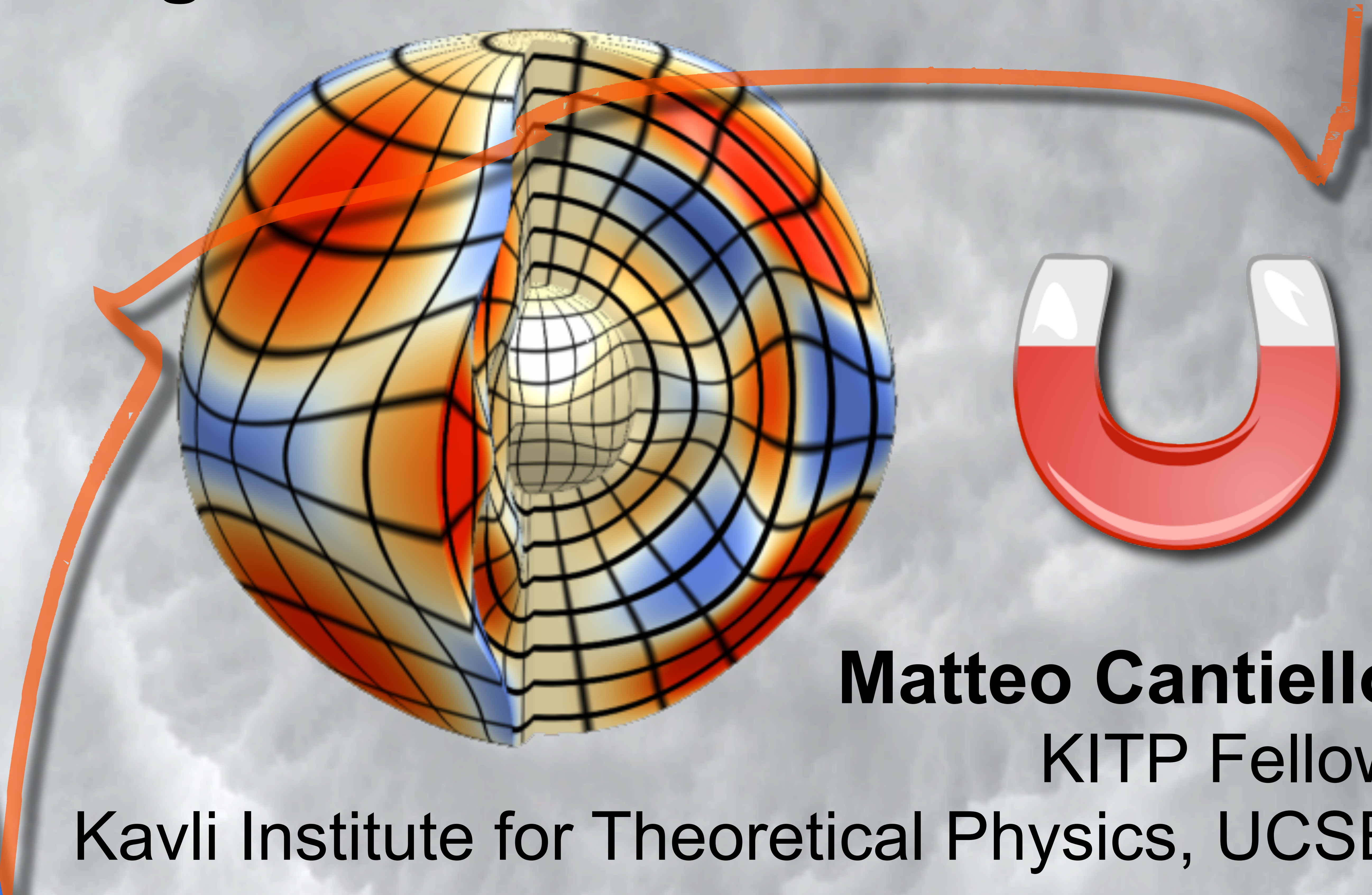
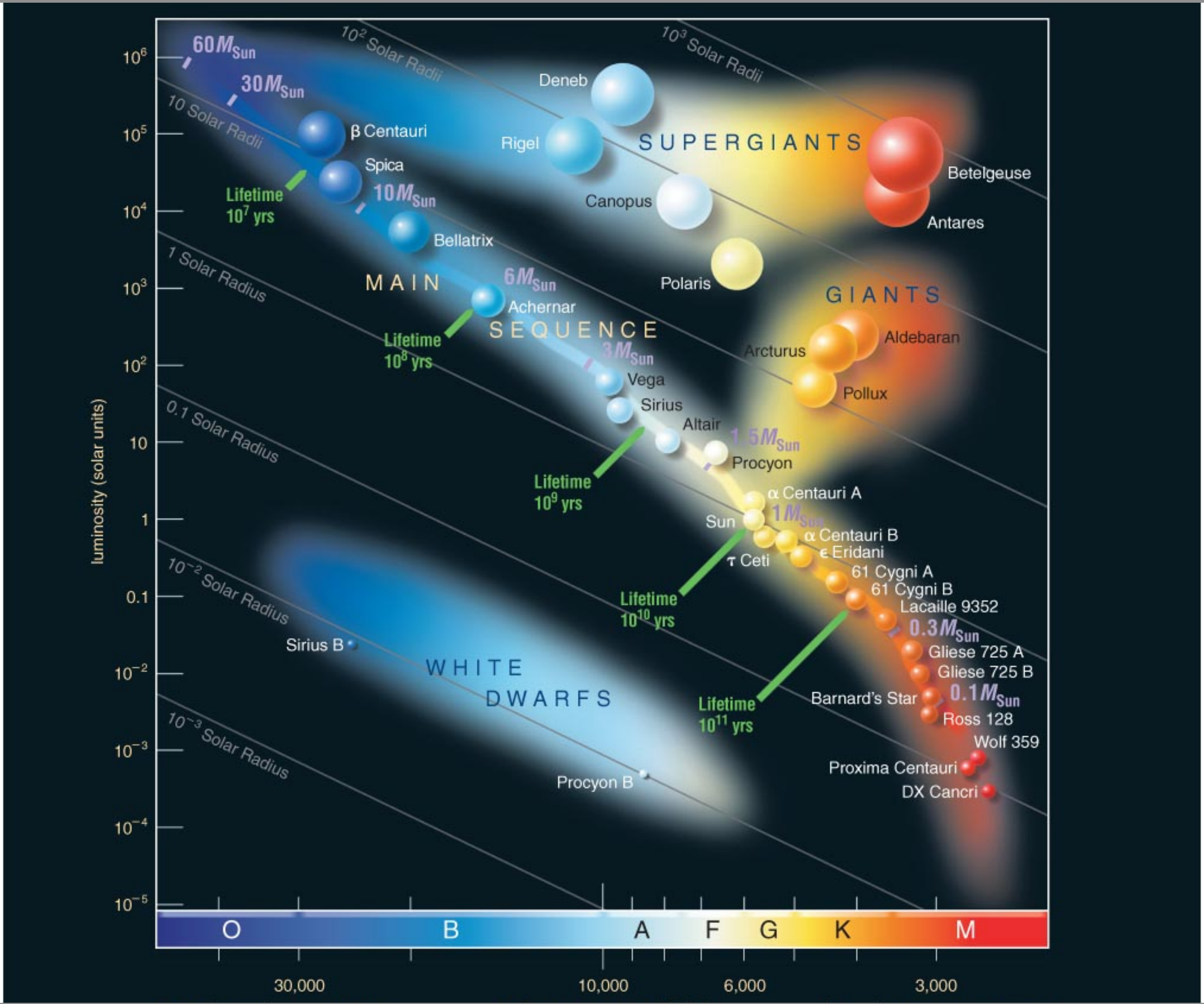
Pulsations, Turbulence and Magnetic Fields in Massive Stars

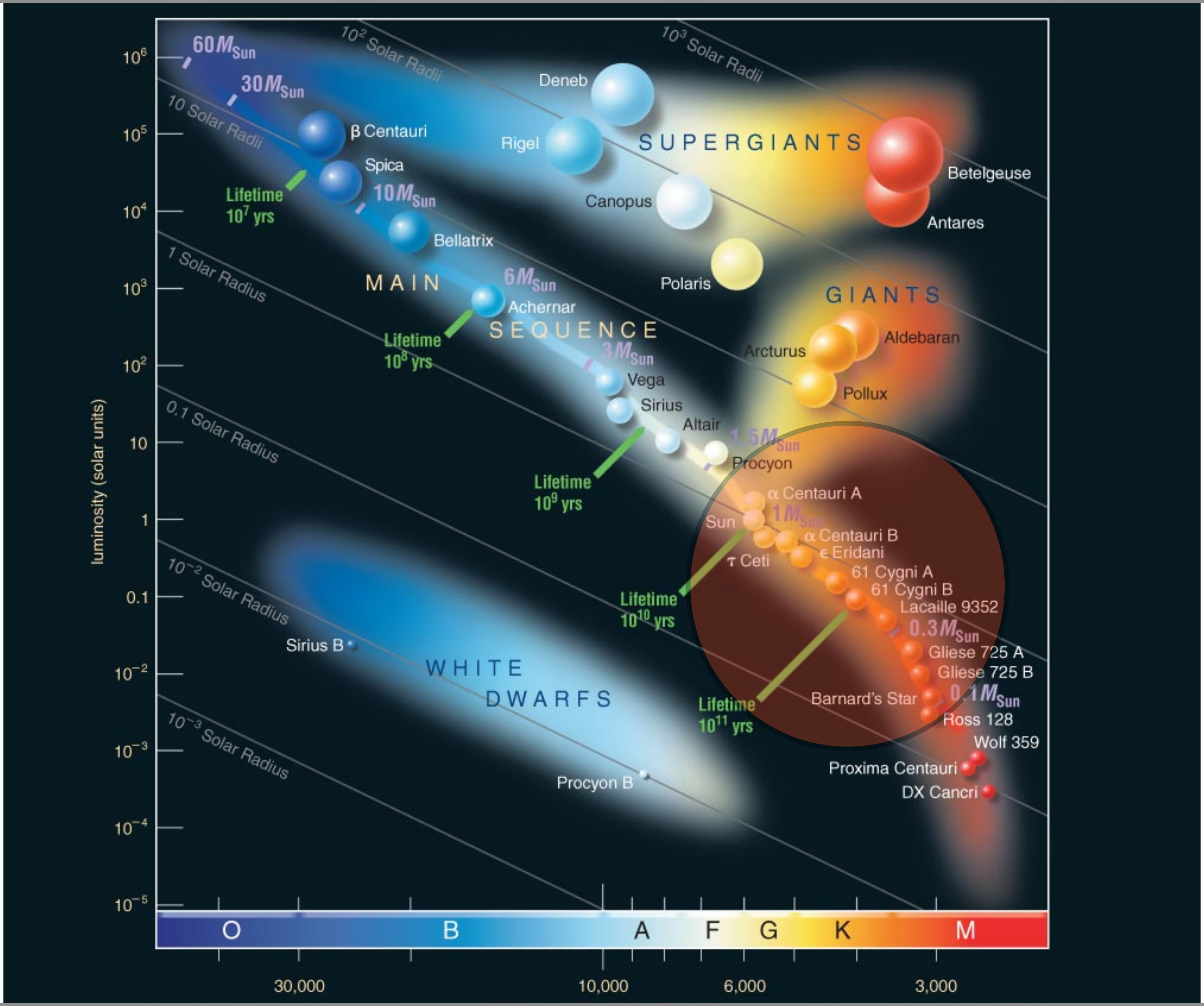


Matteo Cantiello
KITP Fellow
Kavli Institute for Theoretical Physics, UCSB

Massive Stars



Massive Stars



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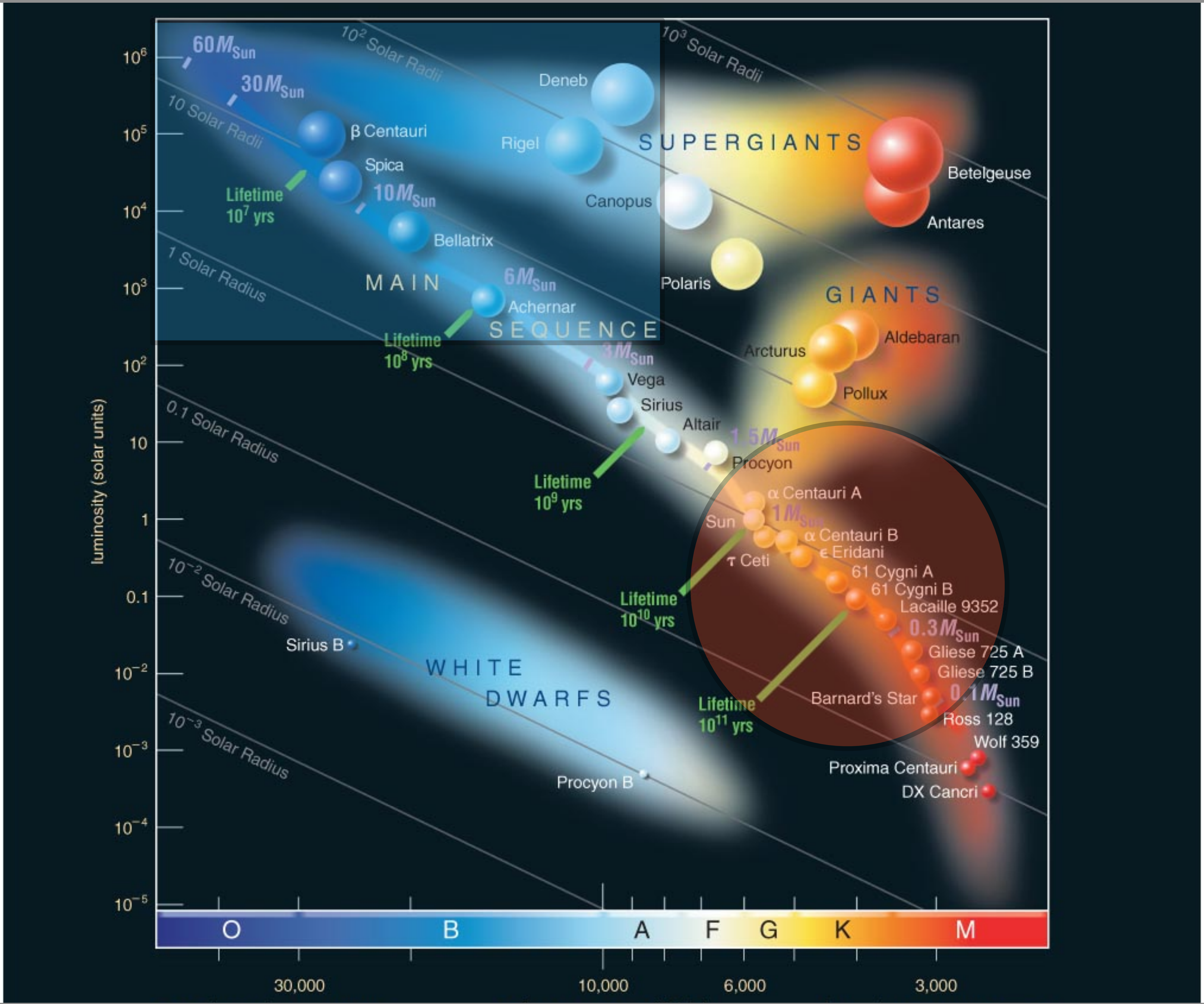
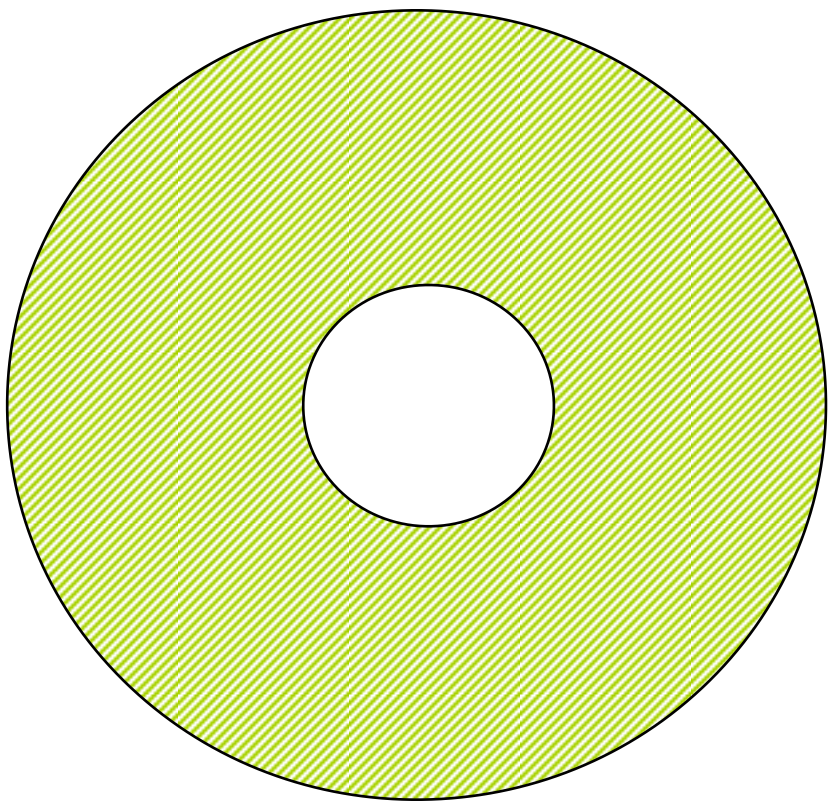


