Curing the Sun, *or*: (not so) sunny prospects for dark matter

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The Standard Solar Model

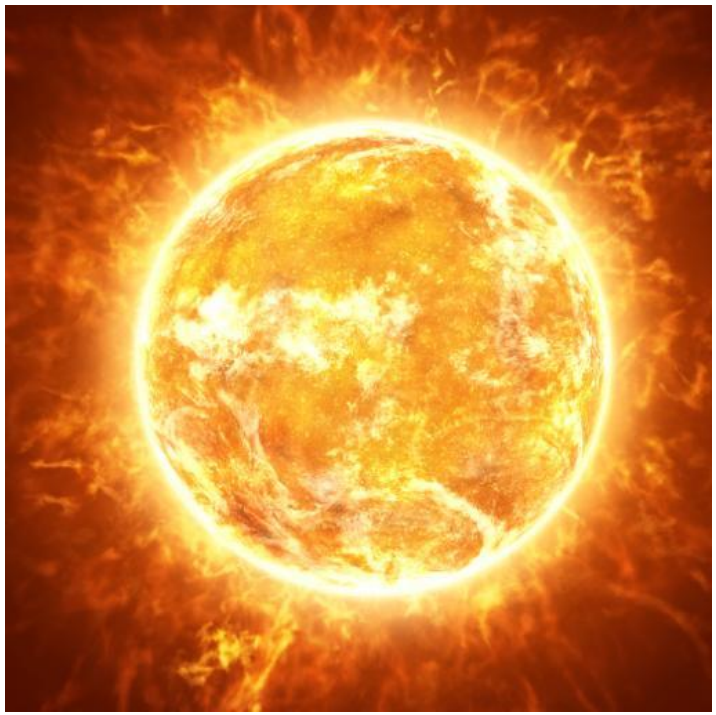
$$
\begin{aligned}
\frac{\partial m}{\partial r} &= 4\pi r^2 \rho \quad \text{[Mass conservation]}\,, \\
\frac{\partial P}{\partial r} &= -\frac{GM_r}{r^2}\rho \quad \text{[Hydrostatic equilibrium]}\,, \\
\frac{\partial l}{\partial r} &= 4\pi r^2 \epsilon(\rho, T, X_i) \quad \text{[Energy conservation]}\,, \\
\frac{\partial T}{\partial r} &= -\frac{GmT\rho}{r^2 P}\nabla \quad \text{[Thermodynamic equilibrium]}\,, \\
P &= P(\rho, T, X_i) \quad \text{[Equation of state]}\,,
\end{aligned}
$$

