Radial differential rotation leading to dipole collapse in pre-main-sequence stars

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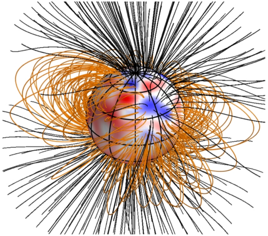
26/08/2026 - PLATO Stellar Science Conference 2026

Outline of the talk

1. Magnetism and rotation in low-mass pre-main-sequence stars
2. Dipole stability criterion in DNS...
3. ...and it's subsequent implementation in CESAM

Magnetism in low-mass stars

Zeeman-Doppler Imaging:



T Tauri TAP 4
Xiang+2023 (ESPaDOnS)

Magnetism in low-mass stars

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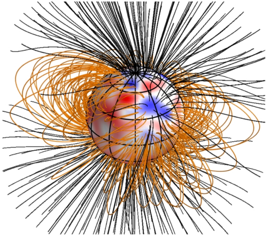

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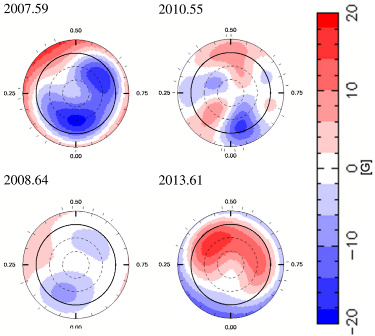

Cyg 61
Boro Saikia+ 2016

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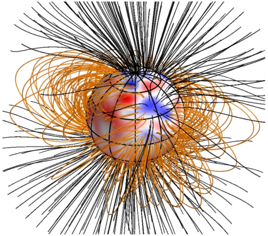

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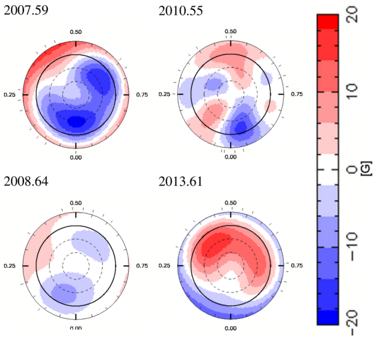

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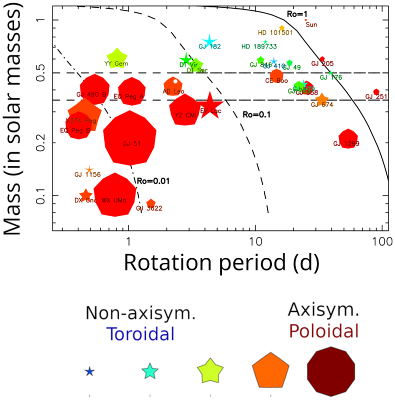
Boro Saikia+ 2016

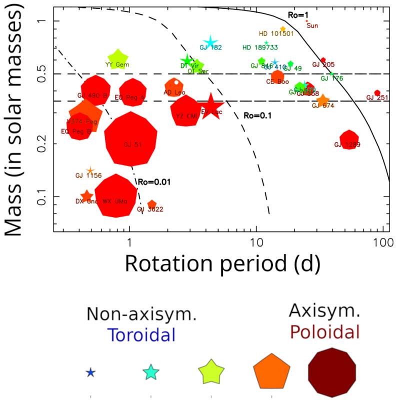
Magnetic fields are crucial for stellar evolution and activity

