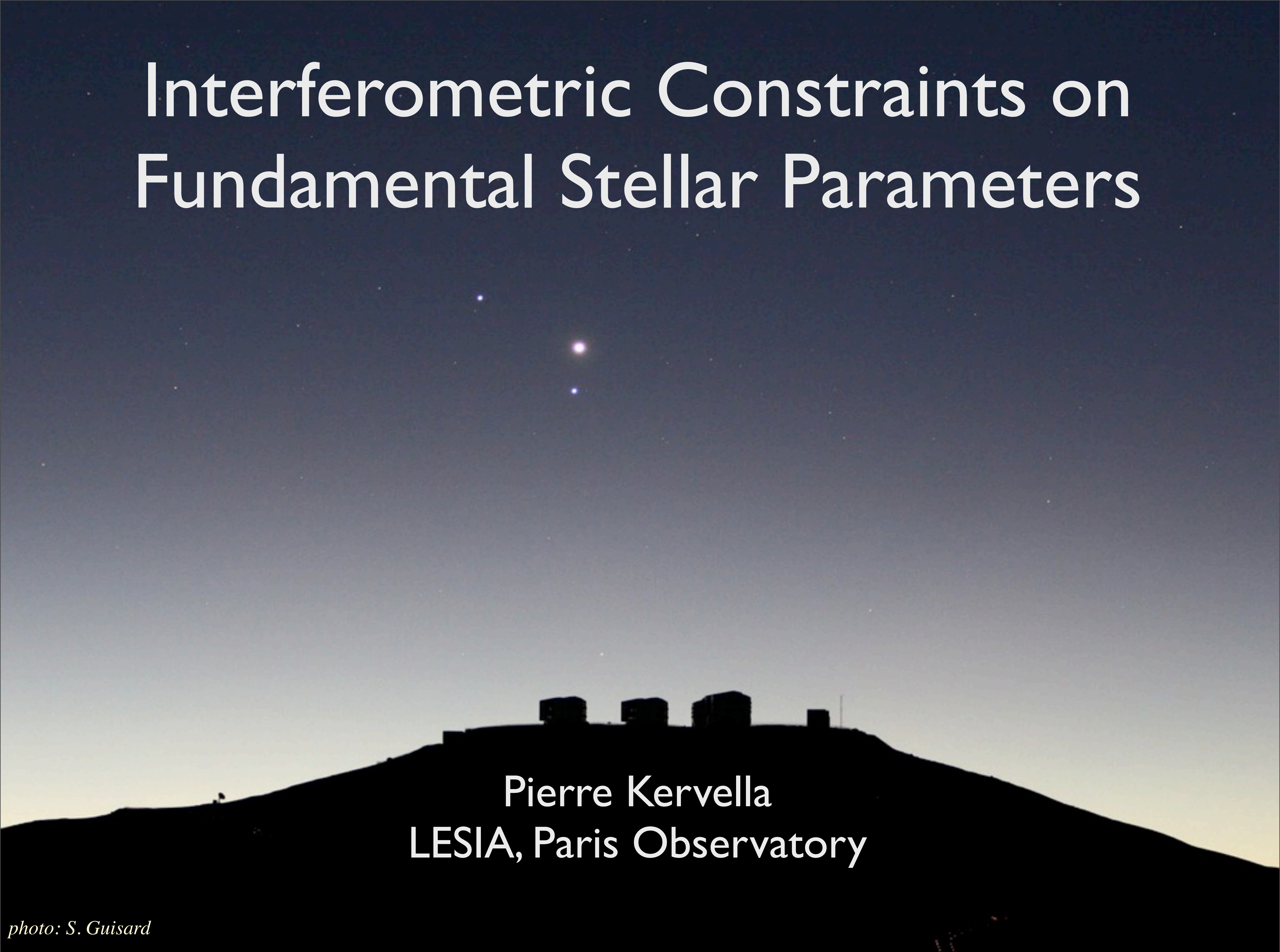
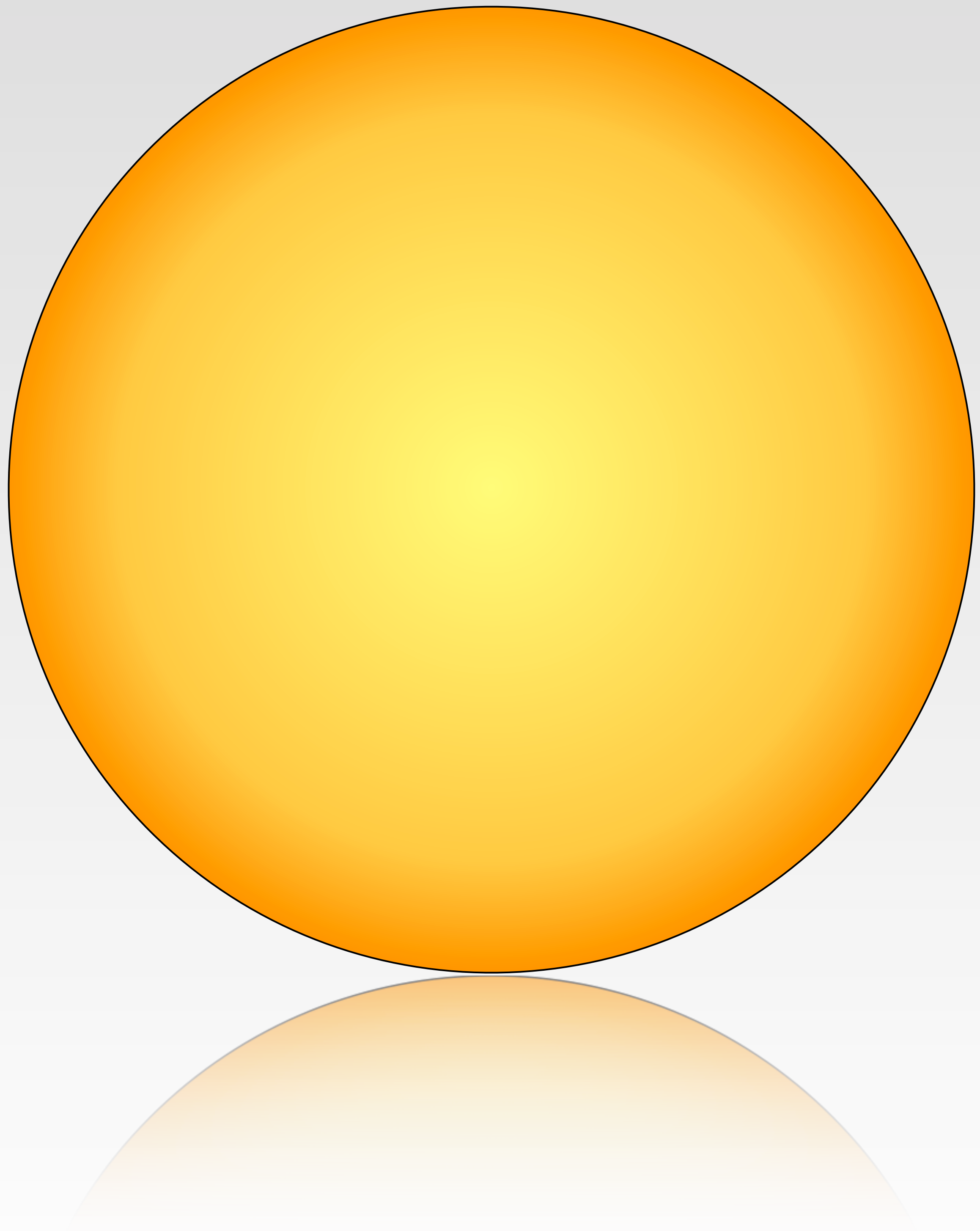
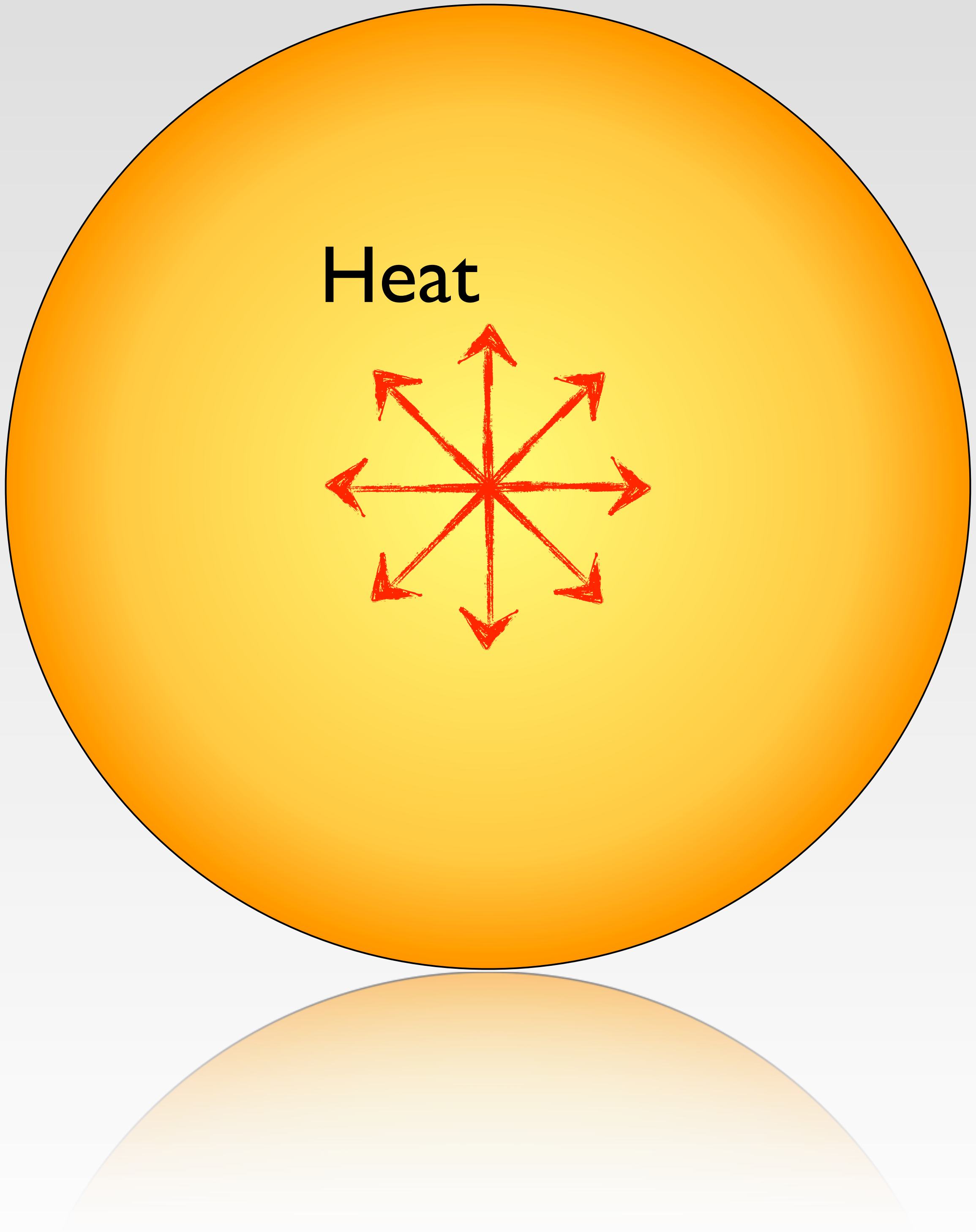
Interferometric Constraints on Fundamental Stellar Parameters

