星震学(Asteroseismology)

ー振動(脈動)から知る恒星内部：主系列星から超新星親星までー

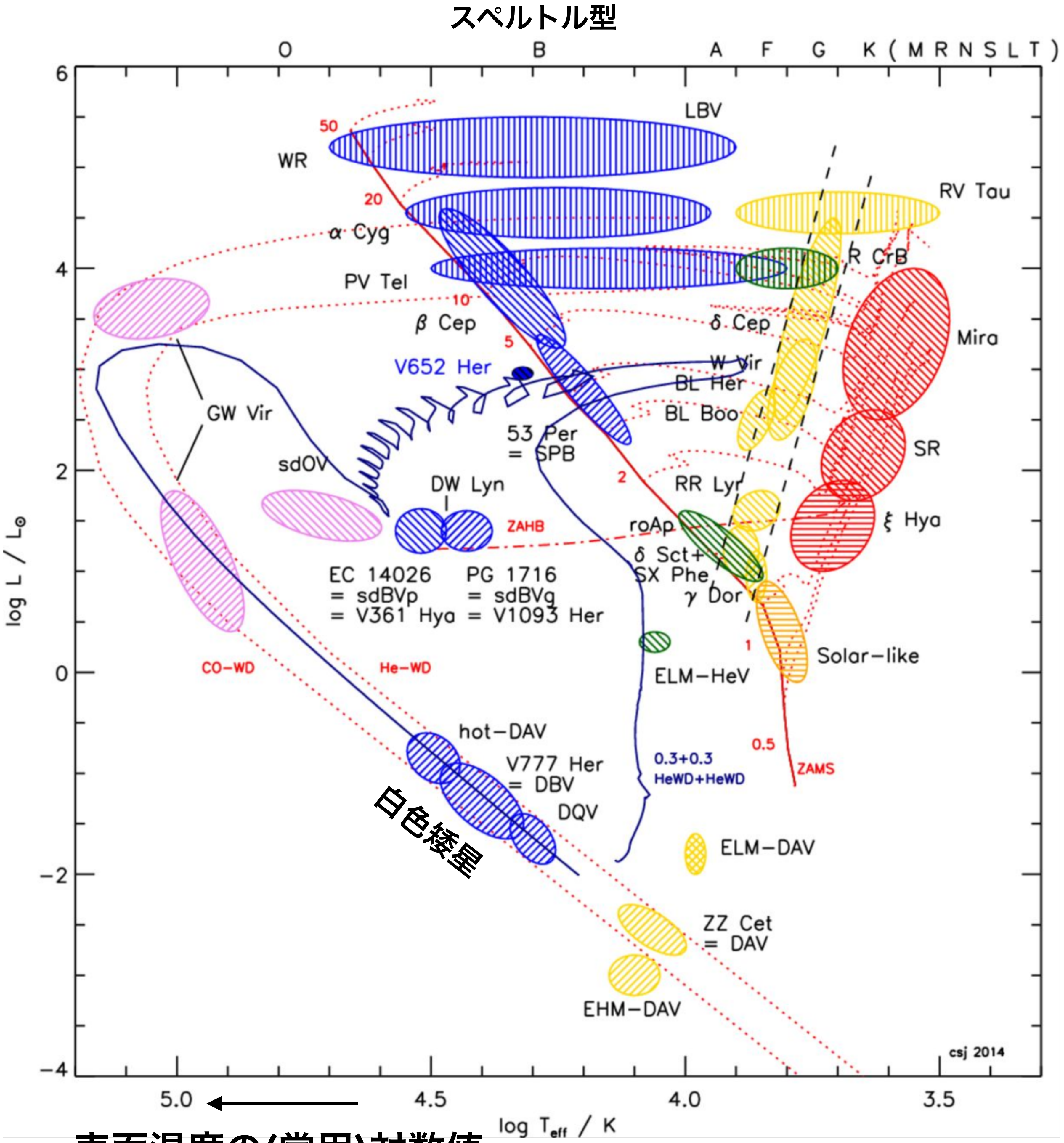
斉尾英行（東北大学）

1. 恒星振動(脈動）の 基本的性質
2. 恒星振動から知る恒星自転速度
3. r (Rossby) mode 振動
4. 脈動周期変化率と恒星進化速度
5. 進化の進んだ大質量星の脈動
6. Betelgeuse (α Ori) の脈動

Pulsational variables in the HRD

L = luminosity
星表面から毎秒放出されるエネルギー

☉ ＝太陽

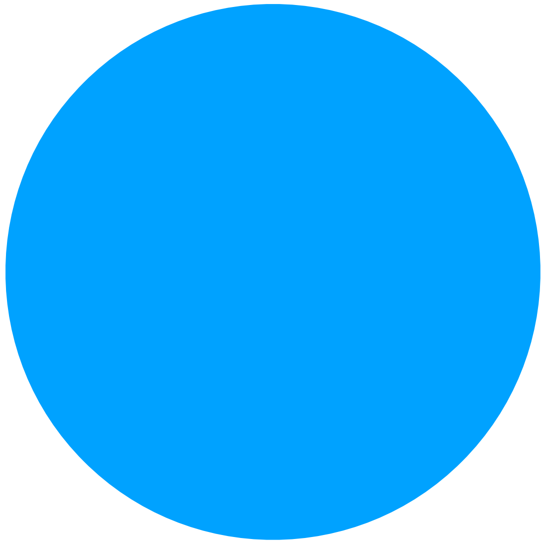


Jeffery et al. (2015)

Radial & Non-radial pulsations

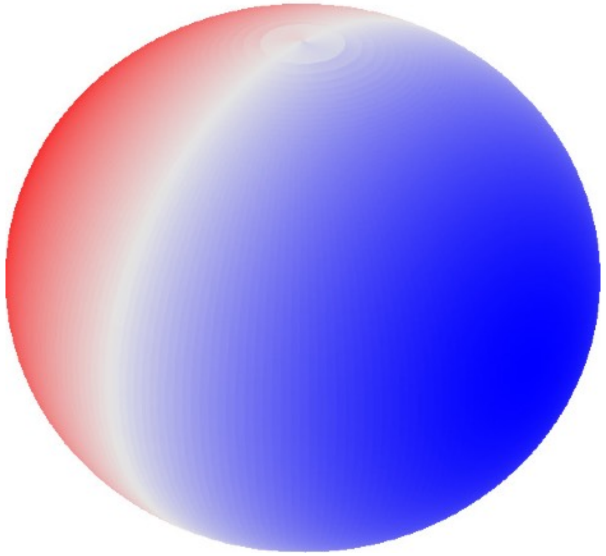
$$Y_\ell^m(\theta,\phi)e^{i\omega t}$$

$\ell = 0, m = 0$

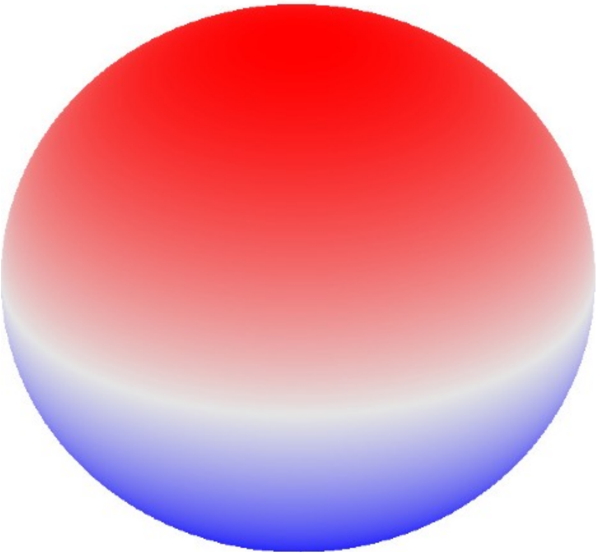


Radial pulsation
(動径脈動)

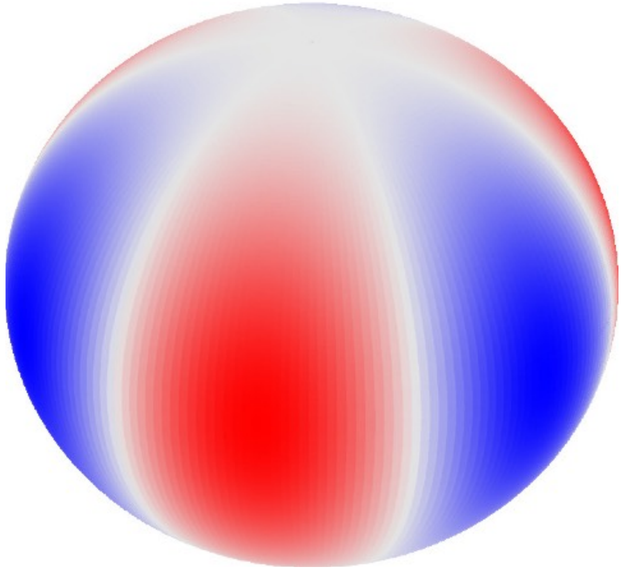
$\ell = 1, m = \pm 1$



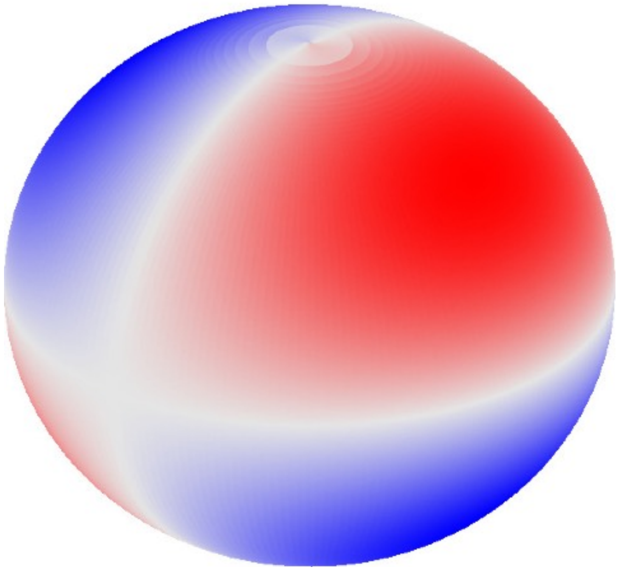
$\ell = 1, m = 0$



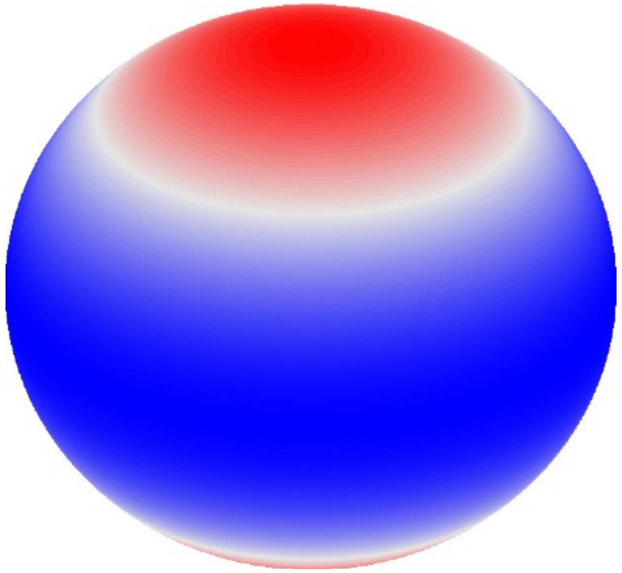
$\ell = 3, m = \pm 3$



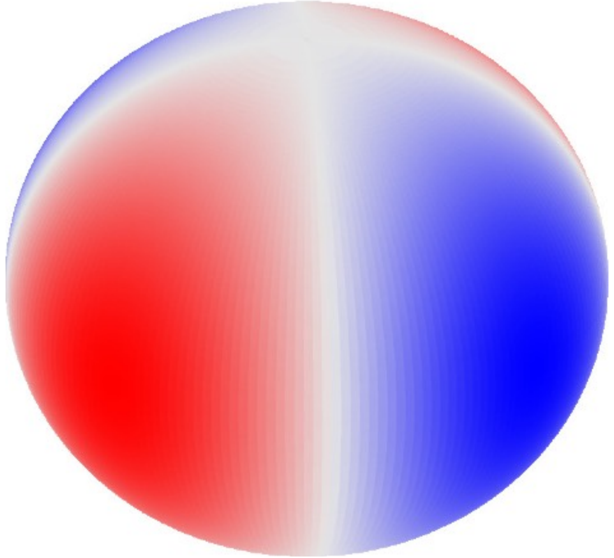
$\ell = 2, m = \pm 1$



$\ell = 2, m = 0$

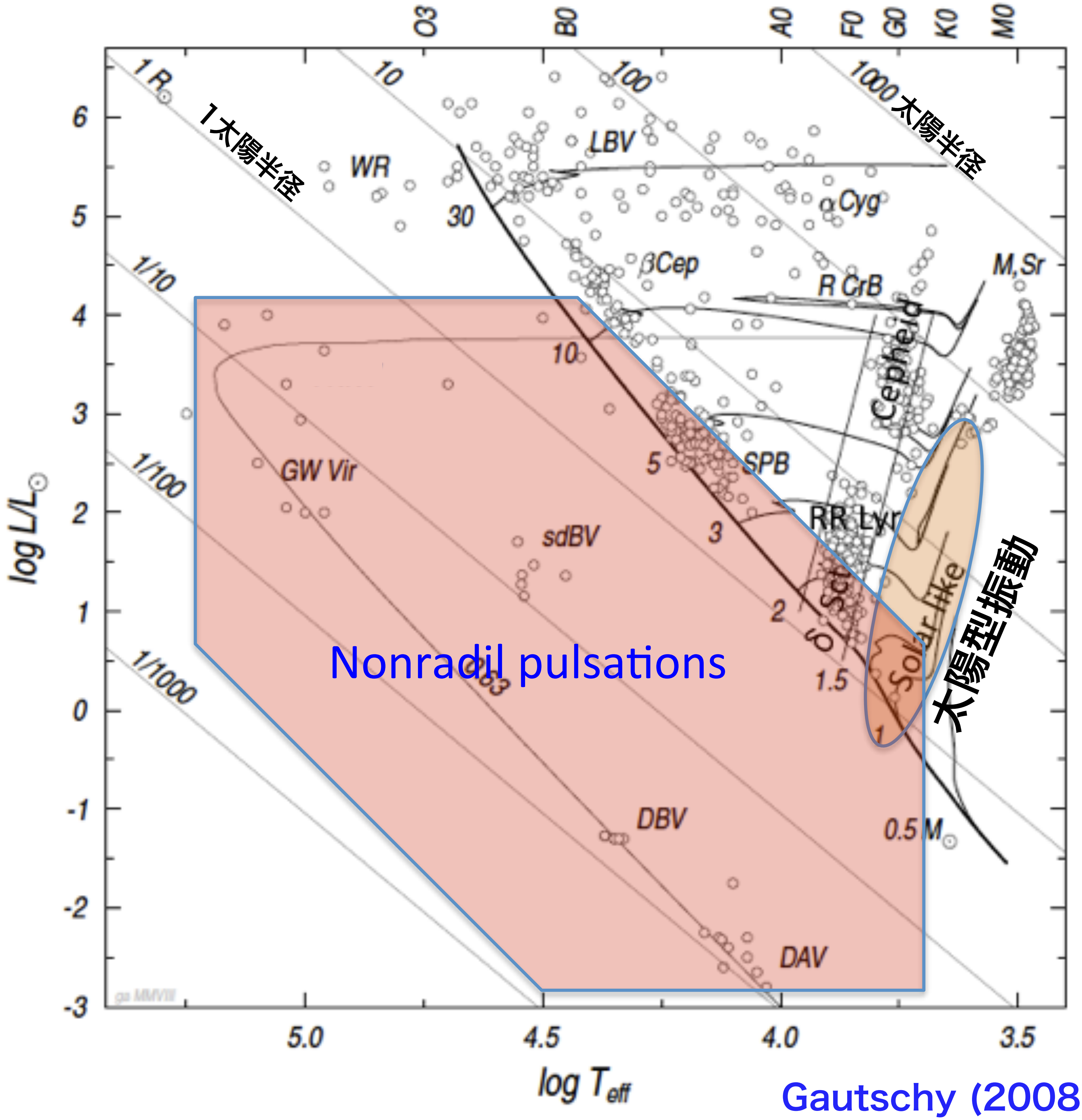


$\ell = 2, m = \pm 2$



Nonradial pulsation (非動径脈動(非動径振動))

種々の脈動変光星サンプルのHR図上の位置



Gautschy (2008)

恒星脈動(振動)の駆動メカニズム

Kappa (opacity) mechanism

Epsilon mechanism　　圧縮高温時にエネルギーを溜め込む

Strange-mode (thermal-dynamical) instability

L/M > 10^4　　外層で　P ~　Prad

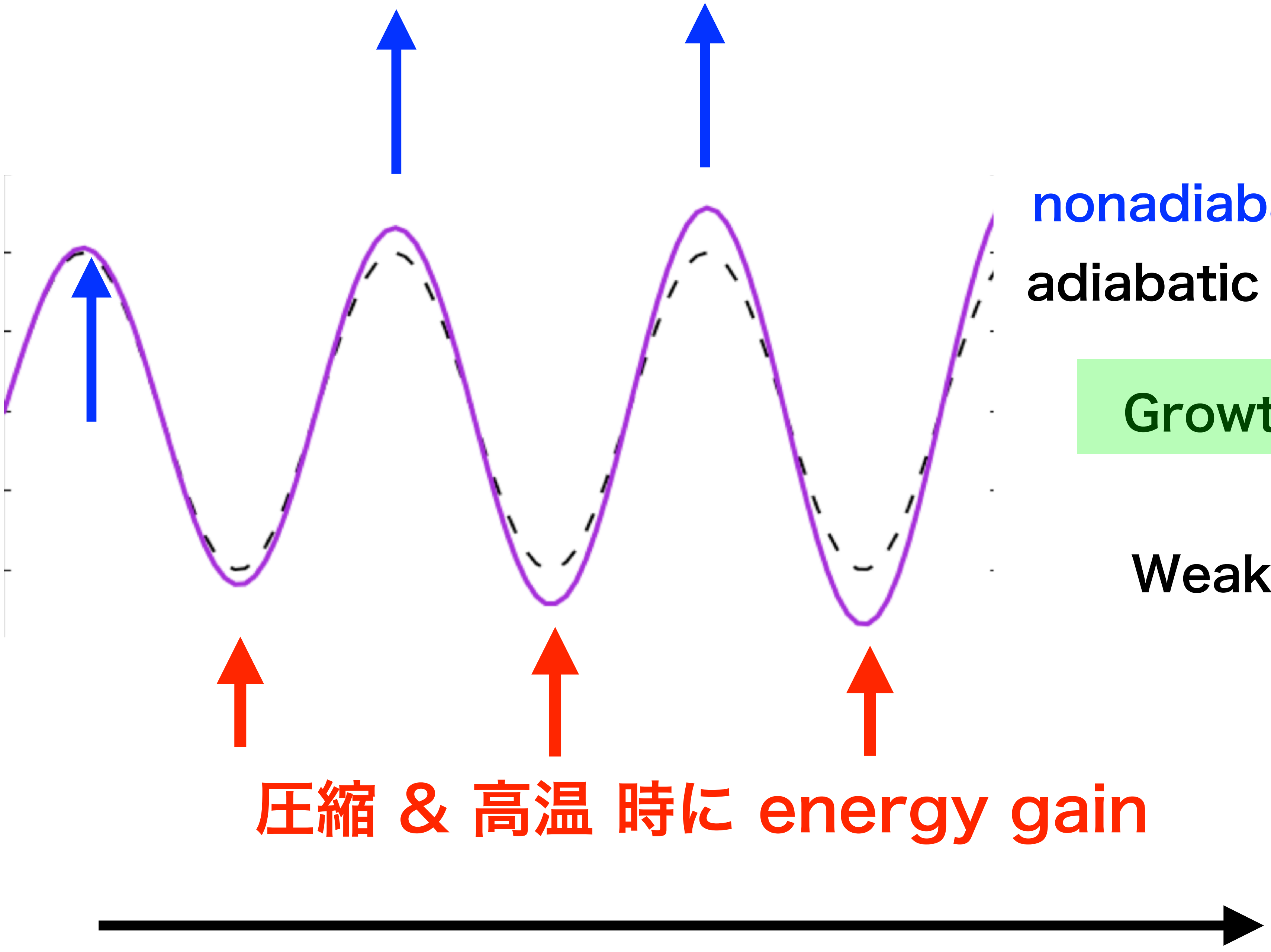
Stochastic excitation mechanism --Solar-like oscillations

対流運動によるランダムな揺らぎ --> 星の固有(p-mode)振動と共鳴

緯度方向の流れの揺らぎとコリオリの力 Rossby waves

＋浮力の効果　ー＞　R (Rossby) mode 振動

Kappa (or opacity) mechanism excitation



規則的な脈動

膨張&低温 時に energy loss

nonadiabatic

adiabatic

圧縮 & 高温 時に energy gain

Time

$$\frac{d}{dr}\left(\kappa_T + \frac{\kappa_\rho}{\Gamma_3 - 1}\right) > 0$$

$$\kappa_T = \left(\frac{\partial \ln \kappa}{\partial \ln T}\right)_\rho \qquad \kappa_\rho = \left(\frac{\partial \ln \kappa}{\partial \ln \rho}\right)_T$$

$$\Gamma_3 - 1 = \left(\frac{d \ln T}{d \ln \rho}\right)_{\rm ad}$$

Growth time >> Period

Weakly nonadiabatic

$$\frac{\Delta P}{P} \approx \Gamma_1 \frac{\Delta \rho}{\rho}$$

ほとんど断熱関係が成り立つ

核反応の起こっている領域では常に高温時にenergy gain

-> Epsilon mechanism (脈動駆動への寄与は小さい)

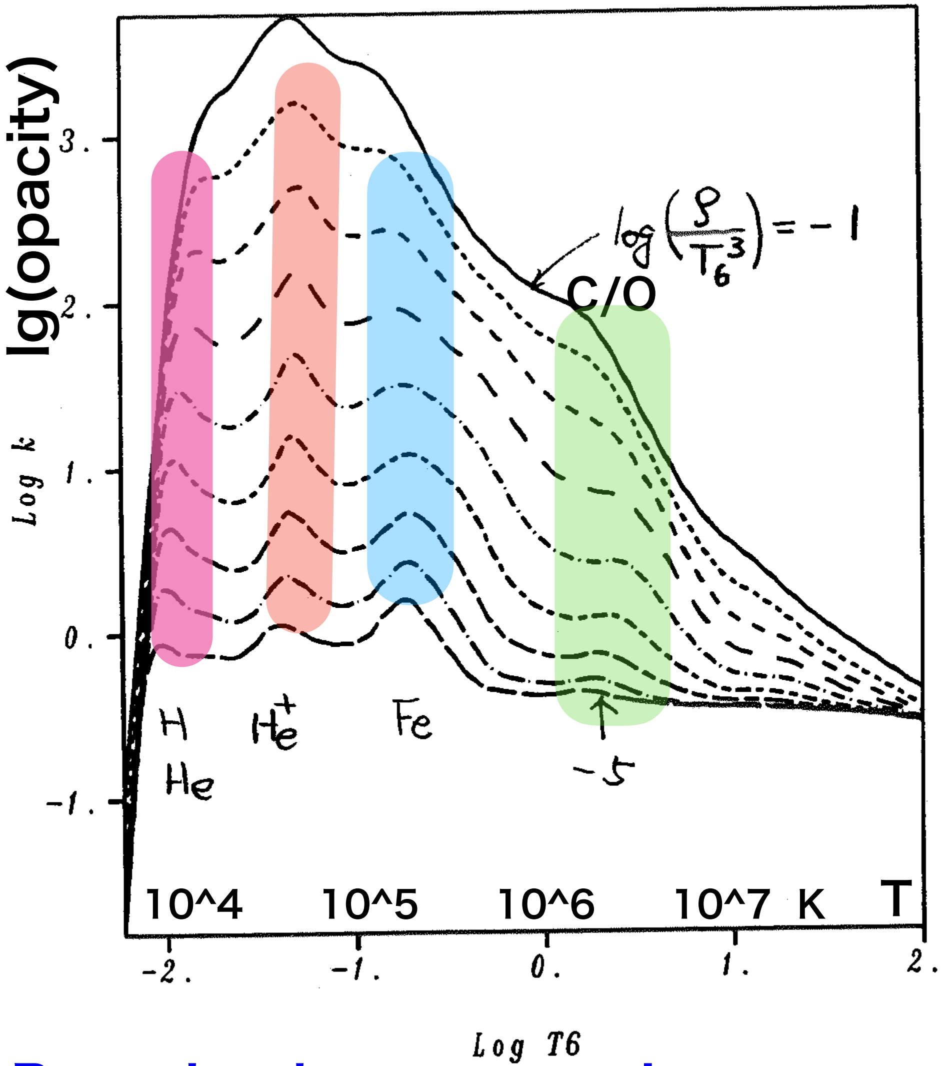
Kappa-mechanismで成長した脈動

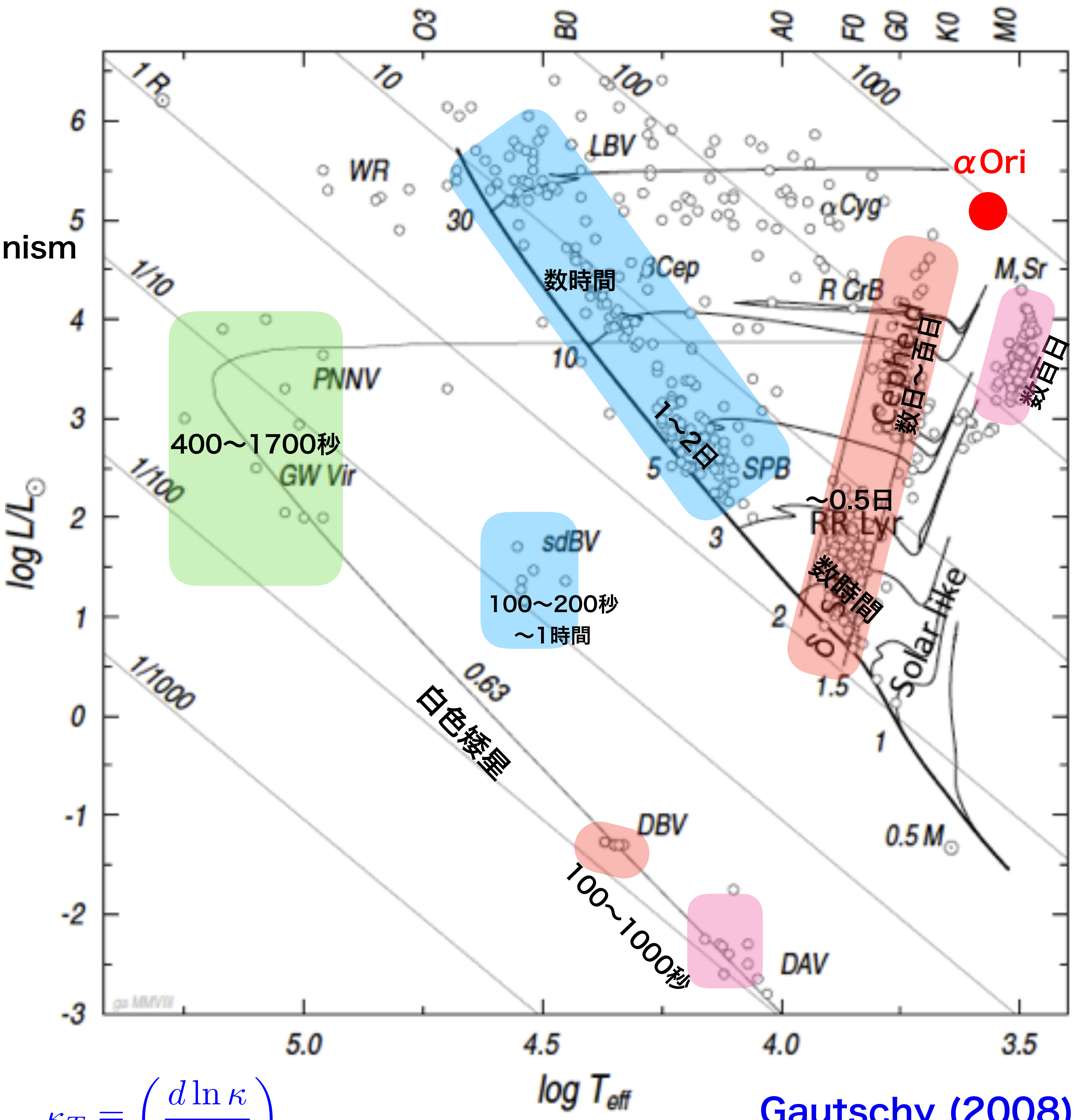
Thermal time ~ Period

となっている層で

$$\frac{d}{dr}\left(\kappa_T + \frac{\kappa_\rho}{\Gamma_3 - 1}\right) > 0$$

kappa mechanism
が働く



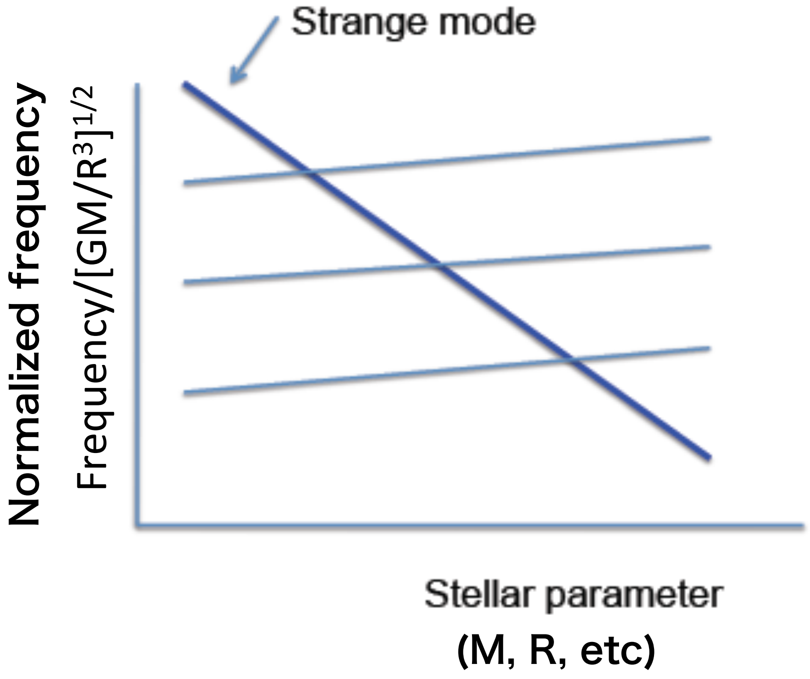


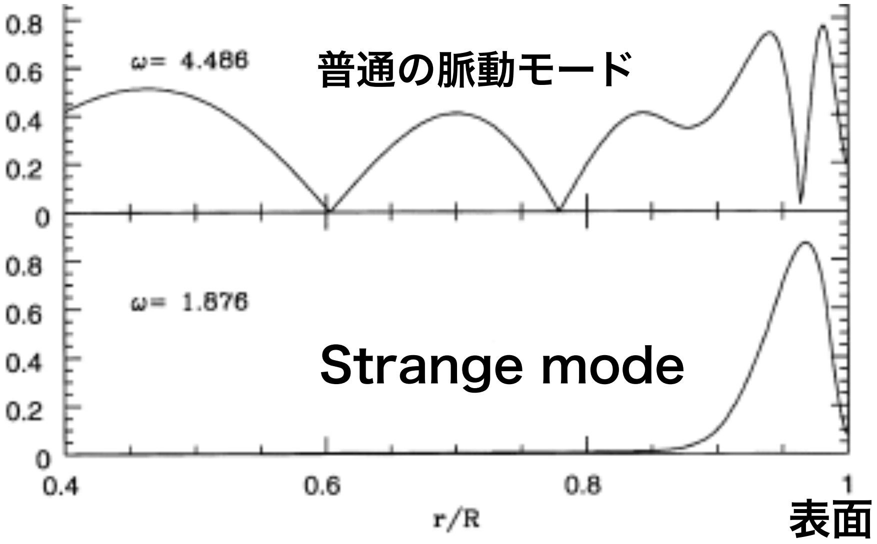
Rosseland mean opacity

$$\frac{1}{\kappa} \equiv \left[\int_0^\infty \frac{dB_\nu}{dT} d\nu\right]^{-1} \int_0^\infty \frac{(dB_\nu/dT)}{\kappa_\nu + \sigma_\nu} d\nu, \quad \kappa_T \equiv \left(\frac{d\ln\kappa}{d\ln T}\right)$$

Gautschy (2008)

Strange-mode (thermo-dynamical) instability





星の内部での脈動振幅分布

Strange modes are trapped in the outer layers where

$$P_{\rm rad} \gg P_{\rm gas}$$

$$\frac{(L/L_\odot)}{(M/M_\odot)} > 10^4$$

$\frac{L}{4\pi r^2} = -\frac{c}{\kappa\rho}\frac{dP_{\rm rad}}{dr}$ **with** $\tau_{\rm thermal} \ll {\rm Period}$ **->** $\frac{\partial \Delta P}{\partial r} \approx \frac{\partial \Delta P_{\rm rad}}{\partial r} \approx -\frac{\kappa_\rho \kappa}{c}\frac{L}{4\pi r^2}\Delta\rho$

ΔPとΔρの位相の不一致　ー＞　Dynamical type instability
Strange mode instability

$$\Delta P, \Delta\rho \propto \exp(i\sigma t - i k_r r)$$

$$\Delta P = i\frac{\kappa_\rho \kappa}{k_r c}\frac{L}{4\pi r^2}\Delta\rho$$

(cf. adiabatic relation $\frac{\Delta P}{P} = \Gamma_1 \frac{\Delta\rho}{\rho}$)

Large phase difference between ΔP & $\Delta\rho$ --> strong instability

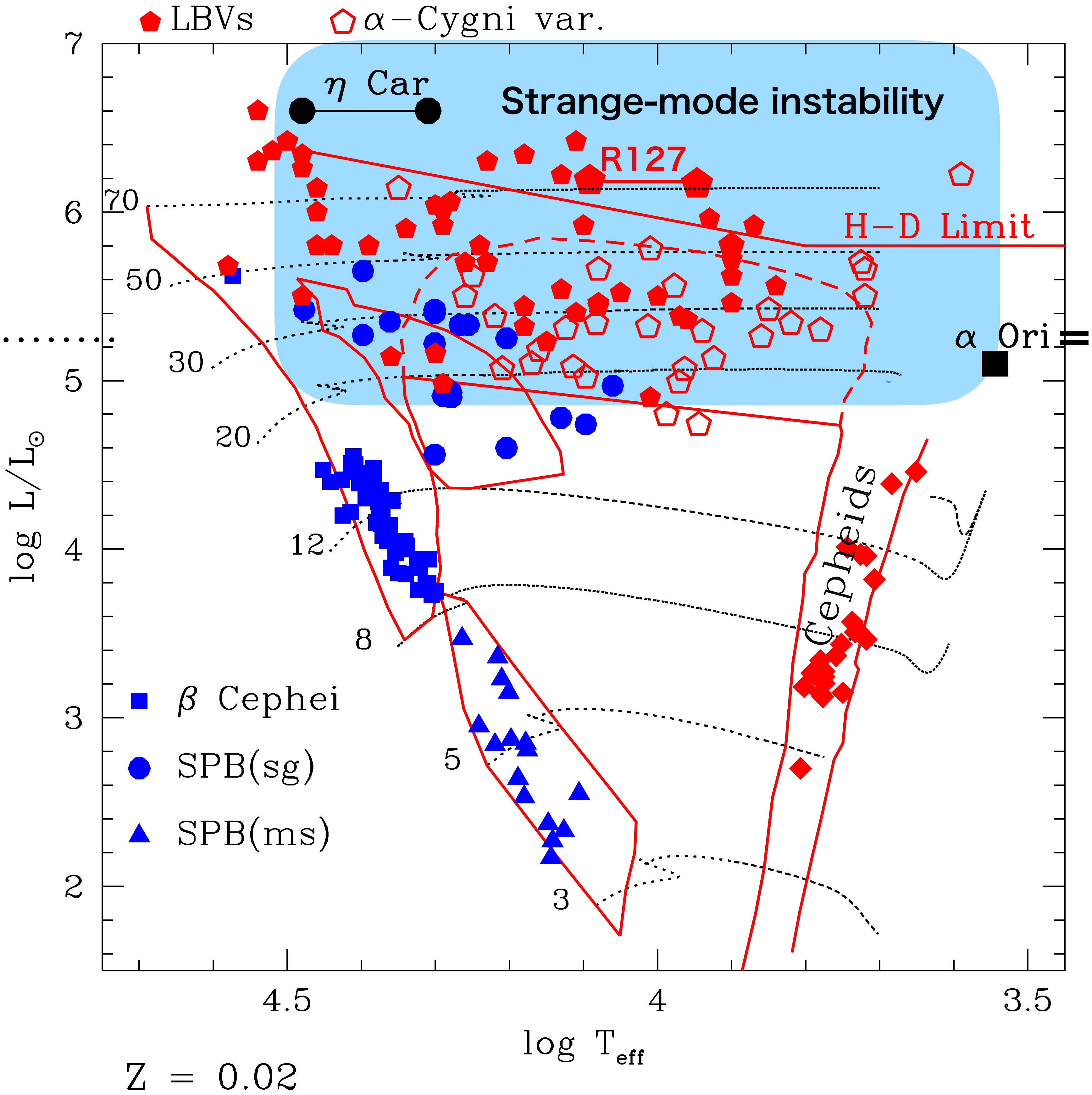
不規則な脈動

Massive (Luminous) variable stars

Strange-mode instability (不規則な脈動)

L/M ～1e4 ……………

kappa-mechanism (規則的な脈動)



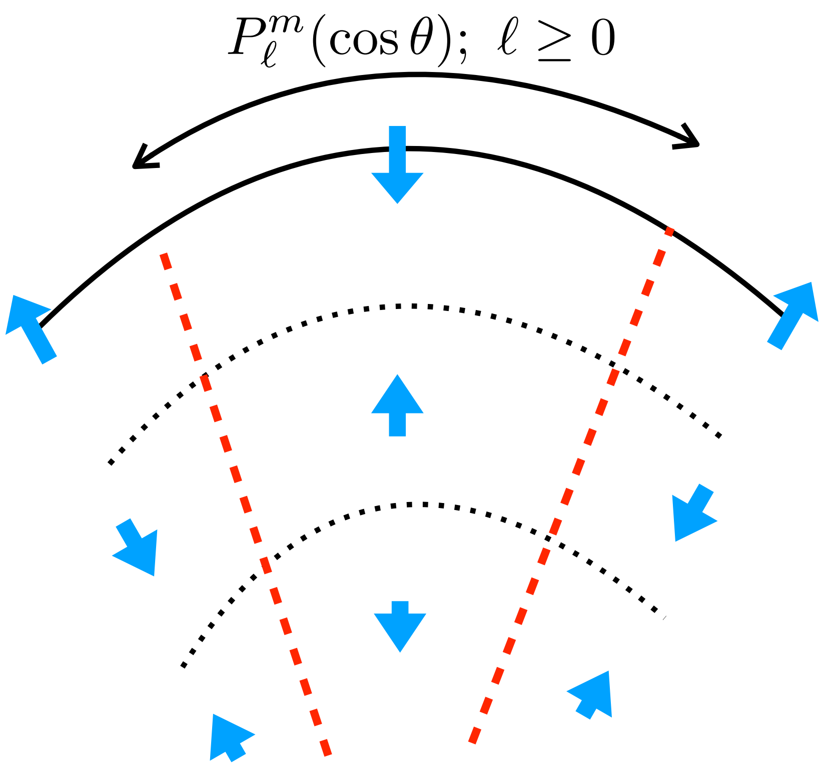
＝ベテルギウス

星の振動（脈動）の２種類のモード

動径方向の運動が優勢

radial または nonradial modes

pモード振動

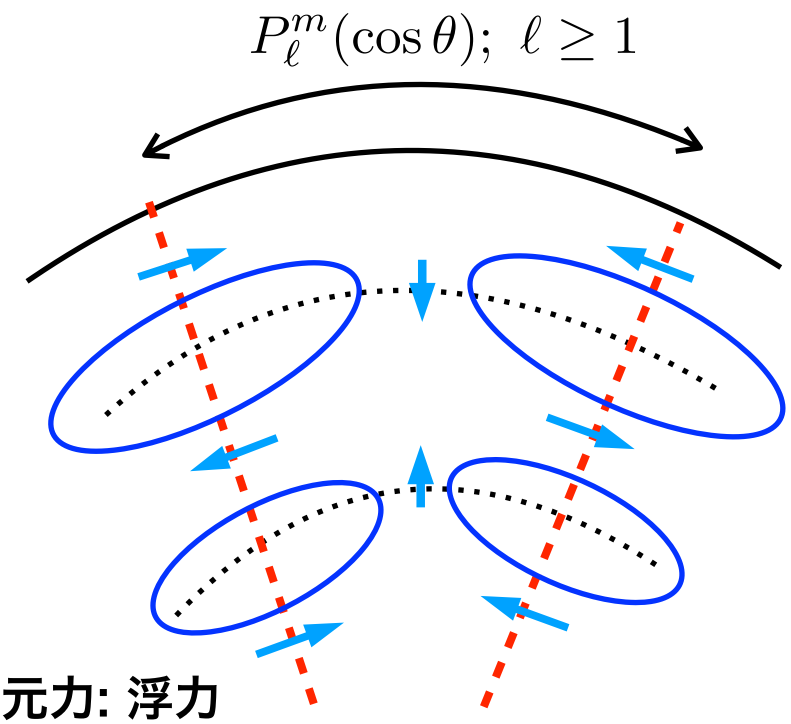


水平方向の運動が優勢

nonradial modes のみ

gモード振動

(＋r モード)



復元力: 圧力(音波)

復元力: 浮力

$$\mathrm{R.F.} \propto g\Delta\rho \propto g\xi_r \quad \& \quad \mathrm{K.E.} \propto (\xi_h/\Pi_g)^2$$

周期が短い

周期が長い

周期：

$$\Pi_p \propto \frac{1}{n+1}\frac{2R}{< c_s >} \quad \ll \quad \longrightarrow \quad \Pi_g \propto \frac{\xi_h}{\xi_r} \sim \frac{n}{\ell}$$

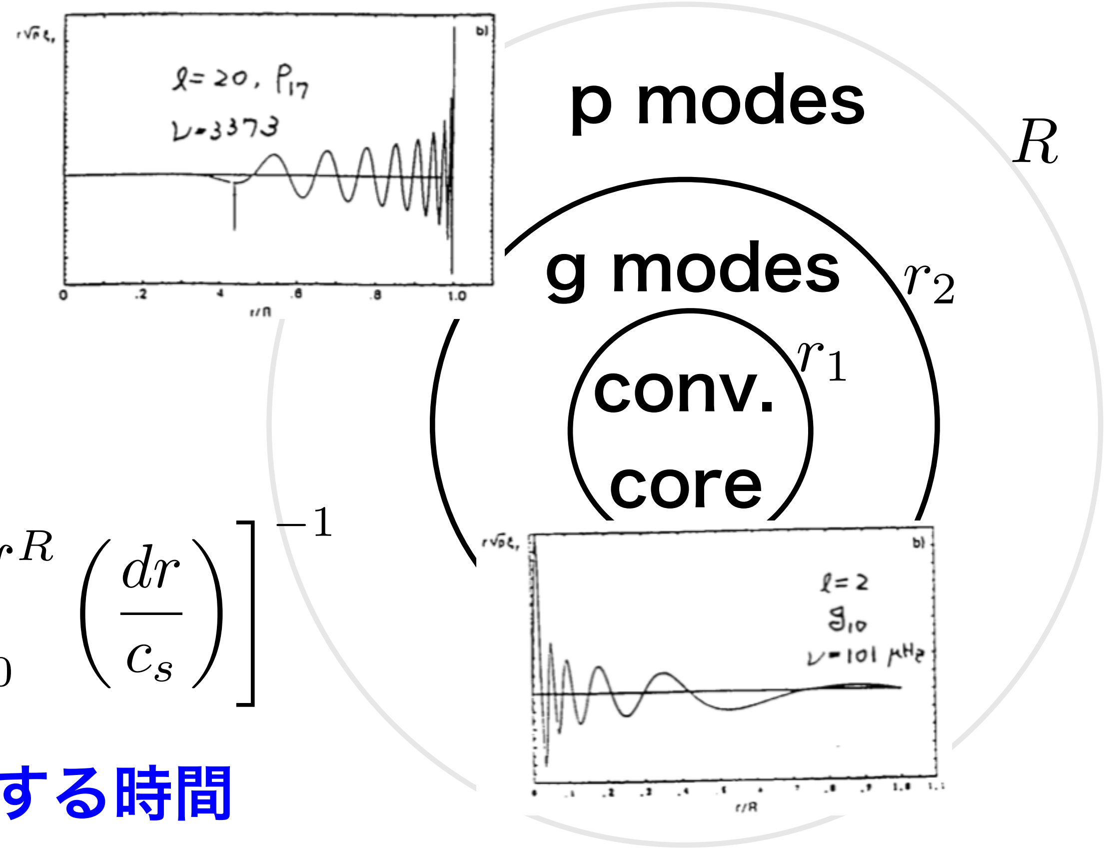
n >> 1 のとき:　Δν＝Δ(1/Π)が一定

ΔΠ= (Π(n+1)ーΠ(n))　周期間隔が一定

セファイド，ミラ，太陽型振動
ベテルギウス，リゲルなど

白色矮星，主系列星(γ Dor, SPBなど)

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



p modes -- 外層部(envelope)

n >> 1　　n= ノードの数

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

p mode の周期 ＝ 隣接するノード間を音波が往復する時間

ー＞上下移動の幅が小さい(n大)と周波数が大きい(周期が短い)

……

g modes -- 深層部(core)

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

$\rho = \mathrm{density}$

Brunt-Väisälä frequency $N^2 = \frac{g}{r}\left[\left|\frac{d\ln\rho}{d\ln r}\right| - \left|\frac{d\ln\rho}{d\ln r}\right|_{\mathrm{ad}}\right]$ (浮力による振動の基本振動数)

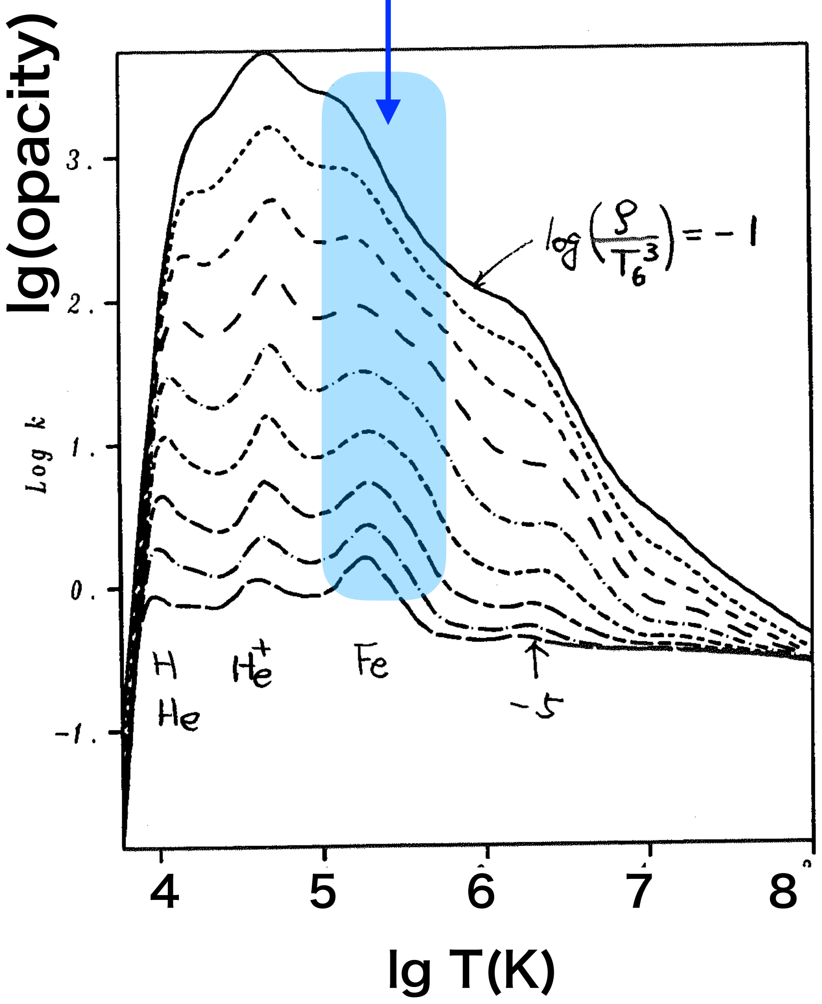
安定な構造では $N^2 > 0$ (上むきの移動に対し負の浮力)

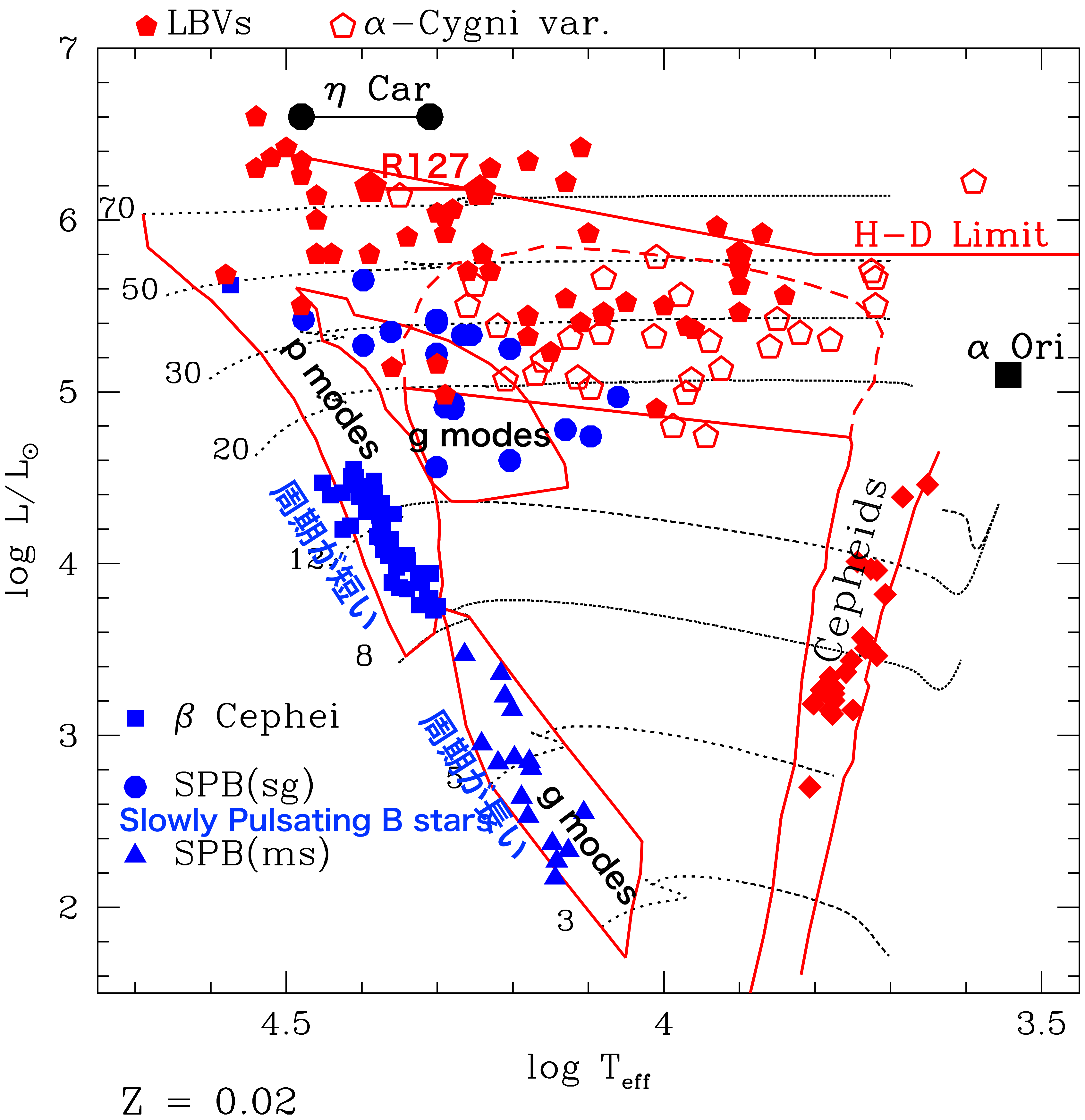
上下移動の幅が小さい(n大)と負の浮力による復元力が小さい ー＞ 周期の長い振動

密度勾配の大きな中心部ほど Nが大きい ー＞ ΔP が小さい

Massive (Luminous) variable stars

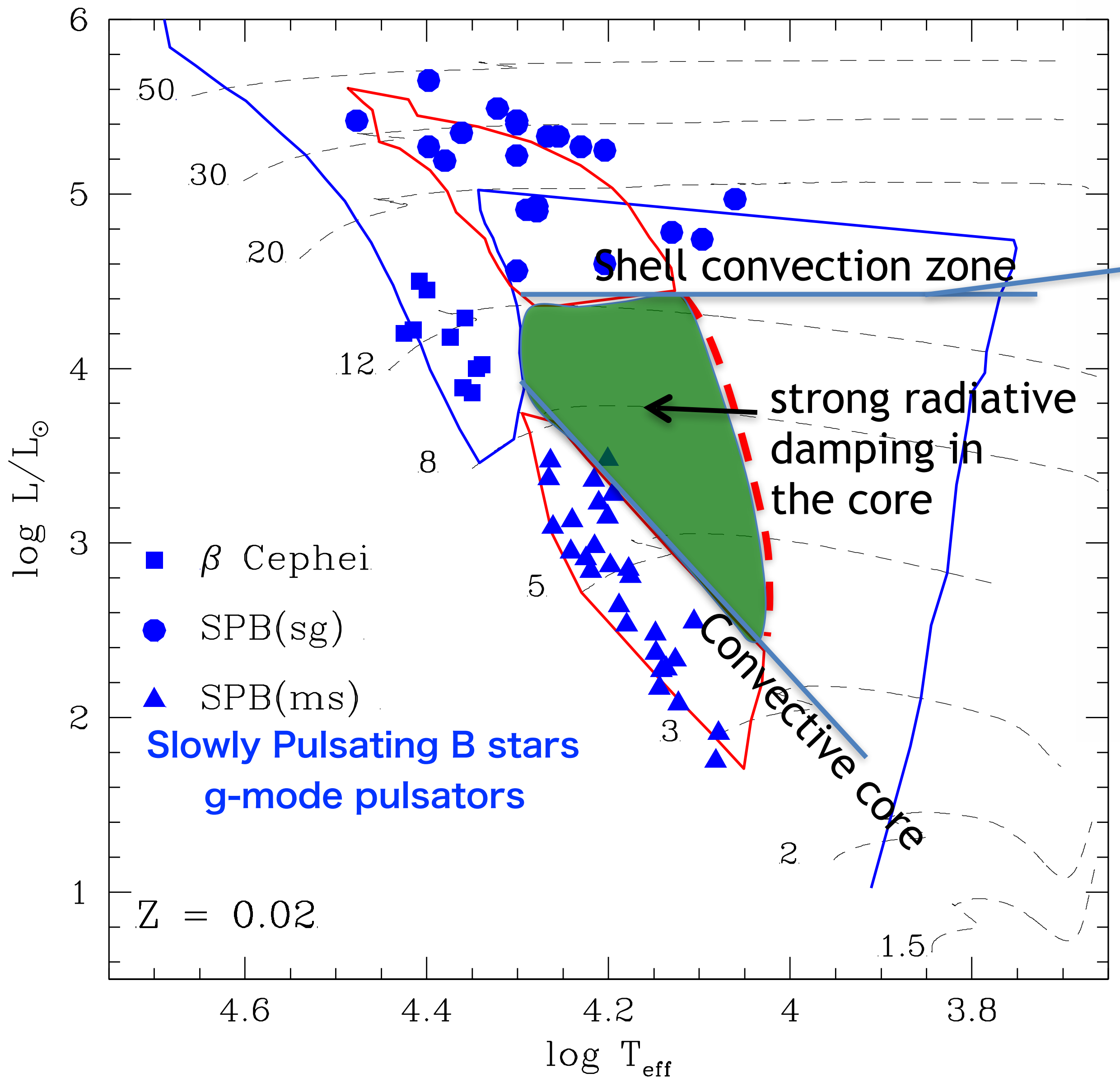
鉄の電離層で
熱交換時間〜脈動周期
となっている時
κ-mechanism励起
（高温度星）

