Stellar Evolution and Asteroseismology

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What are stars?

- Stars are nearly spherical balls of gas which
  - are held together by **gravity**
  - have **internal energy source** (nuclear)
- Stars appear to have different brightnesses
  - Intrinsically different **brightnesses**
  - Distance effect
- Stars appear to have different colours
  - Different **surface temperatures**
- Difference in brightness and temperature is indicative of
  - Difference in **mass**
  - Difference in **age**

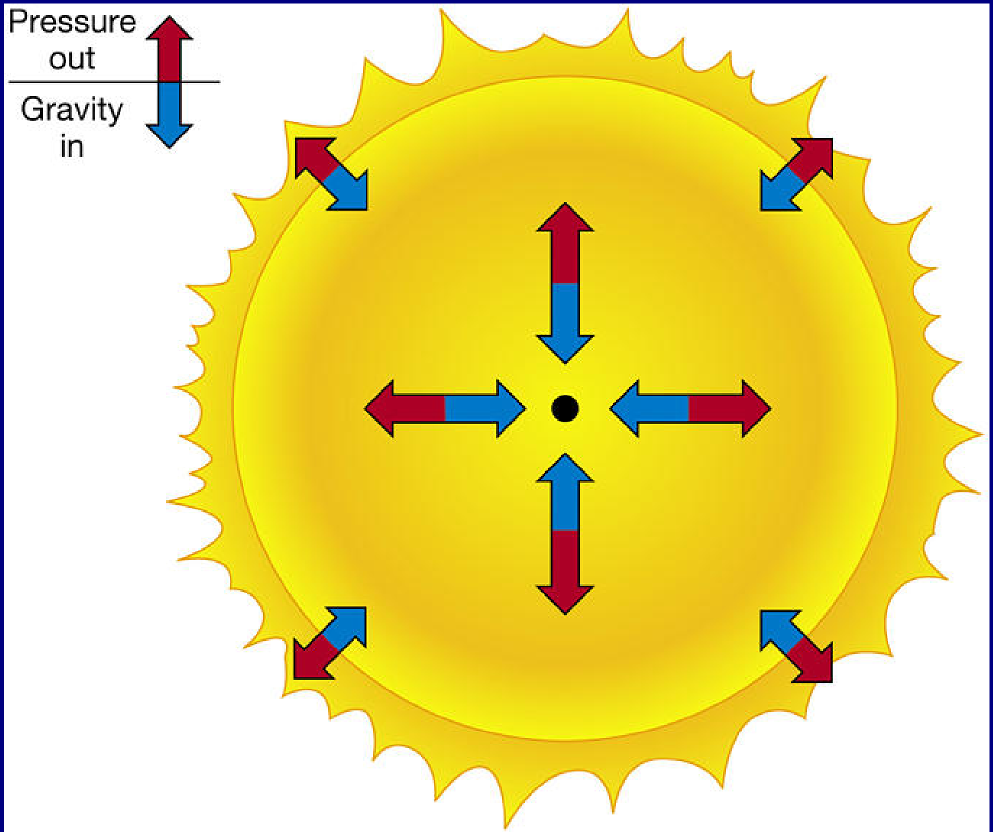
What are stars made of?

- Stars are made of mostly **hydrogen** and some **helium** gas
  - Sun has ~70% Hydrogen and ~28% Helium
  - All other elements ~2% !
- The composition of stars change over time
- The composition is NOT uniform throughout the star
- Huge difference between **surface** and **centre** in
  - Density (**1 g/cc** vs **150 g/cc**)
  - Pressure (**0** vs **10^{15} atm**)
  - Temperature (**6000 K** vs **15 million K**)
- Almost throughout the star, matter is in ionized form: atoms broken up into ions and electrons by extreme heat

A fine balance in a star

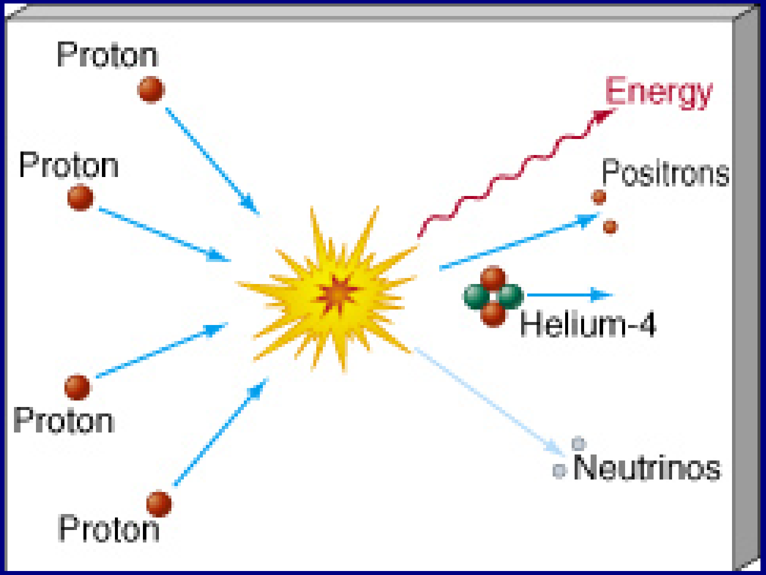
.

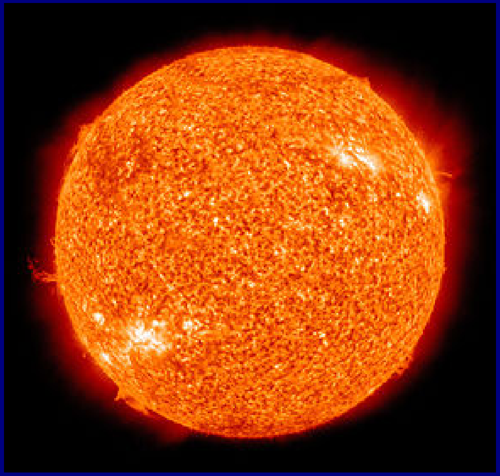
- Throughout its life, a star maintains equilibrium between gravity and gas pressure.
  - **Gravity** tends to collapse the star
  - **Pressure** tends to expand the star



Energy generation in a star

- Energy is continually lost from the surface, but replenished by the **nuclear burning** in the core.
- Nuclear burning takes place only in the central regions.





= 100 billion X

per second !!

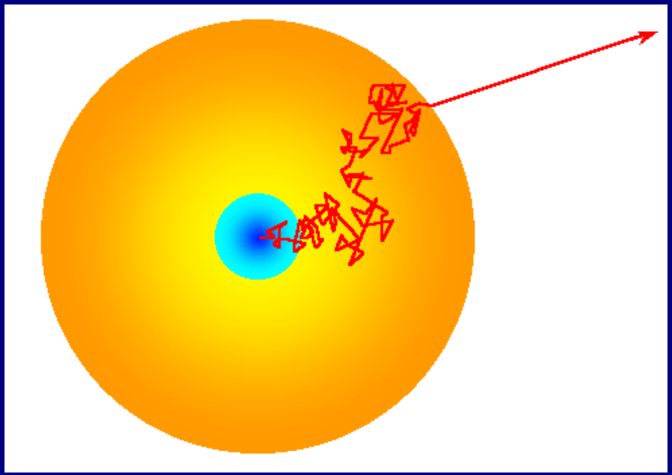
losing 4 million tons of hydrogen per second,

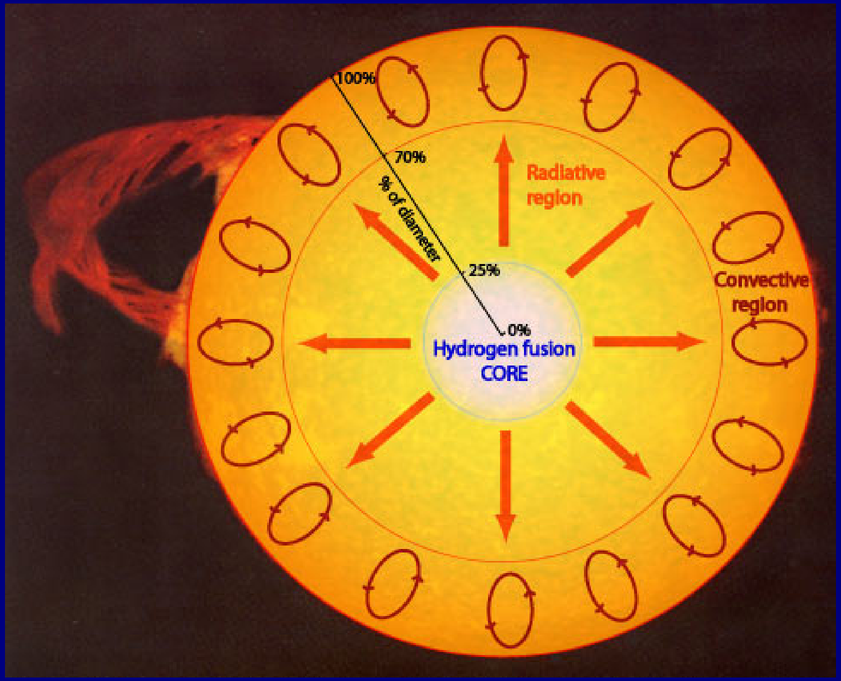
that is, merely 1/4 Earth mass over 10 billion years!

Energy transport in a star

- Energy produced in the core is transmitted through the bulk of the star mainly by
  - **radiation**

    and
  - **convection**.

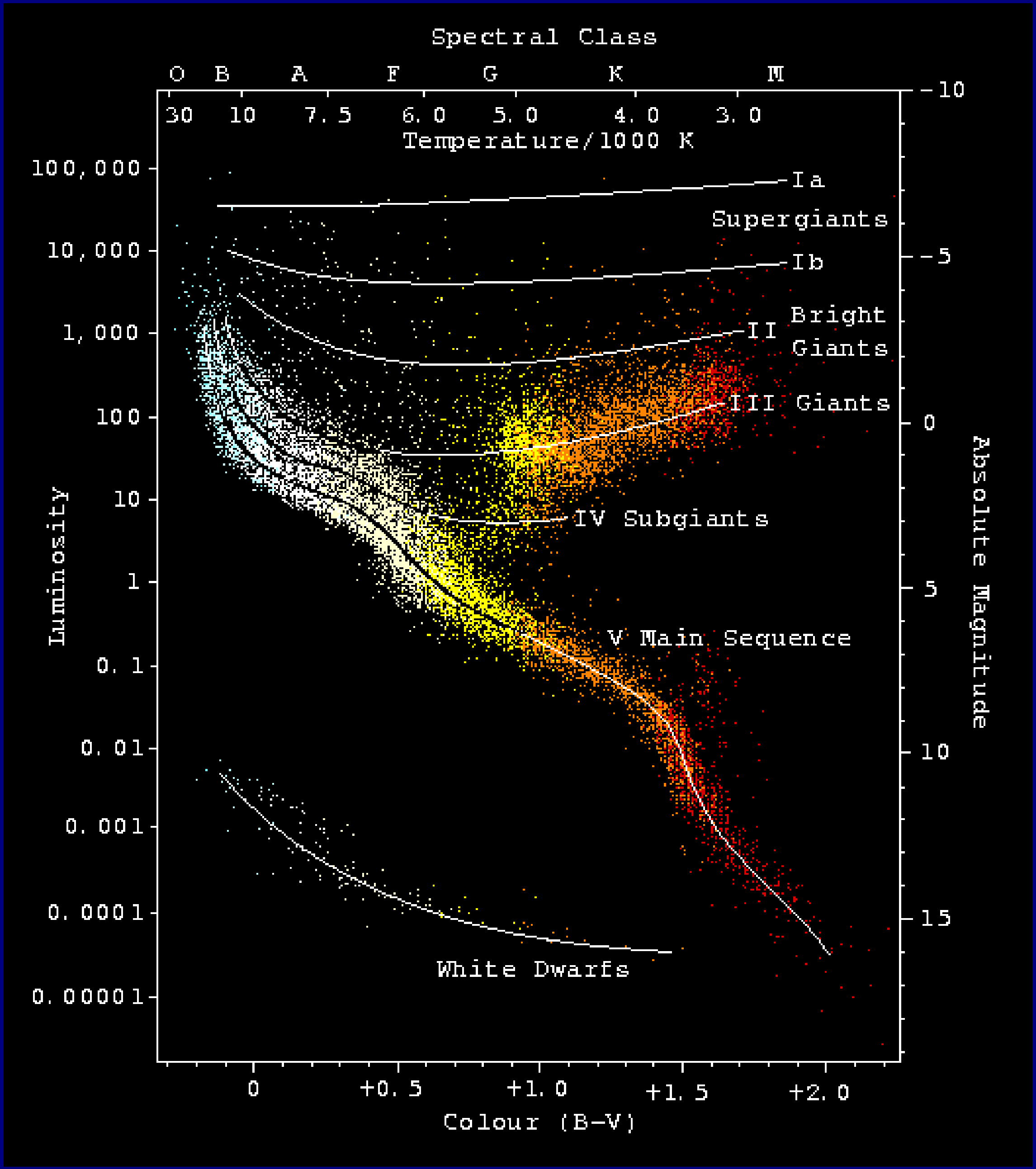




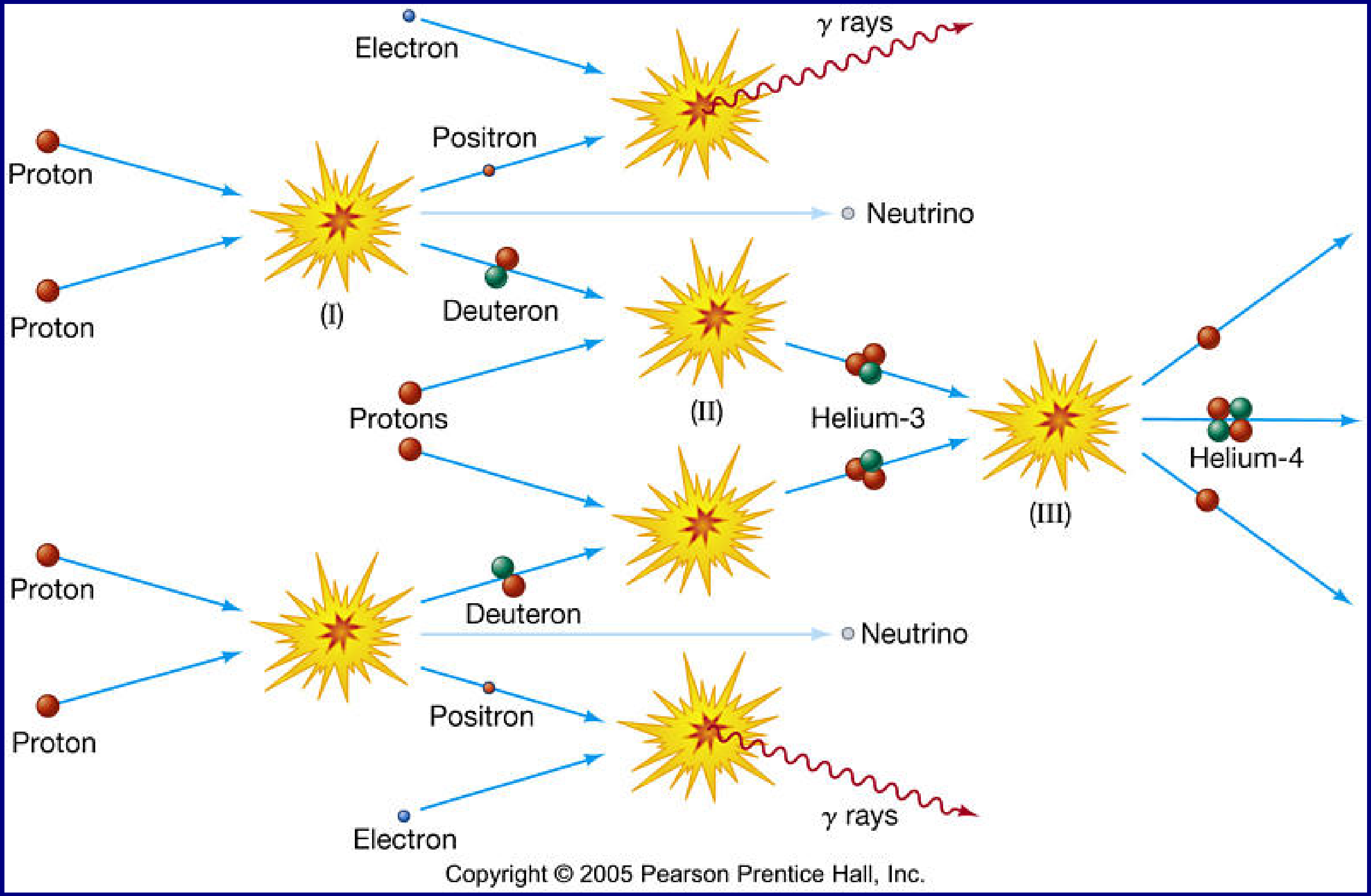
Evolution of Stars

- **All stars evolve over time**, changing their global properties as well as internal structure.
- As a star evolves, its brightness and surface temperature change.

