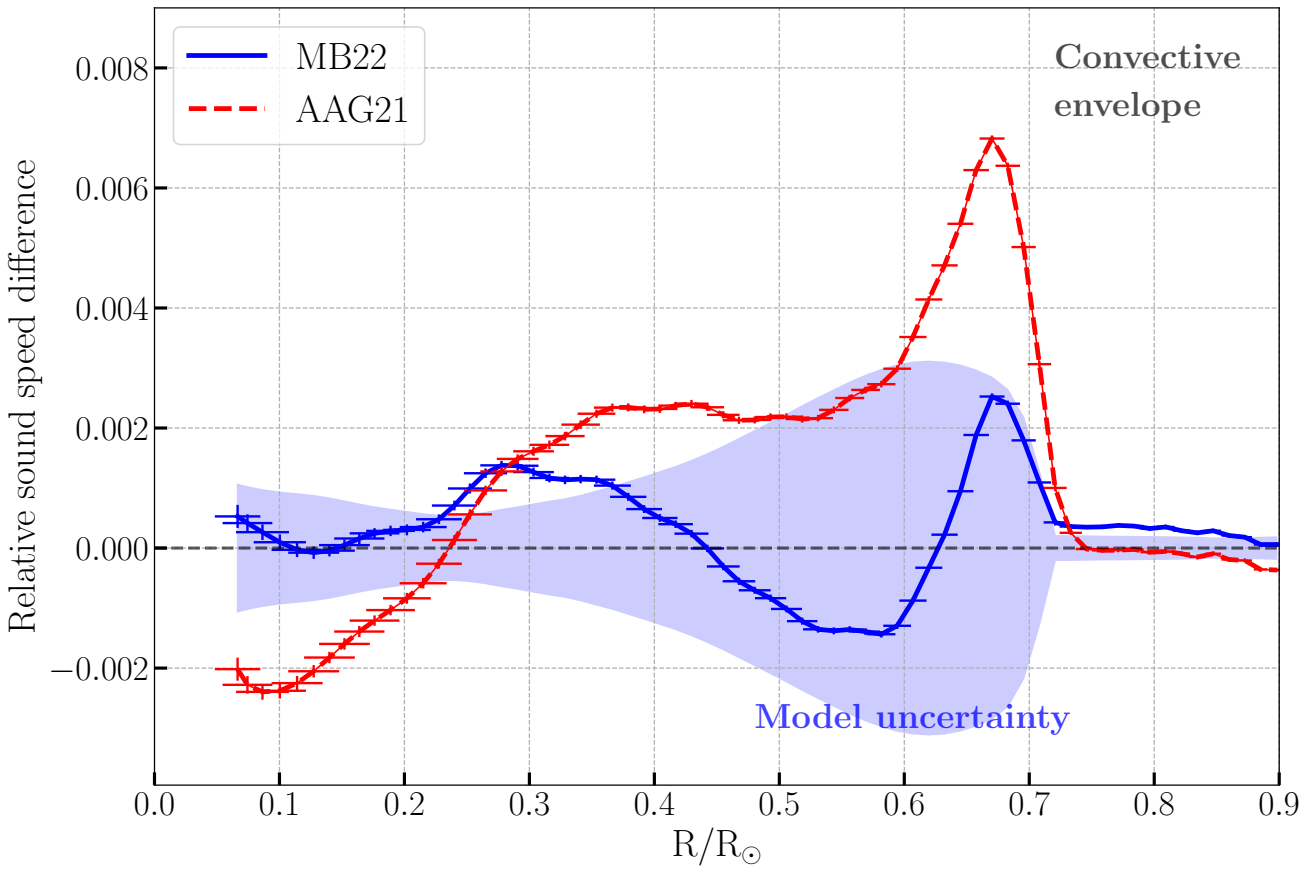
Allows testing theory of stellar evolution by looking at internal structure

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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Solar	**0.713 ±0.001**	**0.2485 ±0.0035**			

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

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

thermal gradient →
"composition + radiative opacities"

Another look from helioseismology

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

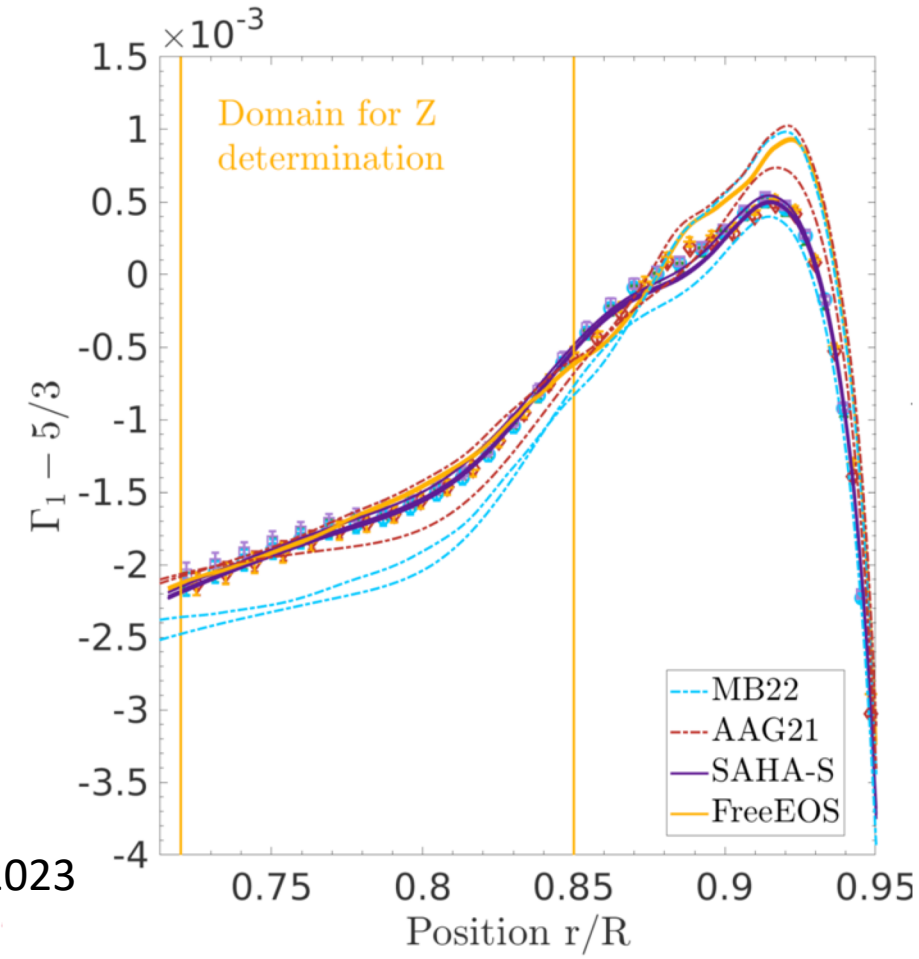
$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\mathrm{ad}}$$

= 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.
- Sensitive to total Z (very difficult to extract individual elements)