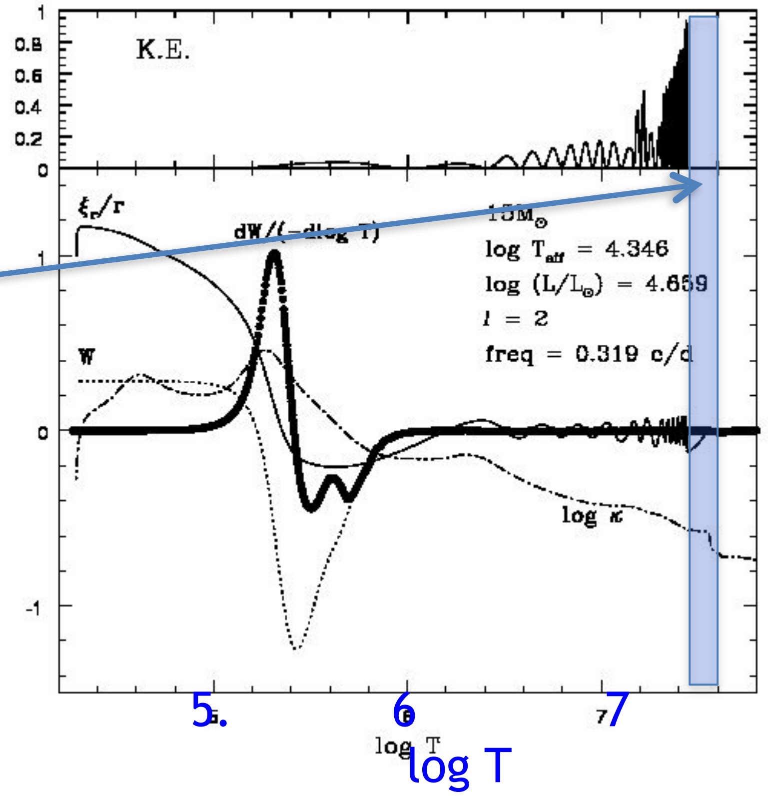




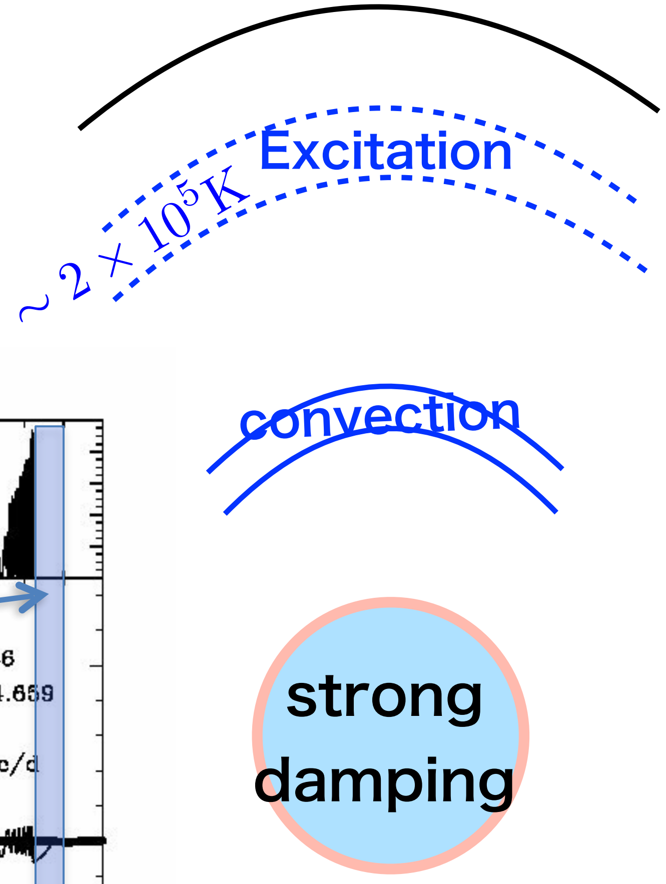
g-mode instability boundaries は対流層の有無に影響される
(shell convection zone or convective core)

g-mode は対流層に侵入できない (N=0)





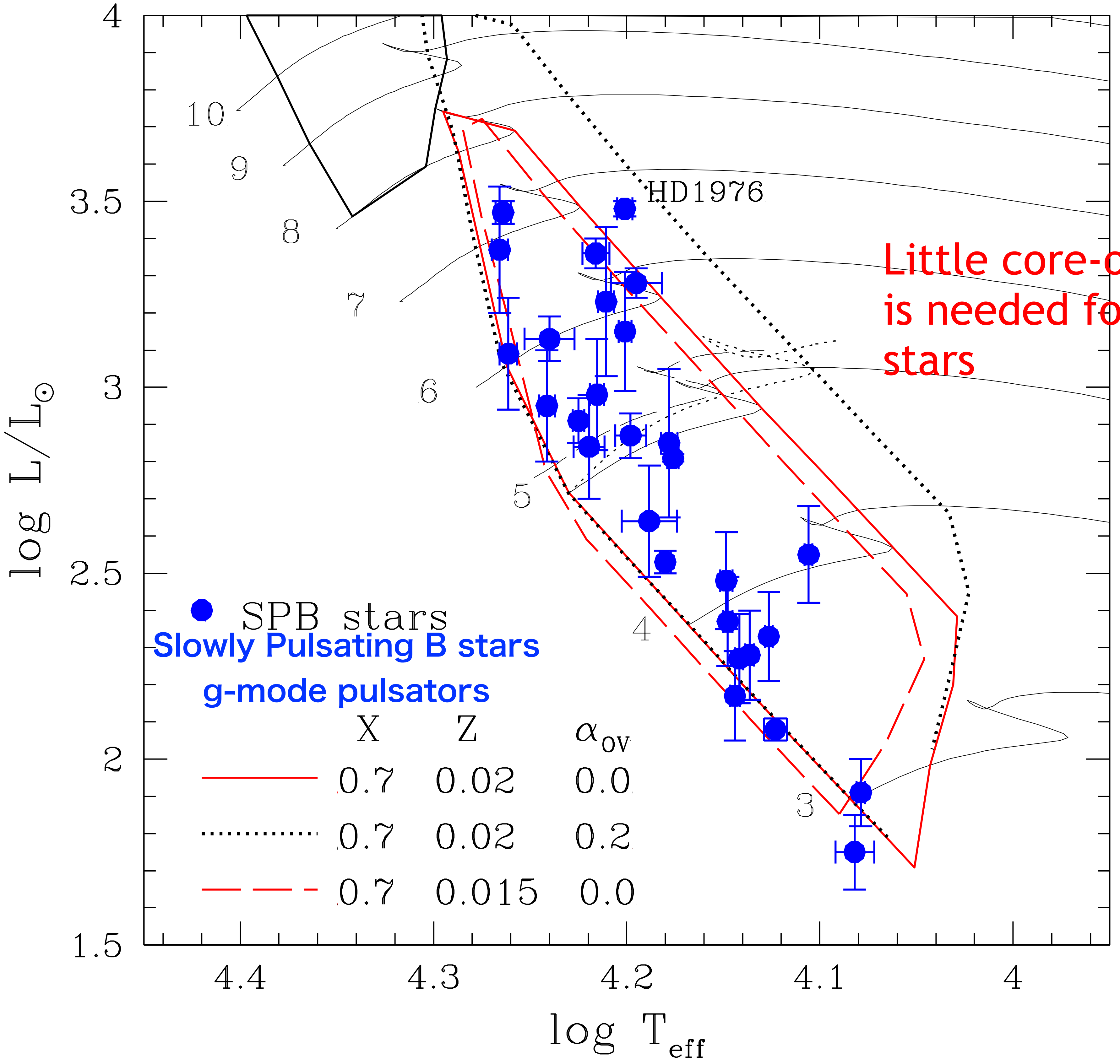
Shell convection zone
reflect g-modes
---- no radiative damping
in the core



radiative core

主系列進化後
の星の構造

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

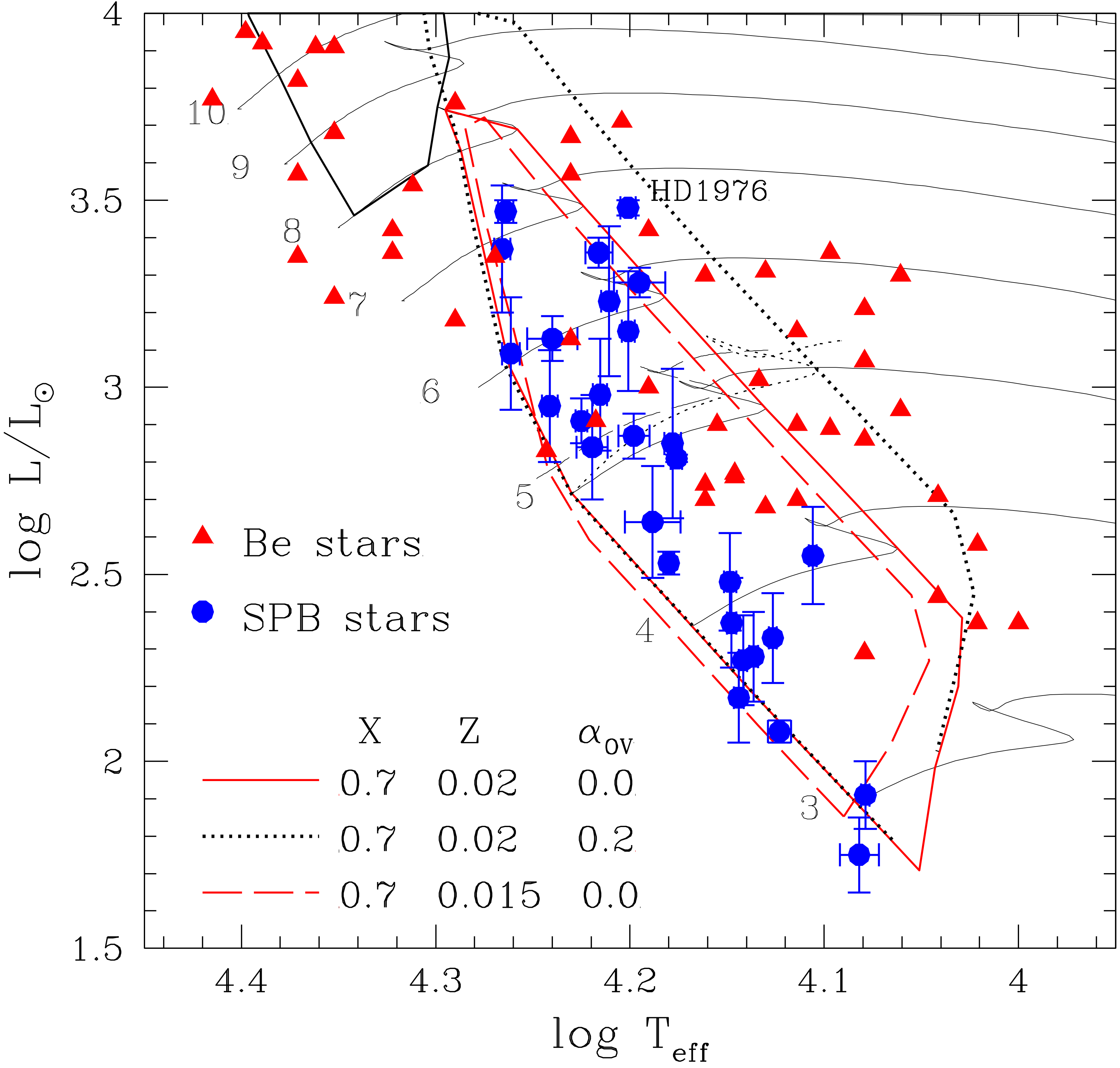


Little core-overshooting is needed for SPB stars

Slowly Pulsating B stars

g-mode pulsators

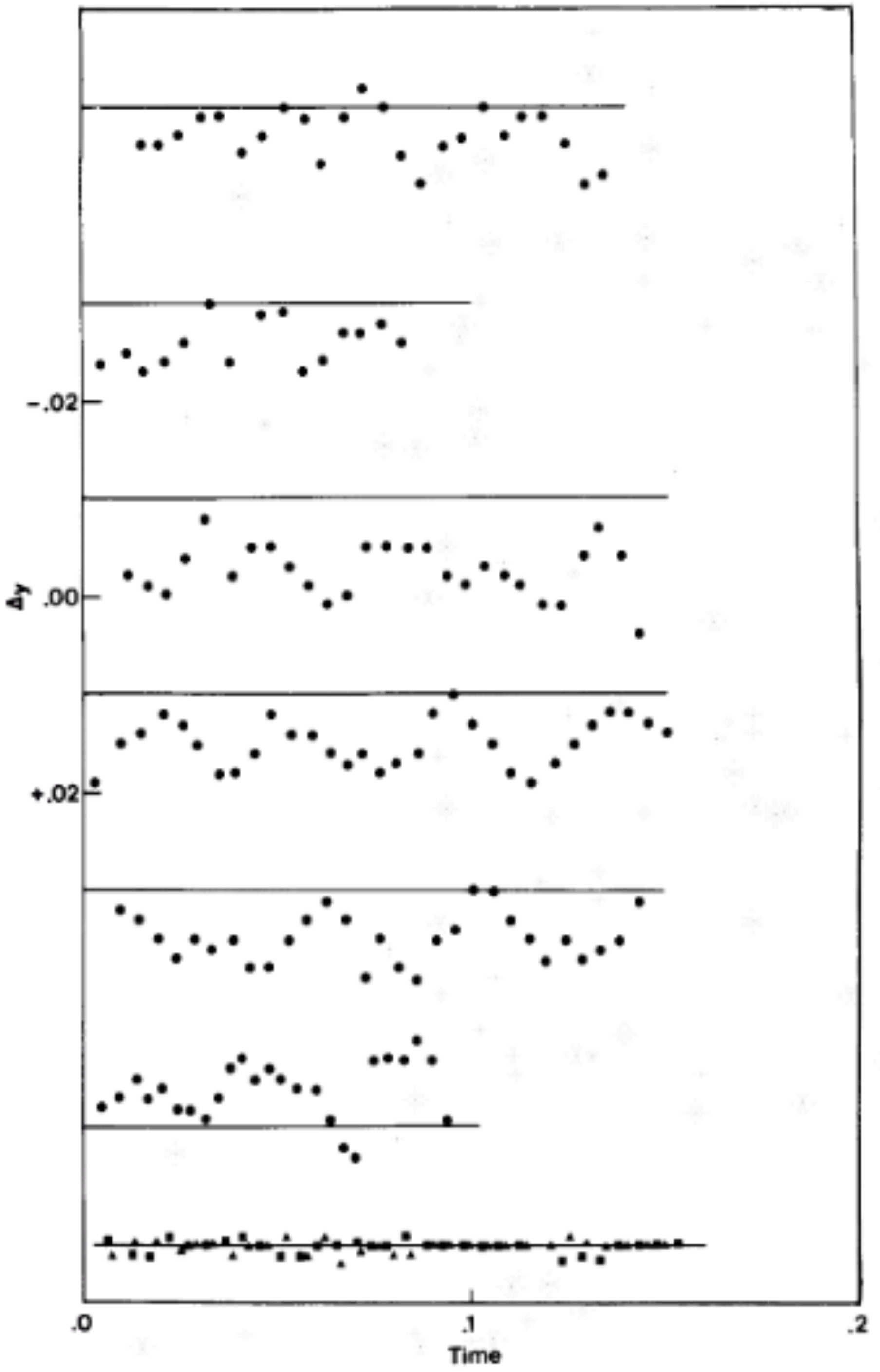
Larger convective core or extensive mixing in rapidly rotating Be stars



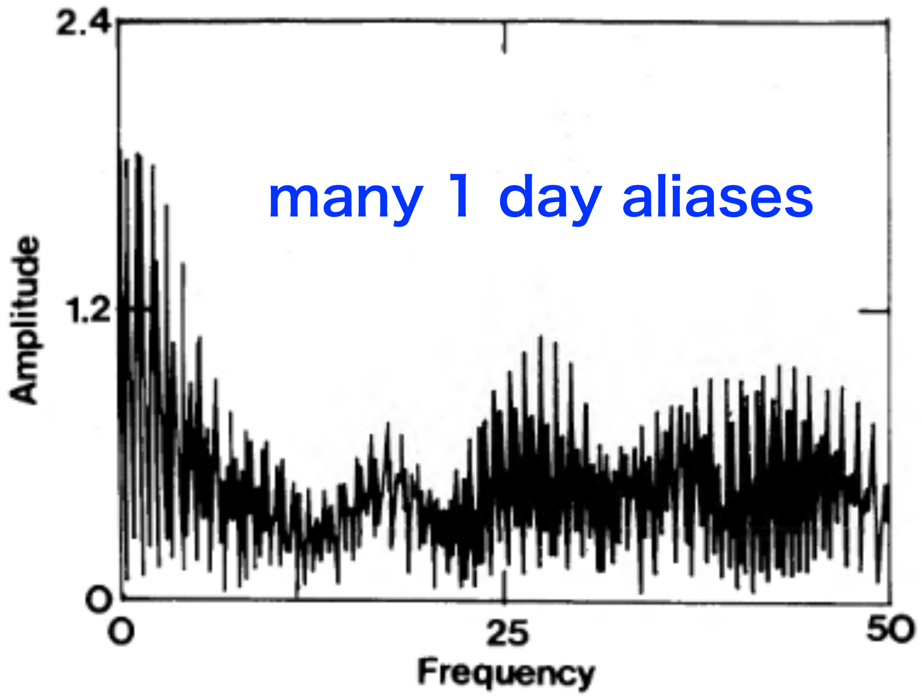
Distribution of Be stars do indicate the presence of substantial overshooting or mixing

恒星の脈動の観測：　測光観測　ー>　フーリエ変換　ー>　脈動周波数(周期)

Single site observations



ight variations in HR 8210. The abscissa is in days and the ordinate in magnitud
ines ($y = 5.95$) fix the apparent magnitude level for each night's observations. '
from top to bottom for JD 2442705, 2442709, 2442711, 2442712 and 2442727



many 1 day aliases

The power spectrum of HR 8210 with the three highest peaks (given in Table 2
n cycle/day. The ordinate is the sinusoidal semi-amplitude in millimagnitudes.

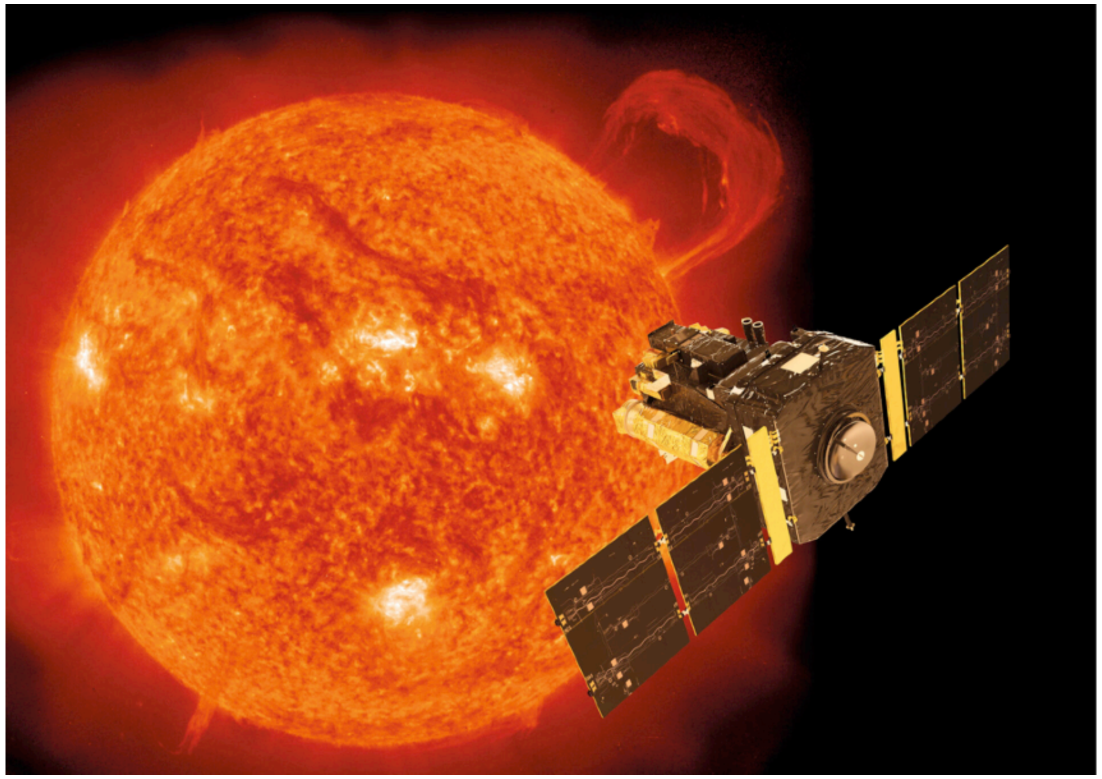
Table 2. Frequencies for HR 8210.

f(c/day)	P (day)	A (mag)	HJD (max. light)
0.642	1.558	0.0043	2442705.787
0.341	2.933	0.0036	2442704.122
22.902	0.044	0.0021	2442705.009

Kurtz (1979)

太陽振動観測装置

GONG (Global Oscillation Network Group) 1995~

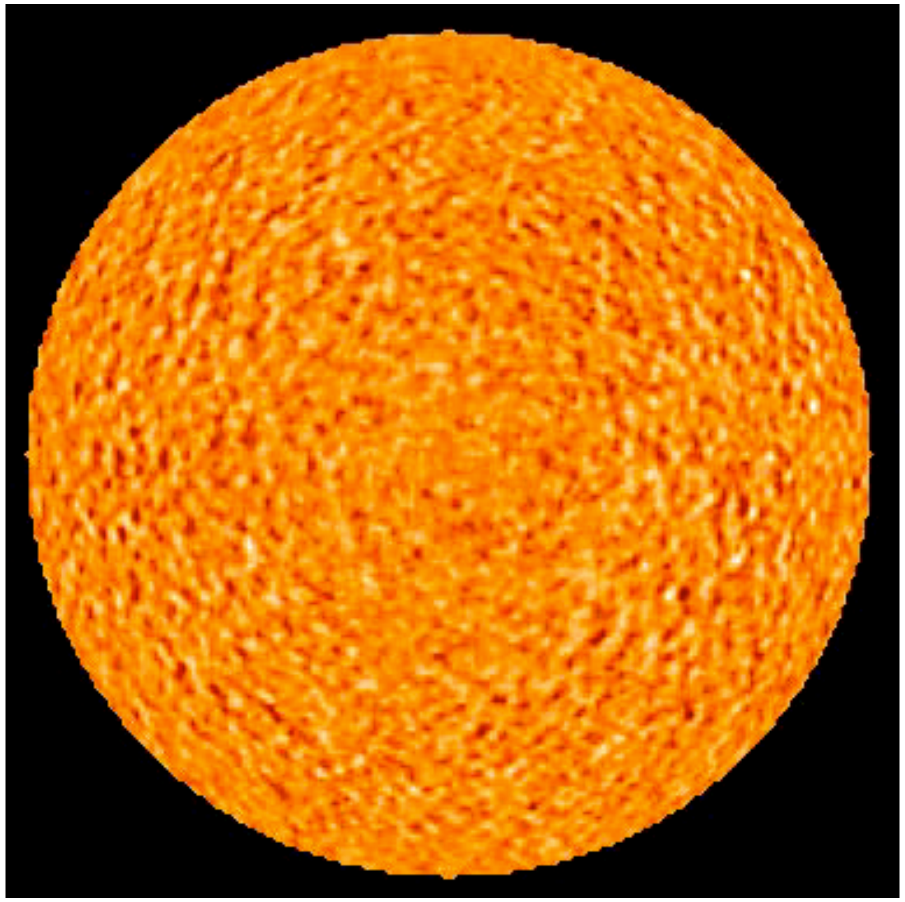


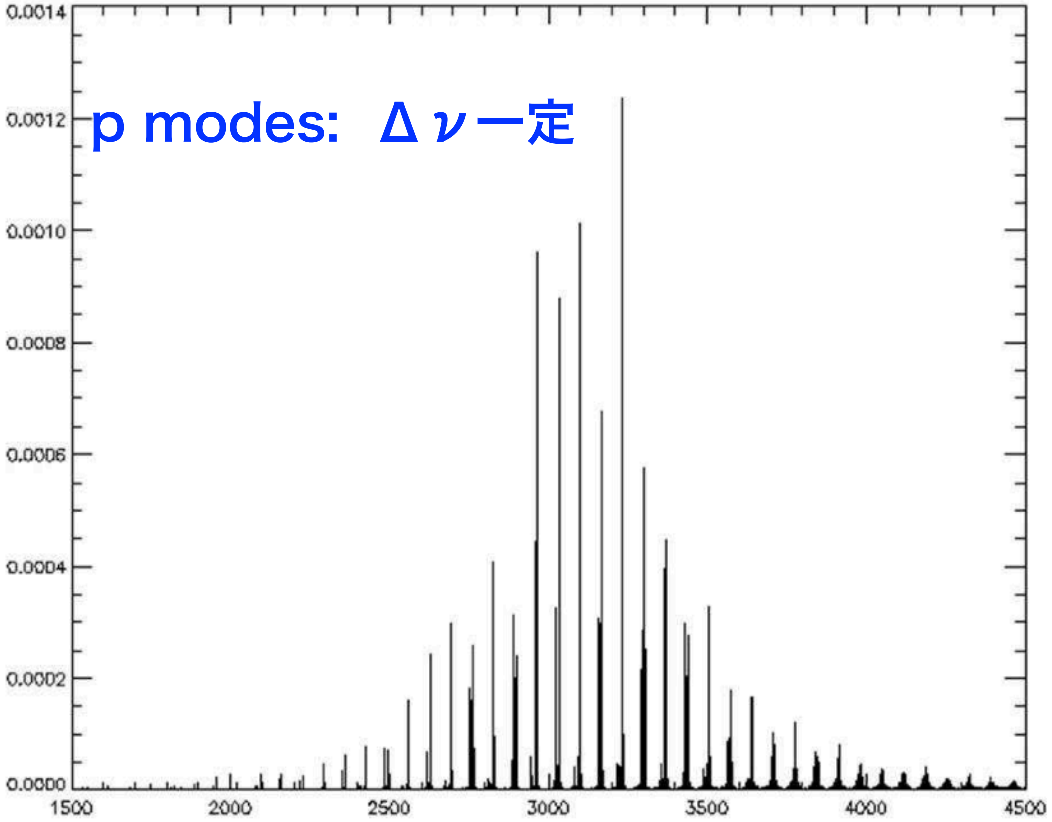
SOHO (1995; ESA/NASA)

SDO (2010; NASA)

太陽振動

Stochastic excitation p mode pulsations by turbulent convection

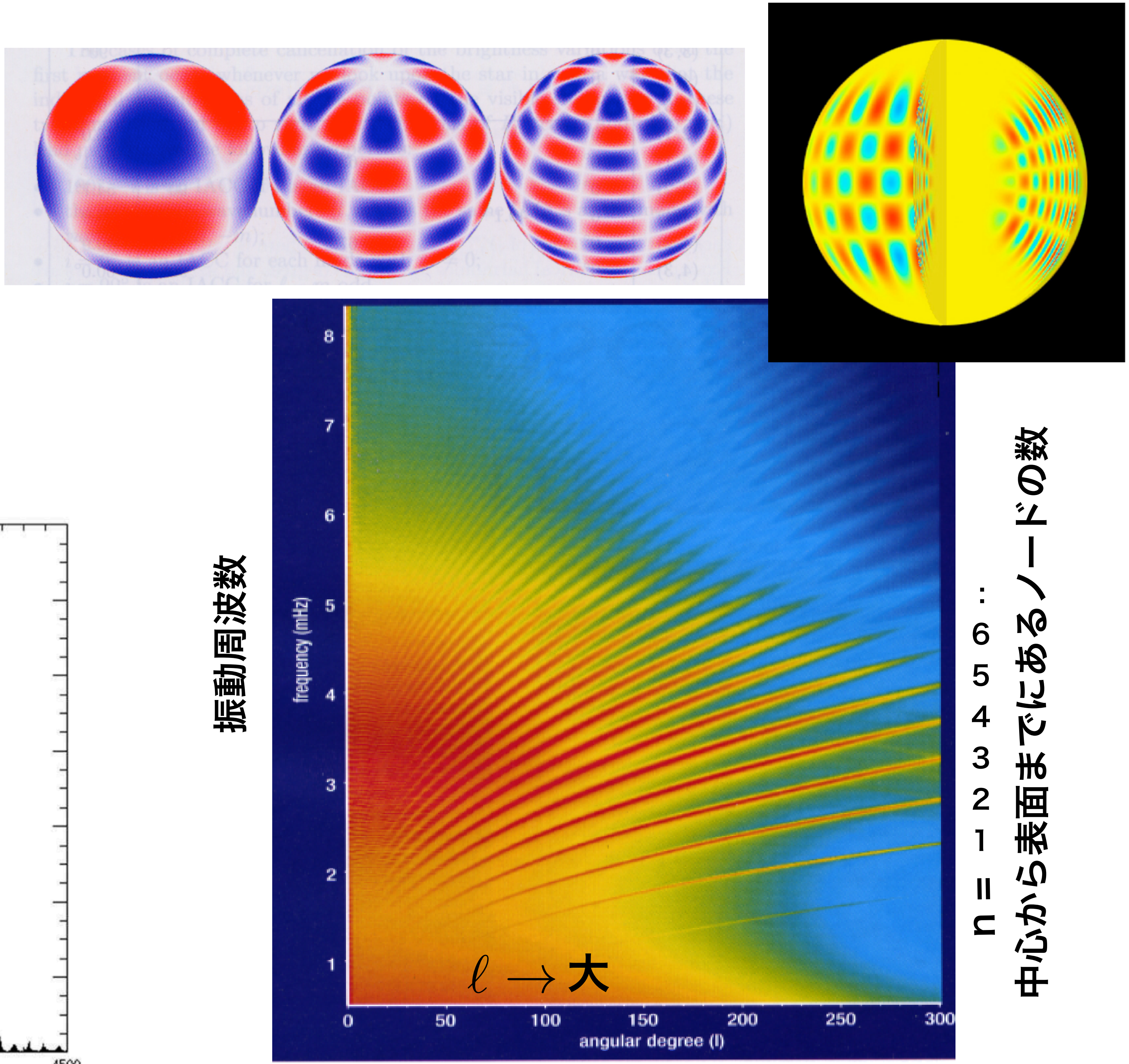




p modes: Δν一定

～5分

μHz



振動周波数

表面分割数/2

n = 1 2 3 4 5 6 :

中心から表面までにあるノードの数

SOHO (Solar and Heliospheirc Observatory)

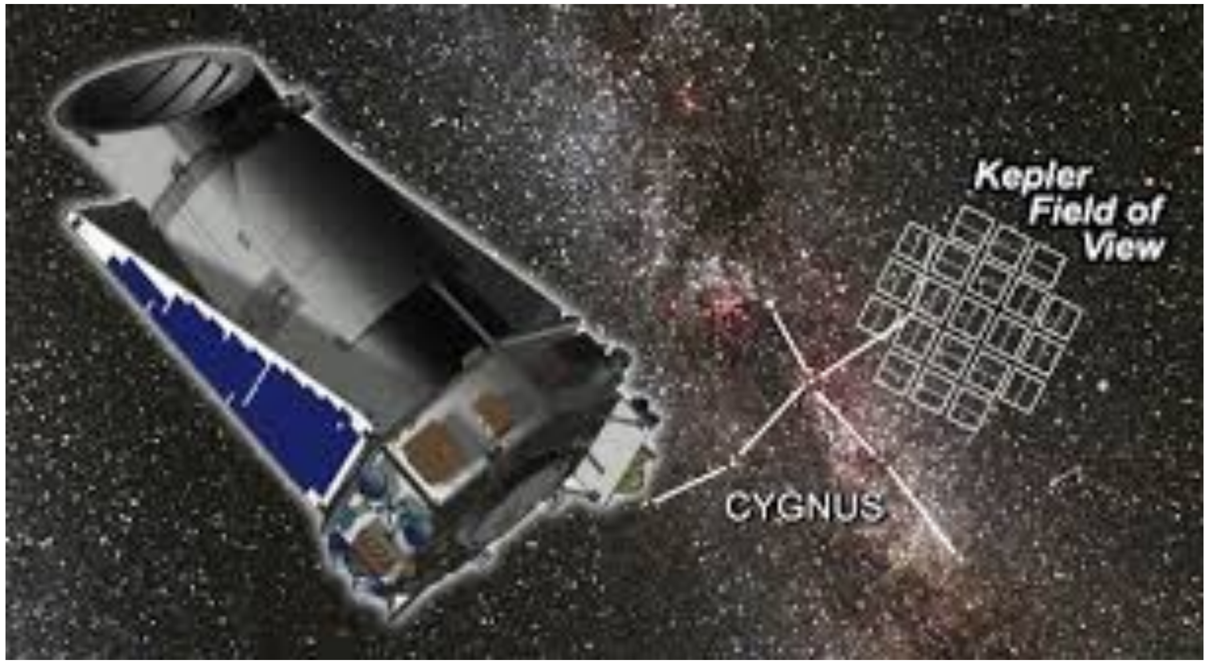
衛星による連続的な精密測光　ー　星震学の飛躍的発展

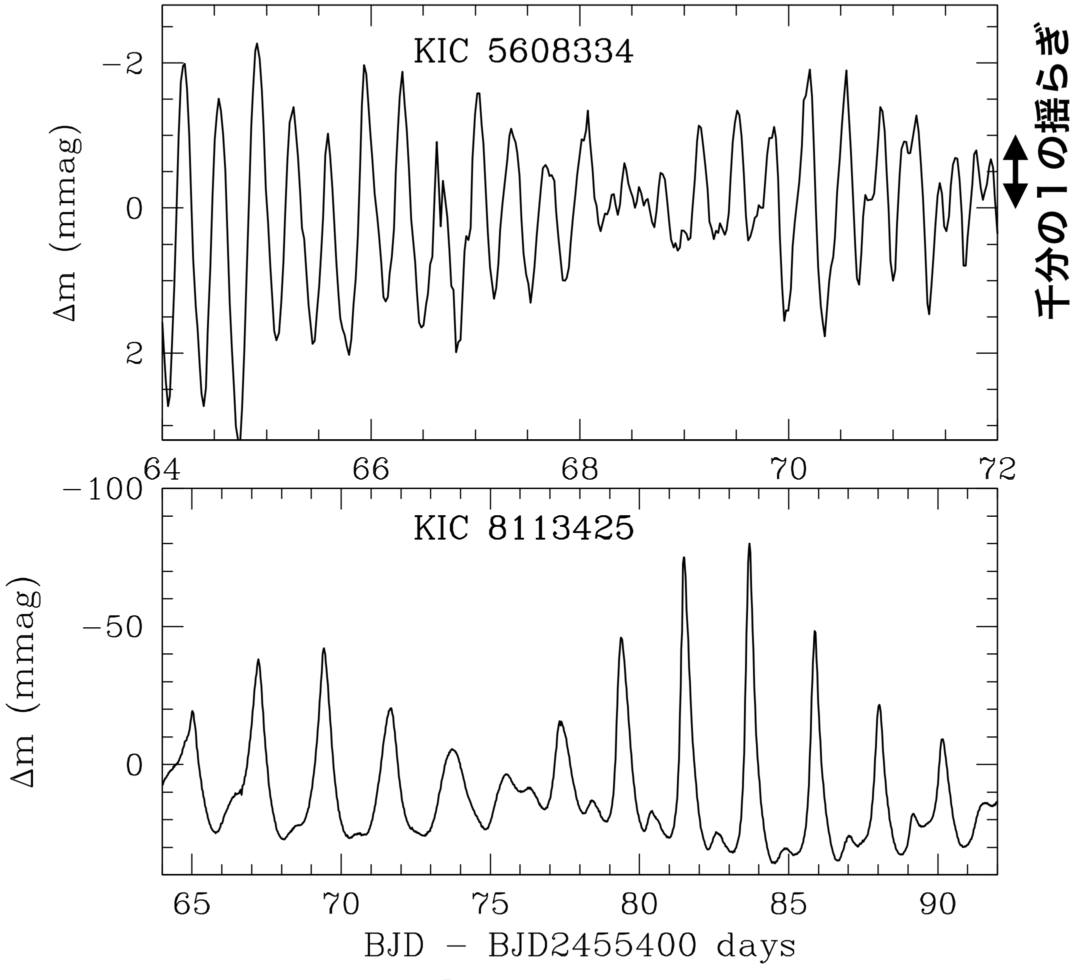
MOST: 2003〜2019

CoRoT 2007〜2014

© CNES - Octobre 2005/Illus. D. Ducros

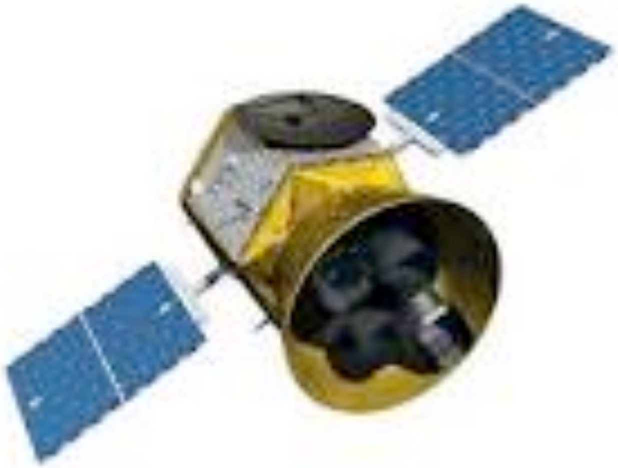
Kepler　2009〜2018





精密で連続的な測光

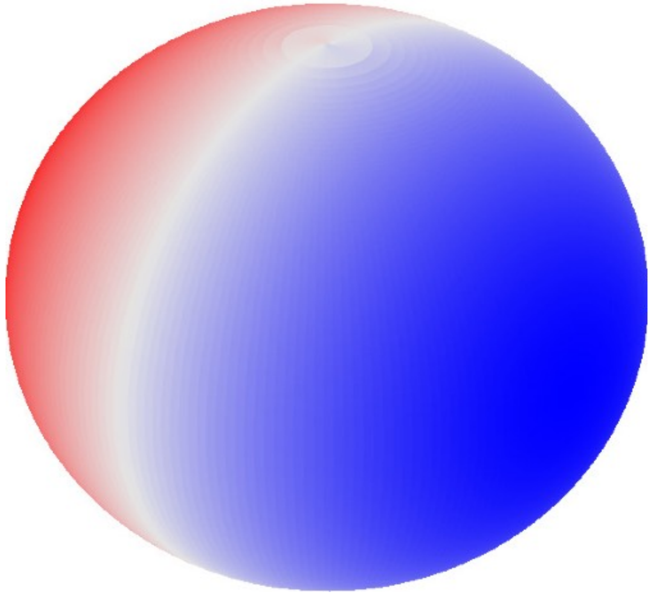
TESS
2018〜



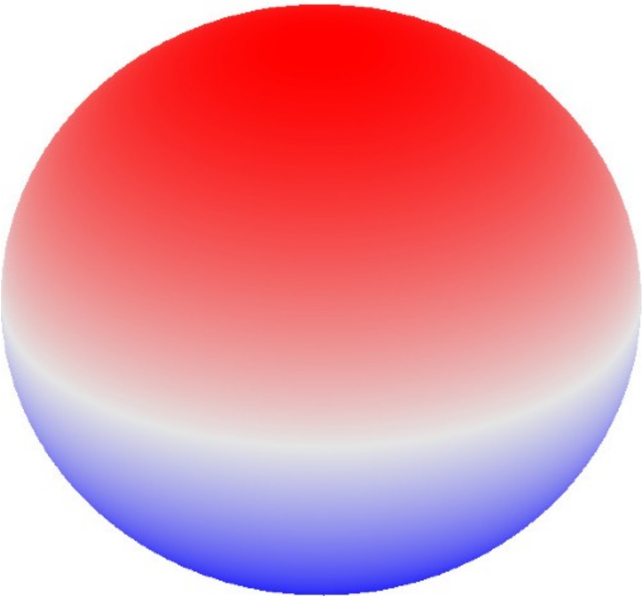
2013 〜

Non-radial pulsationsによる温度変化 $e^{i\omega t}Y_\ell^m(\theta,\phi)$

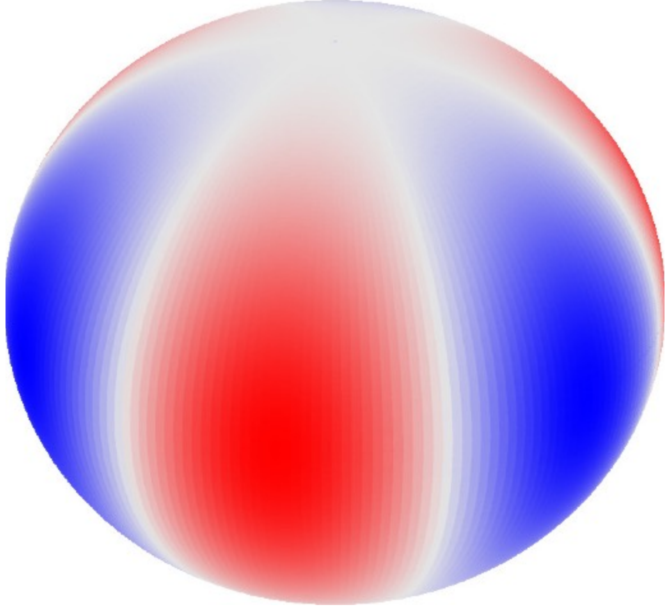
$\ell=1, m=\pm1$



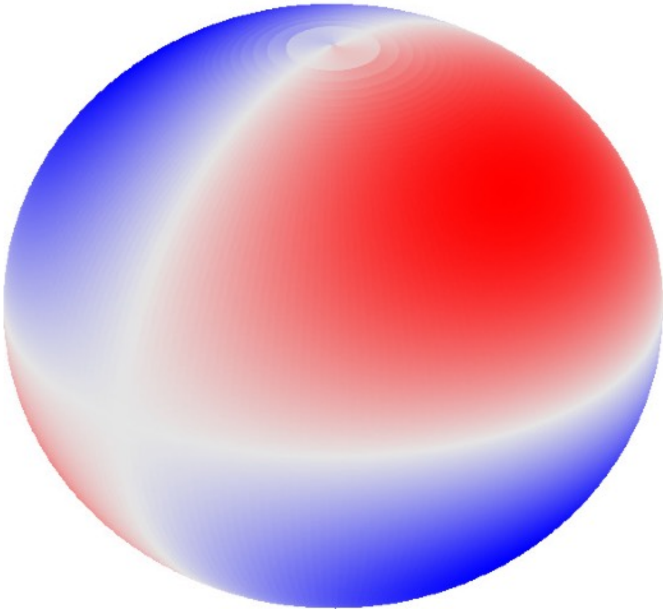
$\ell=1, m=0$



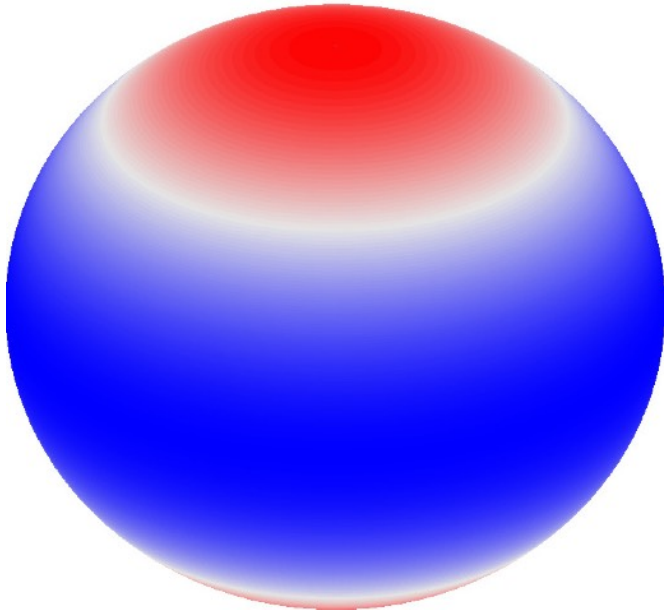
$\ell=3, m=\pm3$



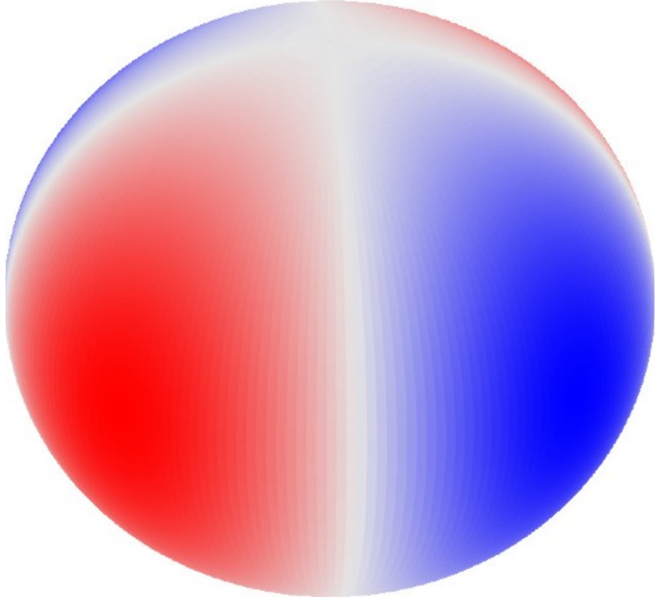
$\ell=2, m=\pm1$



$\ell=2, m=0$



$\ell=2, m=\pm2$



$\ell\leq 3$ の場合, 恒星(点光源)のnon-radial pulsationも観測可能

Solar like oscillations (p-modes)

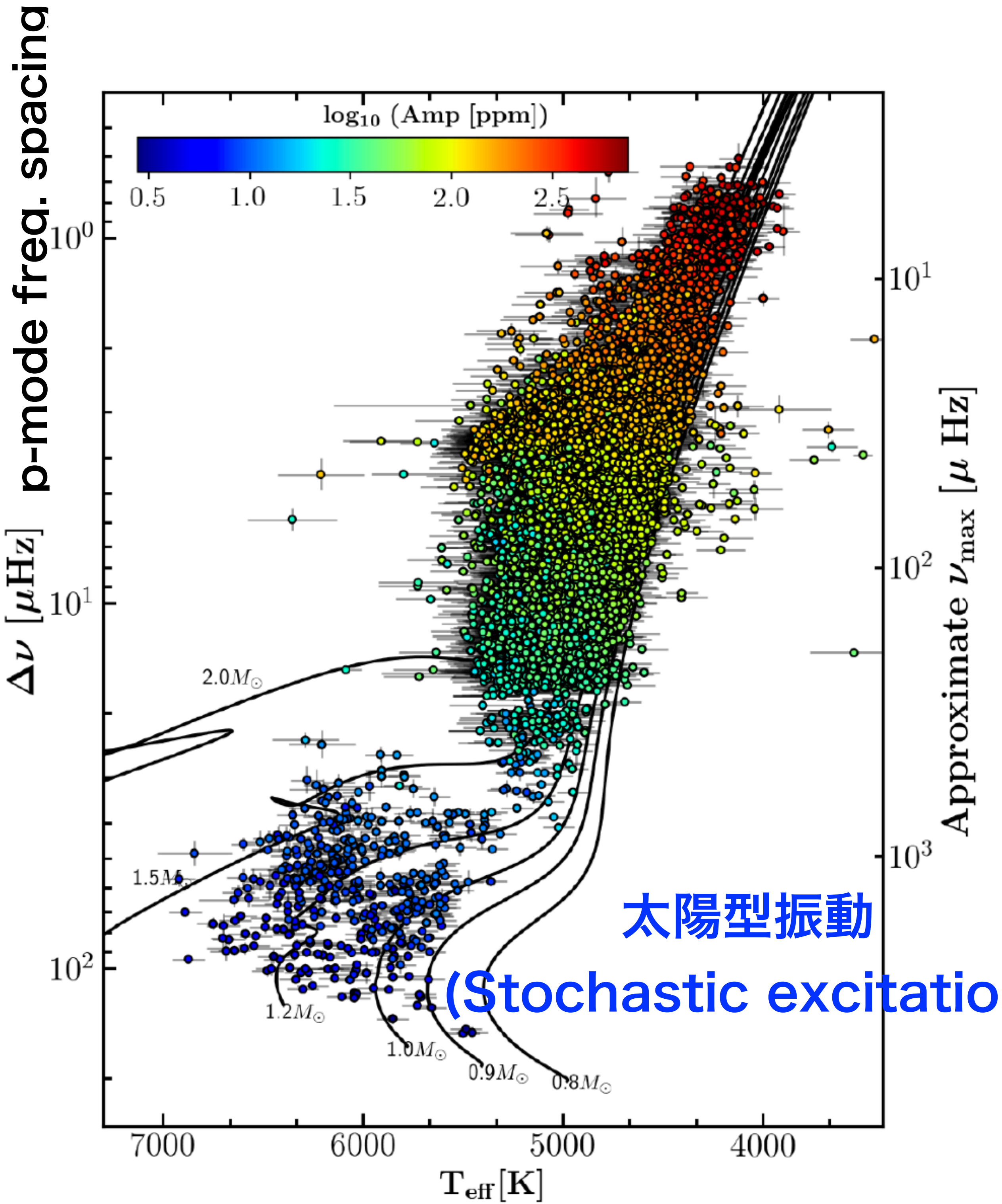
Stochastic excitation

By turbulent convection

$$\nu_{\max} \propto M T_{\rm eff}^{-1} R^{-2}$$

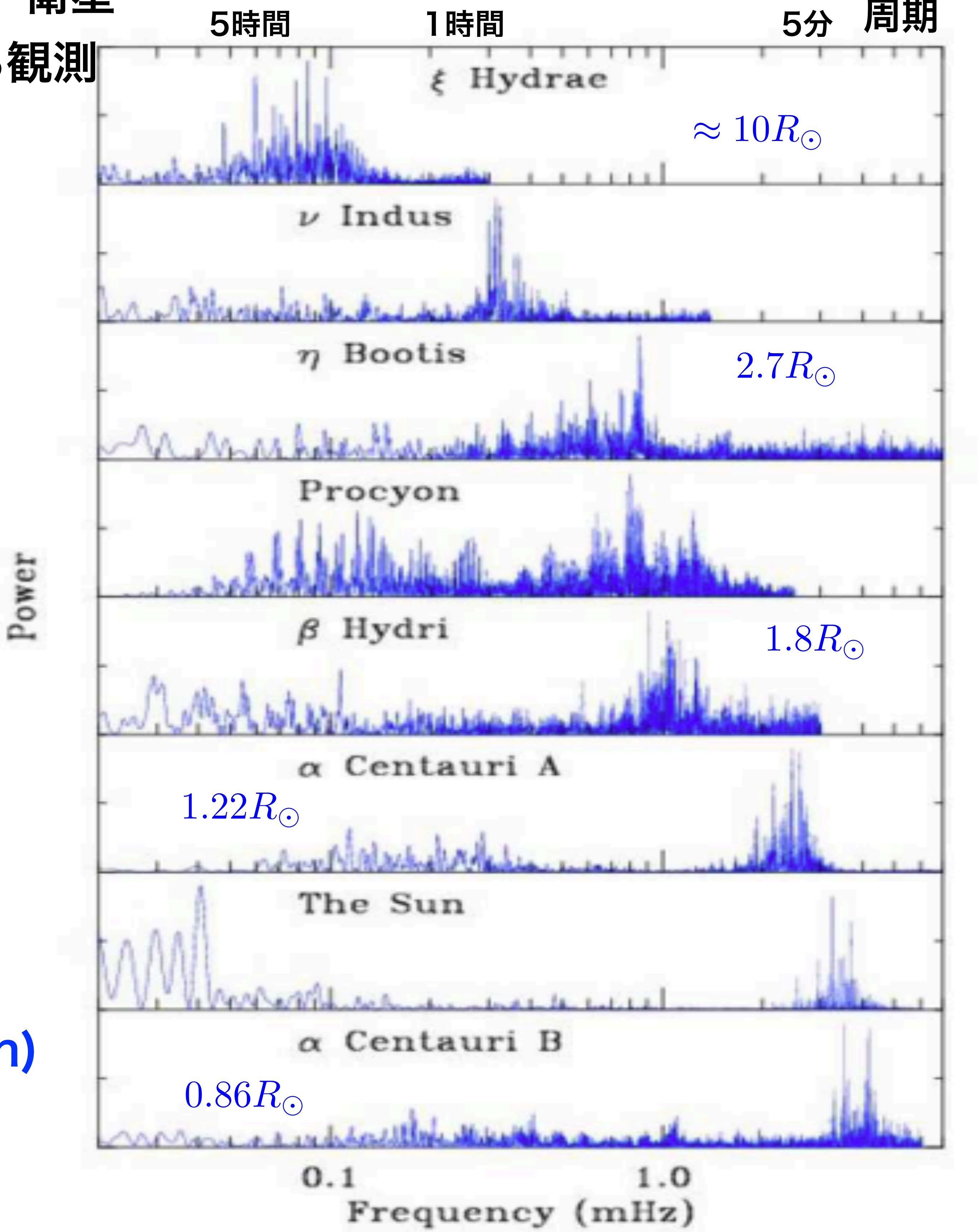
~1/(外層での対流turnover time)

