

Stellar evolution

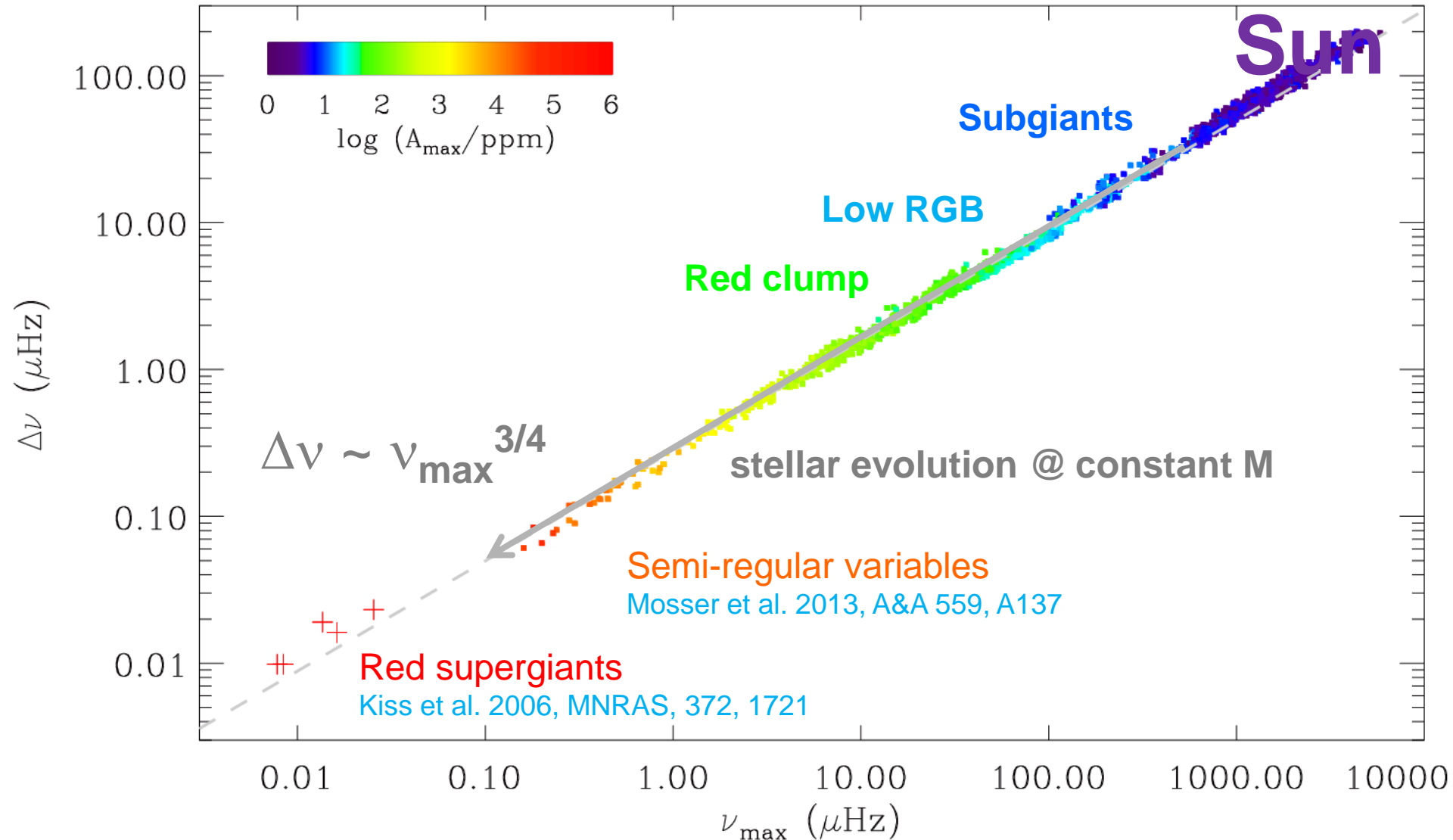


Benoît Mosser

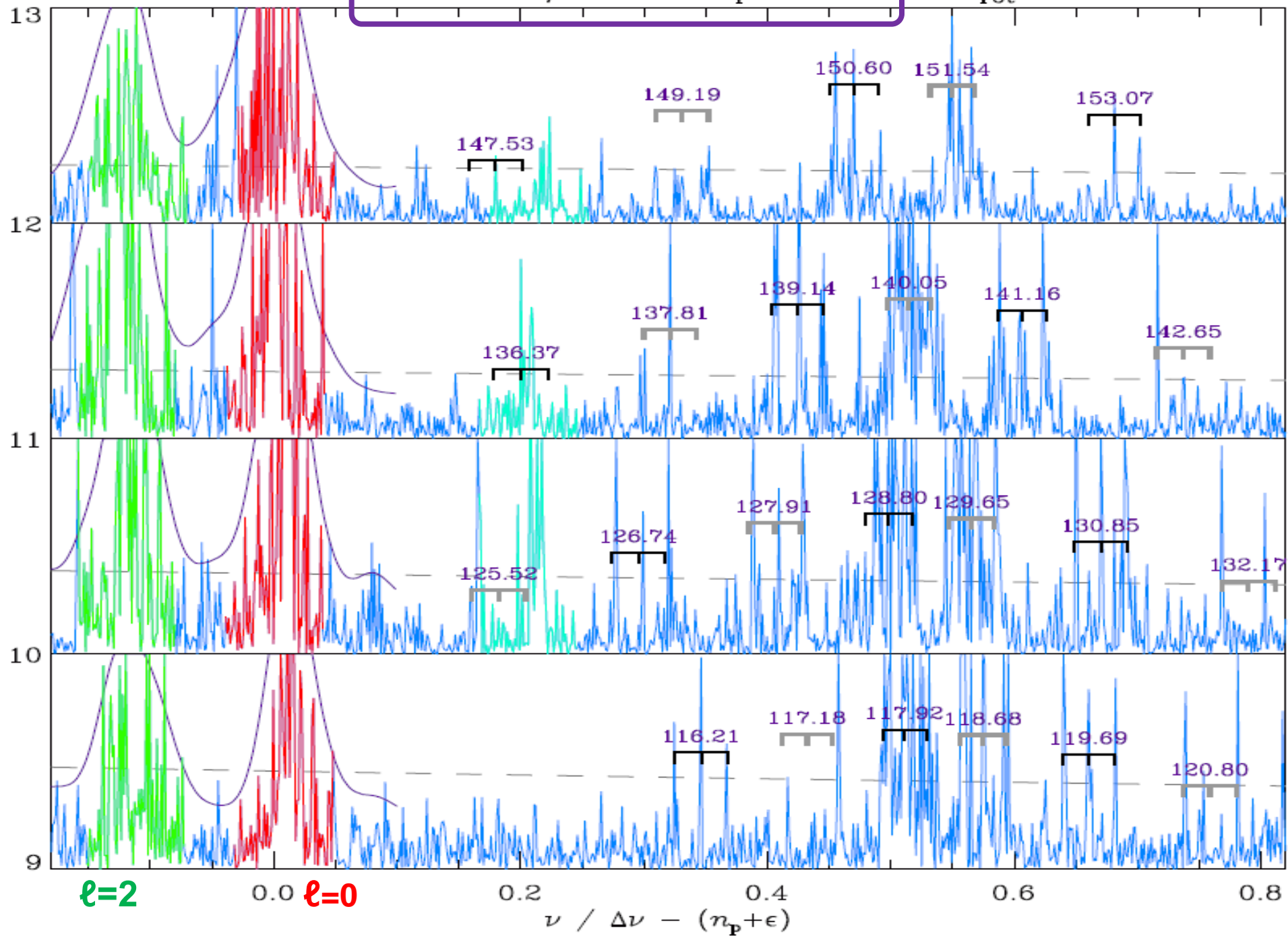
Observatoire de Paris

LESIA

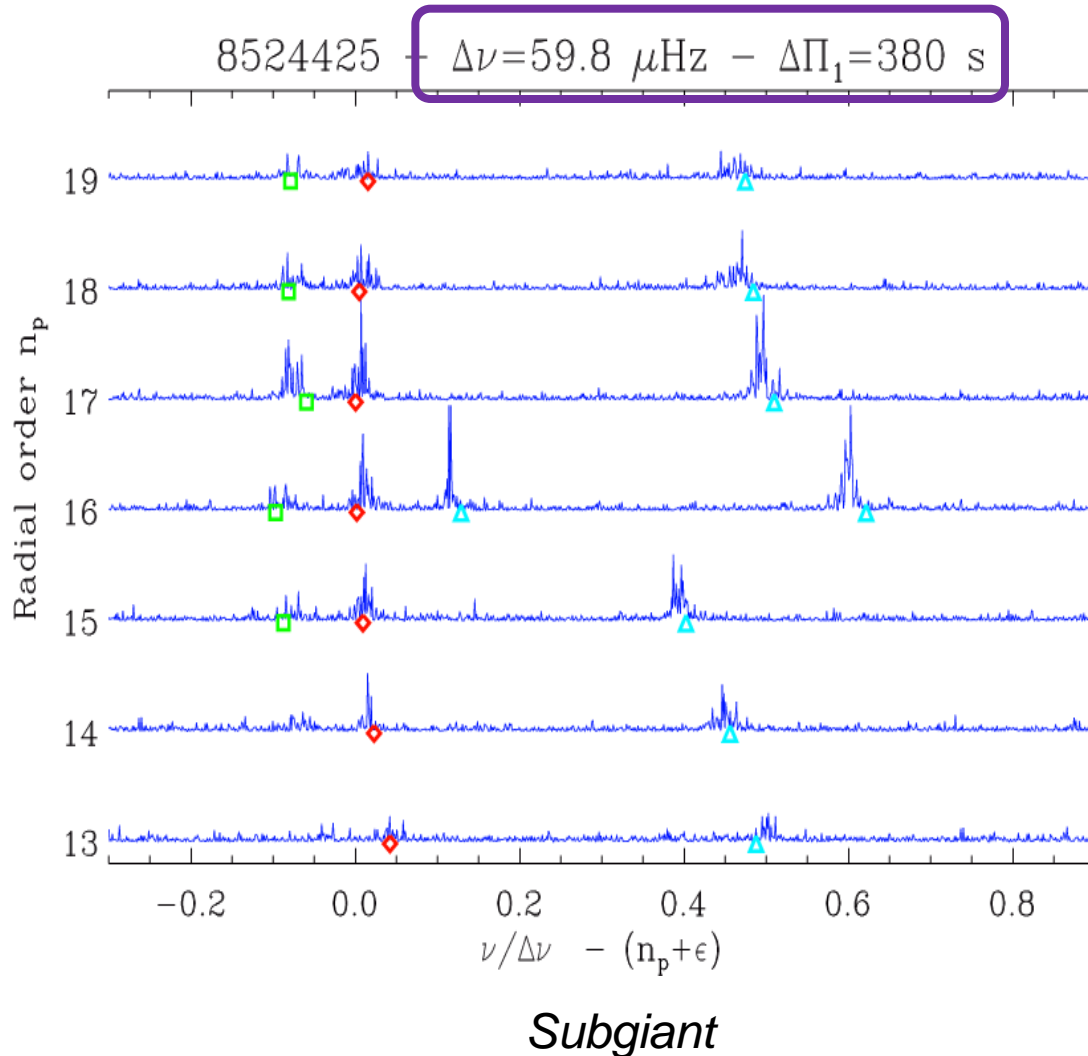
Stellar evolution



6144777 - $\Delta\nu = 11.03\mu\text{Hz}$ - $\Delta\Pi_1 = 79.25\text{s}$ - $\nu_{\text{rot}} = 242\text{nHz}$



Mixed modes – subgiant



Mixed modes probe the inner radiative region
→ Direct view into the stellar core

Identification of the mixed-mode pattern
→ Measurement of $\Delta\Pi_1$

Mosser et al. 2012
A&A 540, A143
A&A 548, A10

Benomar et al. 2012
ApJ 743, L143
A&A 548, A10

Data (Kepler) & method (CoRoT)



Aim = constructing the $\Delta\Pi_1 - \Delta\nu$ diagram (\approx Bedding et al. 2011)