SPIRou data



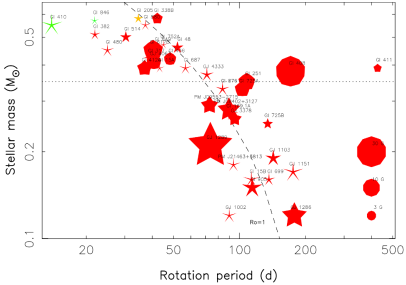
Donati+2009, Moutou+2017

SPIRou data



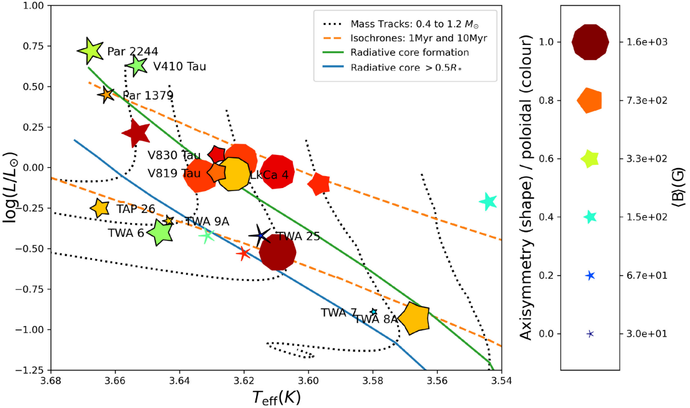
Donati+2009, Moutou+2017

Unexpected dipolar/poloidal fields for slow rotators



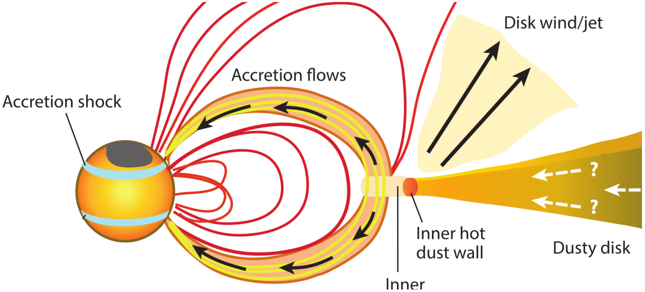
Donati+2023

In protostars: less dipolar fields for older stars



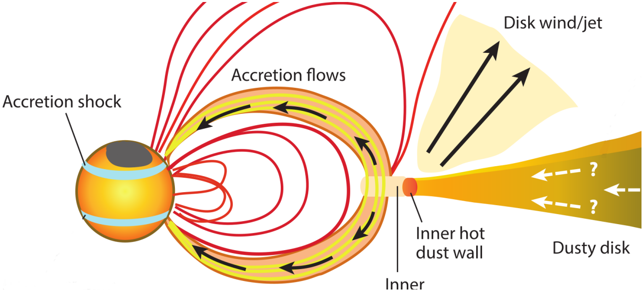
Nicholson+2021

ANR PROMETHEE: protostellar magnetism



- Stars interact with their disks through their magnetic fields

ANR PROMETHEE: protostellar magnetism



- Stars interact with their disks through their magnetic fields
- Large-scale fields:
  Turbulent convection → stretching and twisting of magnetic field → **dynamo action**

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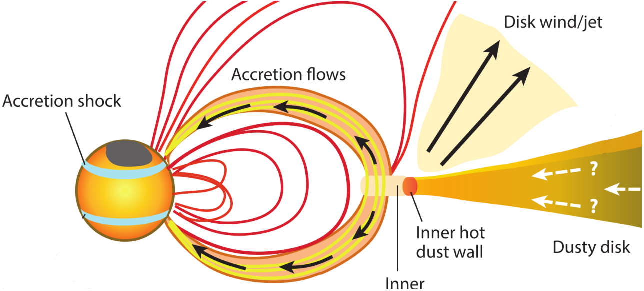

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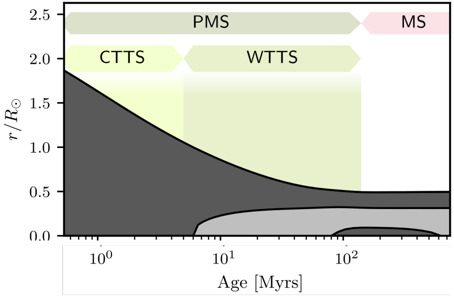
- Large-scale fields:
  Turbulent convection → stretching and twisting of magnetic field → **dynamo action**

How change in conditions during star formation affect the dynamo?

