Current limits in our understanding of solar interior from neutrinos and helioseismology

Aldo Serenelli

Next frontiers in the search for dark matter
GGI - 27/09/2019

Institute of
Space Sciences

CSIC
Consejo Superior de Investigaciones Científicas

IEEC

Brief historical recap

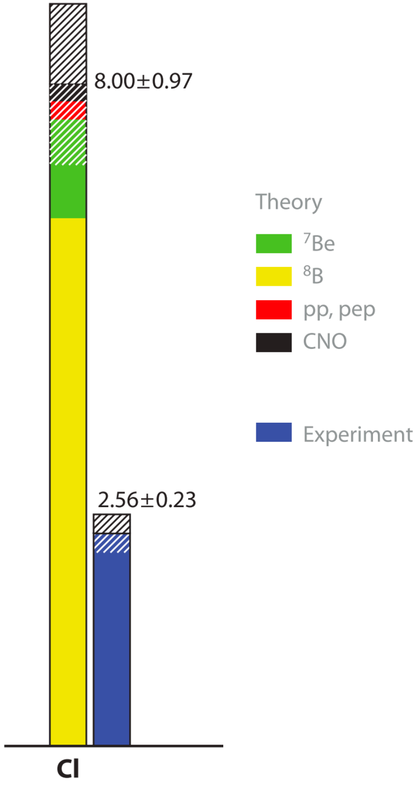
Solar models today

- helioseismic constraints
- solar neutrinos
- status of solar abundance problem

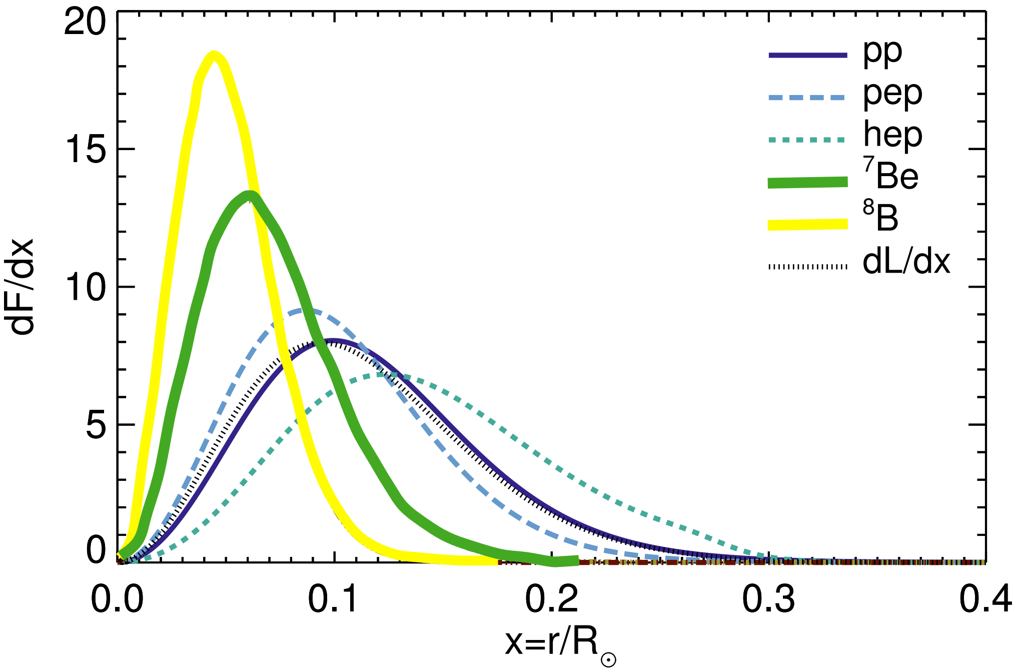
Sun as lab for particle physics: the solar models perspective

Solar models and dark matter – a long history

Solar neutrinos problem – Homestake – ’70s and ‘80s



$$\Phi \propto T_c^n \quad n(^8\mathrm{B}) \approx 24 \quad n(^7\mathrm{Be}) \approx 10$$

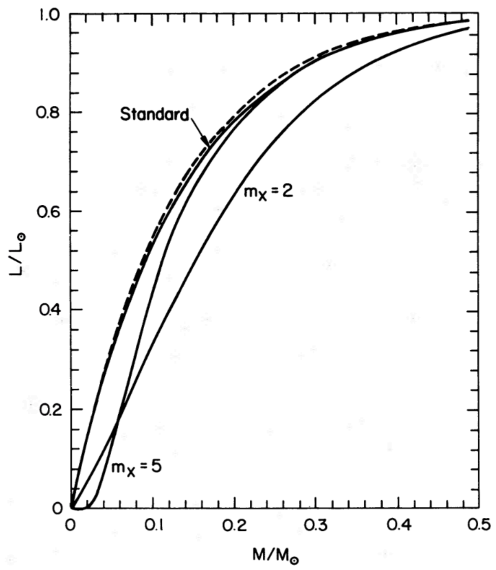


Solar models and dark matter – a long history

Steigman et al. 1978: astrophysical implications of heavy neutrinos

Spergel, Press, Gilliland, Faulkner (1985-1986): accretion, capture, evaporation and (more) detailed energy transport by WIMPs

(2 GeV) → 4 GeV < m_x < 60 GeV would do the trick – cool down inner 10% (in radius)



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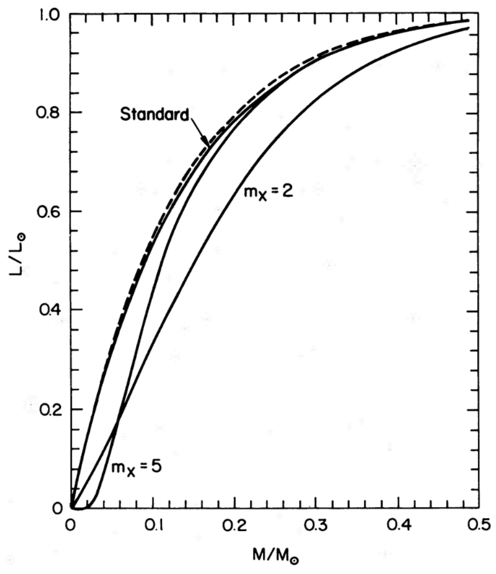

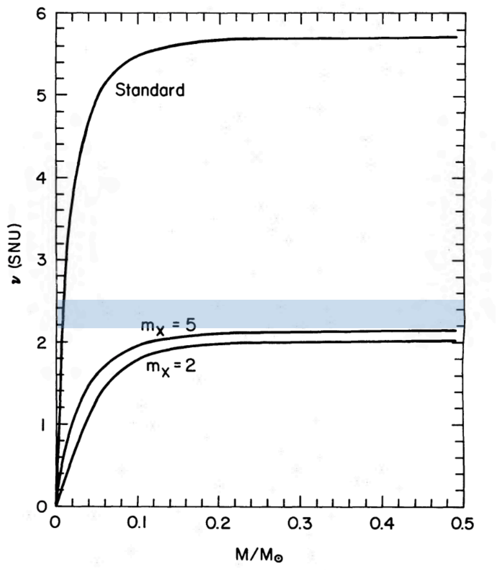

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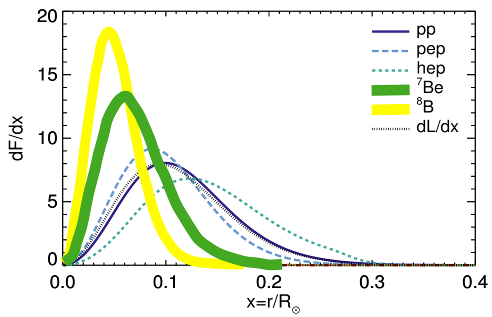

Solar models and dark matter – a long history

Around '80s energy loss argument also used, e.g. for low mass particles such as axions (Raffelt and others)

$$\delta_x = L_x / (L_\gamma + L_x)$$

with δ_x determined by researcher's boldness

E.g. axion production in the Sun

Raffelt 1987

g_{10}	Y_{initial}	δ_x	X_c
0	0.274	0.00	0.362
10	0.266	0.16	0.307
15	0.256	0.32	0.292
20	0.241	0.51	0.245
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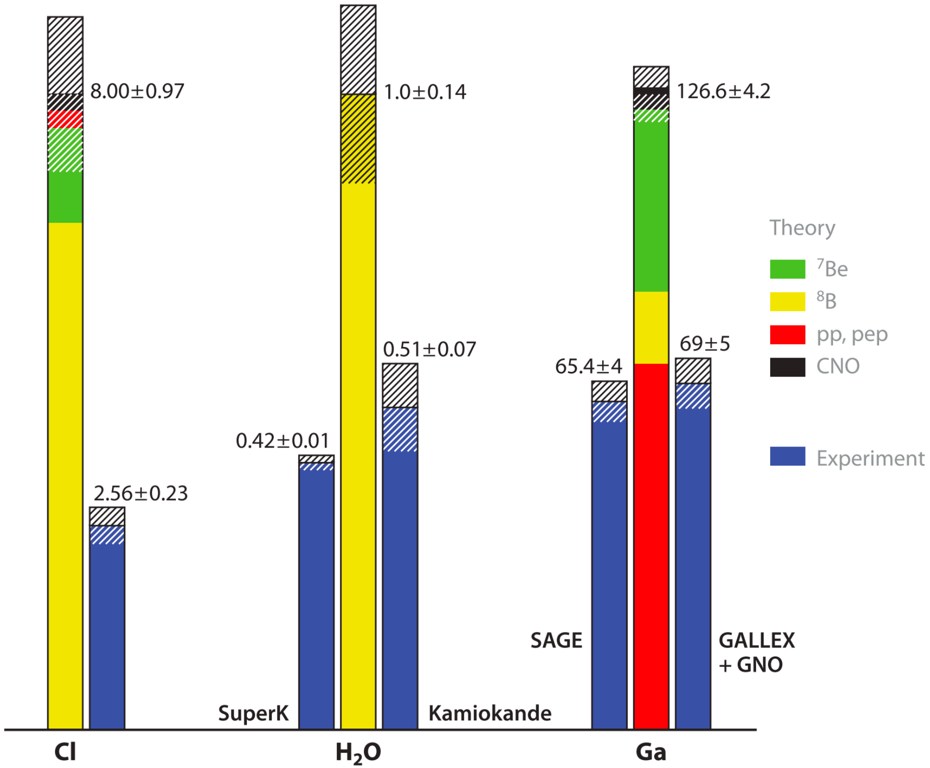
$\Phi \propto T_c^n$ $\quad n(^8\mathrm{B}) \approx 24$

Schlattl, Weiss, Raffelt 1999 – limit at $\delta_x \approx 0.2$

g_{10}	Ga [SNU]	Cl [SNU]	^{8}B [$10^6\ \mathrm{s^{-1} cm^{-2}}$]
0	127	8.0	5.5
4.5	136	9.3	6.6
10	184	17.6	13.0
15	323	48	37
20	806	161	127

In the '90s



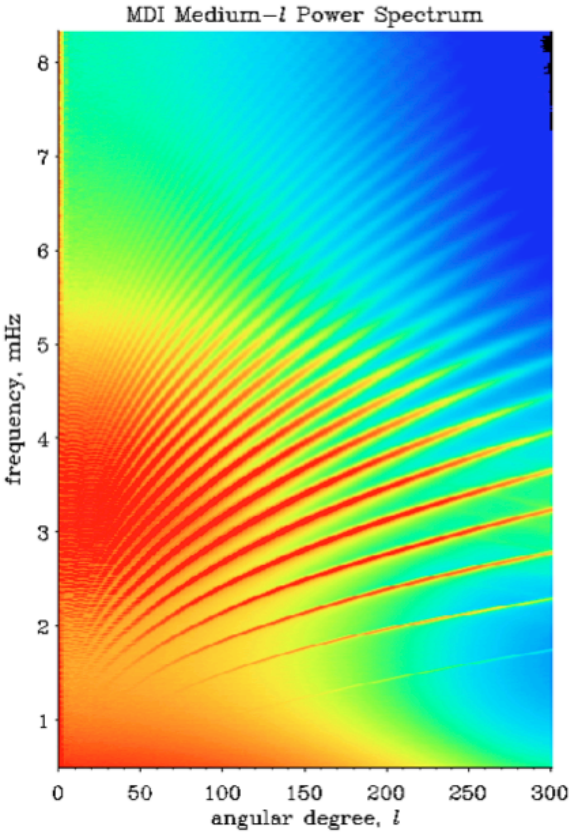
Lower core T became a more difficult solution