HR Diagram: the astronomer's stethoscope

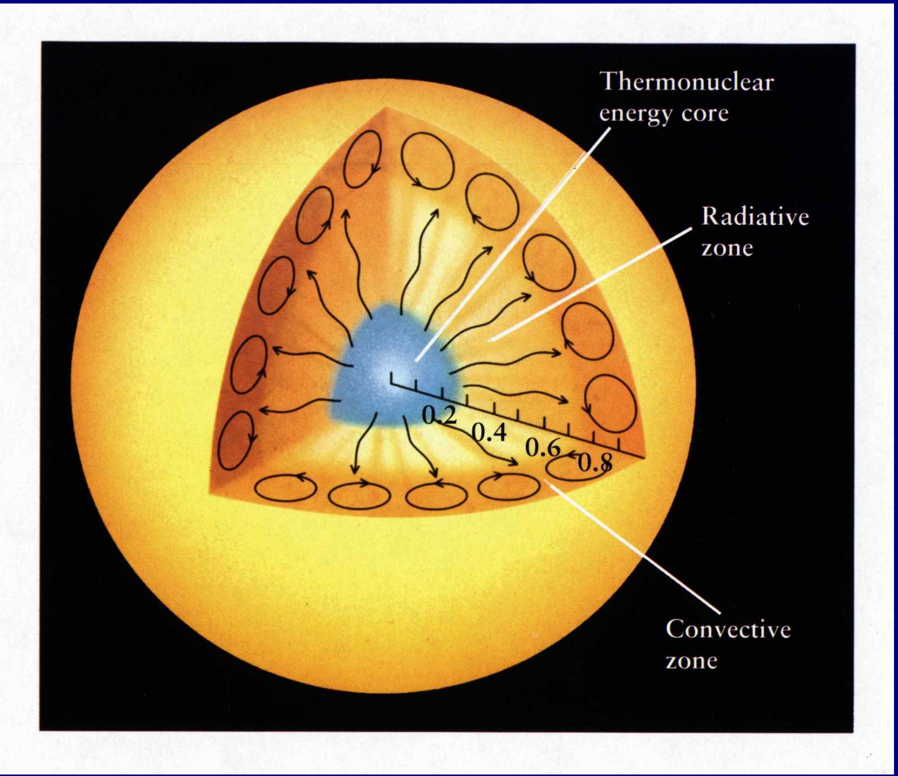


Hydrogen burning



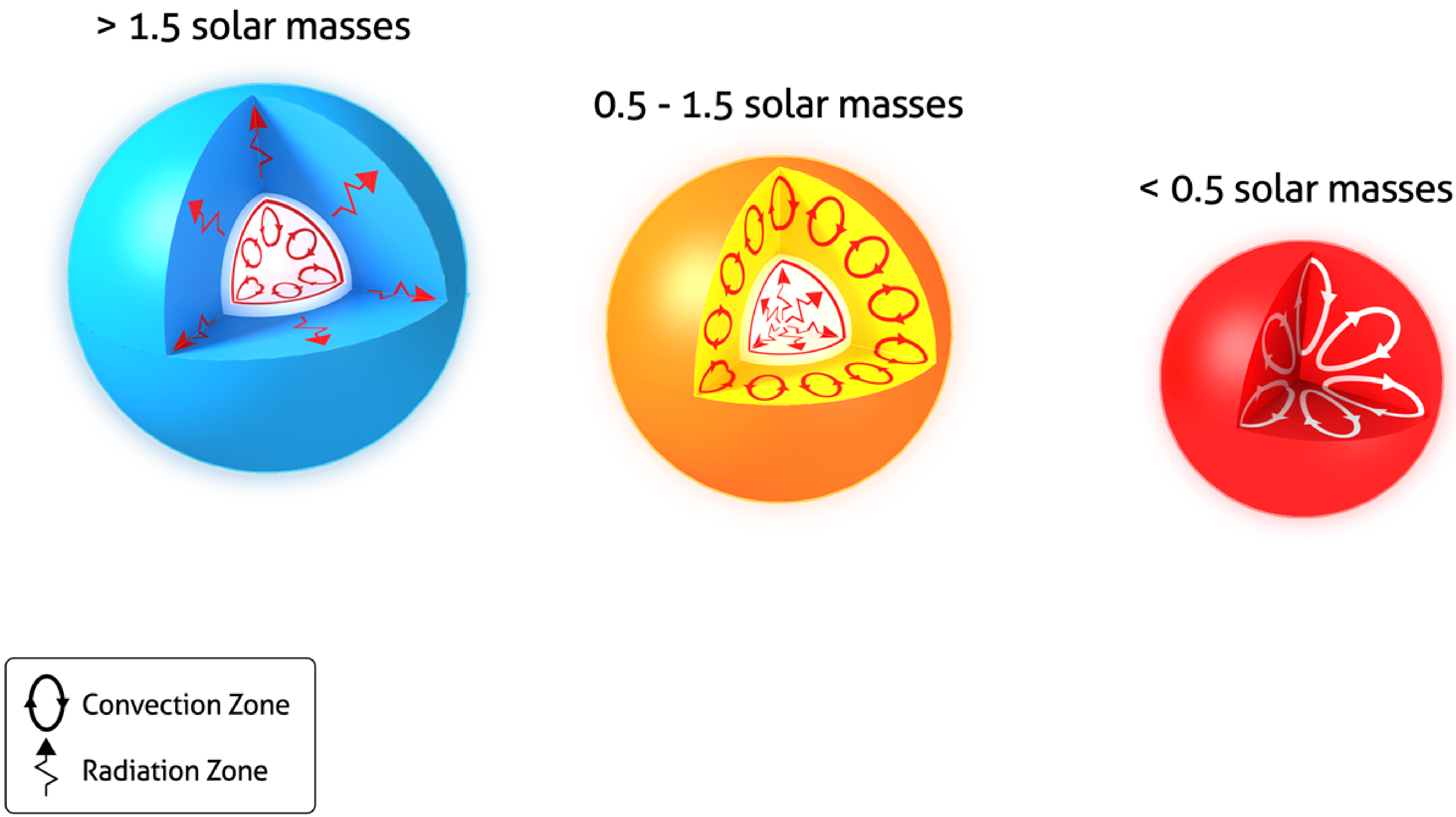
- Minimum temperature: **8 x 10^6 K**
- Main channel: *p-p* chain (**~ T^4**)
- Above 20 x 10^6 K, CNO cycle (**~ T^{17}**) dominates – convective core
- Occurs in all stars during Main Sequence phase

Structure during MS phase



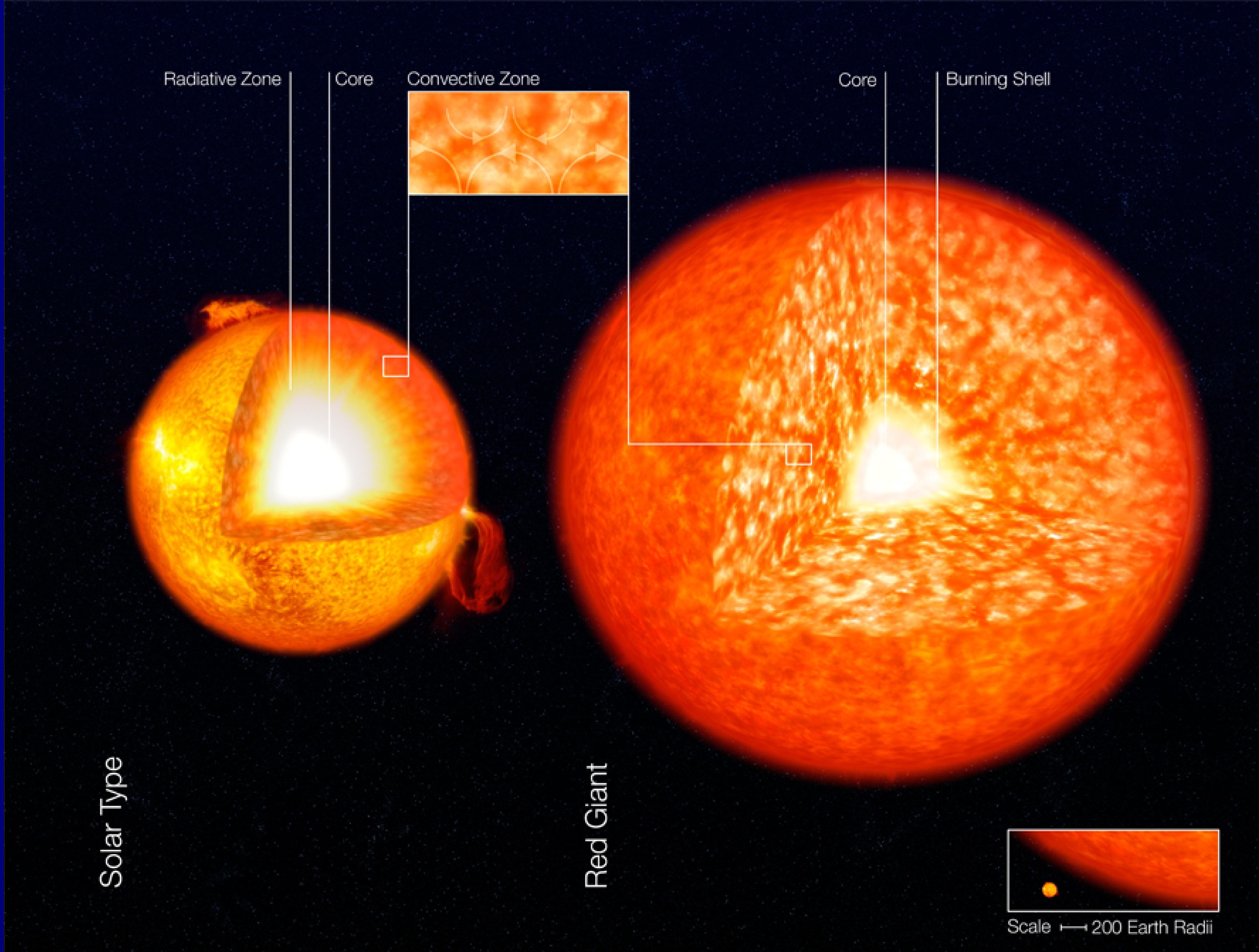
- Nuclear reaction occurs only in central region
  - radiative in low mass (< 1.2 M_{Sun}) stars
  - convective in high mass stars (CNO cycle dominates)
- Outer layers may be convective
  - low T, high opacity
  - thickness of CZ decreases with M
- Intermediate zone is radiative

Heat Transfer of Stars



Red Giant evolution

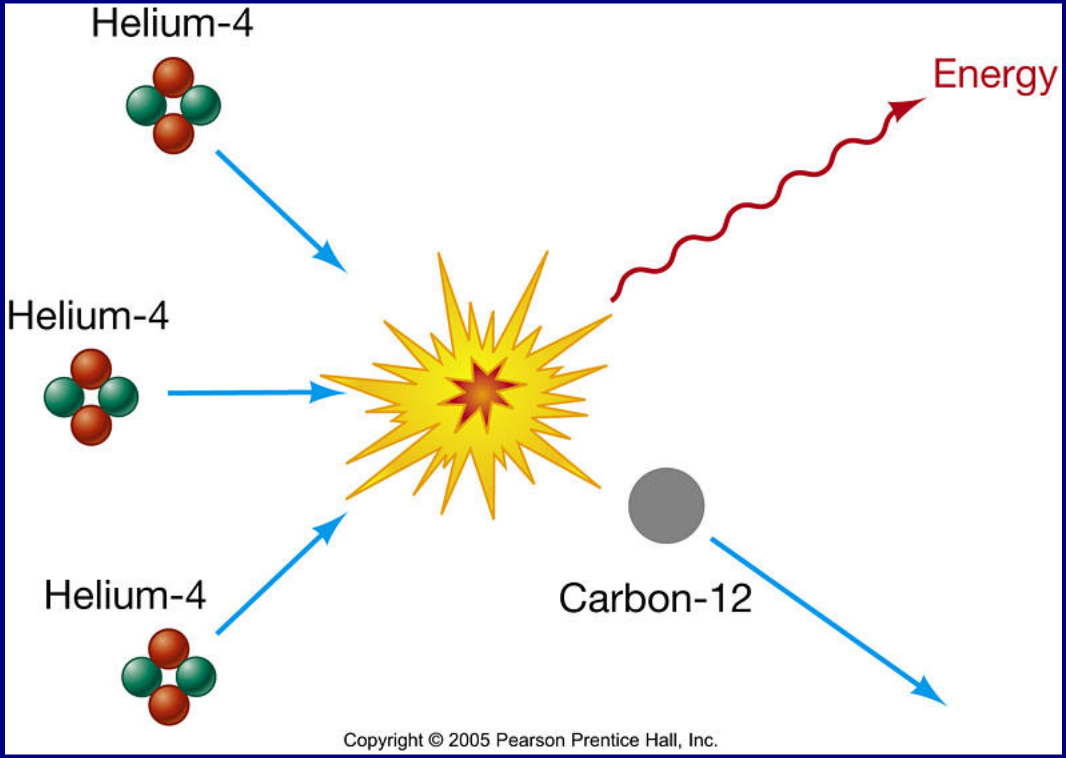
- Exhaustion of H in the core → He core contracts under gravity and heats up
- Gravitational energy released expands the envelope → star radius increases
- Convective zone extends deeper → cooler surface → **Red Giant**
- Layers overlying the core heat up enough to start H-burning → **shell H-burning**
- Radius keeps increasing at almost constant Teff → increasing luminosity
- Core heats up to reach helium-burning temperature → **Helium ignition**



The Structure of Stars

ESO Press Photo 29/07 (6 July 2007)

Helium burning



- Minimum temperature: **10^8 K**
- Above 6 x 10^8 K, Carbon-Helium fusion creates Oxygen
- Highly sensitive to temperature: **~ T^{40}**
- Occurs in all stars after Red Giant phase

Helium Flash

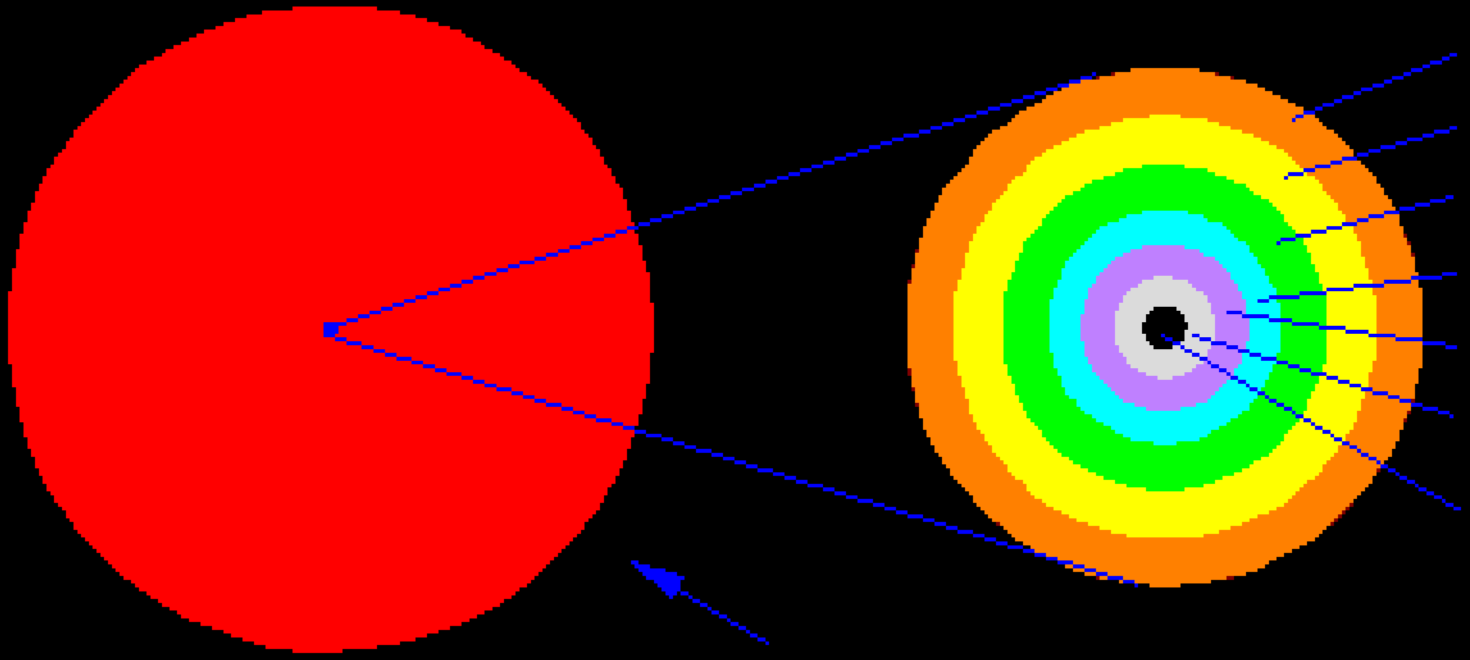
- For low mass stars ($M < 2.2\ M_{Sun}$) the contracting He core develops **electron degeneracy** BEFORE He ignition
    - Pressure due to Pauli Exclusion Principle
    - Electron Degeneracy Pressure supports overlying layers
    - Pressure becomes independent of temperature
    - He ignition raises temperature, but not pressure!
    - Runaway reaction (for a few seconds)

  ⇒ **Helium Flash** ($L_{He} \sim 10^{11}\ L_{Sun}$)

- Higher mass stars start to burn He before reaching degeneracy in the core.

Post-RGB evolution

- During core He burning, the star settles on the **Red Clump** or the **Horizontal Branch**
- He-burning core is surrounded by H-burning shell
- Exhaustion of He in the core → core contraction + envelope expansion → **Asymptotic Giant Branch**
- For stars with M < 8 Msun, no further nuclear burning
- For stars with M > 8 Msun, carbon ignition occurs in the core, surrounded by shell He and H burning
- Progressively higher elements are synthesized in the cores of massive stars



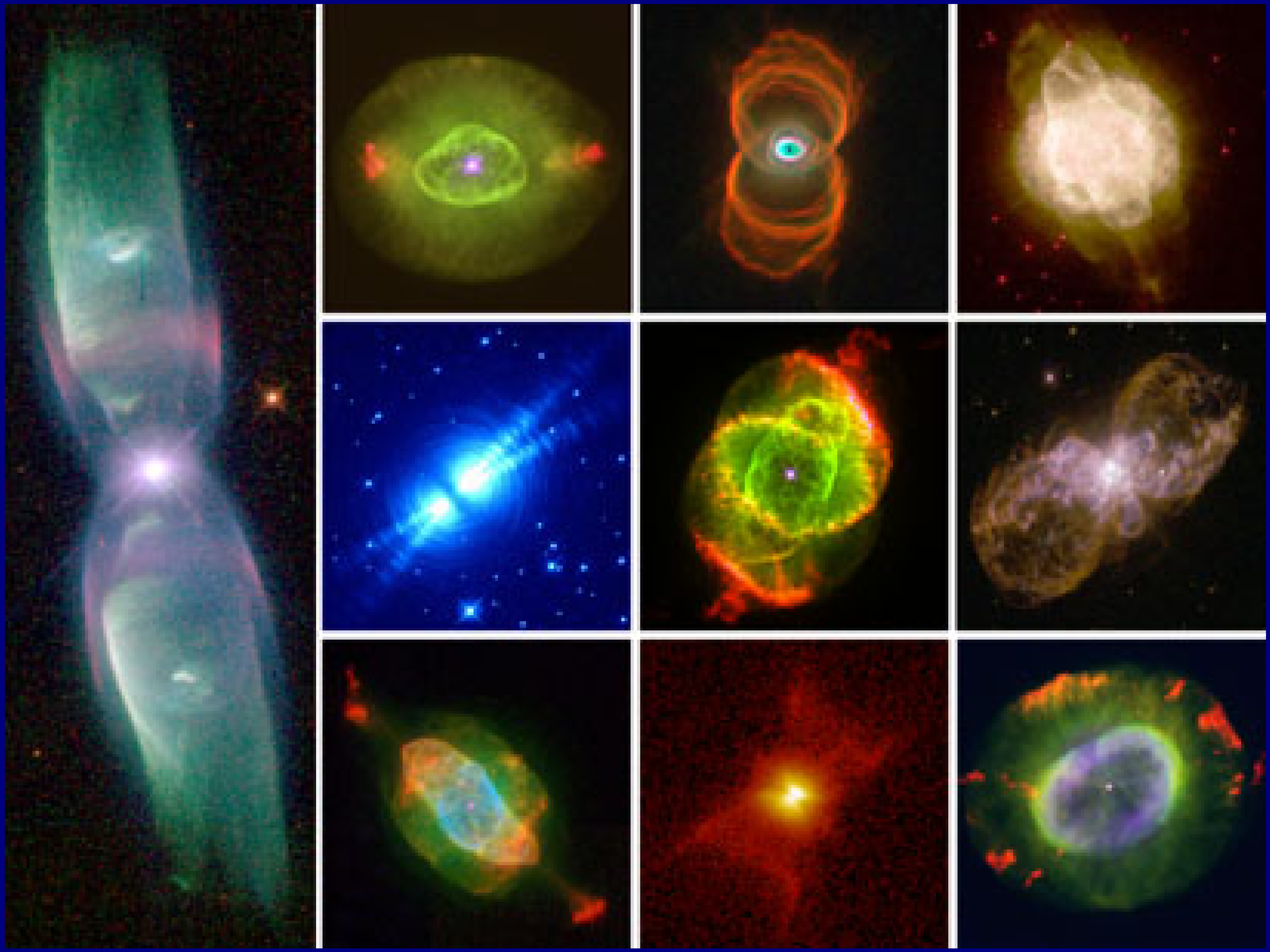
End state of low mass stars

- During later stages of evolution, stars lose lot of mass from the diffuse envelope.
- Low mass stars (< 8 Msun) eject nearly half their mass in the form of Planetary Nebulae
- Stars with mass < 3 Msun are left with cores < 1.4 Msun (Chandrasekhar limit)

  - radius ~ **10^6 m** (Earth-sized)
  - high density ~ **10^9 kg m^{-3}**
  - high surface temperature ~ 10^5 K
  - low luminosity ~ 10^{-3} Lsun

