Ecole Evry Schatzman 2021

Formation et caractérisation des exosytèmes avec SPIRou

Roscoff, 3-8 octobre 2021

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Star formation

an observational perspective

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FAPEMIG

“Star formation spans densities from 10^4 cm^{-3} to 10^{24} cm^{-3}, involves all the known forces of nature, with observational diagnostics across the entire spectrum, and requires experimental access to relevant primitive materials that has no parallel in any other branch of astrophysics.”

Shu et al. (1993)

Outline

- From clouds to star-disk systems
- T Tauri stars
  - ✓ Disks
  - ✓ Magnetospheric accretion models
  - ✓ Stellar magnetic fields
  - ✓ Star-disk interaction
  - ✓ Outflows
  - ✓ Young planets
- Perspectives

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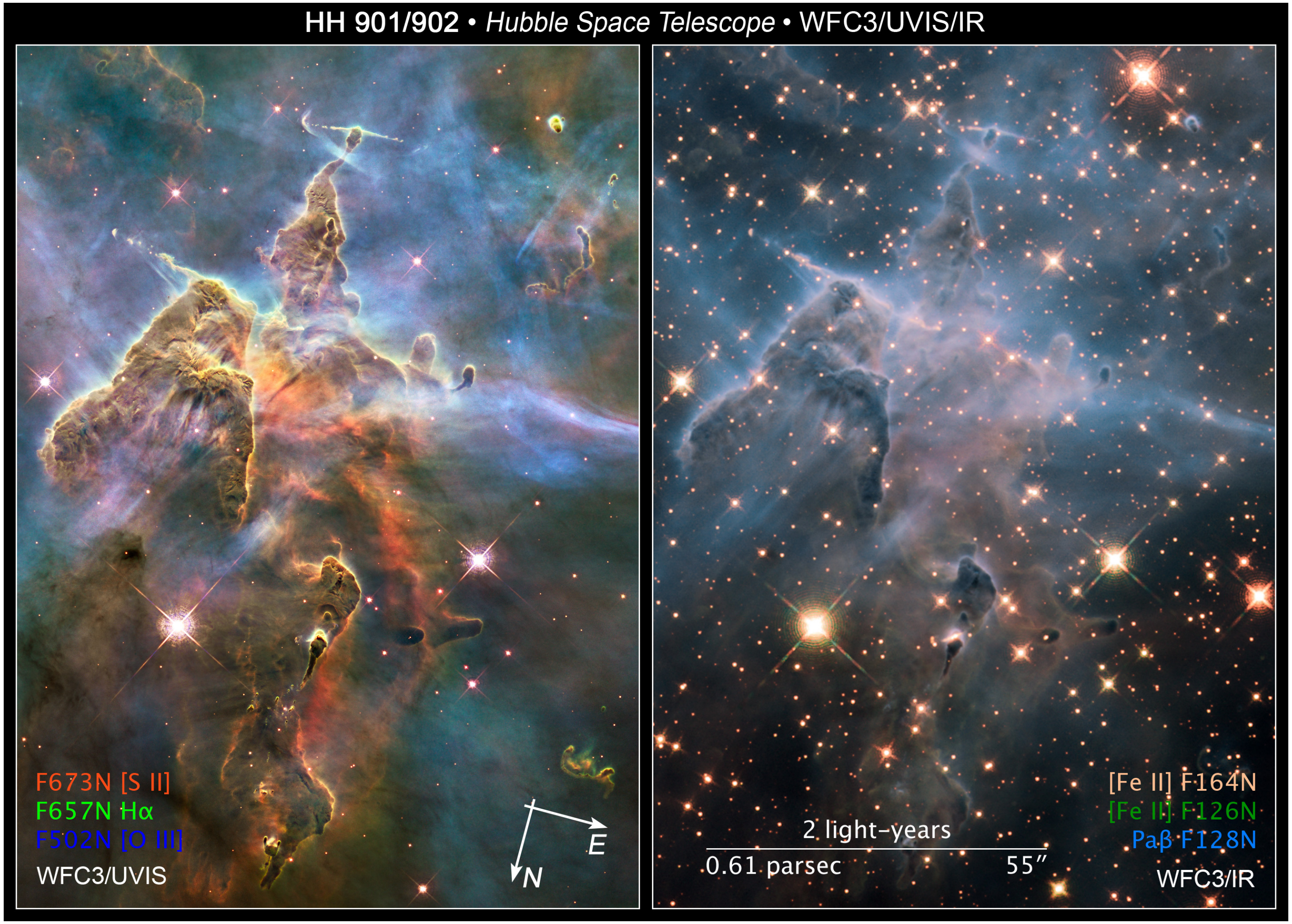
Star formation

Optical

Carina Nebula

Infrared



Hubble Space Telescope

Low mass star formation

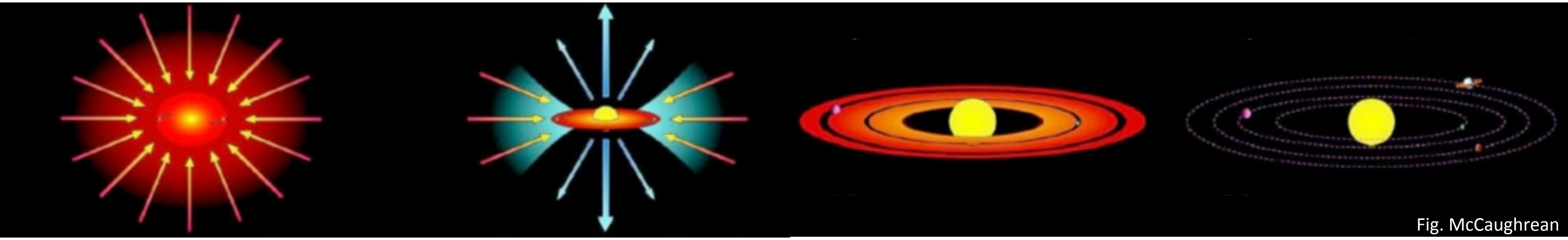


Fig. McCaughrean

10 000 au
$t=0$
Gravitational colapse

500 au
$t=10^5 – 10^6$ years
T Tauri star, disk and outflows

200 au
$t=10^6 – 10^7$ years
Post-T Tauri, evolved disk

100 au
$t > 10^7$ years
Star and planetary system

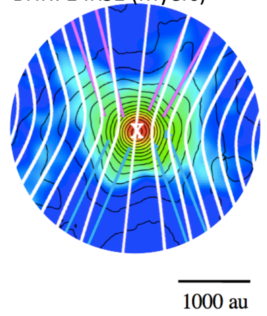
0.1 pc ~ 10 000 au = 1.5e15 m → $1\ R_\odot = 6.96\text{e}8$ m

6 orders of magnitude in size

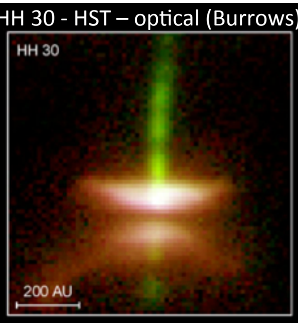
Angular momentum problem

Observations

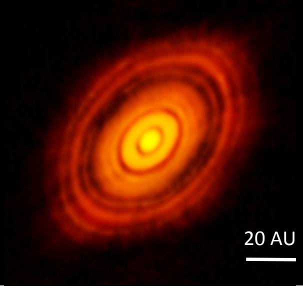
BHR71 IRS1 (Myers)



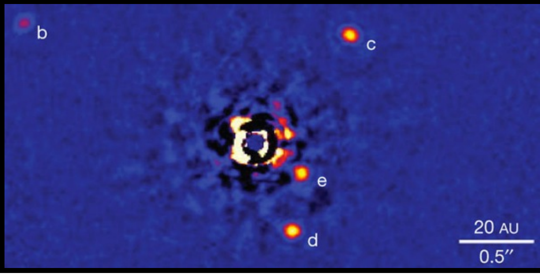
HH 30 - HST – optical (Burrows)



HL Tau – ALMA – 1.3 mm



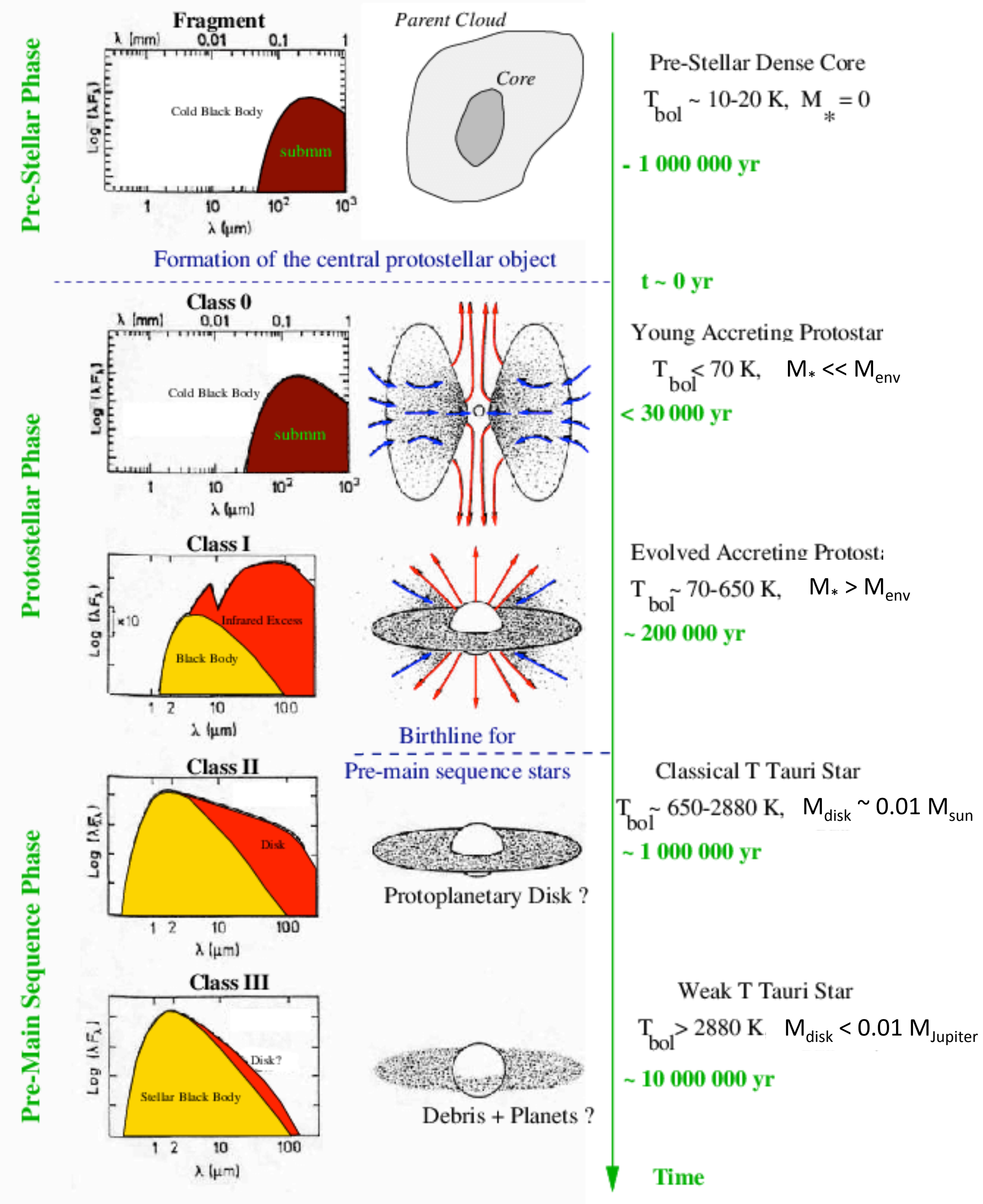
HR 8799 – Keck nIR (Marois)



Young star+disk classification

Lada (1987), André (2002)

Spectral Energy Distribution (SED)



Class 0

Class I

Class II

CTTS

Classical T Tauri star

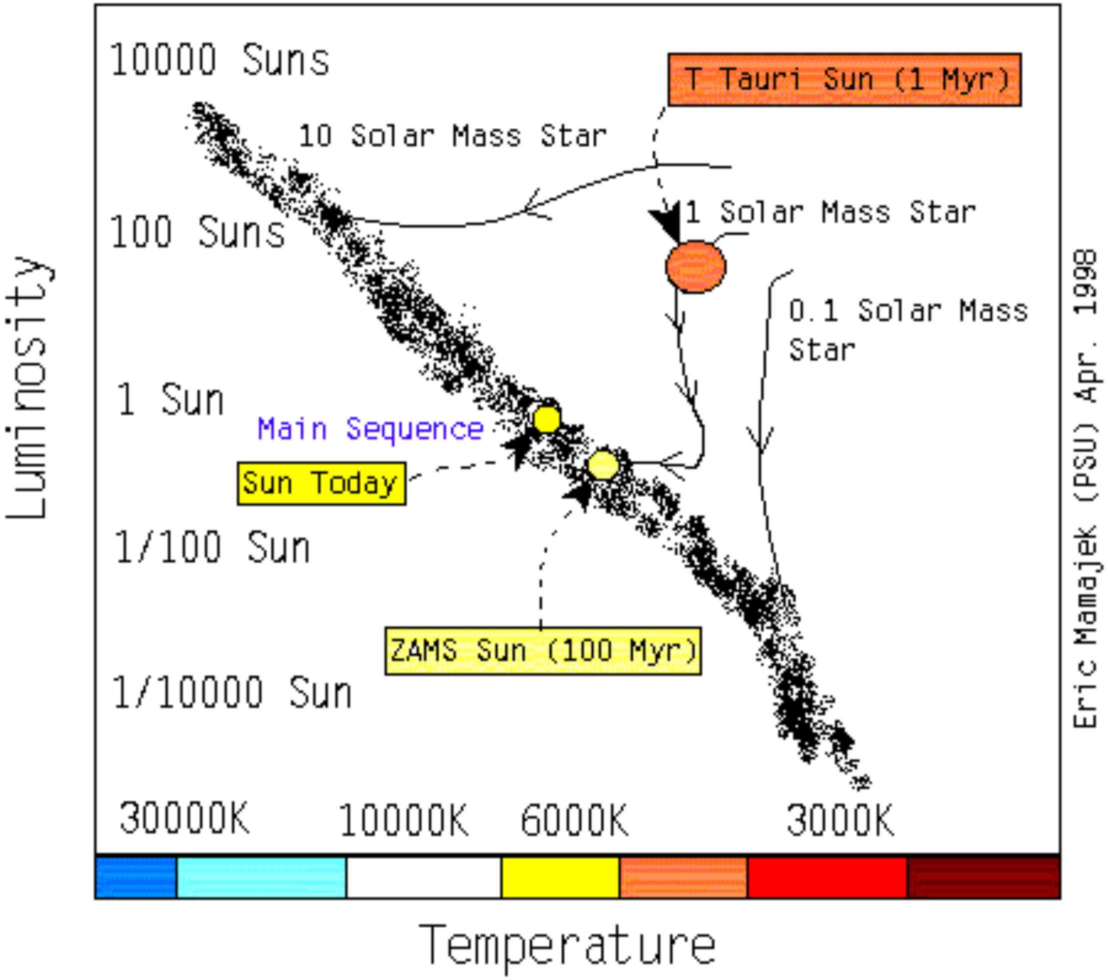
Class III

WTTS

Weak-lined T Tauri star

Hertzprung-Russell Diagram

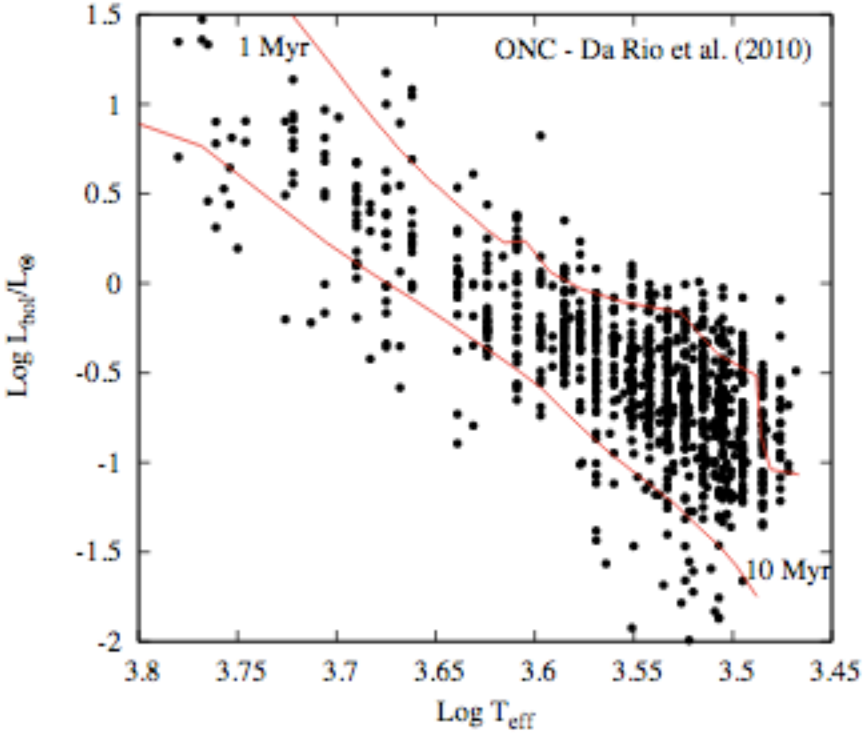
Pre-main Sequence

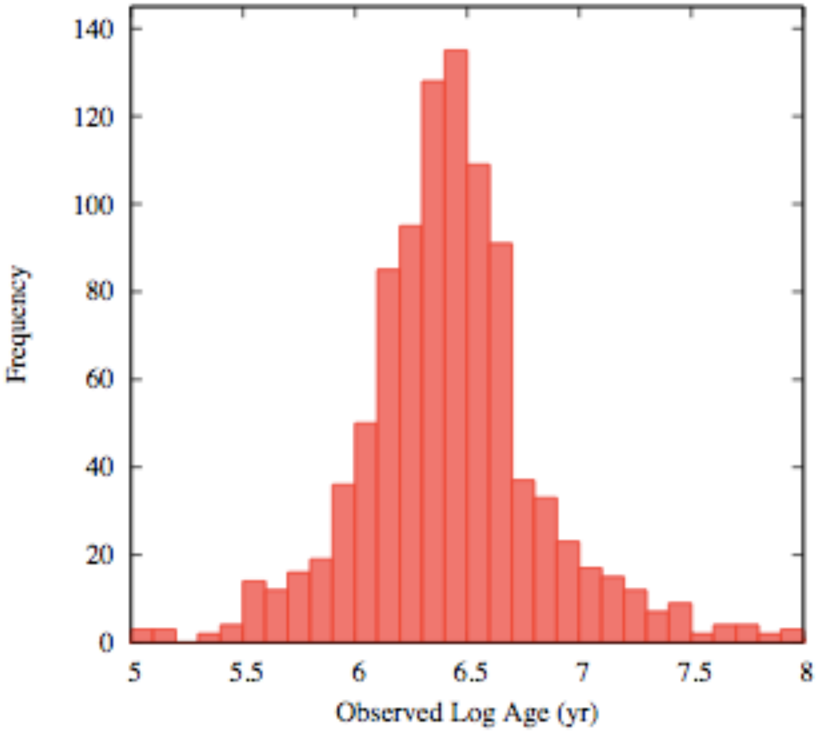


Large luminosity spreads in the HR diagram of young clusters

Translate to age spreads, but are they real?

Spots, accretion, accretion history, circumstellar disk inclination, binaries, accurate distances and reddening will influence the stellar luminosity





Soderblom et al. (2014)

PMS ages may be uncertain at the 20% to 200% level

Large luminosity spreads in the HR diagram of young clusters

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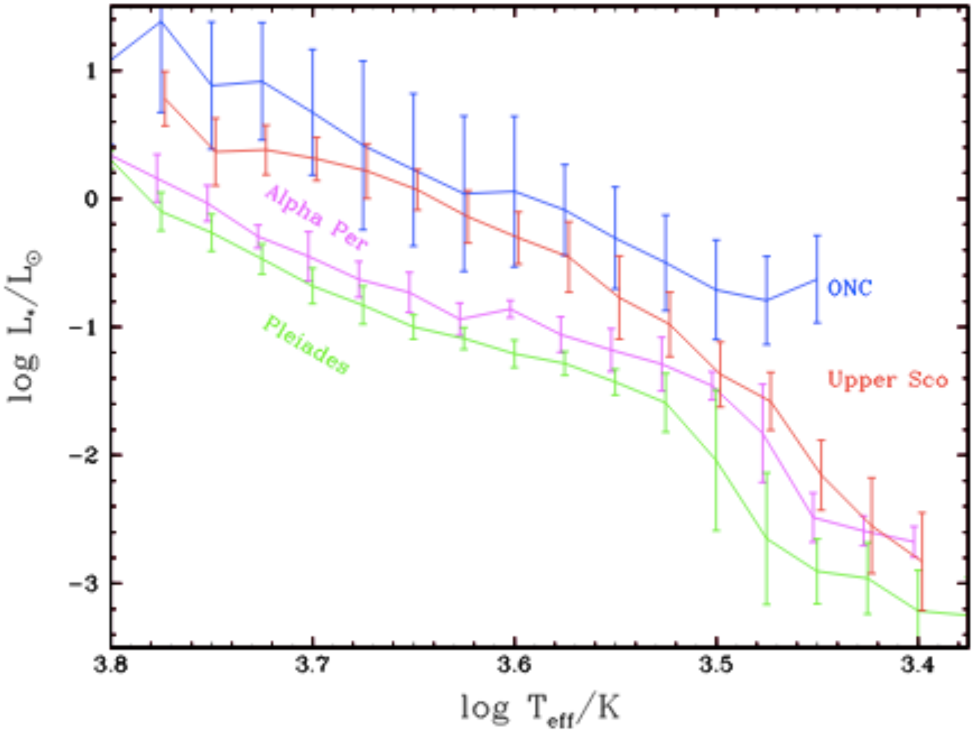


Soderblom et al. (2014)

PMS ages may be uncertain at the 20% to 200% level

The Jeans mass

Critical mass above which gravity dominates

Considering only gravitational and kinetic energy

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2} \rightarrow M_J = 10M_{Sun}\left(\frac{T}{10K}\right)^{3/2}\left(\frac{\rho}{10^4\,cm^{-3}}\right)^{-1/2}$$

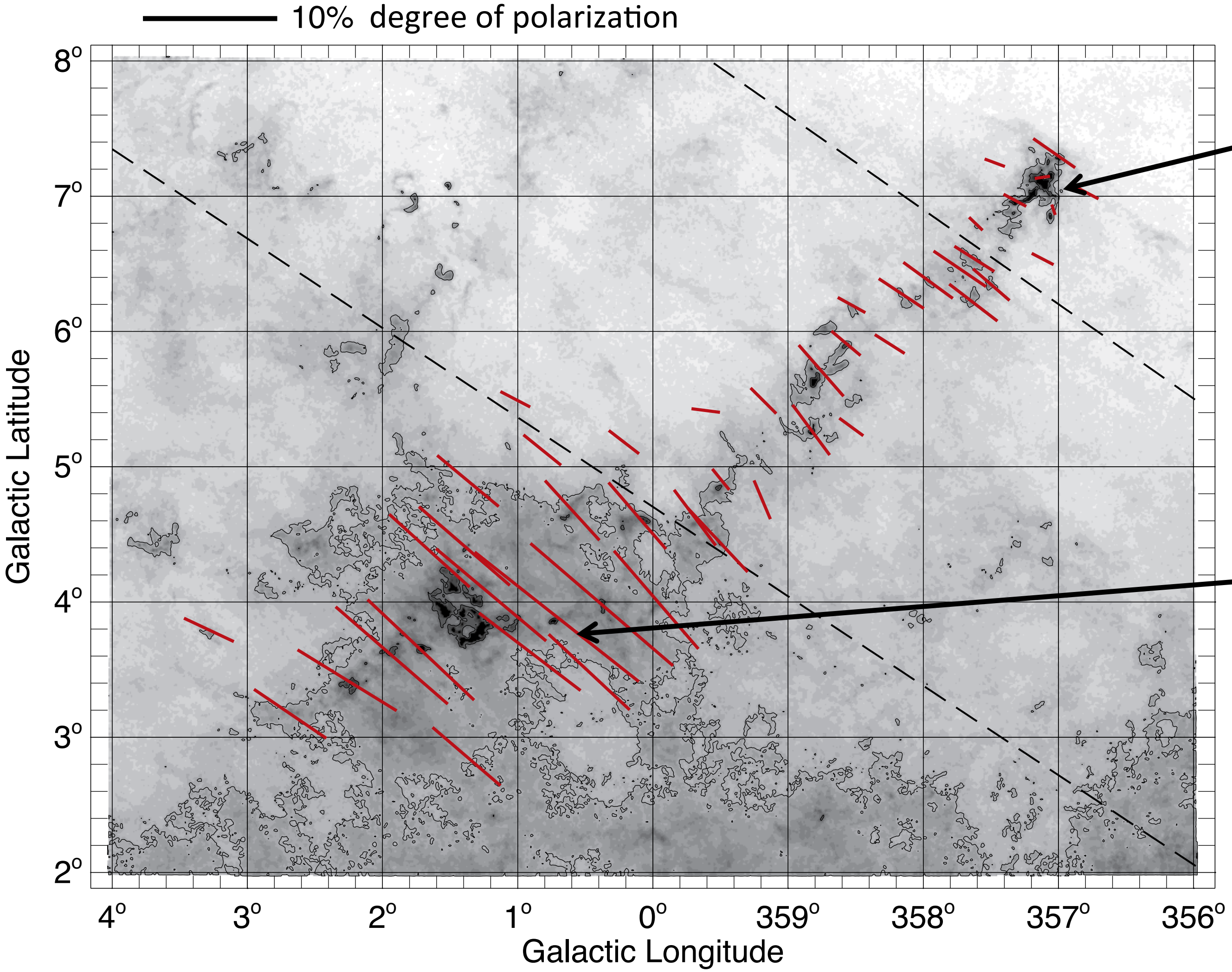
If $M_{cloud} > M_J$, the cloud collapses

Taking magnetic support into account

$$M_{cr} = 0.12\frac{\Phi_M}{G^{1/2}} \sim 10^3 M_{Sun}\left(\frac{B}{30\mu G}\right)\left(\frac{R}{2pc}\right)^2$$

If $M_{cloud} > M_{cr}$, the cloud collapses

Pipe nebula



Star formation

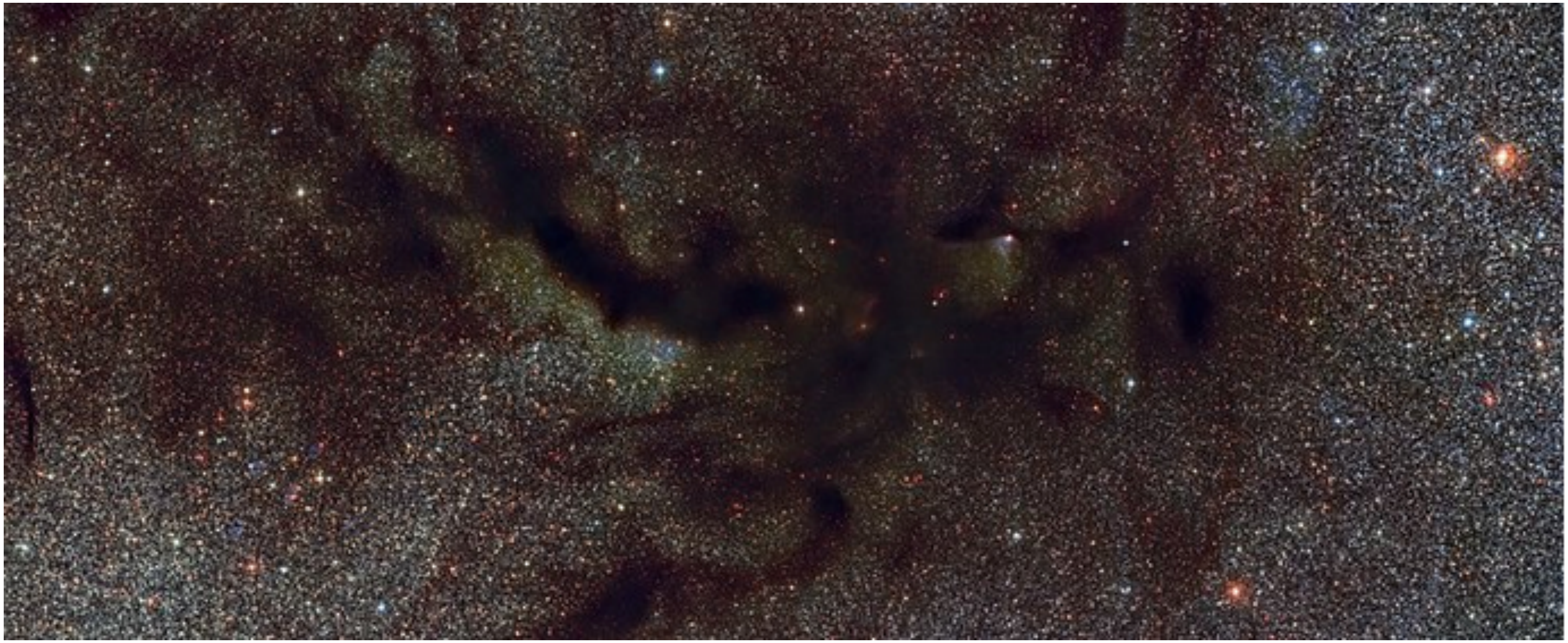
No star formation

Franco et al. (2010)

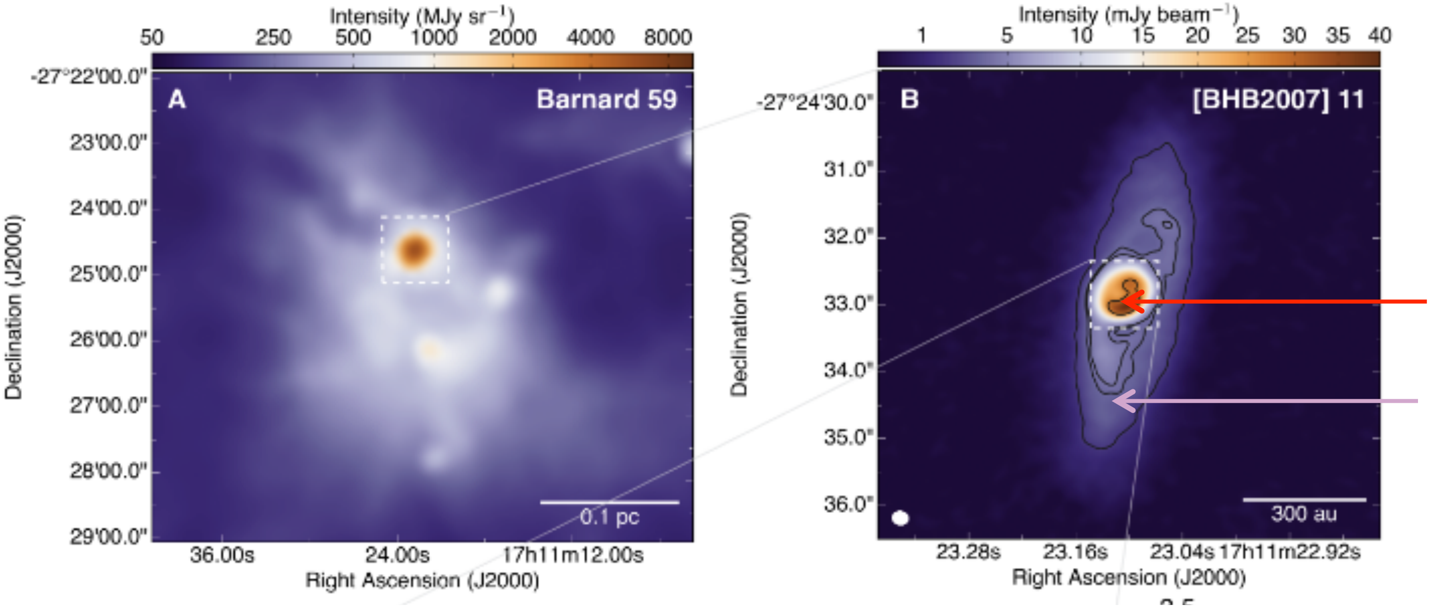
Dust extinction map by Lombardi et al. (2006)

Pipe nebula

Barnard 59 - Wide Field Imager, MPG/ESO



250 µm
Herschel



1.3mm
ALMA

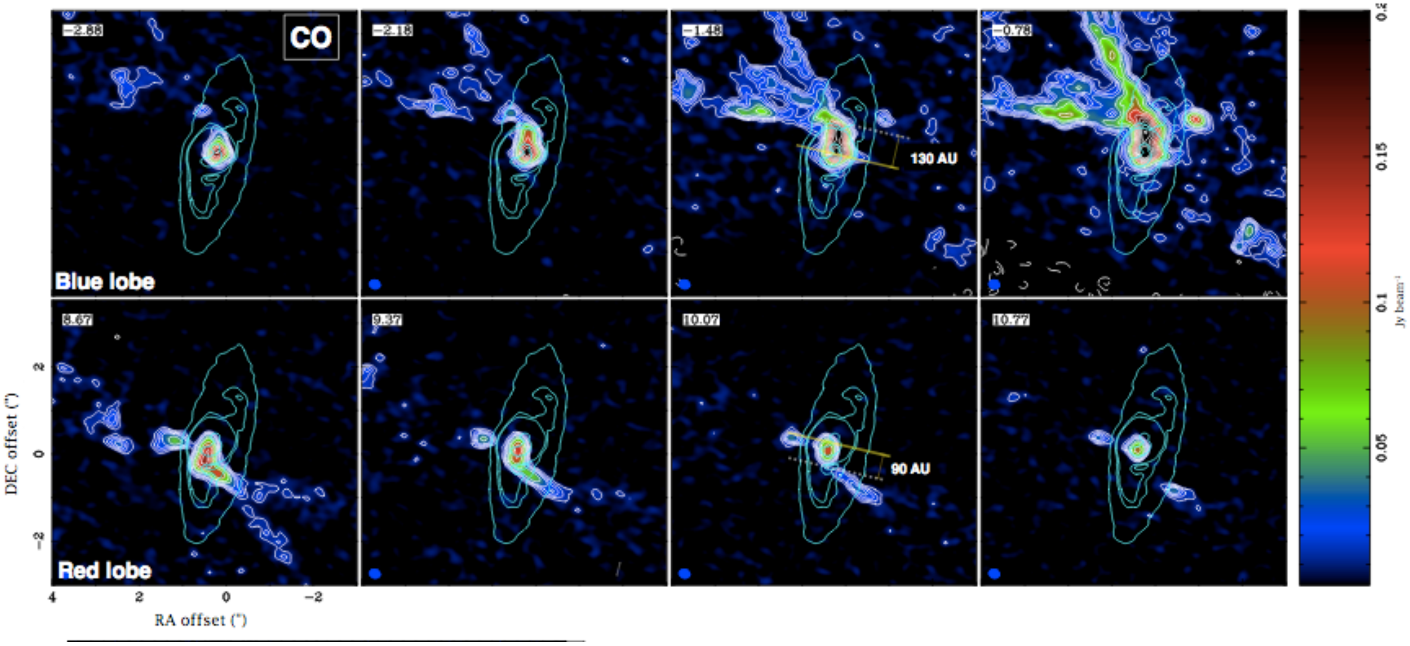
disk

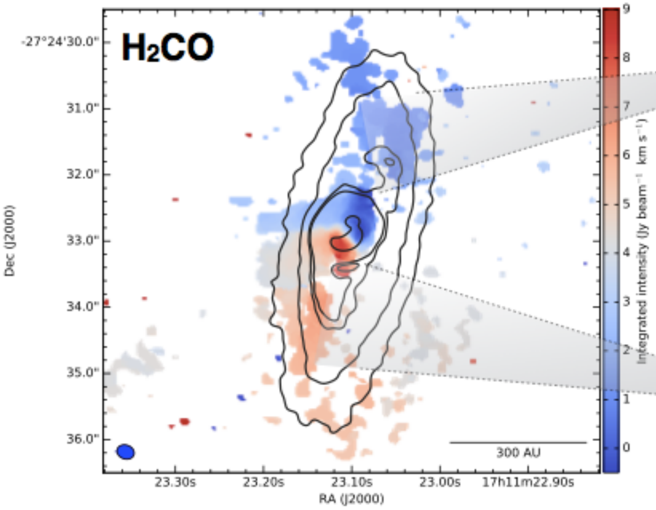
flattened
envelope

[BHB2007] 11, class 0/I object

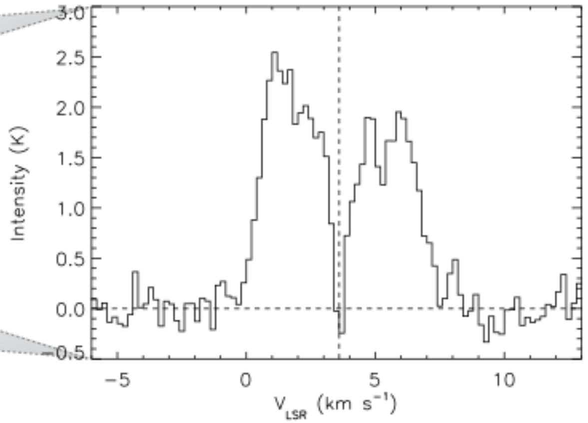
Alves et al. (2017)
Alves et al. (2019)

