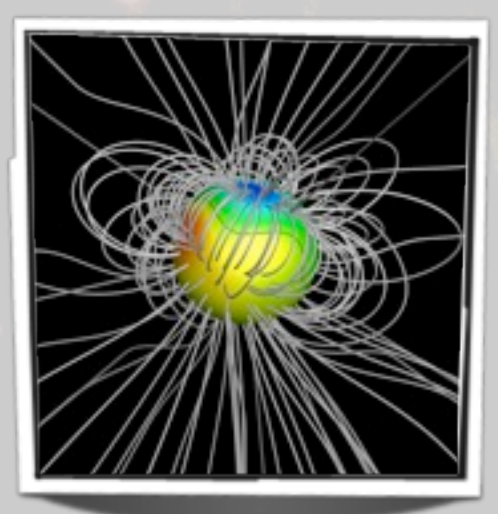
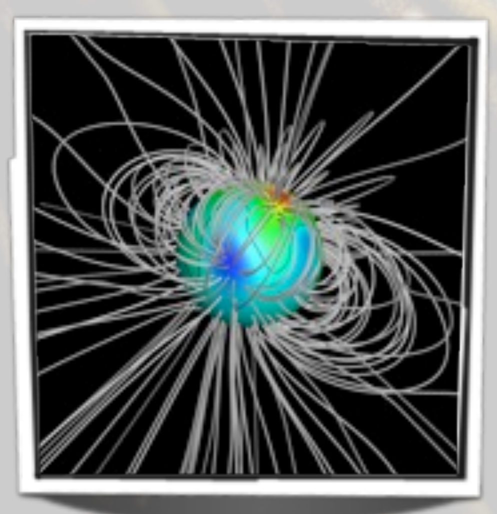
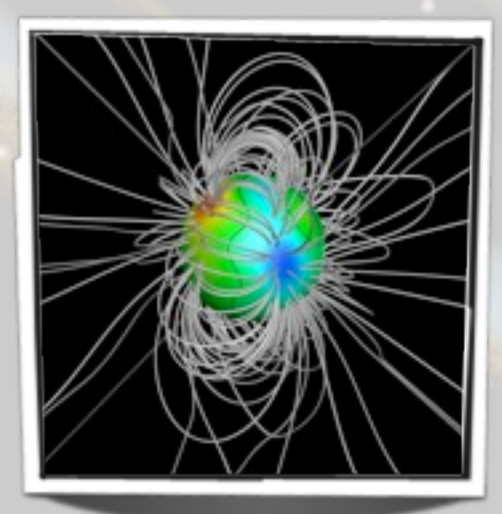
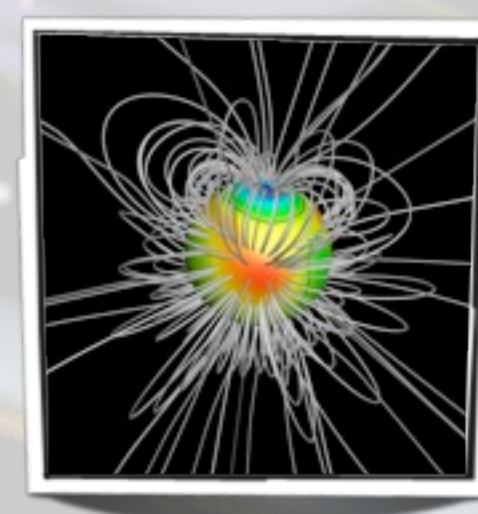
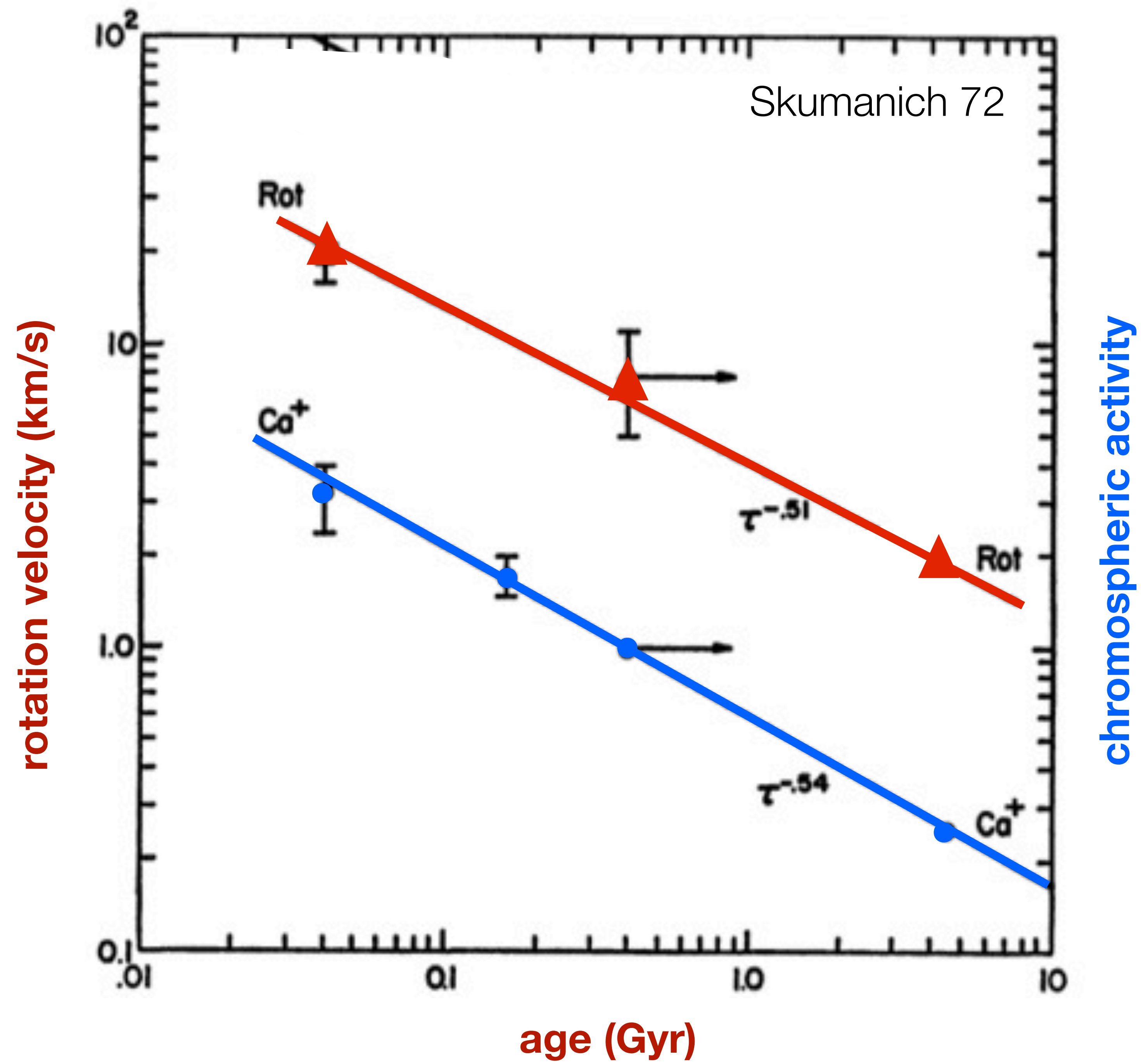
Stellar magnetic fields of young sun-like stars

Aline Vidotto
Swiss National Science Foundation *Ambizione* Fellow
University of Geneva

Age-rotation-activity relation



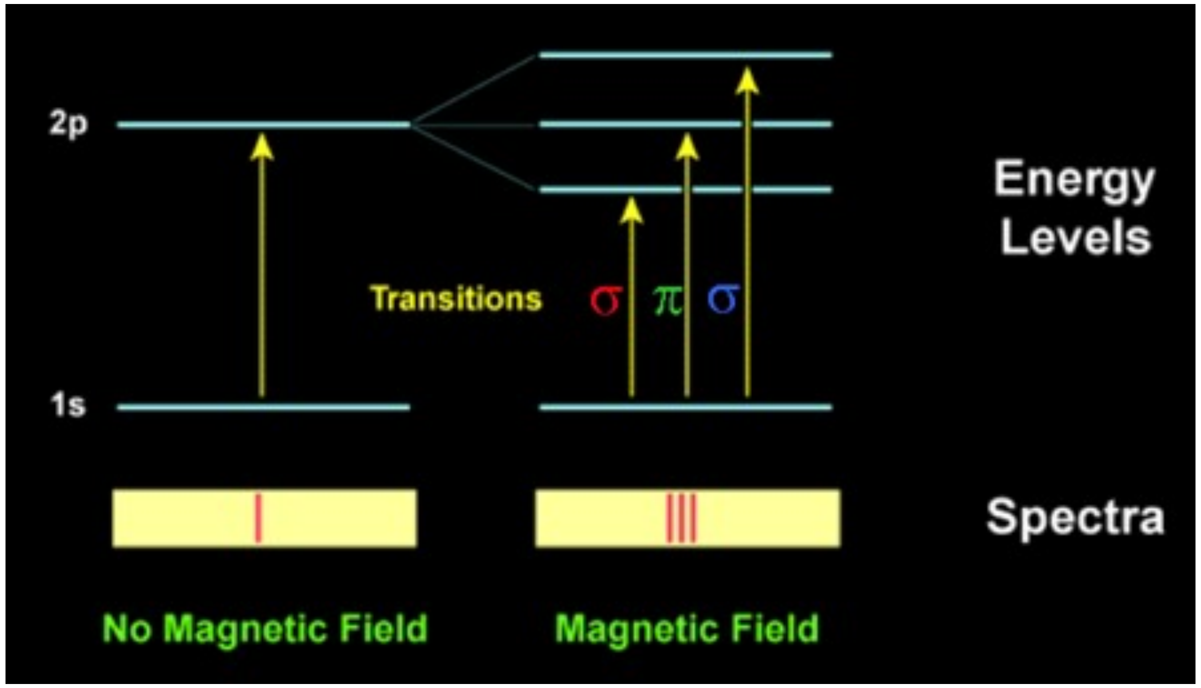
Young stars = fast rotation & high activity

How to measure stellar magnetic fields?

Zeeman Broadening
Zeeman Doppler imaging

Zeeman Broadening

Zeeman splitting



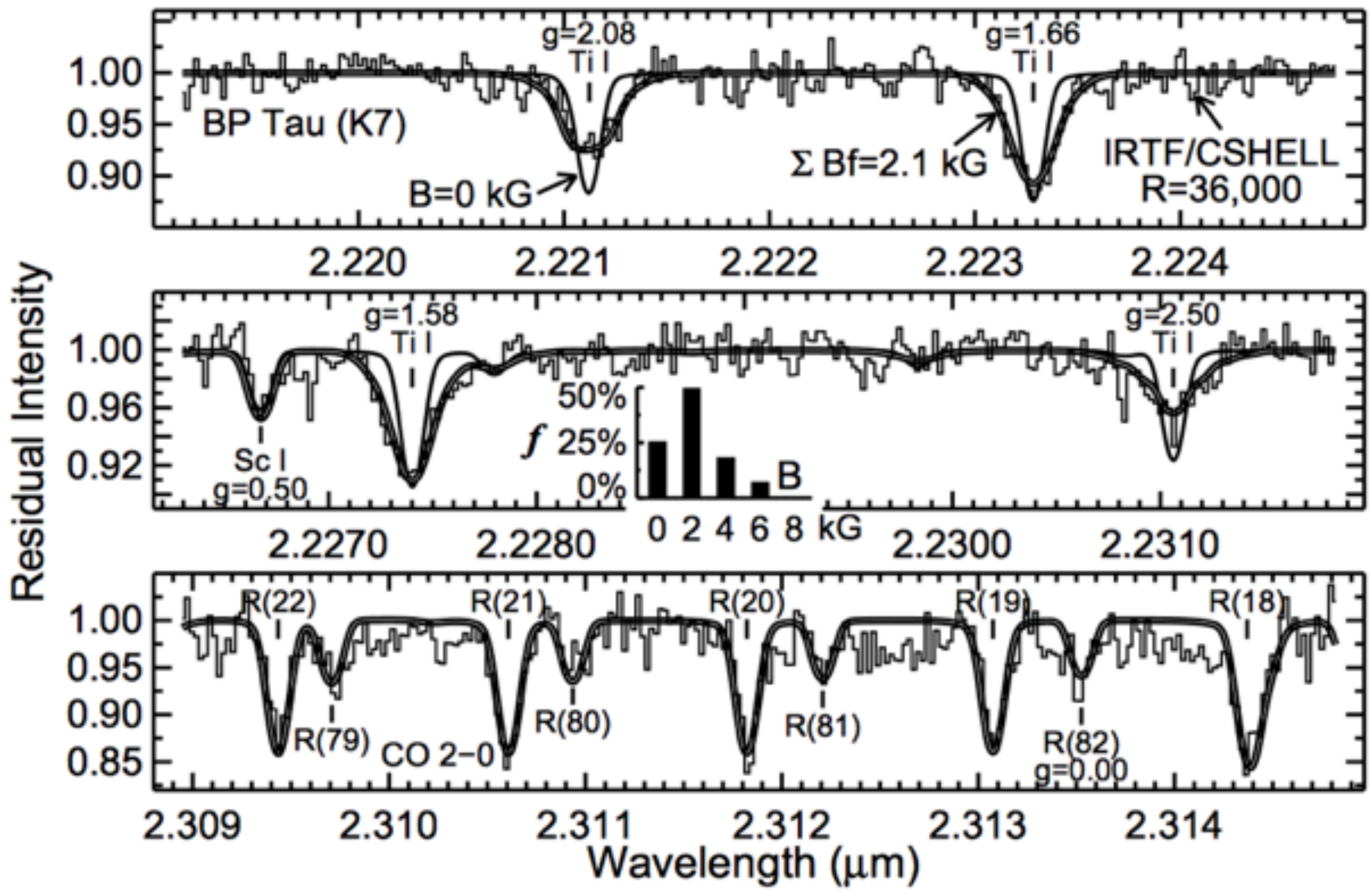
Reiners 12

- Broadening: better sensitivity in the infra-red

$$\Delta\lambda = \frac{e}{4\pi mc^2}\lambda^2 g_{\rm lan} B$$

Zeeman Broadening: example of an accreting star

Magnetic field measurements in integrated light (Stokes I)



Johns-Krull 2009

- Ti I: Zeeman sensitive
- CO: Zeeman insensitive
- Best fit: multiple component-field (distribution of f): $<|B_I|>=\sum|\mathbf{B_i}|f_i$
- Total unsigned magnetic field strength: $<|B_I|>\approx 2.1$kG

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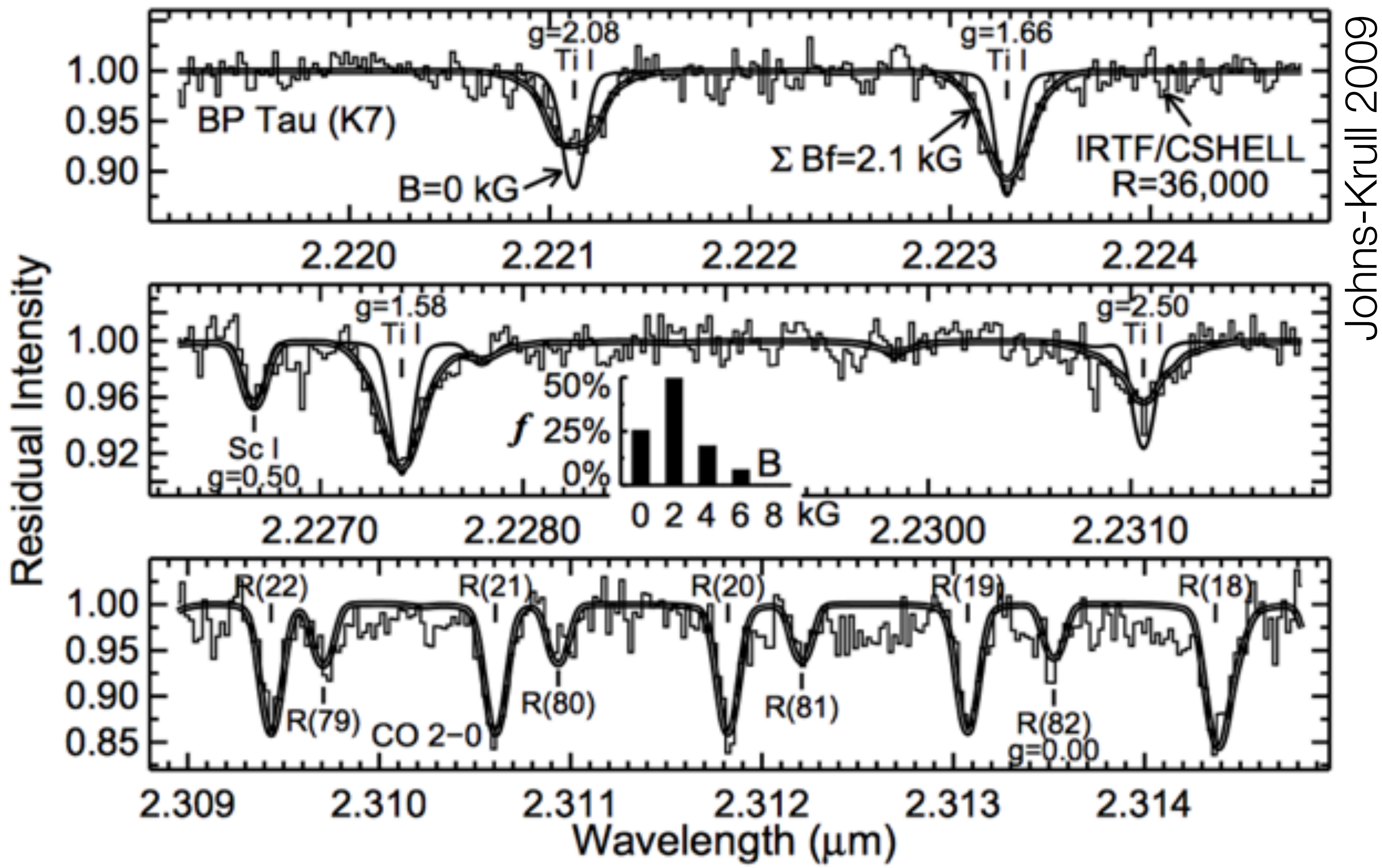

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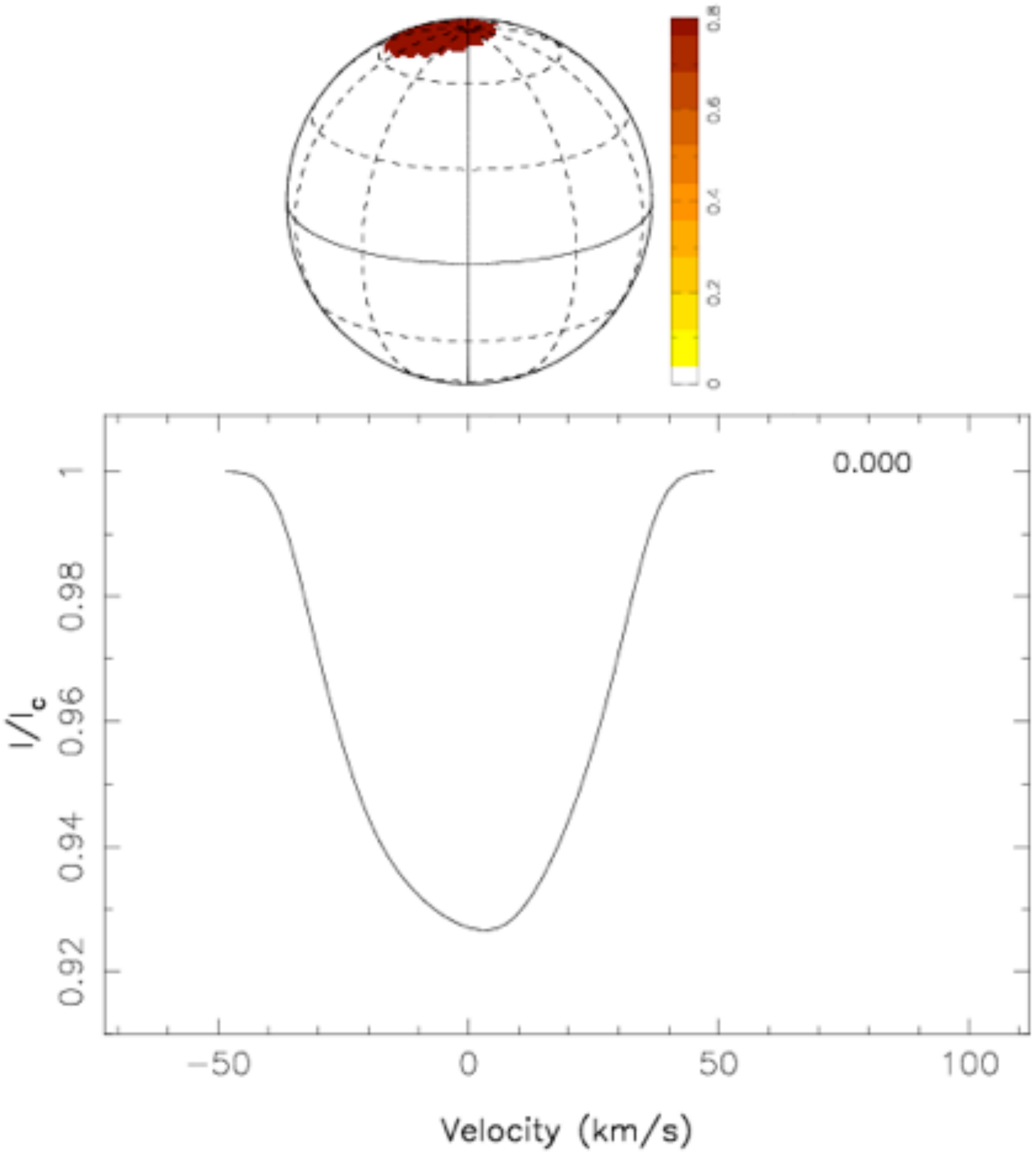
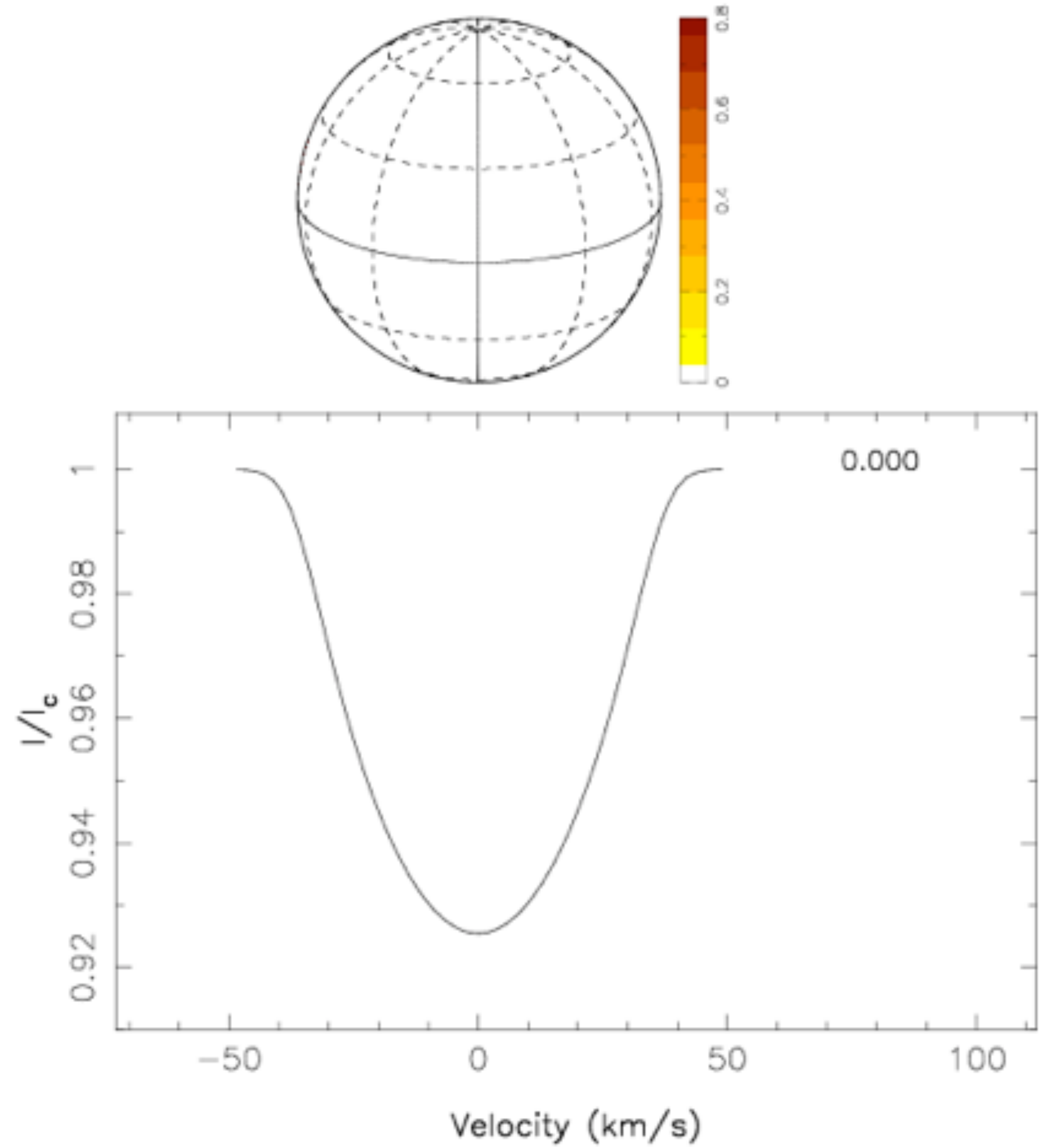
How about the field topology? → tomographic imaging techniques

How do we map stellar surface magnetic fields?

