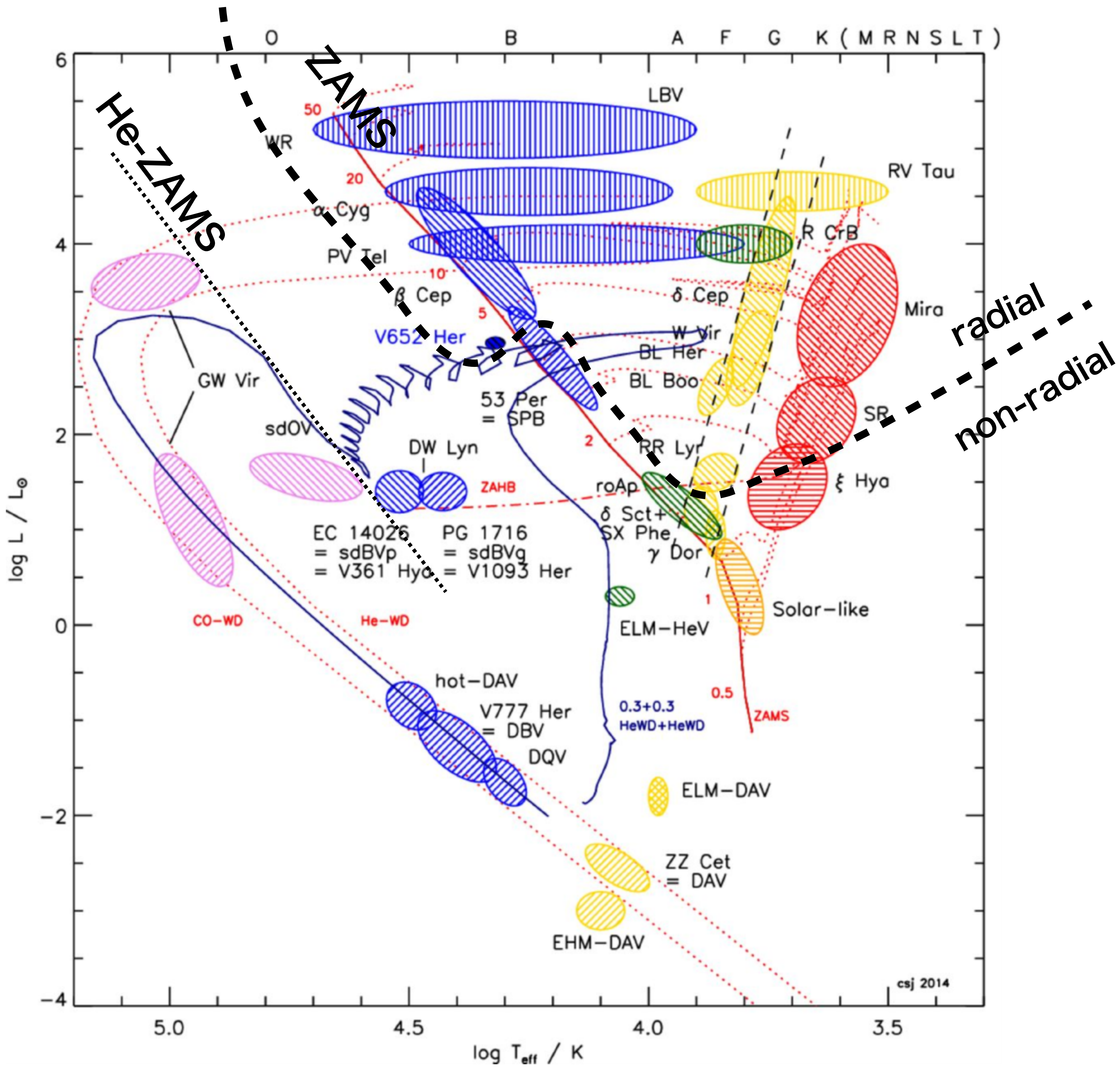
星震学による恒星進化モデルの検証

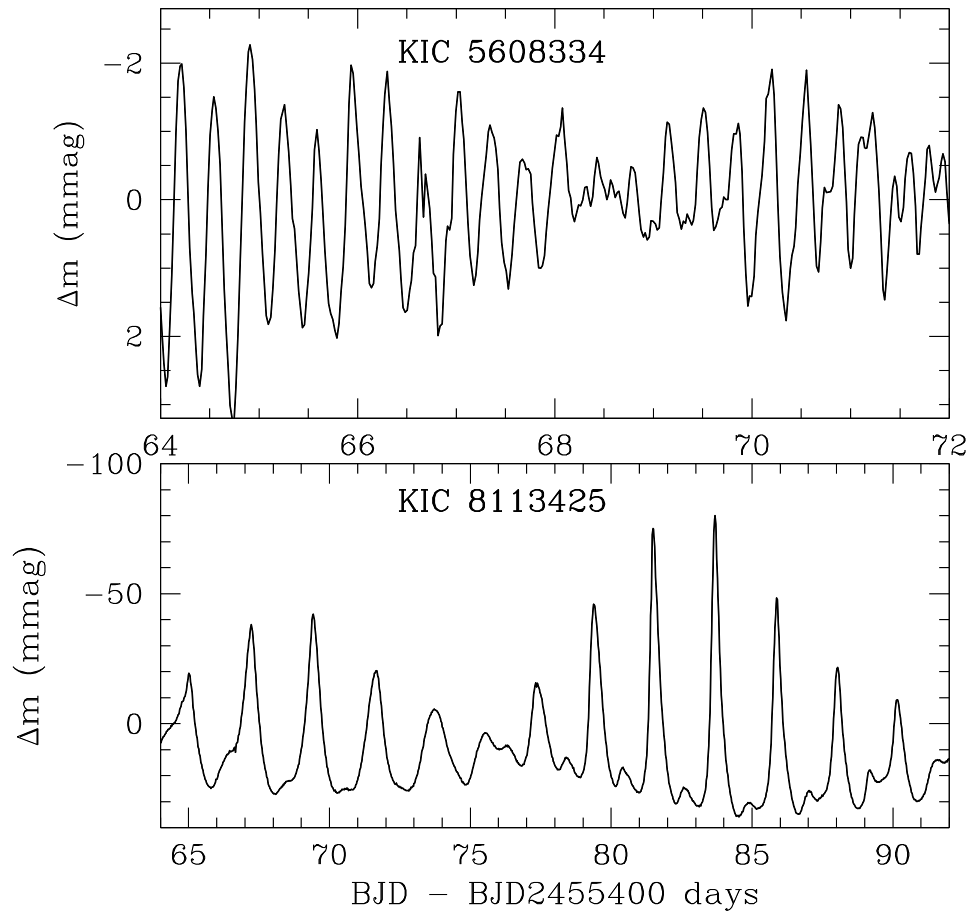
斉尾英行（東北大学）

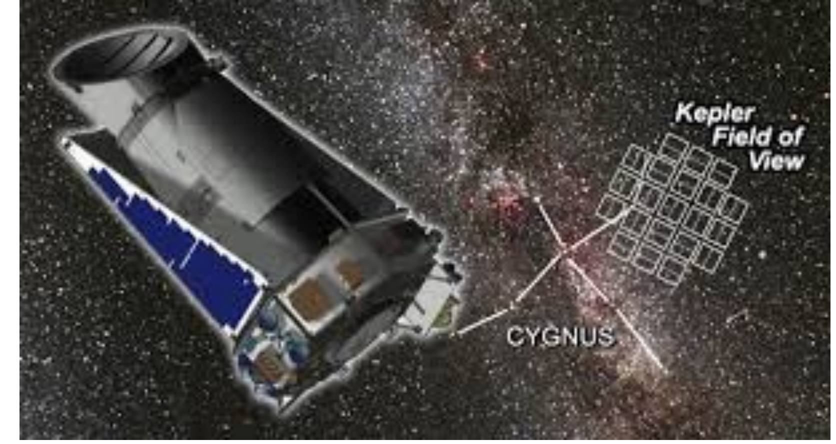
1. 恒星振動(脈動）についての introduction
2. 恒星振動から知る、主系列星・赤色巨星の進化段階と内部自転速度
3. 恒星の振動が示す対流領域の広がり・混合・質量放出など
4. 恒星の振動が示す恒星合体の起こった証拠
5. r modes (Rossby waves in stars)

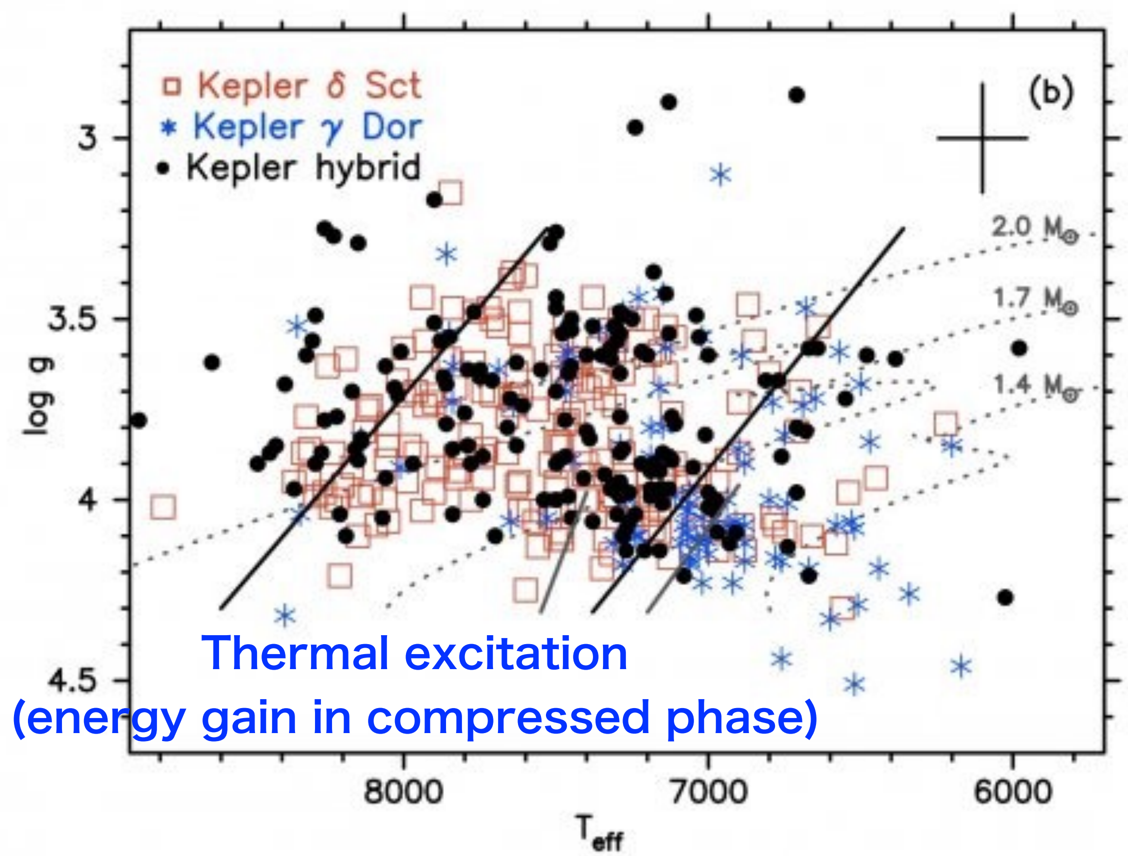
Pulsational variables in the HRD

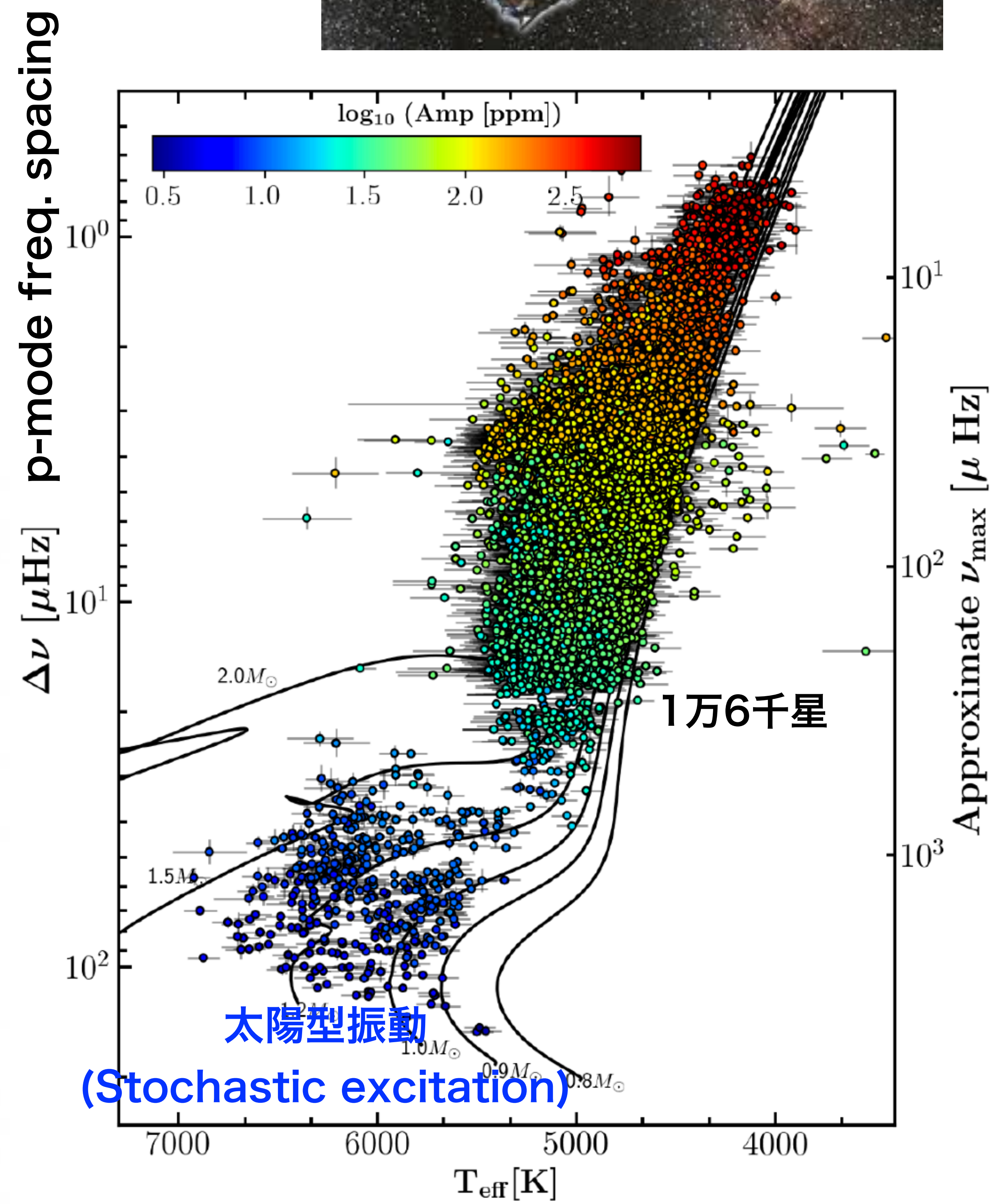


Jeffery et al. (2015)


KIC 5608334
Δm (mmag)
−2
0
2
64
66
68
70
72
KIC 8113425
Δm (mmag)
−100
−50
0
65
70
75
80
85
90
BJD − BJD2455400 days


Kepler
Field of
View
CYGNUS

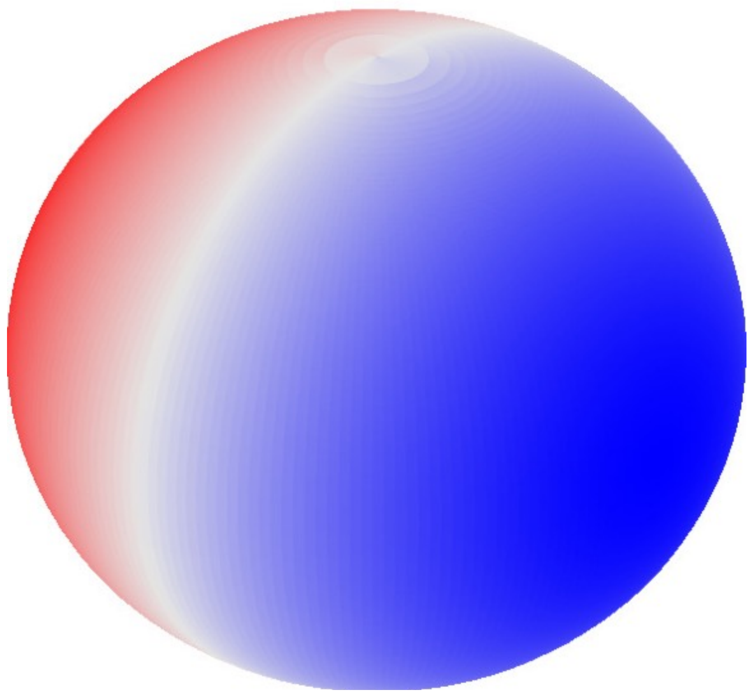

Kepler δ Sct
Kepler γ Dor
Kepler hybrid
(b)
2.0 M⊙
1.7 M⊙
1.4 M⊙
log g
3
3.5
4
4.5
8000
7000
6000
T_eff
Thermal excitation
(energy gain in compressed phase)


p-mode freq. spacing
Δν [μHz]
log₁₀ (Amp [ppm])
0.5
1.0
1.5
2.0
2.5
2.0M⊙
1.5M⊙
1.0M⊙
0.9M⊙
0.8M⊙
1万6千星
太陽型振動
(Stochastic excitation)
7000
6000
5000
4000
T_eff[K]
Approximate ν_max [μ Hz]

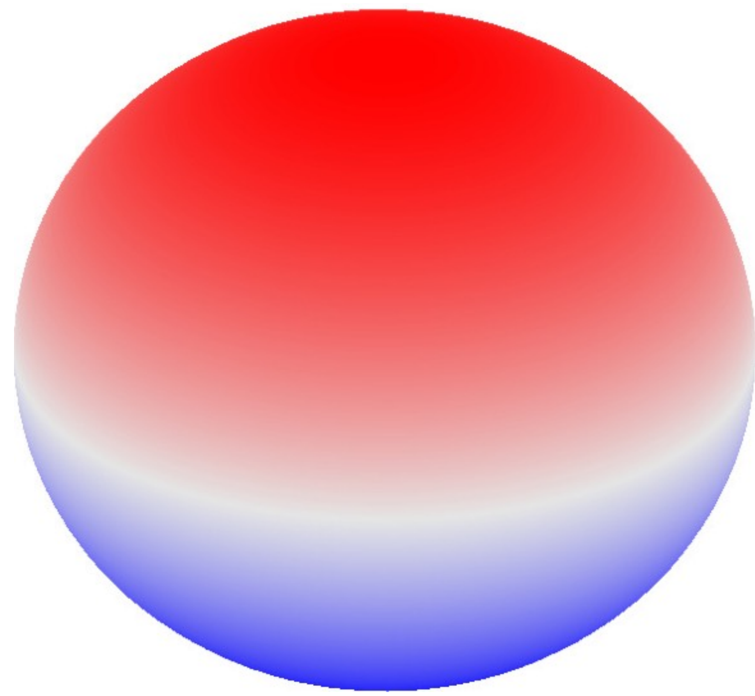
Yu et al. (2018)

Temp. variation of Non-radial pulsations $Y_\ell^m(\theta, \phi)$

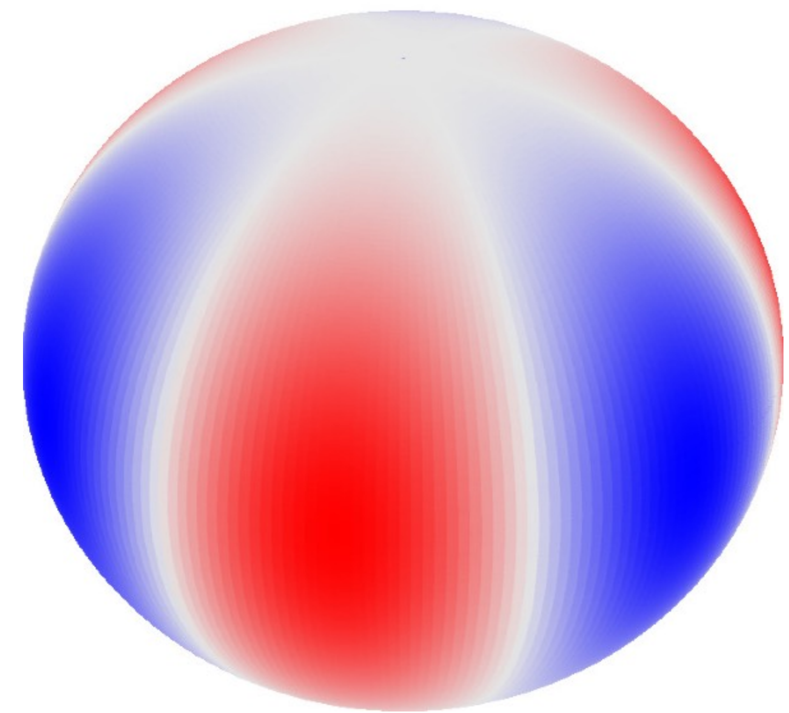
$\ell = 1, m = \pm 1$



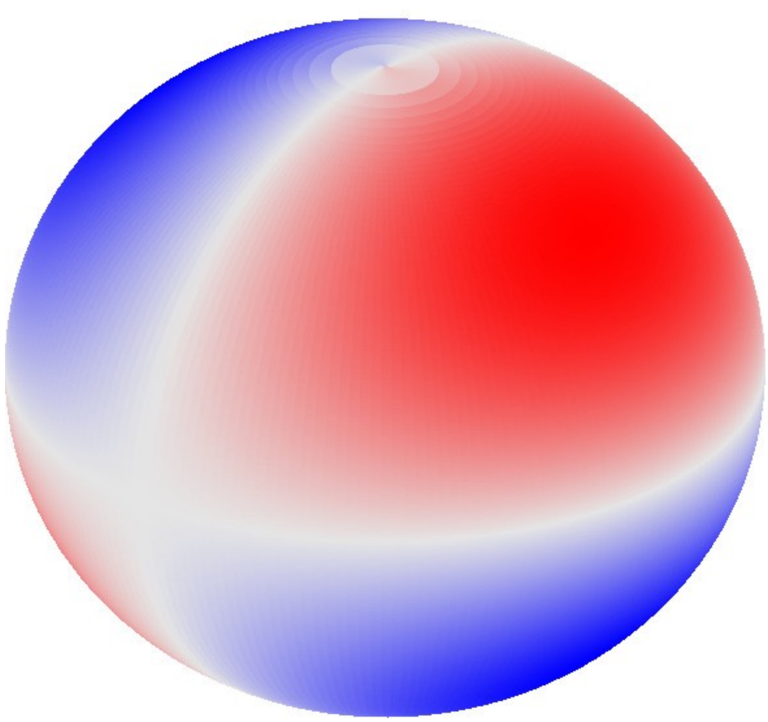
$\ell = 1, m = 0$



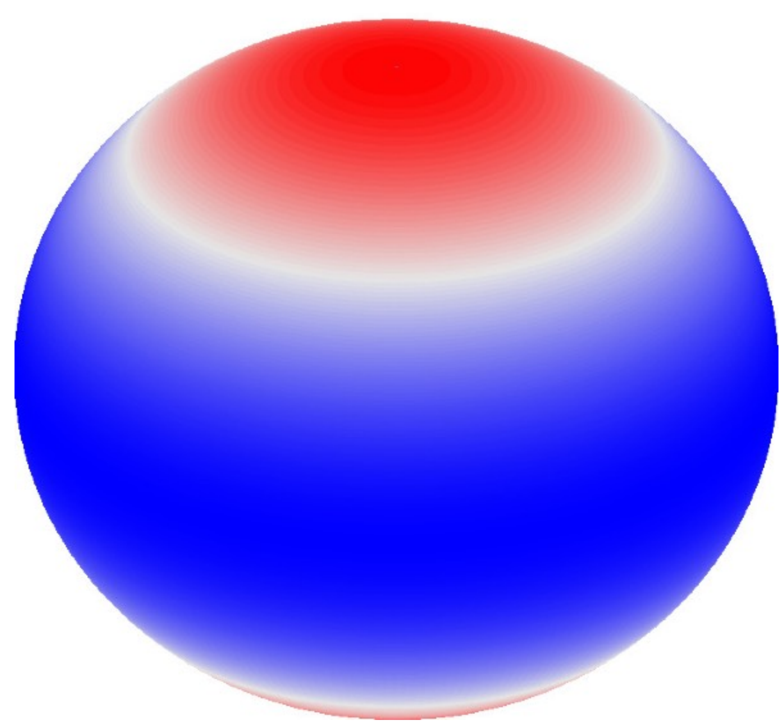
$\ell = 3, m = \pm 3$



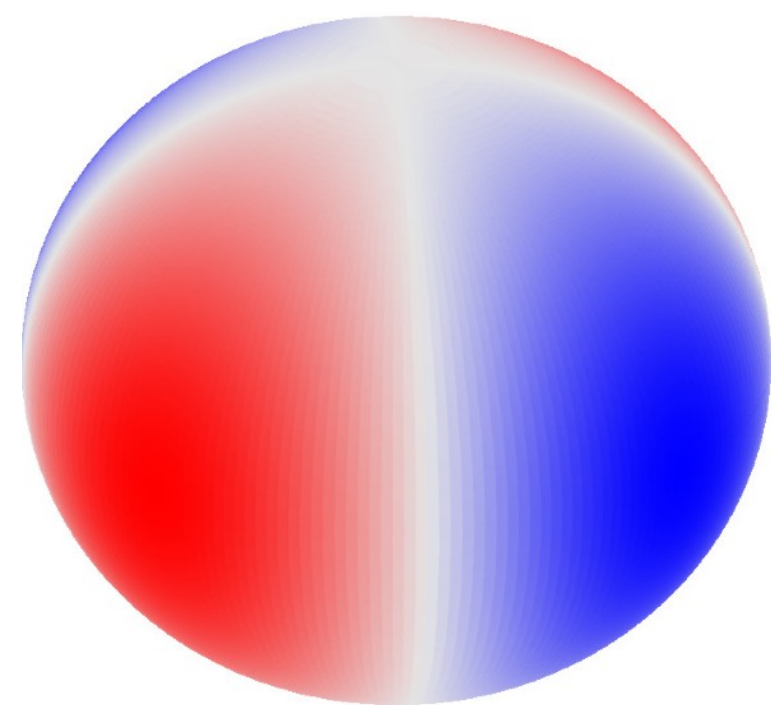
$\ell = 2, m = \pm 1$



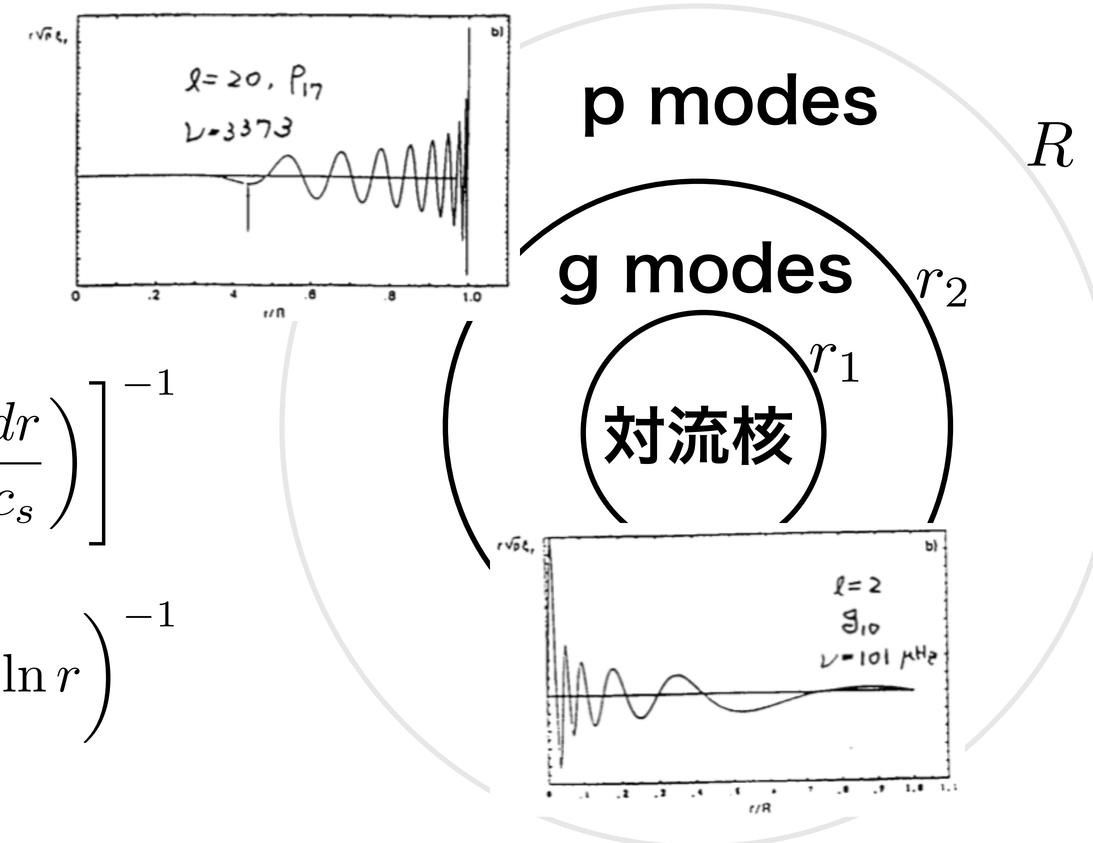
$\ell = 2, m = 0$



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



p modes (radial & non-radial)
と
g modes (non-radial)

