# The activity – rotation relationship for M dwarfs

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With thanks to…
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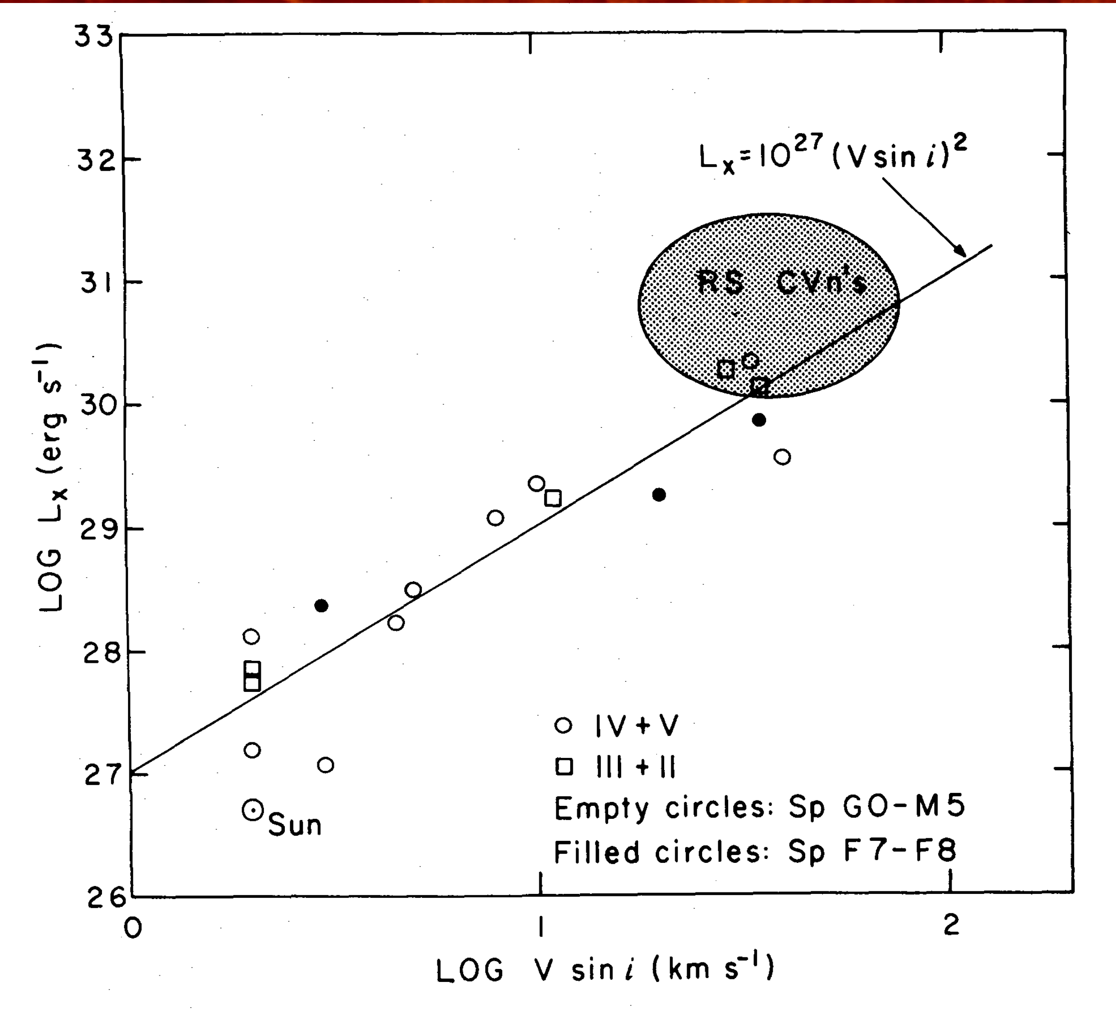
# The Rotation-Activity Relation

Correlation between tracers of magnetic activity and stellar rotation, first seen in X-rays by Pallavicini+ (1981).

Since observed in all solar- and late-type stars (Maggio+ 1987, Pizzolato+ 2003).

X-rays originate from a rarefied thermal plasma at T ~ $10^6$ K known as a corona (Vaiana+ 1981).

Observable manifestation of the stellar magnetic dynamo.




Pallavicini+ 1981

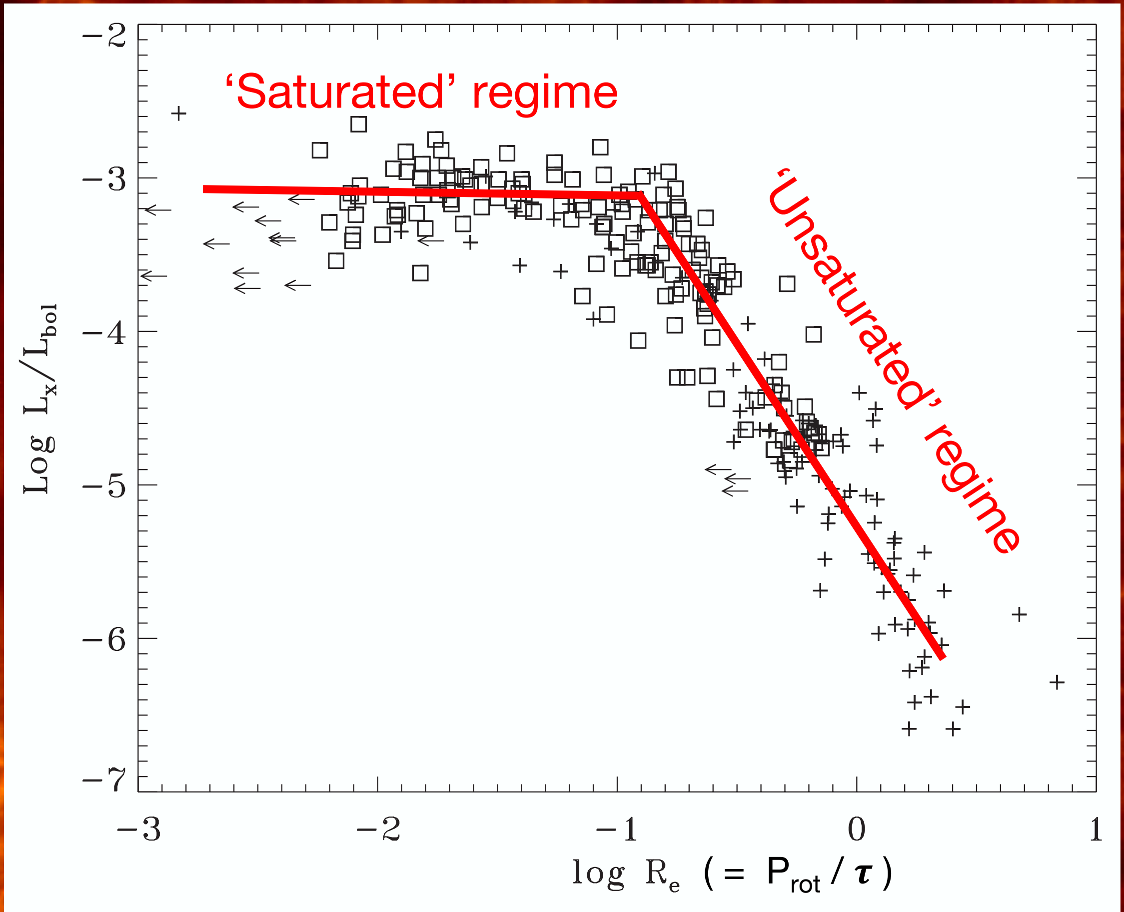
# The Rotation-Activity Relation

Largest sample of the early 2000s from Pizzolato+ 2003.

When plotted as $L_X$ / $L_{bol}$ vs Rossby number (Ro = $P_{rot}$ / $\tau$ Noyes+ 1984) a spectral type – independent diagram is produced.

Power-law relationship seen for slow rotators.

X-ray emission saturates for rapid rotators at Ro ~ 0.1 (Micela+ 1985), the origin of which is still unknown.