Doppler Imaging



Credit: J.-F. Donati



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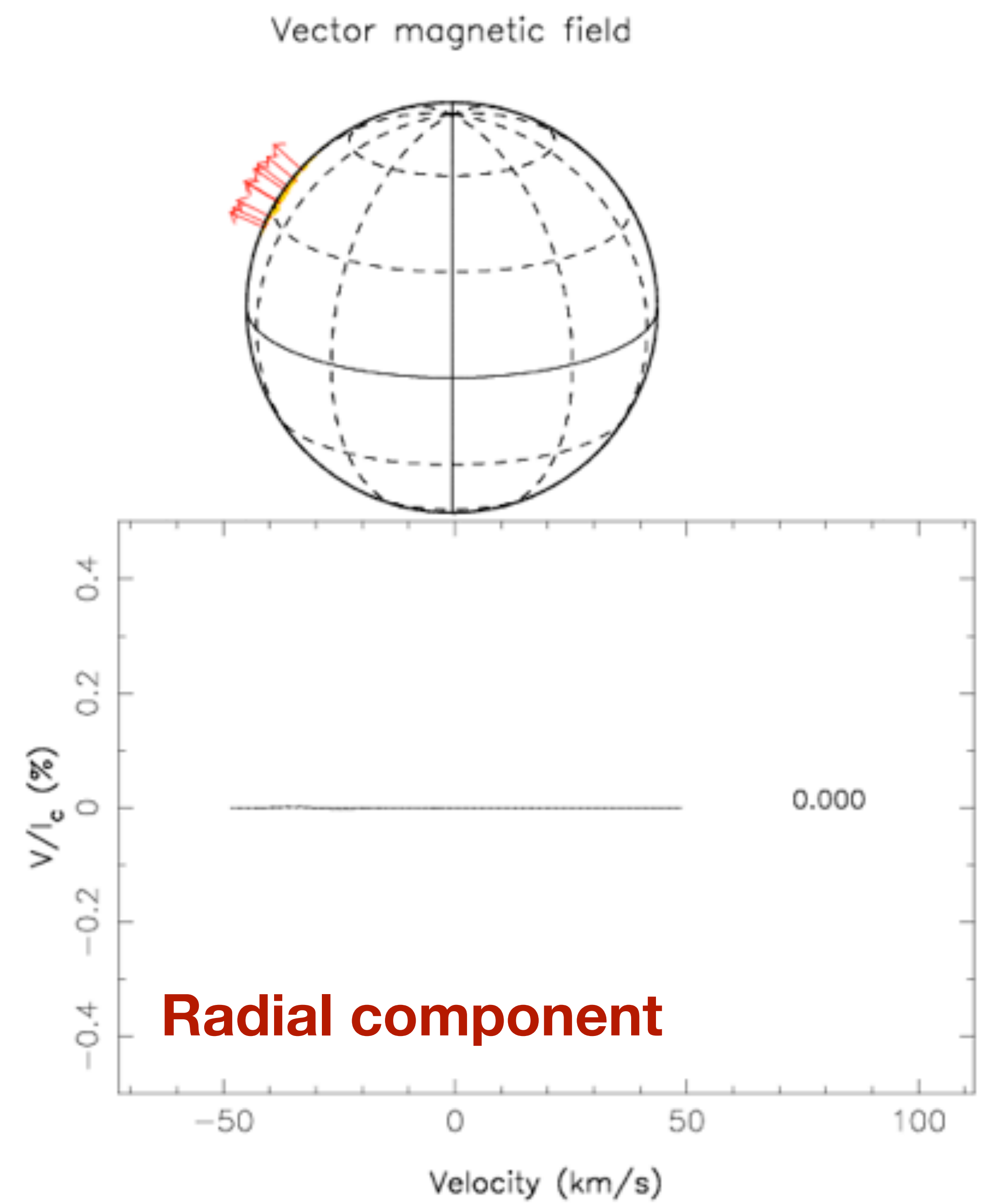

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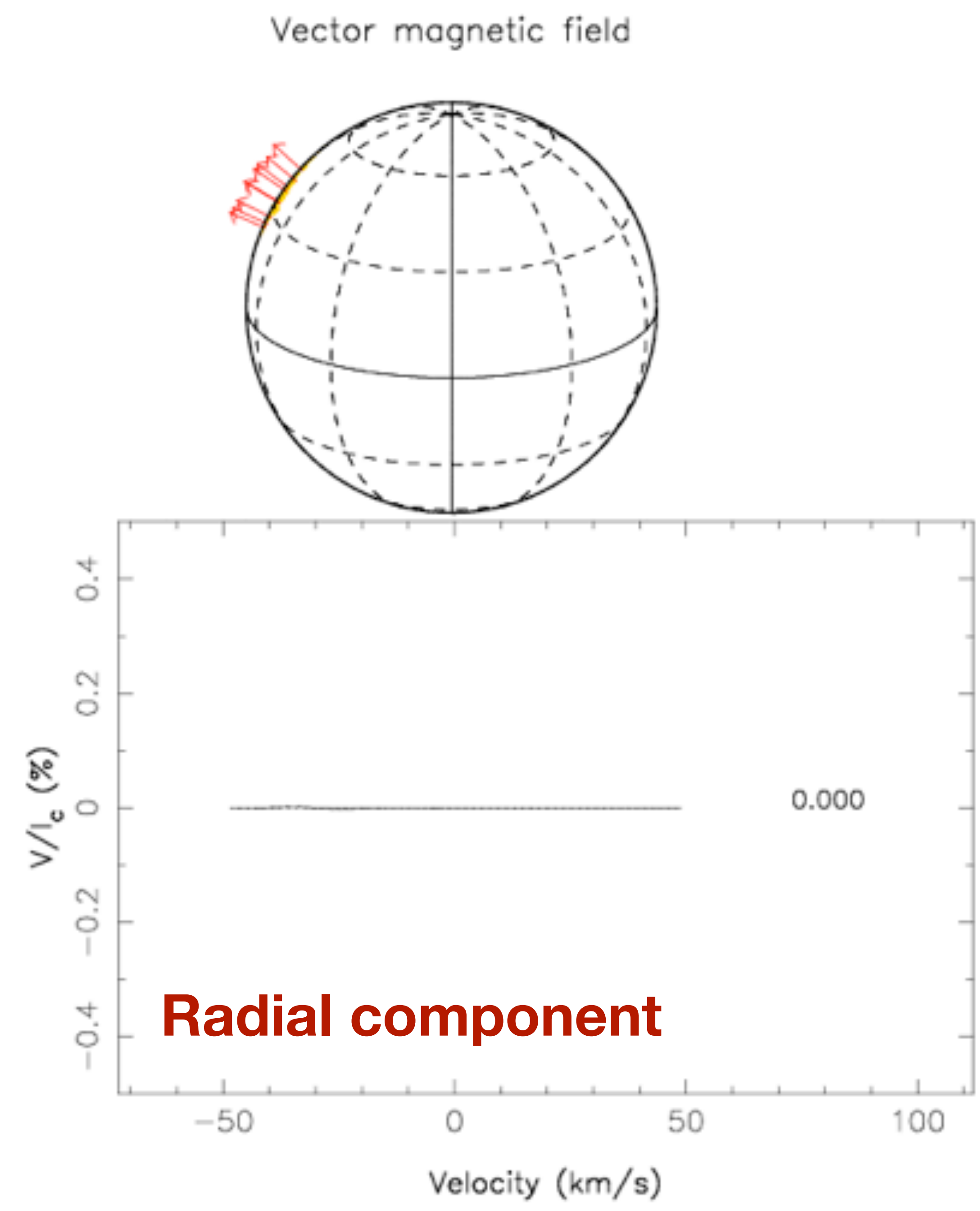
How do we map stellar surface magnetic fields?

Zeeman Doppler Imaging

- Zeeman effect: magnetic field splits lines

- **Stokes V = ⭯ - ⭮**



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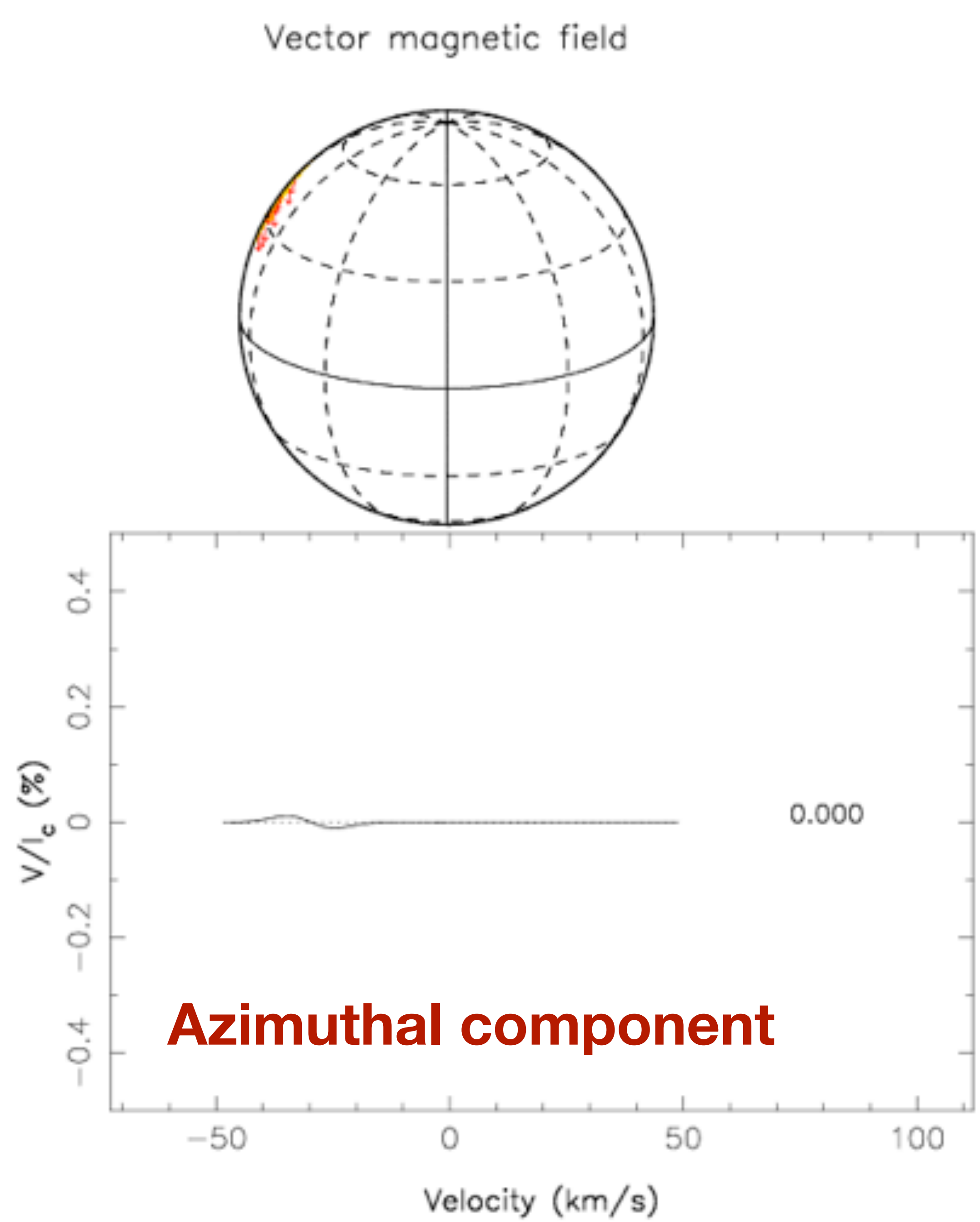

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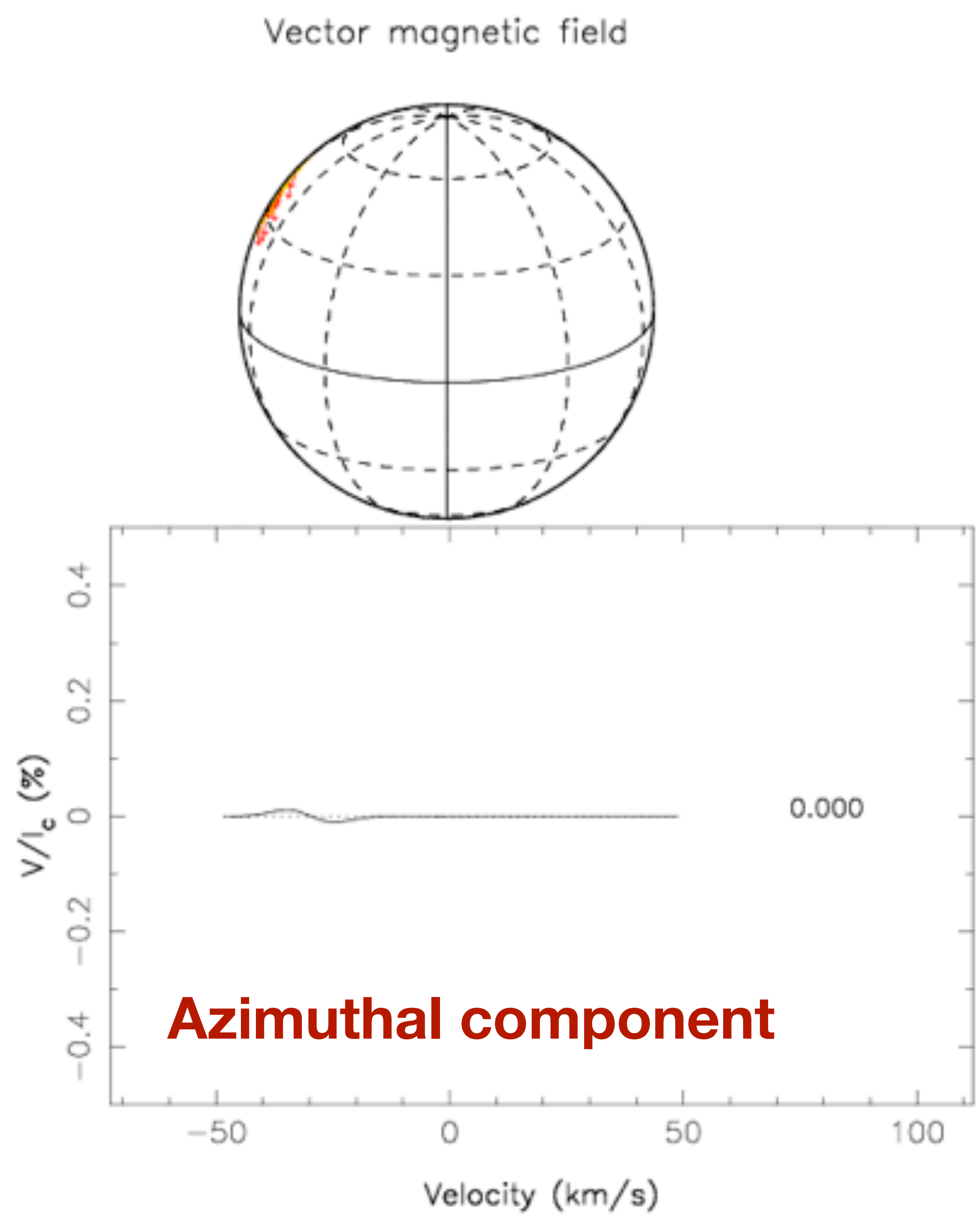
How do we map stellar surface magnetic fields?

Zeeman Doppler Imaging

- Zeeman effect: magnetic field splits lines
- **Stokes V = ↺ - ↻**
- Track Stokes V → get field along observer's direction (B_{los})

$$B_{\rm los} = -2.14 \times 10^{11} \frac{\int v \frac{V(v)}{I_c} dv}{\lambda g_{\rm lan} c \int \left[1 - \frac{I(v)}{I_c}\right] dv}$$



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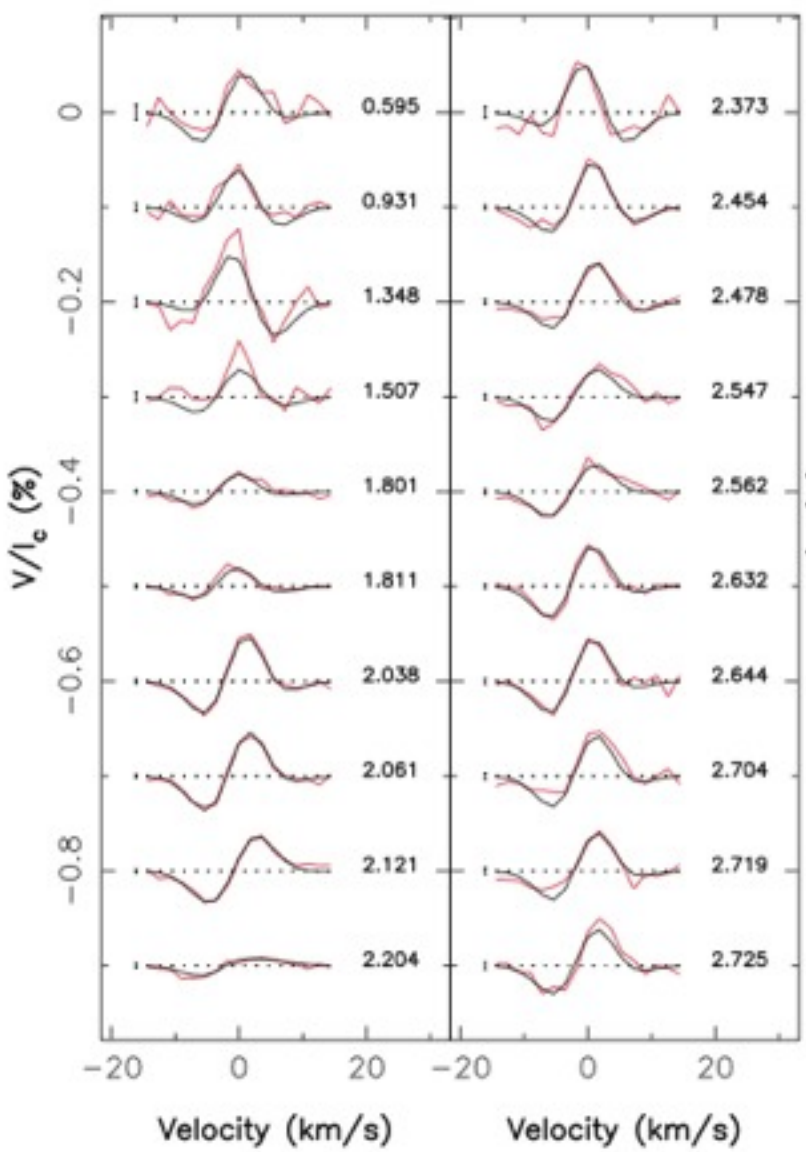
How do we map stellar surface magnetic fields?

- From Stokes V profile → use inversion techniques to derive B_r, B_ϕ, B_θ



HD189733 (K2V)

Fares+(2010)

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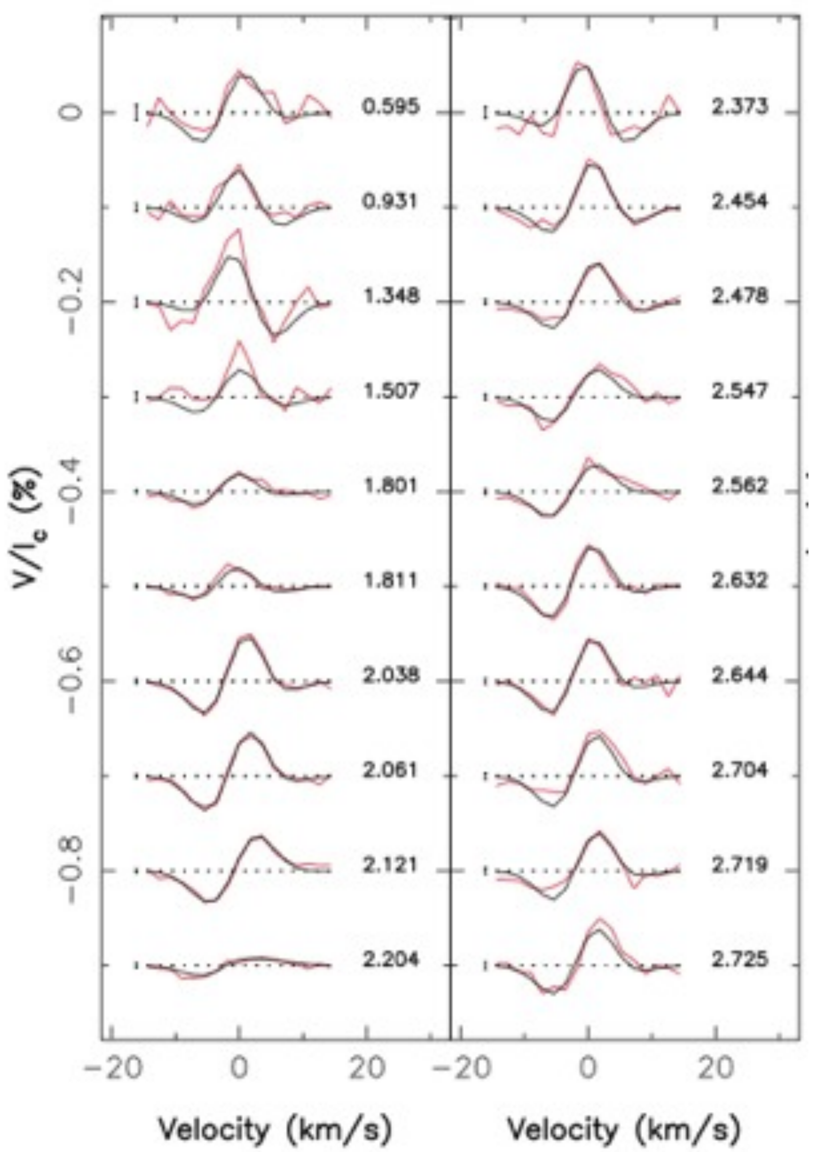


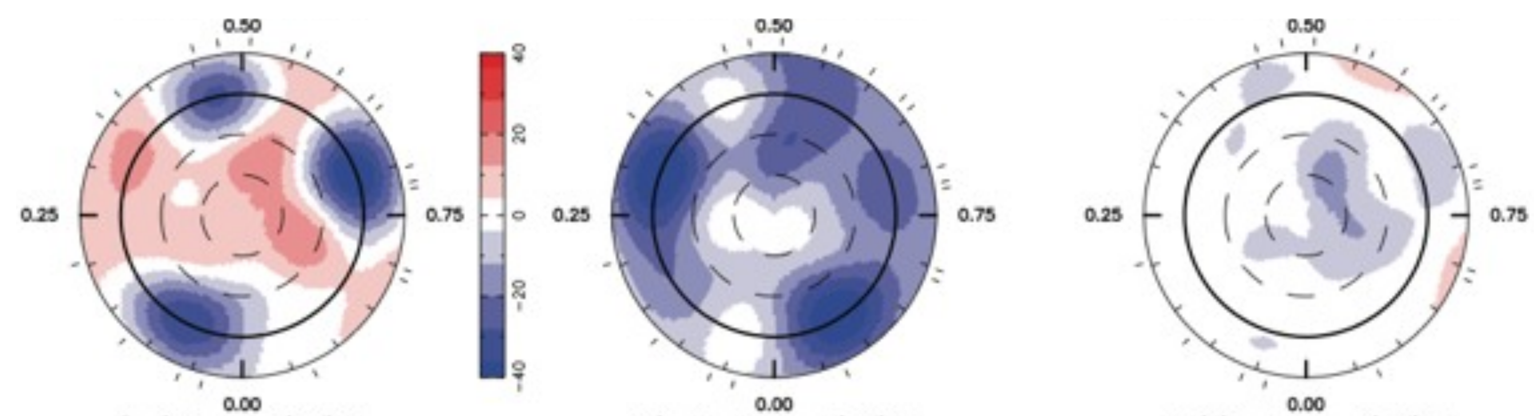
HD189733 (K2V)

Fares+(2010)

radial

azimuthal

meridional



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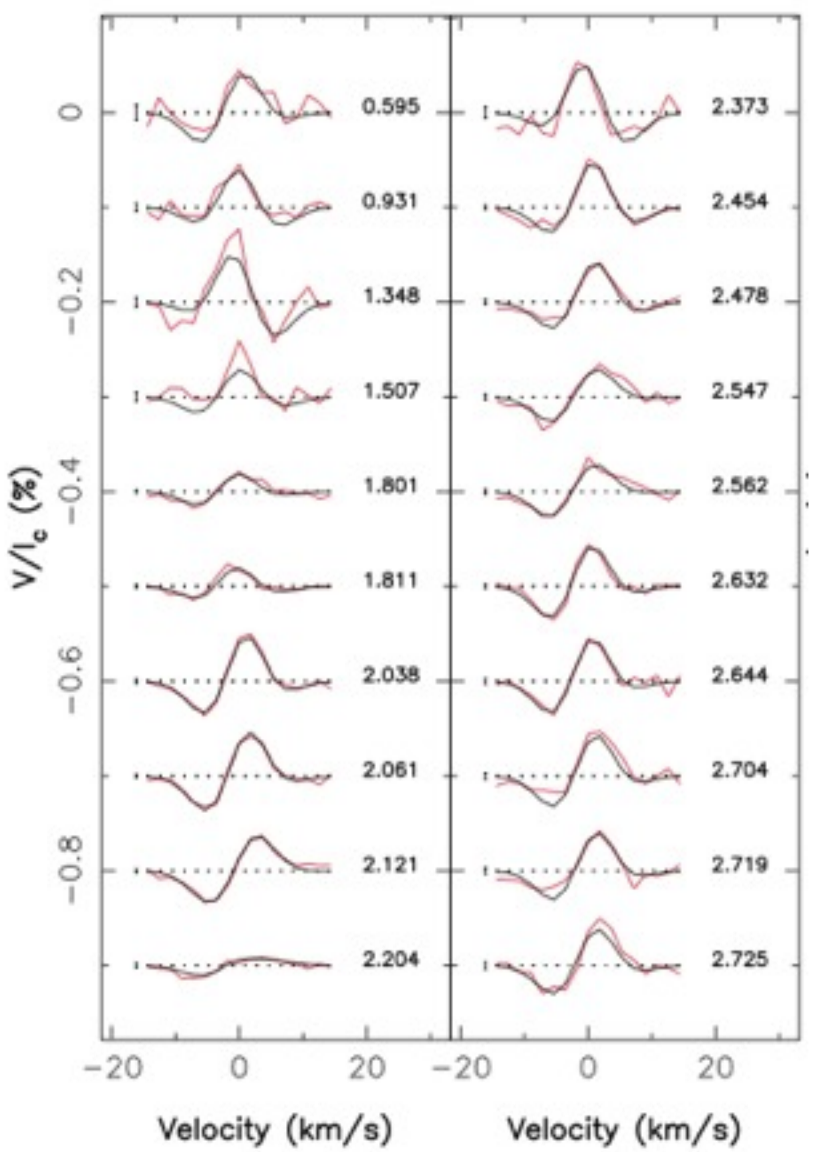

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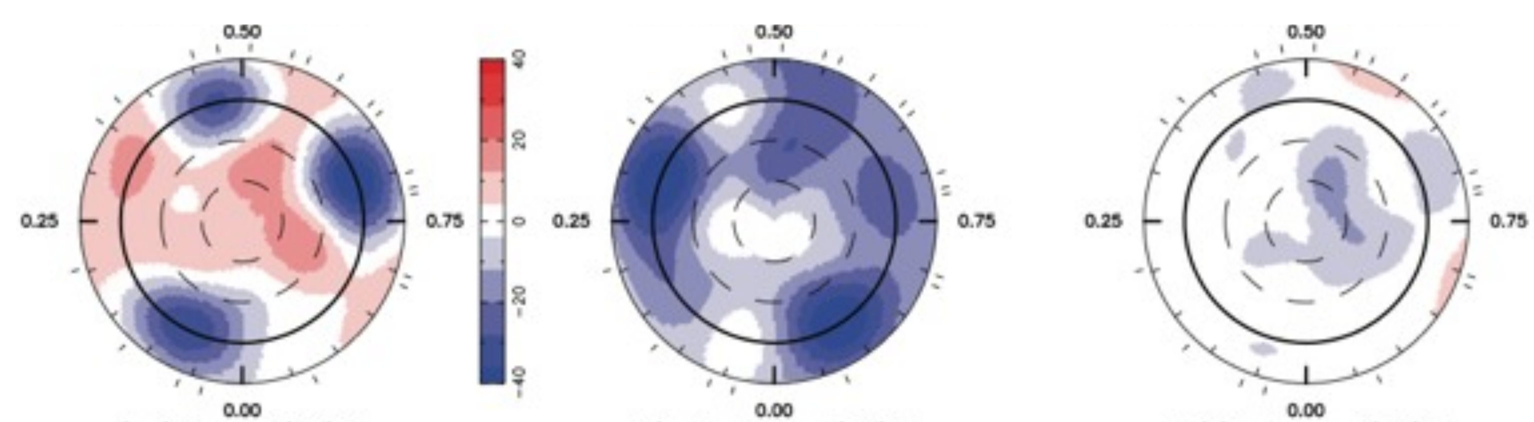
Fares+(2010)