Composition + Equation of State

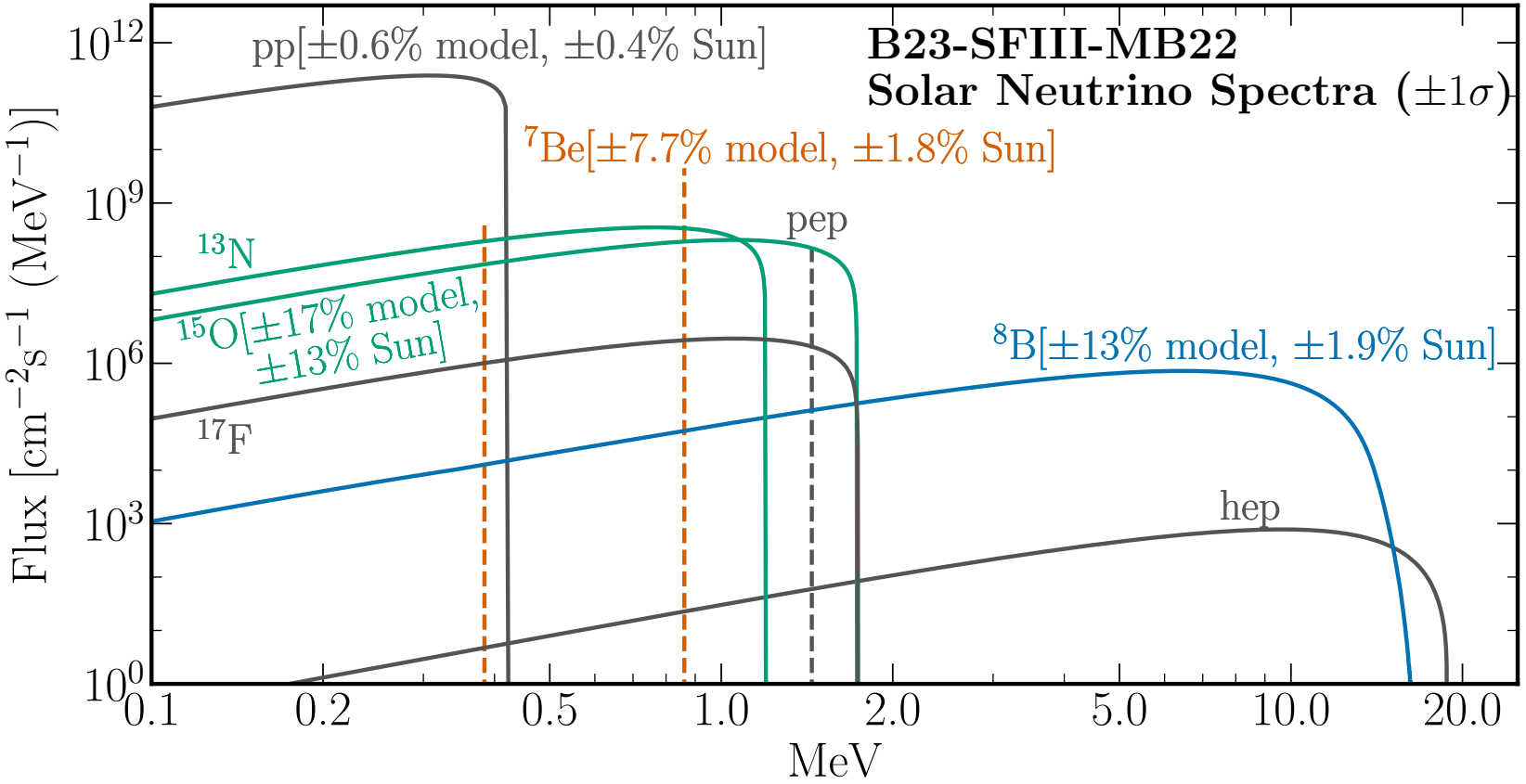
Low-Z favoured over high-Z



Buldgen et al. 2023

A unique view into the Sun: solar neutrinos

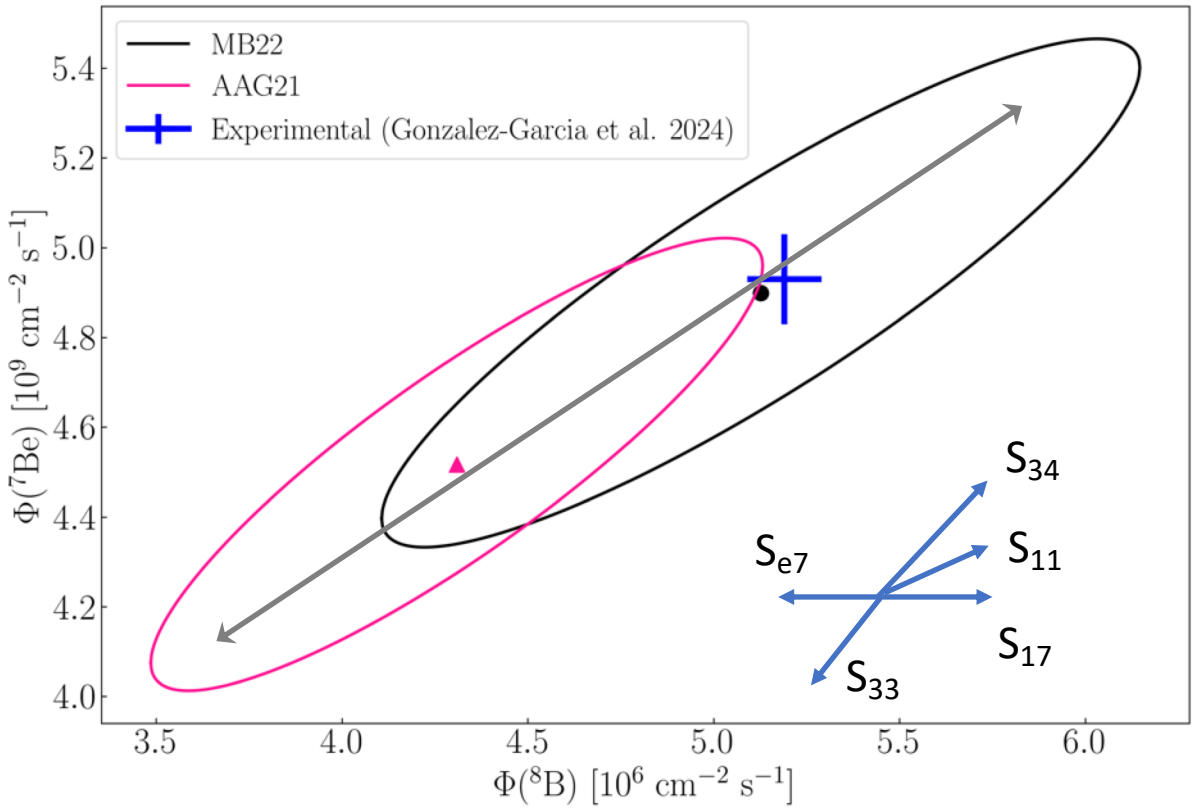
Solar neutrinos → information on solar core, nuclear physics



Model uncertainties >> experimental uncertainties!

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
^{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},S_{11})

6% for ^{7}Be

8% for ^{8}B

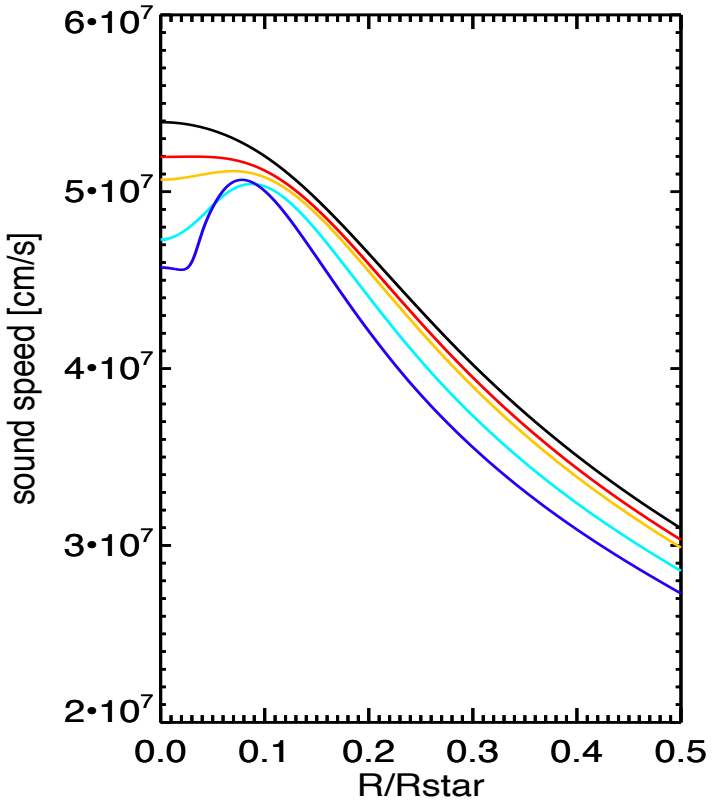
core thermal structure (comp. + opacities)

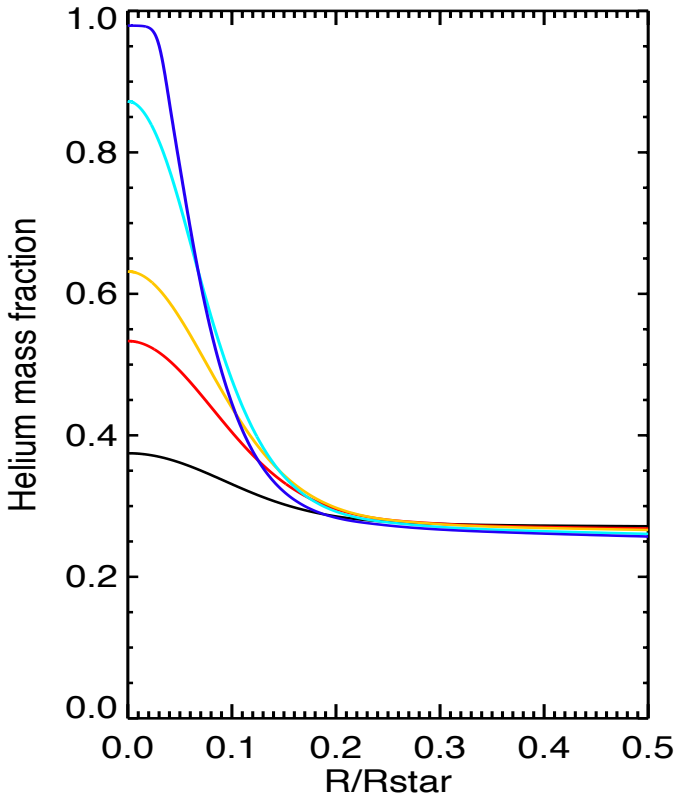
pp-chain neutrinos provide a measure of core temperature

Dating the Sun "as a star"

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

$$\nu_{n,\ell} - \nu_{n-1,\ell+2} \propto \frac{1}{4\pi\nu_{n,\ell}} \int_0^R \boxed{\frac{dc}{dr}\frac{dr}{r}} \longrightarrow$$ sound speed gradient at solar/stellar core as age diagnostics



