An introduction to

Stellar Energy Transport

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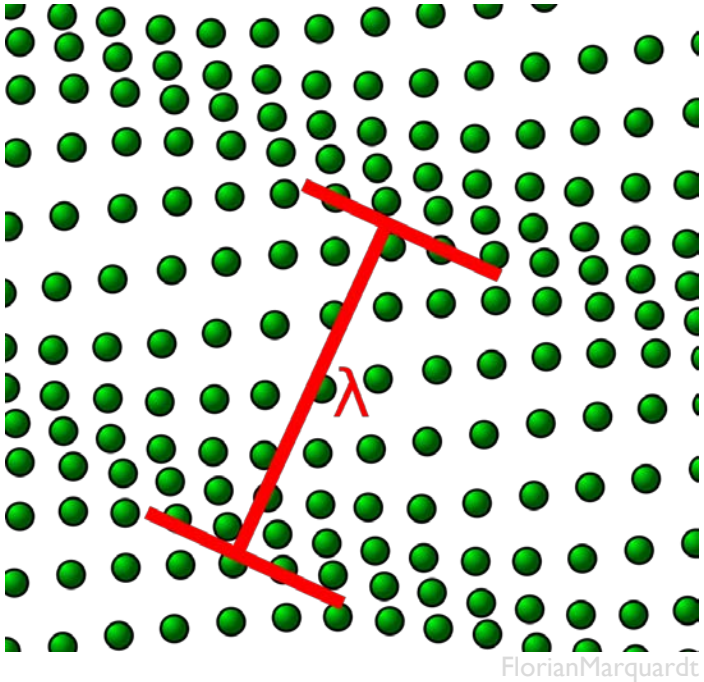
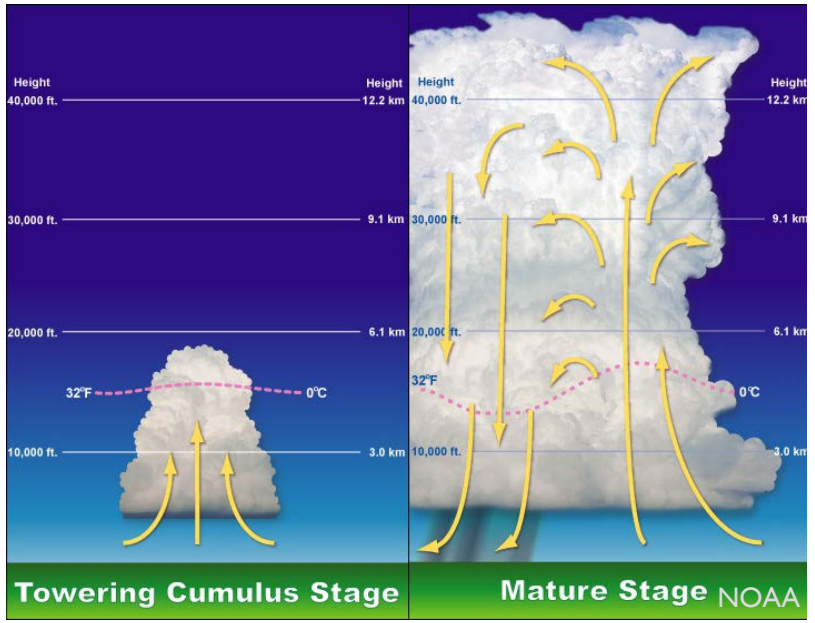
Heat transport mechanisms

