UNIVERSITÉ Grenoble Alpes

TOwards Understanding the sPIn Evolution of Stars

cnrs

PMS evolution: a tale of mass and angular momentum

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Odyssey

PMS evolution

A variety of interconnected processes

- **Mass accretion / Mass ejection** (jets, disk winds, stellar winds, interface winds, CME's, etc.)
- **Disk accretion / Star-disk interaction** (star, inner disk, inner planets, magnetospheric accretion)
- **Accretion shock / Disk evolution** (high-energy irradiation, chemistry)
- **Magnetic fields / Angular momentum** (star-disk interaction, winds, magnetospheric accretion)
- **Structural evolution / Lithium depletion** (differential rotation, magnetic dynamos, radius anomaly)

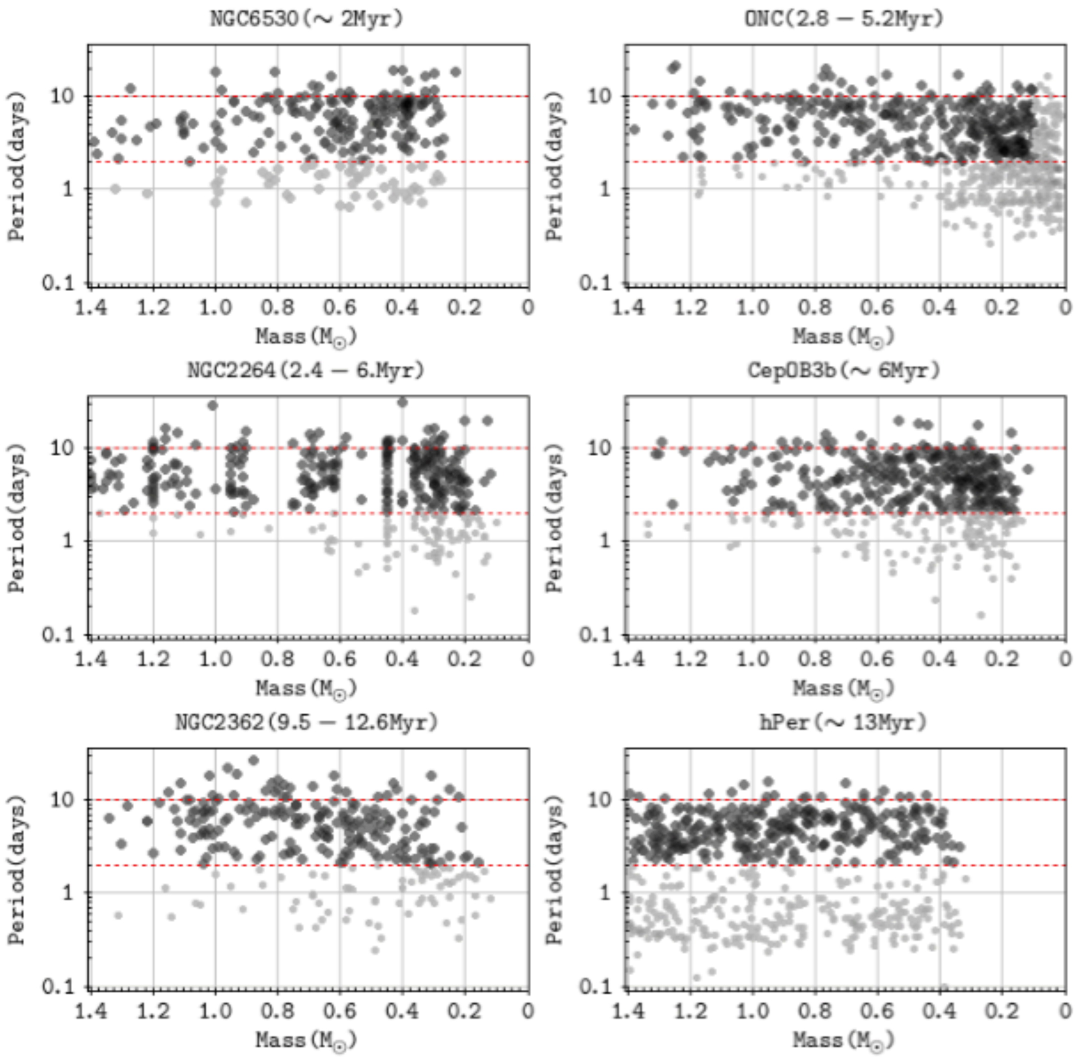
Angular momentum evolution

- **All these processes will impact AM evolution** (accretion, winds and outflows, magnetic fields, star-disk interaction, structural evolution, planet formation/migration, etc.)

  →**Use AM evolution to probe the physical processes at work in young stars.**

- What is the initial AM distribution of young stars? How does it evolve with time?

PMS rotational evolution



Large initial scatter: protostellar evolution

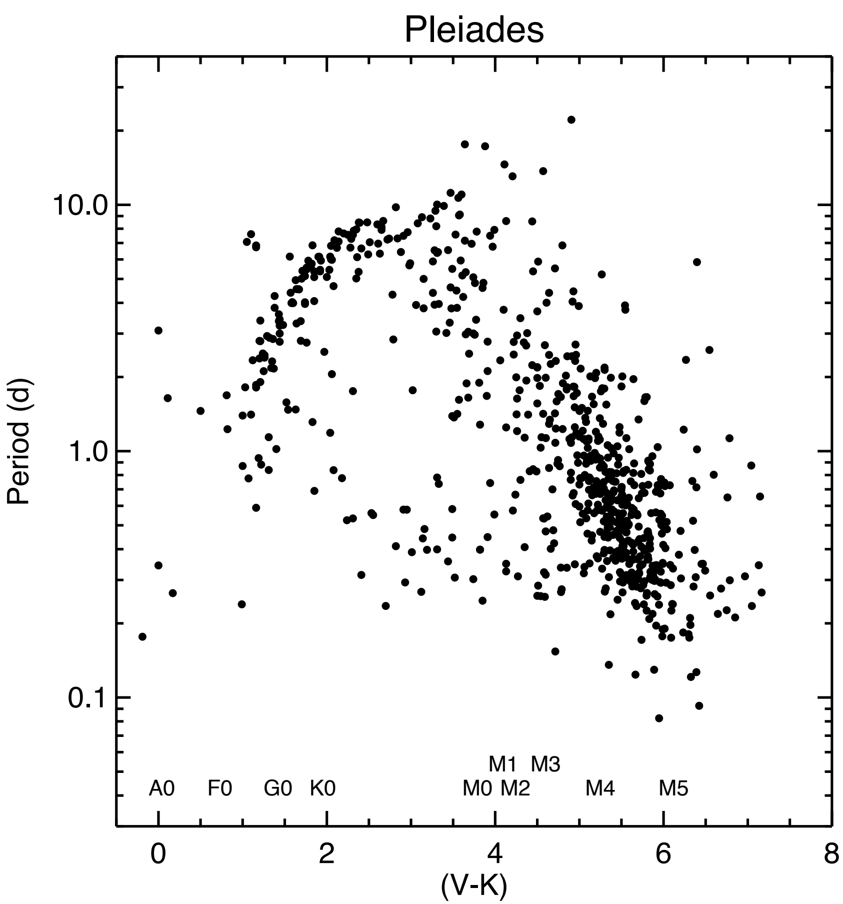
Mass-dependent initial conditions and evolution

Significant evolution of the rotational period distributions during PMS

Compilation from Roquette, Bouvier, Alencar+17 A&A

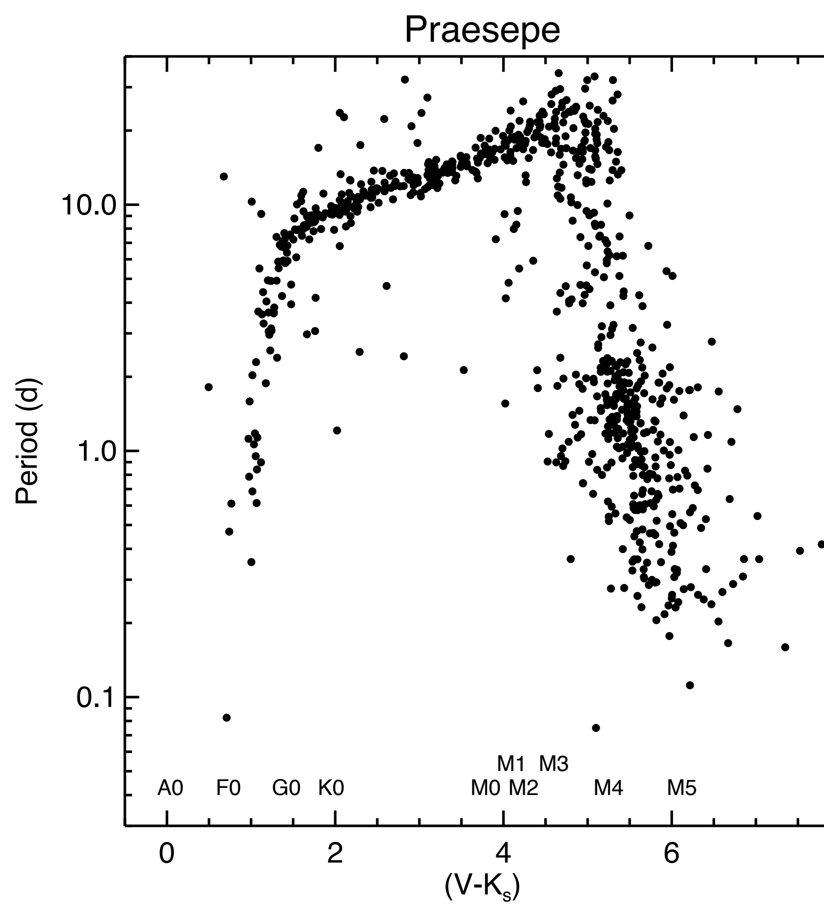
Kepler/K2: Pleiades & Praesepe

Pleiades ~125 Myr



Rebull, Stauffer, Bouvier+16

Praesepe ~700 Myr

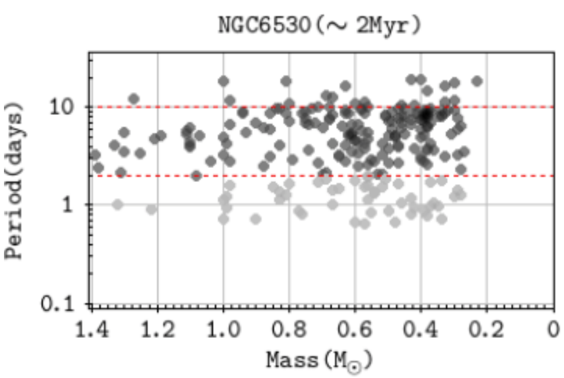


Rebull, Stauffer, Hillenbrand+17

How to account for PMS rotational evolution ?

