Solar models and neutrinos: where do we stand?

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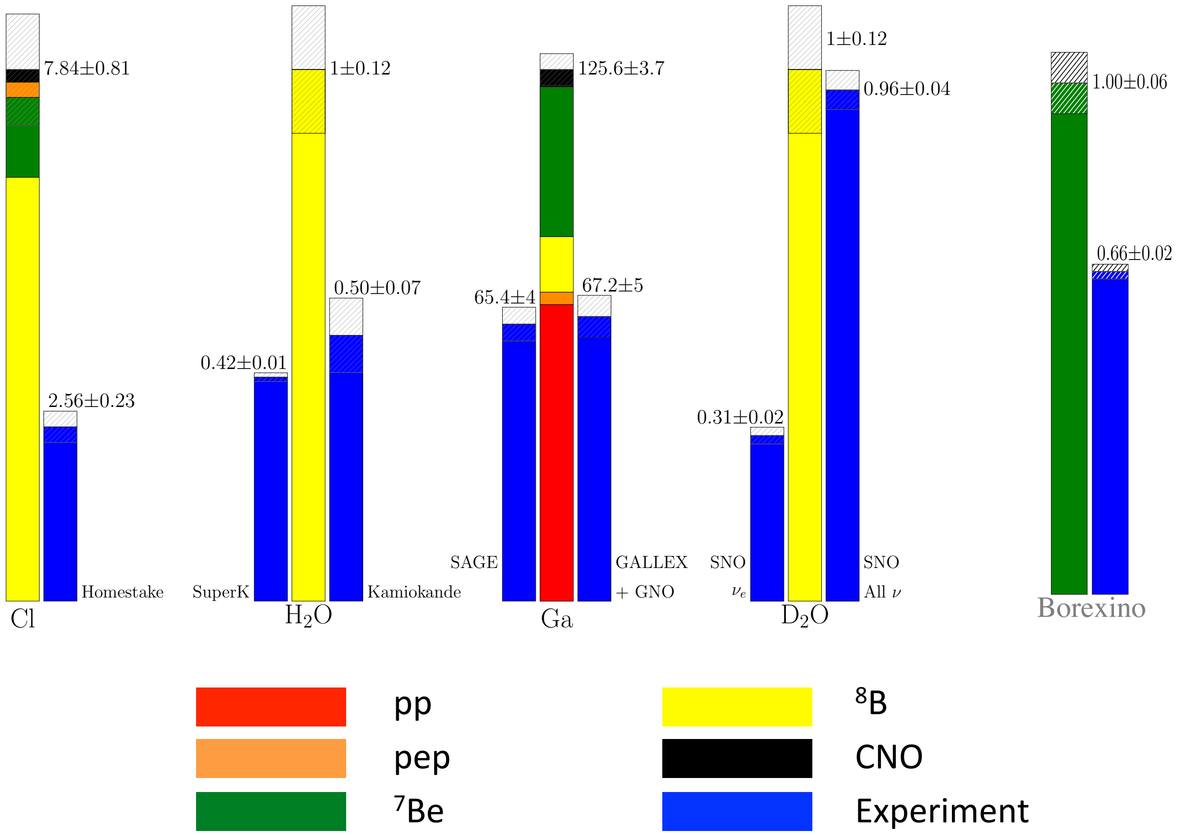
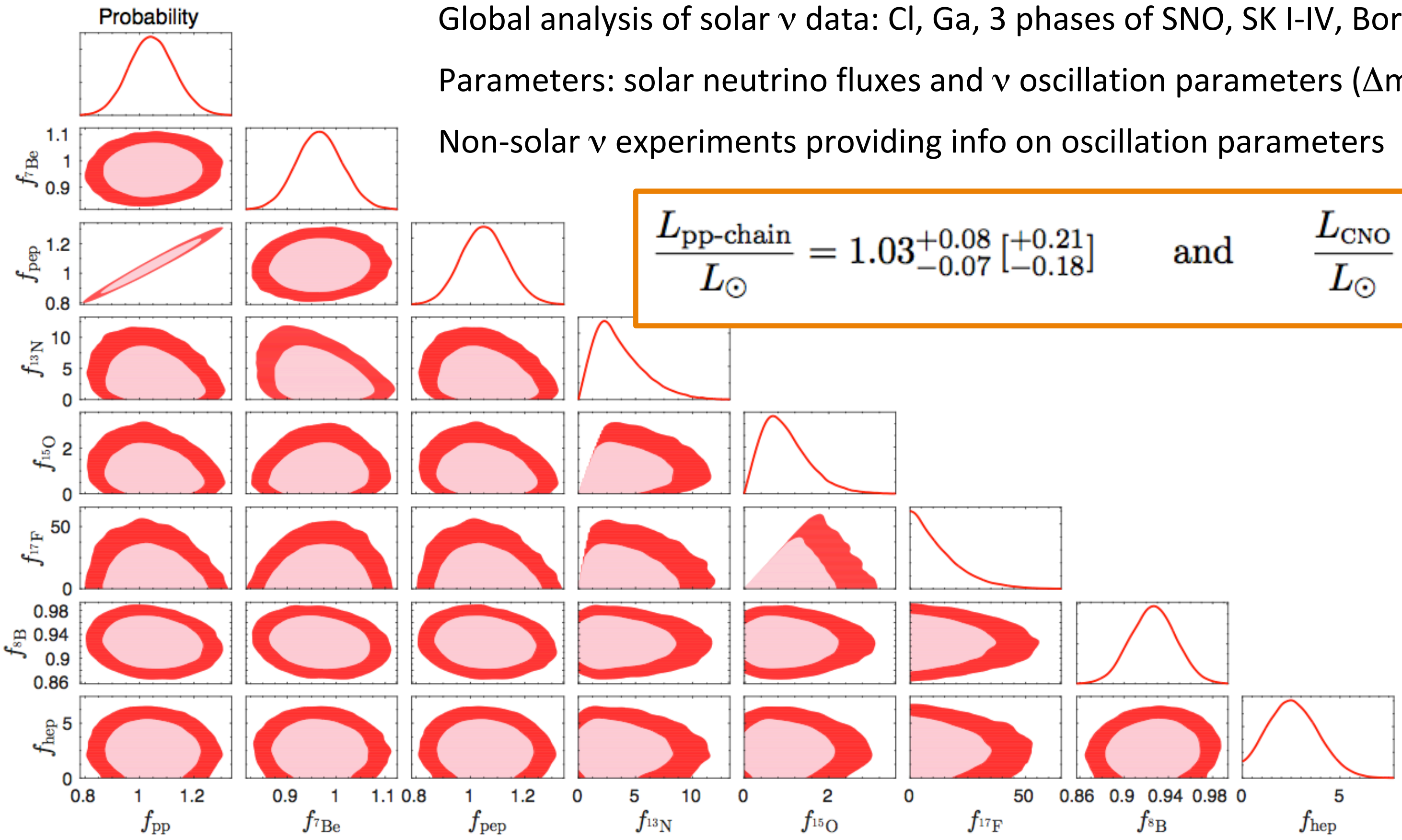
Consejo Superior de Investigaciones Científicas

IEEC

Experiments vs Models





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

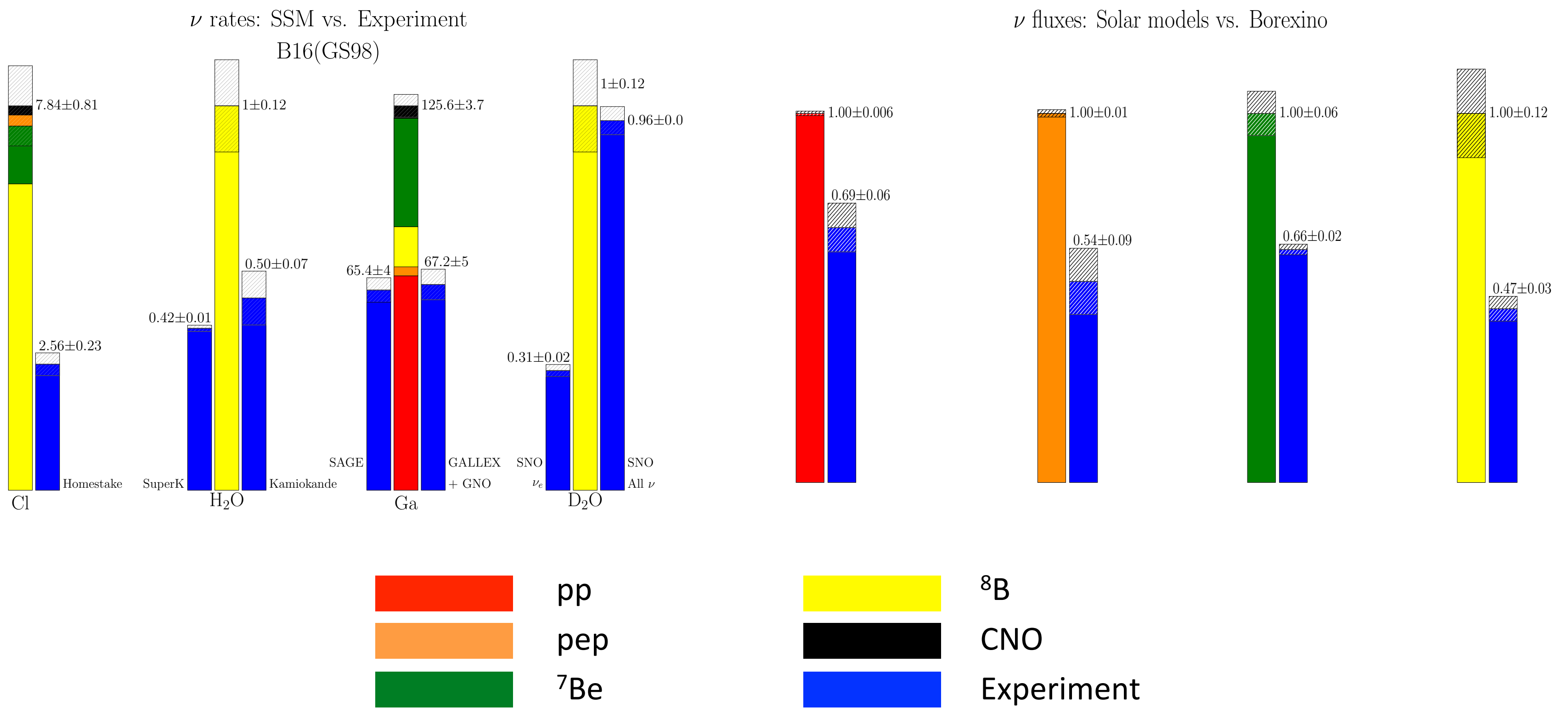
Parameters: solar neutrino fluxes and ν oscillation parameters (Δm^2_{21}, θ_{12}, θ_{13})

Non-solar ν experiments providing info on oscillation parameters

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

Bergstrom et al. 2016

Solar neutrinos: theory vs experiments



How does the Sun shine?