Conduction



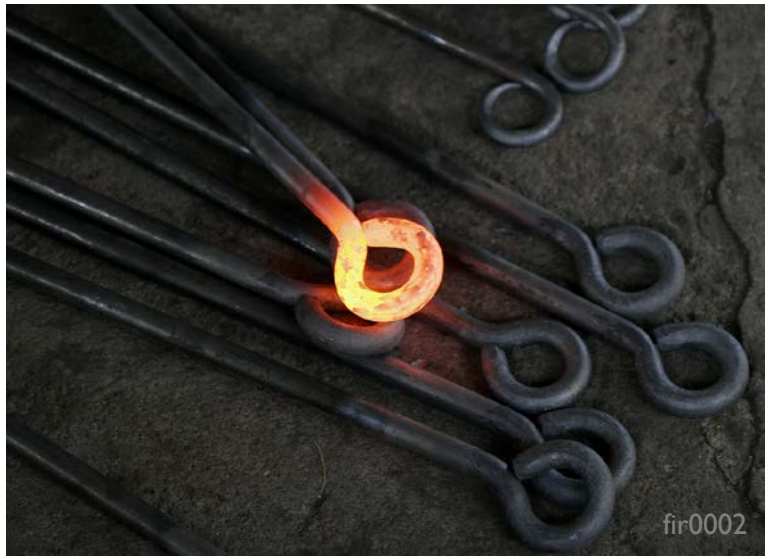
- Molecular vibrations or transferring electrons from one atom to another
- Only relevant for white dwarf and neutron stars

Convection



- Bulk fluid motion due to temperature differences
- Relevant for most stars, though the radial location and extent depends on details