Constraints from stellar evolution

CESAM 2k20 - 1D stellar evolution code (Manchon+2025)

$M = 0.55 M_{Sun}$



Dark grey: convective zone

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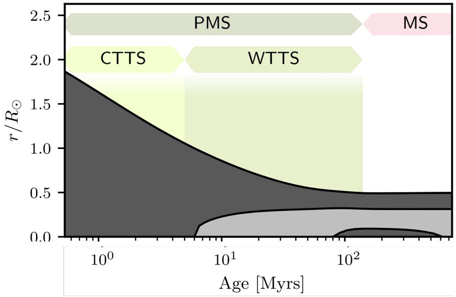
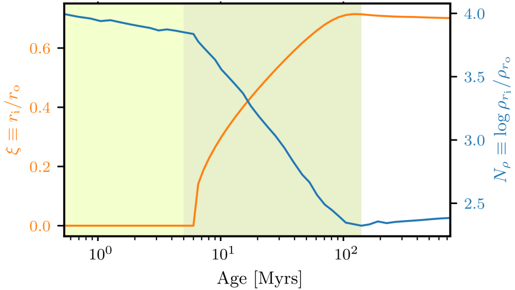


Dark grey: convective zone

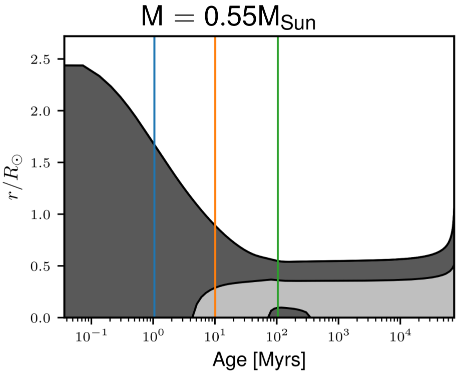
Thickness of convective zone (in orange)
Its density contrast (in blue)



$\xi = r_i/r_o$ ↑: CZ decreases

$N_\rho = \log(\rho_i/\rho_o) = 4.5 \rightarrow 2.5$ (90% of CZ)

Constraints from stellar evolution



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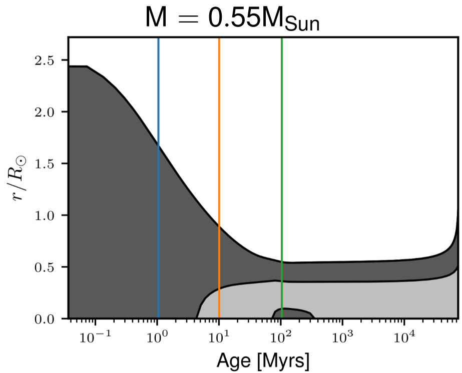

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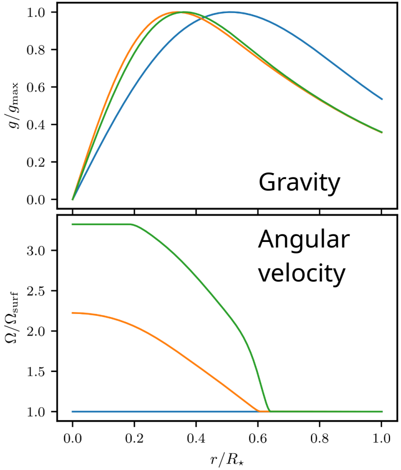

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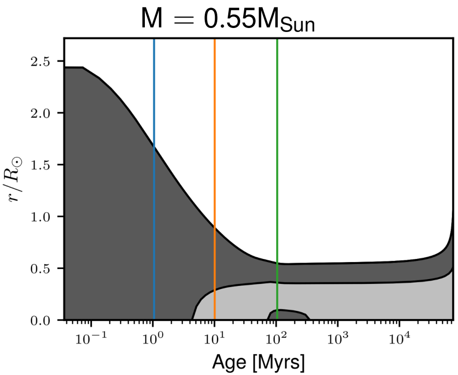