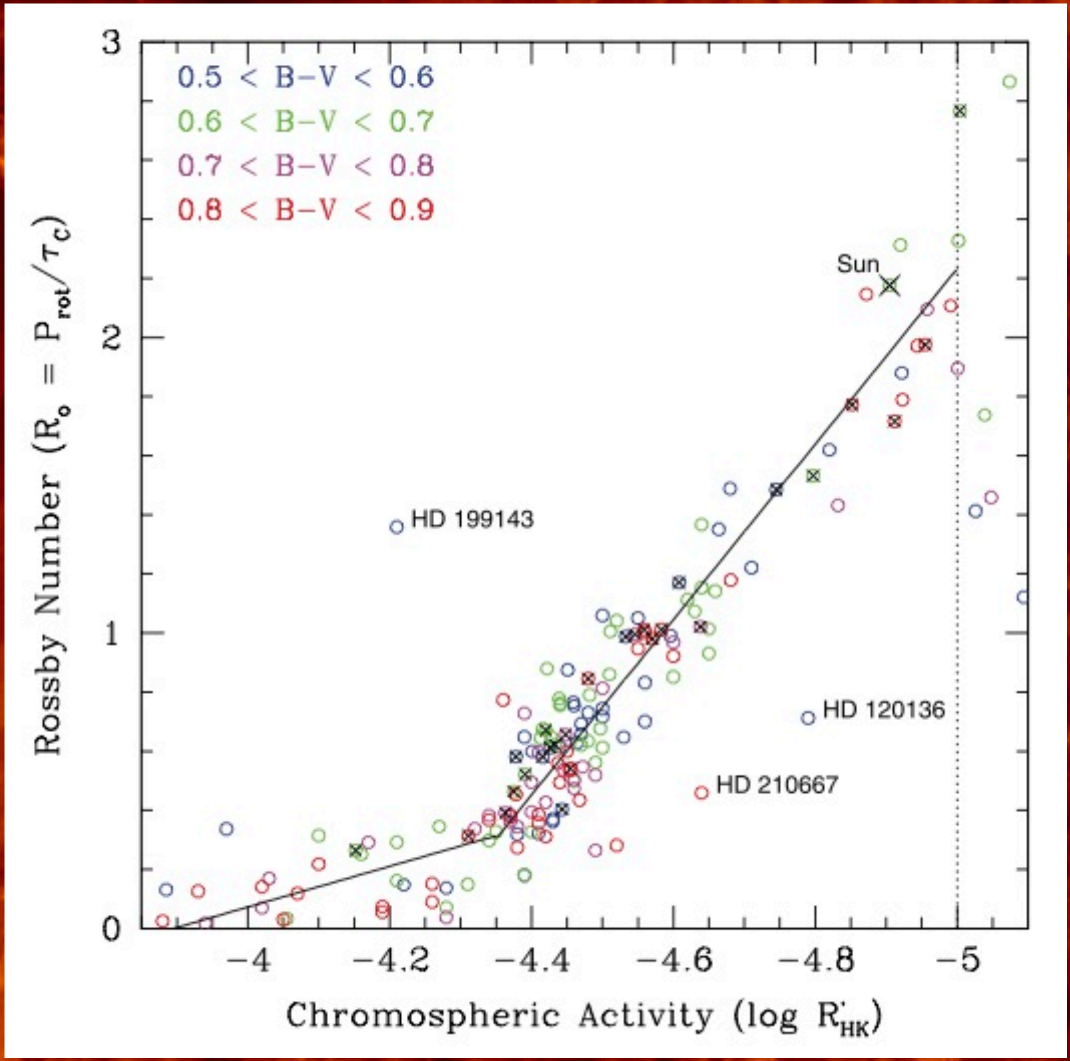



Pizzolato+ 2003

# The Rotation-Activity Relation

Rotation-activity relationship also seen in chromospheric Hα emission (e.g., Mamajek & Hillenbrand 2008, West+ 2015, Newton+ 2017).

Suggestion that the correlation breaks down for rapid rotators (Ro < 0.4, Mamajek & Hillenbrand 2008), with chromospheric emission possibly saturating, but later than for coronal emission (White+ 2007).



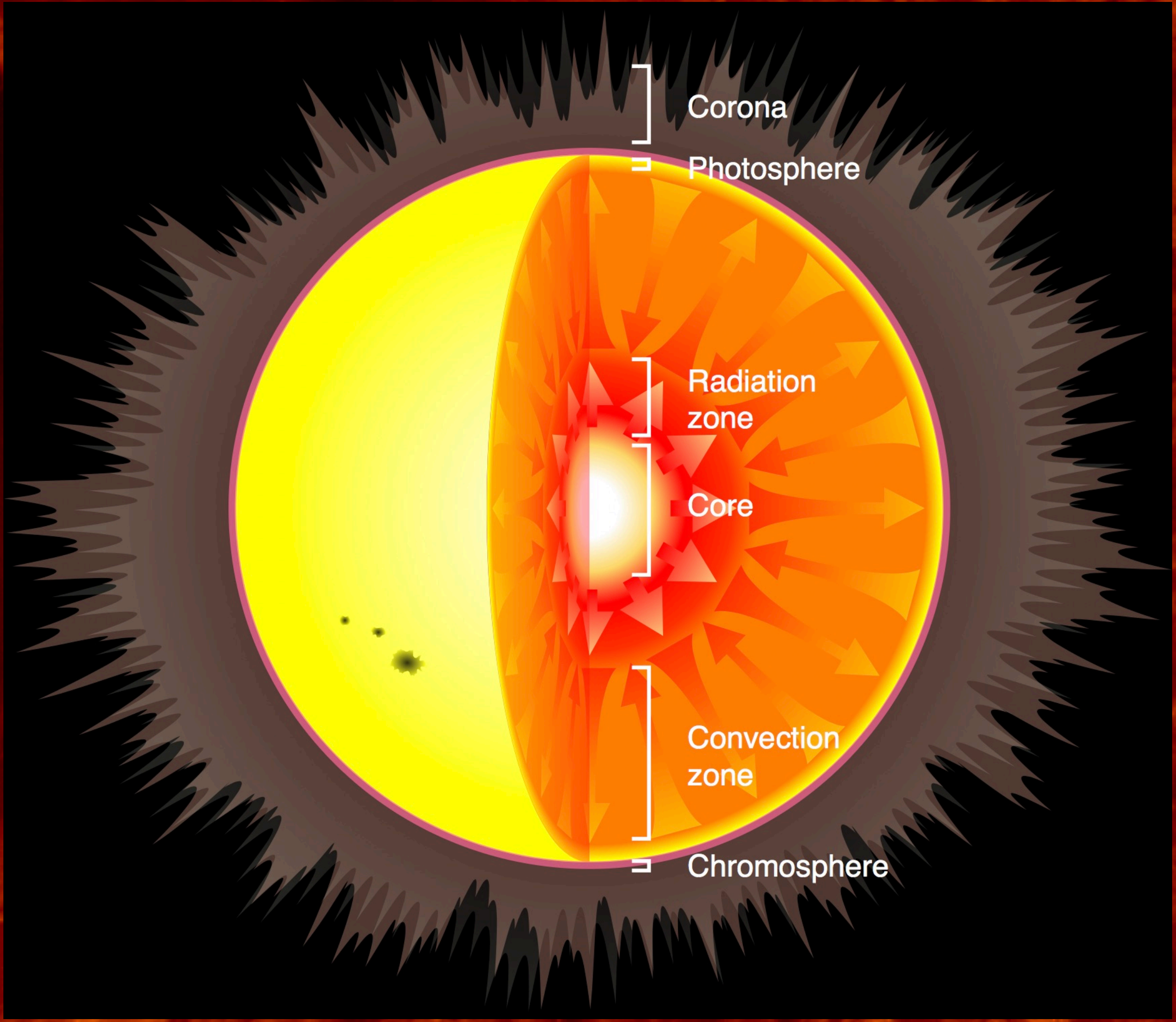

Mamajek & Hillenbrand 2008

# The Solar/Stellar Dynamo

The dynamo in these stars is believed to be the same as in the Sun, an $\alpha\Omega$ dynamo.

Dynamo is driven by a combination of rotation & turbulence.

Thought to exist in stars with radiative cores and convective envelopes (FGKM stars – more on fully convective stars later!).

