From the initial to the present Sun

Known solar data

- Sun is very ordinary star of average mass and in H-MS since about 4.6 Gy.

Solar properties

Quantity	Value	Method
Mass	$(1.9891 \pm 0.0004) \times 10^{33}$ g	Kepler's 3rd law
Radius	$695,508 \pm 26$ km	angular diameter plus distance
Luminosity	$(3.846 \pm 0.01) \times 10^{33}$ erg s^{-1}	solar constant
Effective temp.	5779 ± 2 K	Stefan-Boltzmann law
Z/X	0.0245 ± 0.001	meteorites and solar spectrum
	0.0165	(new determination)
Age	4.57 ± 0.02 Gyr	radioactive decay in meteorites
Base ~~Depth~~ of conv. env.	$0.713 \pm 0.001\ R_\odot$	helioseismology
Env. helium content	0.246 ± 0.002	helioseismology

- One of the current hottest topics in solar physics: solar abundance Z.

From the initial to the present Sun

Known solar data

Element	GN93	AGS05	meteorites
H	12.00	12.00	8.25
C	8.55	8.39	7.40
N	7.97	7.78	6.25
O	8.87	8.66	8.39
Ne	8.08	7.84	-1.06
Na	6.33	6.17	6.27
Mg	7.58	7.53	7.53
Al	6.47	6.37	6.43
Si	7.55	7.51	7.51
S	7.21	7.14	7.16
Cl	5.50	5.50	5.23
Ar	6.52	6.18	-0.45
Ca	6.36	6.31	6.29
Ti	5.02	4.90	4.89
Cr	5.67	5.64	5.63
Mn	5.39	5.39	5.47
Fe	7.50	7.45	7.45
Ni	6.25	6.23	6.19
Z/X	0.0245	0.0165	

- One of the current hottest topics in solar physics: solar abundance Z.

From the initial to the present Sun

Known solar data

Asplund et al. (2009) solar composition ⟶ $Z_{sun} = 0.0134$

		Z_s	Z_s/X_s
revised:	Caffau et al. (2009)	0.0156 ± 0.0011	0.0213
	Houdek & Gough (2011)	0.0142 ± 0.0005	0.0186
	Asplund et al. (2009)	0.0134	0.0181
old:	Grevesse & Noels (1993)	0.0179	0.0244
	Grevesse & Sauval (1998)	0.0169	0.0231

- One of the current hottest topics in solar physics: solar abundance Z.

From the initial to the present Sun

Choosing the initial solar model

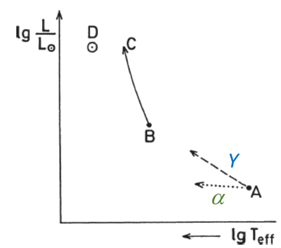
mixing-length parameter α

- With M, R, L, T_{eff} and "Z" known (measured) we have to assume values for Y and ℓ_m/H_p

2 free parameters

- Finding a solar model for given Z/X, $M_\odot$, $R_\odot$, $L_\odot$, $T_{eff,\odot}$ and age $t_\odot$:

start solving (numerically) stellar equations in complete equilibrium for trial values of Y and α,
evolve model until "given" solar age $t_\odot$,
repeat evolution run with new values for Y and α until model @$t_\odot$ matches $R_\odot$ and $L_\odot$,



i.e. until finding a ZAMS model B such that after $t_\odot$ (= model C) will match the observed Sun (D);

changing α leads to a (small) change of R (almost only);

changing Y changes μ and consequently $L \sim \mu^4$.

From the initial to the present Sun

Choosing the initial solar model

mixing-length parameter α

- With M, R, L, T_{eff} and "Z" known (measured) we have to assume values for Y and ℓ_m/H_p

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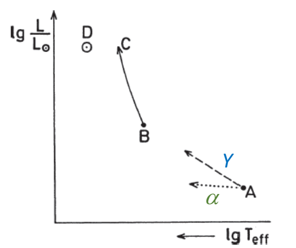


Partial derivatives of column quantities for a present ($t_\odot$) solar model

initial values @t=0

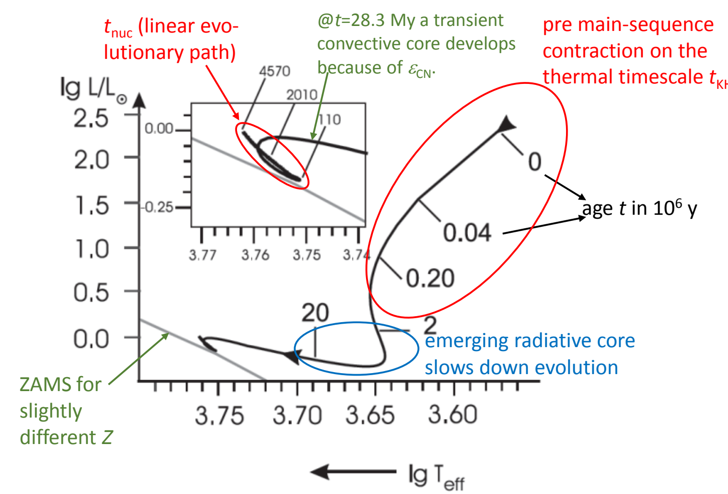
	ℓ_m/H_P	Y_i	Z_i
$L/L_\odot$	0.038	*8.515*	-38.60
$R/R_\odot$	*-0.129*	2.019	-7.05
$(Z/X)/(Z/X)_\odot$	0.043	0.523	*56.0*

