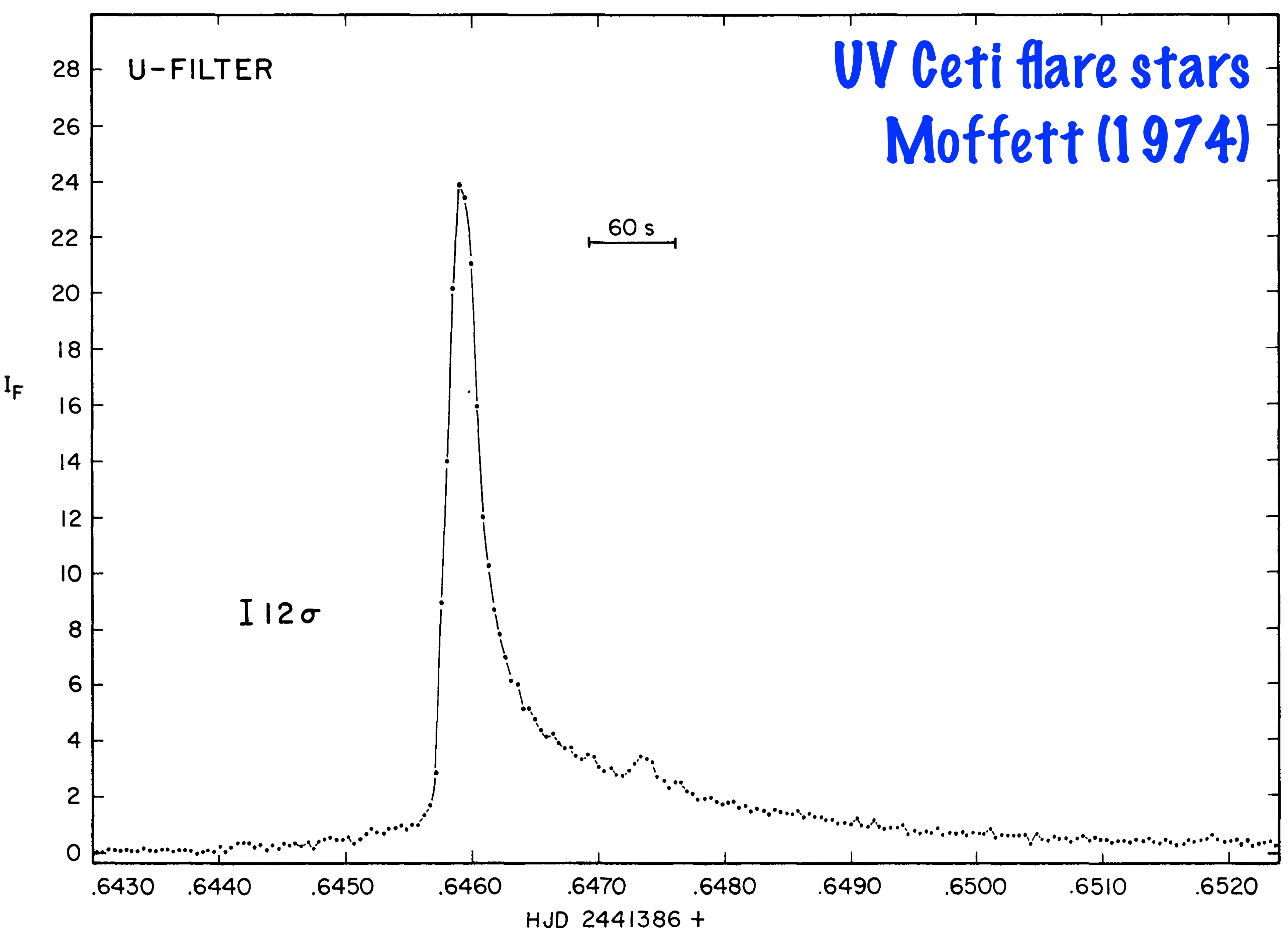
COSMIC MAGNETIC FIELDS

KRZYSZTOF NALEWAJKO, CAMK PAN

Stars

STELLAR FLARES



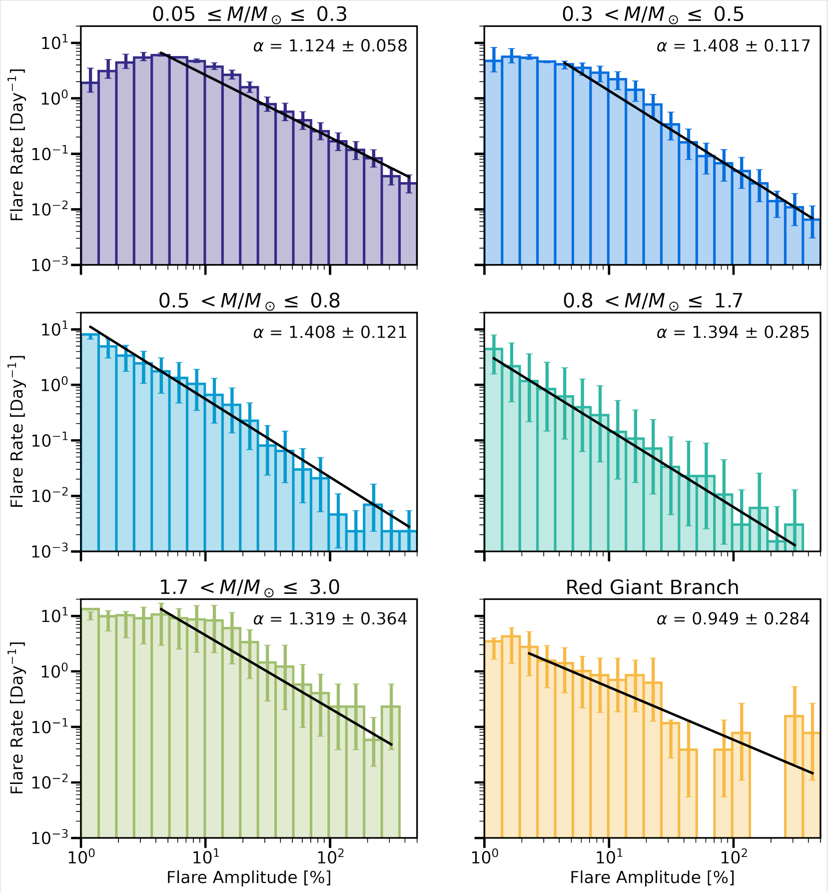
UV Ceti flare stars

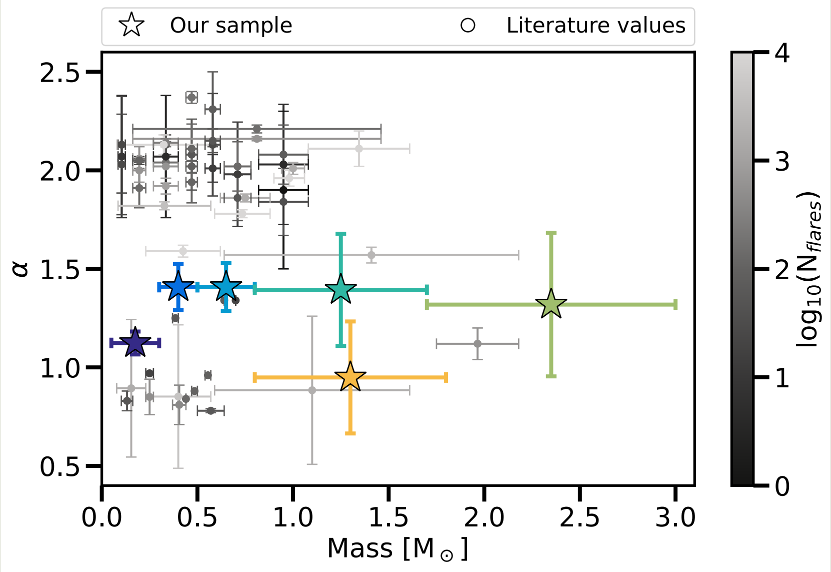
Moffett (1974)

Fig. 4.—Flare No. 26 on YZ CMi. This is an example of a "typical" flare.