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

Purely experimental result – no solar model information

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

Bergstrom et al. 2016

$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.01 \begin{bmatrix}+0.09\\-0.11\end{bmatrix}$$

Borexino et al. 2018
(+ Esteban et al. 2017 ν-osc)

Standard Solar Models

$$L_\odot = \int \frac{\partial L}{\partial m} dm = \int (\varepsilon_{\mathrm{nuc},\nu} + \varepsilon_g)\, dm \approx \int \varepsilon_{\mathrm{nuc},\nu}\, dm = L_{\mathrm{nuc}}$$

$\rightarrow < 10^{-3}$

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$$\boxed{L_\odot = L_{\mathrm{nuc}}}$$

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Experimental constraints

Non Standard Solar Models

$$L_\odot = \int \frac{\partial L}{\partial m} dm = \int (\varepsilon_{\mathrm{nuc},\nu} + \varepsilon_g \pm \varepsilon_x)\, dm \approx \int (\varepsilon_{\mathrm{nuc},\nu} \pm \varepsilon_x)\, dm = L_{\mathrm{nuc}} \pm L_x$$

$$L_\odot = L_{\mathrm{nuc}} \pm L_x \neq L_{\mathrm{nuc}}$$

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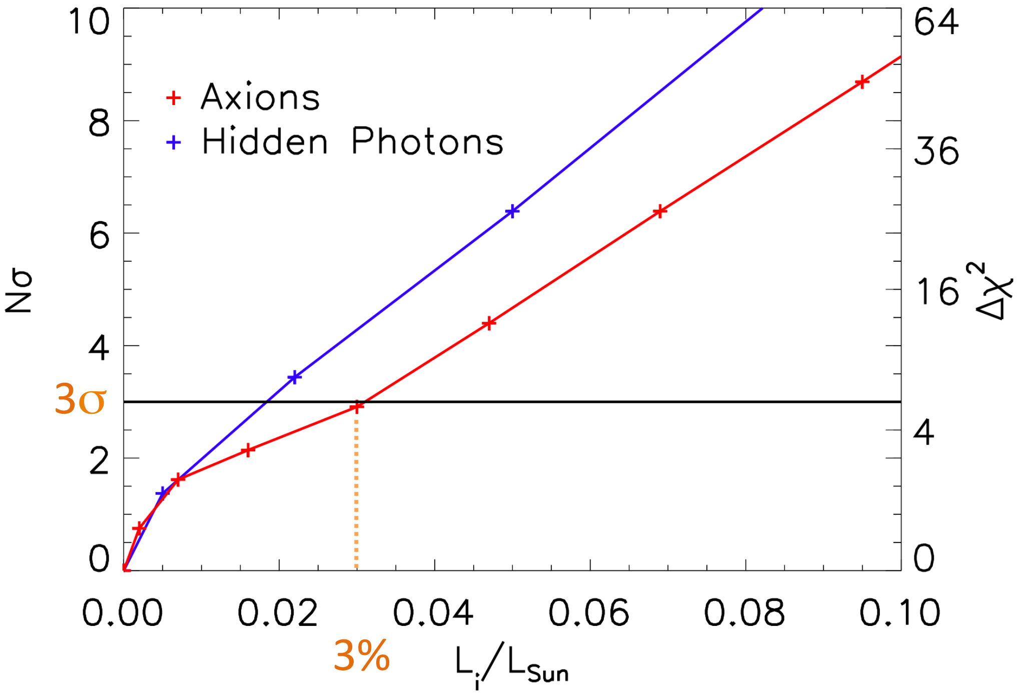
$$\frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.04 \left[{}^{+0.07}_{-0.08}\right] \left[{}^{+0.20}_{-0.18}\right] \qquad \frac{L_{\rm nuc}(\text{neutrino-inferred})}{L_\odot} = 1.01 \left[{}^{+0.09}_{-0.11}\right]$$

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% (1-σ)

Goal should be 1% - but pp neutrinos are very difficult

Model dependent example

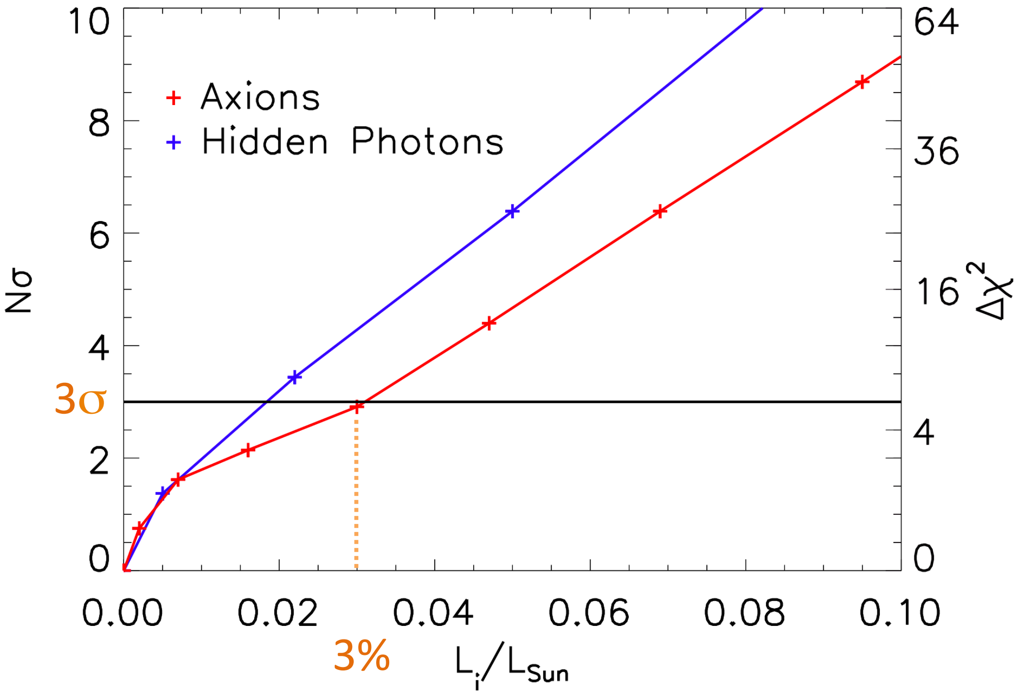


Vinyoles et al. 2015

Model dependent limits

Neutrinos (^8B, ^7Be)
Helioseismology

~ 1% L_x @ 1σ



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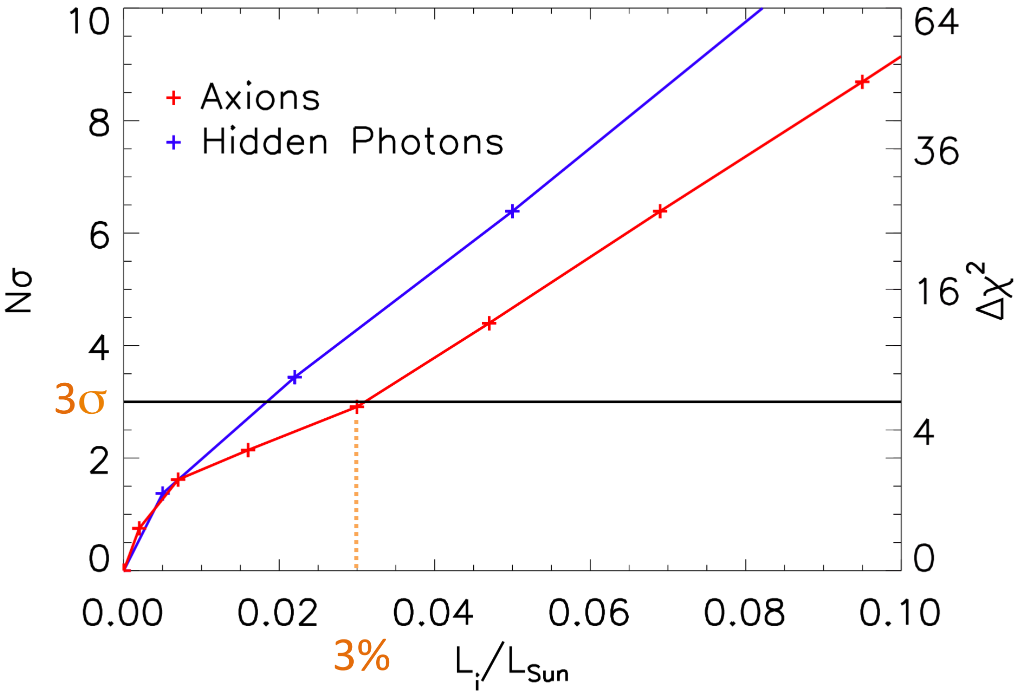
Other science cases (e.g. ADM)

$$L_x = \int \varepsilon_x dm = 0$$

Model dependent example



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High quality solar models needed

