Solar models, neutrinos and helioseismology

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Consejo Superior de Investigaciones Científicas
IEEC

Outline

(Standard) Solar models

Solar neutrinos
- **current status**
- **origin of solar luminosity**

Helioseismology
- **solar abundance problem**
- **energy transport (opacity)**
- **opacity – composition degeneracy**

Near-term prospects for CNO neutrinos measurement

Basic facts about the Sun

Luminosity – $L_\odot$	3.842×10^{33} erg/s
Radius – $R_\odot$	6.9598×10^{10} cm
Mass – $M_\odot$	1.9891×10^{33} g
Age (solar system oldest meteorites) – $\tau_\odot$	4.57×10^{9} yr
Surface metal to hydrogen abundance ratio – $(Z/X)_\odot$	0.018 – 0.024

The Sun is a typical middle aged low-mass star

Quantitative predictions: Solar models

Compute the evolution of a $1M_\odot$ stellar model

initial homegenous composition

evolve up to $\tau_\odot$

Adjust initial composition (two parameters) and one free parameter of convection to match

Luminosity – $L_\odot$	**3.842×10^{33} erg/s**
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Result: model of present day structure of the Sun – internal thermodynamic profiles

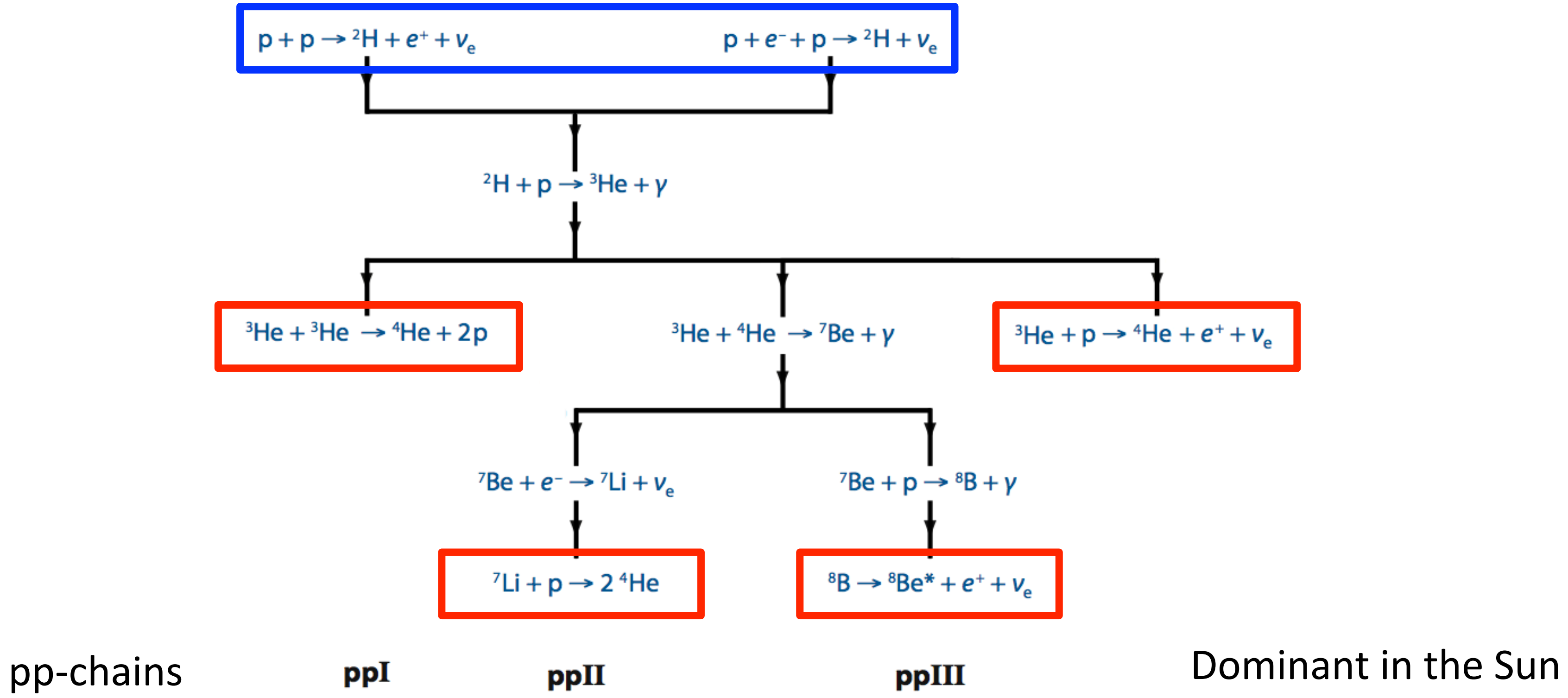
Two main ways to test models: solar neutrinos & helioseismology

Hydrogen burning & solar neutrinos

$$4p \dashrightarrow {}^{4}He + \underline{2\nu_e} + 2e^{+}$$

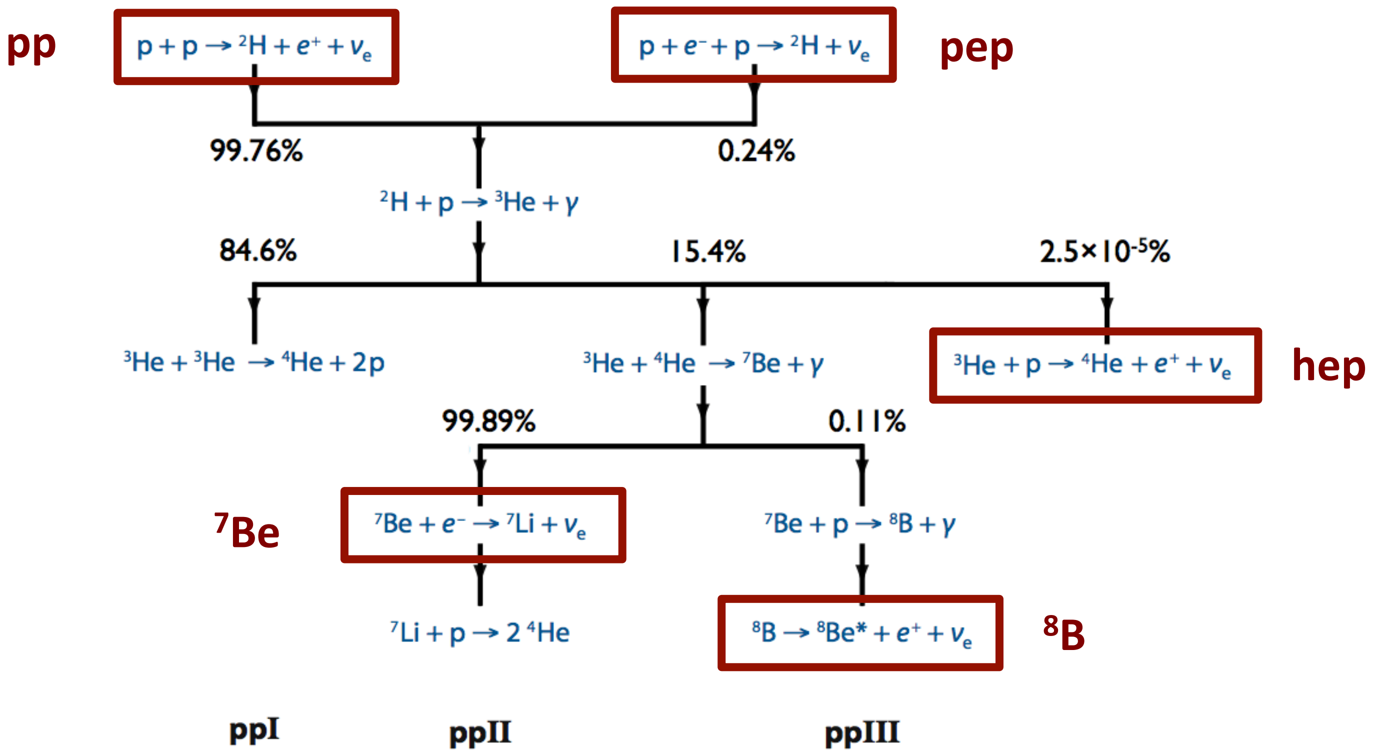
Hydrogen burning – pp-chains

Several paths to: $4p \dashrightarrow {}^4He + 2\nu_e + 2e^+$



Hydrogen burning – pp-chains

Five different neutrino sources



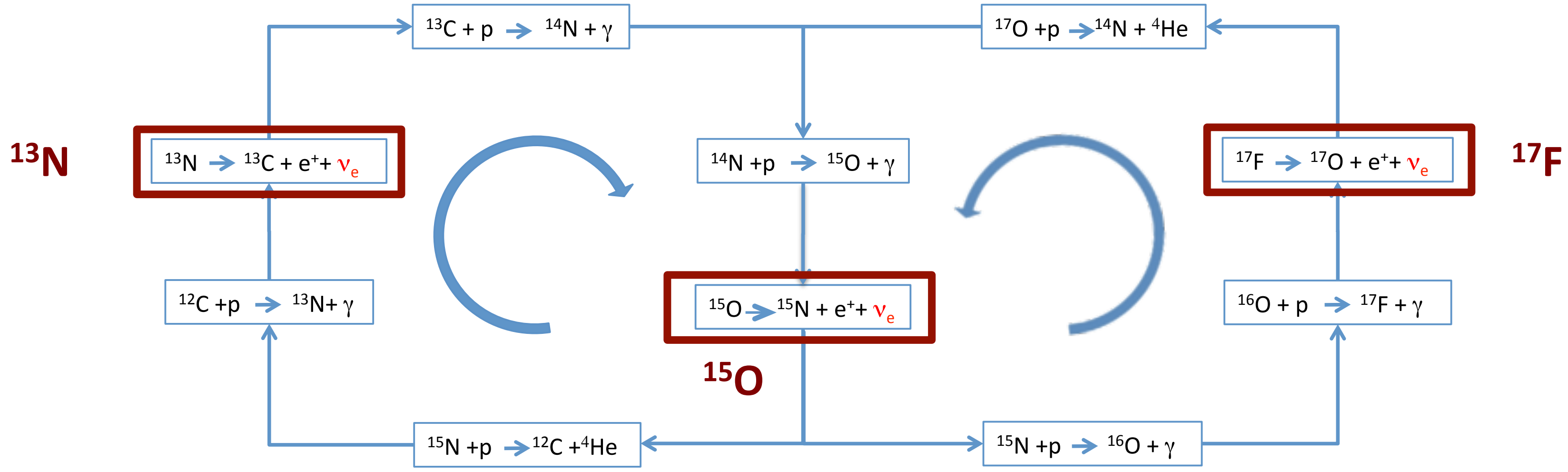
Hydrogen burning – CNO-cycles

CNO-cycles – dominates at higher temperatures (more massive stars)

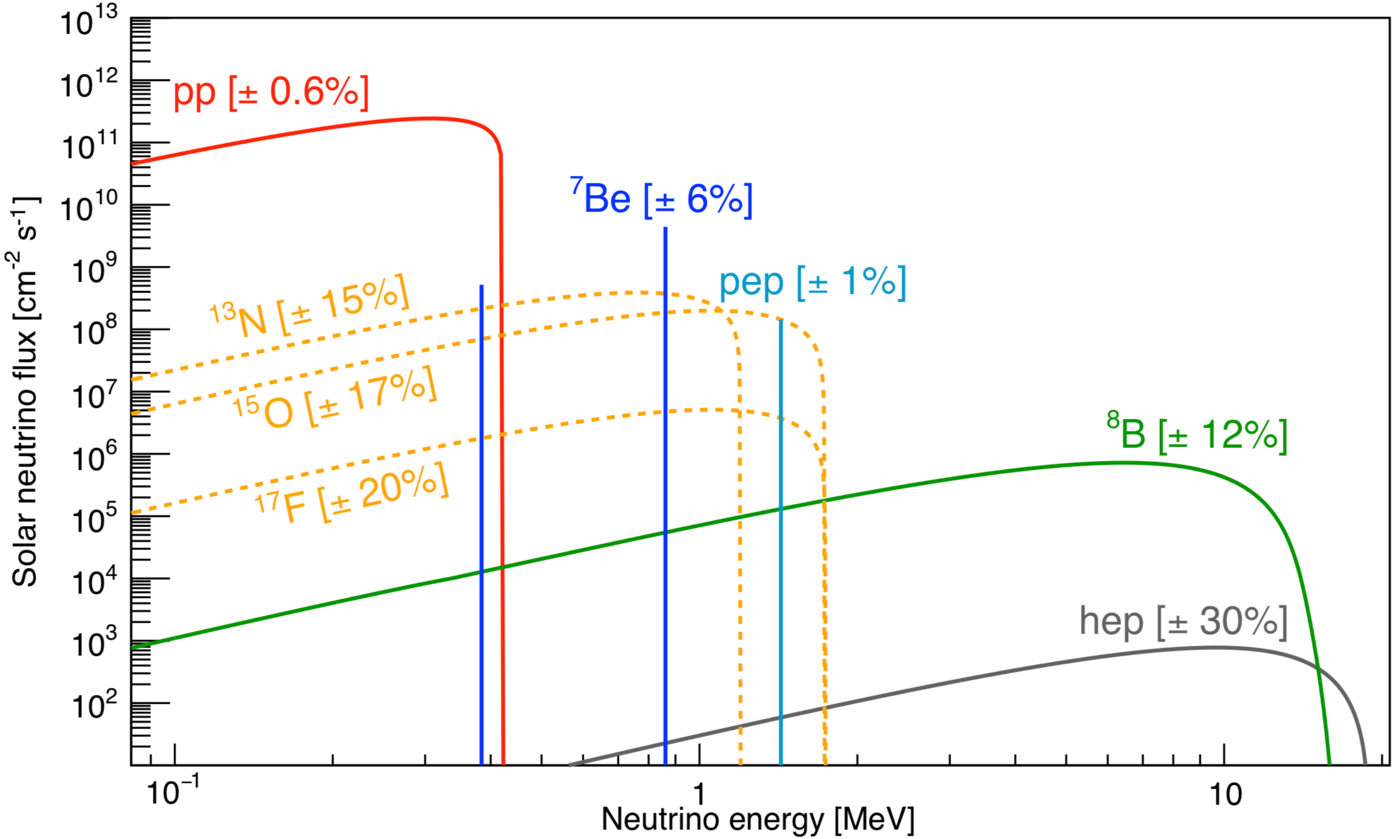
Marginal in the Sun

Three different neutrino sources

Catalyzed by C+N(+O) abundance



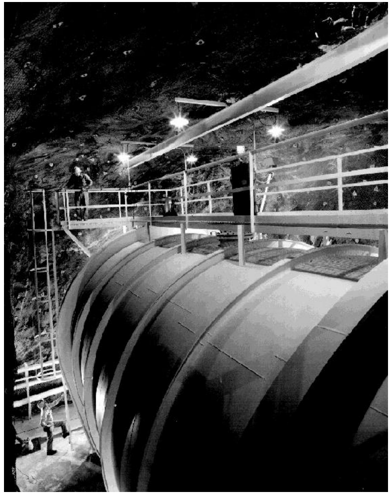
Solar neutrino spectrum



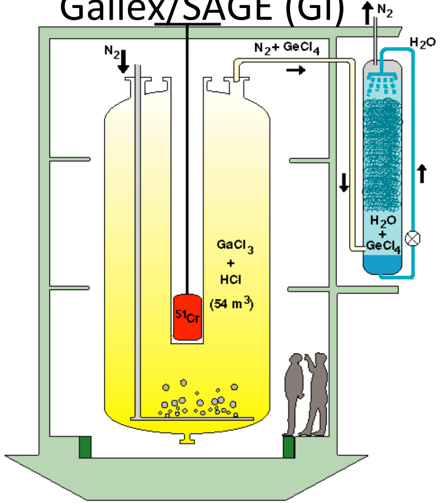
Flux	SFII-GS98 $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
pp	5.98×10^{10}
pep	1.44×10^{8}
hep	8.04×10^{3}
^{7}Be	5.00×10^{9}
^{8}B	5.58×10^{6}
^{13}N	2.96×10^{8}
^{15}O	2.23×10^{8}
^{17}F	5.52×10^{6}