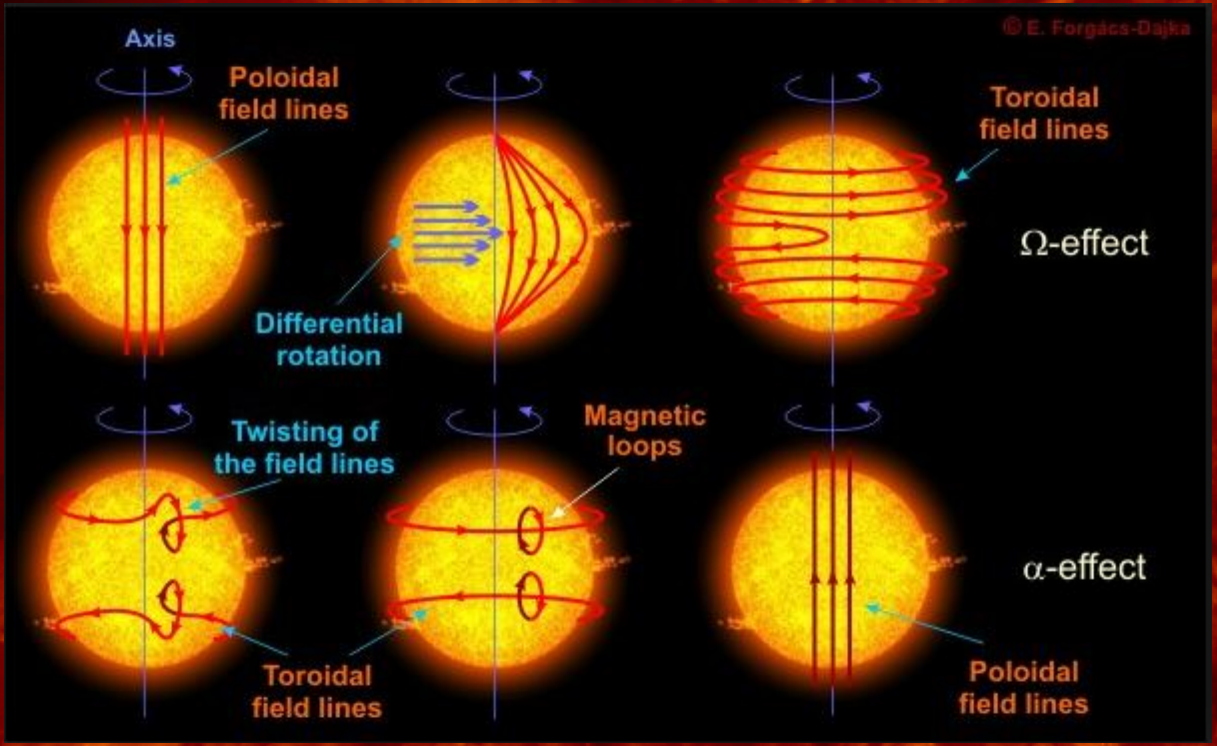



Credit: Wikipedia / Sakurambo

# The Solar/Stellar Dynamo

The $\alpha\Omega$ dynamo combines the $\Omega$–effect (due to differential rotation) and the $\alpha$-effect (from turbulence).

These processes convert a poloidal magnetic field into a toroidal field and back again.

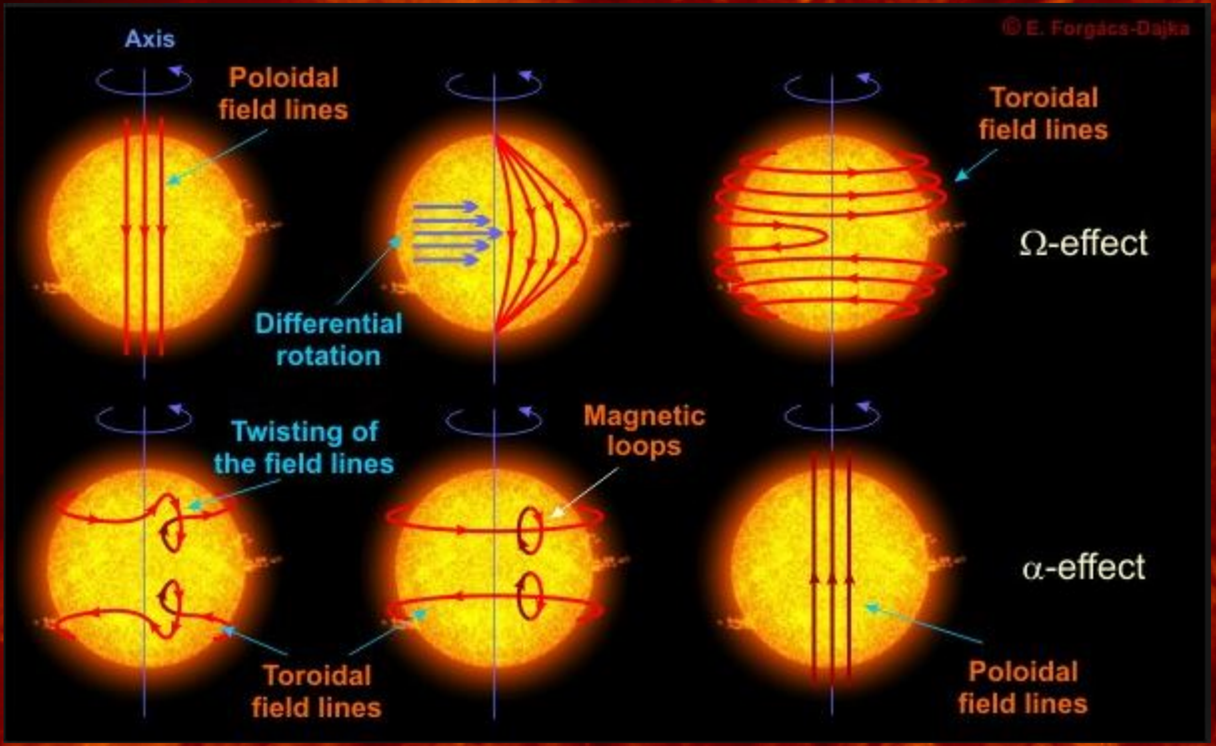



Credit: Forgacs-Dajka

# The Solar/Stellar Dynamo

The ***Ω***–effect:

- Poloidal magnetic field lines twisted by differential rotation to create a toroidal field (Bullard & Gellman 1954).
- Magnetic buoyancy causes this material to rise to the surface.
- Produces sunspots and other solar cycle activity (Parker 1955, Babcock 1961).

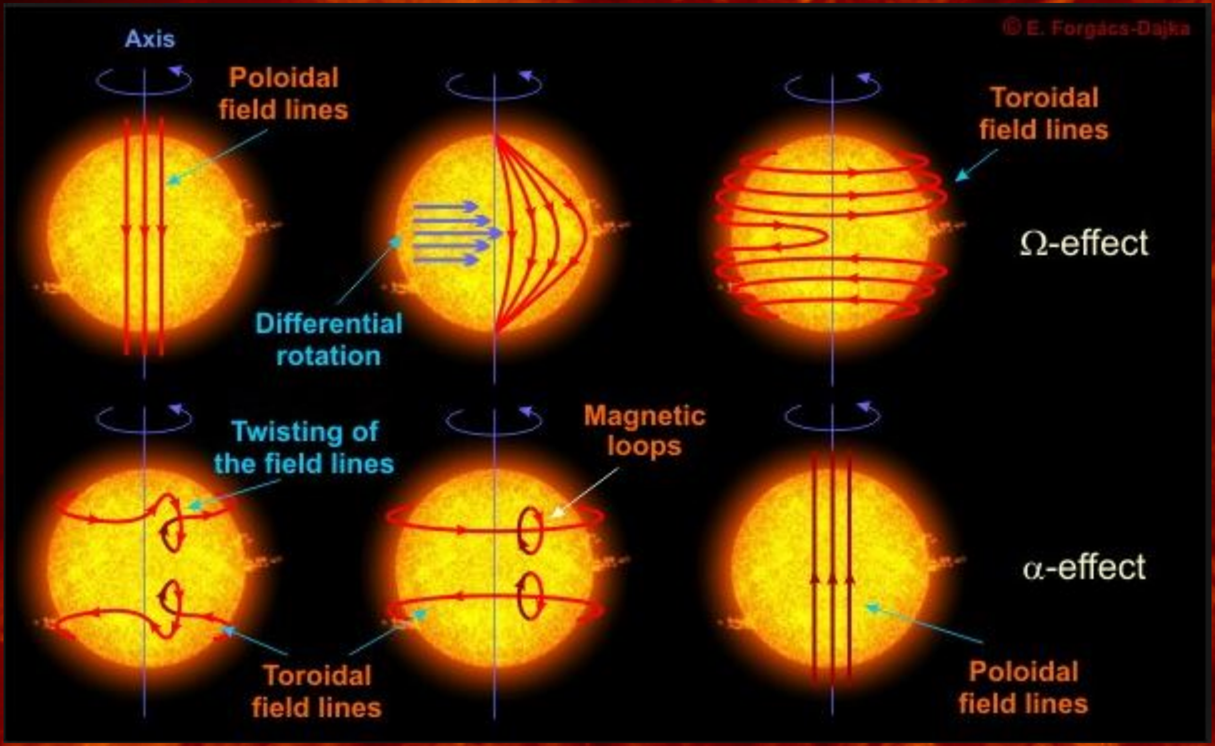



Credit: Forgacs-Dajka

# The Solar/Stellar Dynamo

The $\boldsymbol{\alpha}$–effect:

- Toroidal magnetic field twisted by cyclonic convection and the Coriolis force to create magnetic loops (Parker 1955).
- Loops coalesce due to magnetic diffusivity, creating a large-scale poloidal field.



