Institute of
Space Sciences

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CHETEC INFRA

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Standard Solar models and uncertainties in the predicted solar axion flux

@Cosmic Wispers Kick-off Meeting – Feb23rd-24th

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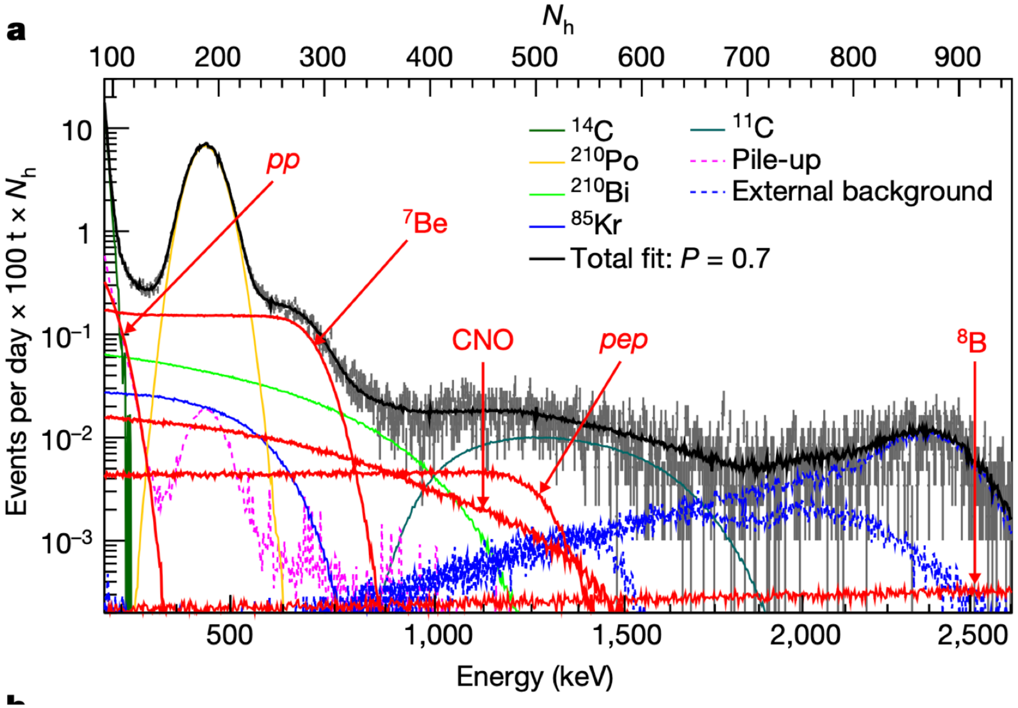
Institut d'Estudis Espacials de Catalunya

Standard Solar Model: why do we need them?

Energy conservation:

$$L_\odot = \int (\varepsilon_{\mathrm{nuc}} + \varepsilon_{\mathrm{g}} - \varepsilon_\nu \pm \varepsilon_x)\, dm$$

Nuclear energy tied to solar neutrinos → Borexino pp (& 7Be) measurements



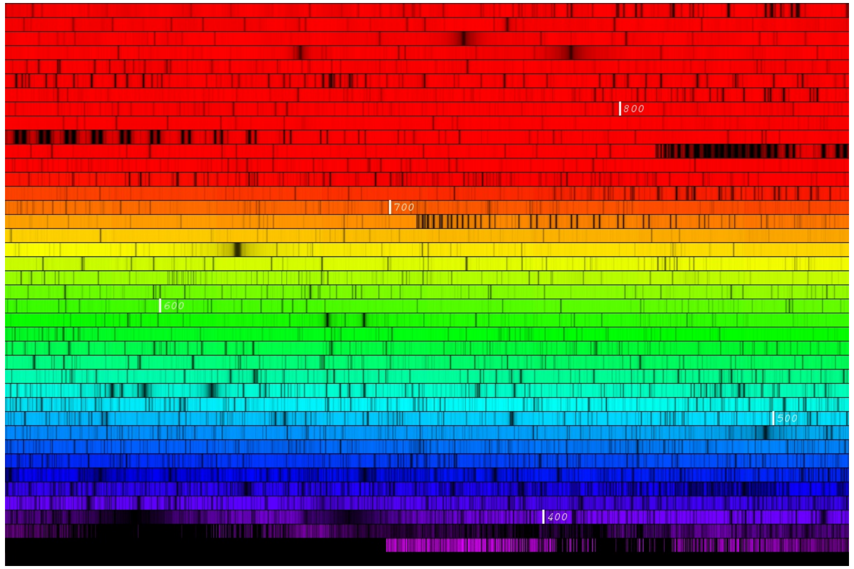
$$L_\odot \simeq L_{\mathrm{nuc}} \pm 9\%$$

Model independent constraint on solar energetics

Borexino Coll. 2018

Standard Solar Model: state-of-the-art

Solar abundances from solar spectrum, solar atmosphere model, radiative transfer modeling



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1D atmos

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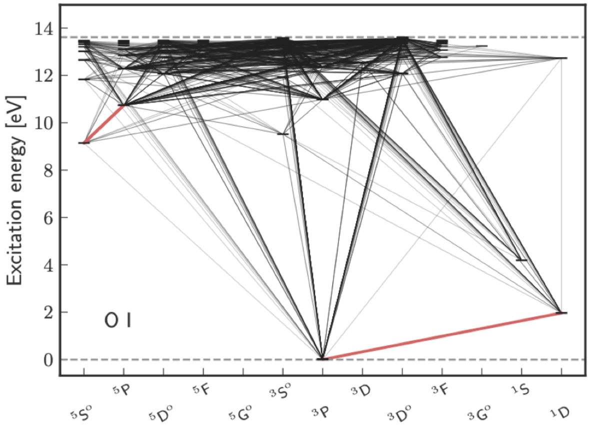

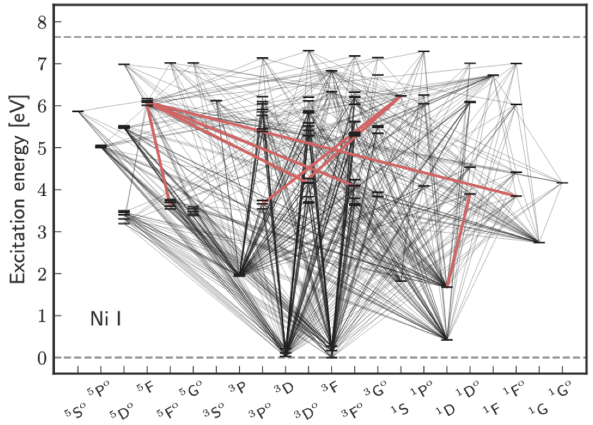

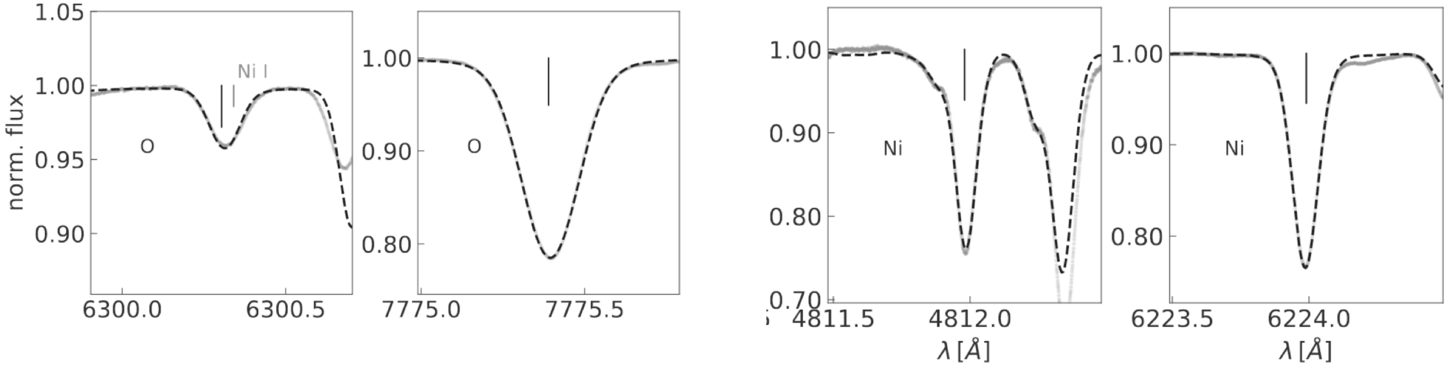

Standard Solar Model: state-of-the-art

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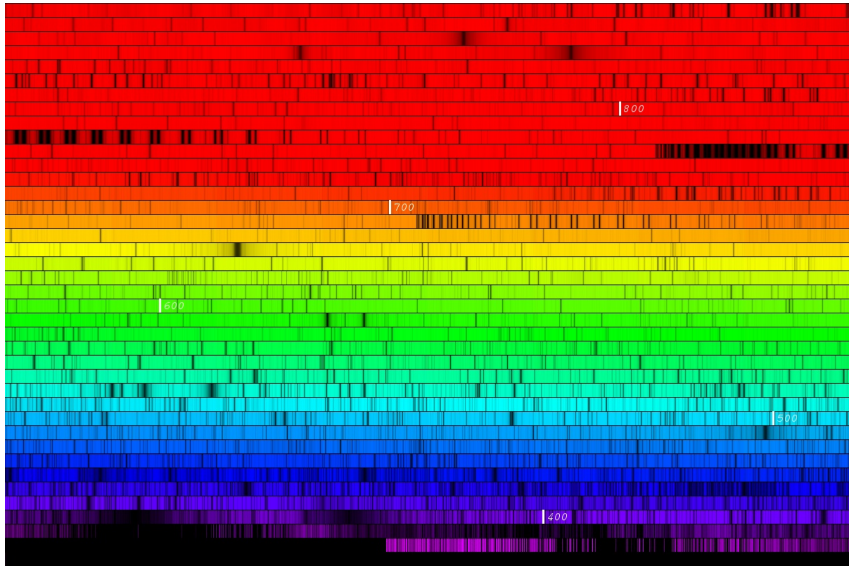

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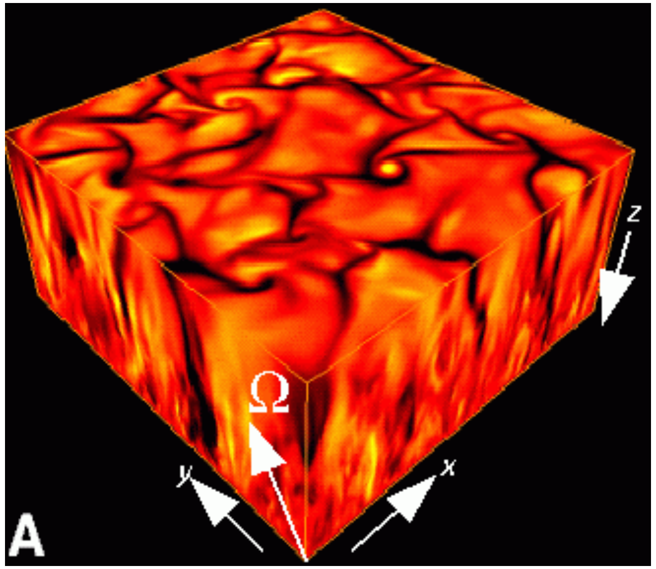

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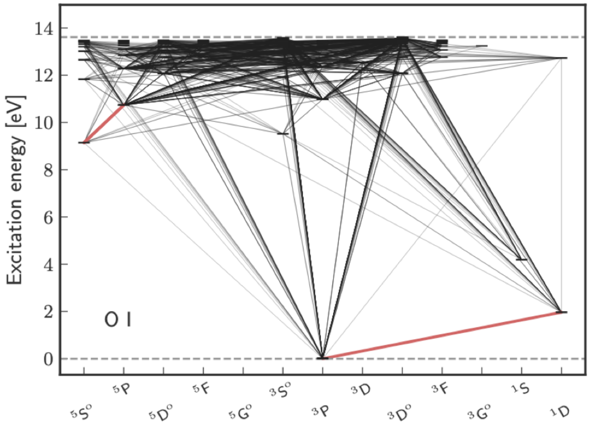
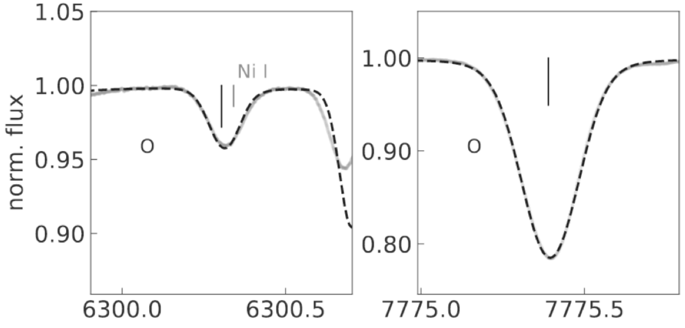
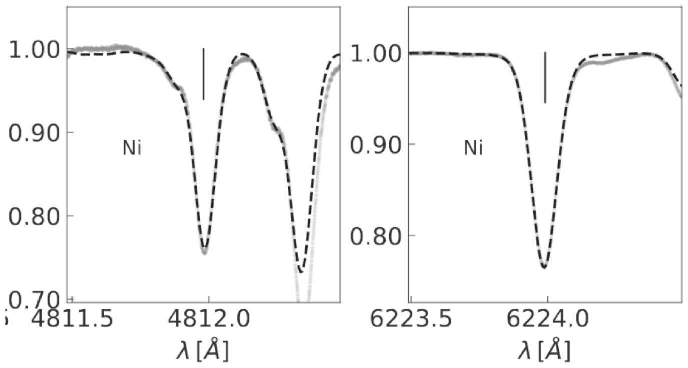
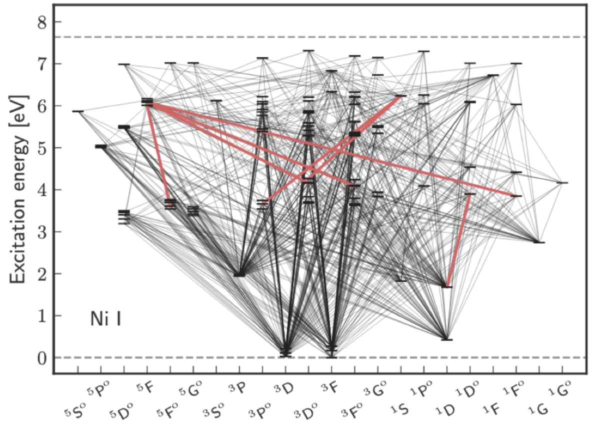








