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

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A star's childhood…

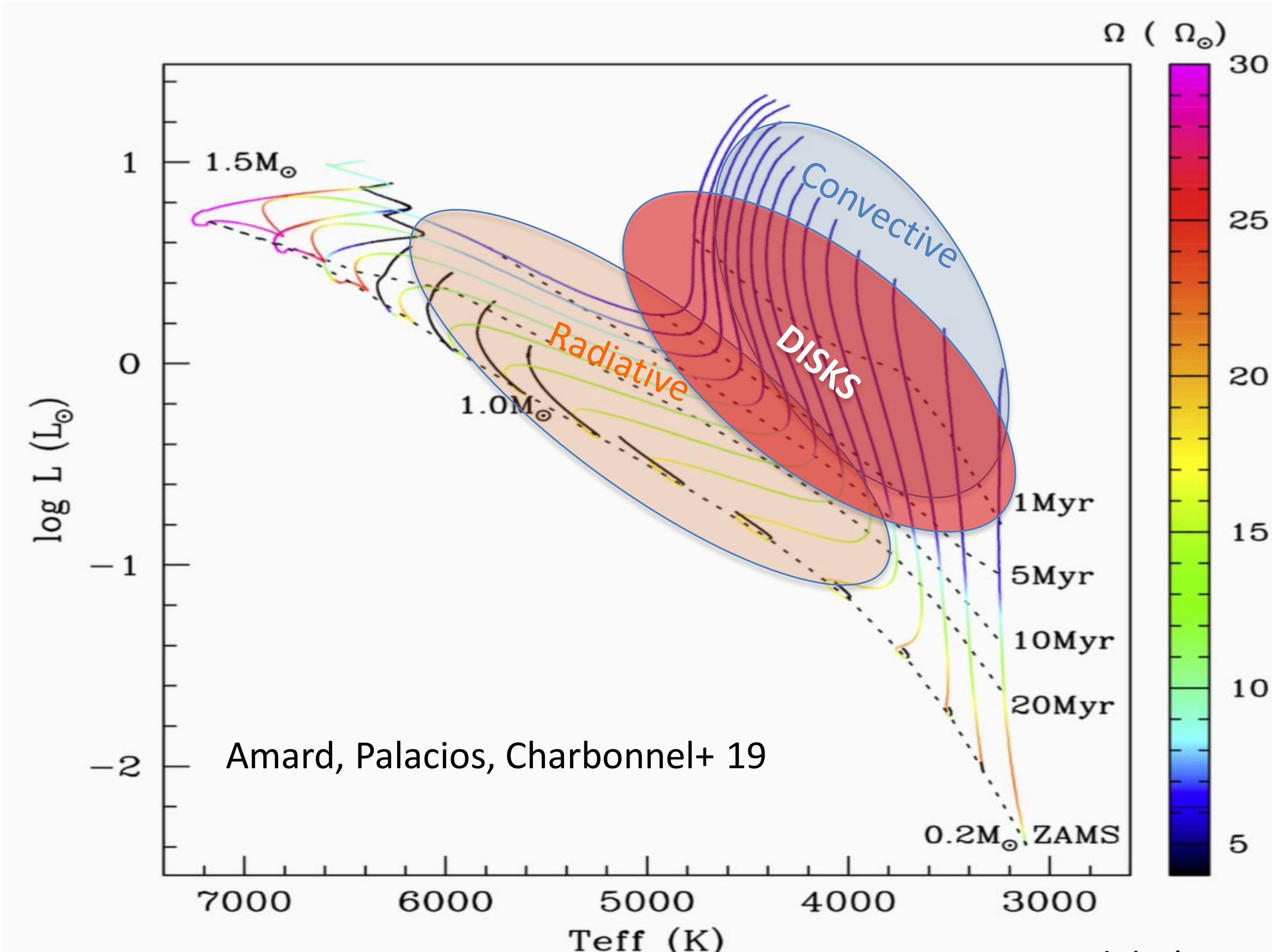
(Almost) everything happens before 3 Myr!

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)
- **Planet formation** in the disk (structuration, migration, dissipation, engulfment)
- **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.

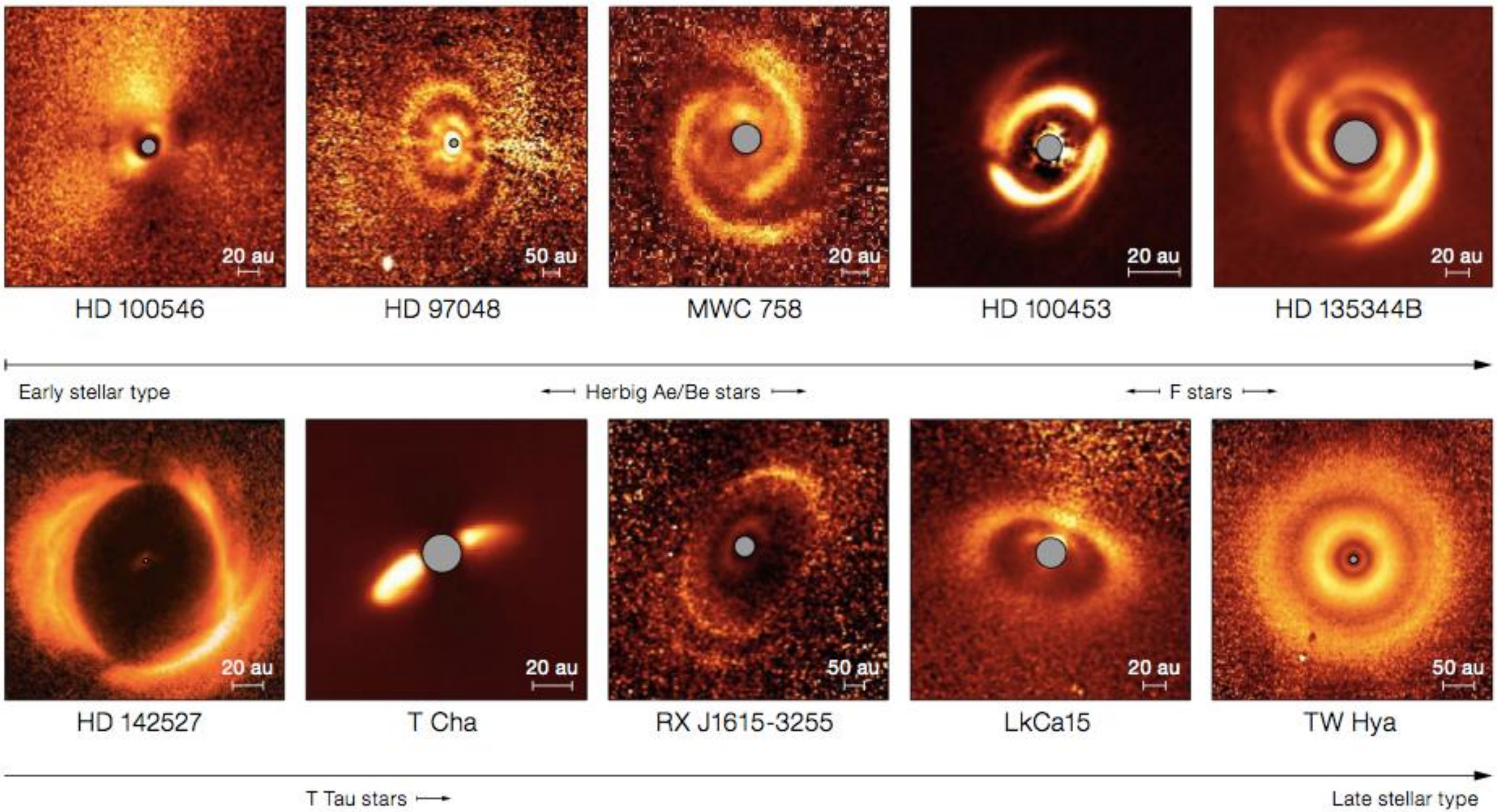
Pre-main sequence models



+ Magnetic PMS models *(e.g. Feiden 2016)*

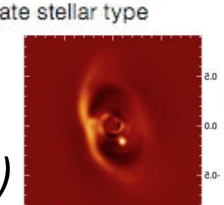
Circumstellar disks around young stars

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

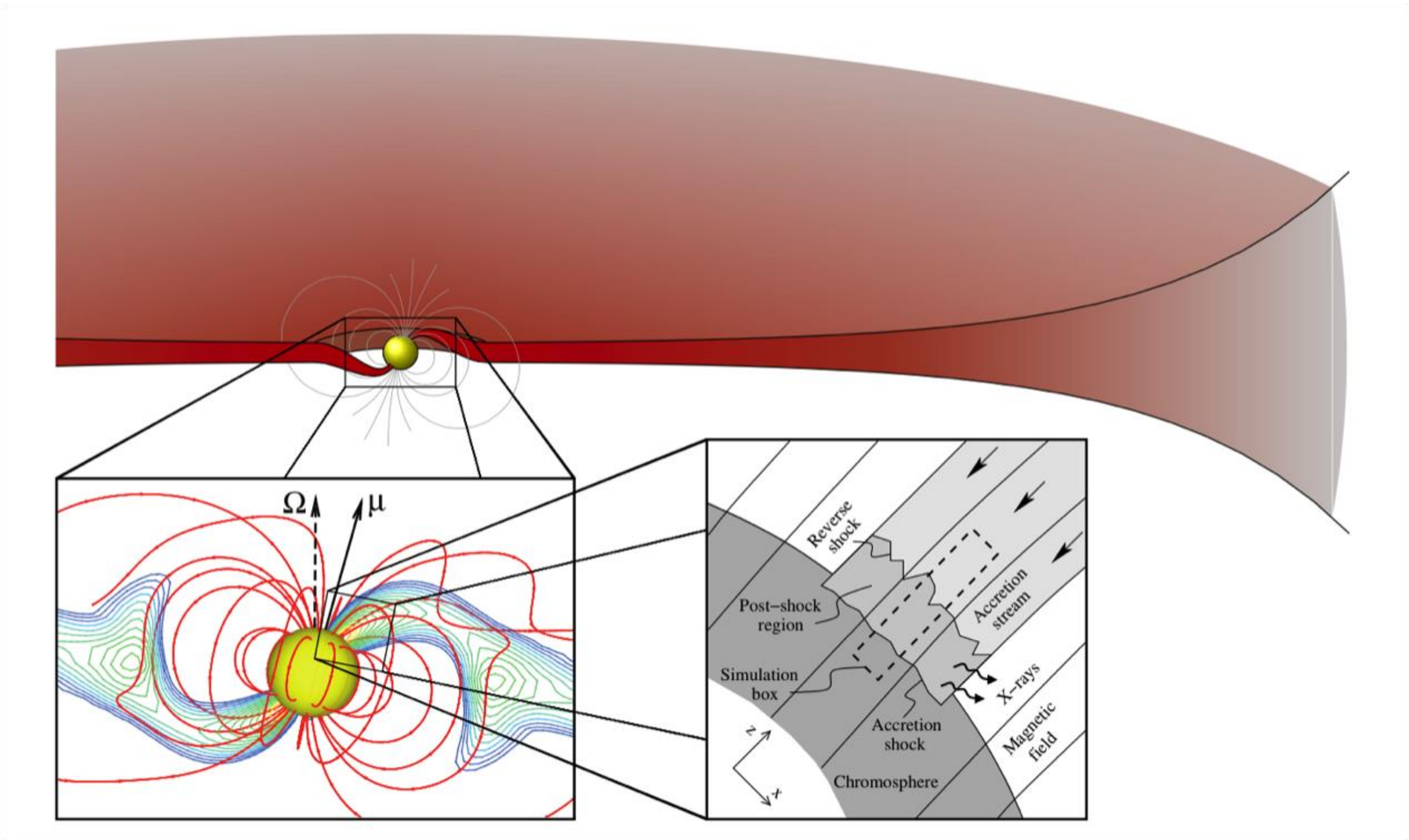


Sculpted by nascent planetary systems?

e.g., PDS 70 *(Muller+18)*



Star-disk interaction



de Sá, Chièze, Stehlé+ 2014

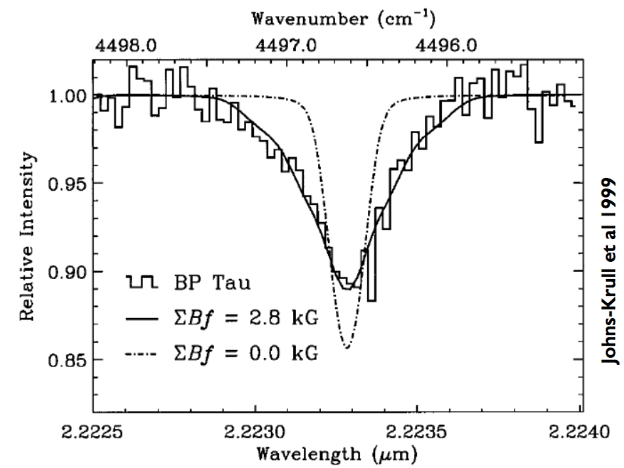
- Defines many of the properties of low-mass YSOs
- Primarily relies on the star's magnetic field intensity and topology

I. PMS stellar magnetic fields

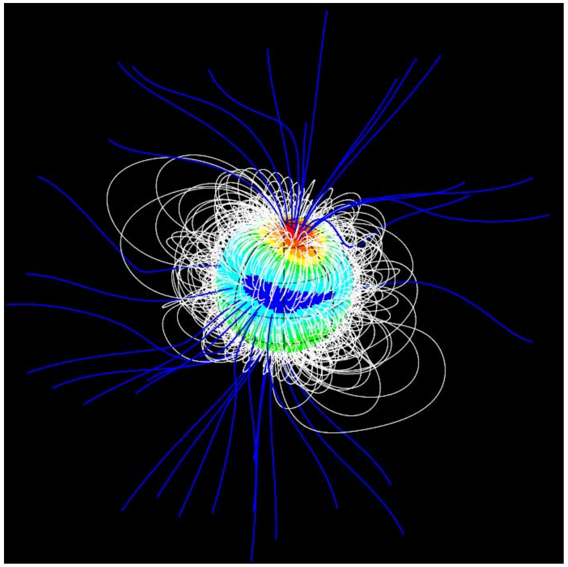
A key ingredient of PMS evolution

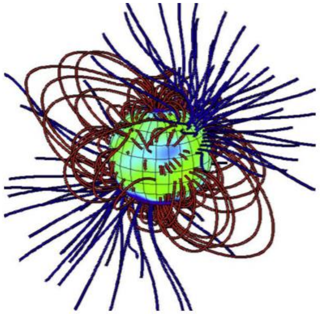
Measuring surface magnetic fields

- Direct Zeeman broadening
  – Small scale photospheric field
  (Johns-Krull and collaborators)



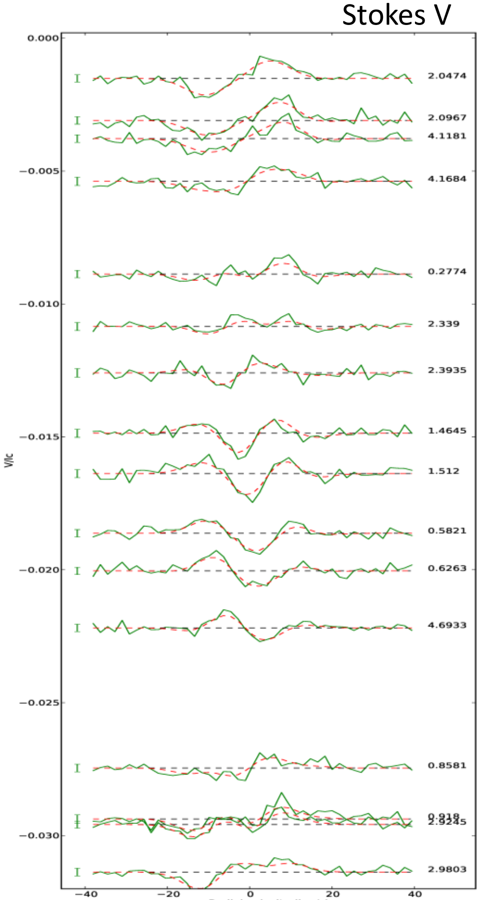
- Spectropolarimetry
  – Large scale surface field
  (Donati and collaborators)