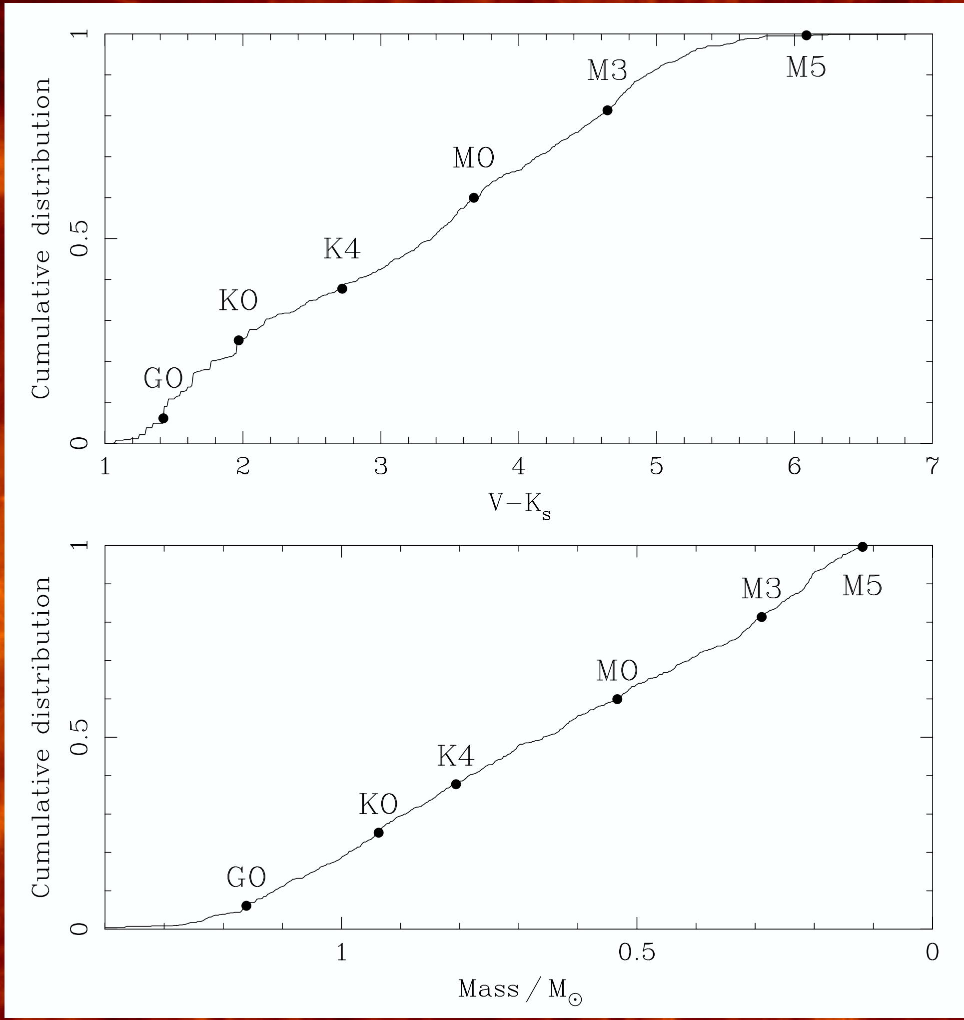

Credit: Forgacs-Dajka

# New sample of activity and rotation

Greatly enlarged sample of 824 stars with rotation periods and X-ray luminosities (Wright+ 2011).

Homogenisation: X-ray luminosities recalculated for all stars from count rates and hardness ratios. New photometry ($V-K_s$) and parallaxes (Hipparcos) from the literature.

Clean sample: Known T-Tauri, close binaries and variable X-ray sources removed.




Wright+ 2011

# New sample of activity and rotation

New sample allows the form of the rotation-activity relationship to be quantified in detail:

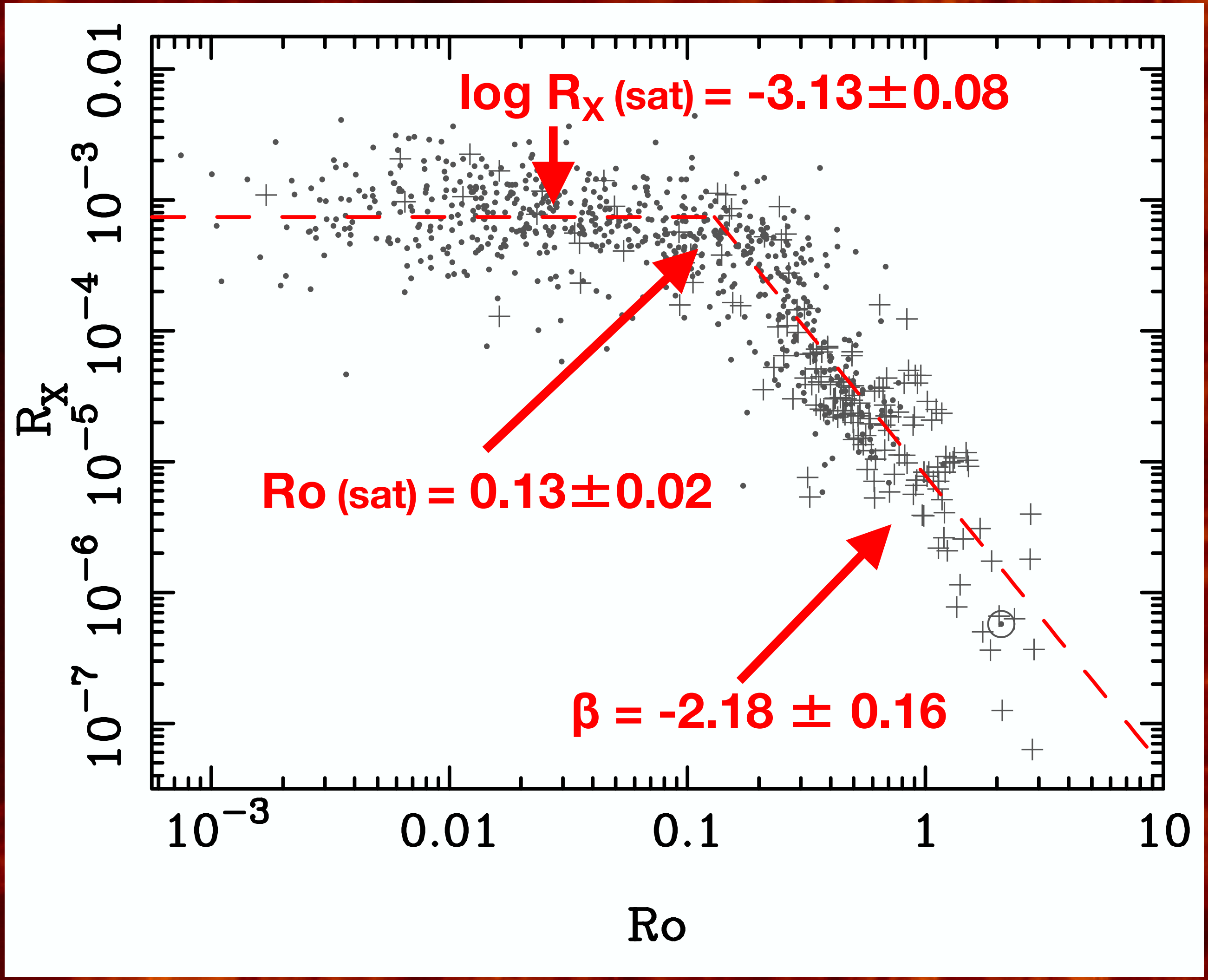
$L_X / L_{bol} = 10^{-3.13}$

for Ro < 0.13

$L_X / L_{bol} \propto Ro^{-2.18}$

for Ro > 0.13

However, this sample has a significant luminosity bias!