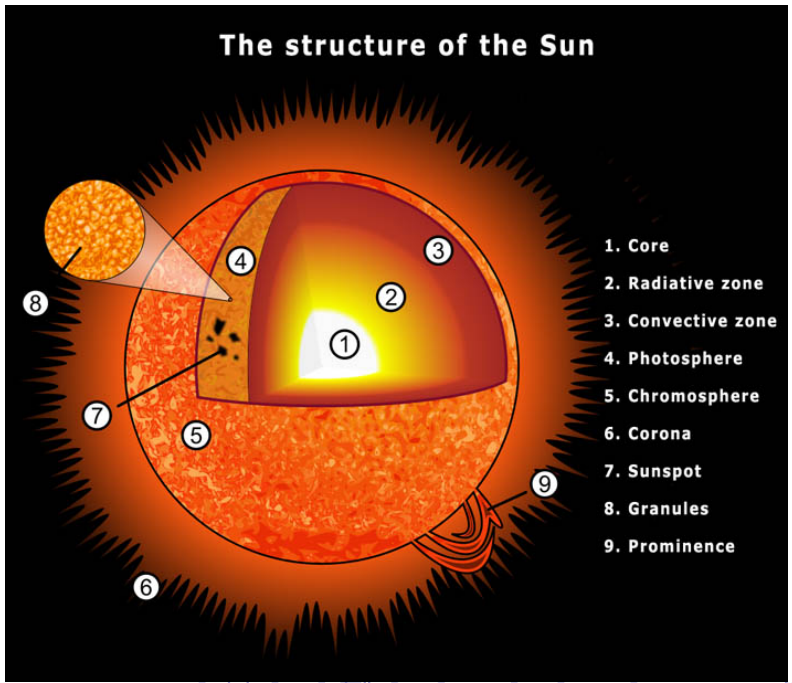
where

$$
\nabla_{\text{rad}} \equiv \frac{3}{16\pi acG}\frac{\kappa(\rho, T, X_i) l P}{m T^4} \quad , \quad \nabla_{\text{ad}} \simeq 0.4
$$

SSM inputs

- Four structure equations + EoS
- Boundary conditions: match luminosity $L_\odot$ and radius $r_\odot$ at age of the Sun $t_\odot$
- Two free parameters to "fit" observed Sun: initial Helium abundance Y_{ini} and mixing length parameter (used to model convection)
- *Key input*: elemental composition of the Sun



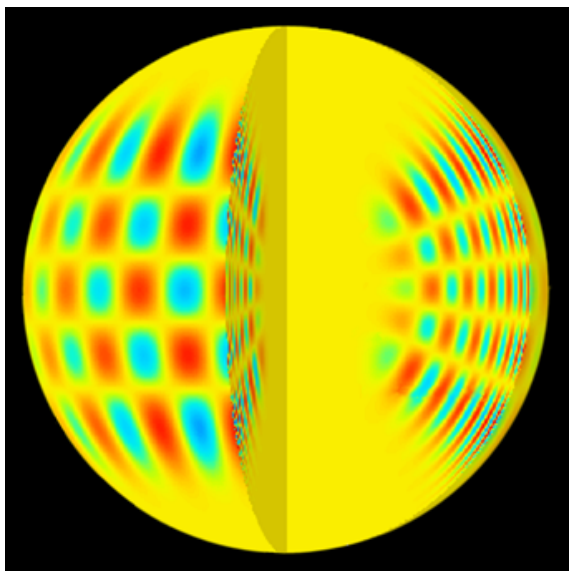


SSM outputs: helioseismology observables

- Sound speed $u(r)$
- Surface Helium fraction Y_s
- Convective zone boundary (CZB) R_b, occurs where $\nabla_{\text{rad}} = \nabla_{\text{ad}}$
- Neutrino fluxes: Φ_{pp}, Φ_{Be}, Φ_B, Φ_{CNO}

Helioseismology:

- Studies propagation of acoustic p-waves
- Modes defined by three wavenumbers: ω_{nlm}. Frequency splitting: $\delta\omega_{nlm} = \omega_{nlm} - \omega_{nl}$
- Inversion techniques infer sound speed and differential rotation from oscillation data



What's the metallicity of the Sun

Composition of the Sun: $\simeq 75\%$ Hydrogen, $\simeq 24\%$ Helium, $\lesssim$ (?)2% "metals" (C, N, O, Ne, Mg, Si, S, Fe).

