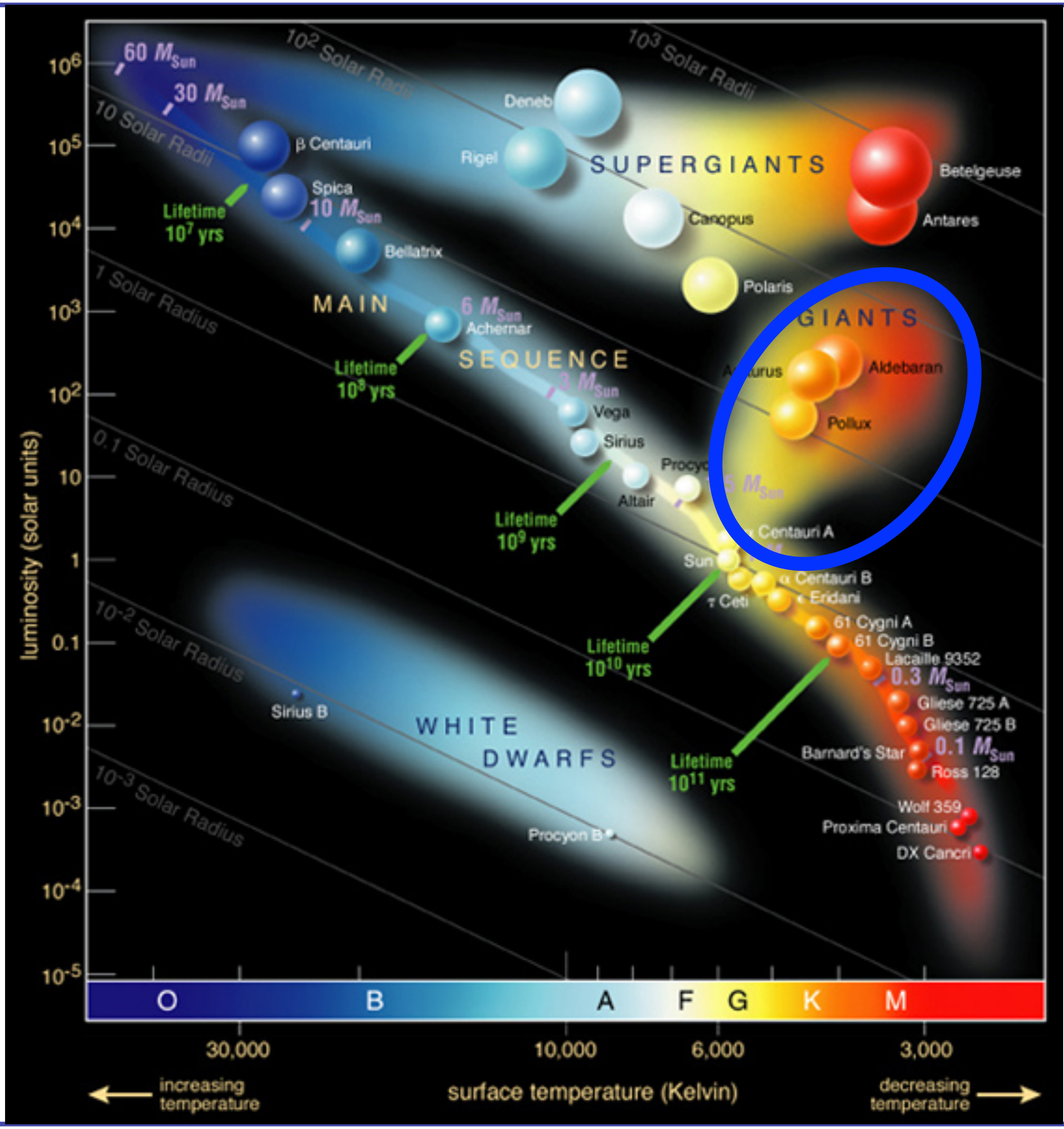
Asteroseismology of Red Giants & Galactic Archeology

About me

- 2003 MSc Applied Physics Delft
- 2007 Phd Leiden (A. Quirrenbach, C. Aerts, I. Snellen)
- 2008 Postdocs ROB (CoRoT)
- 2009 – 2010 Postdoc UoB (Kepler)
- 2011 – 2013 Veni fellow Amsterdam
- 2013 – 2018 ERC-group MPS, Göttingen
- 2015 – 2019 Independent group leader MPS, Göttingen


60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
3 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Sun
SUPERGIANTS
Betelgeuse
Antares
Canopus
Polaris
GIANTS
Aldebaran
Pollux
Centauri A
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
MAIN
SEQUENCE
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
WHITE DWARFS
Sirius B
Procyon B
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

red-giant stars

Noname manuscript No.
(will be inserted by the editor)

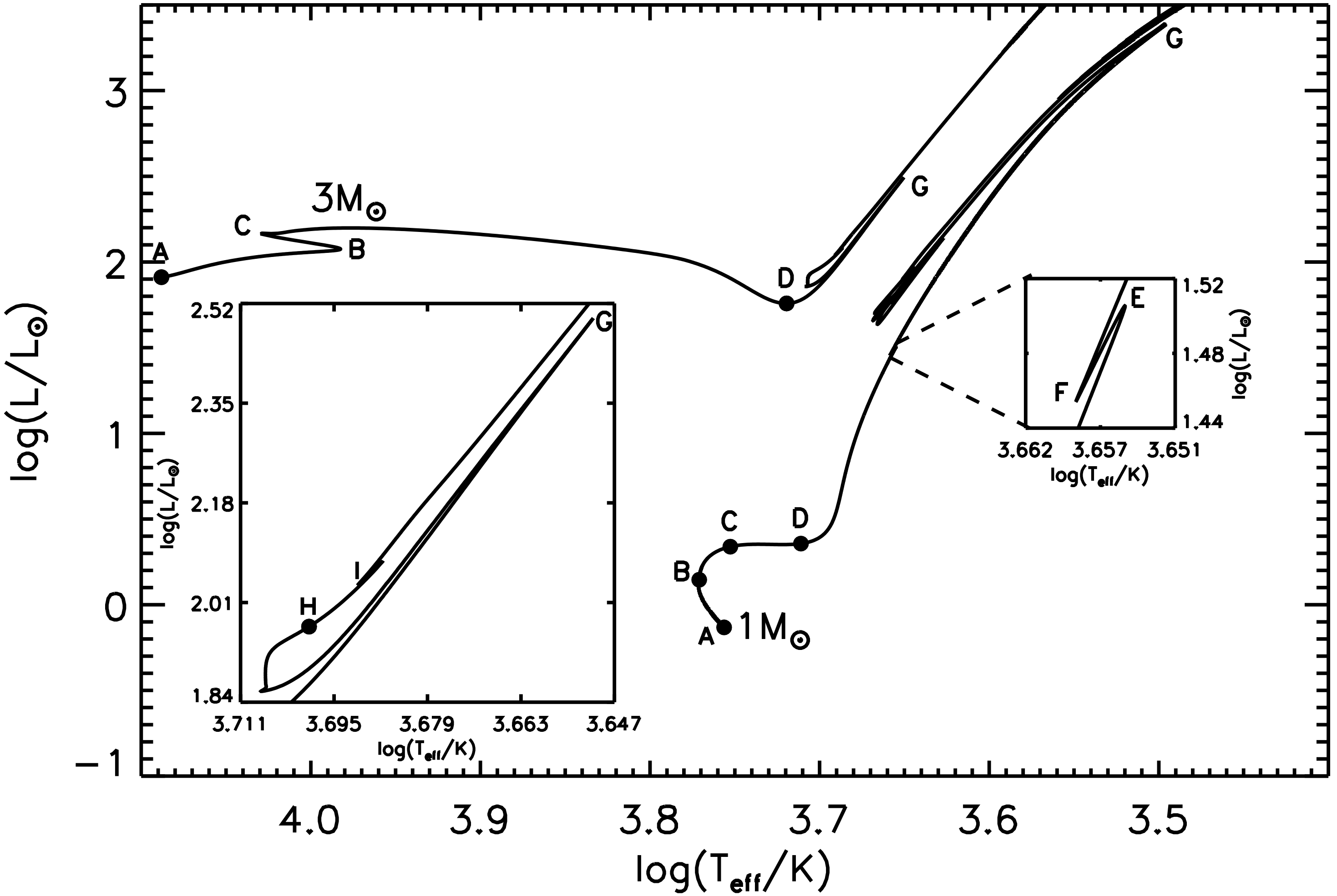
Giant star seismology

S. Hekker · J. Christensen-Dalsgaard

Received: date / Accepted: date

Abstract The internal structures of stars in the red-giant phase undergo significant changes on relatively short timescales. Quasi-direct observations of these internal structures have now been enabled by dedicated space missions such as CoRoT and *Kepler* using long near-uninterrupted high-precision photometric timeseries observations. The seismic inferences from these observations are confronted with predictions from theoretical models to improve our understanding of stellar structure and evolution. Our knowledge and understanding of red giants has indeed increased tremendously, and we anticipate that more information is still hidden in the data. Unraveling this will further improve our understanding of stellar evolution. This will also have significant impact on our knowledge of the Milky Way Galaxy as well as on exoplanet host stars. The latter is important for our understanding of the formation and structures of planetary systems.

Stellar evolution

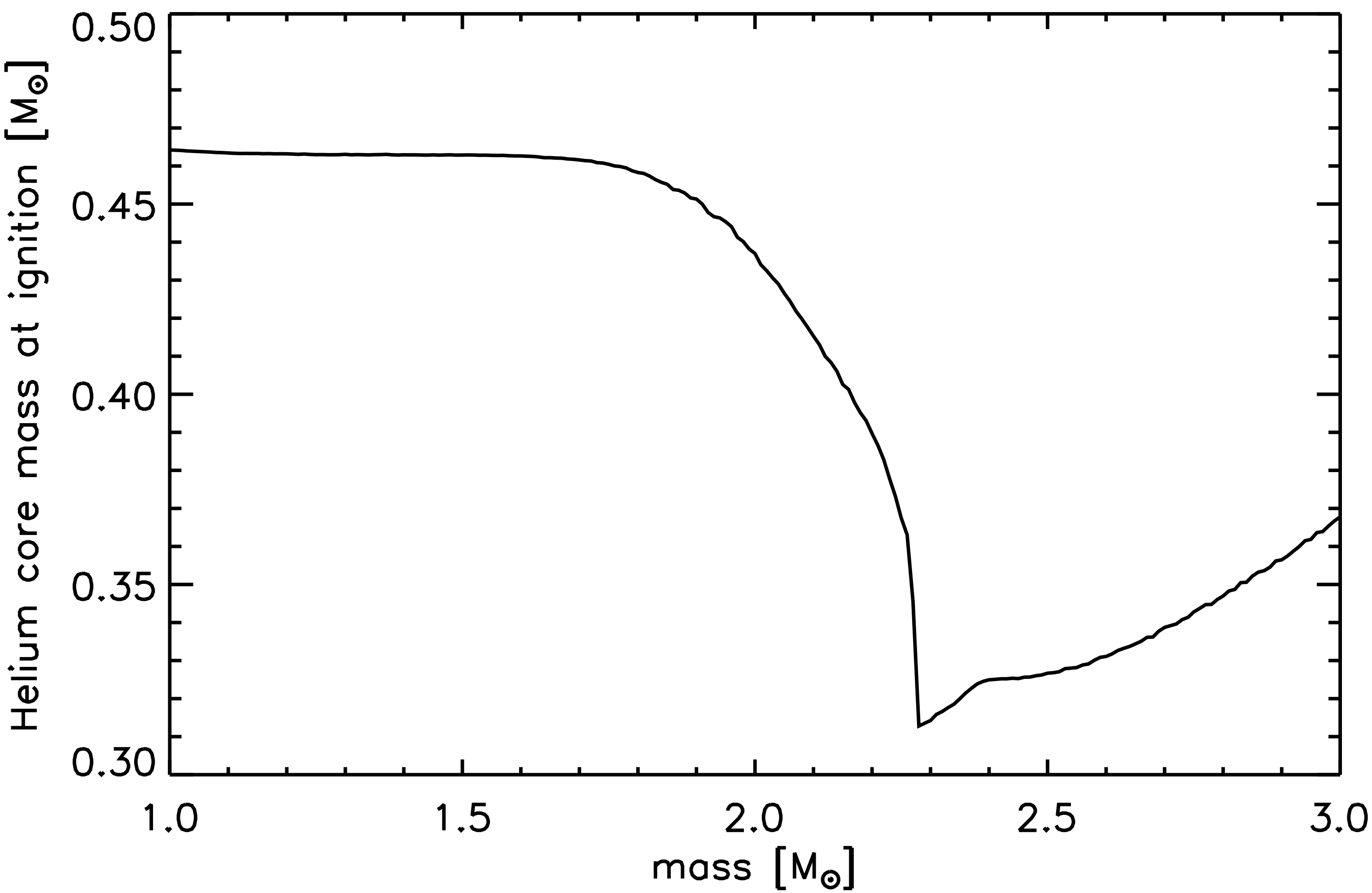


Hekker & Christensen-Dalsgaard in prep.

Question?

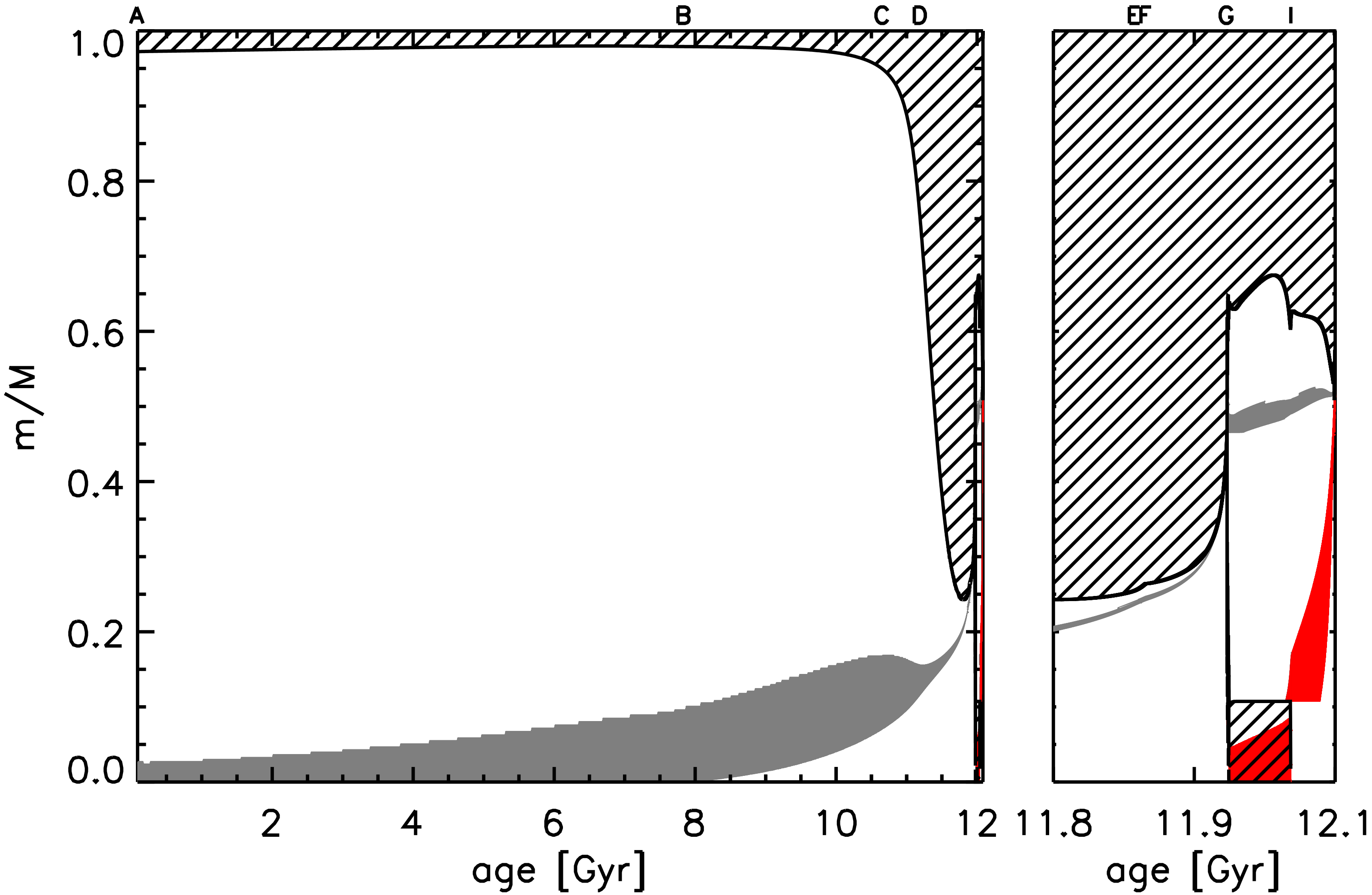
What physical phenomenon describes the difference between low and intermediate mass stars?

Low / intermediate mass stars



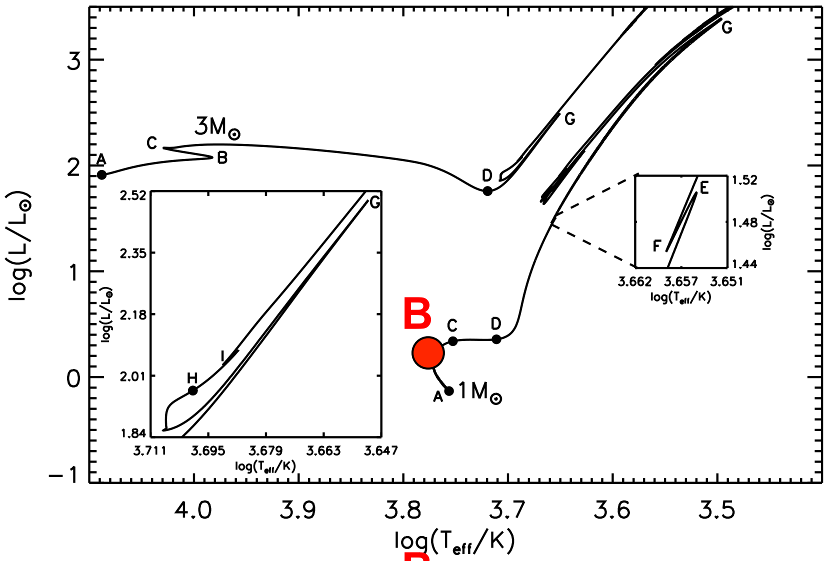
Hekker & Christensen-Dalsgaard in prep.

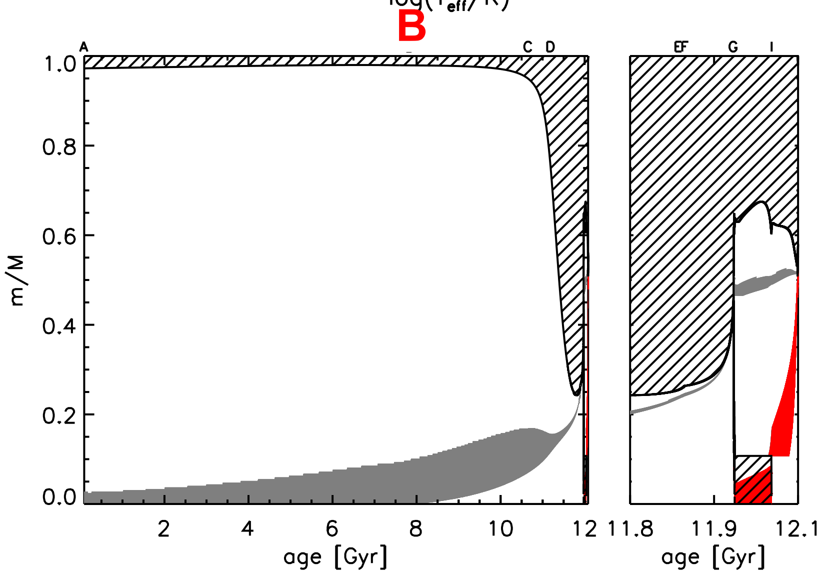
Kippenhahn diagram 1 $M_\odot$ star

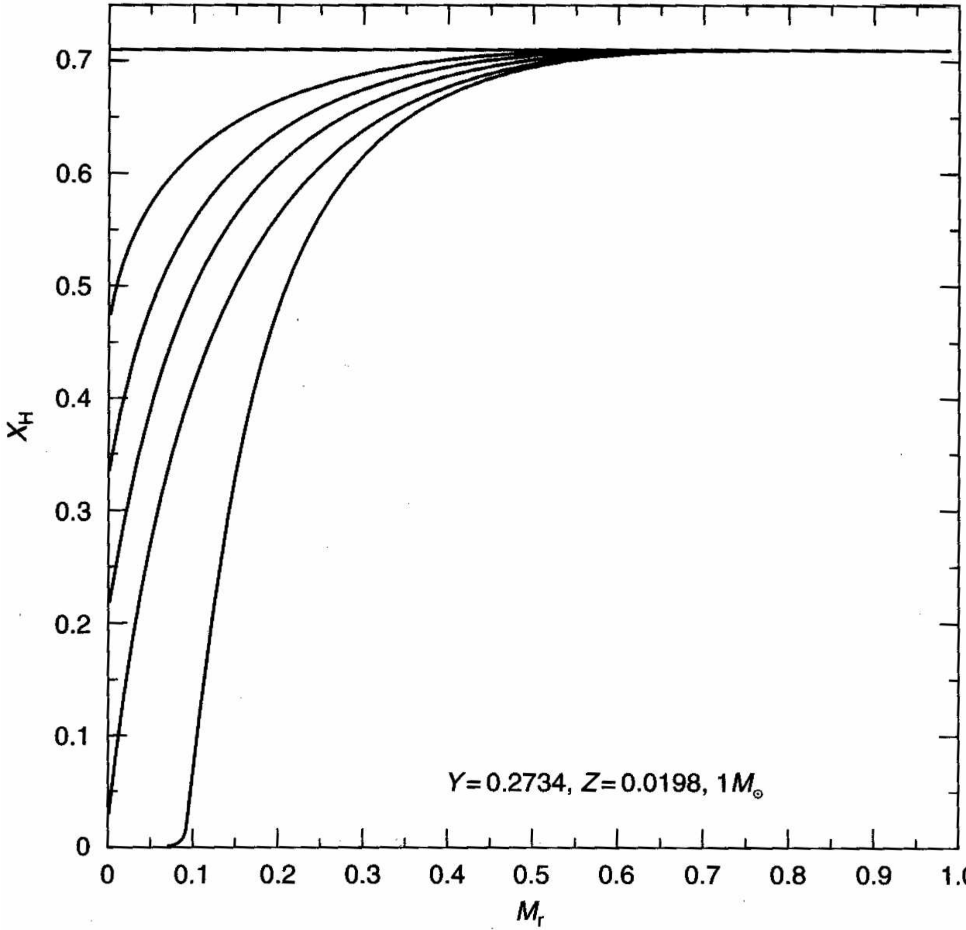


Hekker & Christensen-Dalsgaard in prep.

Start of thick shell burning

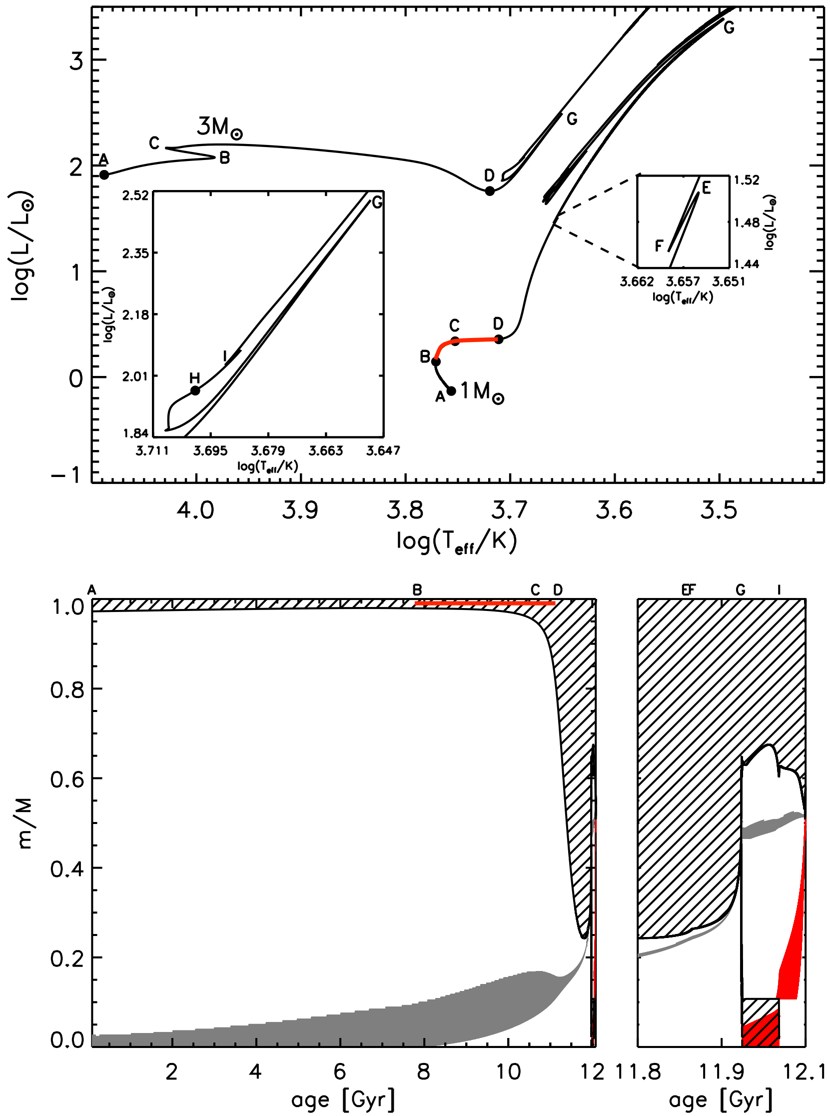






Pols 2011

Subgiant branch



- thermal and hydrostatic equilibrium with a degenerate isothermal core
- core contraction
- expanding and cooling envelope

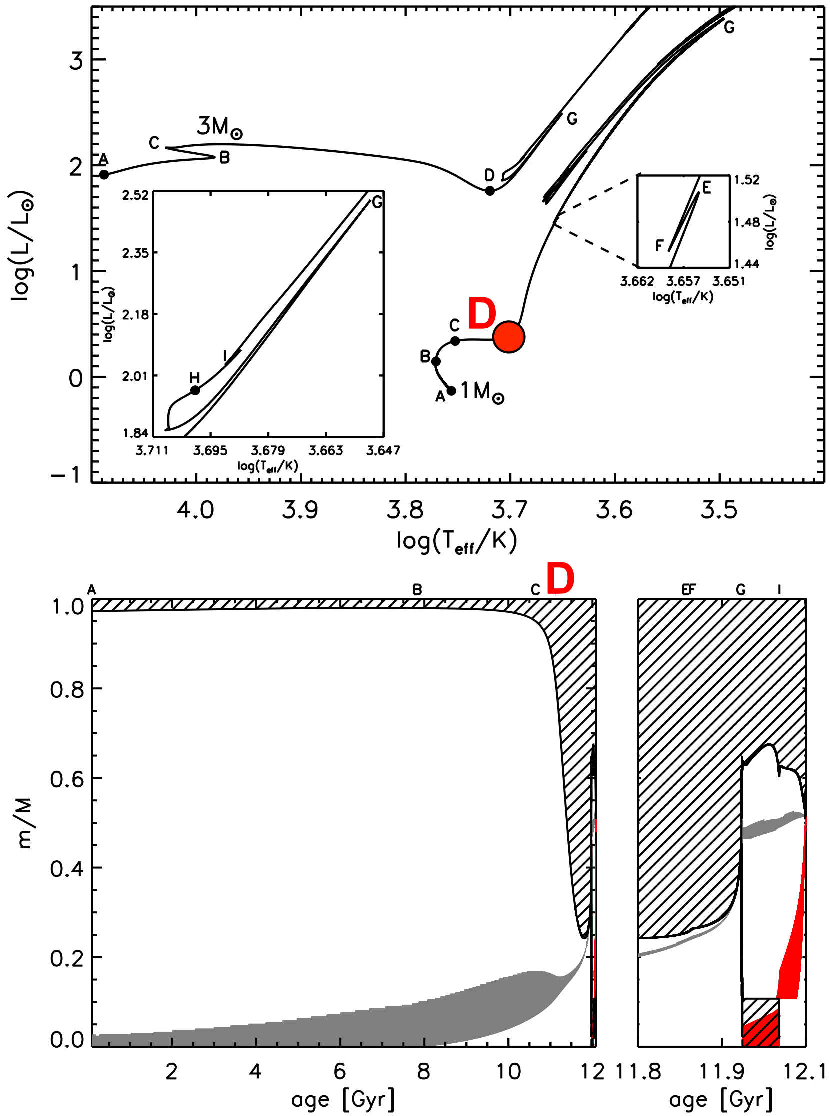
Mirror principle

Mirror principle

"When the region within a burning shell contracts, the region outside the shell expands; and when the region inside the shell expands, the region outside the shell contracts."

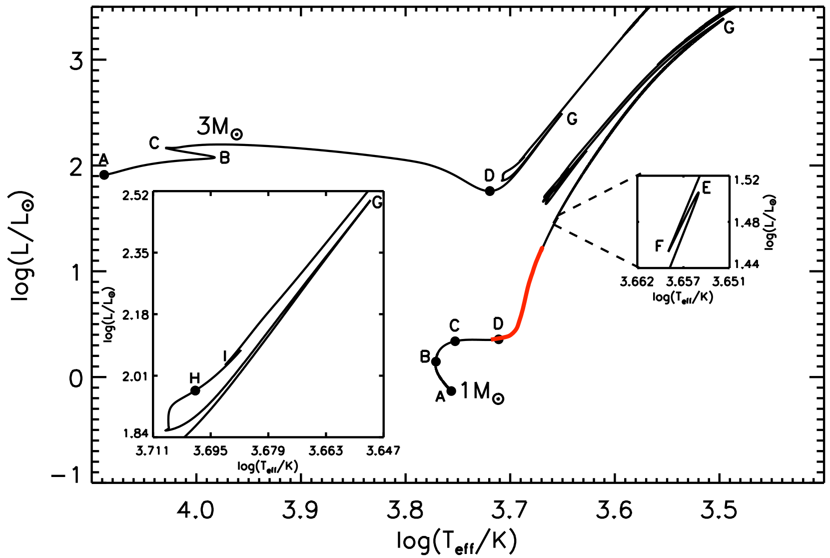
This is not a physical law as such, but an empirical observation, supported by the results of numerical simulations.

