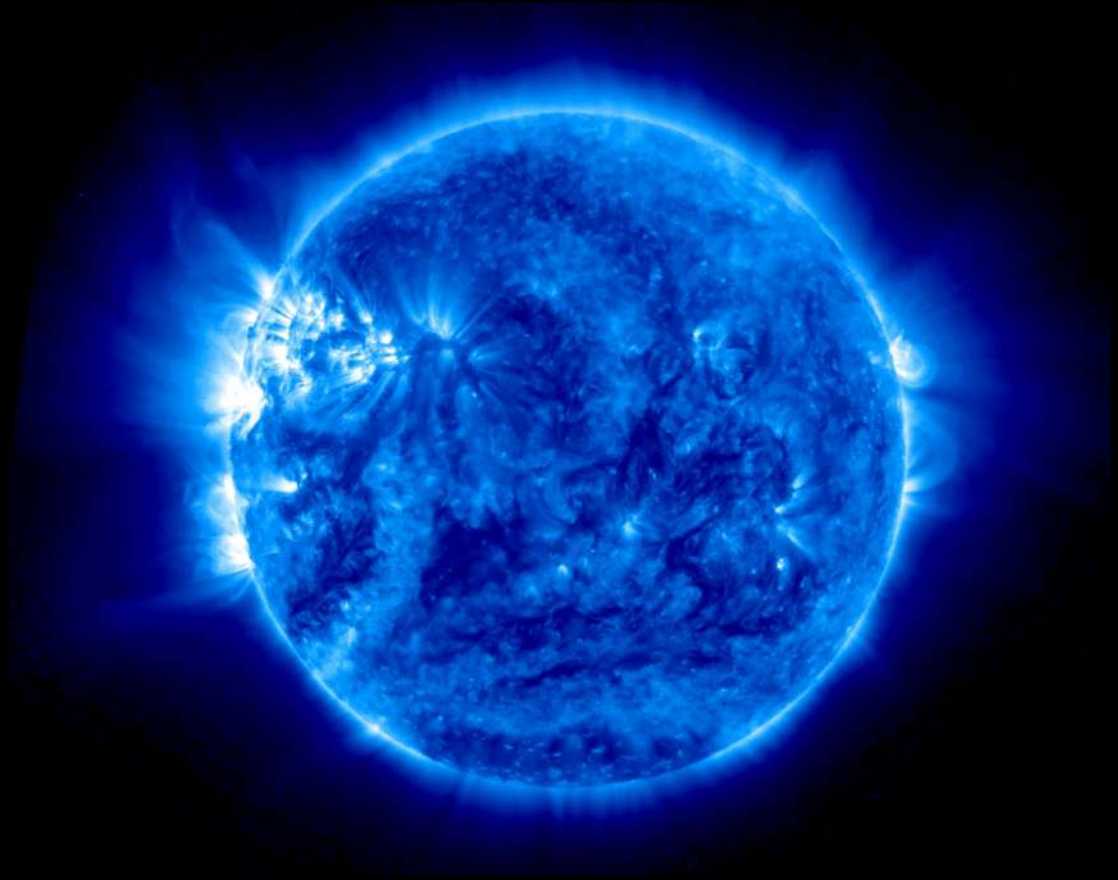
The Standard Solar Model

with Helioseismology and Solar Neutrino Constraints

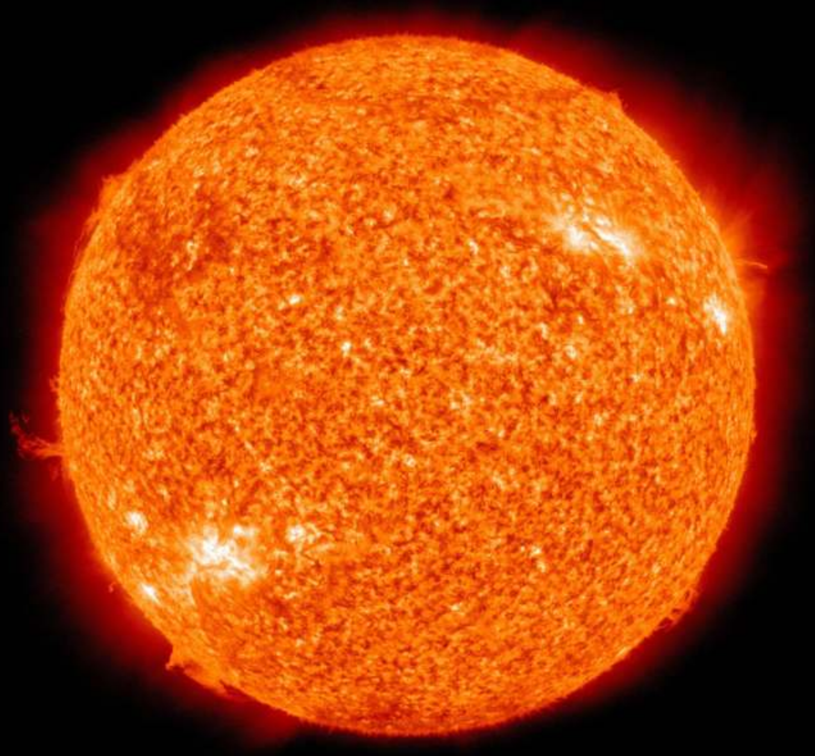


Ryan Hazlett

What is the Standard Solar Model?

Standard Solar Model Breakdown

Hydrostatic Equilibrium	Thermonuclear Reactions
Internal Composition	Energy Transport

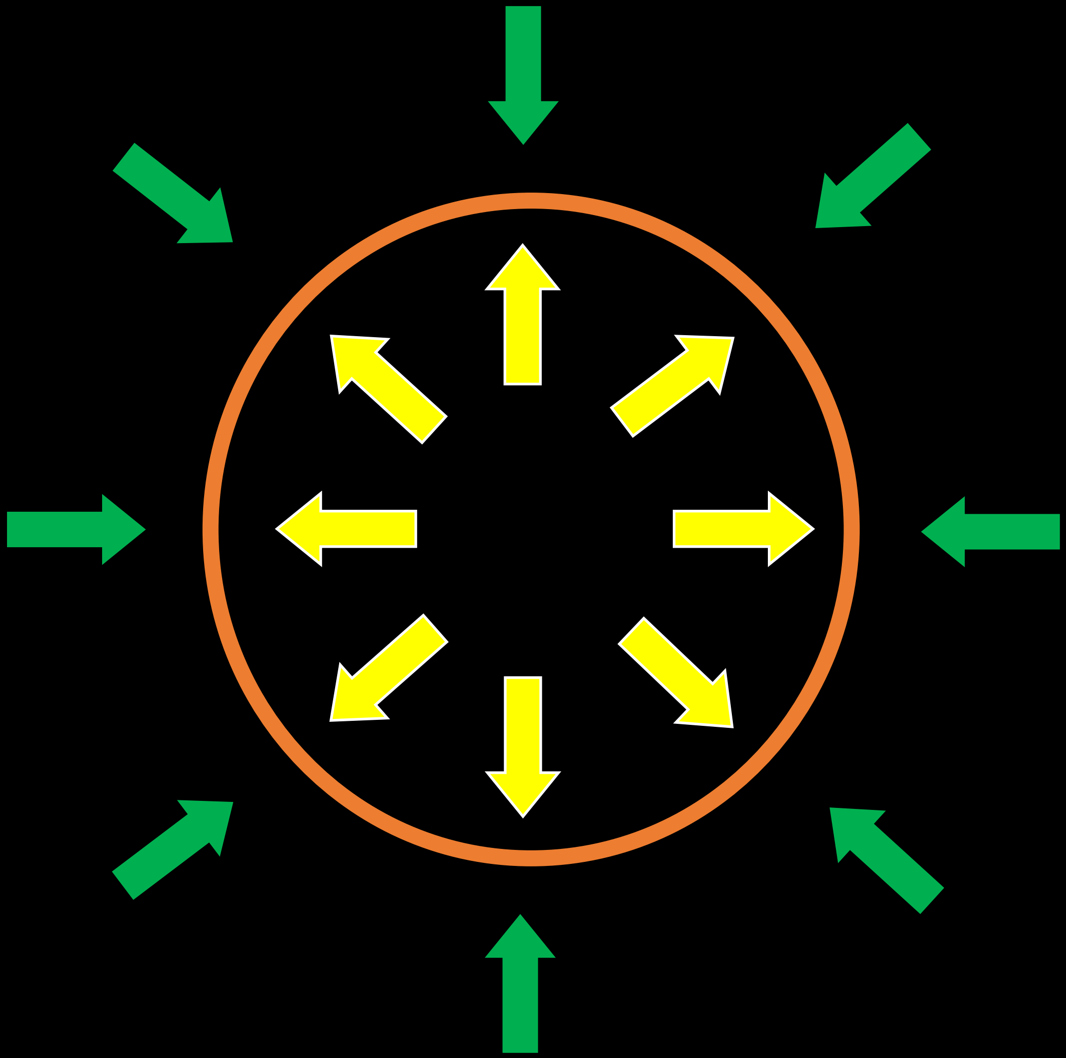


$L_\odot$

$R_\odot$

Age

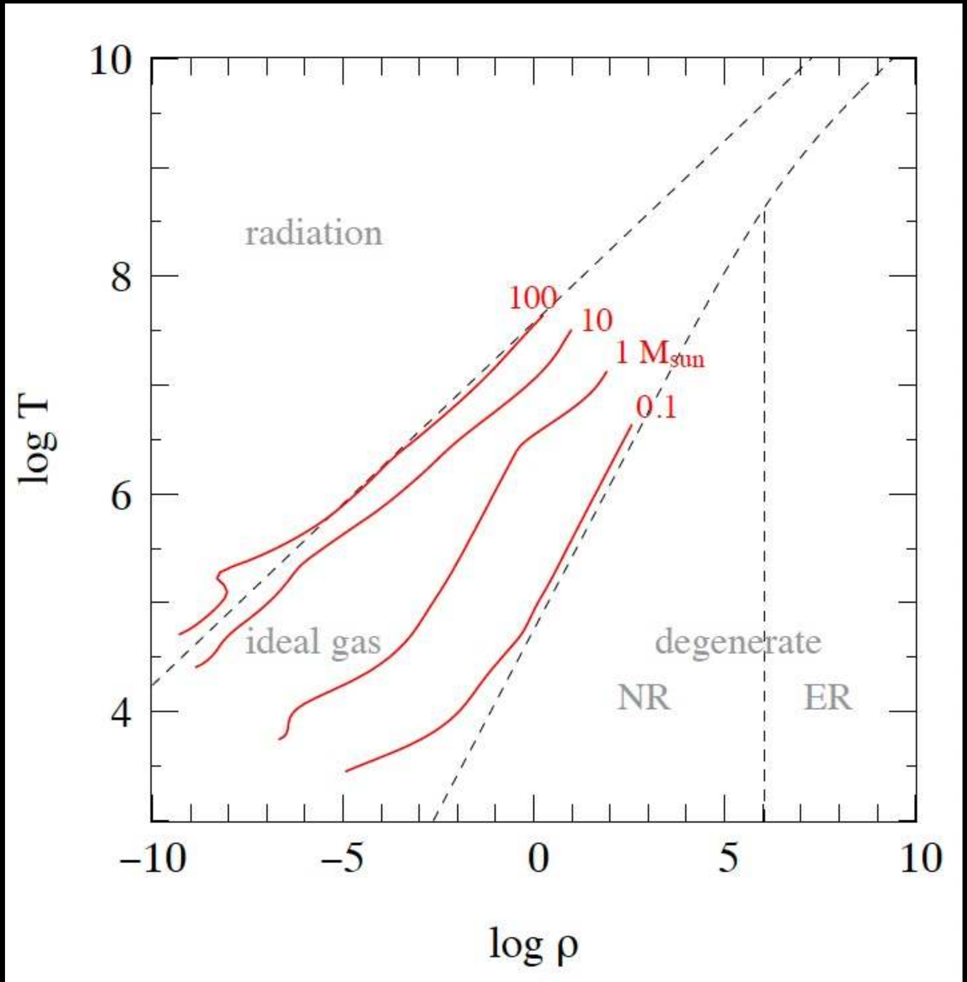
Hydrostatic Equilibrium



Pressure = Gravity

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$$

Hydrostatic Equilibrium, Equation of State



Credit: O. R. Pols

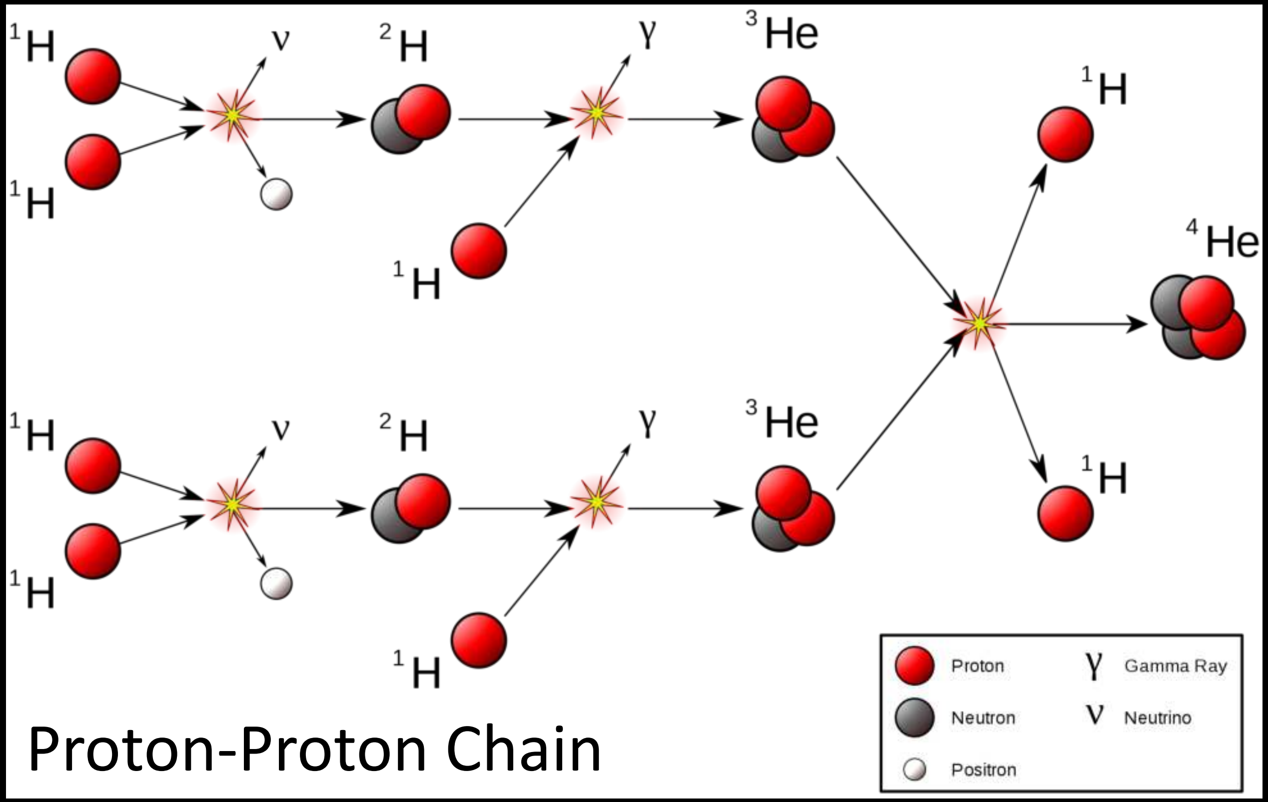
Assuming an Ideal Gas:

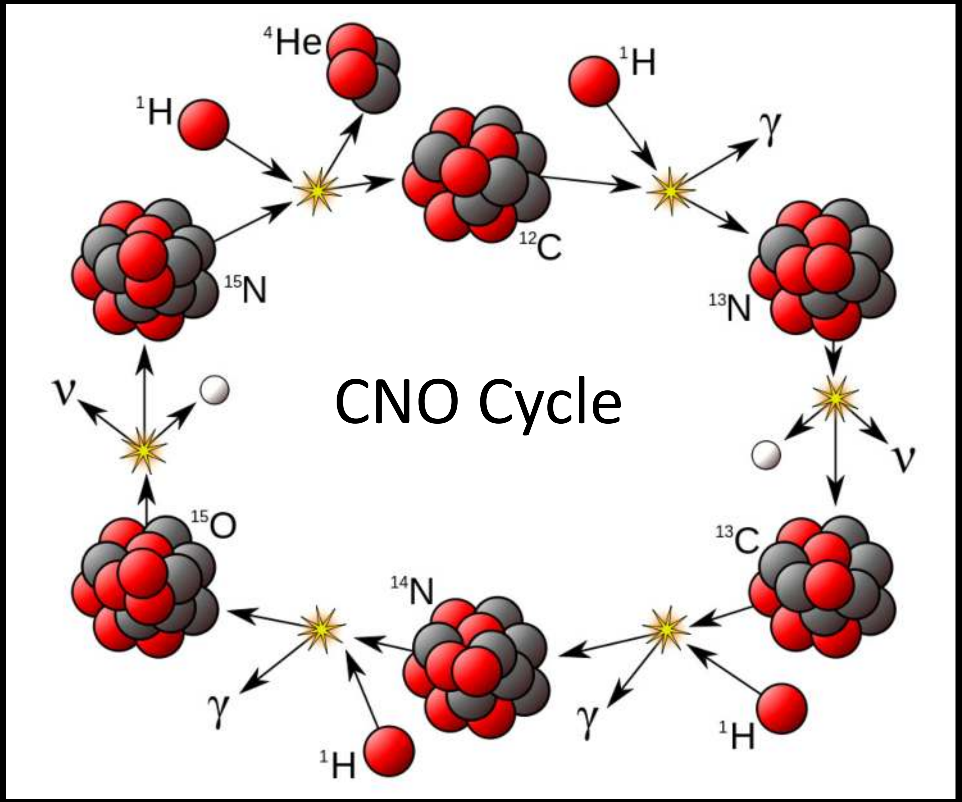
$$P = P_R + P_g = \frac{1}{3} a T^4 + \frac{\rho k T}{\mu m_H}$$

Model Parameters:

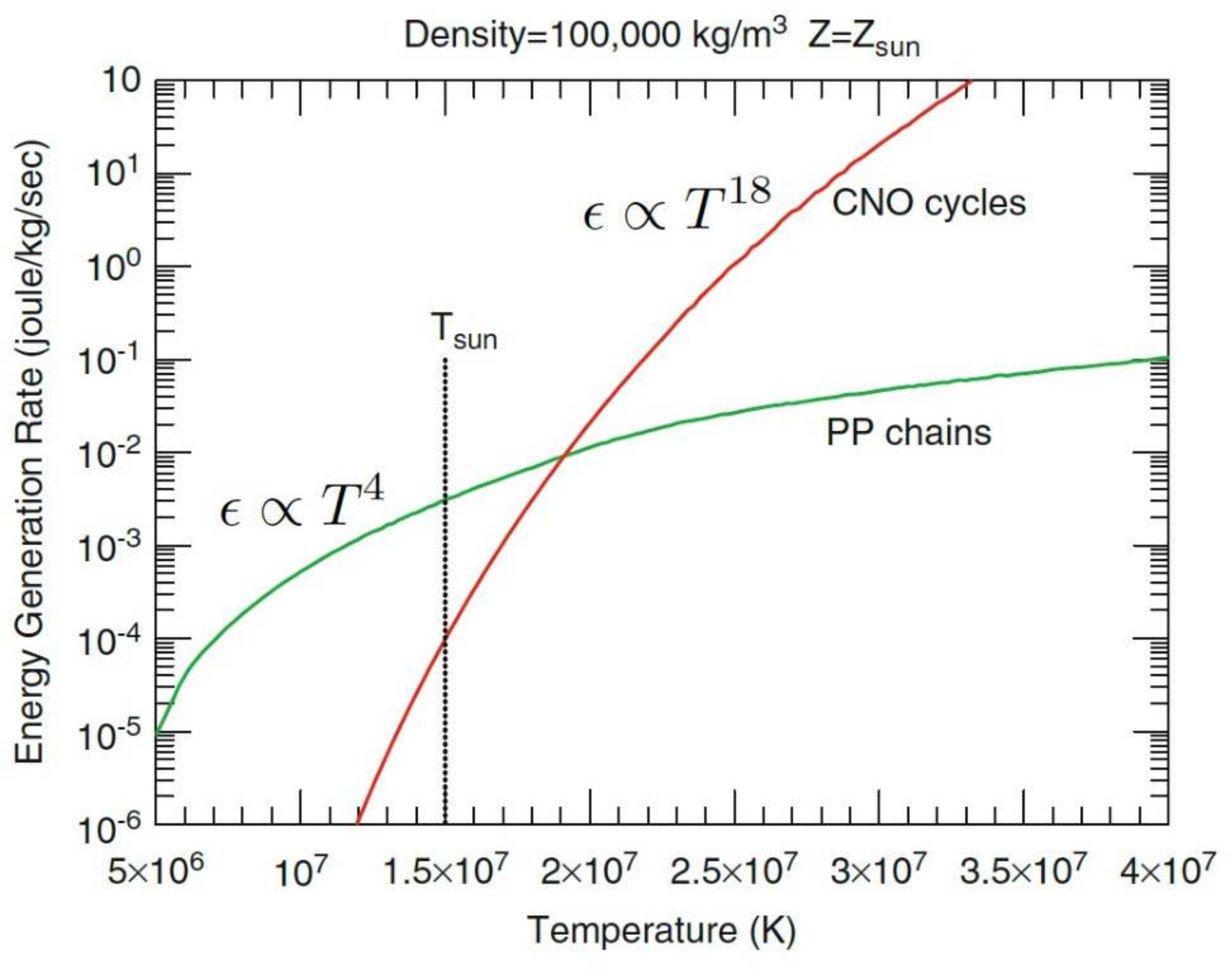
- ρ: Density
- T: Temperature
- μ: Mean Molecular Mass

Thermonuclear Reactions in the Core





Proton-Proton Chain Dominant in the Sun



Credit: O. R. Pols

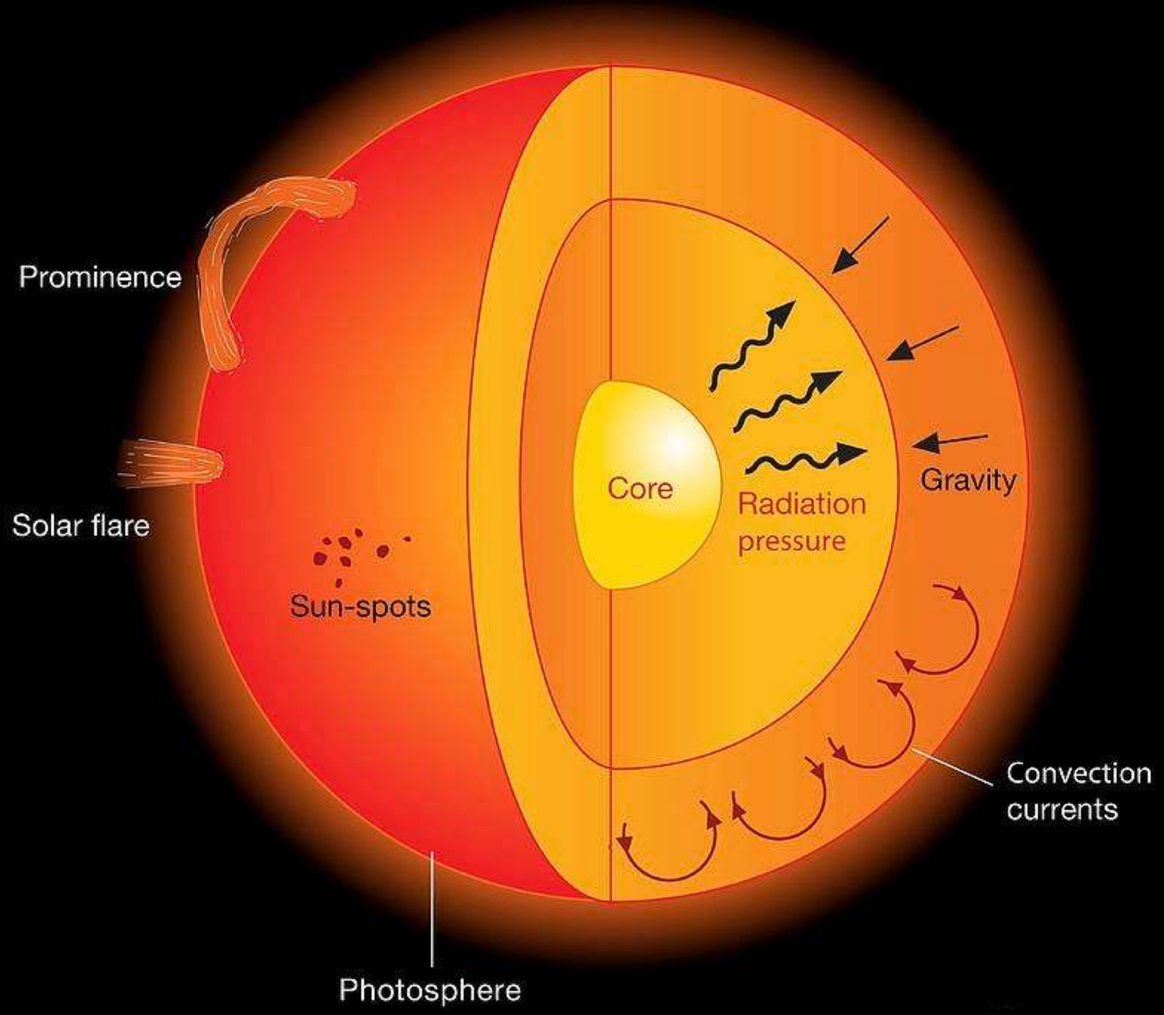
Model Parameters:

- ρ: Density
- T: Temperature
- $C(t)$: Composition

Nuclear Reactions Produce:

- L: High Energy Photons
- ν_e: Electron-Neutrinos

Internal Composition and Structure



Important Details:

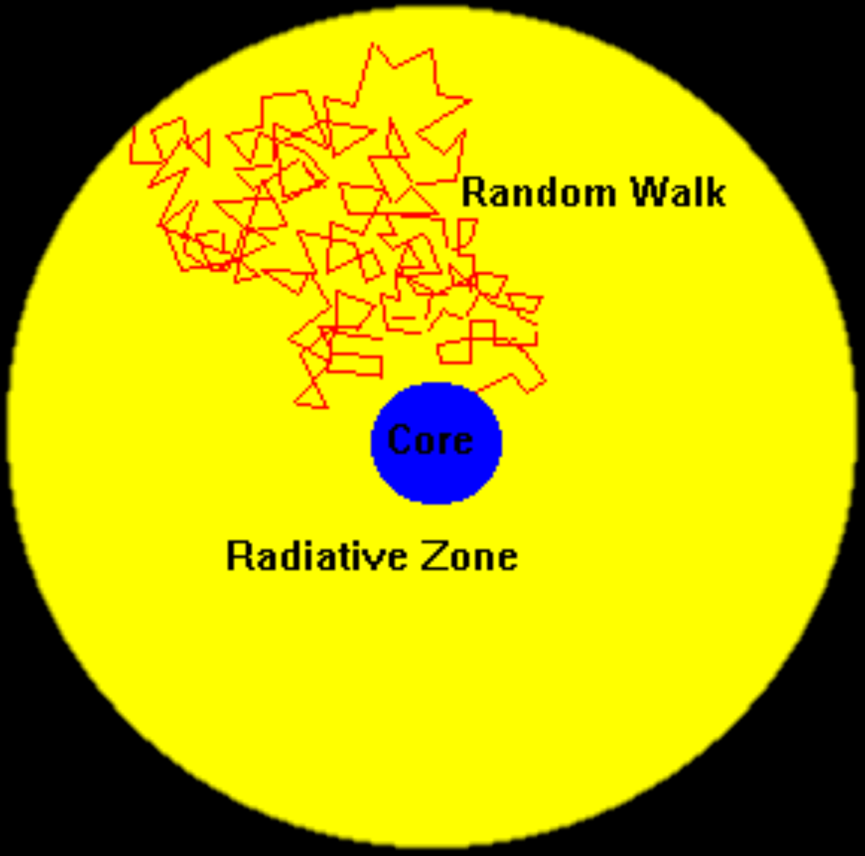
1. Inner radiative zone surrounded by an outer convective zone.

2. Abundance and Distribution of:
   - Hydrogen: $X(r)$
   - Helium: $Y(r)$
   - Metals: $\mathrm{Z}(r)$

3. Changes as the Sun evolves

Credit: Science Photo Library

Radiative Energy Transport



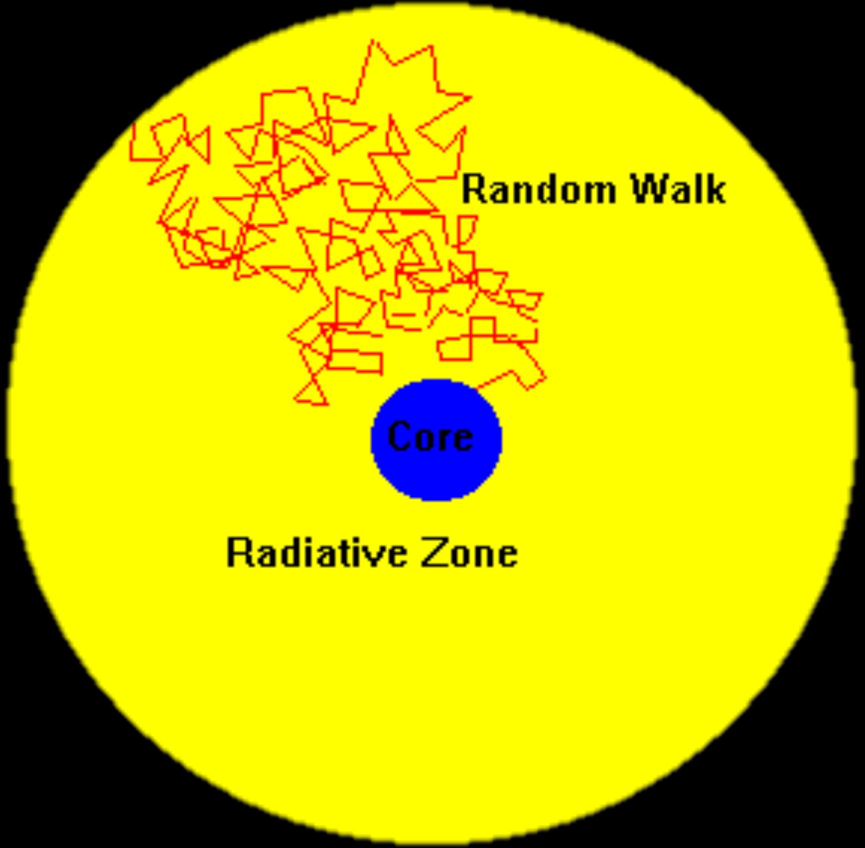
Given a luminosity and opacity, need a ∇T to carry energy.

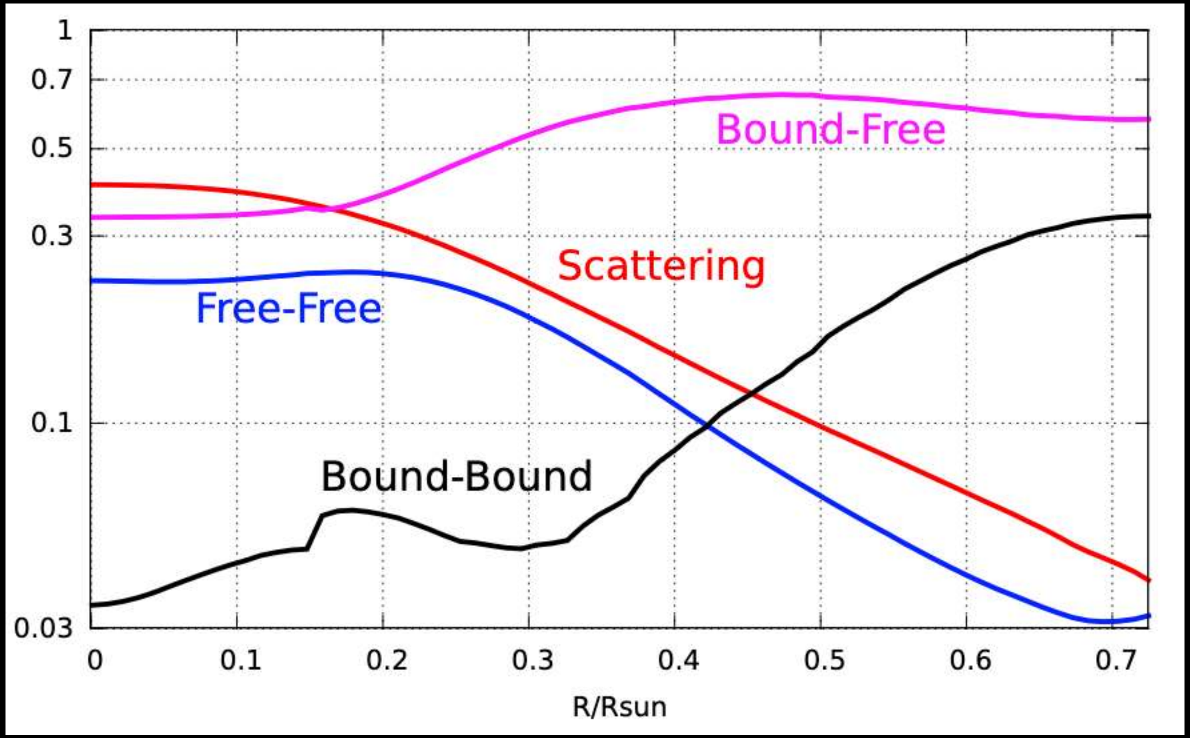
$$\frac{dT}{dr} = -\frac{3\kappa\rho L}{16\pi a c r^2 T^3} \propto -\frac{\kappa\rho L}{r^2 T^3}$$

Model Parameters:

- κ: Opacity
- ρ: Density
- L: Luminosity
- T: Temperature

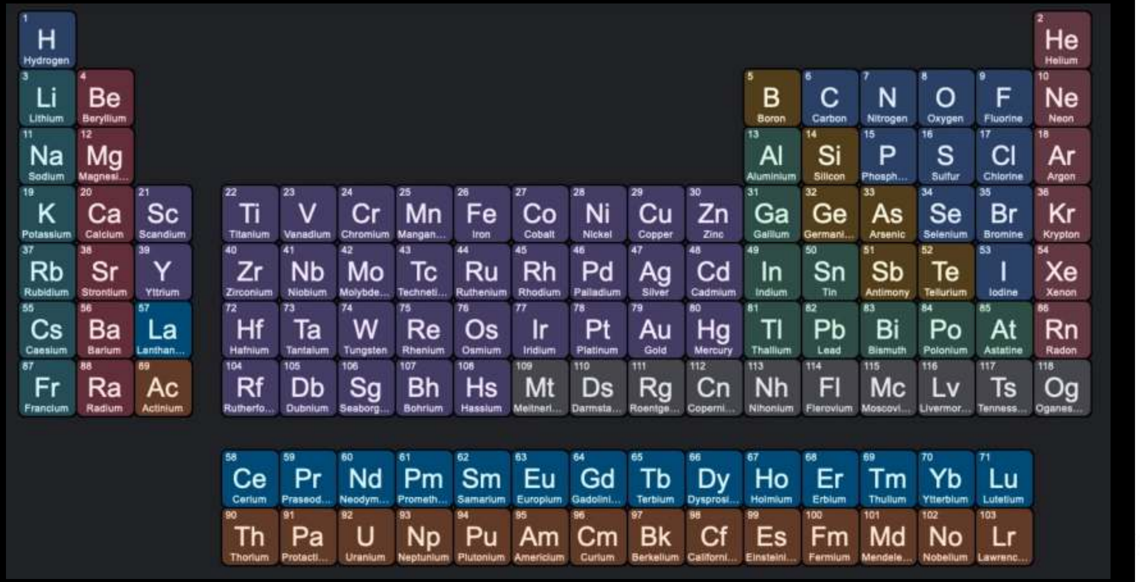
Many Sources of Opacity

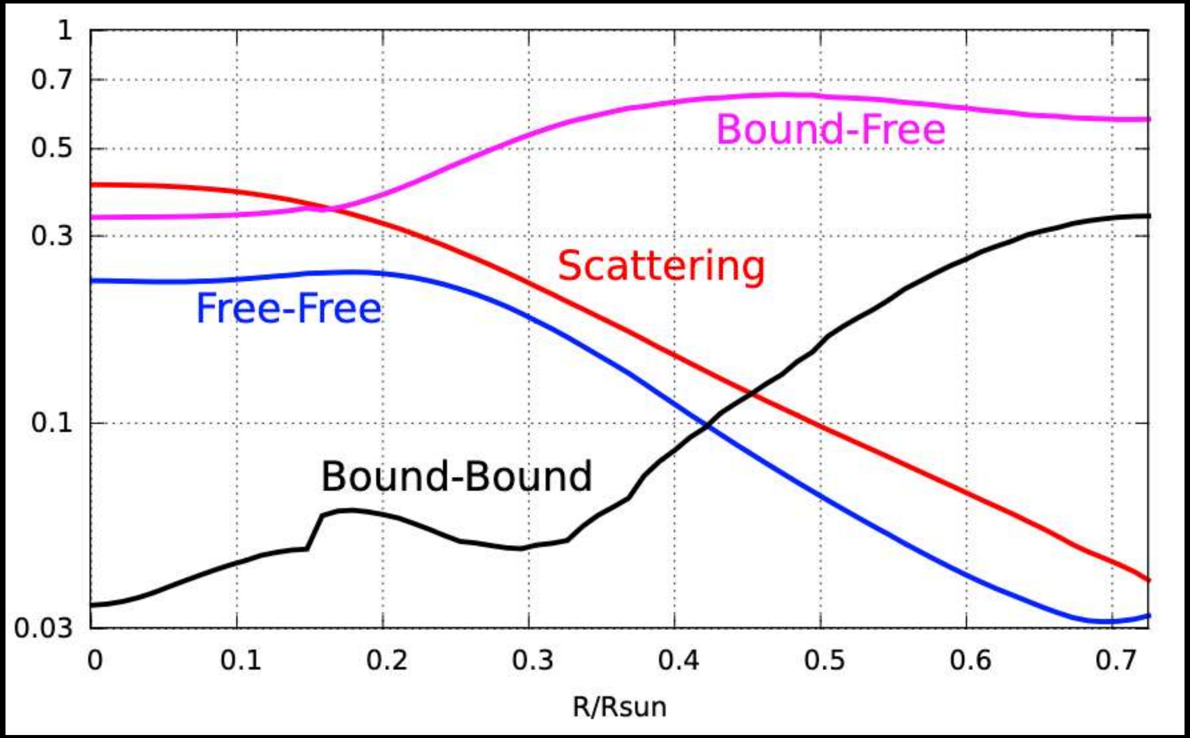




Kreif et al. 2021

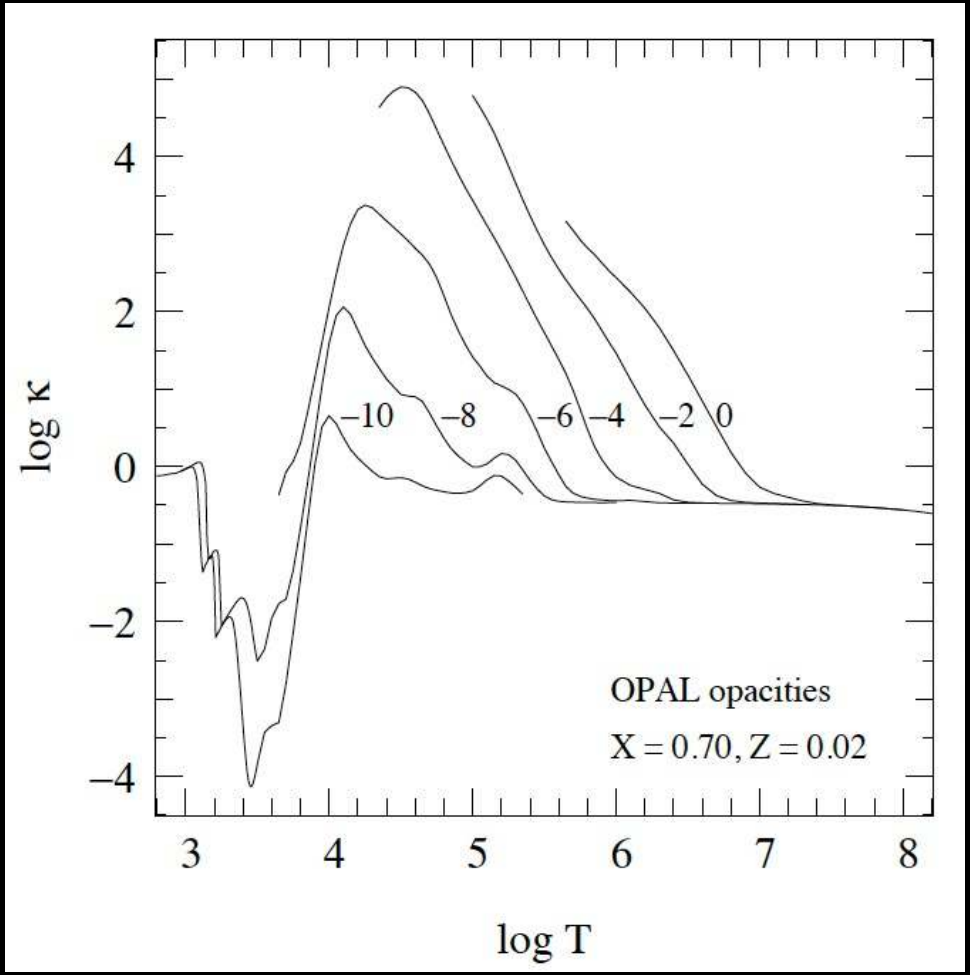
Composition causes drastic changes





Kreif et al. 2021

Opacity is Complicated



Iglesias et al. 1996

Given a luminosity and opacity, need a ∇T to carry energy.

$$\frac{dT}{dr} = -\frac{3\kappa\rho L}{16\pi a c r^2 T^3} \propto -\frac{\kappa\rho L}{r^2 T^3}$$

Model Parameters:

- κ: Opacity
- ρ: Density
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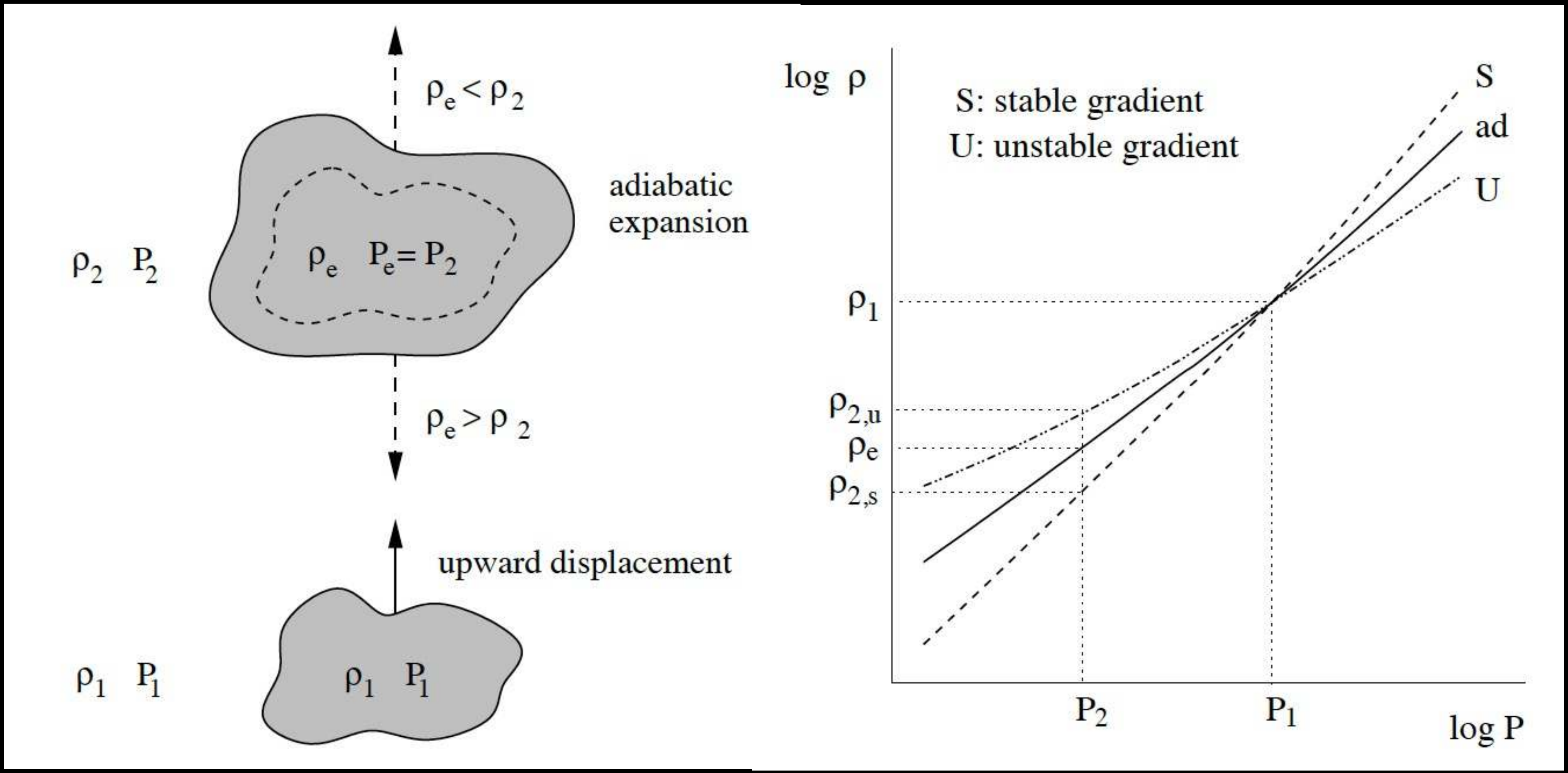
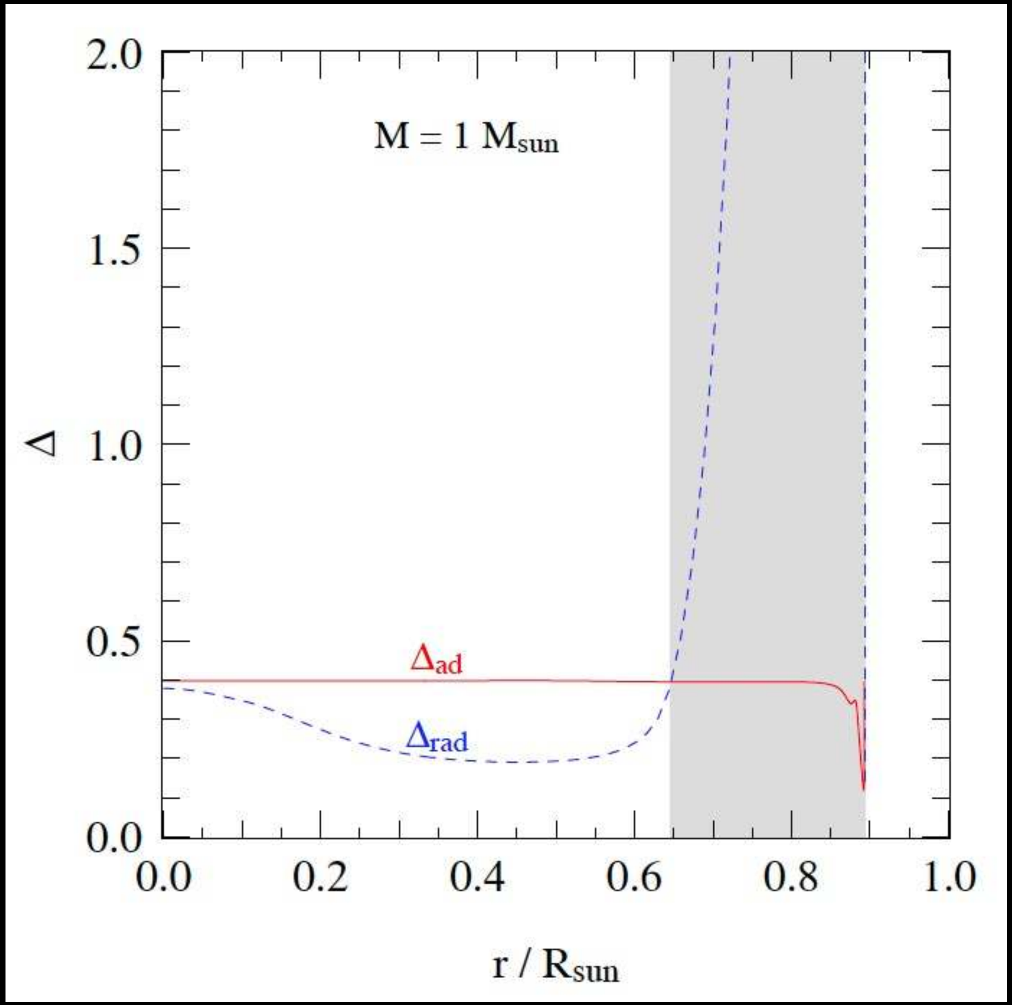
Energy Transport through Convection



Credit: O. R. Pols

Energy Transport through Convection



Credit: O. R. Pols

When does convection happen?

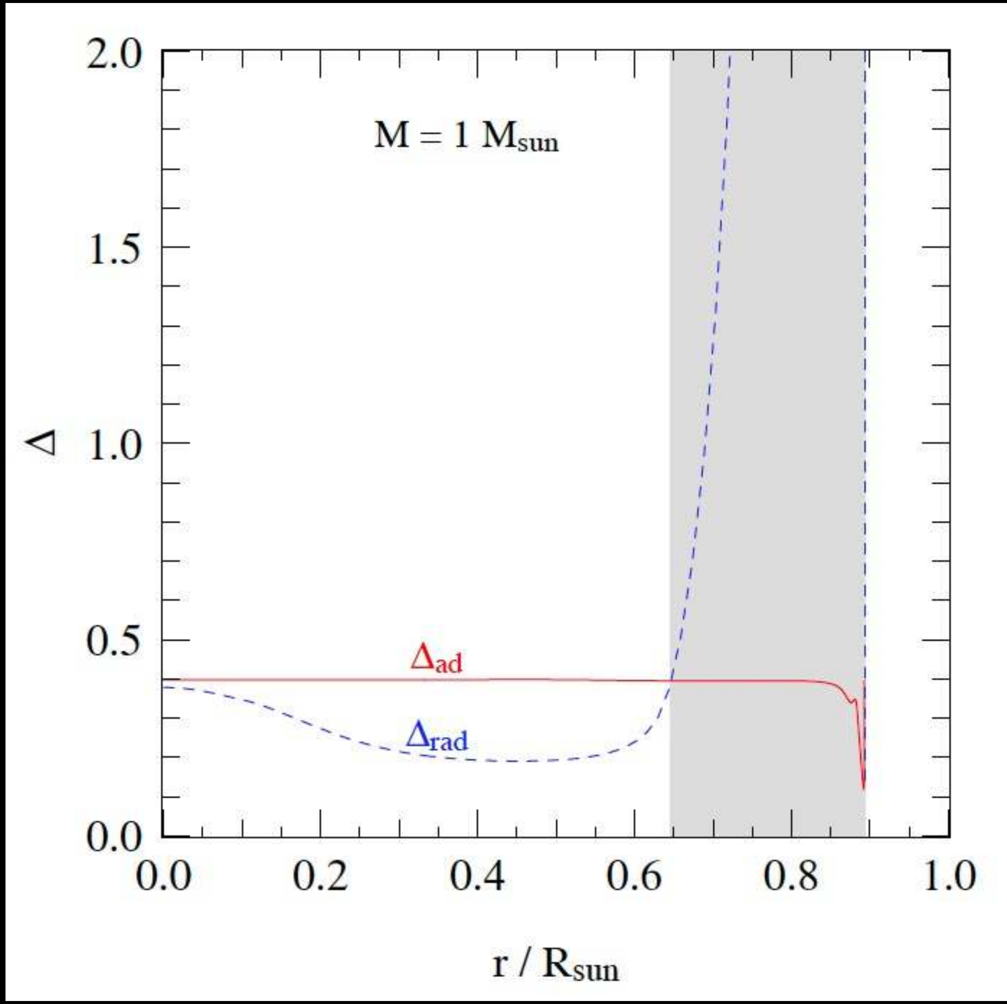
Schwarzschild Criterion:

$$\nabla_{ad} < \nabla_{rad}$$

How can we increase ∇_{rad}?

$$\nabla_{rad} \propto -\frac{\kappa \rho L}{r^2 T^3} \qquad \kappa \uparrow$$

Energy Transport through Convection



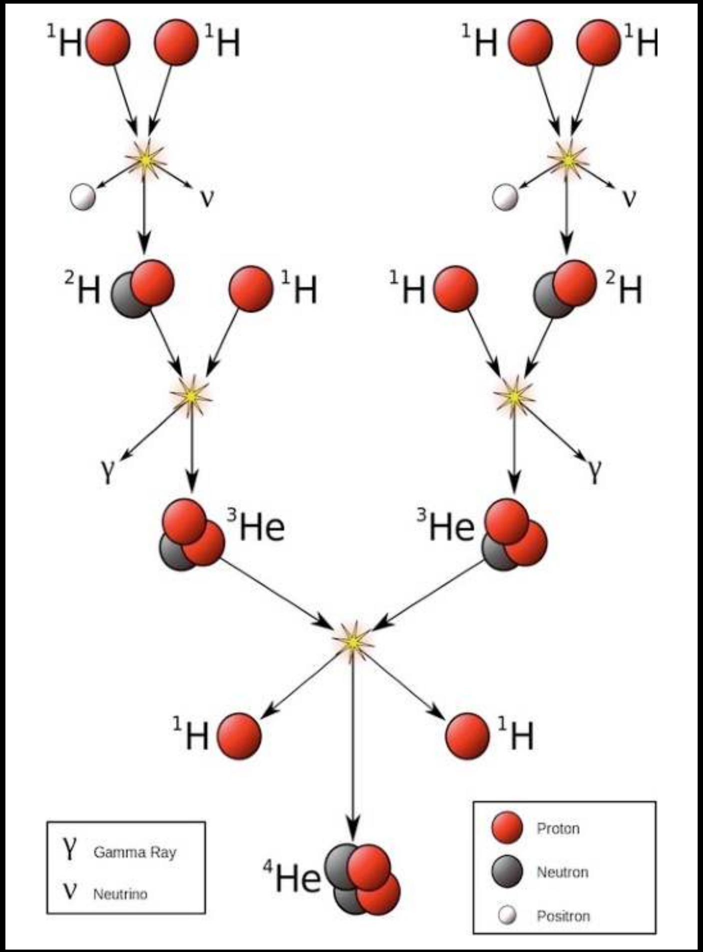
Credit: O. R. Pols

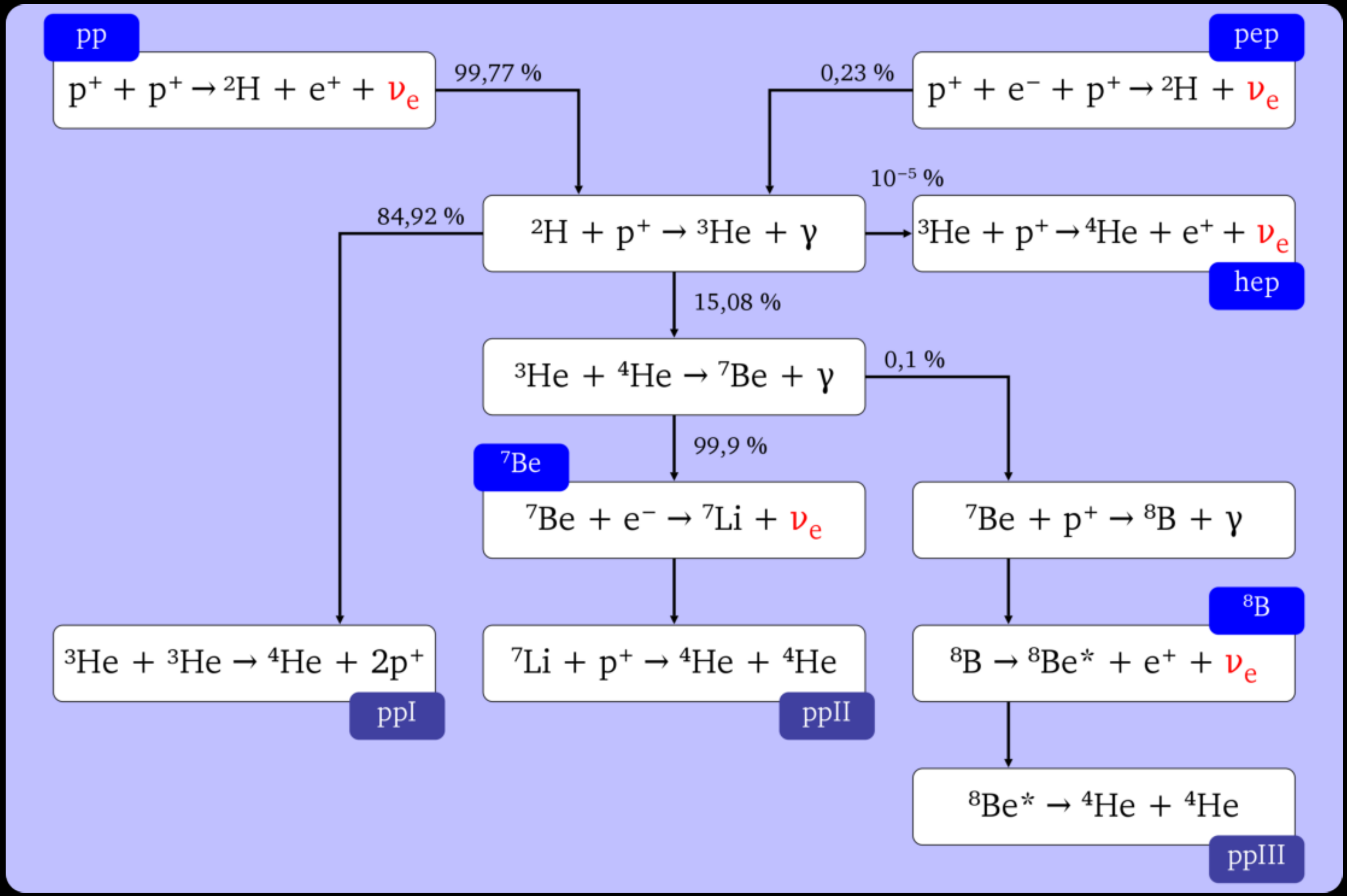
How deep into the interior does the convection zone reach?