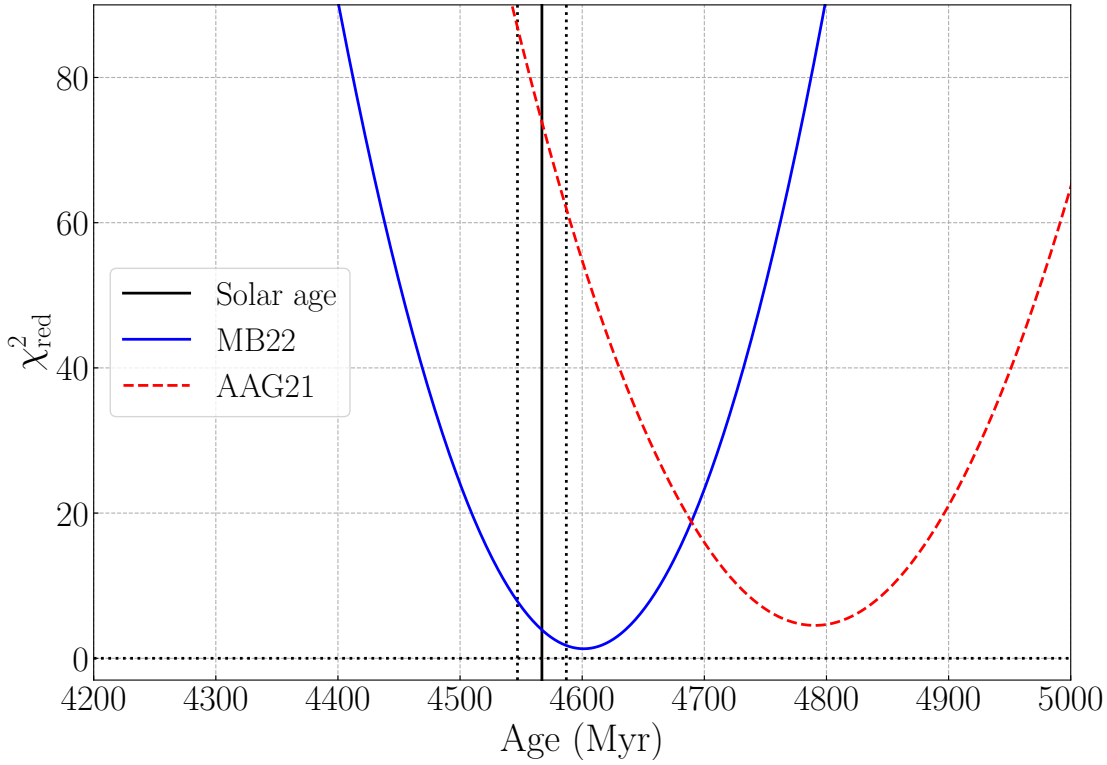


$$c^2 \propto \frac{T}{\mu}$$

The Sun as a star – only independent age calibrator

No independent age for other stars

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

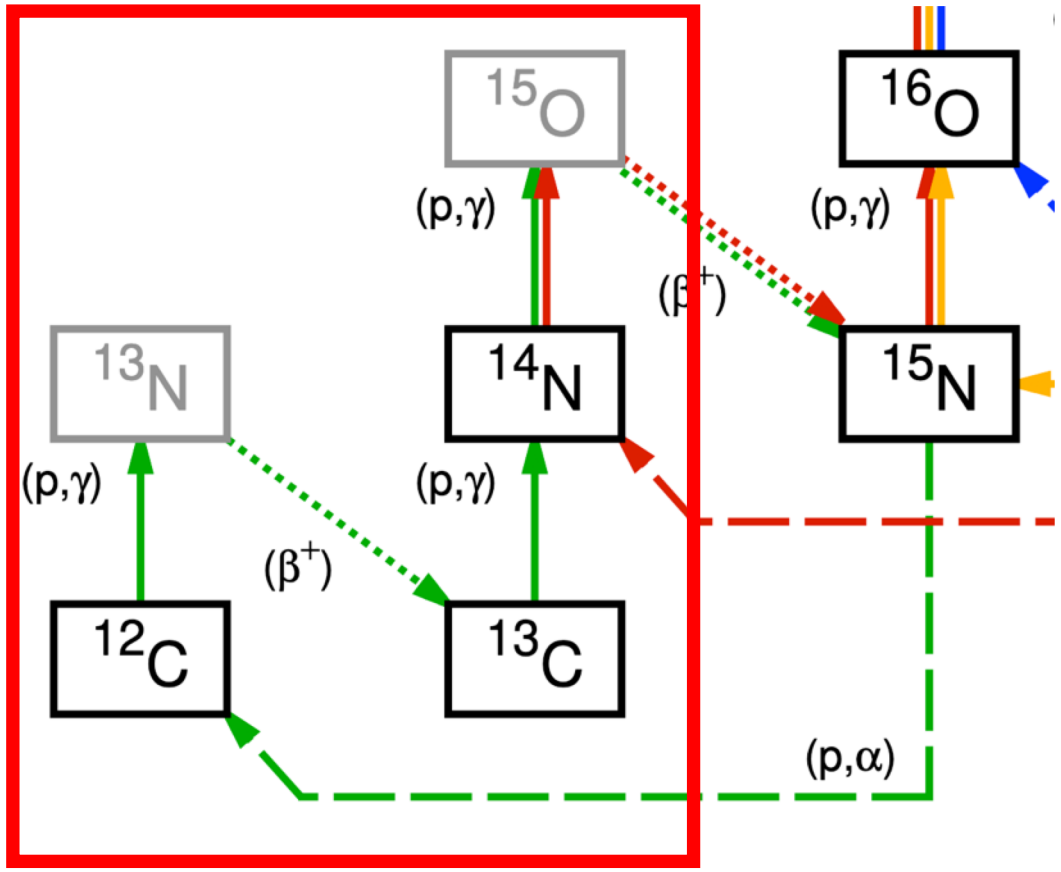


	Solar age (Gyr)
Sun	**4.568 ± 0.020**
AAG21	4.790 ± 0.034
MB22	4.611 ± 0.032

Composition+opacities introduces a systematic effect on age determination of about to 250Myr (5%)

CN-cycle is a trace contribution to solar structure

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

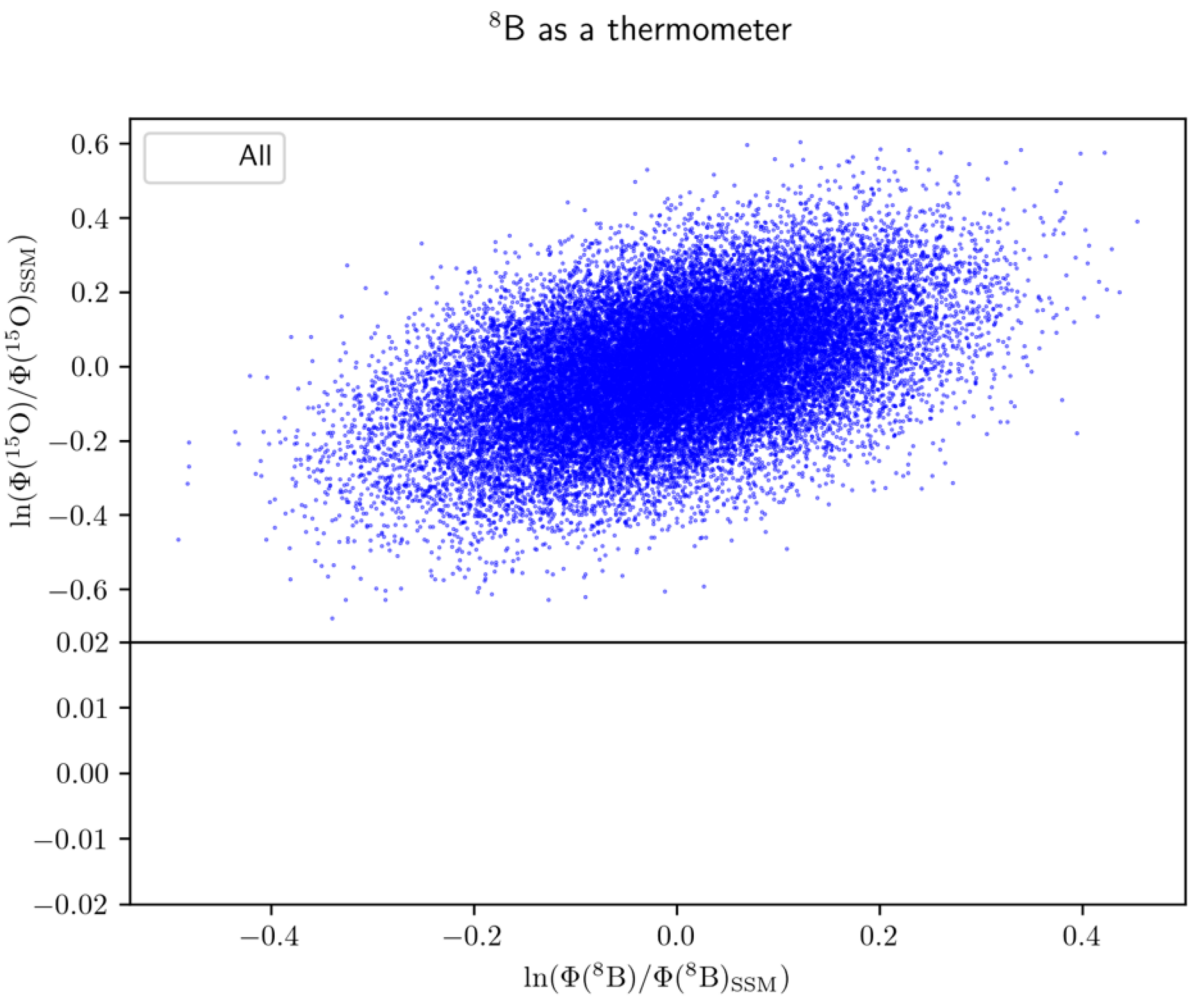


Changes in physics affecting CN do not change structure, **i.e. core temperature**,

→ 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



Updated from Serenelli et al. 2013

Neutrino fluxes depend on:

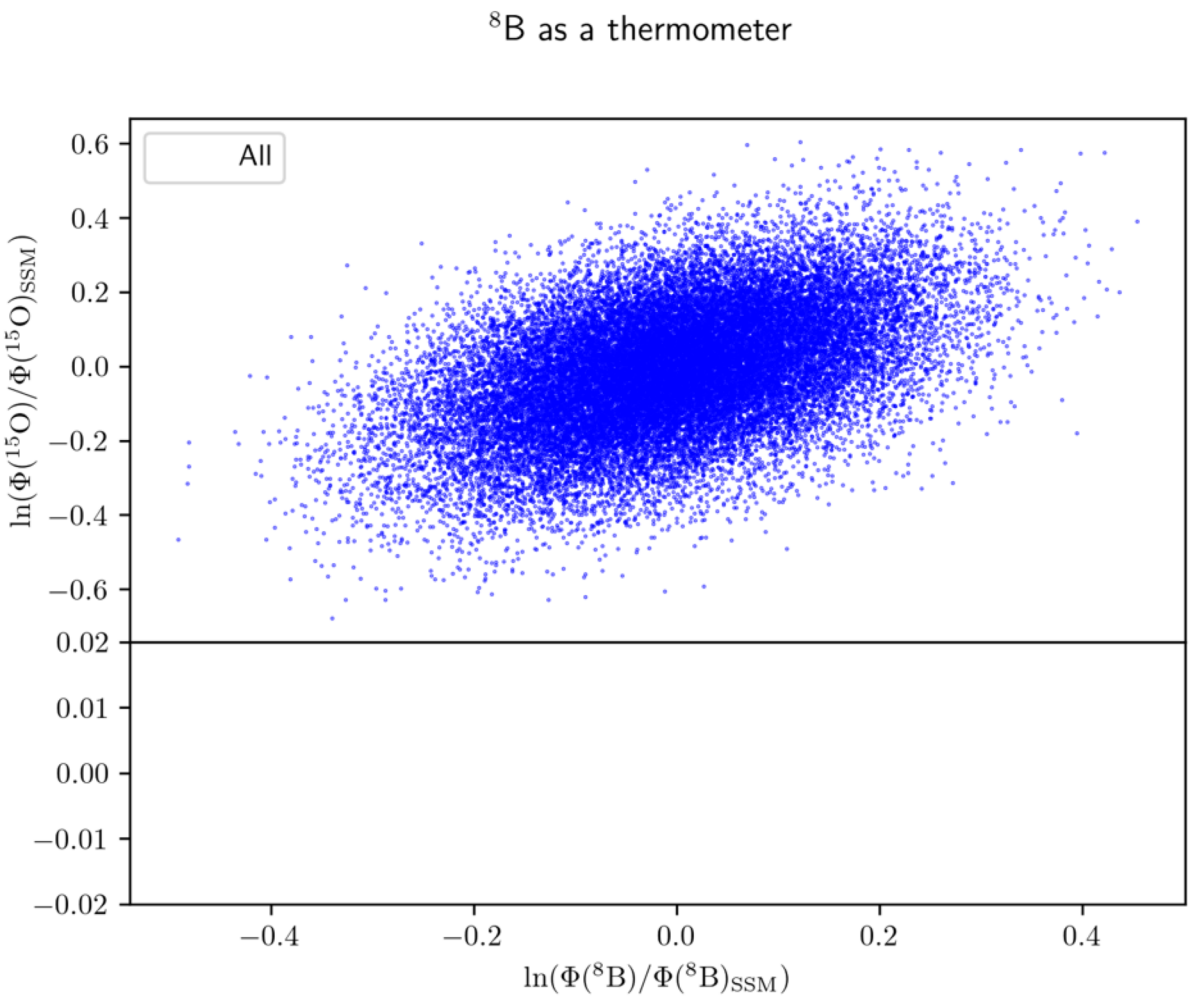
- **solar core temperature – environmental quantities**
  opacity
  heavy elements (Si, Mg, Fe)
  luminosity, age