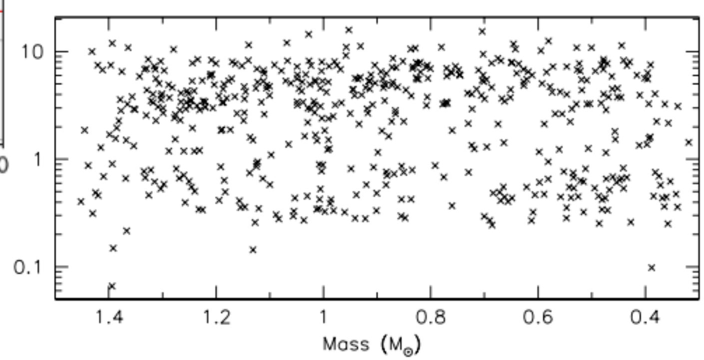
- 1- 10 - 100 Myr rotational period distributions : initial spread -> dichotomy -> anamorphosis

NGC 6530 (2 Myr)



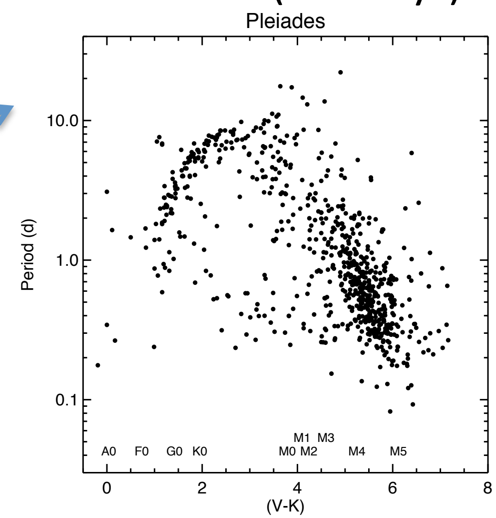
Henderson & Stassun 2012

h Per (13 Myr)



Moraux, Artemenko, Bouvier+13

Pleiades (125 Myr)



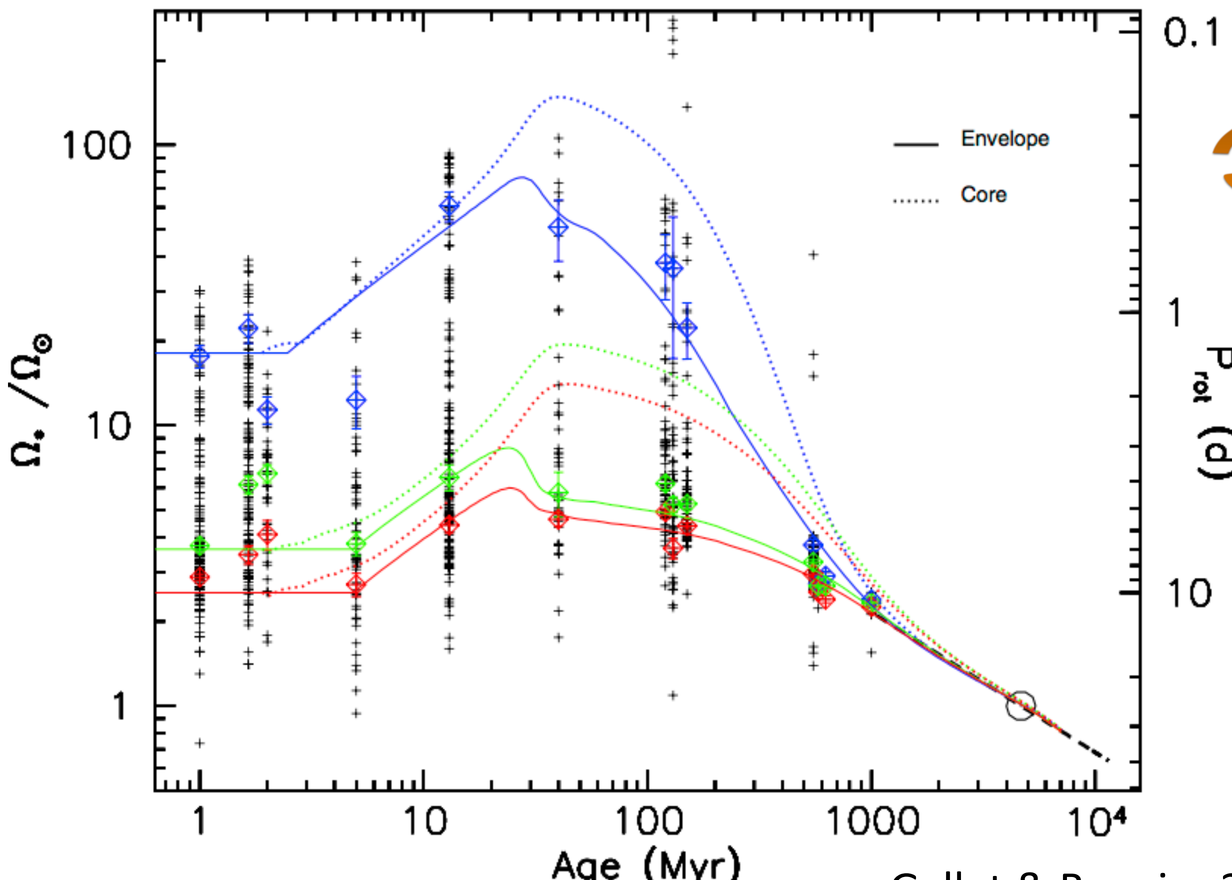
Rebull, Stauffer, Bouvier+16

AM evolution models

- A number of models are available, which differ slightly, but have the same ingredients, namely:
  1. Initial AM spread: 1-10 days initial periods
  2. Star-disk "locking" assumption: constant angular velocity while accreting from the disk
  3. AM loss by magnetic winds and differential core/envelope PMS spin-up

AM evolution models

Evolution of angular momentum + lithium-rotation connection -> constraints on disk lifetimes, mass-loss rates, magnetic braking, and internal transport processes



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Gallet & Bouvier 2013, 2015

AM evolution models: implications

- Star-disk locking (1-5 Myr):
  - Longer disk lifetime (~5 Myr) in initially slow rotators
  - Shorter disk lifetime (~2 Myr) in initially fast rotators

  Why ? Does the protostellar disk mass dictates both the overall disk lifetime and the initial stellar AM ?

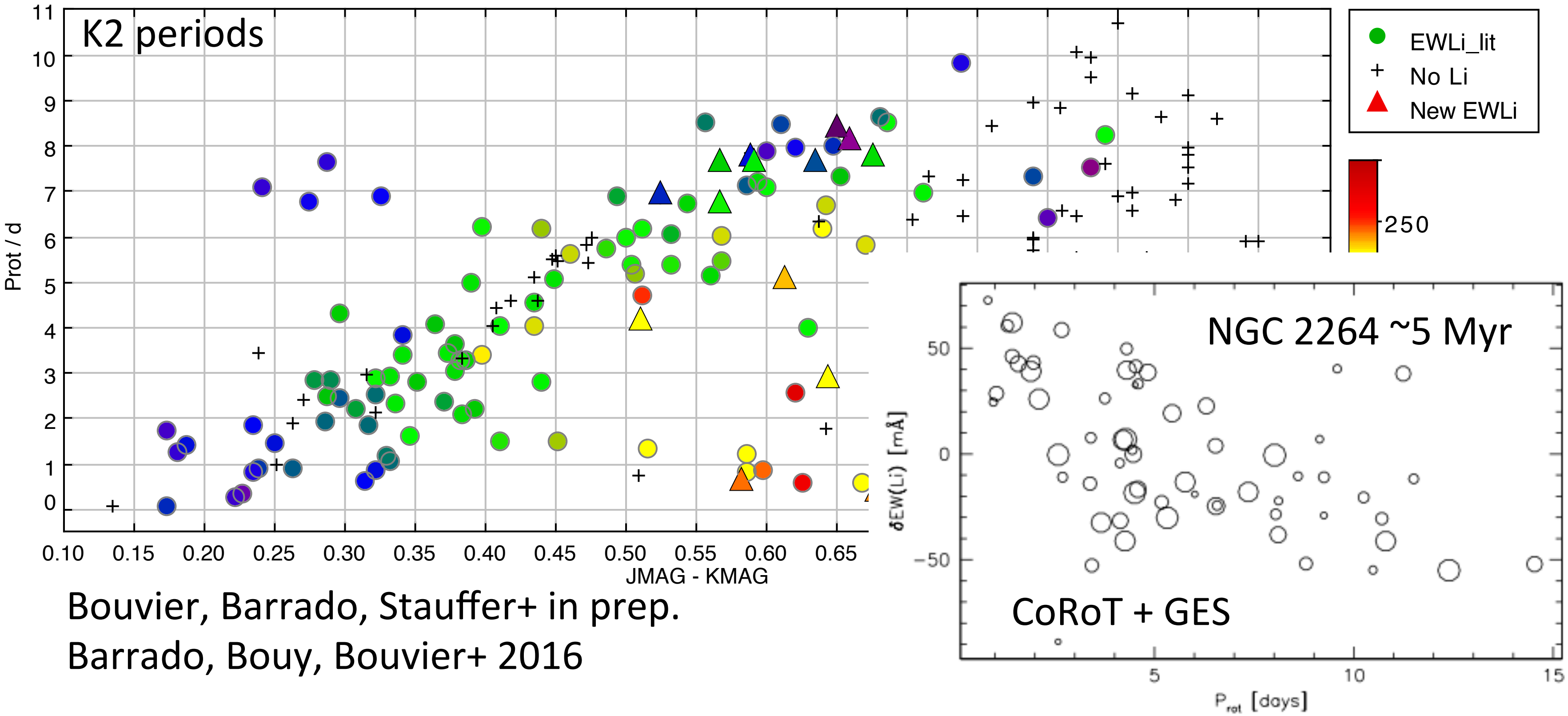
- Core-envelope decoupling (5-100 Myr)
  - Larger core-envelope decoupling in slow rotators -> rotational mixing -> more lithium depletion

  Enhanced PMS lithium burning in slow rotators ?

The lithium-rotation connection

Lithium abundances and rotation rates are inversely correlated in the PMS up to ZAMS

Pleiades ~125 Myr

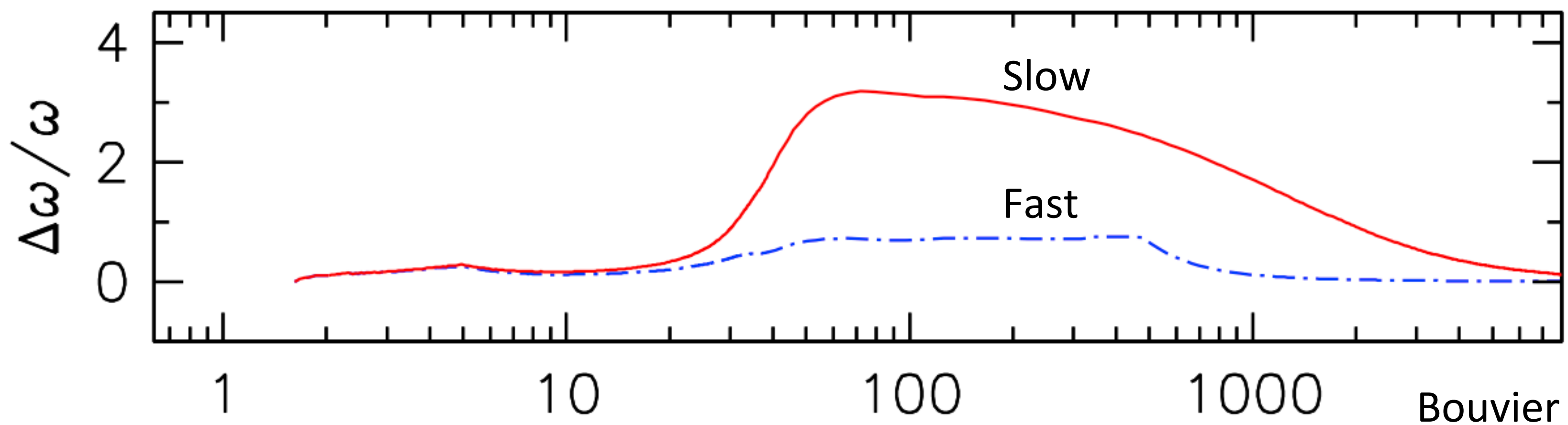


Bouvier, Barrado, Stauffer+ in prep.
Barrado, Bouy, Bouvier+ 2016

Bouvier, Lanzafame, Venuti+16

When does it develop? How does it evolve?
Is the lithium-rotation pattern a consequence of "disk locking"?

Francesco's inspiration?