radial azimuthal meridional



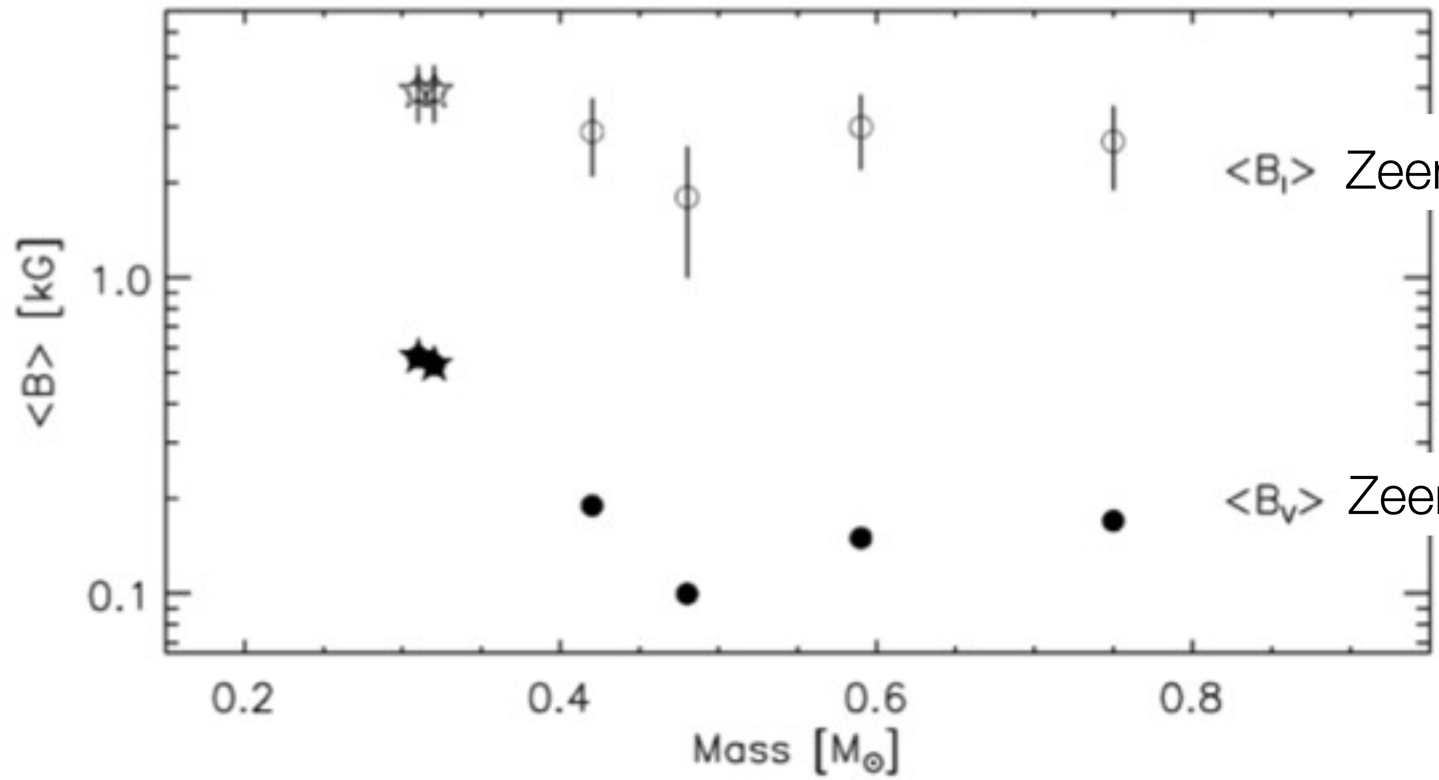
$<|B_V|>\sim 22G$

57% of $E_{toroidal}$

26% of $E_{axisymmetric\ poloidal}$

Comparison between both techniques

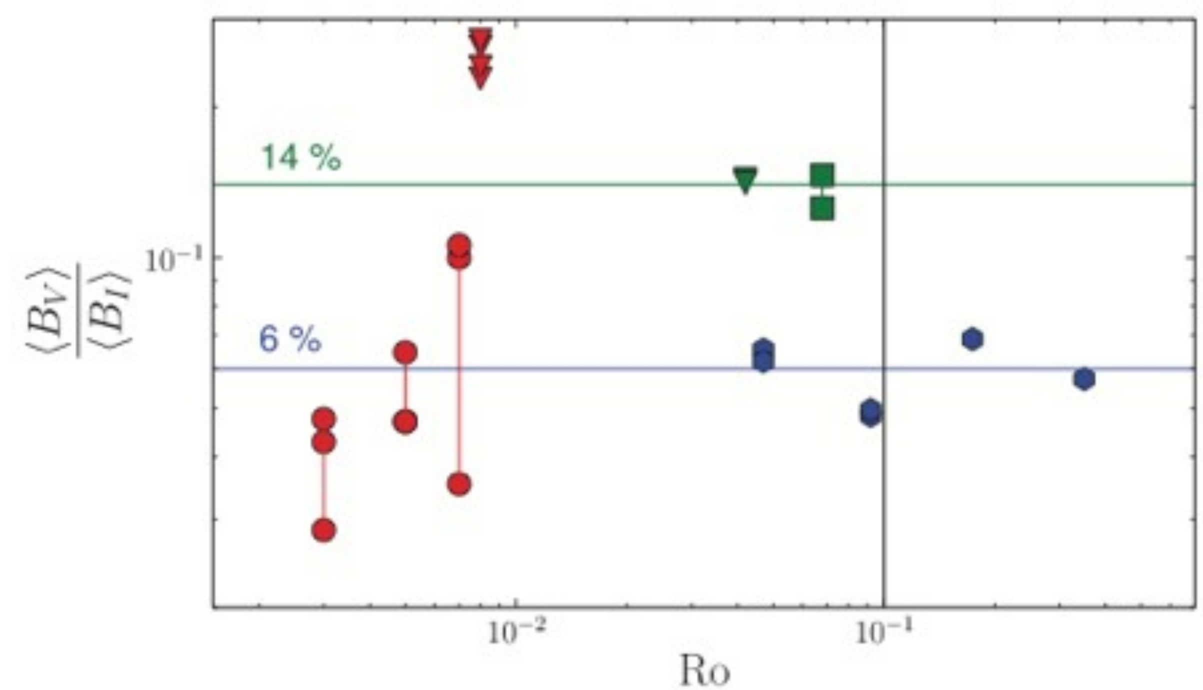
Reiners & Basri 2009



$\langle B_I \rangle$ Zeeman broadening: total field

$\langle B_V \rangle$ Zeeman Doppler Imaging: vectorial field

Morin et al 2010



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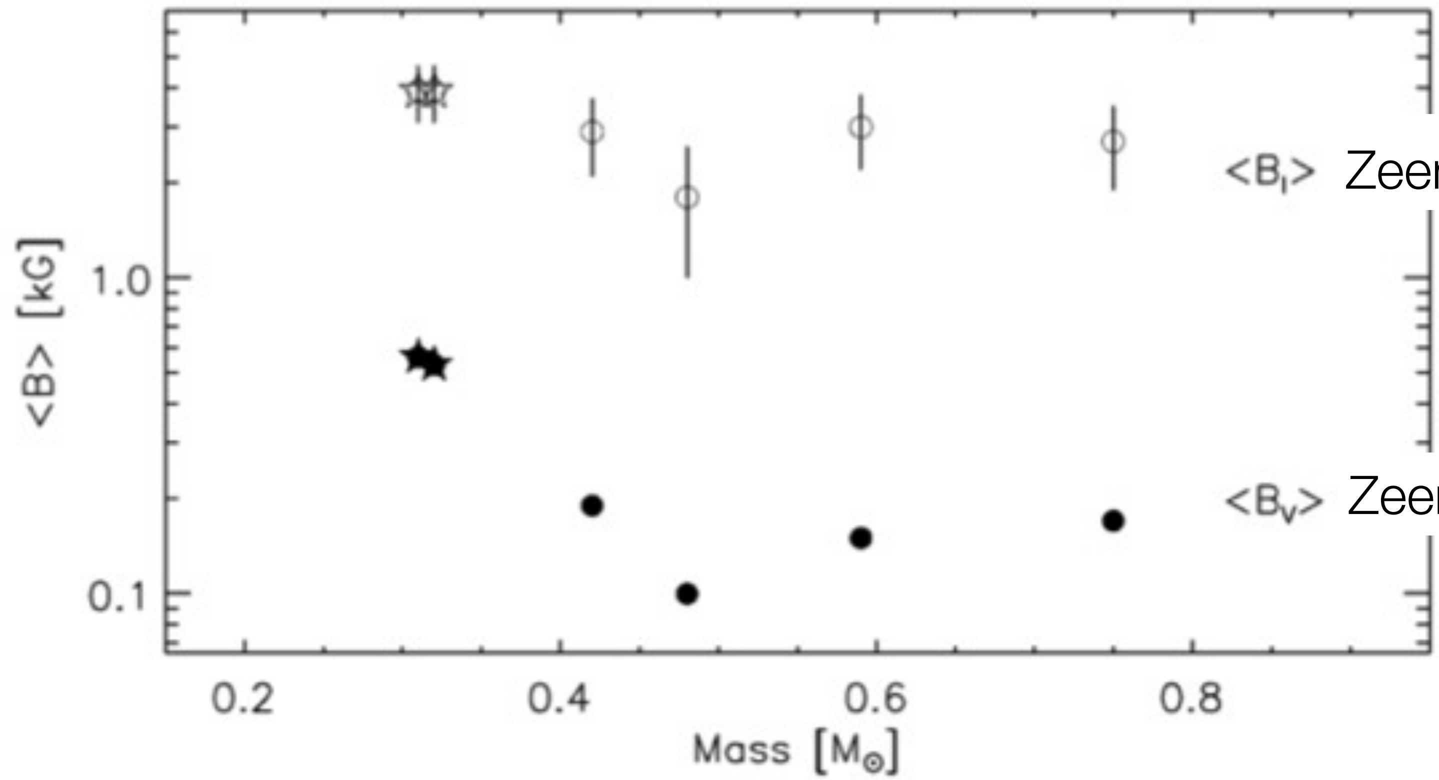

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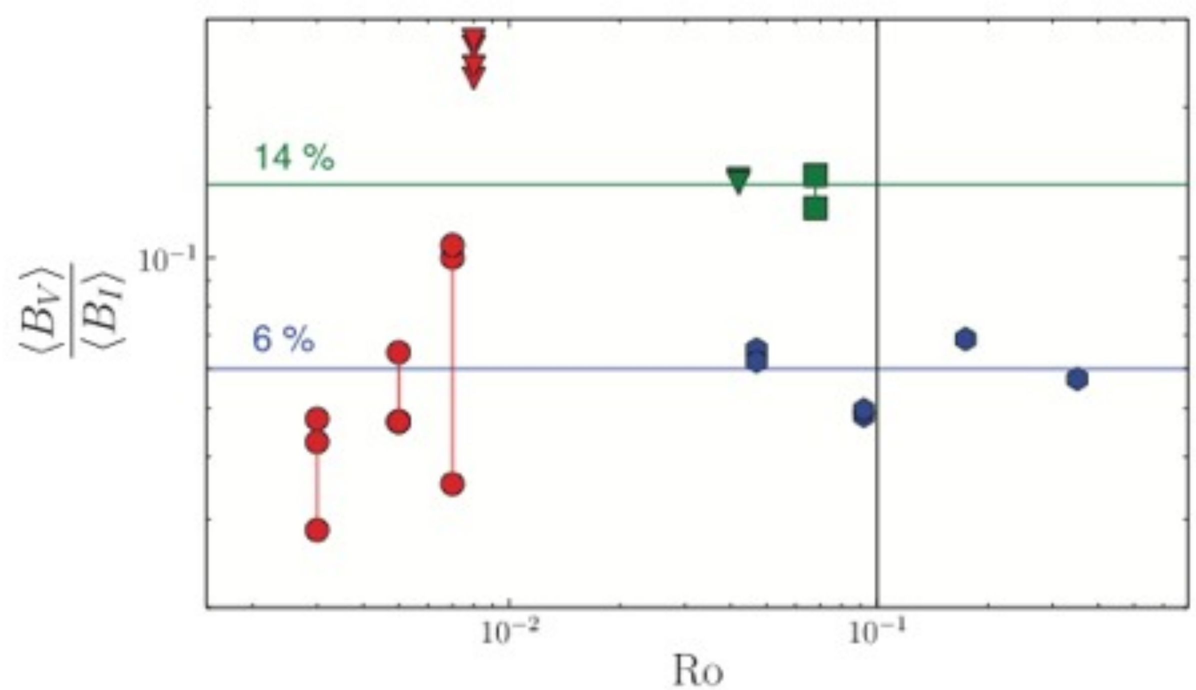

- ZDI reproduces ~ 5 - 15% of the field observed by ZB
- What causes this discrepancy?
  A: flux cancelation of unresolved regions of opposite polarity field (small scale)

ZDI typical resolution

- B_r, B_ϕ, B_θ: described as spherical harmonics. Example:

$$B_r(\theta, \phi) = \sum_{l,m} b_{lm} P_{l,m}(\cos\theta) e^{im\phi}$$

- where the highest order component is

$$l_{\max} \simeq 2\pi \frac{v \sin i}{\mathrm{FWHM}}$$

- Stellar magnetograms: $l_{\max}$ ~ 5 to 10

Star	l_{max}	
V374 Peg	10	Morin et al. (2008)
GJ 51	5	Morin et al. (2010)
GJ 1156	6	Morin et al. (2010)
GJ 1245	4	Morin et al. (2010)
WX UMa	4	Morin et al. (2010)
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GJ 3622	2	Morin et al. (2010)
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TW Hya	5	Donati et al. (2011)
τ Boo	8	Fares et al. (2009)
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ξ Bootis A	10 (5)	Morgenthaler et al. (2011)

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Credit: Colin Johnstone

ZDI: probes the large-scale field of the star

What does this mean?

	Zeeman Broadening (Stokes I)	Zeeman Doppler Imaging (Stokes V)
Total field measured?	**Yes:** large and small scales	**No:** limited to large-scale fields ($l_{max} \lesssim 10$)
Topology studied? (ie, vector **B**)	**No:** average over entire surface only	**Yes:** surface distribution of B_r, B_ϕ, B_θ
Ideal targets	slow rotators (no rotational broadening)	moderate/fast rotators

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Complementary techniques

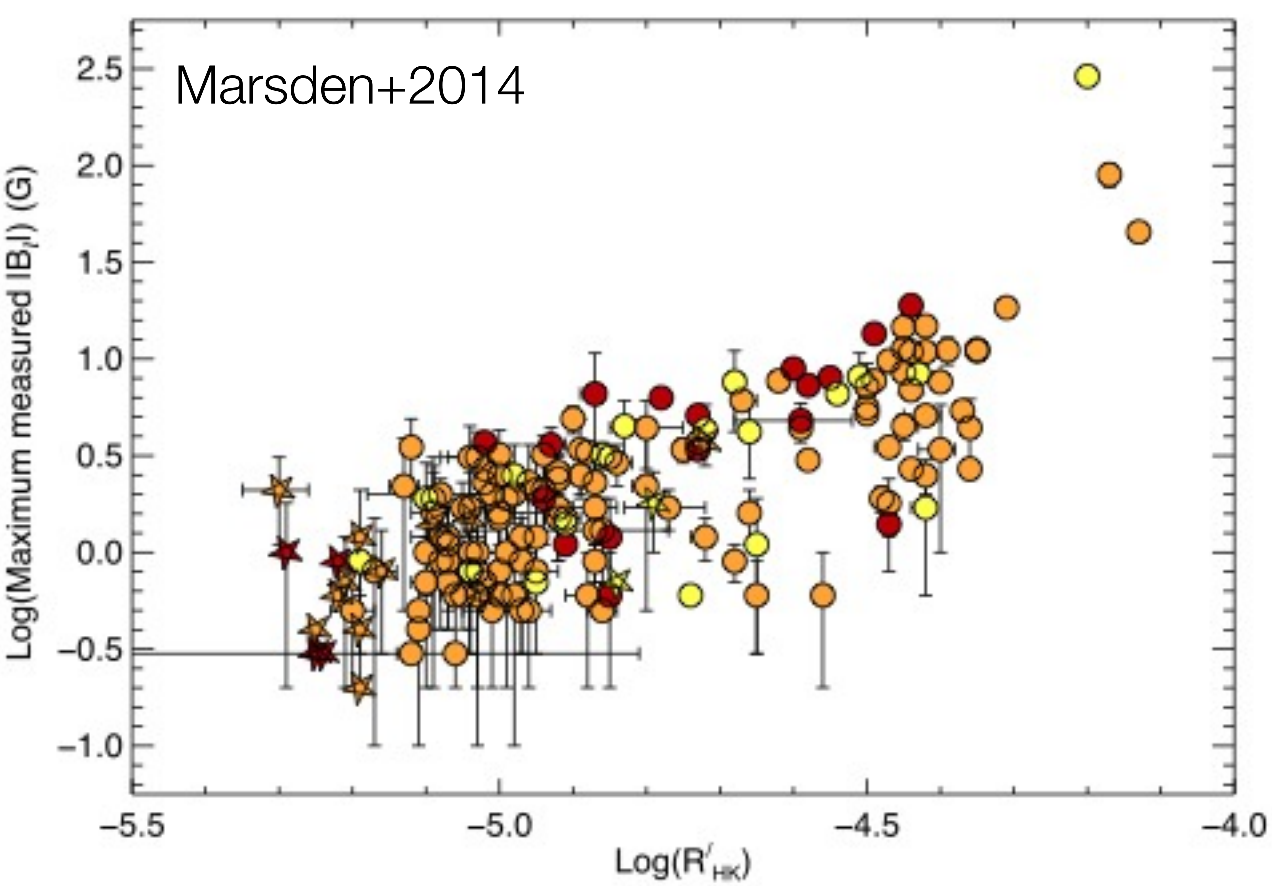
What have we learned so far?

Results from large-scale field measurements

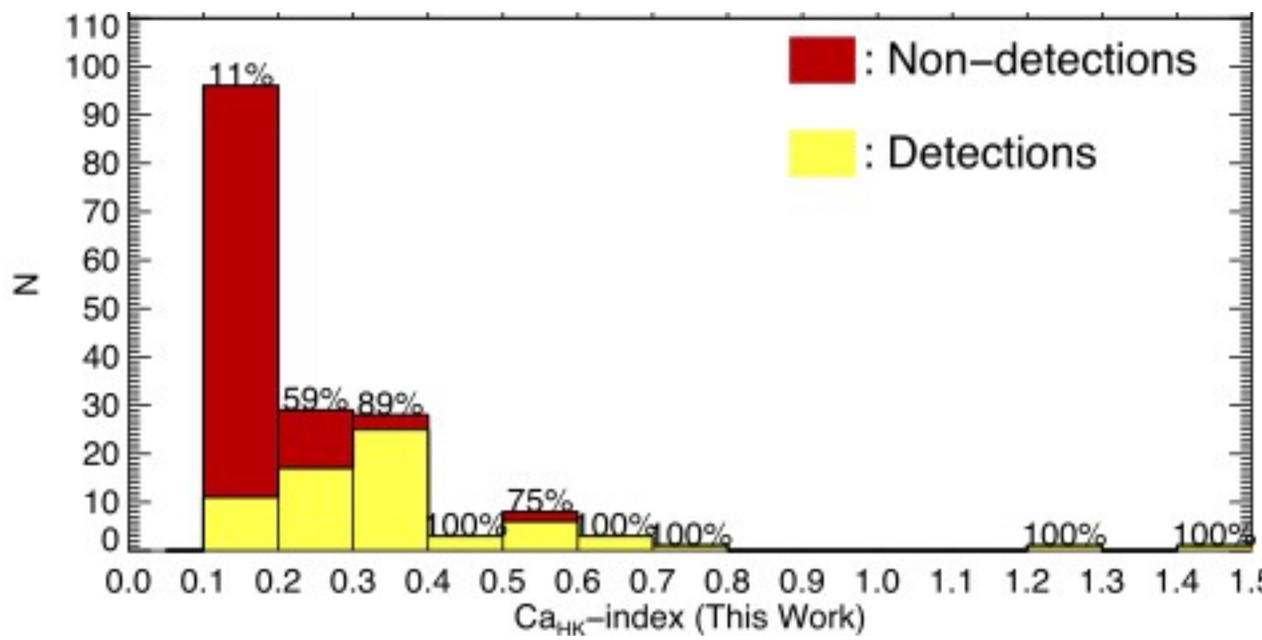
Magnetism increases towards more active stars

- Stokes V (snapshot) survey of 167 solar-type stars with ages up to 9 Gyr
- Mean value of $|B_{los}|$ is 3.9 G (F-stars), 3.4 G (G-stars) and 6.1 G (K-stars)

$|B_{los}|$ increases with Ca H&K emission



Marsden+2014



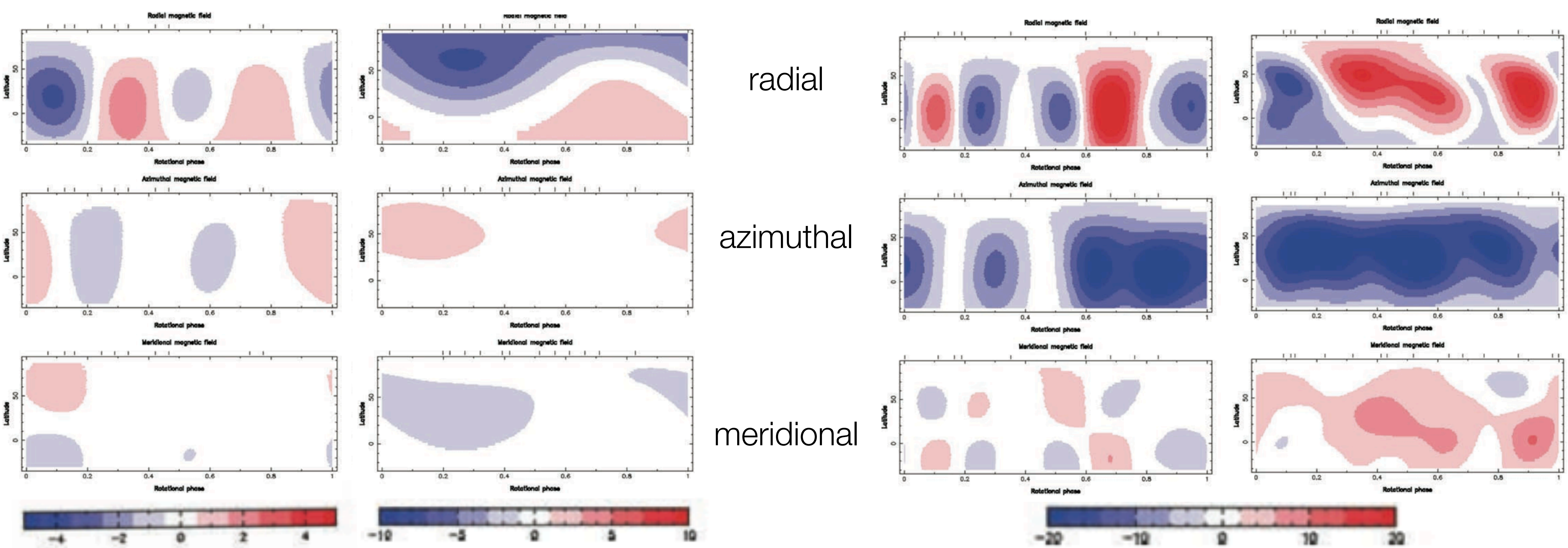
Magnetic field detection rate almost 100% when Index(Ca_{HK})>0.3

Field topology depends on rotation

Petit+08

- Solar twins
  - mostly poloidal for low rotation rates,
  - significant large-scale toroidal component for fast rotators

slow rotators: $P_{rot}\sim$ 20 to 23 days   fast rotators: $P_{rot}\sim$ 9 to 12 days



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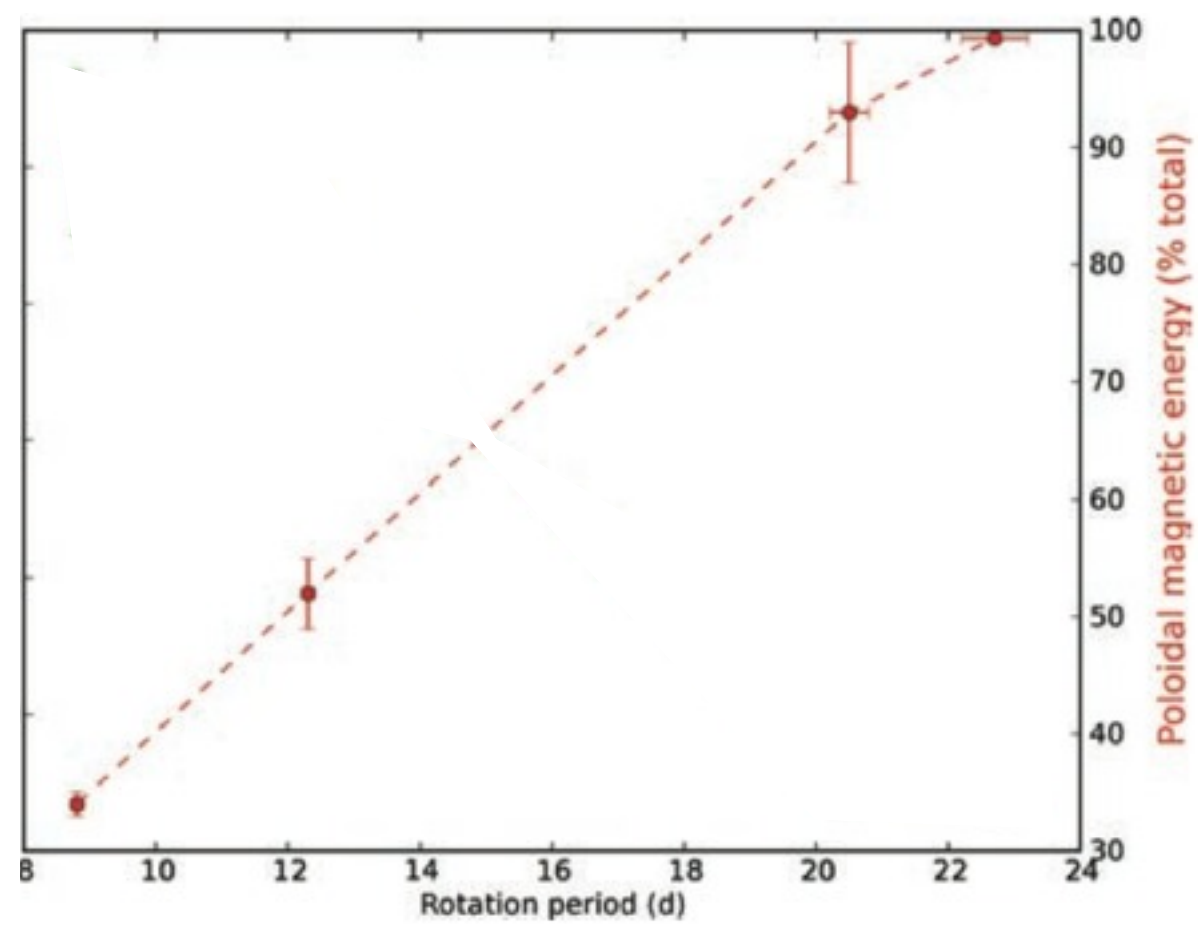

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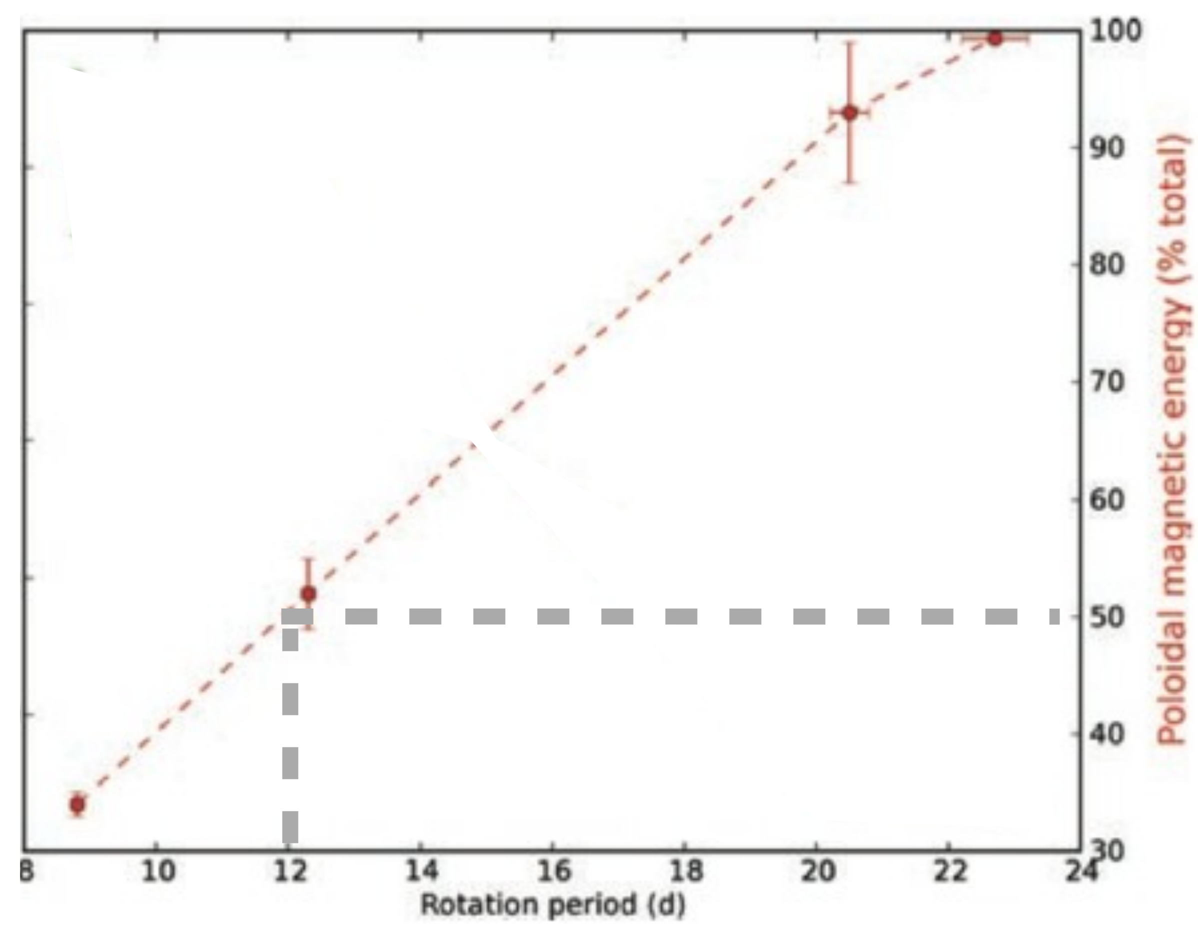