Kepler 衛星
による観測



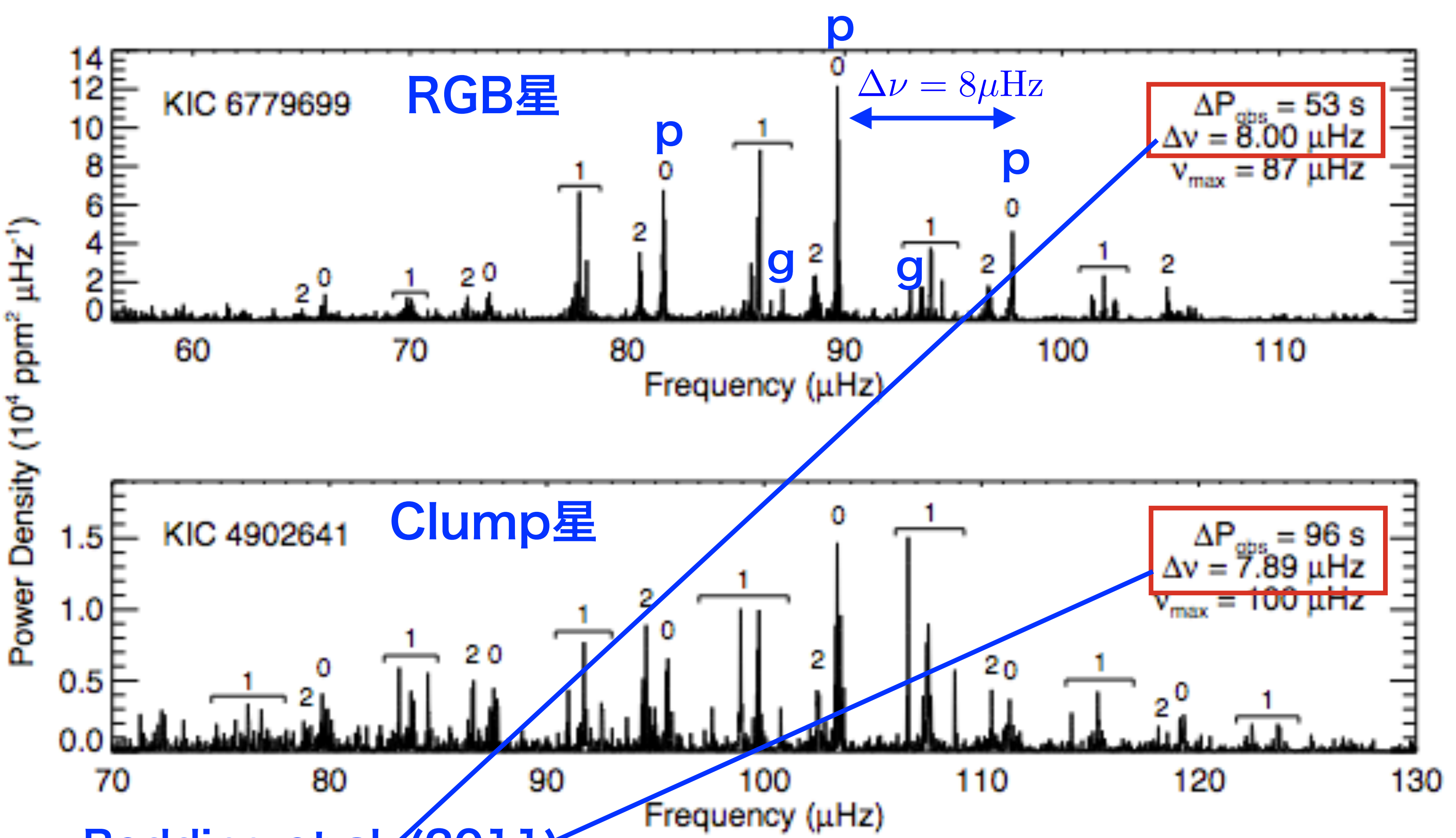
太陽型振動
(Stochastic excitation)

Yu et al. (2018)



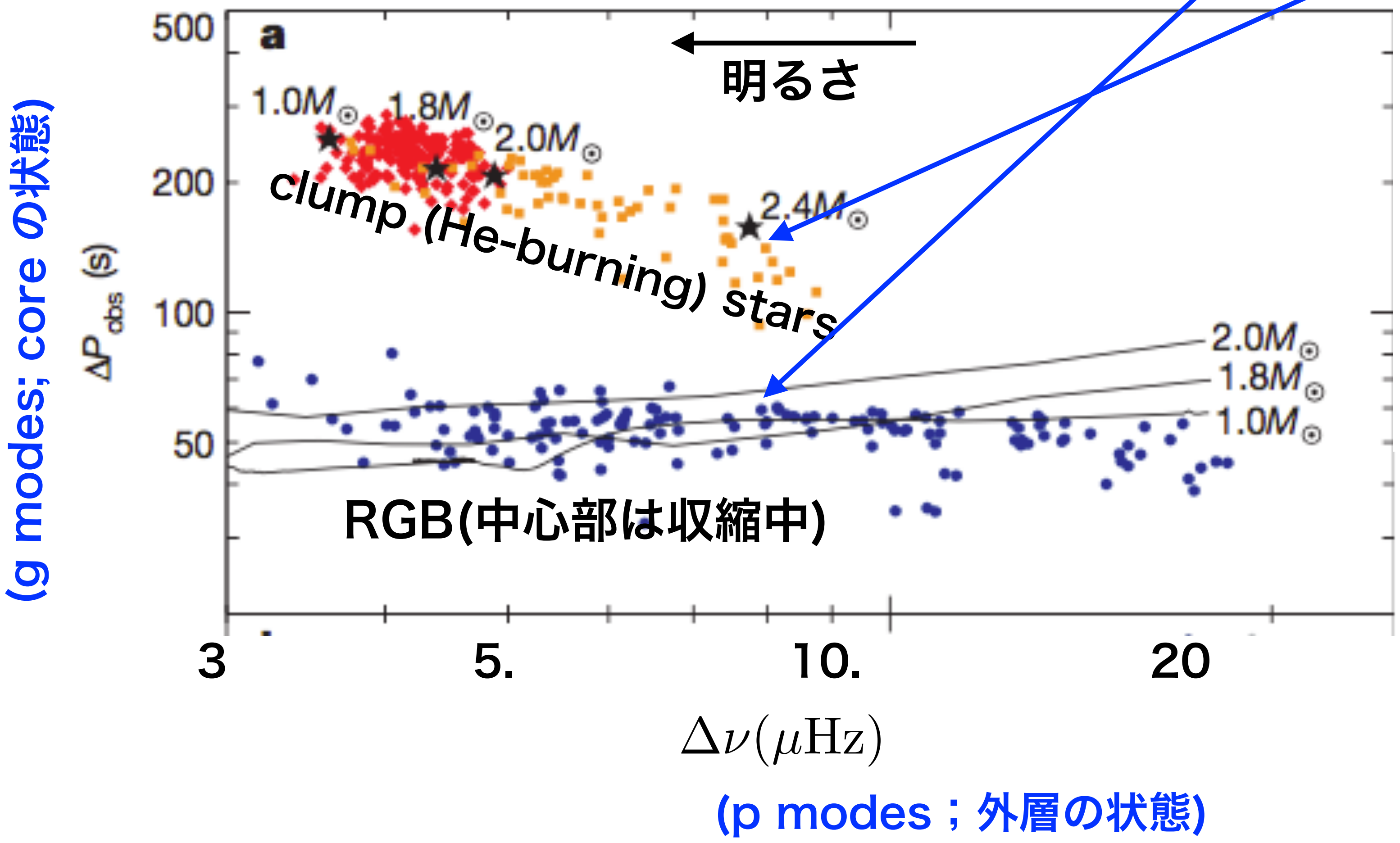
Bedding & Kjeldsen(2003)

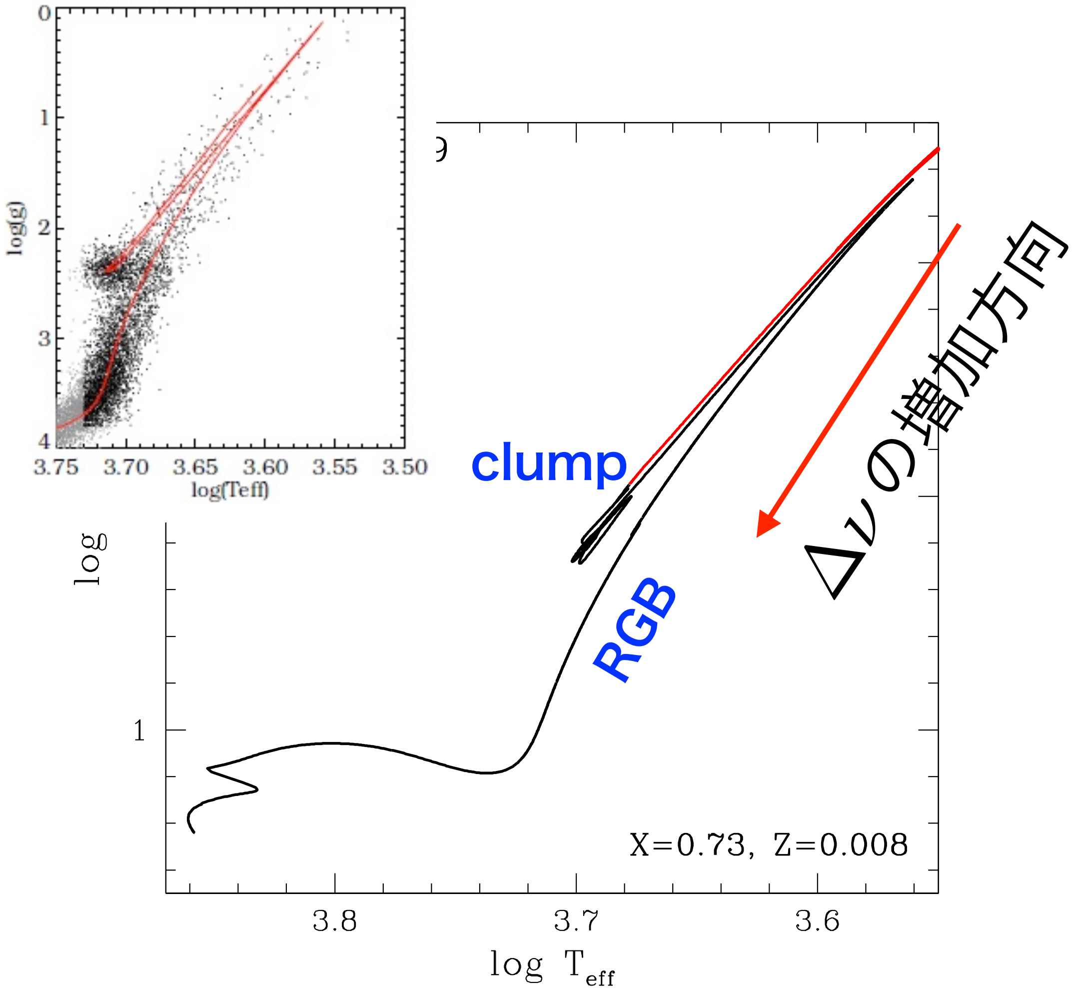
RGB星(中心は収縮中)
と
Clump星(He-burning)



Bedding et al. (2011)

clump星の中心部はHe燃焼により高温なので密度勾配がRGB 星中心部より穏やかで N が比較的小さいので Delta Pgが比較的長い



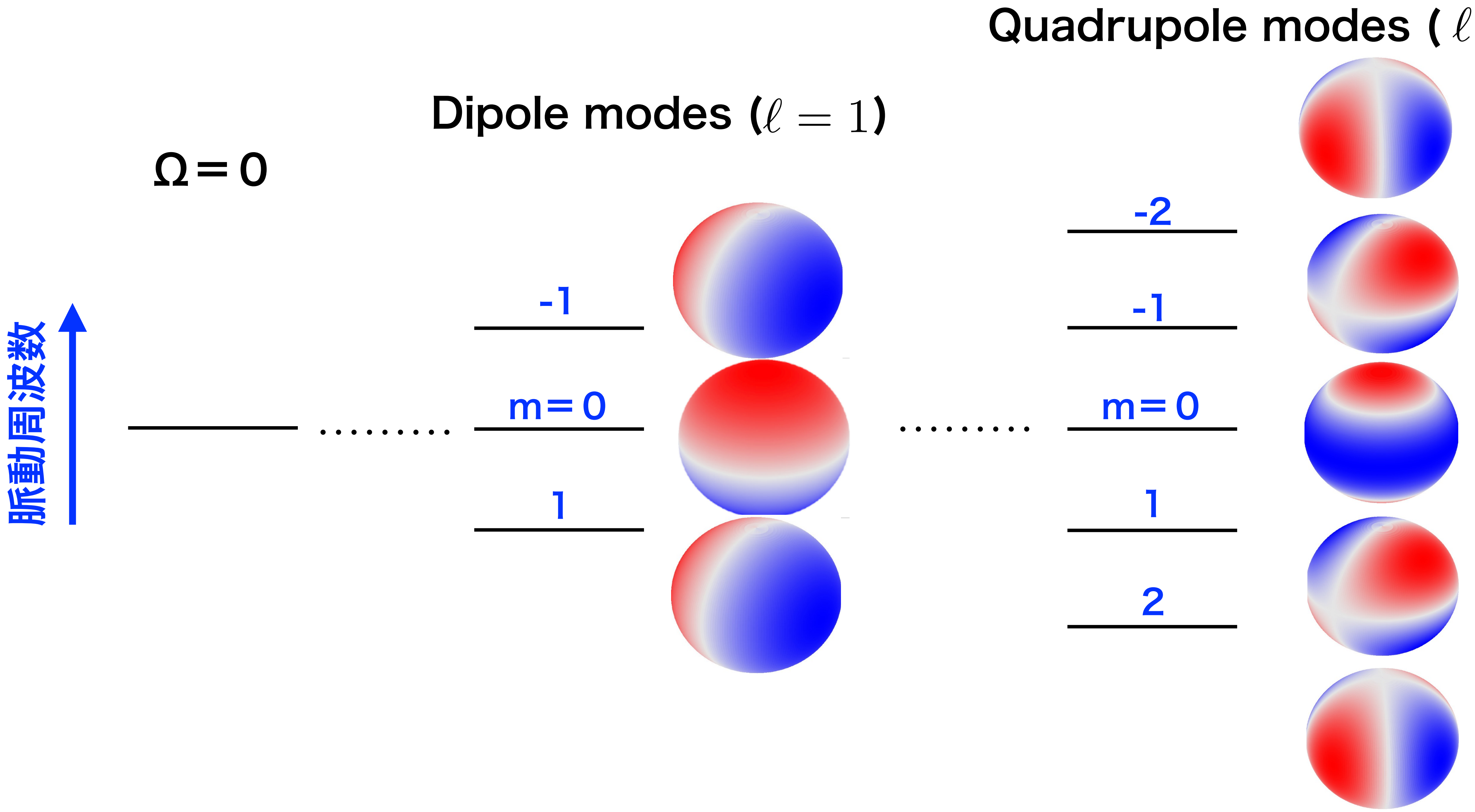


1. 恒星振動(脈動）の 基本的性質
2. 恒星振動から知る恒星自転速度
3. r (Rossby) mode 振動
4. 脈動周期変化率と恒星進化速度
5. 進化の進んだ大質量星の脈動
6. Betelgeuse (α Ori) の脈動

Non-radial pulsations の周波数　ー>　恒星の表面及び内部の自転

自転によるの振動周波数のsplitting

$$\delta T(r,\theta,\phi,t) = \delta T_n(r) Y_\ell^m(\theta,\phi) e^{i\omega t}, \qquad \omega = \omega_0 - m(1 - C_{\ell,n})\Omega; \qquad (\Omega \ll \omega_0)$$



Quadrupole modes ($\ell = 2$)

Dipole modes ($\ell = 1$)

Ω=0

脈動周波数

-1

m=0

1

-2

-1

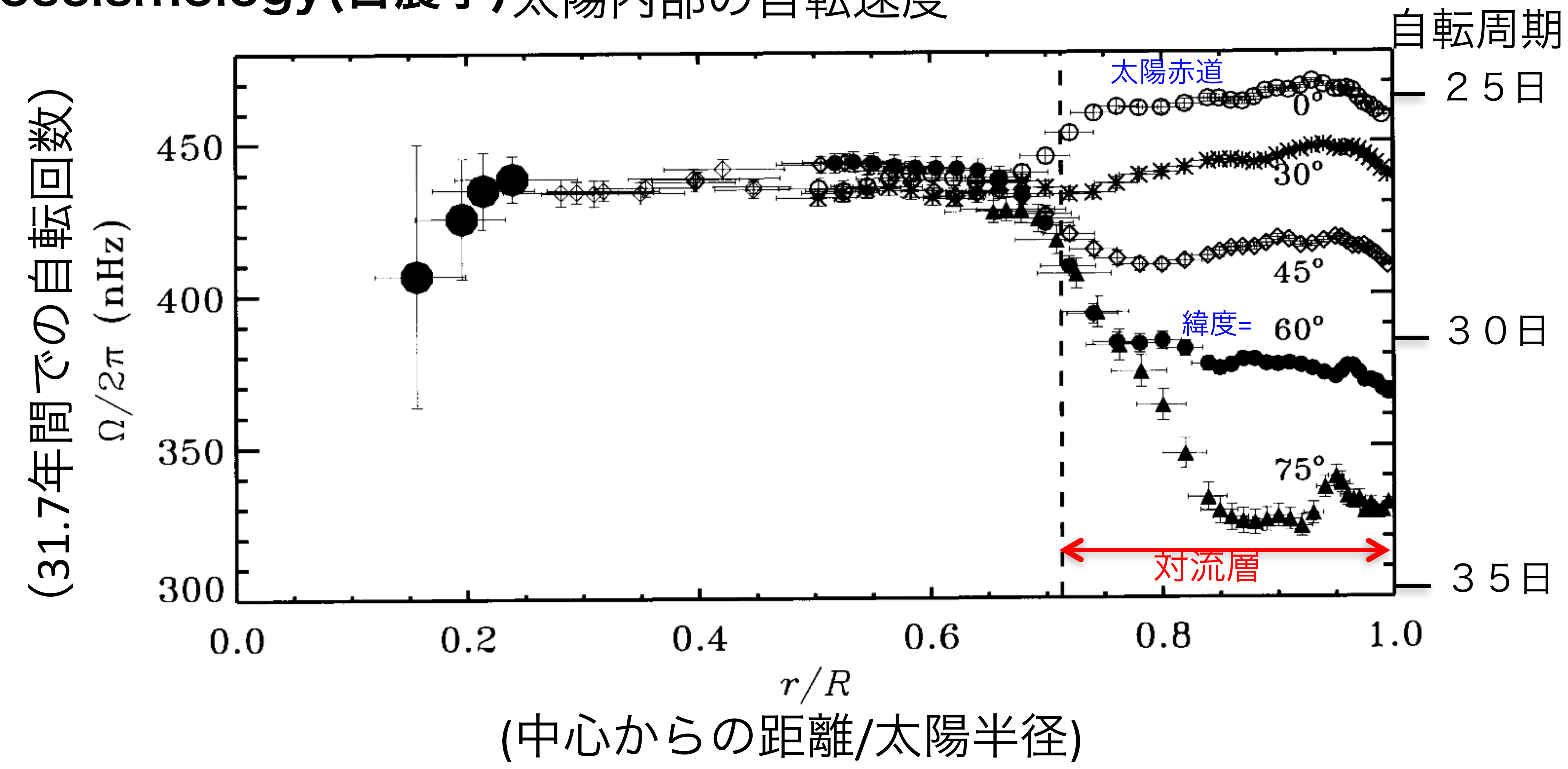
m=0

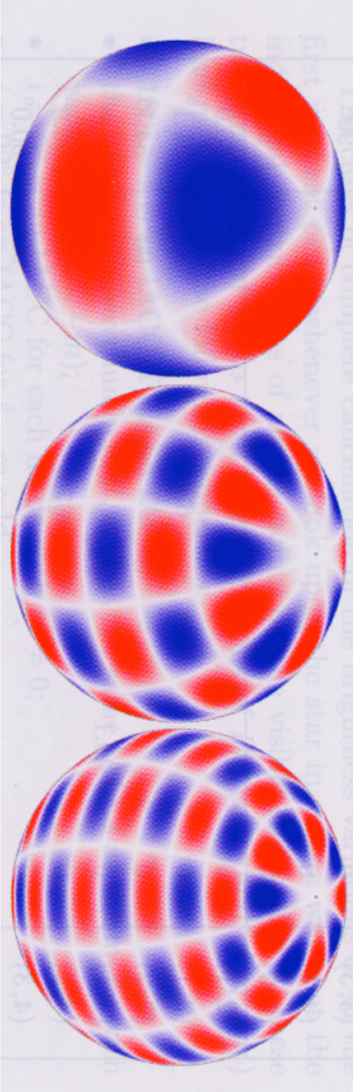
1

2

恒星の自転の影響

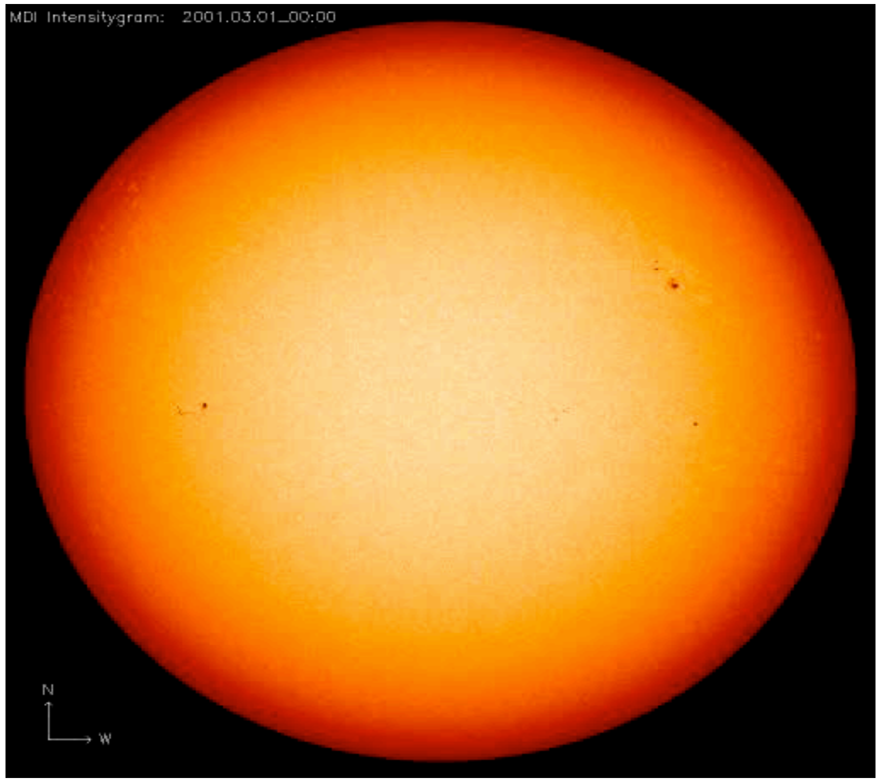
Helioseismology(日震学)太陽内部の自転速度



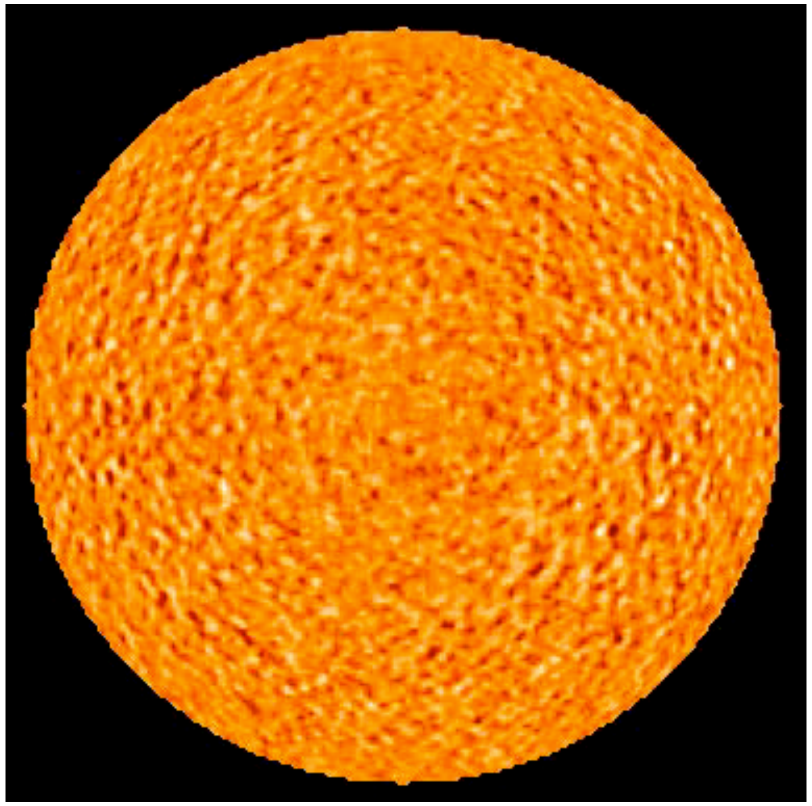


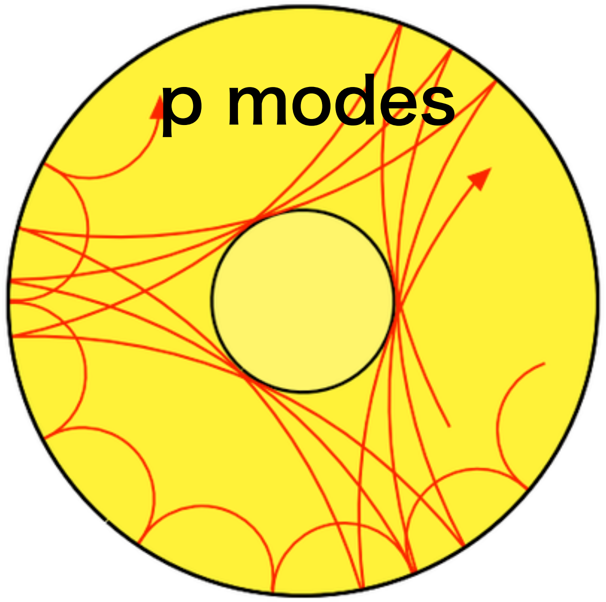
(Christensen-Dalsgaard & Thompson 2007)

太陽表面の自転速度は黒点の位置の動きから



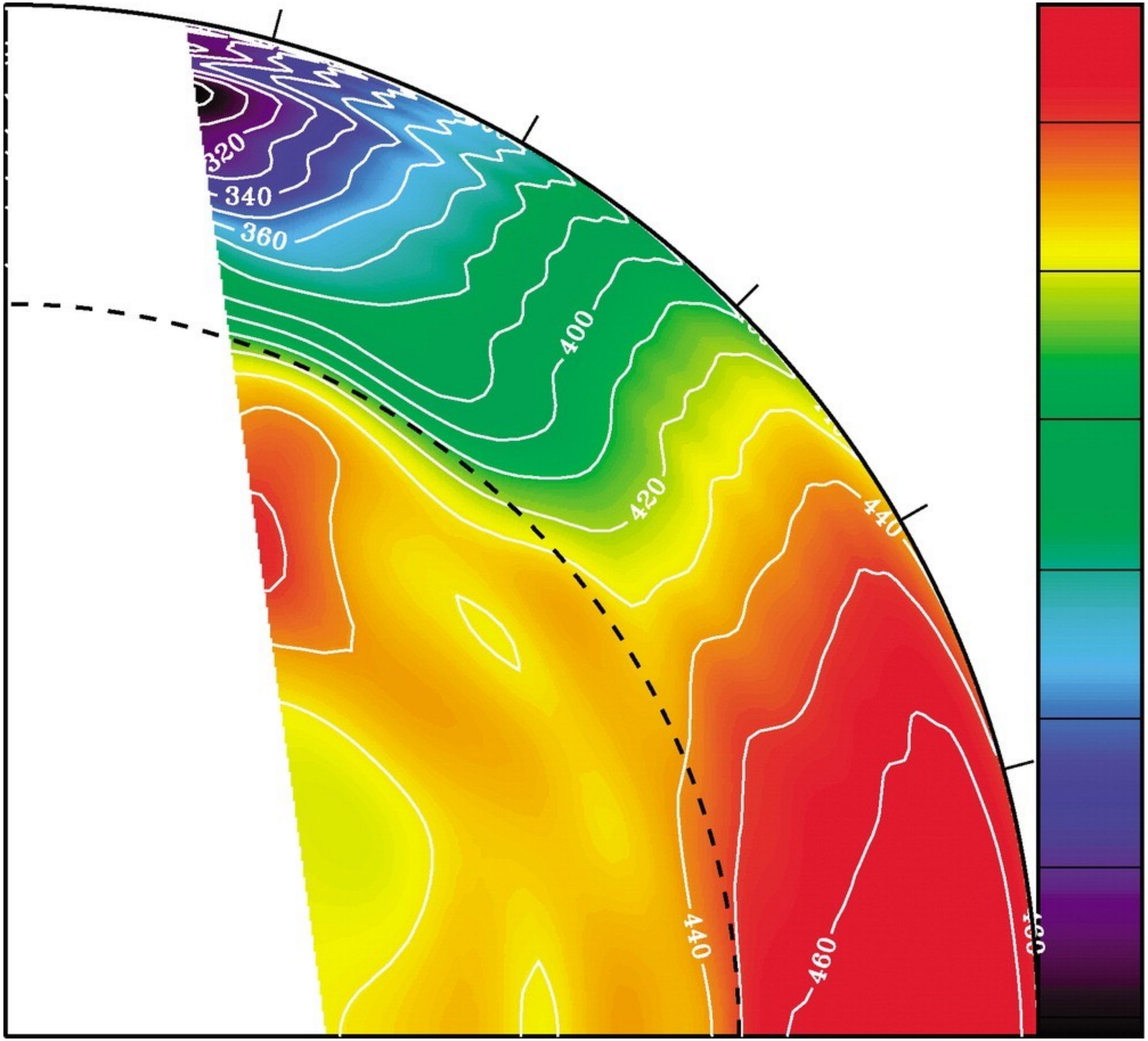
内部の自転速度は太陽振動で





波長の短いモードほど外層の情報

太陽振動を使って得られた太陽内部の自転速度分布



対流層

$0.7\,R_\odot$

自転速 10^{-9}回/秒	自転周期
450 nHz	25.7日
425	27.2 日
400	28.9 日
375	30.9 日
350	33.1 日
325	35.6 日
300	38.6 日

NCAR/HAO

自転による振動周波数のsplitting

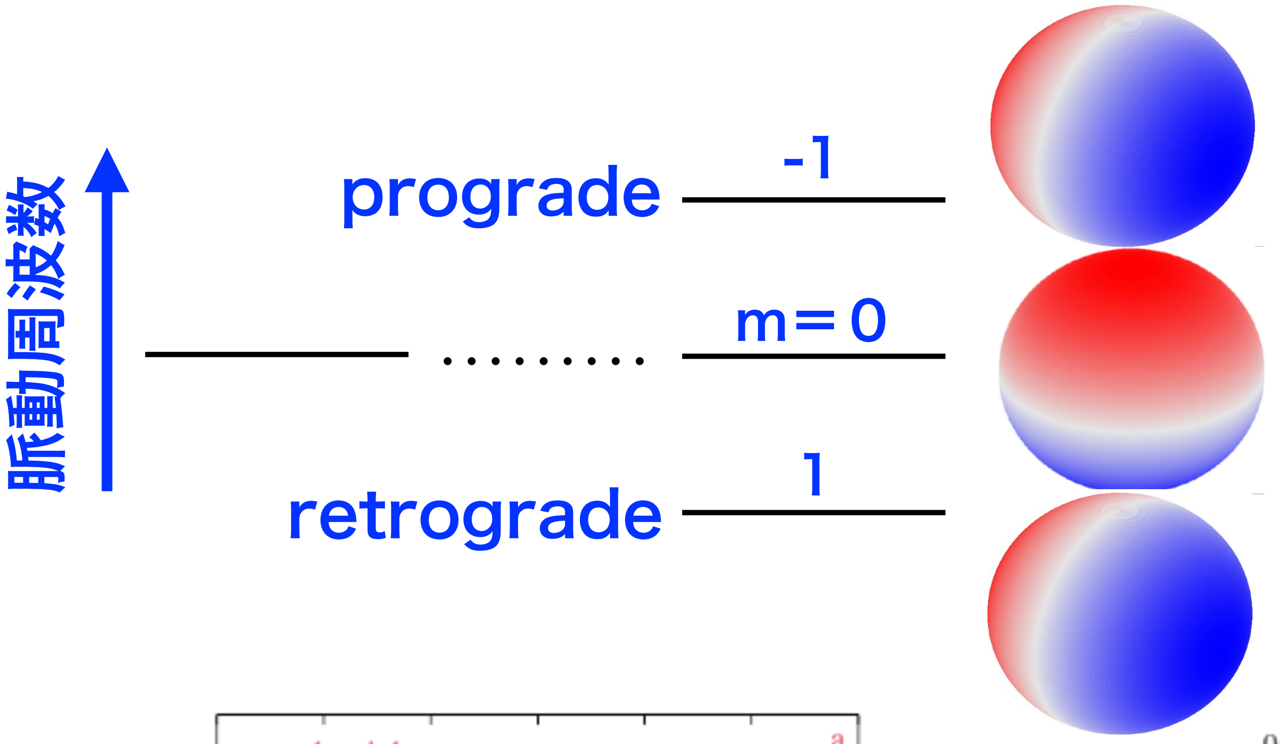
$$\delta T(r,\theta,\phi,t) = \delta T_n(r) Y_\ell^m(\theta,\phi) e^{i\omega t}, \qquad \omega = \omega_0 - m(1 - C_{\ell,n})\Omega; \qquad (\Omega \ll \omega_0)$$

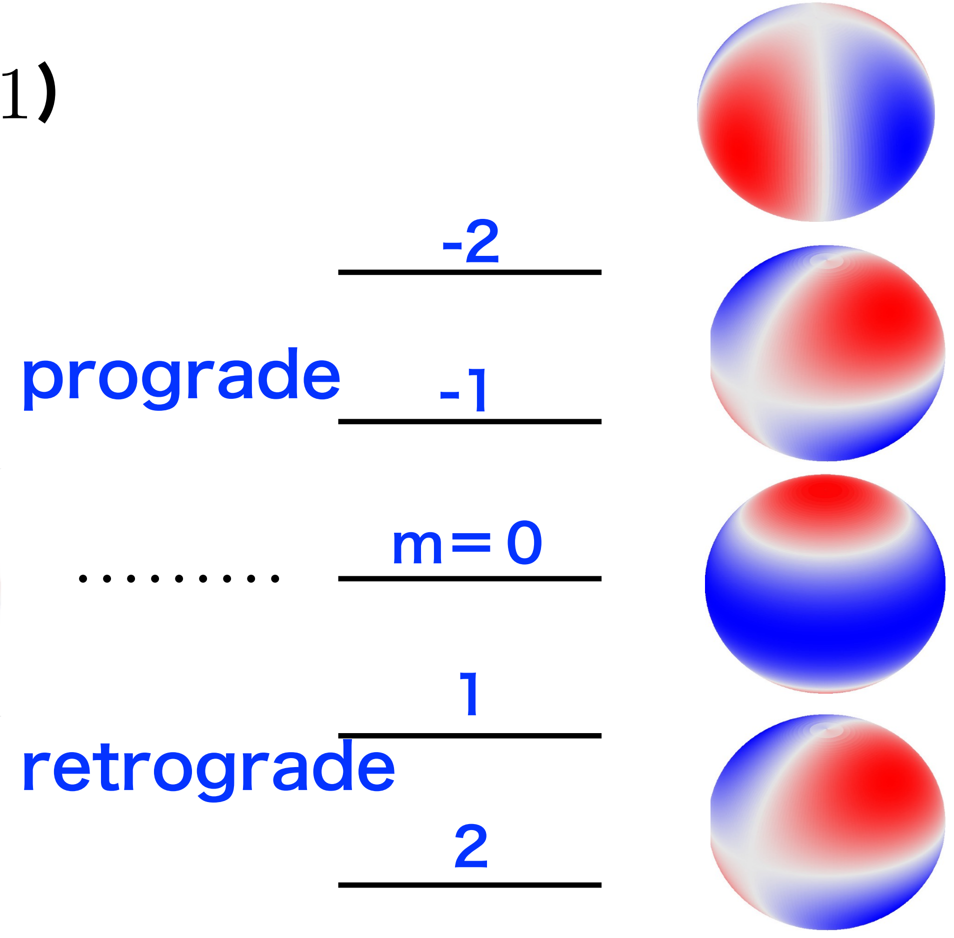
主にp modes で Ω<< ω

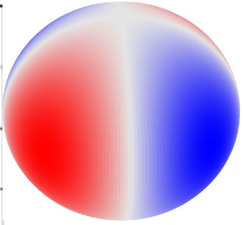
Quadrupole modes ($\ell = 2$)

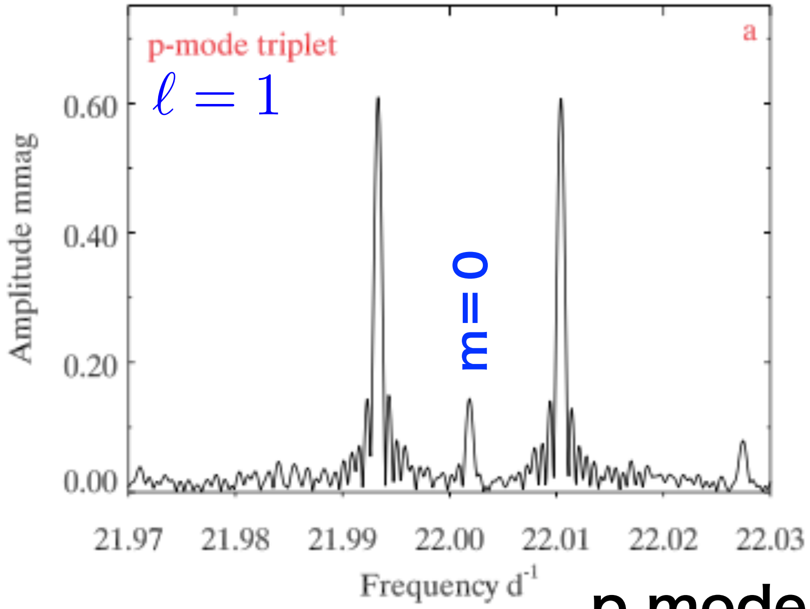
Dipole modes ($\ell = 1$)

Ω=0

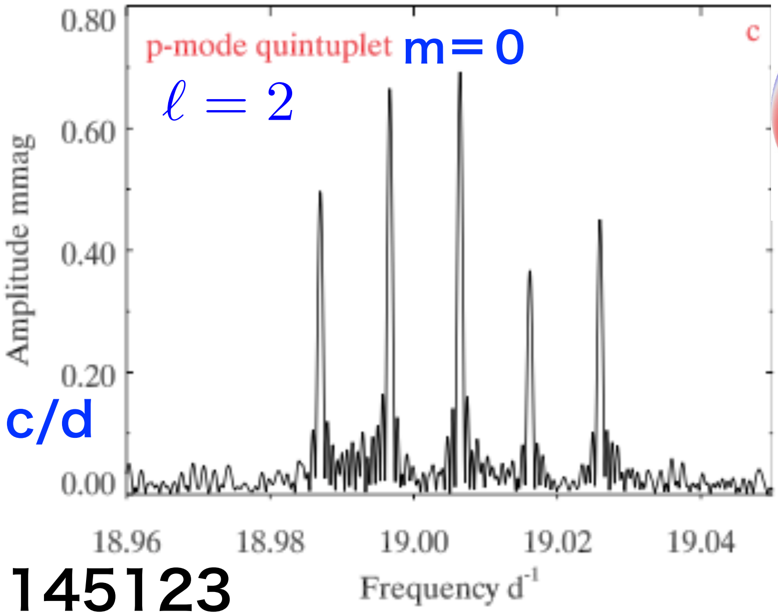








νrot ~ 0.01 c/d

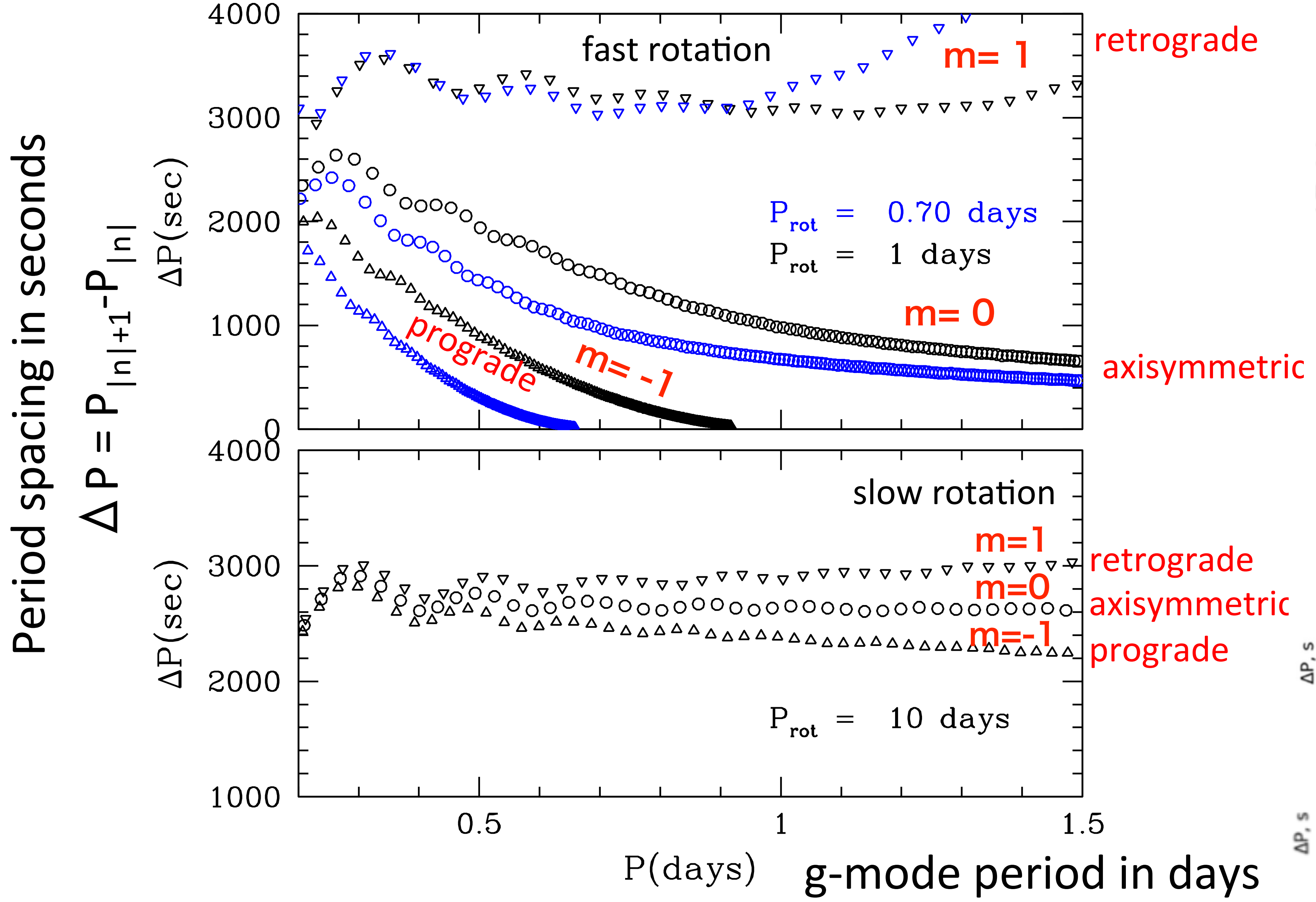


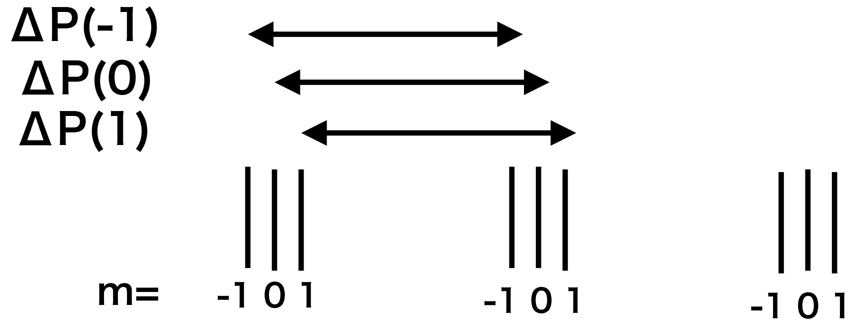
p modes in KIC 11145123

自転が速い時(２Ω＞ω)のg modes (ΔPg)の振る舞い

g modes ではしばしば Ω > ～ω

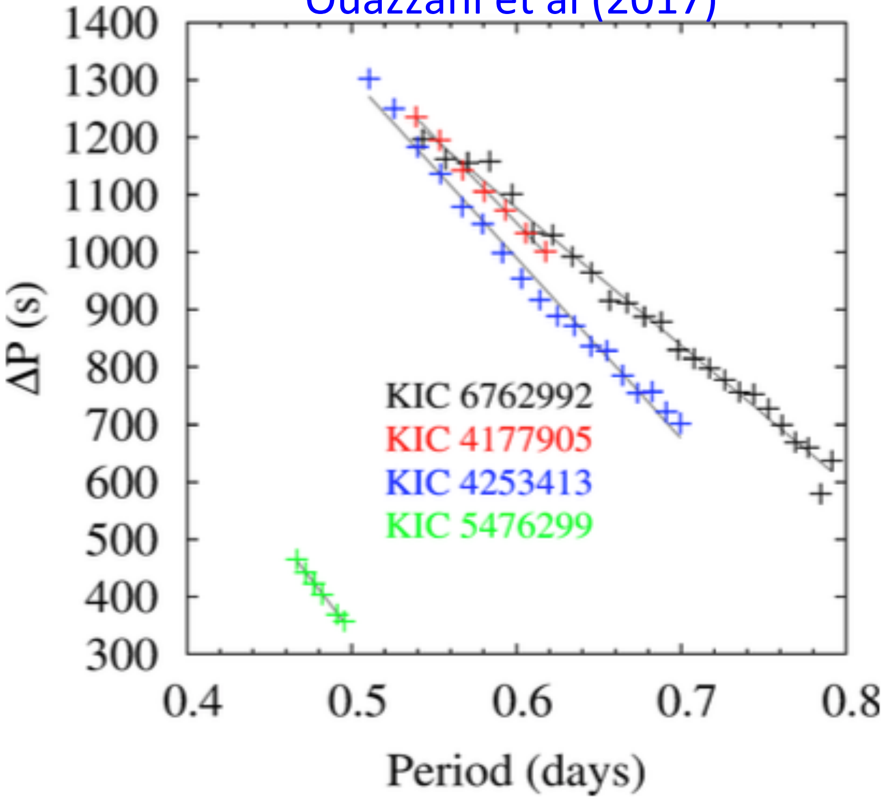
それぞれのmに対するΔPg−Pg関係の予想



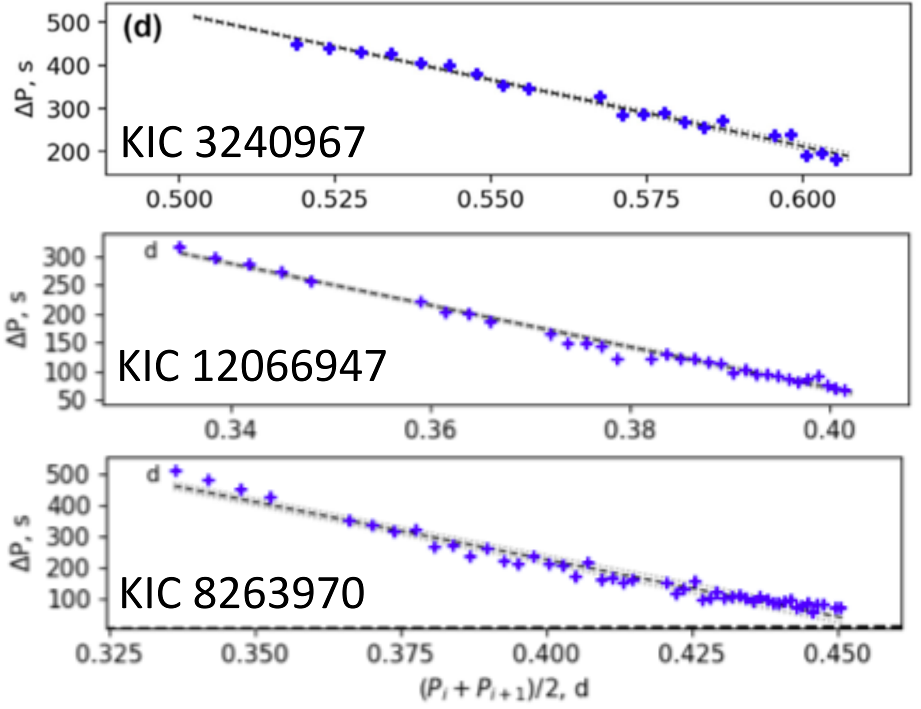


Kepler の観測から
得られたΔPgの例

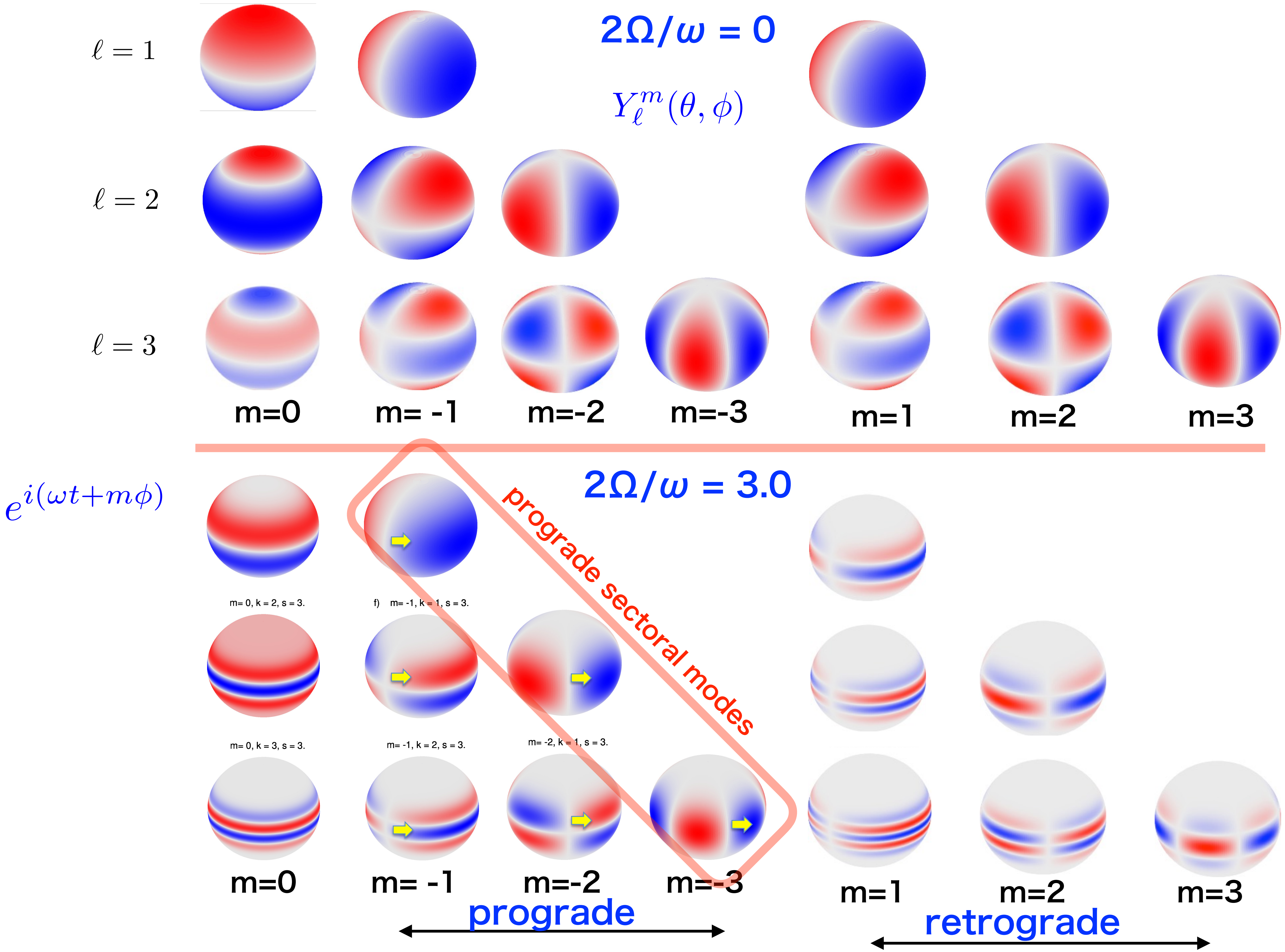
Ouazzani et al (2017)



