# Pre-main sequence evolution: accretion, magnetic field, and star-disk interaction

Jérôme Bouvier
IPAG

# L’enfance (agitée) des étoiles (et des planètes)

Jérôme Bouvier
IPAG

Programme National de Physique Stellaire

# A star's childhood…

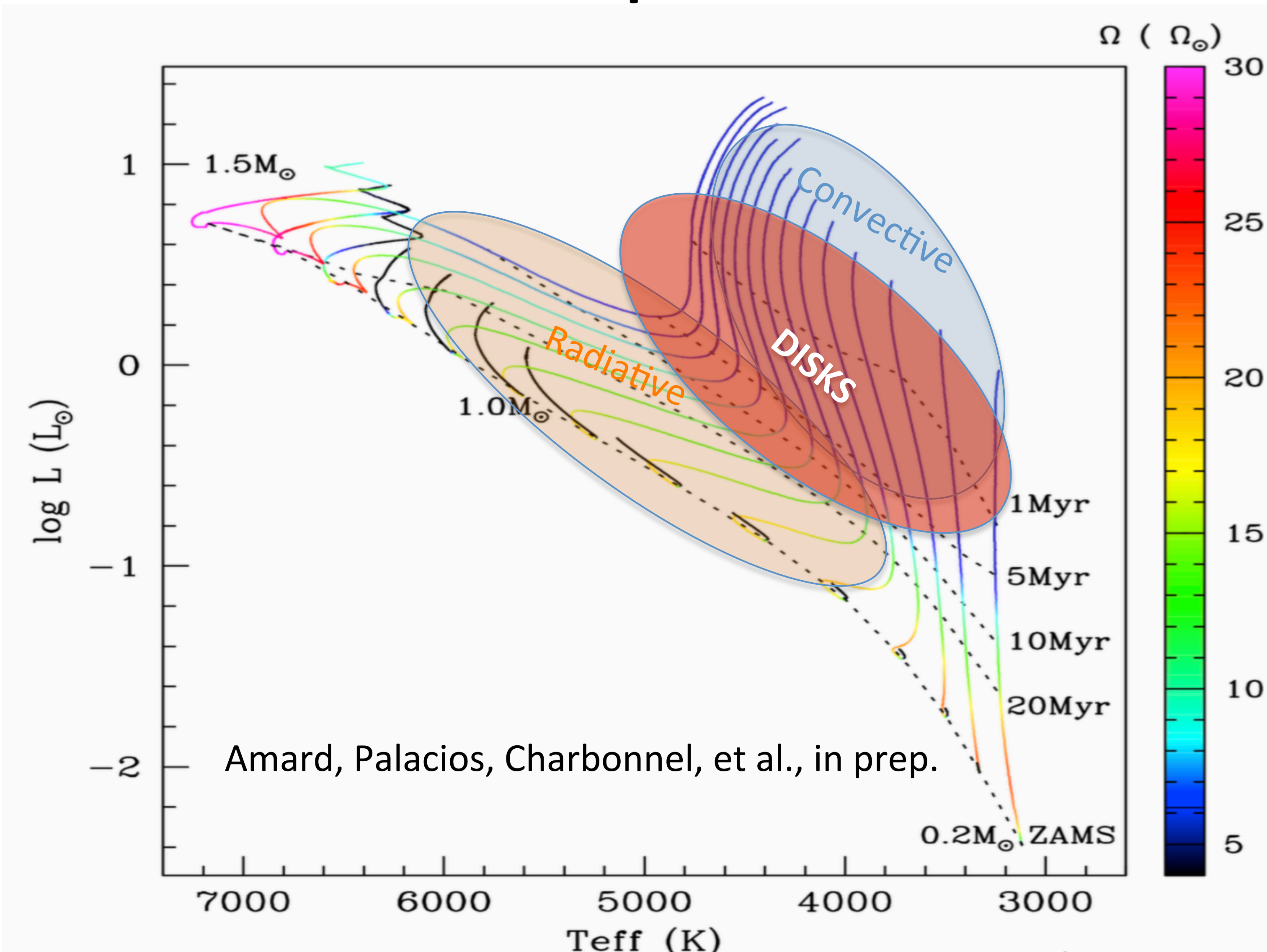
*(Almost) everything happens before 3 Myr!*

**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)

**All of these processes impact on the evolution of the central star and its disk, and thus define the initial and environmental conditions for planet formation.**

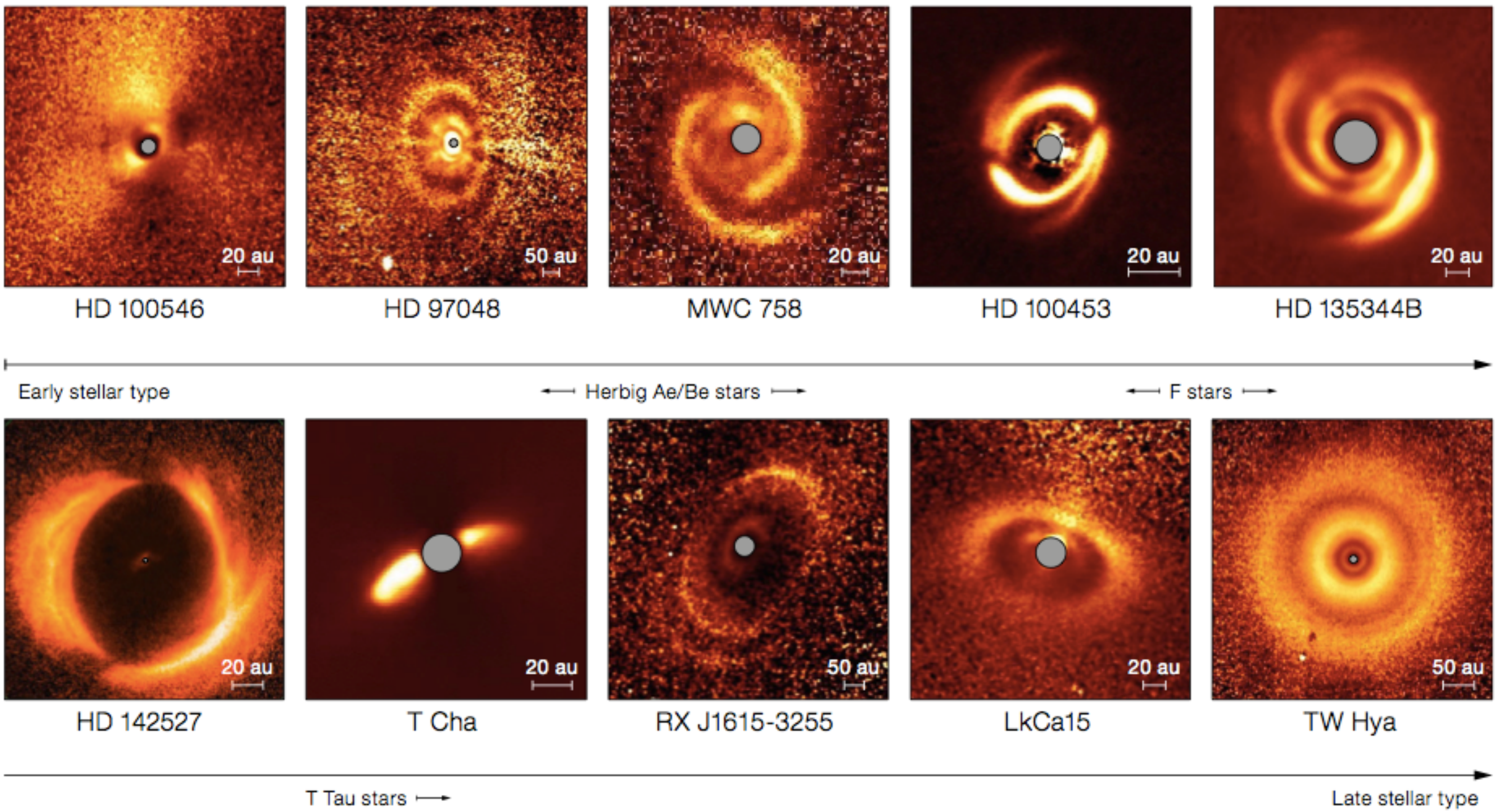
# Pre-main sequence models




Courtesy: L. Amard

# Circumstellar disks around young stars

Garufi, Benisty, Stolker et al. 2017, VLT/ SPHERE




# Sculpted by nascent planetary systems?

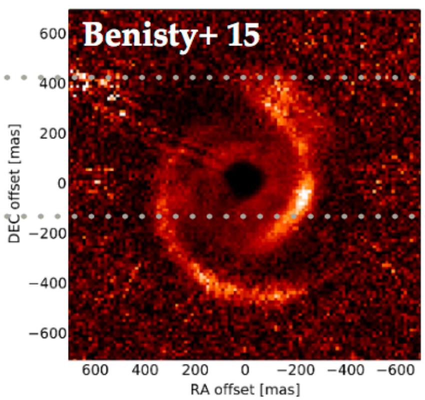
# Lopsided rings in the MWC 758 disc: two vortices?

Baruteau, Barazza (MSc) et al., to be subm.

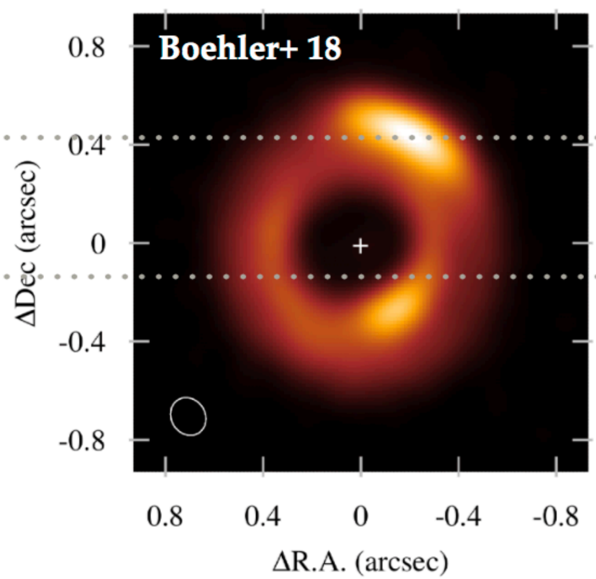
**observations**

Courtesy: C. Baruteau

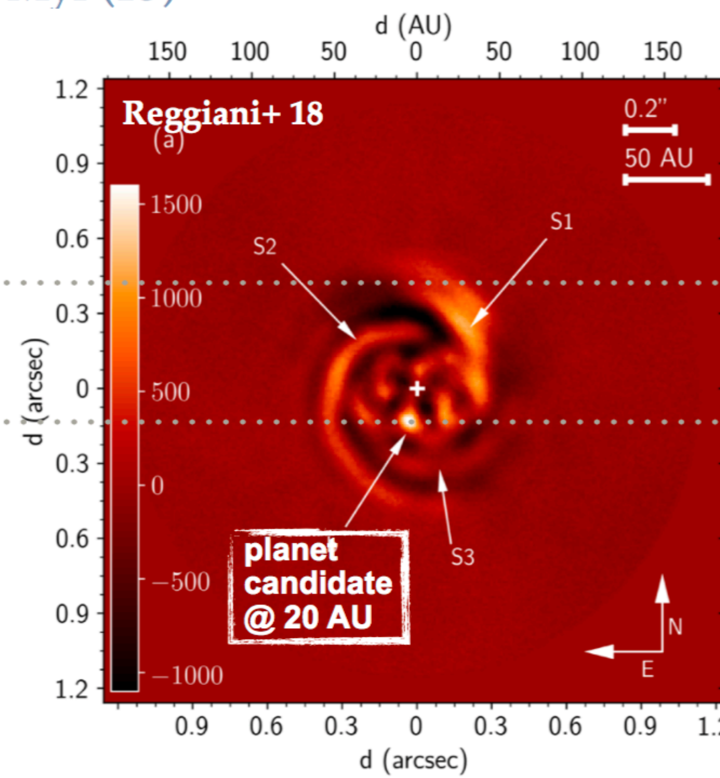
- **distance:** $151^{+9}_{-8}$ pc (Gaia)
- **star:** Herbig A5, mass $1.5 \pm 0.2\ M_\odot$ ($1\sigma$), age: $3.5 \pm 2.0$ Myr ($1\sigma$)