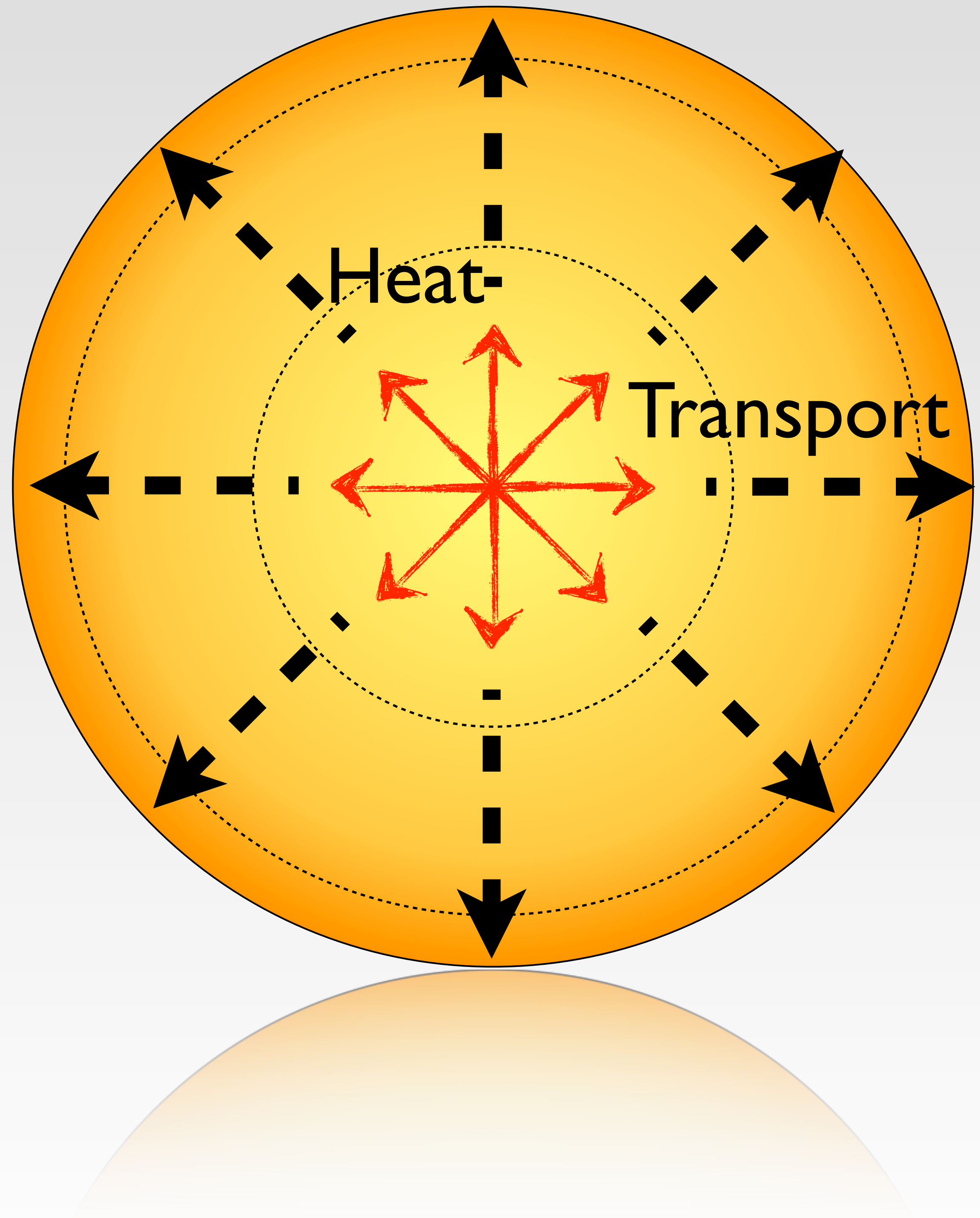


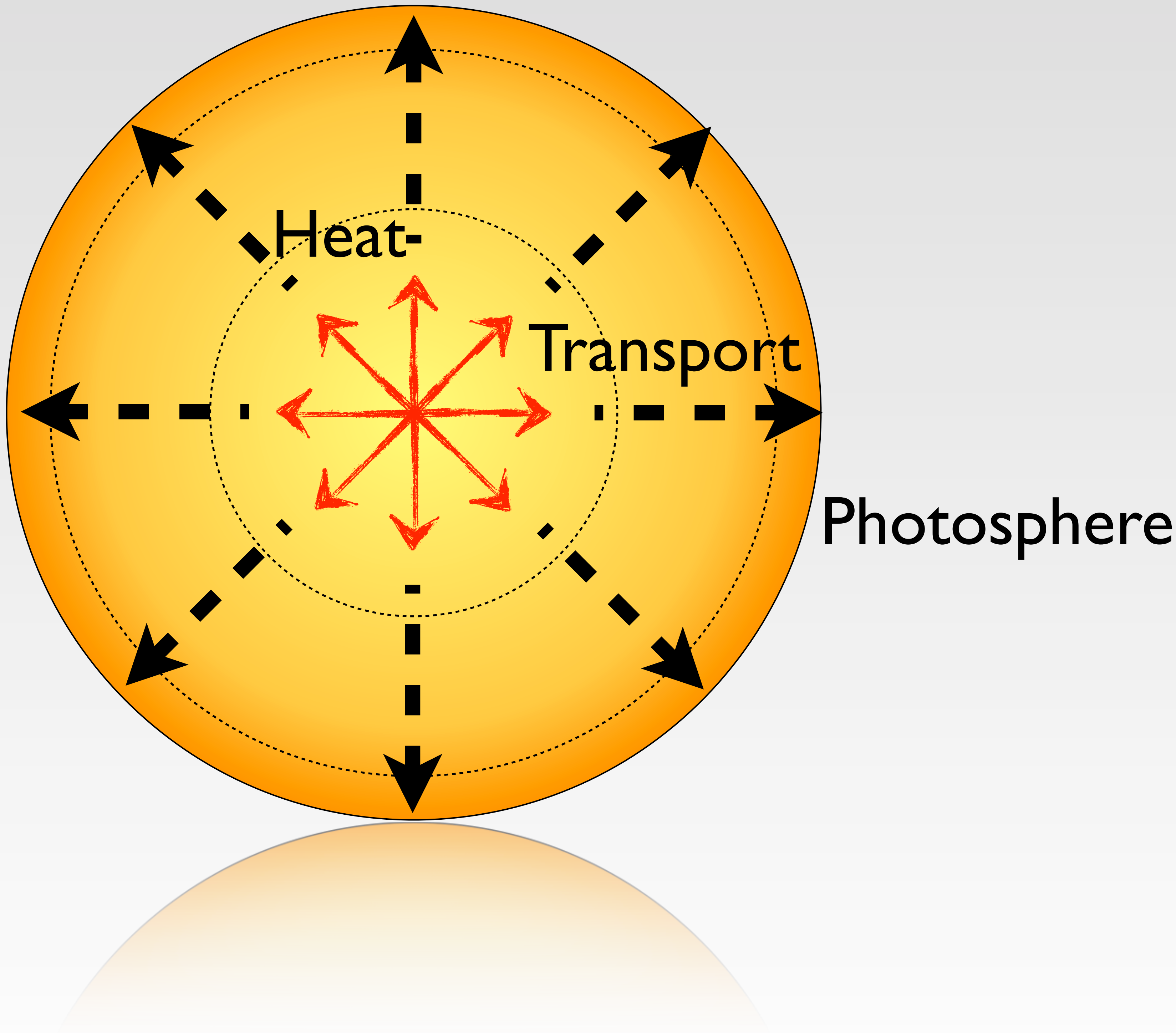
Pierre Kervella
LESIA, Paris Observatory

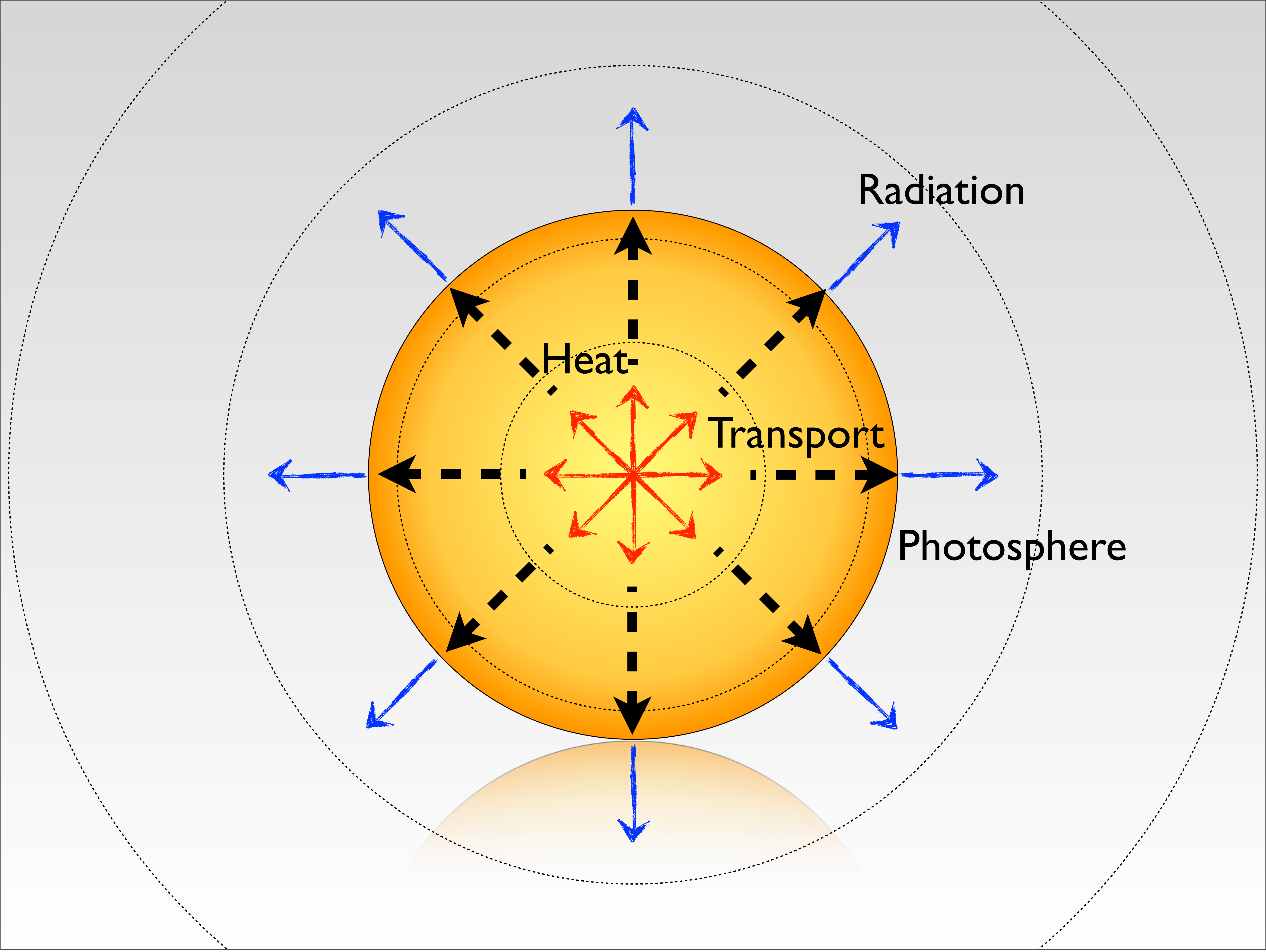
photo: S. Guisard

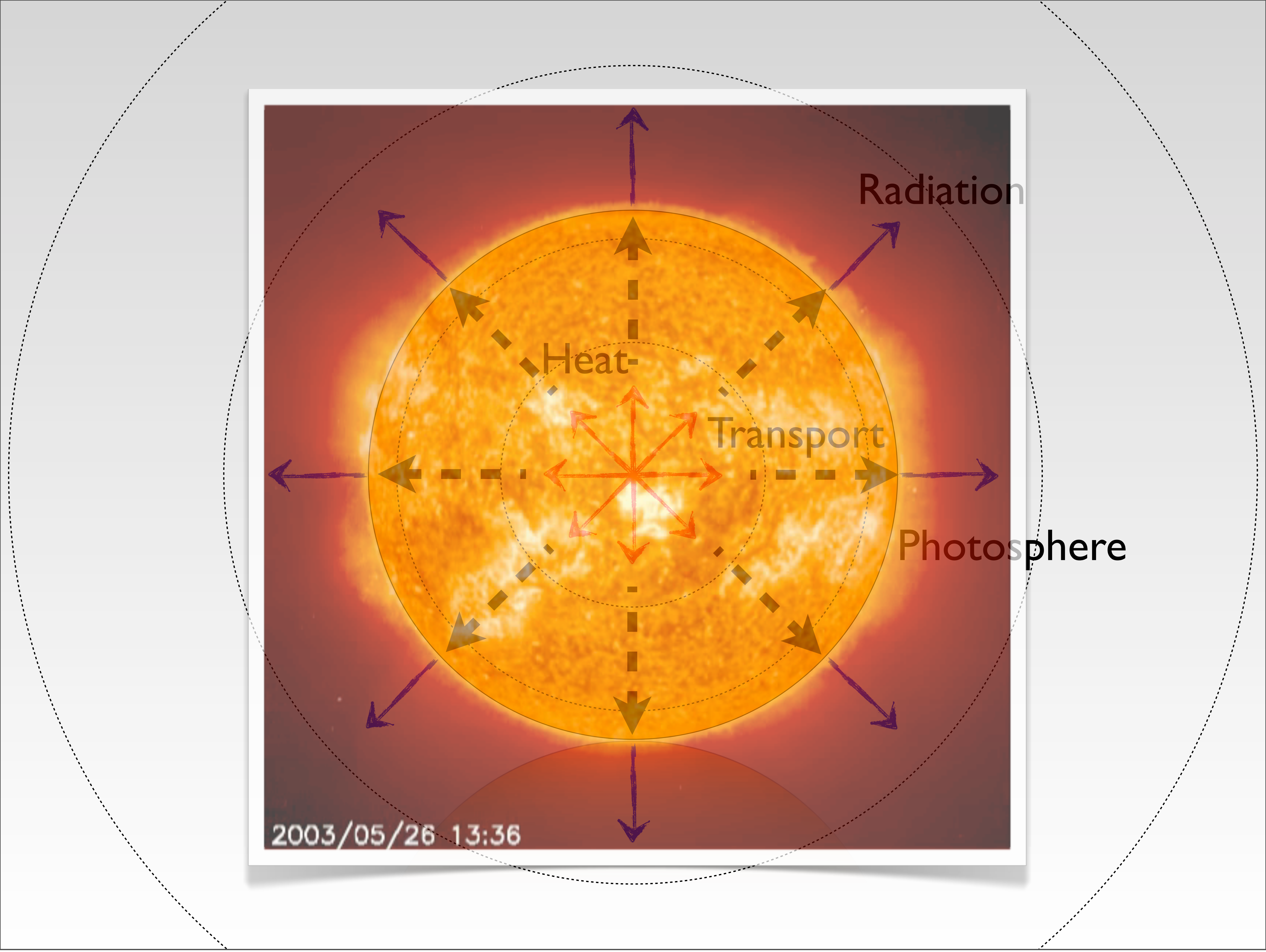



Heat


Heat
Transport


Heat
Transport
Photosphere


Radiation
Heat
Transport
Photosphere


Radiation
Heat
Transport
Photosphere
2003/05/26 13:36

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- The fundamental parameters: M, L, R, T_{eff}
- Also important: rotation, mass loss, metallicity, binarity,... but « second order »

- M is the source of the star’s gravity, and the quantity of «fuel» it can burn
- L is the «power of the star», i.e. its energy production rate.
- R and T_{eff} are linked and essentially characterize the energy transportation mechanism inside the star
- Optical interferometry can constrain the radius R and the mass M

Stellar radius in the HR diagram

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- UD angular diameter + Limb Darkening + Parallax = Linear photospheric radius R