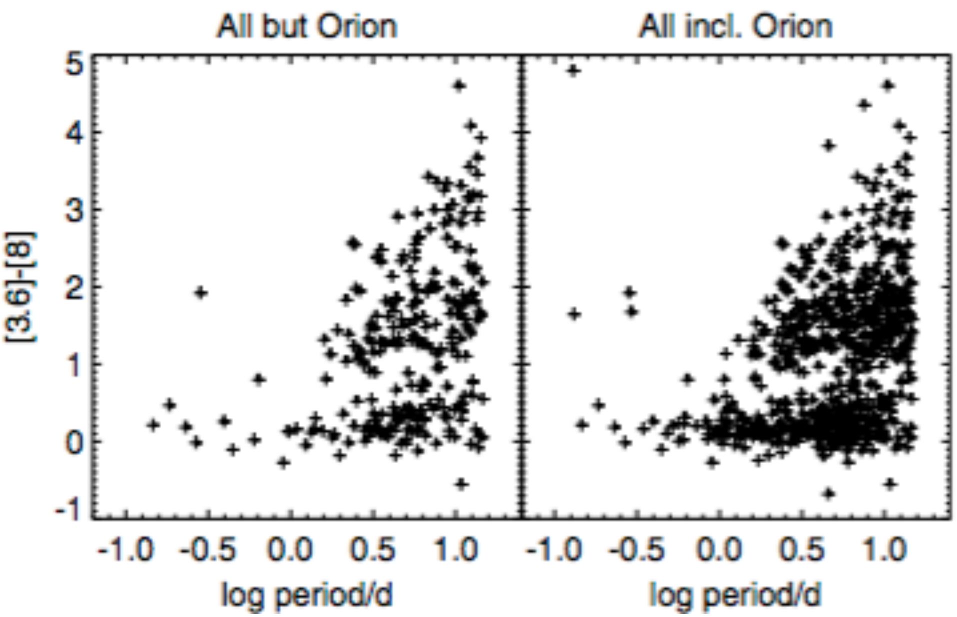


Bouvier 2008

Empirical evidence for disk locking

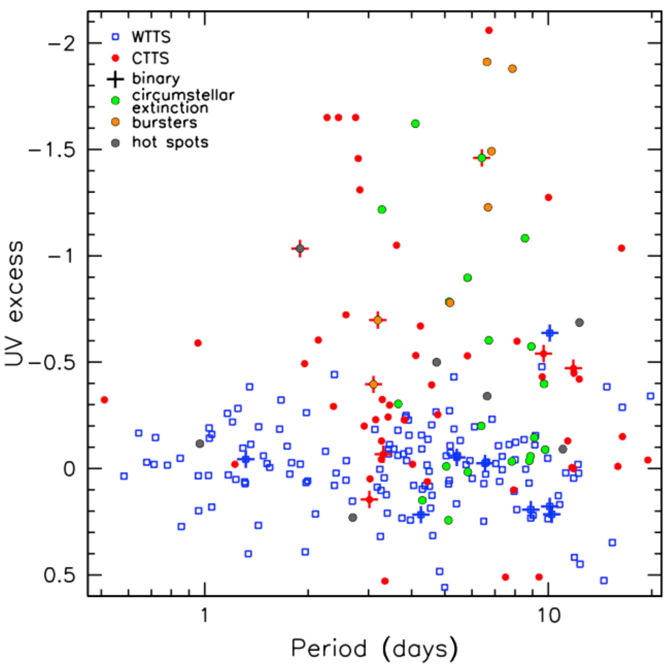
Accreting stars are more likely to be slow rotators than non accreting ones.

YSOVAR: **IR excess (**dusty disk)



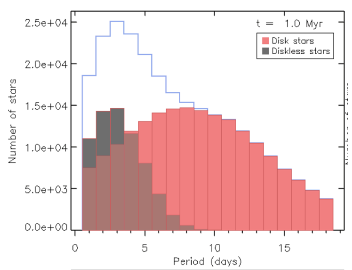
Rebull, Cody, Covey+14

CSI2264: **UV excess (**accretion shock)



Venuti, Bouvier, Cody+17

PMS rotational evolution: simulations

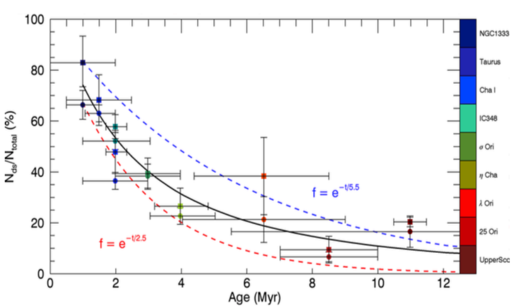


Initial period distribution

+

dMacc/dt ≈ $M_*^{1.4}\ t^{-0.5}$

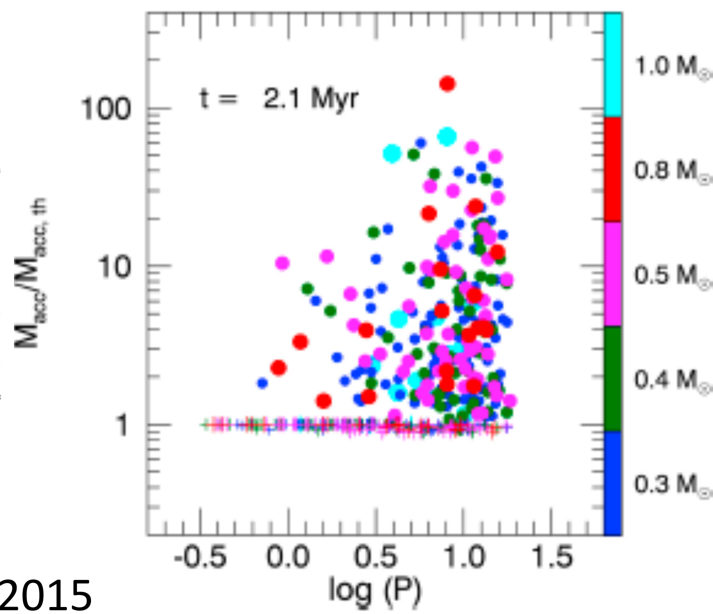
+

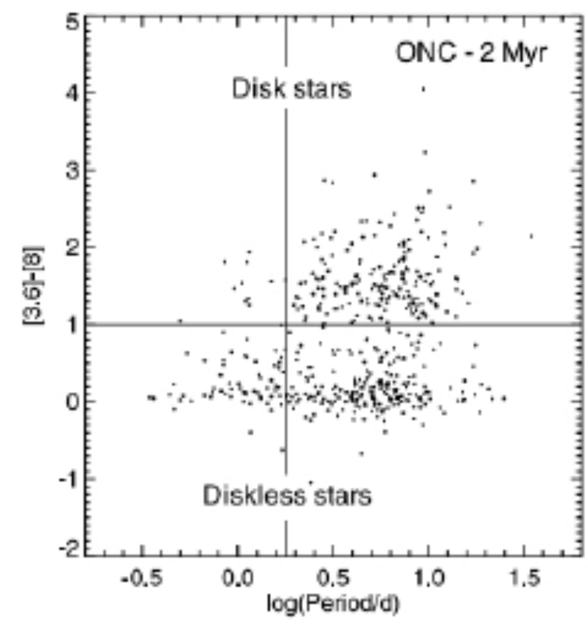


Disk survival time distribution

Monte Carlo simulations: an initial rotational period distribution is evolved forward in time, assuming:

- accreting stars remain at constant angular velocity (no spin up)
- non-accreting stars spin up as they contract

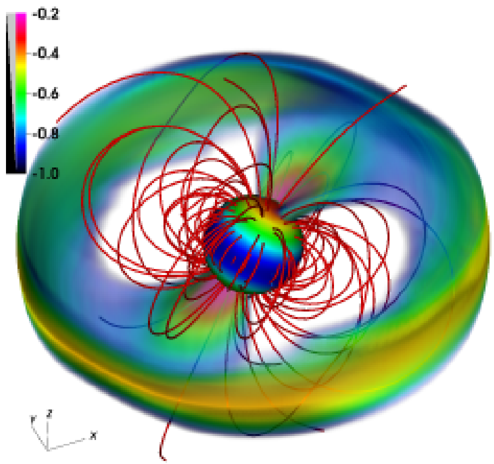




Vasconcelos & Bouvier 2015

PMS star-disk interaction

Kurosawa & Romanova 2013



Why do young stars rotate slowly ?

How to compensate for the accretion spin-up torque ?

$$\dot{J}_{\rm acc} = \dot{M}_{\rm acc} R_t^2 \Omega_{\rm d}$$

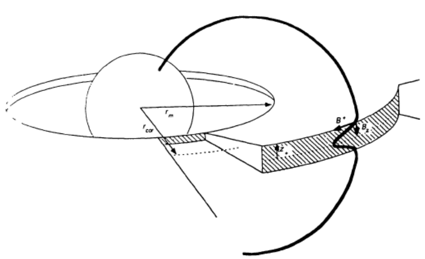
T Tauri stars have strong magnetic fields that truncate the inner disk at a distance :

$$\frac{r_{\rm t,\,th}}{R_*} \simeq 2\, m_{\rm s}^{2/7} B_*^{4/7} \dot{M}_a^{-2/7} M_*^{-1/7} R_*^{5/7}$$

Bessolaz, Zanni, Ferreira+ 2008

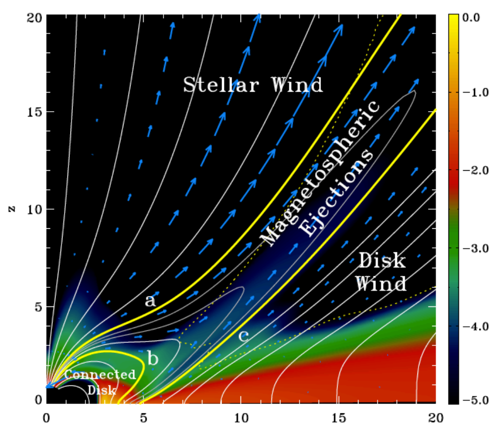
Can the magnetic star-disk interaction brake the central star?

Star-disk connection



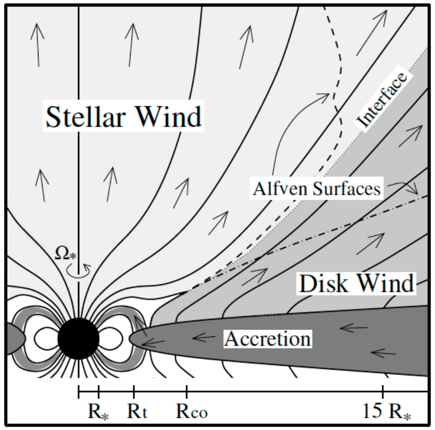
Gosh & Lamb 1979; Collier Cameron et al. 1995

Magnetospheric ejections



Zanni & Ferreira 2009, 2013

Accretion-powered stellar winds

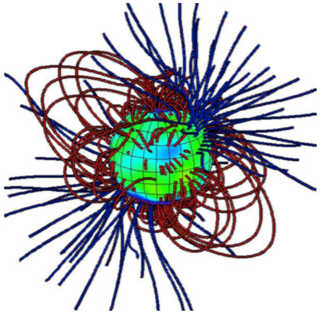


Matt & Pudritz 2005

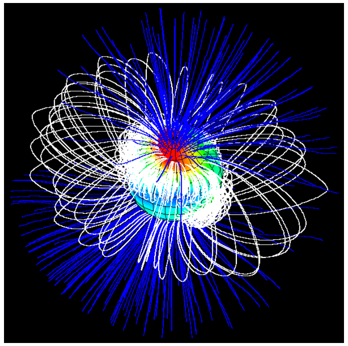
Star-disk interaction

Stellar magnetic field vs. mass accretion rate

- What do we know of PMS magnetic fields ?
- How do they evolve during PMS ?
- How (un)predictable are mass accretion rates ?
- How do they depend on stellar properties ?