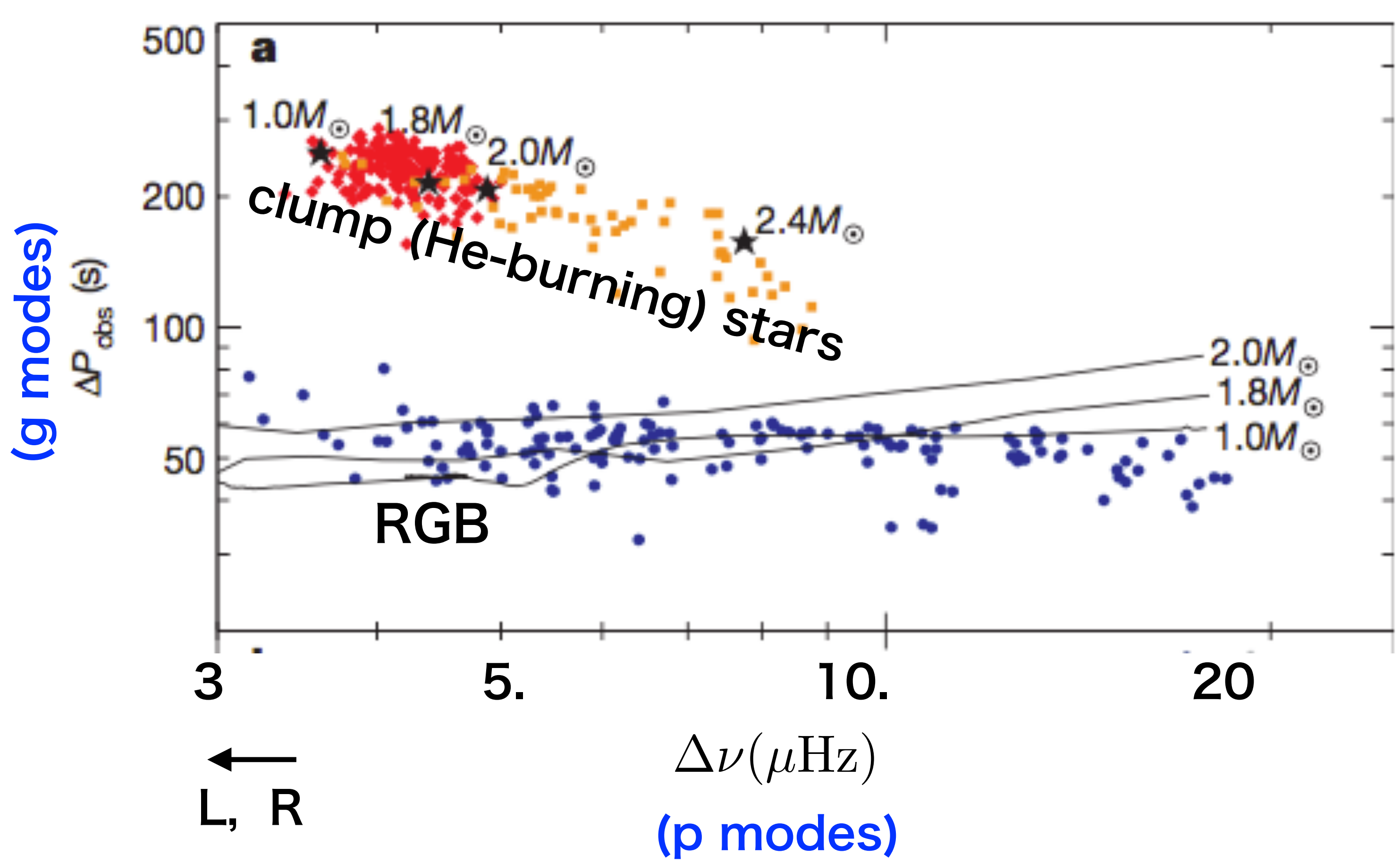


n >> 1

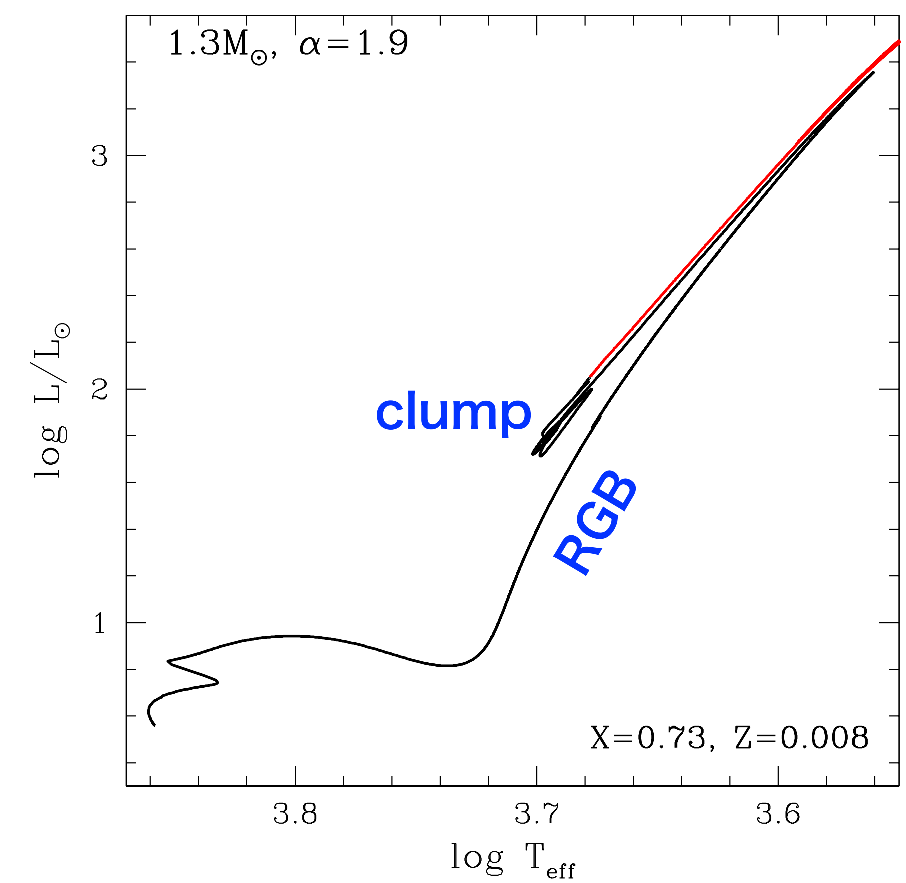
$\nu(\text{p mode}) \approx n\Delta\nu$ **振動数間隔一定** $\Delta\nu = \left[2\int_0^R \left(\frac{dr}{c_s}\right)\right]^{-1}$

$P(\text{g mode}) \approx n\Delta P$ **周期間隔一定** $\Delta P = \frac{\pi}{\sqrt{2}}\left(\int_{r_1}^{r_2} N d\ln r\right)^{-1}$

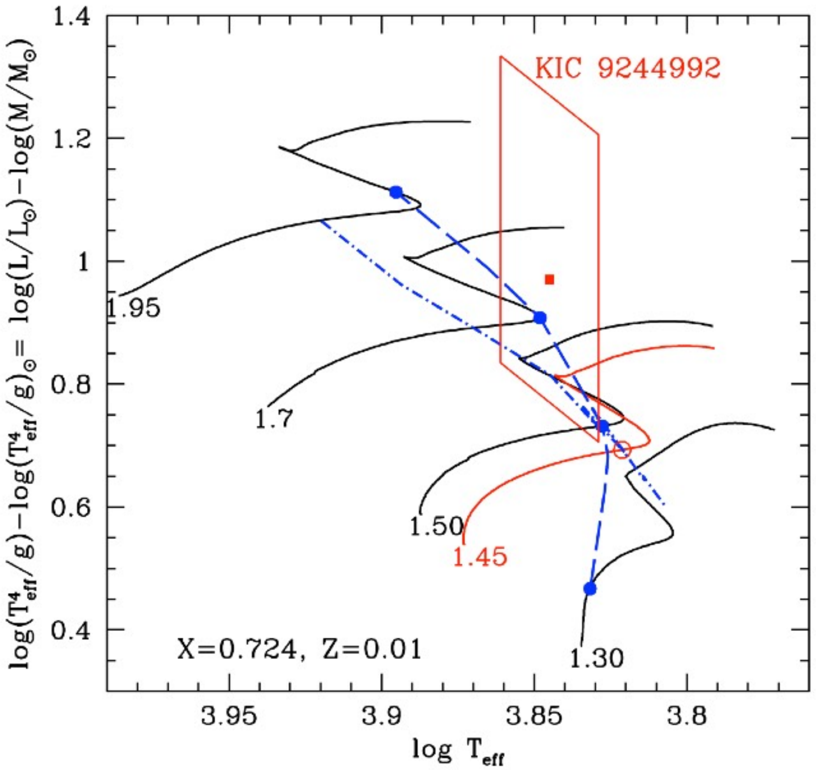
Brunt-Väisälä frequency $N \propto \frac{g}{c_s}$
(浮力による振動の基本振動数)

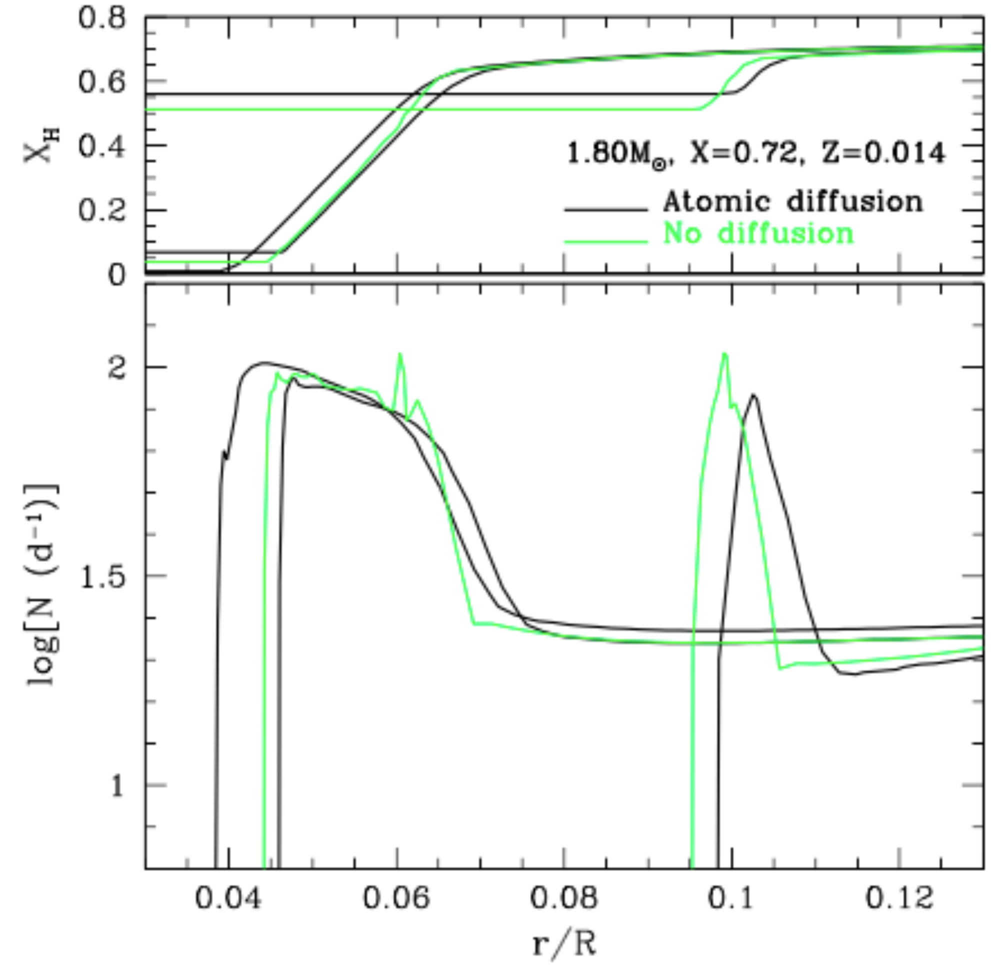


Bedding et al. (2011)

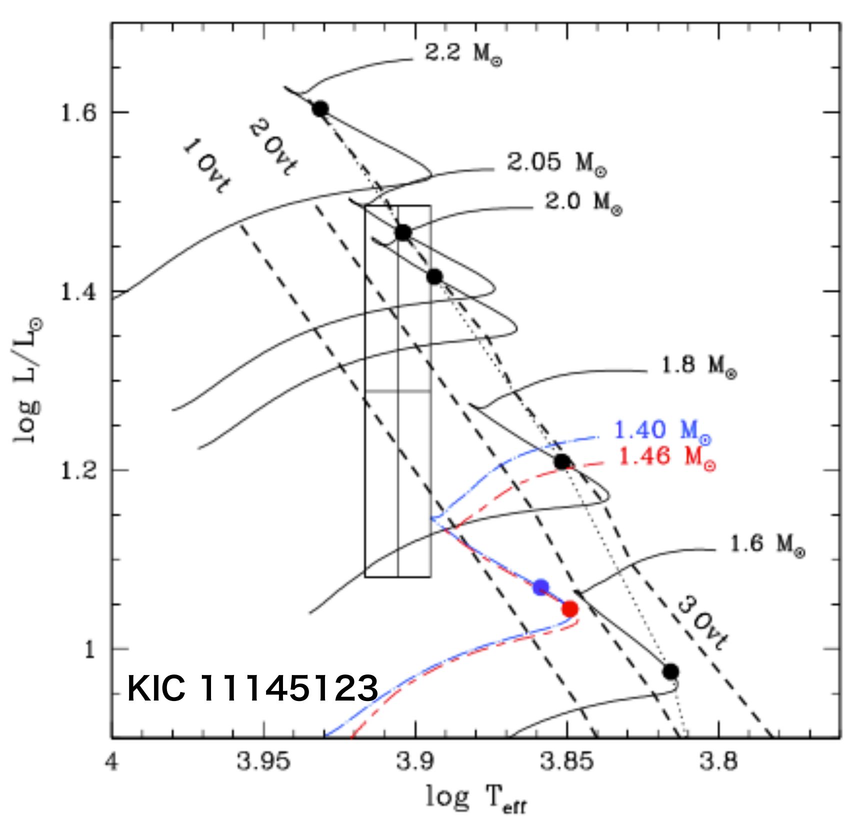


Period spacing of g modes
-- evolution stage &
atomic (or turbulent) diffusion

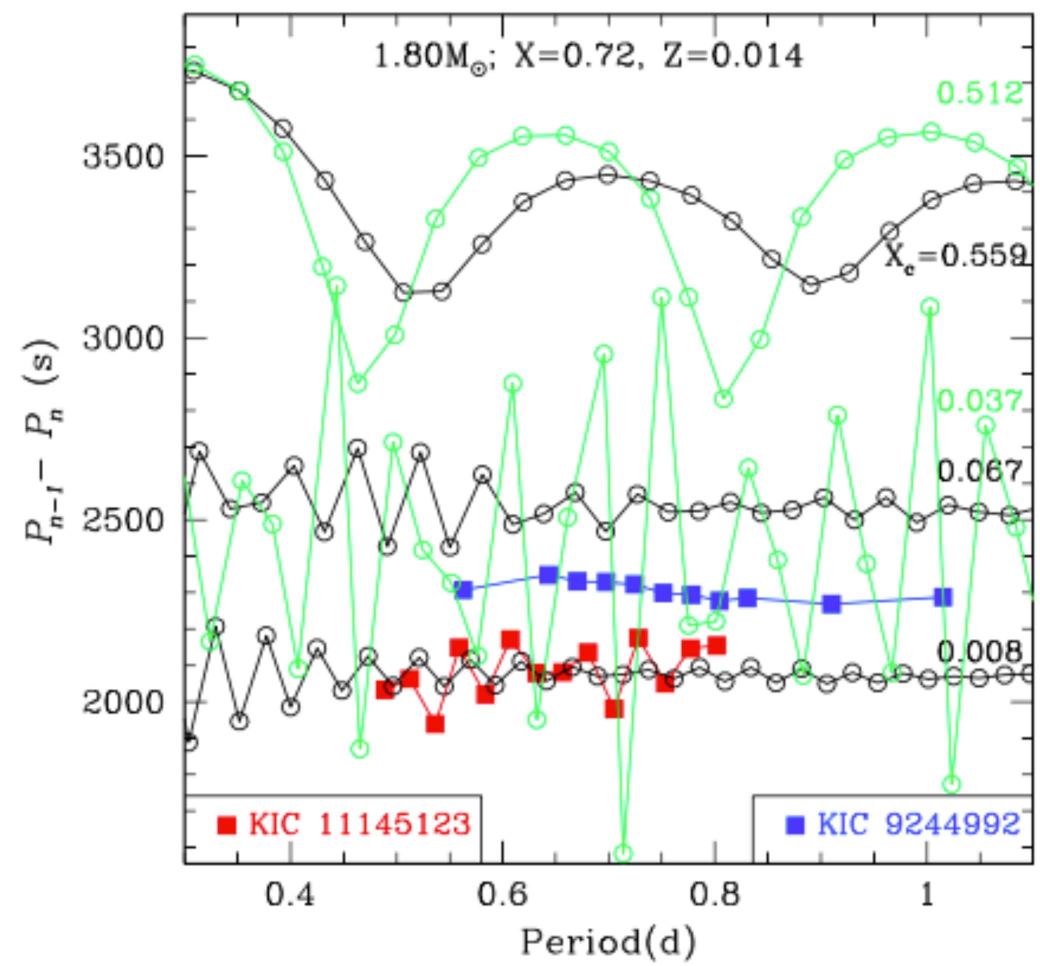




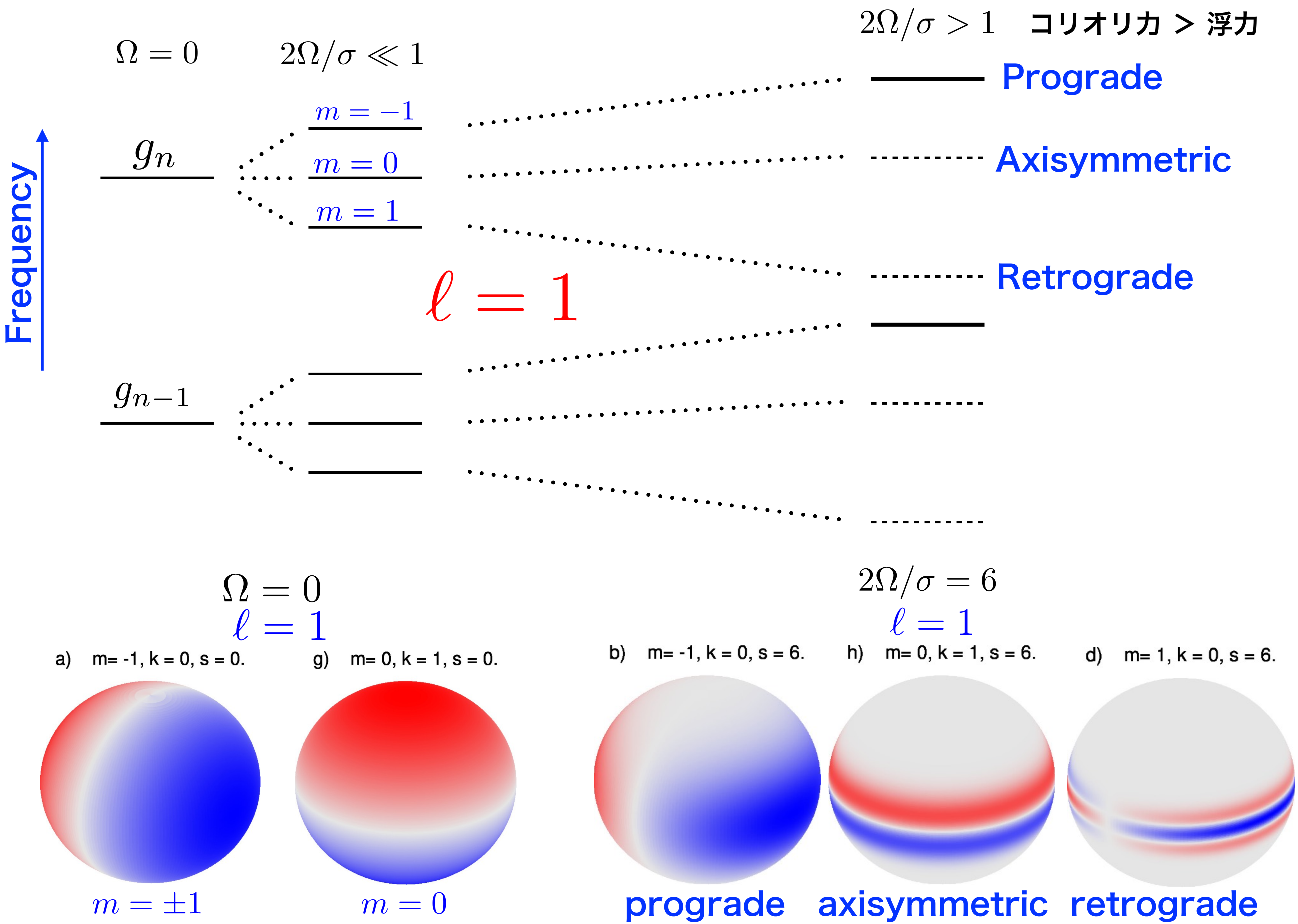
Atomic diffusion
or diffusion by weak
turbulence must be
occurring