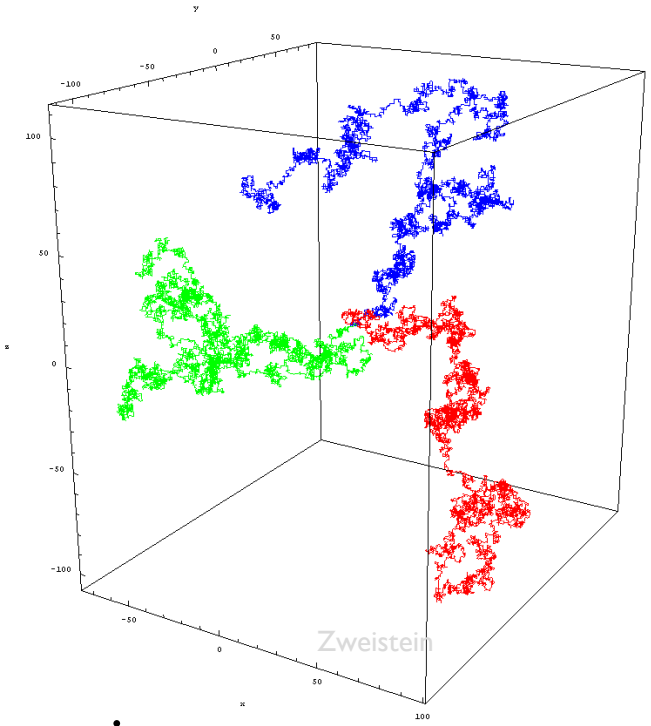
Radiation

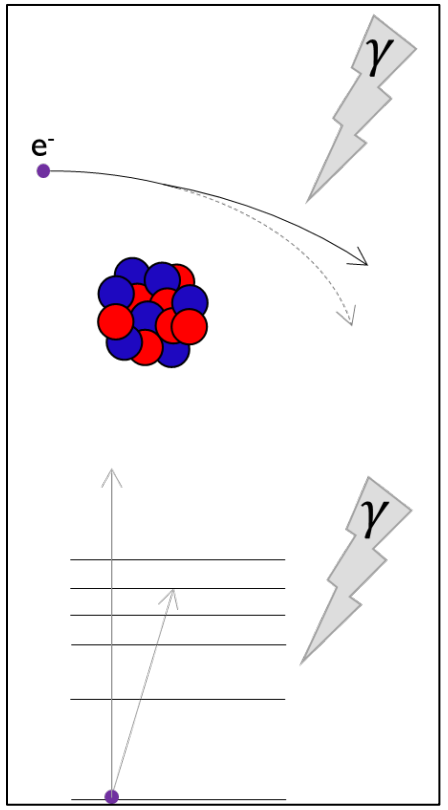


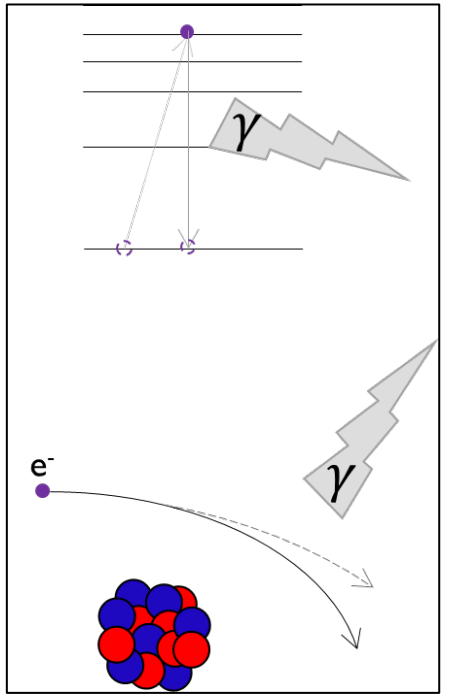
- Photons carrying energy away
- Relevant for most stars, though the radial location and extent depends on details

Radiation from the sun's core

- Neutrinos stream straight out (see Introduction to Stellar Nuclear Power lecture), but the photons follow a more convoluted path
- A photon can be scattered or absorbed and the energy re-emitted.
- Ultimately "the" photon performs a random walk out of the star, requiring N steps to escape
- For a photon making it to the stellar radius $R \sim l\sqrt{N}$, where l is the "mean free path" a photon travels before interaction
- For the solar core, $\langle l \rangle \sim 0.02\ cm$, so the photon diffusion time $\tau_{diff} \sim \frac{Nl}{c} \sim \frac{R^2}{lc}$ …for the sun ~200 kyr