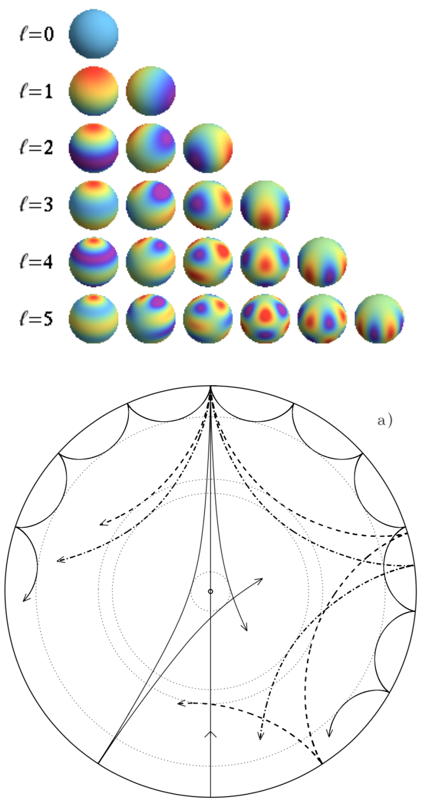
pp + pep large contribution to Ga experiments

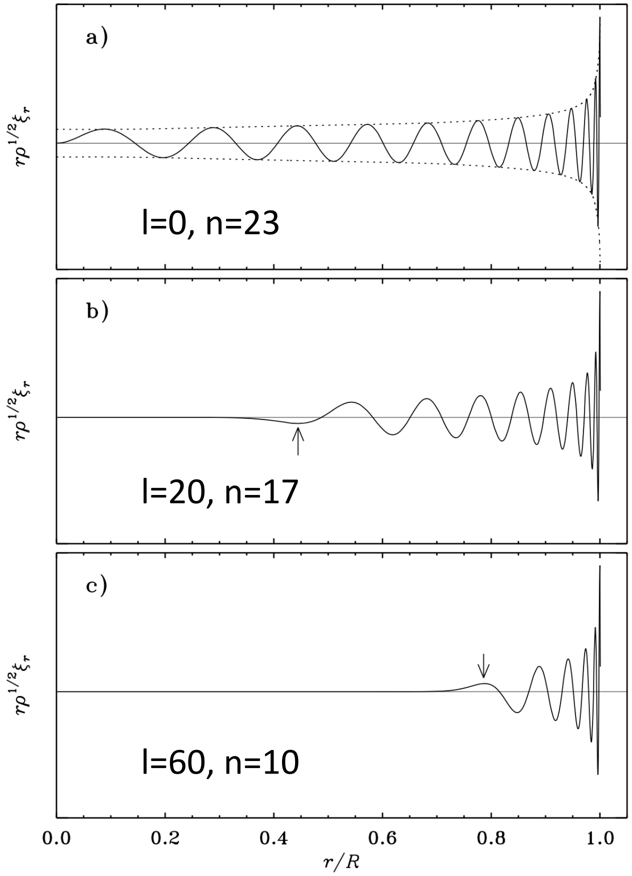
pp provides 90% $L_\odot$

Helioseismology

Global sound waves observed as radial velocity and brightness variations



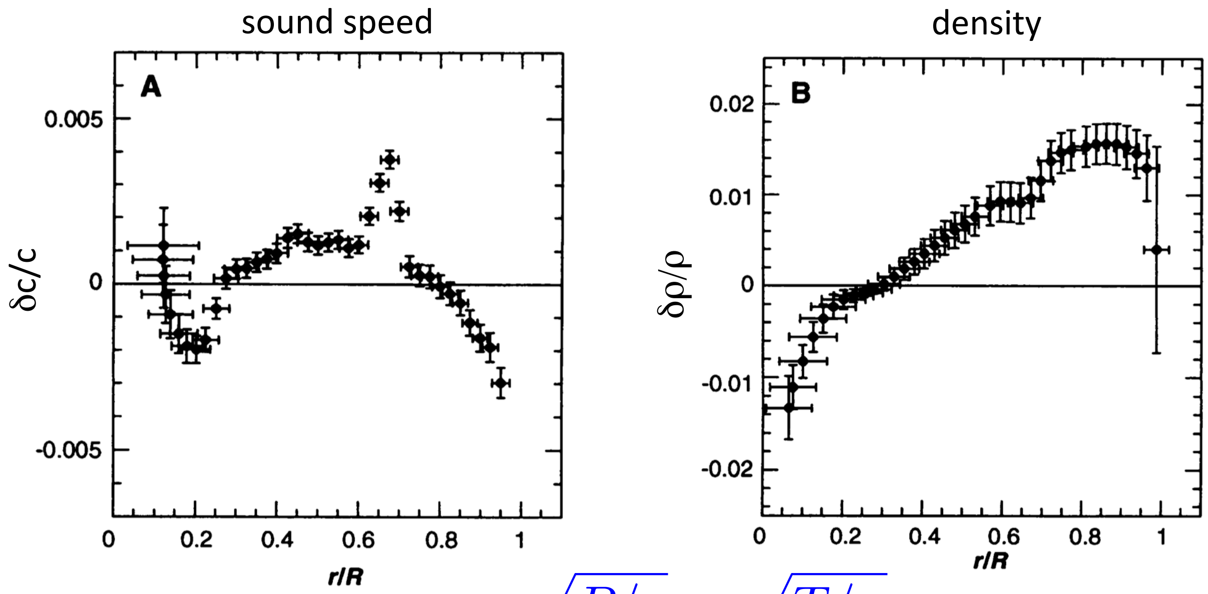




Helioseismology

Inversion of solar structure: **sound speed and density difference wrt reference solar model**

$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\frac{\delta c^2}{c^2}(r)dr + \int K^i_{\rho,c^2}(r)\frac{\delta\rho}{\rho}(r)dr + F_{\rm surf}(\omega_i)$$



Gough et al. 1996

$$c \propto \sqrt{P/\rho} \propto \sqrt{T/\mu}$$

By mid '90s it was clear not much room for non-standard physics in solar models

Standard solar model

SSM assumes

Initially fully mixed composition due to convection in pre-MS
constant solar mass $M_\odot$ and known age 4.57 Gyr

"Standard physics" – tries to avoid ad-hoc and/or "over calibrated" physics
– minimizes number of adjustable parameters

3 free parameters

Convection parameter: α_{MLT}

Initial composition – helium and metal content $\mathbf{Y_{ini}}$ and $\mathbf{Z_{ini}}$

to match 3 observables

solar radius $R_\odot$

solar luminosity $L_\odot$

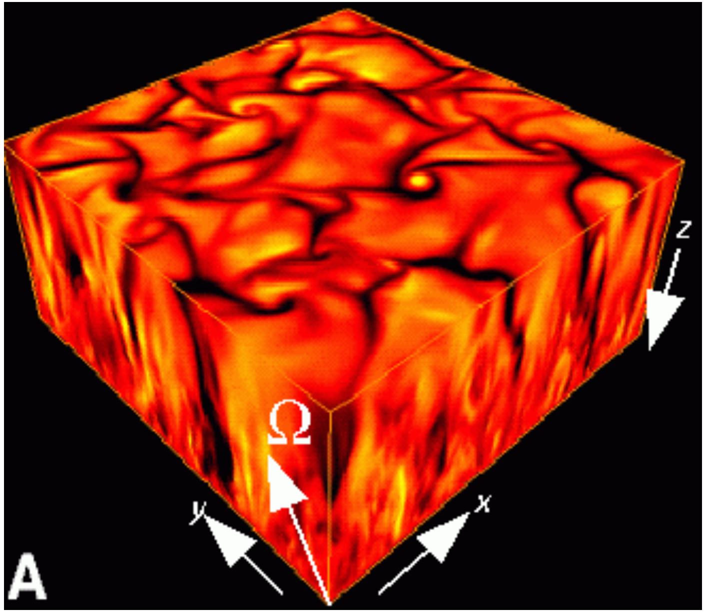
metal-to-hydrogen abundance ratio $(Z/X)_\odot$

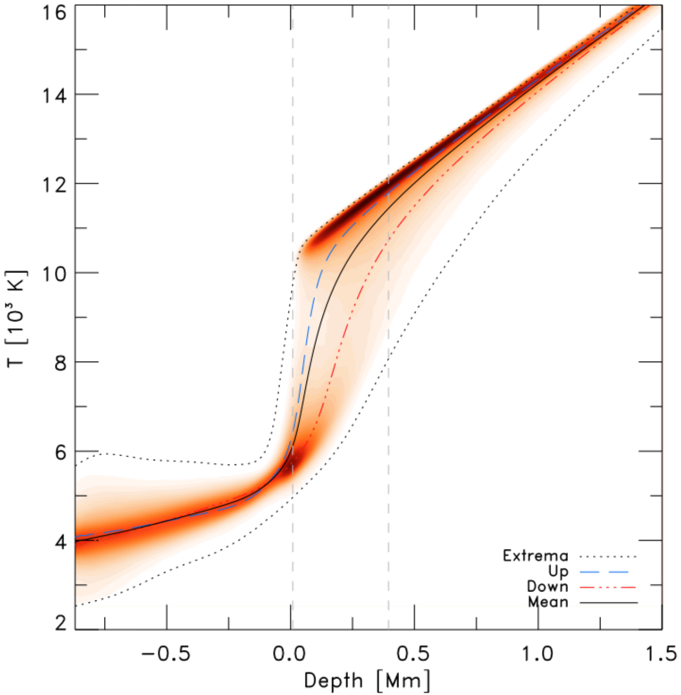
Standard solar model

Change of paradigm in solar composition:

Grevesse & Sauval 1998 → Asplund et al. 2005, 2009, 2015 – Caffau et al. 2011

- 3D solar atmosphere models
- refined atomic data and line selection
- non-LTE treatment of line formation





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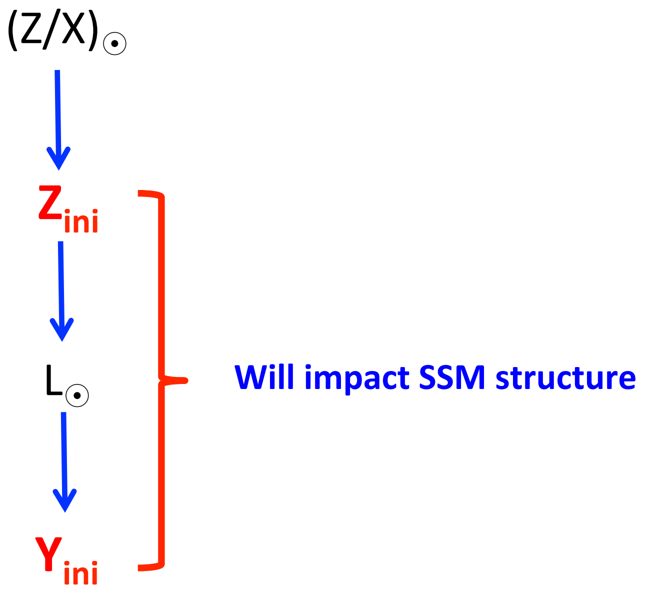
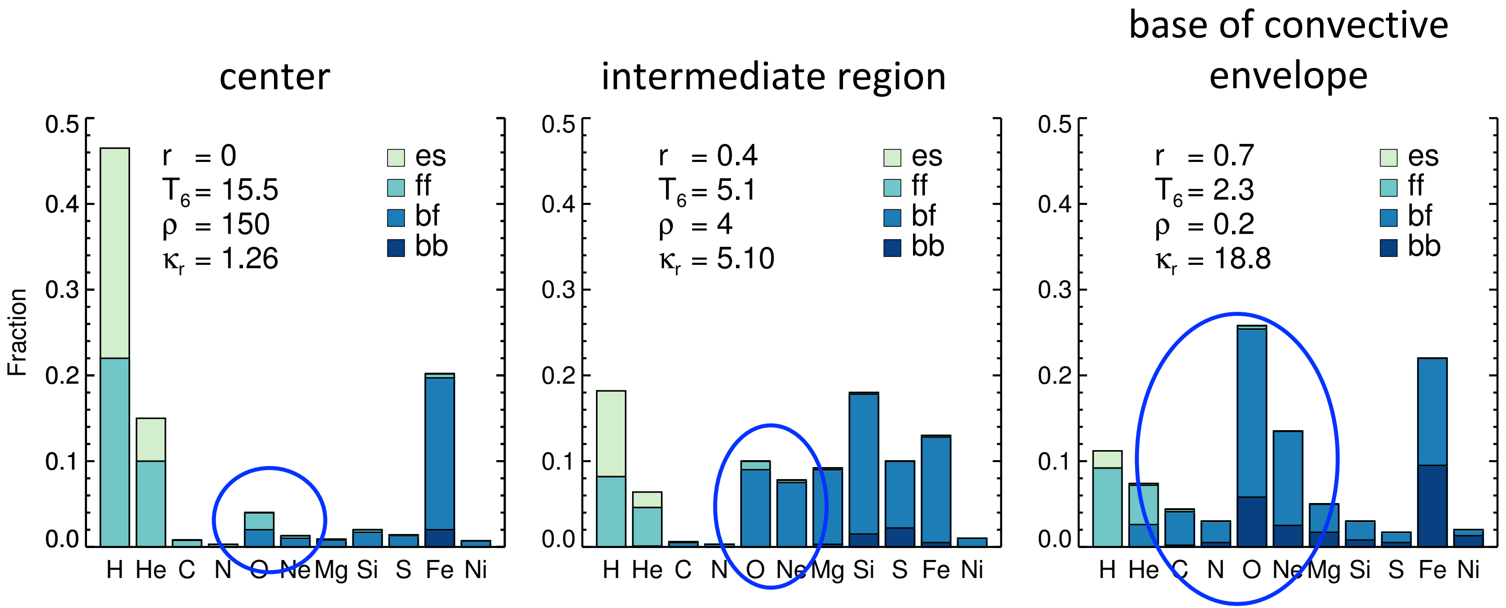
Elem.	GS98	AGSS09met	Change
C	8.52 ± 0.06	8.52 ± 0.05	23%
N	7.92 ± 0.06	7.83 ± 0.05	23%
O	8.83 ± 0.06	8.69 ± 0.05	38%
Ne	8.08 ± 0.06	7.93 ± 0.10	41%
Mg	7.58 ± 0.01	7.53 ± 0.01	12%
Si	7.56 ± 0.01	7.51 ± 0.01	12%
S	7.20 ± 0.06	7.15 ± 0.02	12%
Fe	7.50 ± 0.06	7.45 ± 0.01	12%
$(Z/X)_\odot$	0.0229	0.0178	29%