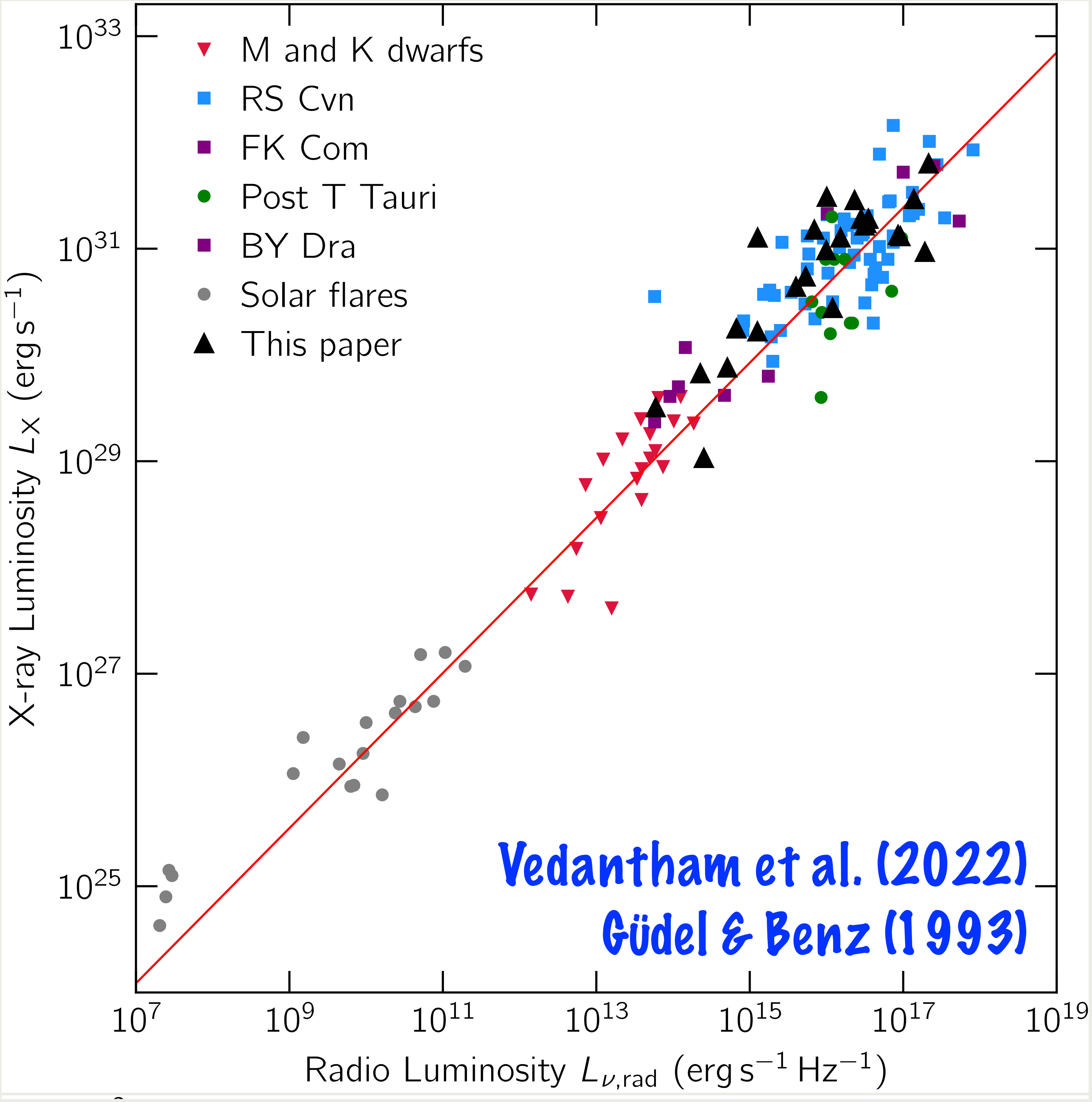
SELF-ORGANIZED CRITICALITY

- Dissipative dynamical systems at a critical point with no intrinsic scale. Generate events with power-law energy distribution with $\mathrm{d}N/\mathrm{d}E \propto E^{-(\simeq 1.4)}$.
- Examples: sand/snow pile -> avalanches, earthquakes, forest fires, rainfall, extinction, traffic jams, financial markets, etc.
- Solar/stellar flares: release of magnetic energy (via reconnection) stored in twisted coronal loops.
- TESS survey with machine learning: 1M flares identified from 160k stars (Feinstein et al. 2021).