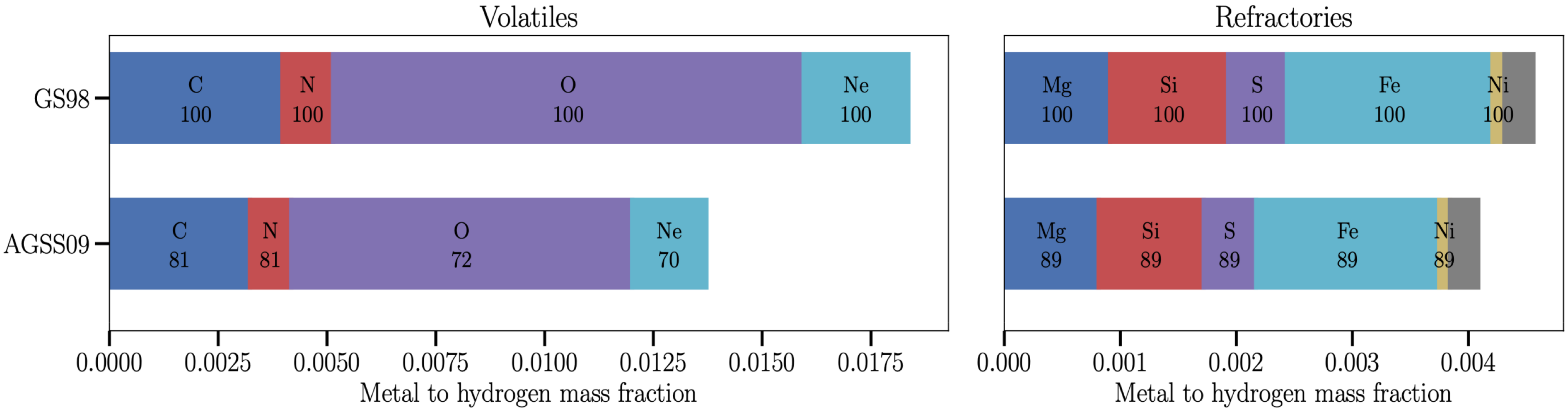
Standard Solar Model: state-of-the-art

Solar abundances are an input for SSM construction, widely used:

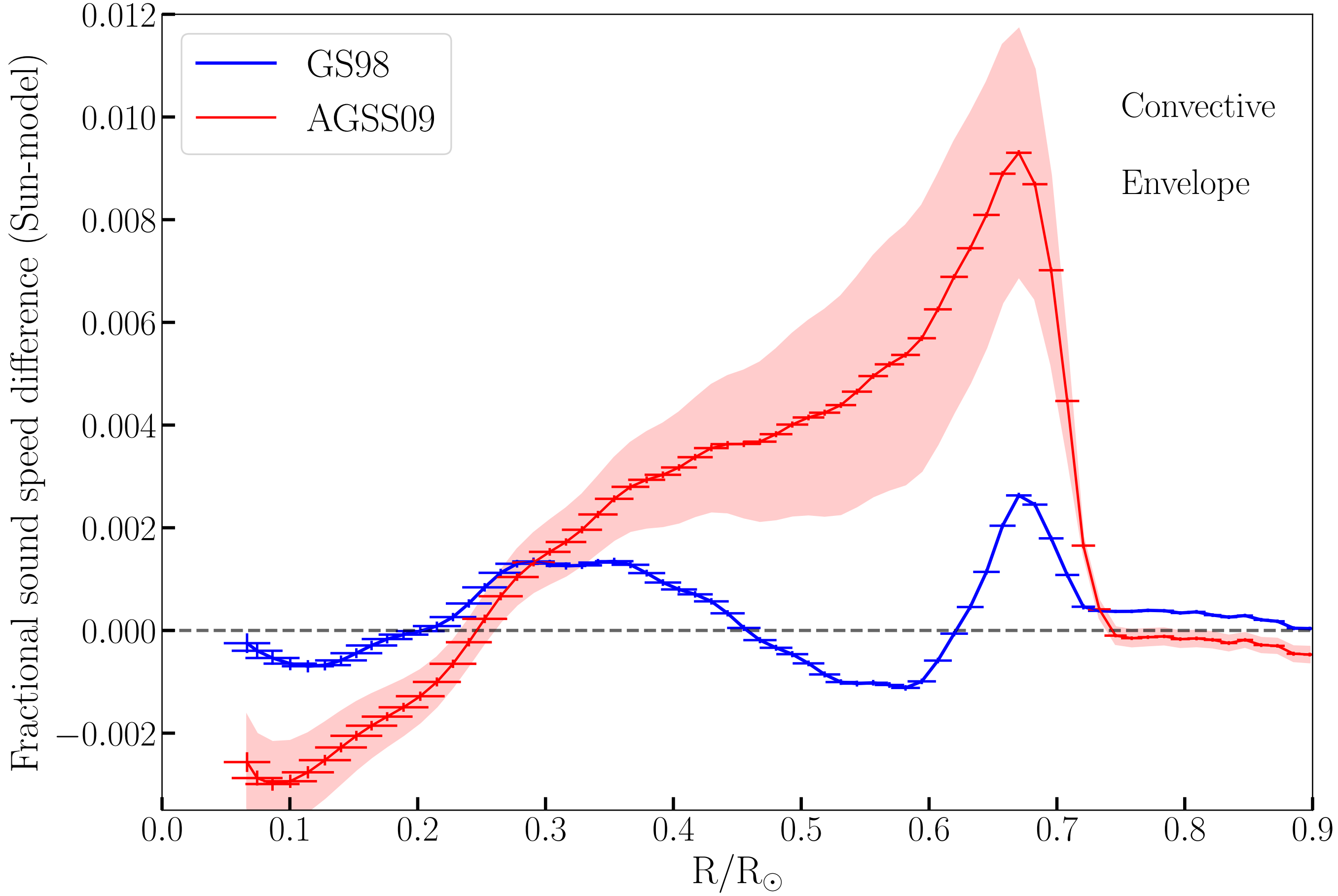
GS98 – Grevesse & Sauval 1998
AGSS09 – Asplund, Grevesse et al. 2009

1998
1D - LTE

2009
3D – LTE/NLTE



Standard Solar Model: state-of-the-art



Discrepancies due to abundances provided radiative opacities are correct

Solar abundance problem
Long-standing since ~2005

Standard Solar Model: state-of-the-art

New revisions of solar abundances in 2021(Asplund et al. – AAG21) and 2022 (Magg, Bergemann et al. MB22)

Similar techniques – 3D, NLTE (in most cases)

Differences: higher resolution solar spectrum, better atomic data for O, Ni in NLTE (key for O) (MB22)

Standard Solar Model: state-of-the-art

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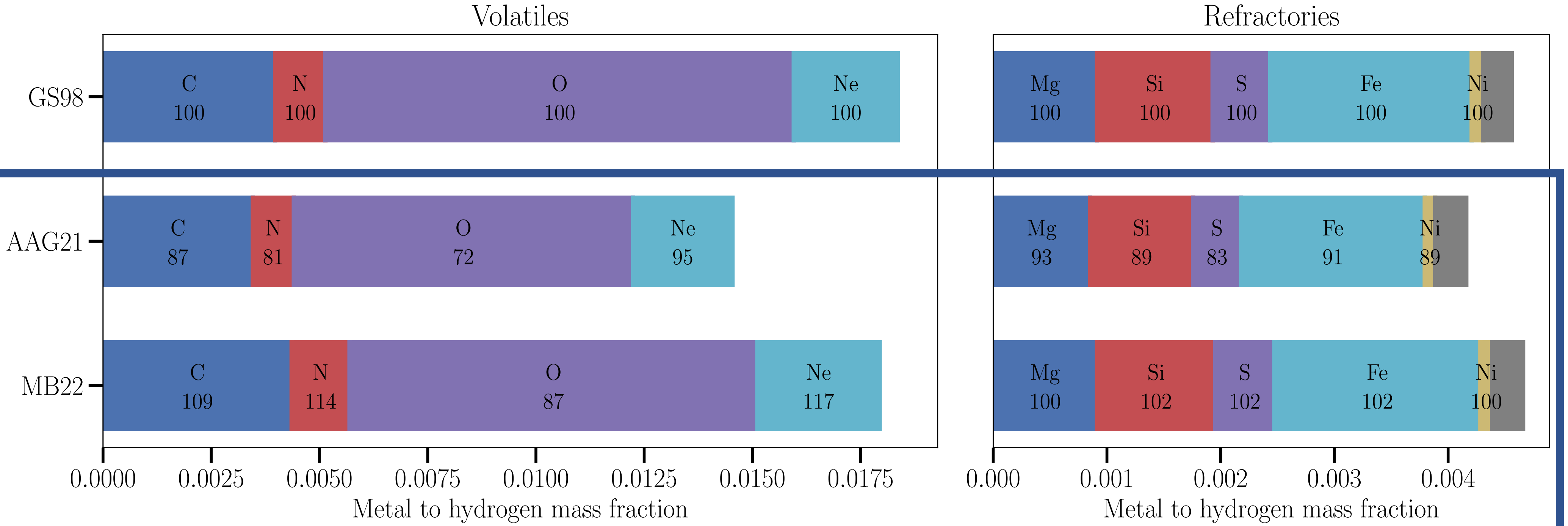
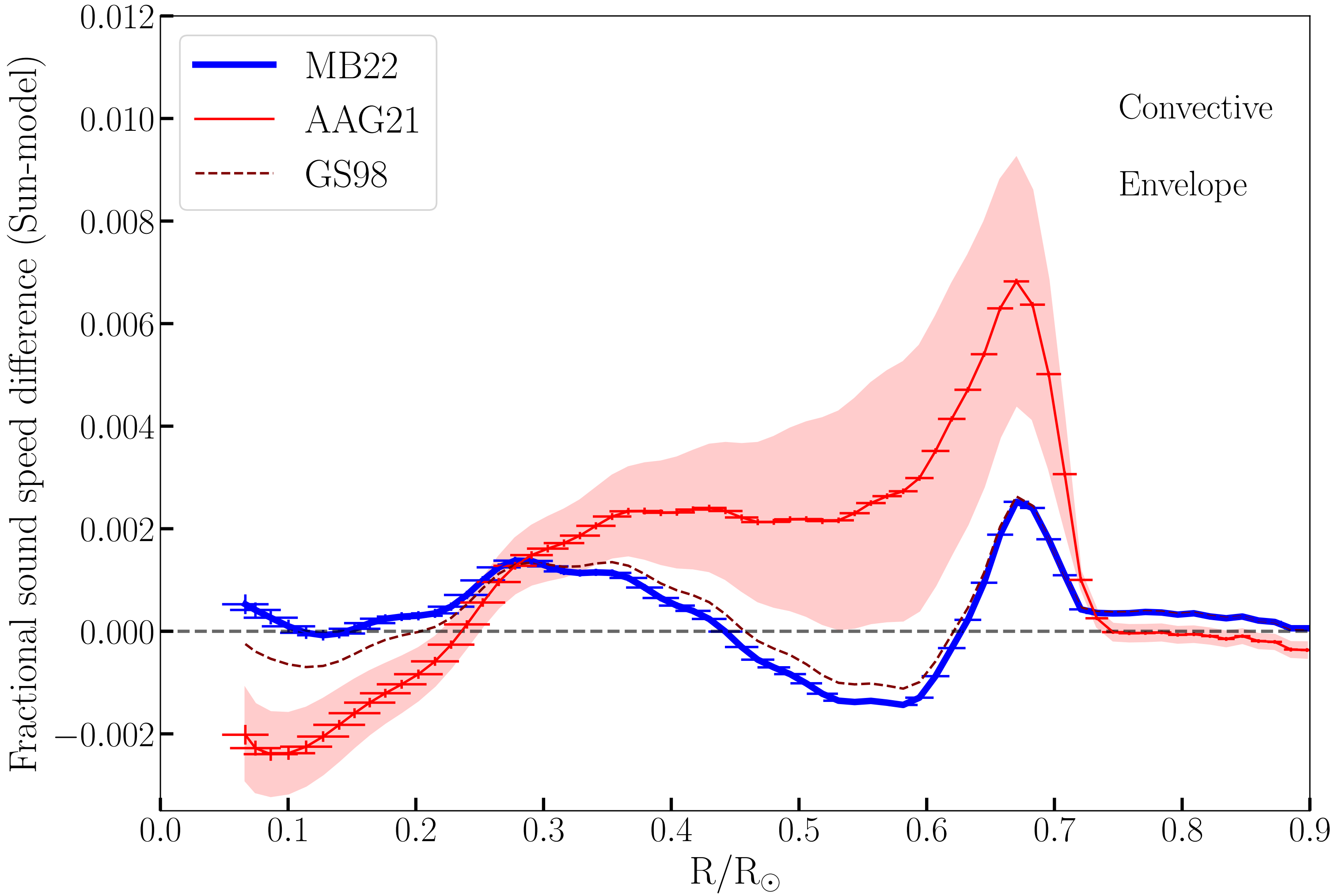
1998
1D - LTE