White Dwarf

Planetary Nebulae

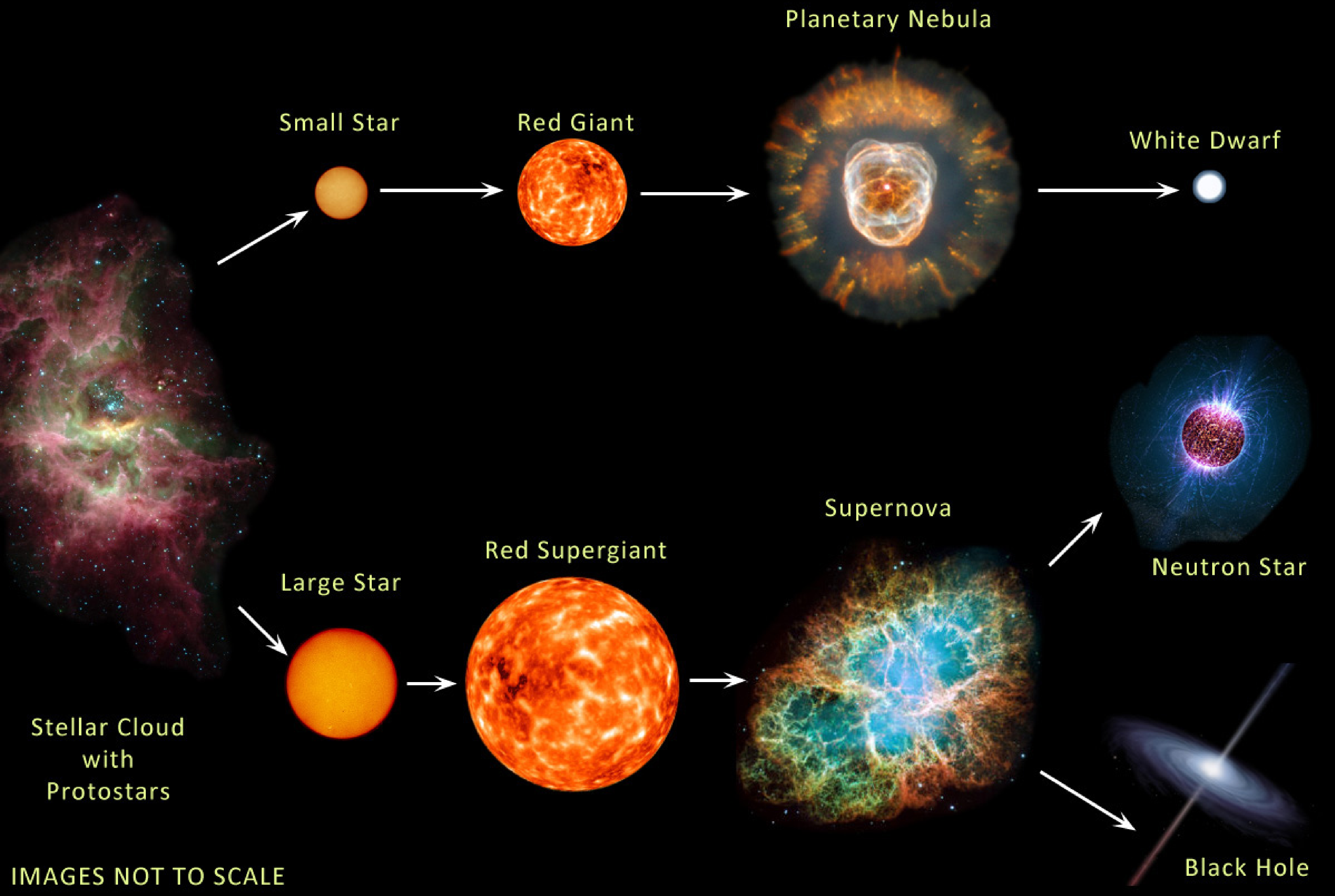


End state of high mass stars

- More massive stars are left with cores > 1.4 Msun
    - Electron degeneracy pressure cannot support the gravitational collapse
- Iron core collapse leads to a neutron core with $T \sim 10^9$ K and density $\sim 10^{17}$ kg m^{-3}
    - Neutron degeneracy pressure stops further infall of overlying layers and "bounce" them back
    - Explosive release of energy (~ 10^{46} J) and matter

      → **Supernova**
- Remnant from supernova is either
    - a **Neutron Star** (progenitor < 30 Msun) or
    - a **Black Hole** (progenitor > 30 Msun)

EVOLUTION OF STARS

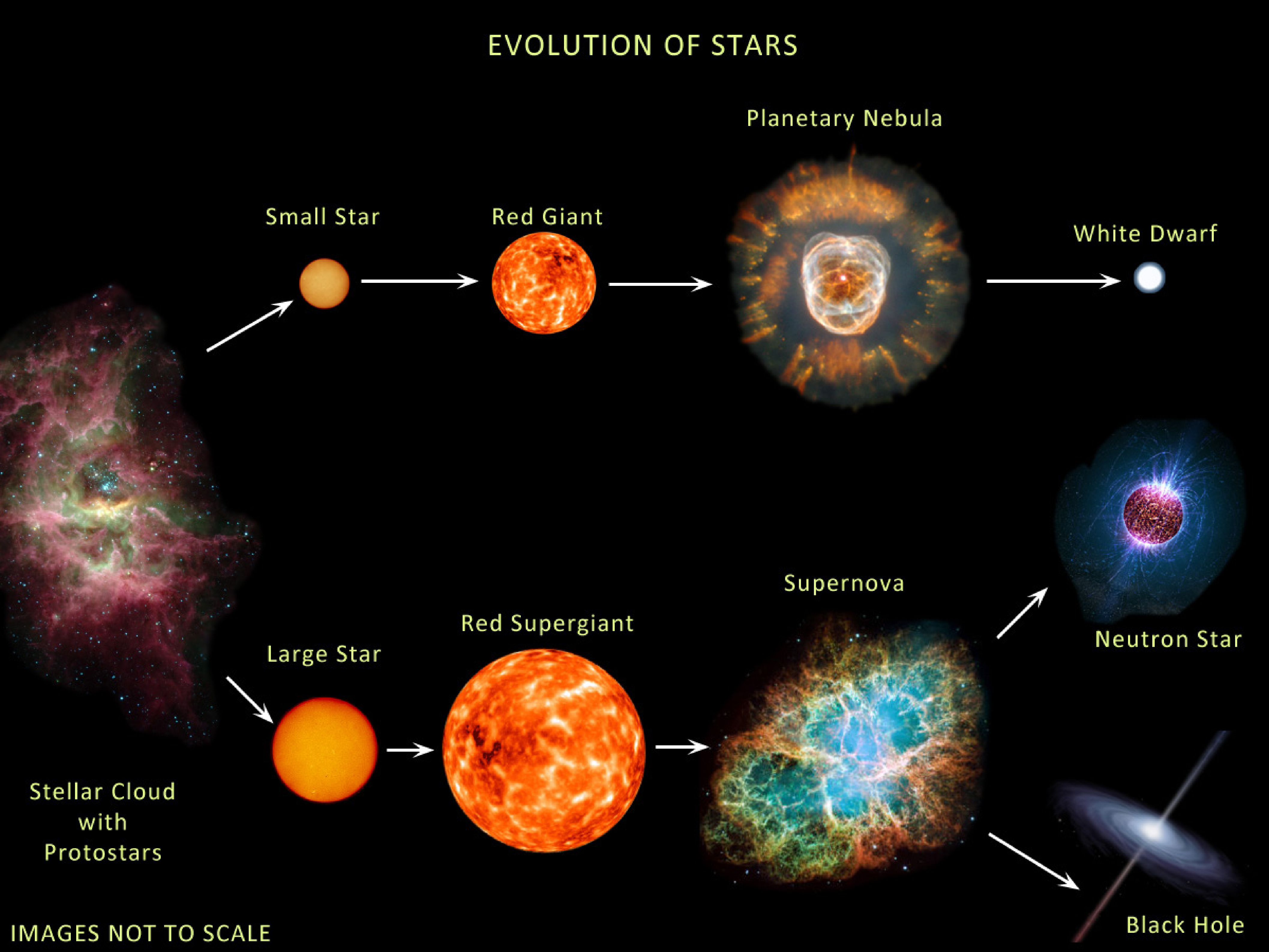


Evolution of Stars

- **All stars evolve over time**, changing their global properties as well as internal structure.
- As a star evolves, its brightness and surface temperature change.
- Time scale of evolution varies from **several million years (for very massive stars) to few billion years (for low mass stars)**.
- During their lifetime cores of stars become hotter and hotter and they produce progressively heavier elements through nuclear fusion.
- **Mass is the single most important quantity which determines the life and ultimate fate of a star**.

Evolution of Stars

- All stars **burn H to He in their cores** for ~ 90% of their lifetimes – **Main Sequence**
- Main Sequence stars have smoothly varying structure
- When H is exhausted in the core, the star evolves faster and becomes a sub-giant and later a **Red Giant**
- Red Giants are powered by
    - **H burning in a shell** outside the core
    - Additionally, **He burning in the core** for older stars
- Both types of red giants have similar observed properties – cannot be distinguished easily
- Red giants have **very dense cores** (density ~10^6 g/cc) and **very diffuse envelopes** (density ~10^{-6} g/cc)


EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Cloud with Protostars
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
IMAGES NOT TO SCALE

Evolution of Stars

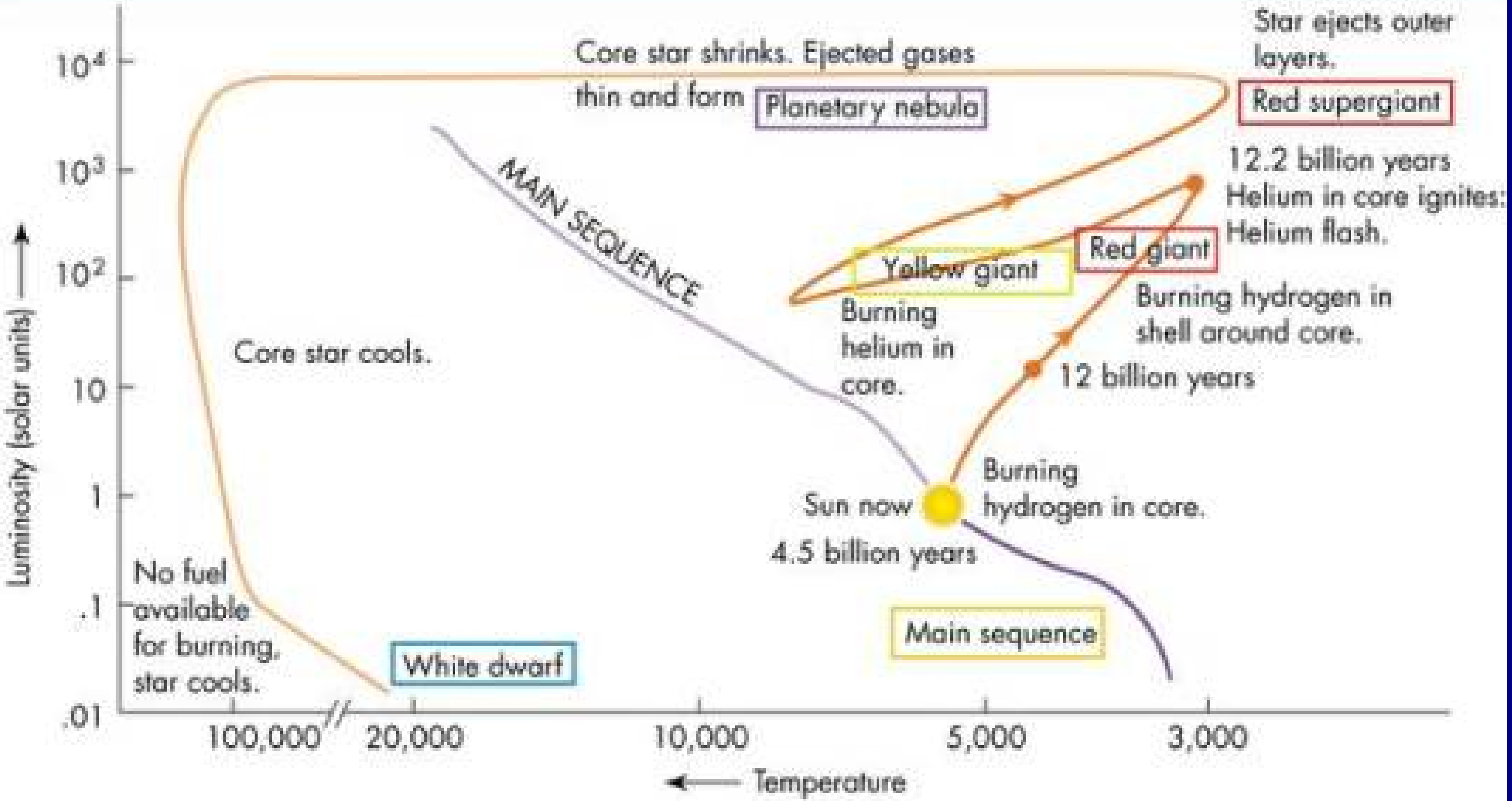
- **Low mass stars (< ~ 3 Msun)**
  - Do not burn elements heavier than He
  - Shed their outer envelopes slowly – **Planetary Nebula**
  - Electron degeneracy pressure supports C-O core against gravity
    - **Chandrasekhar limit (~ 1.4 Msun)**
  - Core cools slowly over billions of years – **White dwarfs**
- **High mass stars (> ~ 3 Msun)**
  - Burn progressively heavier elements in the core
  - Electron degeneracy is not enough to fight gravity
  - Catastrophic implosion-explosion → **Supernova**
  - Remnant of supernova becomes either
    - **Neutron star** (~ 3 – 8 Msun)
      - supported by neutron degeneracy
    - **Black hole** (> ~ 8 Msun)
      - ultimate victory of gravity

Timescales of stellar evolution

Estimated Stellar Lifetimes(in units of 10^6 years)					
MASS (solar masses)	**SPECTRAL TYPE ON THE MAIN SEQUENCE**	**PERIOD OF CONTRACTION TO MAIN SEQUENCE (10^6 yrs)**	**ESTIMATED LIFETIME ON THE MAIN SEQUENCE (10^6 yrs)**	**PERIOD FOR MAIN SEQUENCE TO RED GIANT (10^6 yrs)**	**RED GIANT DURATION (10^6 yrs)**
30	**O5**	**0.02**	**4.9**	**0.55**	**0.3**
15	**B0**	**0.06**	**10**	**1.7**	**2**
9	**B2**	**0.2**	**22**	**0.2**	**5**
5	**B5**	**0.6**	**68**	**2**	**20**
3	**A0**	**3**	**240**	**9**	**80**
1.5	**F2**	**20**	**2,000**	**280**	**400**
1.0	**G2**	**50**	**10,000**	**680**	**1000**
0.5	**M0**	**200**	**30,000**		
0.1	**M7**	**500**	**10^7**		

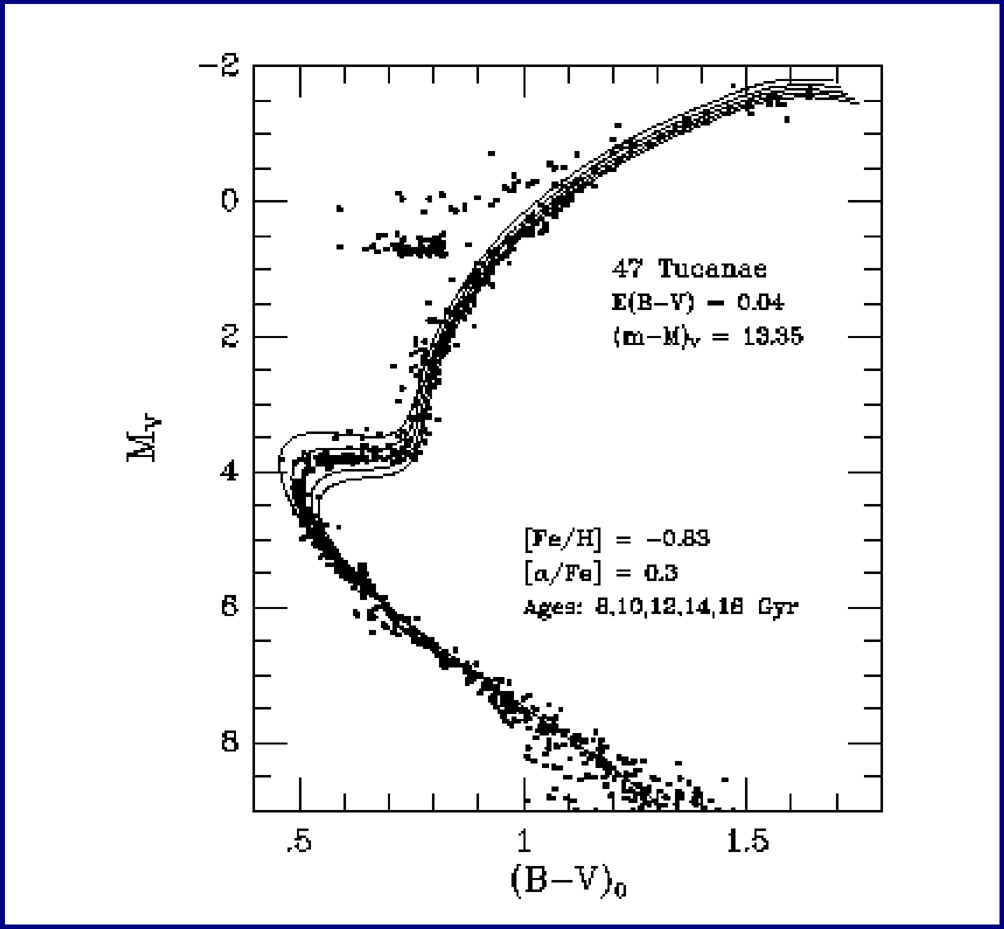
Source: Fundamental Astronomy, edited by H. Karttunen et al., 1994

	~9 billion yrs	~1 billion yrs	~100 million yrs	~10,000 yrs	
Time spent as	Main sequence →	Red giant →	Yellow giant →	Planetary nebula →	White dwarf
Sun's age	4.5 billion yrs (now)	12.2 billion yrs	12.3 billion yrs	12.3305 billion yrs	12.3306 billion yrs



How do we check if the theory is correct?

- Theoretical explanation of the observed HR diagram
- Accurate prediction of star cluster HR diagram
- Assures that "global" properties are consistent with the theory of stellar structure and evolution
- Still, no test of the **interior** structure and composition of stars



Probing the interiors of stars

- Stars are extremely opaque objects
- All the light that we receive from a star comes from its “photosphere” or the “skin”

- Conditions inside might be very different
- No visual probe inside a star

Looking Inside Stars

"*What appliance can pierce through the outer layers of a star and test the conditions within?*"
– A. S. Eddington,
Internal Constitution of Stars (1926)

The only tool to probe stellar interiors is

ASTEROSEISMOLOGY

The study of stellar oscillations

Stellar Oscillations

- Stellar oscillations are **sound** or **gravity** waves that penetrate into the interior of a star and can be observed at the surface as variations in luminous flux or velocity.

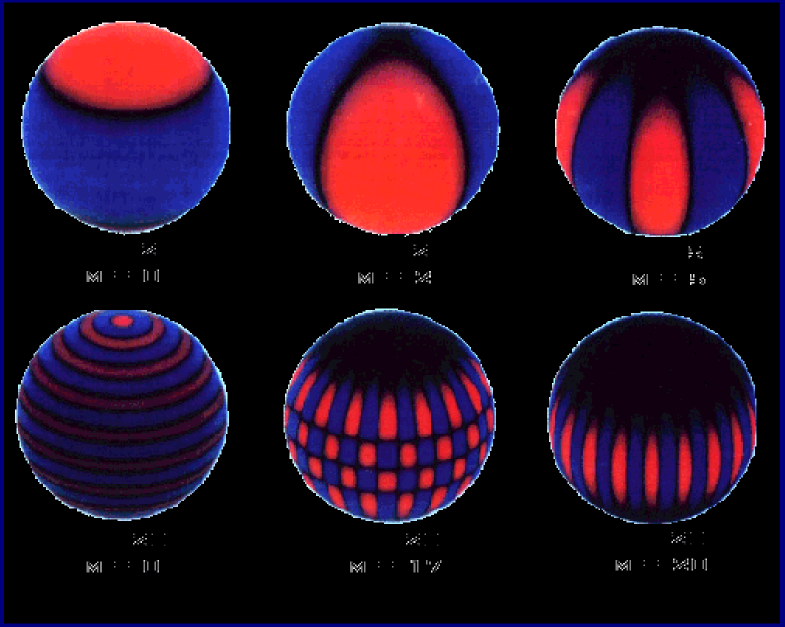
- Oscillations occur in a number of discrete modes, each characterised by a unique frequency, ranging from **few μHz to few mHz**
  - Periods range from minutes to months.