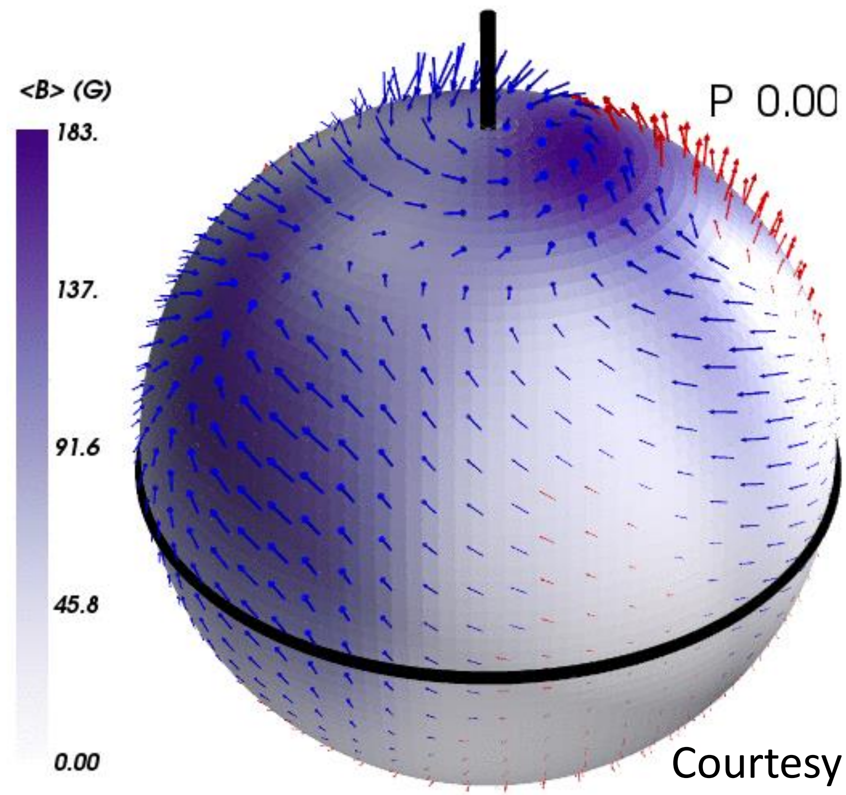




YSOs magnetic fields

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

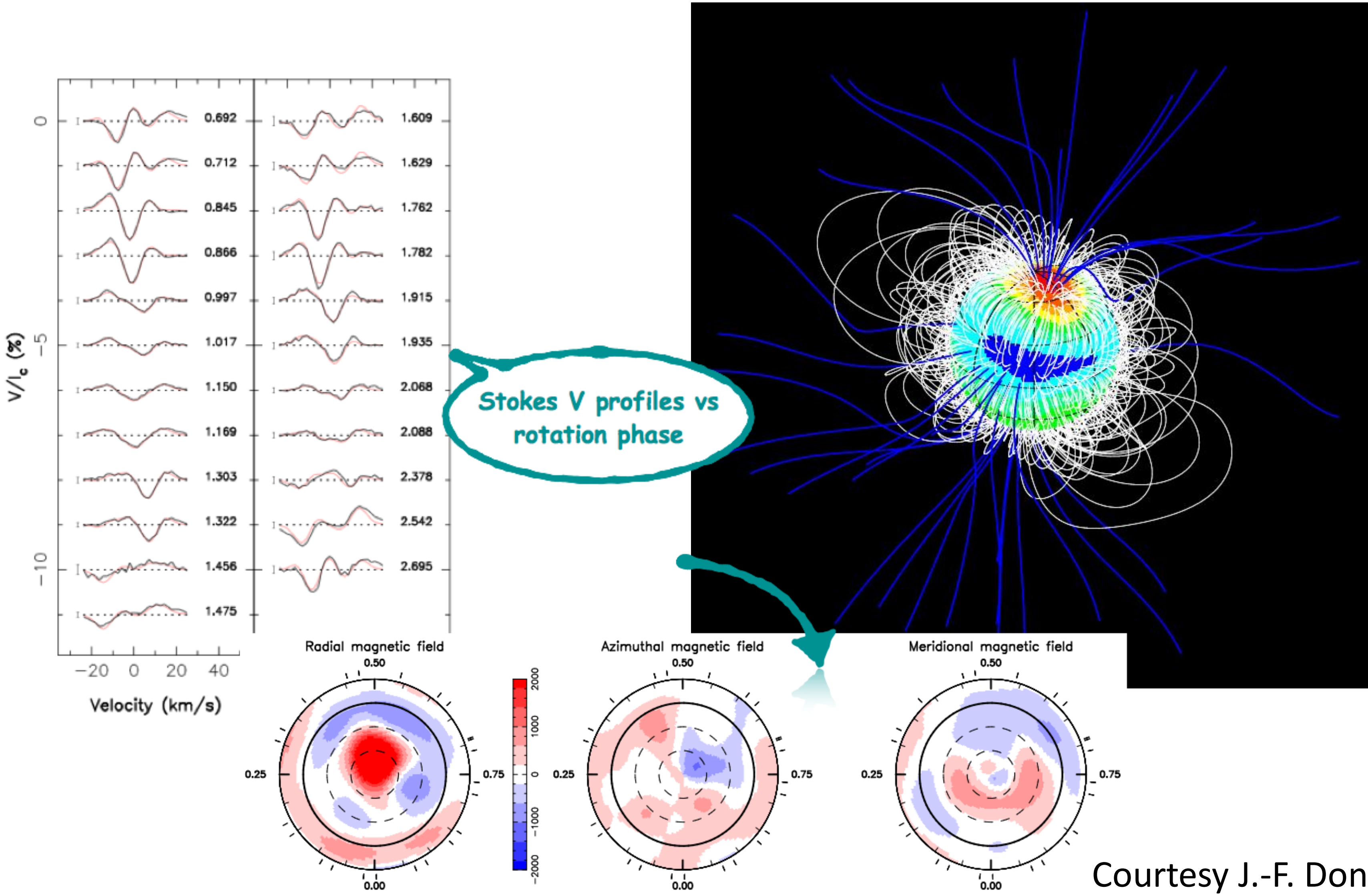




Courtesy C. Folsom

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

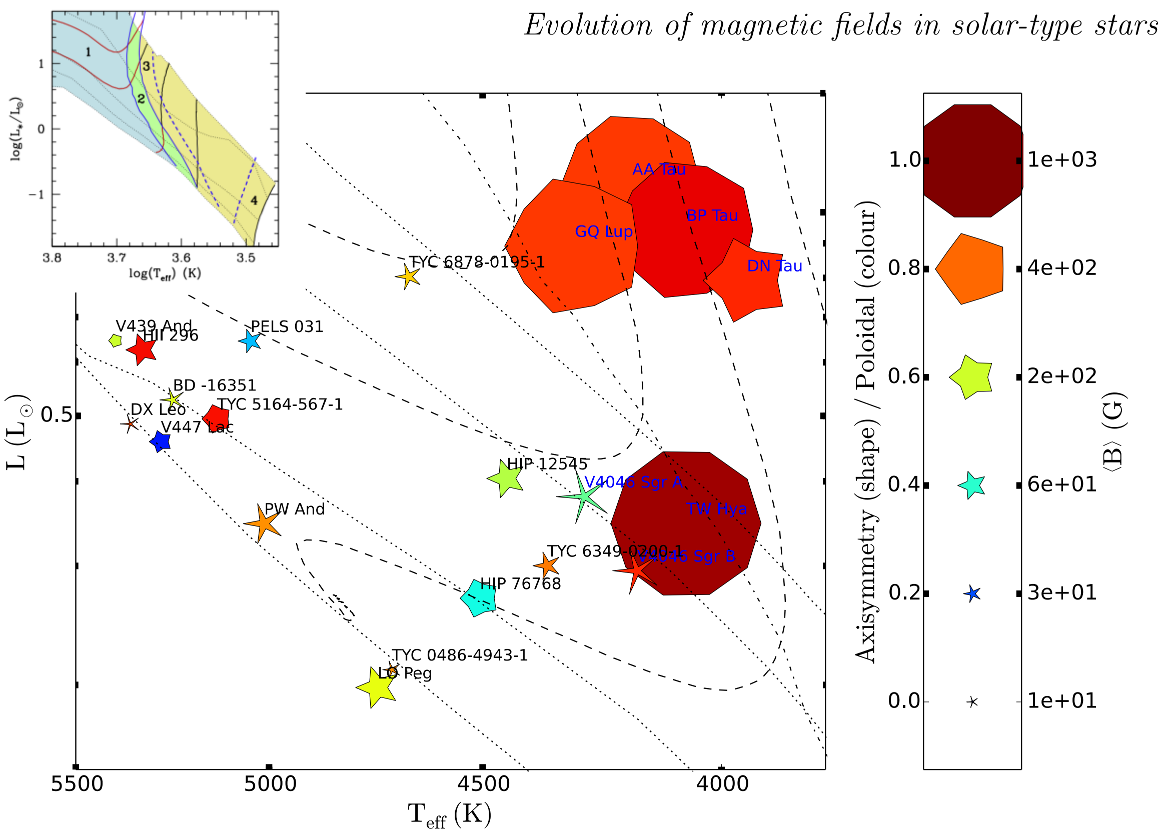
Zeeman-Doppler Imaging



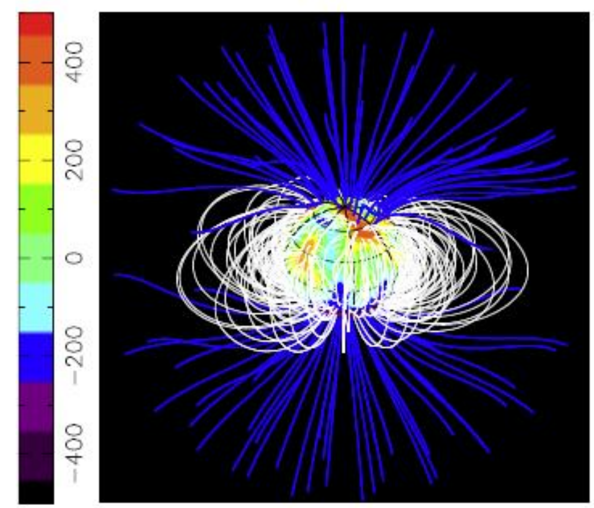
Courtesy J.-F. Donati

PMS stellar magnetic fields

Strong dynamo fields in YSOs are primarily linked to their fully convective interior

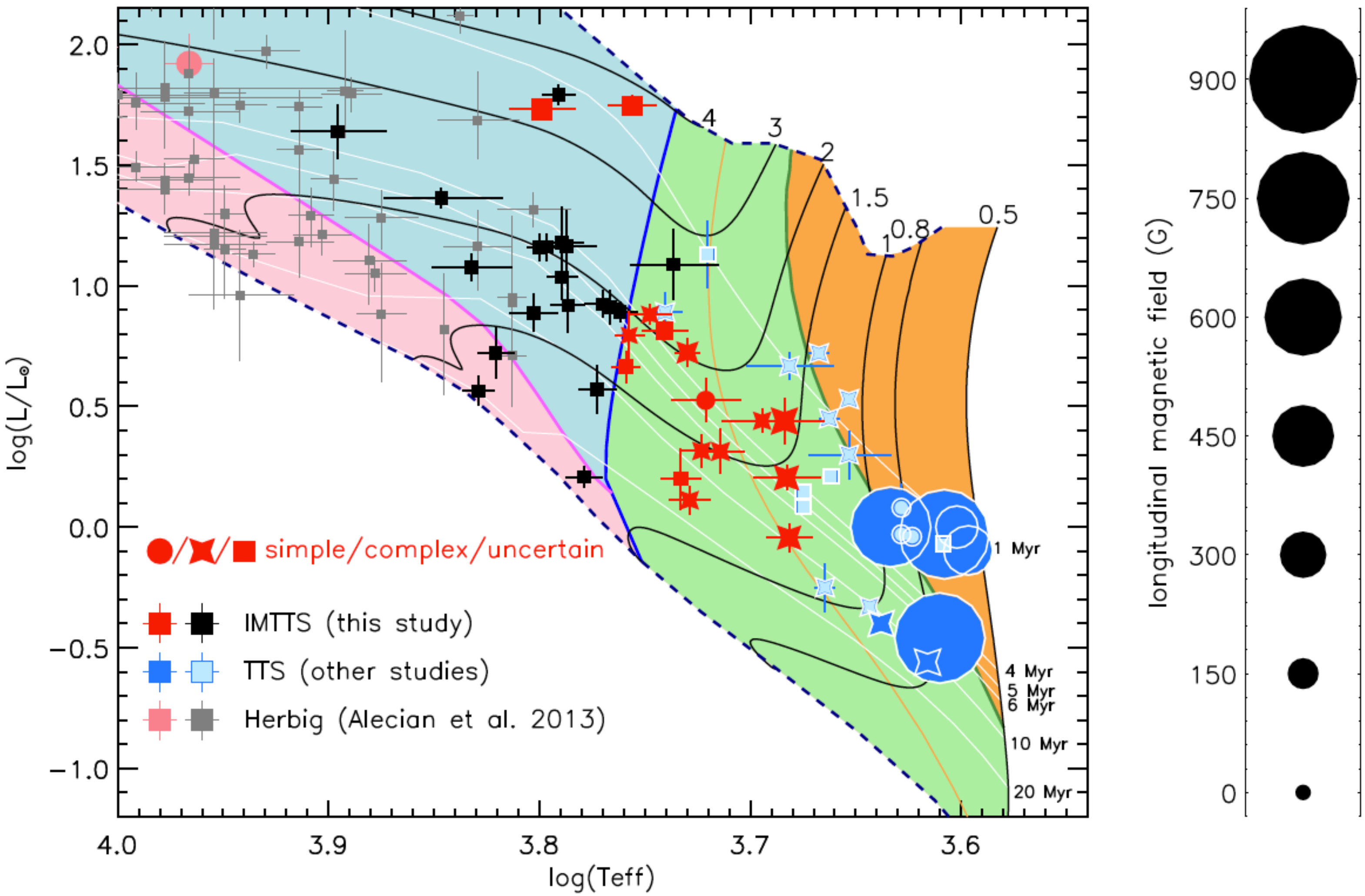


Hill, Folsom, Donati+19
Folsom, Petit, Bouvier+16
Donati, Gregory, Alencar+13
Gregory, Donati, Morin+12



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

PMS magnetism: intermediate-mass stars

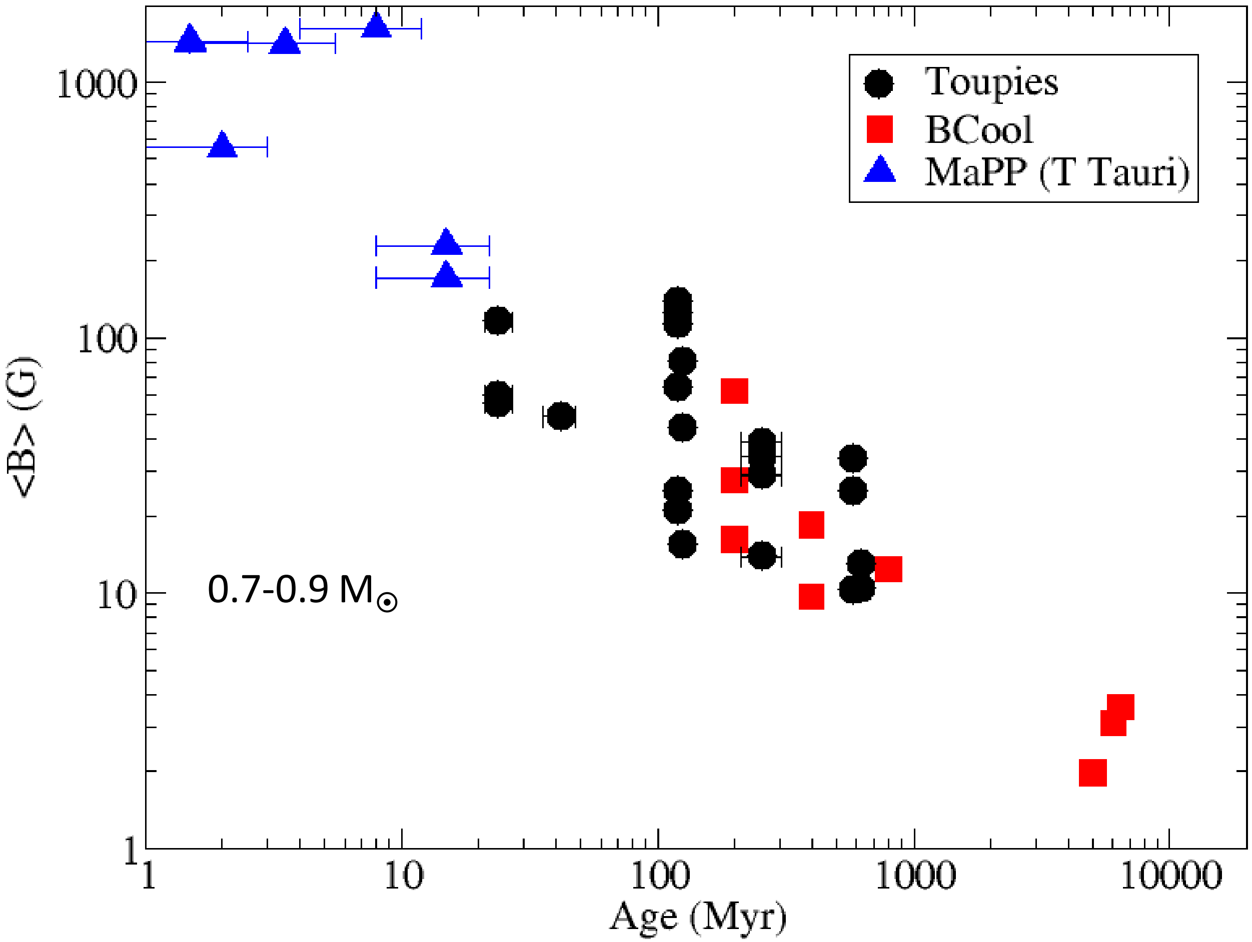


Villebrun , Alecian, Hussain et al. 2019

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

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)

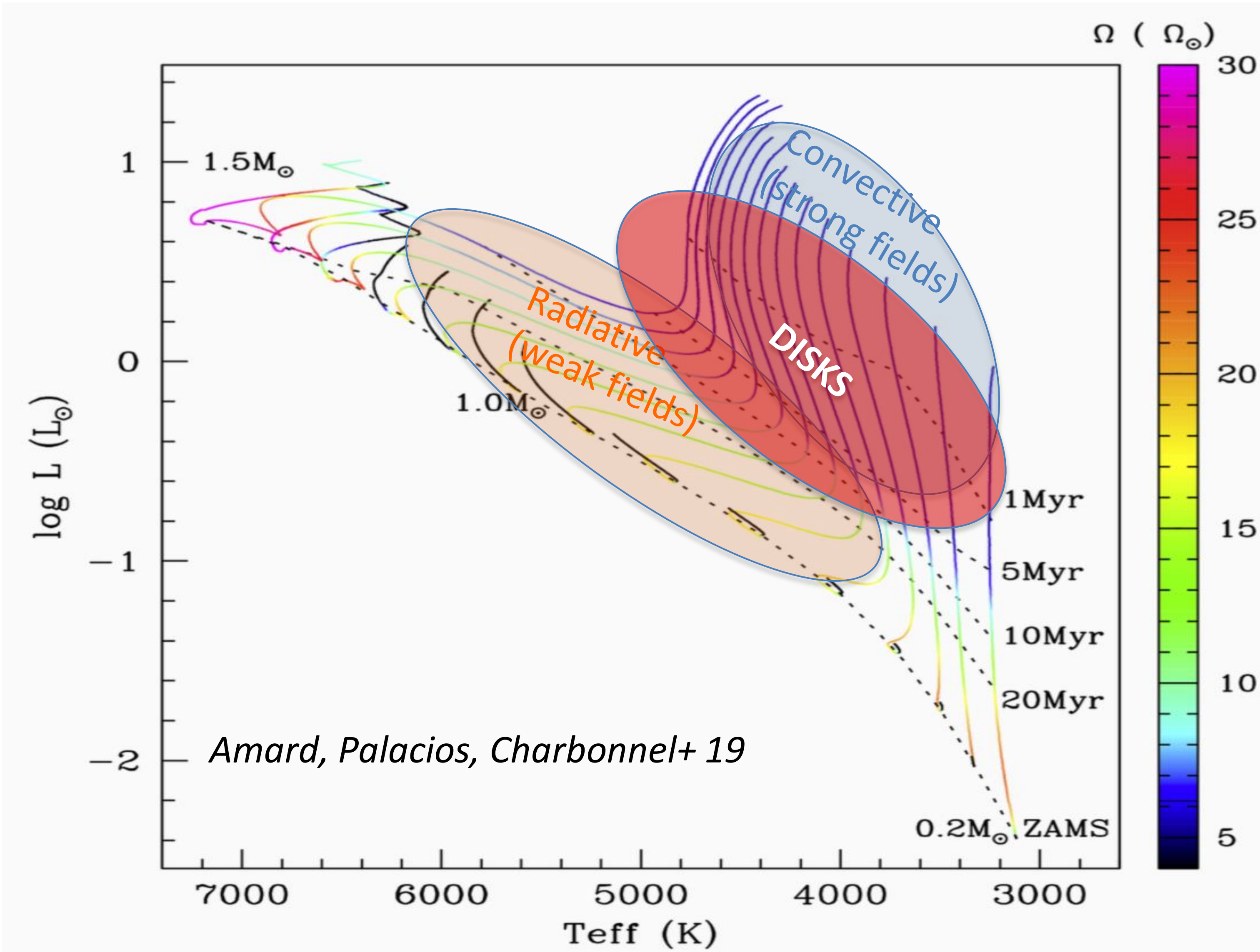
ZAMS & MS B evolution due to rotational braking