2021
3D – NLTE

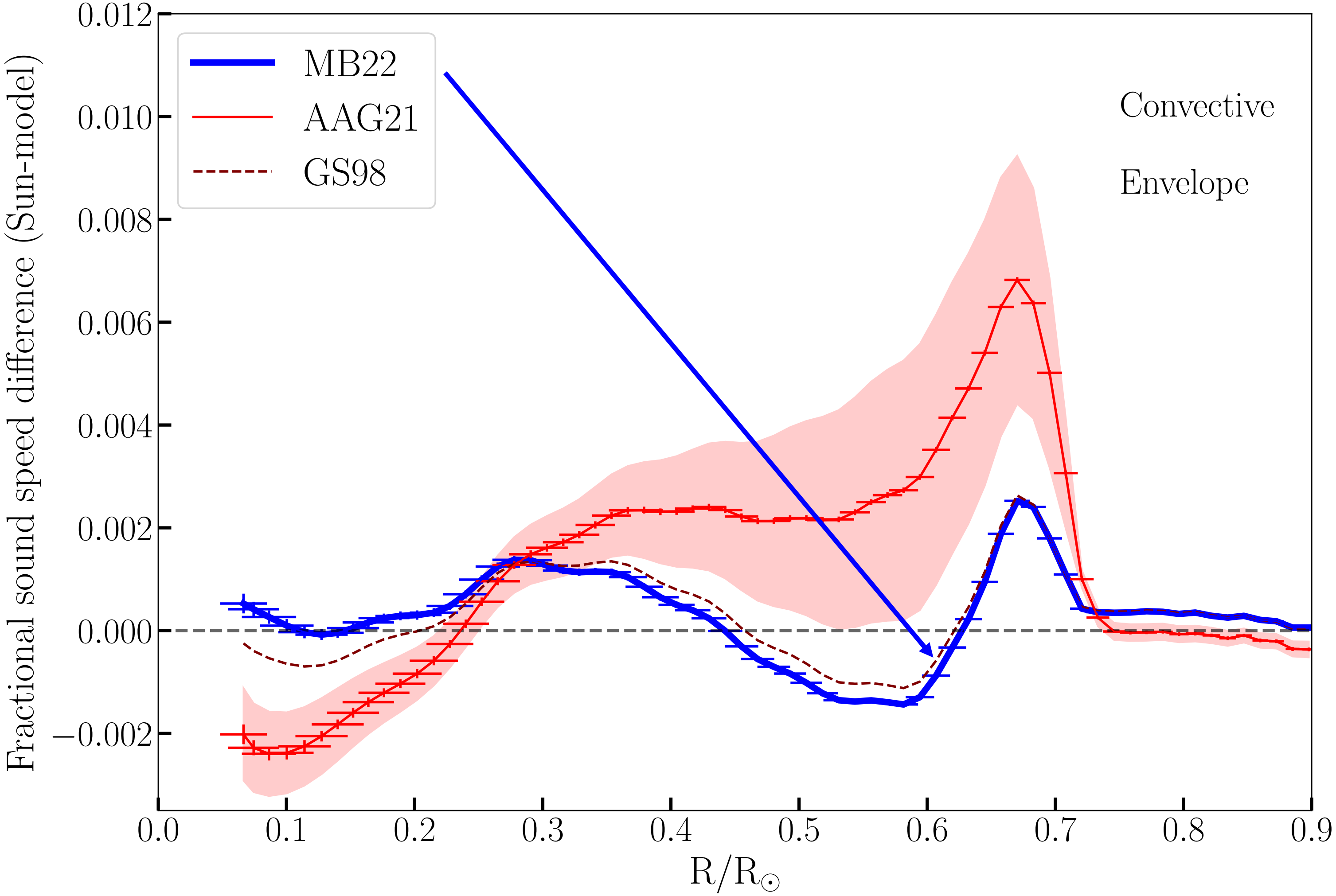
2022
3D – NLTE



Standard Solar Model: state-of-the-art



Standard Solar Model: state-of-the-art



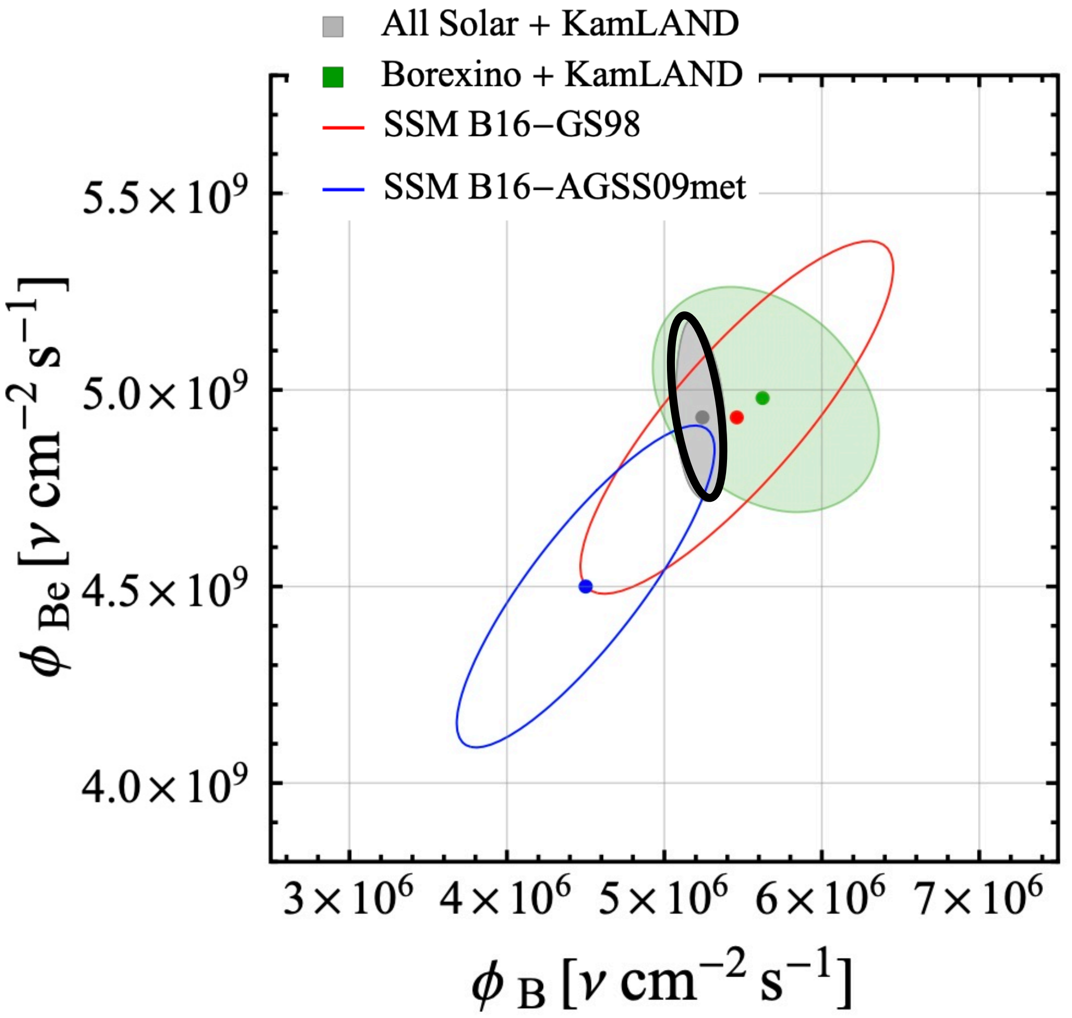
First time ever

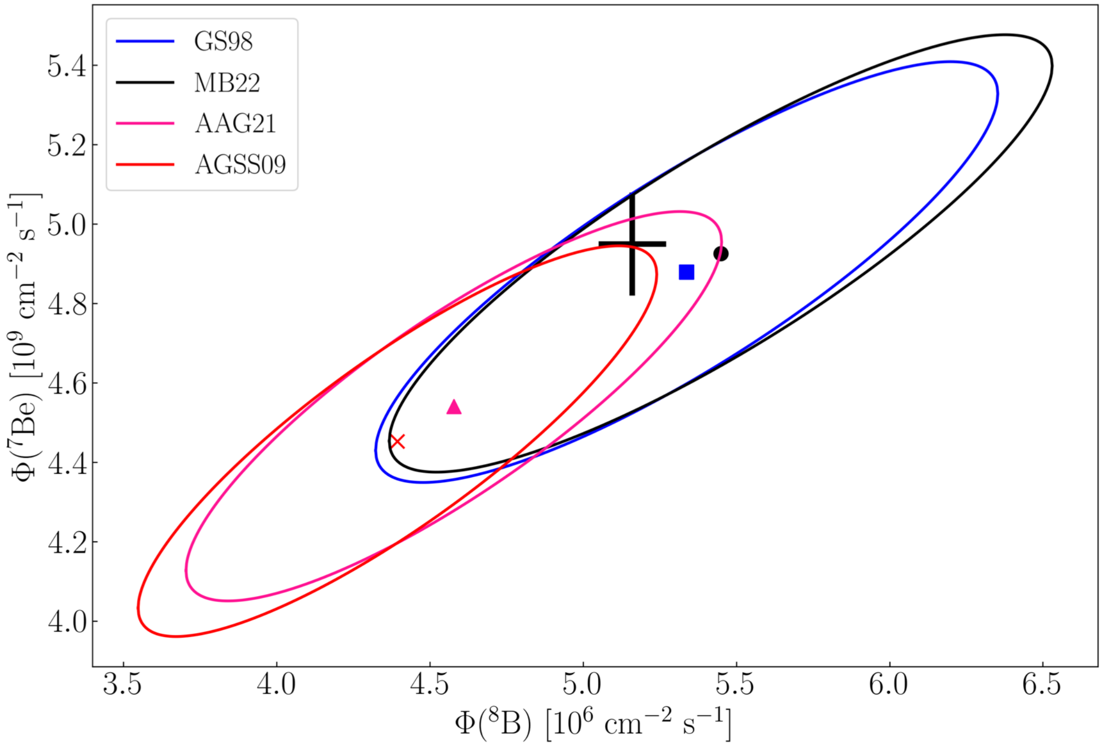
3D based solar abundances (MB22) lead to SSM in good agreement with helioseismic constraints

Confidence that the solar abundance Problem has been solved

Solar Neutrinos: pp-chains

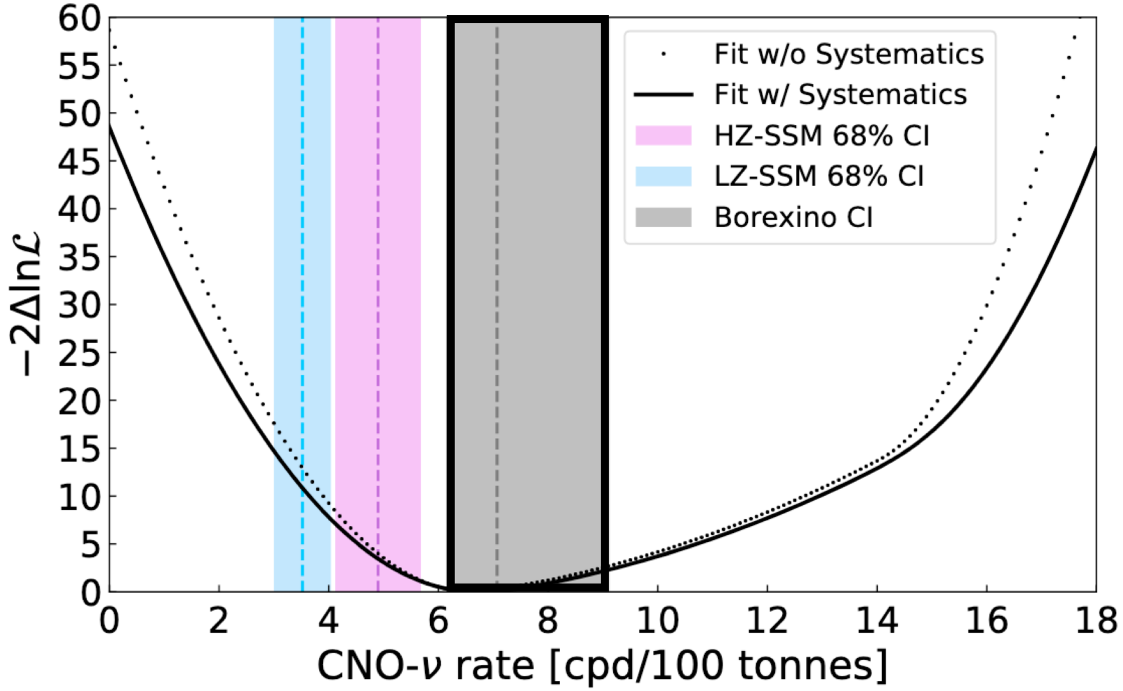
Borexino (PRL 2022)

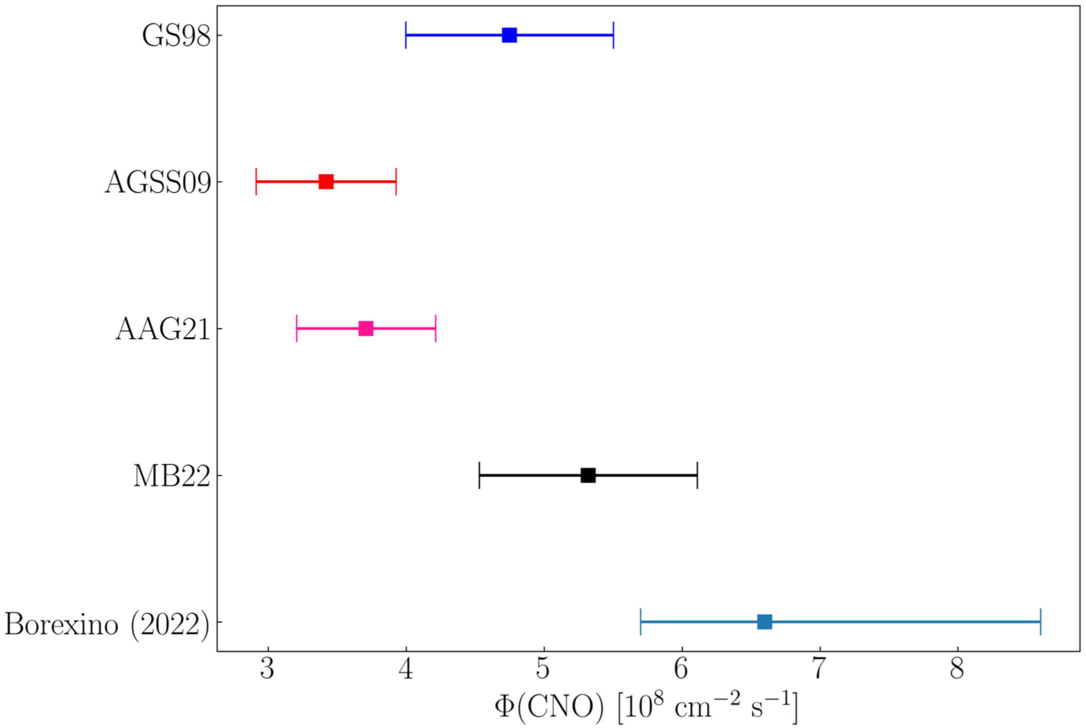




Solar Neutrinos: CN(O)-cycles

Borexino (PRL 2022)





SSM based on MB22 composition reproduces helioseismic and solar neutrino data

Solar model uncertainties for axion flux

1) Standard solar models – 21 input parameters with uncertainties – statistical uncertainties

    solar composition (C, N, O, Ne, Mg, ….)

    nuclear cross sections (S11, S33, S34, S17, ….)

    gravitational settling rate

    solar luminosity and age

    parametrization of radiative opacity uncertainties

2) Choice of solar abundances (systematic)

3) Choice of opacity calculations (systematic)