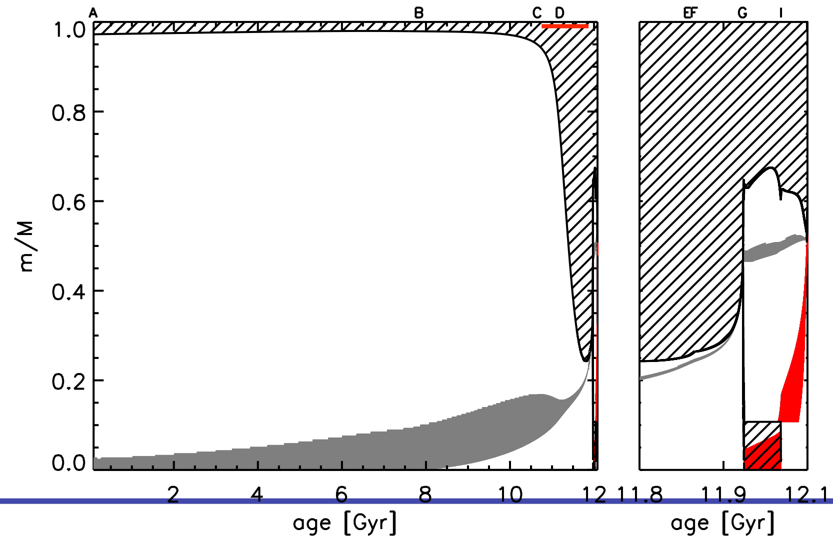
Bottom red-giant branch



- expanding cooling star approaches Hayashi line: locus in HRD of fully convective stars
- further increase of radius: increase in luminosity
- large convective region develops

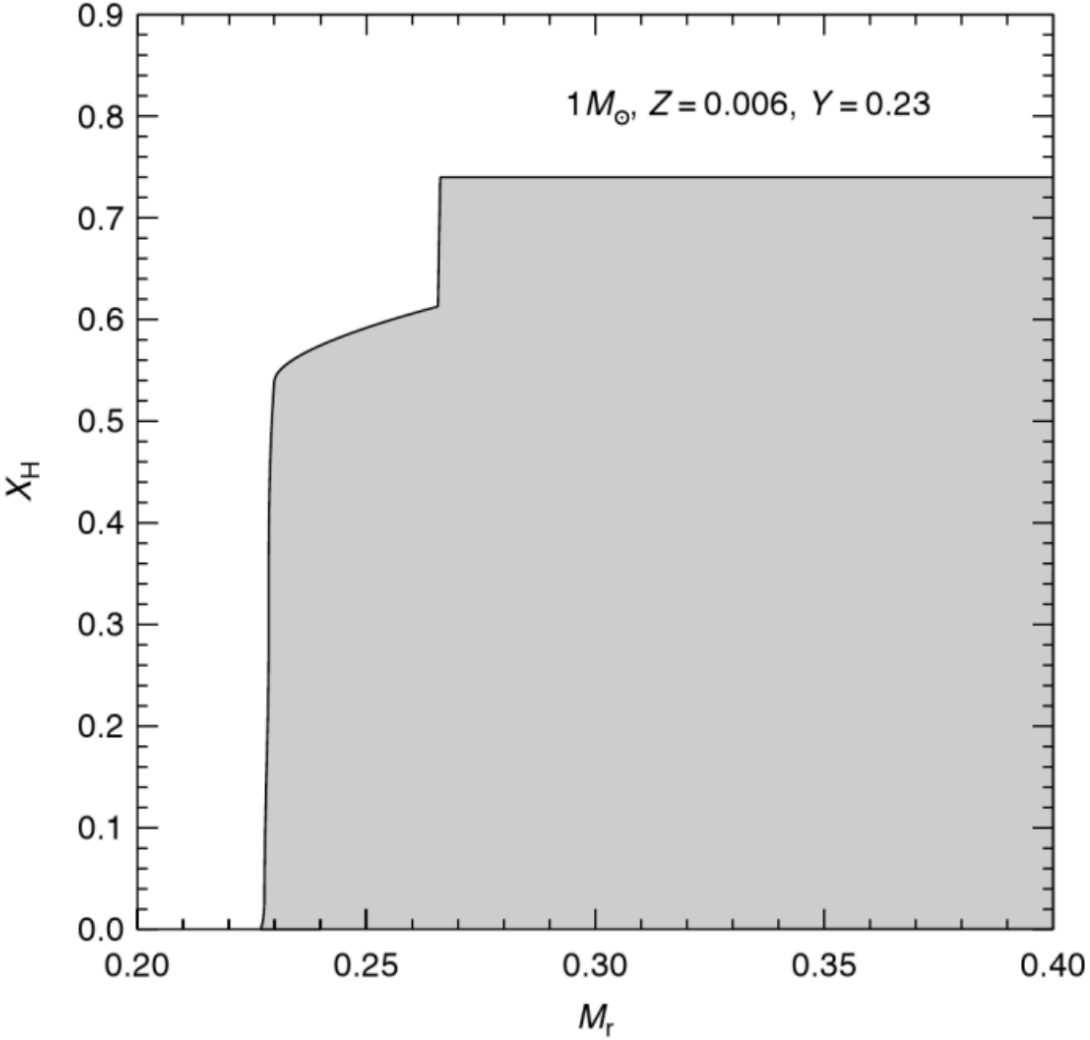
First dredge-up





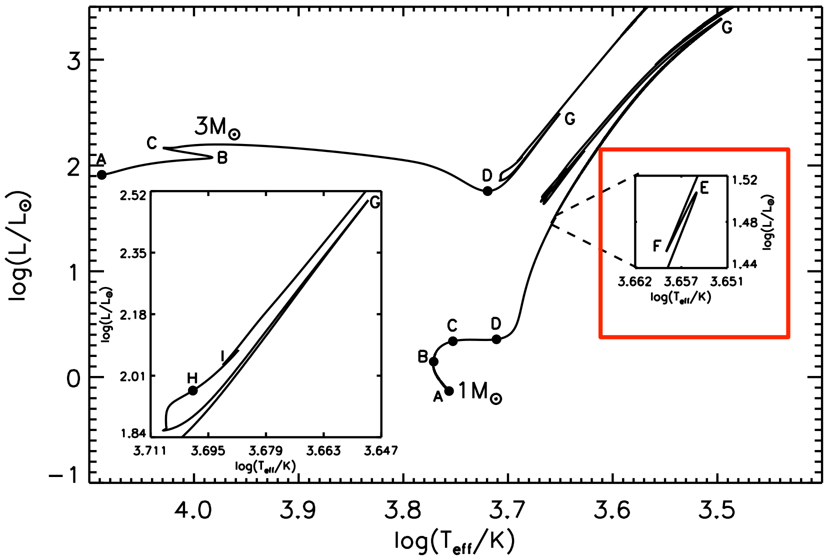
- convective envelope penetrates deep into the star reaching regions
- processed material is transported by convection to the surface: $^{12}C/^{13}C$ decrease
- convective region reaches maximum depth in mass and recedes leaving a chemical discontinuity

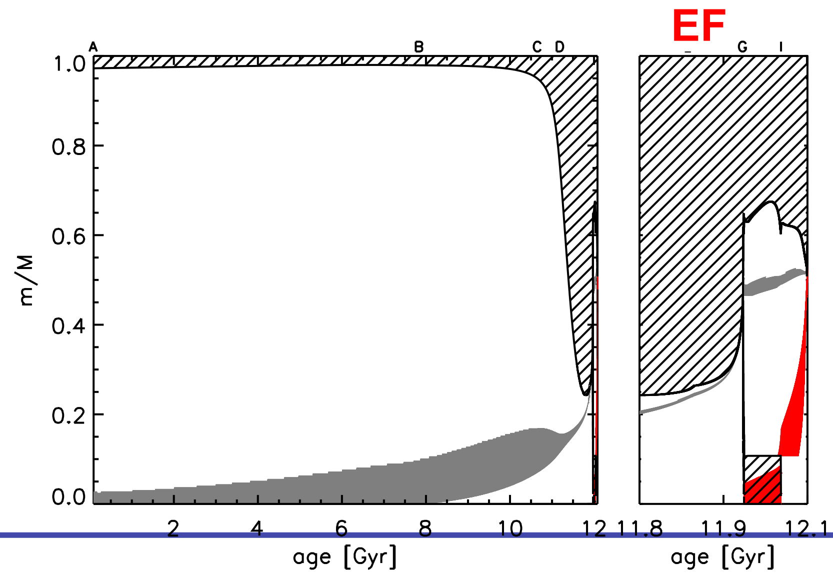
Chemical discontinuity



Salaris & Cassisi 2005

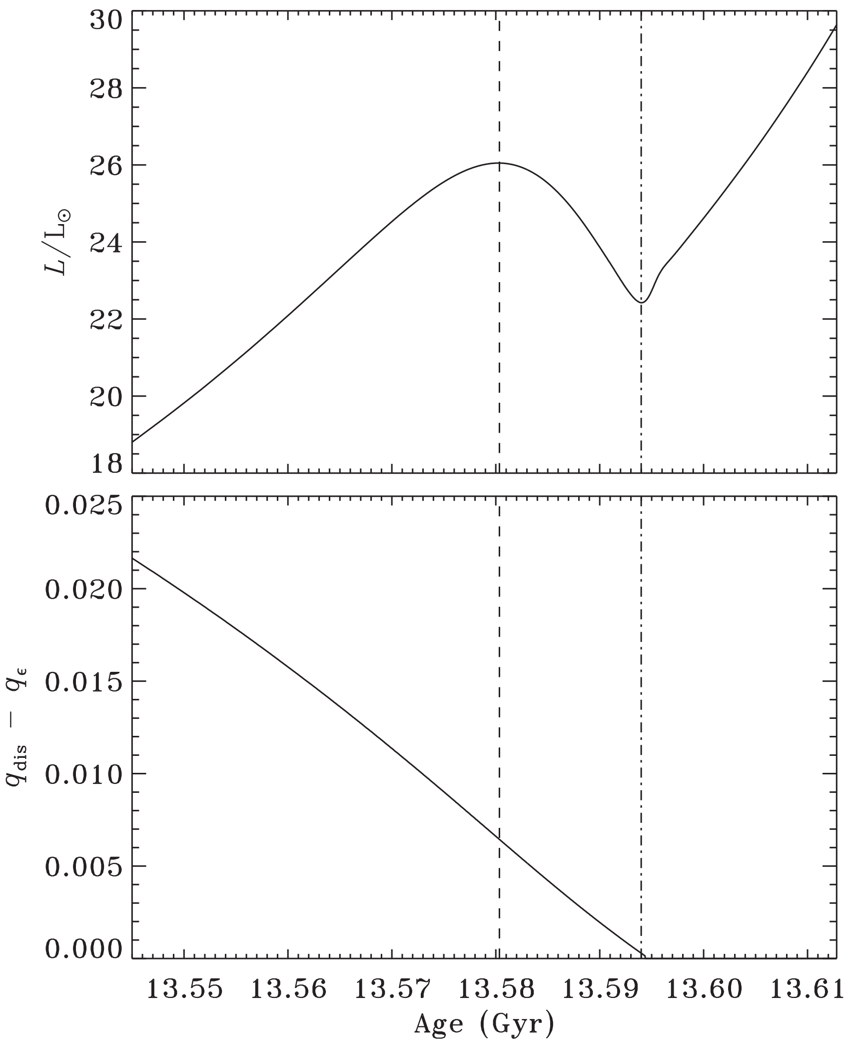
Luminosity bump





- H-burning shell moves outwards
- at chemical discontinuity the star readjusts to new composition before it continues its evolution

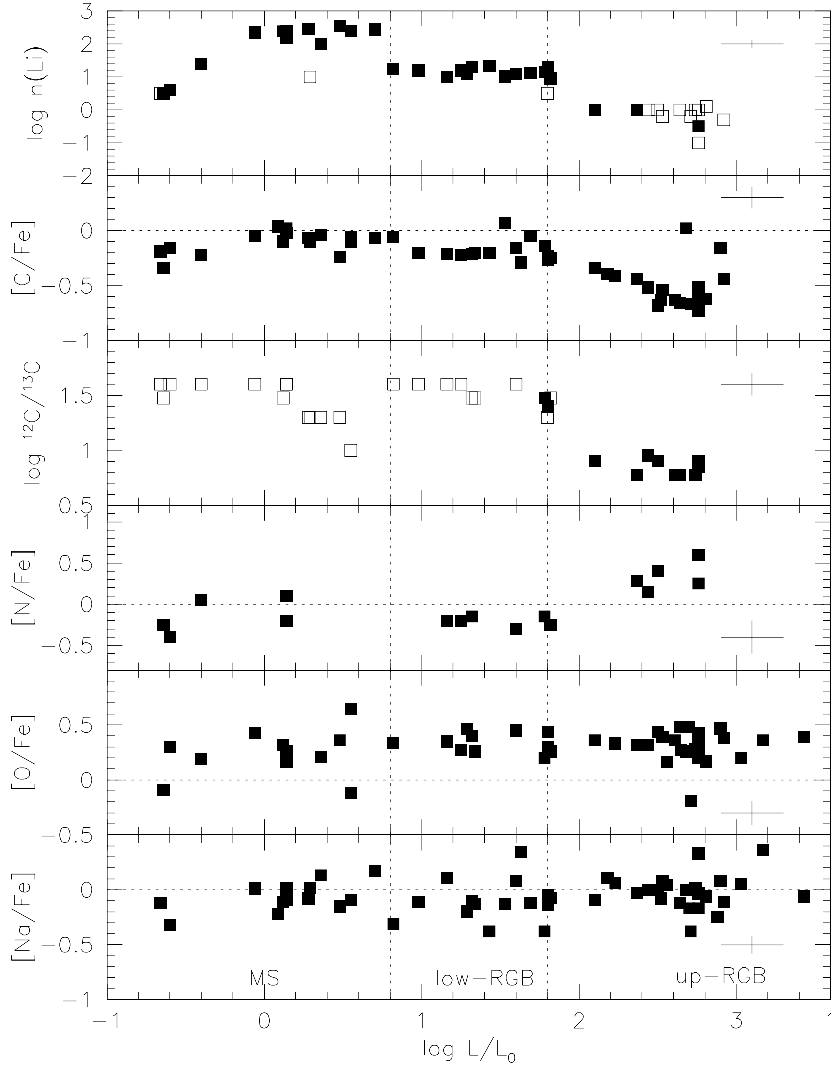
Luminosity bump



- q_ε fractional mass of hydrogen-burning shell (maximum energy generation)
- q_{dis} fractional mass of chemical discontinuity
- at $q_{dis} - q_\varepsilon = 0$ luminosity starts to increase again

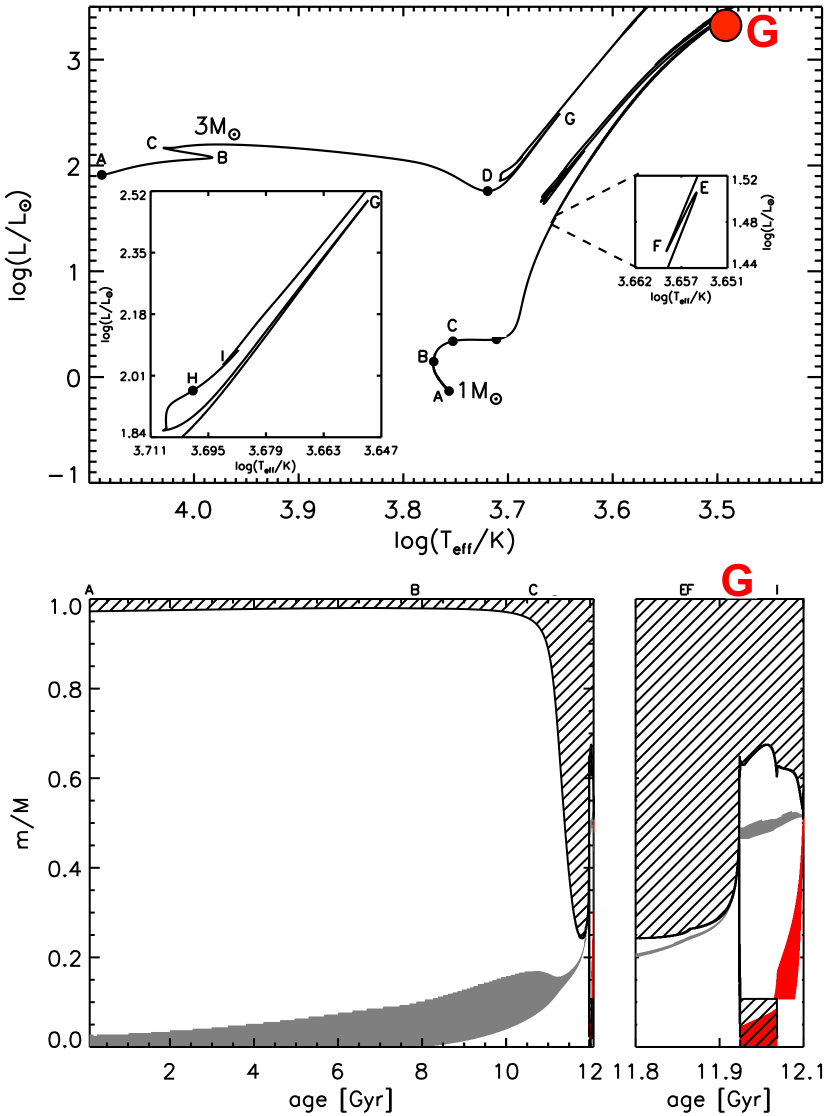
Christensen-Dalsgaard 2015

Luminosity bump



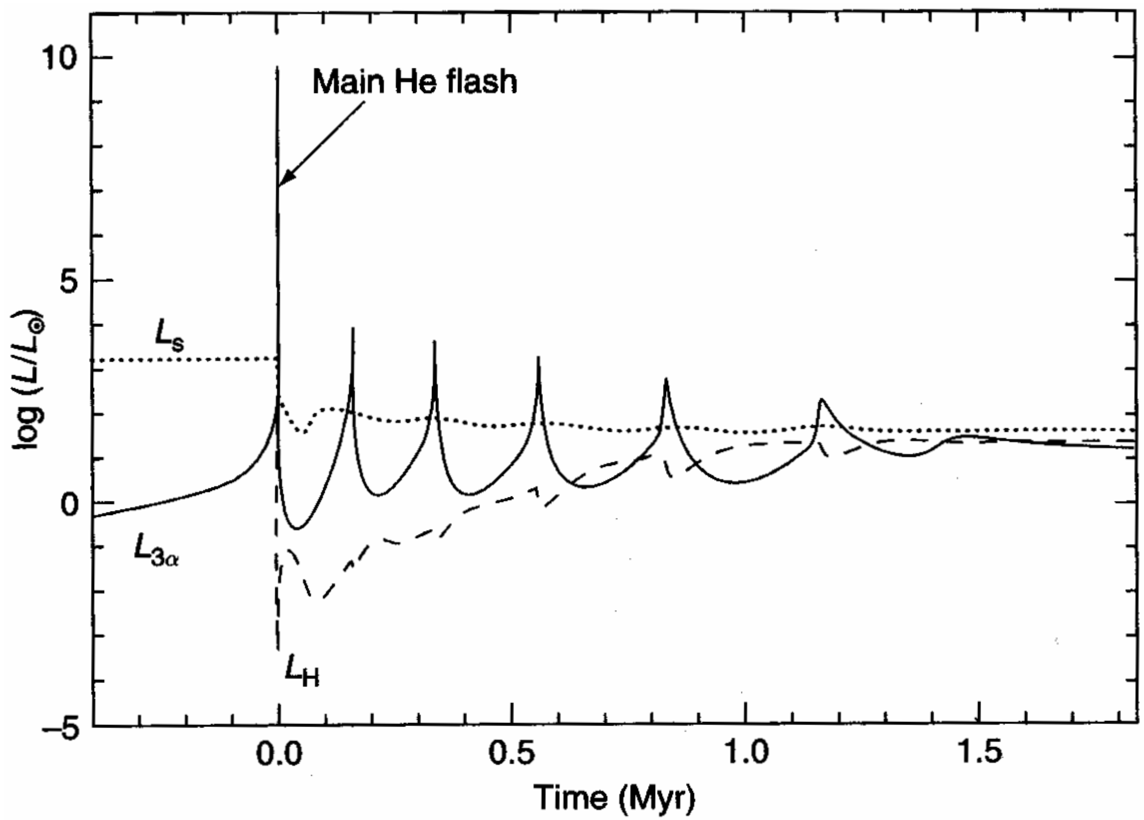
Gratton et al. 2000

Onset of He-core burning: He-flash



- degenerate core: P does not depend on T
- ~10^8 K start 3α process
- thermal run away process for a very short time
- energy absorbed by non-degenerate layers

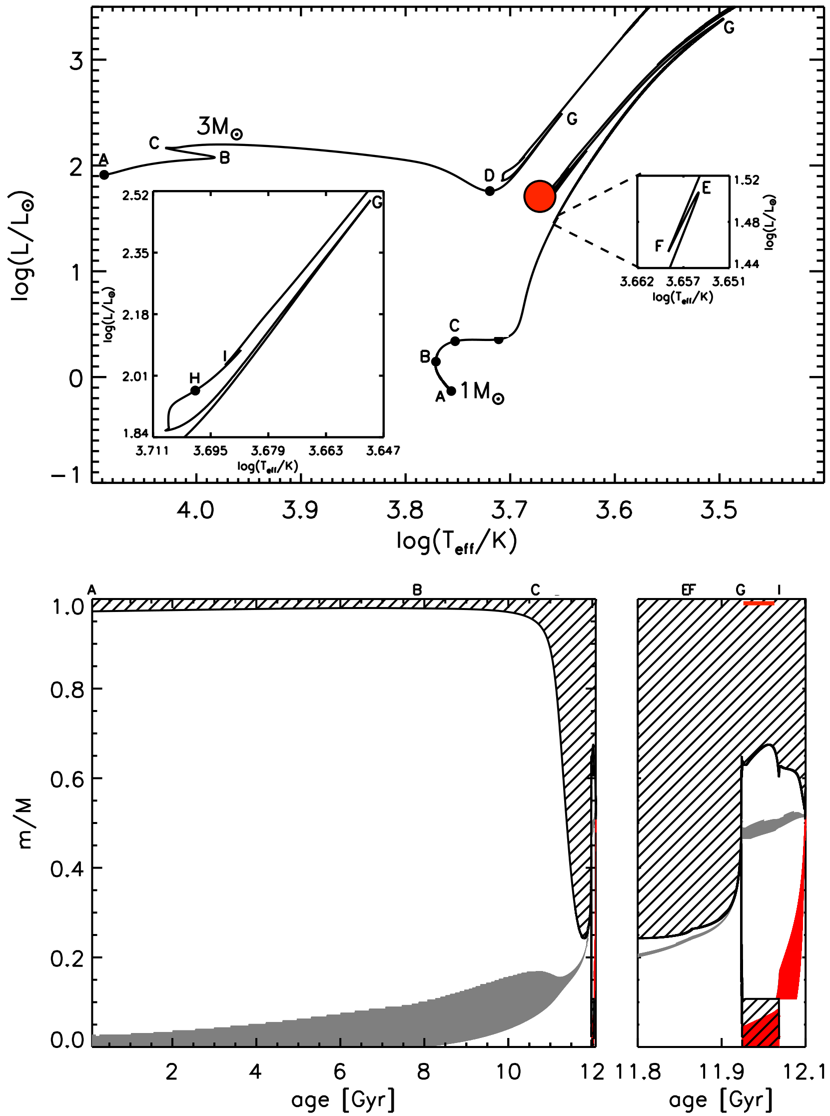
He-flash



- L_s surface luminosity
- $L_{3\alpha}$ He-burning luminosity
- L_H H-burning luminosity

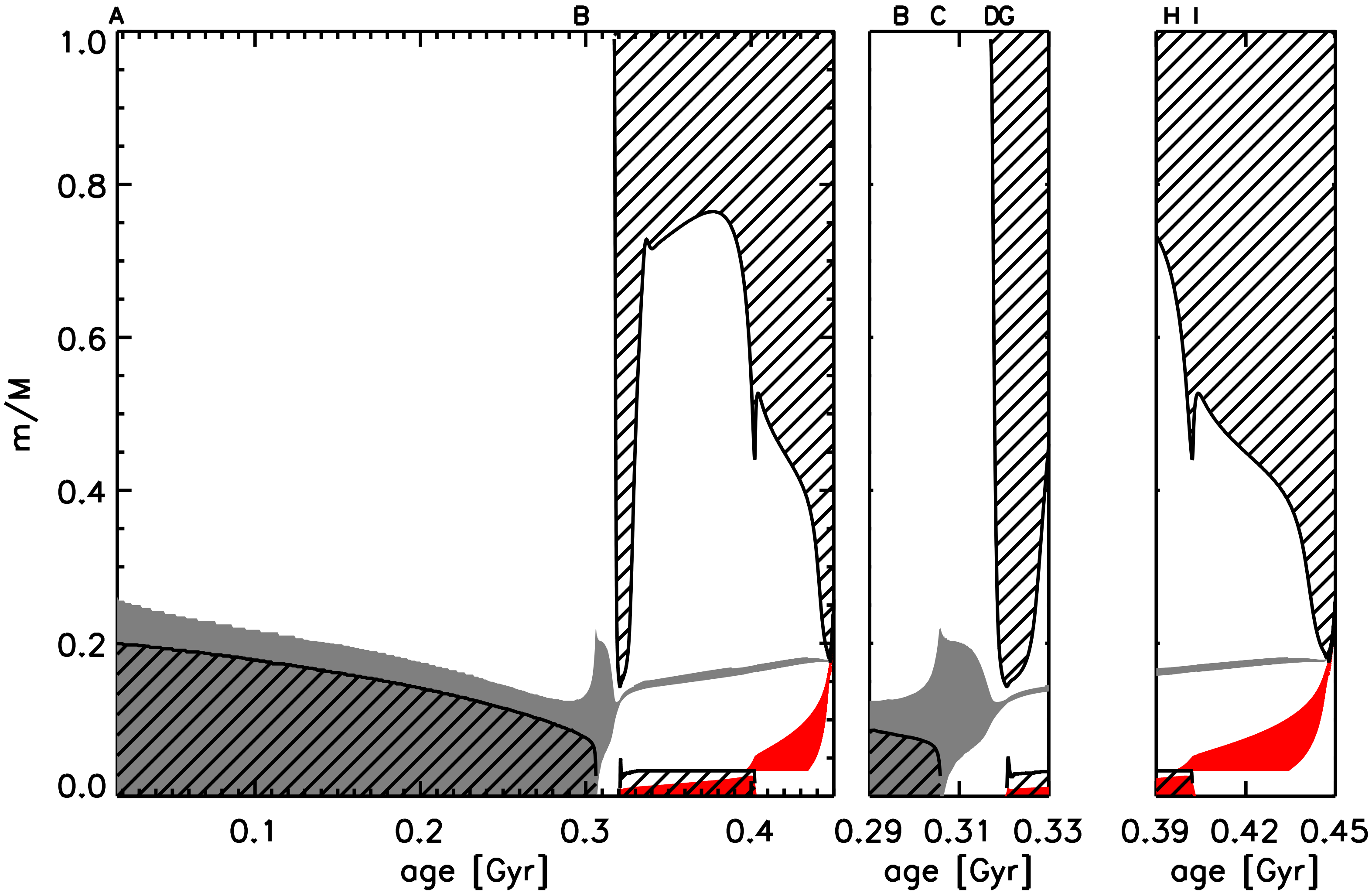
Pols 2011

Red-clump stars



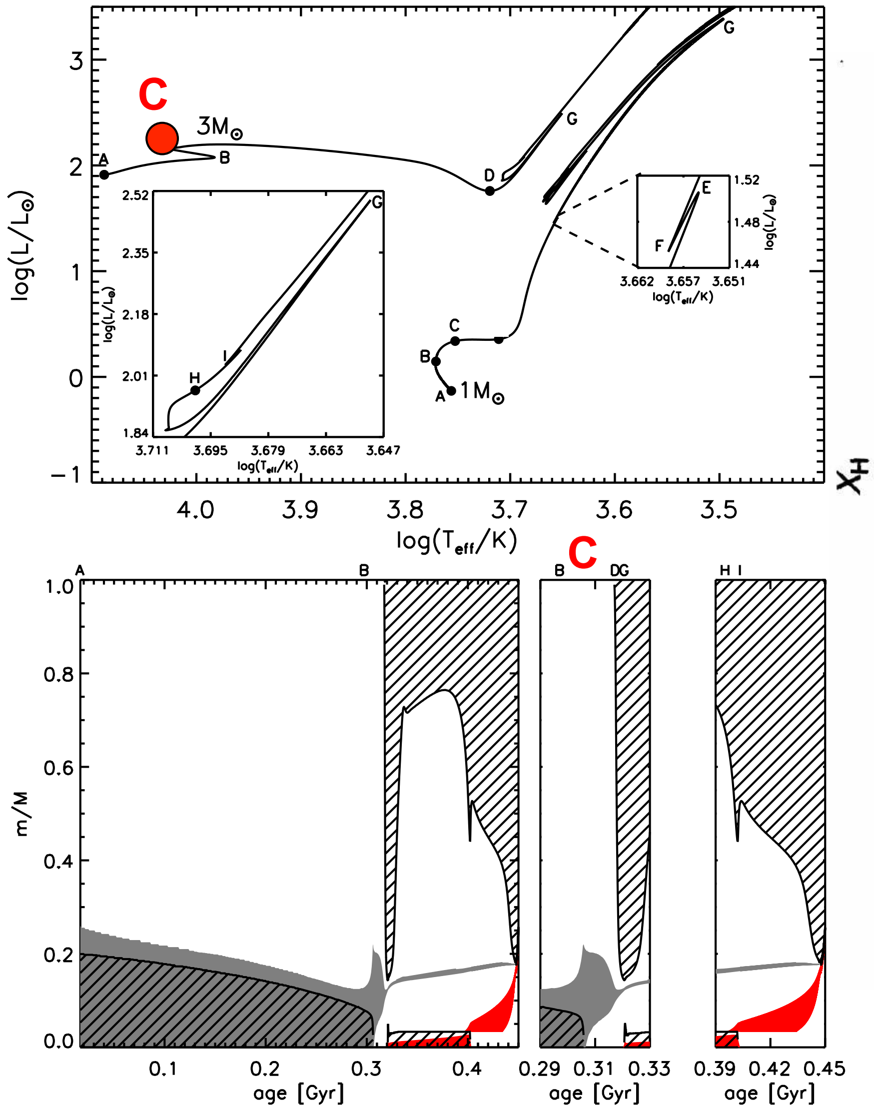
- He-core burning + H-shell burning
- all stars that undergo He-flash have similar core-mass, i.e. very similar position in HRD
- stars have a convective core and discontinuities due to sub-flashes

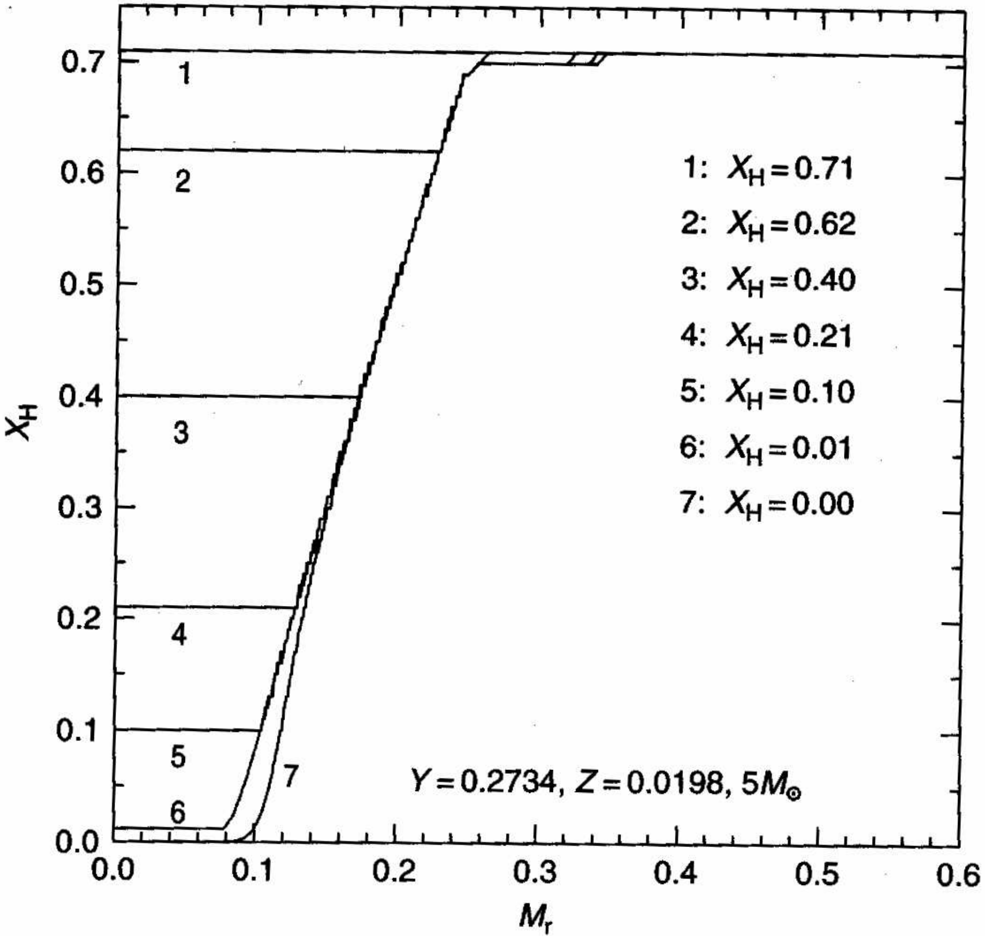
Kippenhahn diagram 3 $M_\odot$ star



Hekker & Christensen-Dalsgaard in prep.

Start of shell burning



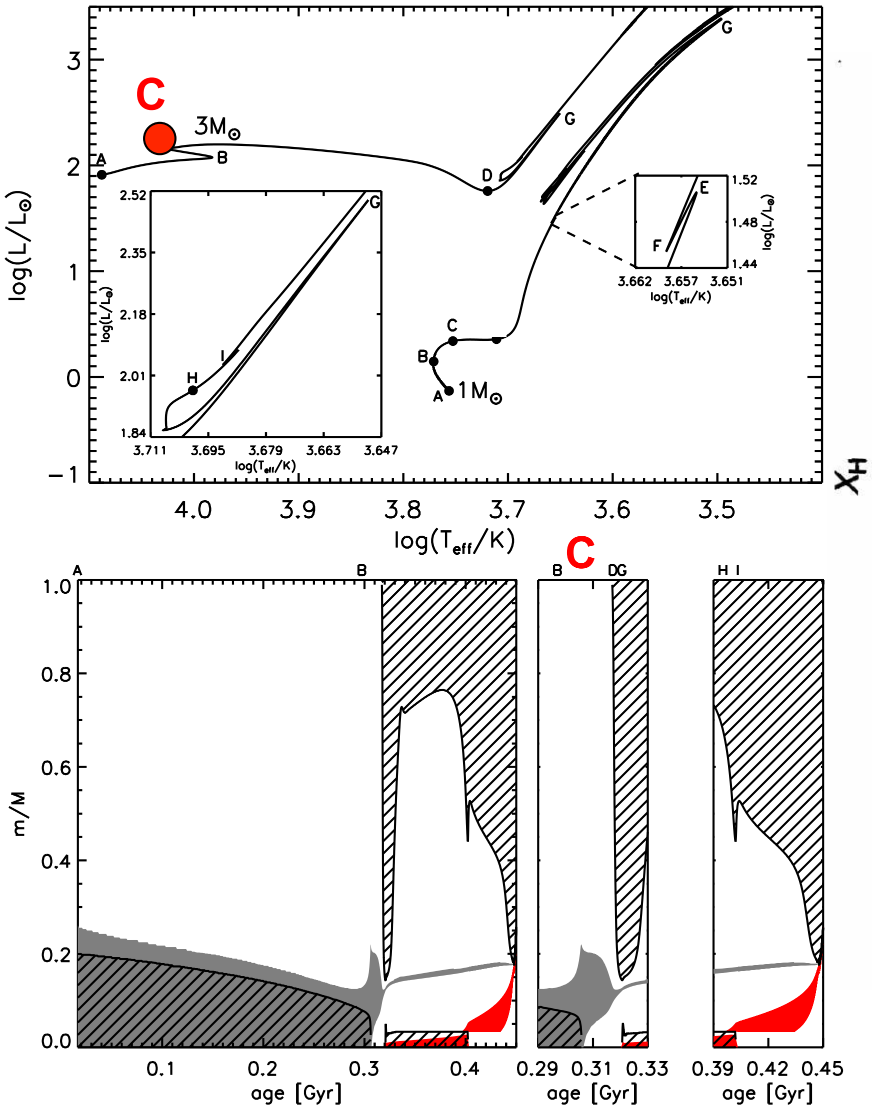


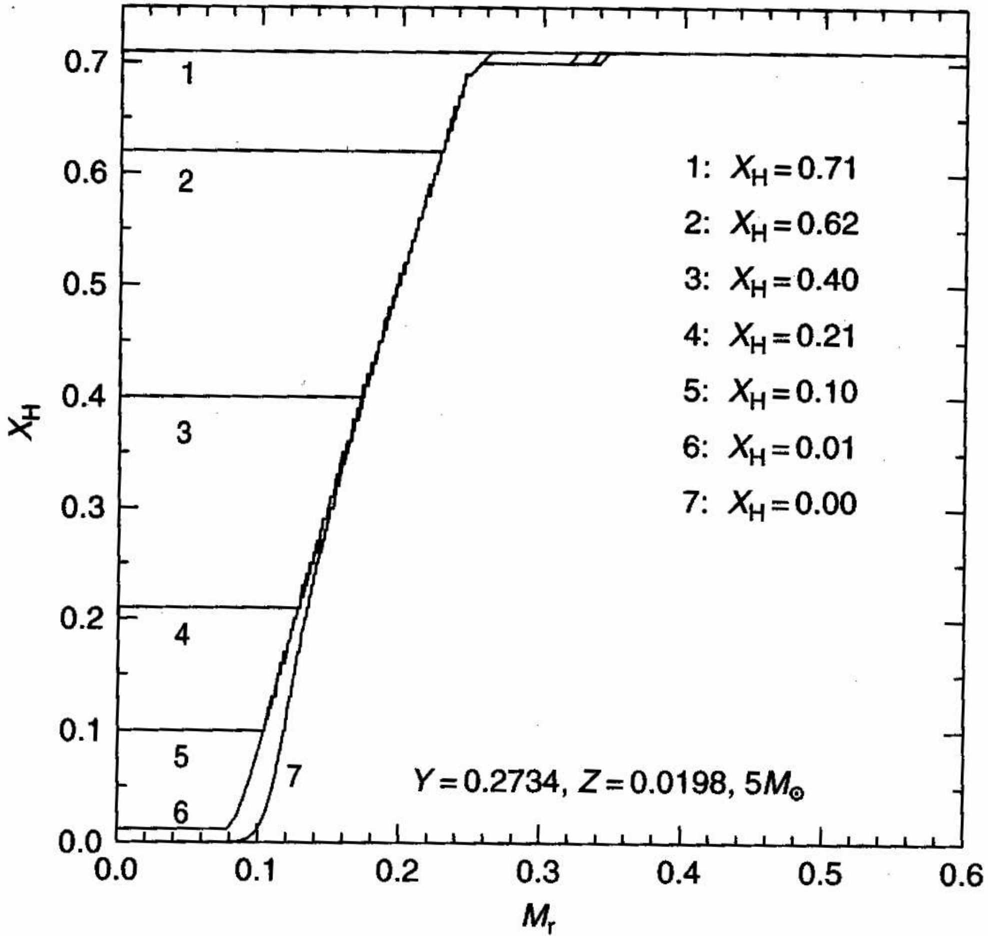
Pols 2011

Question?

What physical phenomenon takes place in the "hook" at the end of the main sequence?

