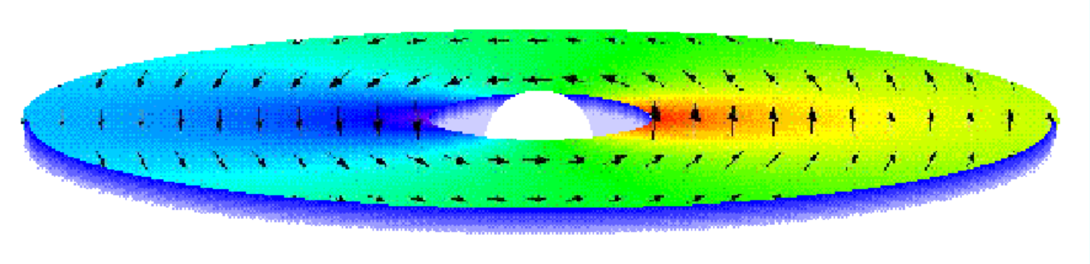
Be stars and the Be phenomenon



Coralie Neiner
LESIA, Paris Observatory

Outline

- Classical Be stars
  - Emission from the disk
  - The Be phenomenon
- Magnetism
  - Magnetic Be stars and magnetospheres
  - Magnetism in classical Be stars
- Pulsations
  - Pulsations and rapid rotation effects
  - CoRoT results
  - Be outbursts
- Summary

Classical Be stars

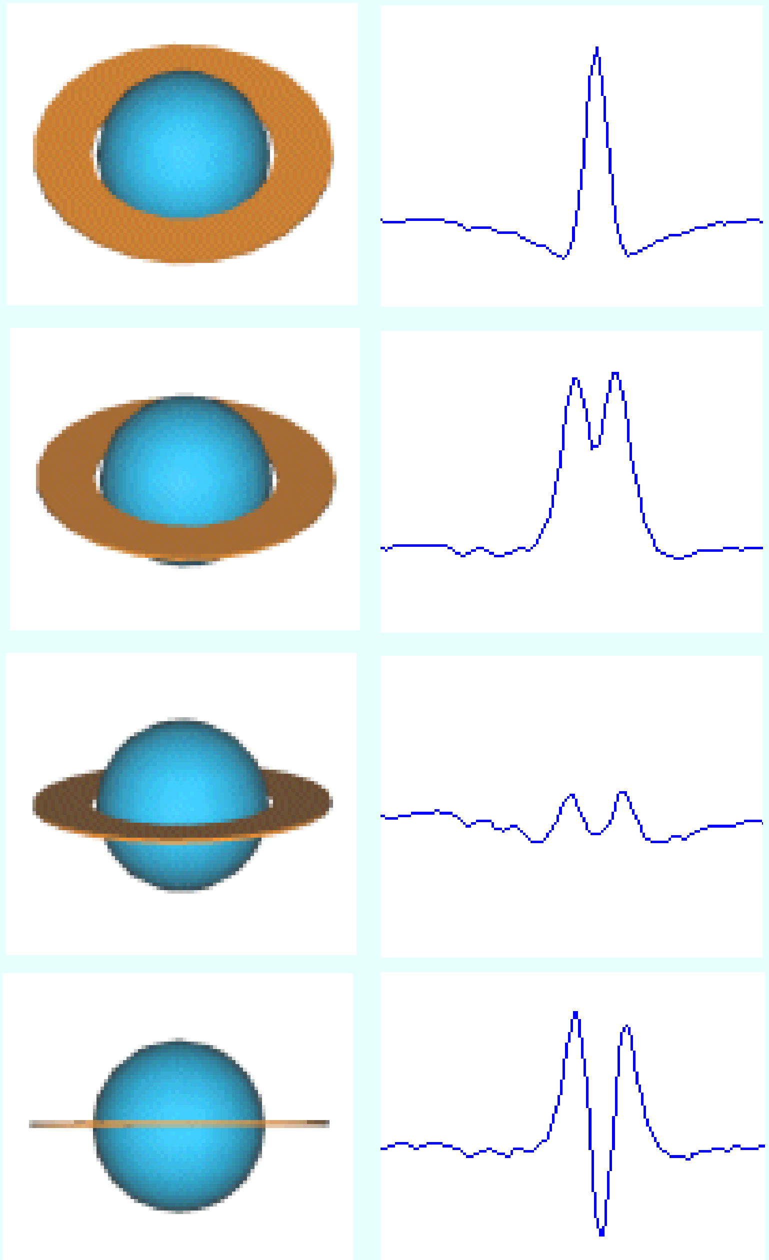
- Non-supergiant hot stars (O7 → A2) with emission lines
- ~20% of all B stars
- Peculiar type of stars or stellar evolutionary stage?

  B –> Be –> B –> Be

- Cool circumstellar disk + hot polar wind
- Rapid rotation: ~250 km/s

  → variations on all timescales
  → great laboratory for stellar physics !

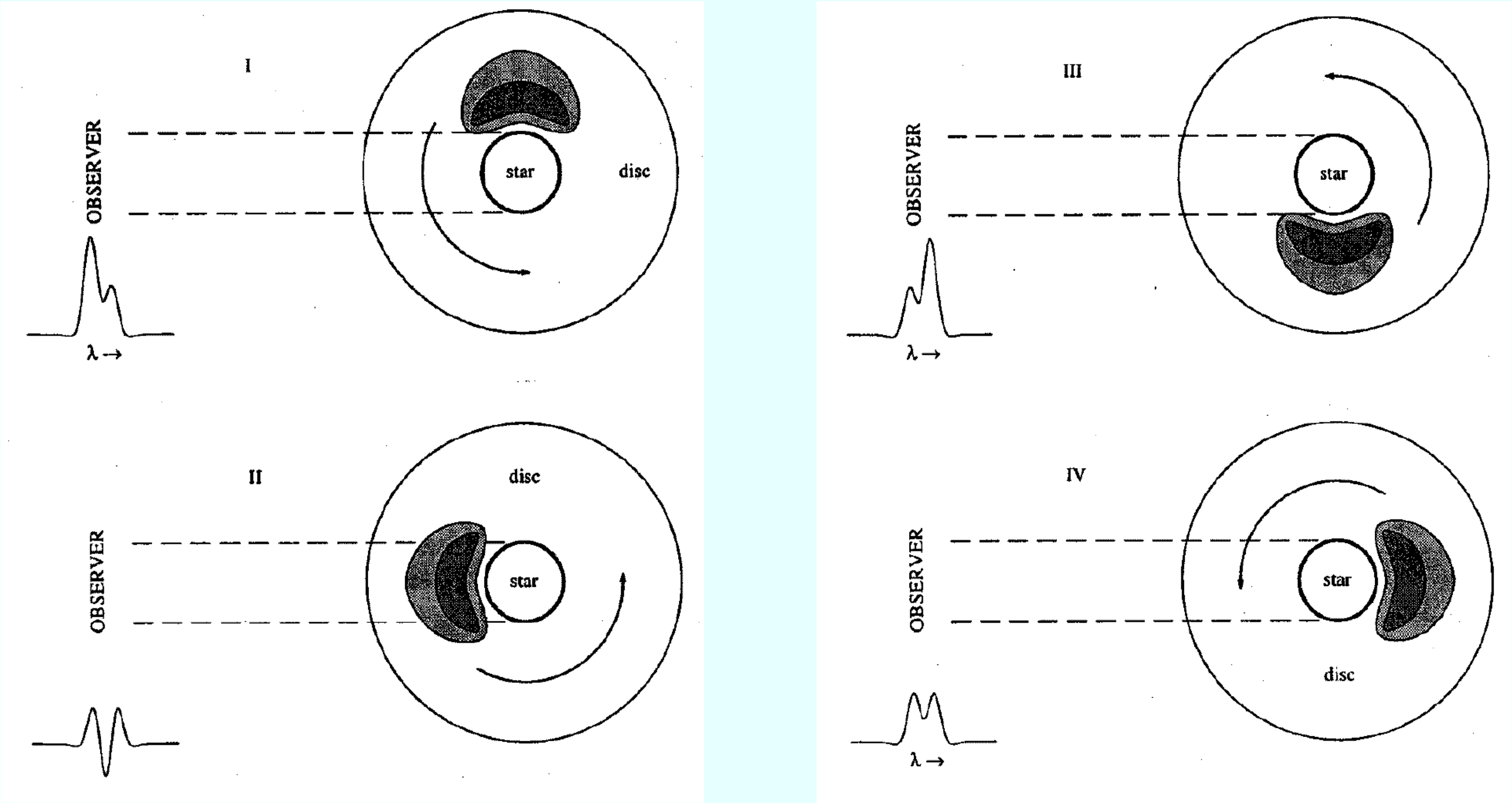
Signature of the disk: emission line profiles



Sletteback 1979

→ depends on the inclination under which we observe the disk

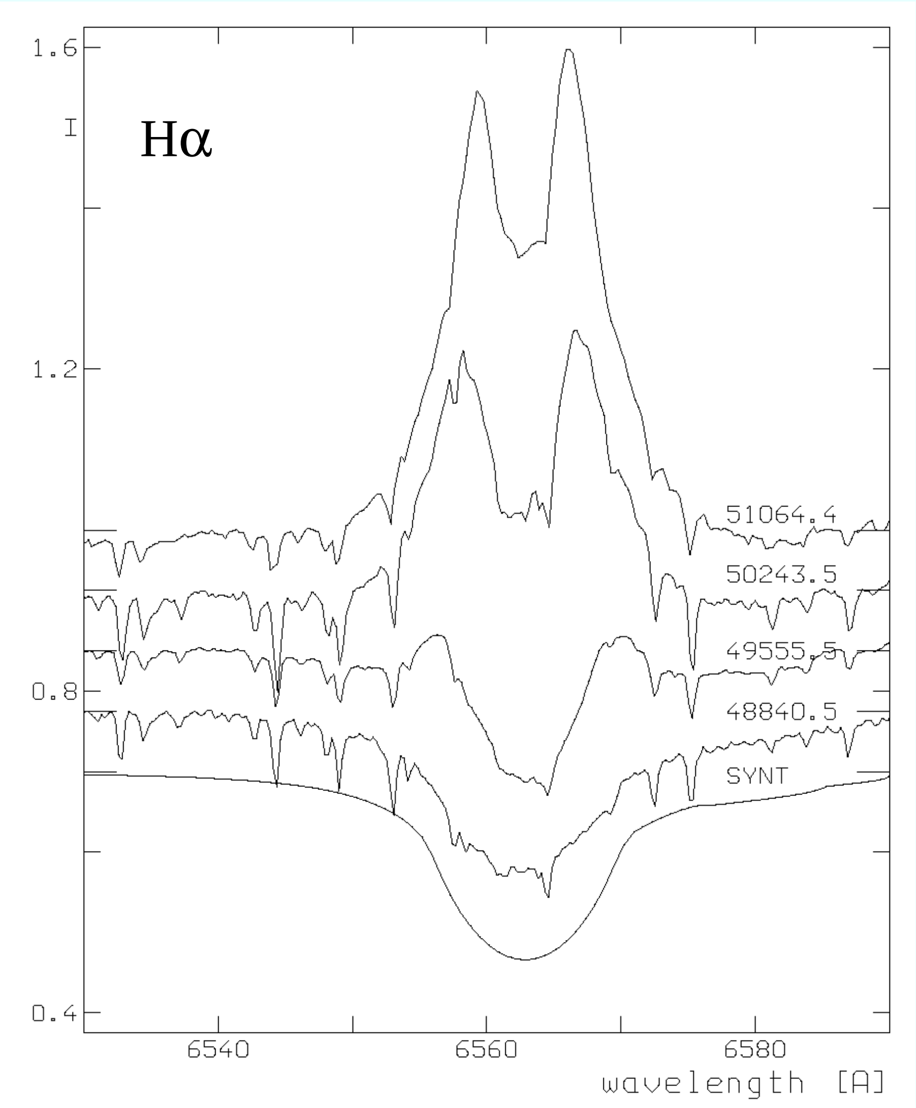
Signature of the disk: emission line profiles



Telting 1996

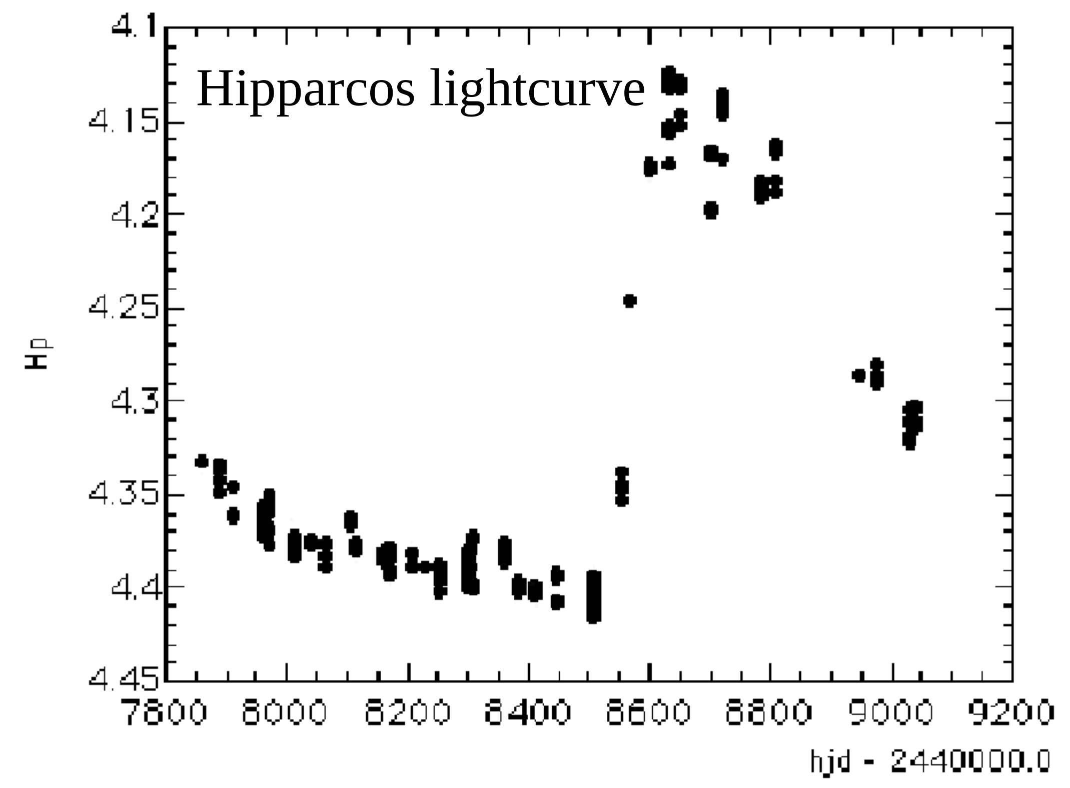
→ depends on inhomogeneities in the disk

Signature of the disk: emission line profiles



Koubsky et al. 2000

→ depends on time compared to time of last outburst

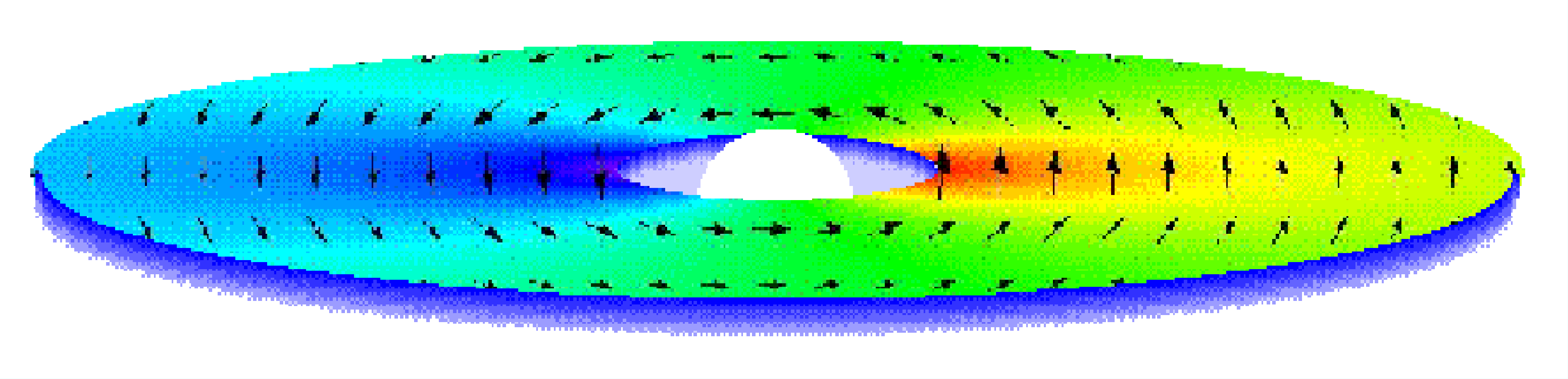


Hubert & Floquet, 1998

The Be phenomenon

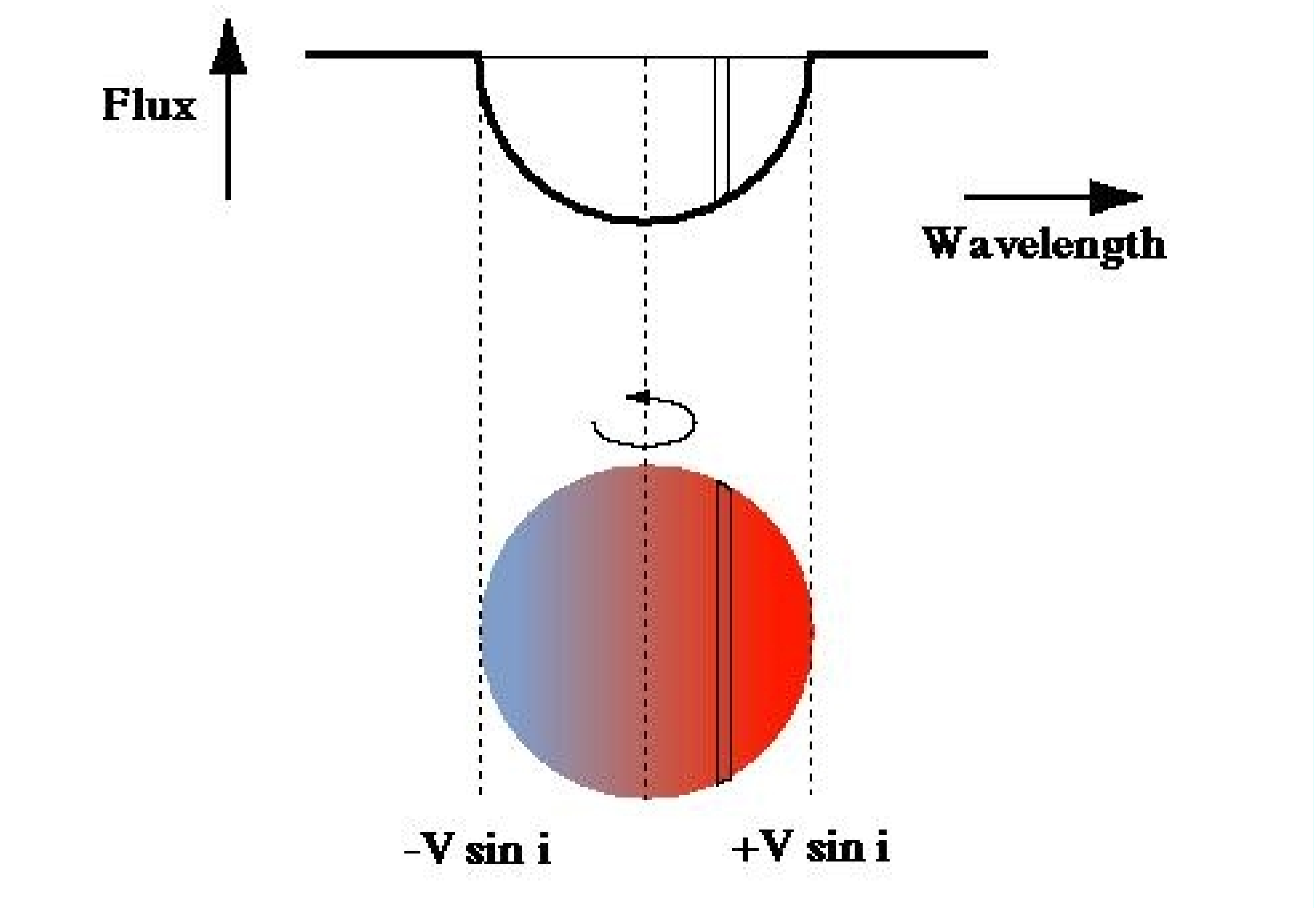
- Decretion disk fed by ejections of matter

→ **How does the star eject matter ?**

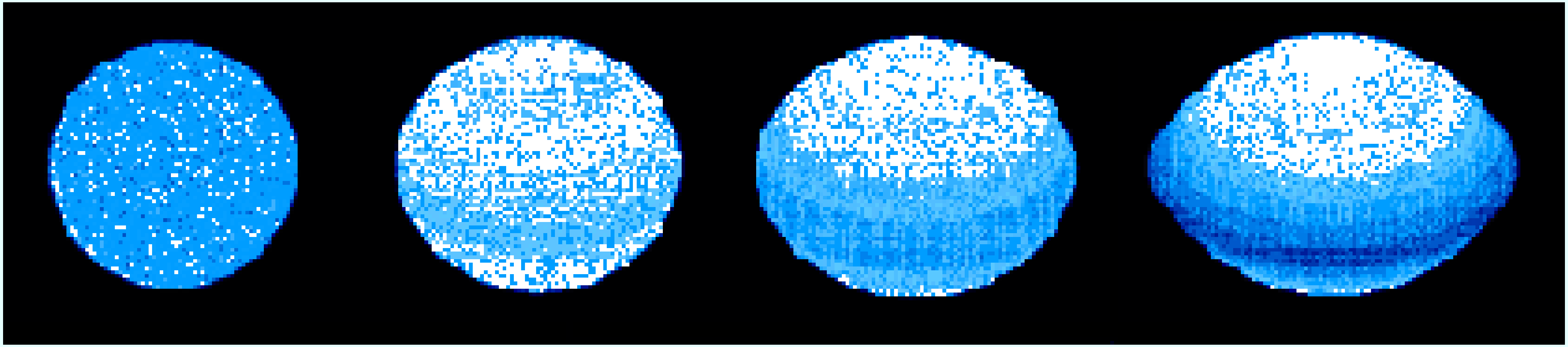


Thanks to rapid rotation?