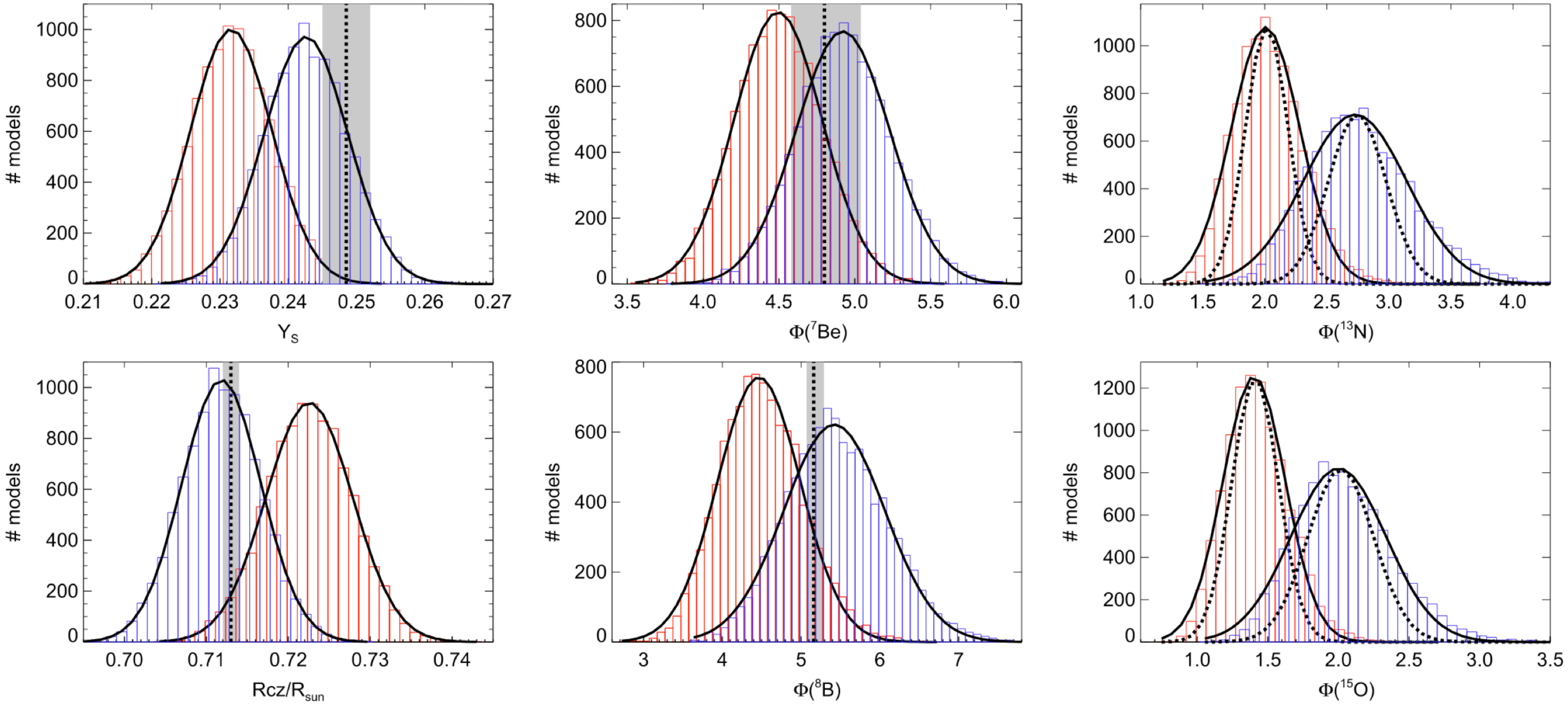
4) Solar magnetic field

Solar model uncertainties for axion flux

Hoof et al 2021 – comprehensive study of solar uncertainties in axion fluxes

Direct assessment of “statistical uncertainties” and “solar abundance choice”

2x10000 SSMs from Monte Carlo simulations in Vinyoles et al 2017

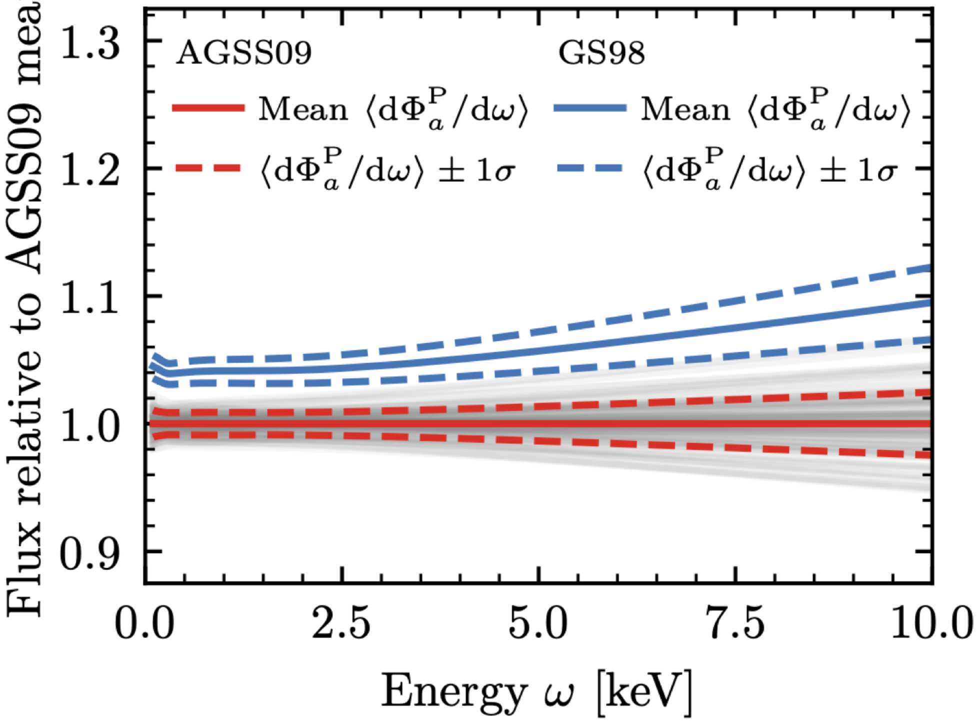


B16-GS98
B16-AGSS09

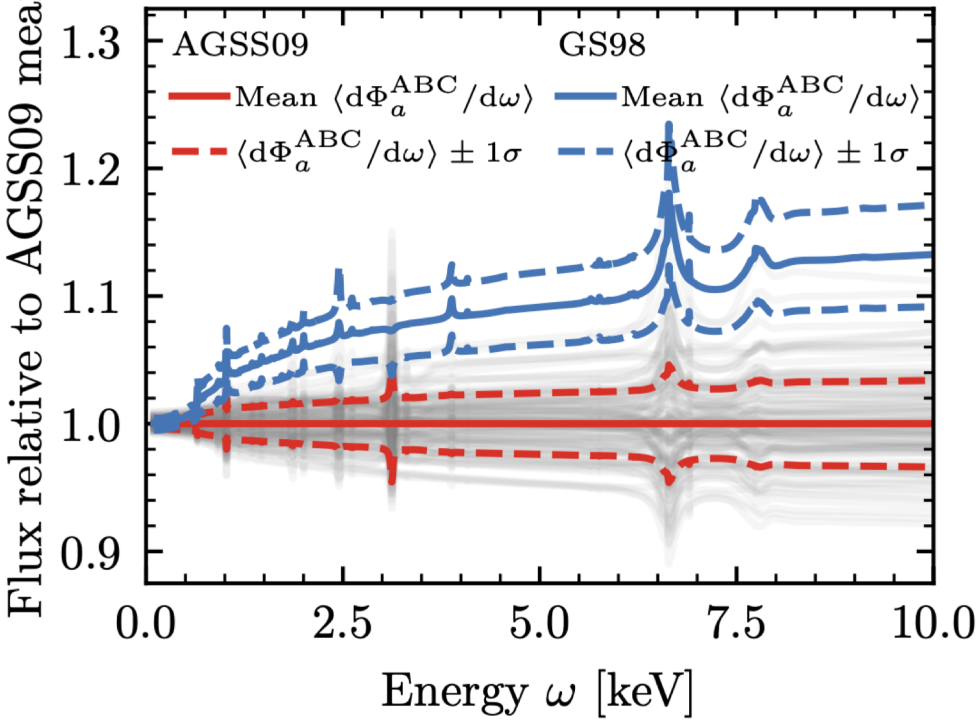
Solar model uncertainties for axion flux

Hoof et al 2021 – statistical uncertainty: temperature – composition (Debye scale for a-γ and opacity for a-e)

Axion-photon



Axion-electron



Solar model uncertainties for axion flux

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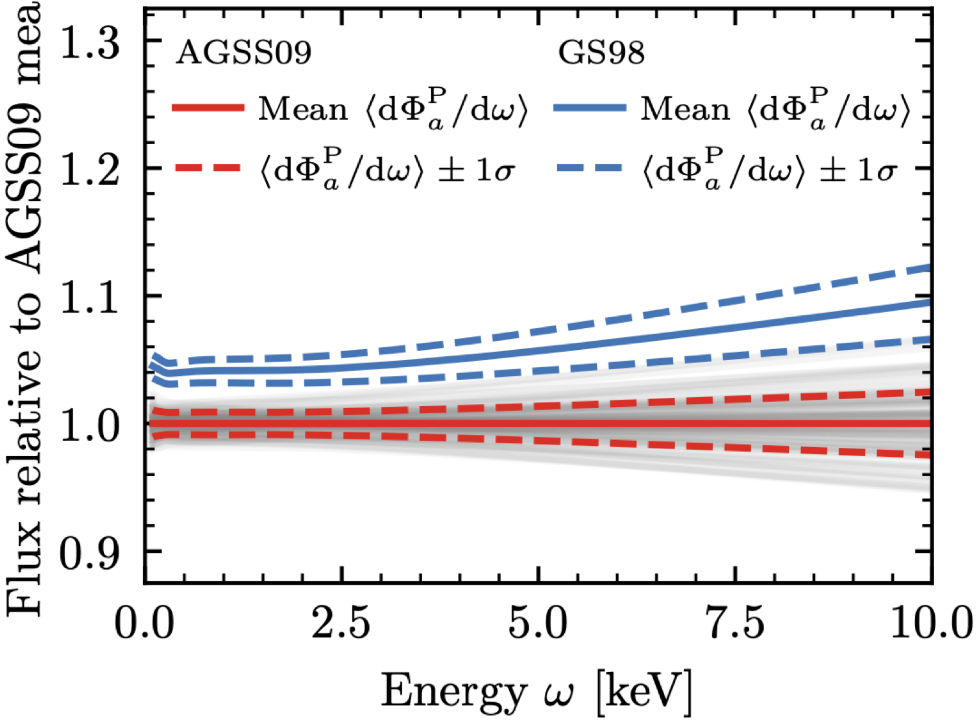
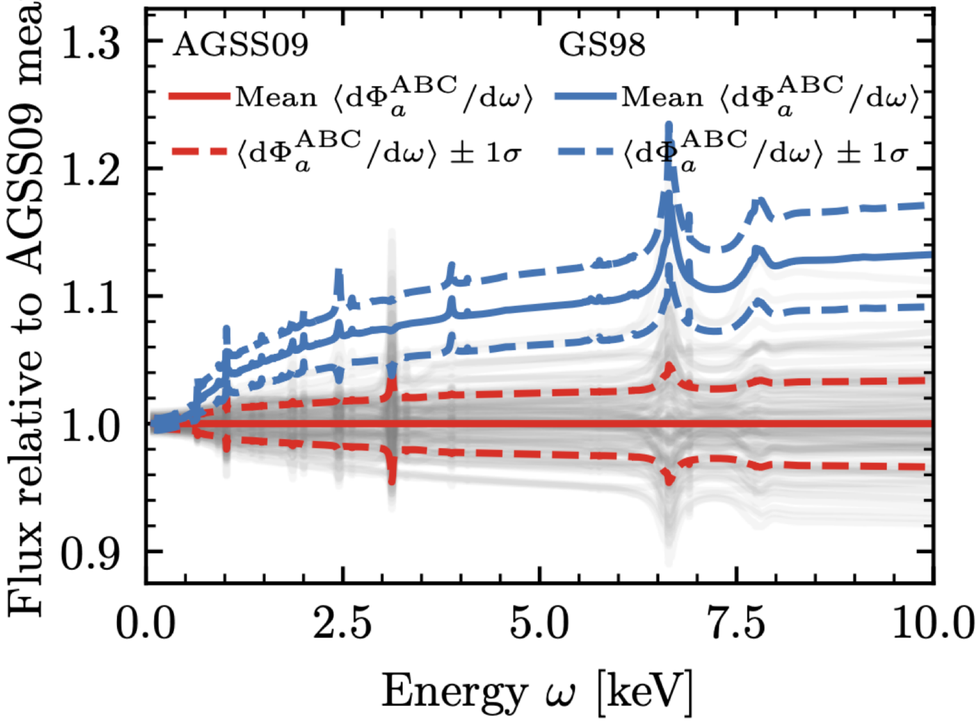


Axion-electron



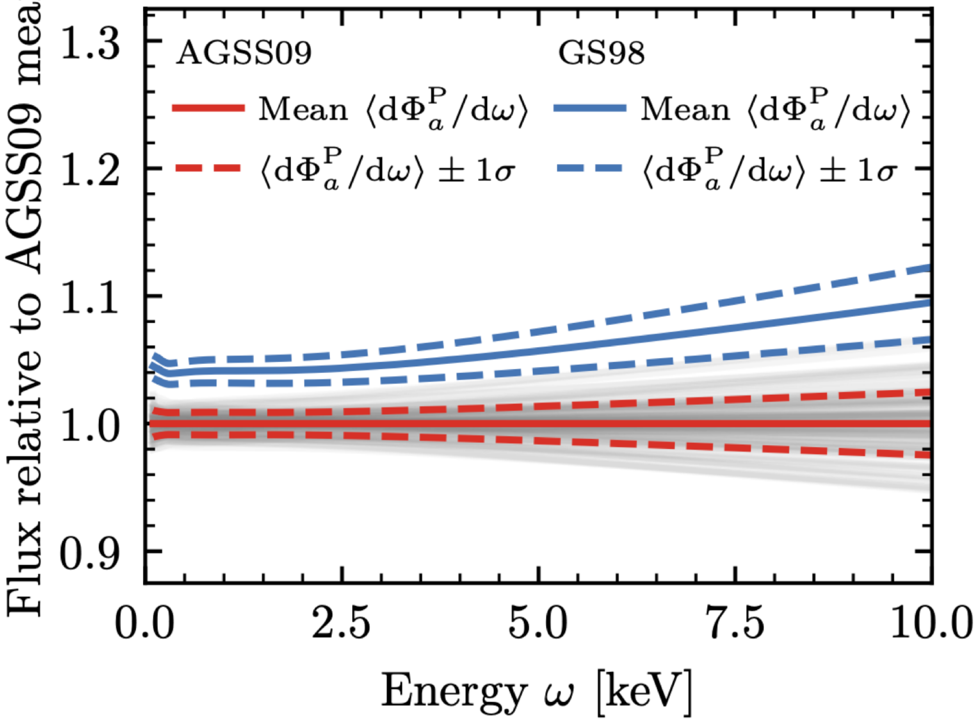
$\langle\delta\Phi_{a\gamma}\rangle = 1\% \quad \delta\Phi_{a\gamma} < 2.5\%$ $\quad \langle\delta\Phi_{ae}\rangle = 1.5\% \quad \delta\Phi_{ae} < 5\%$