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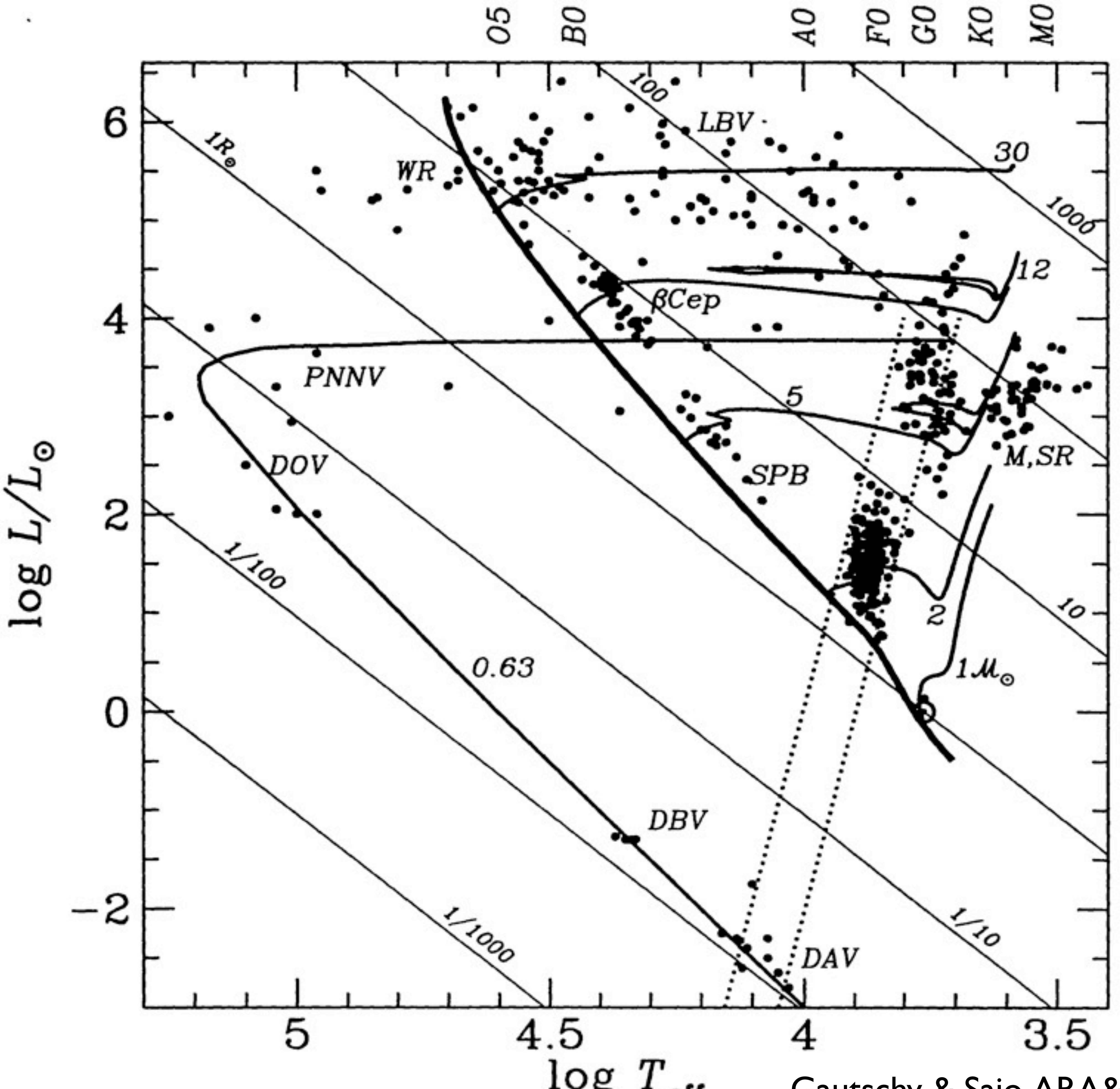
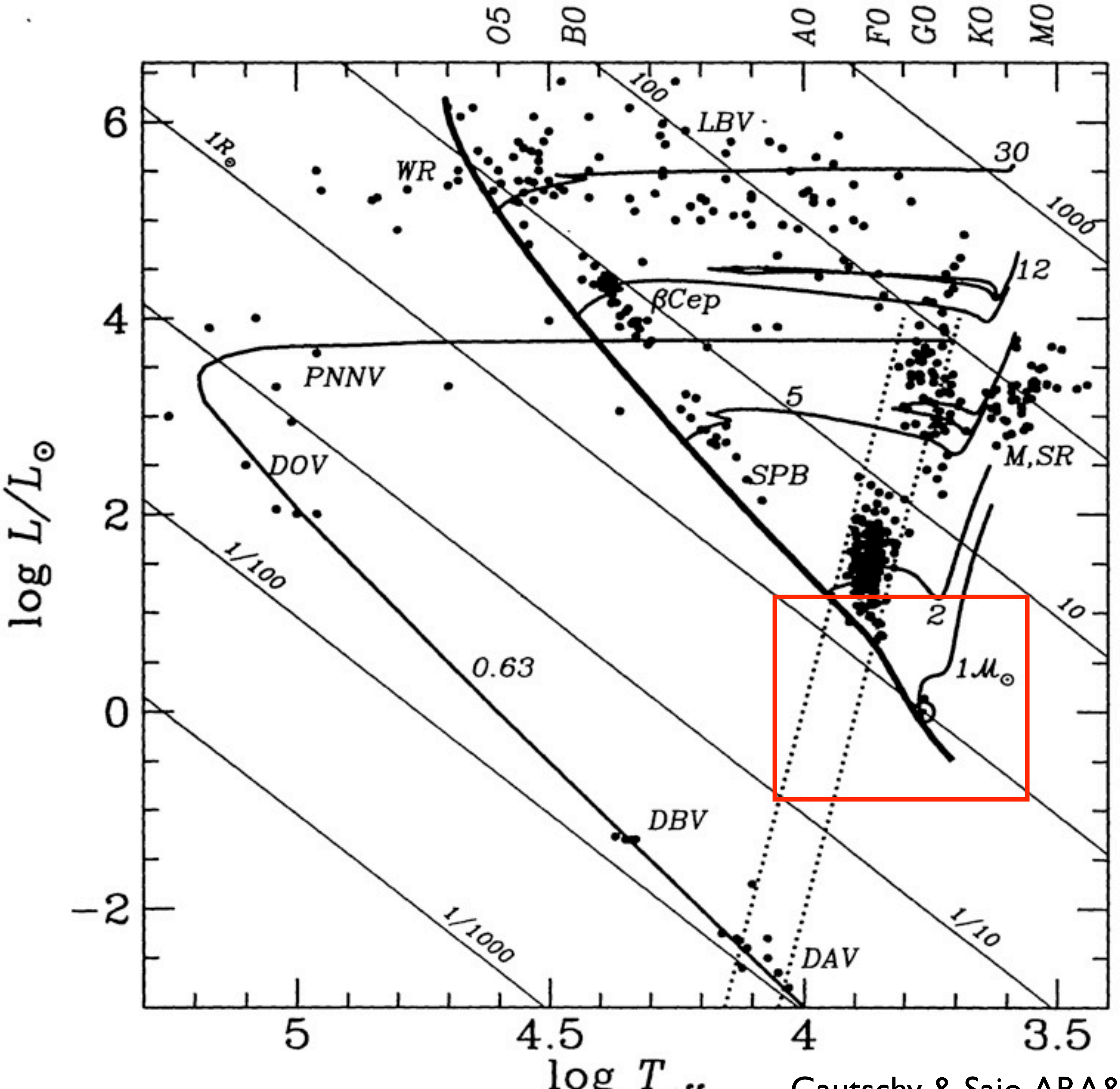
- in Log, constant radius curves are:

$$\mathrm{Log}\, L = 4\, \mathrm{Log}\, T_{eff} + 2\, \mathrm{Log}\, R + K$$



Gautschy & Saio, ARA&A 33, 75 (1995)



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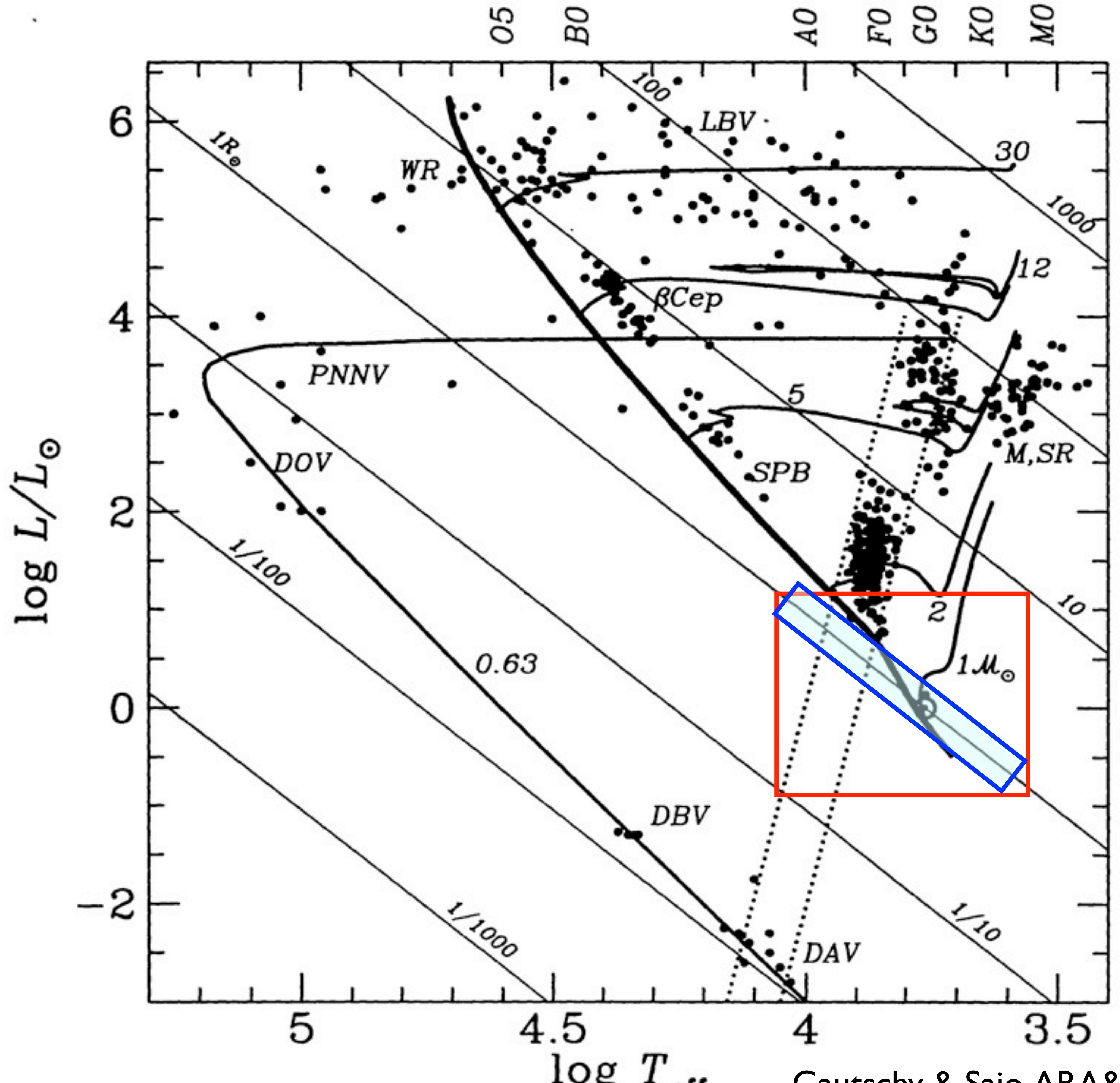

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Very low mass stars

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- Interferometric observations of VLMS:

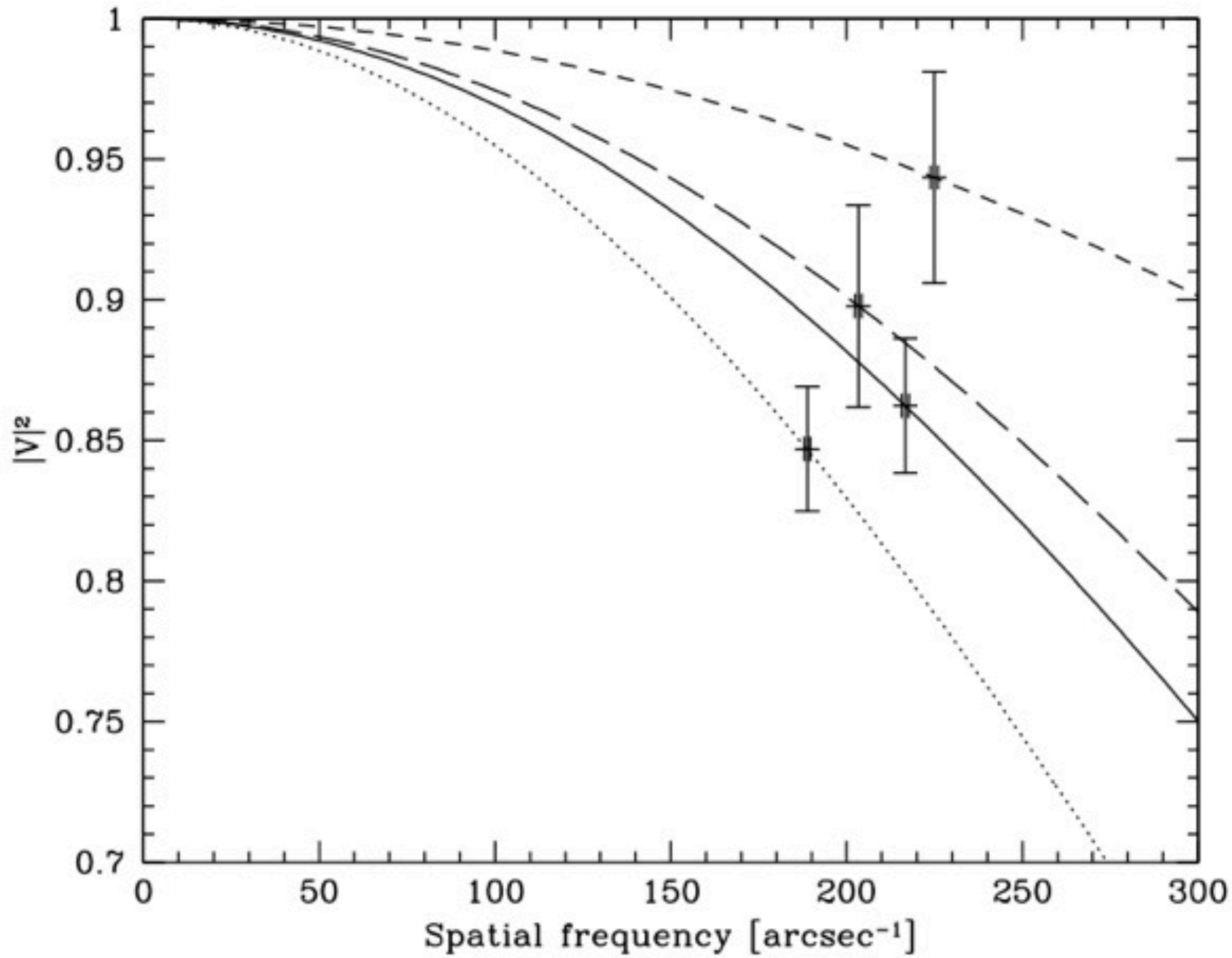
Lane et al. (2001, ApJ, 551, L81)