From the initial to the present Sun

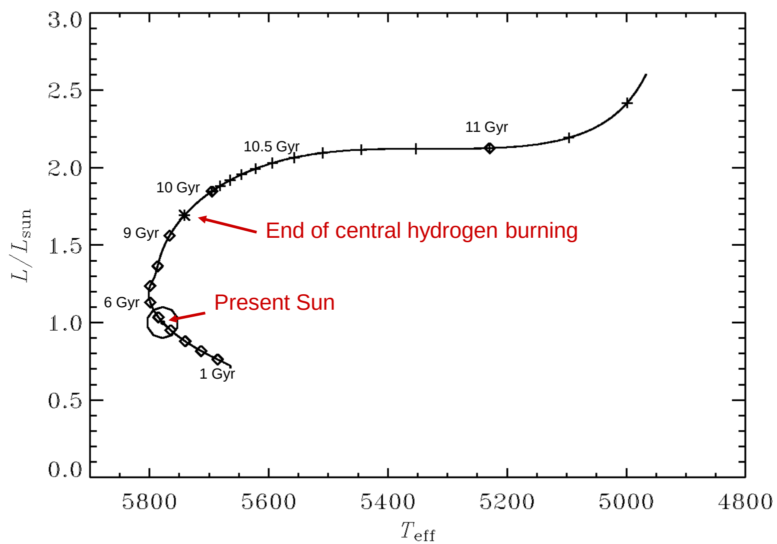
A standard solar model

Z/X=0.0245 (Grevesse & Noels 1993).

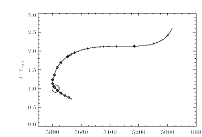
$R_\odot$, $L_\odot$ agree within 1 part of 10^4.



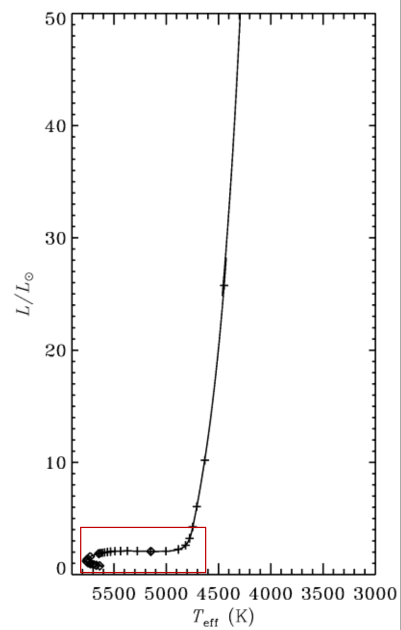
Solar evolution



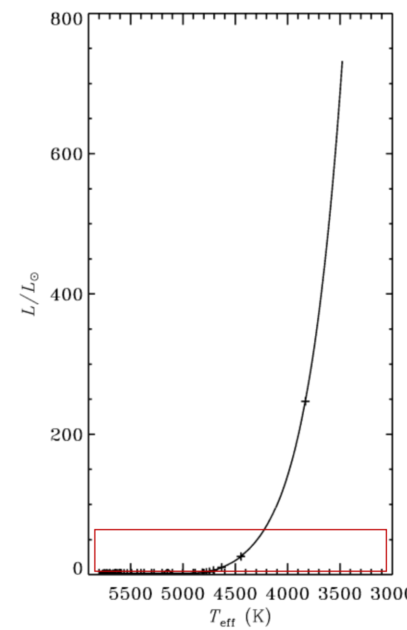
Solar evolution



Solar
evolution



Solar
evolution



From the initial to the present Sun

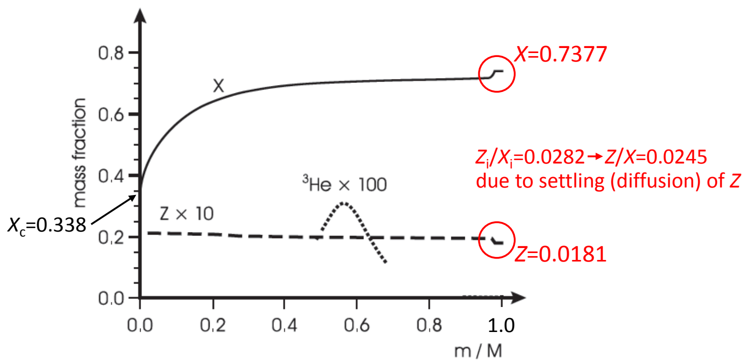
A standard solar model

Z/X=0.0245 (Grevesse & Noels 1993).

$X_i = 0.7058$, $Y_i = 0.2743$, and $Z_i = 0.0199$.

Z_i/X_i=0.0282.