Uncertainties robust to change to newest solar compositions MB22 (or AAG21)

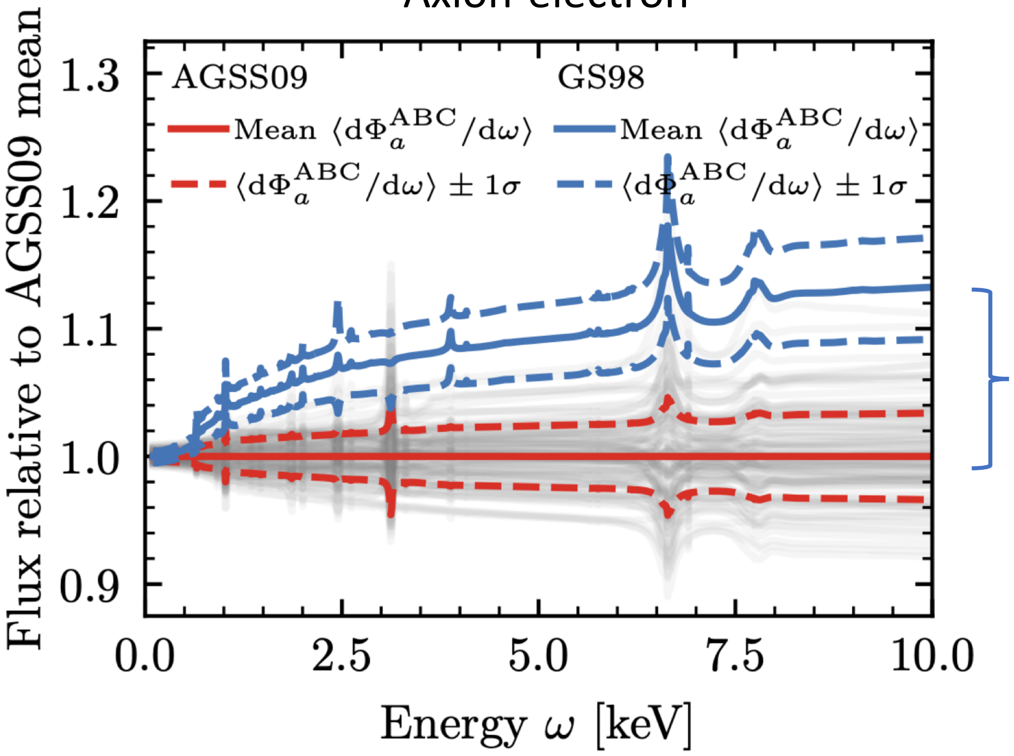
Solar model uncertainties for axion flux

Hoof et al 2021 – systematic uncertainty: temperature – composition (Debye length for a-γ and opacity for a-e)

Axion-photon



Axion-electron

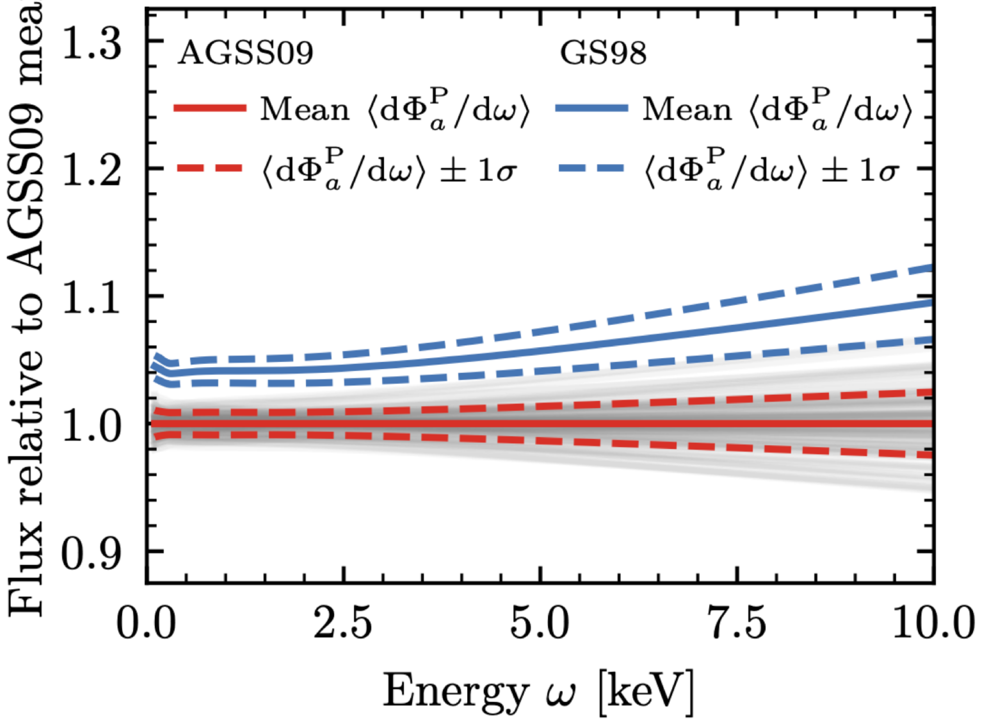


Systematic due
to composition

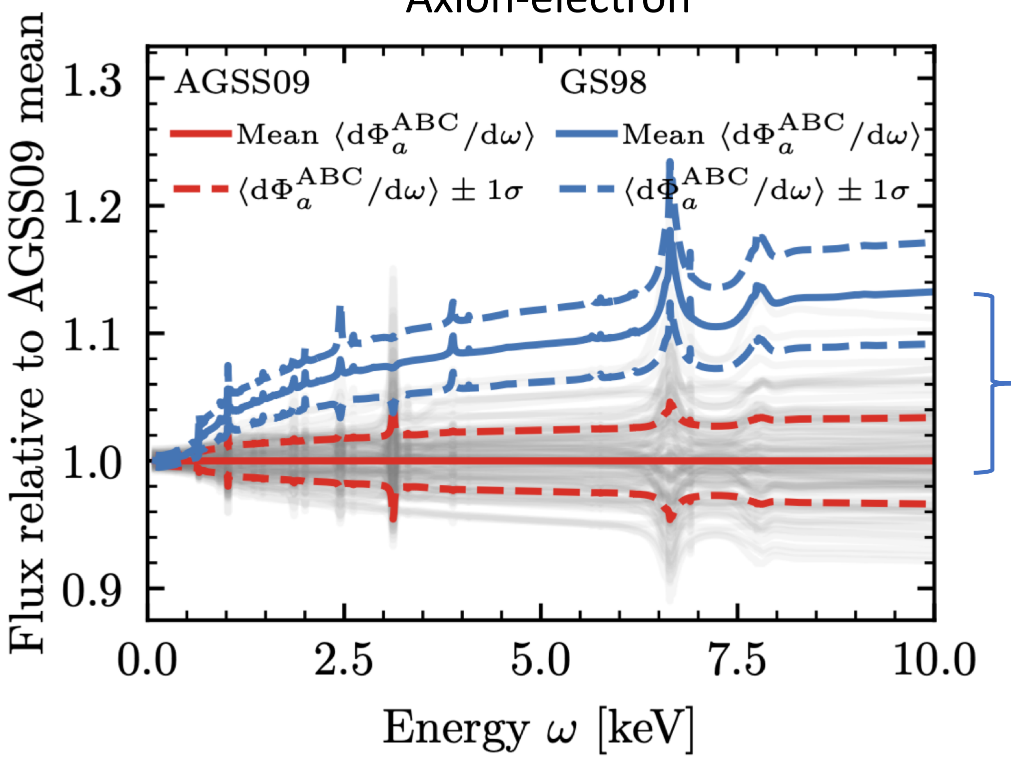
Solar model uncertainties for axion flux

Hoof et al 2021 – systematic uncertainty: temperature – composition (Debye length for a-γ and opacity for a-e)

Axion-photon



Axion-electron



Systematic due to composition

$$\langle\delta\Phi_{a\gamma}\rangle = 5.1\% \qquad \delta\Phi_{a\gamma} < 11\% \qquad \langle\delta\Phi_{ae}\rangle = 5.4\% \qquad \delta\Phi_{ae} < 19\%$$

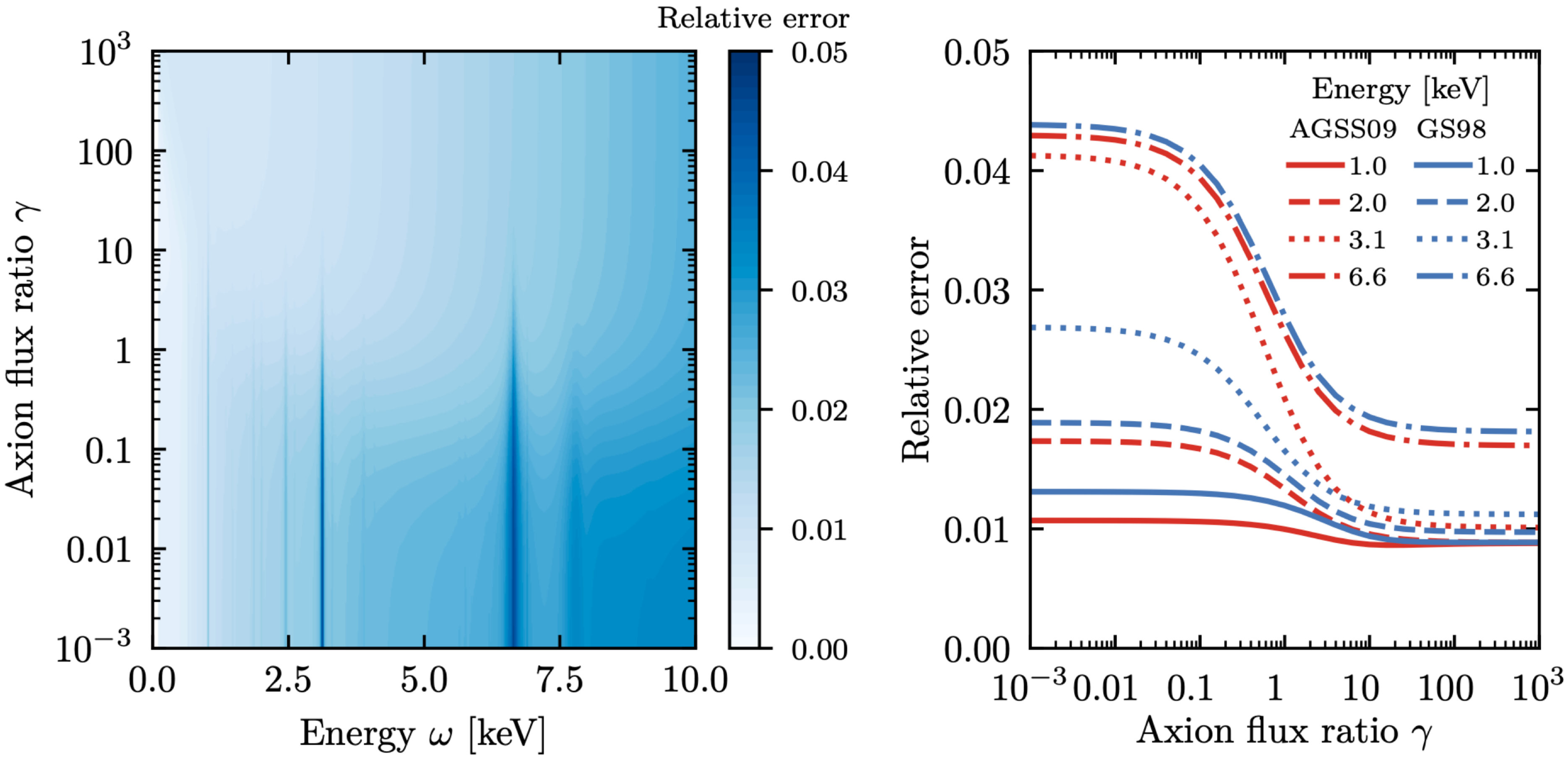
These uncertainties to decrease, approx. 30%, when considering MB22 and AAG21 (closer than GS98 and AGSS09)

Or disappear altogether as MB22 abundances become the standard

Solar model uncertainties for axion flux

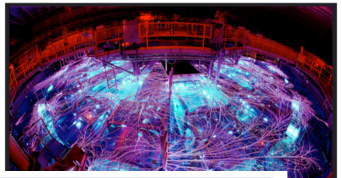
Hoof et al 2021 – systematic uncertainty: temperature – composition (Debye length for a-γ and opacity for a-e)

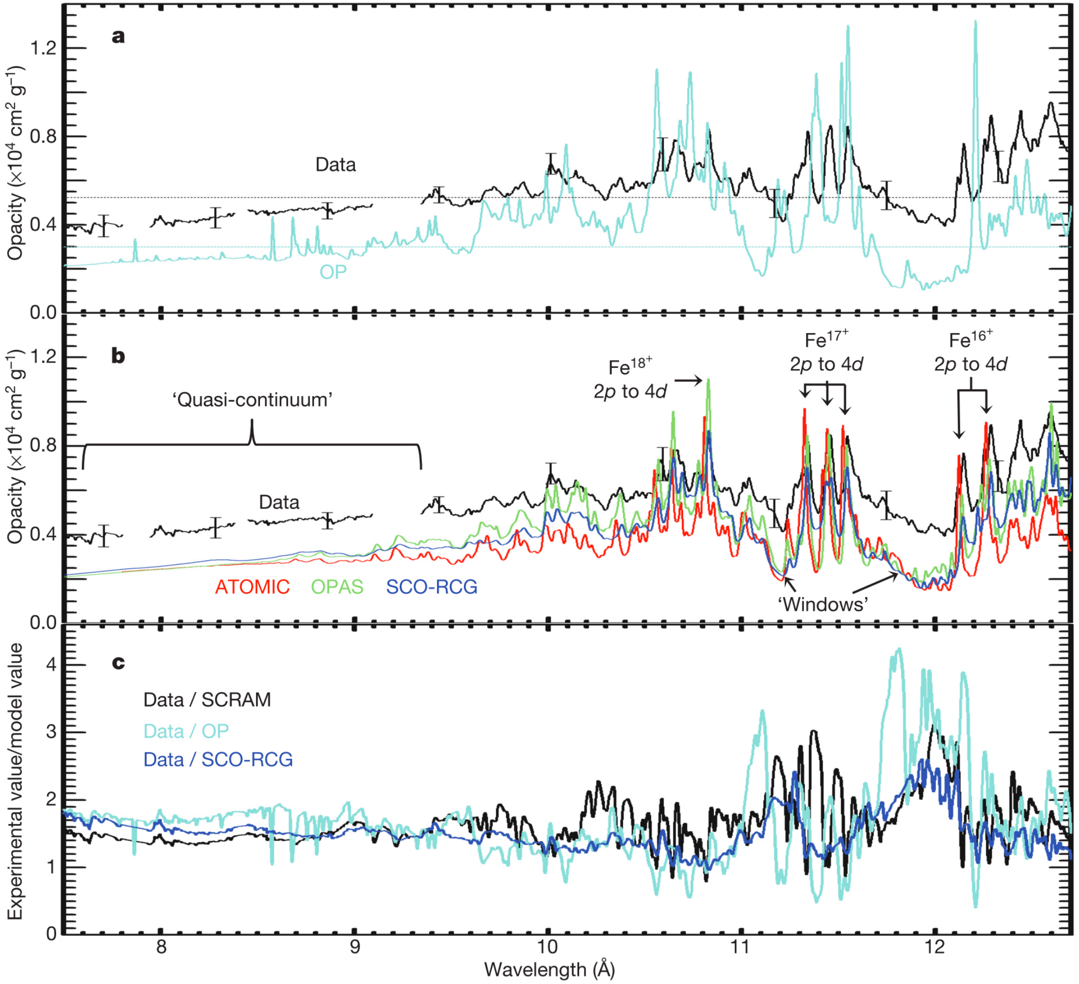
γ = P/ABC



Opacities

Solar/stellar opacities – Experiments are difficult: Z-pinch experiment @Sandia – Fe measurement





