Understanding the evolution of stellar X-ray activity in time

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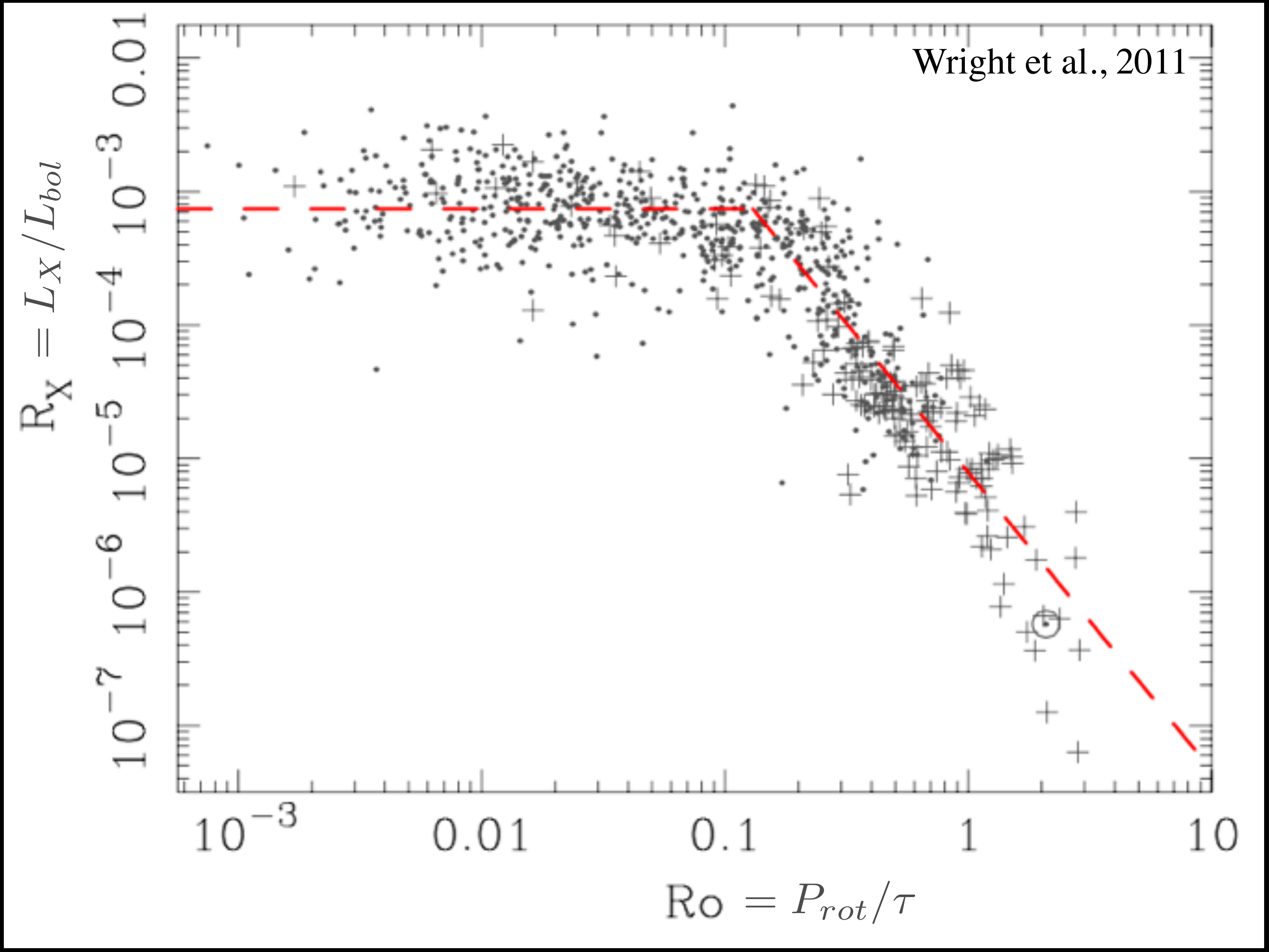
Harvard-Smithsonian CfA

with J. J. Drake, O. Cohen, and N. Wright

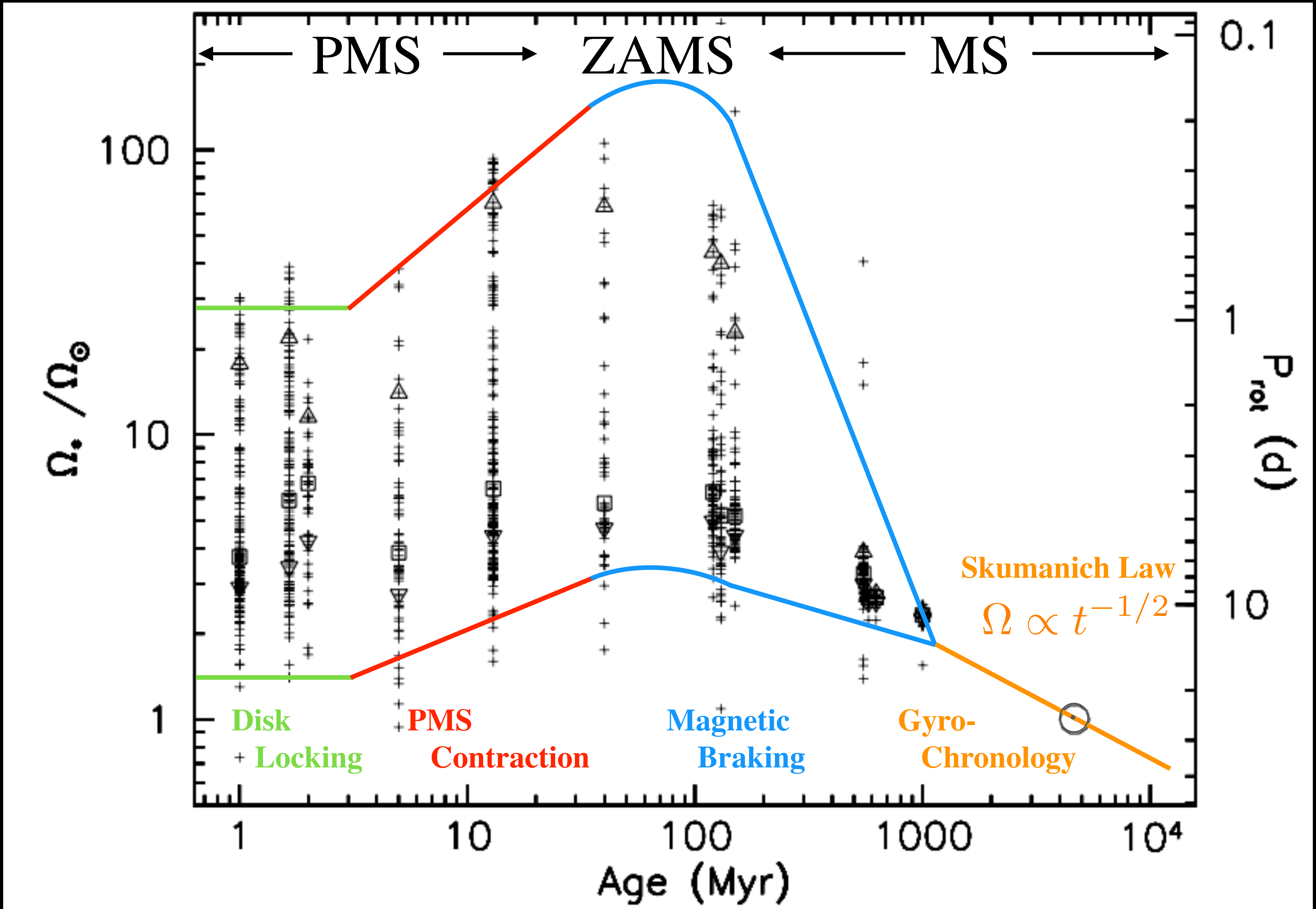
CXO - 8/17/16

Stellar Activity-Rotation

X-ray to bolometric luminosity ratio

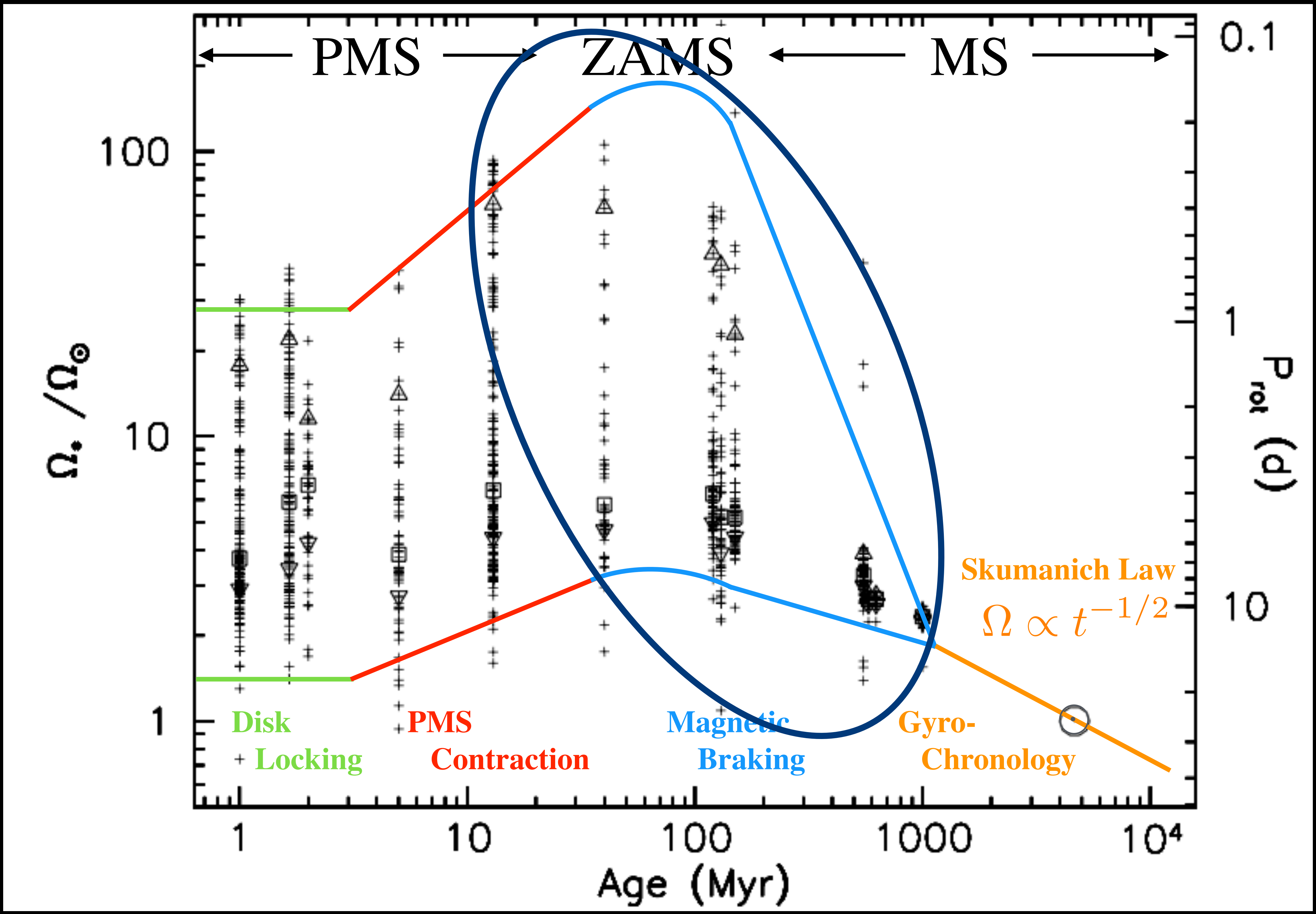


Rotation Evolution of Sun-Like Stars



Adapted from Gallet & Bouvier 2013

Rotation Evolution of Sun-Like Stars



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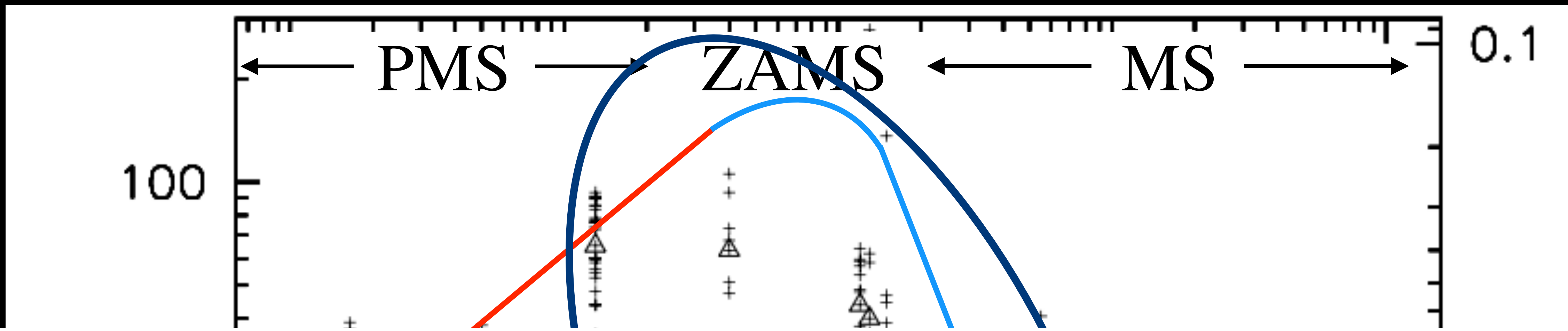
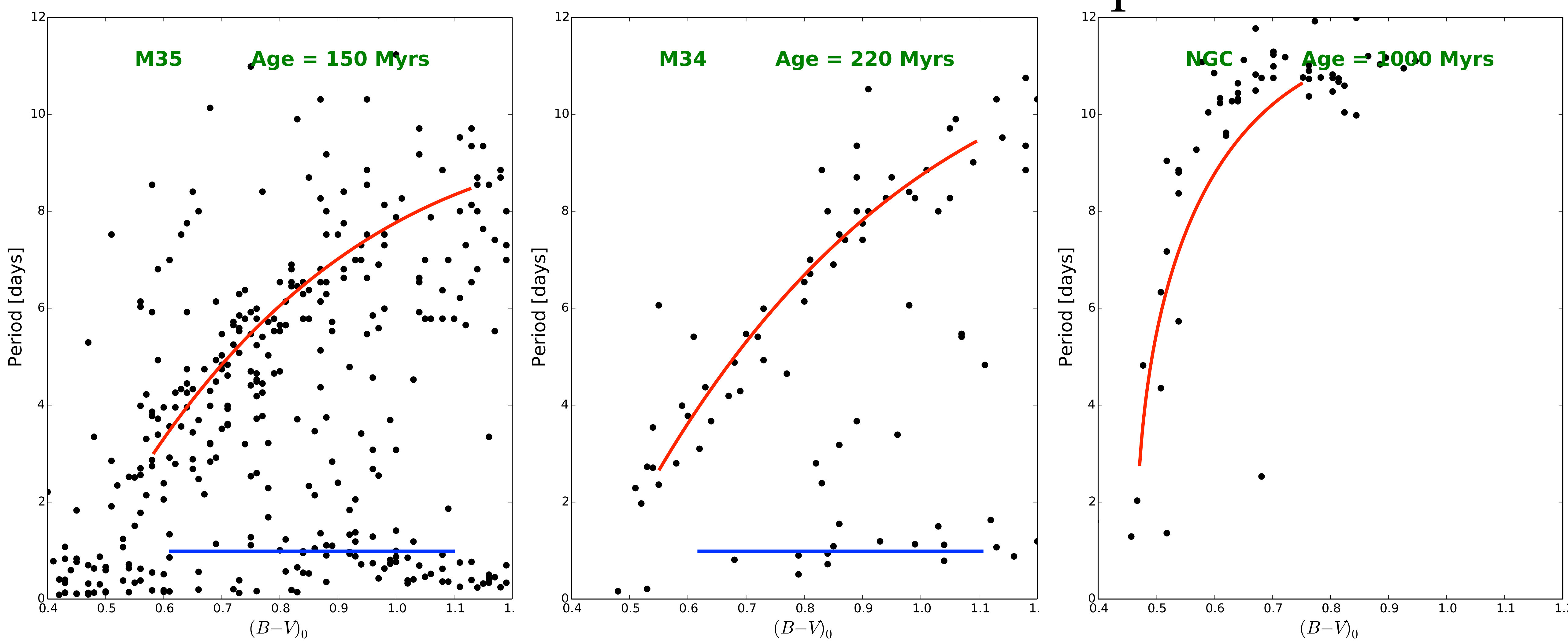
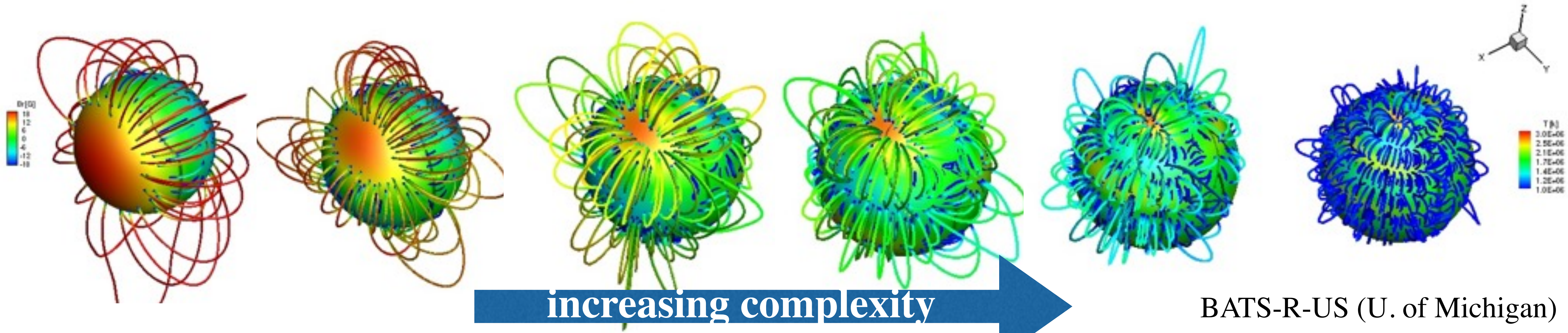
Rotation Evolution of Sun-Like Stars



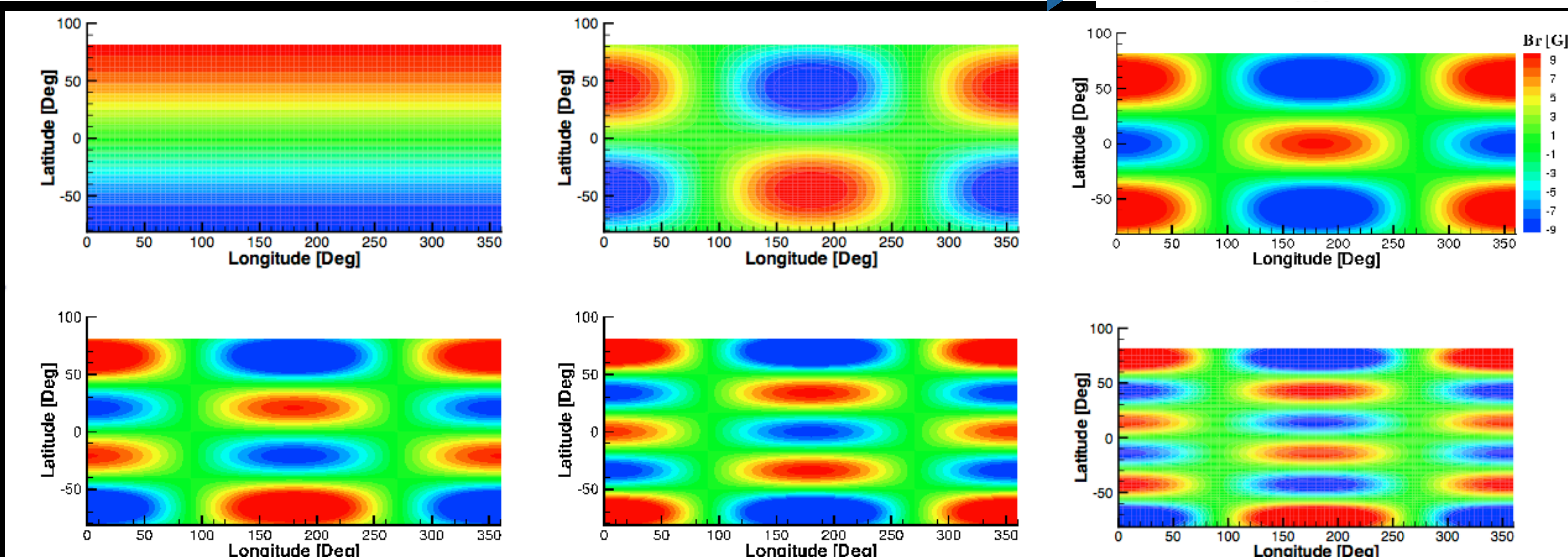
Bimodal distribution of rotation periods



Rotation Evolution of Sun-Like Stars
What is missing?