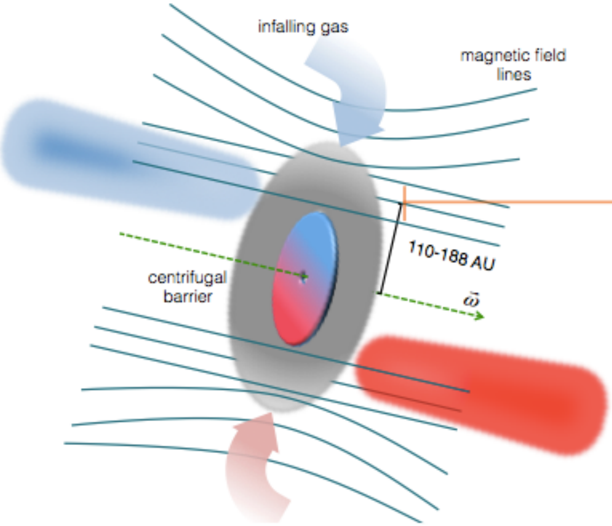
Conical outflow
from the outer
edge of the disk

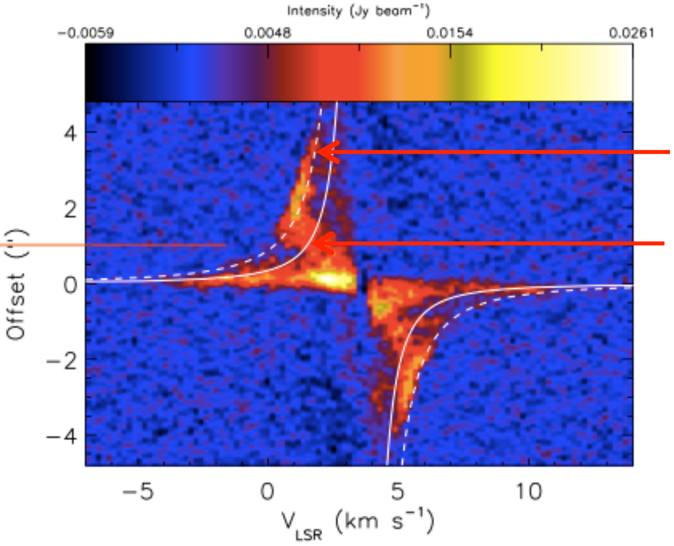




Infall motion profile







Infalling envelope

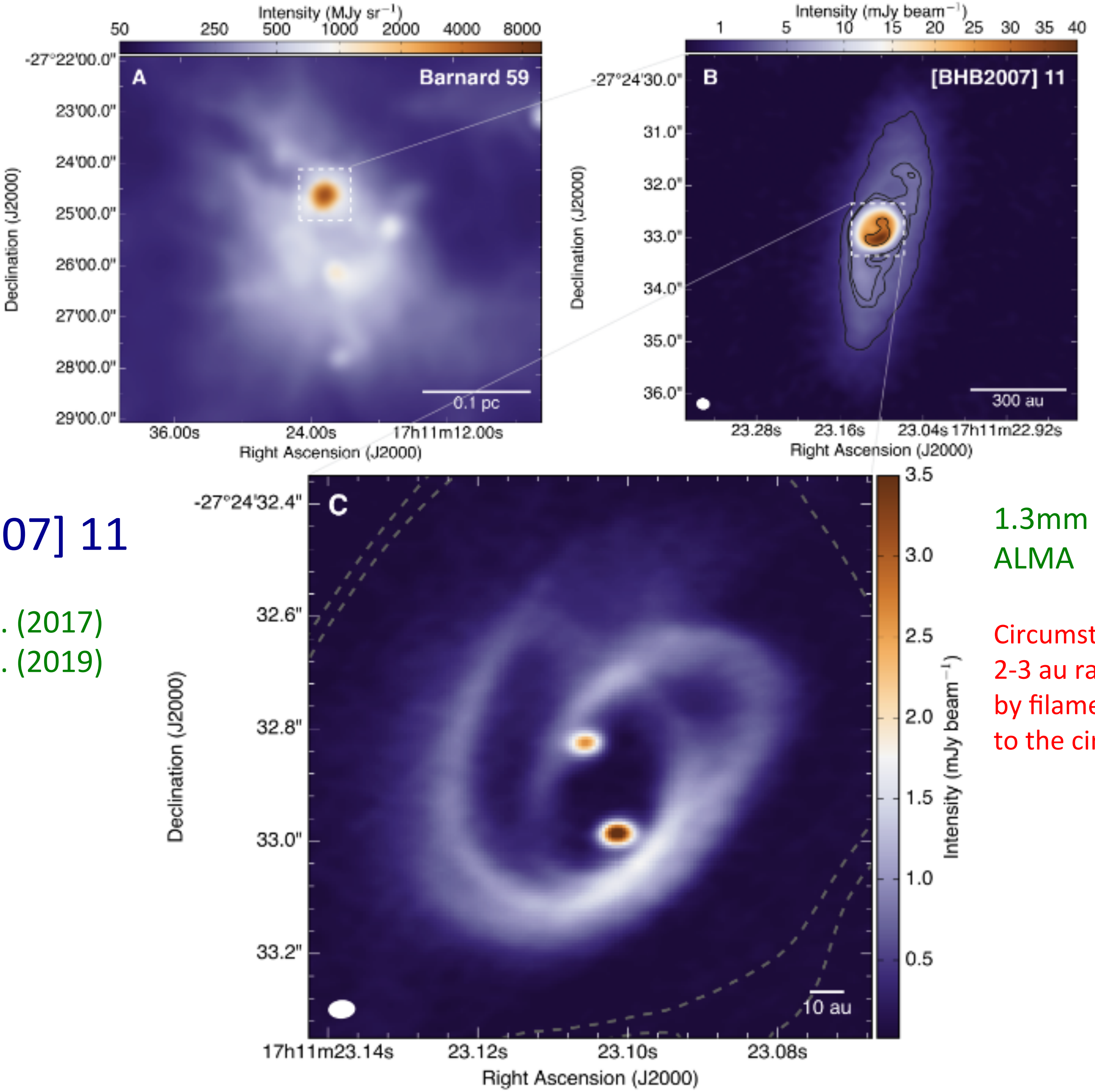
Keplerian fit to the disk

Position-velocity diagram from a cut along the source long axis

ALMA - Alves et al. (2017)

[BHB2007] 11

Alves et al. (2017)
Alves et al. (2019)



250 µm
Herschel

1.3mm
ALMA

1.3mm
ALMA

Circumstellar disks with 2-3 au radii surrounded by filaments connecting to the circumbinary disk.

MHD simulations of star formation

Starforge project

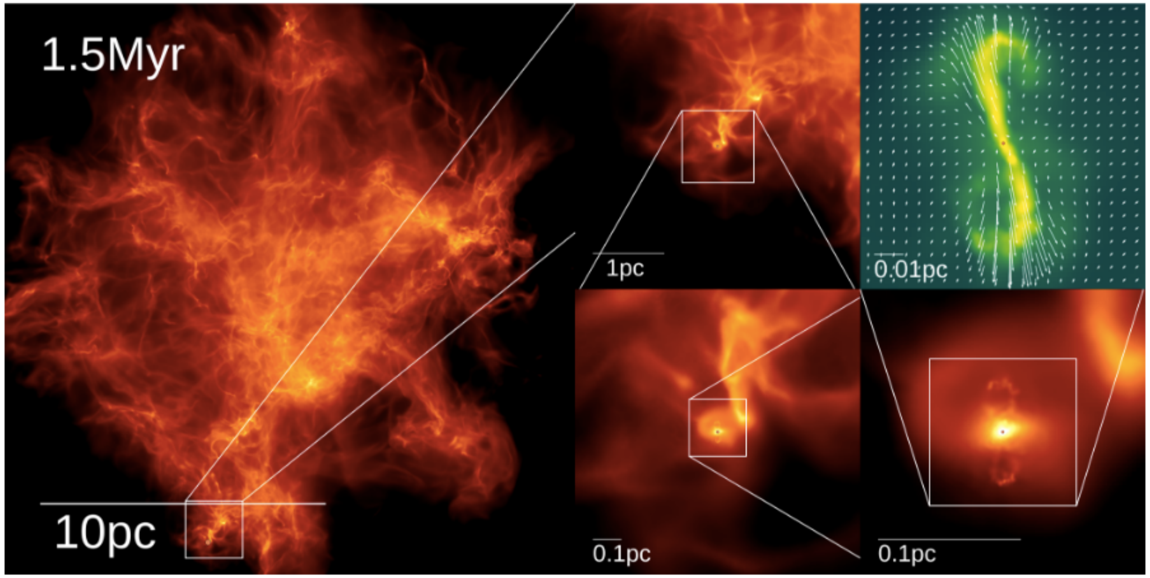
Simulates the evolution of a massive Giant Molecular Cloud (20,000 $M_\odot$)

Includes feedback effects from protostellar jets, stellar winds and core-collapse supernovae

High enough resolution to follow the formation of an individual star

Grudic et al. (2021)
Guszejnov et al. (2021)

https://starforge.space/



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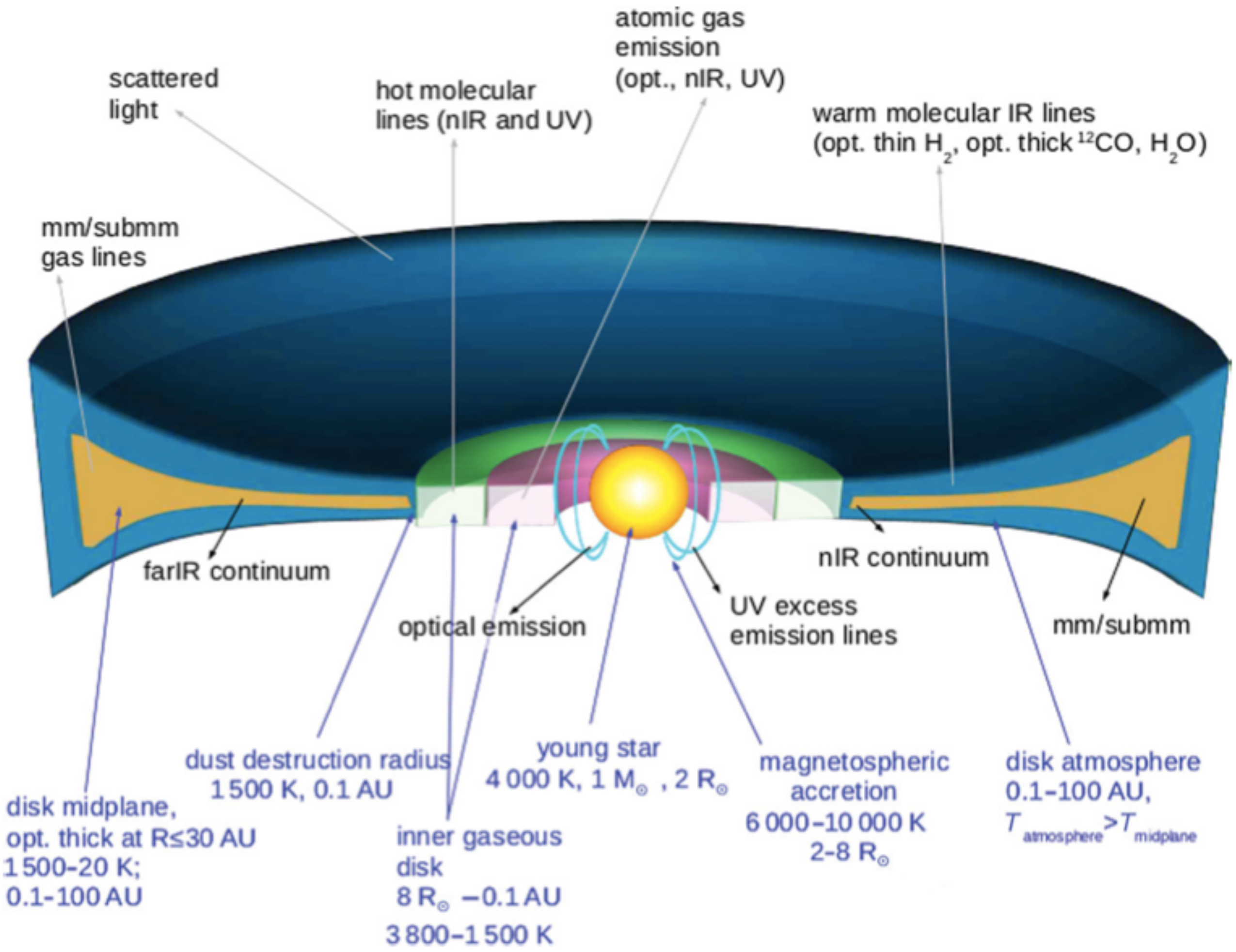
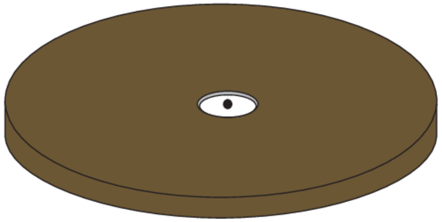
Classical T Tauri star's disk



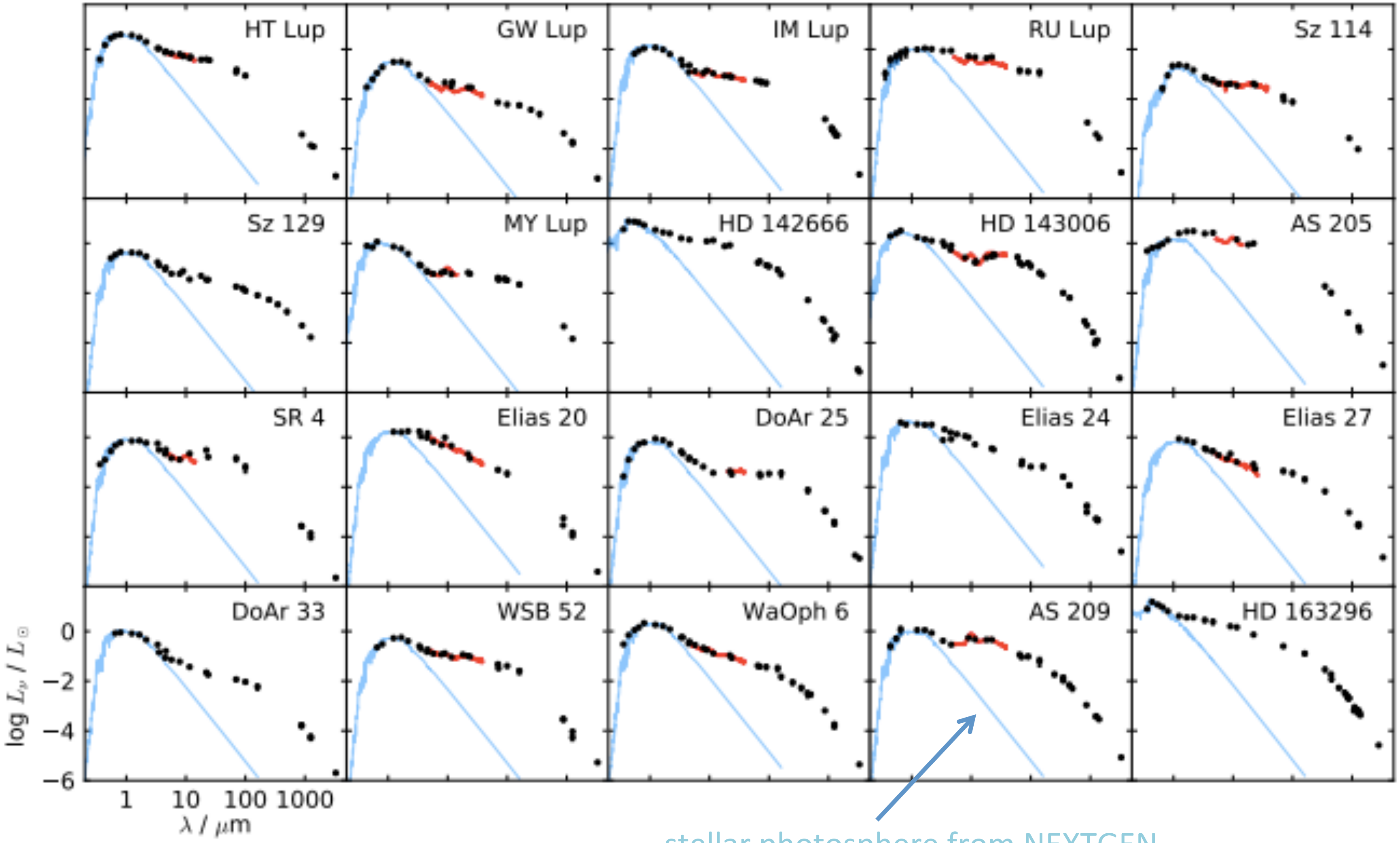
Sicilia-Aguilar et al. (2016)

DSHARP Project - full disks

Andrews et al. (2019)

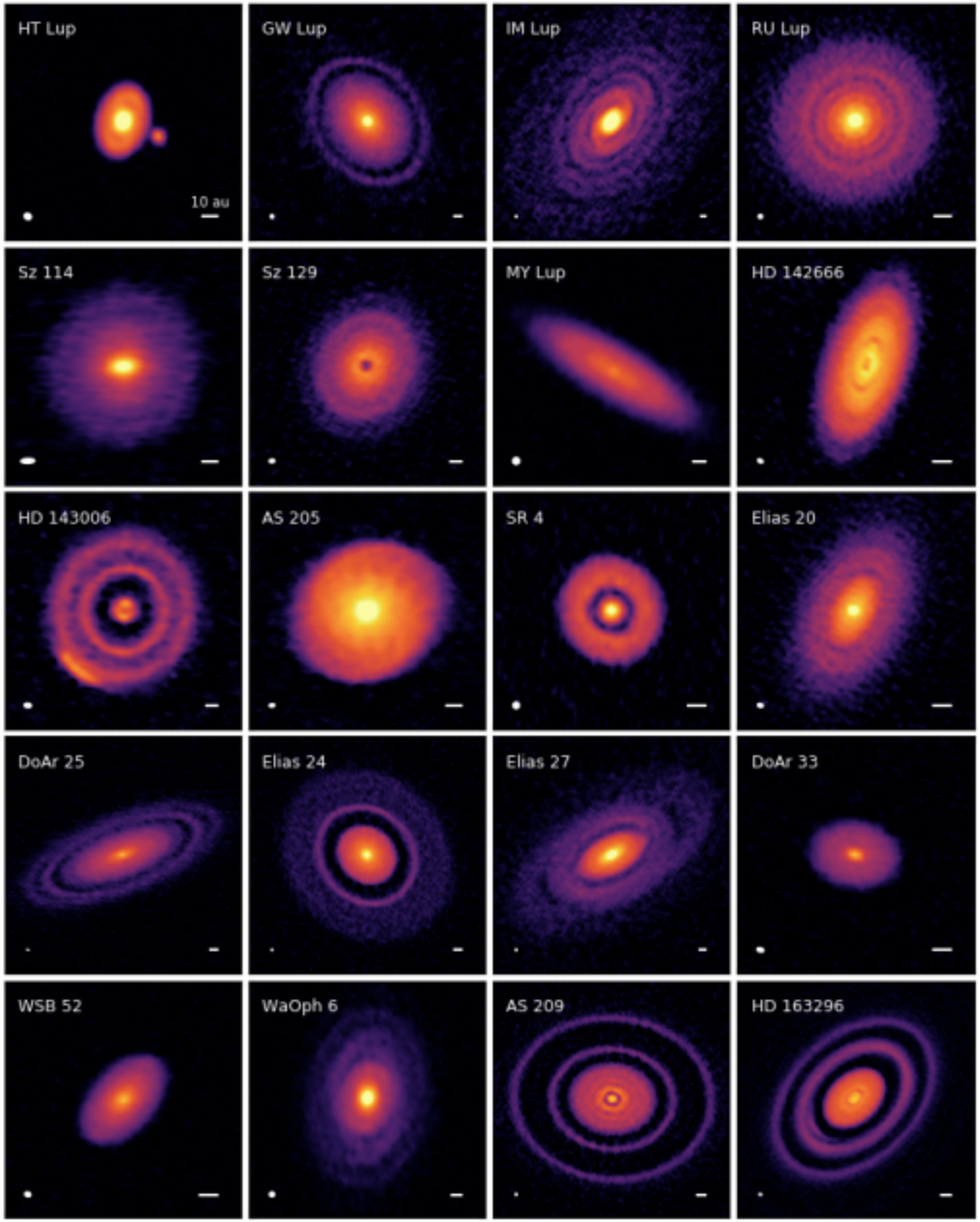


Initially, only SEDs



stellar photosphere from NEXTGEN

(Allard et al. 2003, 2011)



DSHARP Project

Andrews et al. (2019)

ALMA 1.25 mm continuum emission

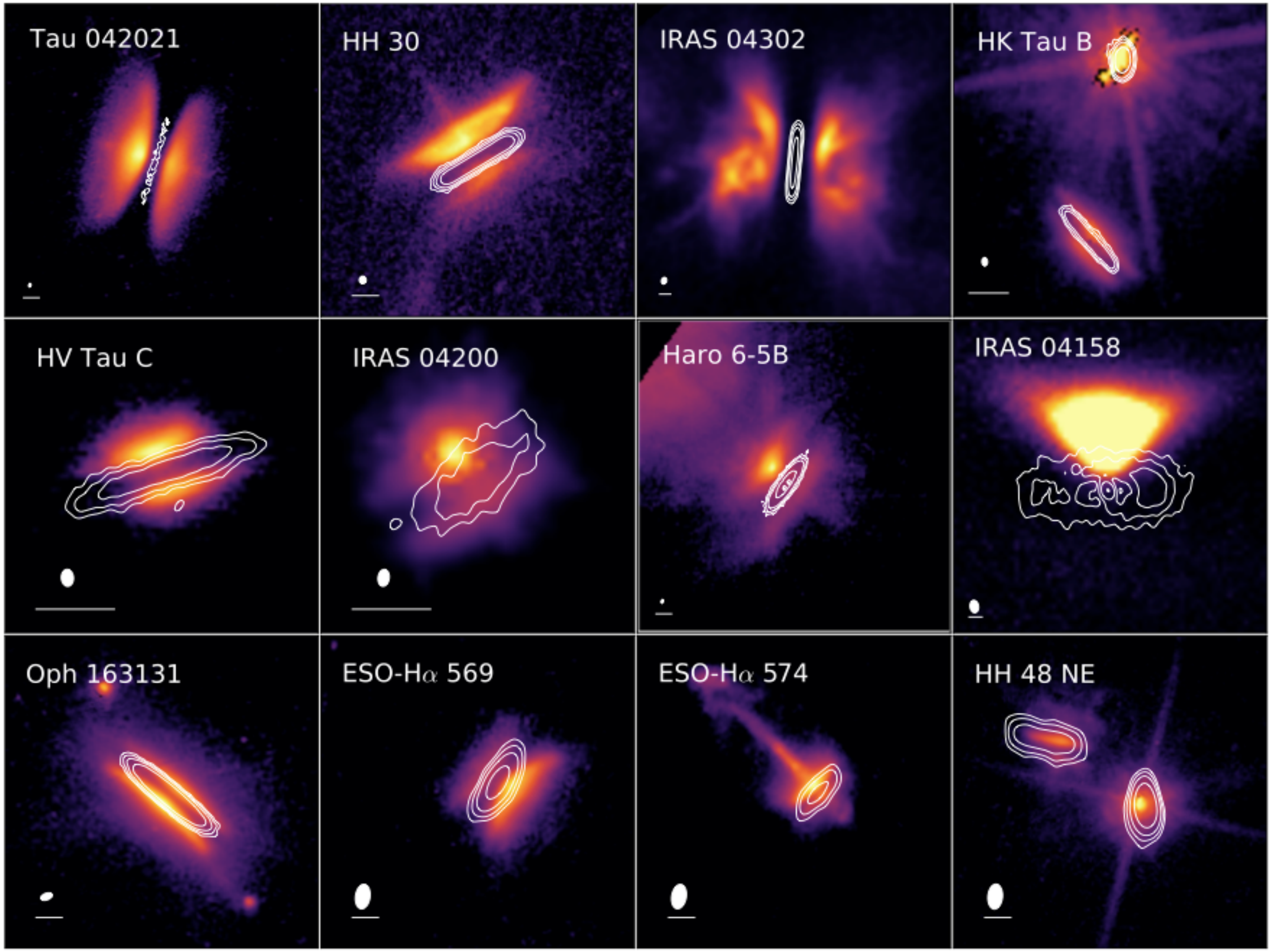
10 au scalebars

Probes the large scale

Probes large dust in the disk midplane

“Full disks” have gaps and rings

Edge-on protoplanetary disks



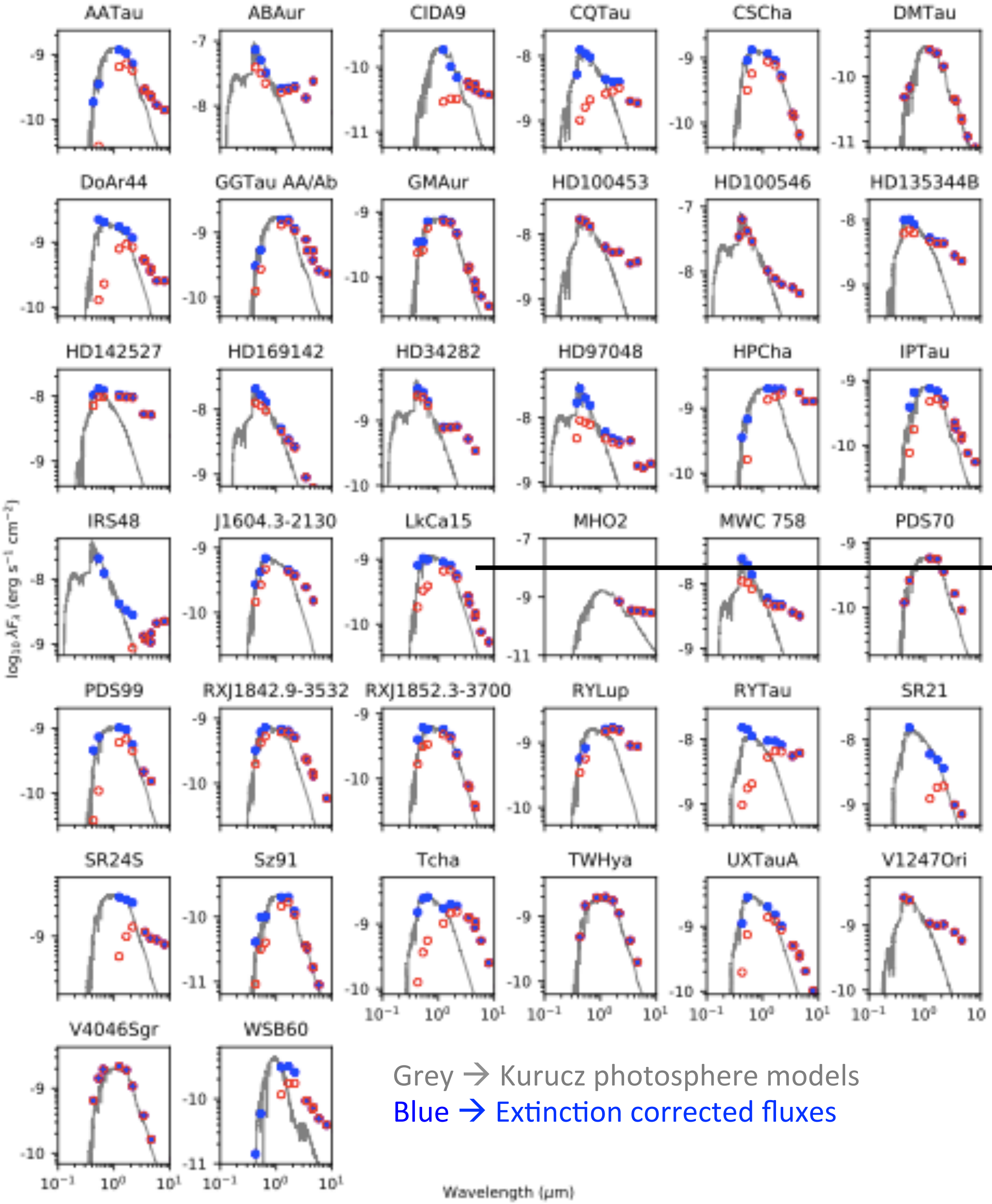
Villenave et al. (2020)

Scattered light, nIR, HST (colors)
Continuum emission, mm, ALMA (white)

Transition disks

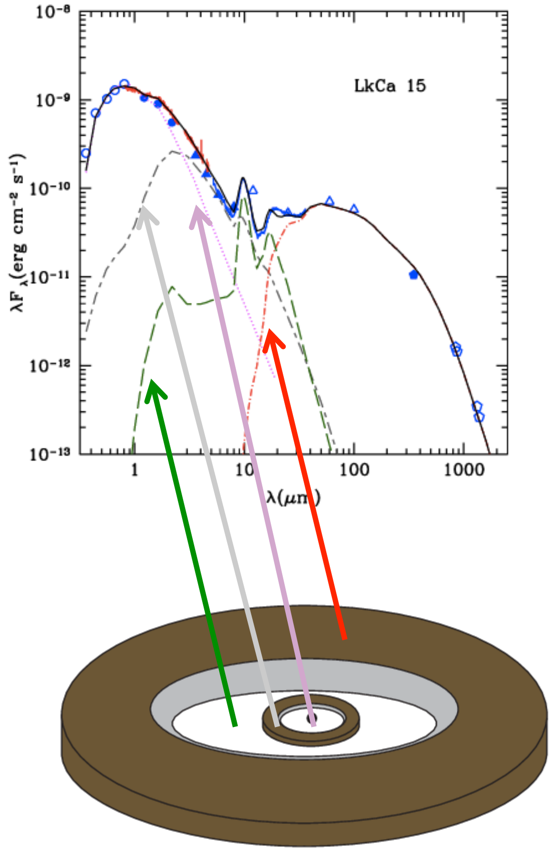
Francis & van der Marel (2020)

CTTS, accreting systems



Grey → Kurucz photosphere models

Blue → Extinction corrected fluxes



Espaillat et al. (2010, 2014)

Transition disks

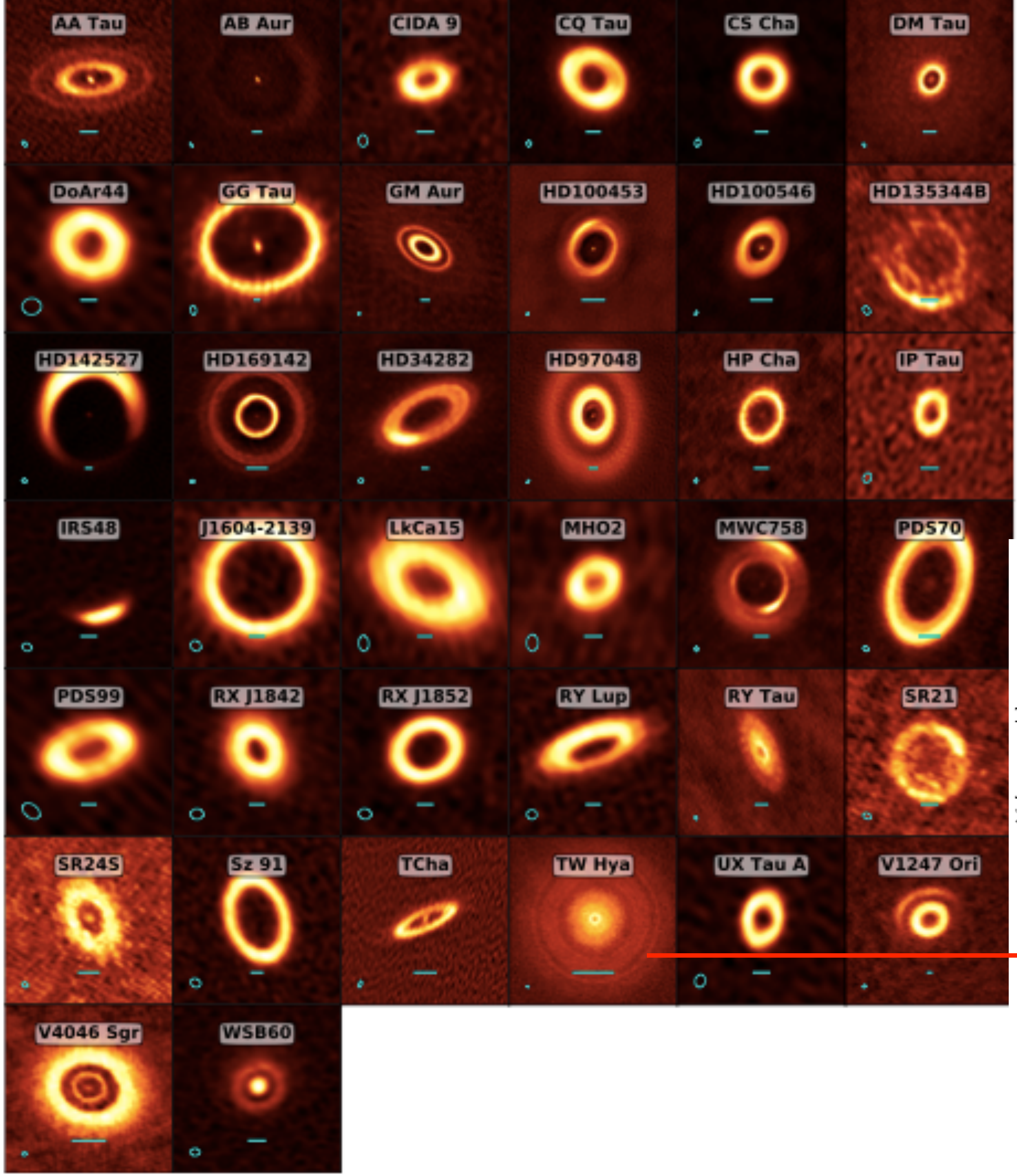
Francis & van der Marel (2020)