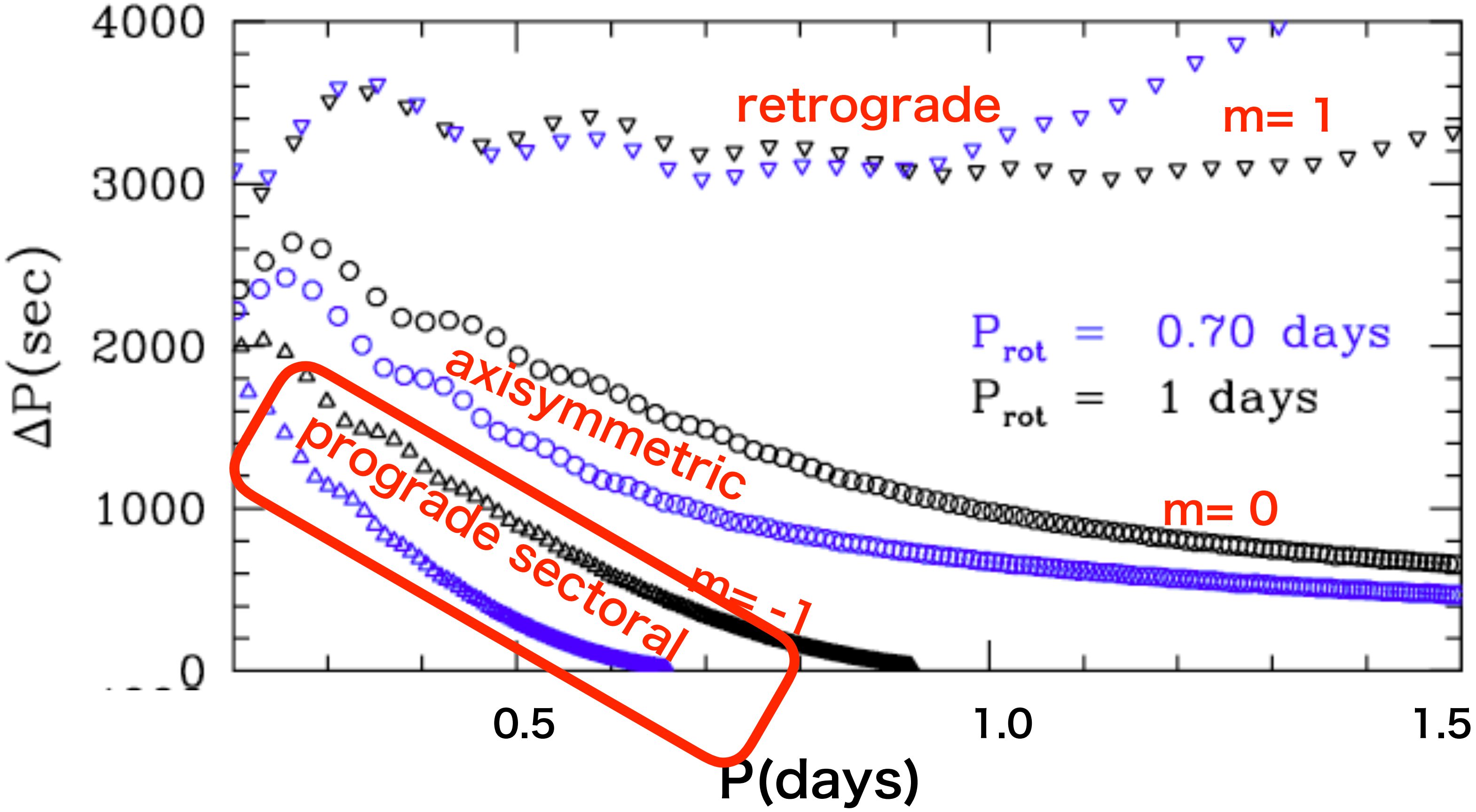
Gang Li et al (2019)



自転(コリオリの力)による振動パターンの変化

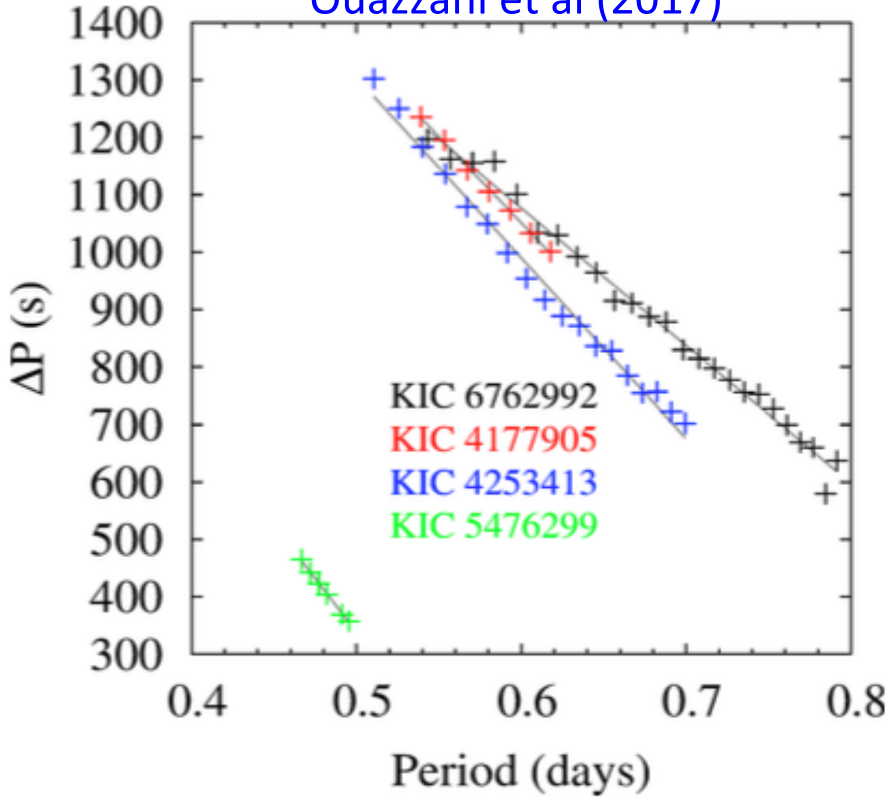


高速自転星でのg modes (2Ω＞ω)はprograde sectoral modes だけが観測される



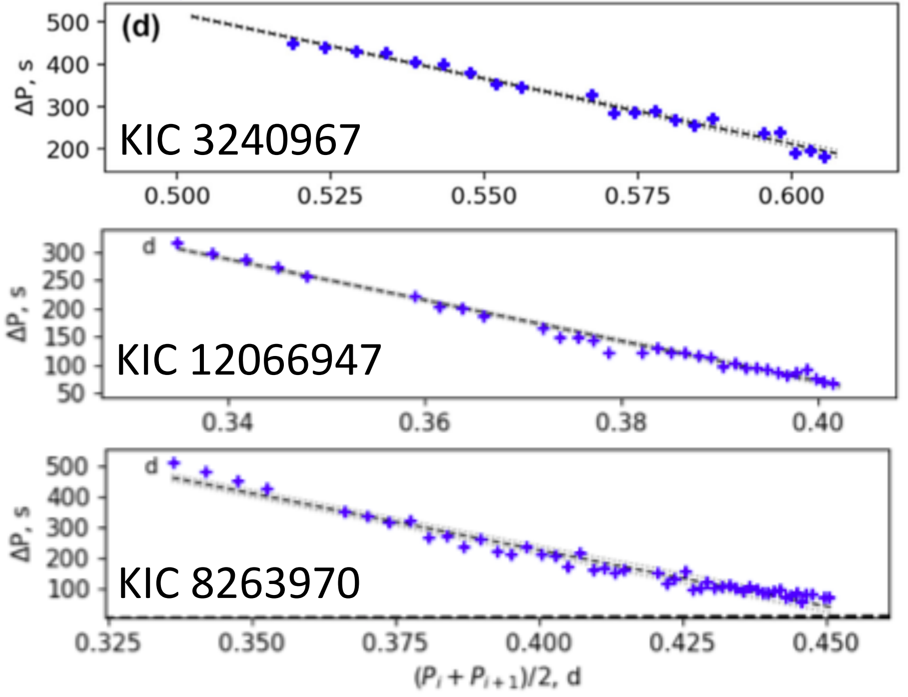
Kepler の観測から得られたΔPgの例

Ouazzani et al (2017)

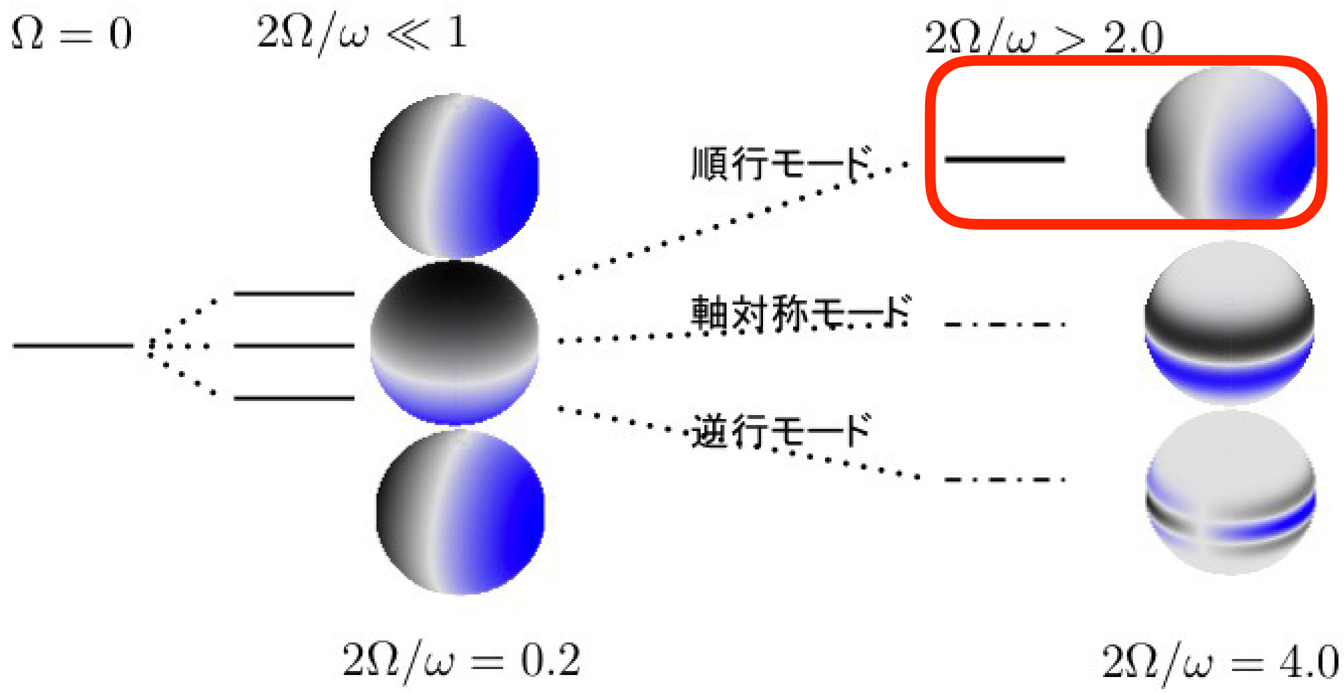


Prograde sectoral modes だけが見える

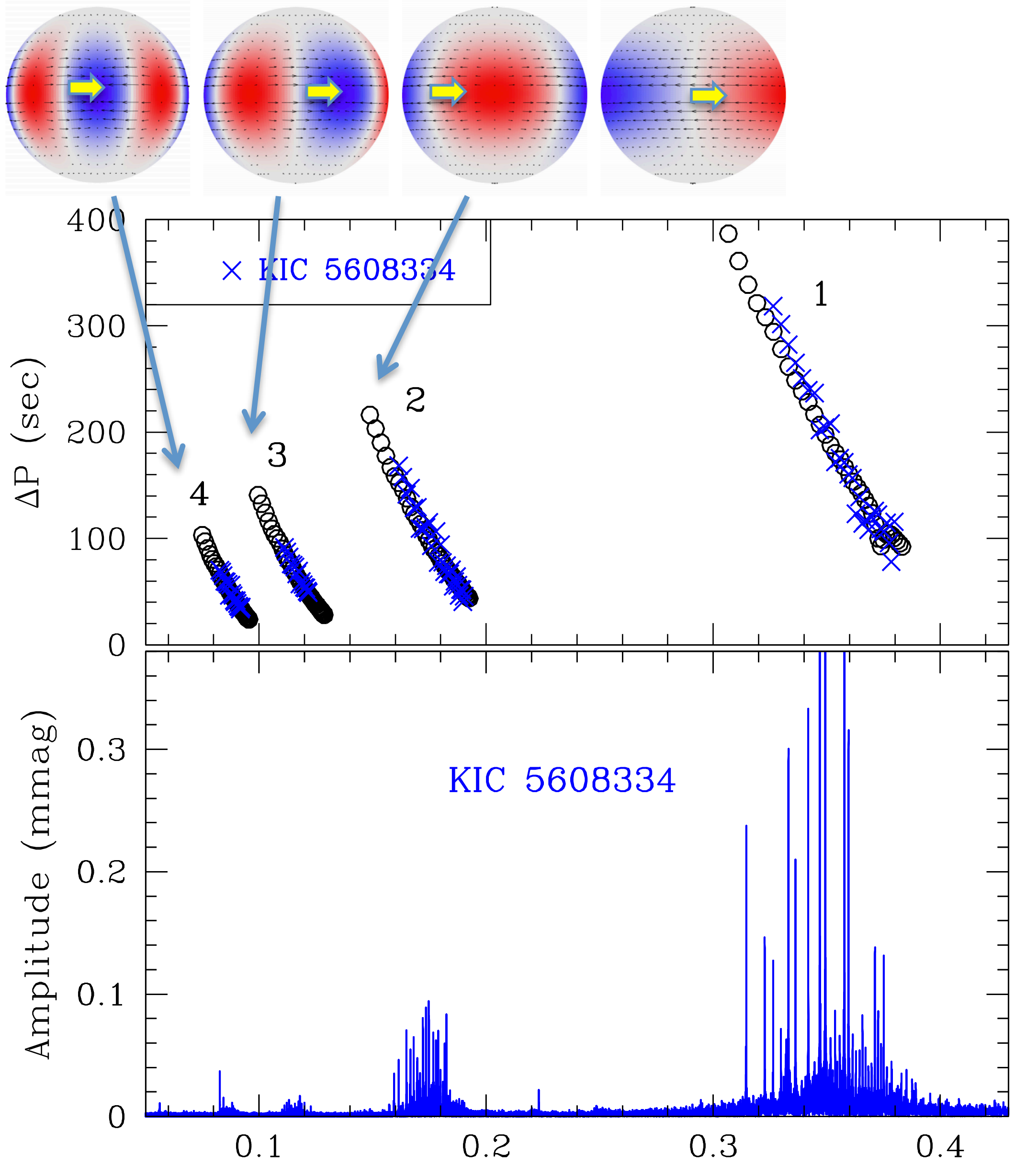
Gang Li et al (2019)



Dipole modes ($\ell = 1$)

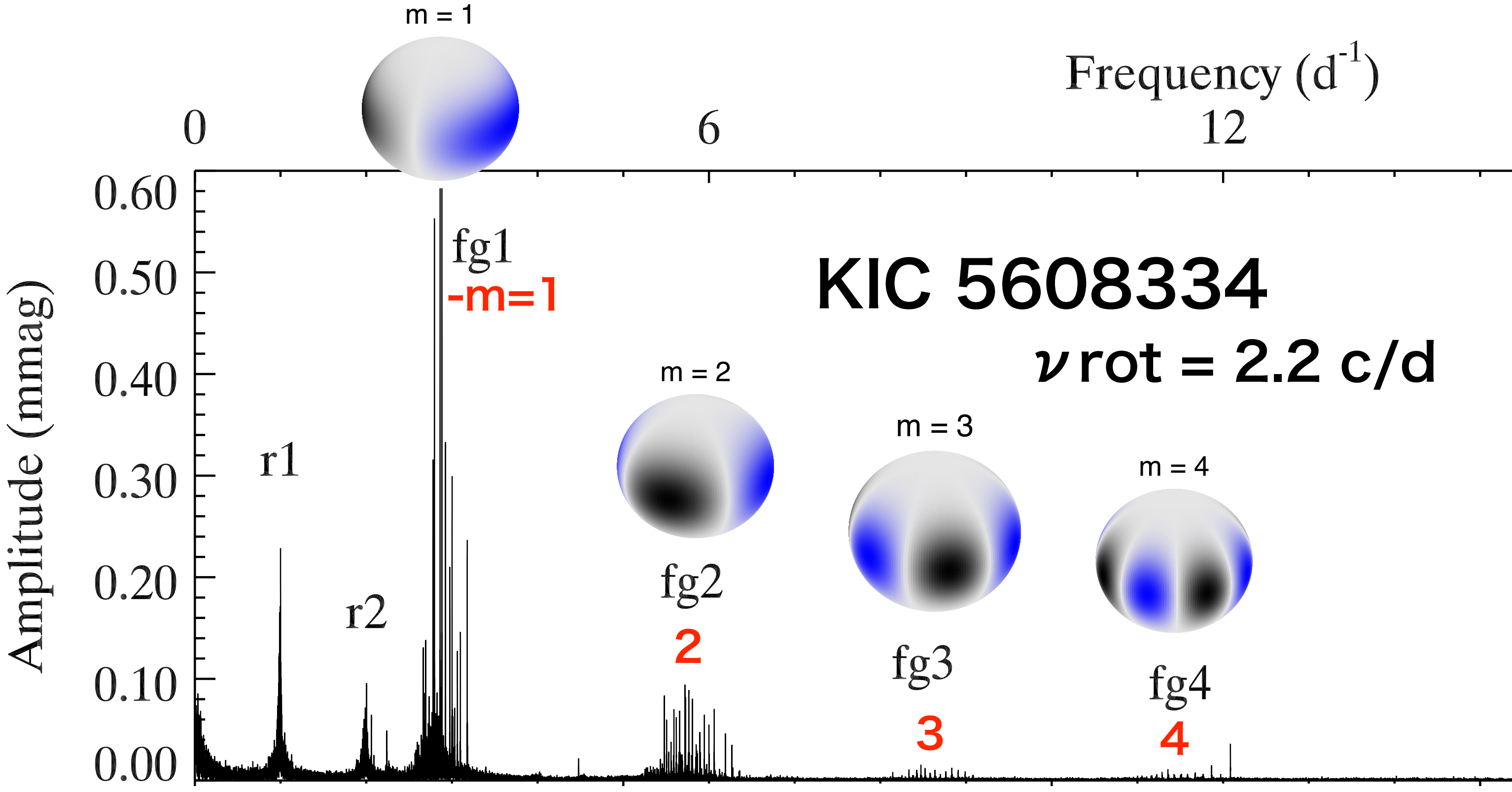


高速自転星ではg modesの
周期または周波数
グループをつくる



Period(days)

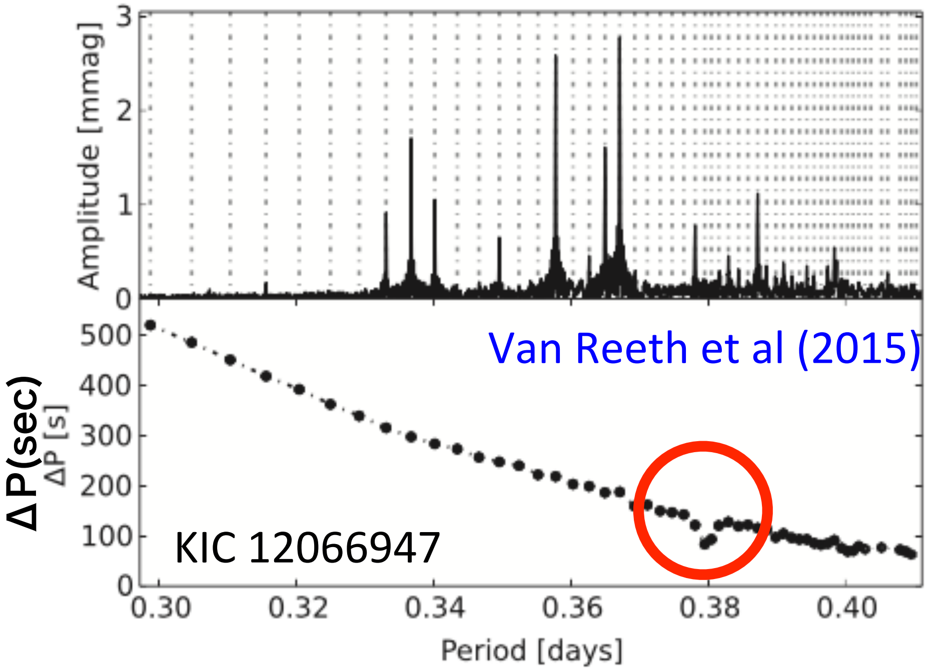
g modes: 2Ω > ω

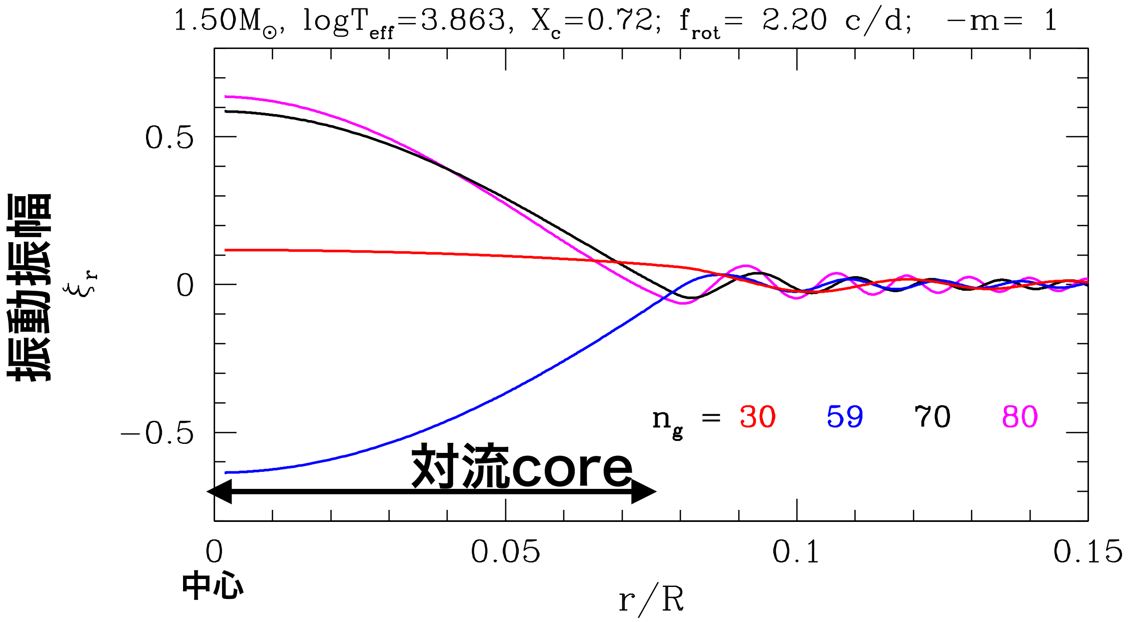


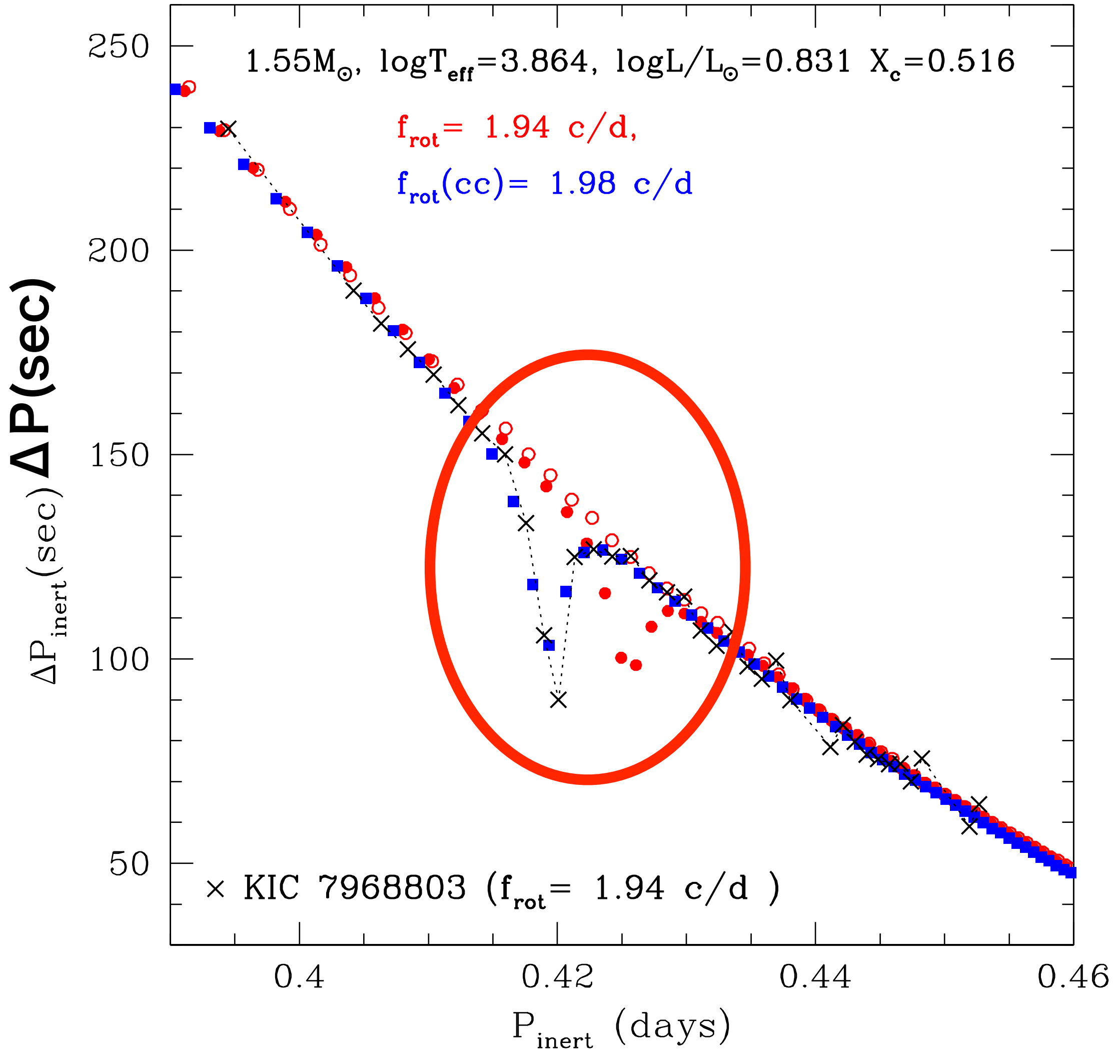
Frequency (c/d)

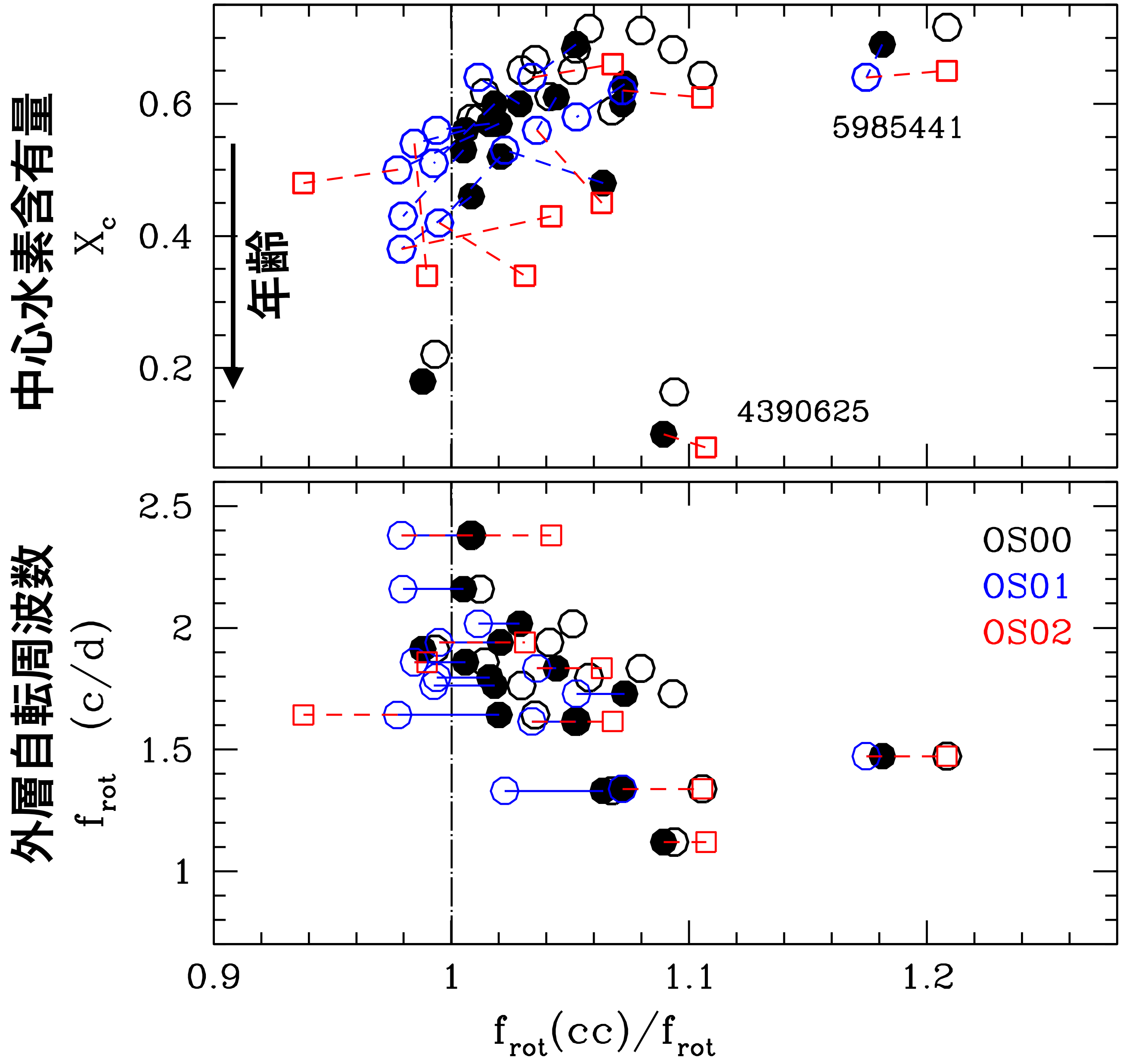
$$\nu_{\rm obs} = \nu_{\rm co-rot} - m\frac{\Omega}{2\pi}$$
$$\approx |m|\frac{\Omega}{2\pi}$$

ΔP—P関係のdip --> 中心対流core の自転速度









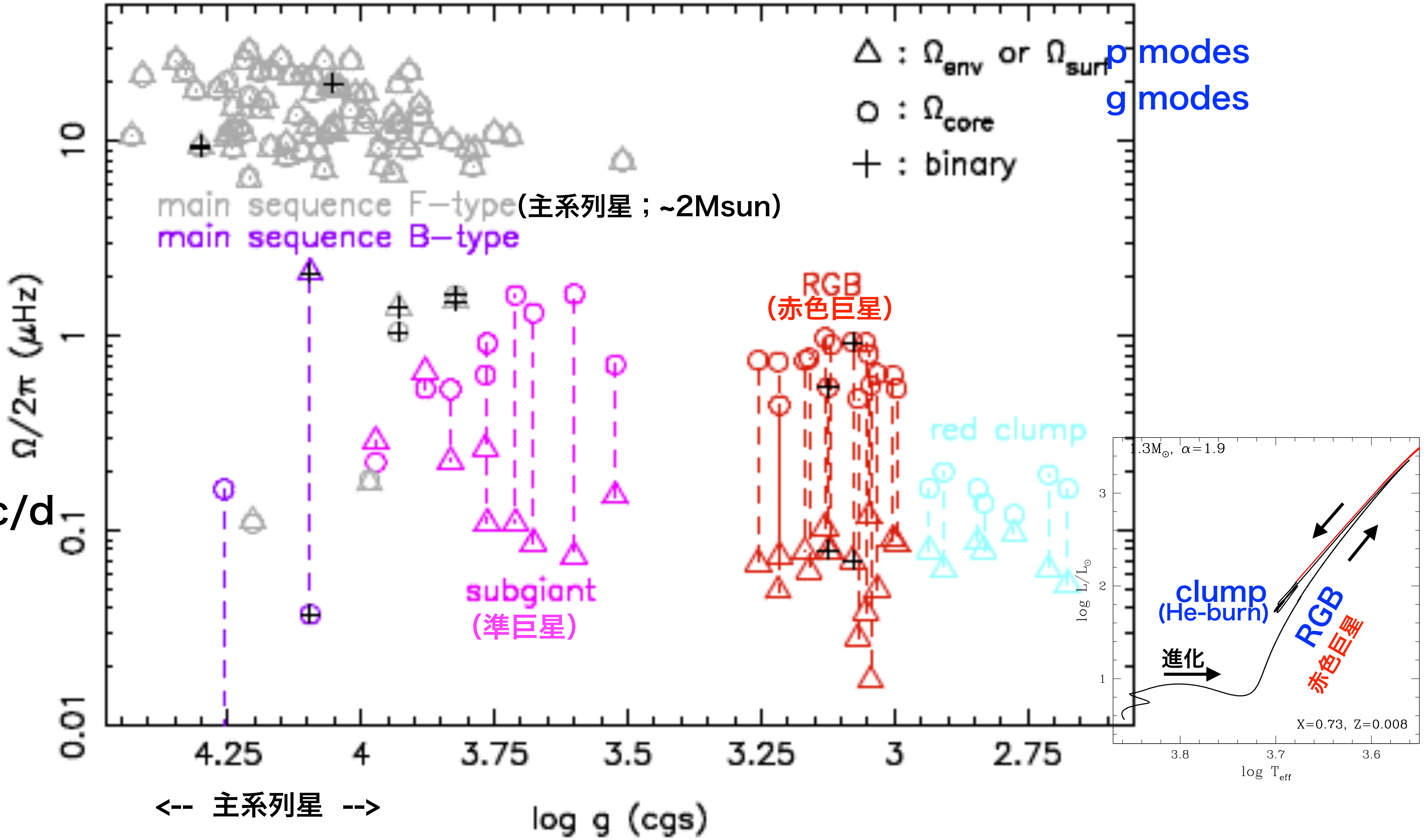
種々の星の中心部○と外層部△の自転周波数

g modes　　p modes

自転速度

1c/d

0.01 c/d



p modes
g modes

(主系列星；~2Msun)

(赤色巨星)

(準巨星)

<-- 主系列星 -->

(表面重力の対数値)

Aerts (2021)

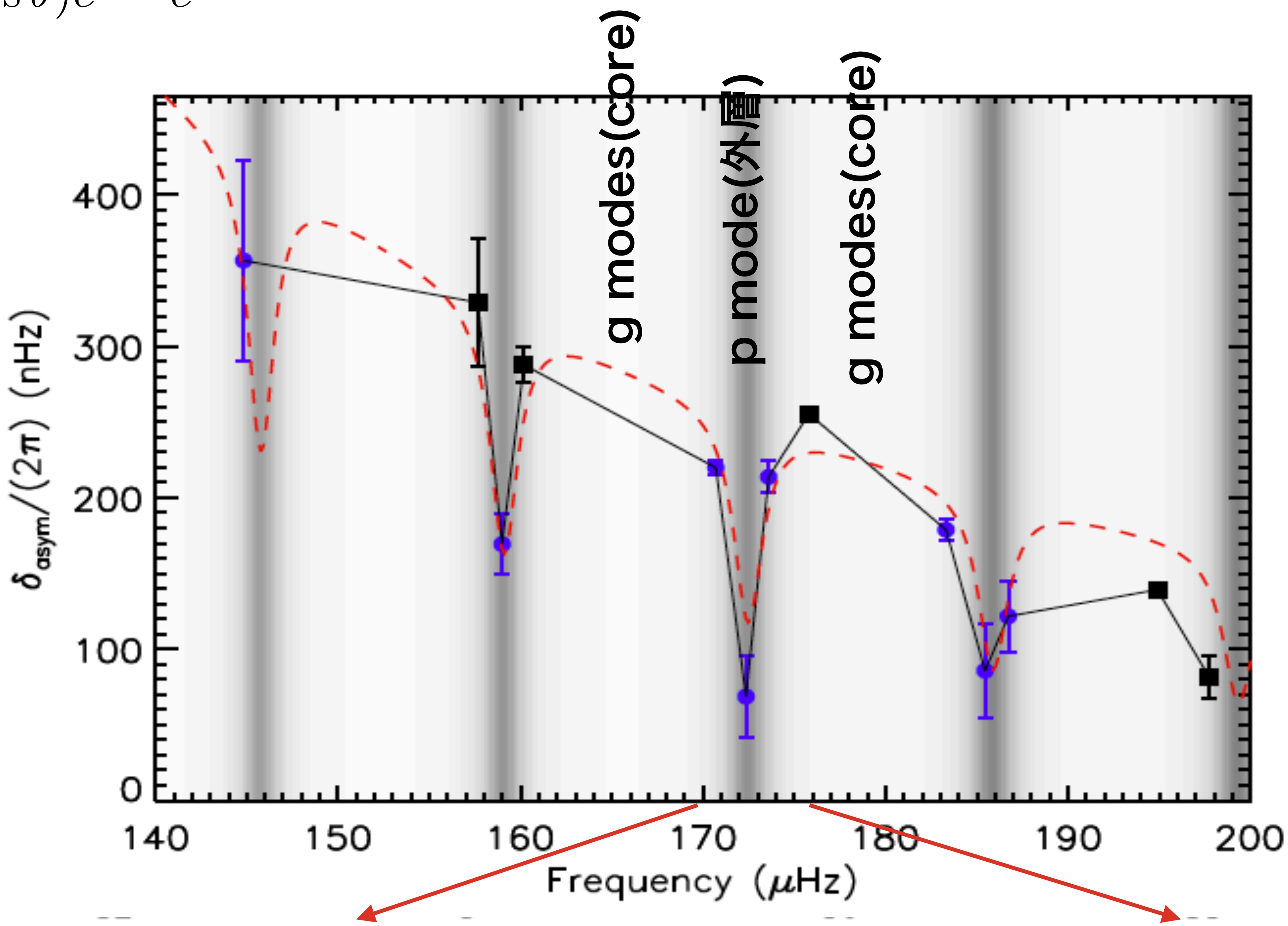
赤色巨星双極振動周波数のrotational splitting Asymmetry

$\ell = 1$

---> 中心部の磁場の強さ

$P_\ell(\cos\theta)e^{im\phi}e^{i\omega t}$

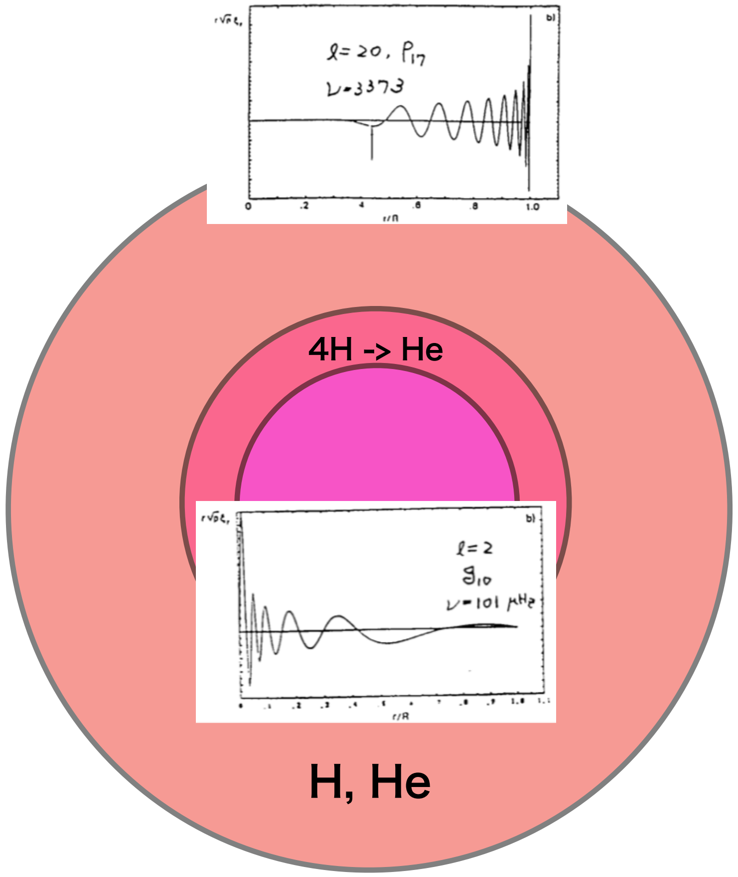
$\delta_{\rm asym} = \omega_{m=-1} + \omega_{m=1} - 2\omega_{m=0}$



g modes(core)

p mode(外層)

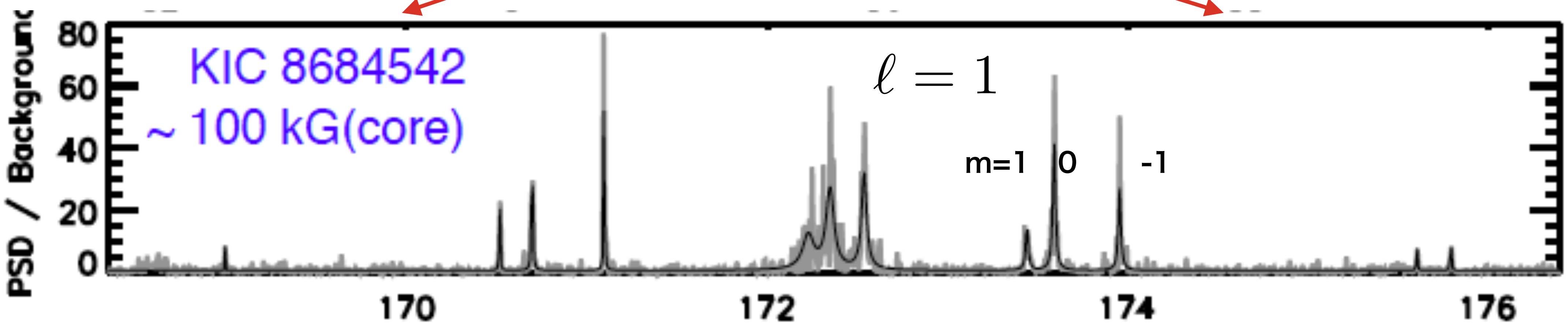
g modes(core)



4H -> He

H, He

Li et al (2022)



KIC 8684542

~ 100 kG(core)

$\ell = 1$

m=1 0 -1

log g= 3.16

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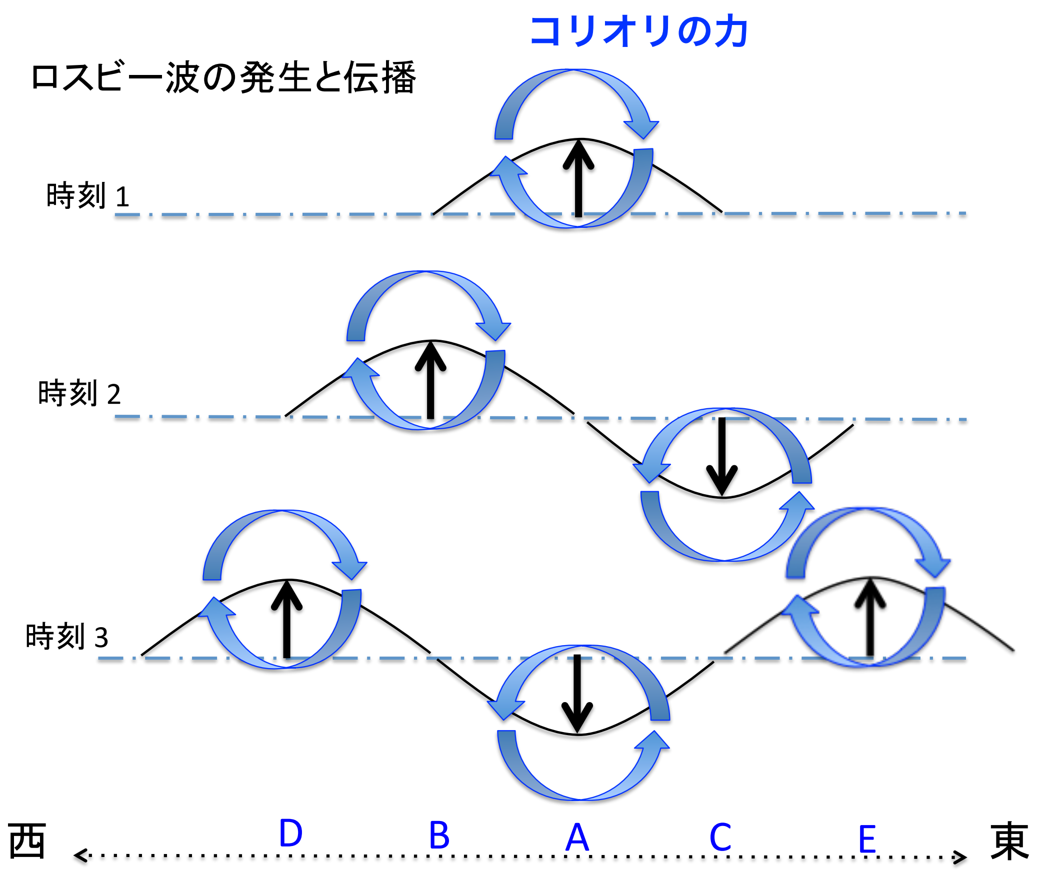
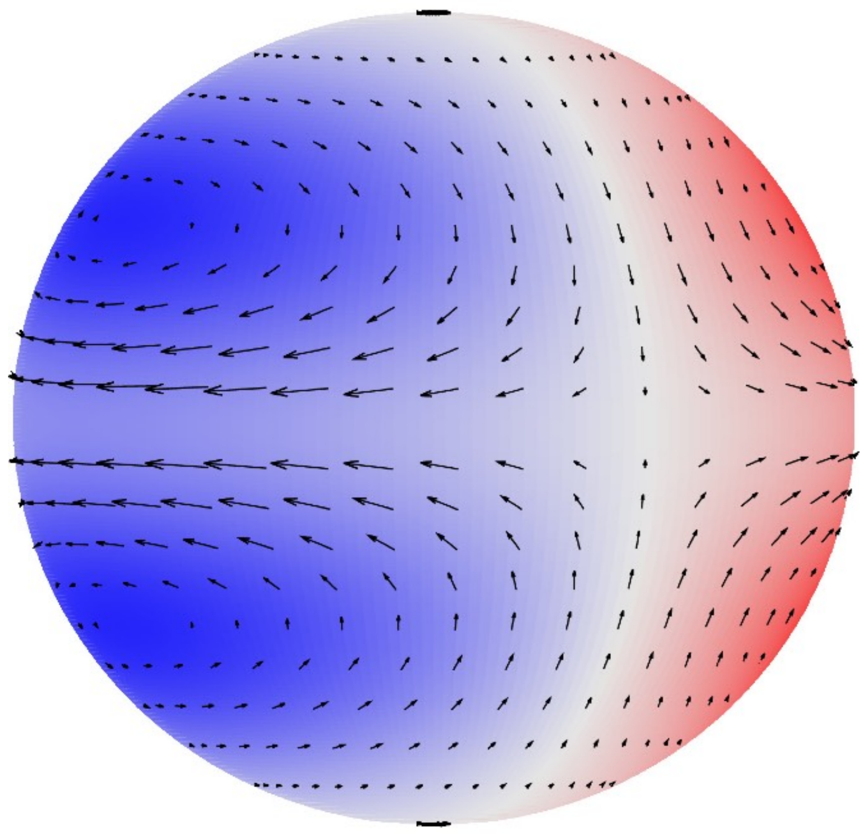
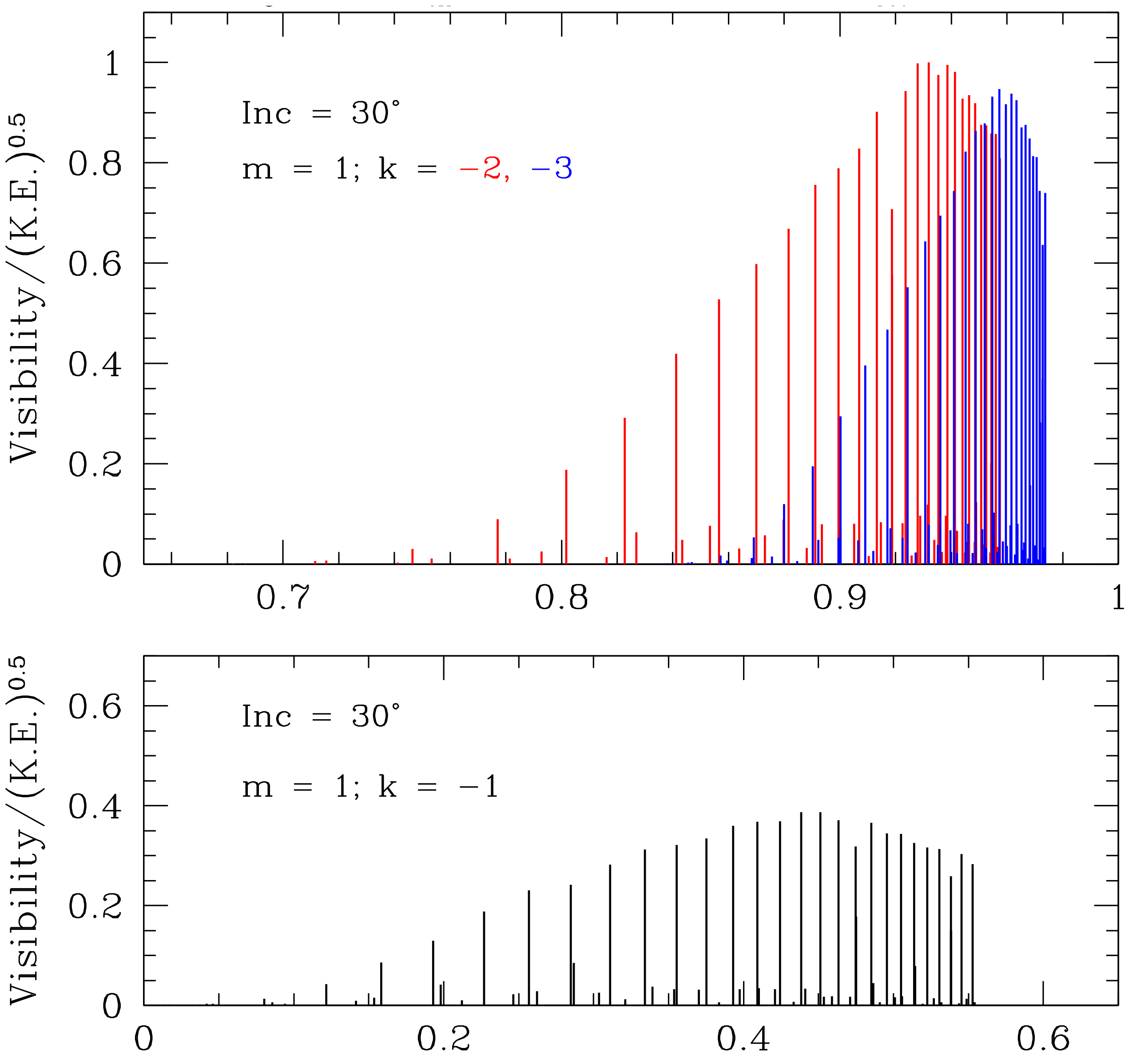
r (Rossby) mode 振動



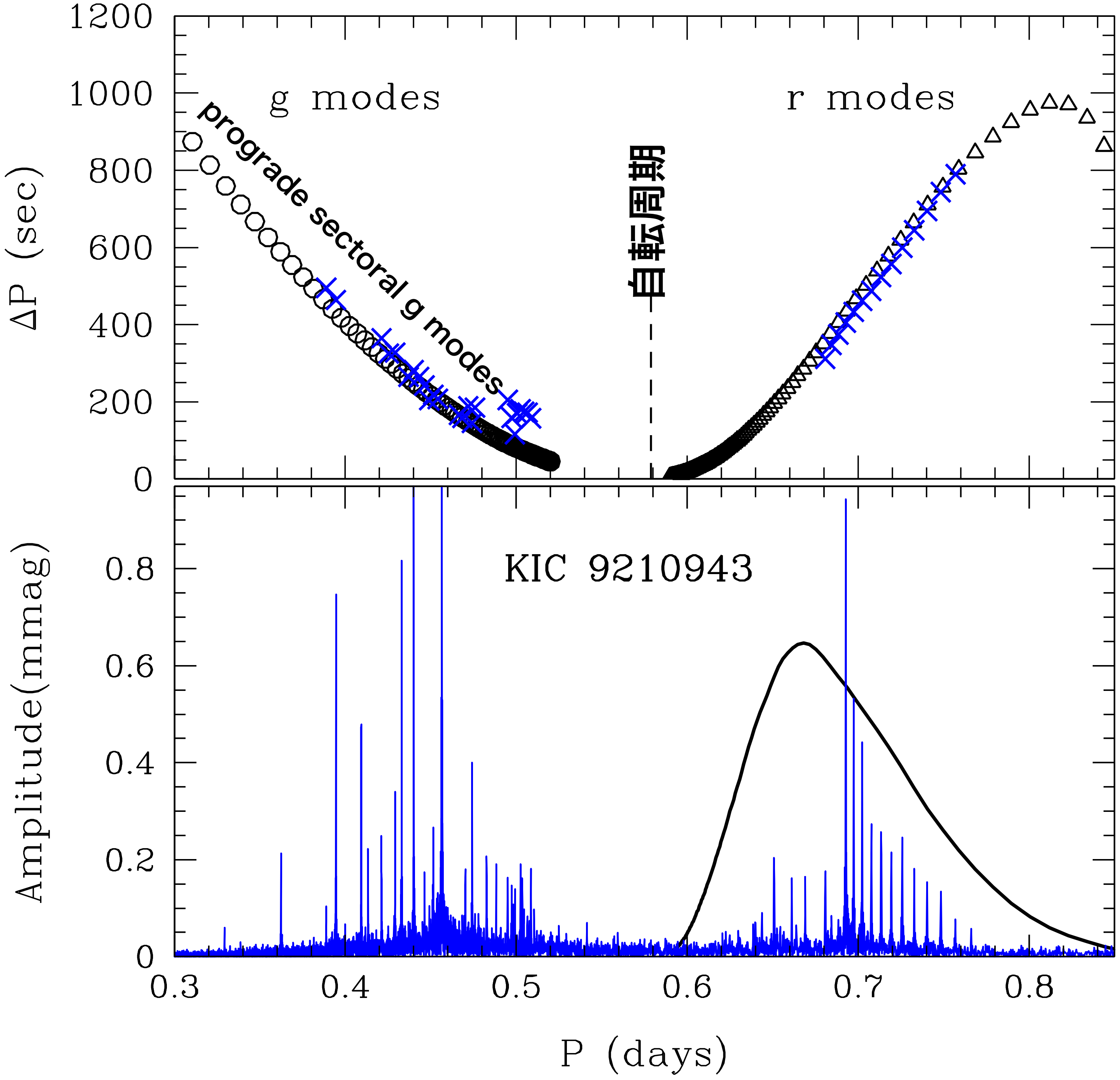


r-modes が現れる周波数領域 と予想される振幅分布



r-mode freq./rotation-freq.

r (Rossby) modes



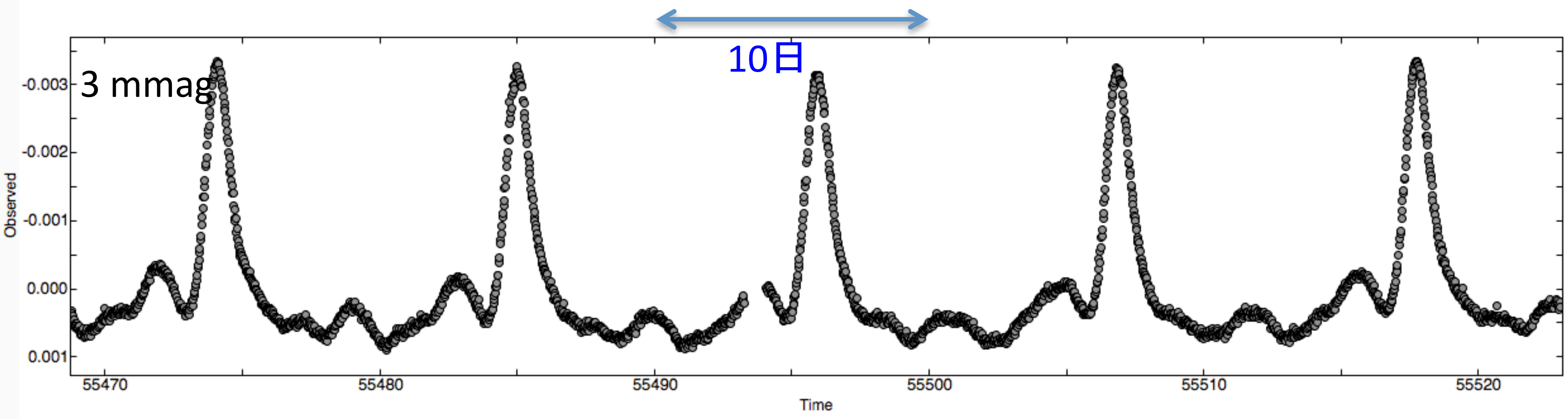
r-mode 振動が実際に存在する事が
Van Reeth et al (2016)によって
主系列星であるγ Dor型変光星で
発見された.