Stellar Structure

Stellar structure

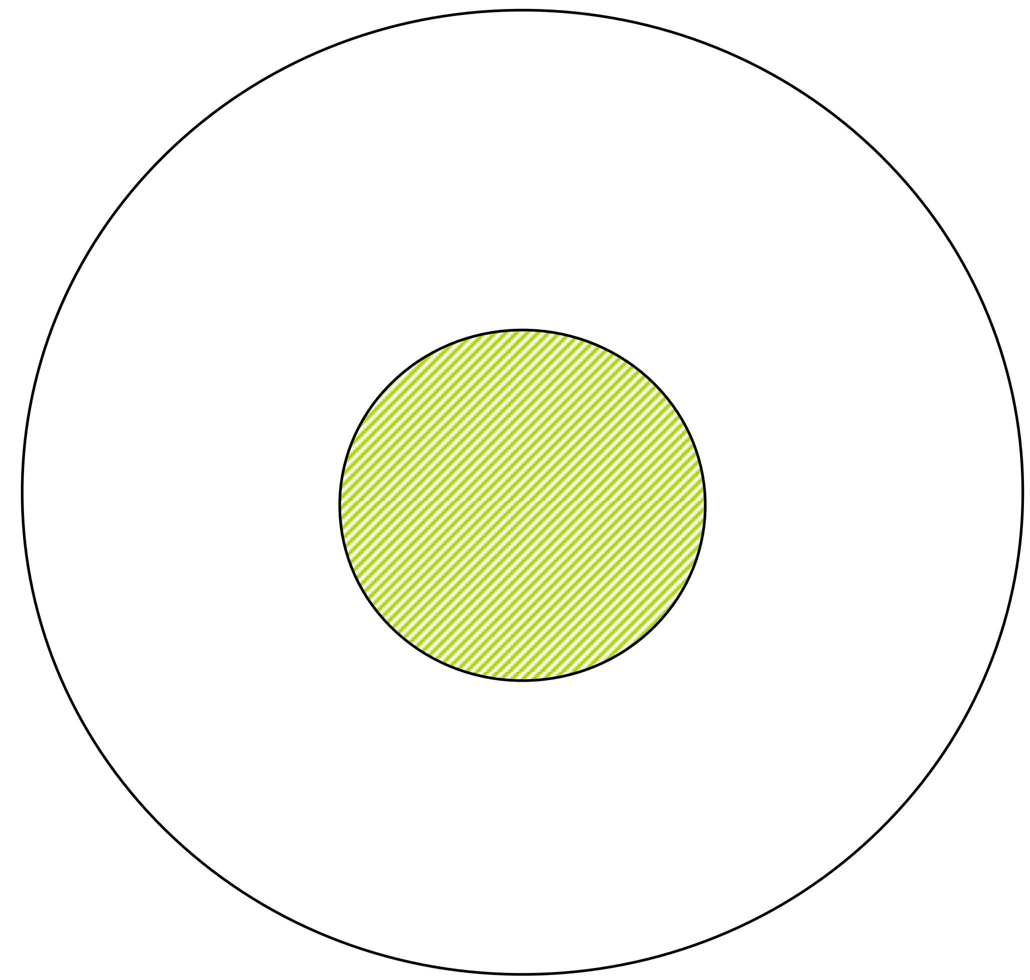
Low Mass stars



e.g $1M_{Sun}$

Radiative core
Convective envelope

Massive stars

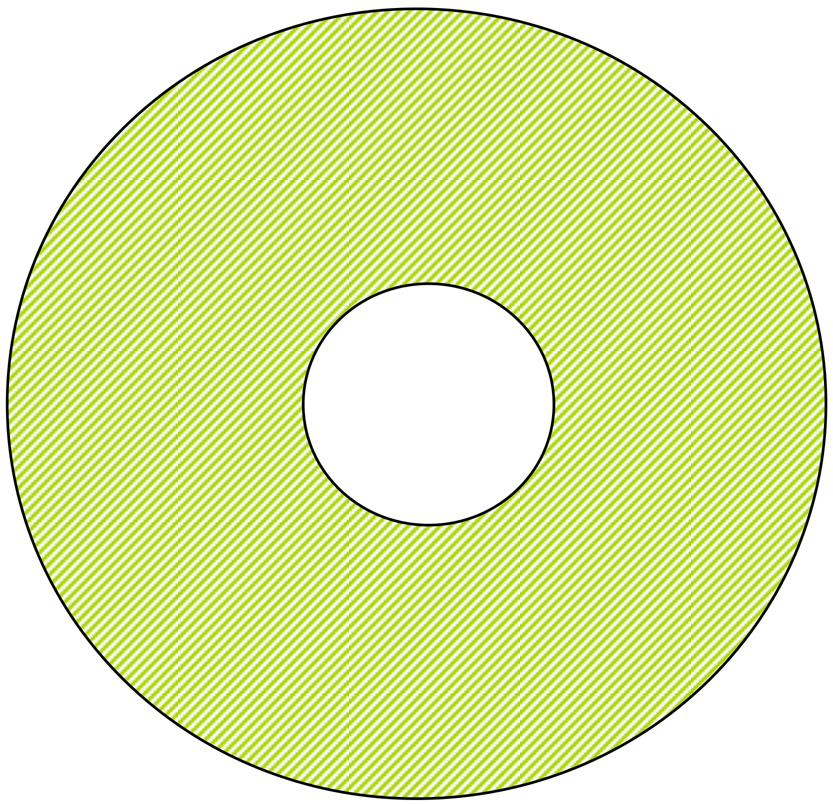


e.g $20\ M_{Sun}$

Convective core
Radiative envelope

Stellar structure

Low Mass stars



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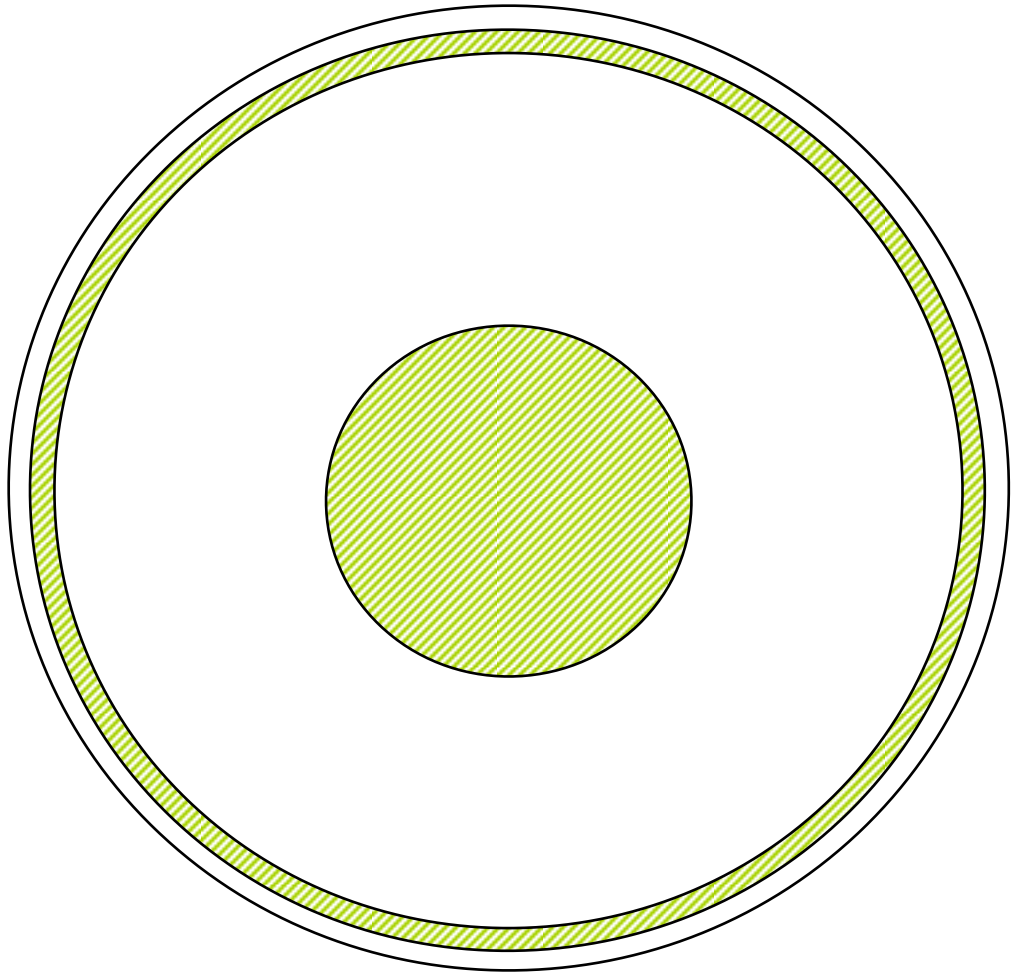

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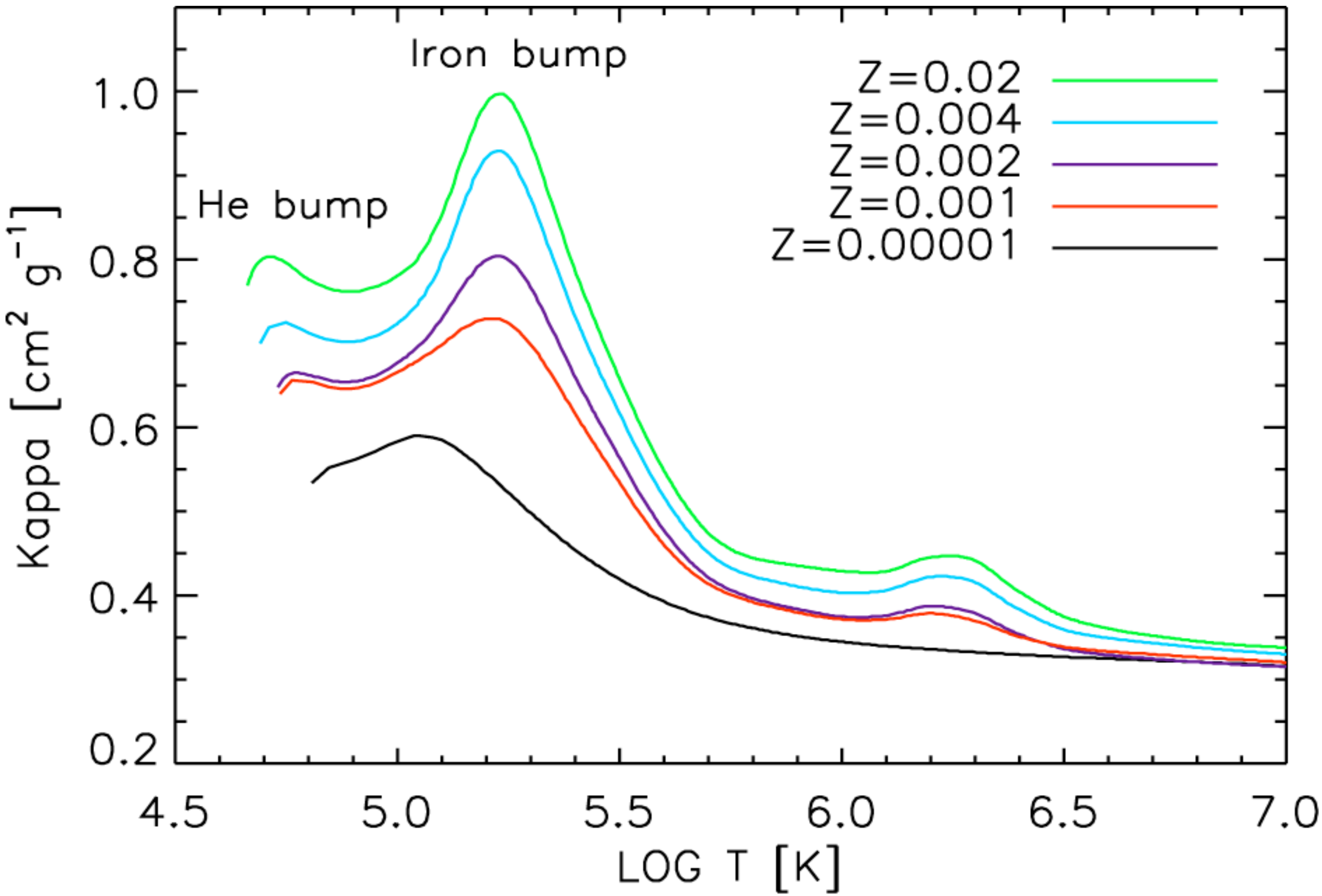
Convective core
Radiative envelope

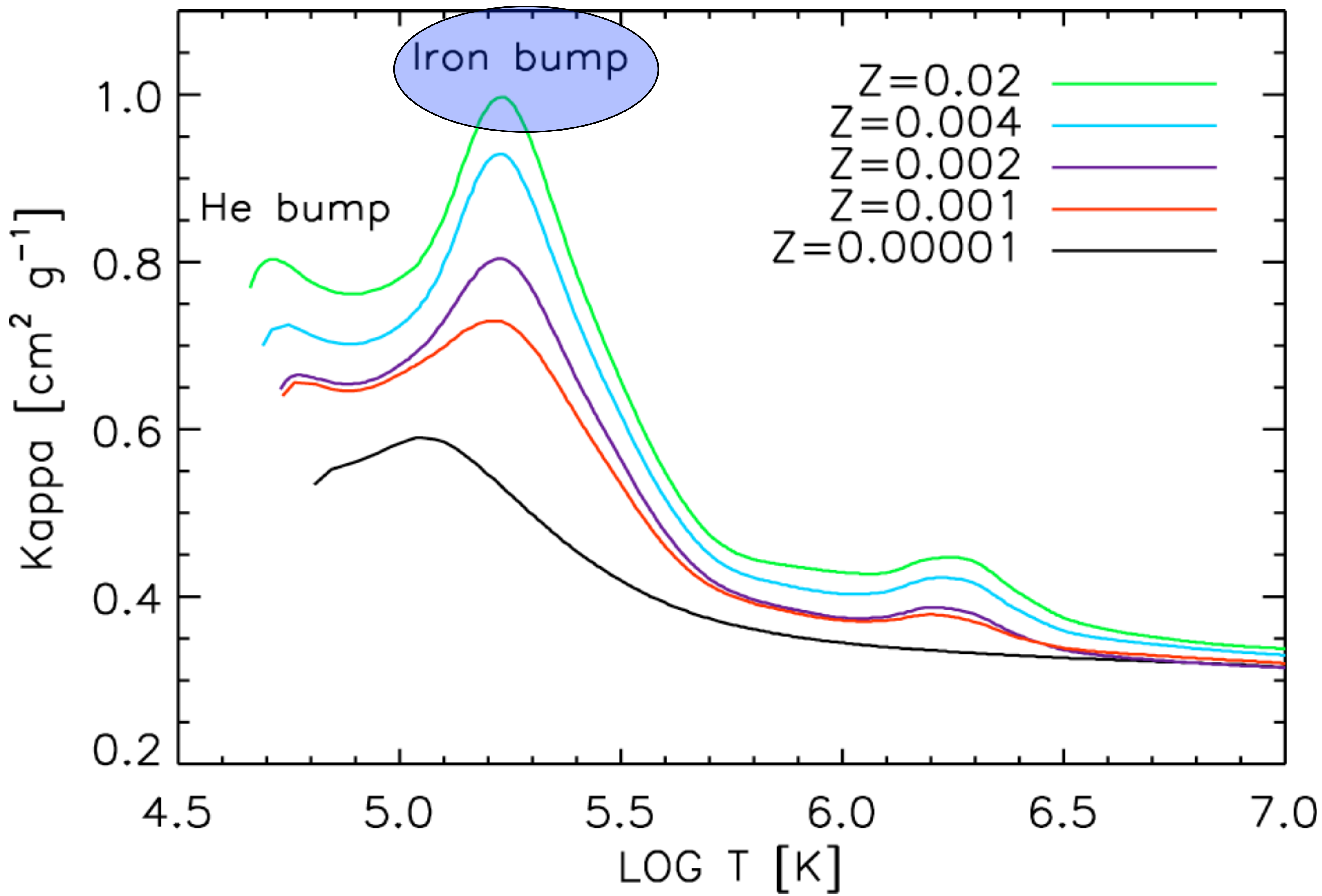
The Iron Convection Zone: Opacity

Inside a massive star



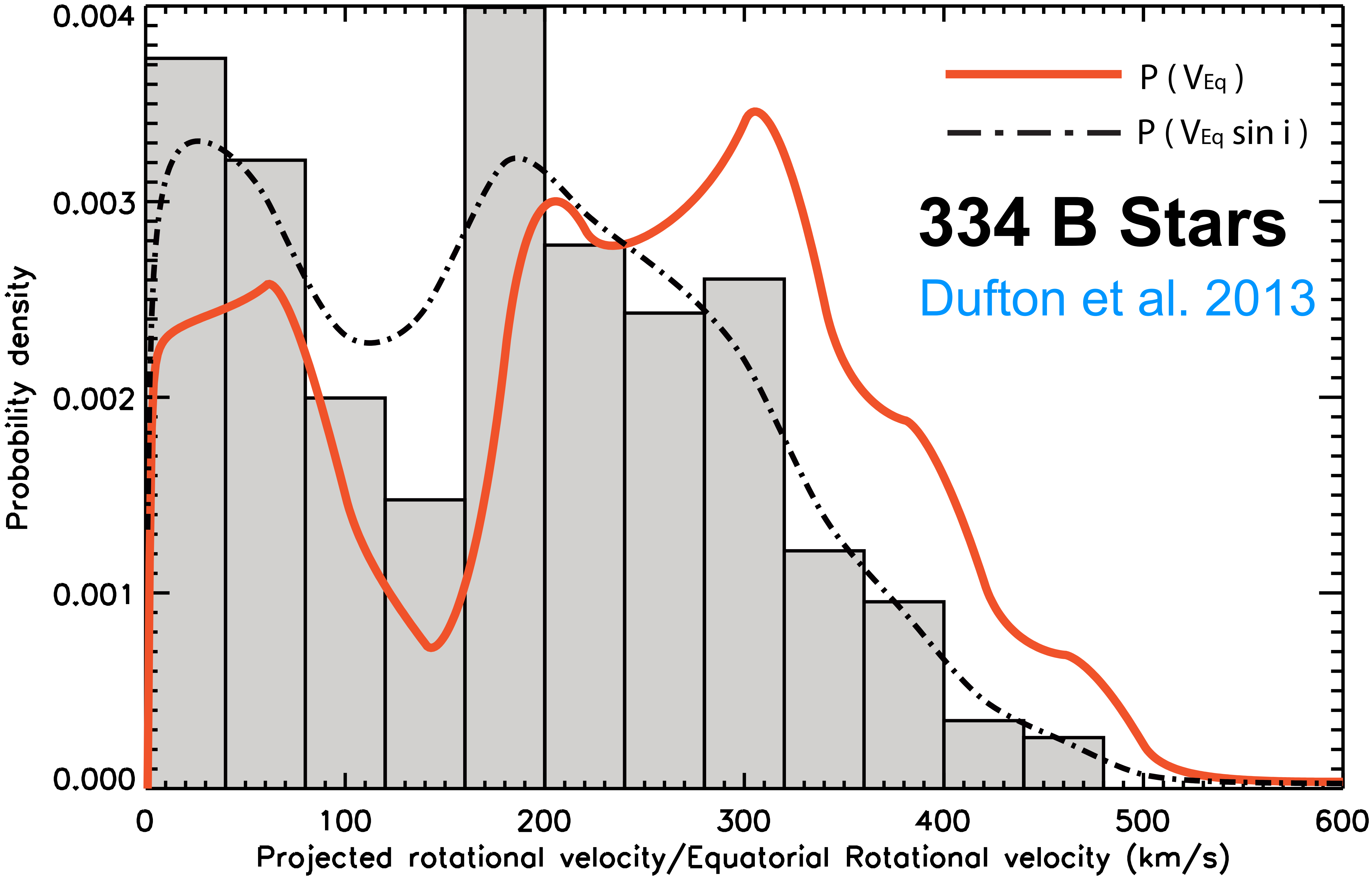
The Iron Convection Zone: Opacity

Inside a massive star



Stellar Rotation

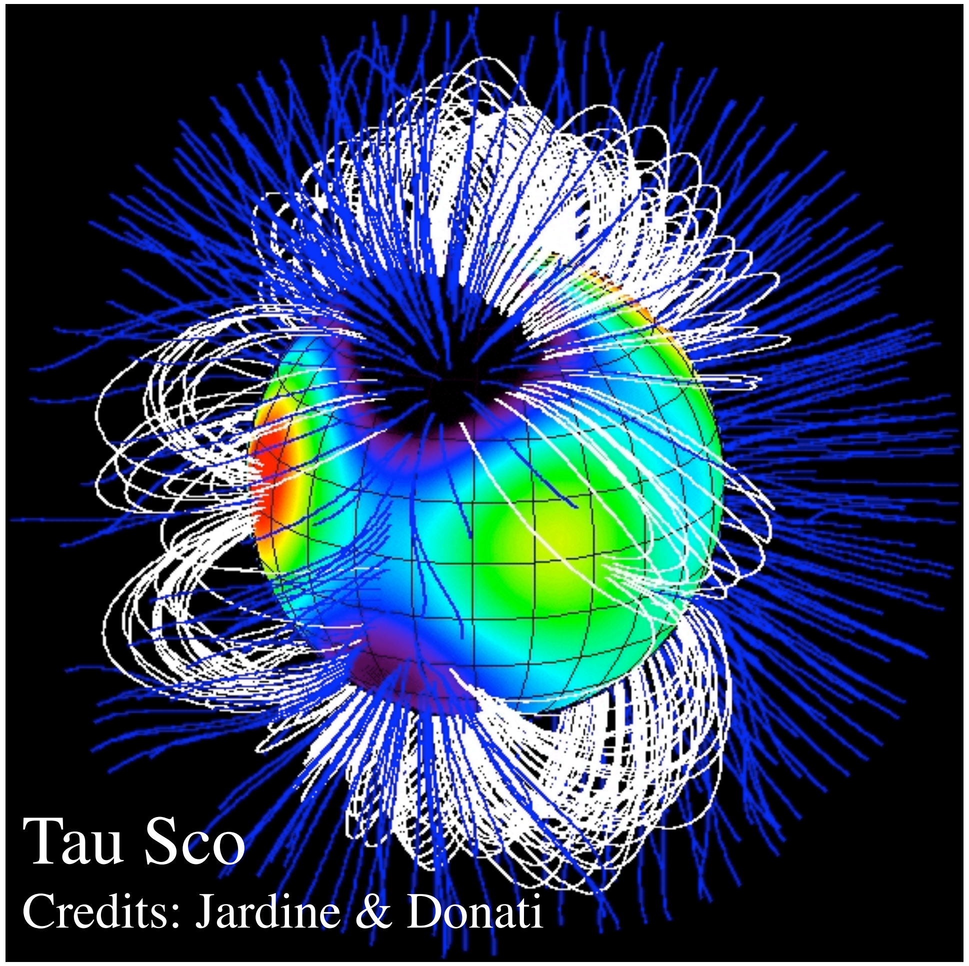
OB stars rotate rapidly



Stellar Magnetic Fields

B-fields in massive stars (direct evidence)

- About 30+ magnetic OB stars found (e.g. Donati, Hubrig, Neiner, Petit)
- Detection through Zeeman spectral signature
- Mostly dipolar, amplitude between 300 G and several kG
- **Bias** toward strong, large scale fields
- Origin unclear. Likely **Fossil** (Wade et al. 2010)
- Similar to A_p/B_p stars ~ 5-15% ?