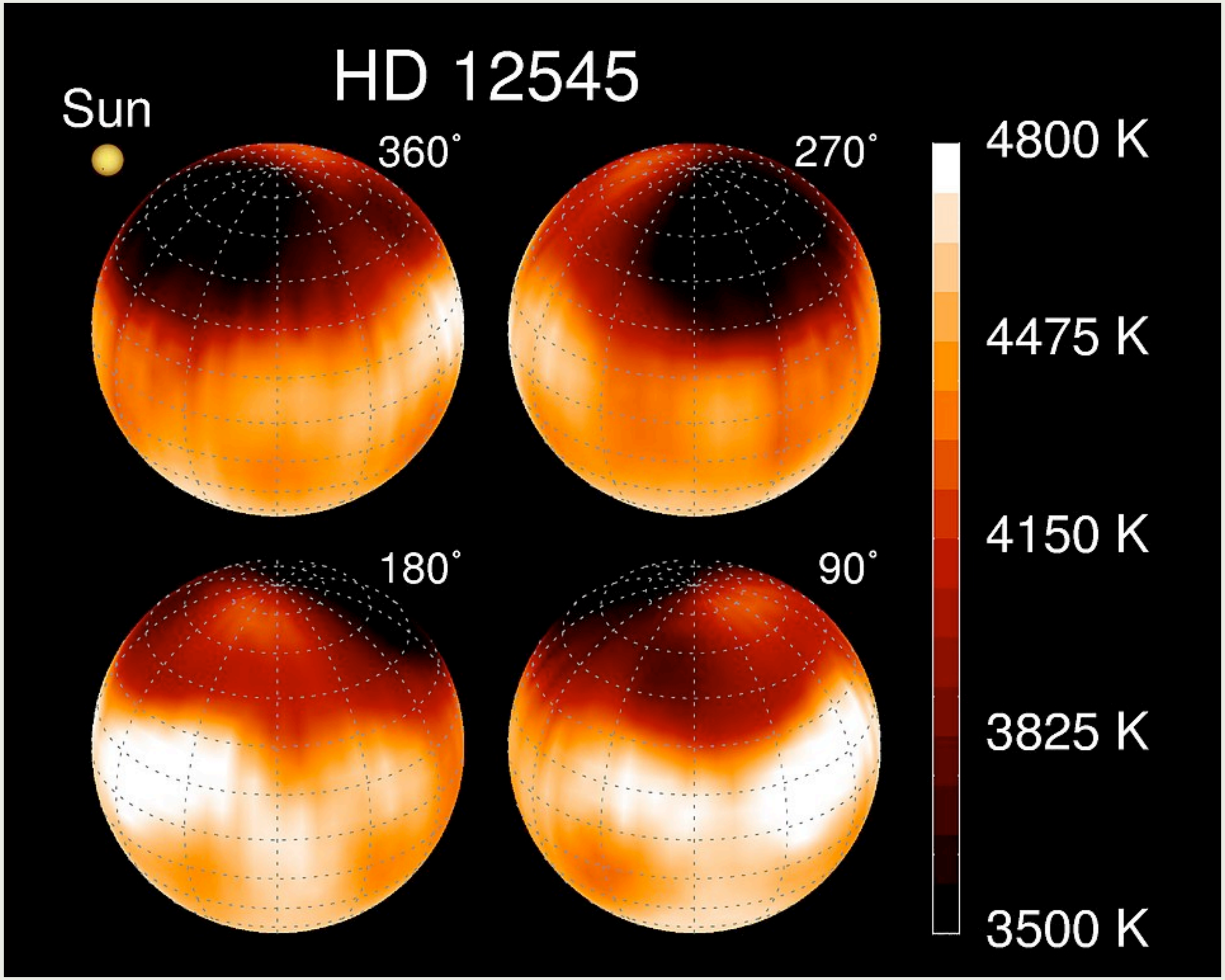


RADIO VS X-RAY LUMINOSITIES



Vedantham et al. (2022)
Güdel & Benz (1993)

STARSPOTS: DOPPLER IMAGING



- image reconstructed from periodic distorsions of emission lines

- north-south degeneracy

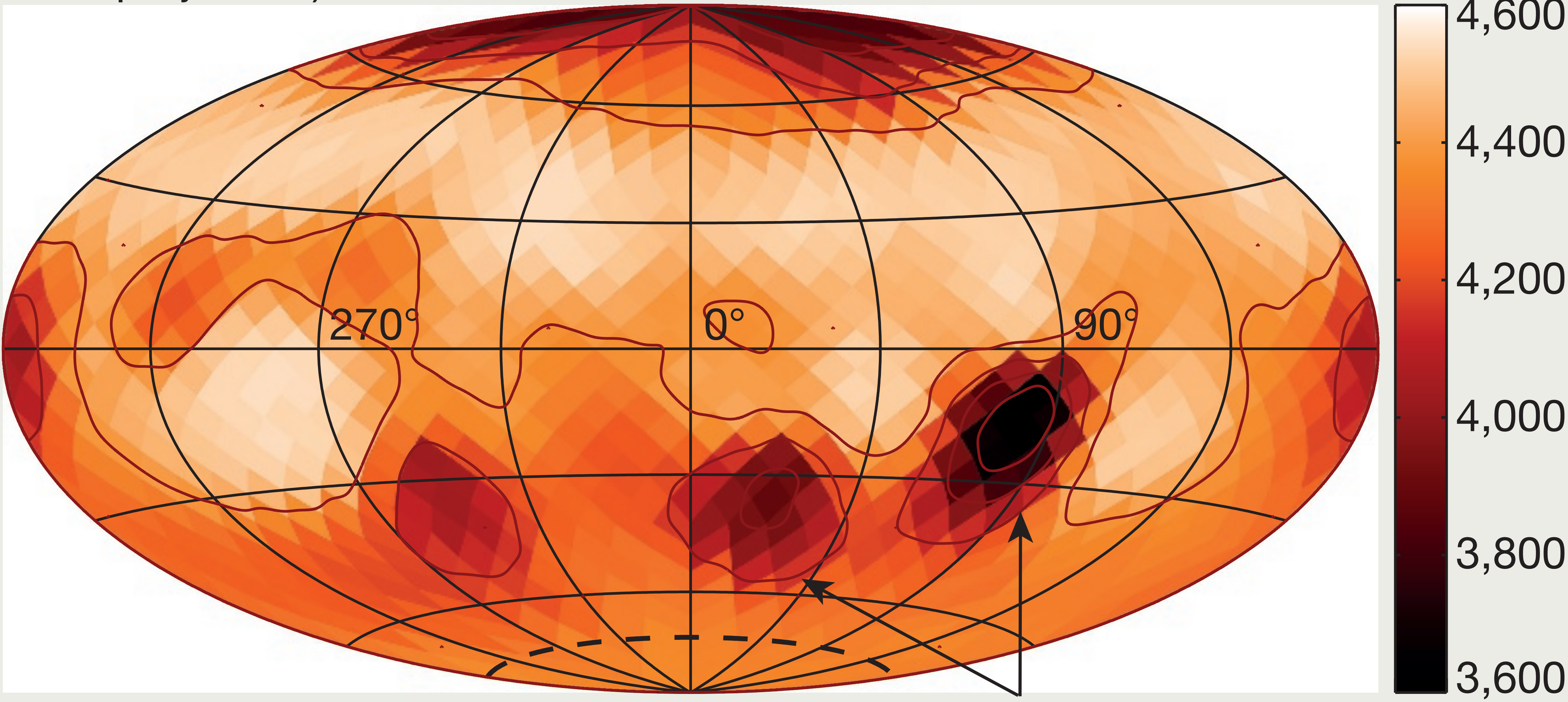
Strassmeier (1999)

STARSPOTS: INTERFEROMETRY (CHARA)

2013 imaging of ζ And
(Aitoff projection)

Persistent polar starspot

Temperature (K)