Bailey et al. 2015

Opacities

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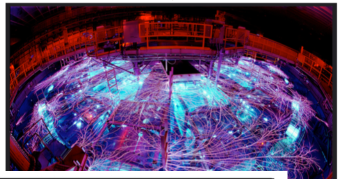
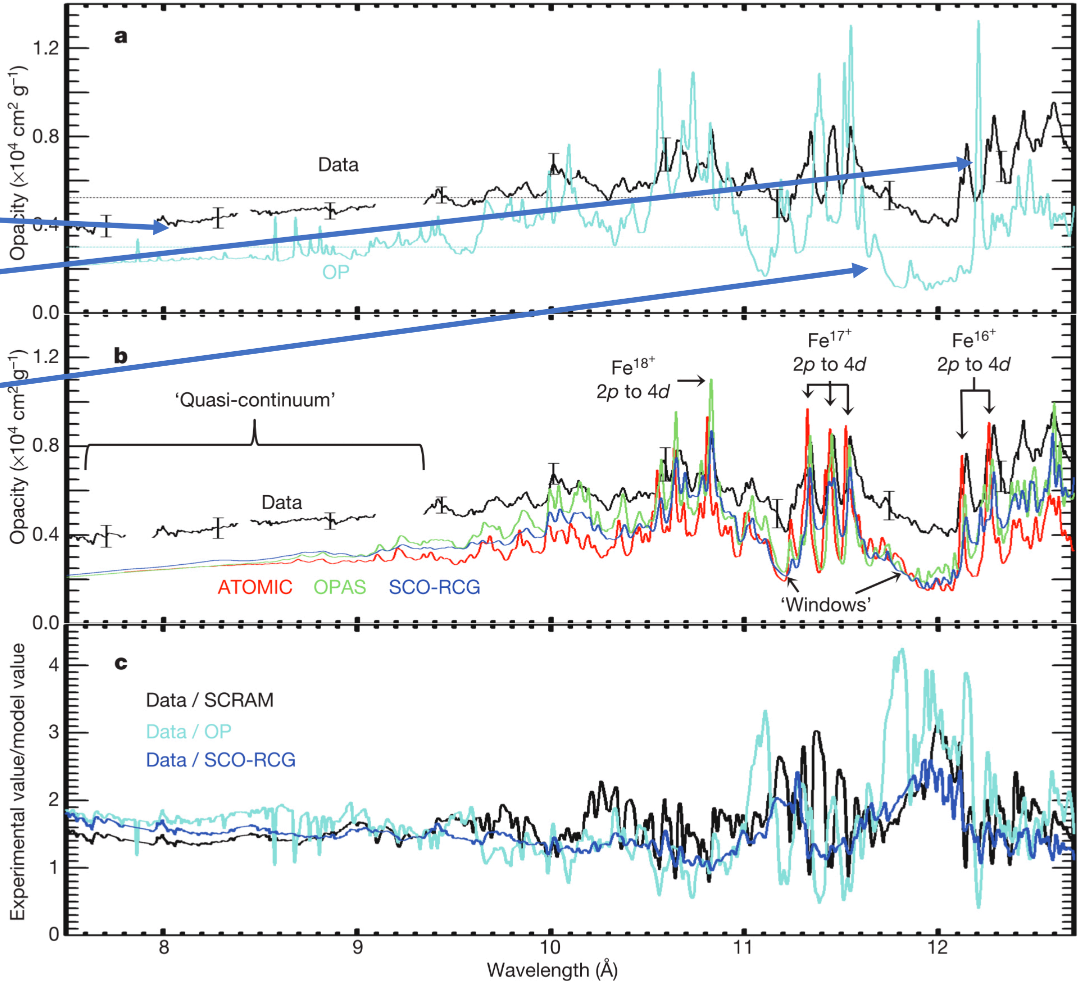


Calculations have:

1) Lower quasicontinuum

2) Narrower lines

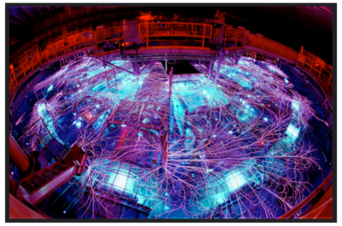
3) Deeper opacity windows



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

Bailey et al. 2015

Opacities



Solar/stellar opacities – Experiments are difficult: Z-pinch experiment @Sandia

Further experiments with Cr and Ni (Nagayama et al. 2019)

1) Narrower lines present in all cases (problem in the models)

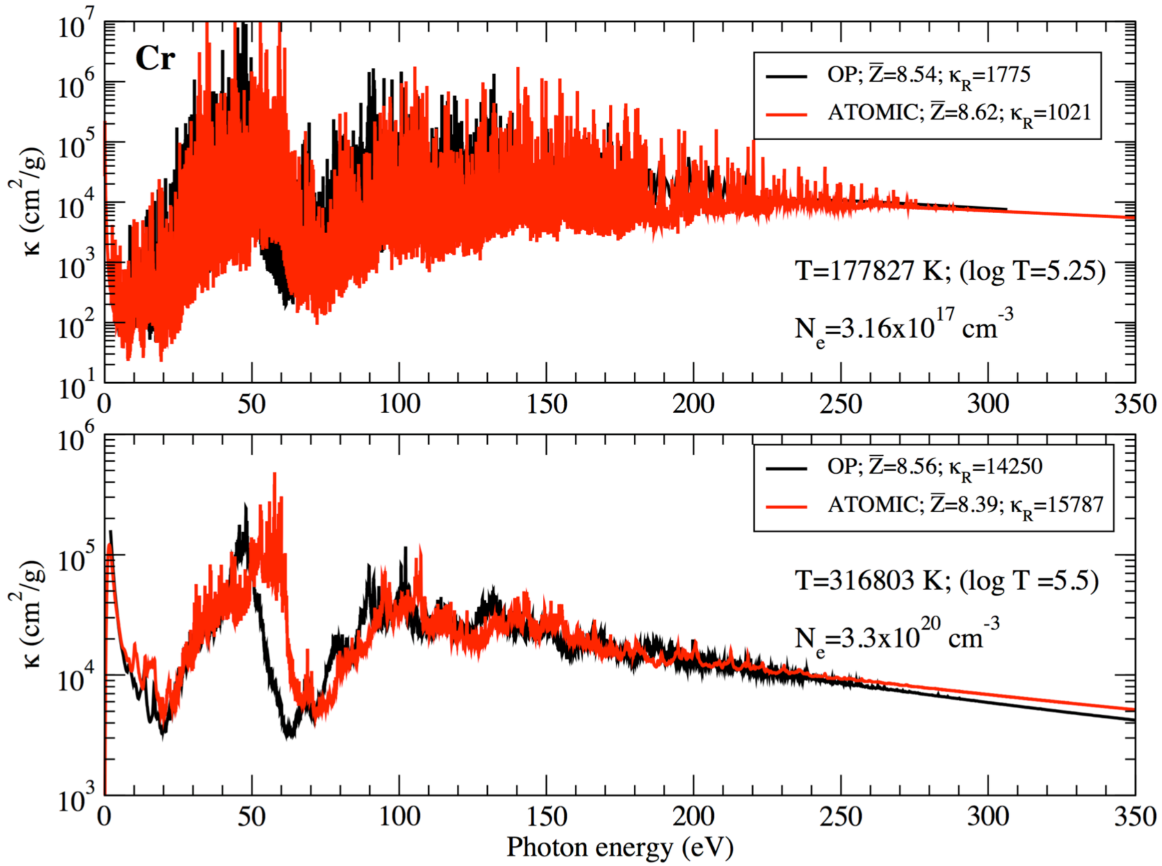
2) Deeper opacity windows – linked to open L-shell (Fe and Cr, not Ni)

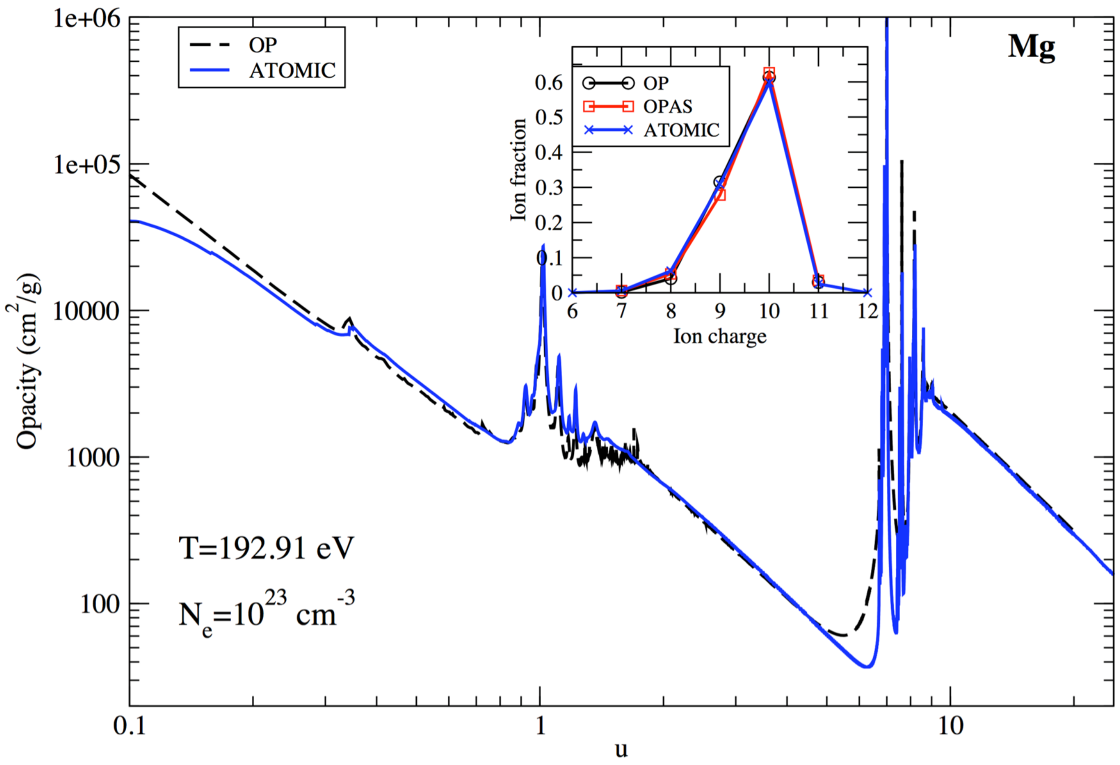
3) No cuasicontinuum problem for Cr and Ni
But experiments were done at lower T

Unknown (non monotonic in Z) dependence missing in models?
Experimental flaw in the hot Fe (T > 180eV) experiments?

Opacities

Solar/stellar opacities – monochromatic opacities are a mess



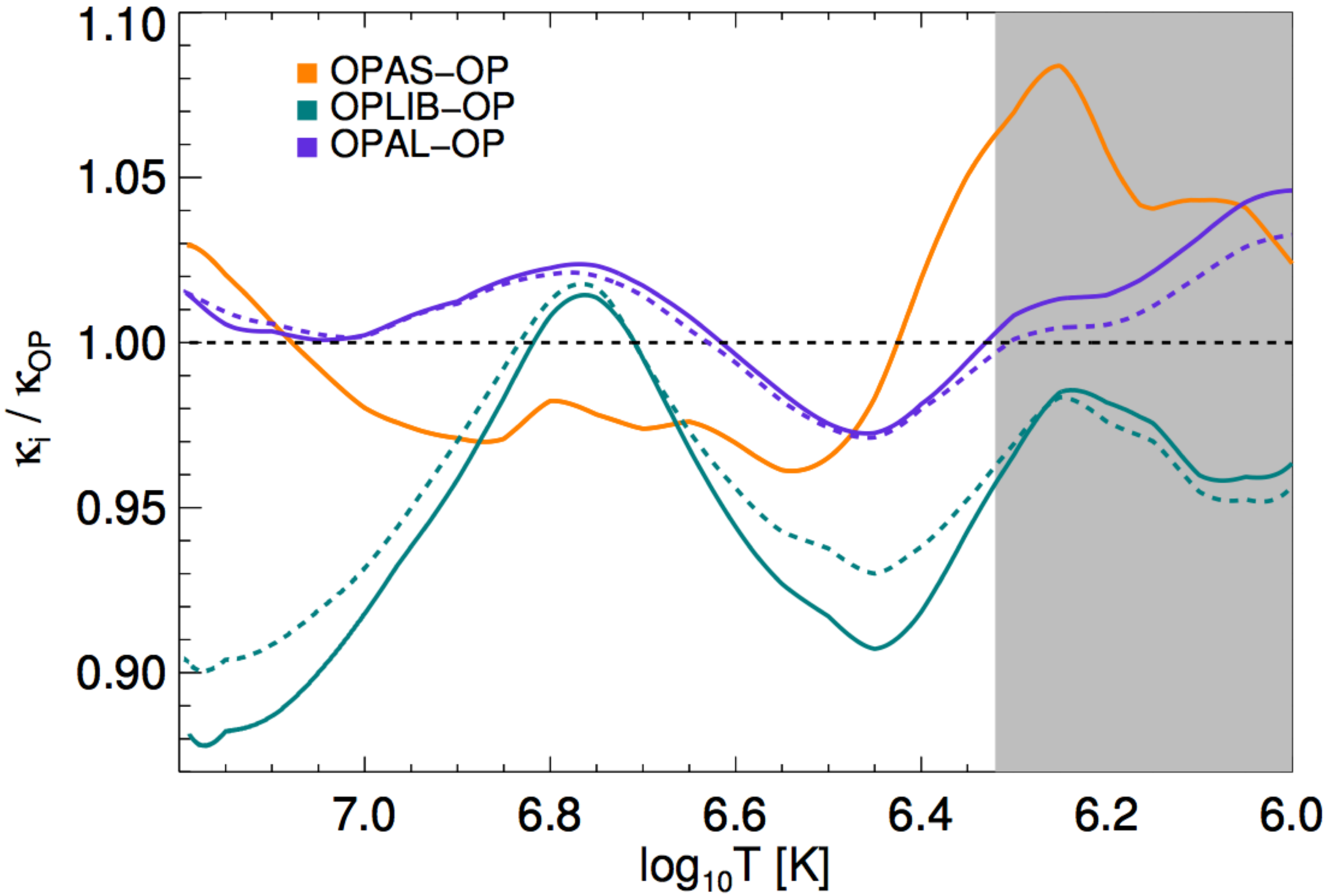


Local large discrepancies might arise (energy offsets?)