Standard Solar Models

Solar mass (constancy)

Age

Radius, luminosity

Surface composition

Eqs. structure and evolution

Equation of state

Nuclear reaction rates

Radiative opacities

Other physics (e.g. convection)

Standard Solar Models

Solar mass (constancy)

Age

Radius, luminosity

Surface composition ⟷ Radiative opacities

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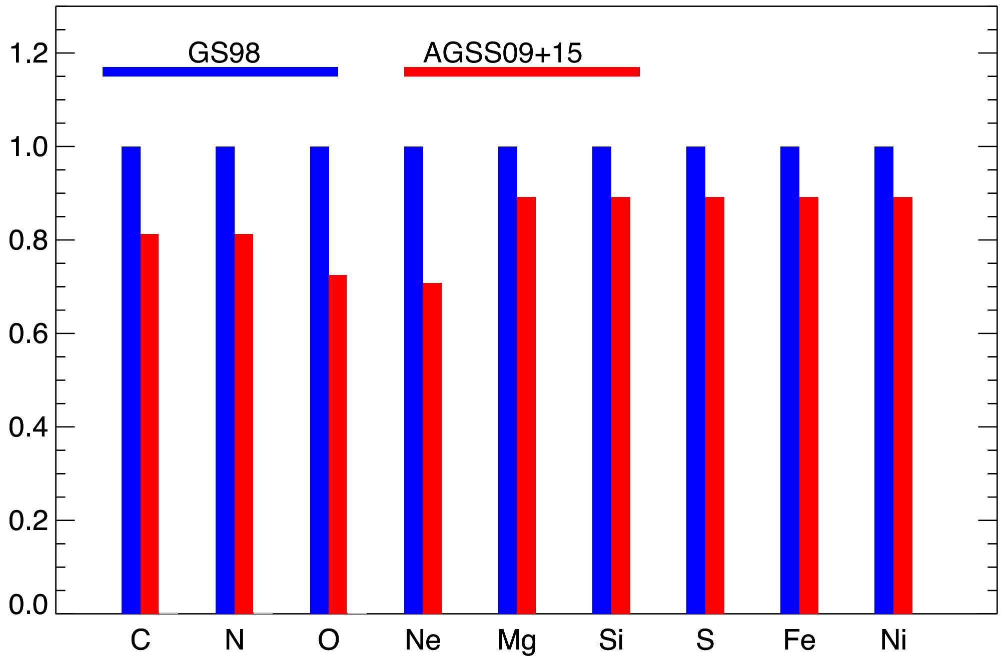
Helioseismology

solar modeling/abundances crisis after ↓ revision of solar abundances (Asplund et al., Caffau et al.)



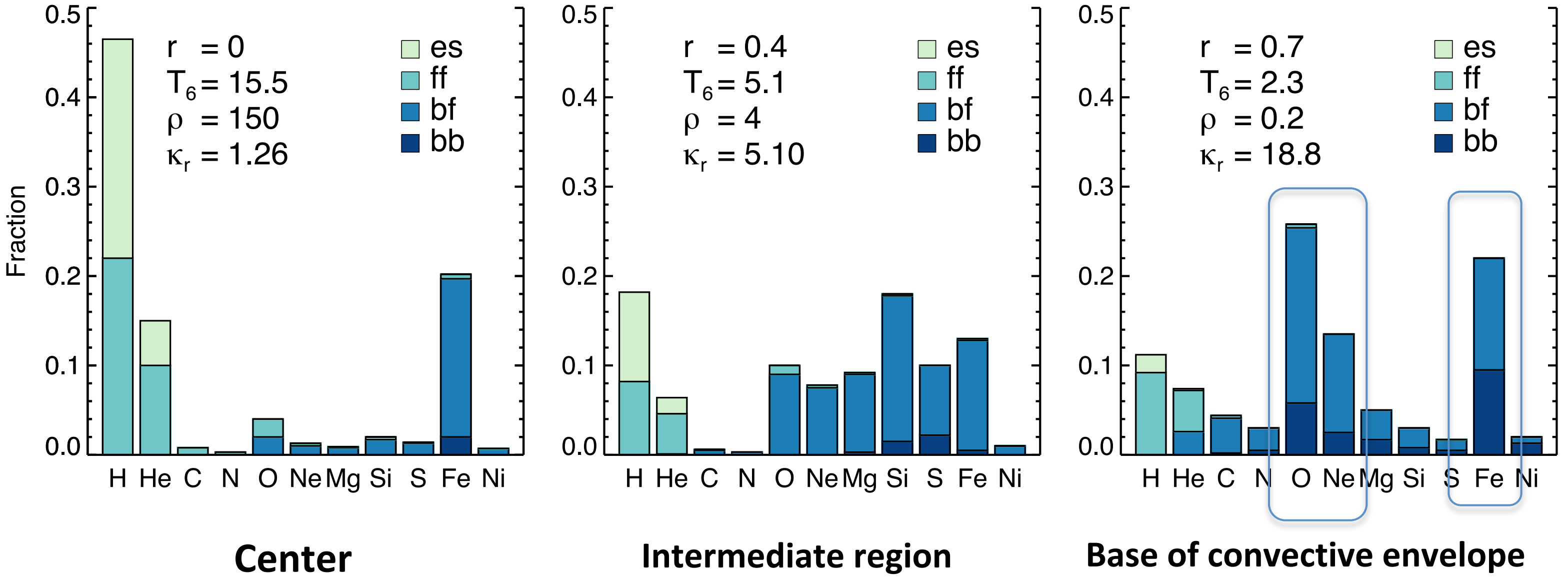
Large CNO reduction ~20-30%
Moderate refractories ~10%

~ half from 3D effects
~ half from atomic data, NLTE, blends

fundamental difference between 3D groups related to choice of lines (good atomic data, blends)

Metals & radiative opacities

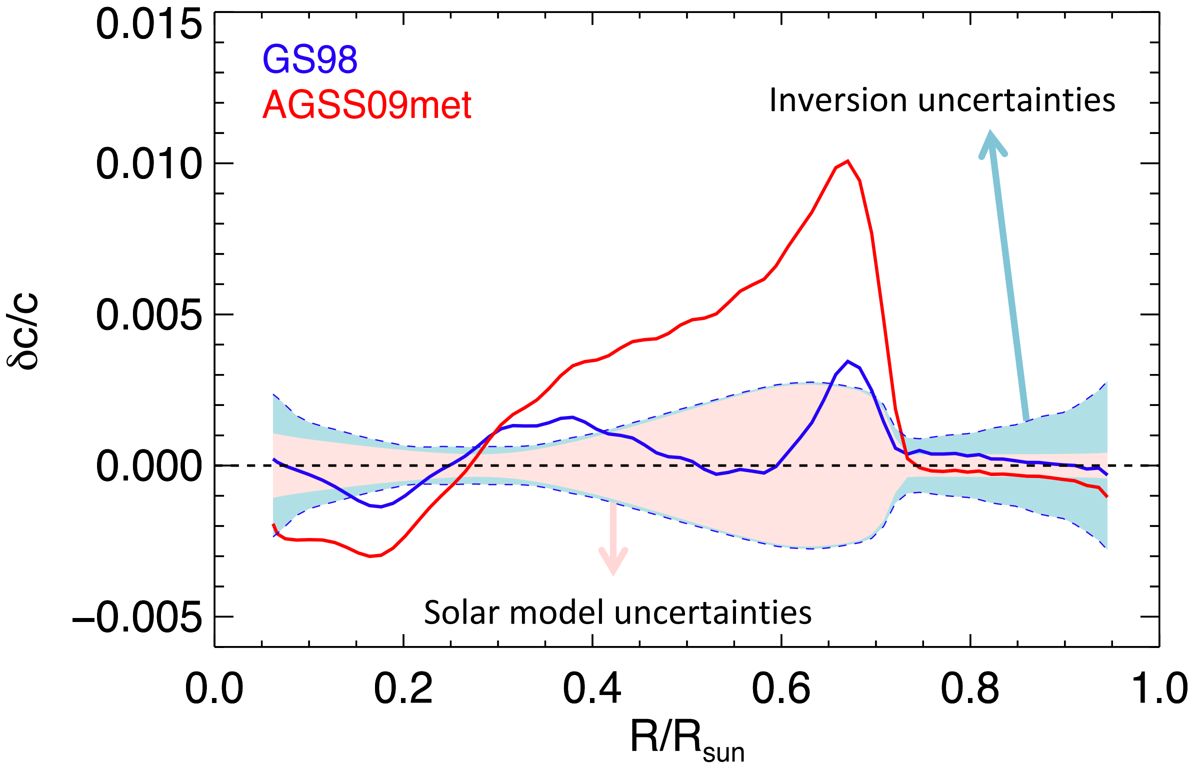
Impact of metals through opacity in radiative interior $\frac{\partial (T^4)}{\partial r} \propto \kappa$