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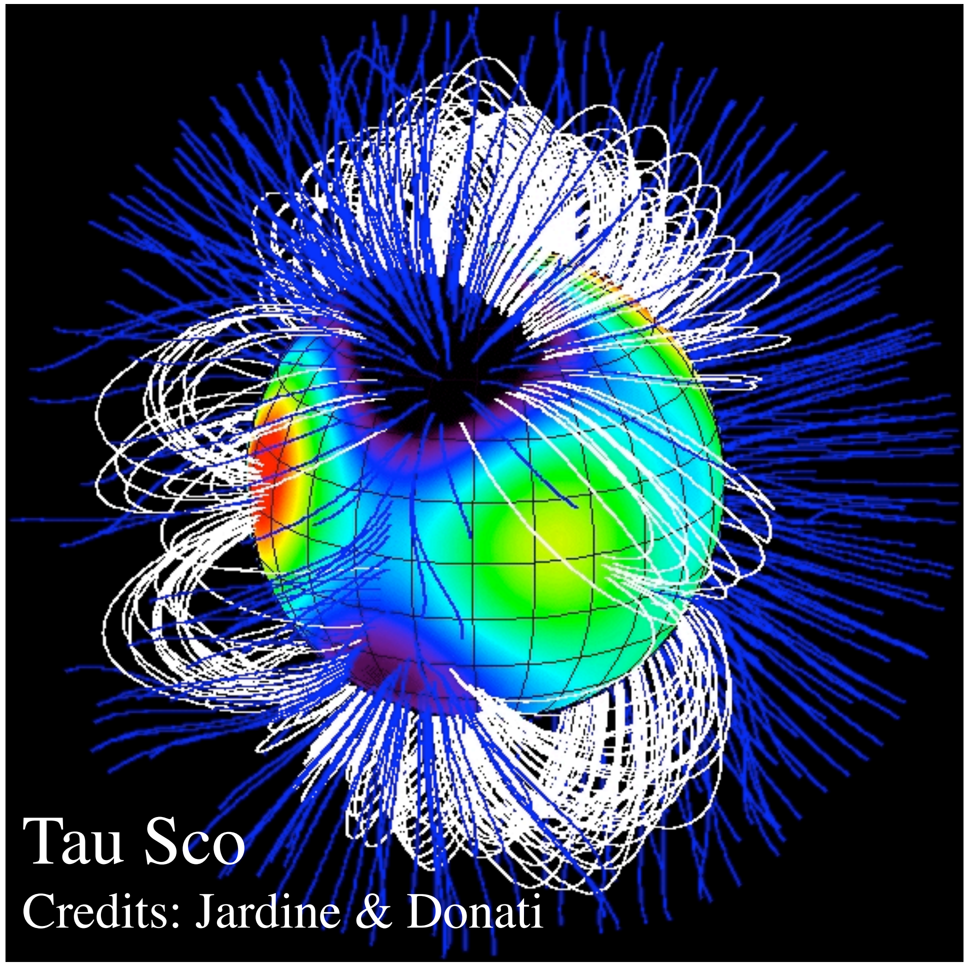
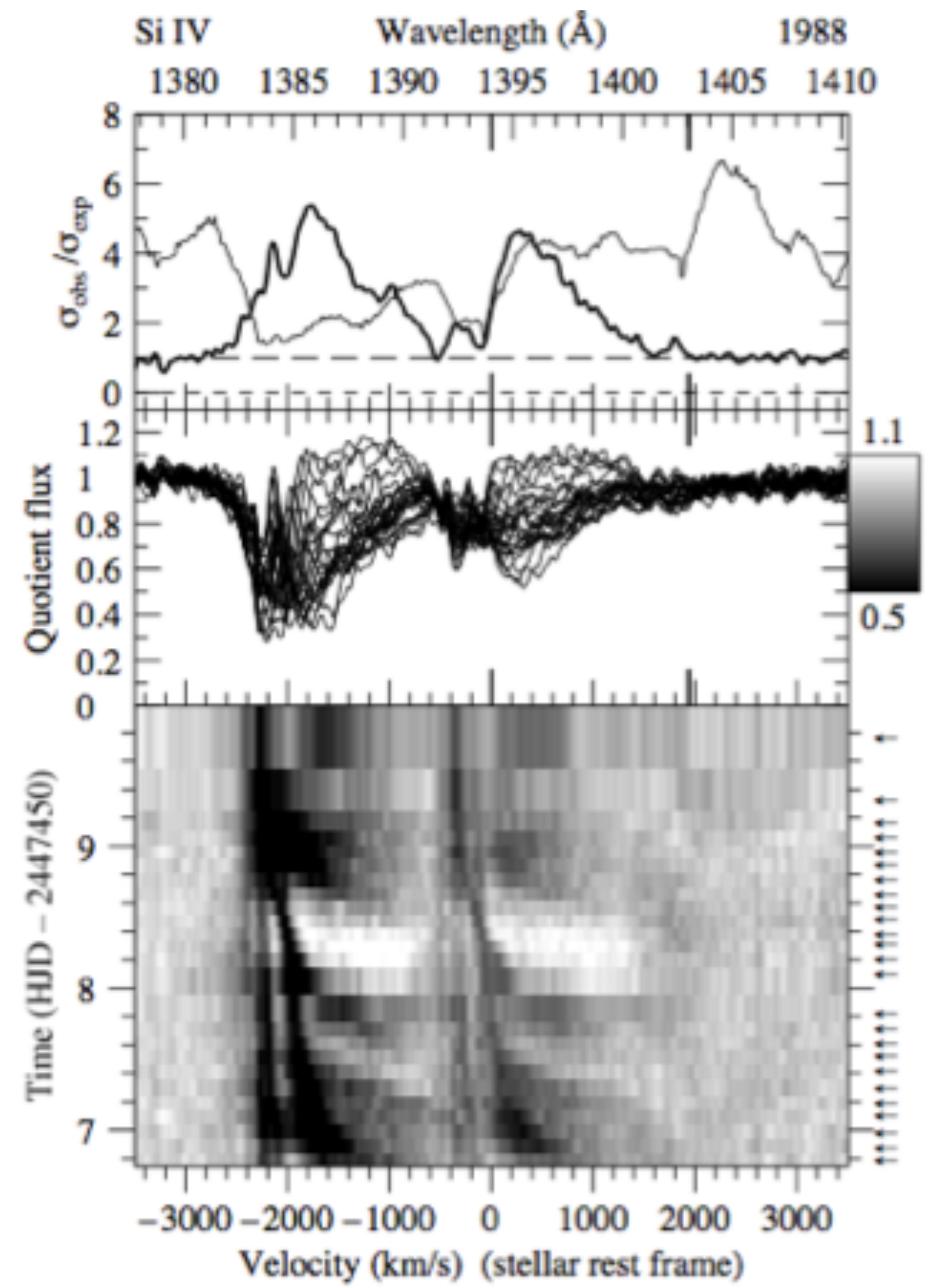


See O. Kochukhov's talk for more details on Zeeman-related techniques and their uncertainties

B-fields in massive stars (indirect evidence)

- OB stars show puzzling surface phenomena
  (e.g. DACs, LPV, Wind Clumping, Solar-Like Oscillations, Photometric variability, X-ray emission...)
- Some of these phenomena are **ubiquitous**. Therefore can not be explained by large scale fields! (e.g. Schnerr+08)
- Small scale / small amplitude fields? (e.g. Cranmer & Owocki 96, Fullerton+96, Kaper+97, Henrichs+05)

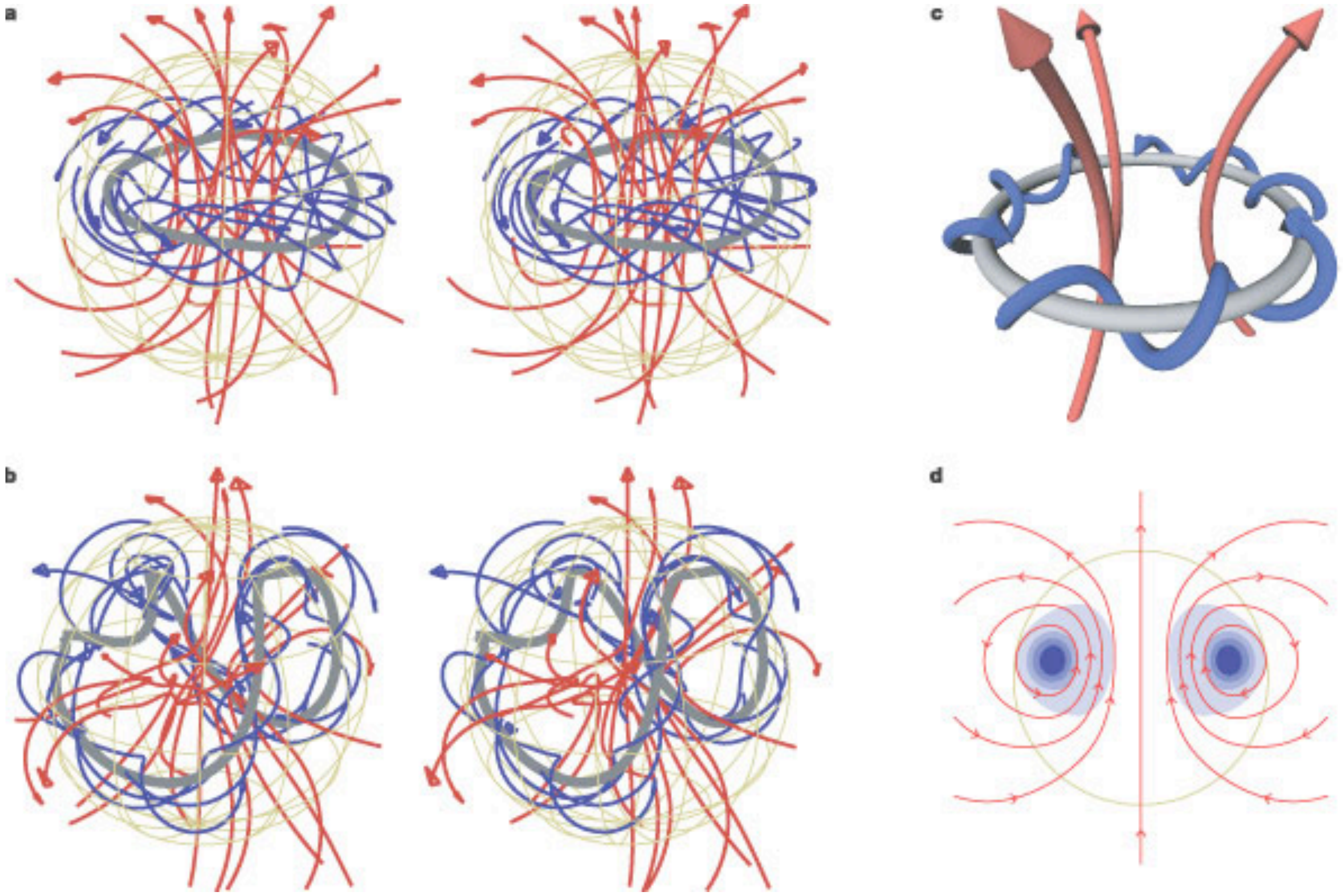


(DACs: Kaper, Henrichs et al. 1999)

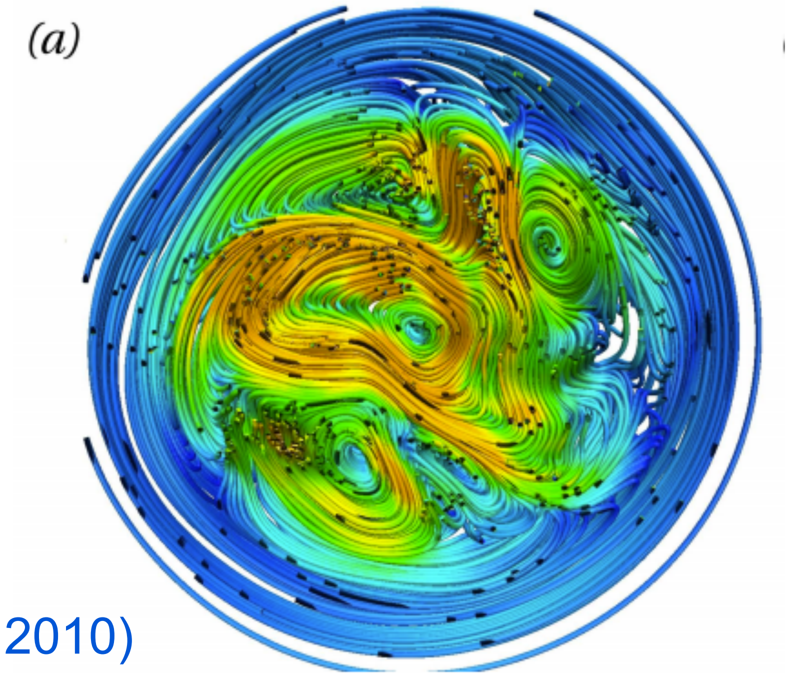
Origin of B-fields in massive stars

- Fossil Fields
  - B-field is produced/retained during star formation
  - Field arranged into a **stable configuration**

(Braithwaite & Nordlund 2006, Duez et al. 2010)

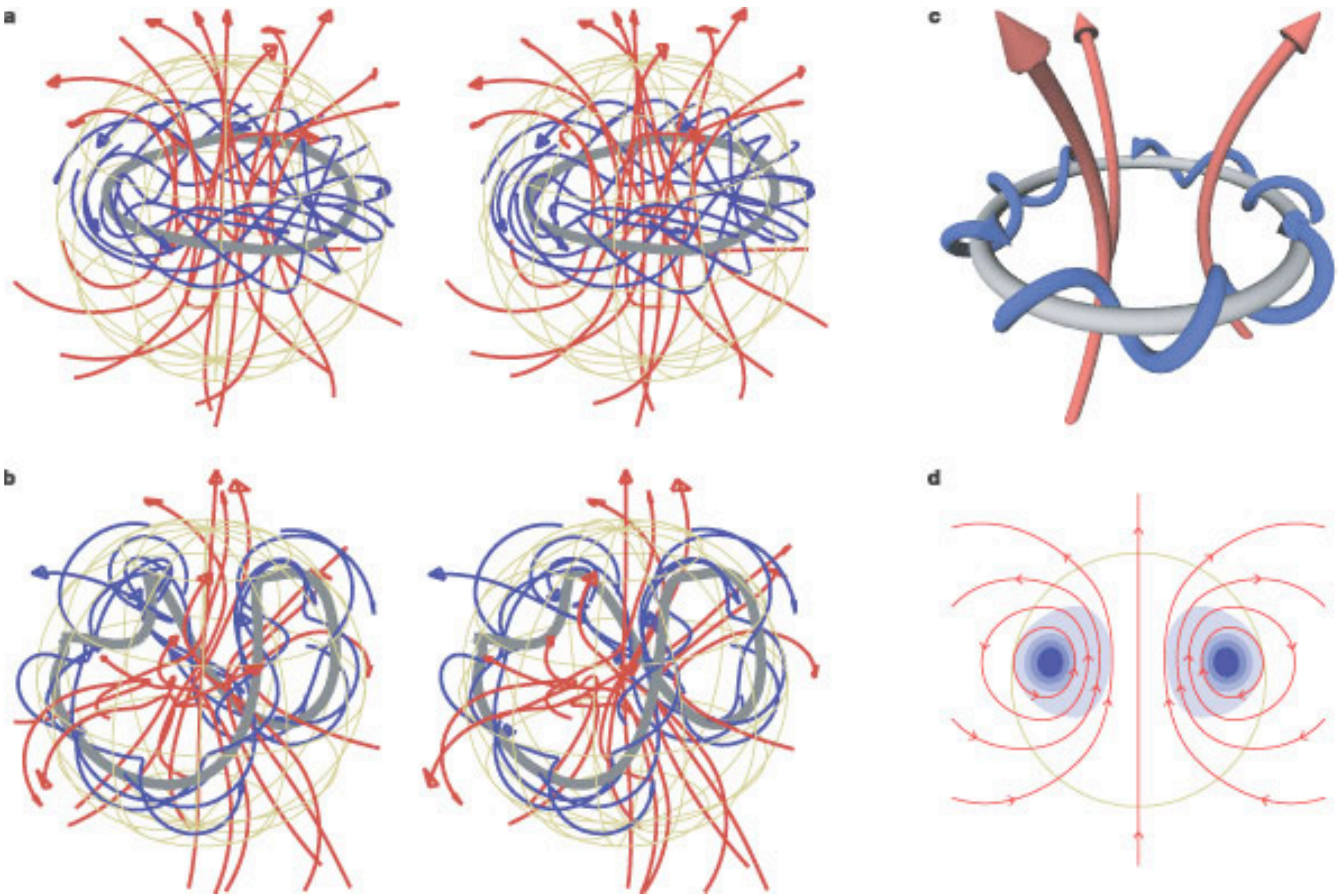


- Contemporary Dynamo Action
  - Configuration of the flow that transforms kinetic energy into magnetic energy. B-field maintained against Ohmic dissipation.



(Cantiello et al. 2010, Augustson et al. 2010)

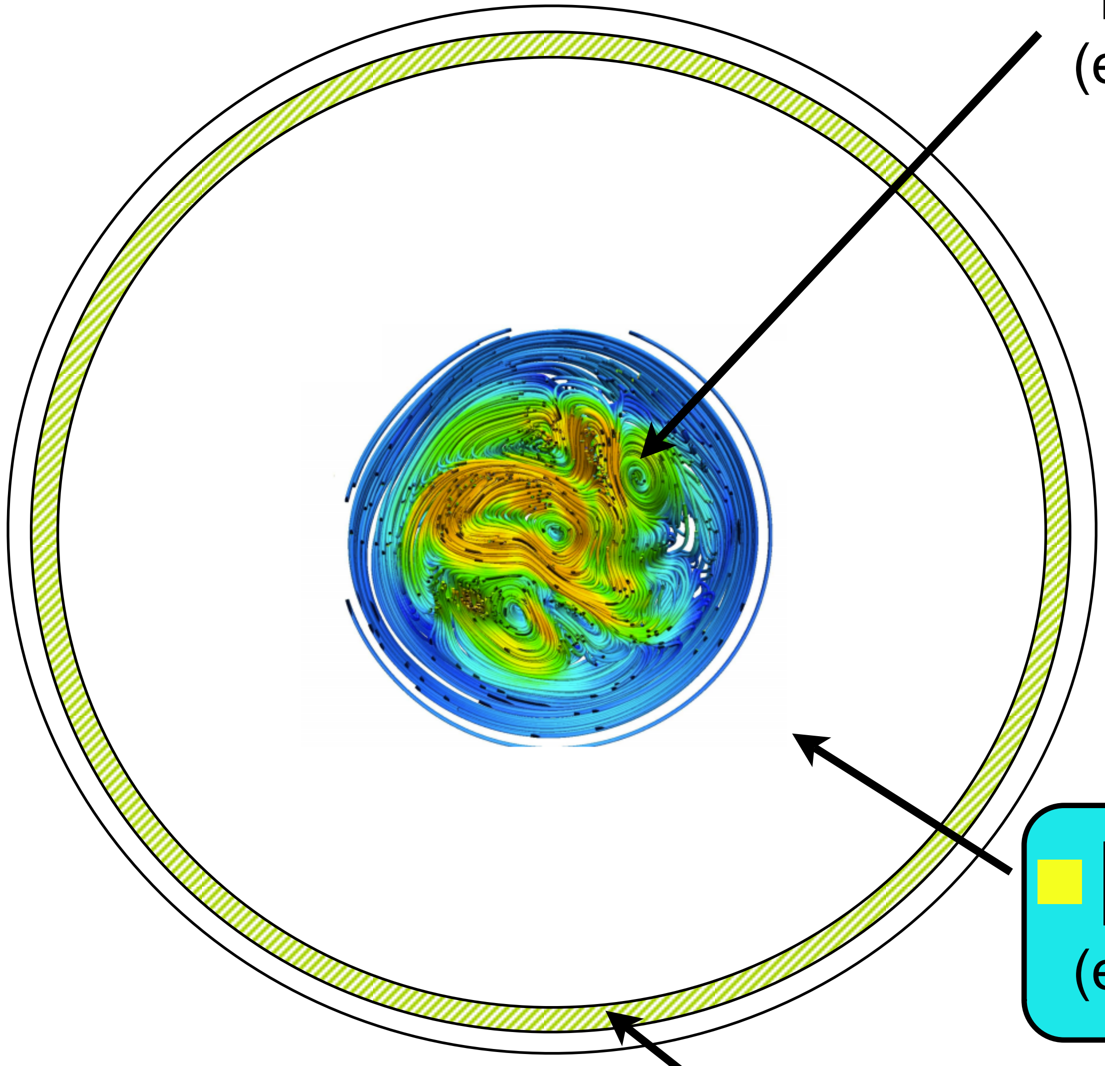
Stable Configurations



Prendergast 1956, Kamchatnov 1982, Mestel 1984, Braithwaite & Nordlund 2006, Duez et al. 2010

Dynamo Action in OB stars

e.g. Main Sequence 10 M_{Sun}

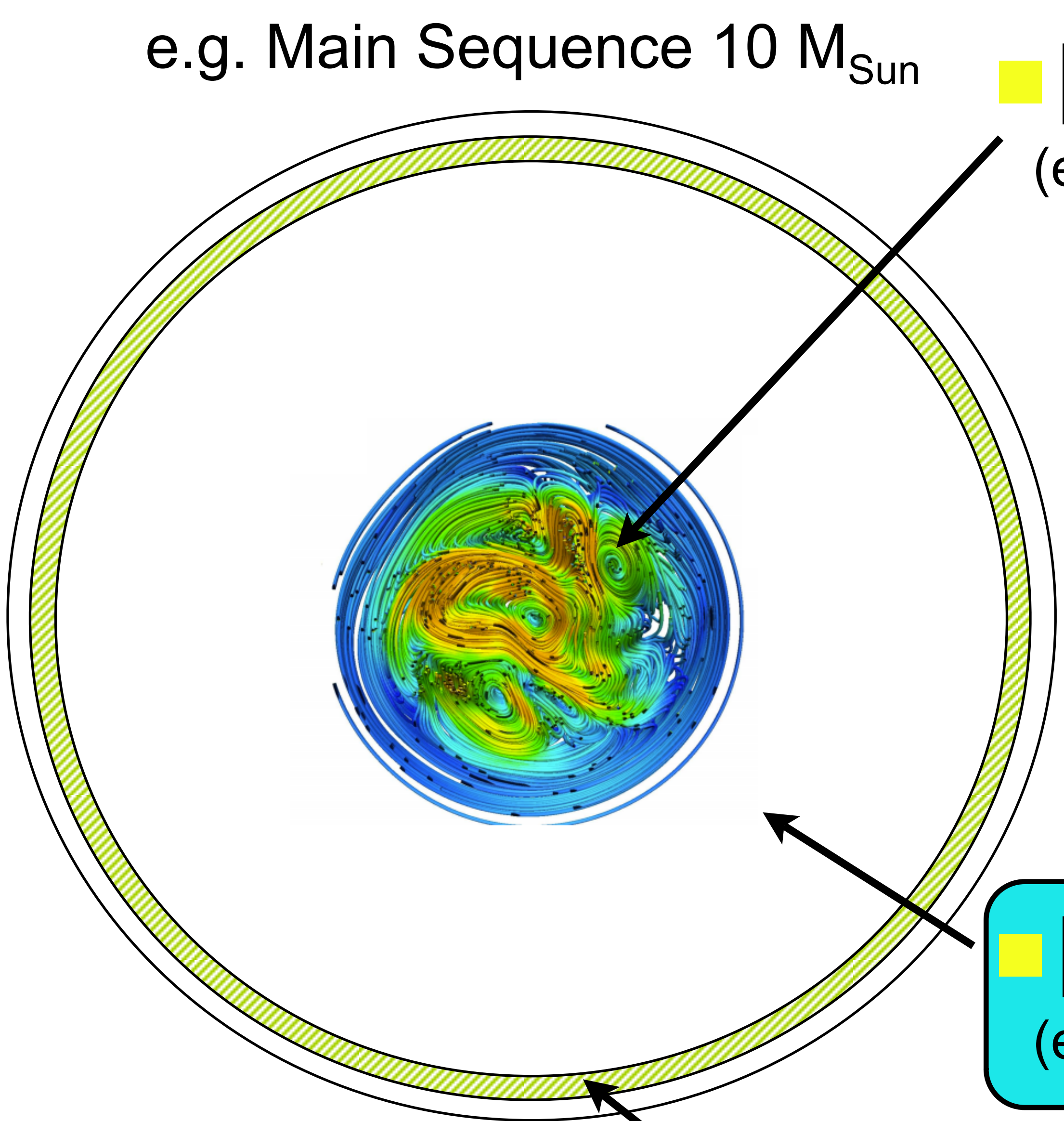


- Dynamo in Convective Core
  (e.g. MacGregor & Cassinelli 2003, Augustson et al. 2010)