Impact of SSM calibration



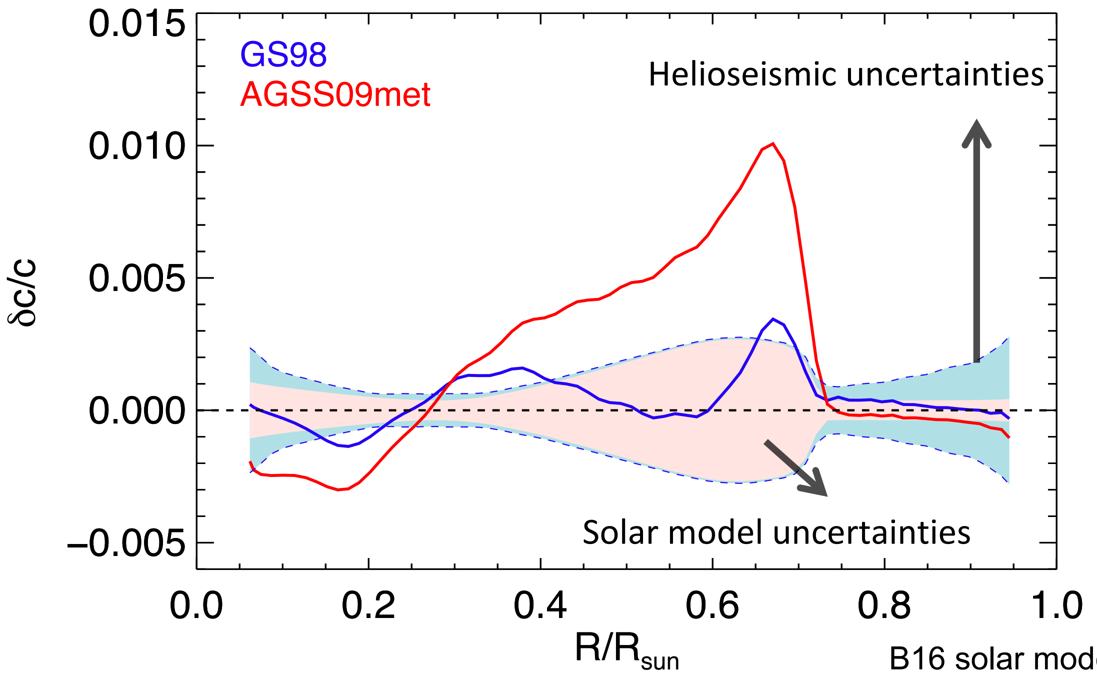
Relevance of metals: opacity



κ changes: few % in solar core up to 20% in base of convective envelope

radiative transport ⟶ $\nabla T^4 \propto \kappa$ ⟶ changes in T profile

Back to helioseismology

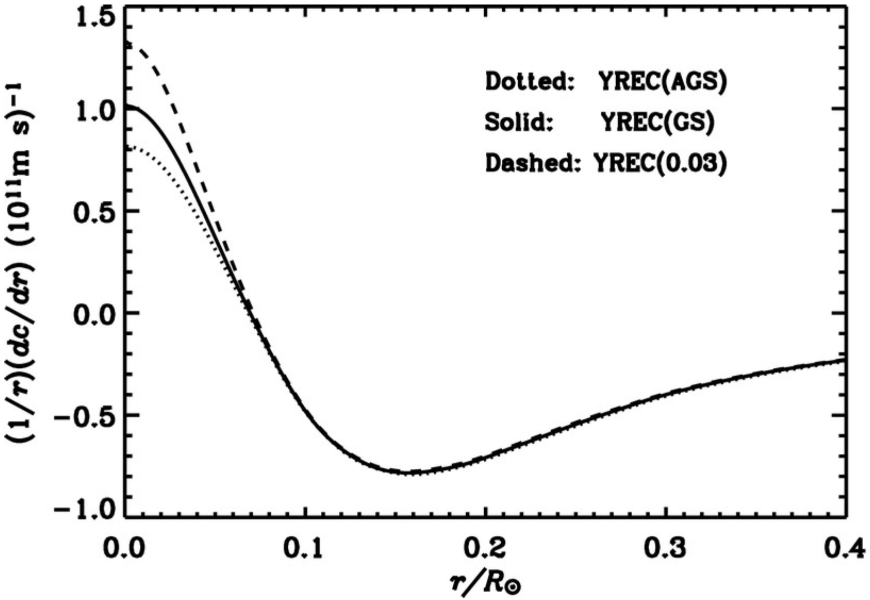


B16 solar models – Vinyoles et al. 2017

Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0[a]

2-3 σ discrepancy for low Z

Back to helioseismology: other probes

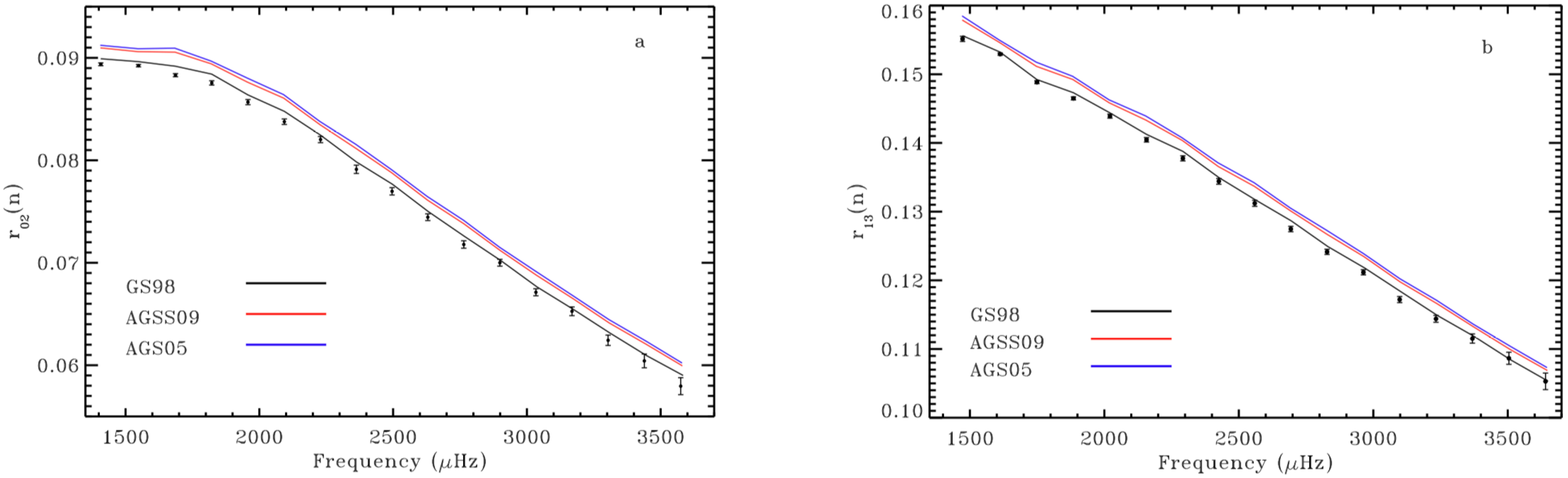


$$r_{02}(n) = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}}$$

$$r_{13}(n) = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}}$$

$$\left.\begin{matrix} r_{02}(n) \\ r_{13}(n) \end{matrix}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$

Back to helioseismology: other probes



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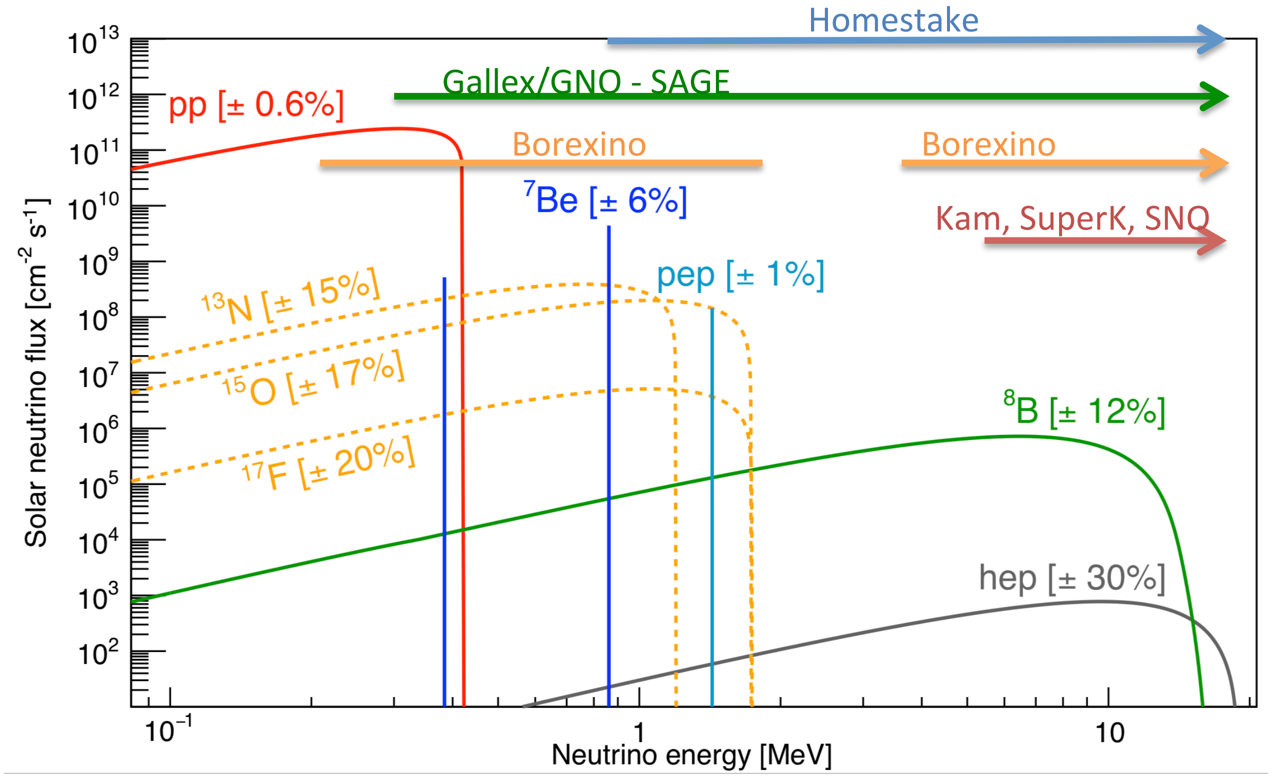
$$\propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$

3-4σ discrepancy for low Z when including model errors

Solar neutrinos



Flux	B16-GS98	B16-AGSS09met
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
$\phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
$\phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