- Oscillations are generally of two types ---
  - Sound waves --- dominant restoring force is pressure gradient: **p-modes**
  - Gravity waves --- dominant restoring force is gravity: **g-modes**

Stars produce music too!

- Just like a musical instrument or orchestra, a star may oscillate in a range of frequencies simultaneously
    - we can “hear” them through telescopes!

- But the frequencies are not random --- they are discrete frequencies determined by the structure and composition of the star
    - “listening” to the frequencies carefully lets us know what the star is made of !

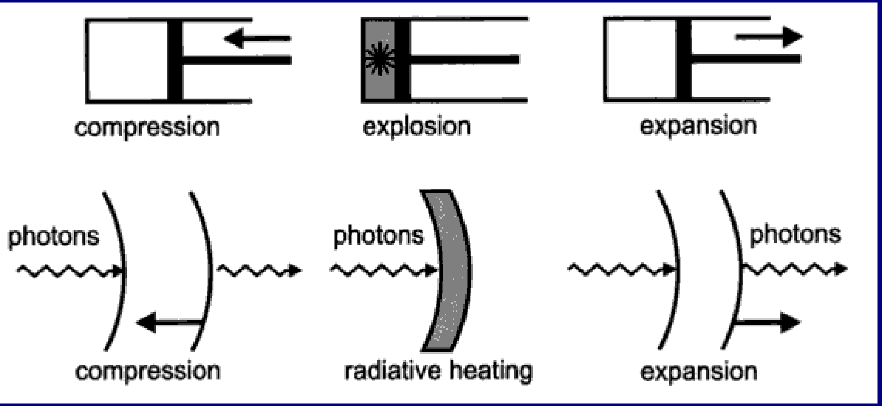


What causes the oscillations?

- Stellar oscillation is a natural consequence of perturbations to the stellar structure caused by internal processes in a star.
- **Driving**: primarily in two ways:
  - **Opacity-driven** (long-lived modes)
  - **Turbulence-driven** (short-lived modes)
- **Damping**:
  - **Radiation at the surface**
  - **Viscosity**
  - **Convective leakage**

Opacity-driven oscillations

- Opacity = resistance to transport of radiation: $$\kappa \sim \frac{\rho}{T^{3.5}}$$
- To drive oscillations, **opacity needs to increase on compression** – happens in **partial ionization zones**
- On compression, density and degree of ionization increases with **minimal increase of temperature**
  - Opacity increases
  - Energy "dammed up"
  - Heating and expansion
- On expansion, **recombination** and decrease of density and temperature
  - Opacity decreases
  - Energy released
  - Layer falls back under gravity



- Few modes with long lifetimes
- Frequencies have very small width
- Large amplitude pulsations

Turbulence-driven oscillations

- Modes are intrinsically stable, but ….
- **Eddies in convective envelope** “shake” the star
- Modes are excited, but **heavily damped**
- Short-lived modes, but continually excited
- Frequencies have intrinsic width
- Many modes excited at the same time

Nature of oscillations

- Amplitude is governed by balance between driving mechanism and damping mechanism.
- Relative amplitude ($\Delta L/L$) varies between 10^{-1} to 10^{-6} depending on the type of star.
- Period varies between few minutes to several days.
- Frequencies scale with the mean density of the star:

$$\nu_0 \propto \sqrt{G\bar{\rho}}$$

Mathematical Description
-- Equations of Stellar Oscillations --

$$\frac{\mathrm{d}\xi_r}{\mathrm{d}r} = -\left(\frac{2}{r} + \frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r}\right)\xi_r + \frac{1}{\rho c^2}\left(\frac{S_\ell^2}{\omega^2} - 1\right)p' - \frac{\ell(\ell+1)}{\omega^2 r^2}\phi'$$

$$\frac{\mathrm{d}p'}{\mathrm{d}r} = \rho(\omega^2 - N^2)\xi_r + \frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r}p' + \rho\frac{\mathrm{d}\phi'}{\mathrm{d}r}$$

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}\phi'}{\mathrm{d}r}\right) = -4\pi G\left(\frac{p'}{c^2} + \frac{\rho\xi_r}{g}N^2\right) + \frac{\ell(\ell+1)}{r^2}\phi'$$

where, $S_\ell^2 = \frac{\ell(\ell+1)c^2}{r^2}$ and $N^2 = g\left(\frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right)$

These equations constitute a complete fourth order system for the four dependent variables.

Mathematical Description

-- Solution to the oscillation equations --

- Solution to the equations require four boundary conditions, provided by the central and surface conditions.
- Analytical solutions exist only for some selected cases (including radial oscillations).
- Non-trivial solutions exist only for specific values of the frequency ω , which is an eigenvalue of the problem.
- Only homogeneous solutions --- absolute amplitudes cannot be determined in the adiabatic approximation.
- Amplitudes must be determined by considering non-linear effects of non-adiabaticity.

Mathematical Description

-- Solution to the oscillation equations --

- Under a reasonable approximation of the gravitational potential perturbation being small, the equations can be reduced to

$$\frac{\mathrm{d}^2\xi_r}{\mathrm{d}r^2} = -\frac{\omega^2}{c^2}\left(1-\frac{N^2}{\omega^2}\right)\left(1-\frac{S_l^2}{\omega^2}\right)\xi_r$$

- Oscillatory solutions are “trapped” only in regions where

$$\begin{array}{llll} \text{either} & |\omega| > |N| \text{ and } |\omega| > S_\ell & — & p\text{-modes} \\ \text{or} & |\omega| < |N| \text{ and } |\omega| < S_\ell & — & g\text{-modes} \end{array}$$

- In other regions, solution is “evanescent”, or exponential.

Mathematical Description
-- 3-dimensional oscillations --

- General solutions for 3-d oscillations are of the form:

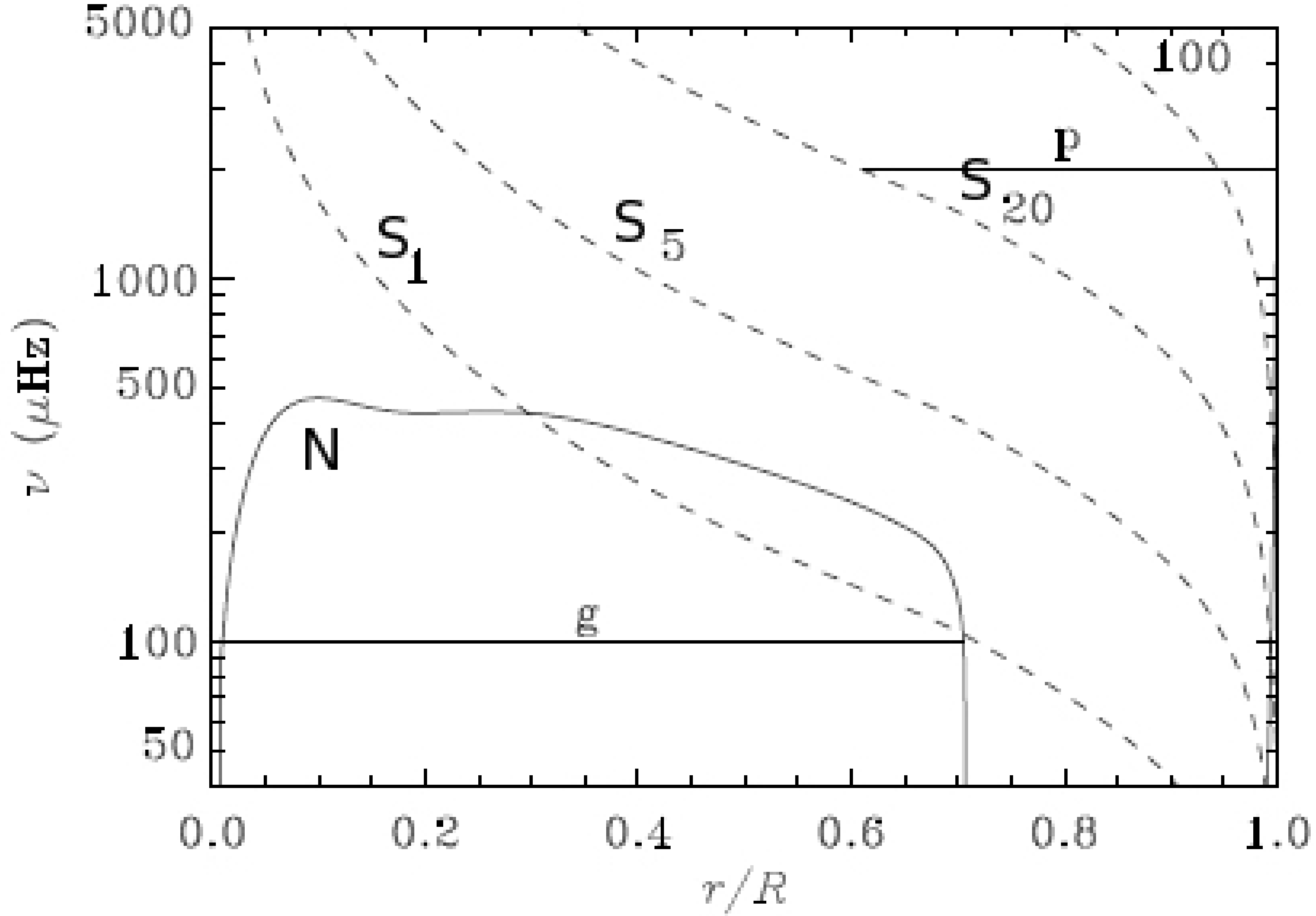
$$
\begin{aligned}
\xi_r(r,\theta,\phi,t) &= a(r) Y_{\ell,m}(\theta,\phi) \exp(-i2\pi\nu t) \\
\xi_\theta(r,\theta,\phi,t) &= b(r) \frac{\partial Y_{\ell,m}(\theta,\phi)}{\partial\theta} \exp(-i2\pi\nu t) \\
\xi_\phi(r,\theta,\phi,t) &= \frac{b(r)}{\sin\theta} \frac{\partial Y_{\ell,m}(\theta,\phi)}{\partial\phi} \exp(-i2\pi\nu t)
\end{aligned}
$$

where

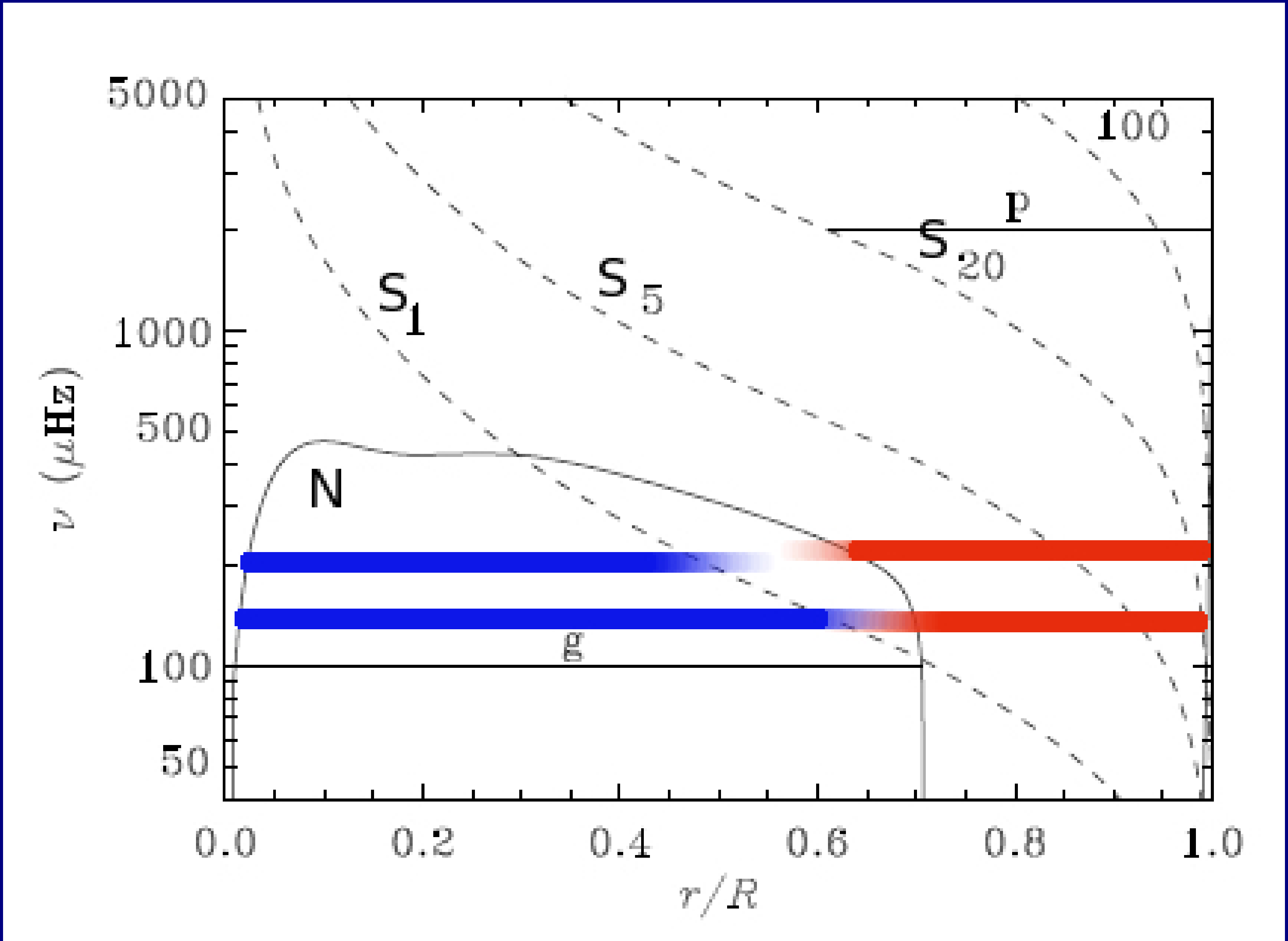
$$
Y_{\ell,m}(\theta,\phi) = (-1)^m \left[\frac{(2\ell+1)(\ell-m)!}{4\pi(\ell+m)!}\right]^{-1/2} P_{\ell,m}(\cos\theta) \exp(im\phi)
$$

are the spherical harmonics of degree ℓ and azimuthal number m.

Propagation Regions of Modes

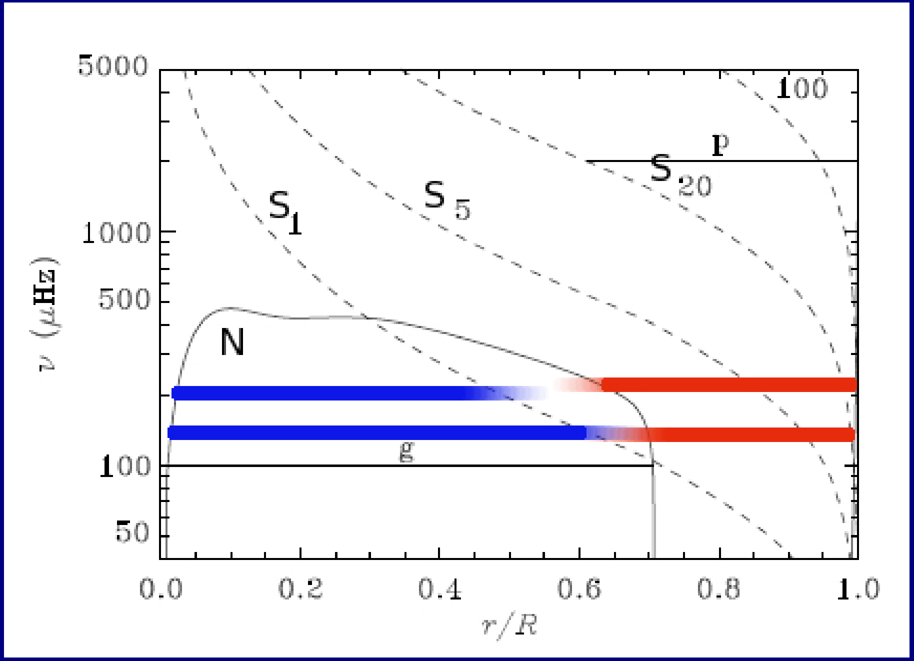


Propagation Regions of Modes



Mixed Modes

- At certain frequencies, trapping regions of p- and g- modes are close.
- Mixed modes are seen which behave as p-modes in the exterior and as g-modes in the interior.



  - Mixed modes break the pattern of uniform mode spacing.
  - Mixed modes are particularly information-rich.

Different Modes of Oscillation

- Small oscillations in spherical objects like stars can be represented by the spherical harmonics:

$$Y_{\ell,m}(\theta,\phi) = (-1)^m \left[\frac{(2\ell+1)(\ell-m)!}{4\pi(\ell+m)!}\right]^{-1/2} P_{\ell,m}(\cos\theta)\exp(im\phi)$$

- Node lines on the surface segregate regions of positive and negative fluctuations.
- There are $\ell - |m|$ “latitudes” and m “longitudes”.
- Large ℓ values cannot be detected in integrated light.