Metals can be mixed into the envelope.

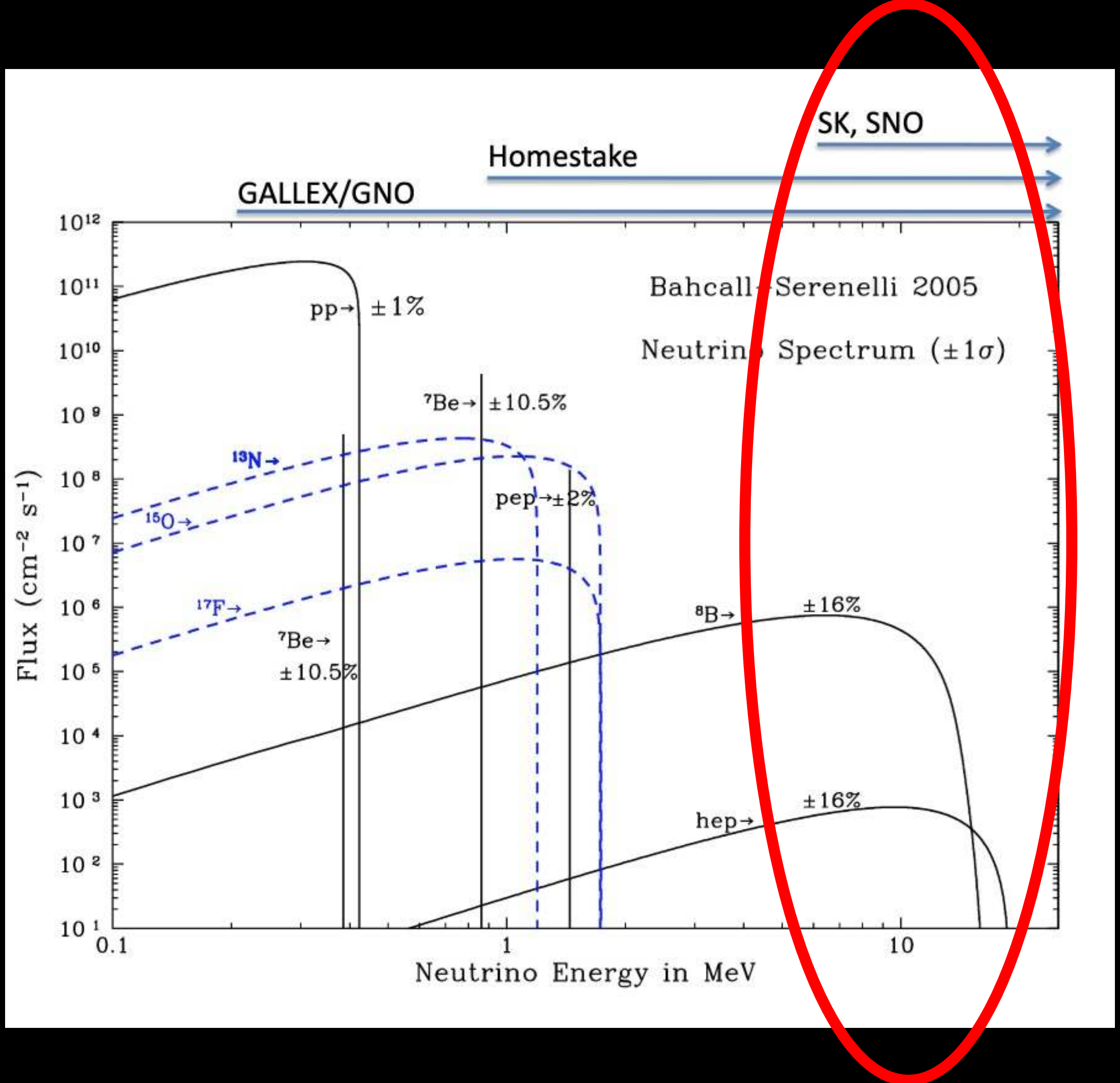
Models often use a mixing length parameter.

Energy transport through Neutrinos

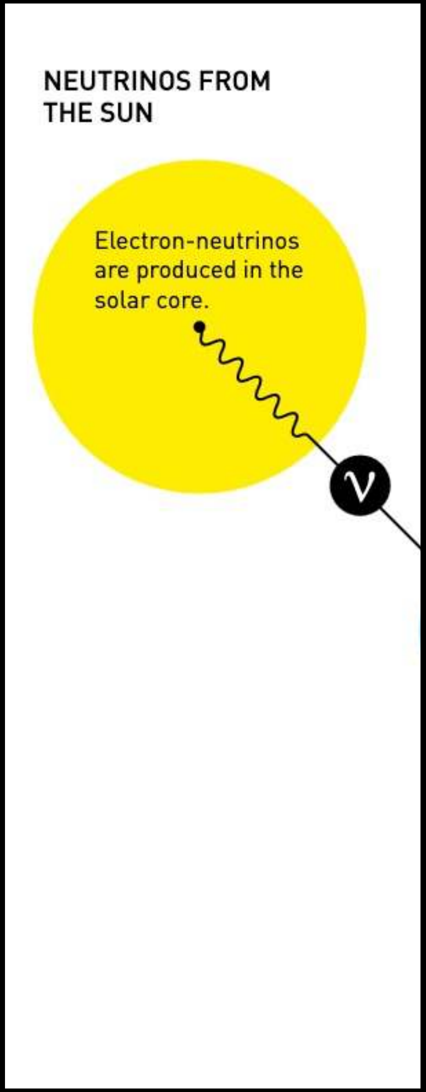




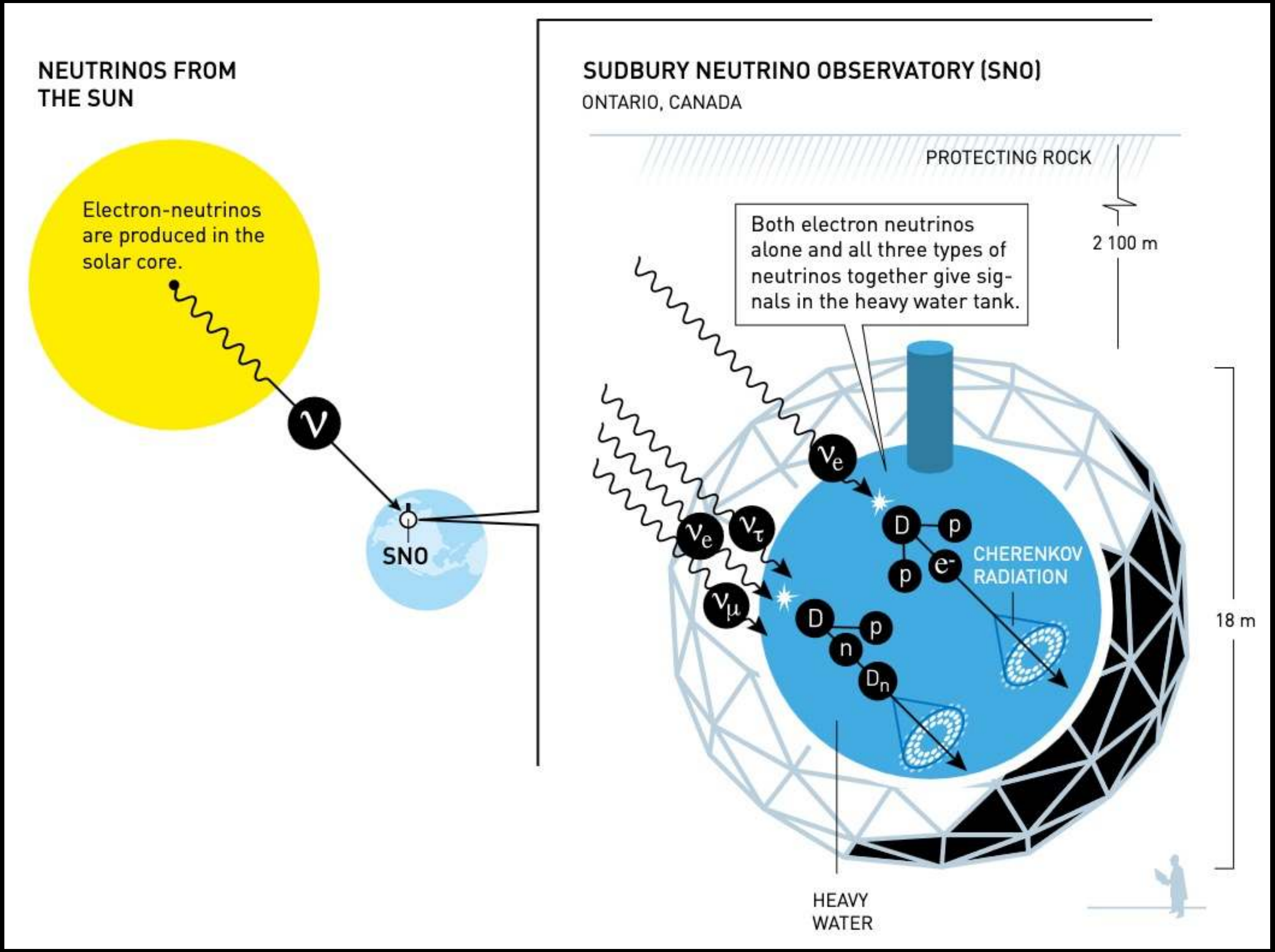
Detection Limits for Solar Neutrinos



How are Solar Neutrinos Observed?

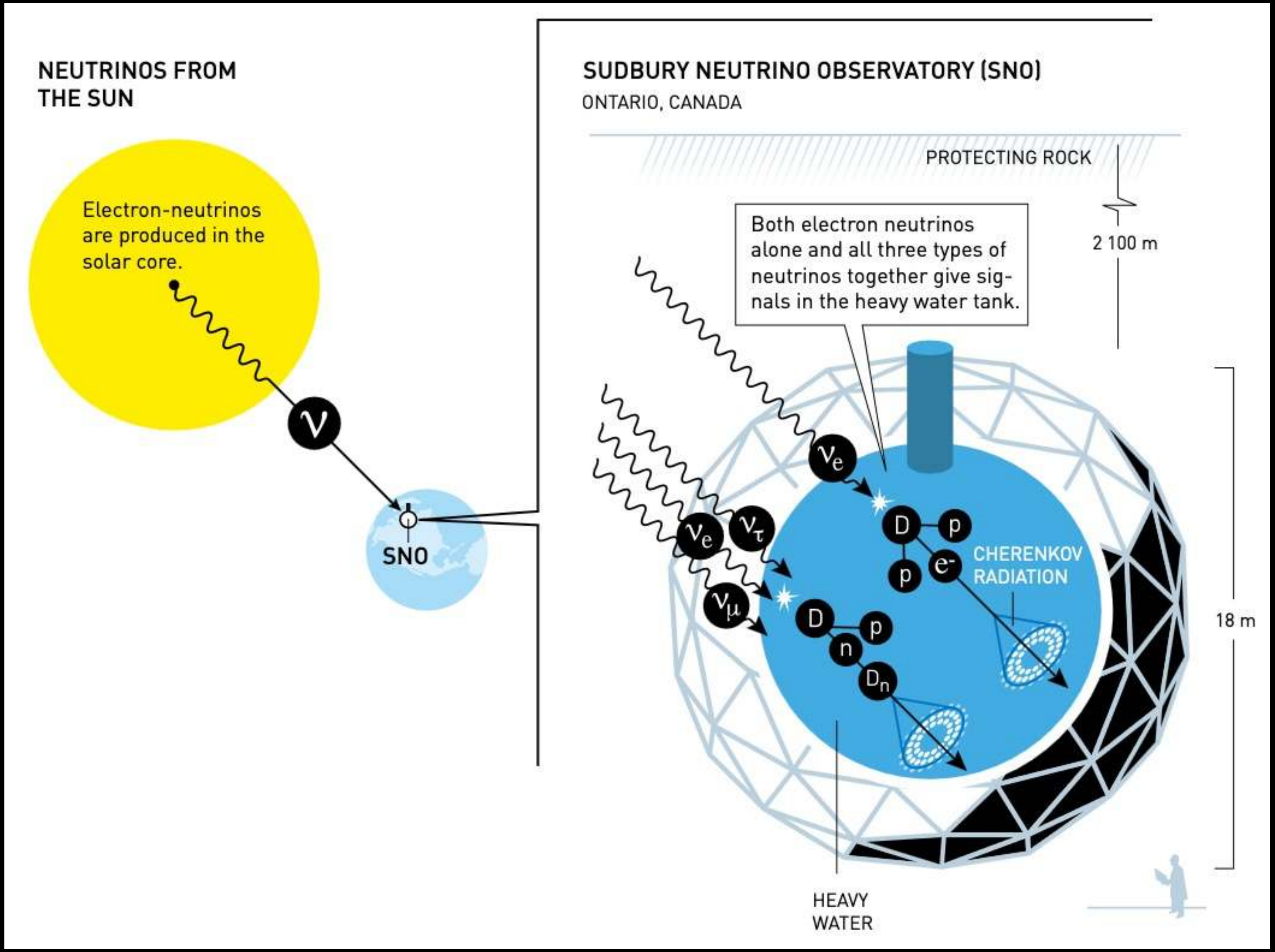


How are Solar Neutrinos Observed?



Credit: 2015 Physics Nobel Prize Press Release

Less Solar Electron-Neutrinos than expected



Credit: 2015 Physics Nobel Prize Press Release

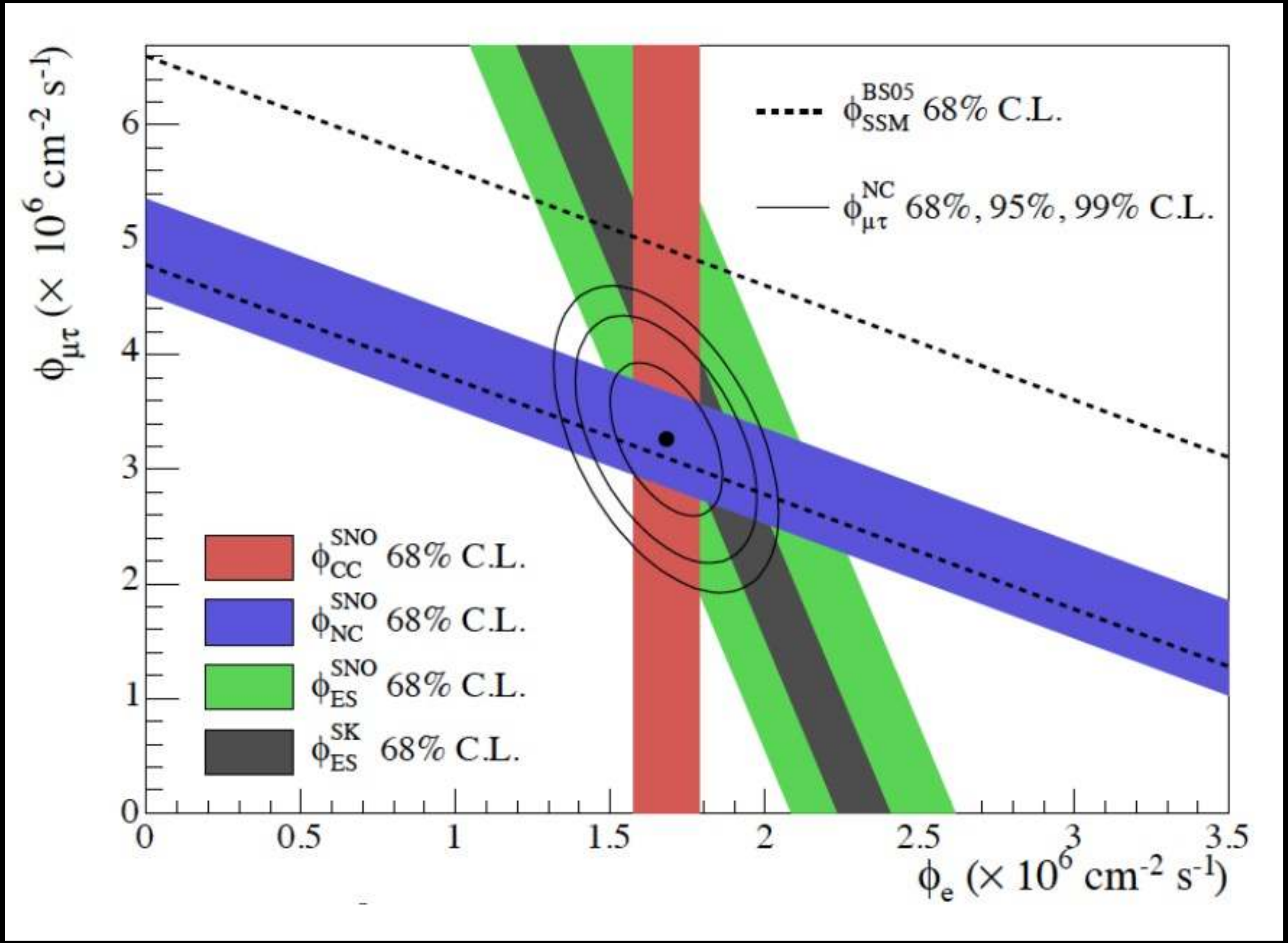
Observations:

- Total number of neutrinos match.
- Only a third of the expected electron-neutrinos

Conclusion:

- Neutrino Oscillation

Neutrino Observations Consistent with SSM



Confidence Levels:

- Red: Electron-Neutrinos
- Blue: All Neutrinos
- Green: Electron-Neutrino Dominated

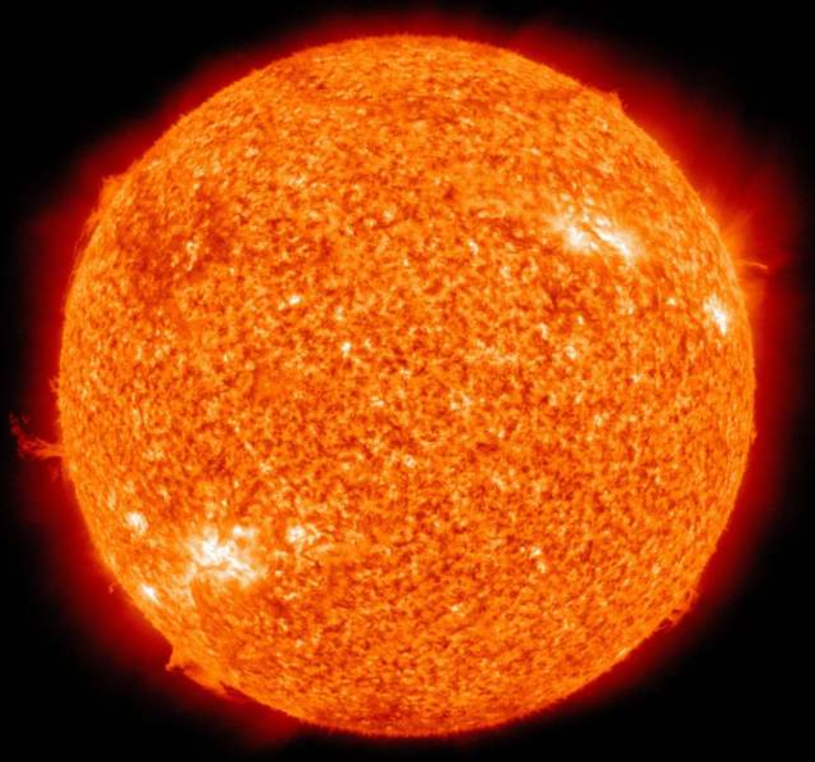
Parameter Constraints:

ρ: Density
T: Temperature

Nakamura et al. 2014

Reframing the Standard Solar Model

Hydrostatic Equilibrium	Thermonuclear Reactions
Internal Composition	Energy Transport



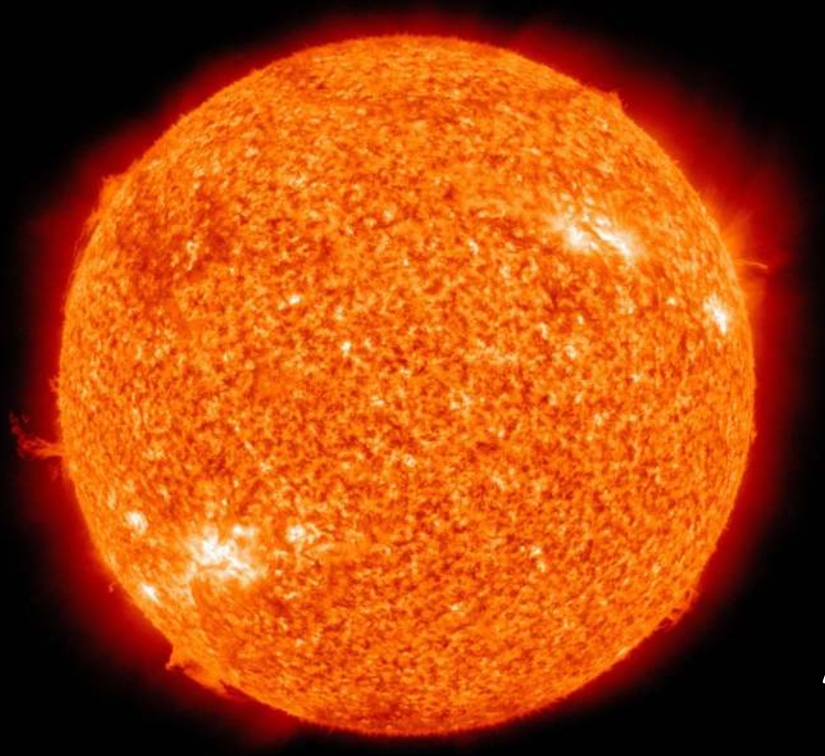
$L_\odot$

$R_\odot$

Age

Need Parameters Consistent with Sun

Density $\rho(r)$	Neutrinos υ_e
Composition $X(r), Y(r), Z(r)$	Temperature $T(r)$



$L_\odot$

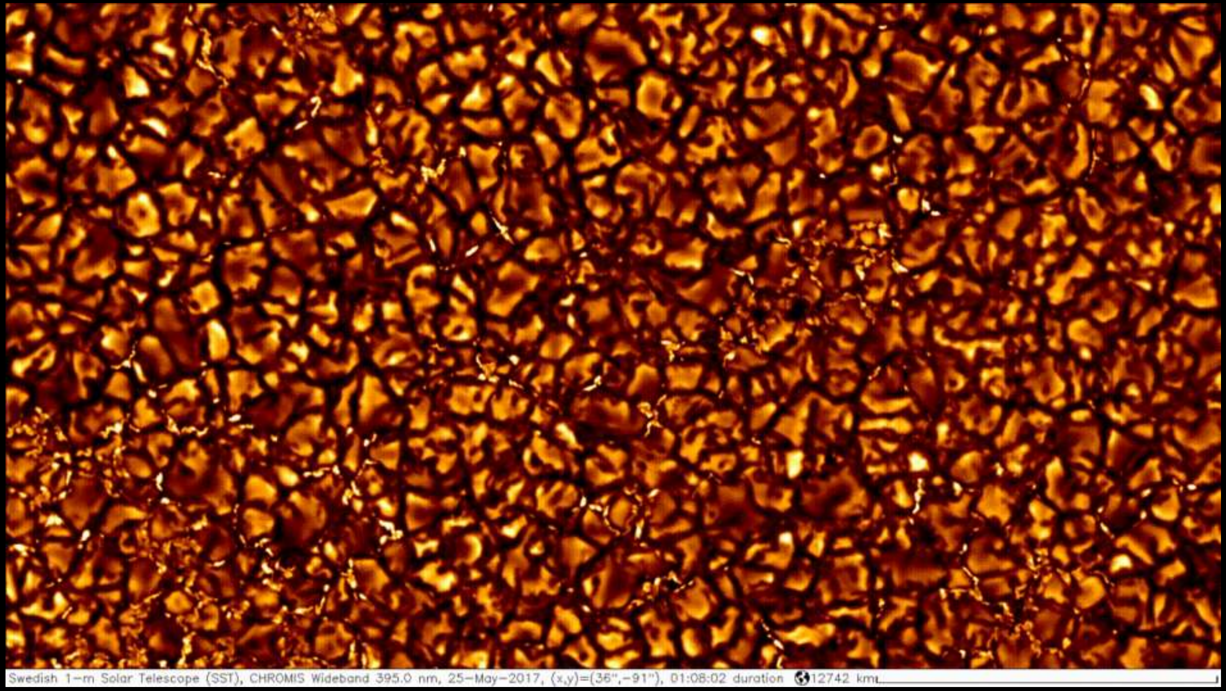
$R_\odot$

Age

What work has been done over the past 30 years to constrain parameters?

Do the models match observations of the Sun?

Helioseismology and Interior of the Sun



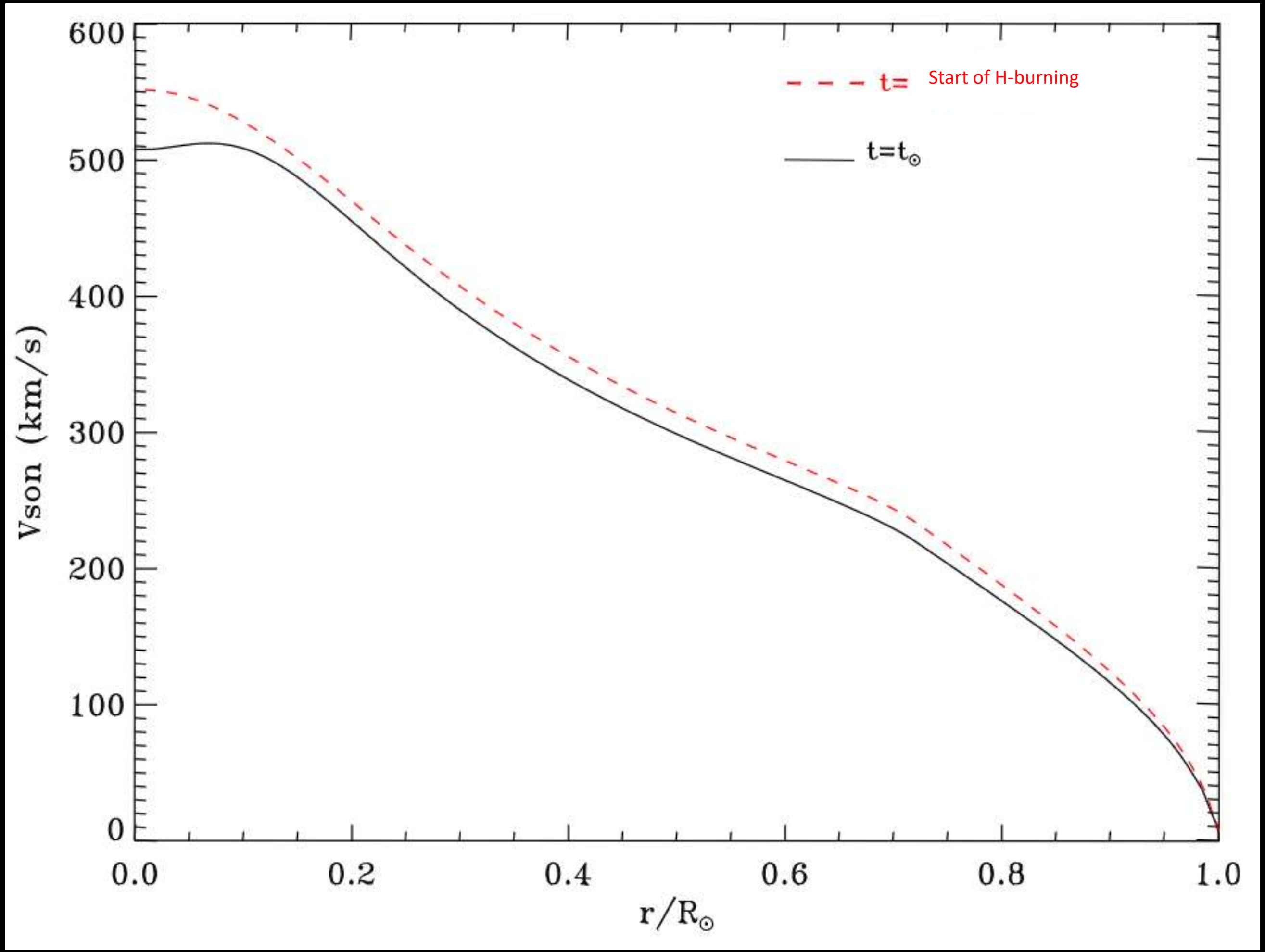
Credit: Swedish Solar Telescope

- Acoustic waves generated by granulation on solar surface
- Propagate inside Sun to a depth depending on velocity

Grant's Talk Next Week

- Measure Interior:
  - c_s^2: Squared Sound Speed
  - ρ: Density

Ideal Gas Sound Speed related to Temperature



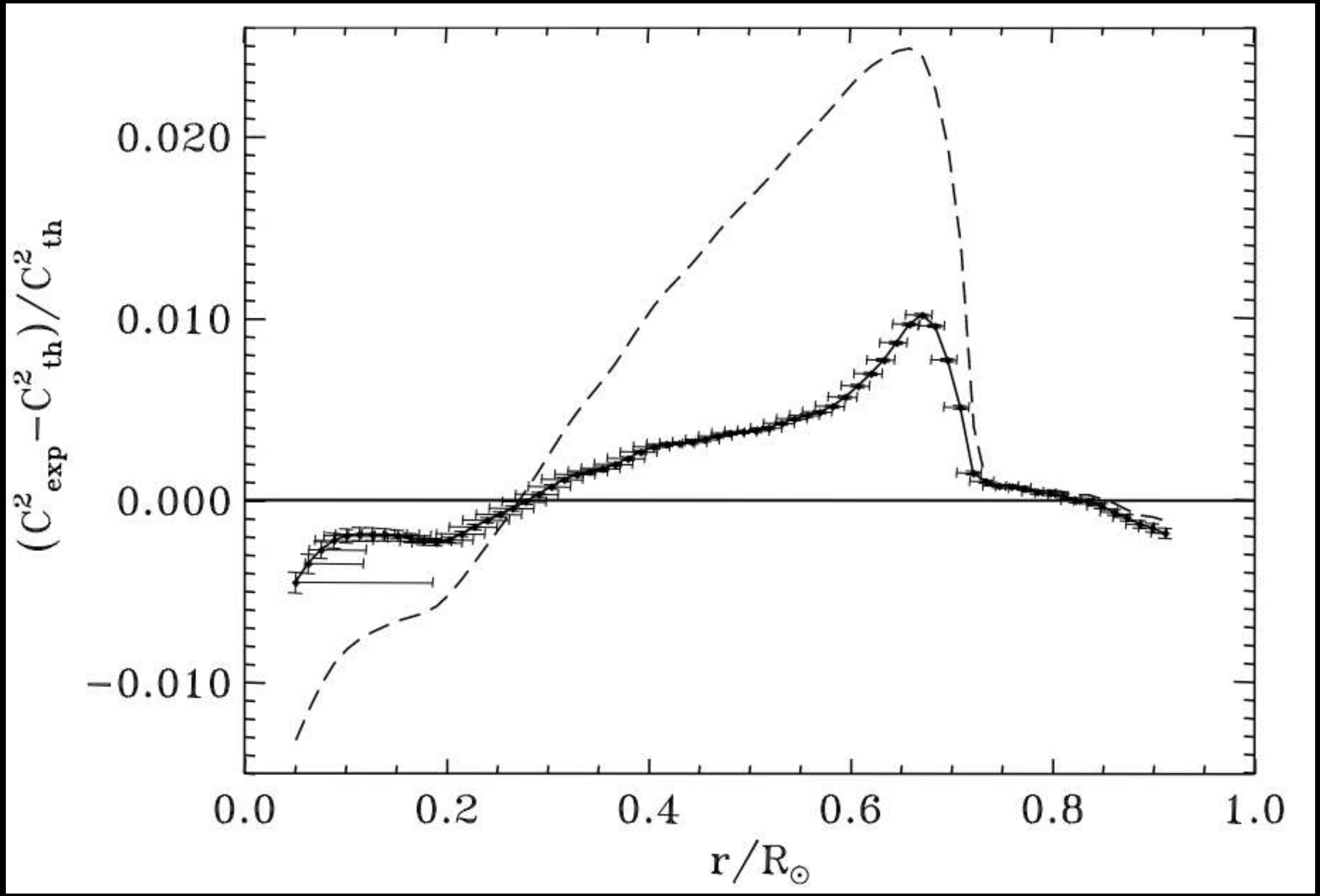
Turck-Chieze et al. 2011

$$c_s^2 = \frac{\gamma R T}{\mu}$$

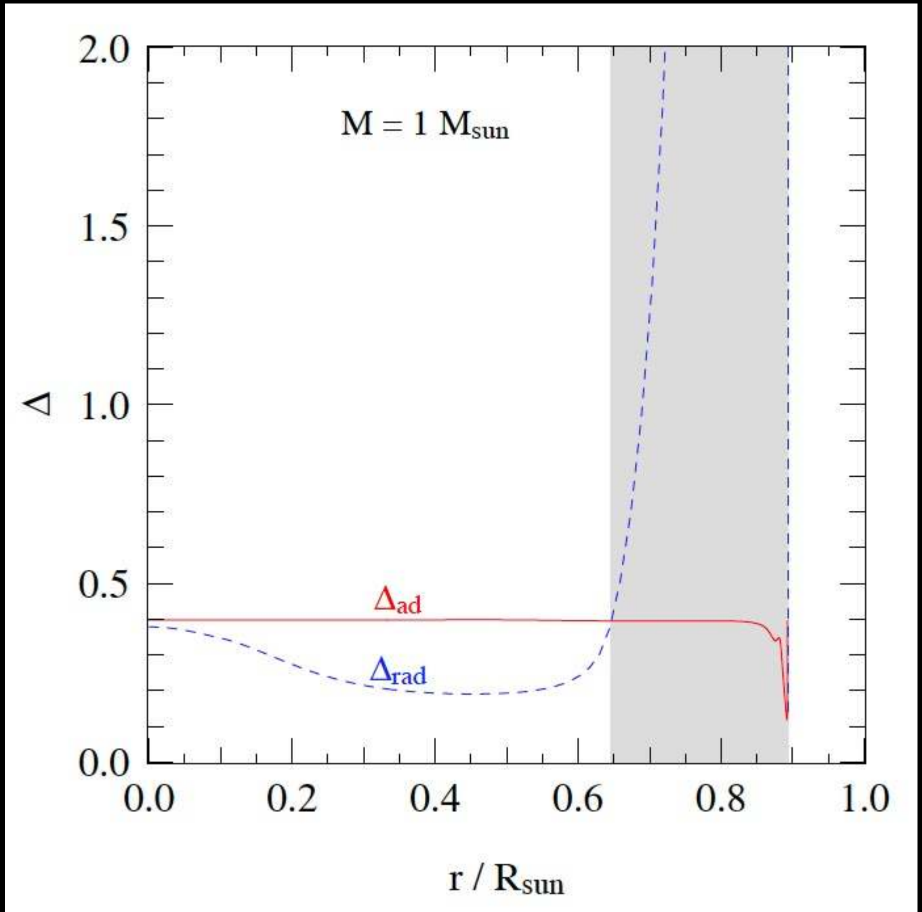
Measure Interior:

- T: Temperature

Models Failing near Edge of Convection Zone

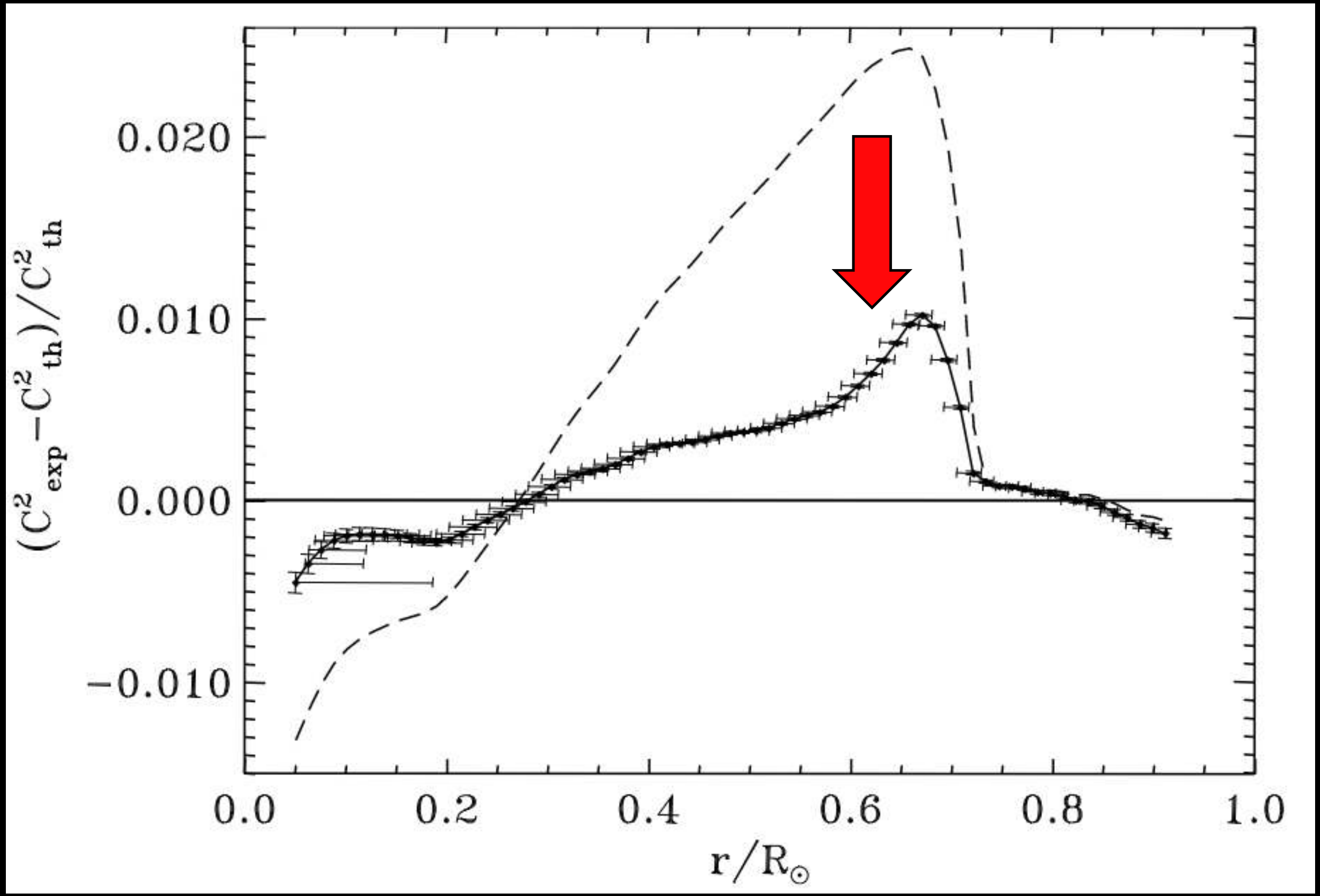


Brun et al. 1998



Credit: O. R. Pols

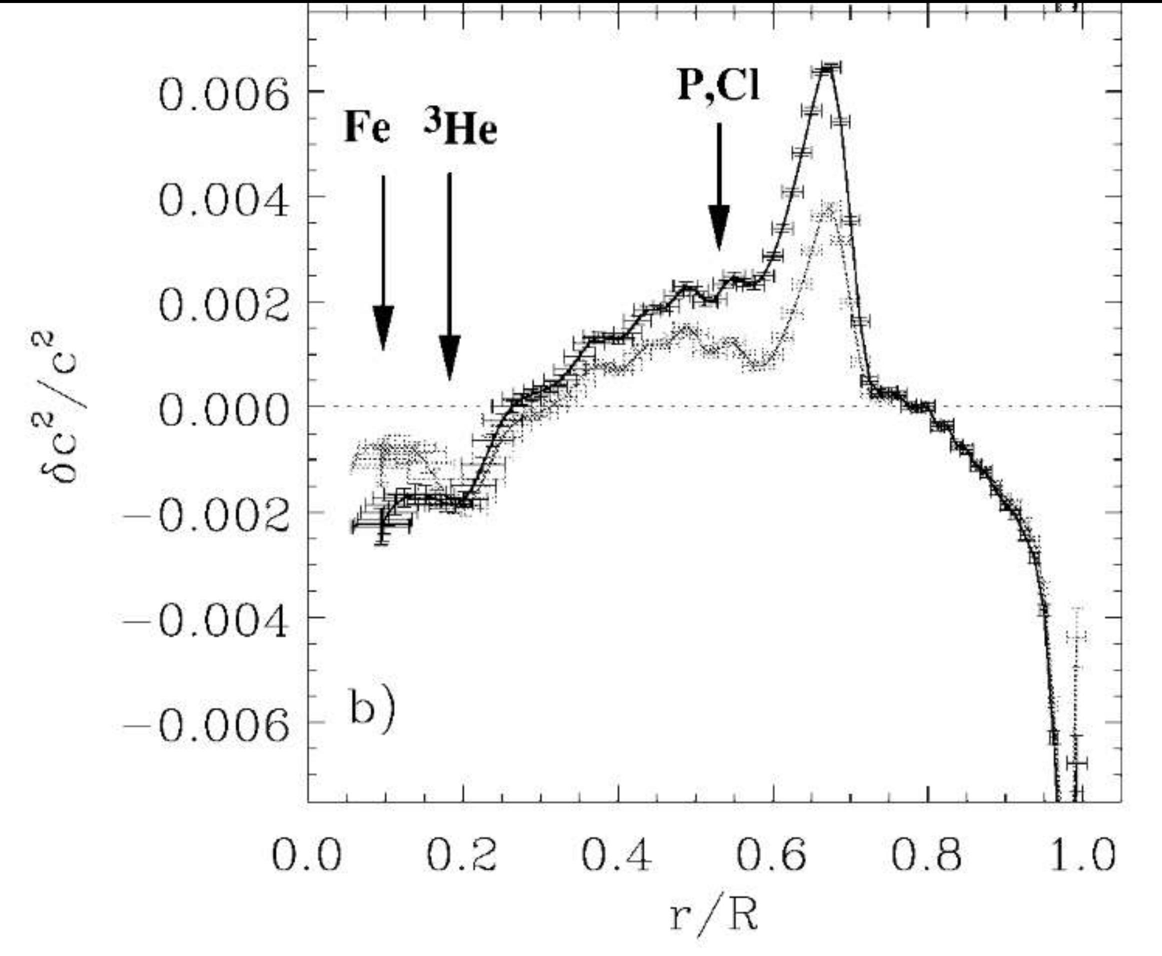
Time Evolution of Composition



Brun et al. 1998

- Depletion of ^{7}Li and ^{9}Be in outer envelope difficult to reproduce.
- Heavy elements slowly diffuse towards center of Sun
- Two important effects:
  - Microscopic Diffusion
  - Turbulence between radiative and convective zone

Abundance & Reaction Rate Dependence



Turck-Chieze et al. 2001b

Table 7. Sensitivity of the sound speed to the physical processes.

Quantity	Variation	$\Delta c^2/c^2$ variation
T	1%	1%
κ	1%	0.1%
$X_c\,{}^{56}$Fe	4%	0.1%
$X\,{}^3$He	25%	0.1%
(p, p) reaction rate	1%	±0.1%
(^{3}He, ^{3}He) reaction rate	−25%	−0.1%
(^{3}He, ^{4}He) reaction rate	−25%	+0.2%
(p, ^{7}Be) reaction rate	10%	None
(p, ^{16}O) reaction rate	−50%	−0.1 to 0.2% just at the center

Turck-Chieze et al. 2011

The Standard Solar Model seems to be doing well!

Agreement with sound speed within 1%

New Solar Metallicity Estimates

Determine Initial Composition of the Sun

Earth

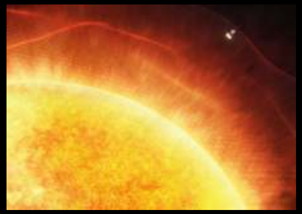
Isotope Ratios

Loss of Volatile Elements: C, N, O

Meteorites

Elemental Abundances

Loss of Volatile Elements: H, C, N, O



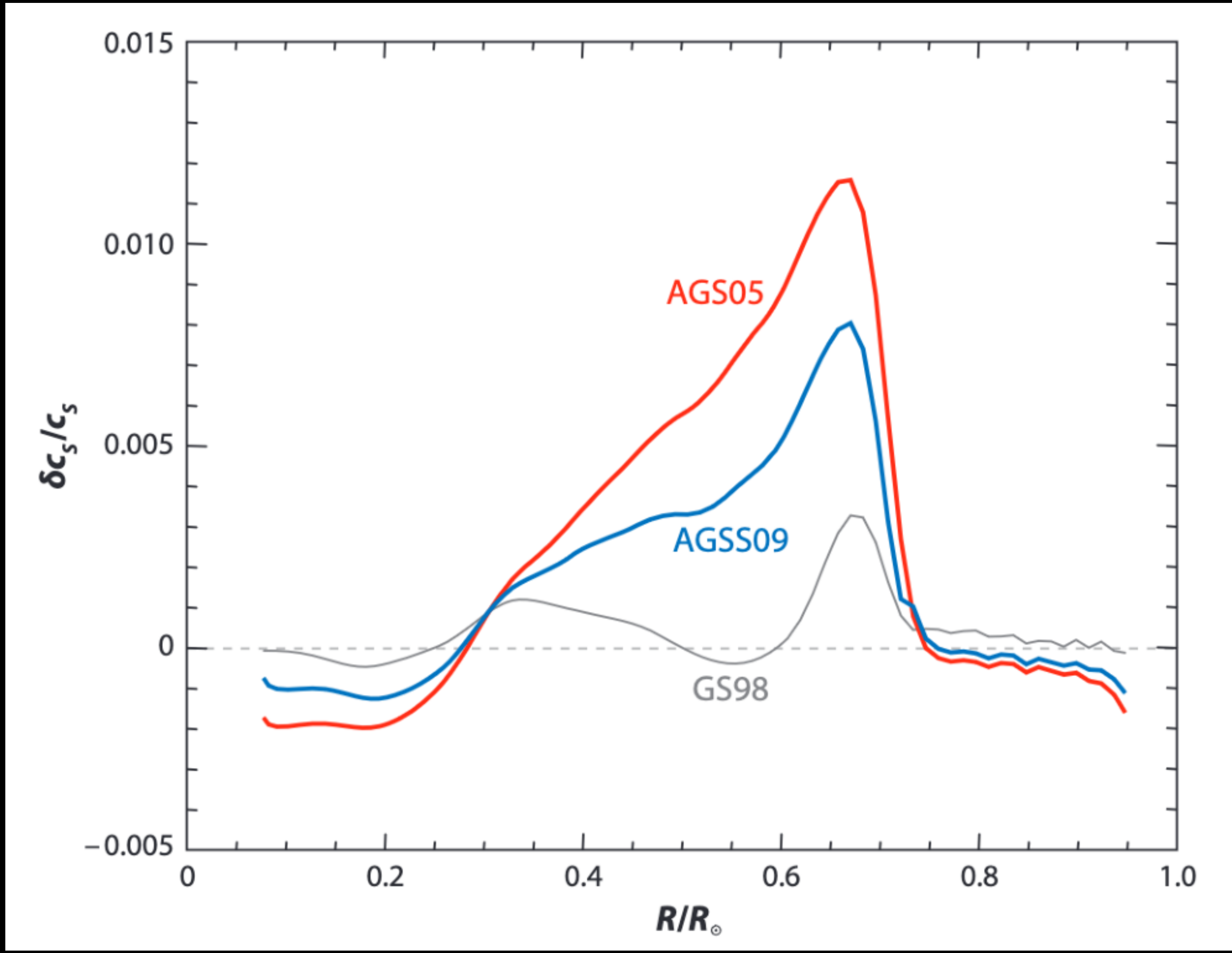
Solar Photosphere

Elemental Abundances

Do we understand the Solar Spectra?

Solar Metallicity Decreases by ~35%

- 3D hydrodynamical model of solar atmosphere
- Departures from LTE
- Updated Atomic Data (Oscillators strengths)

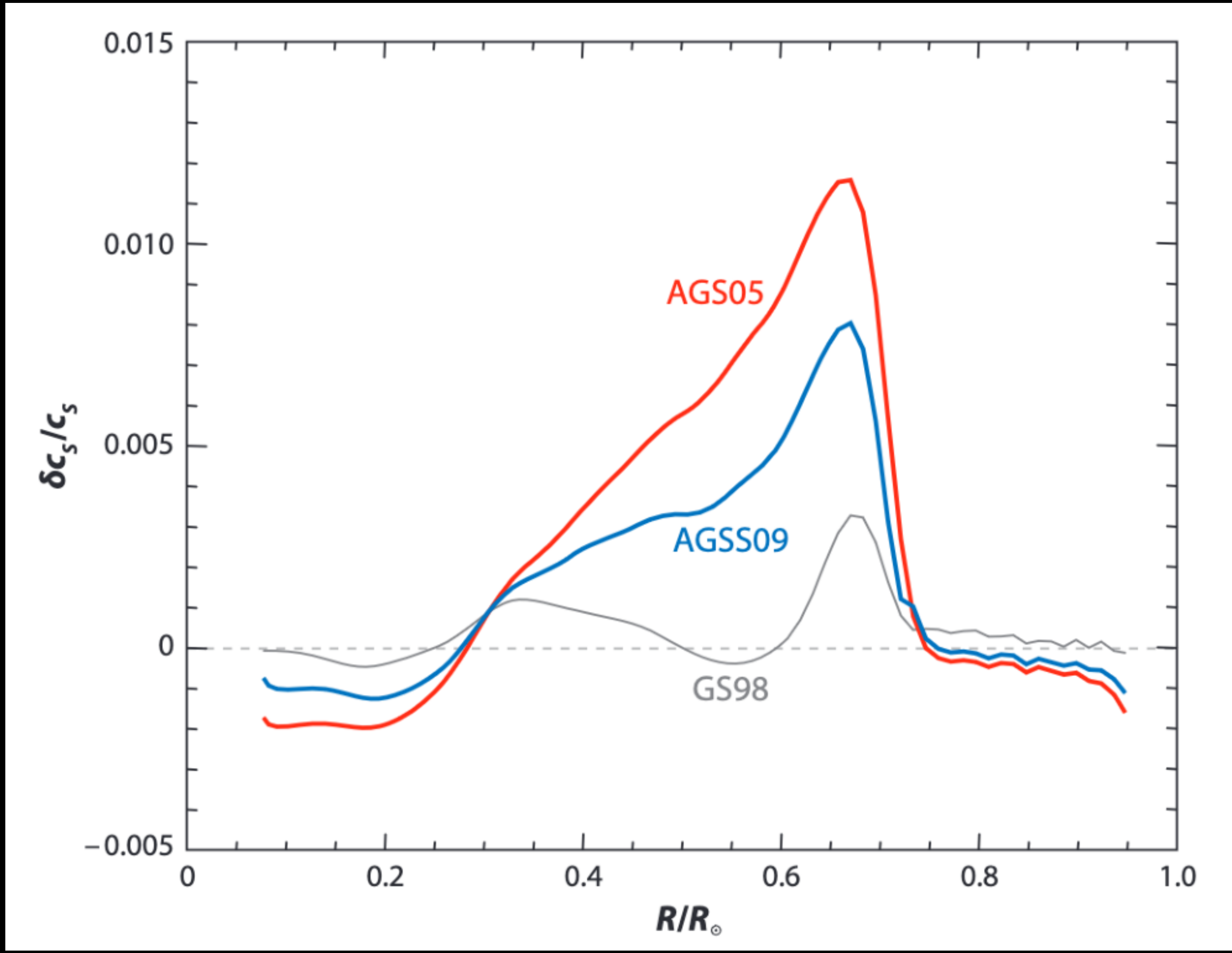


Asplund et al. 2009

Solar Metallicity Decreases by $\sim$35%

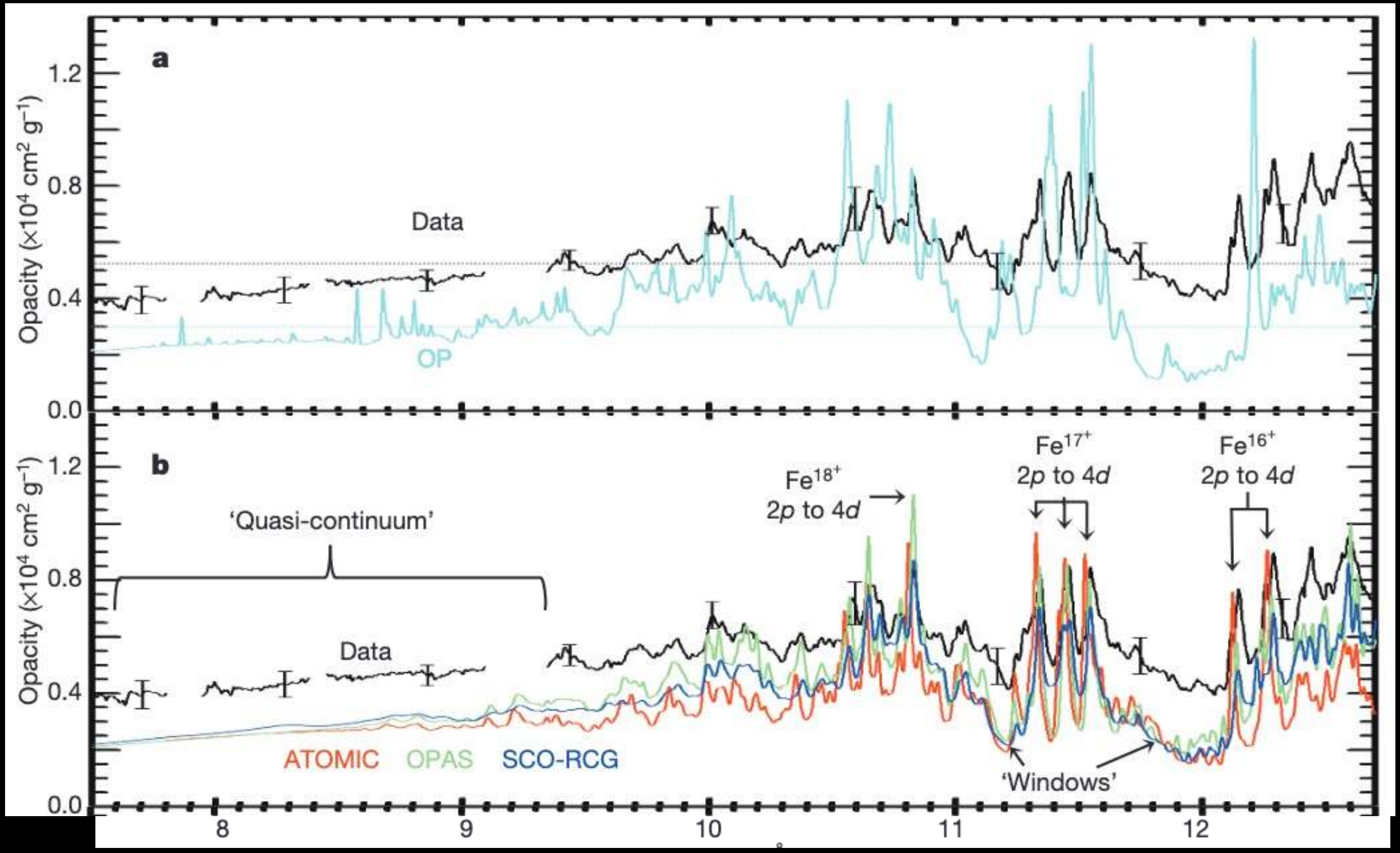
- $\sim 30\%$ decrease in abundance of C, N, O
- Decrease in $Z_{\odot}$