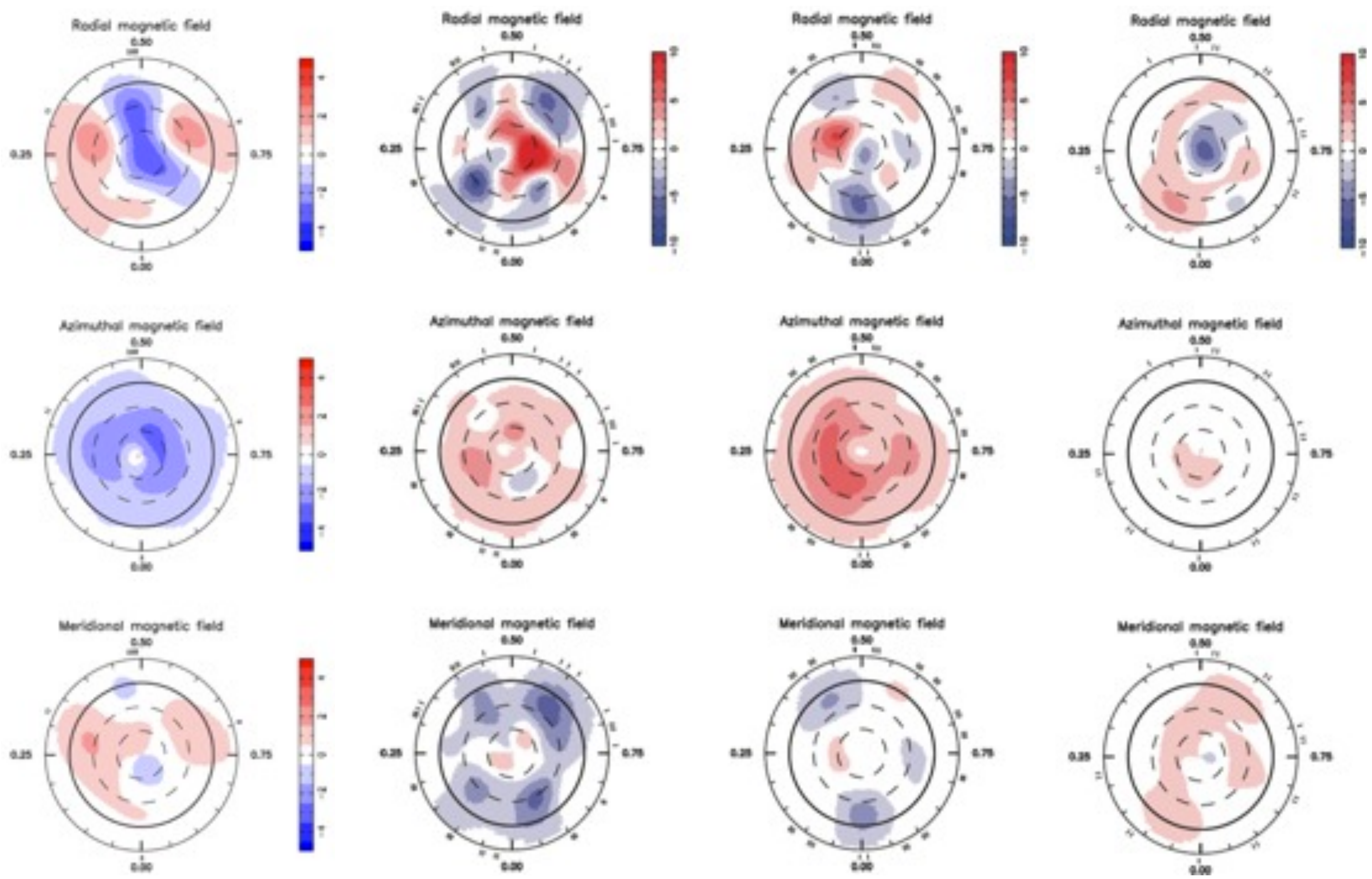
Magnetic Cycles: τ Boo

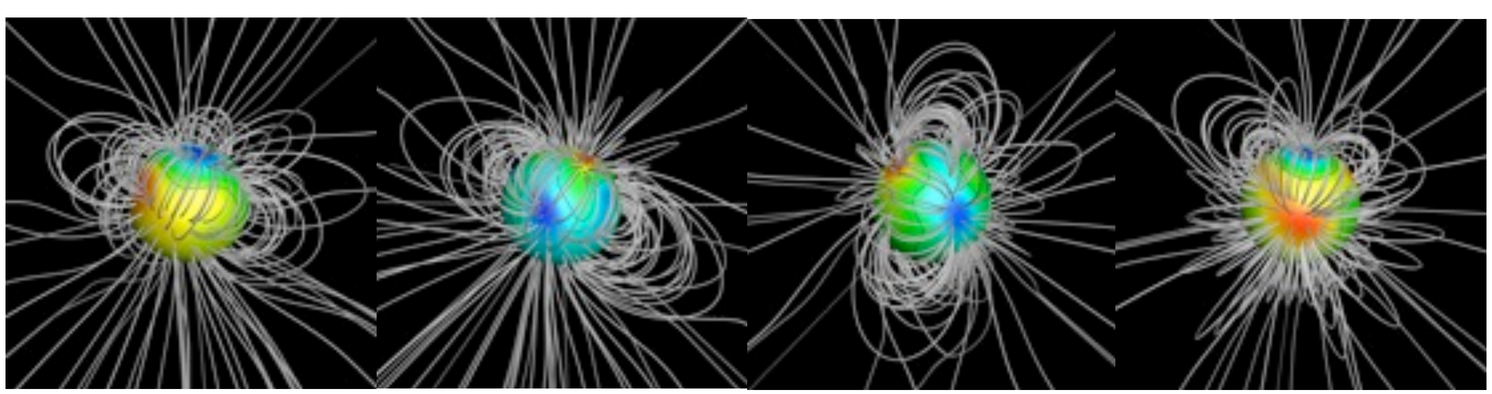
	June/06	June/07	January/08	July/08
	(Catala+07)	(Donati+08)	(Fares+09)	(Fares+09)

radial

azimuthal

meridional





Vidotto+2012

Planet-host star:

- 1.34 $M_\odot$
- P_{rot}=3 days
- age ~ 2.5 Gyr

P_{cycle} = 2 years (Fares+09)

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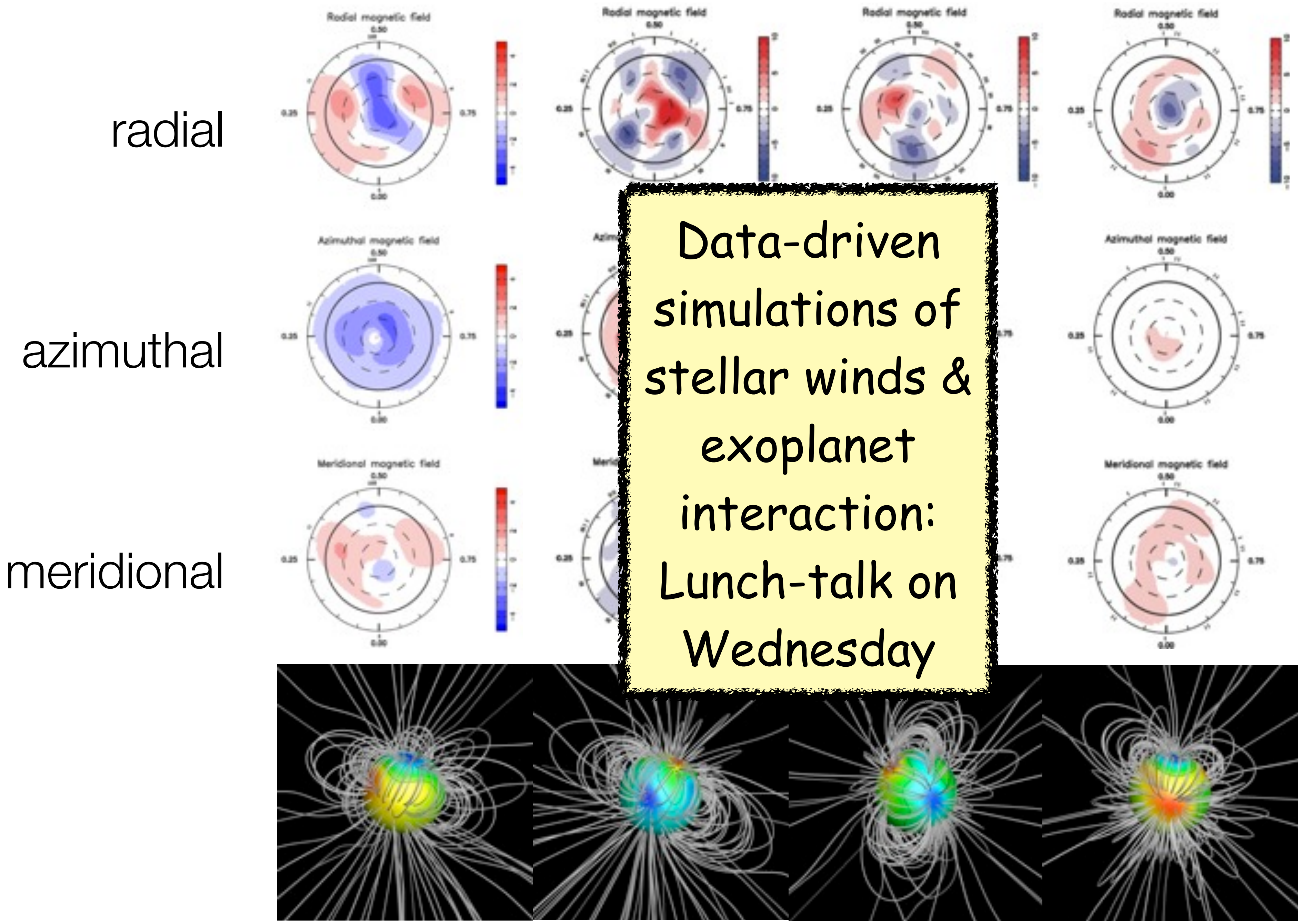

Data-driven simulations of stellar winds & exoplanet interaction: Lunch-talk on Wednesday

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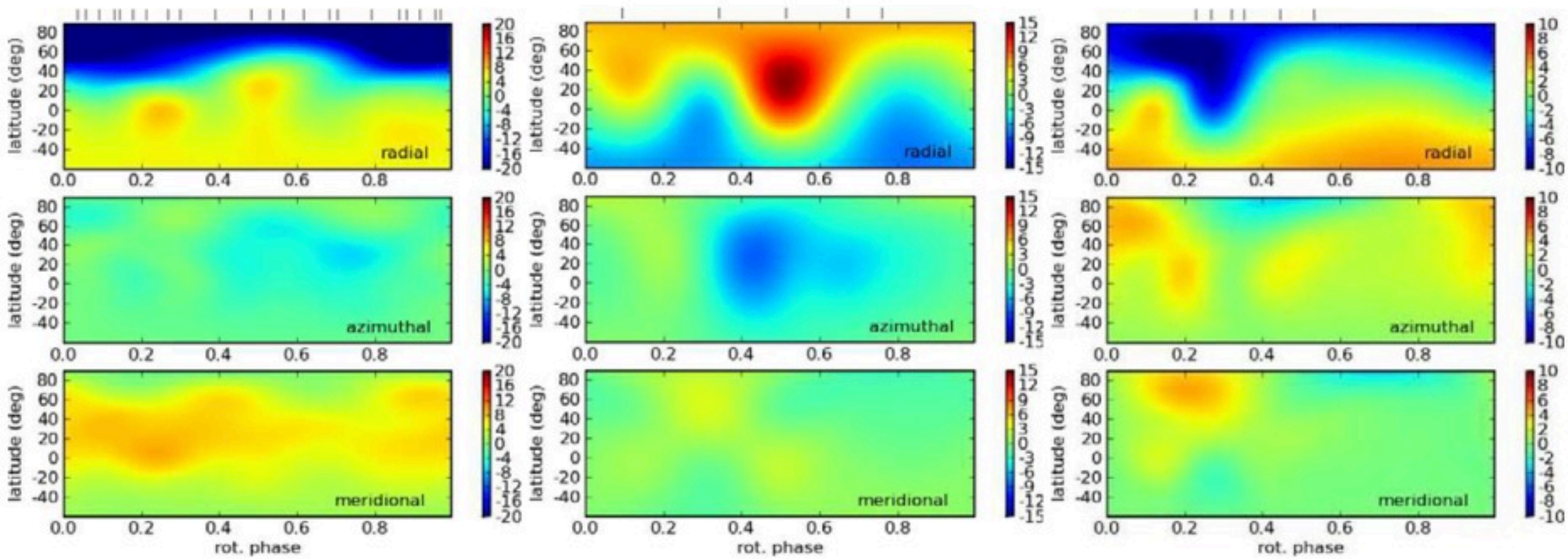
Magnetic cycles: HD 78366

- 1.34 $M_\odot$
- P_{rot}=11.4 days
- age ~ 2.5 Gyr

‣ 2 polarity reversals within 3 years

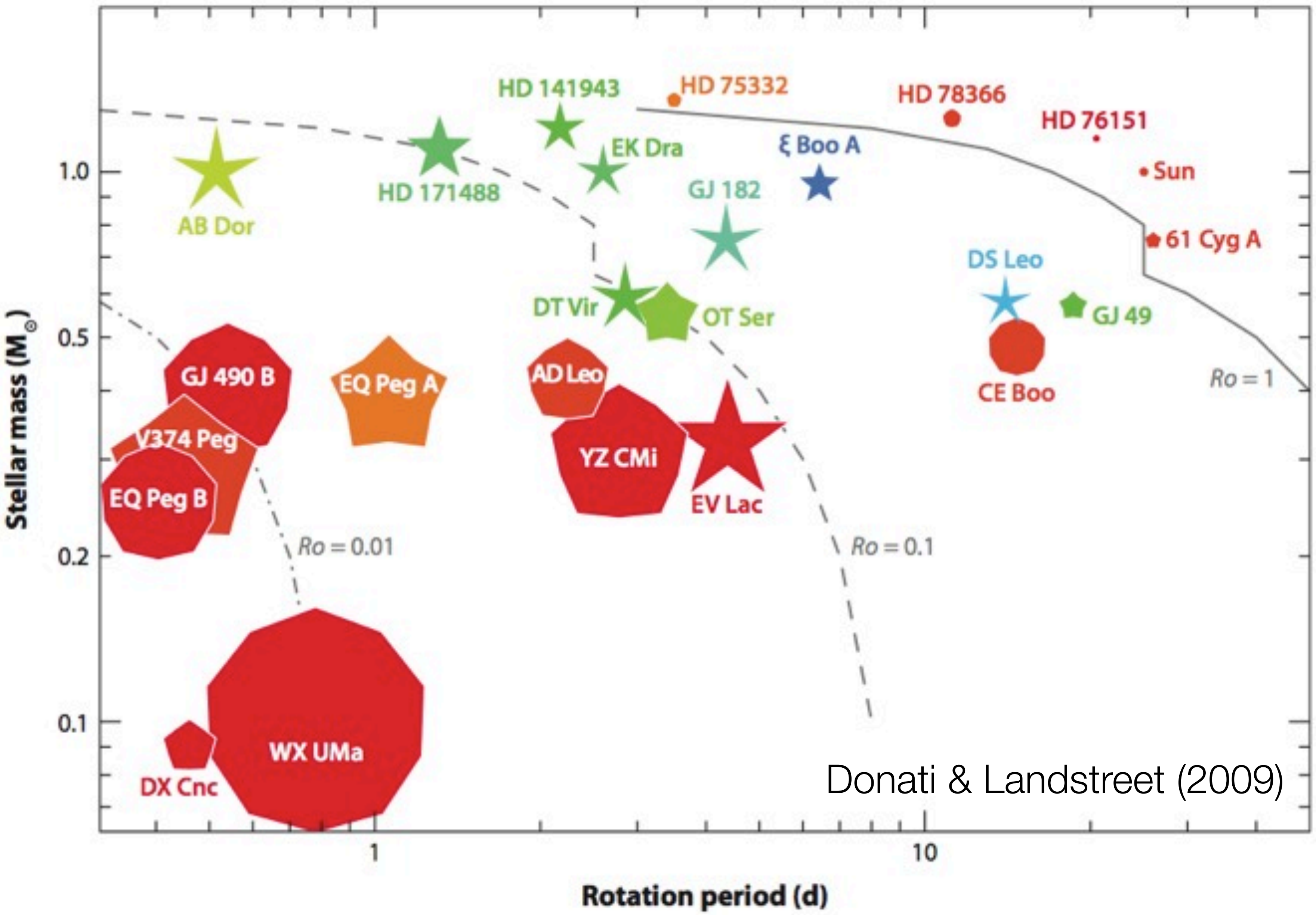
Morgenthaler+11



2008 2010 2011

Magnetic field topology is very diverse...

Zeeman Doppler imaging: large-scale magnetic fields



Donati & Landstreet (2009)

- Size: magnetic energy
- Colour: purely toroidal (blue) or poloidal (red) fields.
- Shape: purely axisymmetric (decagon) or non-axisymymmetric (star).

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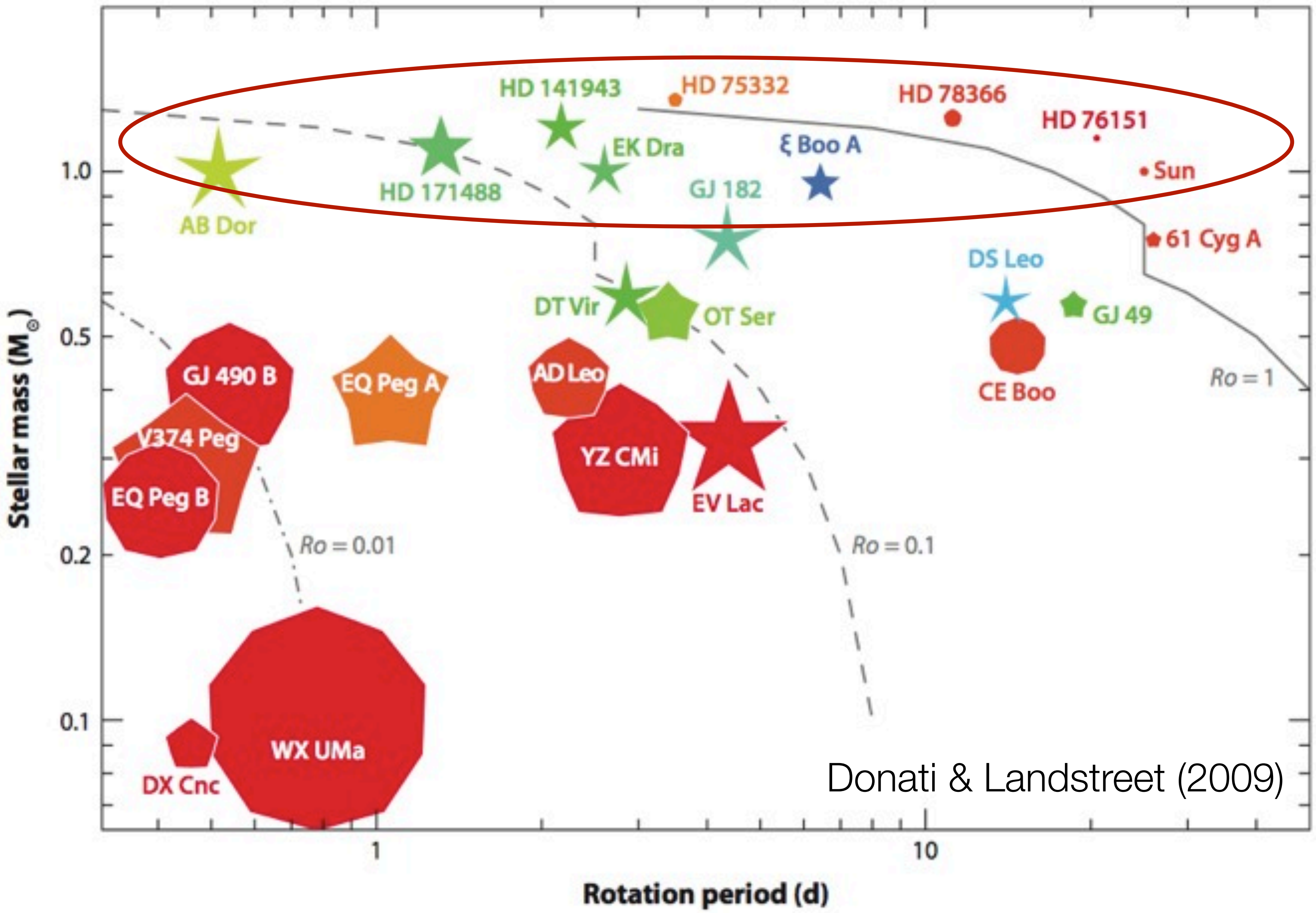

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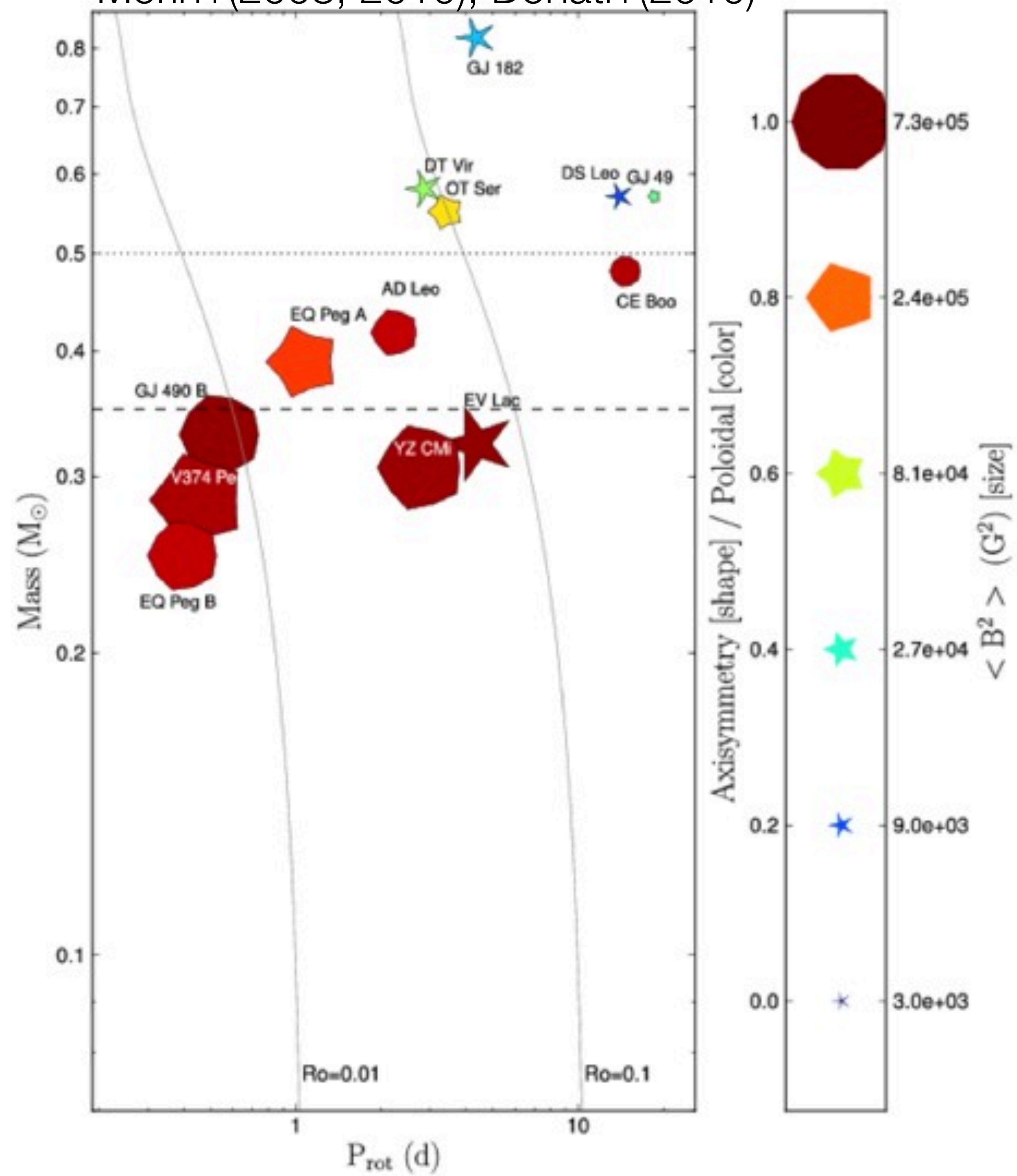
Variety of intensities and topologies

.. and topology depends on the internal structure I

M-dwarf stars:

- sharp transition at ~0.5 $M_\odot$
- Multipolar **B** → dipolar **B**
- partially → fully convective
- due to lack of tachocline?

Morin+(2008, 2010); Donati+(2010)



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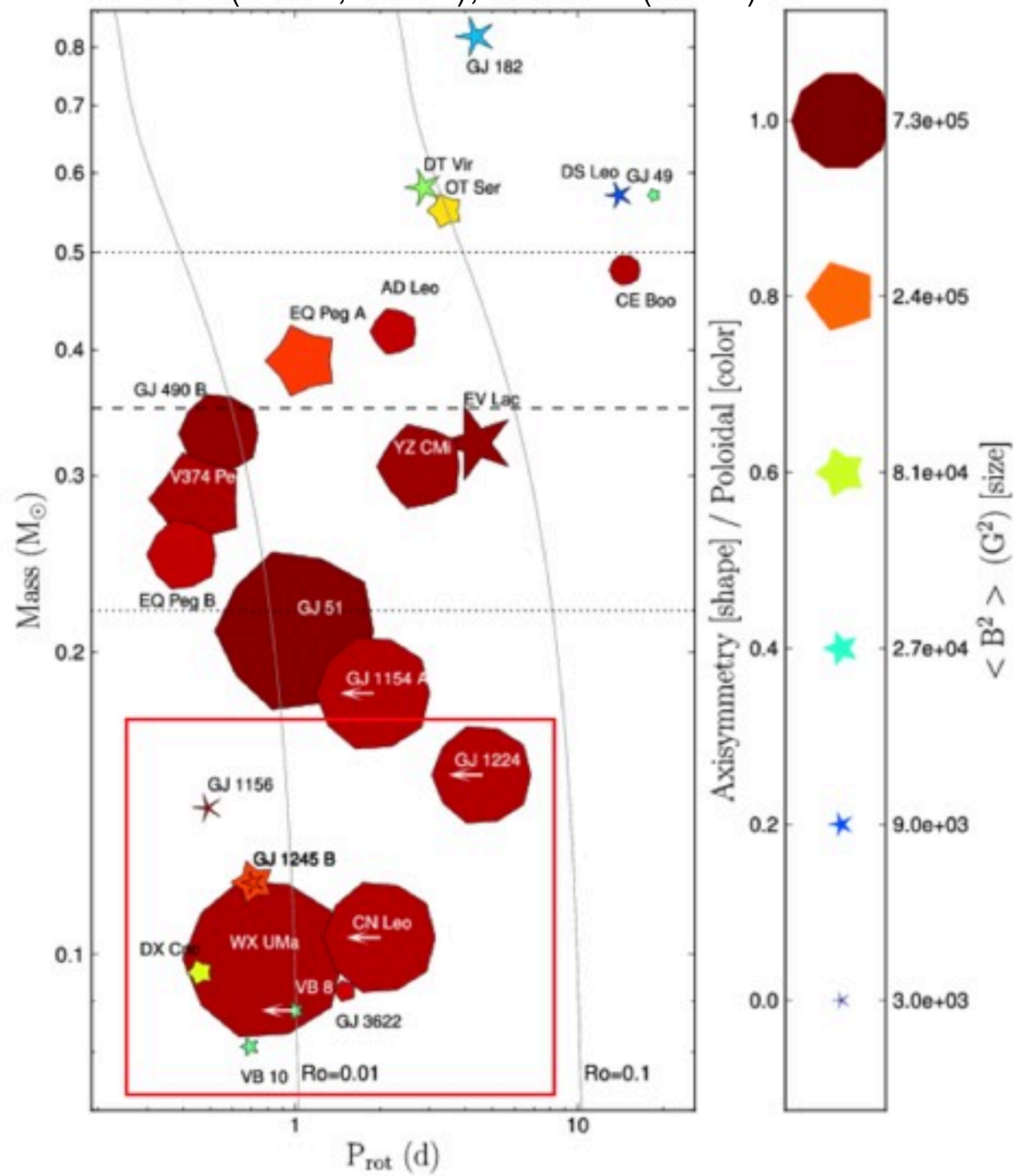
- very low mass ($M_* < 0.3 M_\odot$):
  - strong dipolar *versus* weak multipolar: dynamo bistability? (Morin+2011, Gastine +2013)

Morin+(2008, 2010); Donati+(2010)