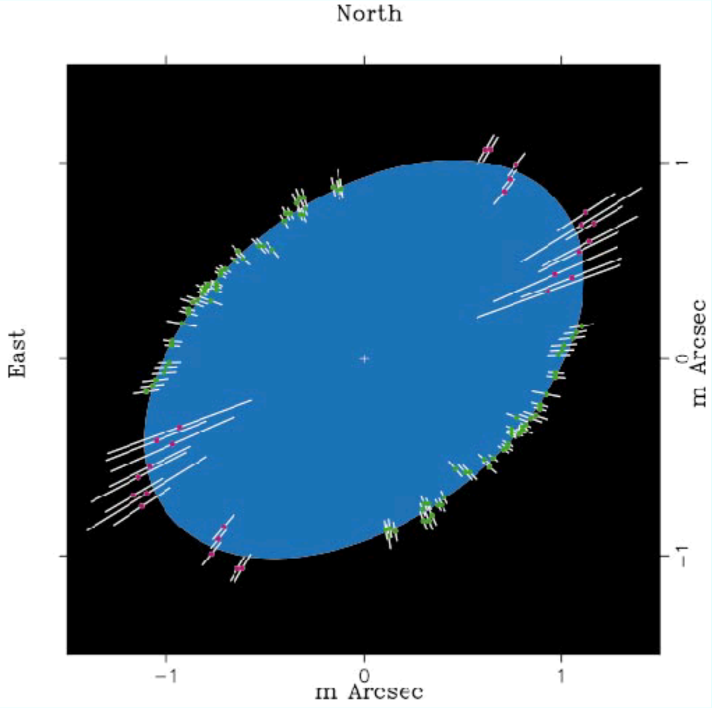
Rapid rotation: Doppler broadening of the lines



Rapid rotation: flattening of the star



V=0 Rotation velocity → fast

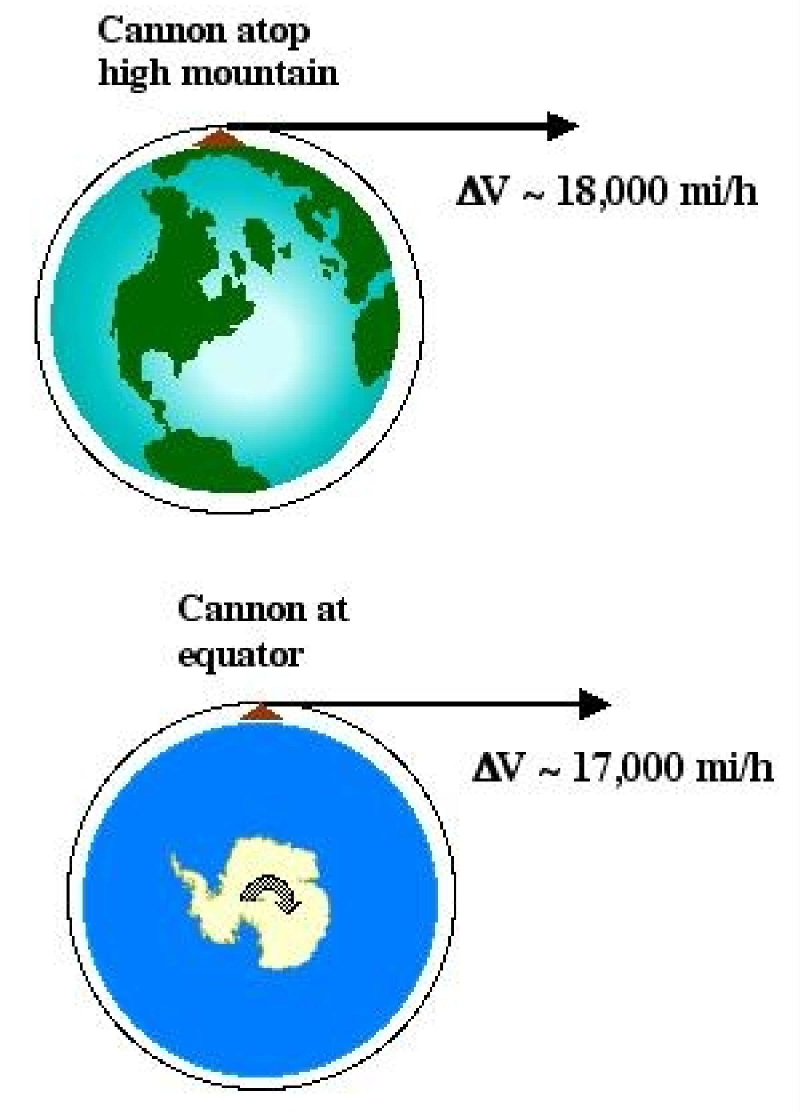


α Eri observed at VLTI,

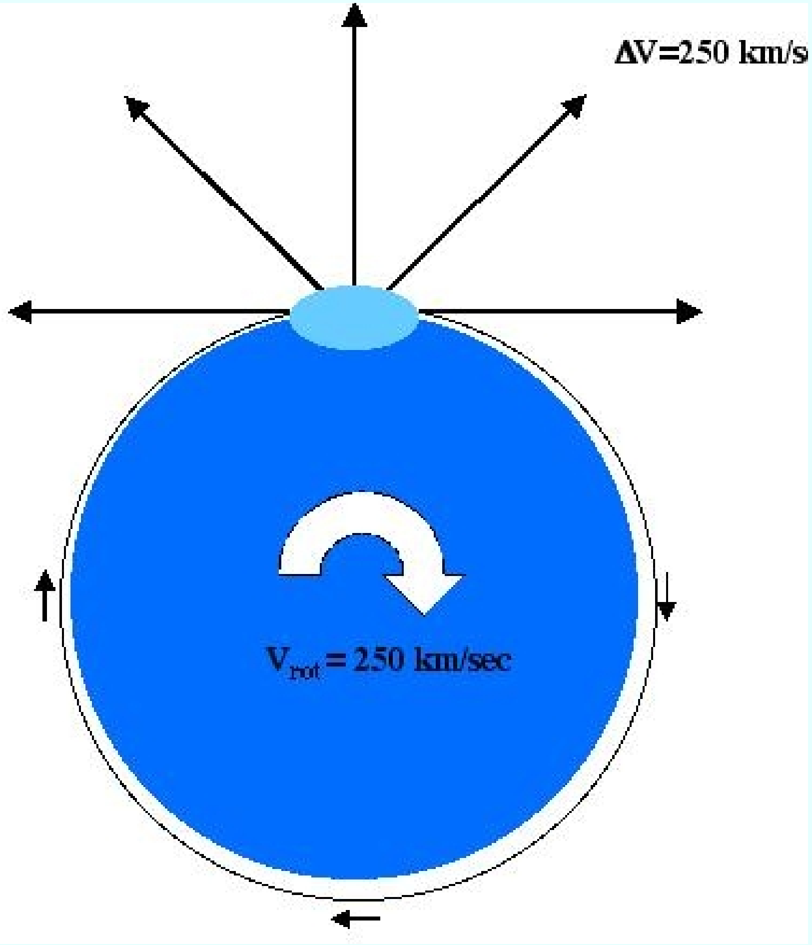
(Domiciano de Souza et al. 2003)

Req=1.56 Rpol

Ejection of matter



Be star

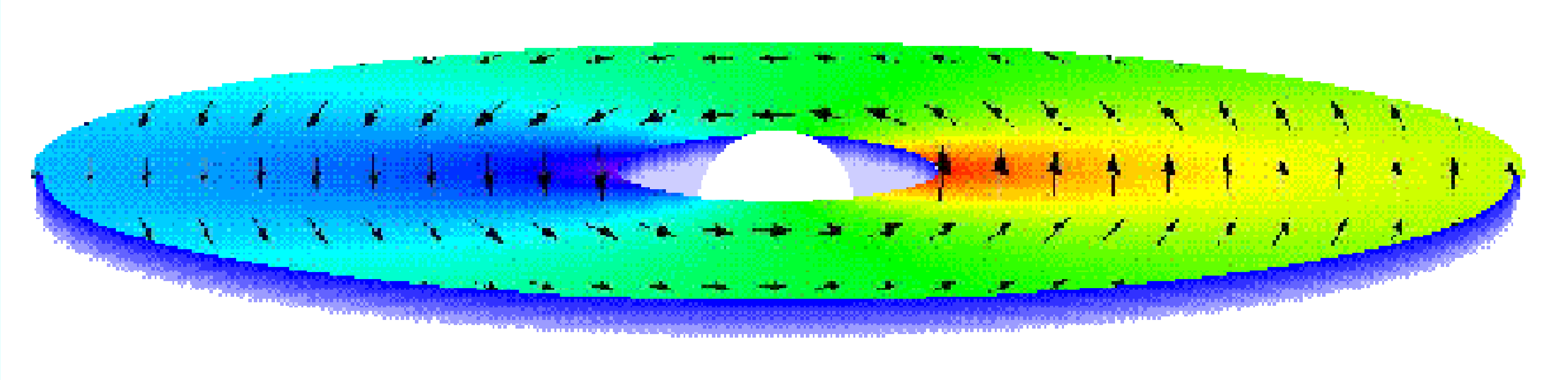


Ejection is easier at the equator, but rotation is not sufficient: only ~90% of needed critical velocity

The Be phenomenon

- Decretion disk fed by ejections of matter

  → How does the star eject matter ?

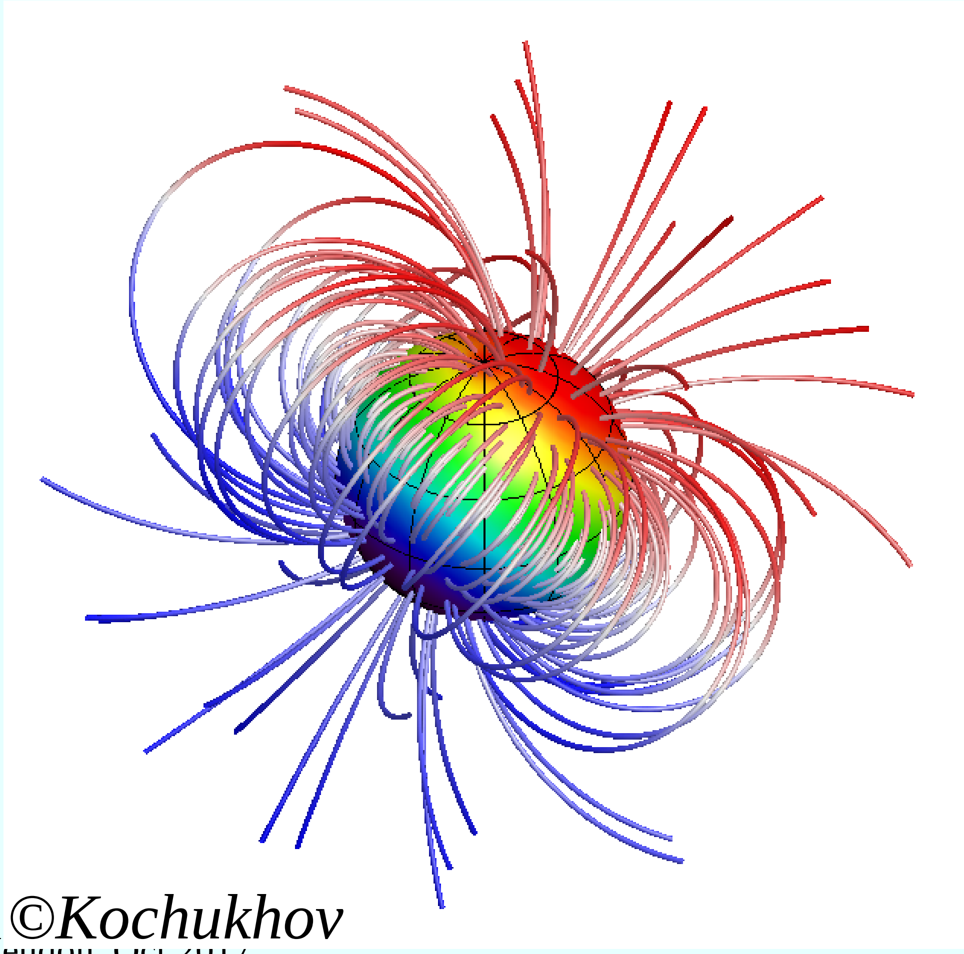


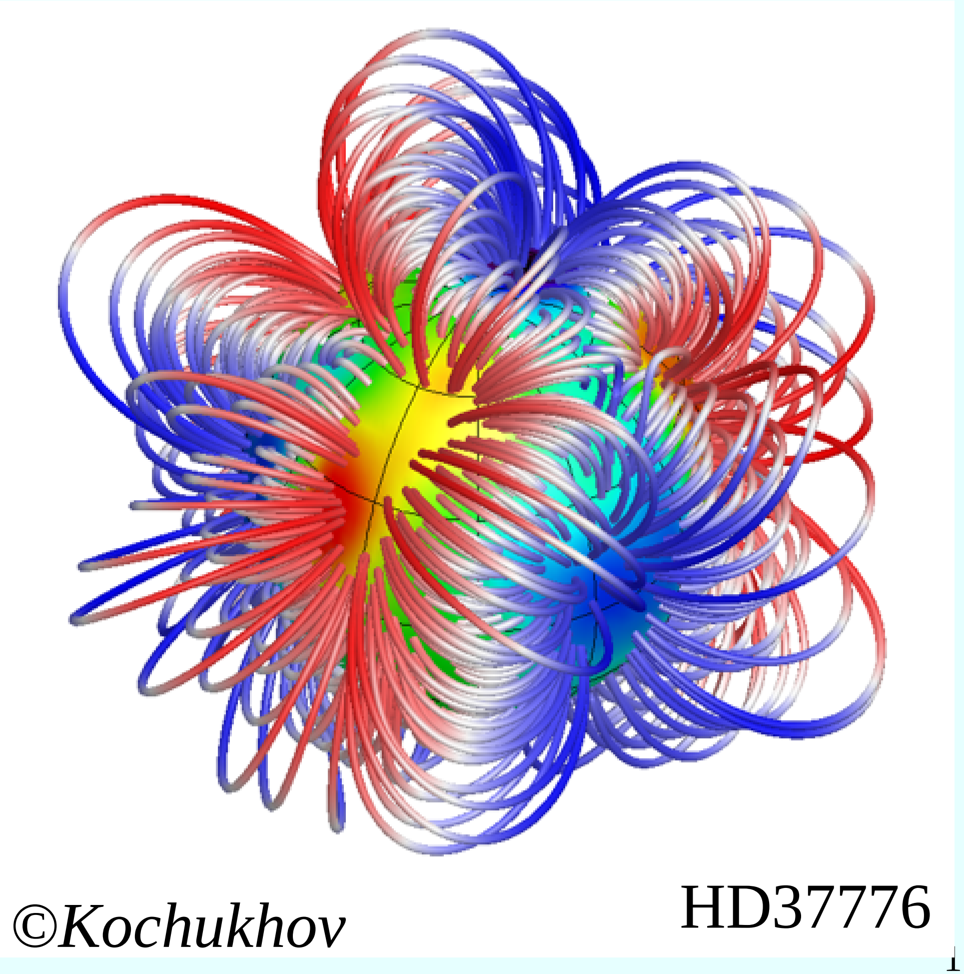
- Rapid rotation plays an important role but is not enough
- Additional ingredient: Magnetism ? Pulsations ?

Magnetism in Be stars?

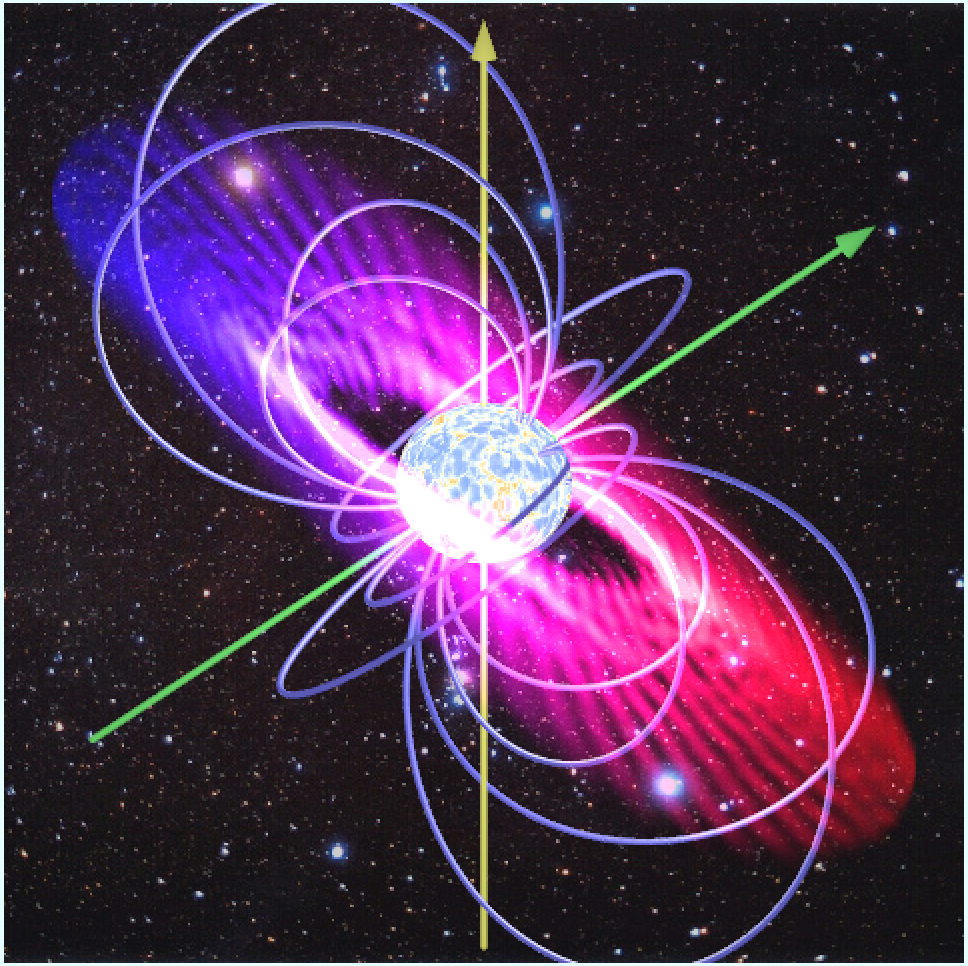
Magnetism in hot stars

- Fossil fields
- Usually simply structured, but some exceptions
- Strong inside the star, weak at the surface
- ~10% of all hot stars are magnetic (B_{pol} > ~50 G)





Oblique dipole and magnetospheres



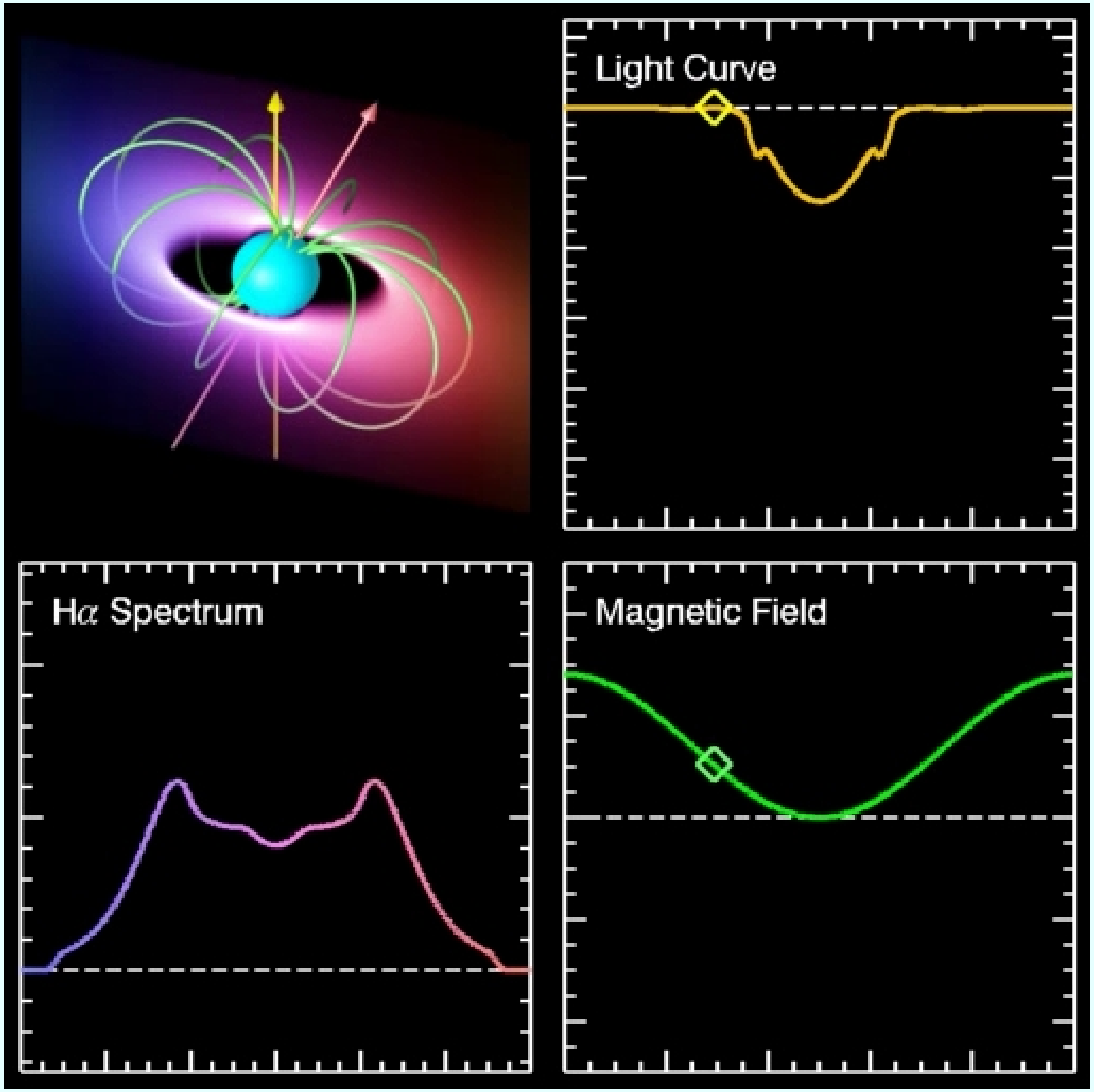
©Townsend

Oblique dipole field
→ Rotational modulation of :
- Longitudinal field
- Photospheric lines if spots
- UV wind lines

Confined wind in the magnetosphere
→ Rotational modulation of :
- X-rays emission
- Photometric lightcurve
- Hα emission