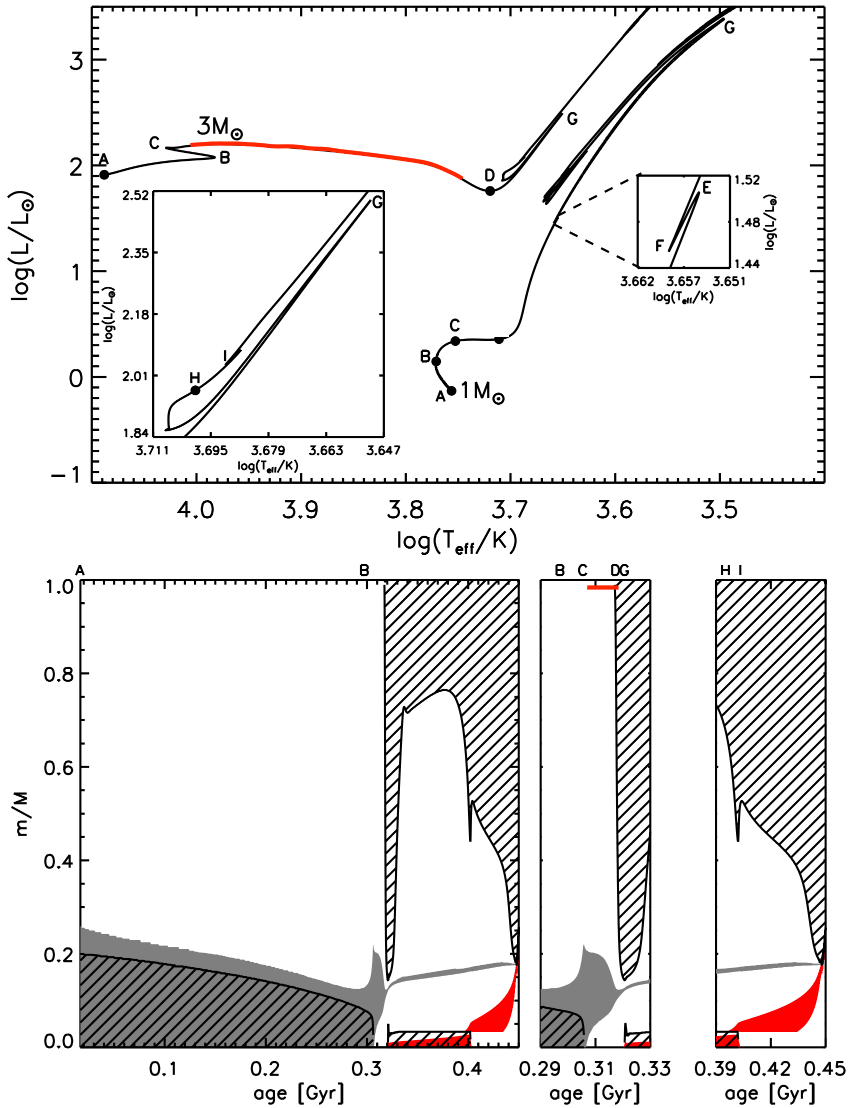
Start of shell burning





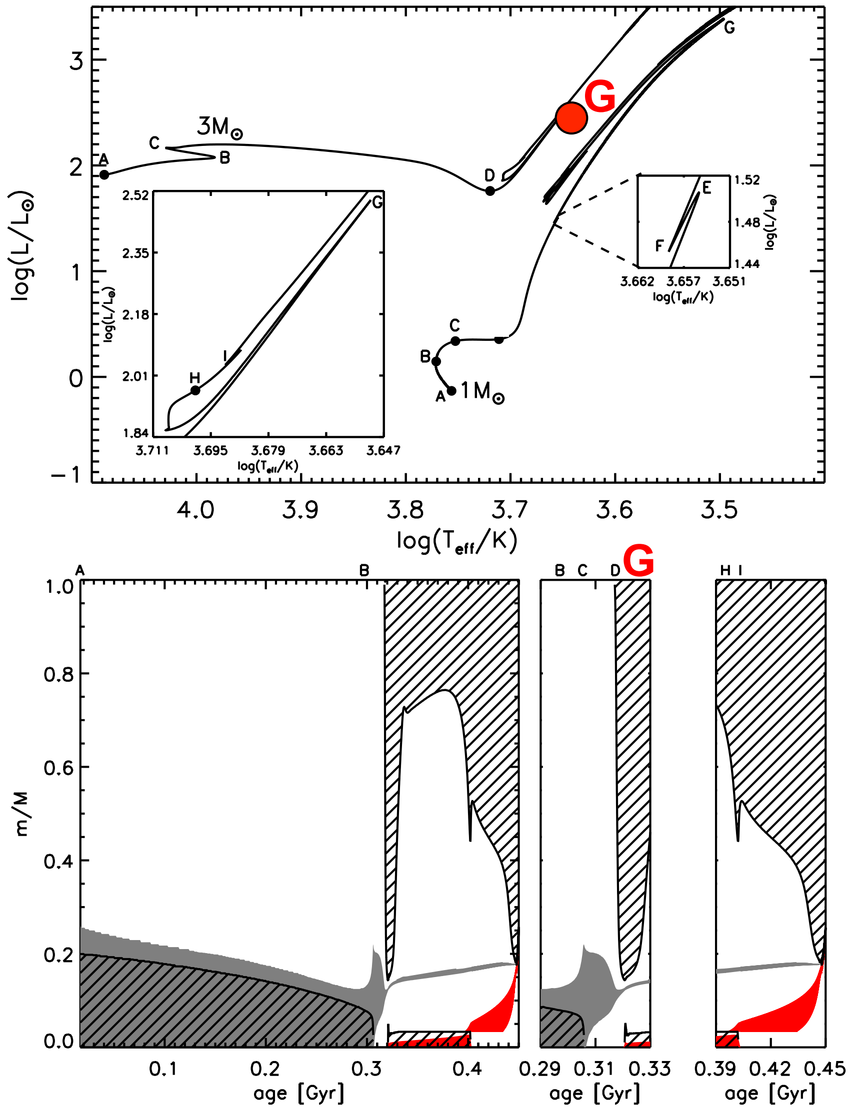
Pols 2011

Hertzsprung gap



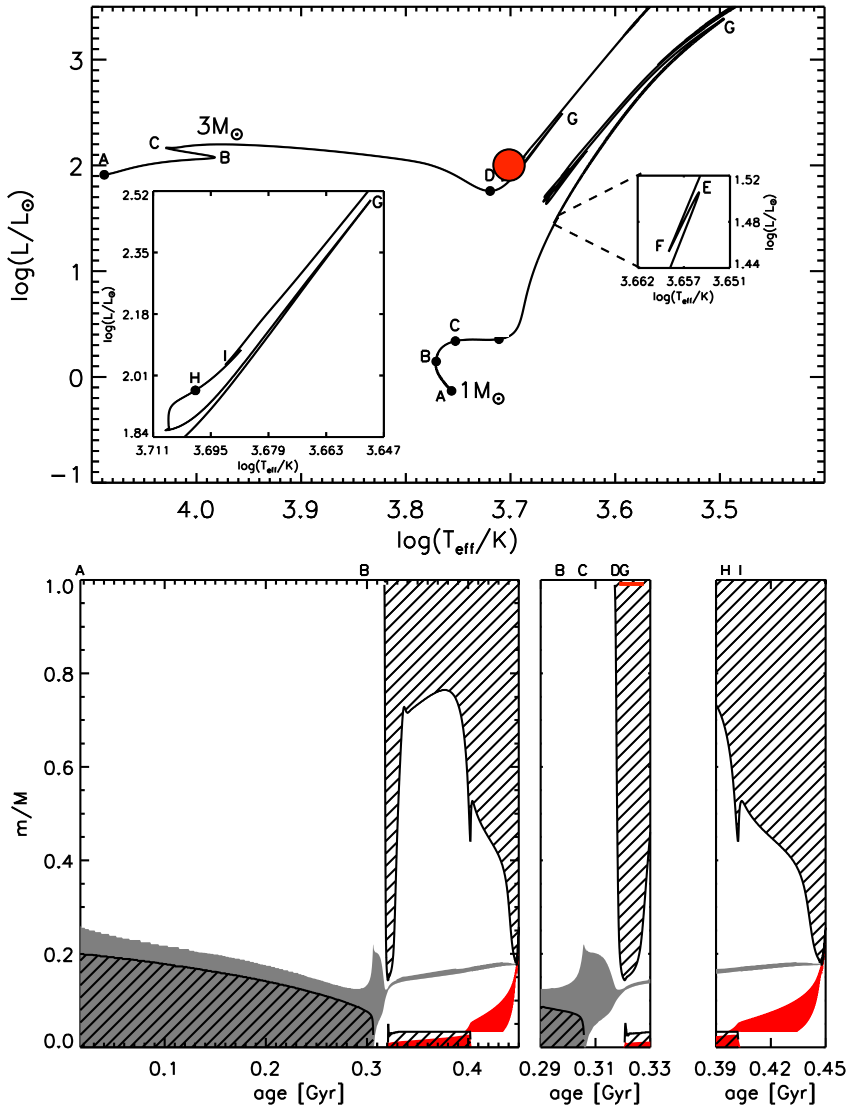
- non-degenerate core: no sufficient pressure support
- contraction on Kelvin-Helmholtz scale to maintain equilibrium
- stars cross the HRD rapidly
- deficiency of stars

Onset of He-core burning



- core contracts and heats on RGB till ~10^8 K where He ignites gently
- Luminosity at which He ignites is a monotonically increasing function of core mass

Secondary clump



- He-core burning + H-shell burning
- more spread out in positions in HRD due to core mass dependent He-ignition

Question?

Why do stars become red giants?

Why do stars become red giants?

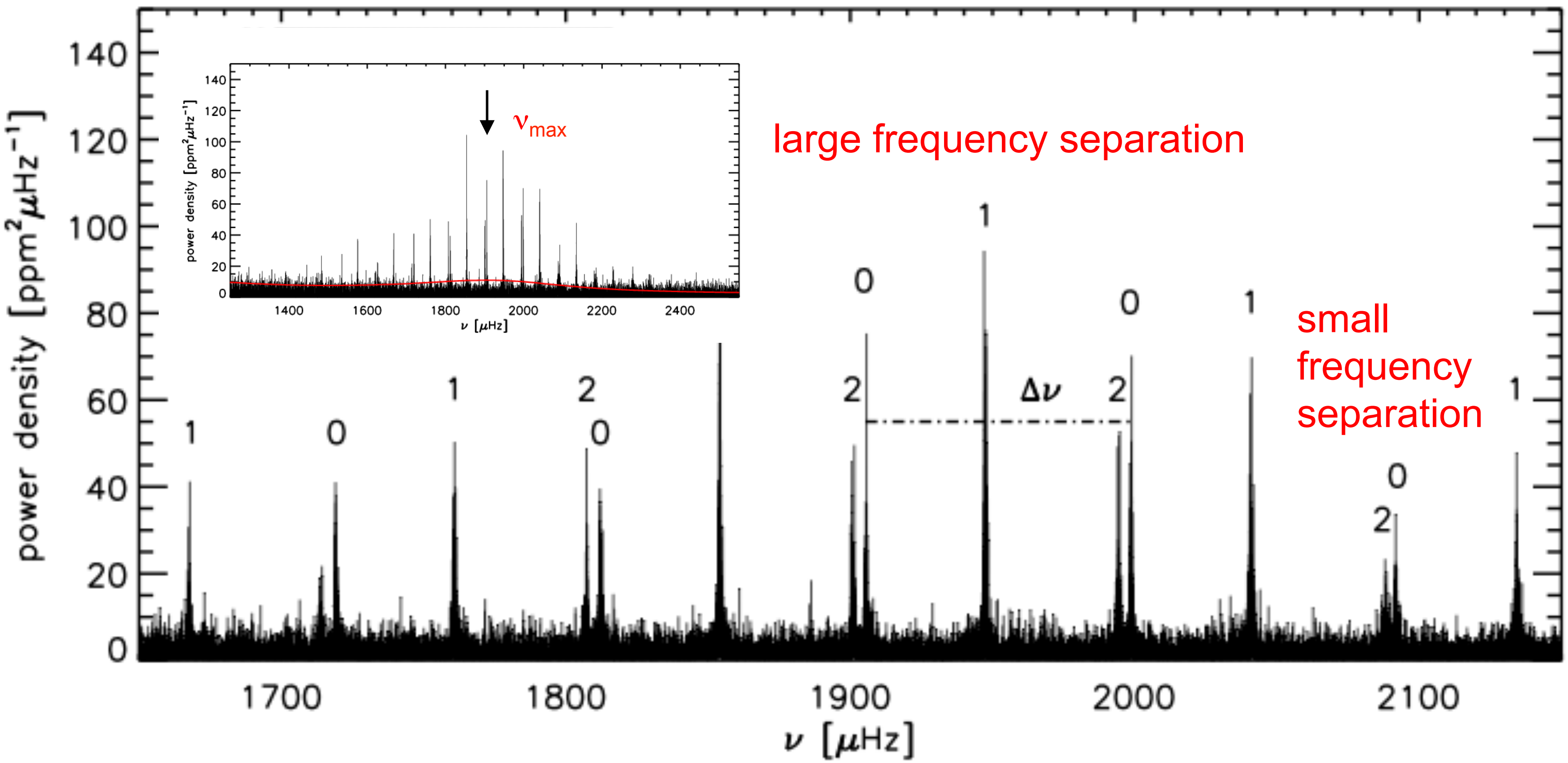
- mirror principle seems to play an essential role
- not understood what physical mechanism(s) drive the mirror
- what other physical mechanism(s) are essential?

strong gravitational field
mean molecular weight gradient

necessary but may not be sufficient

asteroseismology of red-giant stars

Solar-like oscillations: main sequence



Asymptotic approximation: high-order p modes

$$\nu_{nl} \cong \Delta\nu\left(n + \frac{l}{2} + \varepsilon\right)$$

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}$$

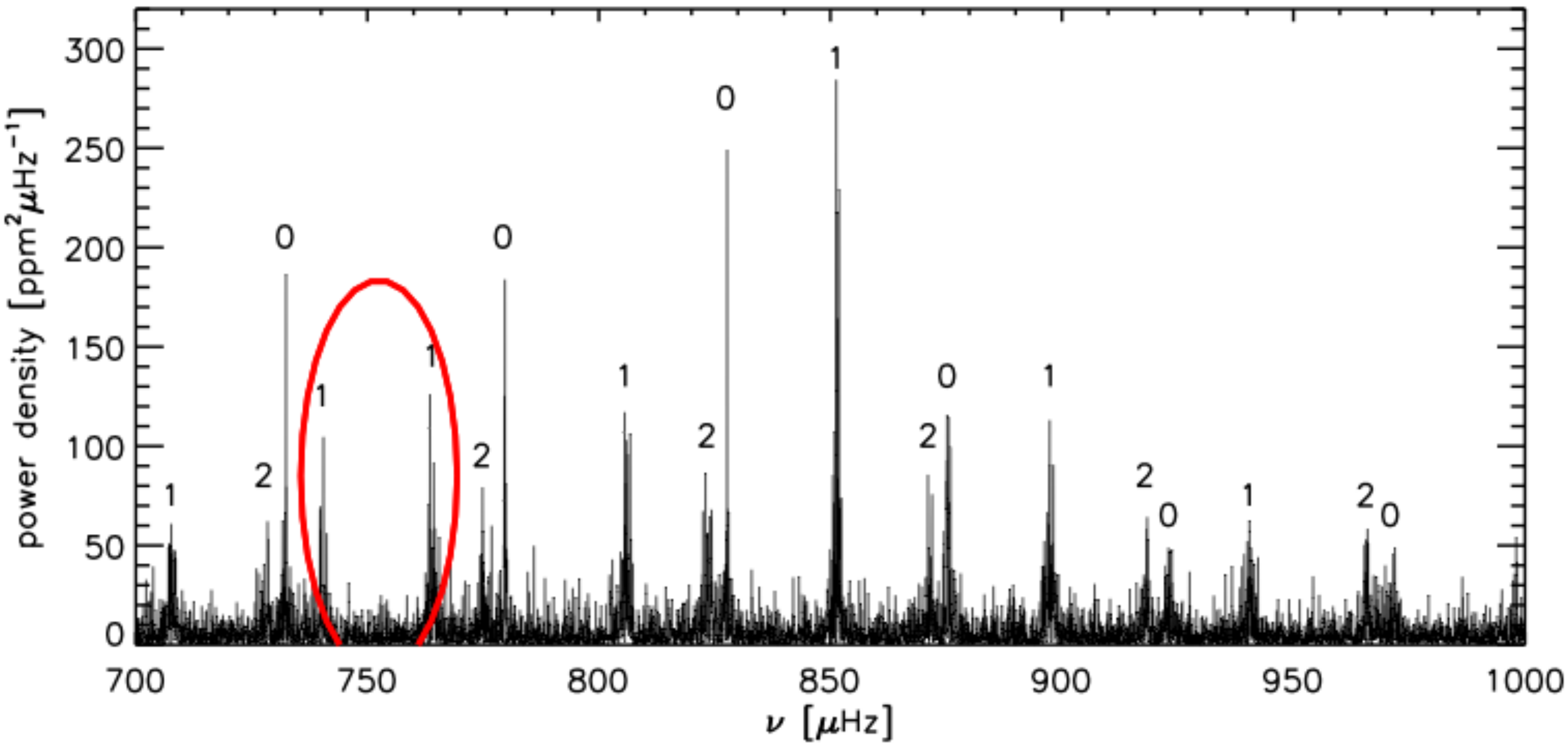
$$\Delta\nu \propto \sqrt{\frac{M}{R^3}} \propto \sqrt{\bar{\rho}}$$

Asteroseismic scaling relations

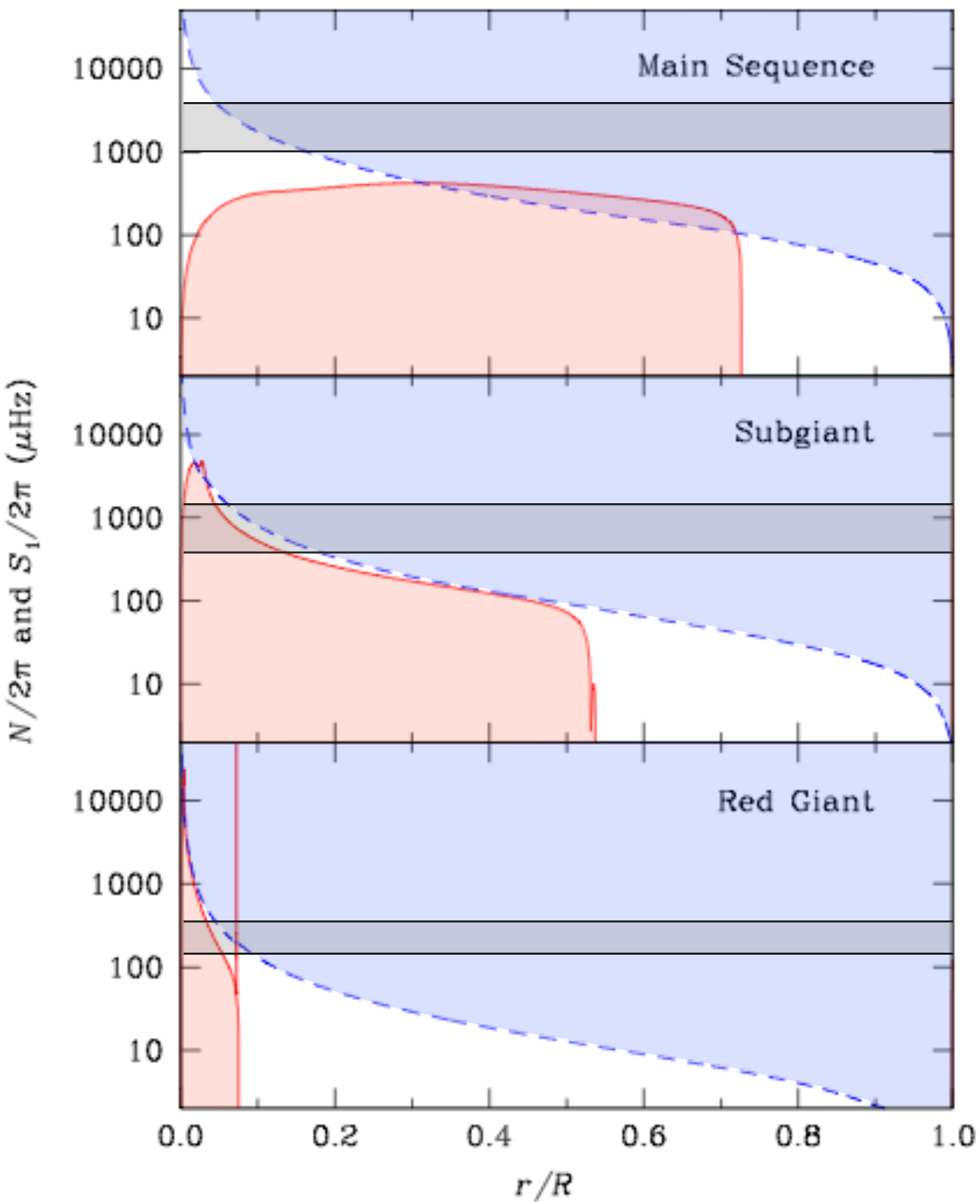
$$\Delta\nu \propto \sqrt{\frac{M}{R^3}} \propto \sqrt{\bar{\rho}}$$

$$\nu_{\max} \propto \frac{g}{\sqrt{T_{eff}}} \propto \frac{M}{R^2\sqrt{T_{eff}}}$$

Subgiant



Hekker & Mazumdar 2014



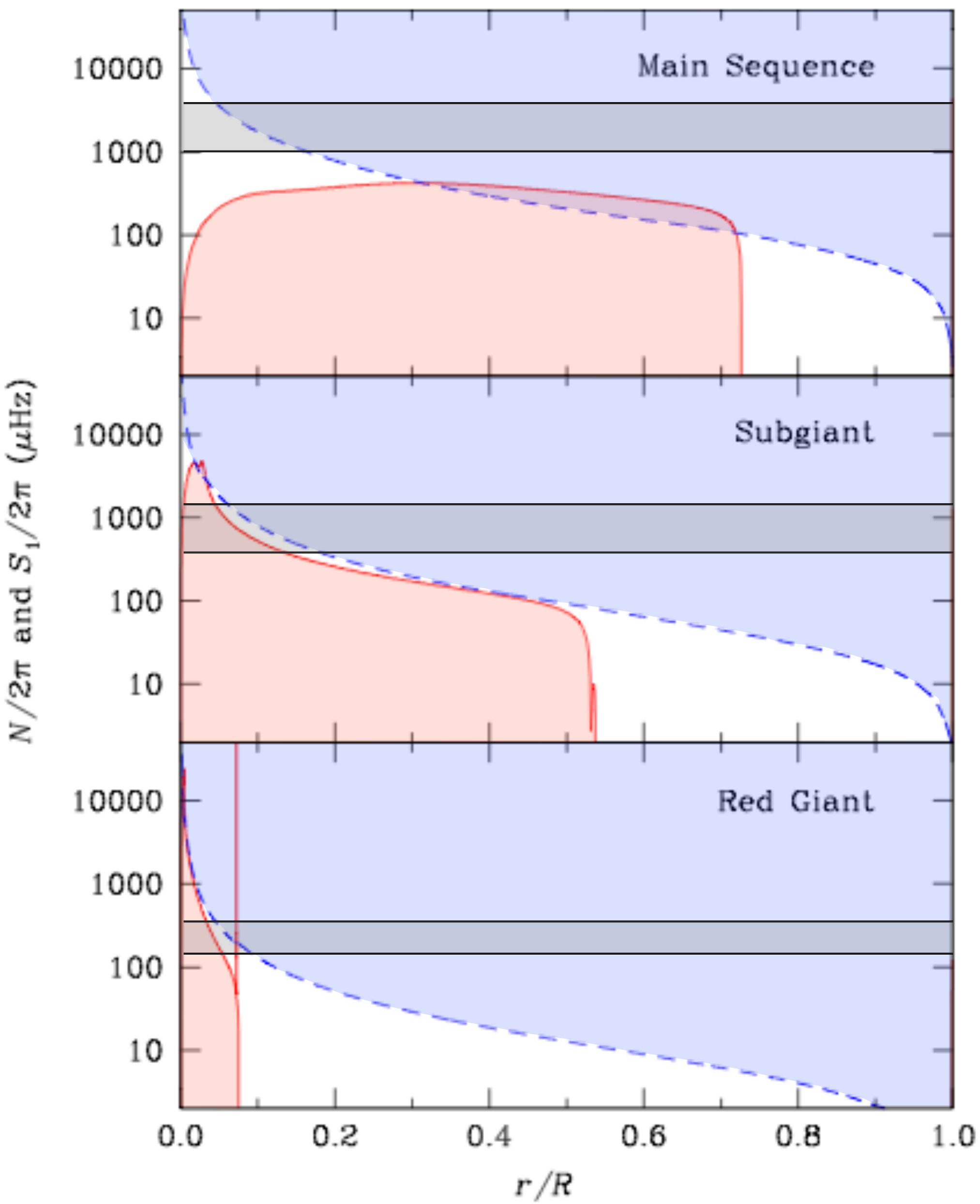
Hekker & Mazumdar 2014

Question?

Where in these diagrams can oscillations propagate?

Where are the oscillations gravity modes?

Where are the oscillations acoustic modes?