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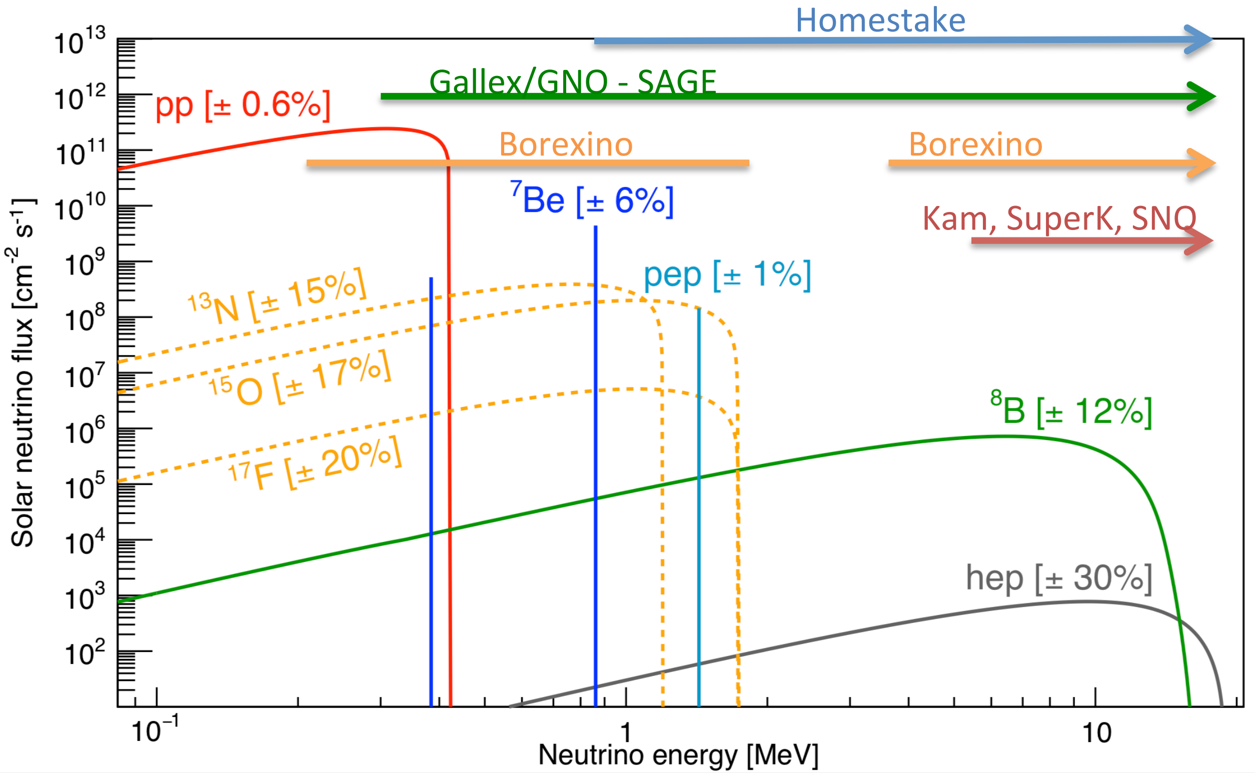

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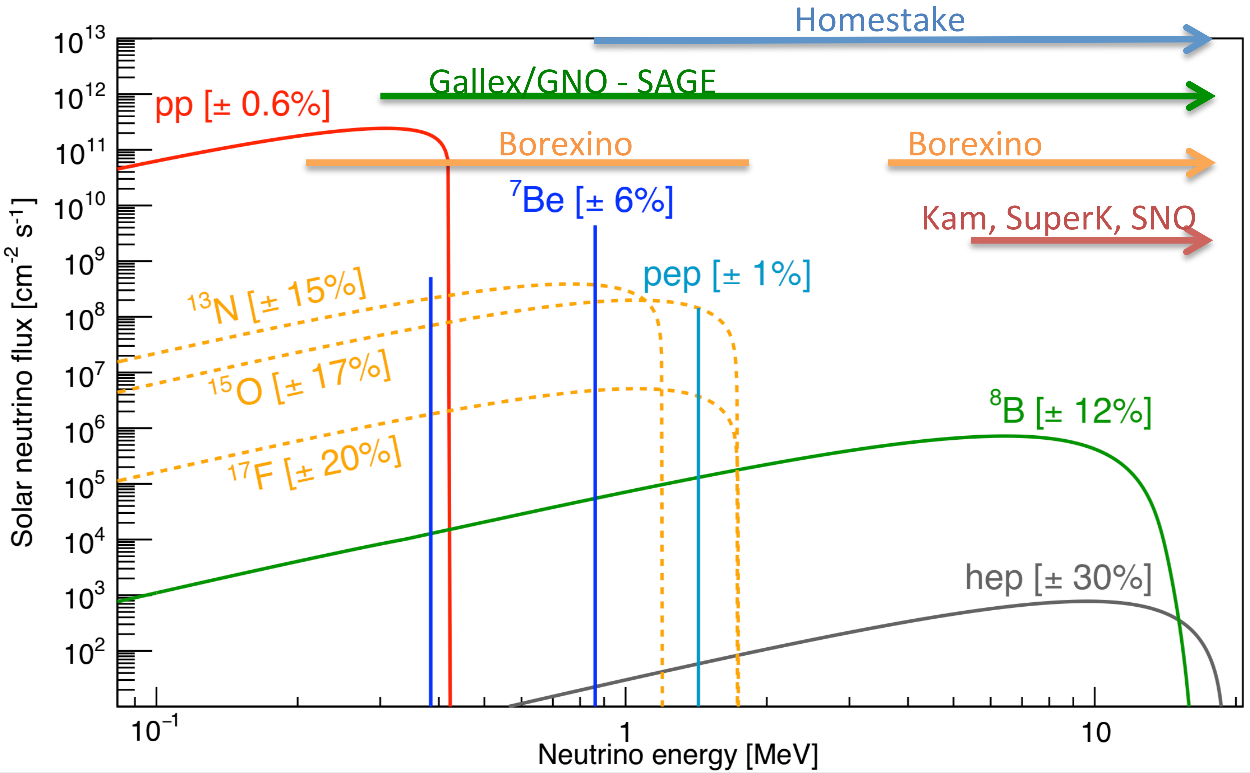
10% - ^7Be
20% - ^8B

Solar neutrinos



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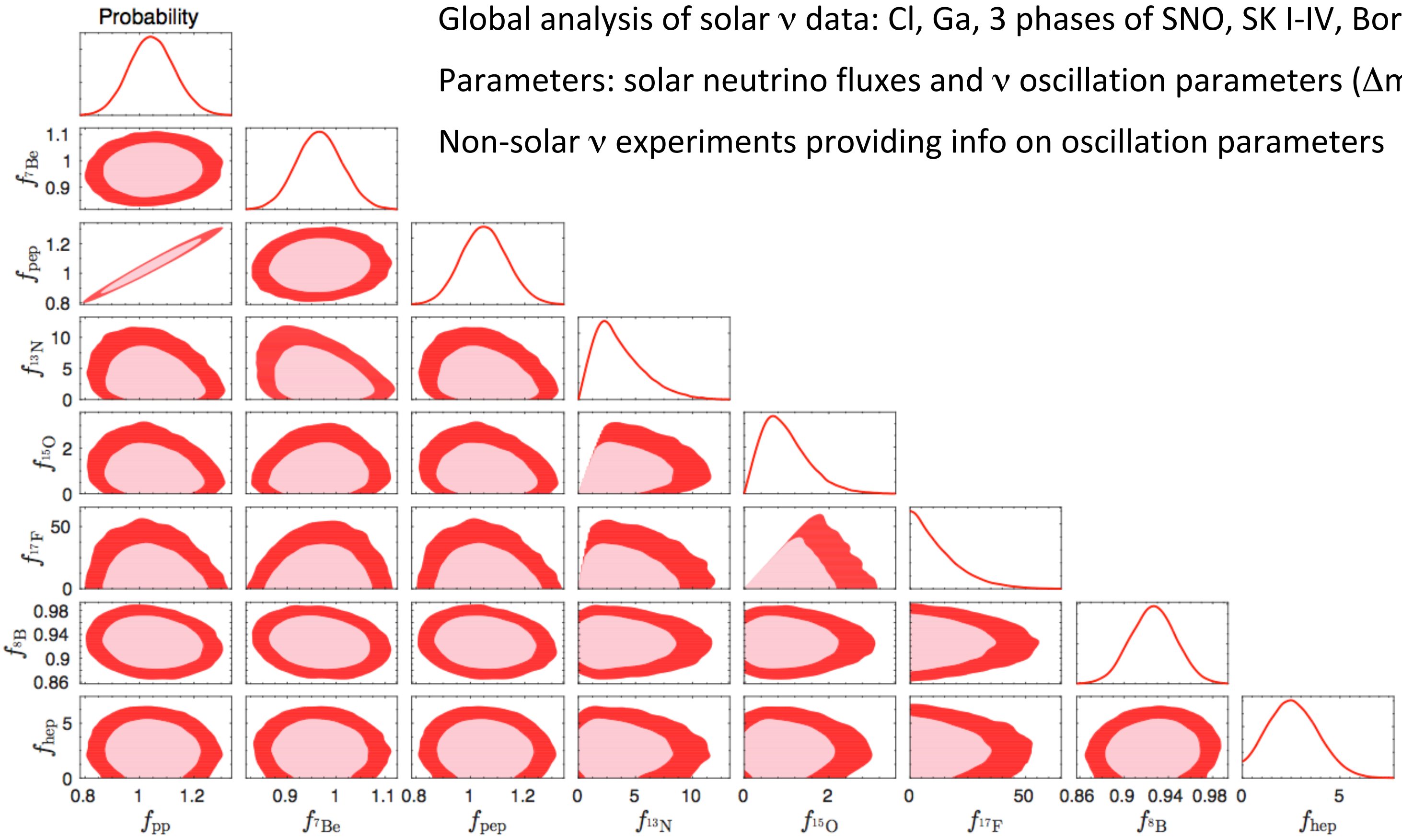
30-40% - CN

Solar neutrinos



Global analysis of solar ν data: Cl, Ga, 3 phases of SNO, SK I-IV, Borexino Phase 1&2

Parameters: solar neutrino fluxes and ν oscillation parameters (Δm^2_{21}, θ_{12}, θ_{13})

Non-solar ν experiments providing info on oscillation parameters

Bergstrom et al. 2016

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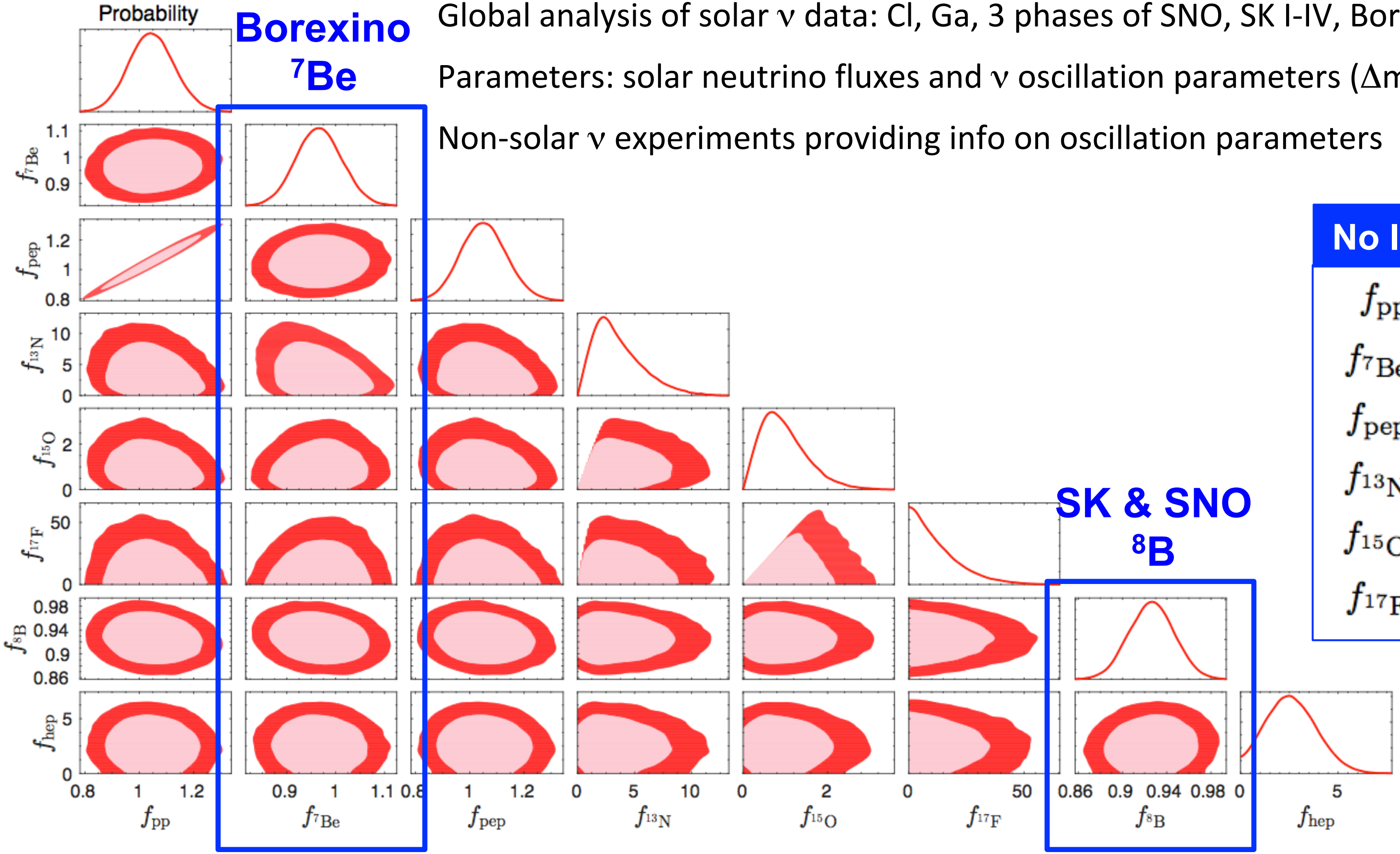