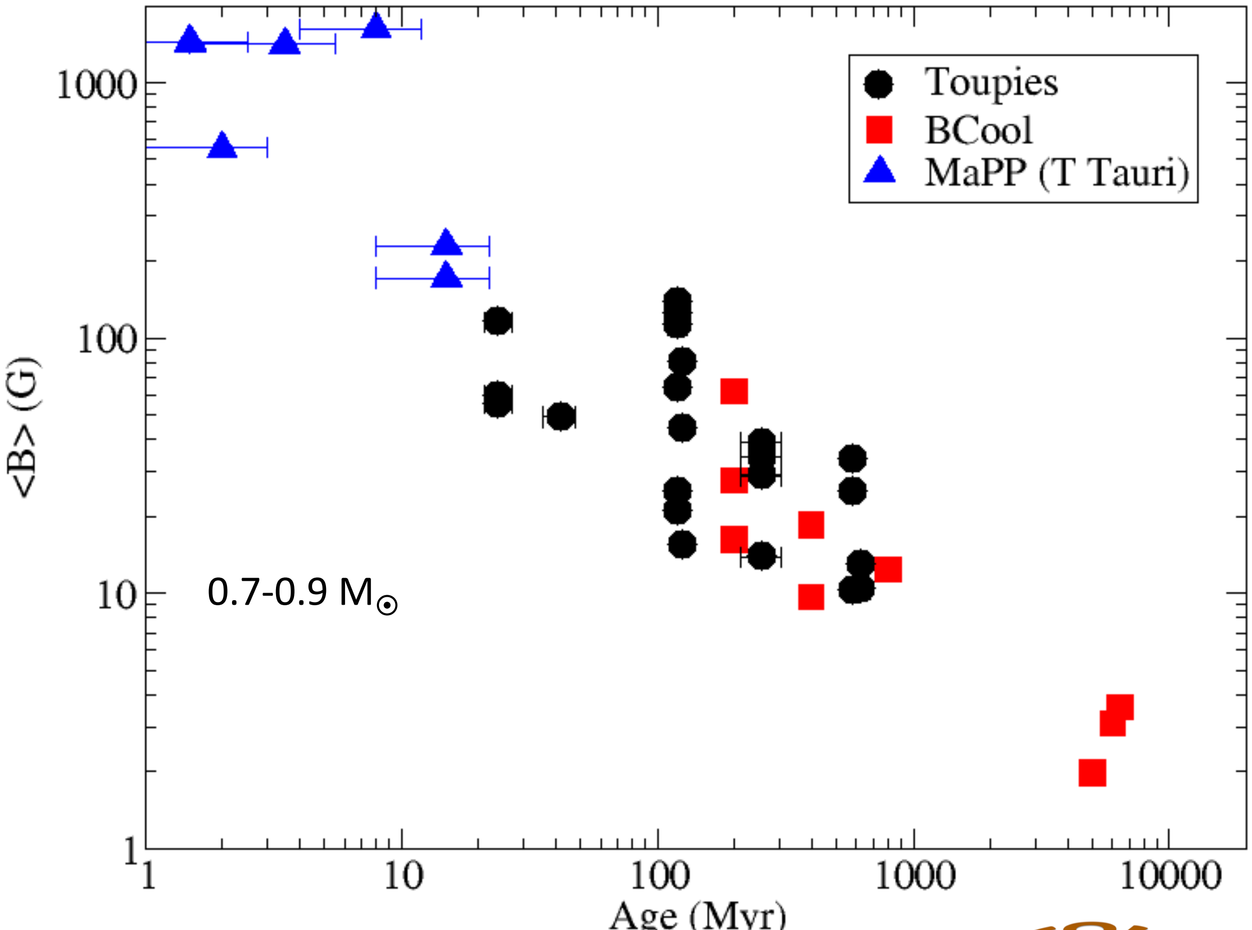
YSOs magnetic fields



- Spectropolarimetry → **field strength and topology** (e.g., Donati et al., Johns-Krull et al.)
- In YSOs, the magnetic fields range **from a few 100G to a few kG**
- Magnetic field topology **evolves during the PMS** and seems to primarily depend on internal structure (convective/radiative)
- Strong implications for **star-disk interaction** and angular momentum evolution

Evolution of stellar magnetic fields

Steady decrease of magnetic field strength from the early PMS through the ZAMS and MS



Zero-age main sequence dwarfs
Solar-type main sequence stars
Accreting T Tauri stars

PMS B evolution due to structural properties (not linked to rotation)

ZAMS & MS B evolution due to rotational braking

Folsom, Petit, Bouvier+16
Vidotto, Gregory, Jardine+14
Gregory, Donati, Morin+12

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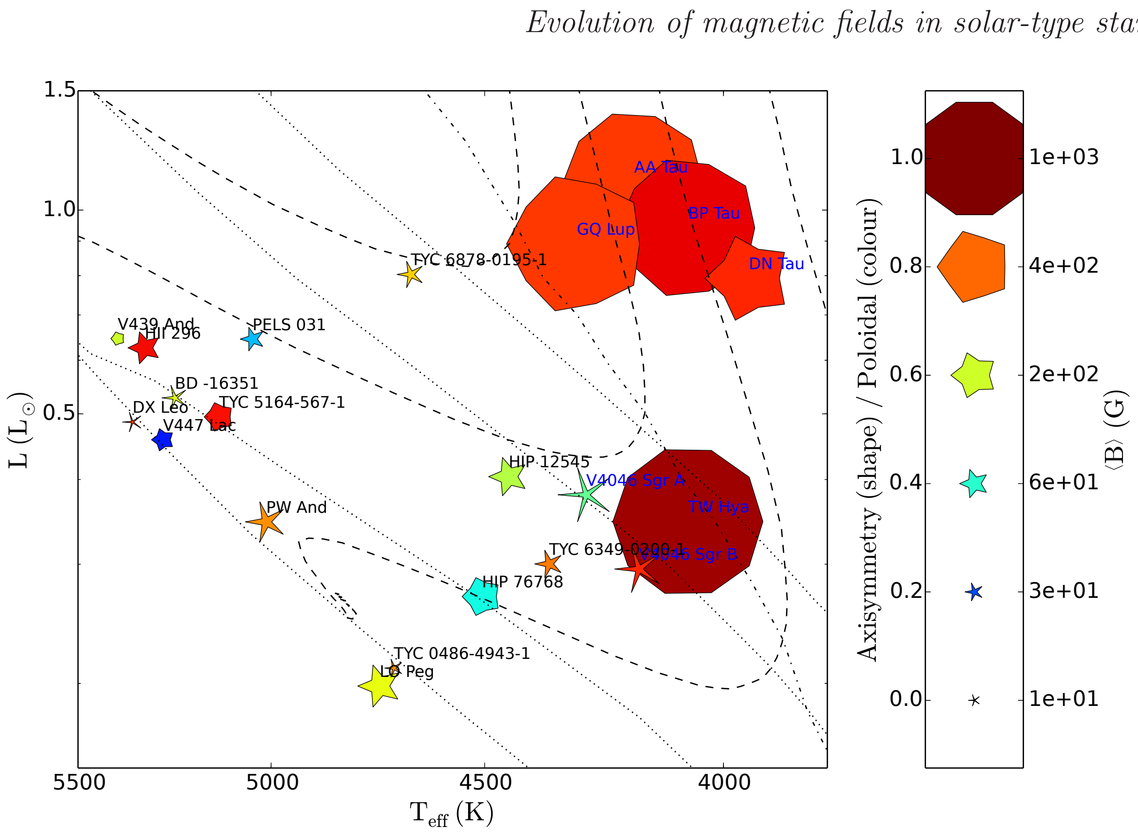
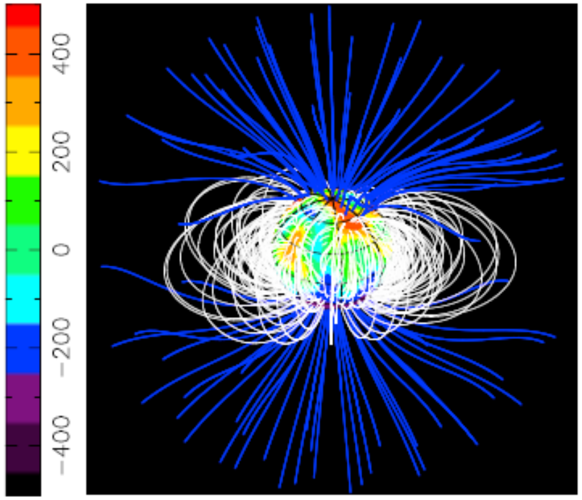
PMS magnetic field evolution

Strong magnetic fields in YSOs primarily linked to their fully convective interior



Folsom, Petit, Bouvier+16,
Donati, Gregory, Alencar+13
Gregory, Donati, Morin+12



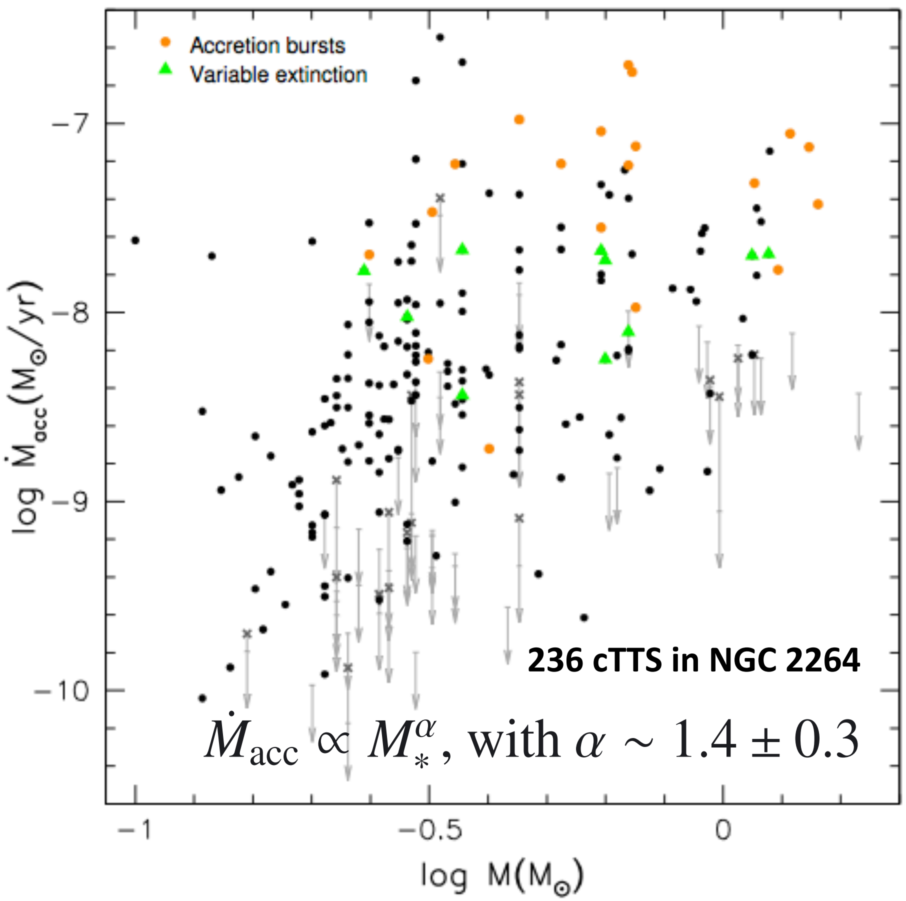
Strong magnetic fields, **mostly dipolar**, in fully convective PMS stars (-> star-disk interaction)

Mass accretion rate: NGC 2264

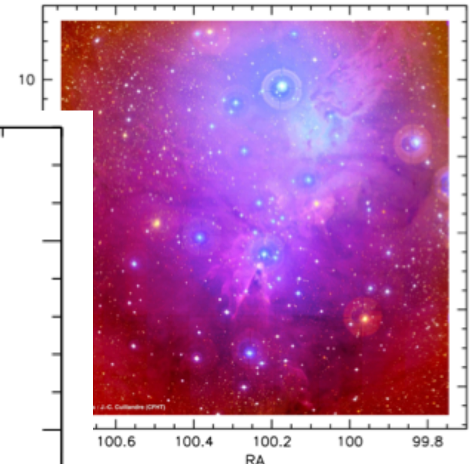
Mass accretion rate measured from UV excess