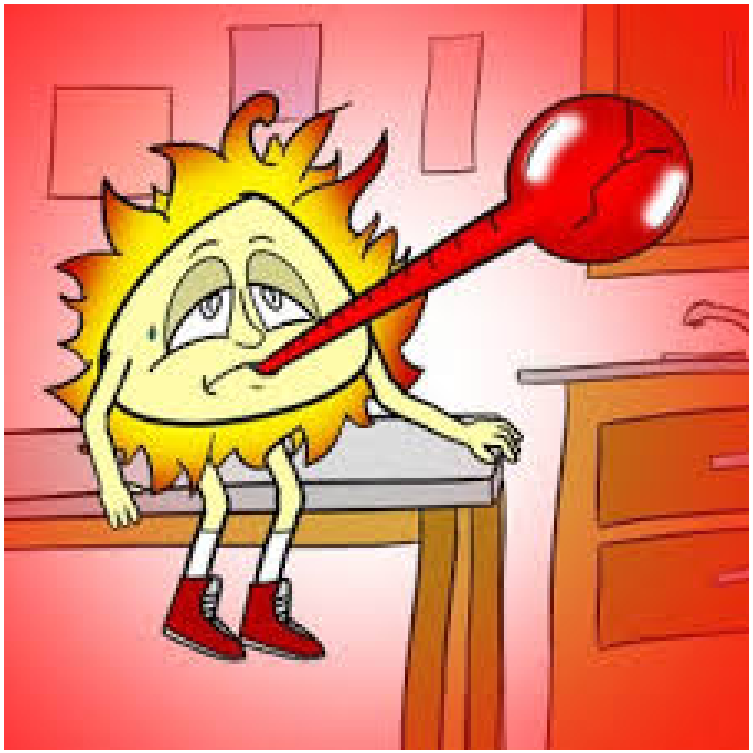
Metallicity is measured via photospheric spectroscopy and has undergone severe downward revision in recent years:

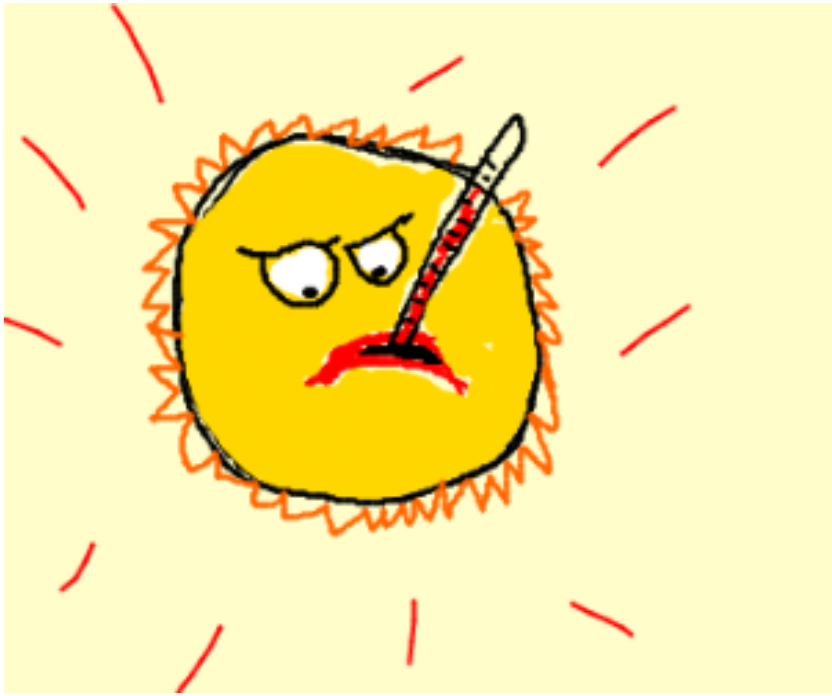
- AG89: Anders & Grevesse 1989, $Z_\odot = 0.0202$
- GS98: Grevesse & Sauval 1998, $Z_\odot = 0.0170$
- AGS05: Asplund, Grevesse & Sauval 2005, $Z_\odot = 0.0124$
- AGSS09: Asplund, Grevesse, Sauval & Scott, $Z_\odot = 0.0134$.
- C05BOLD: Caffau et al. 2010, $Z_\odot = 0.157$

AGSS09 is considered the state-of-the-art for spectroscopically determined metallicity (almost 2500 citations!)