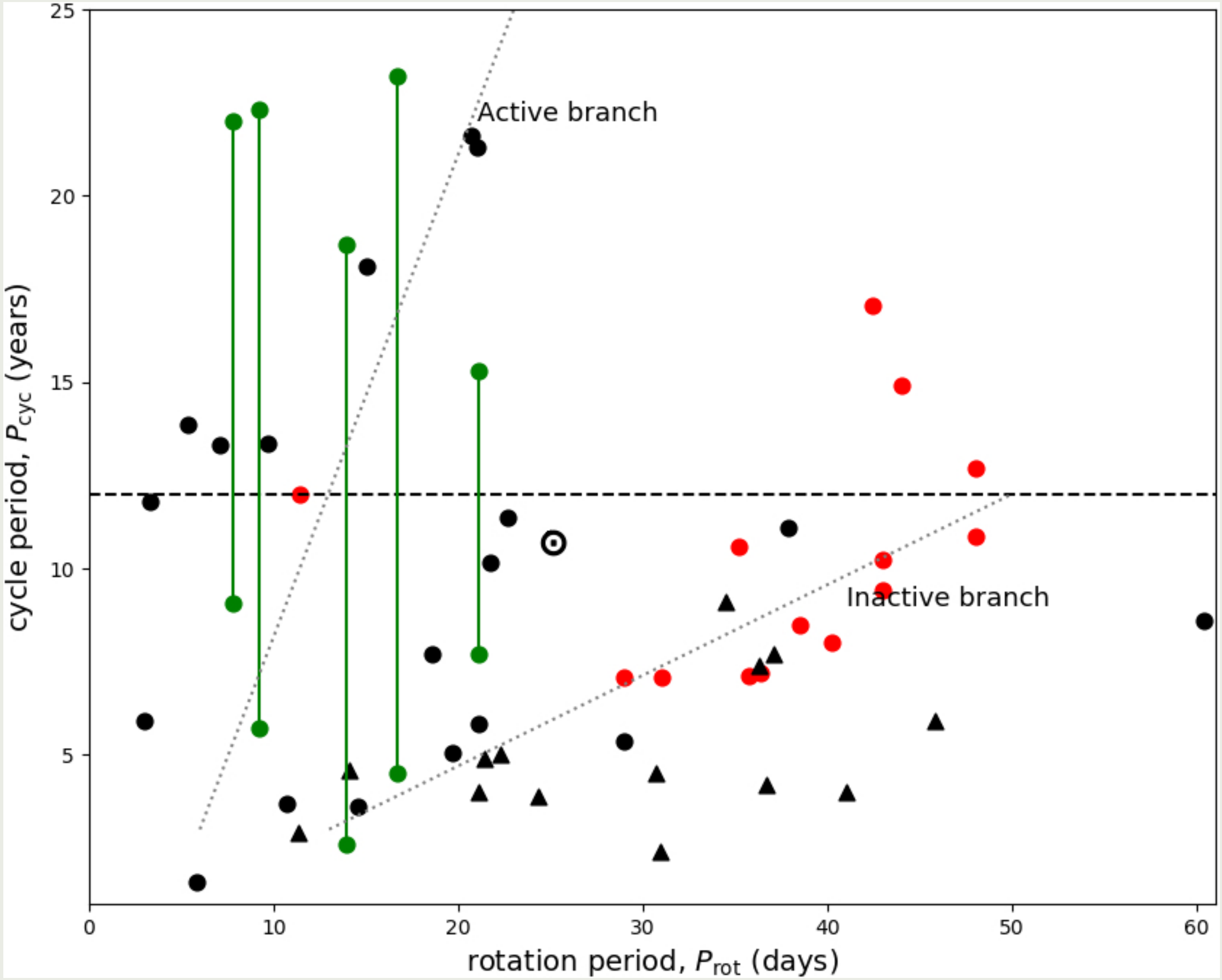


Transient starspots

Roettenbacher et al. (2016)

STELLAR ACTIVITY CYCLES

$$\frac{P_{\rm cyc}}{P_{\rm rot}} \sim 10^2 - 10^3$$



well-defined cycle

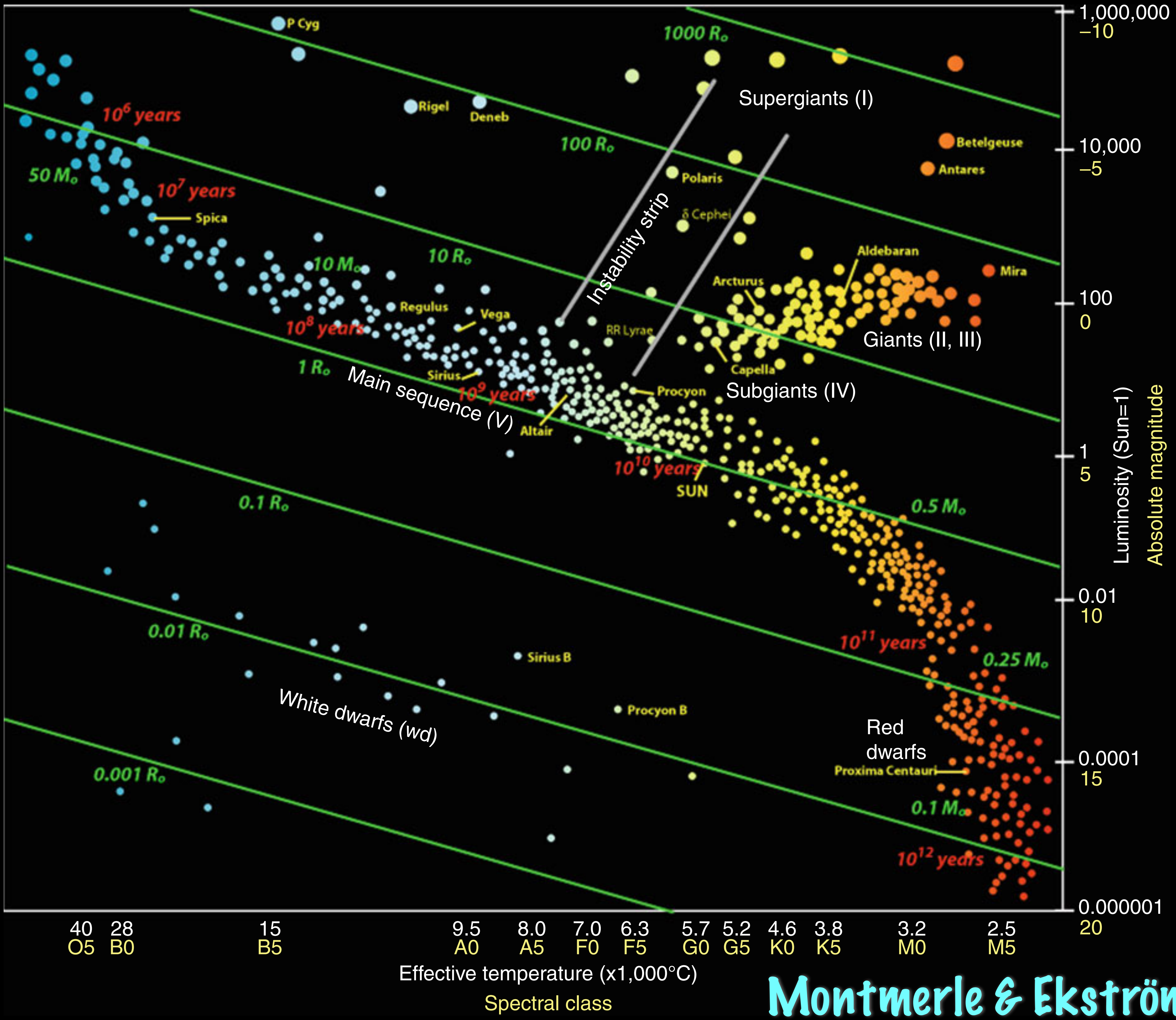
multiple/chaotic cycles

unconfirmed cycle

Fig. 9. Activity-cycle period in years as a function of rotation period in days for stars in Table A.2. The symbols are as same as Fig. 8. The black dotted lines show the active and inactive branch according to Böhm-Vitense (2007). The black horizontal line marks the midpoint of the maximum cycle length of 25 yr.

Boro Saikia et al. (2018)

HERTZSPRUNG-RUSSELL DIAGRAM



Montmerle & Ekström (2011)