Venuti, Bouvier, Irwin+15

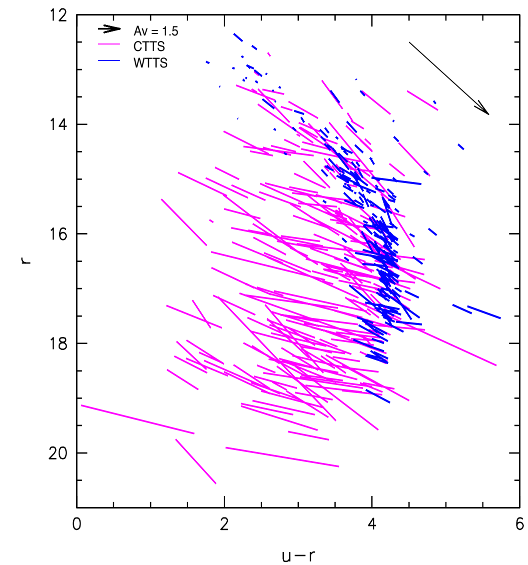
Large scatter in M_{acc} at any mass…



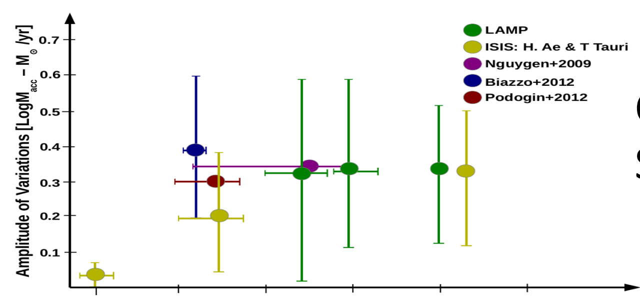
Venuti, Bouvier, Flaccomio+14



2 weeks timescale variability



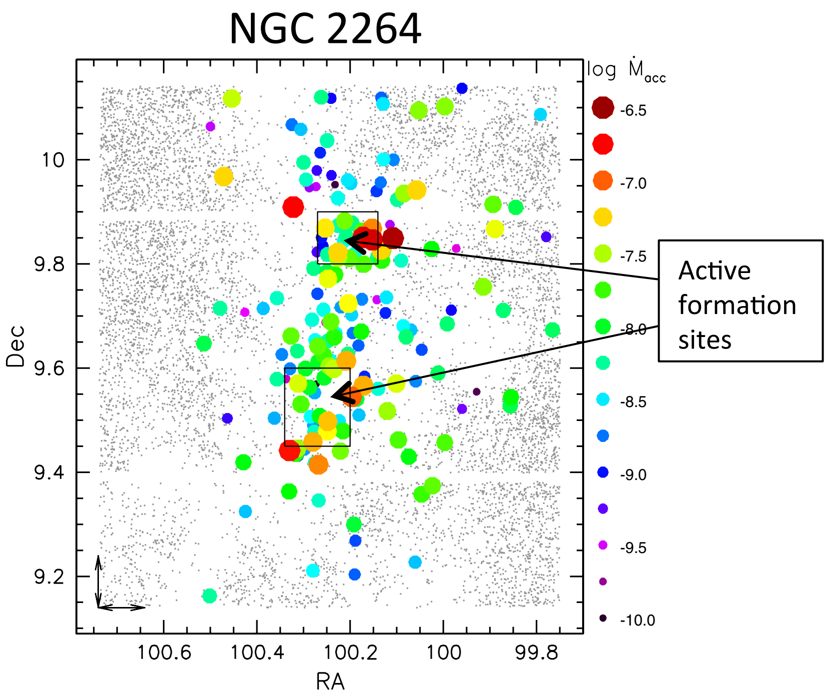
… cannot be accounted for by short or mid-term variability.



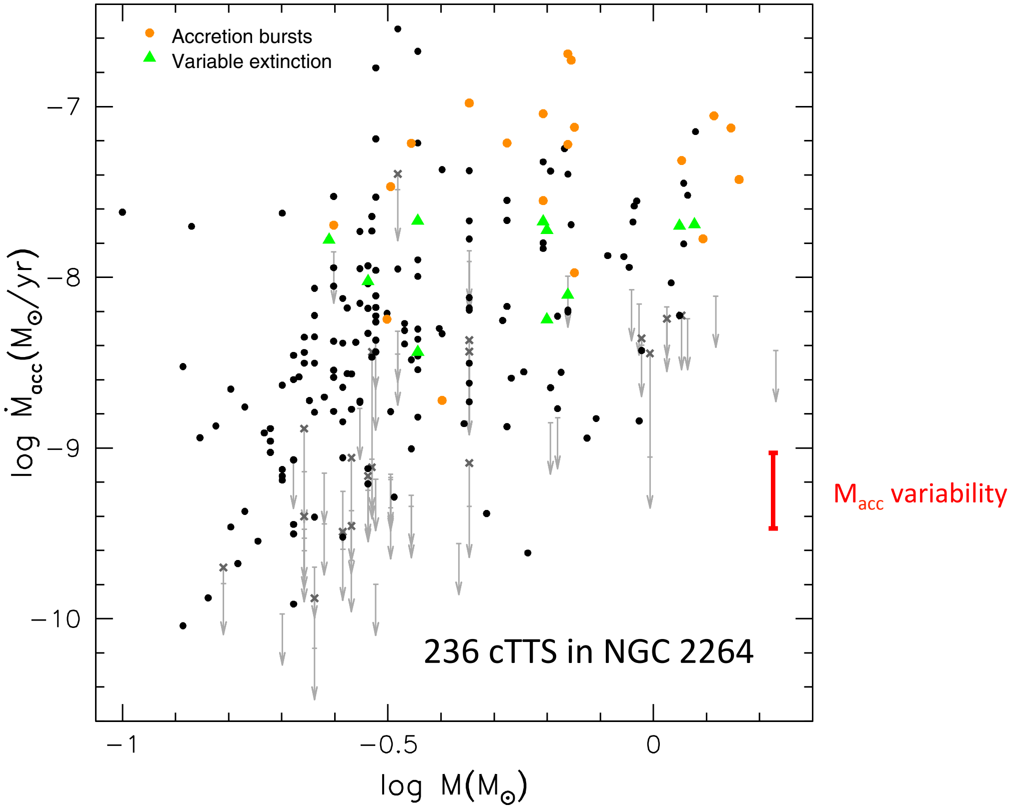
Costigan, Vink, Scholz+14

Mass accretion rate scatter

Age dispersion?



Spatial distribution // age dispersion?

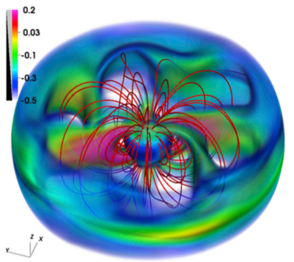


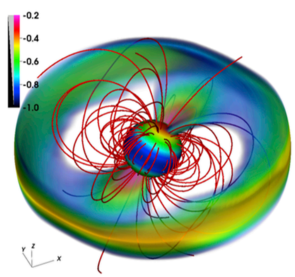
Venuti, Bouvier, Flaccomio+14

Mass accretion rate scatter

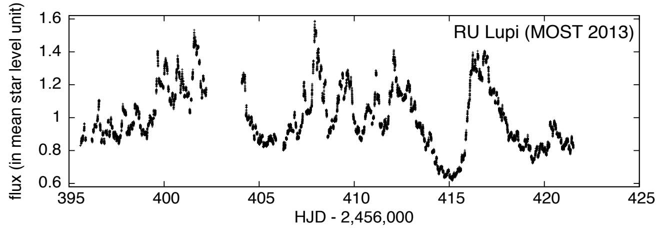
Different accretion regimes?

Kurosawa & Romanova 2013

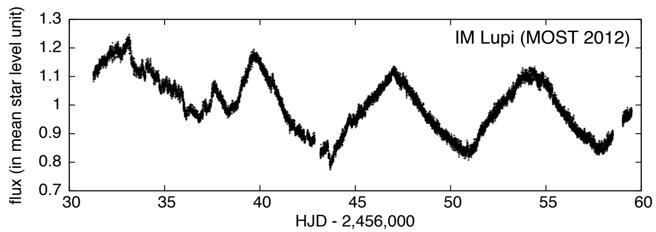




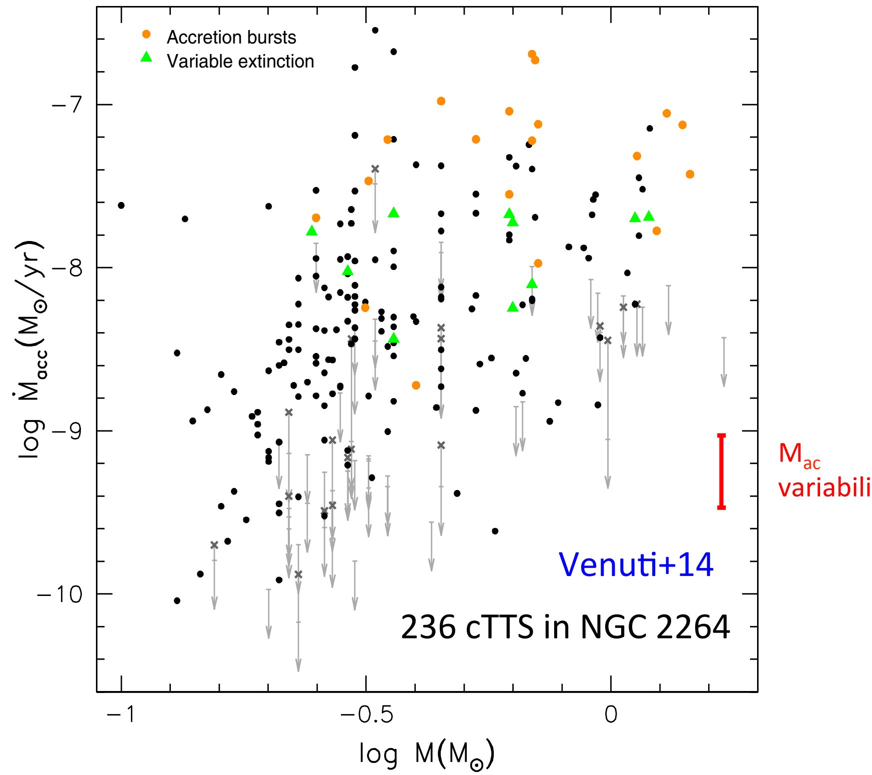
Macc ≈ 10^{-7} $M_\odot$/yr



Macc ≈ 10^{-11} $M_\odot$/yr



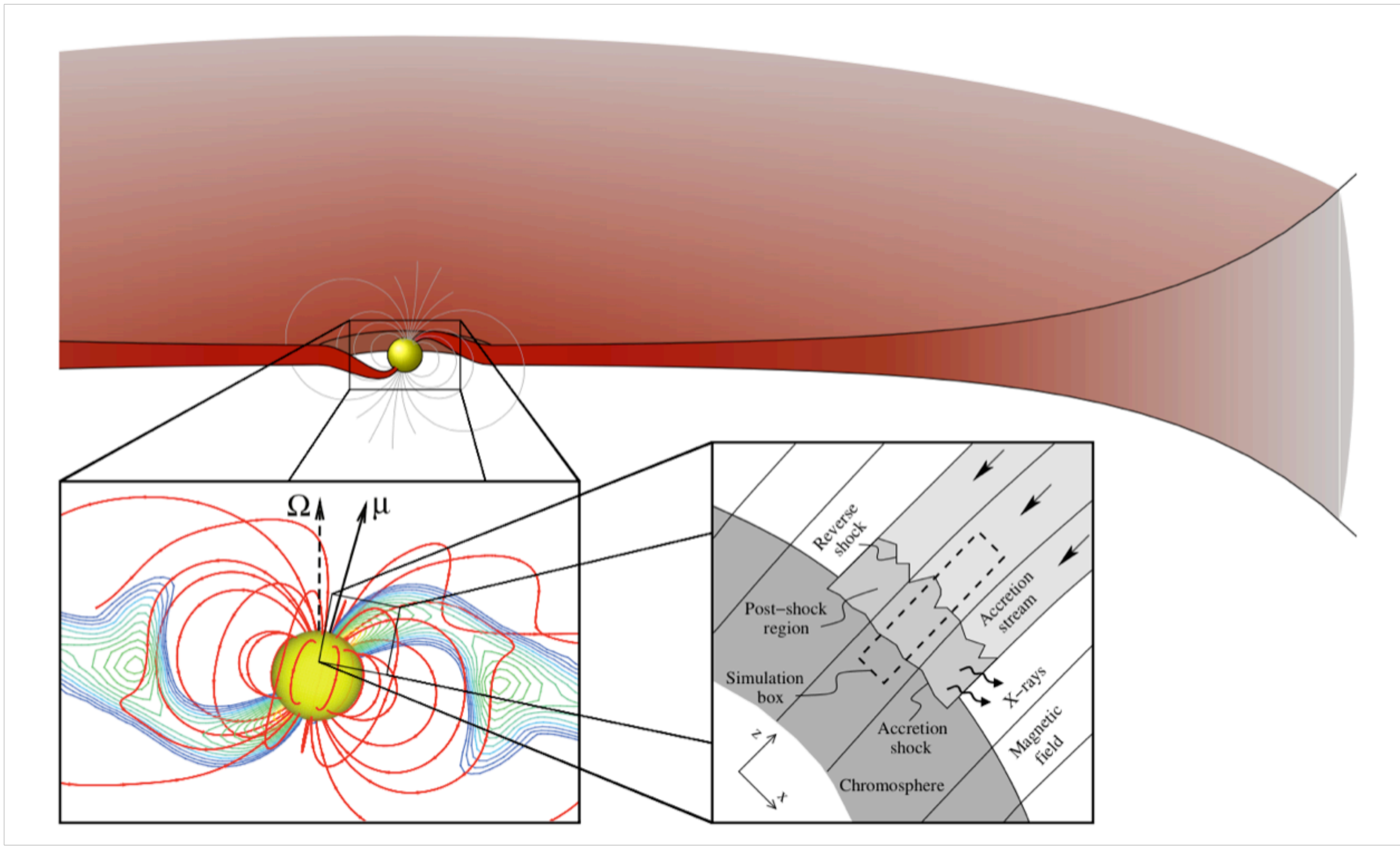
Siwak, Ogloza, Rucinski+16



Different accretion regimes onto the star?