その後種々の星でも r-modes
が観測されている.

r-mode oscillationsの周波数から
その星の自転周期を正確に決める事
ができる

Heartbeat 星　ー　心電図に似た光度曲線を示す連星系

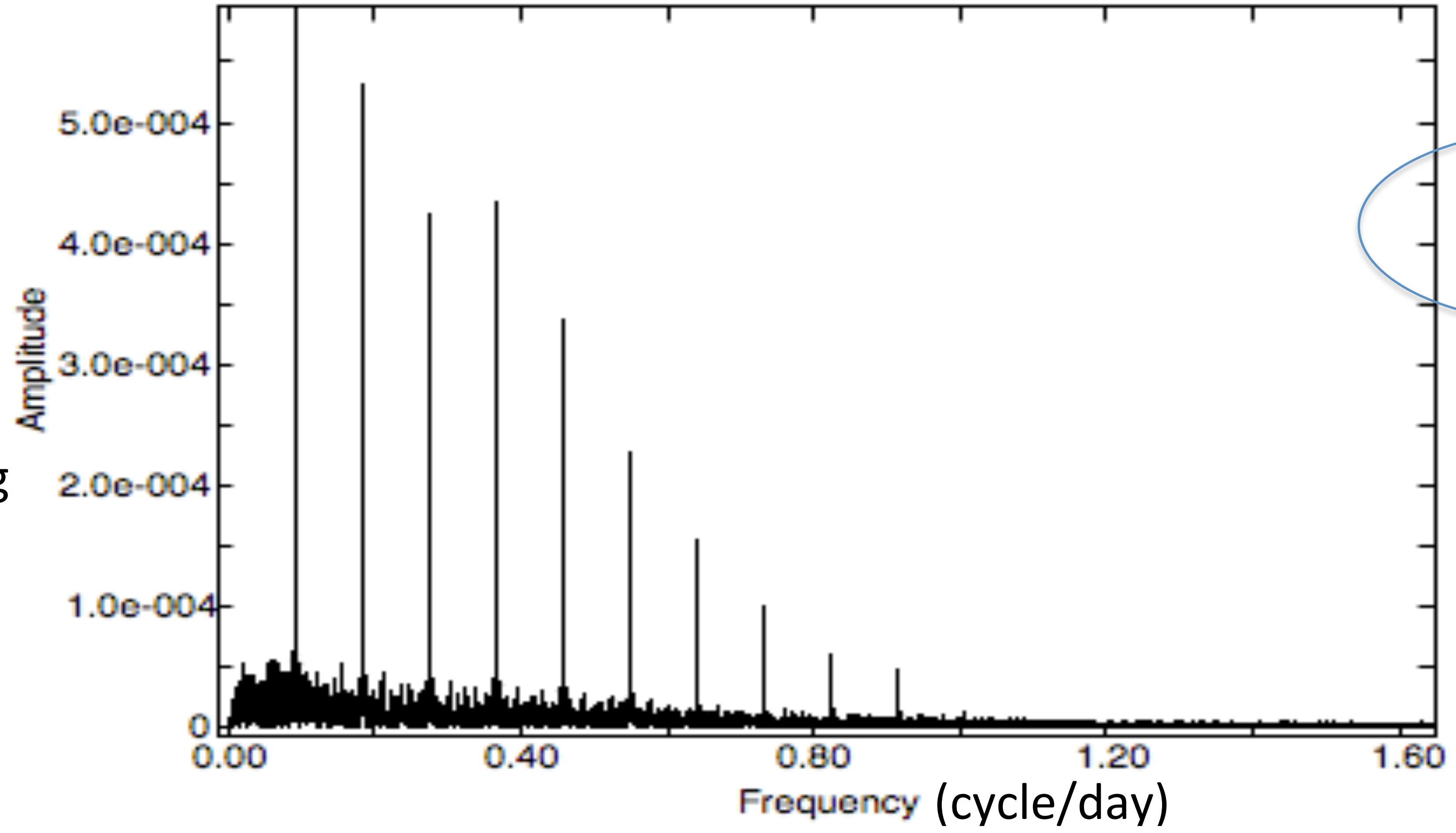
KIC 9899216 (軌道周期=10.92 日, e=0.647)

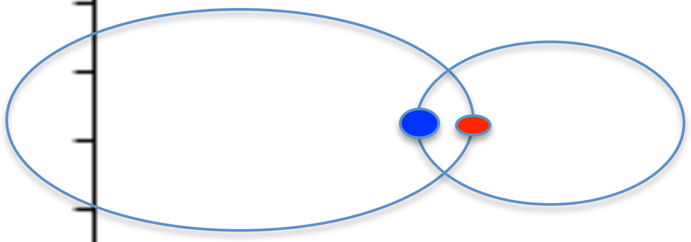

3 mmag

10日

フーリエ変換

0.2 mmag





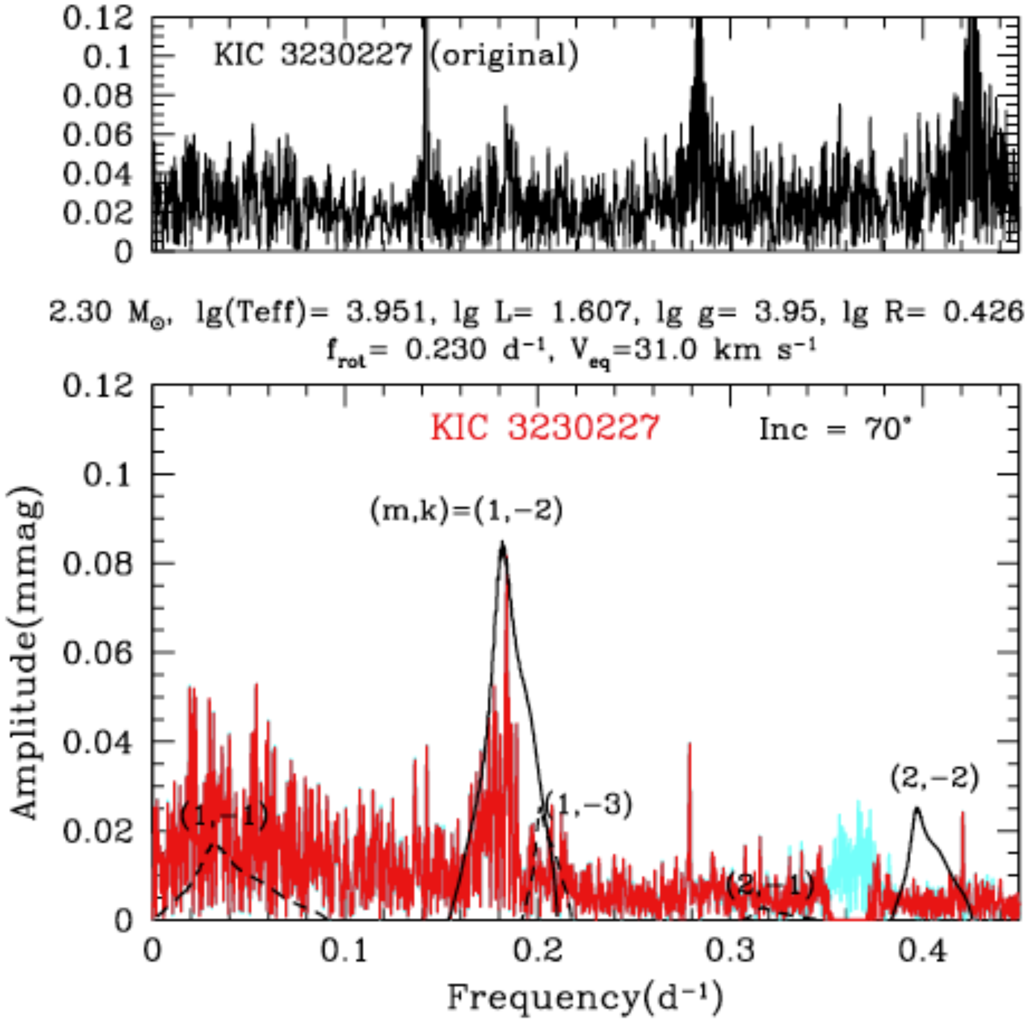
Kepler:　172
TESS:　200
OGLE:　991

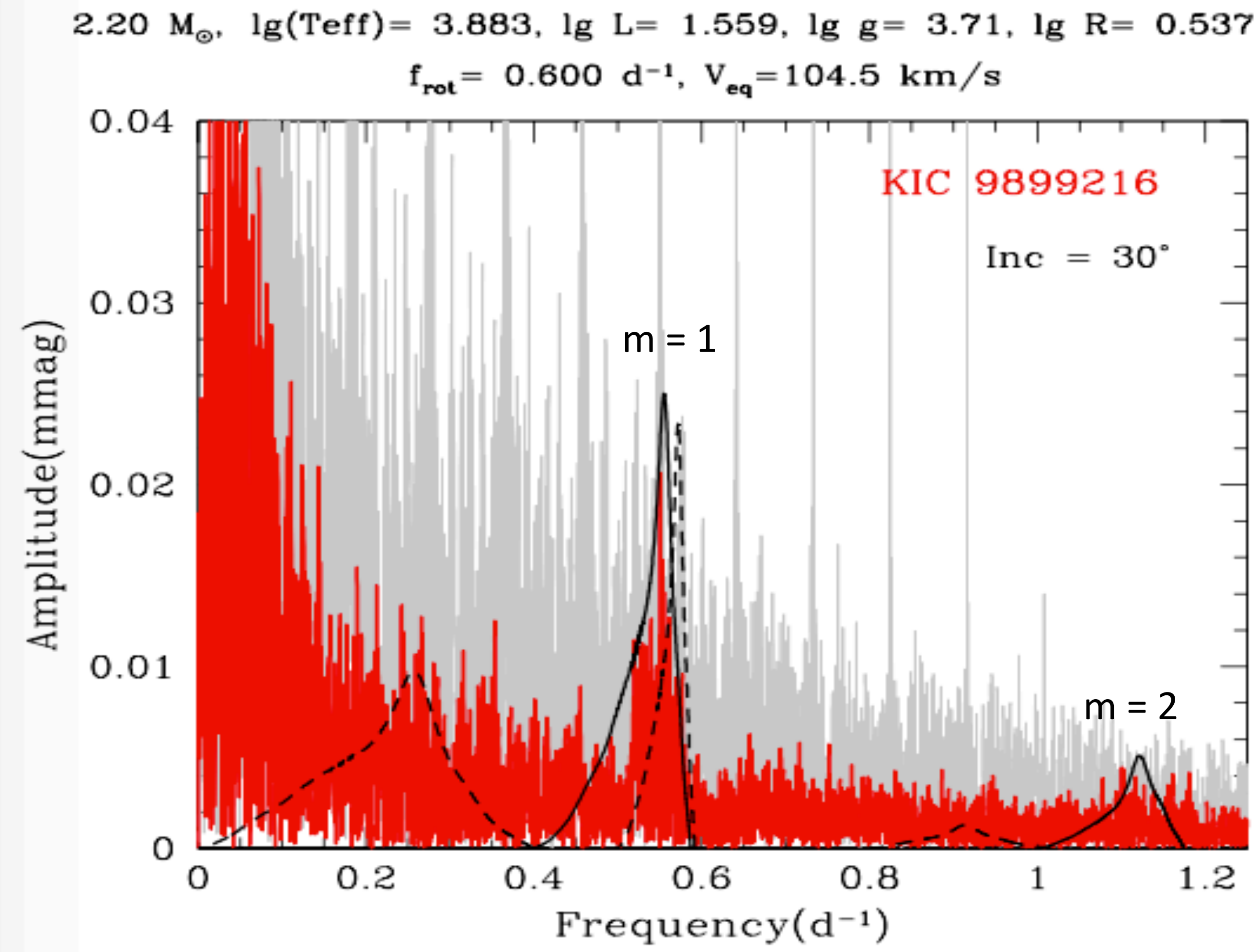
軌道運動によって生じる多くの周波数ピークを

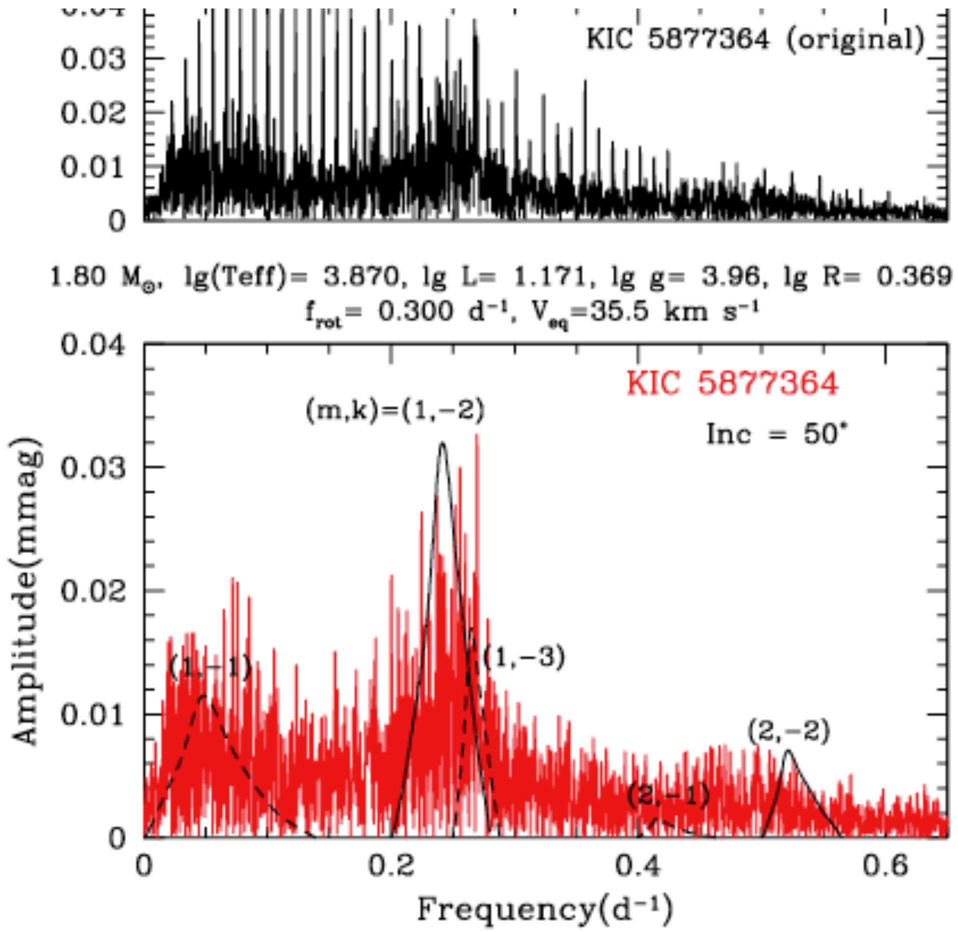
$$\sum_{j=1}^{jmax} A_j \sin[2\pi(j f_{\rm orb}(t-t_0)+\phi_j)]$$

のように表してデータから取り除くと,
r-mode 振動に起因する周波数グループが現れる

それをmodel-fitting することによる自転周期
を知ることができる

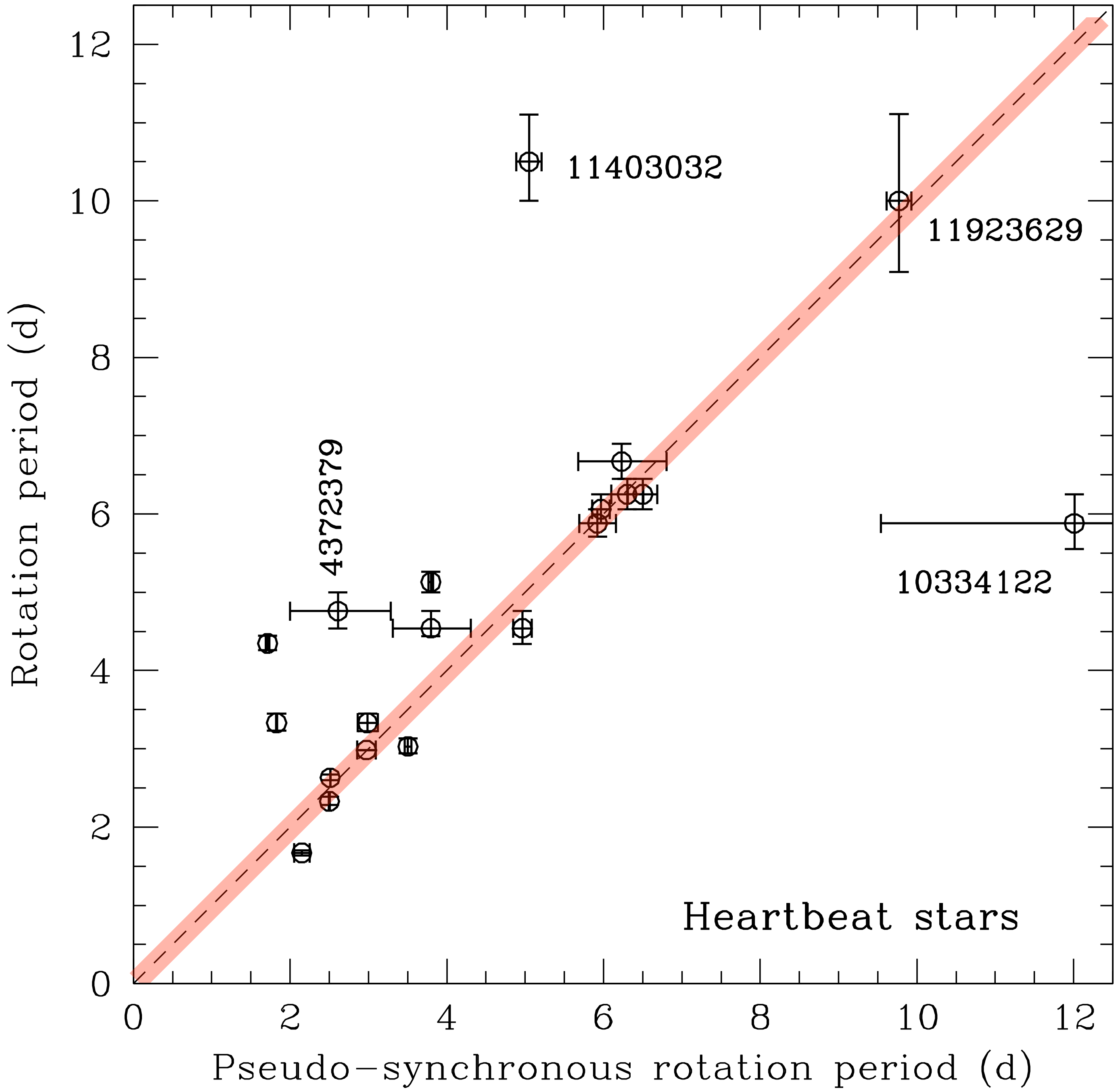






r (Rossby) modes in Heartbeat stars

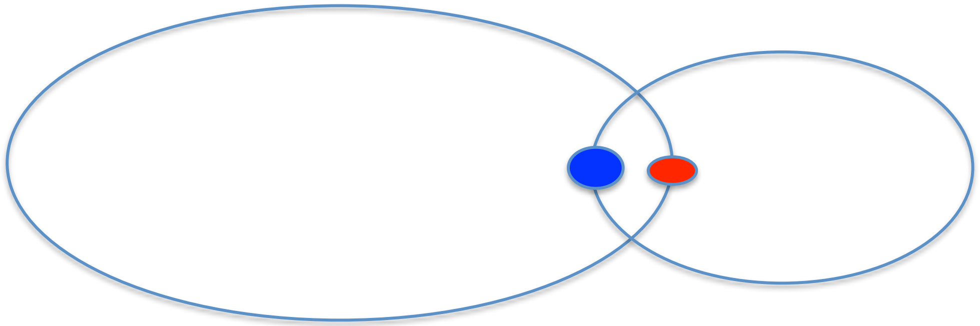
Piet Hut (1981)による Pseudo-synchronous rotation 理論がconfirm された！



Saio & Kurtz (2022)

Pseudo-synchronous rotation (Hut 1981)

自転角速度 =~0.8 軌道角速度 at 近星点



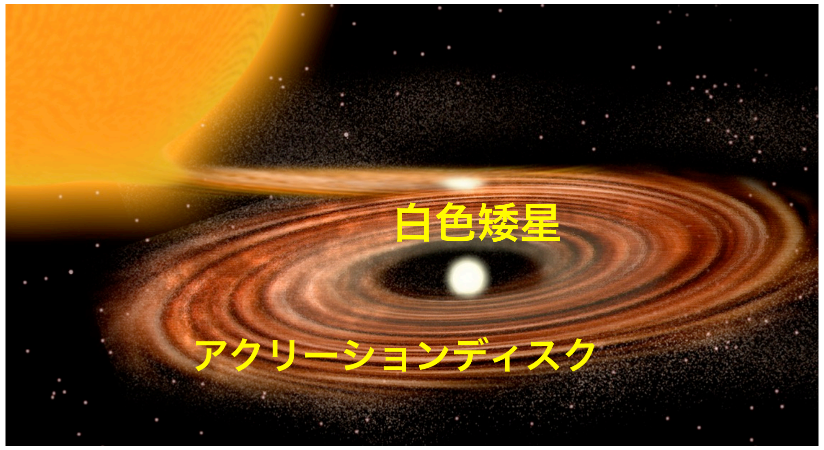
$$P_{\text{ps-rot}} = \frac{(1 + 3e^2 + \frac{3}{8}e^4)(1 - e^2)^{3/2}}{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6} P_{\text{orb}}.$$

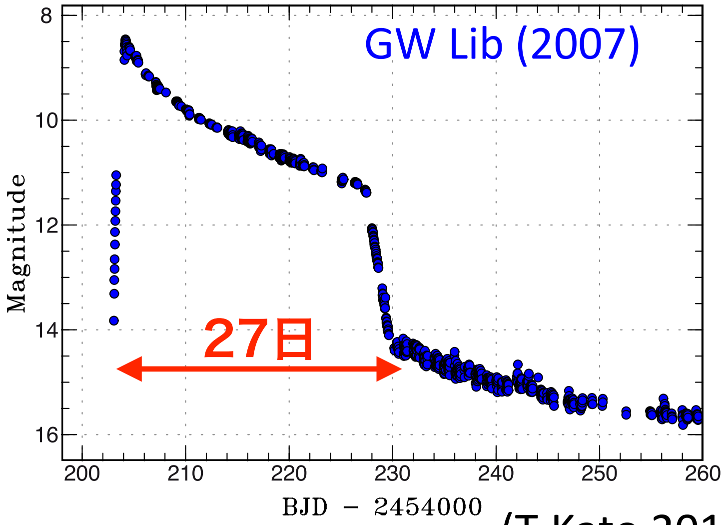
Hut (1981)

Rossby modes in accreting white dwarfs

Dwarf Nova(矮新星):

accretion disk が稀に
instabilityを起こし
diskのガスが急激に
白色矮星に落ちていく
-> 多量の重力エネルギー
が解放されてdisk が
明るく輝く





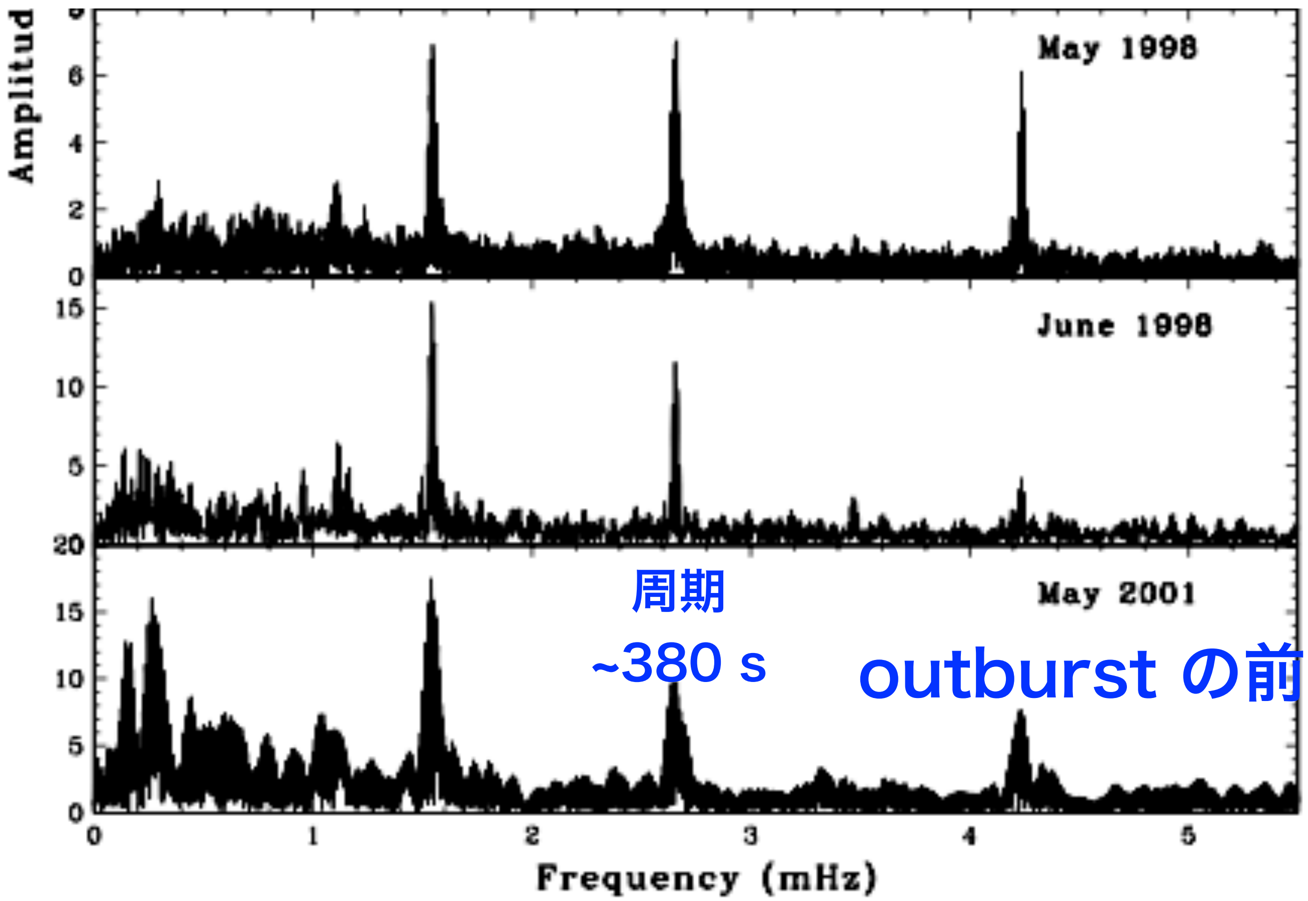
軌道周期
1.28 hr

(T.Kato 2015)

GW Lib outbursts in 1983 & 2007

白色矮星のnonradial pulsationsの観測

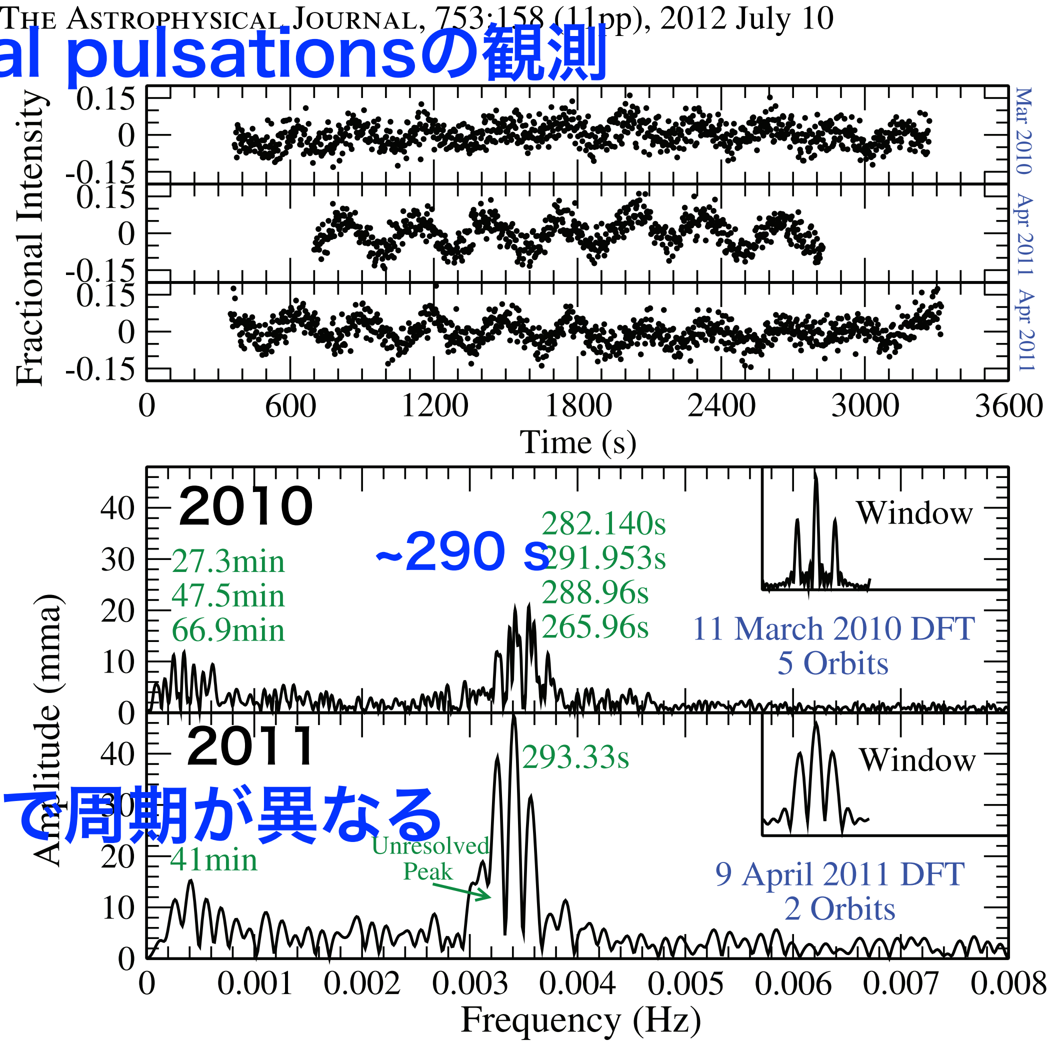
GW Lib: outburst 以前の変光観測



周期
~380 s

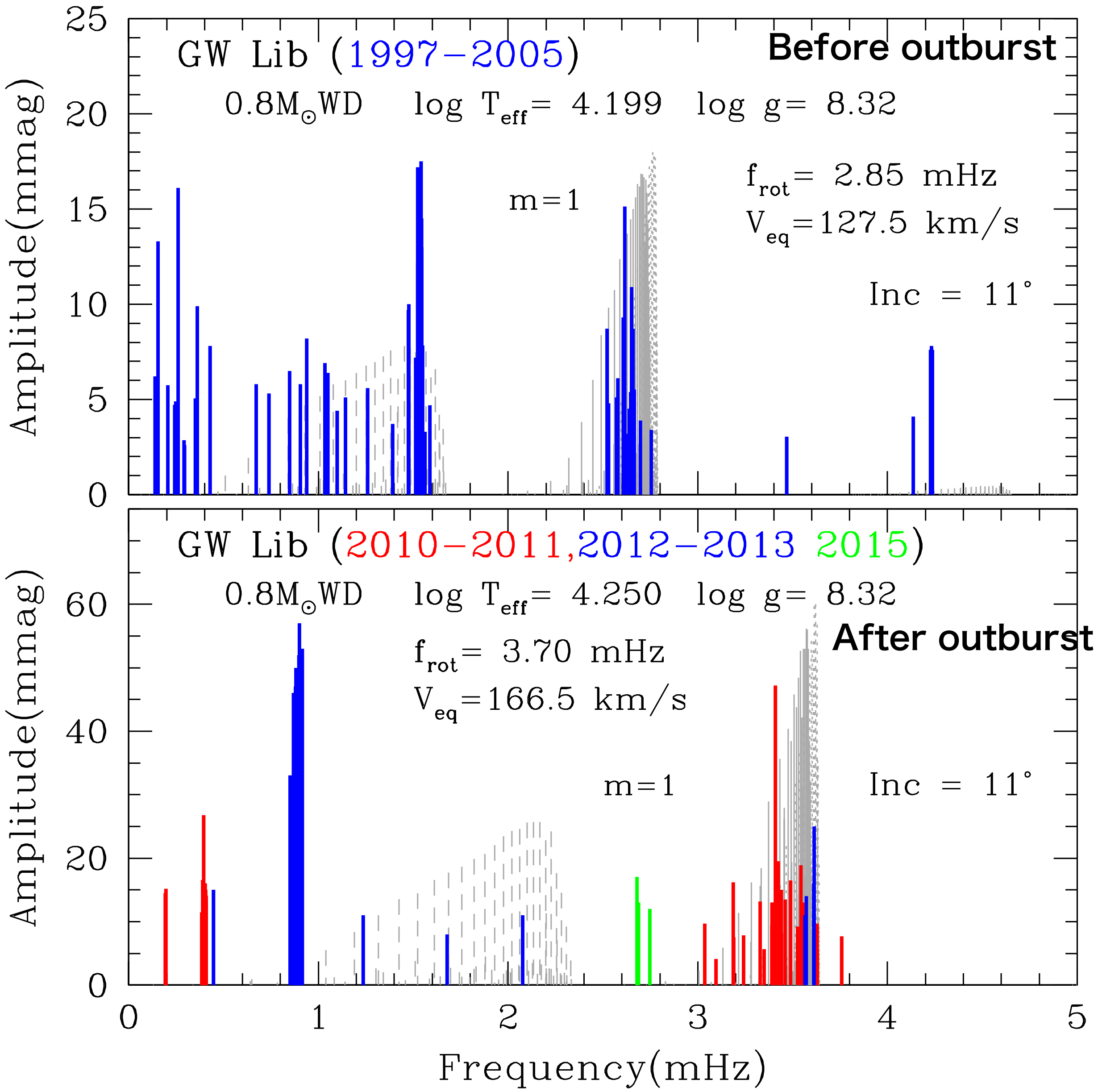
outburst の前後で周期が異なる

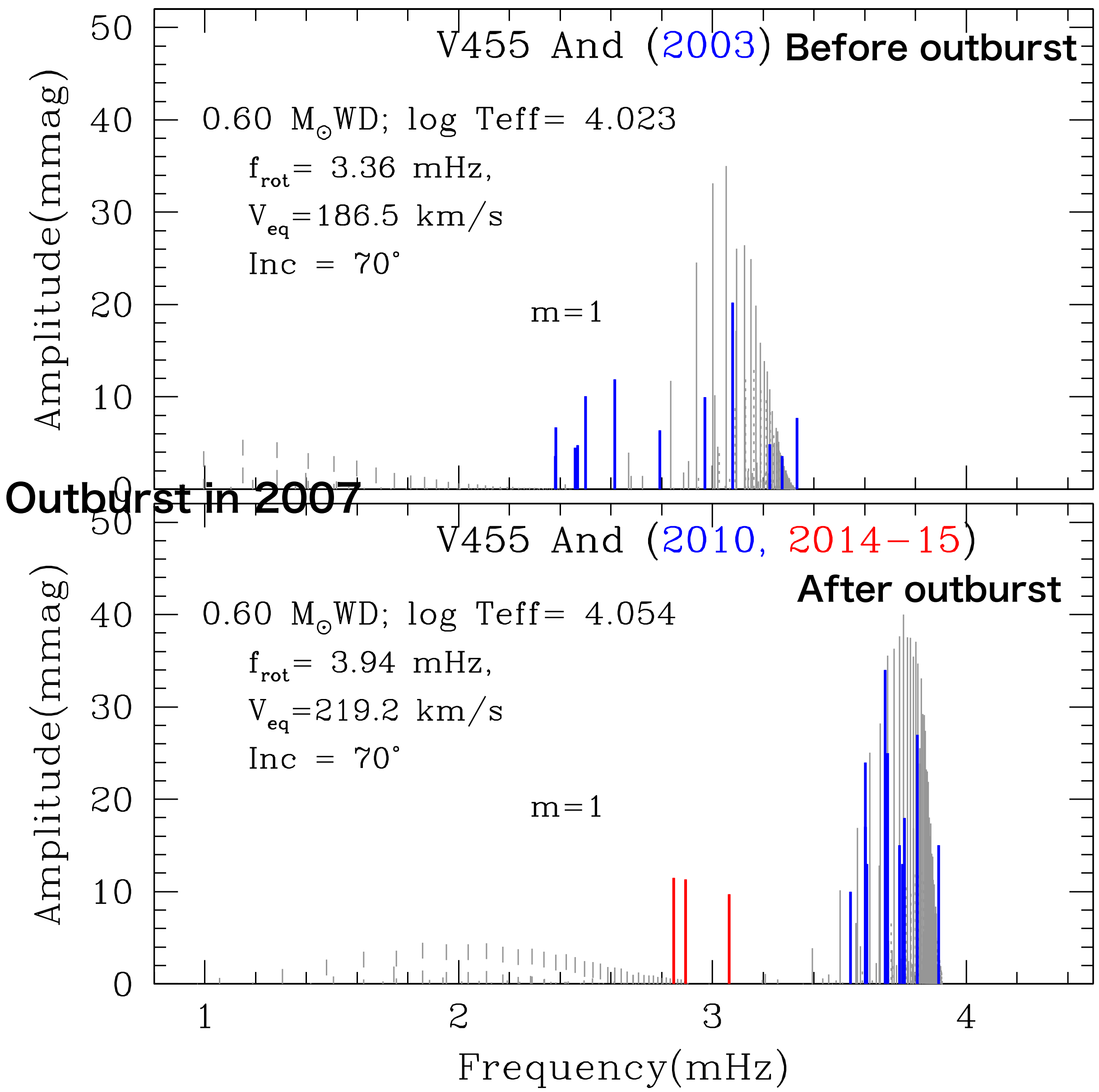
Van Zyl et al. (2004)


The Astrophysical Journal, 753:158 (11pp), 2012 July 10

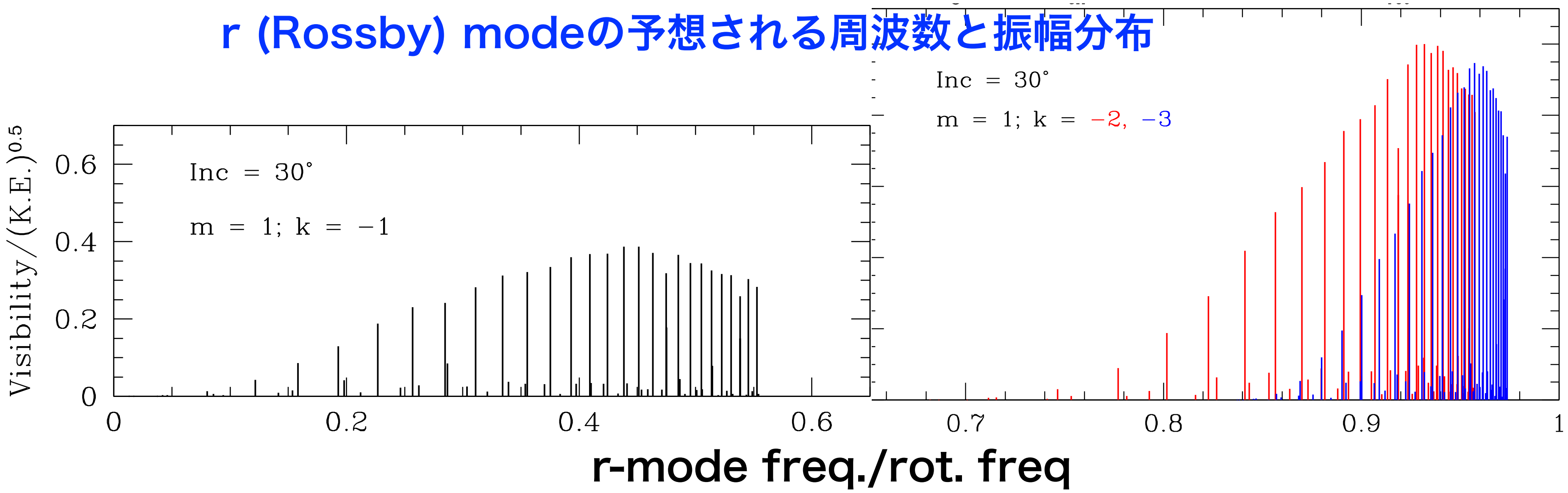
Szkody et al. (2012)

r mode振動と仮定　Outburst 前後での振動周波数の変化　Accretionによる自転の加速





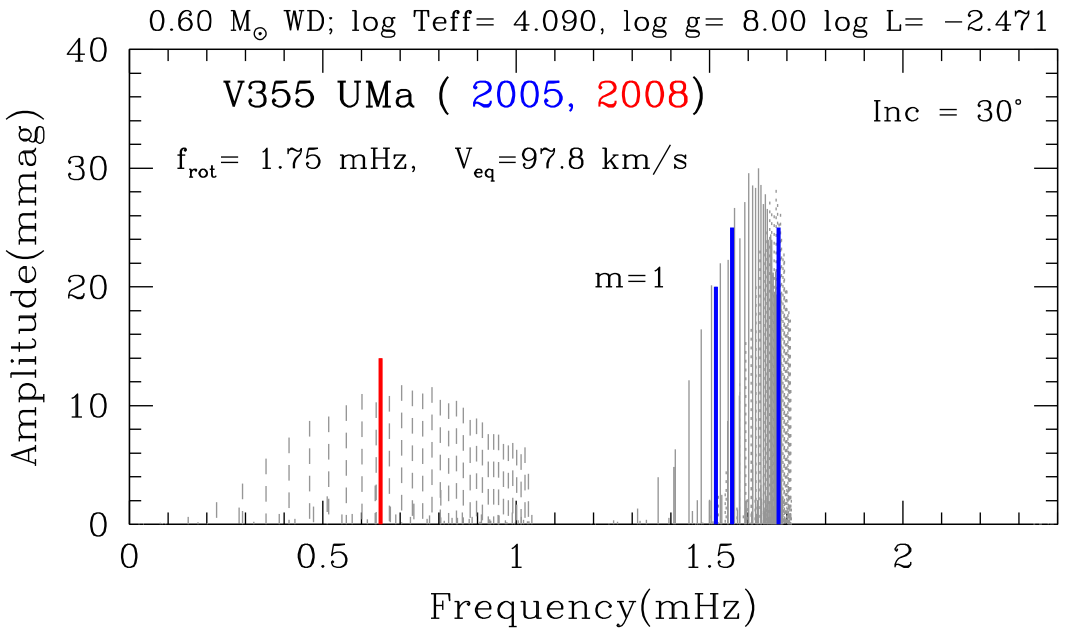
r (Rossby) modeの予想される周波数と振幅分布



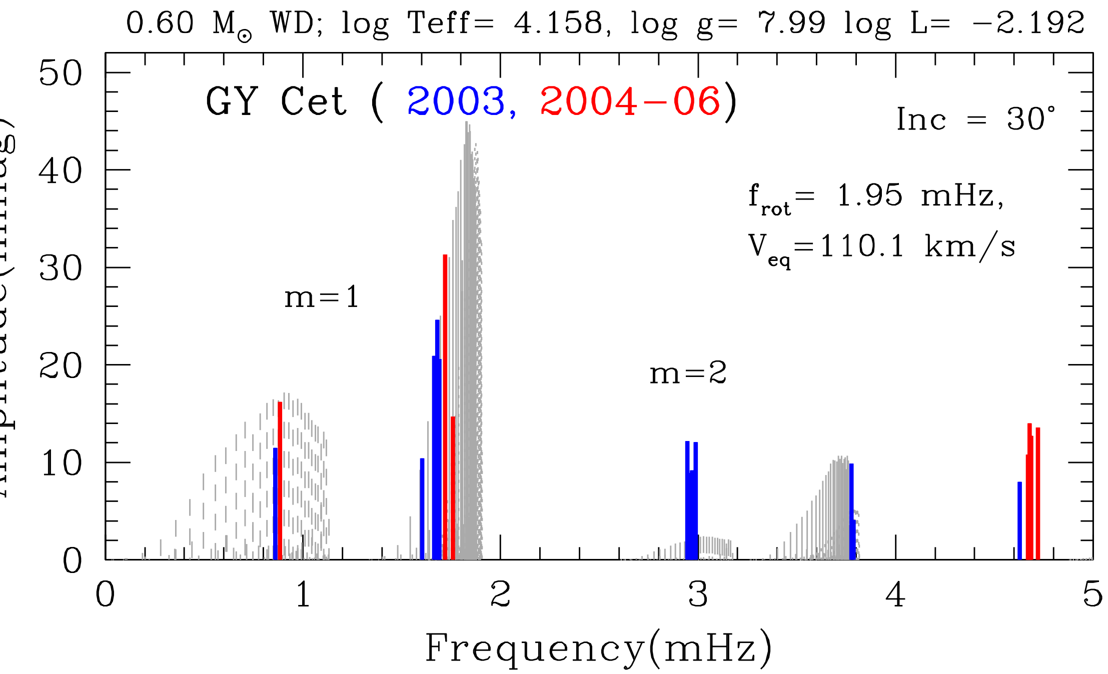
r (Rossby) modes in accreting WD

Accreting white dwarf の自転速度は accretion rateに相関

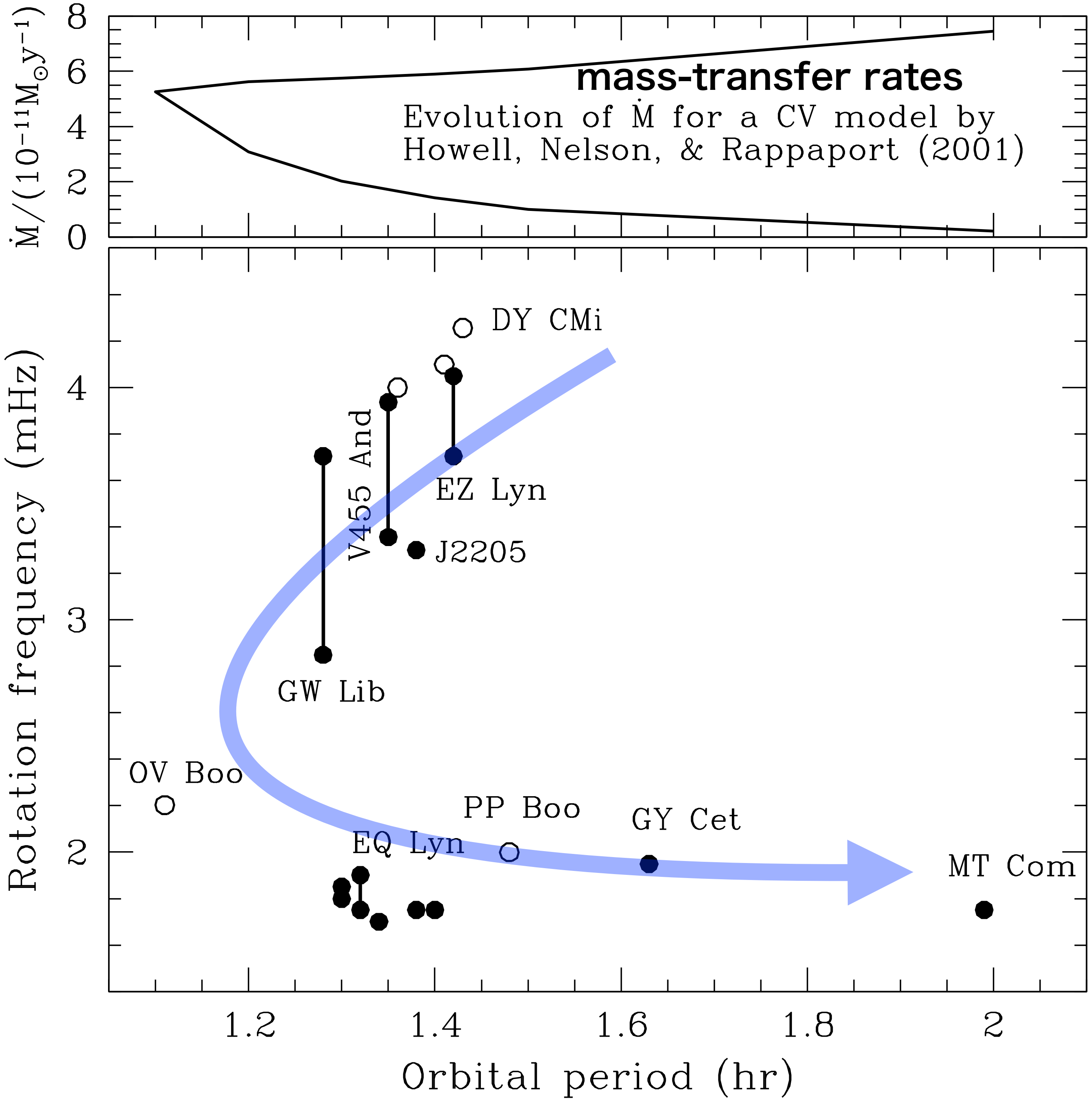
Outburst 以前の観測



V355: Outburst 2011

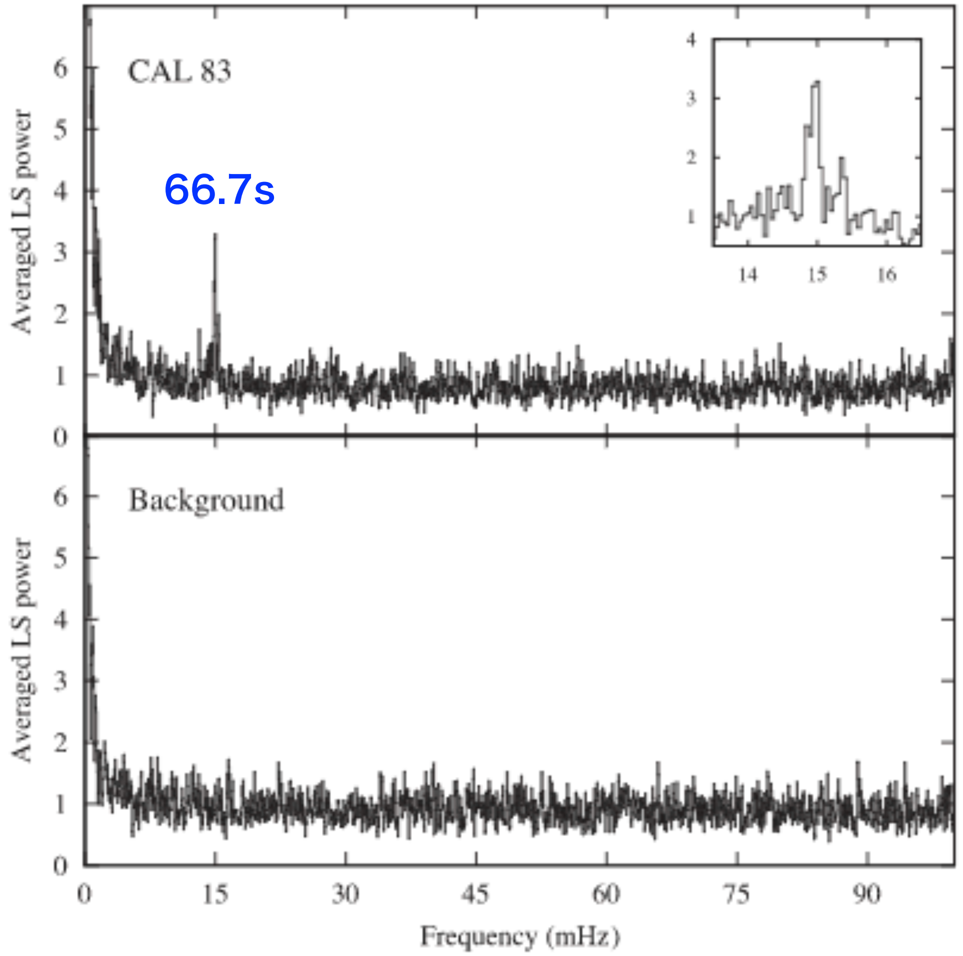


GY Cet; Outburst 2020 7~8月

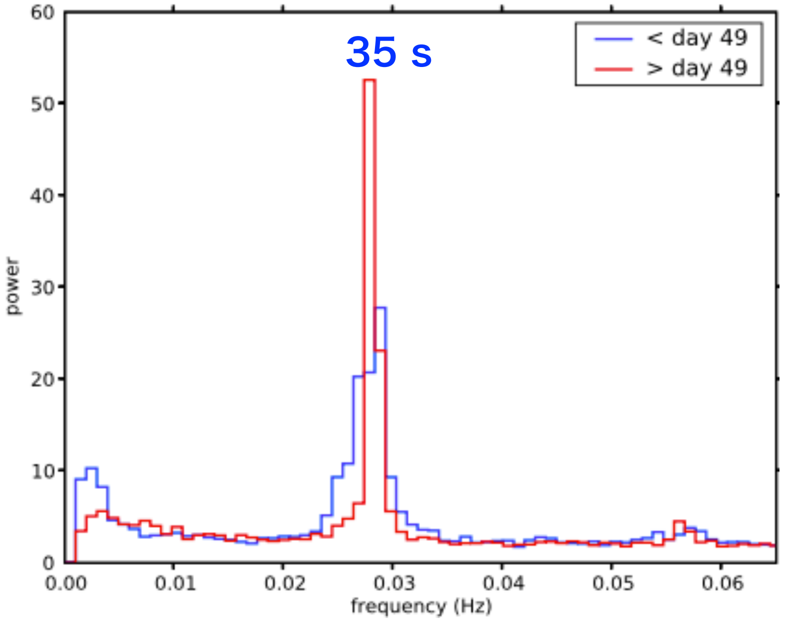


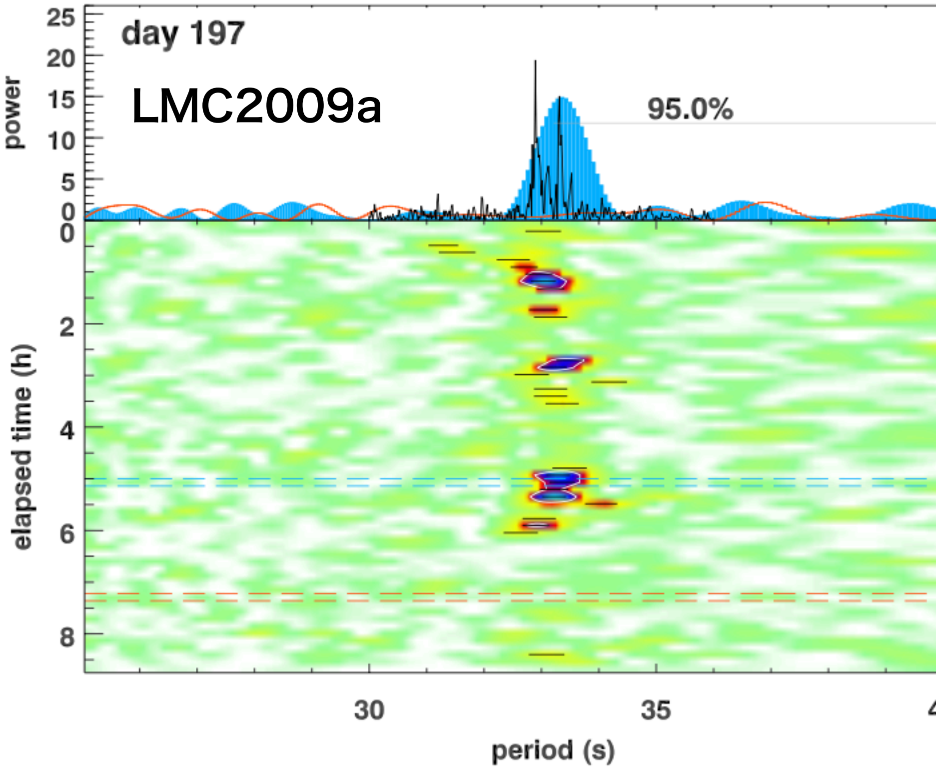
Short period oscillations in Super Soft Xray Souses

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



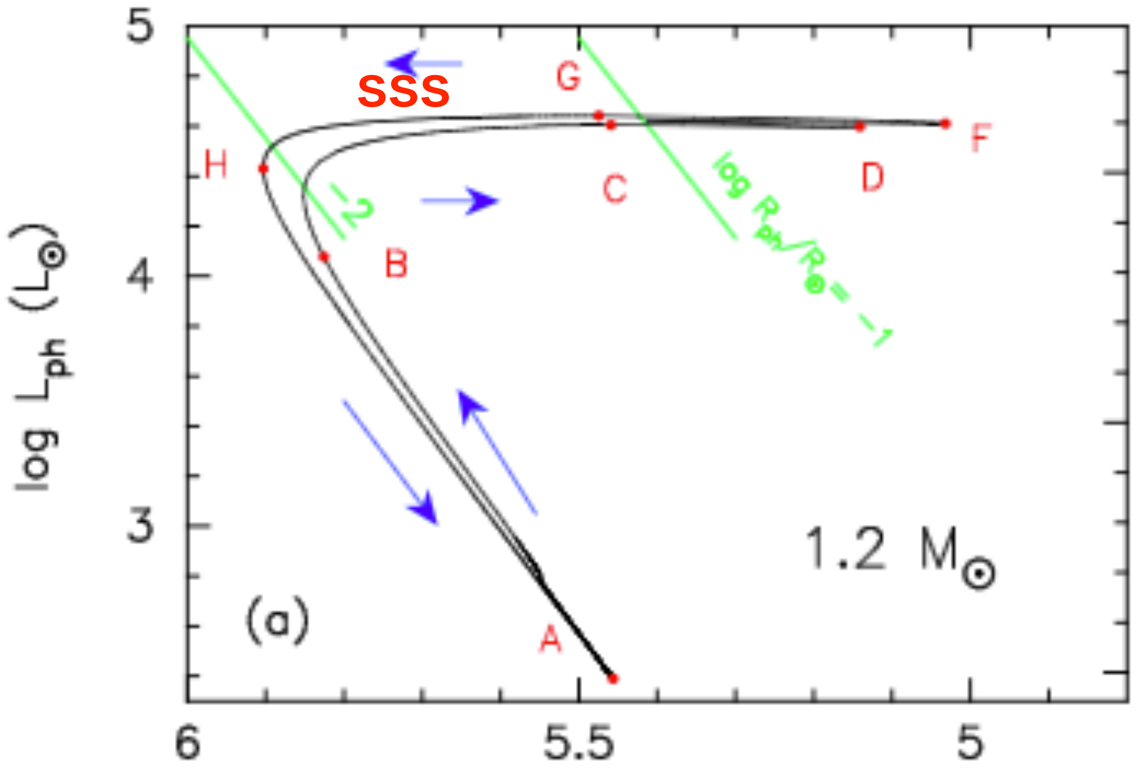
Osborne et al.(2011) RS Oph





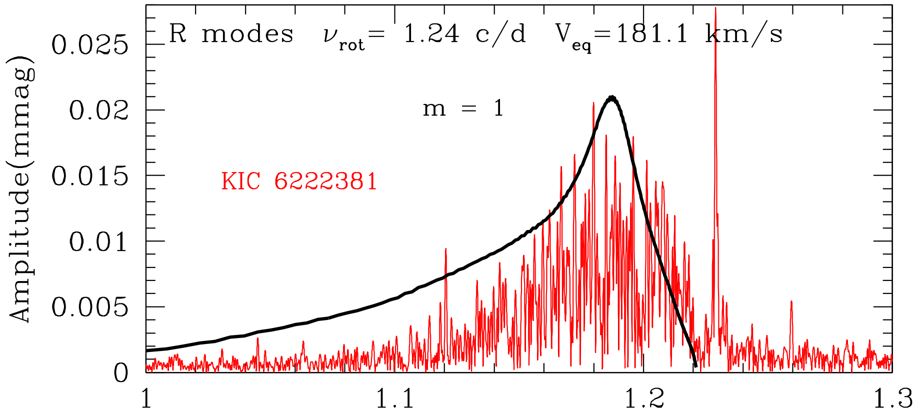
Ness et al. (2015)

r modes ??