Treatment of broadening?

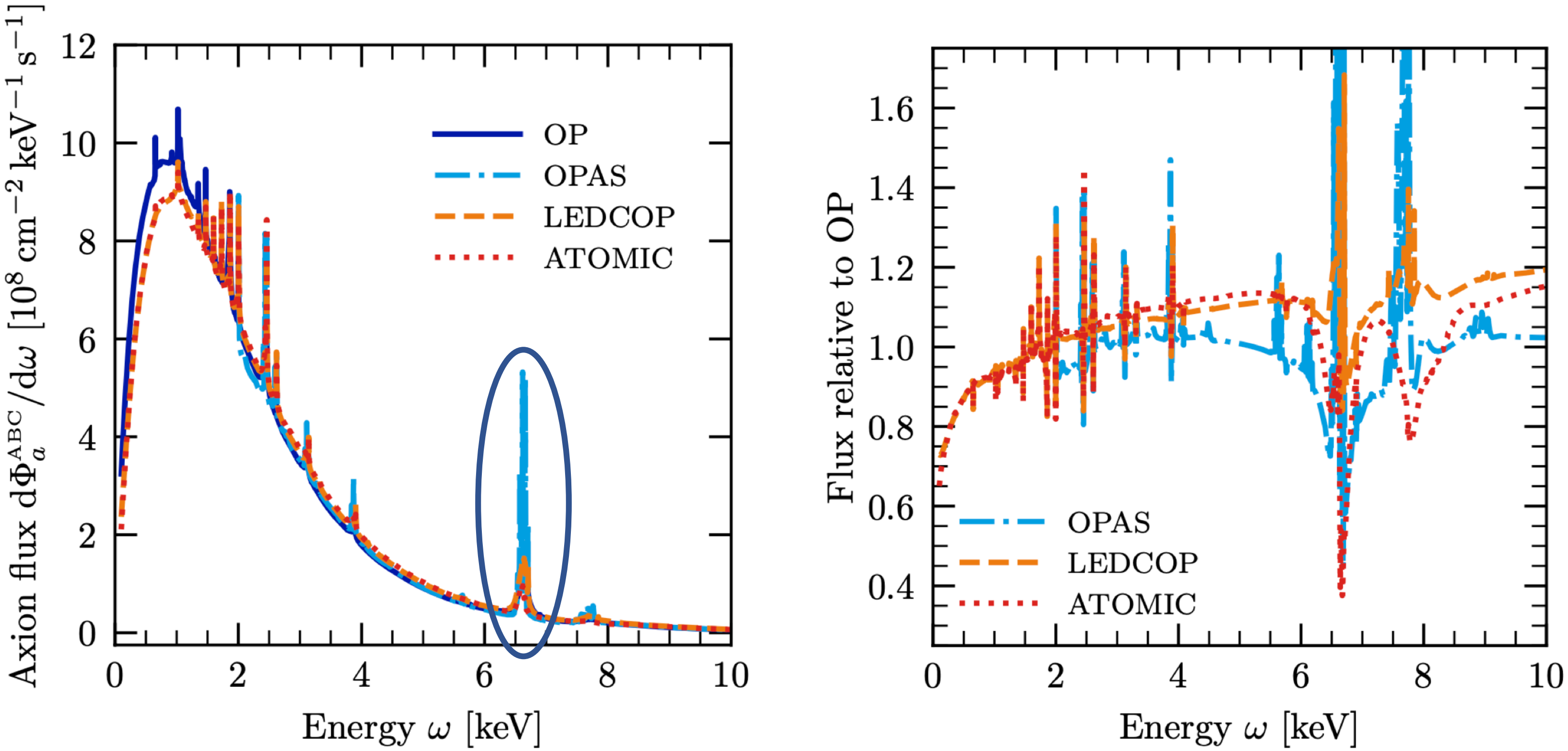
Opacities

Solar/stellar opacities – Rosseland means opacities are still difficult



Solar model uncertainties for axion flux

Impact on monochromatic opacities (Hoof et al. 2021, following initial work by Redondo 2013)



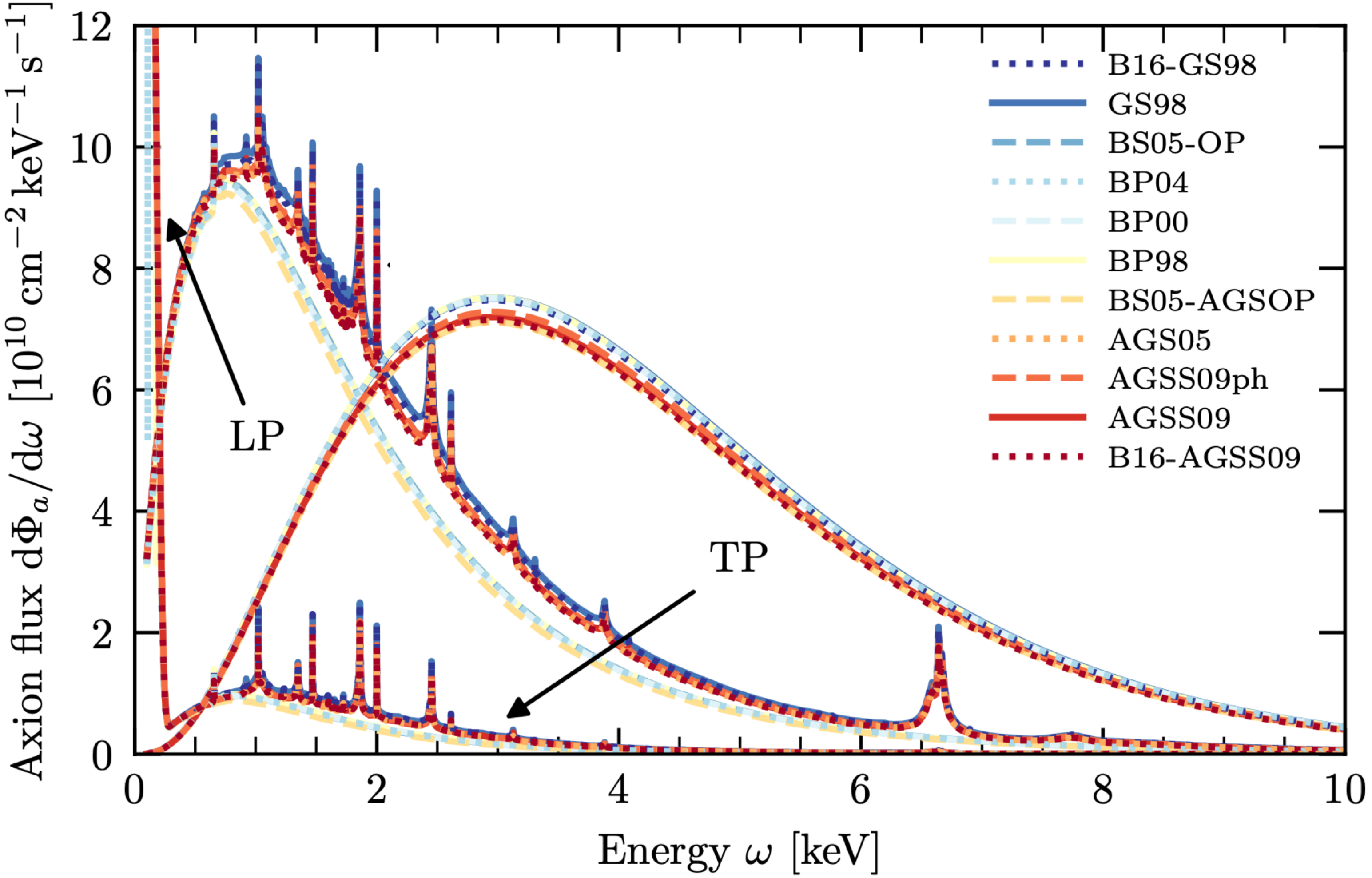
Very large differences at localized energies (resemblance of opacity comparison) – nitty gritty details?

$\langle \delta\Phi_{ae} \rangle = 1 - 3\%$ For monochromatic, but result of cancellation in energy dependence

$\langle \delta\Phi_{ae} \rangle < 1\%$ For Rosseland, assuming 7% at base of CE and 2% at center

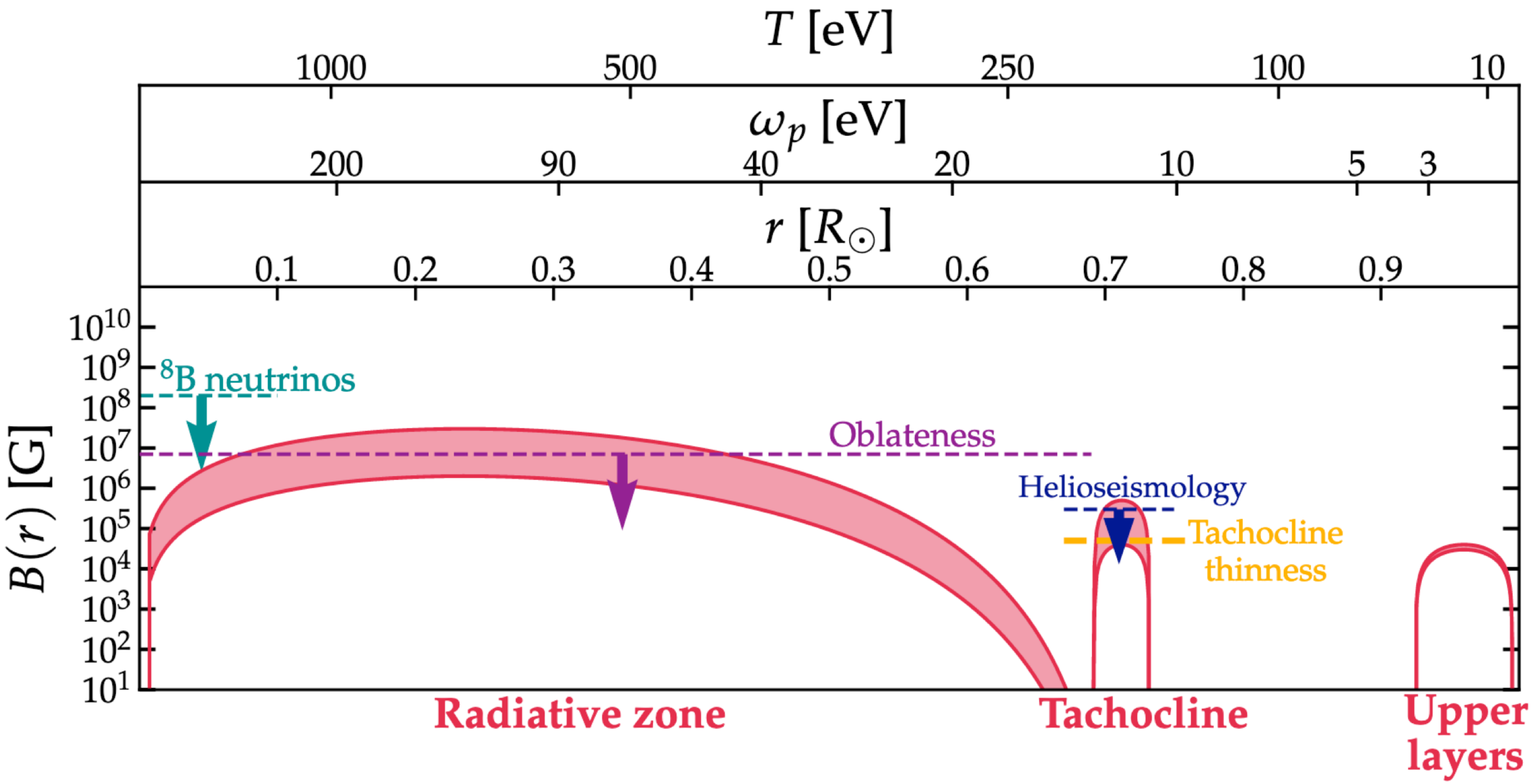
Solar model uncertainties for axion flux

Solar magnetic field for LP and TP components (Hoof et al. 2021)



Solar model uncertainties for axion flux

LP and TP components based on O'Hare et al. 2020 solar magnetic field:



Structure of magnetic field taken from

Couvidat et al 2002
Antia et al. 2000

None is a measurement, upper limit at best

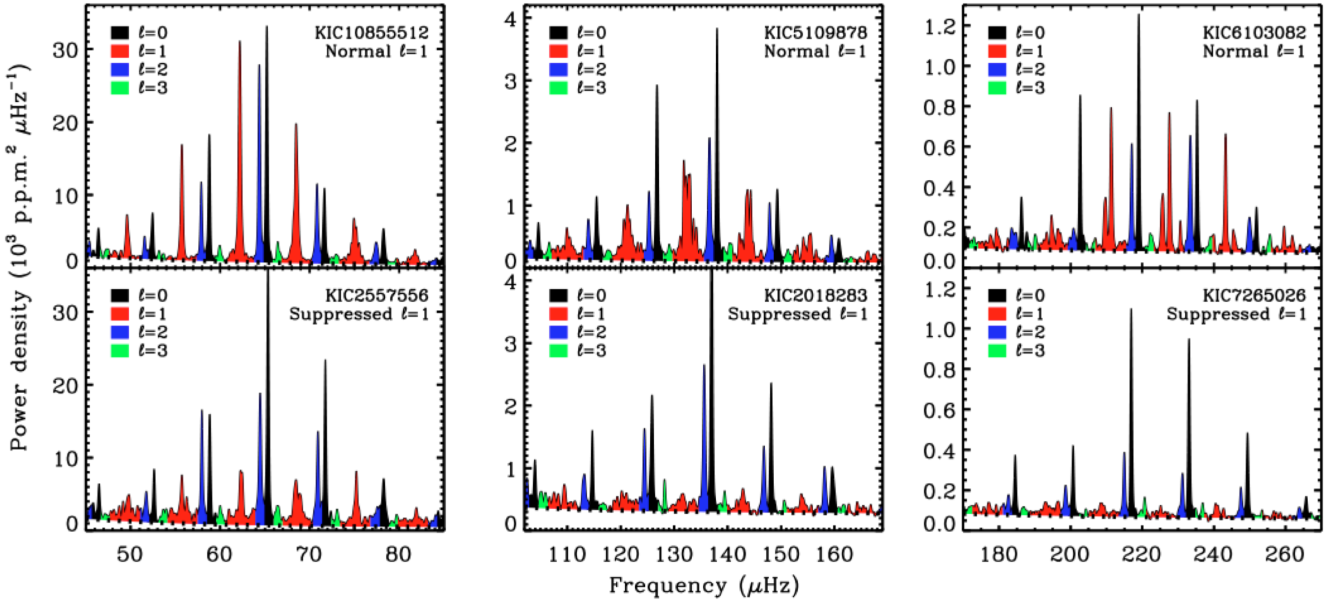
No strong support to B from seismic data especially in radiative interior

No robust quantification in other regions

Solar model uncertainties for axion flux

Indirect arguments against strong B field in radiative interior:

Suppressed l=1 modes in some red giants (Stello et al. 2016)



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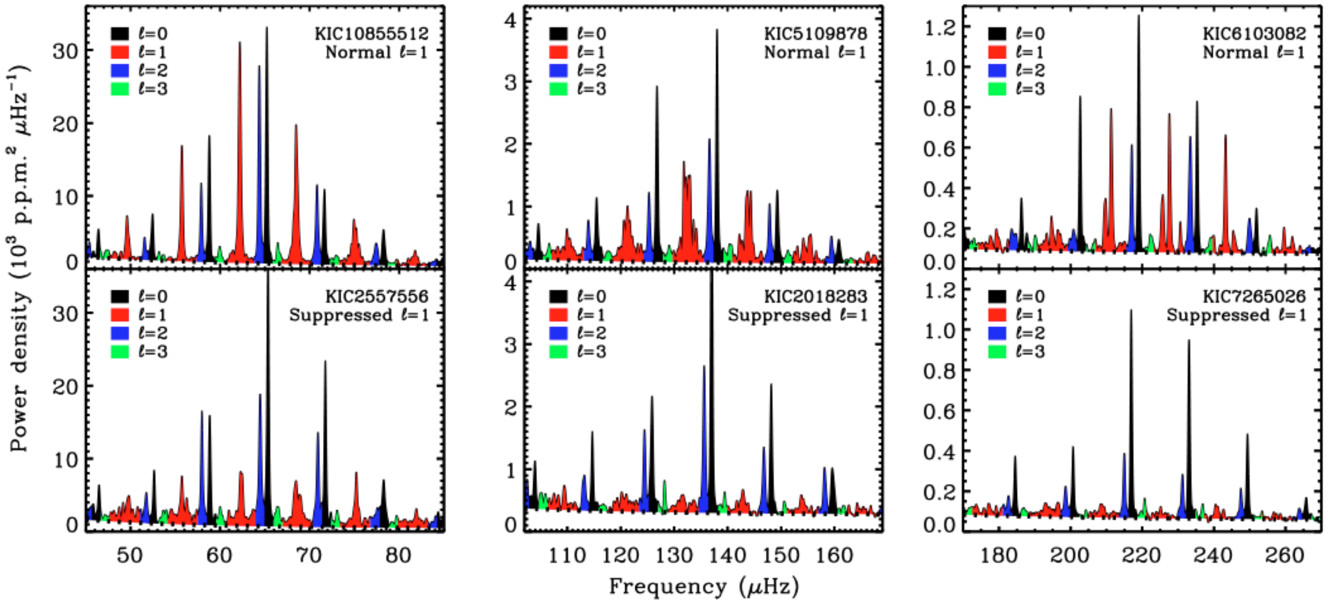
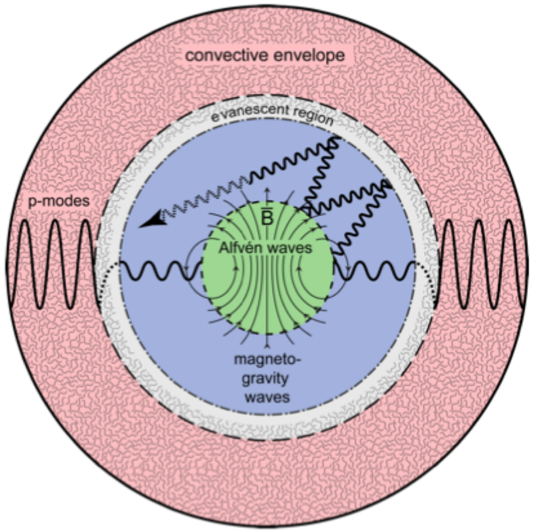


Magnetic green-house effect



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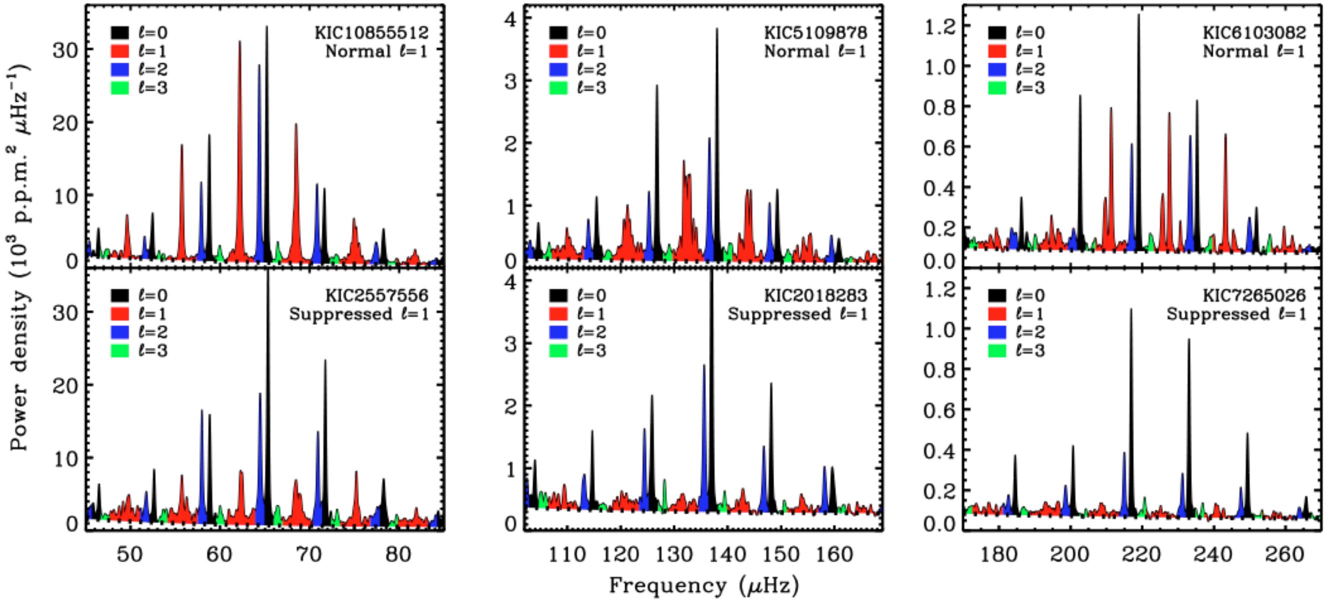
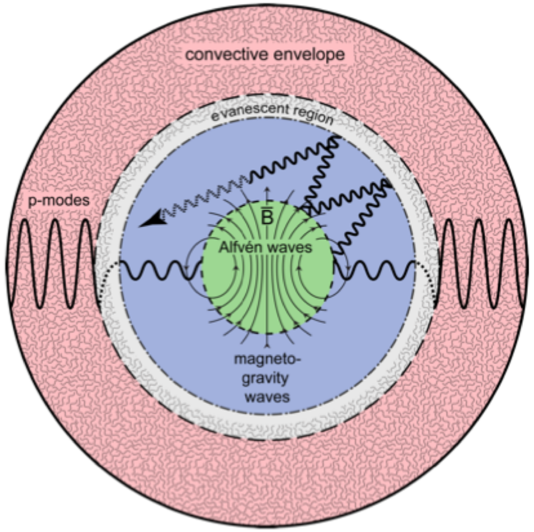


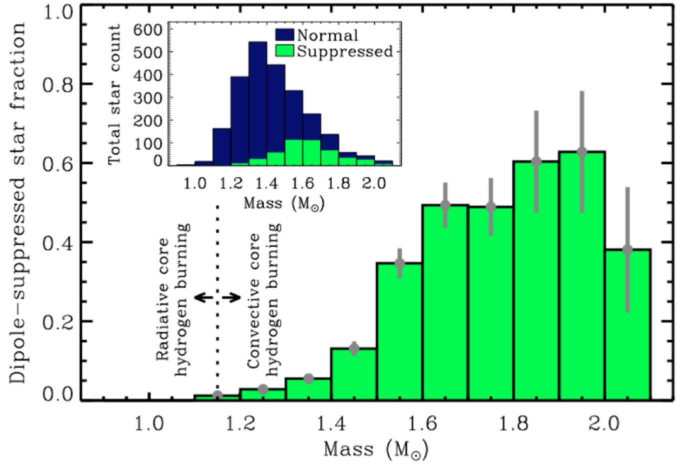
Not present in $1M_\odot$ stars

$B=10^6$ G enough

Flux conservation → $B > 10^{10}$G and this is not seen for $1M_\odot$

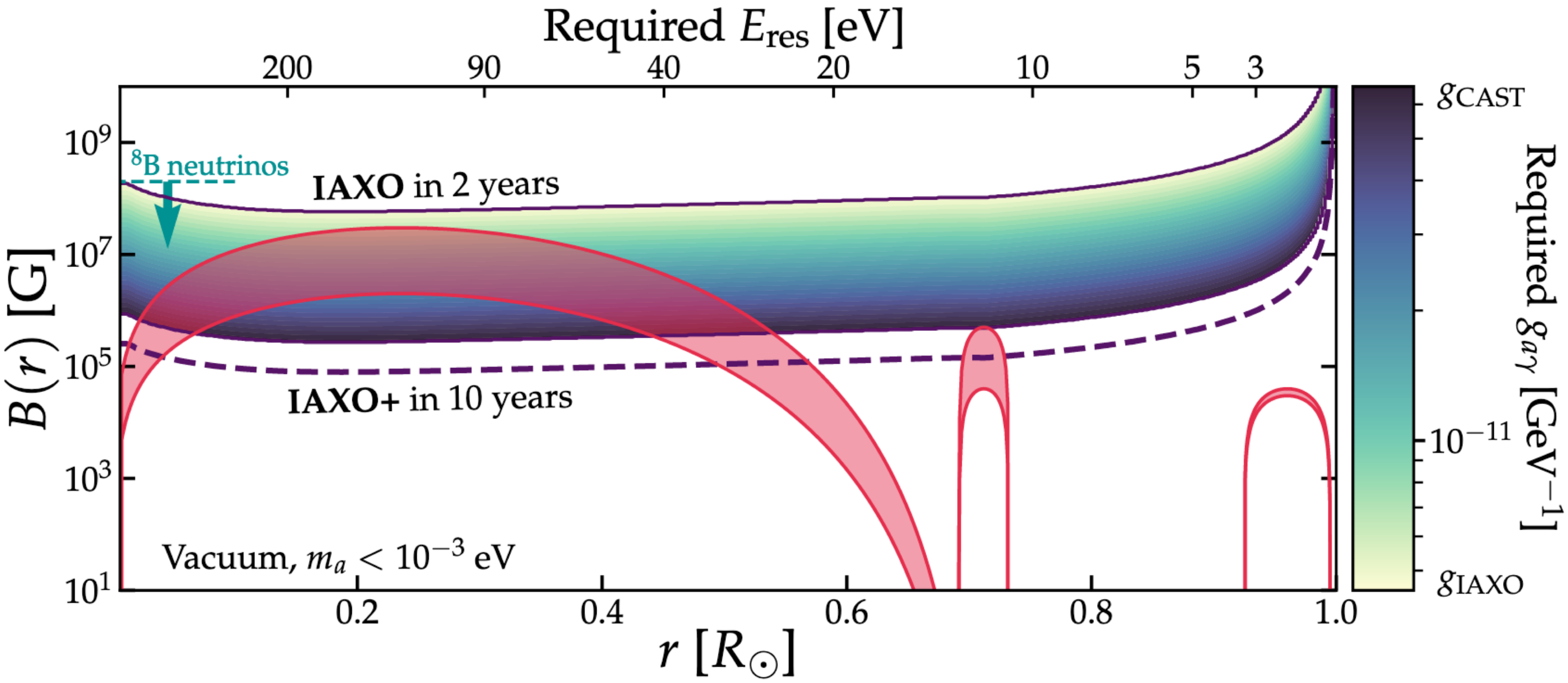
Magnetic green-house effect





Solar model uncertainties for axion flux

But using next-gen helioscopes as magnetometers is certainly a great idea! (O'Hare et al. 2020)



Summary

- New solar abundances MB22 solve the solar abundance problem
  New generation of detailed SSMs in preparation – will be advertised within COSMIC WISPERS
  we accept requests as to what information should be included:
  detailed composition, ionization stages, etc (when possible)

- Statistical uncertainties in solar $\Phi_{ae} < 5\%$ and $<\Phi_{ae}>= 1.5\%$
- Statistical uncertainties in solar $\Phi_{a\gamma} < 2.5\%$ and $<\Phi_{a\gamma}>= 1\%$

- Systematic uncertainties (opacities) in solar $<\Phi_{ae}>=1\text{-}3\%$ and very large localized peaks

- Systematic uncertainties (composition) in solar $\Phi_{ae}<19\%$ and $<\Phi_{ae}>=5\%$
- Systematic uncertainties (composition) in solar $\Phi_{a\varepsilon}<11\%$ and $<\Phi_{a\gamma}>=5\%$
- **But → as new solar abundances seem to have solved the solar abundance problem**

- LP and TP components from B – very little (if any) information on solar internal and no robust evidence for strong B