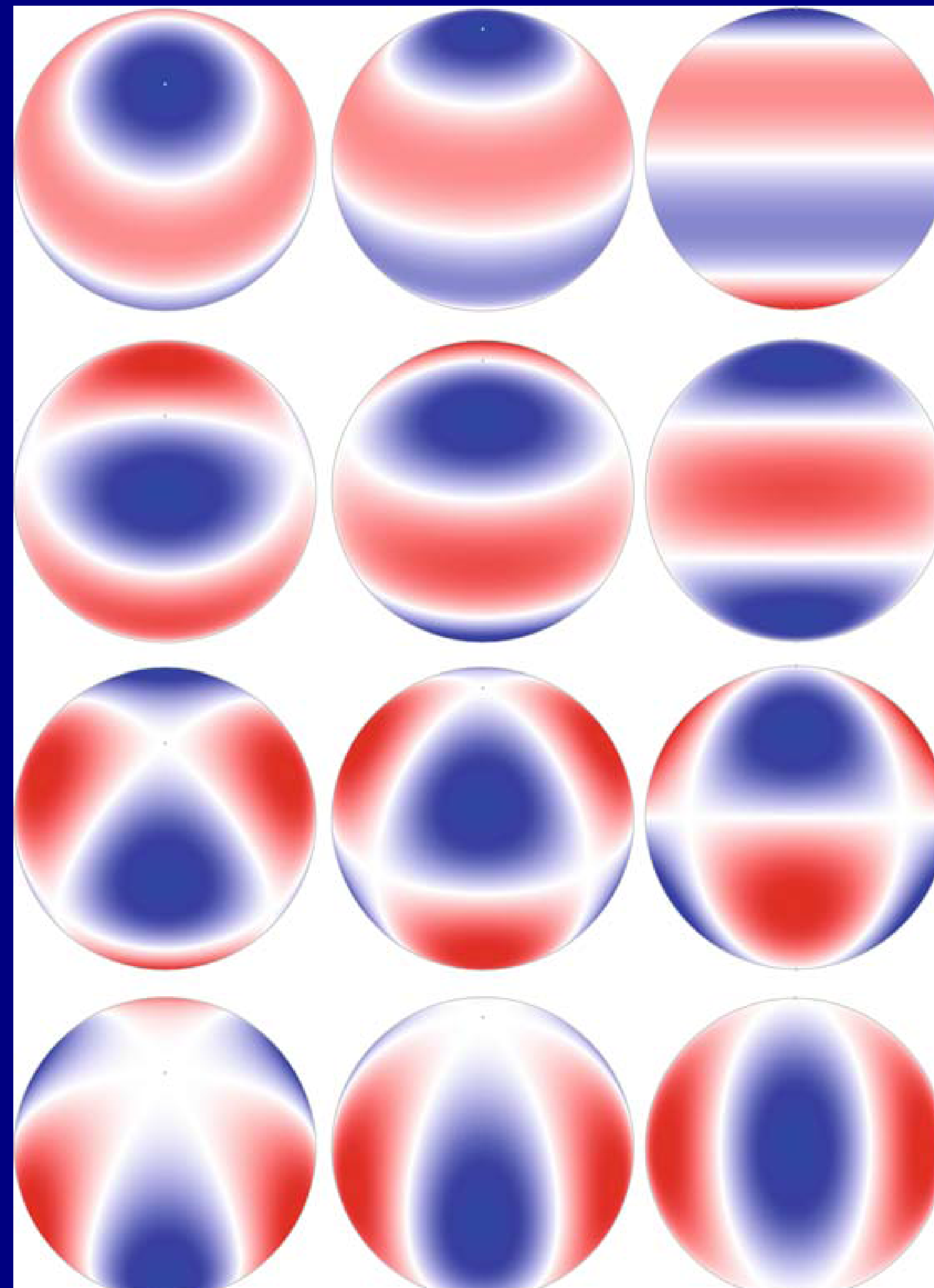
i=30° i=60° i=90°

$\ell = 3, m = 0$

$\ell = 3, m = \pm 1$

$\ell = 3, m = \pm 2$

$\ell = 3, m = \pm 3$

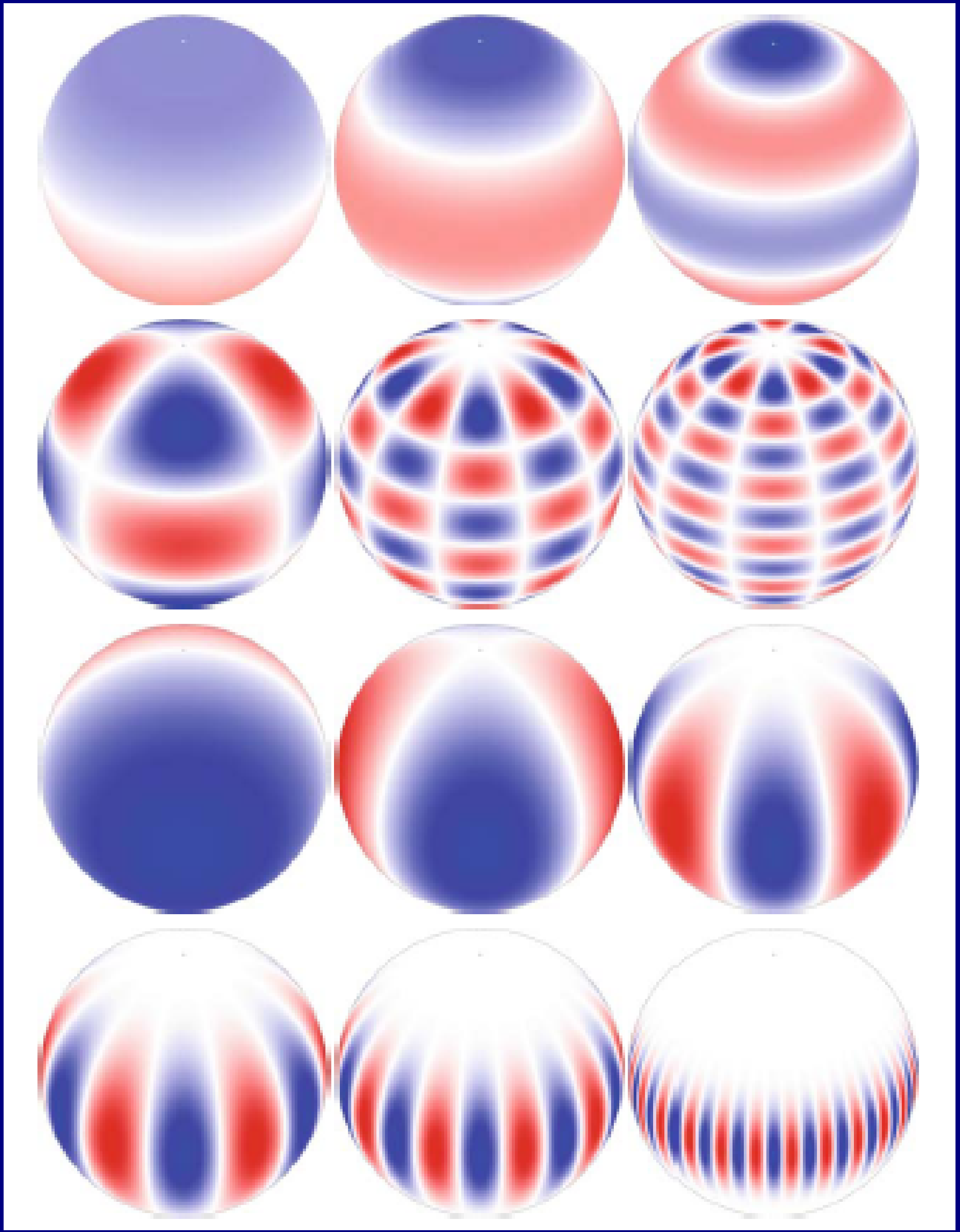


$(1,0)$, $(2,0)$, $(4,0)$

$(4,2)$, $(10,5)$, $(15,5)$

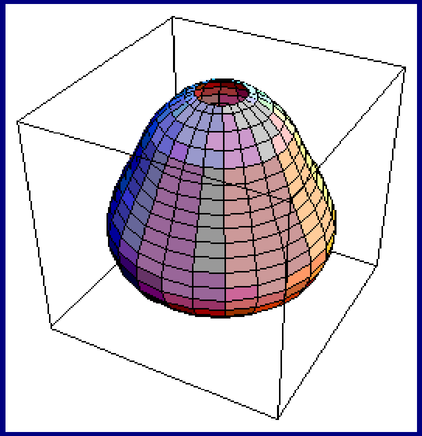
$(1,1)$, $(2,2)$, $(4,4)$

$(6,6)$, $(10,10)$, $(25,25)$

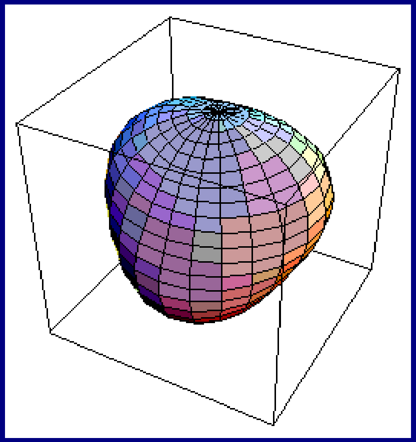


Different Modes of Oscillation

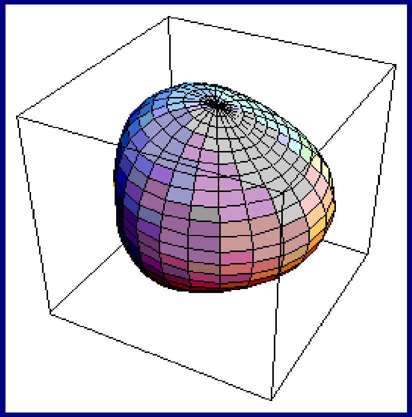
l=3, m=0



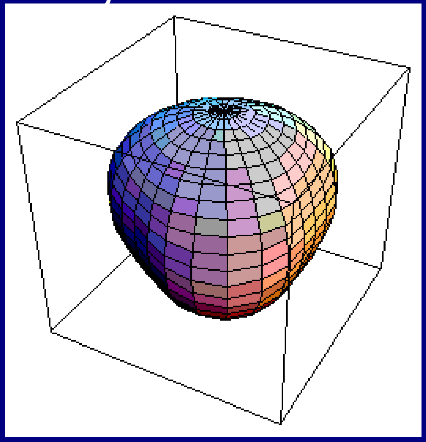
l=3, m=2



l=3, m=1

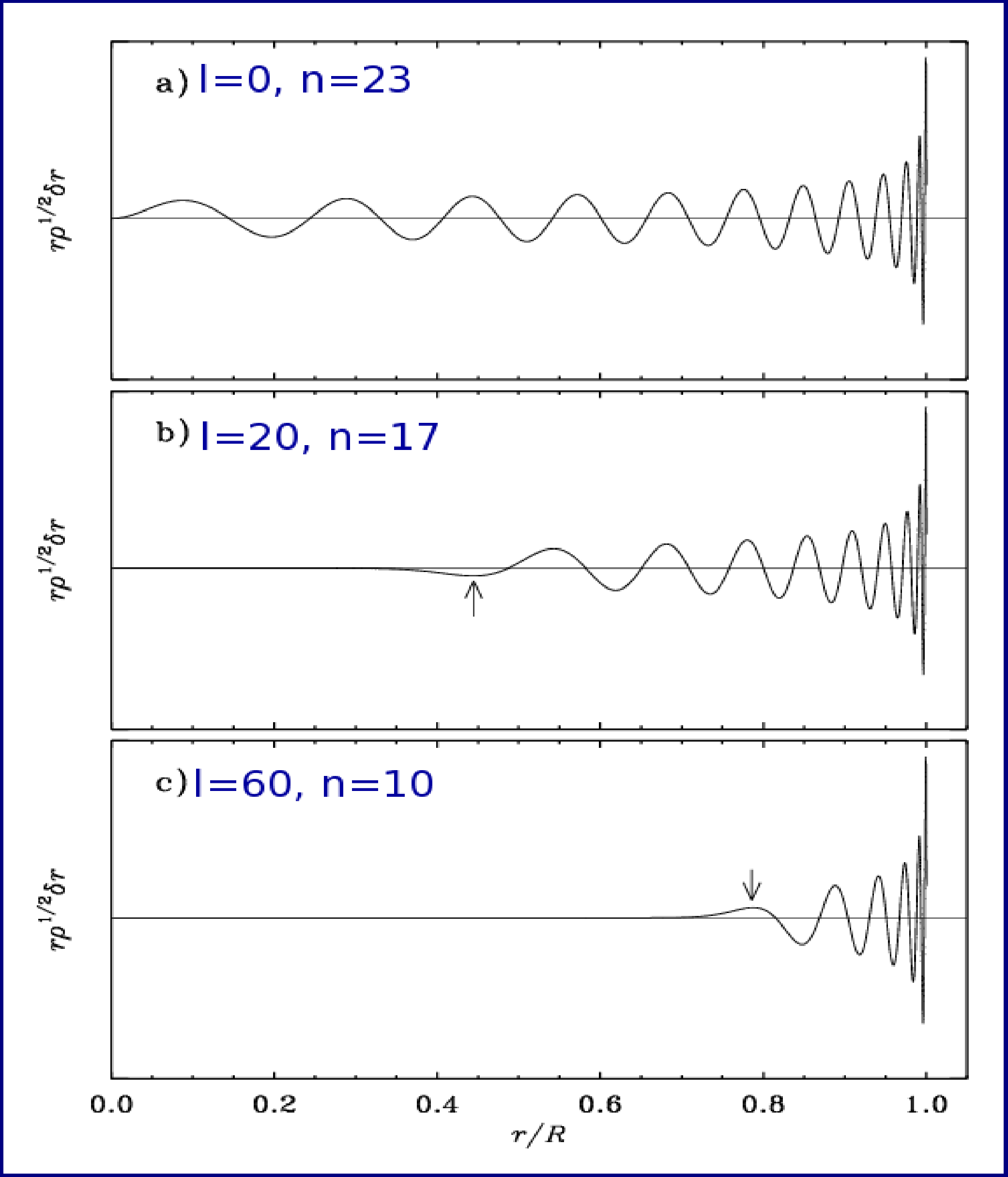


l=3, m=3



Different Modes of Oscillation
-- Radial behaviour --

- Inside the star, the wave is reflected at the boundary of oscillatory and evanescent regions – inner turning point.
- Outer turning point is close to the surface.
- Number of “zero-crossings” determine radial order: n.
- Higher ℓ modes penetrate less into the star.

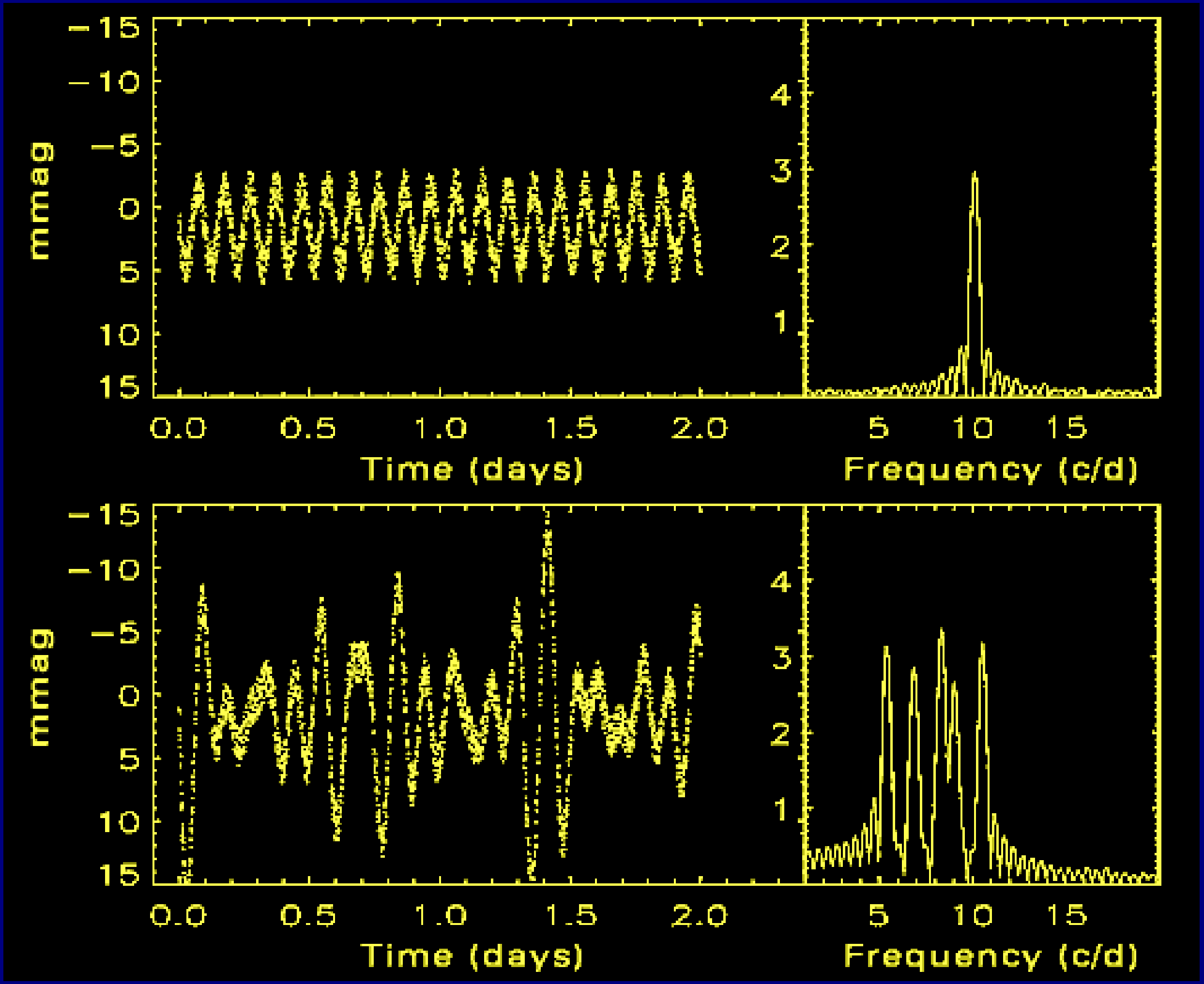


How come I never see the stars oscillating?!!

- Amplitude of oscillation is very small compared to the average brightness of the star
  - Typically few parts per million (ppm)
  - Indistinguishable to the human eye (but detectable through instruments)
- Most stars oscillate in multiple modes
  - Difficult to separate out the different sounds in the orchestra

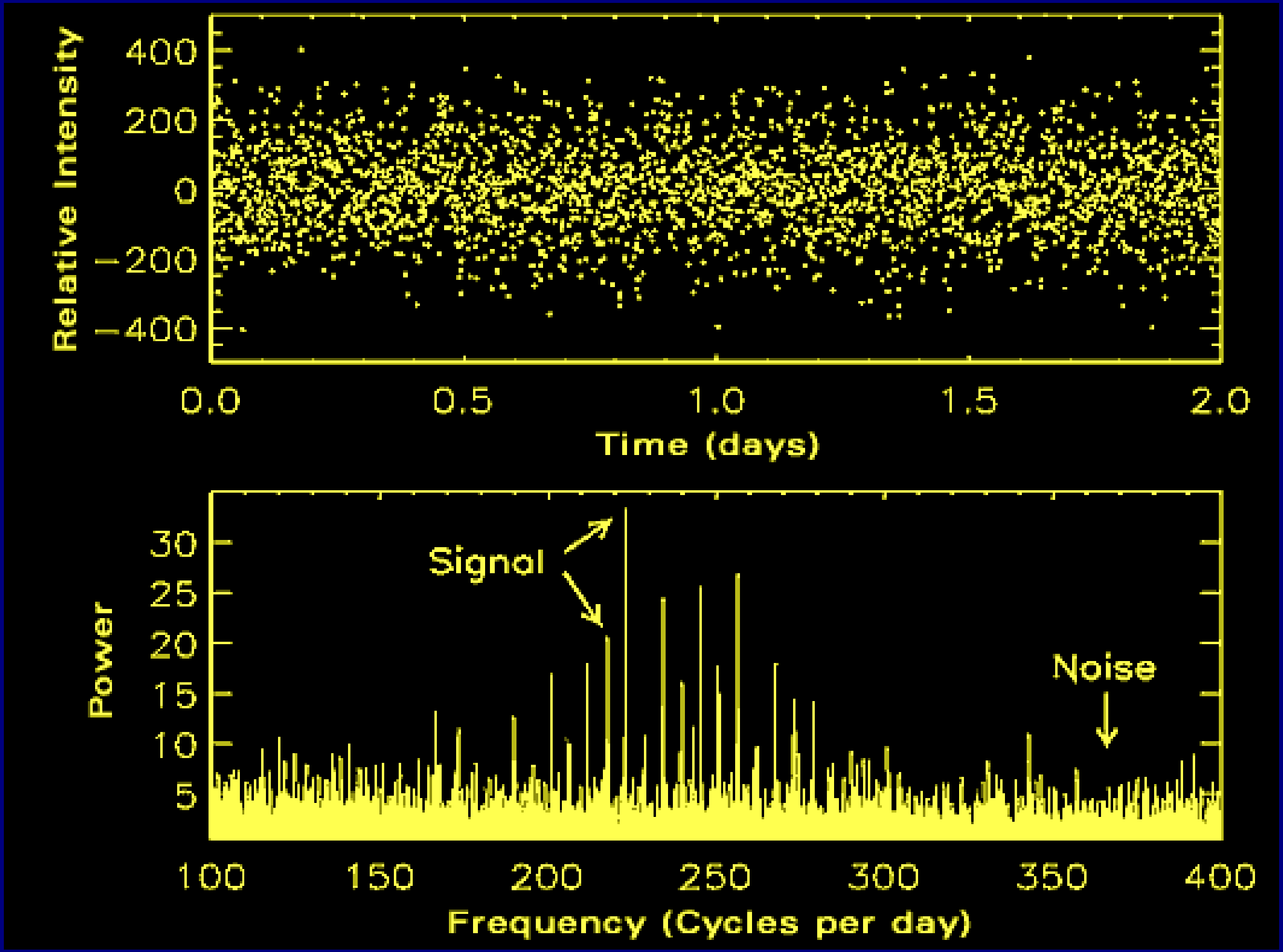
Seismology by Photometry

- Monitoring the light emitted by a star very precisely over a long time lets us see the oscillations
- Frequencies of oscillation can be determined by **Fourier analysis** of the "light curve"