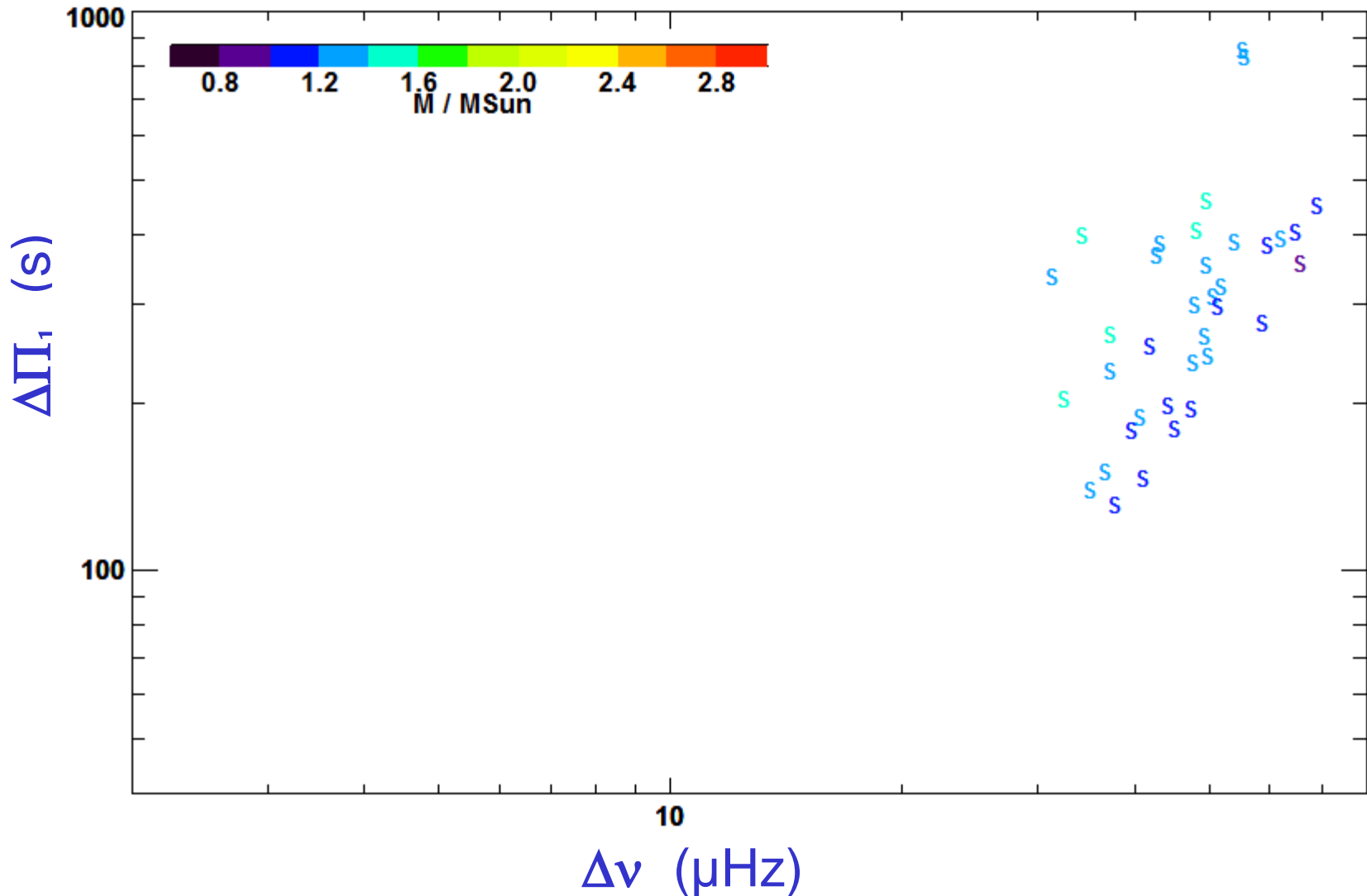
$\Delta\nu$ properties of the envelope

$\Delta\Pi_1$ properties of the core

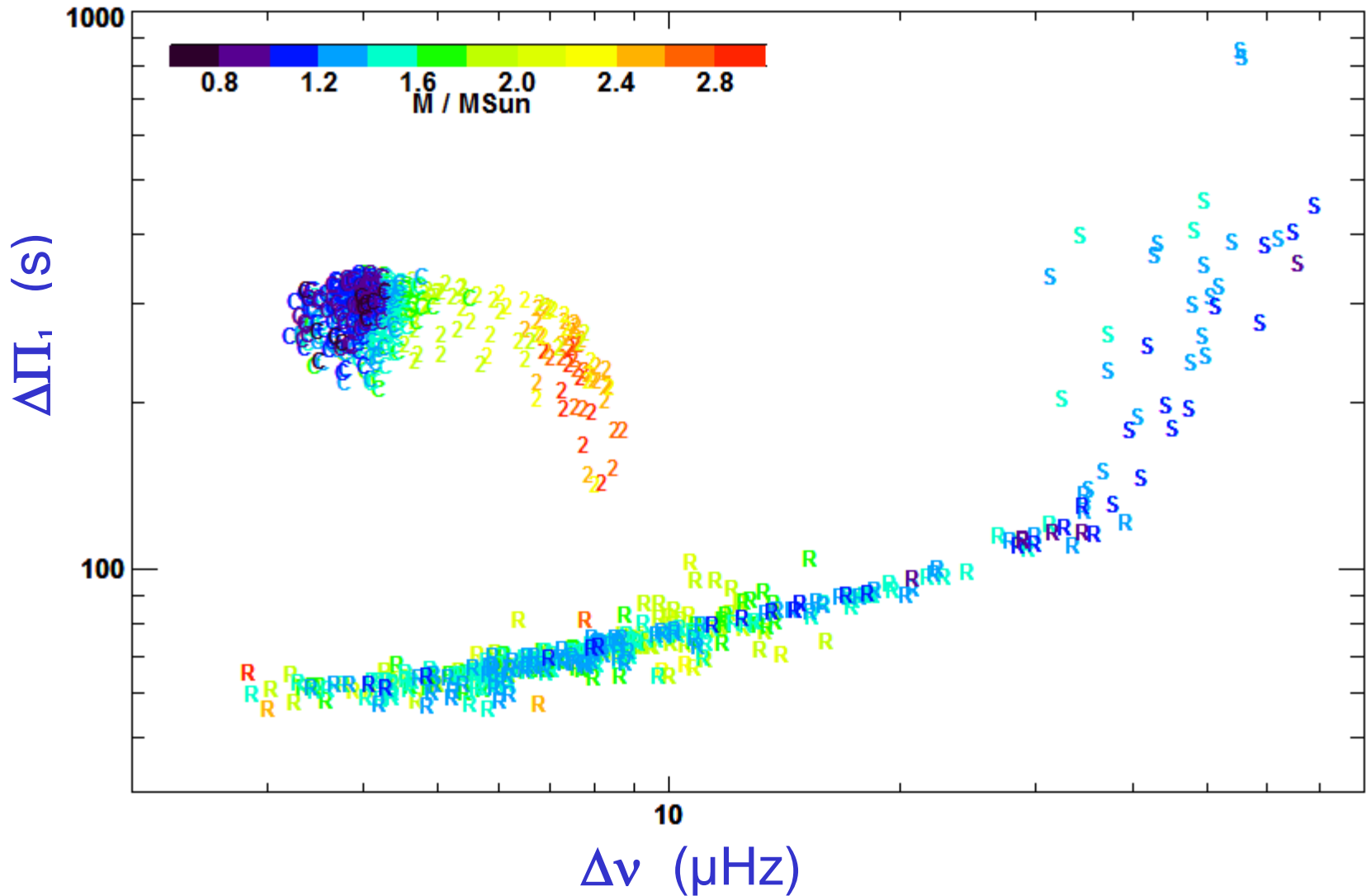
Kepler public data; 13 000 red giants showing solar-like oscillations (Stello et al. 2013)

Operations	Methods	Observables	References
Radial oscillation pattern	Second-order asymptotic expansion; glitch-free measurement	$\Delta\nu$	Mosser et al. (2011) Mosser et al. (2013) Vrard et al. (2014) + poster
Mixed mode pattern	Asymptotic mixed mode expansion	$\Delta\Pi_1$	Unno et al. (1989) Mosser et al. (2012)
Rotational splitting	Averaged kernels	$\delta\nu_{\text{rot}}$	Mosser et al. (2012) Goupil et al. (2013)
Stellar masses, radii	Scaling relations calibrated on 80 stars	M, R	Mosser et al. (2013)