BATS-R-US (U. of Michigan)



Garraffo et al., ApJL 2015

Rotation Evolution of Sun-Like Stars
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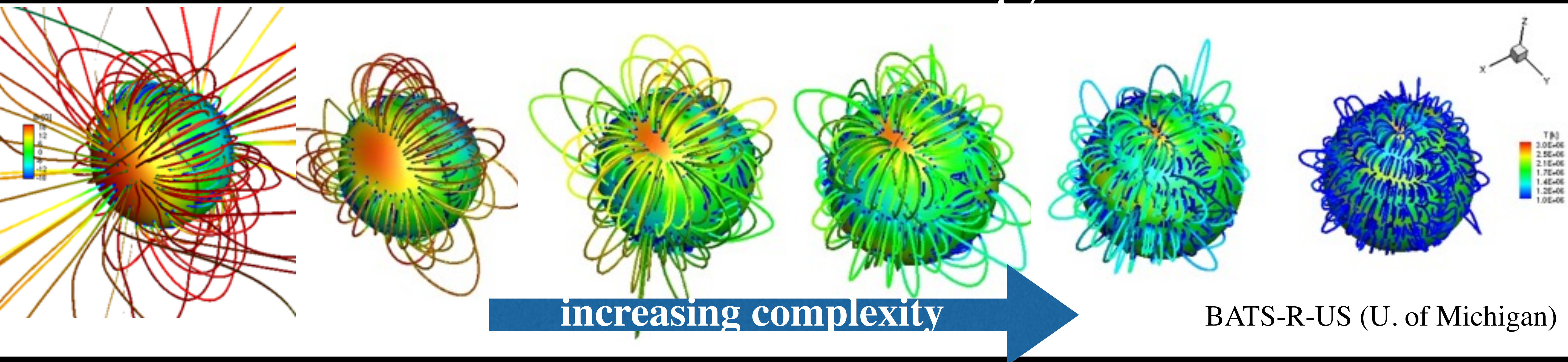

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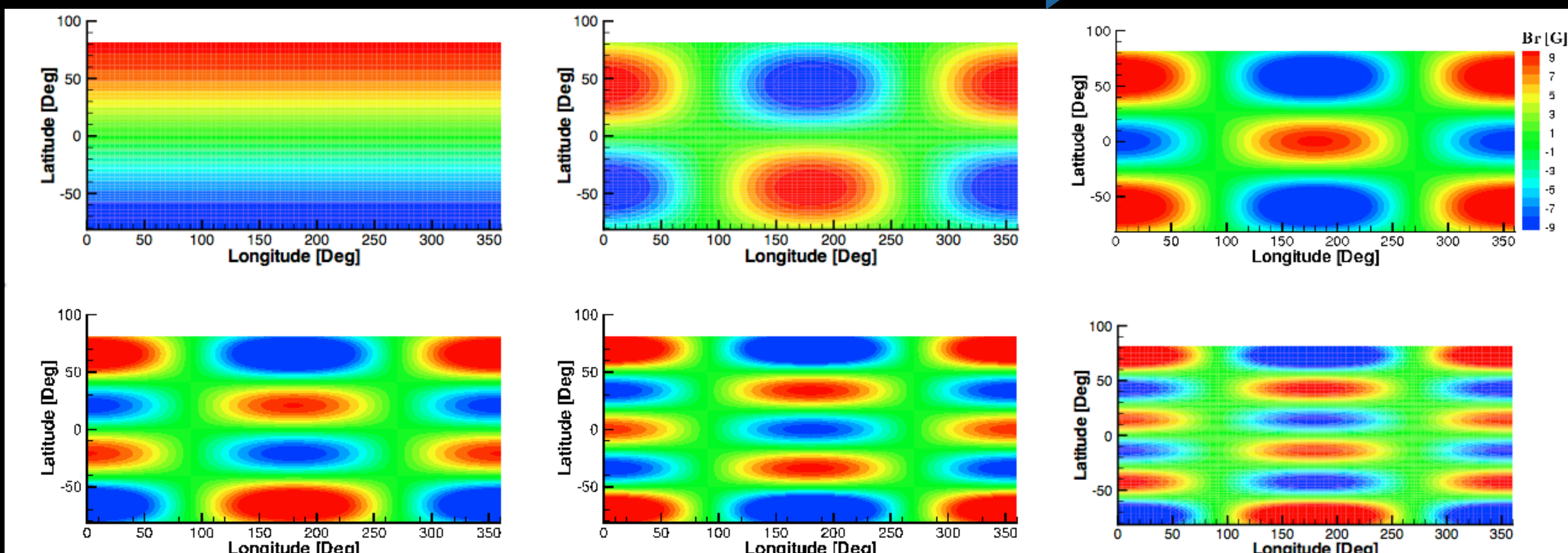
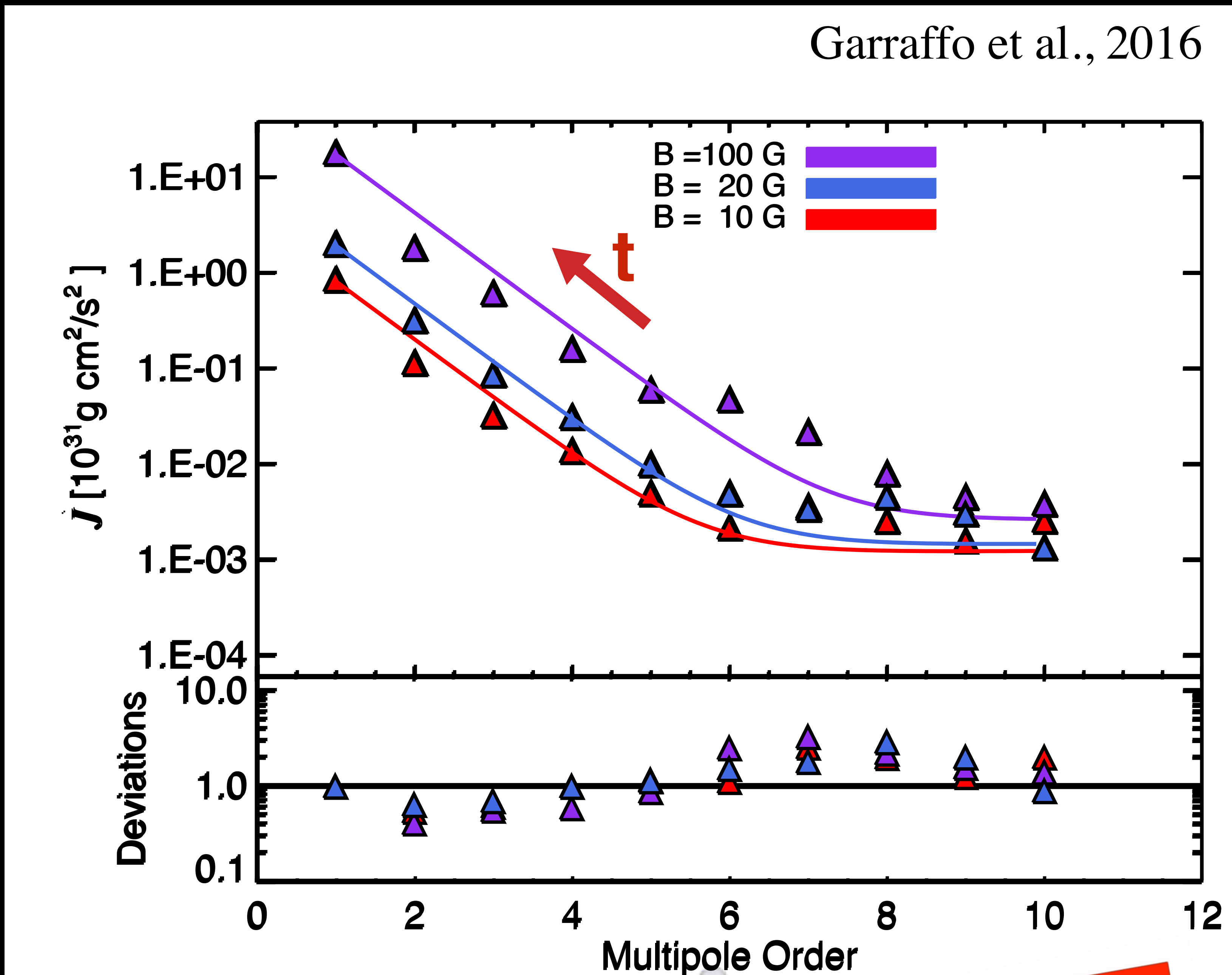
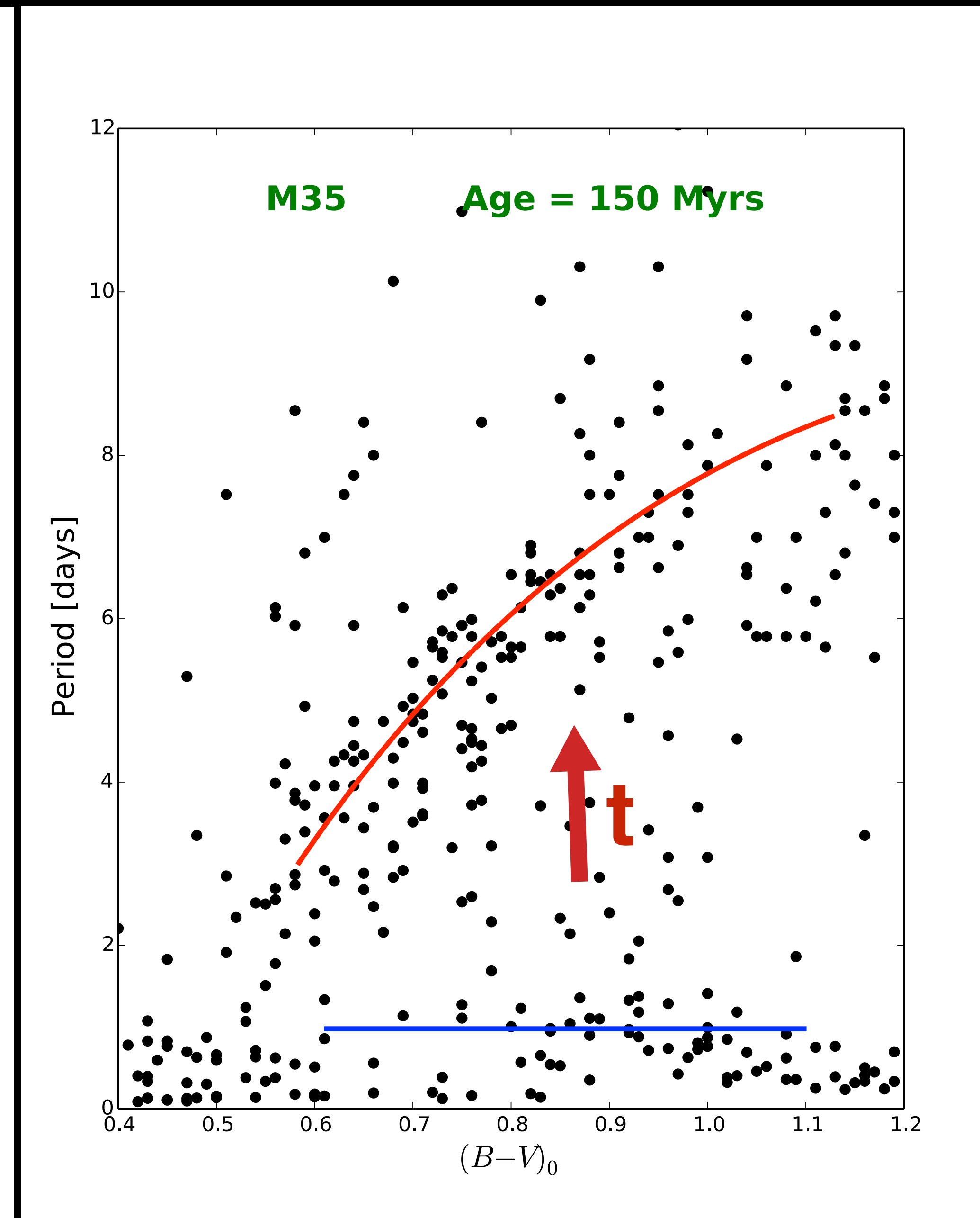


Garraffo et al., ApJL 2015

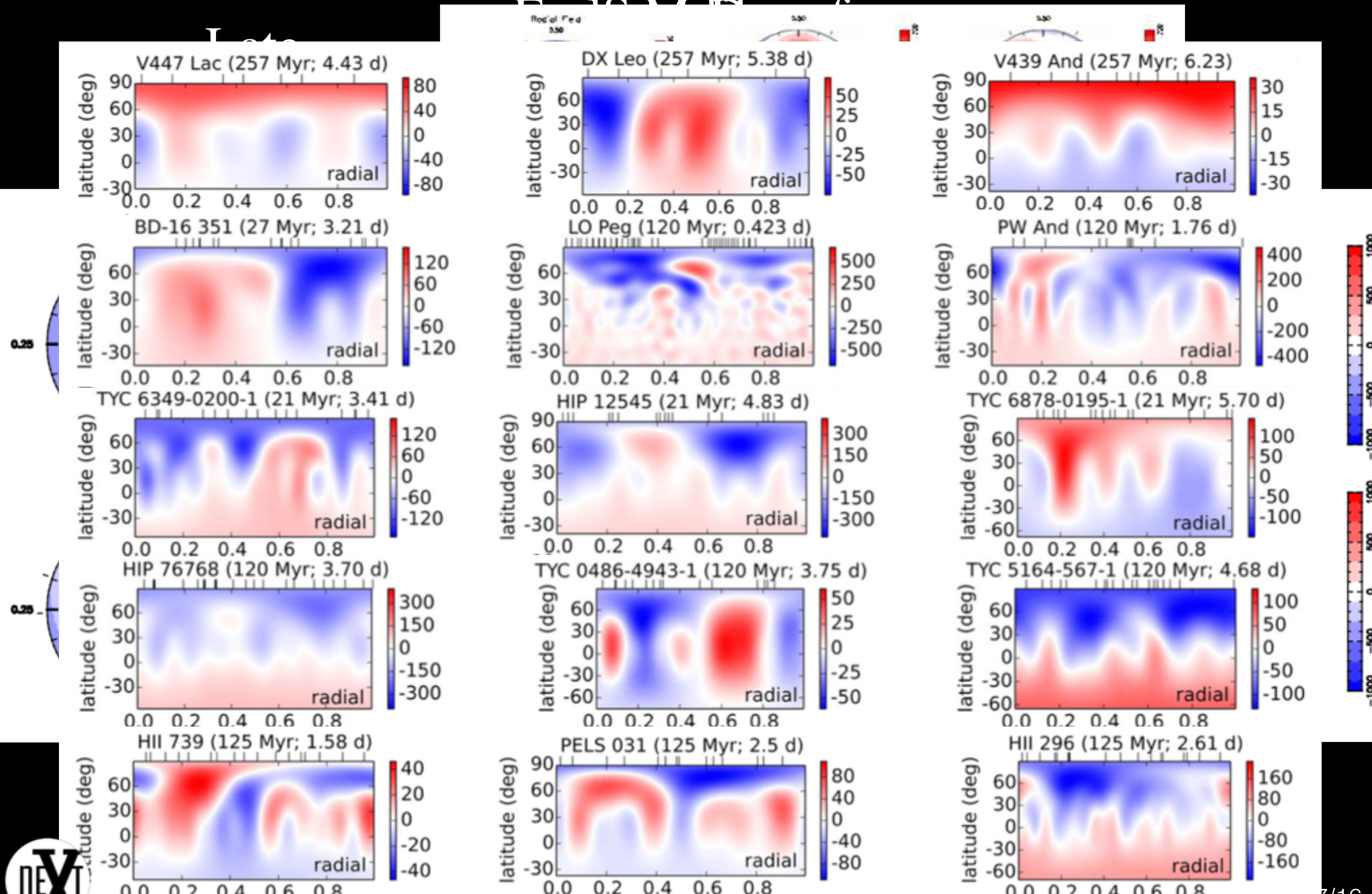
Analytic Morphology Term: Scaling Laws





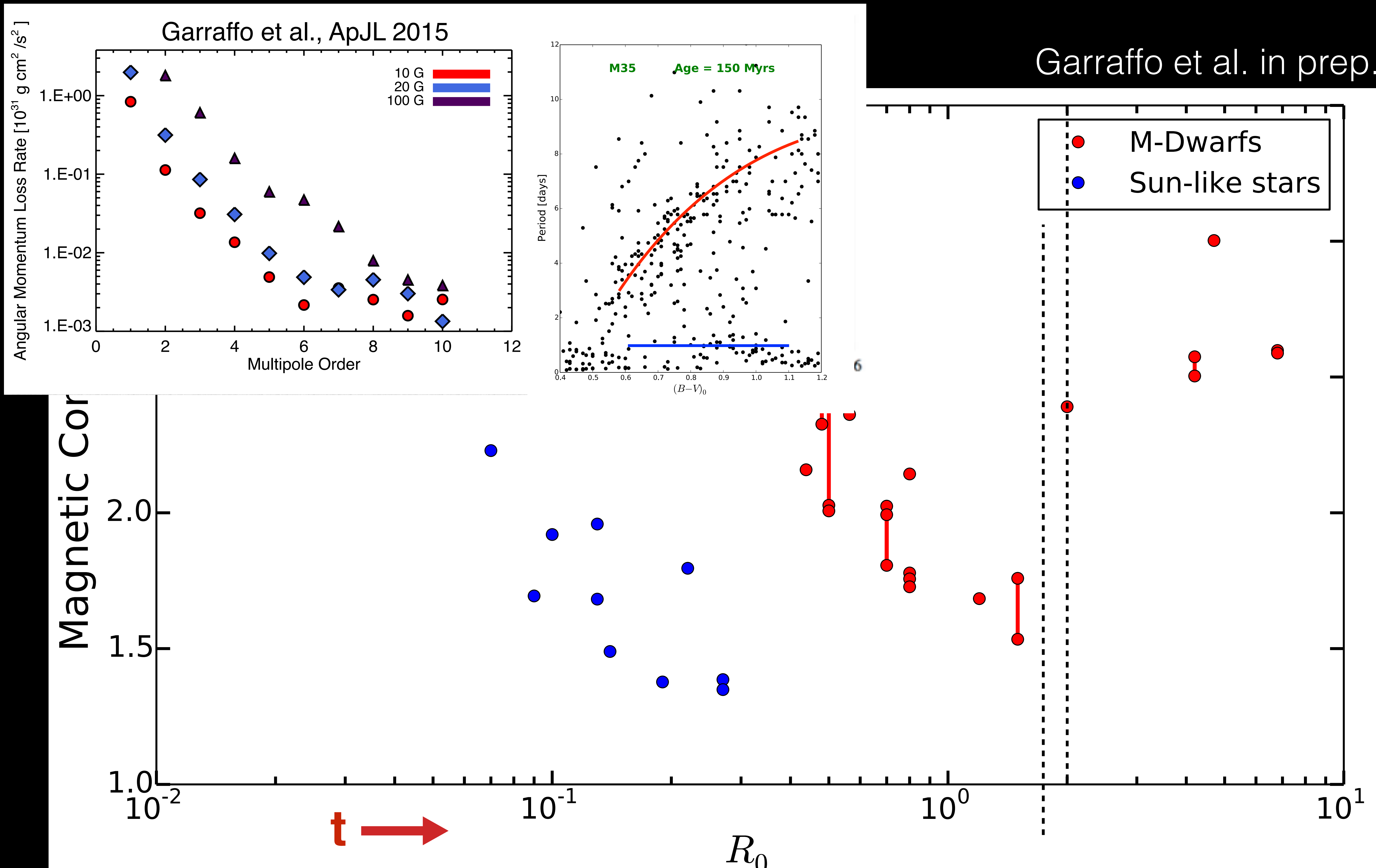
AM loss rates strongly suppressed

Morphology in Time

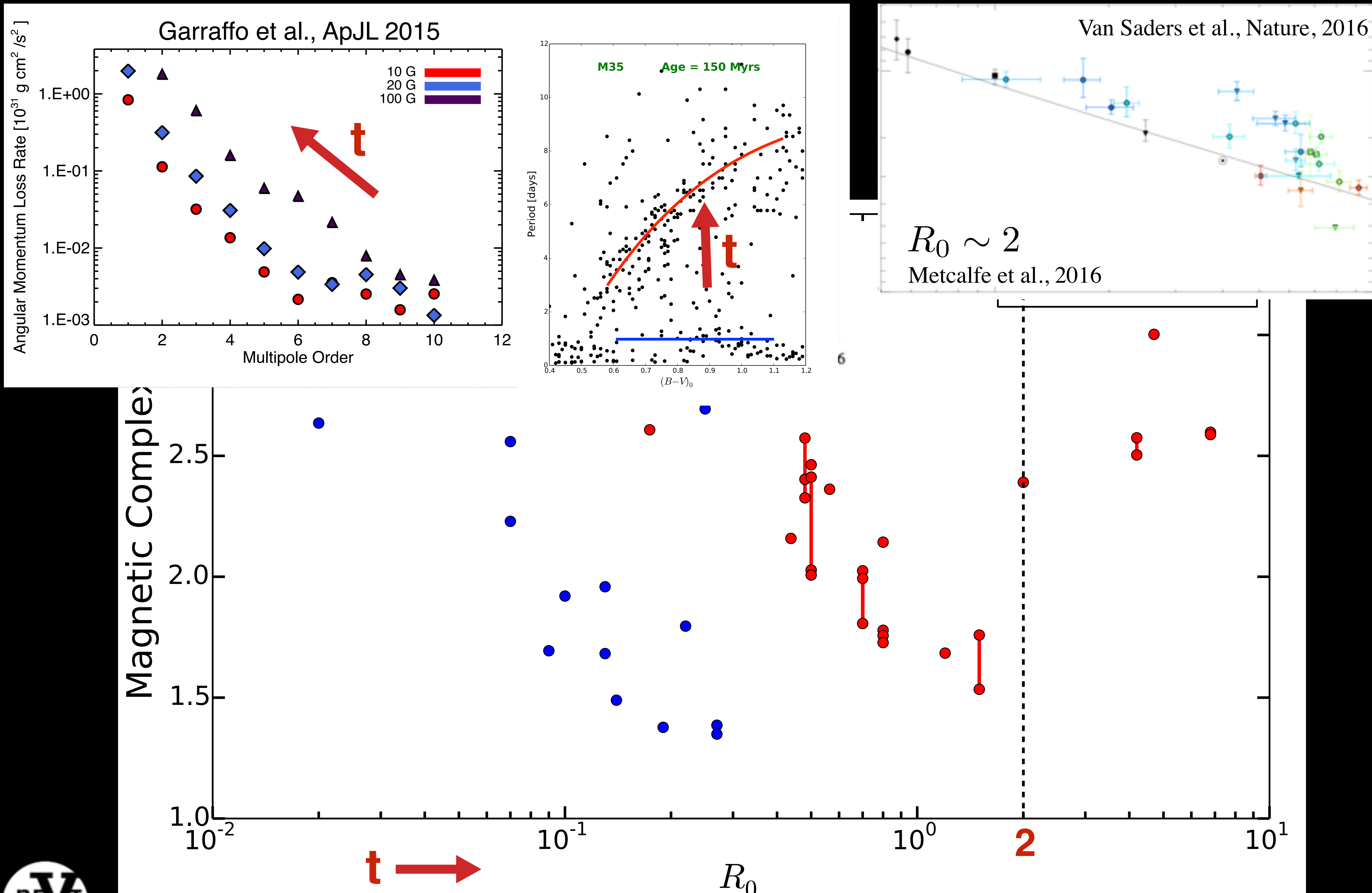


Morphology in Time

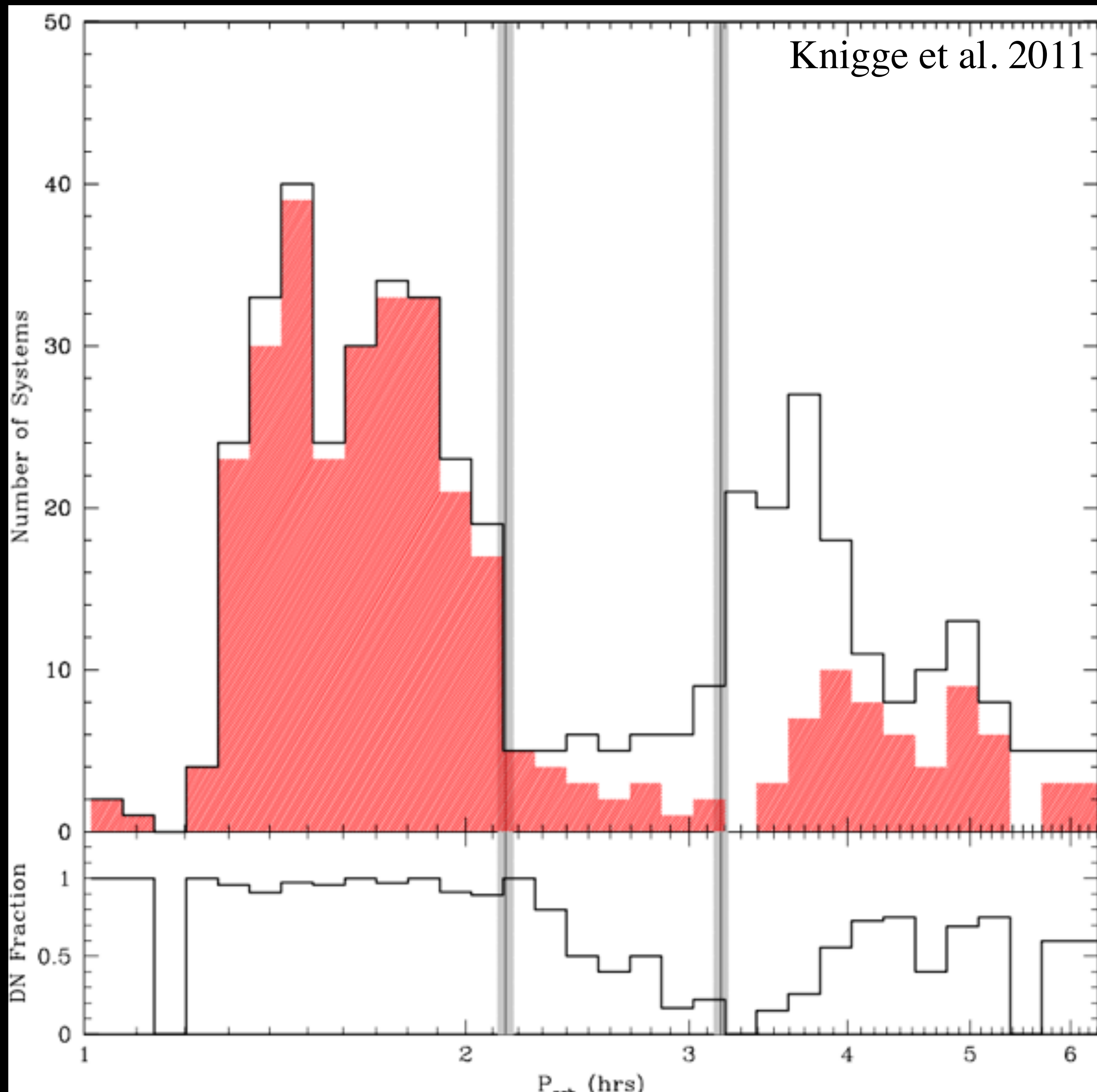
Garraffo et al. in prep.