polarized intensity
@ 1 $\mu$m w/SPHERE




continuum emission
@ 0.9 mm w/ALMA



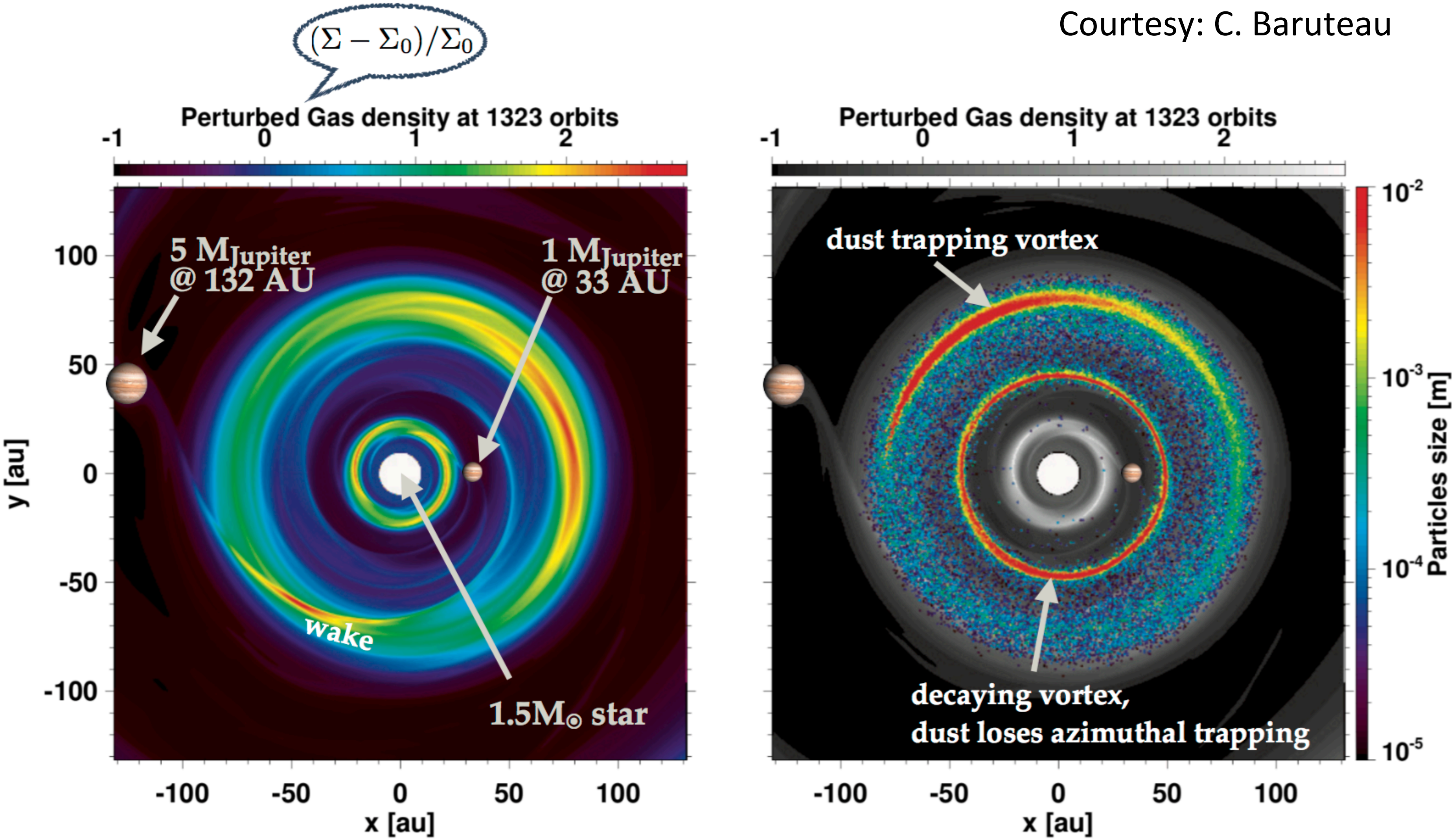

angular differential imaging
@ 3.8 $\mu$m w/KECK

# Lopsided rings in the MWC 758 disc: two vortices?

Baruteau, Barazza (MSc) et al., to be subm.

**2D gas+dust hydrodynamical simulations**

Courtesy: C. Baruteau




assuming moderately 'porous' dust
with internal density = 0.1 g cm$^{-3}$

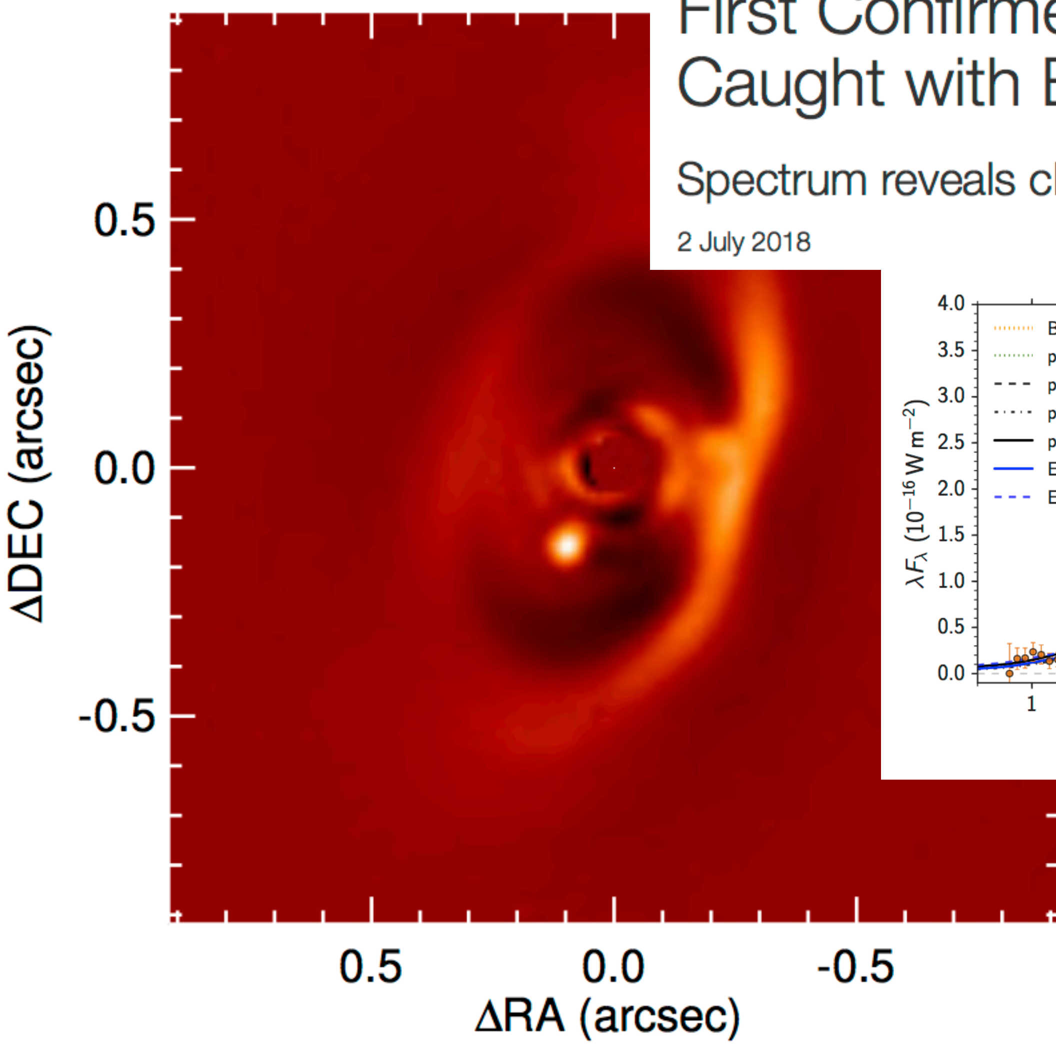
# PDS 70: a massive planet @ 22 AU

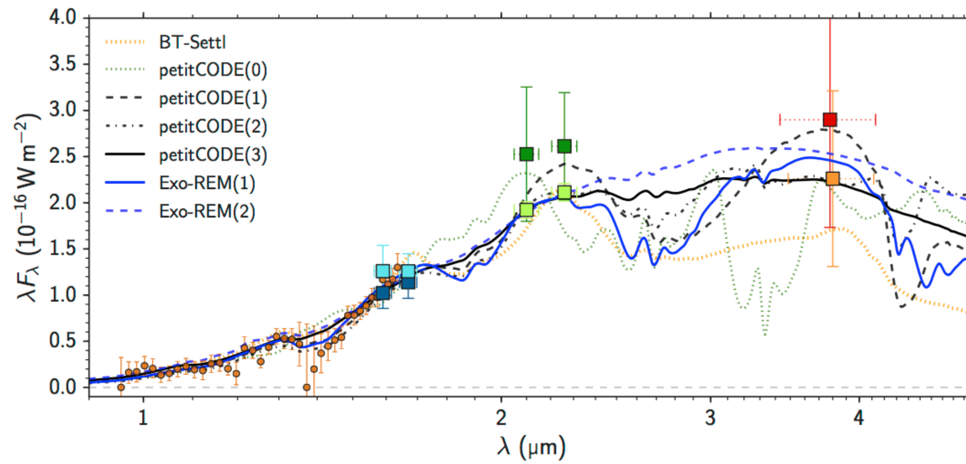
eso1821 — Science Release

## First Confirmed Image of Newborn Planet Caught with ESO's VLT

Spectrum reveals cloudy atmosphere

2 July 2018

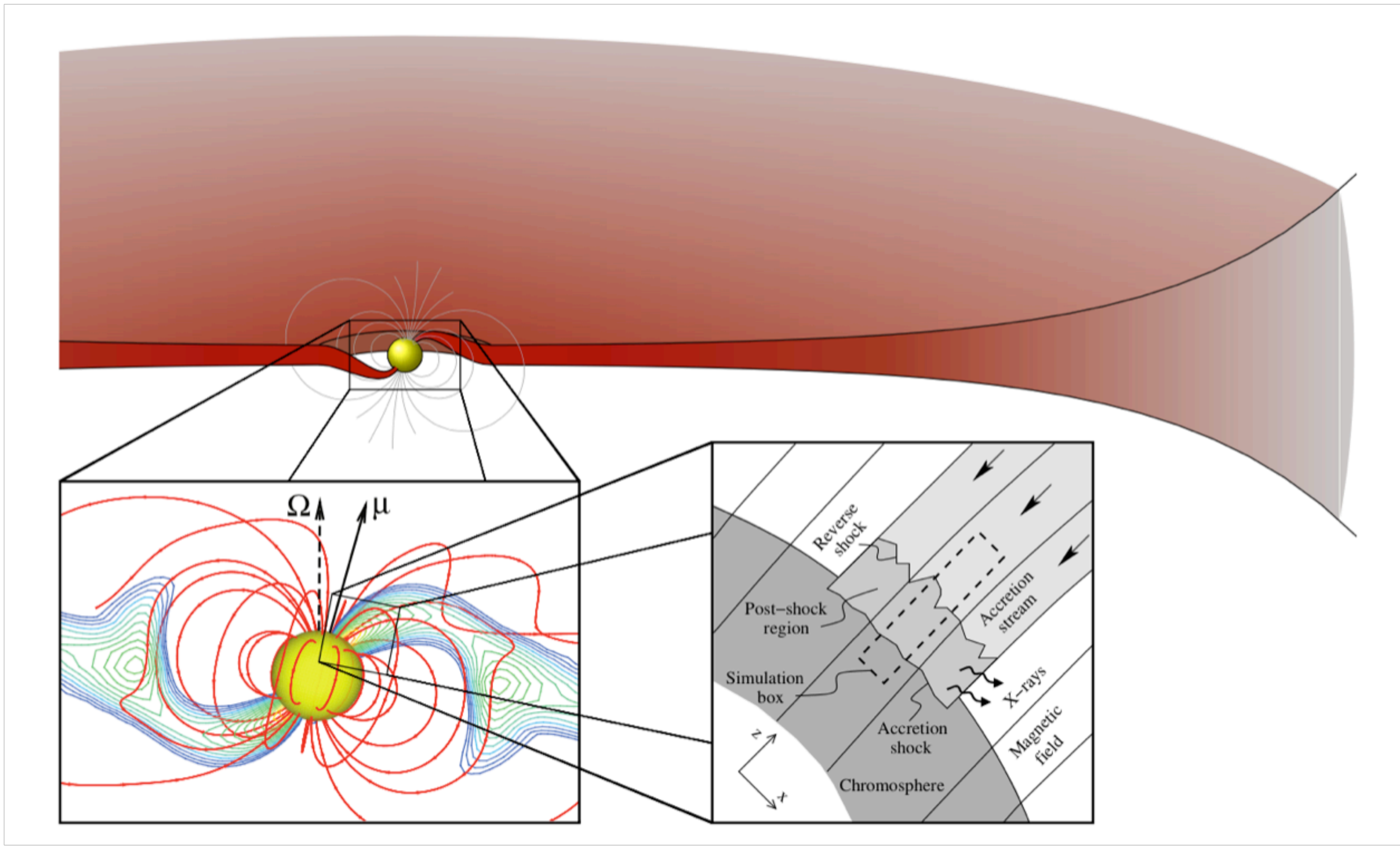



VLT/SPHERE

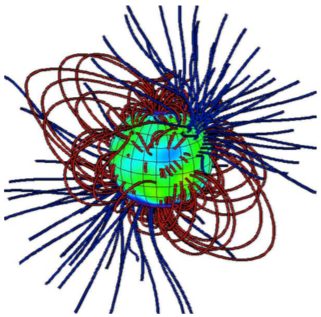
Keppler, Benisty, Muller, et al. 2018
Muller, Keppler, Henning, et al. 2018

# Star-disk interaction: magnetospheric accretion

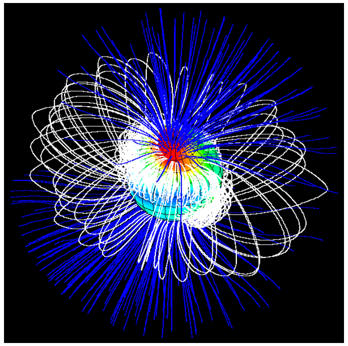



de Sá, Chièze, Stehlé+ 2014

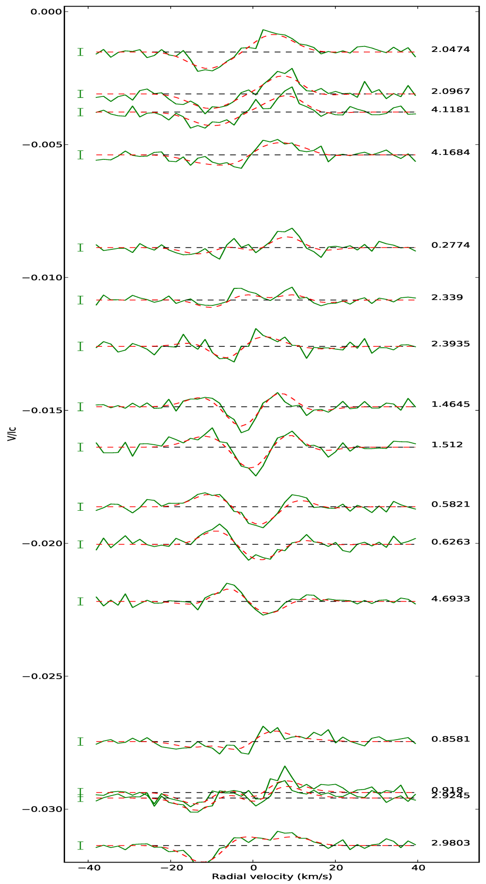
**Primarily relies on the star's magnetic field intensity and topology**