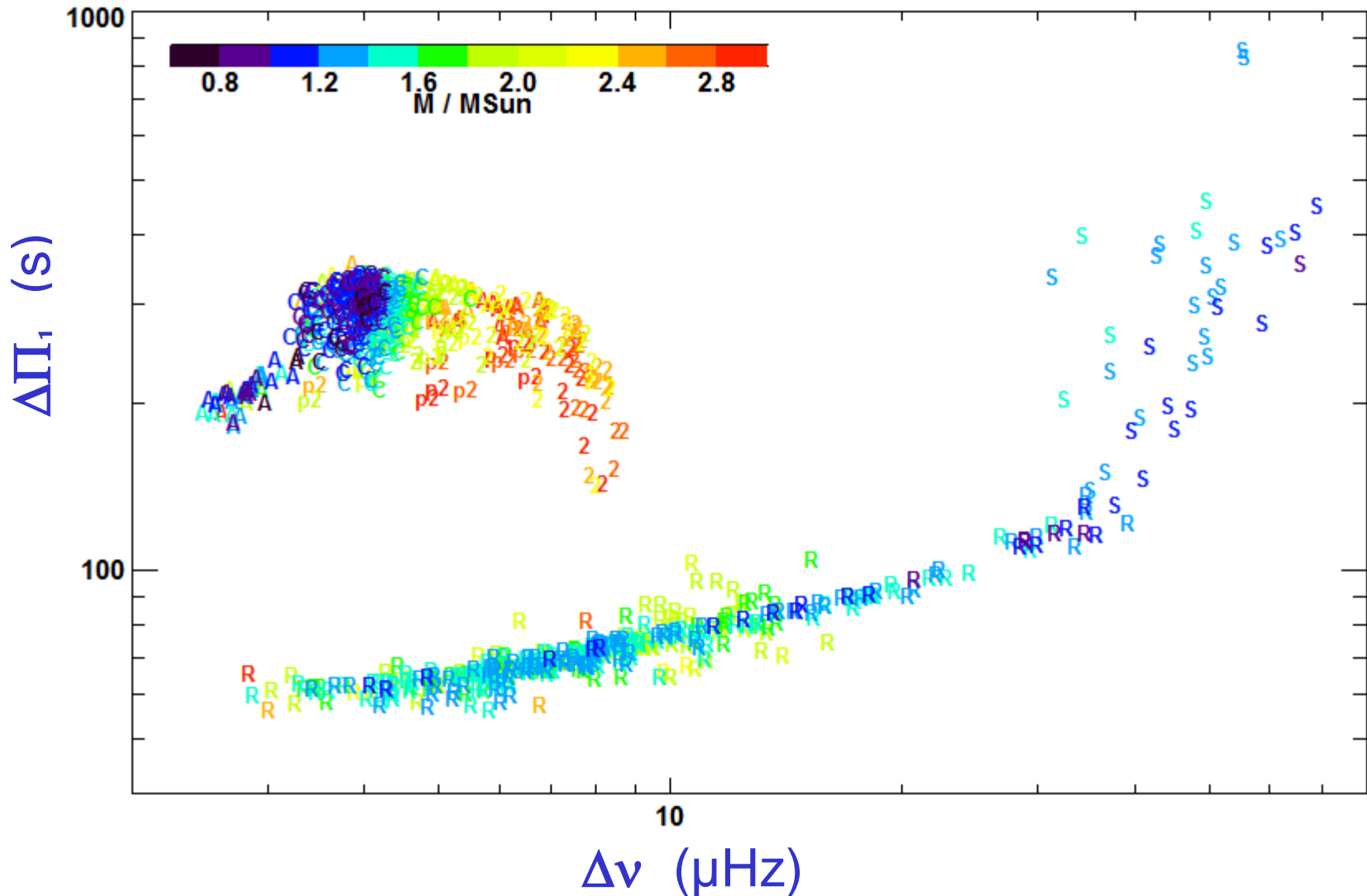
$\Delta\Pi_1 - \Delta\nu$ diagram



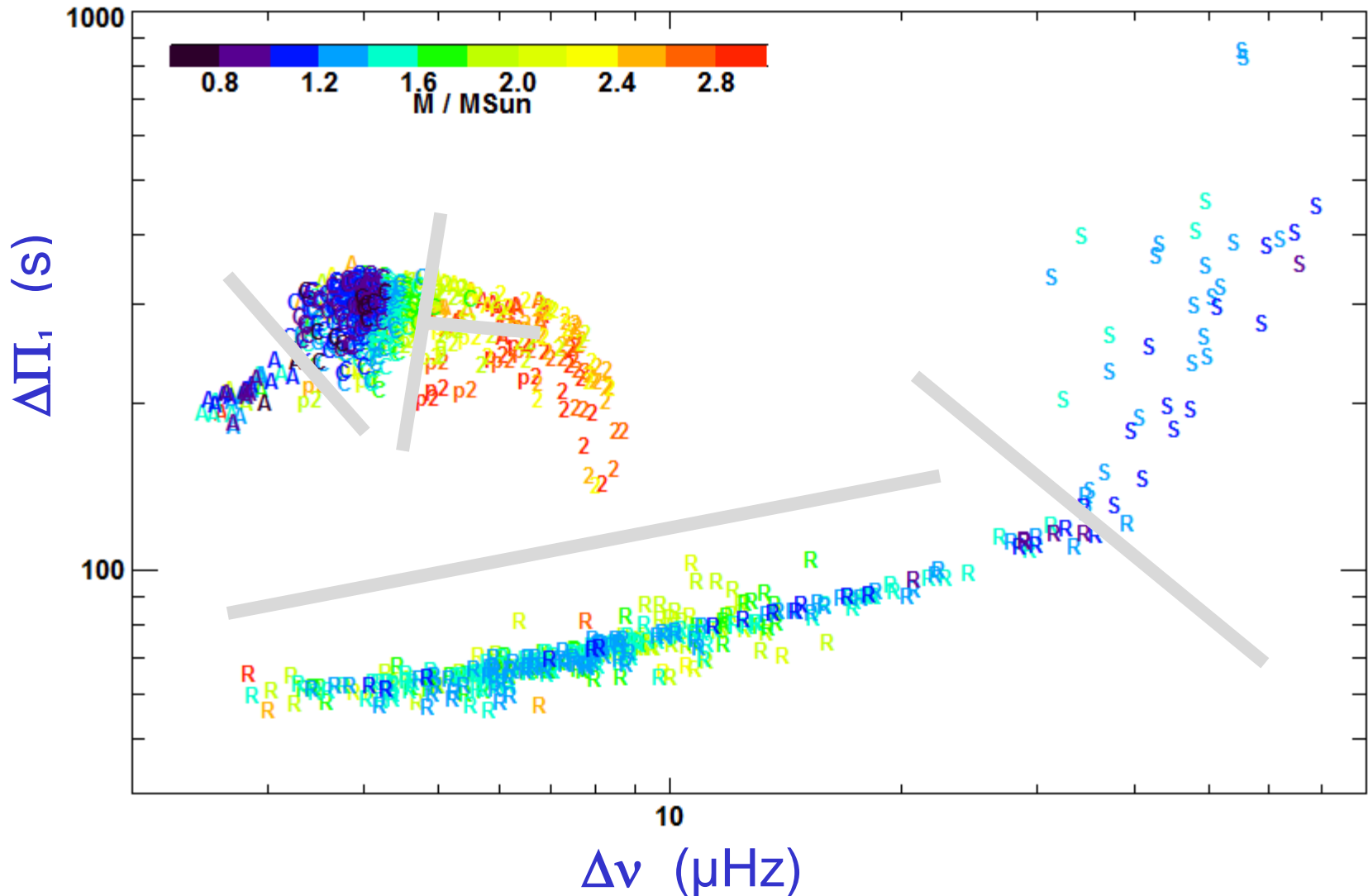
$\Delta\Pi_1 - \Delta\nu$ diagram



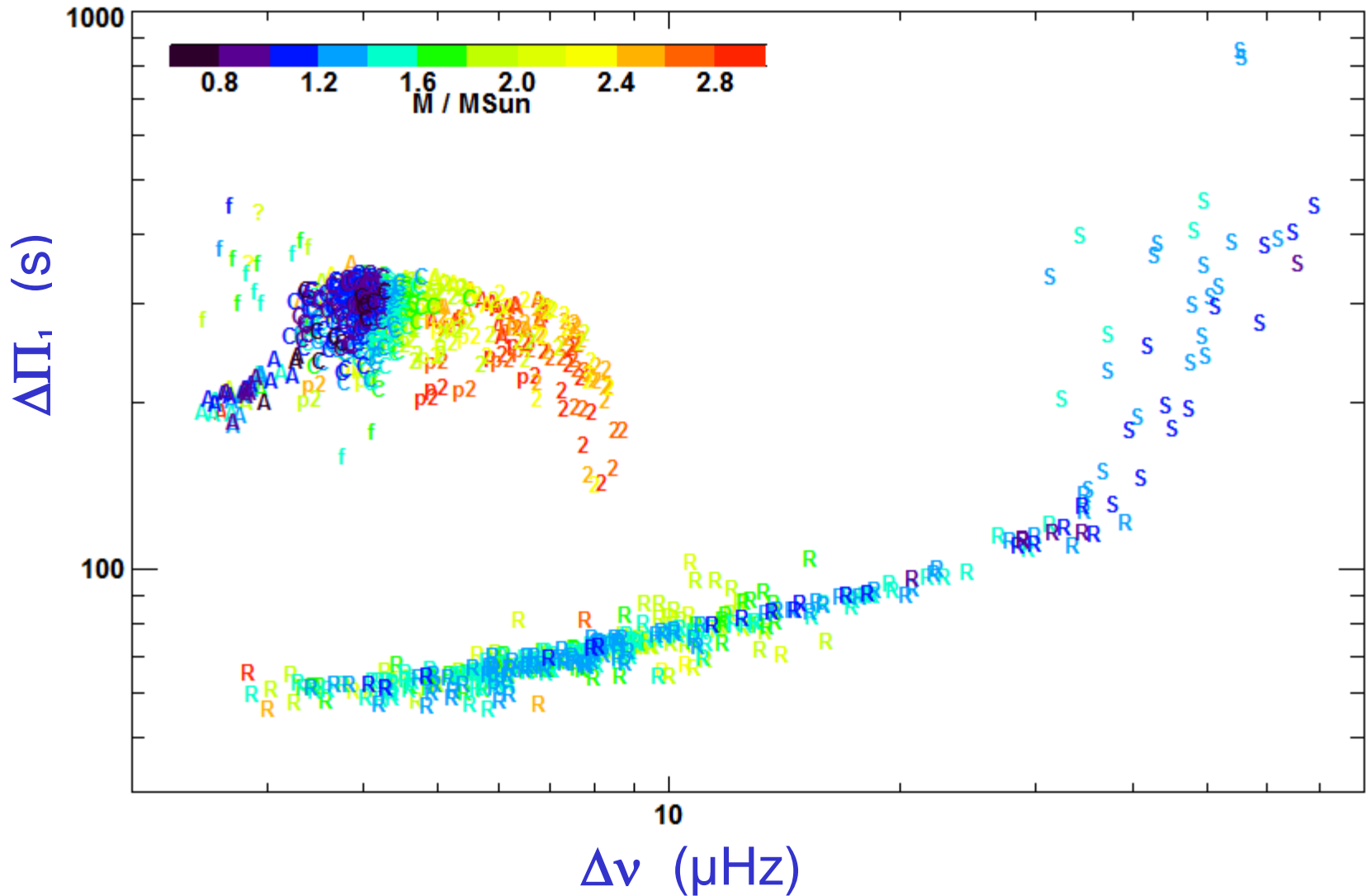
$\Delta\Pi_1 - \Delta\nu$ diagram