  Before: $Z_{\odot} = 0.02$
  After: $Z_{\odot} = 0.013$
- Work ongoing to find which metallicity is "correct"



Asplund et al. 2009

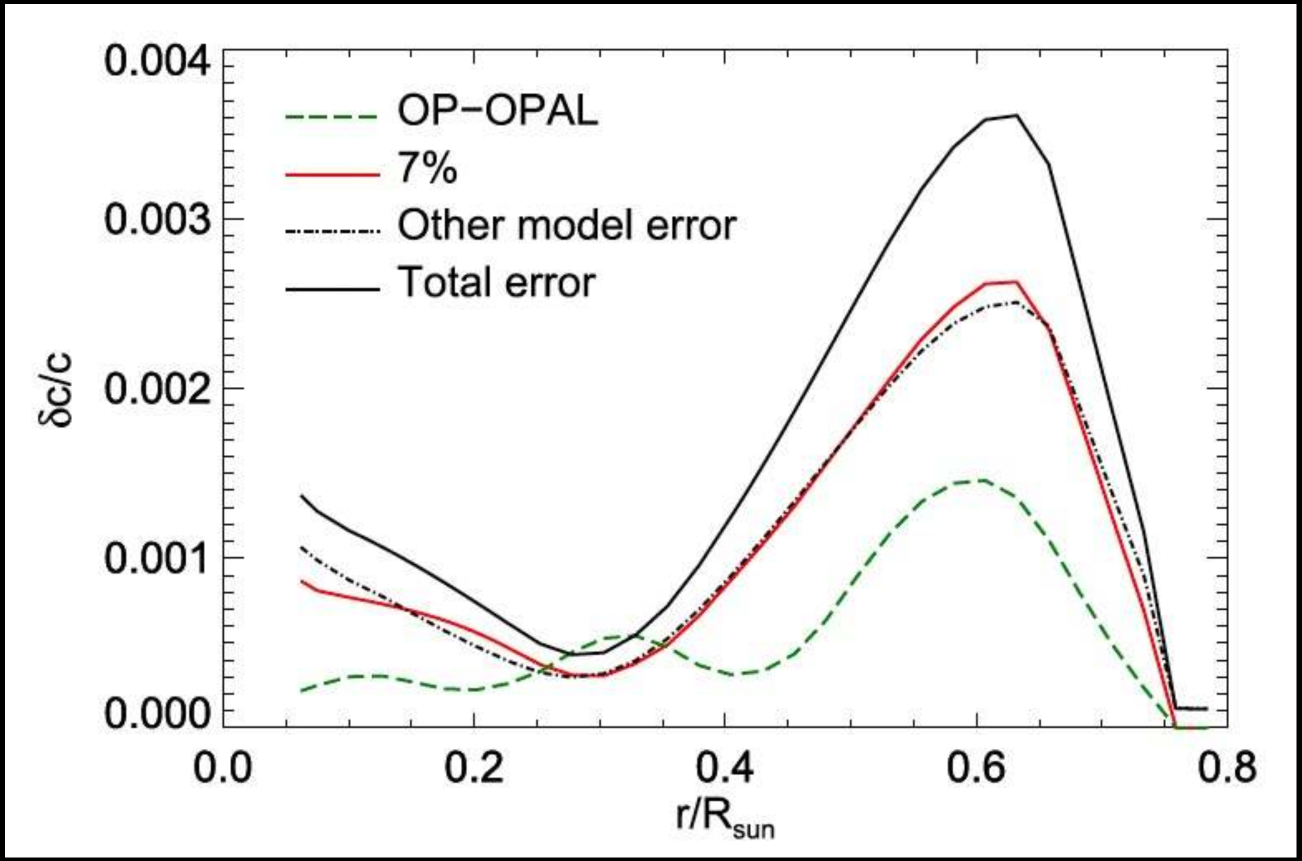
Opacities too small at Bottom of Convective Zone



Bailey et al. 2015

- Solar models use opacities that are too low
- $\Delta\kappa = 7 \pm 4\%$
- 50% of opacity change needed for sound speed difference

Present day: Convective Zone Transition Issues Unsolved



Vinyoles et al. 2017

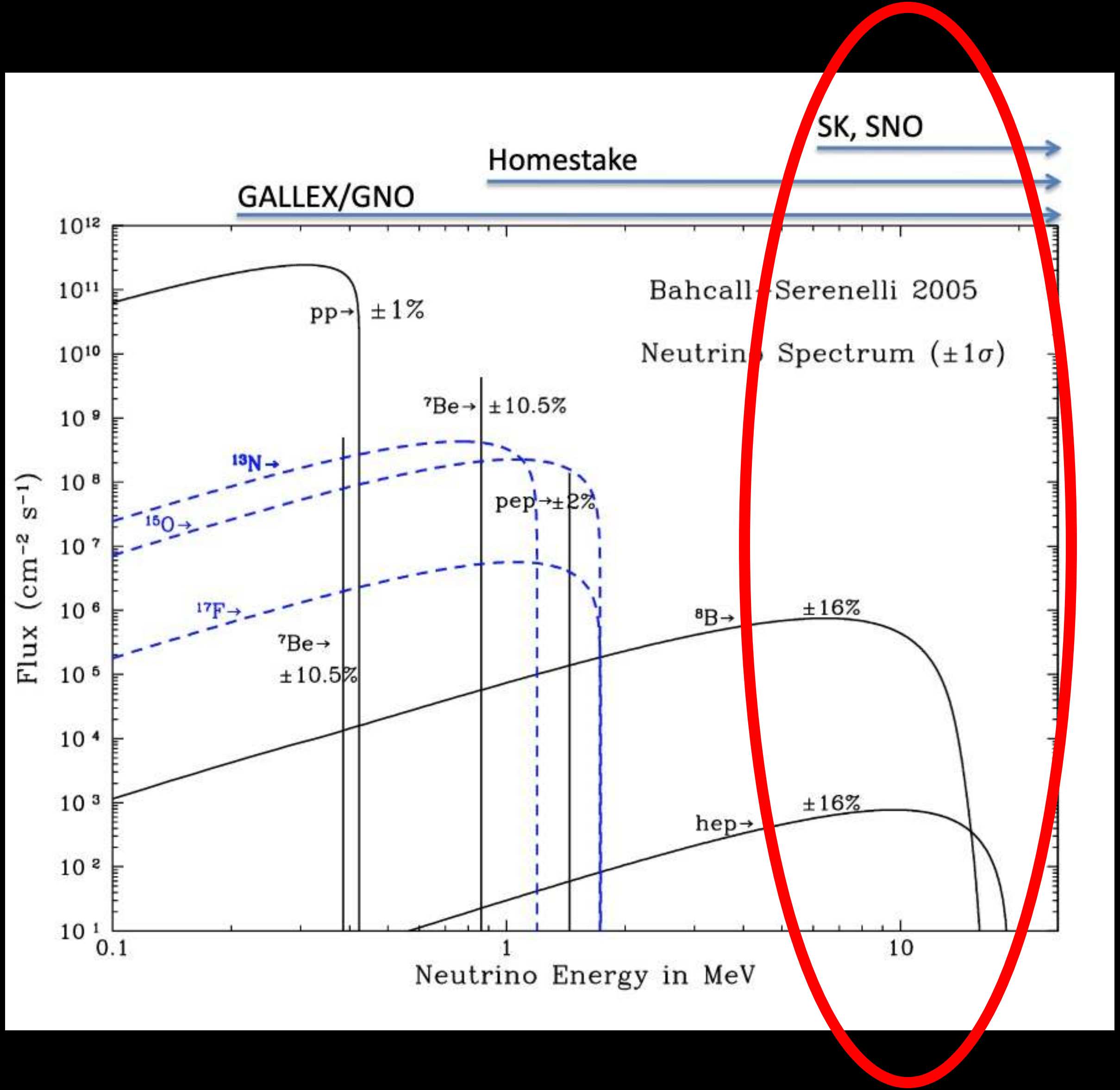
Possible explanations?

- Smoother chemical profile from turbulent mixing (Anita et al. 1998)
- Smoother transition between adiabatic and radiative ∇T (Christensen-Dalsgaard et al. 2011)

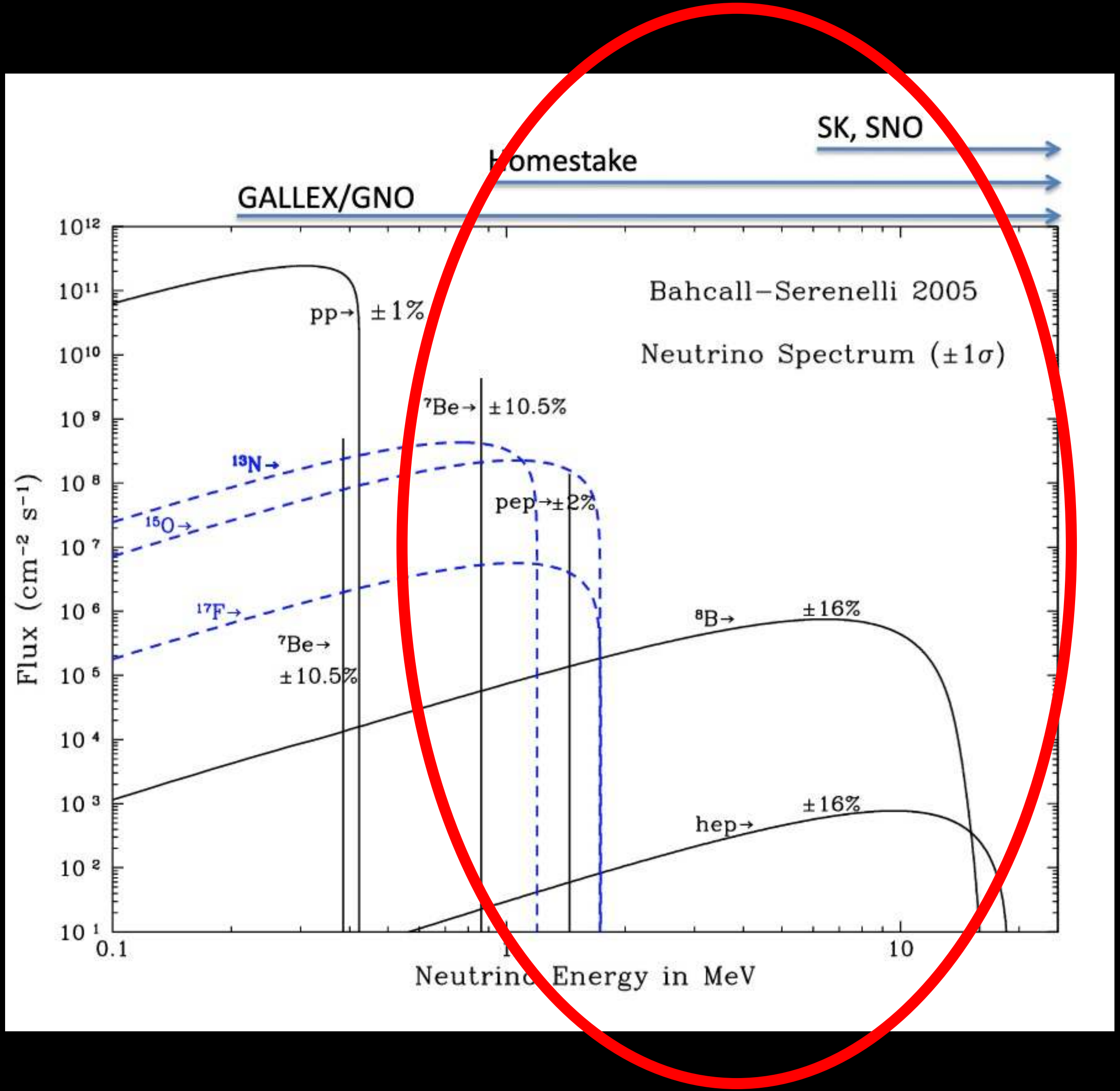
Beyond the Standard Solar Model

- Expanded and improved solar neutrino measurements
- Dynamical view of the Sun including internal rotation and magnetic fields

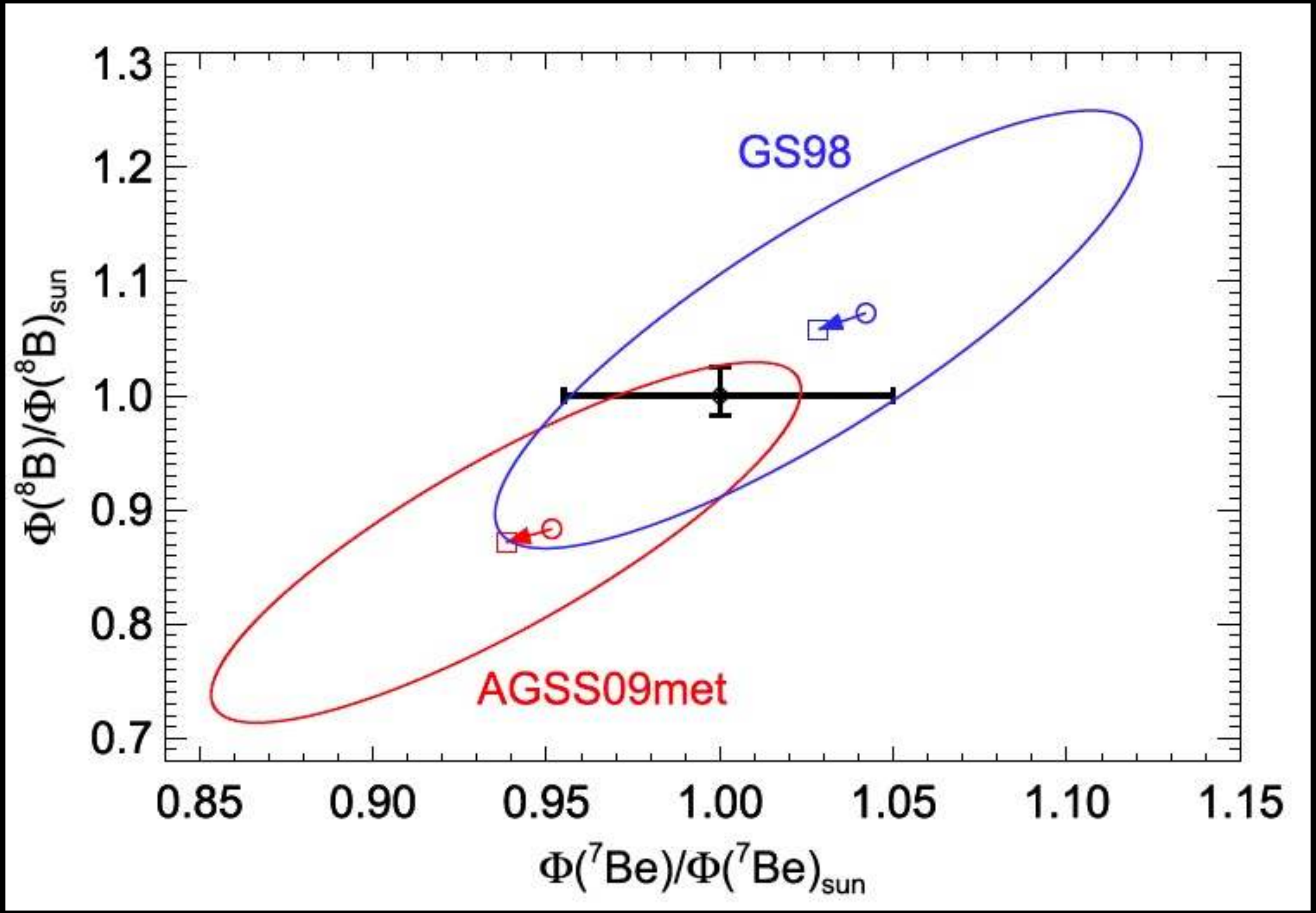
New Facilities Increasing Detection Limits



New Facilities Increasing Detection Limits

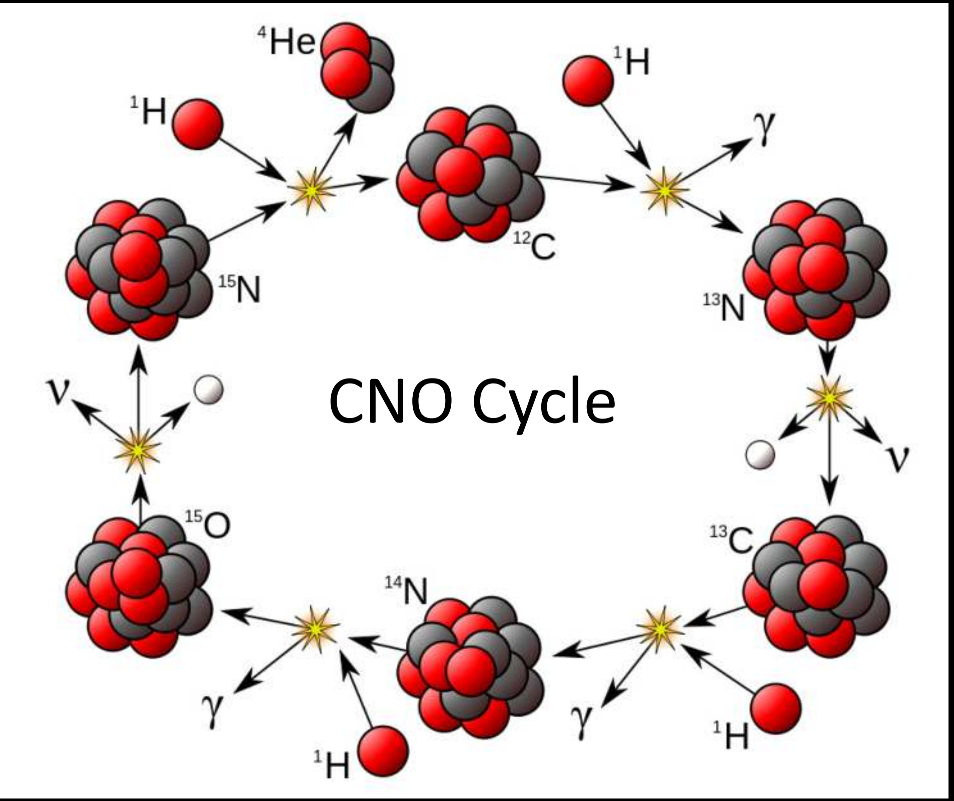


Higher Metallicity Suggested by $^7\mathrm{Be}$ from PP-Chain?