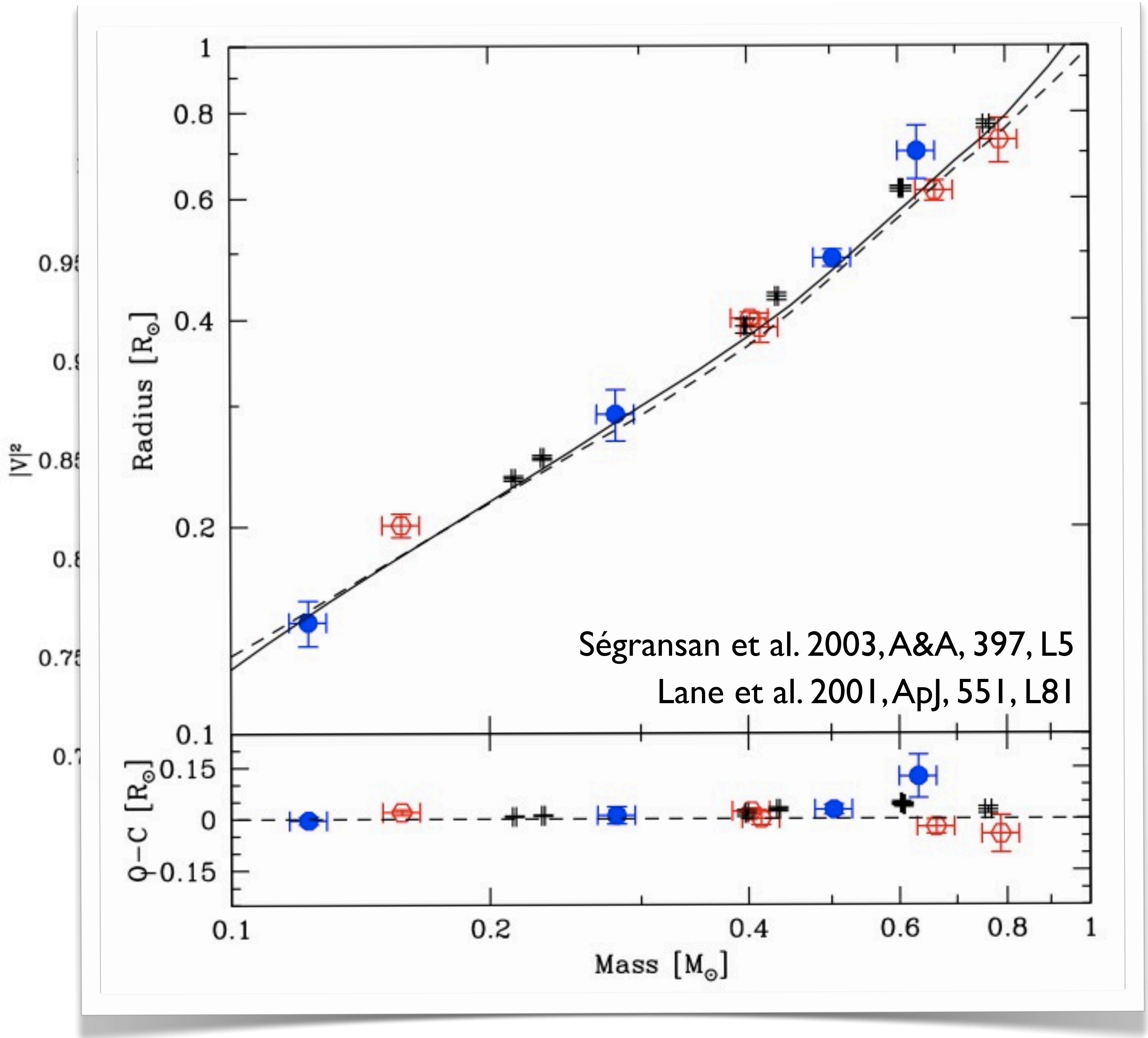
Ségransan et al. (2003, A&A, 397, L5)

Berger et al. (2006, ApJ, 644, 475)

Boyajian et al. (2009, ApJ, 683, 424)

Demory et al. (2009, ApJ, 505, 205)


1
0.95
0.9
0.85
0.8
0.75
0.7
|V|²
0
50
100
150
200
250
300
Spatial frequency [arcsec⁻¹]



Radius [R⊙]
Mass [M⊙]
O−C [R⊙]
Ségransan et al. 2003, A&A, 397, L5
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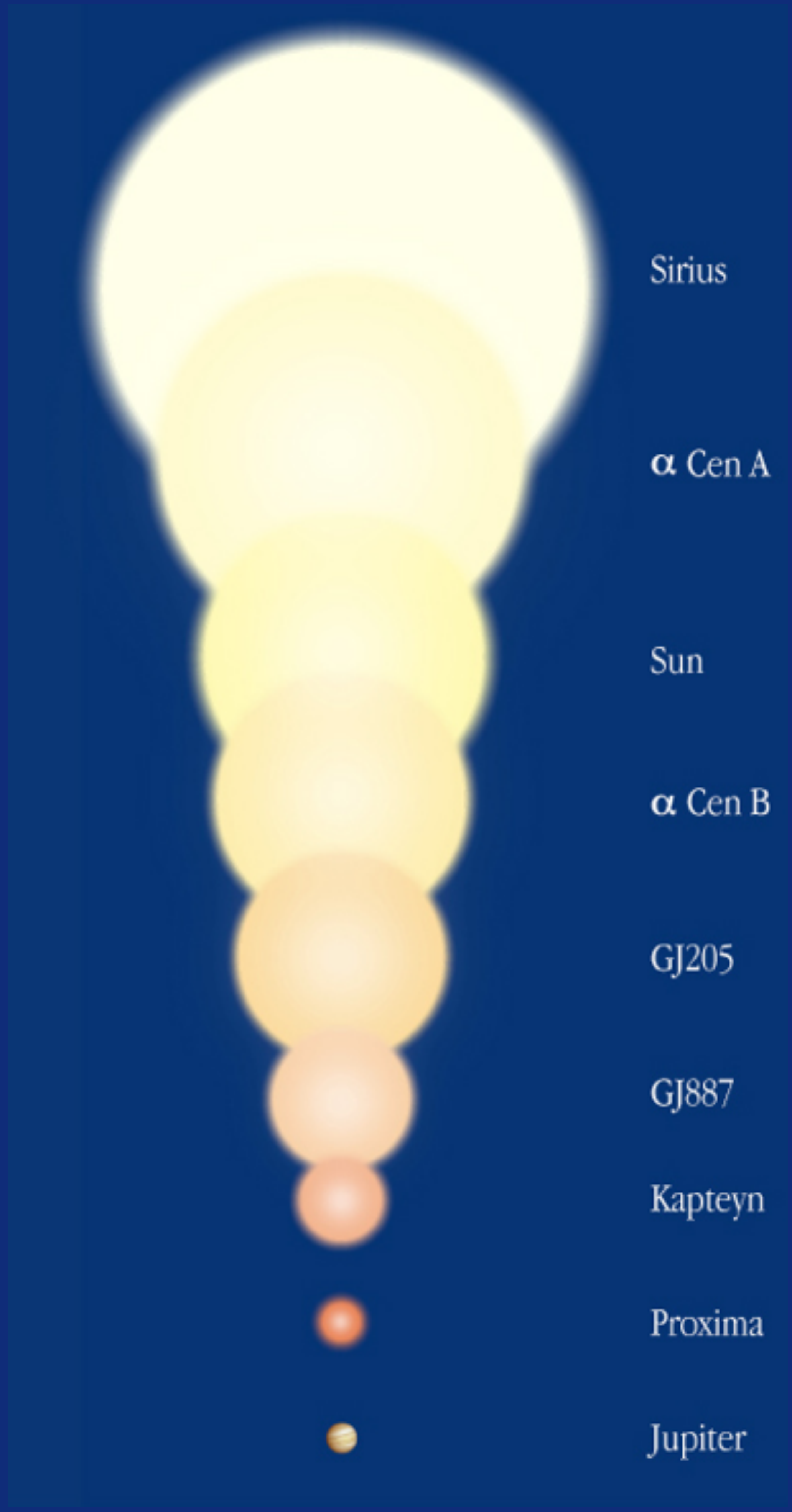
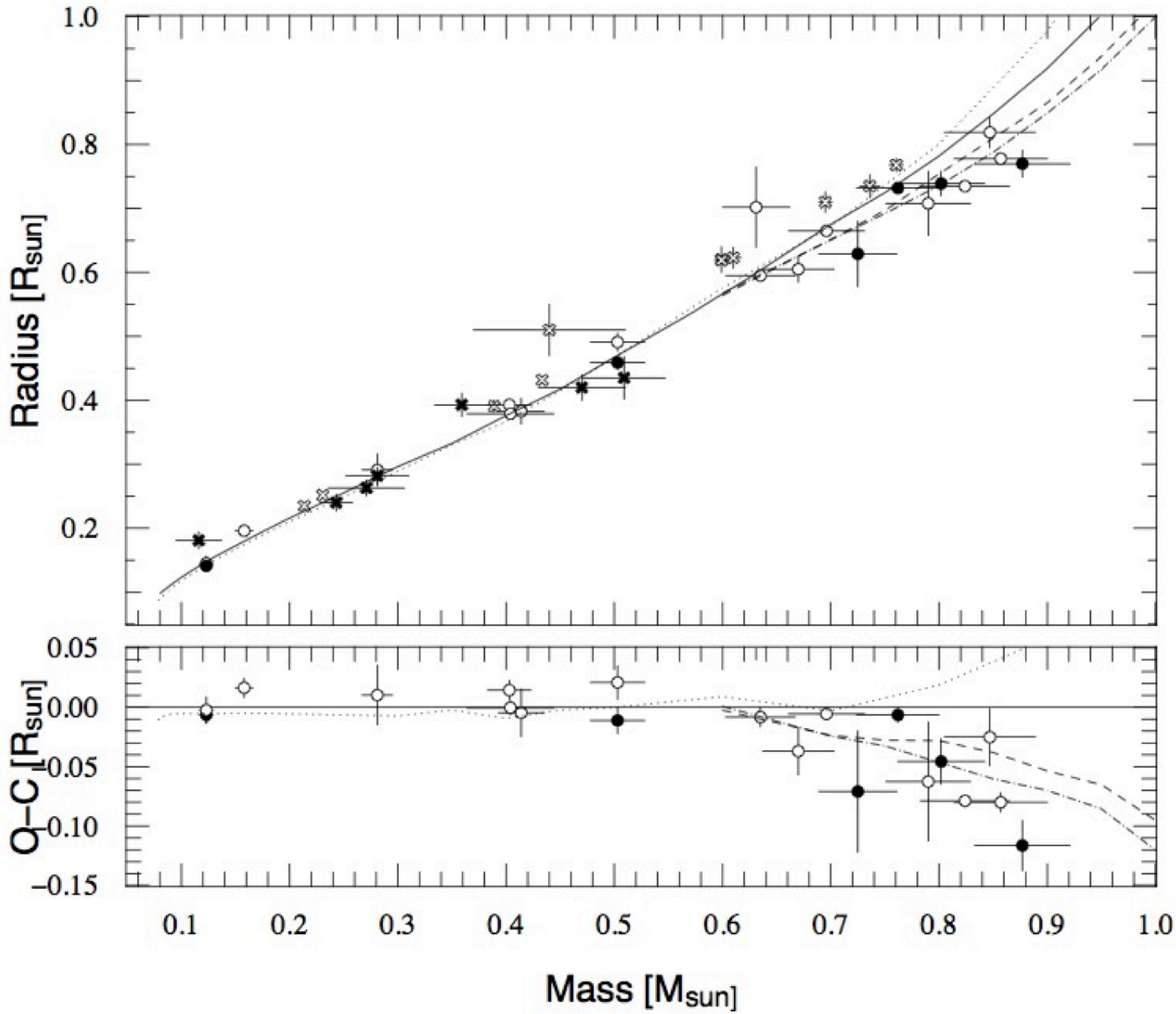

Sirius
α Cen A
Sun
α Cen B
GJ205
GJ887
Kapteyn
Proxima
Jupiter



Demory et al. 2009, ApJ, 505, 205

- Ségransan et al. (2003): An accurate empirical mass-radius relation is an essential constraint on stellar interior structure, evolutionnary models and atmospheric physics. The interior structure is largely determined by the equation of state, whose derivation for very low mass stars, brown dwarfs, and planets involves the complex physics of strongly correlated and partially degenerated quantum plasma (Chabrier & Baraffe 2000).

- Demory et al. (2009): Radii of single inactive M dwarfs measured by interferometry are in excellent agreement with models from Baraffe et al. (1998). Thus, discrepancies pointed out by Torres & Ribas (2002) and Ribas (2003) only concern fast rotating stars, confirming the fact that rotation strongly affects the internal structure of those objects. Models are in good agreement with the observations, confirming a correct understanding of the underlying physics of low and very low mass stars.