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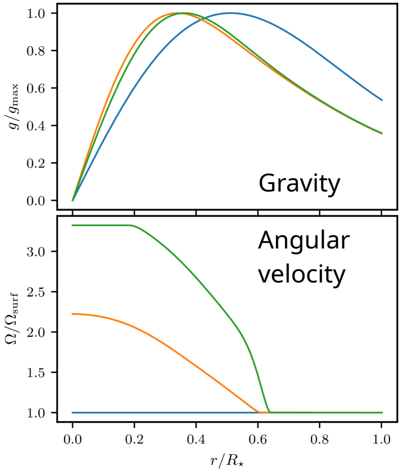
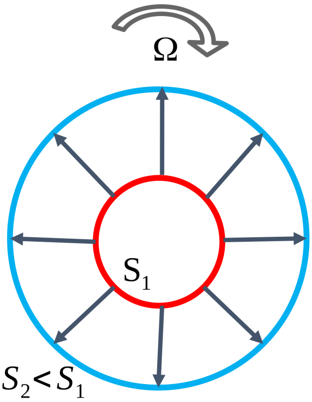


This work: influence of rotation on stellar dynamos in WTTS phase

Outline of the talk

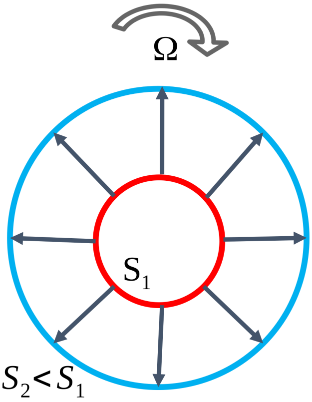
1. Magnetism and rotation in low-mass pre-main-sequence stars
2. Dipole stability criterion in DNS...
3. ...and it's subsequent implementation in CESAM

Numerical setup



- Anelastic dynamo model:
  3D equations for magnetic field, momentum and energy
  MagIC - Gastine & Wicht 2014
- Convection: by entropy gradient across the shell
- Density contrast: $N_\rho = \log(\rho_i/\rho_o) = 2.5$
- Boundary conditions model speed-up of the stellar interior
  - $\Omega_i = \Omega_{sh}$: imposed velocity
  - $\Omega_o = 0$: constrained by the disk

Numerical setup



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- Boundary conditions model speed-up of the stellar interior
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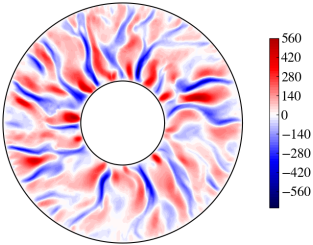
- New parameter: shear Rossby number $Ro_{sh} = \Omega_{sh}/\Omega$

Dipole collapse as rotation increases

Radial convective velocity



Convective Rossby:

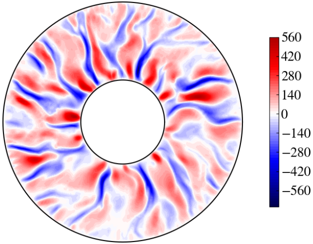
$$\mathrm{Ro_{conv}} = \mathrm{P_{rot}} / \mathrm{P_{conv}}$$

Flow helicity:

$$\mathrm{H} = \langle \mathbf{u} \cdot \nabla \times \mathbf{u} \rangle_{\phi}$$

Dipole collapse as rotation increases

Radial convective velocity



Convective Rossby:

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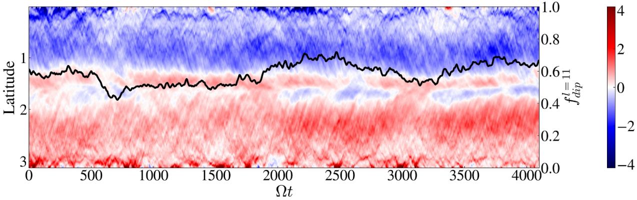
Flow helicity:

$\mathrm{H} = \langle \mathbf{u} \cdot \nabla \times \mathbf{u} \rangle_\phi$

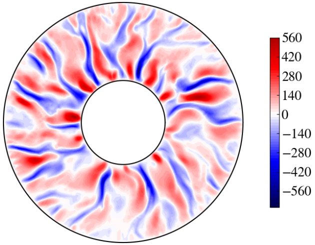
$\mathrm{Ro_{sh}} = \Omega_{\mathrm{sh}} / \Omega = 0.01$



In black - strength of the dipole

Dipole collapse as rotation increases

Radial convective velocity



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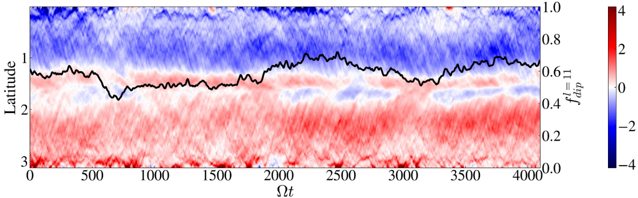
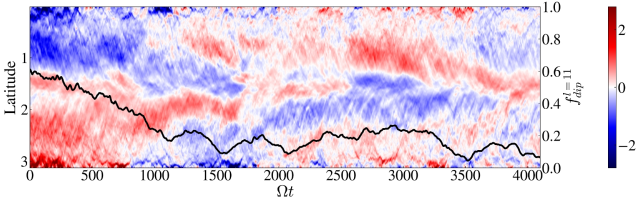


$Ro_{sh} = \Omega_{sh} / \Omega = 0.05$

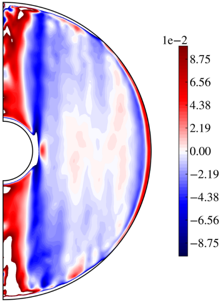


In black - strength of the dipole

The suspect: local shear disrupting dynamo

Local shear

$Ro^l_{sh} = (r/\Omega)\partial\Omega/\partial r$



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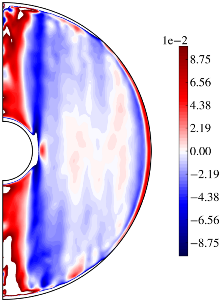
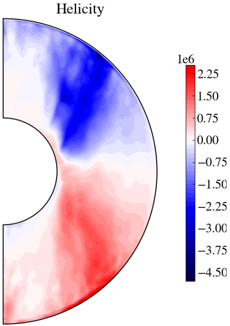


Flow helicity ($\propto Ro_{conv}$):



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Local shear
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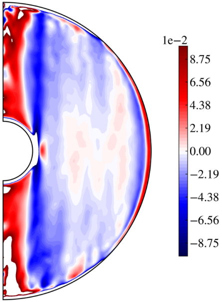

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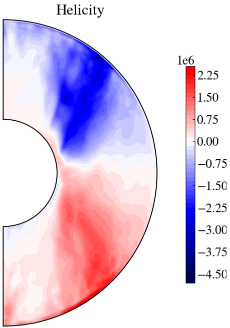
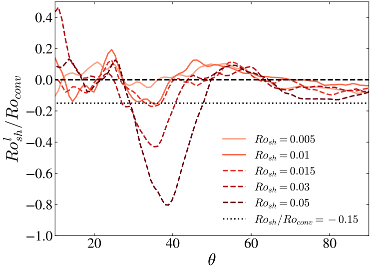
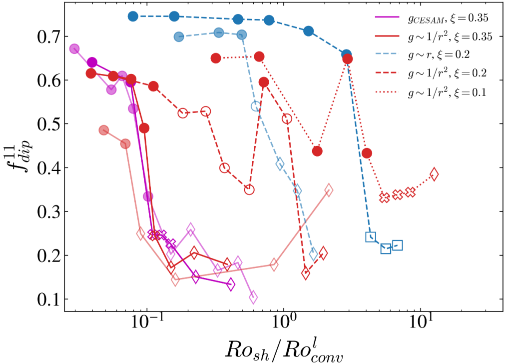