Morphology in Time



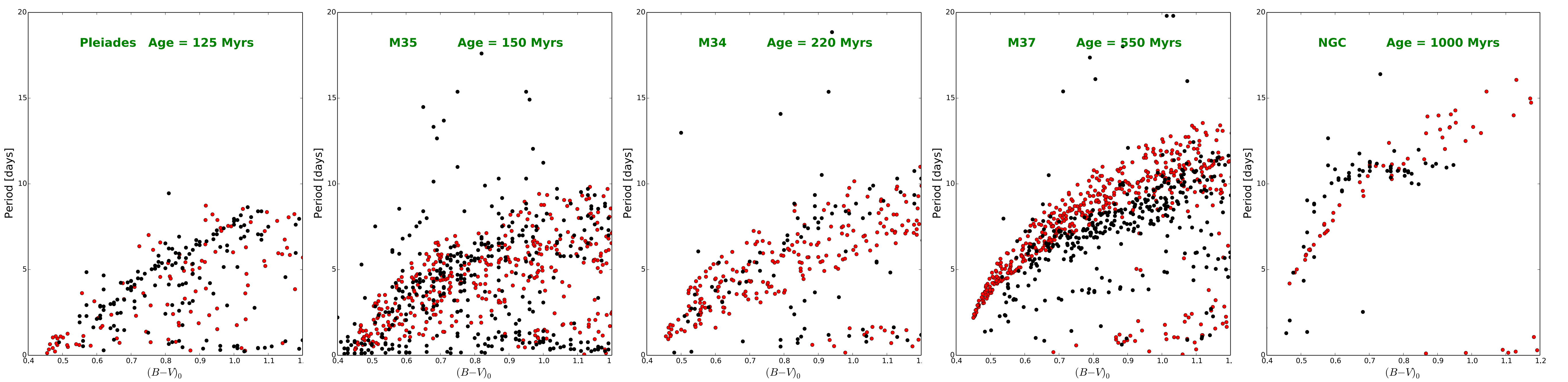
Morphology in Time
Explaining CV period gap?



Morphology in Time

$$\dot{J} = \dot{J}_{Dip} Q_J(n), \qquad Q_J(n) = 4.05\; e^{-1.4n} + \frac{(n-1)}{(60\,n\,B)}$$

$$n(t) = ?$$



Garraffo et al. in prep.

work in progress…

$$\dot{J} = \dot{J}(t) \qquad P_{rot} = P_{rot}(t)$$

Morphology in Time

$$\dot{J} = \dot{J}_{Dip} Q_J(n), \qquad Q_J(n) = 4.05\ e^{-1.4n} + \frac{(n-1)}{(60\, n\, B)}$$

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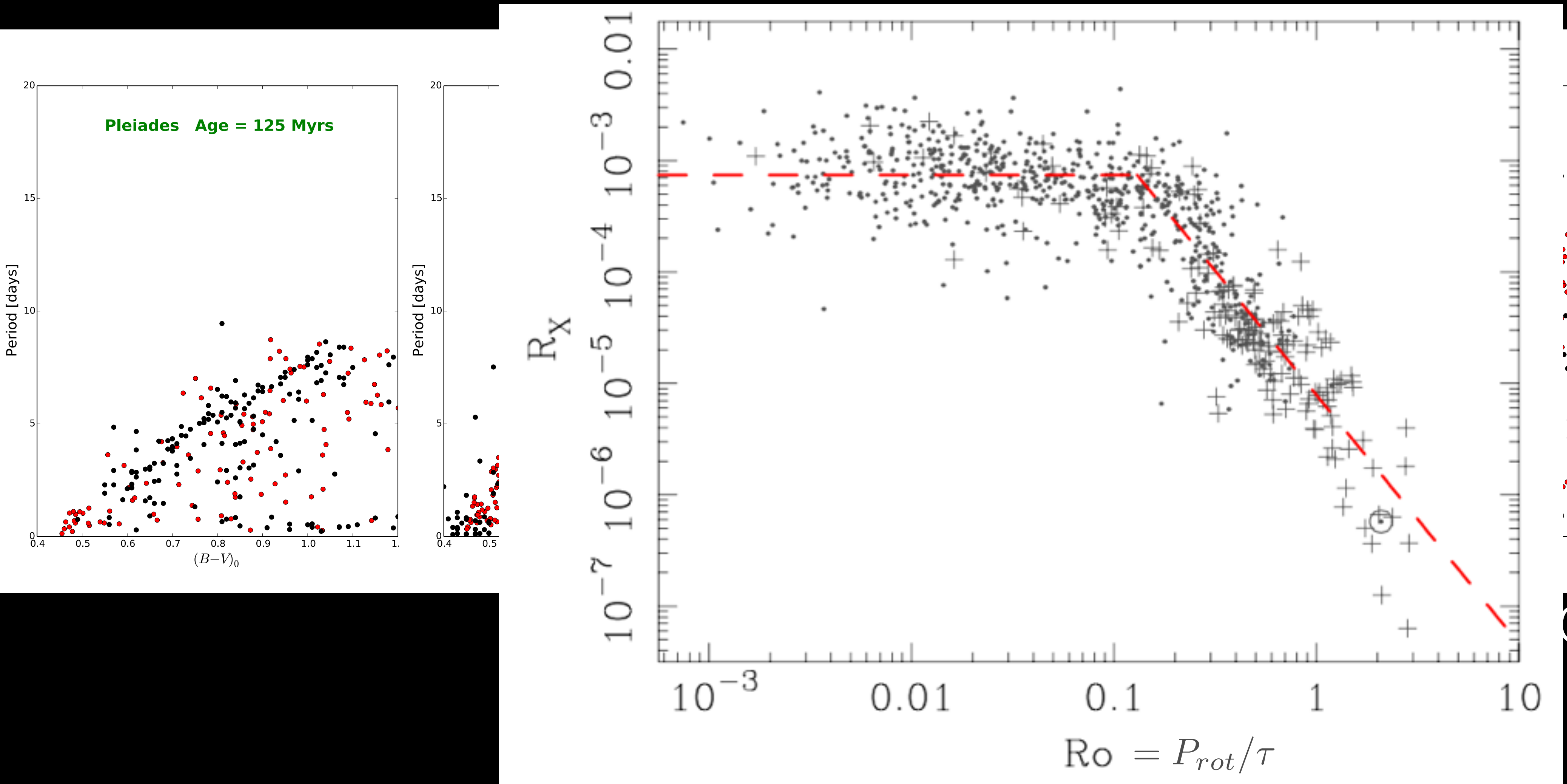
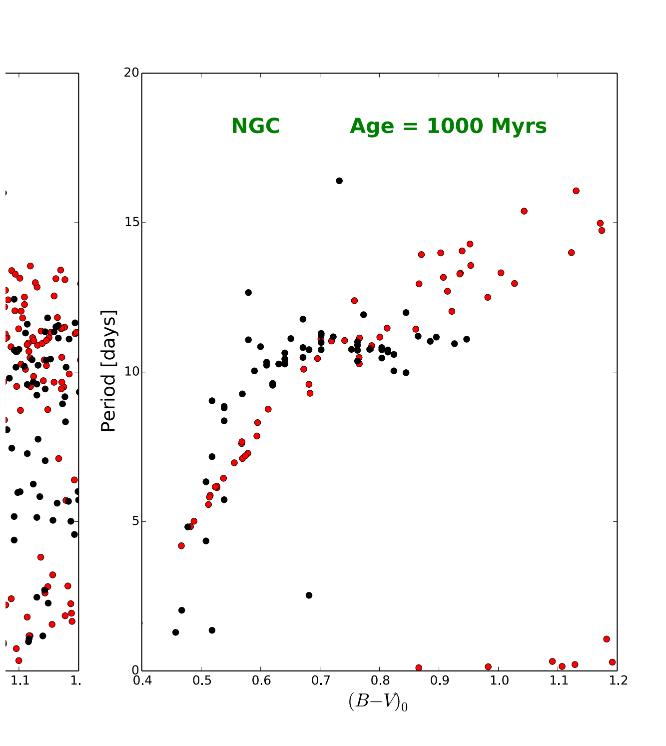




Garraffo et al. in prep.

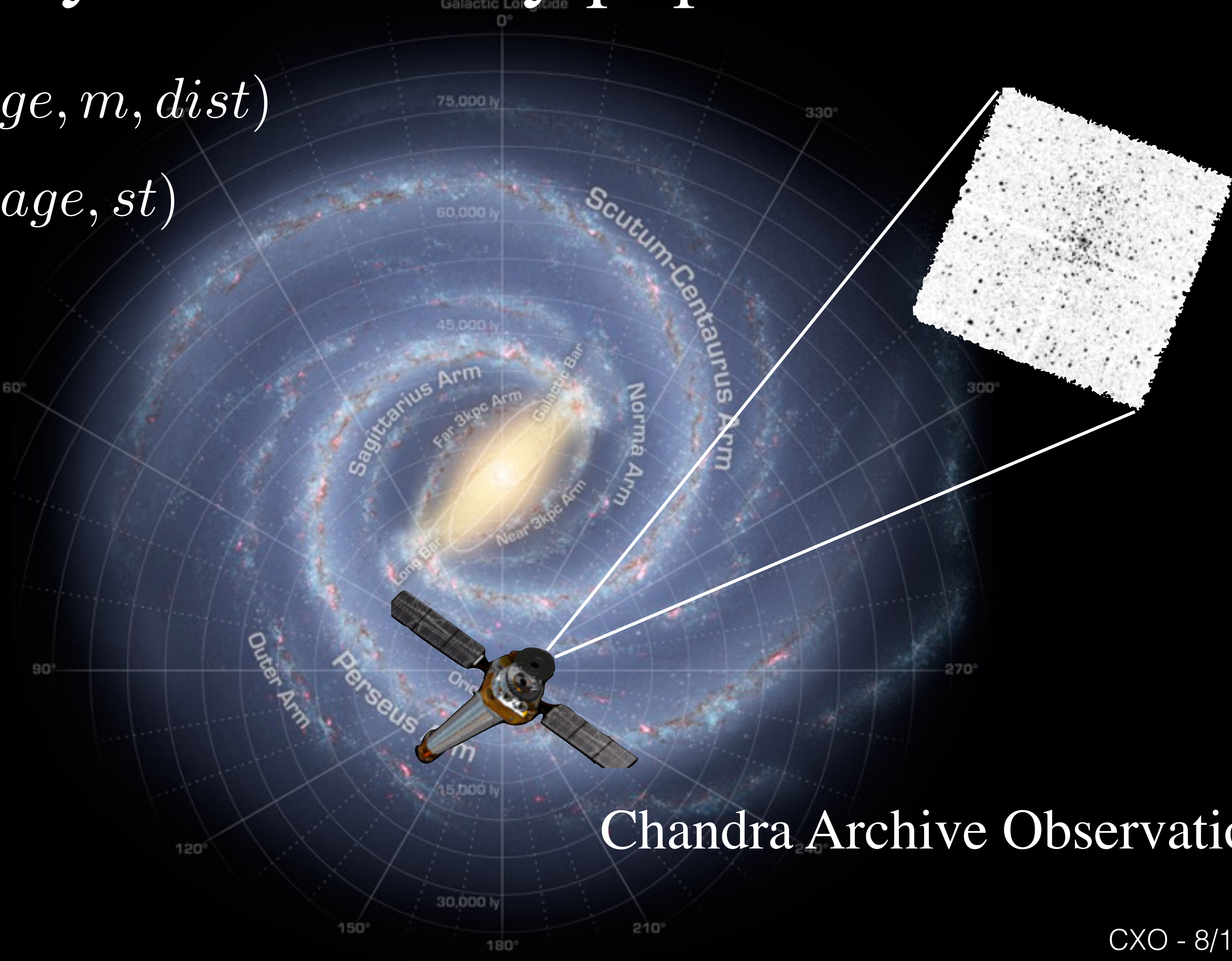
$$\dot{J} = \dot{J}(t) \qquad P_{rot} = P_{rot}(t) \qquad \boxed{R_X = R_X(t)}$$

Future Work

Synthetic X-ray populations

$$N = N(age, m, dist)$$

$$R_X = R_X(age, st)$$



Chandra Archive Observations

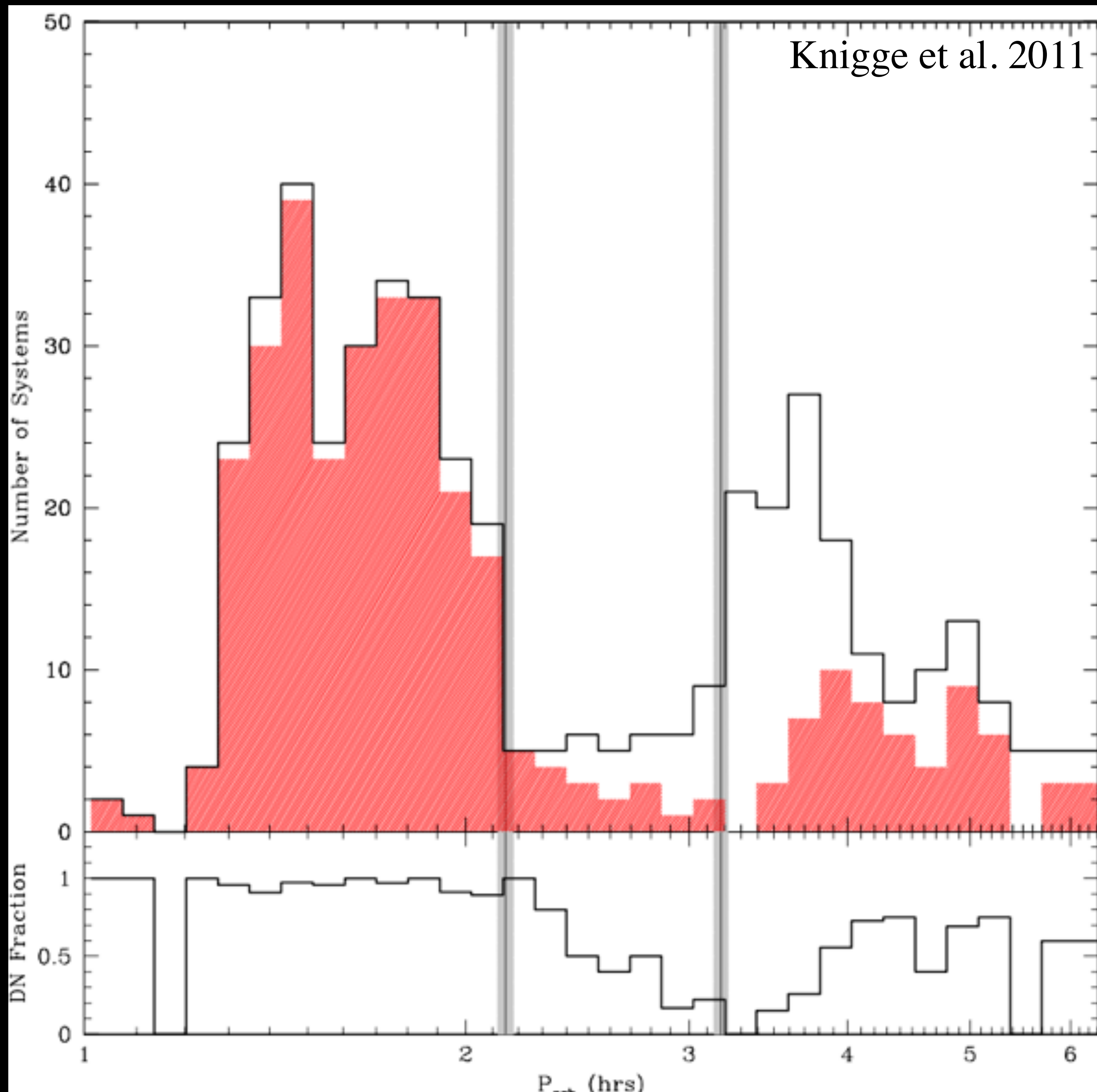
Thank you!

Conclusions

- Large scale magnetic morphology explains deviations from gyrochronology at early and late ages
- Based on 73 simulations we derived analytical expressions to estimate mass, angular momentum loss rates, and changes in X-ray activity based on total magnetic flux and magnetic complexity.
- We can use observations of open clusters to infer the magnetic morphology and X-ray evolution with time.
- We plan to use X-ray evolution with time to produce synthetic X-ray populations and compare with Chandra Archival Observations.

Backup Slides

Morphology in Time
Explaining CV period gap?



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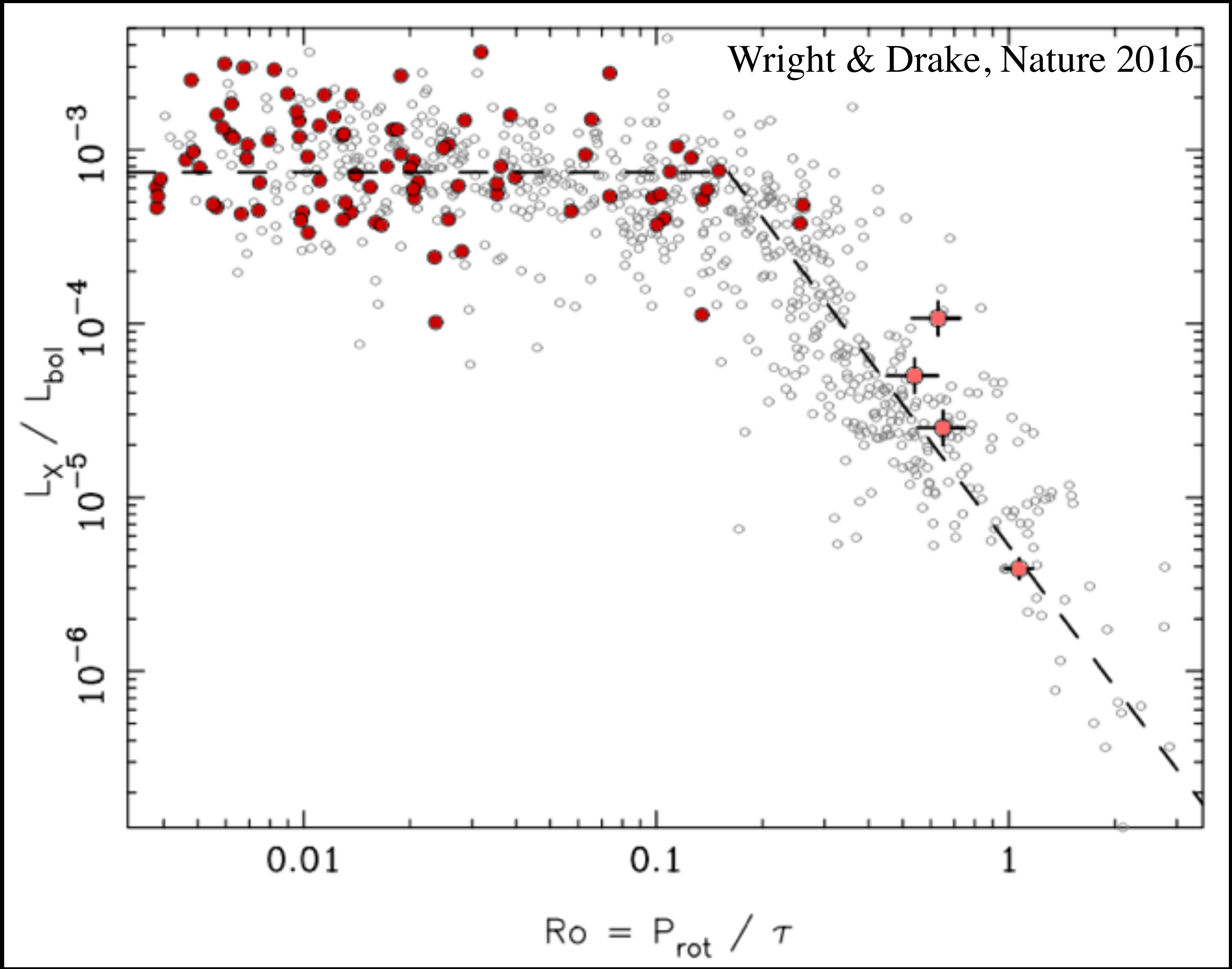

Morphology in Time
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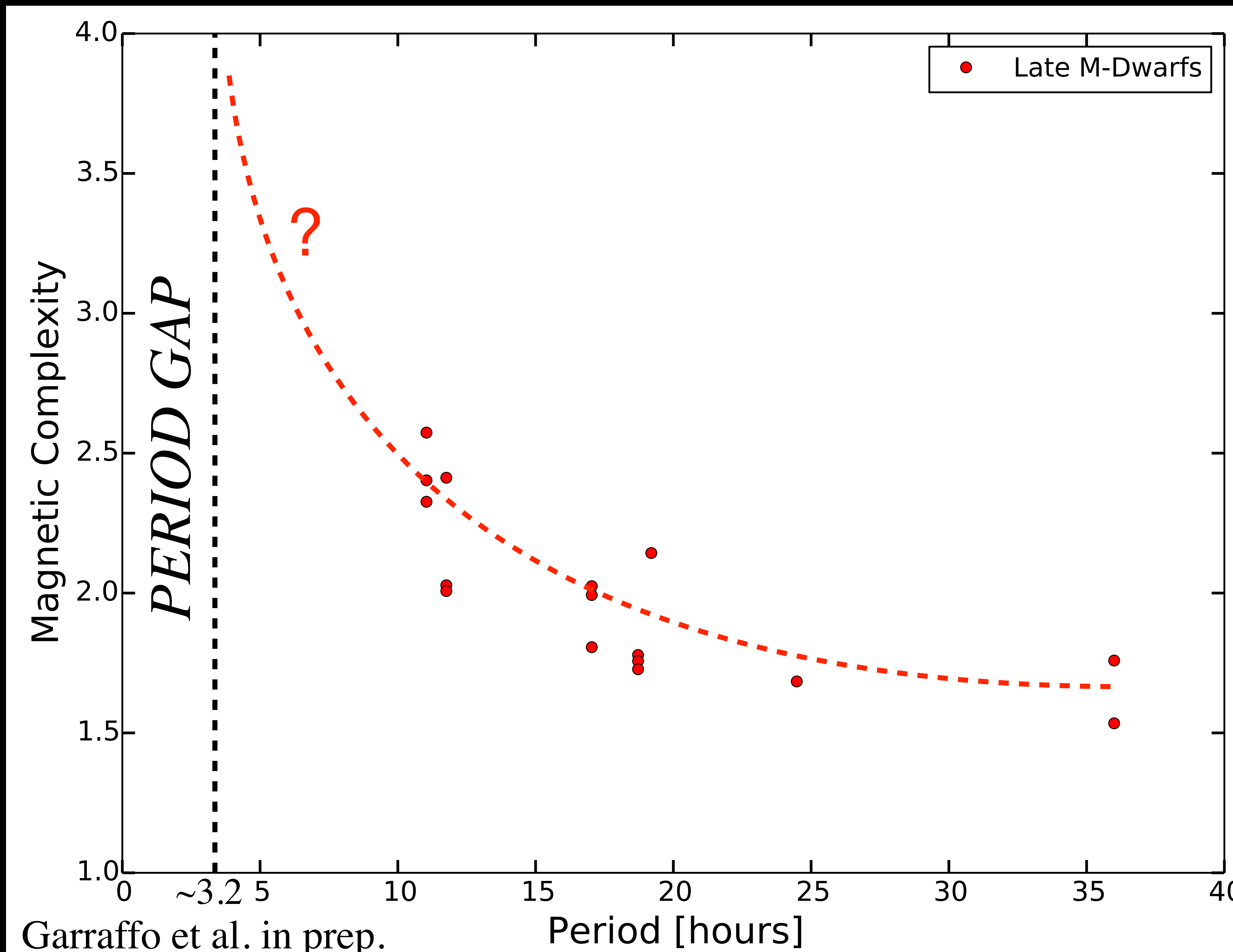
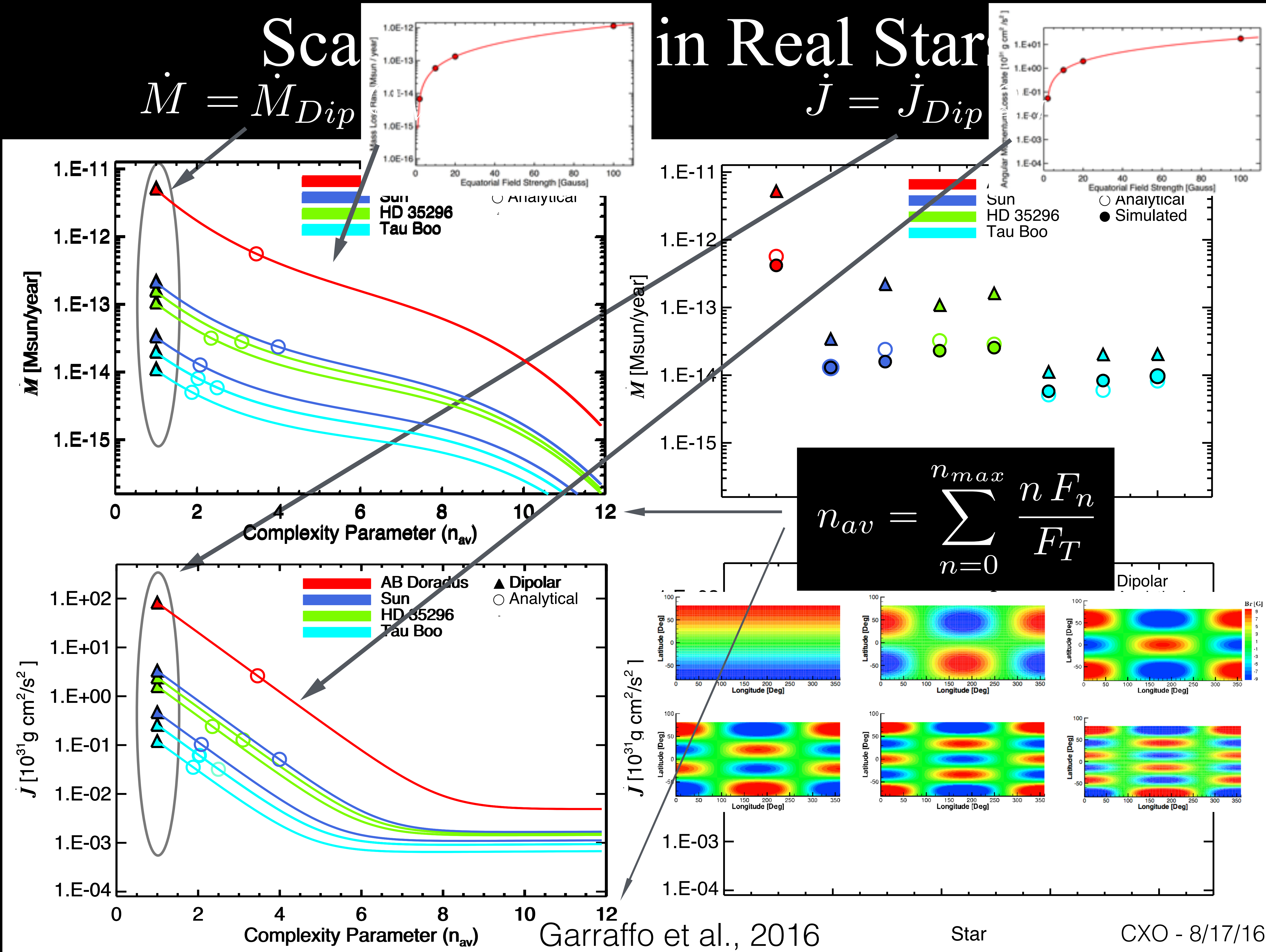