Wright+ 2011

# New sample of activity and rotation

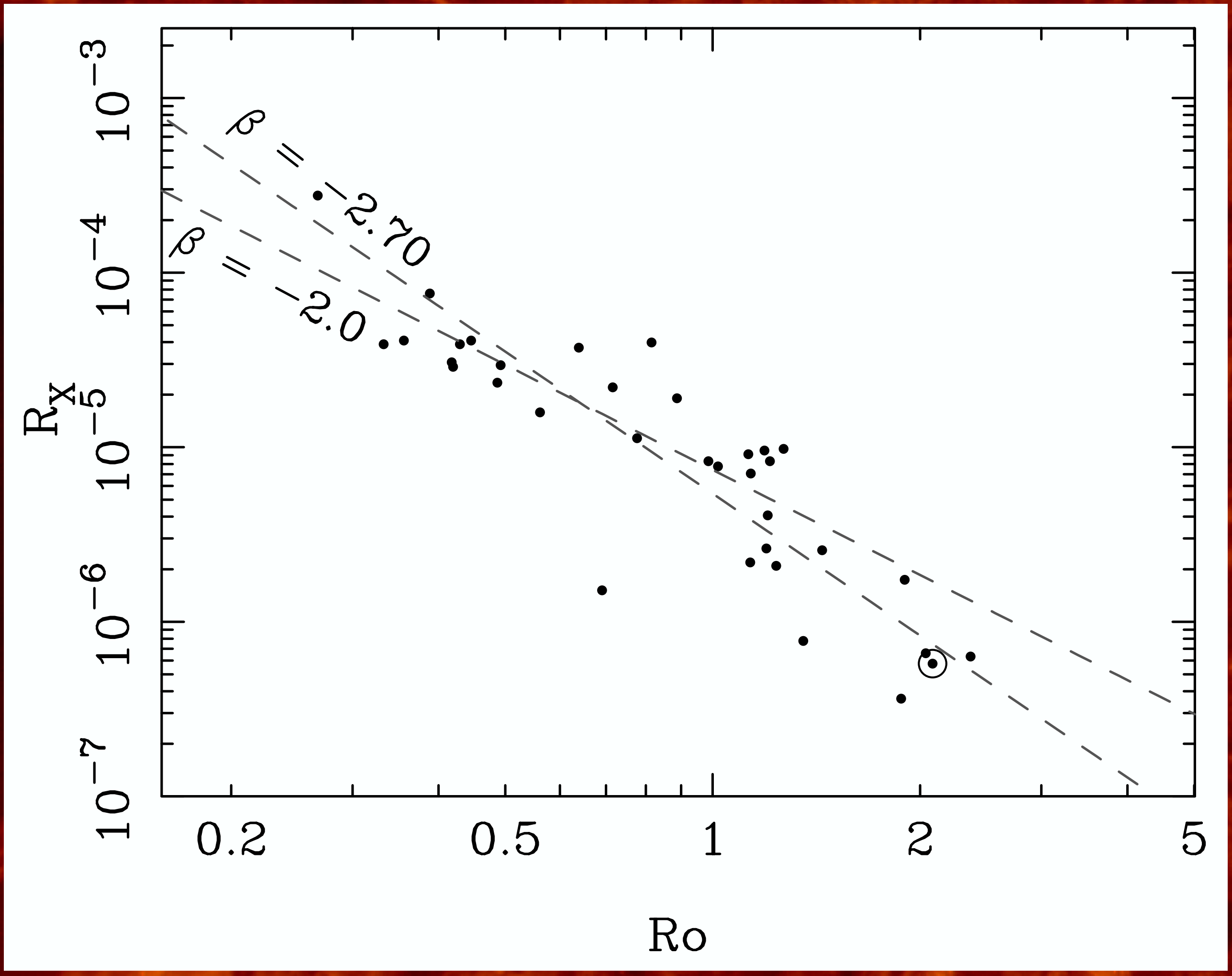
Luminosity bias at low X-ray luminosity / high Rossby number.

To overcome this we use an unbiased subset of stars: the 36 Mt. Wilson stars, all detected in X-rays.

Single power-law fit:

$L_X / L_{bol} \propto Ro^{\beta}$

$\beta = -2.70 \pm 0.13$

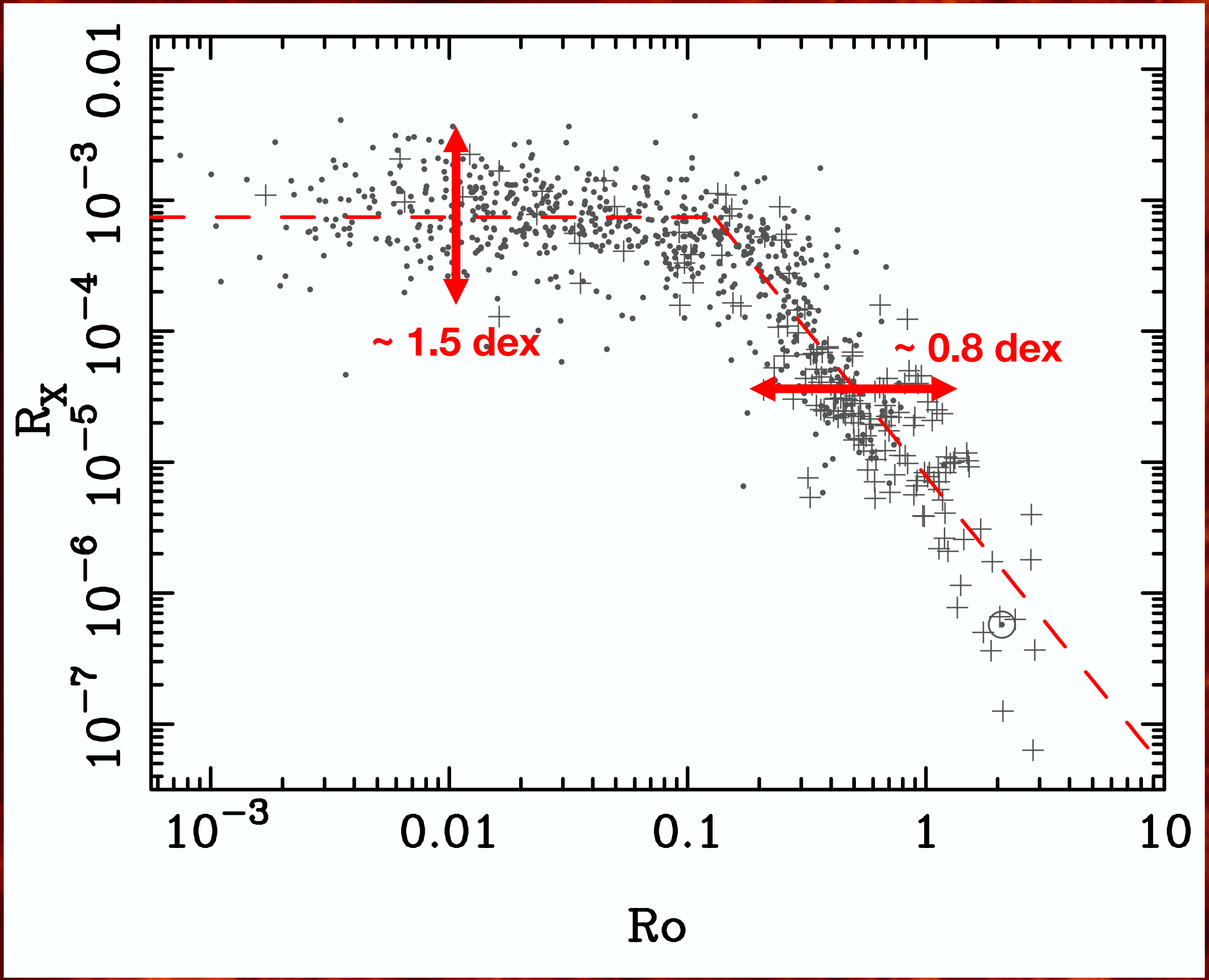



Wright+ 2011

# Spread in the Rotation-Activity diagram

Observed spread could be due to:

- Intrinsic variation in $L_X$ / $L_{bol}$ (dynamo)
- $L_X$ measurement uncertainties
- X-ray flaring in short observations
- Uncertainties in $L_{bol}$ (e.g., due to binarity)
- Uncertainties in measuring $P_{rot}$
- Uncertainties in inferring $\tau$ from V-K
- Intrinsic variations in $\tau$ from star to star