Low metals ←→ low opacity

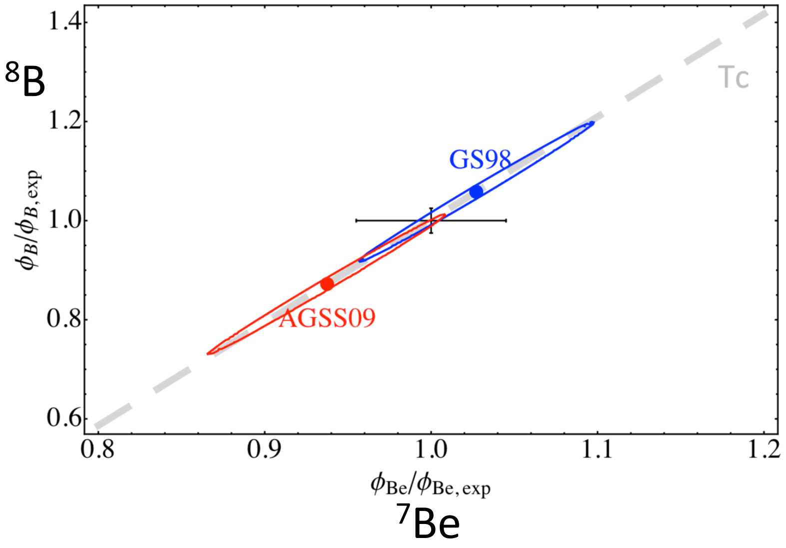
Solar models - helioseismology

Sound speed fractional difference from helioseismic inversions – **Temperature gradient**

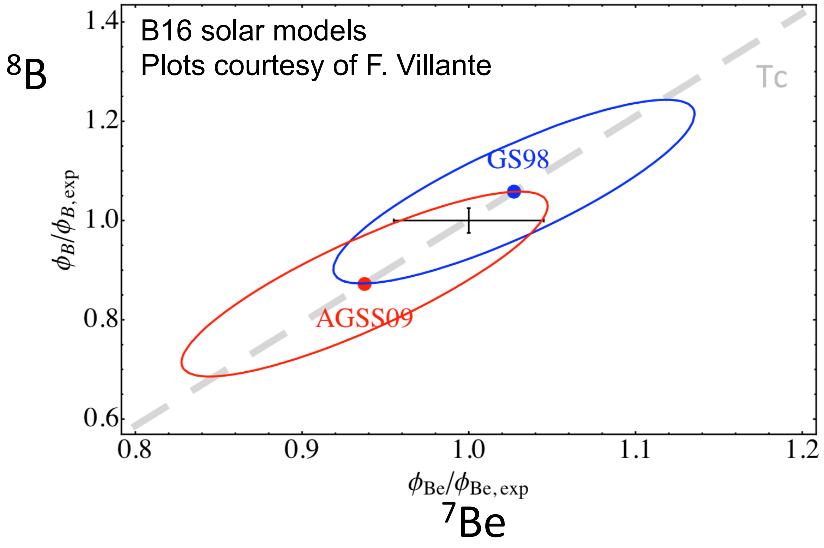


Solar composition: neutrinos

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



+ nuclear rate uncertainties



Environmental (temperature) uncertainties
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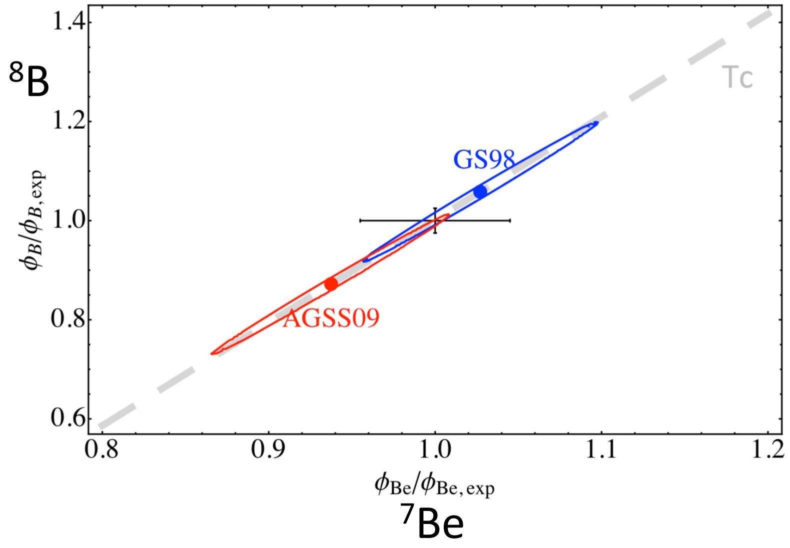
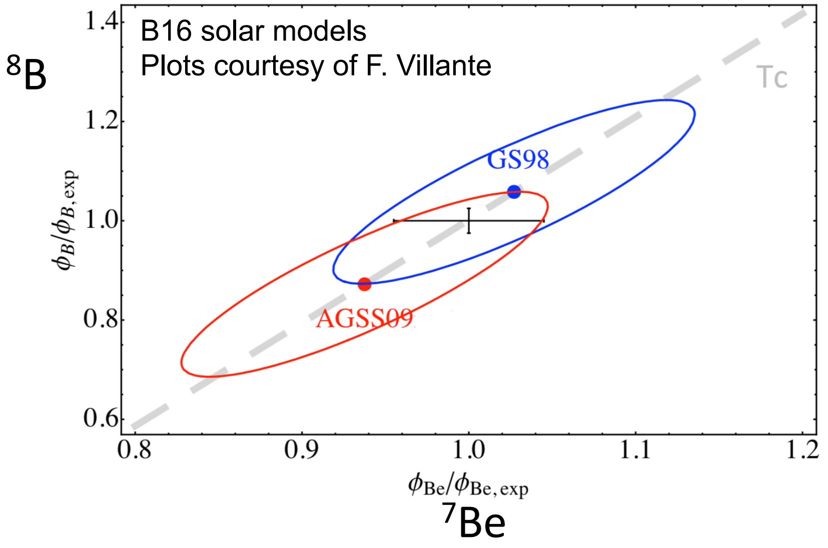
+ nuclear rate uncertainties





Composition → determines opacity

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

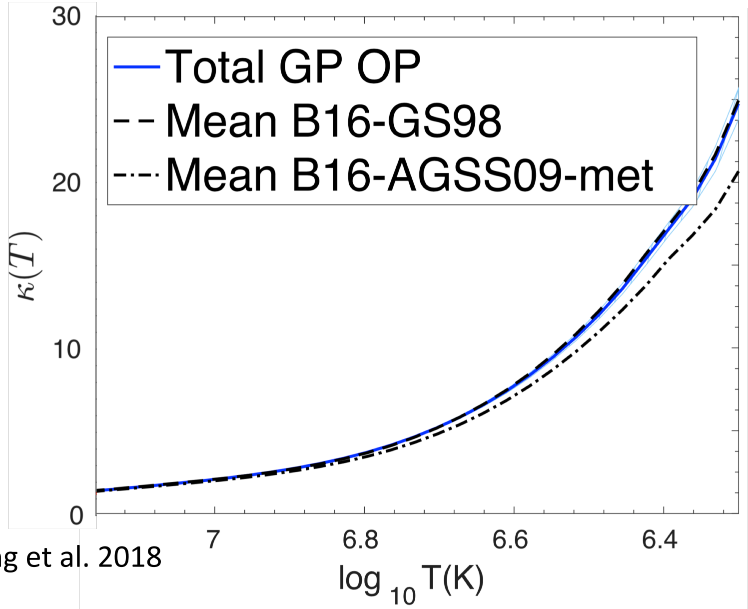
Even if experiment would rule out one model, it would be linked to effective opacity, not composition

Opacity profile from solar data

Non-parametric study including intrinsic uncertainty in opacity calculations

$$\kappa_{\mathrm{eff}} = \kappa_{\mathrm{ref}} + \underbrace{\delta\kappa_{\mathrm{comp}}} + \underbrace{\delta\kappa_{\mathrm{func}}}$$

$\delta\kappa_{\mathrm{func}}$ modeled with a Gaussian Process – different composition priors used



Song et al. 2018

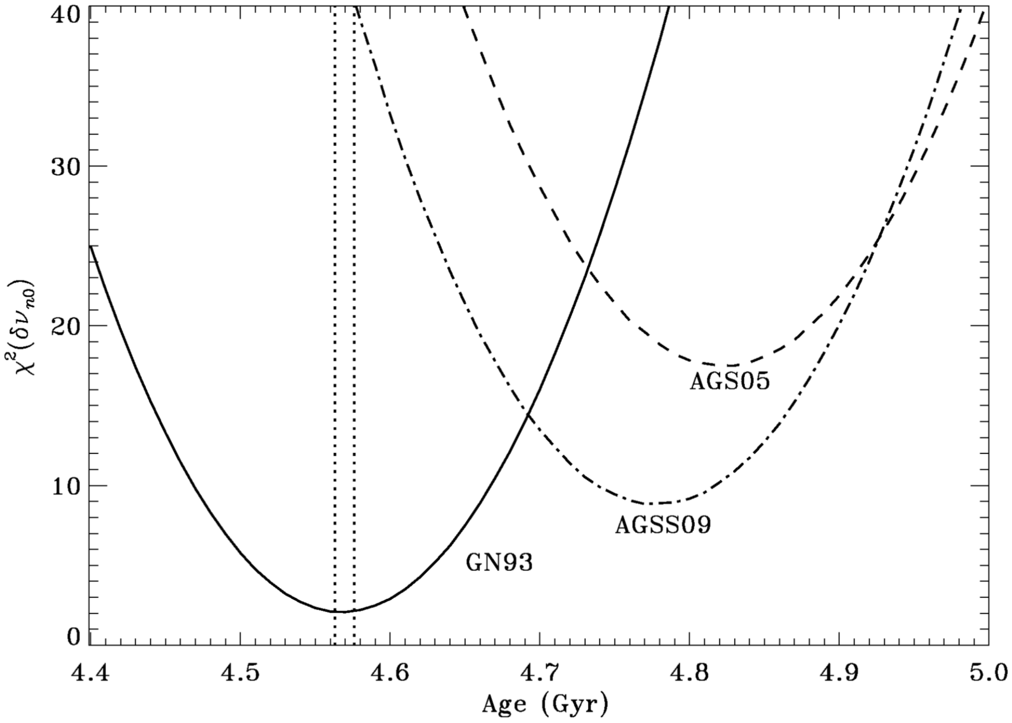
Difference between best fit and AGSS09 model:

few % in core
18% base of conv. envelope

Result similar to κ profile from GS98 SSM

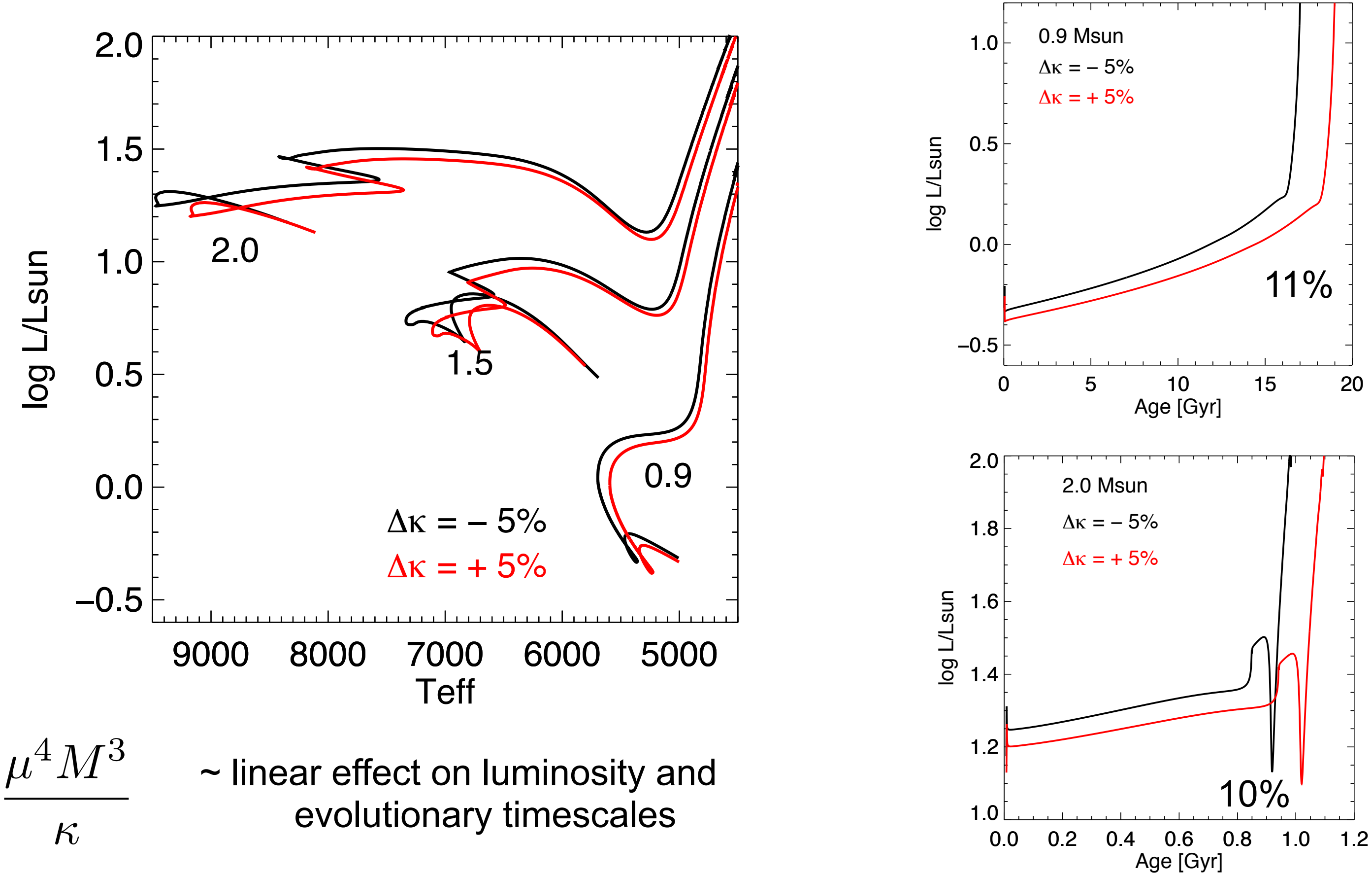
Should we care? An asteroseismic look at the Sun

Solar age from low degree oscillation modes (Sun as a star)



from J. Christensen-Dalsgaard

Opacity uncertainty: Impact on stellar modeling



$$L \propto \frac{\mu^4 M^3}{\kappa}$$

~ linear effect on luminosity and evolutionary timescales

Experimental result for Fe opacity in quasi solar conditions

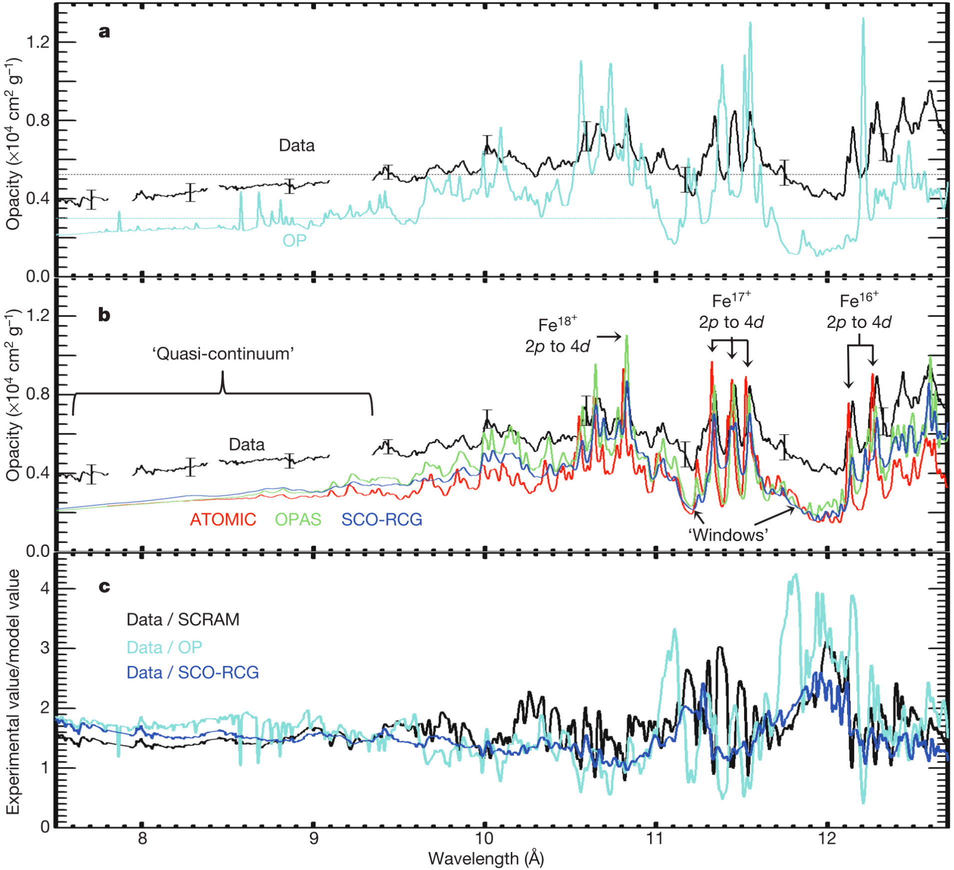
Fe-Rosseland mean +40%

Total Rosseland mean +7±4%

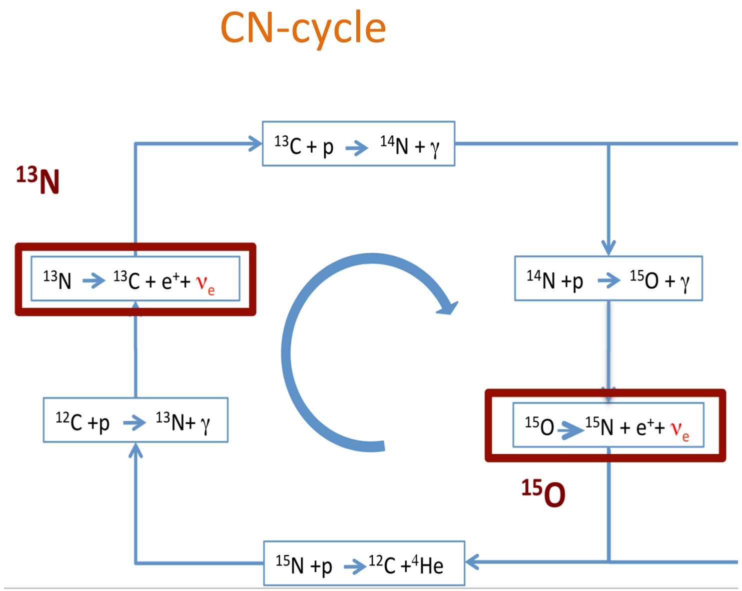
Strong discrepancy in the continuum with all available models not understood

Other elements in the queue (O most relevant)

Solar and stellar models rely on theoretical calculations – typical scatter few % < 18%



Breaking the degeneracy between opacity and composition



In stars dominated by CNO

Increase CN abundace → increase energy release
→ lower temperature
→ CNO energy release self-regulated
(negative heat capacity of stars)

In stars like the Sun, CNO << pp-chains

Increase CN abundace → increase CN energy release
→ total energy unchanged (pp)
→ **linear relation between CN abundances & CN energy/neutrinos**