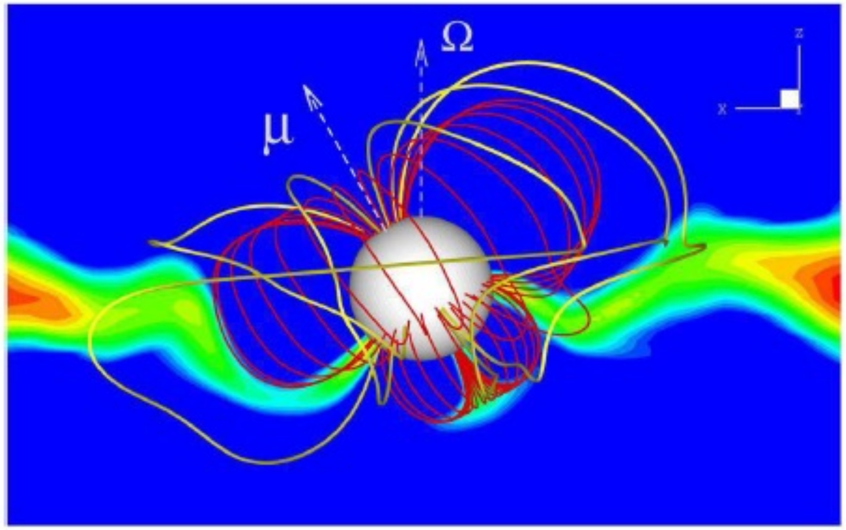
How does it relate to magnetic topology?

Investigating the star-disk boundary: magnetospheric accretion



de Sá, Chièze, Stehlé+ 2014

Magnetospheric accretion



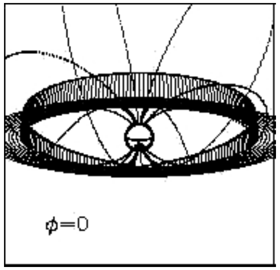
Long, Romanova, & Lovelace 2007

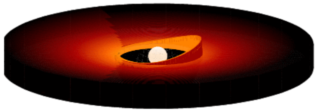
- How is the disk material accreted onto the star?
- How stable vs. dynamical is the magnetospheric accretion process?
- How does it impact the inner disk structure?
- How does it modify PMS evolution?

Star-disk interaction

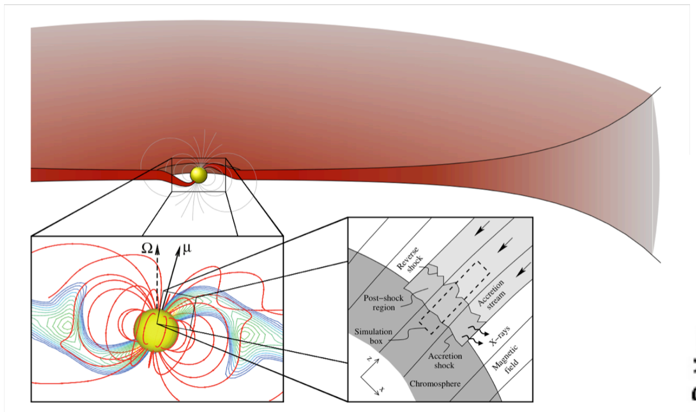
de Sa 2014; Matsakos+13;
Romanova & Owocki 2016

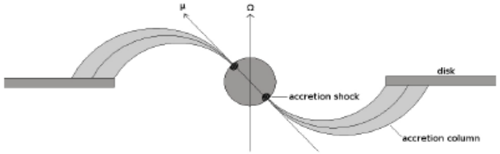
Bouvier, Alencar, Boutelier+07
Donati, Skelly, Bouvier+10



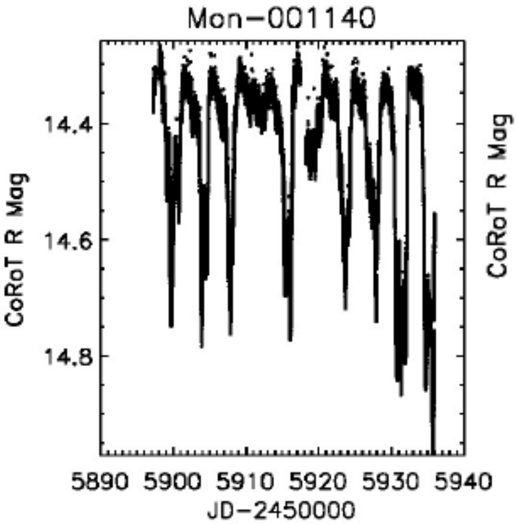


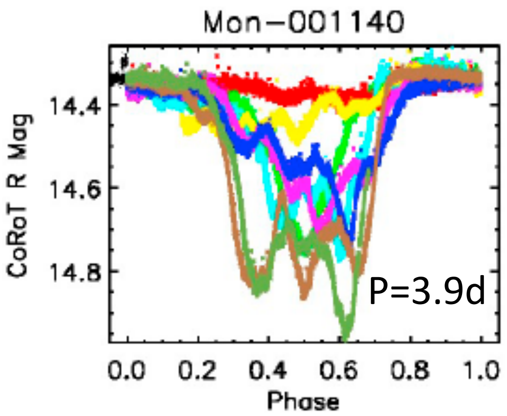
AA Tau's or dippers





Periodic obscuration; very dynamic on a timescale of days



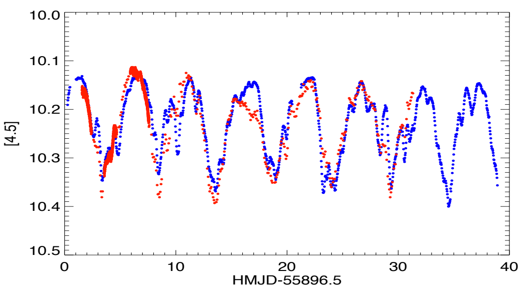


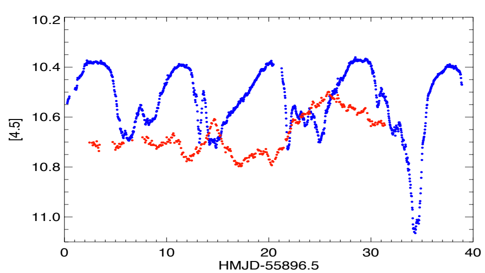
Approx. 20-30% of Class II YSOs

Stable accretion funnel flows and accretion shocks at the stellar surface

Inner disk warp, stable but dynamical (changes on a timescale of weeks)

Alencar+10; Cody+14; Fonseca+14;
McGinnis+15; Sousa+15



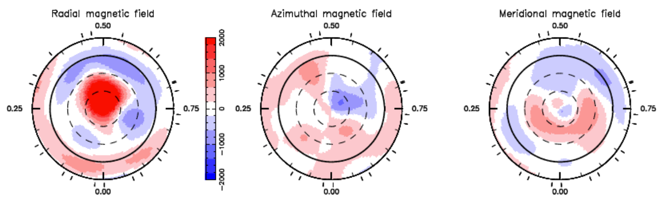


Optical (CoRoT, blue) and IR (Spitzer, red) not always correlated!

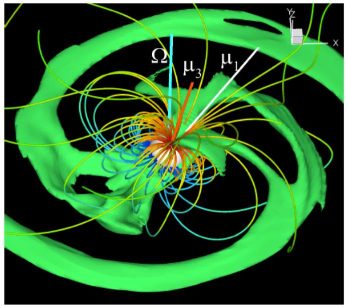
Star-disk interaction: the magnetospheric accretion process

e.g., V2129 Oph

CFHT/ESPaDOnS spectropolarimetry yields:
2.1 kG octupole + 0.9 kG dipole



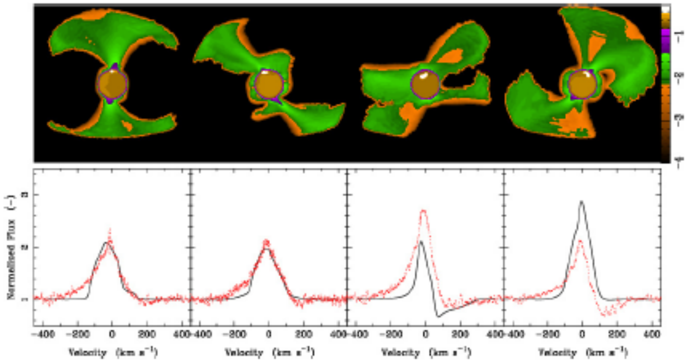
Donati, Bouvier, Walter+11



3D MHD simulations predict the accretion flow geometry

Romanova, Long, Lamb +11

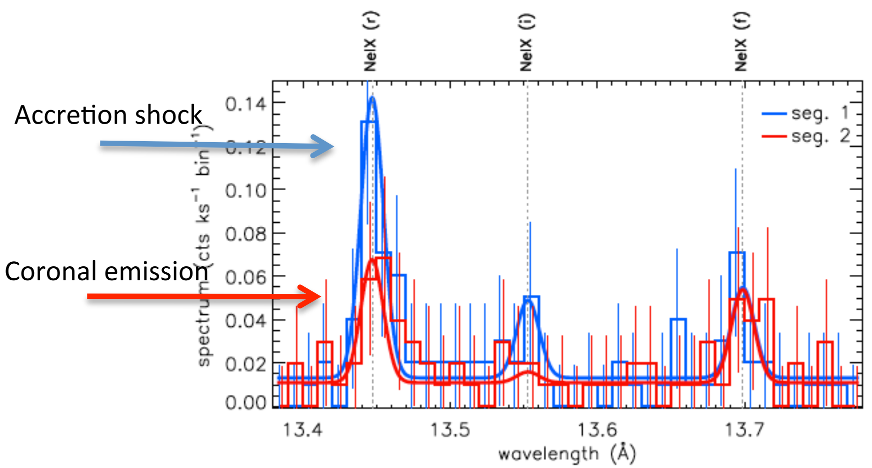
ESO/Harps line profile variability + 3D RT models reveals accretion dynamics