i=60°, β=30°

Magnetosphere



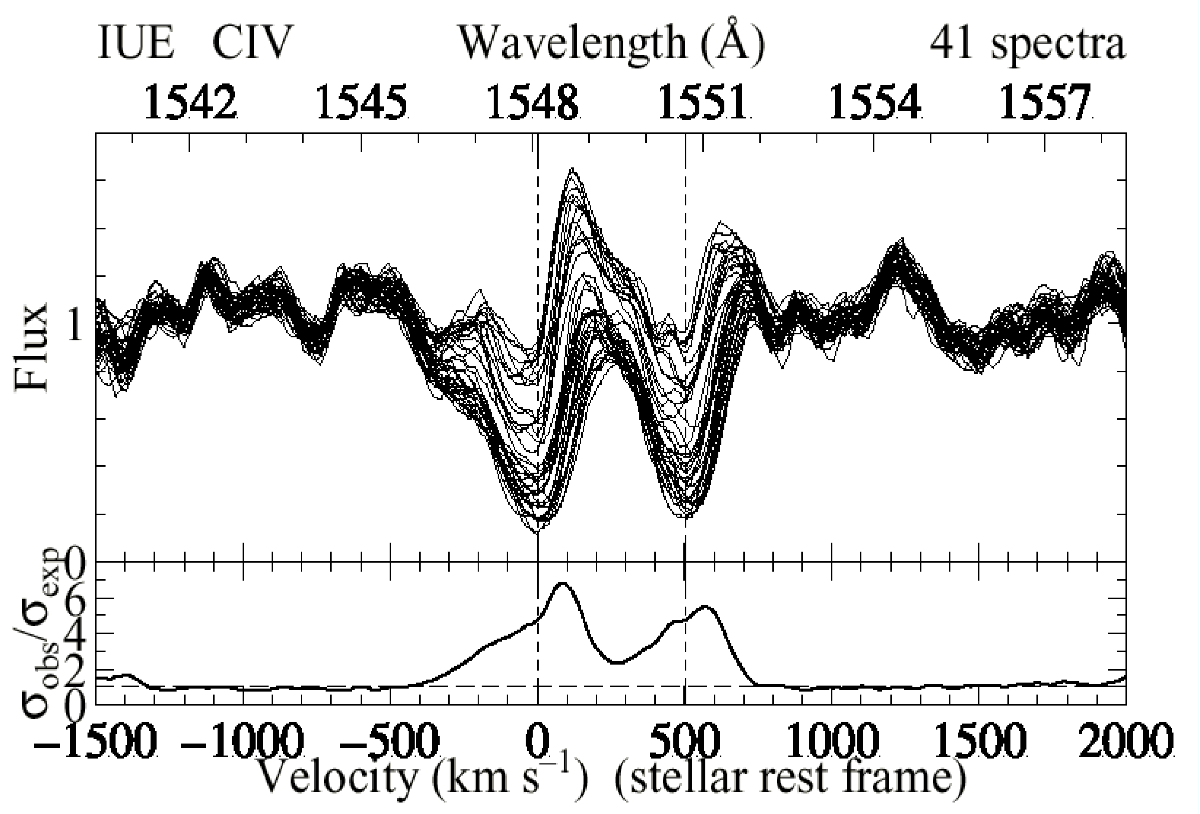
Lightcurve

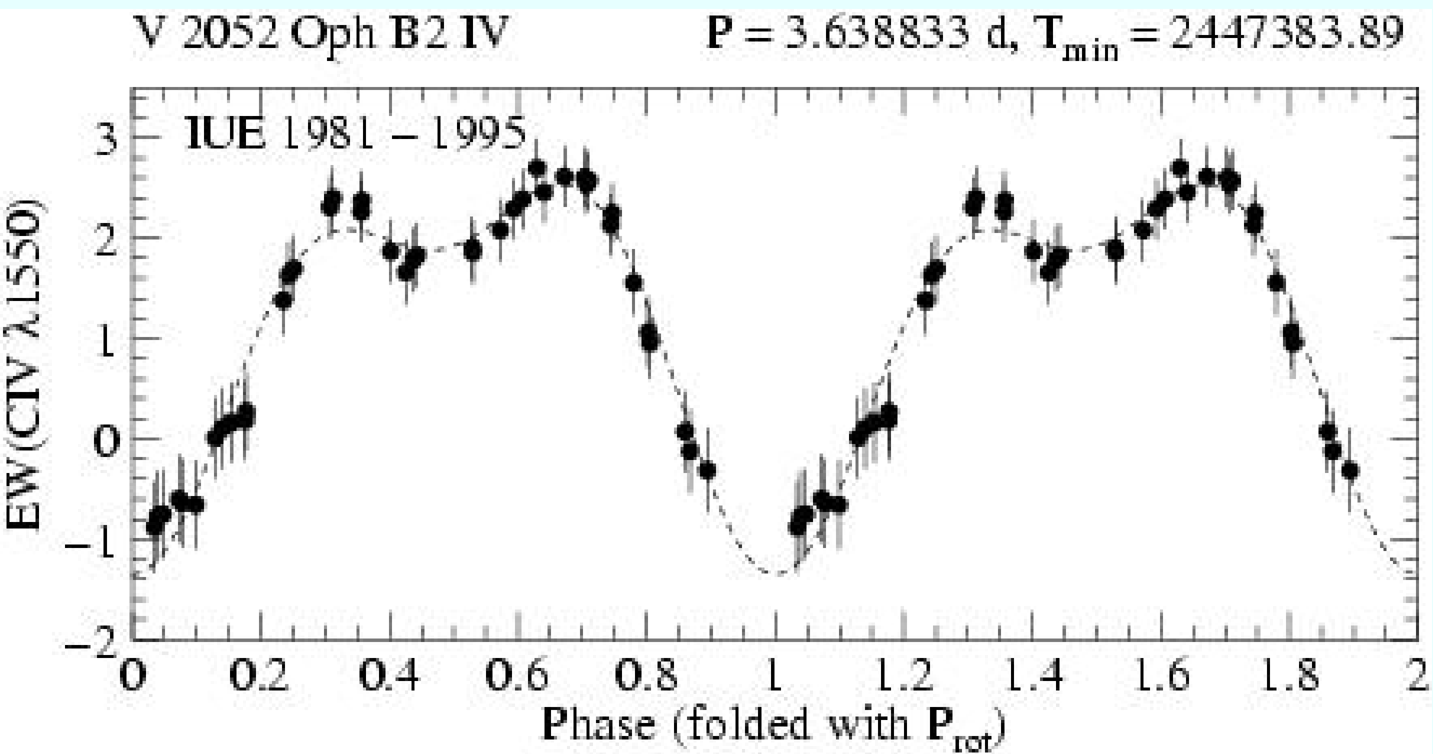
Hα emission

Longitudinal magnetic field

©Townsend

UV wind lines



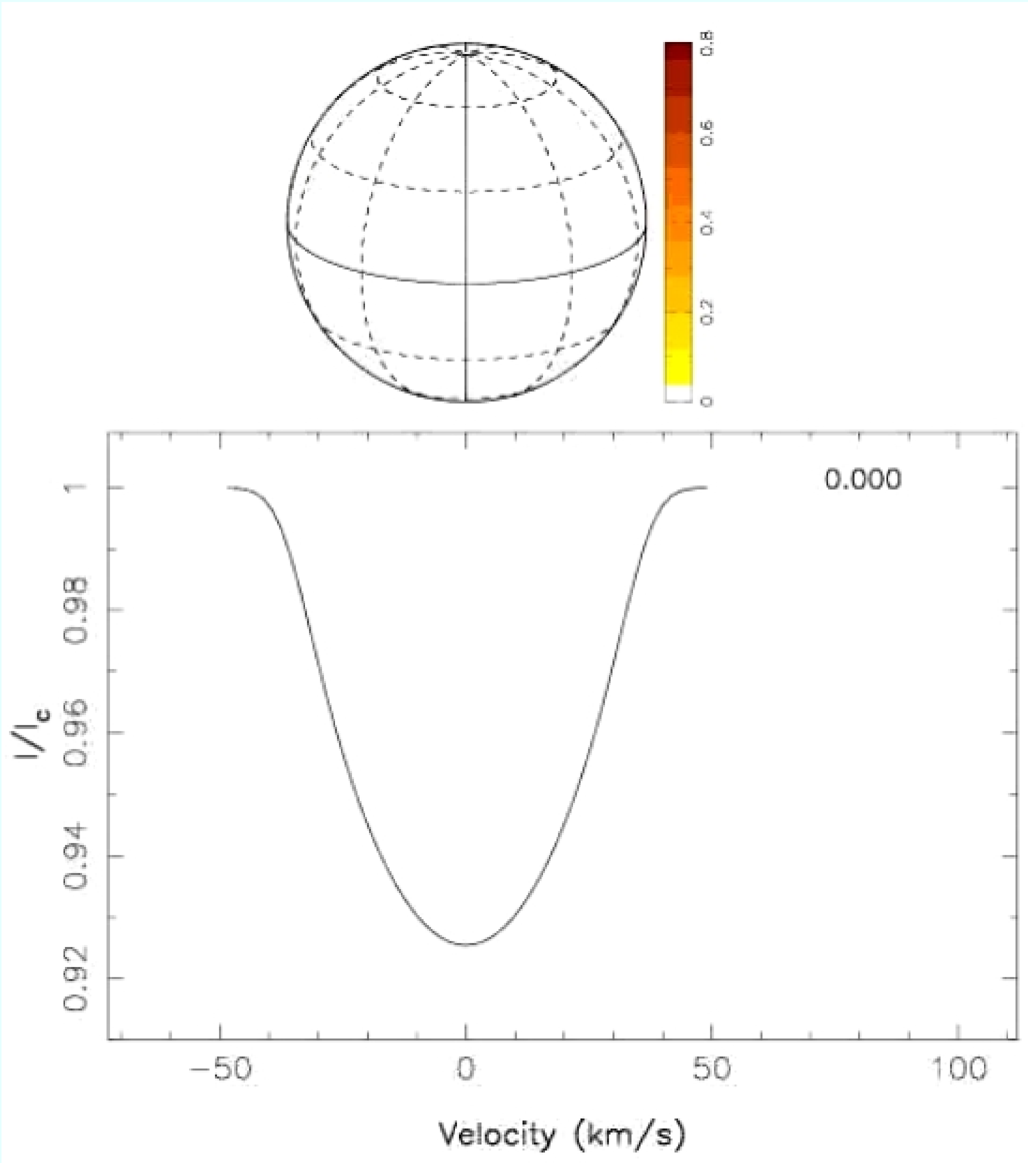


→ Rotation period

→ geometry (i, β)

Neiner et al. 2003a

Spots at the surface



©*Donati*

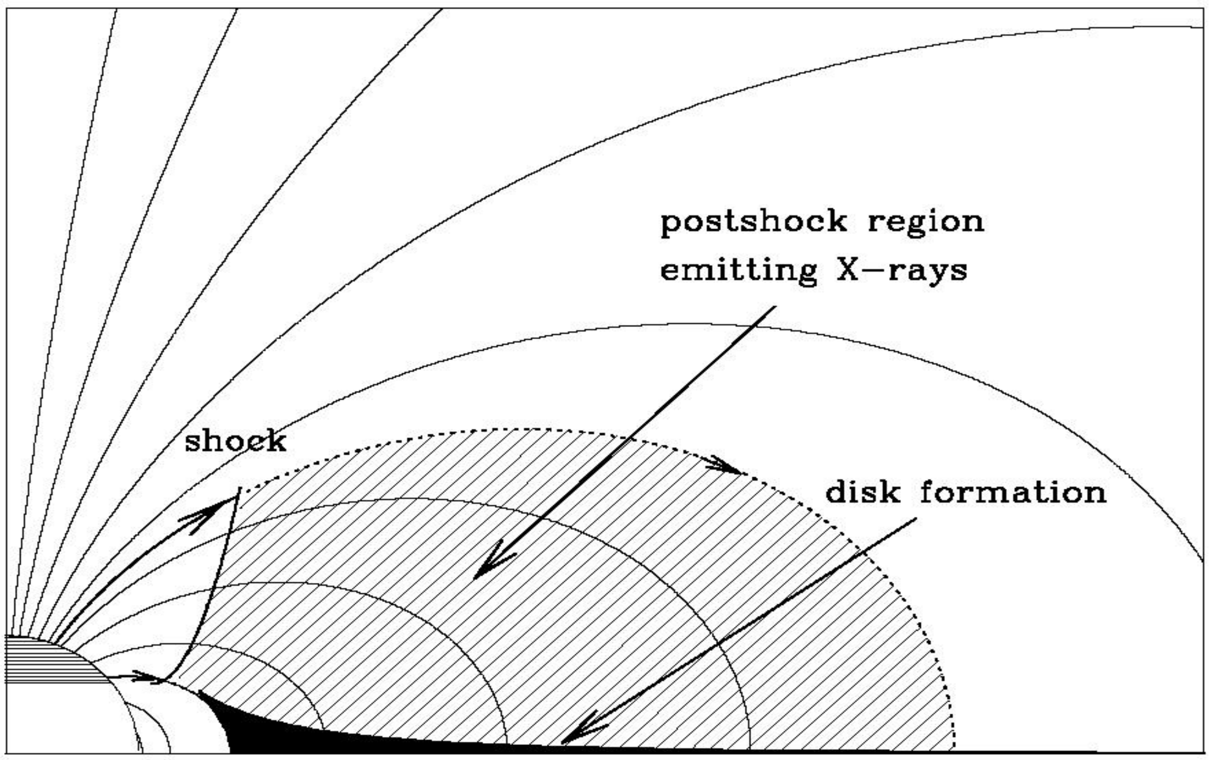
Surface chemical inhomogeneities due to magnetic fields
→ produce variations in spectral and photometric quantities
→ visible in the field

Magnetosphere: X-rays

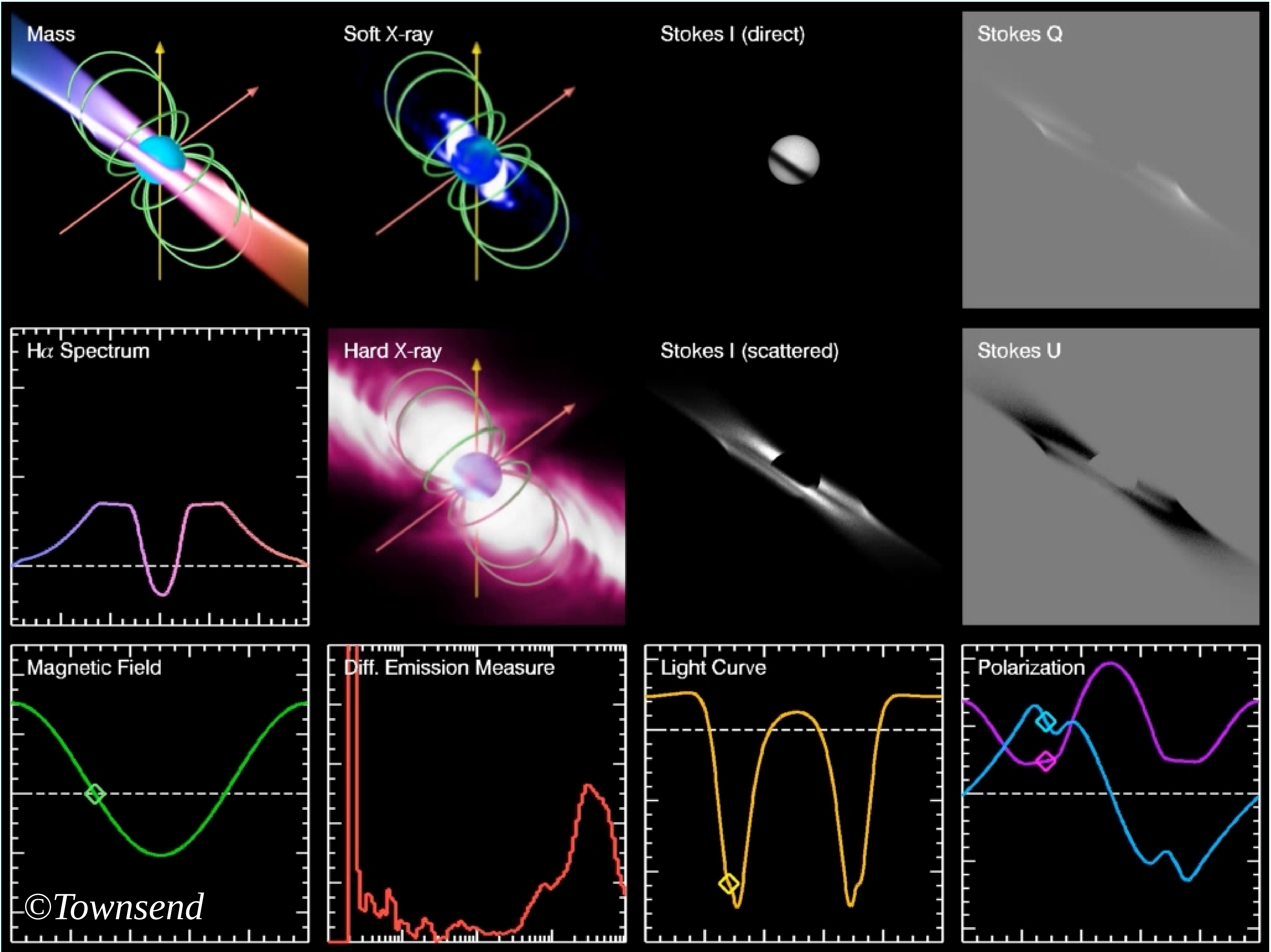
X-rays detections from shocks between wind particles coming from both magnetic poles

→ X-ray emission in the magnetic equator plane

→ X-ray emission modulated by rotation



Babel & Montmerle, 1997



Mass
Soft X-ray
Stokes I (direct)
Stokes Q
Hα Spectrum
Hard X-ray
Stokes I (scattered)
Stokes U
Magnetic Field
Diff. Emission Measure
Light Curve
Polarization
©Townsend

Magnetic confinement

$\eta_* = B^2 R^2 / \dot{M} V_\infty$

$\eta_* > 1 \rightarrow$ confinement

Alfven radius

$R_A / R_* = \eta_*^{1/2n} \rightarrow$ confinement only below R_A

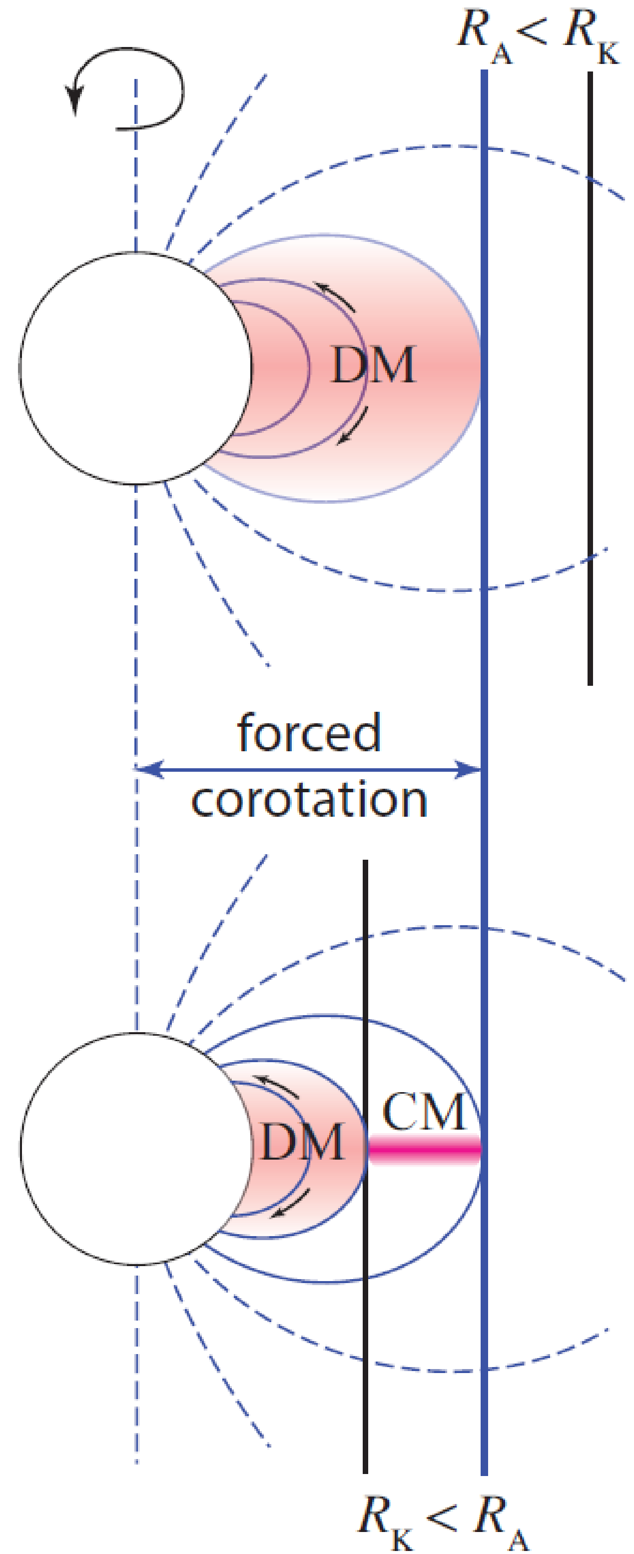
Kepler corotating radius (g force = centrifugal force)

$R_K / R_* = V_{rot} / V_{crit} \rightarrow$ centrifugal support only above R_K

$r < R_A$ and $\eta_* > 1 \rightarrow$ Magnetosphere

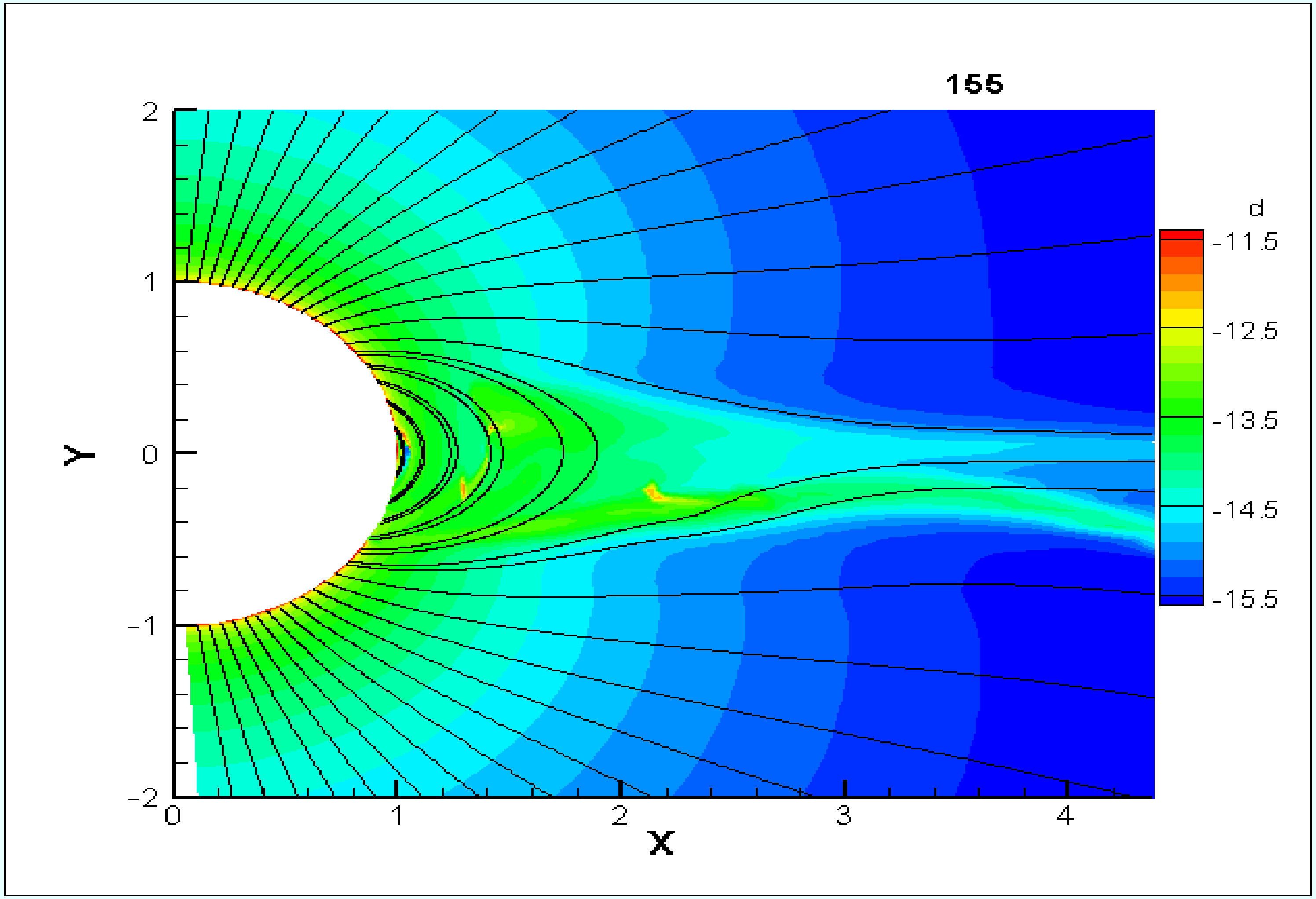
$r < R_K \rightarrow$ Dynamical magnetosphere

$r > R_K \rightarrow$ Centrifugally supported magnetosphere



Petit et al. 2013

Dynamical magnetosphere



MHD simulations

©*Ud Doula*

Magnetic confinement

$\eta_* = B^2 R^2 / \dot{M} V_\infty$

$\eta_* > 1 \rightarrow$ confinement

Alfven radius

$R_A / R_* = \eta_*^{1/2n} \rightarrow$ confinement only below R_A

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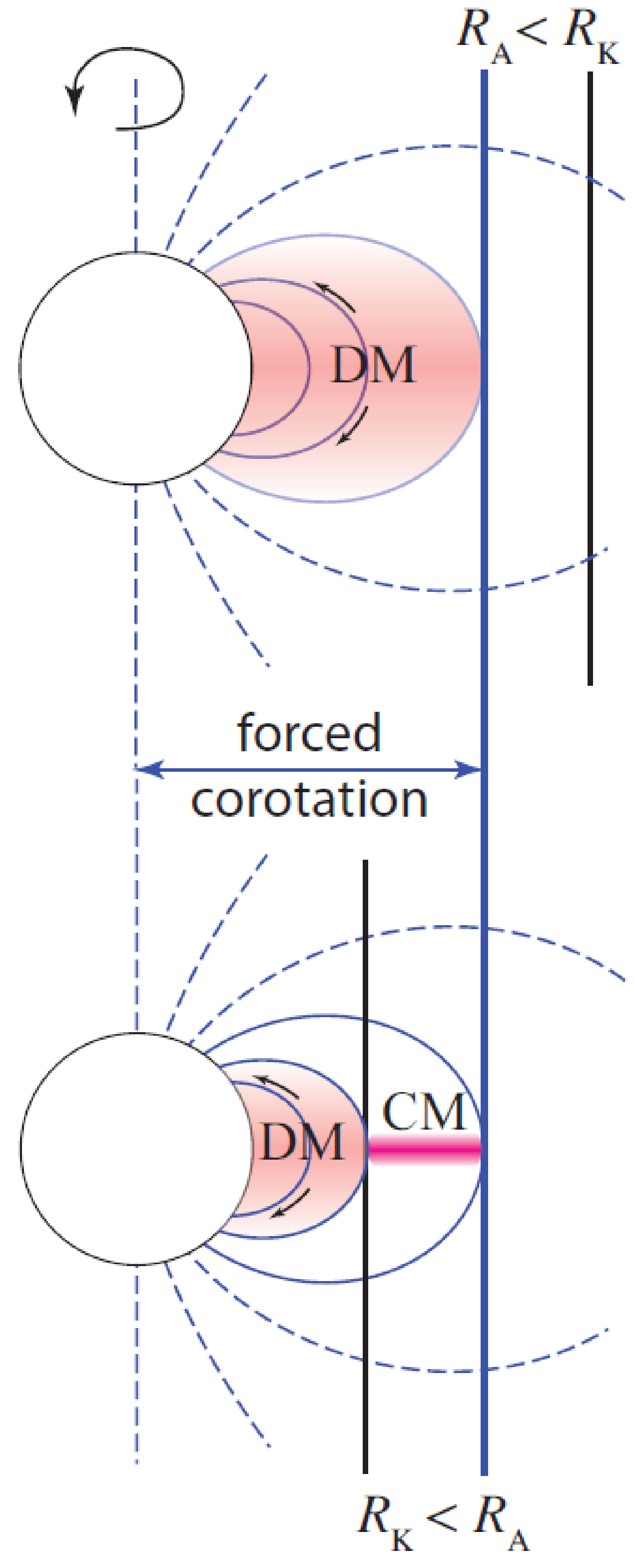
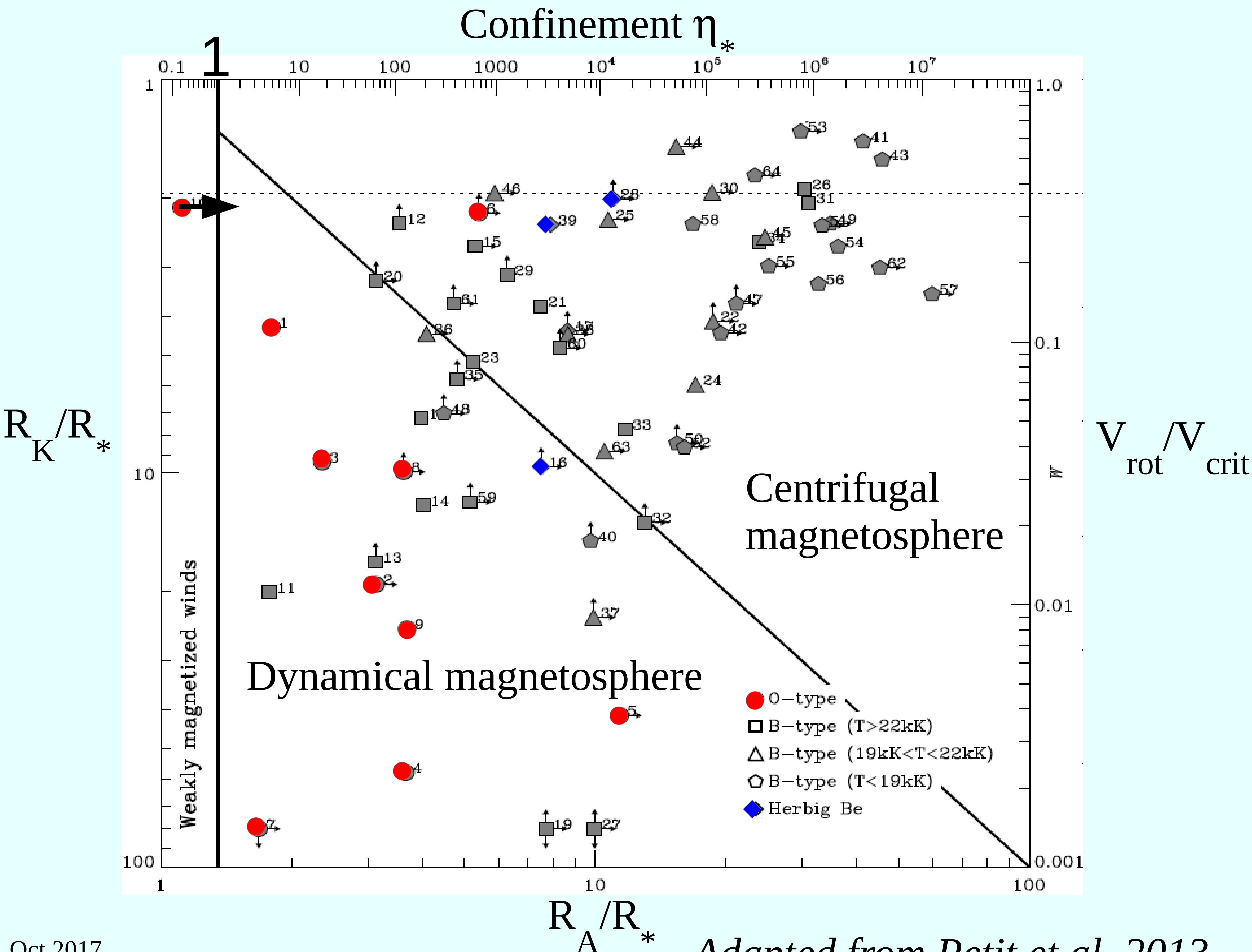