period-spacing of g modes



Rotation effects on Nonradial pulsations

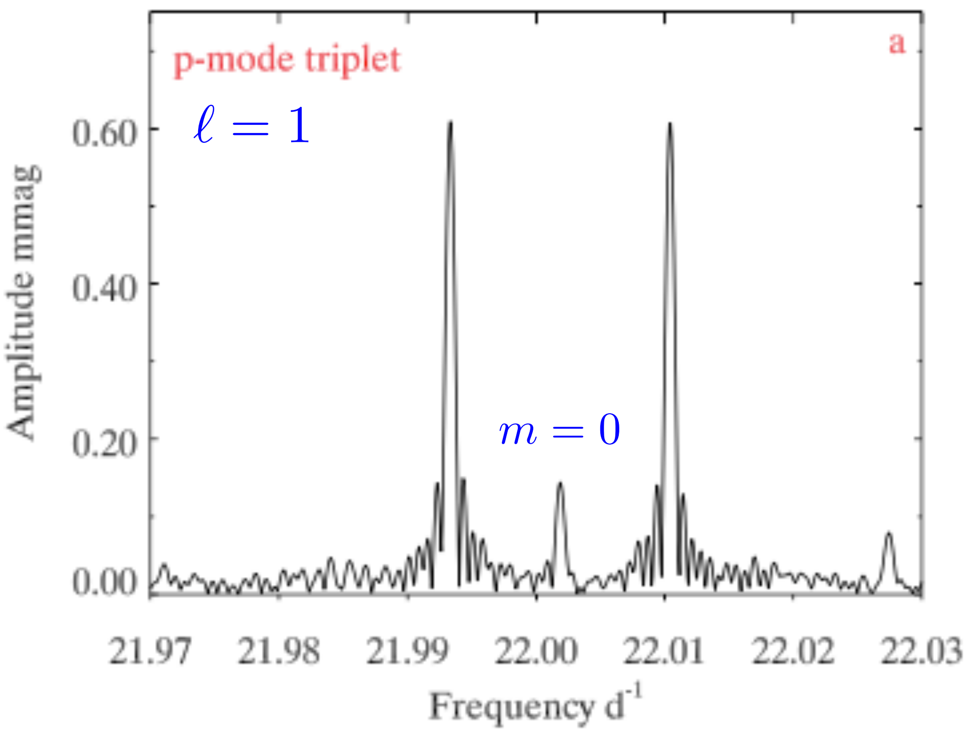


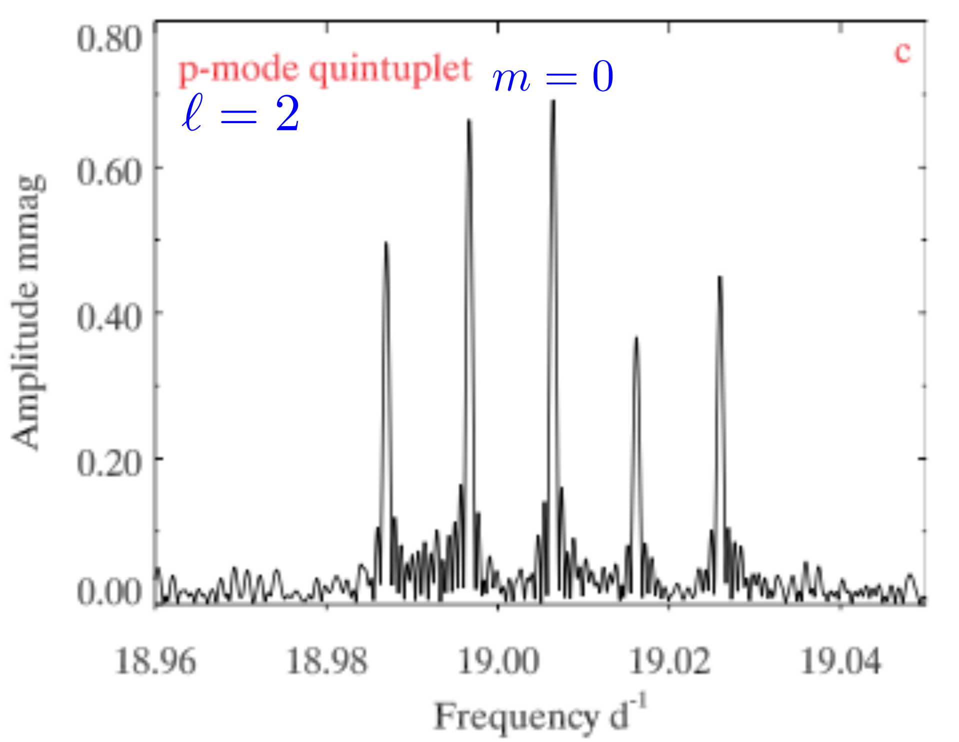
Appearance of rotation effects

Slow rotation

$$\frac{2\nu_{\rm rot}}{\nu_{\rm nonrot}} \ll 1 \;\&\; 2\pi\nu_{\rm rot} \ll \sqrt{\frac{GM}{R^3}}$$

$$\nu_{\rm obs} = \nu_{\rm non-rot} - m(1 - C_{n,\ell})\nu_{\rm rot}$$



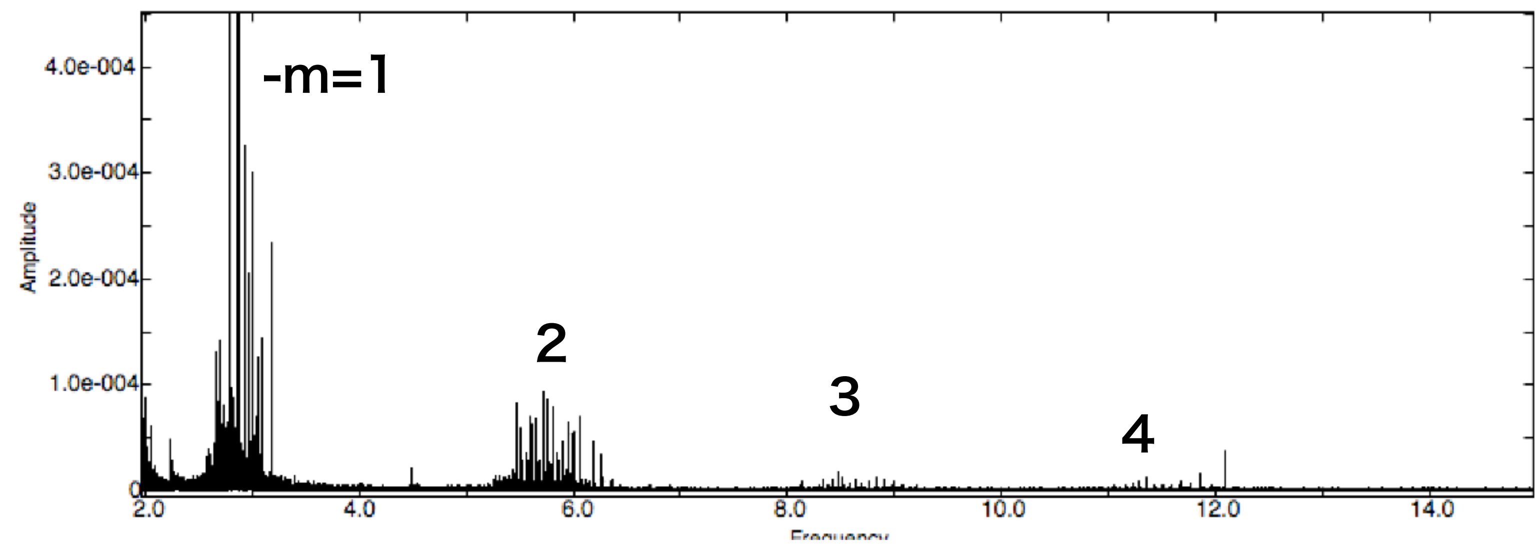


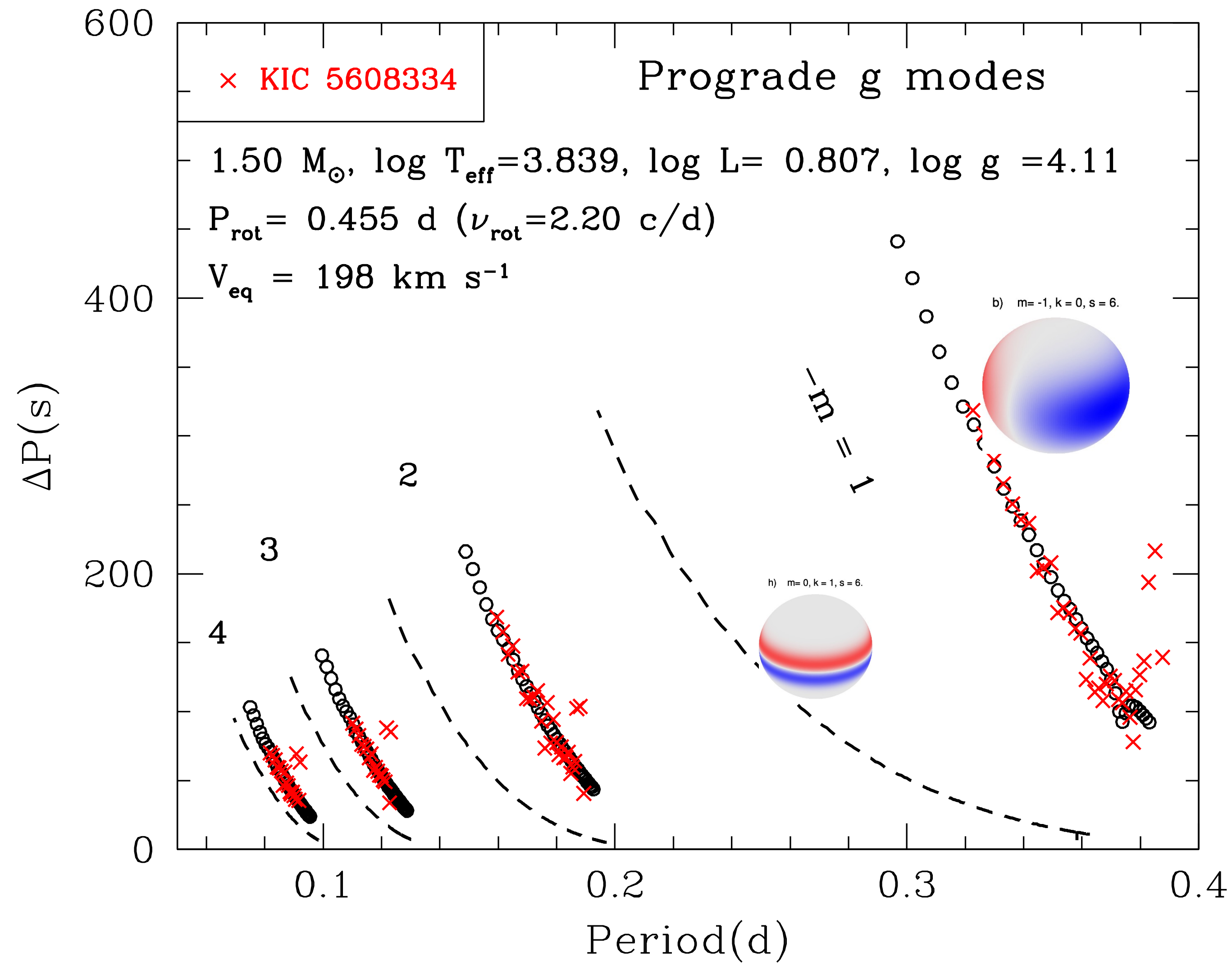
Fast rotation

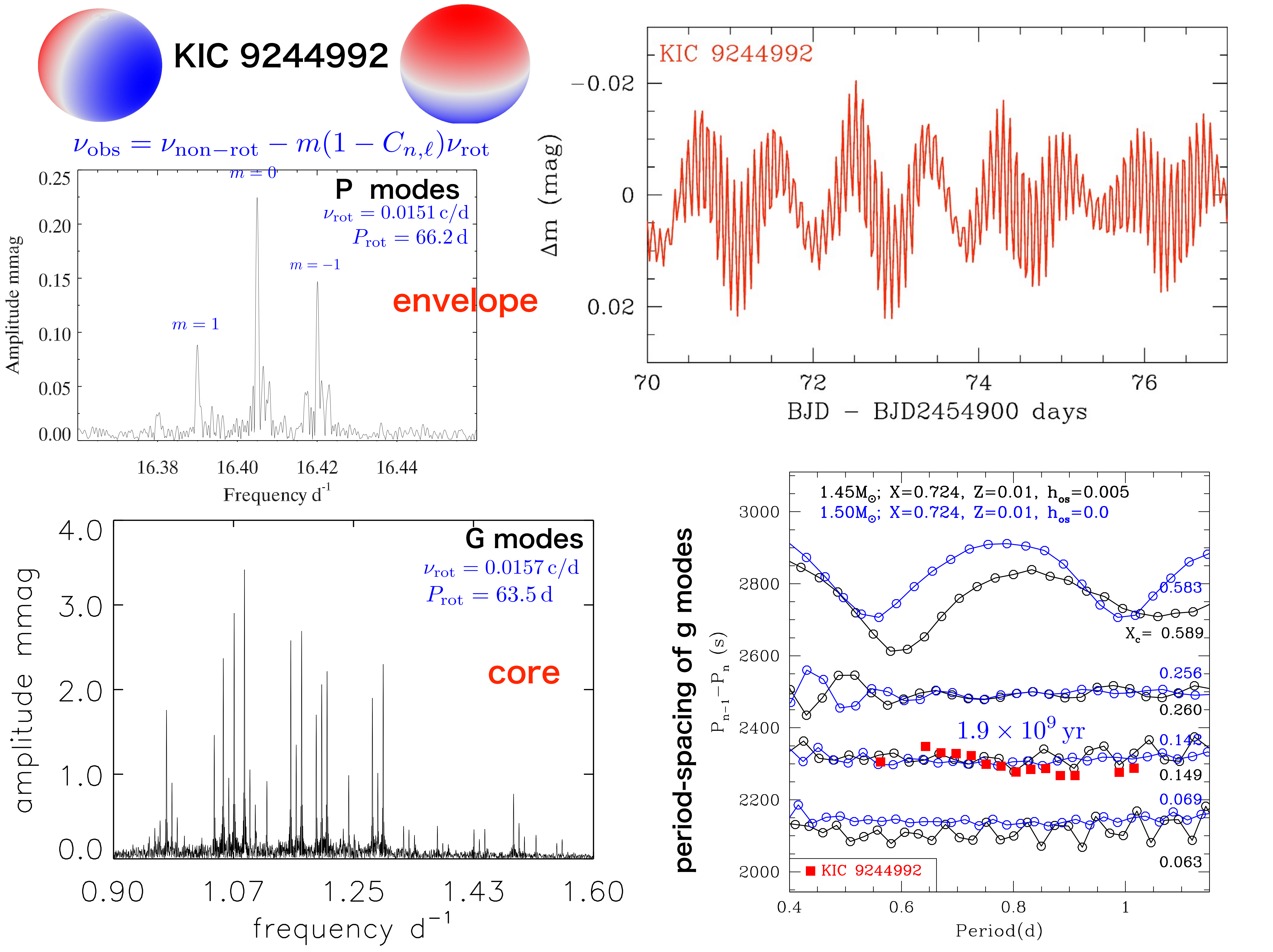
$$2\nu_{\rm rot} > \nu_{\rm co-rot}$$

$$P_{\rm obs} = (\nu_{\rm co-cot} - m\nu_{\rm rot})^{-1}$$

g modes







KIC 9244992
$\nu_{obs} = \nu_{non-rot} - m(1 - C_{n,\ell})\nu_{rot}$
P modes
$\nu_{rot} = 0.0151$ c/d
$P_{rot} = 66.2$ d
envelope
m = 0
m = −1
m = 1
Amplitude mmag
Frequency d^{-1}
KIC 9244992
Δm (mag)
BJD − BJD2454900 days
G modes
$\nu_{rot} = 0.0157$ c/d
$P_{rot} = 63.5$ d
core
amplitude mmag
frequency d^{-1}
period-spacing of g modes
$P_{n-1}-P_n$ (s)
1.45M$_\odot$; X=0.724, Z=0.01, h$_{os}$=0.005
1.50M$_\odot$; X=0.724, Z=0.01, h$_{os}$=0.0
X$_c$= 0.589
0.583
0.256
0.260
1.9×10^9 yr
0.142
0.149
0.069
0.063
KIC 9244992
Period(d)

Rotation speeds in the core and the envelope

(g modes) (p modes)

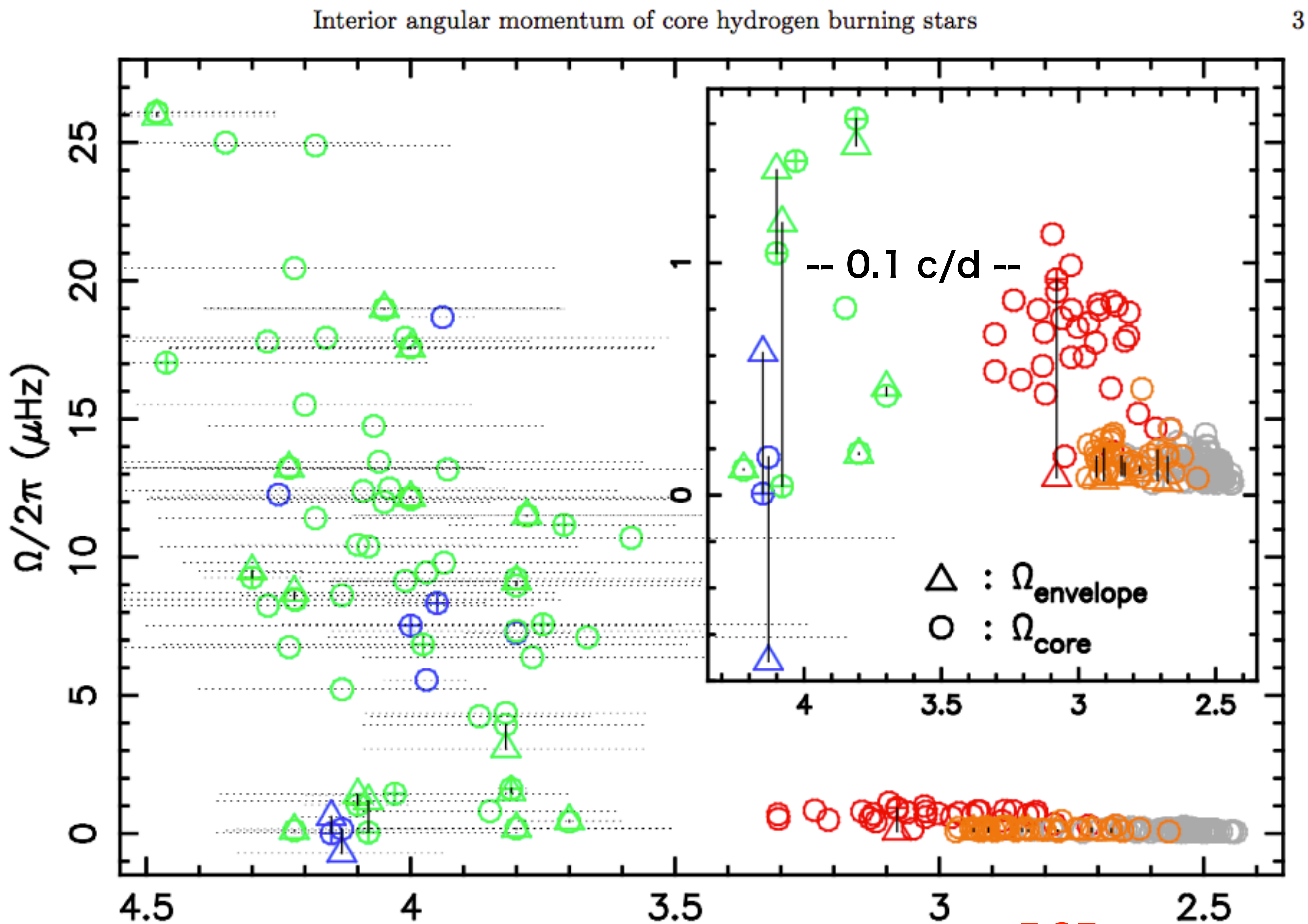
Rotation frequency

2 c/d

1 c/d

0.5 c/d

0.1 c/d



main sequence

log g (cgs)

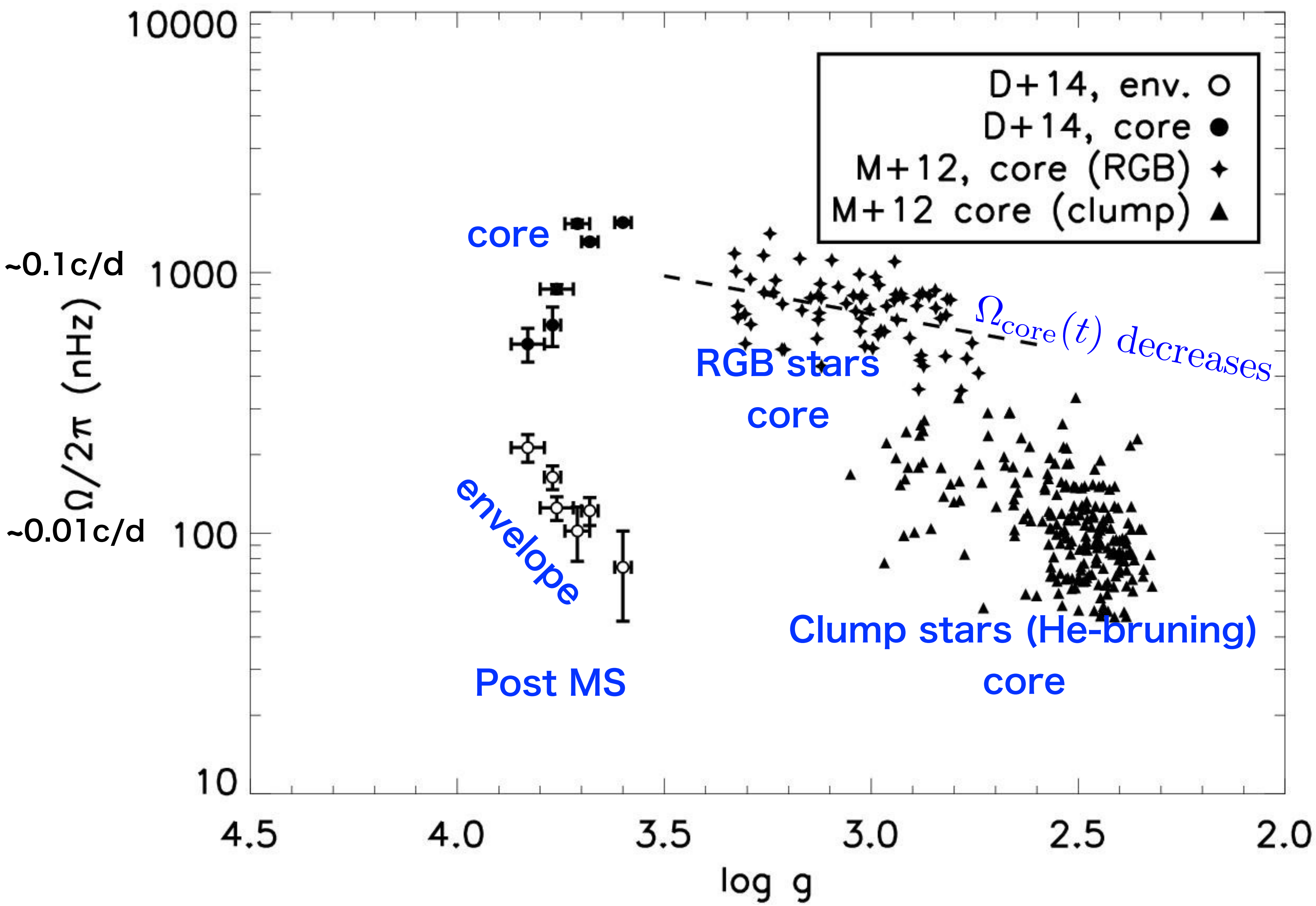
RGB

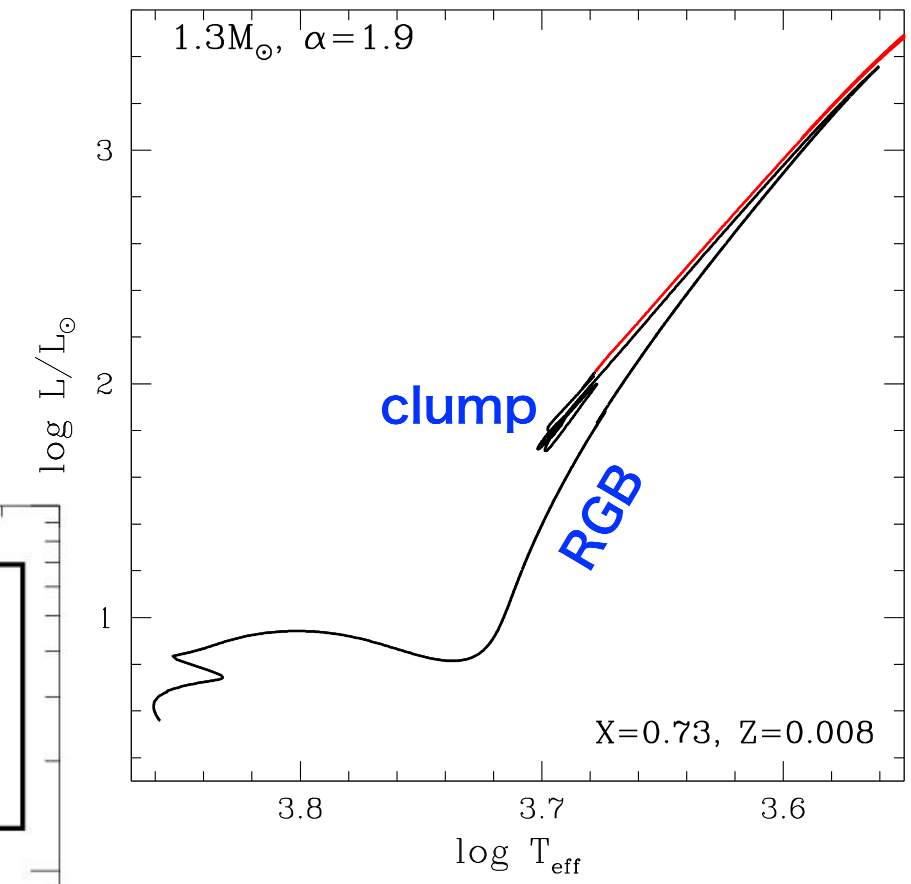
red clump

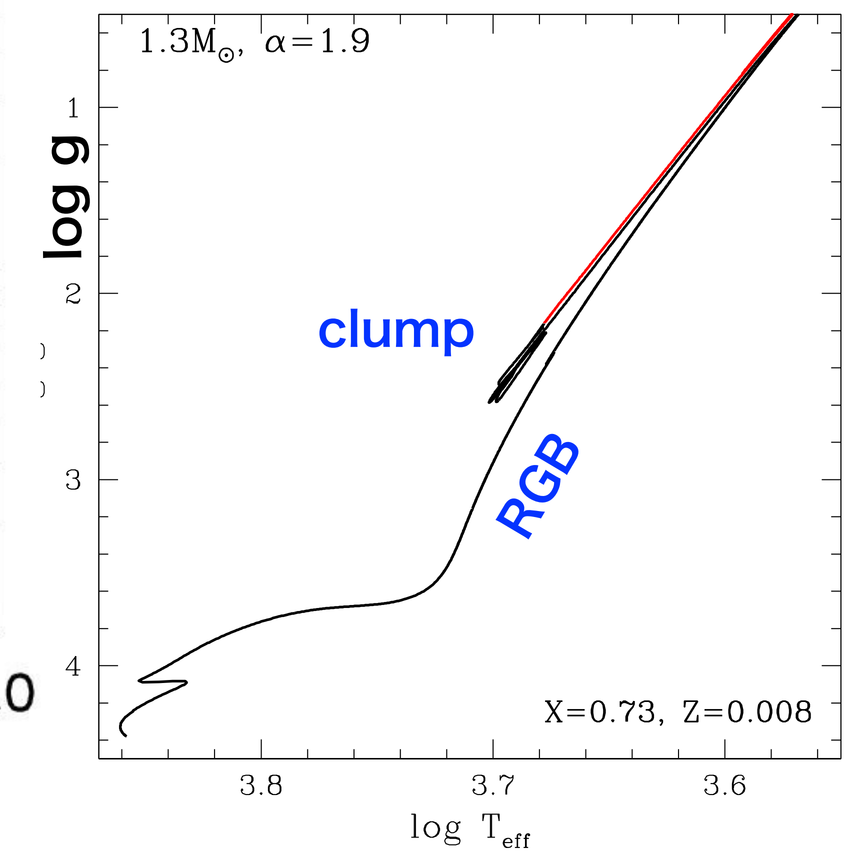
$1.6 \sim 2.0 M_\odot$ $3 \sim 5 M_\odot$