50 years of solar neutrinos experiments

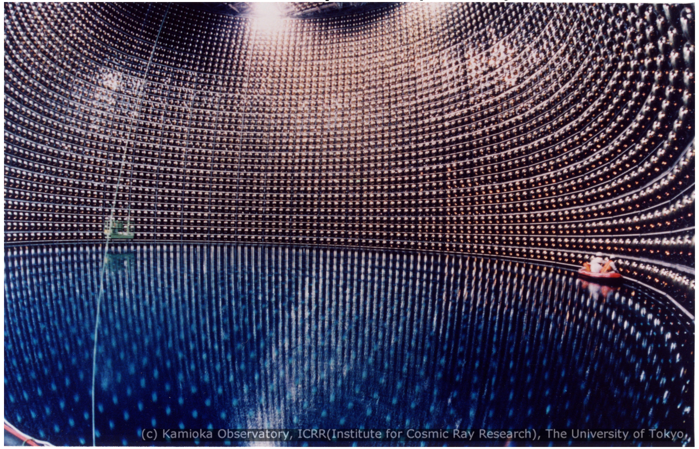
Homestake (Cl)



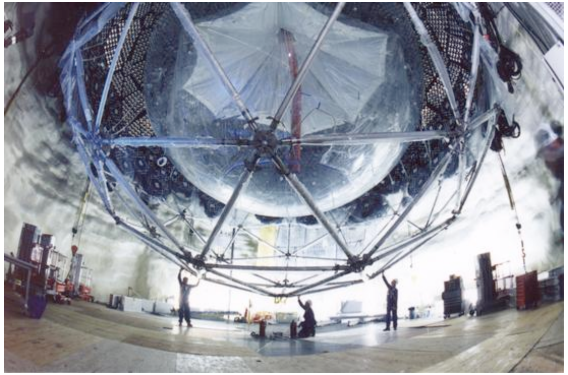
Gallex/SAGE (Gl)

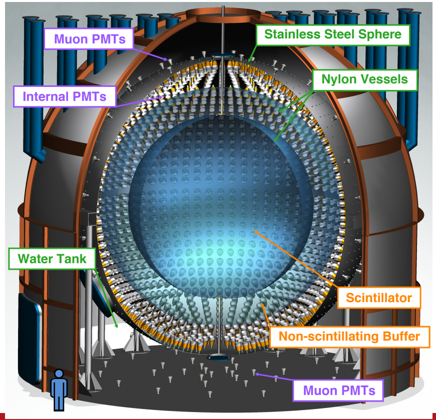


Kamiokande/SuperK (H2O)



SNO (D2O)





Borexino (Scint.)

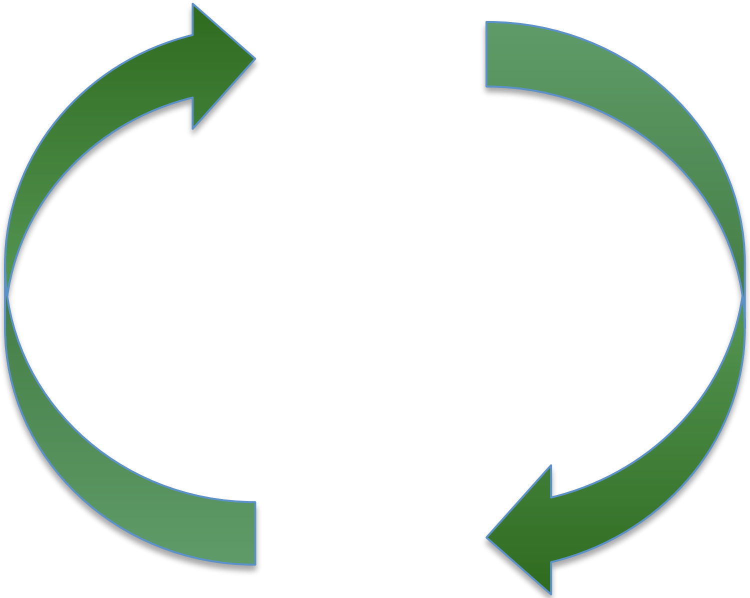
Coming full circle

How does the Sun shine?
Which is the solar core temperature?

Radiochemical experiments
Kamiokande

Solar neutrino problem

Standard model(s) crises!

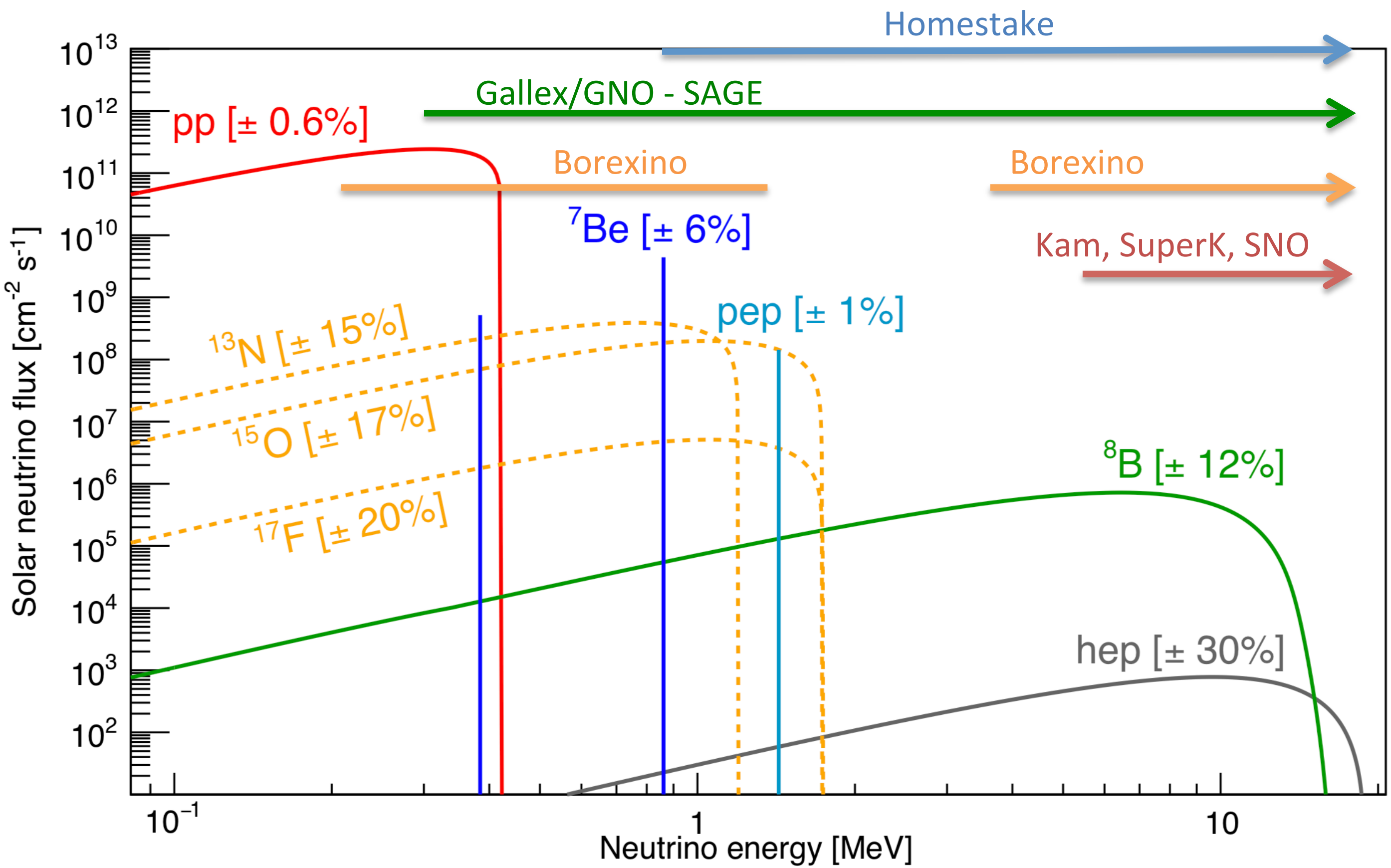


Helioseismic inference of
solar structure → agreement with solar models
→ Physics solution (circa 1996)

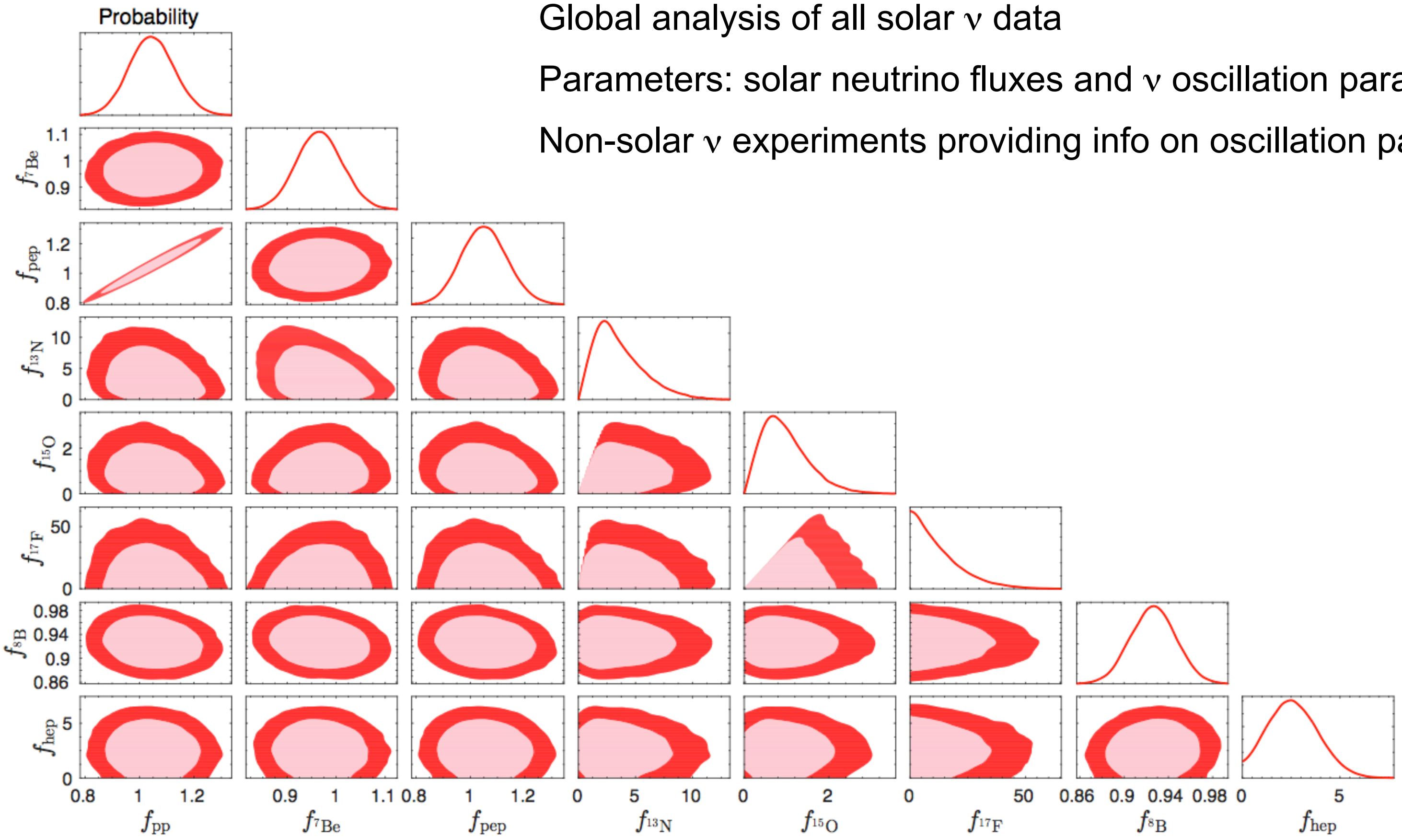
SuperK & SNO
ν oscillations

Solar νs as sensitive
probes of solar core

Solar neutrino spectrum



How does the Sun shine?