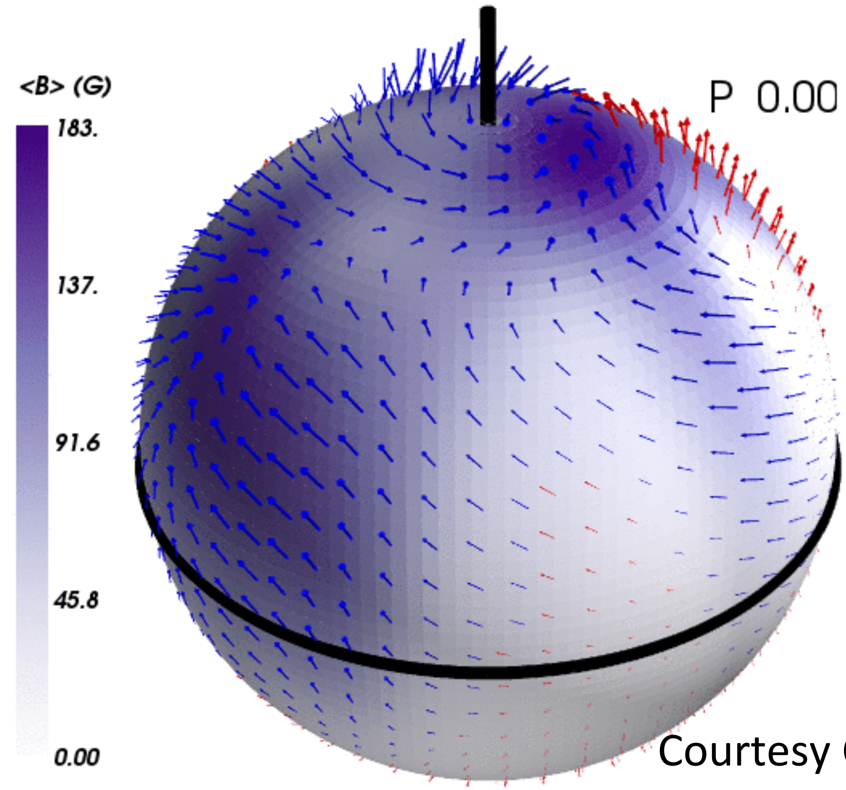


# YSOs magnetic fields



- Spectropolarimetry: reconstruct magnetic **field strength and topology** from Zeeman-Doppler Imaging

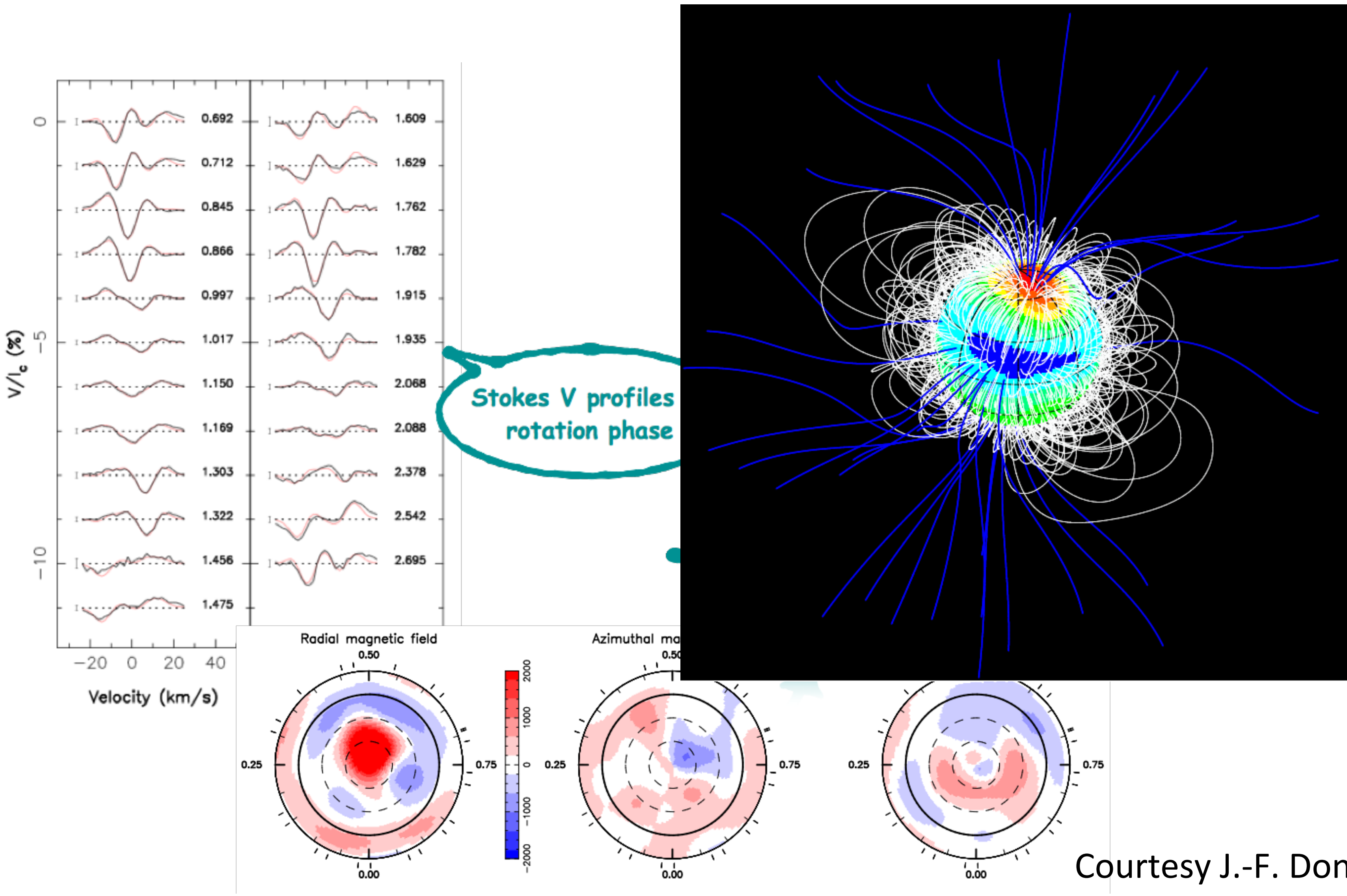



Courtesy C. Folsom

e.g. ESO/HARPS-Pol, CFHT/Espadons-Spirou, TBL/Narval-Spip

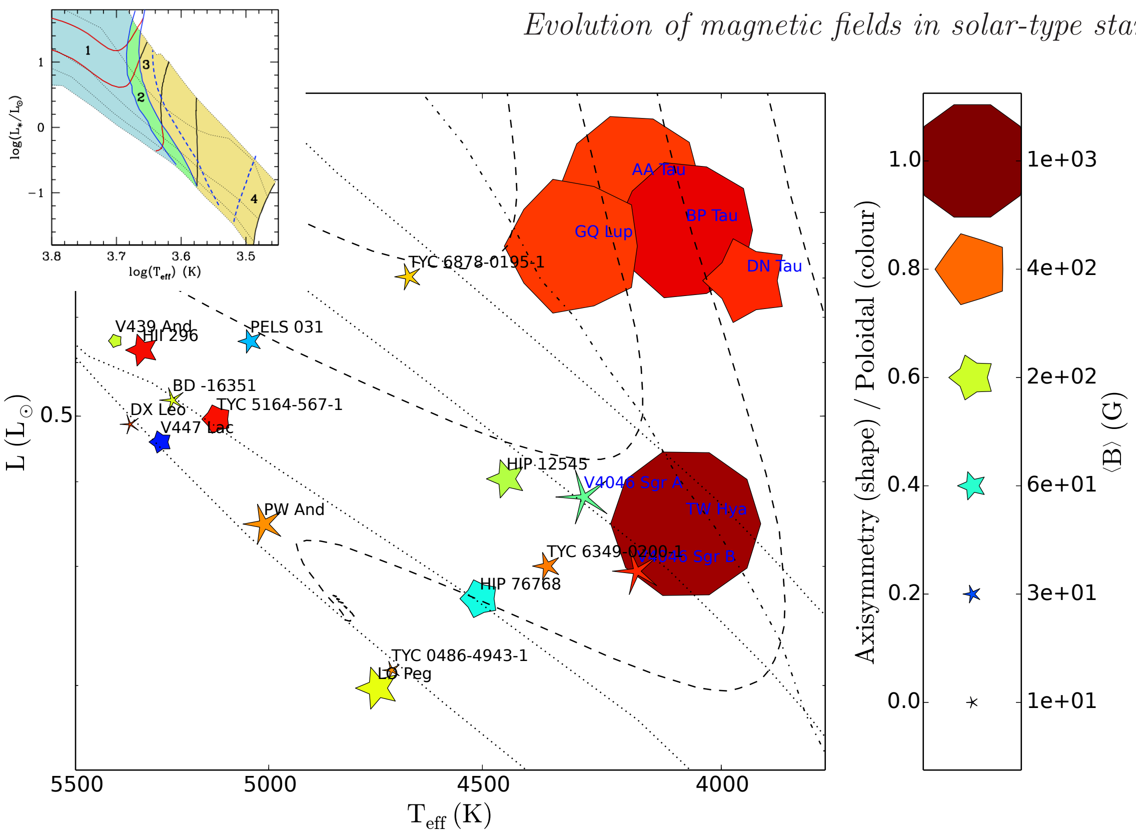
# Zeeman-Doppler Imaging



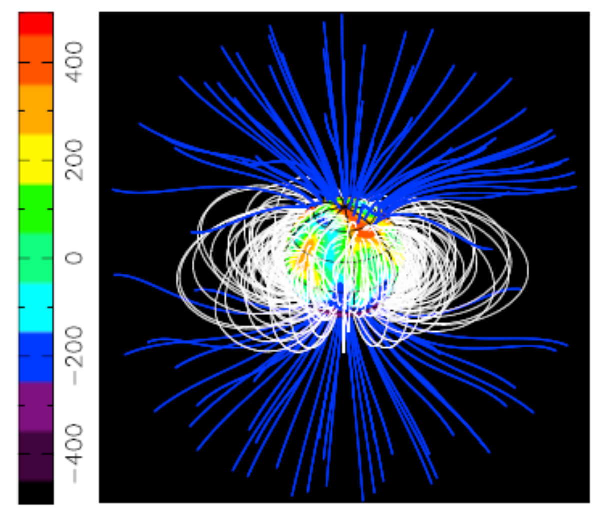

Courtesy J.-F. Donati

# PMS magnetic field evolution

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



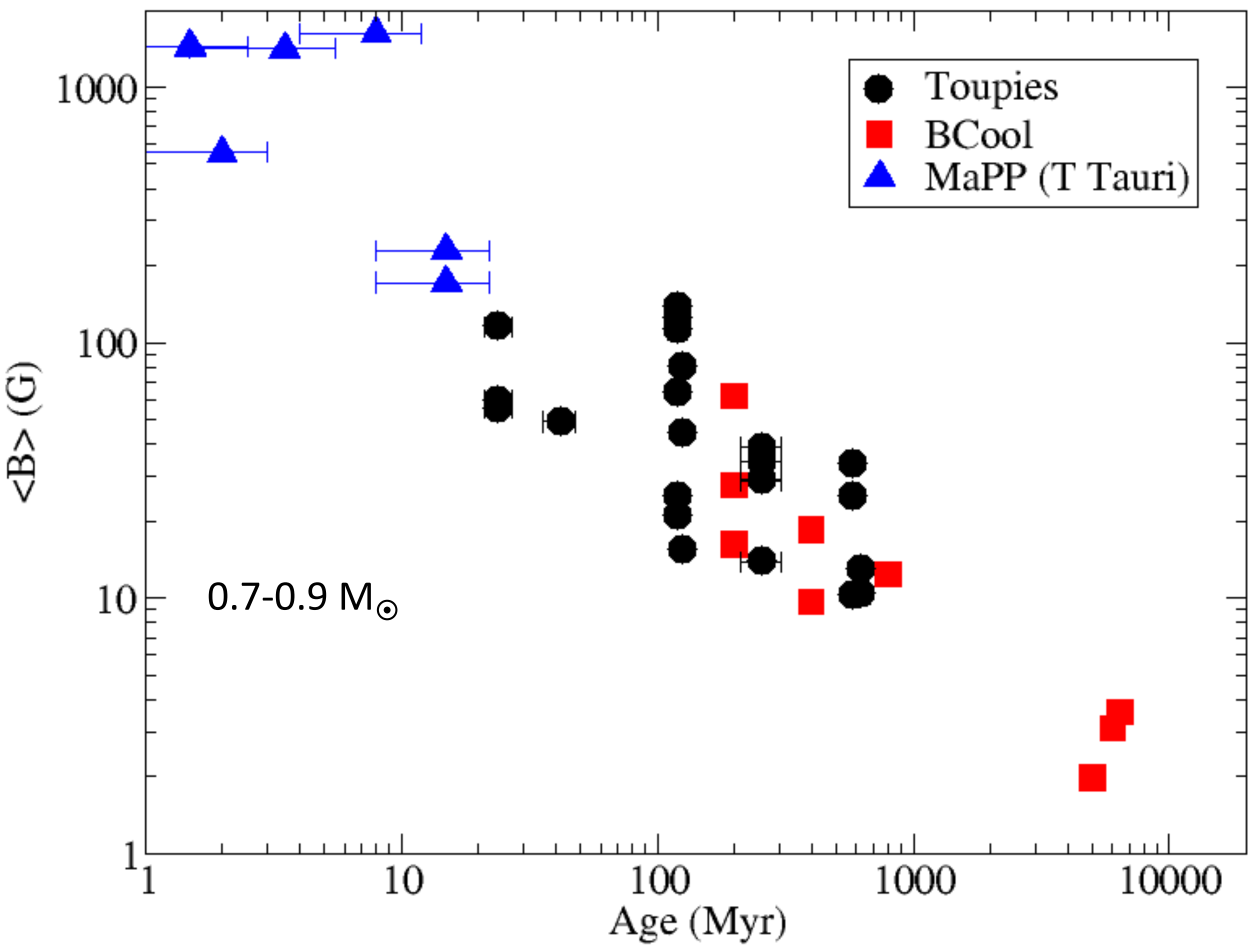

*Folsom, Petit, Bouvier+16*
*Donati, Gregory, Alencar+13*
*Gregory, Donati, Morin+12*