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

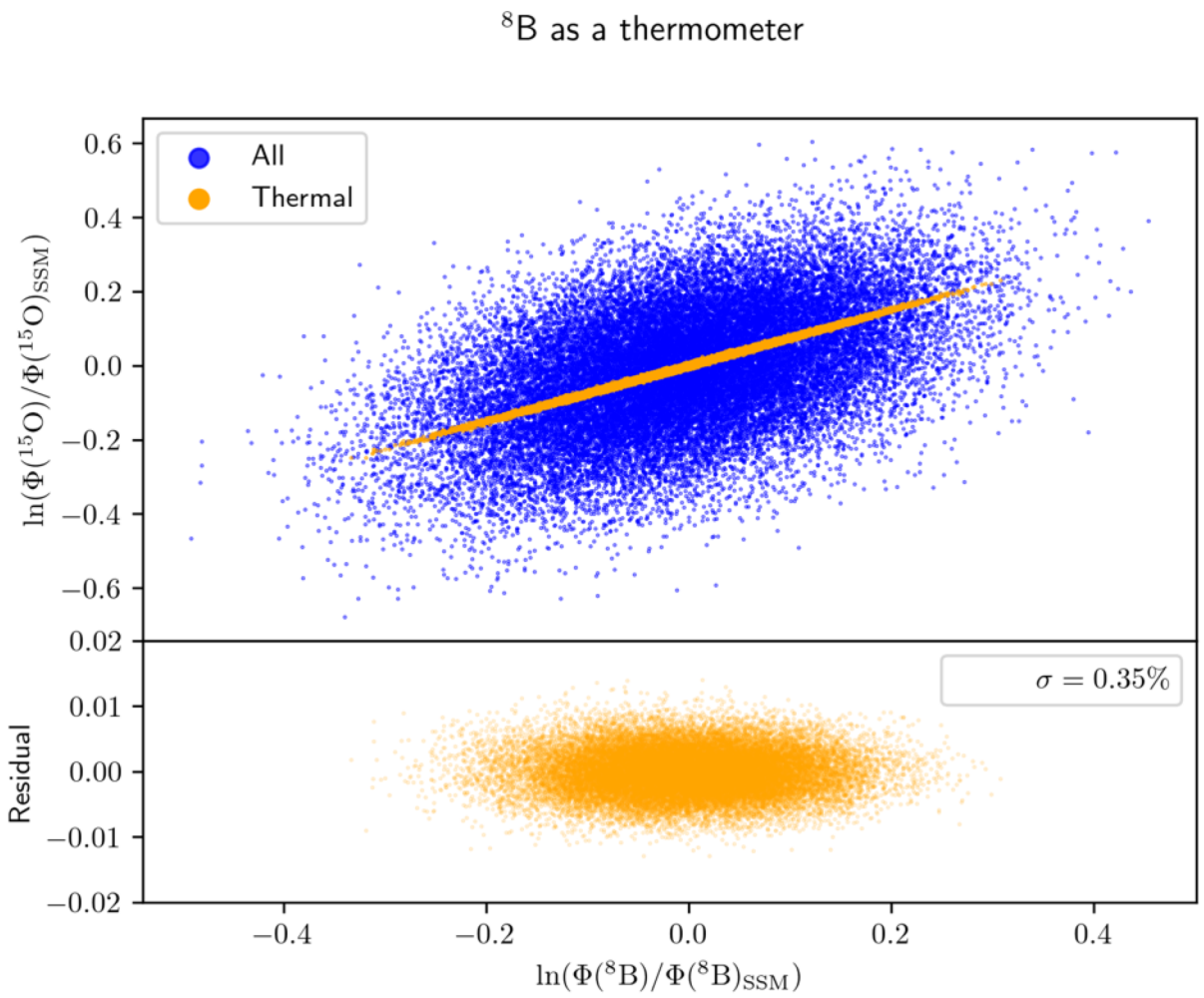


Neutrino fluxes as power-laws expansions:

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

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

What CN solar neutrinos tell us



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

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

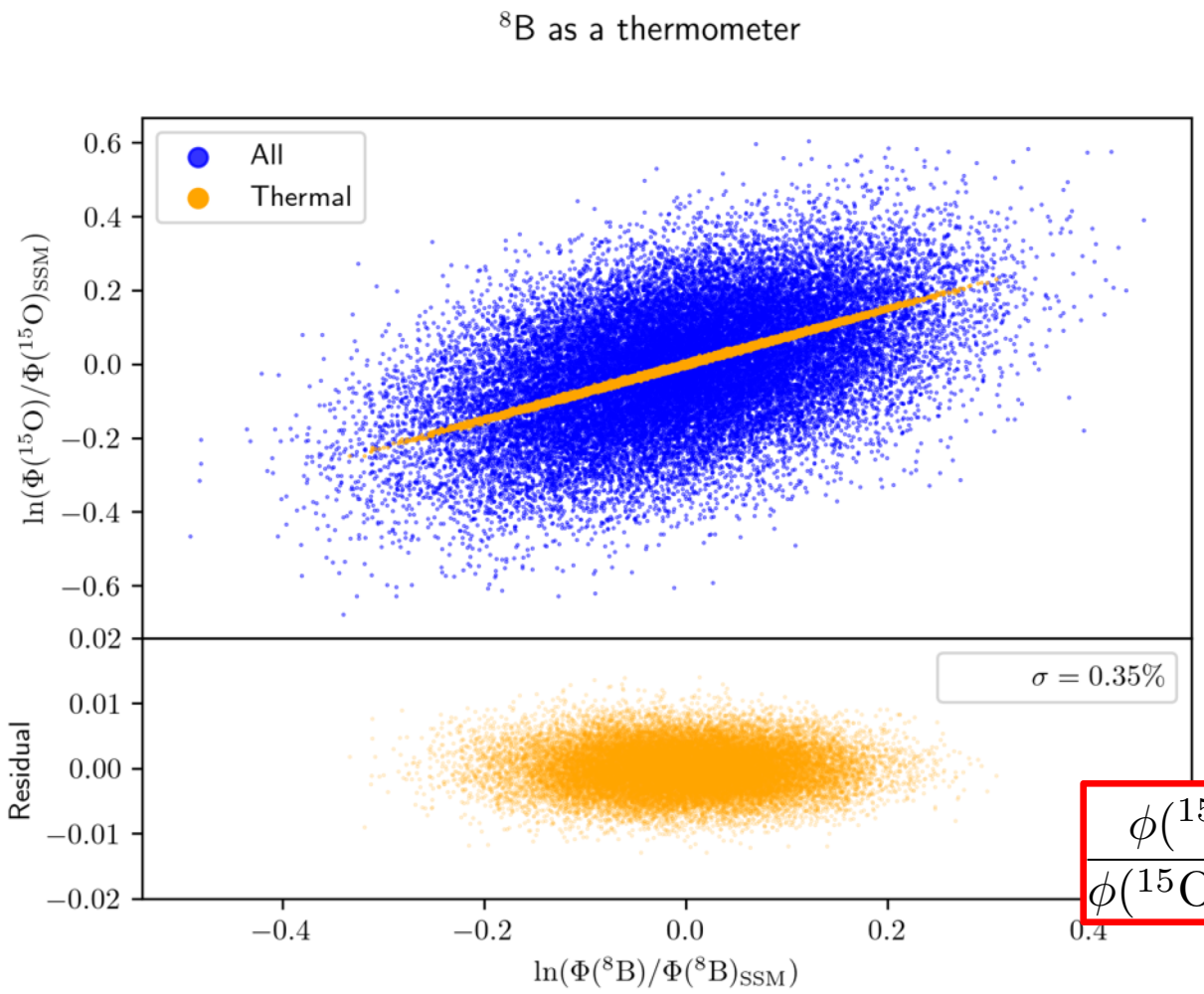
$$\times \left[L_\odot^{0.515} O^{-0.016} A^{0.308}\right]$$

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

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

0.3% uncertainty

What CN solar neutrinos tell us



Linear dependence on C+N

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

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

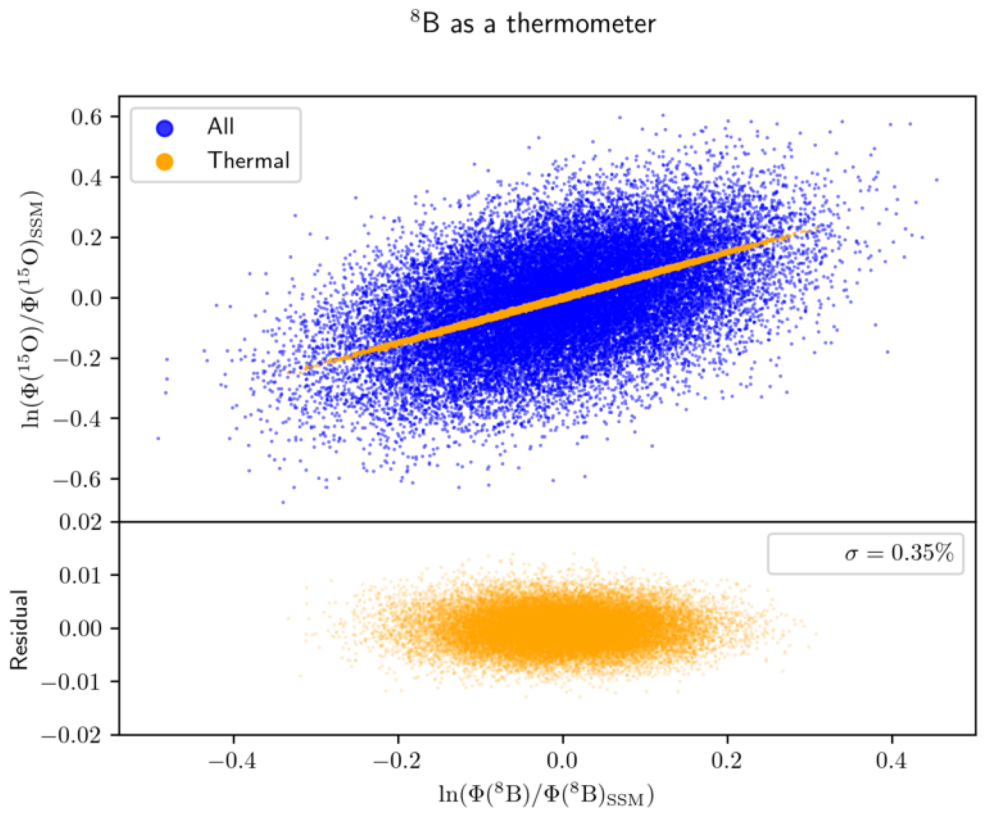
$$\boxed{\times \left[\mathrm{S}_{11}^{-0.831}\ \mathrm{S}_{33}^{0.342}\ \mathrm{S}_{34}^{-0.685}\ \mathrm{S}_{17}^{-0.785}\ \mathrm{S}_{e7}^{0.785}\ \mathrm{S}_{114}^{0.995}\right]}$$

$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.} \quad {}^{01} x_{\mathrm{Fe}}^{0.003}\right]$$