Sca in Real Stars

$\dot{M} = \dot{M}_{Dip}$ $\dot{J} = \dot{J}_{Dip}$



$$n_{av} = \sum_{n=0}^{n_{max}} \frac{n\,F_n}{F_T}$$

Garraffo et al., 2016

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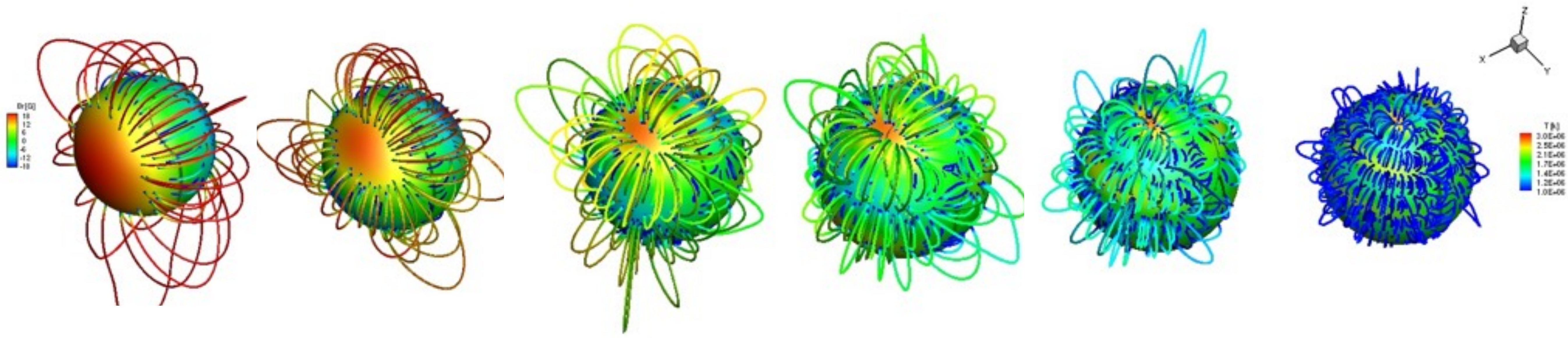
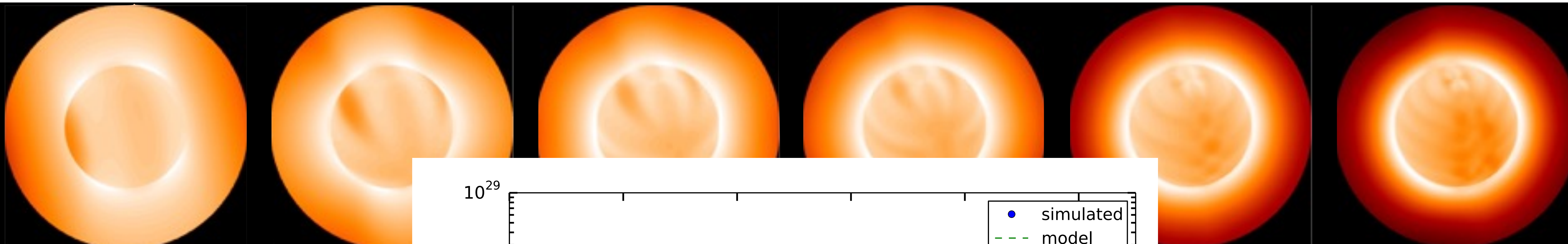
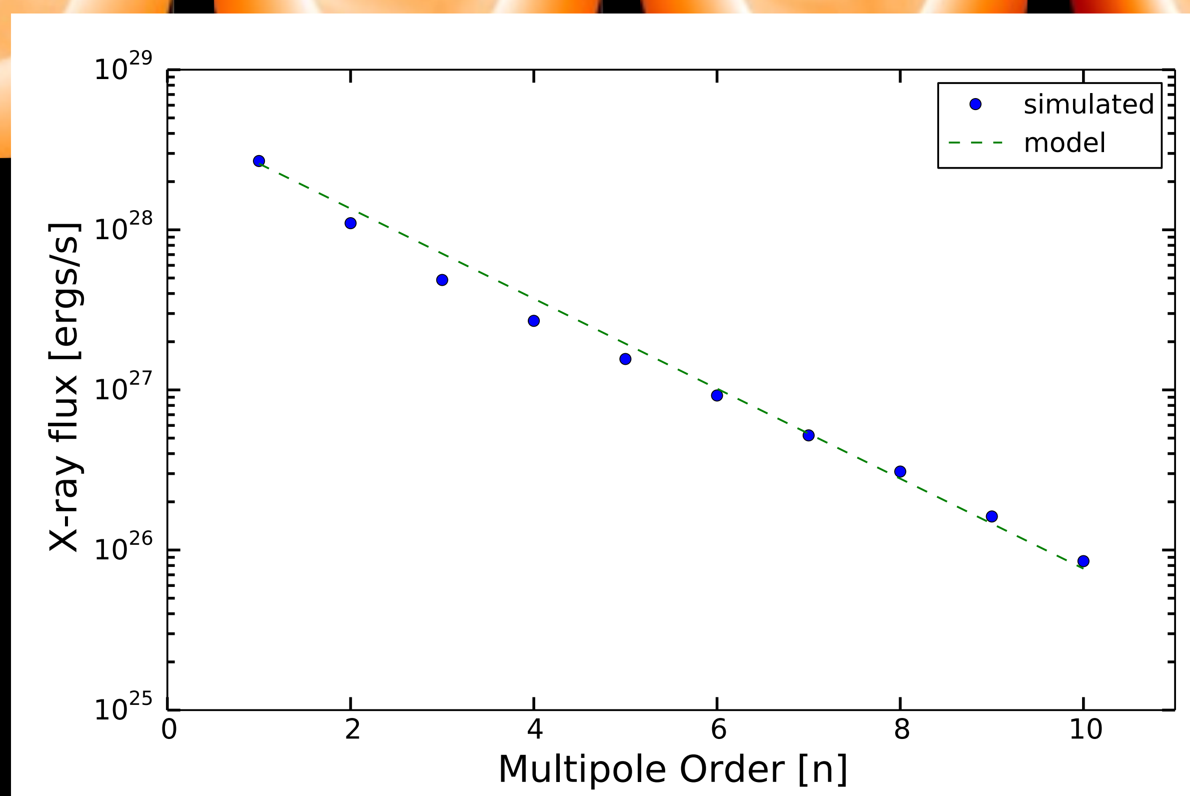
X-ray Activity in Time

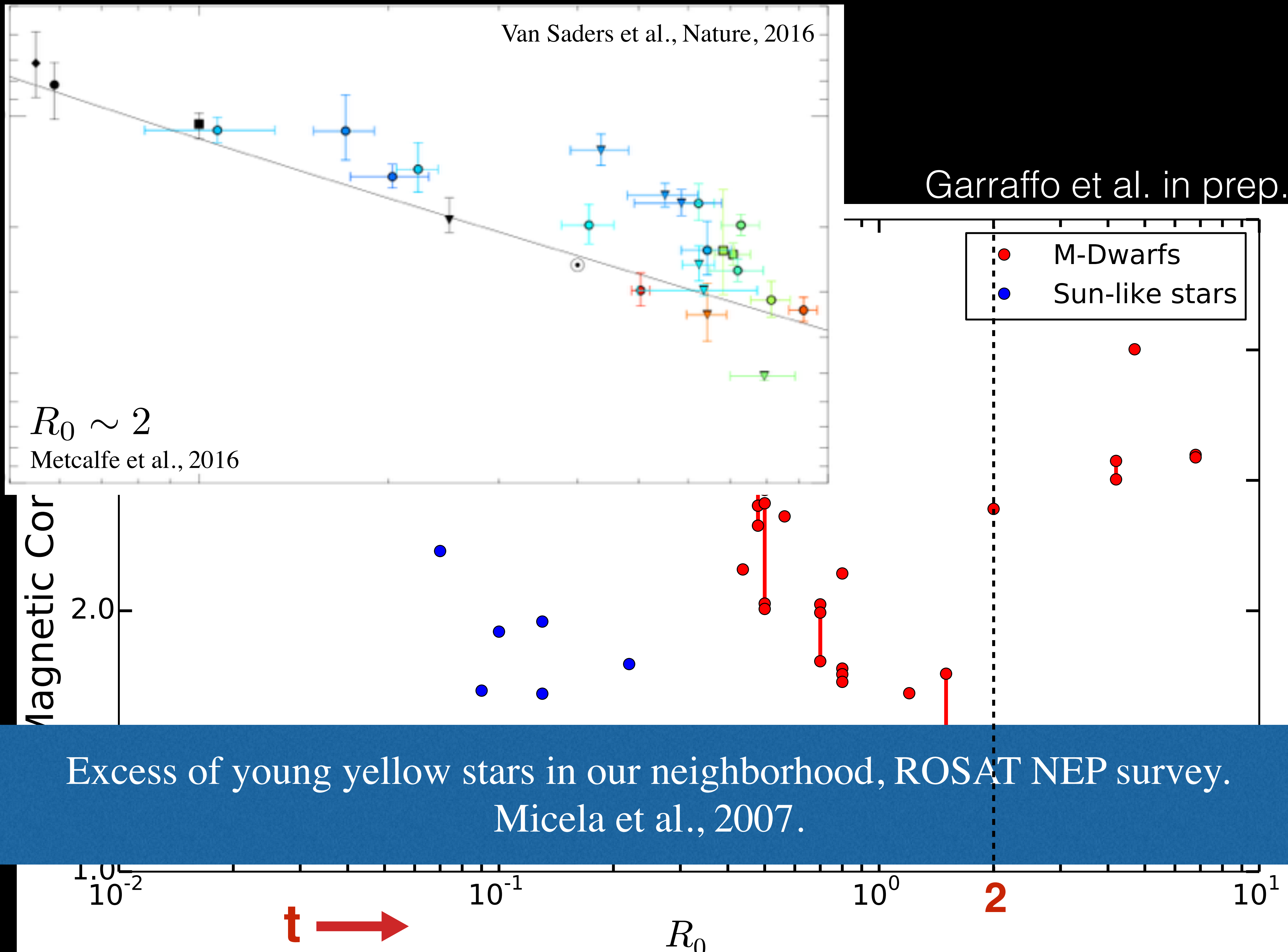
Garraffo et al. in prep.







Morphology in Time



Excess of young yellow stars in our neighborhood, ROSAT NEP survey.
Micela et al., 2007.

Rotation Evolution of Sun-Like Stars

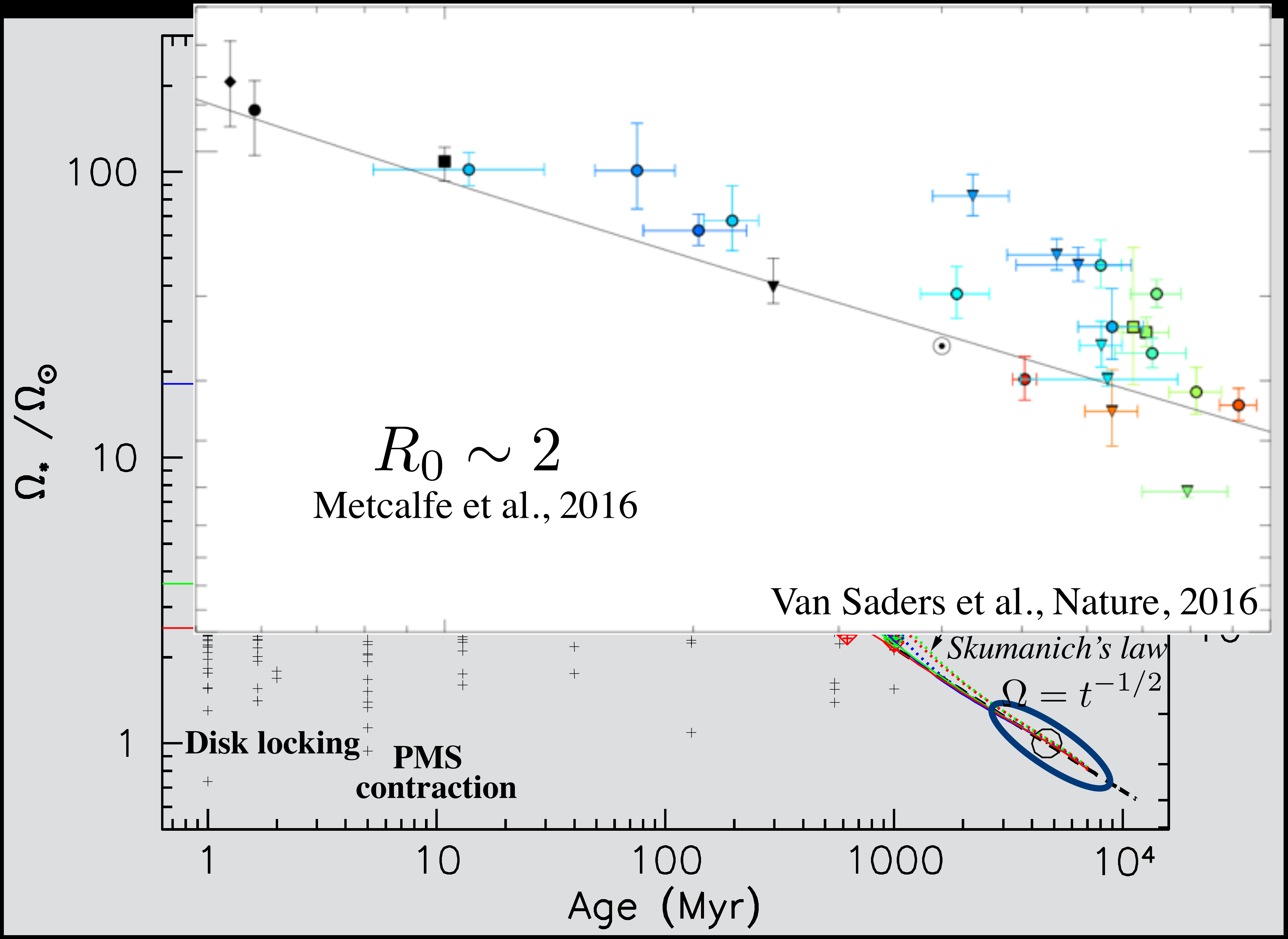


Figure from Jeffries 2014, adapted from Gallet & Bouvier 2013

Rotation Evolution of Sun-Like Stars

Bimodal distribution among these populations

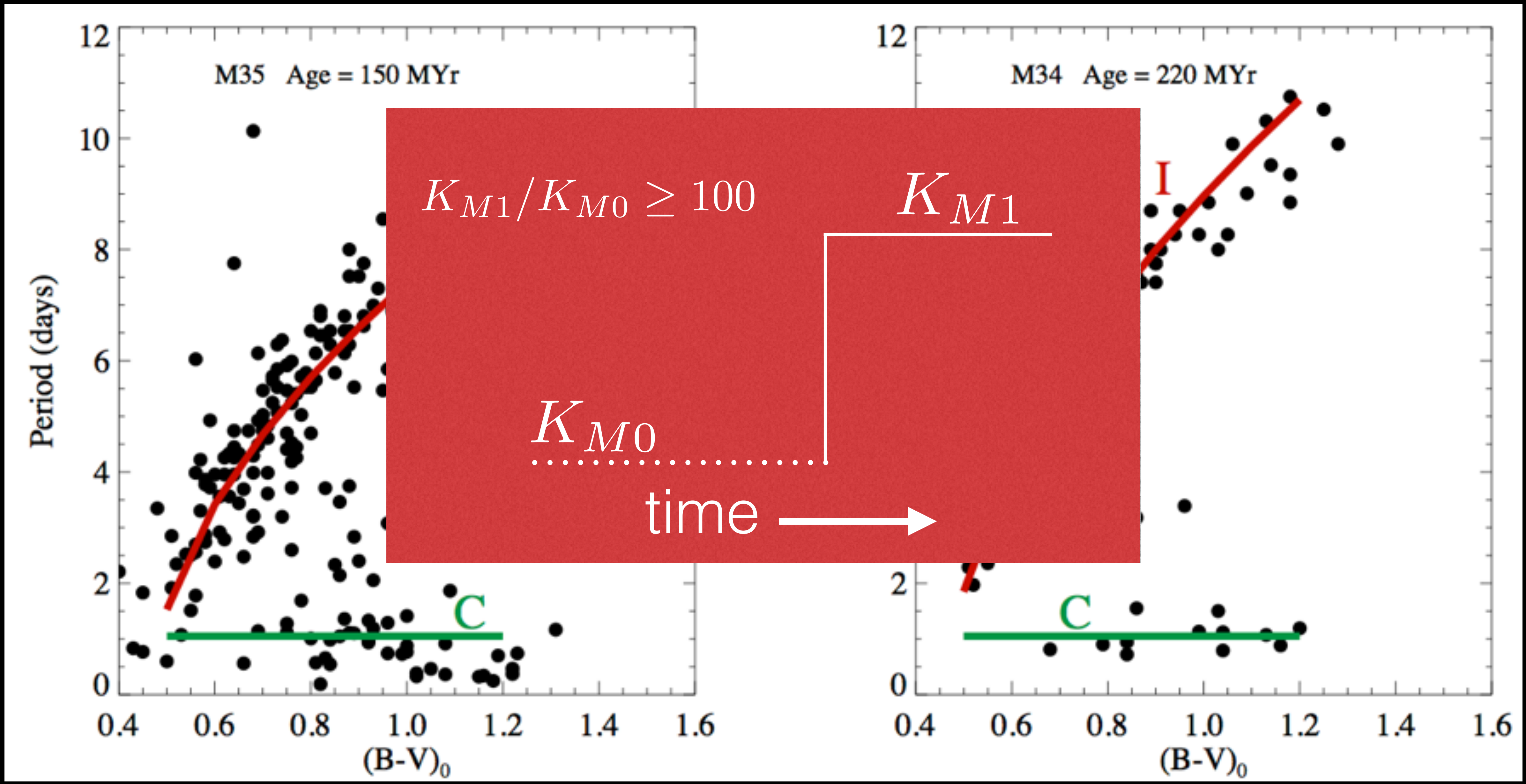


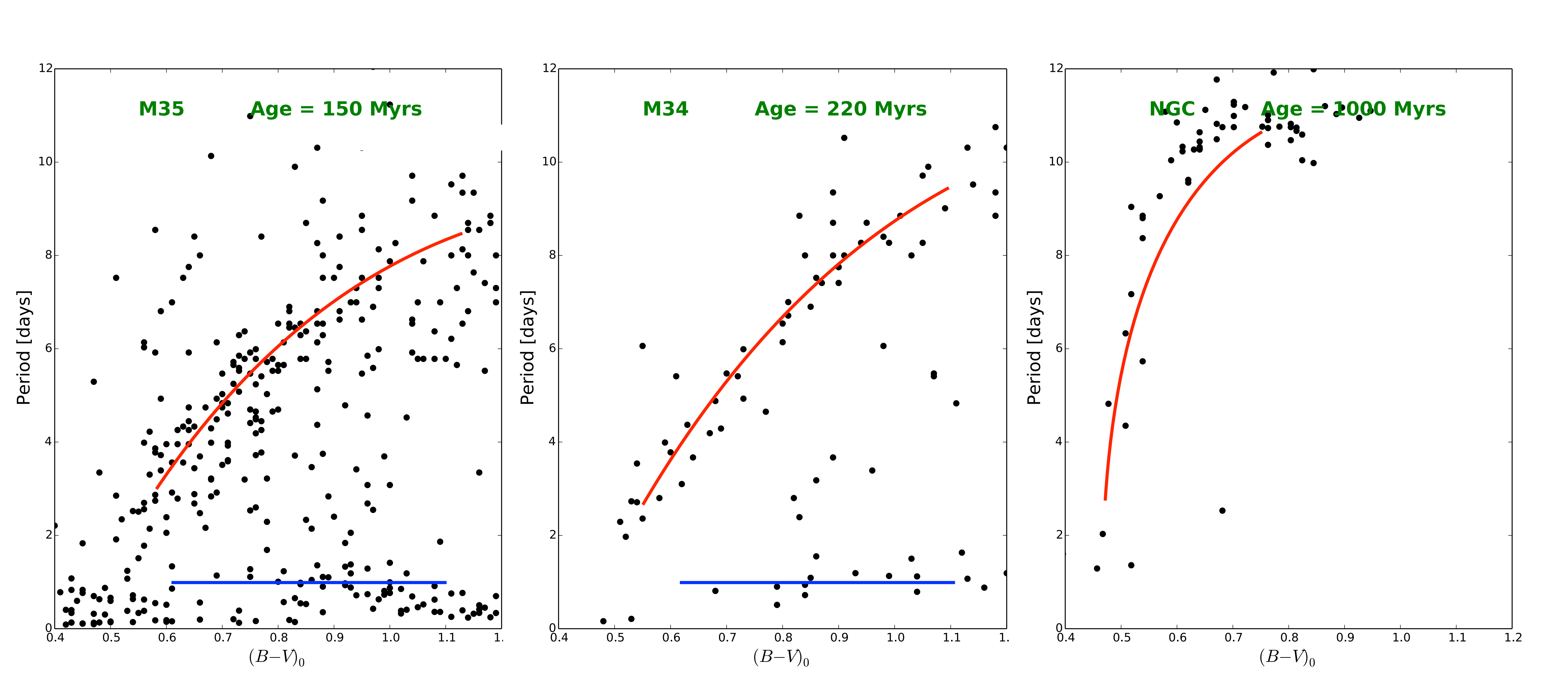
Figure from Brown 2014, data from Meibom et al. 2009, 2011