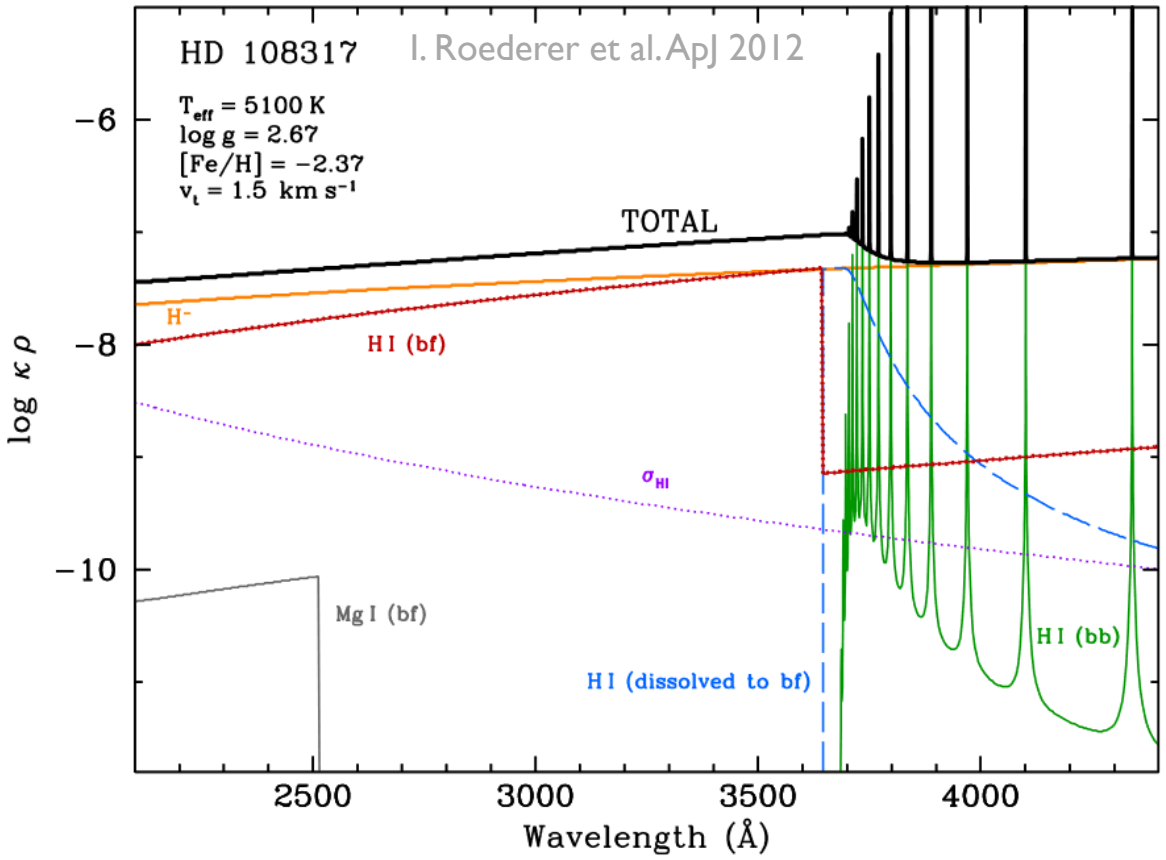


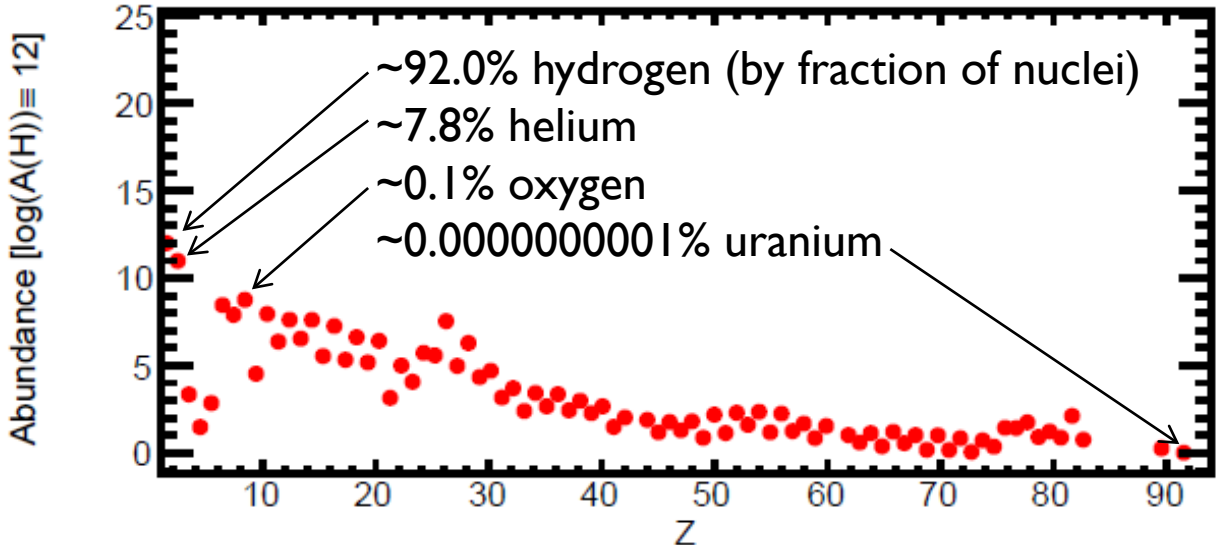


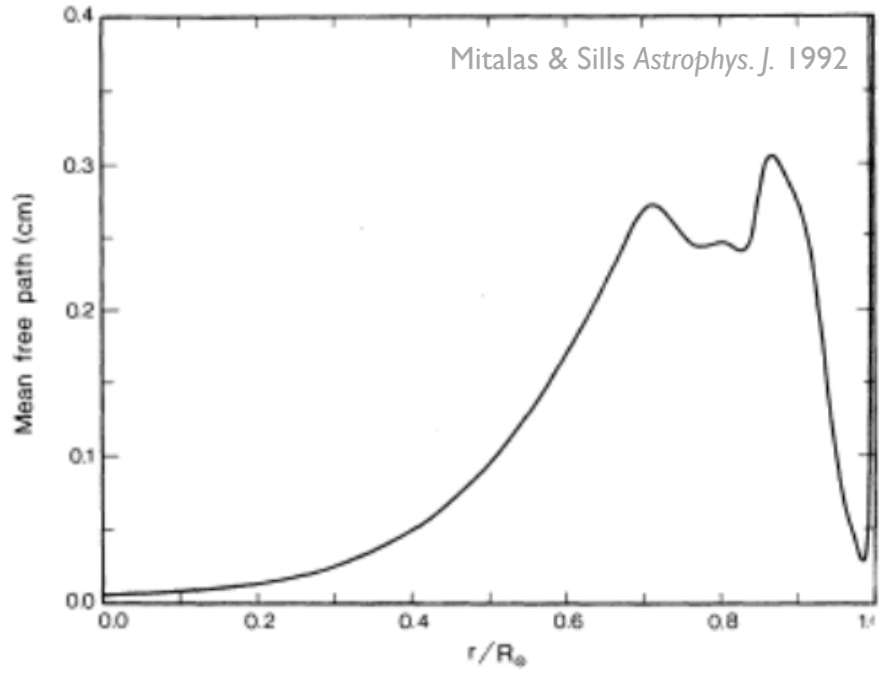


Radiation transport is sensitive to details

- The photon's mean free path, l, depends on the composition, temperature, and density