Alencar, Bouvier, Walter+12
Kurosawa, Romanova, & Harries 2011

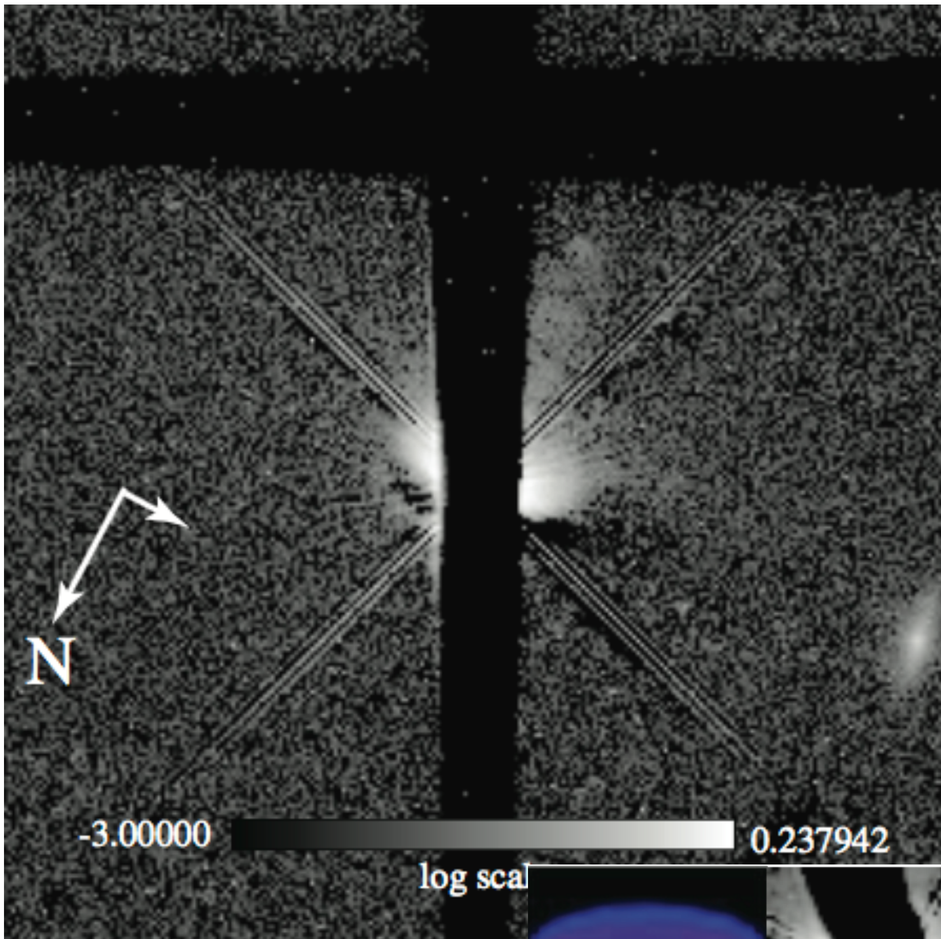
Chandra X-ray monitoring reveals accretion shock

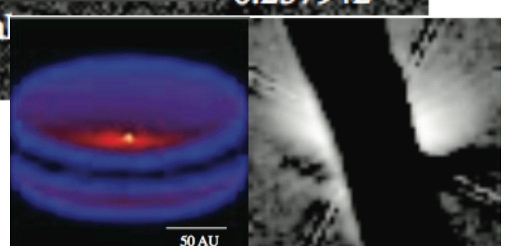
Argiroffi, Flaccomio, Bouvier+11



A grazing line-of-sight: AA Tau

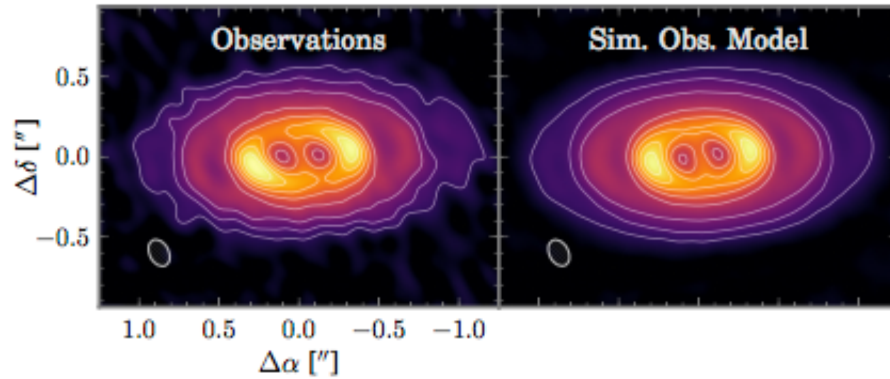
HST/STIS: Cox, Grady, Hammel+13





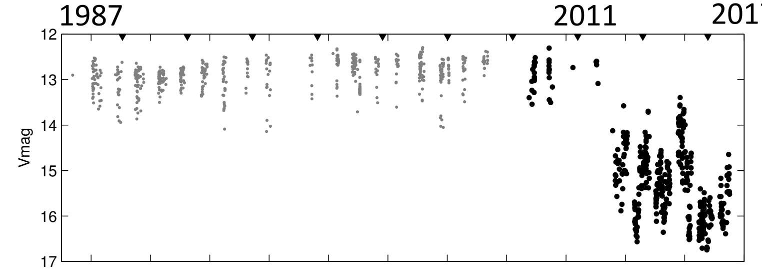
Outer disk inclination:
~71 +/- 1 deg.

ALMA: Loomis, Oeberg, Andrews+17



Disk inclination: 59.1 +/-0.3 deg.
+ possible evidence for inner disk warp

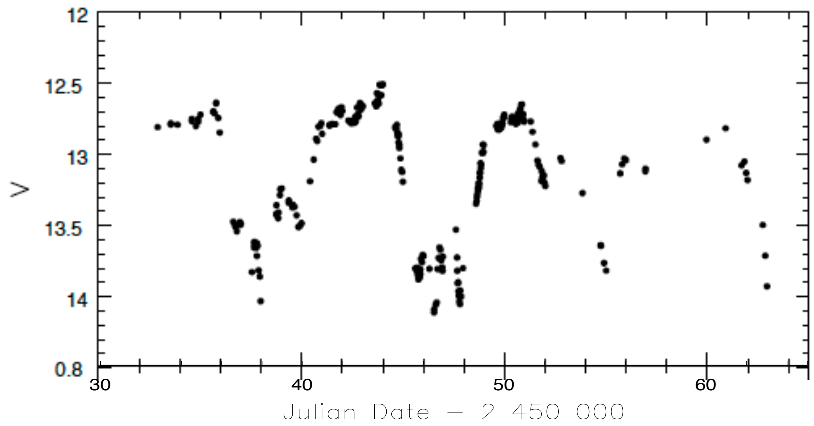
AA Tau's 30 year-long light curve

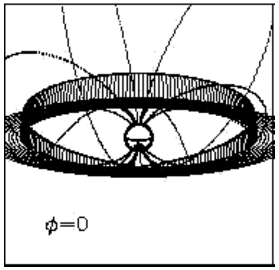


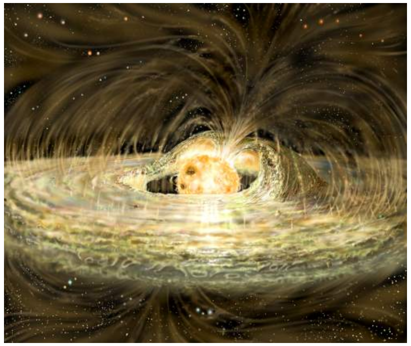
~4 mag additional extinction
on the line-of-sight since 2011

Bouvier, Grankin, Ellerbroek+13

AA Tau: the prototype of dippers

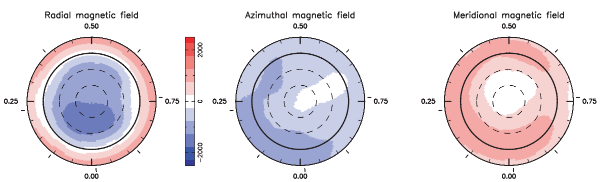






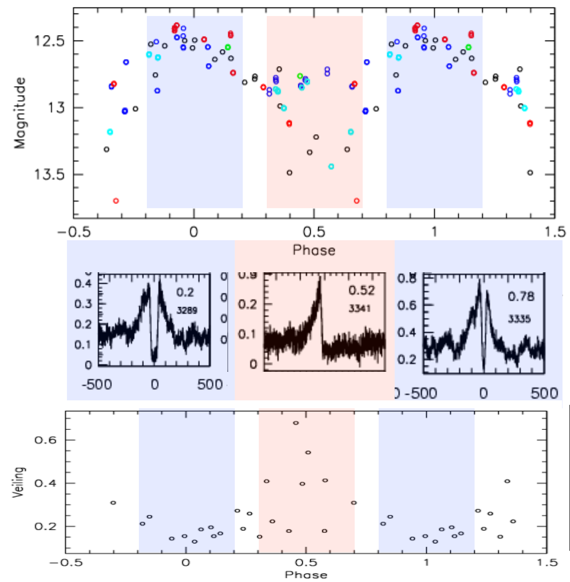
Bouvier, Alencar, Boutelier+07

Inclined magnetosphere



2-3 kG tilted dipole field

Donati, Skelly, Bouvier+10



Periodic eclipses
(disk warp)
(P=8.22d)

Balmer lines
(accretion funnel)

Veiling
(accretion shock)

Supports tilted stellar magnetosphere + inner disk warp + accretion columns + accretion shock, all occurring at the same azimuth, i.e., physically connected.

CSI2264: Coordinated Synoptic Investigation of NGC 2264

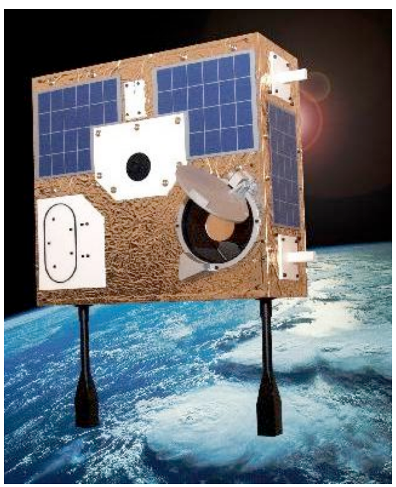
A REVOLUTION IN SPACE BASED MONITORING OF YOUNG STARS

(December 2011)

P.I. J. Stauffer, G. Micela

NGC 2264
Distance ~ 760 pc
Age ~ 3-5 Myr
Known members: ~2000

- Spitzer: 30d @ 3.6, 4.5 µm
- CoRoT: 40d, optical
- Chandra/ACIS: 300ks (3.5d)
- MOST: 40d, optical
- VLT/Flames: ~20 epochs
- Ground-based monitoring
  U-K bands: ~3 months



(includes CFHT/MegaCam
u + r-band monitoring)

The revolution of space photometry

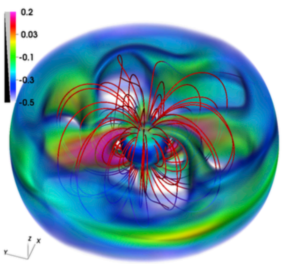
- CoRot, Spitzer, Kepler K2, soon: Gaia, TESS, PLATO…
- **CSI 2264*:*** YSOs variability classes (Cody+, Stauffer+ 2014-2017 paper series)
  - Spotted, dippers, bursters, stochastics, and some others…
- Not a mere classification, but **the reflection of different physical processes / accretion regimes / circumstellar absorption events.**