Breaking the degeneracy between opacity and composition

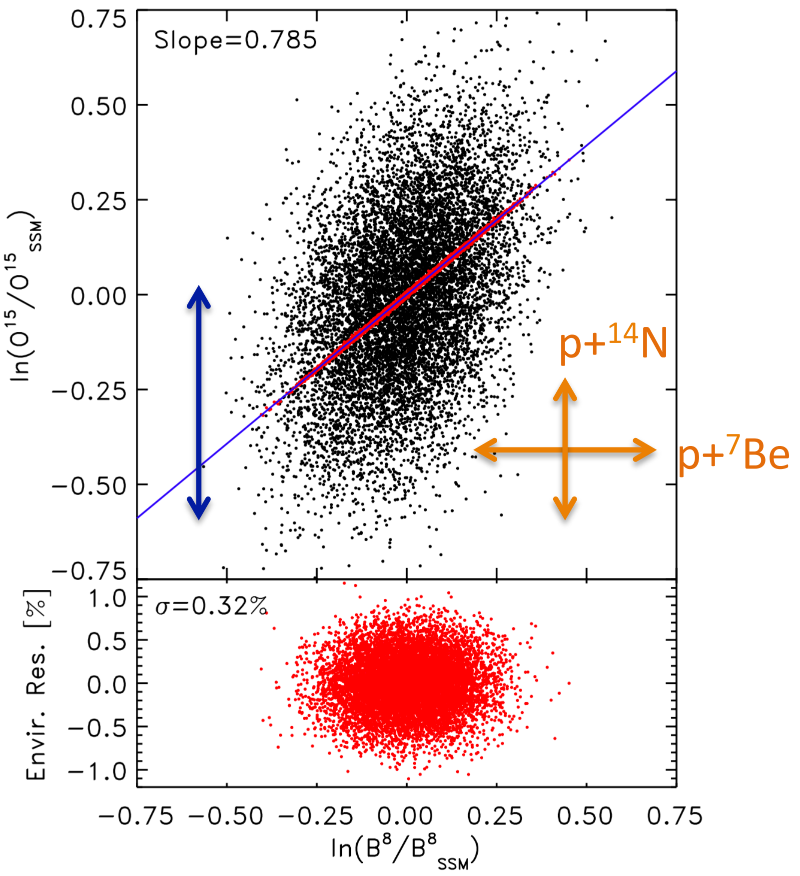
Rate of nuclear reaction depends on:
- environmental factors (temperature)
- nuclear rate
- composition of a given element(s)

Environmental: opacity, age, luminosity, composition (other than C & N)

Tight correlation between ^{15}O & ^{8}B

Nuclear rates: orthogonal variations

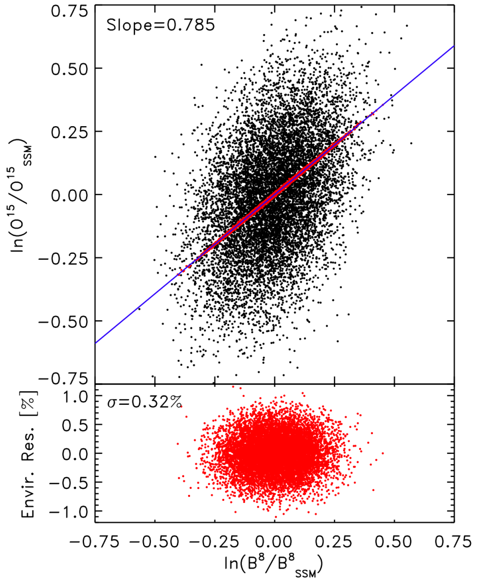
C+N core abundance



Breaking the degeneracy between opacity and composition

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

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



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

^{13}N/^{15}O neutrino measurement directly converted to core C+N abundance
10% + experimental uncertainty in ν measurement – comparable to spectroscopy

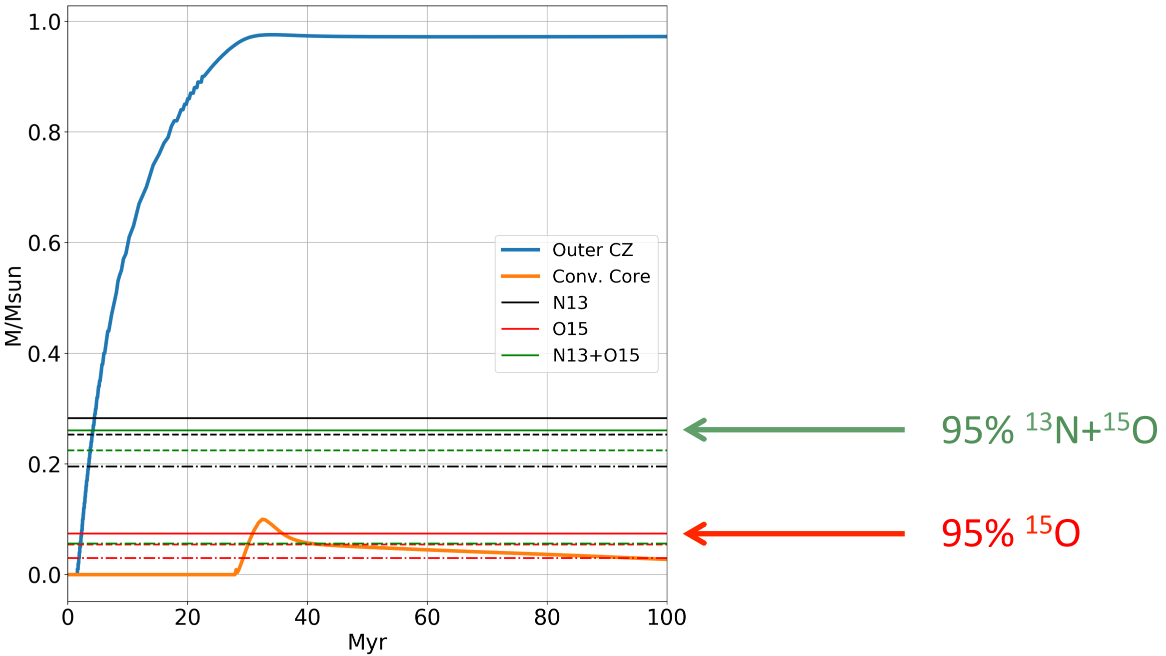
Potential applications of measurement of core abundances

- Break degeneracy between opacities and composition
- Surface / core ratios
  information on chemical mixing processes
- **Core composition – closest to primordial solar system composition**

Early Sun

Core isolated at ~3Myr

Info on primordial C+N



Conclusions

- Solar luminosity of nuclear origin – uncertainty not so good
- Accurate solar models required for particle physics applications
- Solar abundances – radiative opacities problem
  - Impact on solar models – interior structure, solar age (Sun as a star)
  - Impact on stellar models – uncertainty in opacity/abundance direct impact on properties
- Composition – opacity degeneracy: a Temperature problem
- CN neutrinos excellent possibility
  - Solar core composition (10% experimental error → 15% uncertainty in composition)
  - Tests of chemical mixing in the Sun
  - Primordial composition of the protosolar nebula (solar system)

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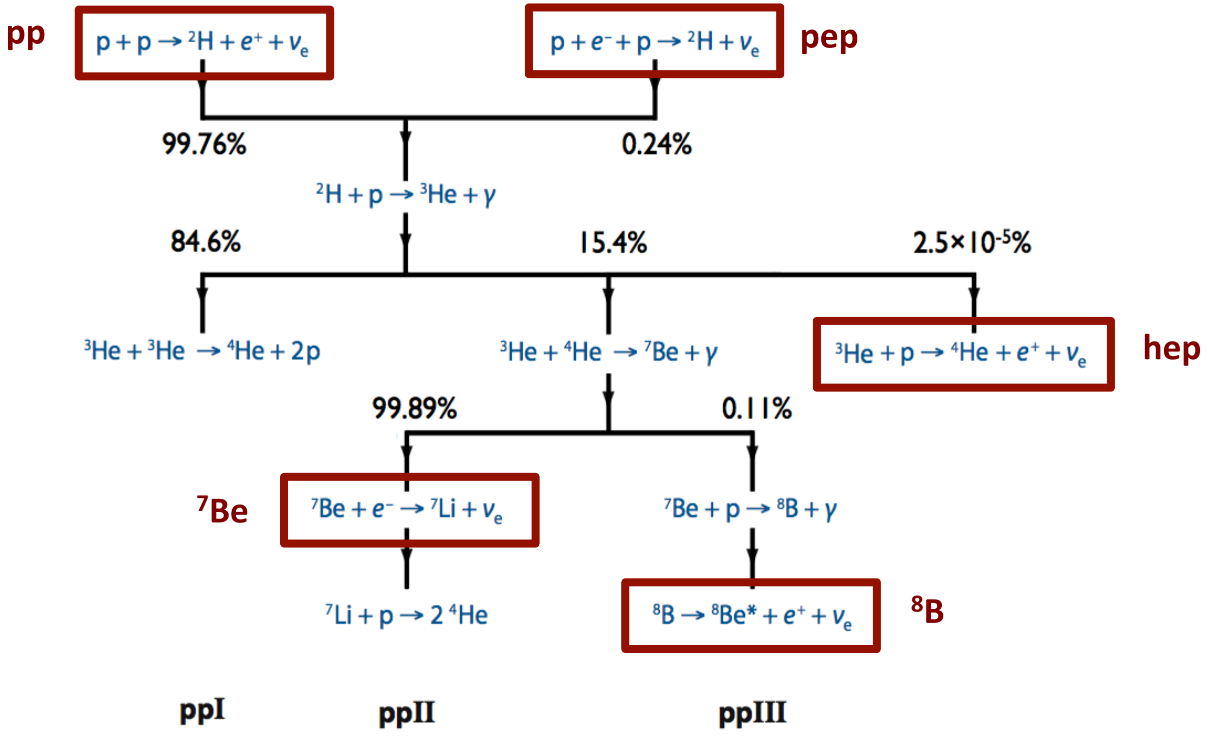
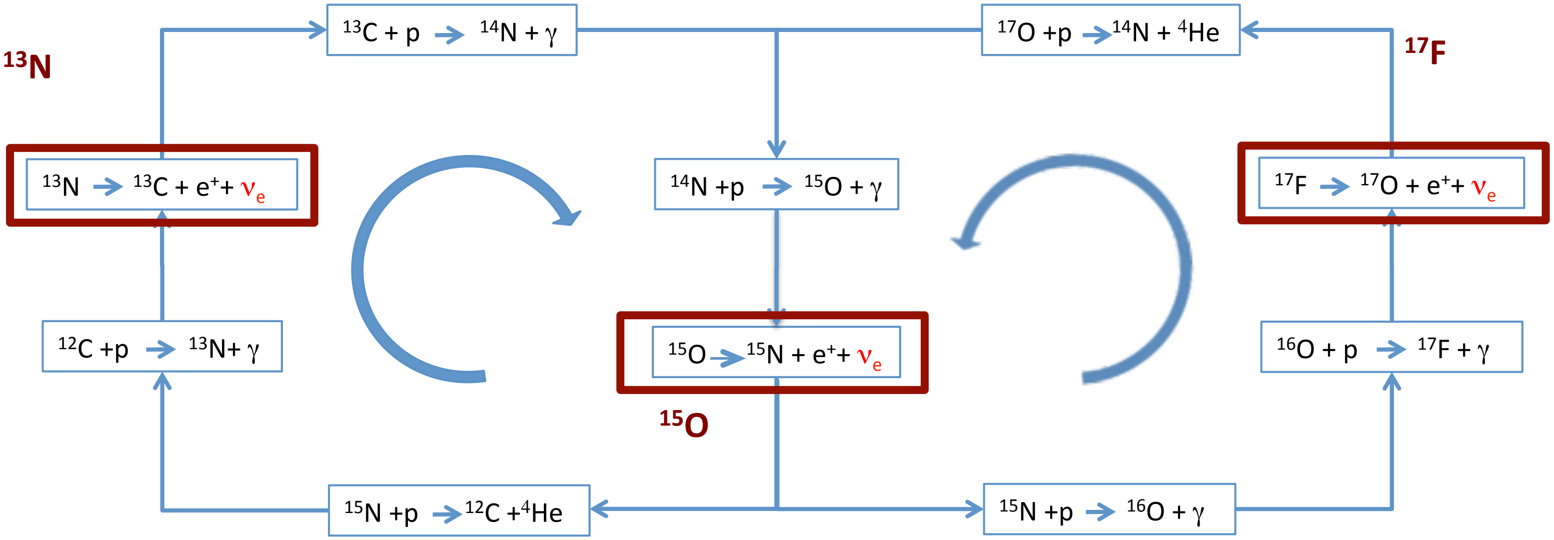
Extra slides