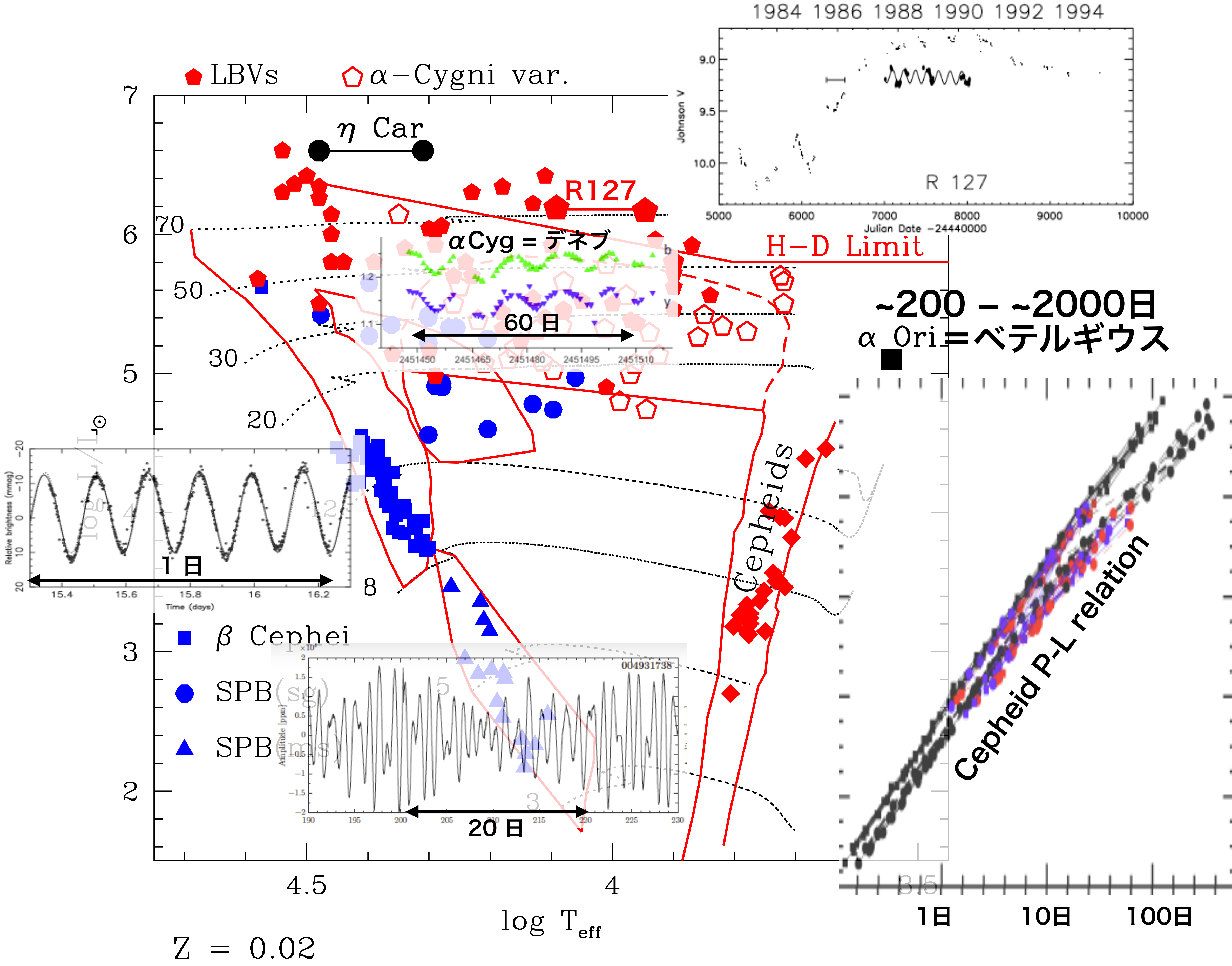
Kato et al (2017)

A-type 主系列星 r modes



1. 恒星振動(脈動）の 基本的性質
2. 恒星振動から知る恒星自転速度
3. r (Rossby) mode 振動
4. 脈動周期変化率と恒星進化速度
5. 進化の進んだ大質量星の脈動
6. Betelgeuse (α Ori) の脈動

Massive (Luminous) variable stars

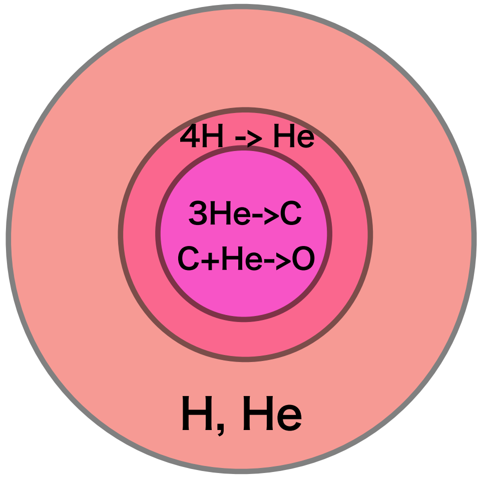


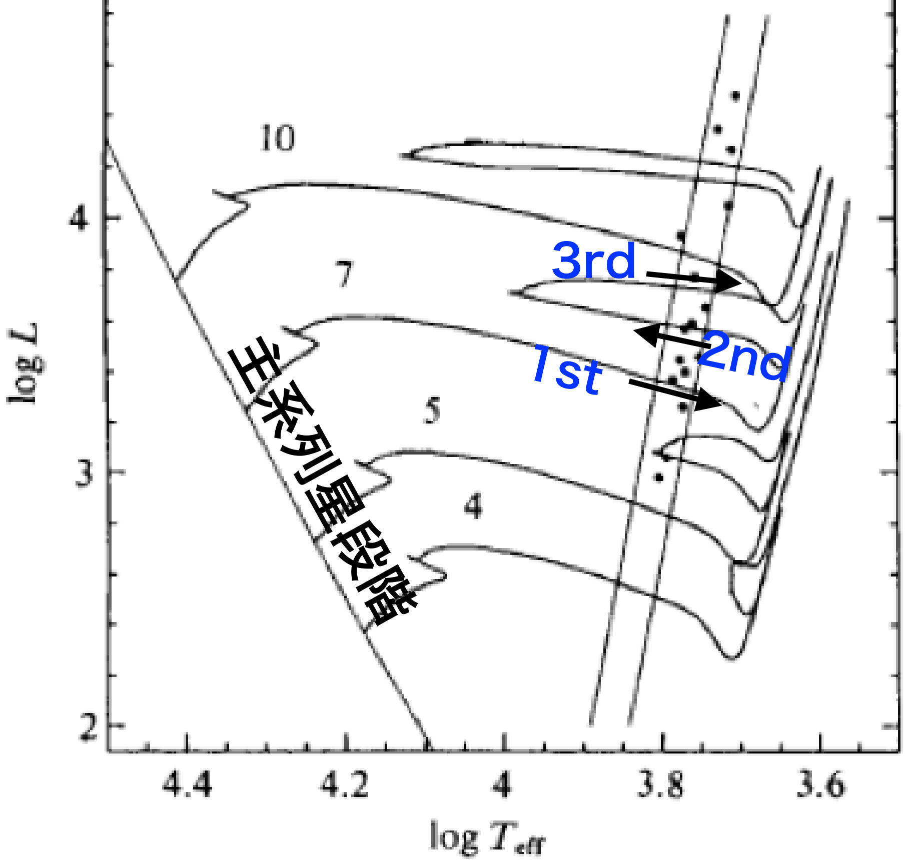
セファイド変光星の周期永年変化

周期変化率 ~ 0.1 -- 100 秒／年

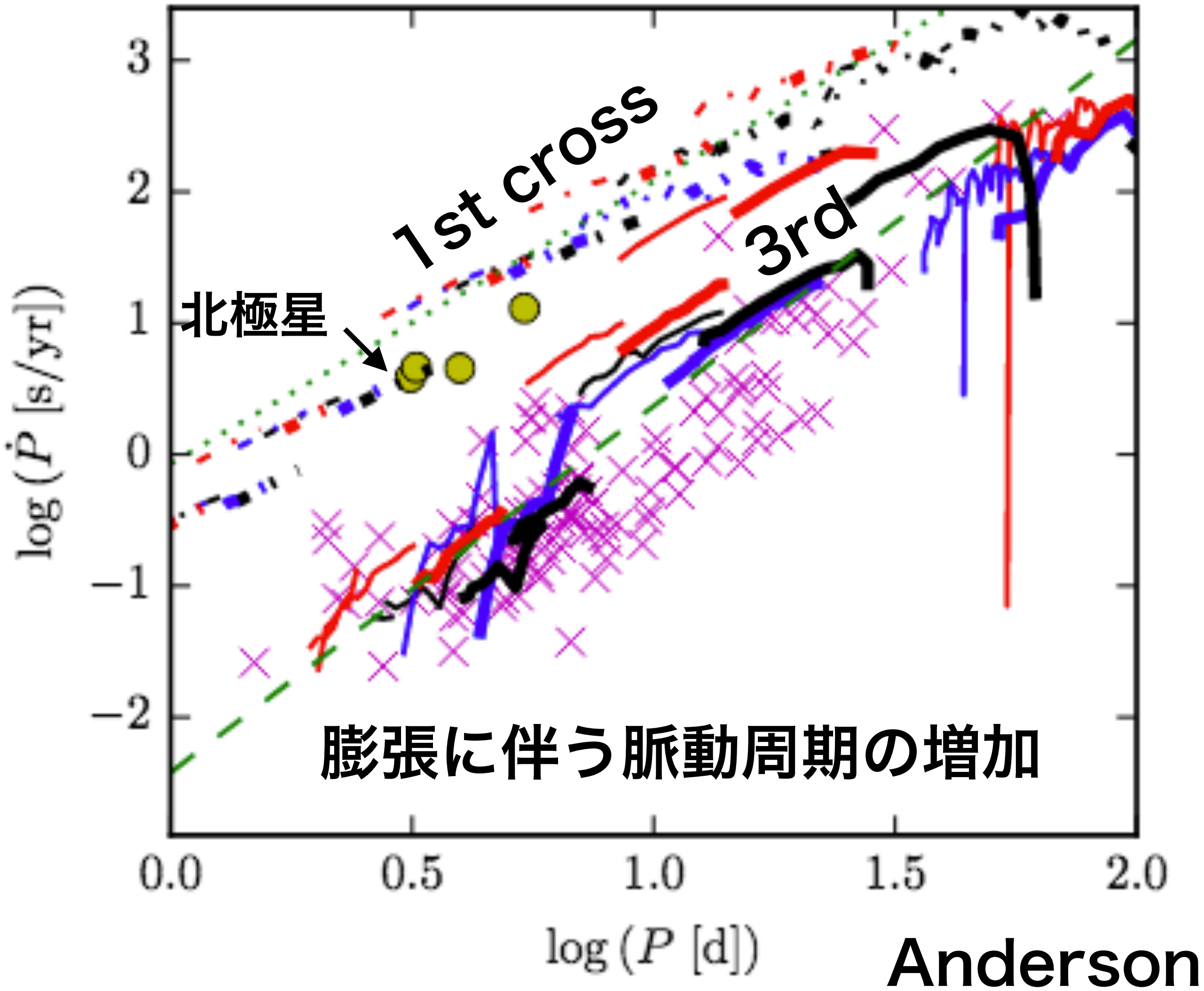
Period $\propto R^{1.5} M^{-0.5}$

$$\frac{d\ln P}{dt} \approx 1.5 \frac{d\ln R}{dt}$$

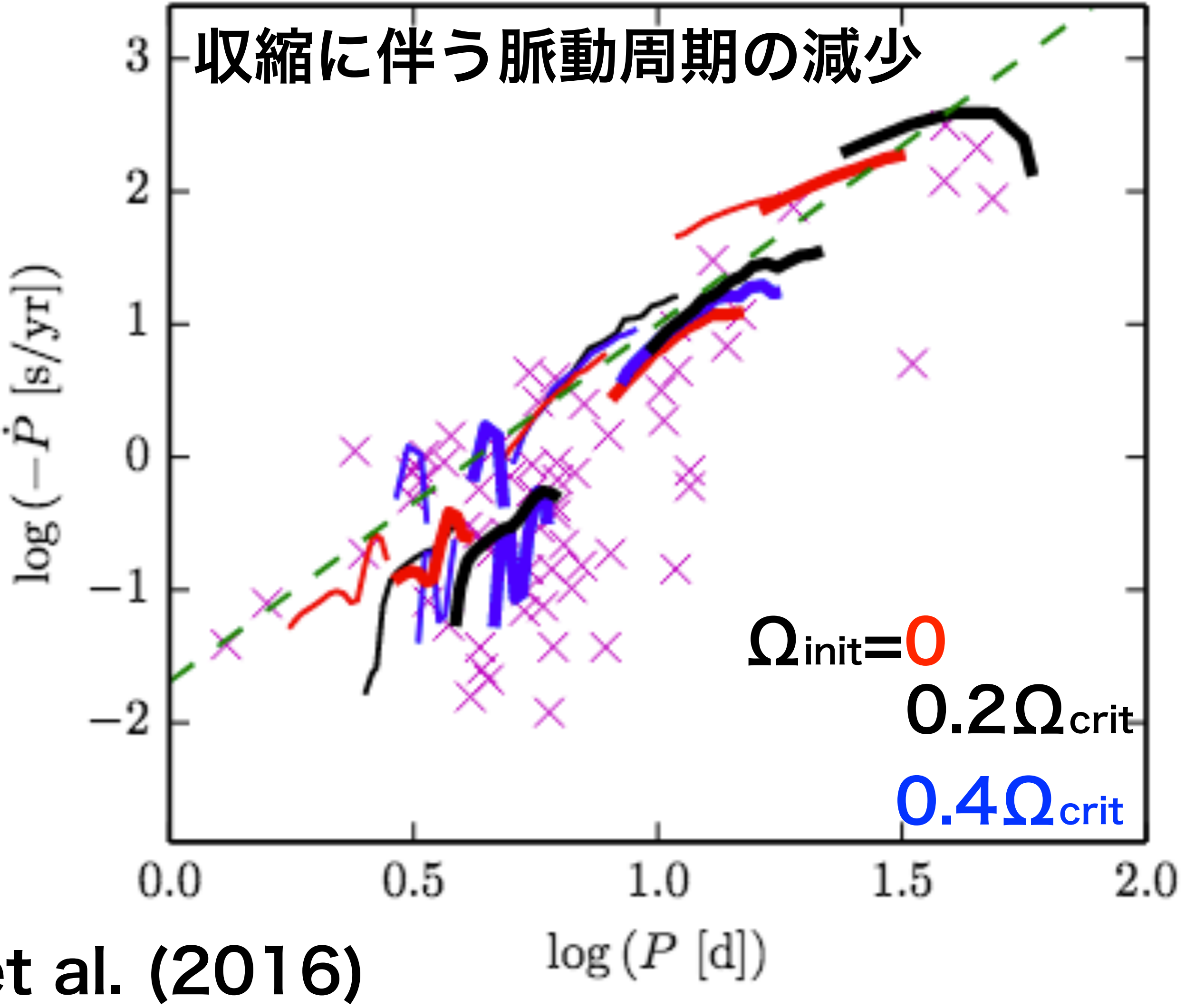




dP/dt >0; 1st & 3rd crossing



dP/dt < 0; 2nd crossing

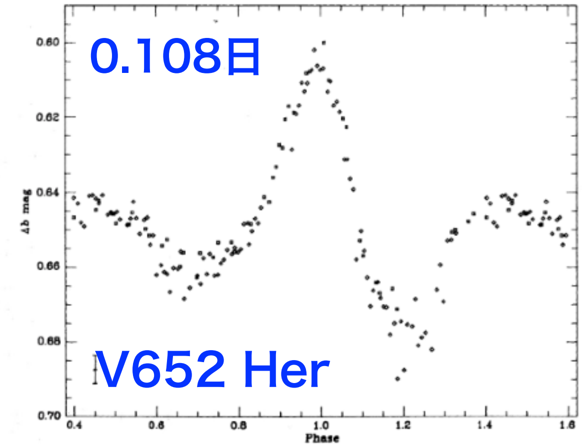


Anderson et al. (2016)

脈動変光星

2つの小質量(He)白色矮星
の合体で形成された
無水素の脈動星
V652 Her, BX Cir
(実視等級 10.5, 12.6等)

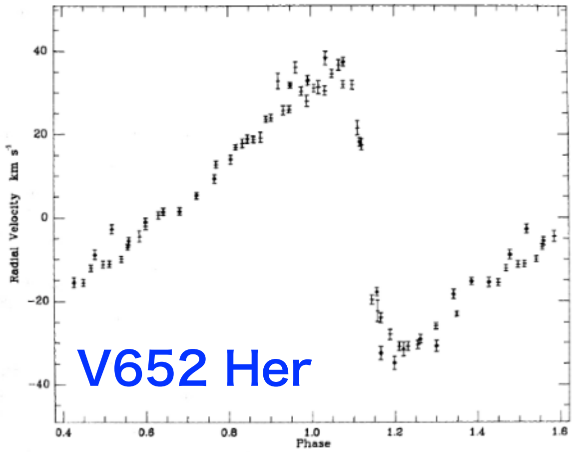
規則的光度曲線



0.108日

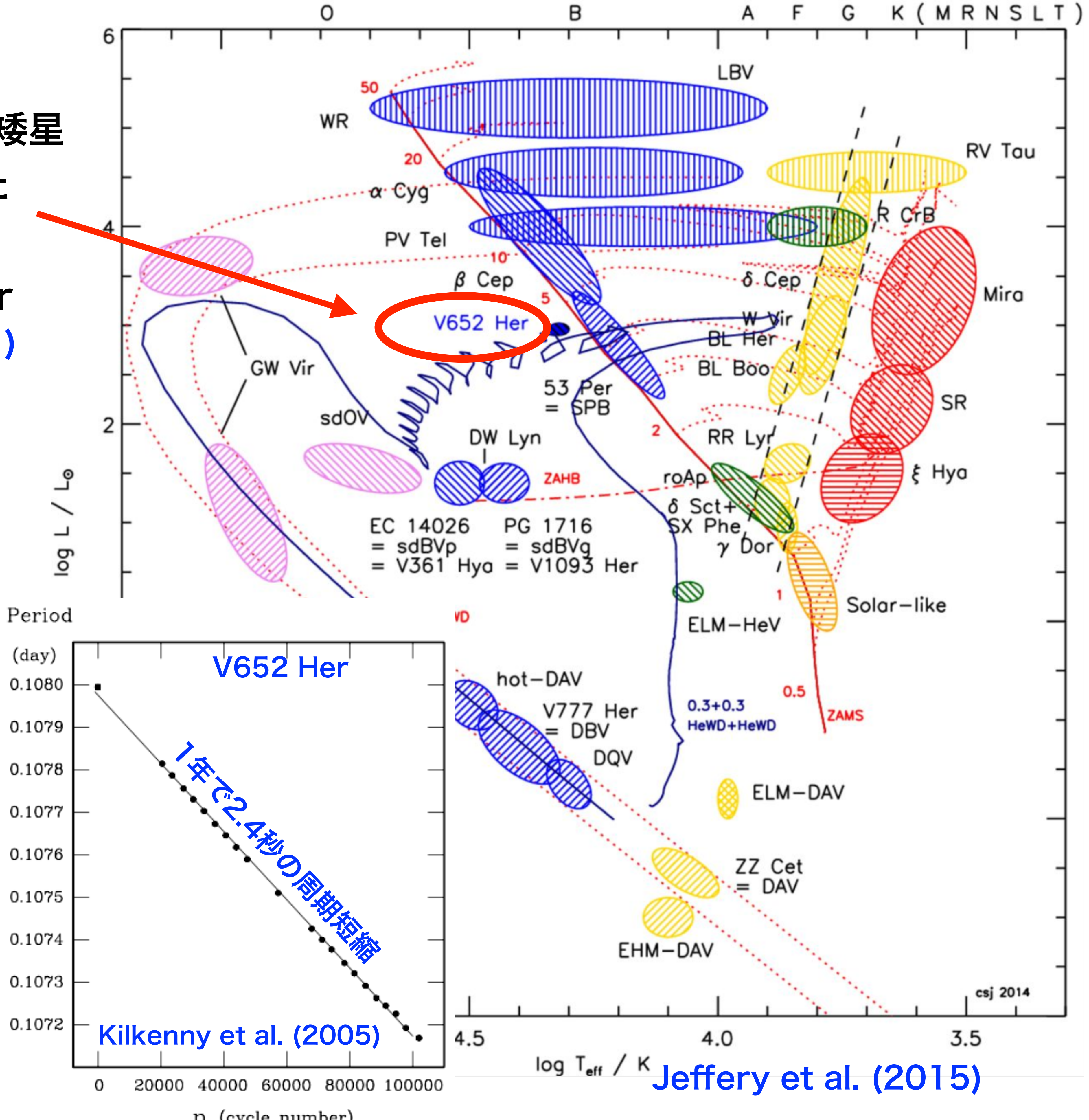
V652 Her

規則的表面速度変化



V652 Her

Jeffery & Hill(1999)



V652 Her

V652 Her

1年で2.4秒の周期短縮

Kilkenny et al. (2005)

Jeffery et al. (2015)

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

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

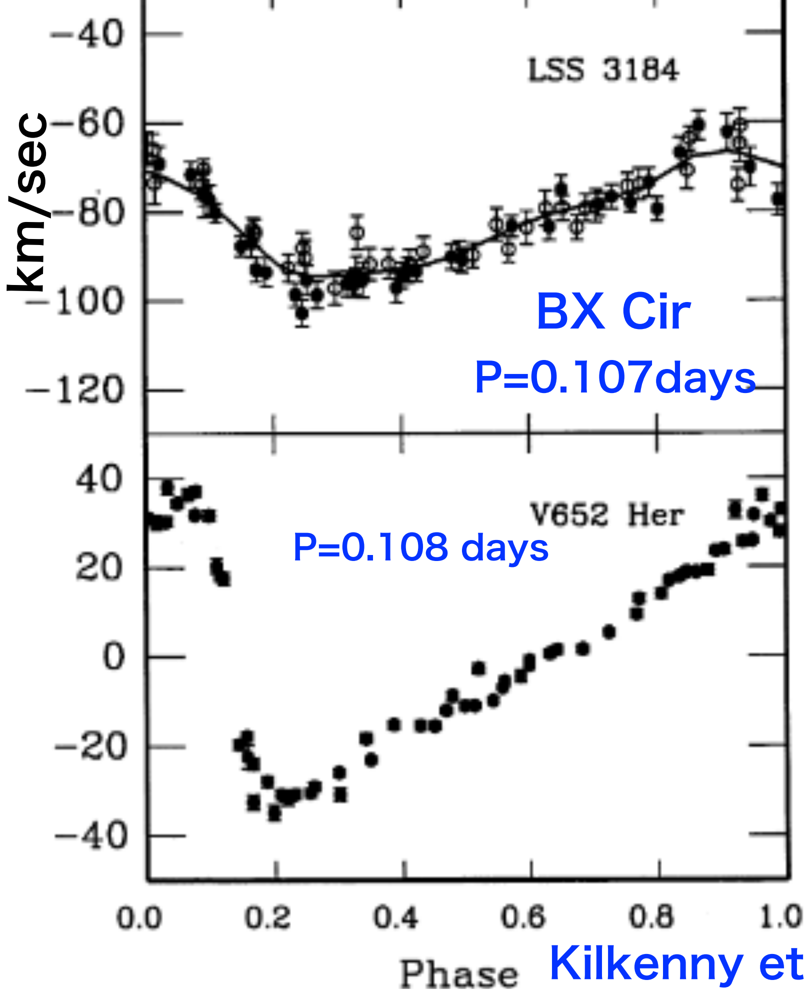
Accretion -> 外層加熱 -> 外層でHe flash発生

He flash が繰り返されながらその発生位置が中心へ

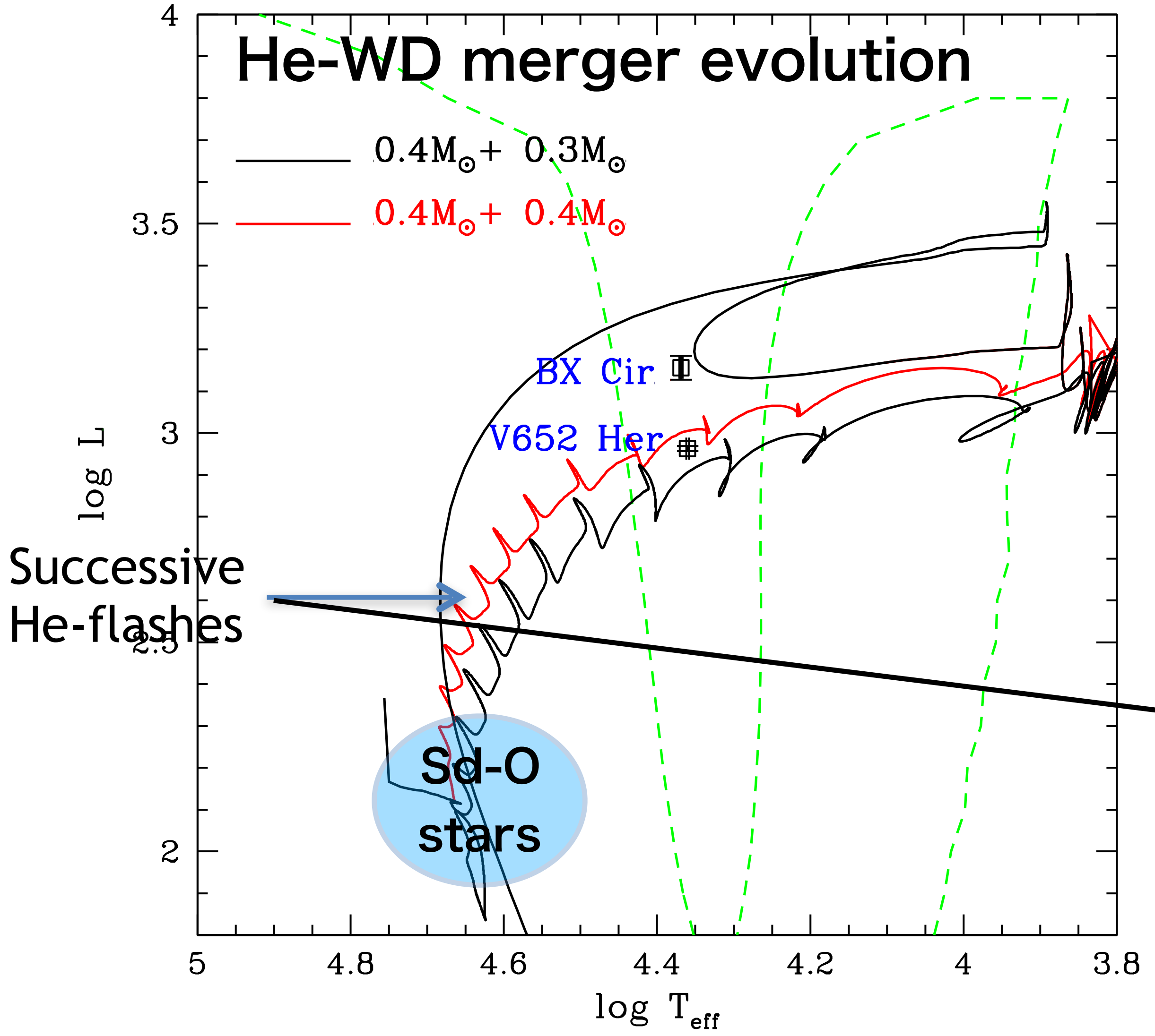
--> Helium ZAMS

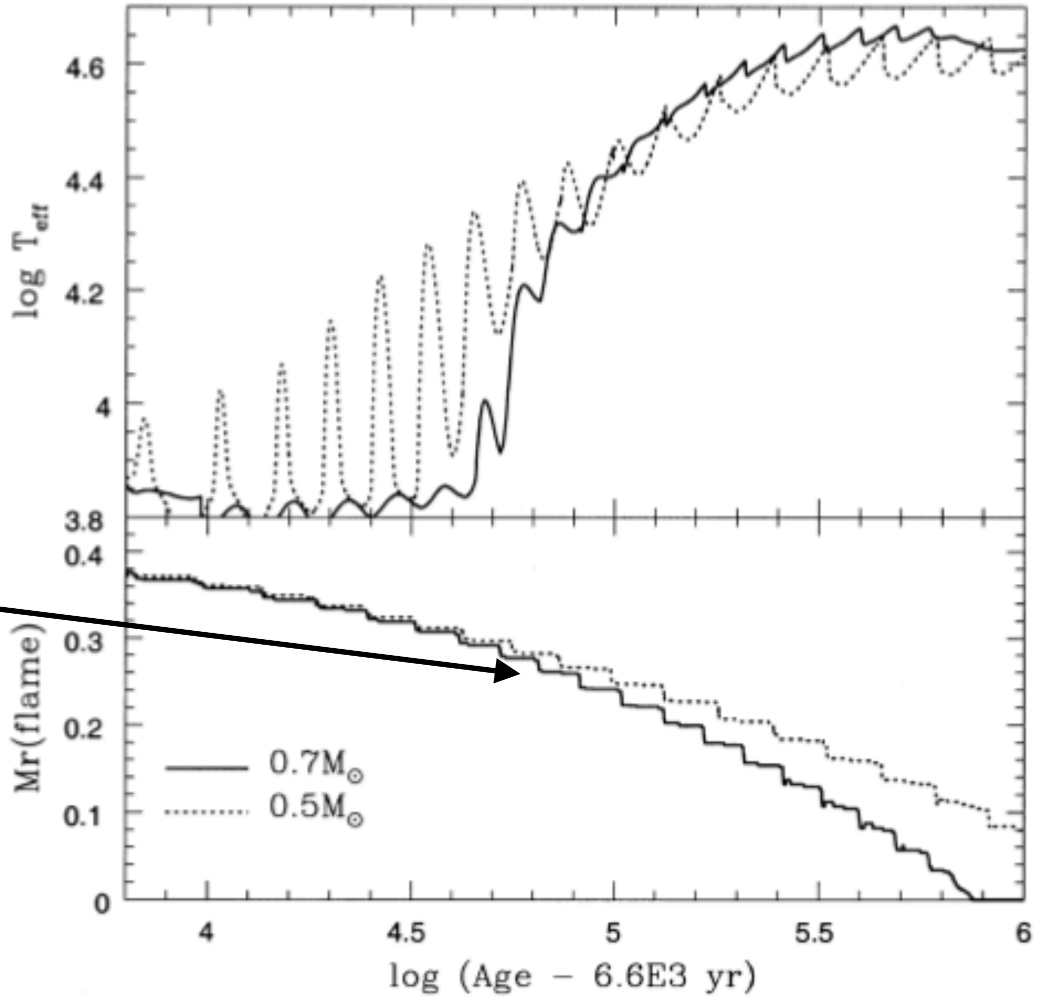
その進化経路の途中に２つのHe星脈動星が存在

$$M \sim 0.7 M_\odot$$

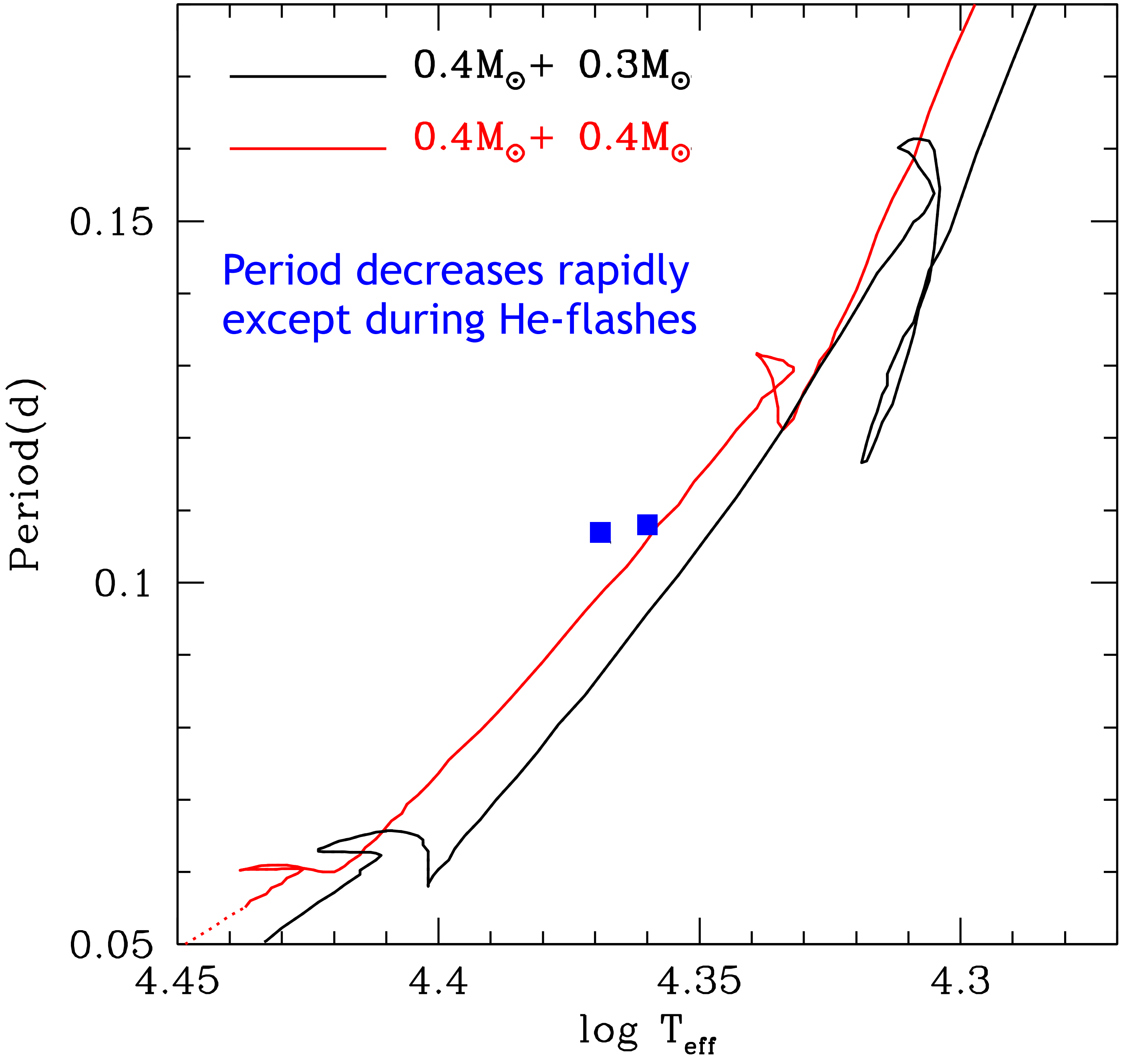


Kilkenny et al. (1999)

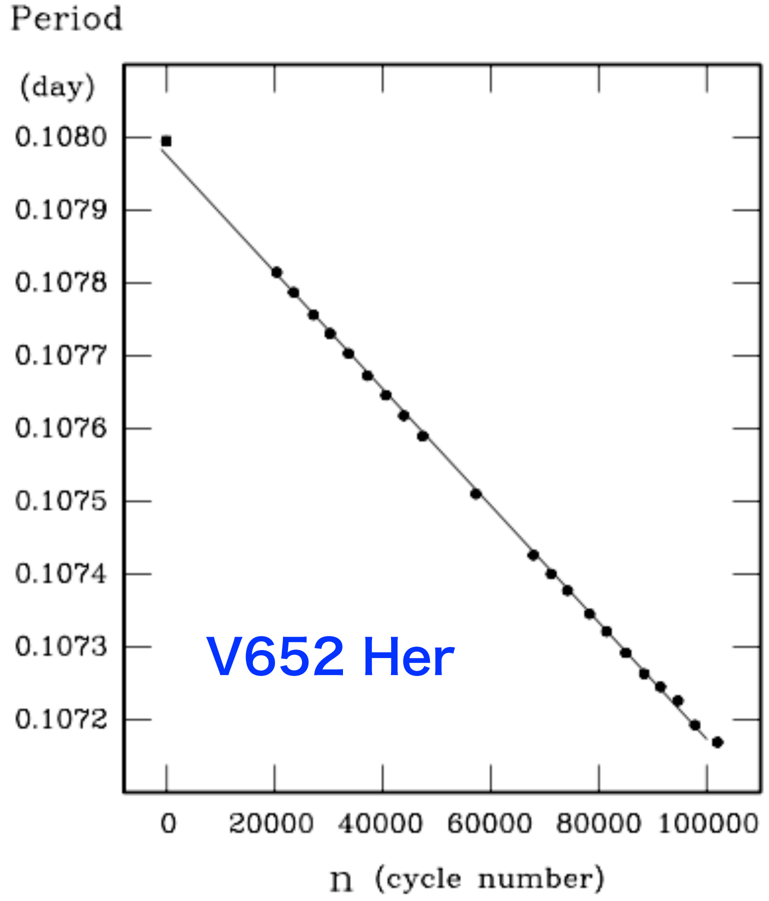




Pulsation period changes with evolution

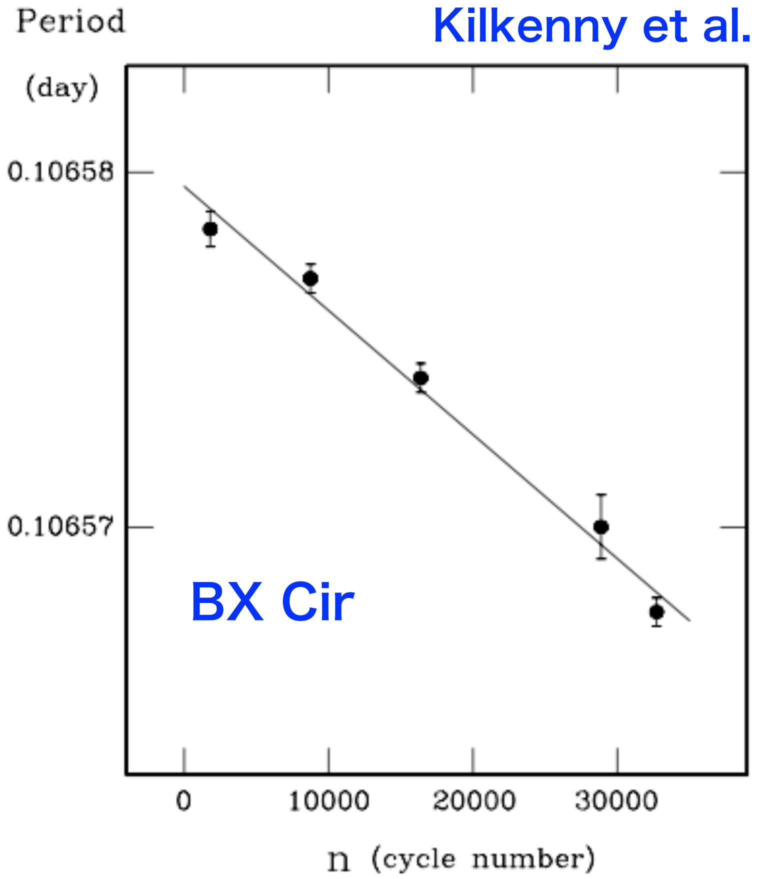


Period decreases rapidly except during He-flashes



V652 Her

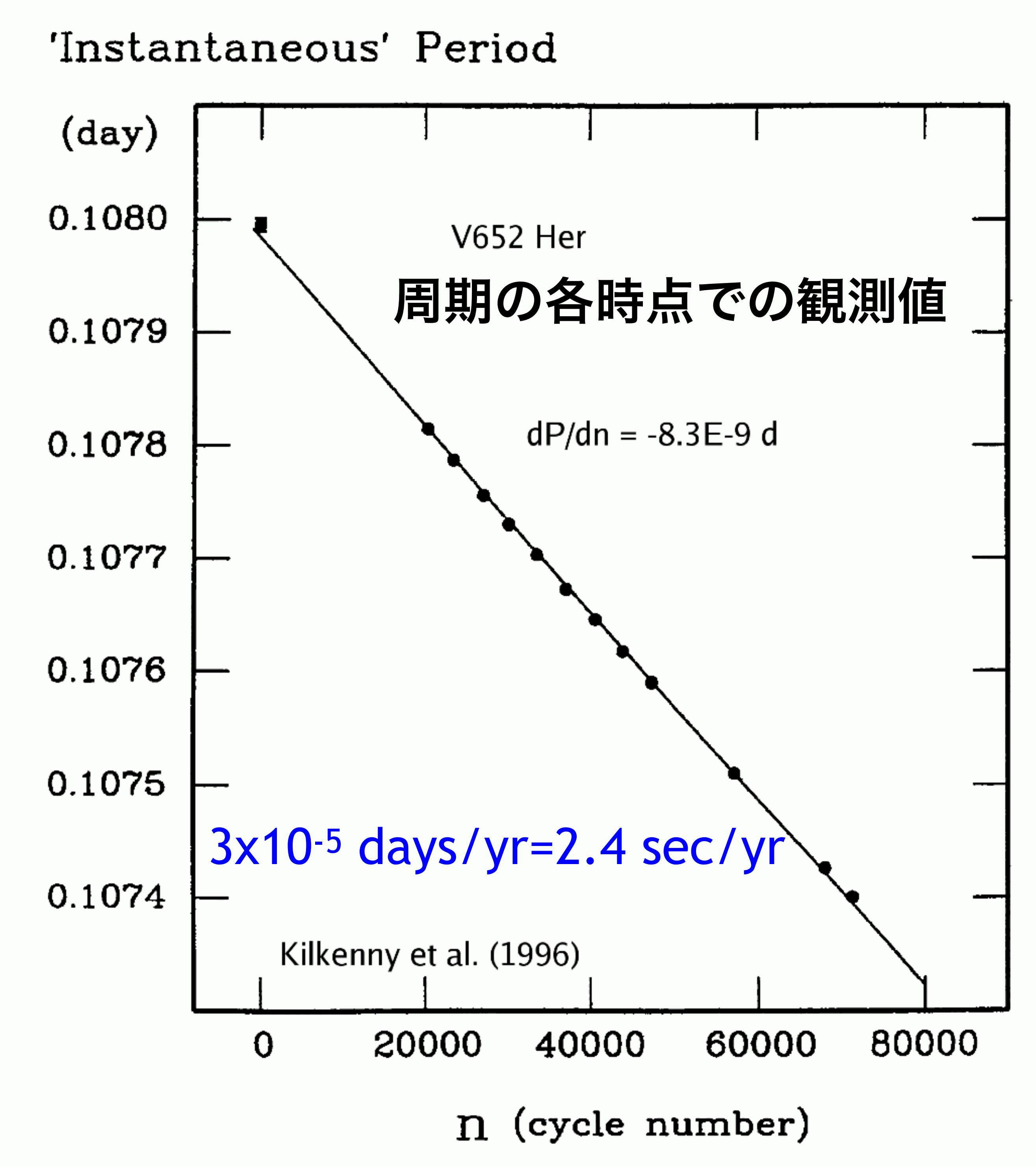
Kilkenny et al. (2005)



BX Cir

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

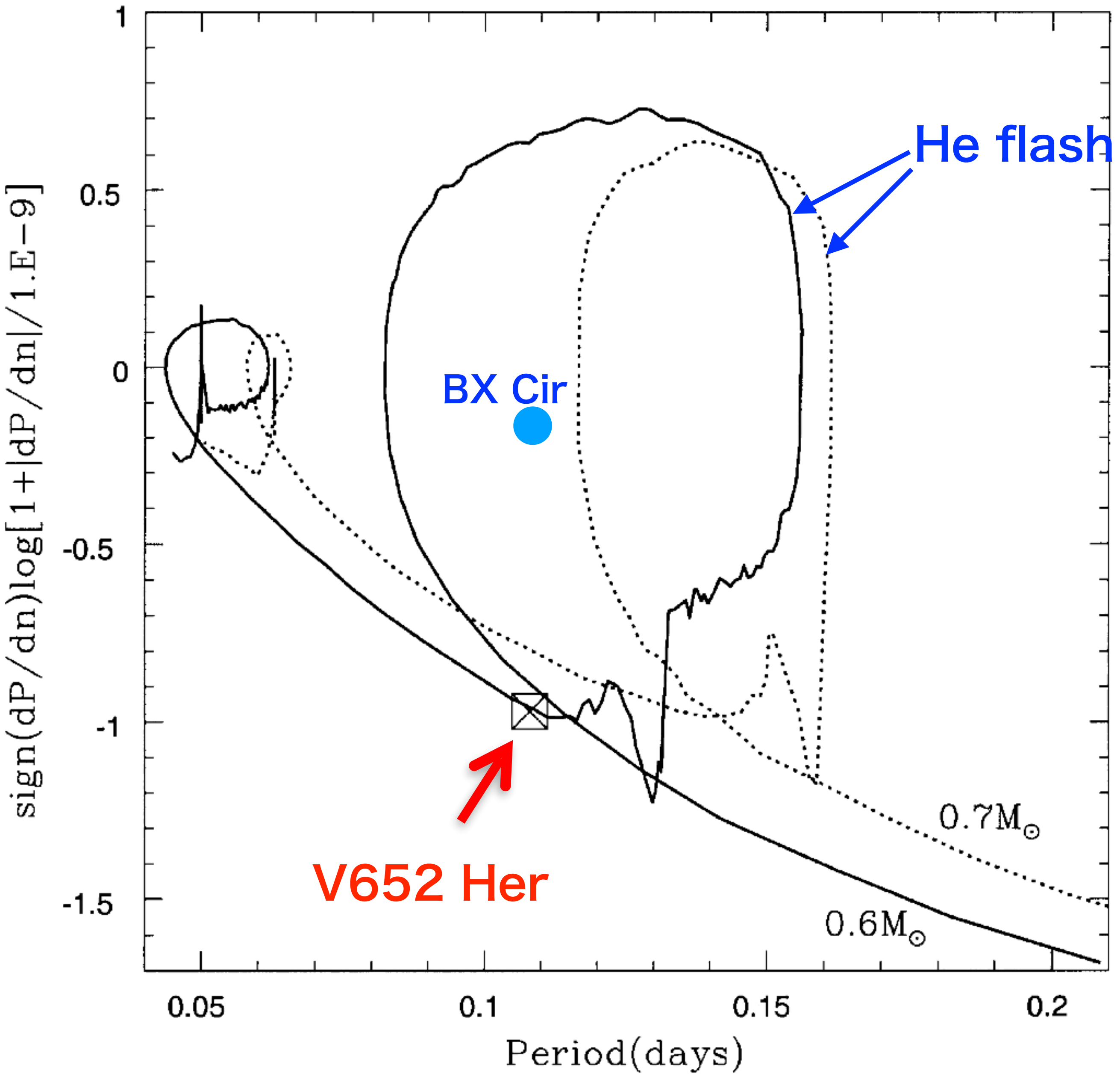
Period decrease rate of V652 Her agrees with a He-WD merger model
---> WD merger が実際に起こった証拠



周期の各時点での観測値

3×10^{-5} days/yr=2.4 sec/yr

Kilkenny et al. (1996)



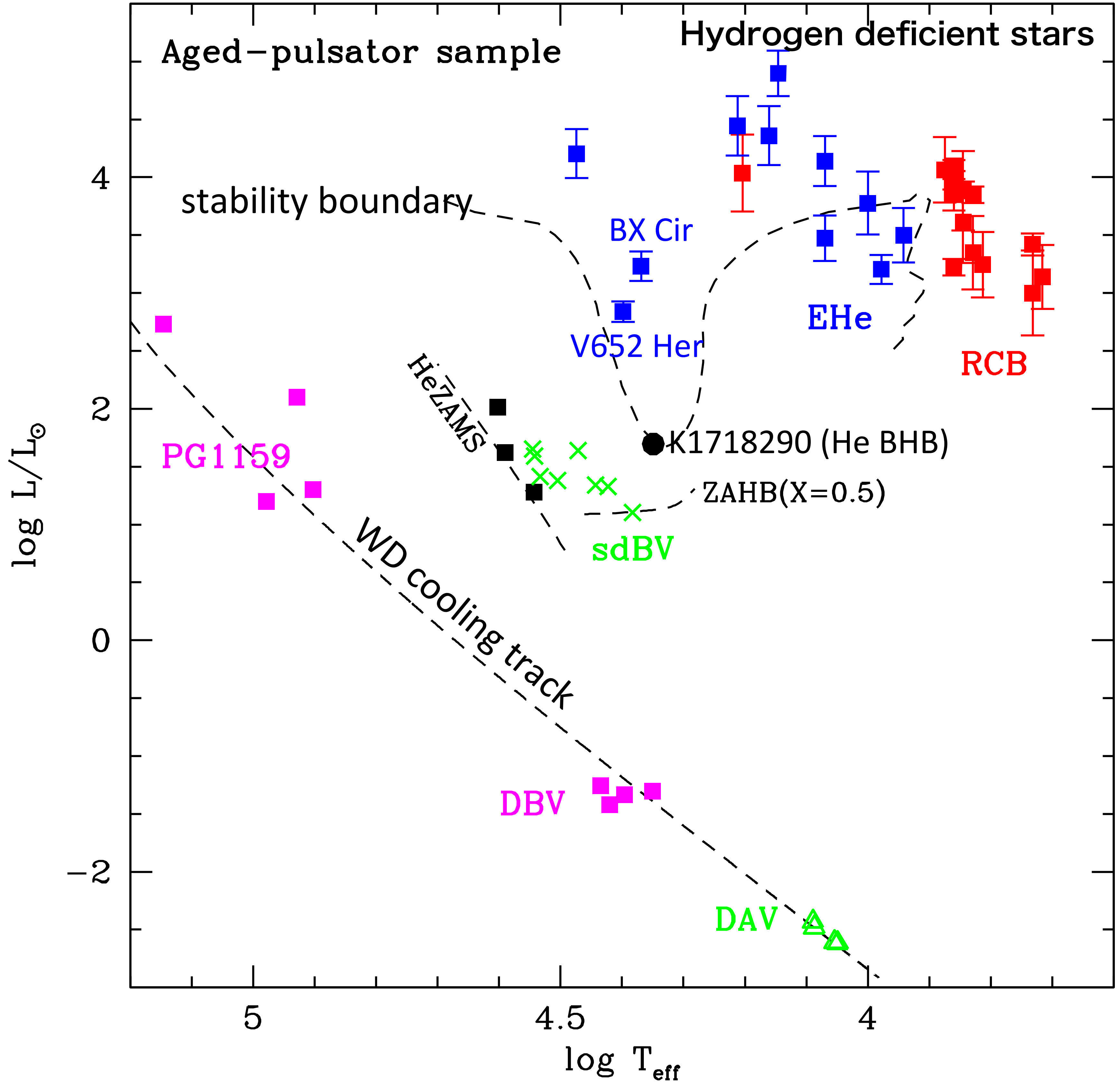
He flash

BX Cir

V652 Her

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).