Element abundance in a solar model



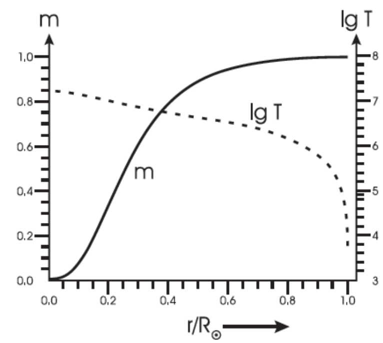
From the initial to the present Sun

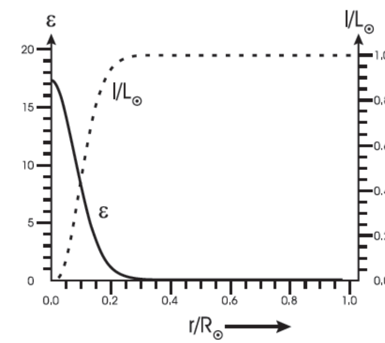
A standard solar model

>80% of M within 40% of R

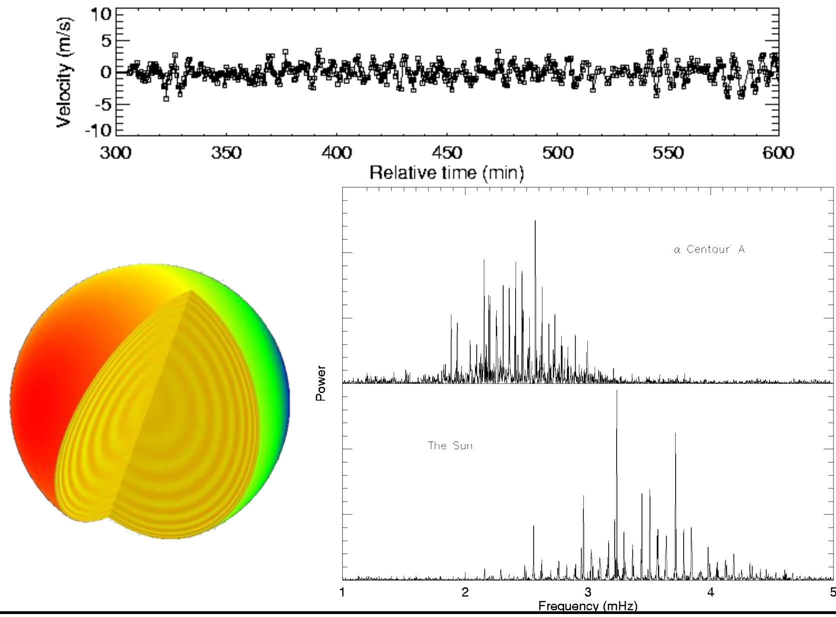
T rises by > 10^2 within outer 20% of R

>90% of L is reached within inner 20% of R



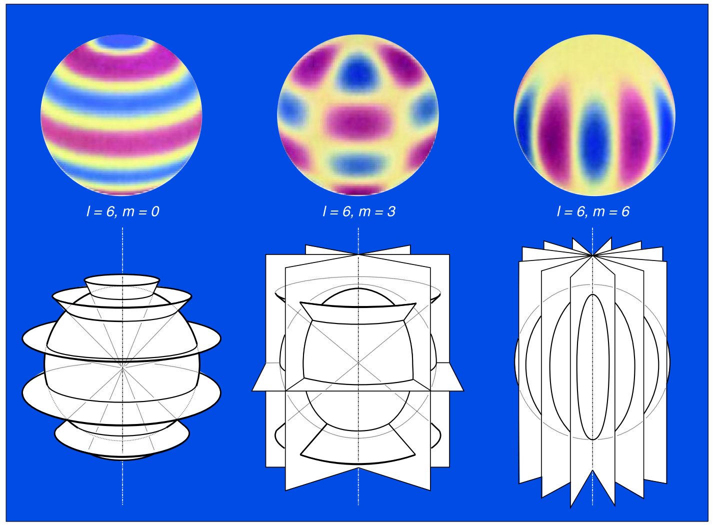


Results from helioseismology



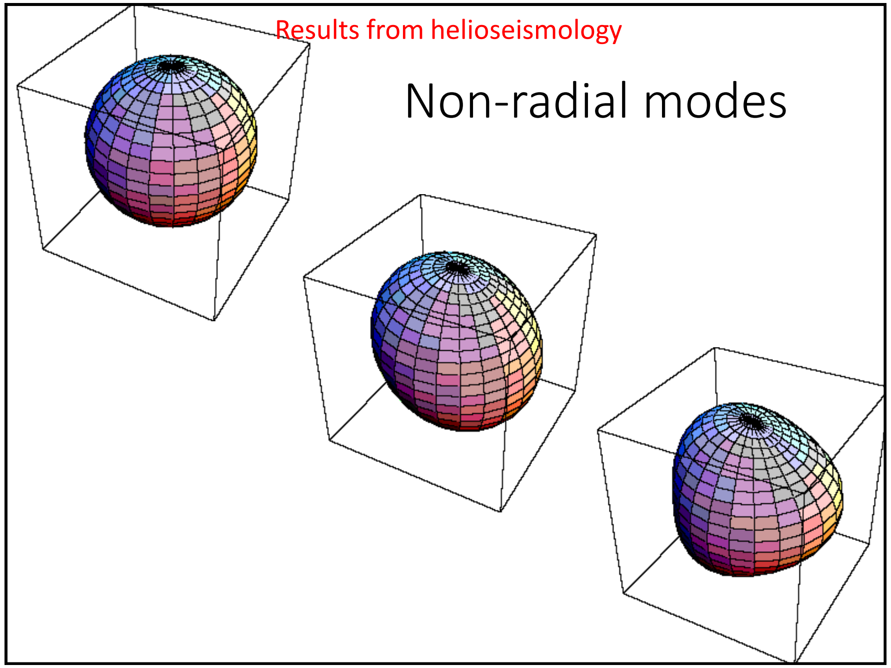