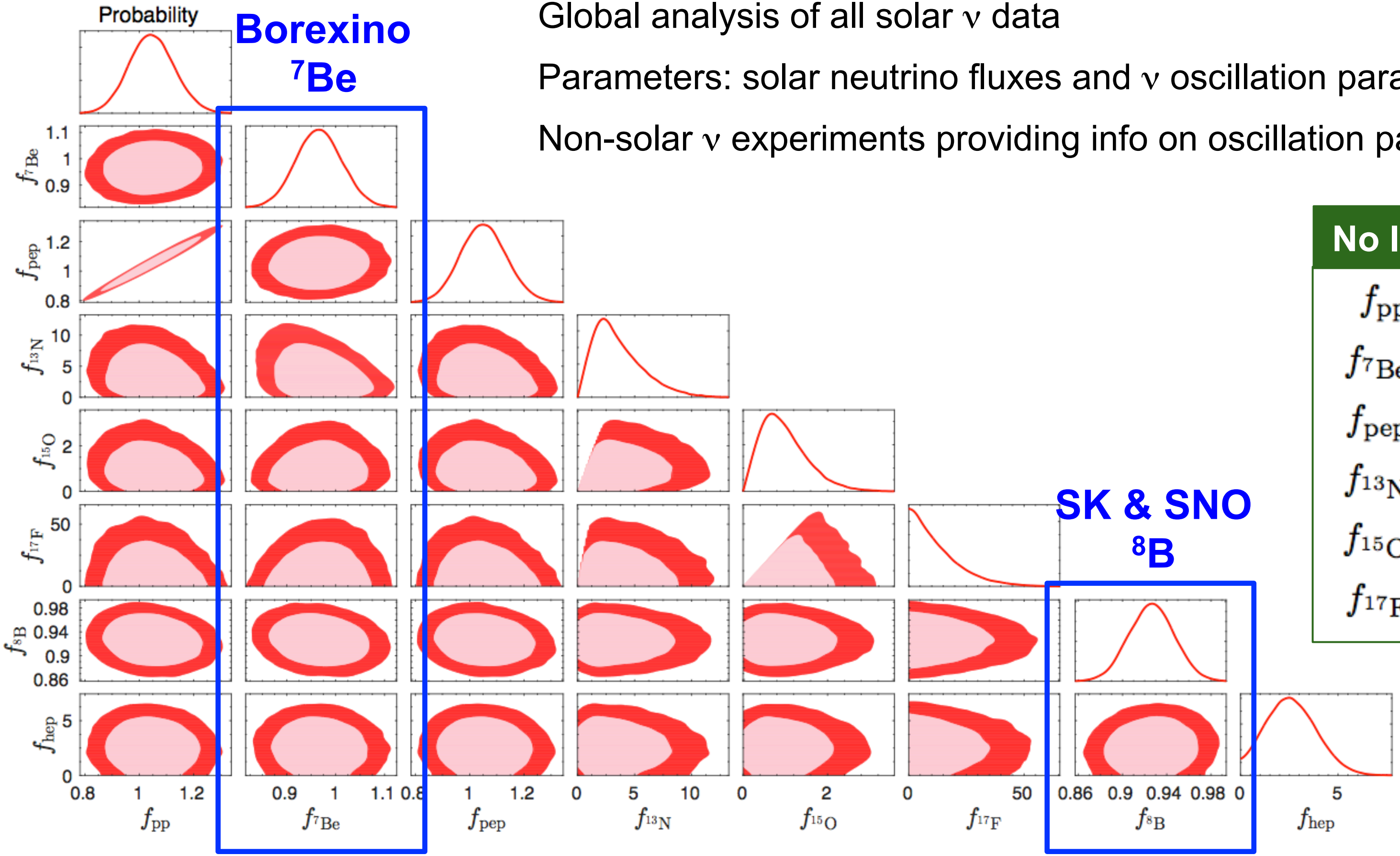
Global analysis of all solar ν data

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

How does the Sun shine?



Global analysis of all solar ν data

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

Non-solar ν experiments providing info on oscillation parameters

No luminosity constraint

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

Bergstrom et al. 2016

How does the Sun shine?

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

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

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

Purely experimental result – no solar model information

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

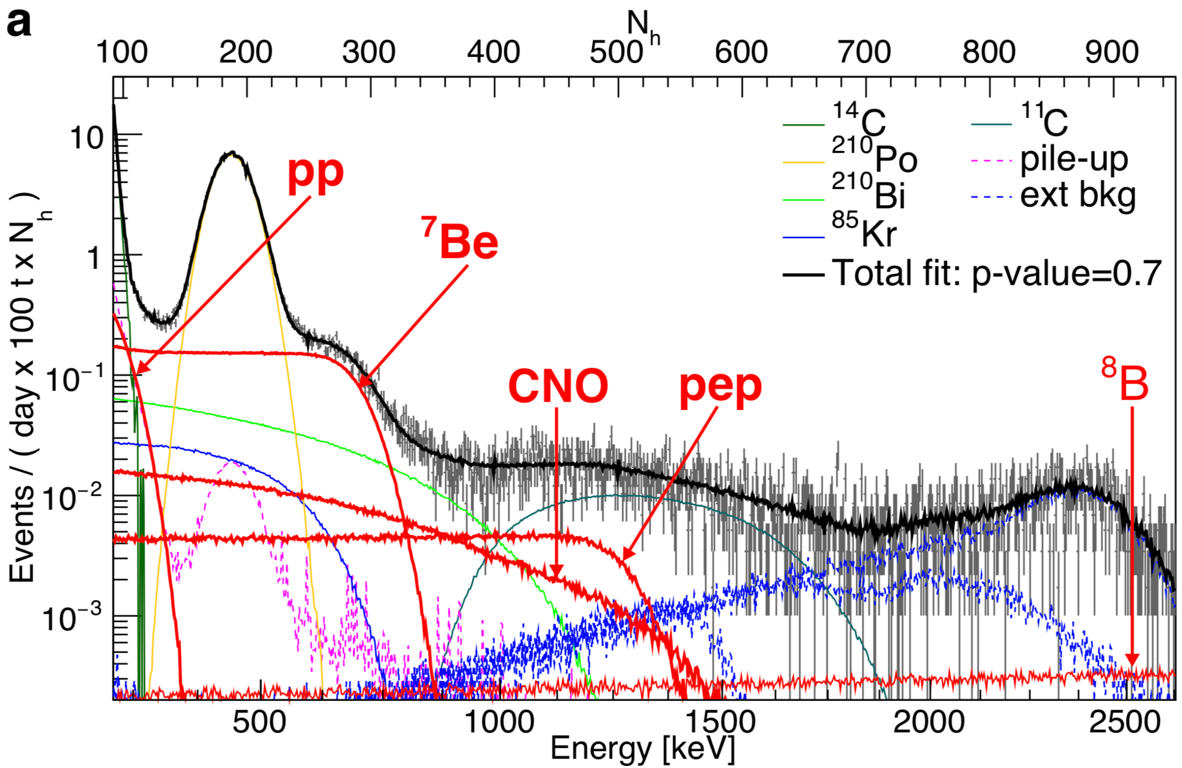
$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.04\,\left[^{+0.07}_{-0.08}\right]\,\left[^{+0.20}_{-0.18}\right]$$

Bergstrom et al. 2016

Latest results from 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

Latest results from 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)

Experimental results after accounting for ν oscillations

Caccianaga et al. 2018

Oscillation parameters

	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$

Esteban et al. 2017

Borexino experimental result

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

How does the Sun shine?

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

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

Standard solar models

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

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

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

How does the Sun shine?

$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.01 \left[{}^{+0.09}_{-0.11}\right] \qquad \frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.04 \left[{}^{+0.07}_{-0.08}\right] \left[{}^{+0.20}_{-0.18}\right]$$

Standard solar models

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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%

How does the Sun shine?

Non standard solar models

$$\frac{\partial L}{\partial m} = \varepsilon_{\mathrm{nuc},\nu} + \varepsilon_g + (\pm\varepsilon_x)$$

$\varepsilon_x < 0$

x particles escape from the star, carrying away energy, analogous to neutrinos, e.g. axions − $L_\odot < L_{nuc}$

$\varepsilon_x > 0$

x particles produce energy in the star, e.g. self-annihilating DM − $L_\odot > L_{nuc}$

$\varepsilon_x > 0$ and $\varepsilon_x < 0$

transport of energy within the star, < 0 where energy is extracted and > 0 where it is deposited, e.g. non-annihilating DM

talks today by P. Scott and A. Vincent

Helioseismology

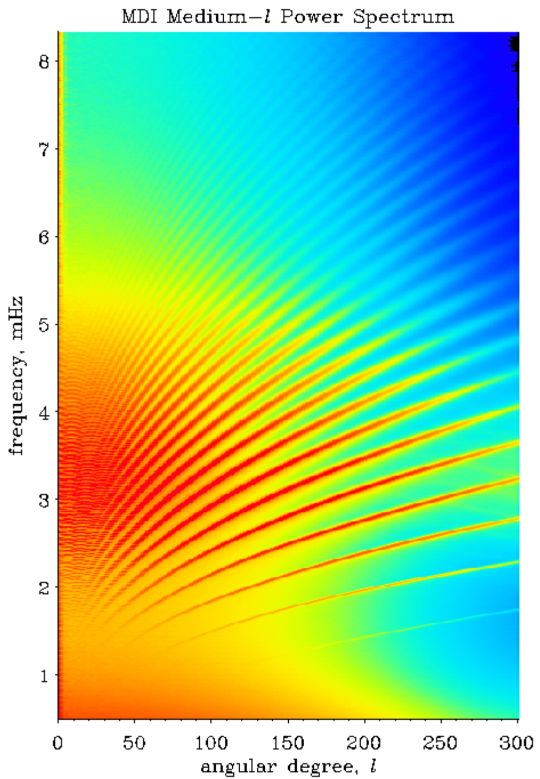
Global solar oscillations – acoustic waves

Key quantities: c^2, p, r, Γ_1

10^5 non-radial individual modes

cm/s amplitudes in radial velocity

ppm amplitudes in brightness



Helioseismology

Global solar oscillations – acoustic waves

Key quantities: c^2, p, r, Γ_1

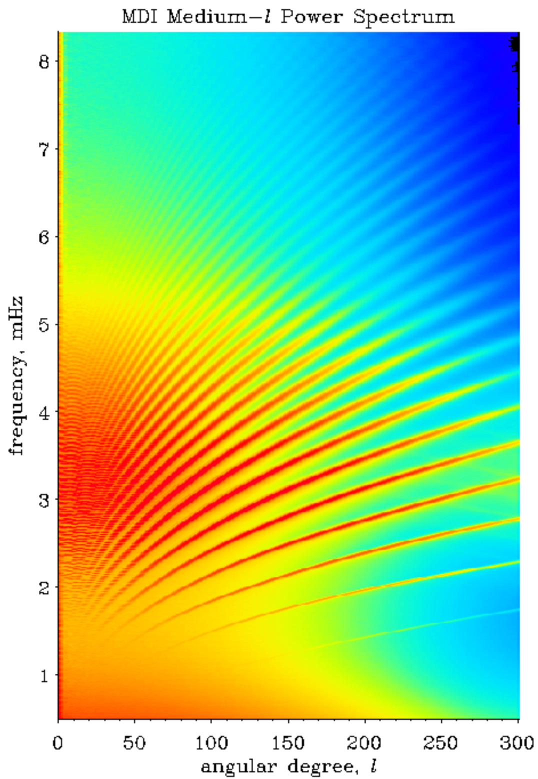
10^5 non-radial individual modes

cm/s amplitudes in radial velocity

ppm amplitudes in brightness

Inversion methods allow reconstructing internal profiles

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



Back to solar models: solar composition

Luminosity – $L_\odot$	3.842×10^{33} erg/s
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Solar composition

Change of paradigm in solar composition:

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

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

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%

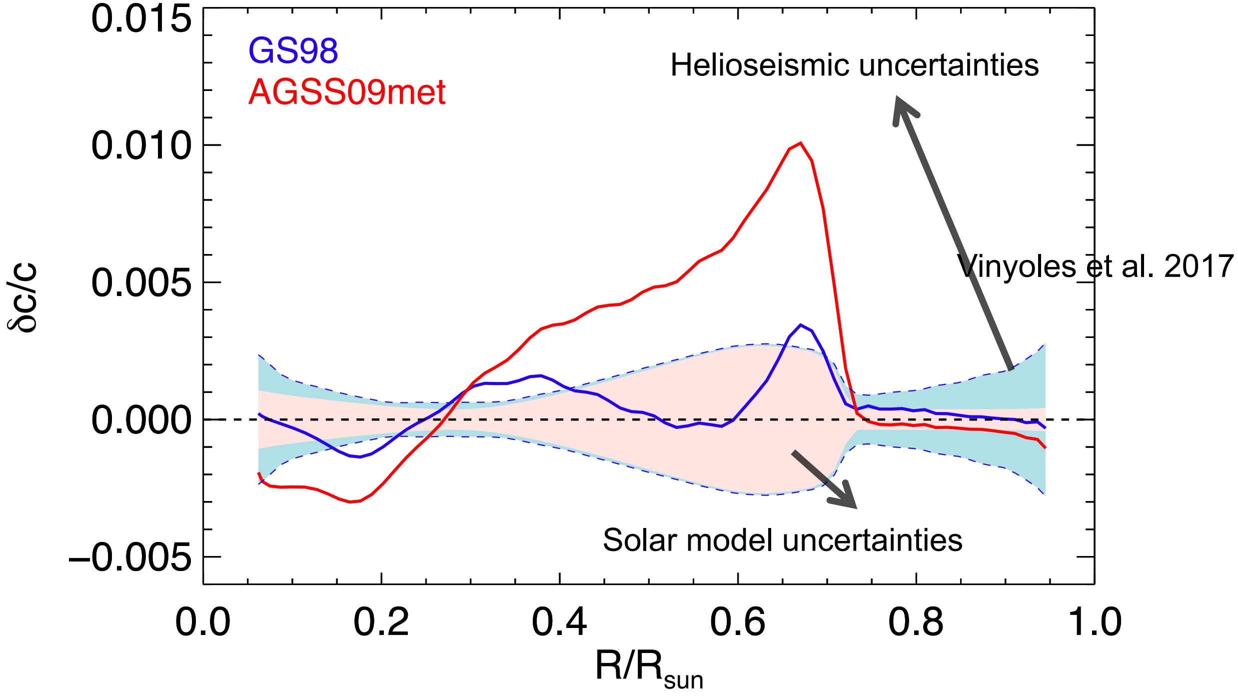
Impact of SSM calibration

	$L_\odot$	$R_\odot$	$(Z/X)_\odot$
$\alpha_{\rm mlt}$	0.06	-0.19	0.06
$Y_{\rm ini}$	2.35	0.56	0.08
$Z_{\rm ini}$	-0.73	-0.14	1.11