The Solar composition problem

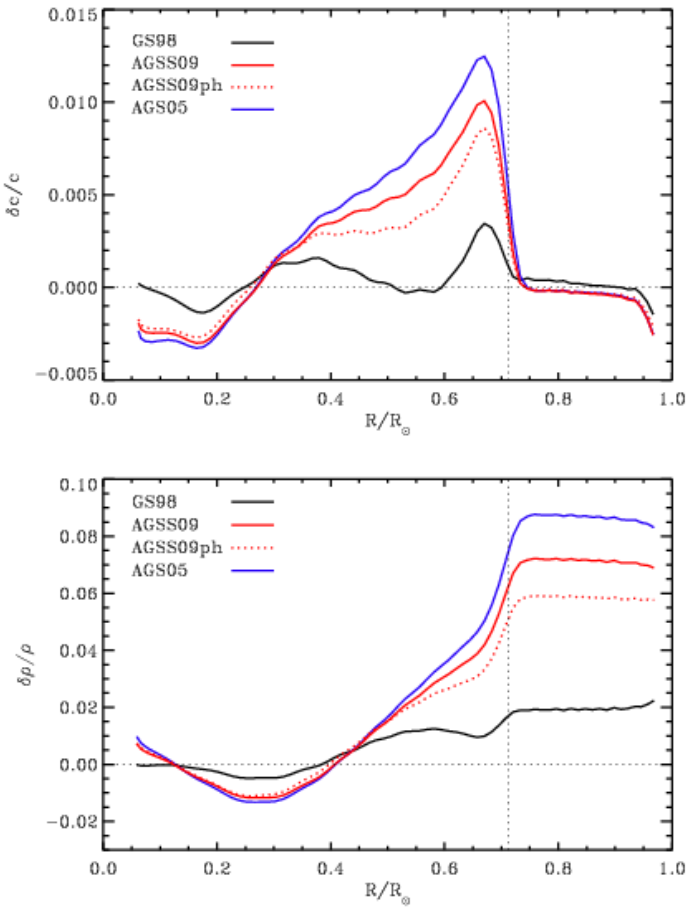
...but as a result the Sun is ill!





The Solar composition problem

- Sound speed is completely off, too low by $\sim 10\sigma$ at CZB
- Surface Helium abundance Y_s too low by $\sim 6\sigma$
- CZB R_b too high by $\sim 15\sigma$
- ^{7}Be and ^{8}B neutrino fluxes mildly too low



Situation reminiscent of "Solar neutrino problem" (1960s-2002), eventually solved by neutrino oscillations

Dark matter as a solution?

- Halo DM captured by Sun and accumulates in core
- DM scatters off nuclei, absorbs energy in core, deposits it further out
- $u(r)$ rises/decreases where temperature rises/decreases
- Energy deposition forces steeper temperature gradient near basis of convective region, decreases R_b
- Best-fit model: 3 GeV asymmetric DM particle, $\sigma_{\chi N} \propto q^2$, $\sigma_0 = 10^{-37}\ \mathrm{cm}^2$ @ $q = 40\ \mathrm{MeV}$ Vincent, Scott, Serenelli, PRL 114 (2015) 081302
- Many DM papers written on this, has even been linked to 750 GeV excess Dev & Teresi, 1512.07243

...but can DM really fix the Sun?

No! Many problems:

- DM cools the core, reduces nuclear fusion rate. Sun has to respond in order to keep $L_\odot$ fixed, increases X (H fraction) and hence reduces Y (He fraction): goes in the opposite direction of what we need!
- Cooler core reduces already too low Φ_{Be} and Φ_{B}, below allowed values
- Need low mass DM, prone to evaporation
- Best-fit ADM-q^2 model ruled our by CRESST-II

...but perhaps the metallicity has not been measured correctly?

Has the metallicity been measured correctly?