Vinyoles et al. 2017

Electron-Neutrinos also produced in CNO



Hydrogen in

$$^{12}C + {}^1H \longrightarrow {}^{13}N + \gamma$$

$$^{13}N \longrightarrow {}^{13}C + e^+ + \nu$$

$$^{13}C + {}^1H \longrightarrow {}^{14}N + \gamma$$

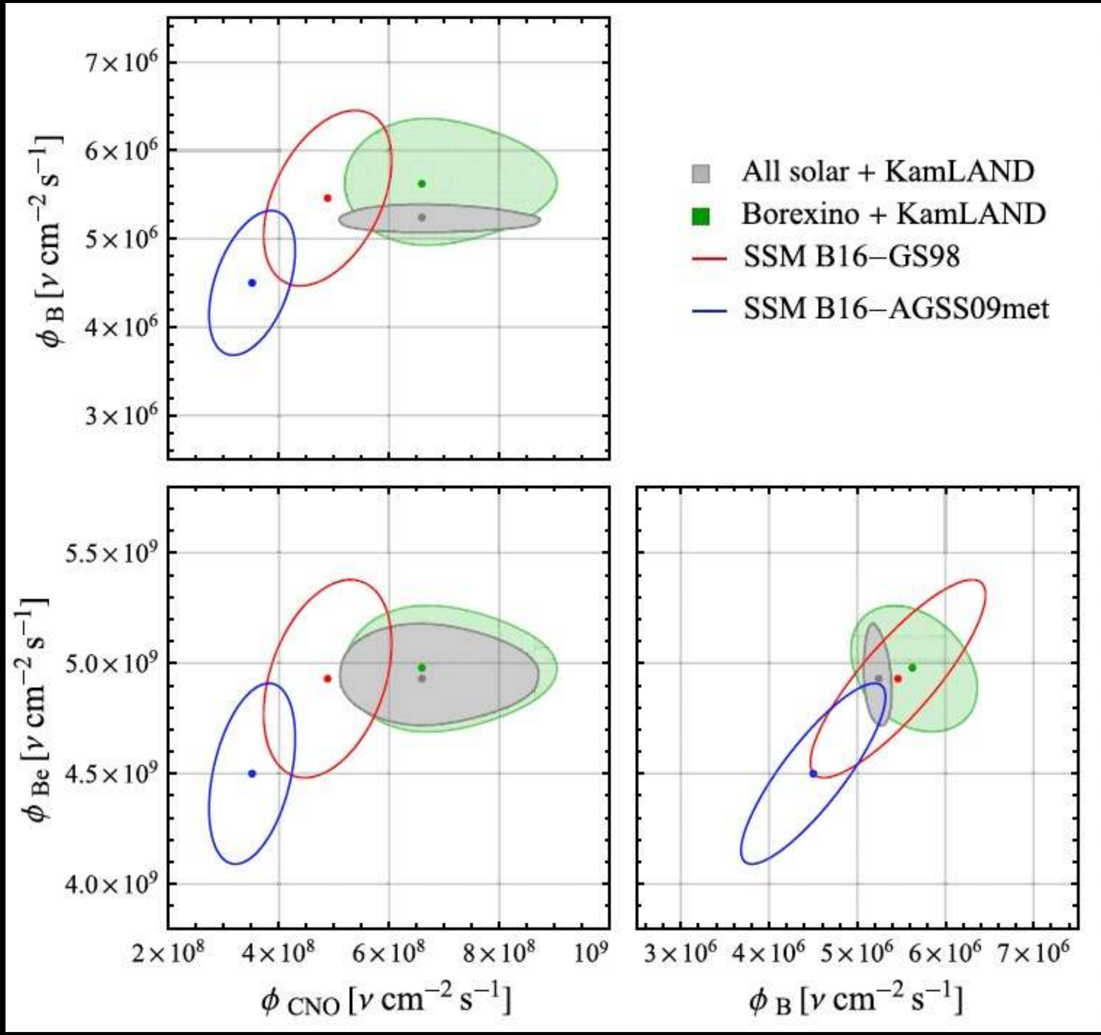
$$^{14}N + {}^1H \longrightarrow {}^{15}O + \gamma$$

$$^{15}O \longrightarrow {}^{15}N + e^+ + \nu$$

$$^{15}N + {}^1H \longrightarrow {}^{12}C + {}^4He$$

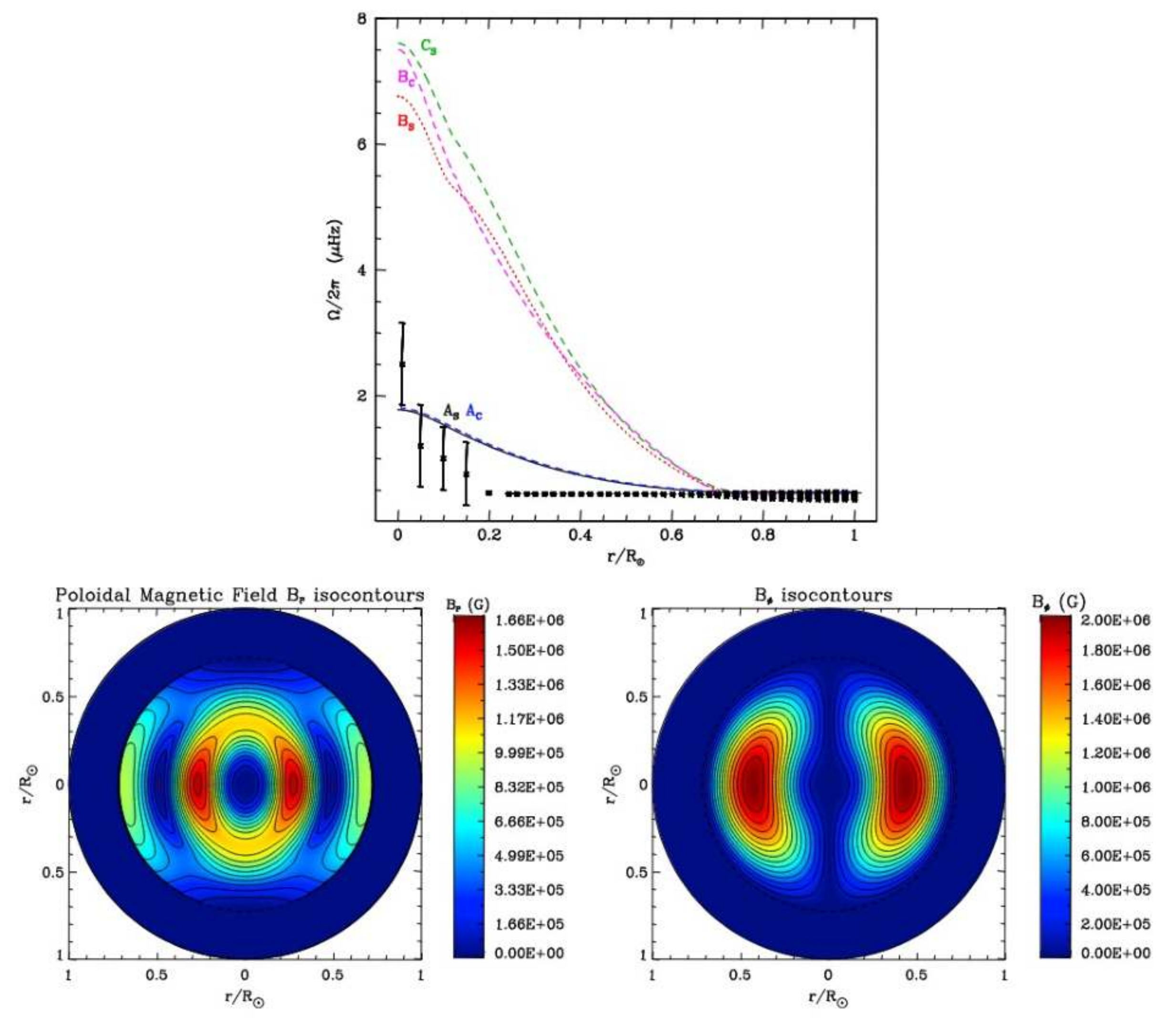
Helium out

Favor Higher Solar Metallicity



Borexino Collab. 2022

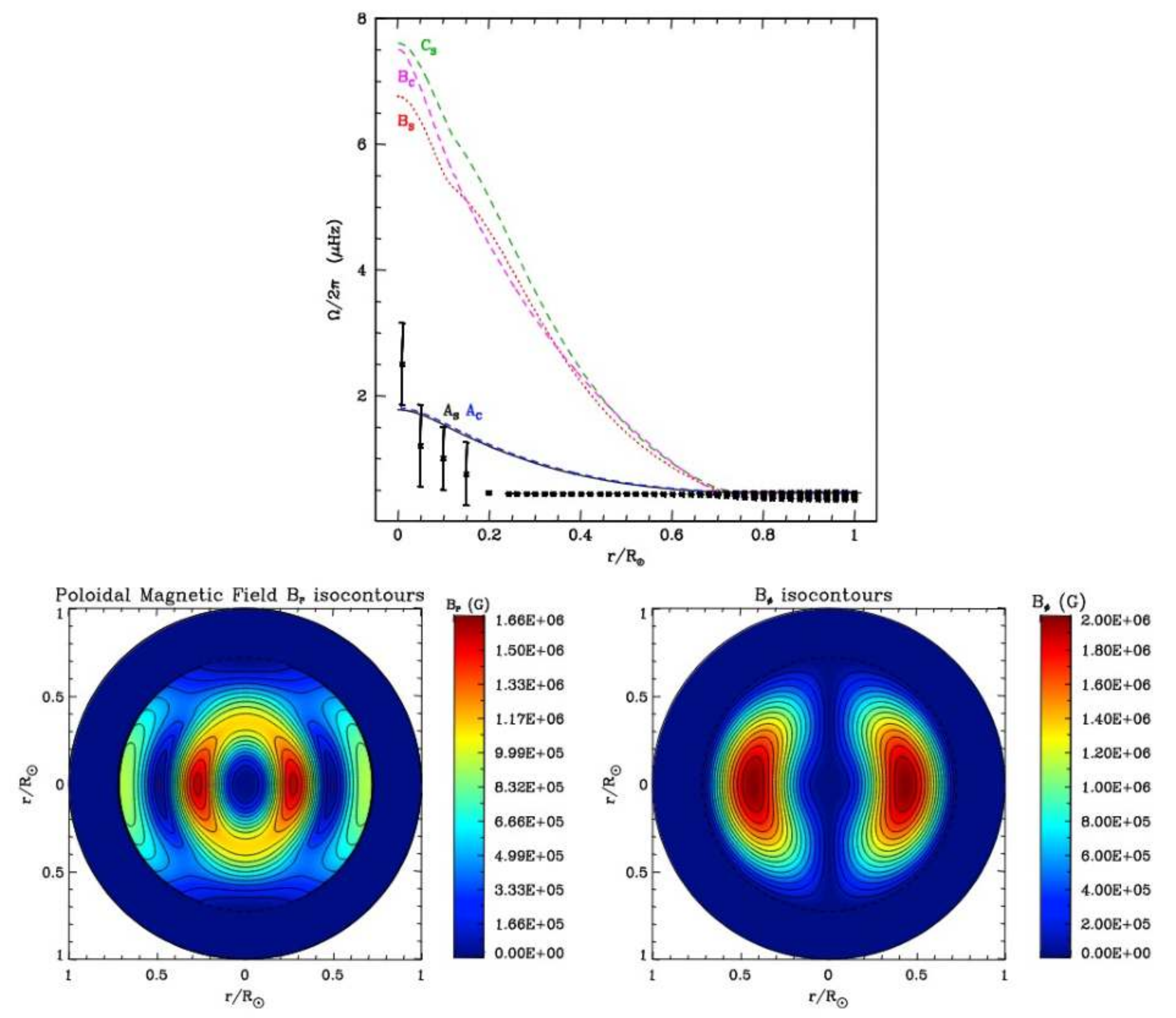
Rotation and Magnetic Fields are Challenging



Turck-Chieze et al. 2010a; Duez et al. 2010

- Horizontal turbulent flow generated at interface of radiative & convective zones
- Sustains a magnetic field that is stretched and amplified.
- Called the tachocline, dynamics could explain sound speed discrepancy

Rotation and Magnetic Fields are Challenging



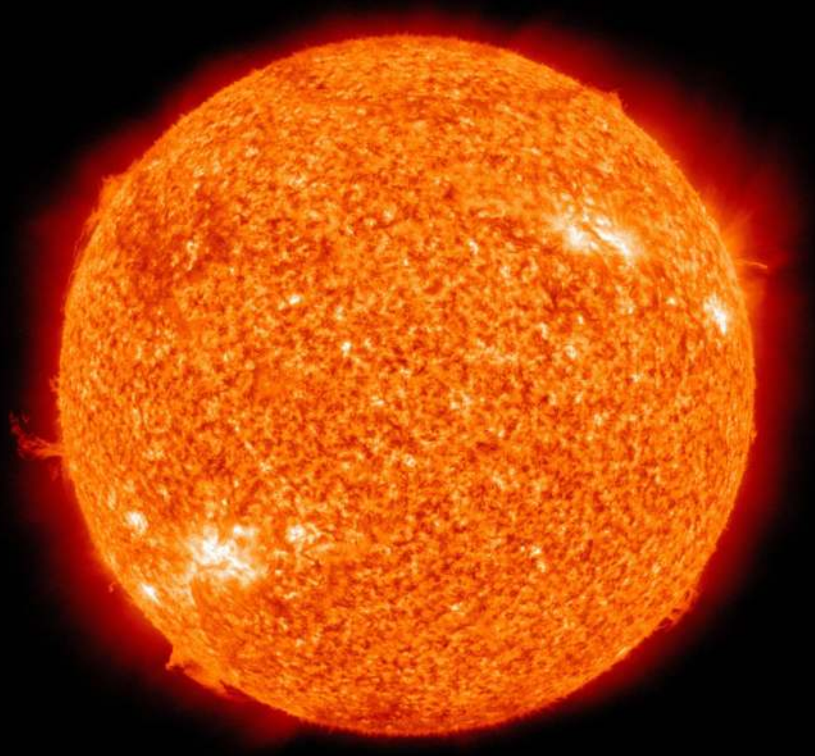
Abigail's Talk

Cory's Talk

Turck-Chieze et al. 2010a; Duez et al. 2010

The Standard Solar Model

Hydrostatic Equilibrium	Thermonuclear Reactions
Internal Composition	Energy Transport



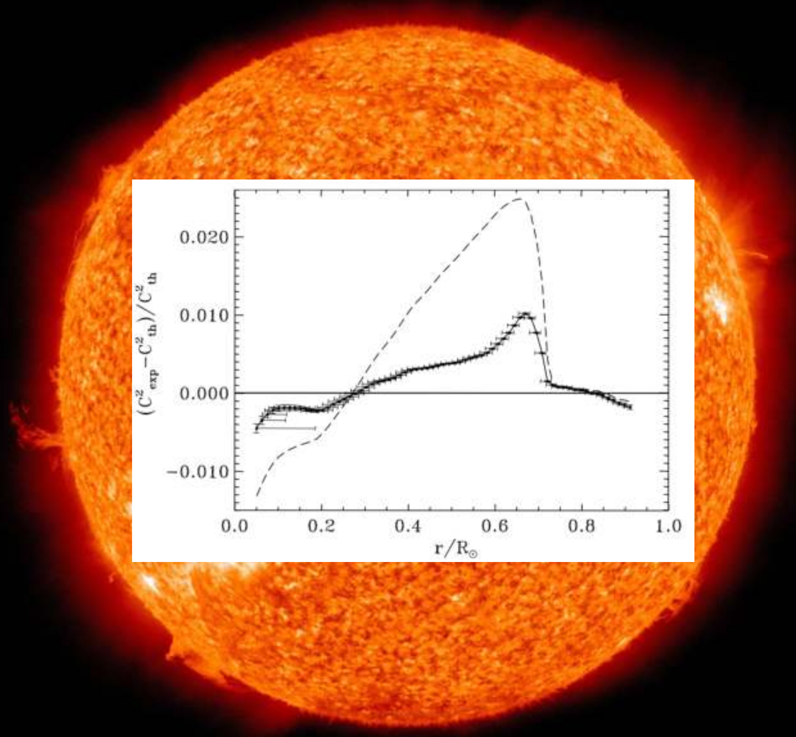
$L_\odot$

$R_\odot$

Age

Helioseismic and Neutrino Constraints

Density $\rho(r)$	Neutrinos ν_e
Composition $X(r), Y(r), Z(r)$	Temperature $T(r)$



$L_\odot$

$R_\odot$

Age

Beyond the Standard Solar Model

- Solving the sound speed discrepancy at the radiative/convective boundary
- Expanded and improved solar neutrino measurements
- Dynamical view of the Sun including internal rotation and magnetic fields

References

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Appendix: (Brun et al. 1998-99)

$$\frac{\partial X_i}{\partial t} = \frac{\partial X_{i,nuc}}{\partial t} - \frac{\partial \left[\left(4\pi\rho r^2 (D_i + D_T) \frac{\partial X_i}{\partial m} - v_i X_i \right) \right]}{\partial m}$$