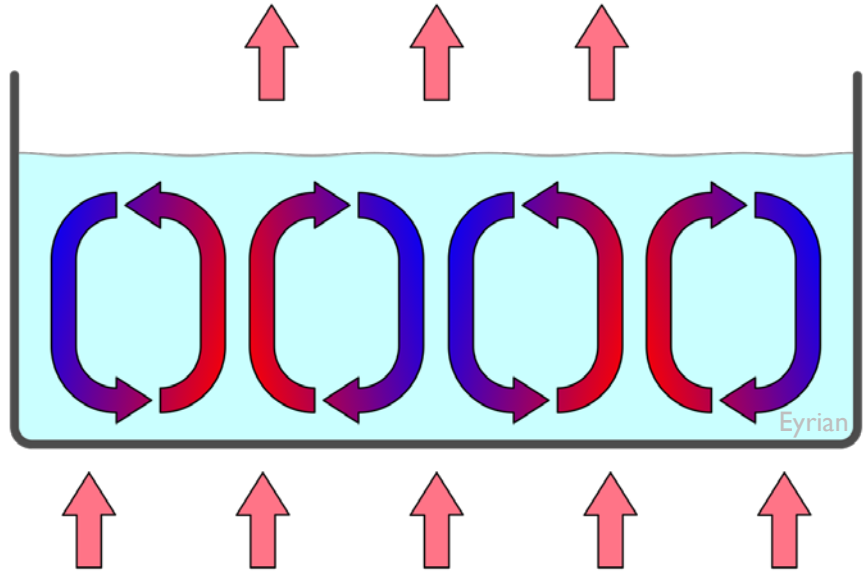






Convection

- A hot blob of gas will expand, making it less dense, causing it to rise
- If the blob isn't efficiently cooling some other way, it will continue to rise until it cools into equilibrium with the surrounding environment.
- The cool, more dense, blob will now sink
- The process repeats, transferring heat outward
- In the sun, the round-trip takes about a week, but it can be ~10 ms on a neutron star