Saio & Jeffery (2000)



Strange-mode instability

$$\frac{\partial \Delta P}{\partial m} \approx -\frac{\kappa_\rho \kappa F}{c}\frac{\Delta \rho}{\rho}$$

Violent excitation

---

kappa-mechanism excitation

$$\frac{\Delta P}{P} \approx \Gamma_1 \frac{\Delta \rho}{\rho}$$

Slow excitation

1. 恒星振動(脈動) の 基本的性質
2. 恒星振動から知る恒星自転速度
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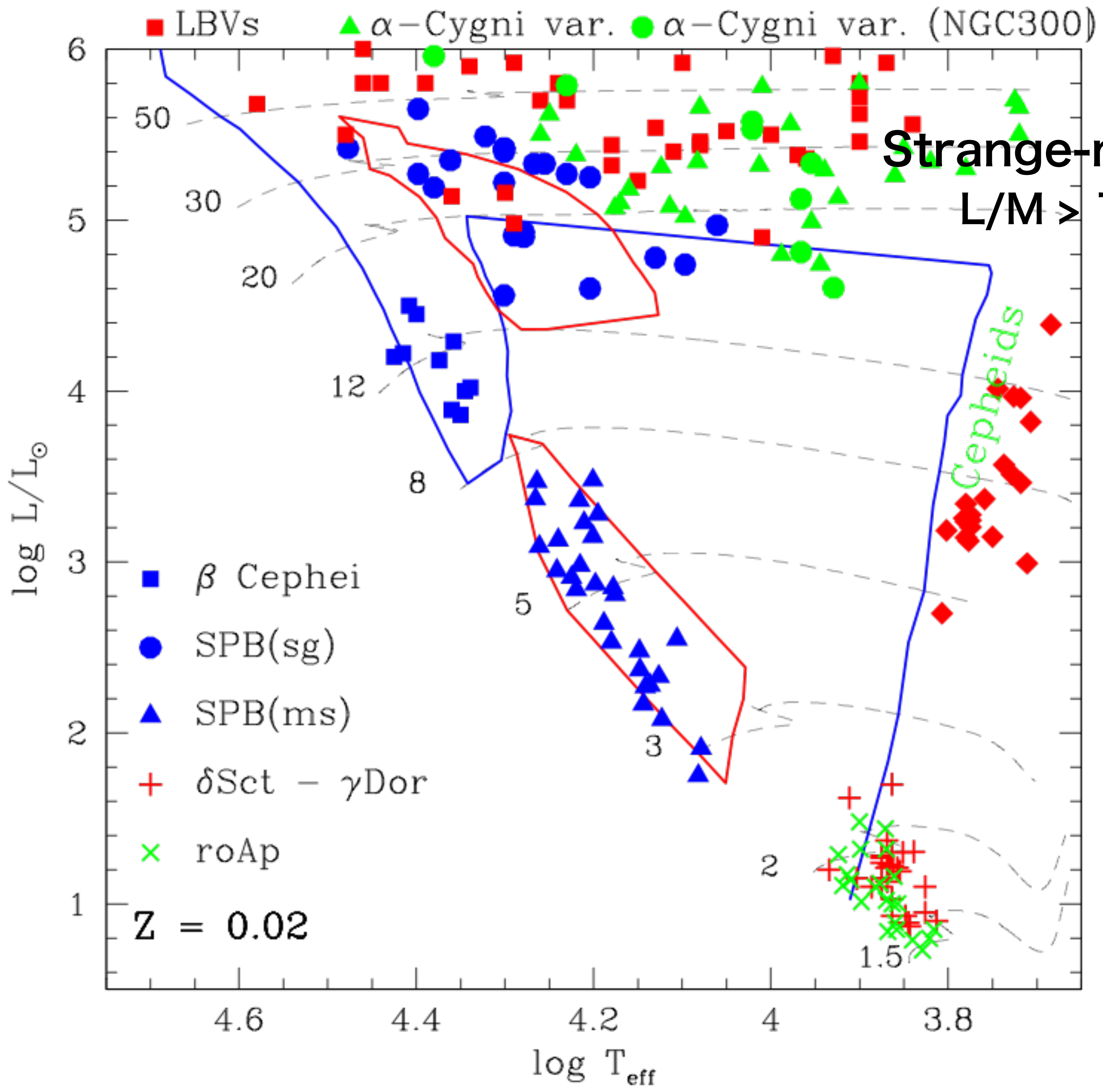
5. 進化の進んだ大質量星の脈動
6. Betelgeuse (α Ori) の脈動

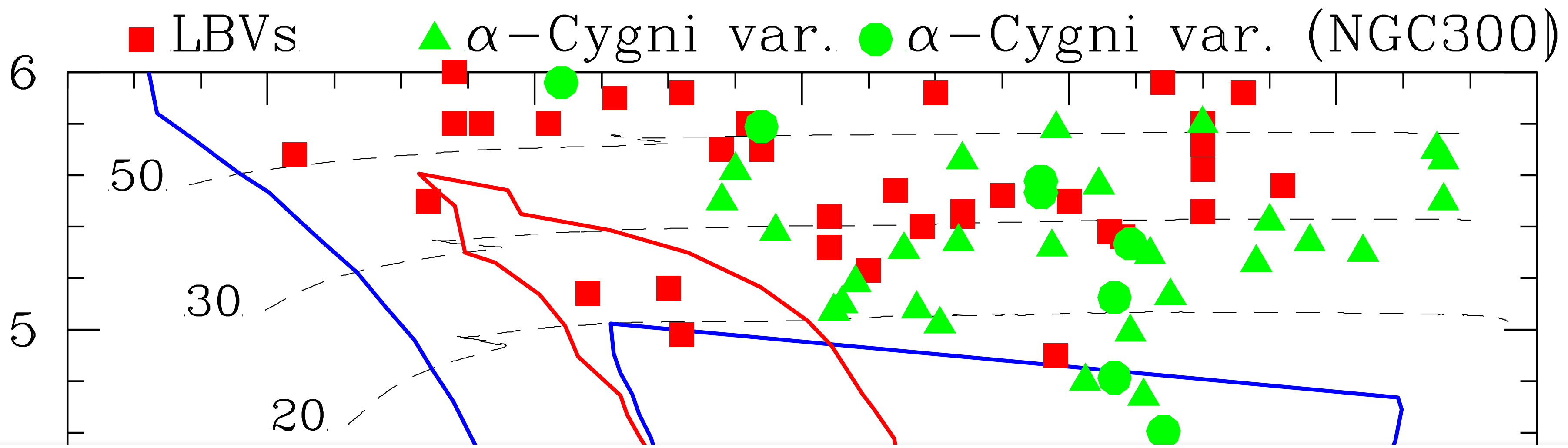
B-A type pulsators and instability boundaries

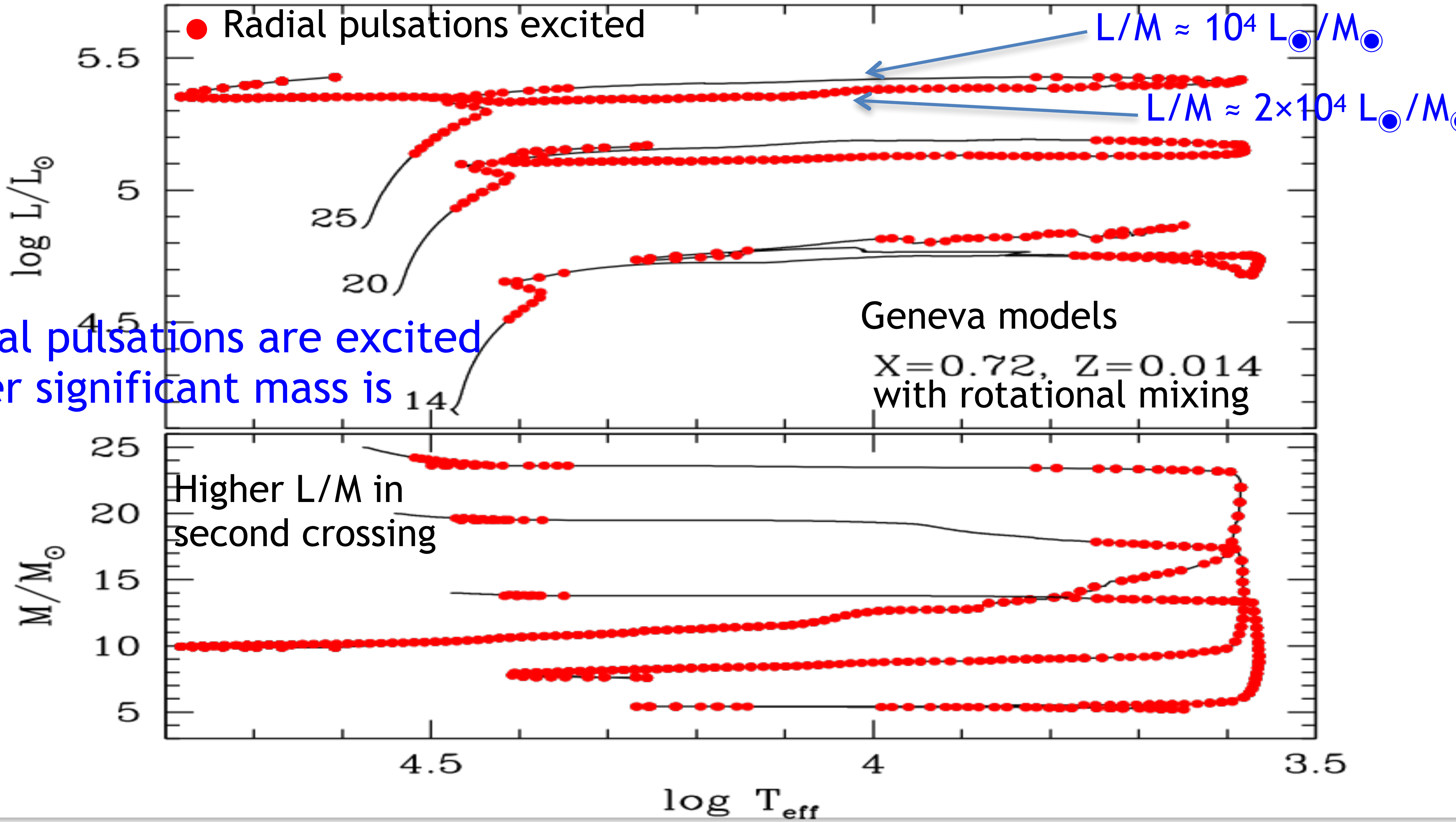


Strange-mode instability

L/M > 1e4 (solar units)

α Cygni variables





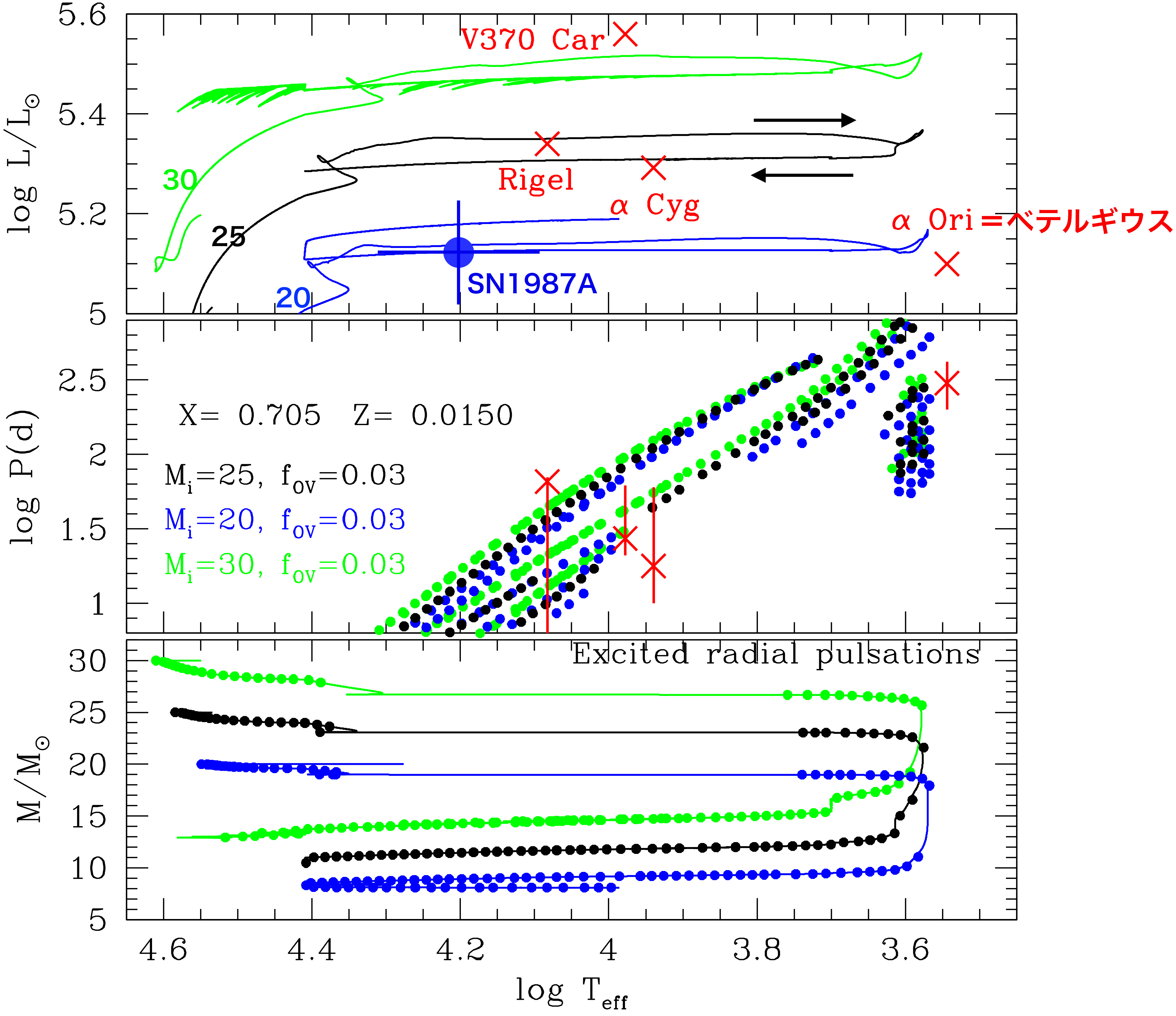
L/M ≈ 10^4 L$_\odot$/M$_\odot$

L/M ≈ 2×10^4 L$_\odot$/M$_\odot$

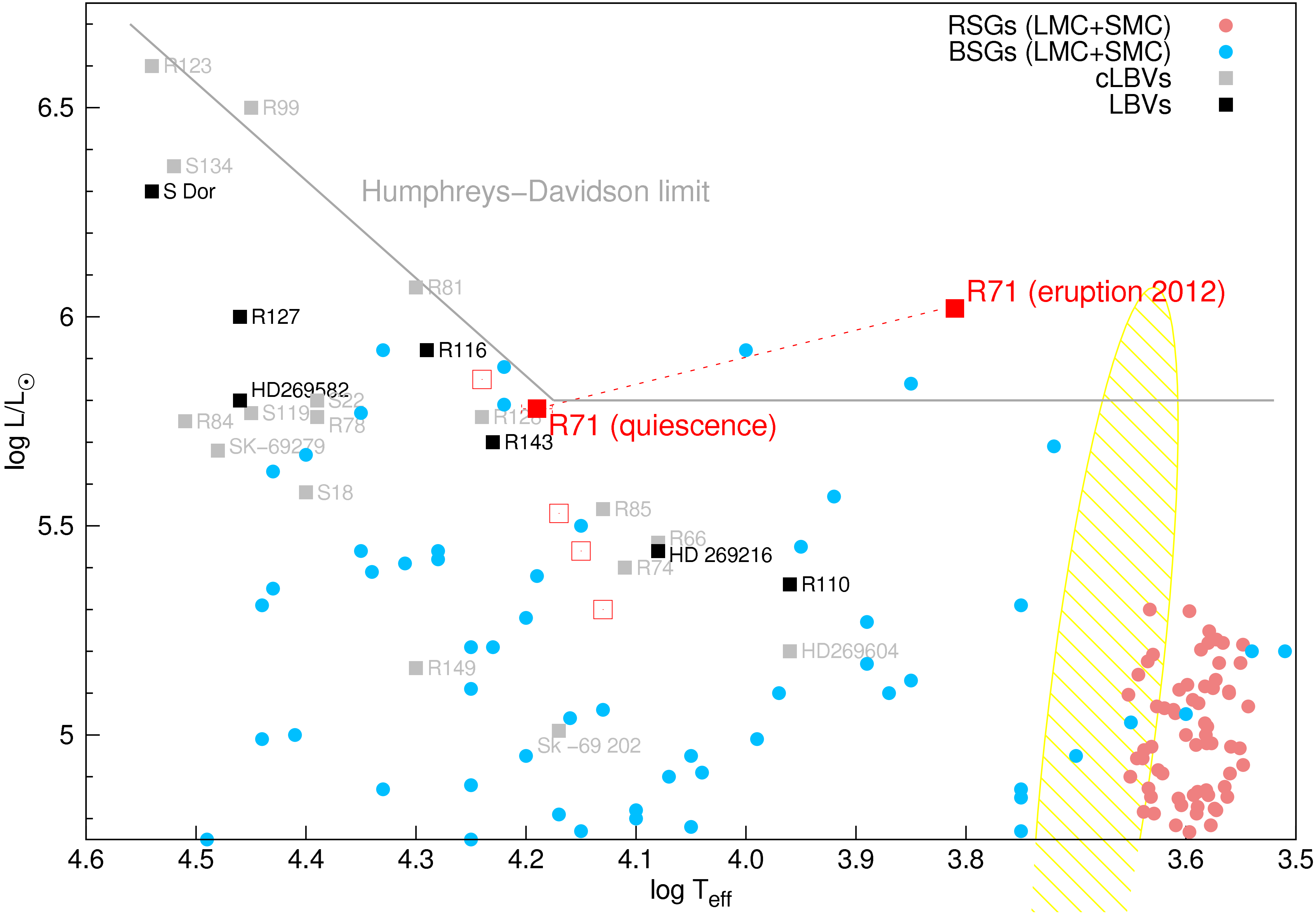
Radial pulsations are excited after significant mass is lost

Higher L/M in second crossing

リゲル，デネブは赤色超巨星の時代に十数太陽質量を放出した後
青色超巨星に戻ってきた

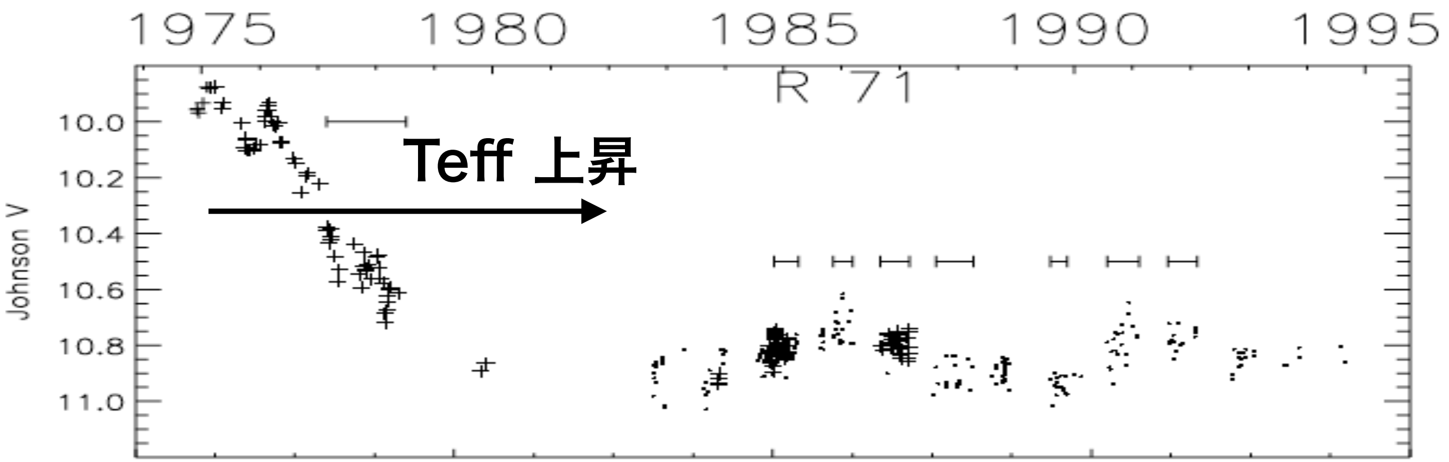


■ LBVs (Luminous Blue Variables)



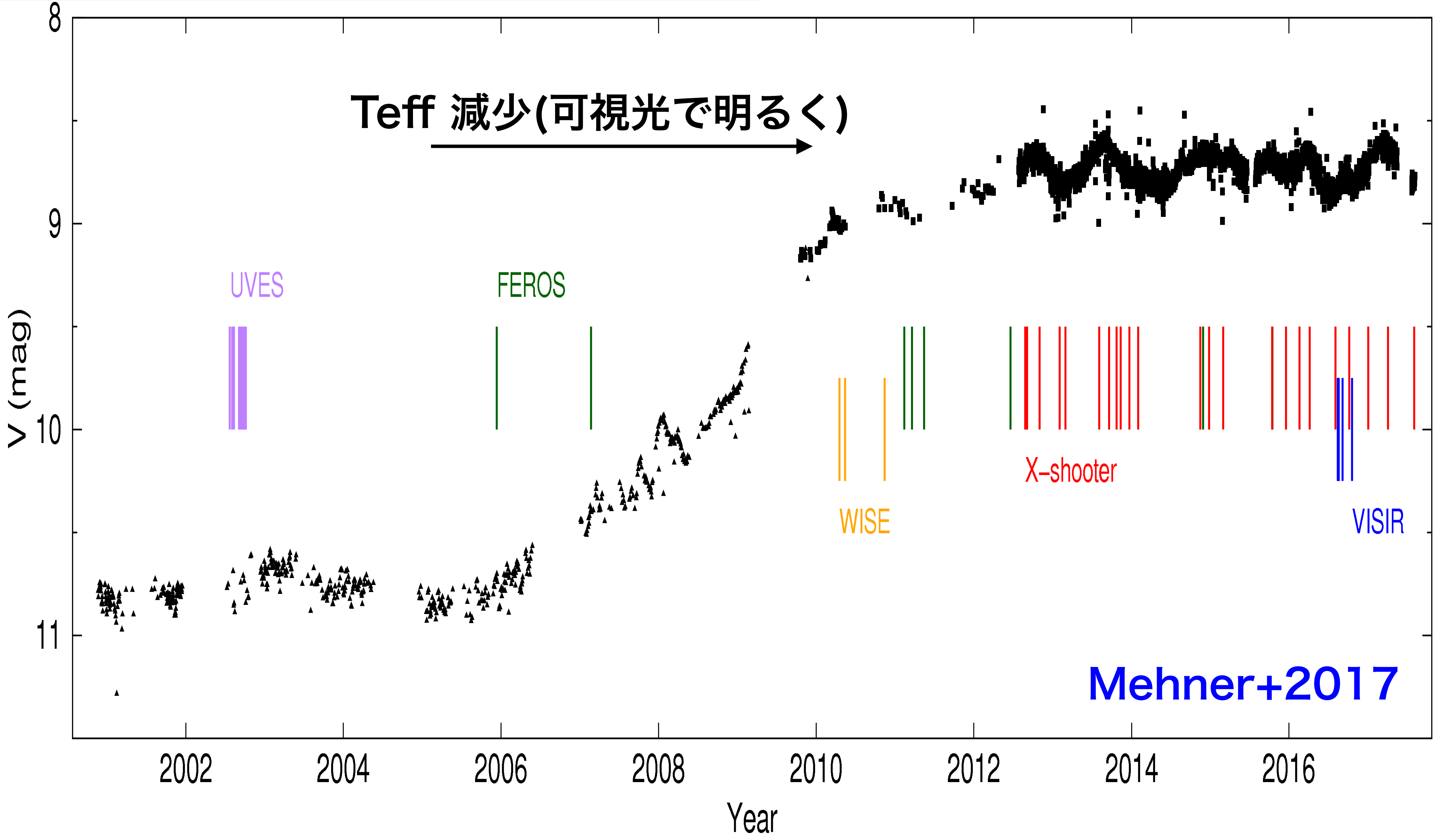
Mehner+2017

LBV (Luminous Blue Variable) R71 in LMC



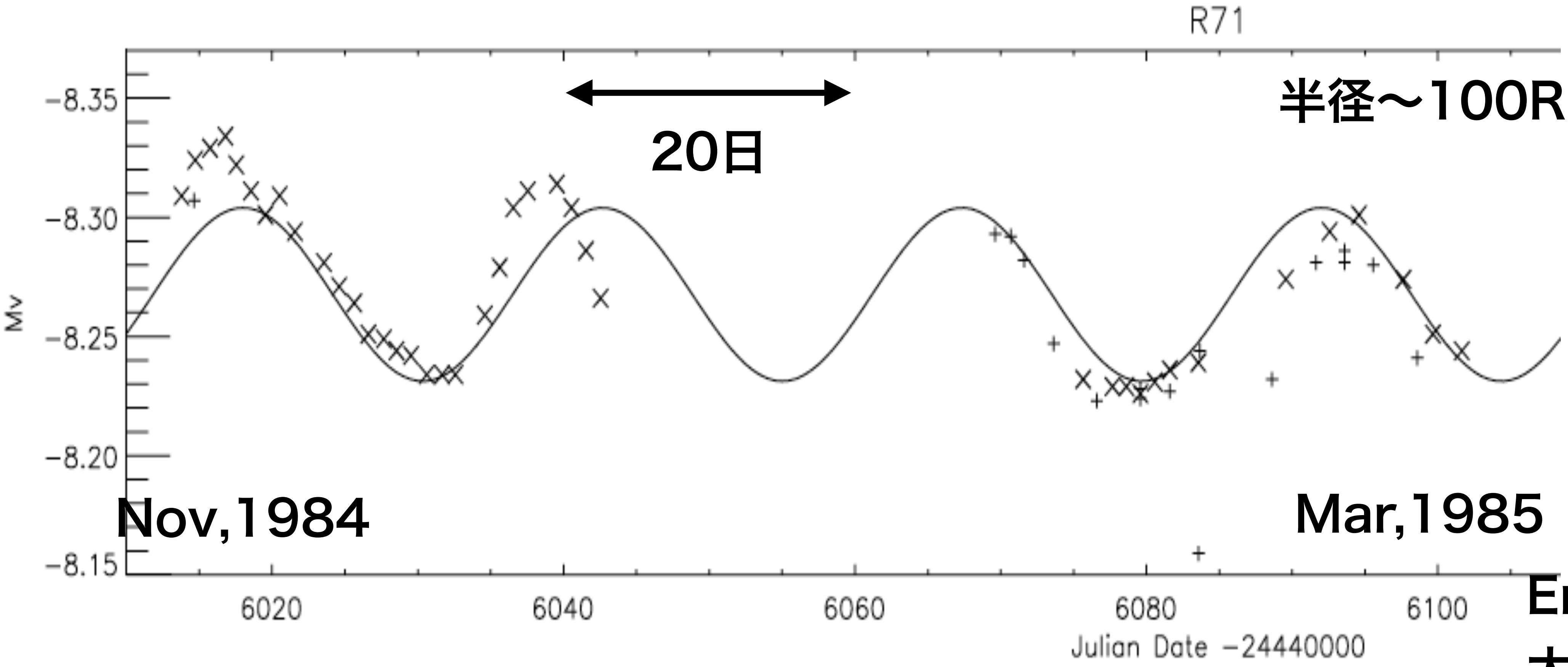
Teff 上昇

Lamers+1998



Teff 減少(可視光で明るく)

Mehner+2017



20日

半径～100Rsun

Nov,1984

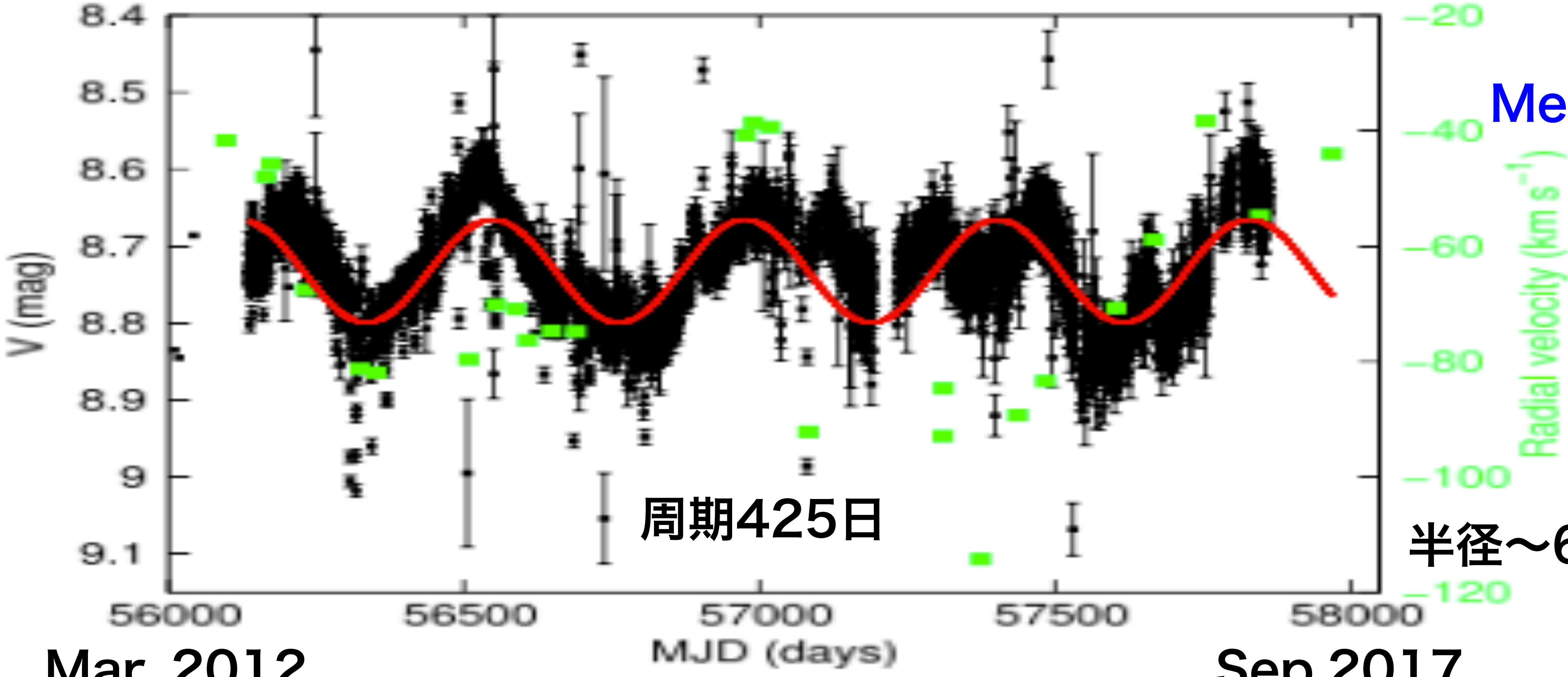
Mar,1985

Eruption 前
(high Teff)

Lamers+1998

Eruption で半径が
大きくなるにつれて
脈動周期が伸びる

Pulsations of the LBV R71 in LMC



周期425日

Mar, 2012

Sep,2017

Mehner+2017

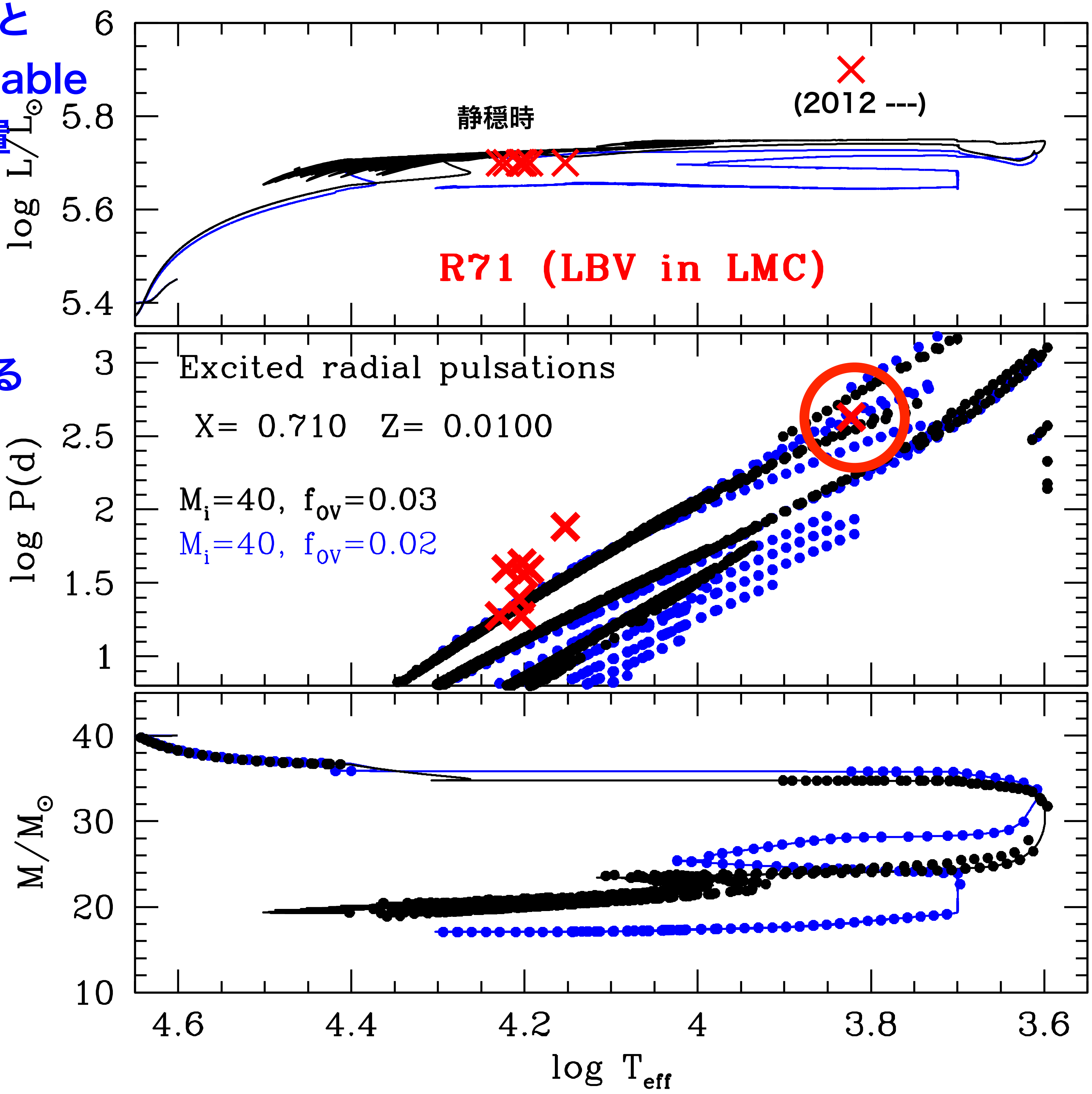
Eruption 中
(low Teff)

半径～600 Rsun

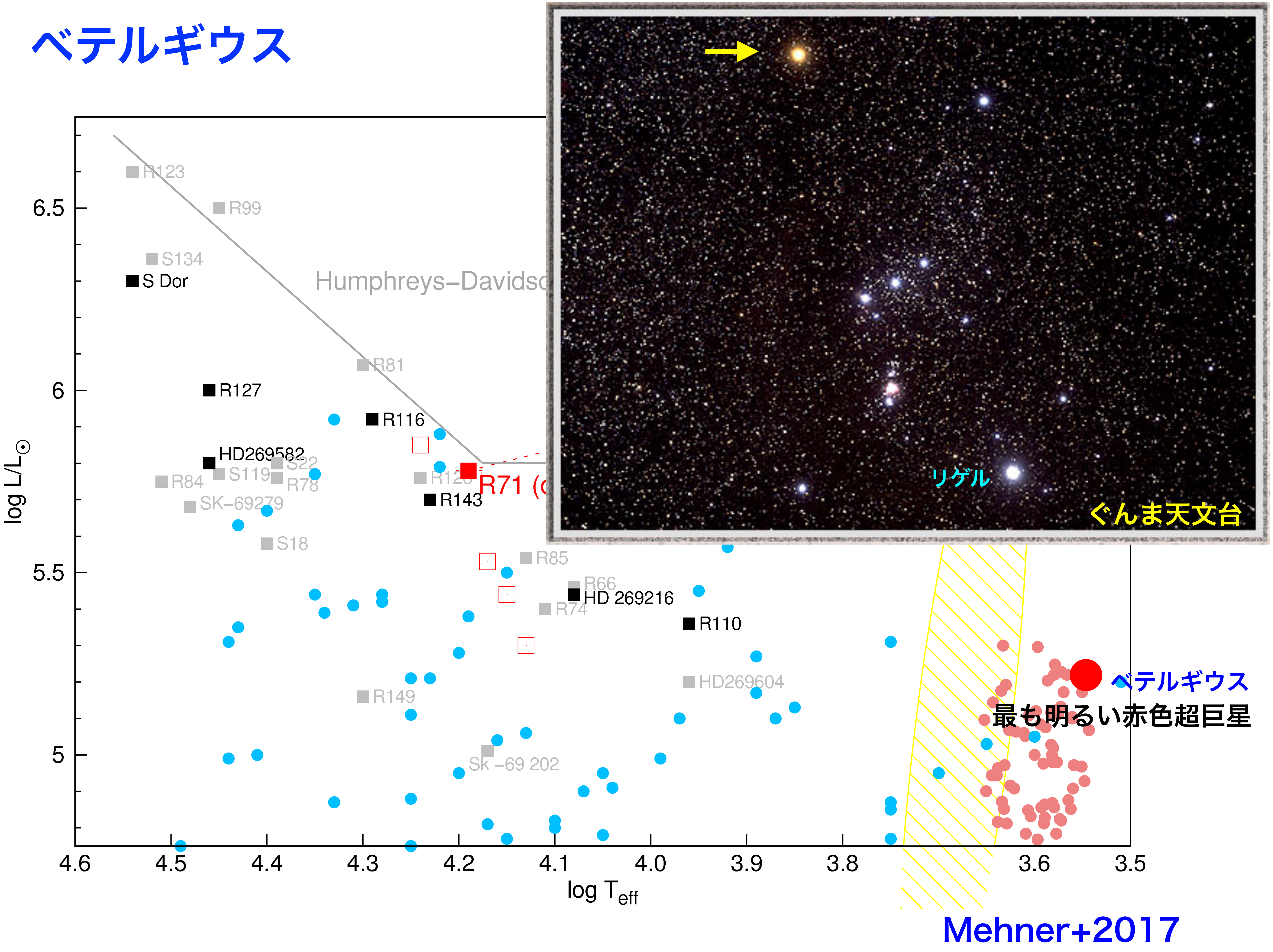
初期質量=40Msunの
Model の進化経路と
Luminous Blue variable
(LBV) R71の位置

進化の途中で予想される
脈動周期 - Teff
関係とR71の
脈動周期

進化途中での
質量放出による
質量変化
(質量が十分減少
すると脈動が起こる)



ベテルギウス

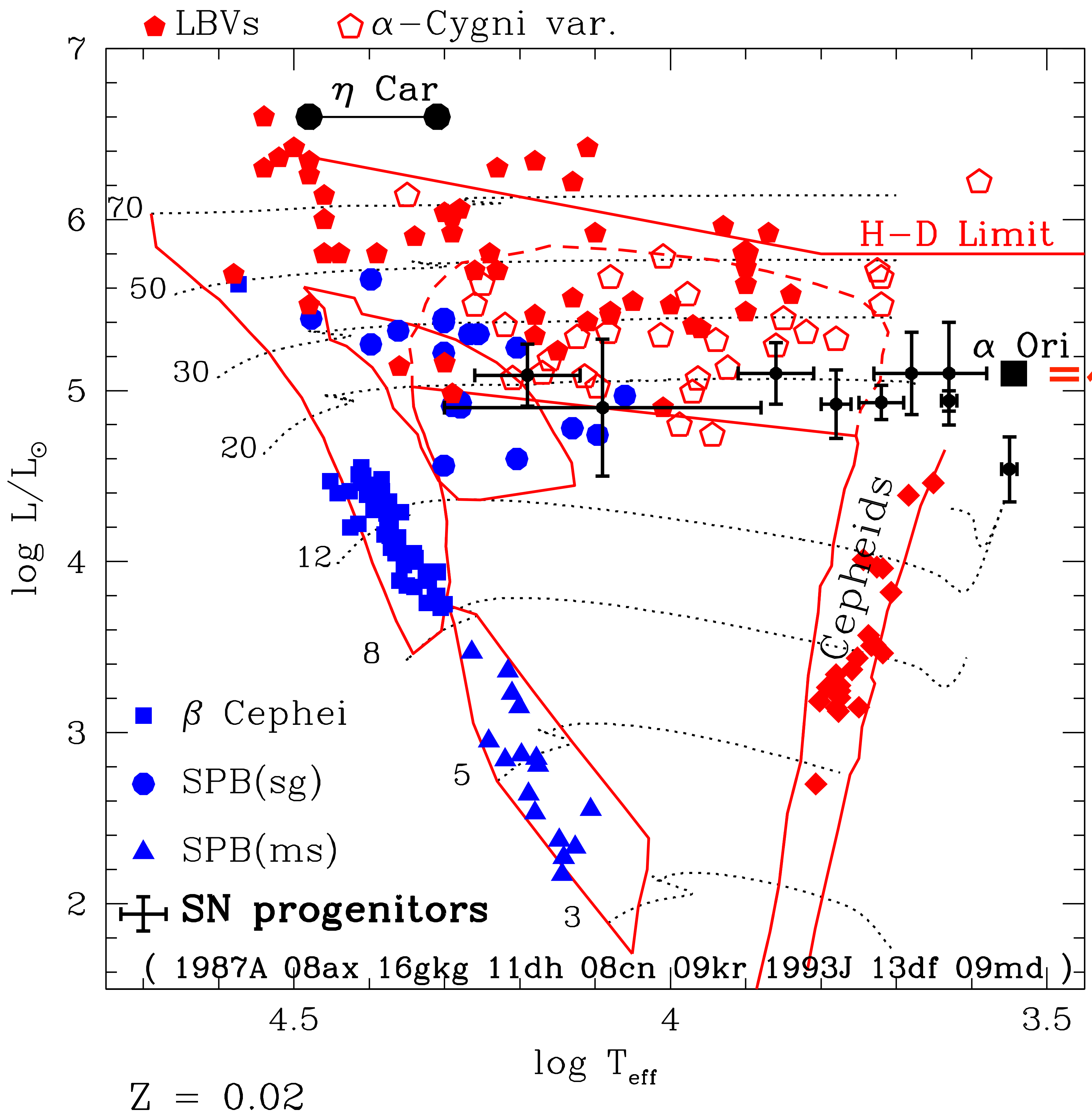


ベテルギウス

最も明るい赤色超巨星

Mehner+2017

Betelgeuse, some SN progenitors , & 大中質量脈動星



=ベテルギウス

パラメータが知られている
ほとんどの超新星親星
と同程度のLuminosity

--> Betelgeuse が将来
(Black hole ではなく)
超新星となることは確実

Betelgeuse (αOri)

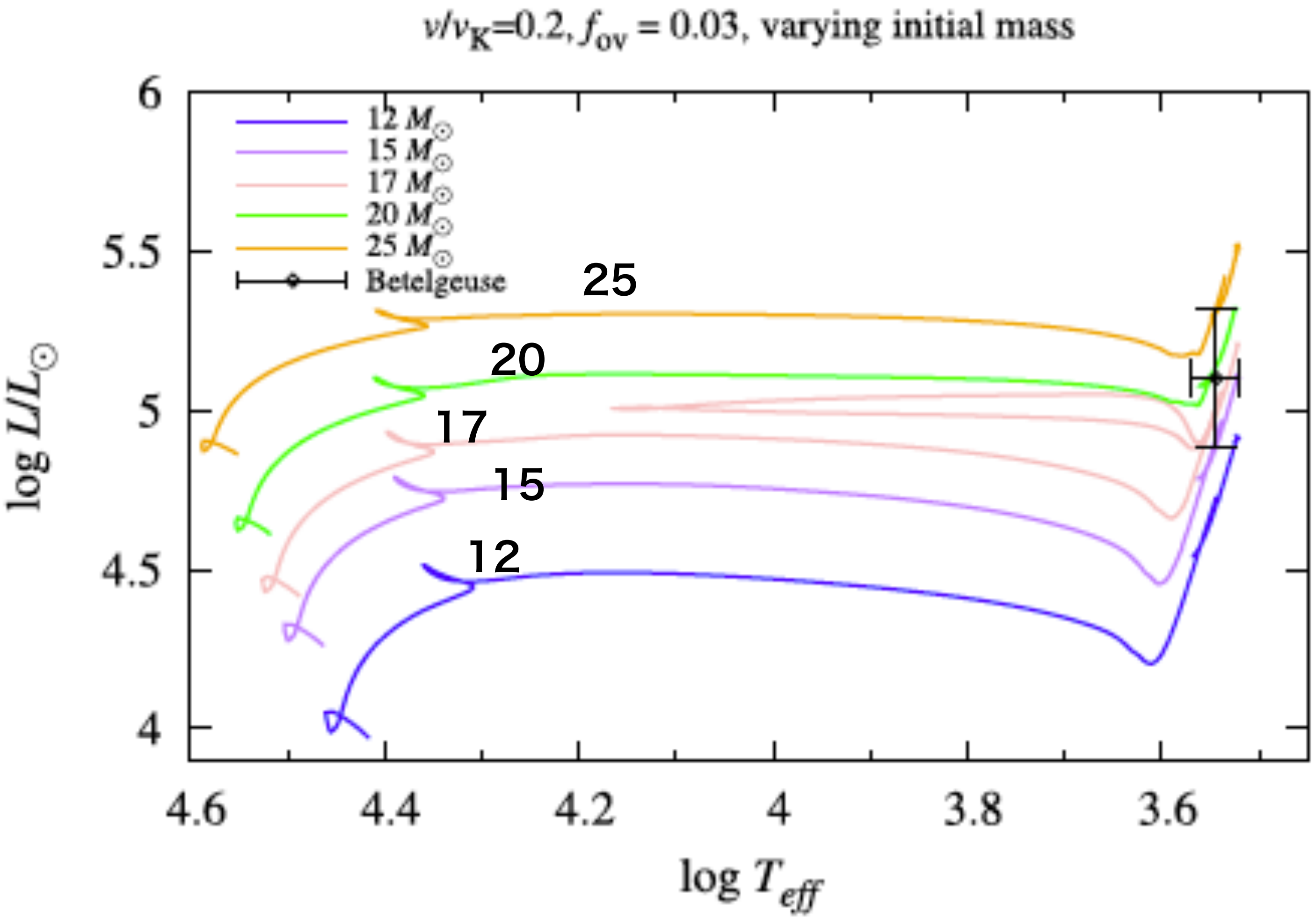
V= 0.42, R= -1.17, I= -2.45 mag, SpType M1-2 Iab-a,

距離：190 pc (620光年) (LMC 約16万光年の0.004倍)

Teff = 3500±200 K, lg(Teff) = 3.544 +/- 0.025

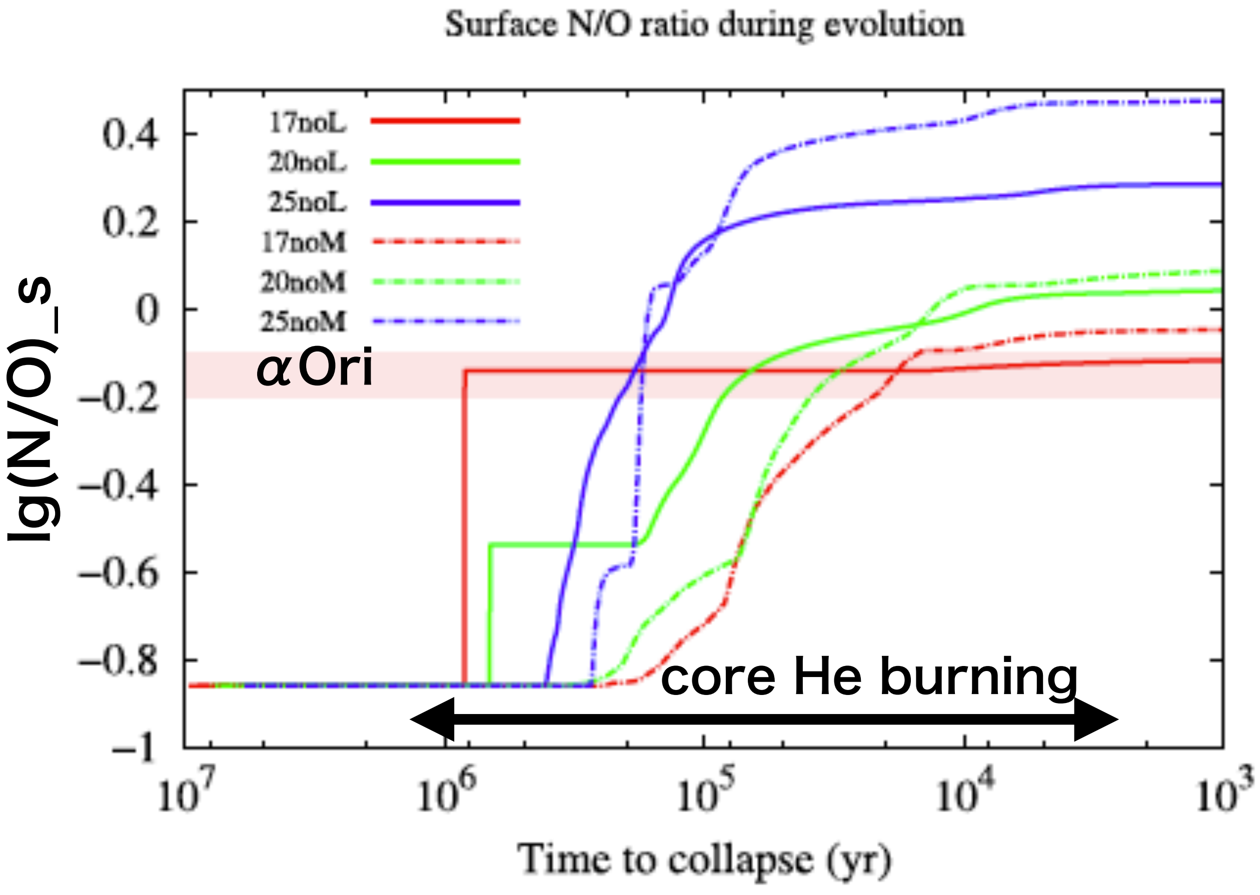
lg L/L⊙ = 5.1±0.22 (Dolan et al. 2016); 5.22 ± 0.16 (Harper et al. 2017)

表面のC,N,O 組成比：lg(N/C) = 0.19 pm 0.25 & lg(N/O)= -0.2 pm 0.36

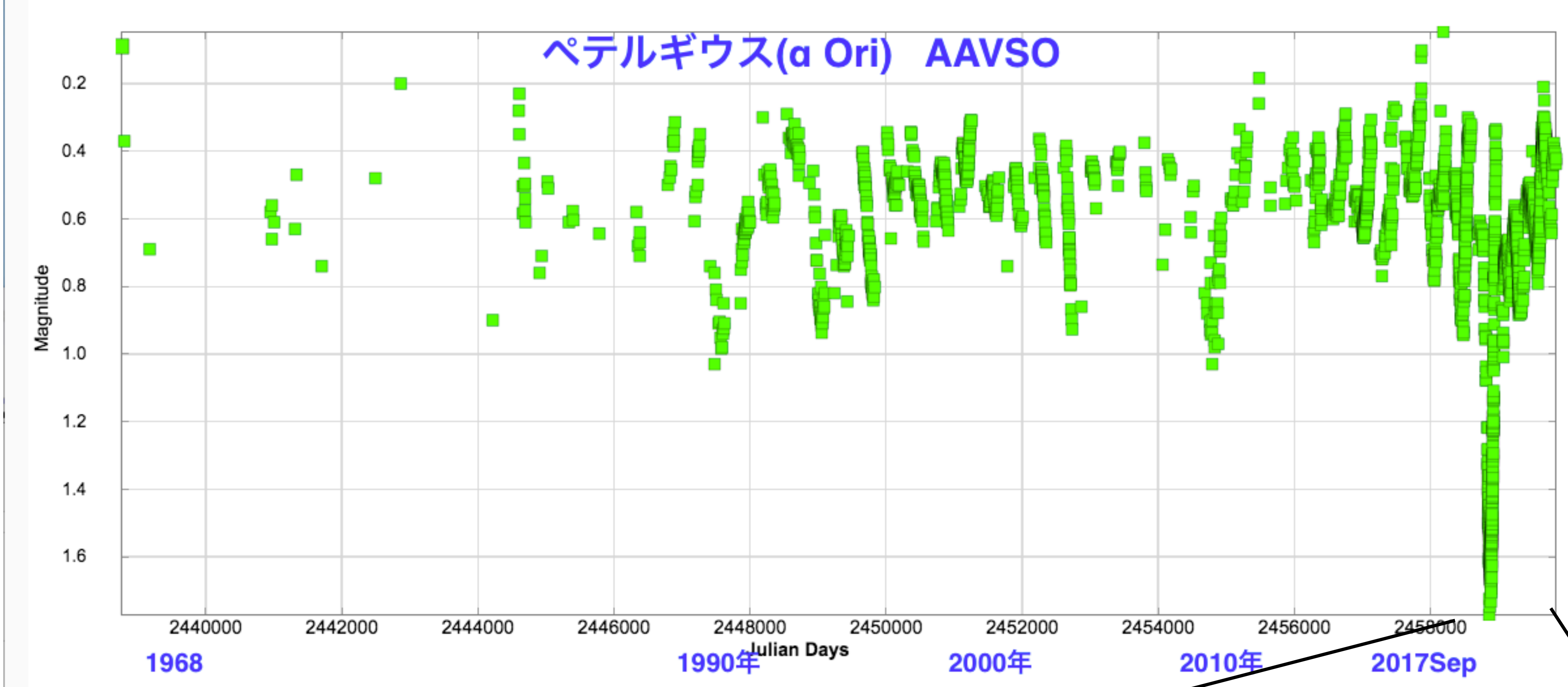


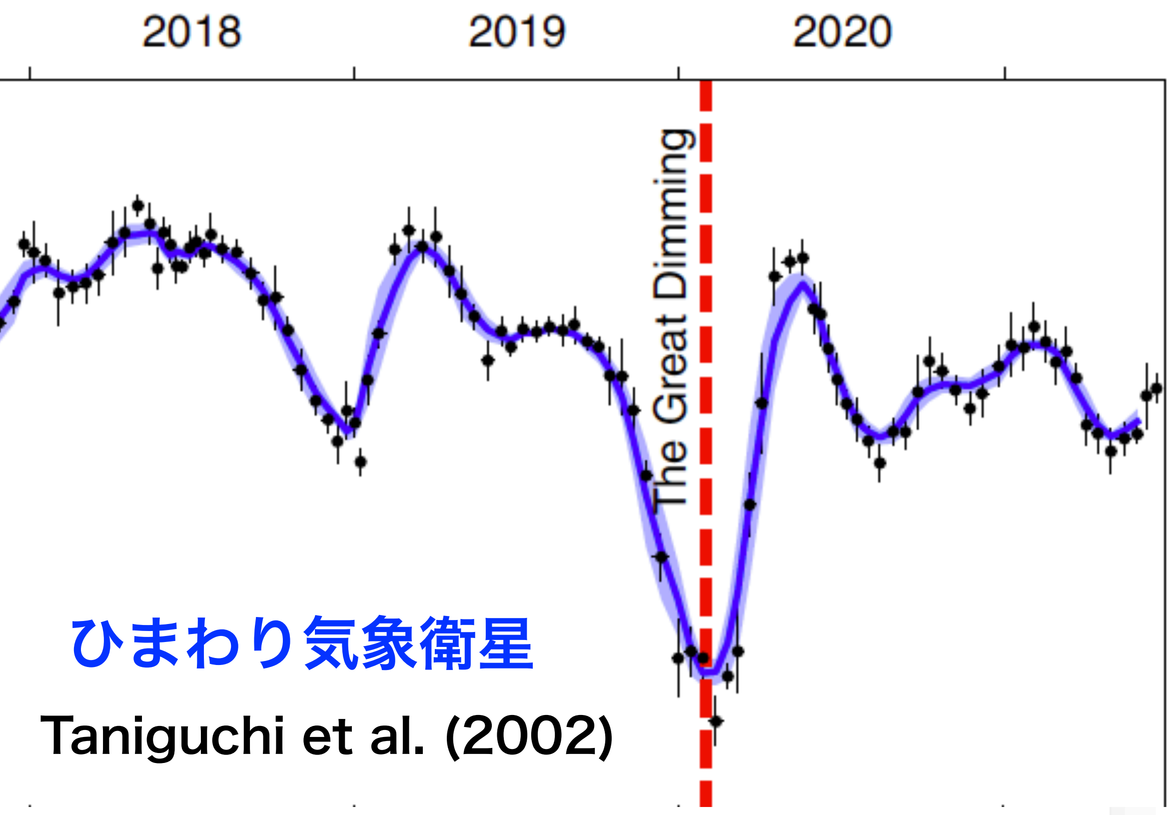
igure 5. Evolution tracks for the 12–25 $M_\odot$ models with $v/v_K = 0.2$ and L_A.