Petit et al. 2013

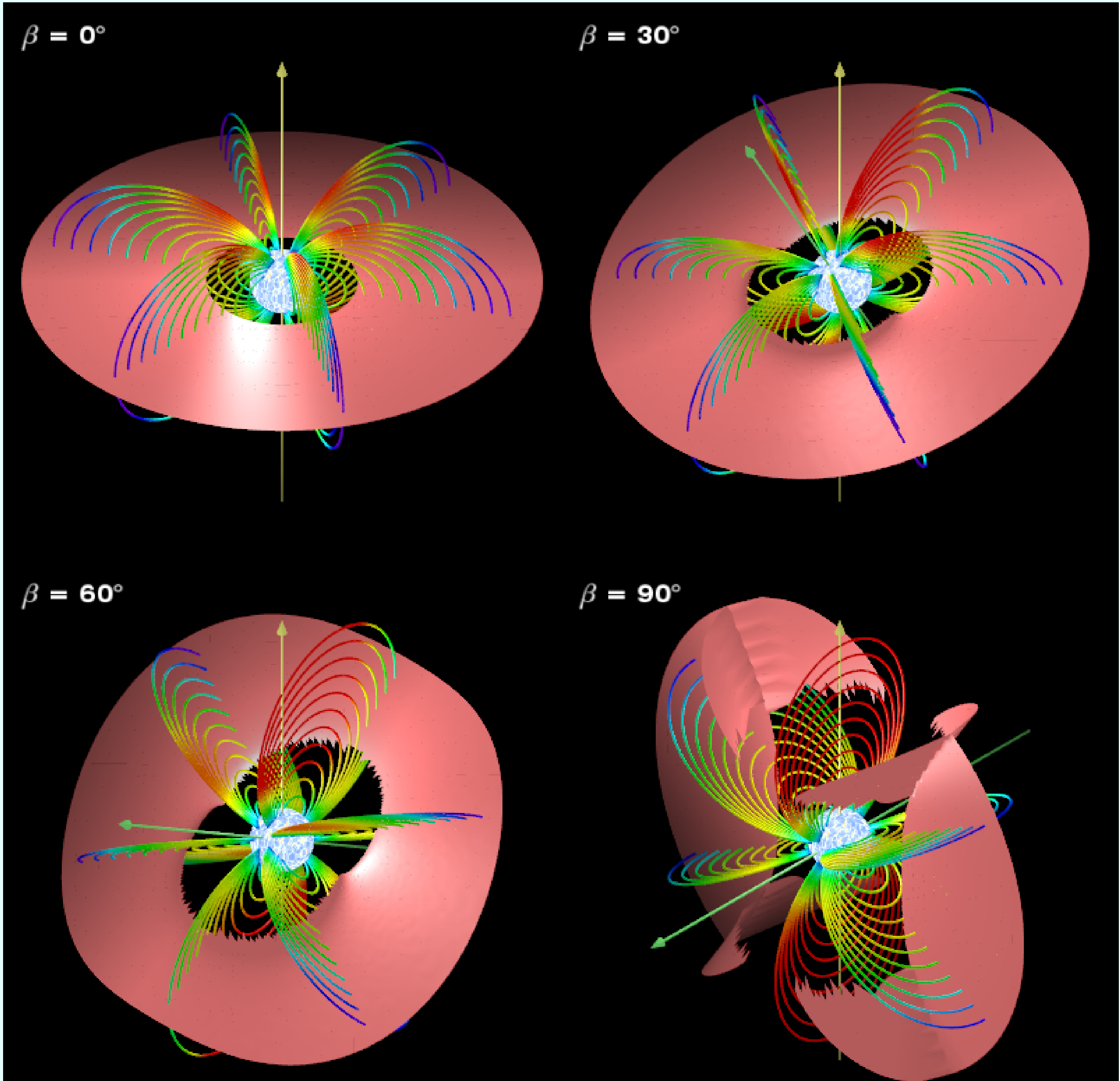
Rotation vs Magnetic confinement diagram



Adapted from Petit et al. 2013

Magnetism in Be stars

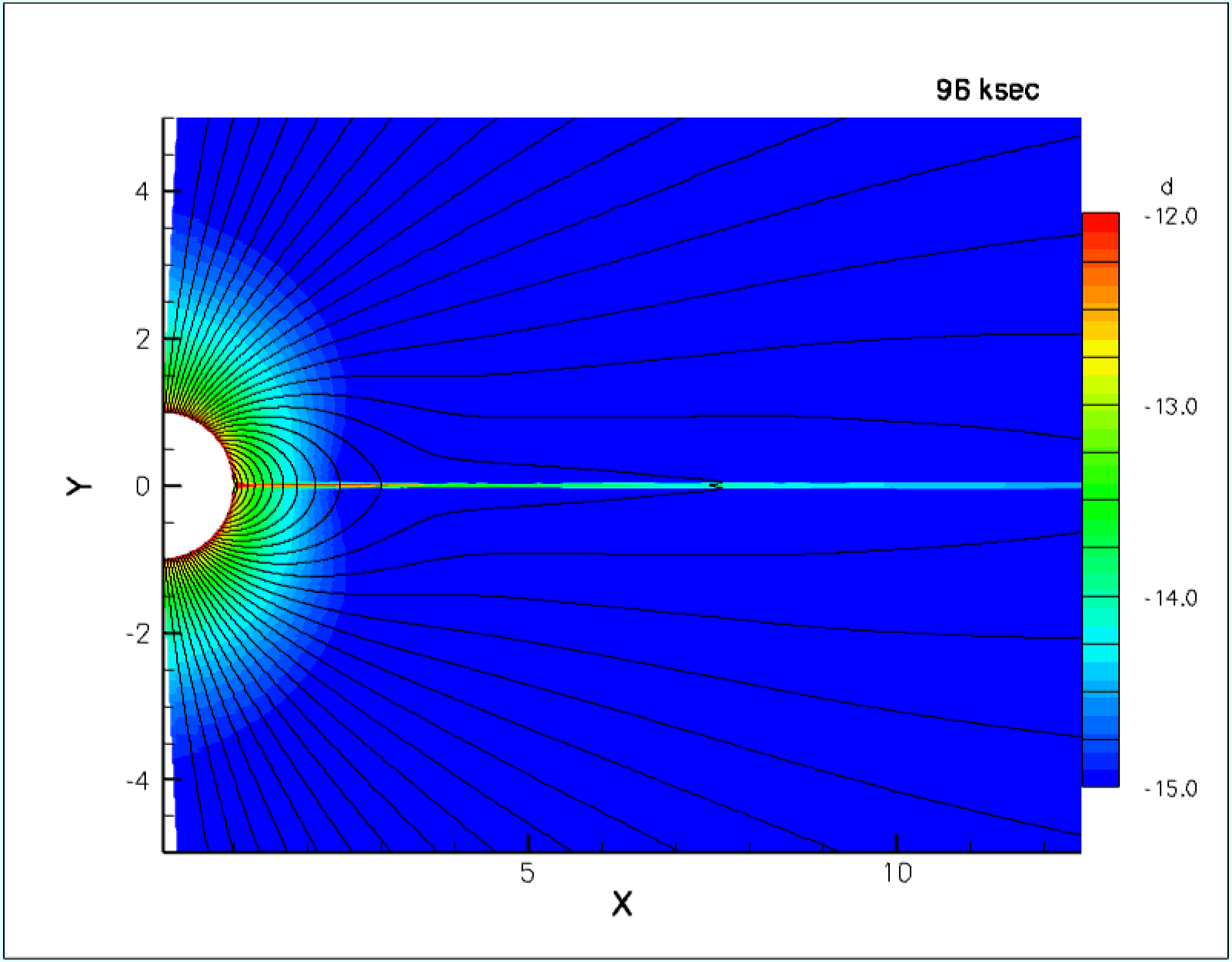
Could the Be disk be a corotating magnetically confined disk?...



Townsend & Owocki 2005

Magnetism in Be stars

… or Keplerian disk fed by breakouts of the field lines?



©Ud Doula

Detecting fields in Be stars is challenging

It is more difficult to detect magnetic fields if :

- the field is weak...
- the star rotates fast (Stokes V signal spread over a larger width)
- the star is hot (less lines for average)
- the star has emission lines (excluded from average)
- the star pulsates (short exposures only)

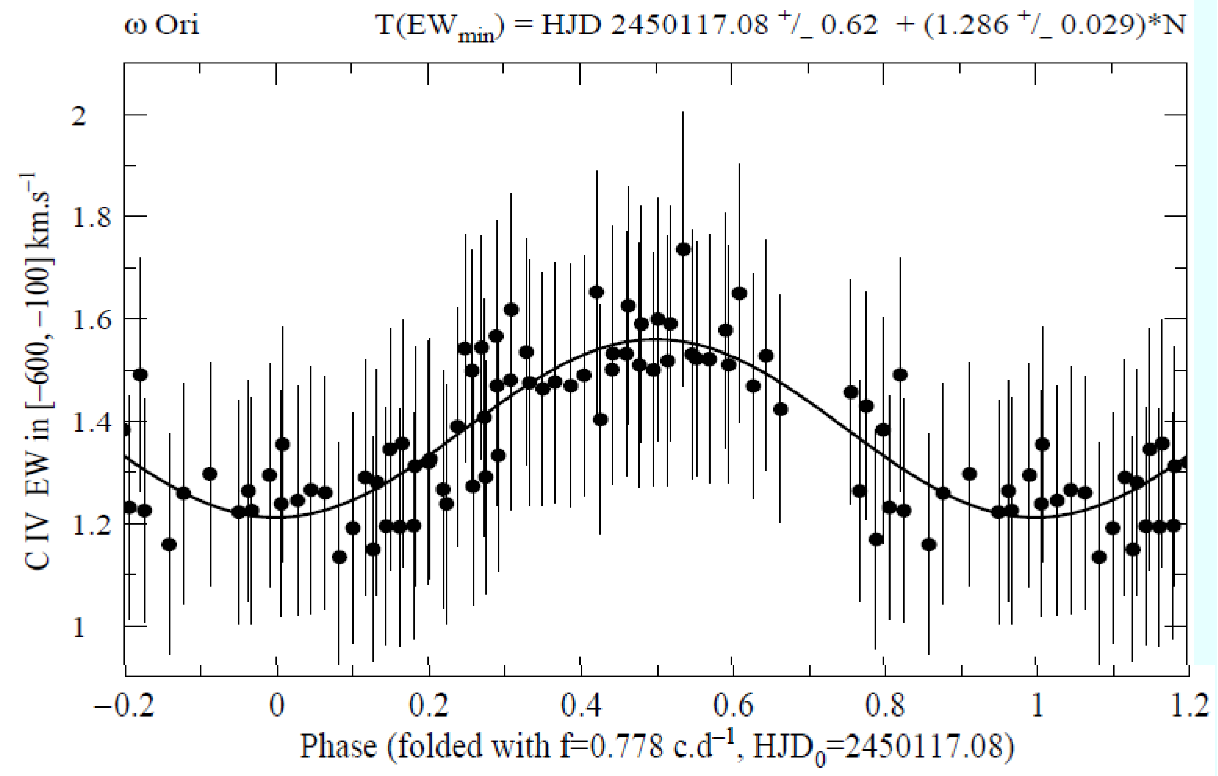
→ particularly challenging for Be stars

Magnetism in Be stars

- 43 Be stars observed with MiMeS
- No direct field detection
- Rather large upper limits on undetected fields (B_l ~ 150 G)

ω Ori (B2IIIe) shows indirect signs of the presence of a magnetic field and confined clouds :

- in the UV wind lines



Neiner et al. 2003c

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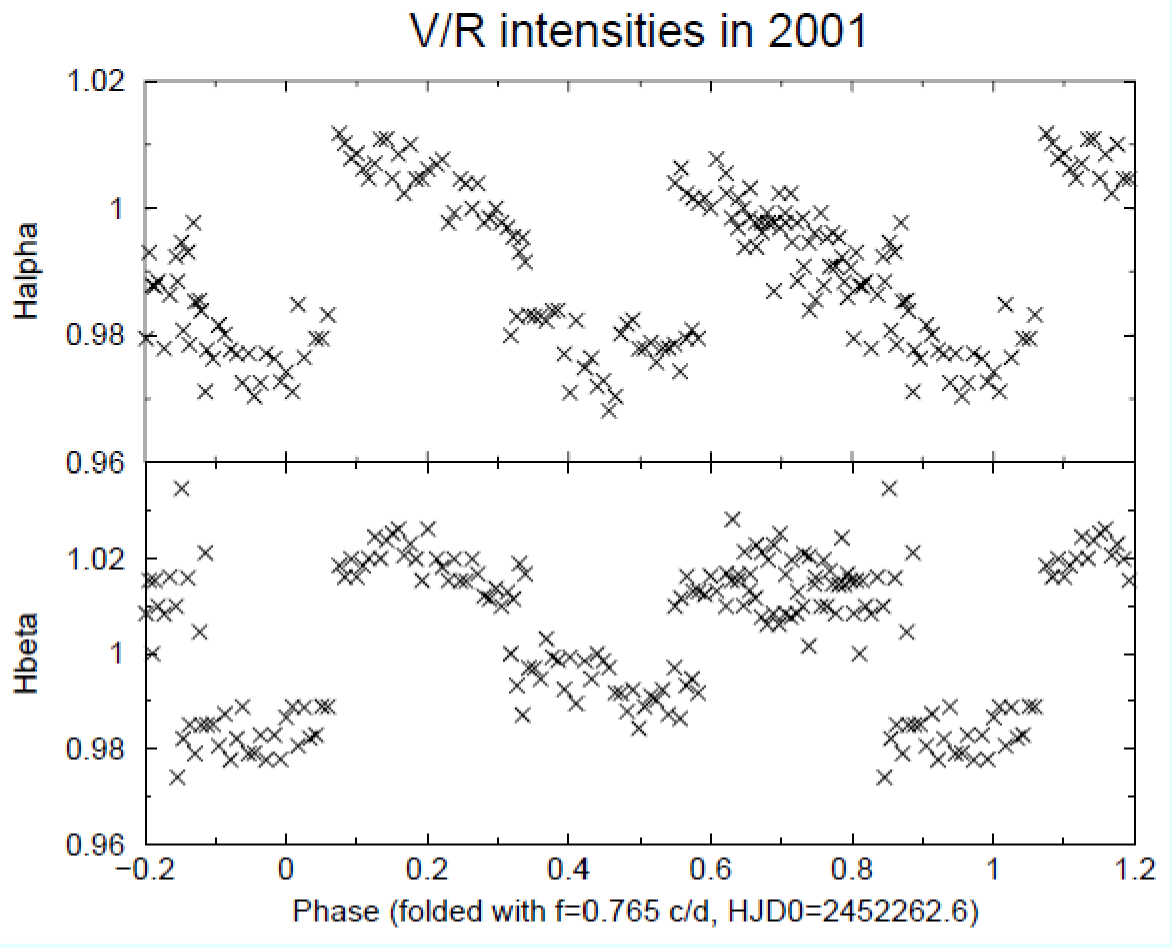

Neiner et al. 2003c

Magnetism in Be stars

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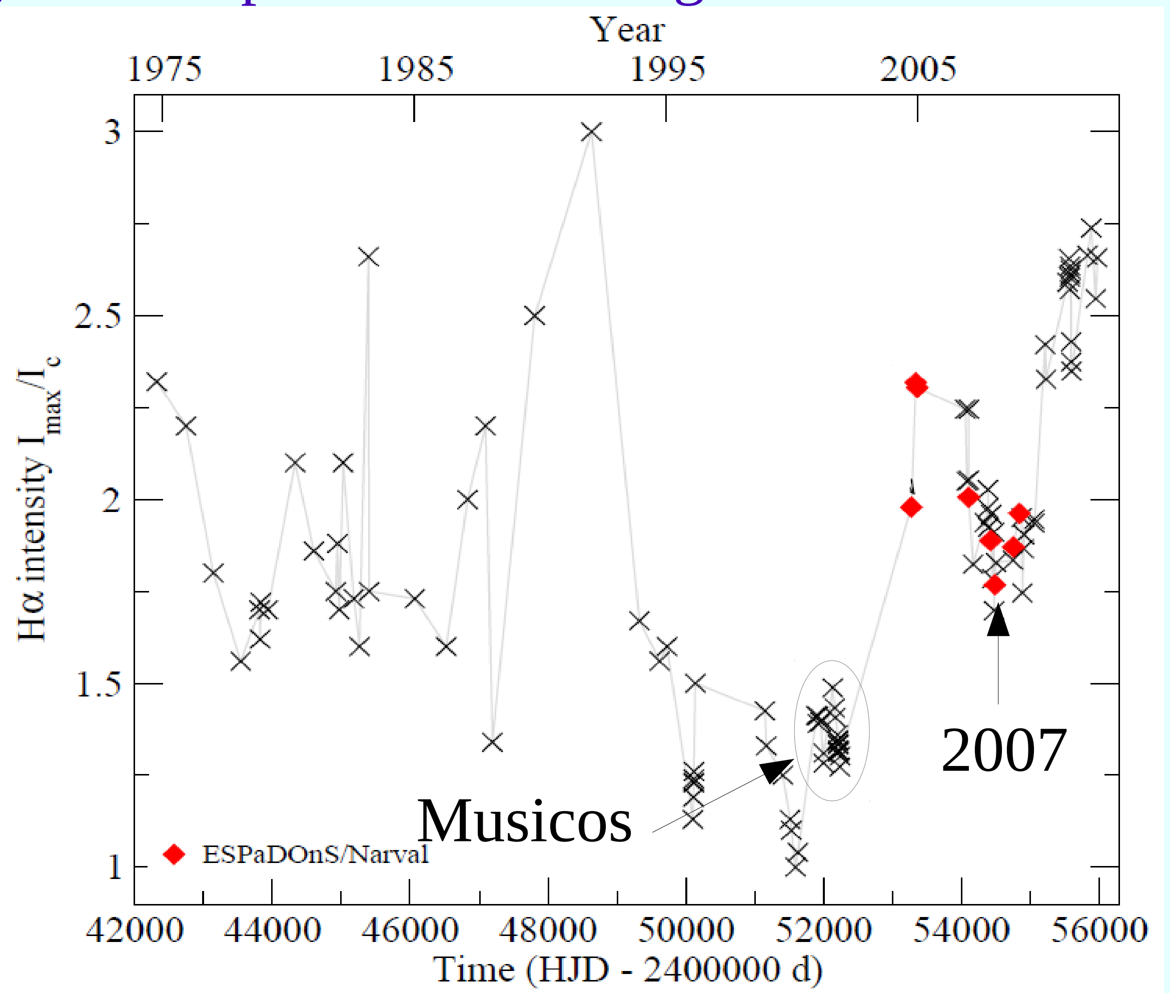
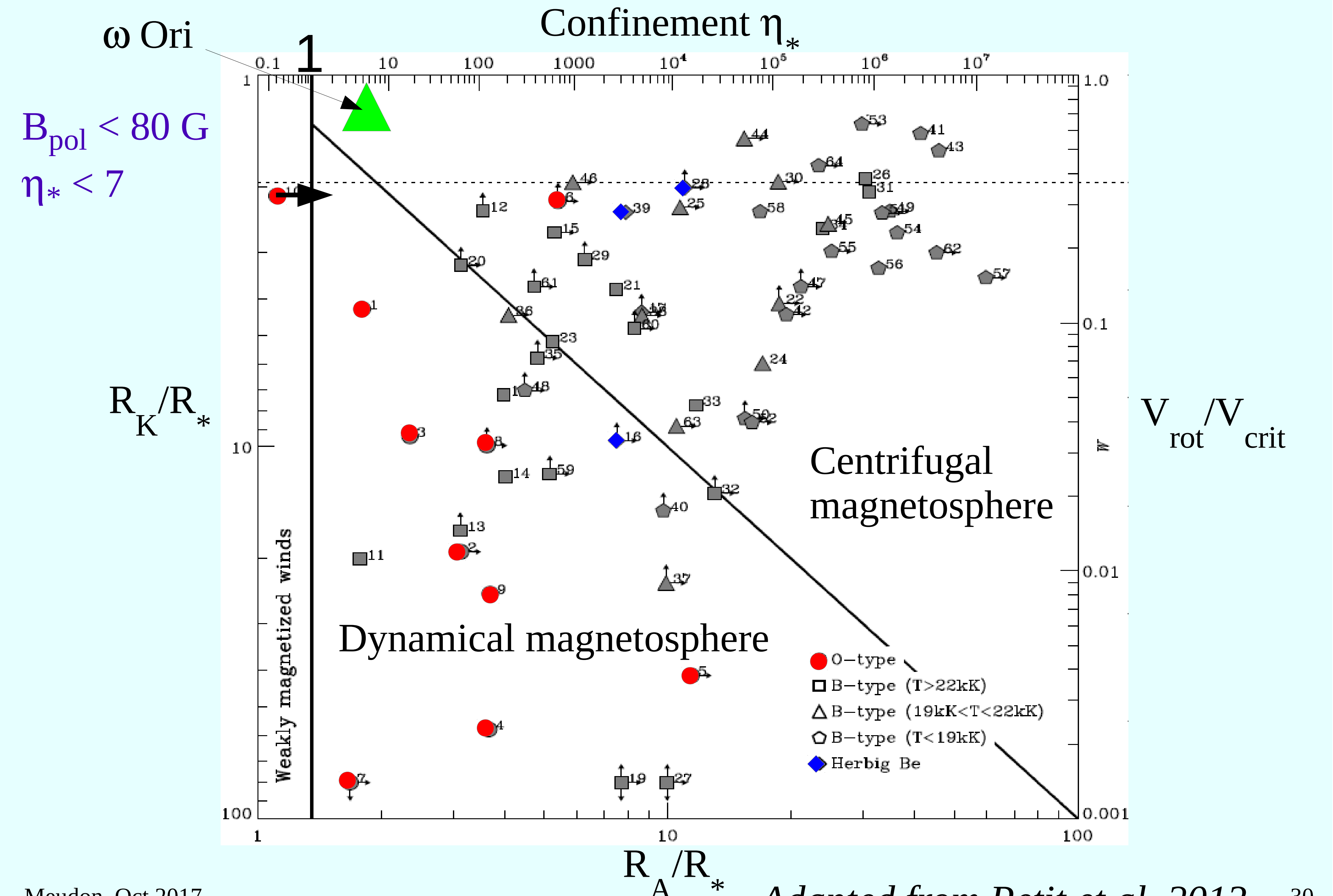
ω Ori (B2IIIe) shows indirect signs of the presence of a magnetic field and confined clouds :

- in the UV wind lines
- in Musicos data from 2001
- in ESPaDOnS/Narval data from 2007 (but not from 2005 and 2008)
  → no signs of confined material at outburst times