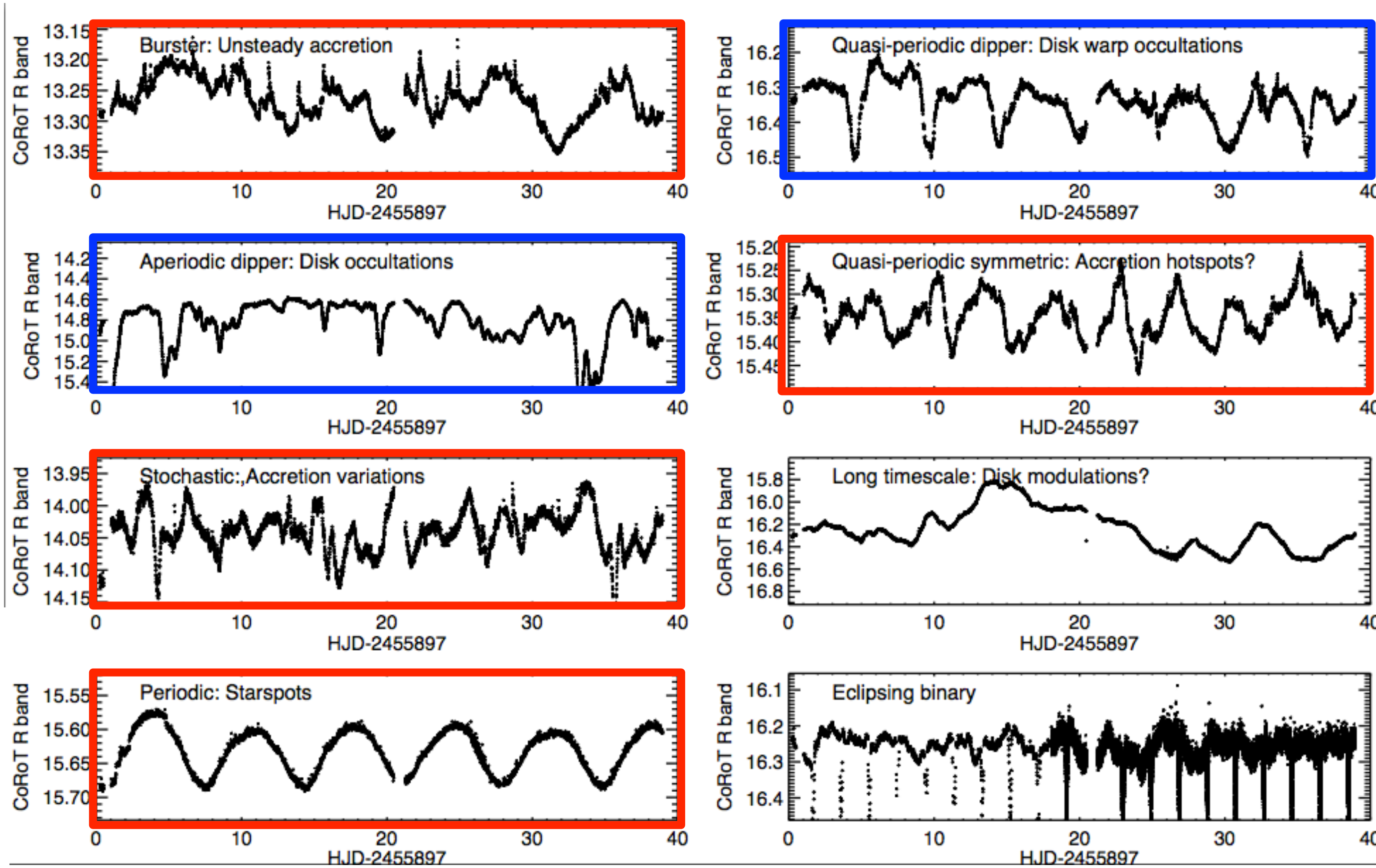
Optical variability

NGC 2264 CoRoT light curves

Accretion

Occultation





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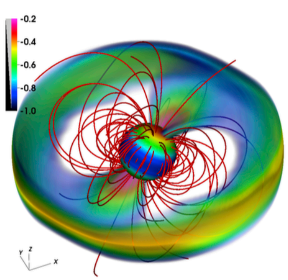
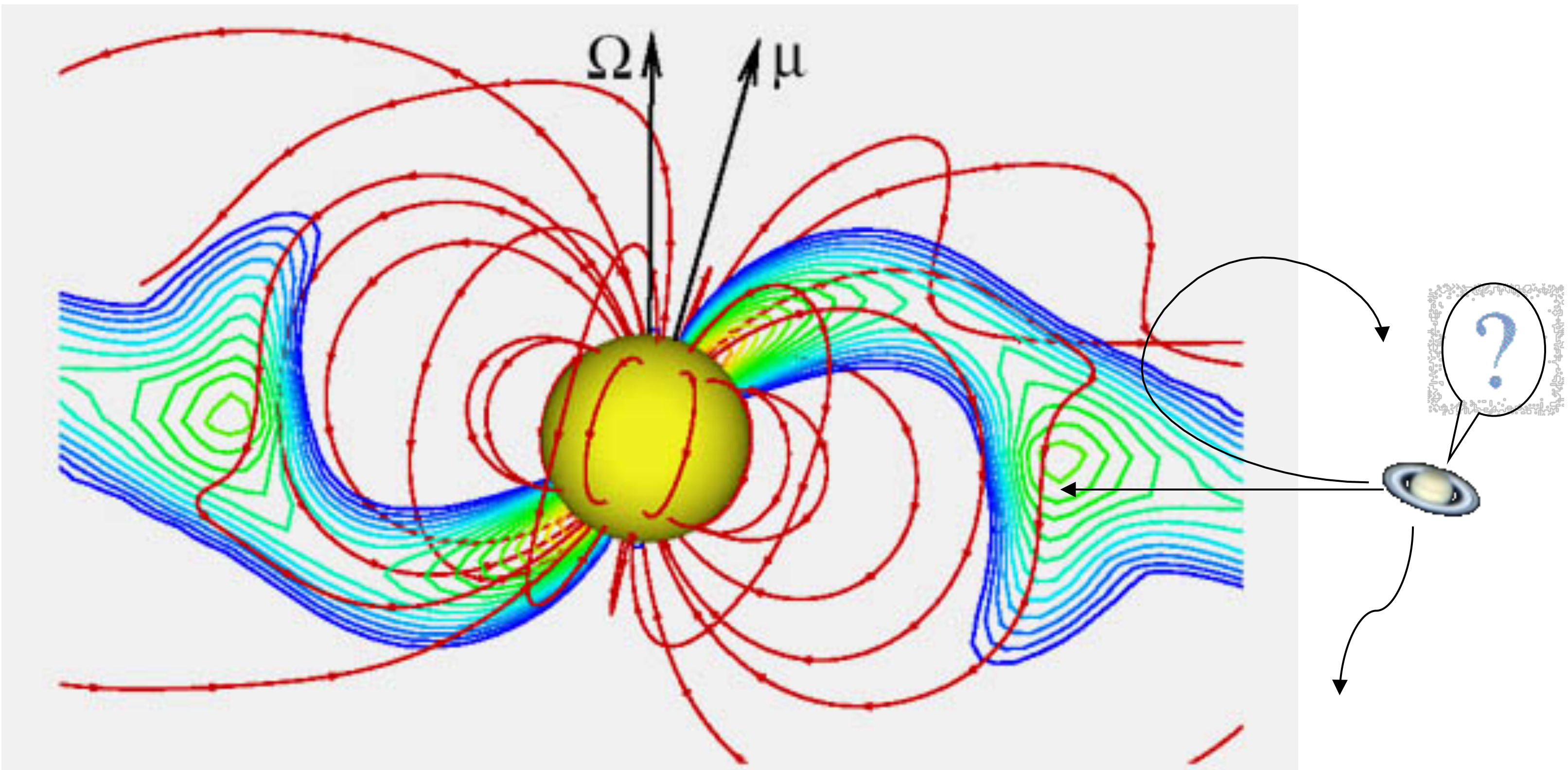
Eclips.Bin



Stable vs. unstable accretion regimes?

Cody, Stauffer, Baglin, Micela, Rebull+14

Star-disk interaction: is that all ?

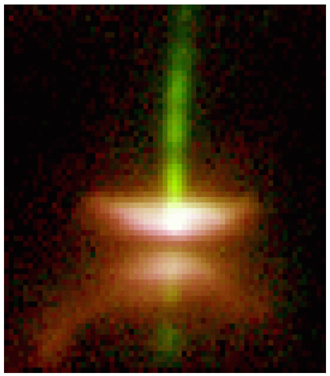


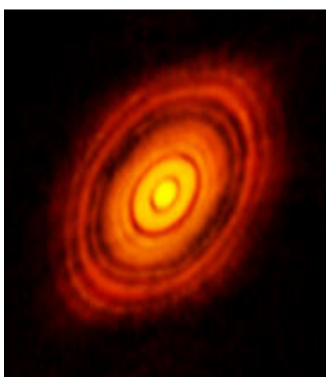
Halting the planetary migration ?

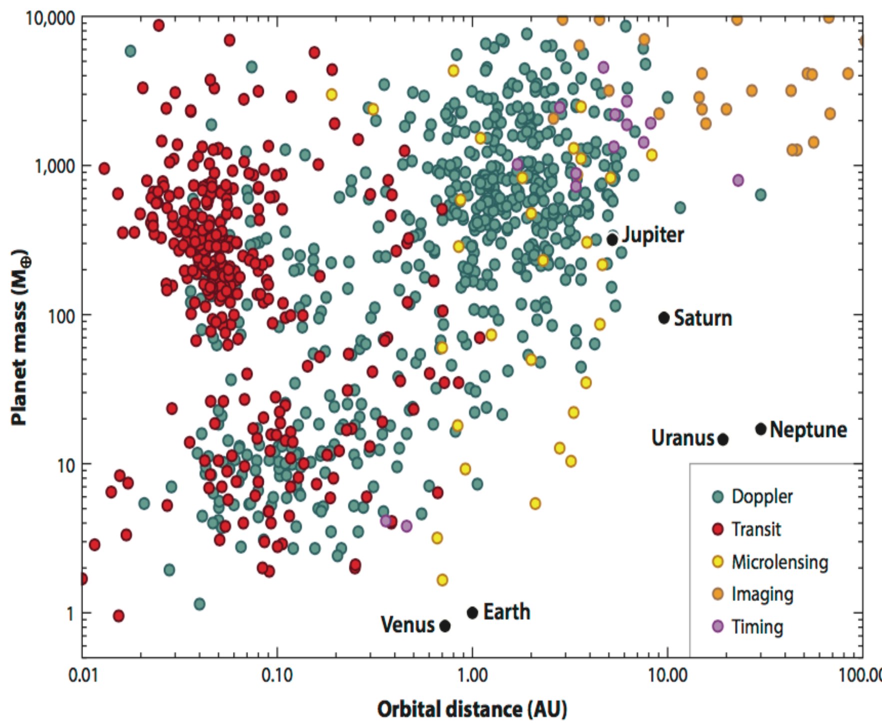
“Hot Jupiters” (or Saturns…)?

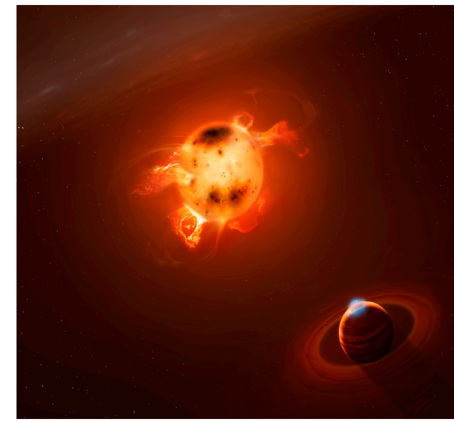
+ inner rocky planets (cf. Kepler)

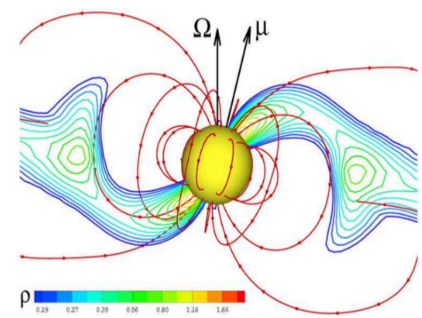
Star – planet(s) – inner disk interactions
(ERC SPIDI)











(Note: postdoc and PhD positions to open at IPAG in early 2018)

Conclusion

- PMS evolution is affected by a variety of non-standard processes: accretion, magnetic fields, rotation.
- A full understanding of the star-disk interaction (accretion regimes, long-term evolution) is needed to ultimately develop realistic PMS evolution models.
- Additional complications on the horizon: Earth- and Neptune-like planets embedded in the inner disk; cf. Kepler.

→Next chapter: **Star-Planets-Inner Disk Interactions (SPIDI)**, a whole new avenue to explore.