- Dynamo in Radiative Zone
  (e.g. Spruit 2002, implemented in stellar evolution codes)

- Dynamo in Iron Convection Zone
  (Cantiello et al. 2009,2010; Cantiello & Braithwaite 2011)

Dynamo Action in OB stars



- Dynamo in Convective Core

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B-Fields probably not observable, but potentially important for evolution and final stages

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(Cantiello et al. 2009,2010; Cantiello & Braithwaite 2011)

Dynamo Action in OB stars

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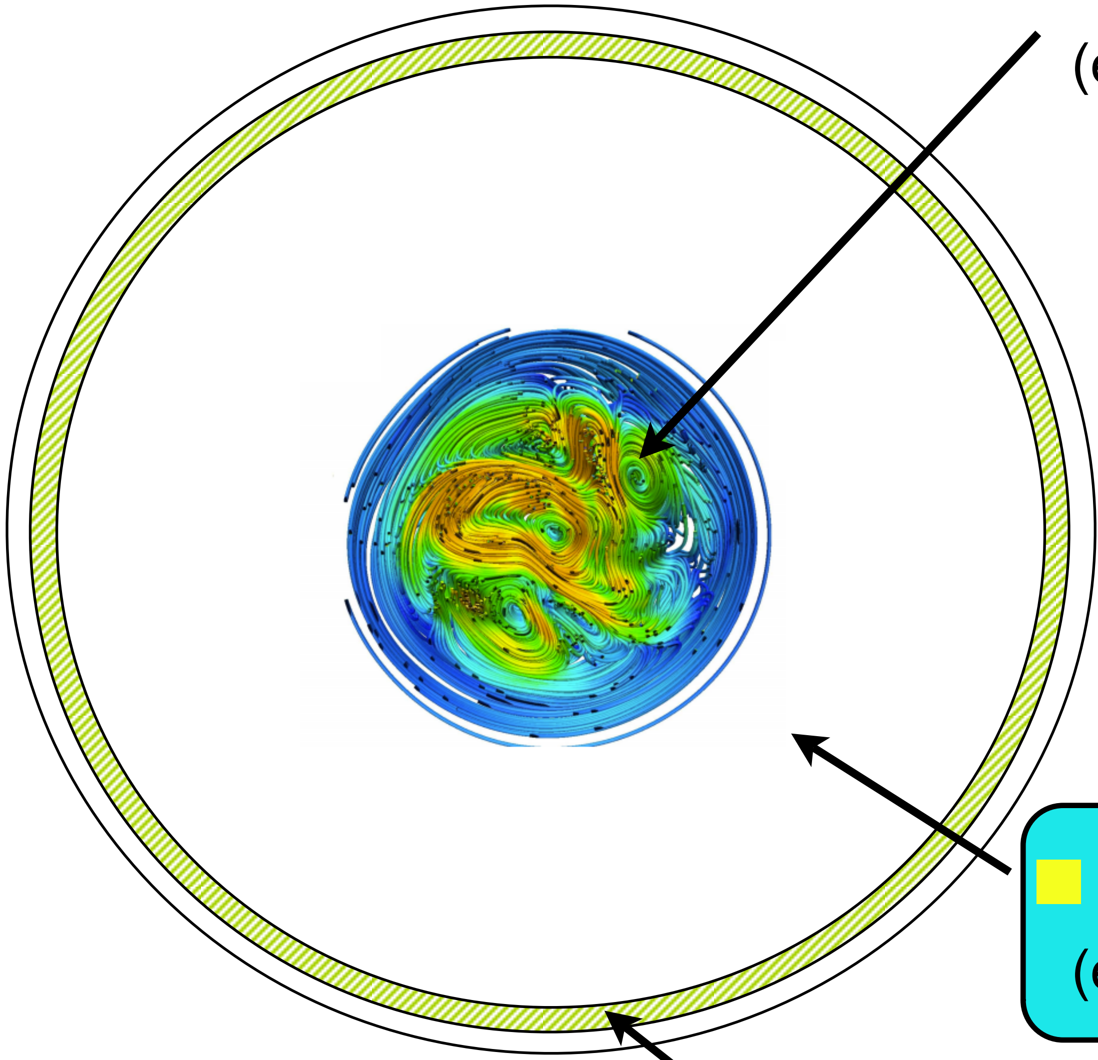


- **Dynamo in Convective Core**
  (e.g. MacGregor & Cassinelli 2003, Augustson et al. 2010)

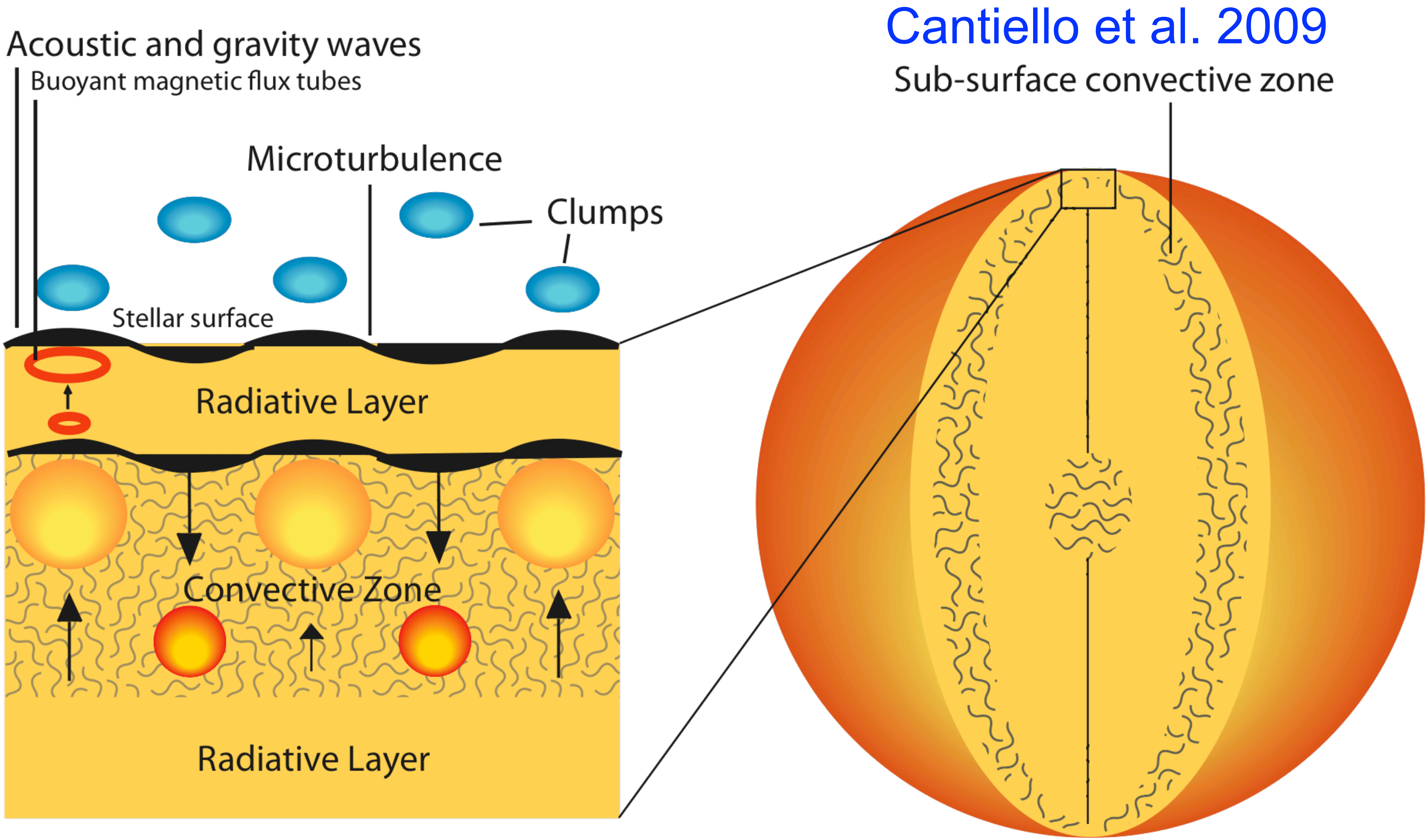
  B-Fields probably not observable, but potentially important for evolution and final stages

See talks from A.Bonanno and J.Braithwaite

- **Dynamo in Radiative Zone**
  (e.g. Spruit 2002, implemented in stellar evolution codes)

- **Dynamo in Iron Convection Zone**
  (Cantiello et al. 2009,2010; Cantiello & Braithwaite 2011)

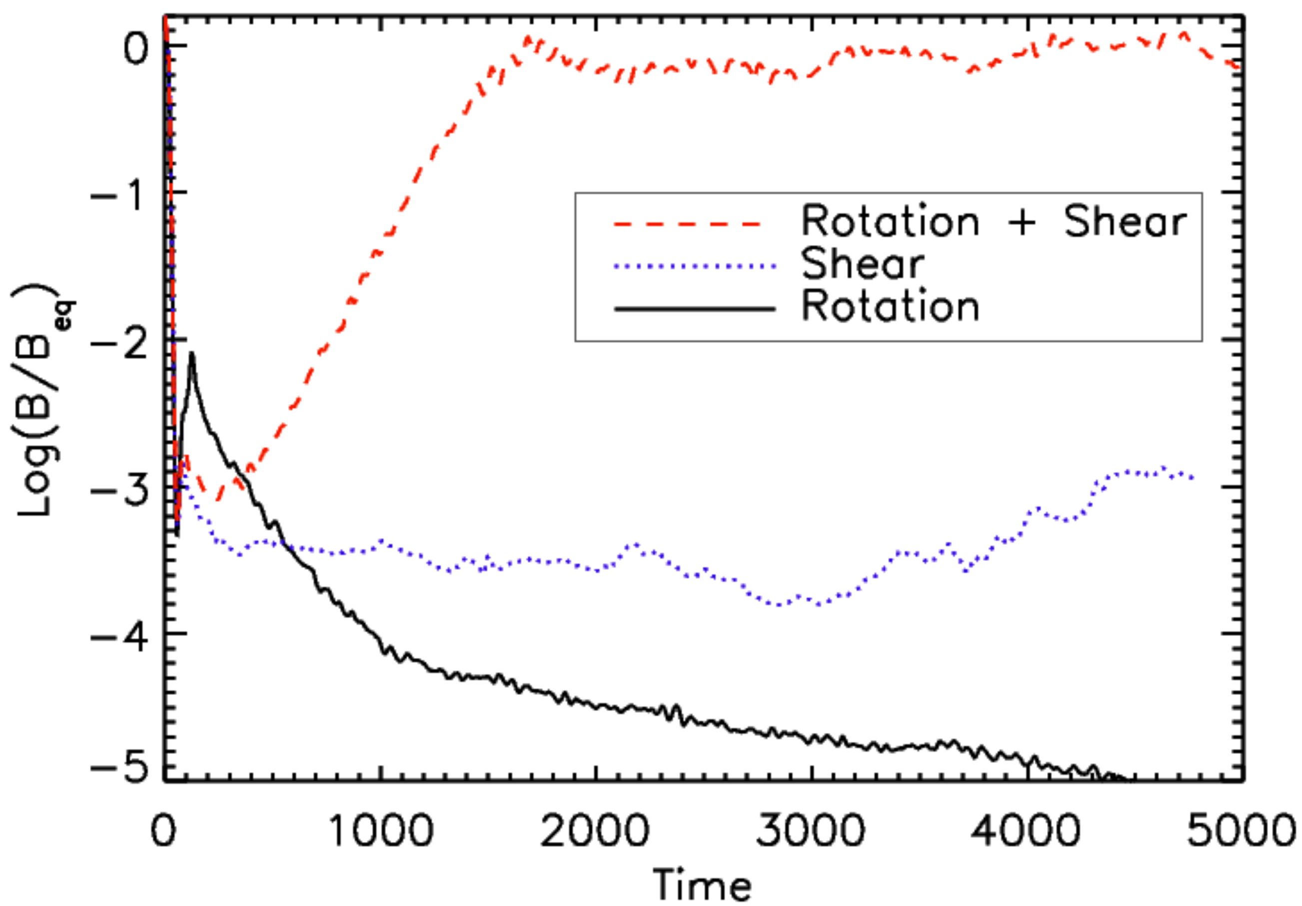
Physics in the FeCZ

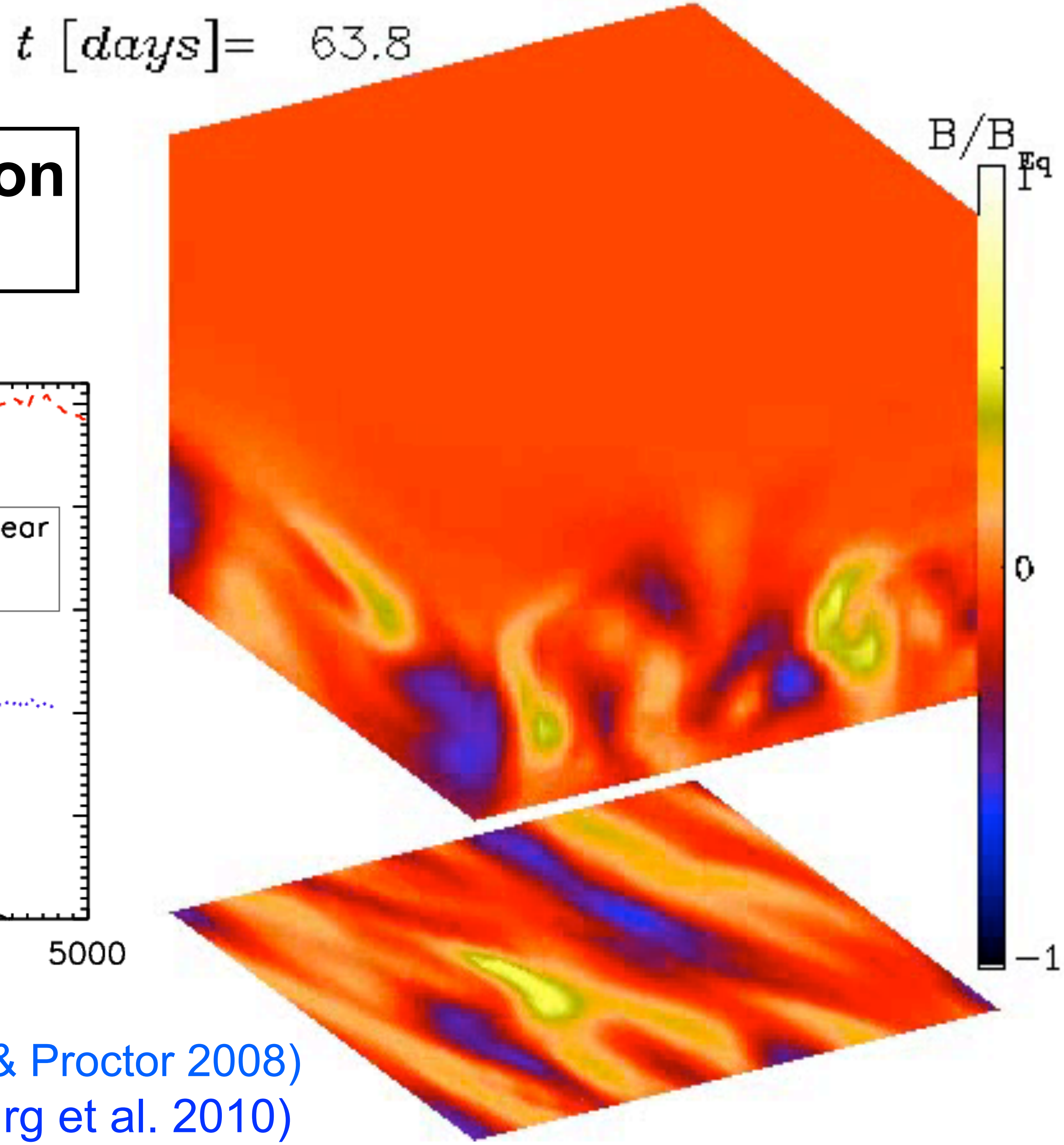


(e.g. Lighthill '52, Stein '67, Edmunds '78, Goldreich & Kumar '90, de Jager et al. '91)

Dynamo Action in FeCZ

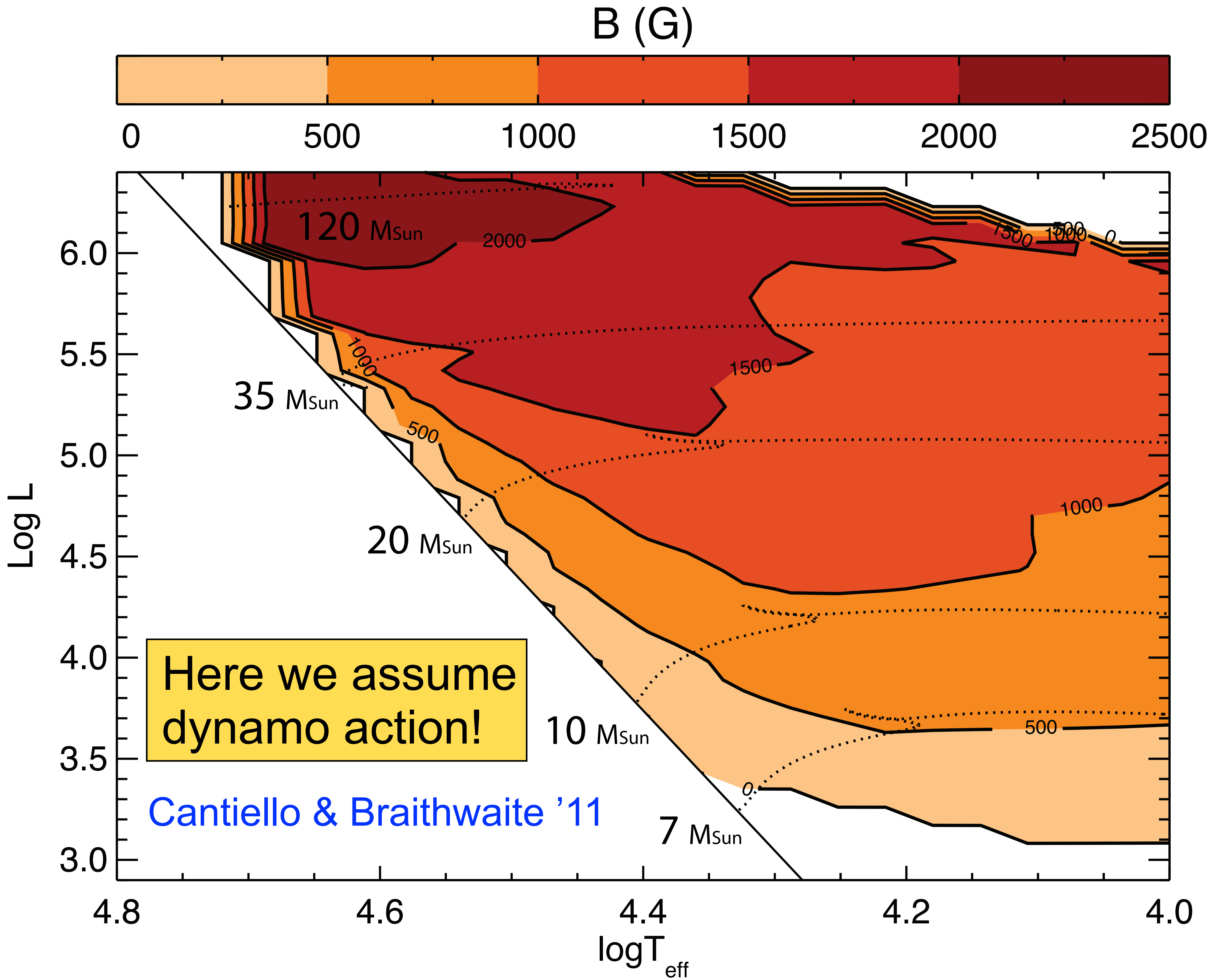
Subsurface convection
Rotation + Shear



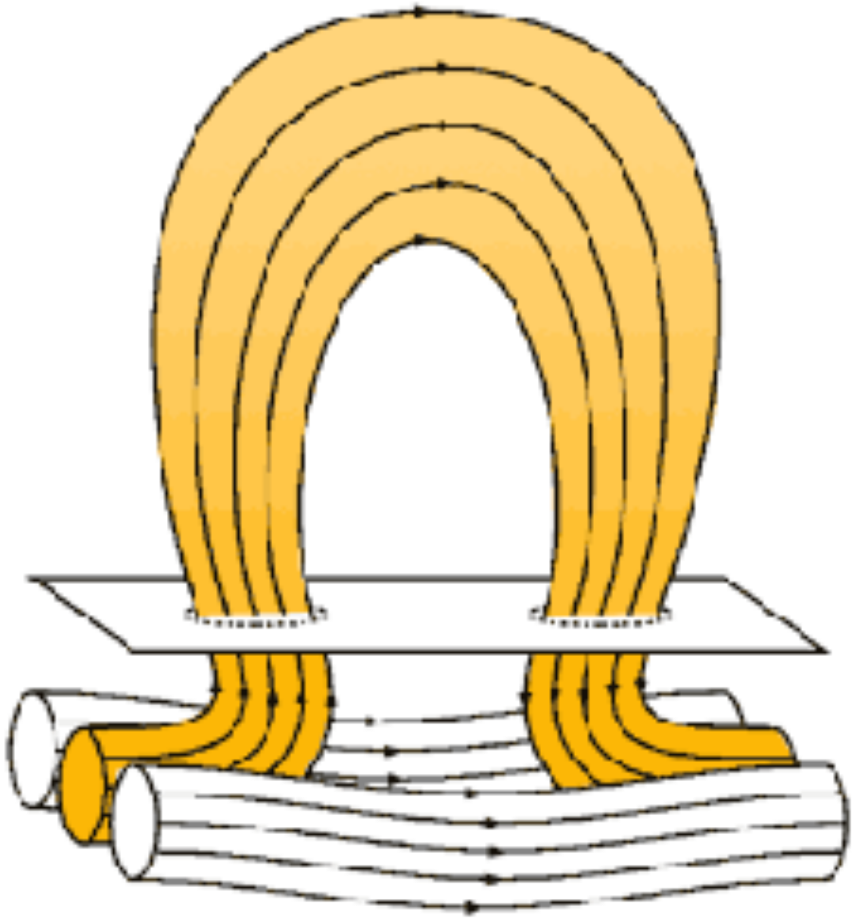


(**Käpylä et al. 2008,2010**; Hughes & Proctor 2008)
(Cantiello, Braithwaite, Brandenburg et al. 2010)