Aerts et al (2017)

sub-giant and RGB stars
の自転速度の進化

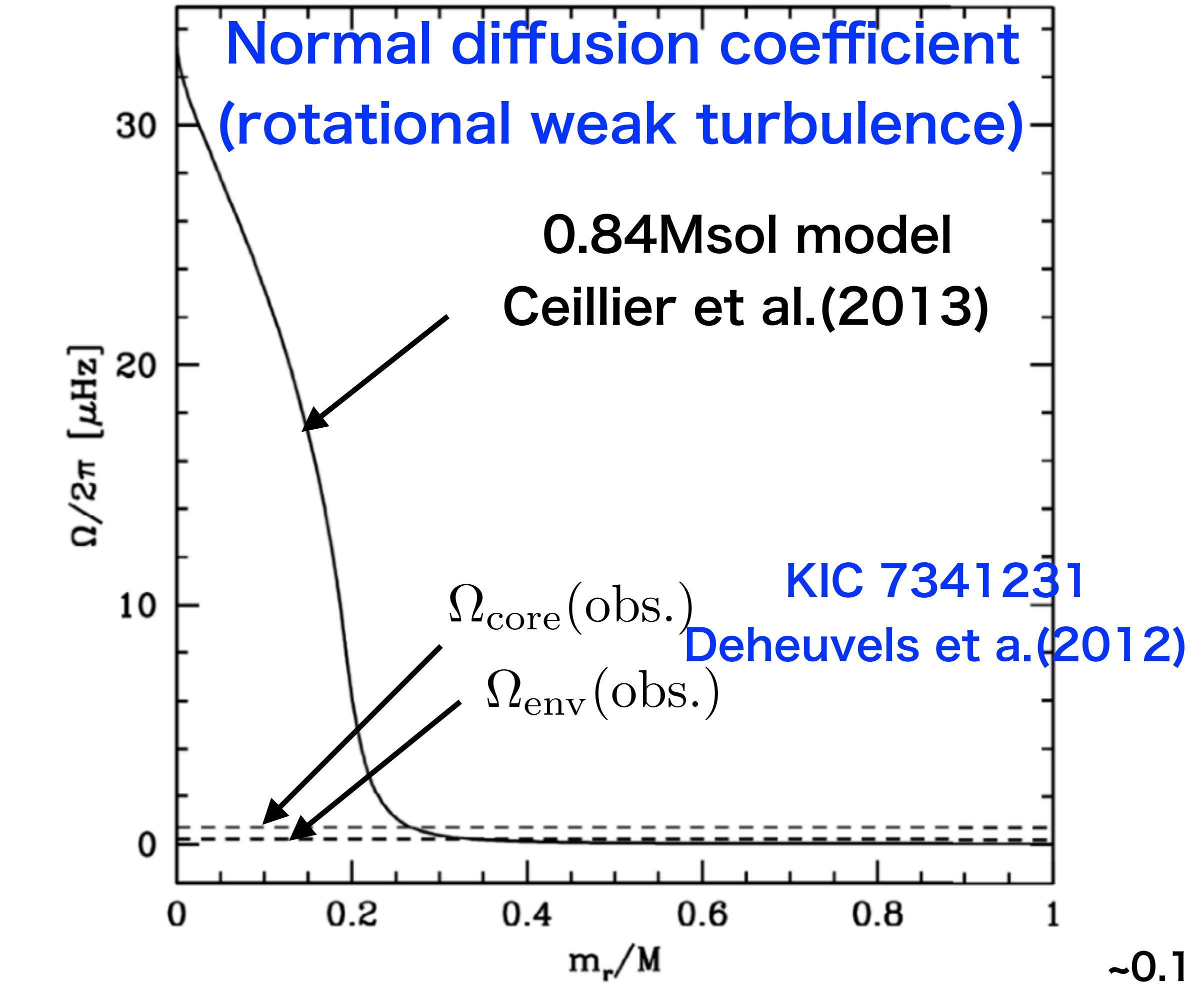






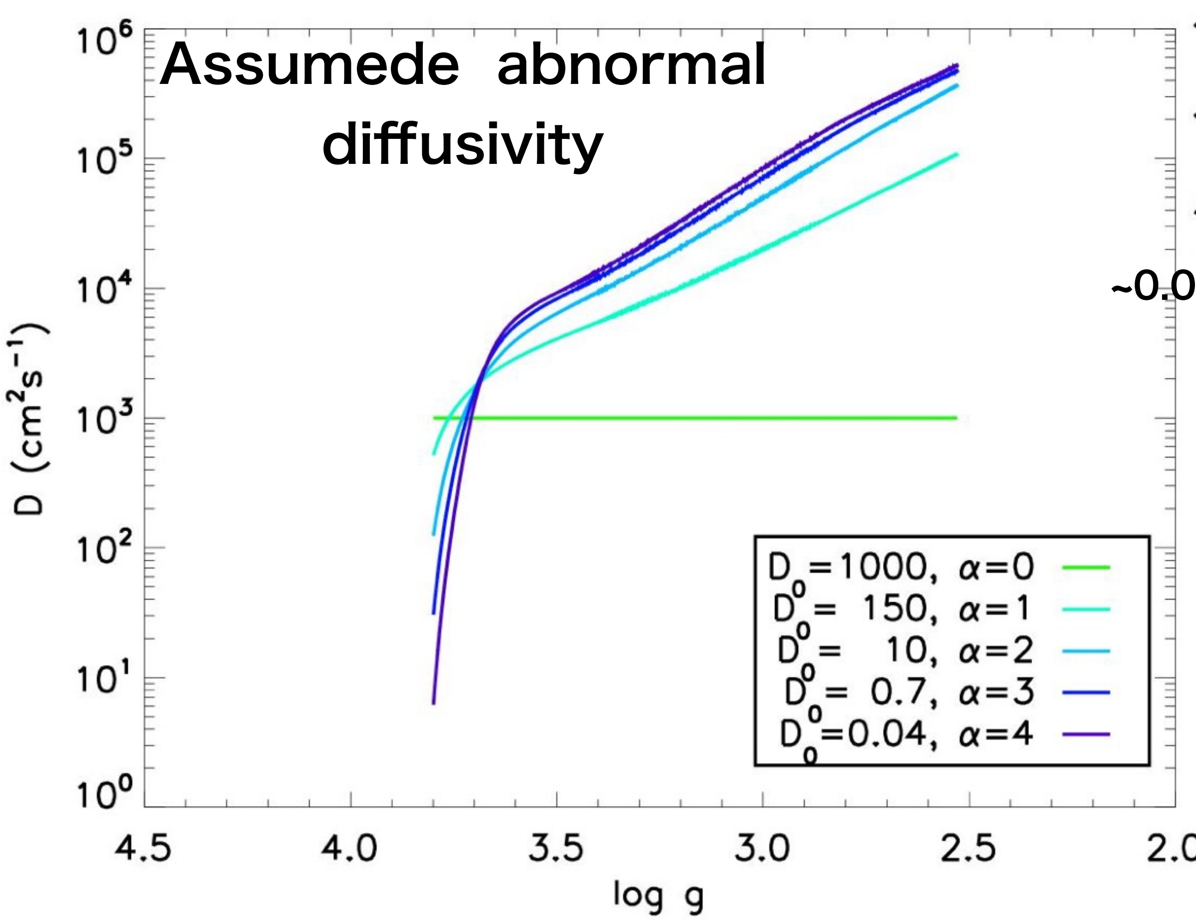
Spada et al. (2016)

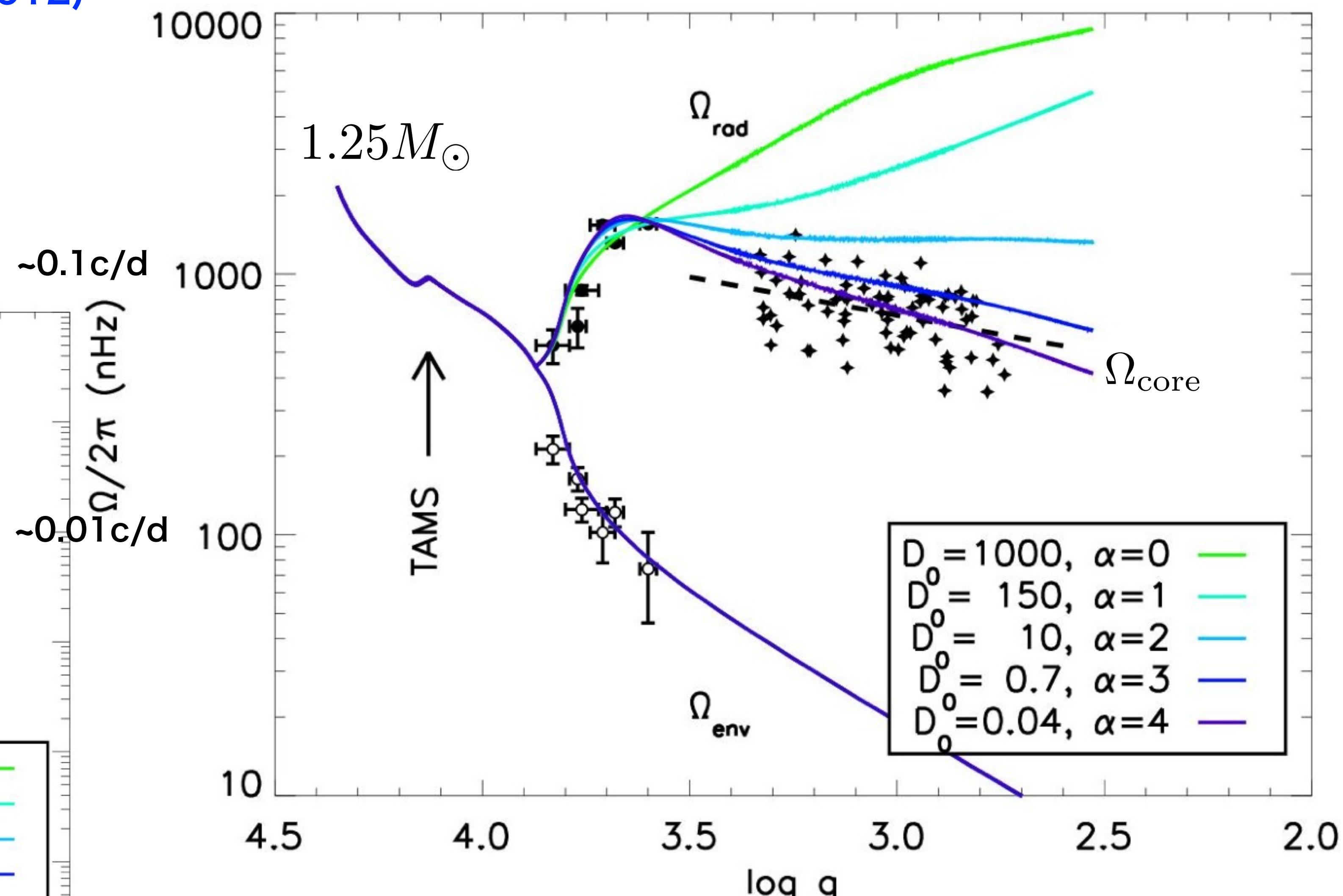
Evolution of the internal rotation frequency



$$\rho r^4 \frac{\partial \Omega}{\partial t} = \frac{\partial}{\partial r}\left[\rho r^4 D \frac{\partial \Omega}{\partial r}\right]$$

$$D = D_0 \left(\frac{\Omega_{\rm core}}{\Omega_{\rm env}}\right)^{\alpha}$$





Spada et al. (2016)

恒星の振動の観測 → 恒星進化段階、内部自転速度

Red giants の Core/envelope differential rotation
予想より格段に小さかった

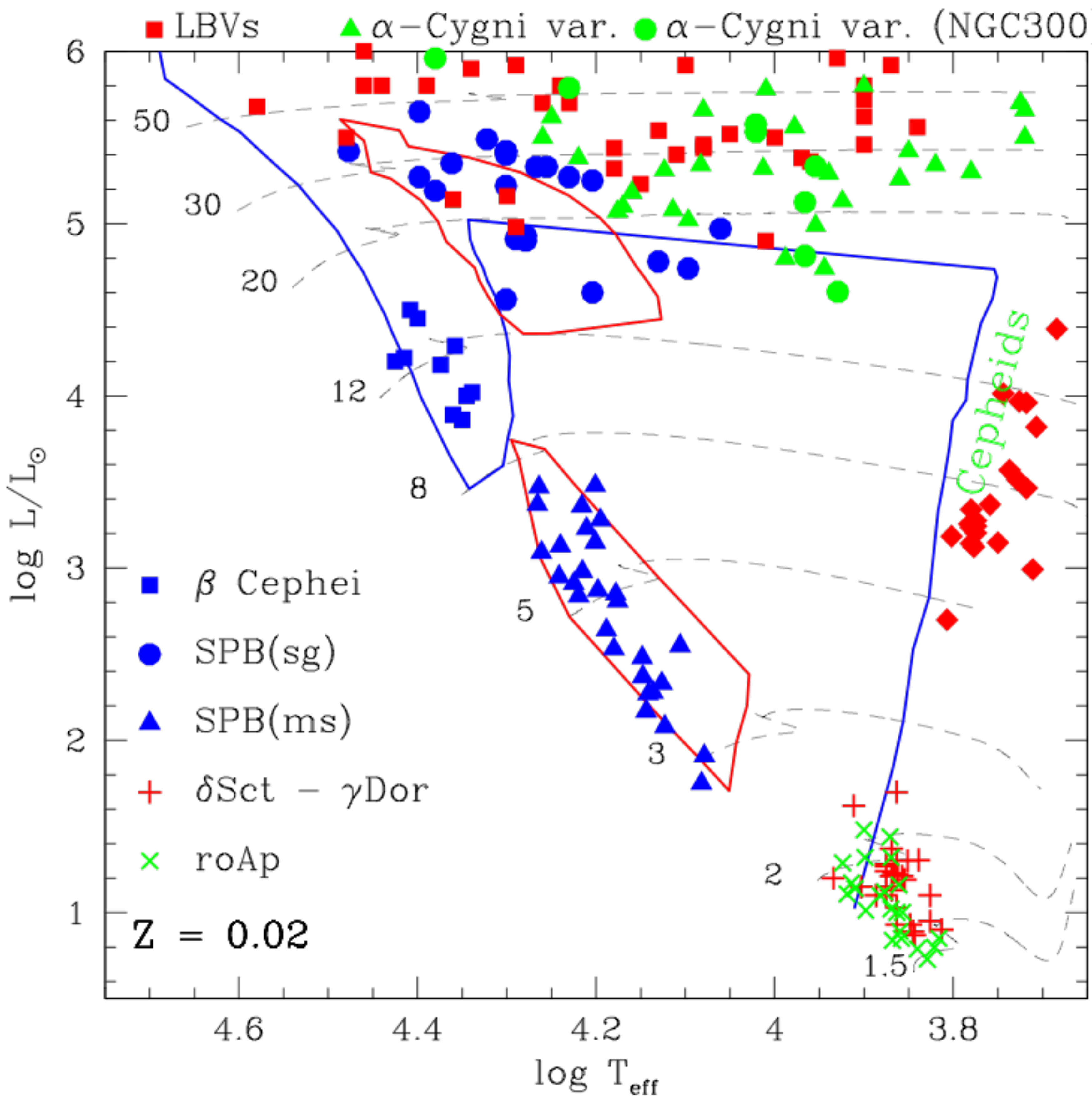
→ 恒星内部の angular momentum transport
は通常考えられていたよりも格段に速い

Diffusion coefficient should increase with time
原因不明

Next :

脈動変光星のHR図上の分布 → 恒星内部の対流層
赤色超巨星の質量放出

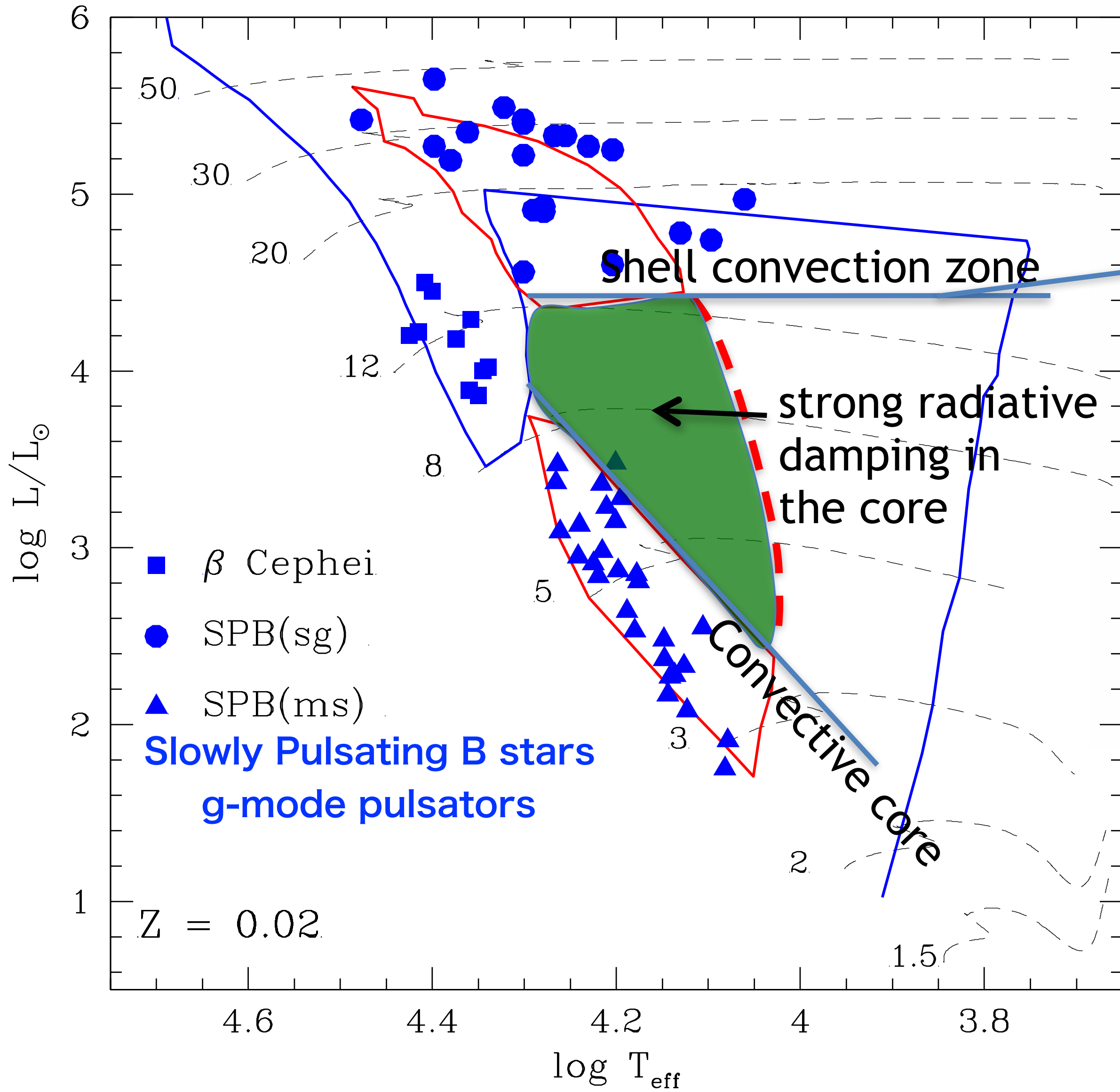
B-A type pulsators and instability boundaries

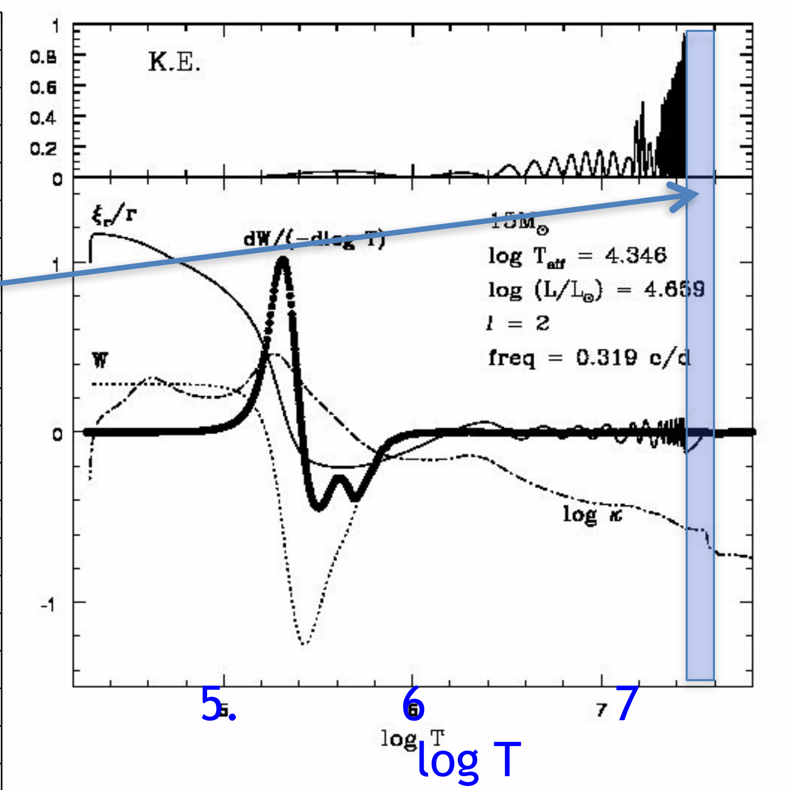


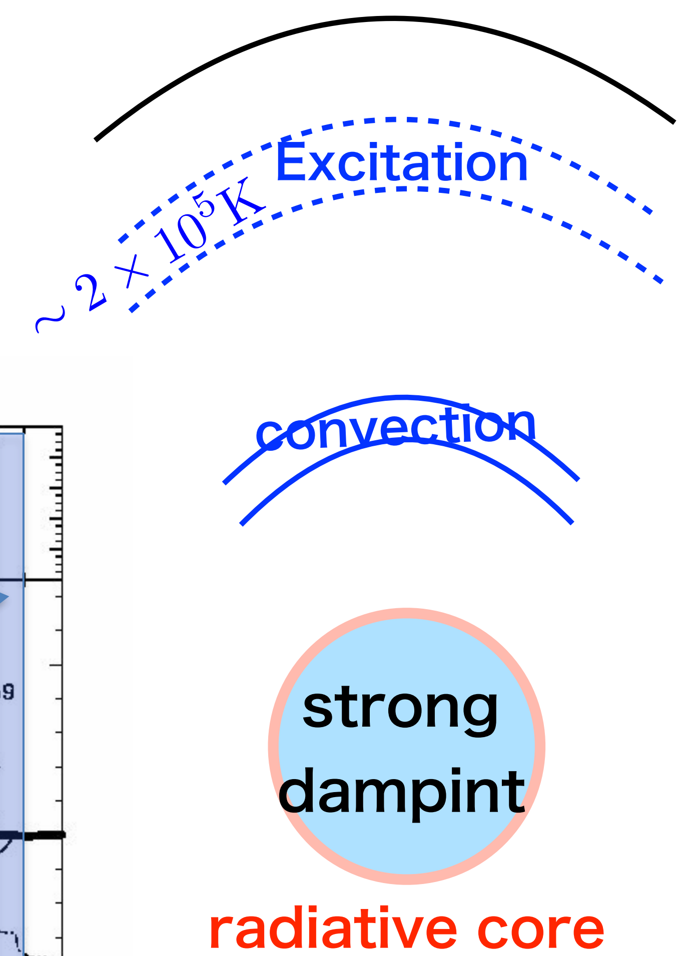
g-mode instability boundaries related with shell convection zone or convective core