Folsom, Bouvier, Petit+18

II. Star-disk interaction

The magnetospheric accretion process

Pre-main sequence models



Magnetospheric accretion in T Tauri stars

- Stellar magnetic field : **$B_* \sim$ 1-3 kilogauss**
- Mass accretion rate : **$dM_{acc}/dt \sim 10^{-9}$-10^{-8} M_{sun}/yr**

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

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

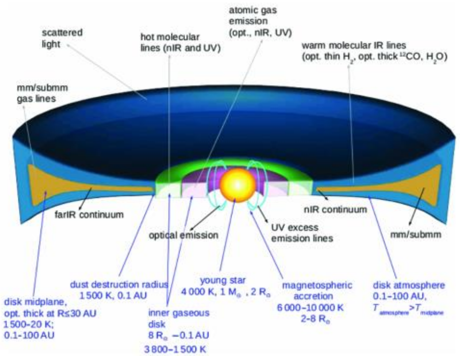
→ **$R_{in} \approx$ 3 – 8 R_***

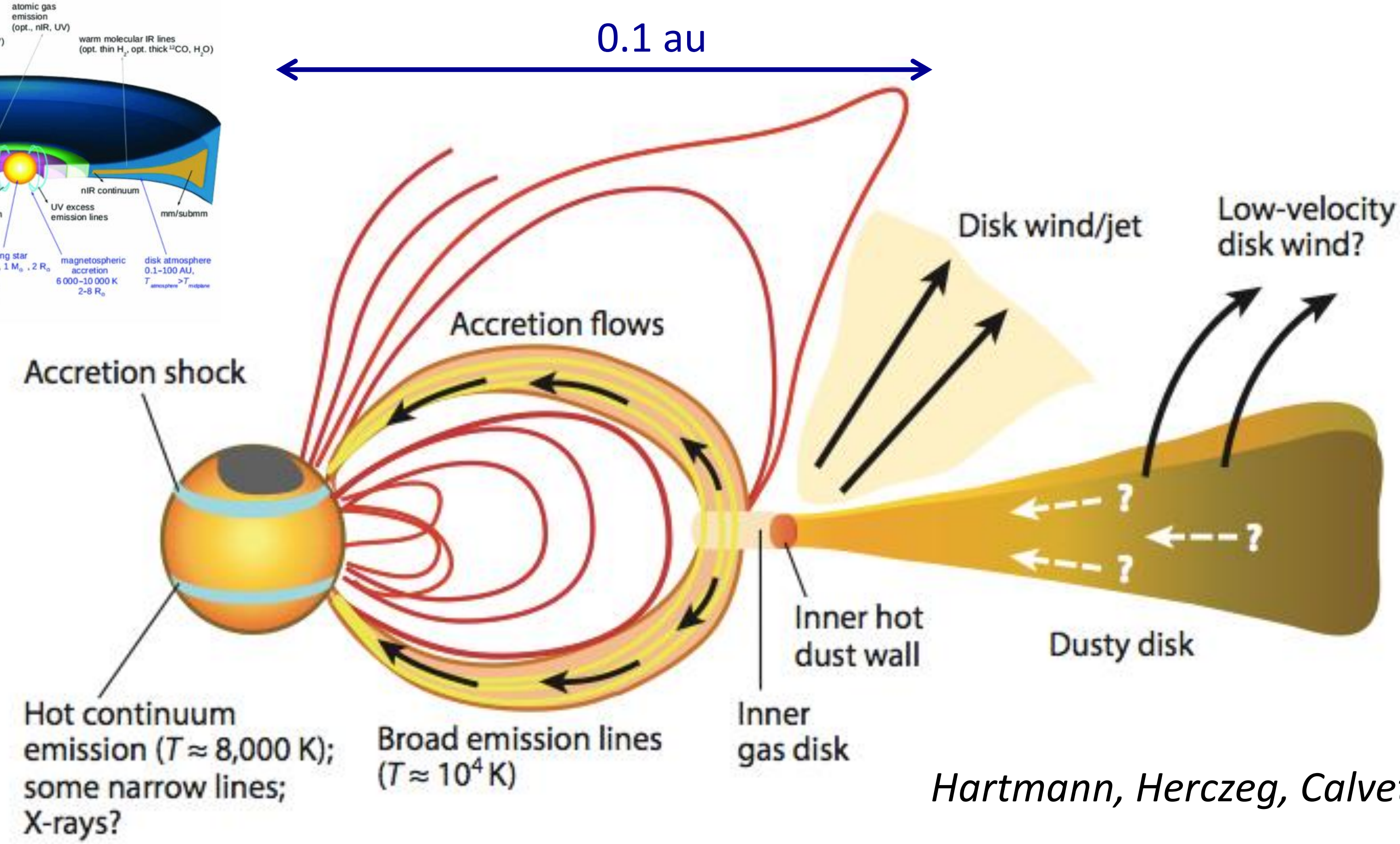
Bessolaz, Zanni, Ferreira+08

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

The magnetospheric accretion paradigm

Sicilia-Aguilar, Banzatti, Carmona+ 16



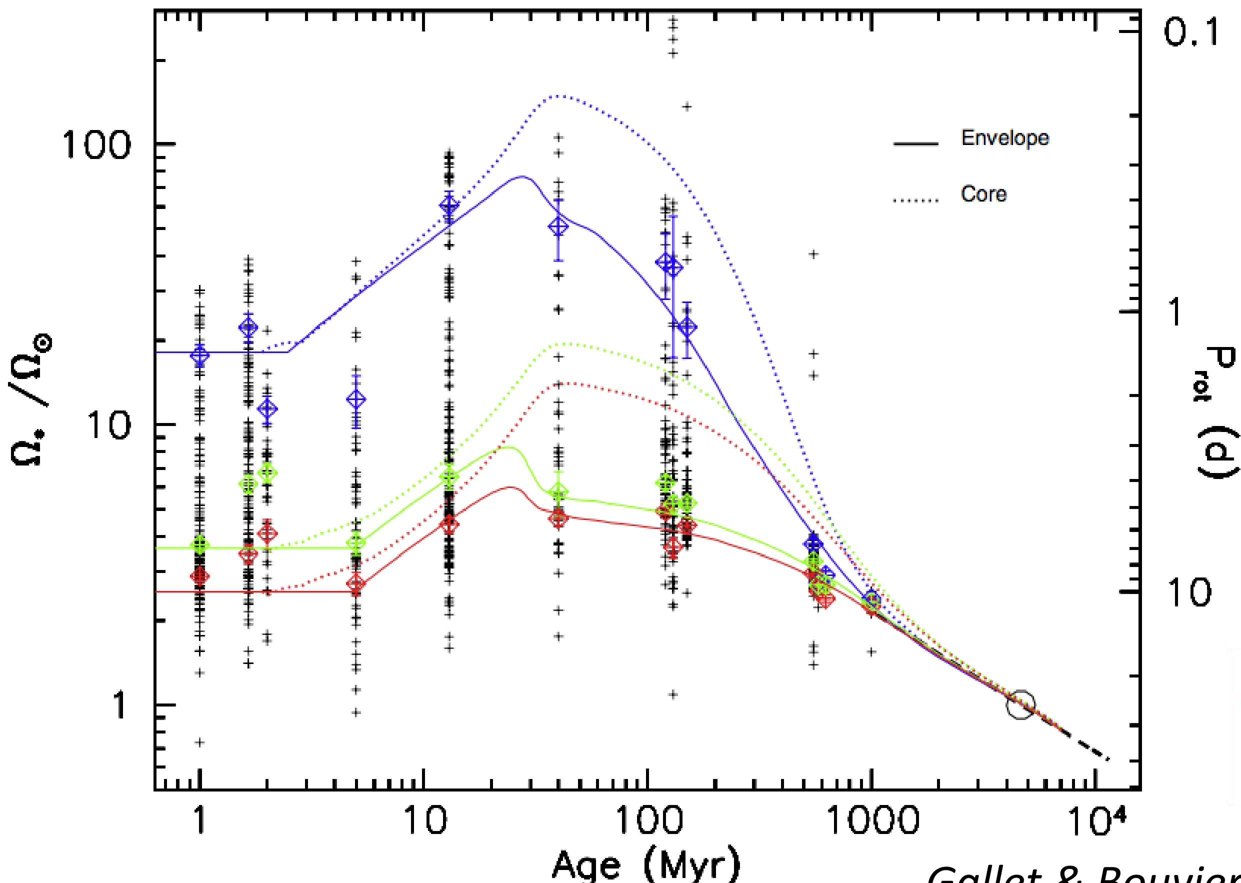


Hartmann, Herczeg, Calvet 2016

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.



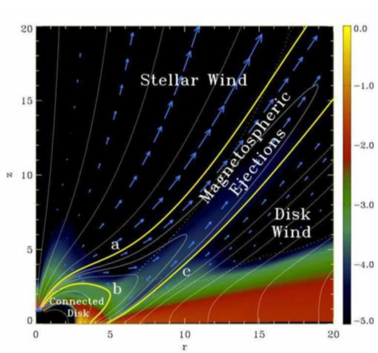
Gallet & Bouvier 2013, 2015

Space photometry (CoRoT, K2) + parametric models

Angular momentum evolution

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

Magnetospheric ejections (Zanni & Ferreira 2013)

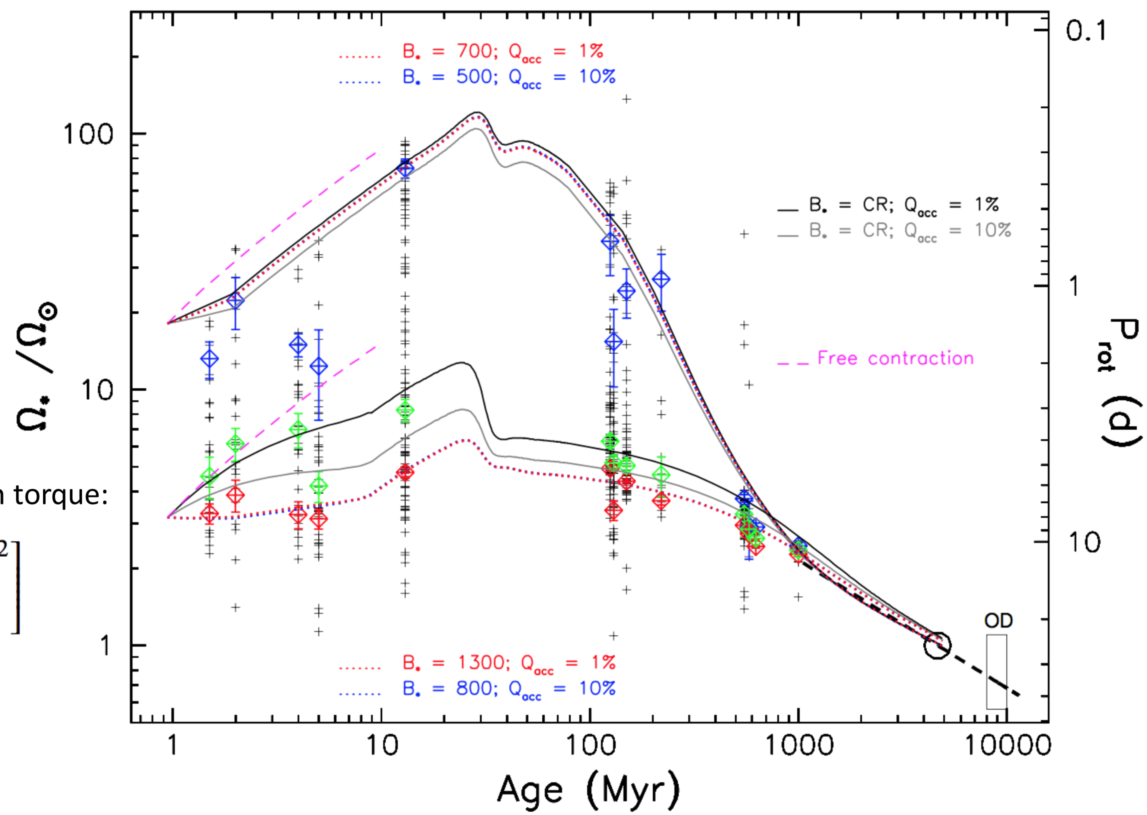


Magnetospheric ejection spin down torque:

$$\Gamma_{ME} = K_{ME} \frac{B_p^2 R_\star^6}{R_t^3} \left[K_{rot} - \left(\frac{R_t}{R_{co}} \right)^{3/2} \right]$$

Accretion spin up torque:

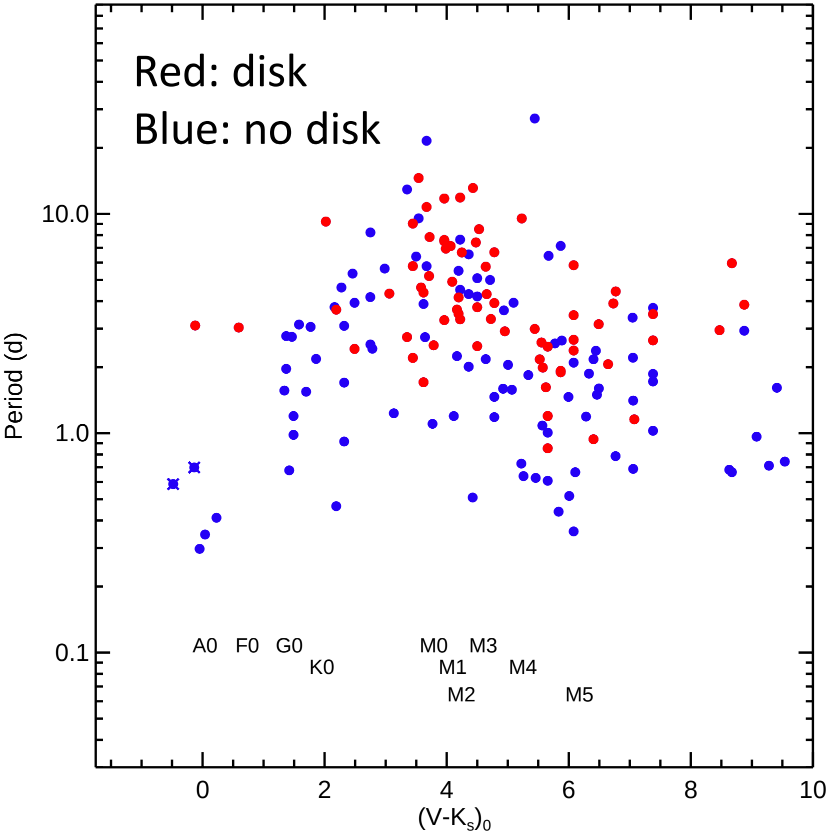
$$\Gamma_{acc} = K_{acc} \dot{M}_{acc} \sqrt{G M_\star R_t},$$



Gallet, Zanni, Amard, submitted

Disk locking / binaries

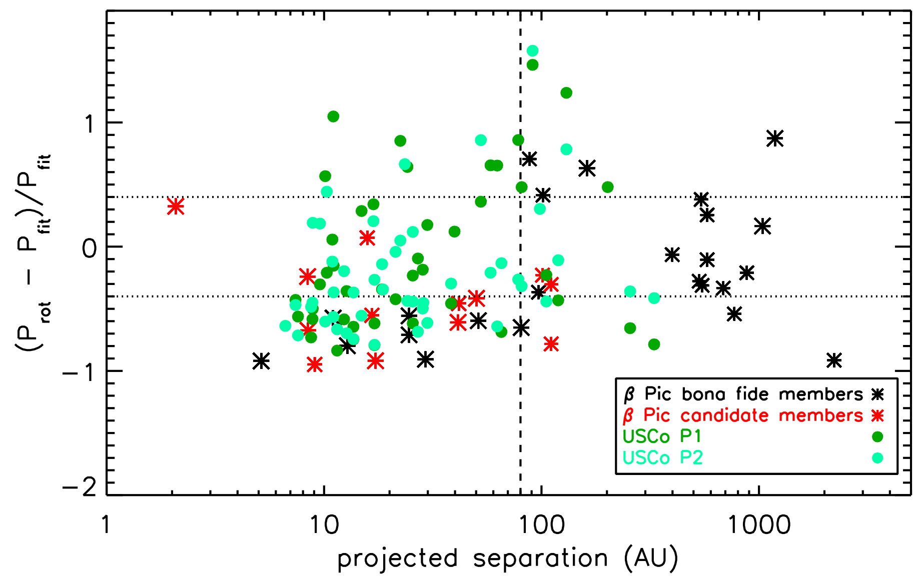
Taurus rotational period distribution
(Kepler – K2 Campaign 13)



Rebull, Stauffer, Cody+ in prep.

Primaries of intermediate separation binaries rotate faster than single stars
-> evidence for early disk disruption in close systems (10-80 au)?