Equipartition B Field in FeCZ



Surface appearance



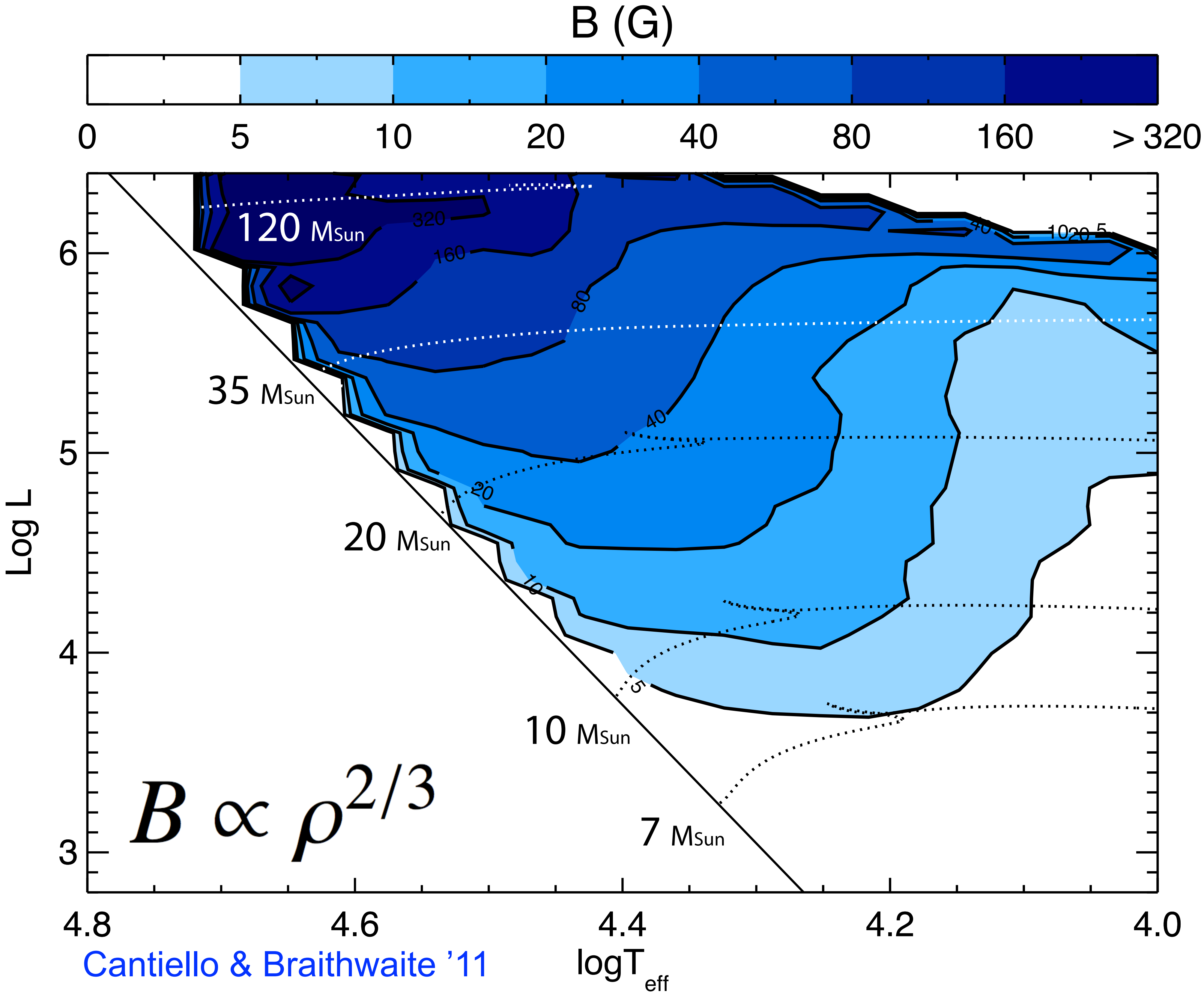
Possible mechanisms

1) Magnetic Diffusion ~ 10^7 yr
2) Wind Advection ~ 1 yr
3) **Magnetic Buoyancy ~ hours**

See also J.Warnecke's talk for another possible ejection mechanism and Y.Fournier for calculations of buoyant B-fields in radiative zones

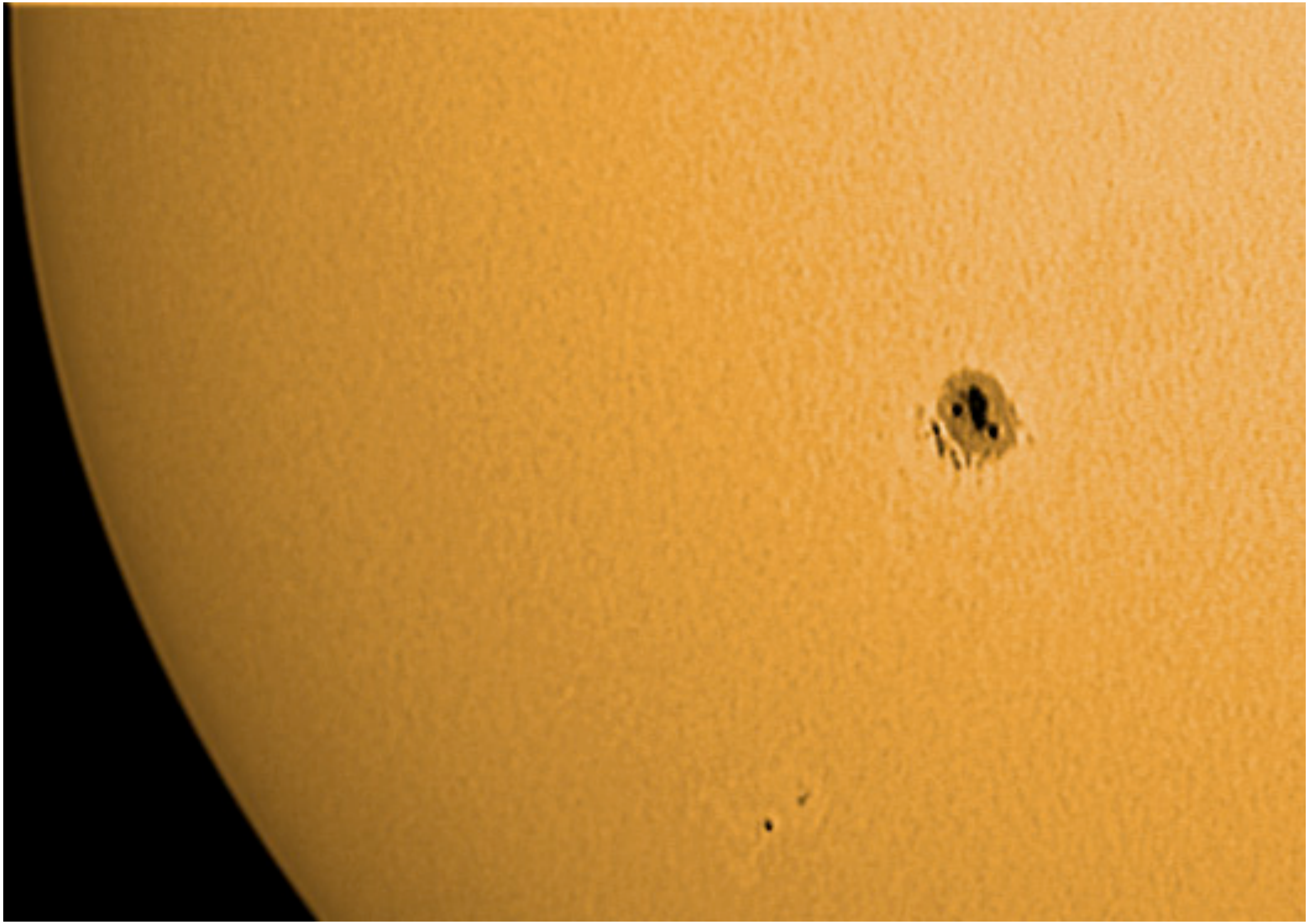
- The amplitude of a self contained magnetic feature scales as $B \propto \rho^{2/3}$
- If the field is still anchored to the convection zone plasma can flow through the tube and higher fields can be reached (up to equipartition with thermal pressure) (Cantiello & Braithwaite '11)

Surface B Field from FeCZ



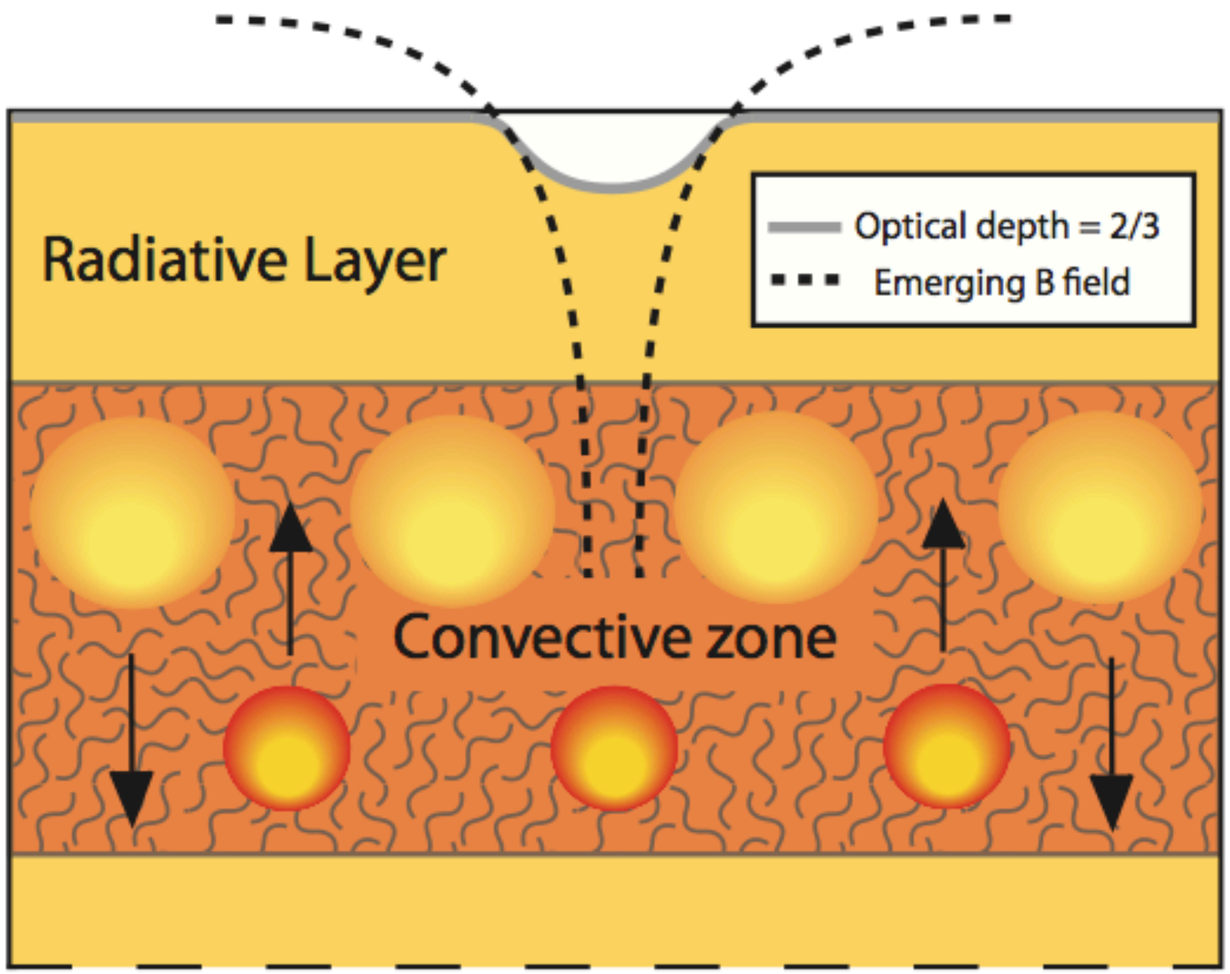
Cantiello & Braithwaite '11

Magnetic Spot in the Sun



How they would look like?

A **very** simple model:
1) Assume hydrostatic equilibrium
2) Assume thermal equilibrium
3) Assume beta >> 1



$$P_e = P_i = \rho_i kT + B^2/8\pi$$

e.g. Parker (1955)

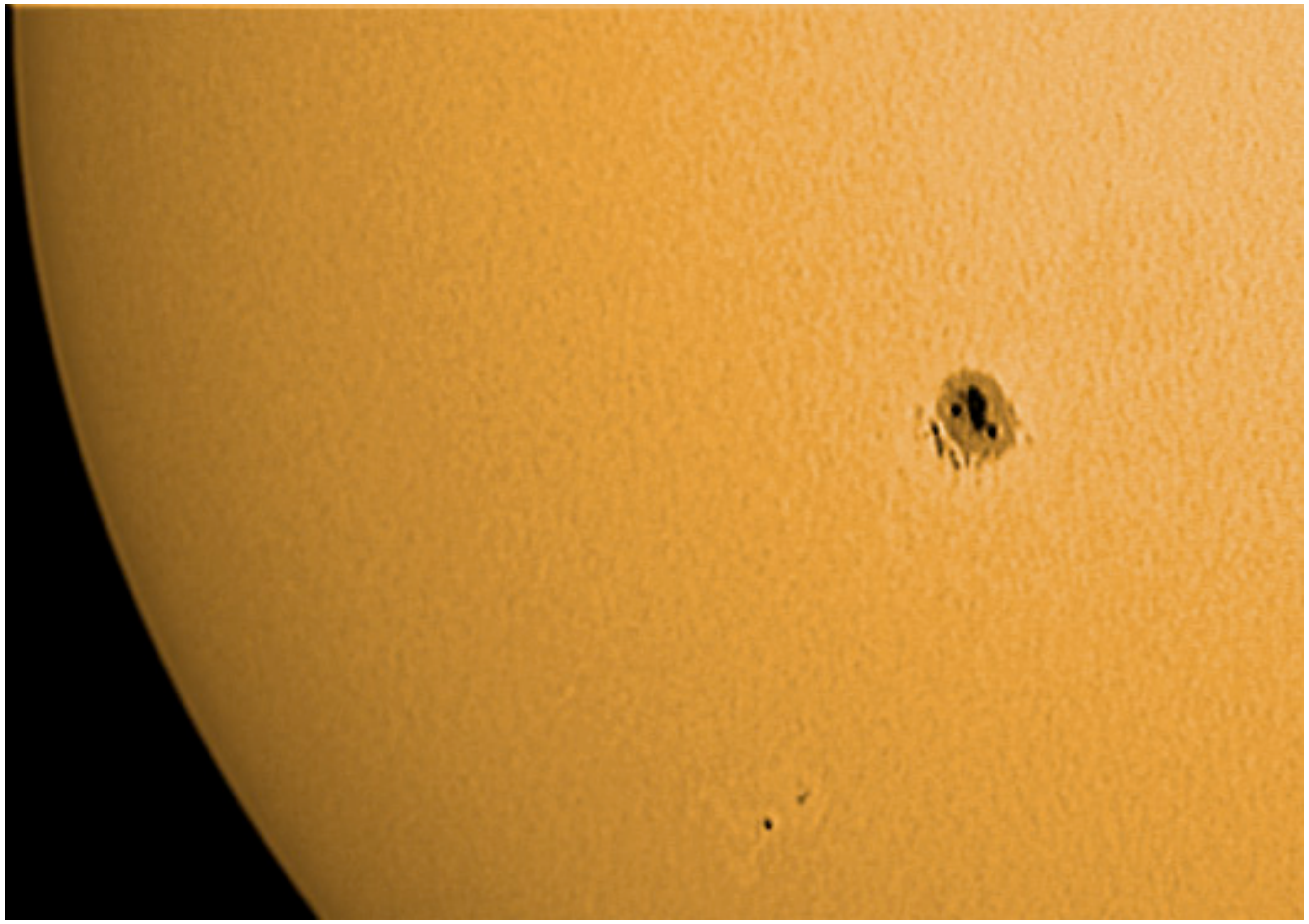
$$\frac{\Delta \ln T}{\Delta \ln P} = \nabla_{\rm rad} \qquad \beta = \frac{\rho k T}{B^2/8\pi}$$

$$\boxed{\frac{\Delta T}{T} = \frac{\nabla_{\rm rad}}{\beta}}$$

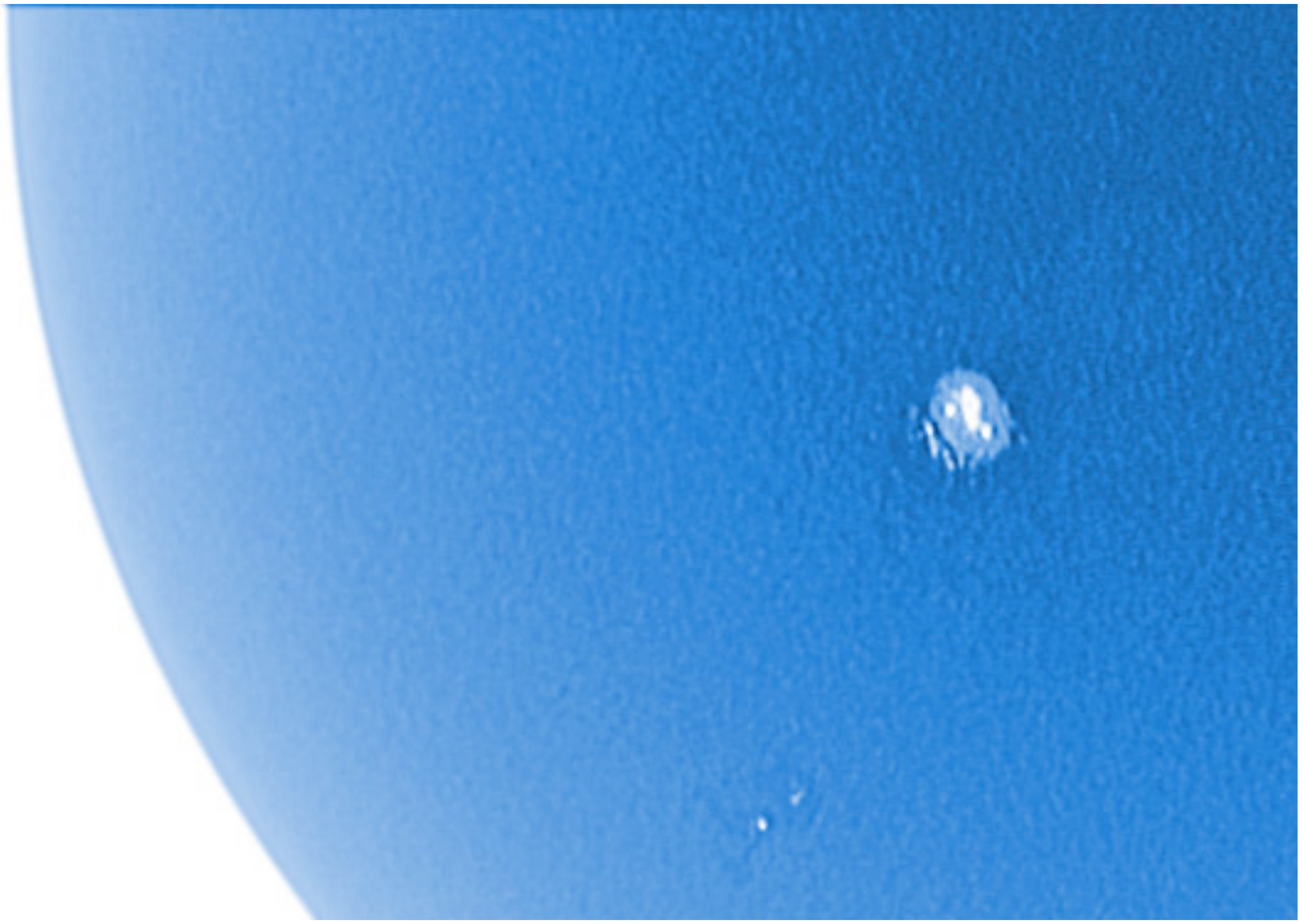
For fields of ~ 100 G emerging at the surface this leads to a temperature increase of ~ 300 K. A **hot, bright spot**

Cantiello & Braithwaite (2011)

How they would look like?