Results from helioseismology

Non-radial modes



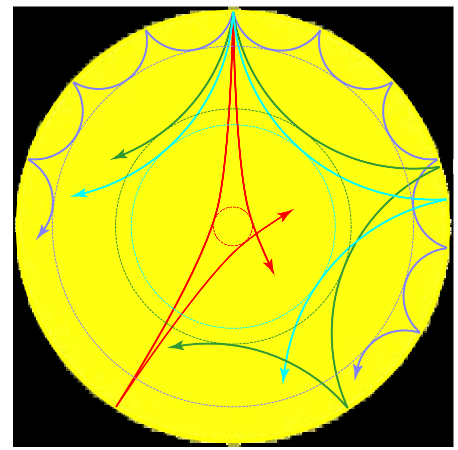
Results from helioseismology

Non-radial modes

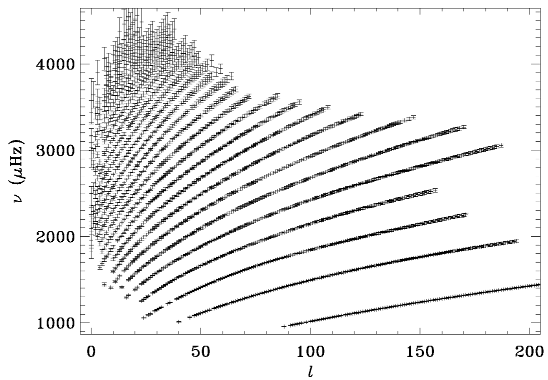


Results from helioseismology

Inversion techniques

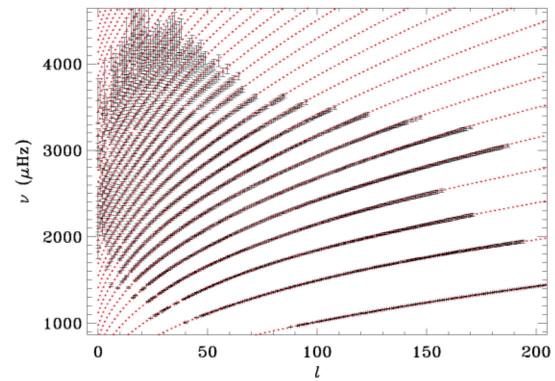


Observed solar frequencies



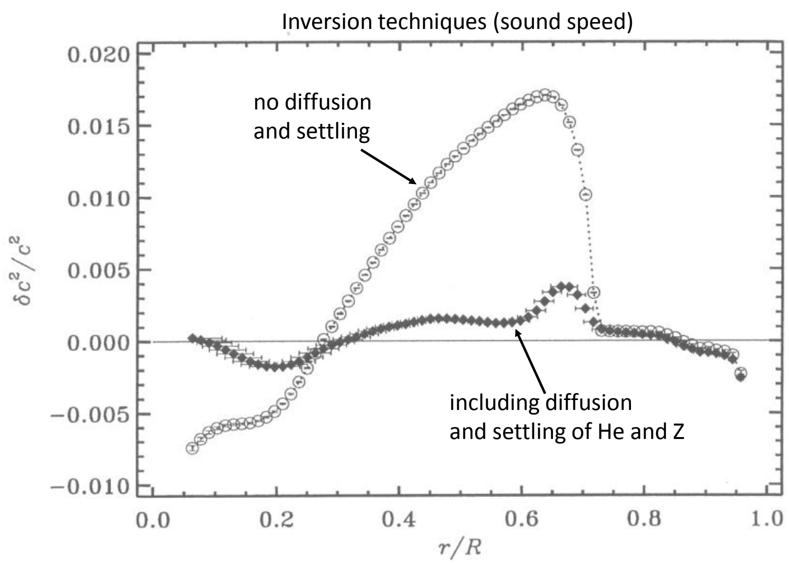
m-averaged frequencies from MDI instrument on SOHO
1000 σ error bars