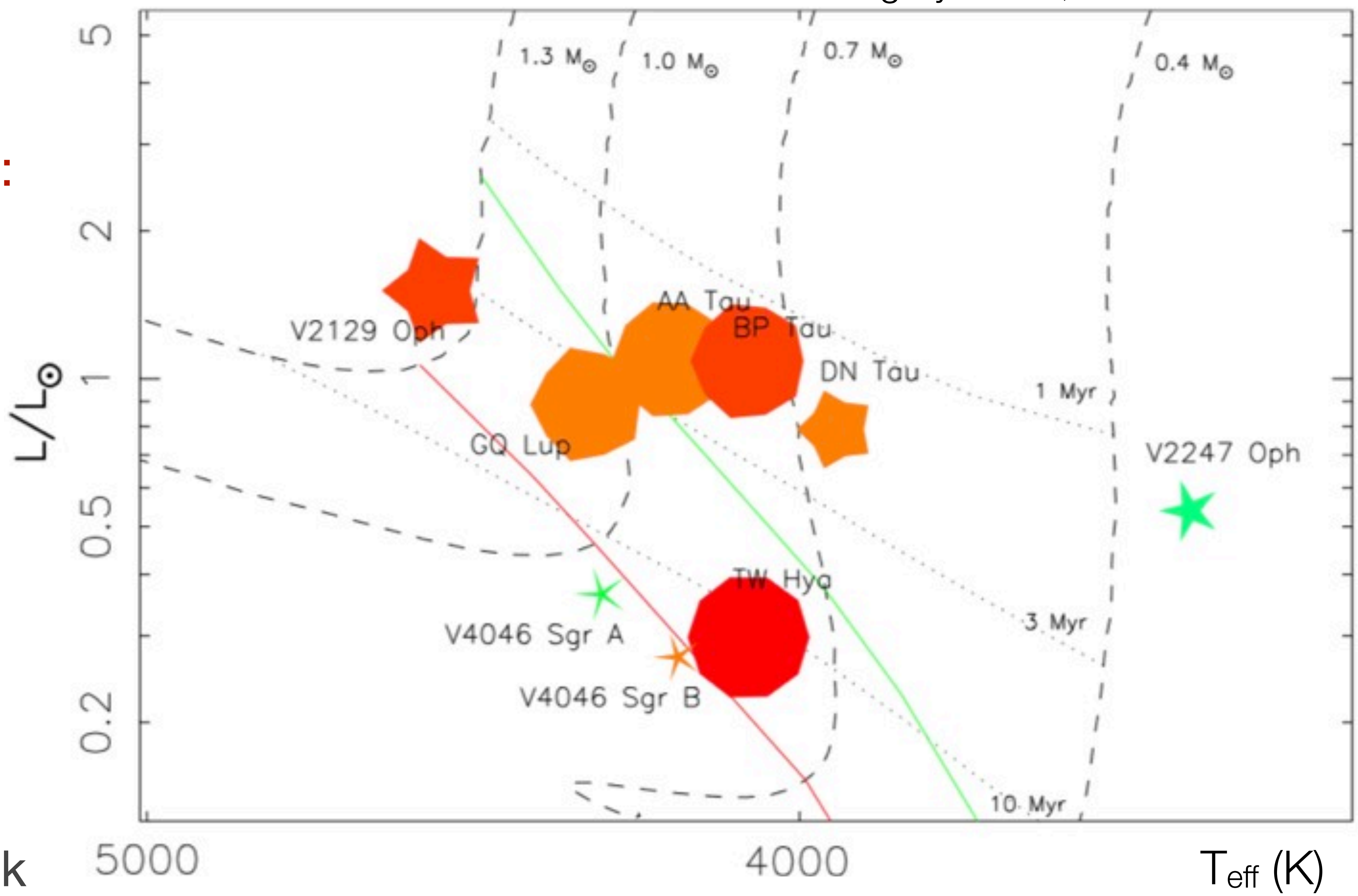


.. and topology depends on the internal structure II

Gregory+2012, Donati+2013

Magnetic field evolution of very young Suns (CTTSs):

1. $M_{conv} \sim M_{star}$: axi-symmetric, strong B_{dipole}
2. $M_{conv}=[0.5,1]\ M_{star}$: axisymmetric, $B_{l>dipole}$ dominates
3. $M_{conv}<0.5\ M_{star}$: complex, non-axisymmetric, weak B_{dipole}



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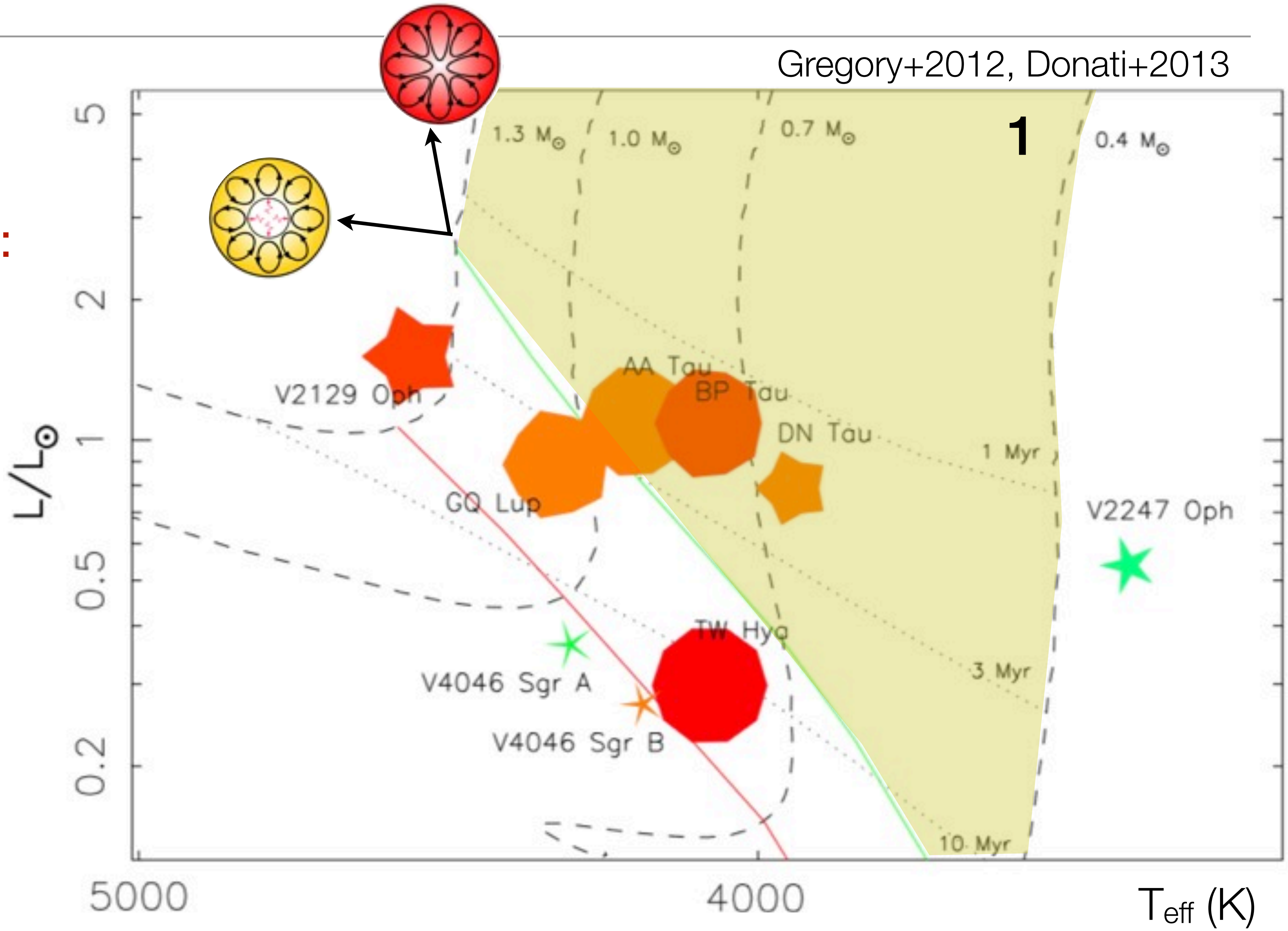

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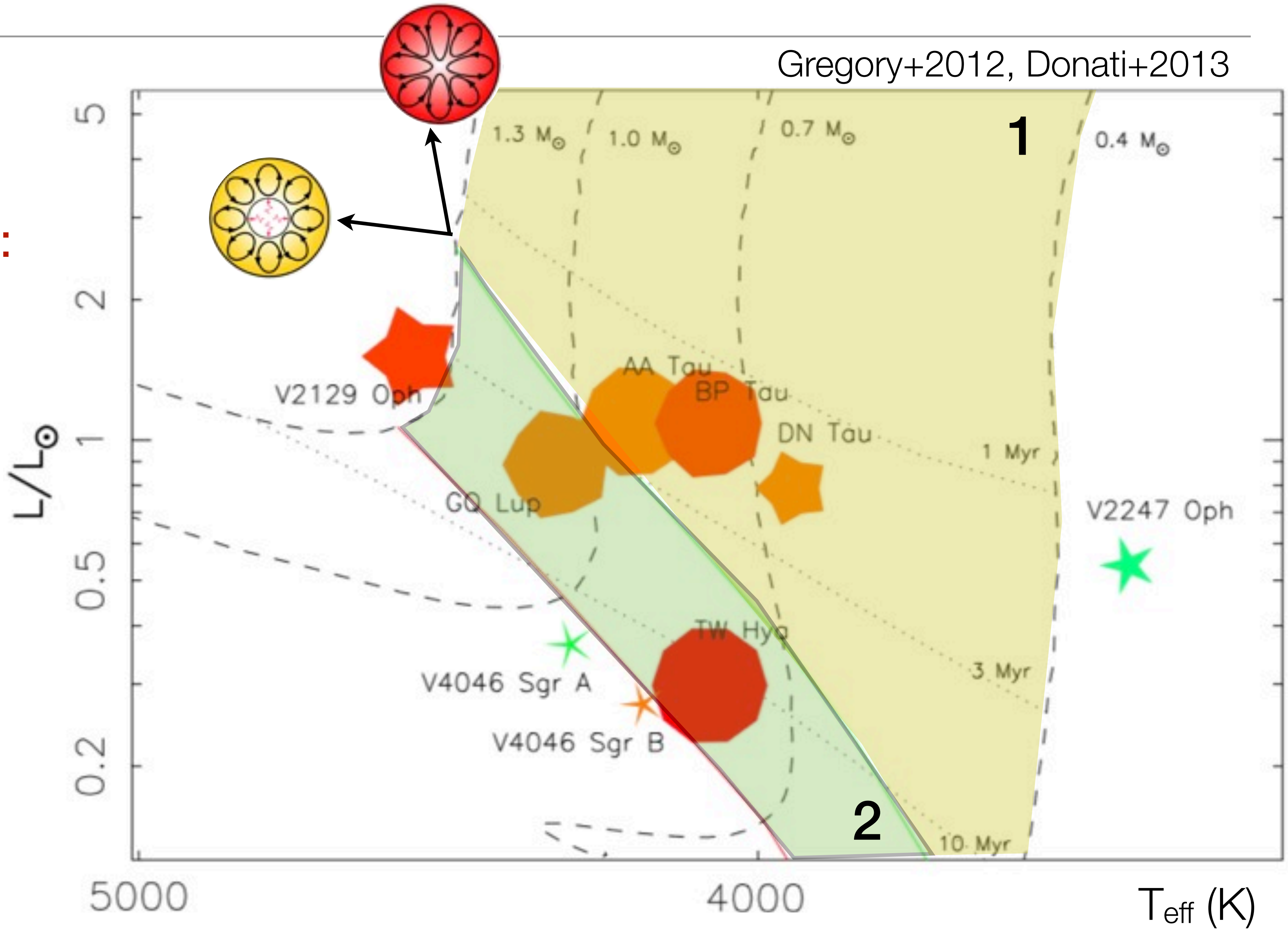

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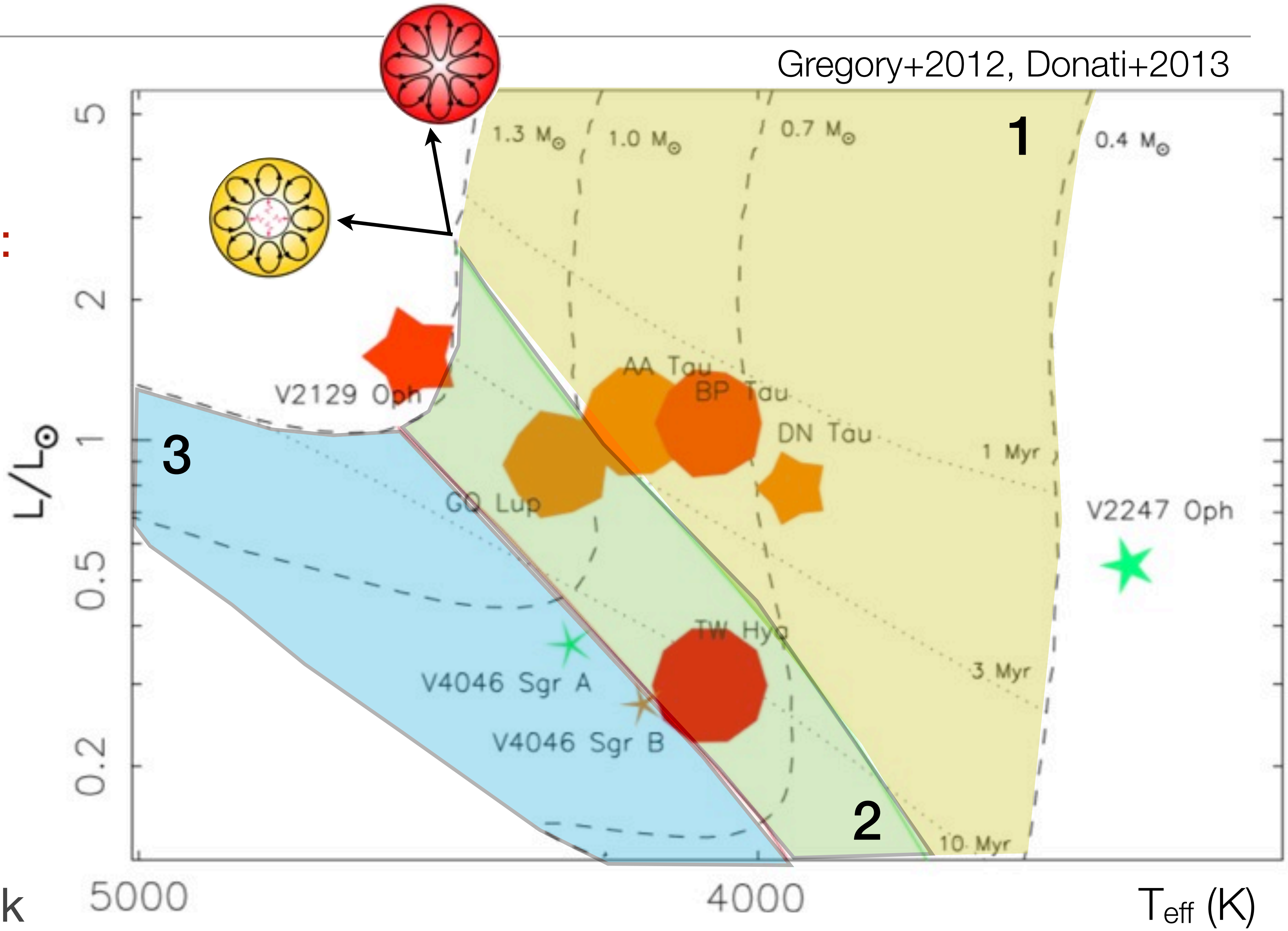

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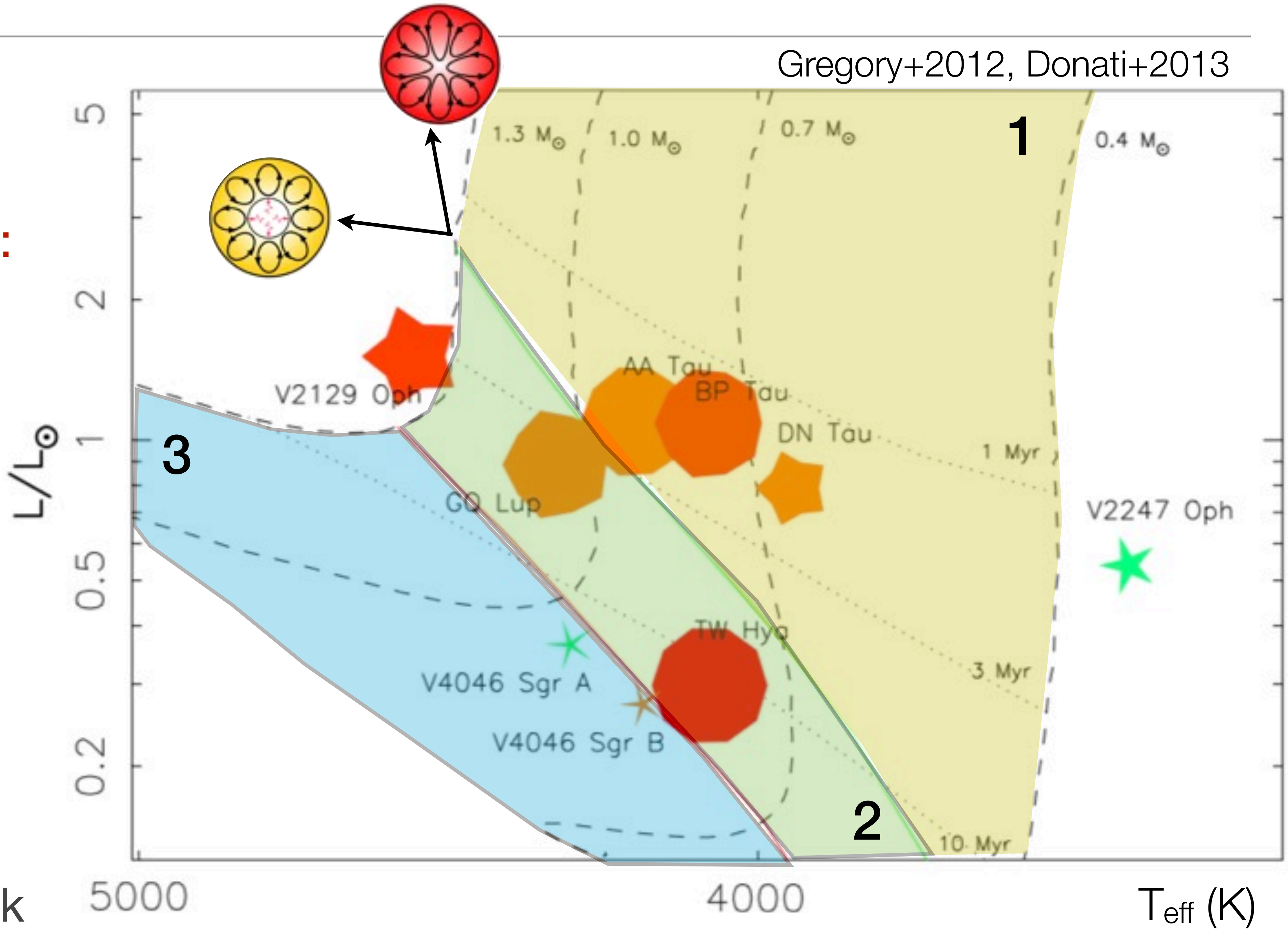
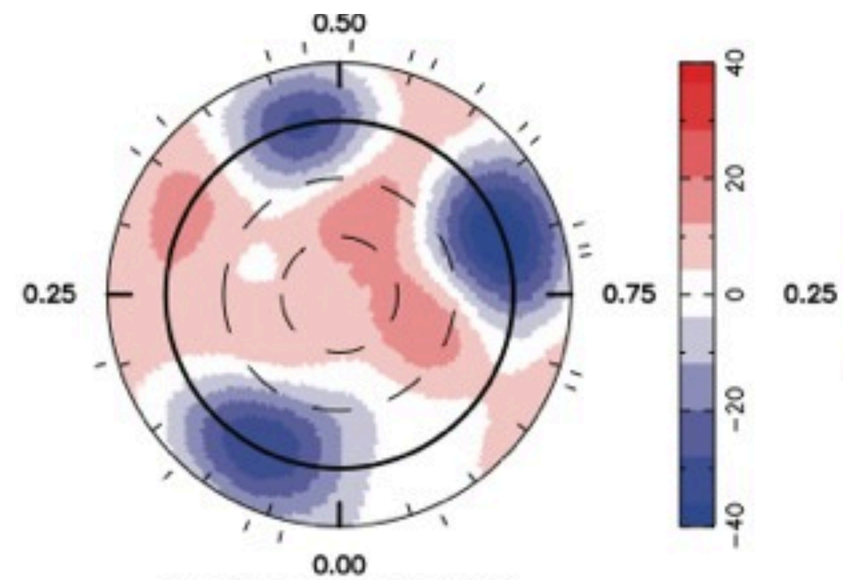


Evolution from strong & simple axisymmetric fields → weaker, complex non-axisymmetric fields

And magnetism evolves in time...

- Global perspective of the sample:
    - average of 104 ZDI maps
    - 90 of which have age estimates

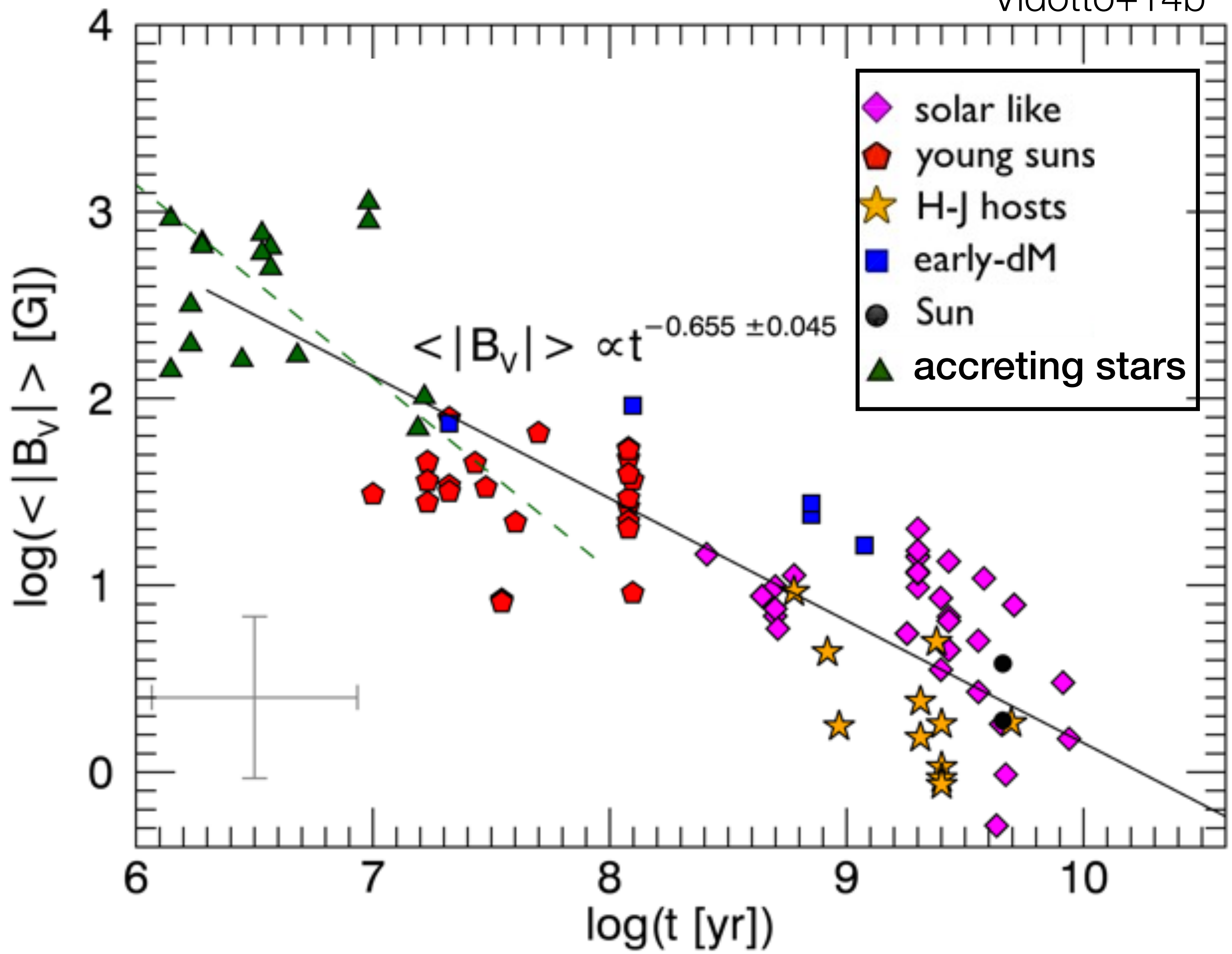


$\langle |B_V| \rangle$

And magnetism evolves in time...

- Global perspective of the sample:
  - average of 104 ZDI maps
  - 90 of which have age estimates
- Large-scale magnetic field correlated with ~age$^{-0.5}$: "magnetochronology"

Vidotto+14b



- Compare to Skumanich's prediction: $B \propto \text{age}^{-1/2}$

What have we learned so far?

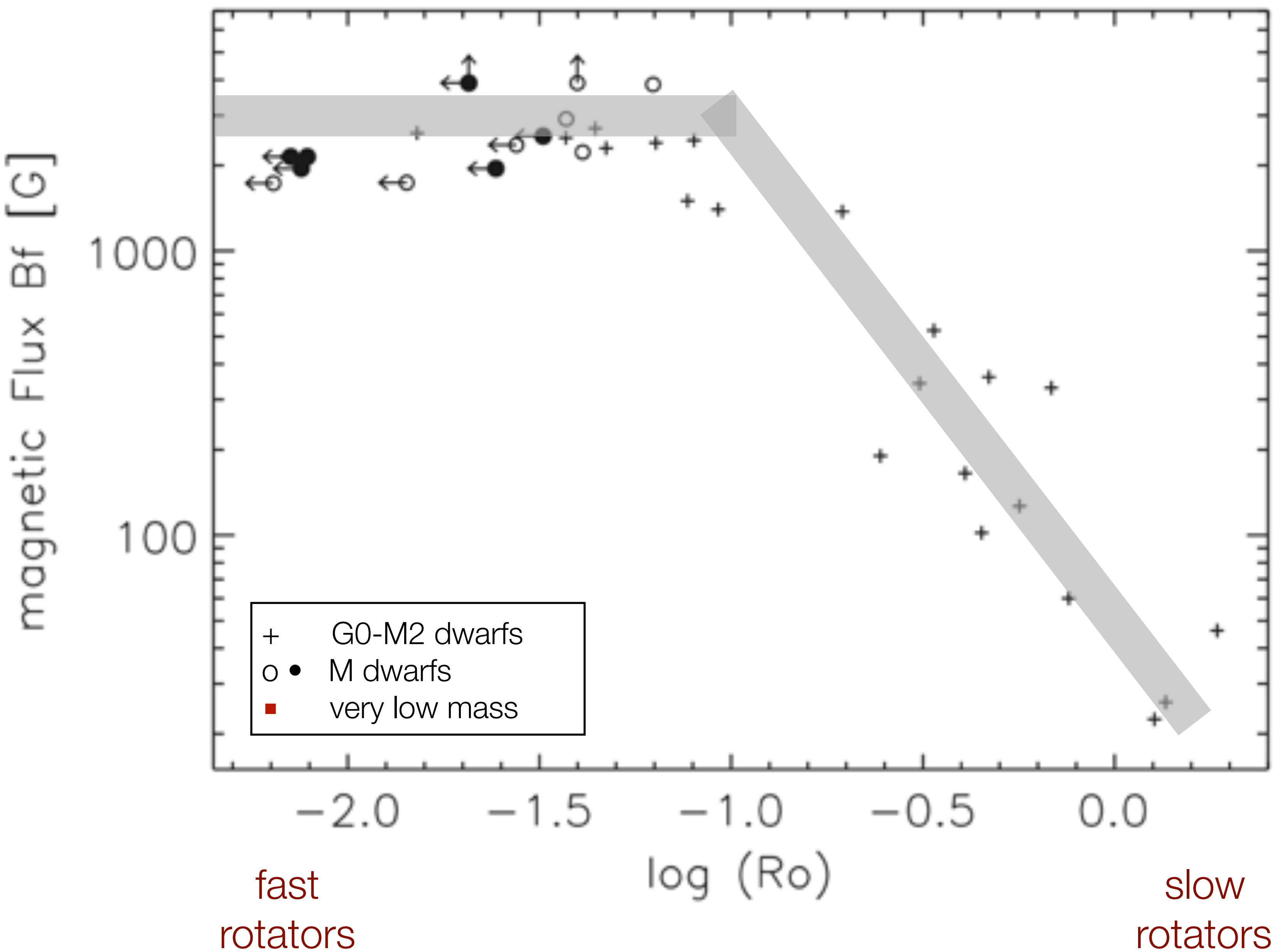
Small/Large-scale vs Large-scale fields

Total field saturates at low Rossby numbers

- Zeeman broadening
  - Saturation occurs at $Ro \lesssim 0.1$, $\langle|B_I|\rangle \approx 3$kG