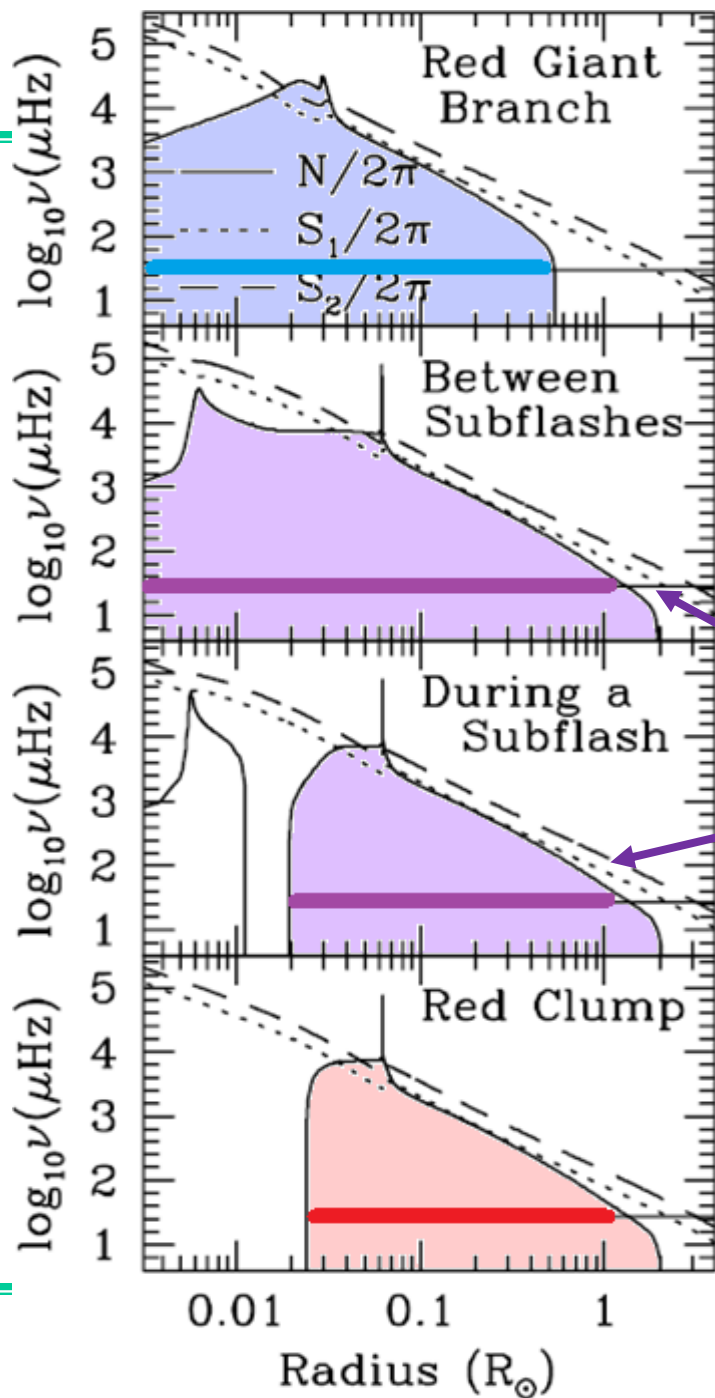


Seismic markers of stellar evolution



Helium flash





Helium flash

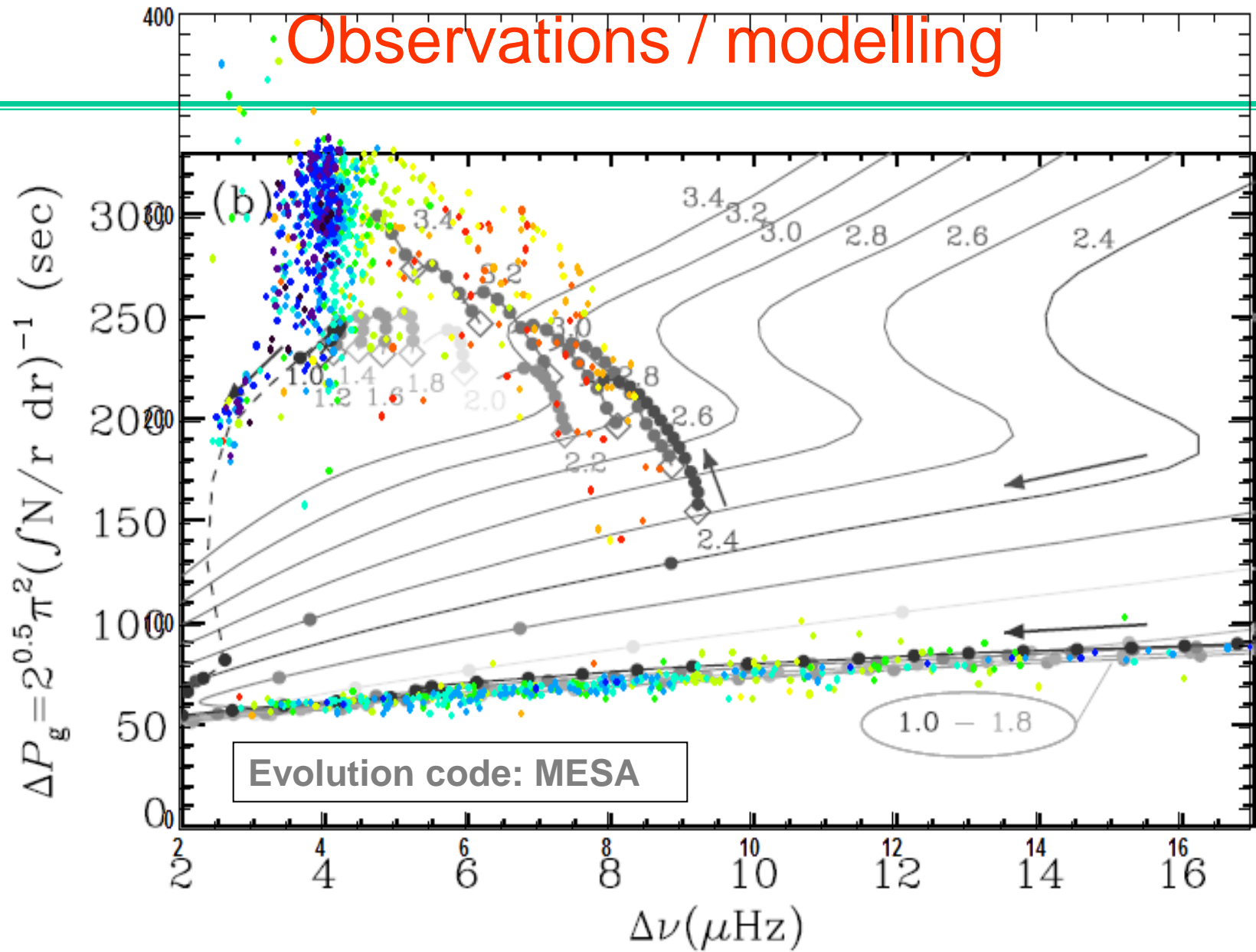
$$\Delta\Pi_{1,\text{RGB}} < \Delta\Pi_{1,\text{clump}}$$