Neiner et al. 2012c

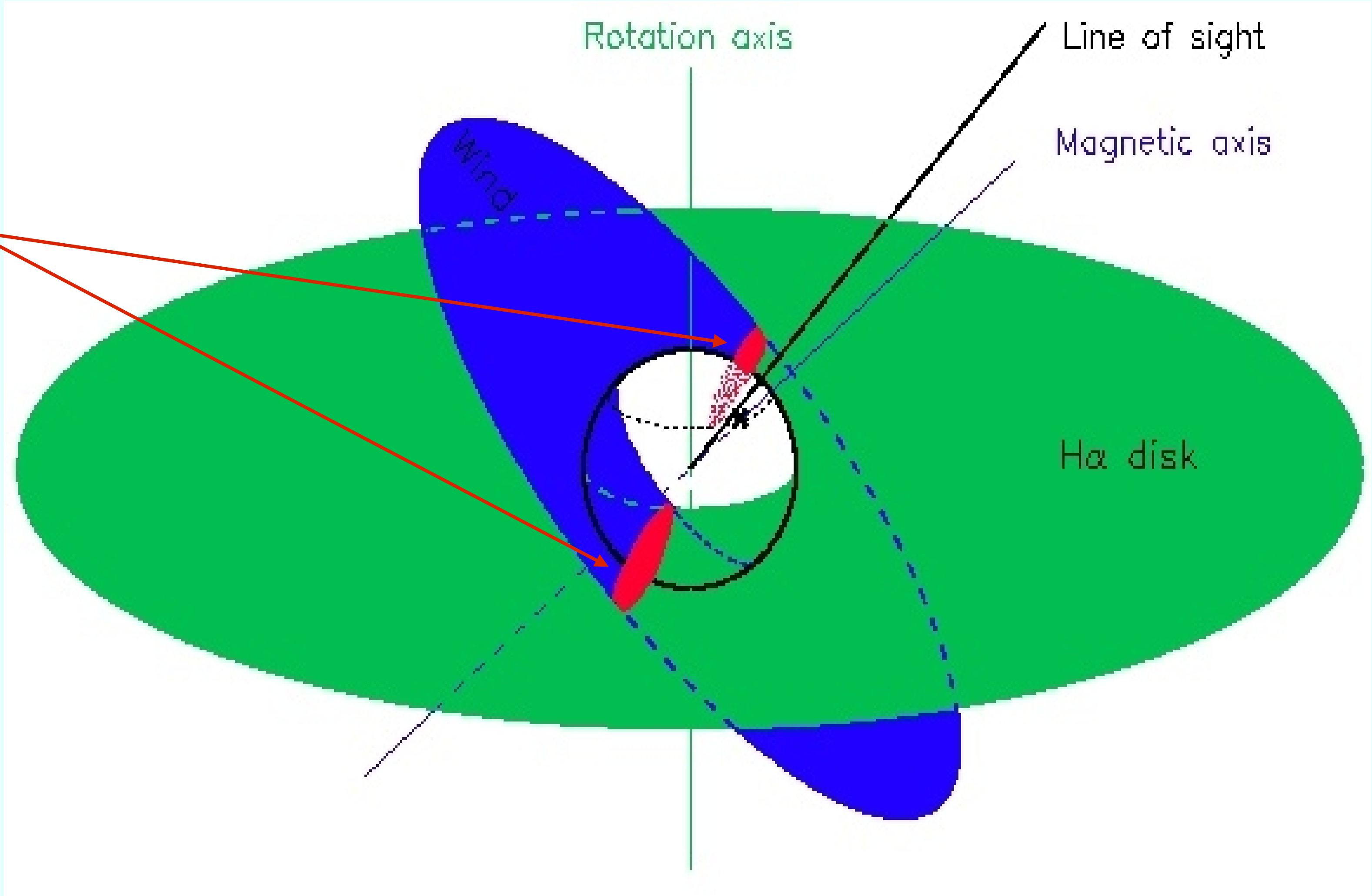
ω Ori: confinement



Adapted from Petit et al. 2013

ω Ori: confinement

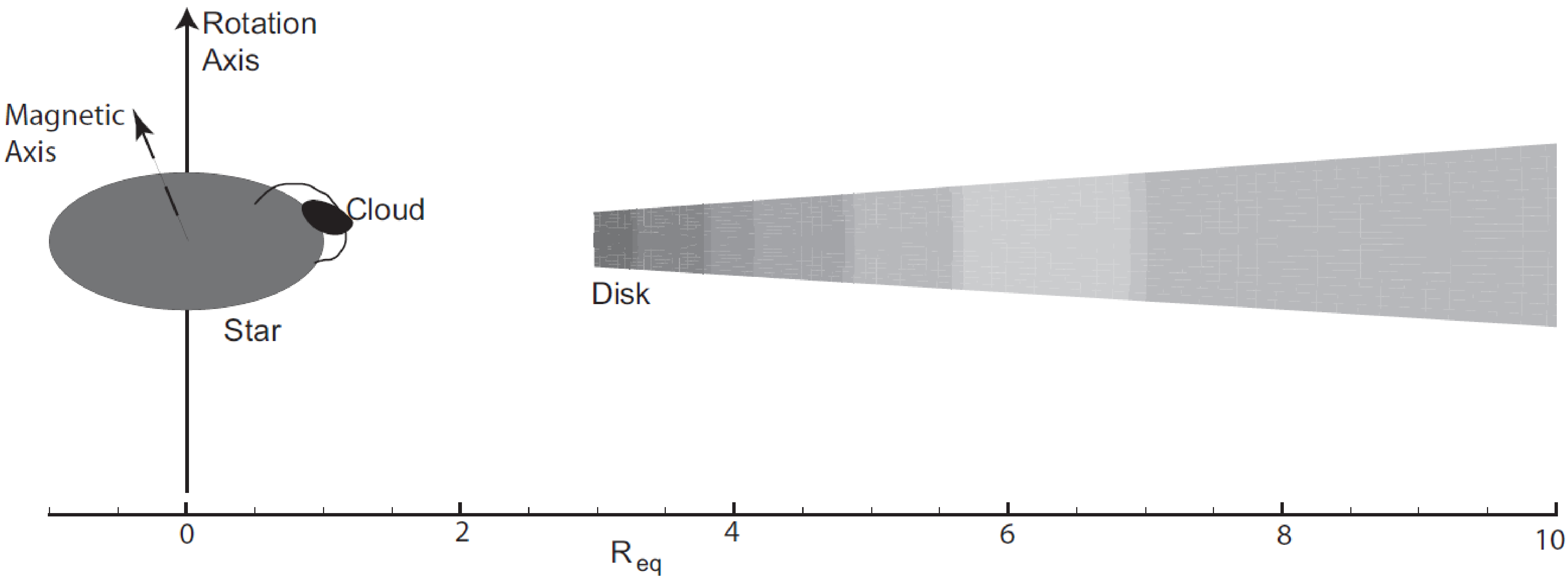
Clouds at the intersection of the equators



Neiner et al. 2003c

→ The clouds are wiped off when an outburst occurs

Magnetic Be stars ?



Neiner et al. 2012c

Magnetic fields in Be stars:

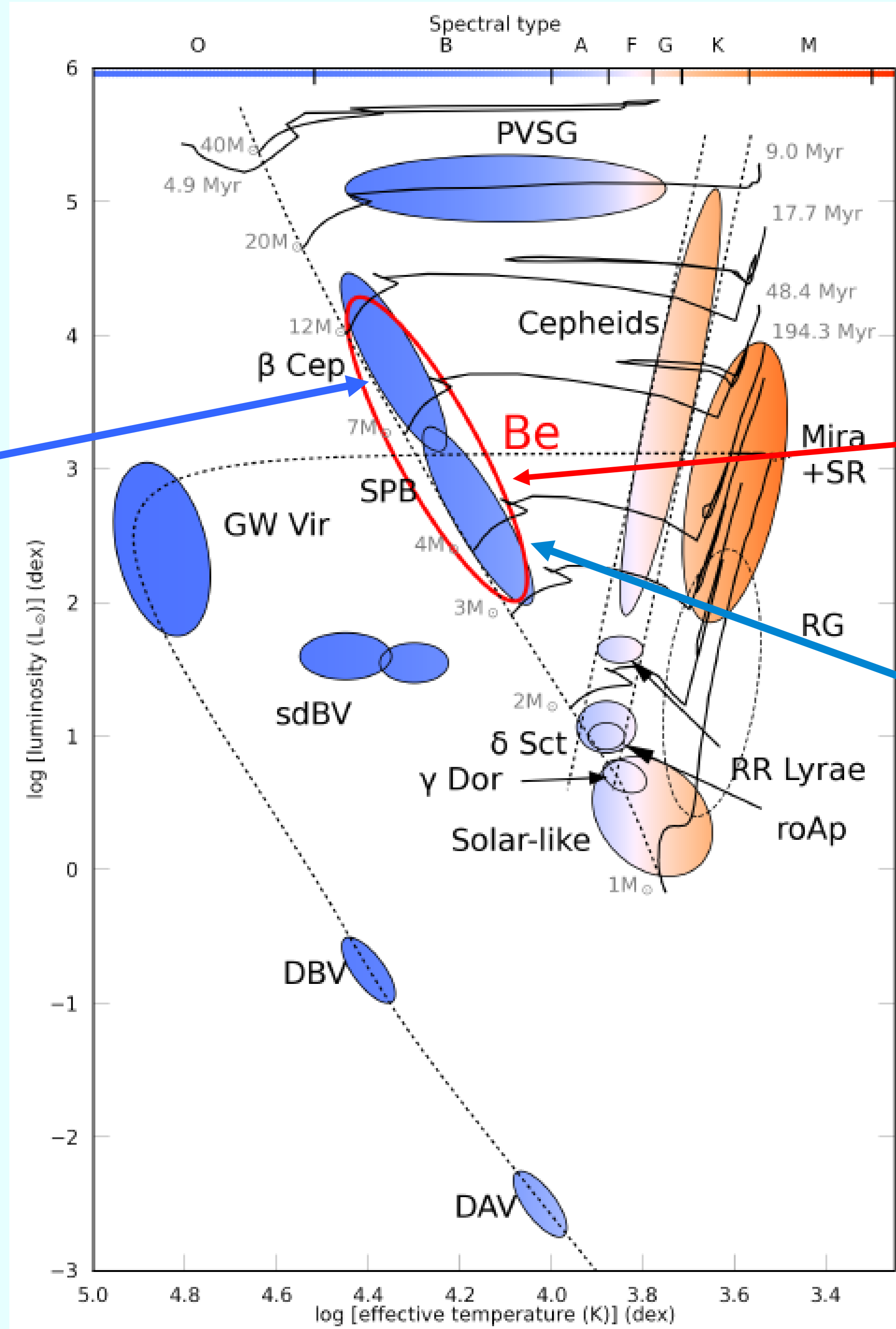
→ can create magnetospheres or clouds close to the star → **magnetic (non-classical) Be stars**

→ can exist in classical Be stars but they are weak (ω Ori)

→ cannot create the Keplerian decretion disk → **The magnetic field is not at the origin of the Be phenomenon**

Pulsations in Be stars?

Pulsations



β Cephei
(p-modes)

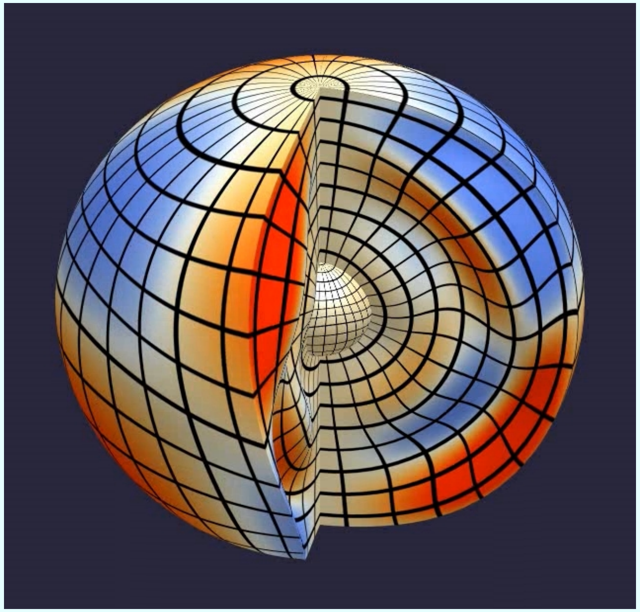
Be
(p and g modes)

SPB
(g-modes)

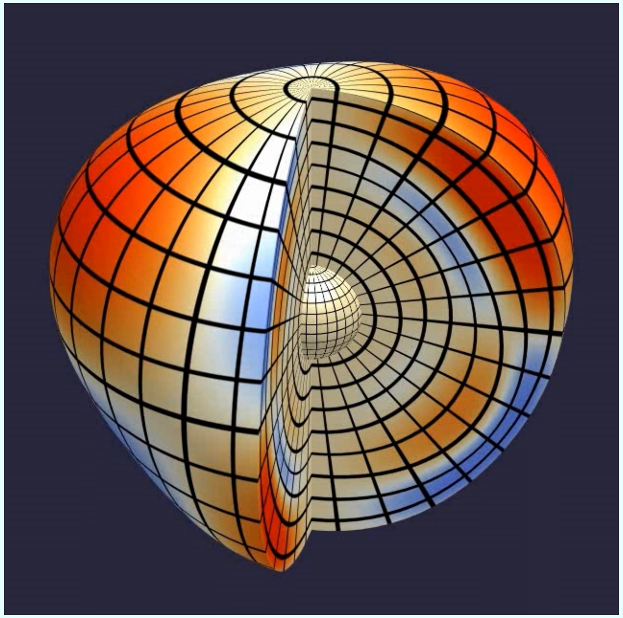
→ κ mechanism

©*Degroote*

g-mode



p-mode



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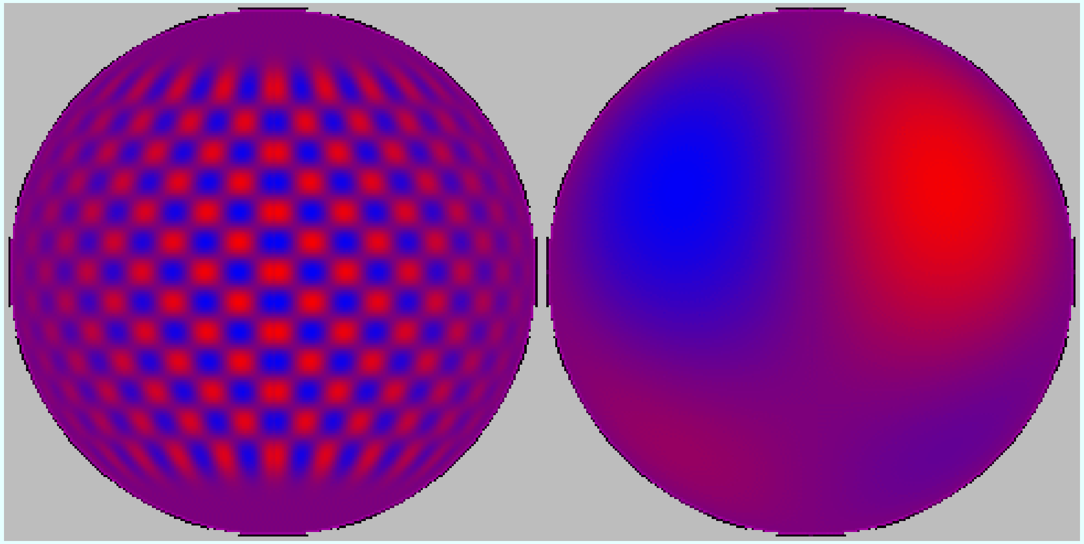
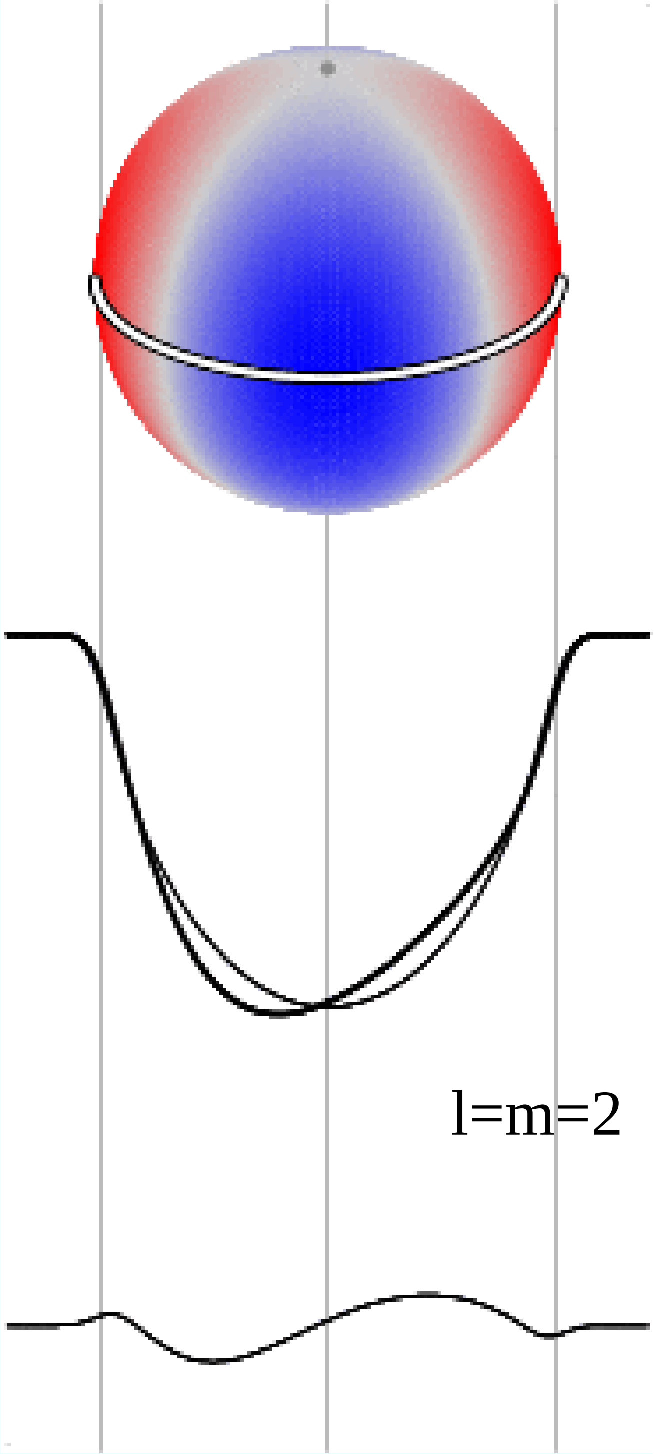




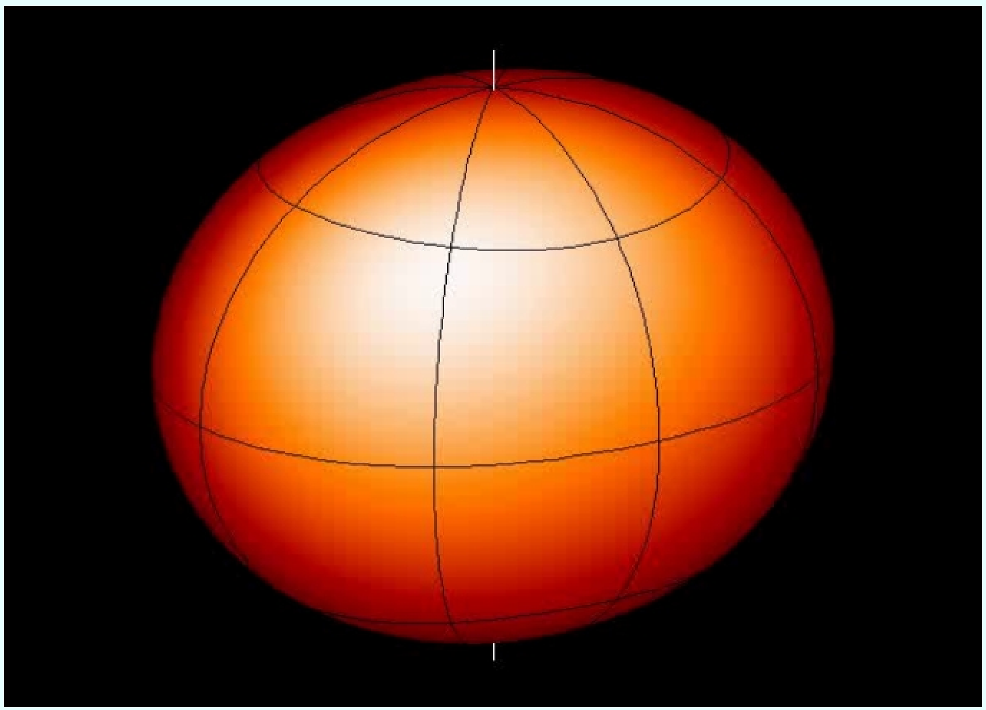
Telting & Schrijvers

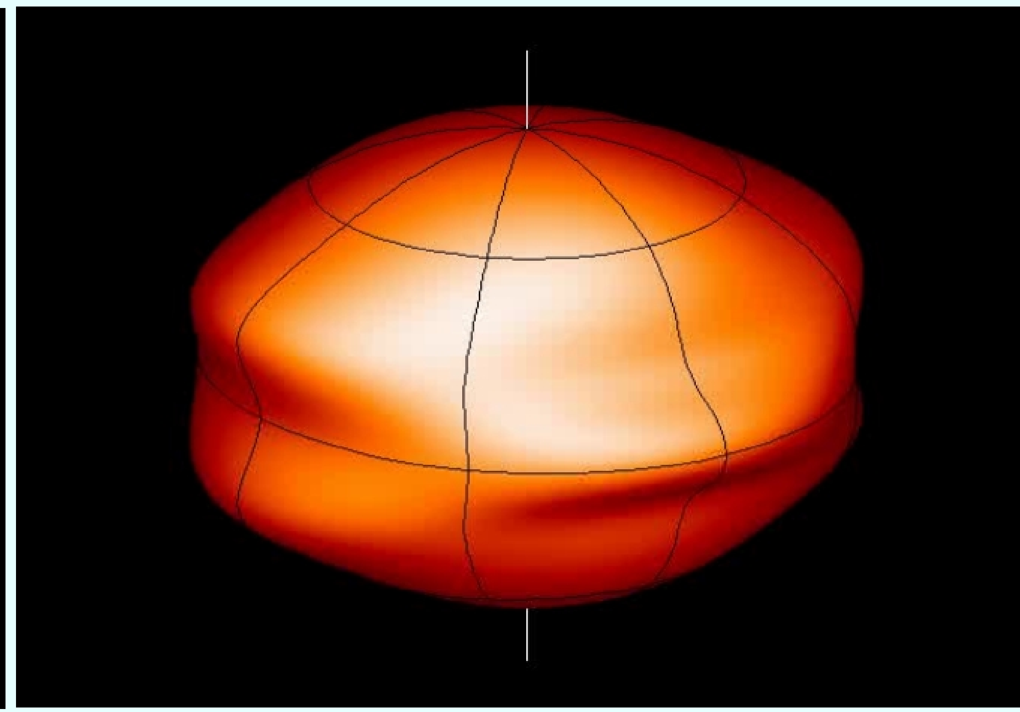
Effect of rapid rotation

Retrograde pulsation mode

No rotation

Rapid rotation

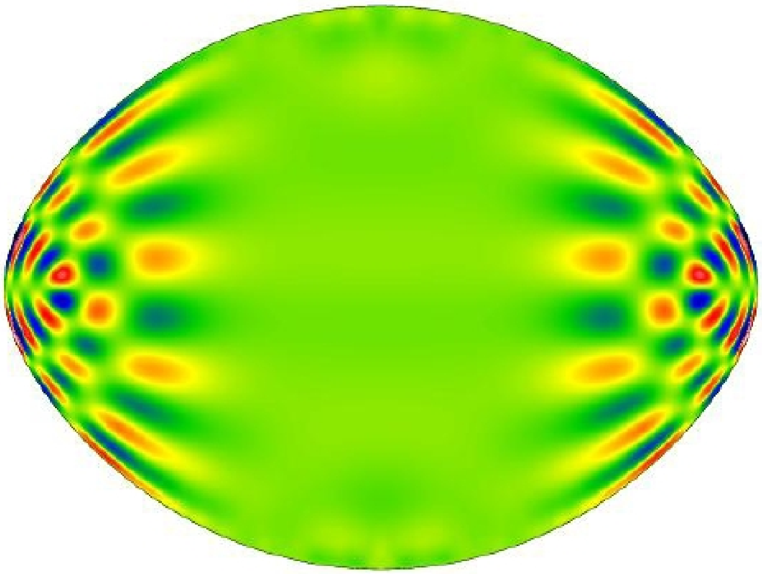




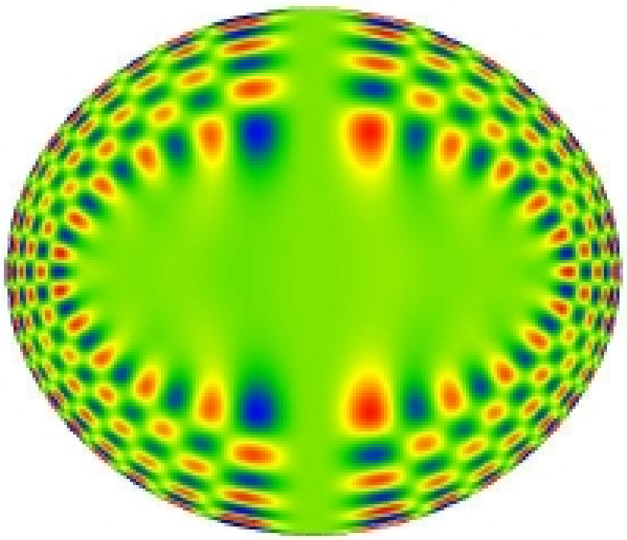
©*Reese*

Rapid rotation produces 3 types of pulsations:

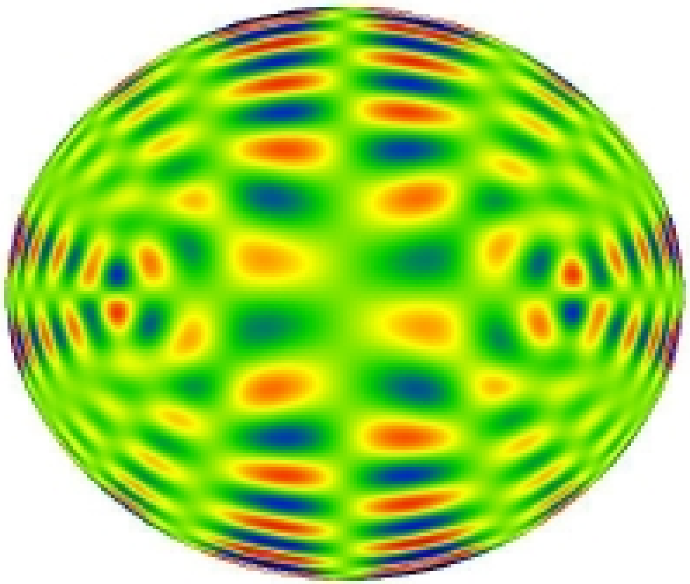
Low degree modes (equatorially focused)



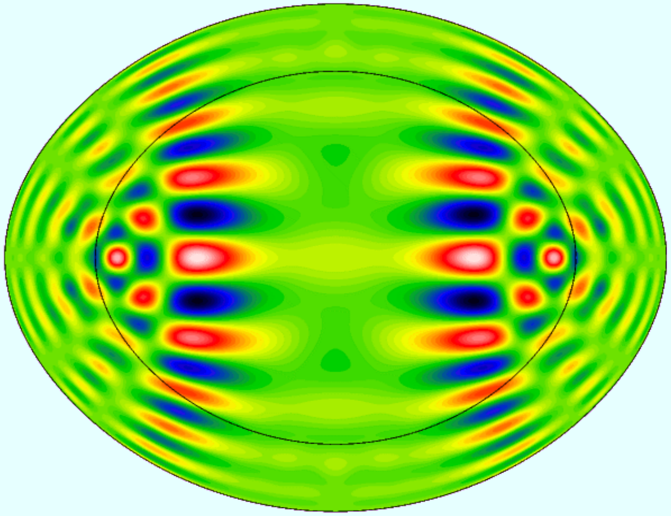
High degree modes (whispering gallery)



Intermediate degree modes (chaotic)



or a mixture of these →

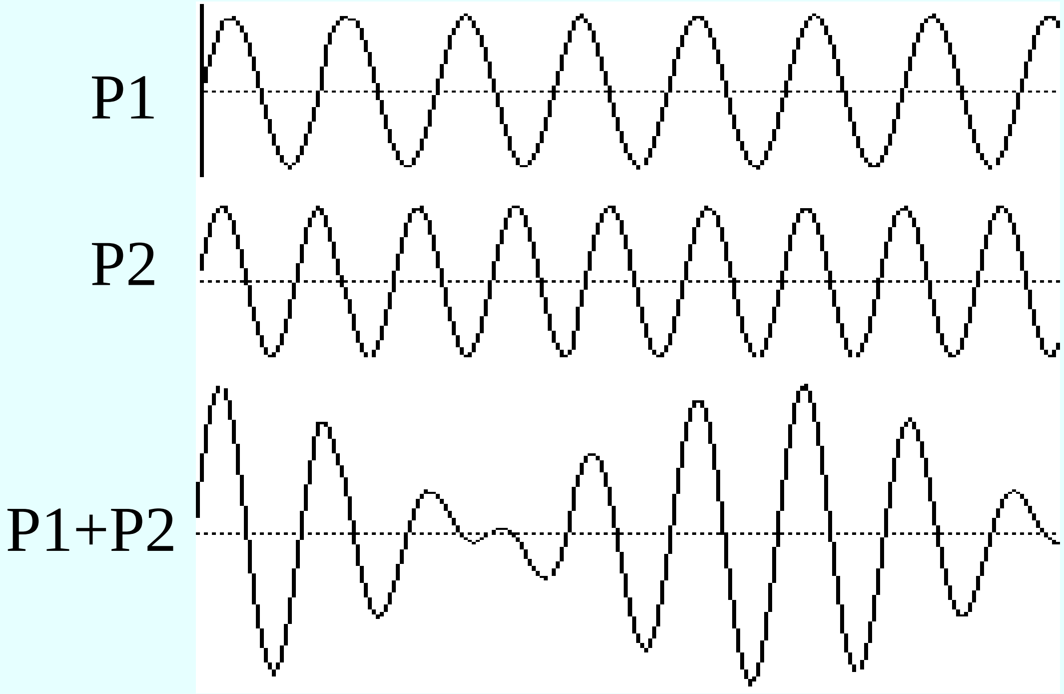


Could pulsations explain Be outbursts ?