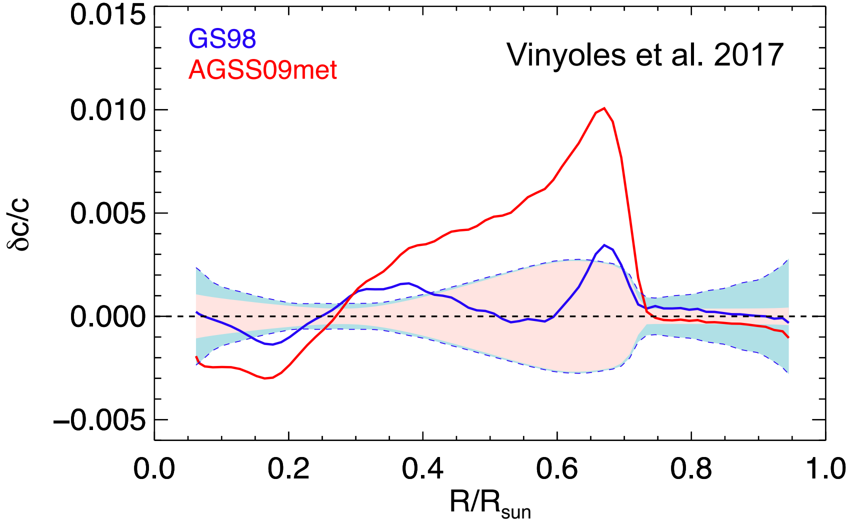
Z/X determines solar model composition: Z_{ini} & Y_{ini}

Solar models - helioseismology

Sound speed inversion



Solar models - helioseismology



Other helioseismic probes:

- Density inversion
- Depth of convective envelope
- Solar core through frequency ratios

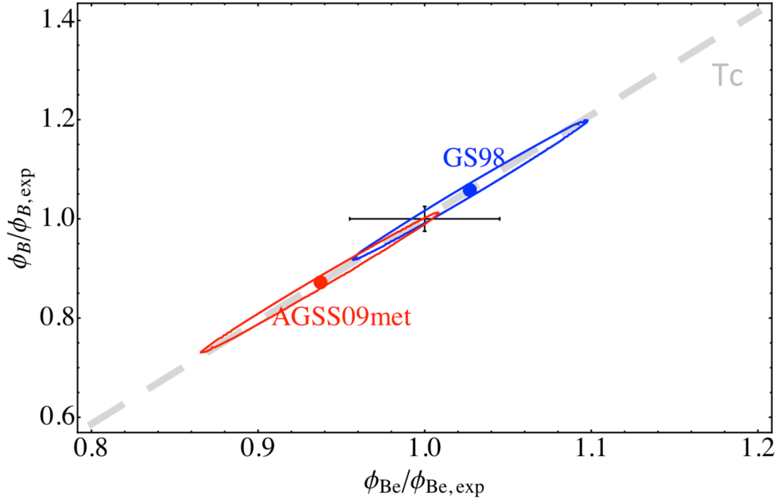
Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	0[a]

2-3 σ discrepancy for low Z

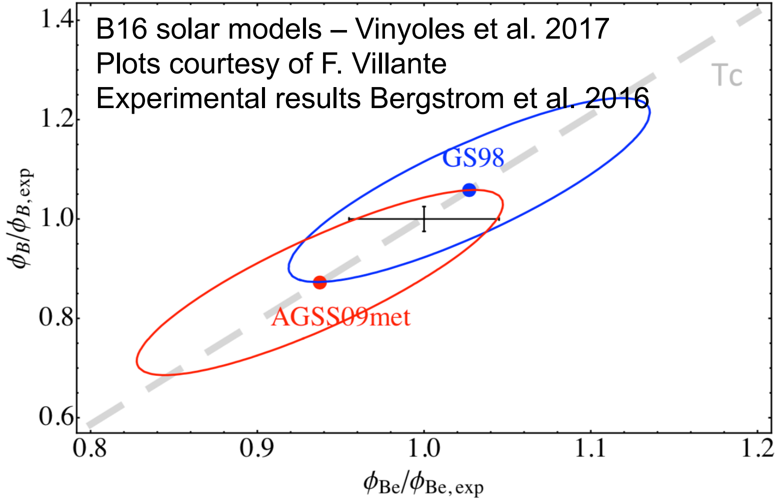
Discrepancy between solar models (new composition) and all helioseismic inferences: solar abundance problem (lots of literature about this)

Solar composition: neutrinos

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



+ nuclear rate uncertainties



Solar composition: neutrinos

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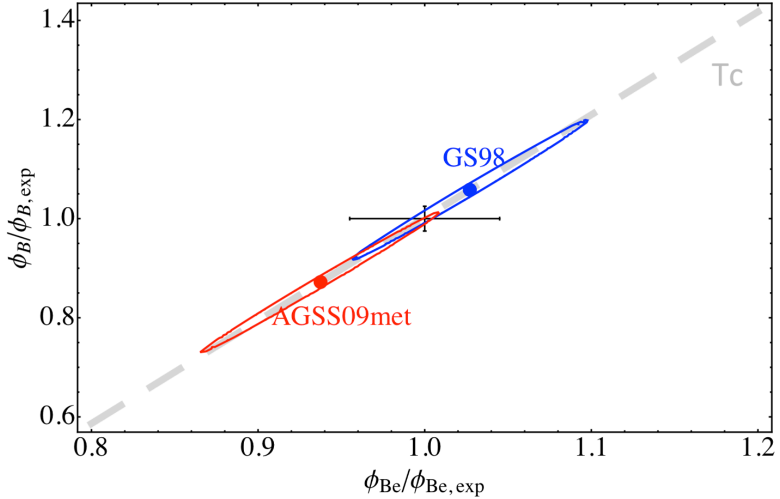

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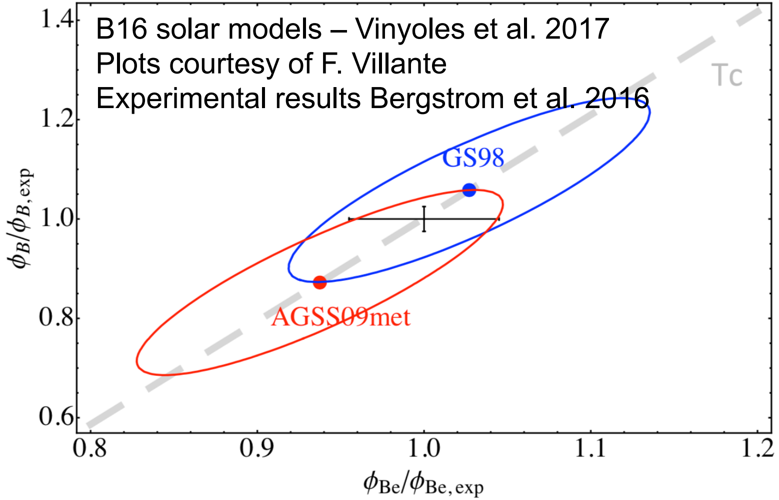

Composition → affects pp-chain fluxes through T_c change

→ 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 models – overall status

		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
$\Phi(^7\mathrm{Be}) + \Phi(^8\mathrm{B})$	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

High-Z models favored by helioseismology

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Vinyoles et al. 2017

ν−fluxes comparably good agreement
(model uncertainties dominate)
because they are from pp-chains

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Vinyoles et al. 2017

Global comparison favors high-Z models

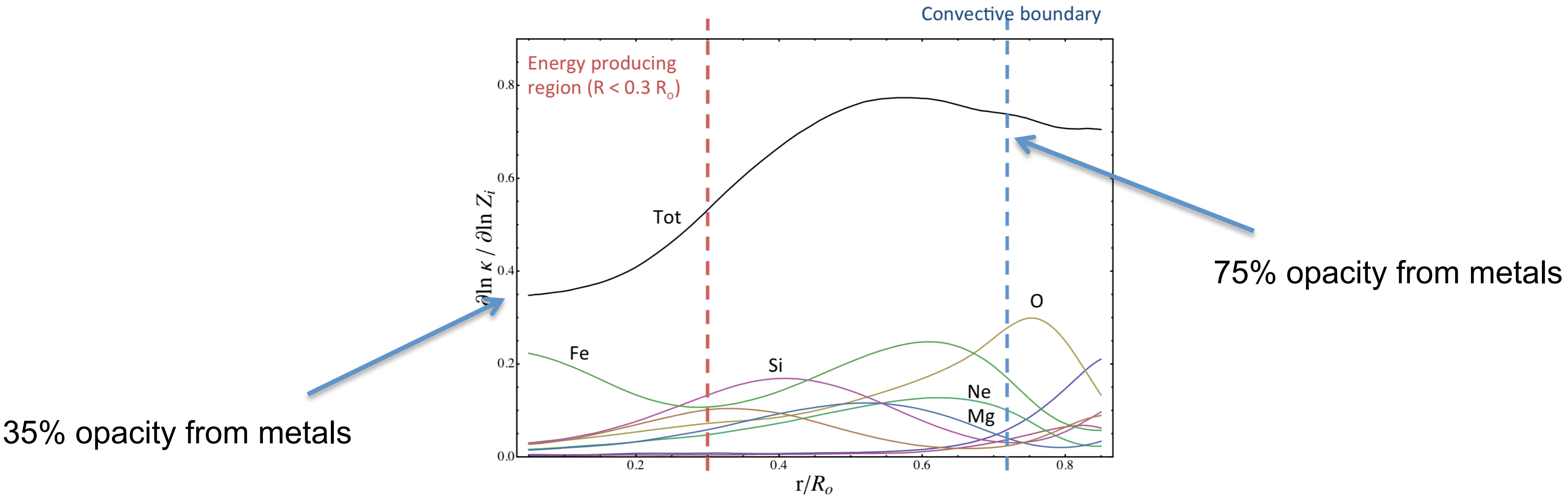
i.e. models with (P, ρ) or (T, μ) profiles consistent with high-Z models

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

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



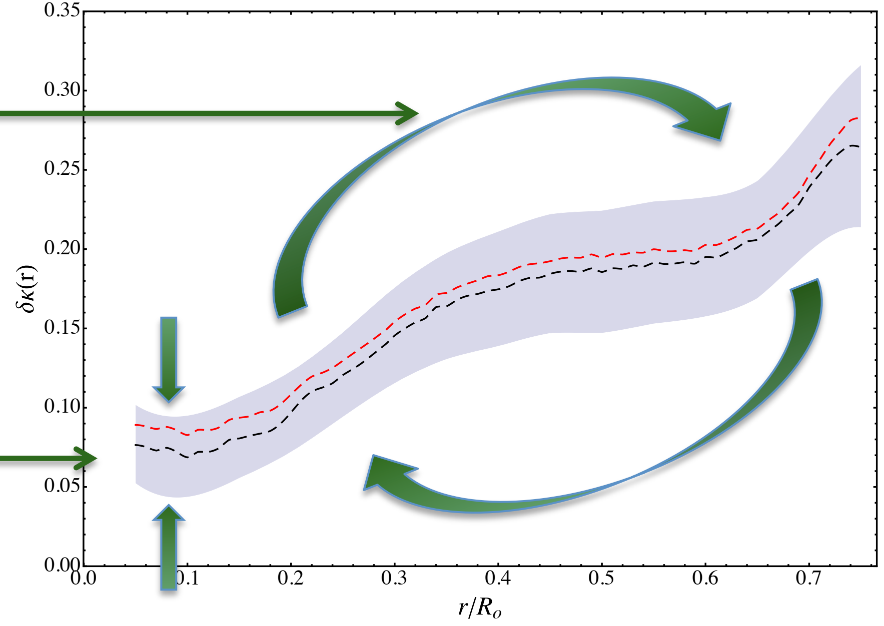
Intrinsic uncertainty + composition induced variation
(δ = fractional variation)

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

Solar opacity from νs and helioseismology

Helioseismology fixes the tilt

Solar neutrinos and Y_S the scaling (core)

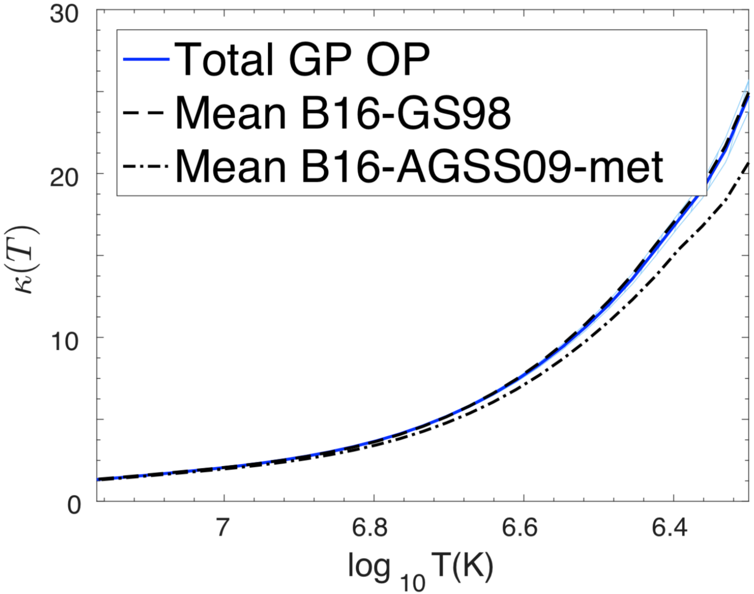


Villante et al. 2014

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 distrib)

Very close to that from GS98 model (unsurprisingly)

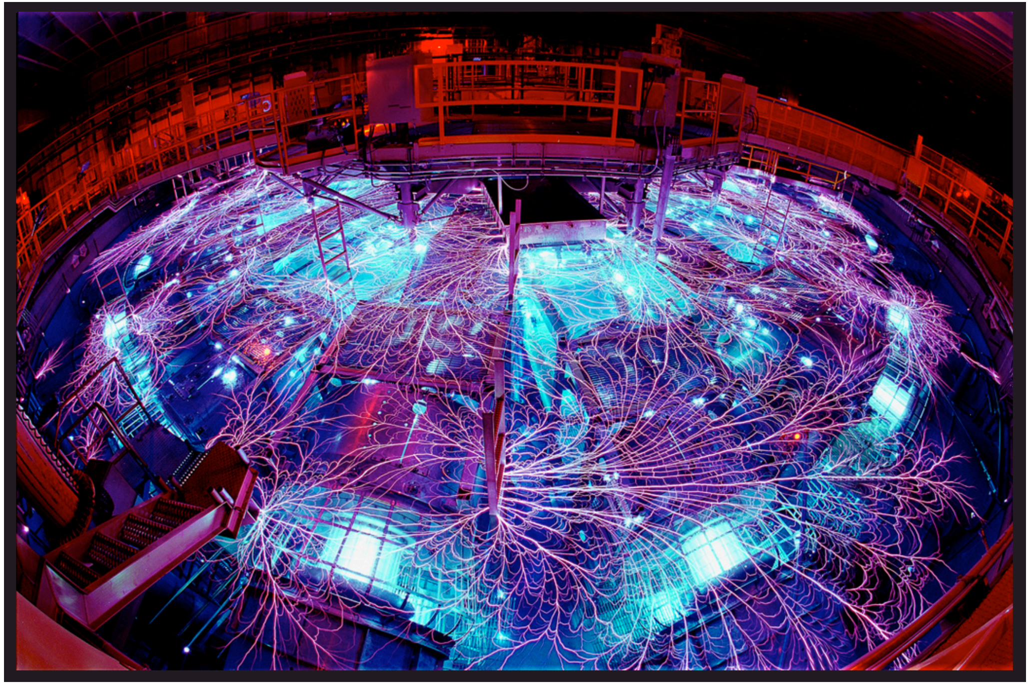
If AGSS09 composition → 20% opacity increase at base of convective zone