$\Delta\Pi_1$ highly variable during the flash

$$\Delta\Pi_{1,\text{inter-subflash}} < \Delta\Pi_{1,\text{RGB}}$$

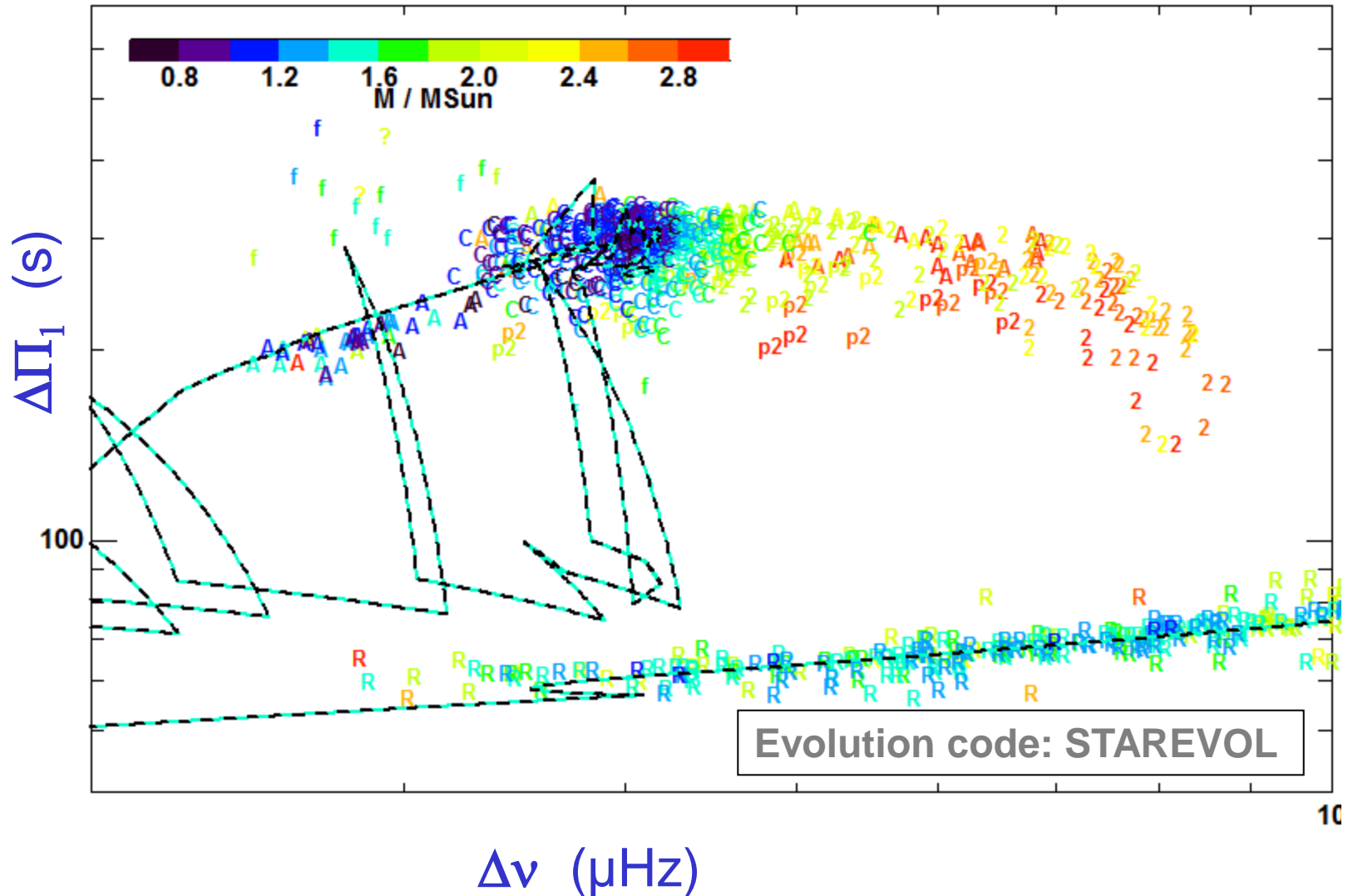
$$\Delta\Pi_{1,\text{subflash}} > \Delta\Pi_{1,\text{clump}}$$