g-mode は対流層に侵入できない

M>12Msol : shell conv. zone occurs in post MS phase

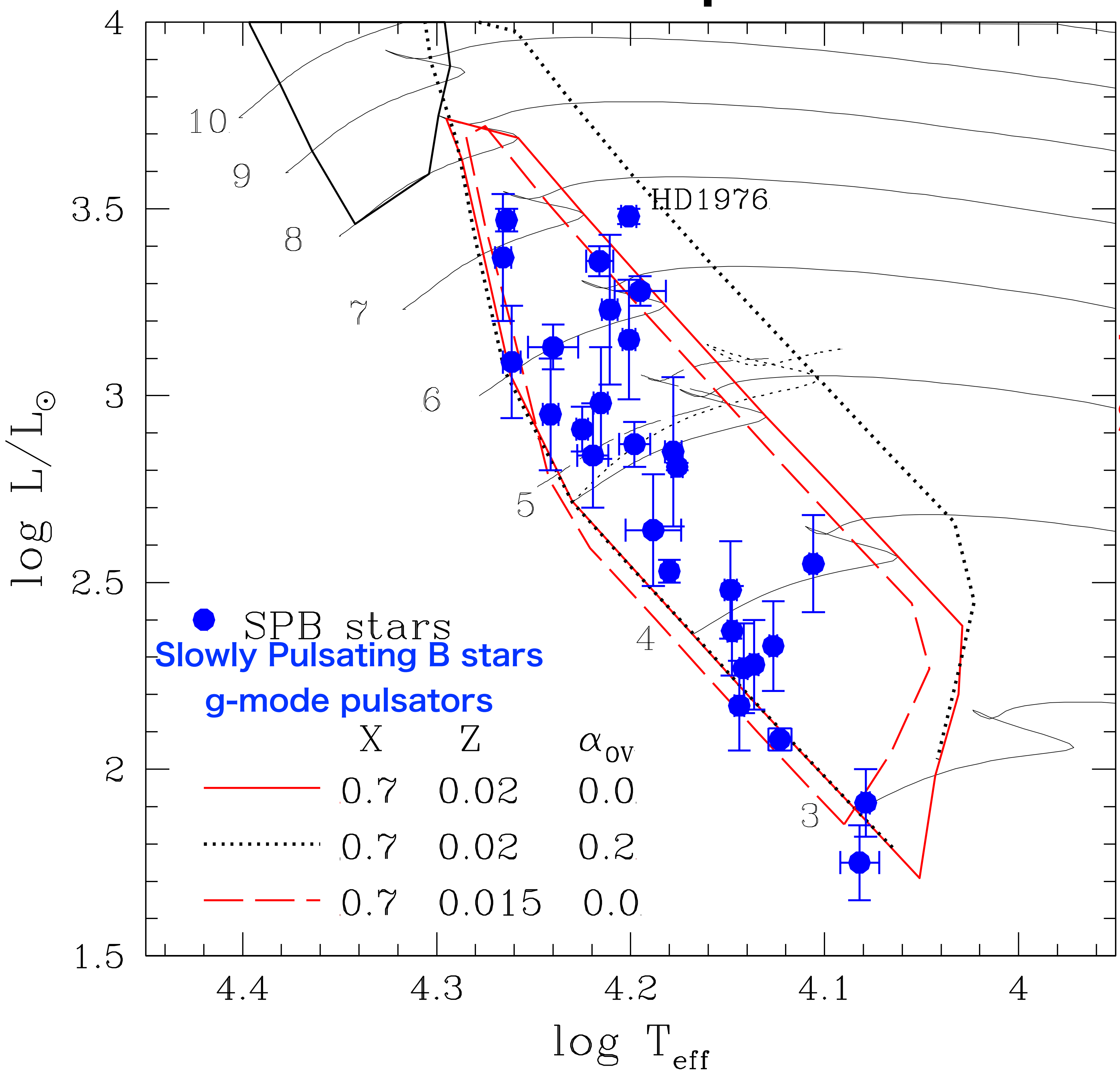




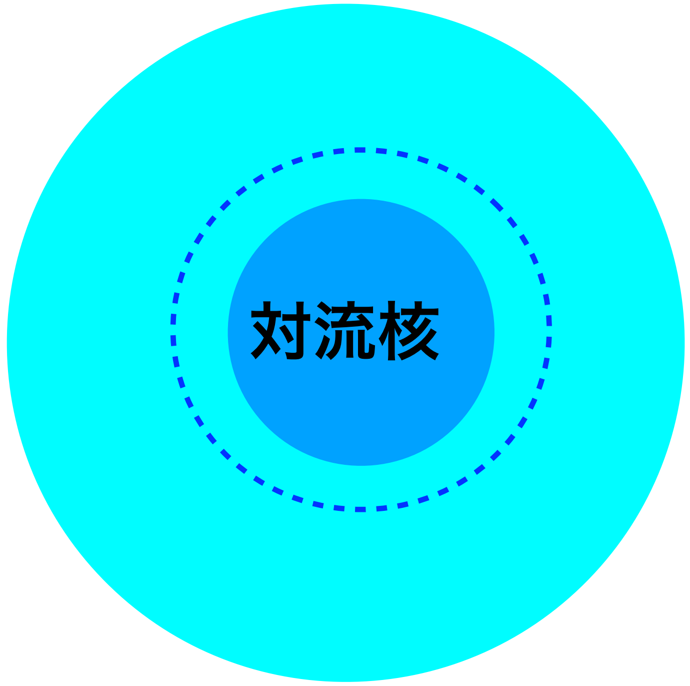


Shell convection zone
reflect g-modes
---- no radiative damping
in the core

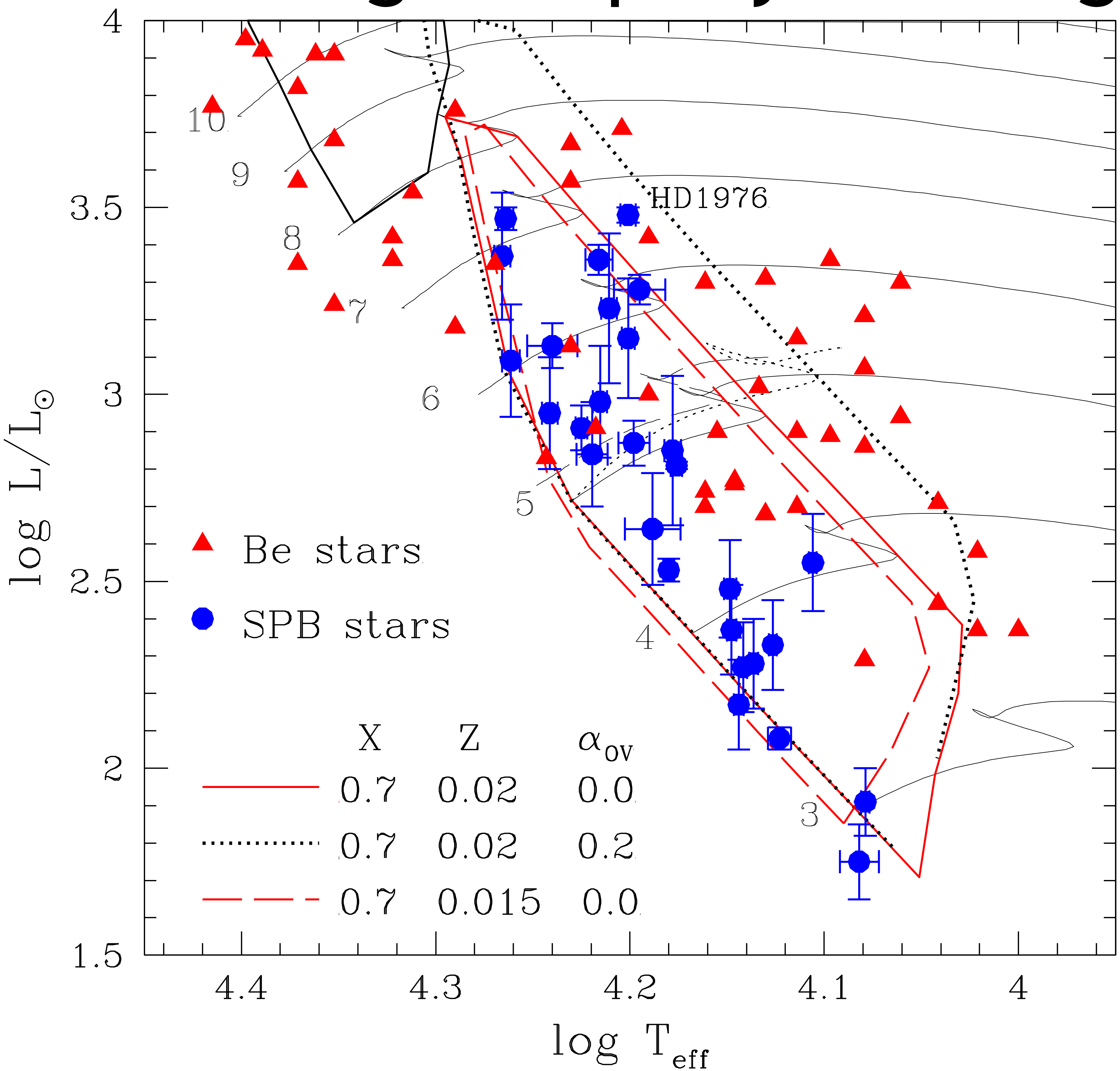
Cool boundary of SPB instability indicate the end of main sequence with a conv. core



No core-overshooting is needed for SPB stars

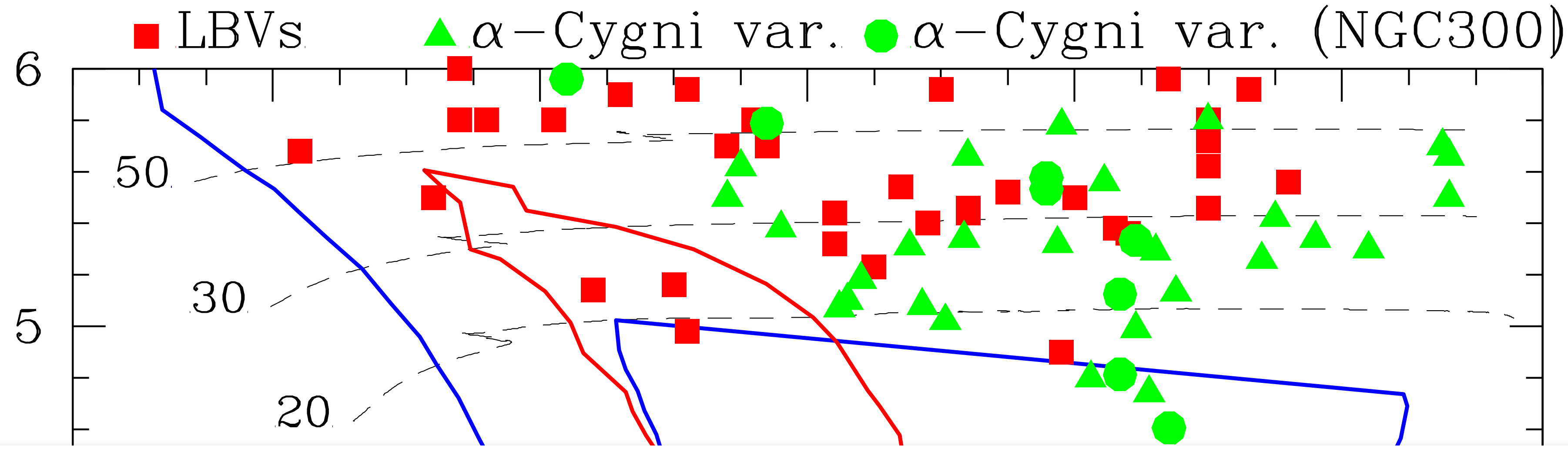


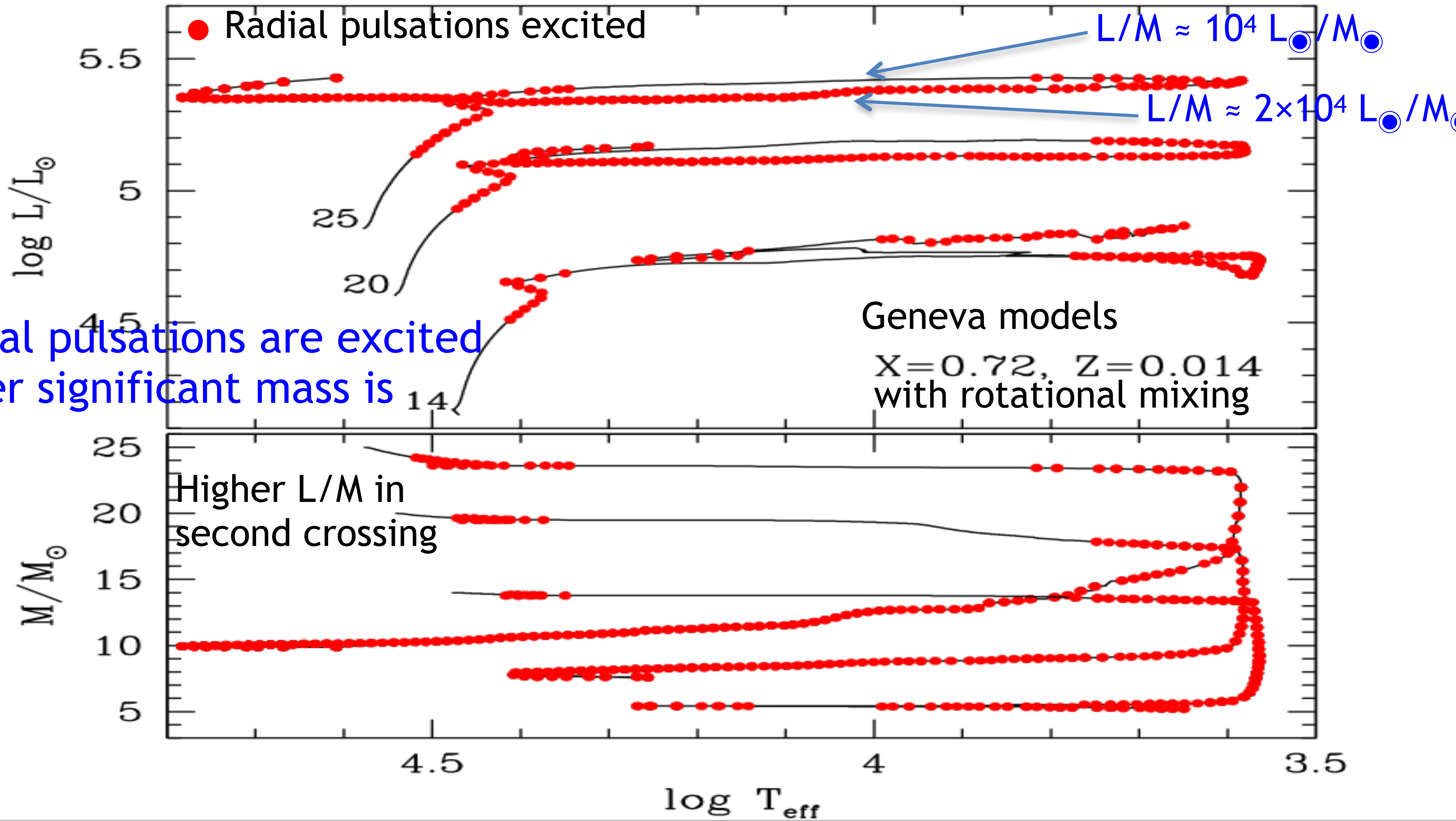
Larger convective core or extensive mixing in rapidly rotating Be stars



Distribution of Be stars do indicate the presence of substantial overshooting or mixing around convective core

α Cygni variables(radial pulsators)





Radial pulsations are excited after significant mass is lost

大中質量脈動変光星分布 ⟶ 恒星内部の対流層、
赤色超巨星からの質量放出

- Slow rotatorのconvective core overshooting は小さい
- Rapid rotator ではconvective core 周囲でのmixing
- M>~12Msol のpost MS stageでshell conv. zone 発生
- M>~20Msol: 赤色超巨星で質量放出後青色超巨星へ

Next:

恒星の脈動が示す恒星合体の証拠

1. Anomalous cepheids

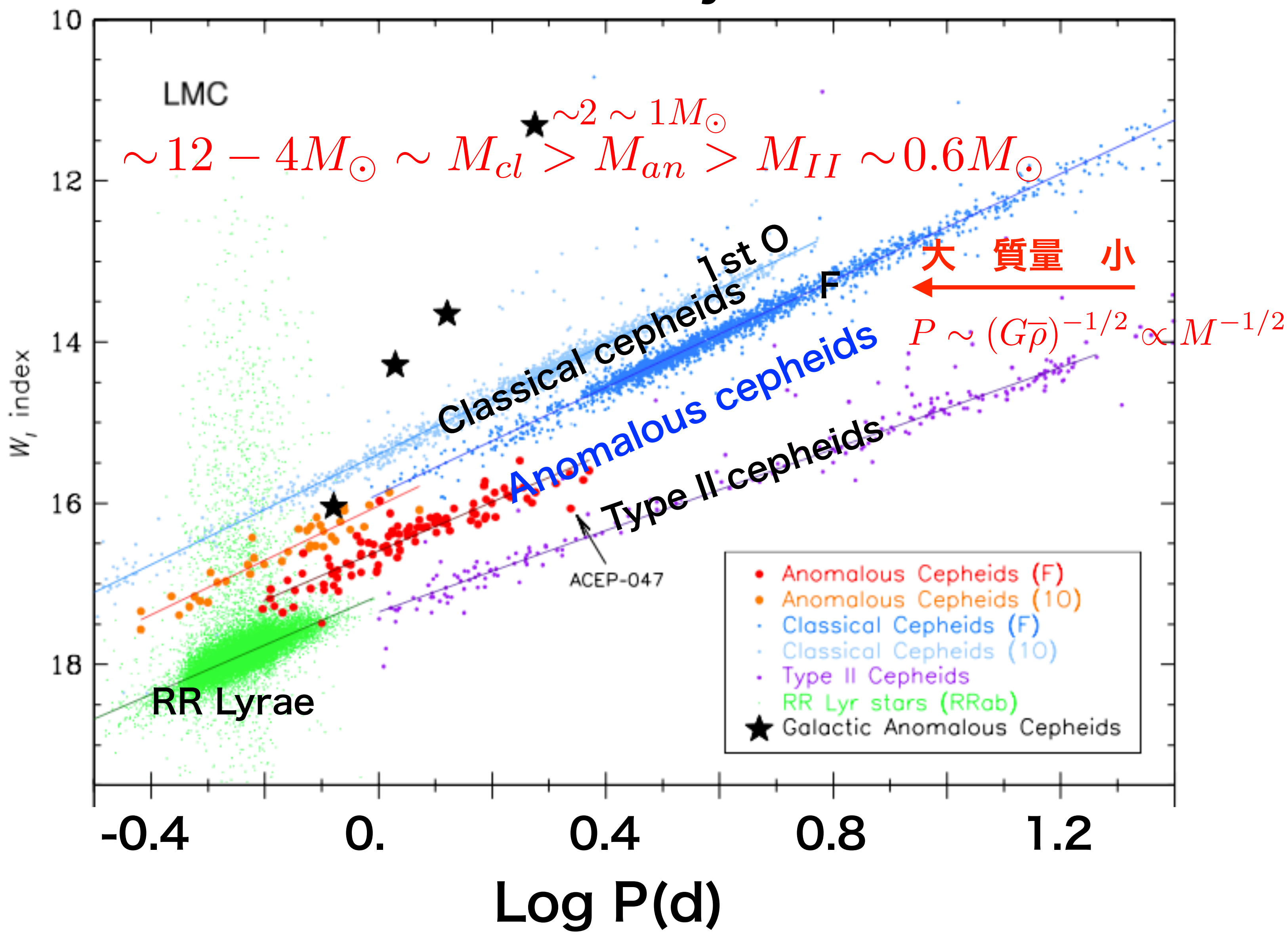
２つのred-giant core の合体？

2. He-star pulsators

Double He-WD (low-mass WD) merger

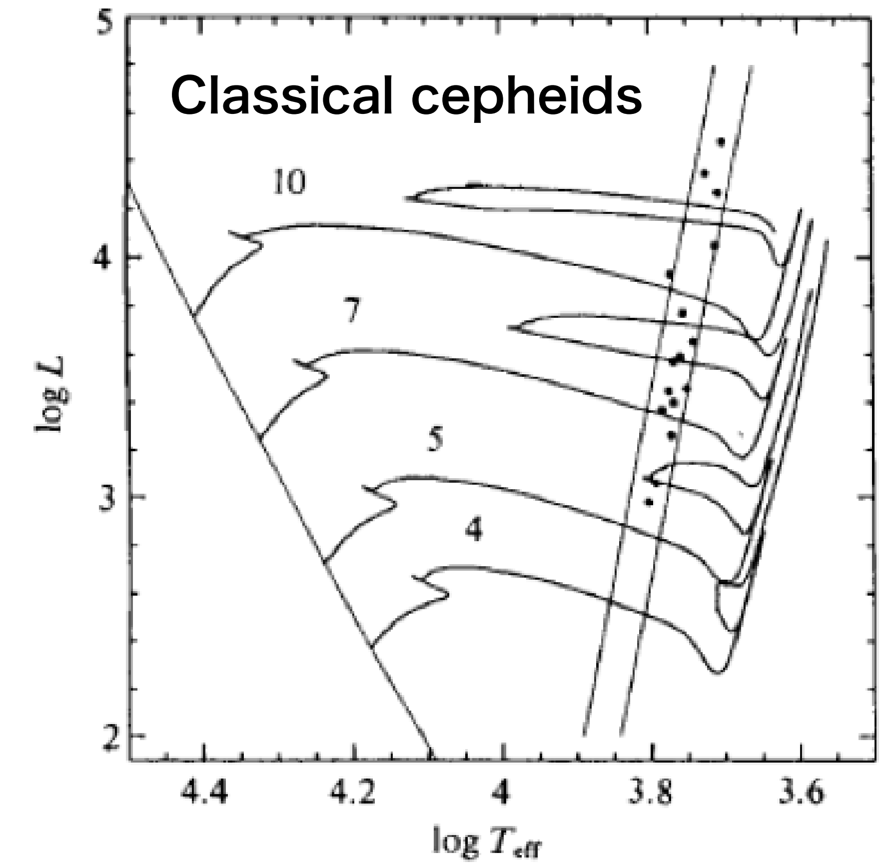
Classical, Anomalous, and Type II Cepheids

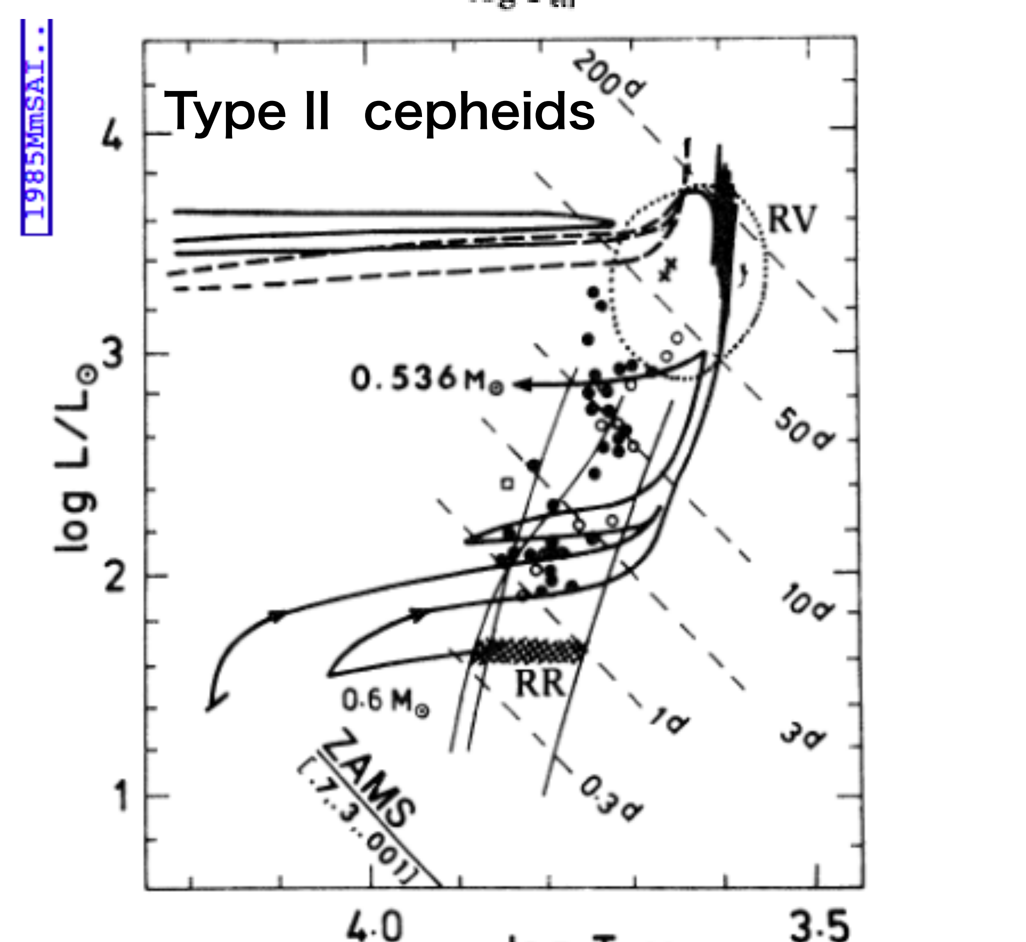
Period-Luminosity relations



Soszynski et al(2015)

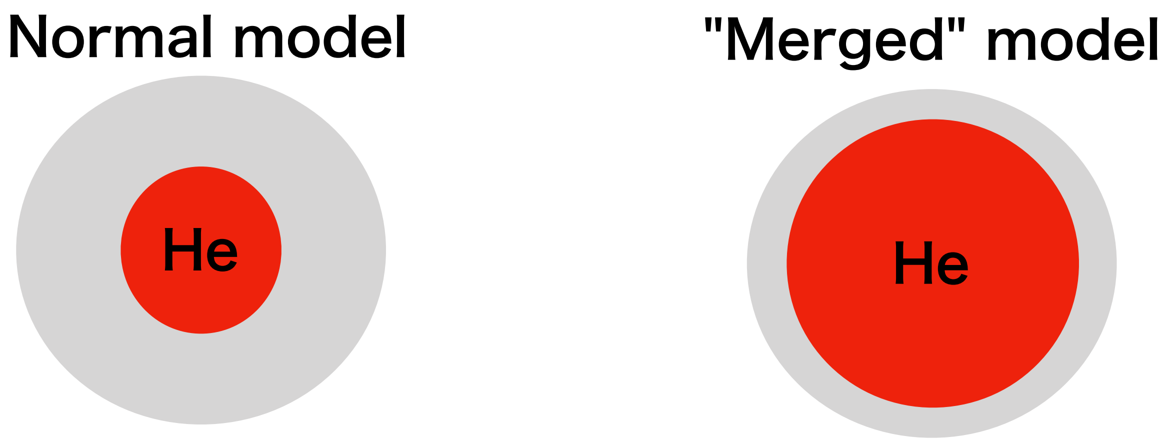
(OGLE)