Observed solar frequencies

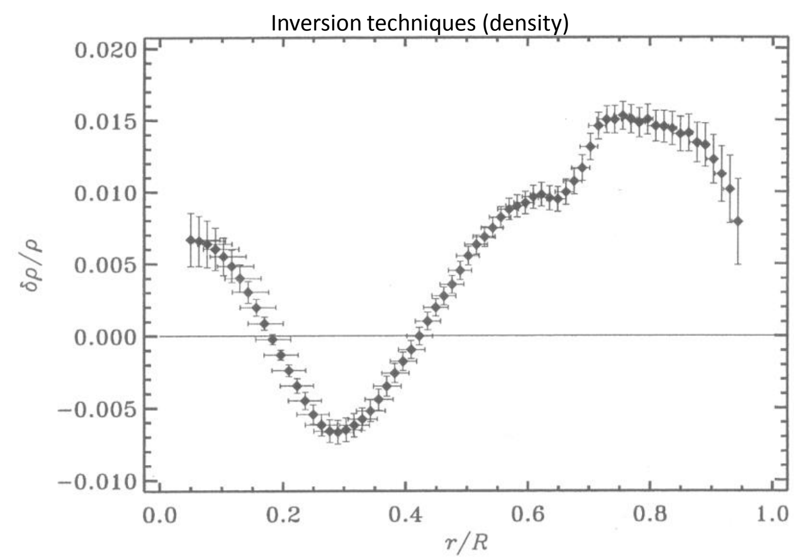


m-averaged frequencies from MDI instrument on SOHO
1000 σ error bars

Results from helioseismology

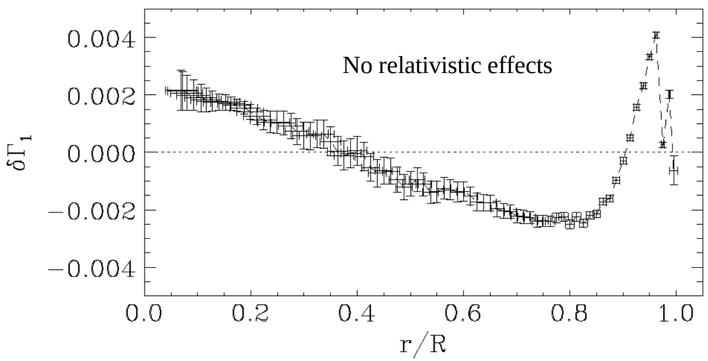


Results from helioseismology



Results from helioseismology

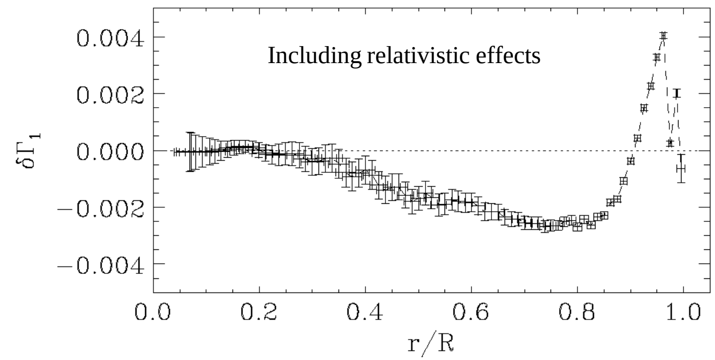
Relativistic electrons in the Sun



Elliot & Kosovichev (1998; ApJ 500, L199)

Results from helioseismology

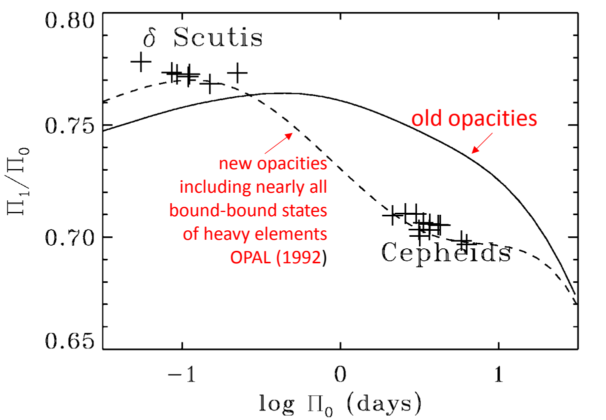
Relativistic electrons in the Sun



Elliot & Kosovichev (1998; ApJ 500, L199)

Classical pulsating stars (Delta Scutis, Cepheids)

How stellar evolution and pulsation can improve macrophysics

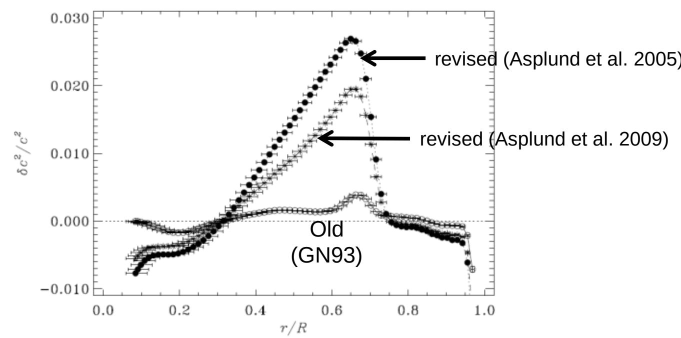


Christensen-Dalsgaard, Petersen (1992)