CONVECTIVE ZONES IN MAIN SEQUENCE STARS

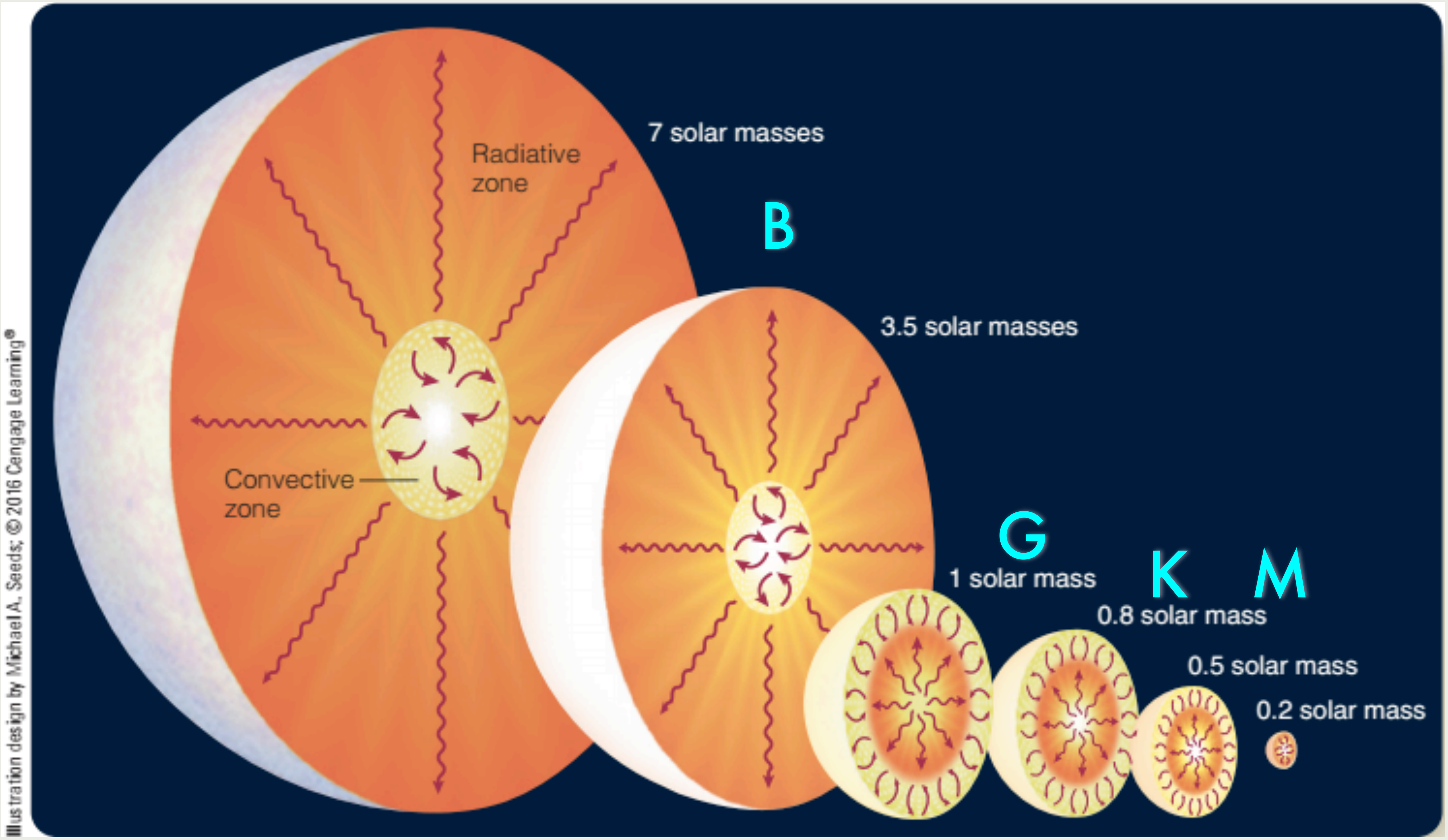
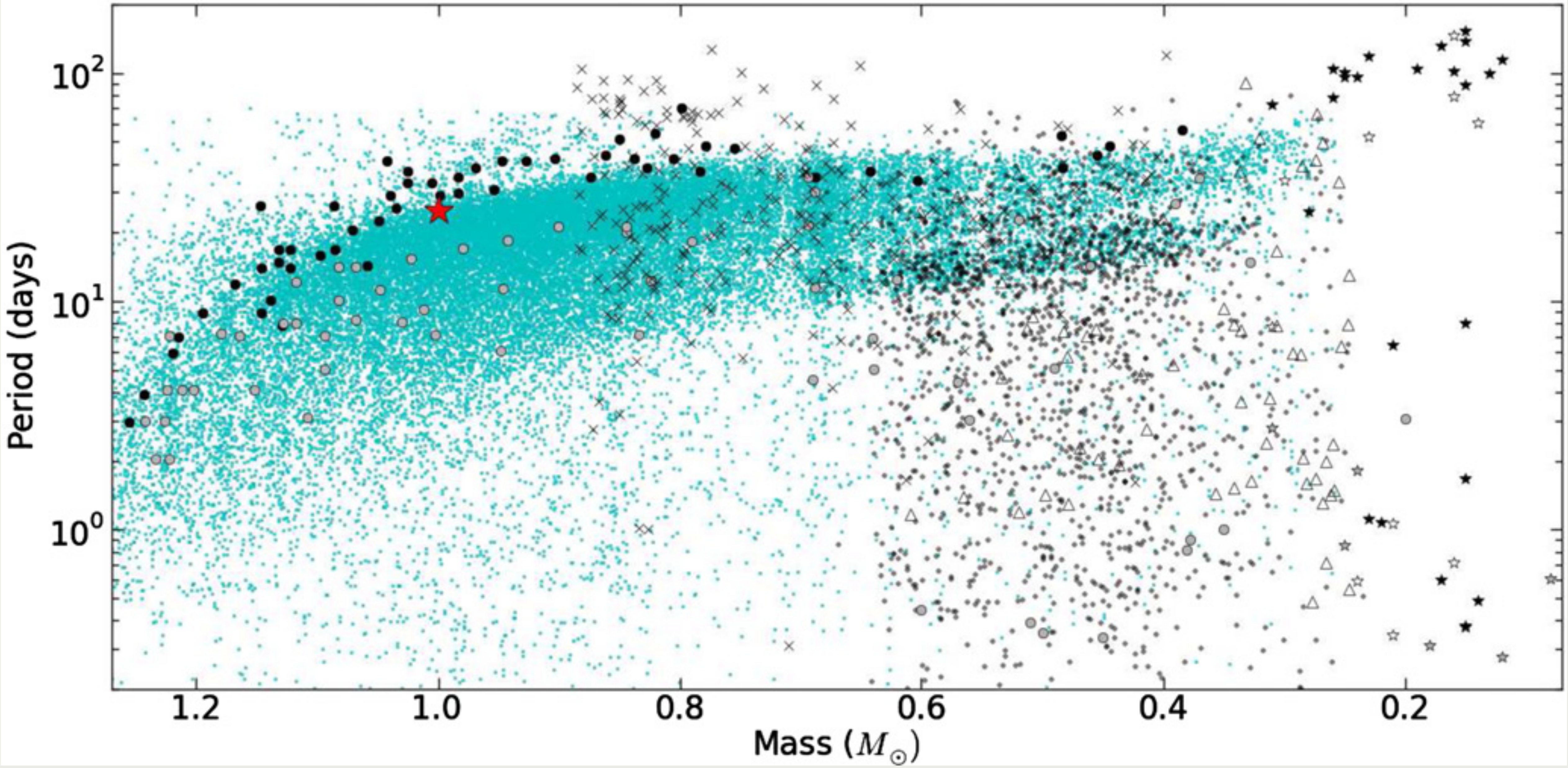