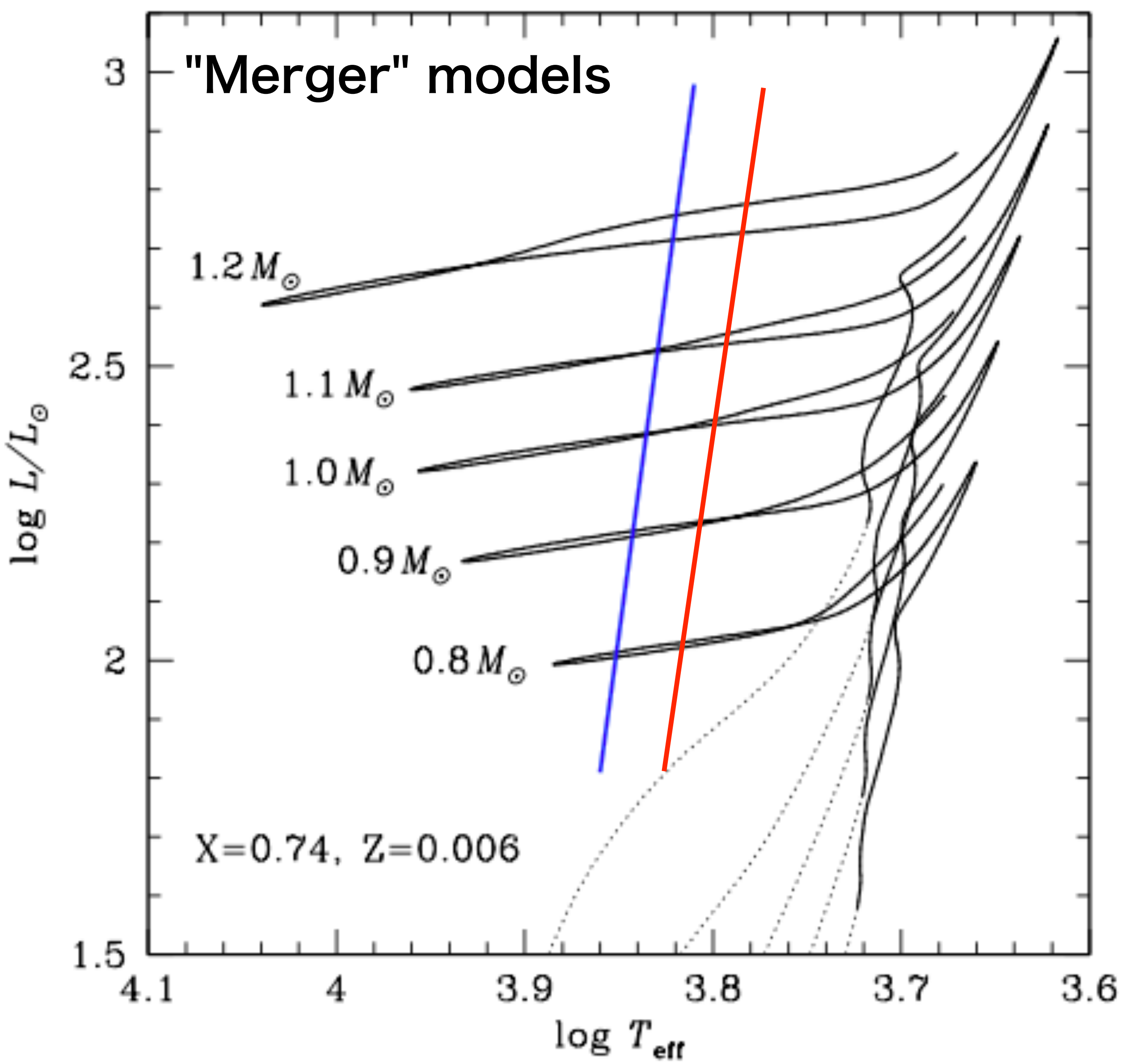


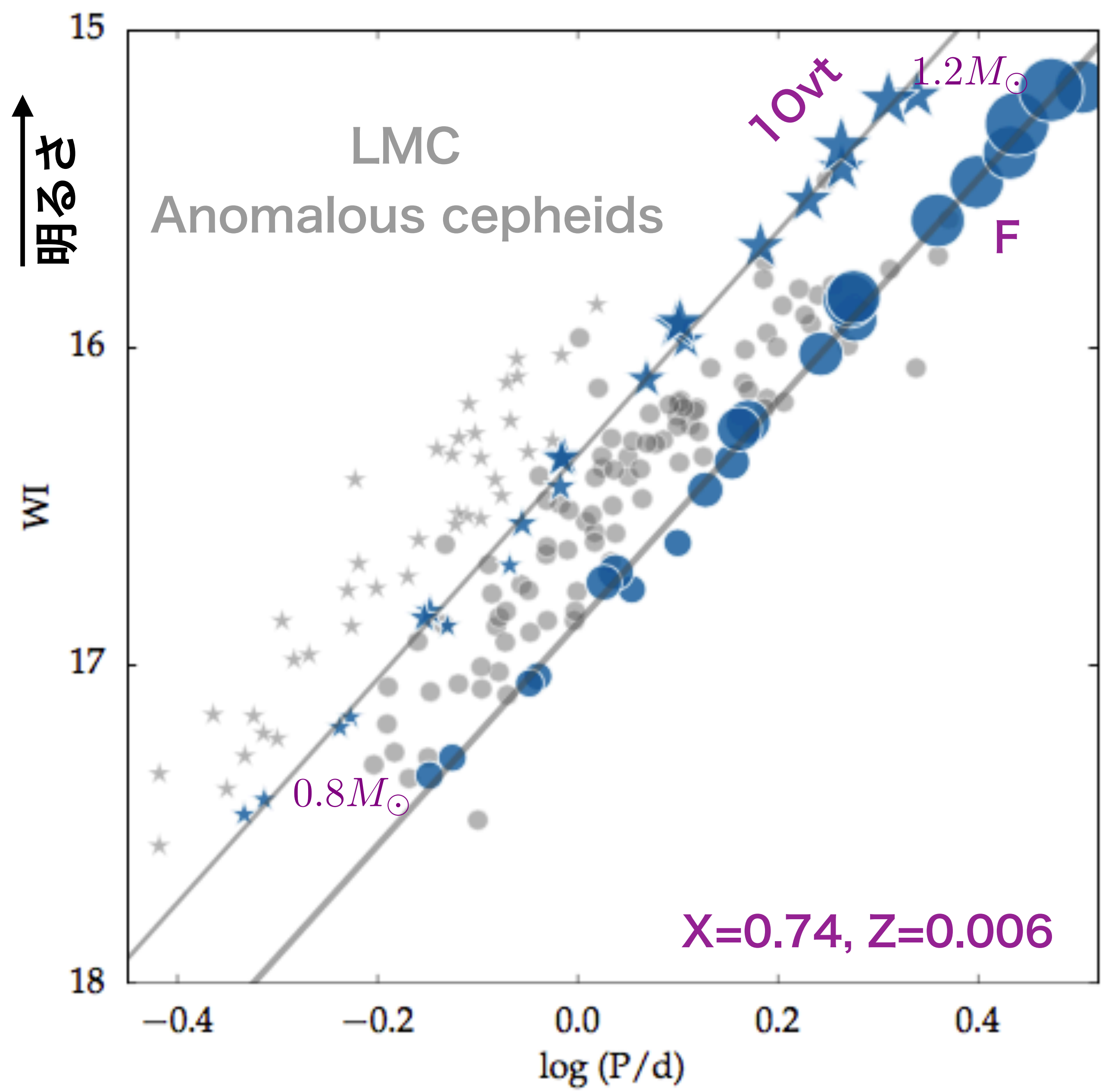


Gingold (1984)

Anomalous cepeheids は Red-giants He-core merger の産物？

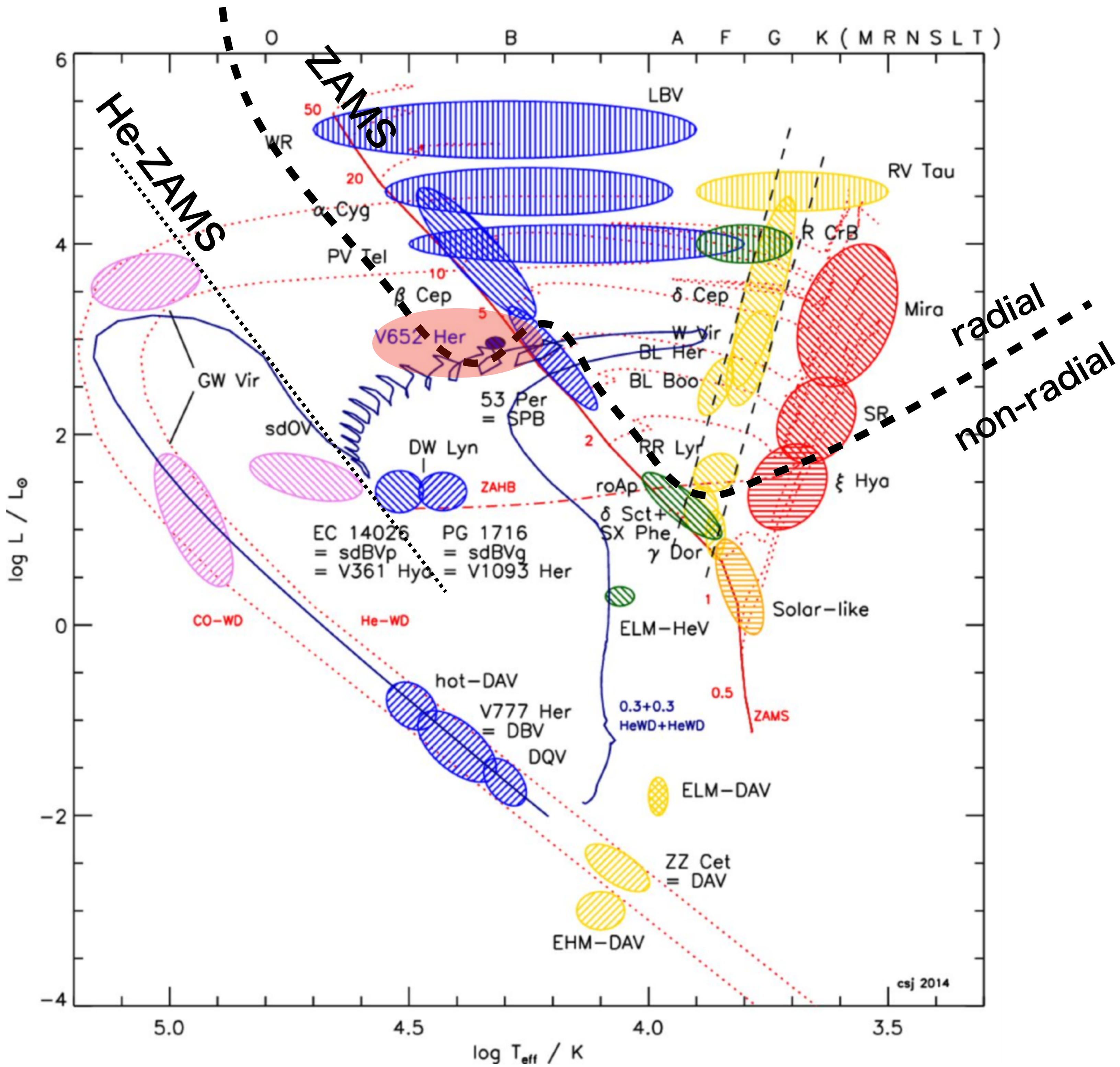






Gautschy & Saio (2017)

Pulsational variables in the HRD

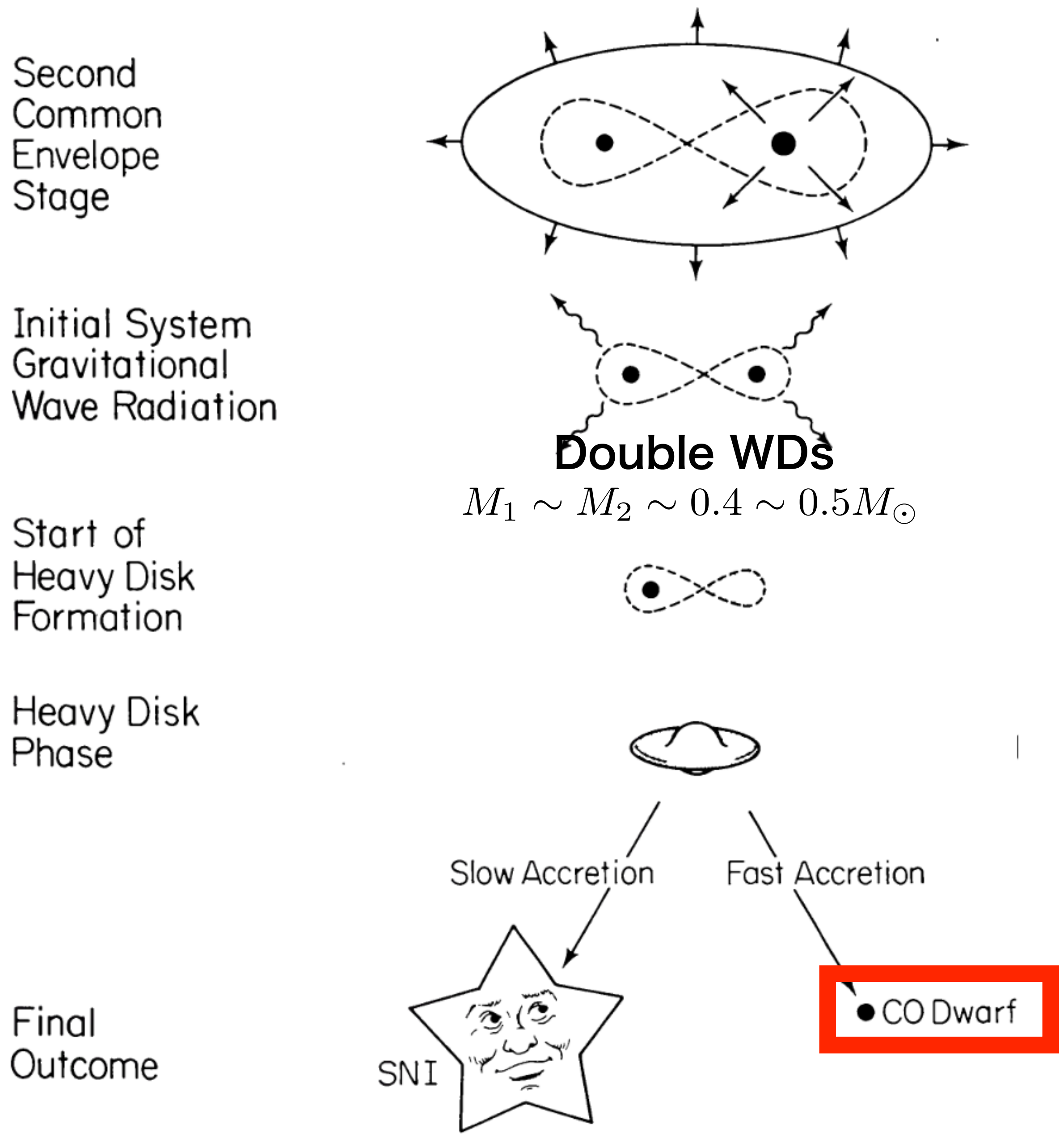


Jeffery et al. (2015)

Merger of double He WDs

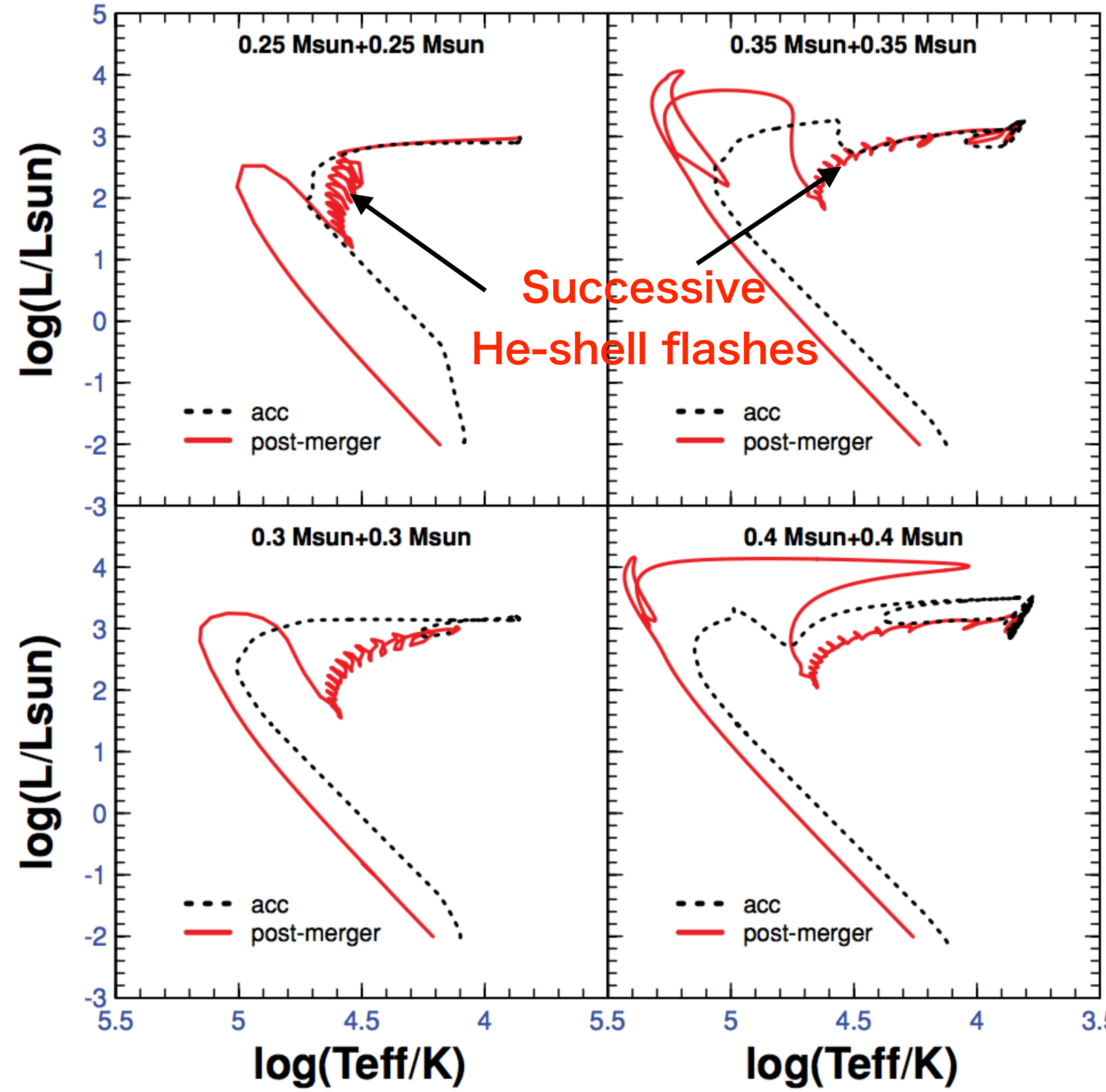
Spherical model: Helium accretion onto a white dwarf

Initial system: $M_1 \sim M_2 \sim 3 \sim 5 M_\odot$



Iben & Tutukov (1984)

Slow merger: Mdot=10^{-5}Msun/year



Zhang & Jeffery (2012)