Nuclear reaction rates

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

What CN solar neutrinos tell us



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

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

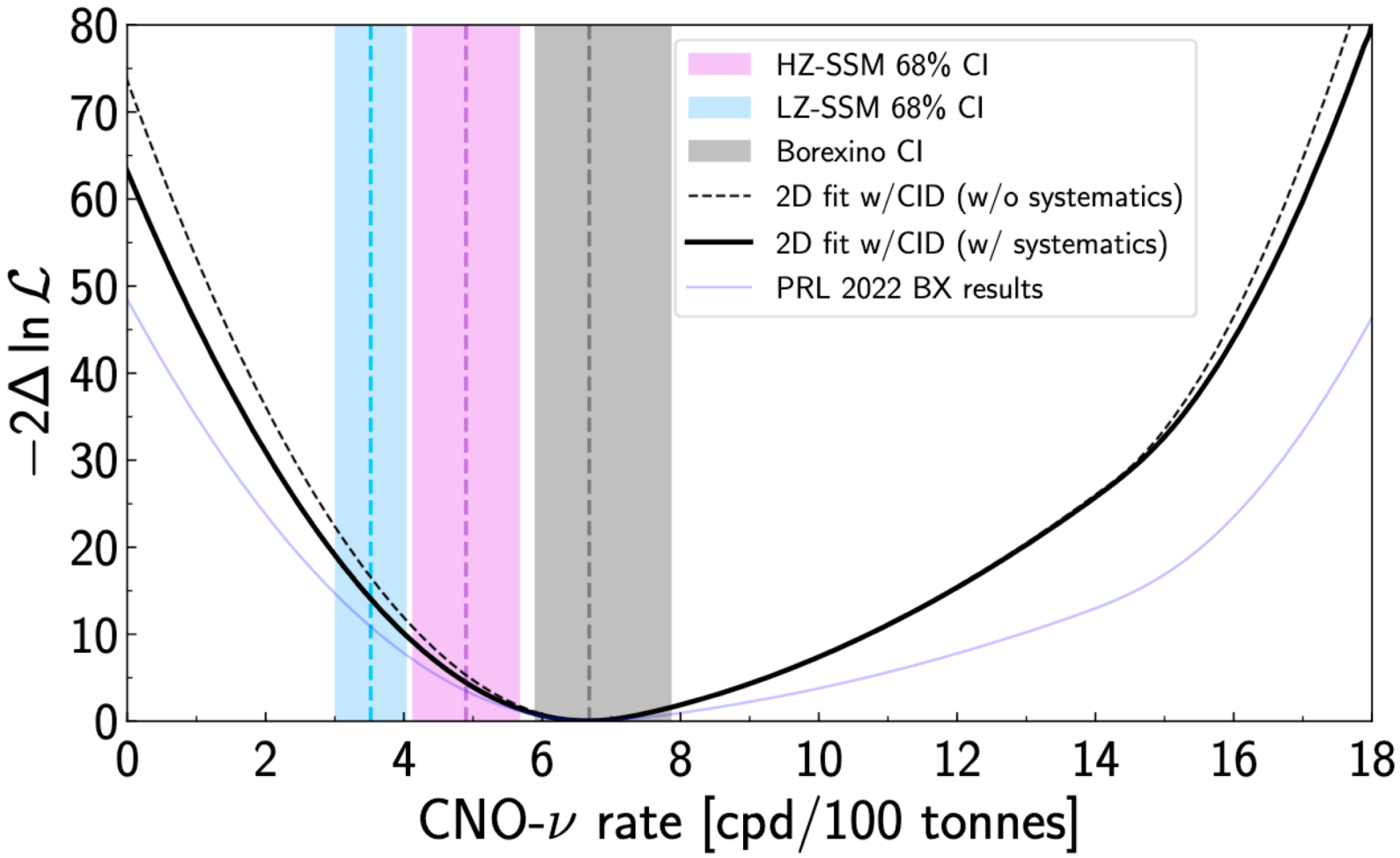
C+N abundance if ^{15}O flux is measured
(or any combination of ^{13}N & ^{15}O fluxes)

10% uncertainty (nuclear rates)
experimental uncertainty in CN-n 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

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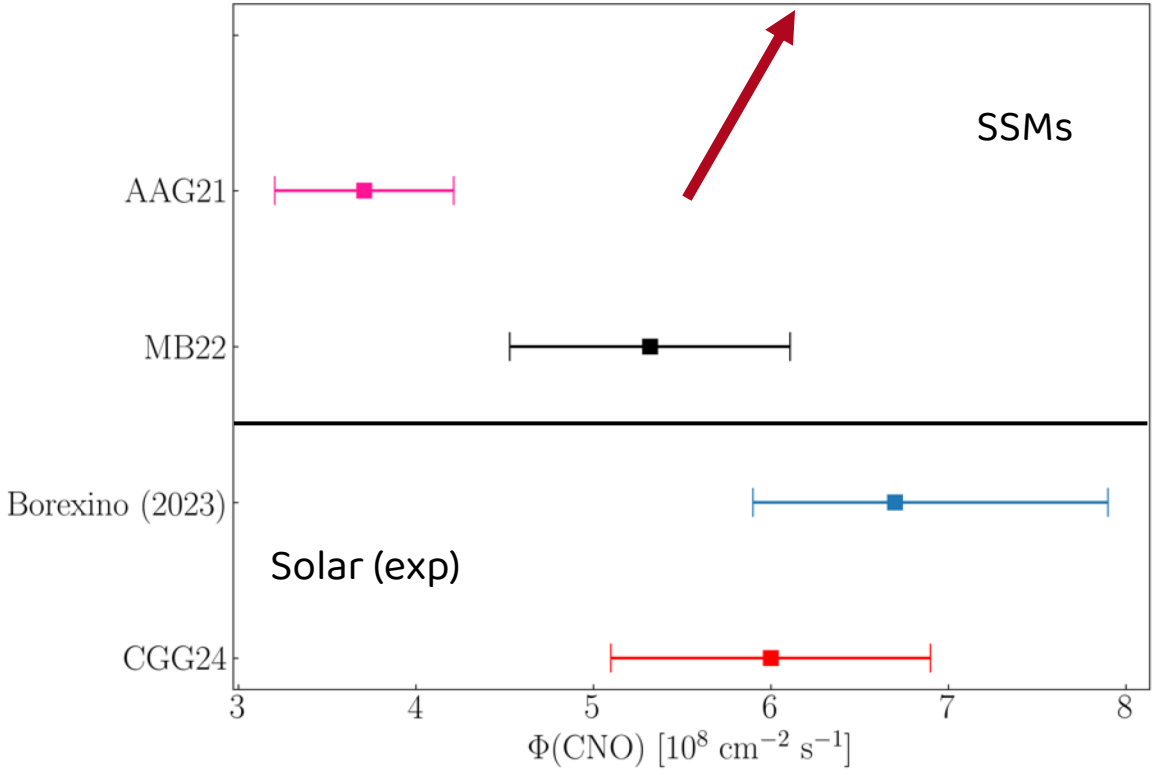

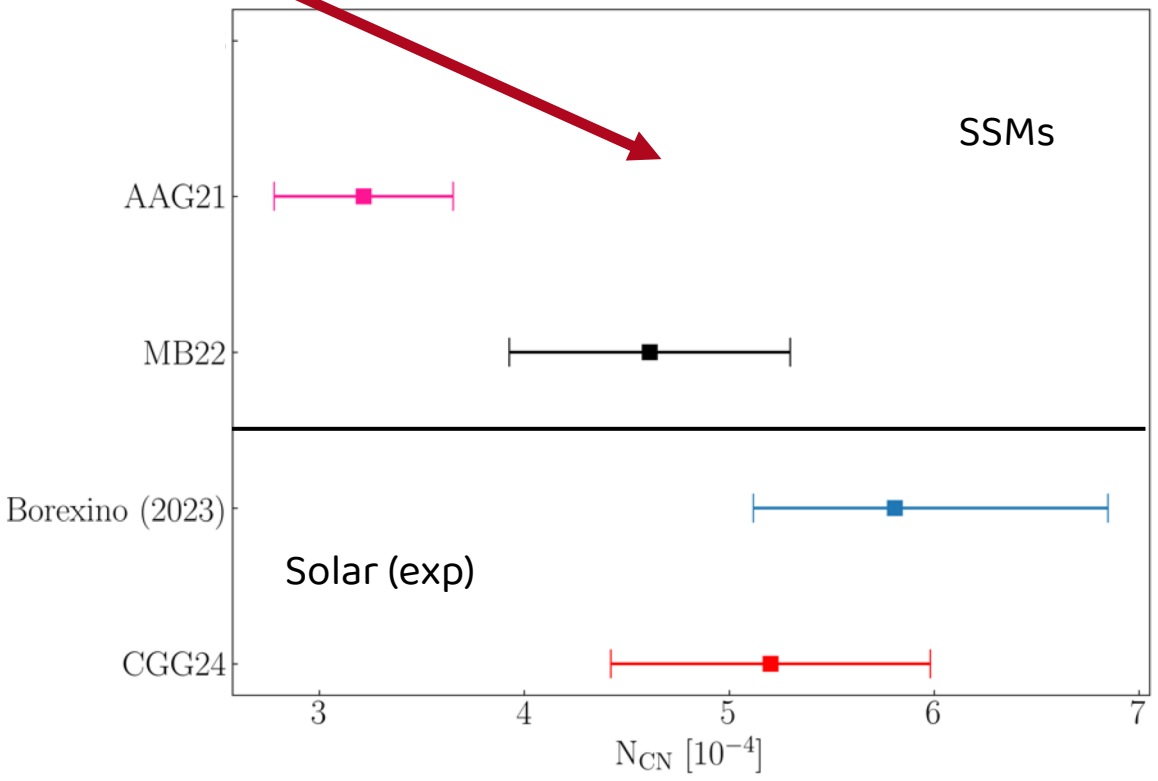

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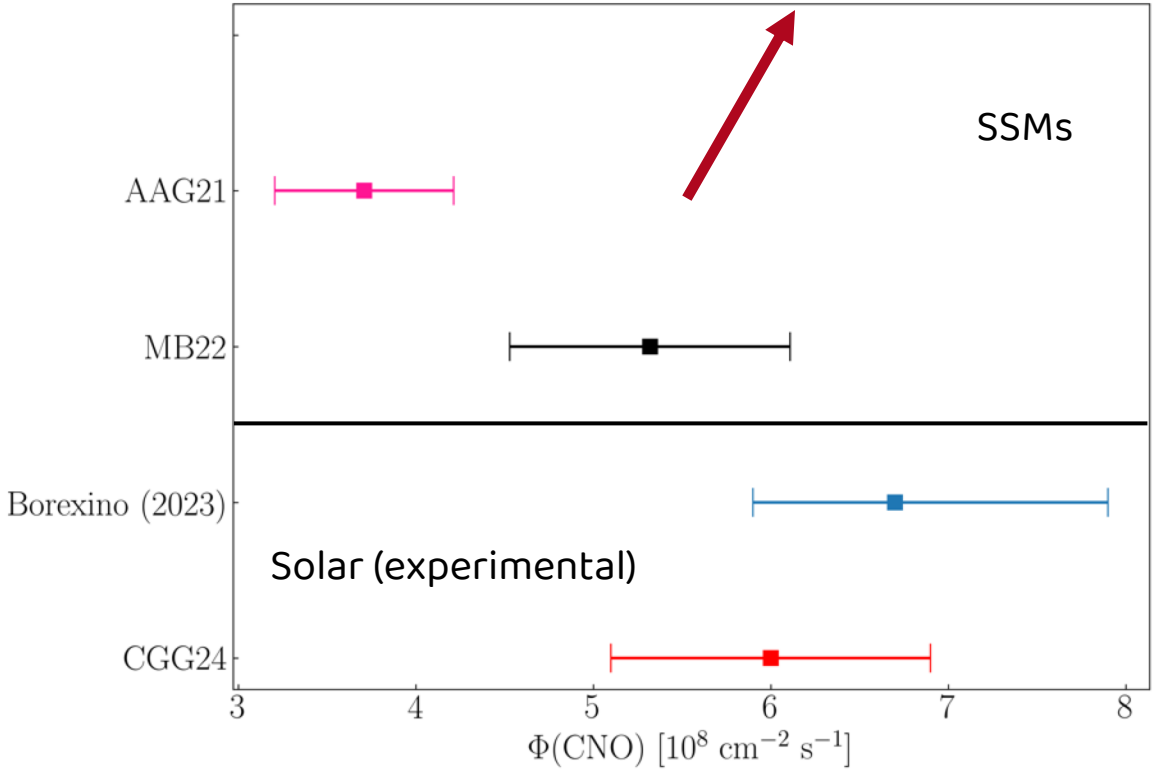