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

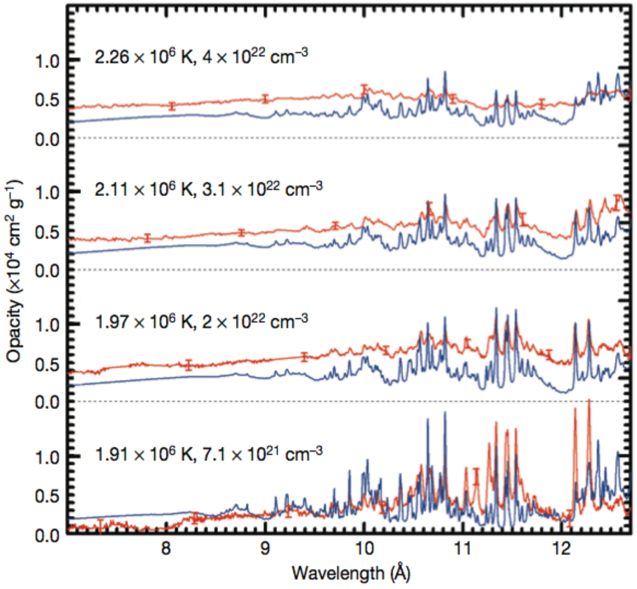


Bailey et al. 2015

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



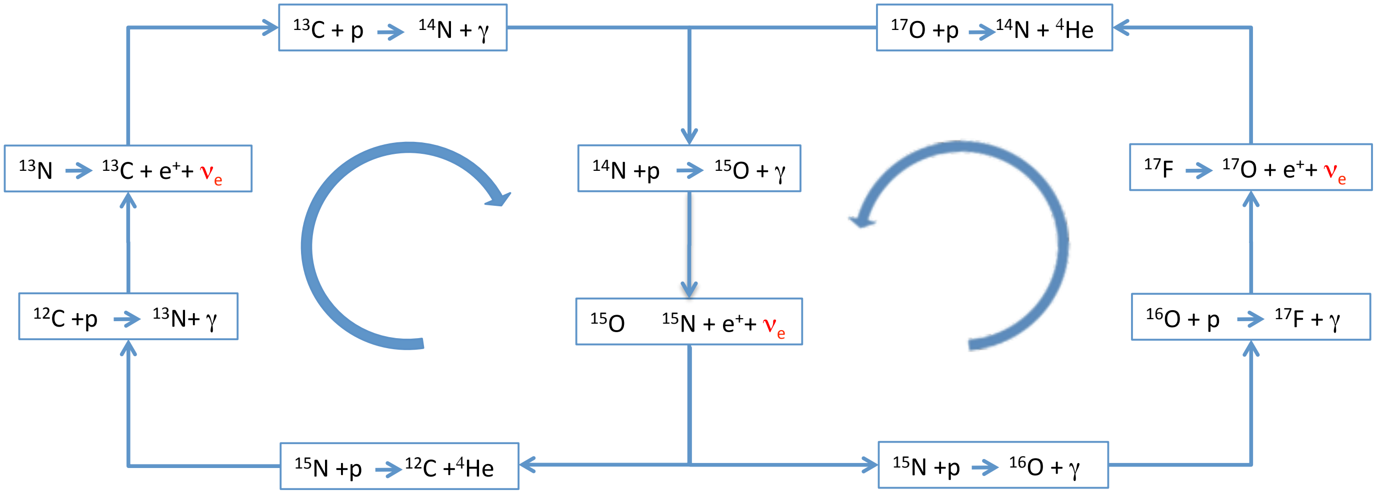
Bailey et al. 2015

$T \sim T_{CZ}$

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

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

CN-νs and solar composition



CN-cycle marginal in the Sun → intrinsic changes in its rate do not alter background state (e.g. T, ρ, X)

→ linear dependence on core C+N abundance and $S_{1,14}$ (for ^{15}O)

$$\frac{\Phi(^{15}\mathrm{O})_{\mathrm{HZ}} - \Phi(^{15}\mathrm{O})_{\mathrm{LZ}}}{\Phi(^{15}\mathrm{O})_{\mathrm{LZ}}} \approx 40\%$$

CN-νs and solar composition

Converting $\Phi(^{15}O)$ measurement into C+N core measurement – use $\Phi(^{8}B)$ as thermometer

$$\Phi(^{8}\mathrm{B}) \propto \mathrm{T}_{\mathrm{c}}^{25} \longrightarrow \mathrm{SuperK+SNO} \longrightarrow \delta \mathrm{T}_{\mathrm{c}}/\mathrm{T}_{\mathrm{c}} \approx 0.1\%$$

Removes many solar model uncertainties (environmental) in predictions of CN neutrino fluxes

CN-νs and solar composition

Converting $\Phi(^{15}O)$ measurement into C+N core measurement – use $\Phi(^{8}B)$ as thermometer

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

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

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

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

→ Temperature dependence

→ Nuclear rates

→ Temperature dependence (opacity)

Serenelli et al. 2013

CN-νs and solar composition

Converting Φ(^{15}O) measurement into C+N core measurement – use Φ(^{8}B) as thermometer

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

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$$\times \left[x_{\mathrm{O}}^{0.003} x_{\mathrm{Ne}}^{-0.005} x_{\mathrm{Mg}}^{-0.003} x_{\mathrm{Si}}^{-0.001} x_{\mathrm{S}}^{-0.001} x_{\mathrm{Ar}}^{0.001} x_{\mathrm{Fe}}^{0.003}\right]$$ → Temperature dependence (opacity)

Reduces to

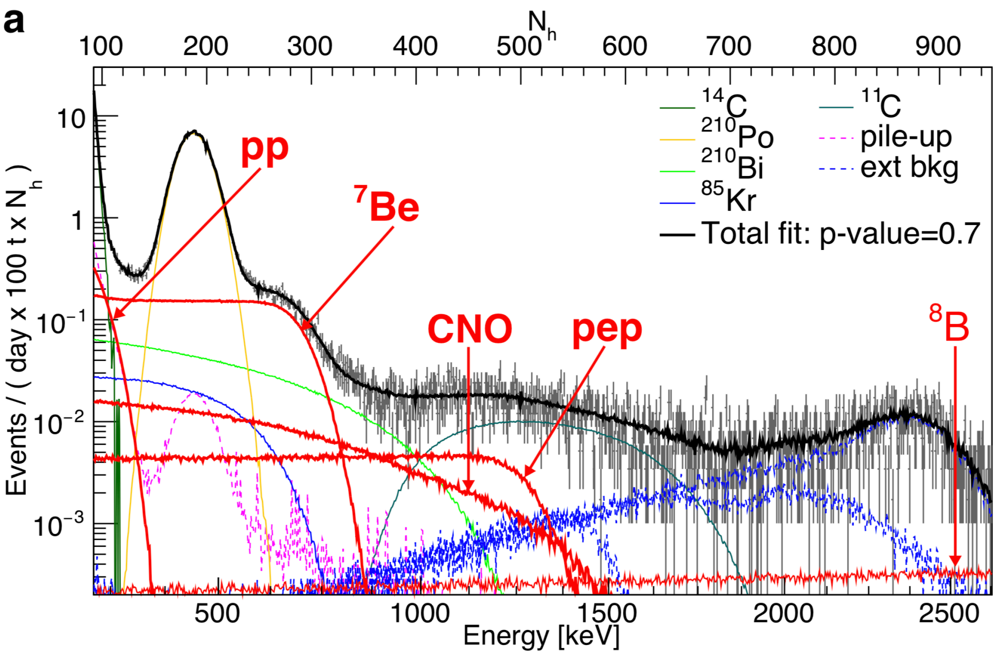
$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} \Big/ \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} = \left[\frac{C+N}{C^{\mathrm{SSM}}+N^{\mathrm{SSM}}}\right] (1 \pm 0.4\%\,(\mathrm{env}) \pm 2.6\%\,(\mathrm{D}) \pm 10\%\,(\mathrm{nucl}))$$

Nuclear uncertainty dominant: $S_{1,14}$ (7%) & S_{17} (5%) – can be potentially reduced further

(Almost) direct measurement of C+N in solar core

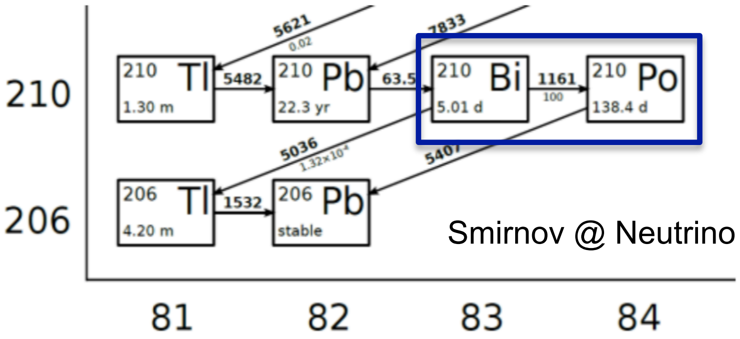
Serenelli et al. 2013

CN-νs at Borexino



CN flux hidden below ^{210}Bi background

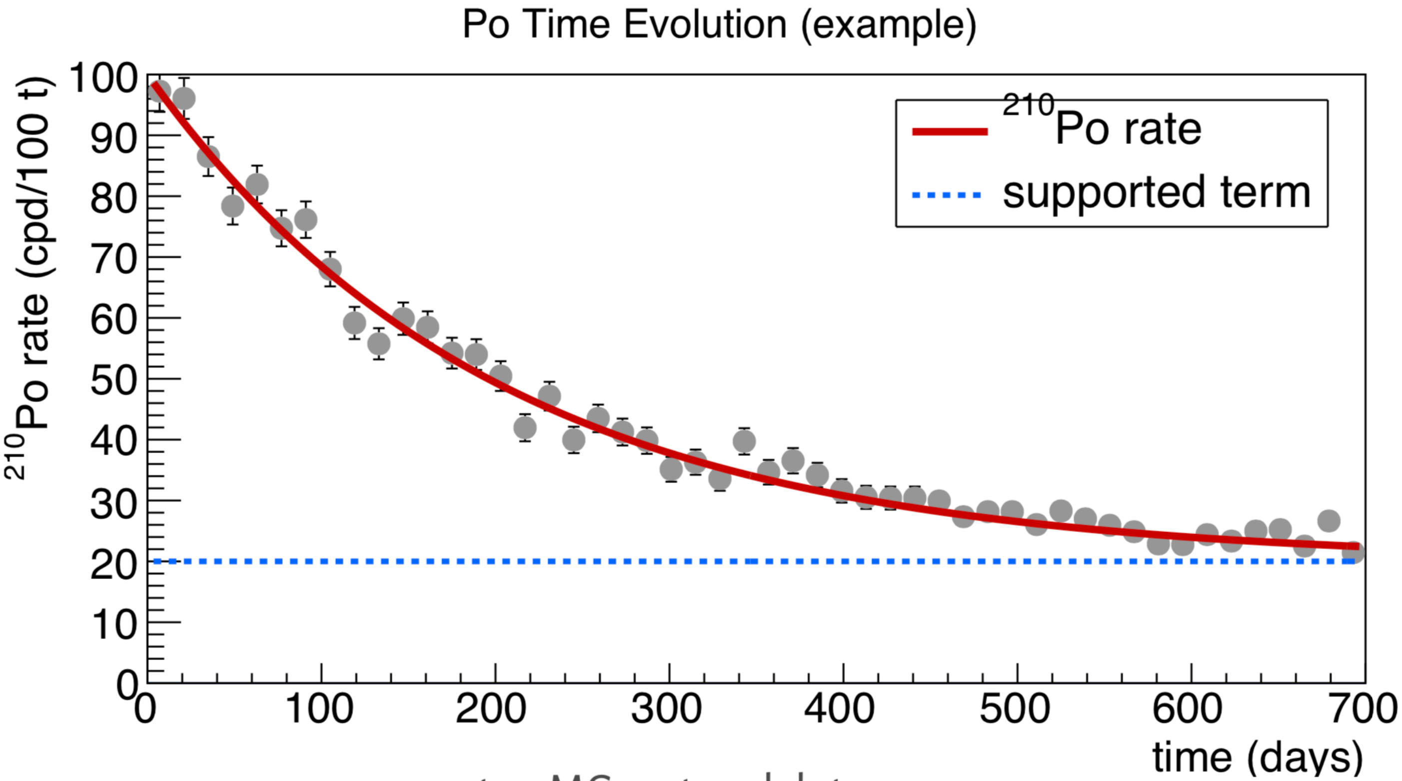
Indirect measurement of ^{210}Bi by evolution of ^{210}Po (Villante et al. 2011) provided ^{210}Bi -- > ^{210}Po only source of ^{210}Po



Smirnov @ Neutrino 2018

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

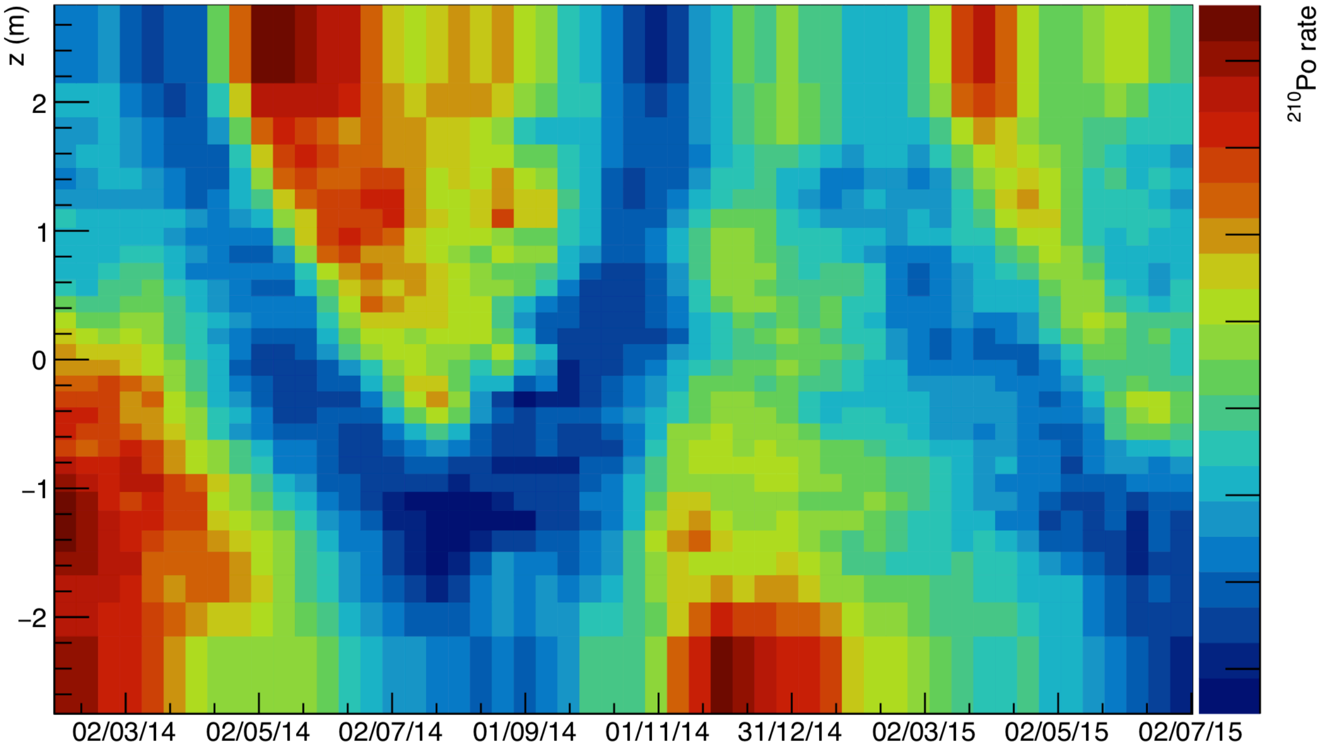
CN-νs at Borexino



toy-MC, not real data

Borexino coll.