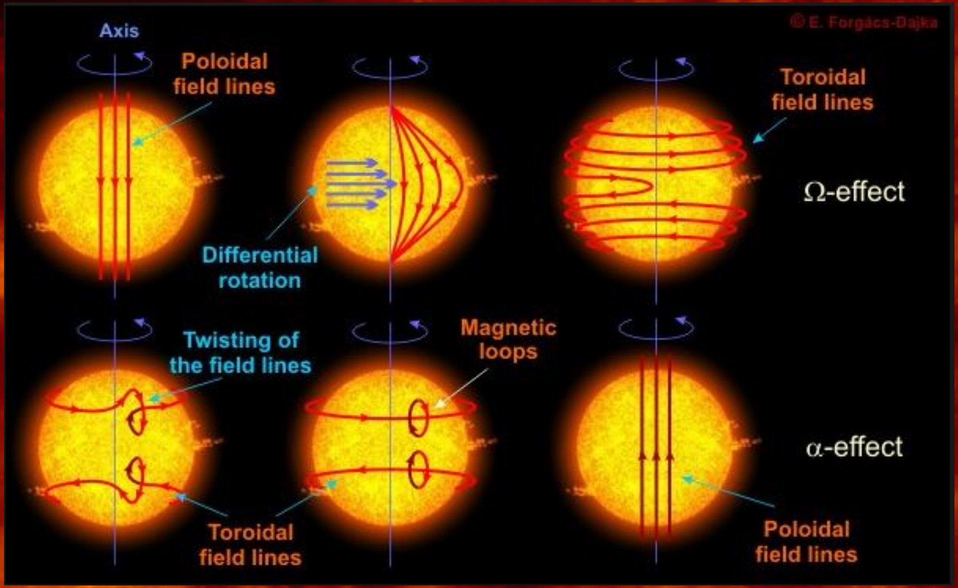

Wright+ 2011

# Dynamos in fully convective stars

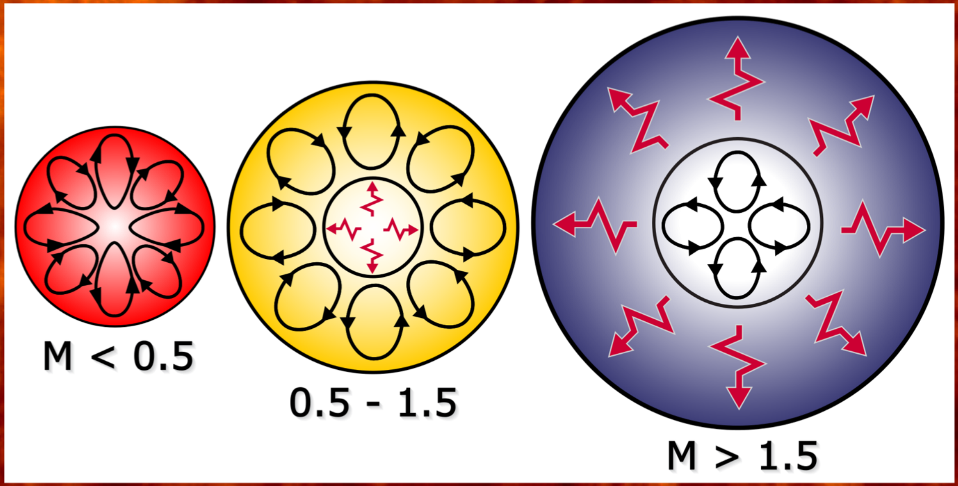
The ***Ω***–effect is thought to take place in the *tachocline*, the shear layer between the radiative core and the convective envelope.

Low-mass, fully-convective stars ($M < 0.3\ M_{\odot}$) lack a tachocline, so should operate a different dynamo (Durney+ 1993).

Fully convective stars exhibit intense magnetic activity, including X-ray and Hα emission, and have strong magnetic fields (Hawley 1993, Johns-Krull & Valenti 1996, Morin+ 2010).




Credit: Forgacs-Dajka

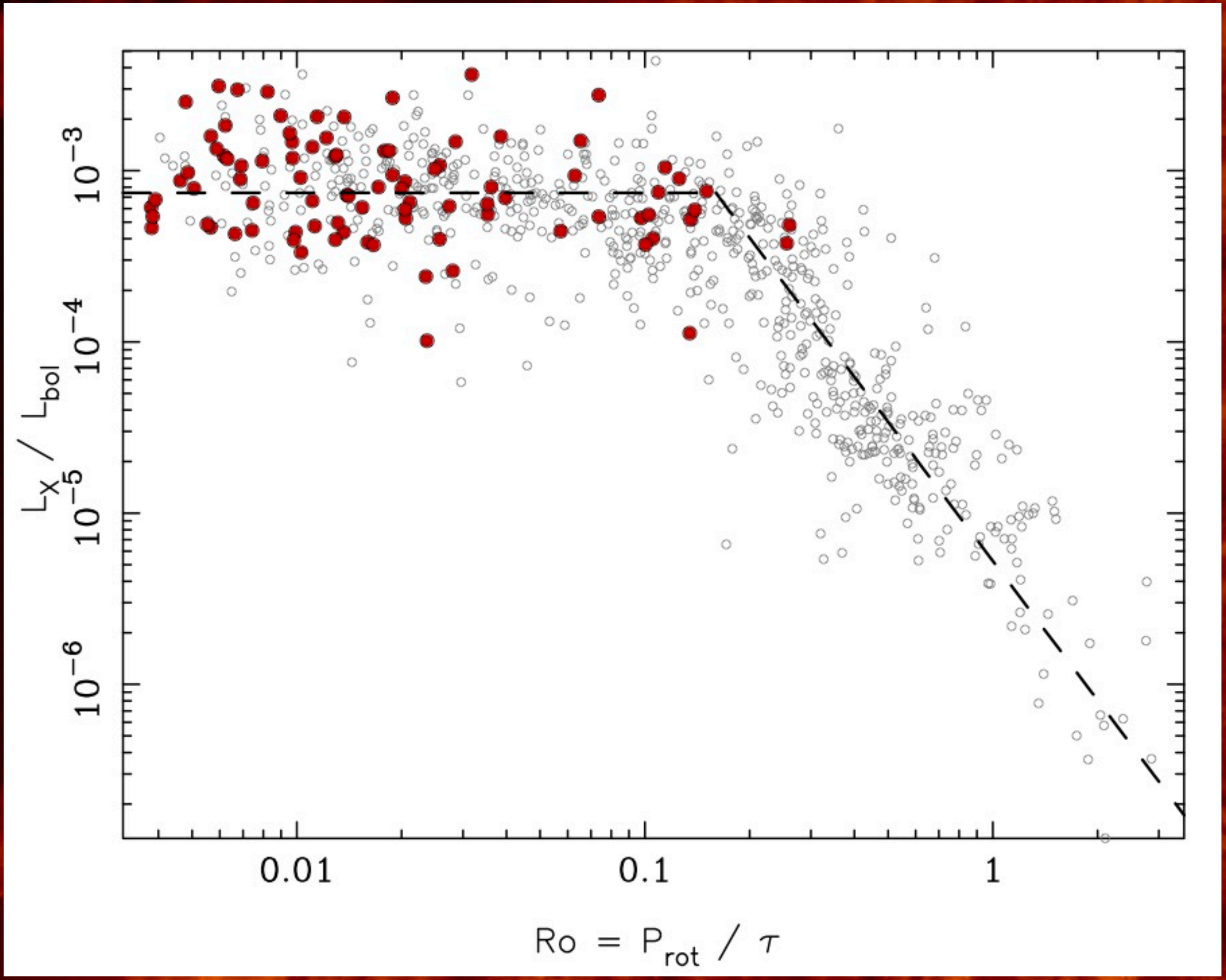



Credit: Wikipedia / Xenoforme

# Dynamos in fully convective stars

All known fully convective stars are ‘saturated’.

Follow-up X-ray observations (2013) target 4 slowly-rotating (Benedict+ 1998, Irwin+ 2011, West+ 2015) stars.