Pulsations could:

- bring additional angular momentum locally when they are at their maximum of amplitude

- create constructive interference (beatings), to bring even more angular momentum



Pulsation beatings

Multiperiodicity in Be star μ Cen, vsini=140 km/s

- 2 groups of periods:

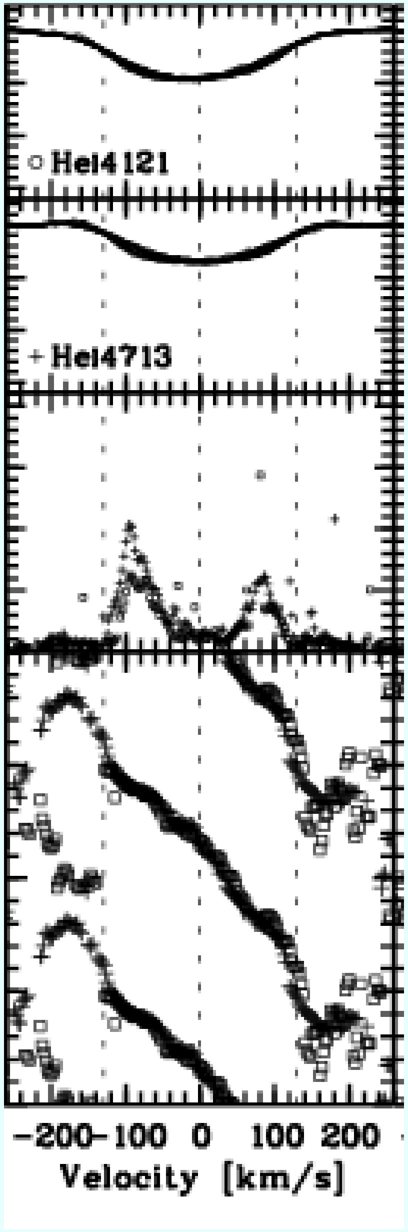
P_1-P_4 ~ 0.505 d

P_5-P_6 ~ 0.280 d

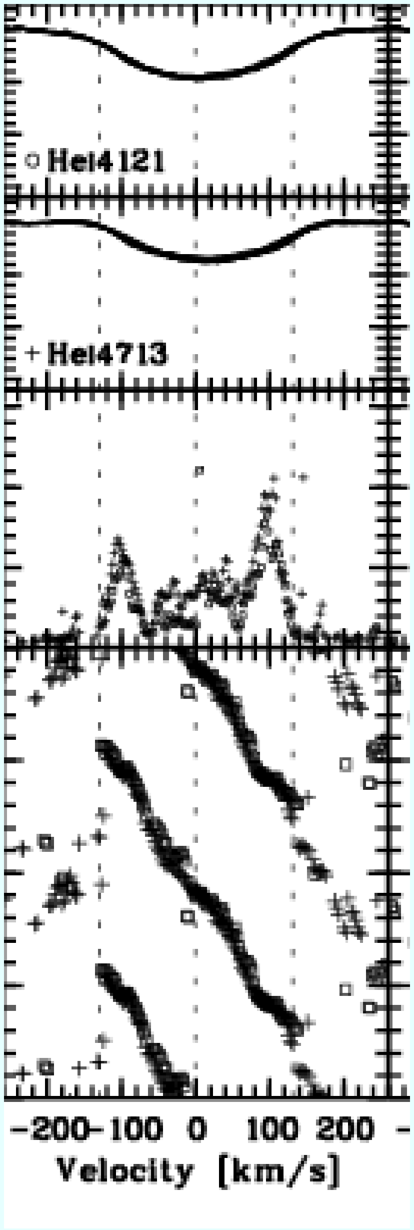
- Separation of peaks in each group: 0.01-0.02d

→ produce beatings

Rivinius et al. 1998a

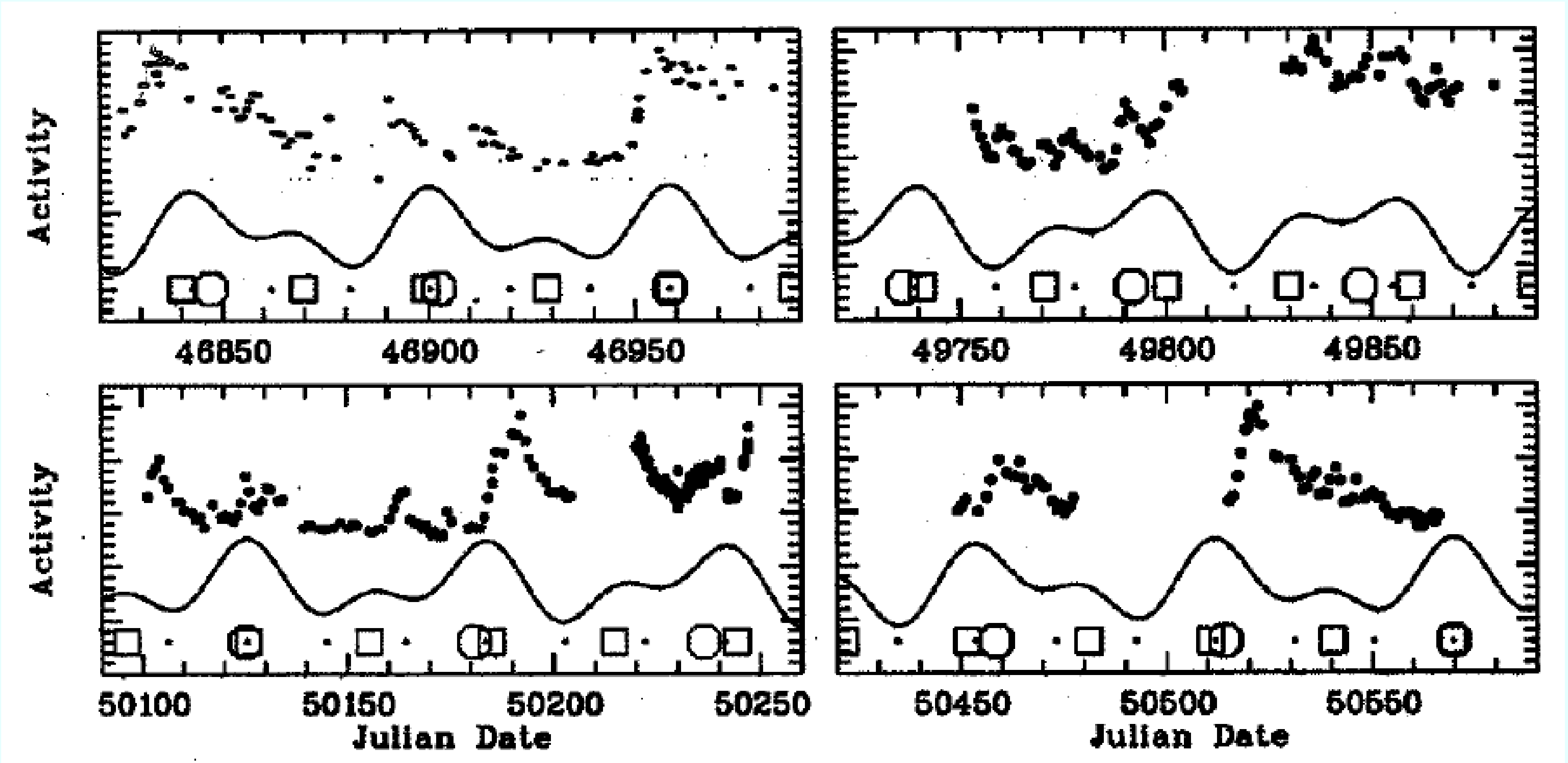


P_1=0.503 d



P_5=0.281 d

Be outbursts

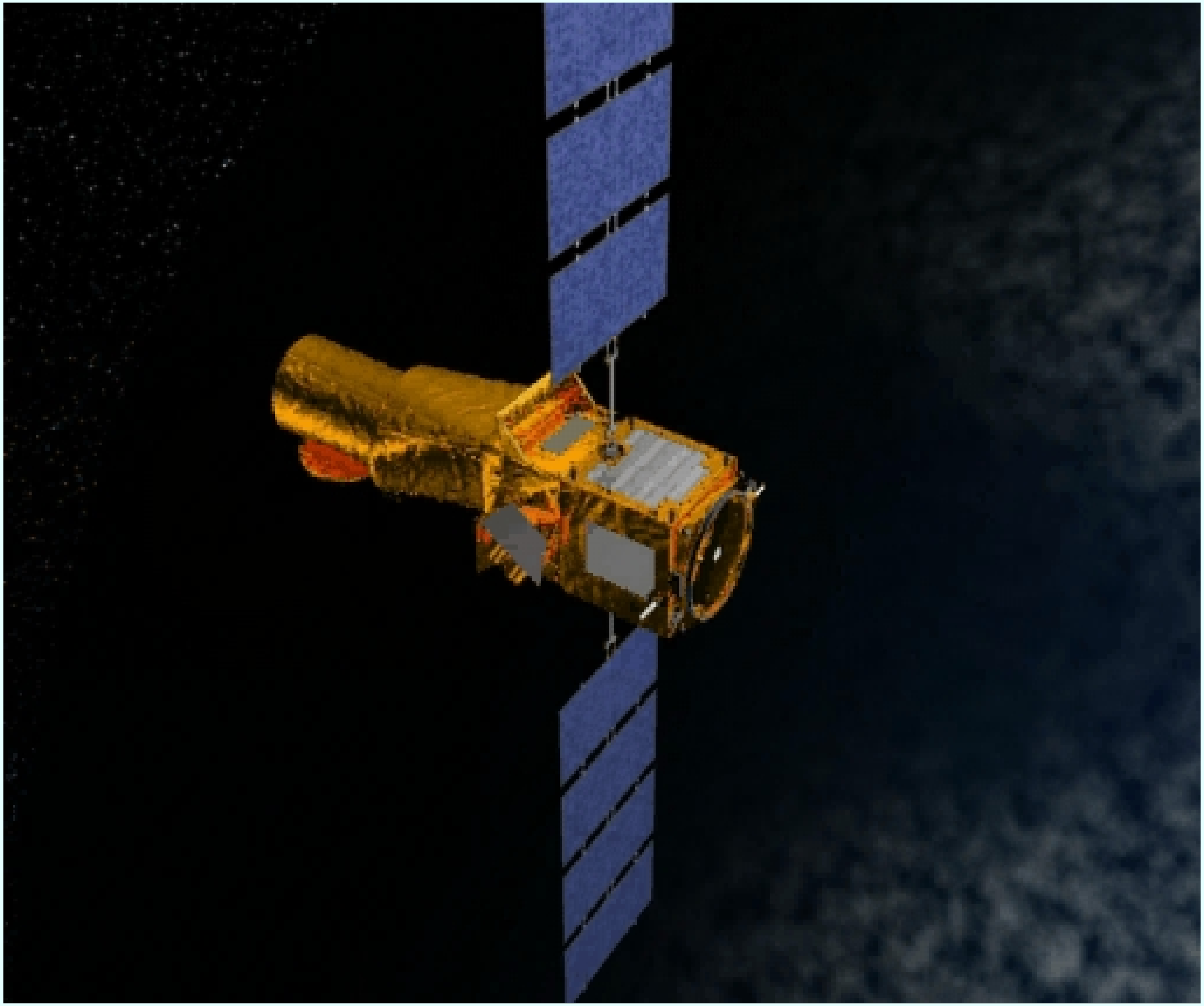


Rivinius et al. 1998b

Possible coincidence of beatings and times of outbursts in μ Cen

→ Never shown in other Be stars from the ground...

The CoRoT era (>2007)



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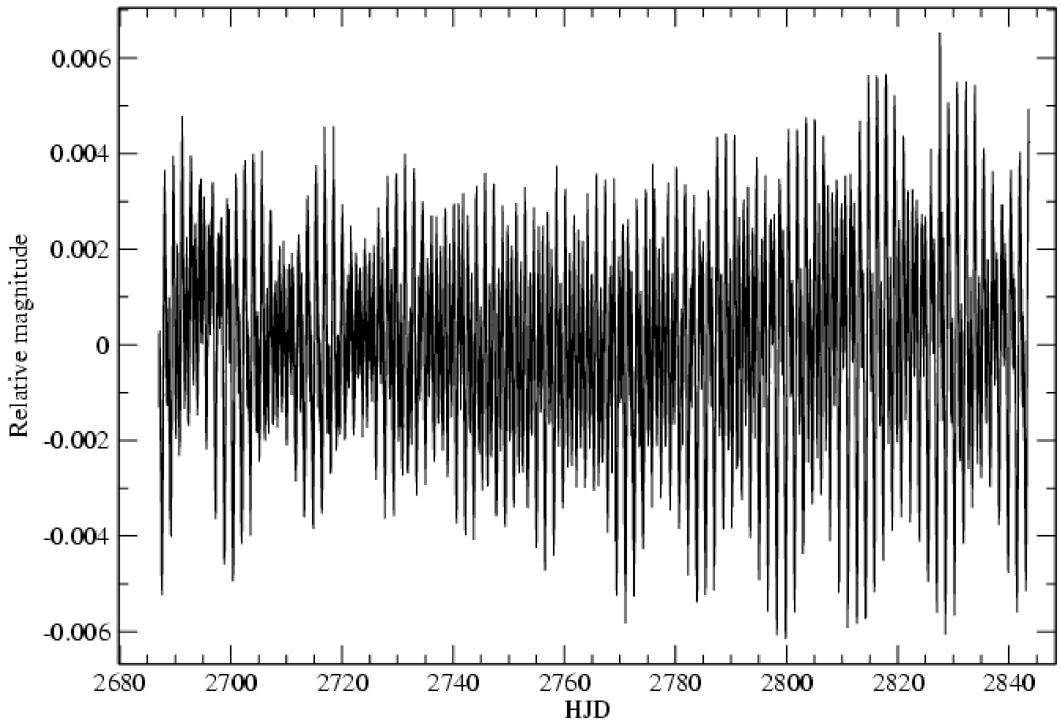
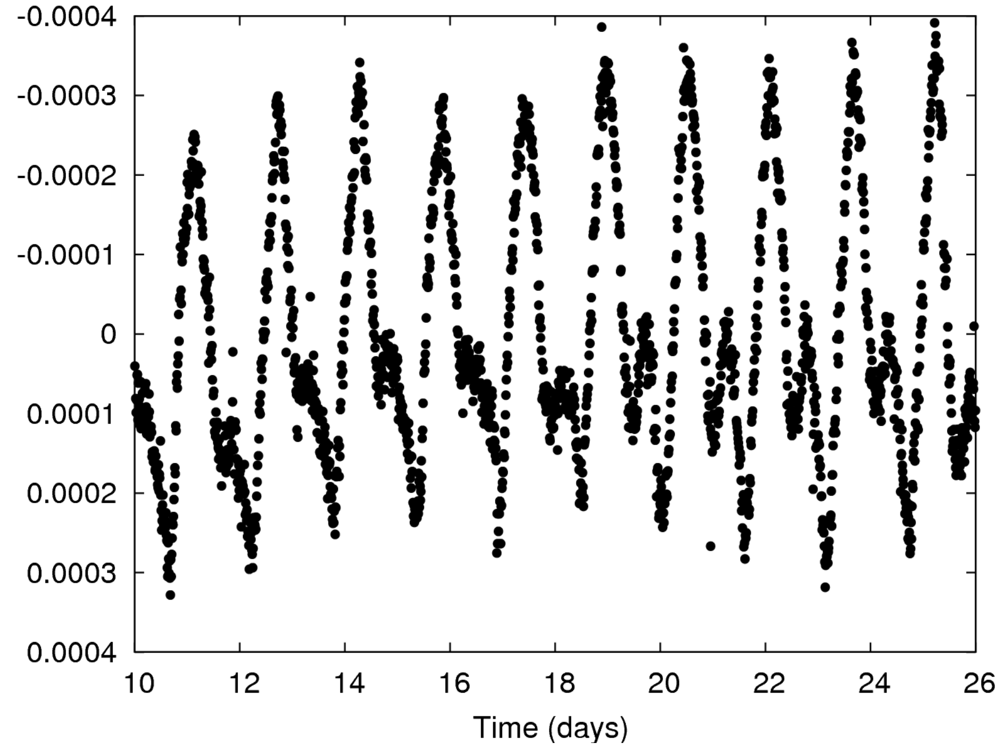
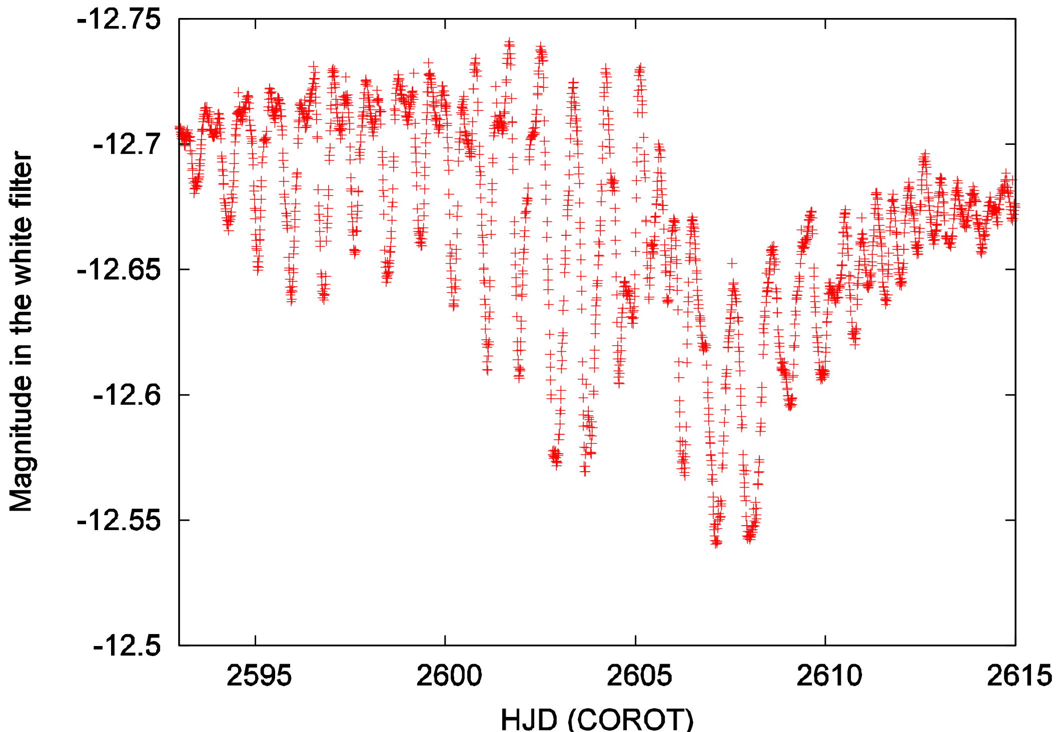
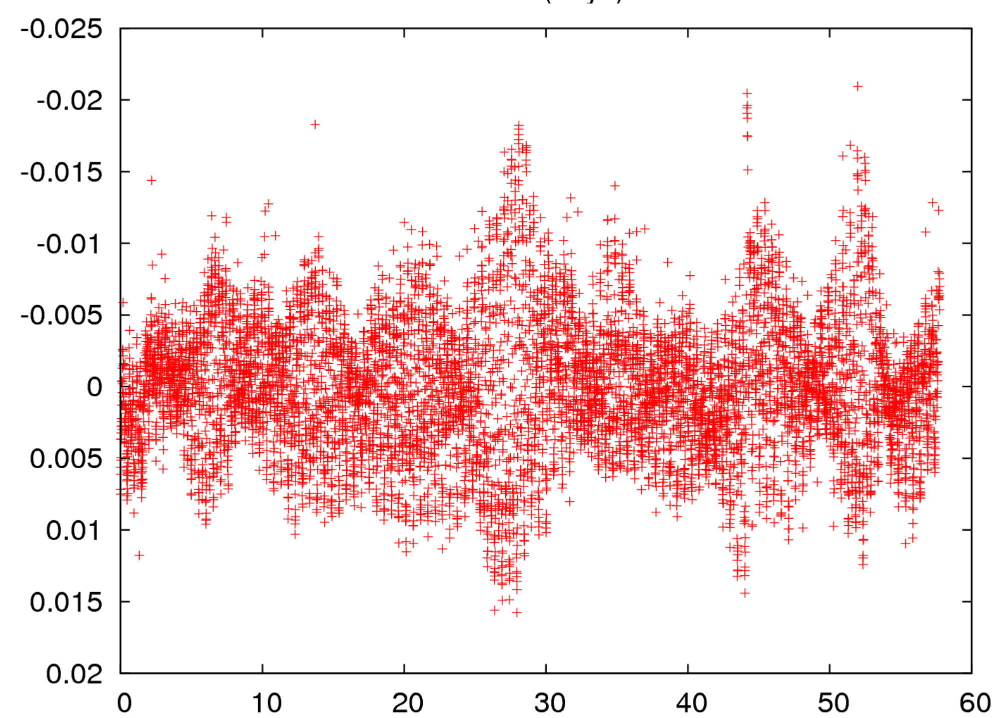
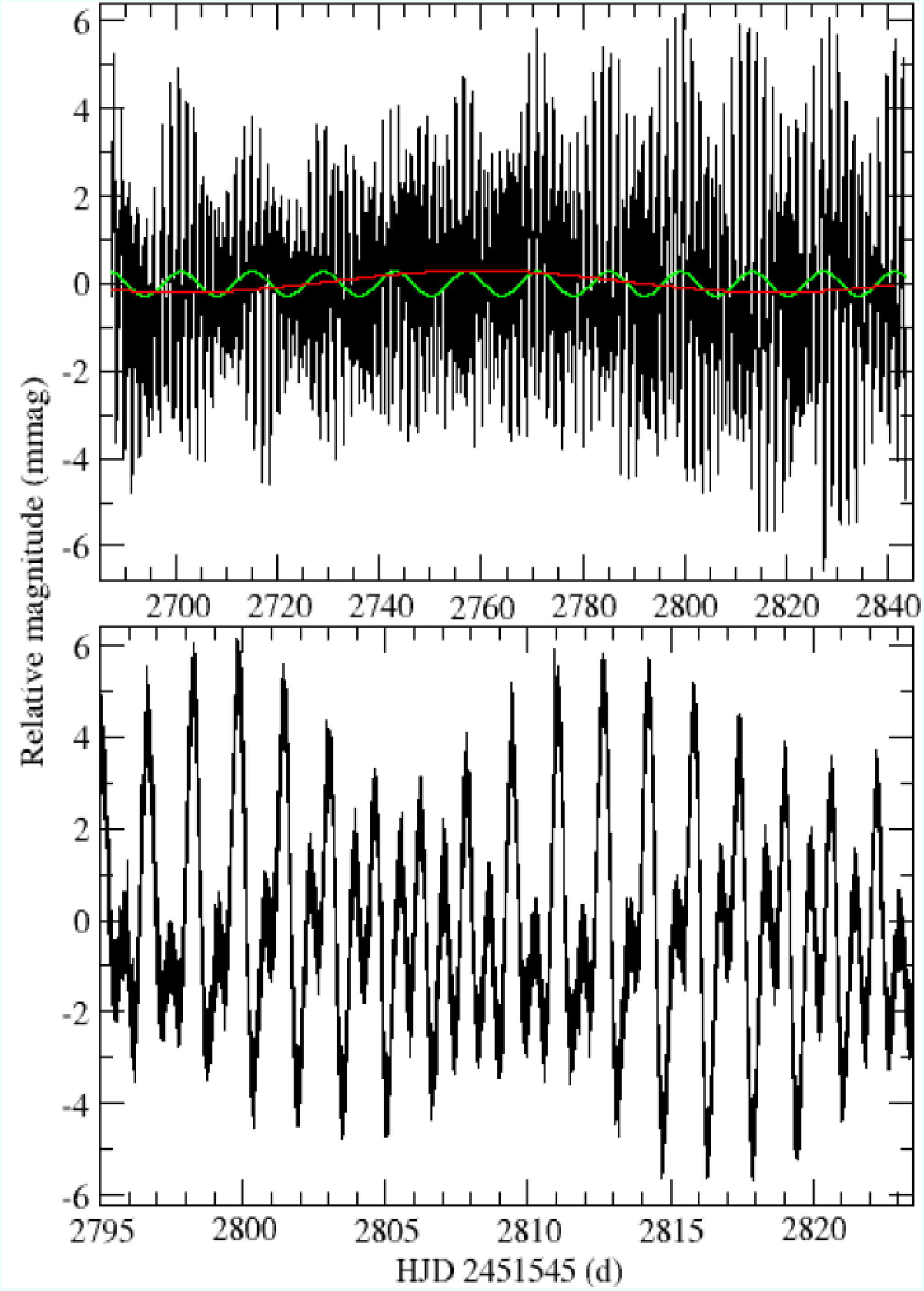
CoRoT light curves of Be stars…