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

# 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

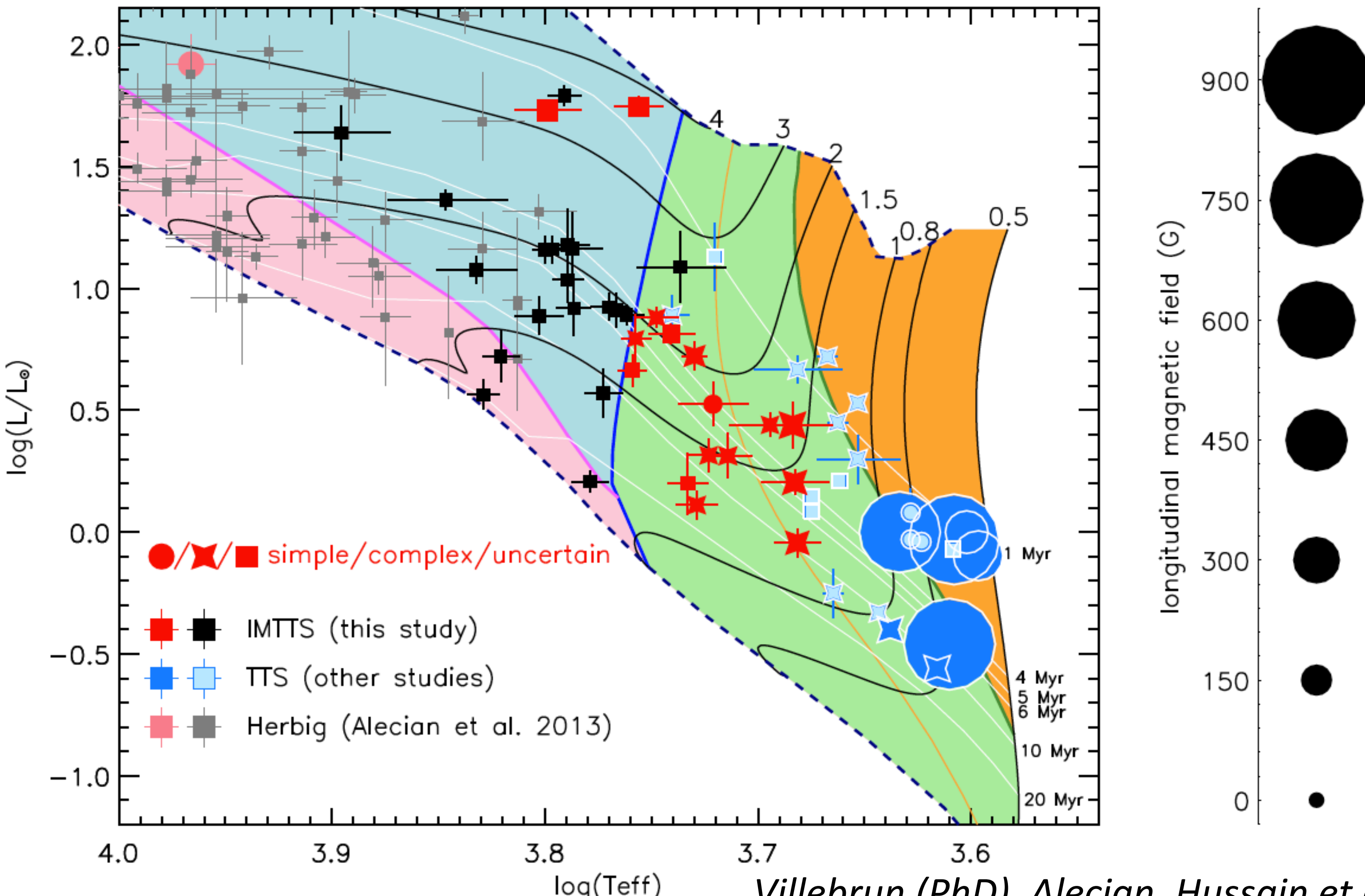
**PMS B evolution due to structural properties (not linked to rotation)**

**ZAMS & MS B evolution due to rotational braking**

*Folsom, Petit, Bouvier+16, 18*
*Vidotto, Gregory, Jardine+14*
*Gregory, Donati, Morin+12*

# PMS magnetism: intermediate-mass stars

5-10% of main sequence A and B stars have strong fossil fields. Why?




Obs: CFHT/ESPADONS , TBL/NARVAL, ESO/HARPS-POL
Modèles: CESTAM

*Villebrun (PhD), Alecian, Hussain et al. 2018*
*Emeriau, Mathis, et al., submitted*

# Magnetic accretion in T Tauri stars

- Stellar magnetic field : **$B_*$ ~ 1-3 kilogauss**
- Disk mass accretion rate : **$dM_{acc}/dt \sim 10^{-8}\ M_{sun}/yr$**

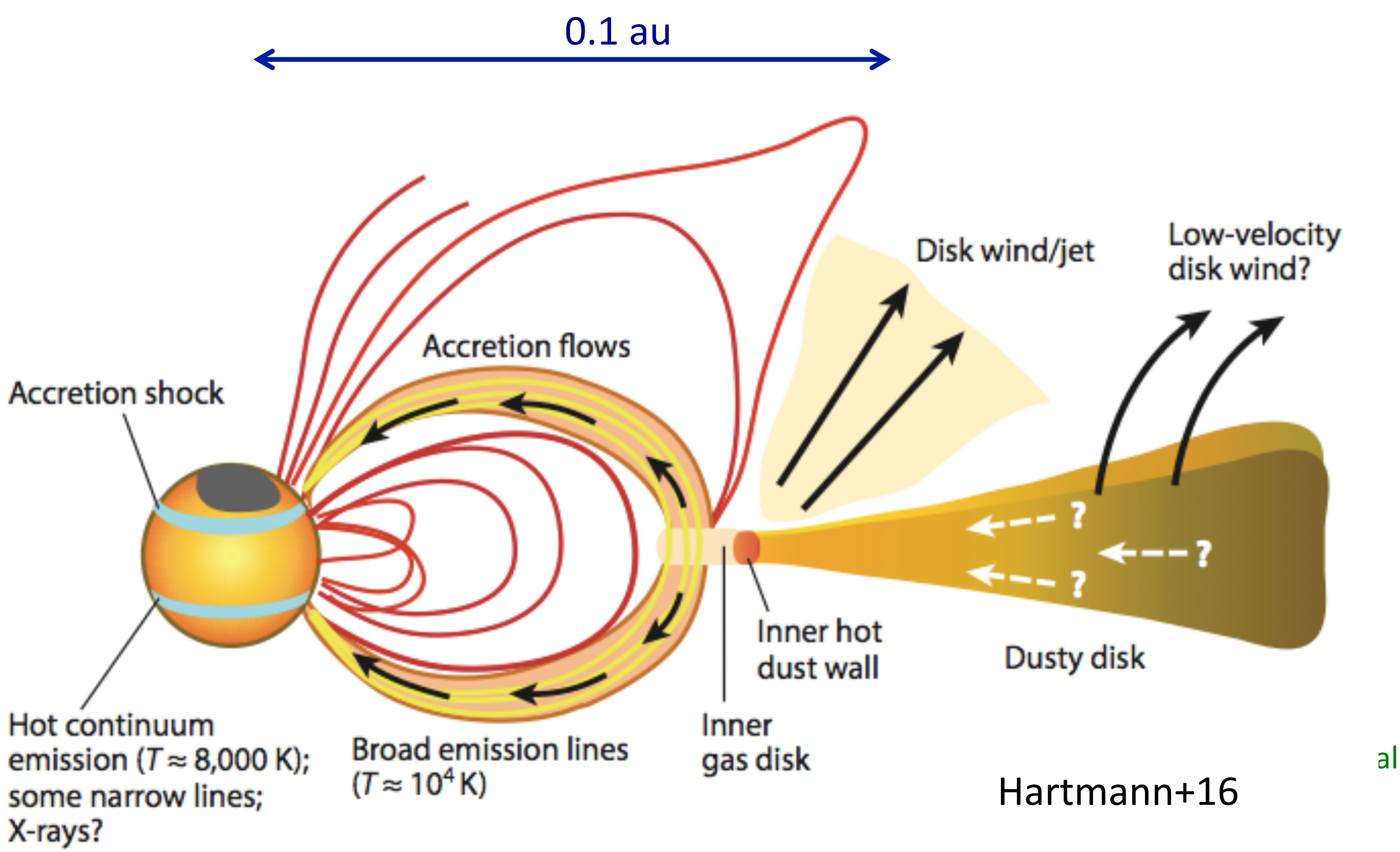
**Magnetic torque ≈ viscous torque at $r = R_{in}$**

$$R_{in} \approx (B_*\, R_*^3)^{4/7} \, . \, (2GM)^{-1/7} \, . \, (dM_{acc}/dt)^{-2/7}$$

→ **$R_{in} \approx 3 - 8\ R_*$**

→ **Magnetospheric cavity, accretion columns, accretion shocks**
(and possibly outflows)

# The magnetospheric accretion paradigm



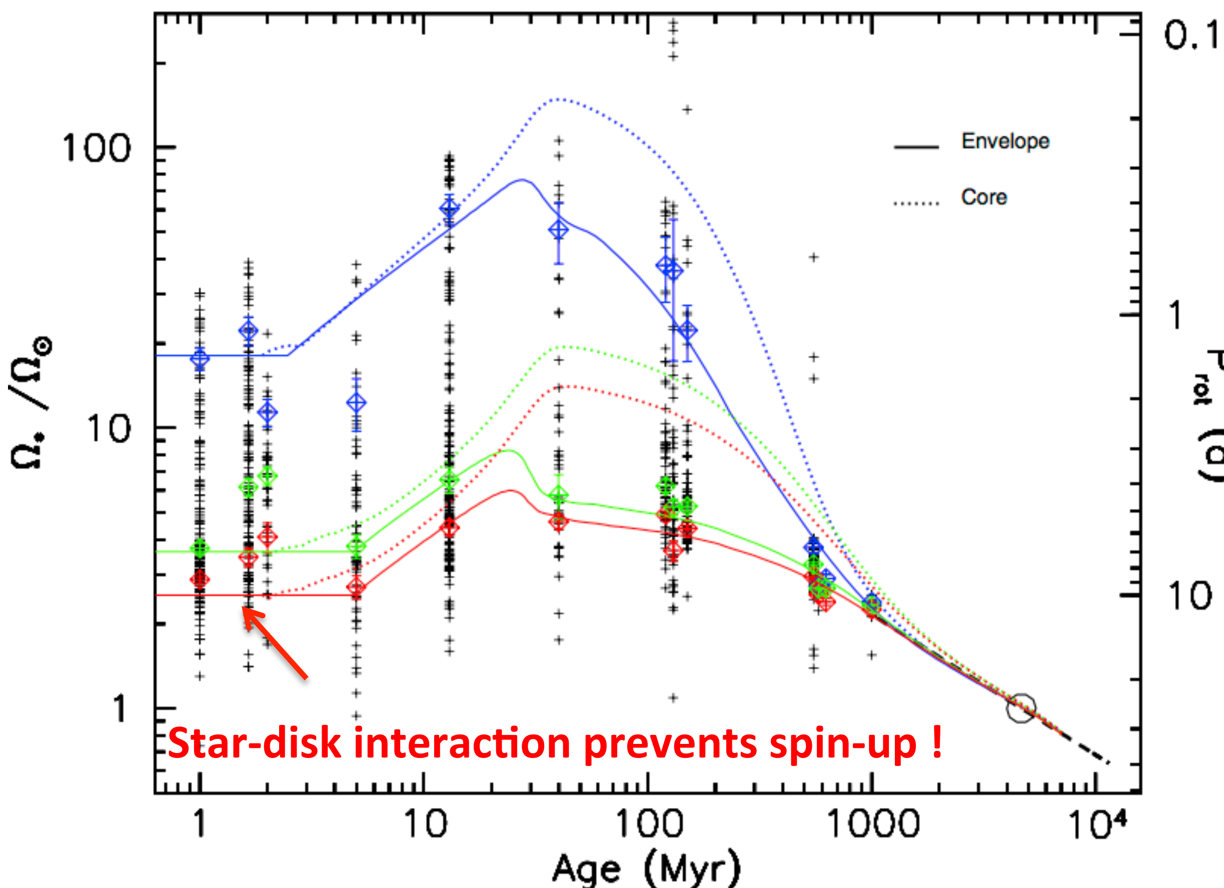

Hartmann+16

**The magnetospheric accretion/ejection process is responsible for most of the properties of young stars** (variability, X-UV excess, emission line spectrum, angular momentum, etc.).

# Angular momentum evolution

The evolution of angular momentum is governed by PMS star-disk interaction, magnetized wind braking, and internal transport processes.