Brown proposes MDM unified spin-down scenario with a coupling constant that can take two values depending on the mode: strongly or weakly coupled to the stellar wind: $dJ/dt = K_M \Omega^3 f^2(B-V)$

Rotation Evolution of Sun-Like Stars

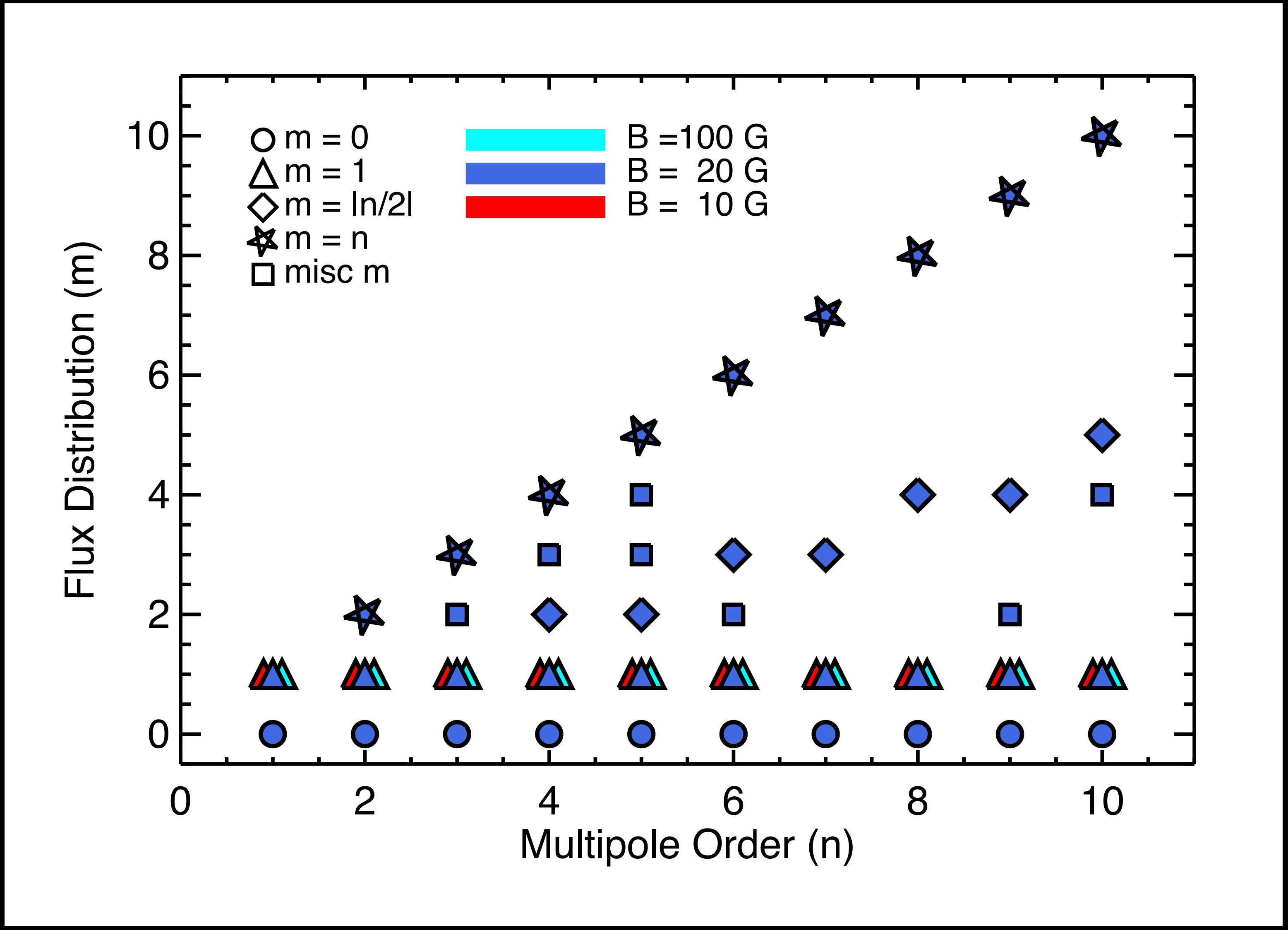
Bimodal distribution among these populations

The schematic *P–t–M* surface for cool stars.



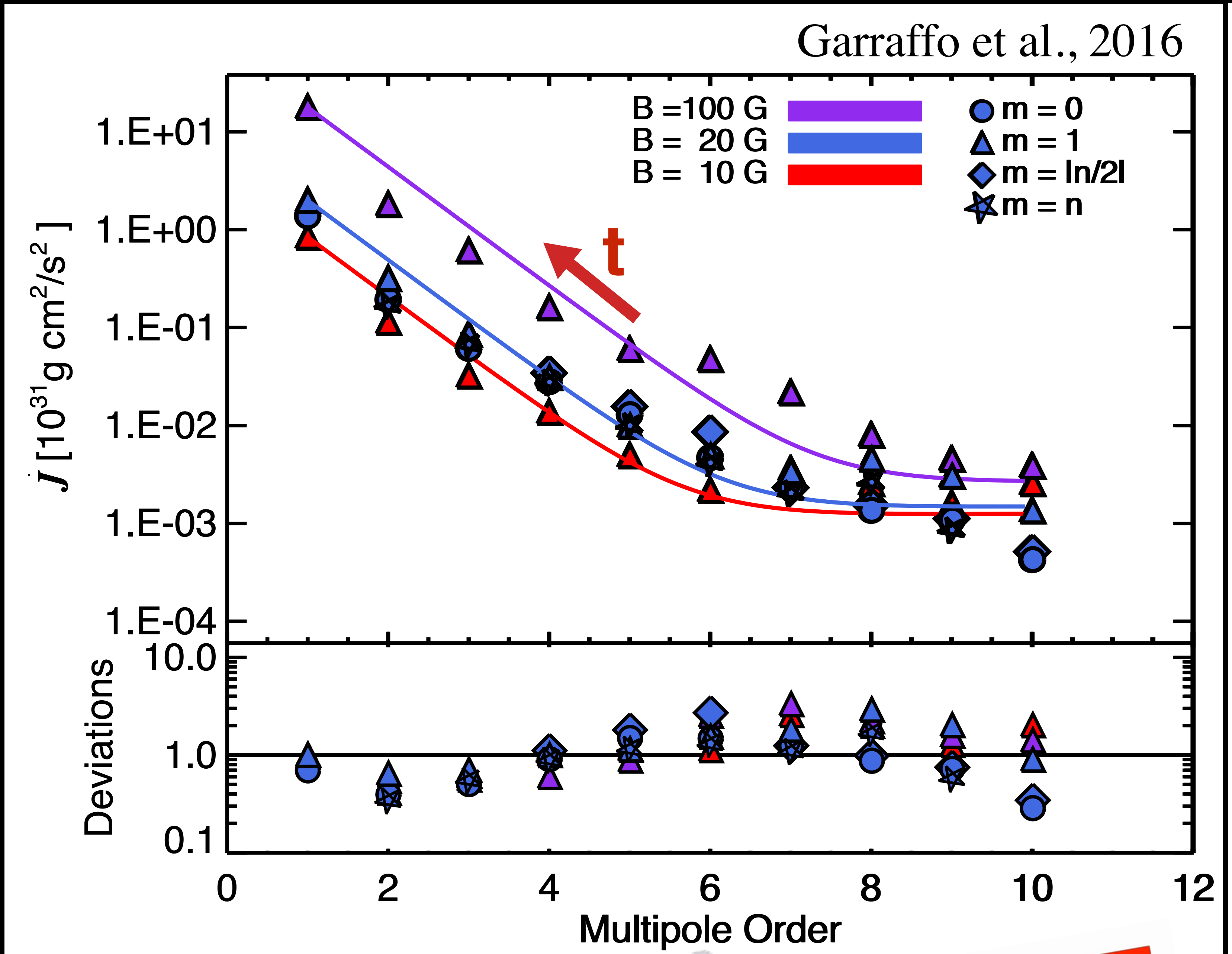
Meibom et al. Nature 2016

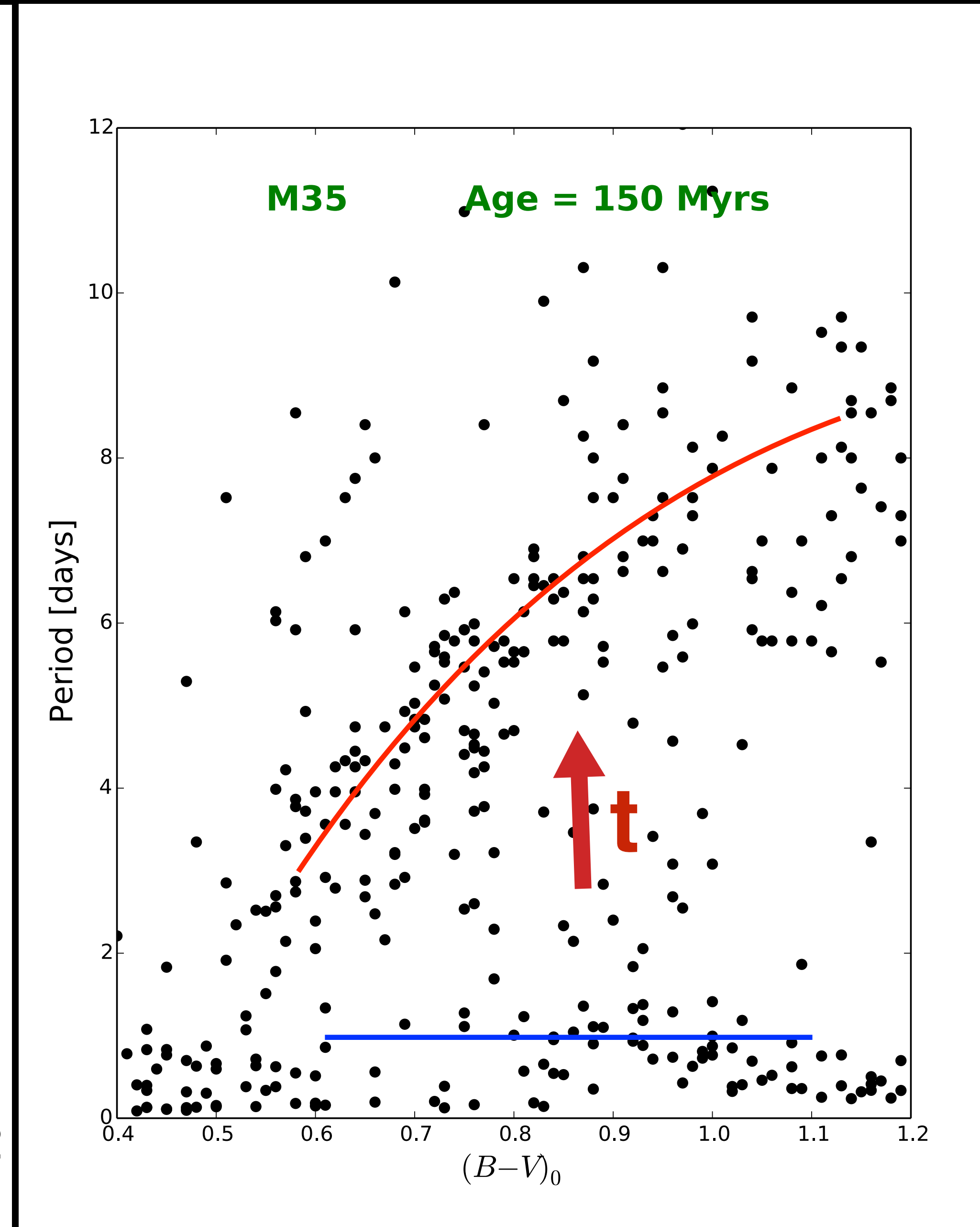
Vican 2012



m = 0
m = 1
m = ln/2l
m = n
misc m
B =100 G
B = 20 G
B = 10 G
Flux Distribution (m)
Multipole Order (n)
0
2
4
6
8
10

Analytic Morphology Term: Scaling Laws

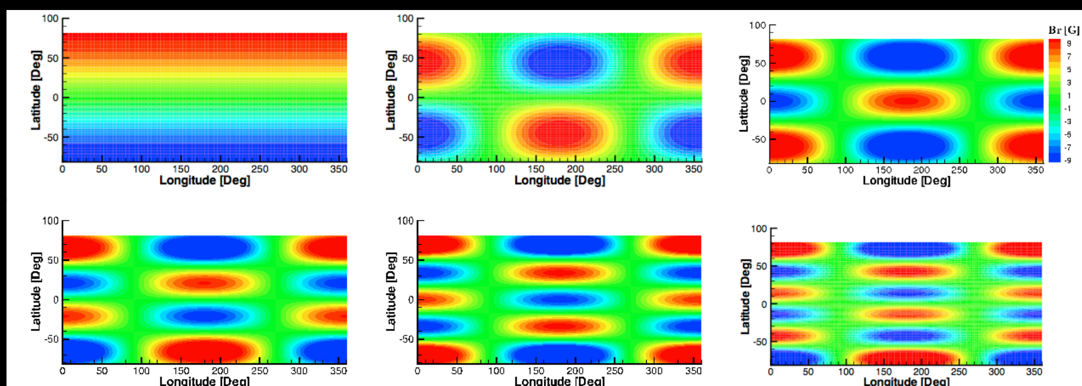




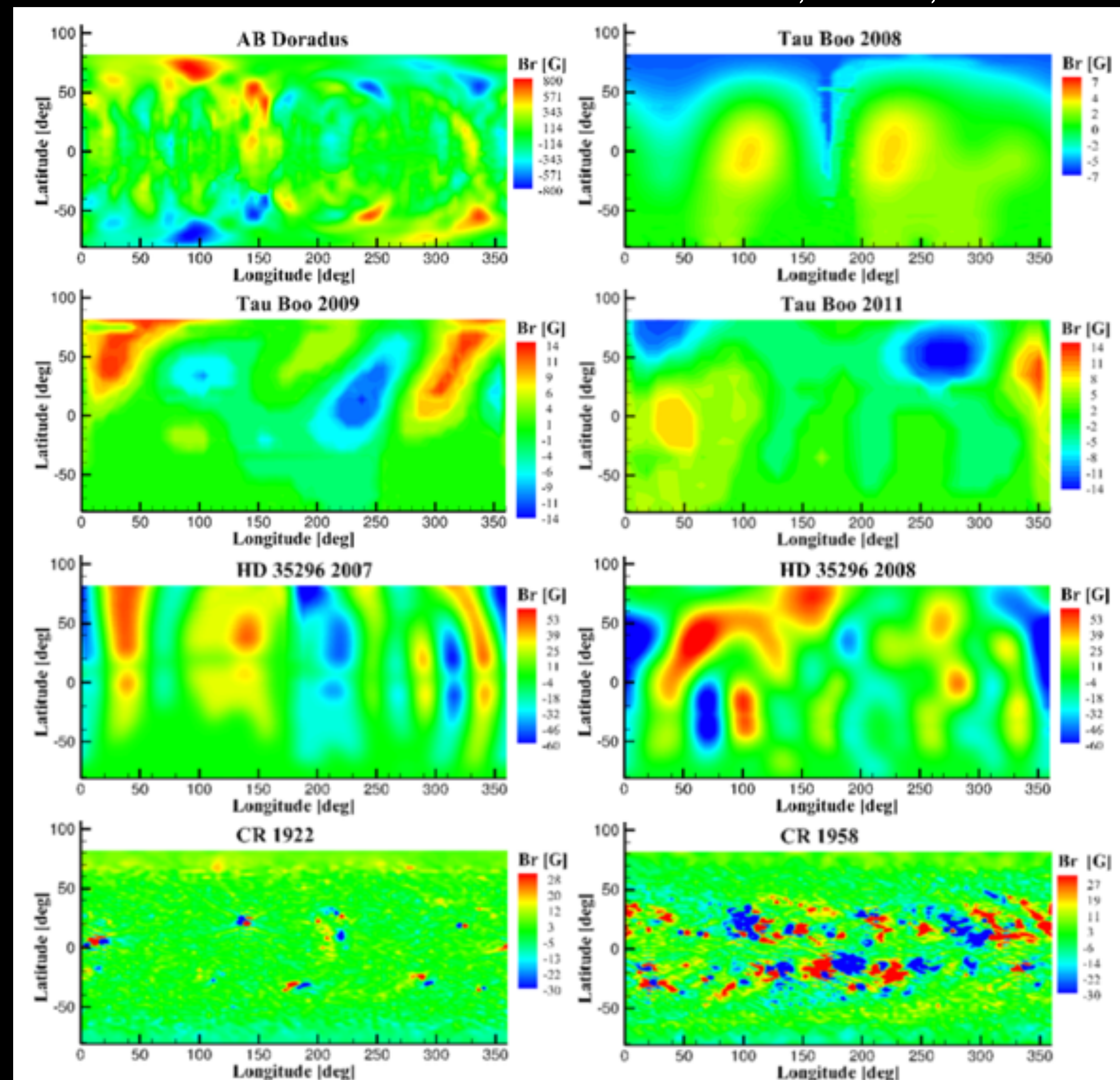
AM loss rates strongly suppressed

Rotation Evolution of Sun-Like Stars
Application to Real Stars

Garraffo et al., 2016, in Press

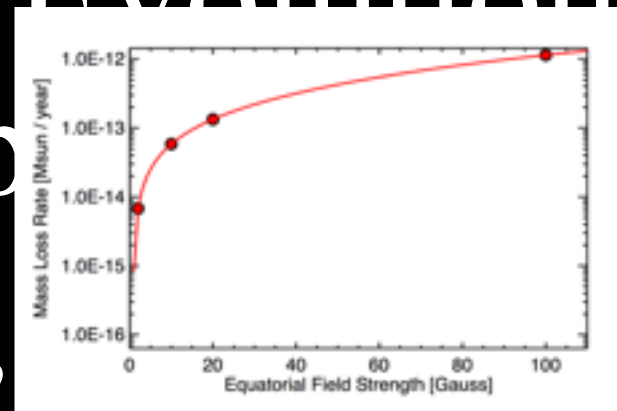


$$n_{av} = \sum_{n=0}^{n_{max}} \frac{n\,F_n}{F_T}$$

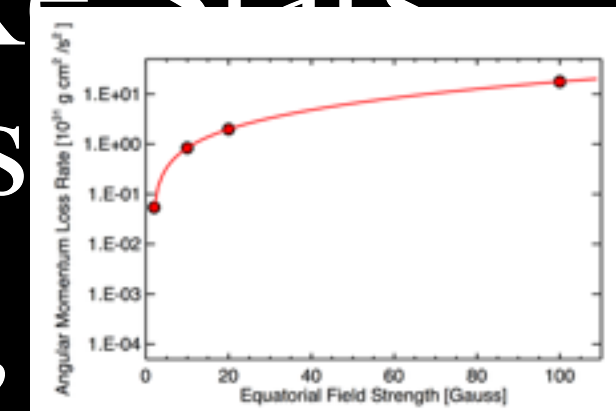


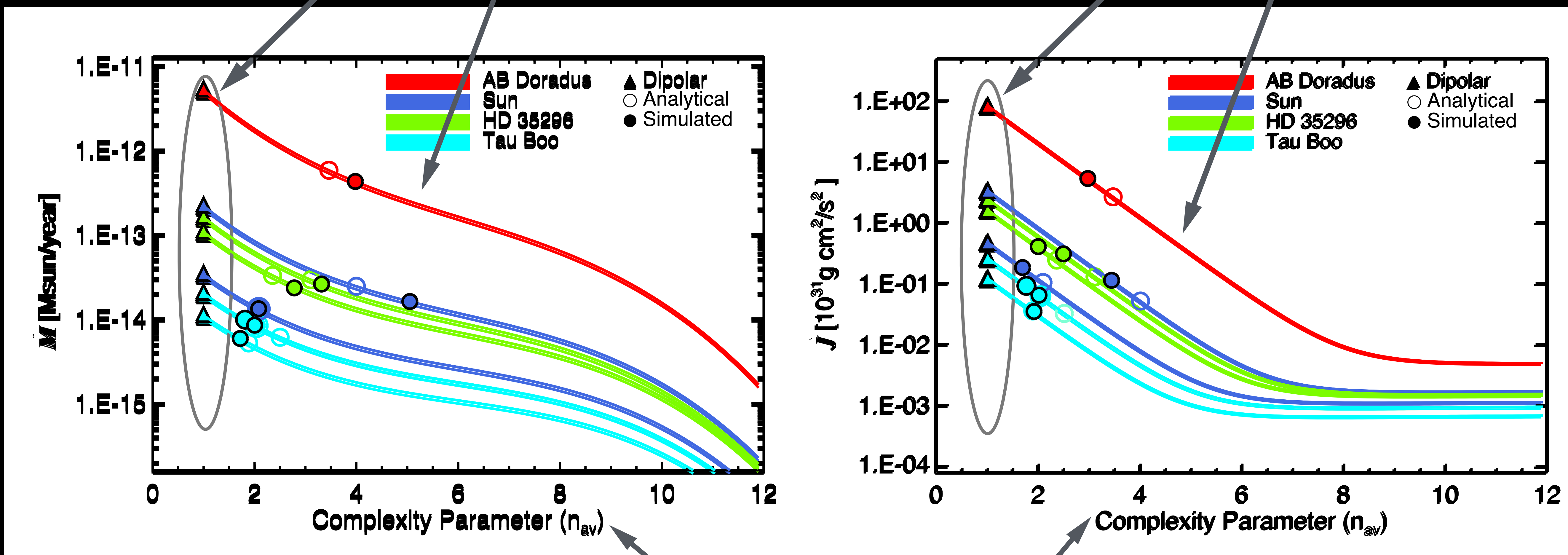
Rotation Evolution of Sun-Like Stars
Ap o Real Stars