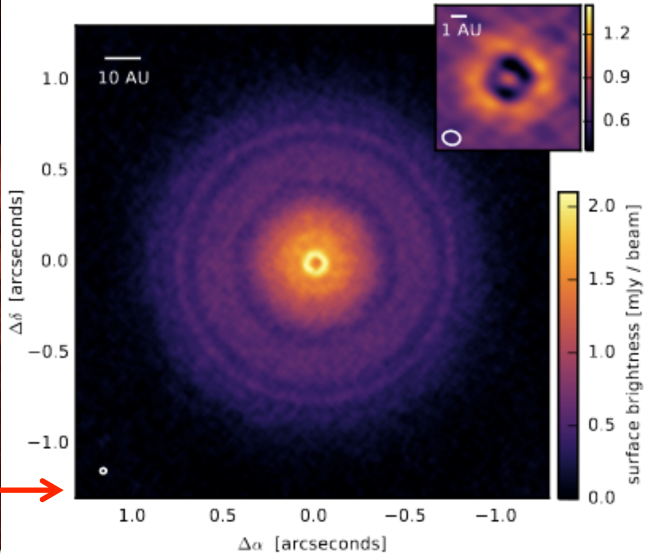
ALMA continuum emission

30 au scalebars

Probes the large scale

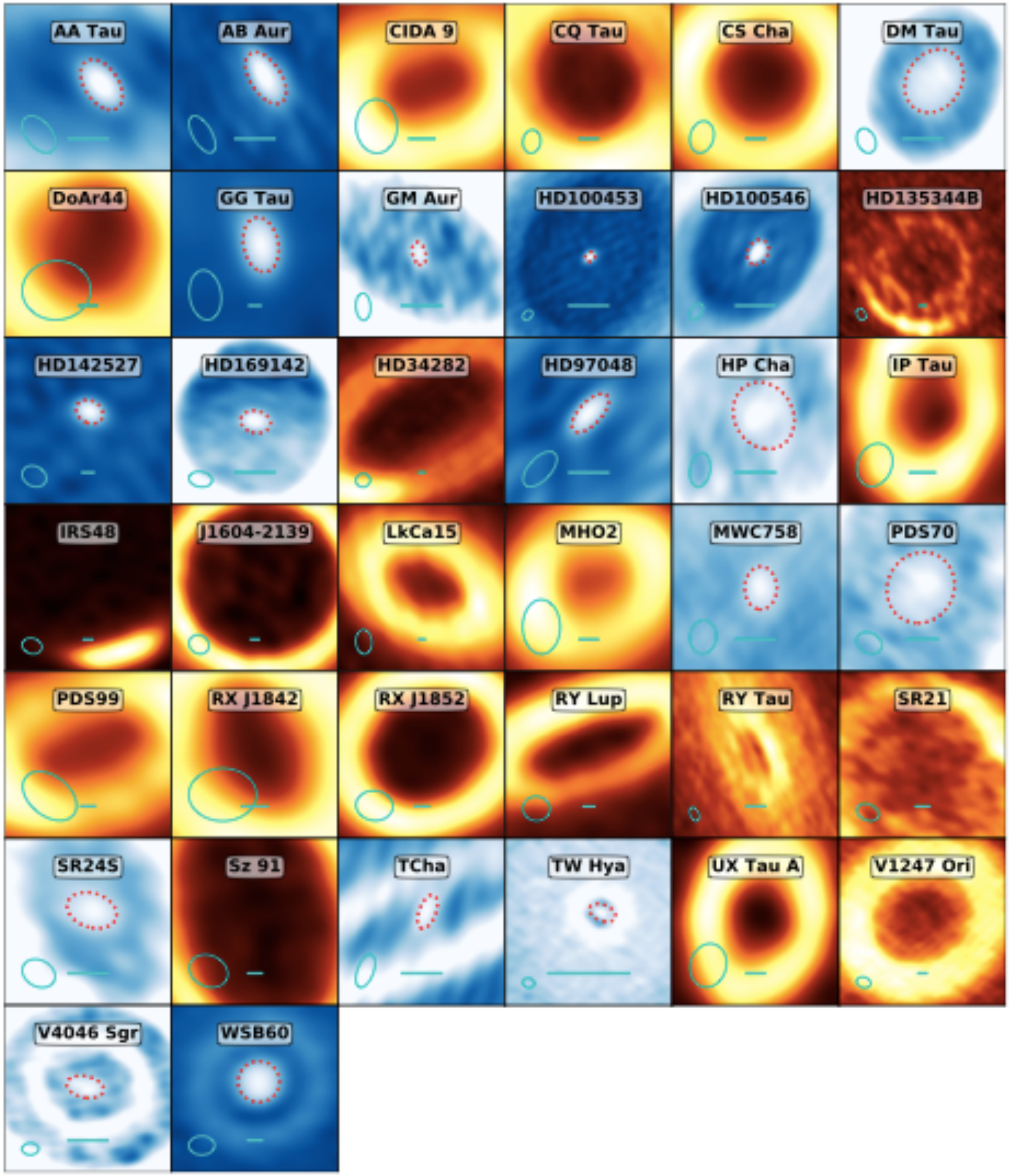
Transition disks have large gaps





Andrews et al. (2016)

ALMA 870 μm continuum emission



Transition disks

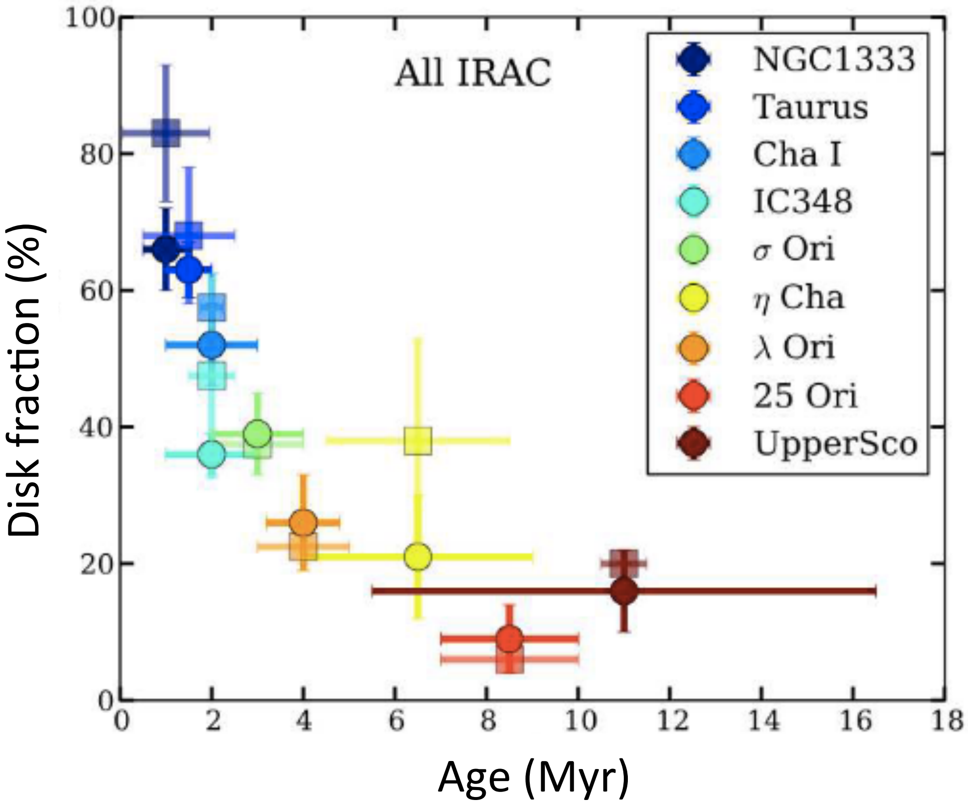
Francis & van der Marel (2020)

Zoom in on the inner disks
ALMA continuum emission

10 au scalebars

Circumstellar disk dispersion

From CTTS to WTTS



How does the dispersion occur?

Accretion

Diskwinds/jets

Photoevaporation by UV and X-ray photons

Giant planet formation and migration

Tidal disruption due to close binary companion

Gorti et al. (2015)

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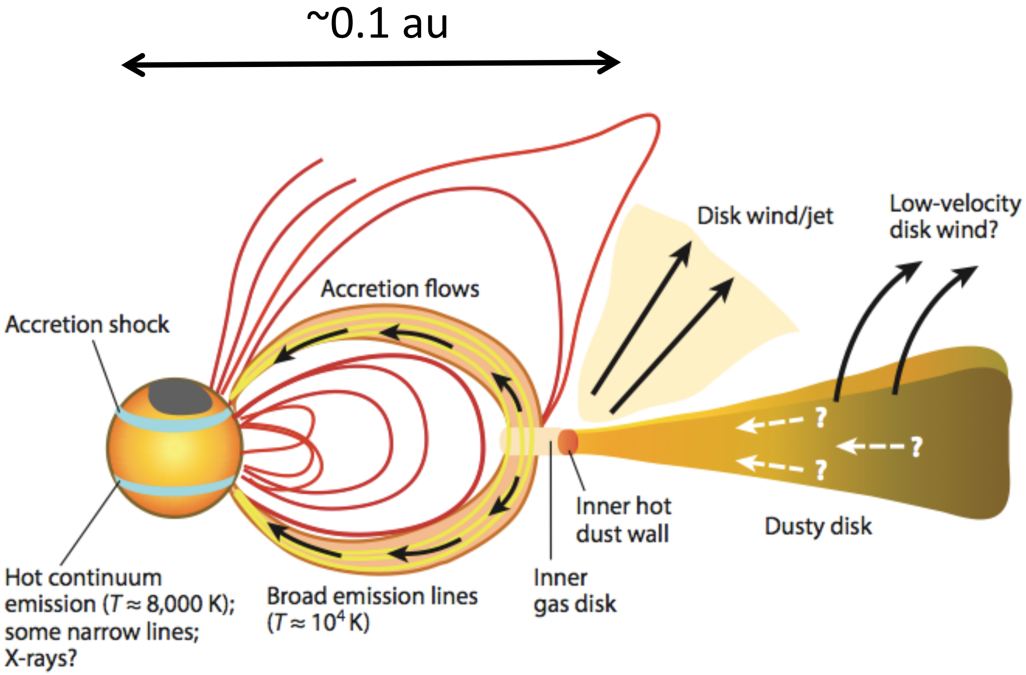
Magnetospheric accretion models

Magnetic fields

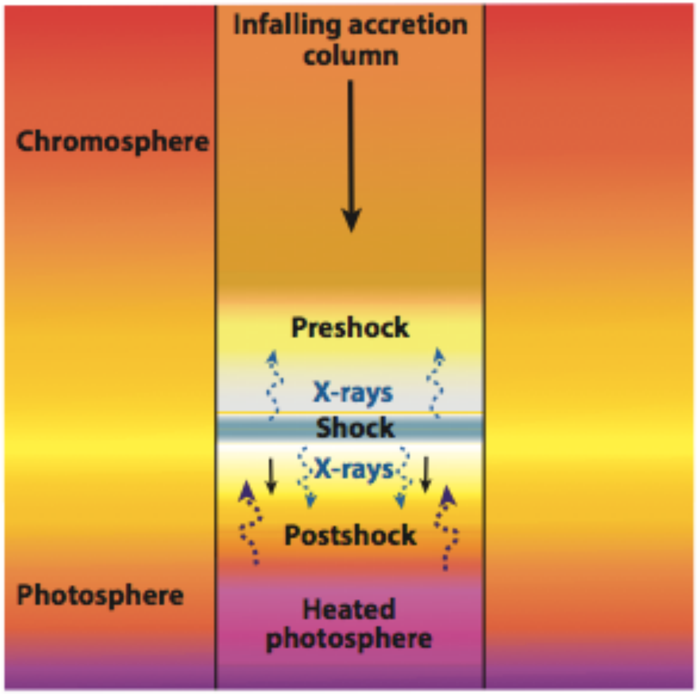
- Activity
- Accretion
- Star-disk interaction
- Inner disk structure
- Outflows (stellar winds, disk winds, jets)
- Angular momentum transport

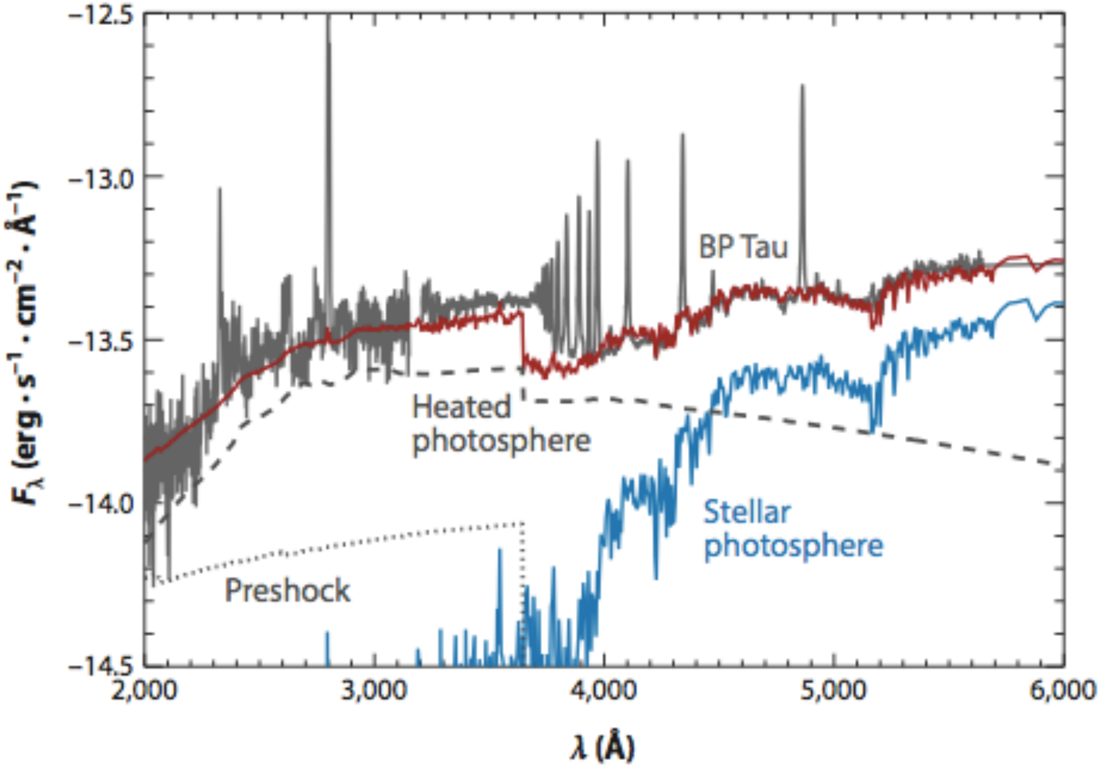


Camenzind (1990) Shu et al. (1994), Hartmann et al. (1994), Muzerolle et al. (1998, 2001), Kurosawa et al. (2006,2011), Lima et al. (2010), Hartmann et al. (2016)

High inclination systems: we can see through all the structures

Observational evidences for magnetospheric accretion

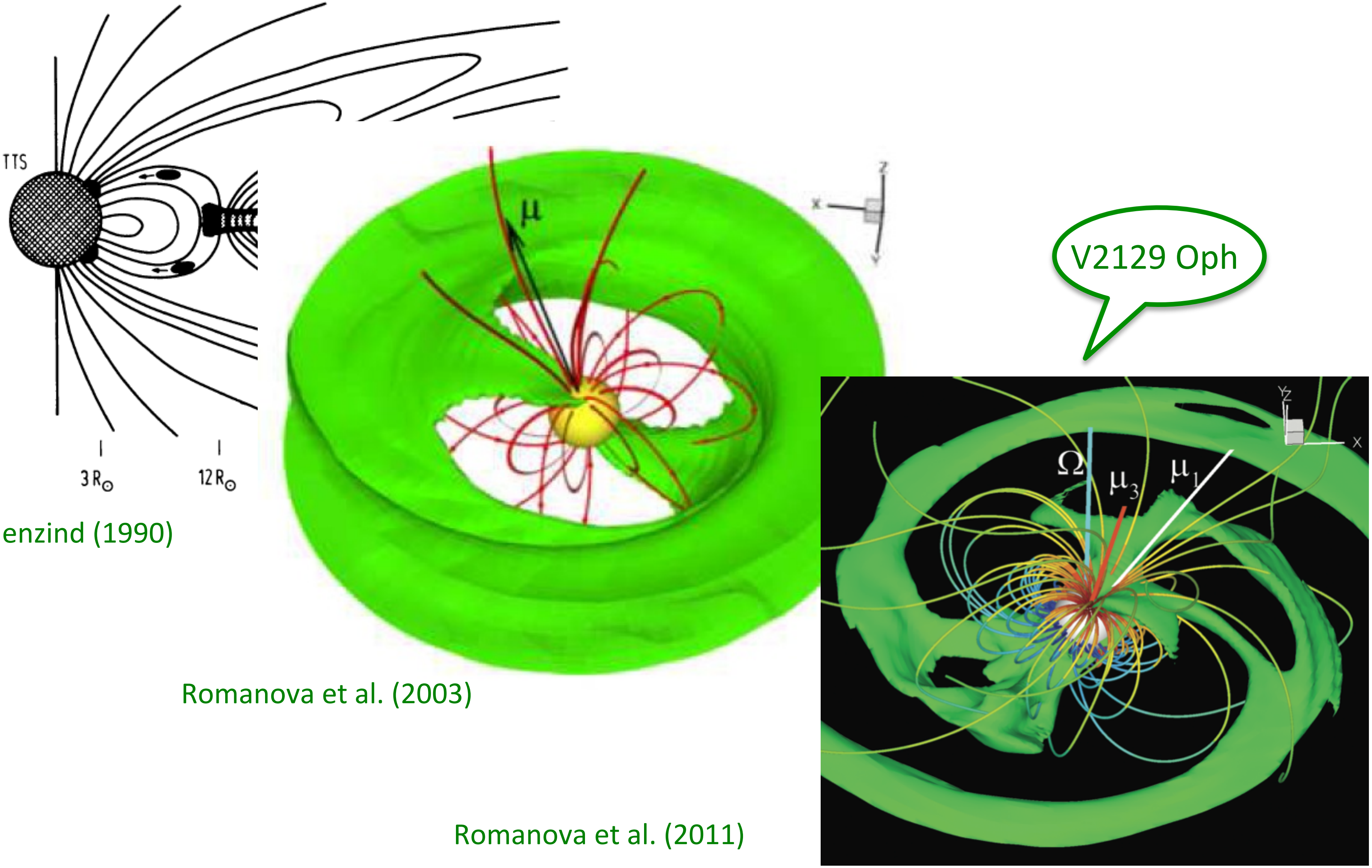




- UV excess and Balmer jump
- Veiling of photospheric lines
- Strong emission lines from accretion columns
- Strong magnetic fields
- X-ray emission
- Winds/jets
- Spectroscopic and photometric variability

Hartmann et al. (2016)

Magnetospheric accretion through complex fields



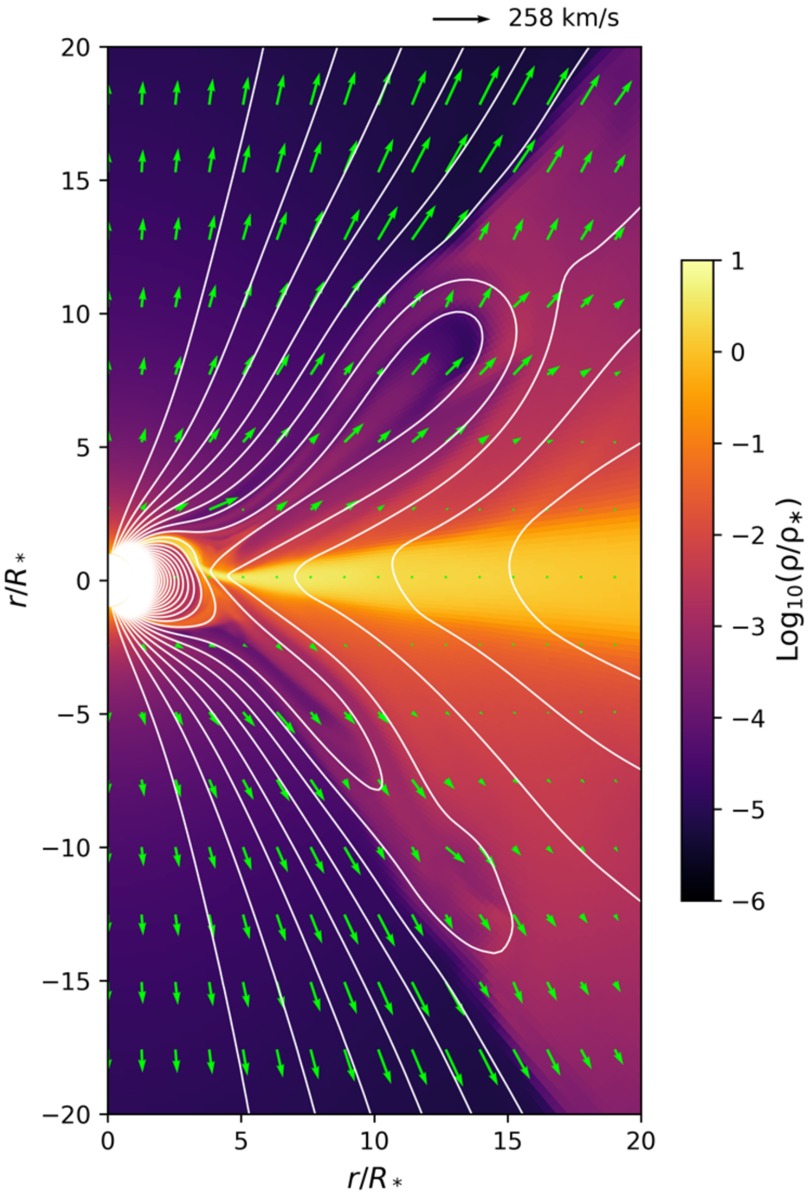
V2129 Oph

Camenzind (1990)

Romanova et al. (2003)

Romanova et al. (2011)

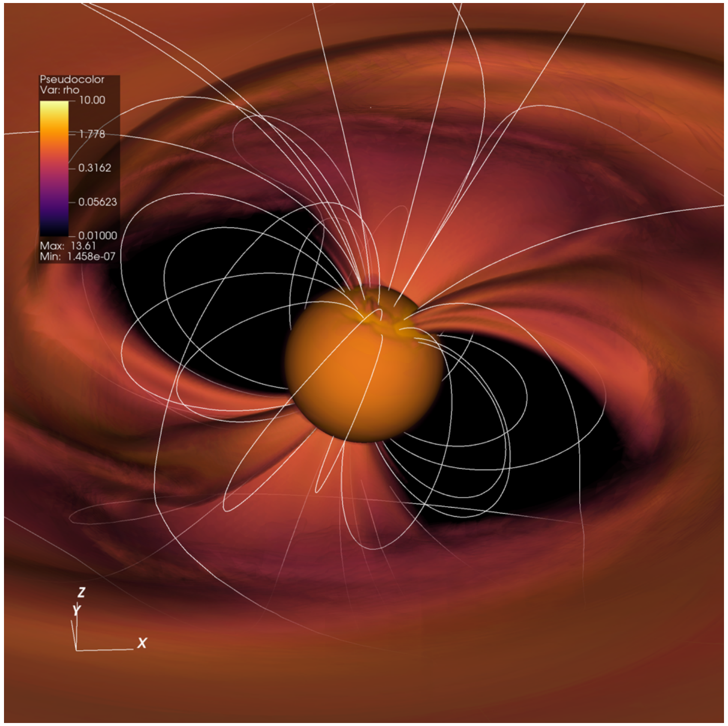
MHD simulations of accretion and outflow



Pantolmos et al. (2020)

3D simulations

Pantolmos et al. (priv. comm.)



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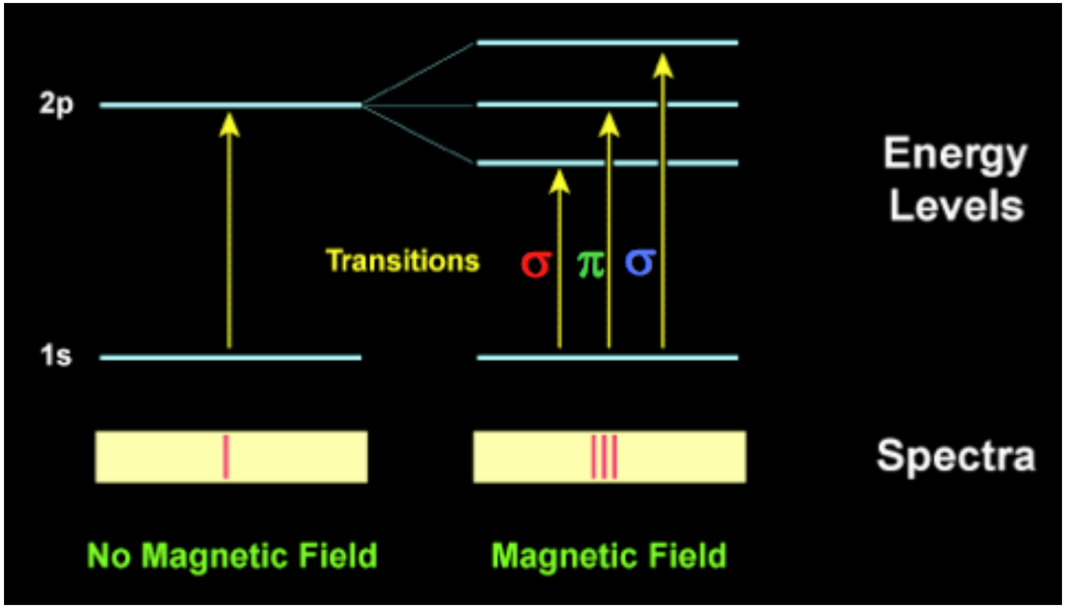
Magnetic field measurements: Zeeman effect

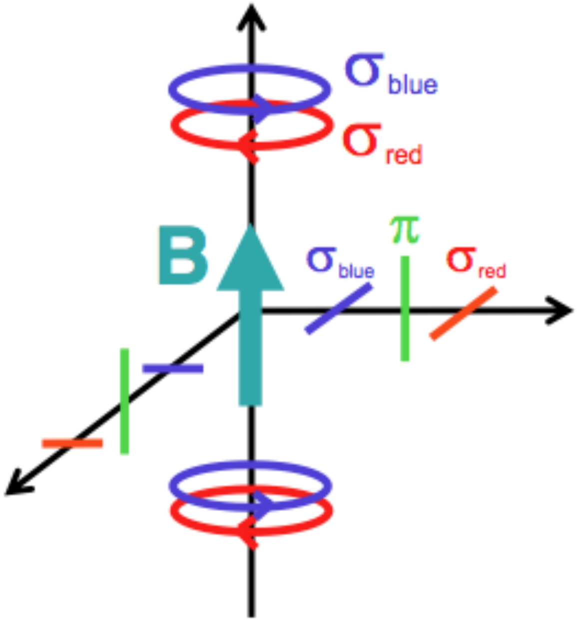
Line-splitting in the presence of a magnetic field



Reiners (2013)

$$\Delta\lambda = \frac{e}{4\pi m_e c^2}\lambda^2 g B$$

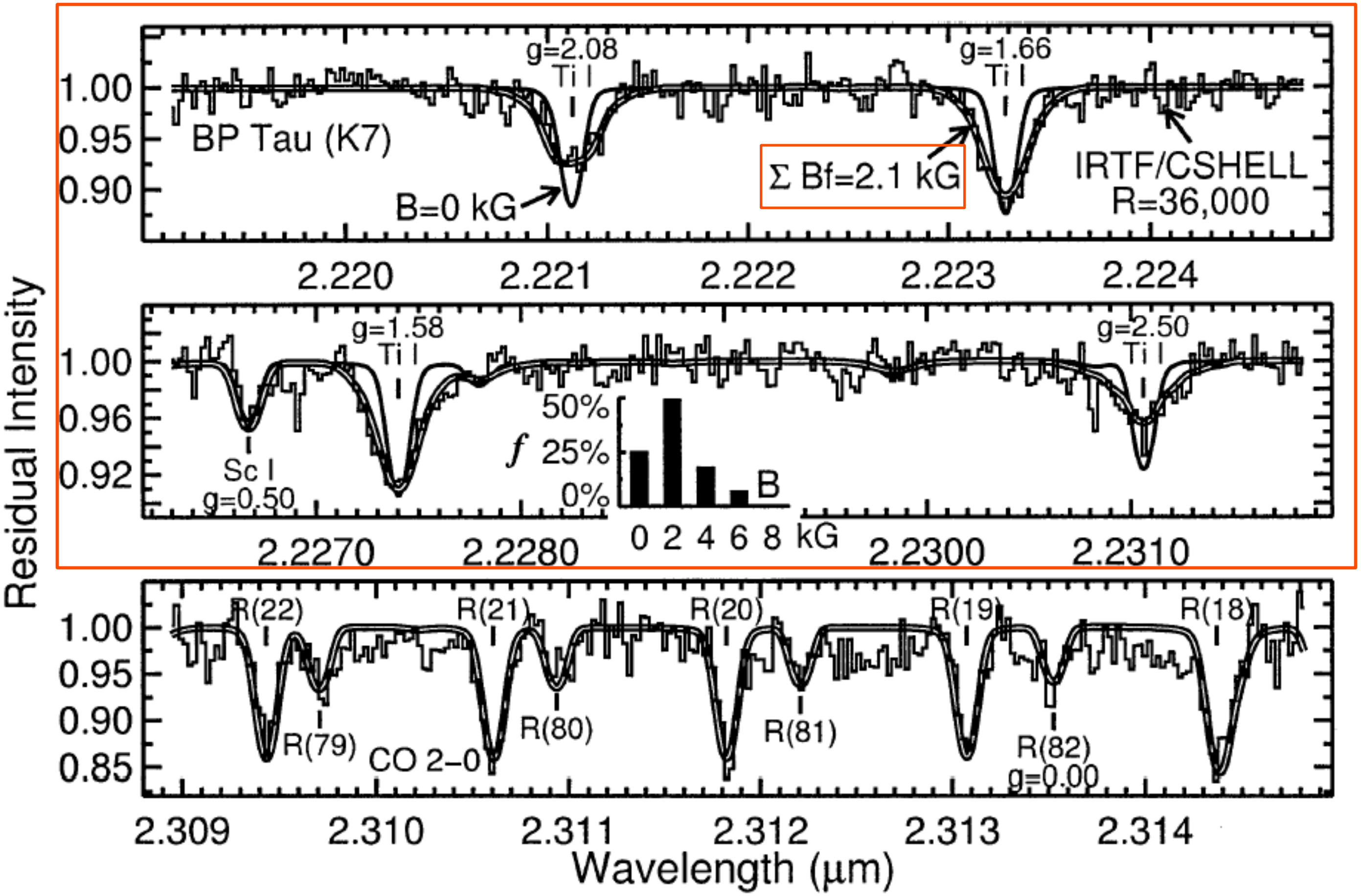
The polarization of the components depends on the viewing angle



Magnetic field intensity: Zeeman broadening

$$\Delta\lambda = \frac{e}{4\pi m_e c^2}\lambda^2 g B$$

Magnetic flux (Bf)

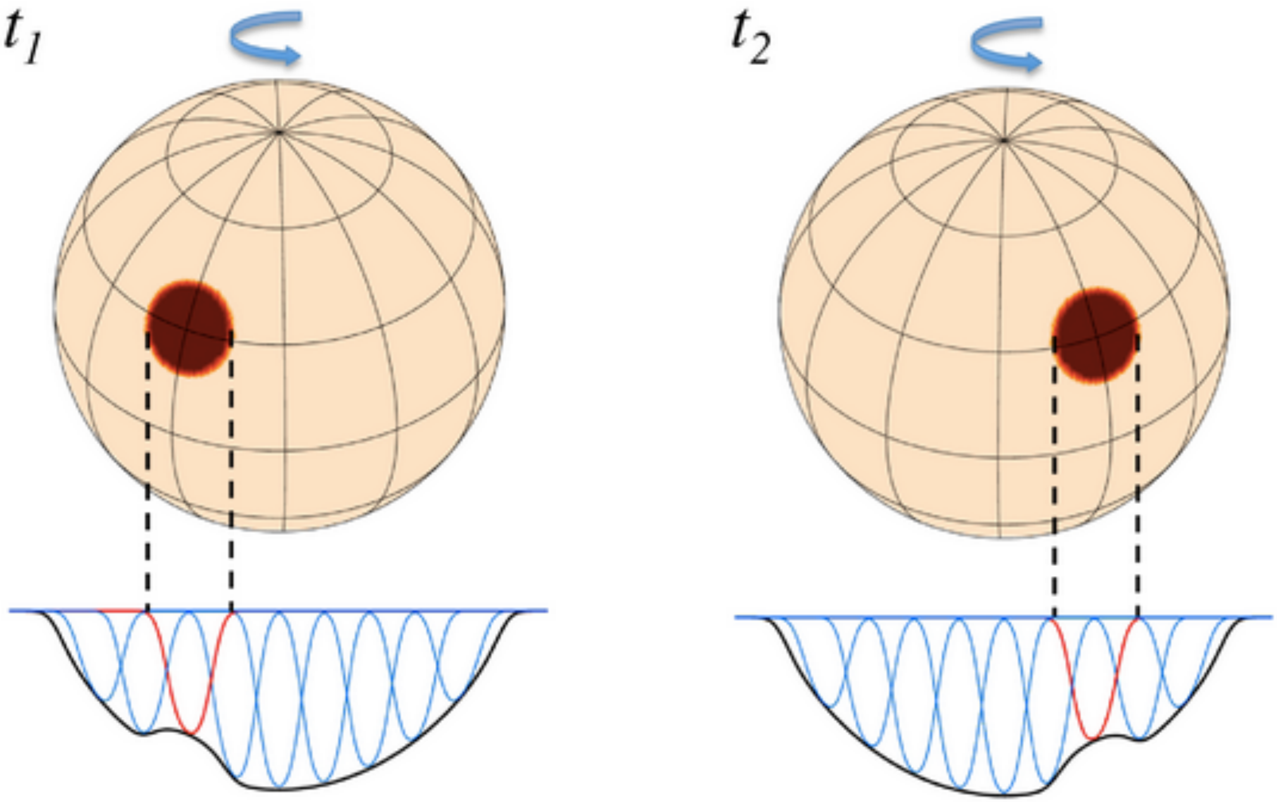


Valenti & Johns-Krull (2004)

Star	<B> (kG)
AA Tau	2.57
BP Tau	2.17
DE Tau	1.35
DF Tau	2.98
DK Tau	2.58
DN Tau	2.14
GG Tau A	1.57
GI Tau	2.69
GK Tau	2.13
TW Hya	2.61
T Tau	2.39

Johns-Krull et al. (1999)
Johns-Krull et al. (2004)
Yang et al. (2005)