Results from helioseismology

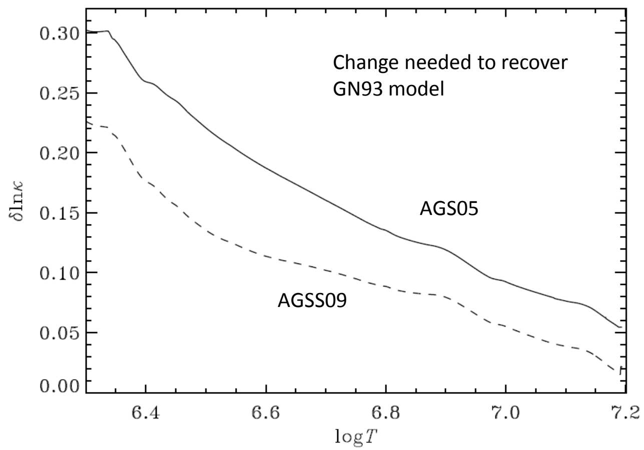
Solar abundance of heavy elements

(Sound speed)^2 difference
Sun - model

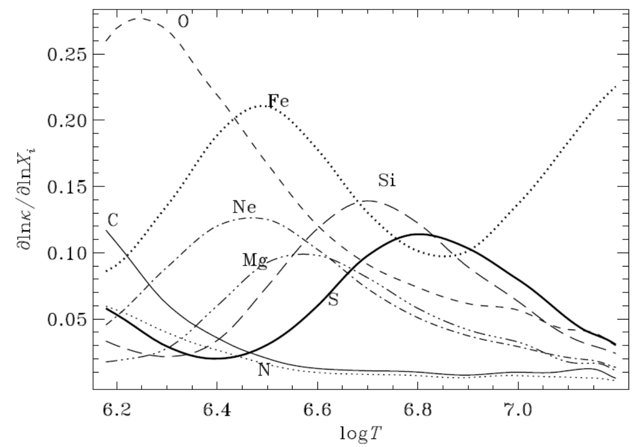


Christensen-Dalsgaard et al. (2010)

Solution: opacity changes?



Opacity contributions



Solar neutrinos

Hydrogen burning

(a) pp chain: $4\,{}^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$

maintain charge balance (conserve lepton number)

no 4-body reactions → sub-reactions

$${}^1\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$$ (controlled by weak interaction) → 14×10^9 y

$${}^2\mathrm{H} + {}^1\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$$ 6 s

$T \sim 15$ mill. K

2x

10^6 y $\quad {}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\,{}^1\mathrm{H}$

(*pp*1)

$Q_{\mathrm{pp1}} = 26.73 - 2 \times 0.263\,\mathrm{MeV}$

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$
$${}^7\mathrm{Li} + {}^1\mathrm{H} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

(*pp*2)

$Q_{\mathrm{pp2}} = 26.47 - 0.80\,\mathrm{MeV}$

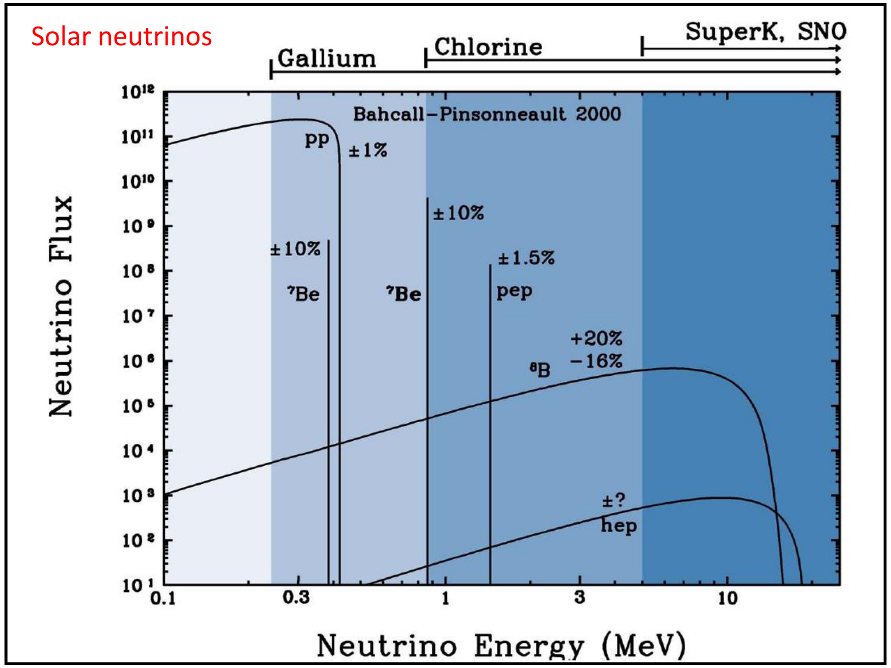
$${}^7\mathrm{Be} + {}^1\mathrm{H} \rightarrow {}^8\mathrm{B} + \gamma$$
$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$$
$${}^8\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