$\dot{M} = \dot{M}_{Dip}$



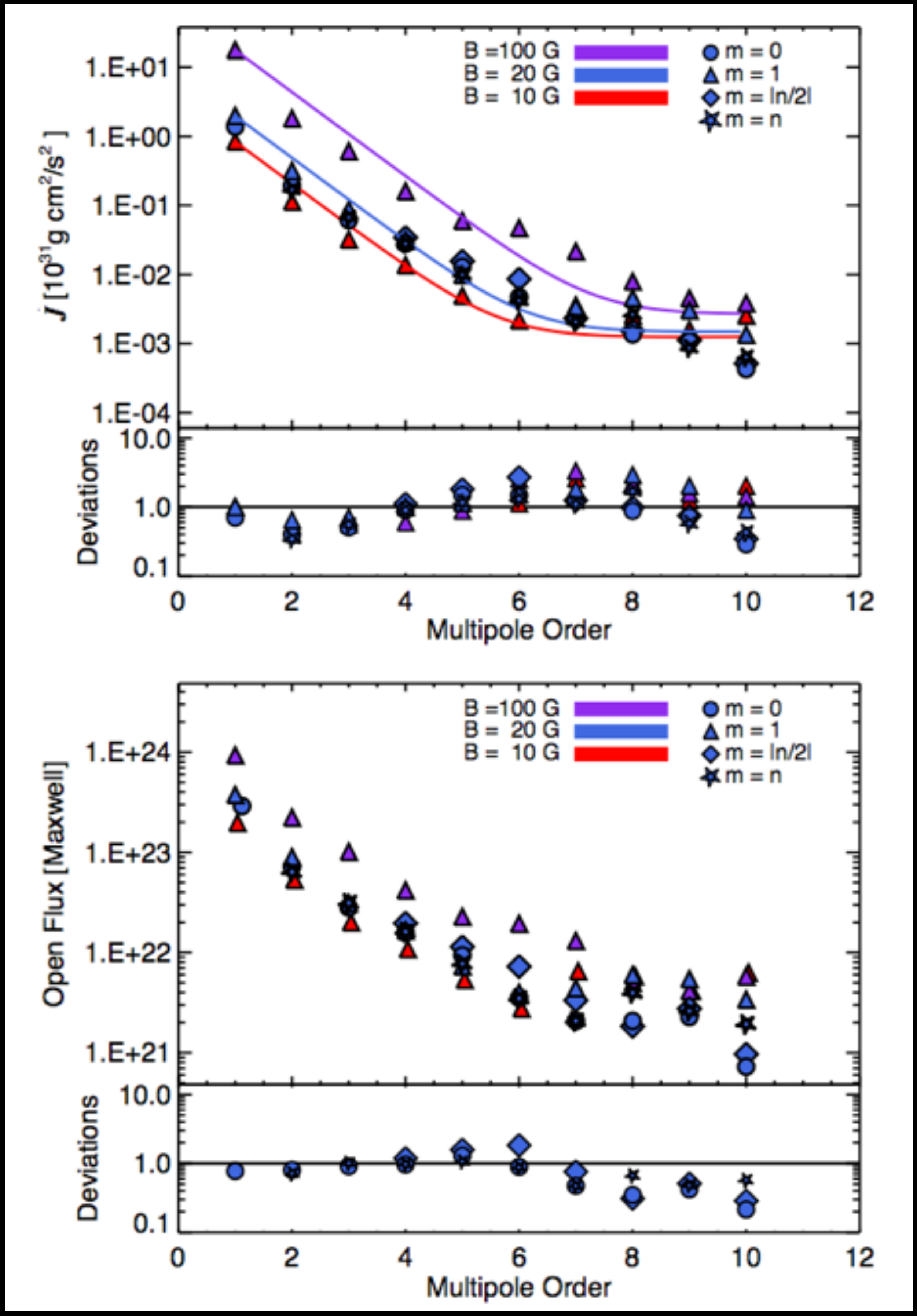
$\dot{J} = \dot{J}_{Dip}$





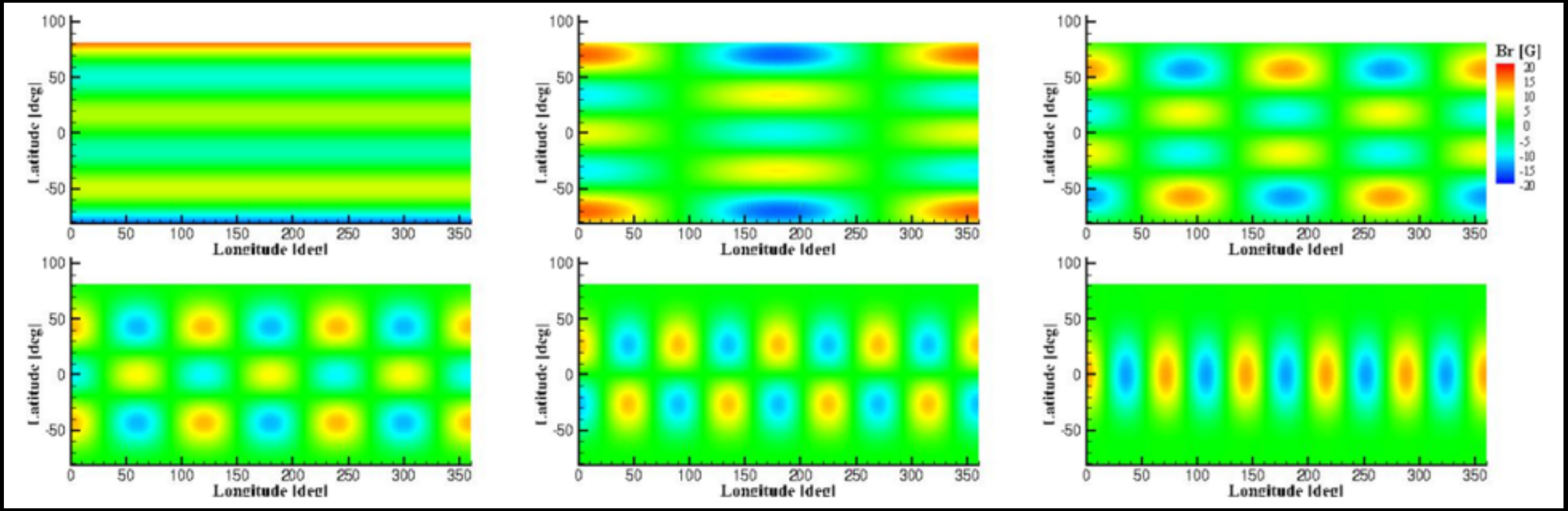
Garraffo et al., 2016, in Press

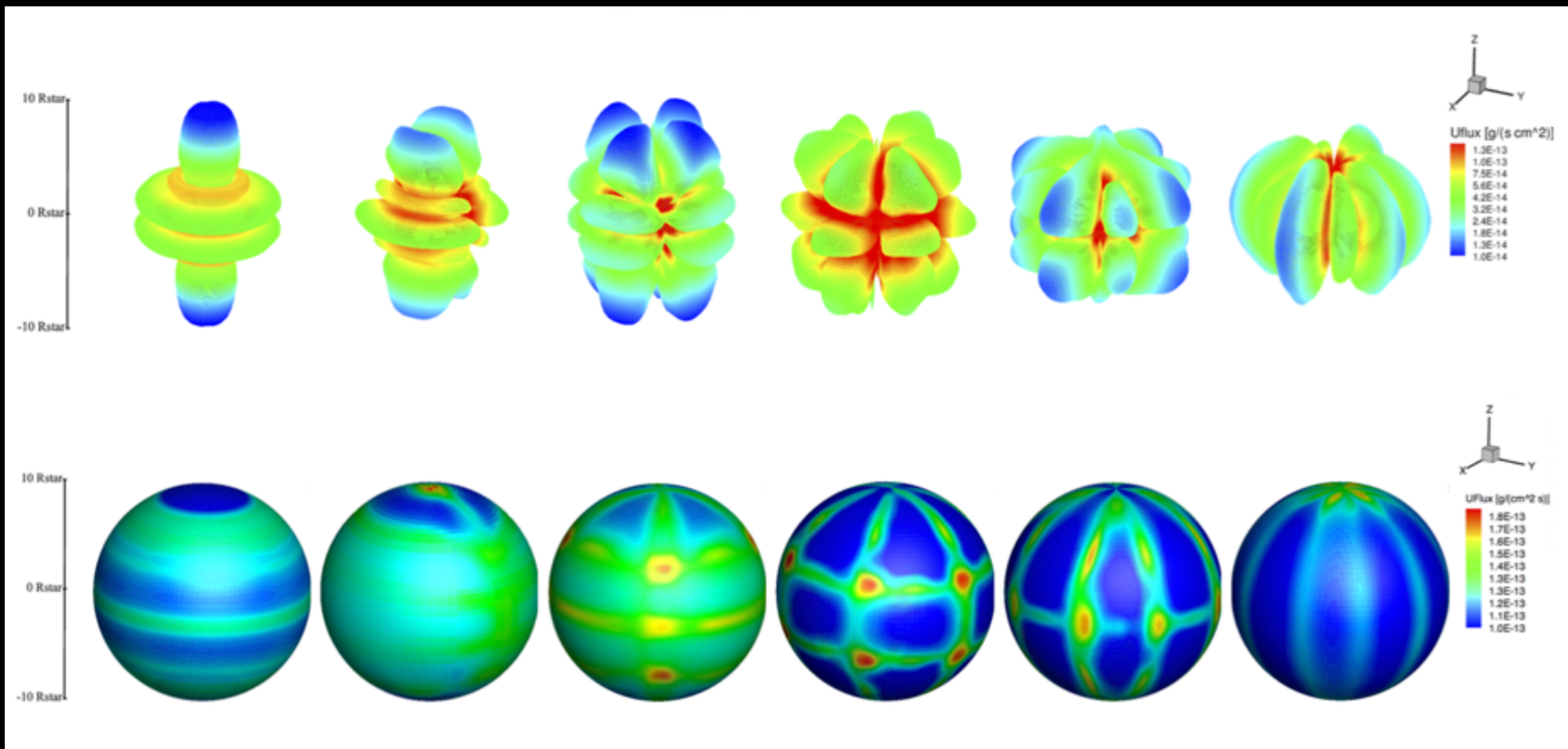
$$n_{av} = \sum_{n=0}^{n_{max}} \frac{n\,F_n}{F_T}$$



B =100 G
B = 20 G
B = 10 G
m = 0
m = 1
m = |n/2|
m = n
$\dot{J}$ [10^{31} g cm^2/s^2]
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
Deviations
10.0
1.0
0.1
0
2
4
6
8
10
12
Multipole Order
Open Flux [Maxwell]
1.E+24
1.E+23
1.E+22
1.E+21

n=5



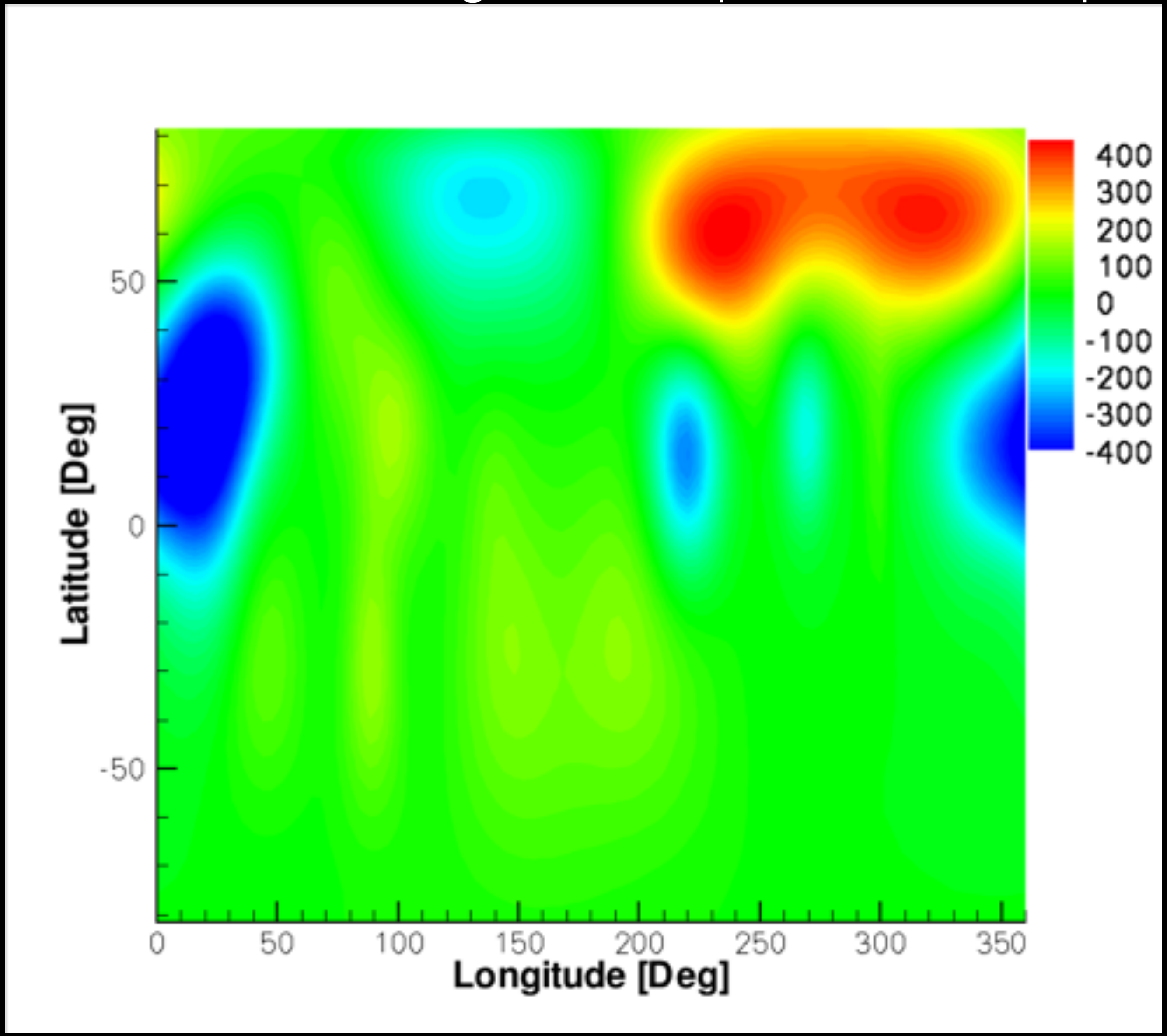

10 Rstar
0 Rstar
-10 Rstar
Z
Y
X
Uflux [g/(s cm^2)]
1.3E-13
1.0E-13
7.5E-14
5.6E-14
4.2E-14
3.2E-14
2.4E-14
1.8E-14
1.3E-14
1.0E-14
10 Rstar
0 Rstar
-10 Rstar
Z
Y
X
UFlux [g/(cm^2 s)]
1.8E-13
1.7E-13
1.6E-13
1.5E-13
1.4E-13
1.3E-13
1.3E-13
1.2E-13
1.1E-13
1.0E-13

Rotation Evolution of Sun-Like Stars

We can in principle use magnetic maps to infer the winds responsible for the angular momentum loss.

1. Is the resolution of the available observations good enough?

ZDI magnetic map for V2129 Oph

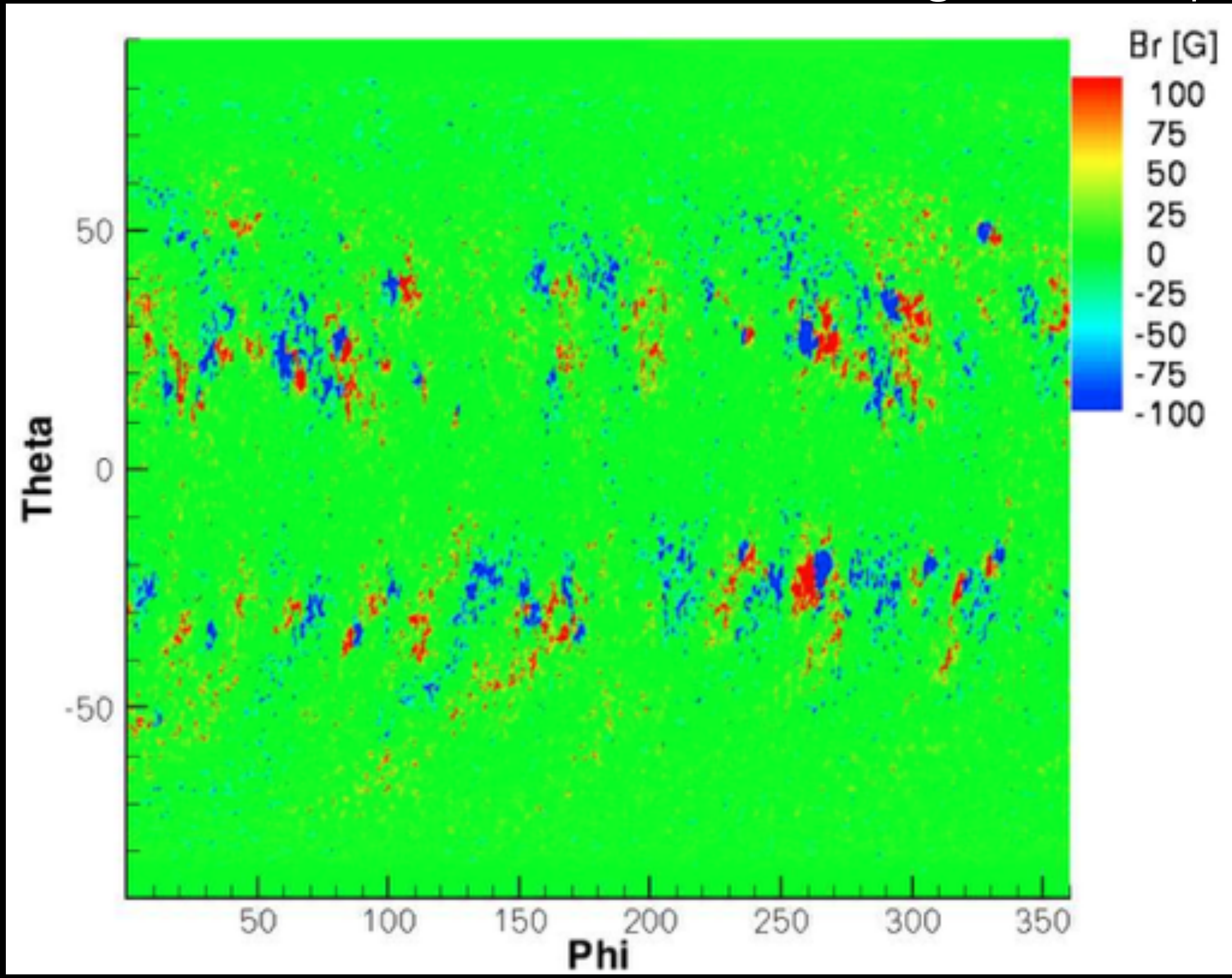


Rotation Evolution of Sun-Like Stars

We can in principle use magnetic maps to infer the winds responsible for the angular momentum loss.

1. Is the resolution of the available observations good enough?
2. Do active regions affect angular momentum loss?

Solar magnetic map

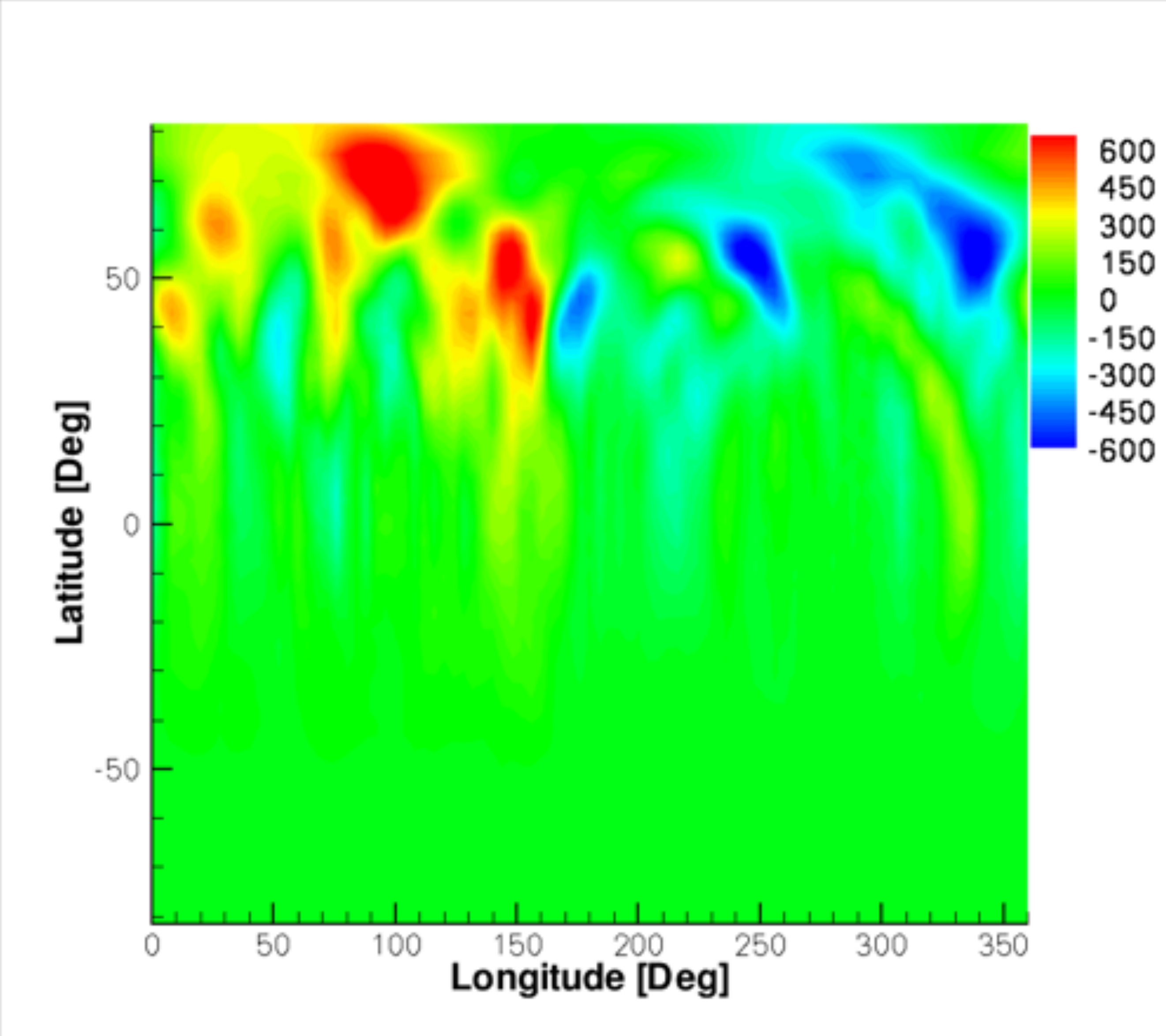


Rotation Evolution of Sun-Like Stars

We can in principle use magnetic maps to infer the winds responsible for the angular momentum loss.

1. Is the resolution of the available observations good enough?
2. Do active regions affect angular momentum loss?
3. How much does large scale morphology matter?