Magnetic field structure: Zeeman-Doppler imaging



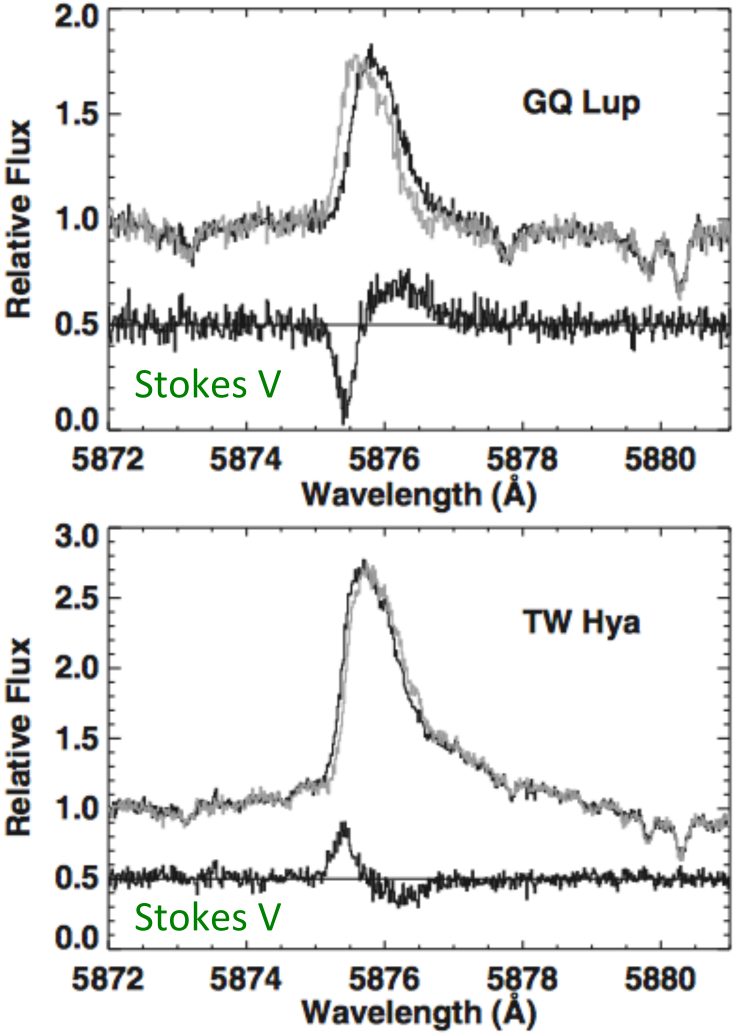
Doppler imaging

Unpolarized line profile: **brightness map**

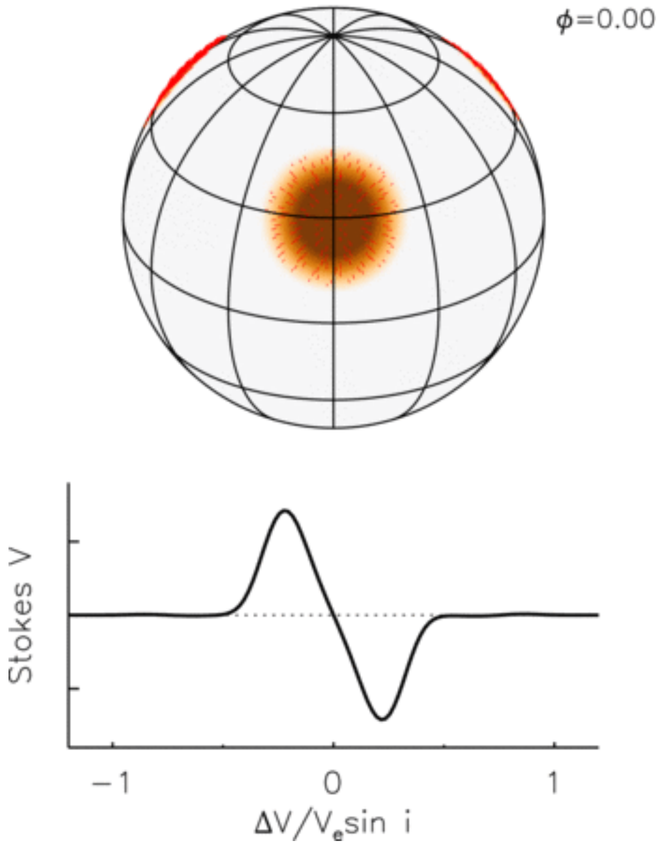
Oleg Kochukov
http://www.astro.uu.se/~oleg/

Magnetic field structure: Zeeman-Doppler imaging

HeI 5876 AA



Johns-Krull et al. (2013)



Zeeman-Doppler imaging

Circularly polarized line profile:

magnetic map: intensity+topology

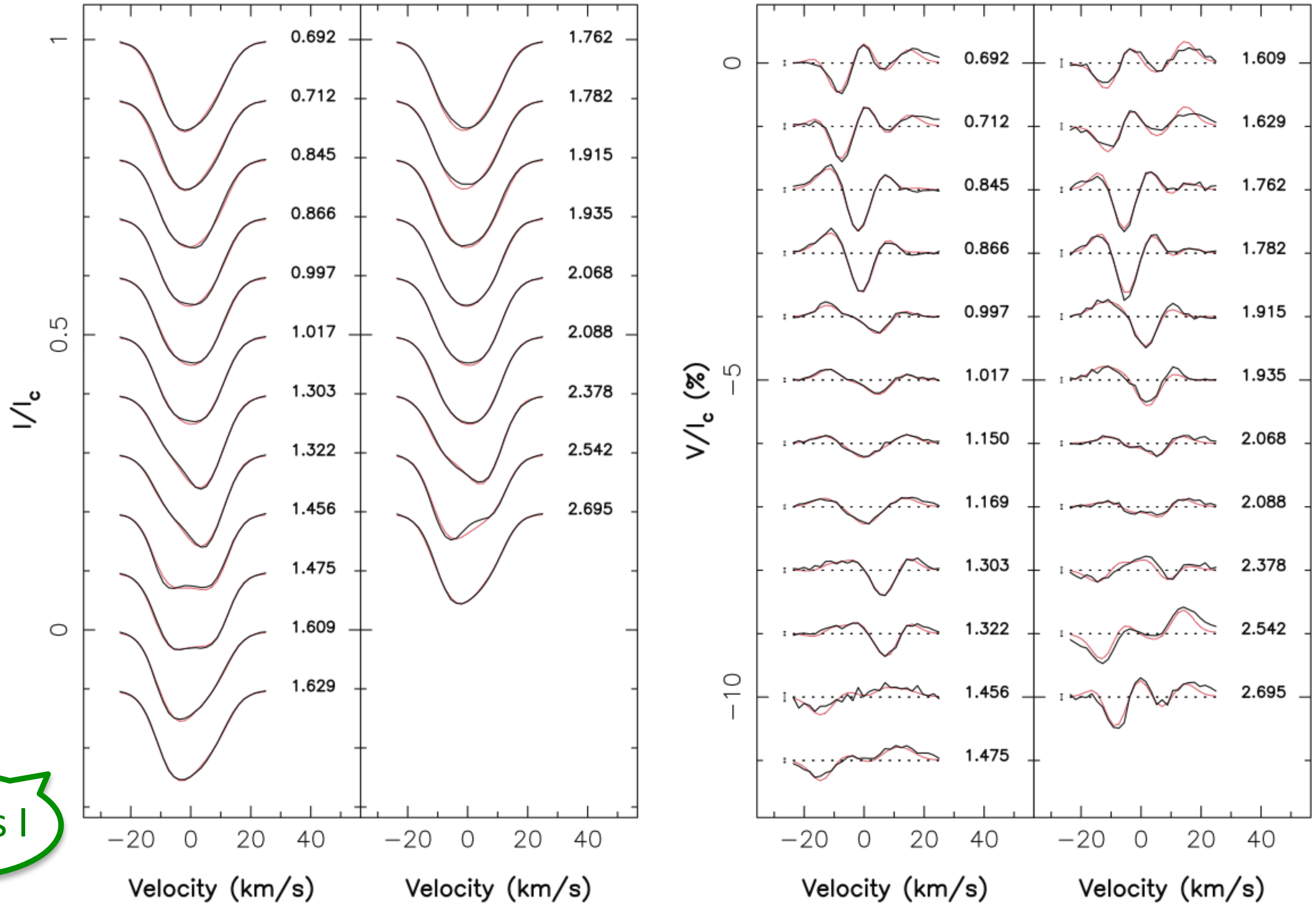
Oleg Kochukov
http://www.astro.uu.se/~oleg/

V2129 Oph – MaPP Large Program at CFHT: ZDI with ESPaD

Non-accreting regions – LSD profiles Donati et al. (2011)

data

model



Stokes I

Stokes V

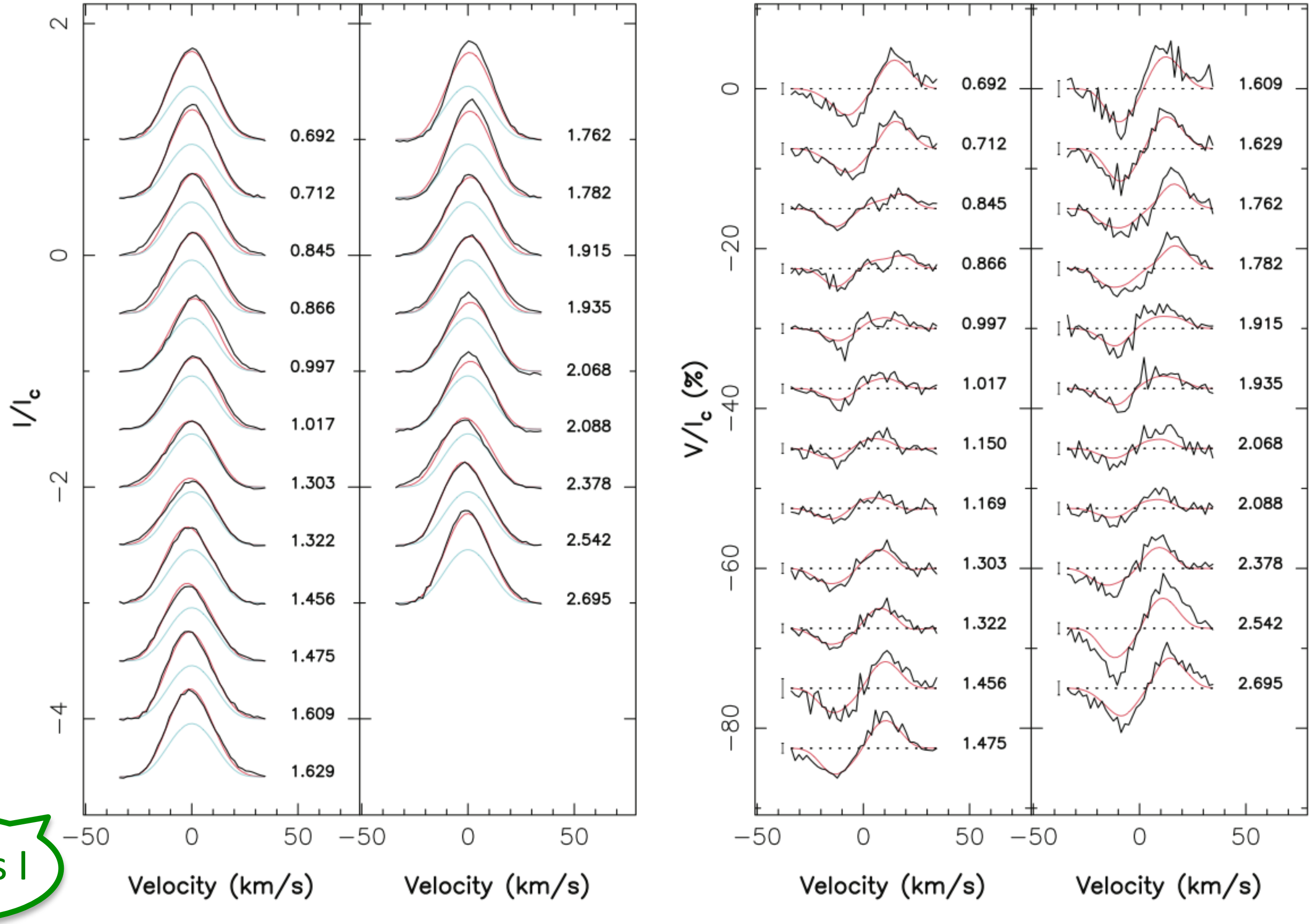
To invert the time series of unpolarized and circularly-polarized spectra into surface brightness and large-scale magnetic maps

V2129 Oph – MaPP Large Program at CFHT: ZDI with ESPaDOnS

Accreting regions – CaII line profiles

data

model



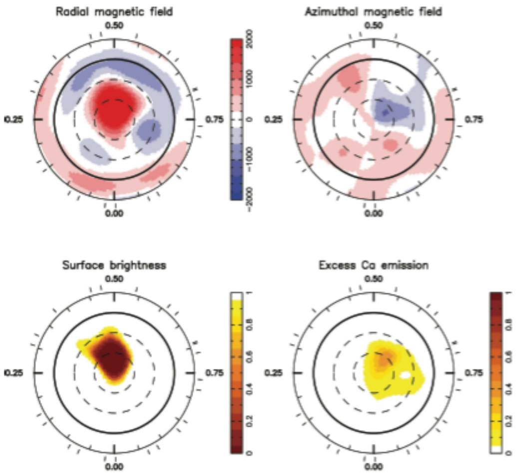
Stokes I

Stokes V

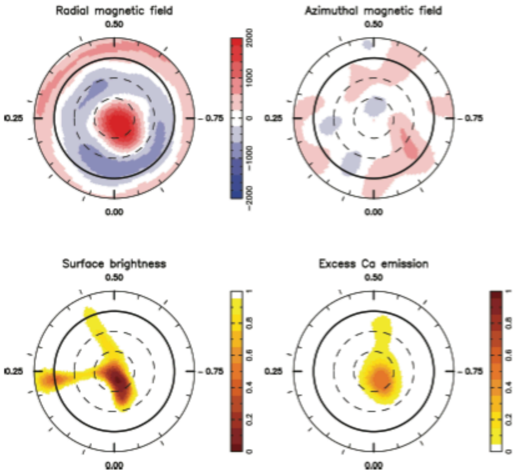
Donati et al. (2011)

V2129 Oph - Axisymmetric, poloidal magnetic field, dominated by the octupole.

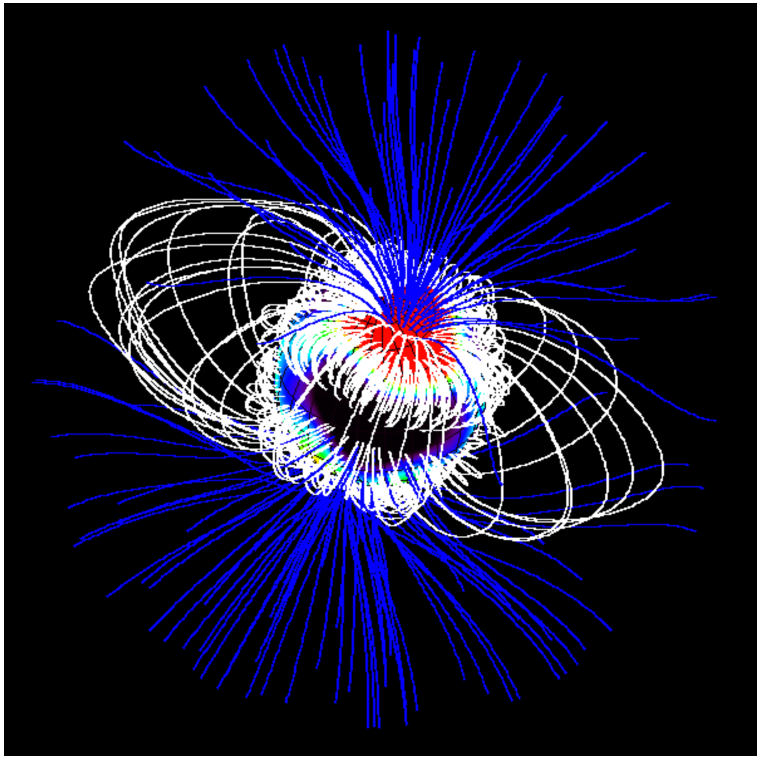
The dipole and octupole components varied between the two epochs of observation.



July 2009

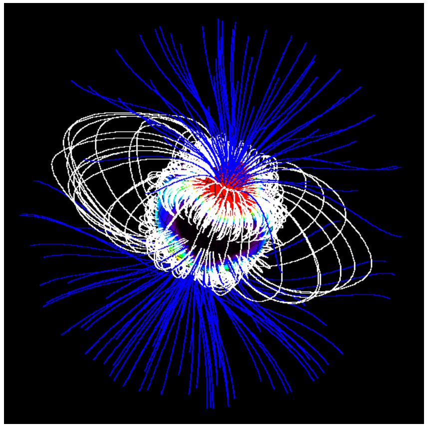


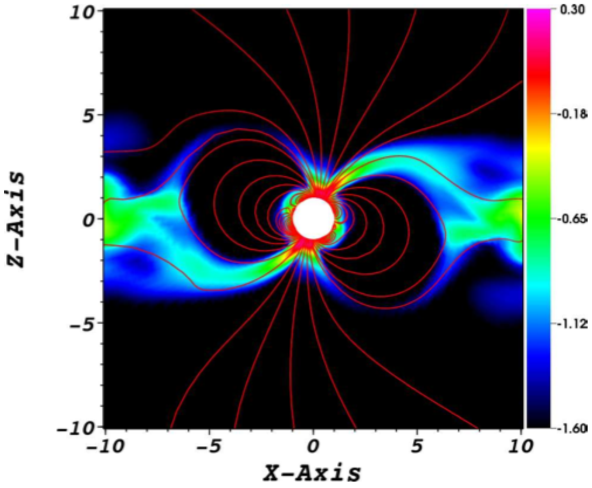
June 2005



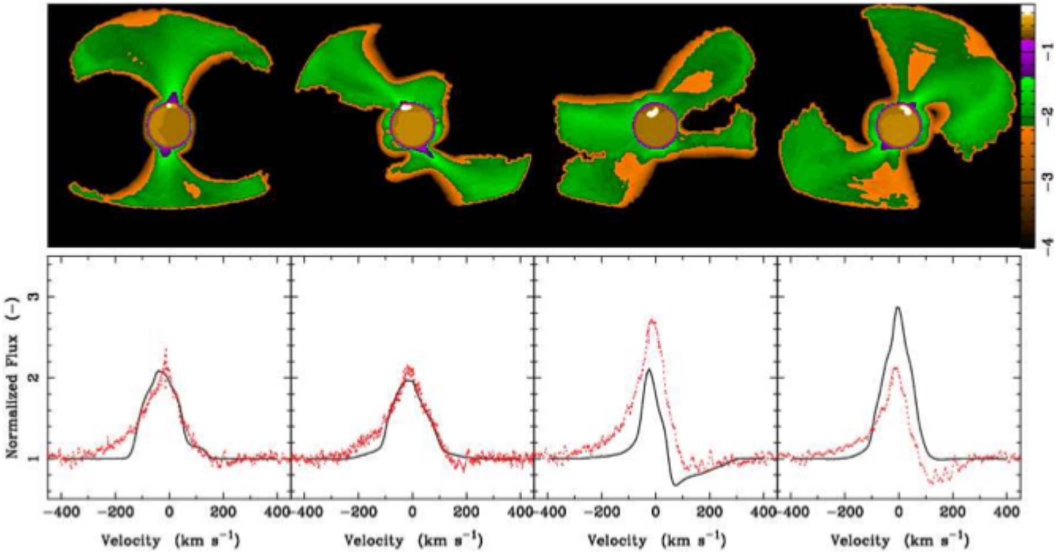
Donati et al. (2007, 2011), Jardine et al. (2008), Gregory & Donati (2011)

V2129 Oph
Simulations and data comparison





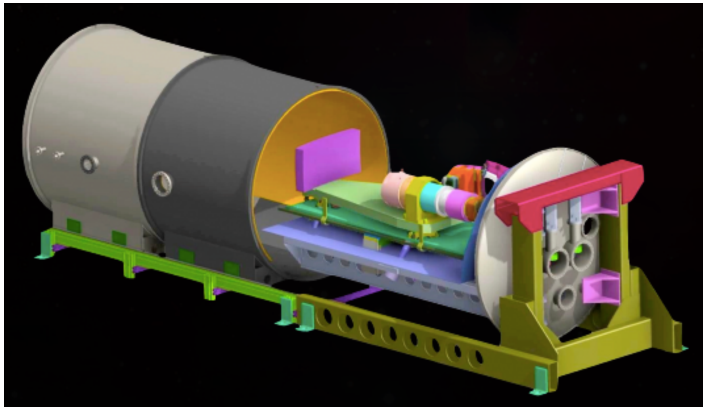
Hβ dipole+octupole



model

data

Alencar et al. (2012)



Near-IR (YJHK – 0.98 μm to 2.5 μm) spectropolarimeter
and high precision velocimeter (1 m/s level)

Available since 2019A

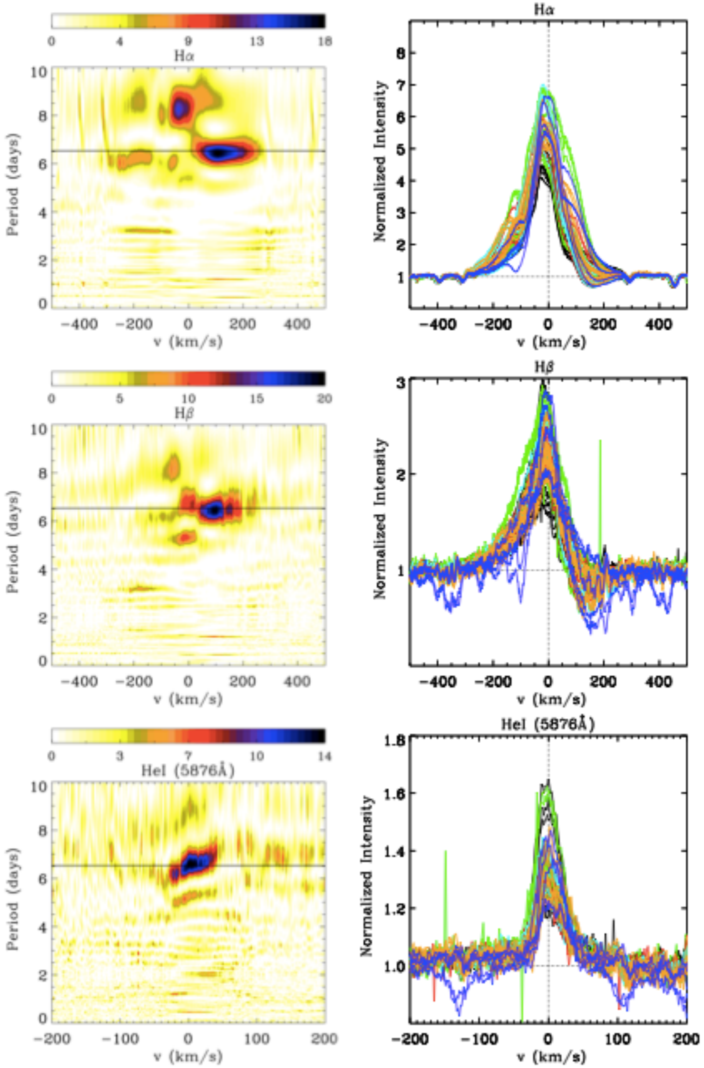
SPIRou Large Survey: 300 nights in 4 years

Work Package 3
Study the impact of magnetic fields in the formation of stars and planets

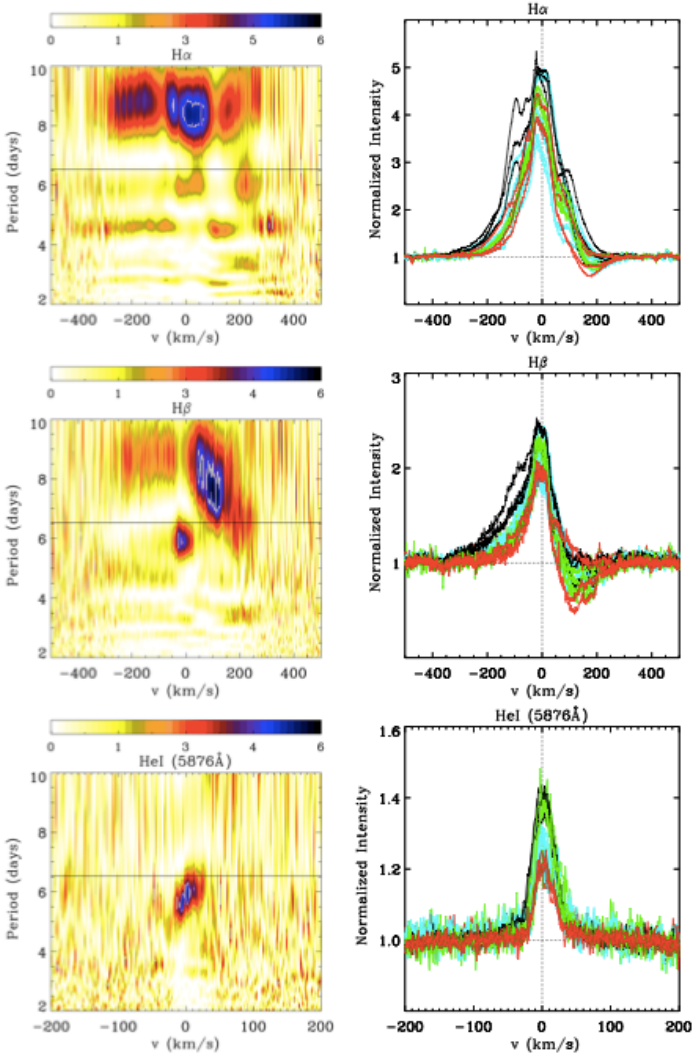
Detect giant planets around young stars

V2129 Oph observed with ESPaDonS

2009 observations



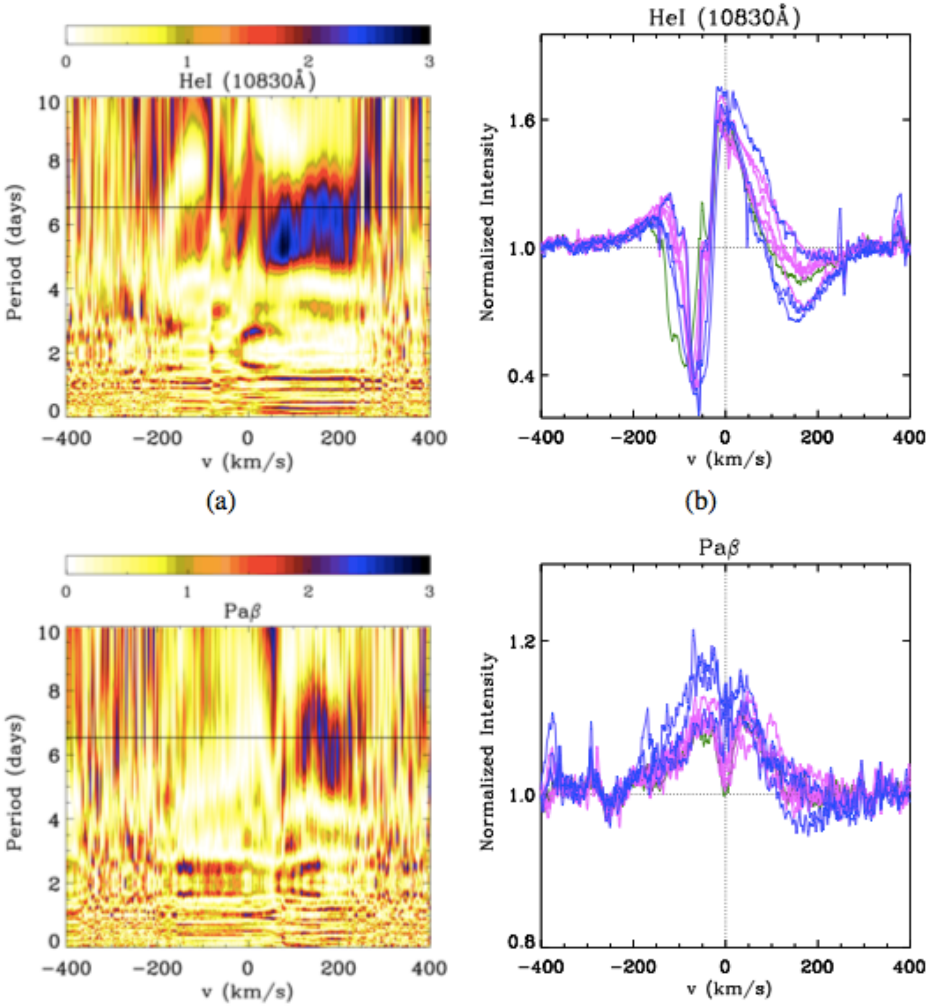
2018 observations



Sousa et al. (2021)

V2129 Oph observed with SPIRou

2018 observations



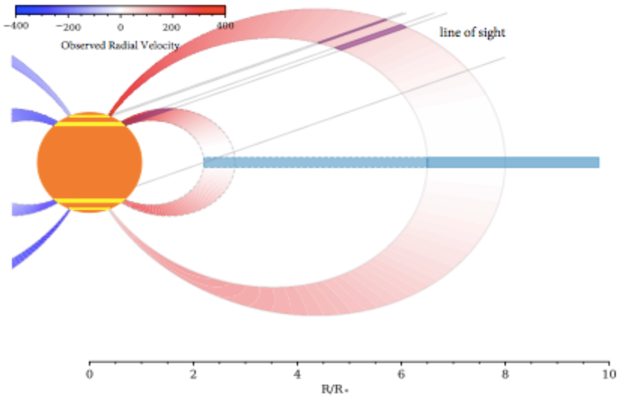
(a) (b)

Sousa et al. (2021)

V2129 Oph observed with ESPaDonS

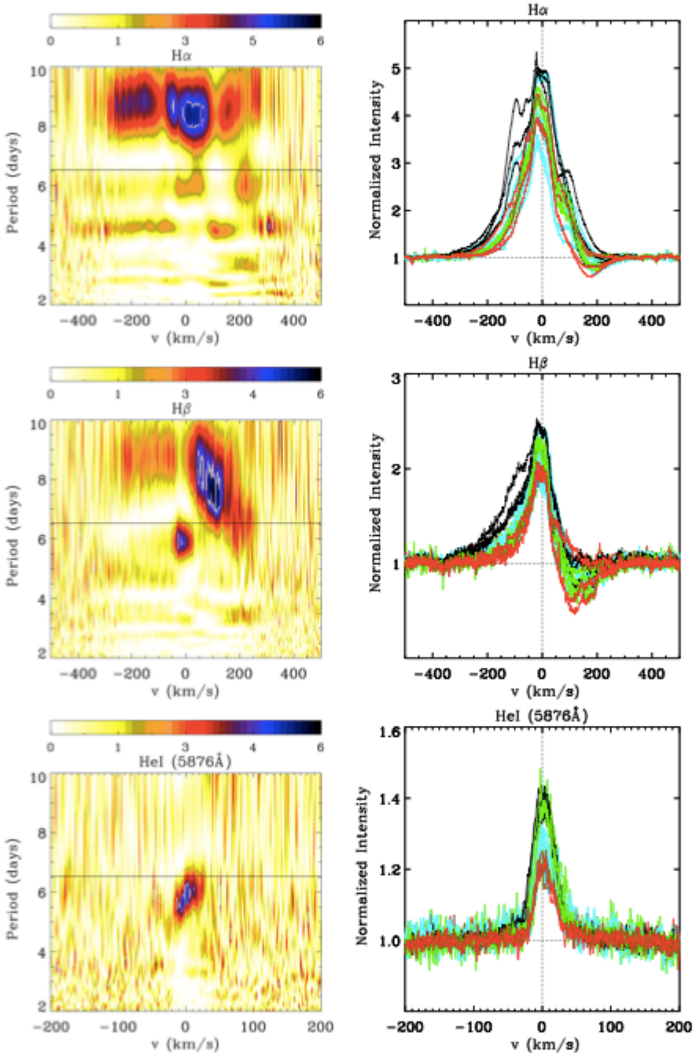
New environment configuration

Trailing funnel flow?
Multiple accretion flows?
External disturbance?