No luminosity constraint

$$f_{\mathrm{pp}} = 1.04 \pm 0.08 \, [^{+0.22}_{-0.20}] \, ,$$
$$f_{^7\mathrm{Be}} = 0.97^{+0.04}_{-0.05} \, [\pm 0.12] \, ,$$
$$f_{\mathrm{pep}} = 1.05 \pm 0.08 \, [^{+0.23}_{-0.20}] \, ,$$
$$f_{^{13}\mathrm{N}} = 1.7^{+2.8}_{-1.0} \, [^{+8.4}_{-1.6}] \, ,$$
$$f_{^{15}\mathrm{O}} = 0.6^{+0.7}_{-0.4} \, [\leq 2.6] \, ,$$
$$f_{^{17}\mathrm{F}} \leq 15 \, [47] \, .$$

Bergstrom et al. 2016

Solar neutrinos

Simple linear relation linking all neutrino fluxes to nuclear energy generation rate

α_i depend only on Q values of reactions and shape of neutrino spectra

$$\frac{L_{\rm nuc}}{4\pi({\rm AU})^2} = \sum_i \alpha_i \Phi_i$$

Purely experimental result – no solar model information

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 1.03^{+0.08}_{-0.07}\,\left[^{+0.21}_{-0.18}\right] \quad \text{and} \quad \frac{L_{\rm CNO}}{L_\odot} = 0.008^{+0.005}_{-0.004}\,\left[^{+0.014}_{-0.007}\right].$$

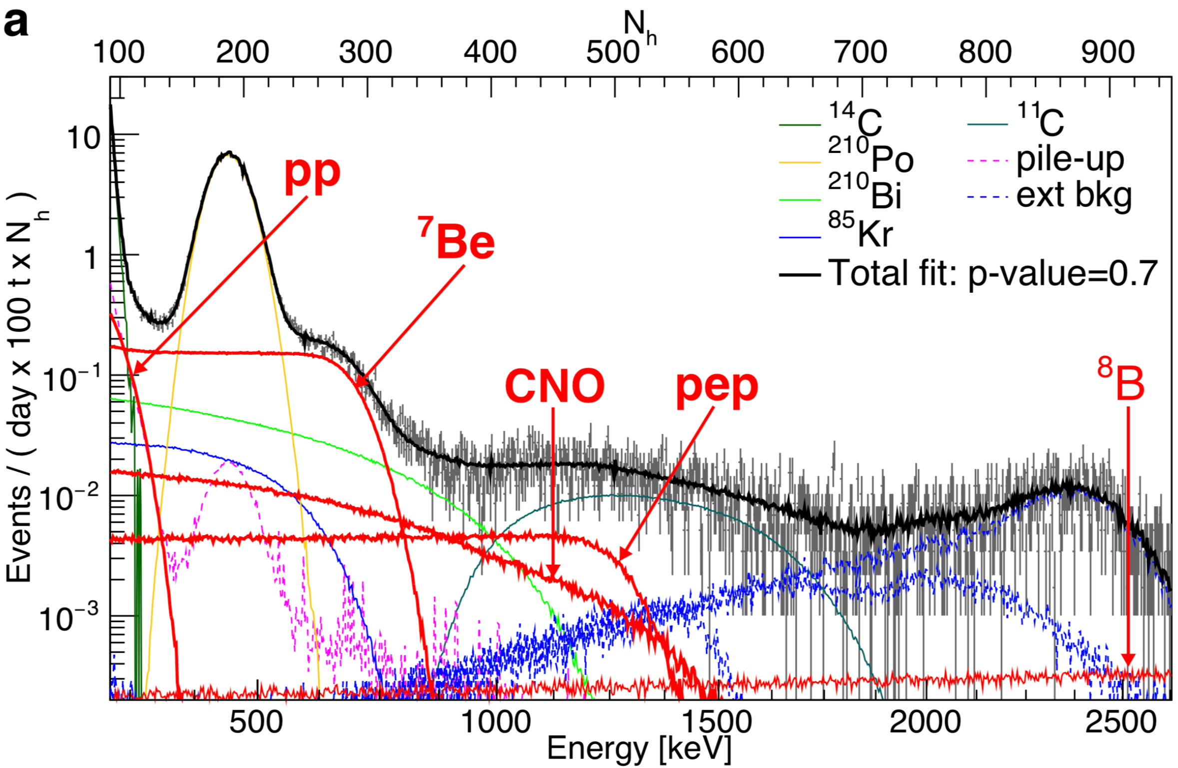
$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.04\,\left[^{+0.07}_{-0.08}\right]\,\left[^{+0.20}_{-0.18}\right]$$

Bergstrom et al. 2016

Solar neutrinos: Borexino

Data taking for more than 10 years

Observed neutrino spectrum – Caccinaga et al. 2018 (Borexino Collaboration)



Some highlights from Borexino

^{7}Be measured to 3%

pp measured to 10%

pep measured to 15%

^{8}B measured to lowest energy

Caccianaga et al. 2018

Solar neutrinos: Borexino

Table 2 | Borexino experimental solar-neutrino results

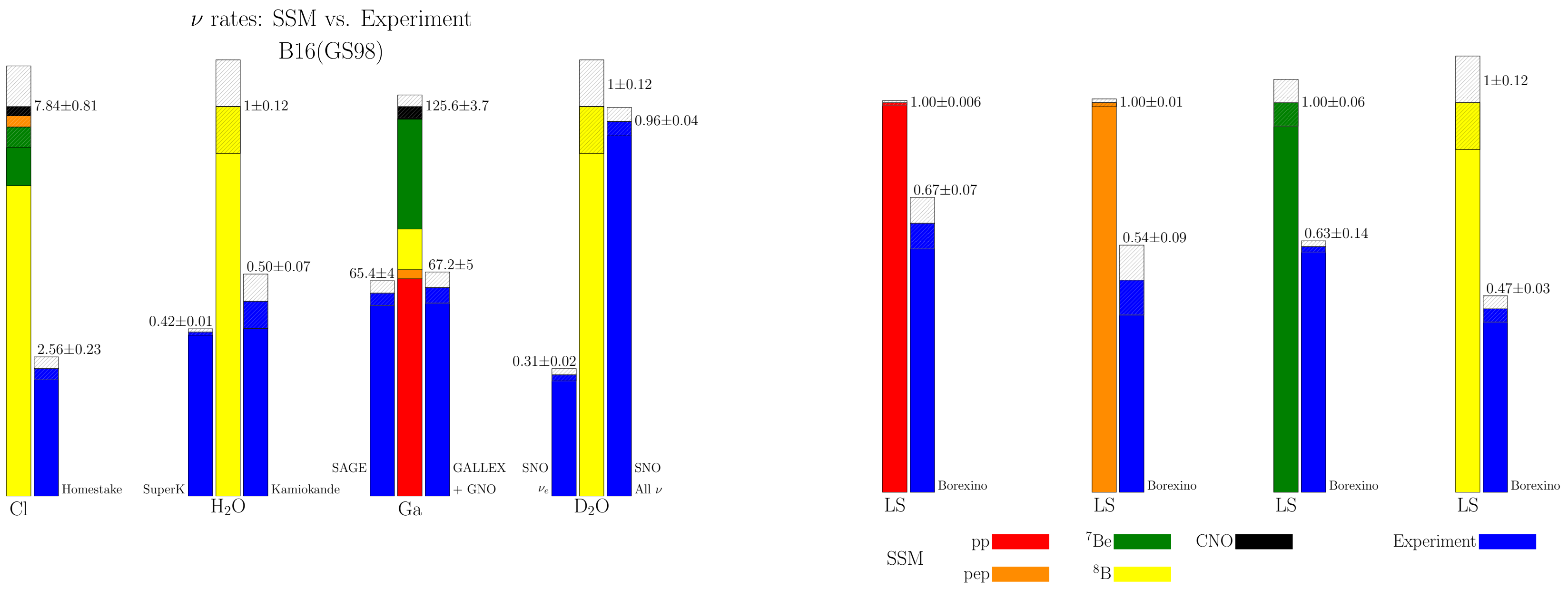
Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2}\ s^{-1}$)	Flux–SSM predictions ($cm^{-2}\ s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER\text{-}II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

Borexino experimental result

$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.01 \left[{+0.09 \atop -0.11} \right]$$

Caccianaga et al. 2018

Solar neutrinos: experiment vs theory



Limits on luminosity

$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.01 \begin{bmatrix}+0.09\\-0.11\end{bmatrix} \qquad \frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.04 \begin{bmatrix}+0.07\\-0.08\end{bmatrix} \begin{bmatrix}+0.20\\-0.18\end{bmatrix}$$

Standard solar models

$$L_\odot = \int \frac{\partial L}{\partial m} dm = \int (\varepsilon_{\rm nuc,\nu} + \varepsilon_{\rm g}) dm = \int \varepsilon_{\rm nuc,\nu} dm \qquad \longrightarrow L_\odot = L_{\rm nuc}$$

But, what if there is an energy source/sink not recognized in standard solar models ...

$$L_\odot = \int (\varepsilon_{\rm nuc,\nu} + \varepsilon_g + \varepsilon_x) dm = L_{\rm nuc} + L_x \longrightarrow L_\odot \neq L_{\rm nuc}$$

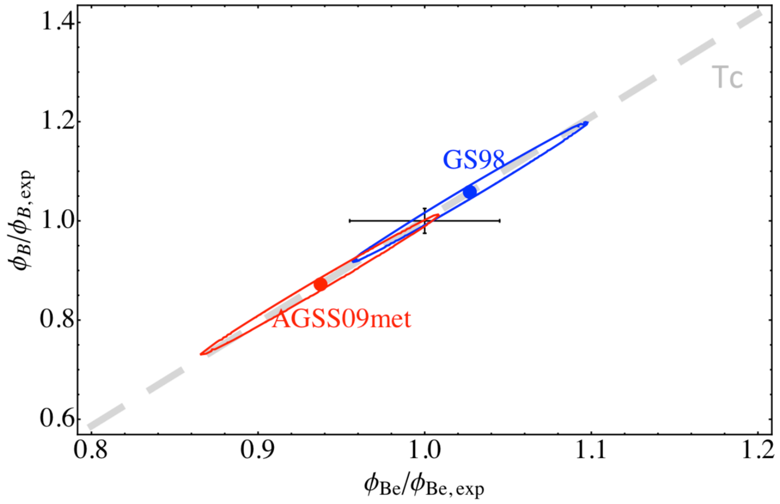
A complete measurement of solar neutrino fluxes offers the only model independent limit on non-standard energy sources in the Sun (and stars)

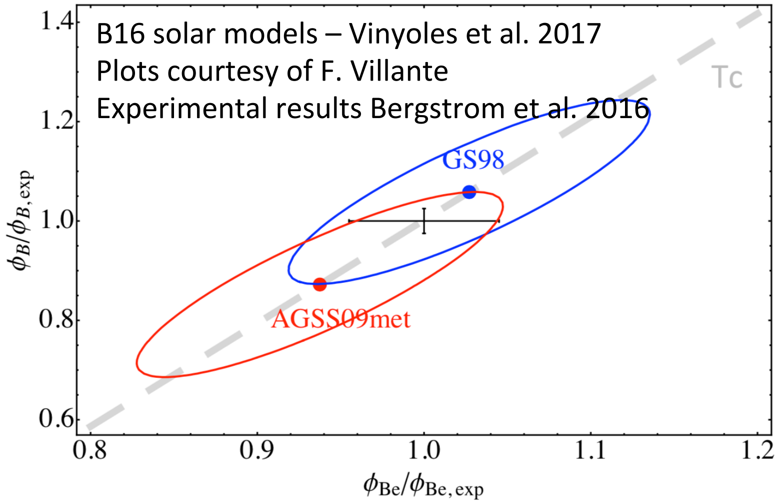
Present-day limit: 8%

Solar neutrinos

Environmental (temperature) uncertainties
composition, opacity, age, luminosity, etc

+ nuclear rate uncertainties





Composition → affects pp-chain fluxes through T_c change

→ determines opacity

→ **pp-fluxes sensitive to opacity (i.e. temperature, only indirectly to composition)**

→ **composition and atomic opacities are degenerate in pp-chain fluxes (and helioseismology)**