CN-νs at Borexino

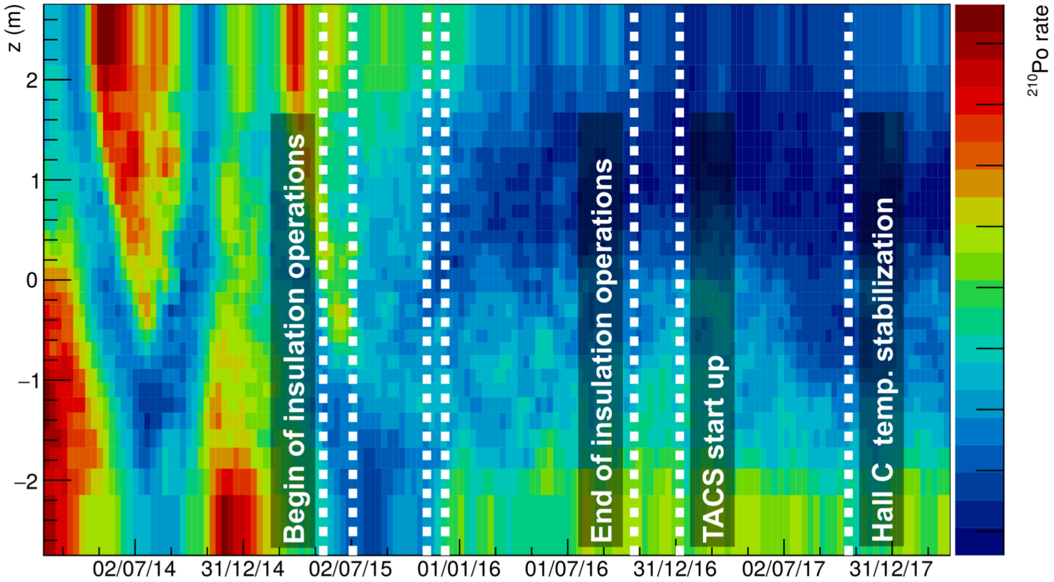


Guffanti 2018 (Borexino coll.) @ 5th International Solar Neutrino Conference

CN-νs at Borexino

Thermal insulation

^{210}Po rate evolution after insulation



Guffanti 2018

Summary

- The Sun shines by pp burning : 1.03 ± 0.08 $L_\odot$ – all neutrino experiments
- The Sun shines by pp burning : 1.01 ± 0.10 $L_\odot$ – Borexino experiment
- Open question: pp neutrinos measurement to 1% needed to test other energy sources in the Sun
- Open question: direct detection of CN fluxes
- Precise determination of solar opacity profile from νs (core opacity) and seismic data
- Solar abundance/model problem remains: opacity ←→ composition degeneracy
  Exporting abundance/opacity problem to other stars: systematic errors in ages by 10-15%
- First experimental opacity measurement @ solar conditions
  hints of higher Fe opacity at right place : 7%
  not enough : ~20% needed
- Open question: are there other mechanisms of energy transport at work (e.g. ADM), modifying ‘effective’ radiative opacity?
- CN fluxes remain necessary and only way to break degeneracy
  Whatever the result, very important measurement → core C+N abudance
  40% solar abundance problem, 15% chemical mixing processes in the Sun (surface/core difference)

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SSM – neutrinos

No luminosity constraint – purely experimental result

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

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

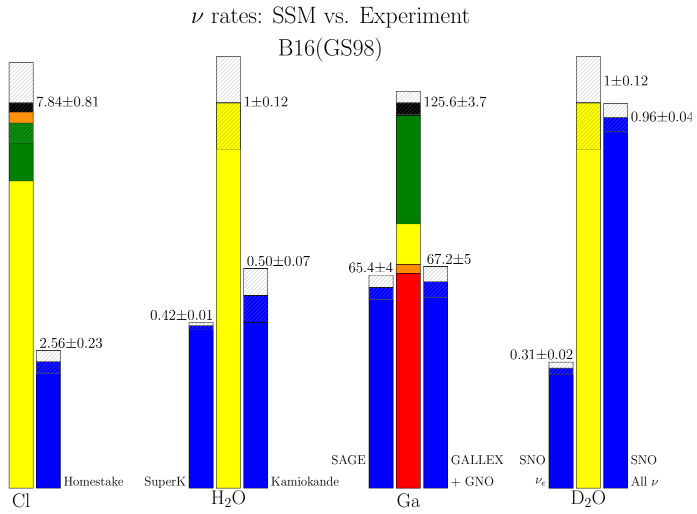
With luminosity constraint – $L_\odot$ = Lnuc

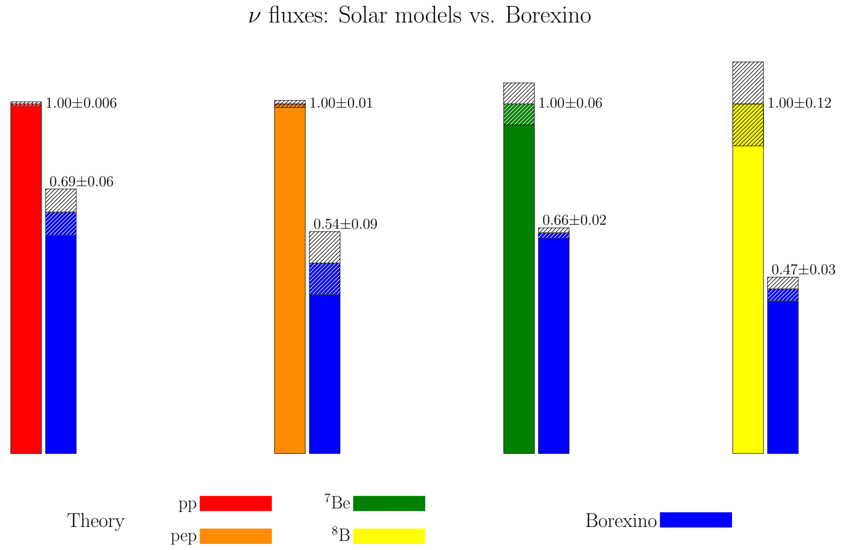
$$\frac{L_{\text{pp-chain}}}{L_\odot} = 0.991^{+0.005}_{-0.004}\,\left[^{+0.008}_{-0.013}\right] \iff \frac{L_{\text{CNO}}}{L_\odot} = 0.009^{+0.004}_{-0.005}\,\left[^{+0.013}_{-0.008}\right]$$

Bergstrom et al. 2016

Global analysis with more recent data needed, e.g. Borexino – see Ianni's talk

Neutrinos: theory vs experiment





Solar core temperature → solar models

Strong T dependence of ν-fluxes

$$\Phi(^8\mathrm{B}) \propto \mathrm{T_c^{25}} \longrightarrow \mathrm{SuperK{+}SNO} \longrightarrow \delta\mathrm{T_c}/\mathrm{T_c} \approx 0.1\%$$

$$\Phi(^7\mathrm{Be}) \propto \mathrm{T_c^{10}} \longrightarrow \mathrm{Borexino} \longrightarrow \delta\mathrm{T_c}/\mathrm{T_c} \approx 0.4\%$$

But this determines only precision – actual T_C determination requires solar models

Problems start here – models depend on inputs

Solar composition
Radiative opacities

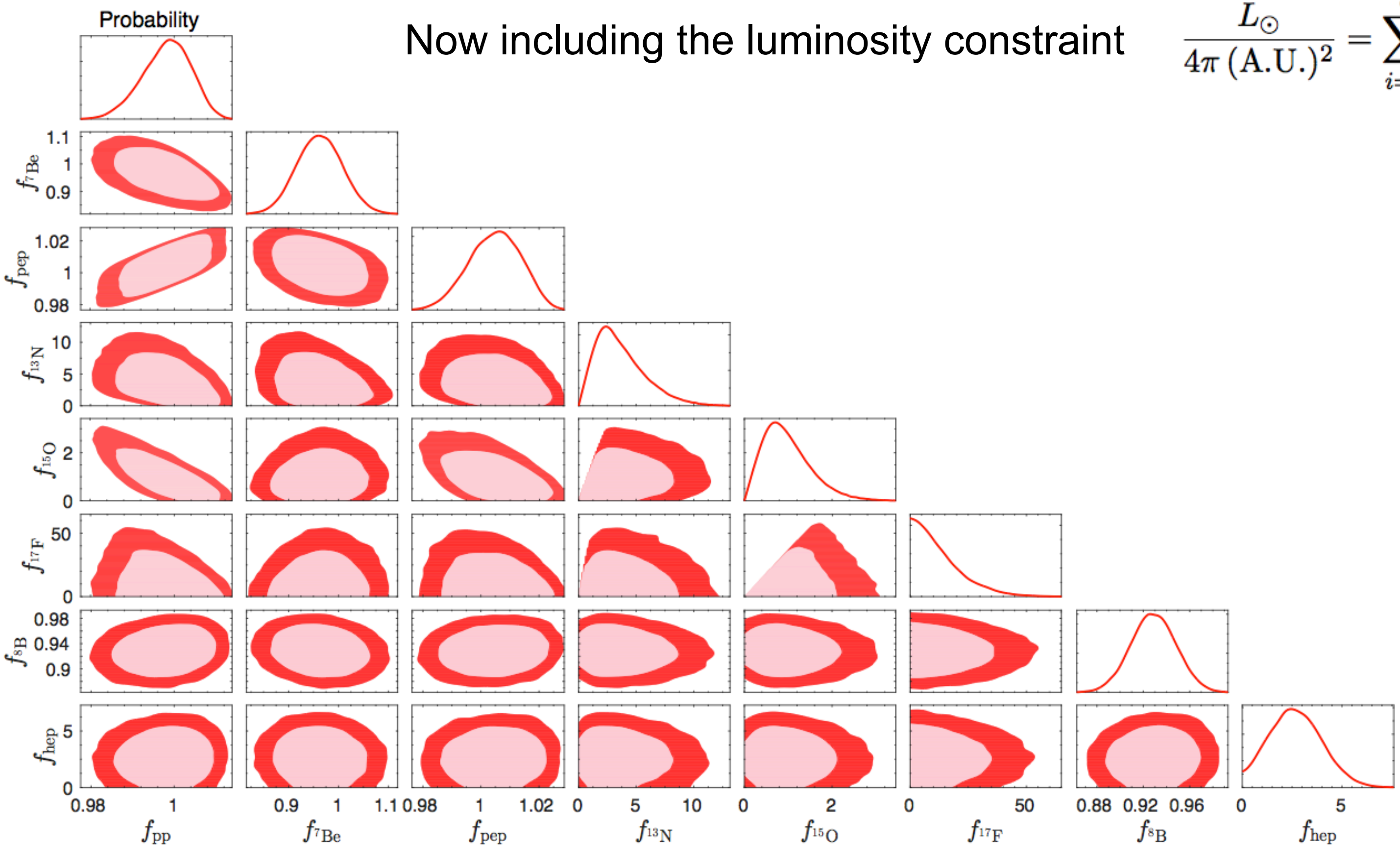
Nuclear reaction rates
Chemical mixing (gravitational settling + other mixing processes)

Equation of state

How does the Sun shine?