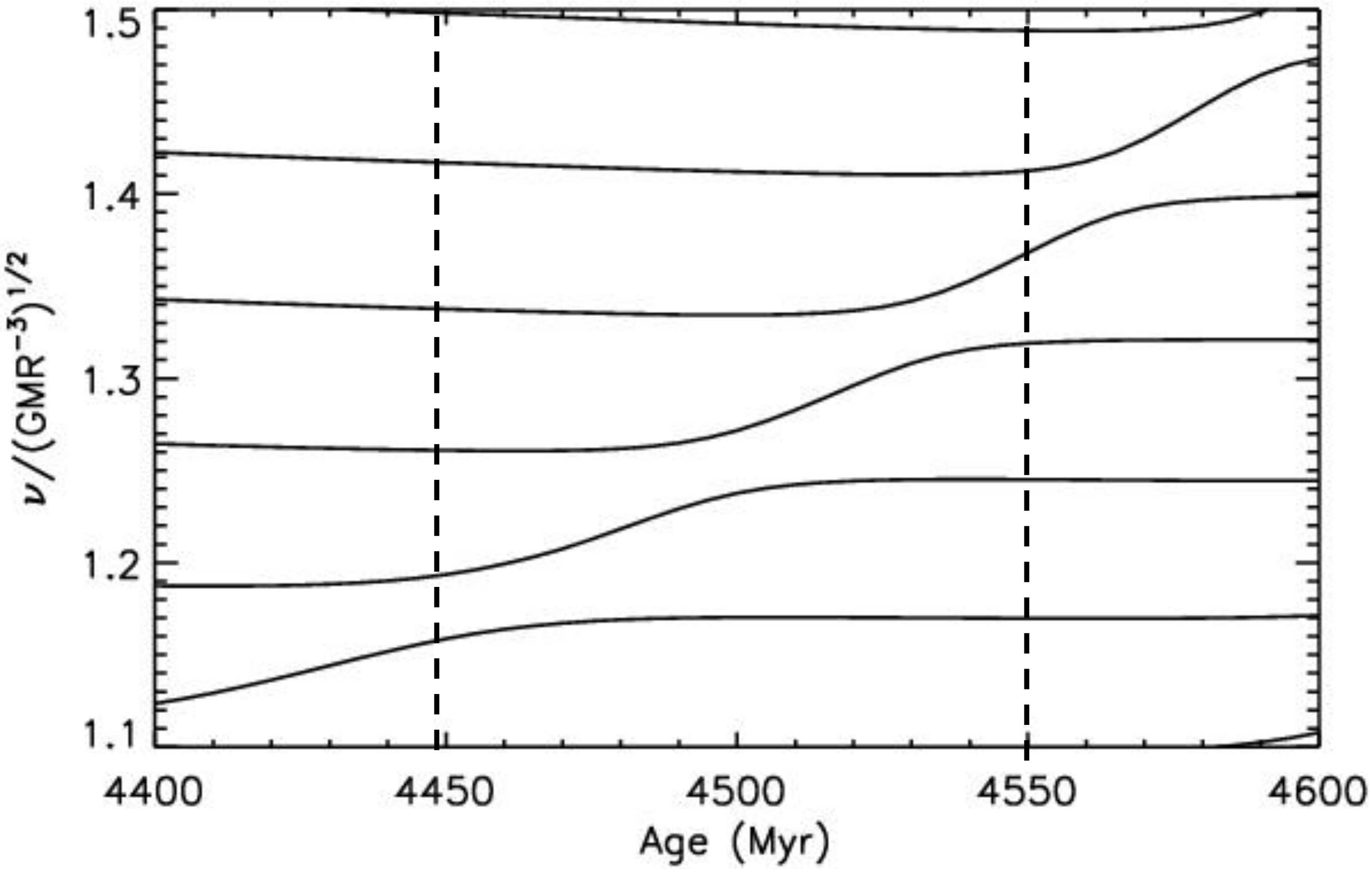


-Brunt-Väisälä frequency
buoyancy cavity

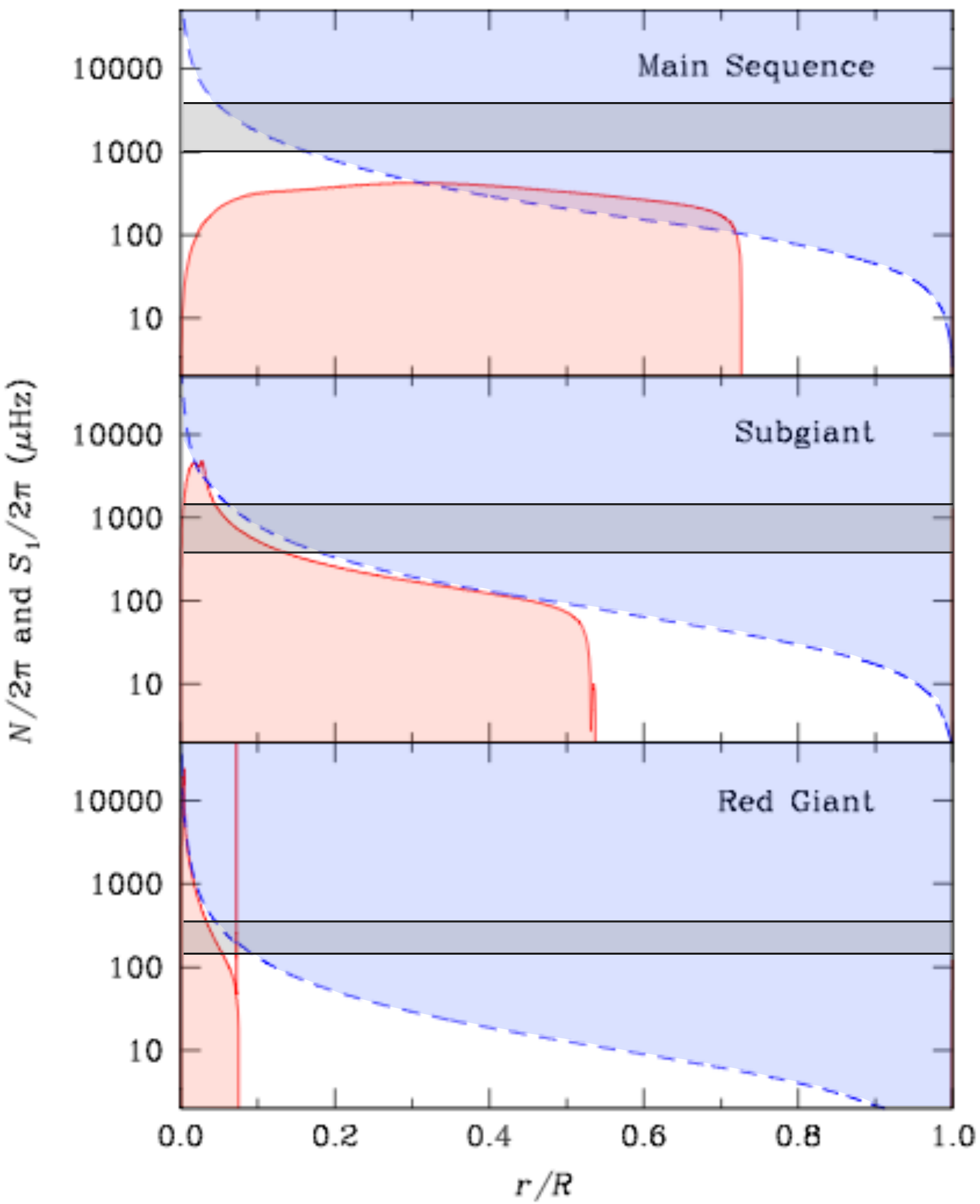
- Lamb frequency
acoustic cavity

Hekker & Mazumdar 2014

Evolution



Deheuvels & Michel 2011

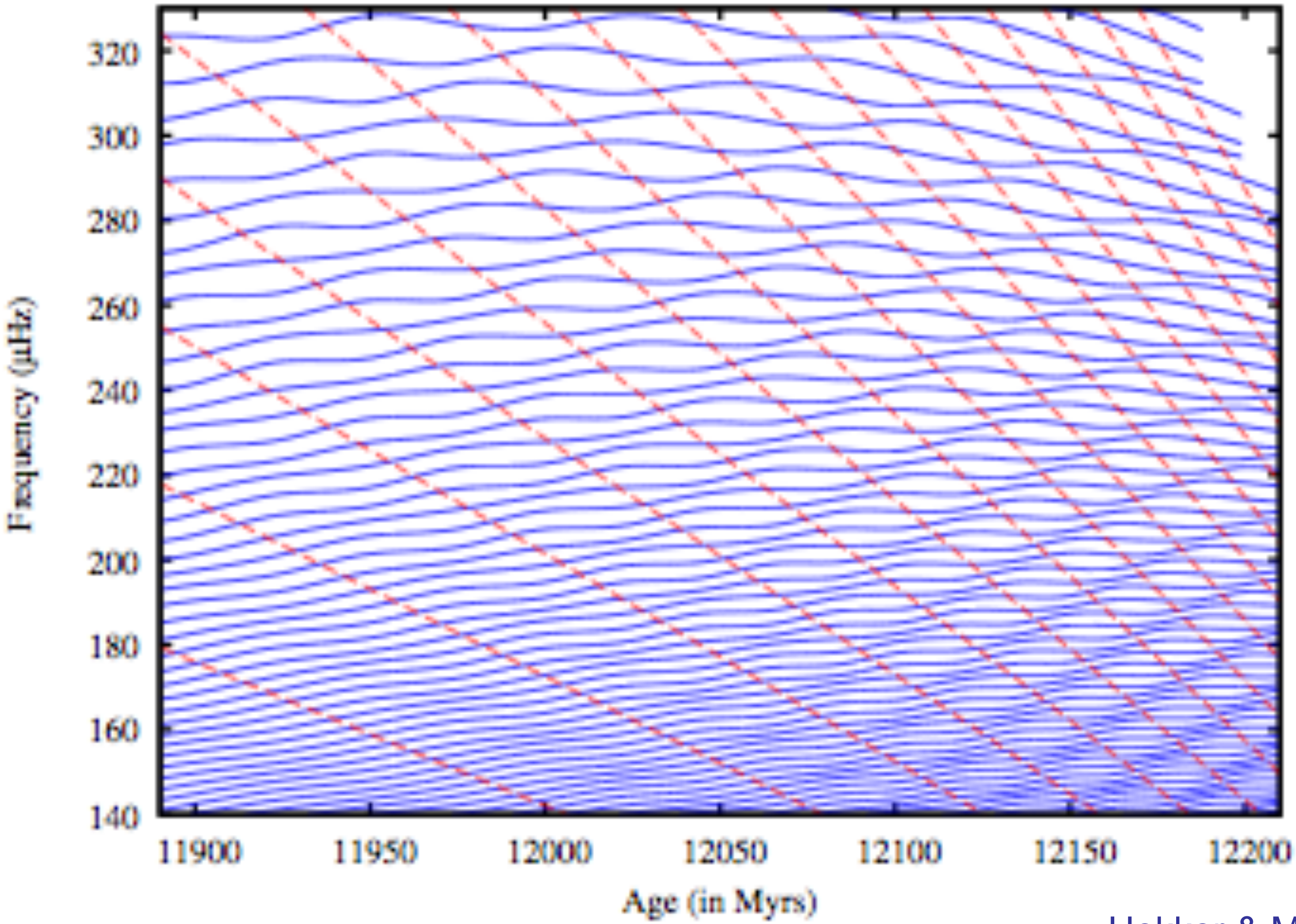


-Brunt-Väisälä frequency
buoyancy cavity

- Lamb frequency
acoustic cavity

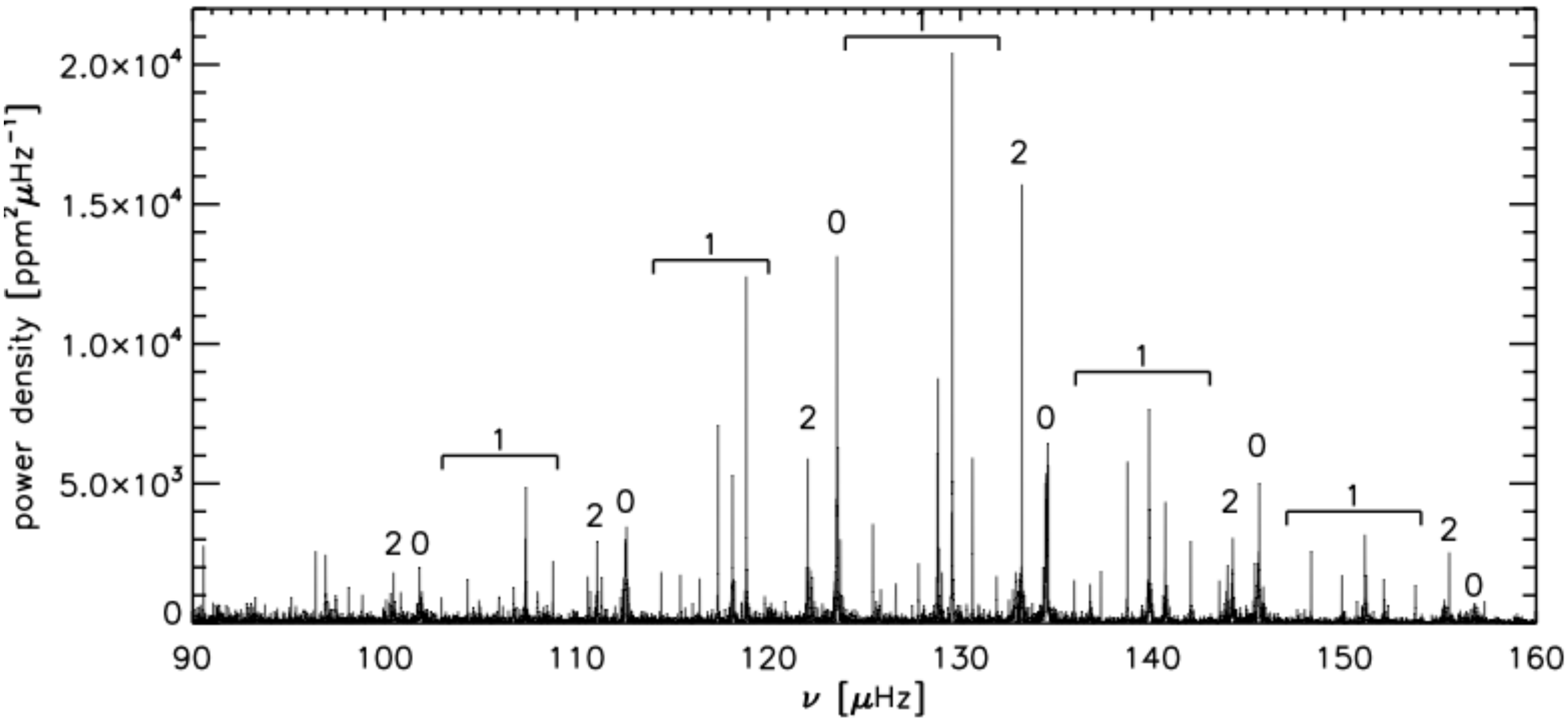
Hekker & Mazumdar 2014

Evolution



Hekker & Mazumdar 2014

Red giant



Hekker & Mazumdar 2014

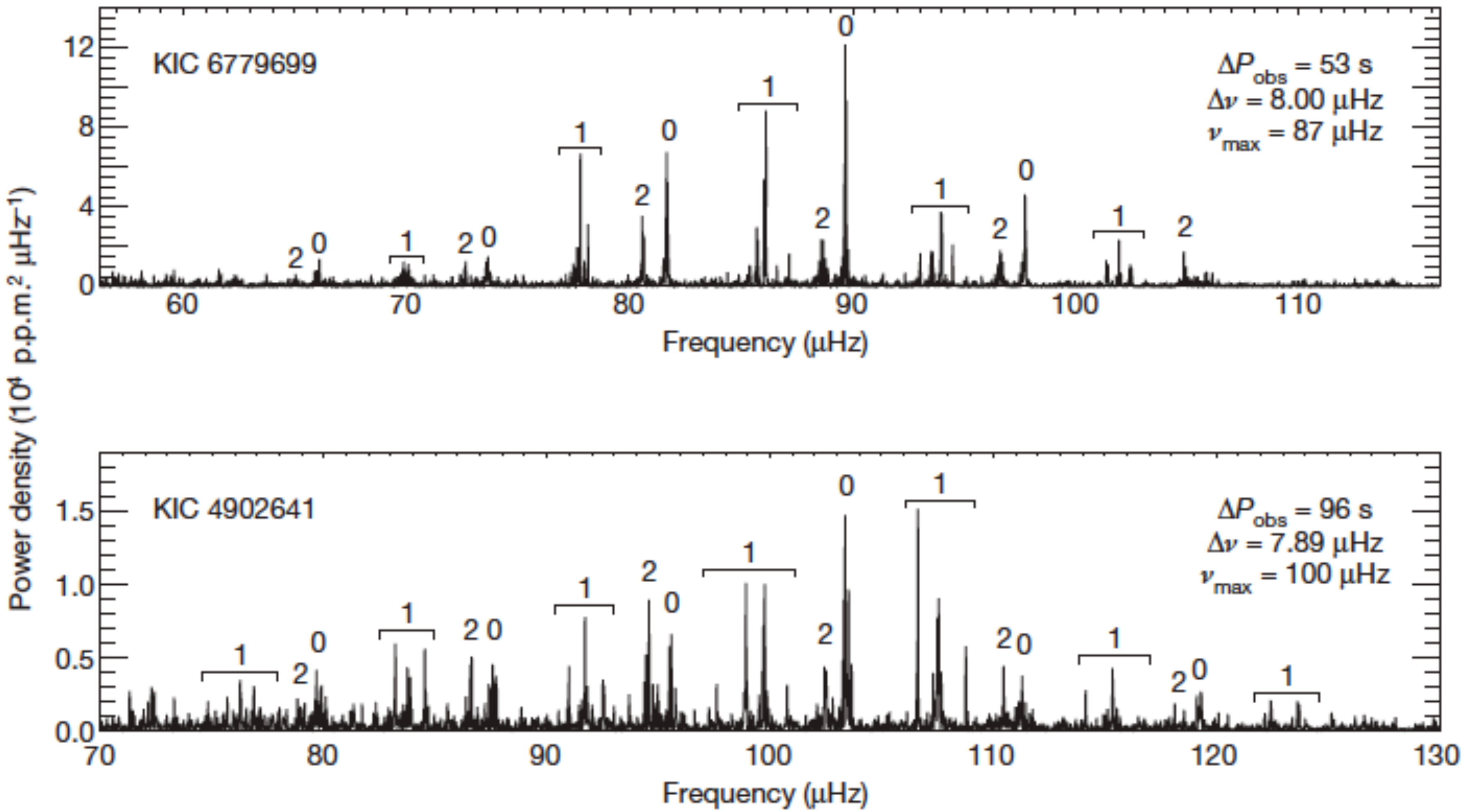
Asymptotic approximation: high-order g modes

$$\Pi_{nl} \cong \frac{\Delta\Pi}{\sqrt{l(l+1)}}\left(n + \frac{l}{2} + \varepsilon\right)$$

$$\Delta\Pi = (2\pi)^2\left(\int_0^R \frac{N(r)}{r}dr\right)^{-1}$$

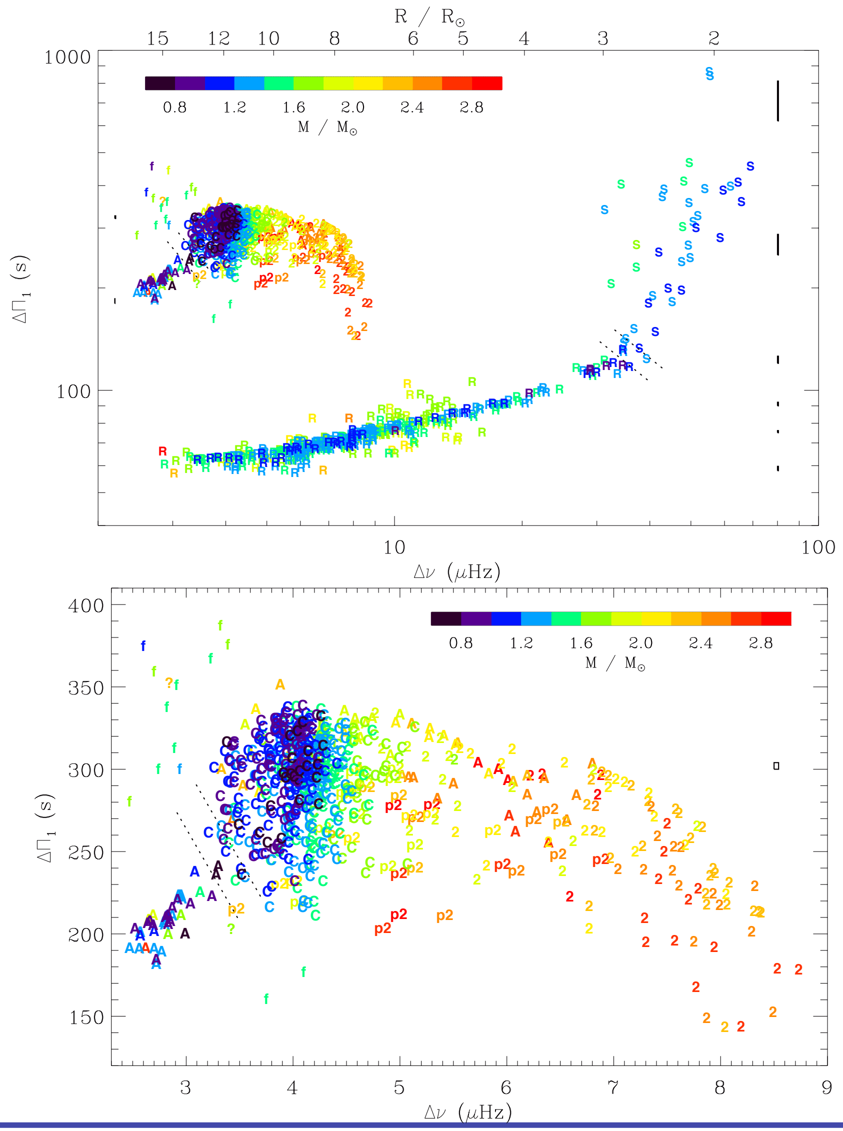
$$N^2 \equiv \frac{Gm}{r^2}\left(\frac{1}{\Gamma_1}\frac{d\ln P}{dr} - \frac{d\ln P}{dr}\right)$$

Mixed modes



Bedding et al. 2011

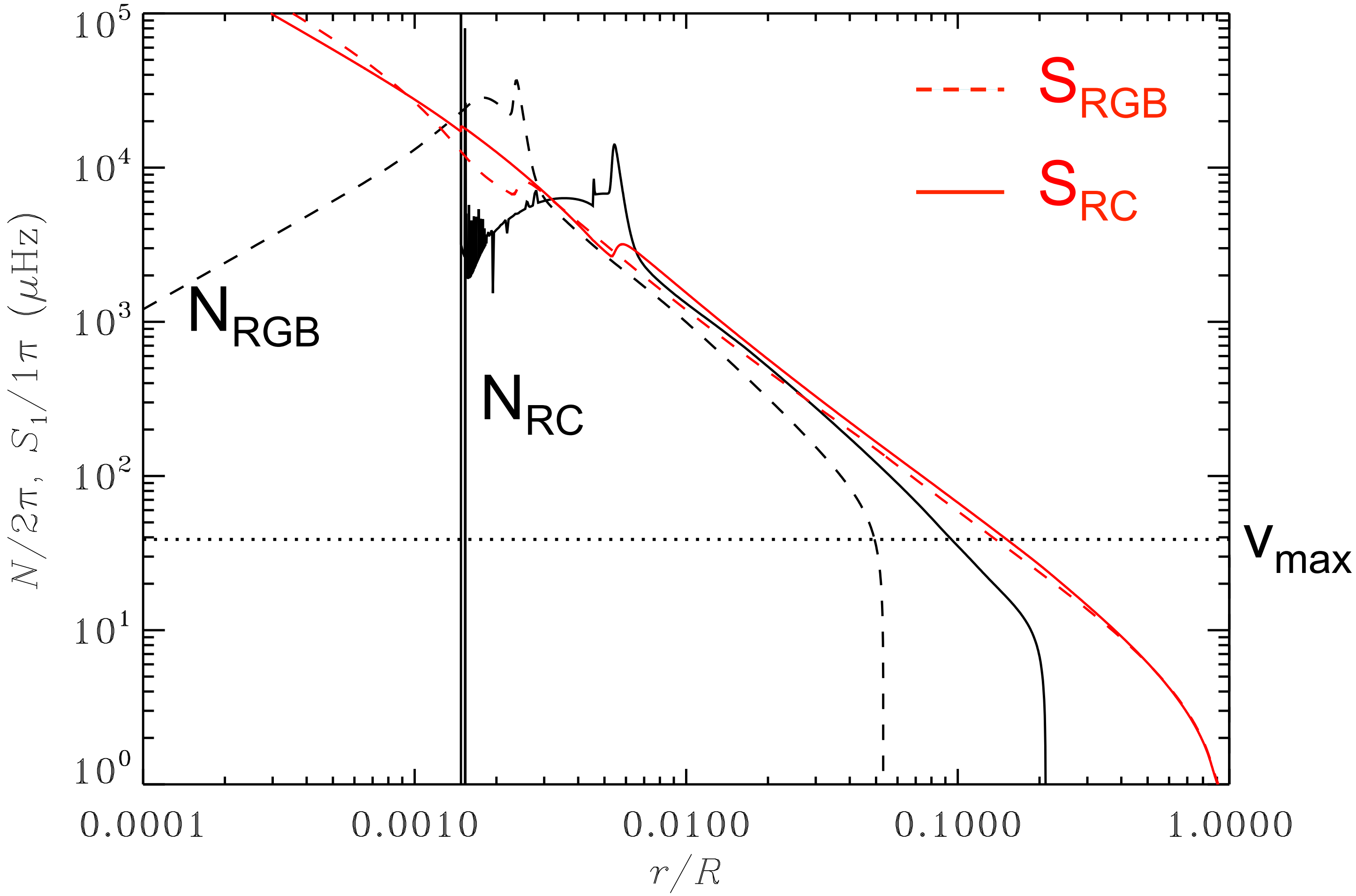
Period spacing



S: subgiant
R: red giant branch star
f: helium subflash stage
C: red clump
p2: pre secondary clump
2: secondary clump
A: stars leaving the clump moving towards AGB

Mosser et al. 2014

Brunt-Väisälä frequency

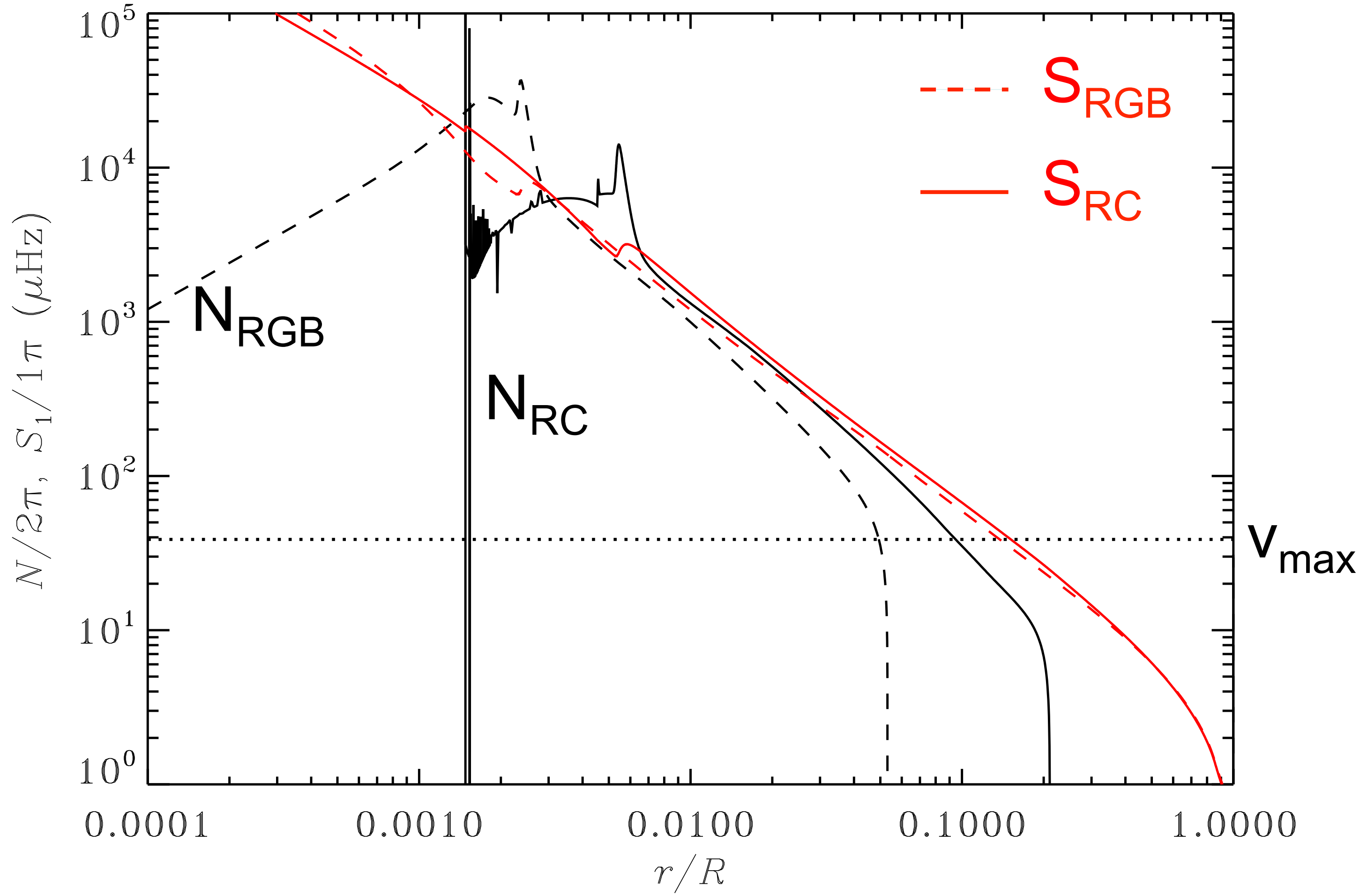


Hekker & Christensen-Dalsgaard in prep.

Question?

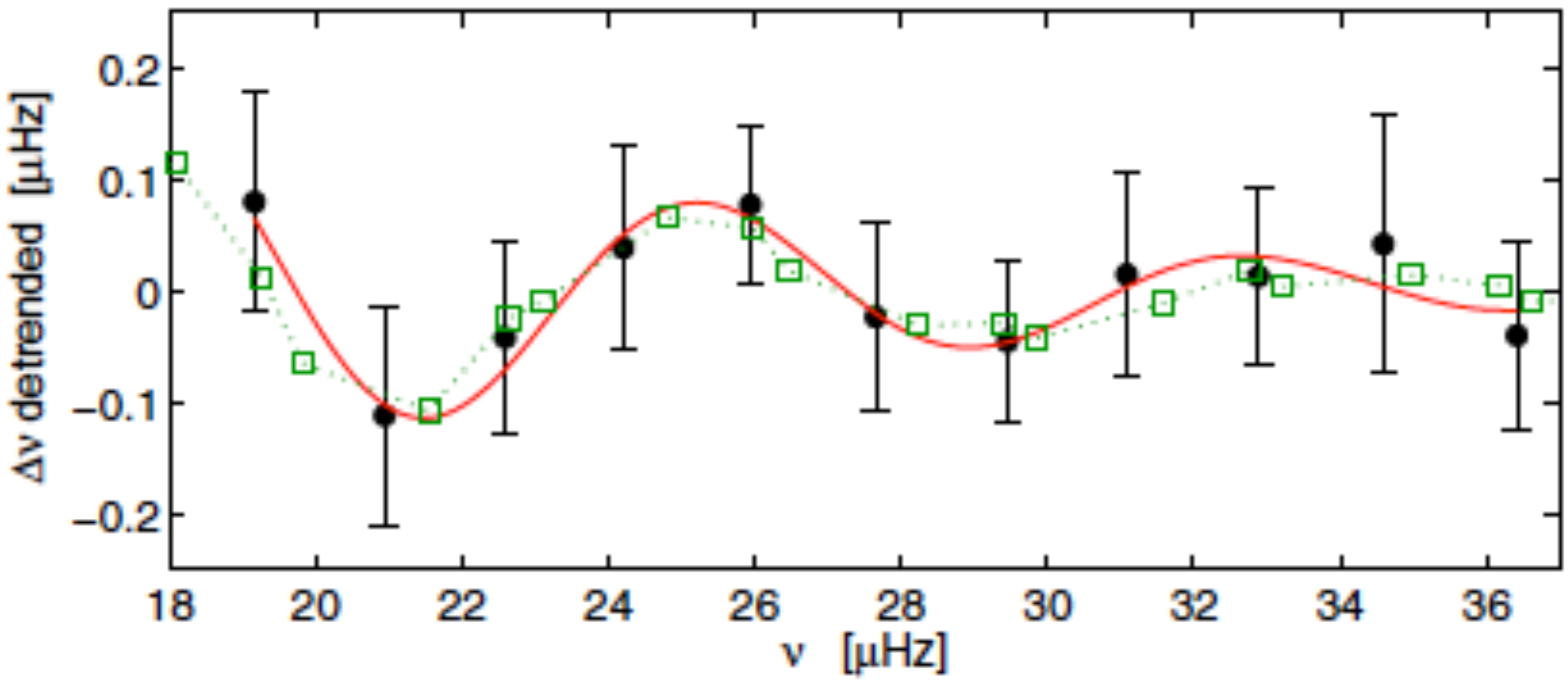
What physical phenomenon is causing the difference in N?

Brunt-Väisälä frequency



Hekker & Christensen-Dalsgaard in prep.

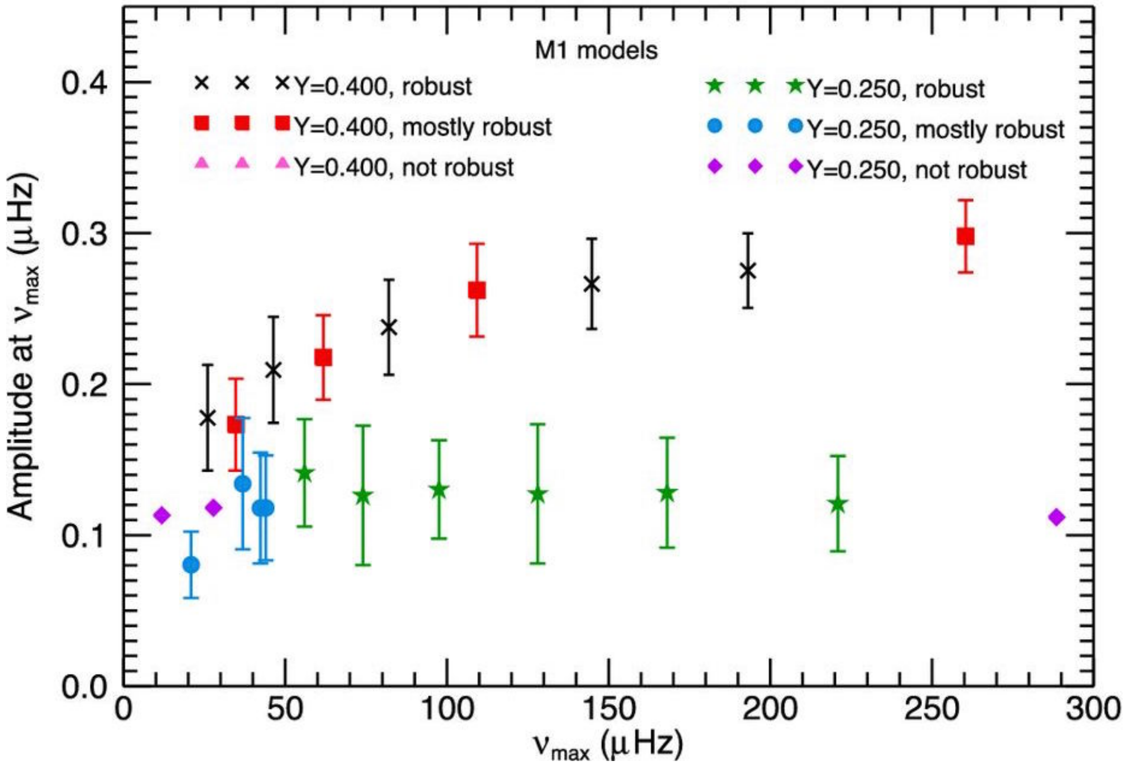
Individual frequencies: acoustic glitches



Miglio et al. 2010

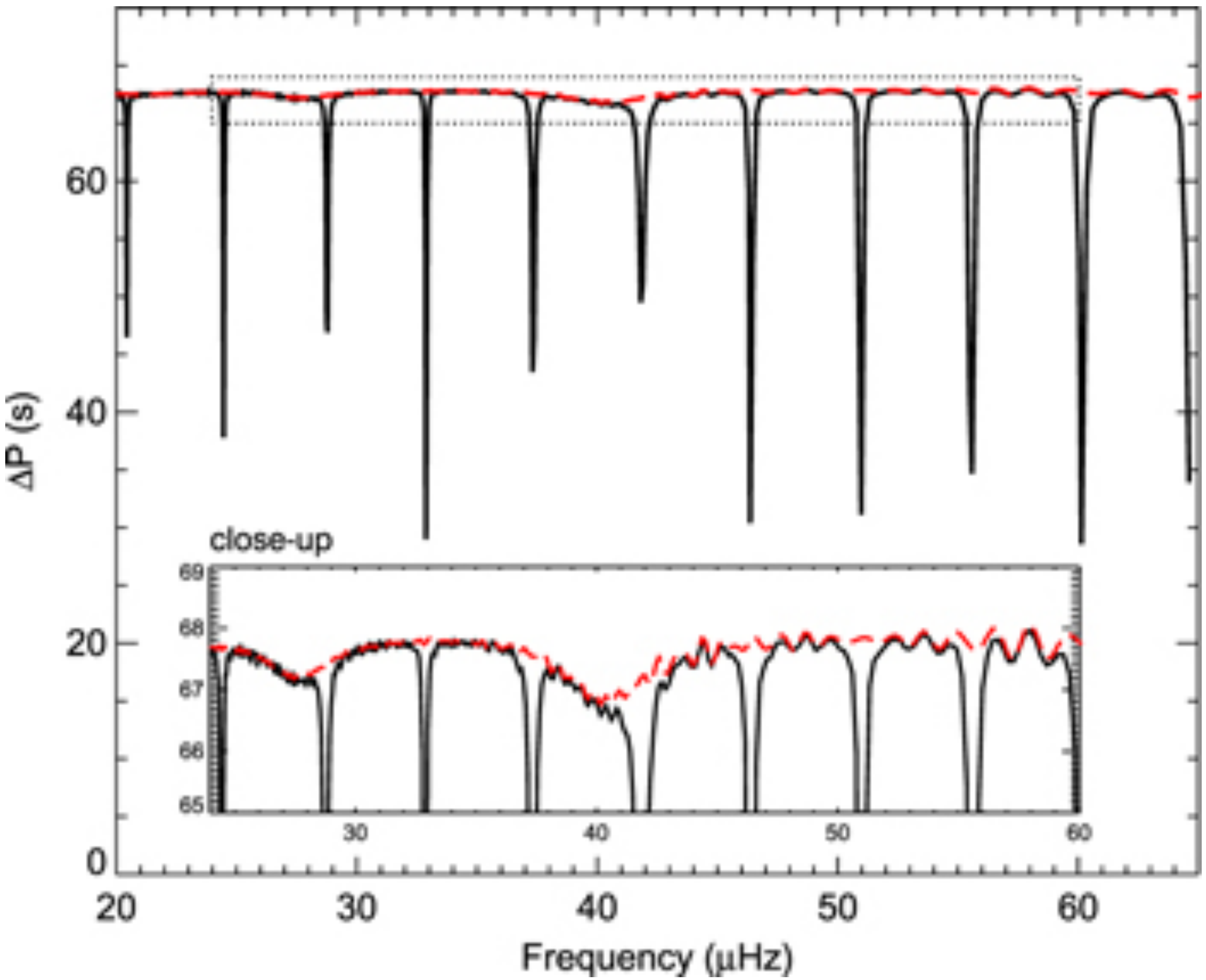
Individual frequencies: acoustic glitches

- (acoustic) radius and strength of He II ionisation zone
- possible indirect measure of He content



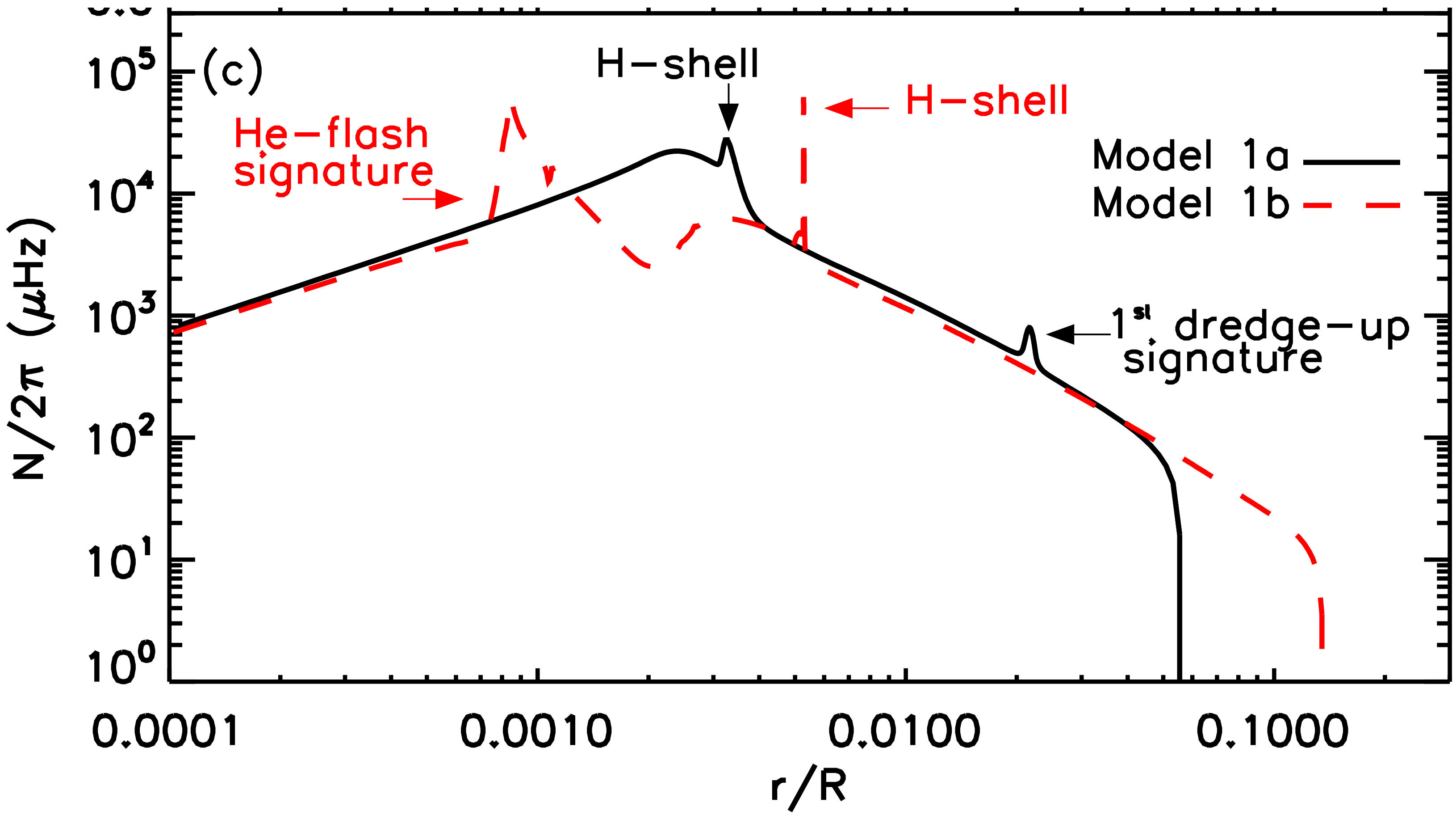
Broomhall et al. 2014

Individual frequencies: buoyancy glitches



Cunha et al. 2015

Individual frequencies: buoyancy glitches

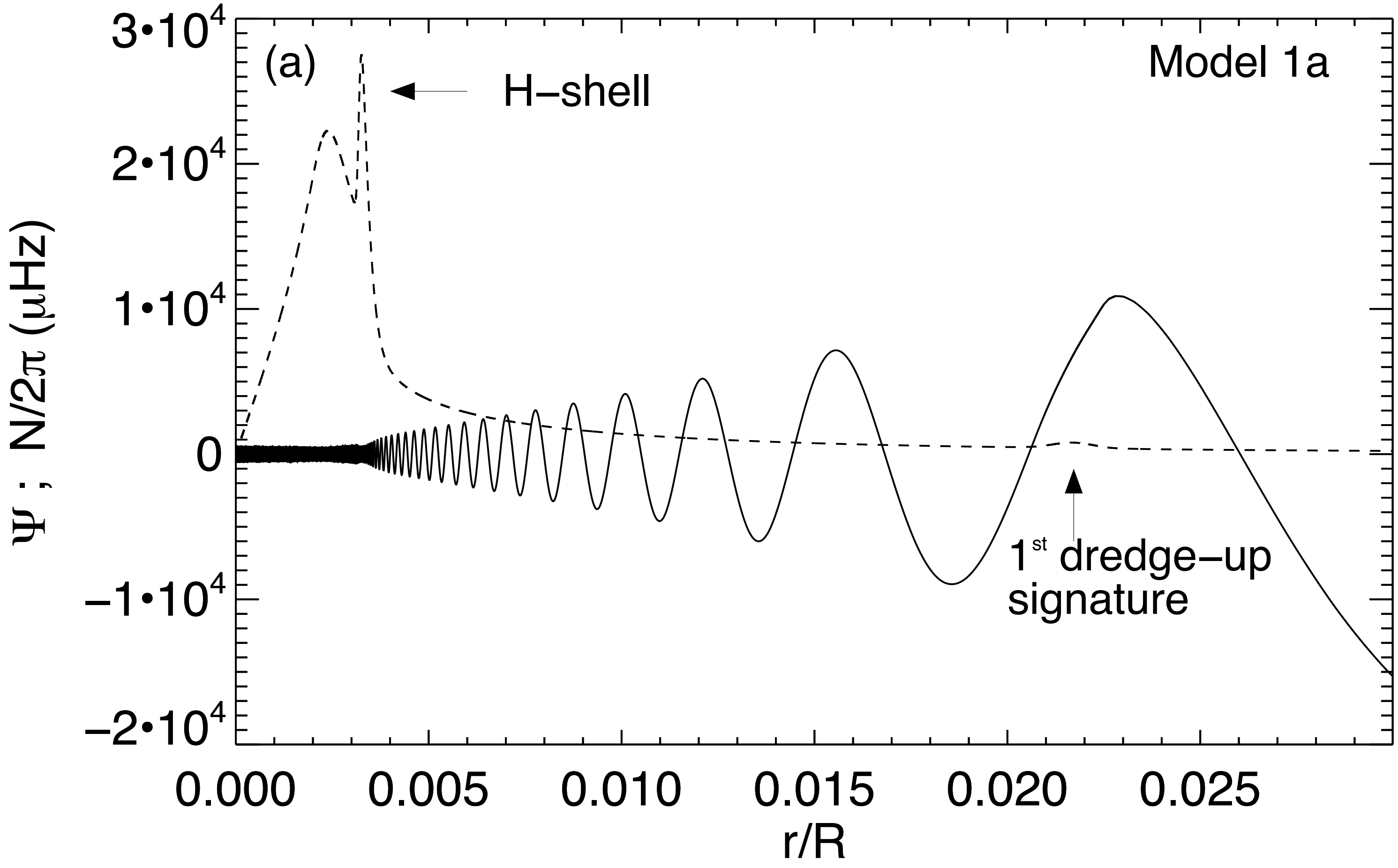


Cunha et al. 2015

Question?