Solar standard models vs observations: summary

		GS98		AGSS09met	
Case	dof	χ^2	p-value (σ)	χ^2	p-value (σ)
$Y_S + R_{CZ}$ only	2	0.9	0.5	6.5	2.1
$\delta c/c$ only	30	58.0	3.2	76.1	4.5
$\delta c/c$ no-peak	28	34.7	1.4	50.0	2.7
$\Phi(^7Be) + \Phi(^8B)$	2	0.2	0.3	1.5	0.6
All ν-fluxes	8	6.0	0.5	7.0	0.6
Global	40	65.0	2.7	94.2	4.7
Global no-peak	38	40.5	0.9	67.2	3.0

Vinyoles et al. 2017

Global comparison favors high-Z models

i.e. models with (P, ρ) or (T, μ) profiles consistent with high-Z models

But interpretation in terms of solar composition is hampered by degeneracy between composition and opacity

Solar standard models vs observations: summary

		GS98		AGSS09met	
Case	dof	χ^2	p-value (σ)	χ^2	p-value (σ)
$Y_S + R_{CZ}$ only	2	0.9	0.5	6.5	2.1
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Global comparison favors high-Z models

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But interpretation in terms of solar composition is hampered by degeneracy between composition and opacity

Radiative opacity is the bottleneck in better solar modeling
Only theoretical calculations + 1 (impressive but limited) experiment available

Sun as lab for particle physics

- Use Sun to constrain non-standard physics

  T-ρ profiles better than 1% despite abundance problem

  unless CNO-Ne ± 30% changes make a difference for you

  ^{8}B, ^{7}Be neutrinos – uncertainties (12% - 6%) model dominated

  solar luminosity from ν-experiments to 8% (1 σ)

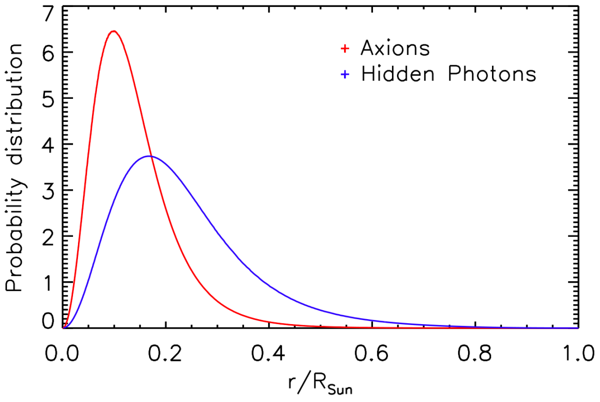
  combine all constraints

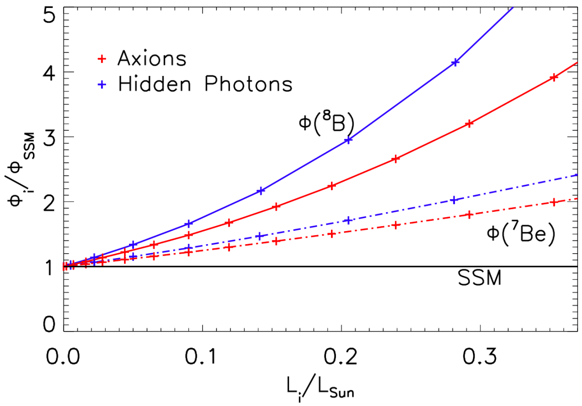
- Introduce non-standard (particle) physics to solve the solar abundance problem

  improve sound helioseismic agreement with neutrino constrains as above

A couple of examples

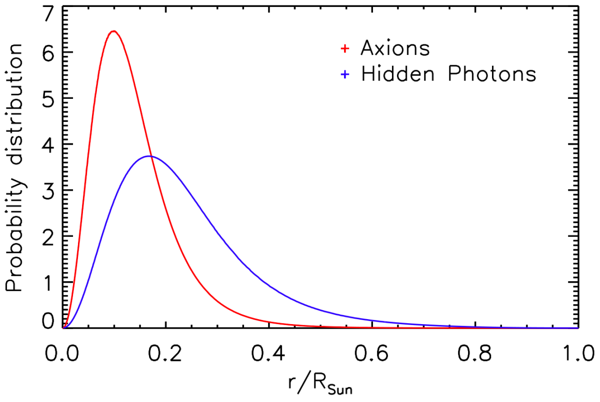
Energy loss cases

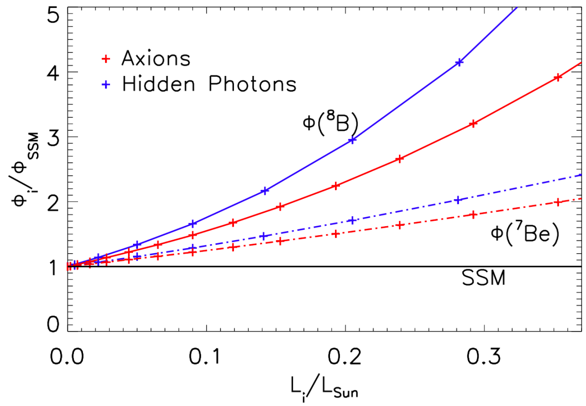


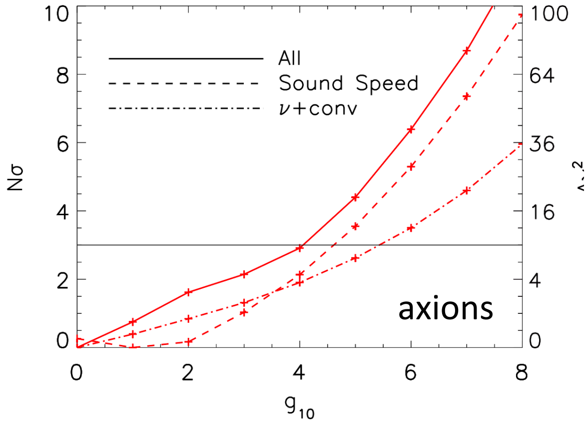


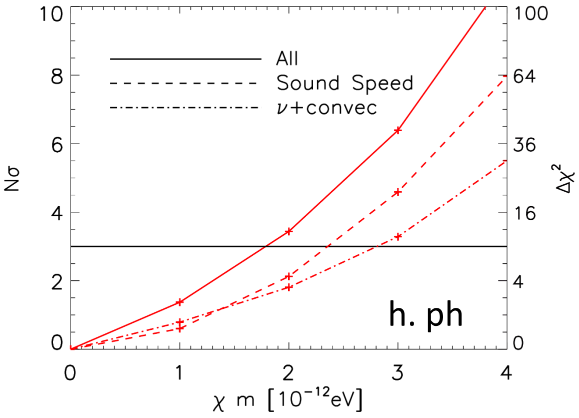
A couple of examples

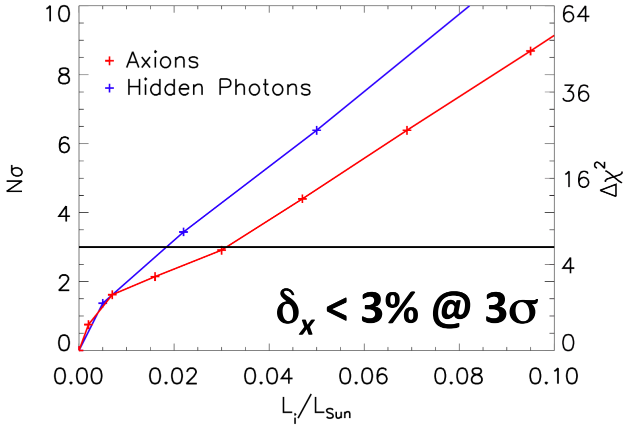
Energy loss cases



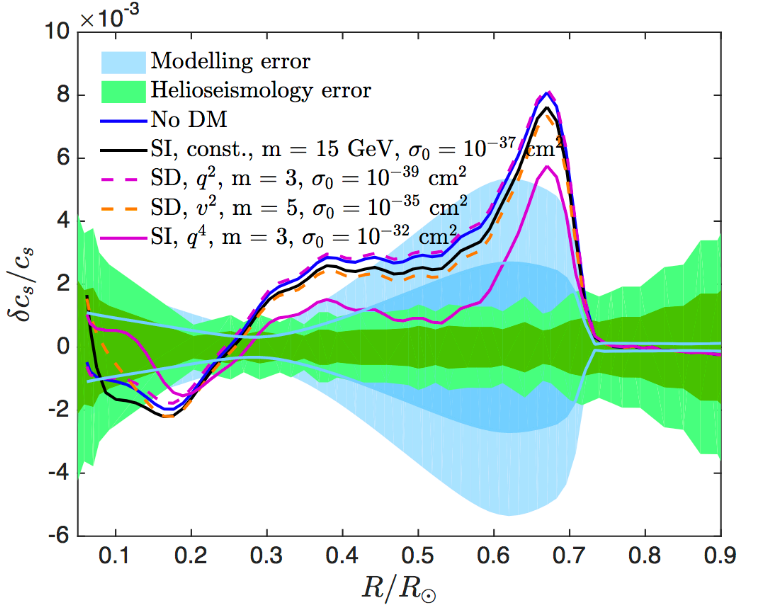


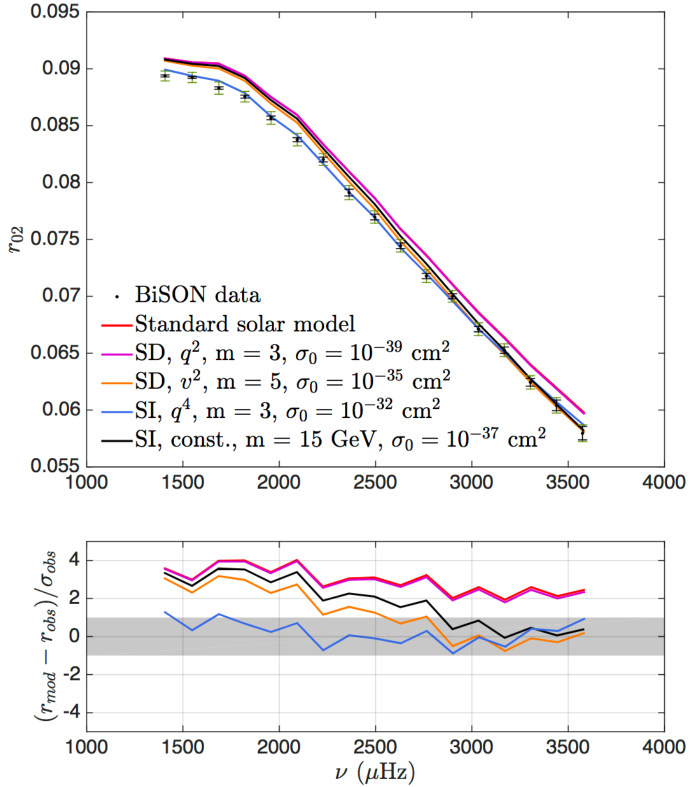






A couple of examples





Possible to find models that improve seismology

But keep νs in sight (always lower ^{8}B and ^{7}Be)

Vincent et al. 2016

Summary

Solar models

- The Sun shines by pp burning : 1.03 ± 0.08 $L_\odot$ – all neutrino experiments (1.01 ± 0.10 $L_\odot$ – only Borexino)
- Open question: pp neutrinos measurement to 1% needed to test other energy sources in the Sun
- **Solar abundance problem persists: opacity ←→ composition degeneracy**
  radiative opacities the bottleneck in solar models
  but this is a 1% effect in T or ρ profiles!
- Open question: direct detection of CN fluxes – break degeneracy between composition and opacities

Limts on DM candidates

- Solar abundance is a problem only if you care about detailed composition
- Combining observables – neutrinos and seismic – lets you improve constraints strongly (e.g. $\delta_x < 3\%$ 3 σ)
- Available data usually underexploited (e.g. frequency ratios or sound speed variation)

Future

- CN fluxes
- Detailed composition? (e.g. axion spectrum - Redondo 2013, Jaeckel & Thormaehlen 2019)