Double He-WD merger models
-- He-star pulsators

$$\dot{M}_{\rm acc} = 1 \times 10^{-5} M_\odot/yr$$

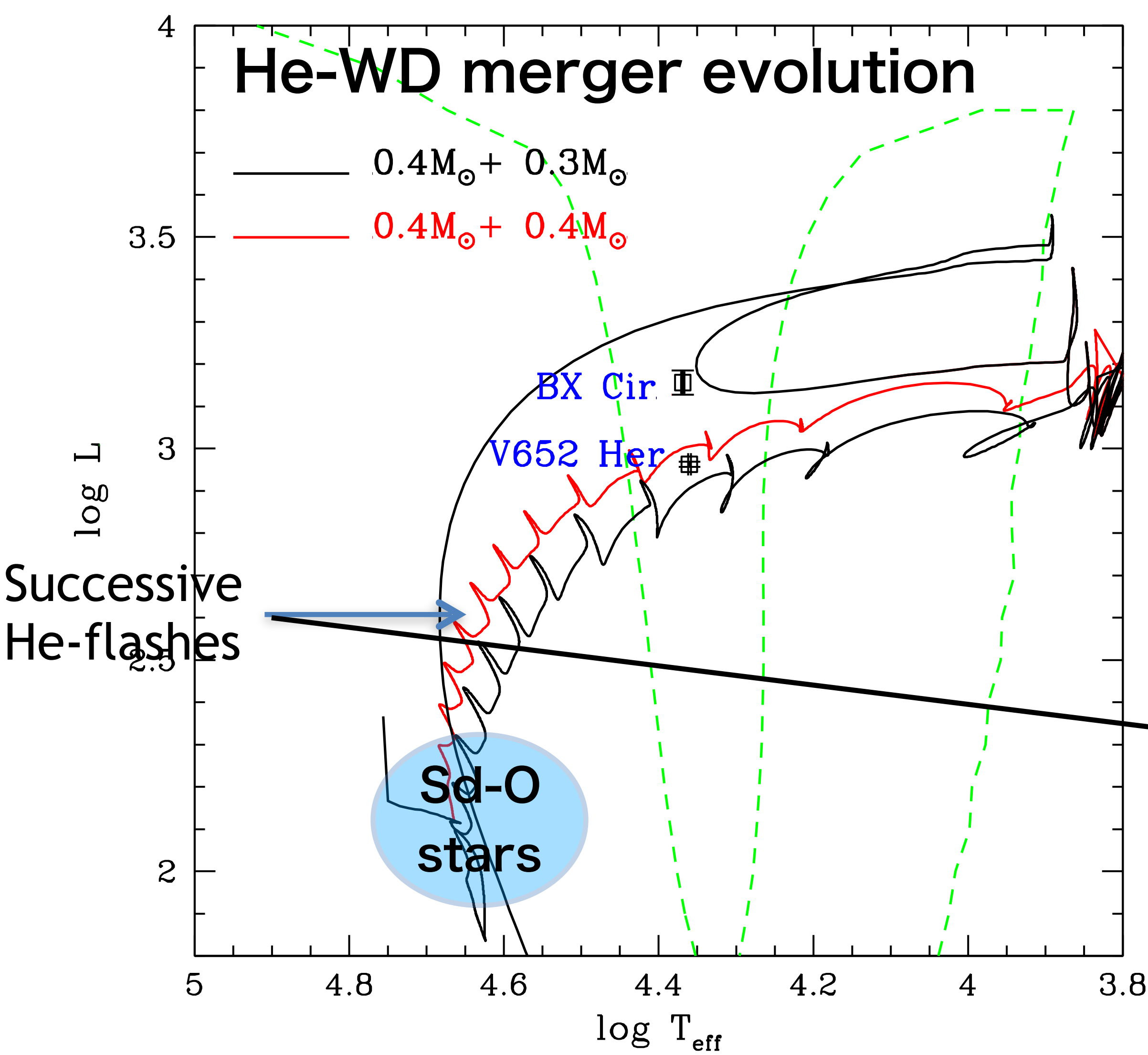
Accretion -> 外層加熱 -> 外層でHe flash発生

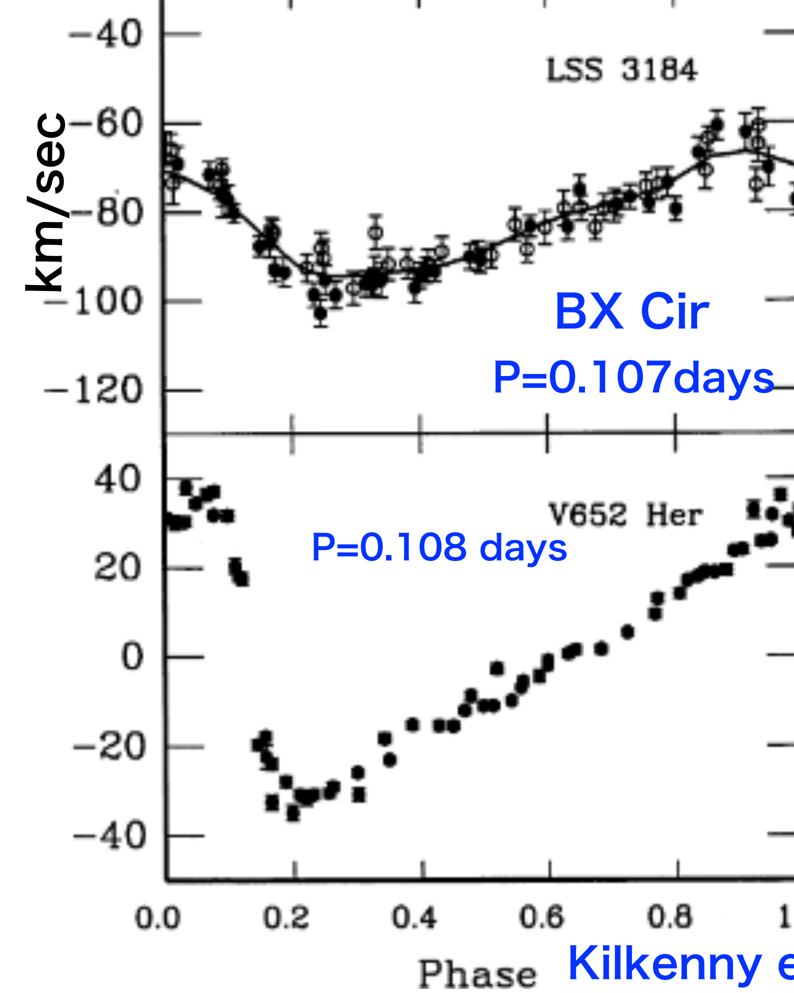
He flash が繰り返されながらその発生位置が中心へ

--> Helium ZAMS

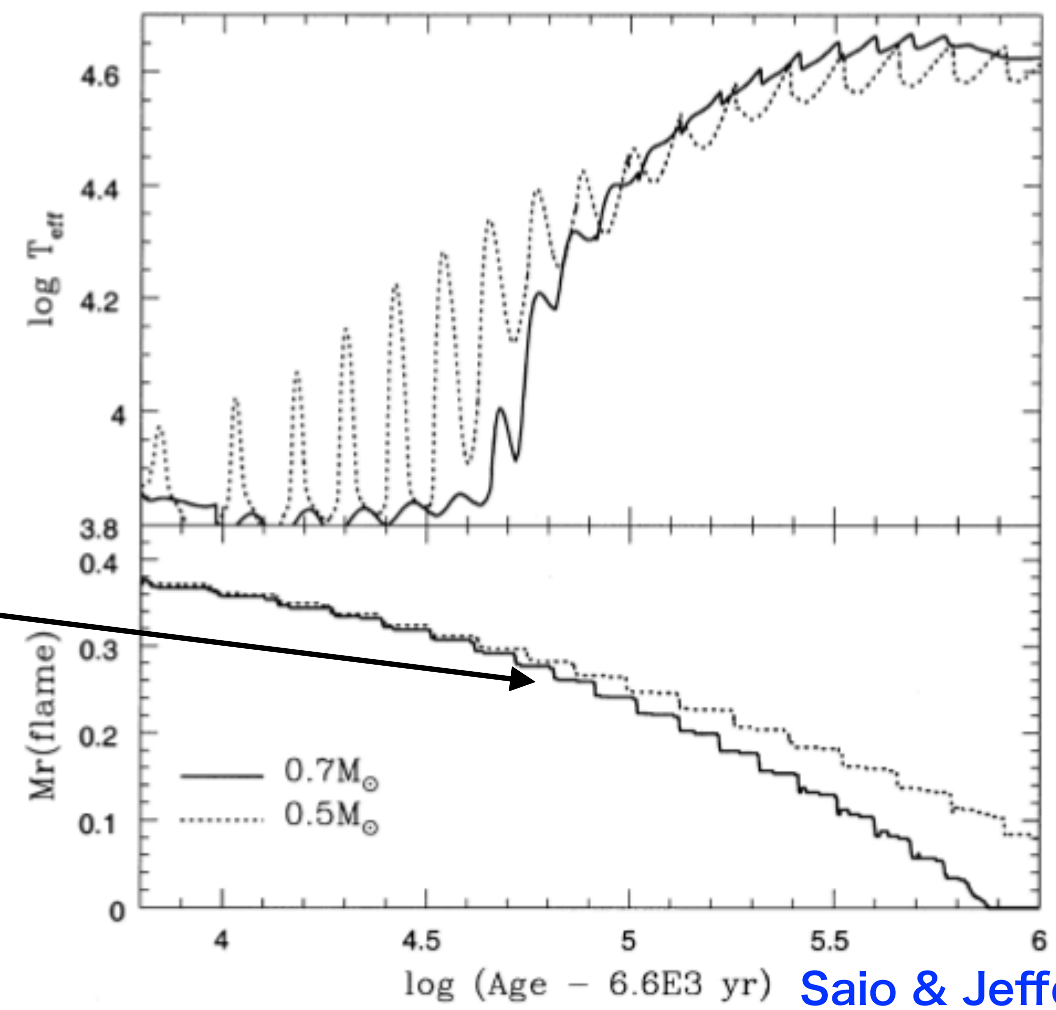
その進化経路の途中に２つのHe星脈動星が存在

$$M \sim 0.7 M_\odot$$



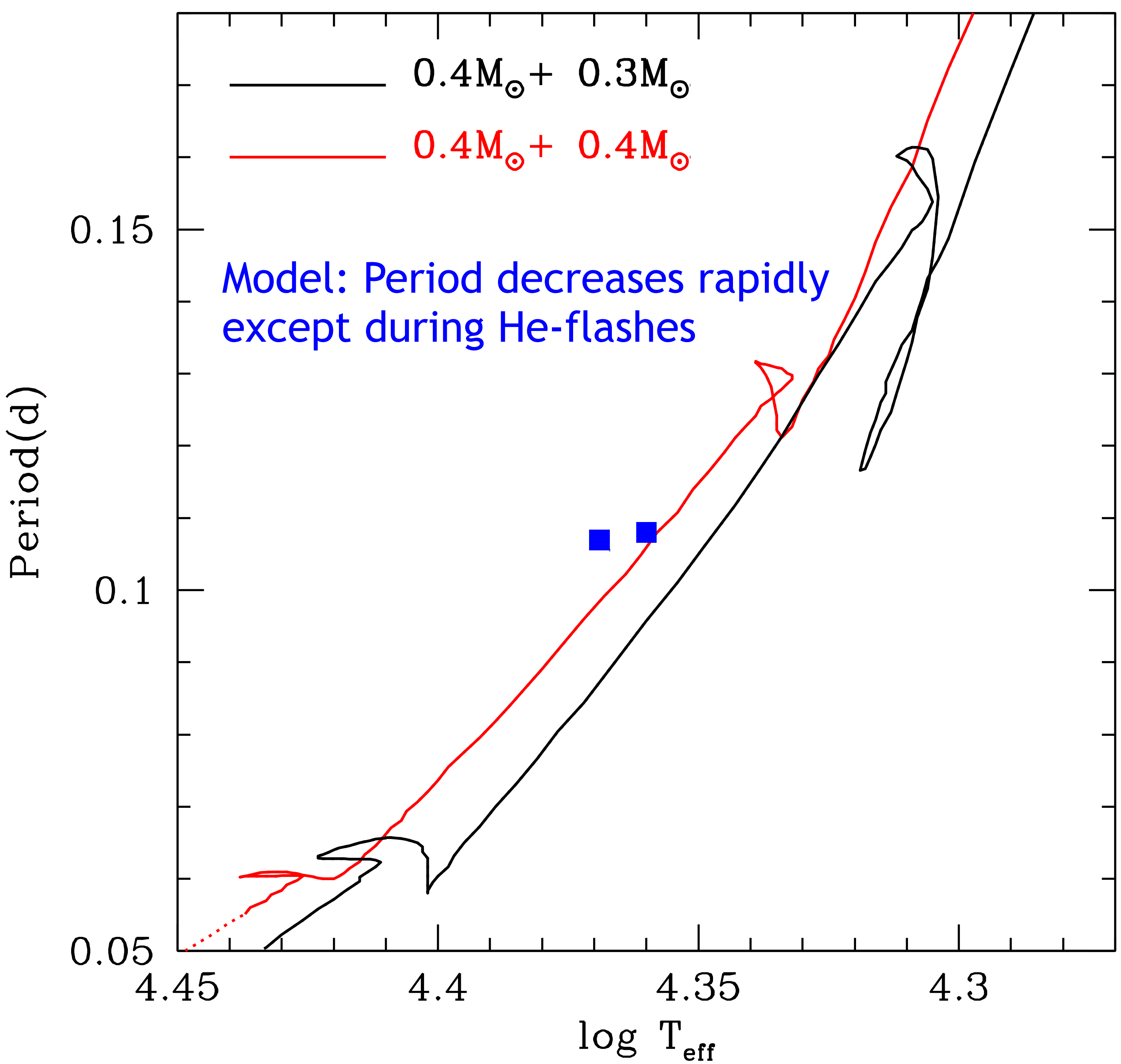


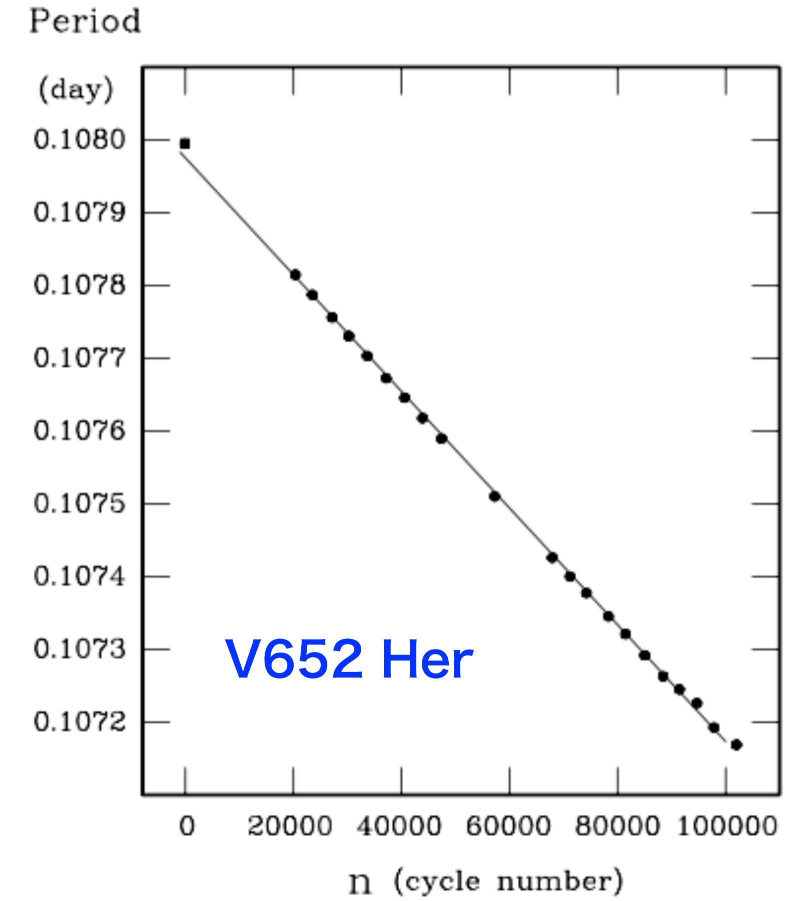
Kilkenny et al. (1999)



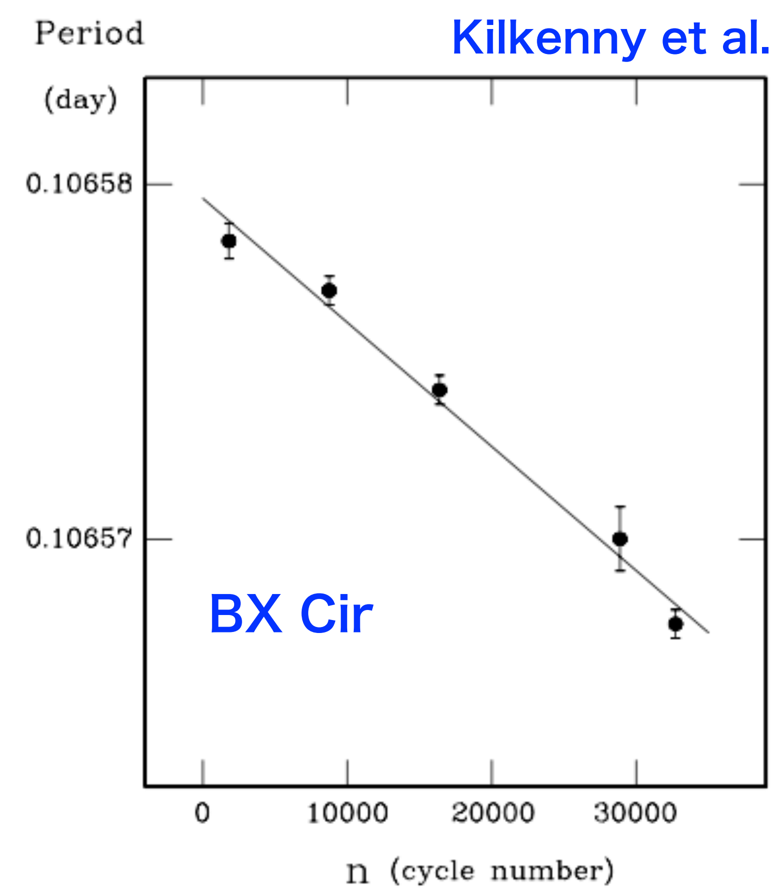
Saio & Jeffery (2000)

Pulsation period changes with evolution





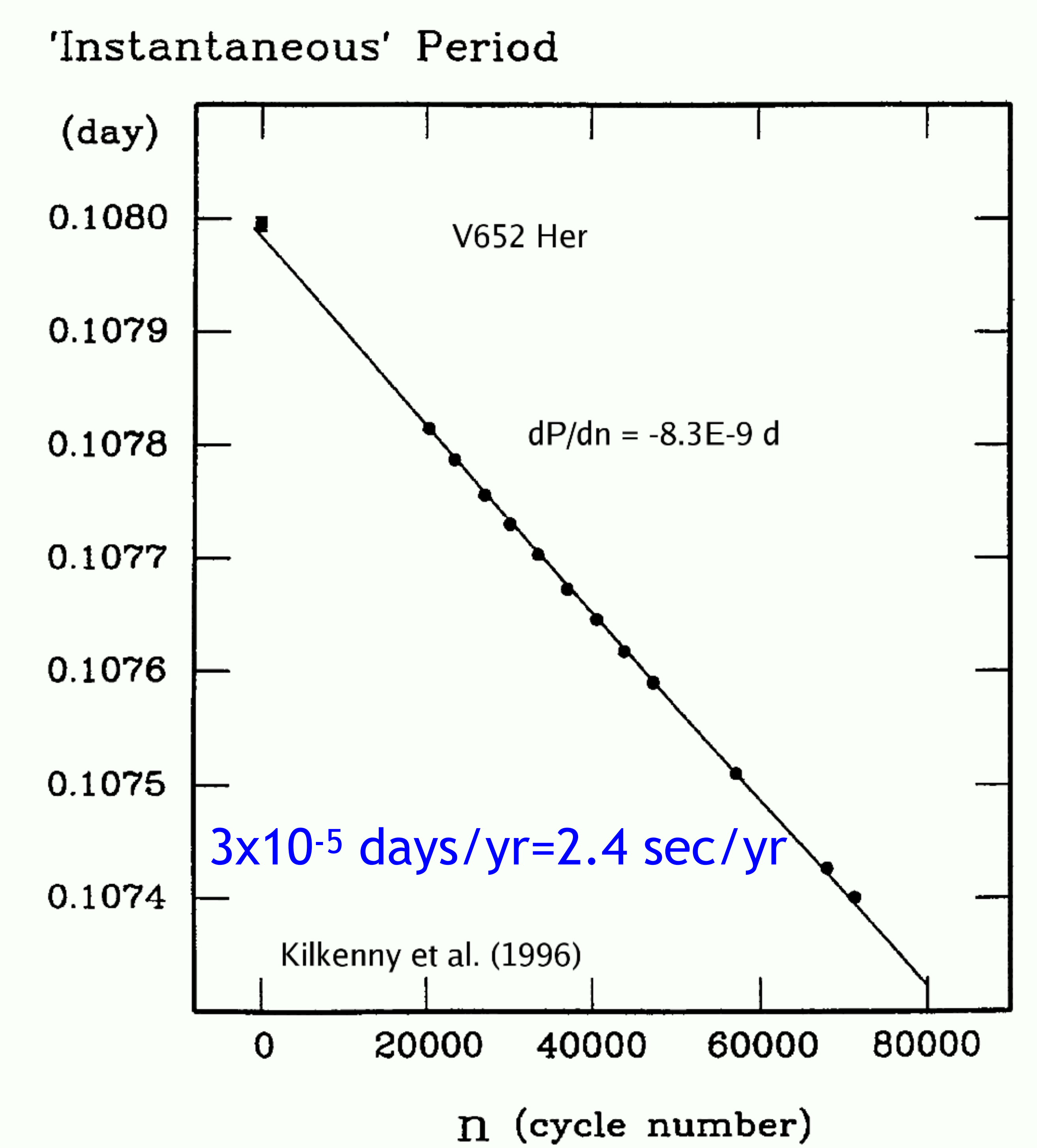
Kilkenny et al. (2005)

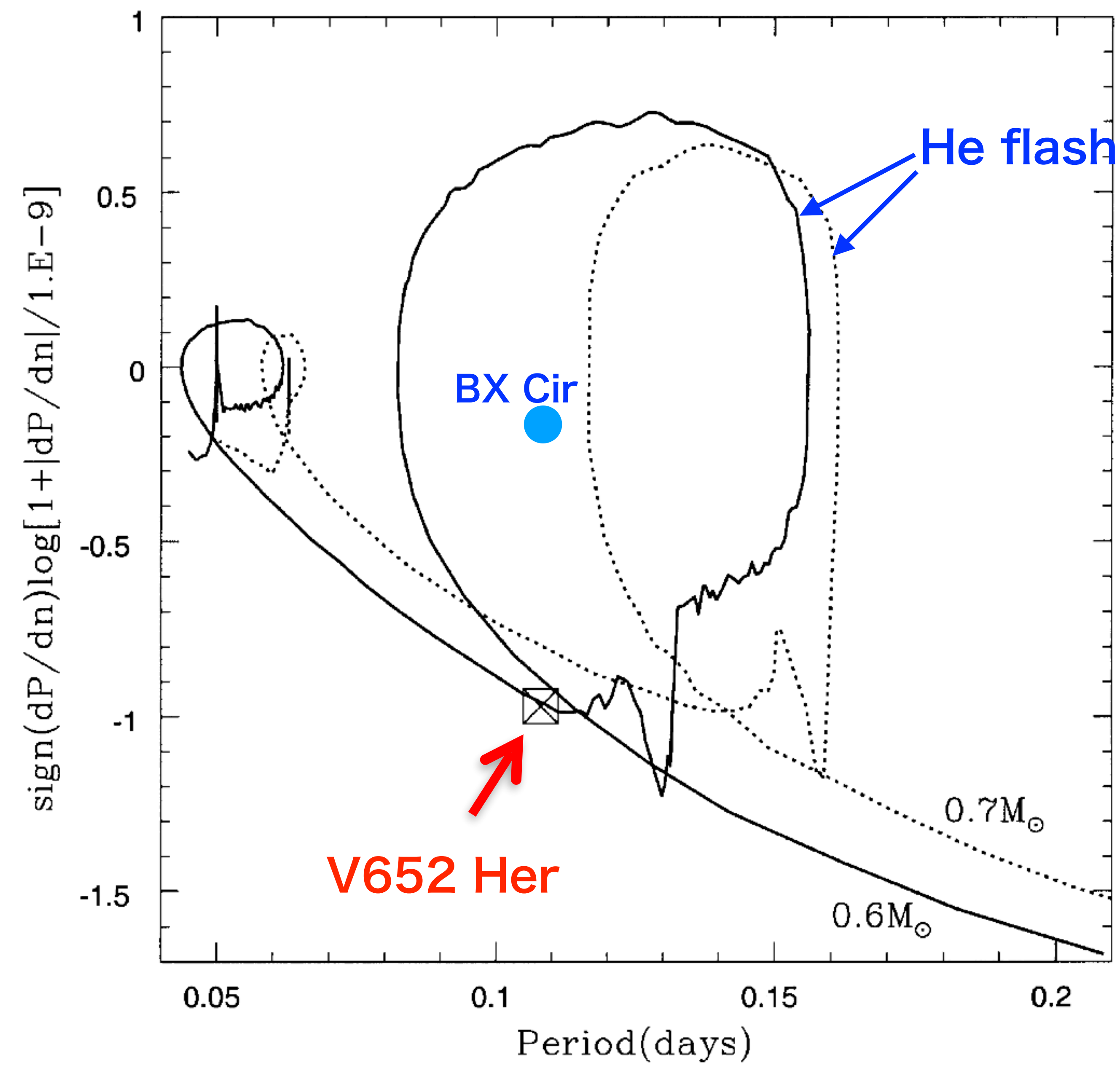


$$\Pi \propto \sqrt{\rho} \propto R^{1.5}$$

Period decrease rate of V652 Her agrees with a He-WD merger model

---> WD merger が実際に起こった証拠

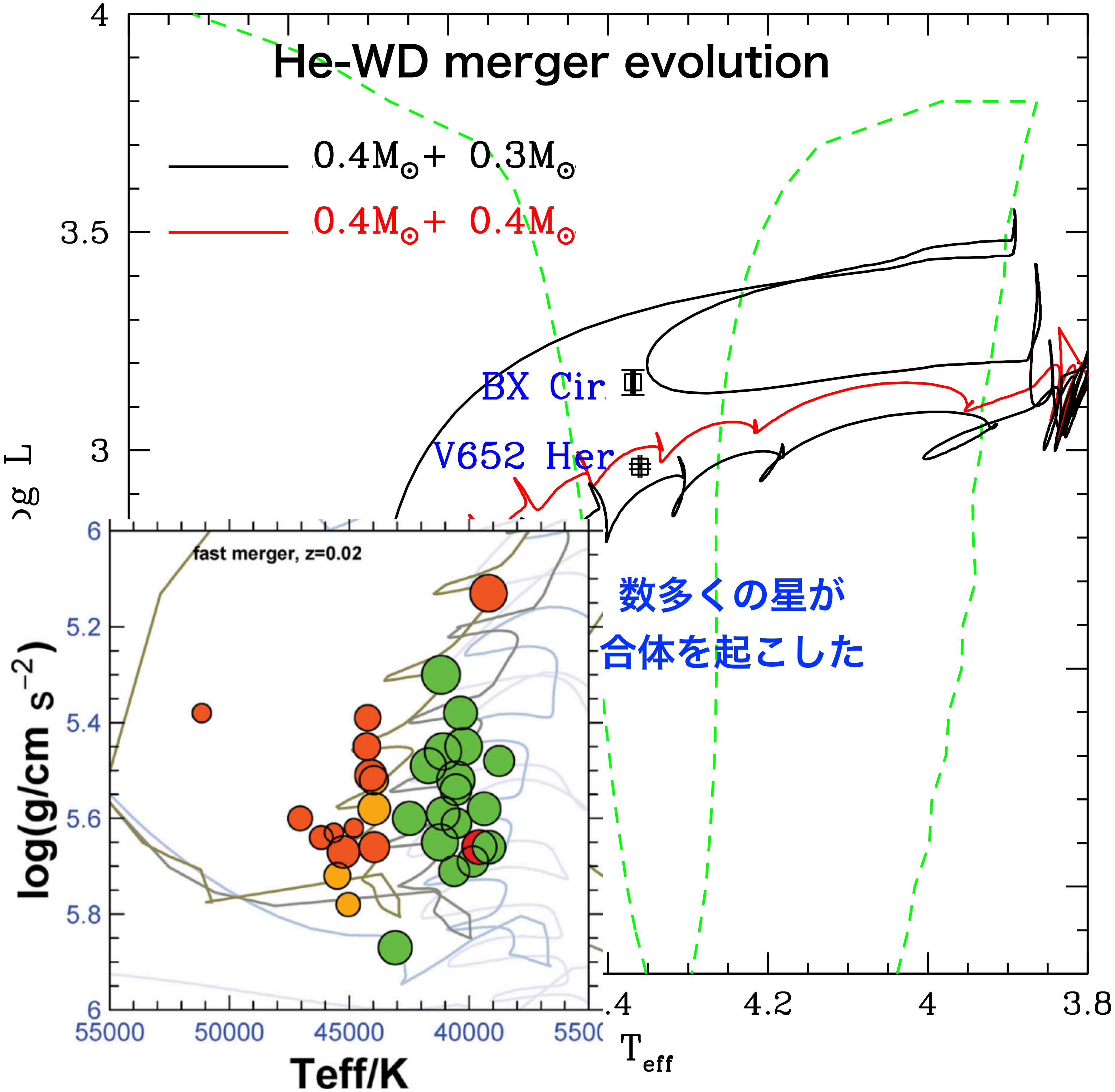


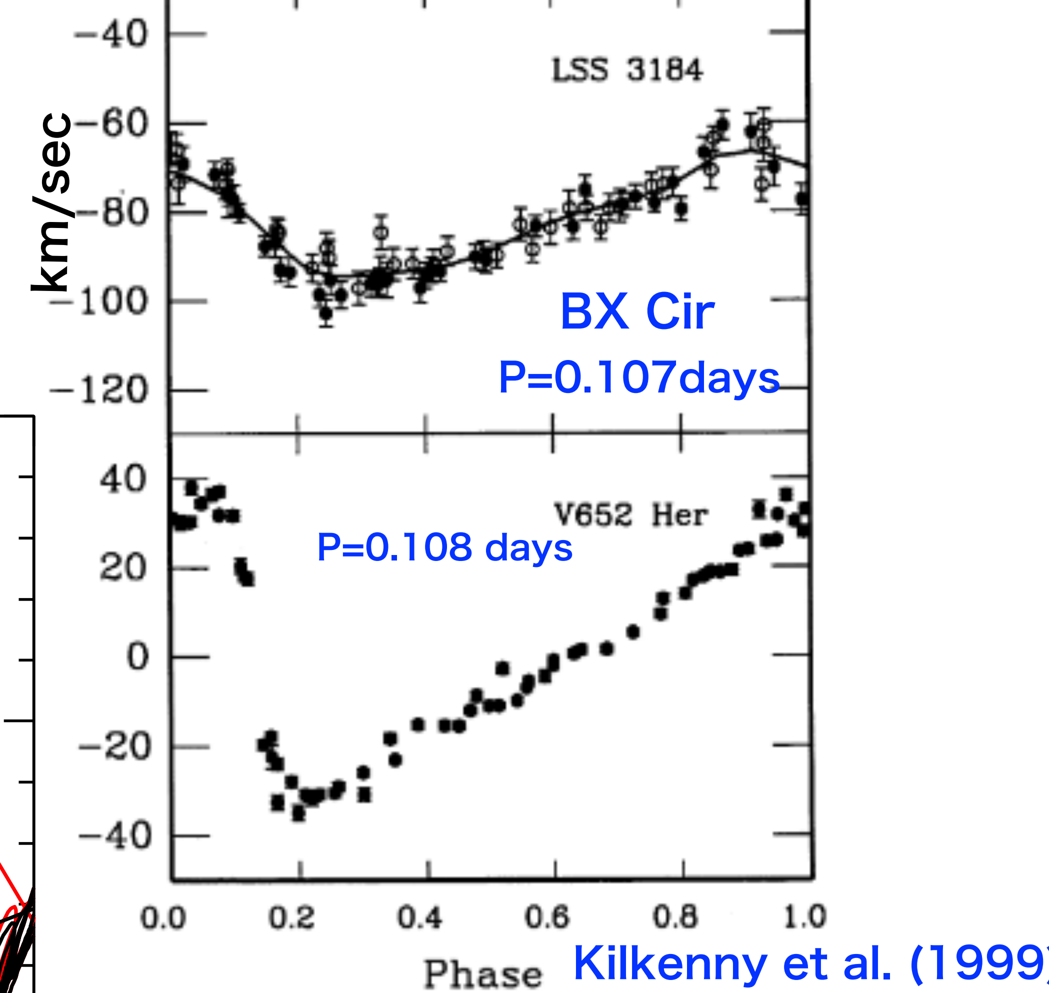


Saio & Jeffery (2000)

Figure 4. The rate of period change versus period for 0.7- and 0.6-$M_\odot$ cases, where dP/dn is the period change per cycle in days. The crossed square indicates the observed period and the period change rate of V652 Her (Kilkenny et al. 1996).

Double He-WD merger models
-- He-star pulsators





Double RGB stars merger → Anomalous cepheids ?