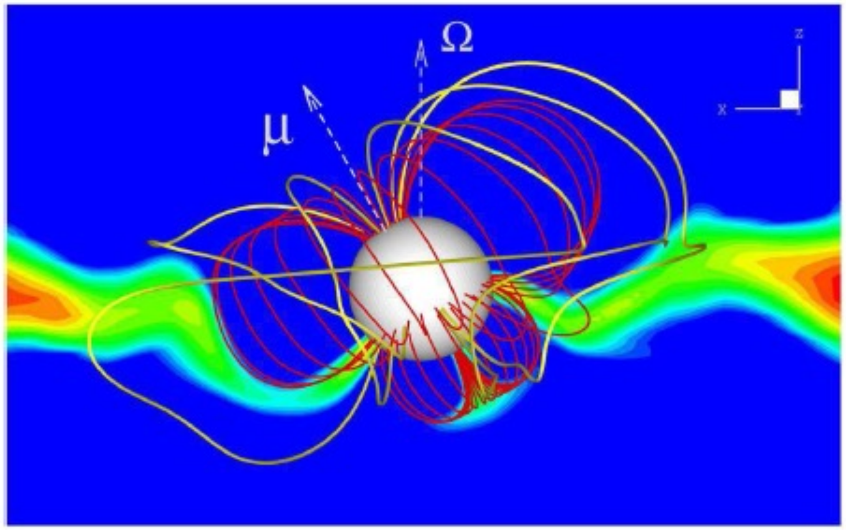
A&A 556, A36 (2013)




Gallet & Bouvier 2013, 2015

*Space photometry (CoRoT, K2) + parametric models*

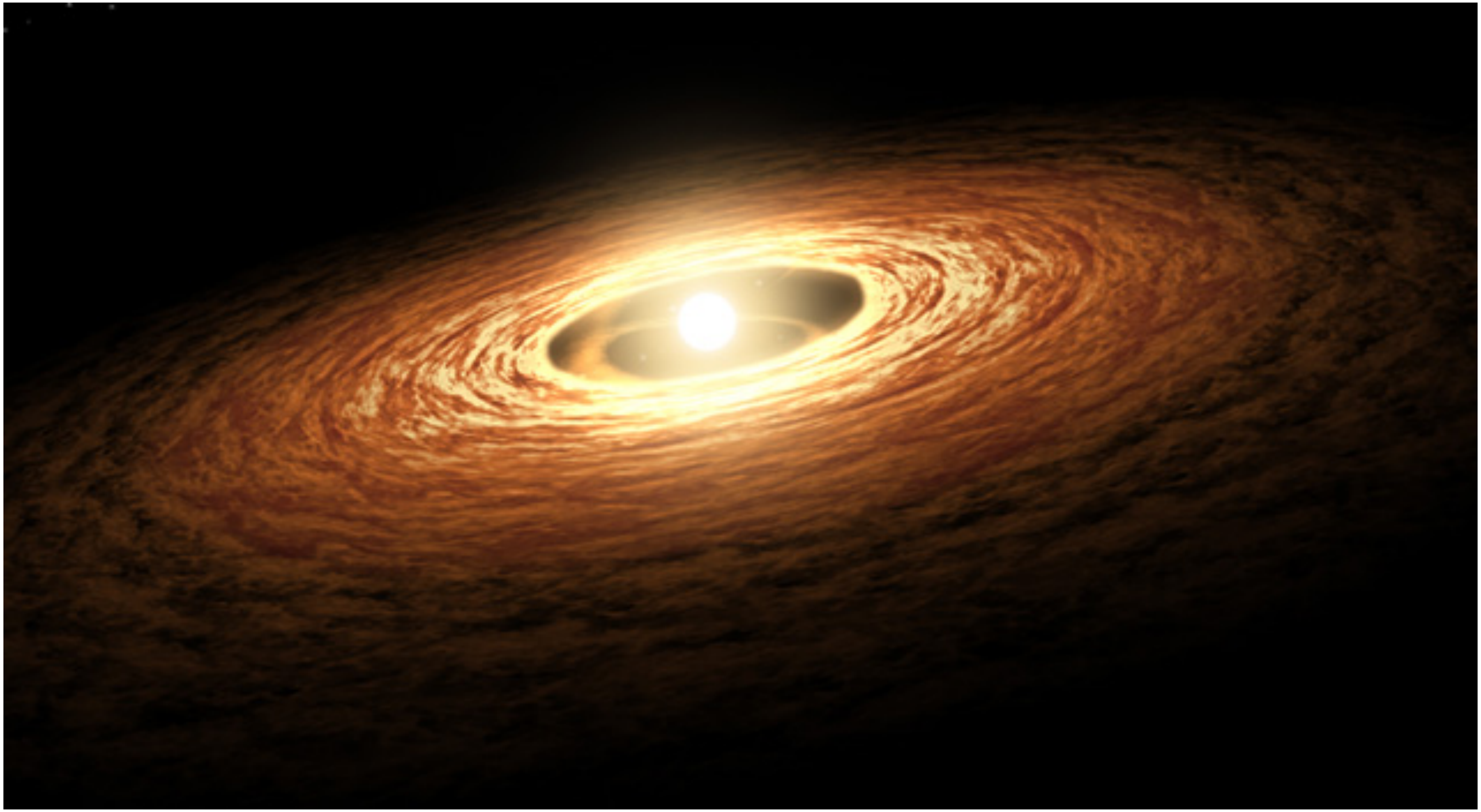
# Magnetospheric accretion



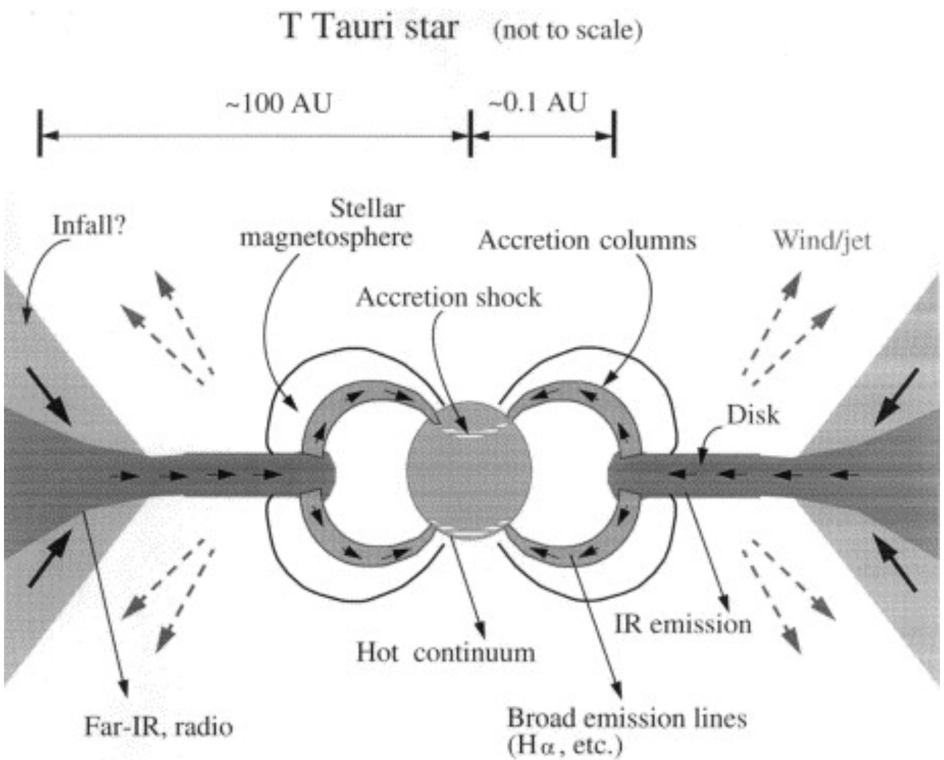

Long, Romanova, & Lovelace 2007

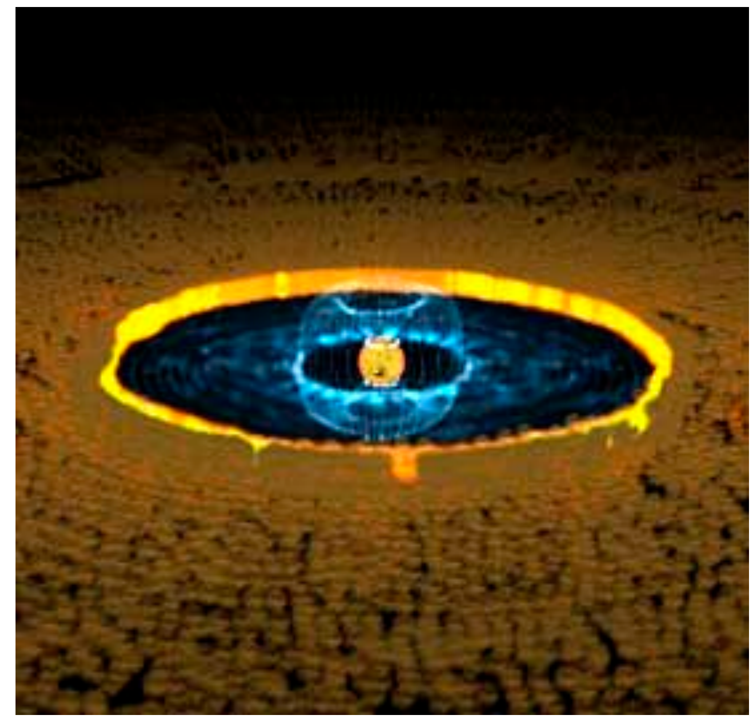
- How is the disk material accreted onto the star?
- How stable vs. dynamical is the magnetospheric accretion process?
- How does it impact the inner disk structure?
- How does it modify PMS evolution?