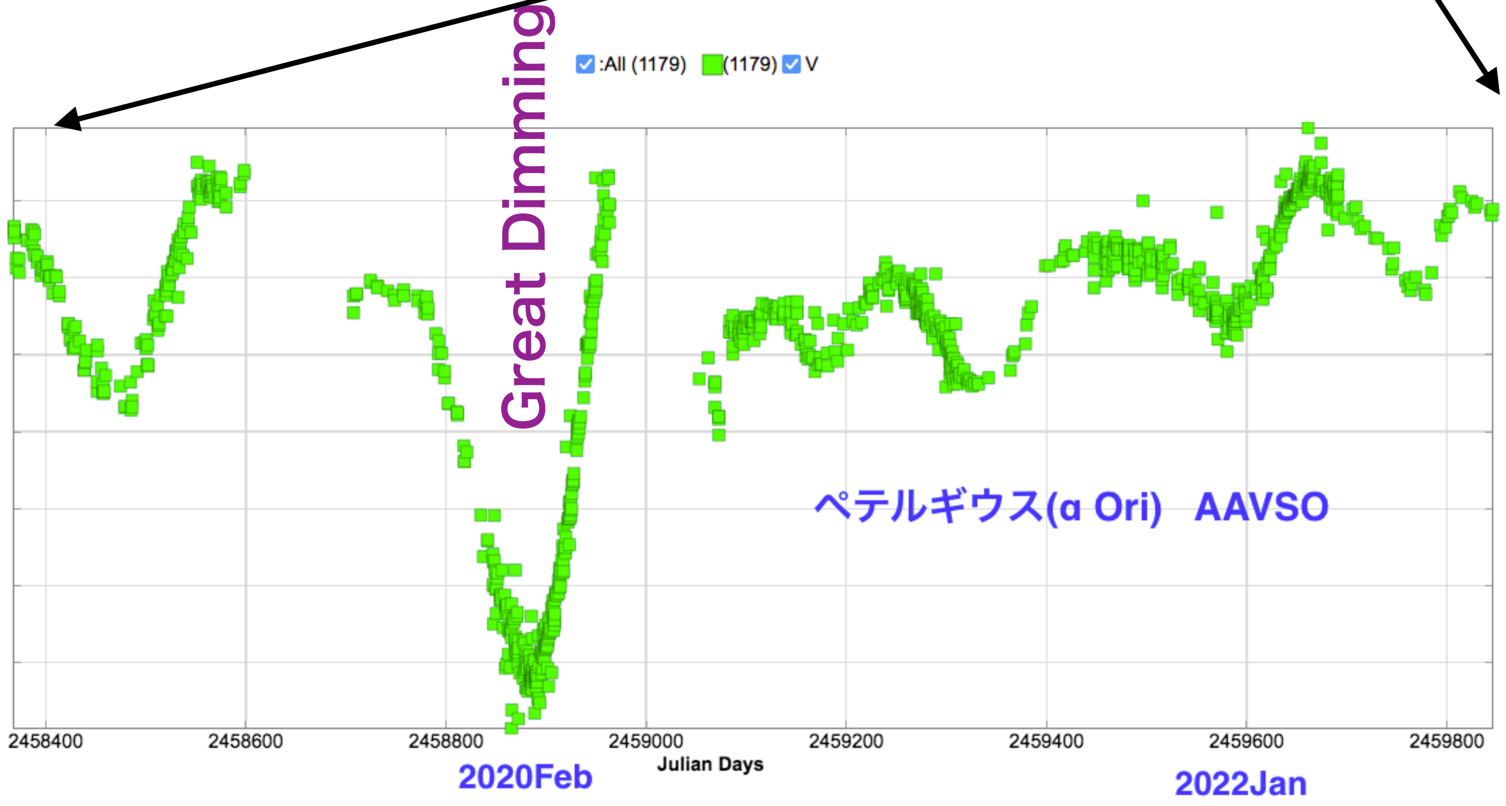
Luo et al. (2022)



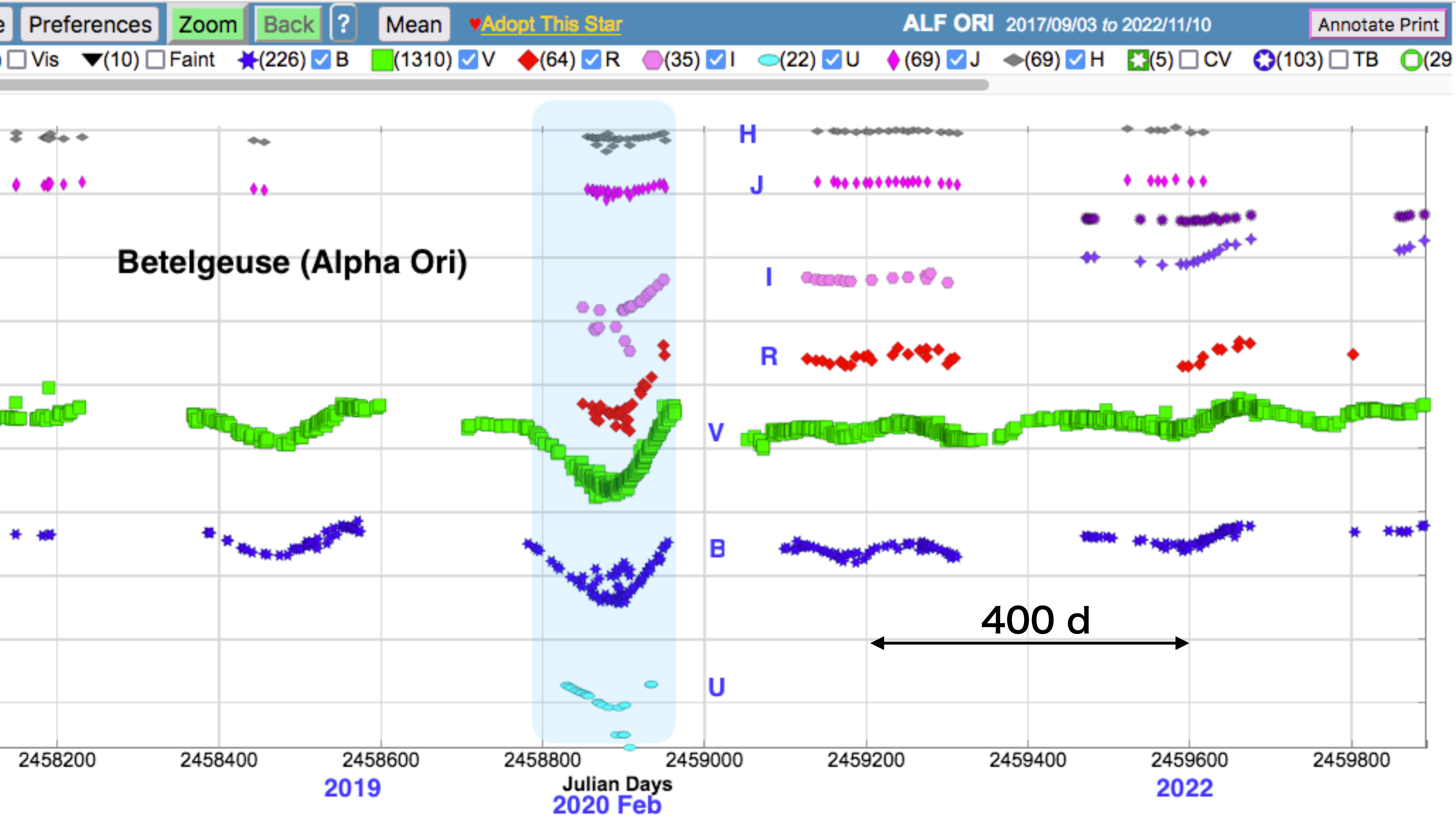
Luo et al. (2022)


ペテルギウス(α Ori)　AAVSO
Magnitude
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2440000
2442000
2444000
2446000
2448000
2450000
2452000
2454000
2456000
2458000
Julian Days
1968
1990年
2000年
2010年
2017Sep


2018
2019
2020
The Great Dimming
ひまわり気象衛星
Taniguchi et al. (2002)


☑:All (1179) 🟩(1179) ☑ V
Great Dimming
ペテルギウス(α Ori)　AAVSO
2458400
2458600
2458800
2459000
2459200
2459400
2459600
2459800
Julian Days
2020Feb
2022Jan

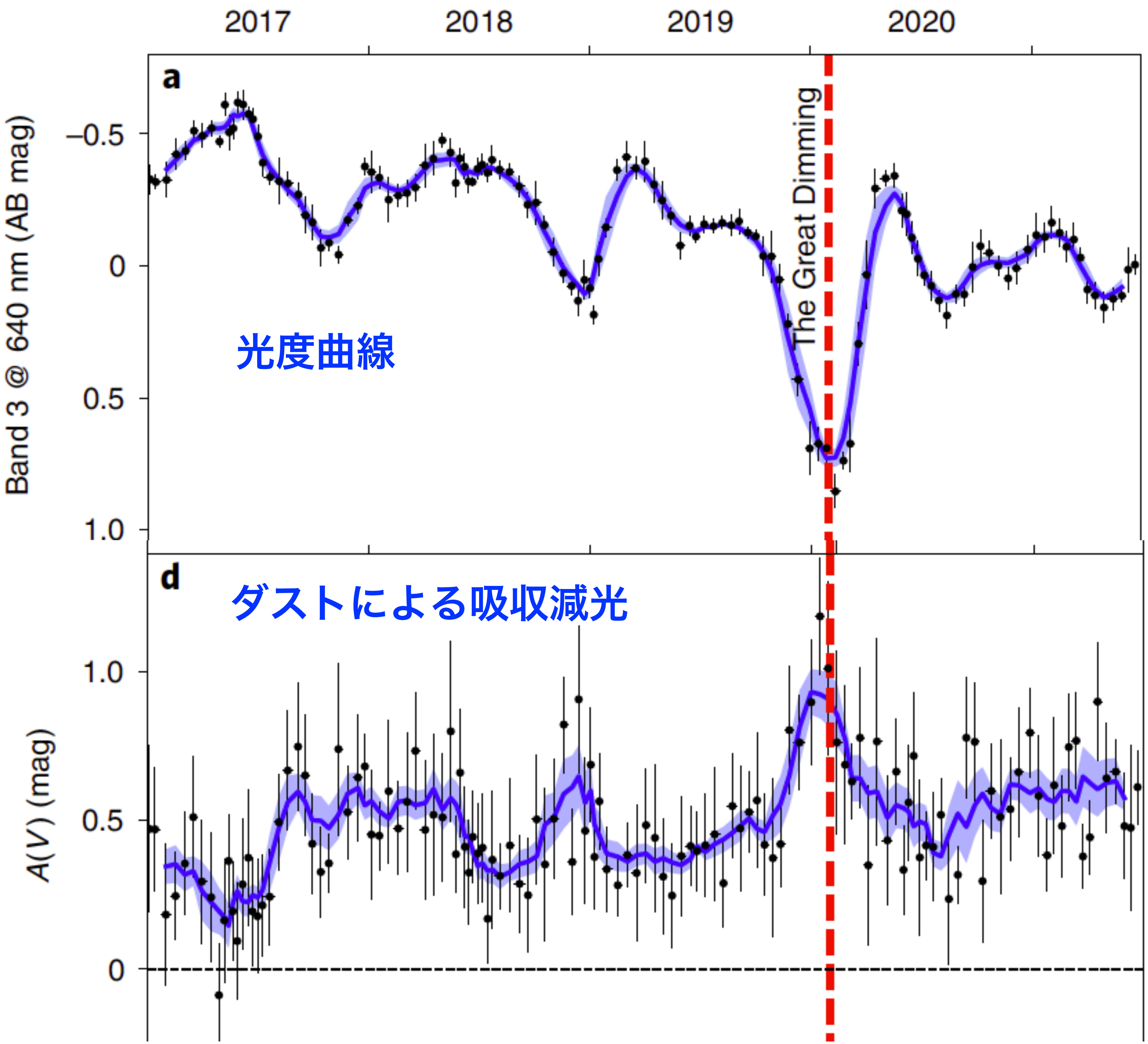
Betelgeuse light curves



AAVSO

赤外領域では大きな変化はなかった

ベテルギウス（ひまわり気象衛星による観測）



光度曲線

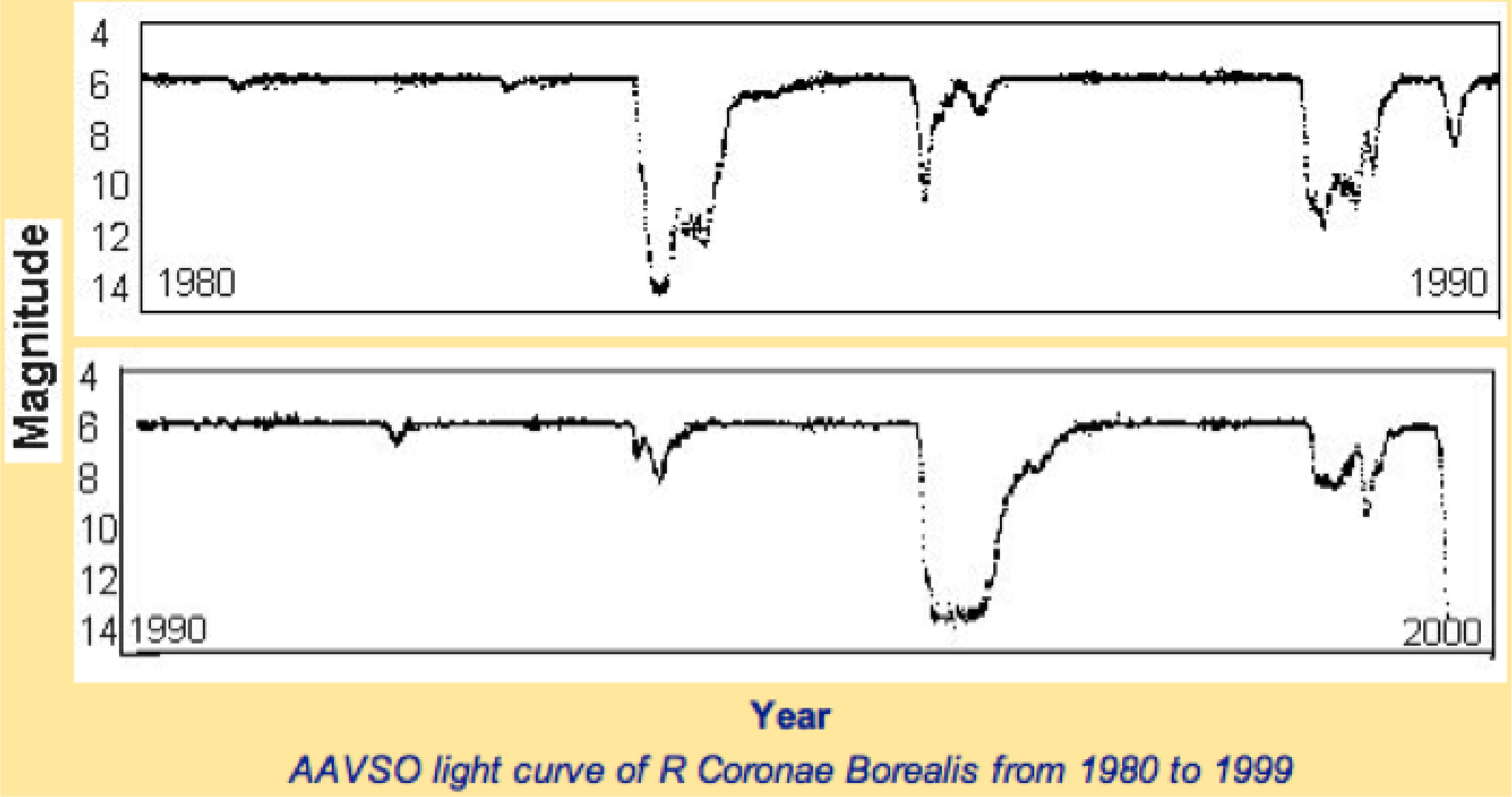
ダストによる吸収減光

Great Dimming
ー 大量のダストの放出

Taniguchi et al. (2022)

Hydrogen-deficient supergiant stars

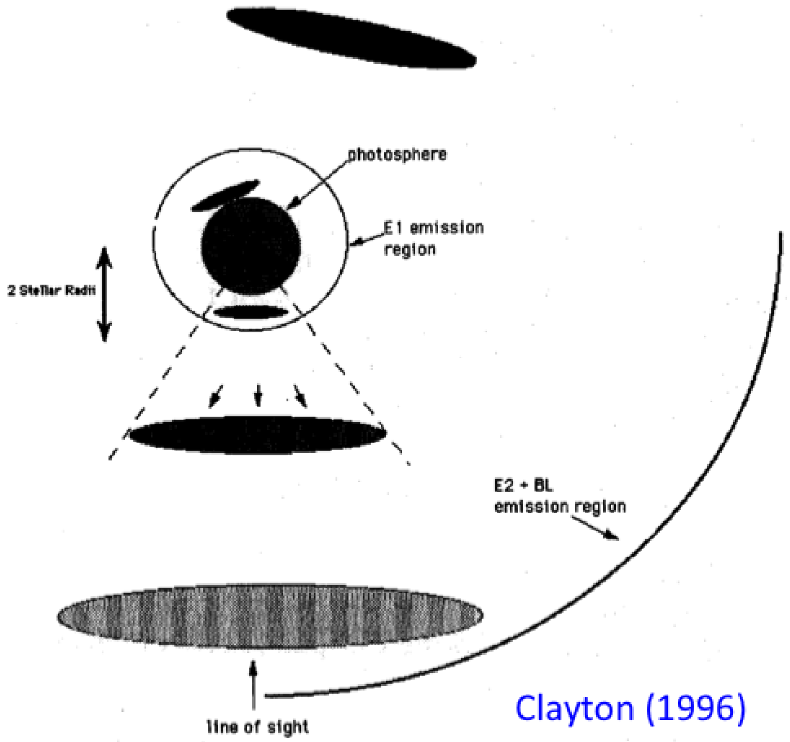
R Coronae Borealis (R CrB) の不規則で大幅な減光



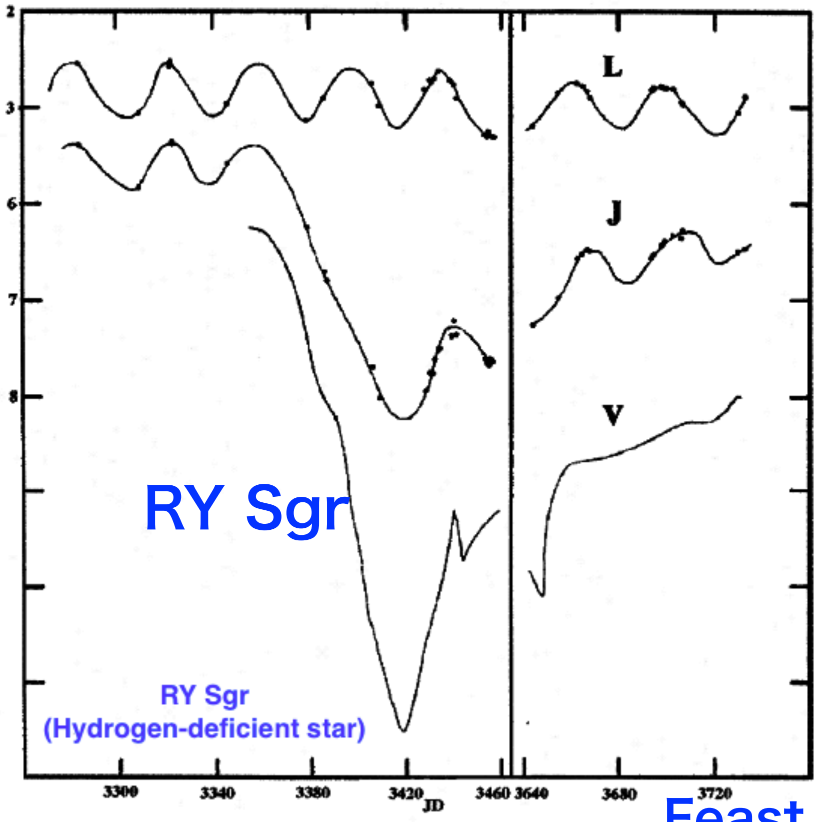
AAVSO light curve of R Coronae Borealis from 1980 to 1999

$$L \approx 10^4 L_\odot$$
$$M \approx 0.8 \pm 0.1 M_\odot$$
$$T_{\rm eff} \approx 8000{\rm K}$$

RCB stars の不規則な減光のモデル
ダストがランダムな方向に形成される



Clayton (1996)

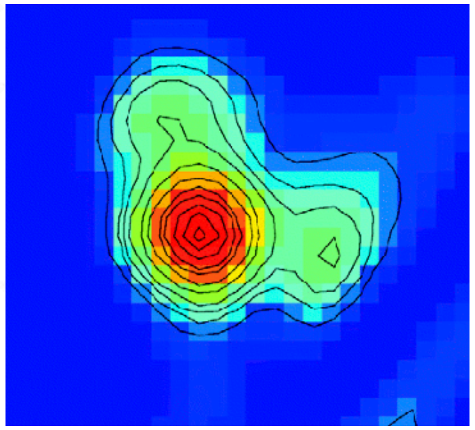


RY Sgr

RY Sgr
(Hydrogen-deficient star)

Feast (1979)

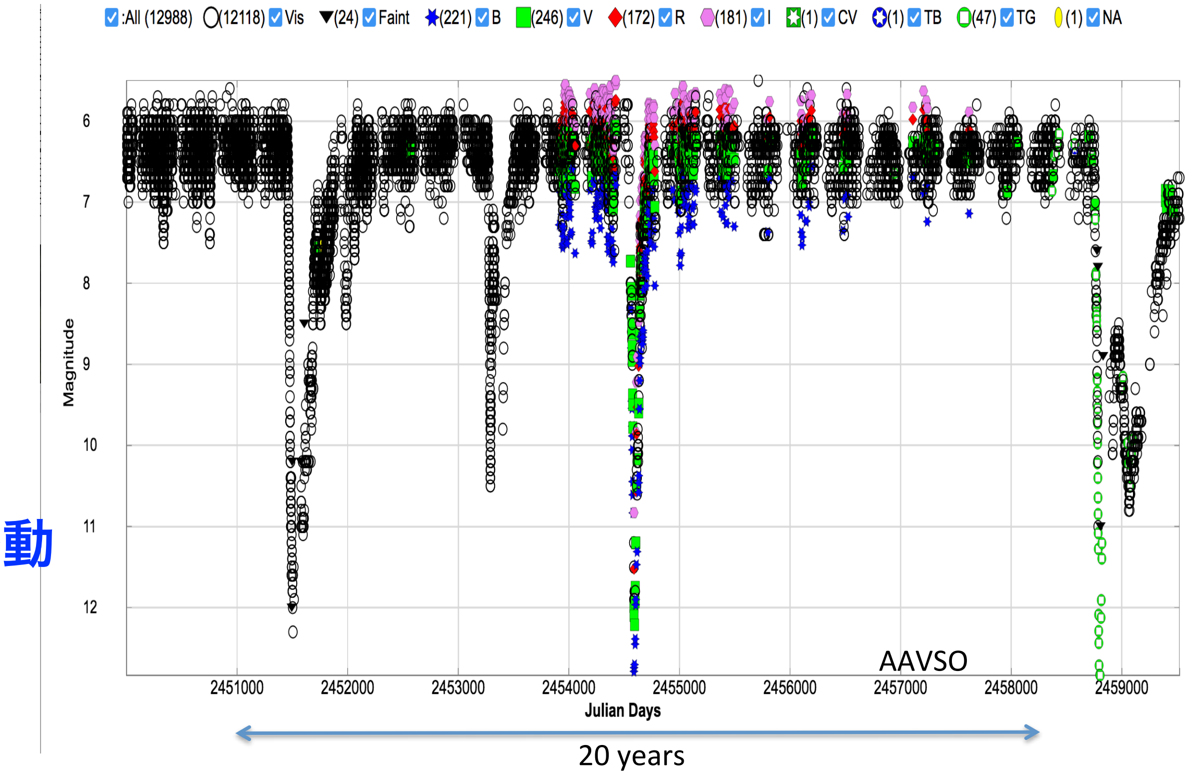
FIG. 6—*V*-band (lower curve), *J*-band (middle curve) and *L*-band (upper curve) photometry through a decline of RY Sgr. The *V* band is mostly stellar flux while the emission in the *L* band is primarily due to circumstellar dust. (From Feast, 1979; © Univ. of Waikato, reproduced with permission.)



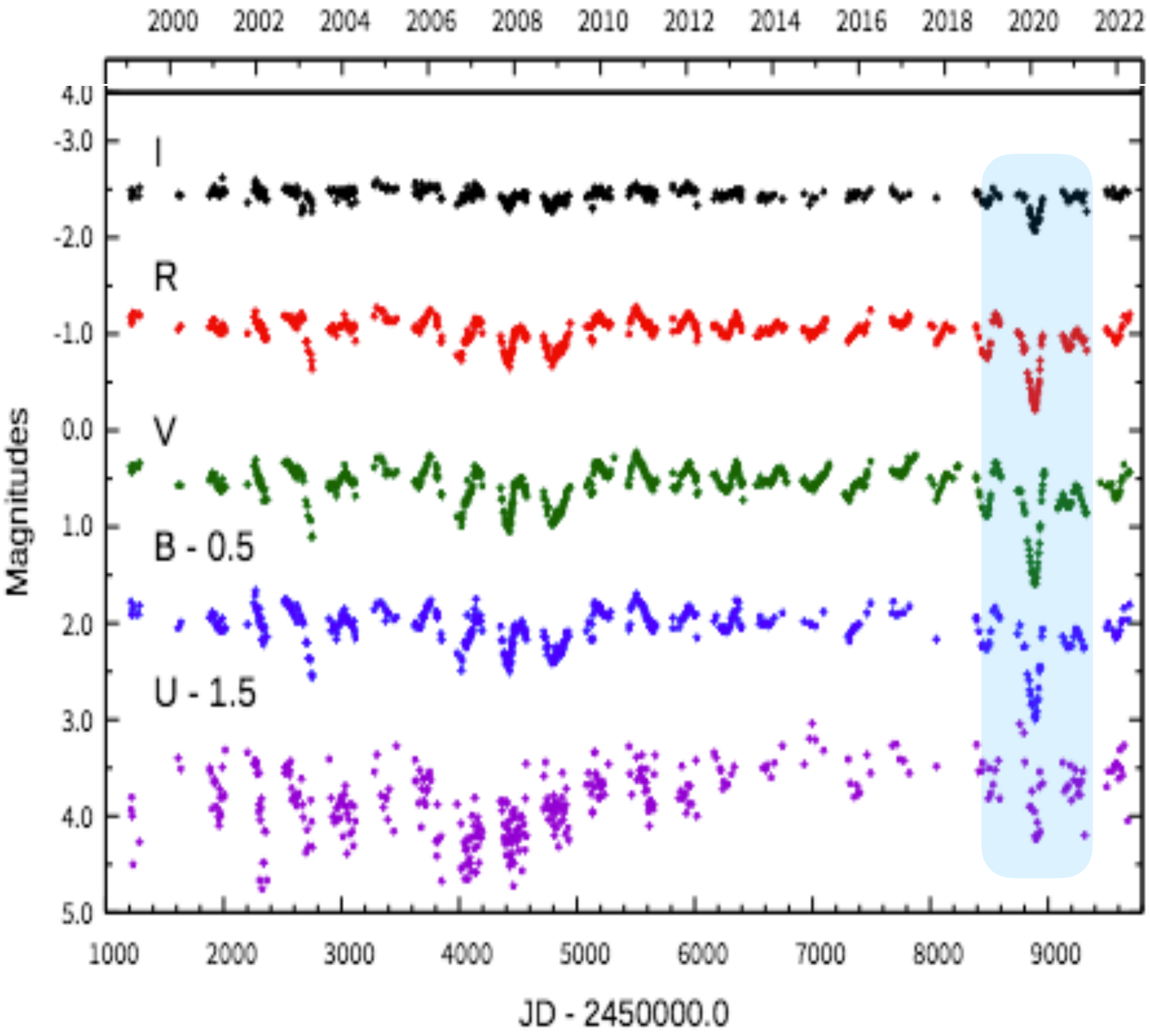
RY Sgr (VLT)

〜40日程度の周期の脈動

RY Sgr (Hydrogen-deficient star)



Betelgeuse は多周期脈動星



Ogane et al (2022)

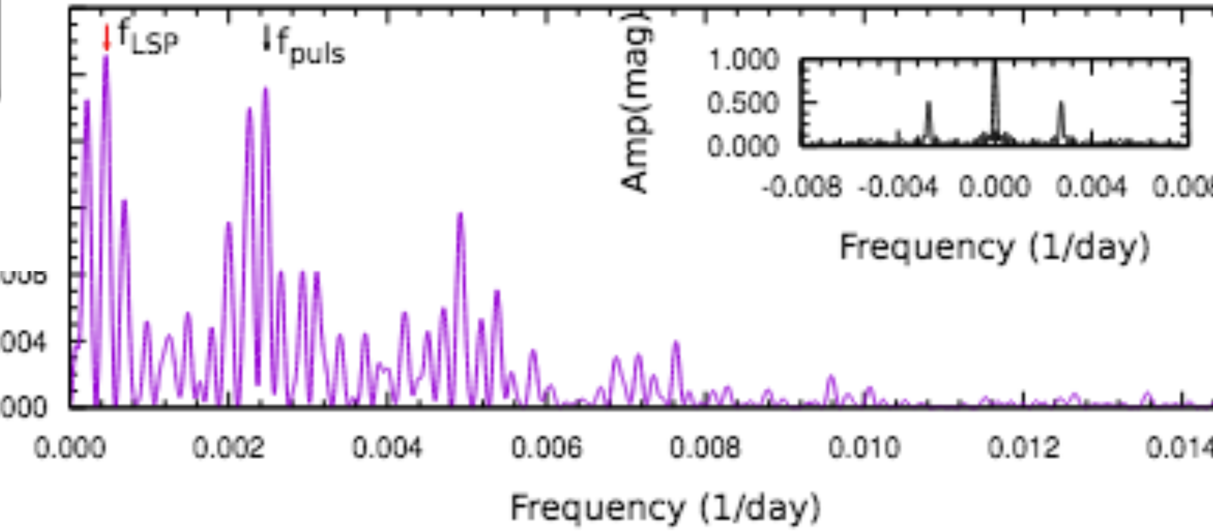
Jadlovsky et al. (2022):

P1 = 2190 ± 270 d
P2 = 417 ± 17 d
P3 = 230 ± 29 d

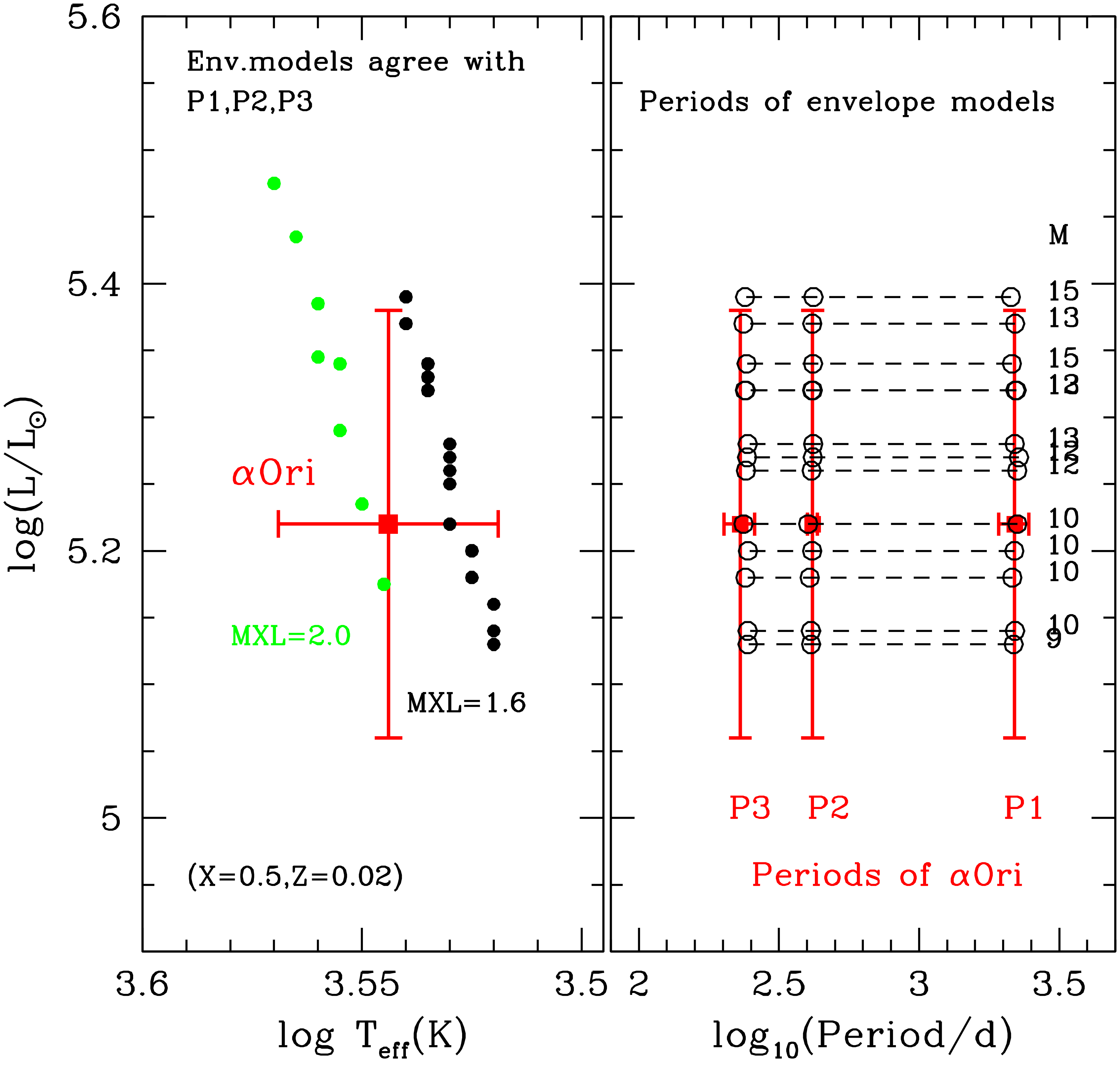
(and 365 ± 75 d ~ 1year
185 ± 4 d ~ 0.5 yr)

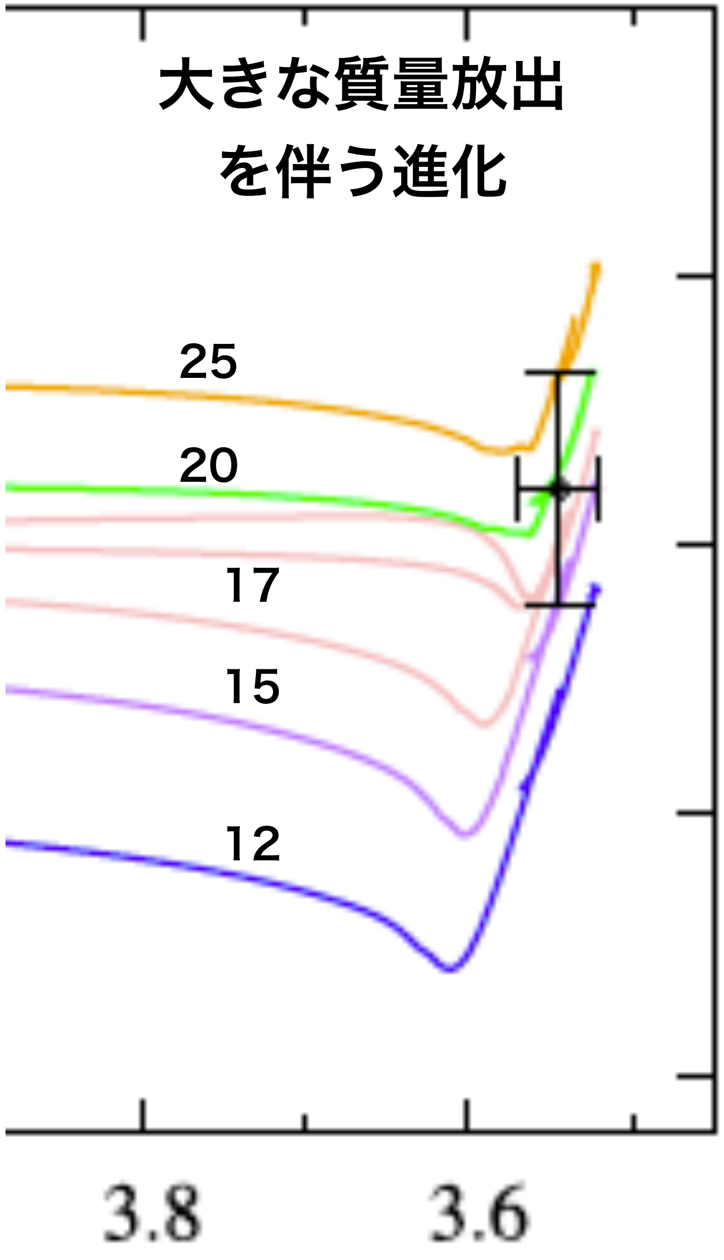
Ogane et al. (2022):
P1=2146 d & P2= 405 d.

Joyce et al(2020):
2365 ±10 d,
416 ± 24 d,
185.5 ± 0.1 d

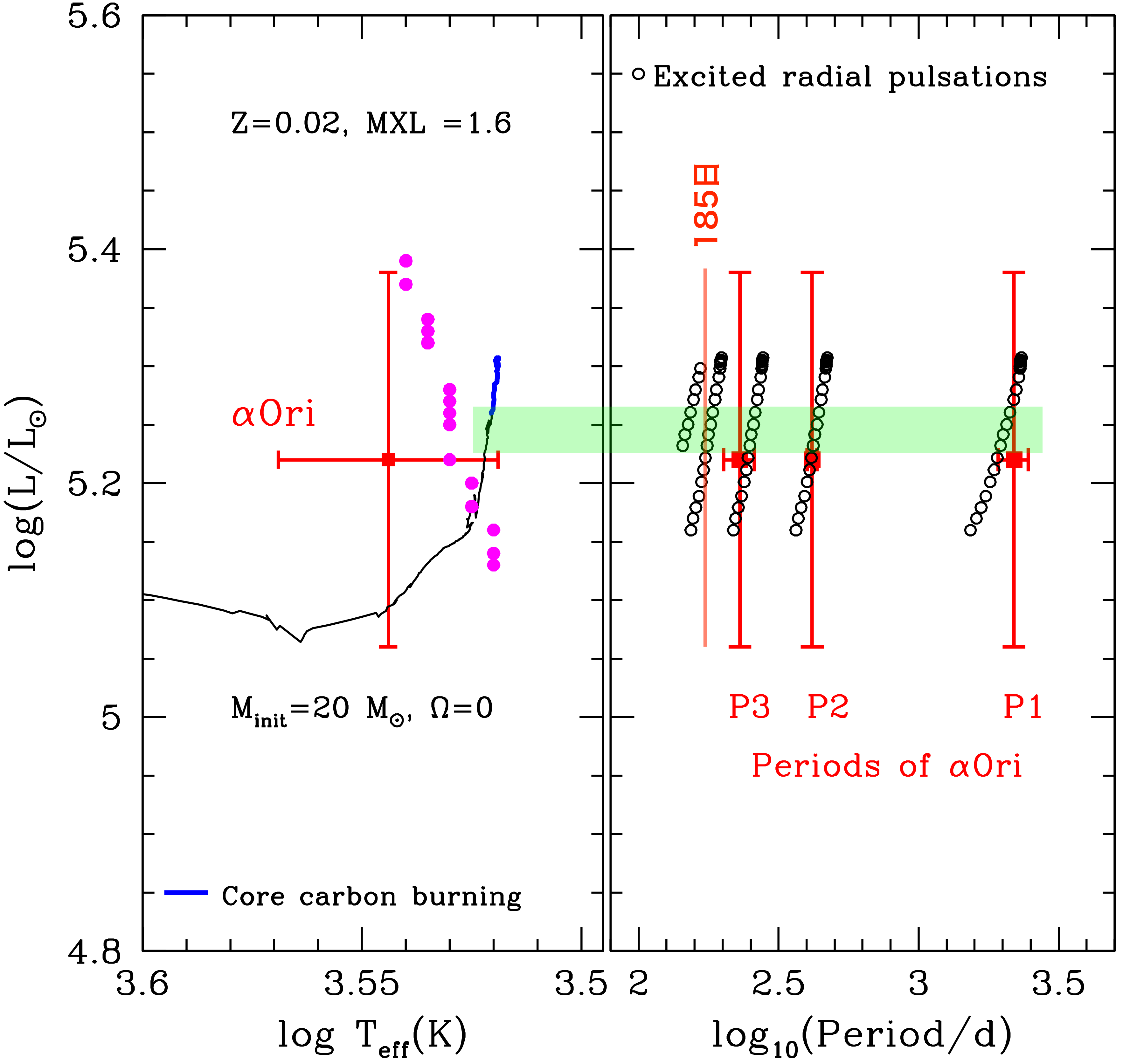


ベテルギウスの脈動周期(P1,P2,P3)と合致する脈動周期を持つenvelope models (M,L,Teff)





Luo et al. (2022)



ベテルギウスの中心の
進化段階は
C-burning 直前(Yc=0)
または
C-burning 初期？

Evolutionary track from Geneva code calculated by Devesh Nandal

各中心燃焼段階でのlifetimes とparameters

(Maeder 2009)

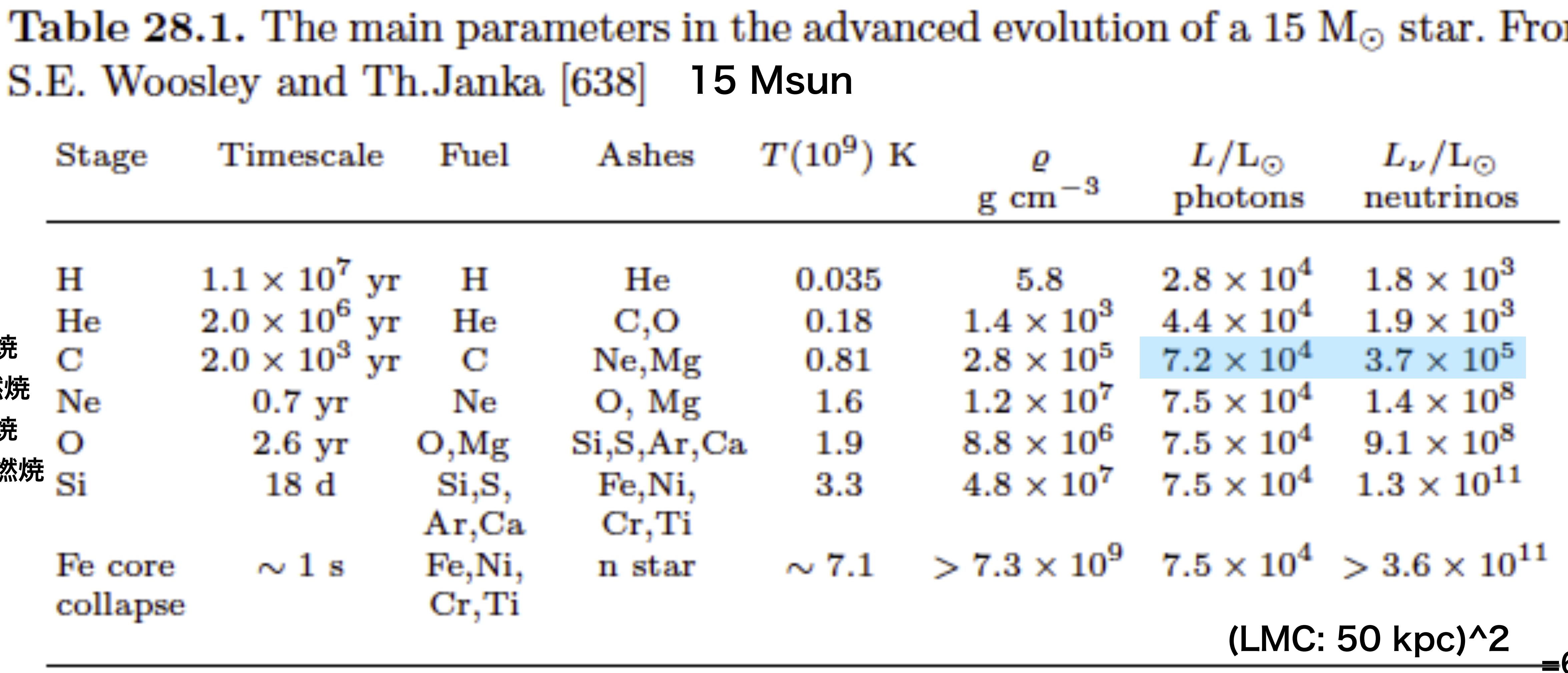


Table 28.1. The main parameters in the advanced evolution of a 15 $M_\odot$ star. From S.E. Woosley and Th.Janka [638]

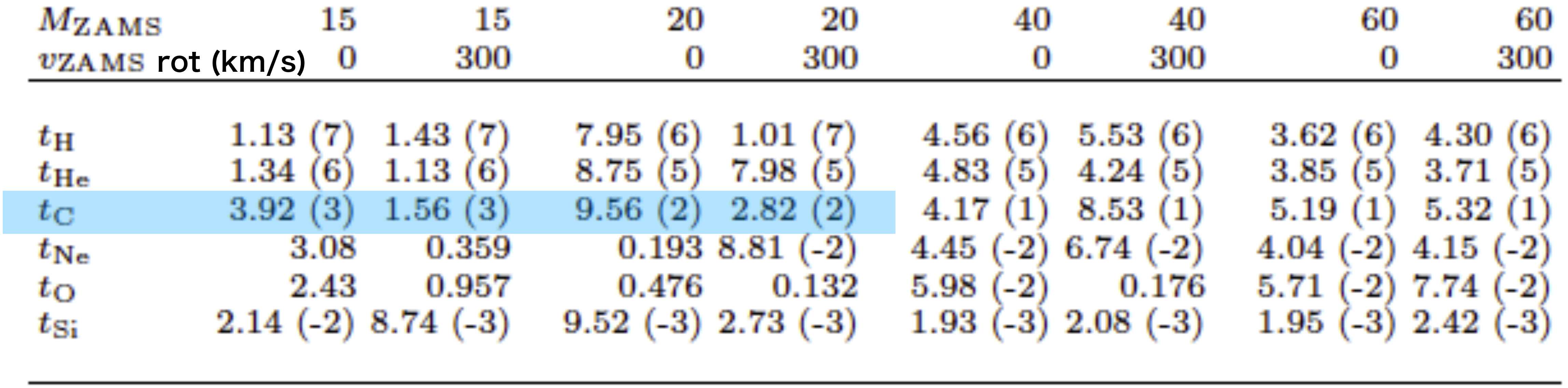
15 Msun

Stage	Timescale	Fuel	Ashes	$T(10^9)$ K	ϱ g cm^{-3}	$L/L_\odot$ photons	$L_\nu/L_\odot$ neutrinos
H	1.1×10^7 yr	H	He	0.035	5.8	2.8×10^4	1.8×10^3
He	2.0×10^6 yr	He	C,O	0.18	1.4×10^3	4.4×10^4	1.9×10^3
C	2.0×10^3 yr	C	Ne,Mg	0.81	2.8×10^5	7.2×10^4	3.7×10^5
Ne	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	7.5×10^4	1.4×10^8
O	2.6 yr	O,Mg	Si,S,Ar,Ca	1.9	8.8×10^6	7.5×10^4	9.1×10^8
Si	18 d	Si,S, Ar,Ca	Fe,Ni, Cr,Ti	3.3	4.8×10^7	7.5×10^4	1.3×10^{11}
Fe core collapse	~ 1 s	Fe,Ni, Cr,Ti	n star	~ 7.1	$> 7.3 \times 10^9$	7.5×10^4	$> 3.6 \times 10^{11}$

炭素燃焼
ネオン燃焼
酸素燃焼
シリコン燃焼

(LMC: 50 kpc)^2
(αOri : 0.2 kpc)^2
=6.25e4

Lifetimes in years (exponent in parenthesis)



$M_{\rm ZAMS}$	15	15	20	20	40	40	60	60
$v_{\rm ZAMS}$ rot (km/s)	0	300	0	300	0	300	0	300
$t_{\rm H}$	1.13 (7)	1.43 (7)	7.95 (6)	1.01 (7)	4.56 (6)	5.53 (6)	3.62 (6)	4.30 (6)
$t_{\rm He}$	1.34 (6)	1.13 (6)	8.75 (5)	7.98 (5)	4.83 (5)	4.24 (5)	3.85 (5)	3.71 (5)
$t_{\rm C}$	3.92 (3)	1.56 (3)	9.56 (2)	2.82 (2)	4.17 (1)	8.53 (1)	5.19 (1)	5.32 (1)
$t_{\rm Ne}$	3.08	0.359	0.193	8.81 (-2)	4.45 (-2)	6.74 (-2)	4.04 (-2)	4.15 (-2)
$t_{\rm O}$	2.43	0.957	0.476	0.132	5.98 (-2)	0.176	5.71 (-2)	7.74 (-2)
$t_{\rm Si}$	2.14 (-2)	8.74 (-3)	9.52 (-3)	2.73 (-3)	1.93 (-3)	2.08 (-3)	1.95 (-3)	2.42 (-3)