$$\Delta\Pi_{1,\text{clump}} > \Delta\Pi_{1,\text{RGB}}$$

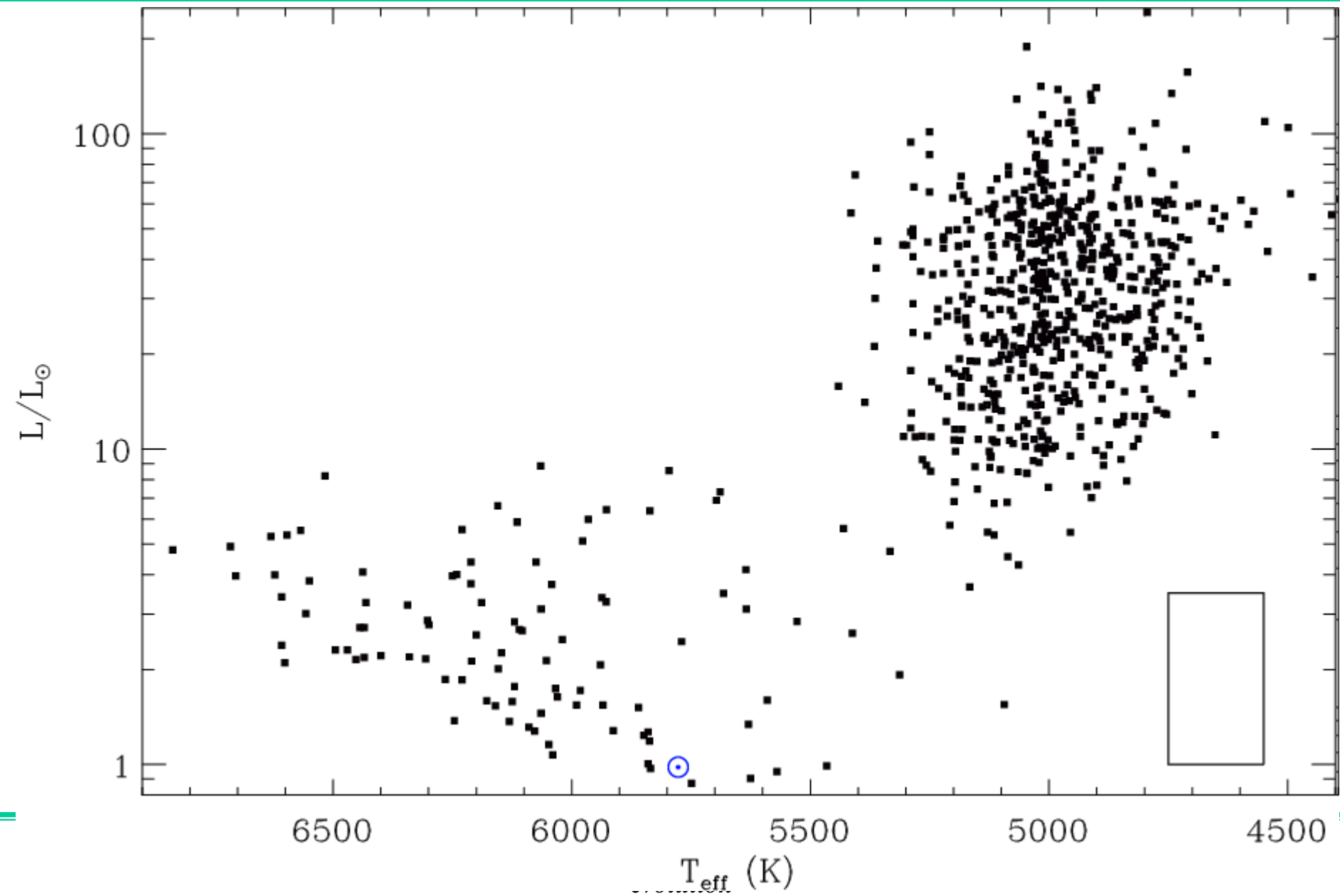


Observations / modelling

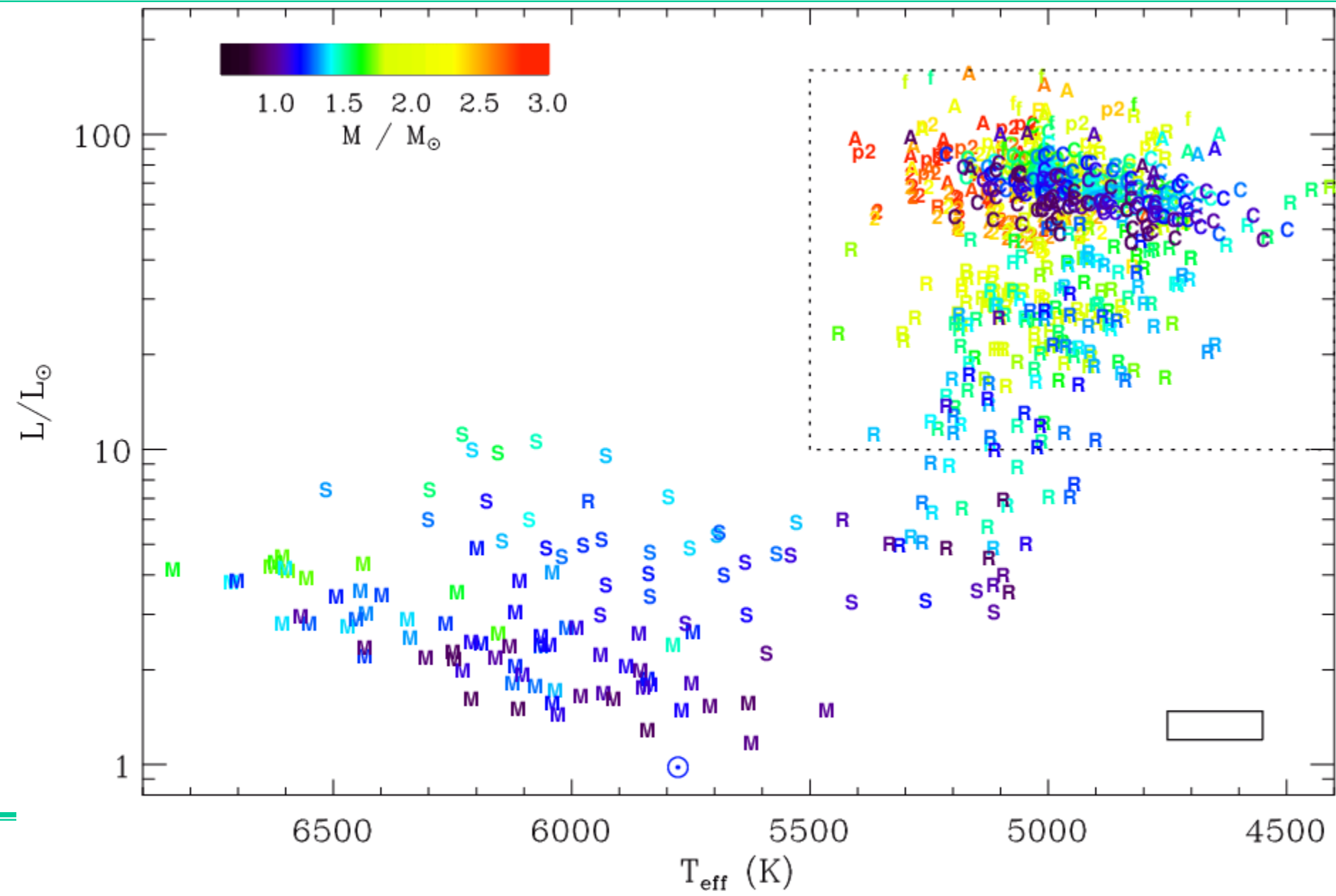
Lagarde et al. 2012, A&A 543, A108



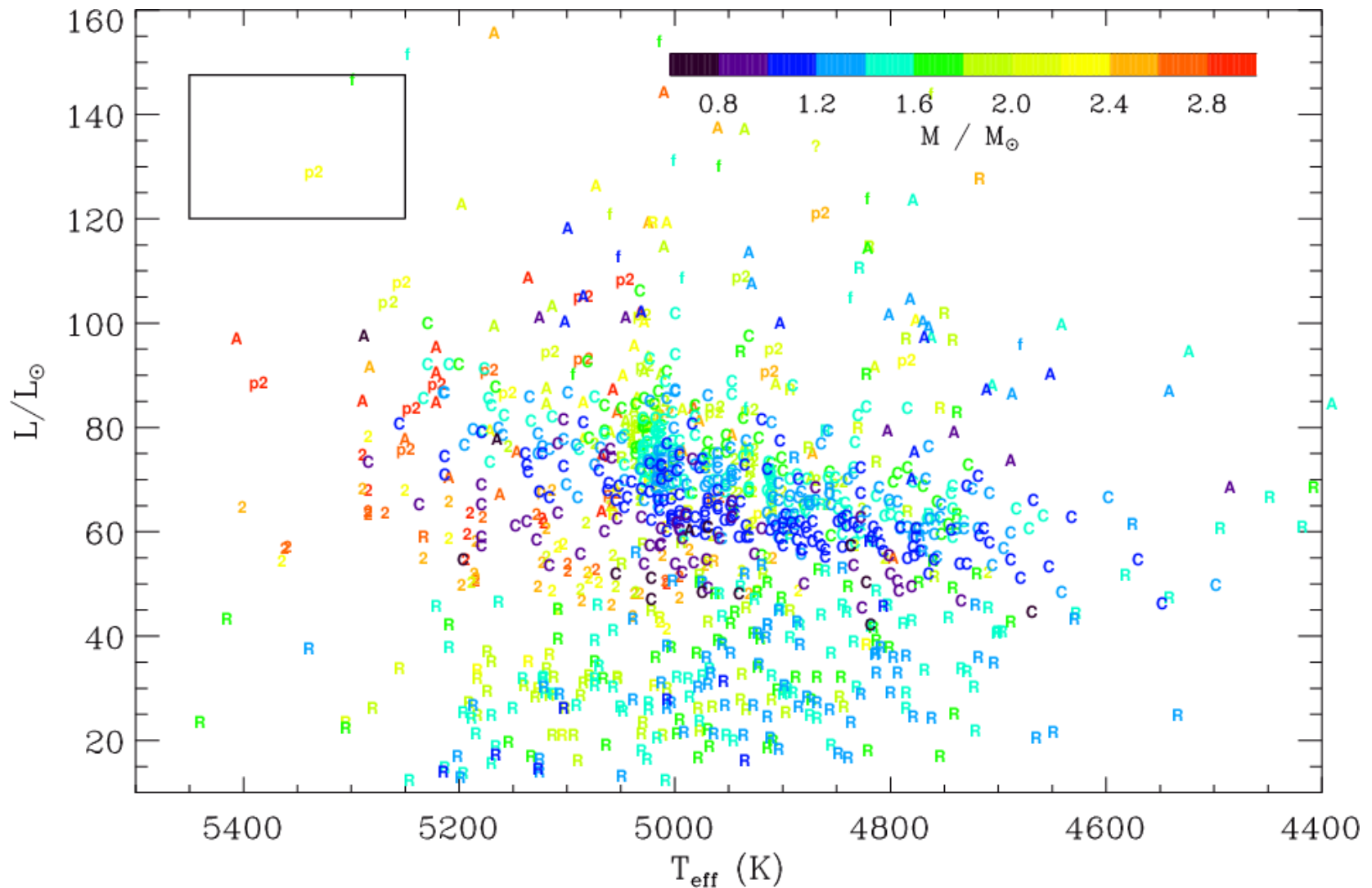
From the classical HR diagram...



... to the seismic enriched HR diagram



Using clump stars as stellar candles



Conclusions

- Mixed modes probe the core region
 - $\Delta\Pi_1 - \Delta\nu$ diagram
 - Seismically enriched Hertzsprung-Russel diagram
- Precise markers of stellar evolution
 - End of the subgiant stage
 - Identification of stars undergoing the helium flash
 - Precise timing of evolution in helium burning phase
 - End of the helium-core burning stage
- Next steps
 - Precise “observed” stellar ages
 - More accurate use of red-clump stars as distance indicators.

Observed evolutionary tracks