Now including the luminosity constraint

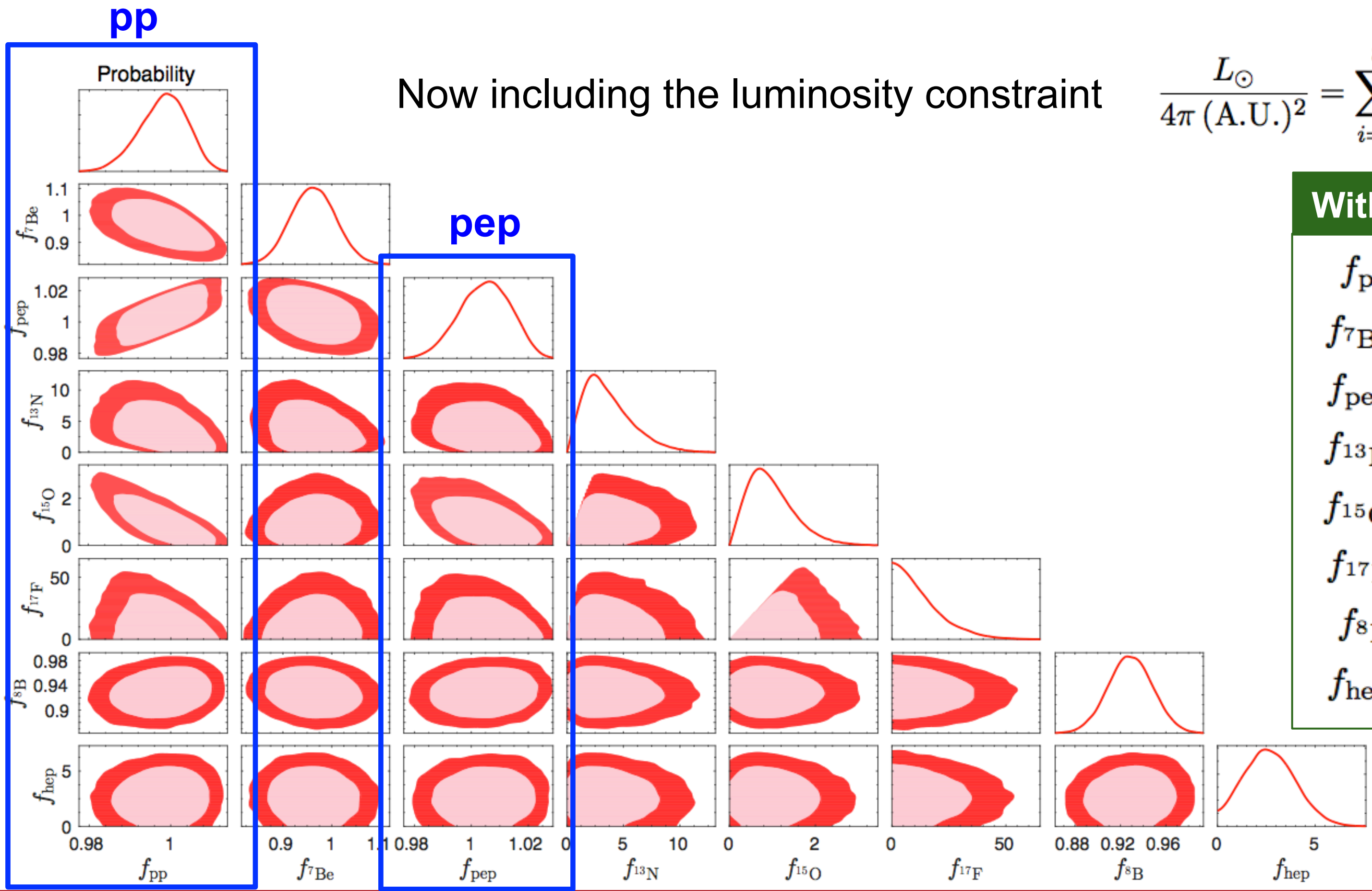
$$\frac{L_\odot}{4\pi\,(\mathrm{A.U.})^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \,.$$



Bergstrom et al. 2016

How does the Sun shine?

Now including the luminosity constraint
$$\frac{L_\odot}{4\pi\,(\mathrm{A.U.})^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \,.$$



With luminosity constraint

$$f_{pp} = 0.999^{+0.006}_{-0.005}\,[^{+0.012}_{-0.016}]\,,$$
$$f_{^7Be} = 0.96^{+0.05}_{-0.04}\,[^{+0.12}_{-0.11}]\,,$$
$$f_{pep} = 1.005 \pm 0.009\,[^{+0.019}_{-0.024}]\,,$$
$$f_{^{13}N} = 1.7^{+2.9}_{-1.0}\,[^{+8.4}_{-1.6}]\,,$$
$$f_{^{15}O} = 0.6^{+0.6}_{-0.4}\,[^{+2.0}_{-0.6}]\,,$$
$$f_{^{17}F} \leq 15\,[46]\,,$$
$$f_{^8B} = 0.92 \pm 0.02\,[\pm 0.05]\,,$$
$$f_{hep} = 2.4^{+1.5}_{-1.2}\,[\leq 5.9]\,,$$

Bergstrom et al. 2016

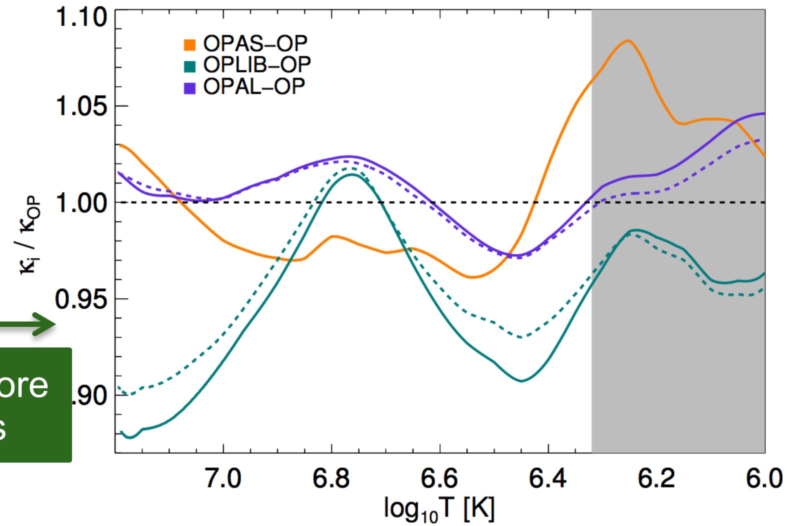
Opacities – new calculations

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



Too low in solar core
Ruled out by νs

Solid – GS98

Dashed – AGSS09

Opacities – new calculations

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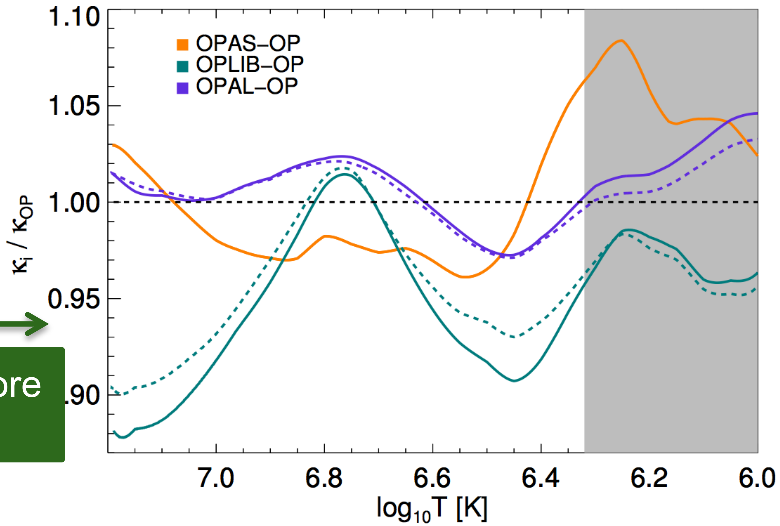


Too low in solar core
Ruled out by νs

Solid – GS98

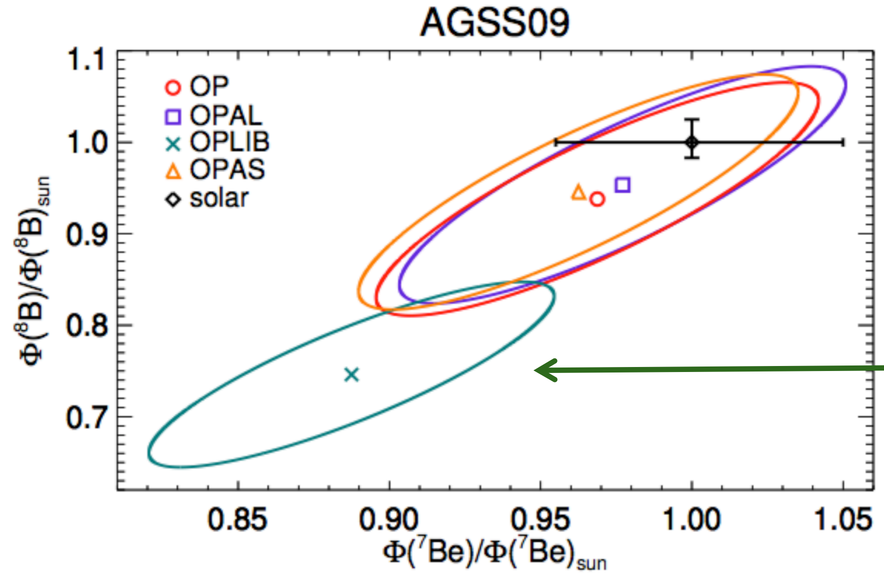
Dashed – AGSS09

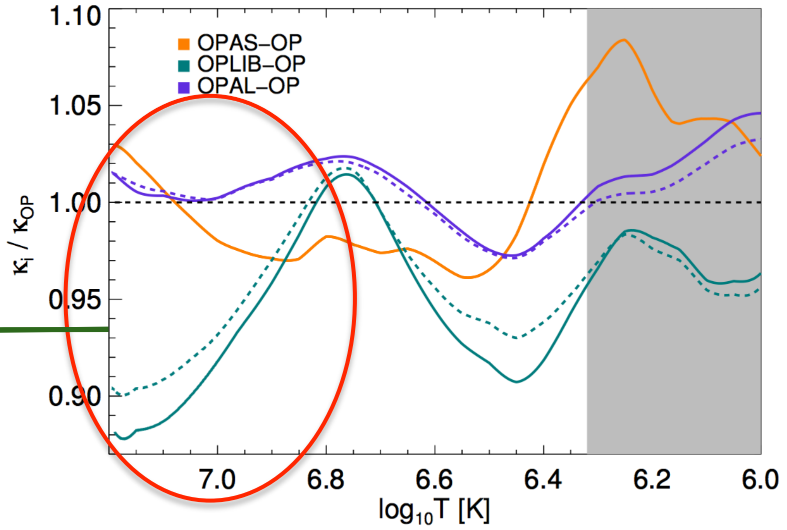
Not guaranteed that newer opacity models lead to higher opacity values

± 5% variations

Current situation unclear

SSM with new opacities

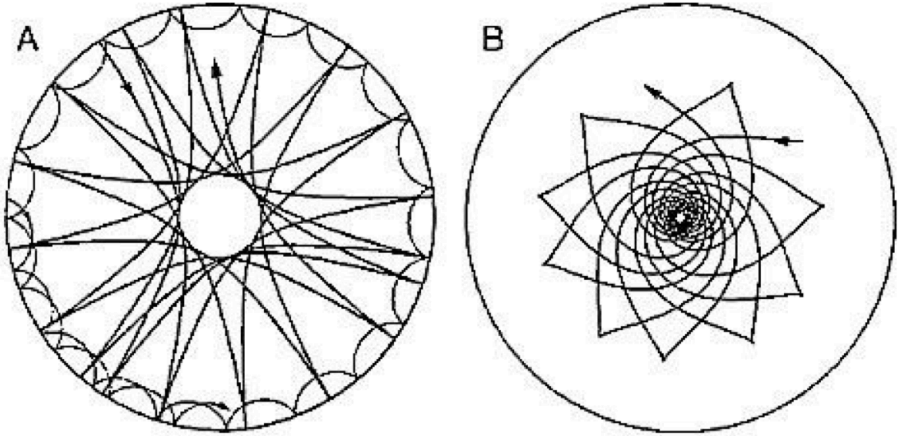




Solar νs rule out OPLIB opacities for low Z models

g-modes detection (finally?)

g-modes probe inner regions – but strongly damped in the surface – tiny amplitudes & high background



direct searches for g-modes have failed (despite claims in Garcia et al. 2007)

Fossat et al. 2017 use new method: long term modulations in p-mode spectrum

Claim detections of more than 200 g-modes of angular degree l = 1 , 2

g-modes detection (finally?)

Two important claims in Fossat et al. 2017

1) Asymptotic period spacings for l= 1 , 2

$$\Pi_\ell = \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left[\int_0^{R_{CZ}} N \frac{dr}{r} \right]^{-1} \qquad N = g \left(\frac{1}{\Gamma_1} \frac{d \log p}{dr} - \frac{d \log \rho}{dr} \right)$$

Fossat et al. P_1 = 1443.1 ± 0.5s - P_2 = 832.8 ± 0.7s

GS98 SSMs: P_1 = 1525 – 1540 s - P_2 = 880 – 890 s

AGSS09 SSMs: P_1 = 1535 – 1560 s - P_2 = 886 – 900 s

2) Rotational splitting -- > solar core rotation ~ x3 faster than intermediate regions
Maybe some impact for chemical mixing in the core – but in direction of lowering ν-fluxes

g-modes detection (finally?)

Two important claims in Fossat et al. 2017

1) Asymptotic period spacings for l= 1 , 2

From Appourchaux et al. 2010 review

> and data-analysis perspectives – to give unambiguous detections of individual g modes. The review ends by concluding that, at the time of writing, there is indeed a consensus amongst the authors that *there is currently no undisputed detection of solar g modes.*

2)

Maybe some impact for chemical mixing in the core – but in direction of lowering ν-fluxes

SSM – B16 models

Flux	B16-GS98	B16-AGSS09met	Solar[a]	Chg.
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$	0.0
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$	0.0
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$	-0.7
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$	-1.4
$\phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$	-2.2
$\phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7	-6.1
$\phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8	-8.1
$\phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85	-4.2

New SSMs - changes in some nuclear rates (Vinyoles et al. 2017)

	$S(0)$	Uncert. %	$\Delta S(0)/S(0)$
S_{11}	$4.03 \cdot 10^{-25}$	1	+0.5%
S_{17}	$2.13 \cdot 10^{-5}$	4.7	+2.4%
S_{114}	$1.59 \cdot 10^{-3}$	7.5	-4.2%

Small changes ^7Be-^8B (S_{11}-S_{17})

Larger for ^{13}N-^{15}O (S_{11}-S_{114})

SSM – B16 models

New SSMs - changes in some nuclear rates (Vinyoles et al. 2017)

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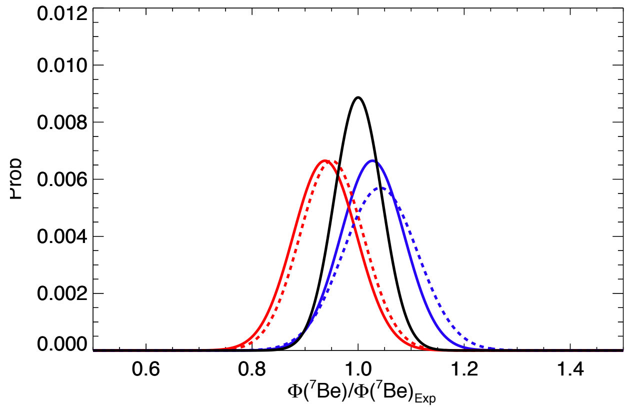
Small changes ^{7}Be-^{8}B (S_{11}-S_{17})