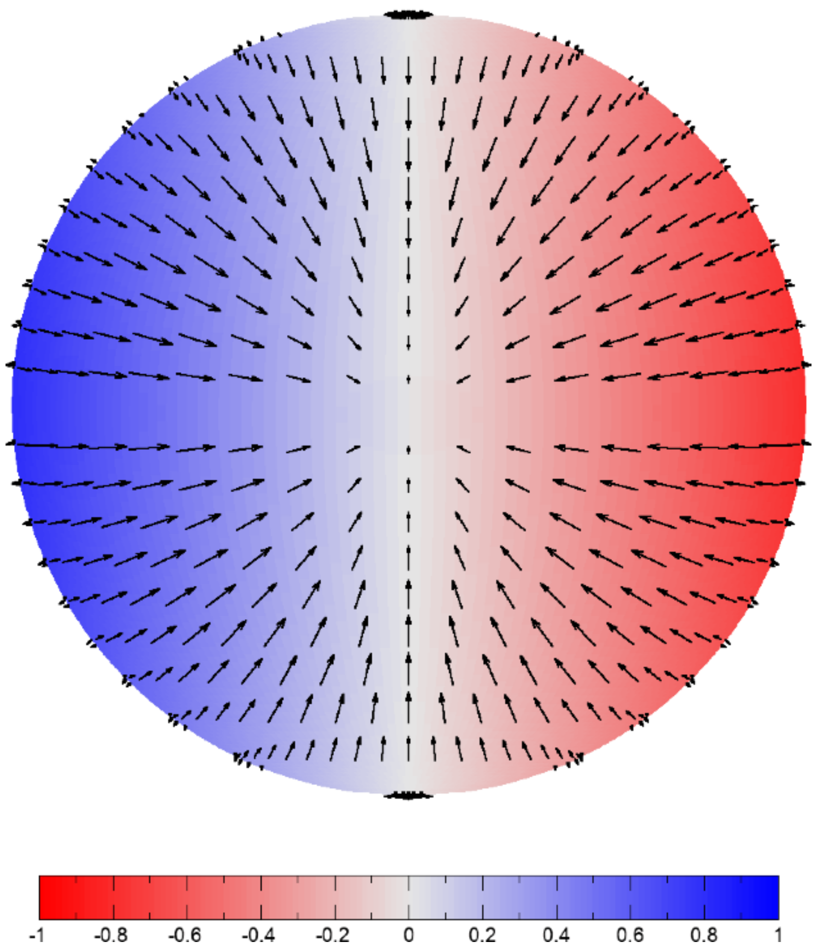
Double He-WD (low-mass WD) merger → He-star pulsators & He-sdO

恒星の合体はさほど稀な現象ではない

g modes と r modes (浮力の影響を受けたglobal Rossby waves)

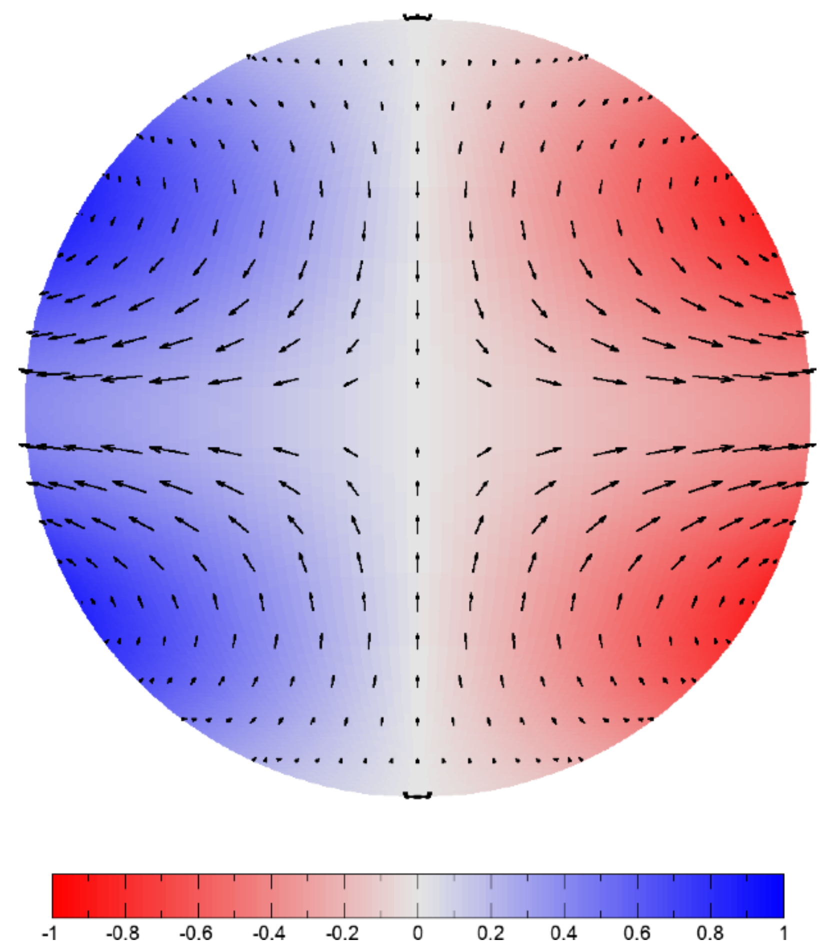
g mode

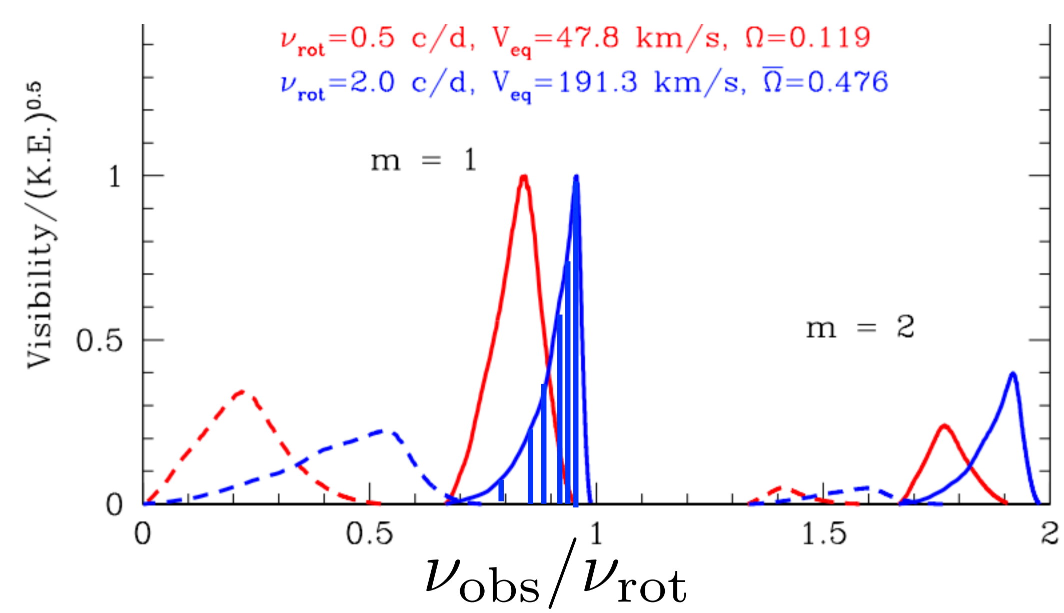
g mode: m = -1, k = 0, spin = 0.2

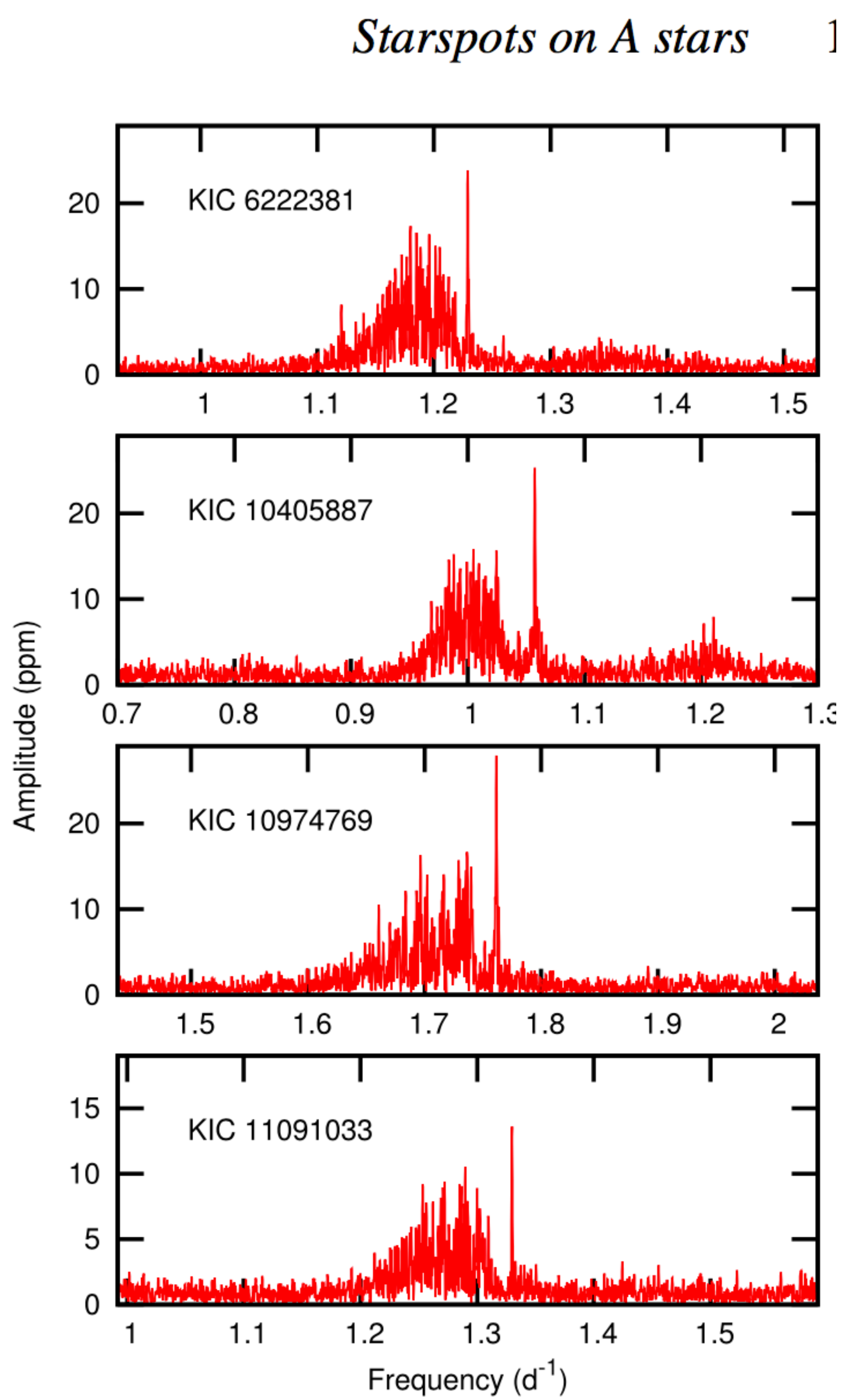


r mode

r mode: m = 1, k = -2, spin = 20.0

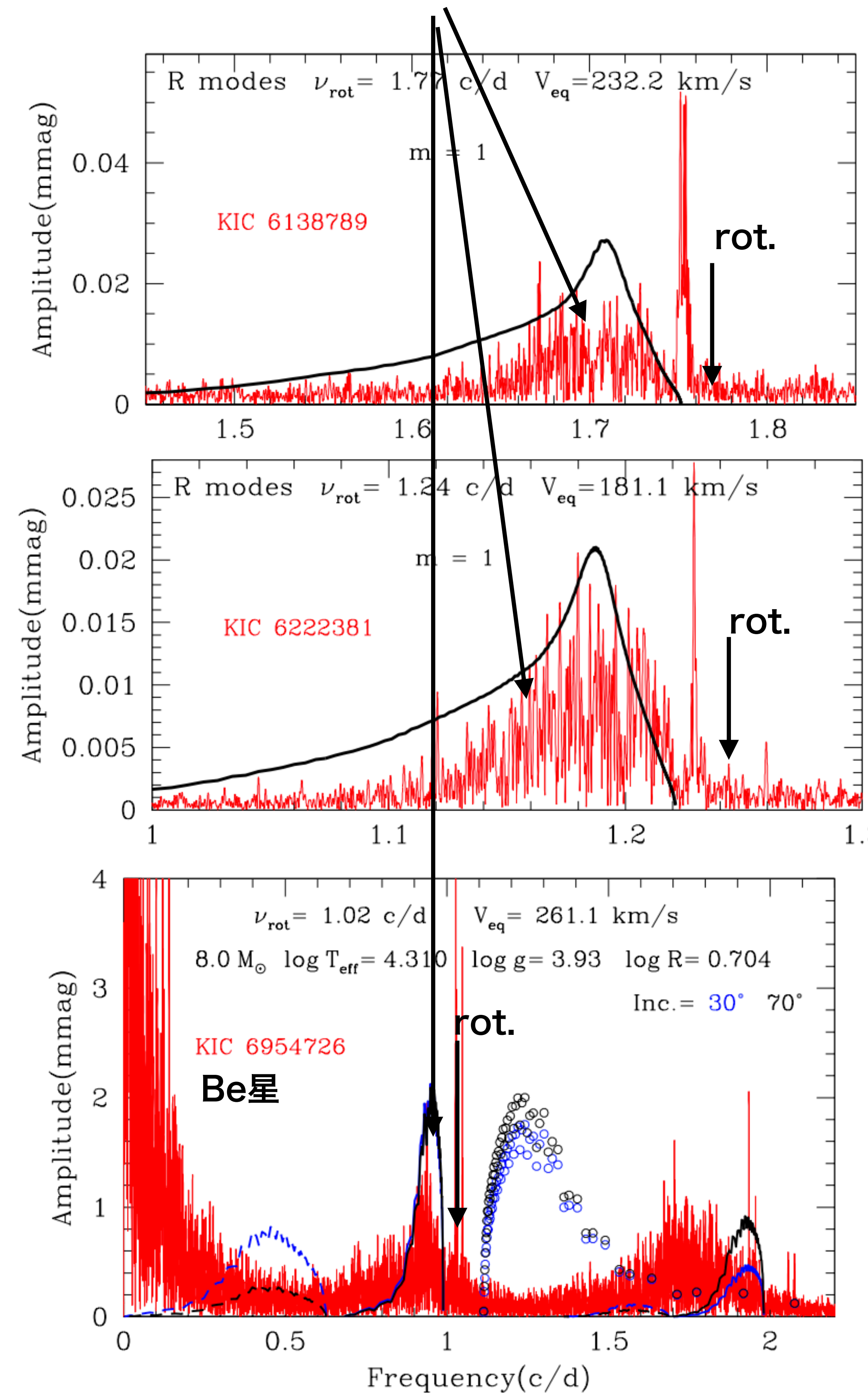






Balona (2017)

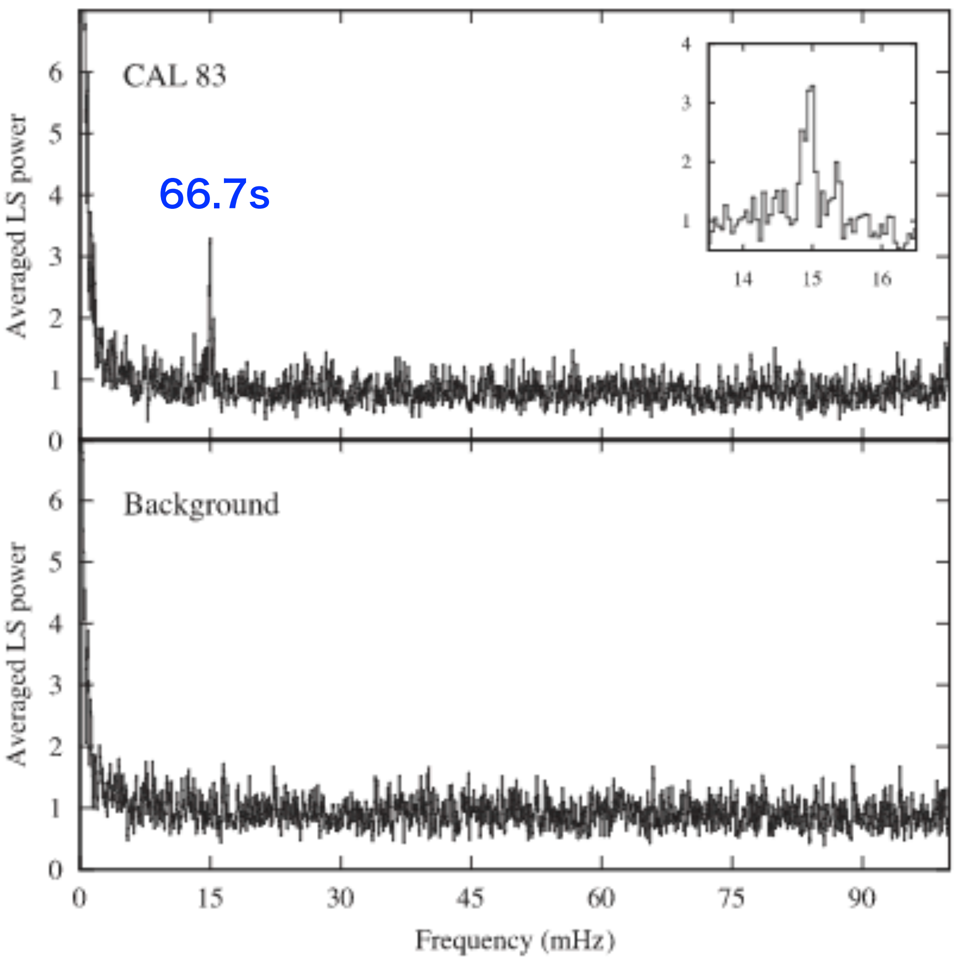
r modes



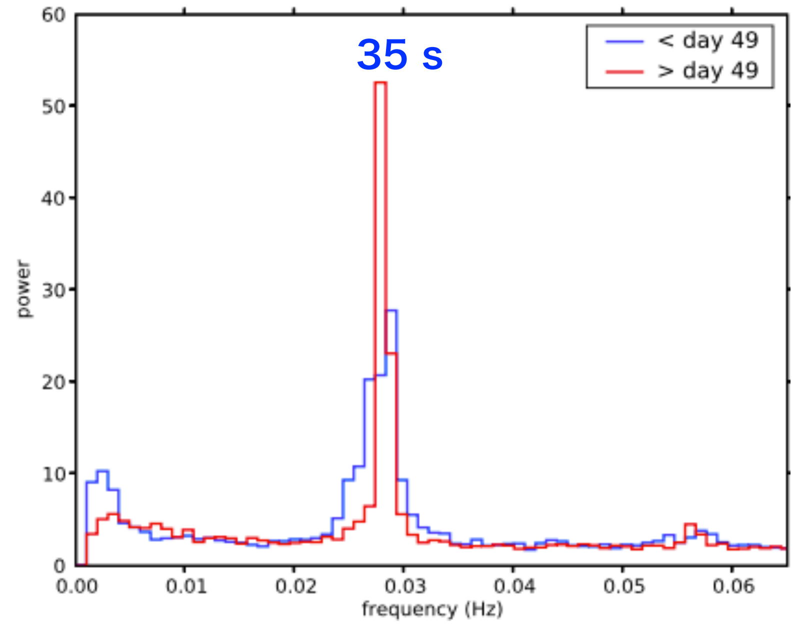
Saio et al.(2018)

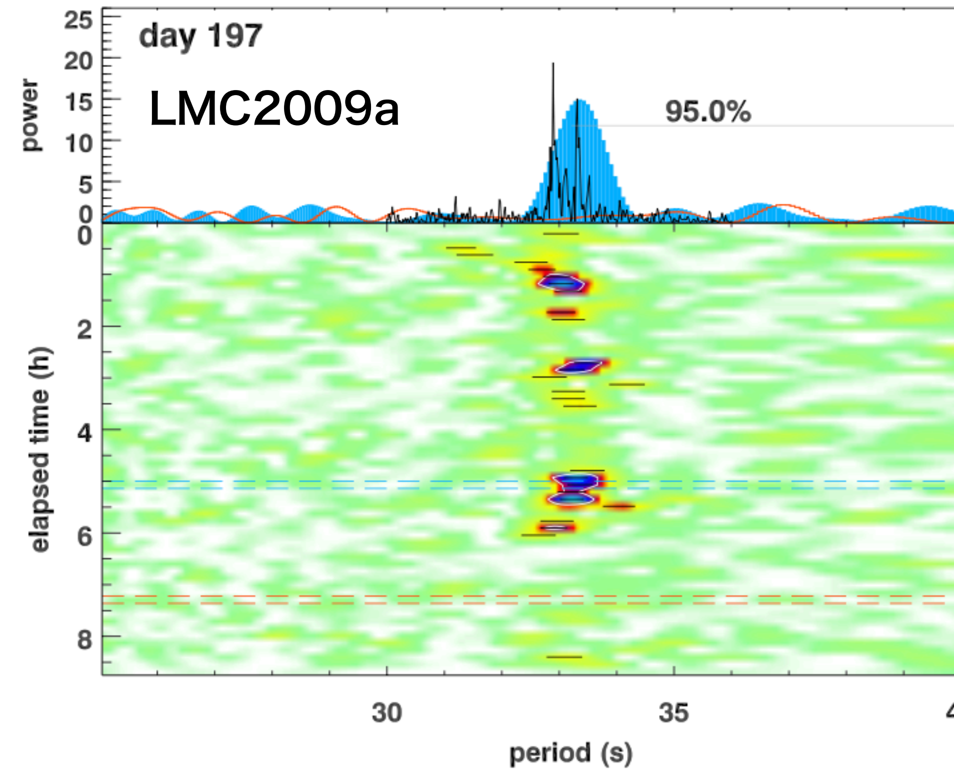
Short period oscillations in Super Soft Xray Souses   r modes??

2952 *A. Odendaal et al.* (2014)



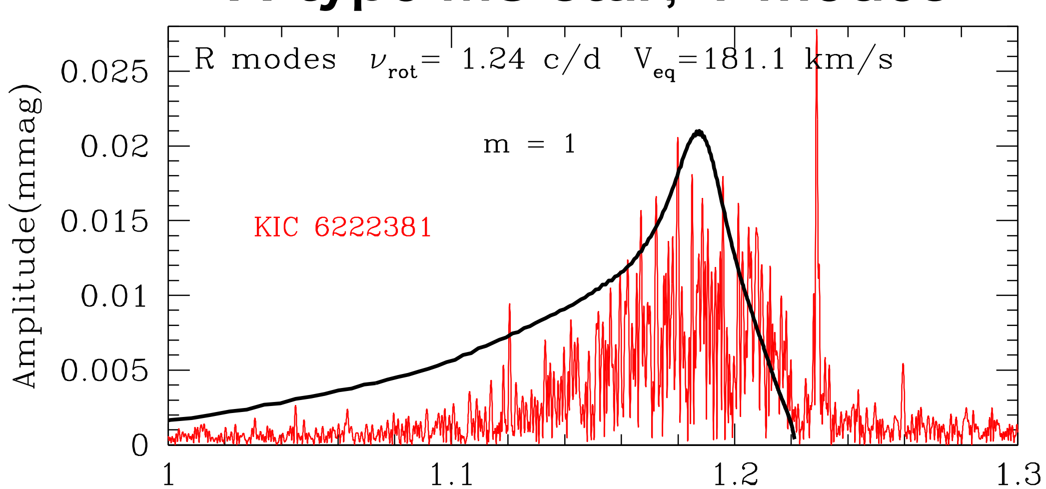
Osborne et al.(2011) RS Oph

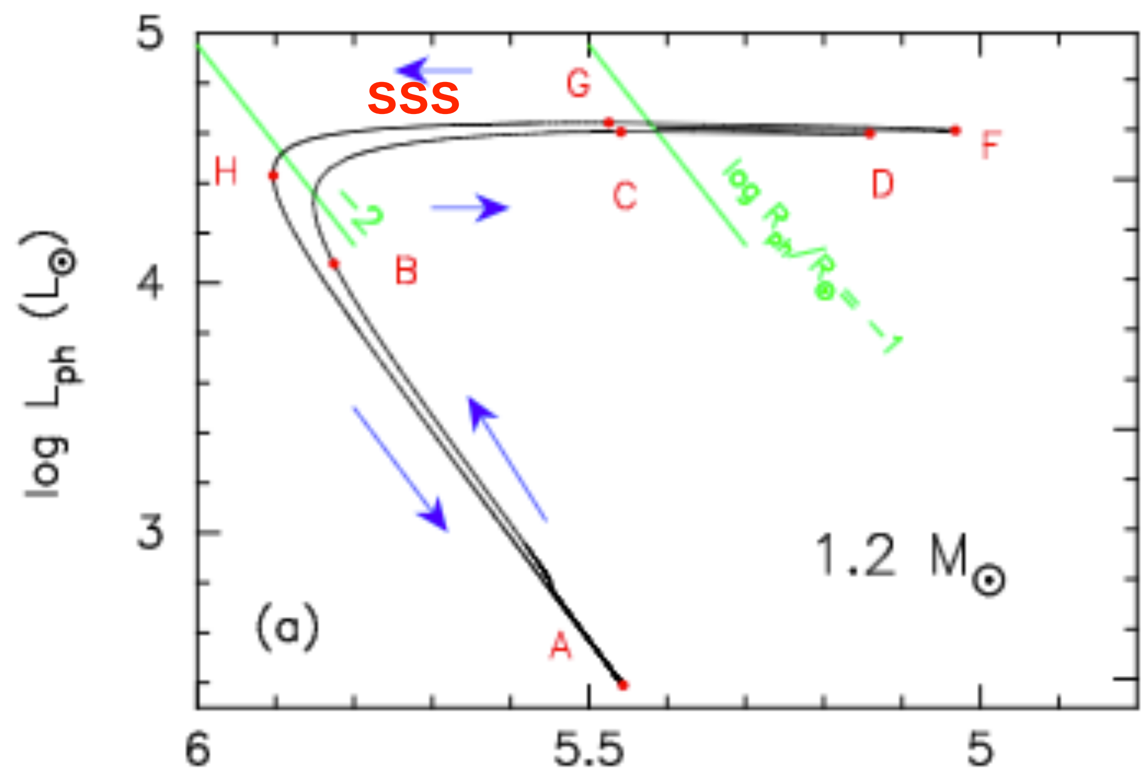




Ness et al. (2015)

A-type MS star; r modes





Kato et al (2017)

星震学による恒星進化モデルの検証

斉尾英行（東北大学）

1. 恒星振動(脈動）についての introduction
2. 恒星振動から知る、主系列星・赤色巨星の進化段階と内部自転速度
3. 恒星の振動が示す対流領域の広がり・混合・質量放出など
4. 恒星の振動が示す恒星合体の起こった証拠
5. r modes (Rossby waves in stars)