Illustration design by Michael A. Seeds; © 2016 Cengage Learning®

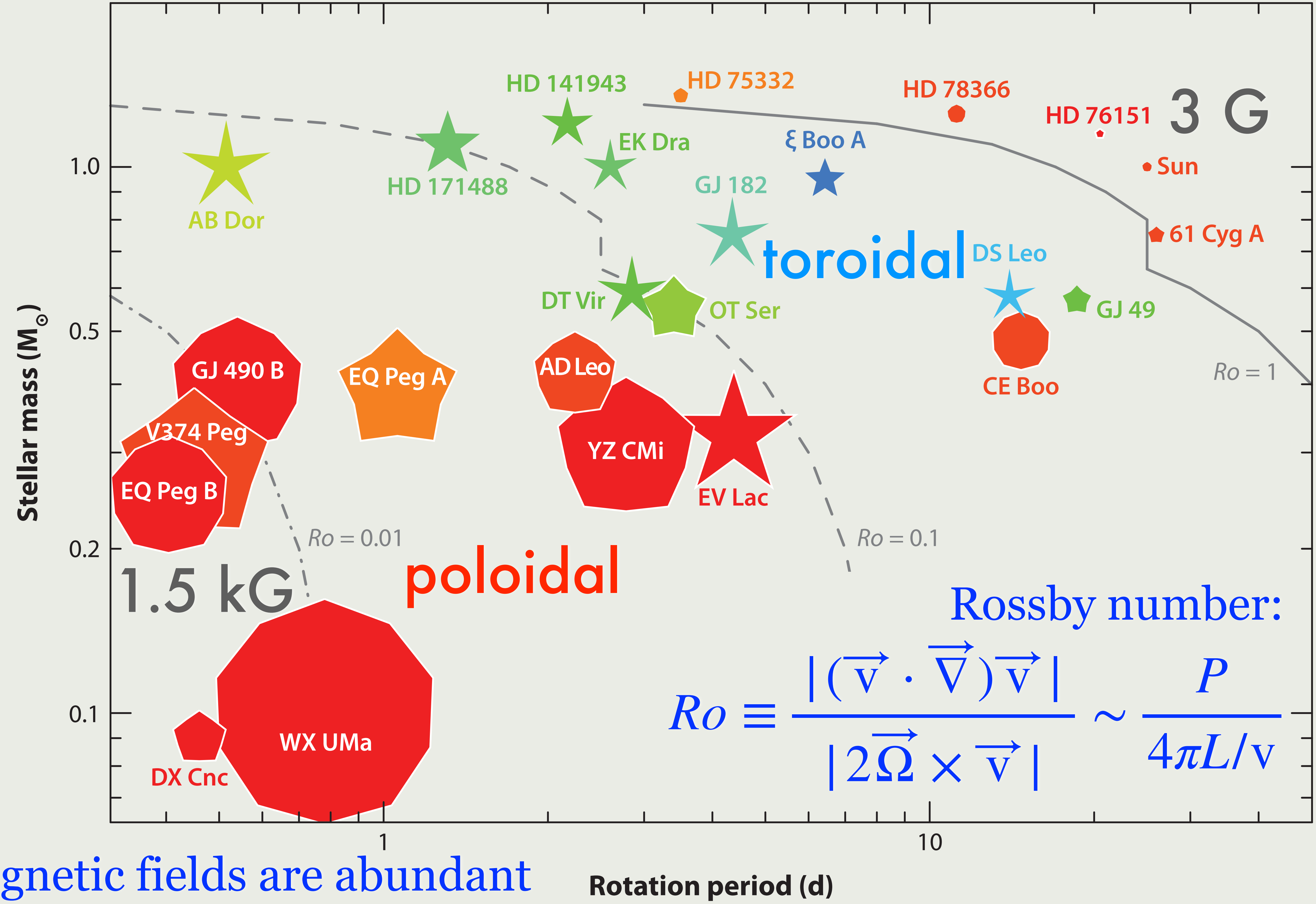
- fully convective: $M \lesssim 0.35 M_\odot$
- outer convective zone: $M \lesssim 1.3 M_\odot$
- inner convective zone: $M \gtrsim 1.3 M_\odot$

LOW-MASS STARS ROTATION PERIODS



Kepler data, McQuillan et al. (2014)

LOW-MASS STARS



Rossby number:

$$Ro \equiv \frac{|(\vec{v} \cdot \vec{\nabla})\vec{v}|}{|2\vec{\Omega} \times \vec{v}|} \sim \frac{P}{4\pi L/v}$$

magnetic fields are abundant in low-mass stars

Donati & Landstreet (2009)

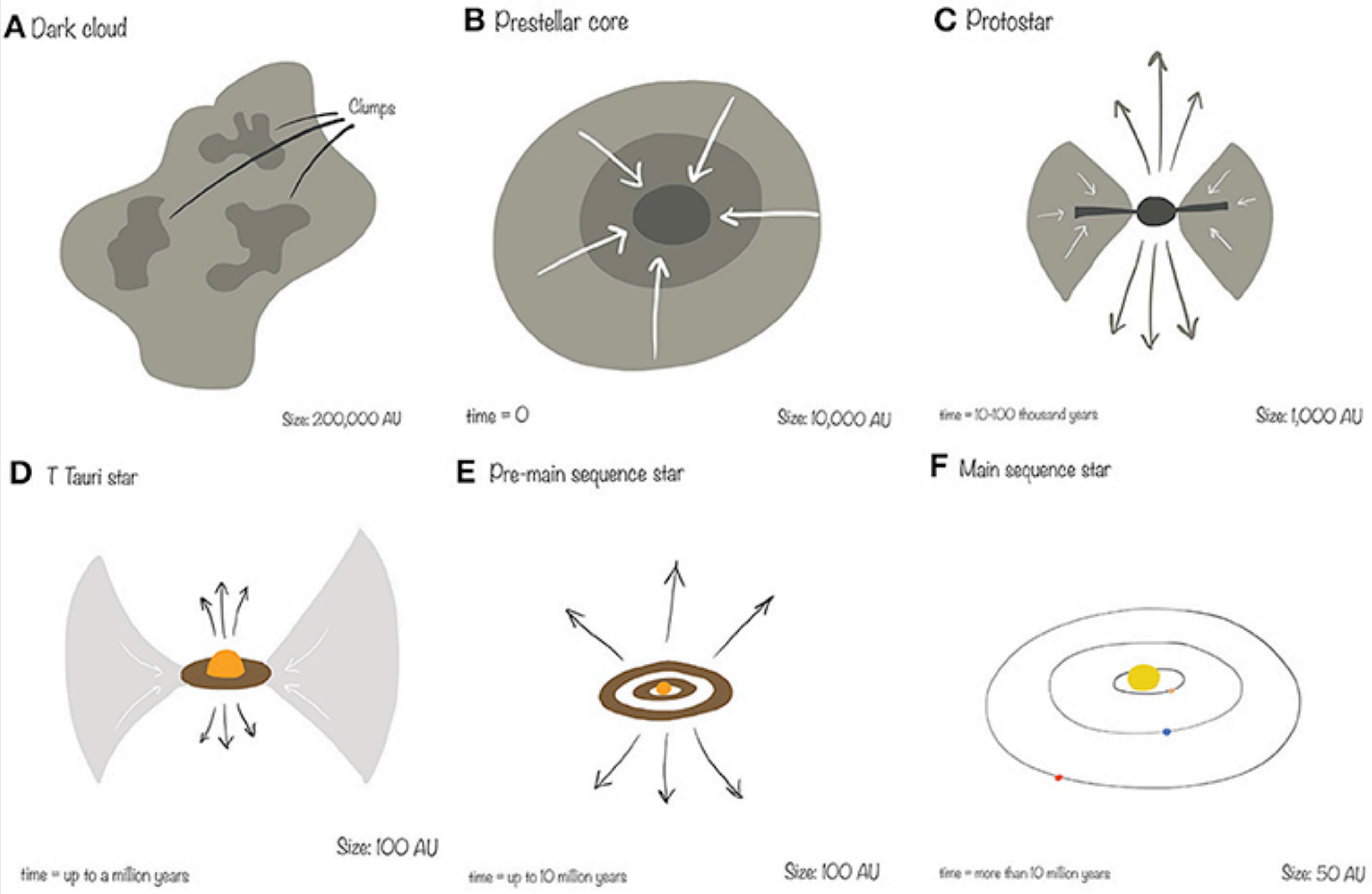
PECULIAR A/B STARS

- Ap and Bp stars are a class of chemically peculiar stars (overabundance of certain metals), a few % of all A/B stars.
- Zeeman effect first detected in Ap star 78 Vir (Babcock 1947), helped by sharp absorption lines due to pole-on view.
- Magnetic field strengths up to ~ 30 kG (HD 215441, Babcock 1960).
- Most of these stars show periodic (1-10 days), roughly sinusoidal variations in field strength, many show polarity reversals, mostly consistent with oblique rotators.