AB Doradus



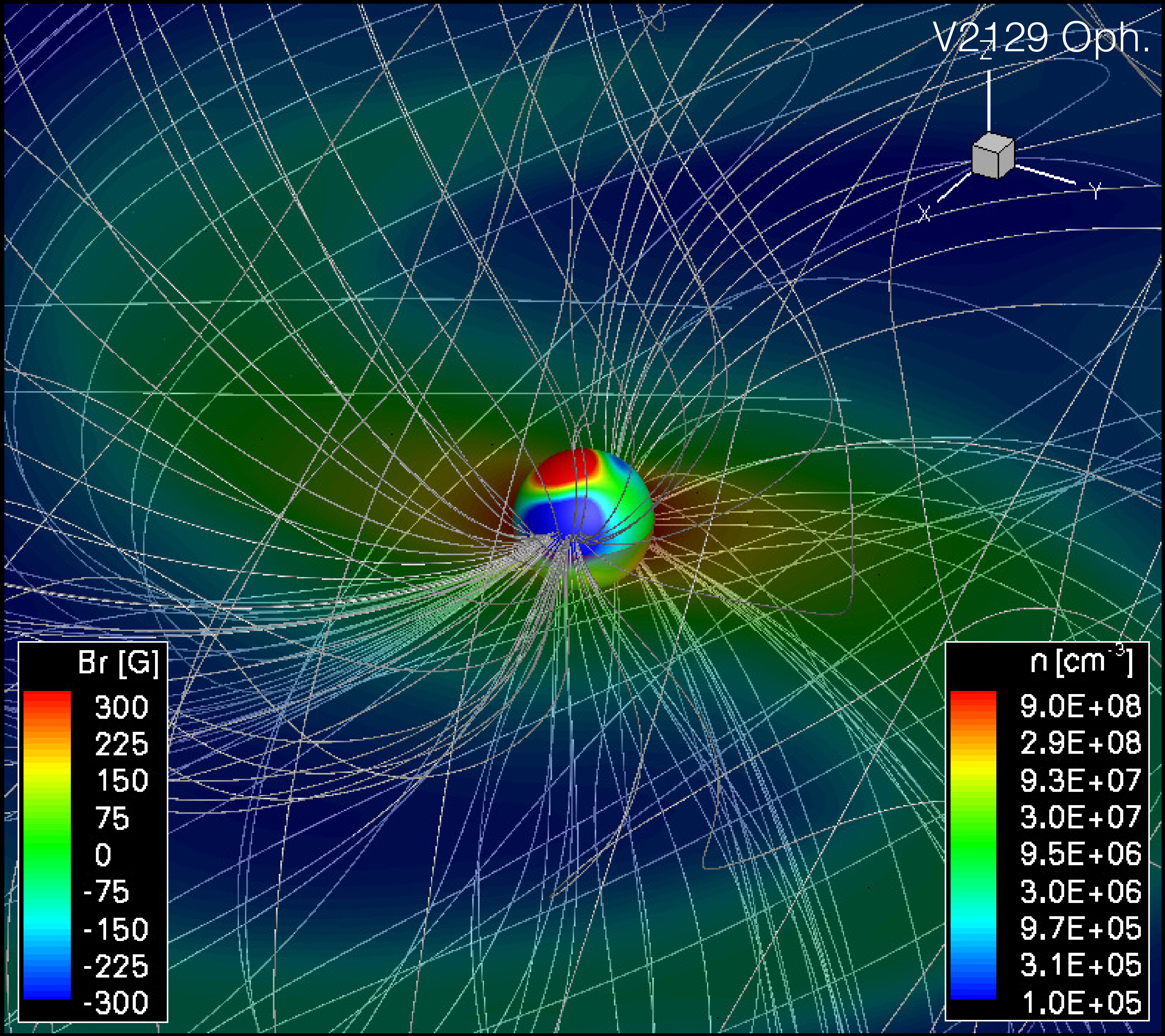
Rotation Evolution of Sun-Like Stars

BATS-R-US
(U. of Michigan)
3D MHD code,
see Ofer Cohen's
poster 268

magnetic map

↓

3D corona
solution



Rotation Evolution of Sun-Like Stars

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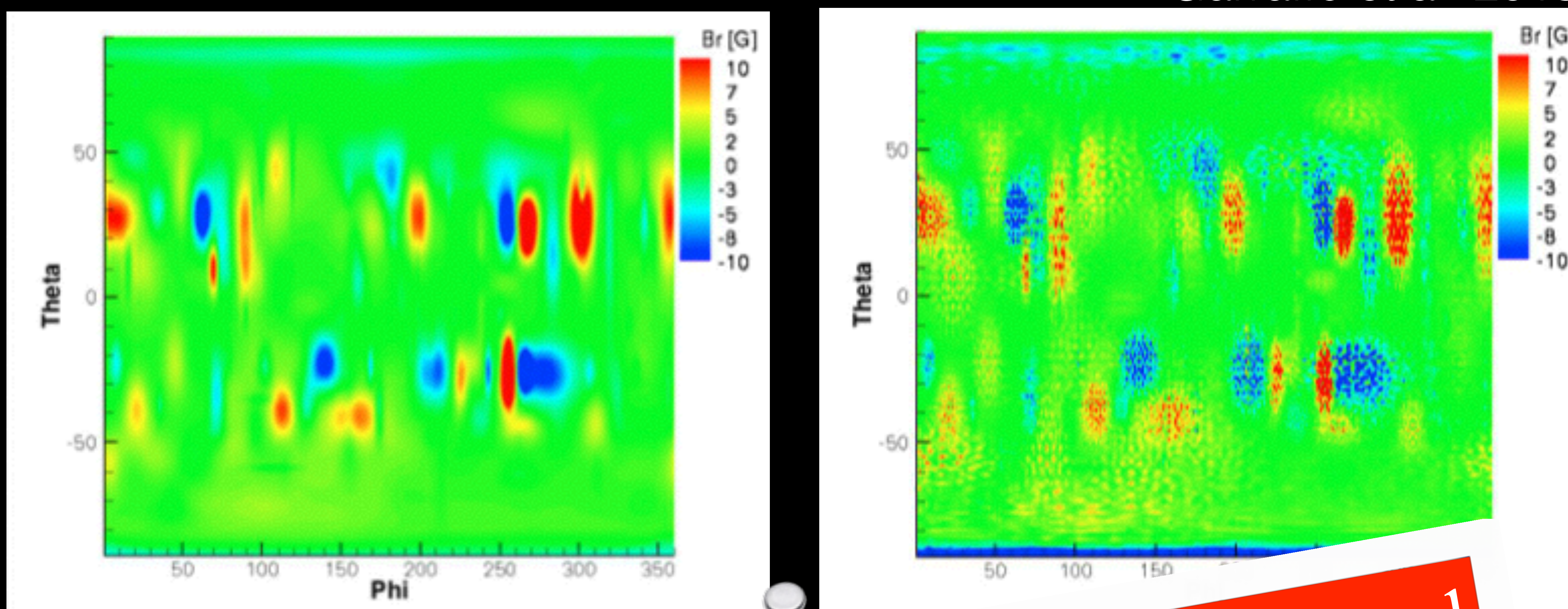
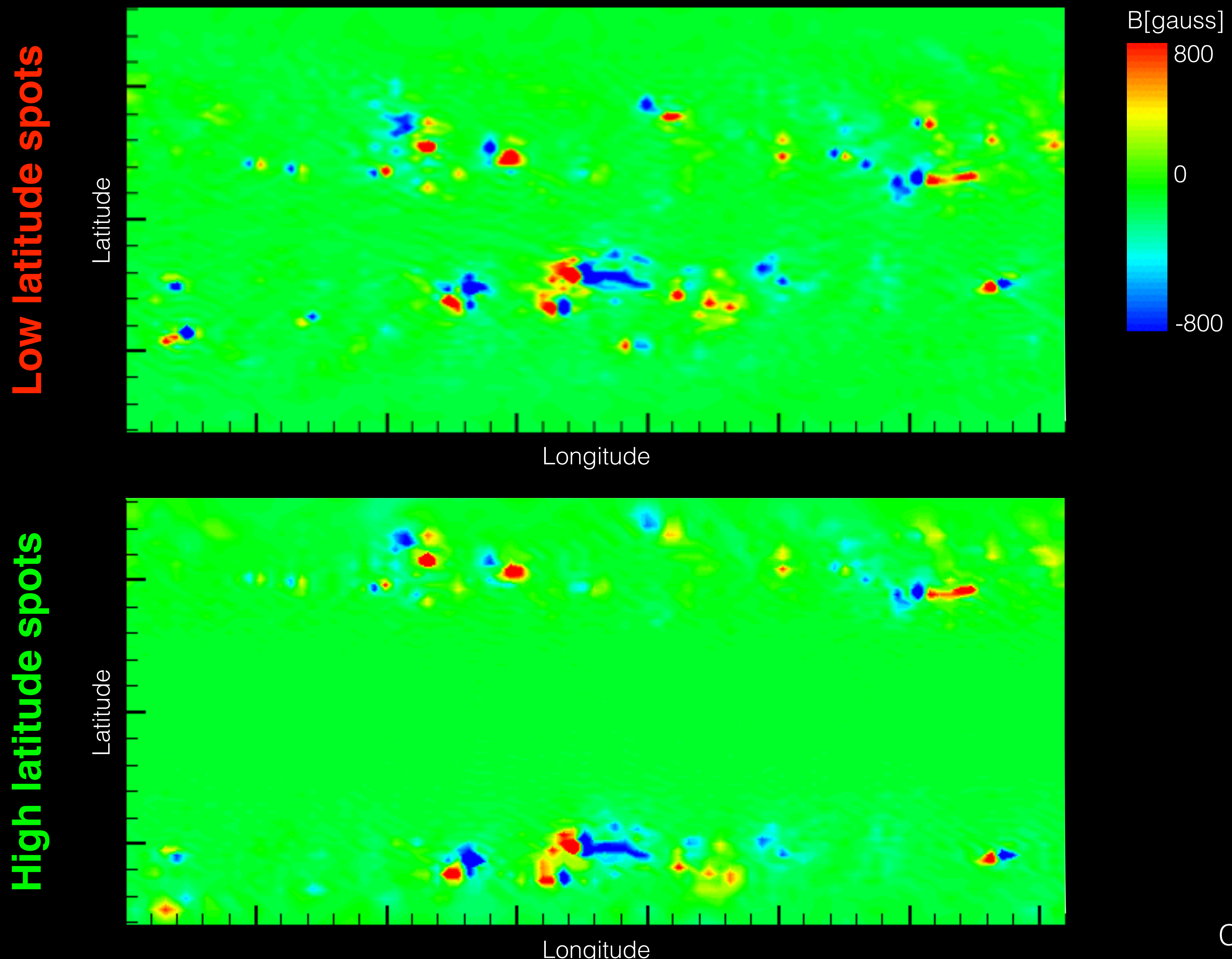
Garraffo et al. 2013



Wind structure is not significantly affected

Rotation Evolution of Sun-Like Stars

2. Do active regions affect angular momentum loss?



Rotation Evolution of Sun-Like Stars

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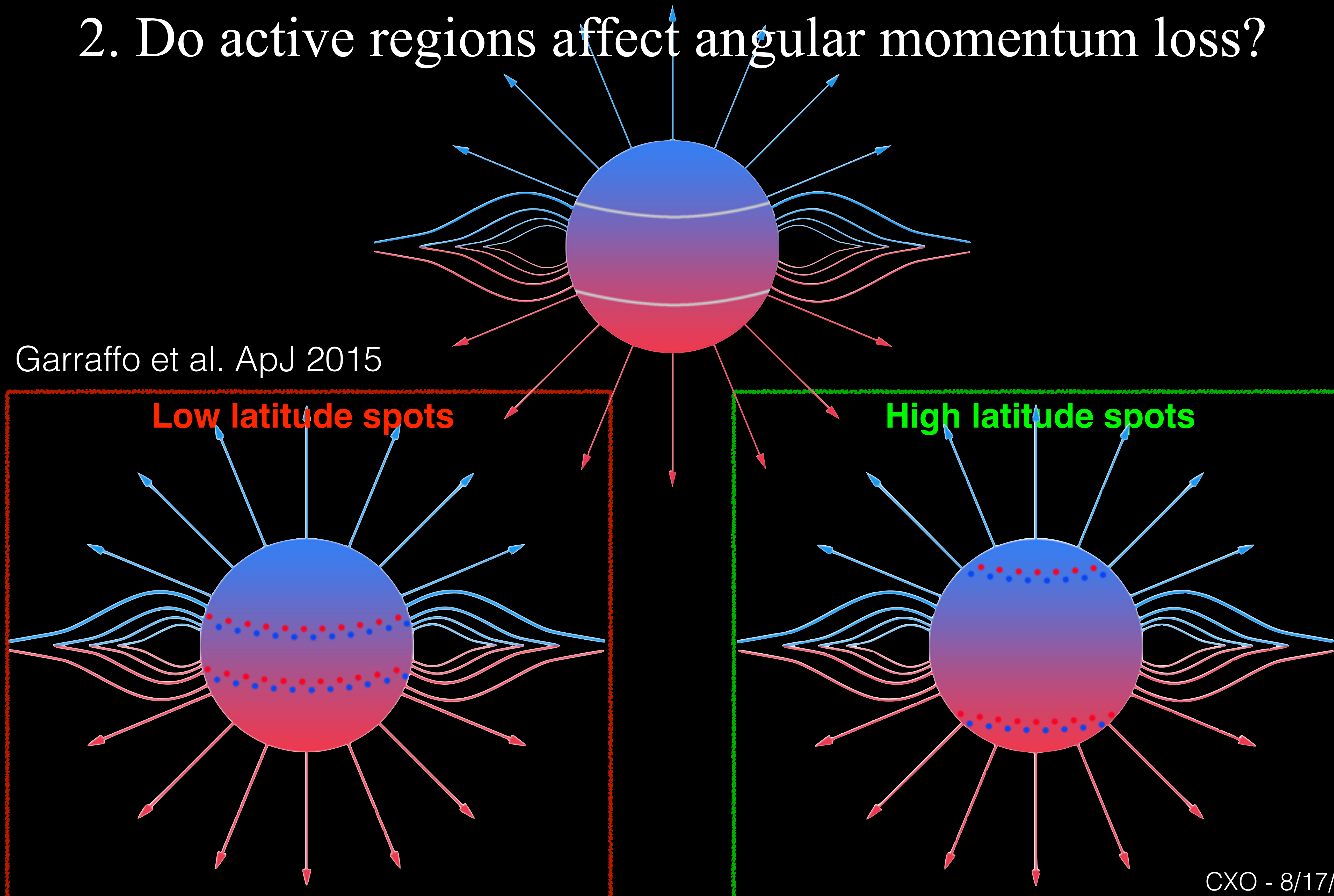
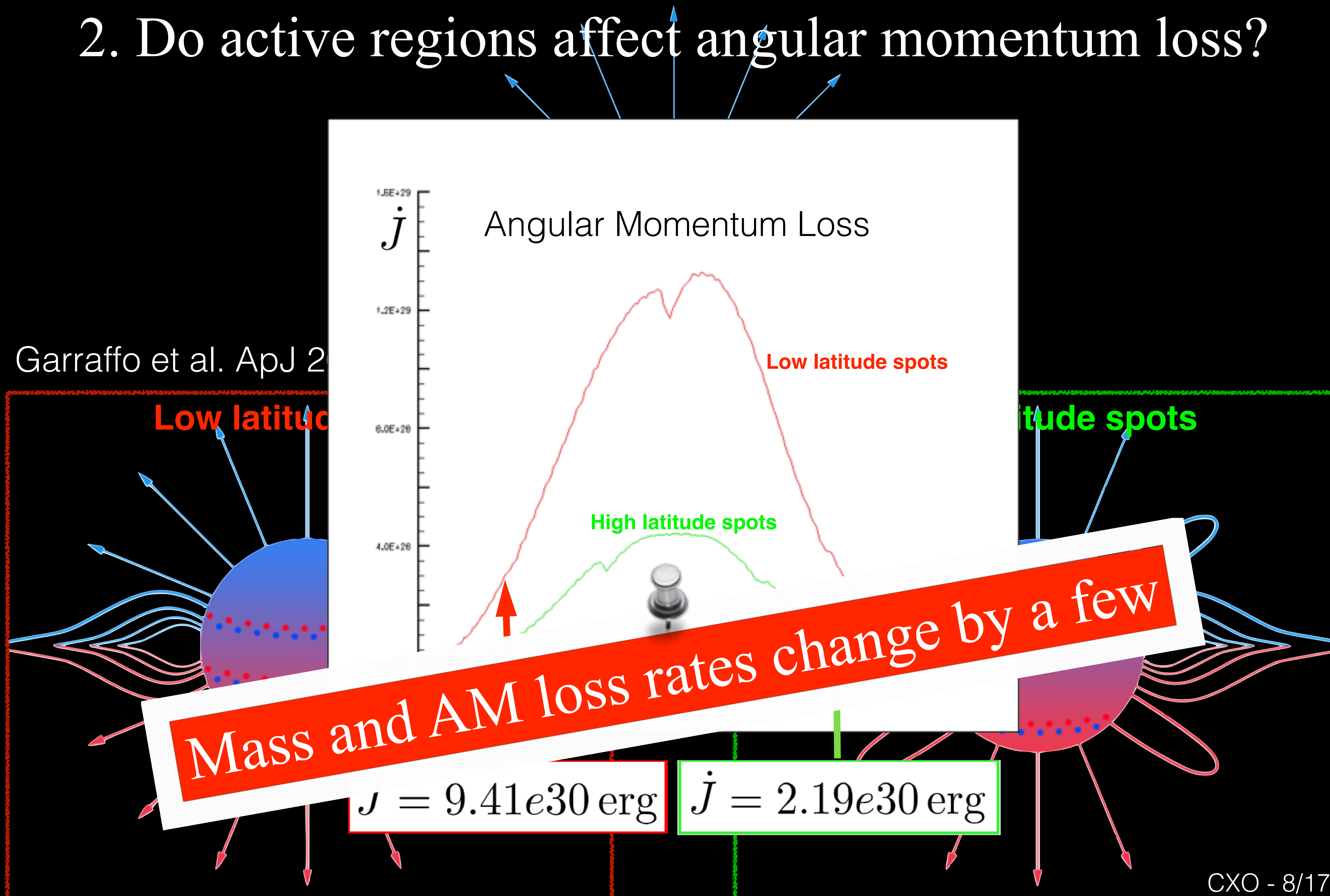


Rotation Evolution of Sun-Like Stars

2. Do active regions affect angular momentum loss?

Garraffo et al. ApJ 2



THE CHANDRA DEEP FIELD–NORTH SURVEY. XVII. EVOLUTION OF MAGNETIC ACTIVITY IN OLD LATE-TYPE STARS. Feigelson et al. 2004

"We examined the complexity of the reconstructed large scale magnetic field, by considering the magnetic energy in all spherical harmonic modes with $l \leq 2$. This includes dipolar and quadrupolar modes, and their corresponding toroidal modes. **We find a trend towards decreasing complexity with increasing rotation period**, illustrated in Fig 8, and a similar trend with increasing Rossby number. Thus it may be that faster rotators, with stronger dynamos, have more complex magnetic fields. This is in contrast to the fully convective T Tauri stars that often have simple magnetic field geometries." Folsom et al. 2016.

"Below Ro ≃ 1, stars more massive than 0.5 M⊙ succeed at producing a substantial (and sometimes even dominant) toroidal component with a **mostly non-axisymmetric poloidal component**." Donati & Landstreet 2009

"Table 4 shows that in all epochs both the poloidal and toroidal magnetic fields are very complex with o**ver 50 percent of the magnetic energy in orders higher than an octupole** (except for the poloidal magnetic energy in 2009 which has only 45 per cent of the magnetic energy in orders higher than an octupole)." HD 141943, Marsden et al. 2011.

"Like HD 171488, **this field is quite complex** and much more than that operating the Sun." Waite et al 2011.

Rotation Evolution of Sun-Like Stars

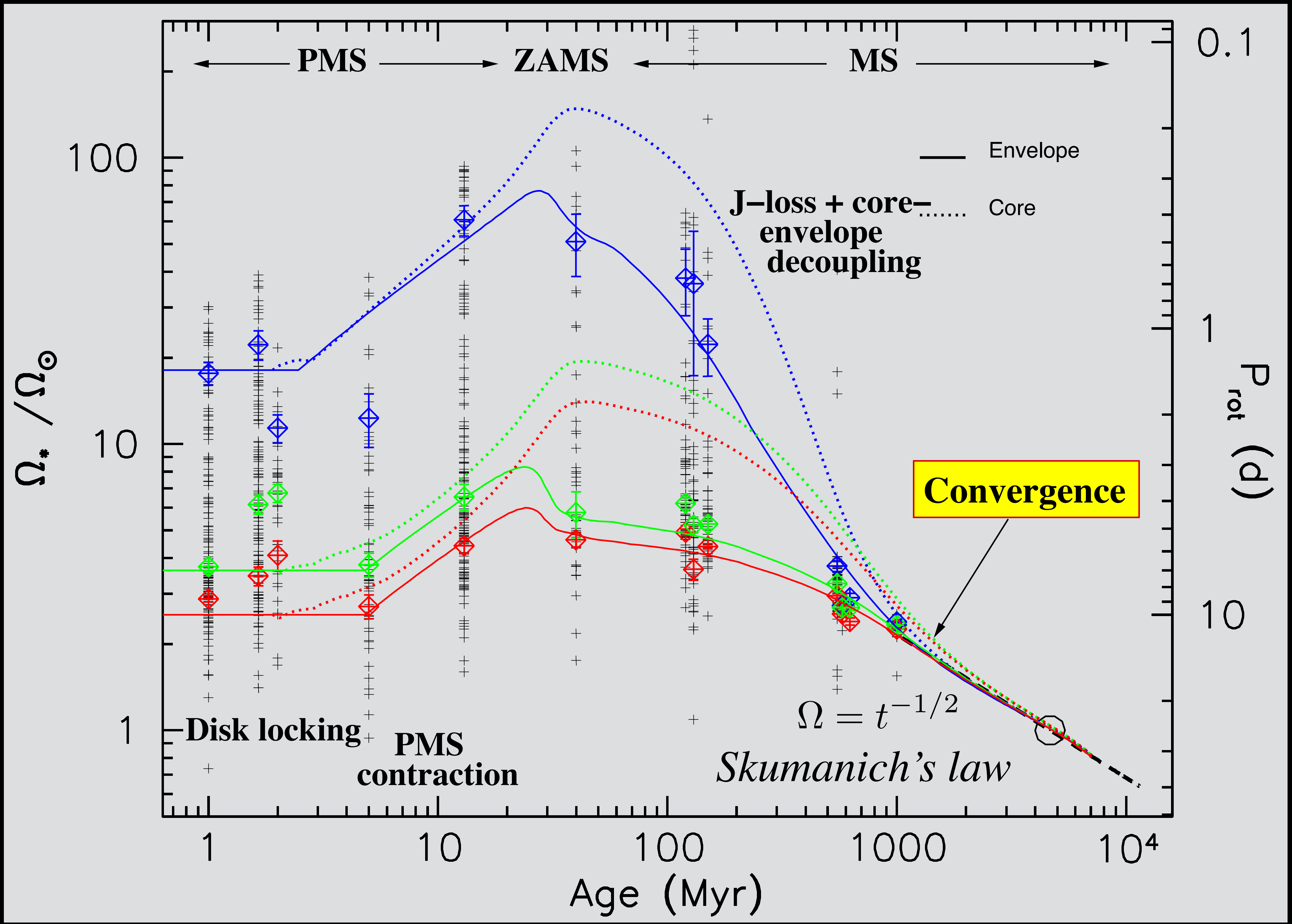
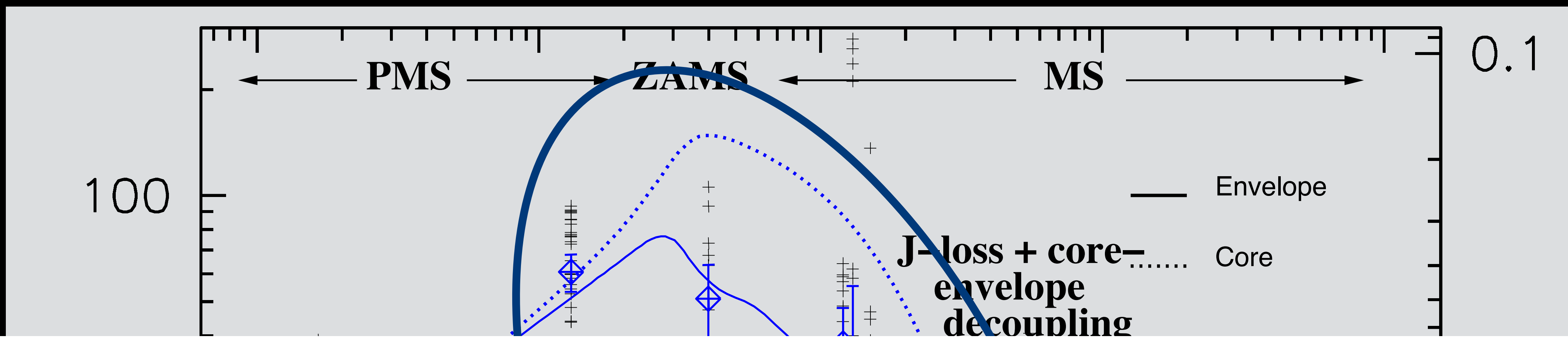
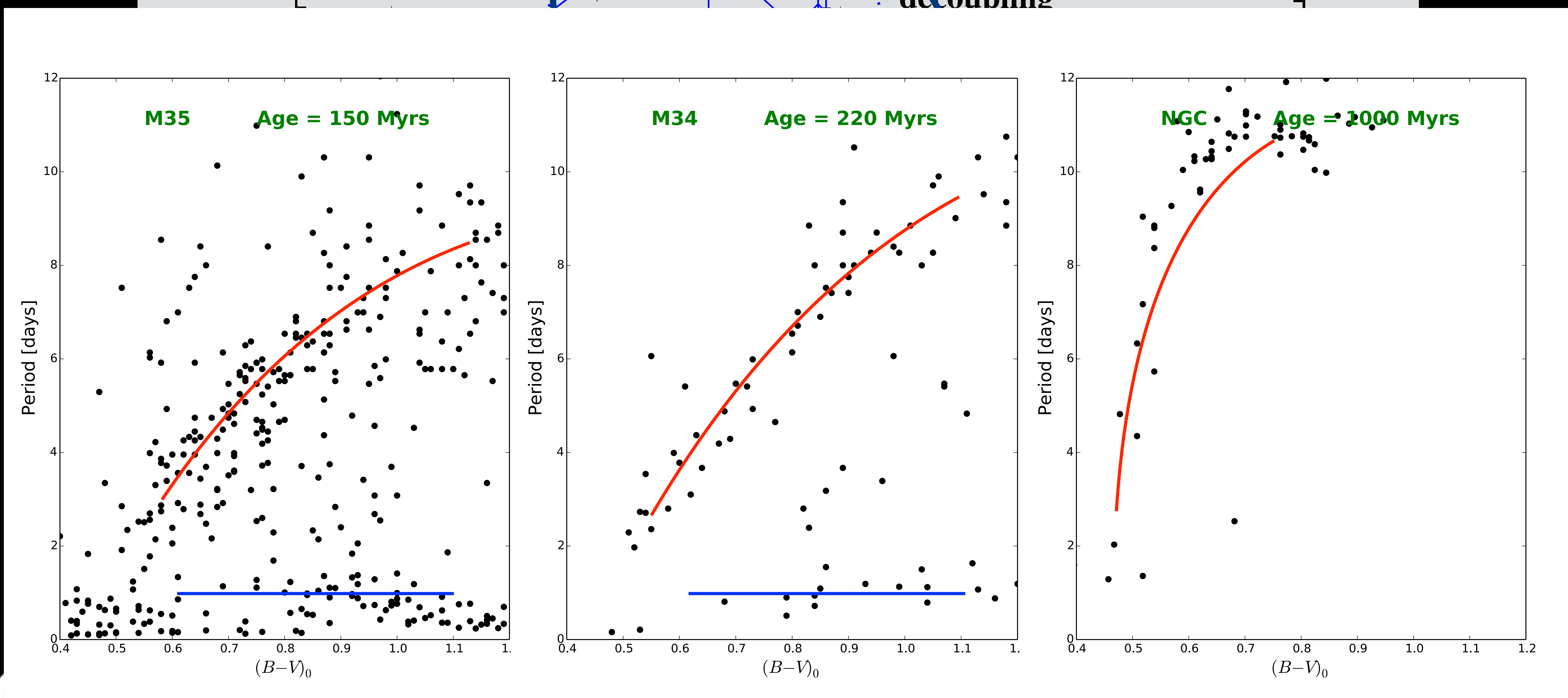