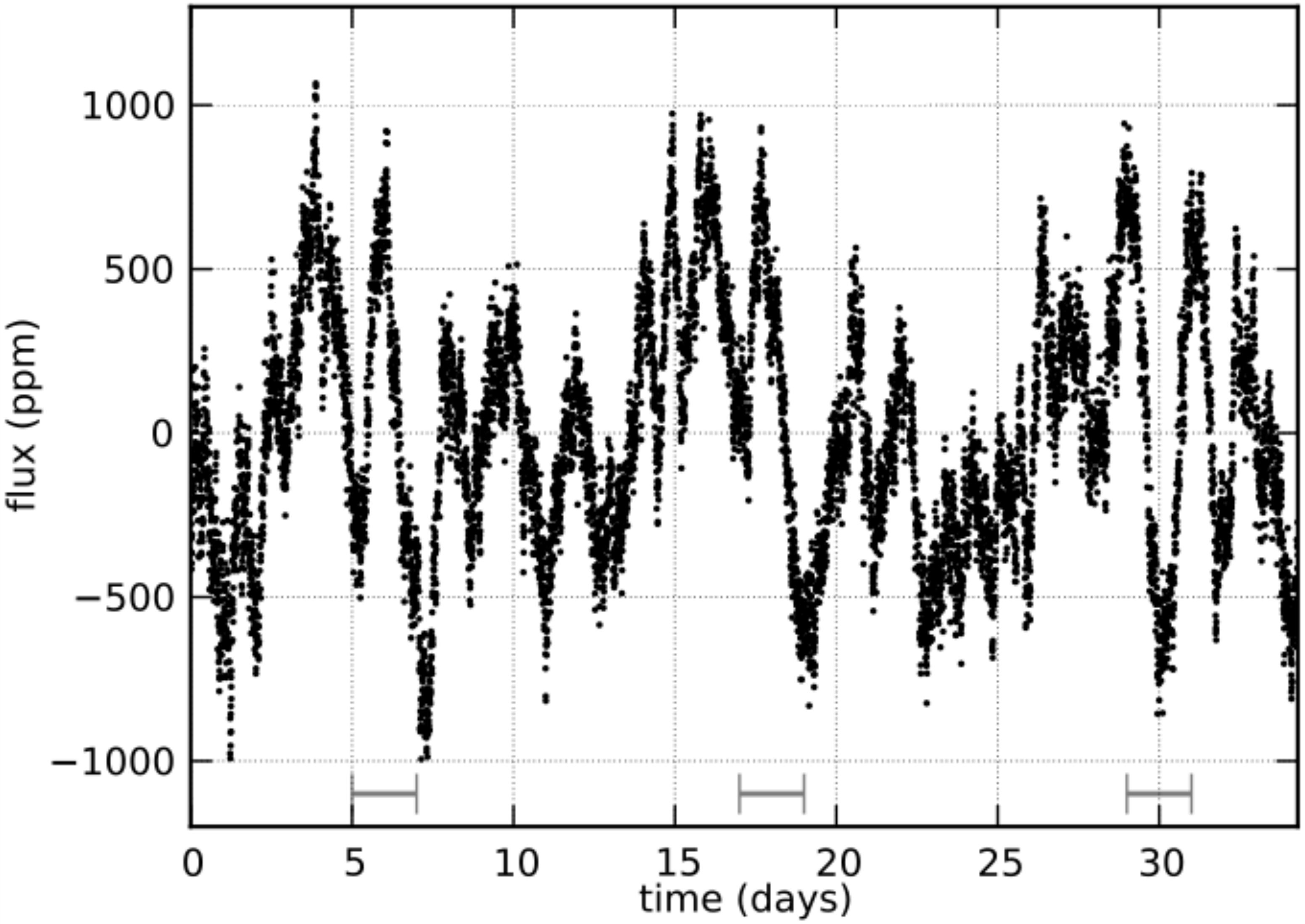


Spot in a convective star



Spot in a radiative star (?)

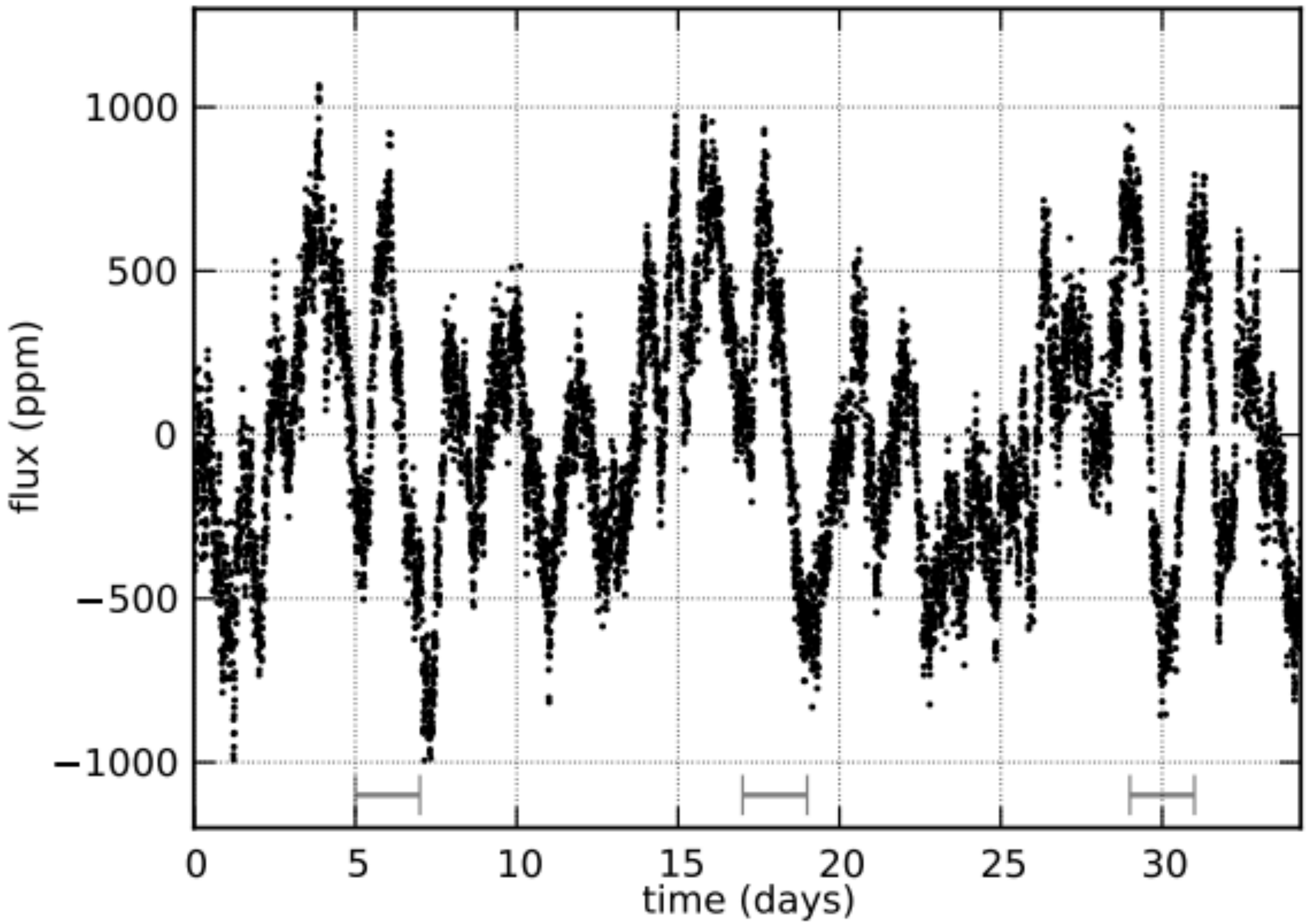
High precision photometry



CoRoT: HD 46149 (Degroote et al. 2010)

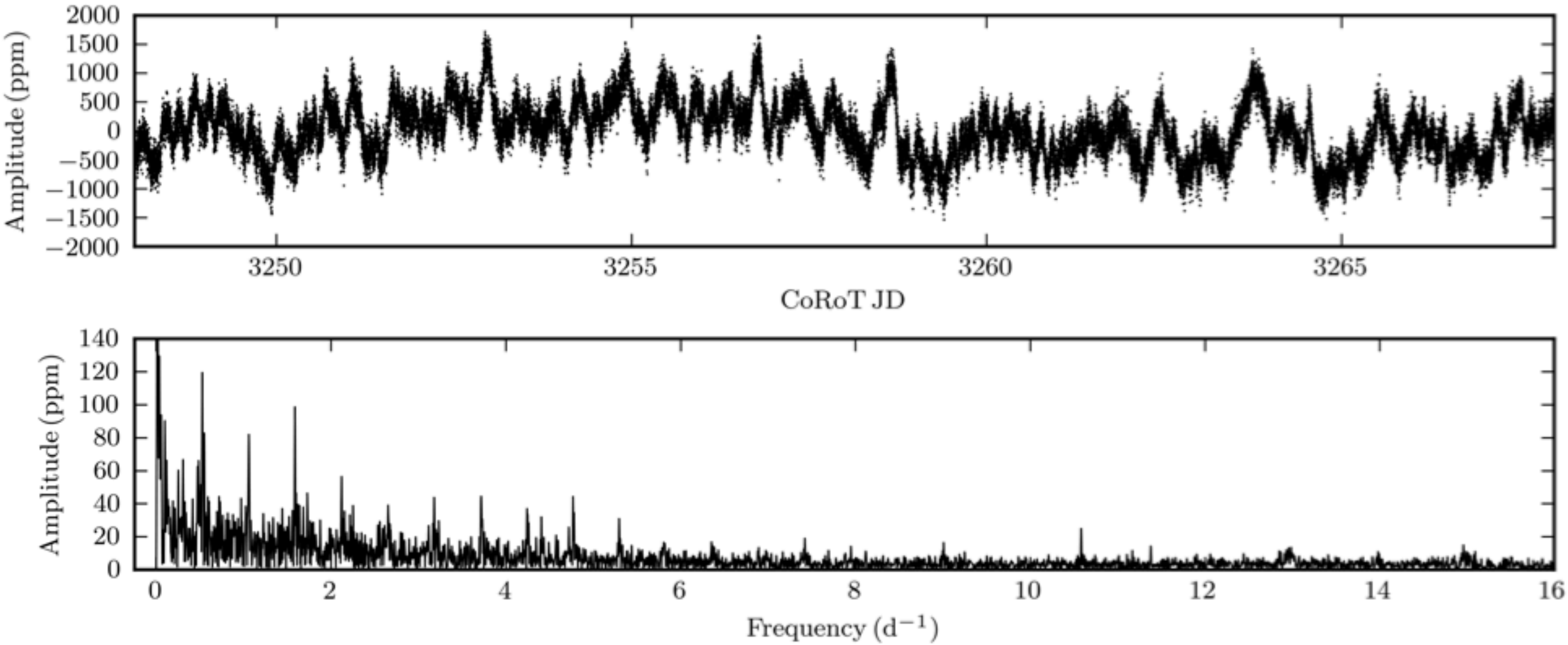
Spots in a O8V star?

HD 46149 (Degroote et al. 2010)



Spots in a B0.5IV star?

HD51756 (Papics et al. 2011)



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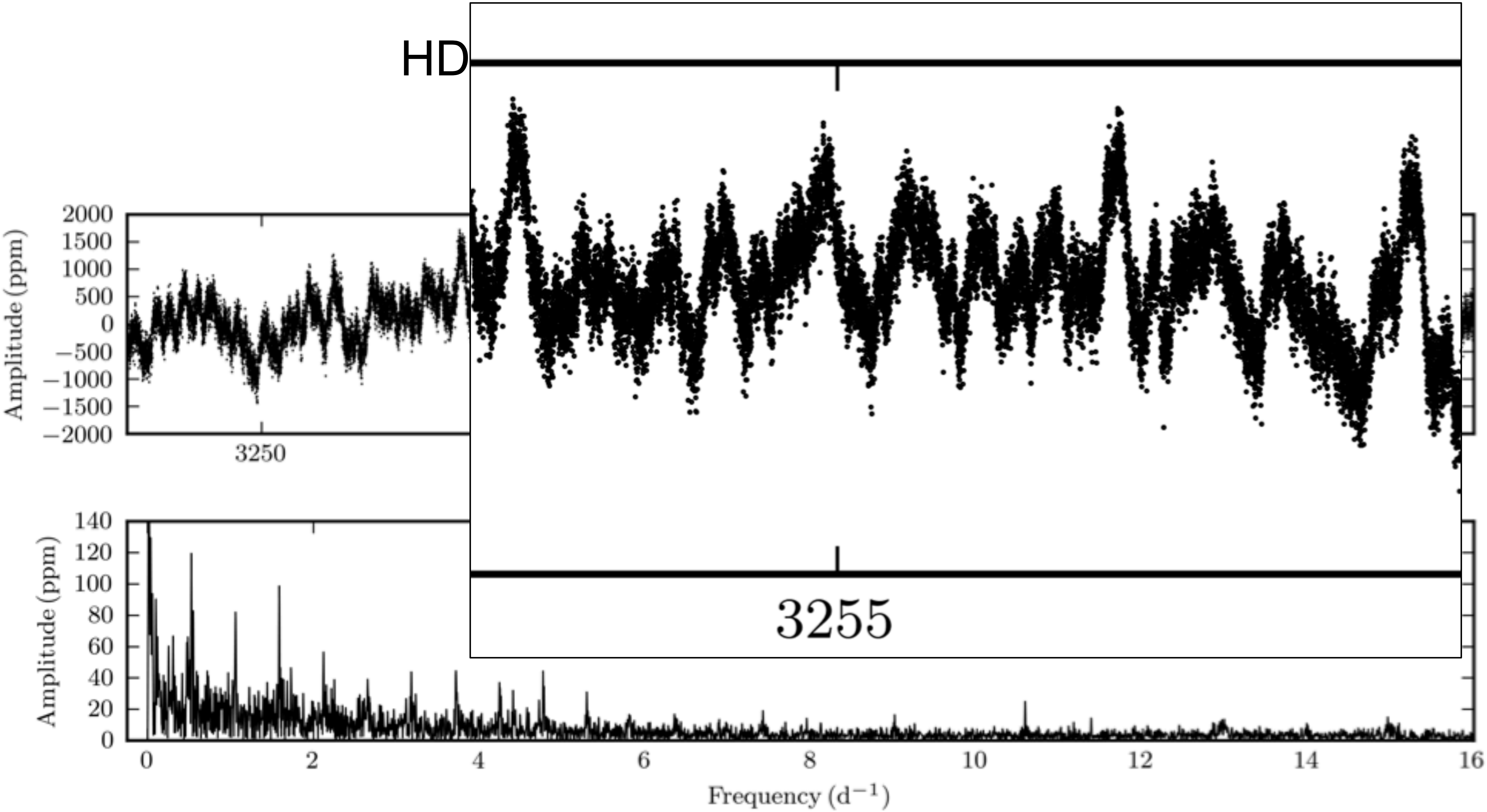
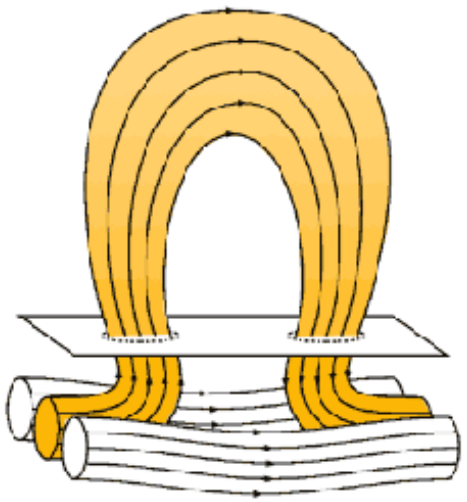


Effects from turbulent convection

Magnetic fields

Magnetic spots

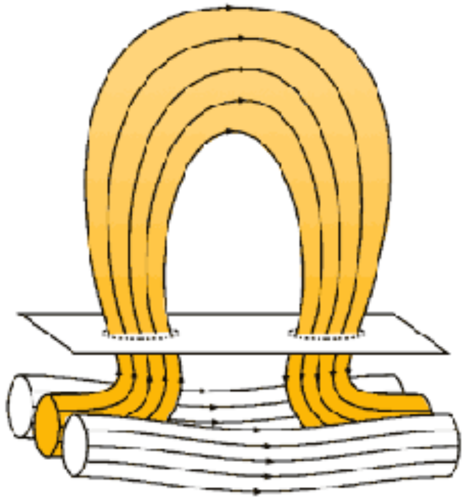


FeCZ

Effects from turbulent convection

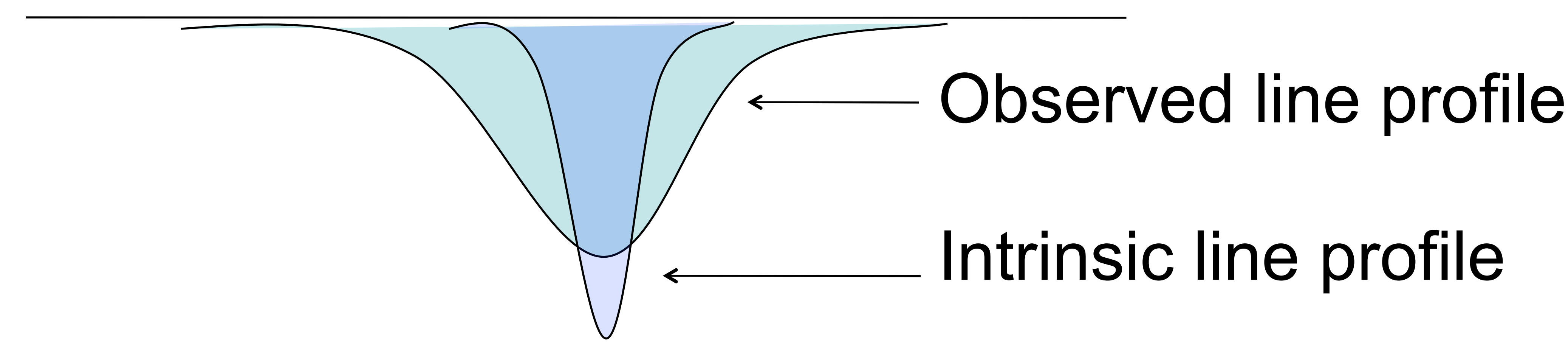
FeCZ → Magnetic fields → Magnetic spots

FeCZ → Running waves → Turbulence

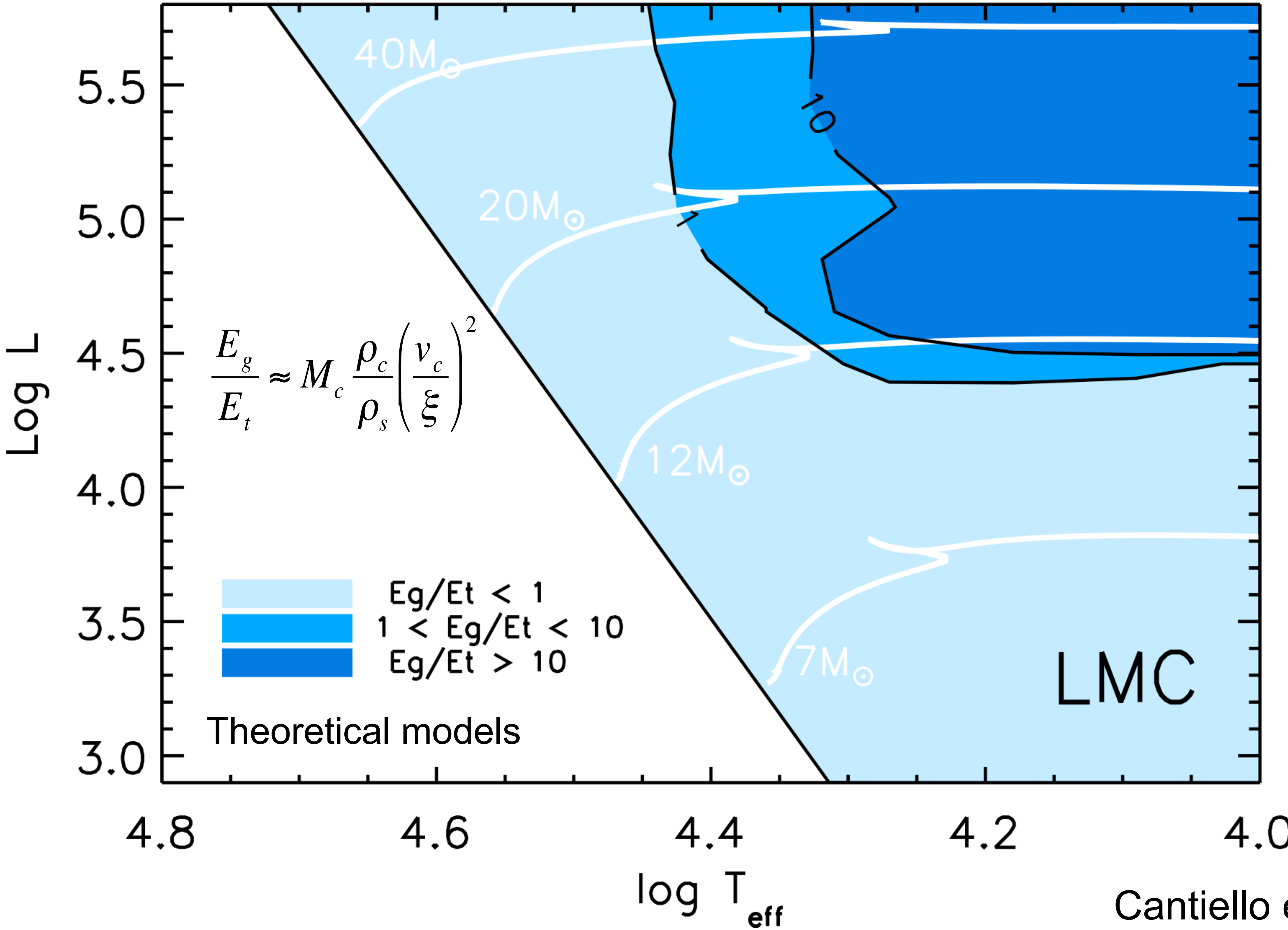


Surface Turbulence

- Can be measured using spectroscopy. Microturbulence and Macroturbulence measure motions with coherence length smaller and larger than the line forming region respectively.
- Tight correlation between FeCZ properties and microturbulence (Cantiello+09, Fraser+10, Firnstein+in prep.)