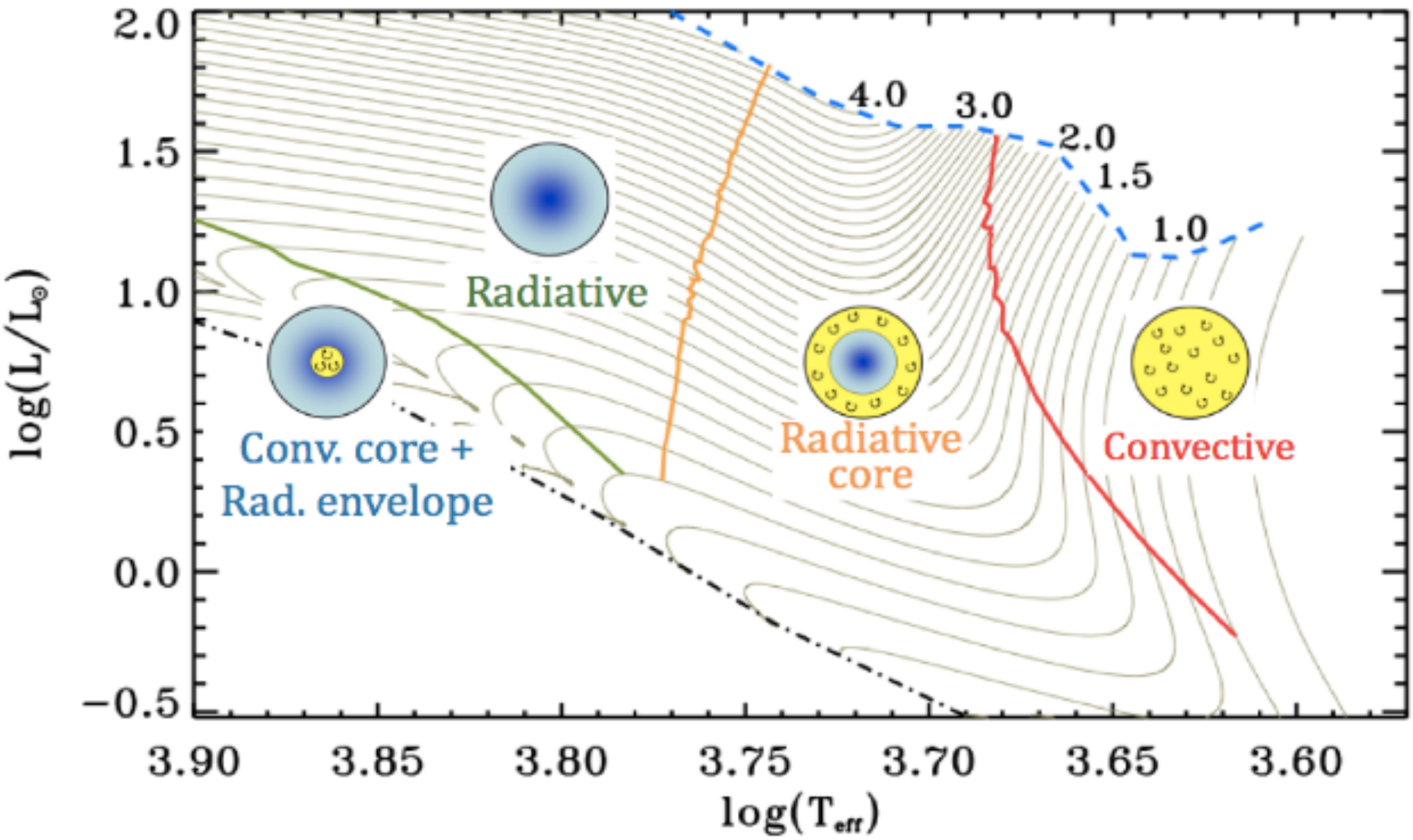
CVSO 1335
Thanathibodee et al. (2019)

2018 observations



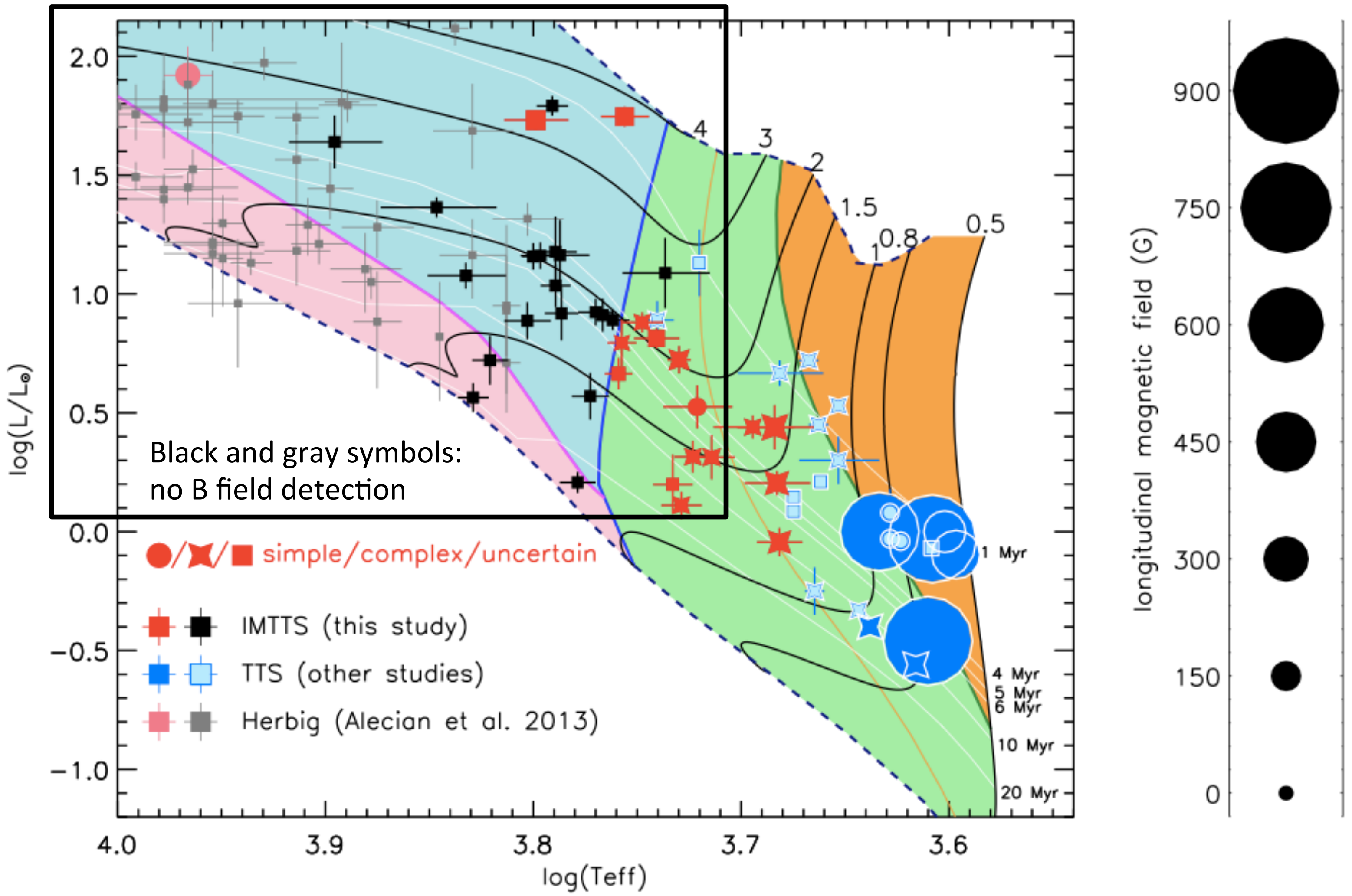
Sousa et al. (2021)

Evolution of the stellar structure in the PMS



Hussain & Alecian (2013)
Behrend & Maeder (2001) evolutionary tracks

Magnetic fields in the PMS across the HR diagram

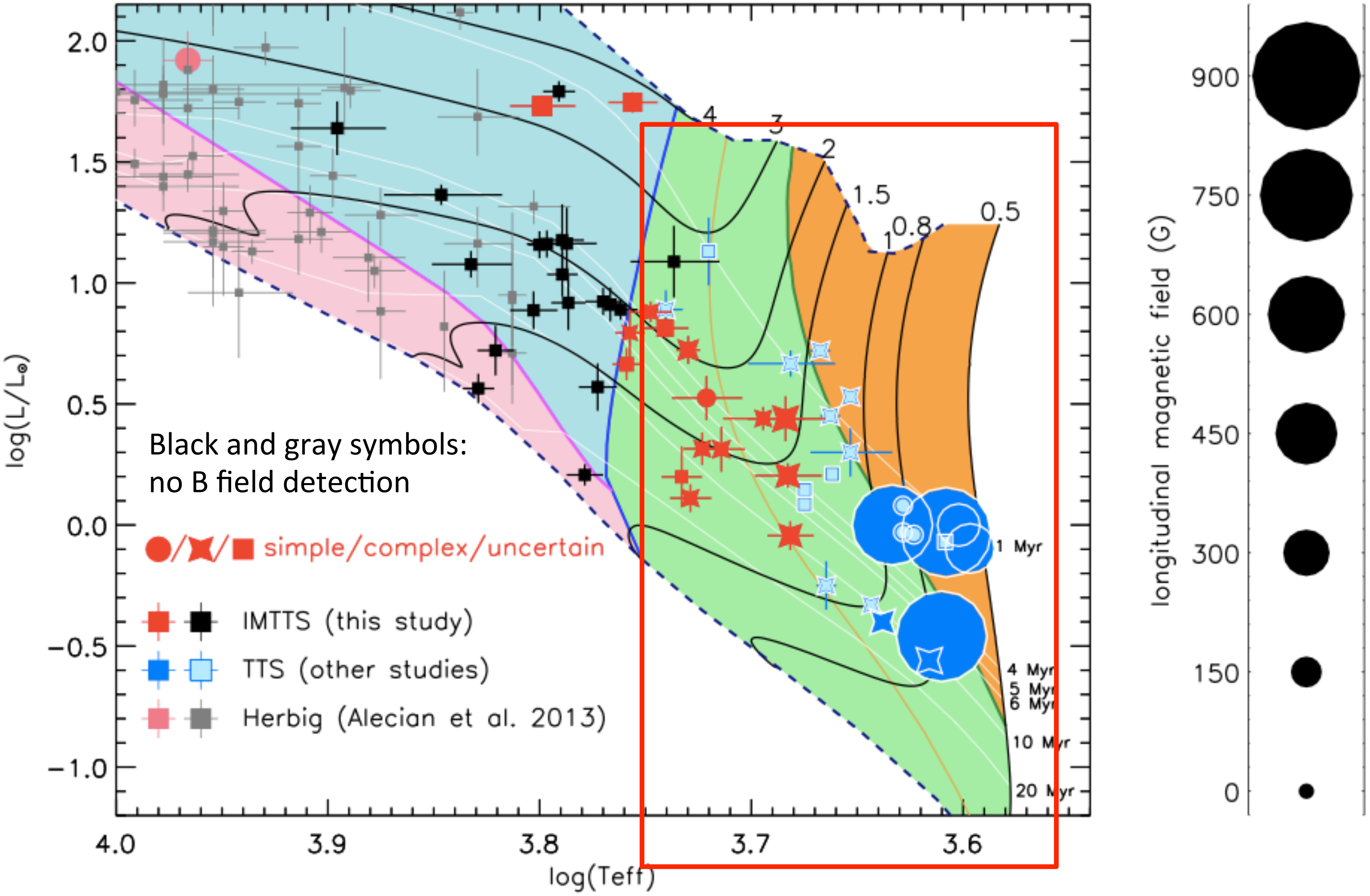


Black and gray symbols:
no B field detection

Villebrun et al. (2018)

CESAM evolutionary tracks and isochrones (Morel & Lebreton 2008)

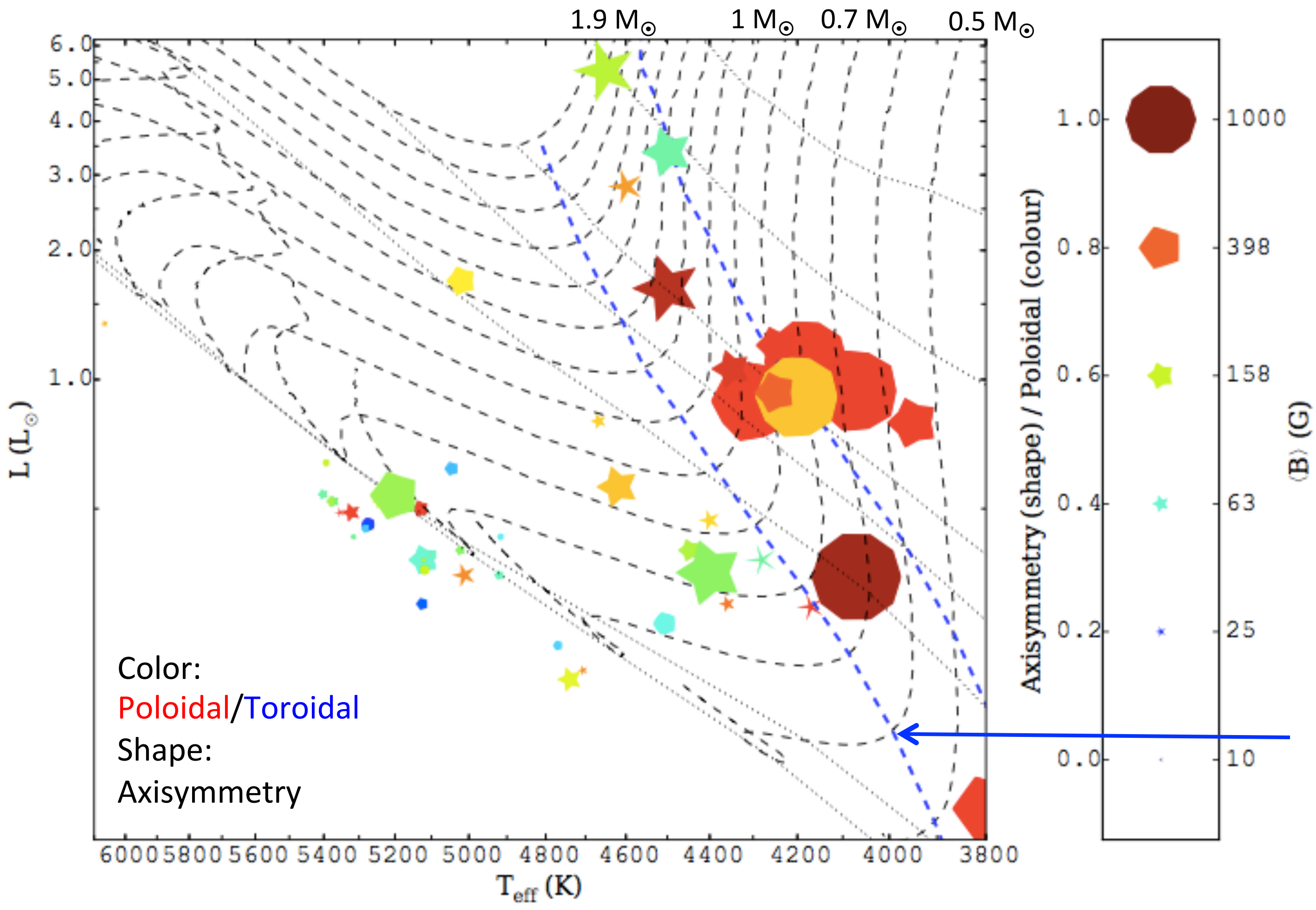
Magnetic fields in the PMS across the HR diagram



Villebrun et al. (2018)

CESAM evolutionary tracks and isochrones (Morel & Lebreton 2008)

Magnetic fields of low-mass PMS stars



Color:
Poloidal/Toroidal
Shape:
Axisymmetry

R_{conv}/R_{star}=0.5

MaPP, MaTYSSE and Toupies LP stars organized by Colin Hill (priv. communication).
Evolutionary tracks and isochrones (0.5, 1, 3, 5, 10, 50, 100 Myr) from Siess et al. (2000).

Outline

- From clouds to star-disk systems
- T Tauri stars
  - ✓ Disks
  - ✓ Magnetospheric accretion models
  - ✓ Stellar magnetic fields
  - ✓ Star-disk interactions
  - ✓ Outflows
  - ✓ Young planets
- Perspectives

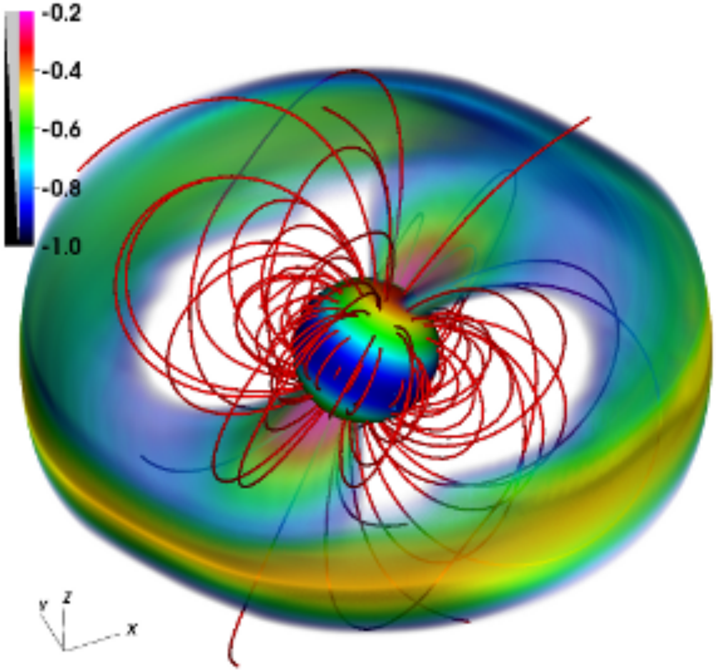
The importance of synoptic photometric and spectroscopic surveys

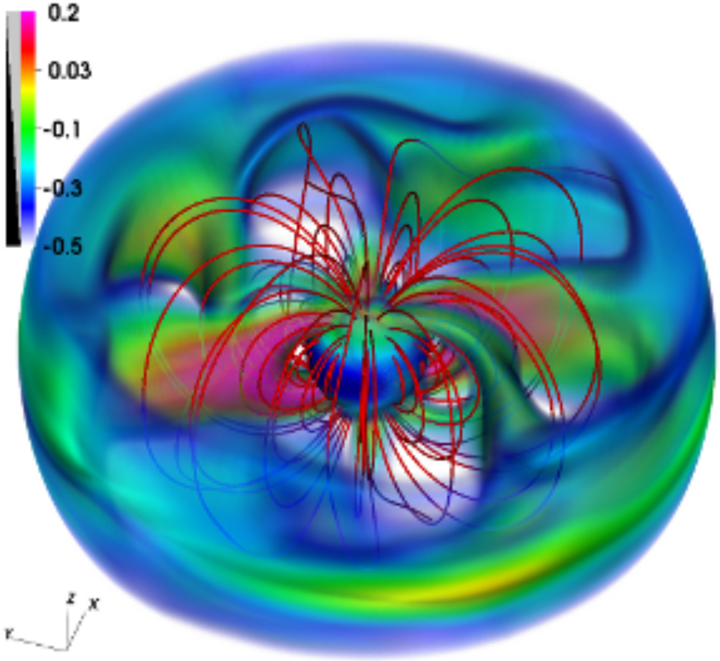
- Probe several timescales (hours/days/months)
- Inner disk structure
- Star-disk interaction
- Accretion process dynamics

High-precision continuous photometry
CoRoT
Kepler K2
TESS

Stable and unstable accretion regimes

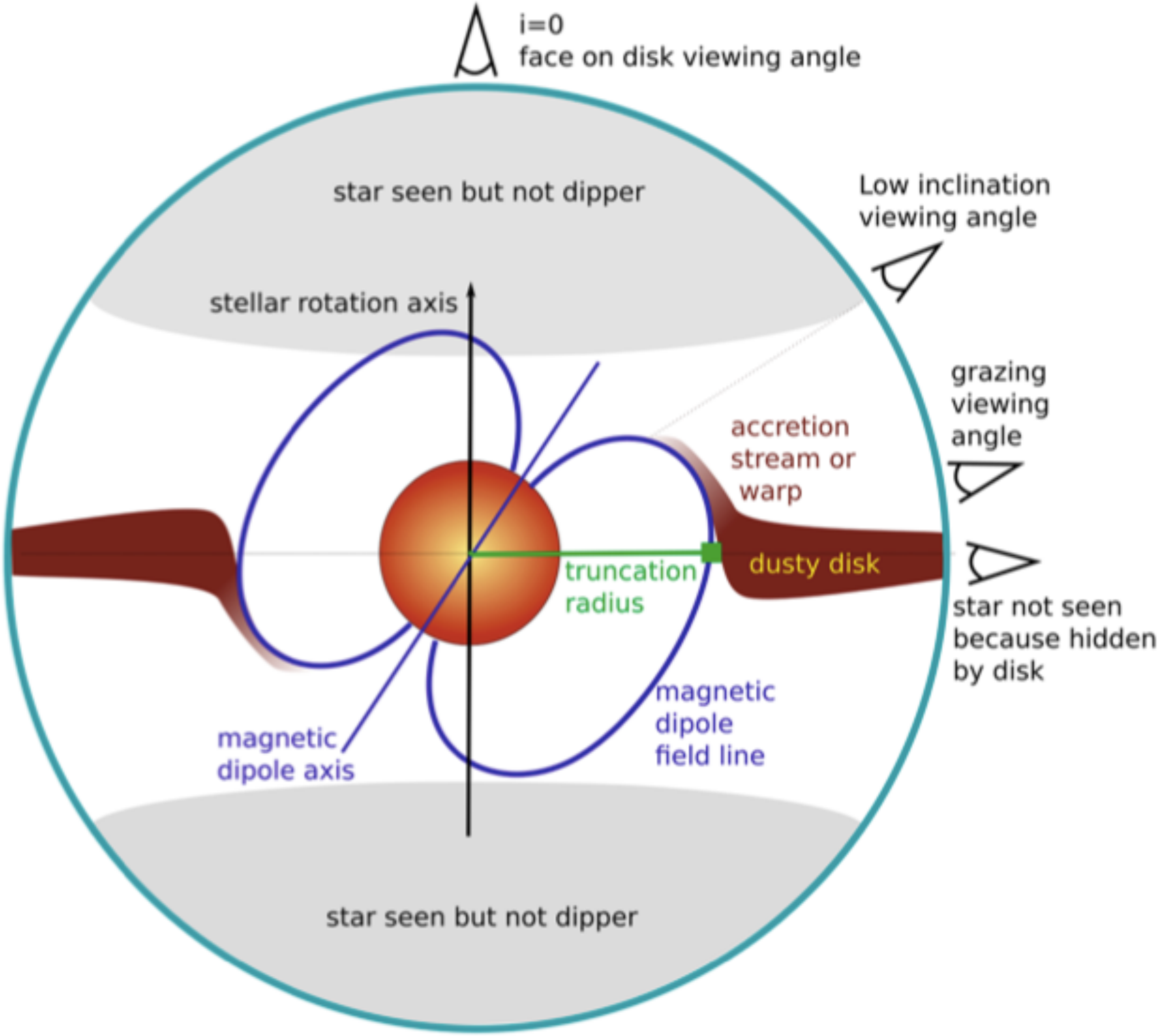
Kurosawa & Romanova (2013), Blinova et al. (2015)





Raileigh-Taylor instability is favored at : small misalignment and $R_m \leq 0.7\ R_{co}$

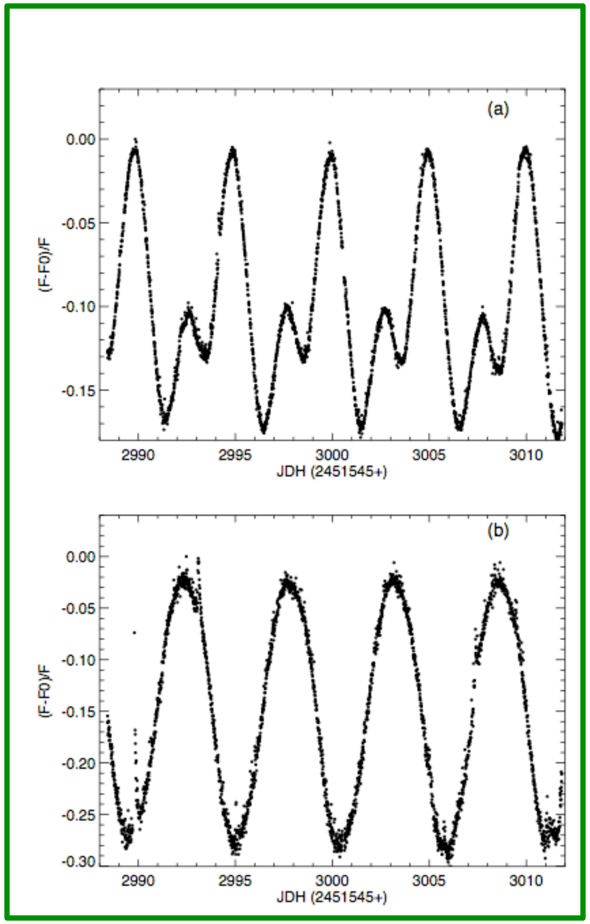
The observed light curve depends on system geometry



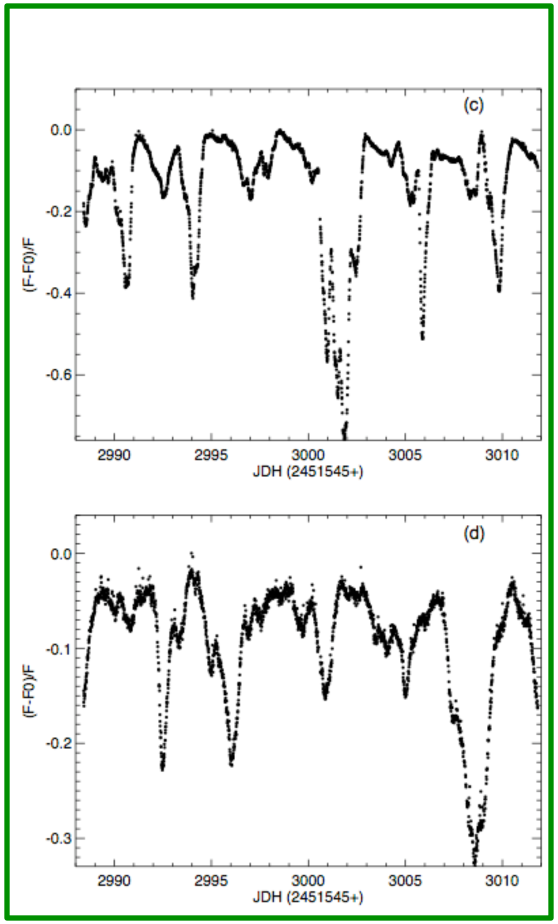
Bodman et al. (2017)

CoRoT light curves of CTTSs in NGC 2264

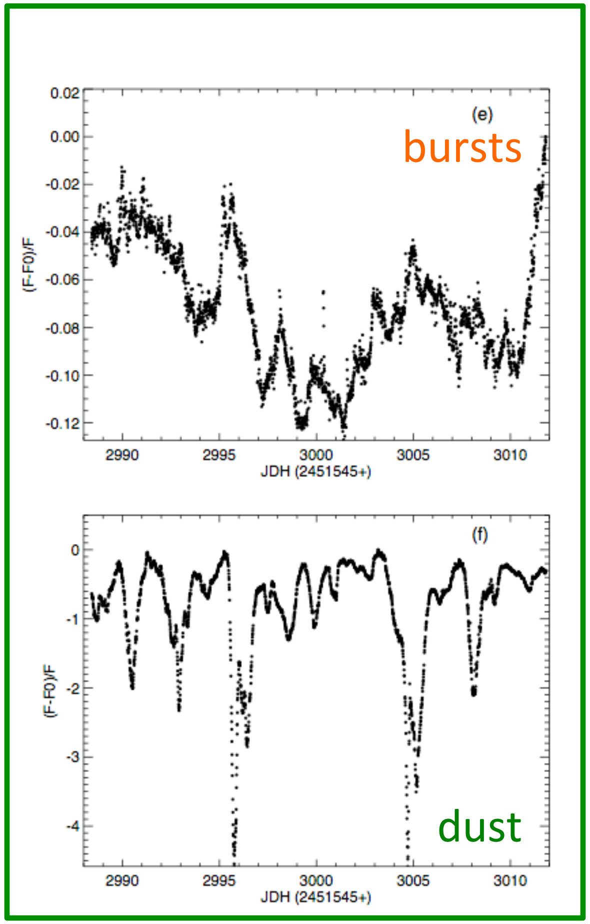
Spot
Periodic



Dipper
Quasi-periodic



Aperiodic



bursts

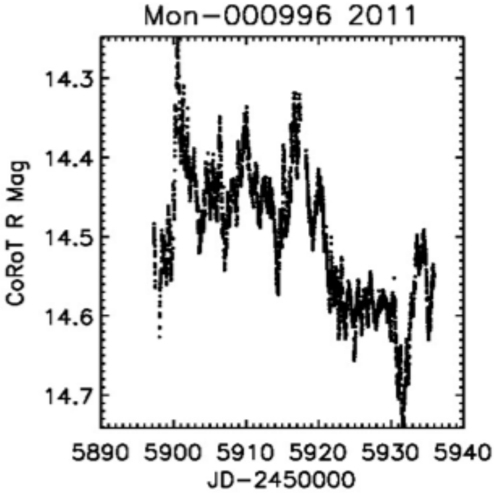
dust

Alencar et al. (2010)

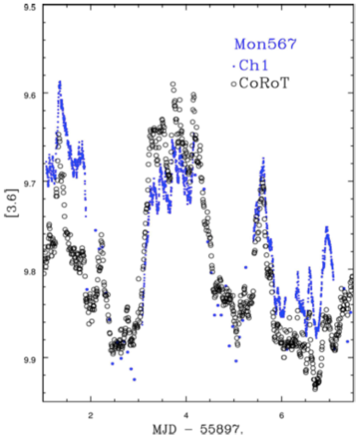
Accretion burst light curves (~12%)

Stauffer et al. (2014), Sousa et al. (2015)

CoRoT light curve

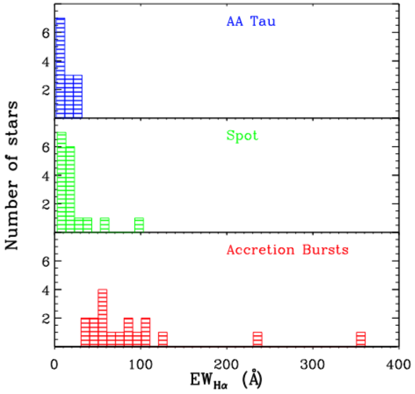


CoRoT + *Spitzer*

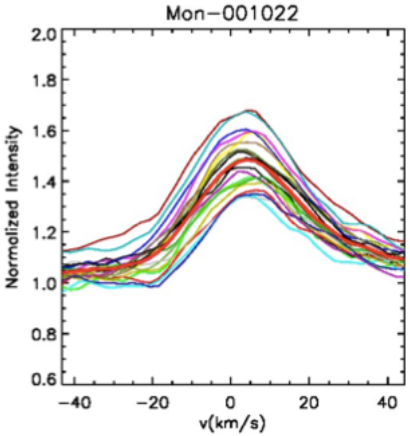


- Aperiodic light curves
- Non-steady accretion
- Burst duration 0.2d-0.5d, 10% amplitude
- Strongest accretors
- HeI 6678 Å in emission (only NC)
- Symmetric or P Cygni Hα profiles
- Strong outflow

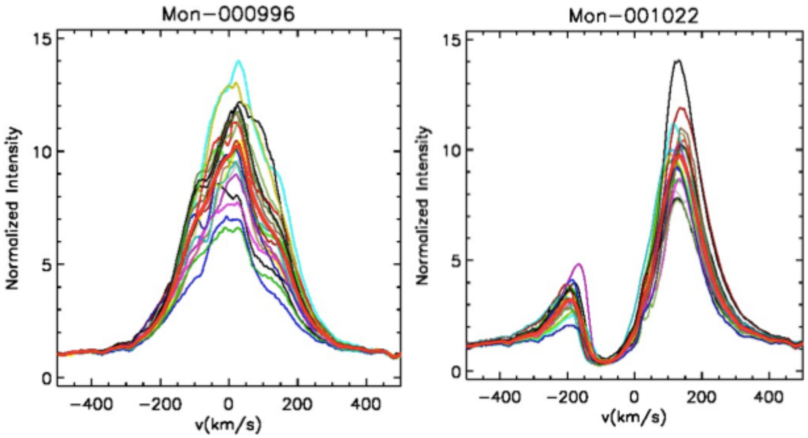
Hα EW



HeI 6678 Å



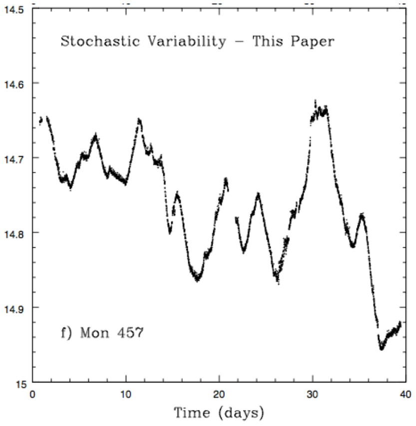
Hα profiles



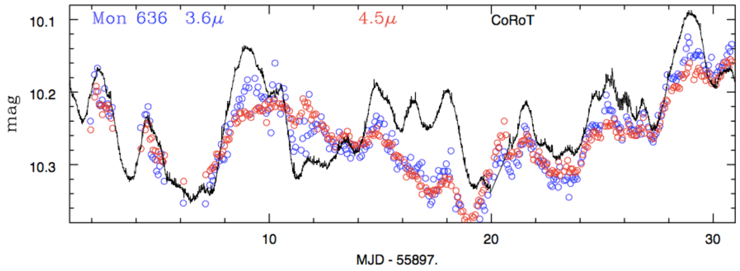
Stochastic light curves (~10%)

Stauffer et al. (2016)

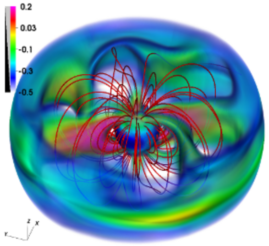
CoRoT light curve



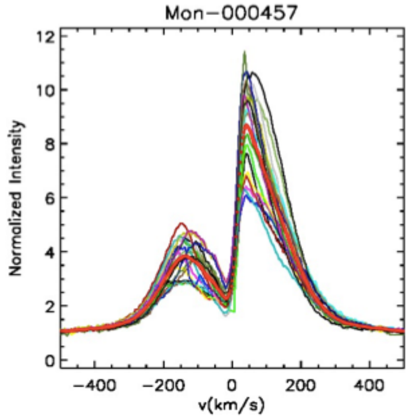
CoRoT and *Spitzer*

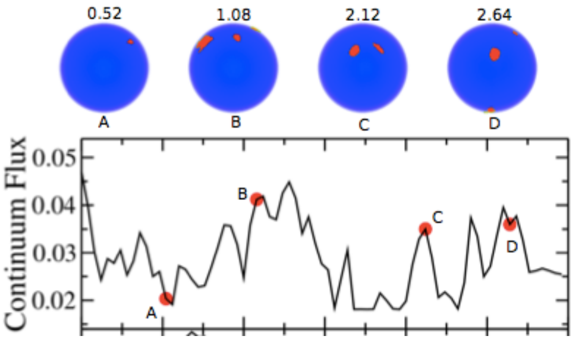


- Aperiodic light curves
- Light curve due to time variable accretion
- Small accretion bursts
- Moderate accretors
- Hα with blueshifted absorption (diskwind)
- Unstable accretion flows



Hα profile



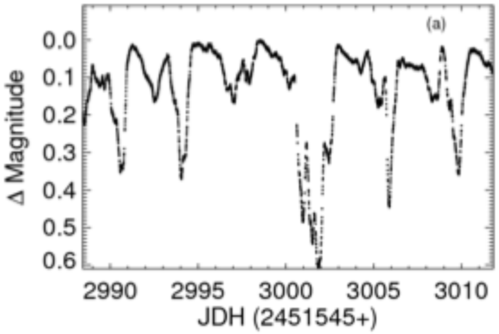


Kurosawa & Romanova (2013)

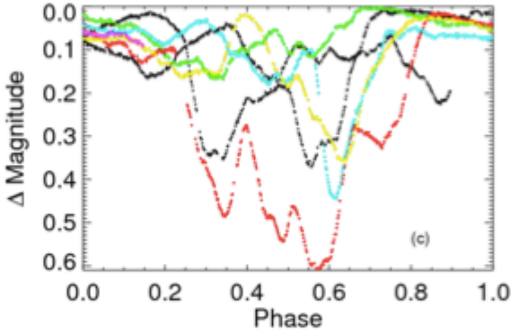
Dipper light curves (~15%) + 10% aperiodic

McGinnis et al. (2015), Sousa et al. (2015)

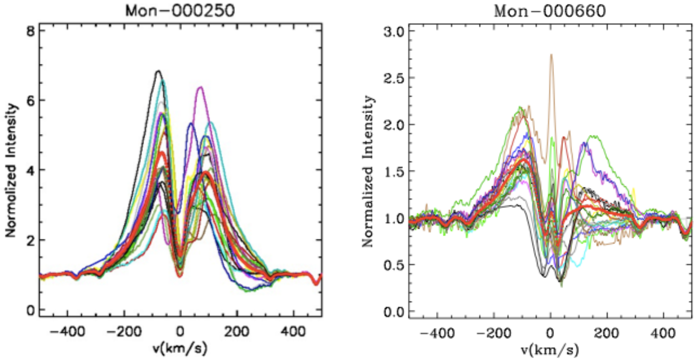
CoRoT light curve

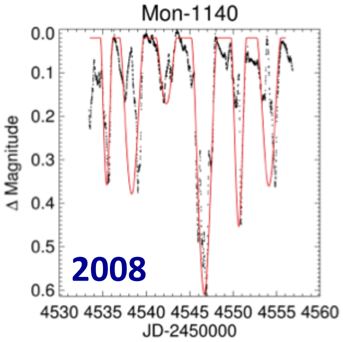


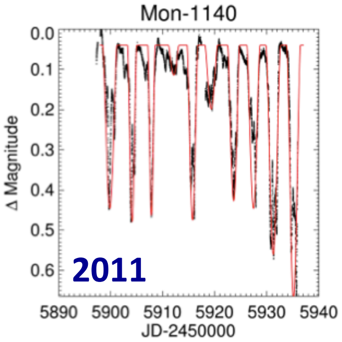
CoRoT light curve

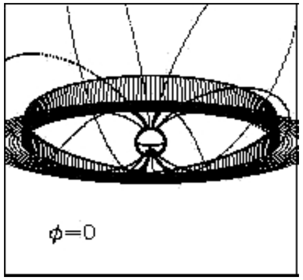


Hα profiles









Occultation models

i=75° ± 2°

2008: h/R= 0.16-0.24

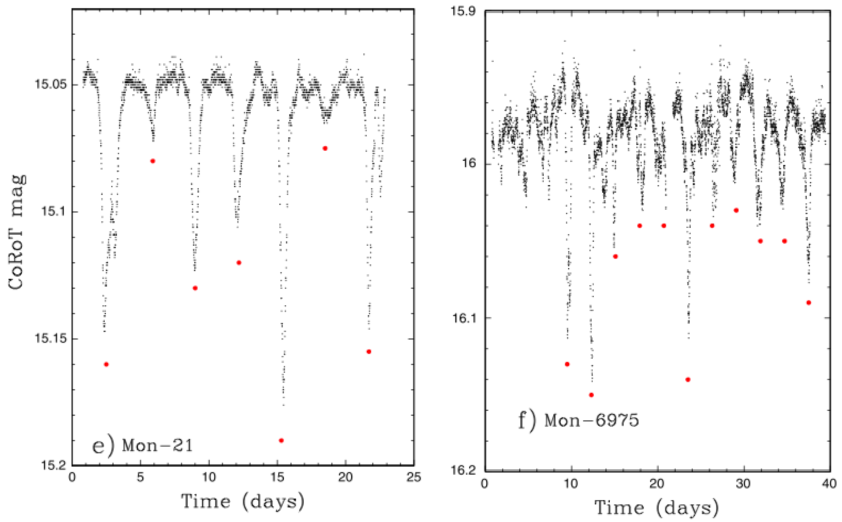
2011: h/R= 0.14-0.24

- High inclination systems
- Periodic broad dips, with periods of 3 to 10 days
- Moderate accretors
- Hα profiles present redshifted and blueshifted absorptions
- Half of the dippers changed from periodic to aperiodic in a timescale of 3 years

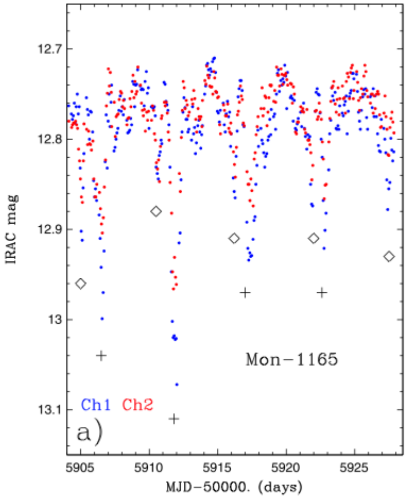
Short duration periodic dippers (~5%)

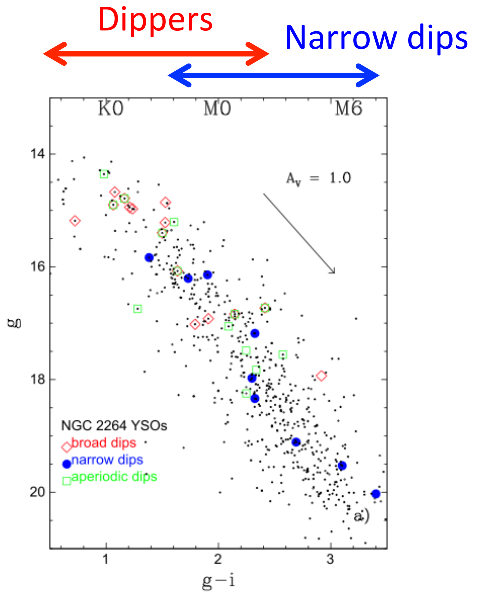
Stauffer et al. (2015)

CoRoT light curves



Spitzer



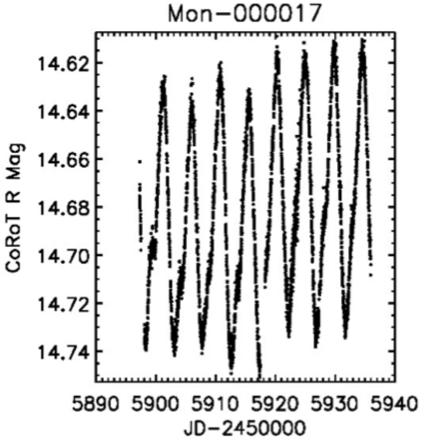


- Short duration (< 1 day) periodic dips (p=3 to 10 days)
- Low amplitude (< 15%)
- Clumps of dust close to co-rotation
- Moderate accretors
- Later SpT than the dippers on average (different magnetic field topology?)