Figure from Jeffries 2014, adapted from Gallet & Bouvier 2013

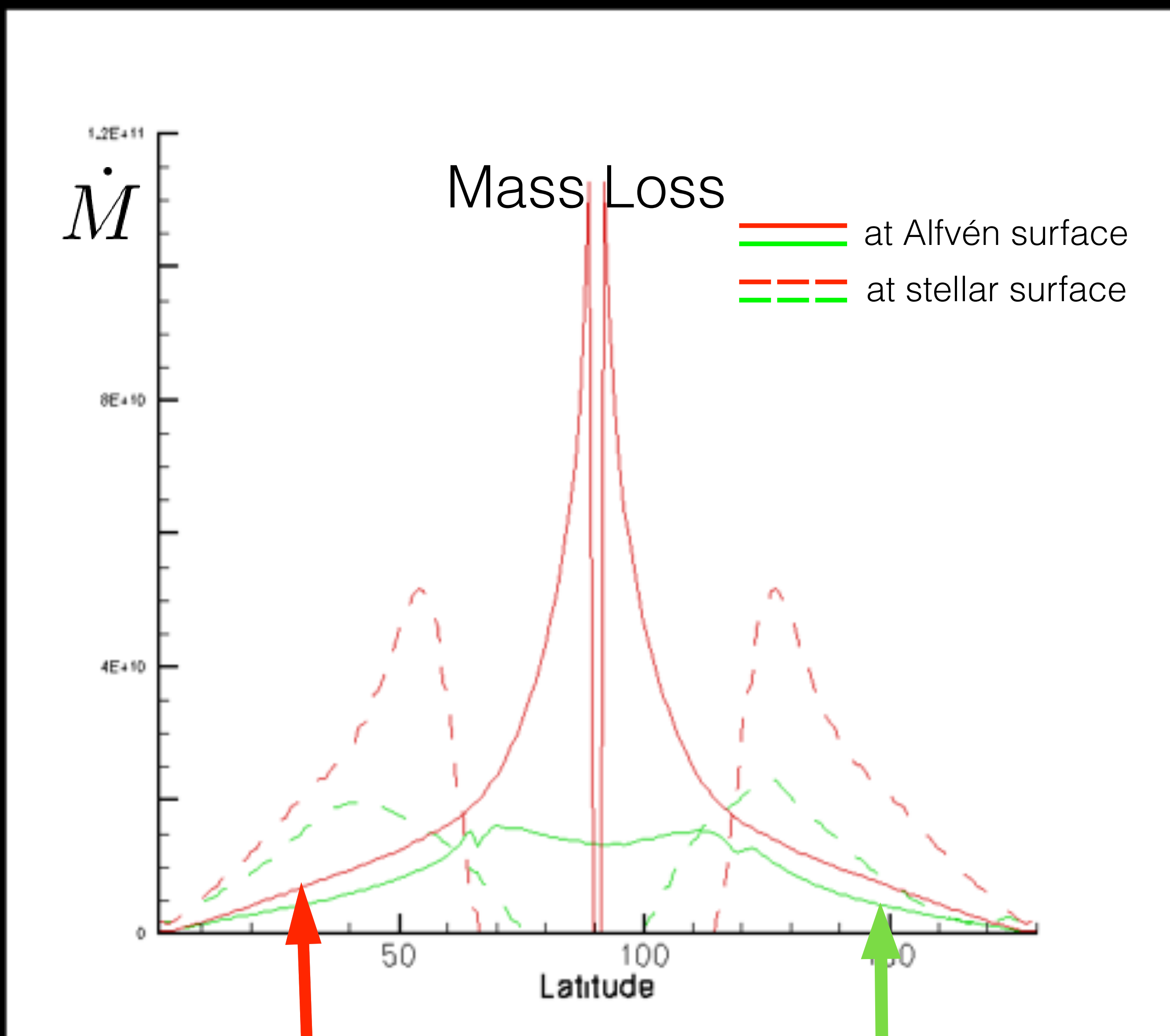
Rotation Evolution of Sun-Like Stars

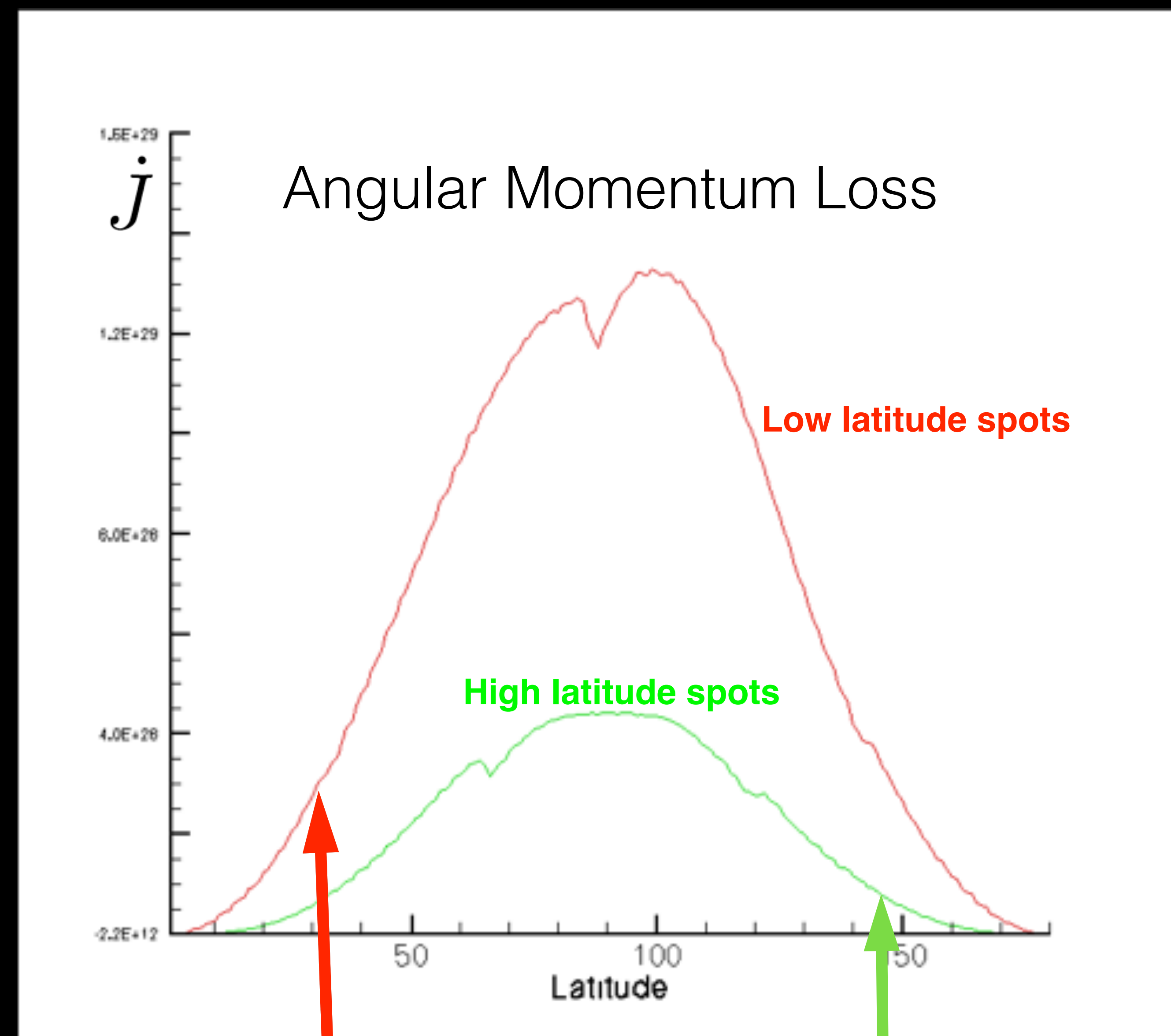




Rotation Evolution of Sun-Like Stars

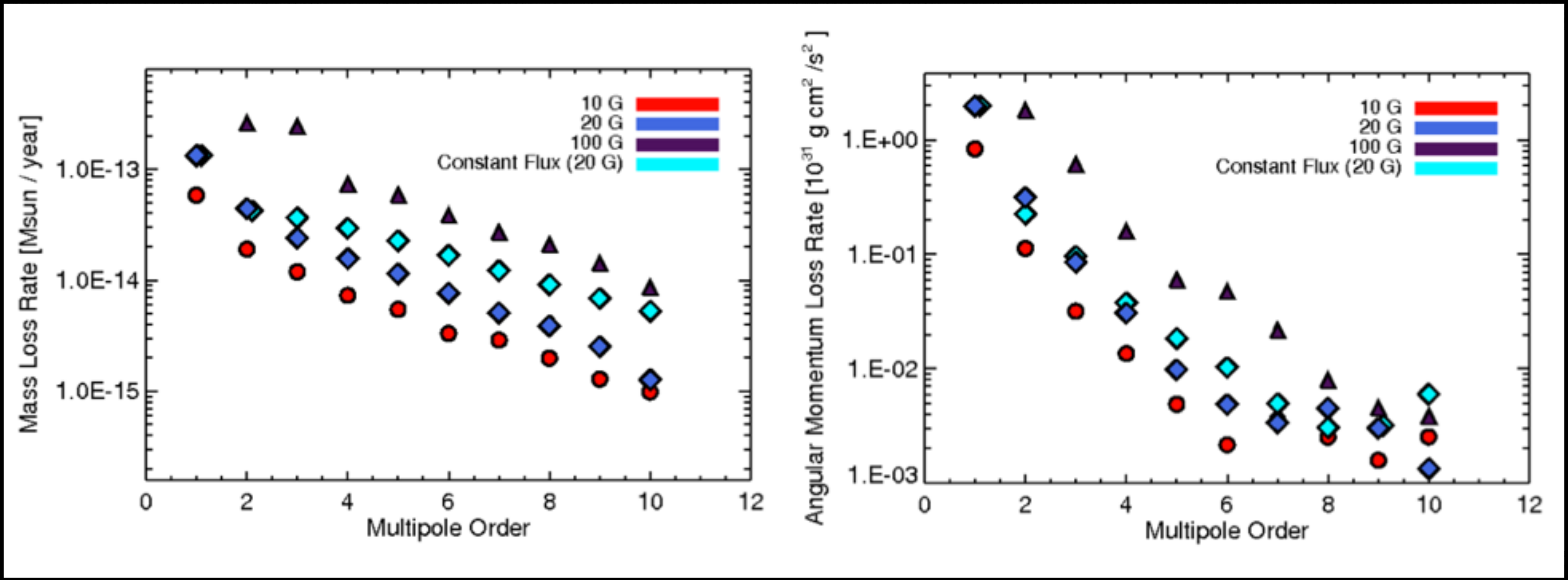
2. Do active regions affect angular momentum loss?





$\dot{M} = 1.49e12\,\mathrm{gr}$ | $\dot{M} = 8.12e11\,\mathrm{gr}$ | $\dot{J} = 9.41e30\,\mathrm{erg}$ | $\dot{J} = 2.19e30\,\mathrm{erg}$

Magnetic Morphology

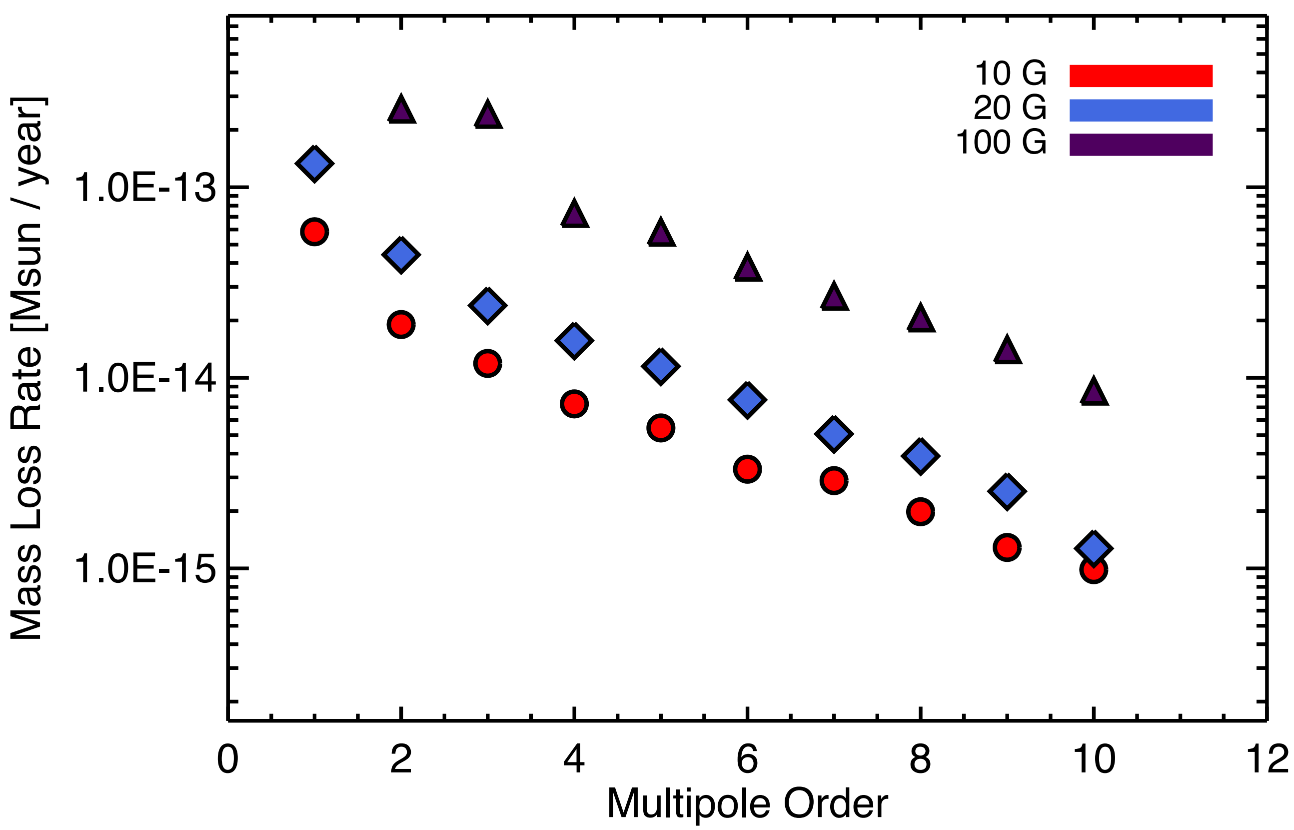


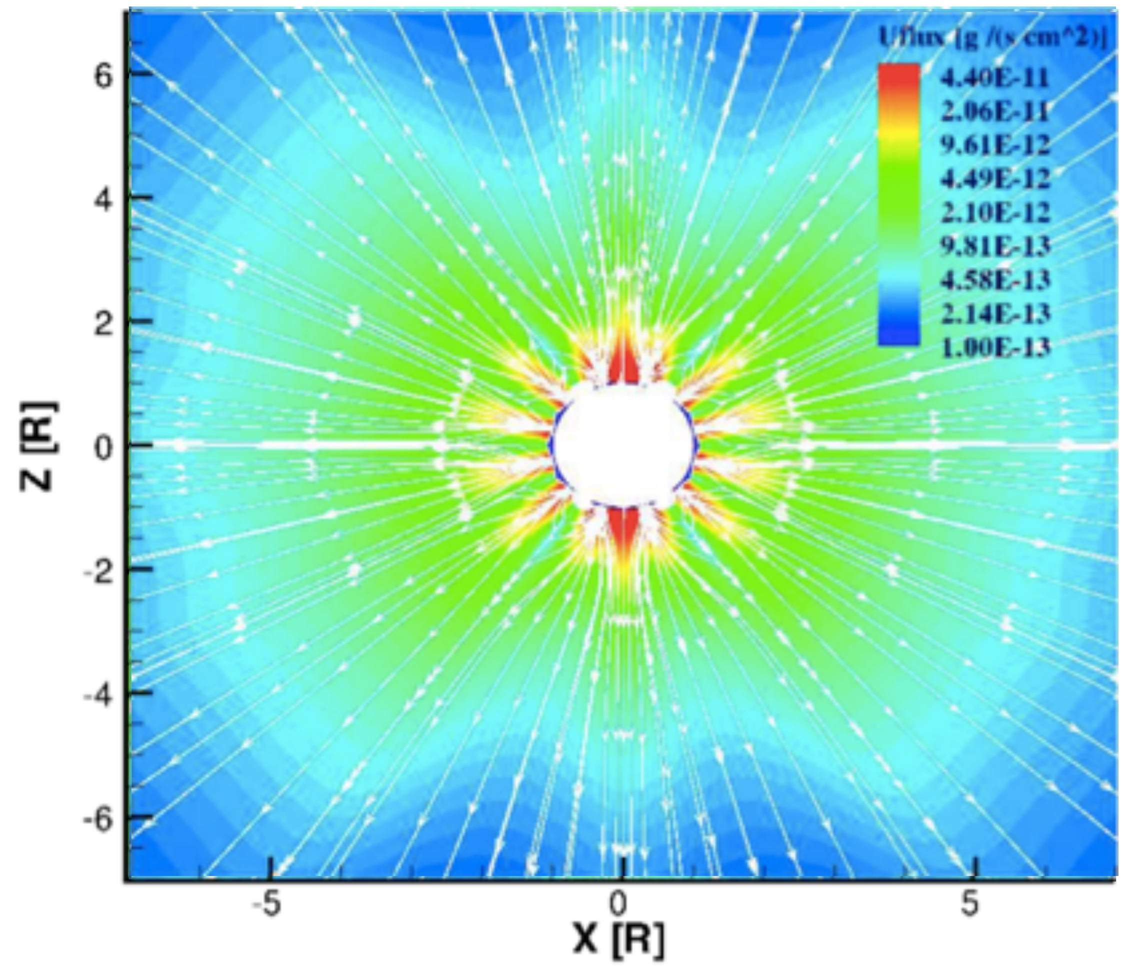
Garraffo et al., ApJL 2015

Legendre Polynomials orthogonality: $\int_{-1}^{1} P_m(x)P_n(x)dx = \frac{2}{2n+1}\delta_{mn}$

Normalization factor: $\sqrt{2/(2\cdot 1+1)}/\sqrt{2/(2\cdot n+1)} = \sqrt{(2\cdot n+1)/3}$

Magnetic Morphology

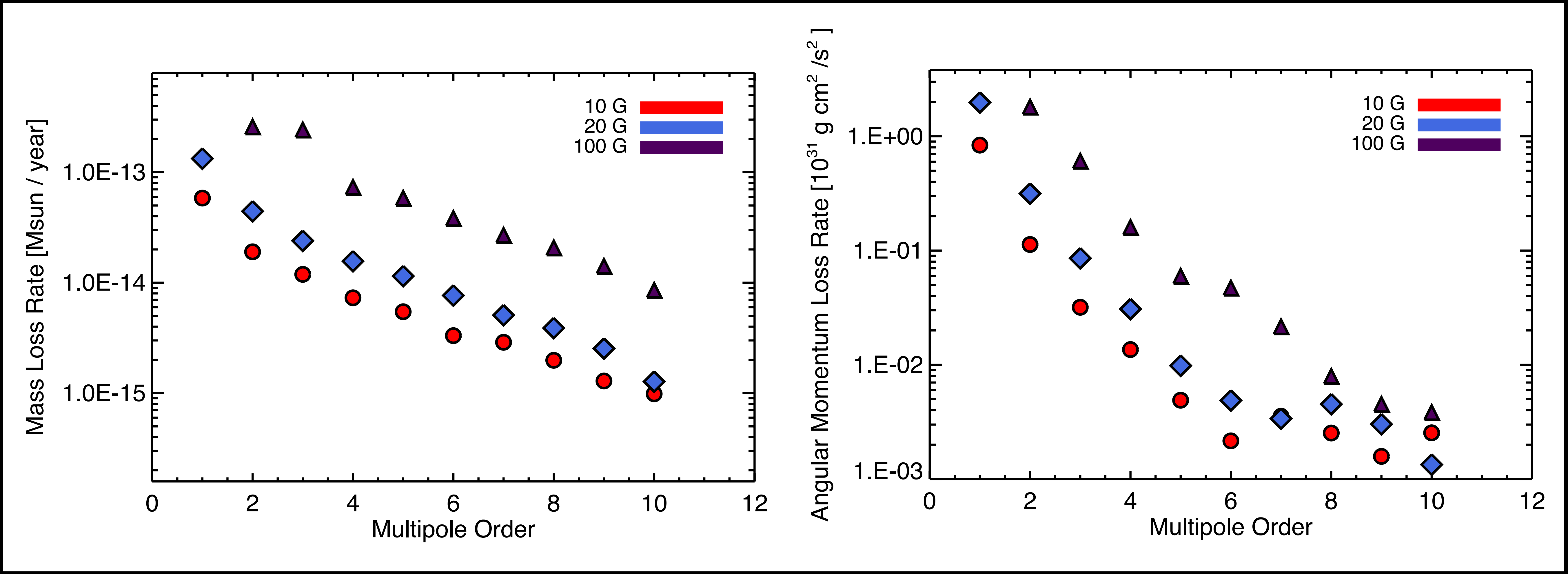




Garraffo et al., ApJL 2015

- Mass loss and spin down rates rapidly suppressed
- Mass loss becomes more homogeneously distributed over latitude
- Alfven surface gets smaller, magnetic flux decreases as $1/r^{n+1}$

Magnetic Morphology



Garraffo et al., ApJL 2015

- Similar to the coupling constant proposed by Brown:

$$\frac{dJ/dt_{dip}}{dJ/dt_{multi}} = \frac{K_{M_1}}{K_{M_0}} > 100$$