Solar neutrinos from pp-chains



Solar neutrinos from CNO-cycle

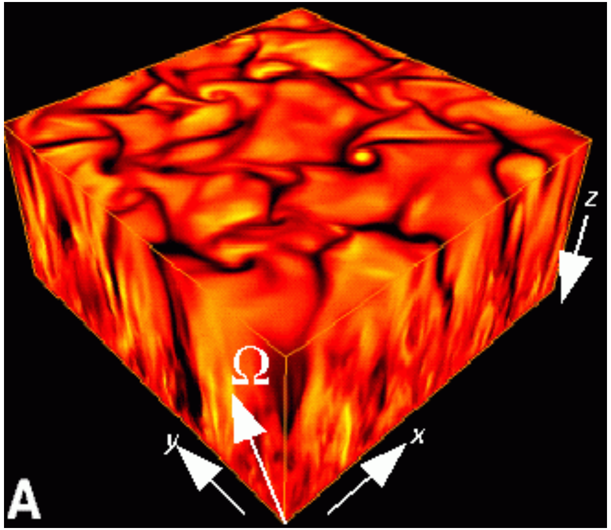


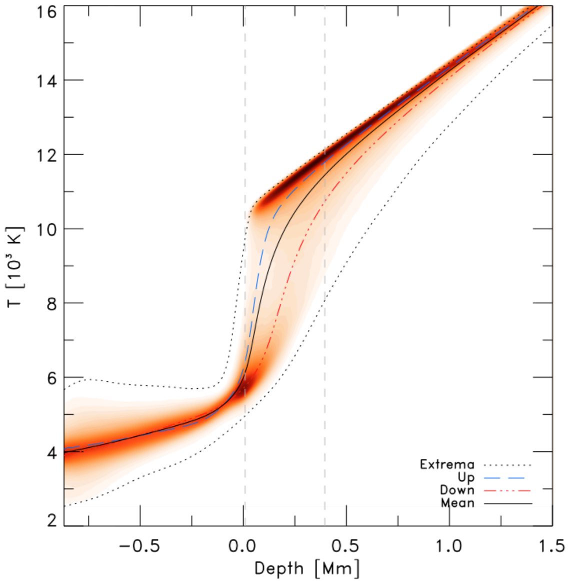
Helioseismology

solar modeling/abundances crisis after ↓ revision of solar abundances (Asplund et al., Caffau et al.)

change of paradigm: 1D → 3D model atmospheres

NLTE treatment of line formation





Solar models – constraints

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 – $(Z/X)_\odot$	**0.024 (GS98 – 1D) 0.018 (AGSS09 – 3D)**

3 free parameters: α_{MLT} – Z_{ini} – Y_{ini}

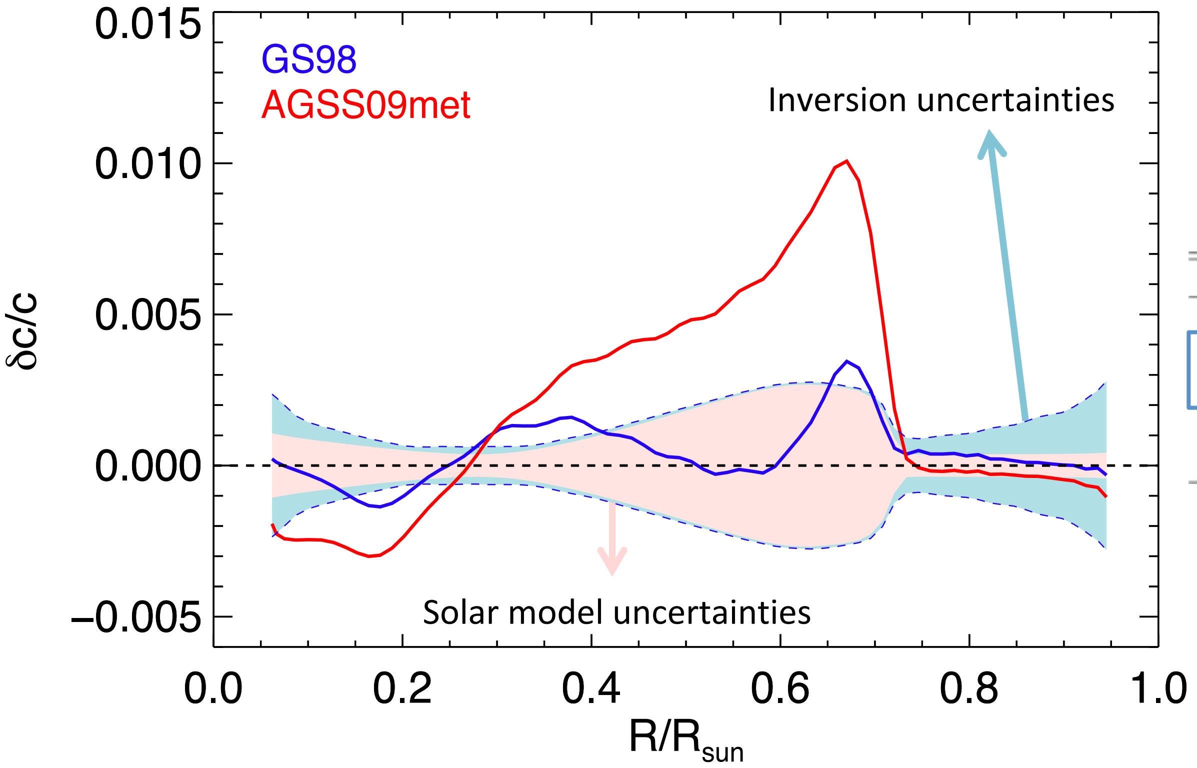
$\alpha_{MLT} \leftrightarrow R_\odot$

$Z_{ini} \leftrightarrow (Z/X)_\odot$

$Z_{ini}, Y_{ini} \leftrightarrow L_\odot$

Solar models - helioseismology

Sound speed fractional difference from helioseismic inversions



More results from helioseismology

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

Convective envelope too shallow

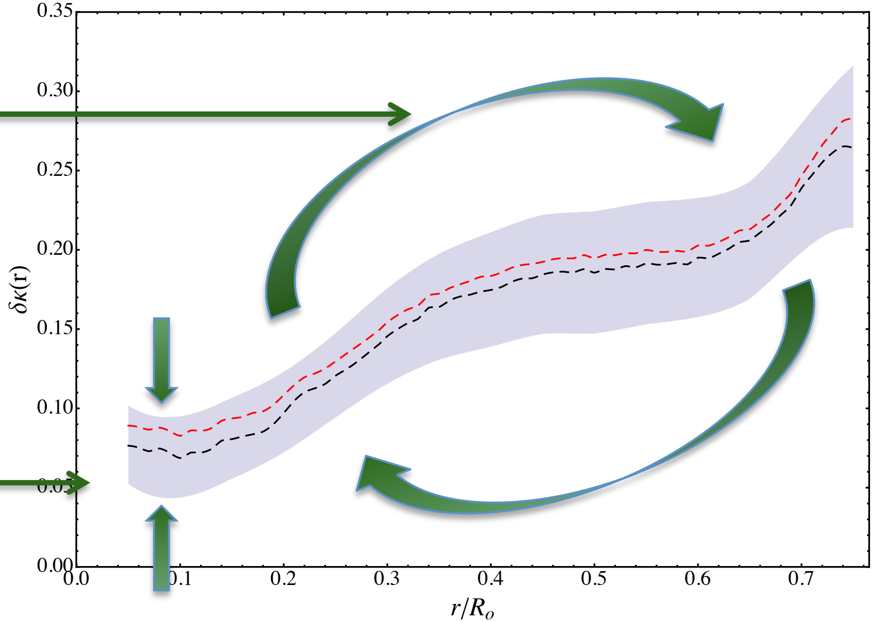
Surface helium too low

Opacity profile from solar data

Parametric study to determine opacity profile (Villante et al. 2014)
What is the opacity profile that best reproduces the seismic and neutrino data?