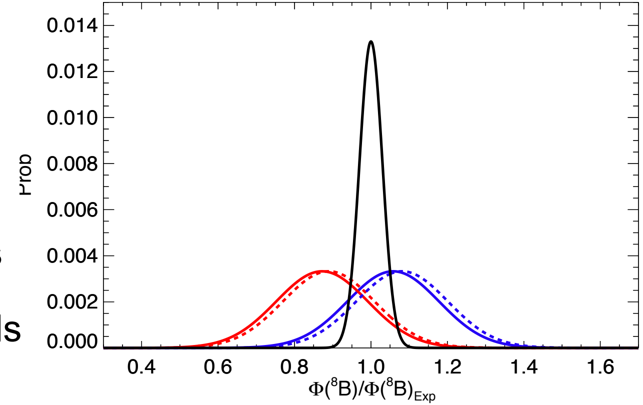
Larger for ^{13}N-^{15}O (S_{11}-S_{114})



ν data fit
AGSS09
GS98

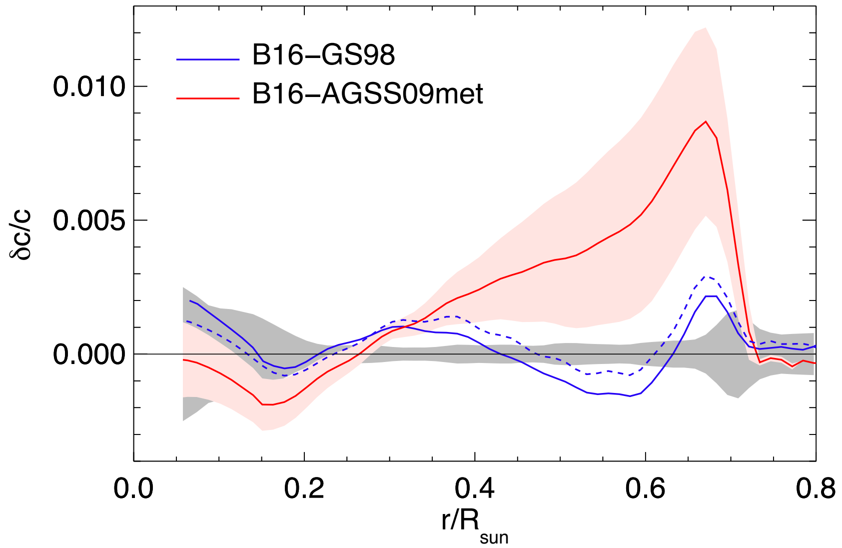
B16 models

Older models



Revision of global analysis including new Borexino data needed

Small changes in helioseismic probes



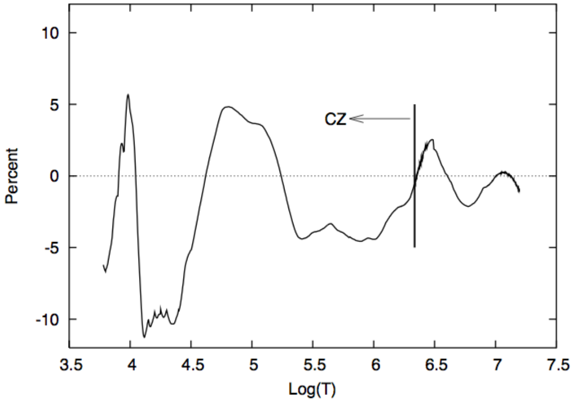
Qnt.	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0005 ± 0.0004	0.0021 ± 0.001	—

Opacities

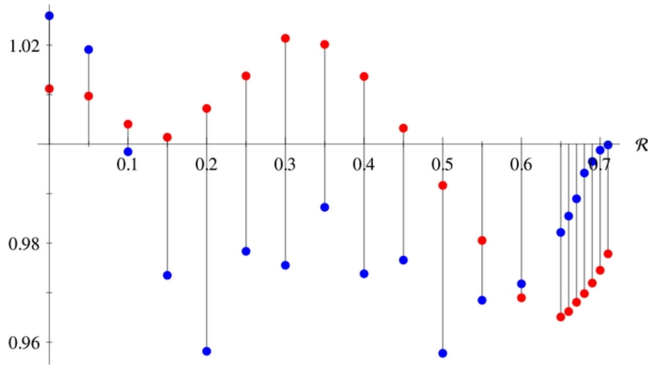
Helioseismic probes and pp νs depend on "effective" opacity profiles: opacity models + composition
details in F. Villante's talk

Status of opacity models in 2014 @ "A special Borexino Event"

OP vs OPAL

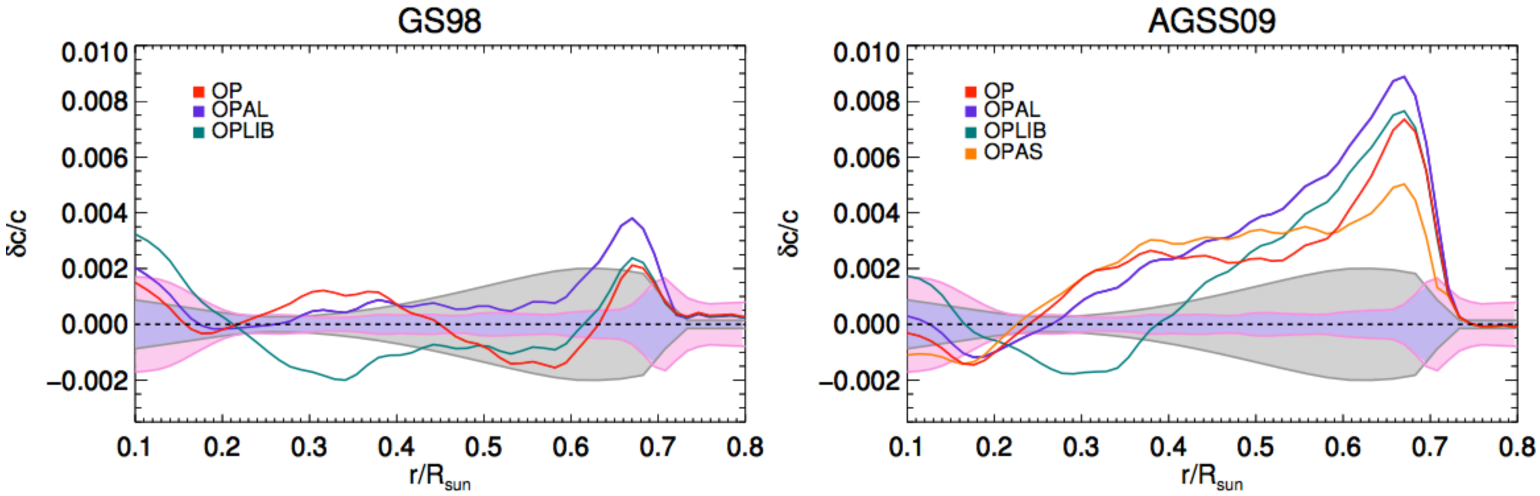


OPAS vs OP (blue)



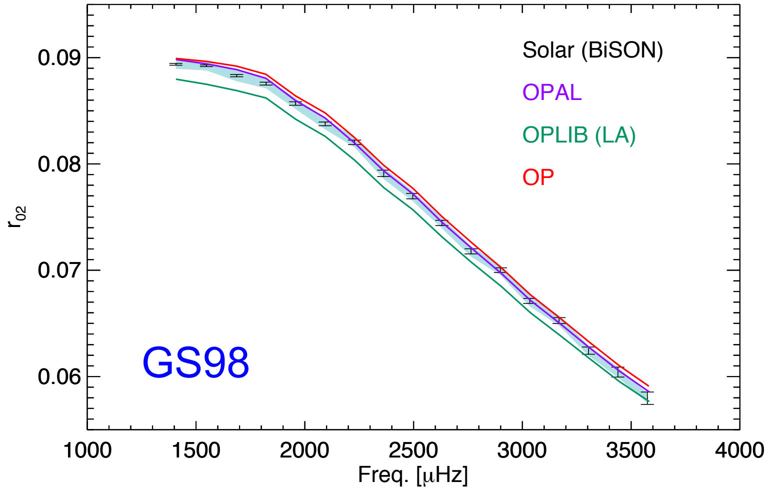
Few percent differences in solar interiors
Only theoretical calculations available

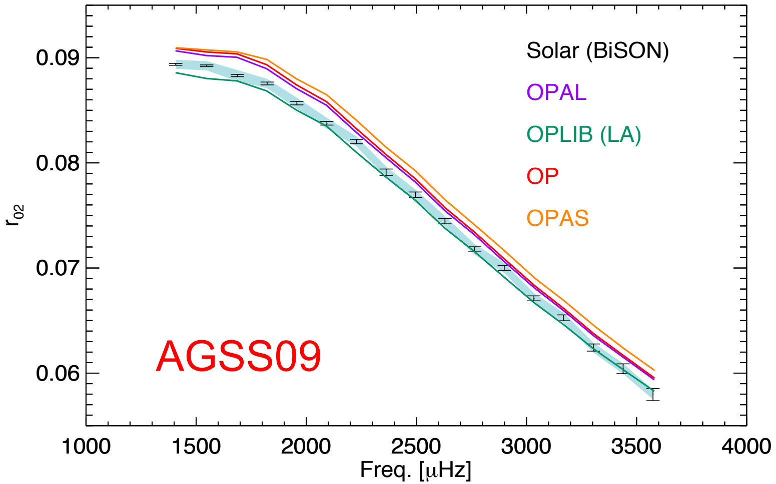
SSM with new opacities



New opacities lead to some variations in sound speed profiles but nothing too dramatic

SSM with new opacities

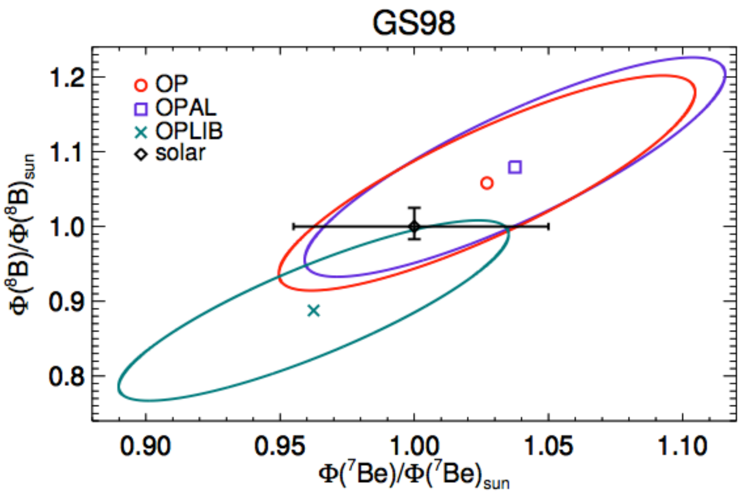


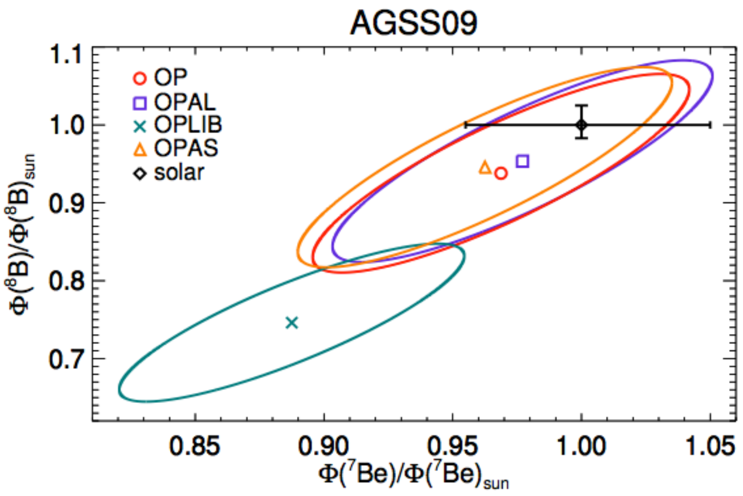


New OPLIB opacities lead to indecisive results for helioseismic probes

not all agree (disagree) with high(low) Z solar models

SSM with new opacities

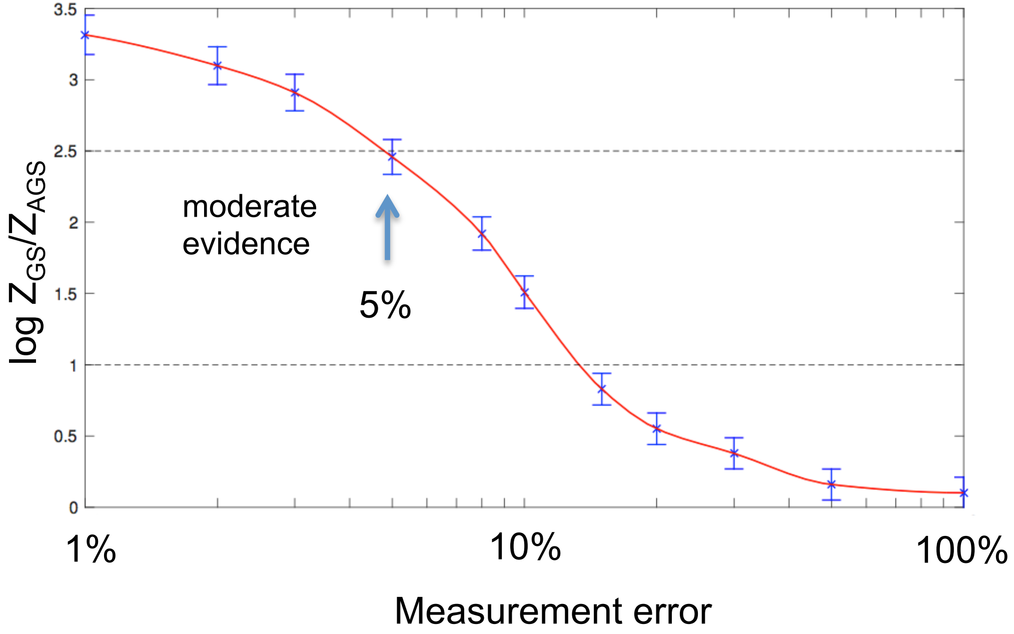




SSM: the need for CN(O)

New opacity calculations do not alter state-of-the-art or complicate matters more

Most robust way to break the opacity < -- > composition degeneracy is through CNO νs



ν-experiments only

Bergstrom et al. 2016

Discriminating power can improve if model information is added (Haxton et al. 2008)

Extra slides