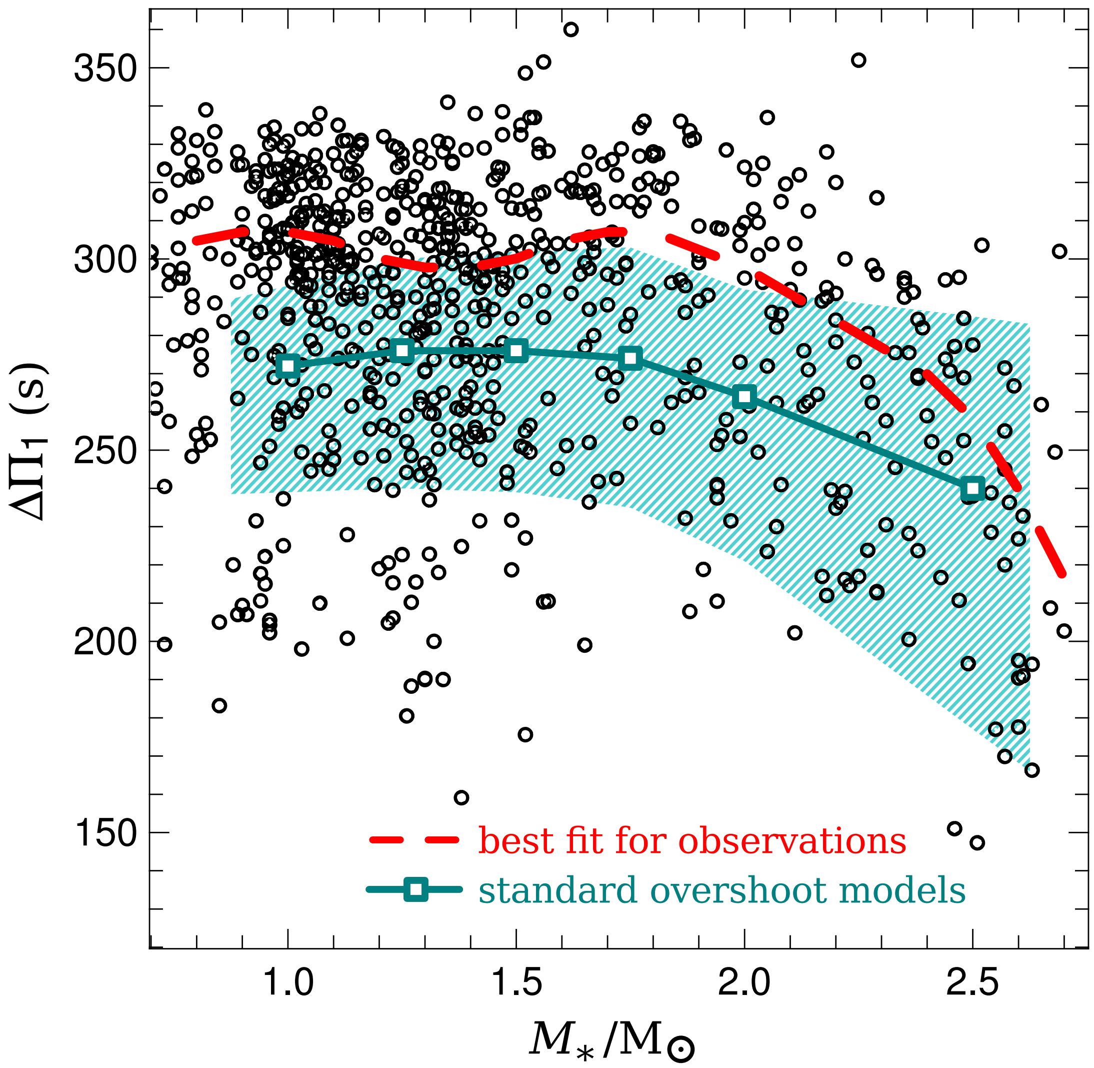
What are the requirements to have a glitch?

Individual frequencies: buoyancy glitch



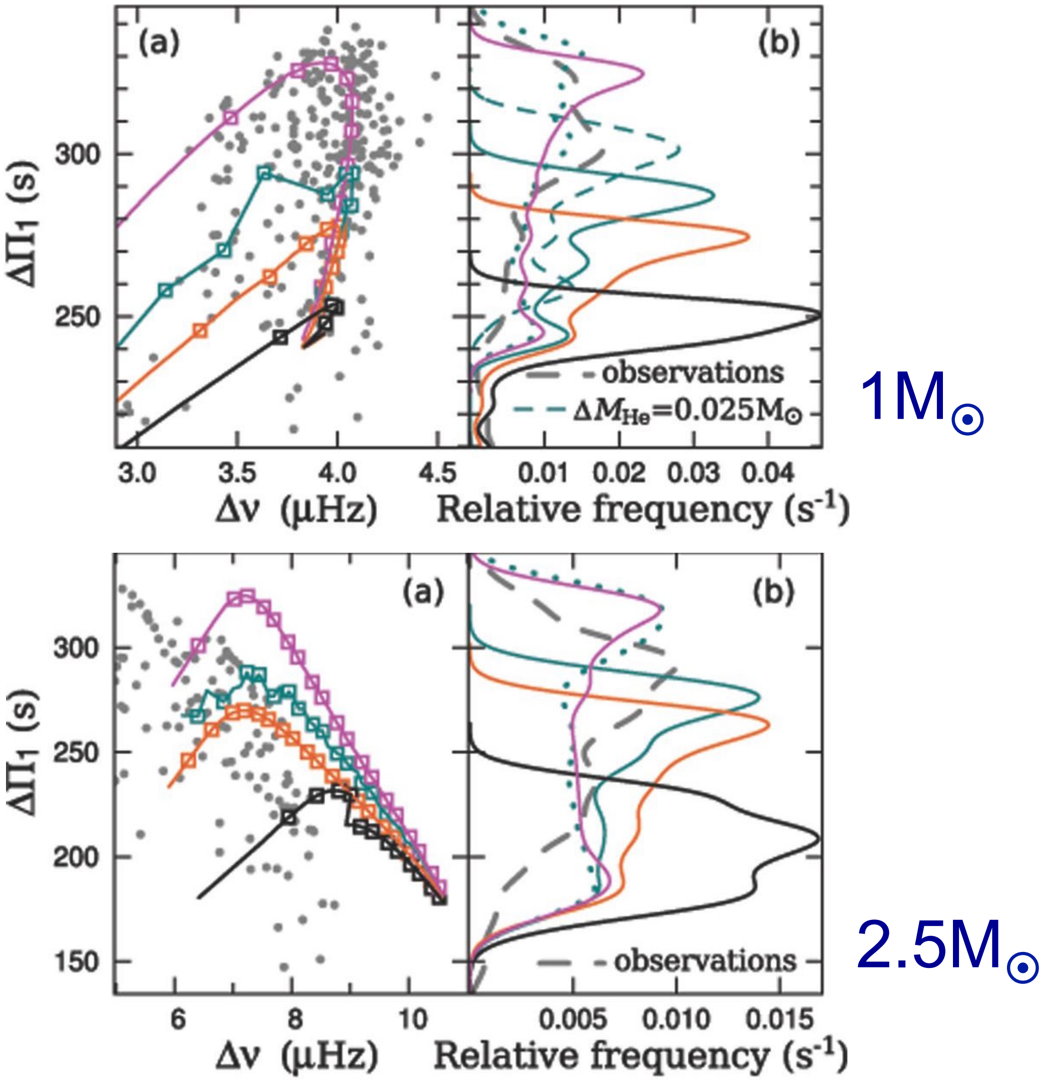
Cunha et al. 2015

Period spacings



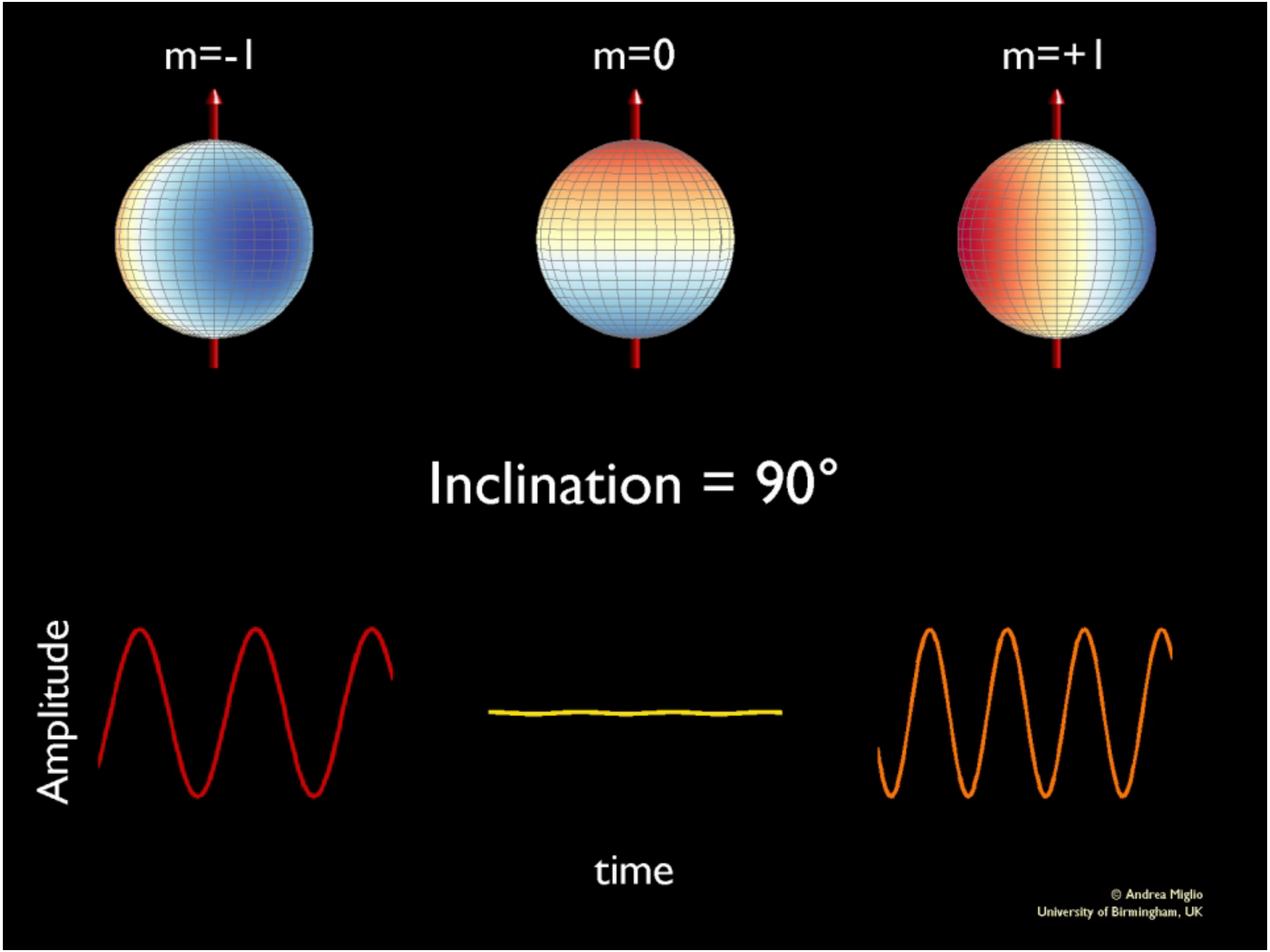
Constantino et al. 2015

Core convective conditions RC stars



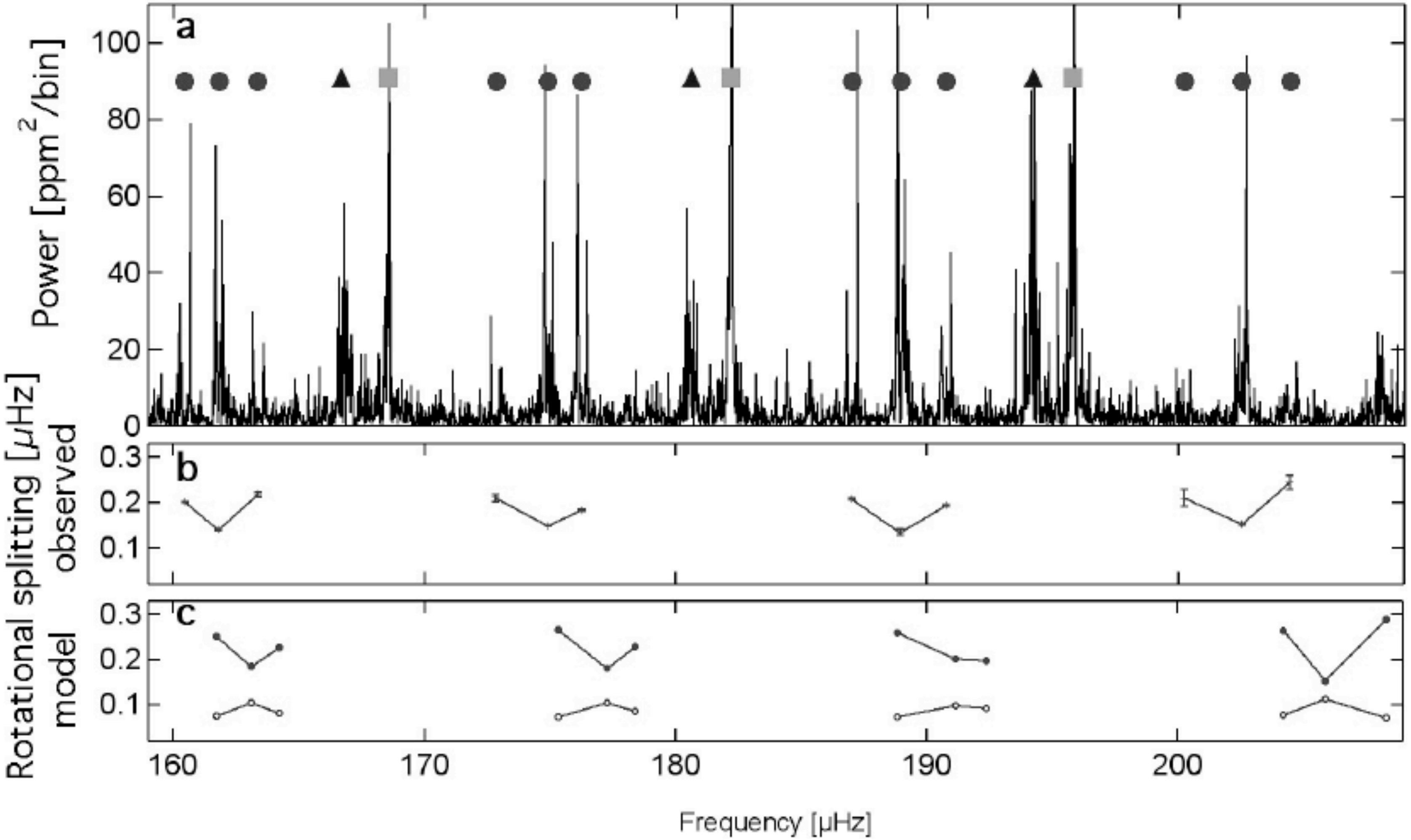
no overshoot
standard overshoot
semiconvection
maximal overshoot
observations

Constantino et al. 2015



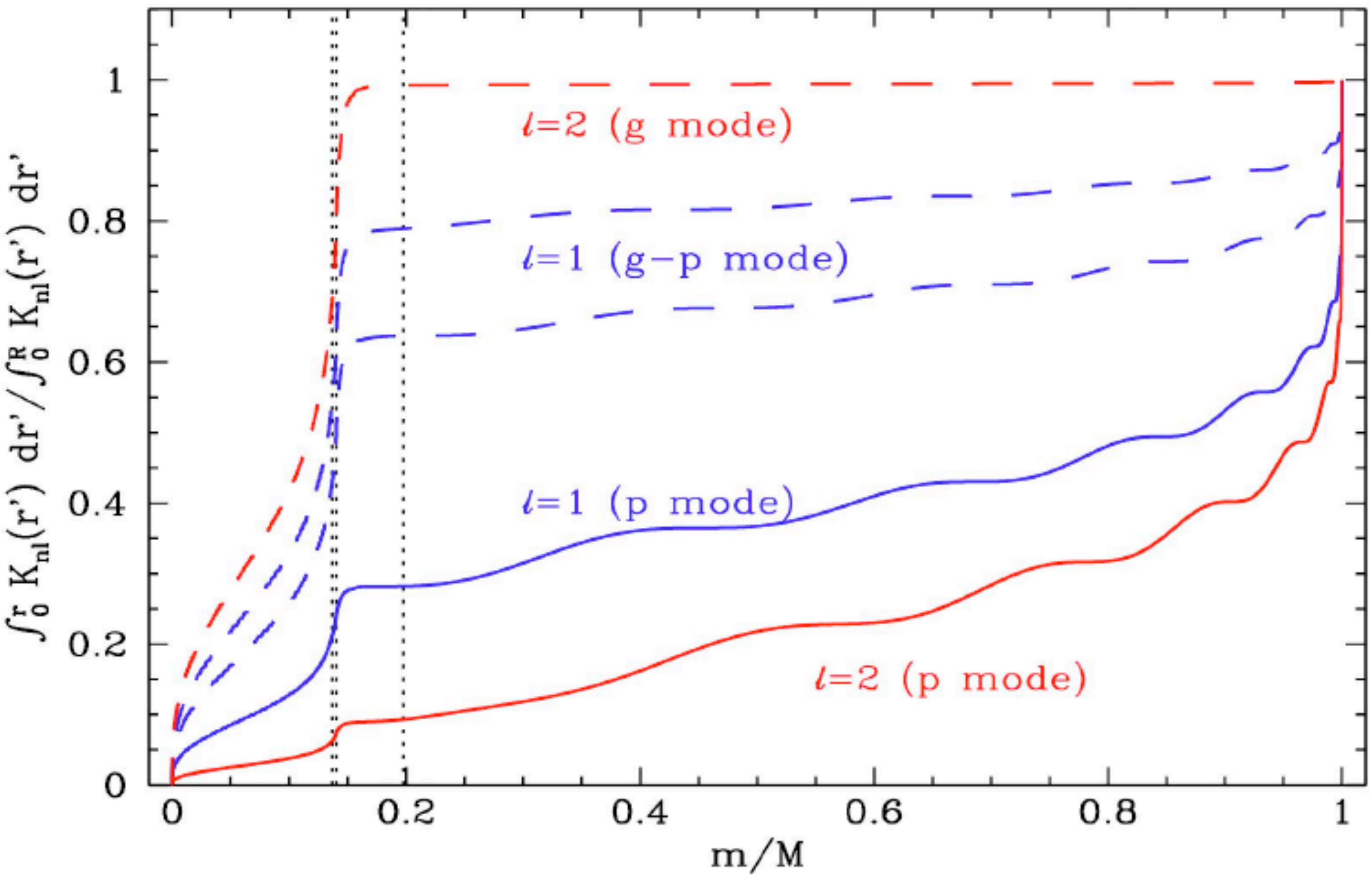
m=-1
m=0
m=+1
Inclination = 90°
Amplitude
time
© Andrea Miglio
University of Birmingham, UK