# We’d like T Tauri disks to look like this:

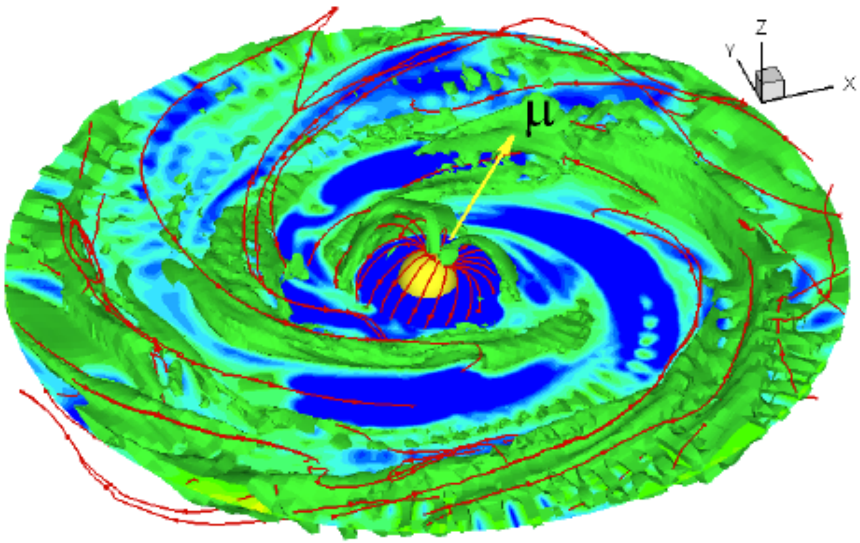


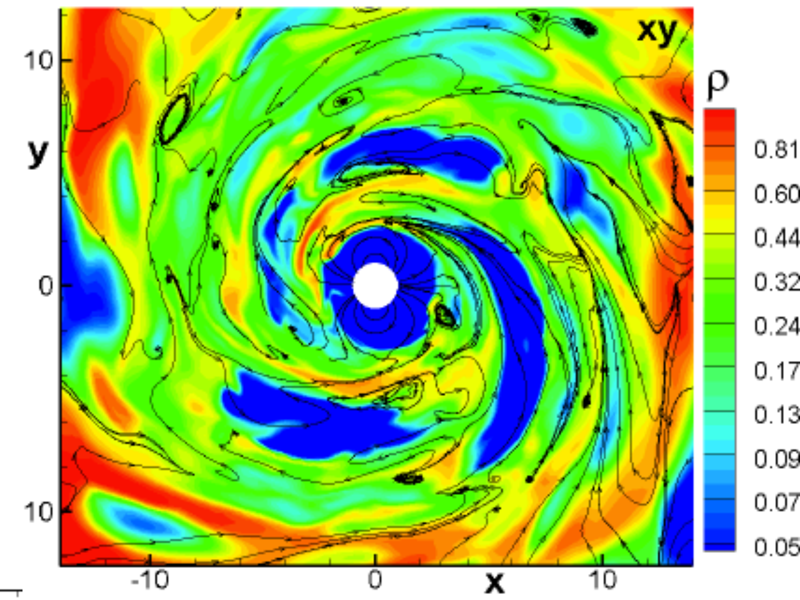
# or even like that…



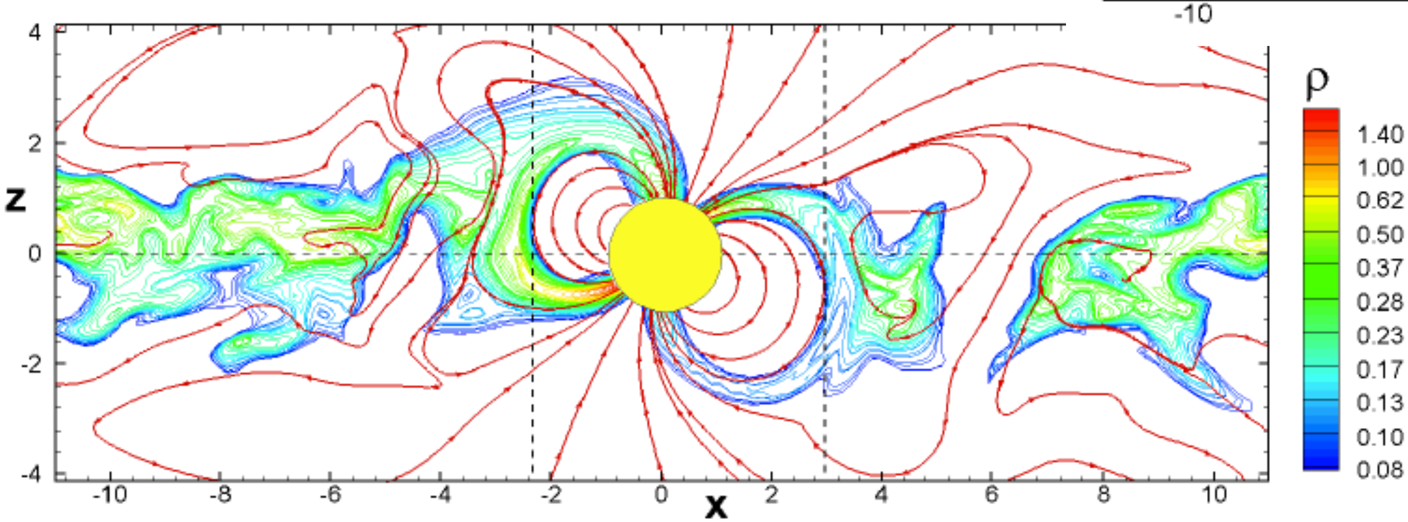



# But they are probably more like this (in the simplest dipolar case!):

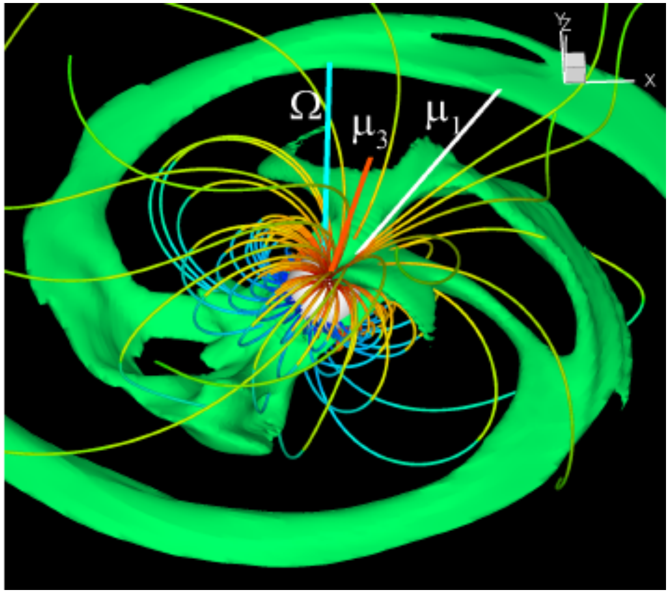



Romanova et al. 2012



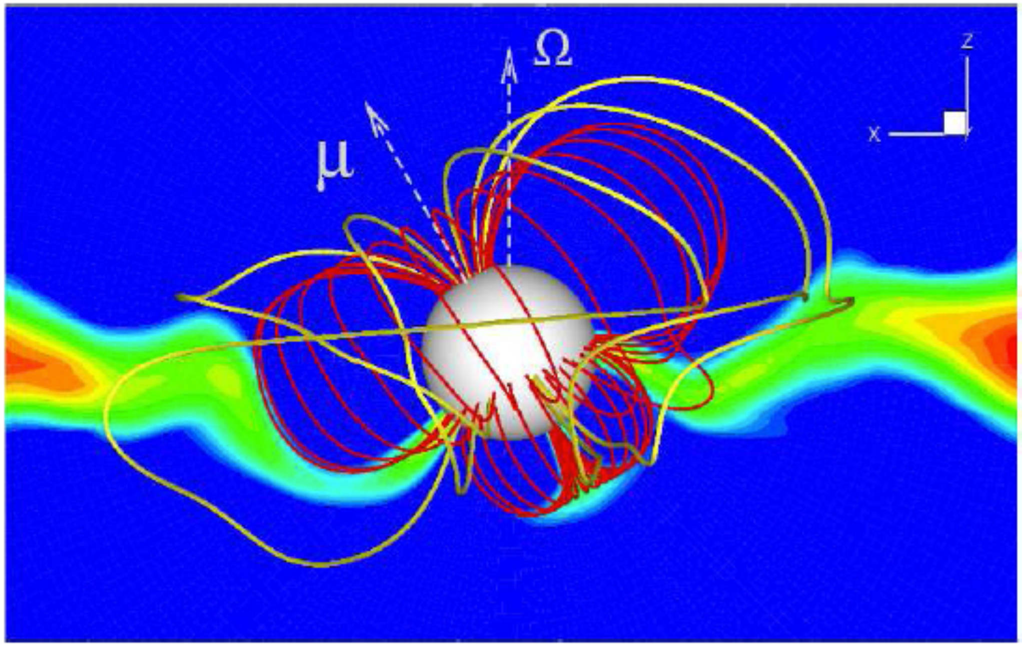
# Or even worse (in most cases?) :



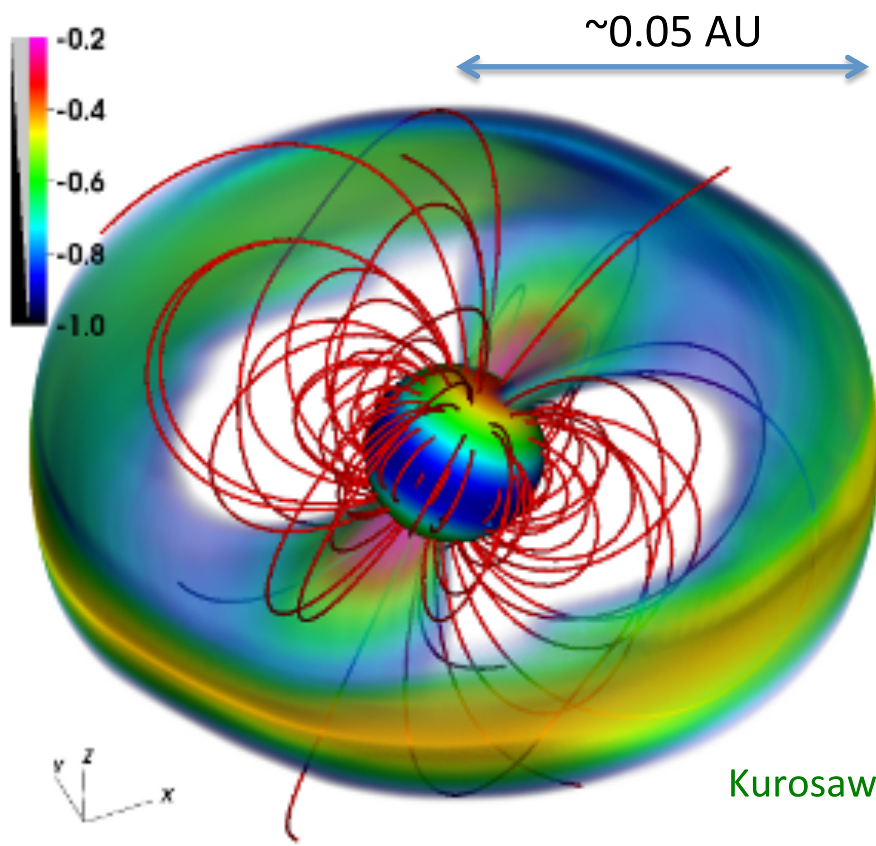

Romanova et al. 2010

Dipole + octupole field

Long et al. 2007



# Stable accretion onto an inclined magnetosphere



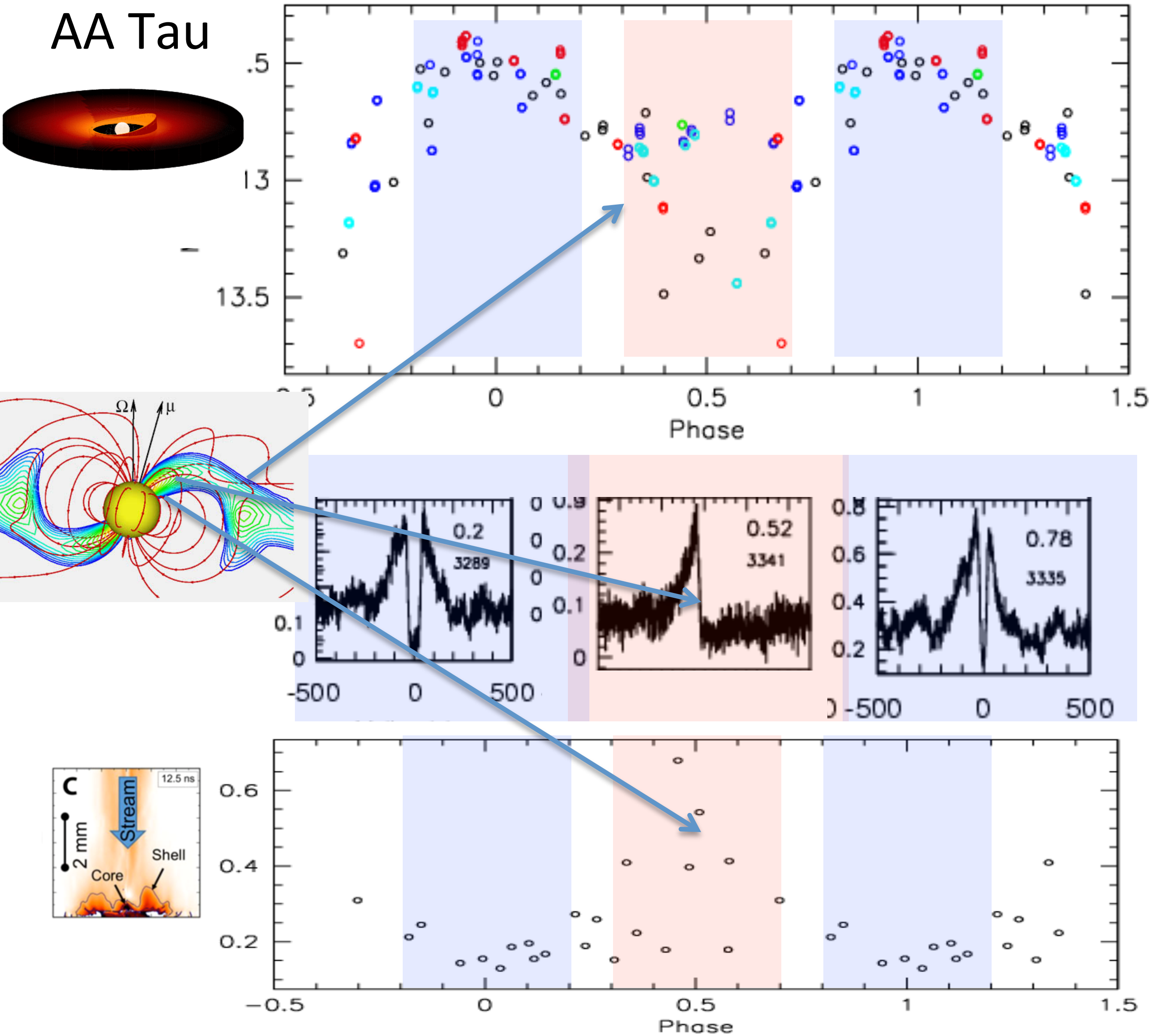

Kurosawa & Romanova (2013)

The whole inner system rotates in ~ a week =stellar rotation period = inner disk Keplerian period

# Inclined magnetosphere: AA Tau, the prototype of dippers

**Disk warp, accretion column, accretion shock : all spatially associated**

AA Tau




**Periodical eclipses**

**(inner disk warp)**

**P=8.22d**

**Balmer lines**

**(accretion funnel)**

**Veiling**

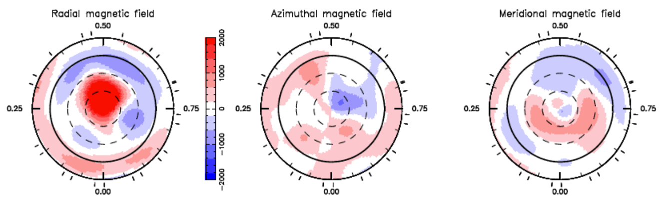
**(accretion shock)**

Bouvier, Alencar, Boutelier+07

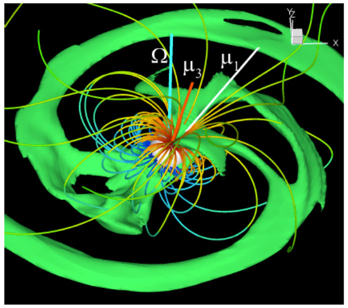
# Star-disk interaction: observations

V2129 Oph (P=6.5 days)

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



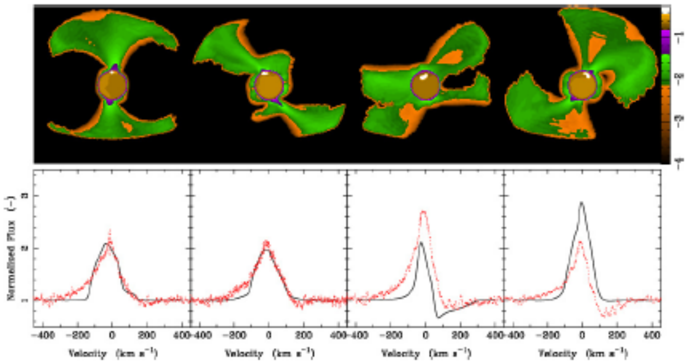

Donati, Bouvier, Walter et al. (2011)



3D MHD simulations predict the accretion flow geometry

Romanova, Long, Lamb et al. (2011)

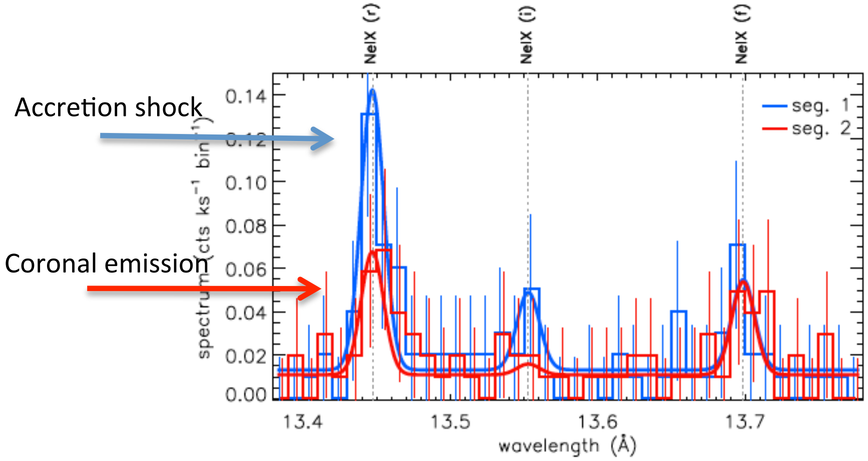
ESO/Harps line profile variability + 3D RT models reveals accretion dynamics