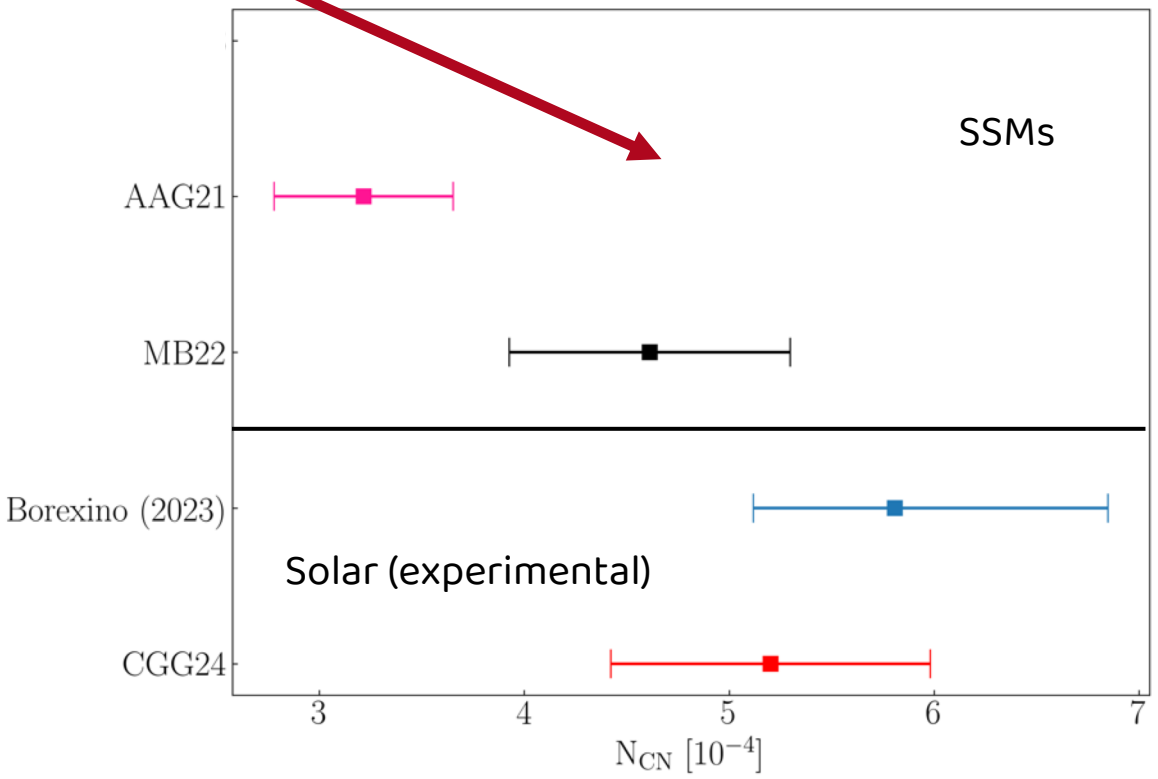

CN neutrinos break the degeneracy between composition and opacity

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

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

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

INT WORKSHOP INT-22-82W

Solar Fusion Cross Sections III

July 26, 2022 - July 29, 2022

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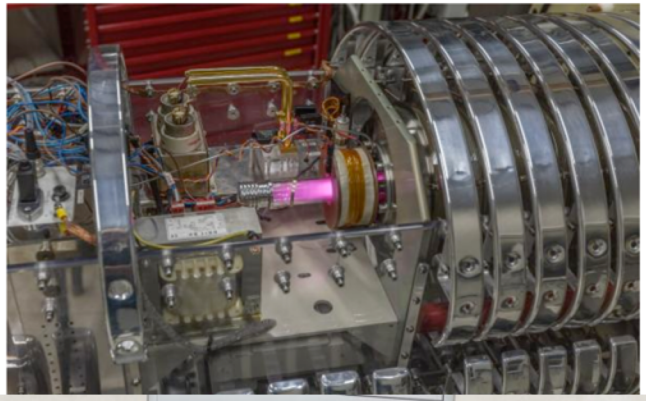

Note to applicants: This workshop will be held in the David Brower Center near the UC Berkeley campus, Berkeley, CA.

WORKING GROUP AND PRESENTATIONS WEBSITE

REVIEWS OF MODERN PHYSICS, VOLUME 97, JULY–SEPTEMBER 2025

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

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arXiv: 2405.06470
RMP, 97, 035002

H-burning x-sections.- uncertainties

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

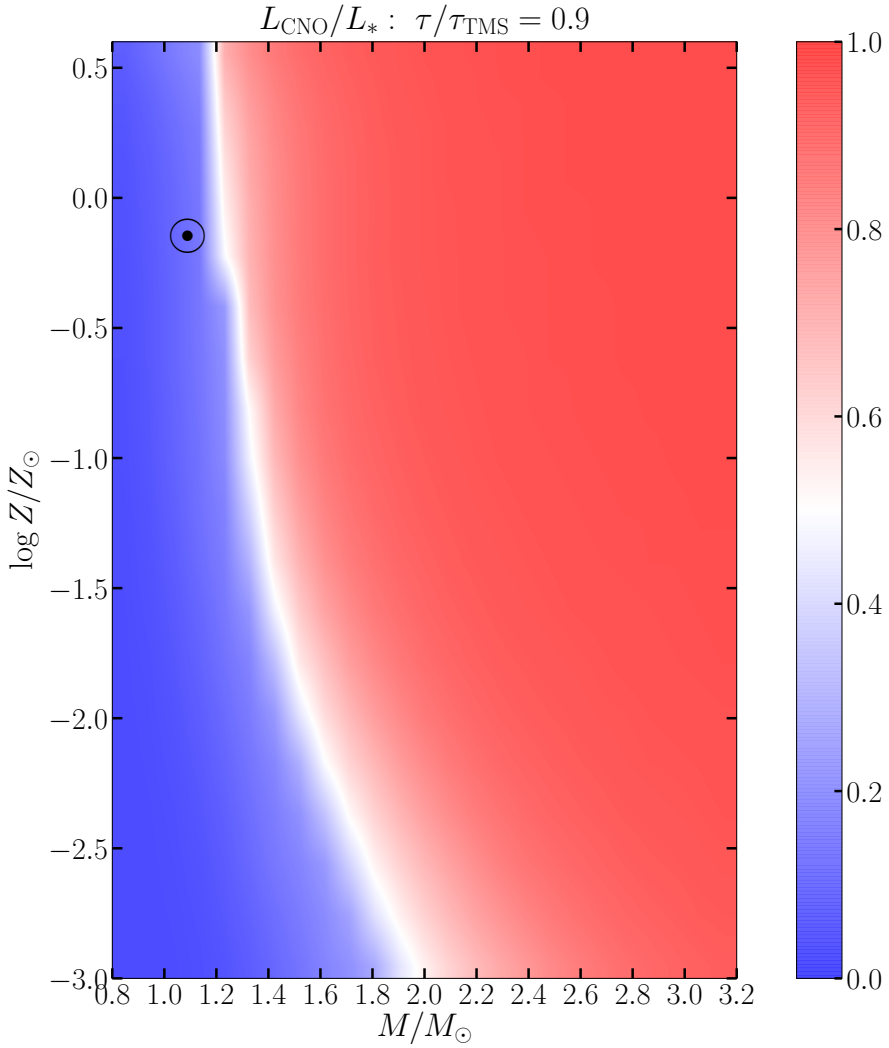
But see Chen et al. arXiv: 2410.16086 15% offset

Not much improvement in terms of precision over the last (long) decade in key reactions

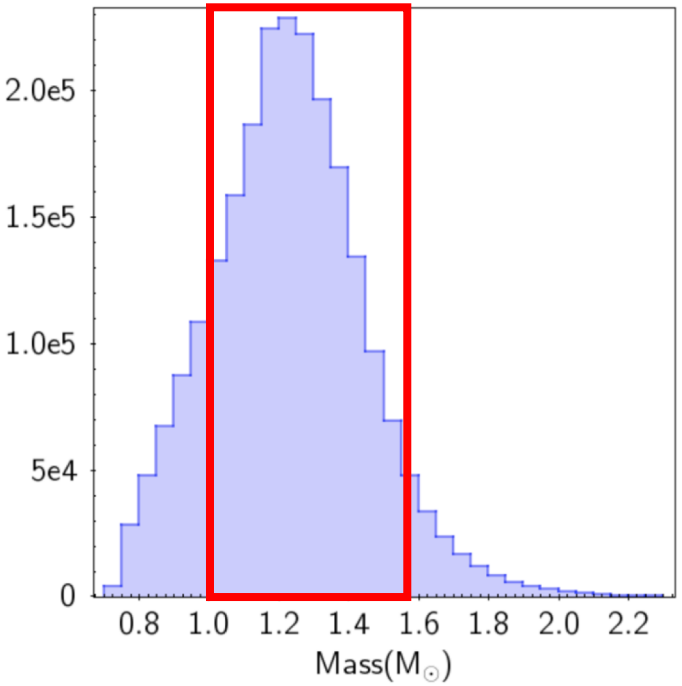
A concerted effort is needed to push down uncertainties to 1%-level