B Pic and USco primaries



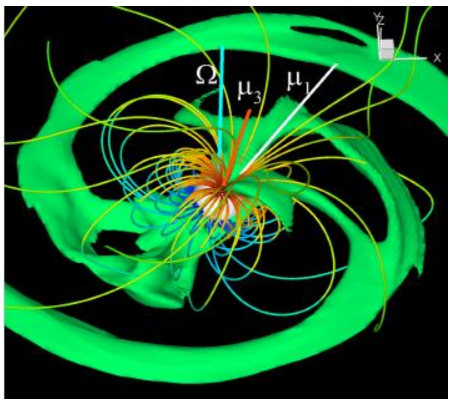
Messina 2019

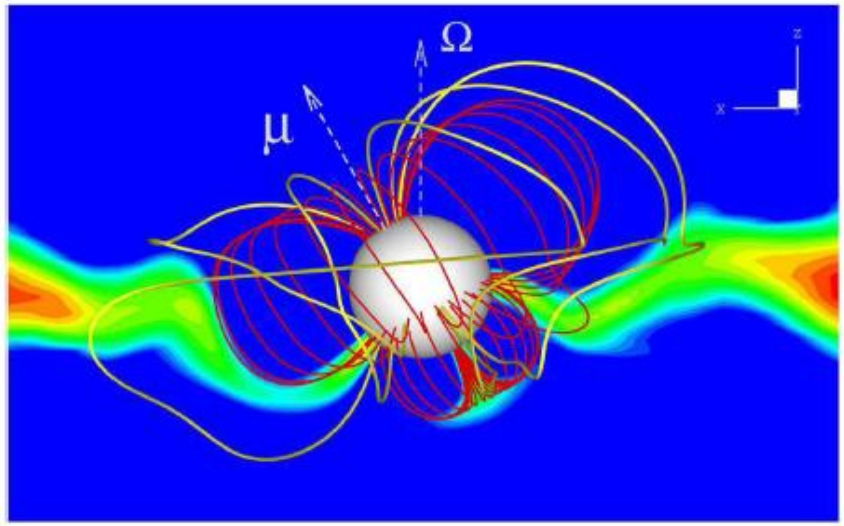
III. How to probe magnetospheric accretion?

Exploring the time domain

Magnetospheric accretion

Romanova et al. 2010

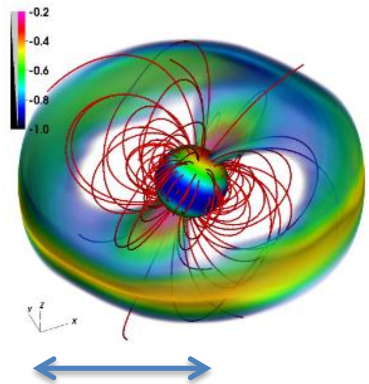




Long, Romanova, & Lovelace 2007

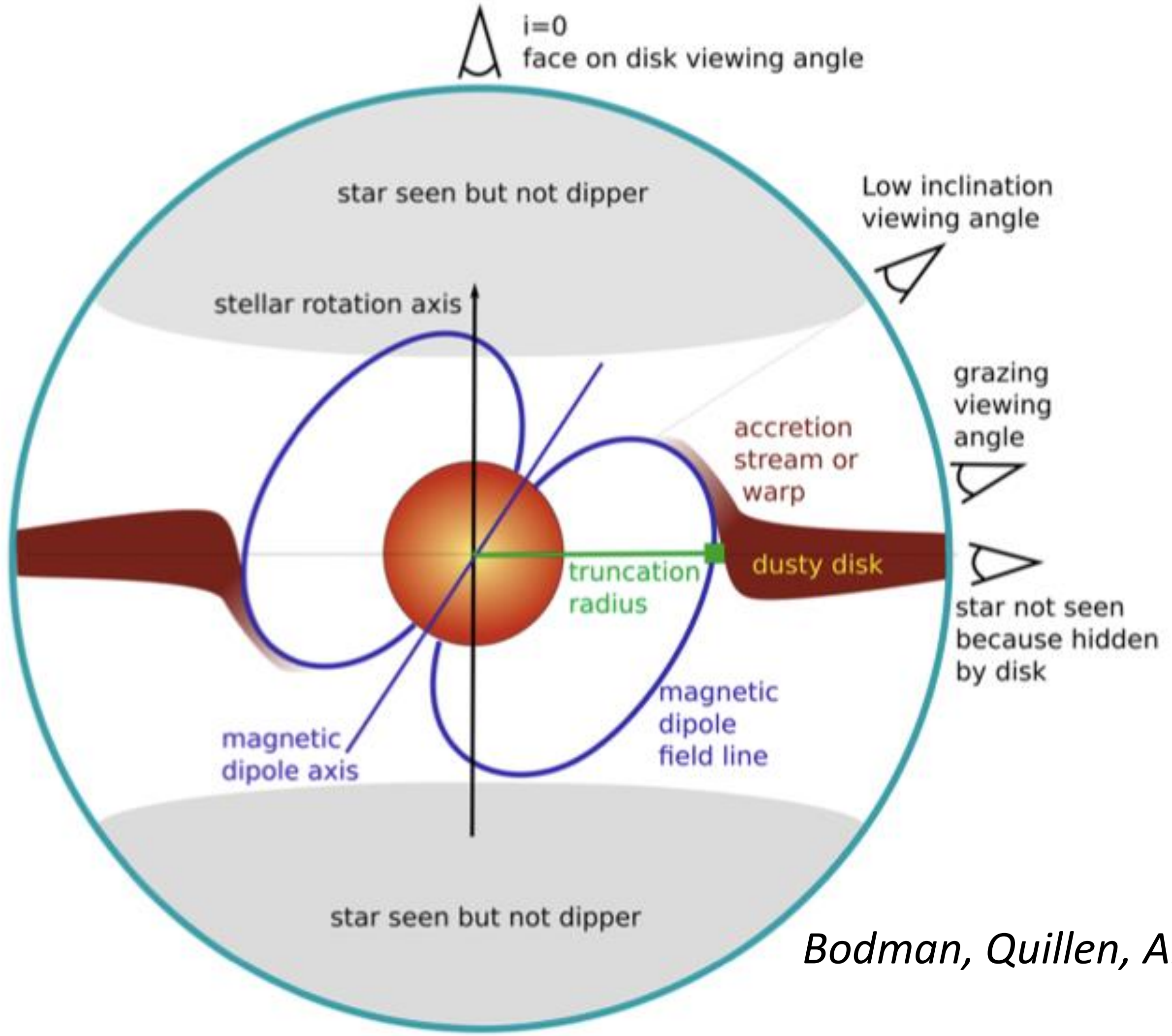
- How is the disk material accreted onto the star?
- How stable vs. dynamical is the magnetospheric accretion process?
- How does it impact the inner disk structure?
- How does it modify PMS evolution?

The variability of young stellar objects



~0.05 AU

Kurosawa & Romanova (2013)

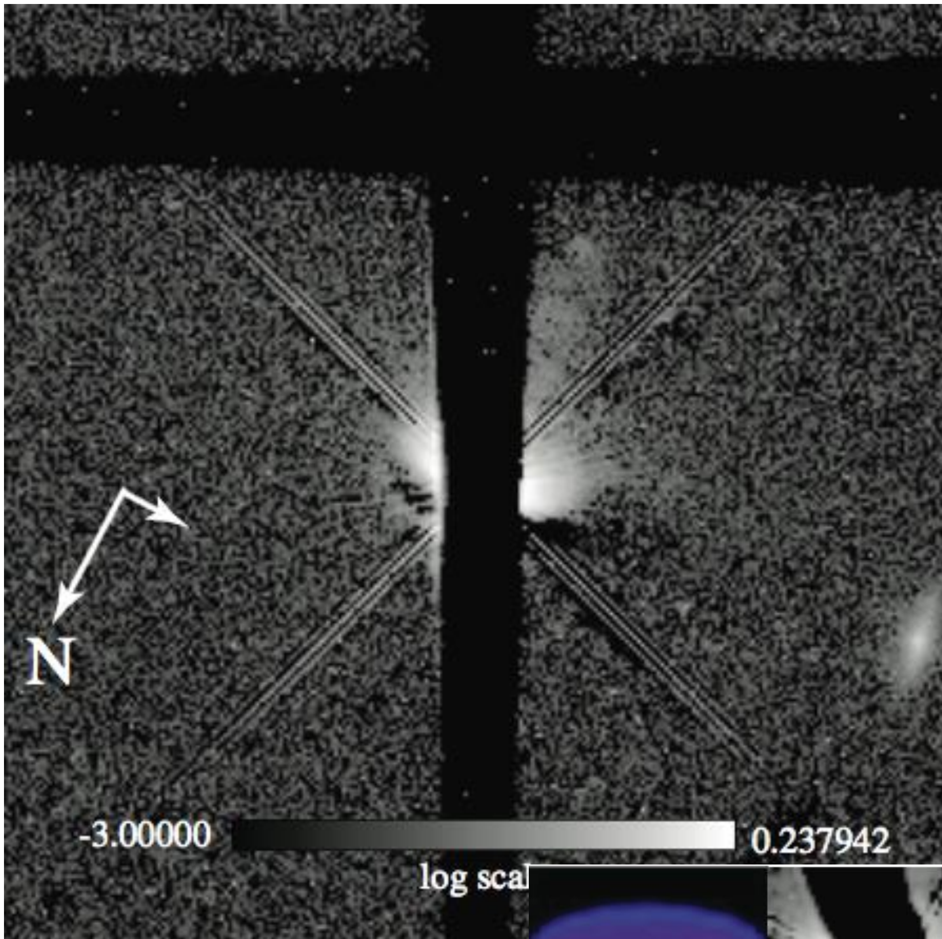


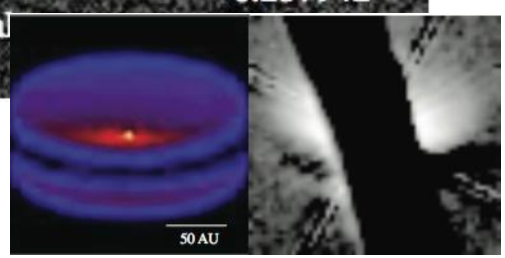
Bodman, Quillen, Ansdell+ 17

The inner system rotates on a timescale of ~1 week
(stellar rotation period and inner disk Keplerian orbit)

A highly inclined system: AA Tau

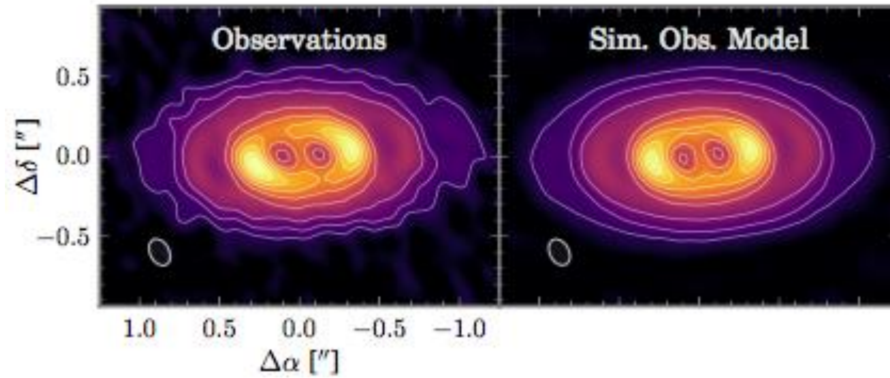
HST/STIS: *Cox, Grady, Hammel+13*





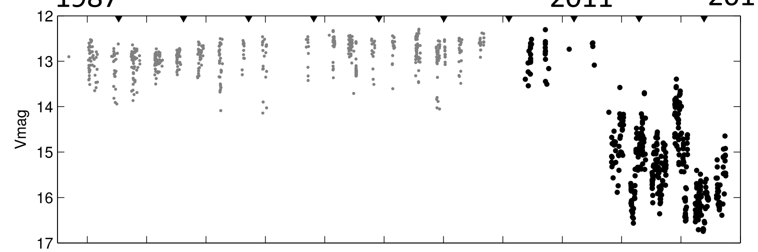
Outer disk inclination:
~71 +/- 1 deg.

ALMA: *Loomis, Oberg, Andrews+17*



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

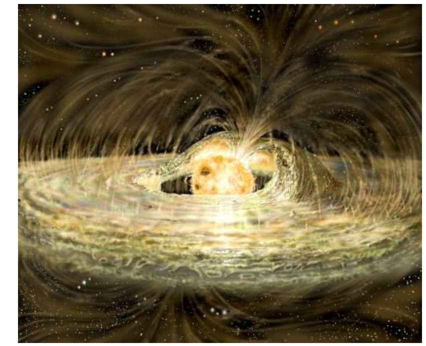
AA Tau's 30 year-long light curve



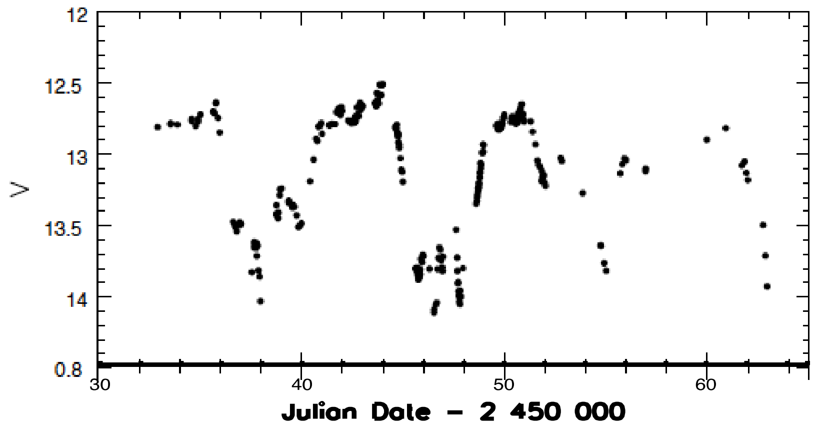
~4 mag additional extinction
on the line-of-sight since 2011

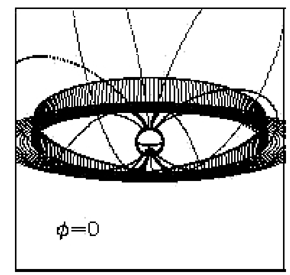
Bouvier, Grankin, Ellerbroek+13

AA Tau: the prototype of dippers

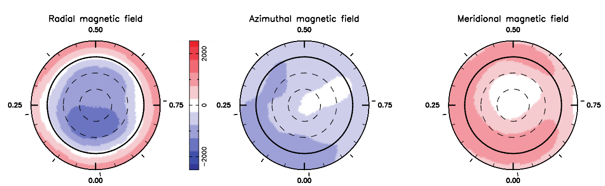


P=8.2 days

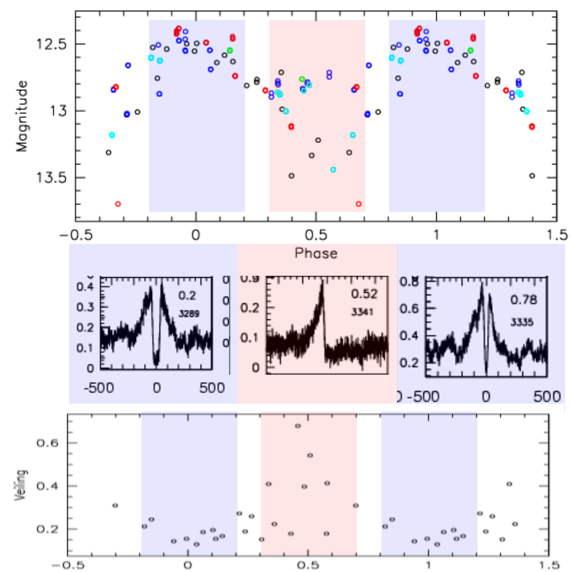




Inclined magnetosphere



2-3 kG dipole magnetic field; 20 deg. obliquity
Donati, Skelly, Bouvier+ 2010



Periodic eclipses

(disk warp)

(P=8.22d)

Balmer lines

(accretion funnel)

Veiling

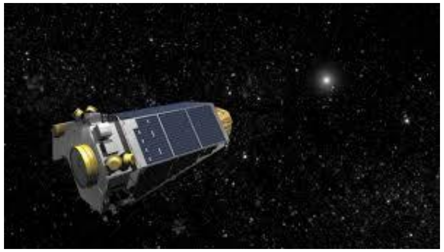
(accretion shock)

Supports inner disk warp resulting from inclined stellar magnetosphere + accretion columns + accretion shock

Bouvier, Alencar, Boutelier+ 2007

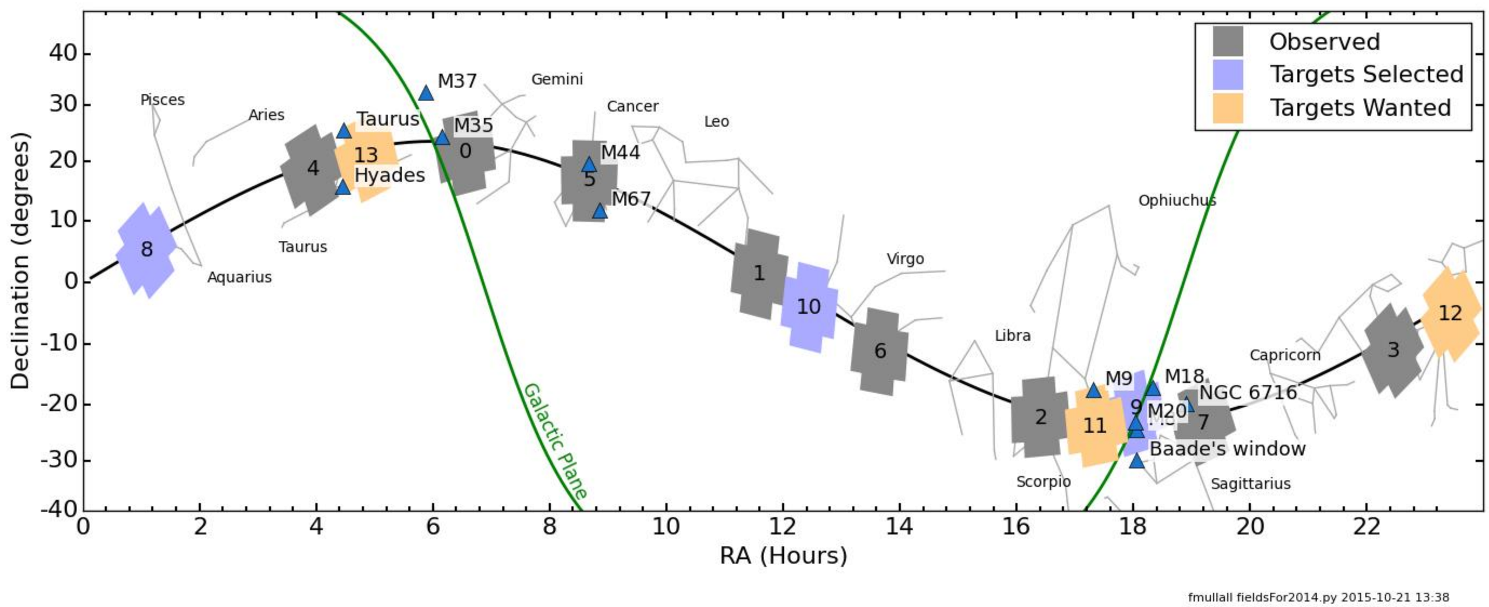
Then, came…

CoRoT & Kepler – K2



A revolution in space based monitoring of young stars

- A unique opportunity to monitor hundreds of young stars in various star forming regions