STAR FORMATION

Carina Nebula, HST

STAR FORMATION



Christensen (2019)

MAGNETIC CRITICALITY

- Magnetic fields are important in the interstellar medium and molecular clouds.
- Given magnetic flux $\Phi_{\rm B} = \pi R^2 B$, a critical mass for gravitational collapse is $M_{\rm crit} \simeq 0.13 \dfrac{\Phi_{\rm B}}{\sqrt{G}}$ (Mouschovias & Spitzer 1976).
- Radio measurements of the Zeeman effect in dense prestellar cores ($B \sim 0.4$ mG at $R \sim 0.1$ pc) are consistent with magnetic criticality (Crutcher 1999).

ANGULAR MOMENTUM PROBLEM

- Specific angular momentum $\frac{\delta L}{\delta M} = r^2 \Omega$ [cm^2/s]:

  - prestellar core: $\sim 10^{21}$

  - protostellar disk: $\sim 5 \times 10^{20}$

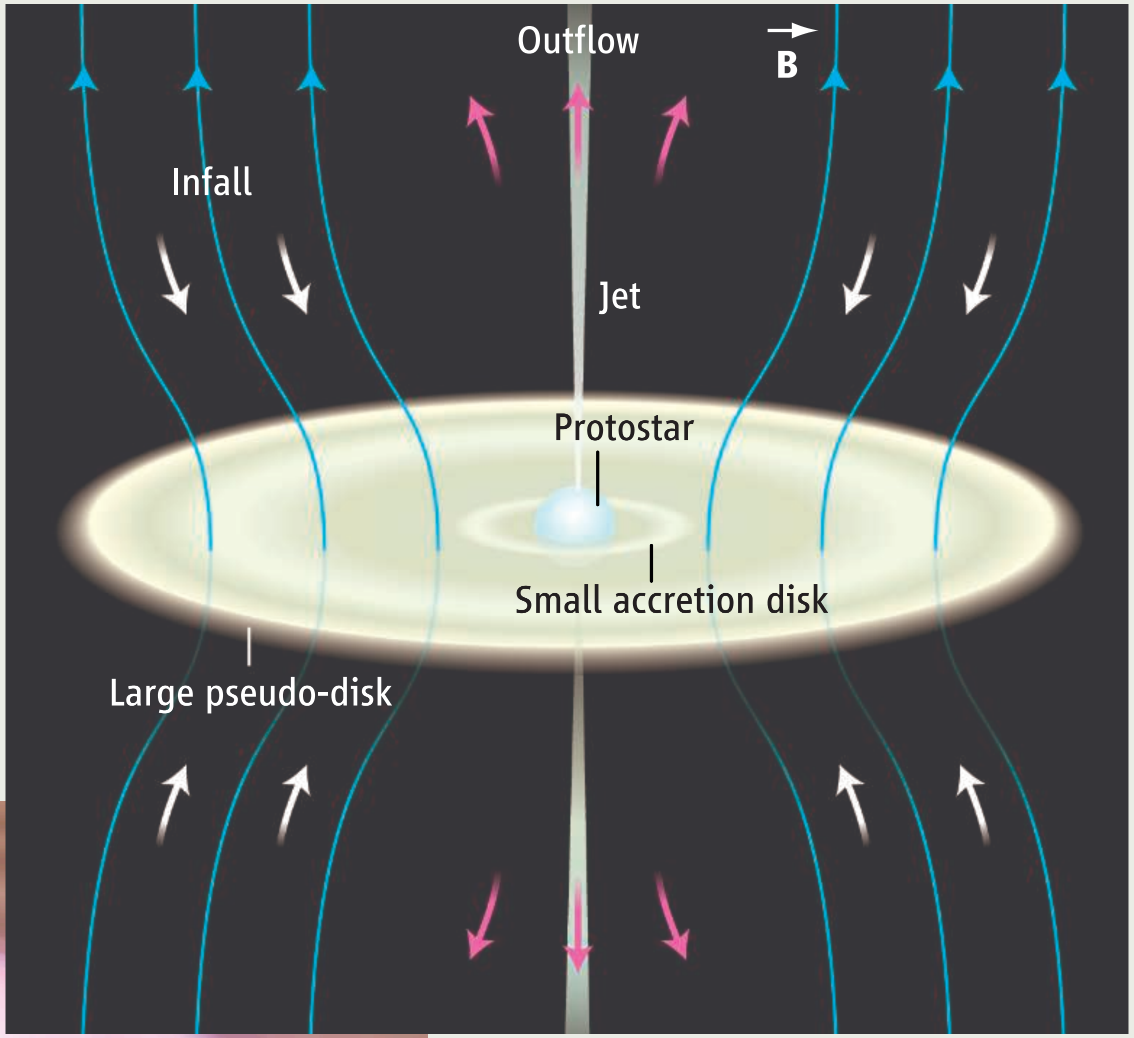
  - protostar (T Tau): $\sim 5 \times 10^{17}$