Impact for Solar-like stars

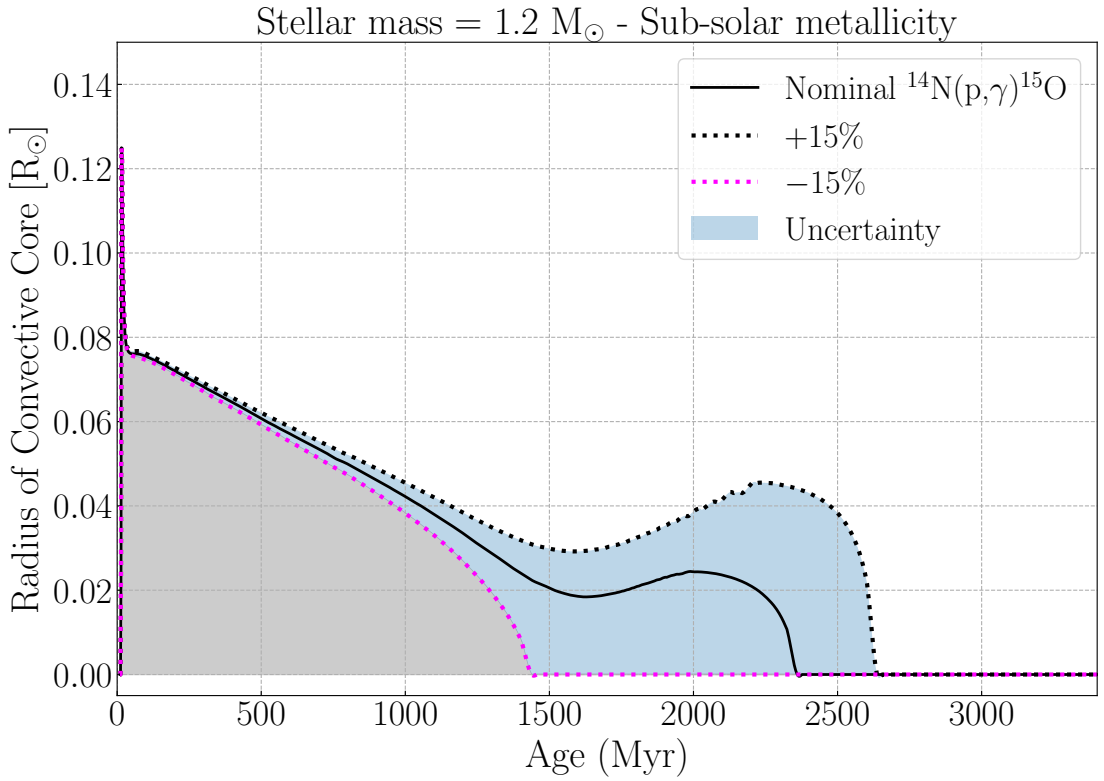
Stellar luminosity: CNO vs pp

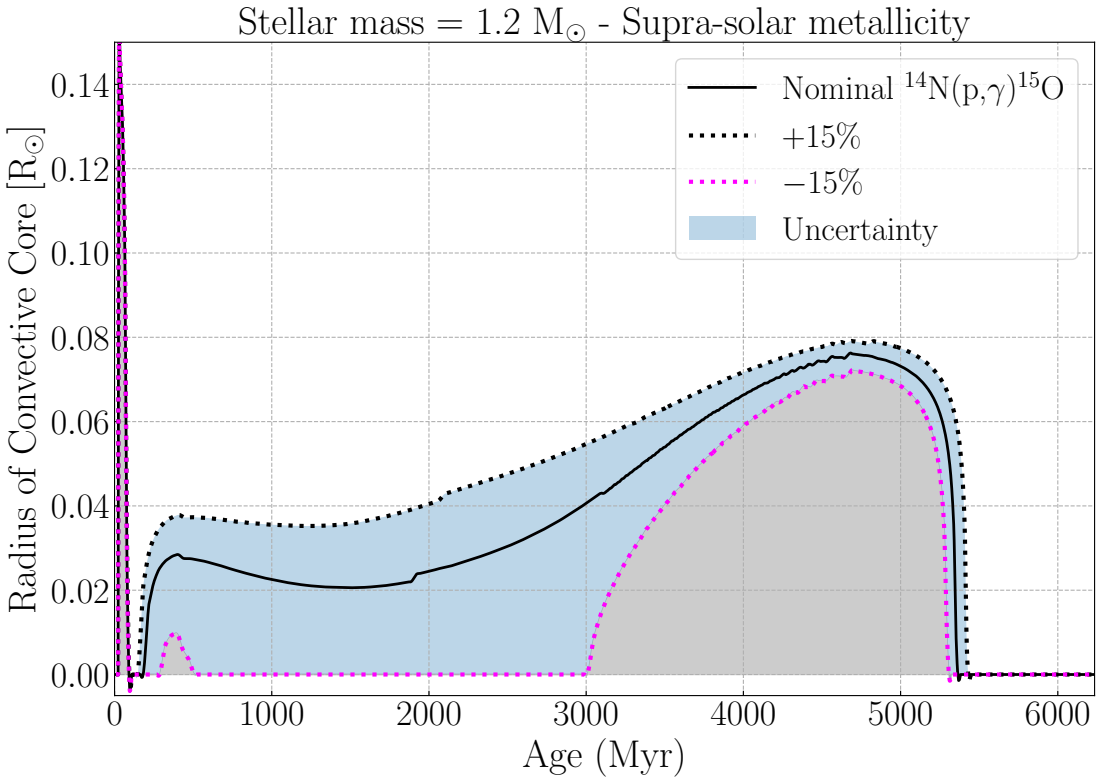


Mass distribution in the Plato Input Catalogue



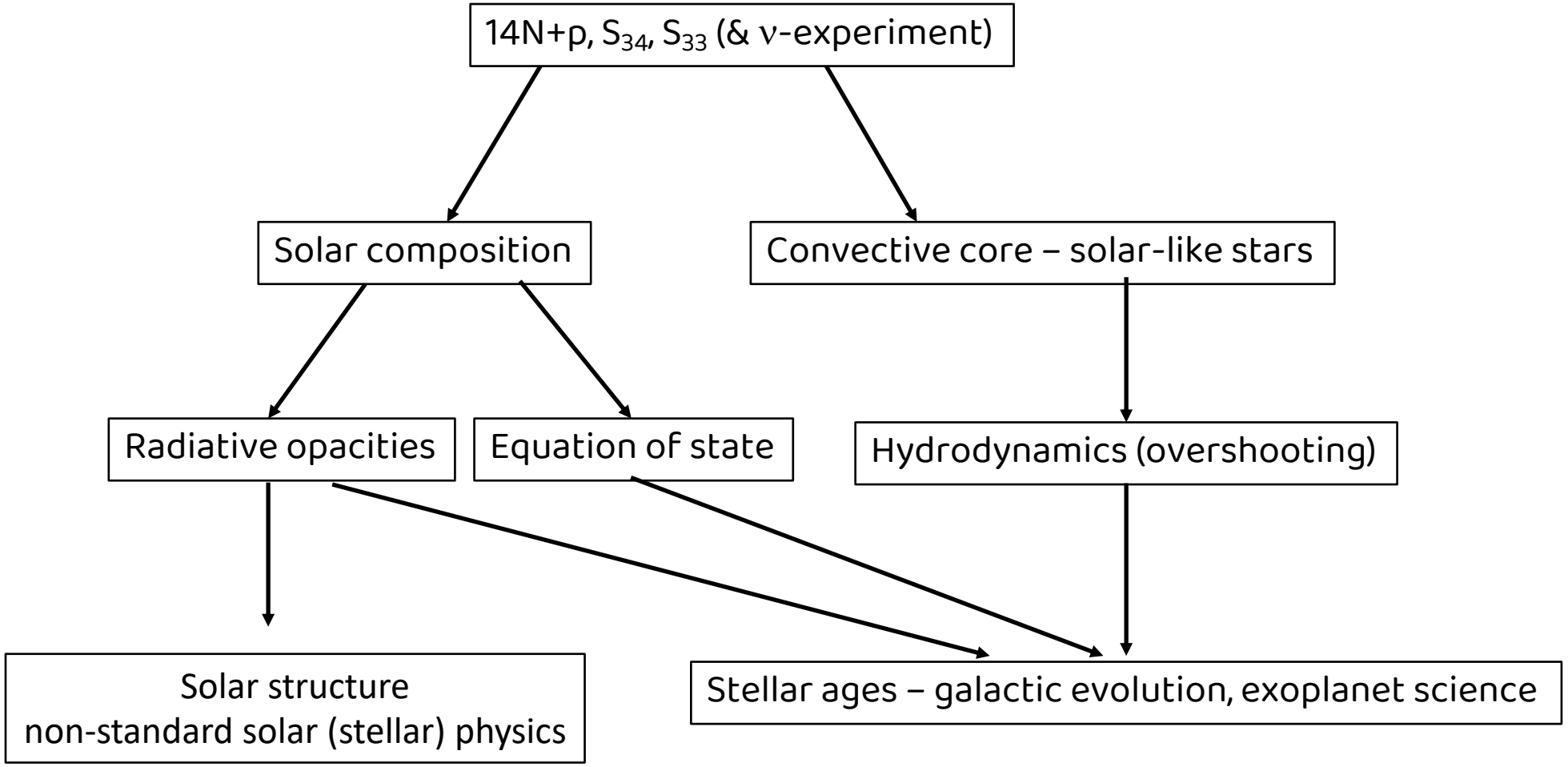
Impact for Solar-like stars: convective cores – to be or not to be





Nuclear cross section vs hydrodynamics (convection & overshooting)

Why 1% level precision x-sections



Summary

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

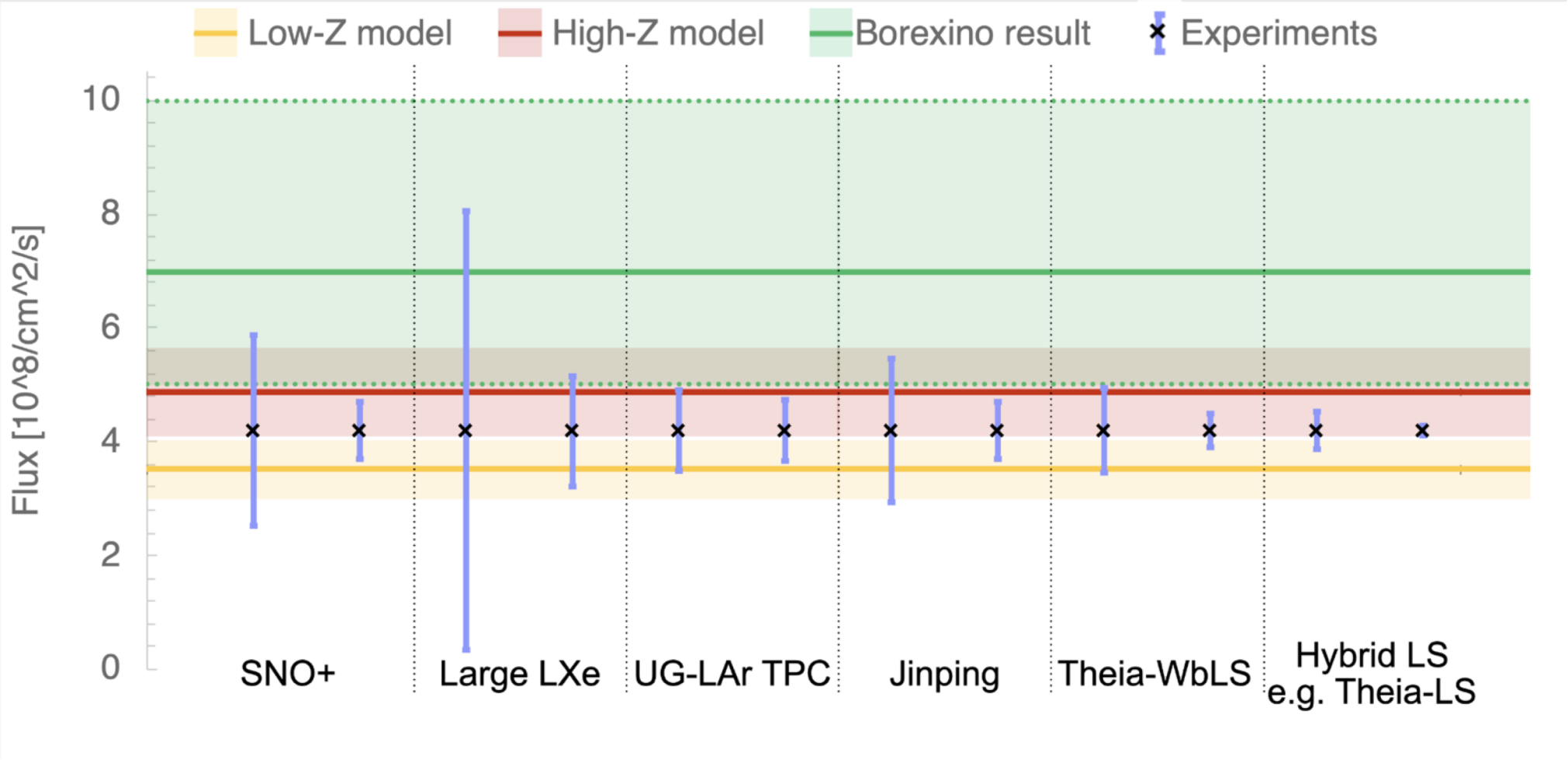
- High solar metallicity is favored by (degenerate with opacity):
  sound speed, surface helium, depth of convective envelope
  pp-chain solar neutrinos
- but lower solar metallicity is favored by (degenerate with equation of state):
  adiabatic index
- CNO neutrino break degeneracy with opacity → nuclear 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 contingent to our knowledge of 14N+p rate