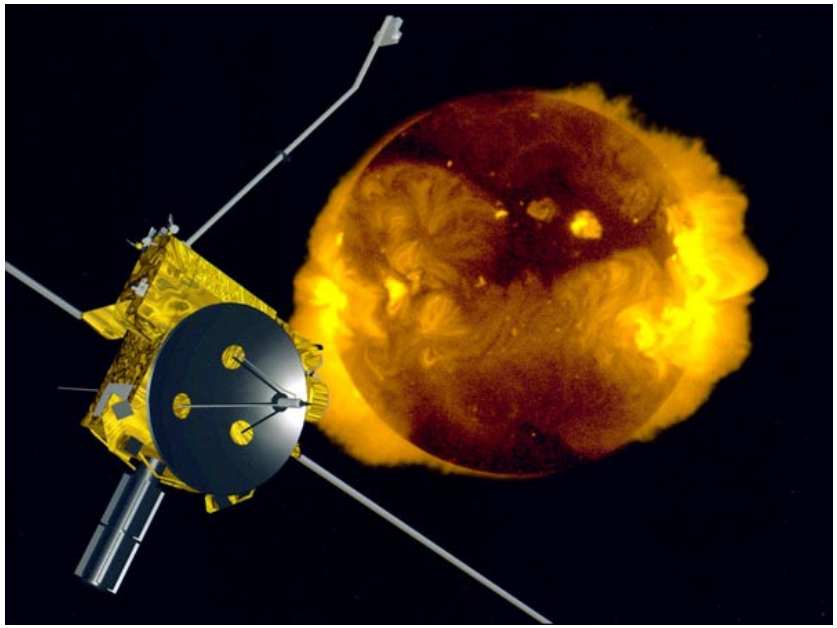
Photospheric spectroscopy widely used but has many technical difficulties:

- Sophisticated 3D hydrodynamical codes
- Need very accurate modelling of photosphere
- Need to model departures from LTE (difficult!)
- Requires knowing line transition probabilities very precisely
- Sophisticated inversion techniques
- Line blending not taken care of accurately

Many systematics at work: do we really understand what's going on?

In situ metallicity measurement

- Idea: measure $Z_\odot$ more directly, by collecting solar samples
- Two current-time sampling techniques: energetic particles or **solar wind**
- NASA *Ulysses* mission provided 19 years of measurement and sampling of solar wind at all latitudes



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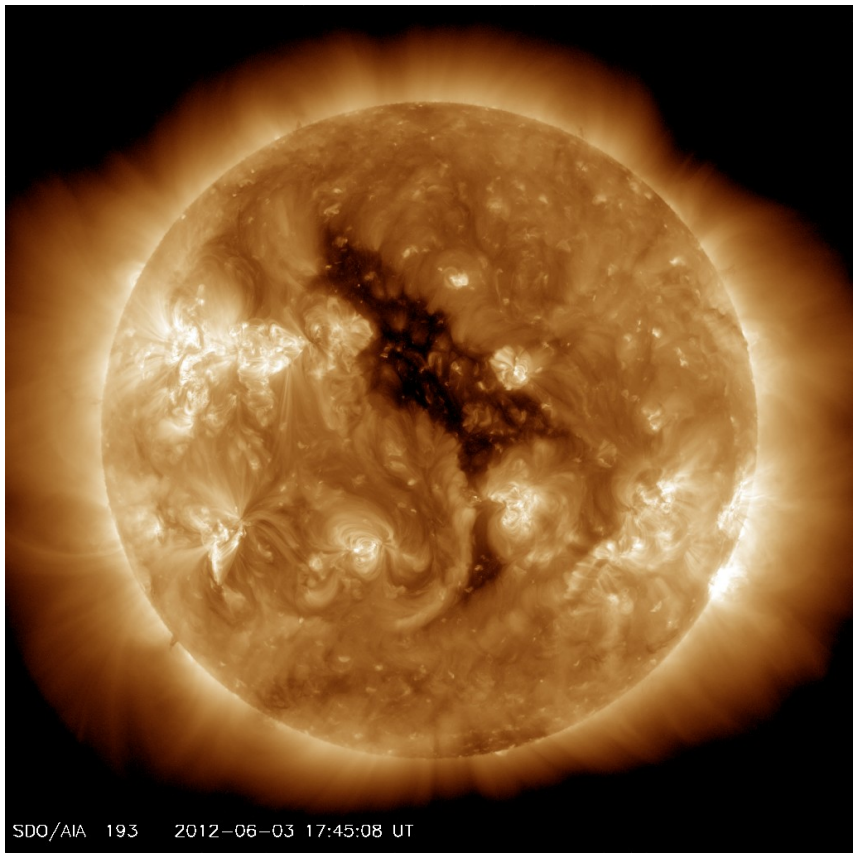
A possible problem...or a strength?