$Ro = P_{rot}/\tau_{conv}$

Reiners+09,10; Saar+96,01



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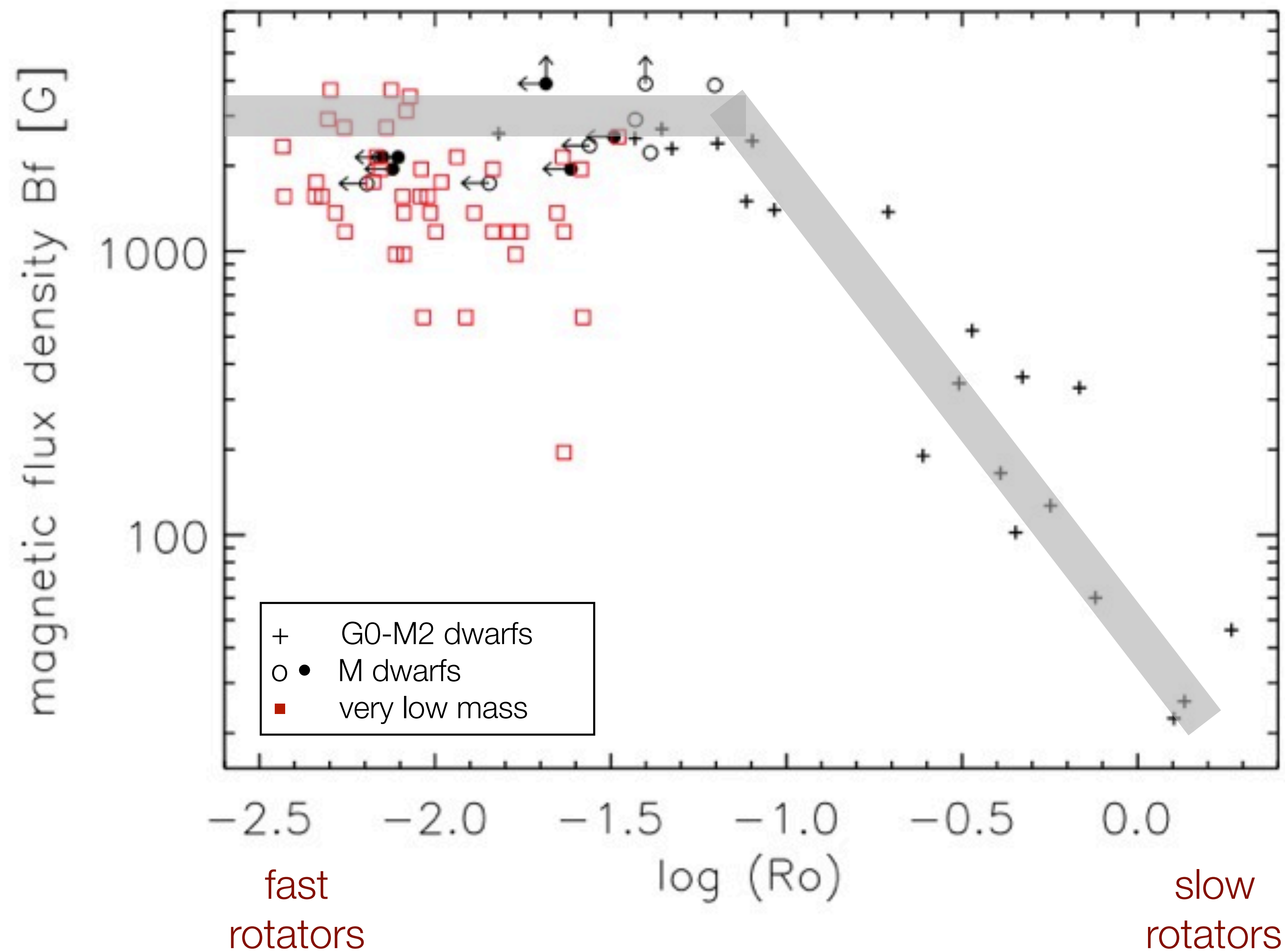

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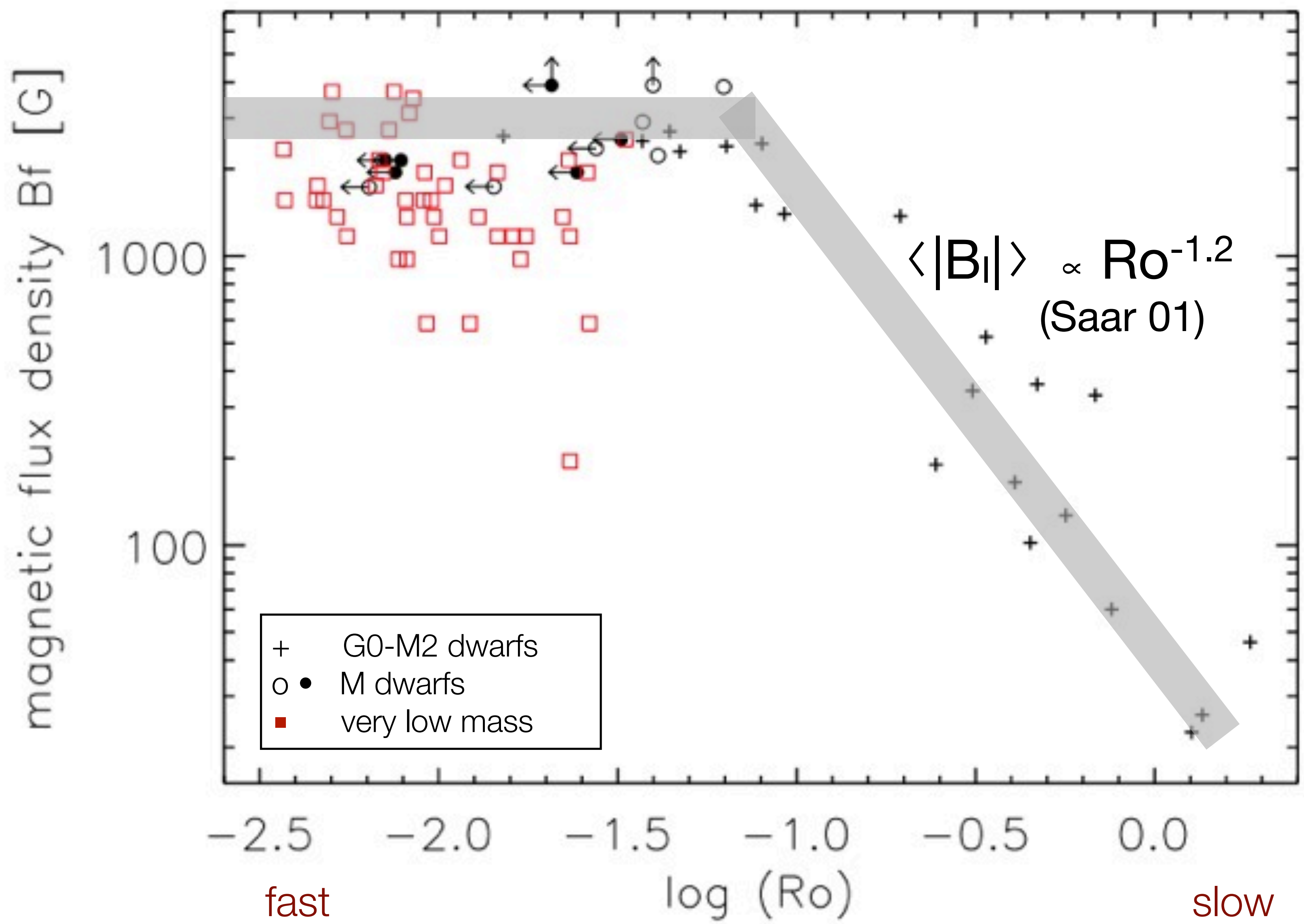
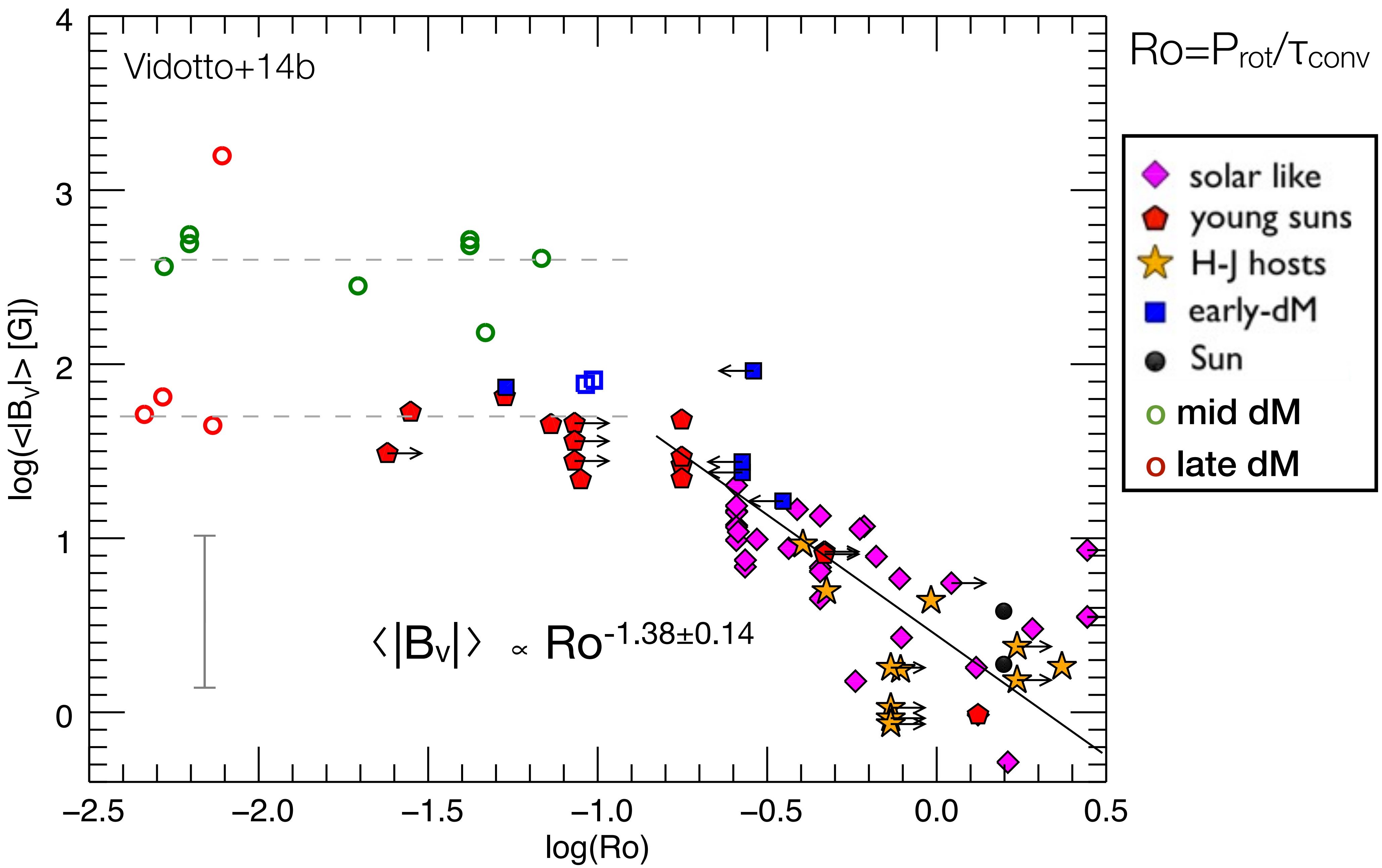


fast rotators

slow rotators

Large-scale field *also* saturates at low Rossby numbers



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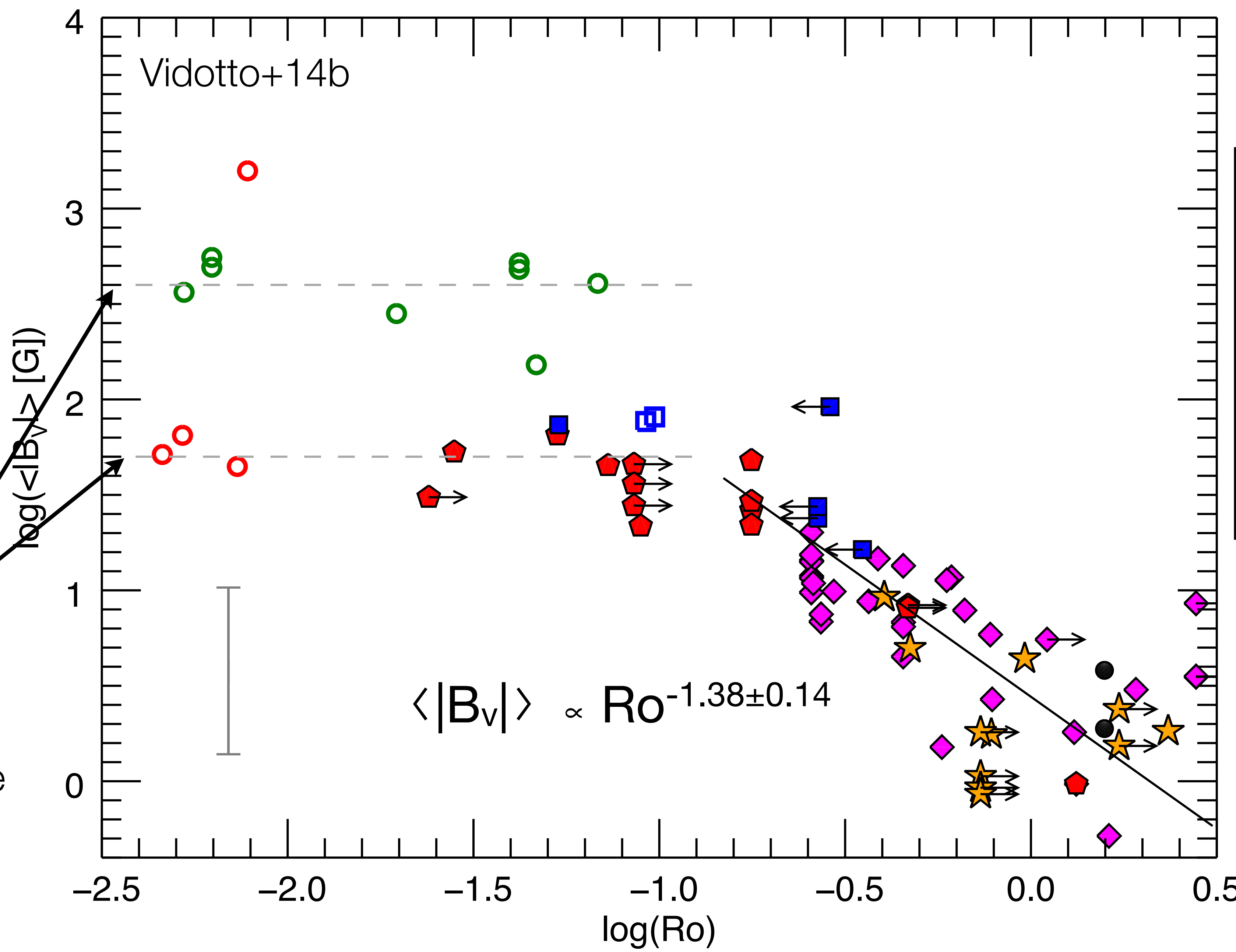

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Different efficiencies at producing small/large-scale fields (Morin+08, Donati+08)

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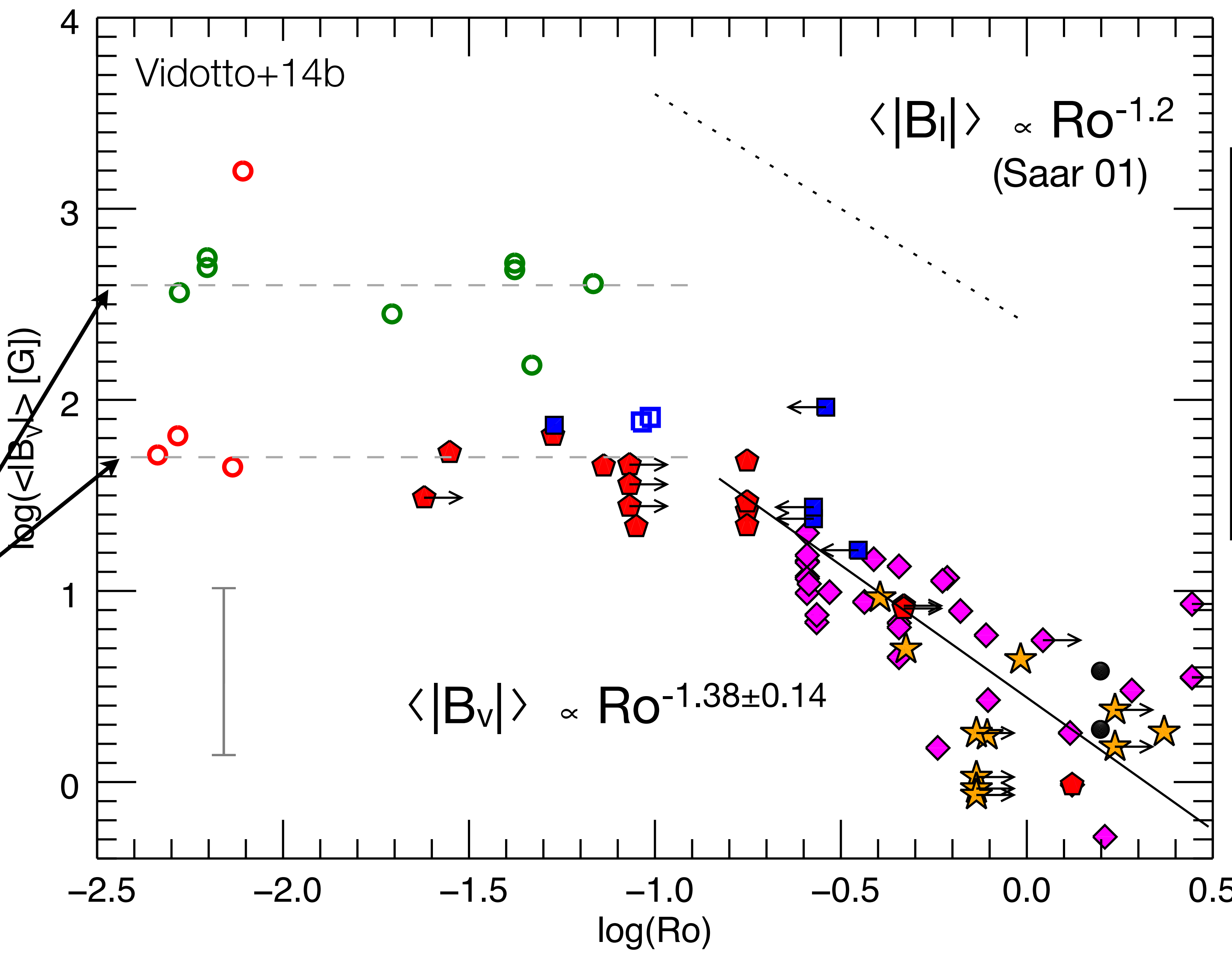

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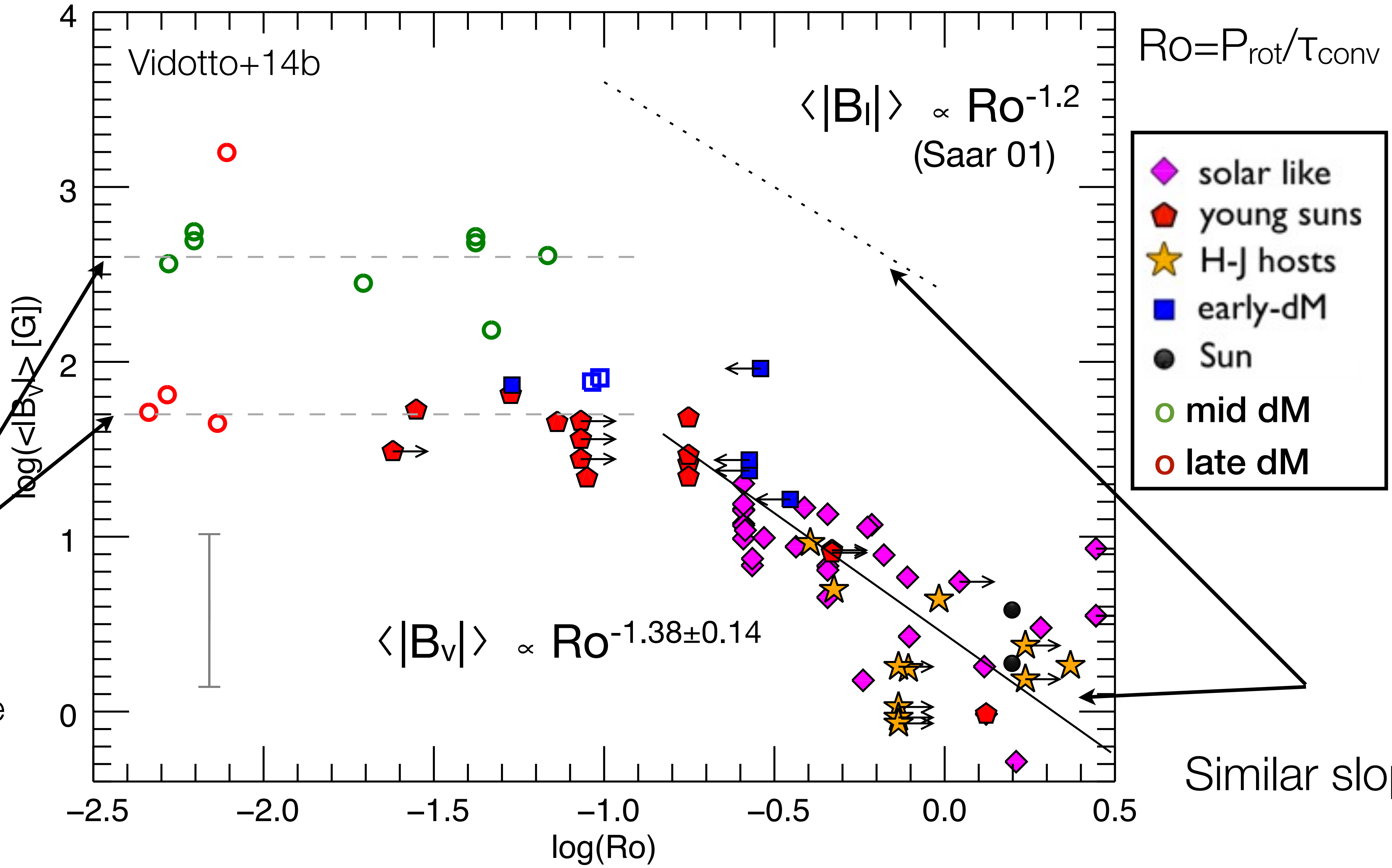

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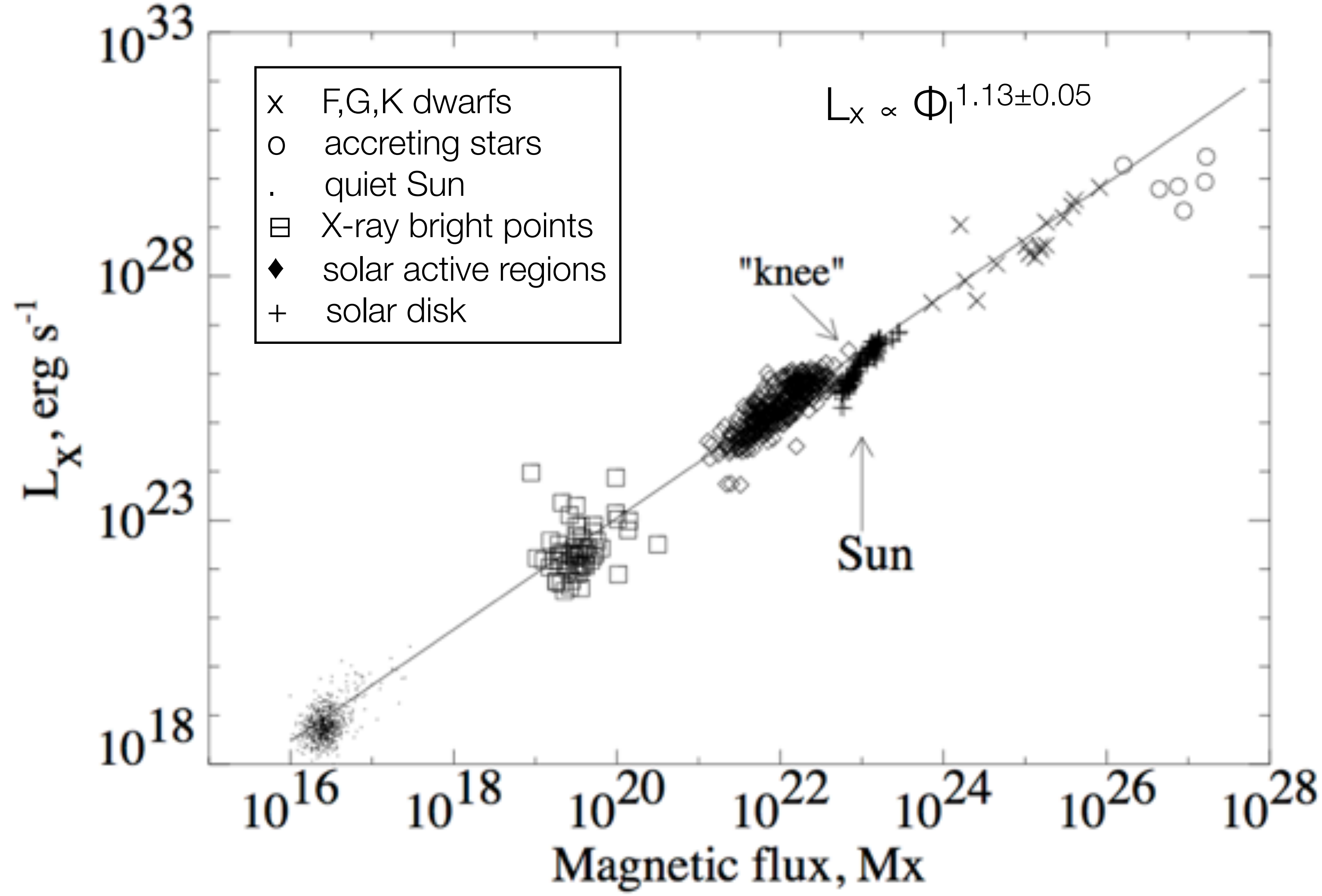
Similar slopes

X-ray correlates with (total) magnetic flux

Magnetic Flux:

$\Phi_l = \langle|B_l|\rangle \; (4\pi R_*^2)$

Pevtsov+03



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  - large scatter

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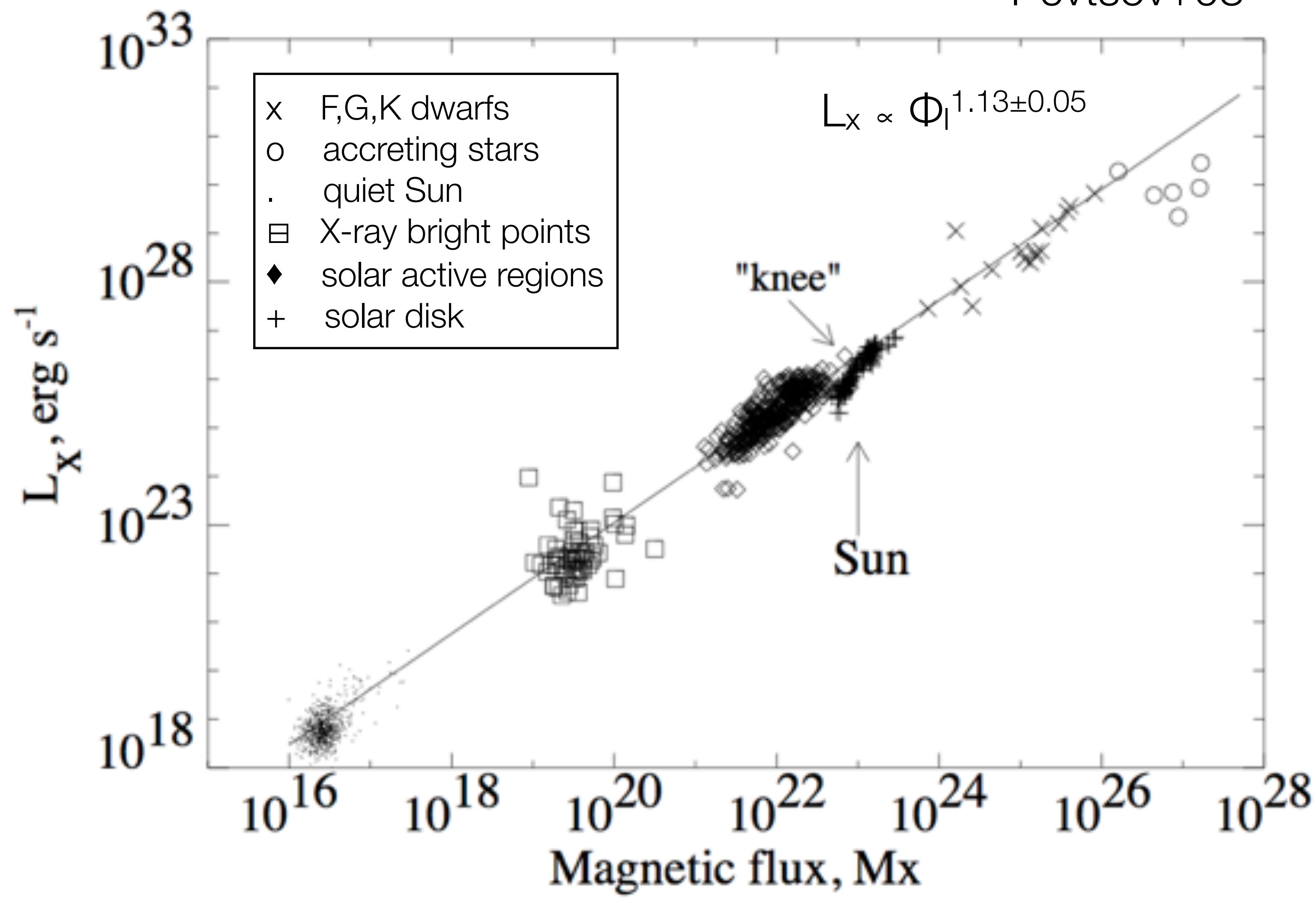