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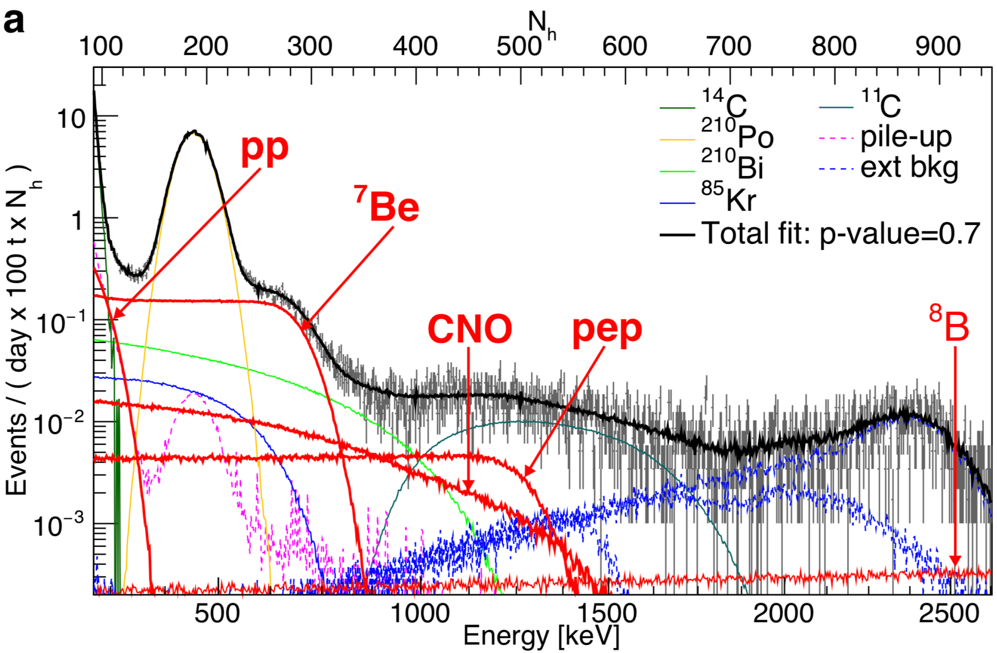
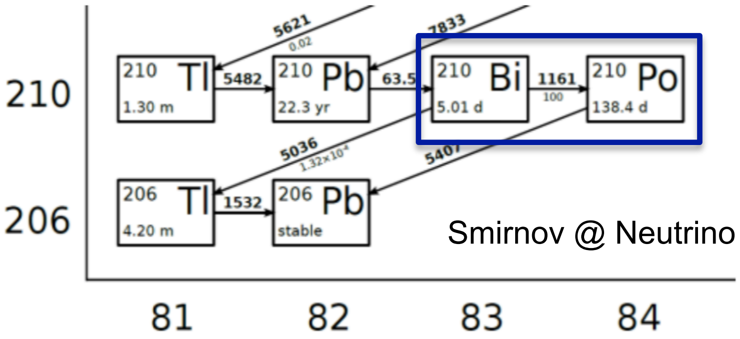
CN-νs at Borexino



CN flux hidden below ^{210}Bi background

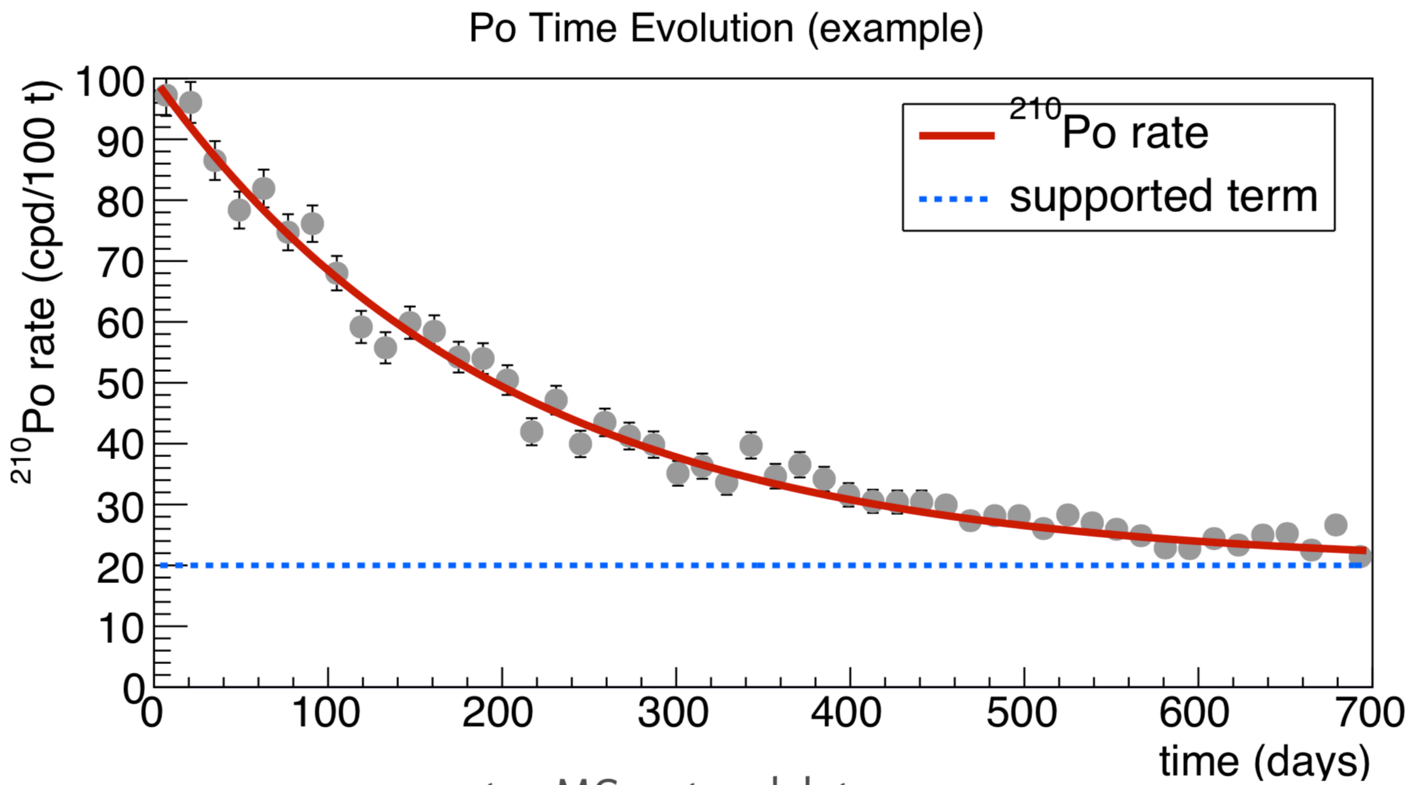
Indirect measurement of ^{210}Bi by evolution of ^{210}Po (Villante et al. 2011) provided ^{210}Bi -- > ^{210}Po only source of ^{210}Po



Smirnov @ Neutrino 2018

But, slow convection in the scintillator was bringing ^{210}Po from the nylon vessel to the fiducial volume

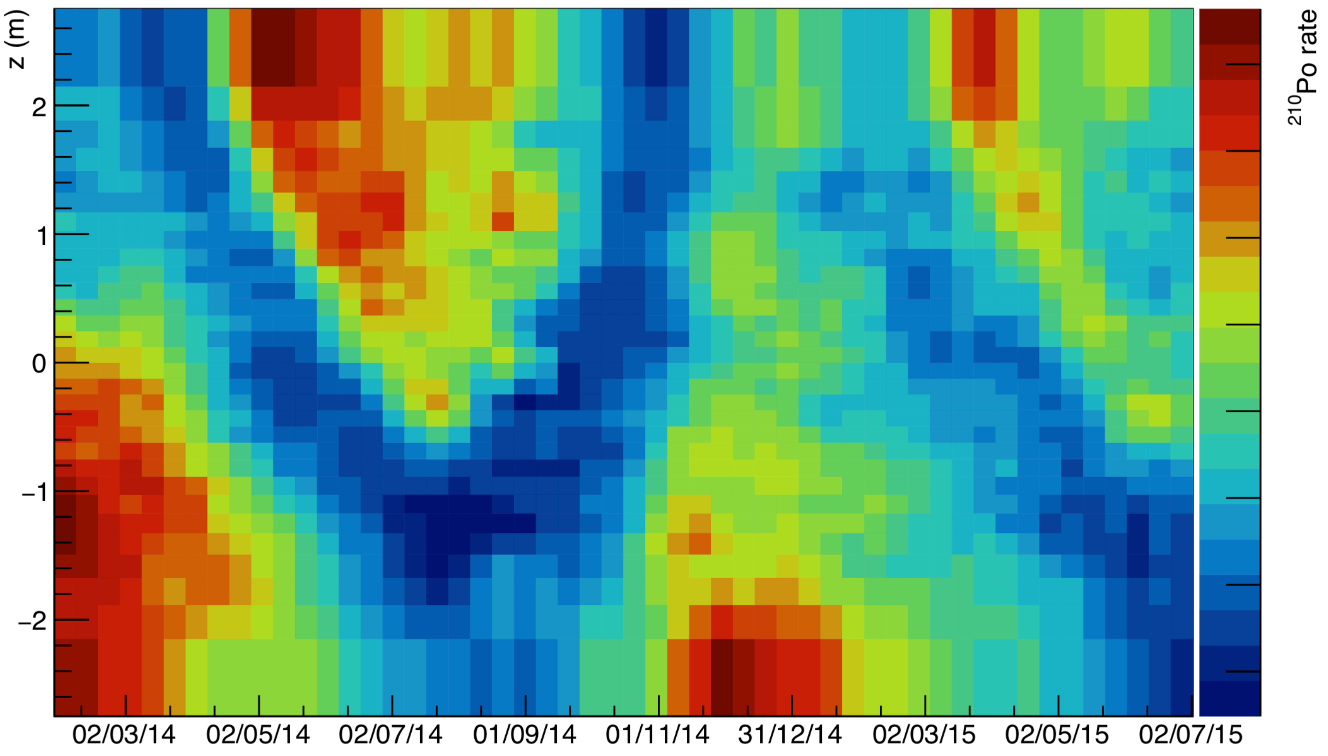
CN-νs at Borexino



toy-MC, not real data

Borexino coll.

CN-νs at Borexino

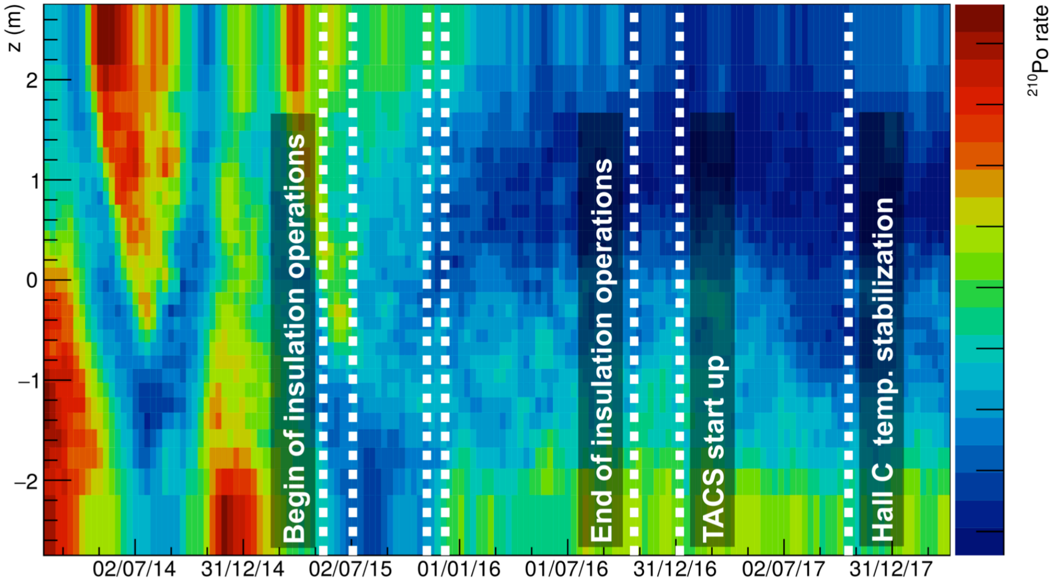


Guffanti 2018 (Borexino coll.) @ 5th International Solar Neutrino Conference

CN-νs at Borexino

Thermal insulation

^{210}Po rate evolution after insulation

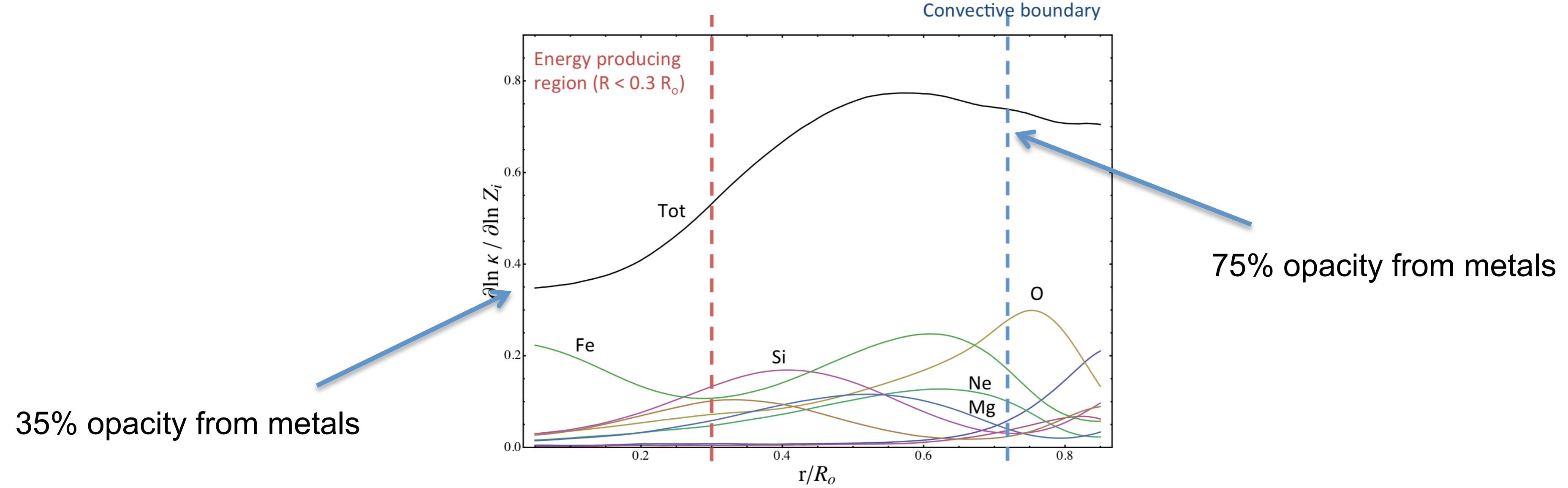


Guffanti 2018

Energy transport: Metals & Opacity

In solar interior ($R < 0.7\ R_\odot$) energy transport by radiation – radiative opacity fundamental quantity