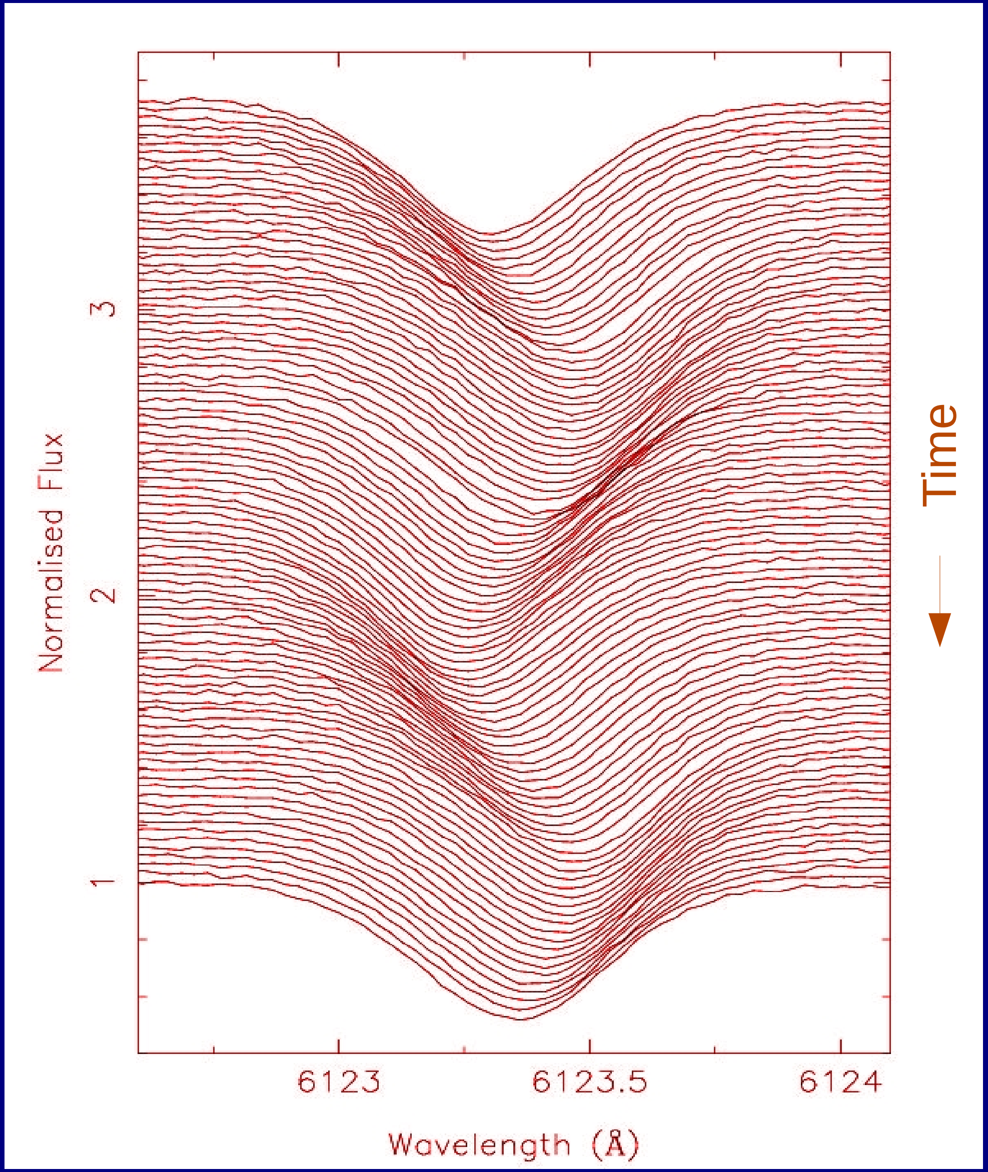
Seismology by Photometry

- Fourier analysis especially helps to remove the noise.
- Typical “power spectrum” has a series of peaks, signifying different modes of oscillation.



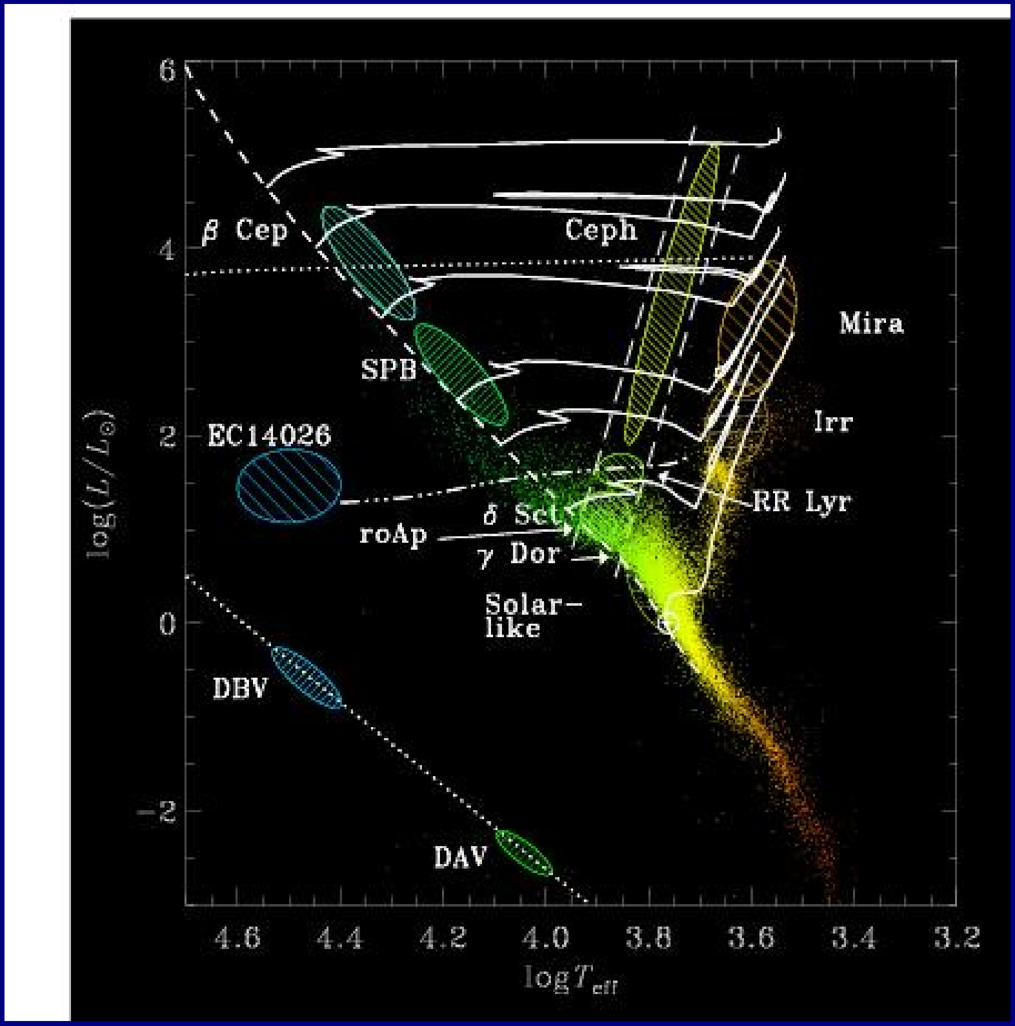
Seismology by Spectroscopy

- Stellar spectrum contains absorption lines which are Doppler-shifted due to radial velocity of the waves.
- Similar Fourier techniques are used to determine frequencies.
- Variation of line profile indicates ℓ

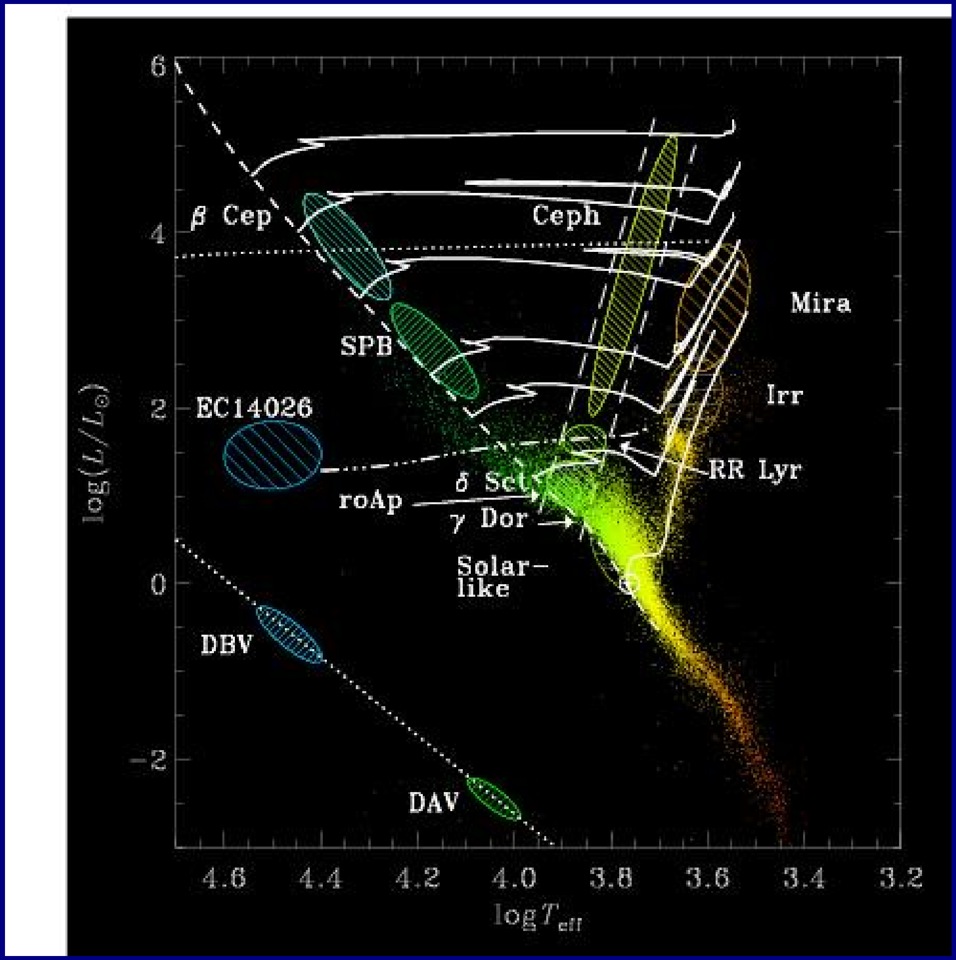


Which stars oscillate?

- Practically all stars oscillate!
- Oscillation mechanism is different in different regions of HR diagram.
- Relative amplitude of oscillation varies from 10^{-6} to 10^{-1}
- Time periods vary from few mins to few months.

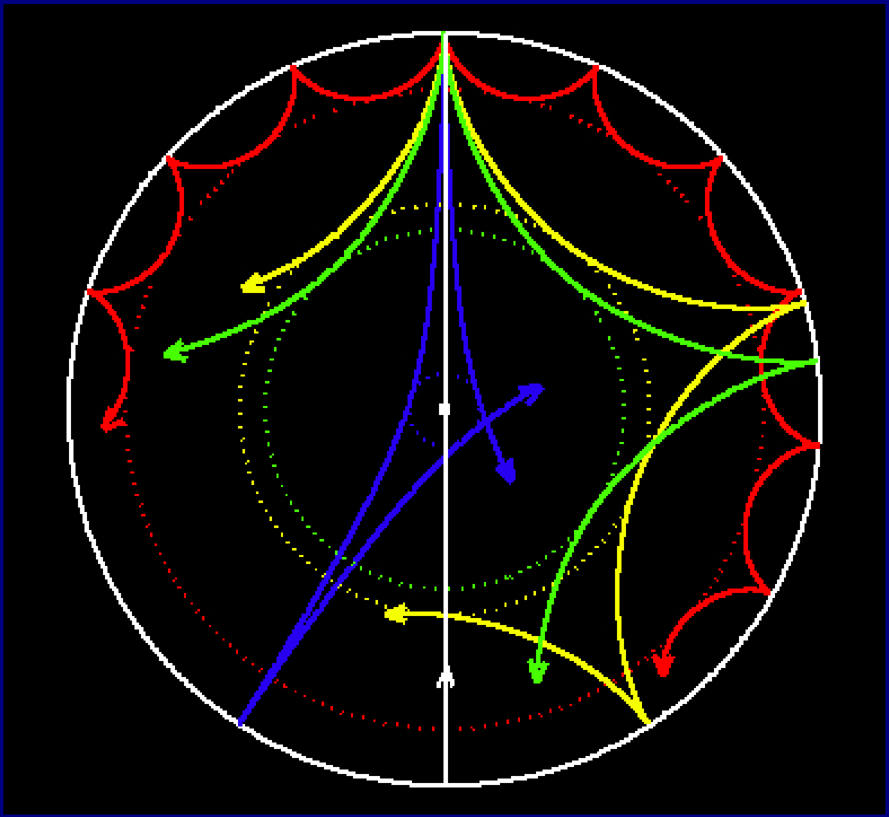


Pulsations across the H-R Diagram



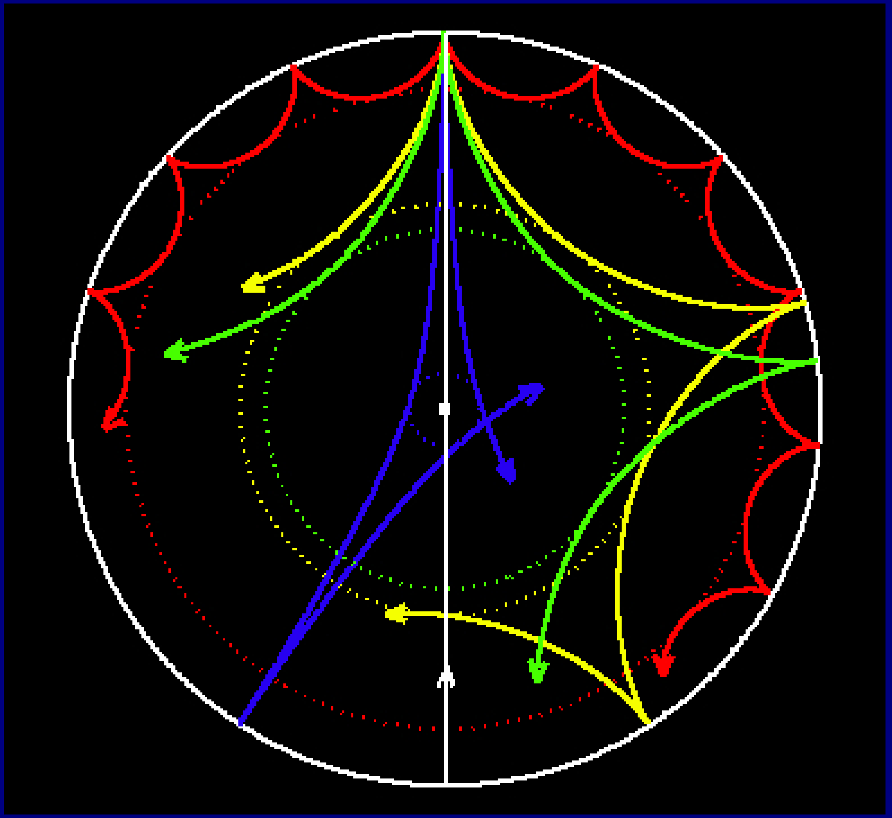
Sound waves inside Stars

- A sound wave **bends** inside the star due to the **changing speed of sound**.
- Total internal reflection at a certain internal layer due to rapid increase in sound speed.
- At the surface also the wave is reflected due to rapid decrease in density.
- **The wave is trapped between the inner and outer turning points.**
- If exactly an integer number of wavelengths fits between the two reflections at the surface, we have a standing wave --- **eigensolution**.



What do we care if stars oscillate?

Different modes penetrate the star up to different layers, and the **frequency of the mode depends on the structure and properties of the resonant cavity**.



- **Frequencies scale with the mean density of a star**:

$$\omega \sim \frac{1}{t_{\rm dyn}} \sim \sqrt{GM/R^3} \sim \sqrt{G\bar{\rho}}$$

– Only direct probe into stellar interiors!

How do we use the oscillations?

- Inverse method:
  - Frequencies are functions of structure parameters:

$$\nu_i = \nu_i(\rho, T)$$

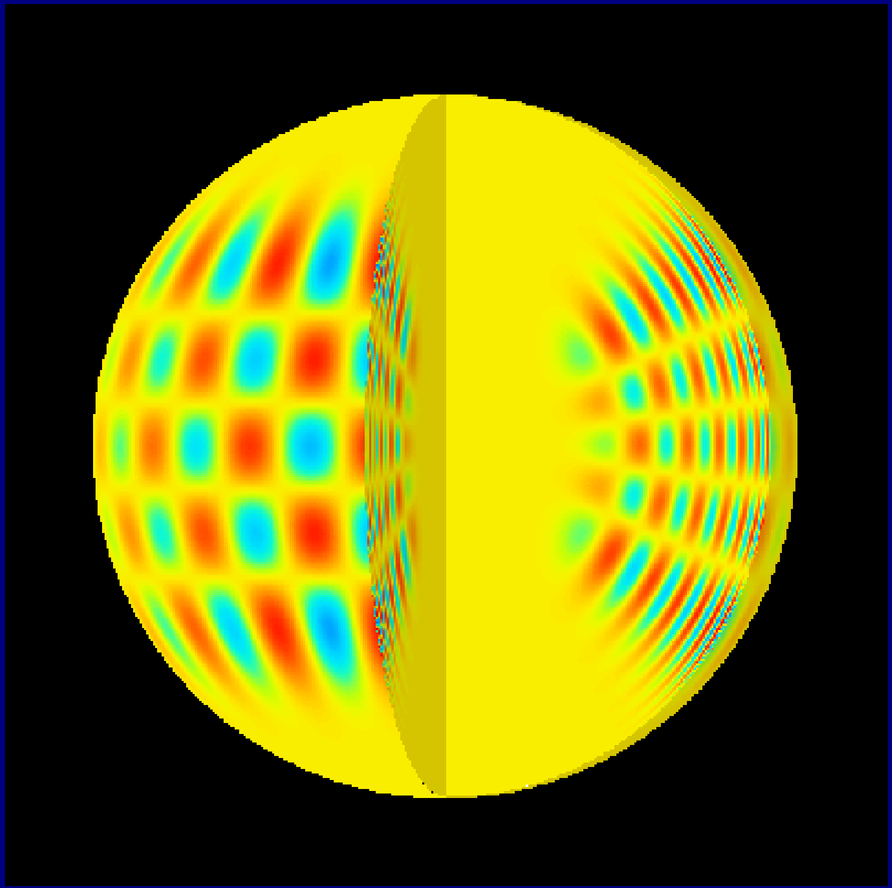
  - Frequencies can be “inverted” to obtain the structure:

$$\rho = \rho(\nu_1, \nu_2, ...)$$

  - Inversion is possible only for large no. of frequencies.
  -
- Forward method:
  - Calculate frequencies from stellar models and match them with observed frequencies to constrain stellar structure model parameters.