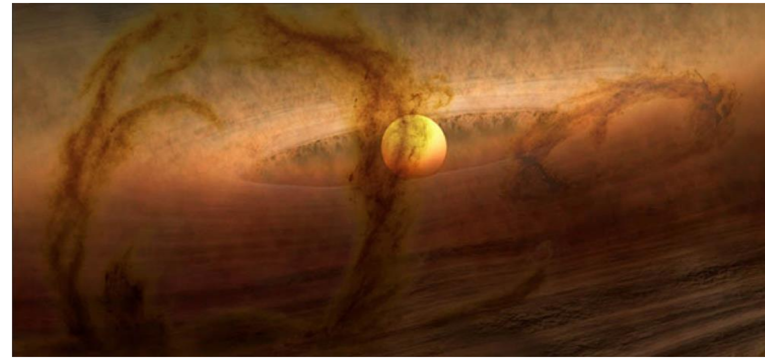


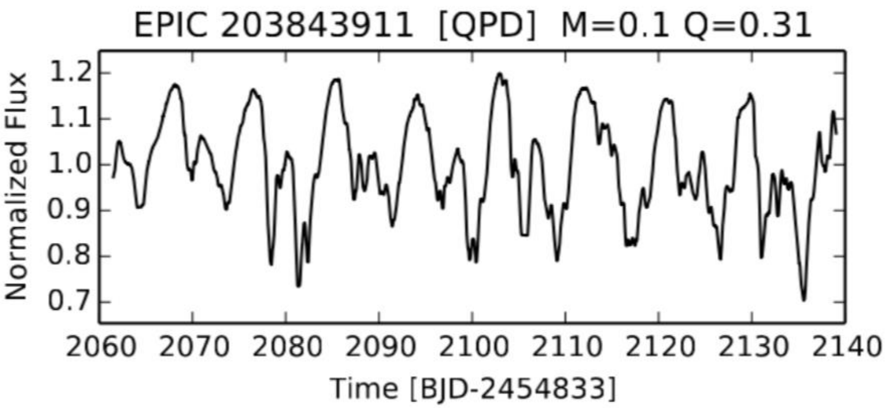
A new era in the study of the photometric variability of young stellar objects

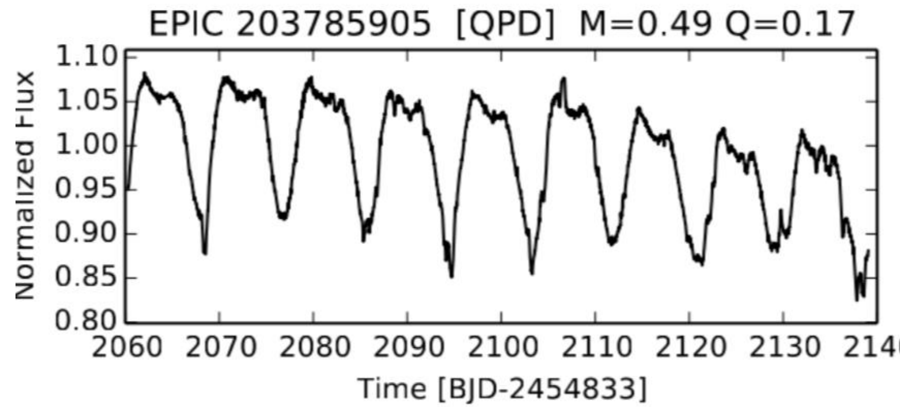
VARIABLE PHOTOMETRY: EXTINCTION-DRIVEN BEHAVIOR

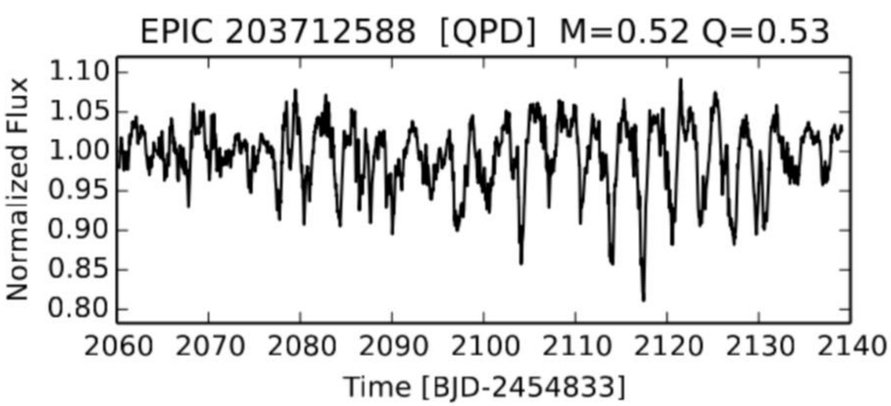
(dippers)

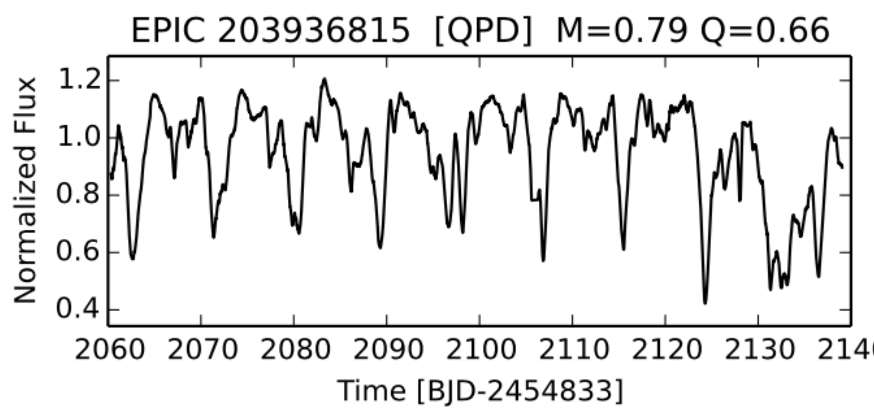
[Cody & Hillenbrand 2018]









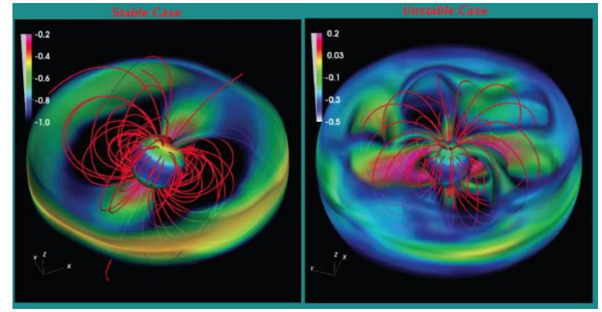


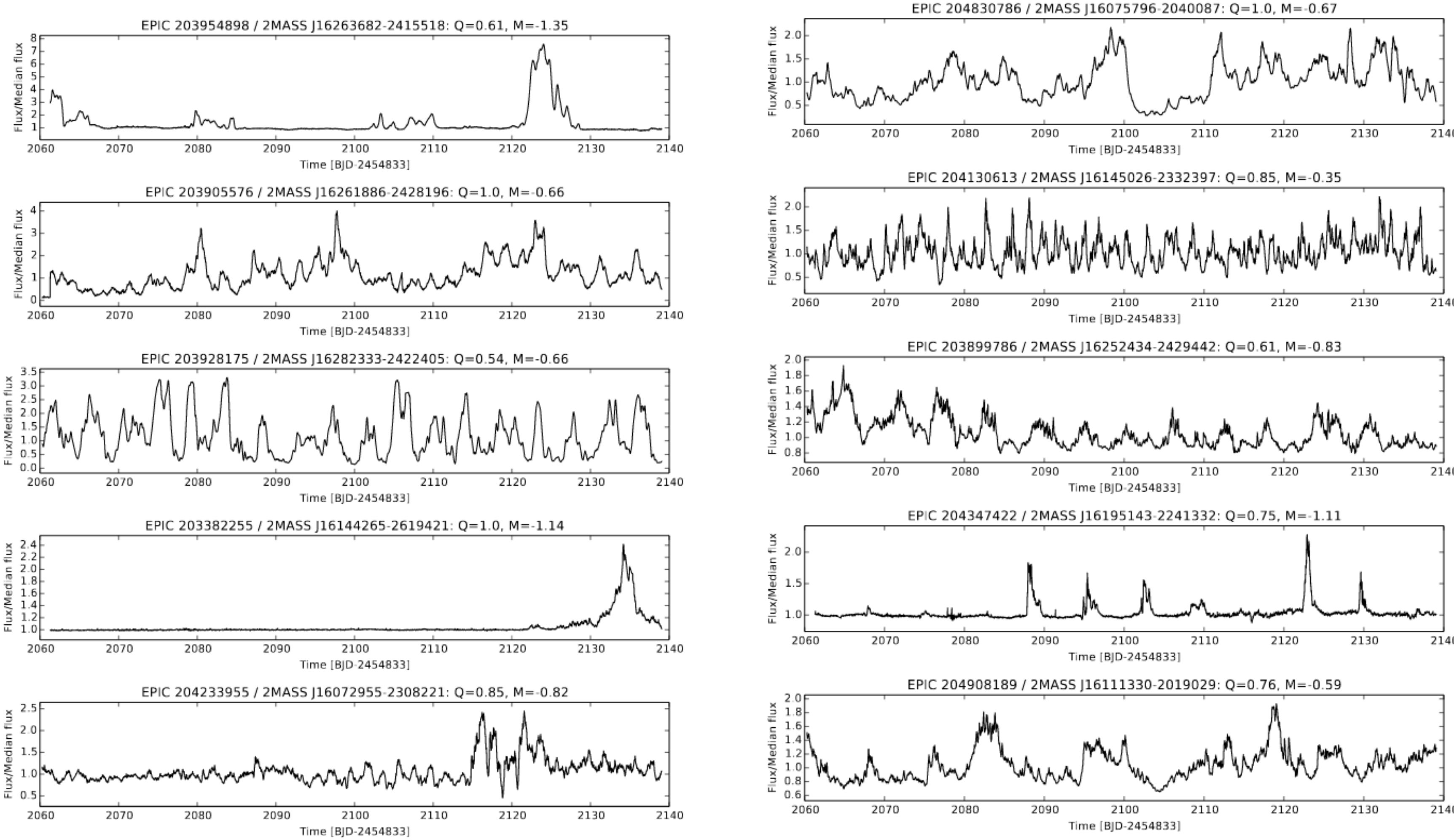
33% of the objects with disks exhibit these types of lightcurves

VARIABLE OPT PHOTOMETRY: ACCRETION-DRIVEN BEHAVIOR

(bursters)

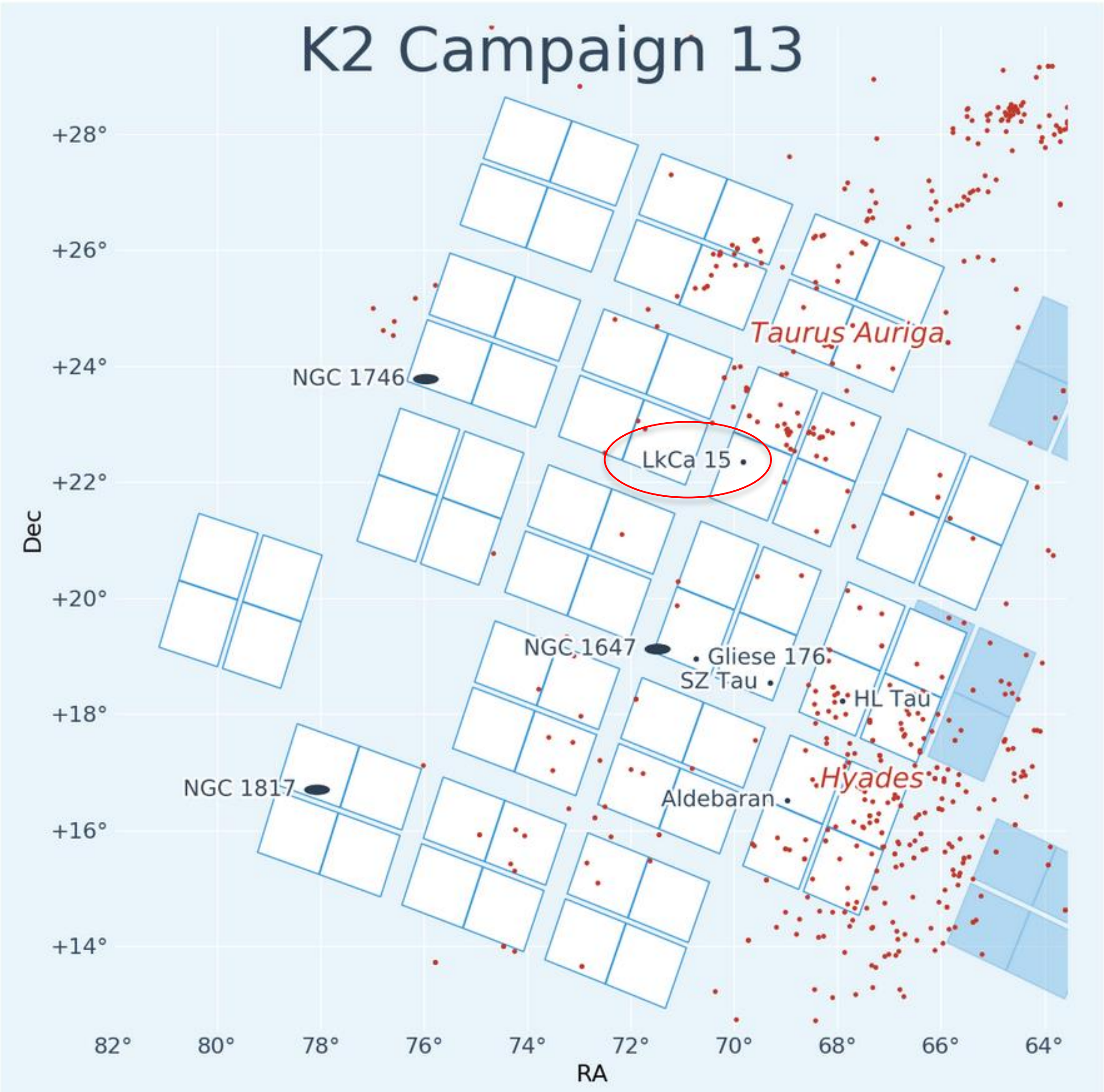
[Cody et al. 2017]



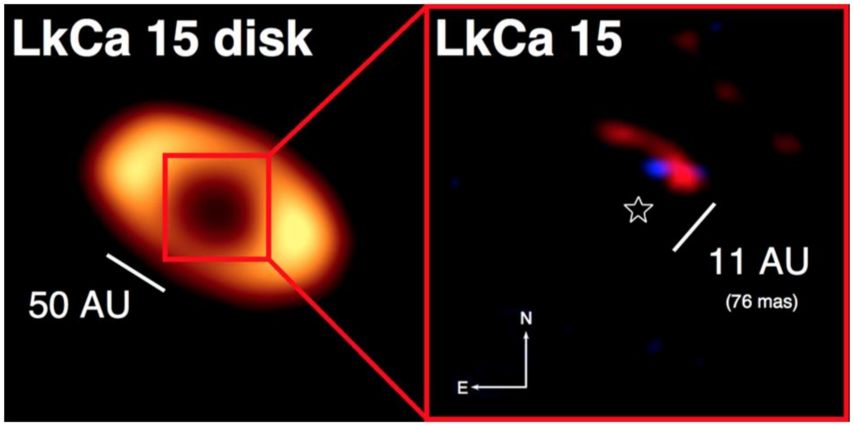


14% of the objects with disks exhibit these types of lightcurves https://keplerscience.arc.nasa.gov/k2-data-release-notes.html#k2-campaign-13

K2 C13: Taurus



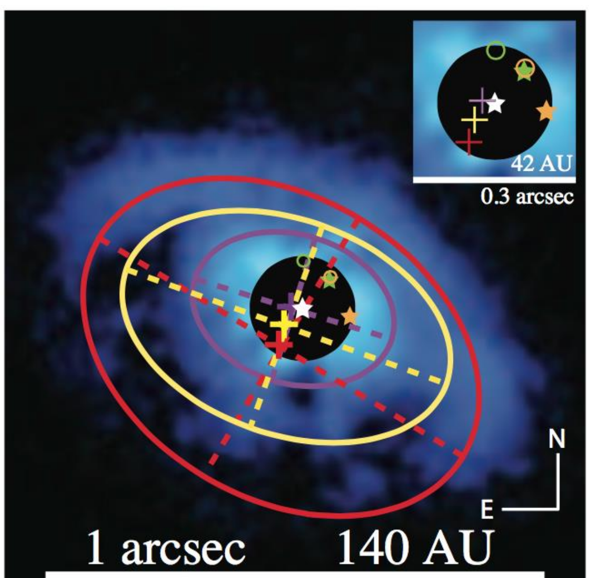
LkCa 15: a planet-forming system?



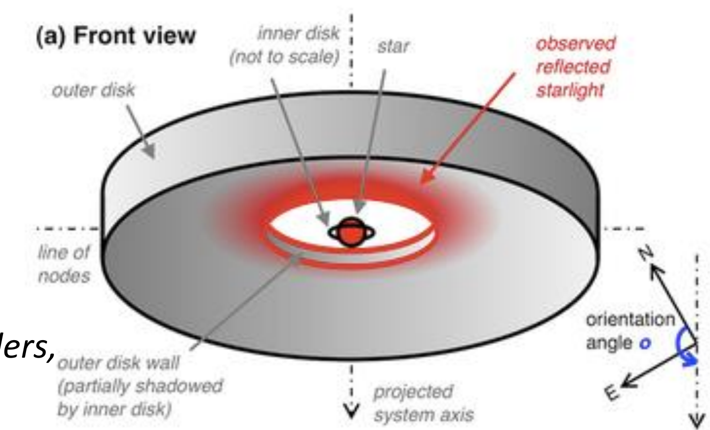
A young accreting system in Taurus
A disk with a large inner cavity (50 AU)
A planetary mass object in the cavity?

A. Kraus & Ireland 2012

Outer disk inclination ~ 44-55 deg
Evidence for a warped inner disk?