Local shear vs convection
($\sim Ro^{l}_{conv}$):



2D is useful, yet we need a 1D criterion for intergration with CESAM

1D criterion for dipole collapse

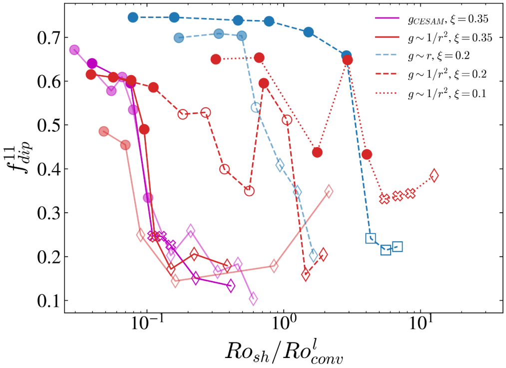


(Integrated across convective zone)

In DNS, we vary:

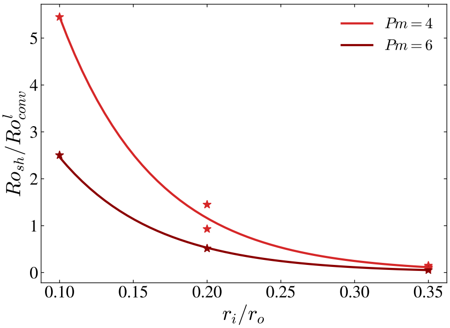
- Convective zone depth $\xi = r_i/r_o$
- Gravity profile
  - $g \sim r$ - uniform density
  - g_{CESAM} (WTTS) - parabolic
  - $g \sim 1/r^2$ (MS)
- Relative strength of magnetic field (Pm)

1D criterion for dipole collapse



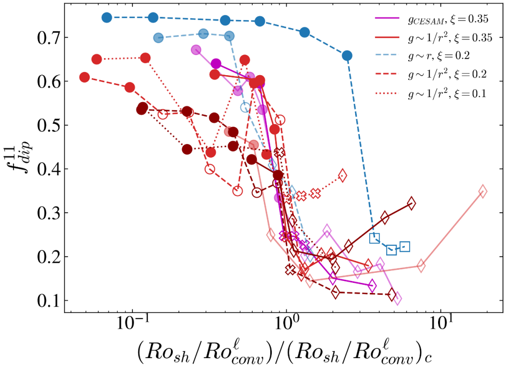
(Integrated across convective zone)

Different field strength:



$\xi = \mathrm{r_i/r_o}$

1D criterion for dipole collapse



(Integrated across convective zone)

Universal criterion for dipole collapse

$$Ro_{sh}/Ro_{conv} \approx C(Pm)\exp(-15.4 r_i/r_o)$$

Outline of the talk

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2. Dipole stability criterion in DNS...
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Back to CESAM

Ro_{sh}/Ro_{conv} in CESAM?