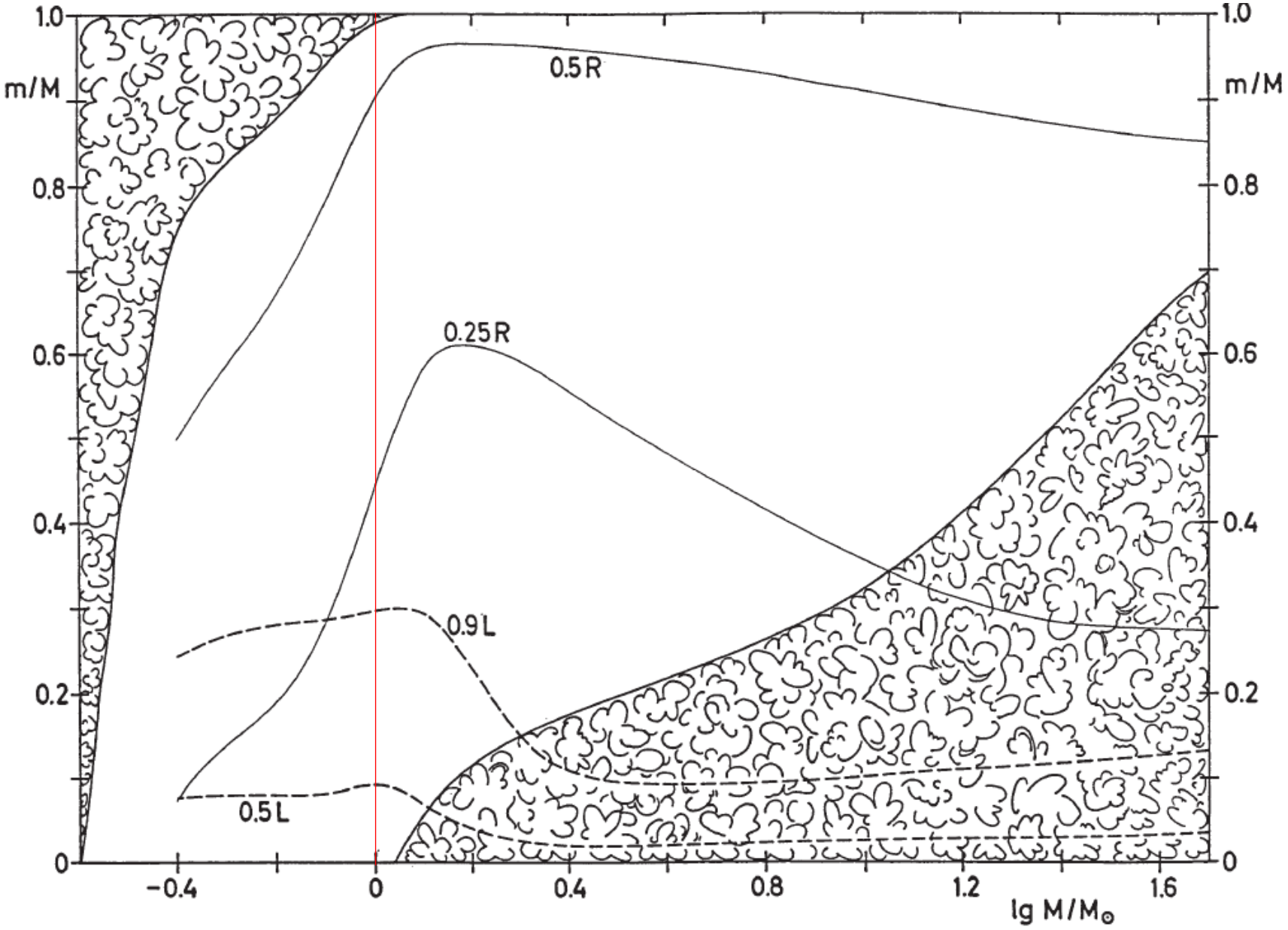


C. Malone et al. ApJ 2011

Convection in Stars

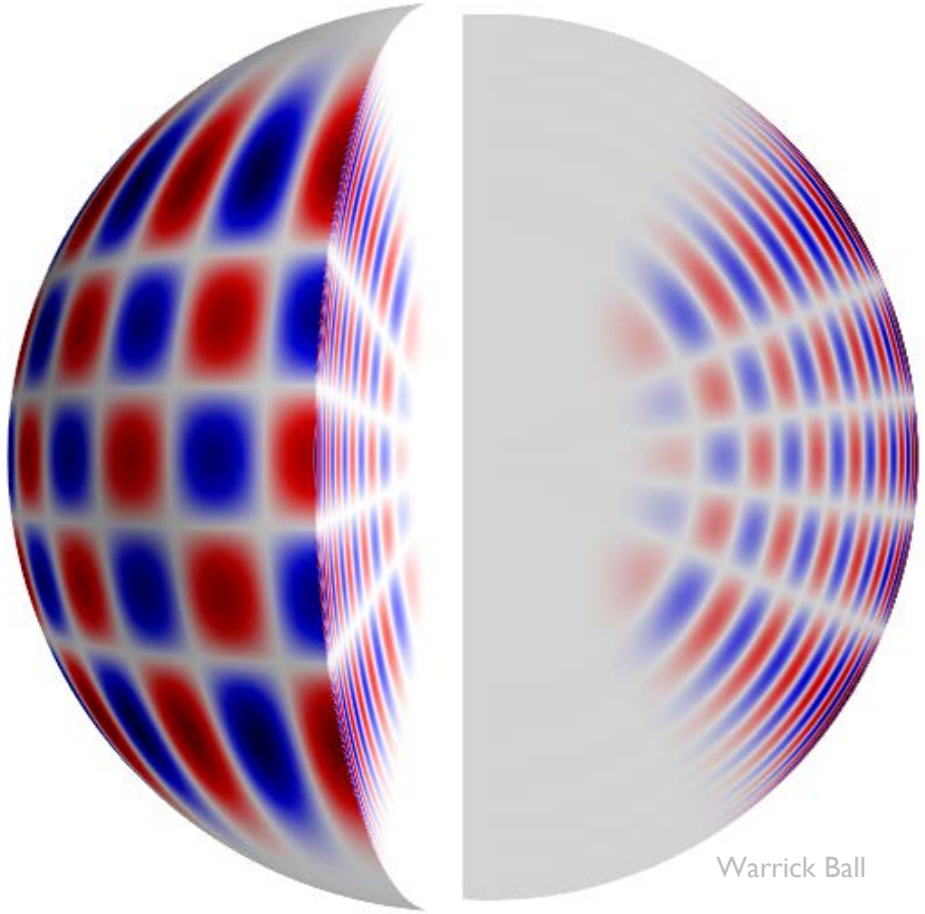
- The location and extent of convective and radiative heat transport in a star burning hydrogen in the core depend on its mass
- Stars more massive than the sun have a convective core, with a larger convection region for larger masses
- Stars around as and less massive than the sun have a convective envelope, with a larger convection region for smaller masses