Oscillations in the Sun: Helioseismology

- Oscillations with **period ~ 5 min** were first detected in the Sun in 1961. Whole disk oscillations confirmed in 1979.
- For the Sun, we can detect **several million modes of different (n,l,m)** by resolving the solar disk and identifying the frequencies through Fourier analysis.
- Other effects like solar activity, granulation can be isolated from the periodic oscillations.
- Amplitude ~ 20 cm/s in v, $\sim 10^{-6}$ in L
- Frequency ~ 1-10 mHz
- **Extremely high precision on frequencies ~ 1 nHz**

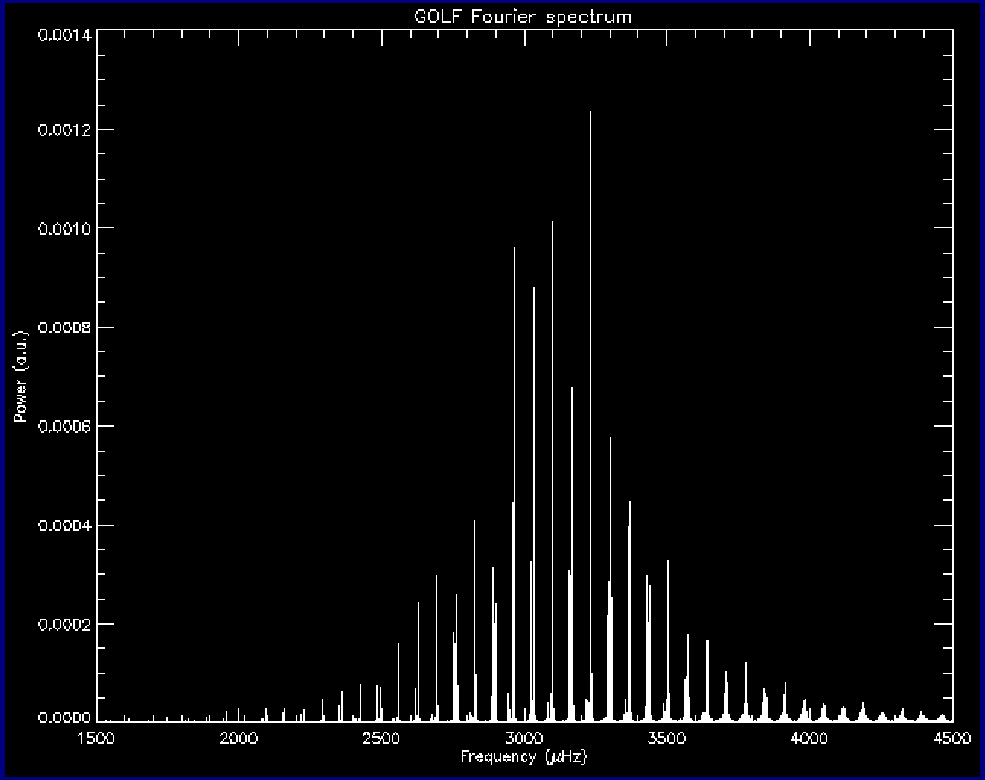


Helioseismology

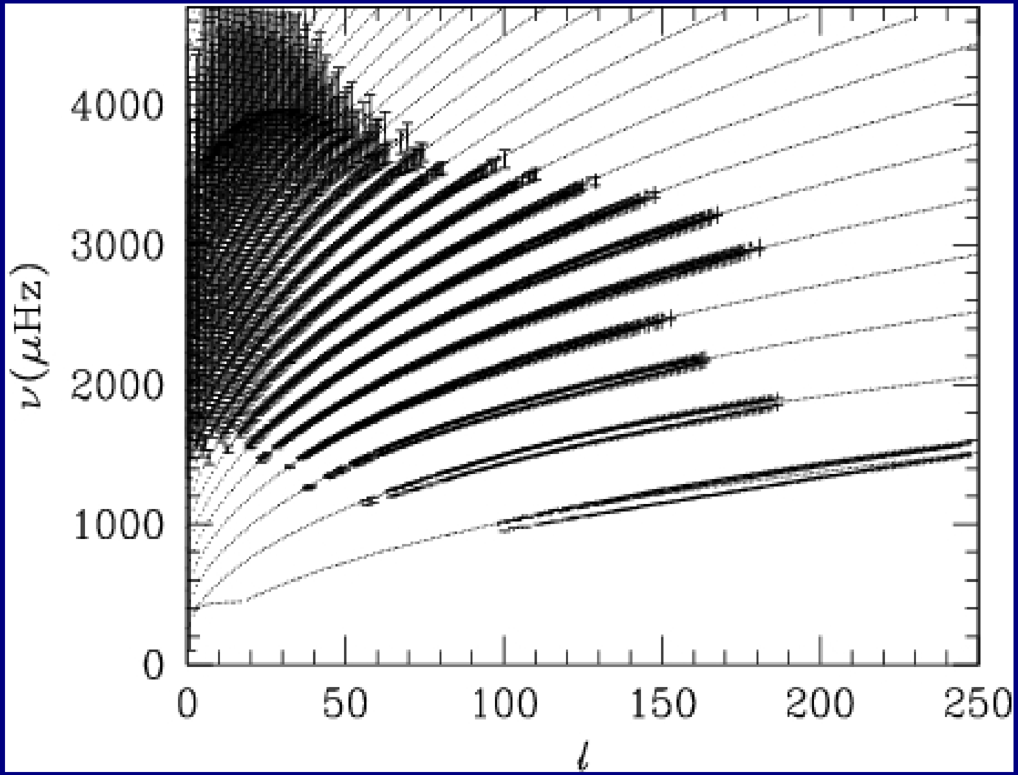
- Nearly 10,000 modes of oscillation have been observed on the Sun
- Frequency ~ 1-10 mHz
- Extremely high precision on frequencies ~ 1 nHz
- Amplitude ~ 20 cm/s in v, $\sim 10^{-6}$ in L
- Continuous observing from ground network (GONG, IRIS) and space (SOHO, TRACE, SDO) over more than 10 years
- Direct inversion – finding stellar quantities as functions of frequency – leads to accurate models

Helioseismology – Sunquakes

Solar power spectrum from the SOHO mission

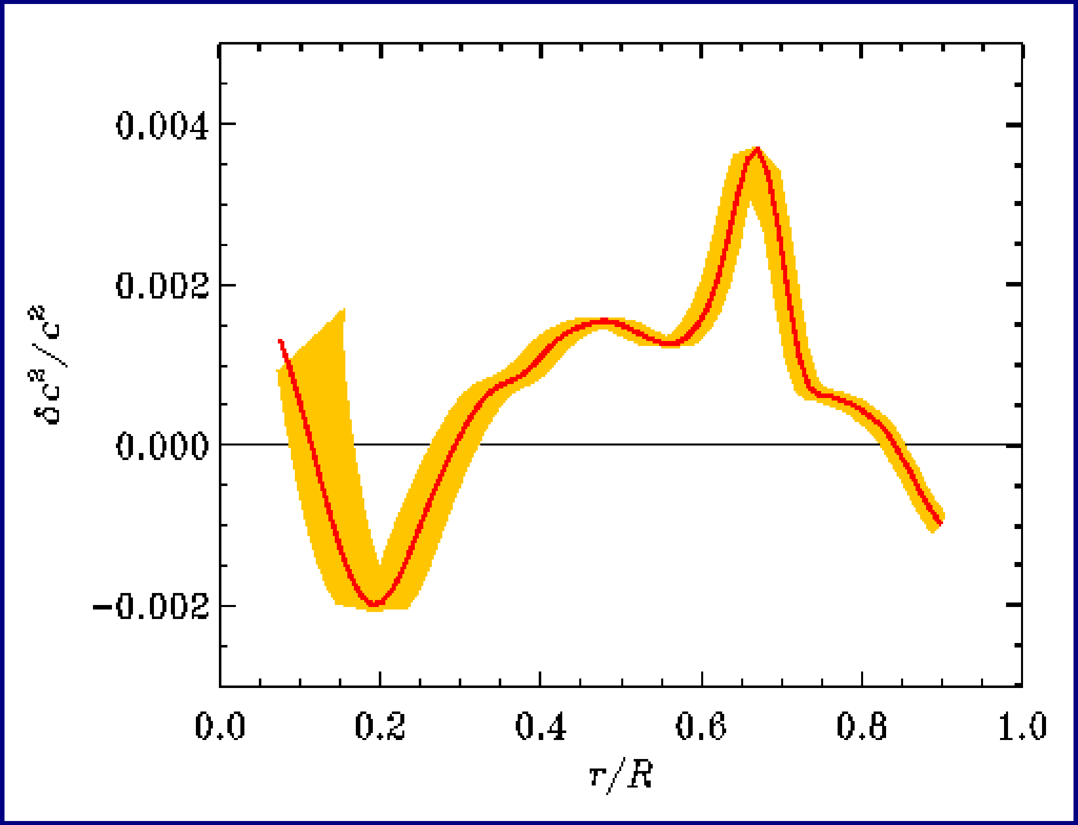


Solar frequencies with 5000σ errorbars



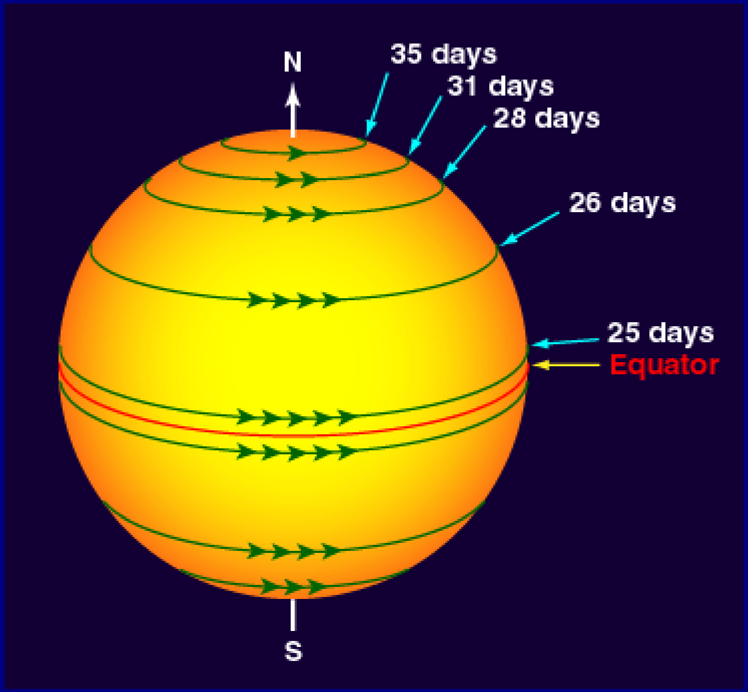
What have we learnt from Helioseismology?

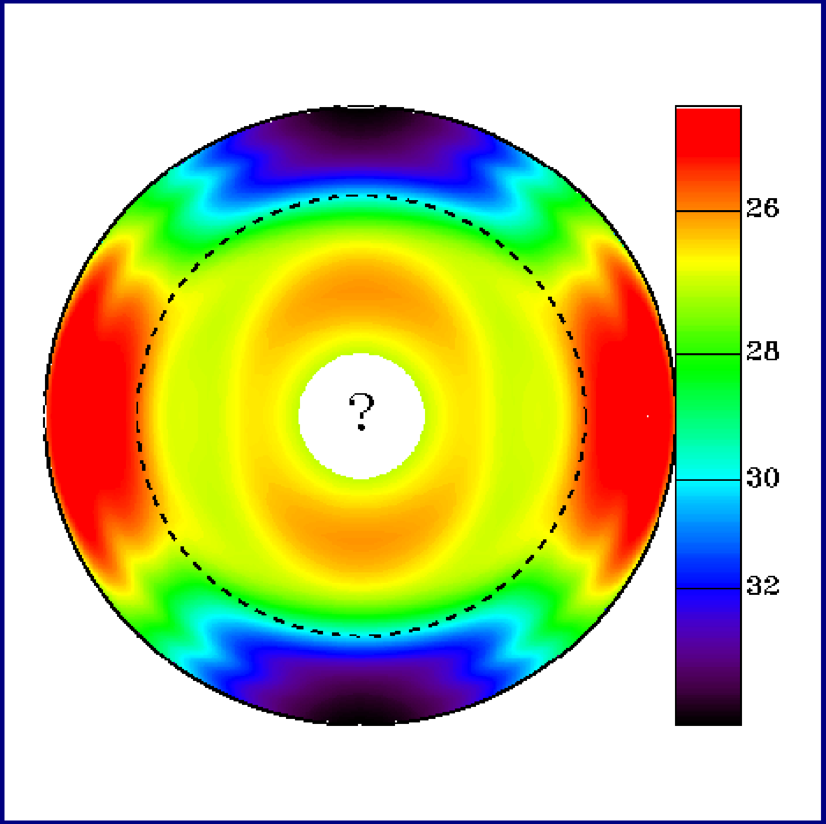
- Standard solar model has been tuned to match the frequencies as closely as possible. Agreement at more than 99% even for worst cases.
- Sound speed inside the sun can be determined by inversion.
- SSM and Sun now agree up to 99.6%!



What have we learnt from Helioseismology?

- Frequency splittings allow us to determine rotation rate inside the Sun.





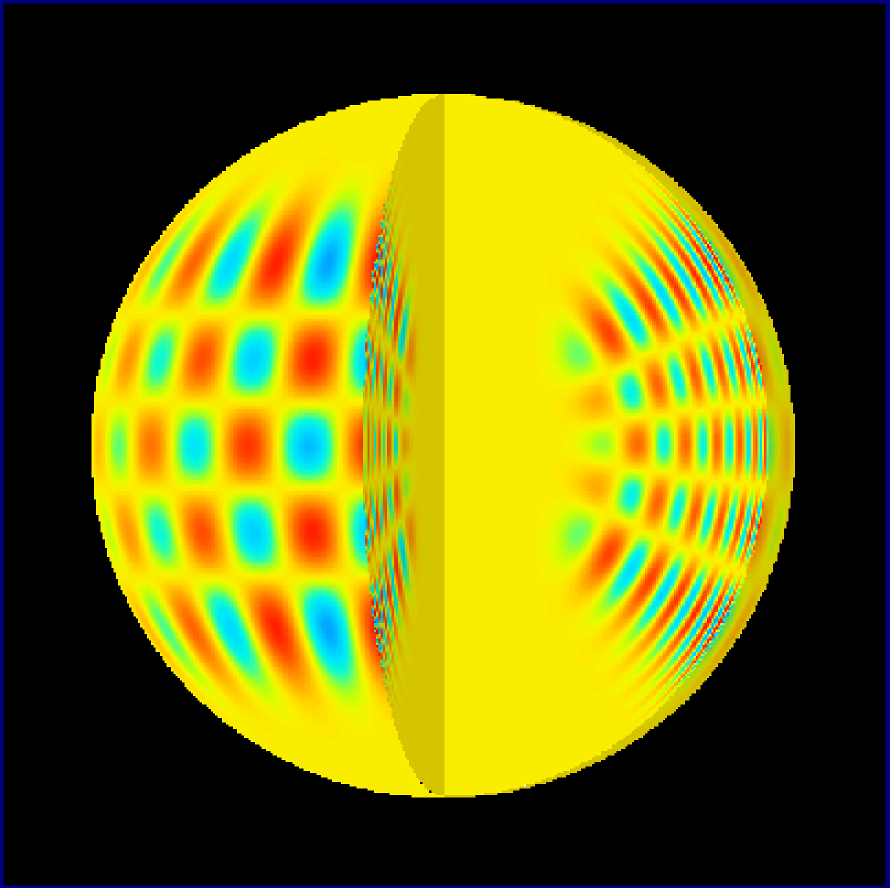
- Inversion shows Sun has differential rotation only in the outer 30% of its radius.

What have we learnt from Helioseismology?

- Long-standing problem of solar neutrino deficiency was solved with input from helioseismology – precise solar model allowed exact calculation of neutrino generation rates.
- Unprecedented accuracy in solar radius (~10 km)
- Base of solar convection zone lies at r = 0.713 Rsun (really!!)
- Current crisis – mismatch between seismic models and new solar abundances
- Recent focus on solar activity and cyclic variations.

Can we see the oscillations in stars?

- For distant stars we have to obtain time series of the variation of flux (or velocity) integrated over the visible hemisphere.
- Modes with large values of {l,m} are difficult to observe due to cancellation on averaging.
- Larger amplitude oscillators are easier to detect, but most multi-mode oscillators have low amplitudes.
- Oscillations in a variety of stars have been detected from the ground.

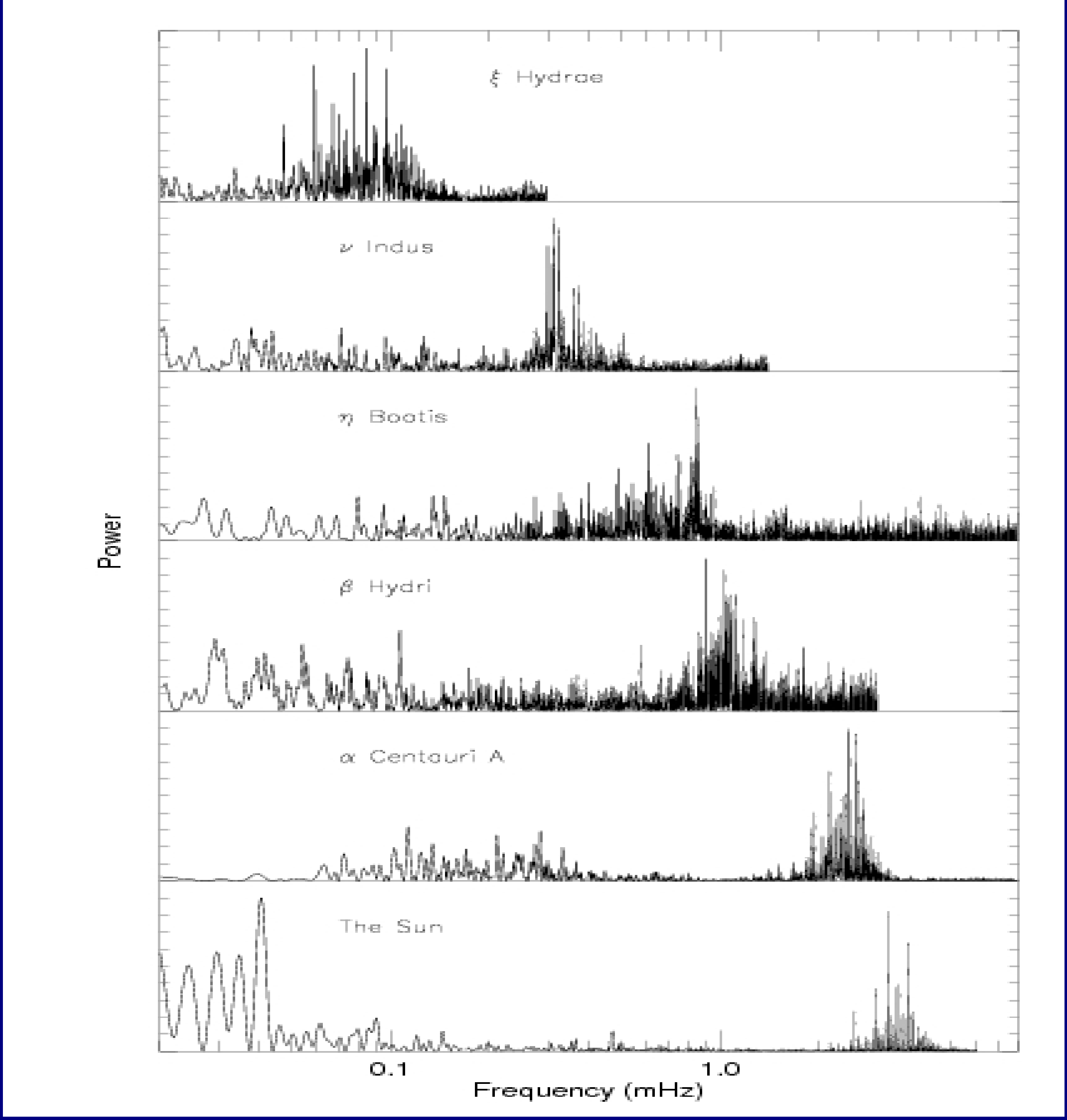


Asteroseismology of distant stars

- Unlike the Sun, only low degree modes (l<4) can be observed for distant stars.
- Fortunately these are the modes that travel deepest inside the stars.
- Total number of modes observed is also limited.
- Error on frequencies higher ~ 0.1 µHz.
- Direct inversion (like in the solar case) is difficult.
- Important constraints can still be put on the stellar structure and rotation.