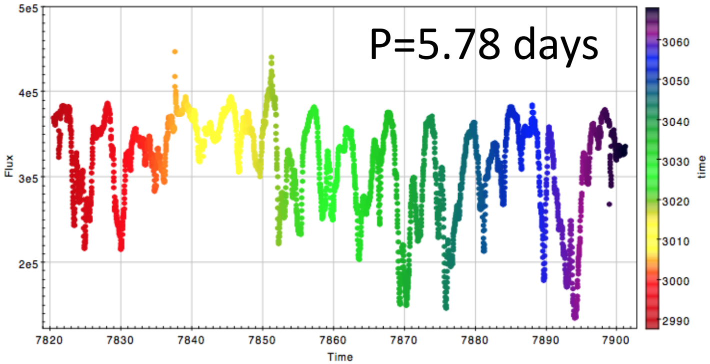
Oh, Hashimoto, Tamura+16

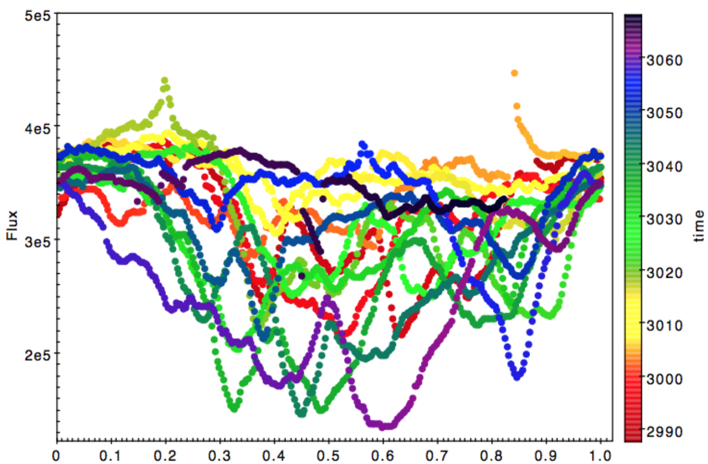


Thalmann, Mulders, Hoddap+14

Magnetospheric accretion in LkCa 15

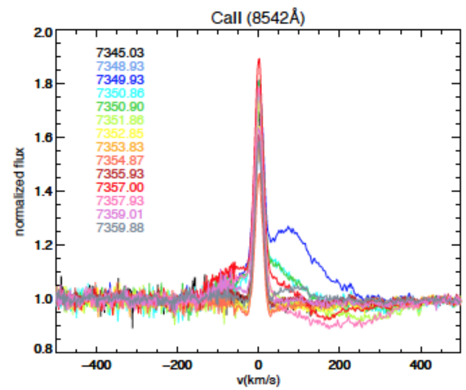
K2 light curve: a periodic dipper!

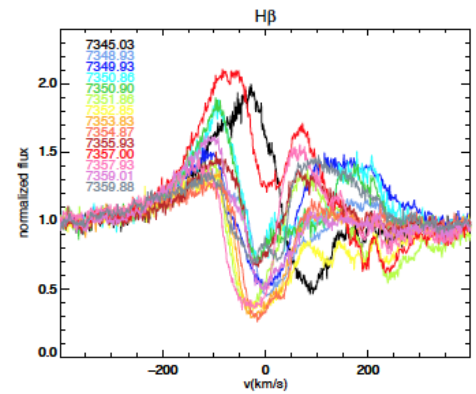


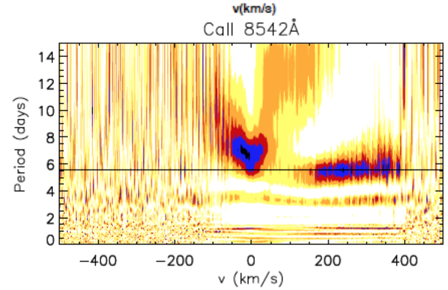


How can a transitional disk object be a dipper ?
An inner circumstellar disk close to the star ?

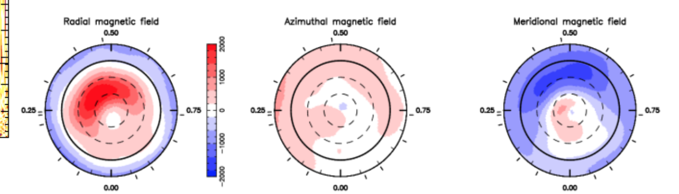
But LkCa 15 outer disk inclination ~40-55 deg
while dippers inclination ~ 60-75 deg (McGinnis+15)

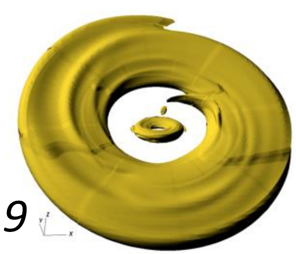






1.35 kG dipole tilted by 20 deg.





A tilted inner disk ?

An AA Tau sibling…

Zhu+19

Alencar, Bouvier, Donati+18; Donati, Bouvier, Alencar+19

Magnetospheric accretion: what have we learnt?

- 3D MHD models of magnetospheric accretion onto inclined, large-scale fields are supported by observations (at least in some cases).
- Stable (albeit dynamical) funnel flows and associated accretion shocks can persist for weeks, possibly longer.
- *Dippers* are pretty common among young accreting stars. Windows on the inner disk structure/dynamics.
- Other types of variability, e.g. *bursters*, might correspond to more unstable accretion regimes. This remains to be investigated.
- The star-disk interaction process is the main source of day-to-day variability of low-mass YSOs

Magnetospheric accretion: remaining issues

- Are there different accretion regimes (stable/unstable)? What are the governing parameter(s)?
- YSOs may change light curve type (e.g. dippers-> stochastic) on a timescale of a few years. Why?
- How do ejection phenomena (transient, winds) relate to the accretion process onto the star?
- Is the magnetospheric accretion process at work in HAe and/or HBe stars?

Changing light curves

- NGC 2264: CoRoT 2008 vs. CoRoT 2011

Table 5. Variations of the morphological classification of the 84 CTTS light curves observed with CoRoT in 2008 and 2011.

Light curve 2008 → Light curve 2011	N° of stars
Spot → AA Tau	0
Spot → non-periodic	9
AA Tau → spot	0
AA Tau → non-periodic	5
Non-periodic → AA Tau	8
Non-periodic → spot	2
Non-periodic → periodic unclassified	1
AA Tau → AA Tau	8
Spot → spot	12
Non-periodic → non-periodic	37
Binary → binary	2

Sousa, Alencar, Bouvier+16

Magnetospheric accretion: remaining issues

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IV. What's next?

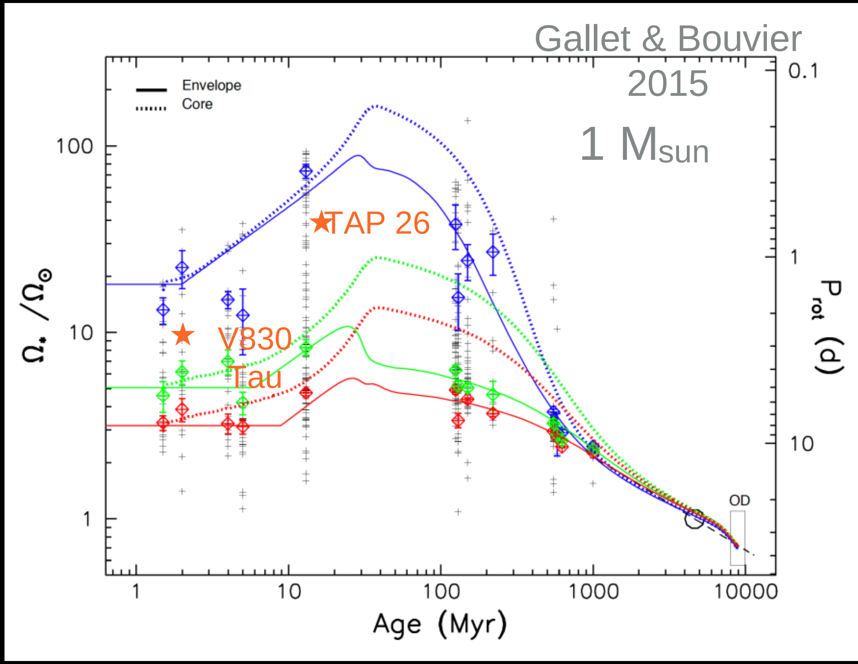
Star-planets-inner disk interactions (SPIDI's)

MaTYSSE Hot Jupiters

2 hot Jupiters found (Vrad)

	V830 Tau	TAP 26
a (Ma)	2	17
$M_\star$ ($M_\odot$)	1.00	1.04
$R_\star$ ($R_\odot$)	2.0	1.17
P_{rot} (d)	2.74	0.71
$M_{P,min}$ (M_{Jup})	0.5	1.7
P_{orb} (d)	4.93	10.79
a (au)	0.057	0.097
a ($R_\star$)	6.1	17.8

- Migration by disc-planet interaction ?

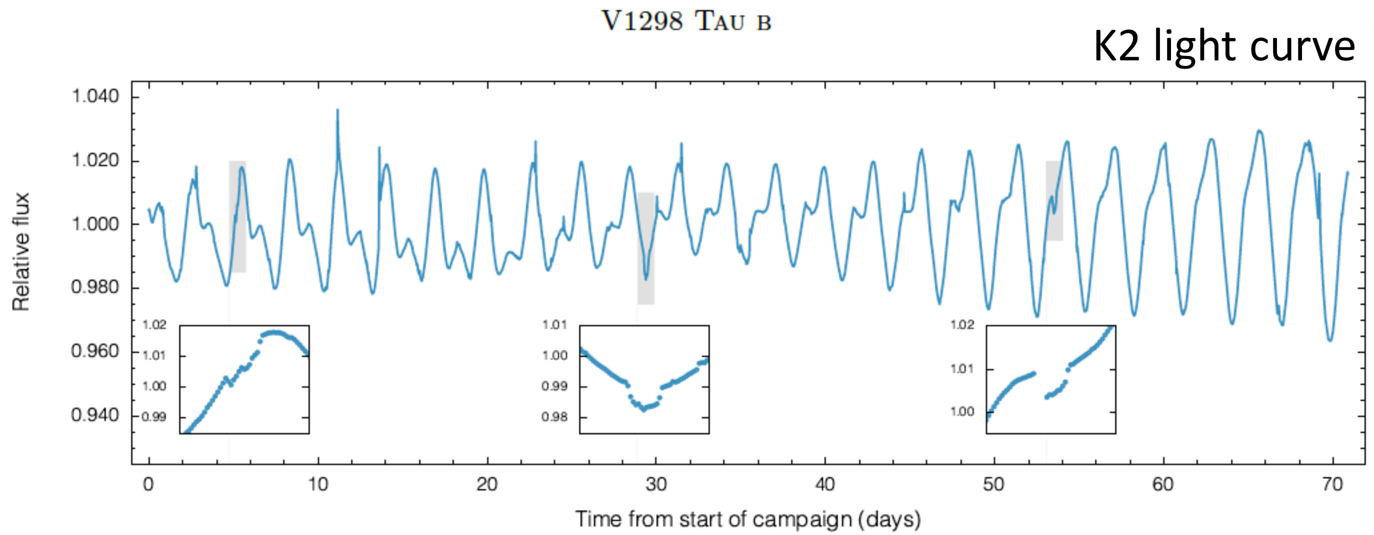


TAP 26 as an evolved version of V830 Tau?

Donati, Moutou, Malo+16
Yu, Donati, Hébrard+17

© L. Yu

Transiting young planets



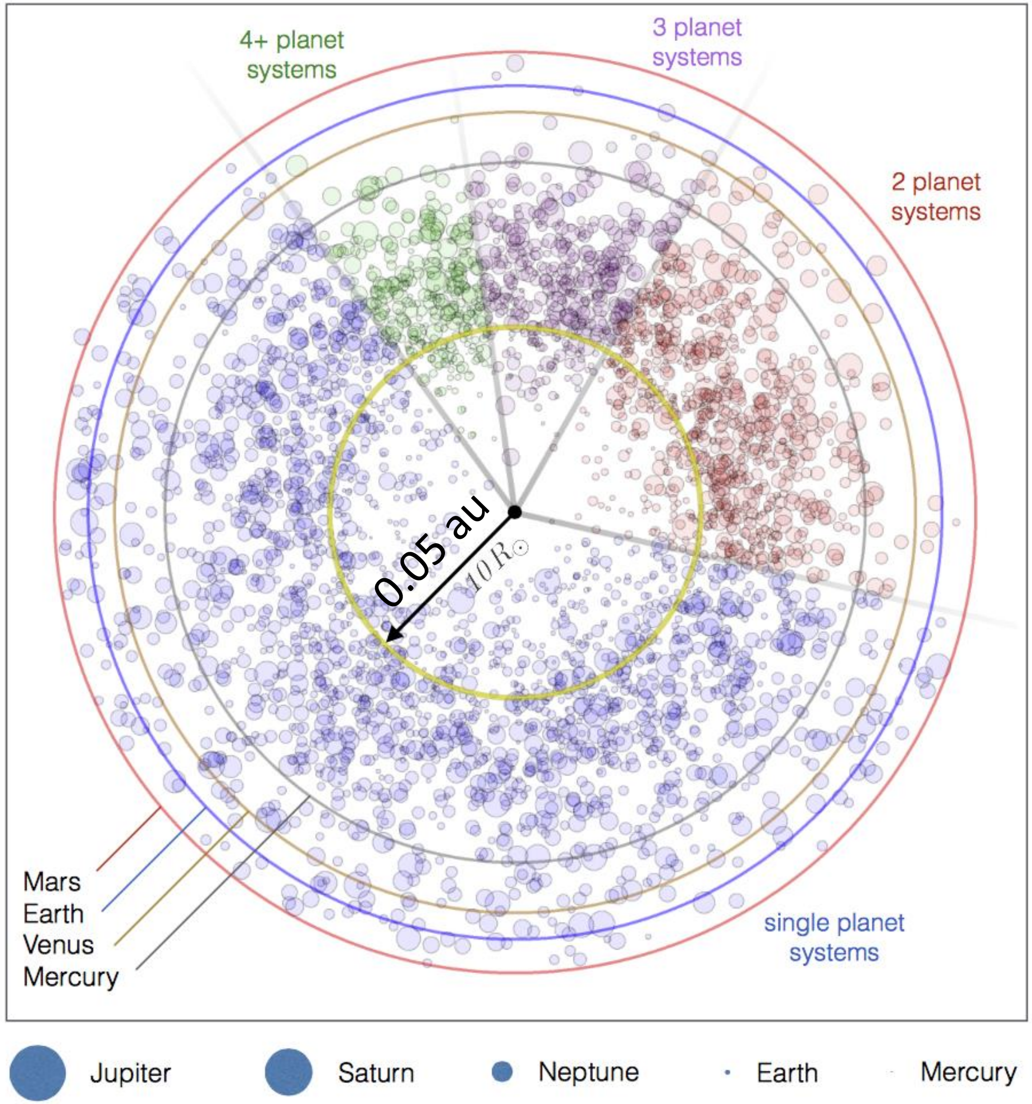
Light curve modeling parameters	
Orbital period (days)	$24.13889^{+0.00043}_{-0.00044}$
Time of mid-transit, t_0 (BJD_{TDB}; days)	$2457091.18842^{+0.00039}_{-0.00038}$
Full transit duration, T_{14} (hours)	$6.386^{+0.048}_{-0.034}$
Total transit duration, T_{23} (hours)	$5.486^{+0.039}_{-0.072}$
Planet-to-star radius ratio, R_p/R_*	$0.07111^{+0.00117}_{-0.00061}$
Scaled semi-major axis, $a/R_\star$	$28.7^{+1.5}_{-2.3}$
Impact parameter, b	$0.23^{+0.16}_{-0.15}$
Cosine of inclination, cos i	$0.0086^{+0.0067}_{-0.0058}$
Inclination, i (deg)	$89.51^{+0.33}_{-0.38}$
Eccentricity, e	$0.087^{+0.216}_{-0.062}$
Longitude of periastron, ω (deg)	92^{+71}_{-72}
Mean stellar density, ρ_* (g cm^{-3})	$0.69^{+0.20}_{-0.26}$
Planet properties	
Planet radius, R_p (R_{Jup})	$0.904^{+0.053}_{-0.048}$
Planet mass, M_p (M_{Jup})	<8.3
Semi-major axis, a (AU)	$0.1688^{+0.0025}_{-0.0026}$
Blackbody equilibrium temperature, T_{eq} (K)	601^{+29}_{-22}

23 Myr-old K0 star, M=1.1Msun
<8.3 Mjup planet on a 24d orbit
(a=0.17 au)

David, Cody, Hedges+19

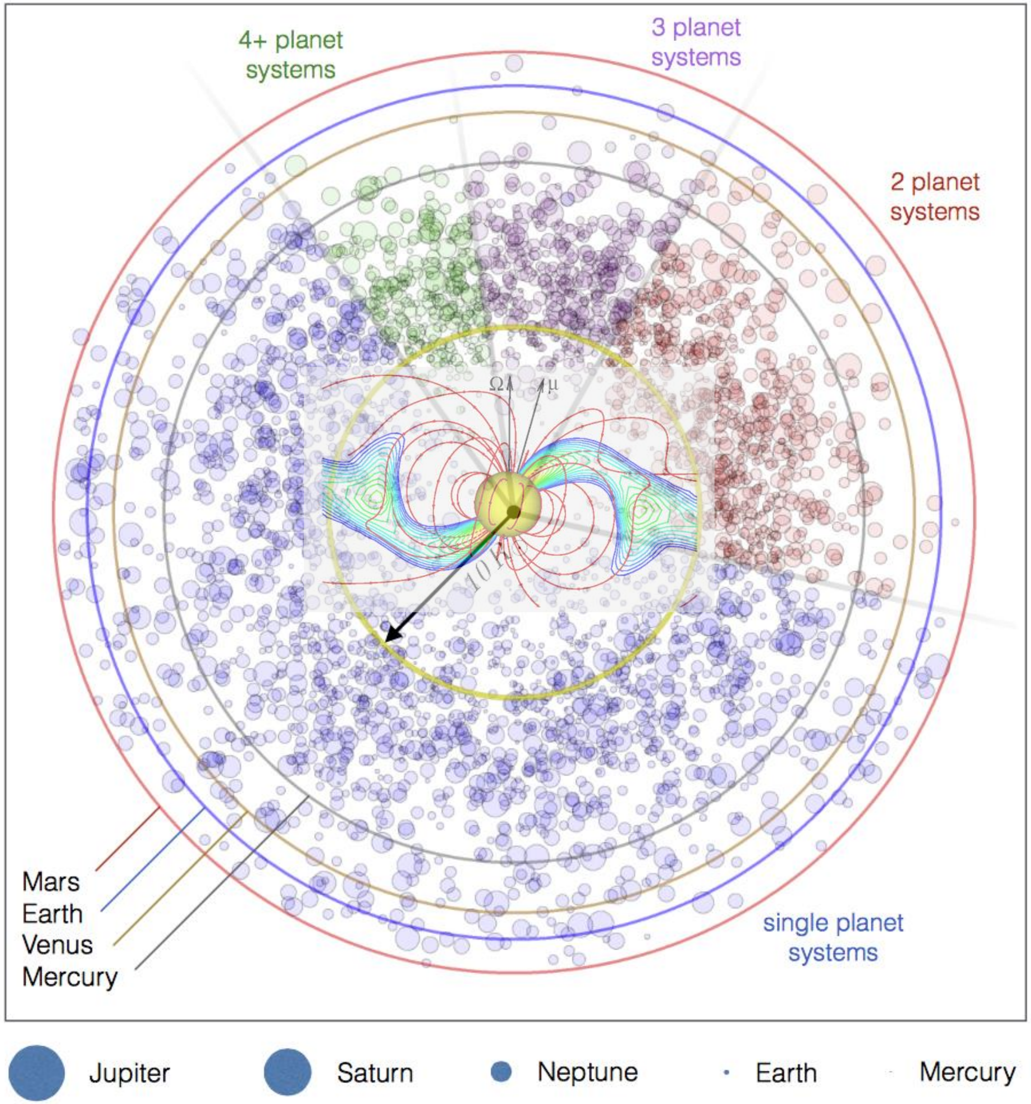
(see also K2-33b in USco, a=0.04 au
David, Hillenbrand, Petigura+16)