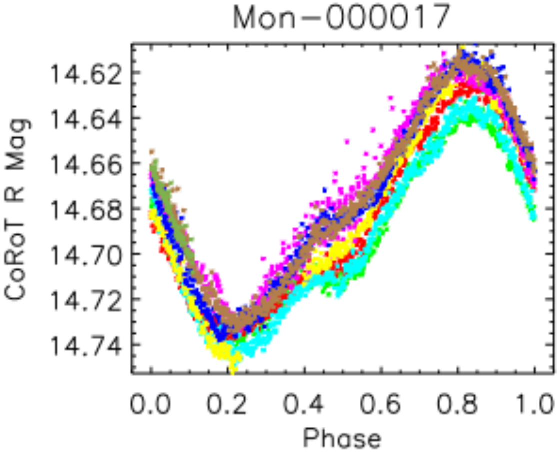
Spotted light curves (~15%)

Sousa et al. (2015)

CoRoT light curve

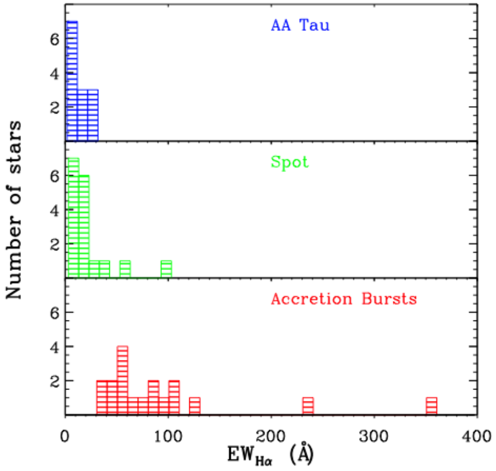


CoRoT light curve

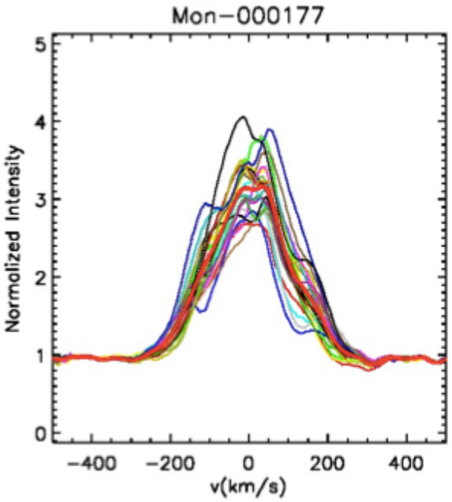


- Hot/cold spots
- Stable light curves
- Typical periods of 3 to 10 days
- Moderate accretors
- Symmetric Hα profiles
- Can change from periodic to aperiodic in 3 years

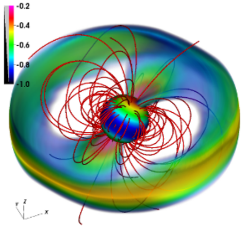
Hα EW



Hα profile

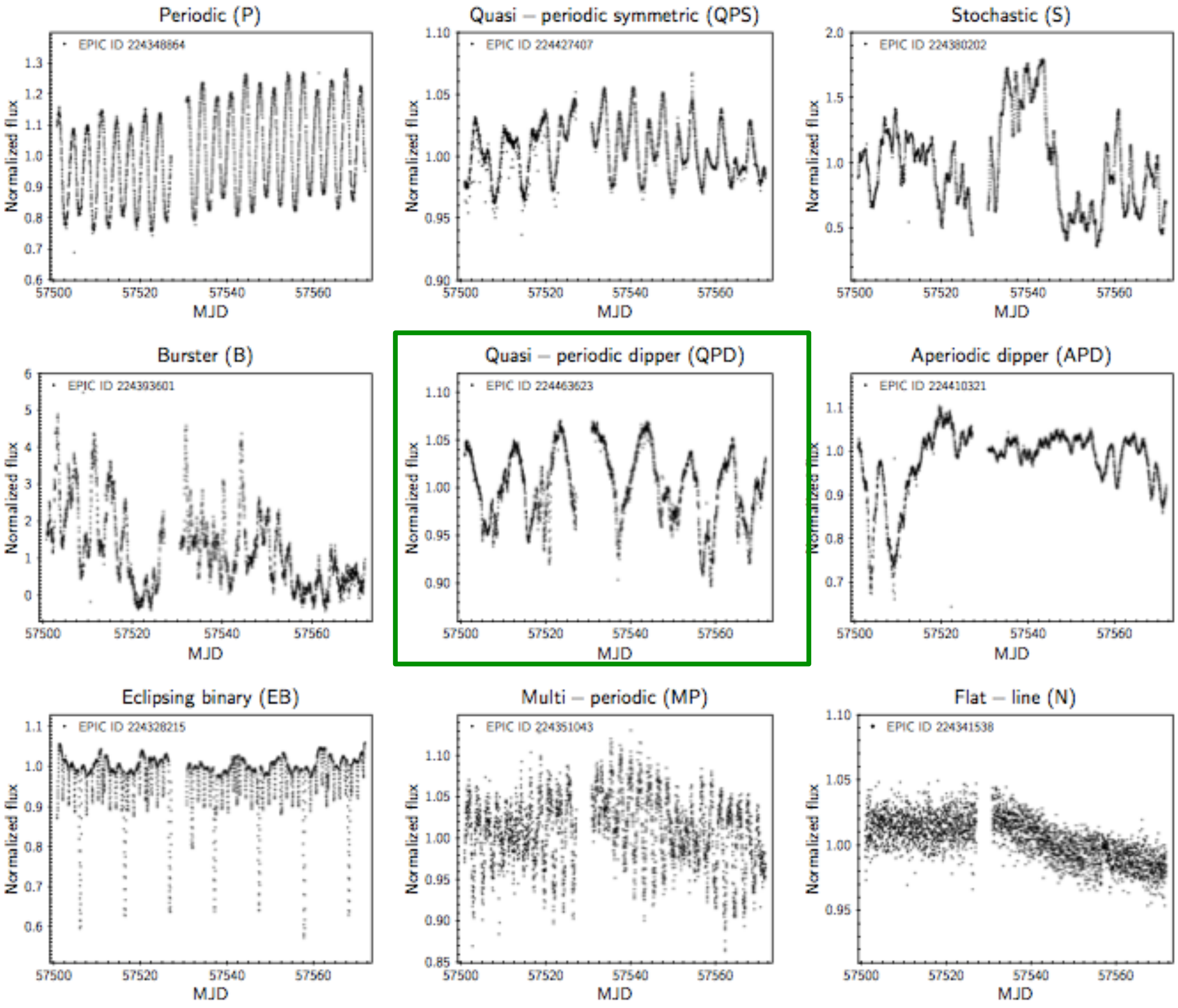


Stable funnel flows: low/moderate inclination counterparts of dippers?



Kurosawa et al. (2013)

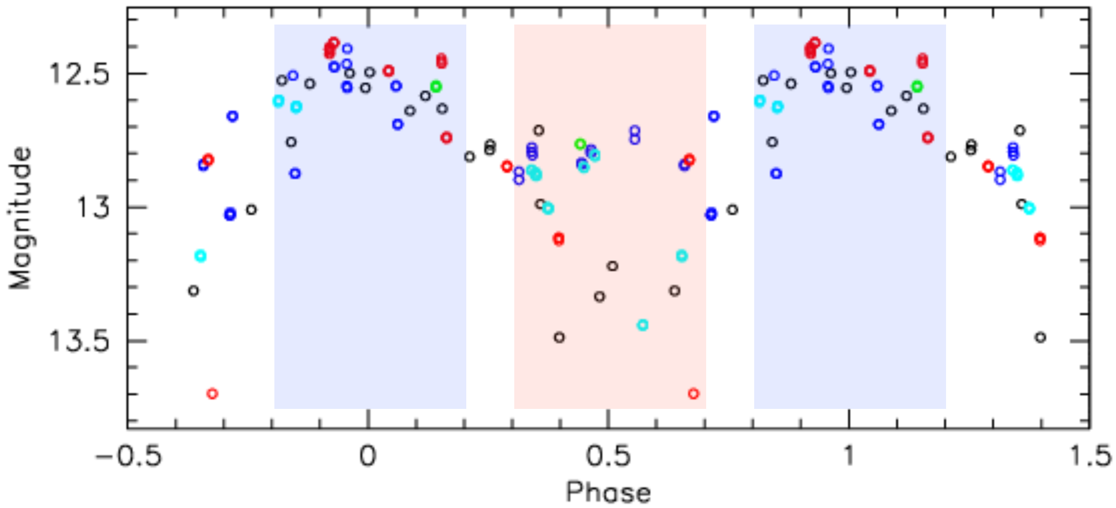
K2 light curves of young stars in the Lagoon Nebula



Venuti et al. (2021)

AA Tau: the dipper prototype

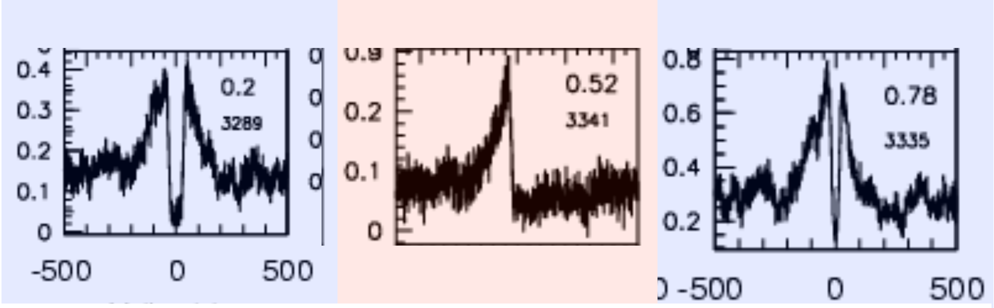
Bouvier et al. (2007)



Periodical eclipses

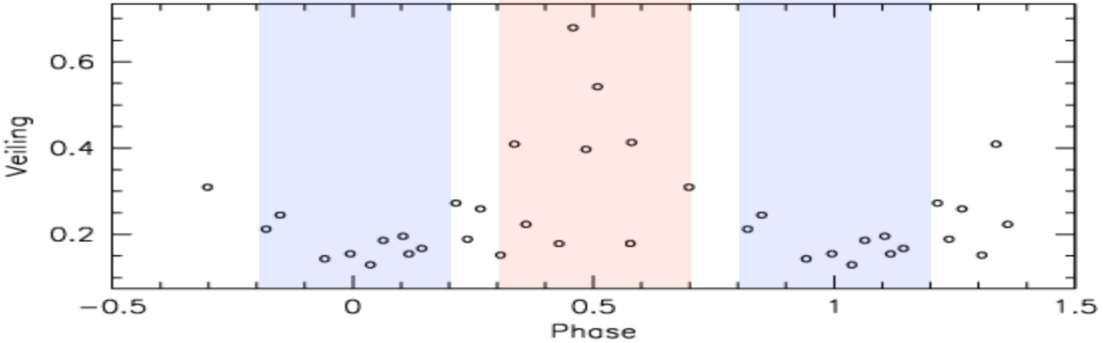
inner disk warp

P=8.22d



Balmer lines

accretion funnel

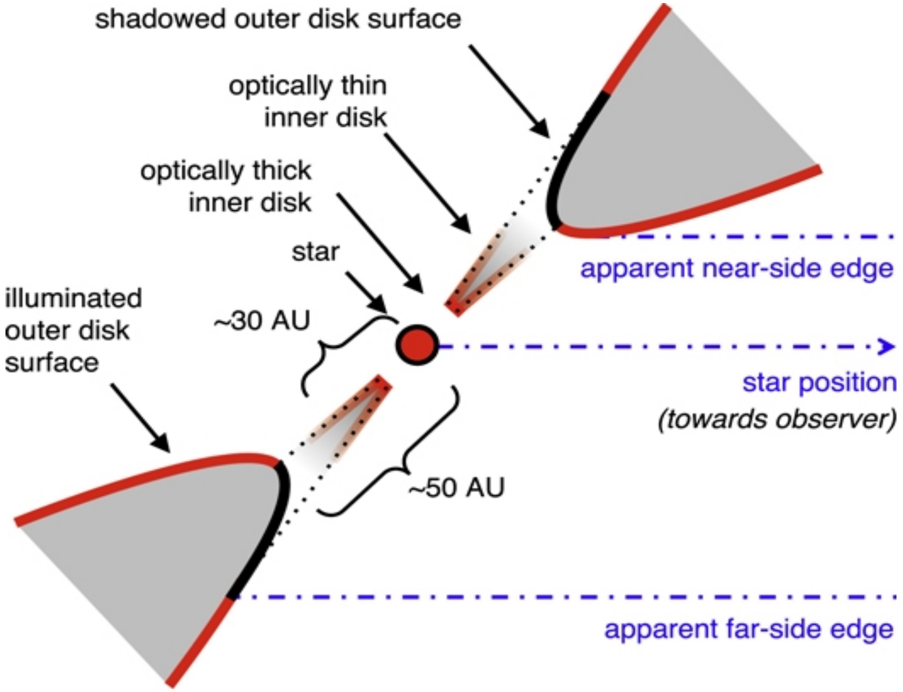


Veiling

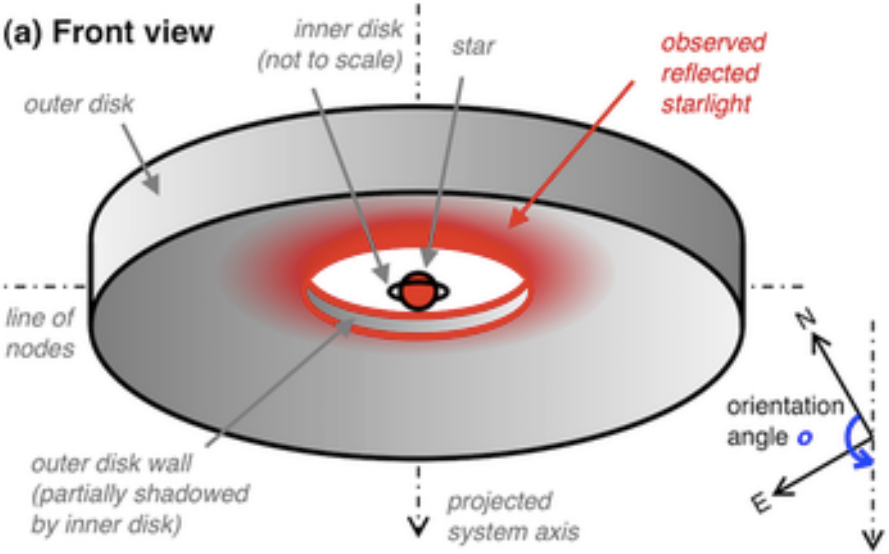
accretion shock

LkCa 15
pre-transition disk

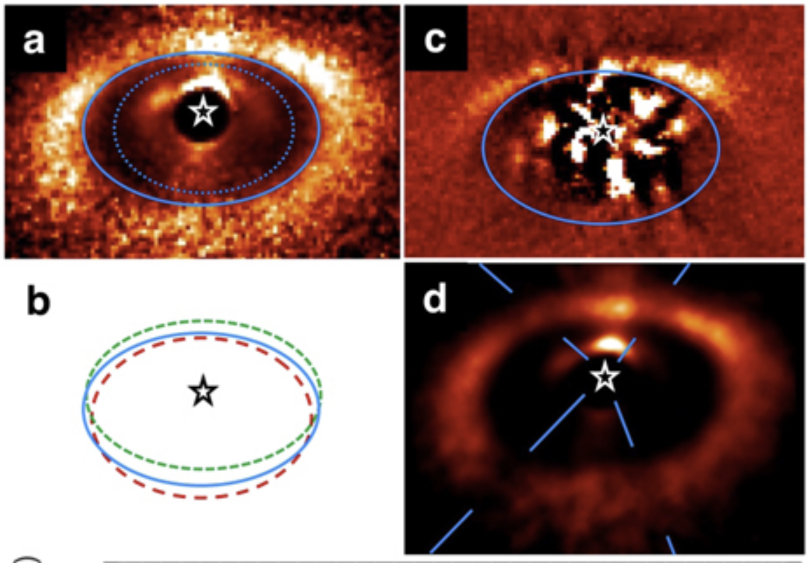
CTTS, 2 Myr, 1.1 $M_\odot$
50 au gap
i_{disk} = 44° – 50°
presence of an inner disk (shadows)



Thalmann et al. (2014, 2015)



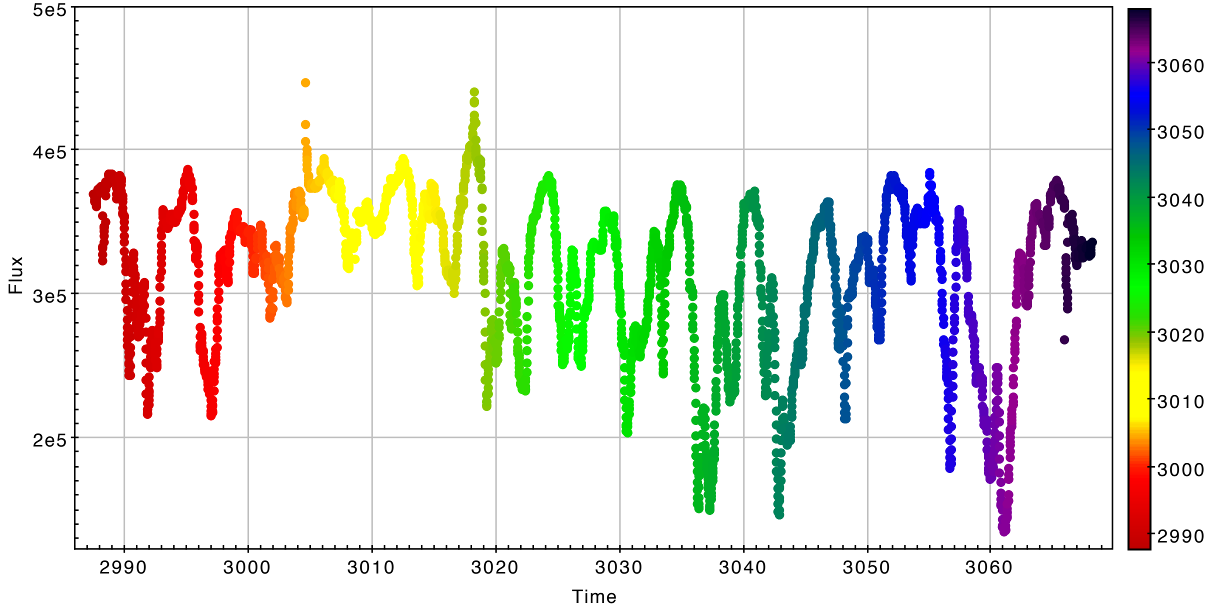
J-band polarimetric imaging with SPHERE



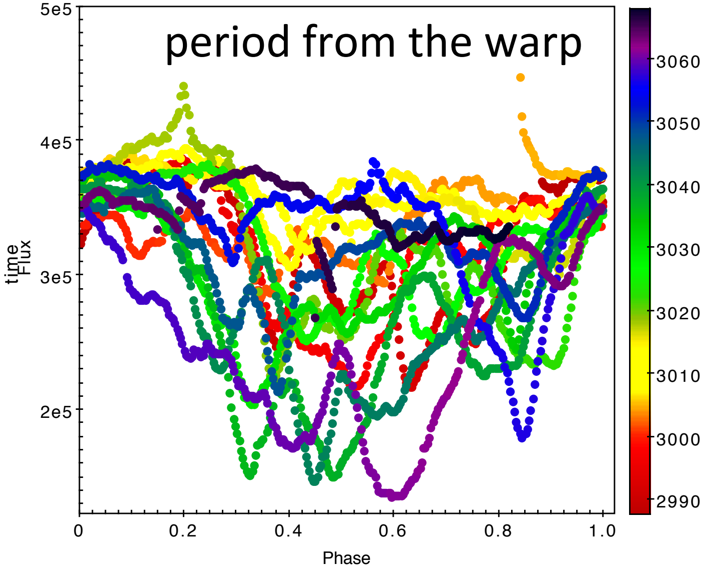
Thalmann et al. (2016)

LkCa 15 - K2 light curve

A periodic dipper!



p=5.70 days



period from the warp

Alencar et al. (2018)

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

But dippers have i ~ 55°-75° (McGinnis et al. 2015)
While LkCa 15's outer disk: i_{disk} ~ 44°-50° (Oh et al. 2016, Thalmann et al. 2014)

A tilted inner disk

vsini = 13.8 km/s, p=5.70d, R=1.5 $R_\odot$(L=0.81 $L_\odot$, Teff=4492 K)→ i > 64°

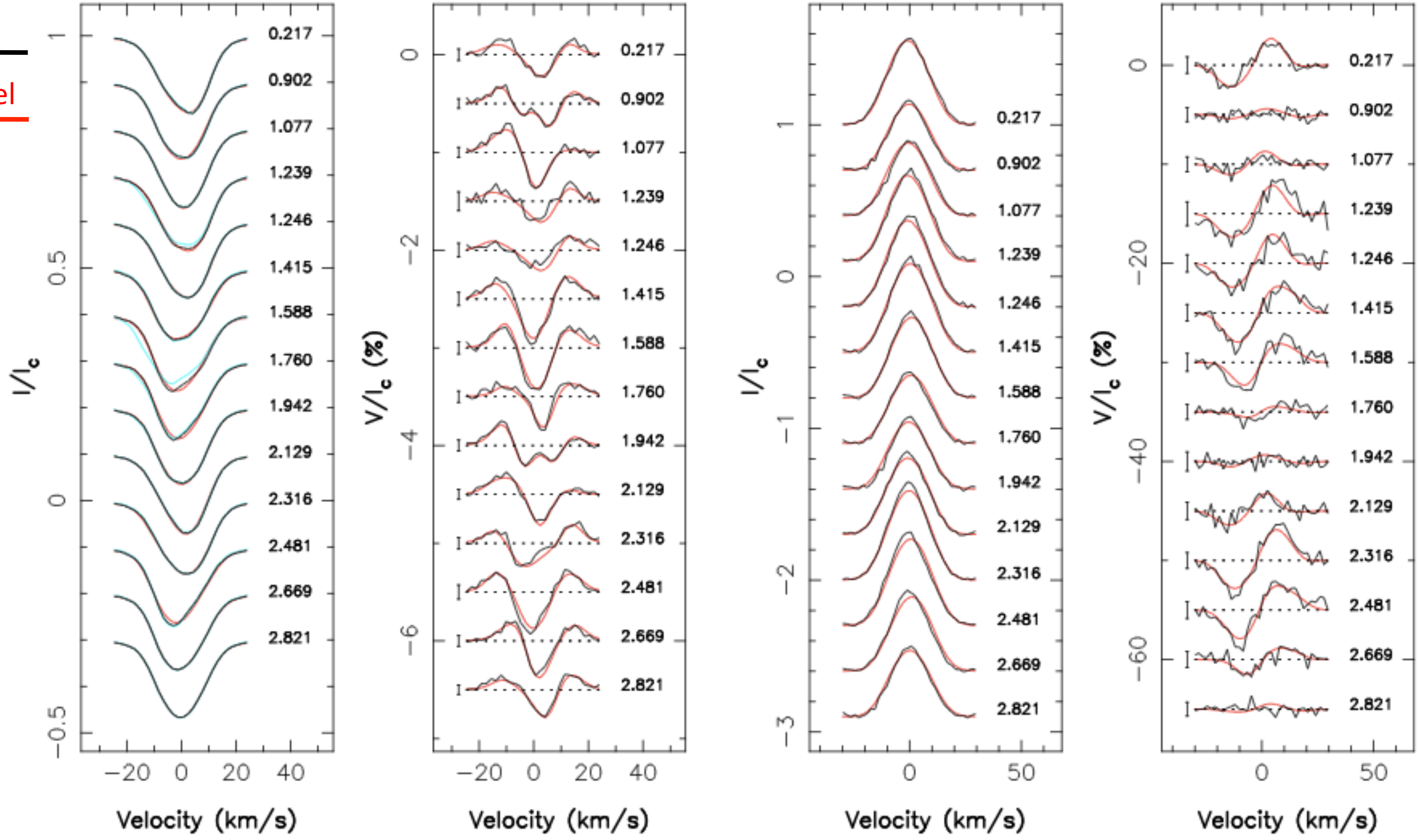
LkCa 15 – Magnetic field

Non-accreting regions – LSD profiles

Accreting regions – Ca II profiles

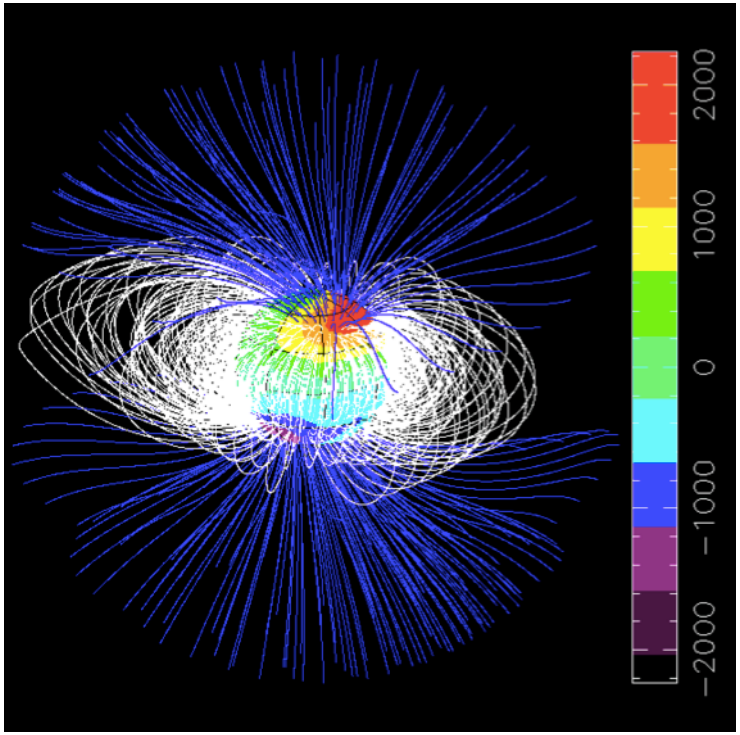
data

model

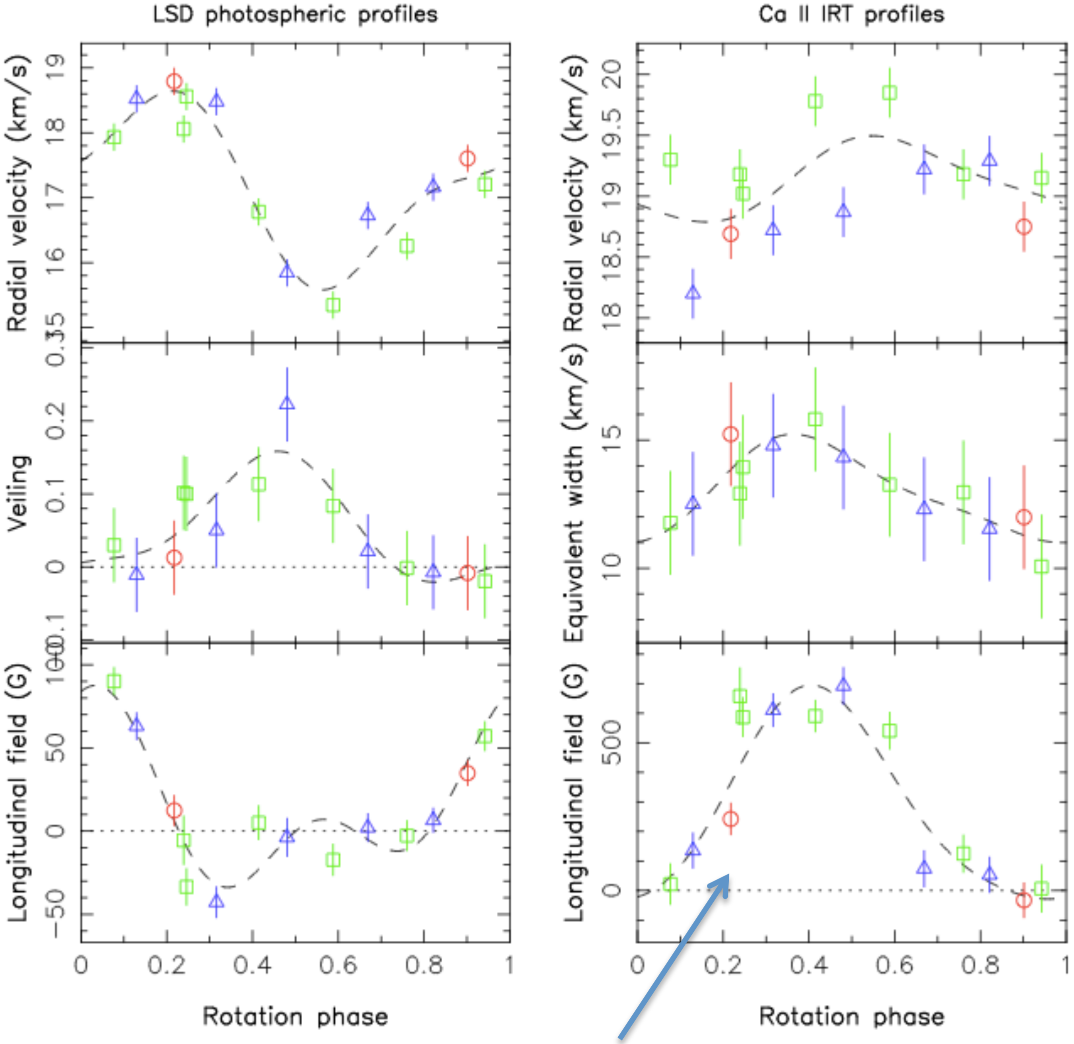


Donati et al. (2018)

LkCa 15 – Magnetic field



In phase with p=5.70d



Axisymmetric, poloidal magnetic field, dominated by the 1.35 kG dipole

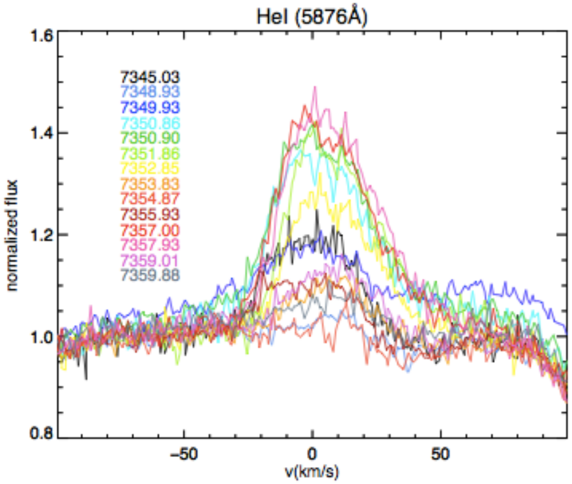
Donati et al. (2018)