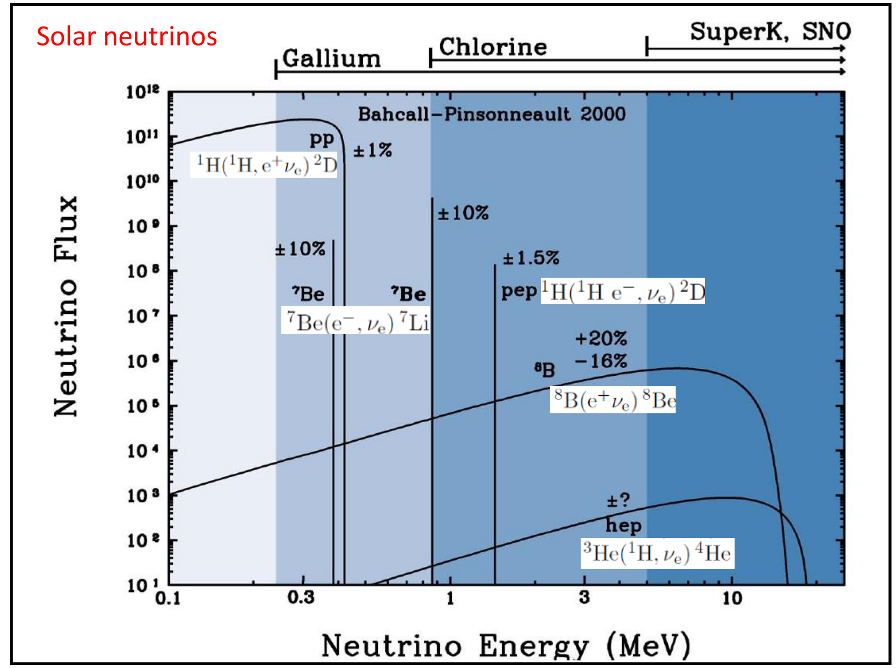
(*pp*3)

$Q_{\mathrm{pp3}} = 26.47 - 7.20\,\mathrm{MeV}$

Neutrinos

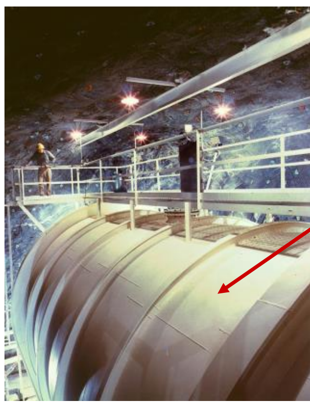
Neutrinos, they are very small.
They have no charge and ~~have~~ no mass
And do not interact at all. **near**
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall.
... ...
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.
—John Updike


Solar neutrinos
Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
pp
±1%
±10%
±10%
±1.5%
⁷Be
⁷Be
pep
+20%
−16%
⁸B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)


Solar neutrinos
Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
pp
$^1H(^1H, e^+\nu_e)^2D$
±1%
±10%
±10%
±1.5%
⁷Be
⁷Be
$^7Be(e^-, \nu_e)^7Li$
pep $^1H(^1H\ e^-, \nu_e)^2D$
+20%
−16%
⁸B
$^8B(e^+\nu_e)^8Be$
±?
hep
$^3He(^1H, \nu_e)^4He$
Neutrino Flux
Neutrino Energy (MeV)

Solar neutrinos
(Chlorine experiment)