Asteroseismology from the ground

- First detection of oscillations in Procyon in 1991.
- Since then several solar type stars, subgiants, red giants and hot stars have been found to oscillate.
- Frequency extraction is difficult due to
  - day-night effect
  - poor SNR.



Asteroseismology from Space

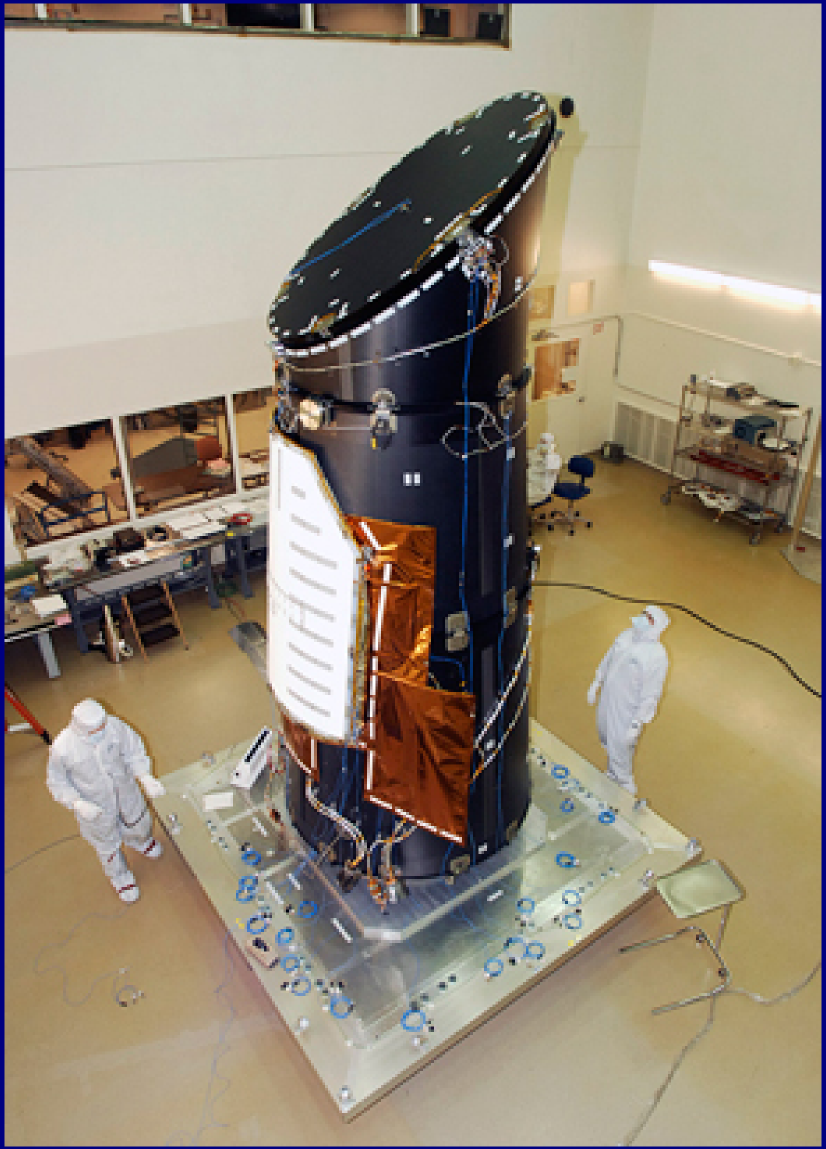
- No atmospheric disturbance
- No day-night effect
- No weather dependence
- Much better photometry

- Spectroscopy is difficult
- Operation of satellite is a challenge
- Costly – few govts want to look inside stars!

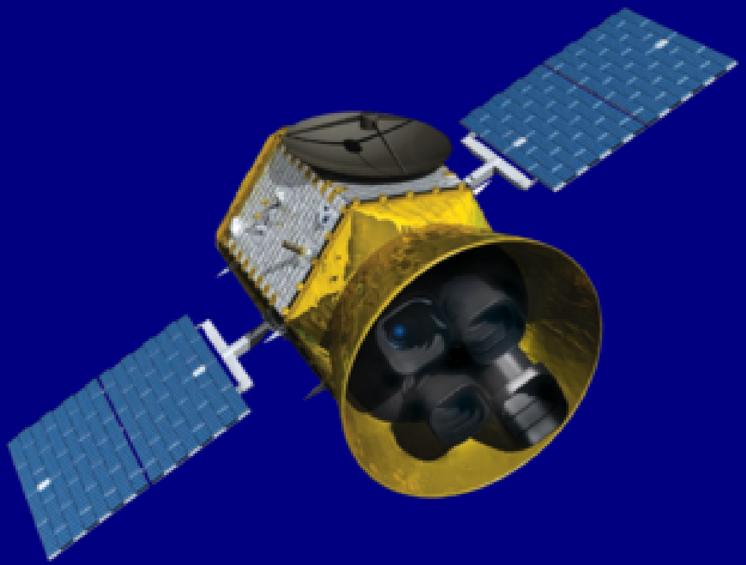
Solution: Tie-up with Extra-solar Planet-hunters!

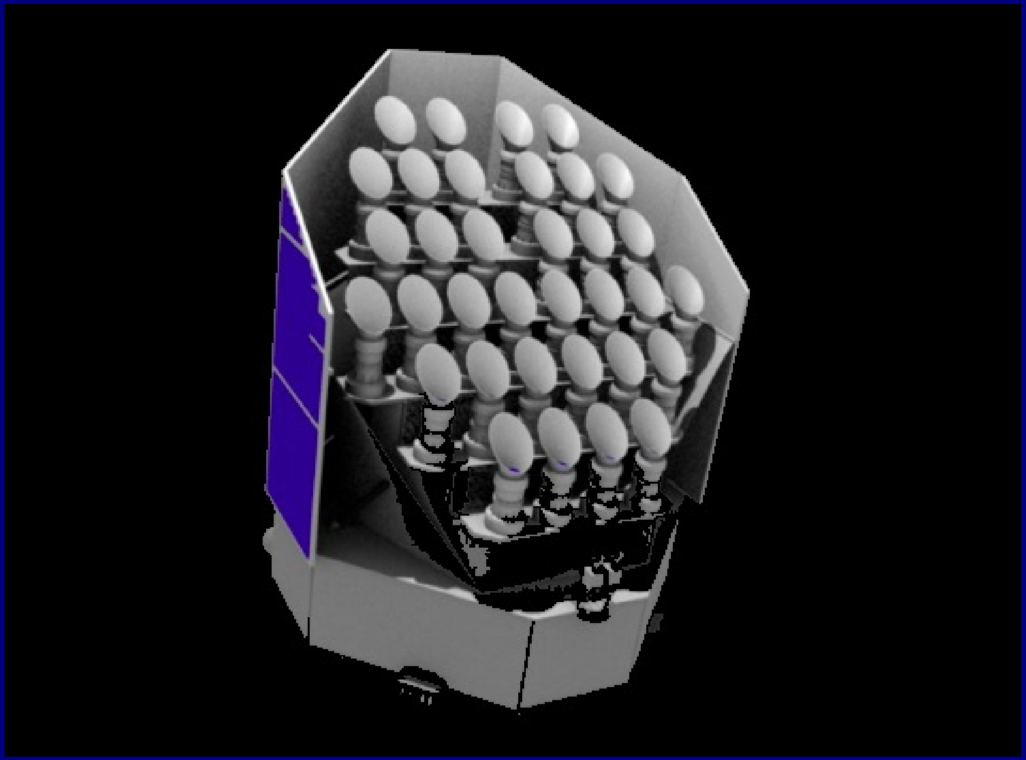
Asteroseismic Missions in Space: ***Kepler***

- Optimized for finding habitable planets in the habitable zone (near 1 AU) of solar-like stars.
- 2009 – 2013 – ??
- 1 m telescope with FOV ~ 100 deg^2 with an array of 42 CCDs.
- Continuously and simultaneously monitored 170,000 stars for 3.5 years!
- *Kepler* Asteroseismic Science Consortium (KASC)
    - 600 members in a FREE collaboration



Future space missions





- TESS

  2-year mission

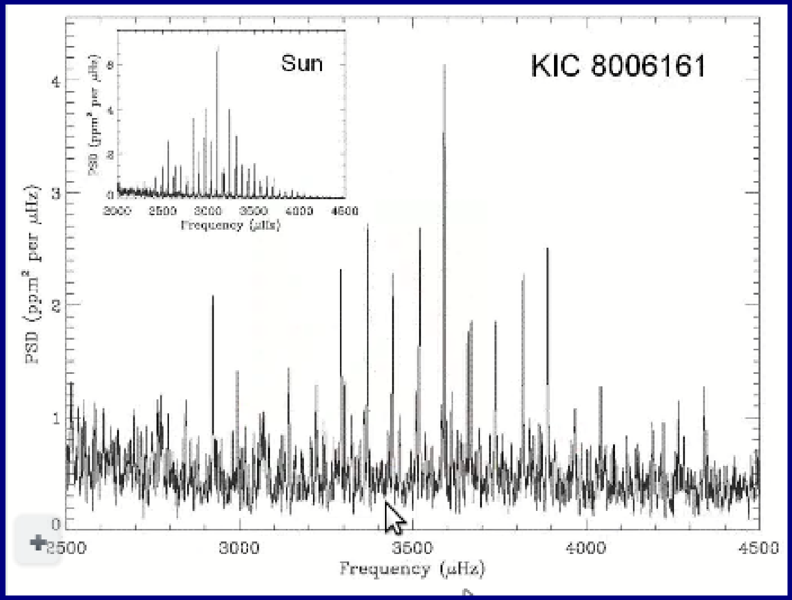
  Launch 2018

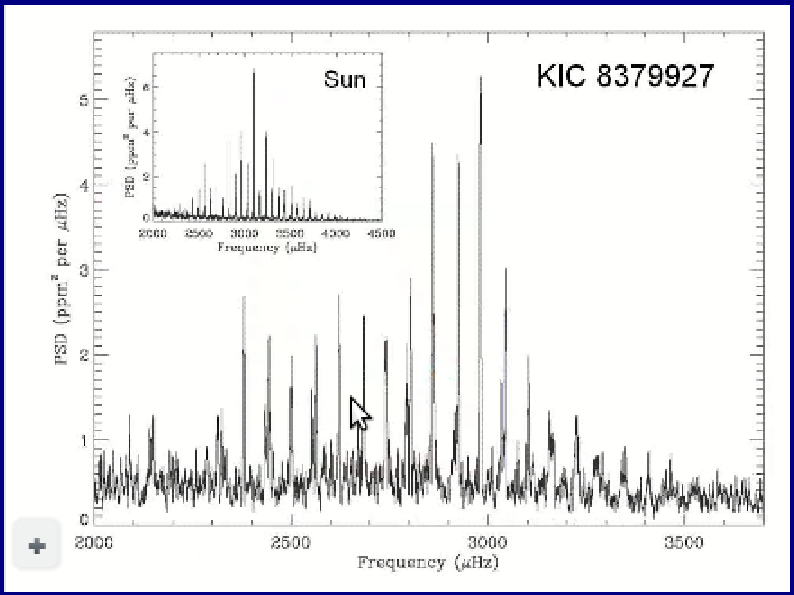
- PLATO

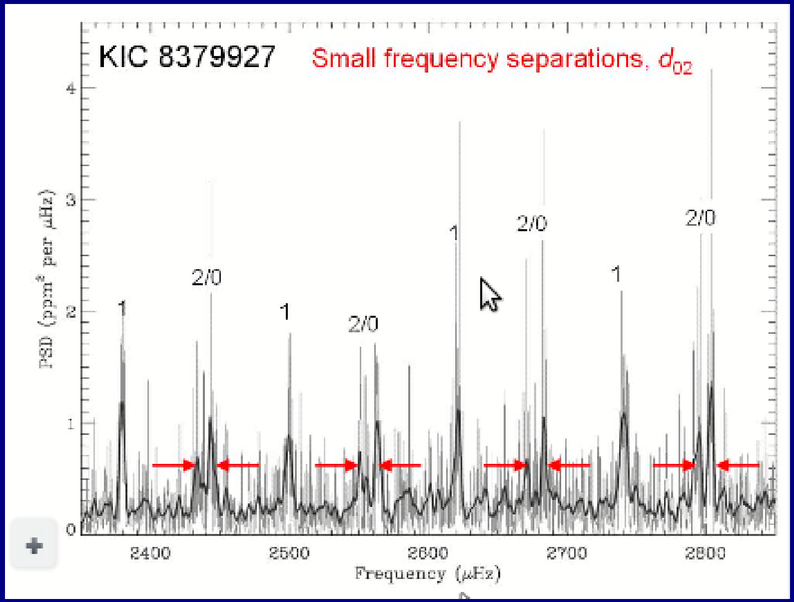
  6-year mission

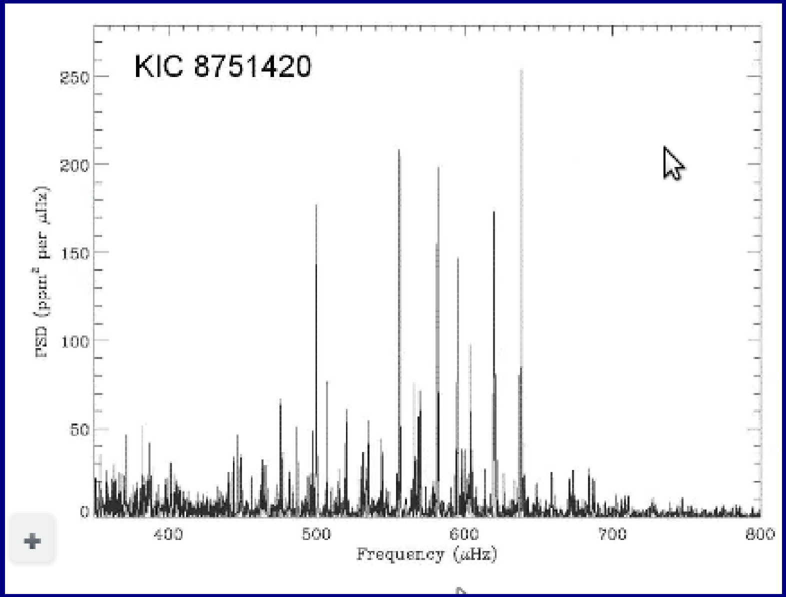
  Launch 2024

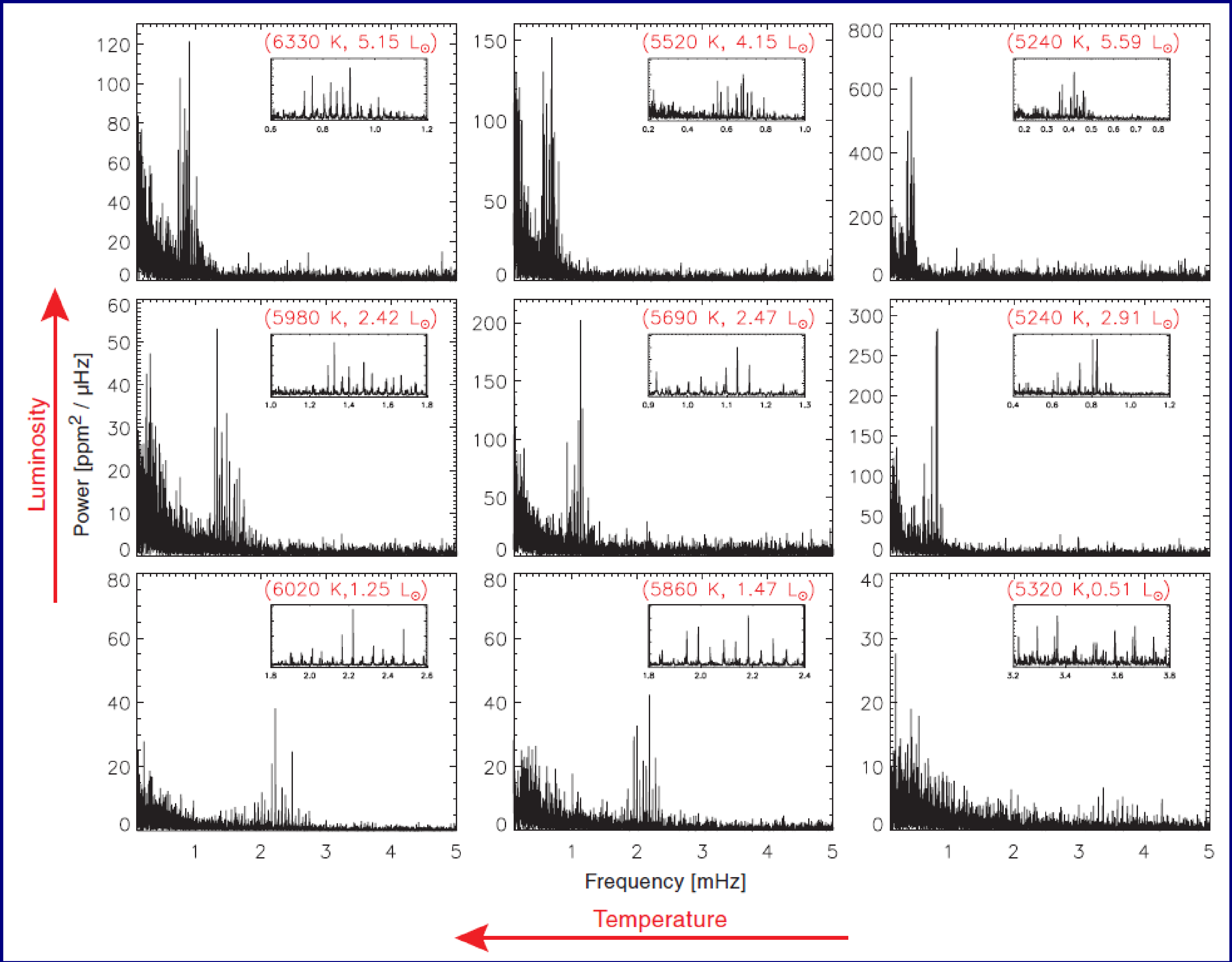
Kepler results











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Highlights from CoRoT and Kepler so far

- **Accurate determination of mass (~10%), radius (~5%) and age (~5%)** of main sequence and red giant stars
- **Ensemble asteroseismology**
  - Allows us to understand trends in stellar populations
  - Better understanding of the effect of mass and age on stellar processes
- **Determination of rotation rates inside stars**
  - Differential rotation inside stars
    - Cores of red giants spin 10 times faster than surface
  - Transport of angular momentum

Highlights from CoRoT and Kepler so far

- **Location of “glitches” inside stars**
  - Constraints on layers of rapid change in sound speed
  - Depth of surface convection zone
  - Helium abundance
- **Determination of evolutionary phase of red giants**
  - Possible to distinguish between shell H-burning and core He-burning stars
- **Determination of extent of convection in stellar cores**
  - Strong constraints on stellar ages
- New discoveries in classical pulsator properties
- Lot more to come!

Conclusions

- Stellar oscillations are powerful probes into the interior of stars.
- Research in asteroseismology is theoretically sound and observationally viable.
- Present and future space missions have opened up a new window into the interior of distant stars.
- Next few years will see a big boost in stellar seismic data which will hopefully solve many outstanding questions in stellar physics.