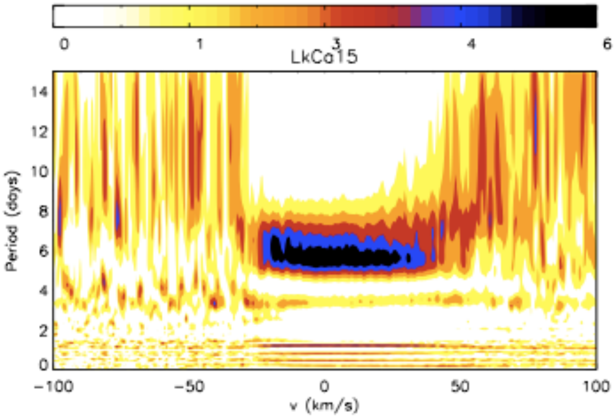
Needs i > 70°

LkCa 15 - HeI 5876Å

Hot spot

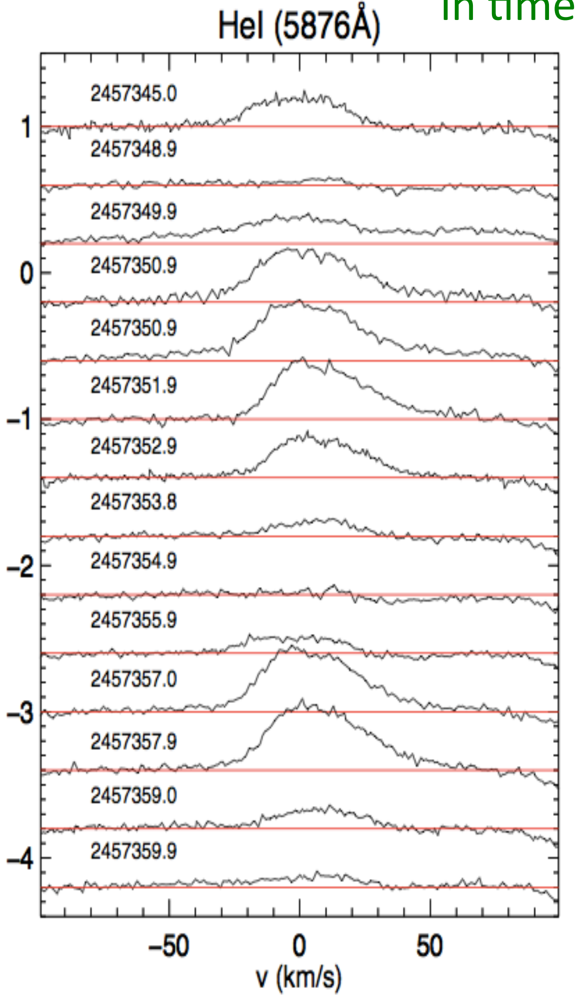
2015B – 14 spectra



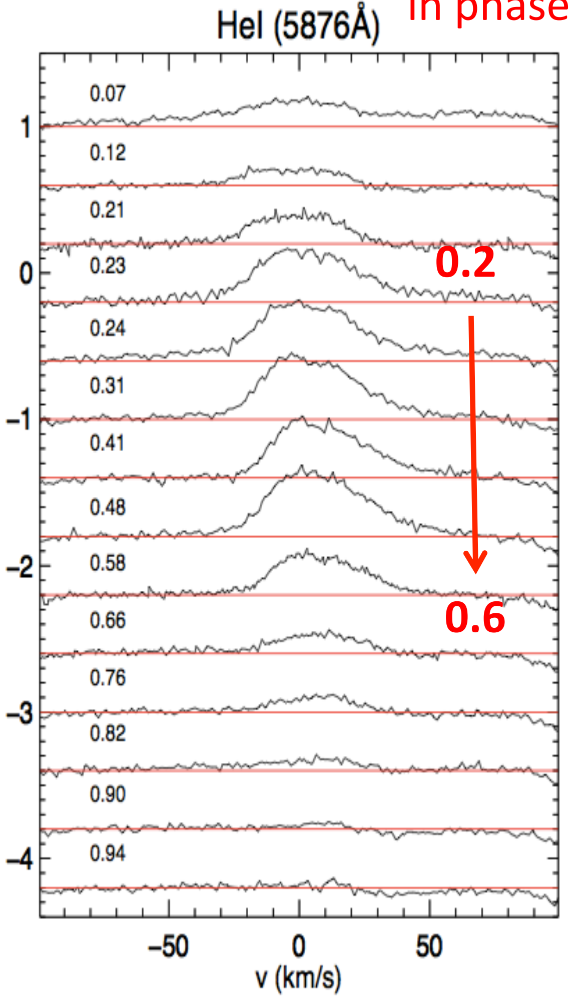


P=5.6 ± 0.7 days

in time



in phase



0.2

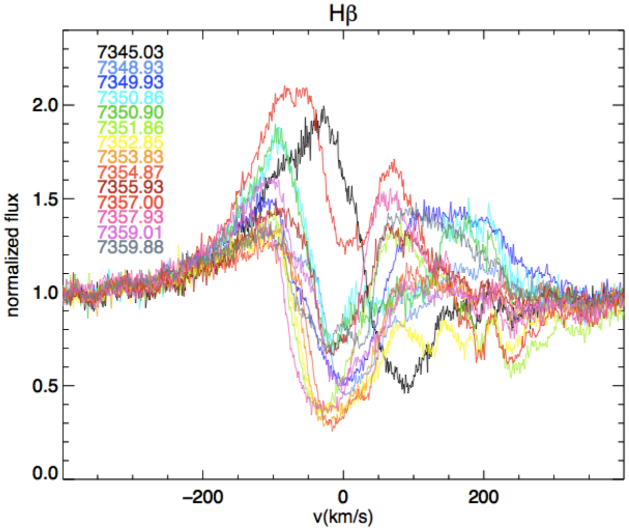
0.6

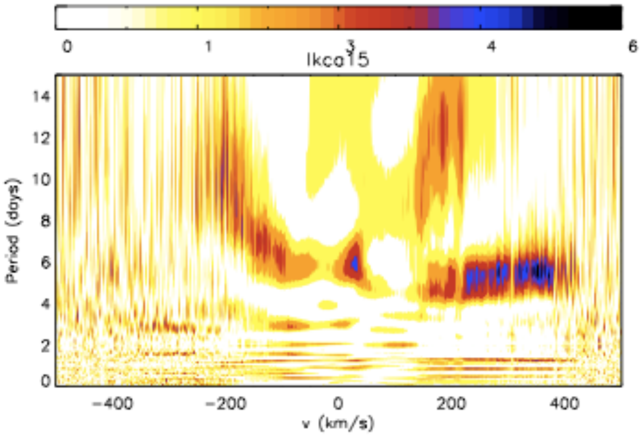
Alencar et al. (2018)

LkCa 15 - Hβ

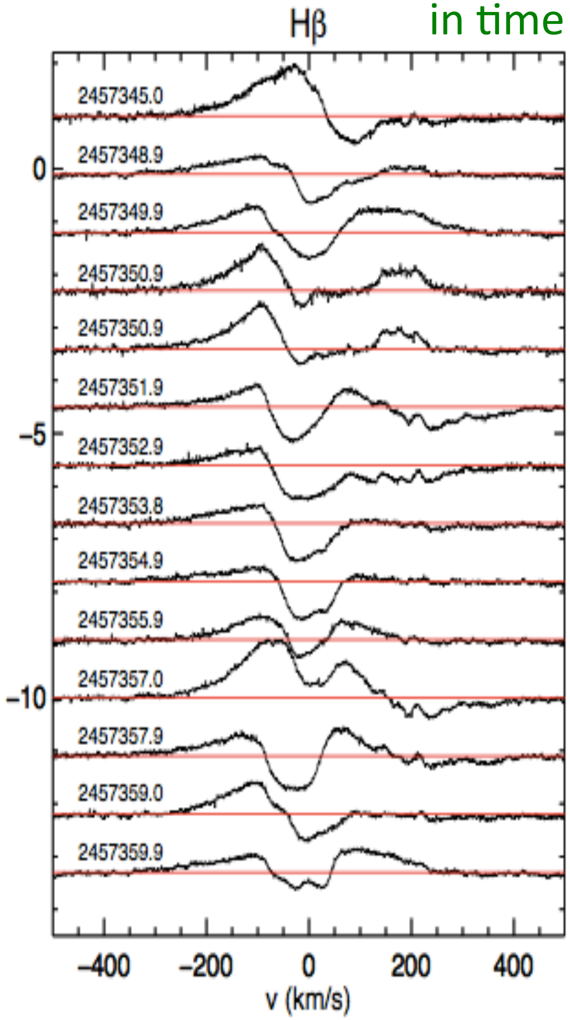
Accretion column

2015B – 14 spectra

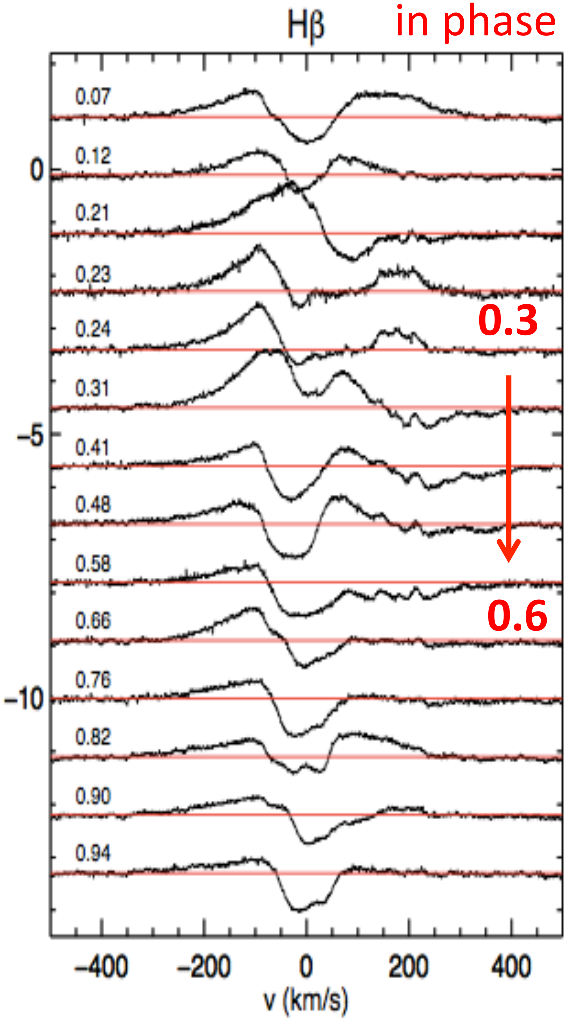




P=5.6 ± 0.7 days



in time



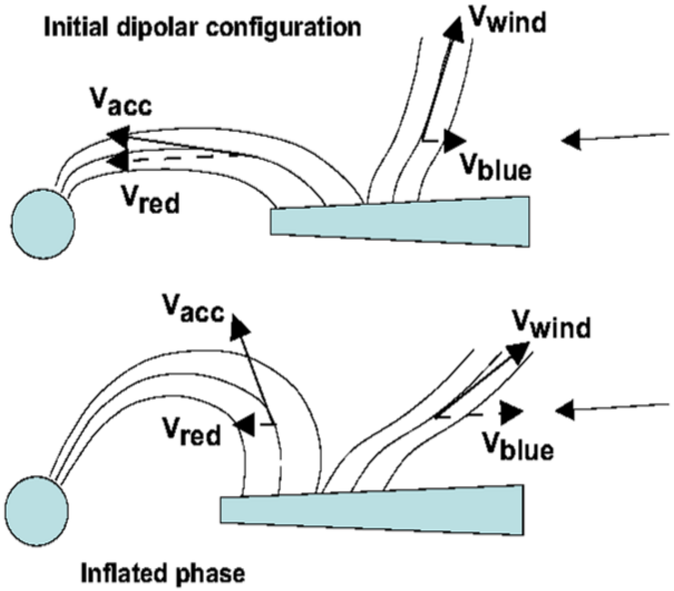
in phase

0.3

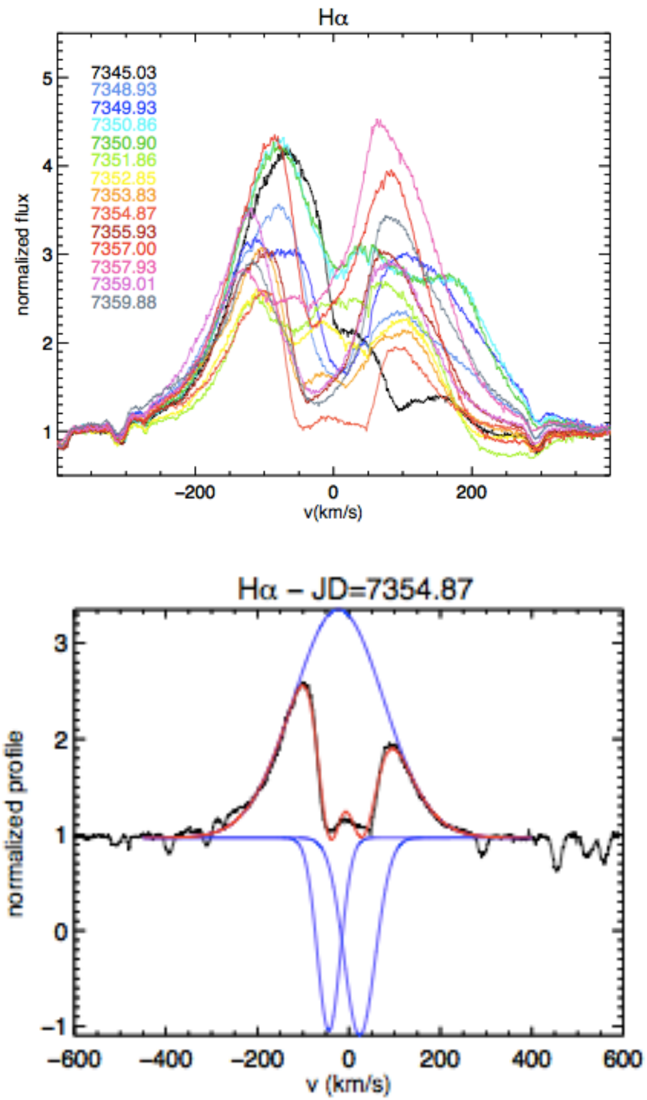
0.6

Alencar et al. (2018)

LkCa 15
Field line inflation



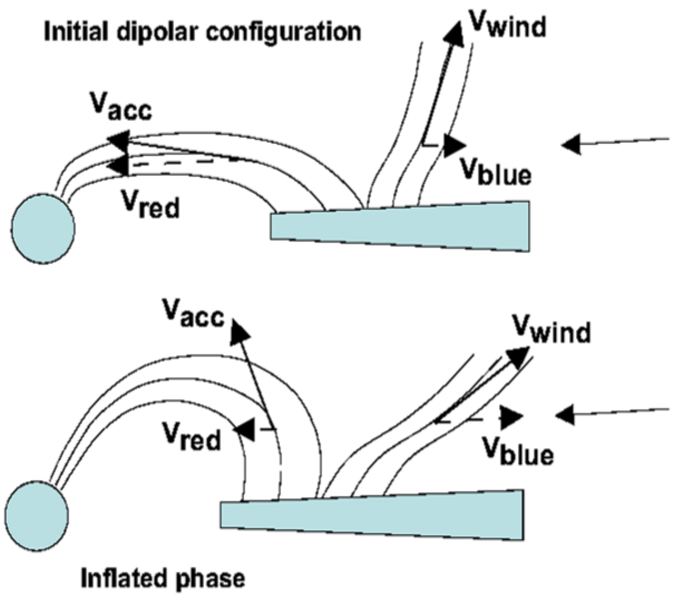
Bouvier et al. (2003)



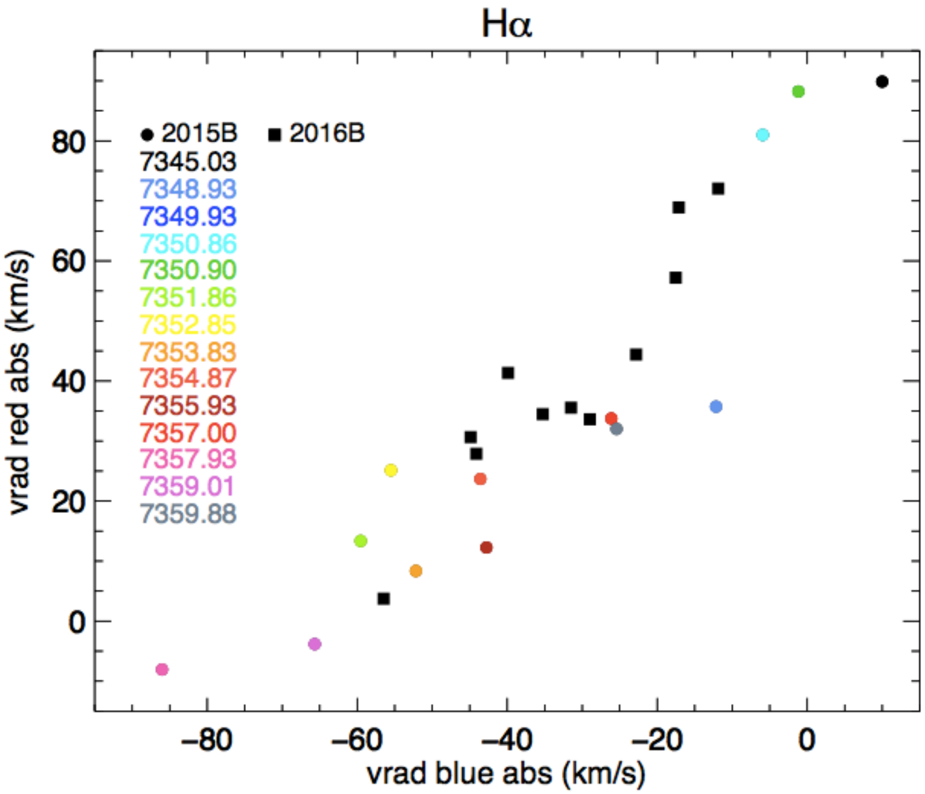
The projected radial velocity of the absorption components of Hα measures the field line inflation

Alencar et al. (2018)

LkCa 15
Field line inflation



Bouvier et al. (2003)



Alencar et al. (2018)

The projected radial velocity of the absorption components of Hα measures the field line inflation

LkCa 15

- LkCa 15 is a periodic dipper
- Poloidal stellar magnetic field, with a strong dipole (1.35 kG)
- The magnetospheric cavity reaches out to the co-rotation radius
- Observational relation between the inner disk warp, accretion columns and accretion shock, mediated by the stellar magnetic field
- Dynamical star-disk interaction
- Magnetic field line inflation
- Misaligned inner disk by 15^{o}-25^{o} inside the 50 au disk gap

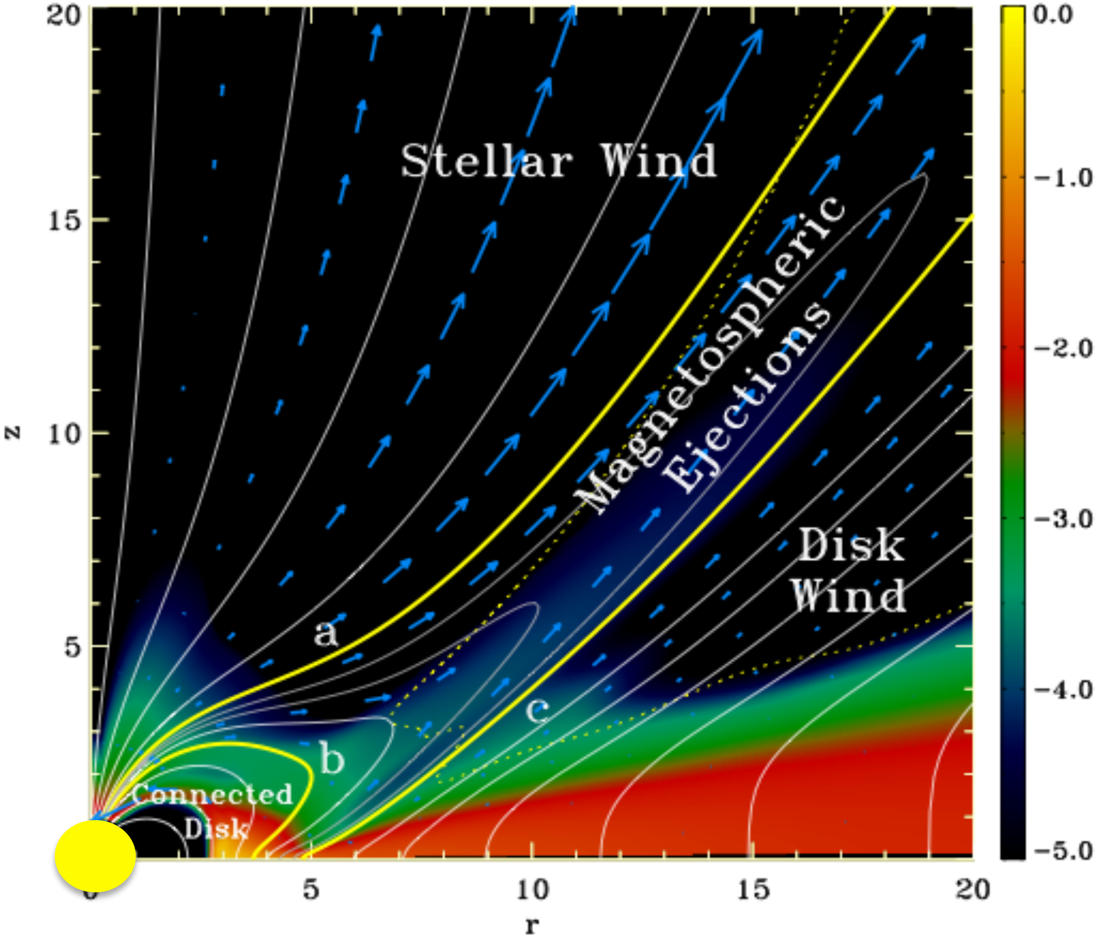
Linking the small scales to the large scales

Outline

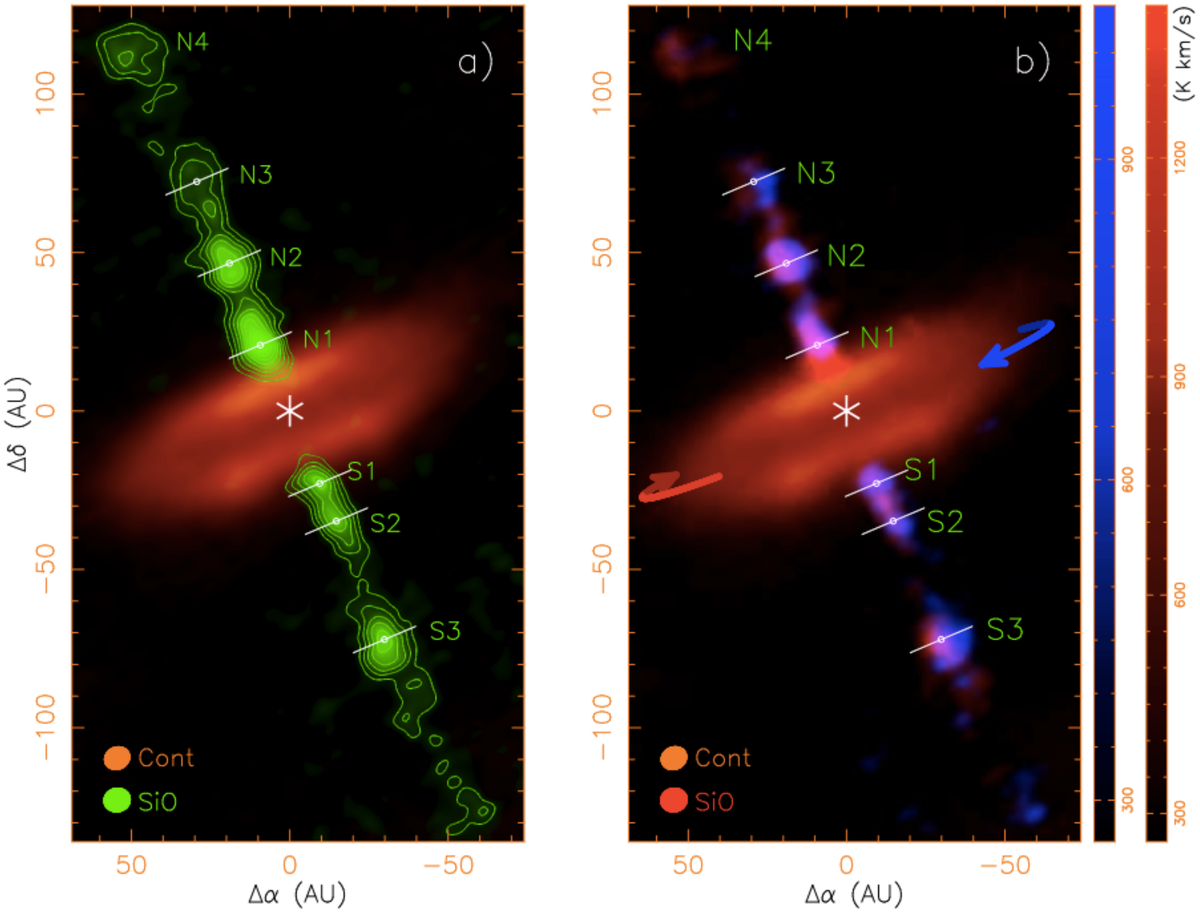
- From clouds to star-disk systems
- T Tauri stars
  - ✓ Disks
  - ✓ Magnetospheric accretion models
  - ✓ Stellar magnetic fields
  - ✓ Star-disk interactions
  - ✓ Outflows
  - ✓ Young planets
- Perspectives

Accretion and outflow in MHD simulations

Zanni & Ferreira (2013)



Spinning jet from the Orion Class 0 protostar HH 212



ALMA map of the jet in SiO, at an angular resolution of ~8 au on top of dust continuum map of the disk with 60 au radius. The measured rotational velocities are consistent with jet launching at ~0.05 au in the disk (Lee et al. 2017)

Cartoon of the innermost region of HH 212

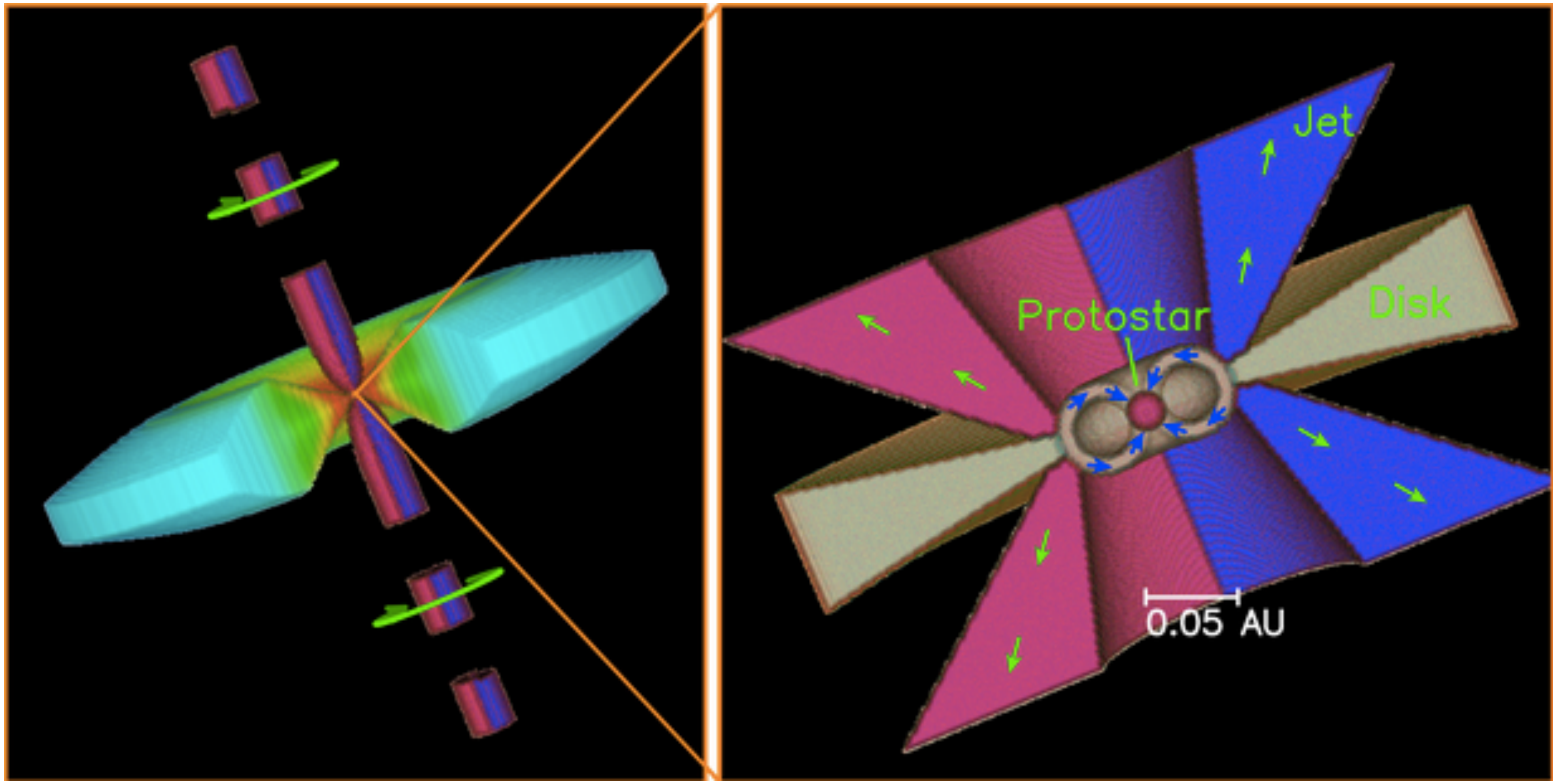
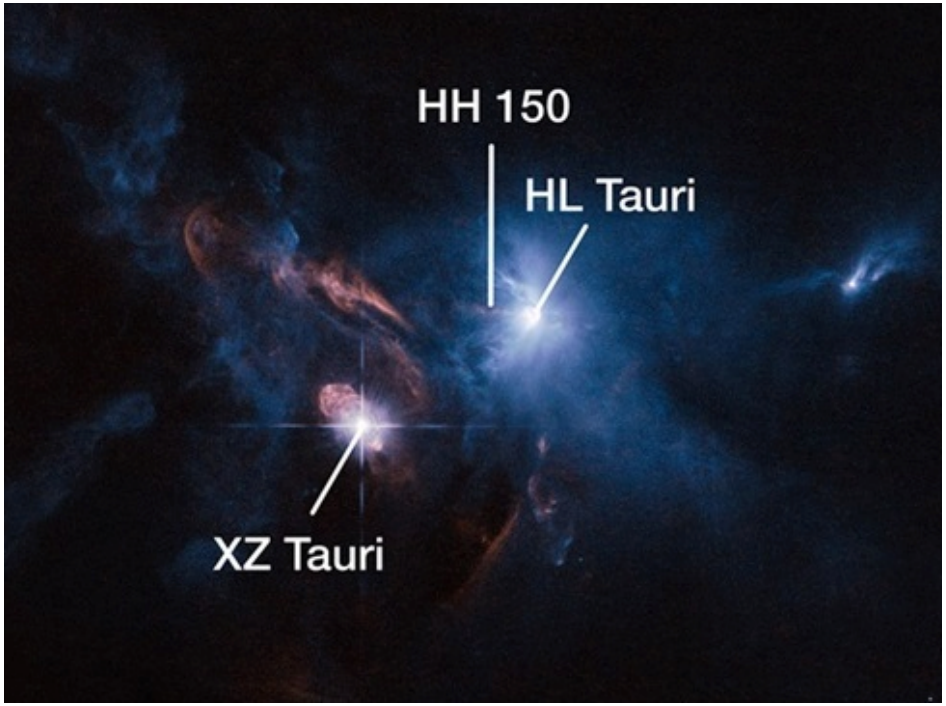


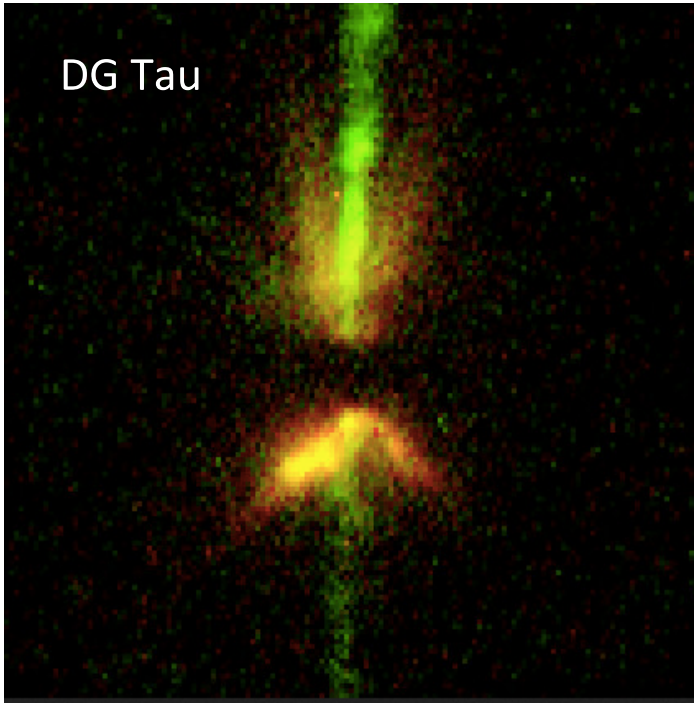
Figure from ALMA press release

Highly collimated protostellar jets remove the residual angular momenta at the ~ 0.05 AU scale, enabling the material in the innermost region of the disk to accrete toward the central protostar (Lee at al. 2017).