Alencar, Bouvier, Walter et al. (2012)

Chandra X-ray monitoring reveals accretion shock

Argiroffi, Flaccomio, Bouvier et al. (2011)



# *CSI2264*: Coordinated Synoptic Investigation of NGC 2264

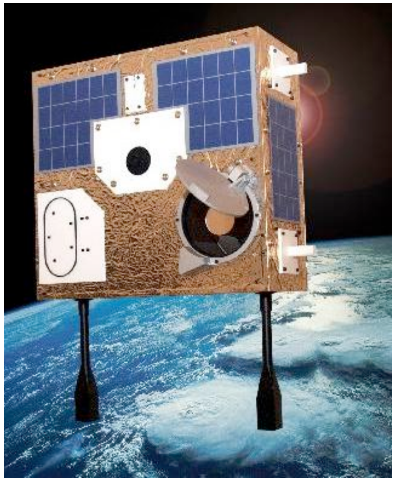
## A revolution in space based monitoring of young stars

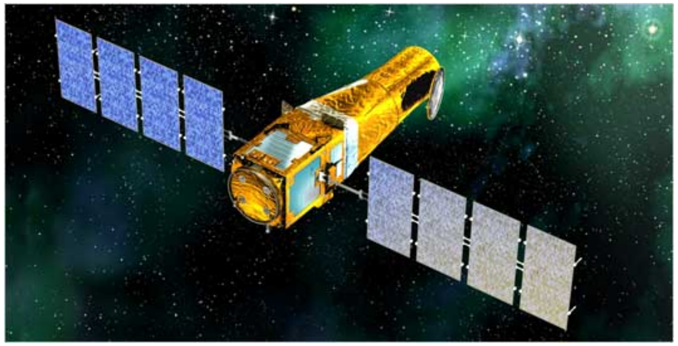
(December 2011)

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





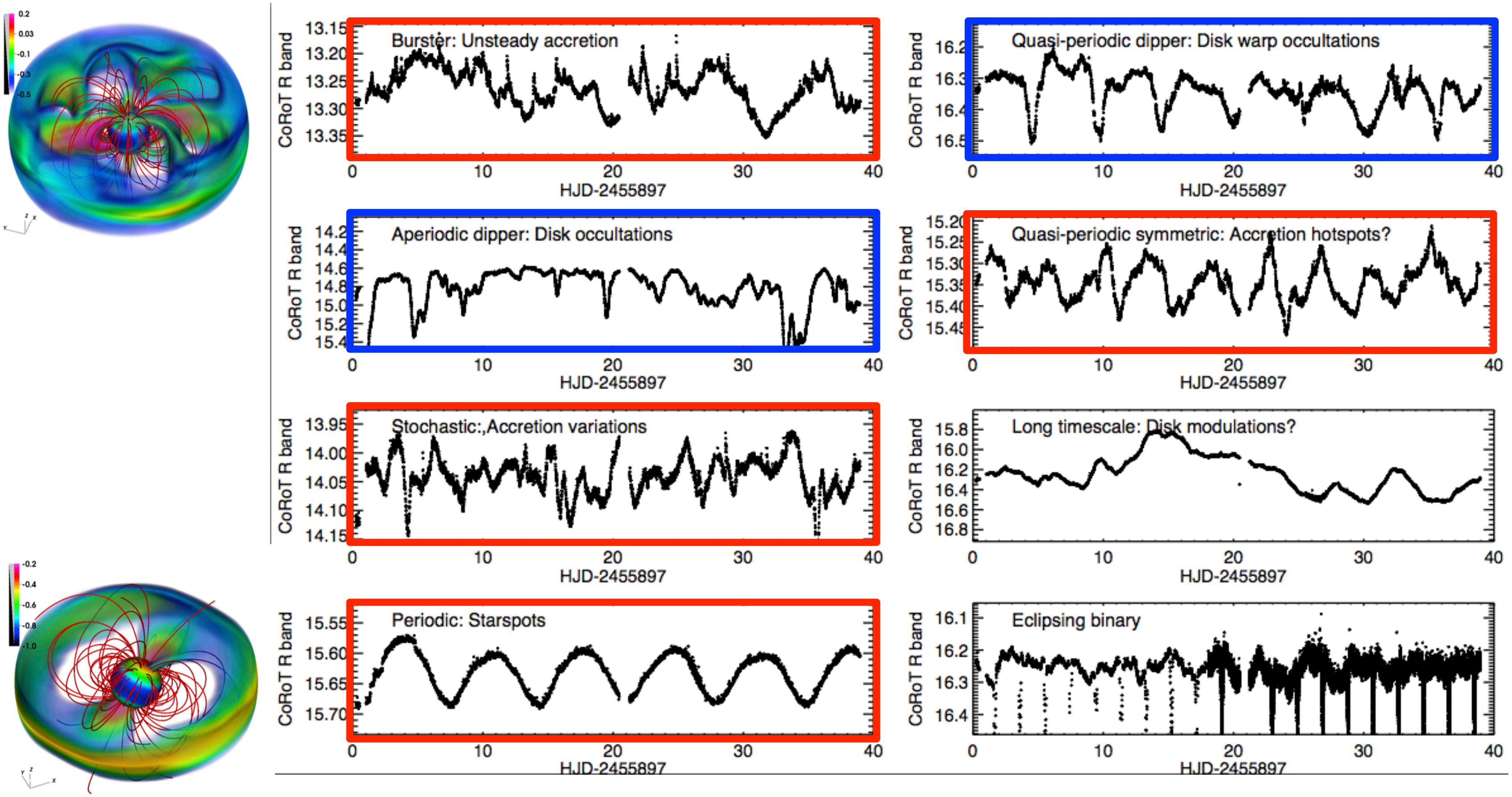
(includes CFHT/MegaCam u + r-band monitoring)

# Optical variability

NGC 2264 CoRoT light curves

Accretion

Occultation




**Stable vs. unstable accretion regimes?**

Cody, Stauffer, Baglin+14

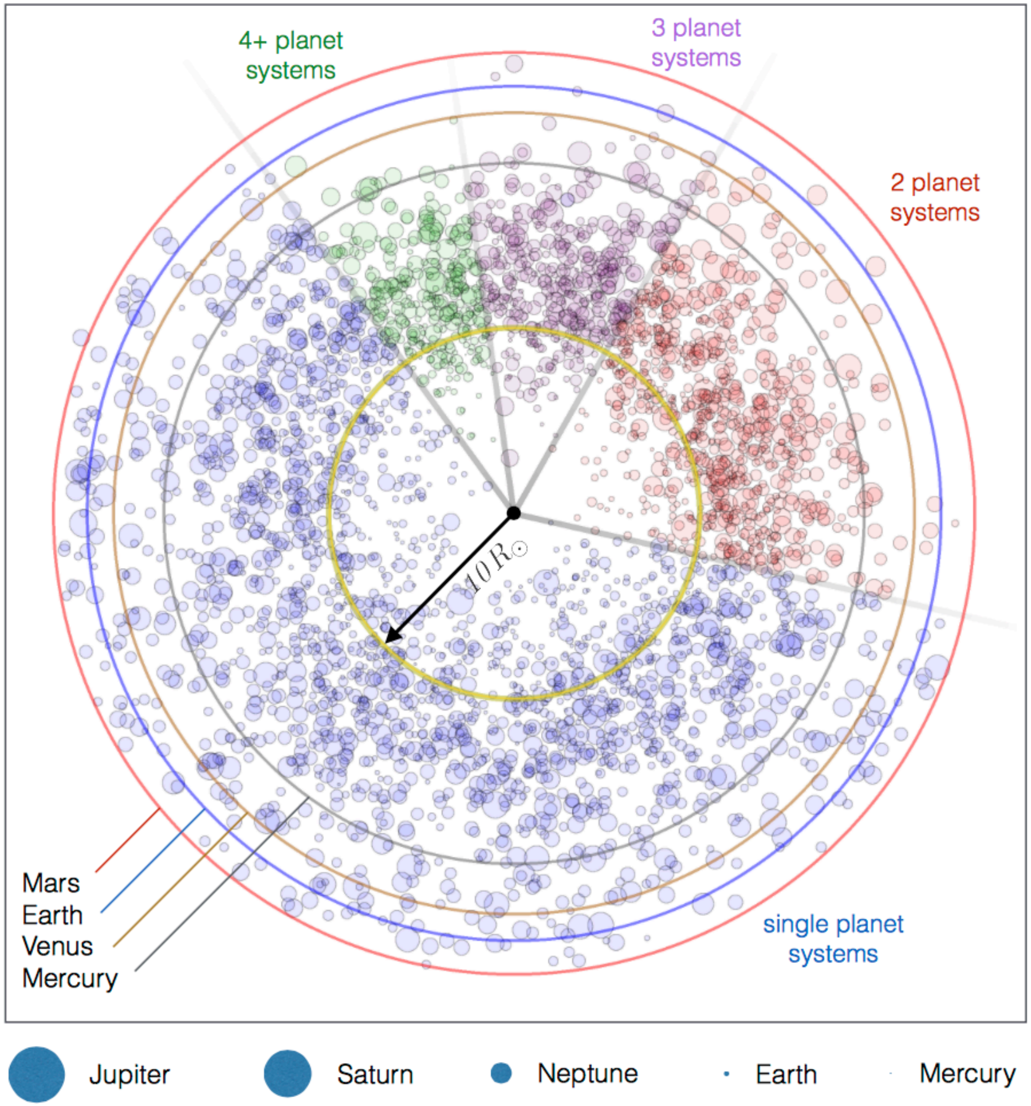
Venuti, Bouvier, Flaccomio+14

# Contemplating complications: (inner) planets?

Migration to the inner disk edge

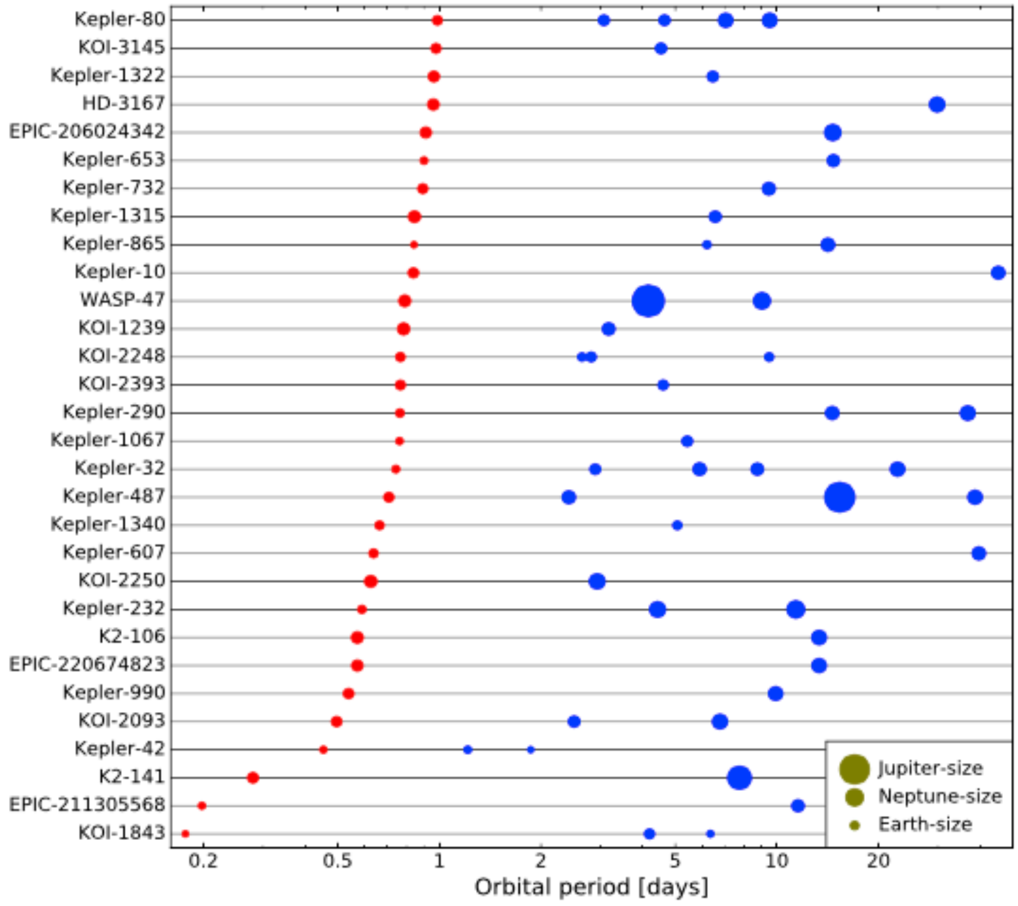
+ in-situ formation?