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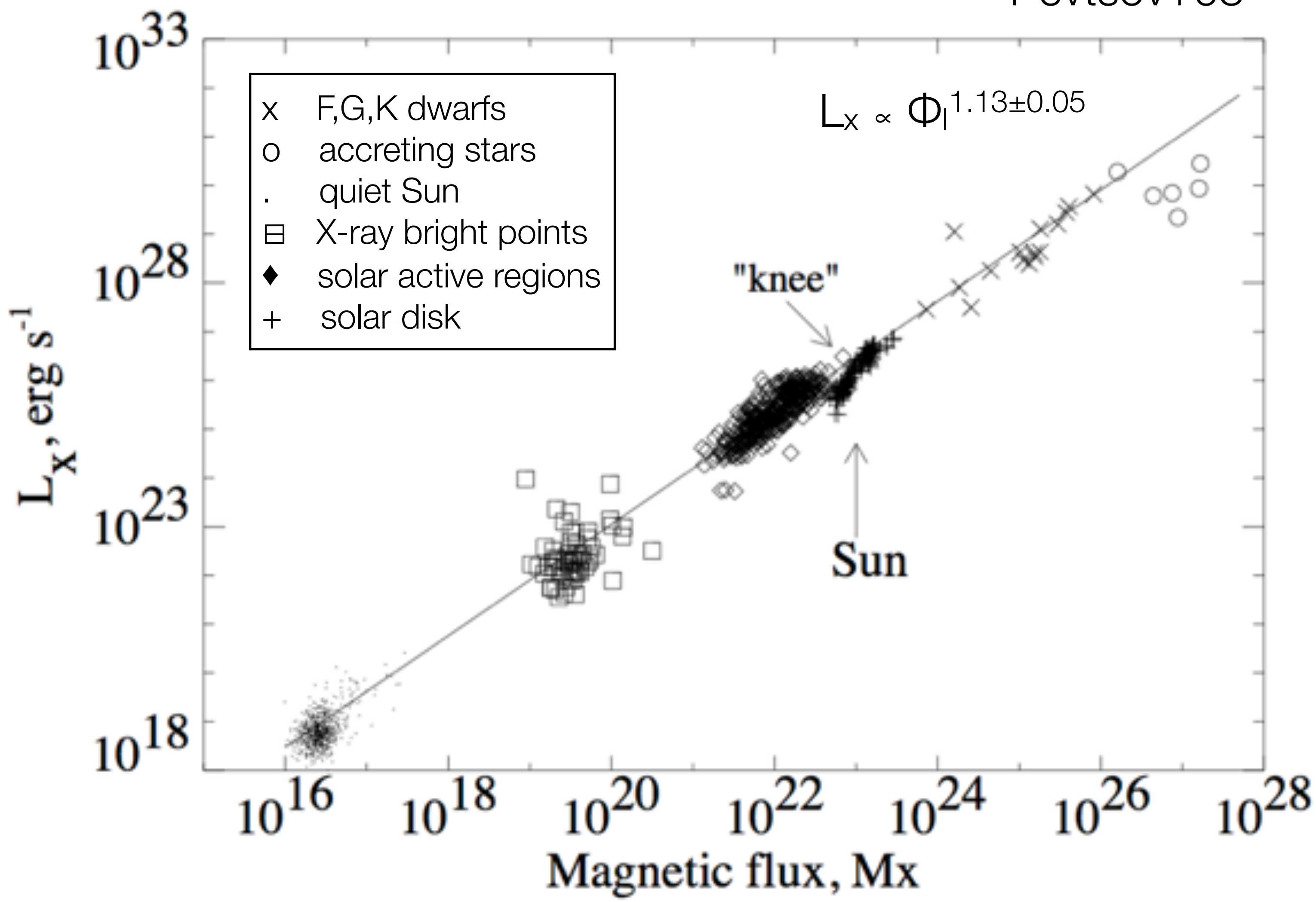

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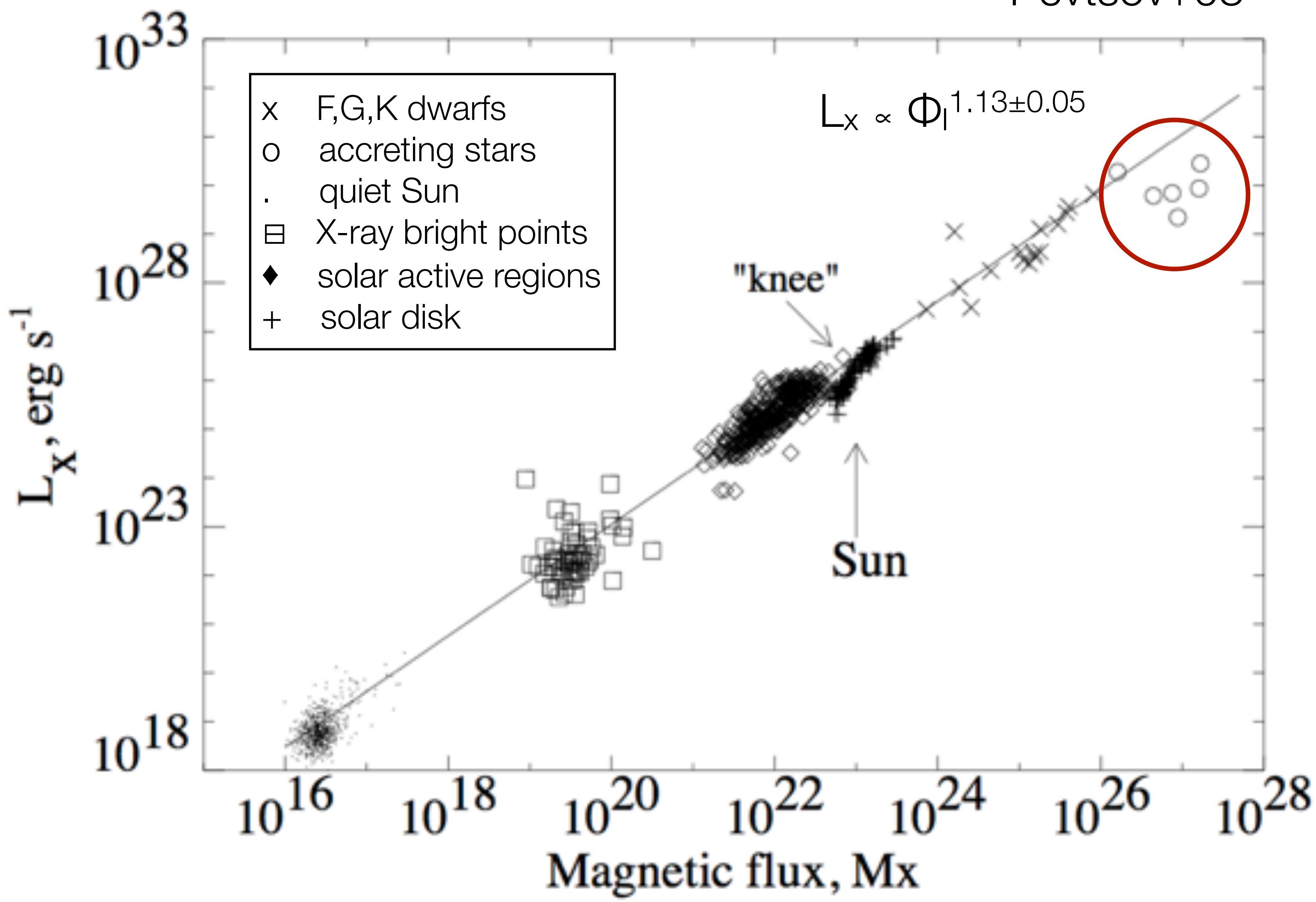

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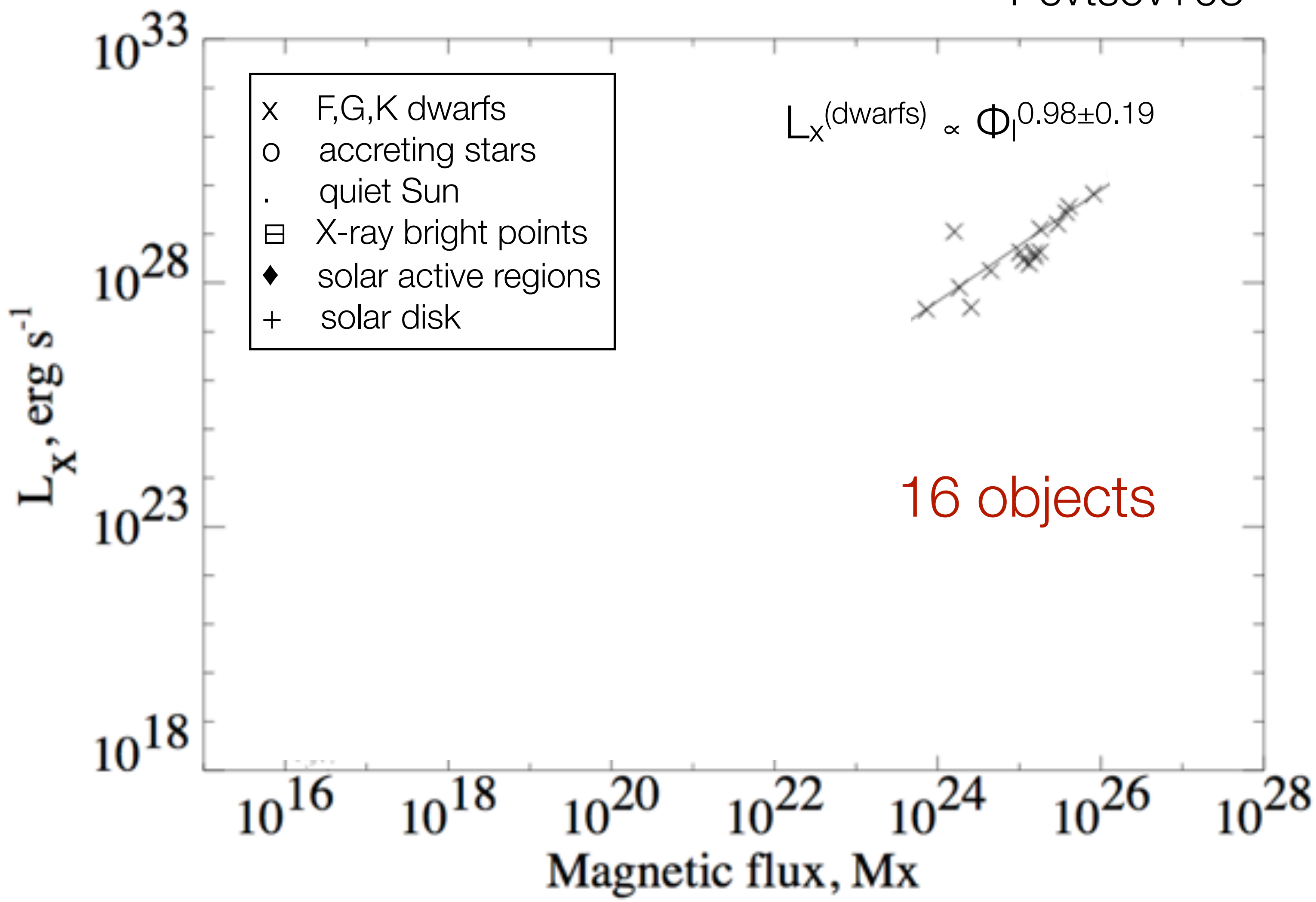

X-ray correlates with (total) magnetic flux

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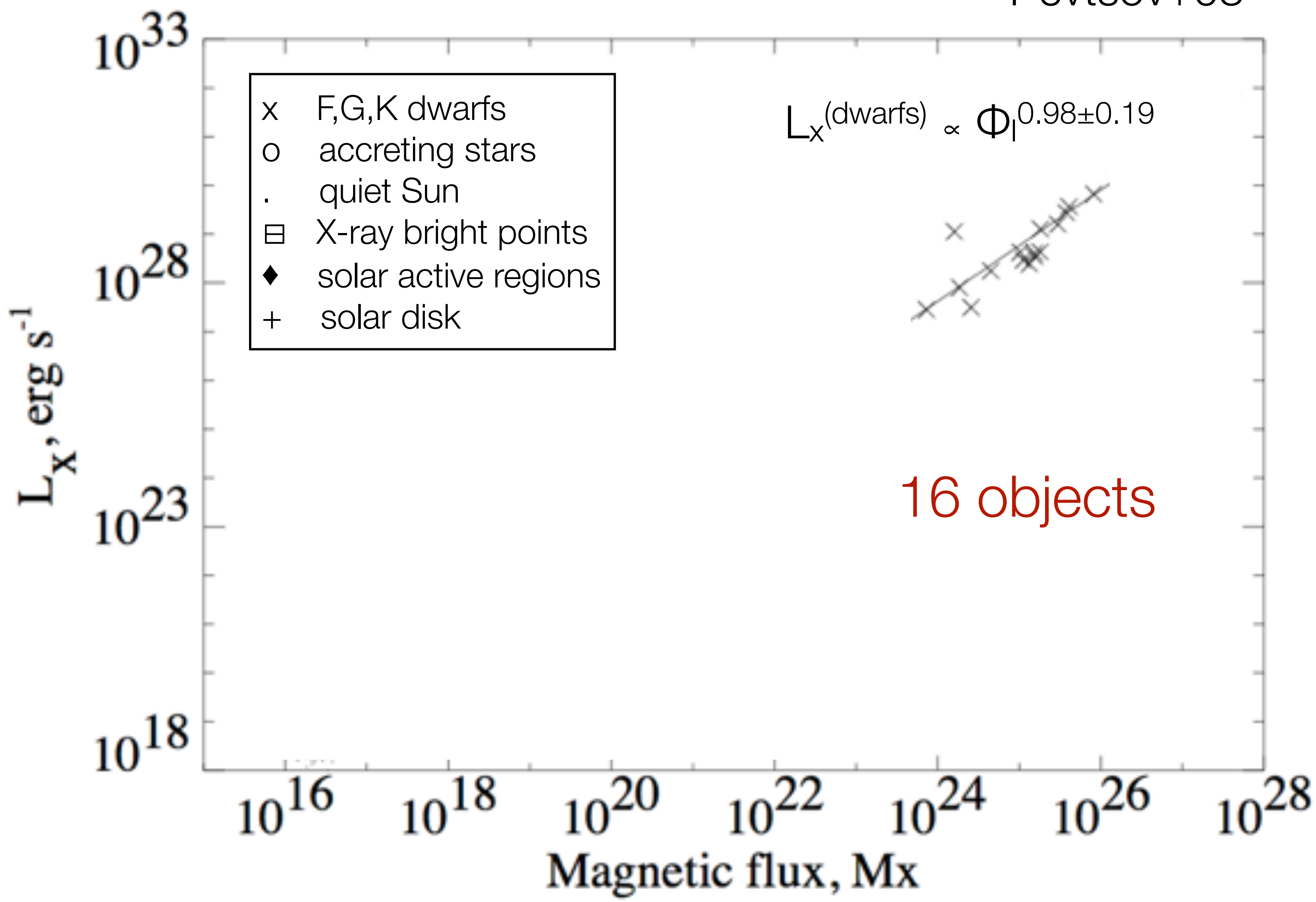
- For the stellar sample: Zeeman broadening measurements
- Do we find similar relation for $\Phi_V = \langle|B_V|\rangle\ (4\pi R_*^2)$?

Magnetic Flux:
$\Phi_I = \langle|B_I|\rangle\ (4\pi\ R_*^2)$

Pevtsov+03



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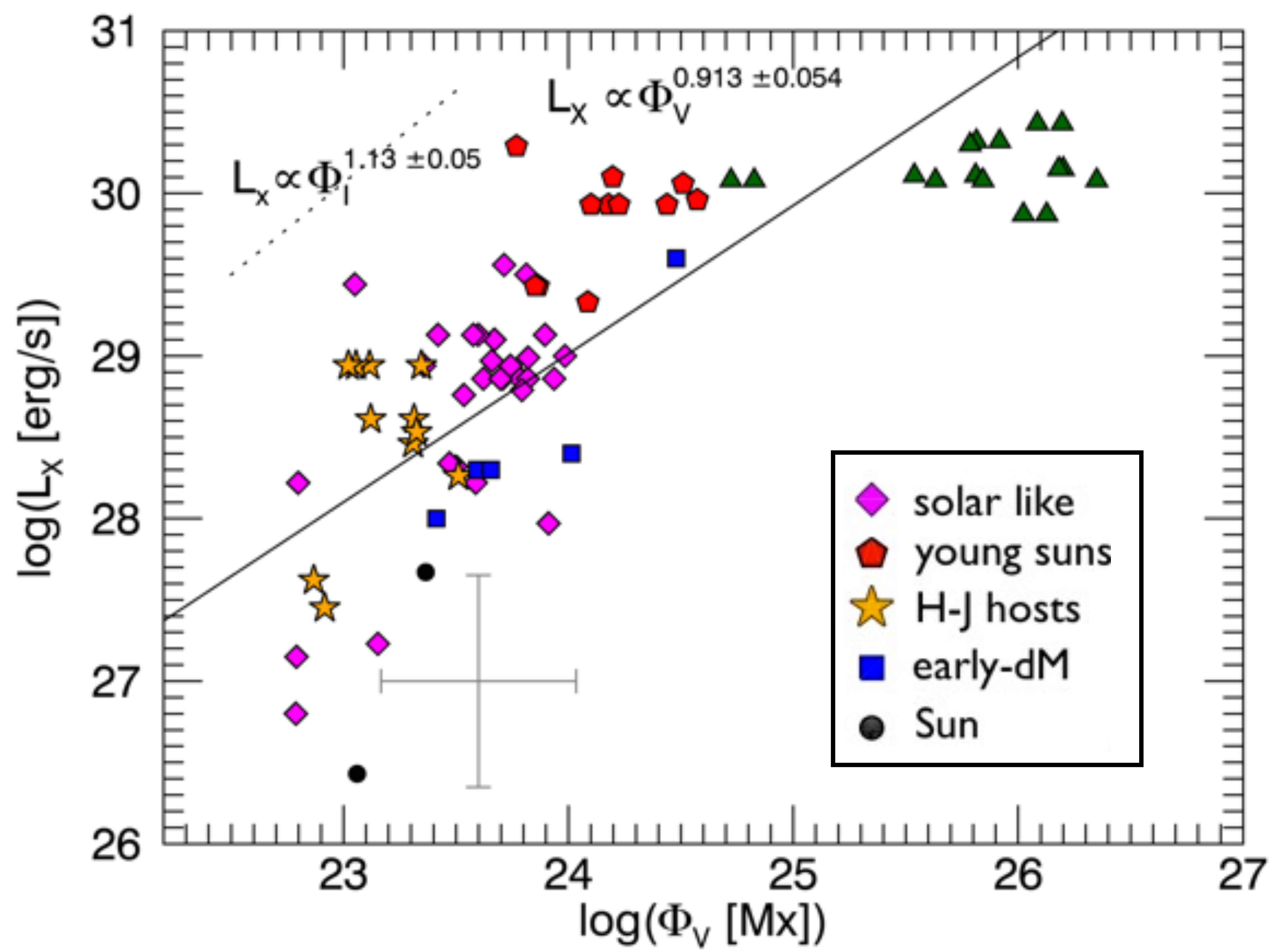
Vidotto+14b



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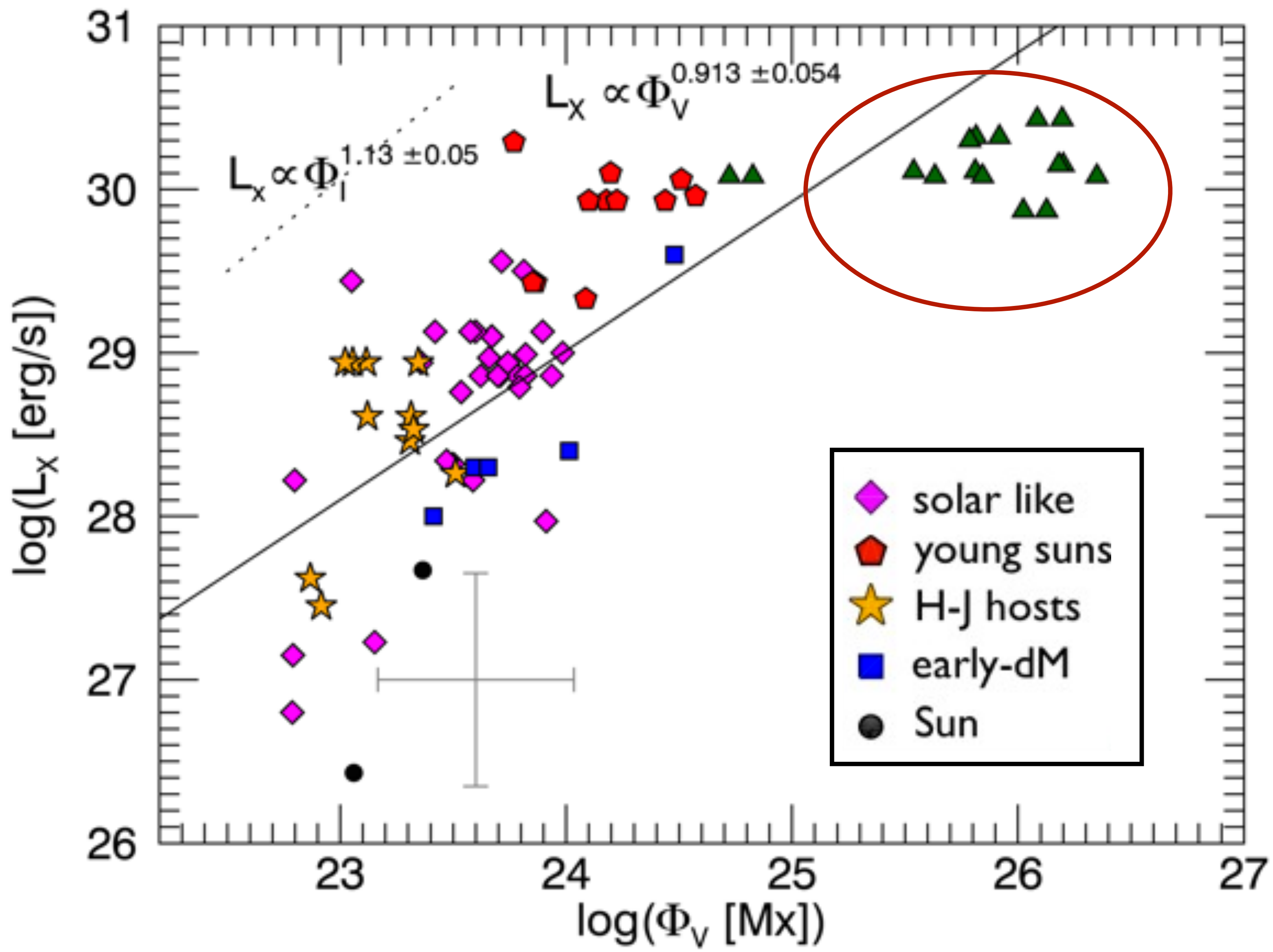

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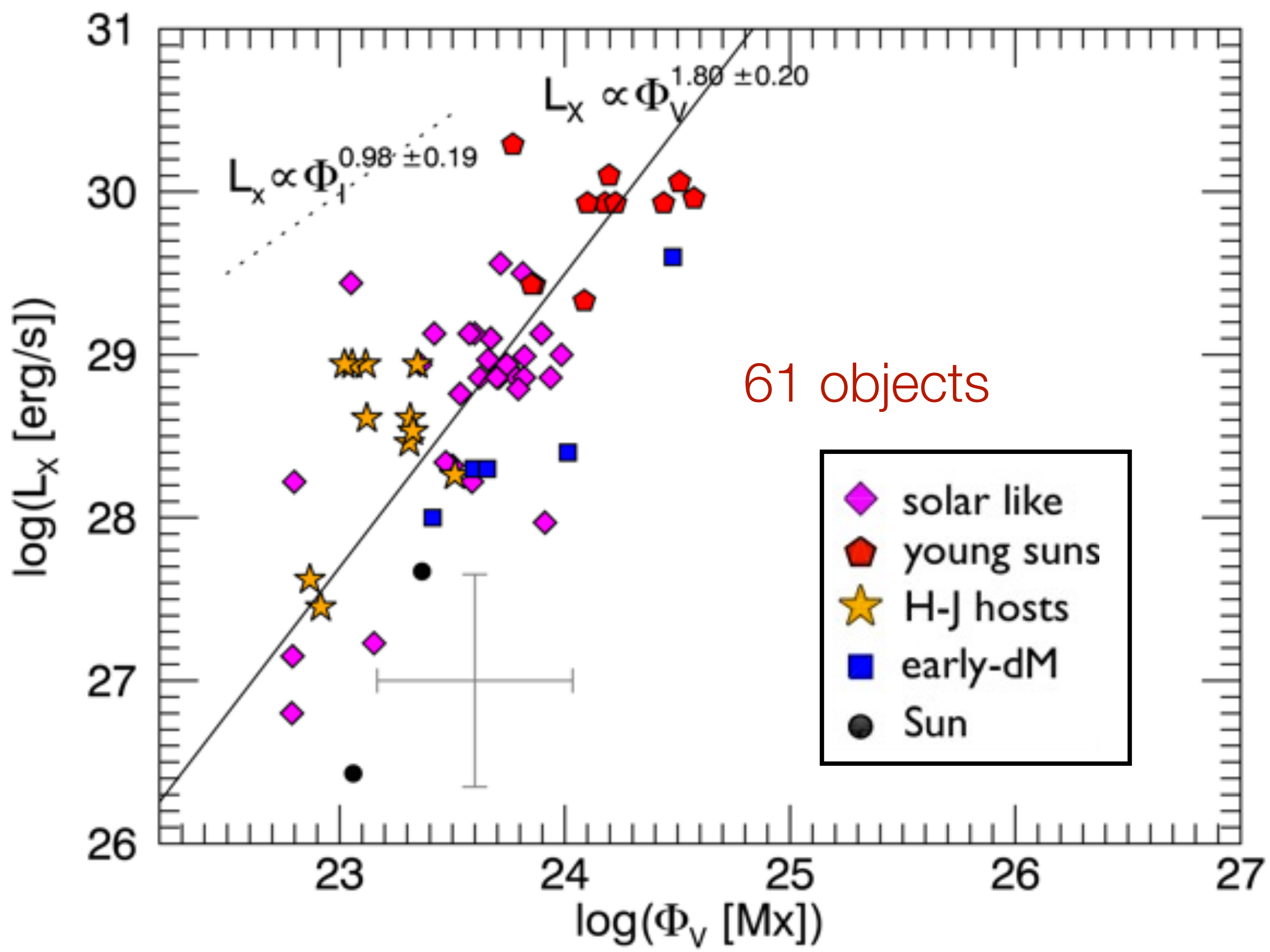

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- $L_x(\Phi_V)$ and $L_x(\Phi_I)$ ~agree
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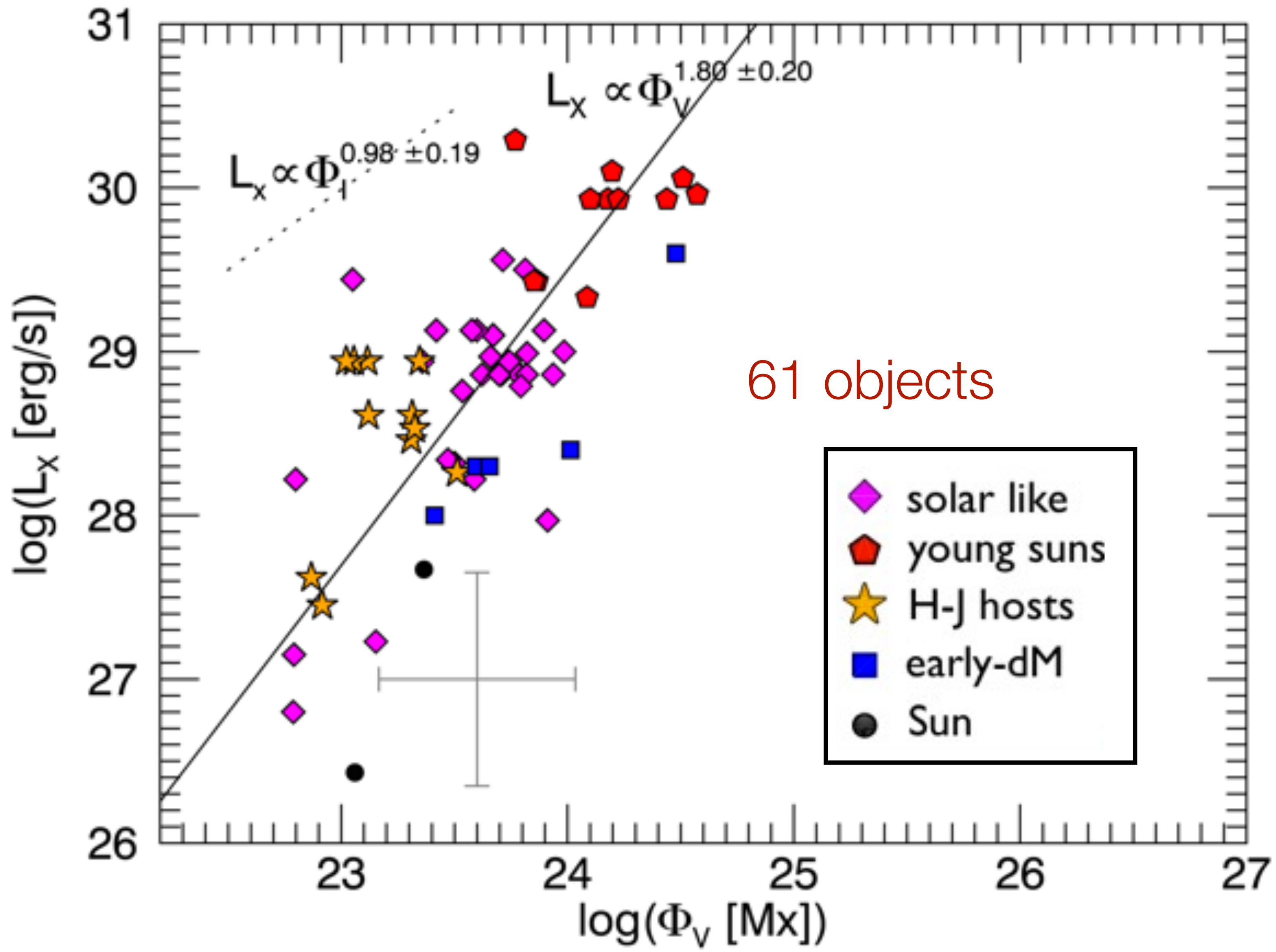
- Further investigation: finding a different power law for Φ_V and Φ_I may shed light on how the small- and large-scale field structures contribute to L_X