- Fractionation: abundances in solar wind samples can be depleted with respect to photospheric abundance
- Solution: fractionation essentially absent in solar wind from polar coronal holes (PCHs)

  Zurbuchen, Ann. Rev. Astron. Astrophys. 45, 297
- Strength: unaccounted fractionation systematically decreases the measured $Z_\odot$
- $Z_\odot$ measured from solar wind is a lower limit on the true metallicity of the Sun



Newly determined set of abundances

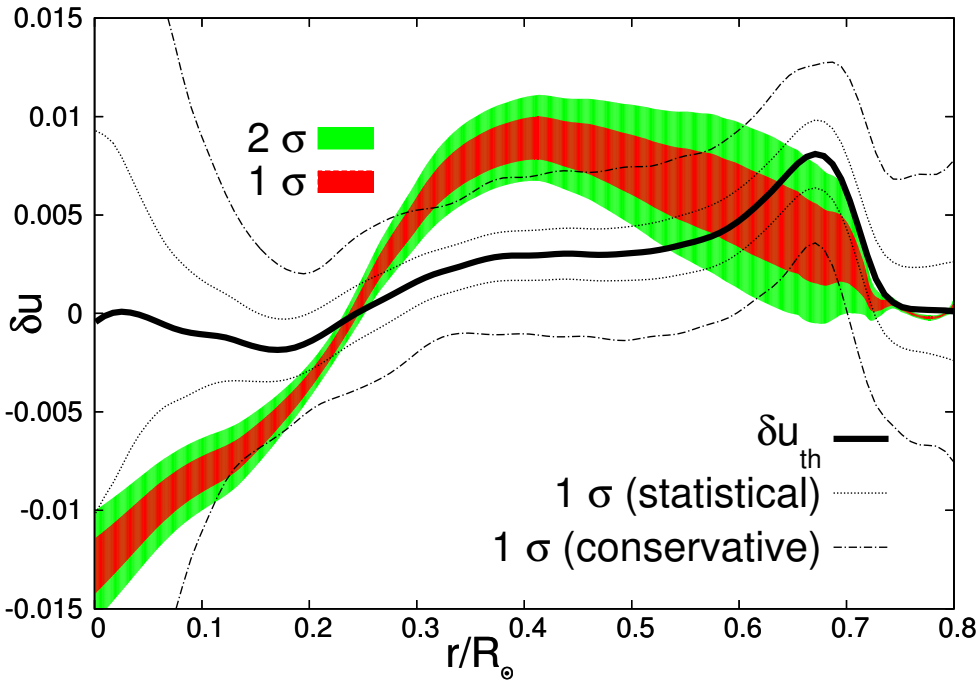
$$\mathbf{Z_\odot = 0.0196 \pm 0.0014}$$