Kippenhan & Weigert "Stellar Structure and Evolution" 1990

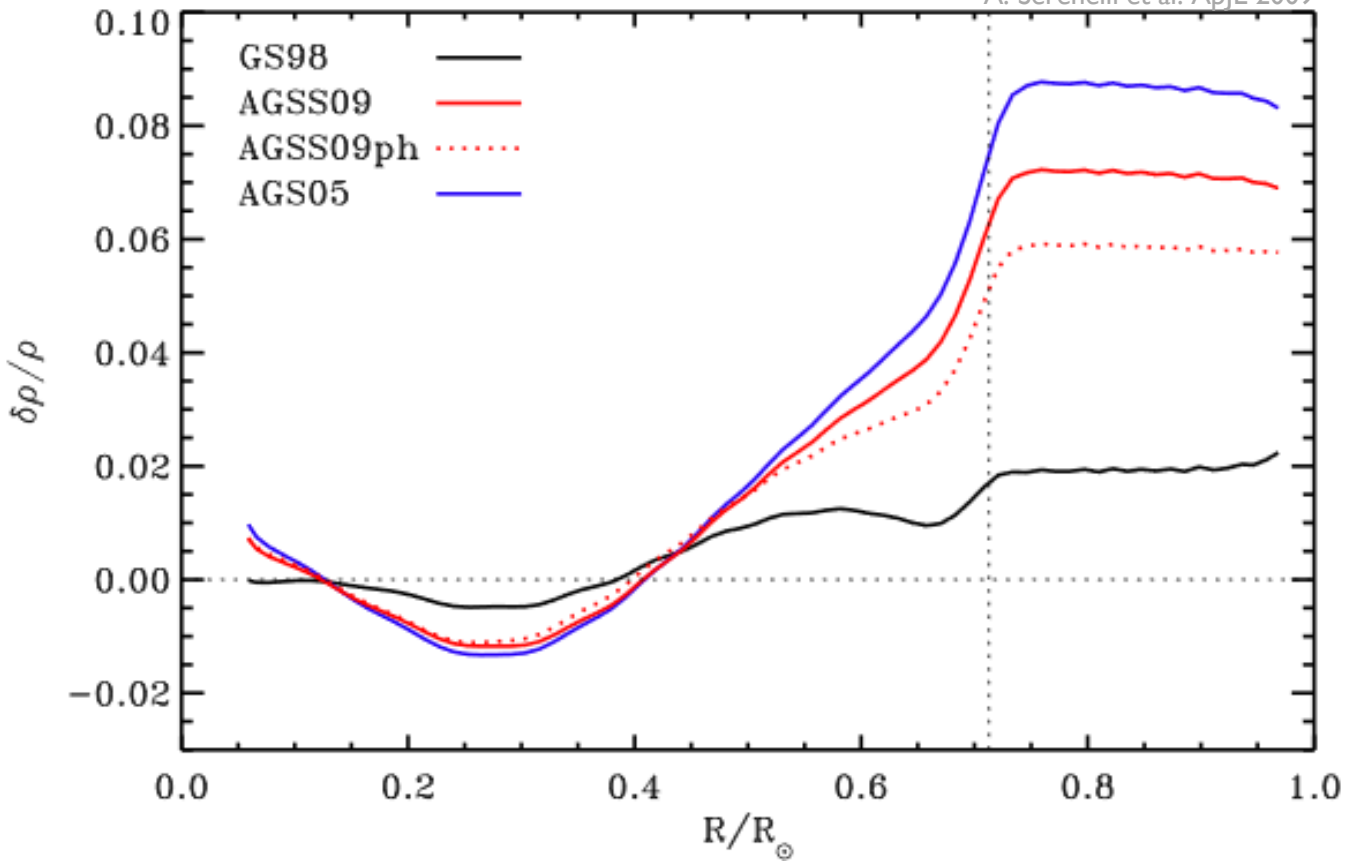


How do we know the sun's structure?

Helioseismology complements neutrino signals and composition measurements from spectroscopy (and meteorites) to give a picture of the sun's structure

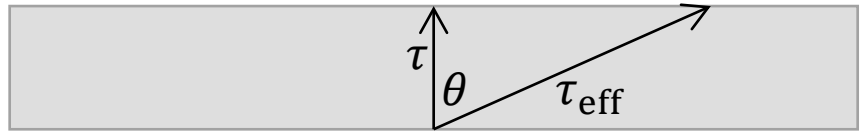


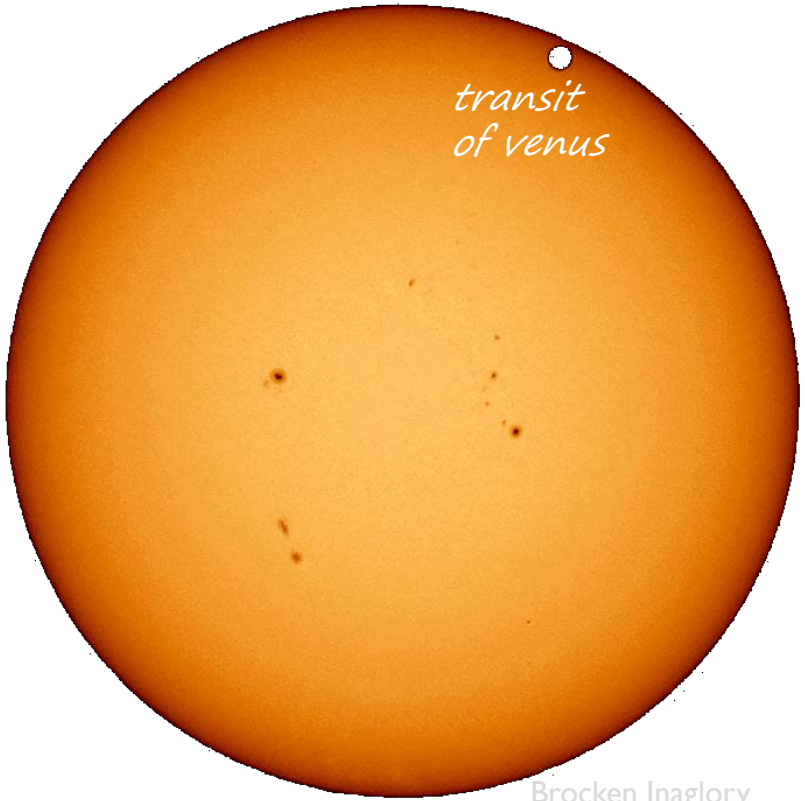
A. Serenelli et al. ApJL 2009



The Photosphere: *What we see when we look at the sun* *(quickly)*

- "A" photon will scatter ~10^{25} times on its way out of the sun
- The photon after the very last scatter is what we see, which comes from roughly the mean free path below the surface
- For the solar photosphere, this is ~100km, which is ~0.01% of the way towards the center
- Near the edges of the sun, a photon traveling to us will go through more material, blocking more photons. This phenomenon is limb darkening





Brocken Inaglory