Wright & Drake 2016

# Dynamos in fully convective stars

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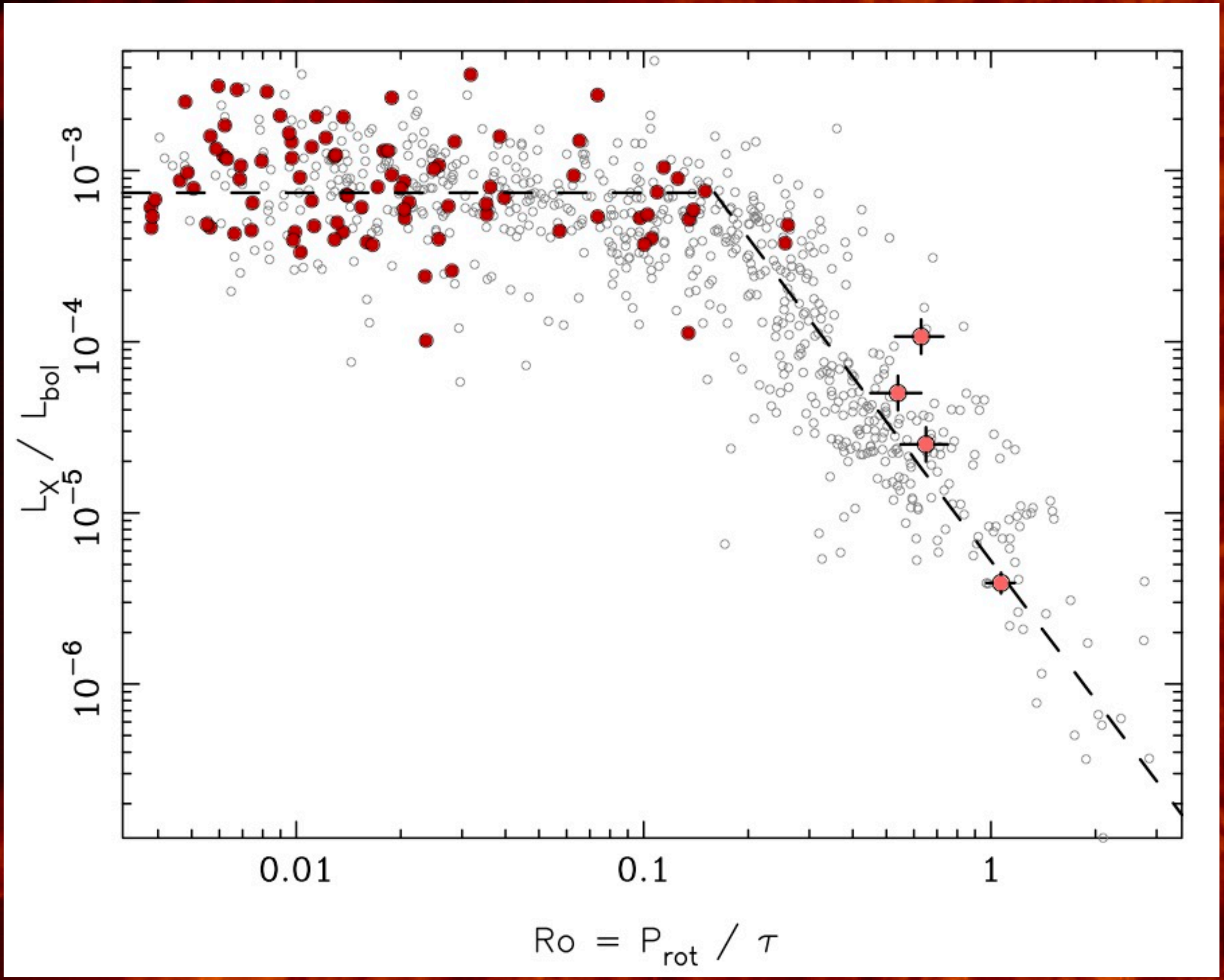
Follow-up X-ray observations (2013) target 4 slowly-rotating (Benedict+ 1998, Irwin+ 2011, West+ 2015) stars.

All on the classical rotation-activity relation (Wright & Drake 2016).

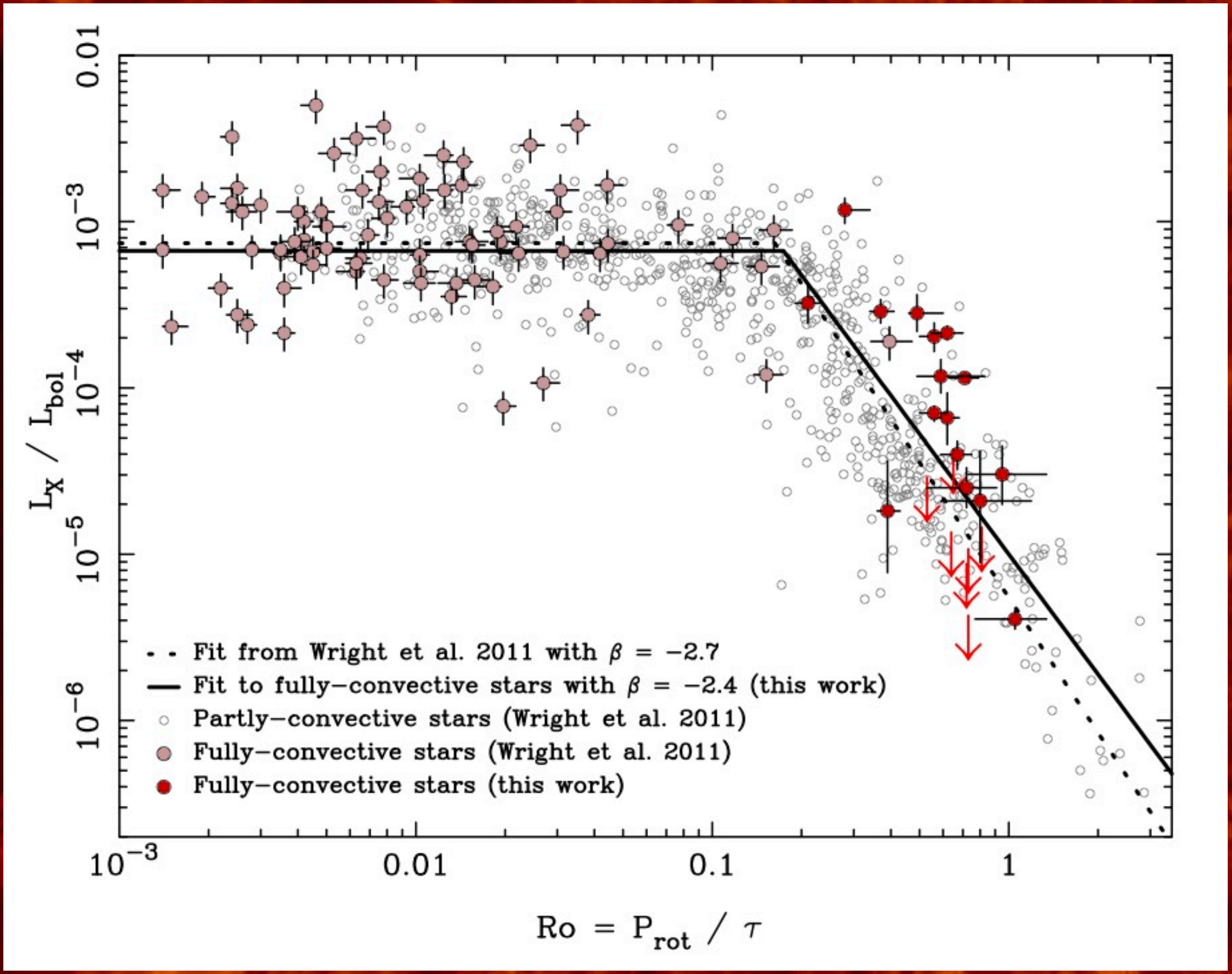



Wright & Drake 2016

# Dynamos in fully convective stars

Further X-ray observations (2017) of 19 more slowly-rotating fully-convective stars (Newton+ 2016, 18).

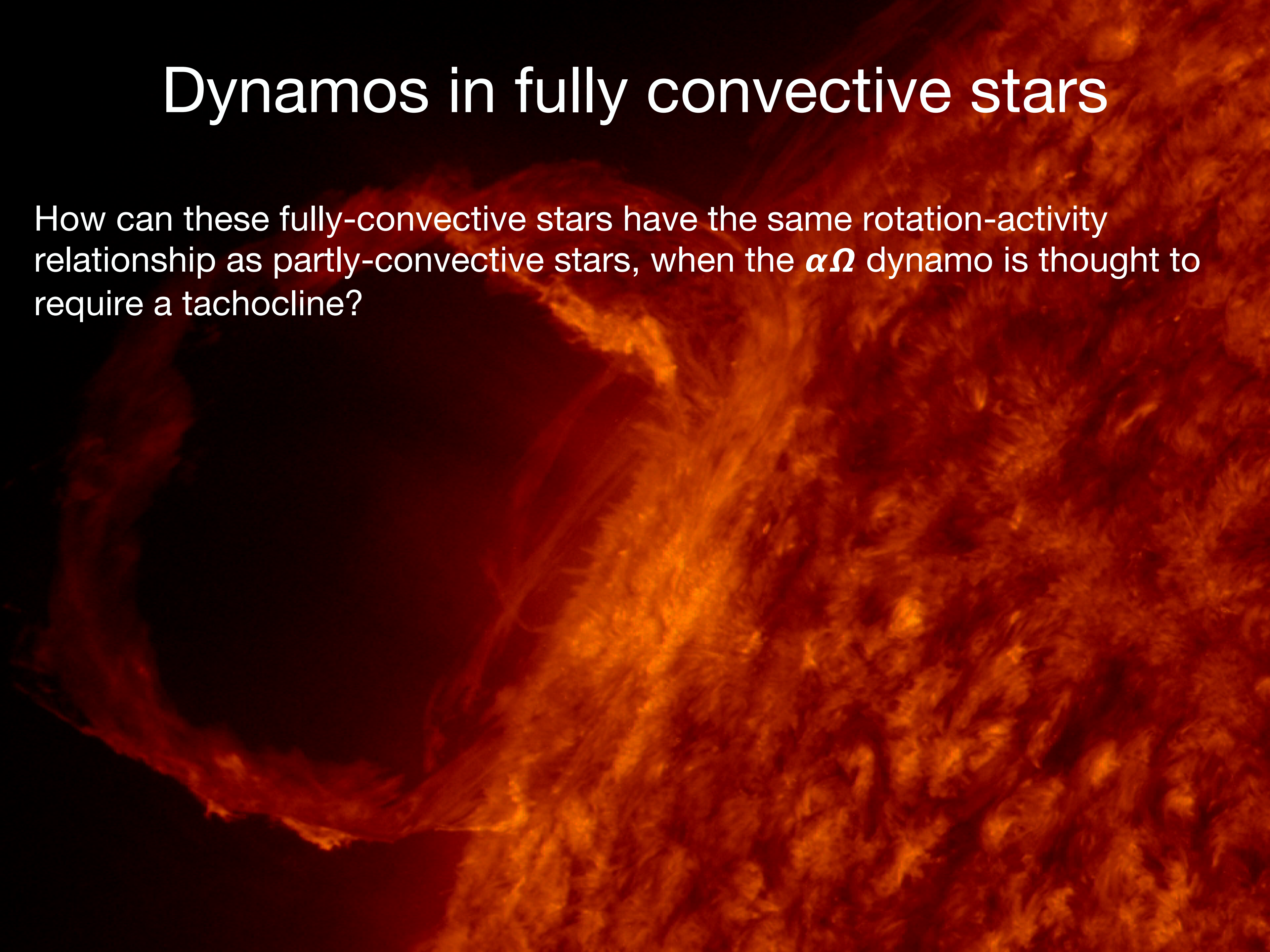
All fully consistent with the rotation-activity relationship seen for partly-convective stars.