# Inner planets



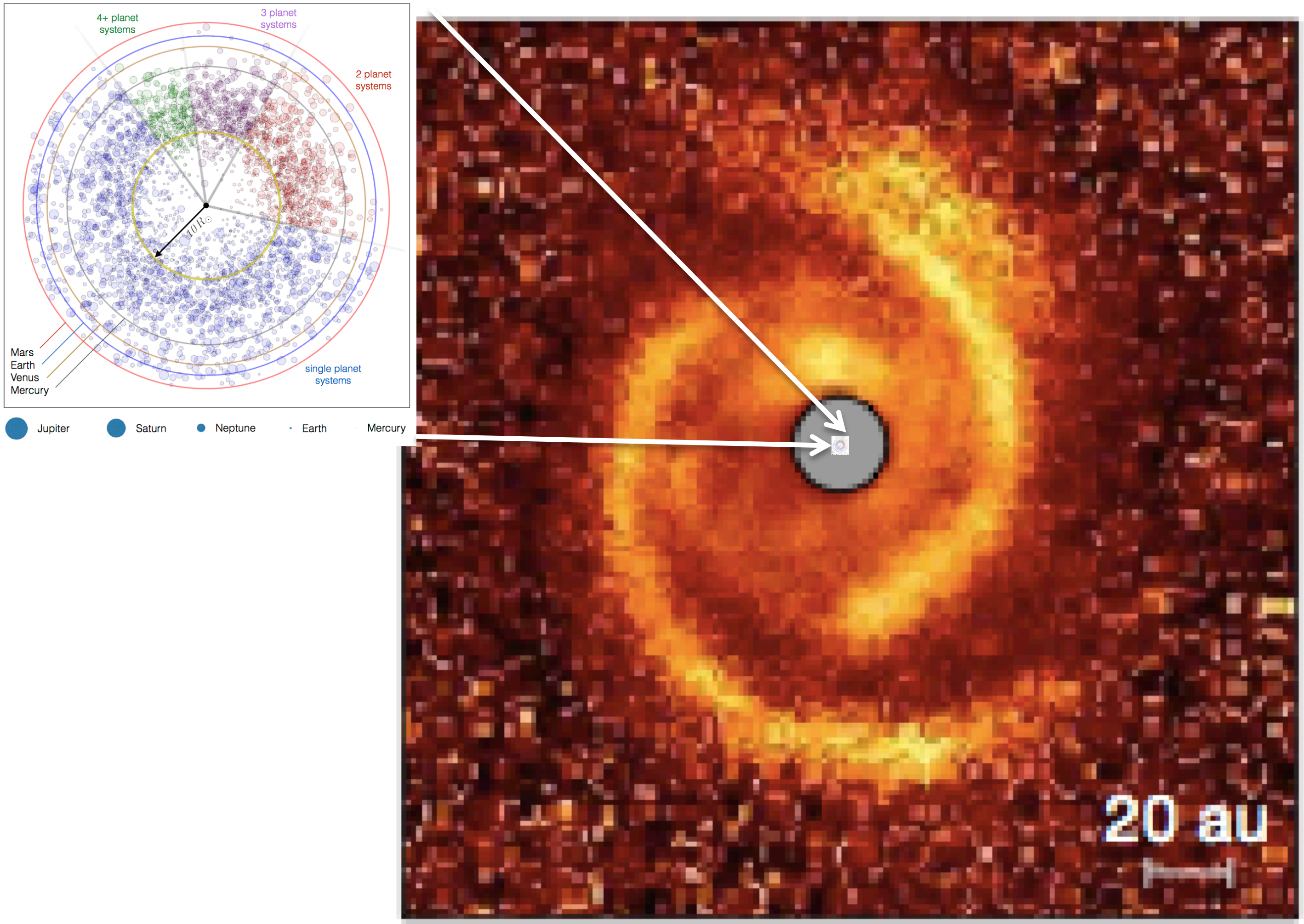

Batigyn & Laughlin 2015

# Ultra-short period planets

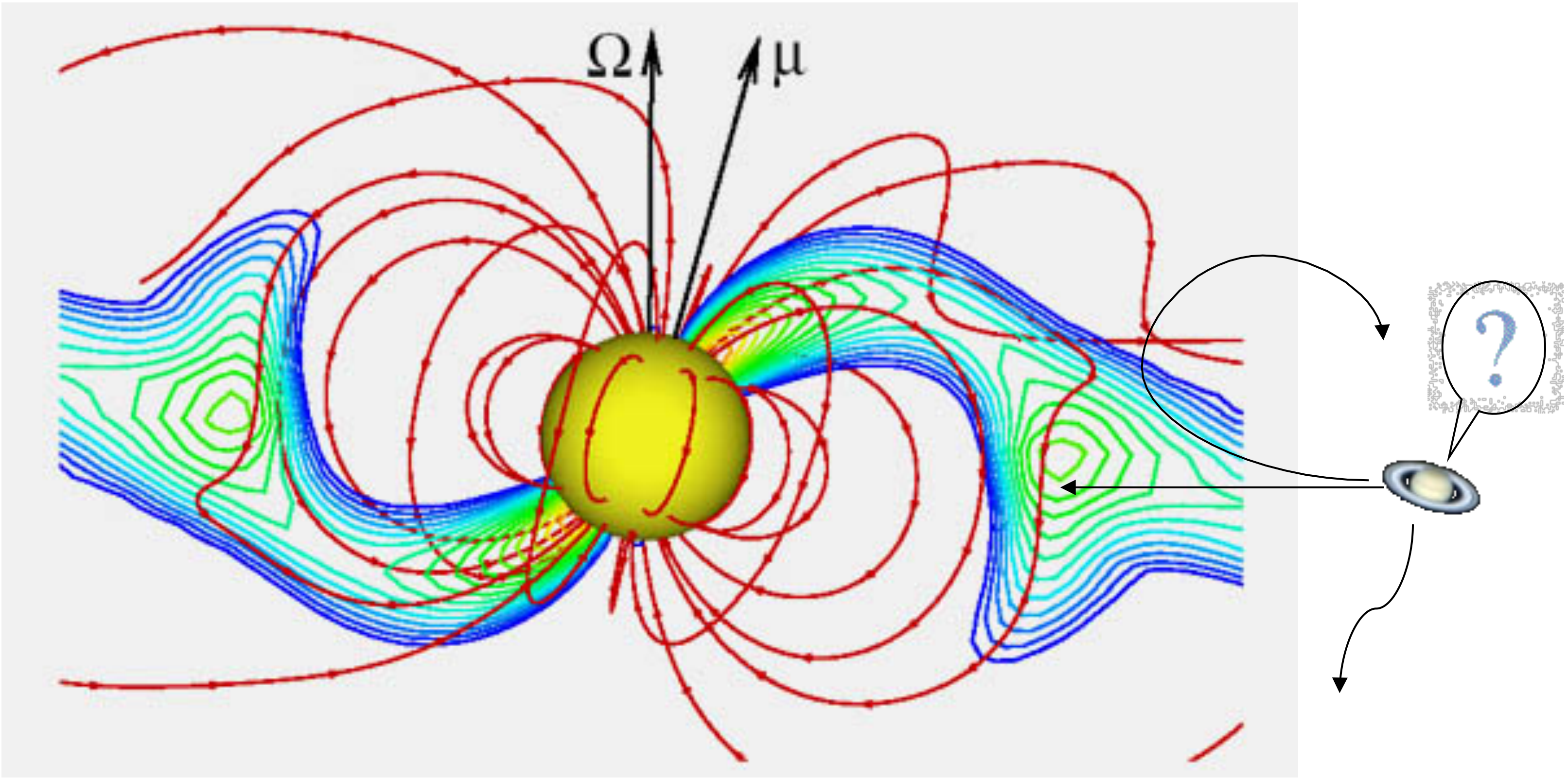



Winn+18

# Disk-embedded inner planets?



# Star-disk interaction: is that all ?

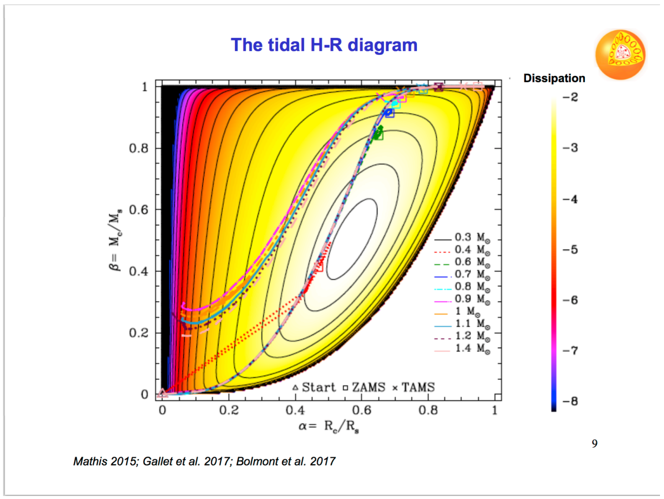


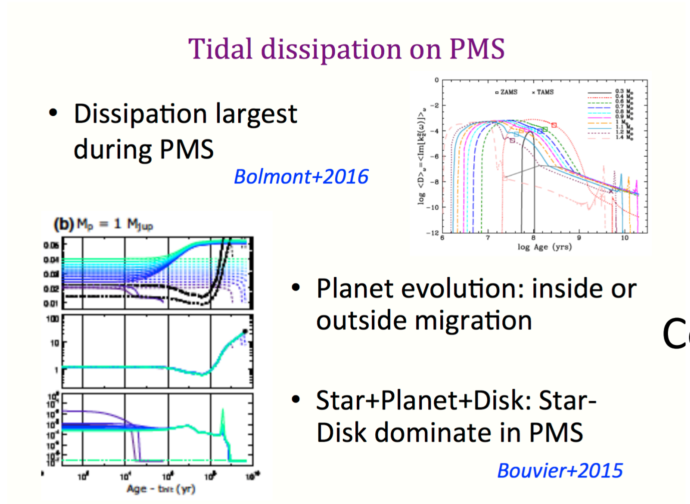

Halting the planetary migration ?

"Hot Jupiters" (or Saturns…)?

+ inner rocky planets (cf. Kepler's results)

# Tidal dissipation in the PMS




Courtesy: S. Mathis

*Mathis, Bolmont, Gallet, Strugarek+ 16, 17, 18*

Ecole PNPS Evry Schatzman 2019

*Interactions étoiles-planètes*

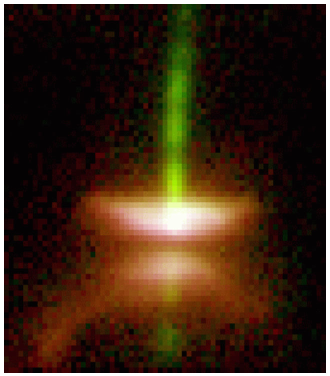
Contact: Lionel Bigot

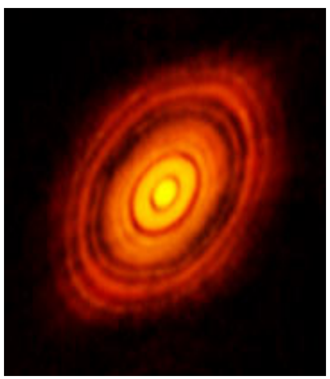
**Stellar physics meets exoplanetary studies and planetary sciences.**

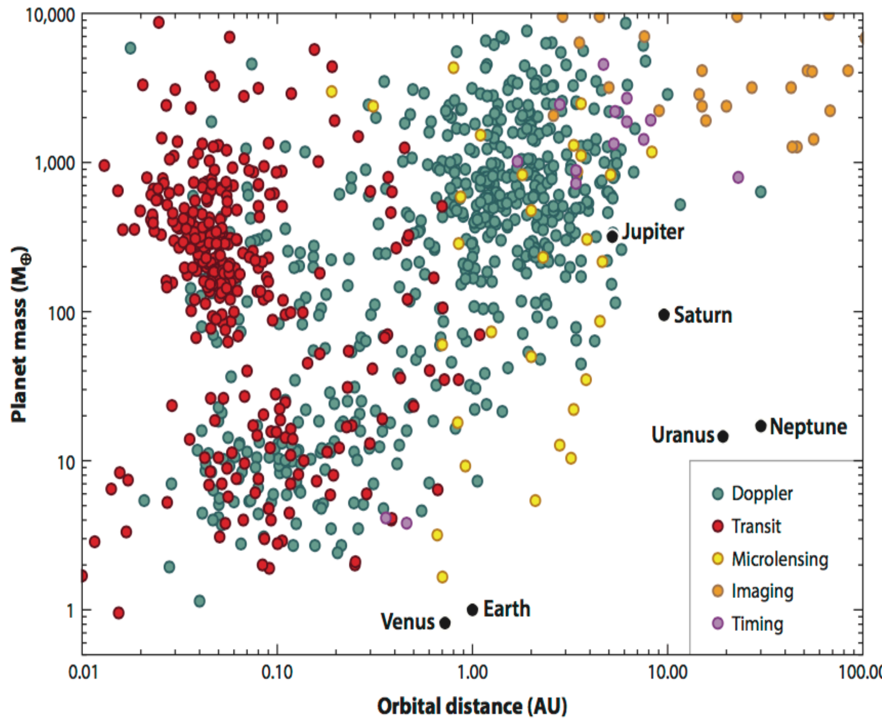
**A new, largely blank chapter to be written.**

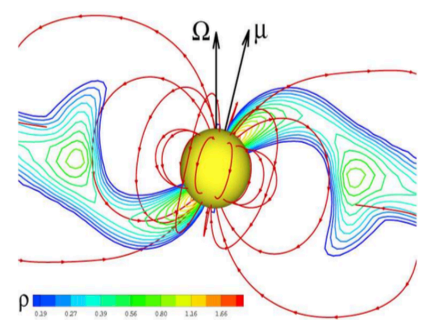
**Great times ahead!**

# Young Stellar Objects: a star, a disk, and planets.








How do the components of the system interact?
How does the integrated system evolve?
How does this evolution shape the architecture of planetary systems?
How does it impact on subsequent stellar evolution?

Courtesy: J.-F. Donati

# SPIRou

## status on tests & TC

- **main science goals**
  - planetary systems around nearby M requires precision velocimetry & spectropolarimetry to filter activity
  - formation of stars & planets requires spectropolarimetry to investigate impact of magnetic fields

# Conclusion

- Youth does not last long… but it has a long-lasting influence on the (complicated) life of star-planet(s) systems.
- Stellar teenagers are dynamic and somewhat unpredictable (like: what about eating a planet for breakfast?). Still, we can try to understand them (sometimes).
- A lot happens before the age of 3 (Myr). Stellar youngsters and their disks set the initial condition for stellar evolution and, ultimately, planetary system architecture (and habitability).
- Still, the best age is 20 (yr? Myr? Gyr?) and …

**PNPS was created in 1998, 20 years ago!**

**(cf. Foundation Meeting, Lyon, Nov. 98).**


Happy Birthday PNPS!
20 years!