Interferometry and asteroseismology

Interferometry and asteroseismology

- Remarkable *complementarity* of the radius and oscillation period:

  - for a pendulum: $P = 2 \pi \sqrt{(l/g)}$

  - for an oscillating star:

  $P \sim \sqrt{(R/(GM/R^2)} \sim \sqrt{(R^3/M)} \sim \sqrt{(\text{density})^{-1}}$

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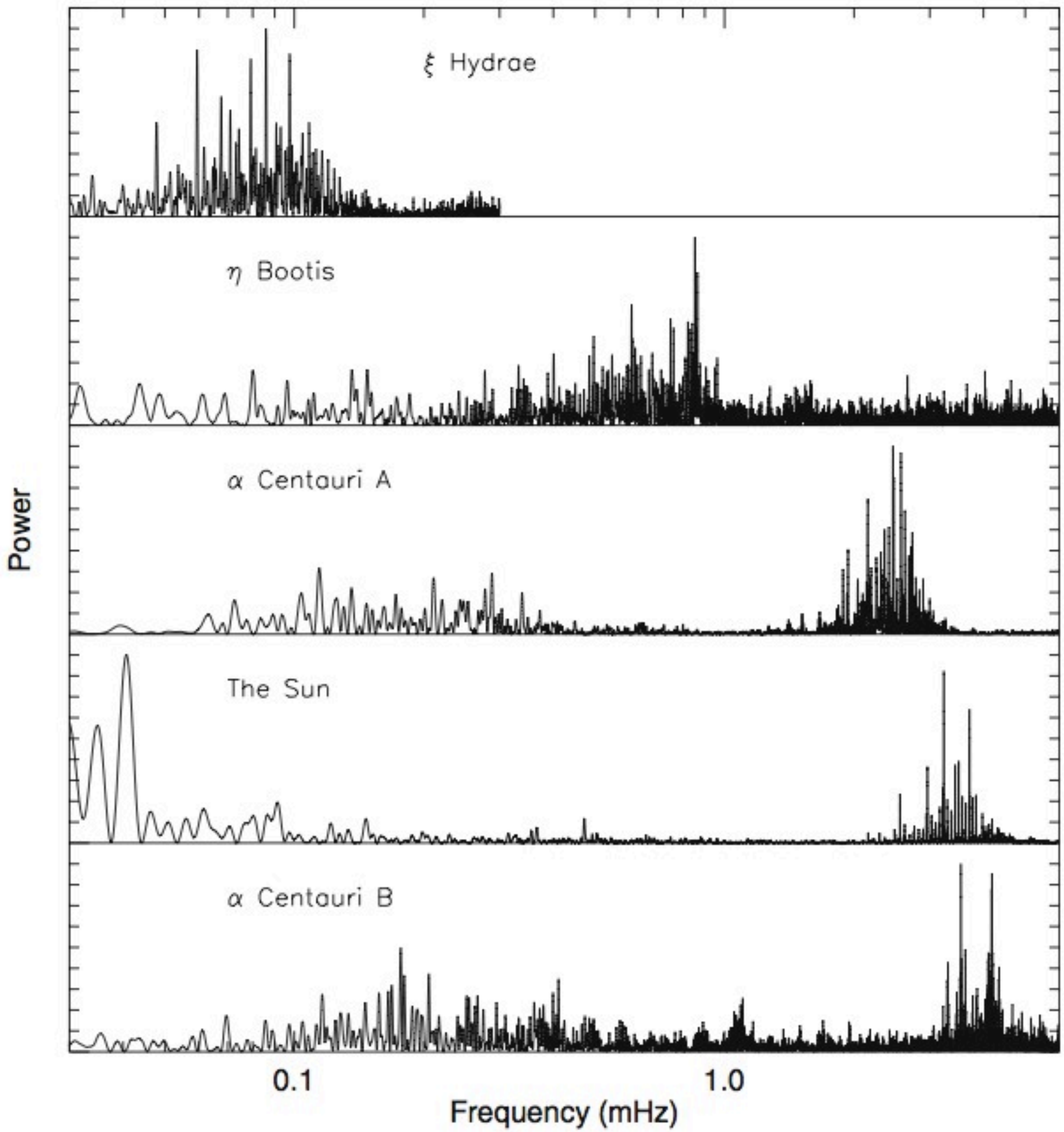
- with R and P we therefore constrain M
- Good match in measurement precision (nearby stars)

- More precisely, a prime asteroseismic observable is the large frequency spacing Δν

$$\overline{\Delta\nu_{\rm osc}} \sim 134.9 \sqrt{\frac{m/M_\odot}{(R_\star/R_\odot)^3}}\ (\mu{\rm Hz})$$

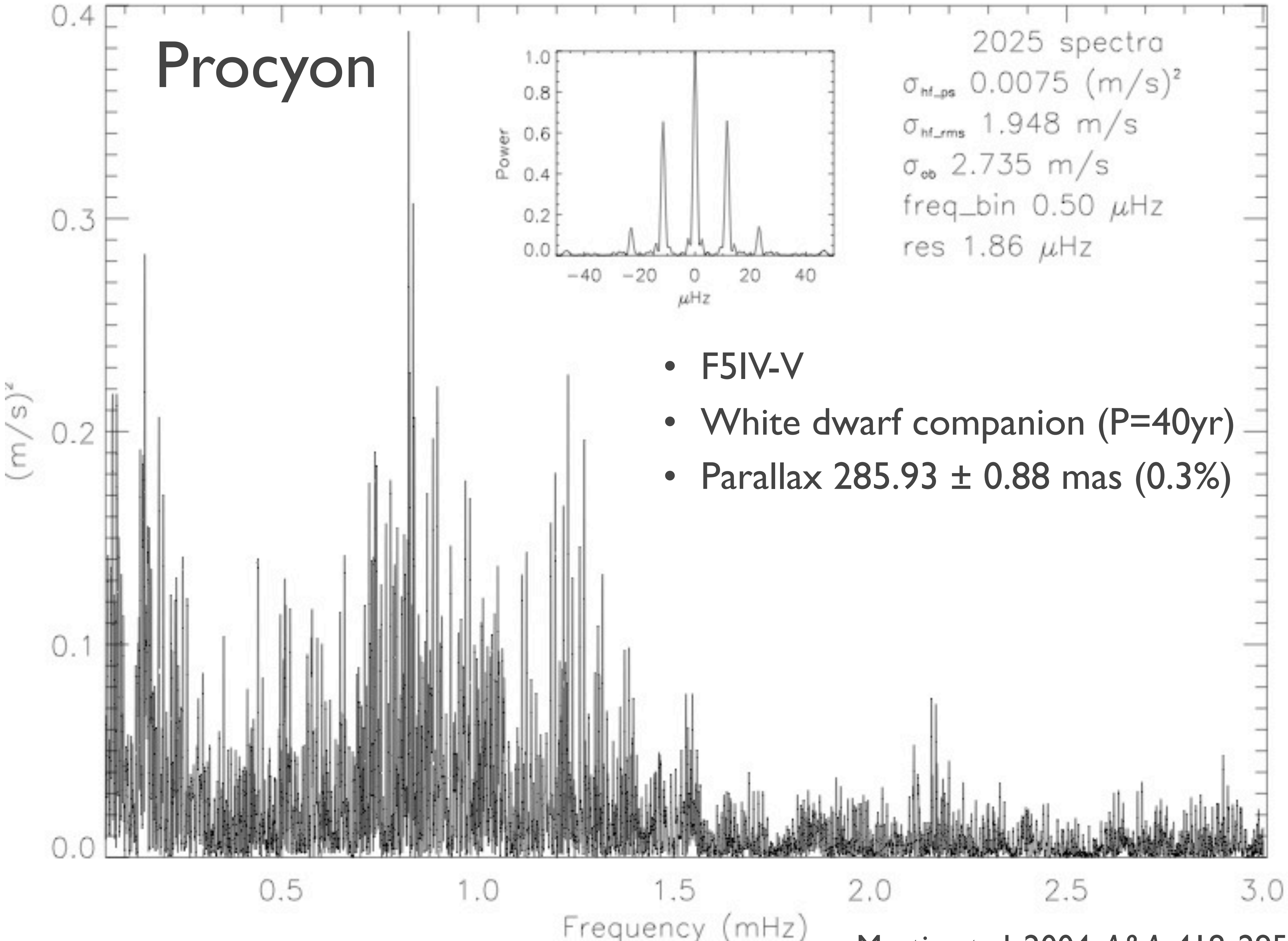
(Kjeldsen & Bedding 1995, A&A, 293, 87)

- R and Δν together give access to the mass, that is difficult to measure for single stars



Cunha et al. 2007, Astron. Astrophys. Rev., 14, 217

Procyon



- F5IV-V
- White dwarf companion (P=40yr)
- Parallax 285.93 ± 0.88 mas (0.3%)

Martic et al. 2004, *A&A*, 418, 295

Evolutionary modeling

- CESAM code (from P. Morel 1997, A&AS, 124, 597)

Constraints:

- L, T_{eff}, log g, [Fe/H] from spectroscopy and photometry
- Mass from the binary orbit: $M = 1.50 \pm 0.04\ M_{\odot}$

  (Girard et al. 2000, AJ, 119, 2428)
- Photospheric radius: $R = 2.03 \pm 0.02\ R_{\odot}$ (1%)

  Angular diameter $\theta_{LD} = 5.45 \pm 0.05$ mas

  Limb darkening from Kurucz models

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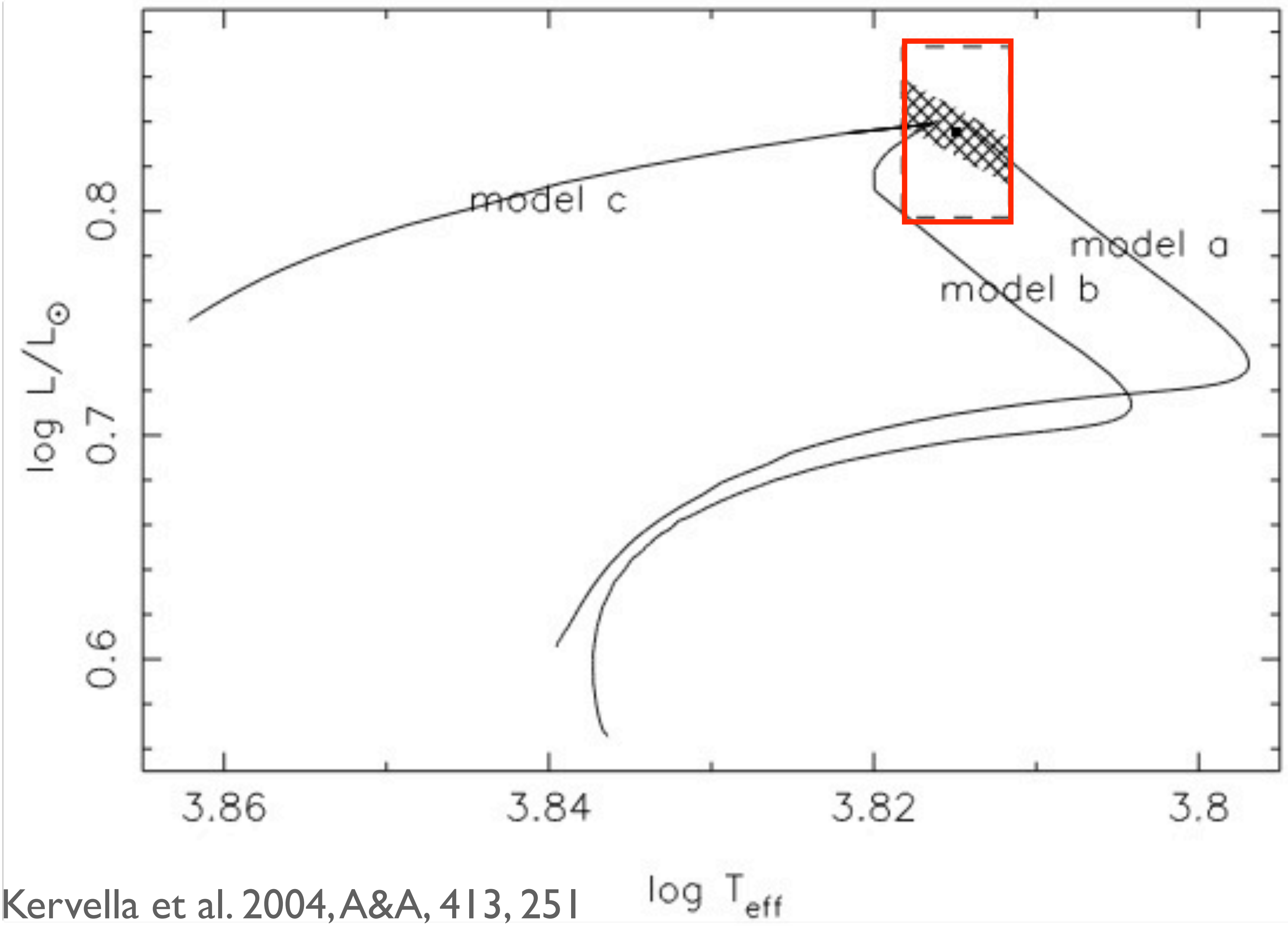
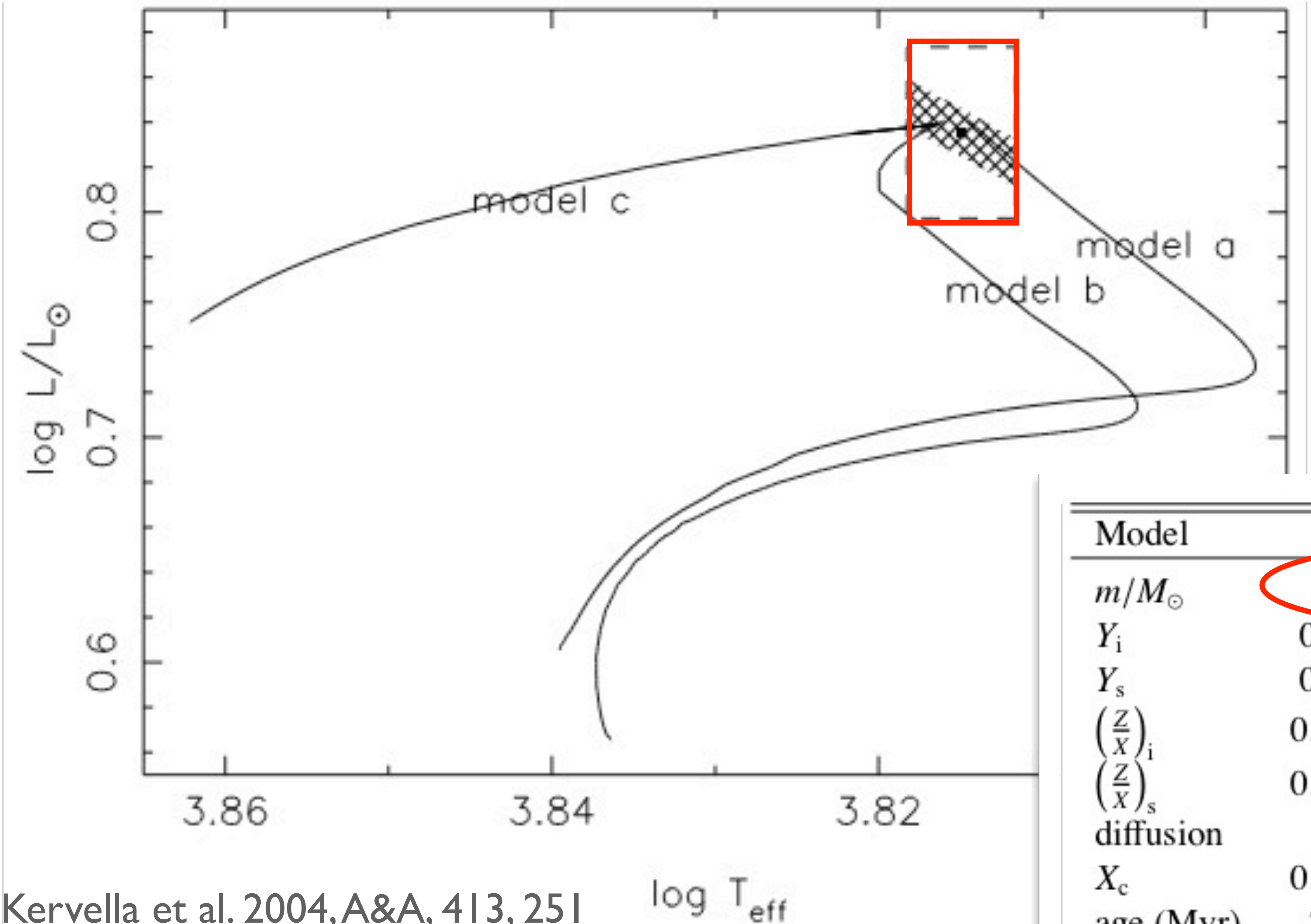