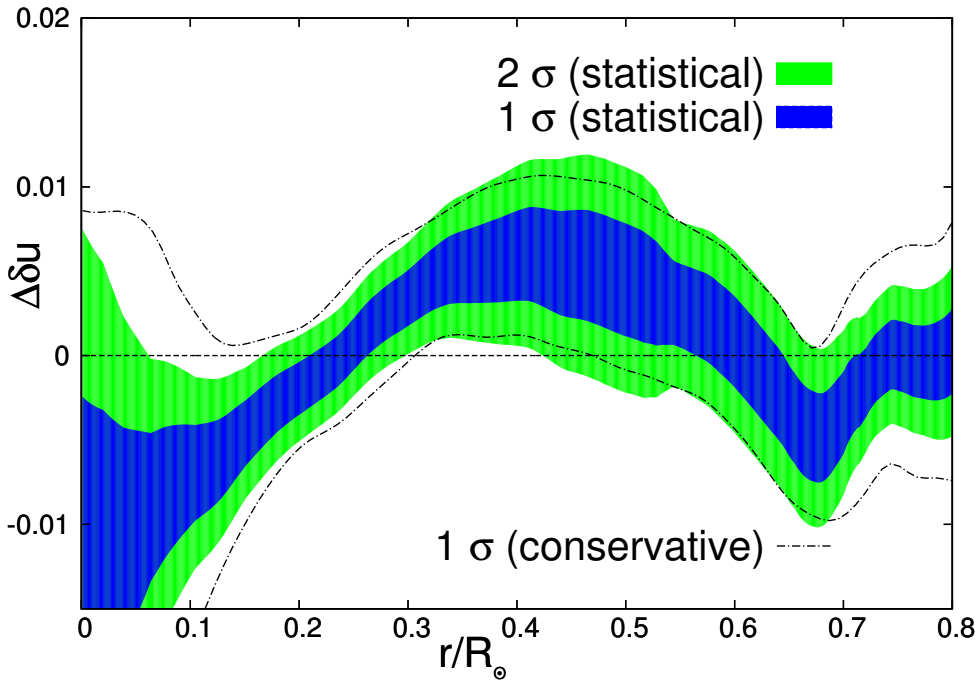
(c.f. with AGSS09 $Z_\odot = 0.0134$)

Element	A_{AGSS09}	A_{new}	δZ_i
C	8.43 ± 0.05	8.65 ± 0.08	0.66 ± 0.15
N	7.83 ± 0.05	8.97 ± 0.08	0.38 ± 0.08
O	8.76 ± 0.07	8.82 ± 0.11	0.35 ± 0.10
Ne	7.93 ± 0.10	7.79 ± 0.08	-0.28 ± 0.08
Mg	7.60 ± 0.04	7.85 ± 0.08	0.78 ± 0.16
Si	7.51 ± 0.03	7.82 ± 0.08	1.04 ± 0.21
S	7.12 ± 0.03	7.56 ± 0.08	1.75 ± 0.35
Fe	7.50 ± 0.04	7.73 ± 0.08	0.70 ± 0.15

$$\delta Z_i = 10^{(A_{\text{new}} - A_{\text{AGSS09}})} - 1$$

Response of helioseismological observables - sound speed





Response of helioseismological observables - Y_s, R_b and Φ_ν

Q	What we have	What we need	Compatibility
Y_s	0.0129 ± 0.0049	0.04 ± 0.02	1.3σ
R_b	-0.012 ± 0.005	-0.008 ± 0.004	0.6σ

^{7}Be and ^{8}B neutrino fluxes also increase by $\simeq 10\%$, restore excellent agreement with Borexino data

BOTTOM LINE: the previously badly discrepant SSM is now fixed!

A provocation: central values a bit in tension, this time putting DM in the Sun *should* go in the right direction

Conclusions

- Revised state-of-the-art spectroscopically detected AGSS09 abundances ($Z_\odot = 0.0134$)
- Determined new abundances *in situ*, using solar wind from polar coronal holes. New metallicity much higher ($Z_\odot = 0.0196$)
- Because of possible residual fractionation, this is a lower limit on the true metallicity $\rightarrow$ spectroscopy systematically underestimates $Z_\odot$?
- Definitive test of these abundances: CNO neutrinos flux measurements by SNO$^+$
- New set of metal abundances remarkably cure the Sun! :-)
- ...whereas Dark Matter does not... :-(
- ...or does it now? :-P

STAY TUNED! THANK YOU FOR YOUR ATTENTION!