Inner planets



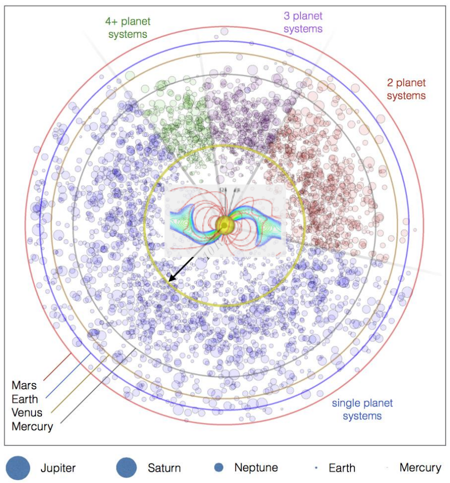
Batigyn & Laughlin 2015

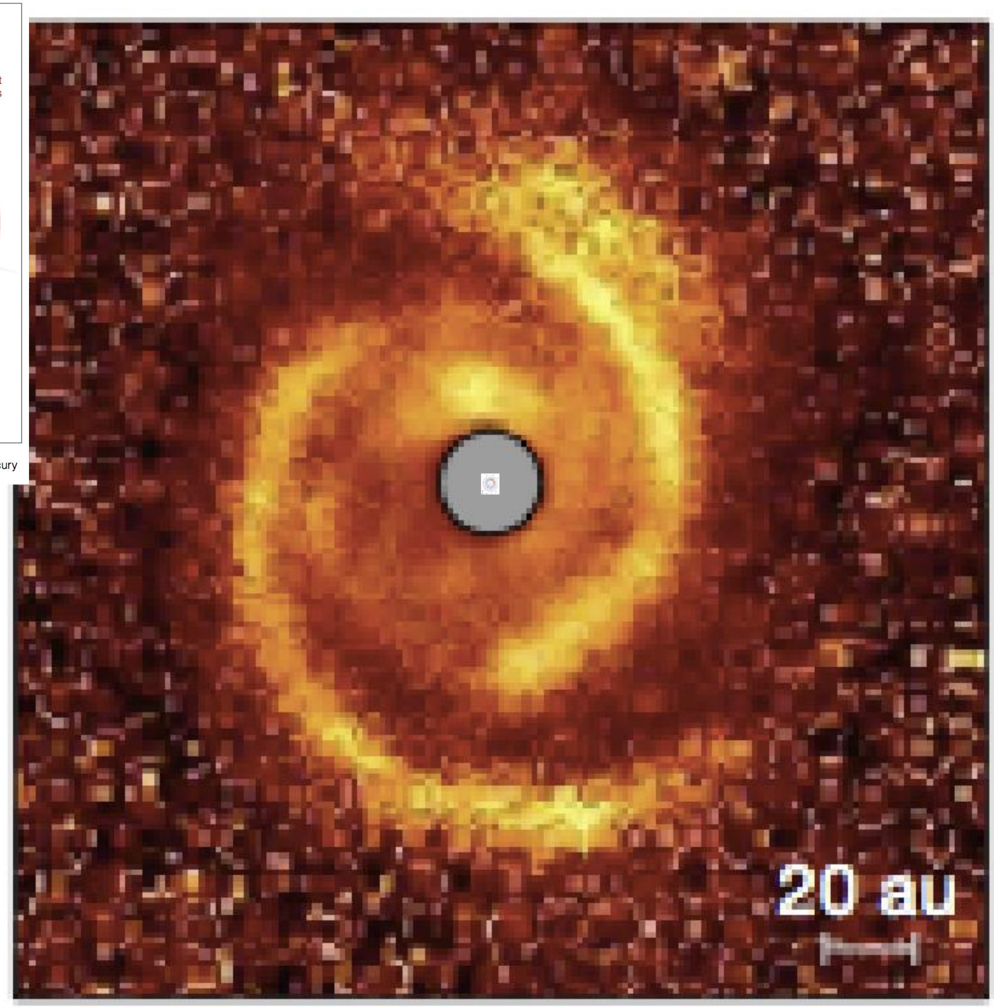
Inner planets



Batigyn & Laughlin 2015
Romanova et al. 2013

Disk-embedded inner planets?





SPIDI: Star-Planets-Inner Disk Interactions

- Search for compact planetary systems embedded in the inner disk
- 3D MHD simulations + radiative transfer to predict the perturbation of the inner disk structure and of the accretion flow.
- Combine various multi-wavelength observational techniques to detect these perturbations, a signature of embedded planets.

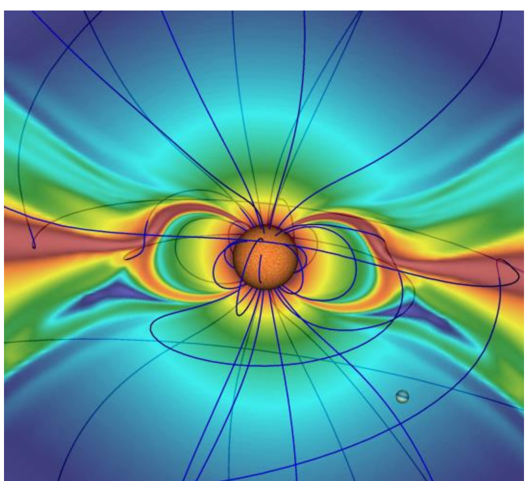
erc European Research Council

SPIDI
star planets
inner disk interactions

3D MHD SPIDI simulations

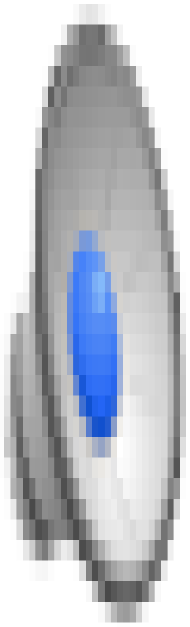
- Work in progress (George Pantolmos, Claudio Zanni)

Next step:

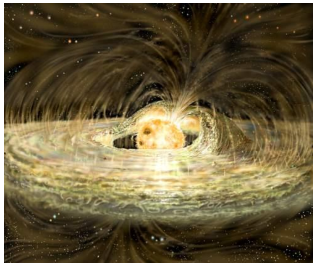


Atomic line radiative transfer

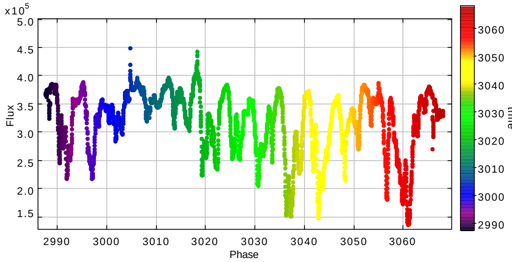
- Work in progress (Benjamin Tessore, Christophe Pinte)
- Develop H, HeI, NaD radiative transfer module in MCFOST

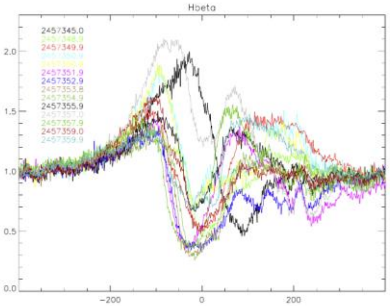


Observing



– Interferometry (VLTI/Gravity, ESO Chili)
– Space photometry (K2, Gaia, TESS, Plato)
– Multi-color ground based photometry
– Optical and infrared HR spectroscopy (ESO VLT/Crires+, ESO HARPS)
– Spectropolarimetry optical and infrared (CFHT Espadons, CFHT Spirou)





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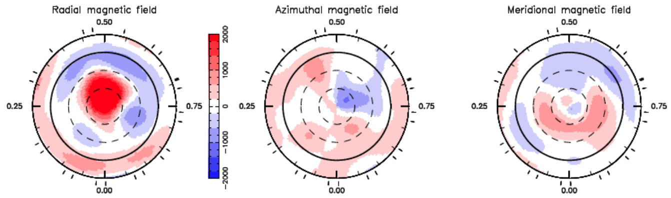
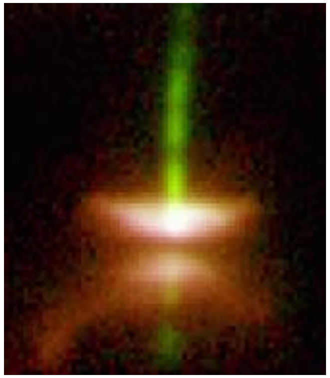
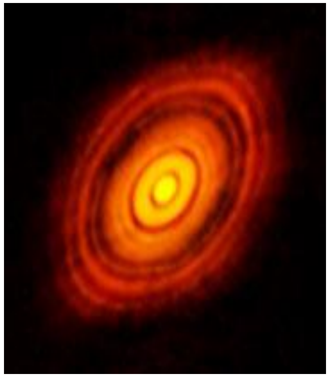
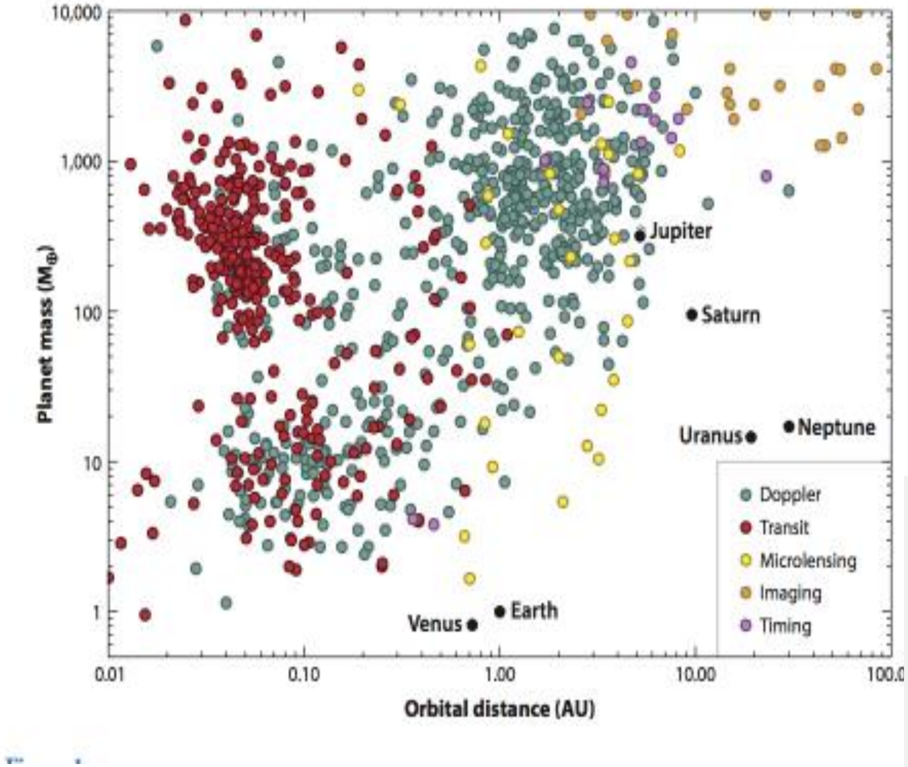
star planets inner disk interactions

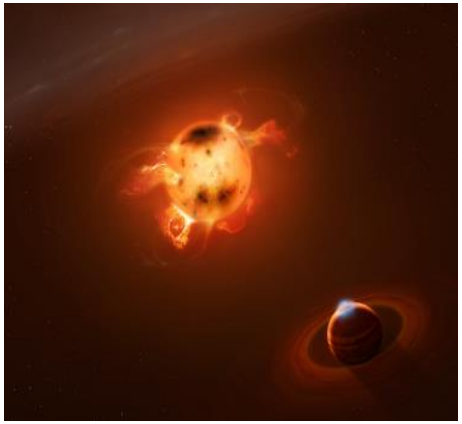


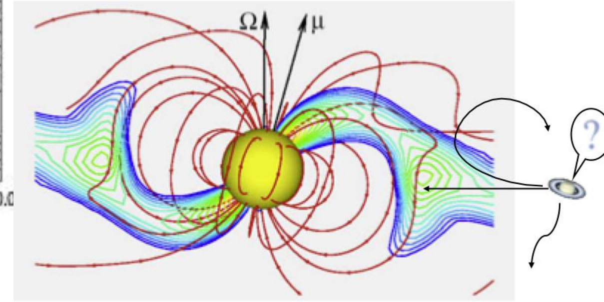
Young Stellar Objects: a star, a disk, and planets.











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?

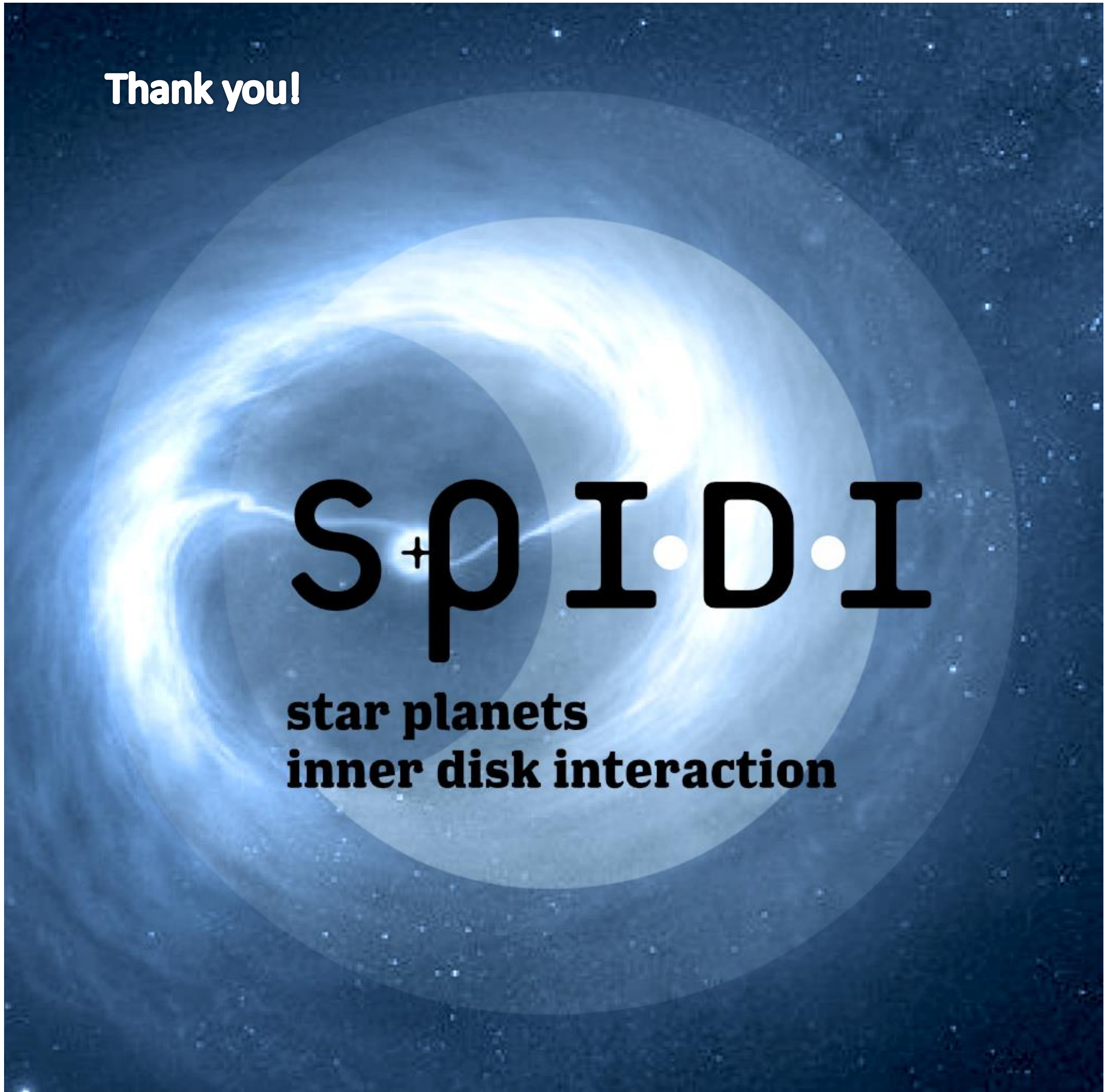
Conclusion

- 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 required to ultimately develop realistic PMS evolution models.
- A new perspective: Earth- and Neptune-like **planets embedded in the inner disk.**

→Next step: **Star-Planets-Inner Disk Interactions (SPIDI)**

(What part of all this also applies to HAeBe stars ?)