κ-driven modes

HD181231 (B5IVe)

54 detected frequencies,
at least 10 independent ones

Beatings at P=14 and 116 d

Neiner et al. 2009

Spectroscopy

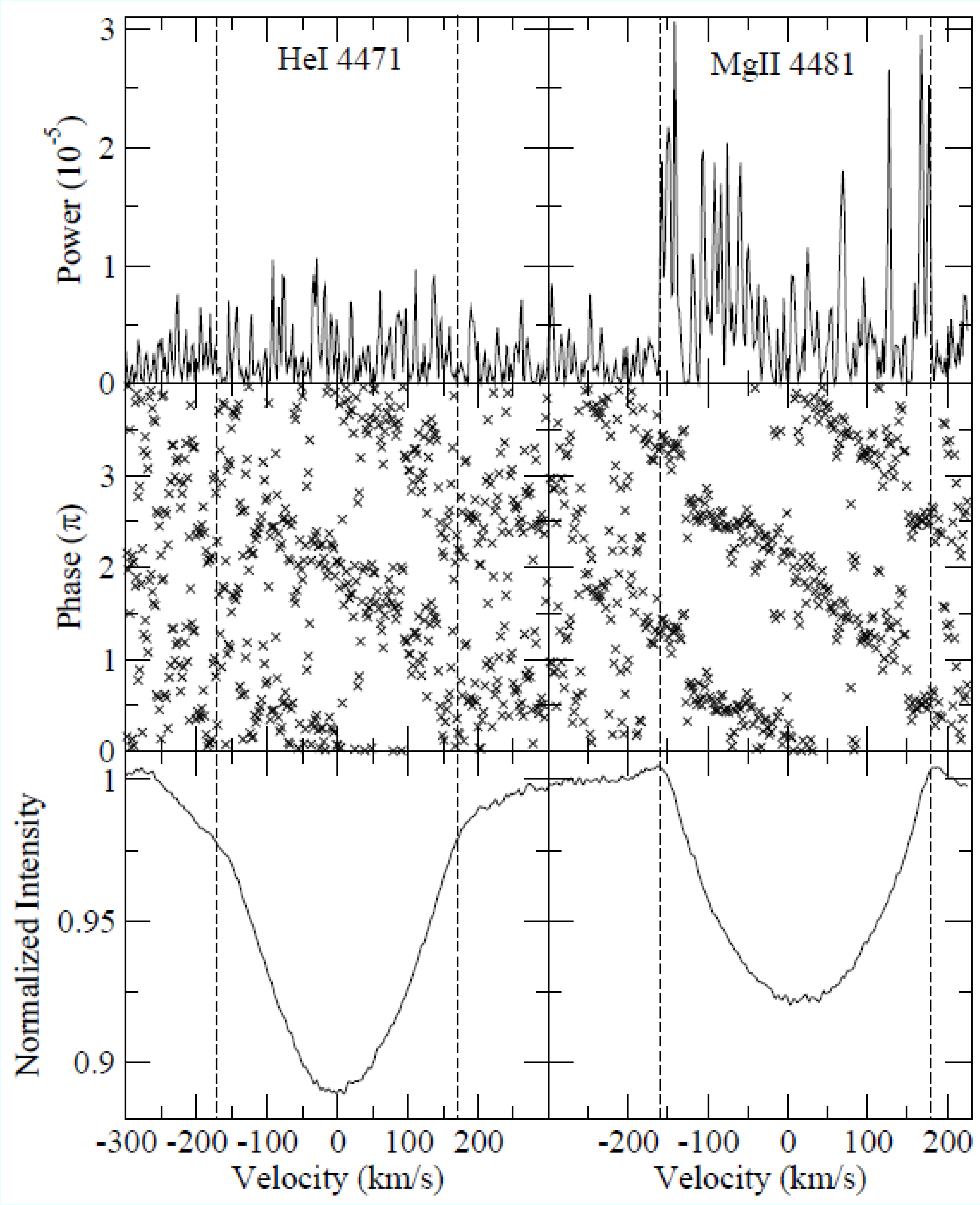
HD181231 (B5IVe)

Some CoRoT frequencies are also detected in spectroscopy

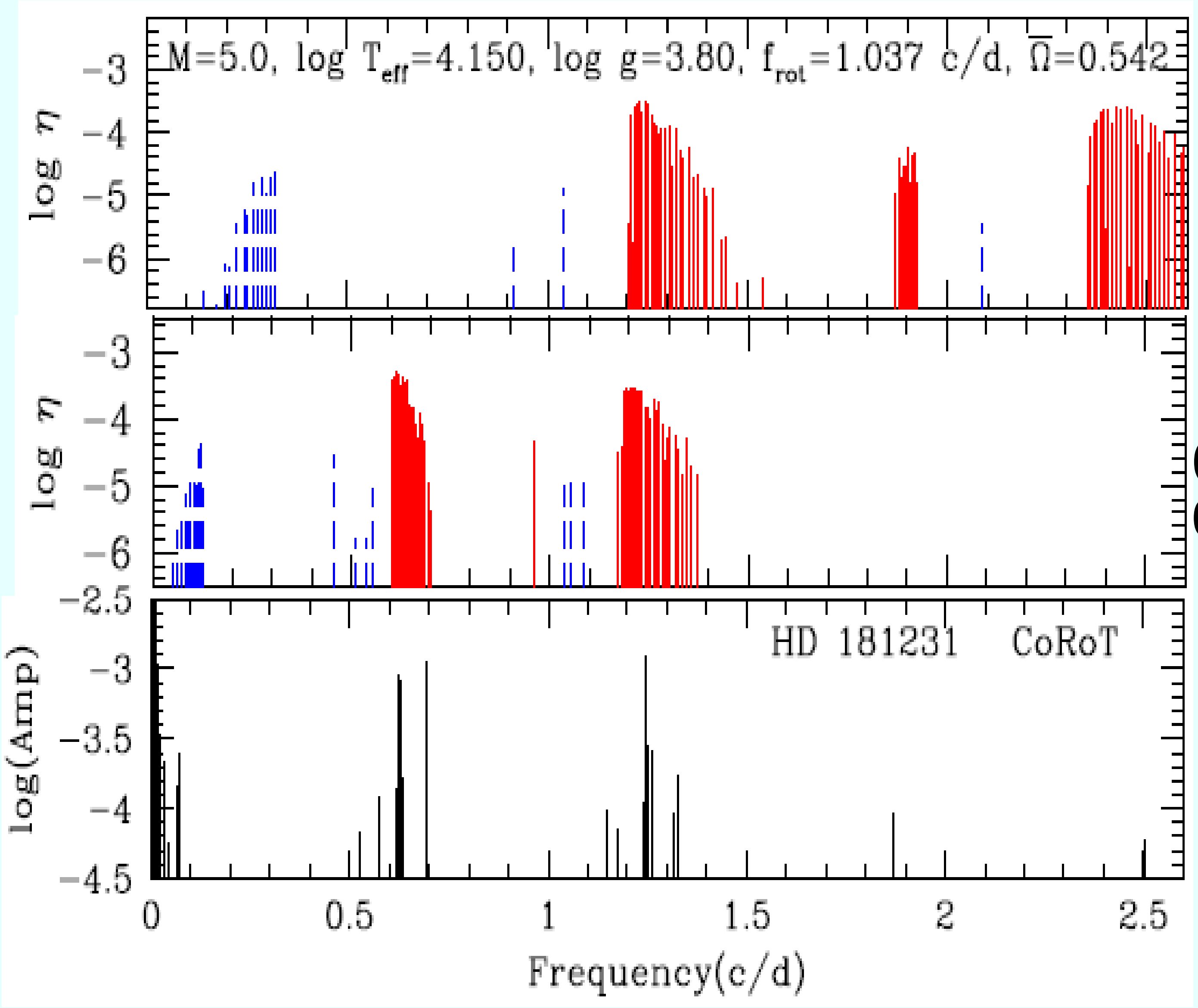
→ allows the identification of these modes

Neiner et al. 2009

f = 0.69 c/d → l=3



Seismic modelling: extra mixing



Tohoku models

← no mixing

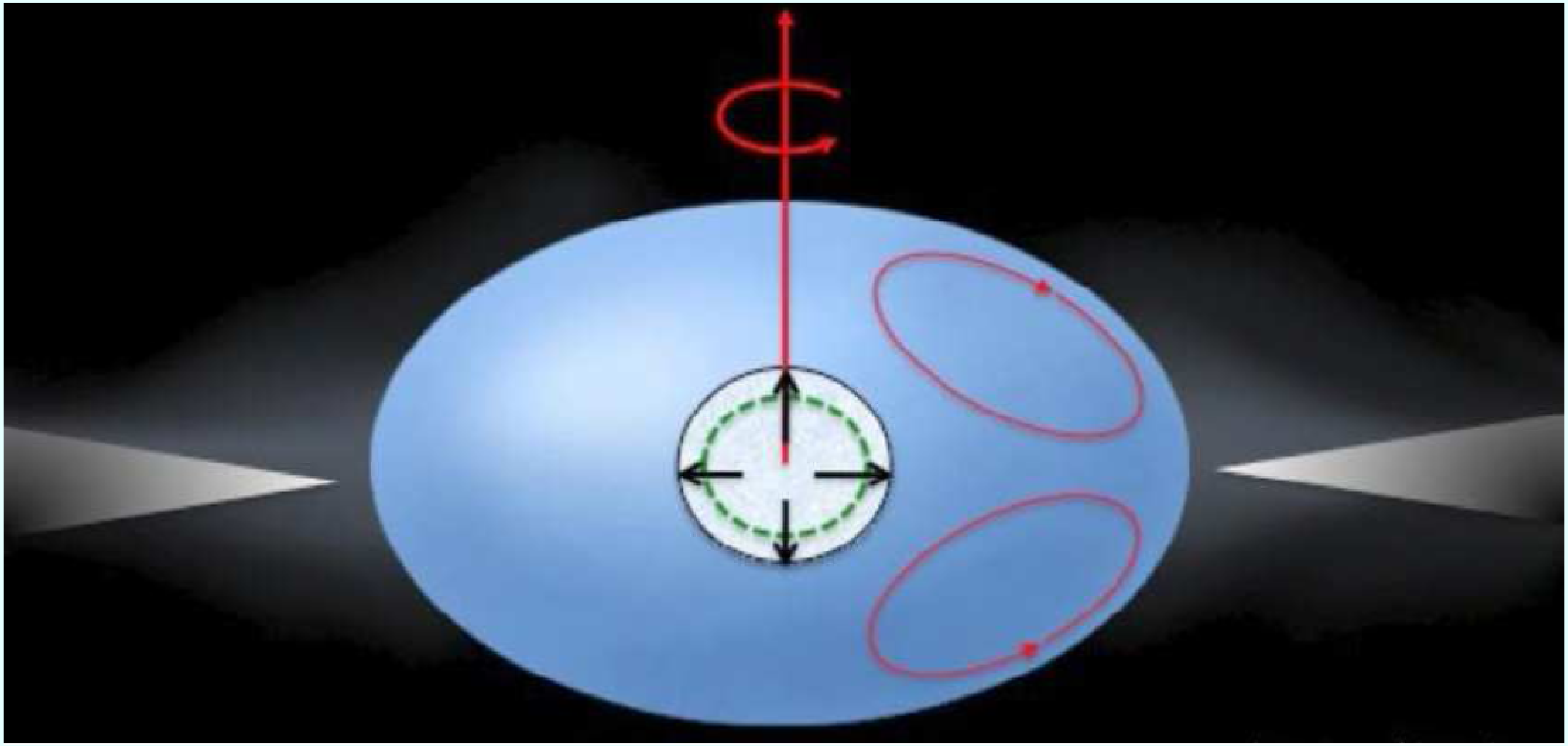
← extra mixing 0.35 Hp (0.15 rotational mixing + 0.2 penetrative convection)

← CoRoT observations

→ Seismic modelling of mid and late Be stars requires extra mixing

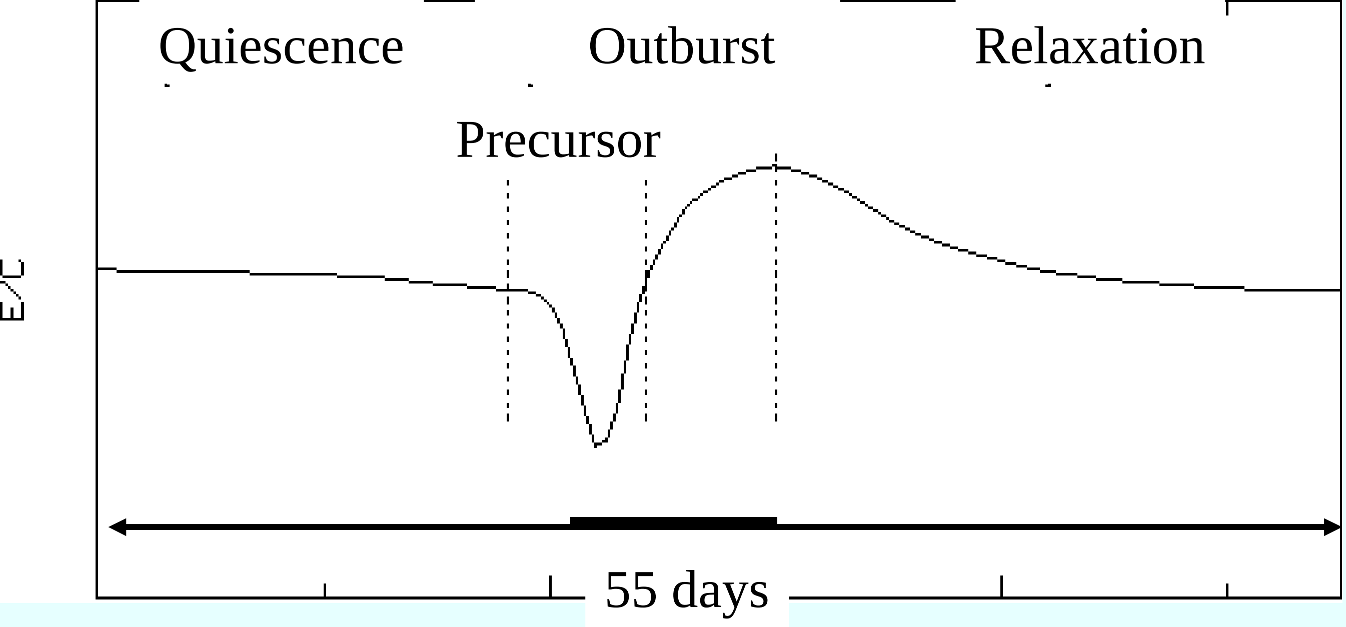
Neiner et al. 2012d

Size of convective core of Be stars



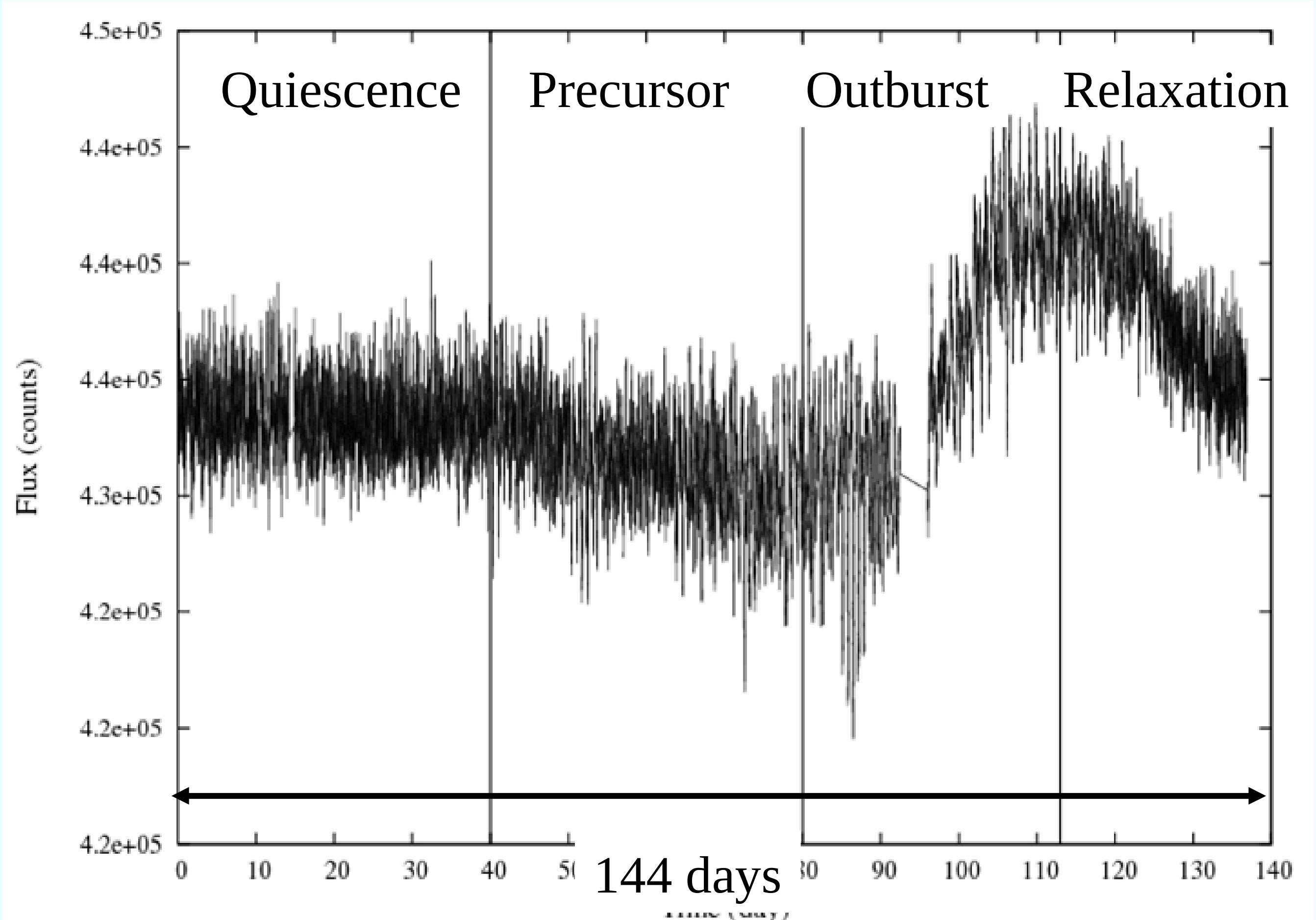
→ Convective core of Be stars are 20% larger and 25% heavier than the core of B stars
→ due to modification of structure by rotational mixing and penetrative convection

Be outburst



Spectroscopy

Rivinius et al. 1998

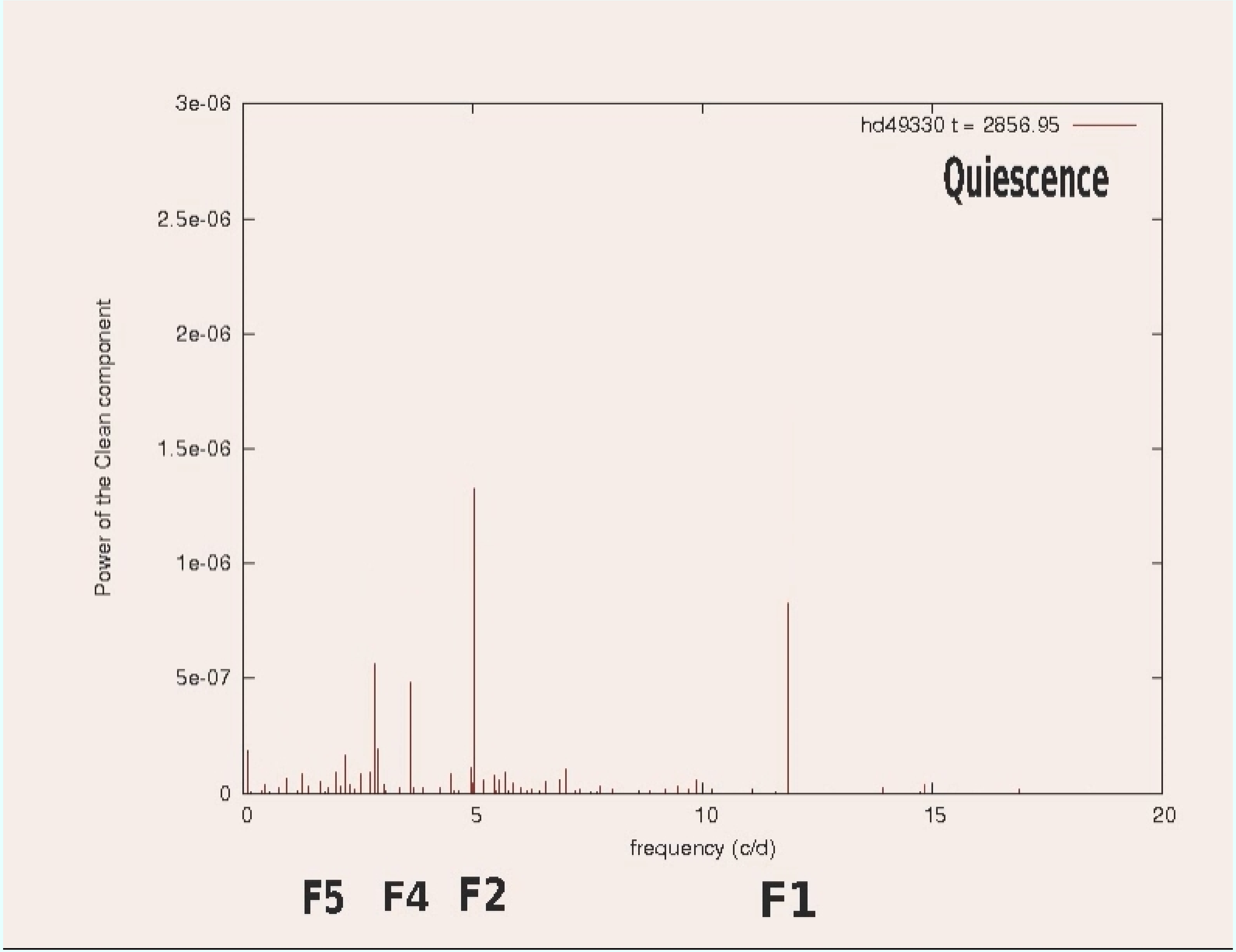


CoRoT photometry

HD49330 (B0.5IVe)
> 300 frequencies and
30 independent ones
p and g modes

Huat et al. 2009

Correlation between pulsations and outbursts



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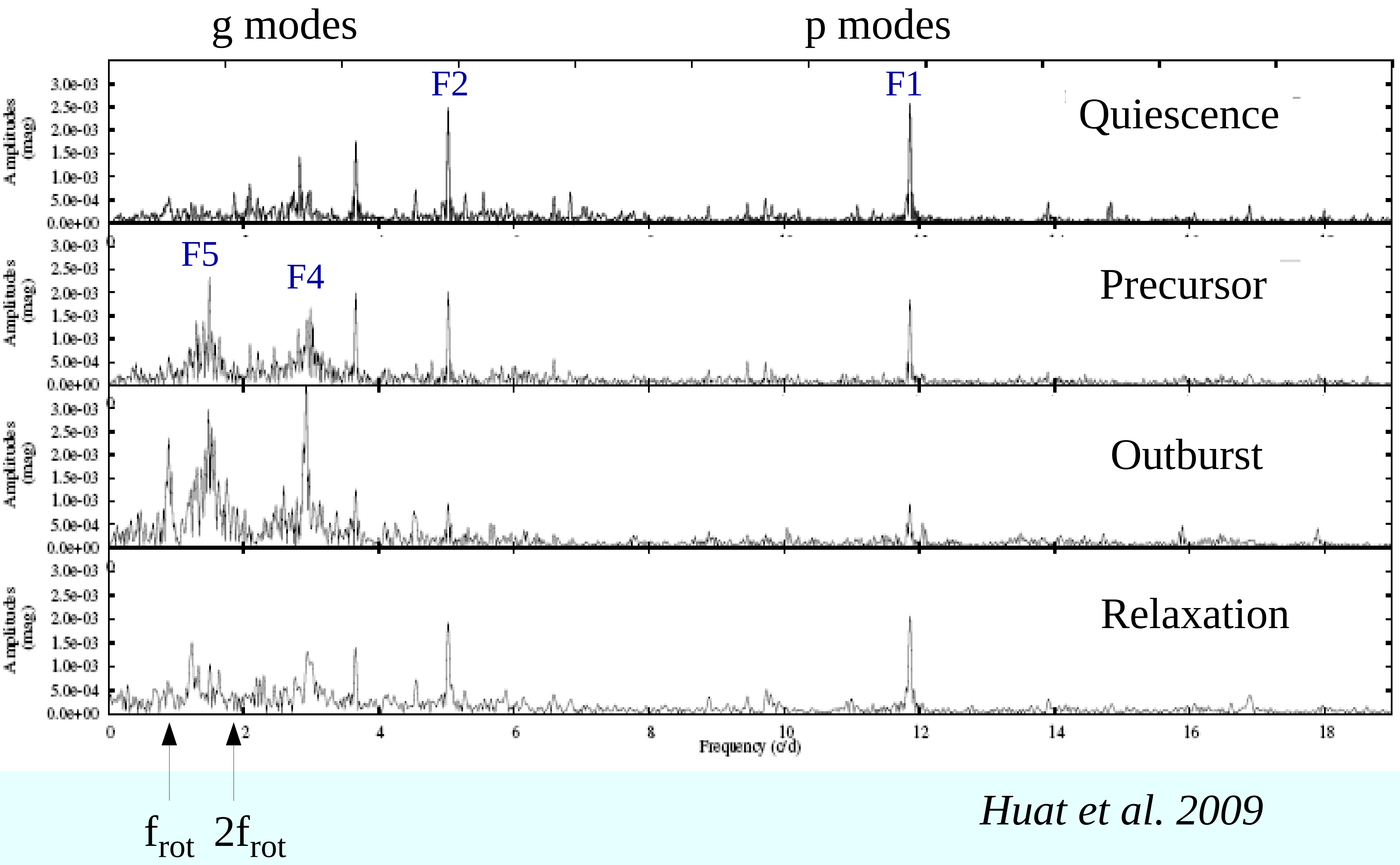
Correlation between pulsations and outbursts