Wright+ 2018

# Dynamos in fully convective stars

How can these fully-convective stars have the same rotation-activity relationship as partly-convective stars, when the $\alpha\Omega$ dynamo is thought to require a tachocline?



# Dynamos in fully convective stars

How can these fully-convective stars have the same rotation-activity relationship as partly-convective stars, when the $\alpha\Omega$ dynamo is thought to require a tachocline?

(1) These stars are not fully-convective.

*Convection can be magnetically inhibited (Cox+ 1981), however the field strengths necessary are $10^7$-$10^8$ G (Moss & Taylor 1970, Mullan+ 2001), orders of magnitude larger than in stellar interiors (Browning+ 2016).*

# Dynamos in fully convective stars

How can these fully-convective stars have the same rotation-activity relationship as partly-convective stars, when the $\alpha\Omega$ dynamo is thought to require a tachocline?

(1) These stars are not fully-convective.

(2) These stars operate a turbulent ($\alpha^2$) dynamo that produces the same rotation-activity relationship as the $\alpha\Omega$ dynamo does.

*Existing simulations for fully-convective stars have been able to generate magnetic fields from a turbulent dynamo (e.g., Browning 2008), but are unable to predict their behavior as a function of rotation rate. To achieve the same rotation-activity relationship in both the saturated and unsaturated regimes would require them to have both the same dynamo efficiency* ***and*** *the same rotational dependence however, which seems unlikely.*

# Dynamos in fully convective stars

How can these fully-convective stars have the same rotation-activity relationship as partly-convective stars, when the $\boldsymbol{\alpha\Omega}$ dynamo is thought to require a tachocline?

(1) These stars are not fully-convective.

(2) These stars operate a turbulent ($\boldsymbol{\alpha}^2$) dynamo that produces the same rotation-activity relationship as the $\boldsymbol{\alpha\Omega}$ dynamo does.

(3) Both types of star operate an $\boldsymbol{\alpha\Omega}$ dynamo that does not require a tachocline to operate.

*Recent 3D MHD simulations have been able to produce magnetic fields without a tachocline, with the field generated entirely within the convective layers and stable against buoyancy (Nelson+ 2013, Fan & Fang 2014).*

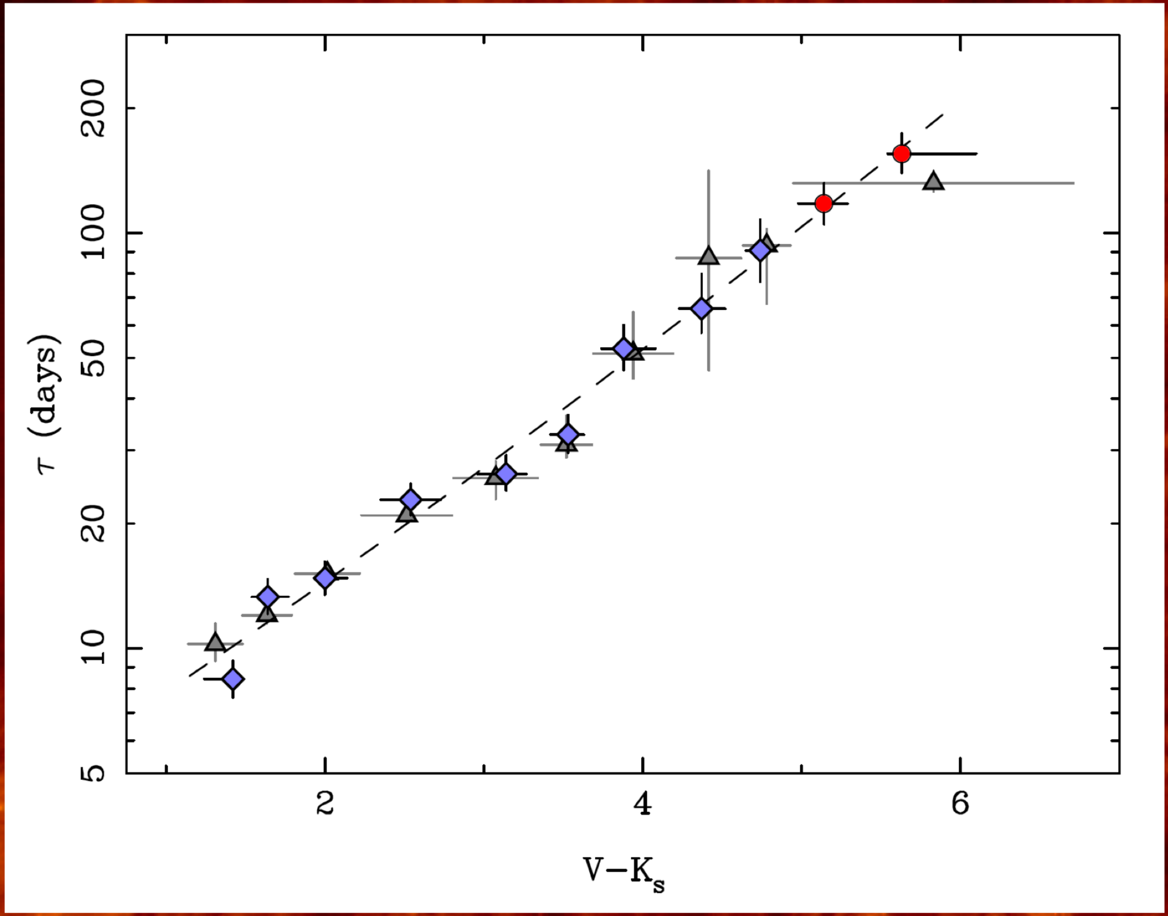
# Revised convective turnover times

New data and improved Bayesian inference / MCMC method used to revise the Wright+ (2011) empirical convective turnover times.

Relationship fitted as:

$$\log \tau = 0.64 + 0.25\,(V\text{-}K_s)$$
[rms ~ 0.045 dex]

Valid over: $1.1 < V\text{-}K_s < 7.0$




Wright+ 2018

# Implications for Planets around M stars

Intense stellar activity of M dwarfs is a concern for the habitability of planets around such stars.

Young M dwarfs are certainly very active, but once they spin down their activity levels may become low enough that these affects are not a concern.

This can take 2 Gyr however (Newton+ 2017), so early effects of this activity may scar the planets for life.

# Summary

- Stellar activity – rotation relationship is a proxy for the underlying stellar magnetic dynamo in solar & late-type stars.
- From an unbiased subset of our 2011 sample we find the power-law slope of the unsaturated regime is $\beta = -2.70 \pm 0.13$.

  (inconsistent with canonical $\beta = -2$ value by $5\sigma$)
- X-ray observations of slowly rotating, fully-convective stars show they follow the same rotation-activity relationship as partly-convective stars.

  (suggesting similar dynamos in both types of star?)
- Implications for planets around M-type stars.