http://spidi-eu.org



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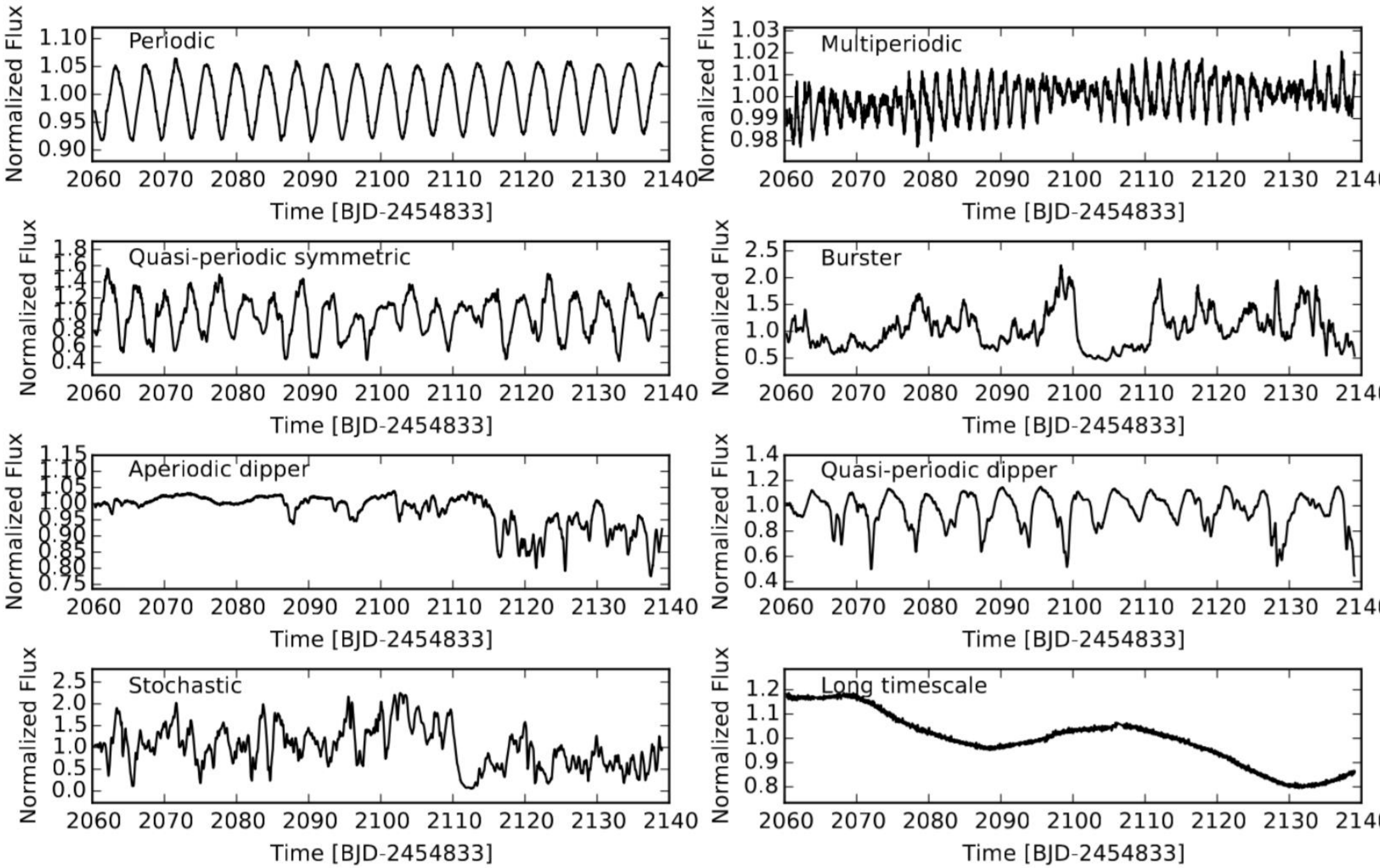
LIGHTCURVE MORPHOLOGY CLASSIFICATION



7% | 5%

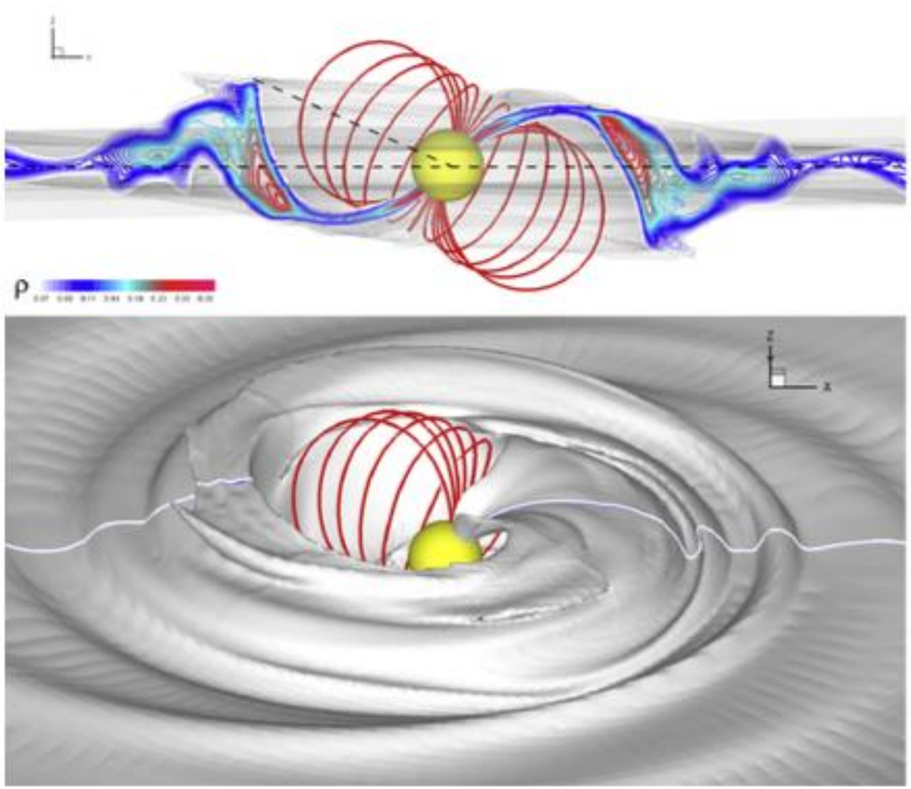
26% | 14%

16% | 17%

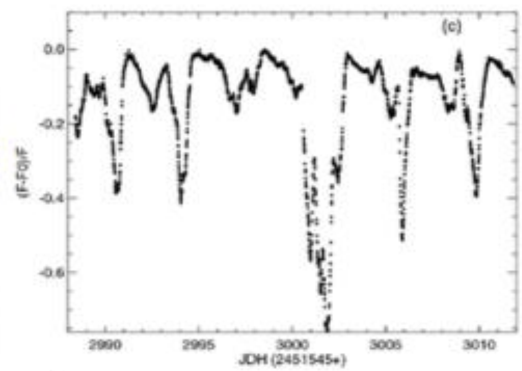
8% | 3%

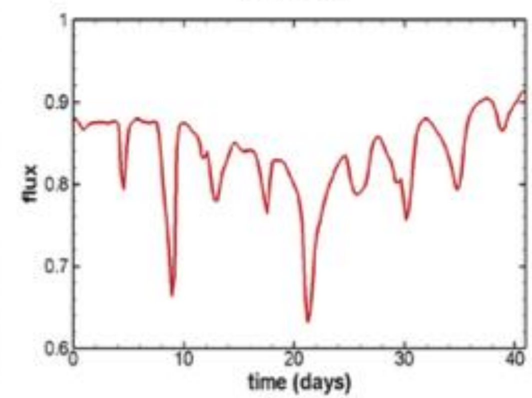
Cody and Hillenbrand (2018)

Photometric modulation



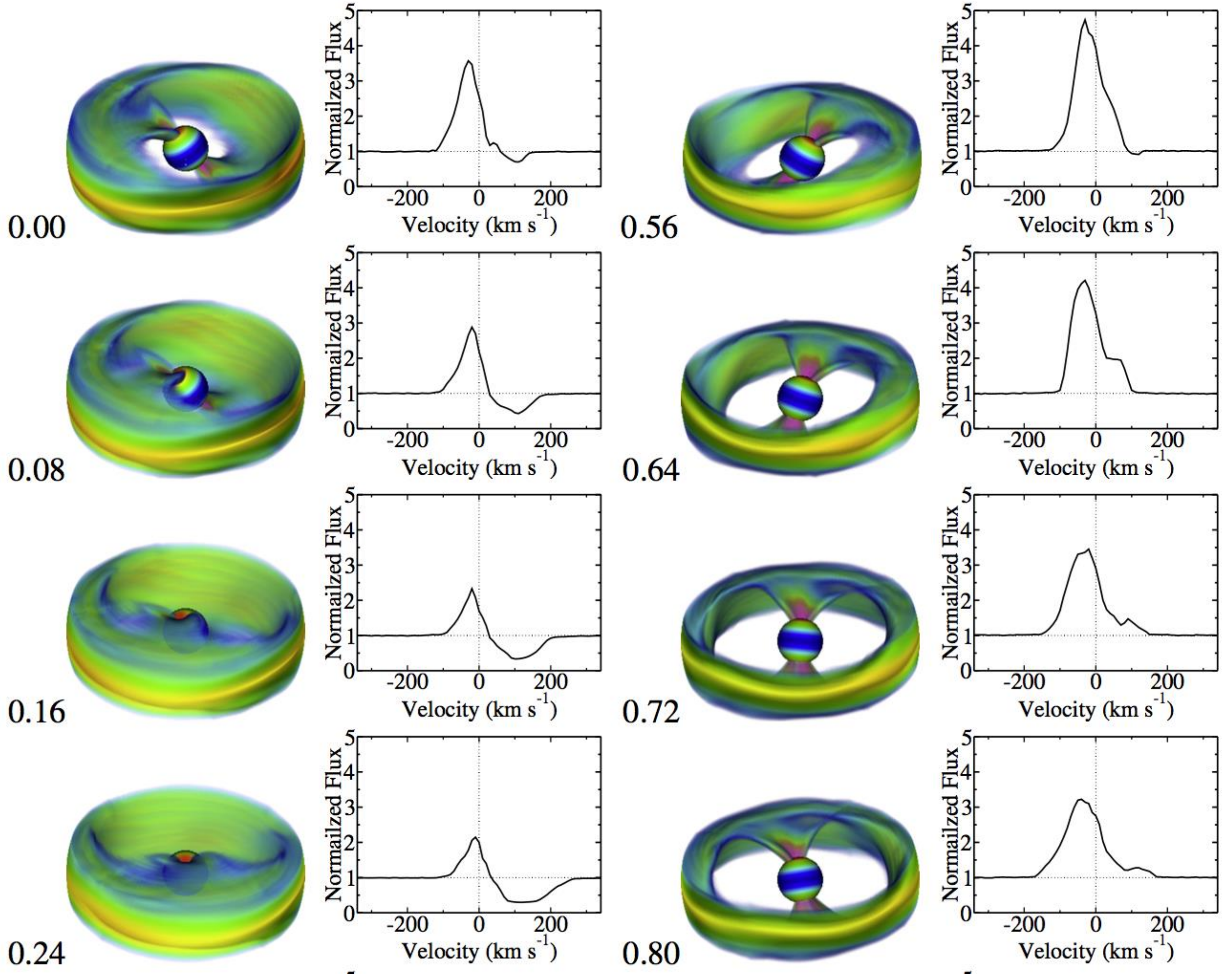
"Dippers"





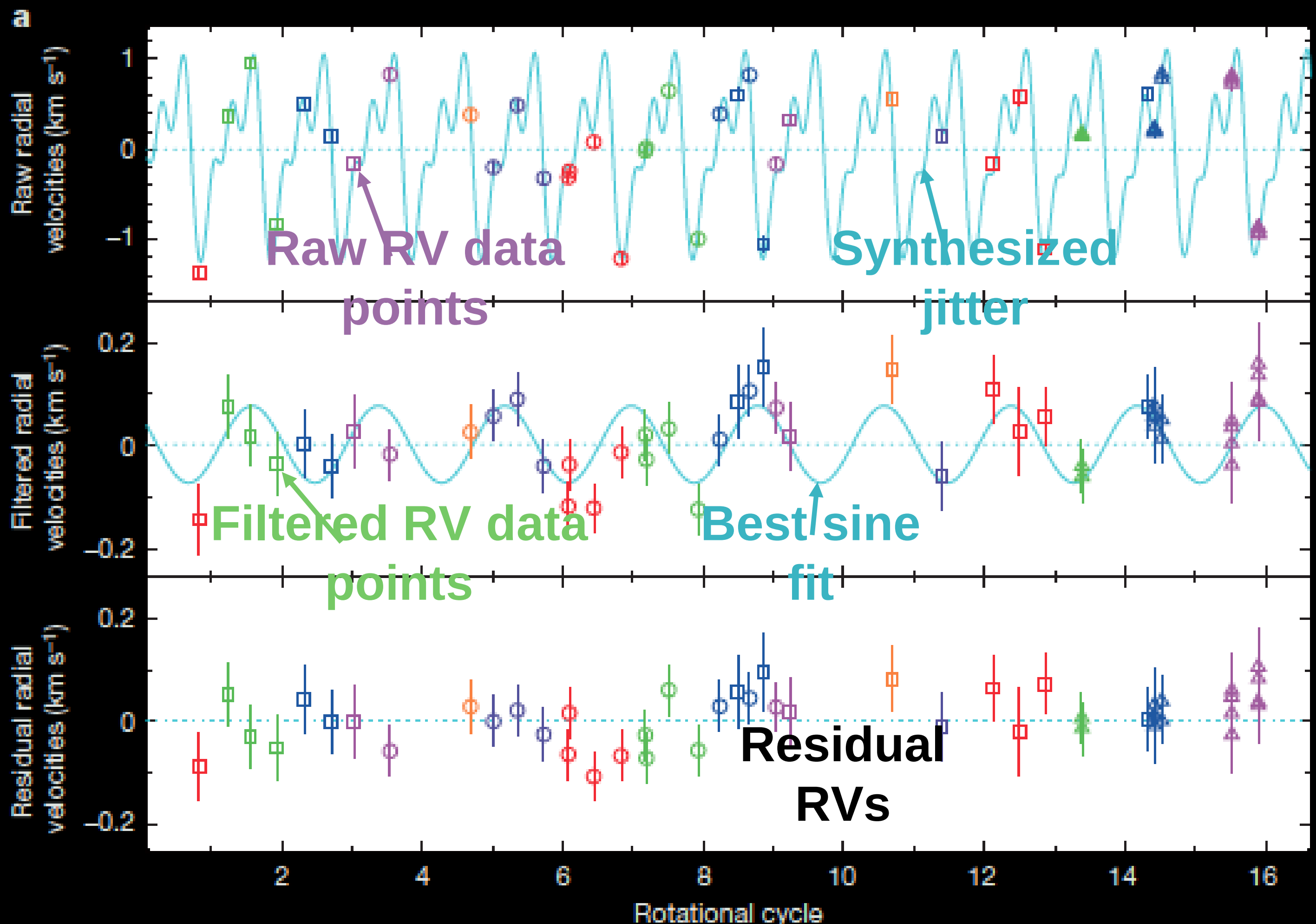
Romanova et al. (2013)

Spectroscopic modulation



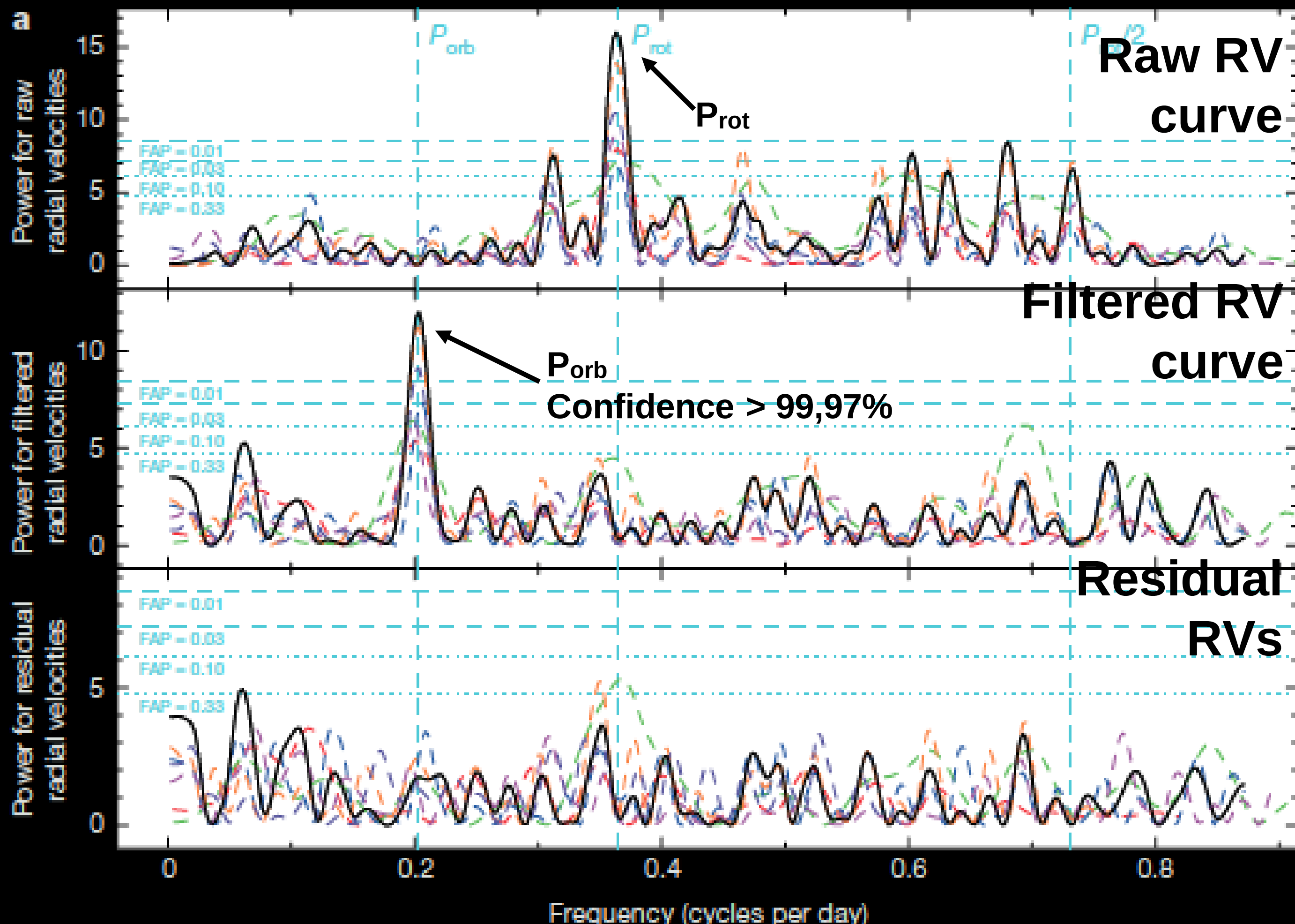
Kurosawa & Romanova 2013

V830 Tau RVs



Donati+16

Periodograms



Donati+16