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

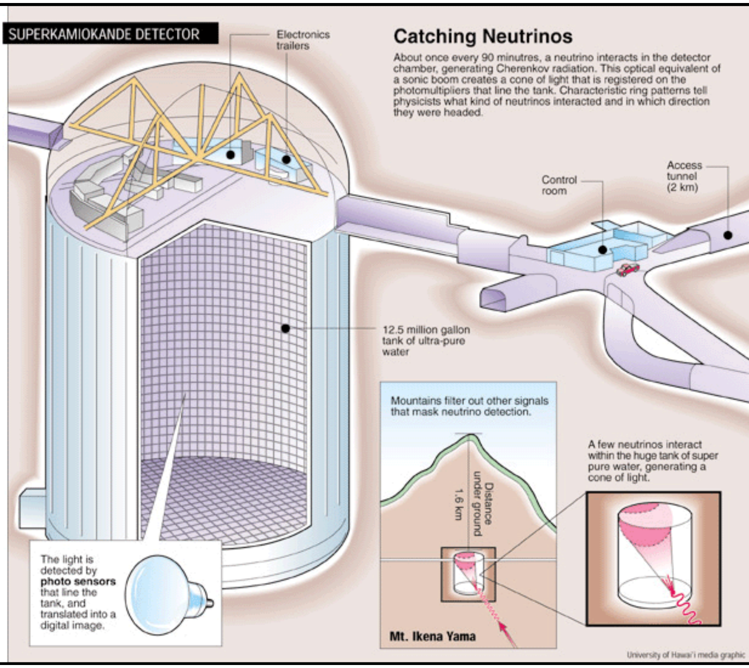


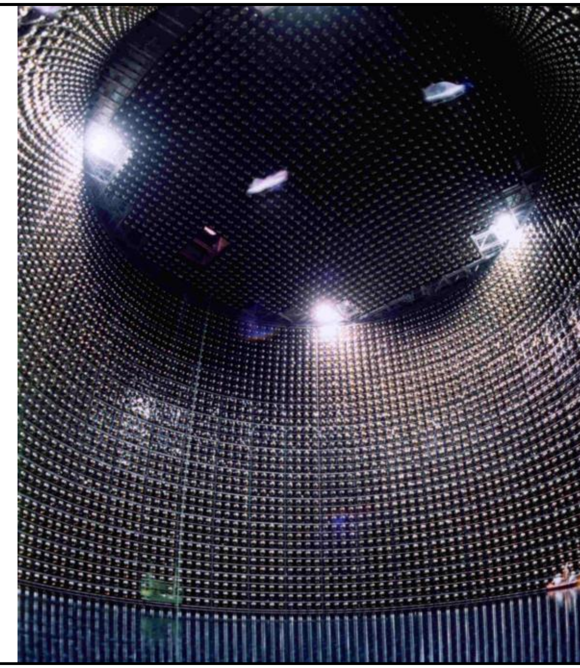
380 000 liter C_2Cl_4

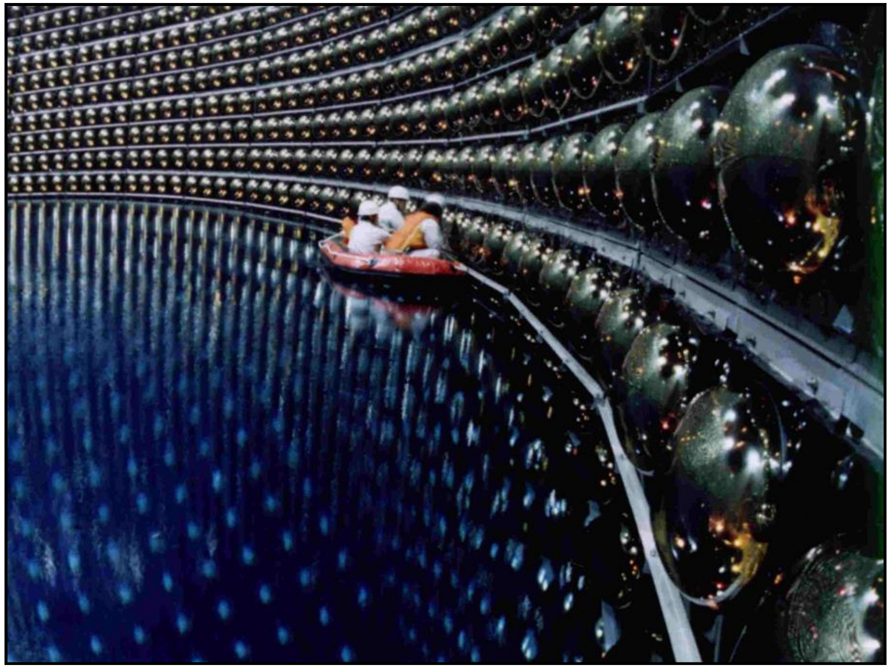
Solar neutrinos
(Super-Kamiokande detector)

Uses scattering of neutrinos on electrons in WATER

in a tank of 50 000 tons of water!


SUPERKAMIOKANDE DETECTOR
Electronics trailers
Catching Neutrinos
About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.
Control room
Access tunnel (2 km)
12.5 million gallon tank of ultra-pure water
Mountains filter out other signals that mask neutrino detection.
Distance under ground 1.6 km
A few neutrinos interact within the huge tank of super pure water, generating a cone of light.
The light is detected by photo sensors that line the tank, and translated into a digital image.
Mt. Ikena Yama
University of Hawai'i media graphic





Solar neutrinos
(Super-Kamiokande detector)

Uses scattering of neutrinos on electrons in WATER

in a tank of 50 000 tons of water!

Experiment sensitive to neutrinos with energies
> 6.5 MeV, i.e. mostly ^{8}B neutrinos

Neutrino-oscillations

$$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$$

Produced neutrinos: ν_e

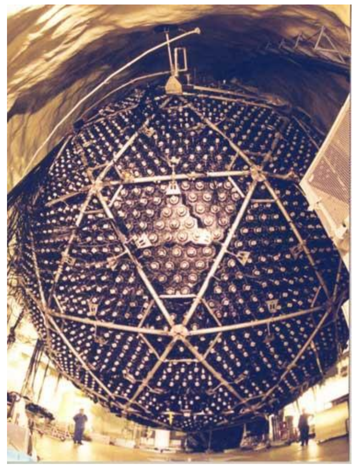
Detected neutrinos:

- ^{37}Cl, ^{71}Ga : ν_e
- H_2O: ν_e

Solar neutrinos (neutrino oscillations)

Mikheyev-Smirnov-Wolfenstein (MSW) effect

Sudbury Neutrino Observatory (SNO, Canada)



measures high-energy neutrinos (^8B) through reactions with deuterium (^2H) in heavy water.

Two relevant reactions with ^2H:

(1) sensitive only to ν_e (charged-current reactions)

(2) sensitive to all three types (neutral-current react.)

↓

Comparison of (1) with (2) provides measure of flavour change between ν_e, ν_τ and ν_μ.

Measurements agree with solar-model predictions within error bars (Ahmad et al. 2002).

Neutrino overview