Rotation in red giants

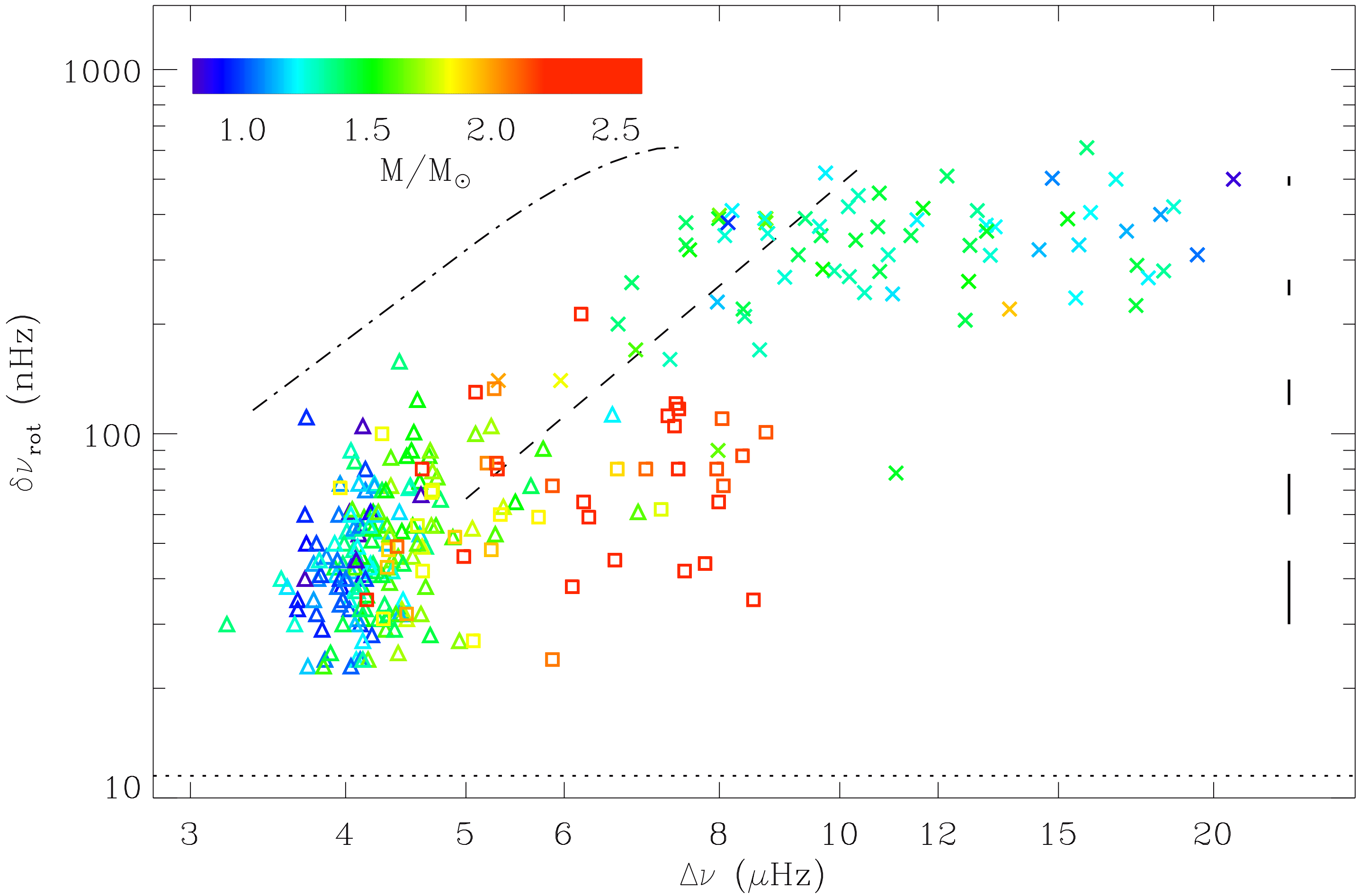


Beck et al. 2011, Nature

Rotation in red giants

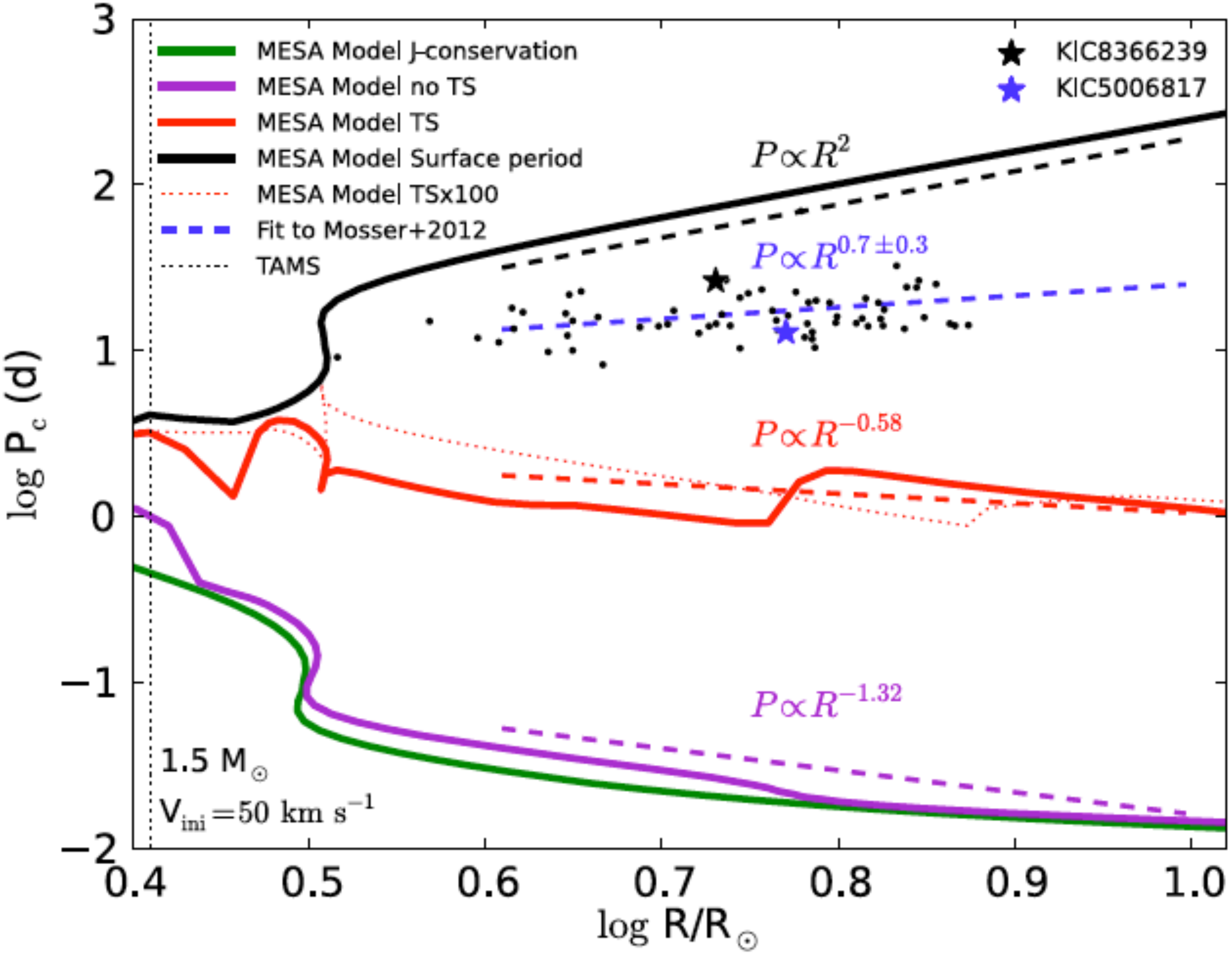


Observed core rotation



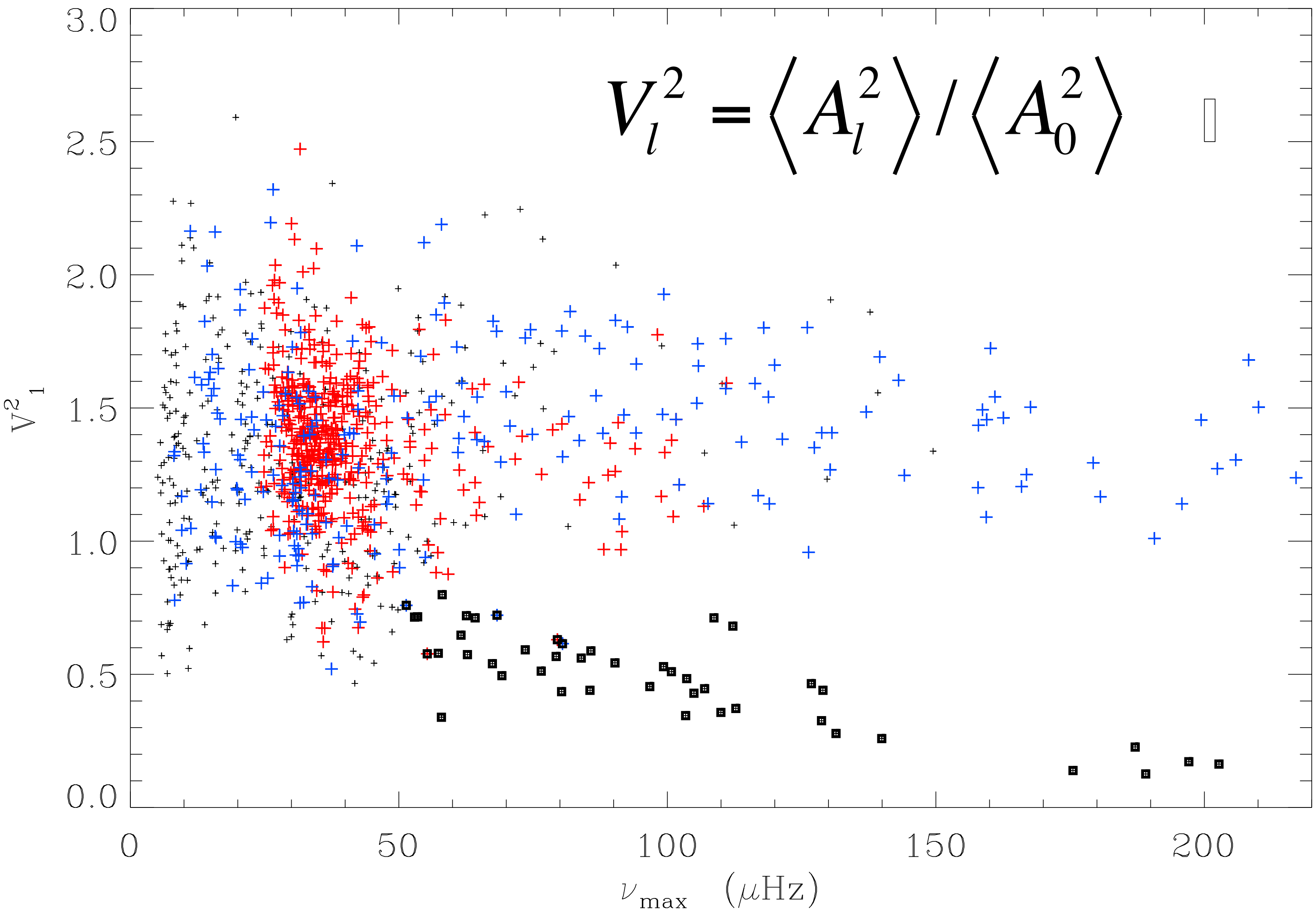
Mosser et al. 2012

Predicted core rotation



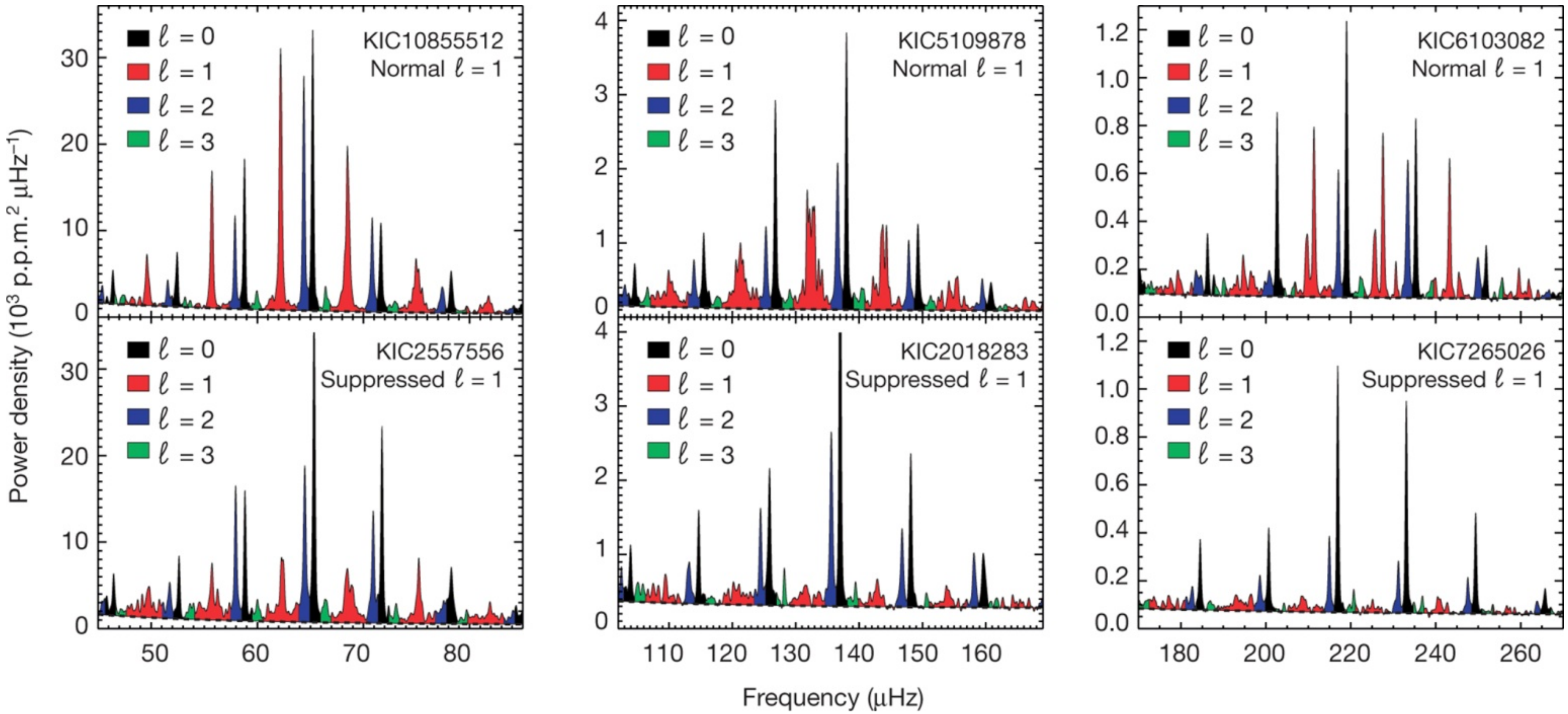
Cantiello et al. 2014

Suppressed dipole modes



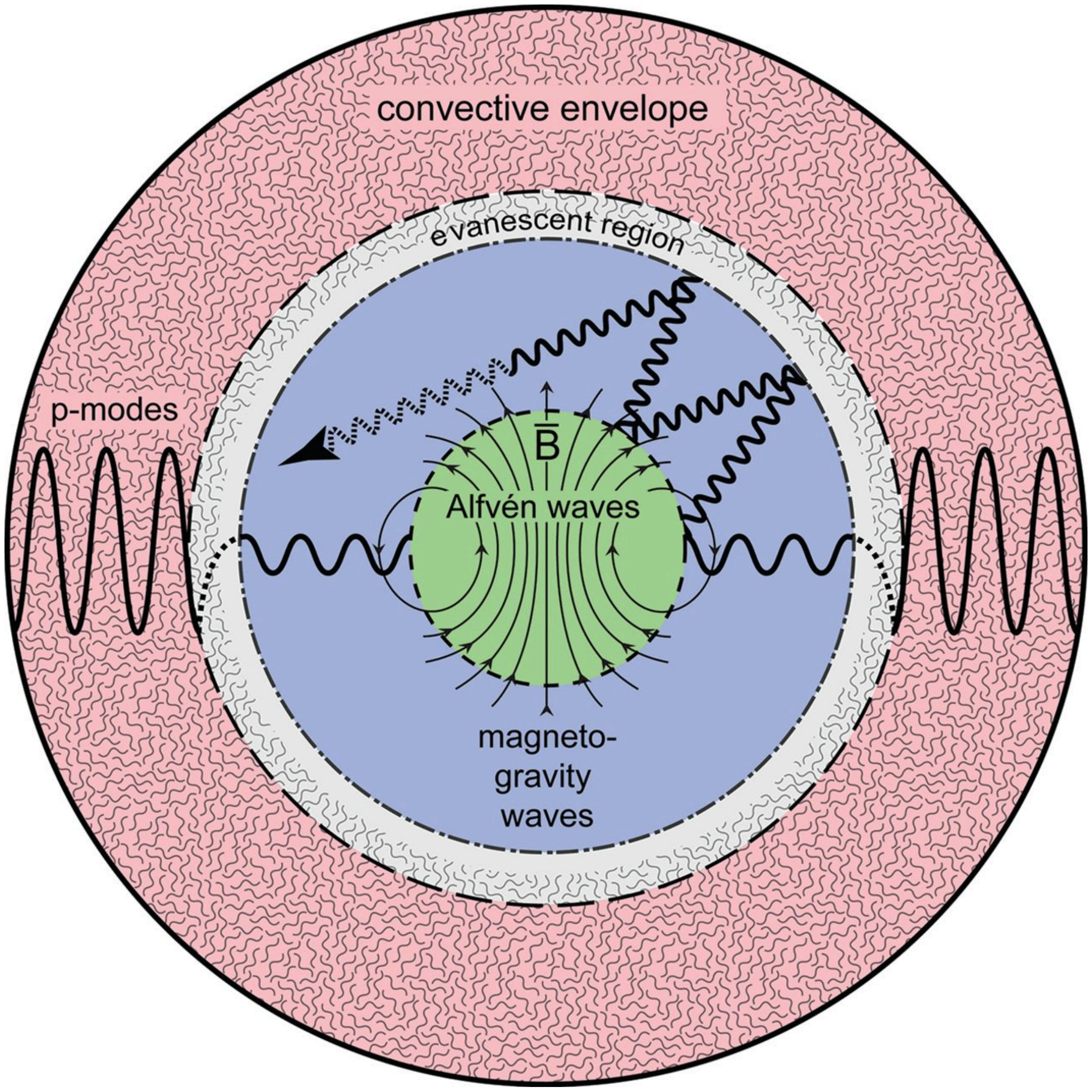
Mosser et al. 2011

Suppressed dipole modes



Stello et al. 2016

Suppressed modes: magnetic greenhouse



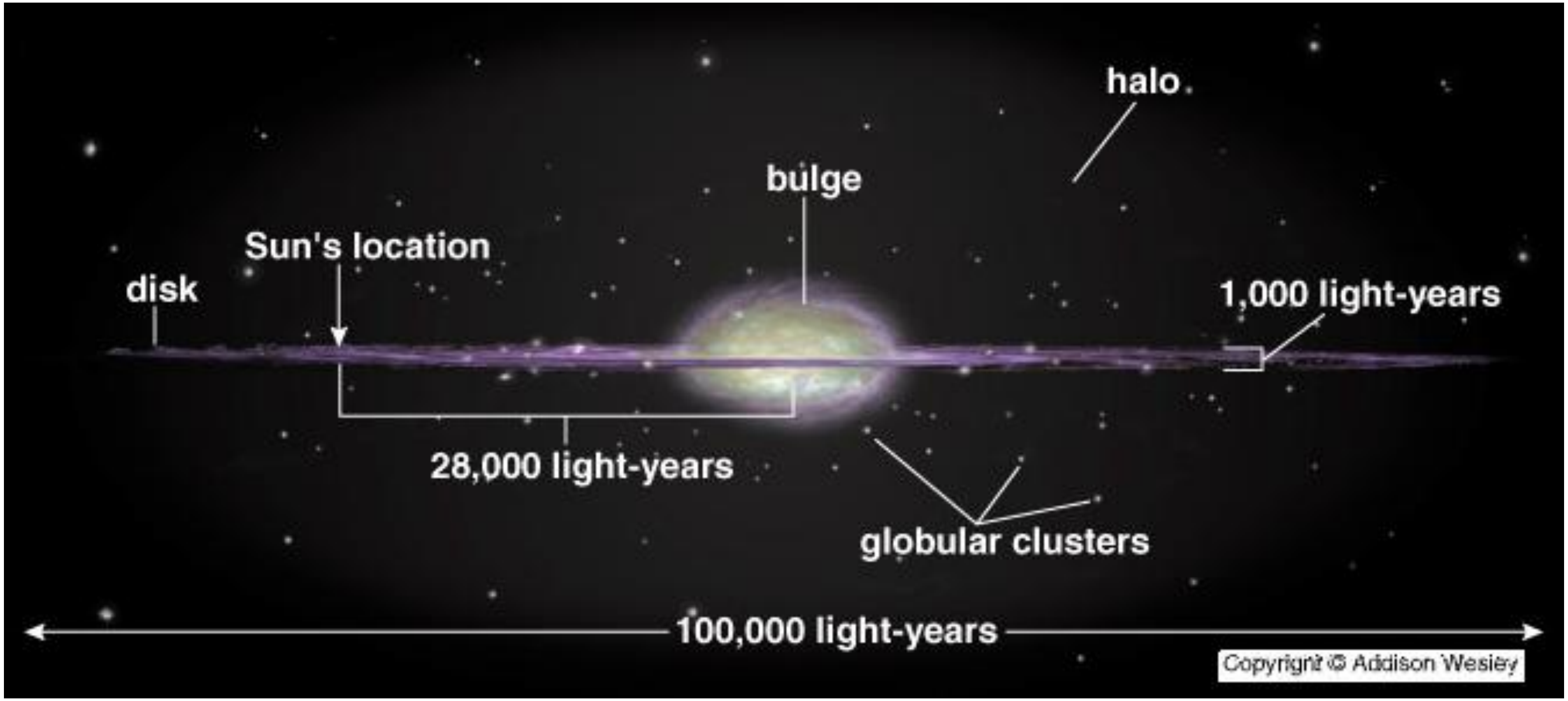
Fuller et al. 2015

Milky Way galaxy

Question?

What are the main components of the Milky Way galaxy?

Milky Way Galaxy



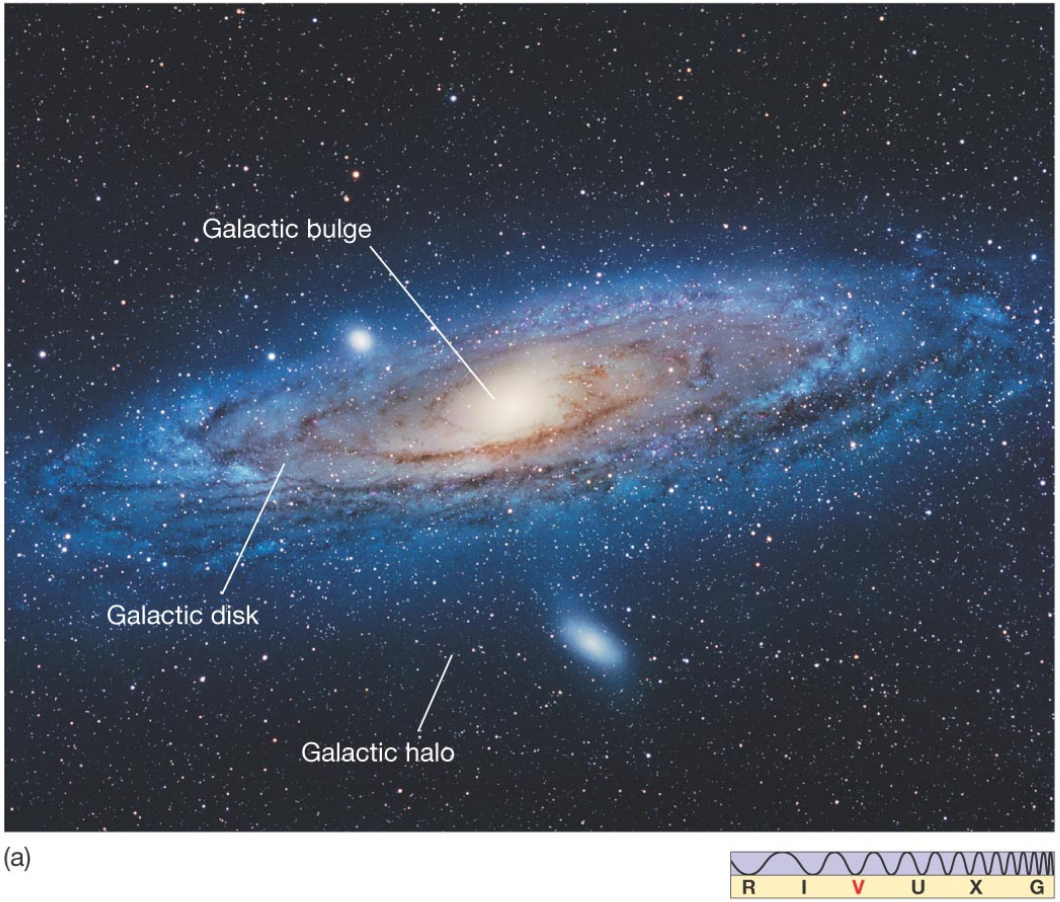
Galactic Halo

- spherical shape
- old stars (Pop II) on random orbits
- sparsely populated
- absence of gas or dust

Globular Clusters

- conglomerations of stars that are gravitationally bound
- old stars (Pop II) stars
- no gas or dust
- multiple populations
- on elliptical orbits around galactic centre
- about 150- 200 in our Milky Way
- by Shapley used to determine location of Sun in MW

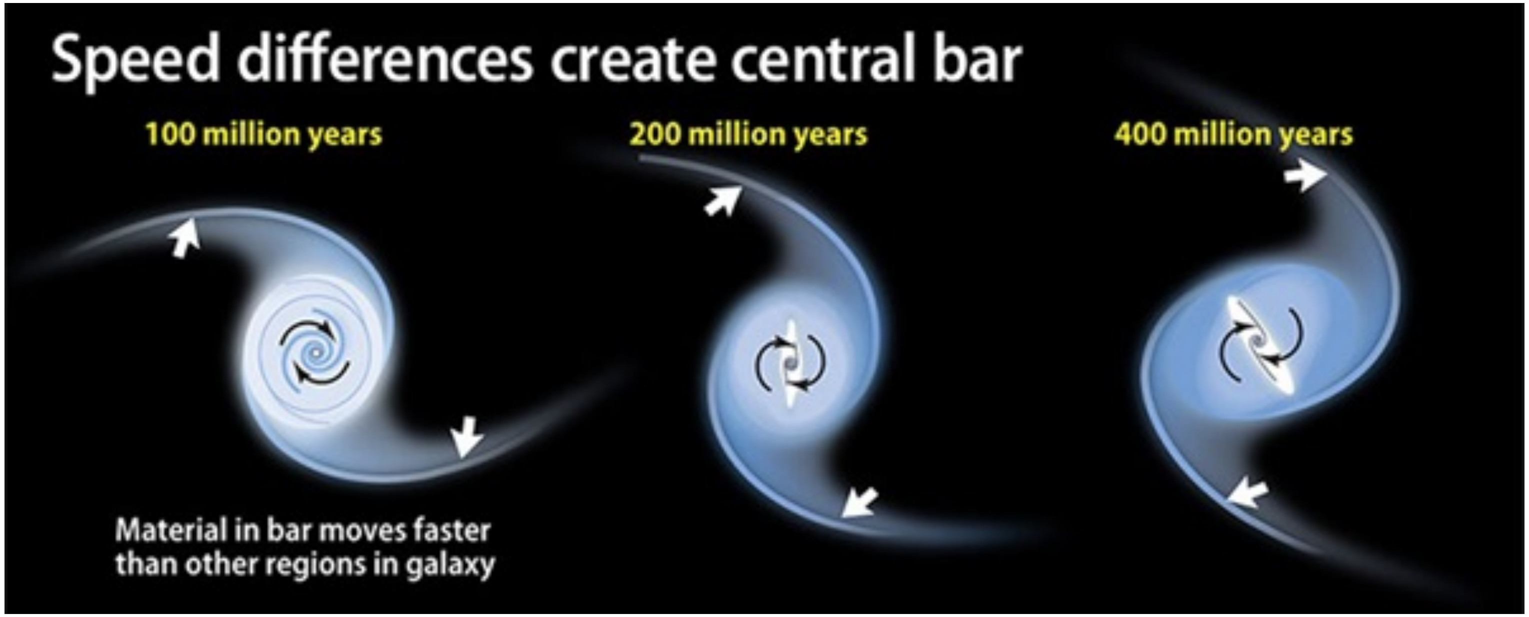
Galactic Bulge



(a)

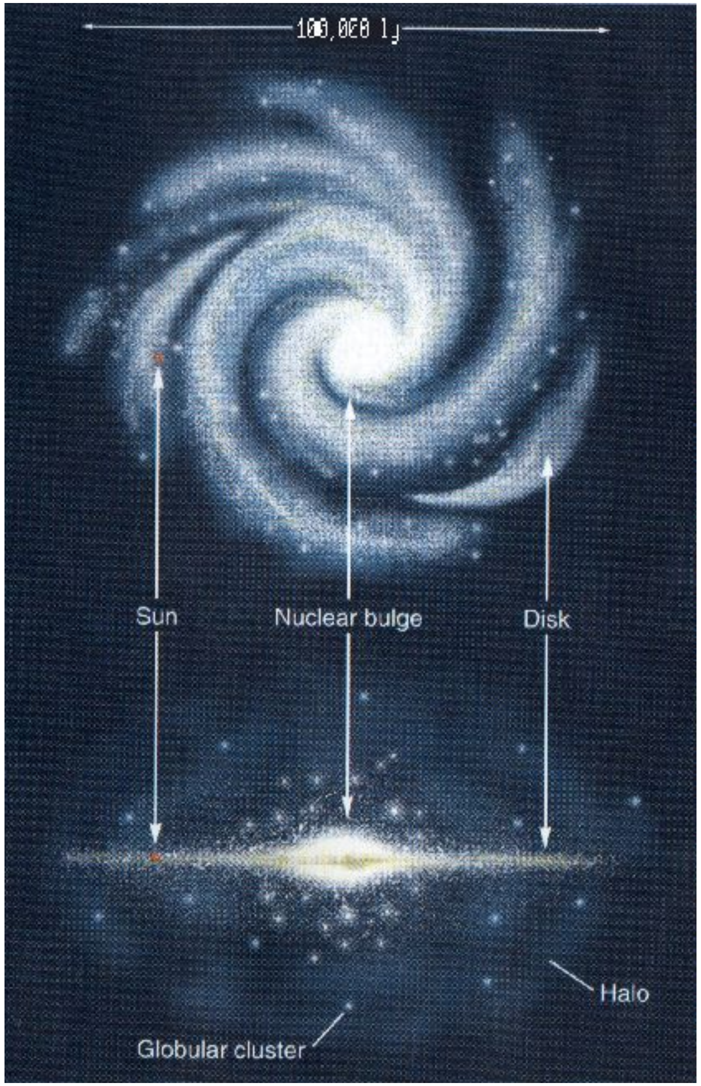
- half as wide as long
- old stars (Pop II) and young (Pop I) stars
- stars on random orbits with net rotation about center
- contains stars and dust in inner region

Galactic bar



- overdensity of stars in bar shape in galactic centre
- gas near the galaxy's center moves at faster speeds than that farther out. This, combined with density waves, helps create the bar.

Galactic Disk



- flattened
- relatively young stars (thin disk) and older stars (thick disk)
- spiral arms
- contains gas and dust

GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	Contains no gas and dust	Contains gas and dust, especially in the inner regions
Site of ongoing star formation	No star formation during the last 10 billion years	Ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	Stars have random orbits in three dimensions	Stars have largely random orbits but with some net rotation about the Galactic center
Spiral arms	No obvious substructure	Ring of gas and dust near center; Galactic nucleus
Overall white coloration, with blue spiral arms	Reddish in color	Yellow-white

Dark matter

Visible mass in the Milky Way not enough to explain the orbital motions: more mass needs to be present!!

Large dark matter halo:

- Black holes
- Brown dwarfs
- White dwarfs
- WIMPs (weakly interacting massive particles)

Galactic Centre

- obscured by gas and dust
- highly luminous in IR, γ-rays, radio and X-rays
- apparent ring of rotating matter
- stars are more densly packed

➔ black hole with $4 \bullet 10^6\ M_\odot$

Galactic Archeology

"the study of the formation and evolution of the Milky Way by reconstructing its past from its current constituents"

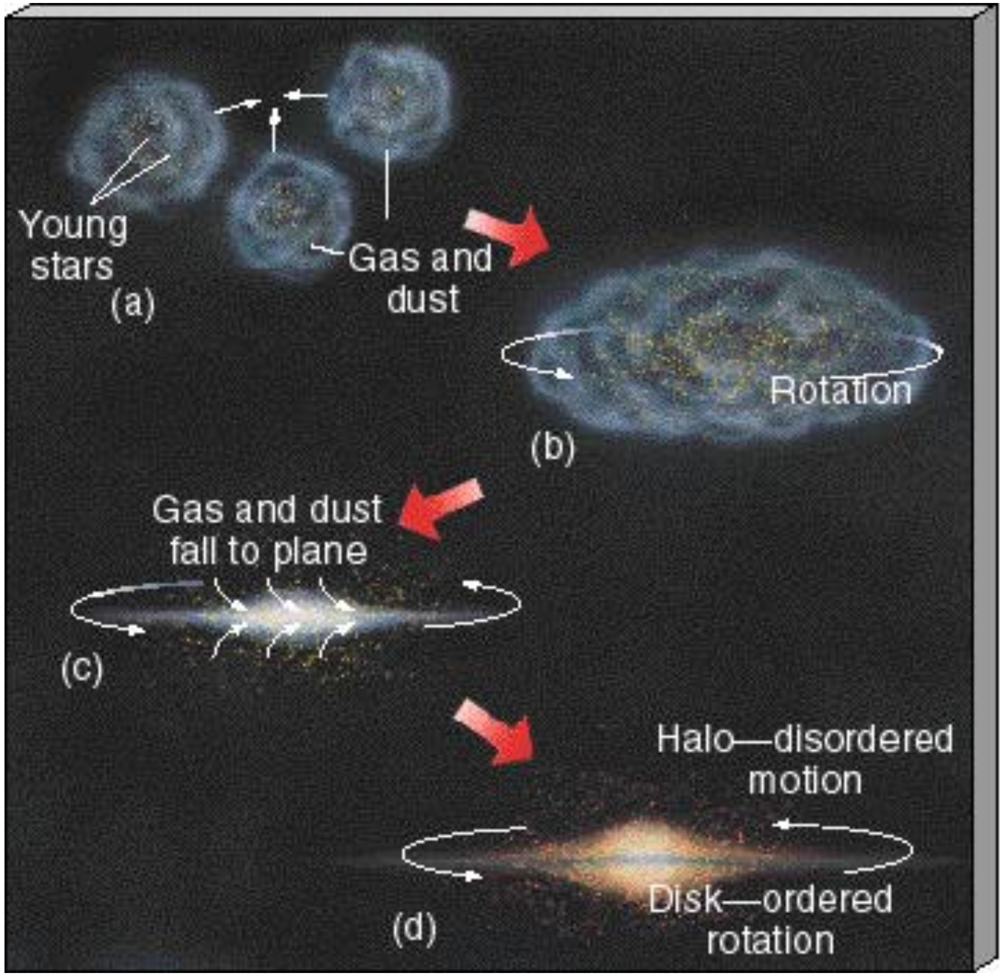
what are the current ingredients for the formation of the Milky Way?

Galaxy formation

Combination of:

- in situ star formation
- merging of smaller galaxies

Galaxy formation: in situ



Galaxy formation: in situ

early star formation:

- massive stars ($M \geq \sim 8M_{\odot}$) with low-Z
- massive stars evolve faster than lower mass stars
- SNeII: when nuclear fusion suddenly becomes unable to sustain the core against its own gravity
  - ➔core collapses enriching ISM
  - ➔relatively large fraction of α-elements compared to Fe

(α-elements are elements formed by capturing an α (^{4}He) particle: e.g. O. Mg, Ne, Si, S, Ca, Ti)

Galaxy formation: in situ

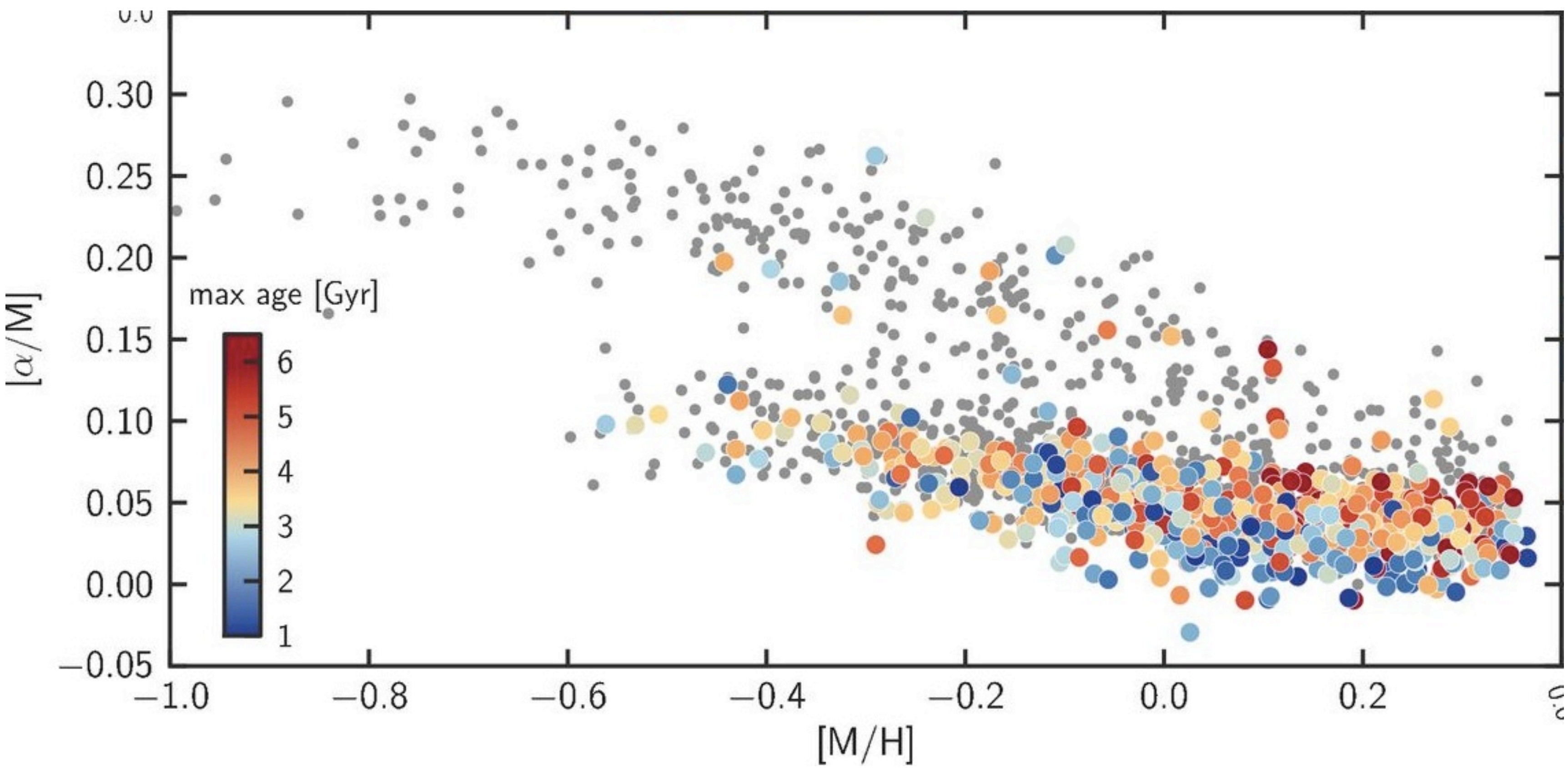
early star formation:

- intermediate mass stars ($M \leq \sim 8M_\odot$) evolve over longer timescales compared to more massive stars
- SNeIa: when white dwarf accumulates sufficient material from companion to raise core T to ignite carbon fusion

  ➔ run away nuclear fusion that disrupts it

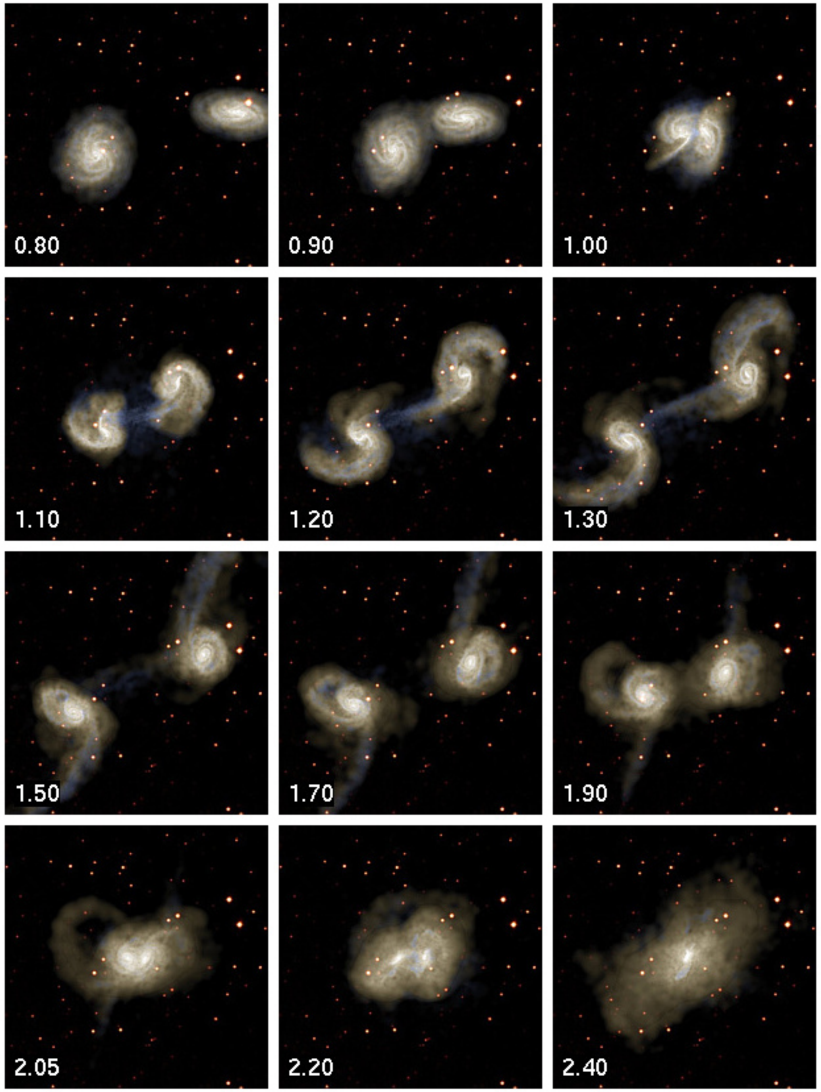
  ➔ Fe pollution of ISM

Chemical evolution

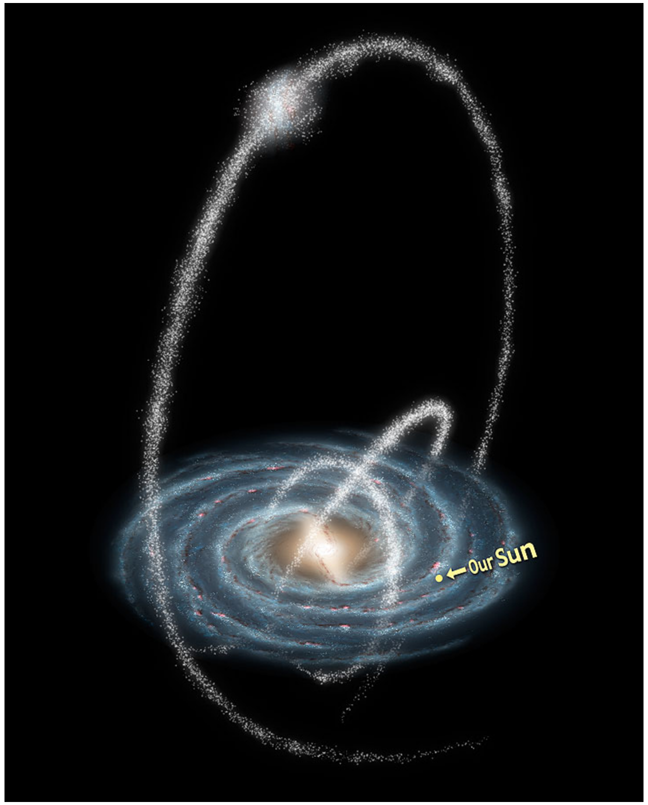


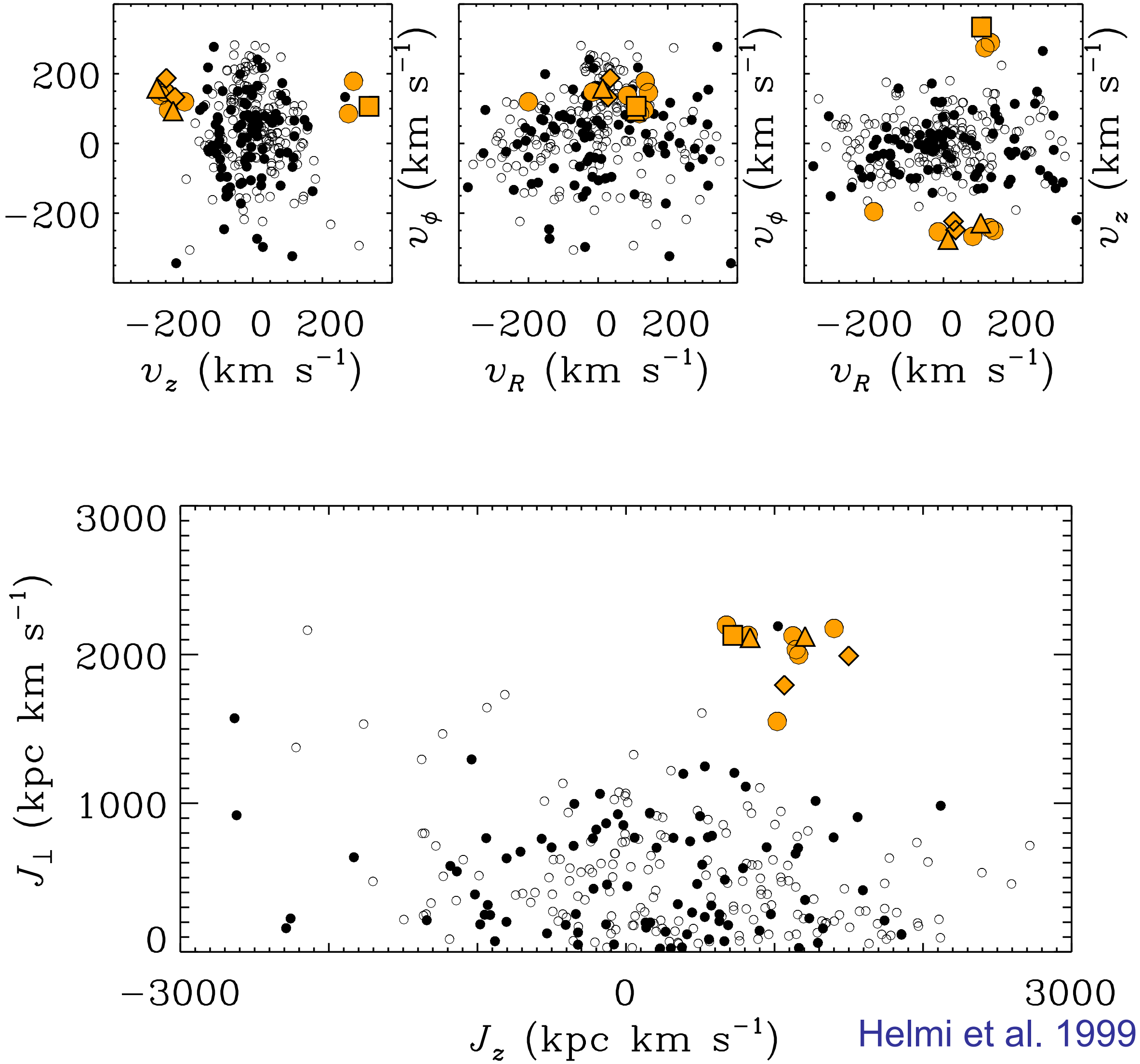
Martig et al. 2015

Galaxy formation: mergers



Streams: visible remnants of mergers

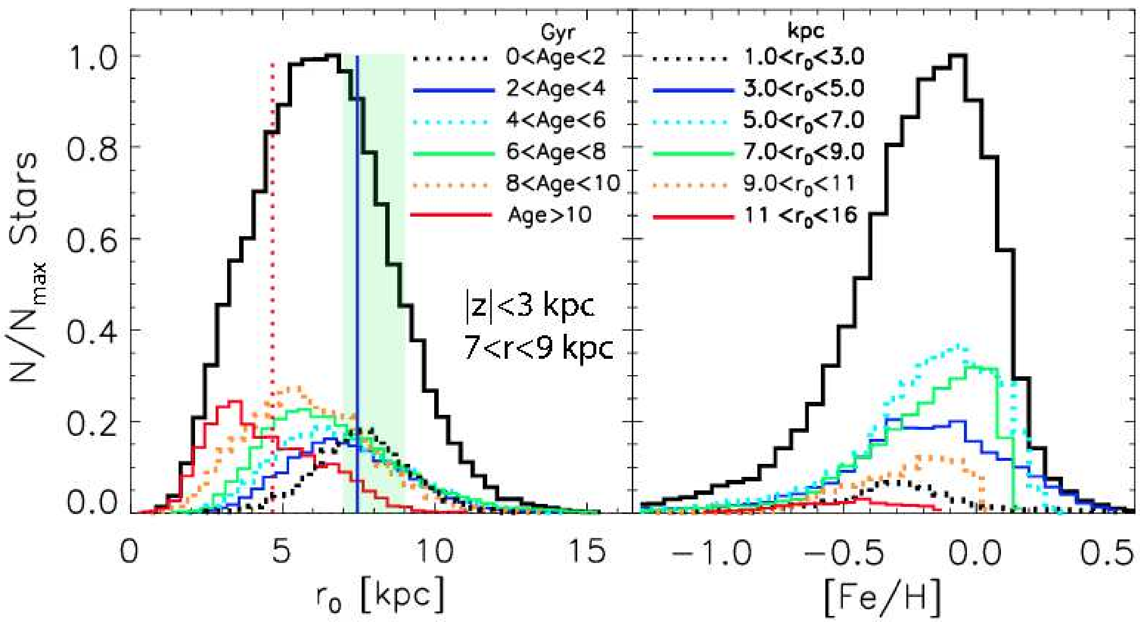




Helmi et al. 1999

Migration!