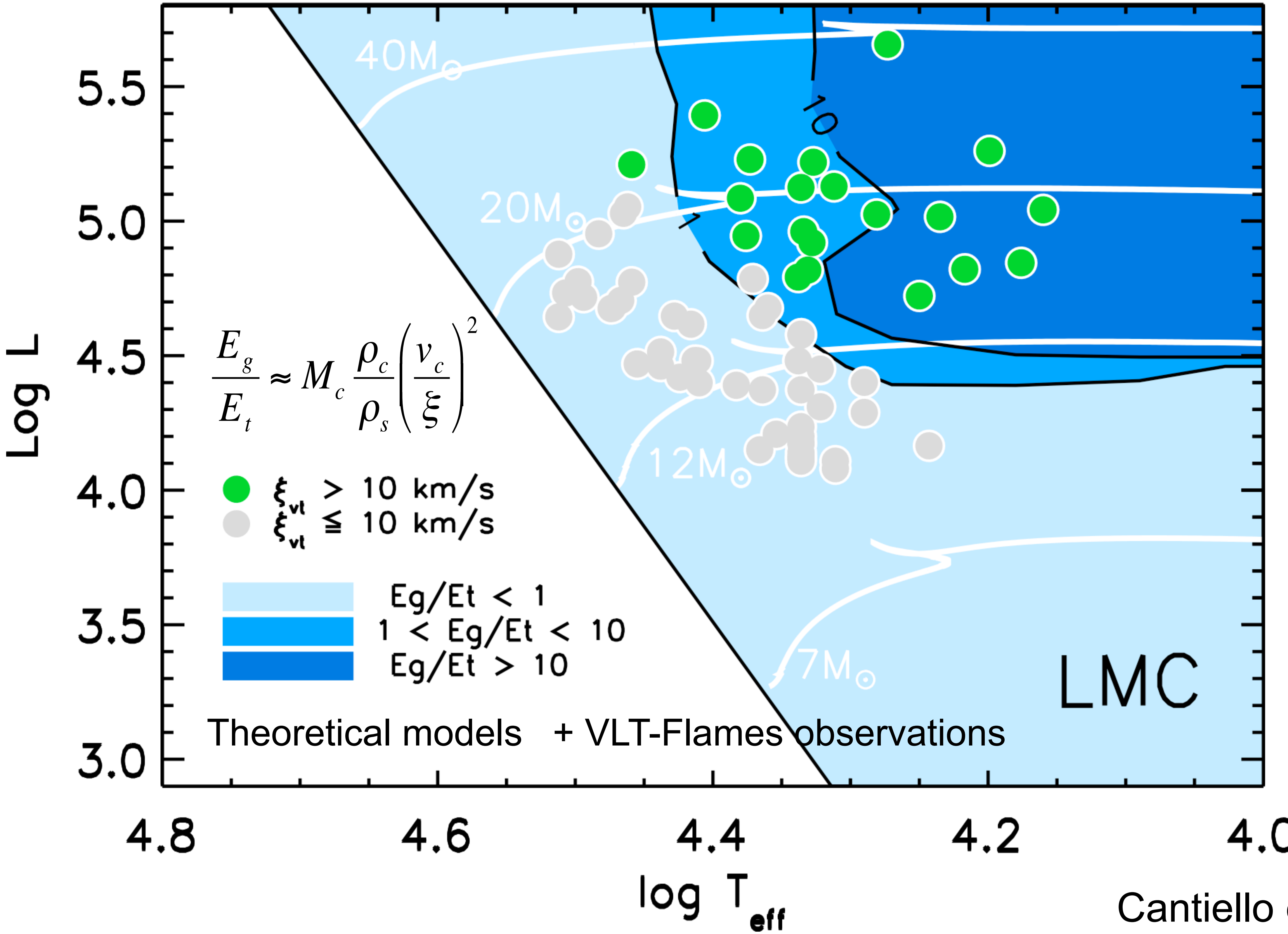
Microturbulence and FeCZ



$$\frac{E_g}{E_t} \approx M_c \frac{\rho_c}{\rho_s}\left(\frac{v_c}{\xi}\right)^2$$

Cantiello et al. 2009

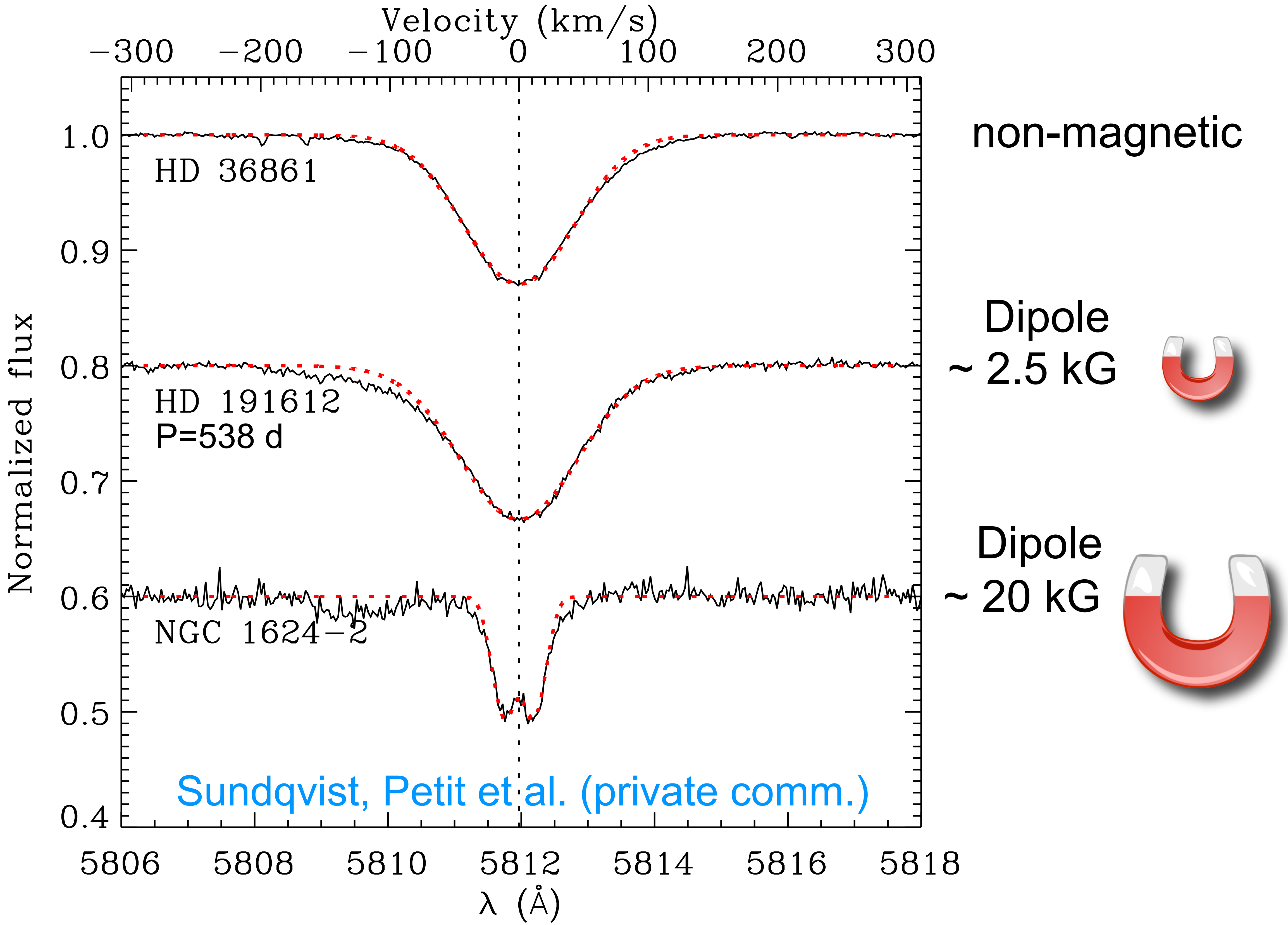
Microturbulence and FeCZ



Cantiello et al. 2009

Macroturbulence in magnetic OB stars

C IV line



Macroturbulence in magnetic OB stars

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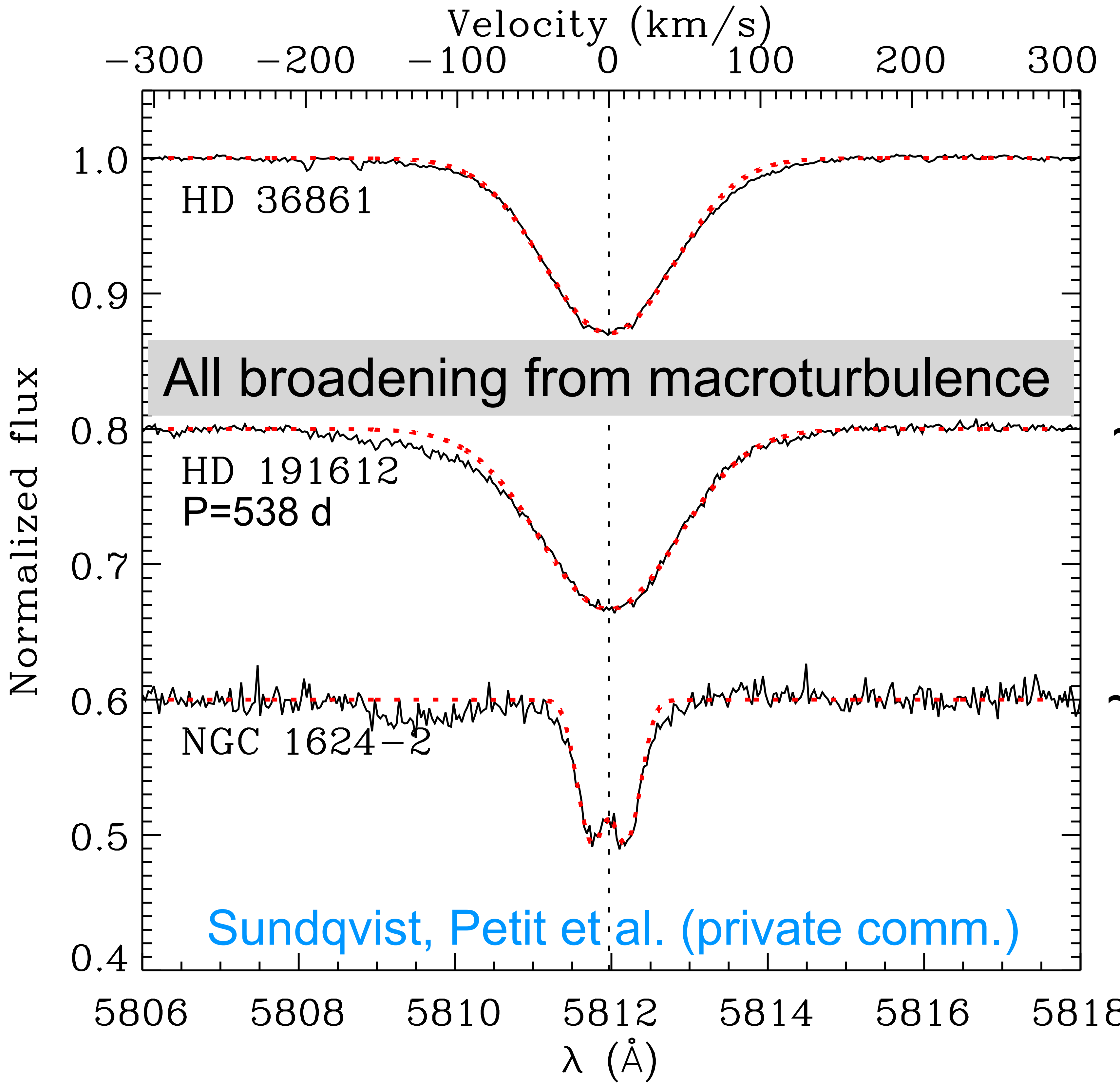


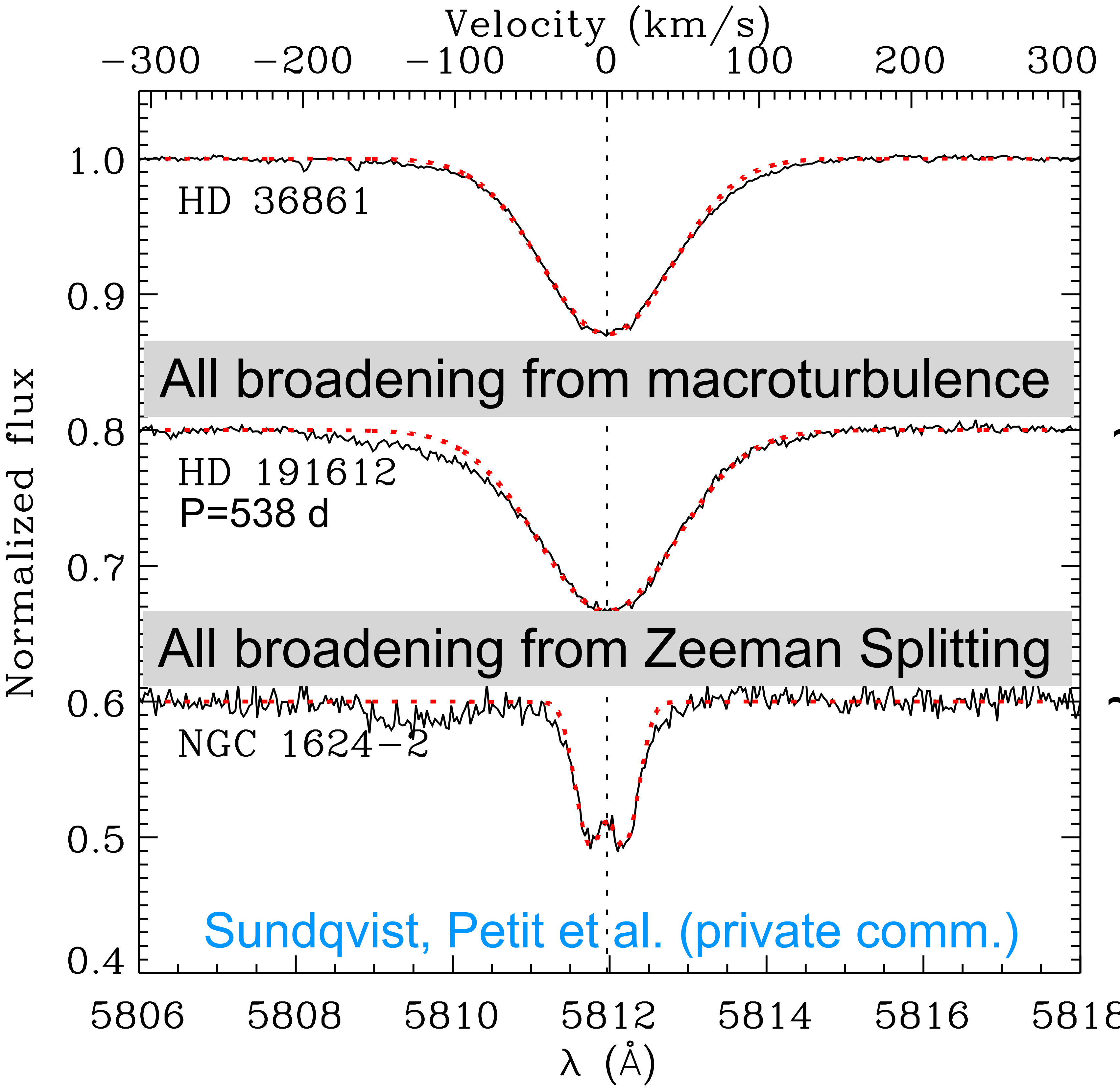
non-magnetic

Dipole
~ 2.5 kG

Dipole
~ 20 kG

Macroturbulence in magnetic OB stars

C IV line



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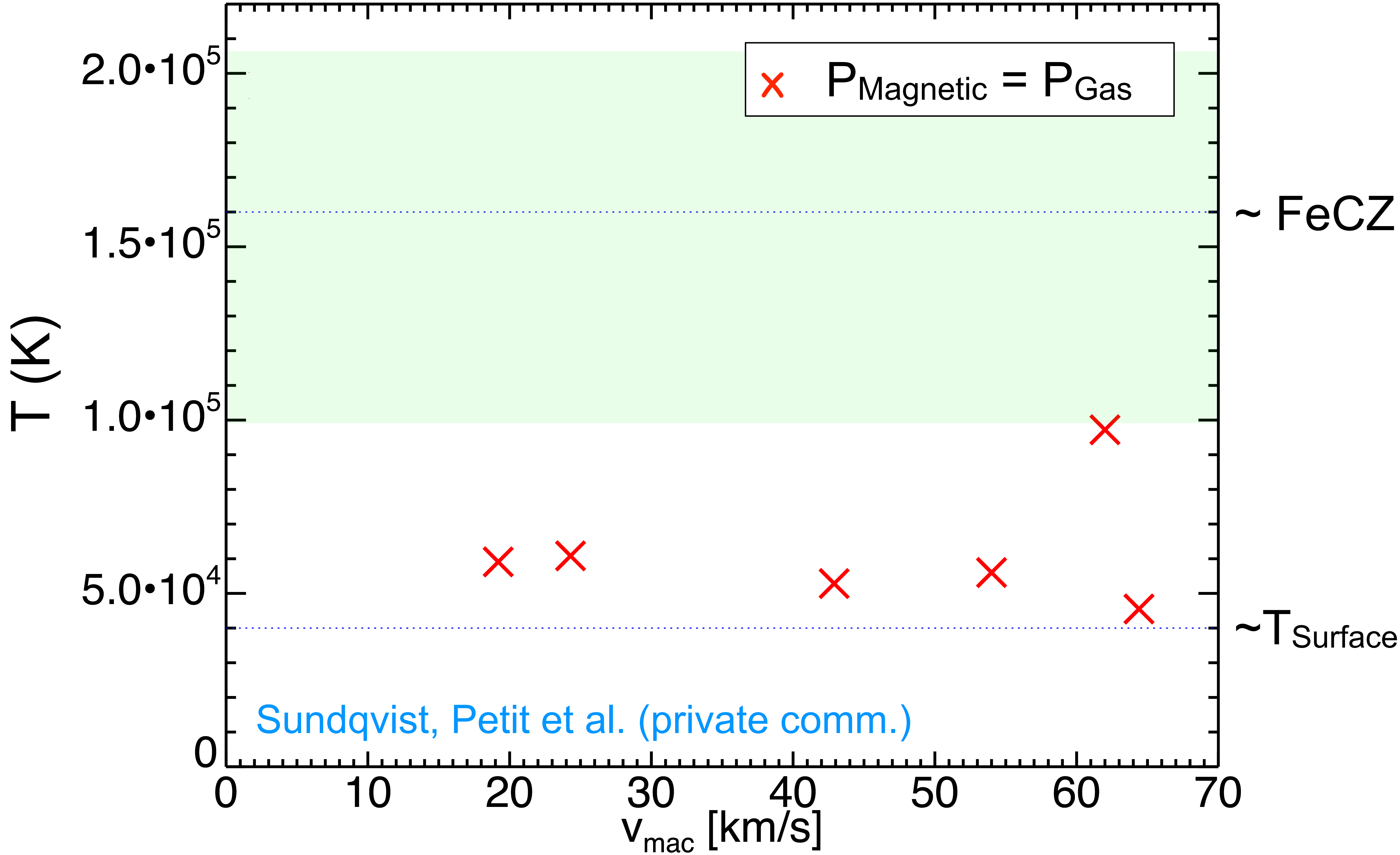
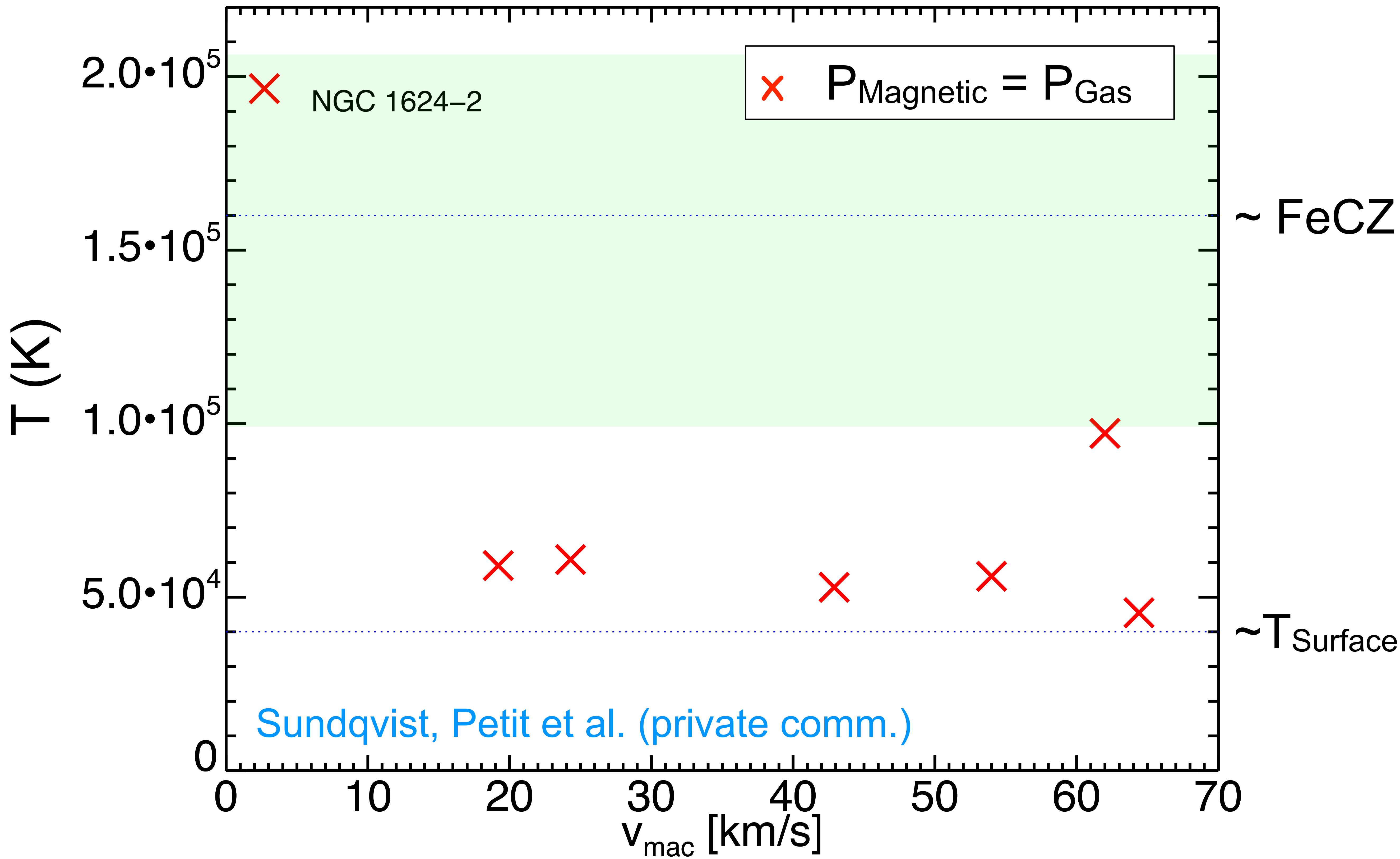