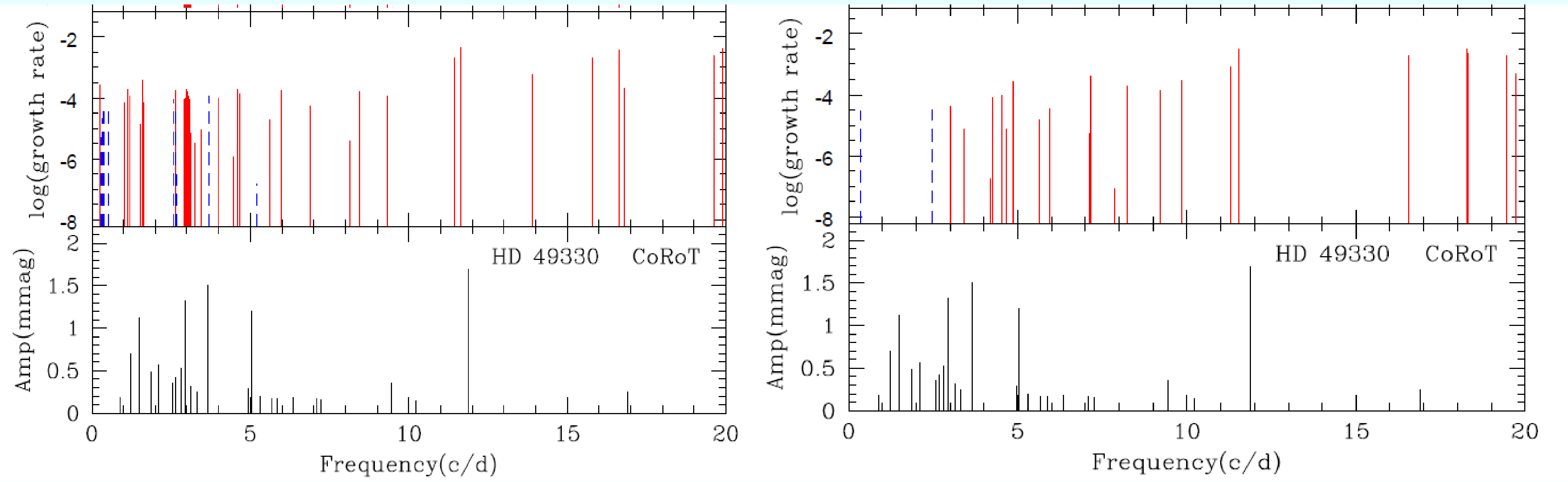


Huat et al. 2009

Seismic modelling of HD49330

Tohoku models, with ROTORC 2D structure, for κ modes

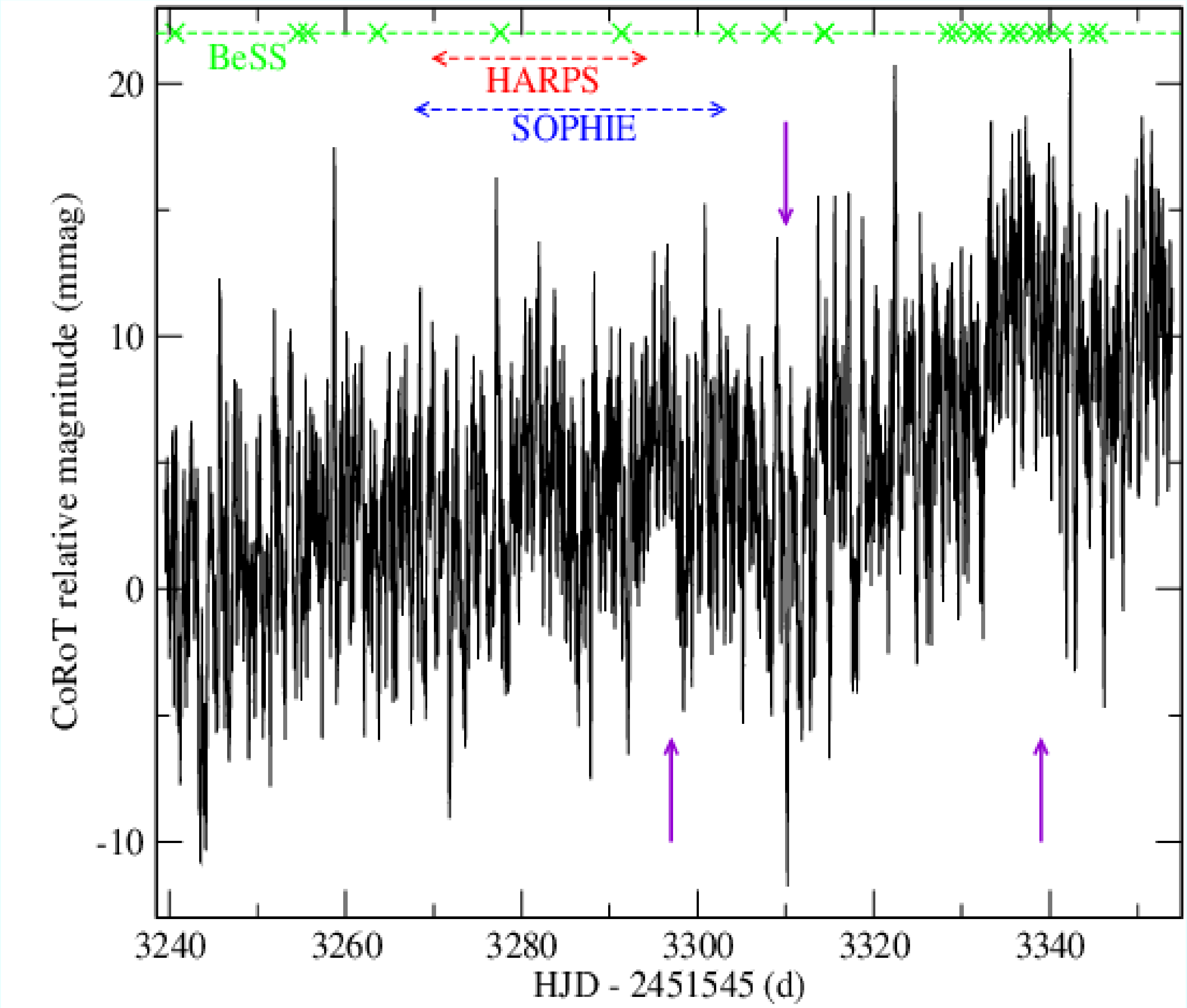
M = 10 $M_\odot$ M = 13 $M_\odot$



But for HD49330: M = 14.4 $M_\odot$

→ impossible to reproduce g modes

HD51452: a hot Be star with g modes

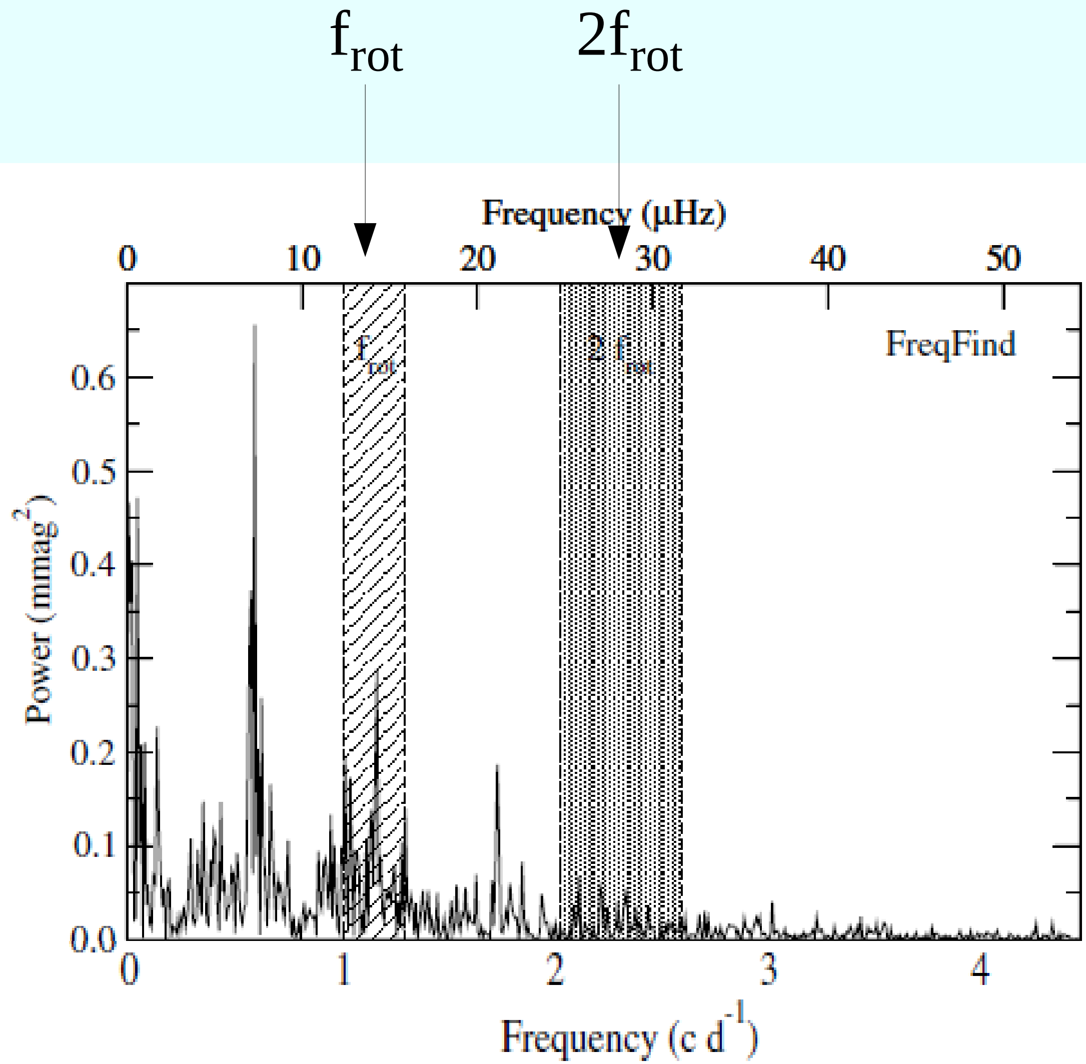


HD51452 (B0IVe)

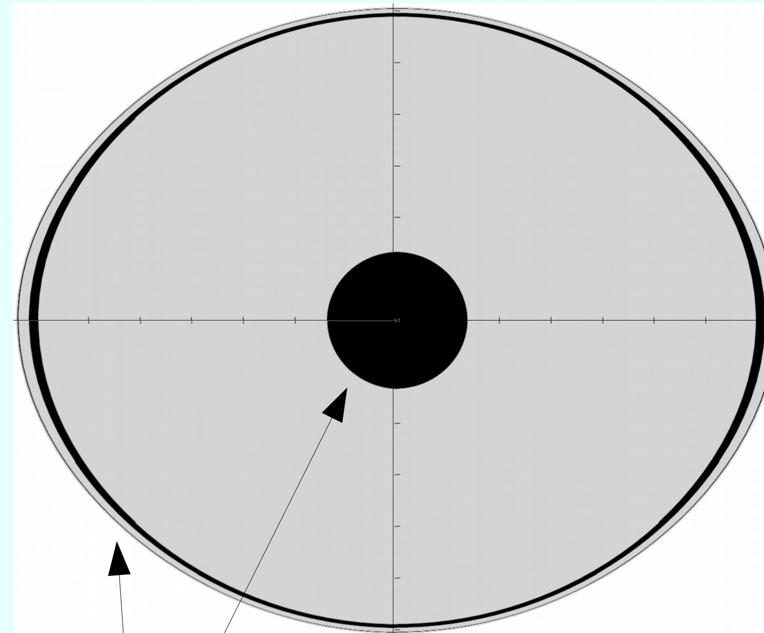
189 detected frequencies

Neiner et al. 2012e

HD51452: stochastically driven modes



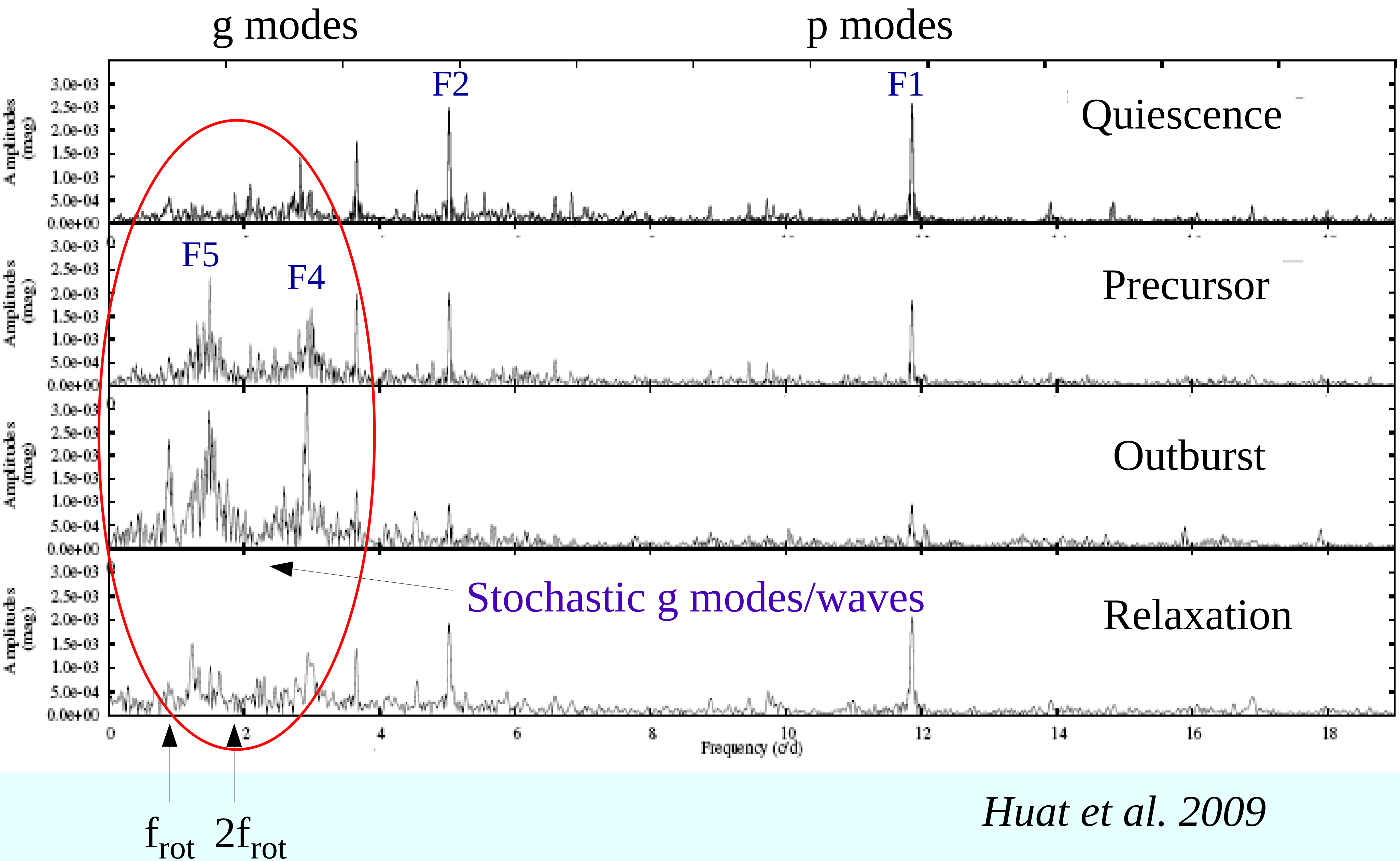
g modes with $f < 2\ f_{rot}$
→ gravito-inertial modes



Stochastic excitation in the core or in the thin subsurface zone

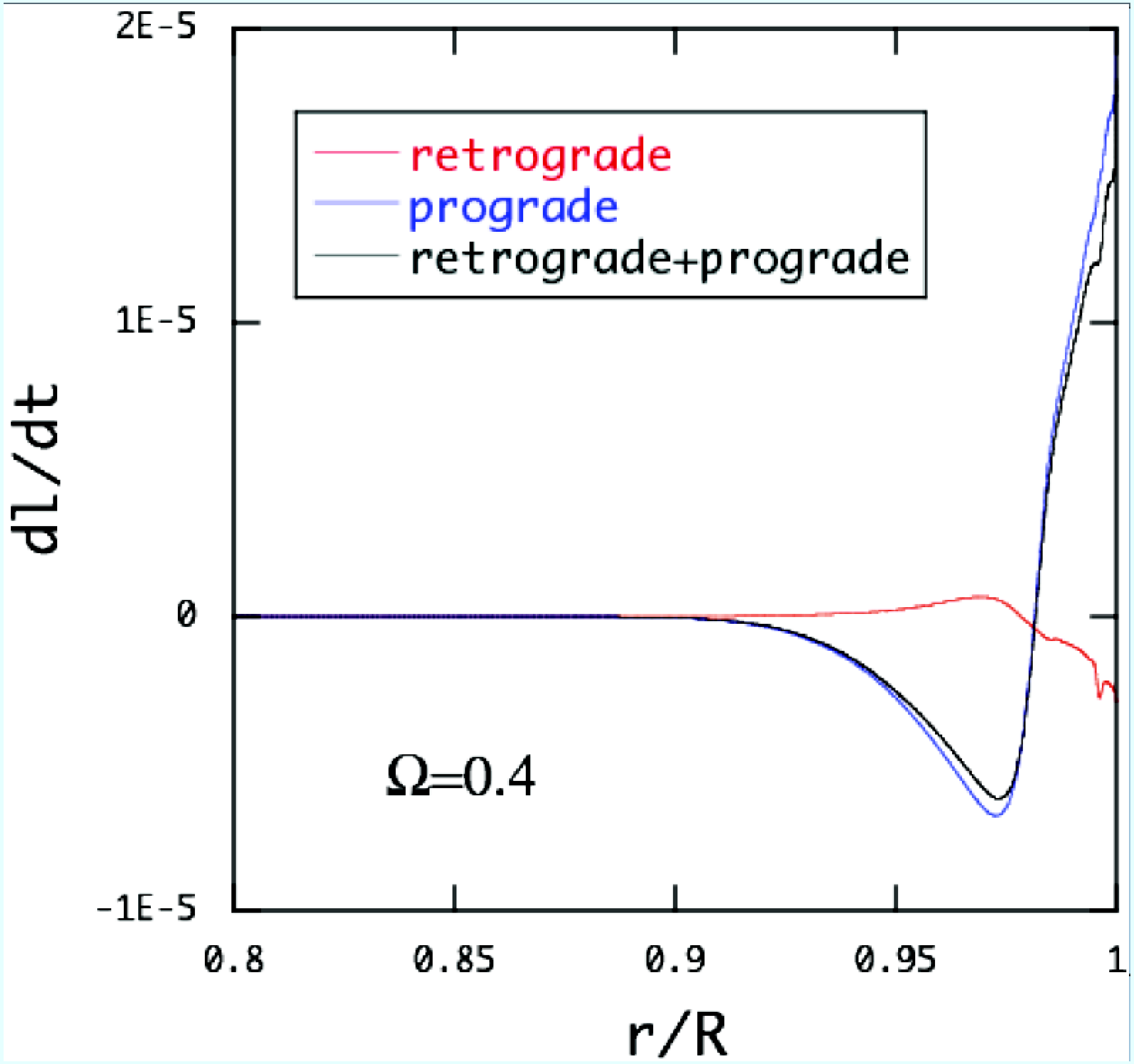
Neiner et al. 2012e

HD49330 (with outburst)



Huat et al. 2009

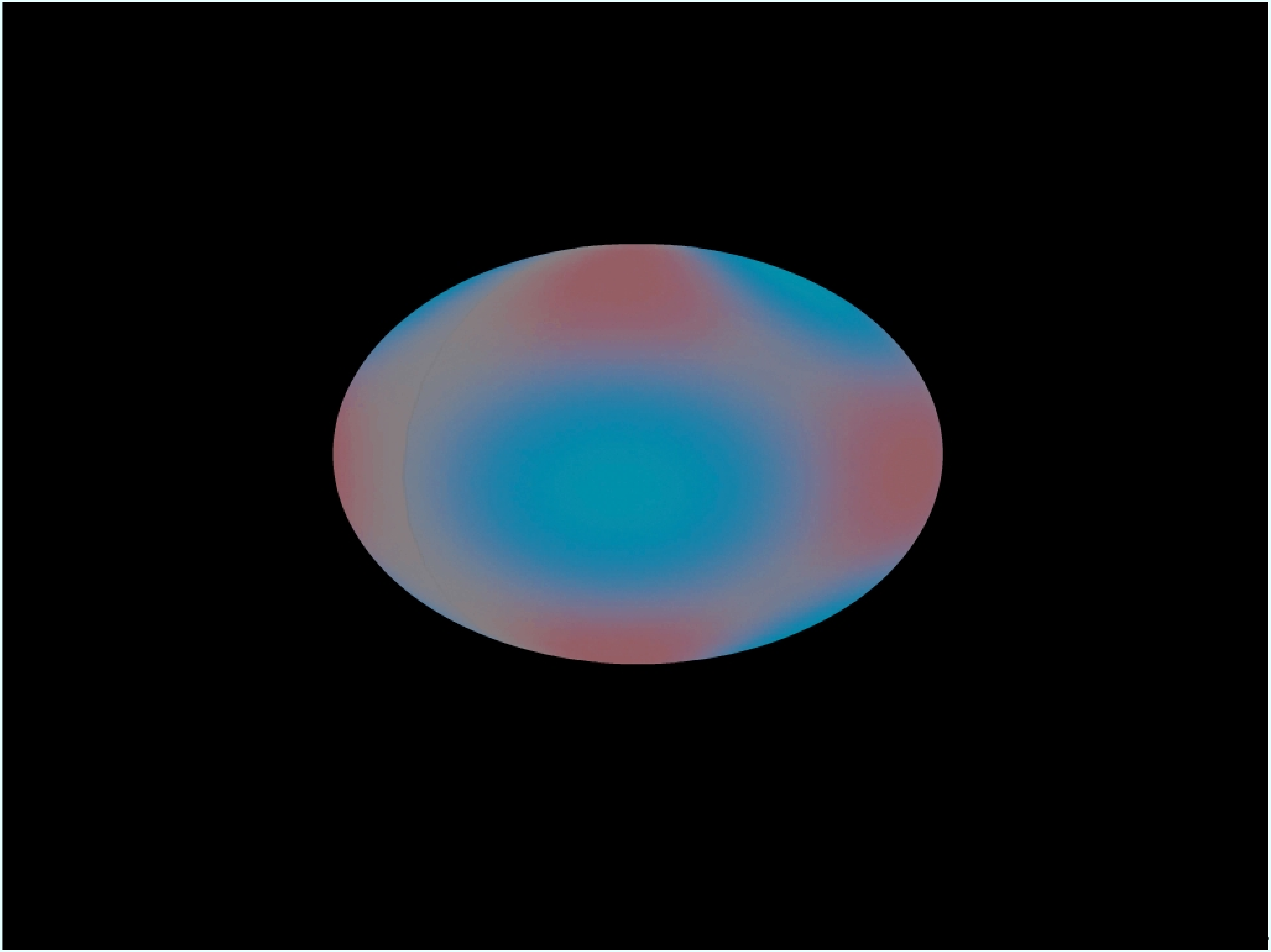
Explanation to the Be phenomenon



Neiner et al. in prep.

→ g modes transport angular momentum

→ stochastic (gravito-inertial) modes in the core transport angular momentum from the core to the surface



Summary

- Be stars are hot stars with emission lines produced by their circumstellar environment
- ~10% of all hot stars are magnetic; most of them have a magnetosphere and are thus magnetic Be stars.
- Weak fields can exist in classical Be stars but they do not produce the Be phenomenon and Keplerian disk.
- Pulsations occur in all Be stars, excited by the κ mechanism but also stochastically.
- There is a clear correlation between pulsation variations and outbursts.

→ Be phenomenon = rapid rotation + angular momentum transported by stochastic gravito-inertial pulsations