Kervella et al. 2004, A&A, 413, 251



Kervella et al. 2004, A&A, 413, 251

Model	*a*	*b*	*c*
$m/M_\odot$	1.42	1.42	1.50
Y_i	0.3012	0.2580	0.345
Y_s	0.2209	0.2580	0.202
$\left(\frac{Z}{X}\right)_i$	0.03140	0.0218	0.0450
$\left(\frac{Z}{X}\right)_s$	0.02157	0.0218	0.0220
diffusion	yes	no	yes
X_c	0.00051	0.00000	0.2180
age (Myr)	2 314	2 710	1 300
T_{eff} (K)	6524	6547	6553
log g	3.960	3.967	3.994
[Fe/H]$_i$	+0.107	–0.051	+0.264
[Fe/H]$_s$	–0.055	–0.051	–0.043
$\log(L/L_\odot)$	0.8409	0.8405	0.8390
$R/R_\odot$	2.0649	2.0495	2.0420
$\overline{\Delta\nu_0}$ (μHz)	54.7	55.4	56.4

Seismic frequencies

$$\overline{\Delta\nu_{osc}} \sim 134.9 \sqrt{\frac{m/M_\odot}{(R_\star/R_\odot)^3}} \ (\mu Hz)$$

Procyon's large freq. spacing:

$\Delta\nu_0$ = 53.6 ± 0.5 μHz

(Martic et al. 2004, A&A, 418, 295)

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(Eggenberger et al. 2004, A&A, 422, 247)

$\Delta\nu_0$ = 55.66 ± 0.15 μHz

(Leccia et al. 2006, MmSAI, 77, 462)

Lower mass favored:

- seismic large freq. spacing
- cooling time of the WD > 1.7 Gyr

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New HST astrometry gives a mass of 1.43 ± 0.03 $M_\odot$

(Gatewood & Han 2006, AJ, 131, 1015)

Masses of Binary Stars

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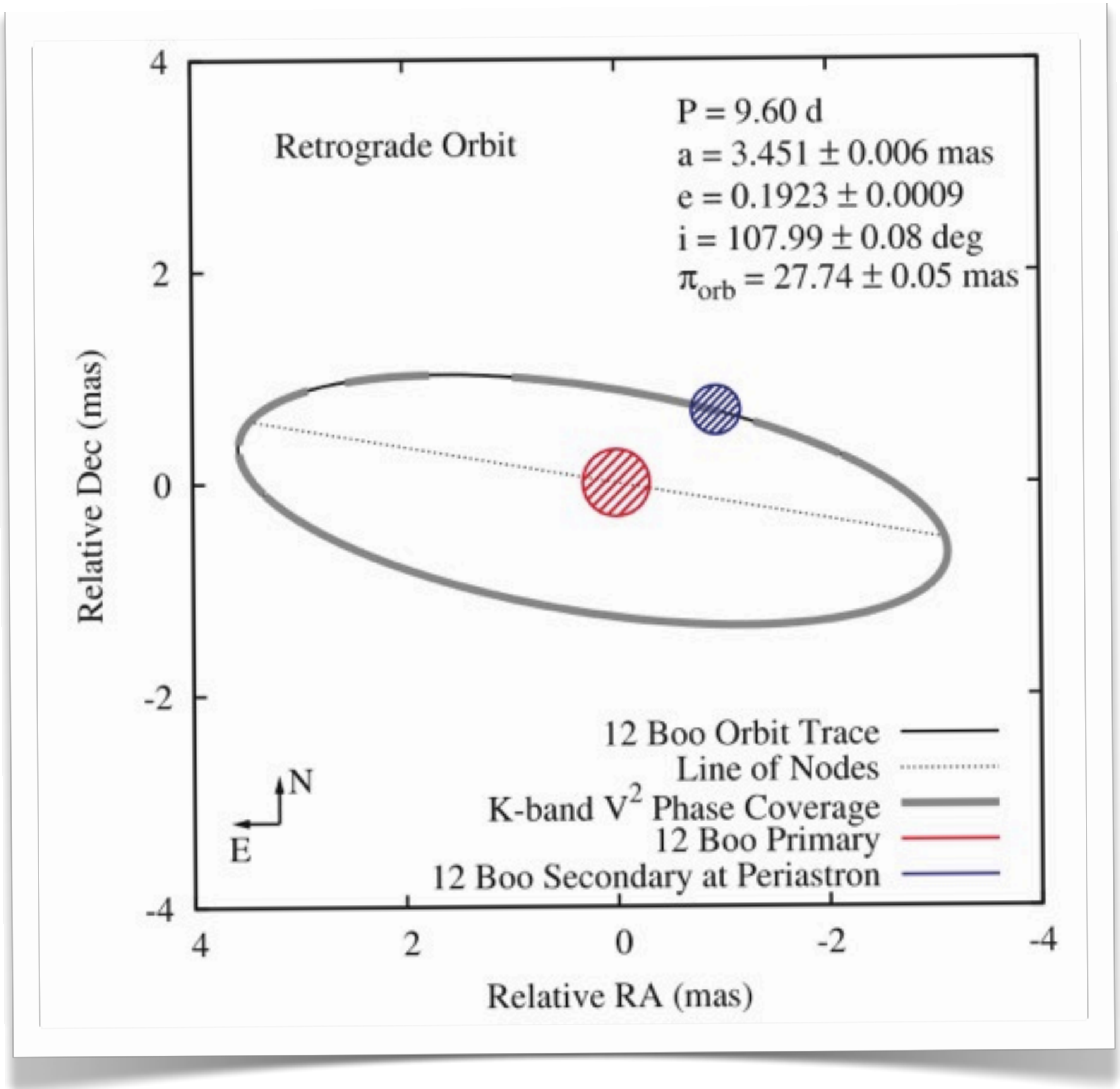
- Classical field of long-baseline interferometry
- Constraints on orbits and angular diameters
- Coeval stars with the same initial metallicities are excellent modeling subjects (e.g. α Cen A & B)

12 Boo



Boden et al. 2005, ApJ, 627, 464

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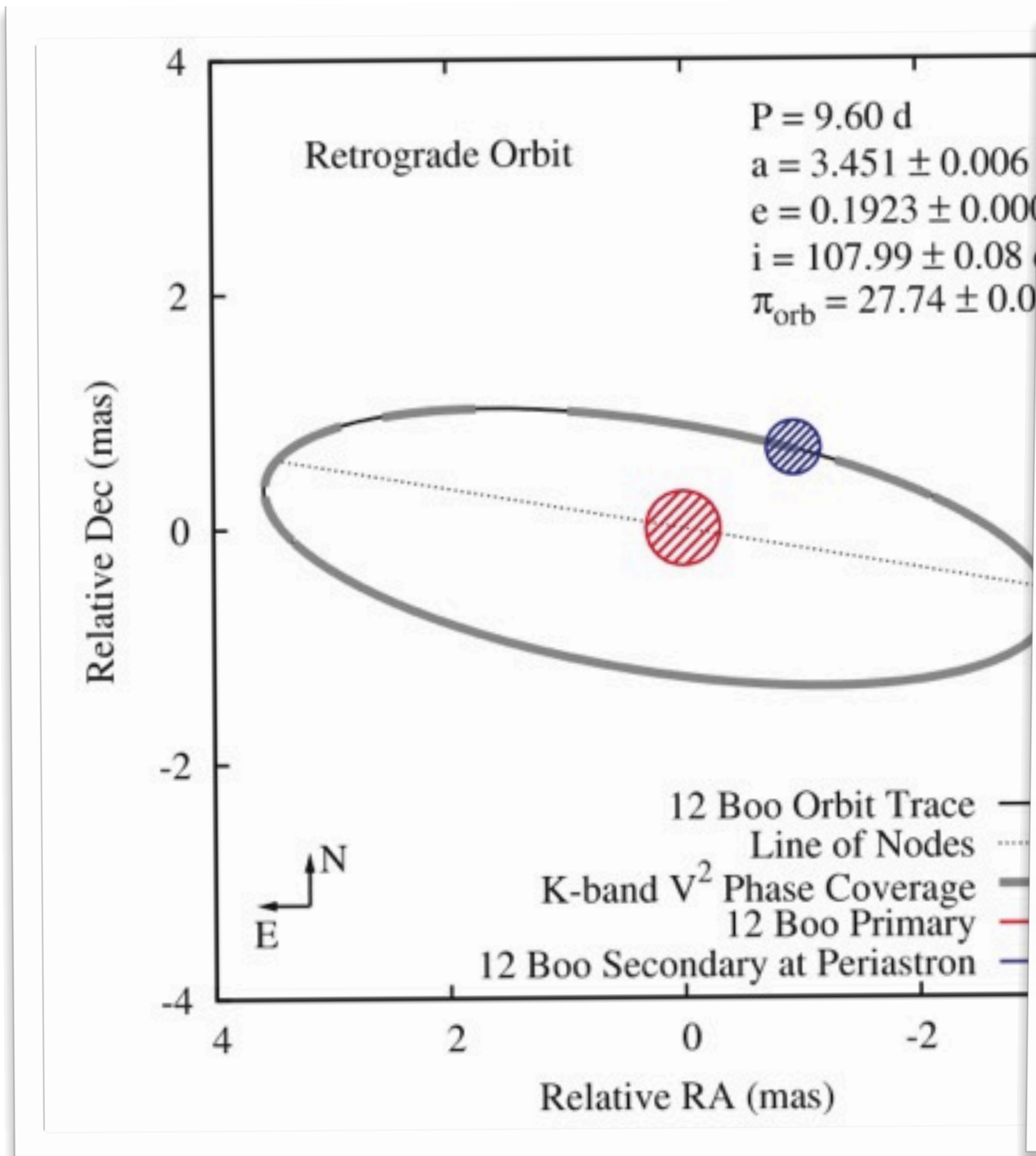