Stars migrate away from birth place: this was not taken into account in MW formation models till about a decade ago! ➔ chemo-dynamical models



Minchev et al. 2013

Thick disk

- extragalactic origin
- created through heating of preexisting thin disk with the help of mergers
- radial migration

Thick disk

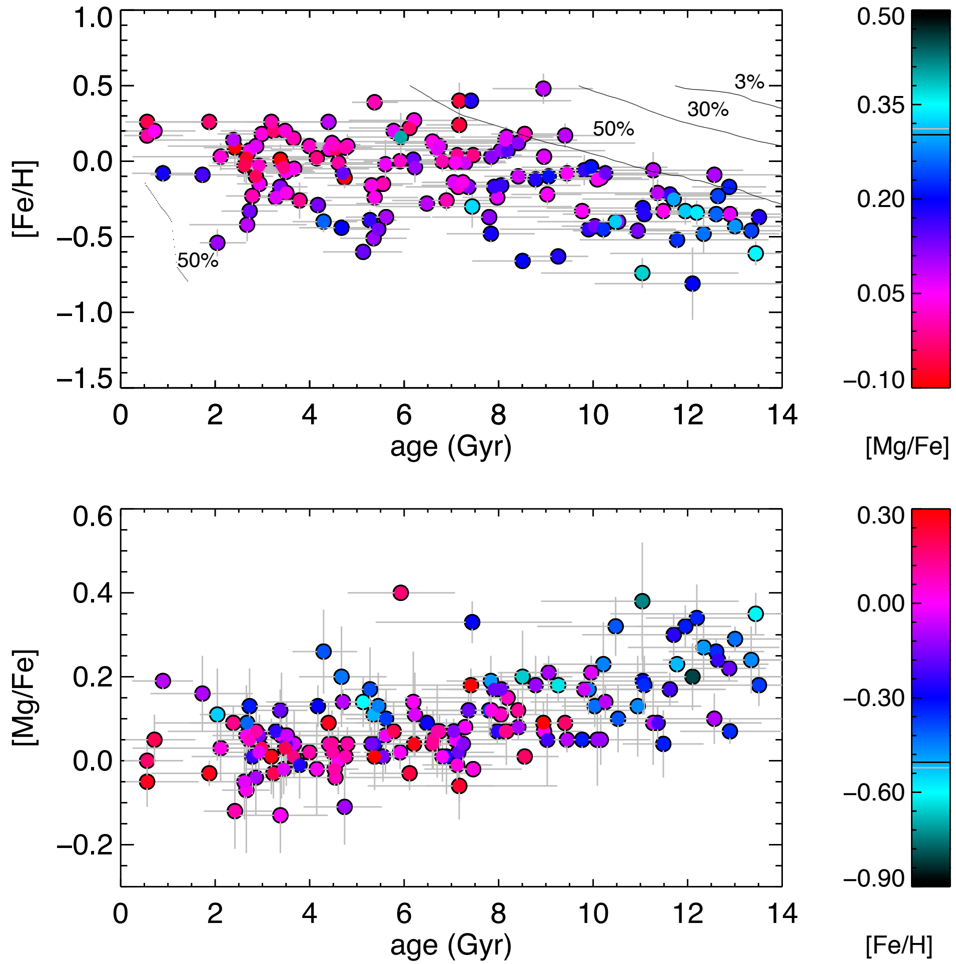
- extragalactic origin
- created through heating of preexisting thin disk with the help of mergers
- radial migration

i) stars born hot and heated by mergers at early times
ii) radial migration
(Minchev et al. 2013)

Age-Metallicity Relation (AMR)

- For a long time, the mere existence of any age metallicity relation has been a matter of great debate.
- The study by Twarog (1980) concluded that ages and metallicities of stars in the disk are uniquely correlated.
- Recent studies show a large scatter in metallicity at all ages, and conclude that the AMR is nearly flat.

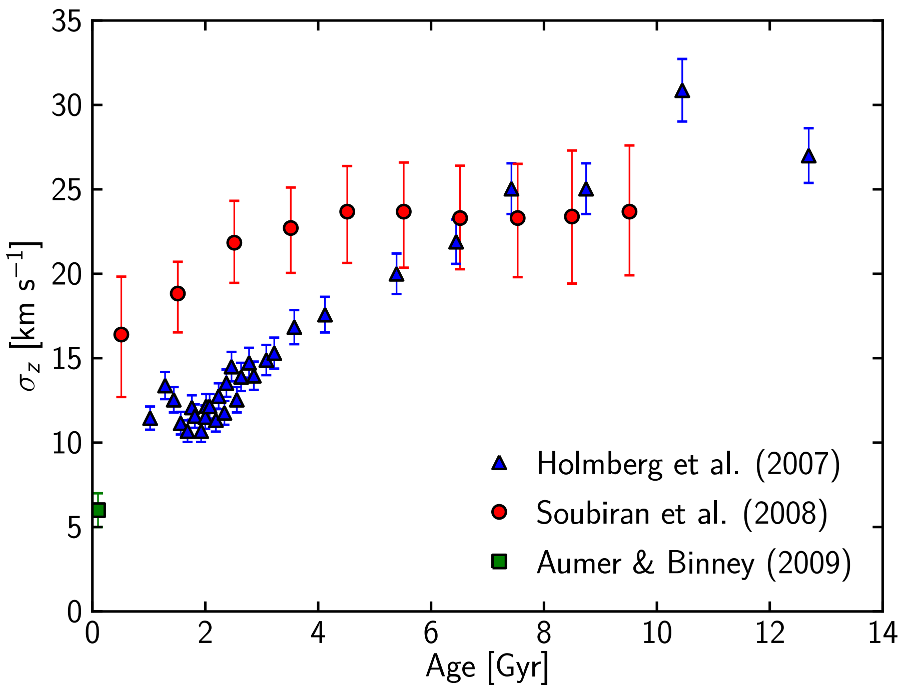
Age-Metallicity Relation (AMR)



Bergemann et al. 2014

Age-Velocity Relation (AVR)

In the solar neighbourhood, the vertical velocity dispersion (σ_z) of stars is correlated with their age.

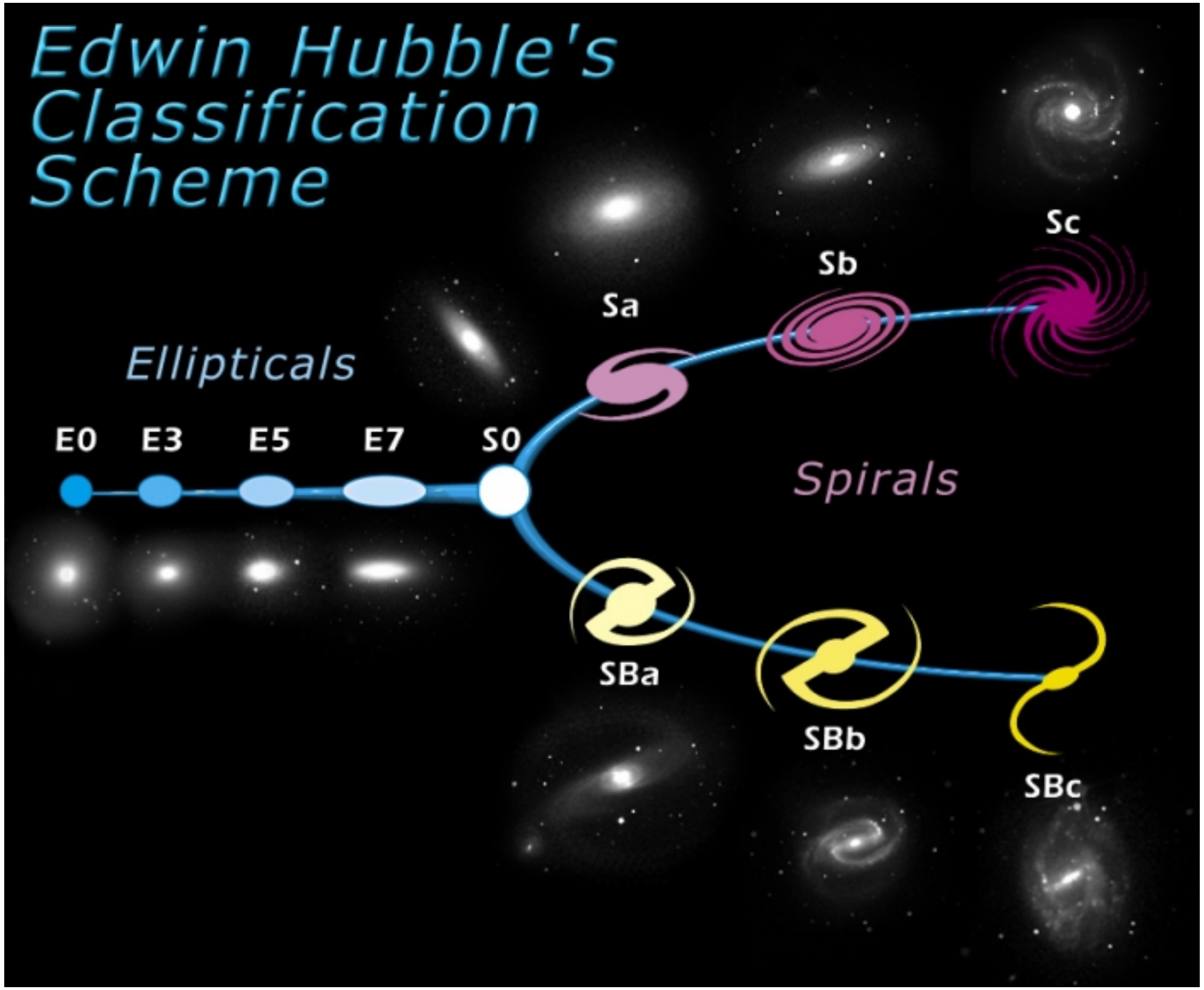


- AVR imprinted at birth?
- AVR due to heating from stars born kinematicaly hot?

- mergers do effect AVR

Martig et al. 2014

Different flavours of galaxies



Galactic archeology

Galactic Archeology

"the study of the formation and evolution of the Milky Way by reconstructing its past from its current constituents"

important parameters:

- position
- distance
- velocity
- chemical composition
- age / evolutionary phase

Gaia!

Galactic Archeology

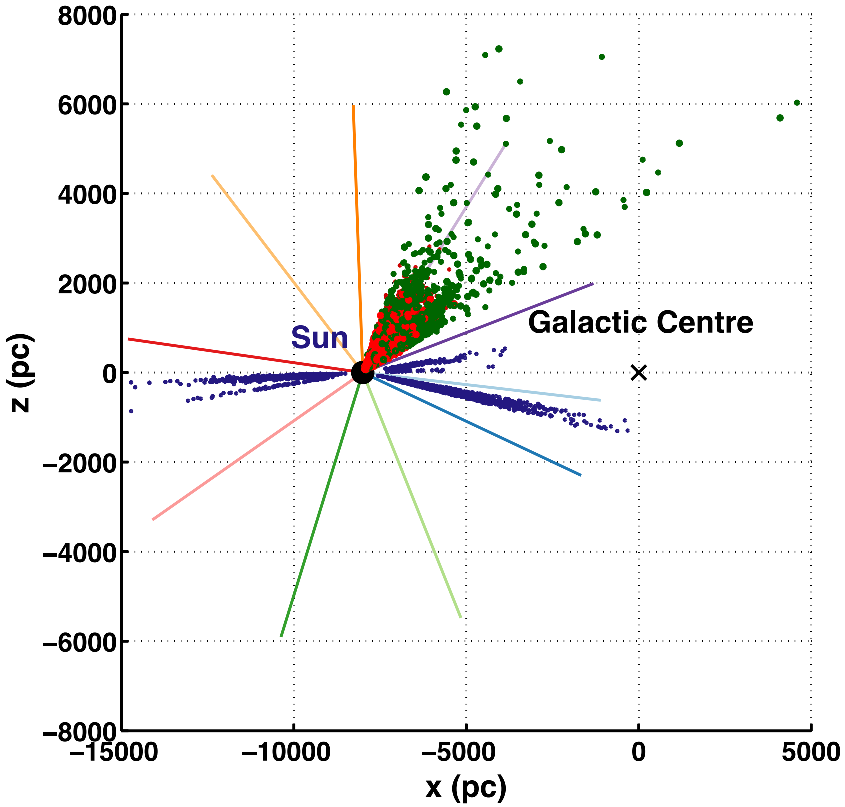
"the study of the formation and evolution of the Milky Way by reconstructing its past from its current constituents"

important parameters:

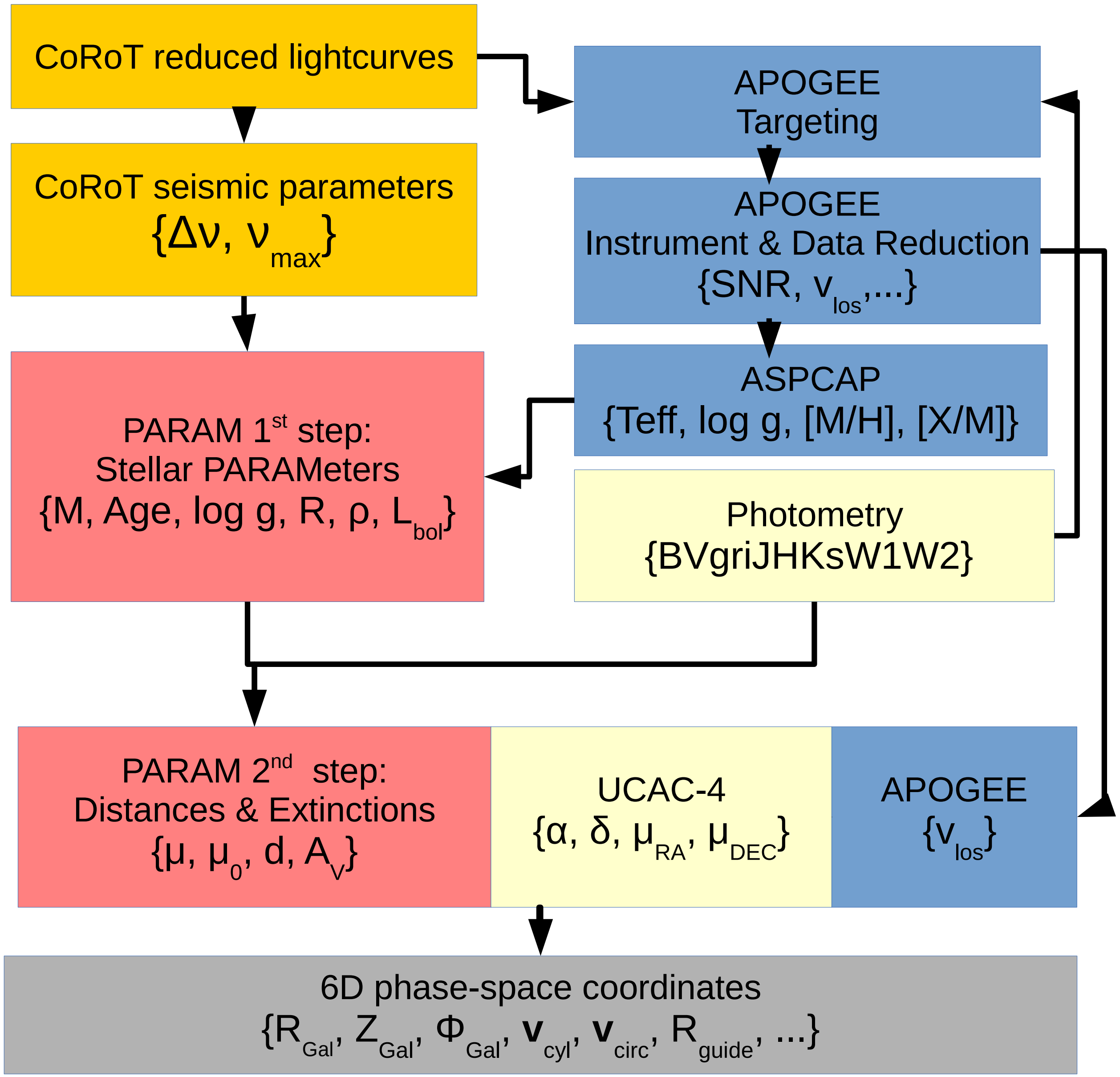
- position
- distance
- velocity
- chemical composition ← RG asteroseismology
- age / evolutionary phase ← RG asteroseismology

Why red giants?

- many
- intrinsically luminous
- present in all parts of MW
- “direct” probes of M and R through scaling relations

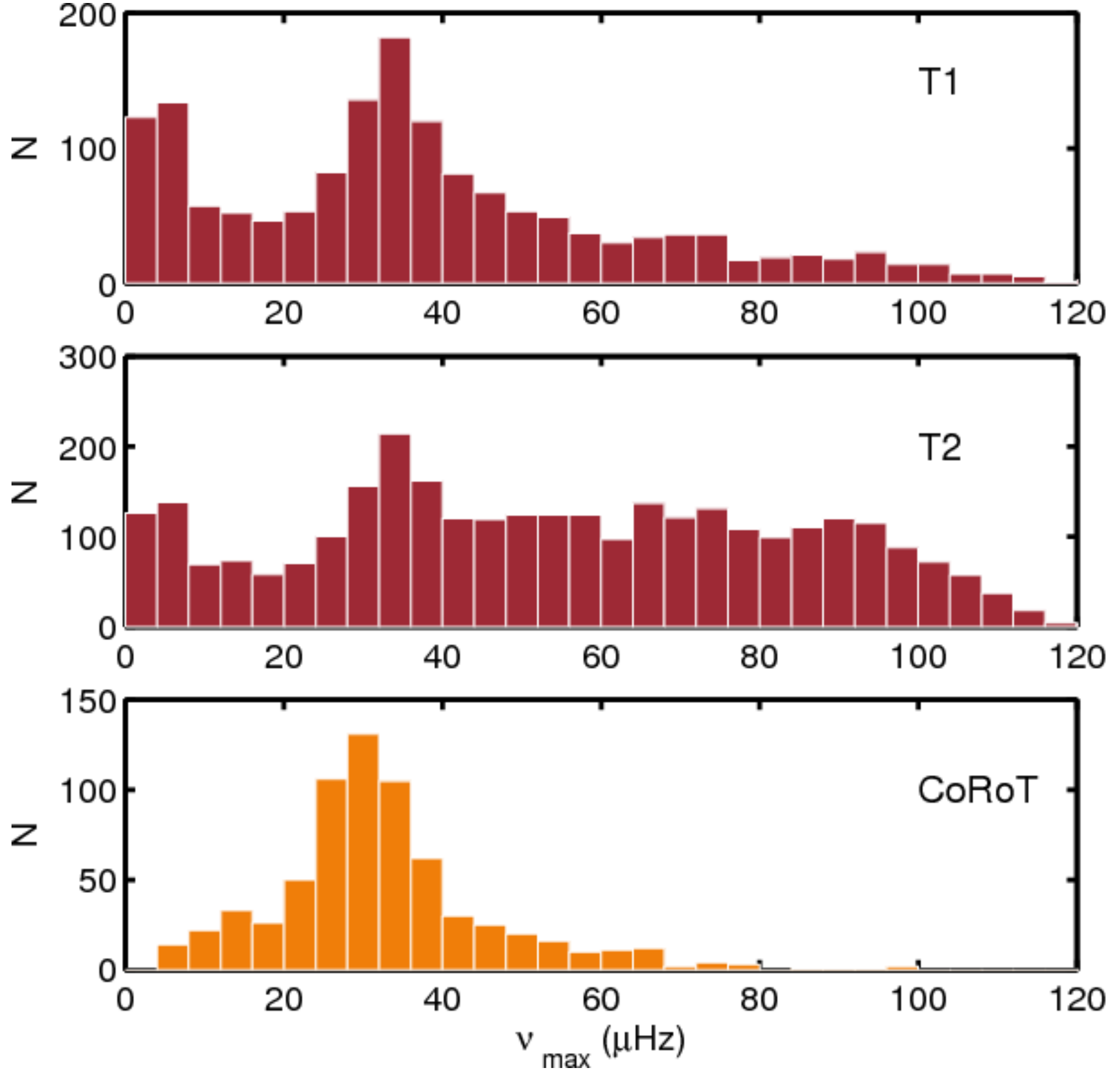


Mathur et al. 2016



Anders et al. 2016

Ensemble / population studies



Simulated population (Miglio et al. 2009)

T1: no recent star burst

T2: recent star burst

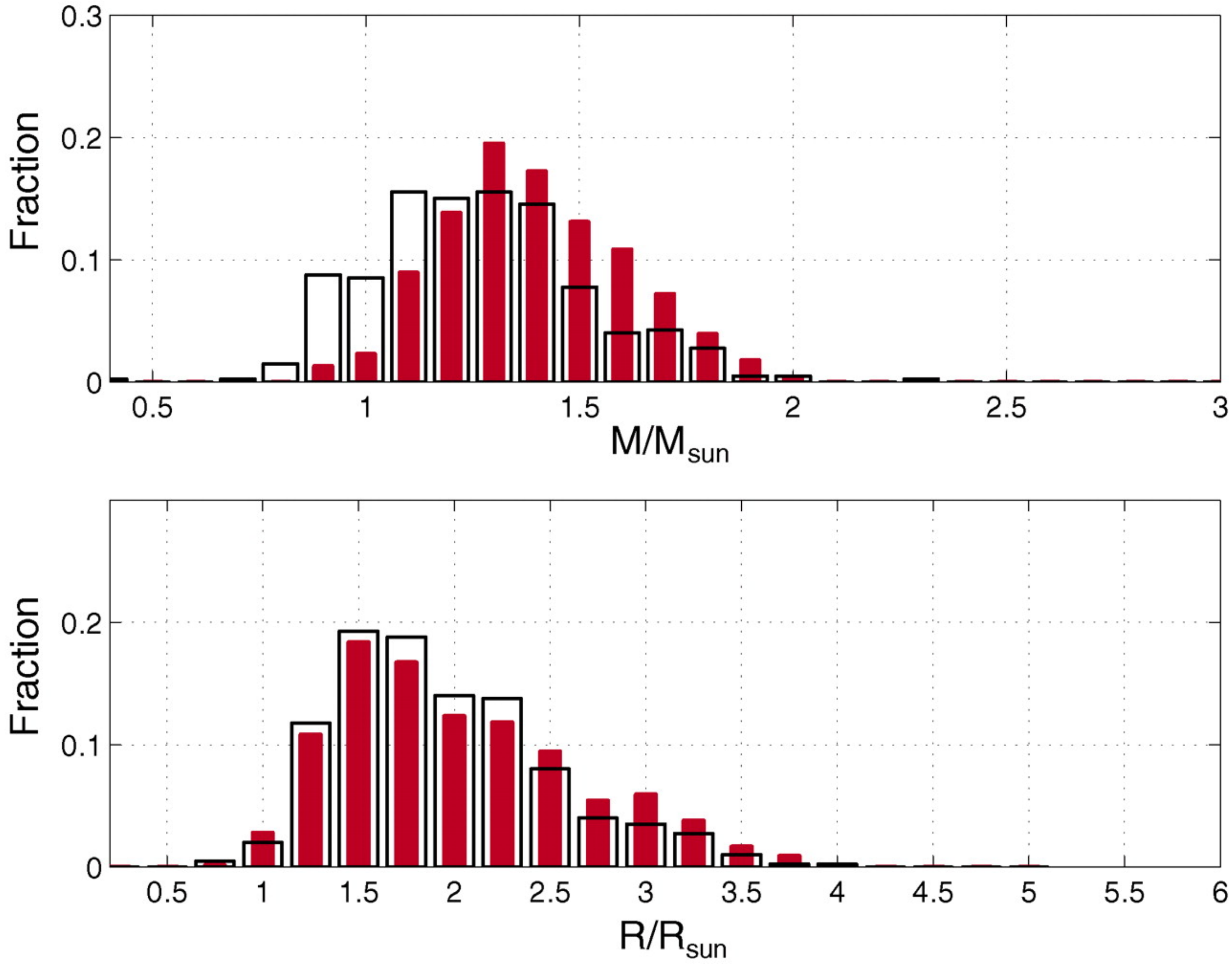
Observations (Hekker et al. 2009)

Note of caution: selection effects / observational biases

Selection effects: which fraction of stars are chosen to be observed out of the total number of stars available

Observational biases: to what parameter space the observations are limited due to limitations of instrumentation / observing strategy