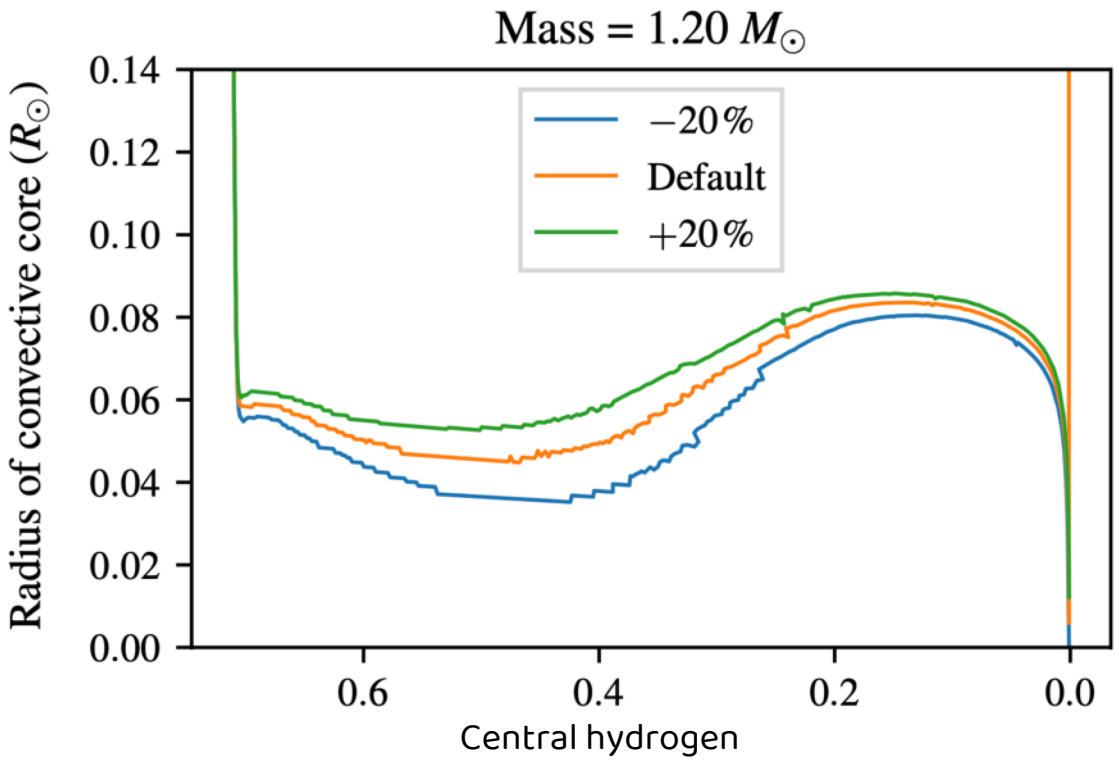
Future



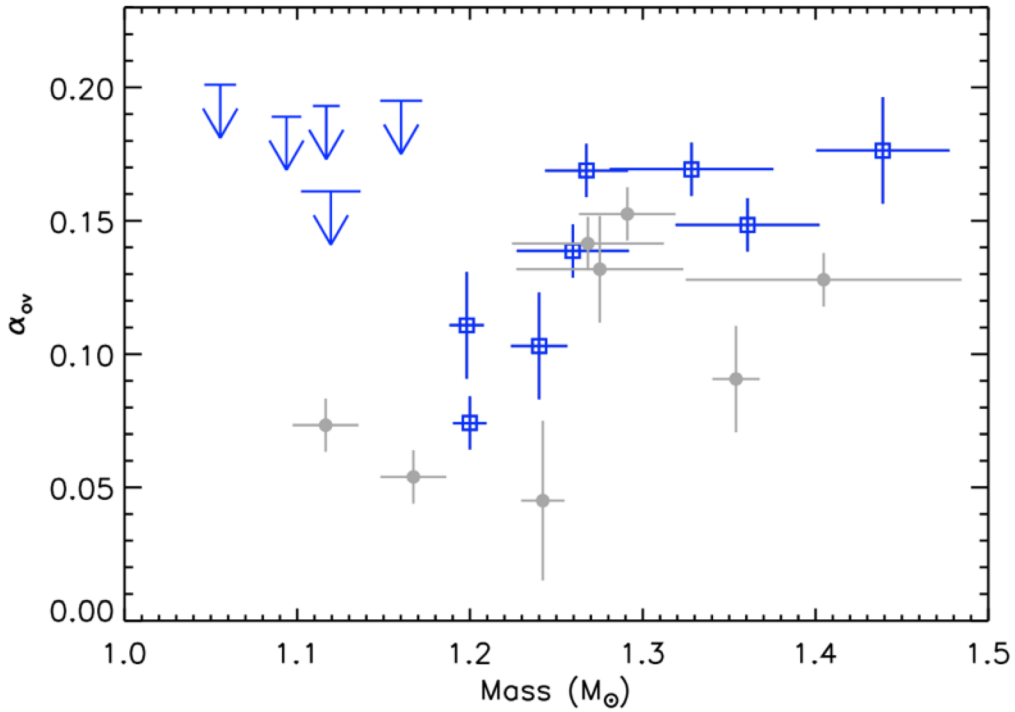
Orebi-Gann et al. 2021

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 stars
Only if N14+p well known



Deheuvels et al. 2016

Size of mixed core: convective boundary + overshooting

Institute of Space Sciences

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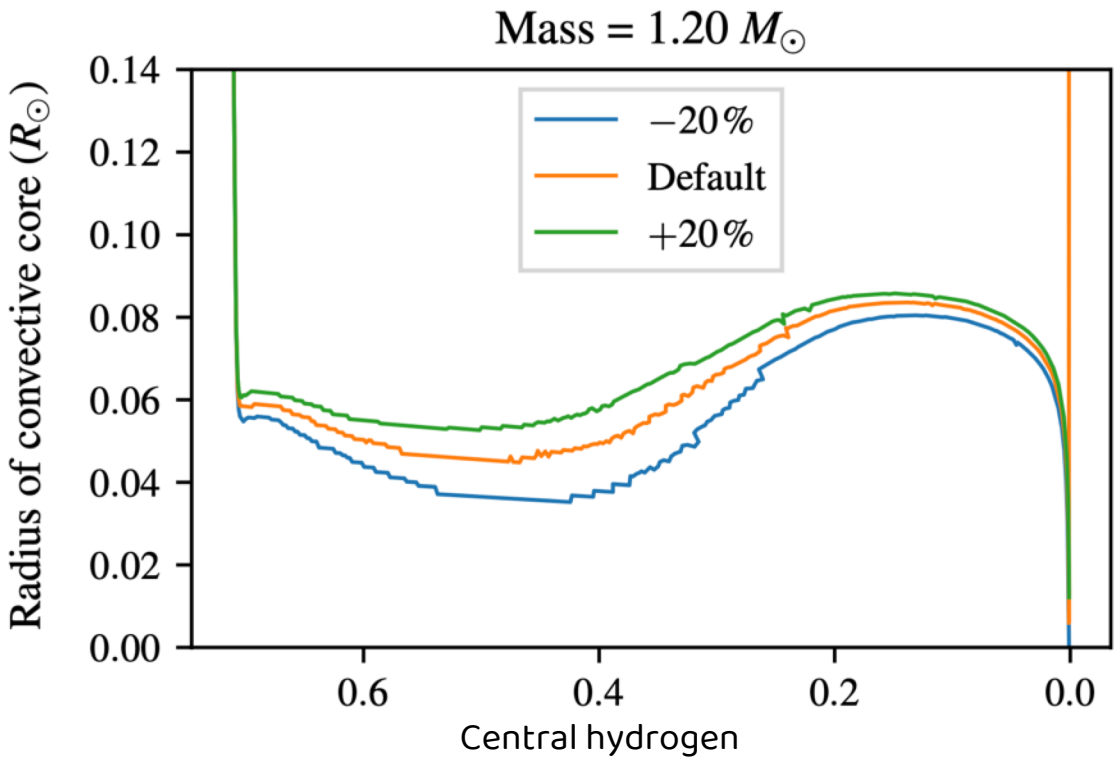
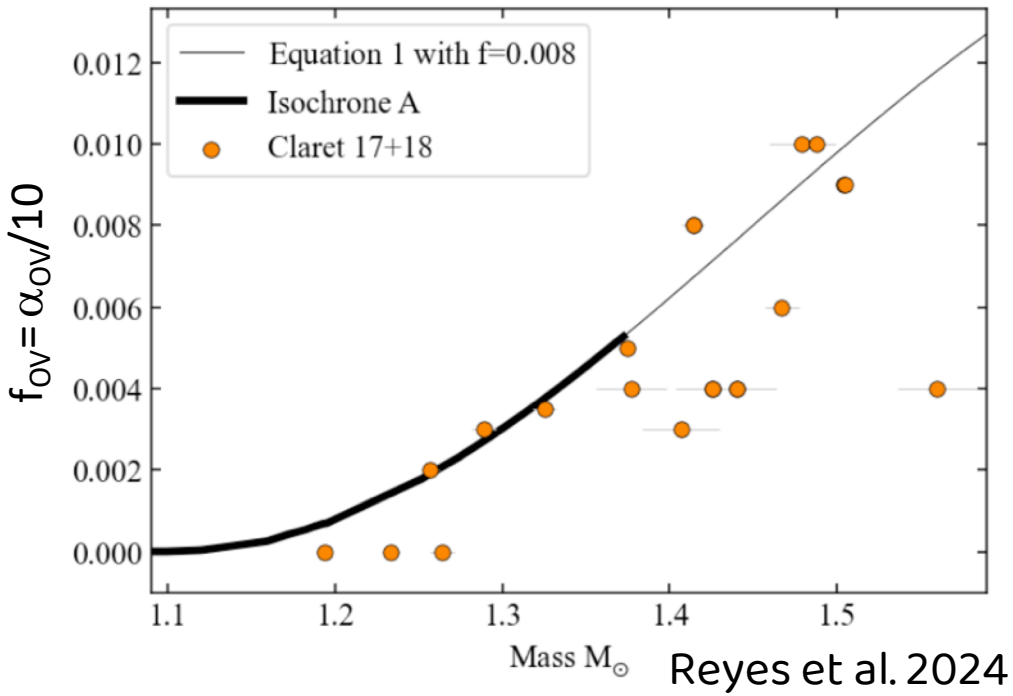


Calibrating OV in M67
Only if N14+p well known



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