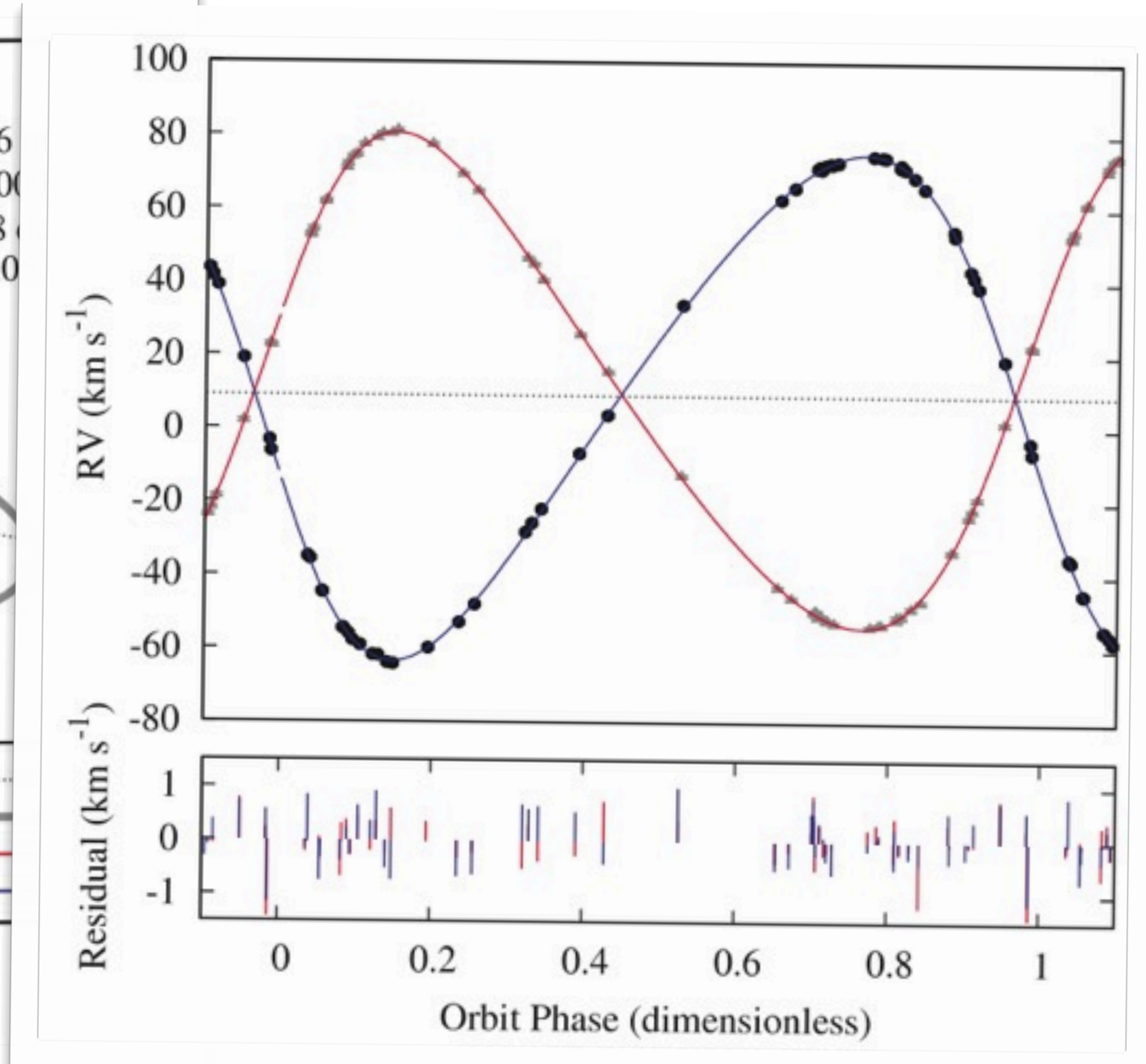

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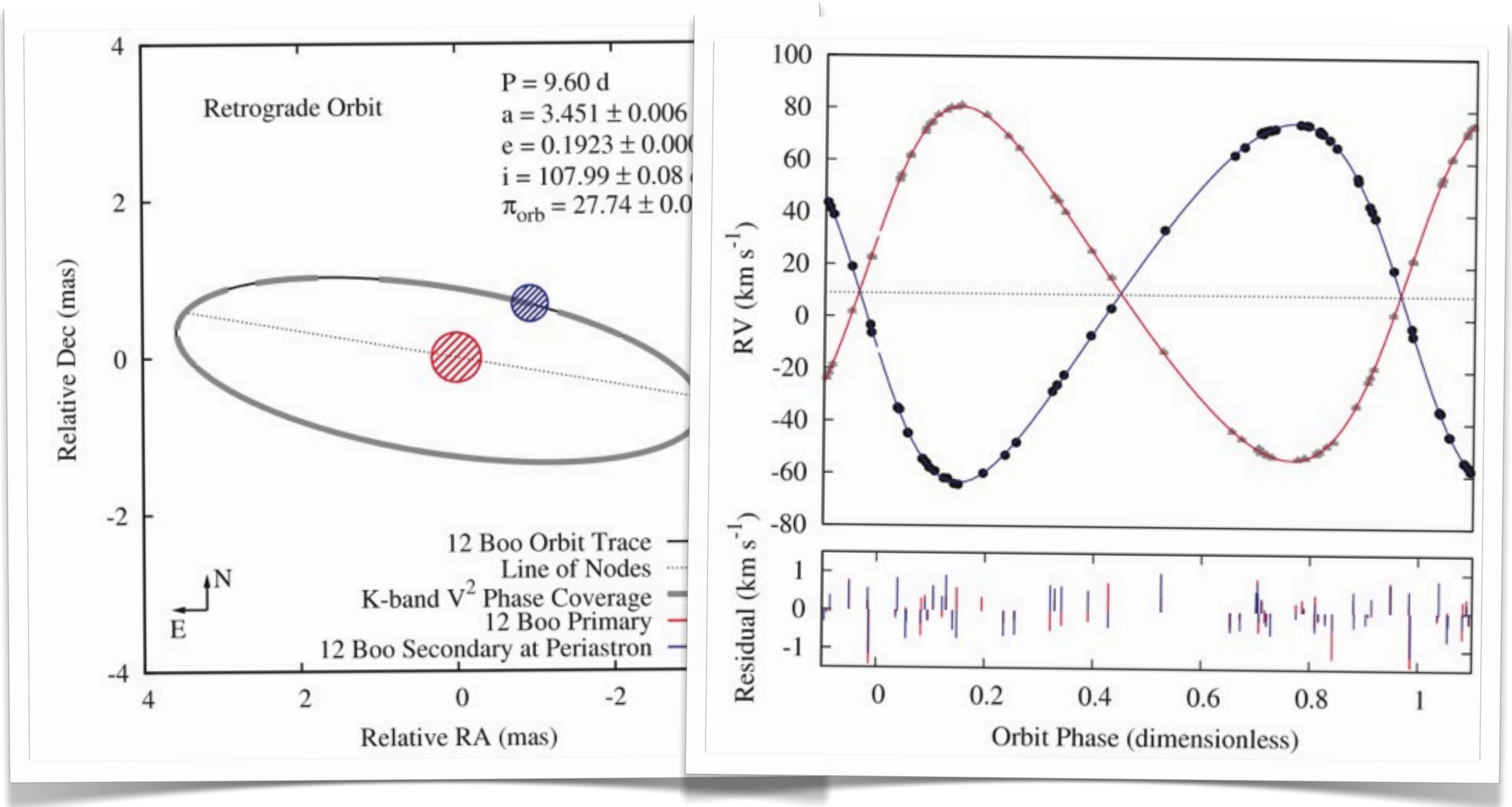
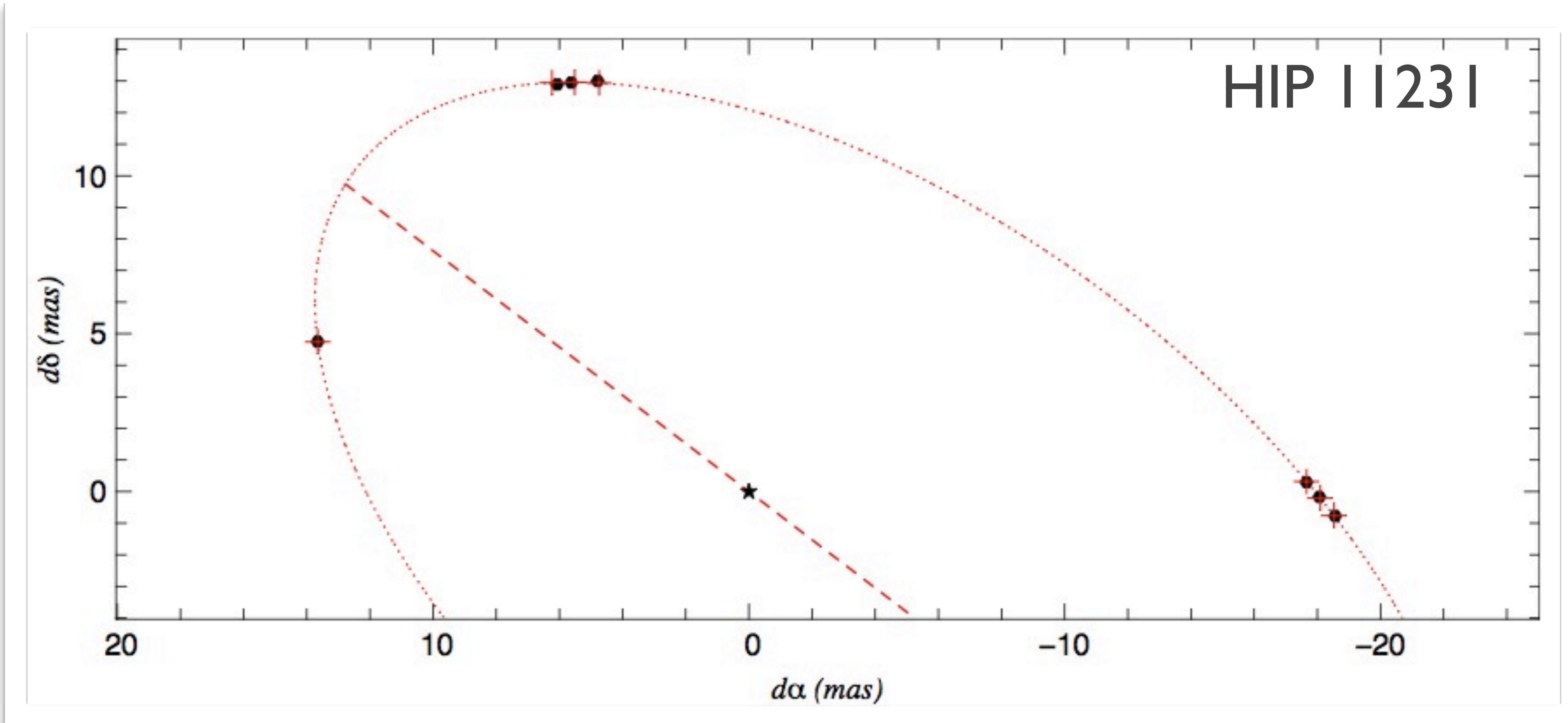


$$M(A) = 1.4160 \pm 0.0049\ M_\odot\ (0.34\%)$$
$$M(B) = 1.3740 \pm 0.0045\ M_\odot\ (0.33\%)$$

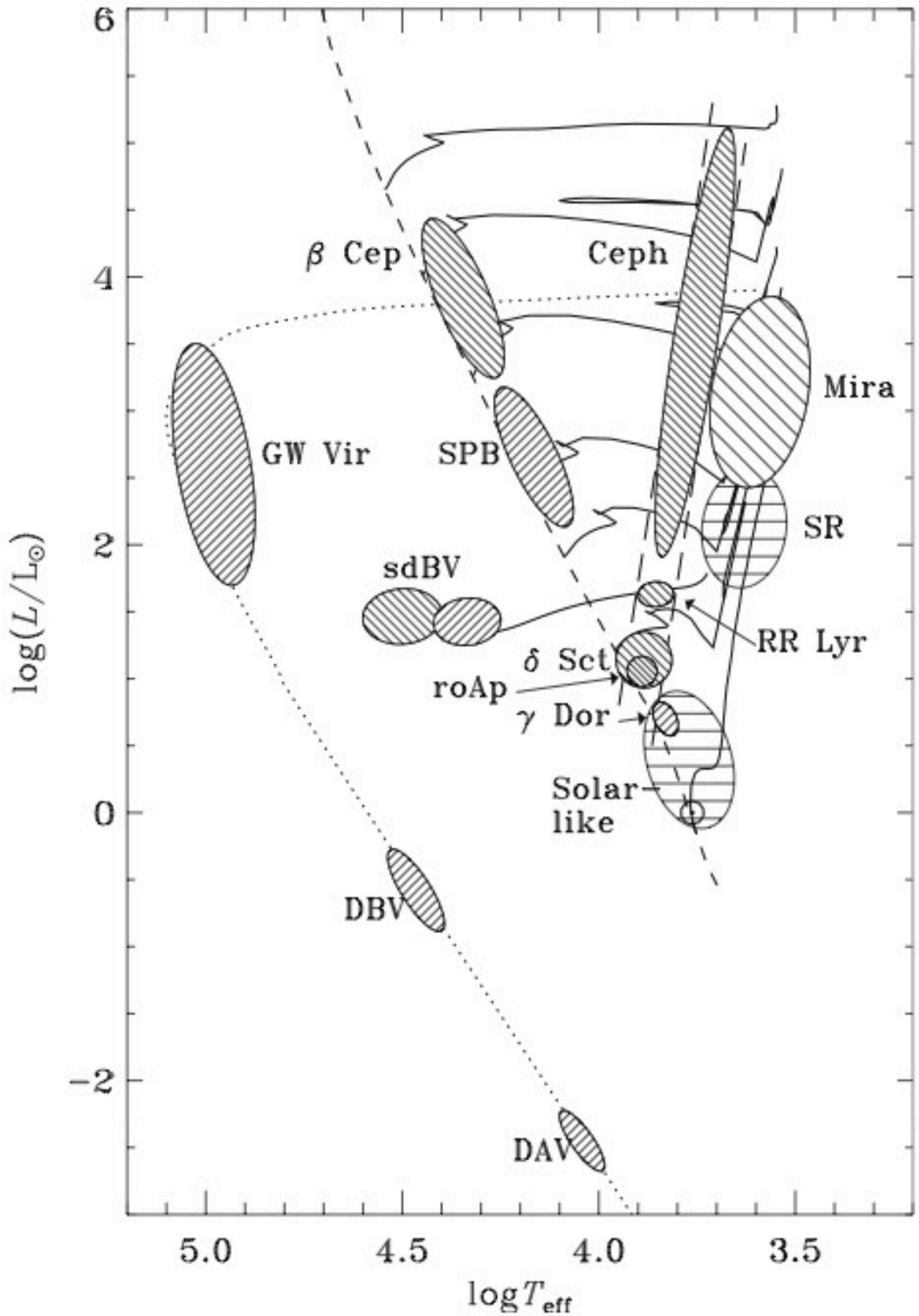
Boden et al. 2005, ApJ, 627, 464

VLTI / PIONIER



Le Bouquin et al. 2011, A&A, in press, arXiv:1109.1918

What next ?



Cunha et al. 2007, Astron Astrophys Rev, 14, 217

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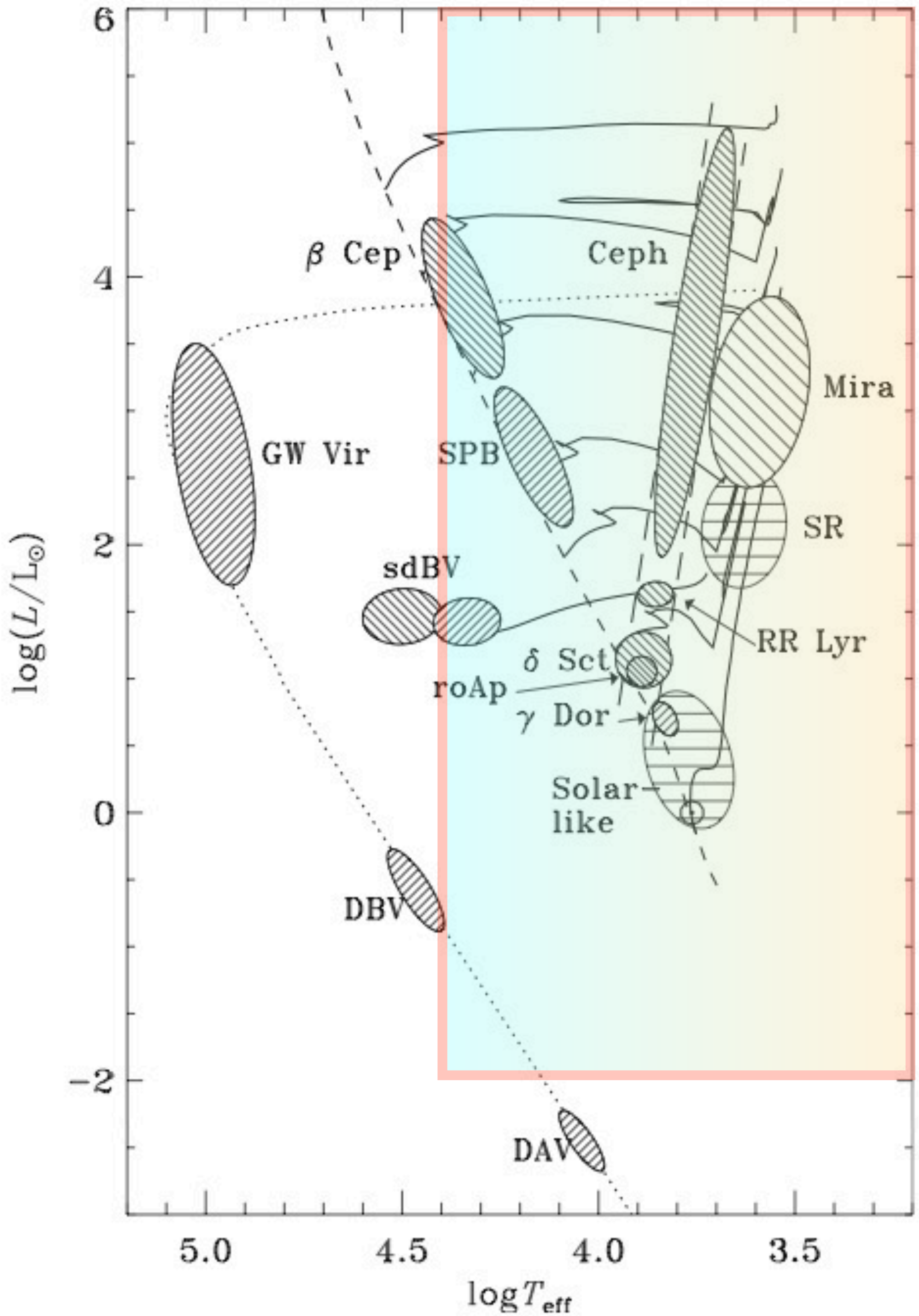