Lack of metals = lack of opacity : hard to disentangle



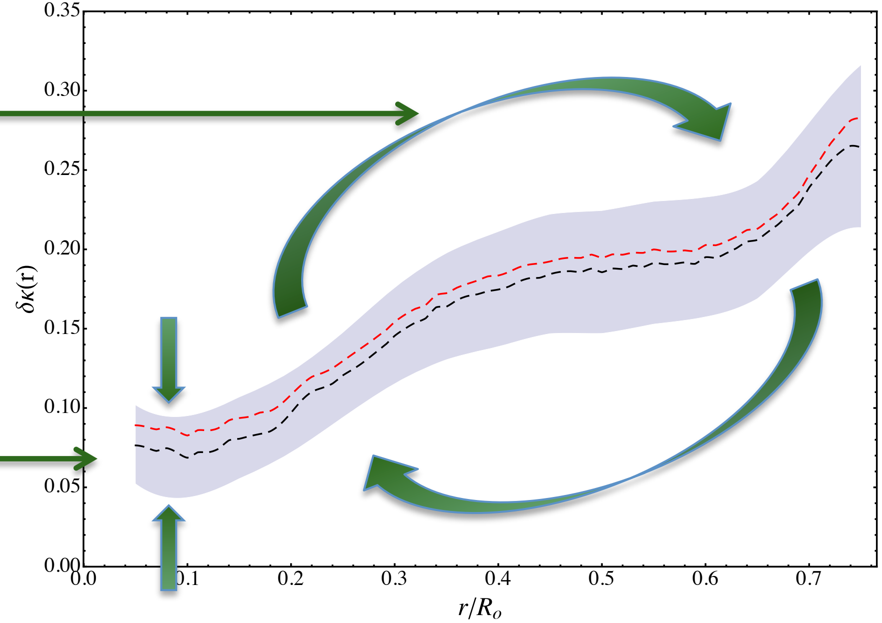
Intrinsic uncertainty + composition induced variation
(δ = fractional variation)

$$\delta\kappa = \delta\kappa_I + \sum \frac{\partial \log \kappa}{\partial \log z_i}\delta z_i$$

Solar opacity from νs and helioseismology

Helioseismology fixes the tilt

Solar neutrinos and Y_S the scaling (core)

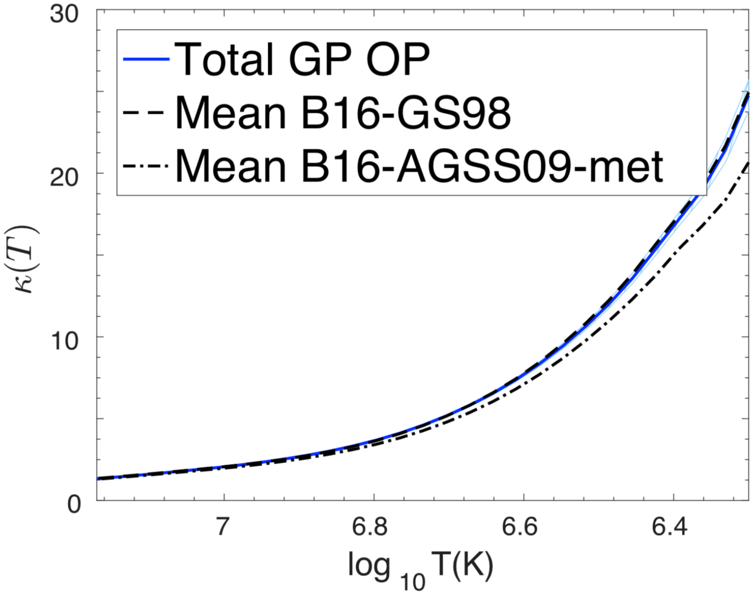


Villante et al. 2014

Solar opacity from νs and helioseismology

$\delta\kappa_I$ is an unknown function → Gaussian Process

$$\delta\kappa = \delta\kappa_I + \sum \frac{\partial \log \kappa}{\partial \log z_i} \delta z_i$$



Song et al. 2018

Bayesian analysis – composition free to vary

Opacity solar profile (posterior distribution)

Very close to that from GS98 model (unsurprisingly)

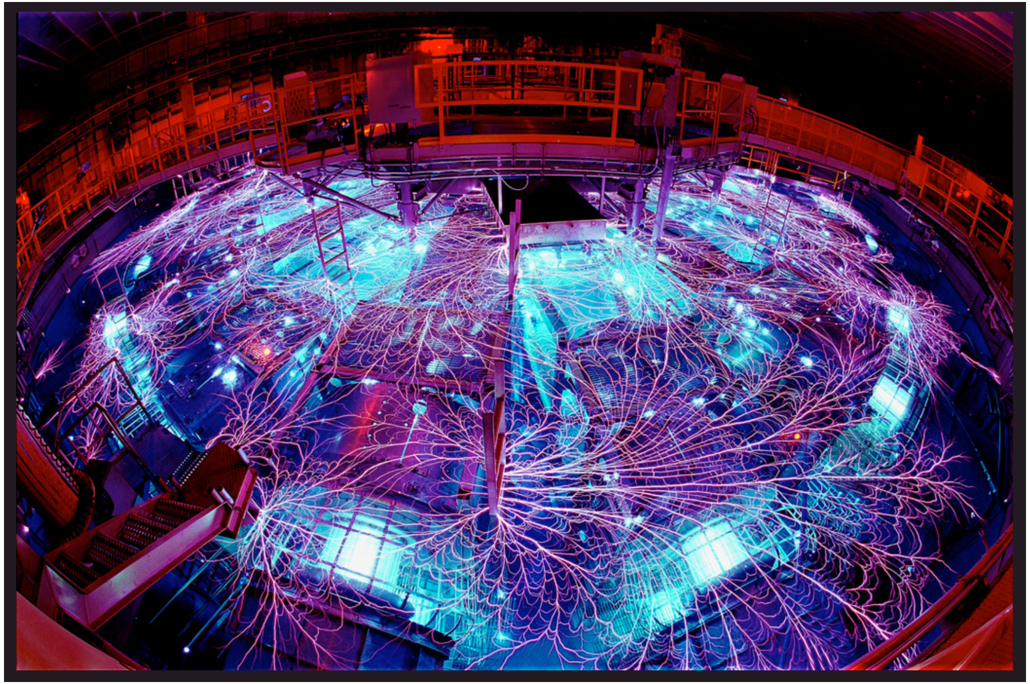
If AGSS09 composition → 20% opacity increase at base of convective zone

Few % opacity increase in solar core

Determine 'effective' opacity profile: cannot disentangle contributions (atomic, composition, other mechanisms, e.g. dark matter)

Opacities – Experimental result

Z-pinch experiment at Sandia Lab
First ever measurement at conditions close to base of the solar convective envelope

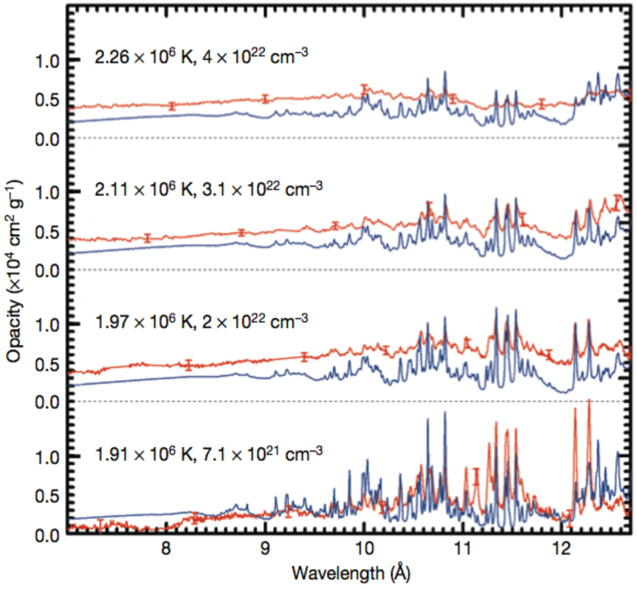


Bailey et al. 2015

Opacities – Experimental result

First ever opacity measurement at conditions close to base of the solar convective envelope

Fe opacity @Sandia Lab -- > 7% increase of Rosseland mean opacity



$T \sim T_{CZ}$

$N_e \sim 1/4\ Ne_{CZ}$

Bailey et al. 2015

Experimental hint of higher opacity than theoretical calculations predict – but situation unclear

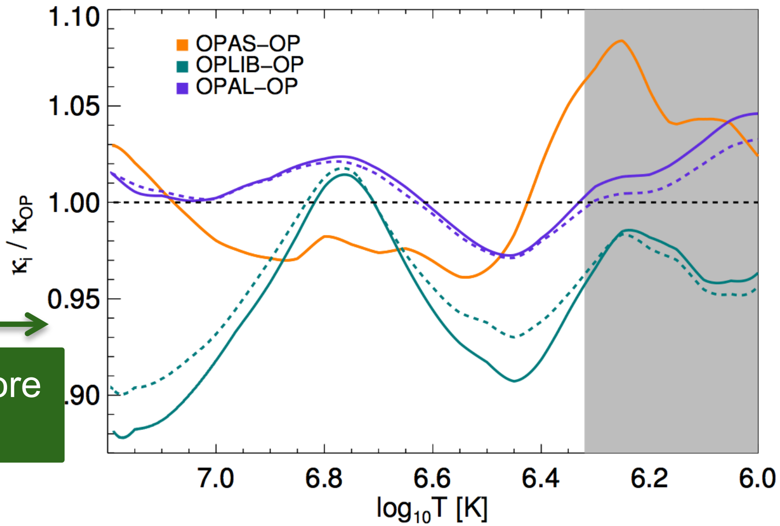
Opacities – new calculations

Old generation

- OPAL – Iglesias et al. 1996
- Opacity Project (OP) – Badnell et al. 2005

New generation

- OPAS – Blancard et al. 2012 – now available Mondet et al. 2015 (only for AGSS09 composition)
- Los Alamos (OPLIB) – Colgan et al. 2016 – Most complete set from new generation



Solid – GS98

Dashed – AGSS09

Too low in solar core
Ruled out by νs

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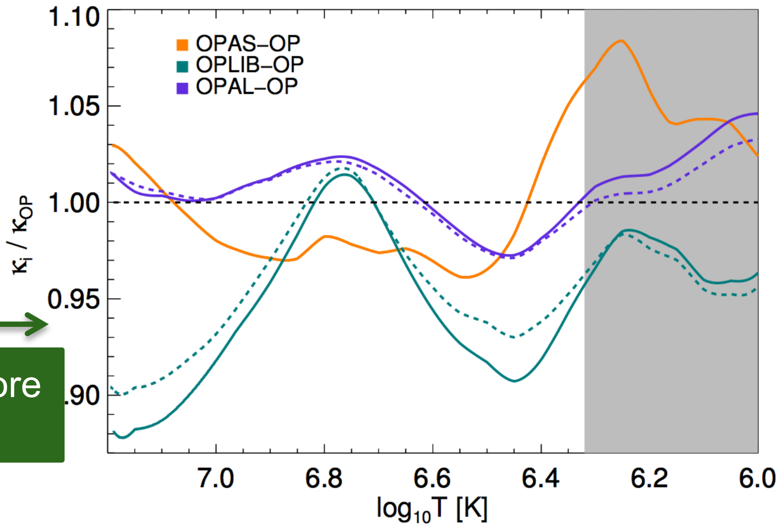

Too low in solar core
Ruled out by νs

Solid – GS98

Dashed – AGSS09

Not guaranteed that newer opacity models lead to higher opacity values

± 5% variations

Current situation unclear

A couple of examples

Energy loss cases: sound speed variations