Ensemble / population studies

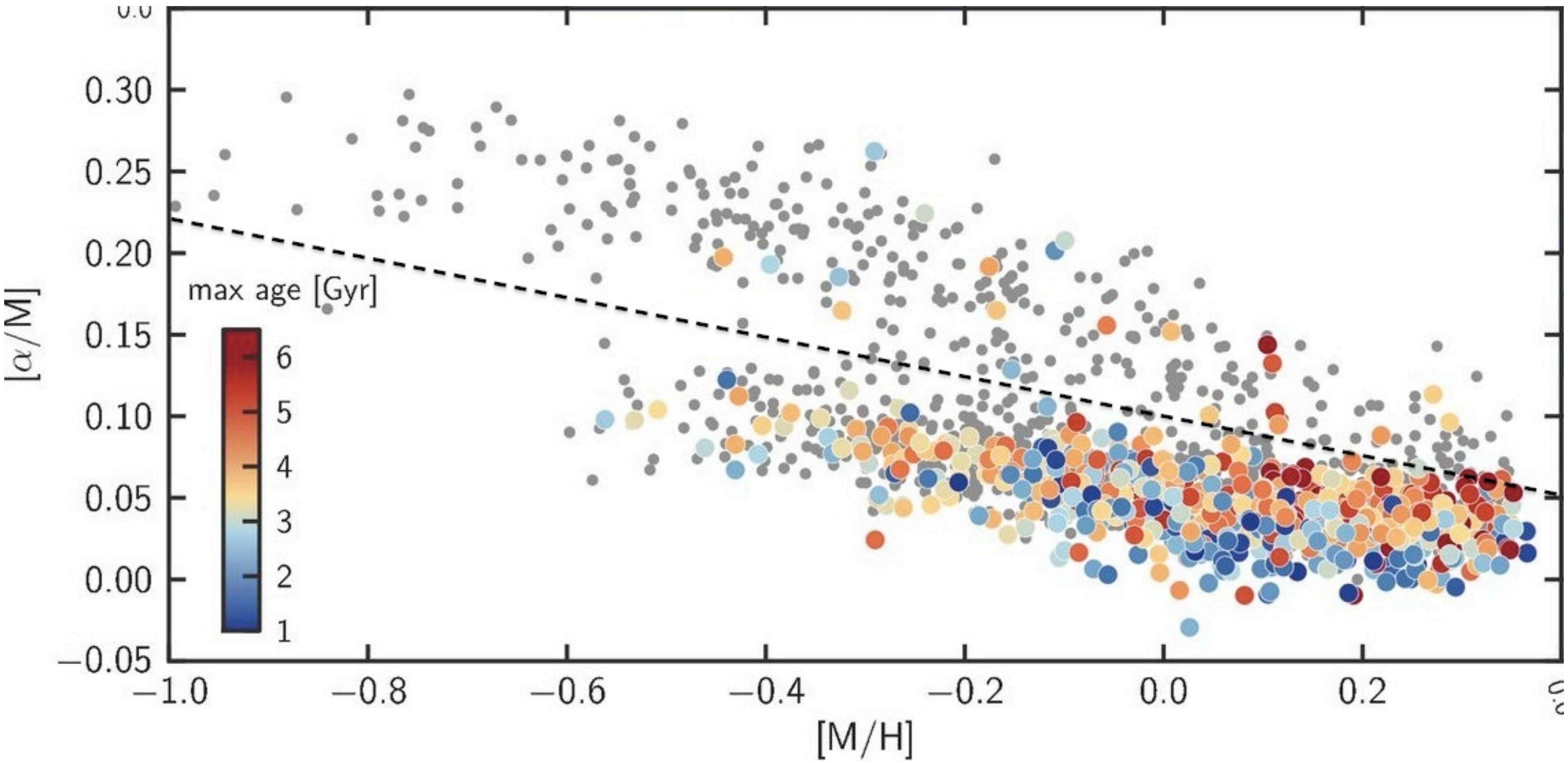


Observations

Population synthesis model

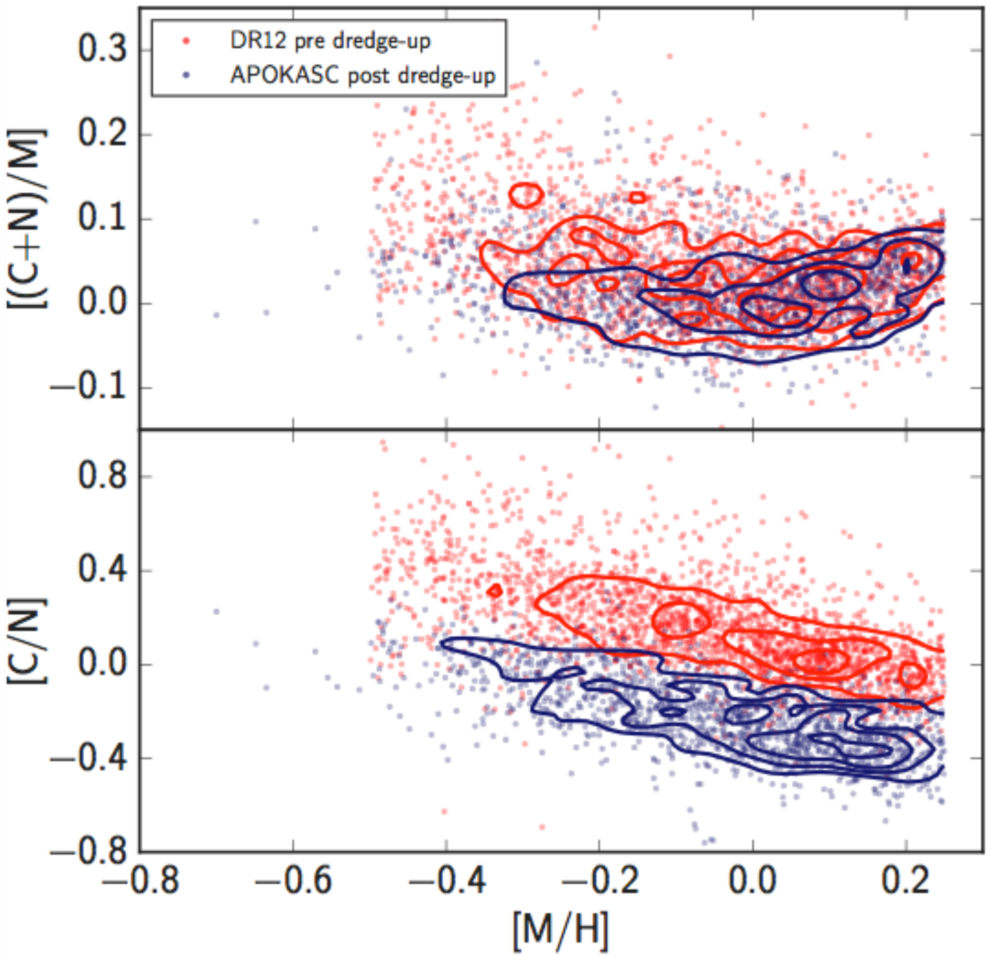
Chaplin et al. 2011

α-rich young stars



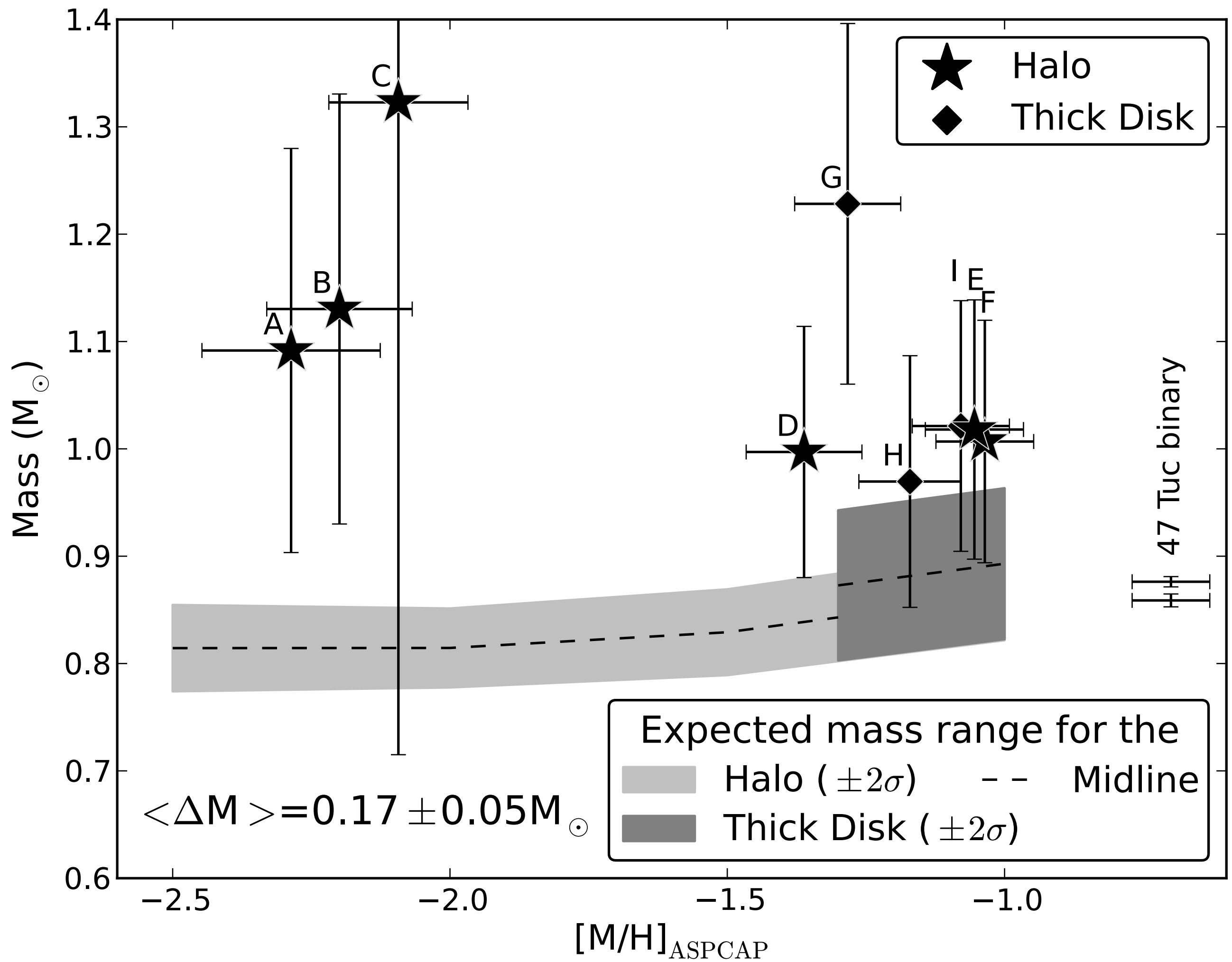
adapted from Martig et al. 2015

Chemical signature of first dredge-up



Martig et al. 2015

Halo stars



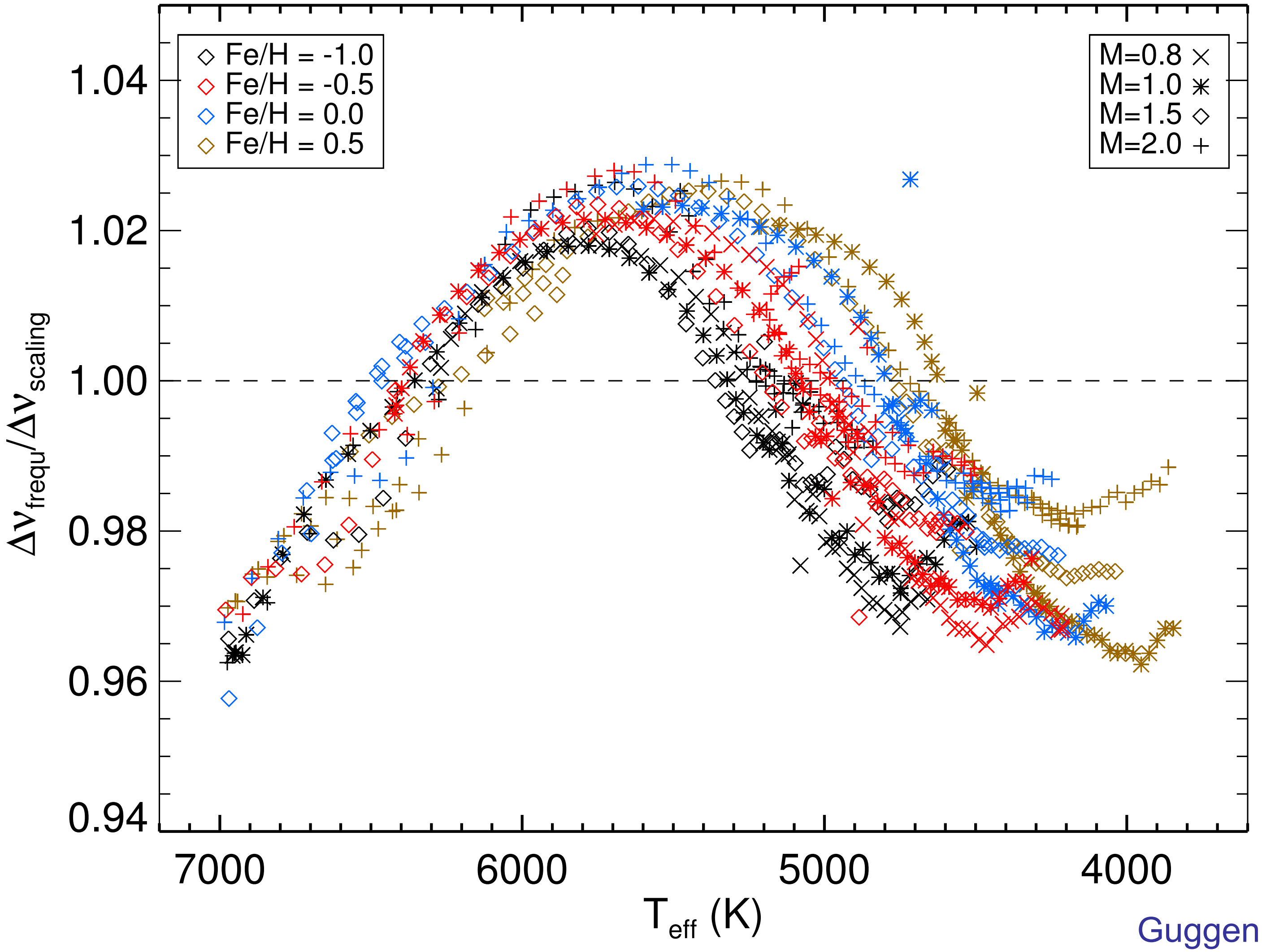
Epstein et al. 2014

Scaling relations

$$\Delta\nu \propto \sqrt{\frac{M}{R^3}} \propto \sqrt{\bar{\rho}}$$

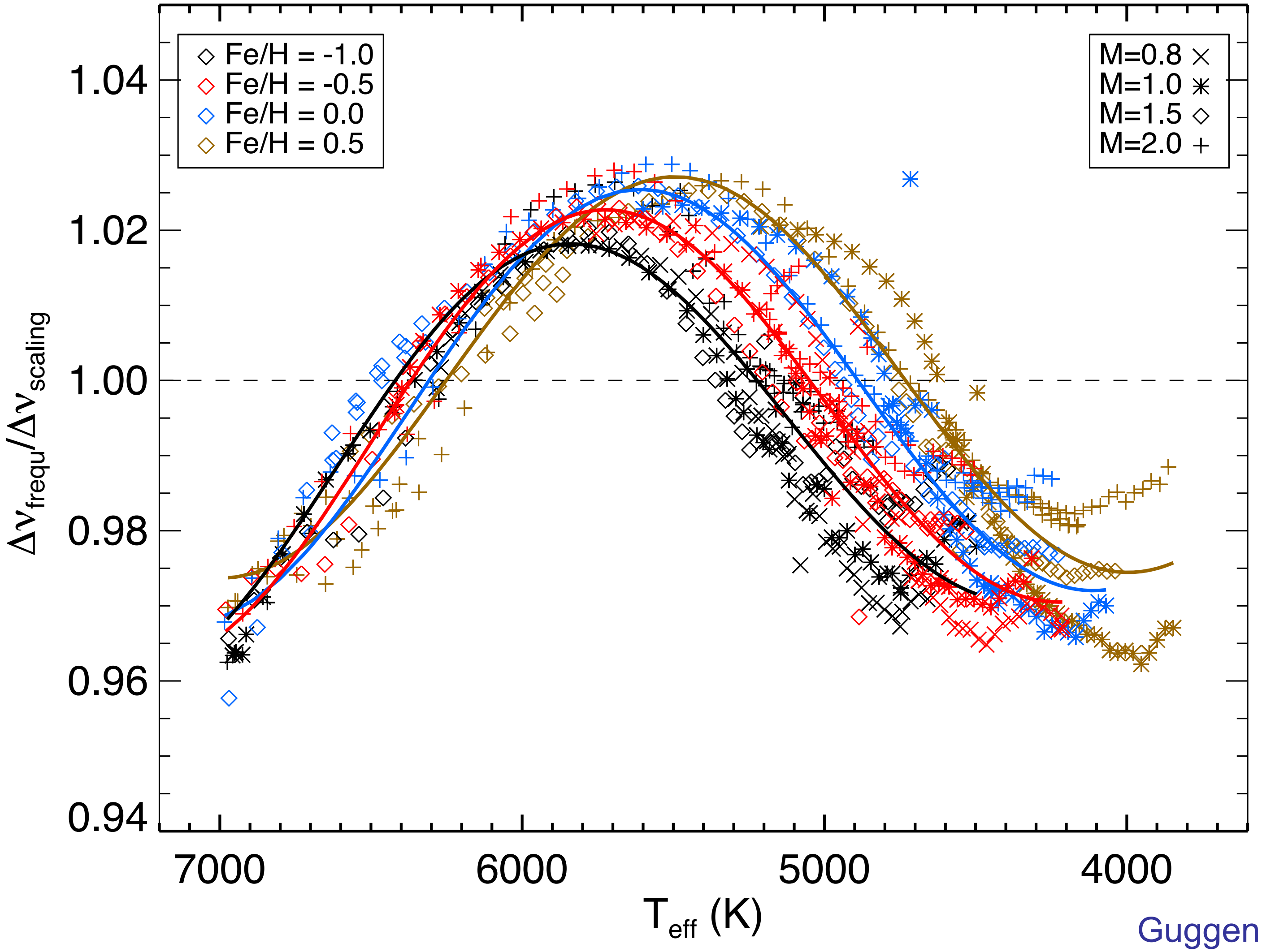
$$\nu_{\max} \propto \frac{g}{\sqrt{T_{eff}}} \propto \frac{M}{R^2\sqrt{T_{eff}}}$$

Reference of scaling relation



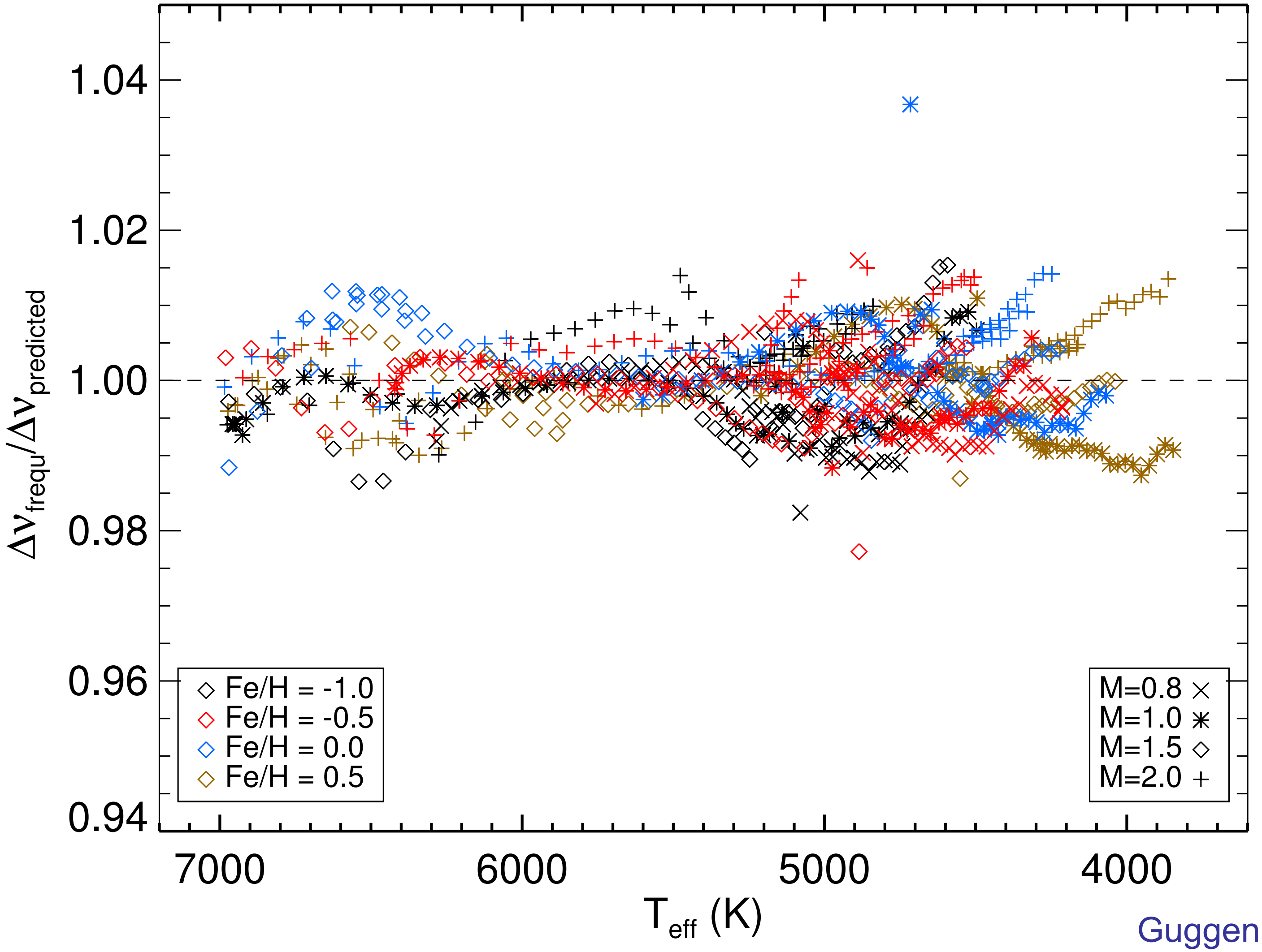
Guggenberger et al. 2016

Reference of scaling relation



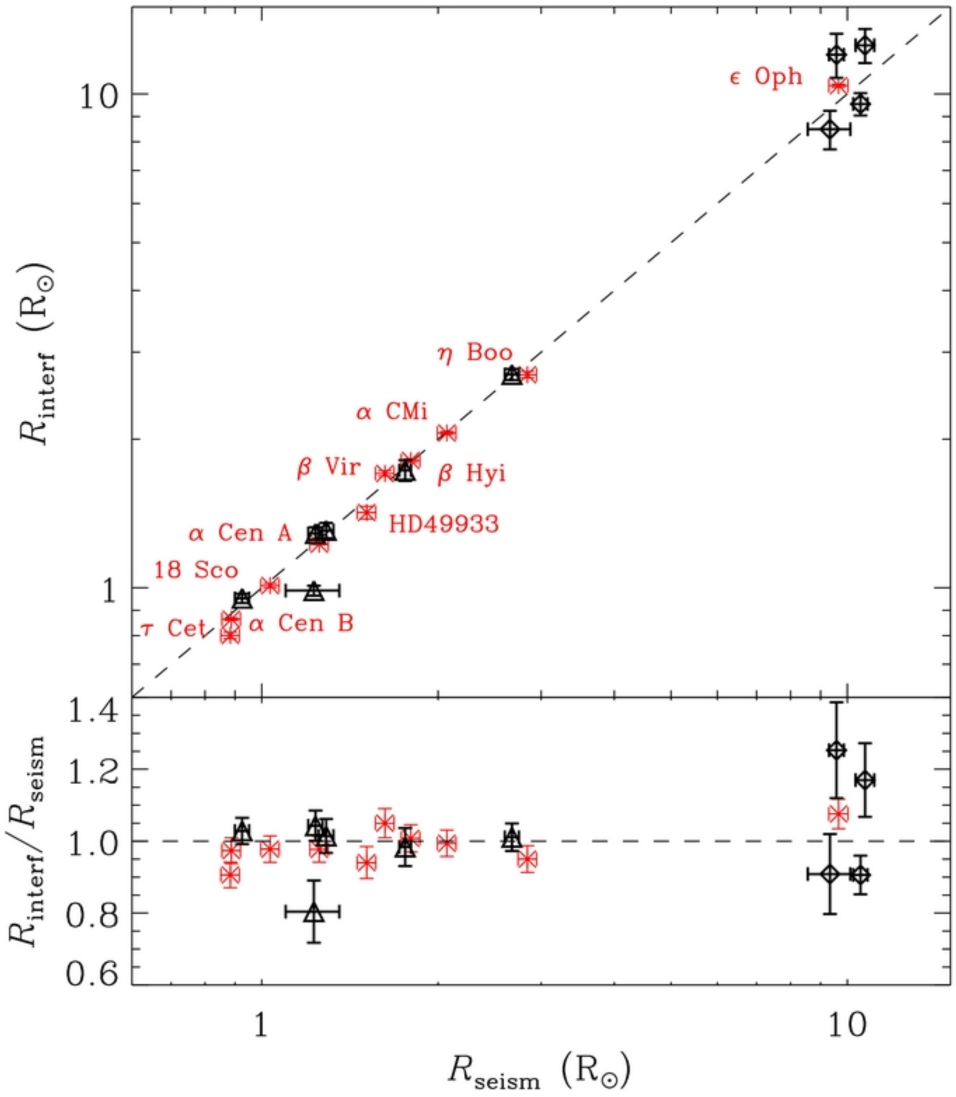
Guggenberger et al. 2016

Reference of scaling relation



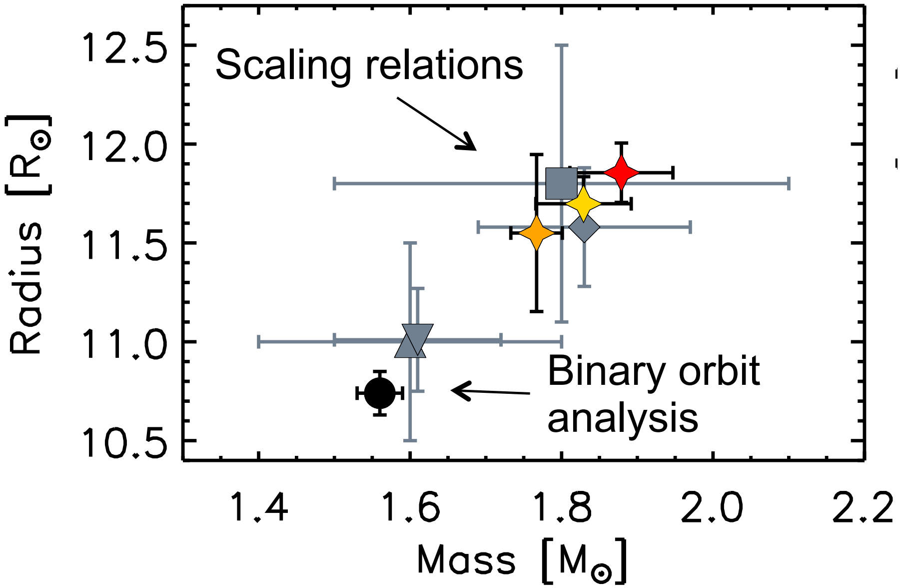
Guggenberger et al. 2016

Testing scaling relations



Huber et al. 2012

Testing scaling relations

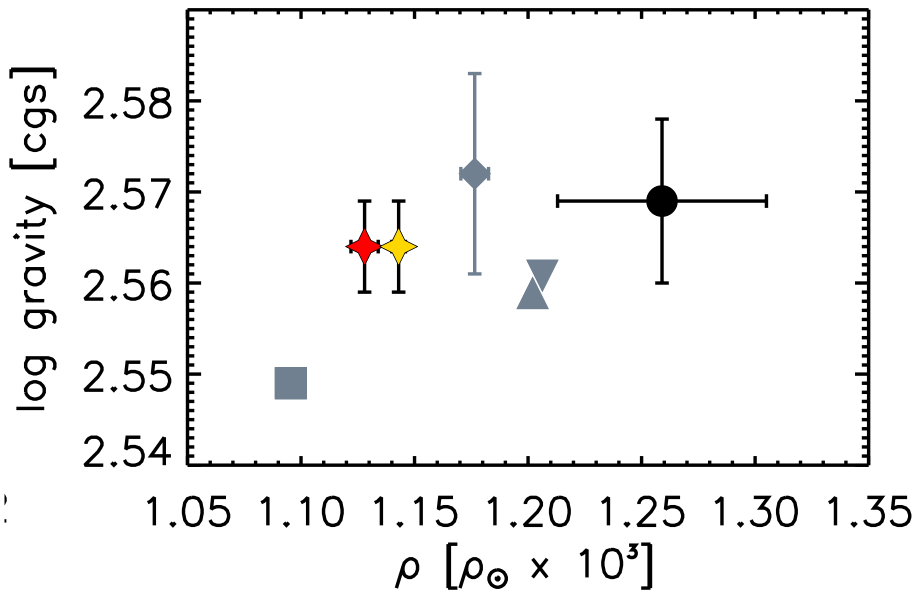


orbital solution

scaling relation + $\Delta\nu_{\odot}$

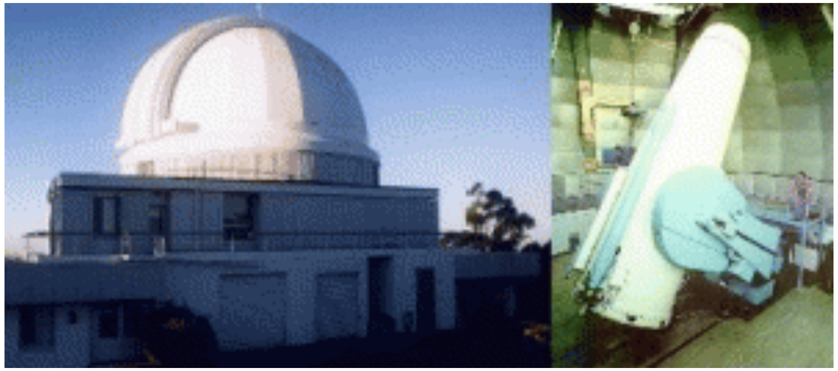
scaling relation + $\Delta\nu_{ref}$

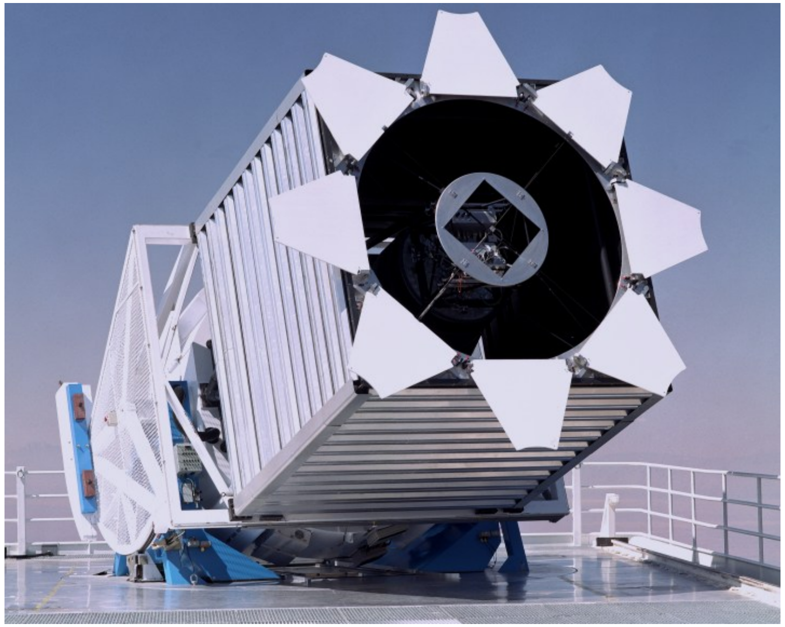
grid-based modeling

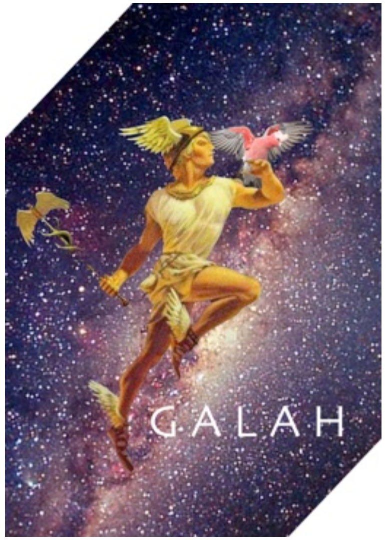


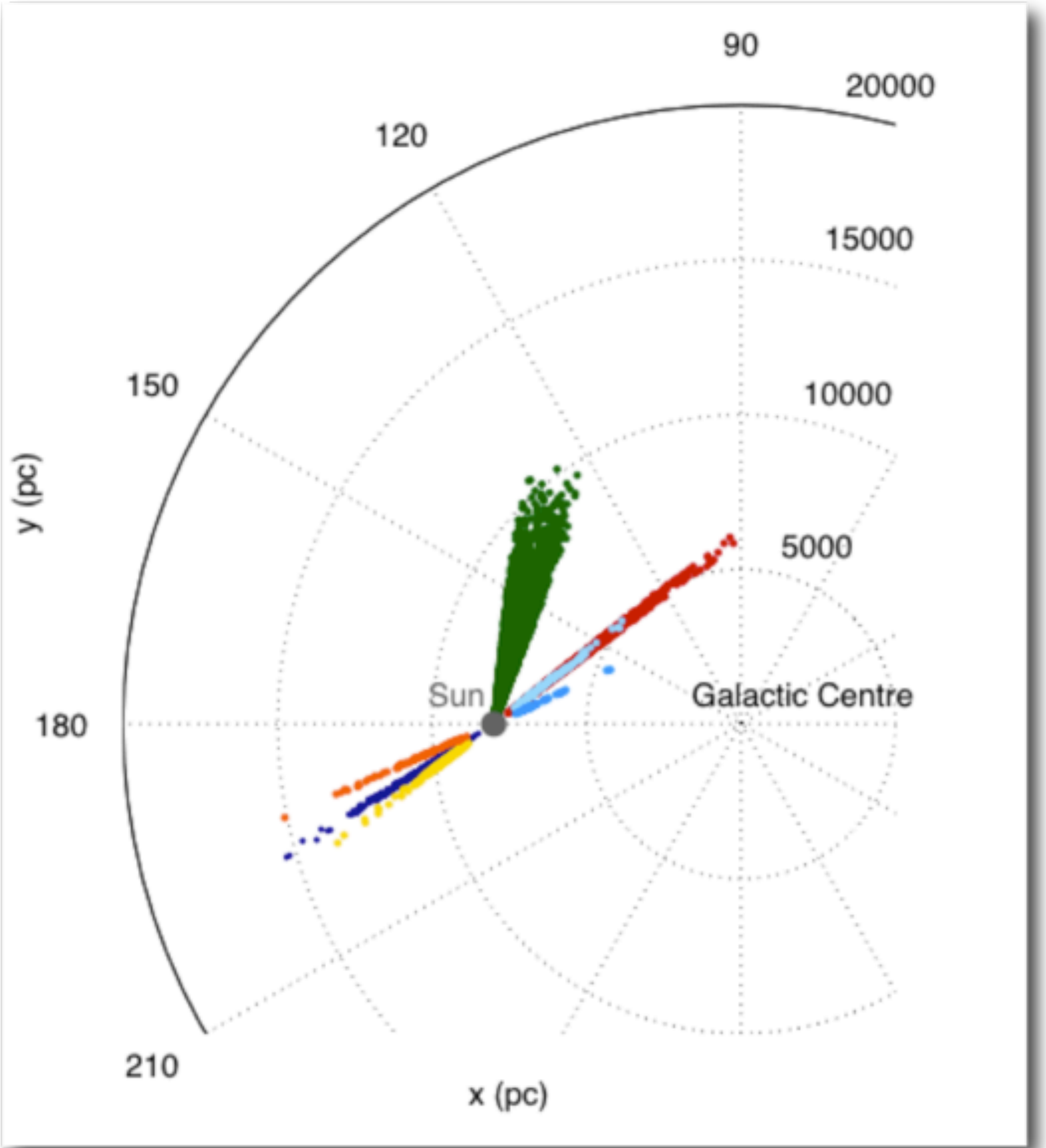
Themeßl et al. in prep.

Spectroscopic surveys

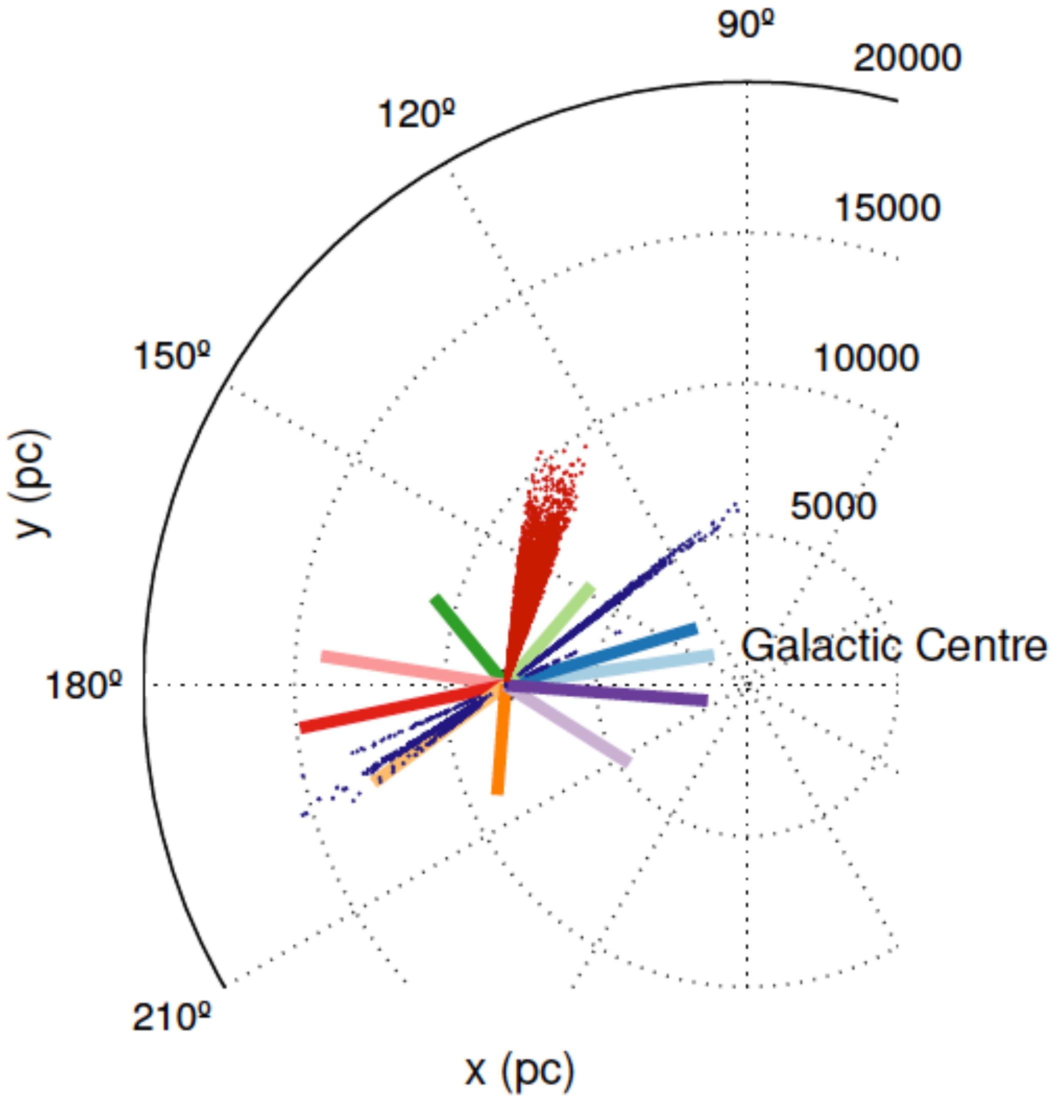






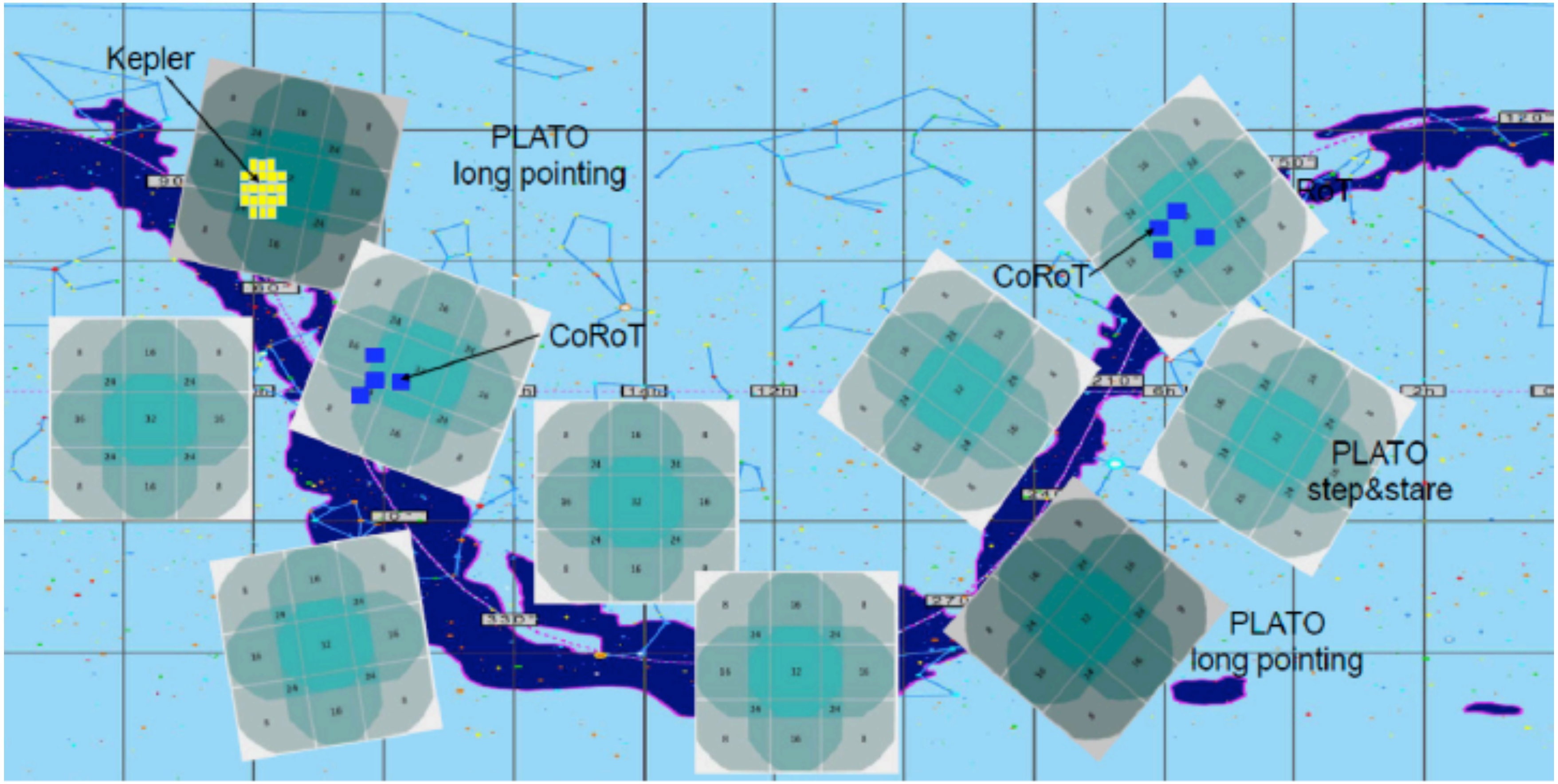


Miglio et al. 2013



Miglio et al. 2014

Plato fields



Question?

What would you want to investigate with all these facilities at hand?