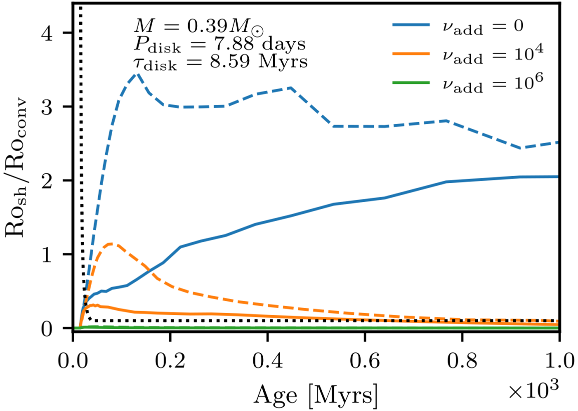
- Ro_{sh} : angular velocity gradient;
  at the bottom of CZ
- Ro_{conv}: Mixing-length theory;
  in the middle of CZ

Back to CESAM

Ro_{sh}/Ro_{conv} in CESAM?

- Ro_{sh} : angular velocity gradient; at the bottom of CZ
- Ro_{conv}: Mixing-length theory; in the middle of CZ

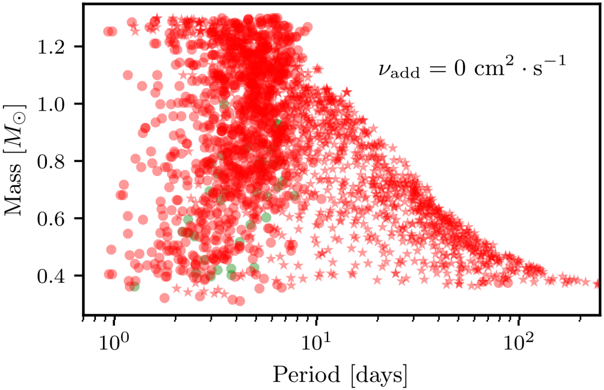
Dotted: $Ro_{sh}/Ro_{conv} \sim \exp(-15.4 r_i/r_o)$
Solid: local rotation
Dashed: global rotation



Predictions for dipole stability from CESAM

- 700 evolution tracks
- $M/M_{Sun} \in [0.3, 1.3]$
- $P_{disk} = 6 - 10$ days
- $\tau_{disk} = 1 - 13$ Myrs
- From each track:
  models are chosen at random
  and dipole stability is evaluated

Circles - MS, stars - PMS



Red - dipole lost; green - maintained

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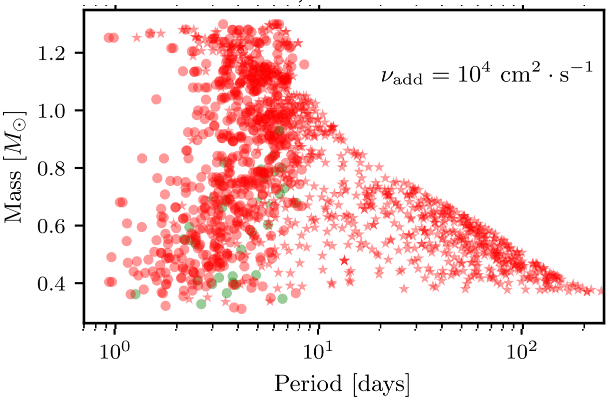

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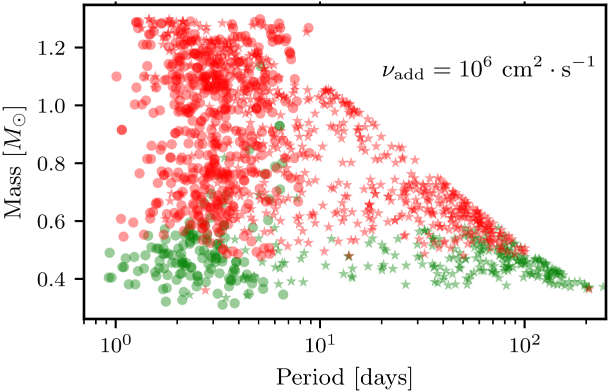