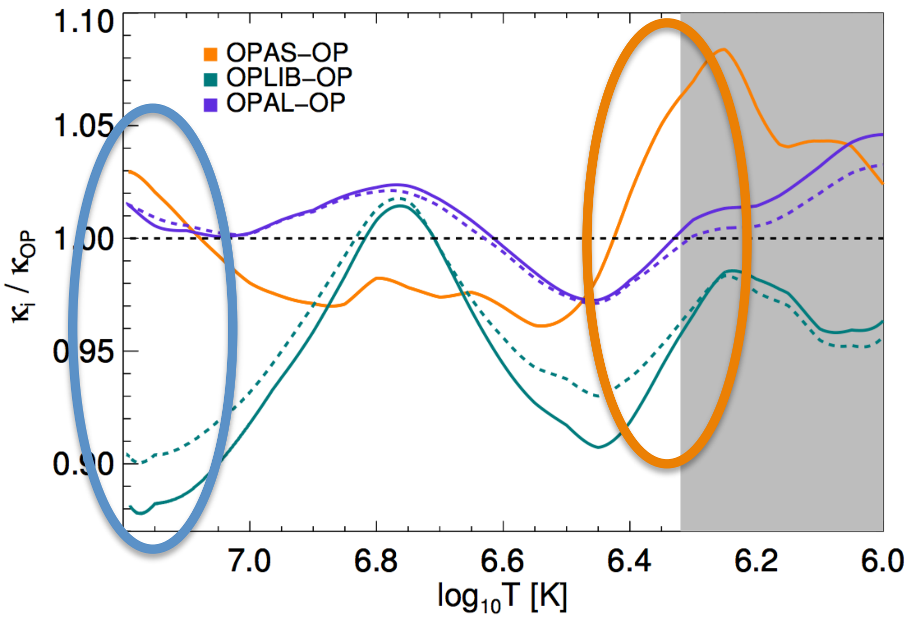
Helioseismology (sound speed) fixes the tilt

Solar neutrinos and Y_S the scaling (core temperature)



Current status of opacity calculations

Status of solar (stellar) opacities
Traditional calculations: OPAL (1996), Opacity Project (2005)
Renewed interest: OPAS (2012, 2015 – Blancard et al., Mundet et al.), Los Alamos (OPLIB; 2016 – Colgan et al.)



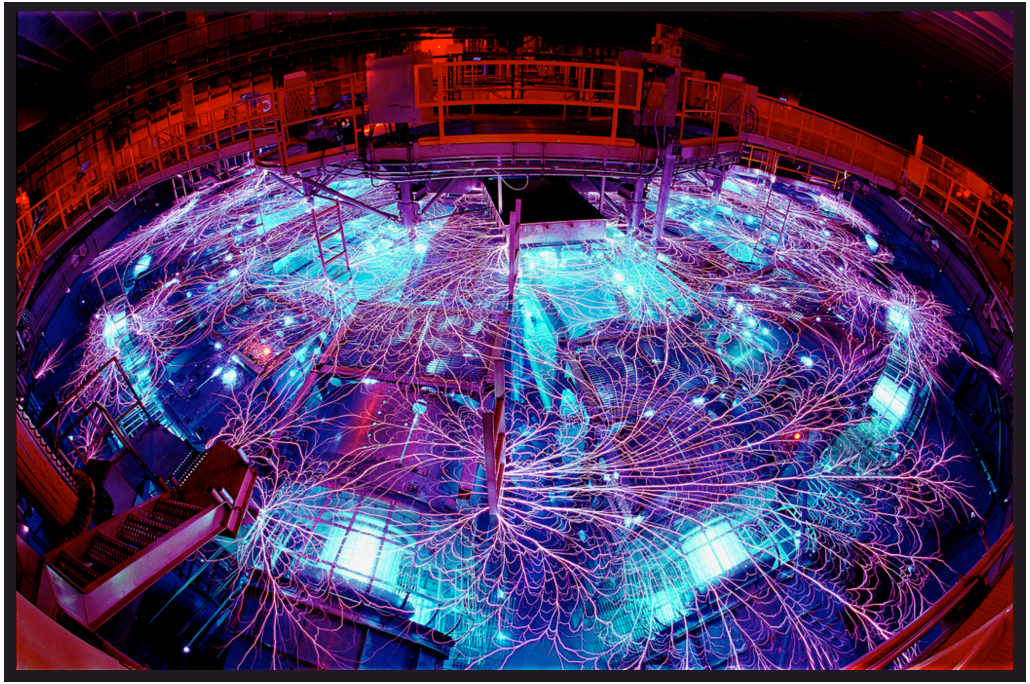
Fractional opacity differences
wrt Opacity Projects

Few % at base of convective envelope too low to compensate 15-18%

OPAS-OP-OPAL ok in center
OPLIB (Los Alamos) up to 15% lower
→ core temperature too low

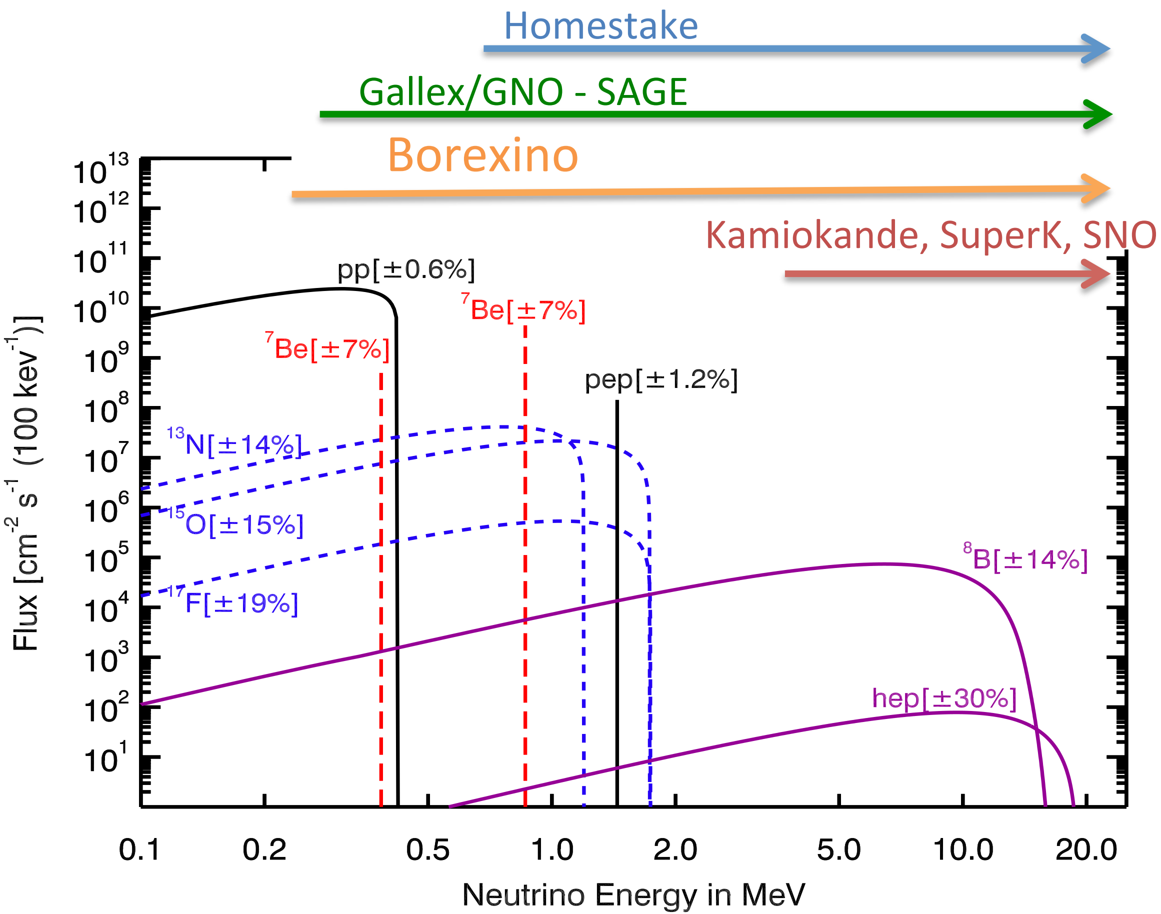
Opacities – Experimental result

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



Bailey et al. 2015

Solar neutrino spectrum



Solar composition and neutrinos

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

Change

^7Be → 10%

^8B → 20%

^{13}N, ^{15}O → 30-40%

pp: 10^{10} - ^{7}Be: 10^9 - pep, ^{13}N, ^{15}O: 10^8 – ^{8}B, ^{17}F: 10^6 – hep: 10^3 [$cm^{-2}s^{-1}$]

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

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