Macroturbulence in magnetic OB stars

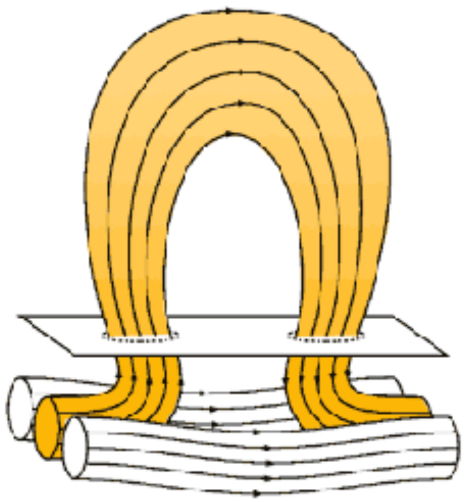


Effects from turbulent convection

FeCZ

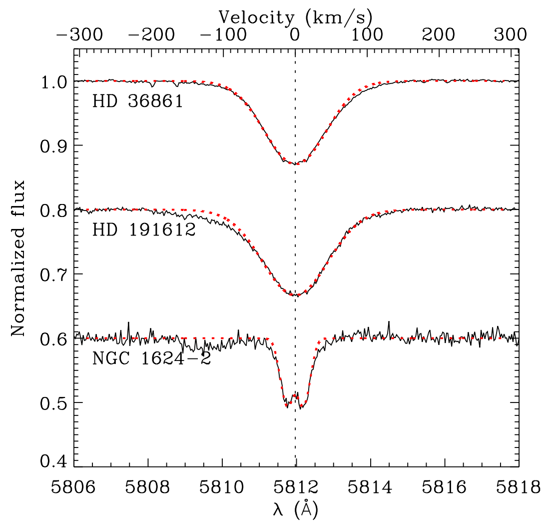
Magnetic fields

Magnetic spots



Running waves

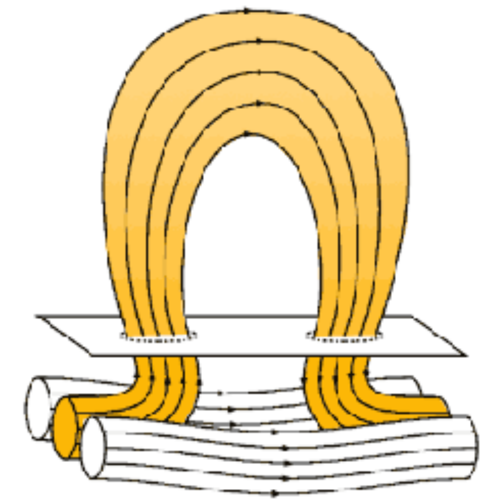
Turbulence



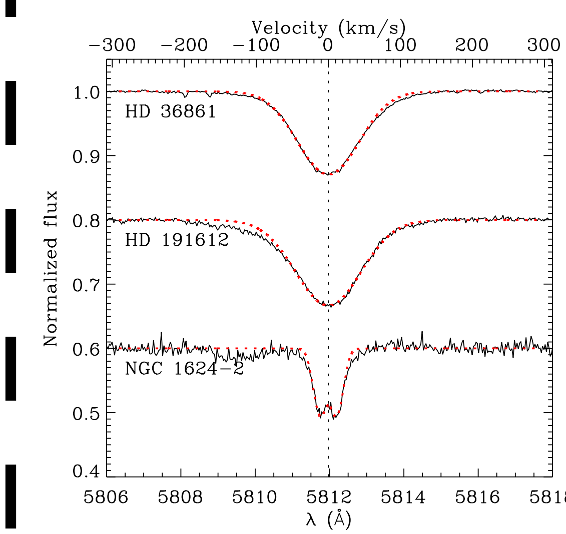
Effects from turbulent convection

FeCZ

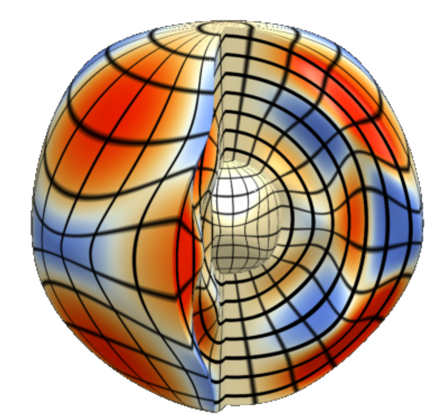
Magnetic fields → Magnetic spots



Running waves → Turbulence



Standing waves → Stochastically excited pulsation



Solar-like oscillations

Solar-like oscillations in massive stars

Cantiello et al. 2009
Suggest that near-surface convection in hot, massive stars could cause stochastically excited pulsations

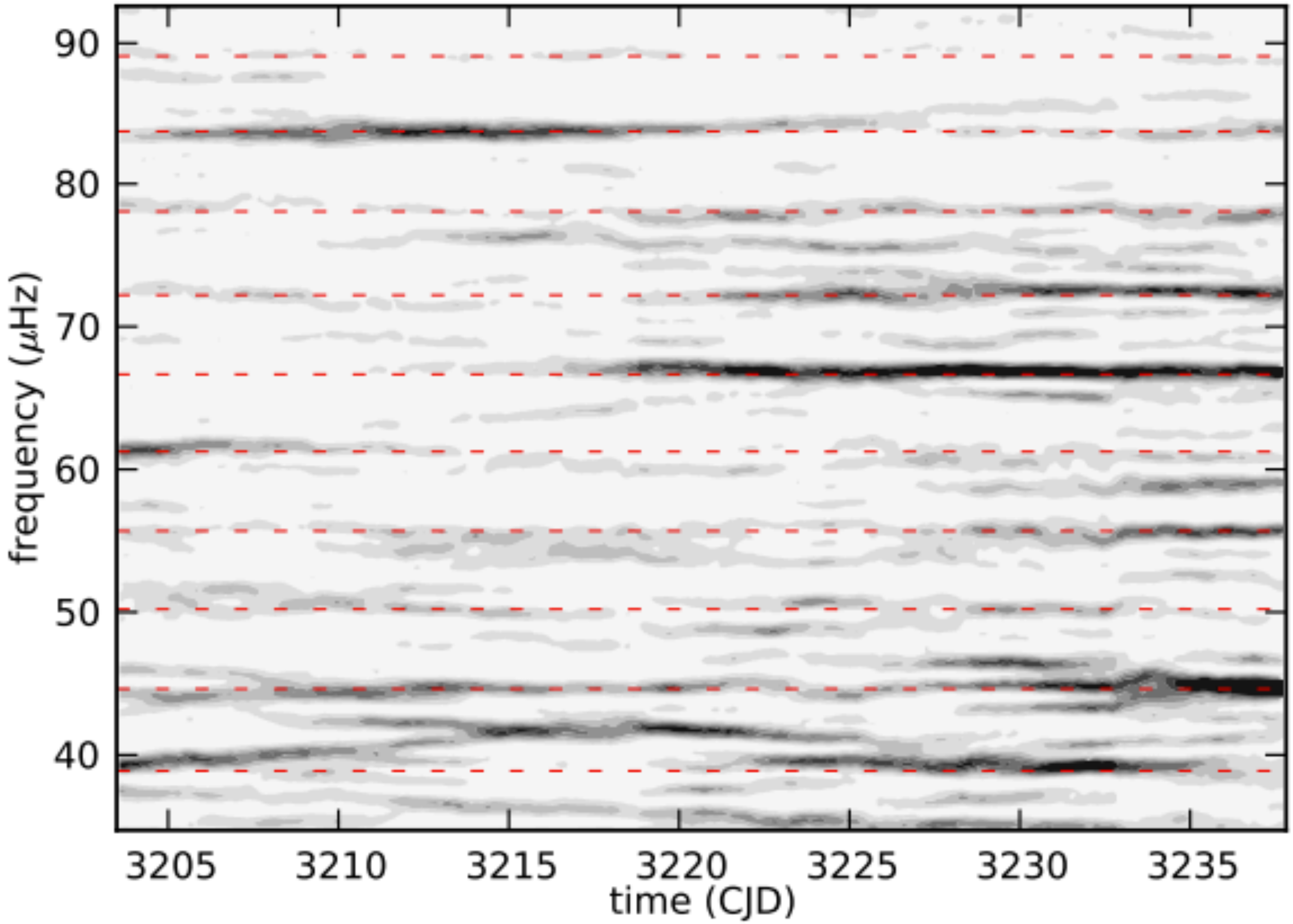
Belkacem et al. 2009
Corot detection of solar-like oscillations in the massive star V1449 Aql (B type Star) [However, see Aerts et al. 2011]

Belkacem et al. 2010
Theoretical calculations of stochastically excited modes from sub-surface convection.

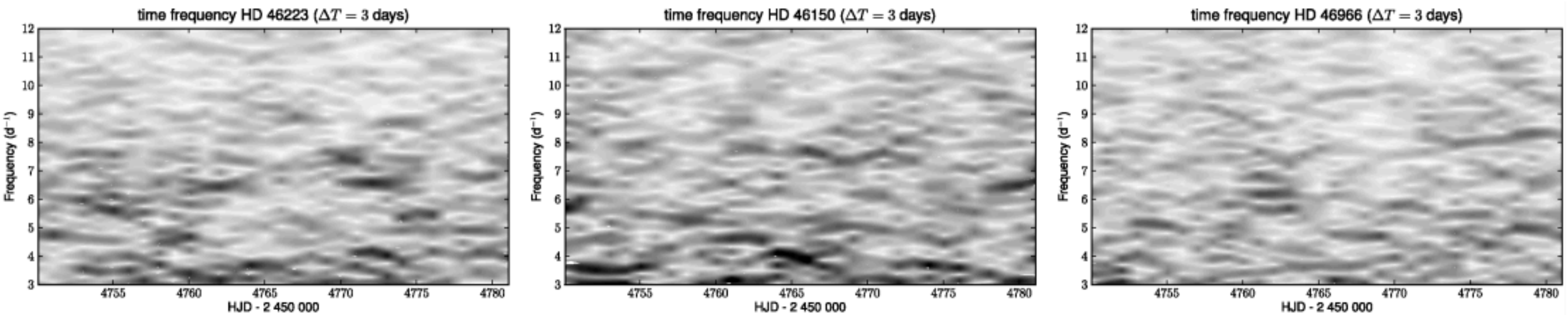
Degroote et al. 2010
Corot detection of solar-like oscillations in an O-type star

Solar-like oscillations in O star

HD 46149 (Degroote et al. 2010)



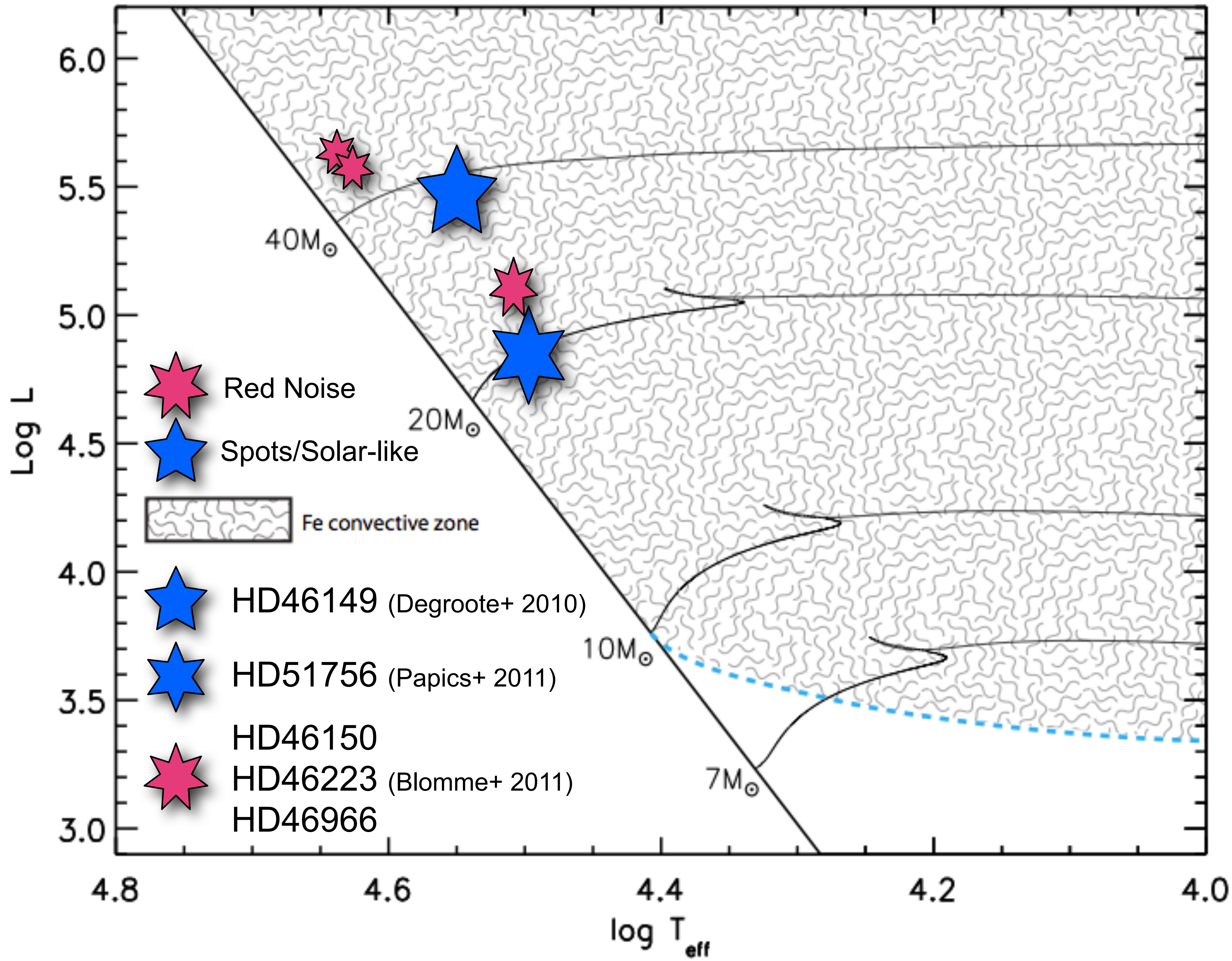
“Red Noise” in O stars



- Variability in the CoRoT photometry of 3 hot O-type stars
- No clear pulsations detected
- Variability of stochastic nature
- Near-surface convection, granulation or wind inhomogeneities

(Blomme et al. 2011)

Photometric variability: HRD location



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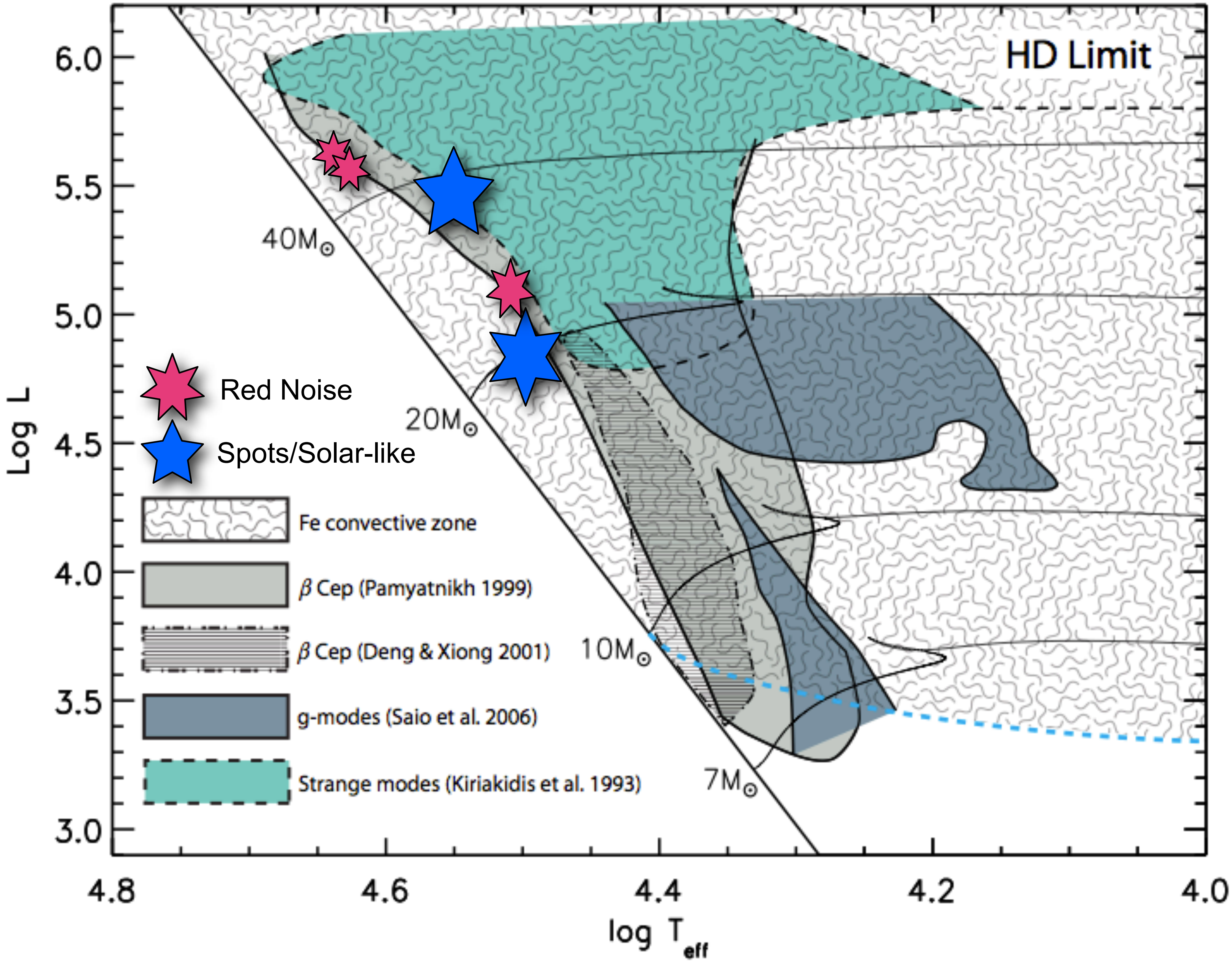

Magnetism, Turbulence, Pulsations

- Massive Stars are Fast Rotators
- They also have a convection zone close to the surface
- This seems to be responsible for micro/macro-turbulence at surface
- A dynamo might be at work as well
- Solar-like oscillations discovered in massive stars

Some open questions

- What is the origin of large scale, large amplitude fields
- Is (sub)surface dynamo ubiquitous
- Are small-scale surface fields ubiquitous
- Bright spots in massive stars
- Can magnetic fields be amplified in the radiative regions of rotating stars (e.g. Tayler-Spruit)
- Impact of B-fields on the evolution