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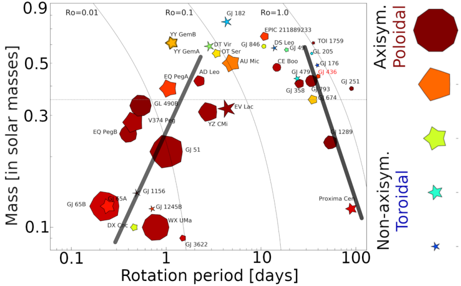
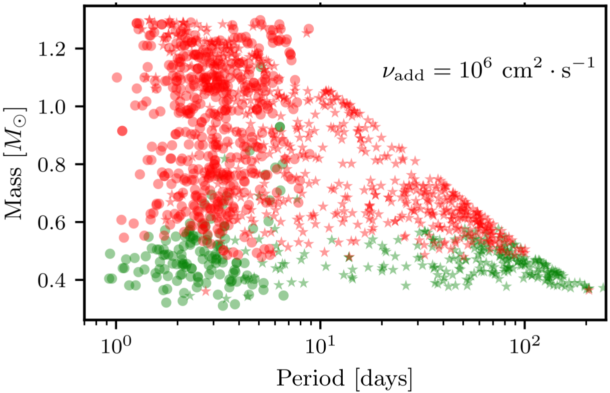
Predictions for dipole stability from CESAM

Compare to spectropolarimetry:



Donati+2009(SPIRou)

Circles - MS, stars - PMS



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Discussion

- Robust criterion of dipole collapse with speed up of the core rotation for pre-main-sequence stars
- Hint for more efficient transport of angular momentum in radiative zones of stars than shear and meridional currents

A. Guseva, L. Manchon, L. Petitdemange and C. Pinçon, A&A, 707, A45 (2026)

Auxiliary slides

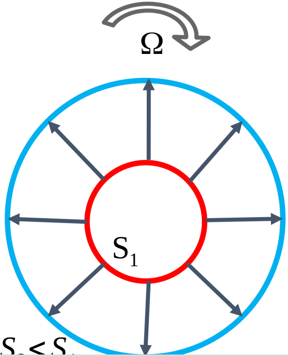
Anelastic model of stellar dynamo

Polytropic reference state : $\overline{P} = P_c w^{n+1}$, $\overline{\rho} = \rho_c w^n$, $\overline{T} = T_c w$, $w = c_0 + \frac{c_1 d}{r}$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\vec{\nabla}\vec{v} = -\frac{Pm}{E}\vec{\nabla}\left(\frac{P'}{w^n}\right) + \frac{RaPm^2}{Pr}\frac{S}{r^2}\vec{e}_r - 2\frac{Pm}{E}\vec{e}_z \wedge \vec{v} + \frac{Pm}{Ew^n}(\vec{\nabla}\wedge\vec{B})\wedge\vec{B} + Pm\vec{F}_\nu ,$$

$$\frac{\partial S}{\partial t} + \vec{v}\cdot\vec{\nabla}S = \frac{Pm}{w^{n+1}Pr}\vec{\nabla}\cdot\left(w^{n+1}\vec{\nabla}S\right) + \frac{Di}{w}\left[\frac{(\vec{\nabla}\wedge\vec{B})^2}{Ew^n} + Q_\nu\right] ,$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\wedge\left(\vec{v}\wedge\vec{B}\right) + \vec{\nabla}^2\vec{B}, \quad \vec{\nabla}\cdot\vec{B} = \vec{\nabla}\cdot(w^n\vec{v}) = 0$$



Rayleigh number Ra: strength of convection

Density contrast N_ρ: flow stratification

$$Ra = \frac{GMd\Delta S}{\nu\kappa c_p} \sim (10 - 10^2)Ra_{cr}, \quad (Ra \sim 10^{20} \text{ in the Sun!})$$

$$N_\rho = \ln\left[\frac{\rho(r_i)}{\rho(r_o)}\right] \in [2,6], \quad \rho_i/\rho_o \in [7,400]$$

Code: MagIC (Gastine & Wicht 2012)