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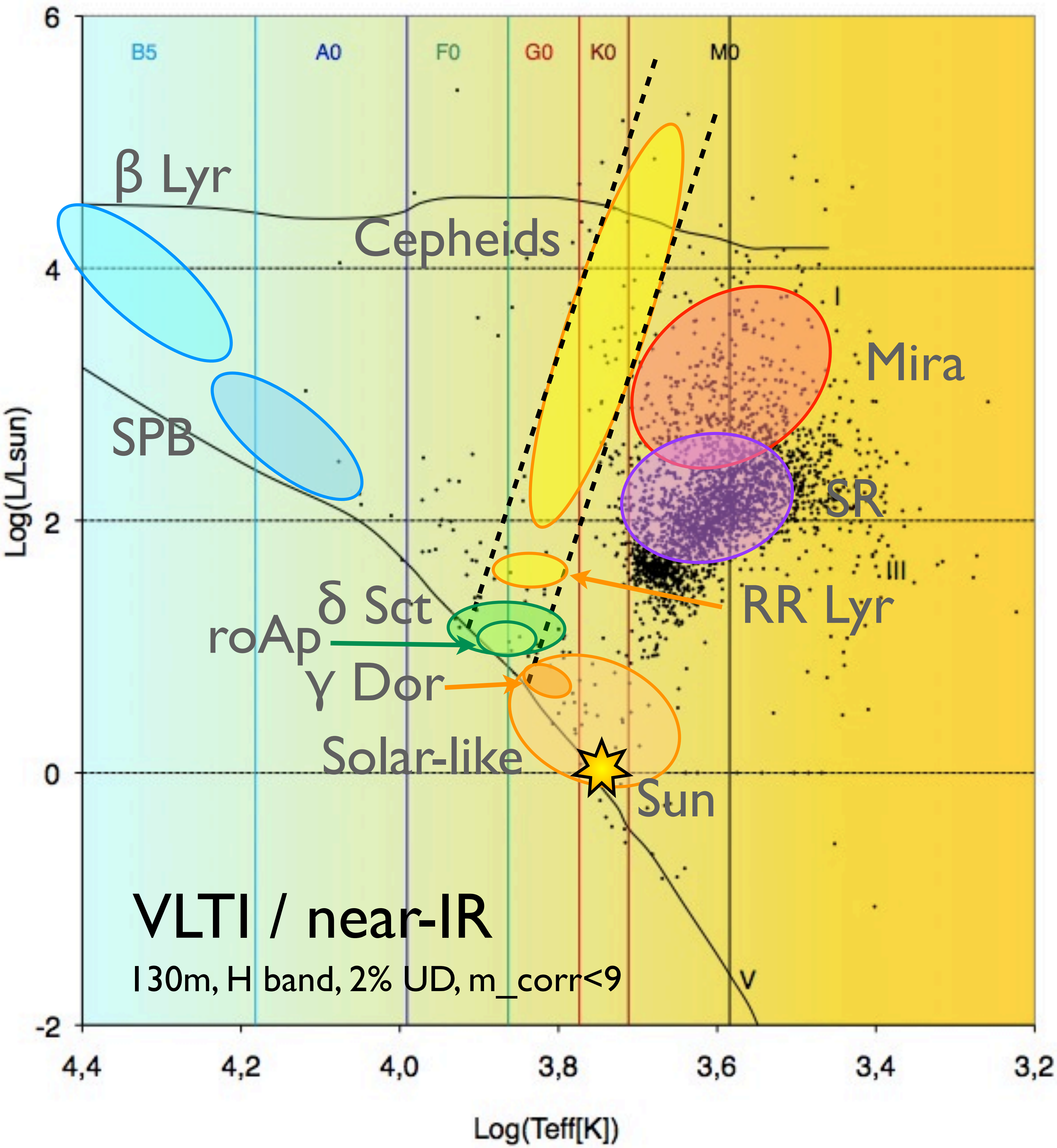
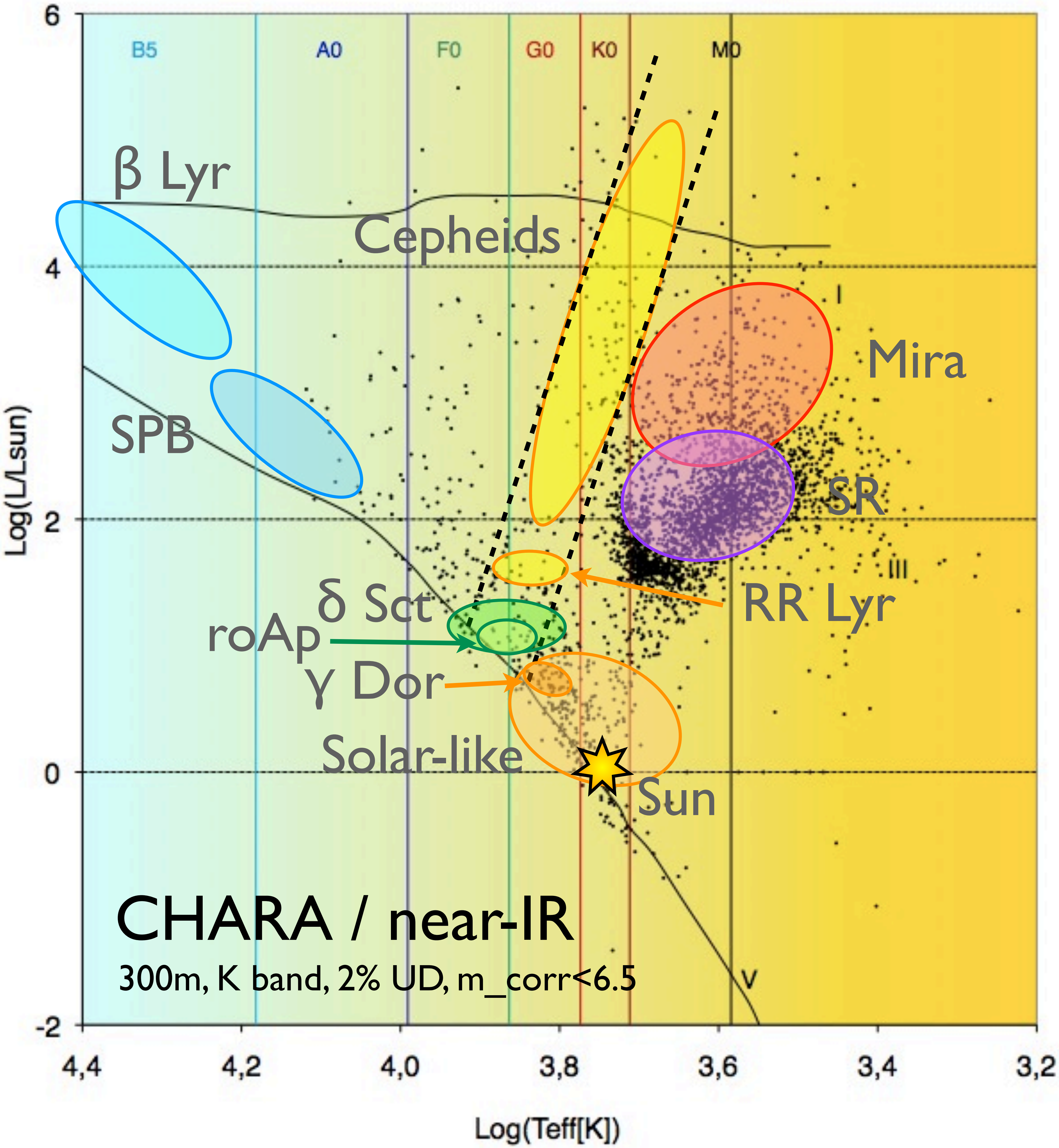

B5
A0
F0
G0
K0
M0
β Lyr
Cepheids
SPB
Mira
SR
RR Lyr
δ Sct
roAp
γ Dor
Solar-like
Sun
I
III
V
VLTI / near-IR
130m, H band, 2% UD, m_corr<9
Log(L/Lsun)
Log(Teff[K])
6
4
2
0
-2
4,4
4,2
4,0
3,8
3,6
3,4
3,2


B5
A0
F0
G0
K0
M0
β Lyr
Cepheids
Mira
SPB
SR
δ Sct
RR Lyr
roAp
γ Dor
Solar-like
Sun
I
III
V
CHARA / near-IR
300m, K band, 2% UD, m_corr<6.5
6
4
2
0
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Log(L/Lsun)
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4,2
4,0
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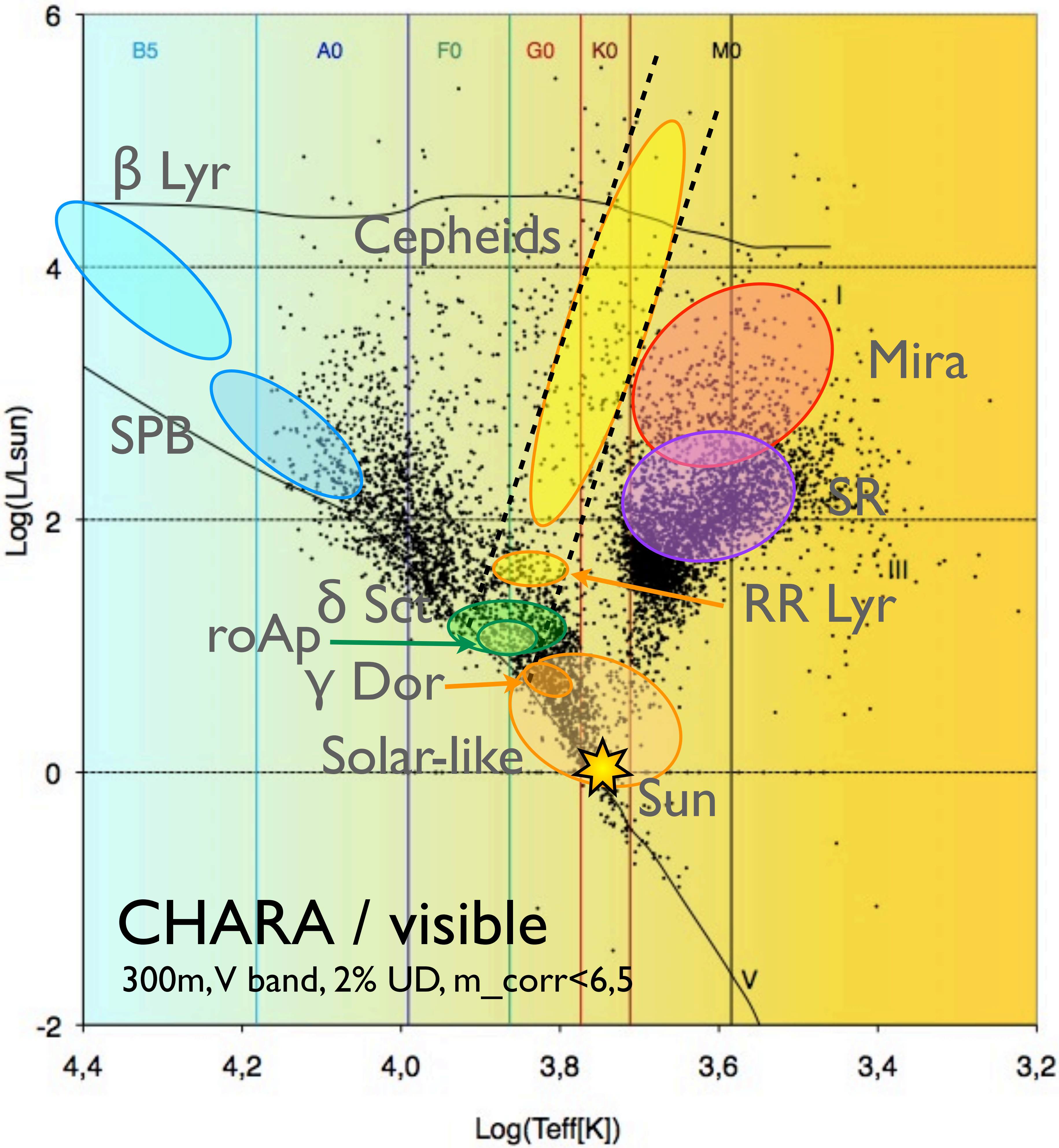
3,2
Log(Teff[K])



B5
A0
F0
G0
K0
M0
β Lyr
Cepheids
SPB
Mira
SR
RR Lyr
δ Sct
roAp
γ Dor
Solar-like
Sun
I
III
V
CHARA / visible
300m, V band, 2% UD, m_corr<6,5
6
4
2
0
-2
Log(L/Lsun)
4,4
4,2
4,0
3,8
3,6
3,4
3,2
Log(Teff[K])

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- Increasing the VLTI angular resolution (B=200m, shorter wavelength) would open up exciting new possibilities