  - Sun: 10^{15}

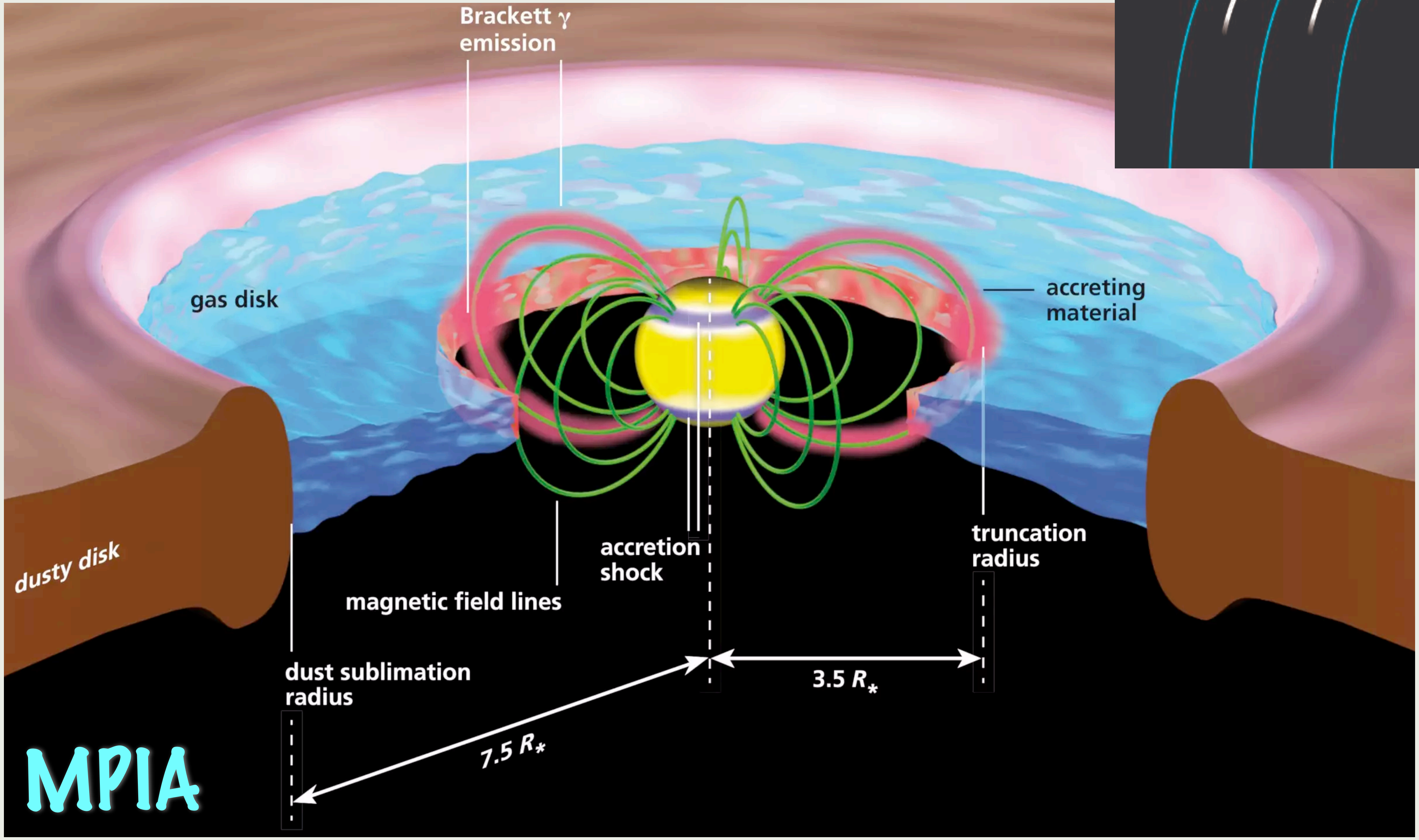
  - Jupiter (orbital): 10^{20}

- Efficient reduction of angular momentum requires magnetic braking and/or turbulent viscosity (MRI).

PROTOSTELLAR MAGNETIC FIELDS



Crutcher (2006)

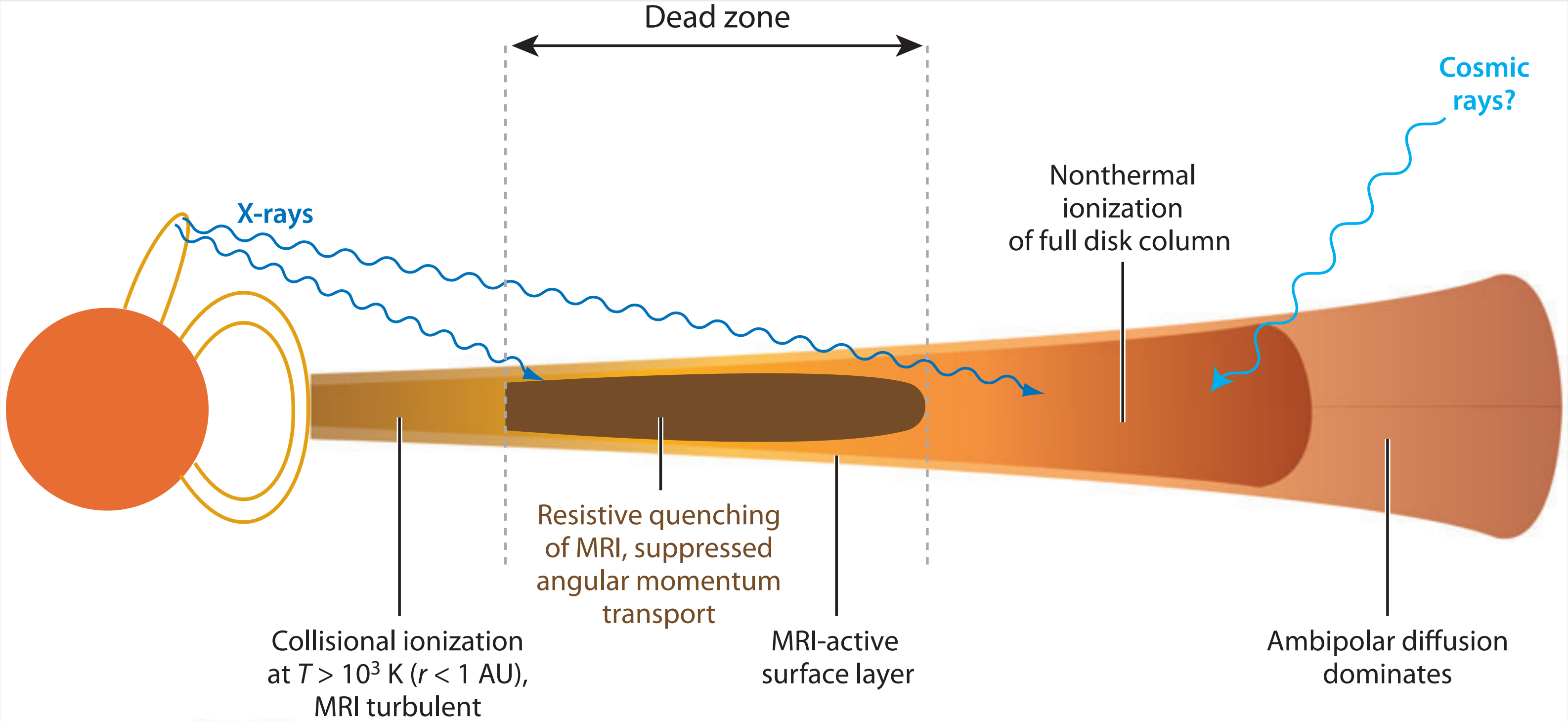


MPIA

AMBIPOLAR DIFFUSION

- Prestellar cores and inner parts of protostellar disks are sufficiently cold and shielded from radiation fields to become weakly ionized, with many neutral atoms.

- Neutral atoms are not frozen to the magnetic flux, they can slip across the magnetic field lines. In a collapsing molecular cloud the magnetic fields will be dragged at a slower rate.



Armitage (2011)

ORIGIN OF STELLAR MAGNETIC FIELDS

- Fossil field: primordial field amplified by compression (conservation of magnetic flux).
  - needs sufficient magnetic flux
  - needs to survive resistive and turbulent decay
  - needs stable topology
  - does not scale with rotation rate

- Dynamo: field amplification by convective motions
  - needs a source of kinetic energy (convection, differential rotation)
  - quenching mechanisms limit the field strength
  - scales with rotation rate

PROBLEM 5: STELLAR MAGNETIC FLUXES

- Estimate (order-of-magnitude) magnetic fluxes Φ_B across:
  - a molecular cloud ($B \sim 0.4$ mG, $R \sim 0.1$ pc);
  - a low-mass (T Tau) protostar ($B \sim 200$ G, $R \sim 0.05$ AU);
  - a low-mass ($0.1 M_\odot$) M star ($B \sim 1$ kG);
  - the Sun ($B \sim 2.5$ G);
  - a high-mass ($2.5 M_\odot$) Ap star ($B \sim 30$ kG);
  - a white dwarf ($B \sim 10^8$ G);
  - a pulsar ($B \sim 10^{12}$ G);
  - a magnetar ($B \sim 10^{15}$ G).

  Stellar radii R can be read from the HR diagram.
  For neutron stars adopt $R \simeq 12$ km.

- Create a log-log diagram of radius R vs. magnetic flux Φ_B. What basic conclusions can be made?

This problem is worth 5 points. Solutions should be sent as 1-page PDF files to knalew@camk.edu.pl before the next lecture.

SUMMARY

- Low-mass stars ($M < 1.3M_\odot$) have outer convective zones and produce ubiquitous magnetic fields (up to kG) of complex structure and cyclic activity.
- High-mass stars ($M < 1.3M_\odot$) have inner convective zones, only a few % (Ap/Bp, some O) are strongly magnetized (up to 30 kG) with simple structure and little variability.
- Magnetic fields are roughly in equipartition in star-forming molecular clouds, magnetic flux and angular momentum need to be strongly reduced in the resulting stars.