Vidotto+14b



Small+large-scale *vs* large-scale fields

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Large-scale field	Large+small scale field	
$\langle|B_V|\rangle \propto Ro^{-1.38\pm0.14}$ (Vidotto+14b)	$\langle|B_I|\rangle \propto Ro^{-1.2}$ (Saar 01)	✓
$\langle|B_V|\rangle \propto P_{rot}^{-1.32\pm0.14}$ (Vidotto+14b)	$\langle|B_I|\rangle \propto P_{rot}^{-1.7}$ (Saar 96)	$\simeq$
$L_X \propto \Phi_V^{1.80\pm0.20}$ (Vidotto+14b)	$L_X \propto \Phi_I^{0.98\pm0.19}$ (Pevtsov+03)	$\simeq$

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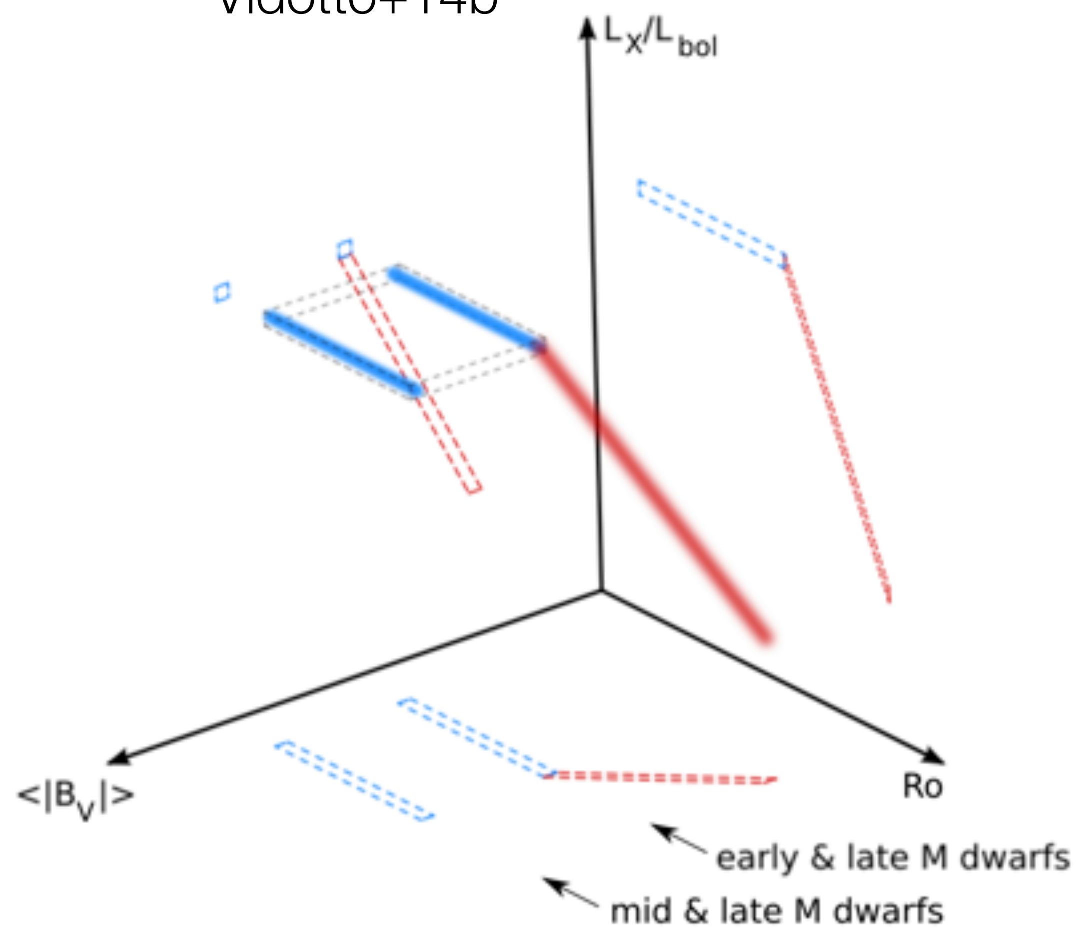
- Agreement between 2 techniques:
  - possible coupling between $\langle|B_V|\rangle$ & $\langle|B_I|\rangle$
  - only one dynamo process that generates both fields?

One-slide summary: unified interpretation

Vidotto+14b



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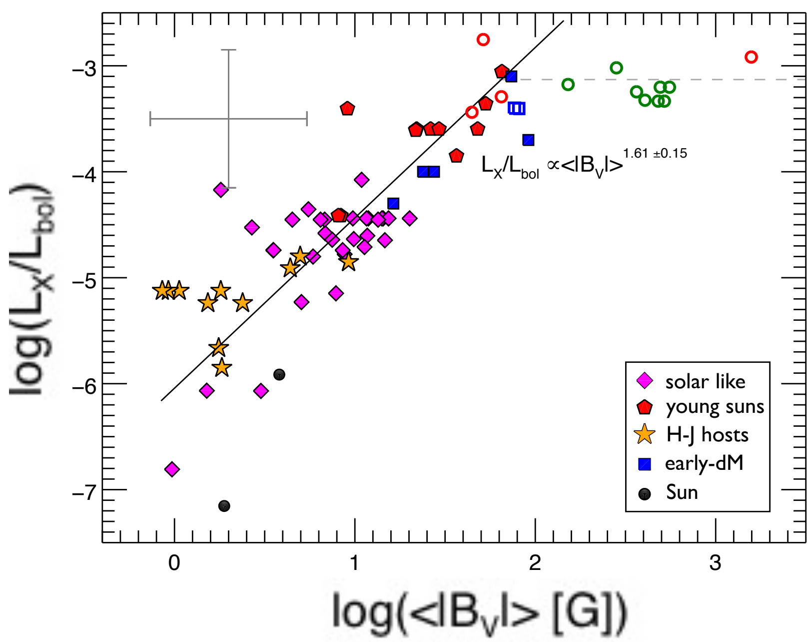

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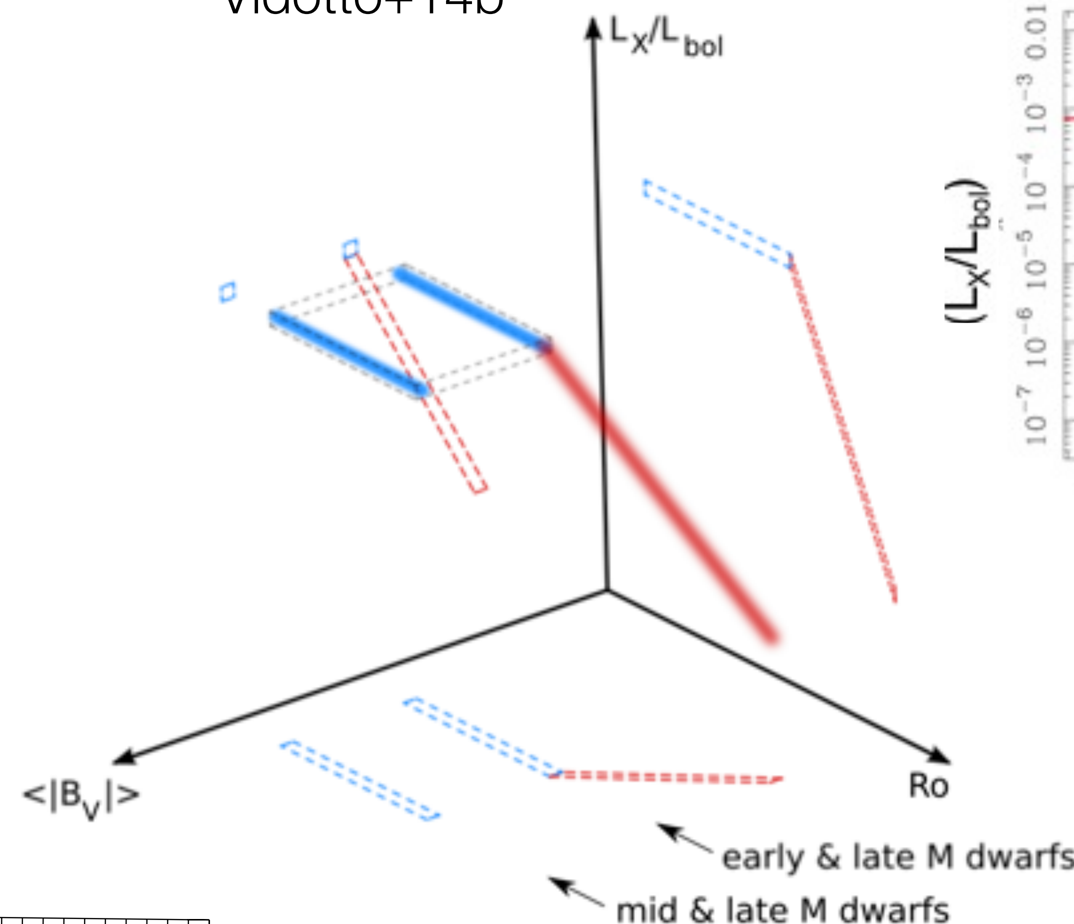
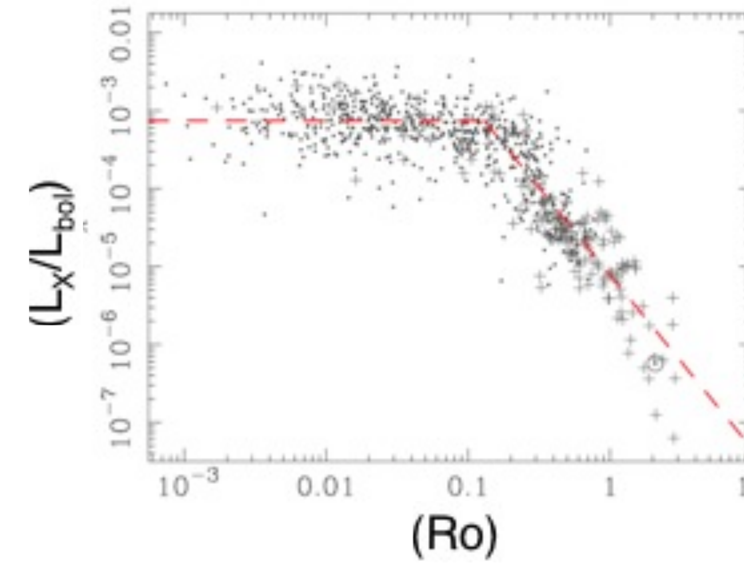
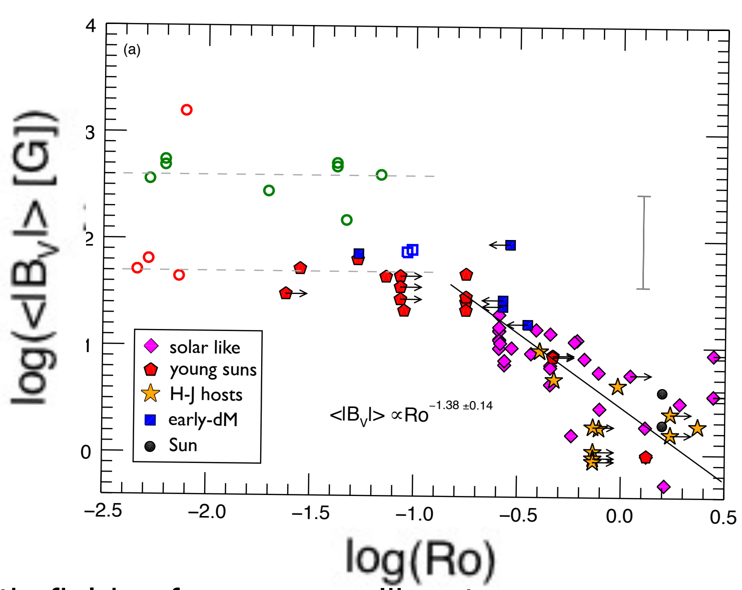




Wright+11



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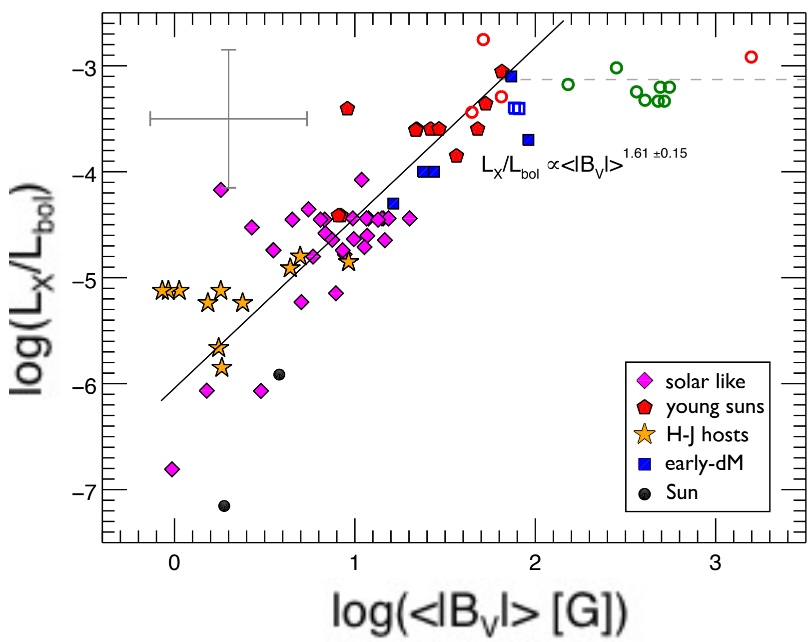

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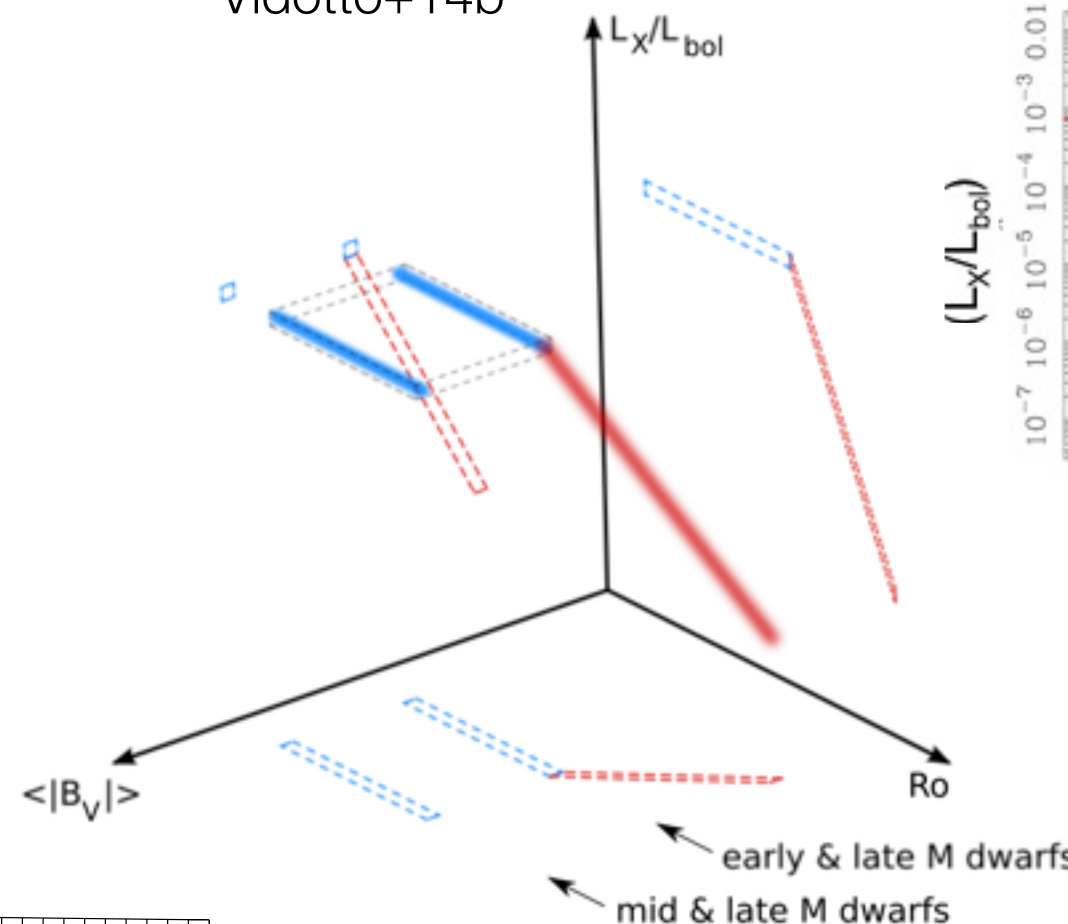

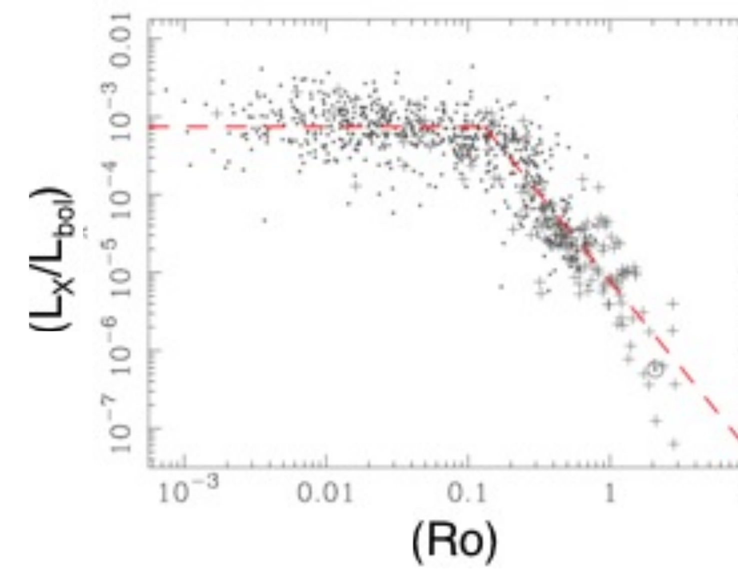

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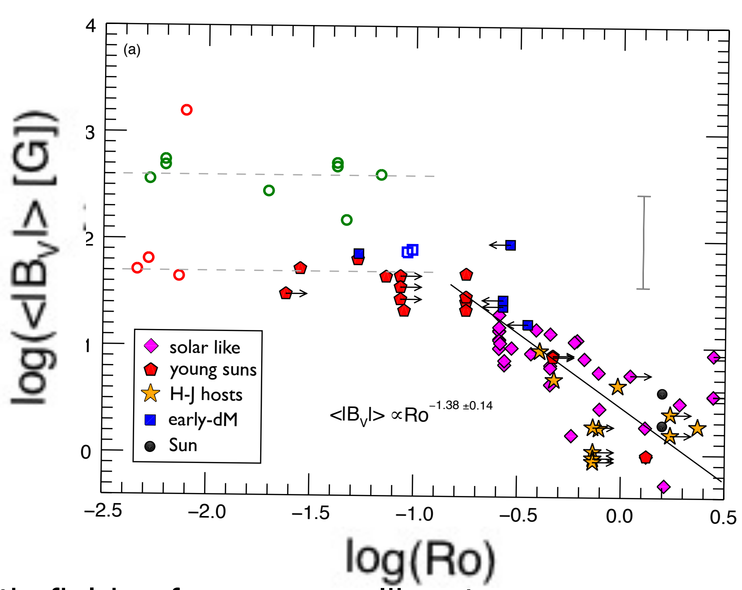

Stellar magnetism is a complex function of many variables: age, mass, rotation, activity, internal structure...

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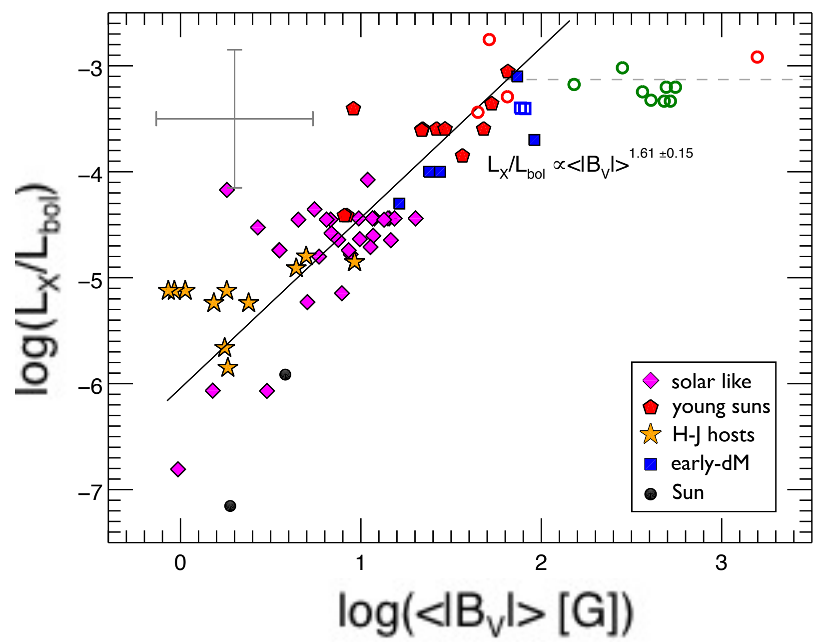

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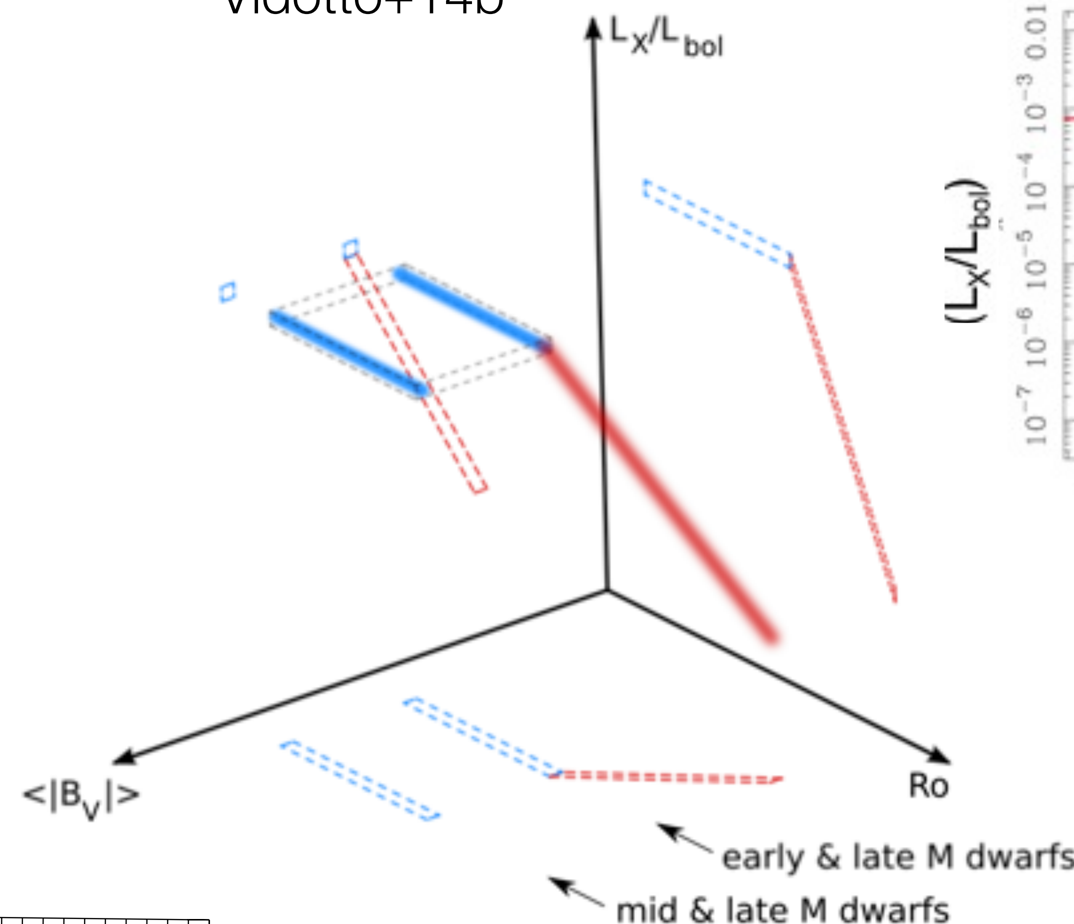
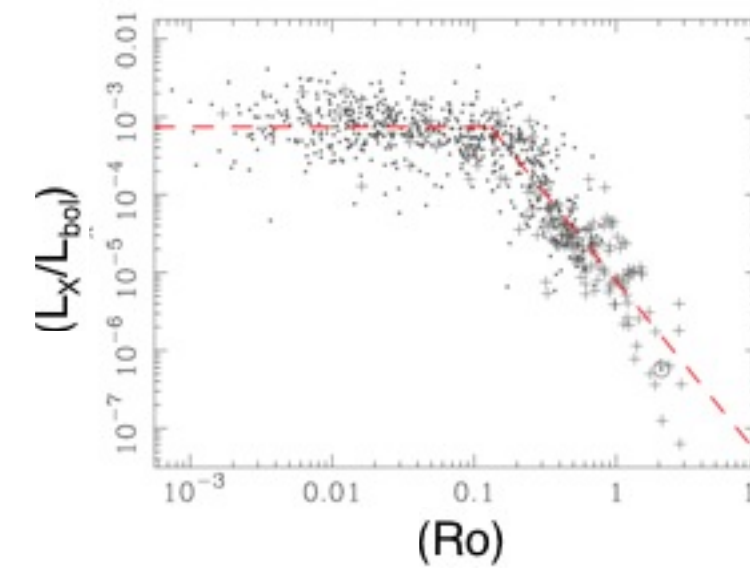
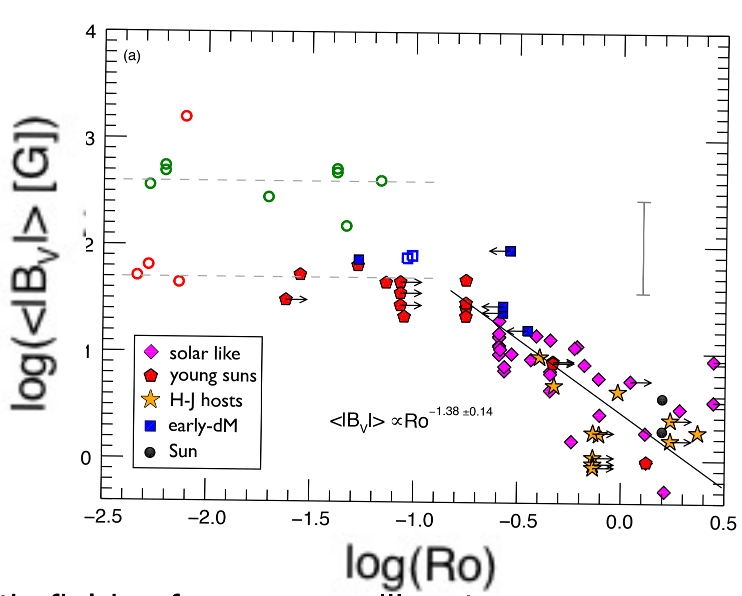




Wright+11

Thank you!



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