Jets from Classical T Tauri stars

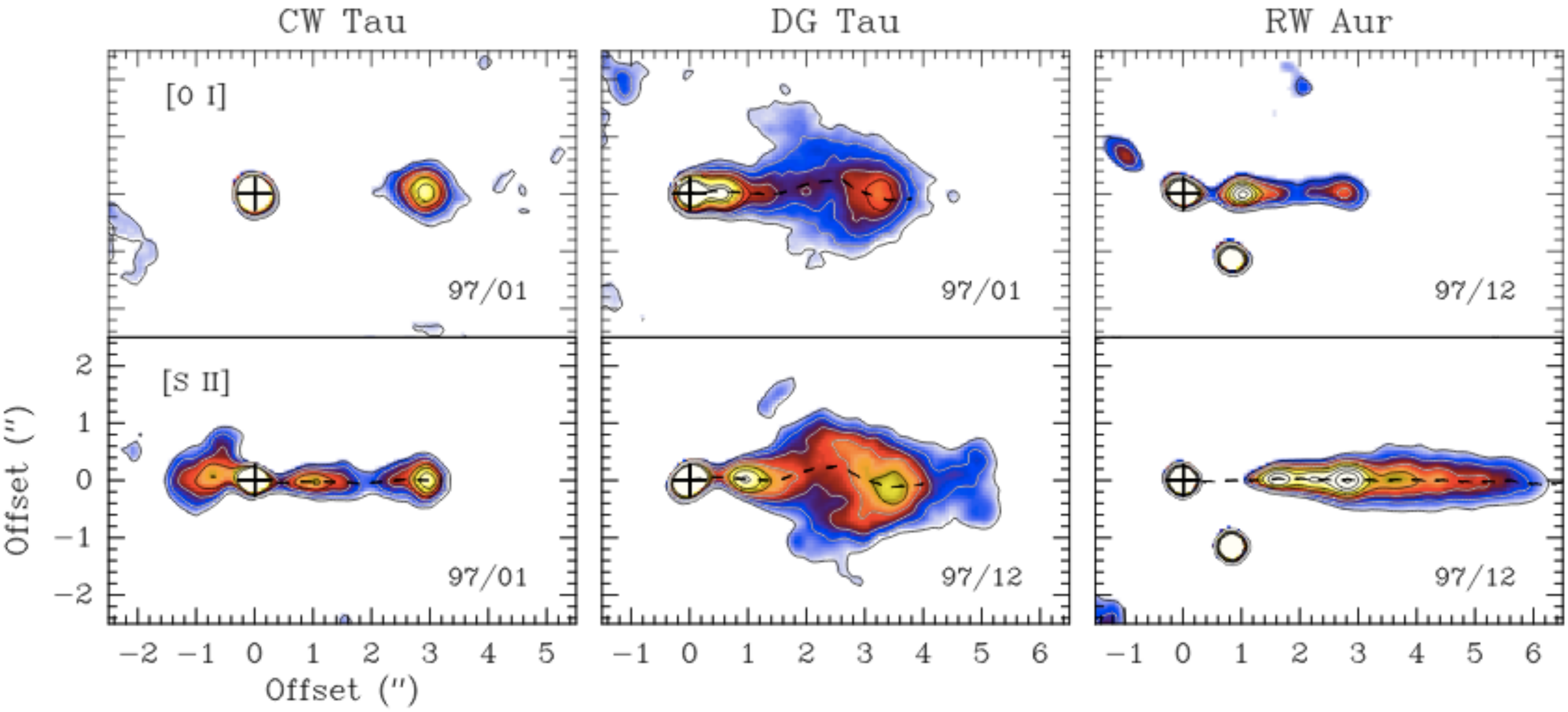


Judy Schmidt, ALMA (ESO/NAOJ/NRAO), ESA/ Hubble and NASA



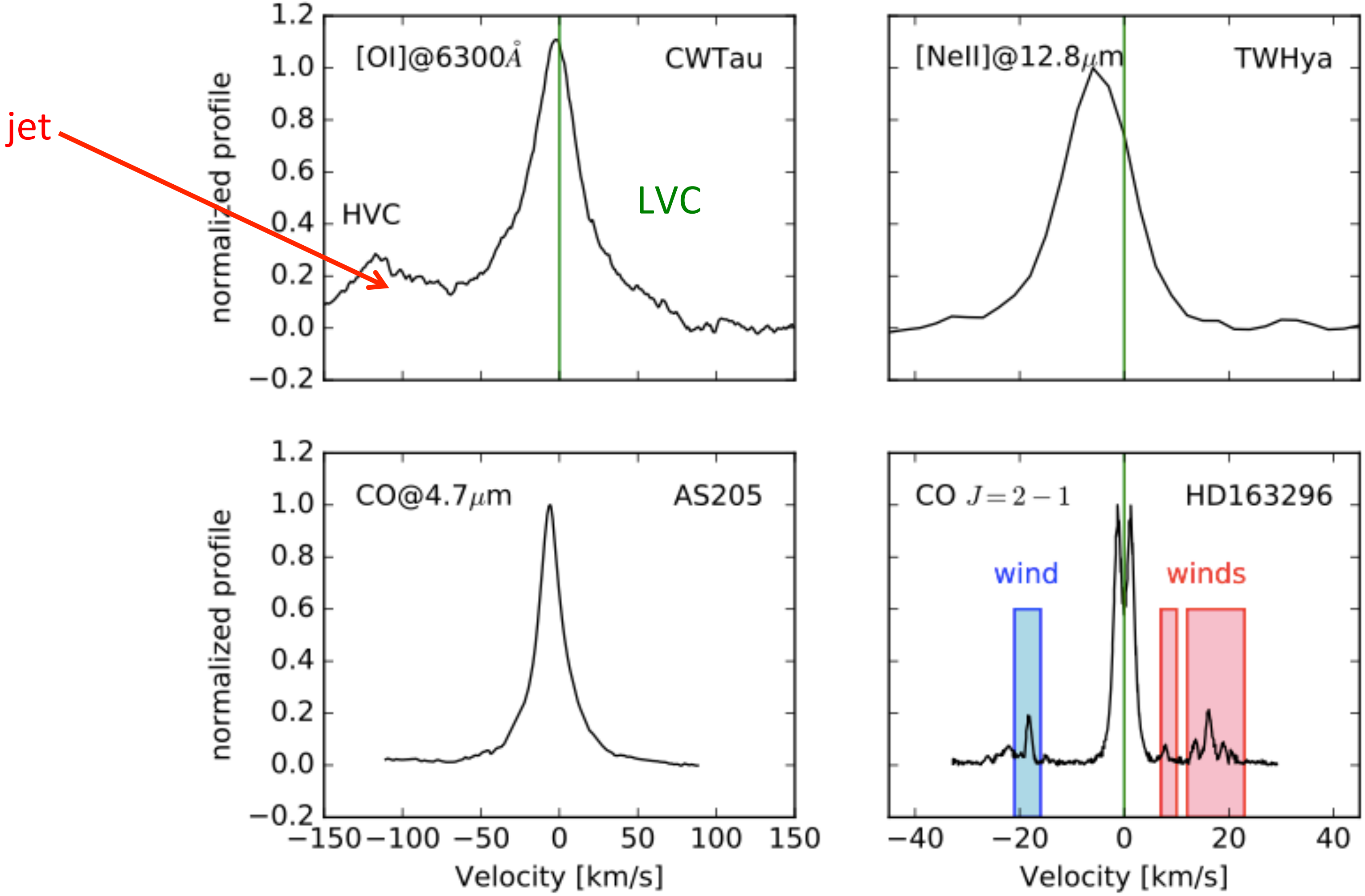
Chris Burrows (STScI), the WFPC2 Science Team and NASA/ESA

Jets from Classical T Tauri stars



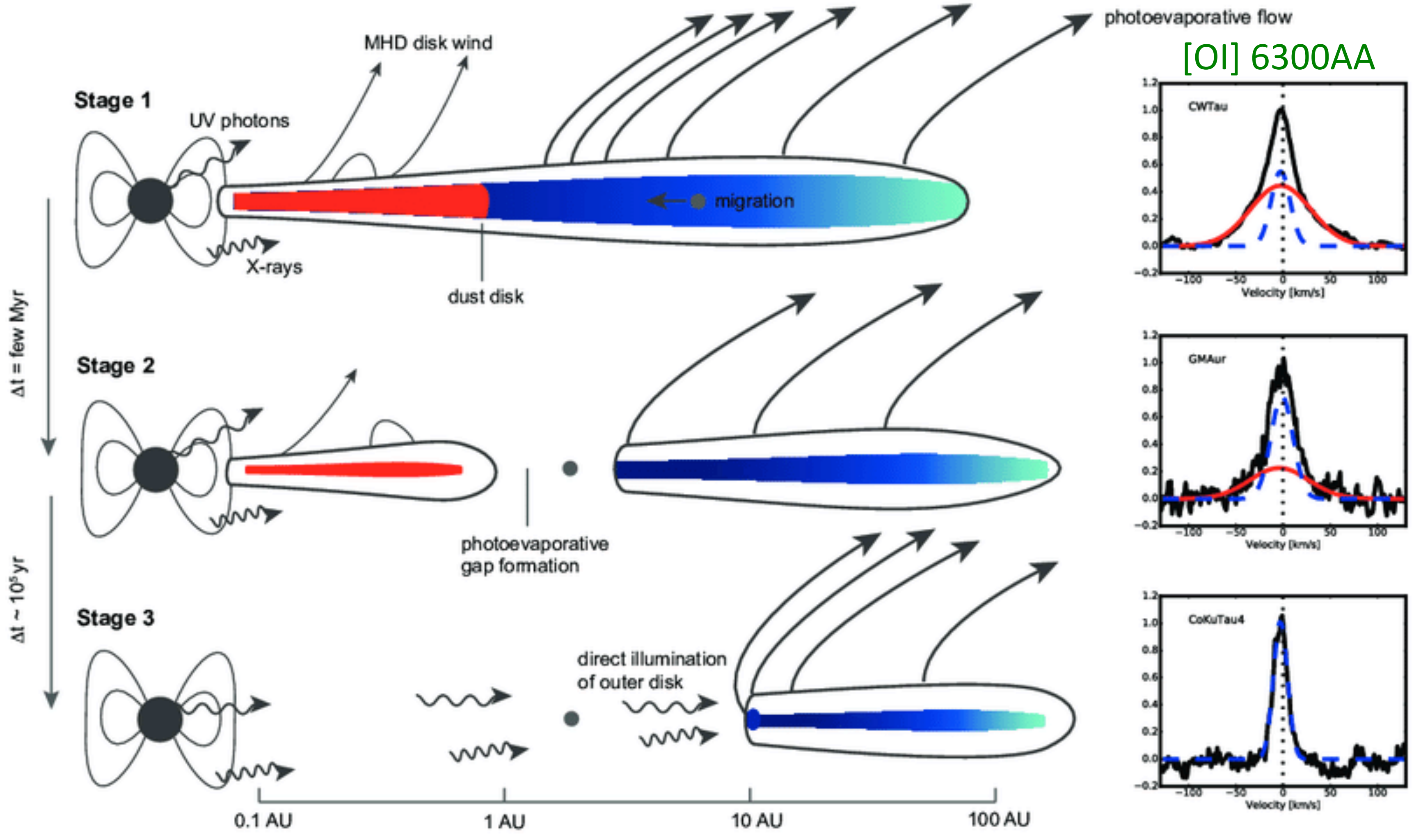
Dougados et al. (2000)

Examples of diskwind diagnostics



Blueshifted low-velocity emission is indicative of unboud gas. Molecular tracers of outflows probe a low velocity component whose intensity decreases while the opening angle increases from Class 0 to Class II (Ercolano & Pascucci 2017).

Origin of the NC – Photoevaporative winds?



[OI] 6300AA

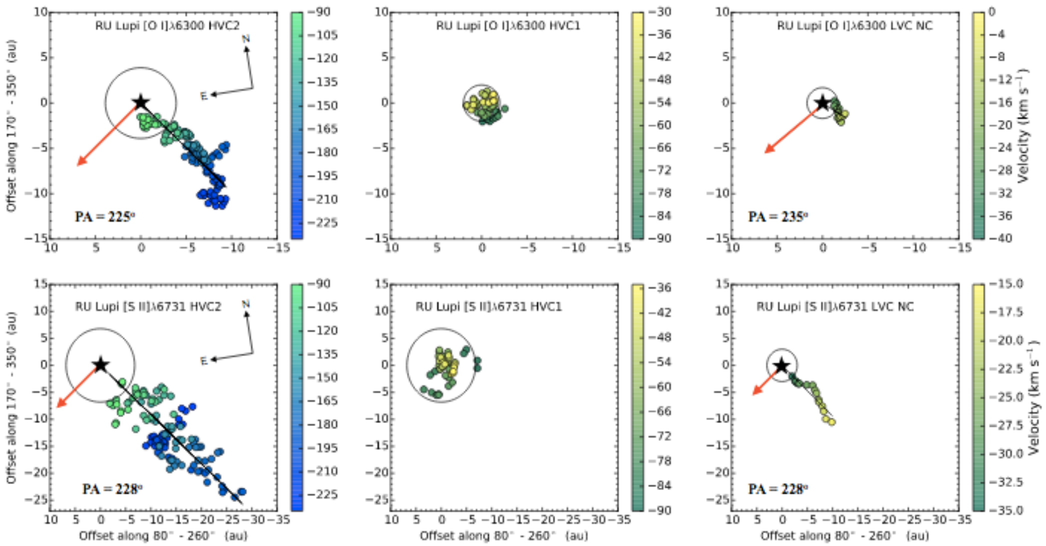
Ercolano & Pascucci (2017)

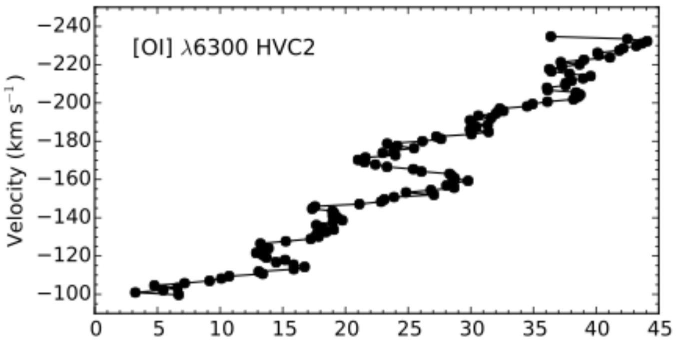
Origin of the NC – MHD diskwind?

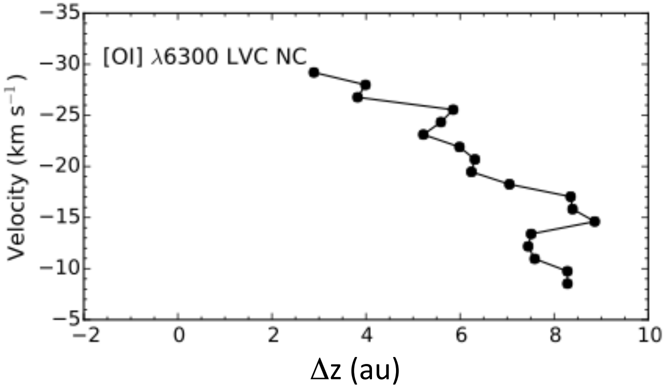
RU Lup

UVES Spectro-astrometry

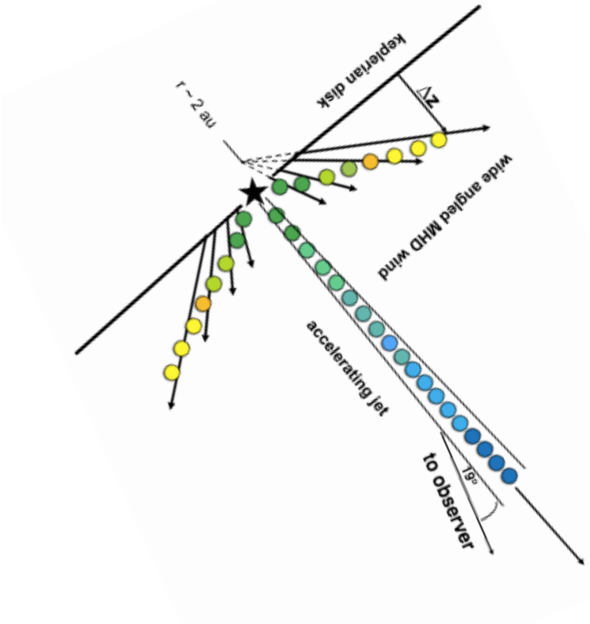
MHD diskwind origin for the LVC







Whelan et al. (2021)

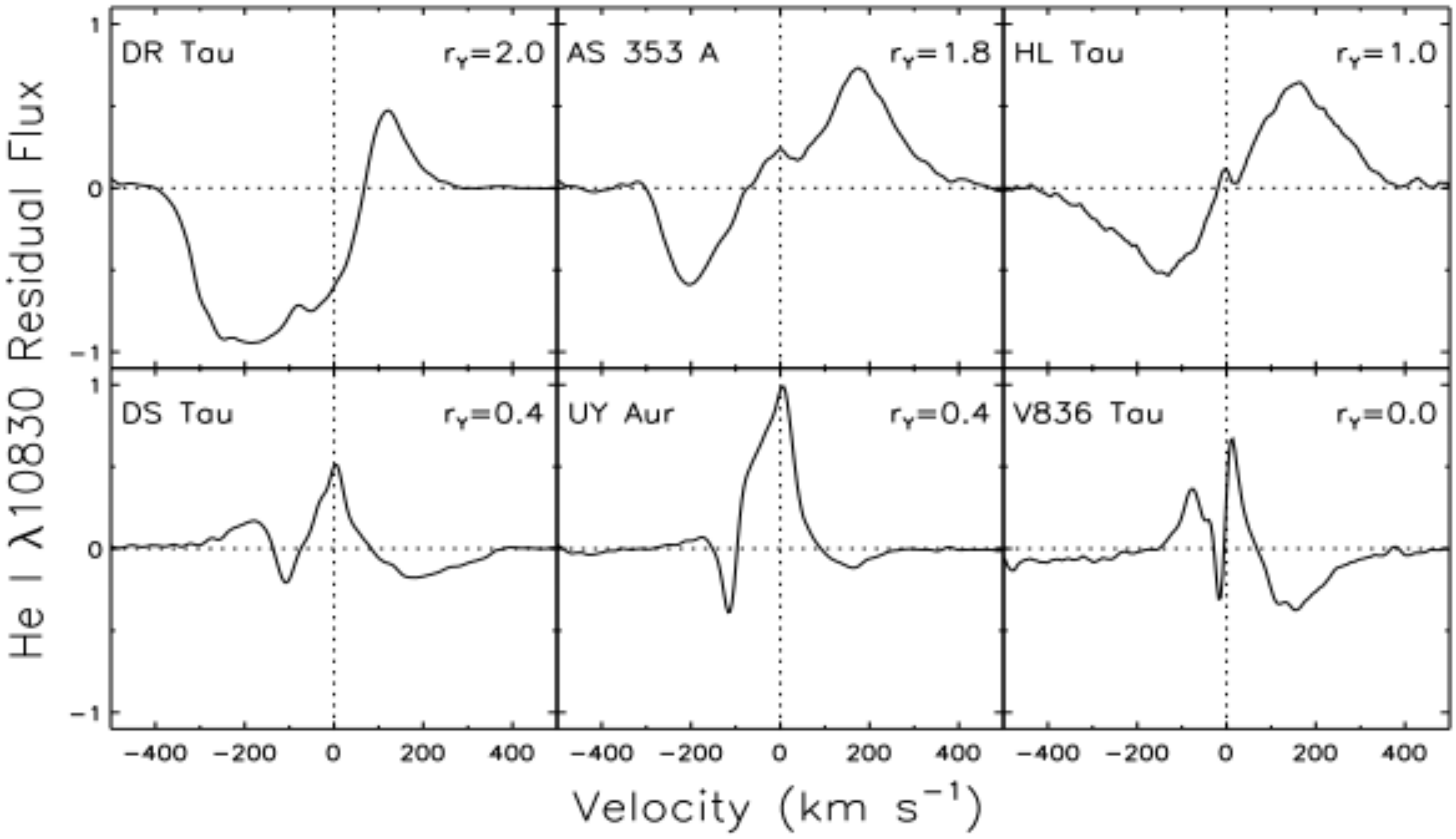


NC offset along the same PA as the HVC from the jet.

NC displacement from the star along the rotation axis is increasing with decreasing velocity.

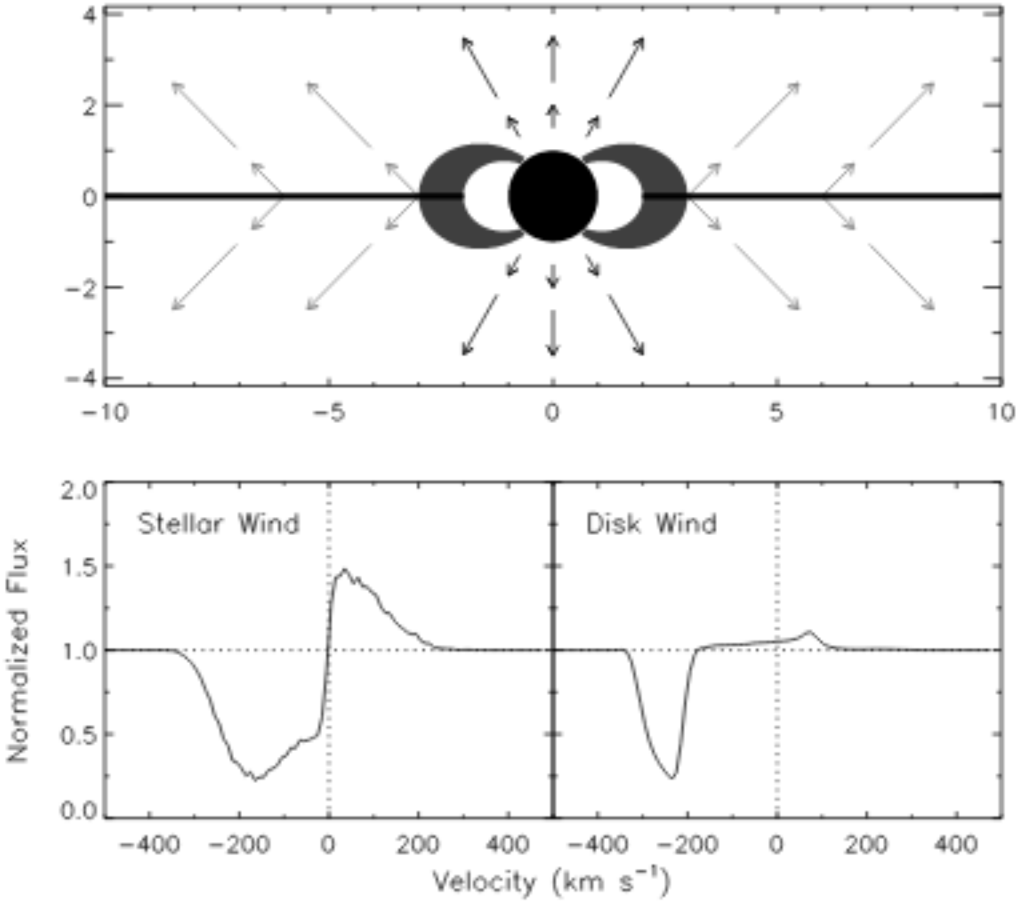
NC traces a wide angle MHD diskwind.

Wind diagnostic with the HeI line at 1.08 μm



Edwards (2007, 2009)

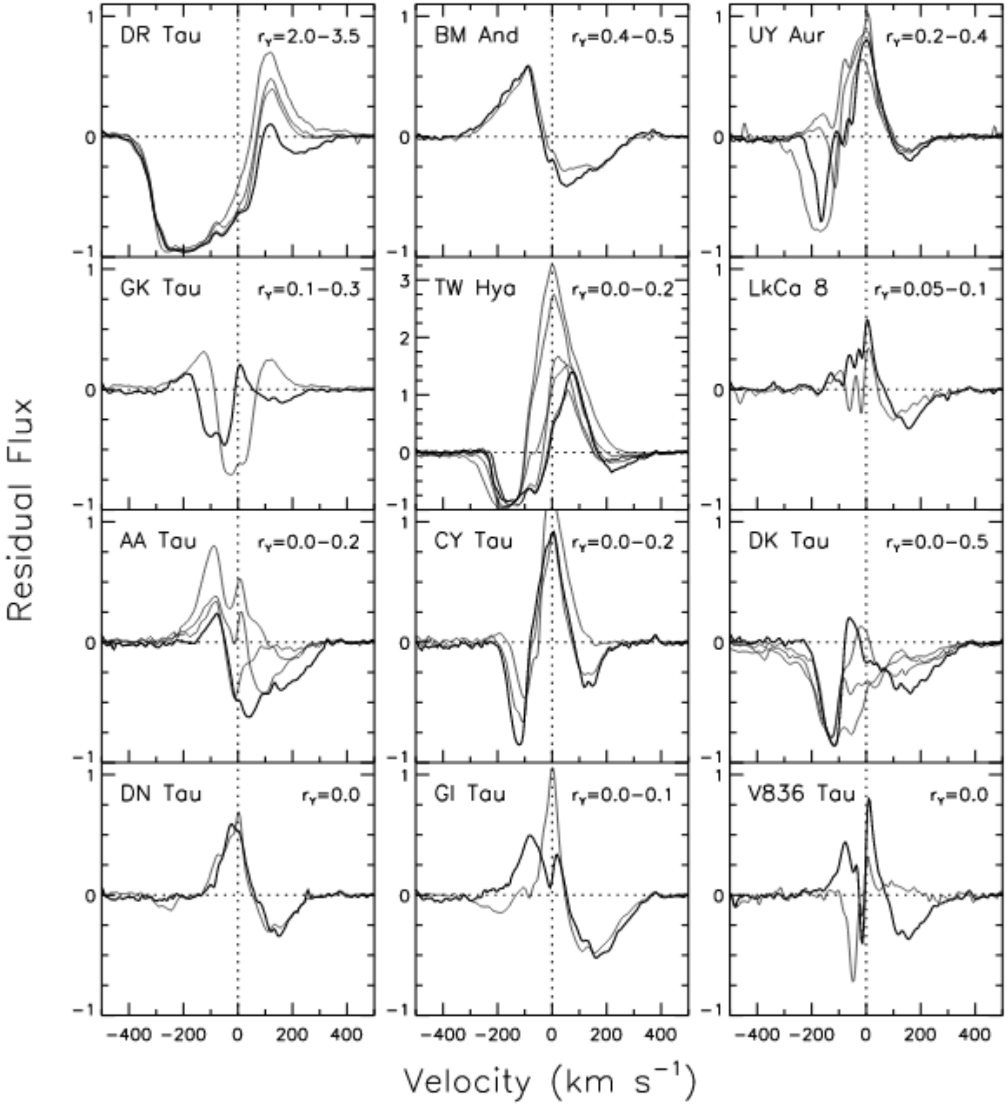
Wind diagnostic with the HeI line at 1.08 μm



Edwards (2007, 2009)

Accretion and outflow dynamics

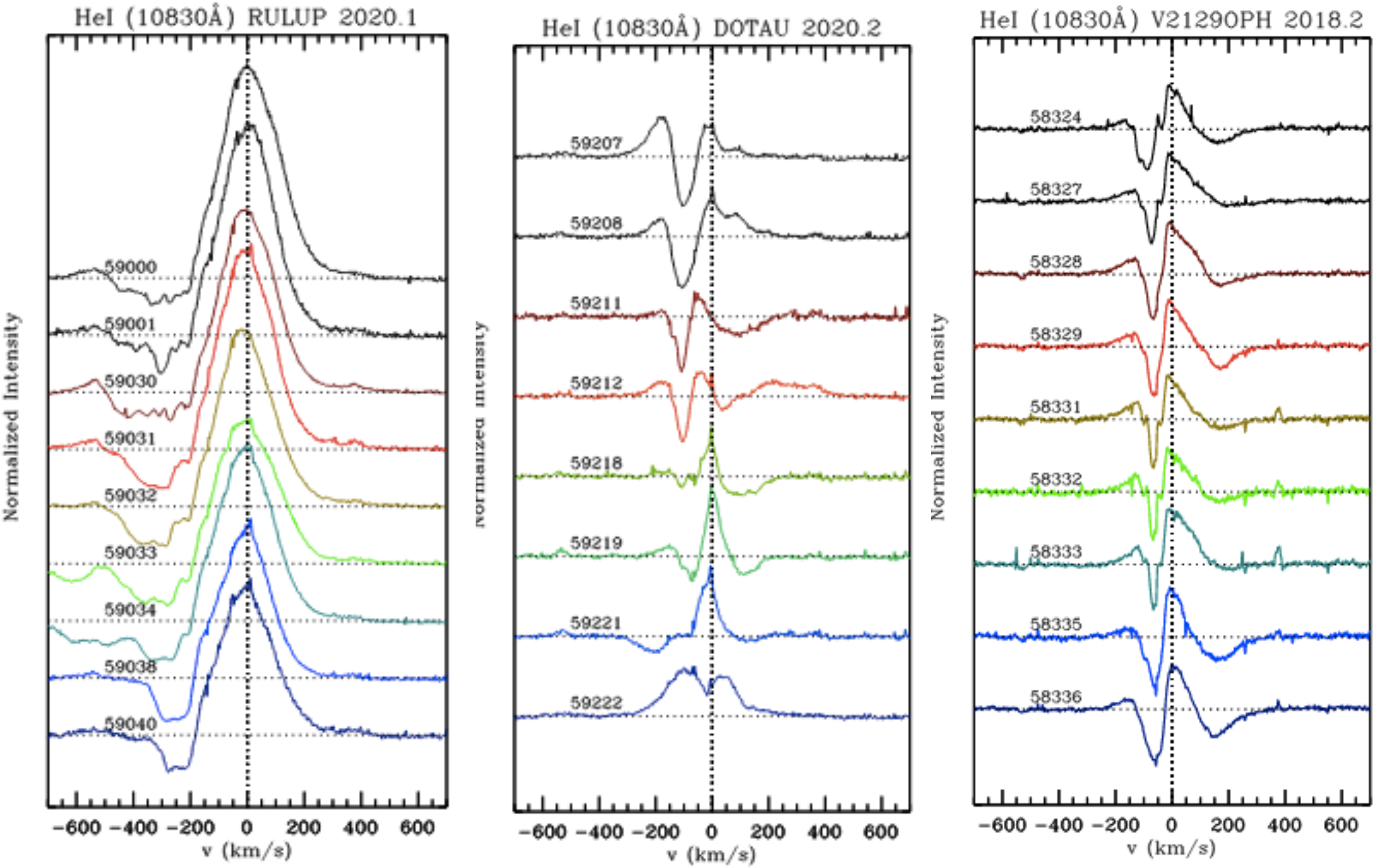
HeI 1.08 μm
Keck NIRSPEC



Fischer et al. (2008)

Accretion and outflow dynamics

HeI 1.08 μm - SPIRou



Sousa et al. (in preparation)

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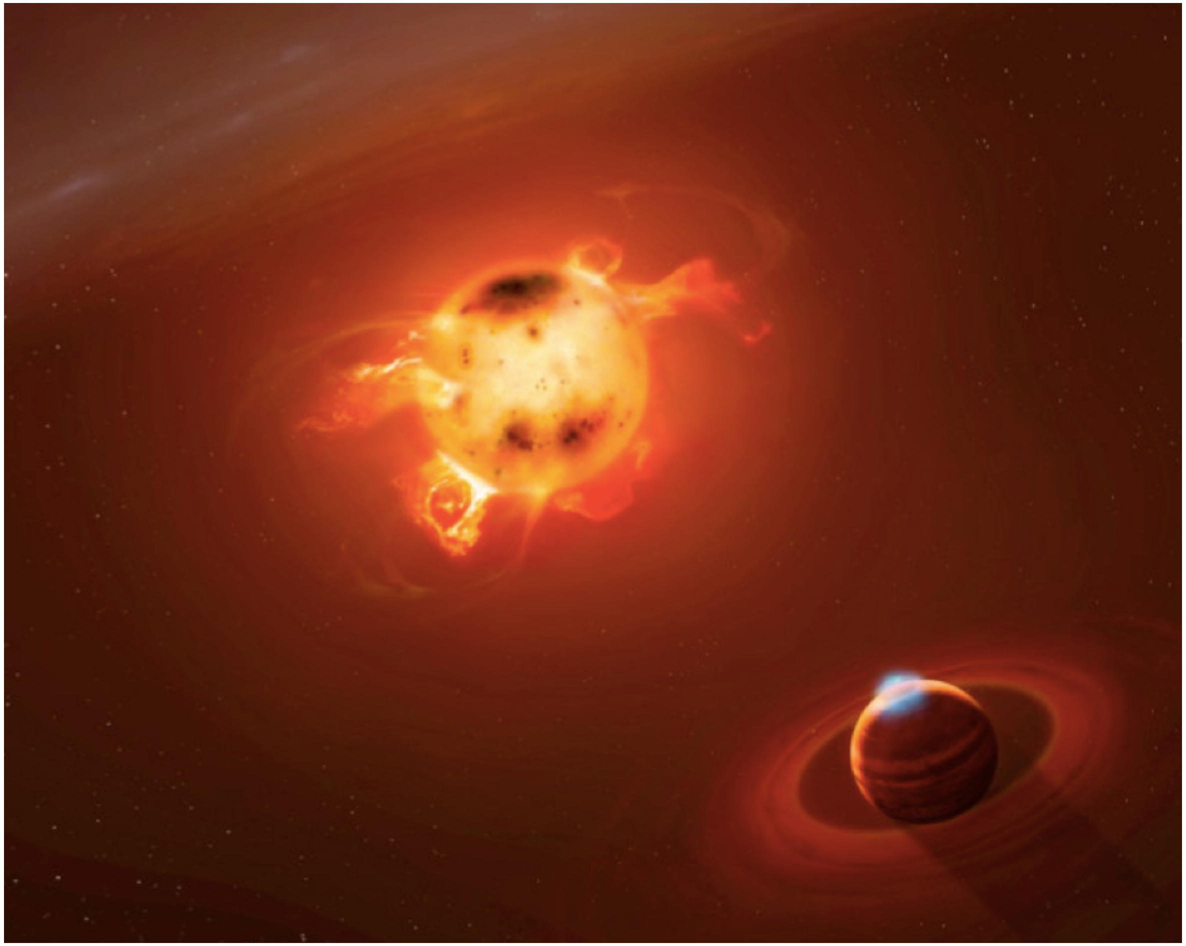
Planets around young stars



Mark A. Garlick / markgarlick.com

Direct Imaging

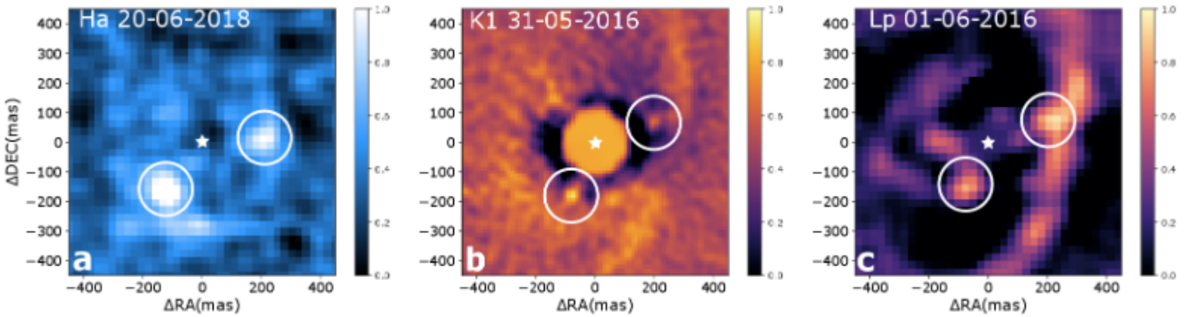
PDS 70

K7, M_*=0.76 $M_\odot$, 5.4 Myr
Transitional disk
Centaurus SFR

PDS 70b
3 Jupiter mass planet
P=119.2 yr, e=0.19
22 au from the star
Keppler et al. (2018)

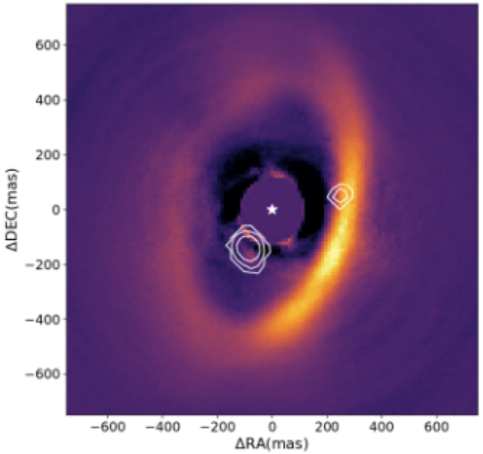
PDS 70c
2 Jupiter mass planet
P=227.5 yr, e=0.11
34 au from the star
Haffert et al. (2019)

Wang et al. (2020)



MUSE/VLT SPHERE/VLT NACO/VLT

Haffert et al.(2019)



SPHERE H-band (colors)
Hα contours (white)

Direct Imaging

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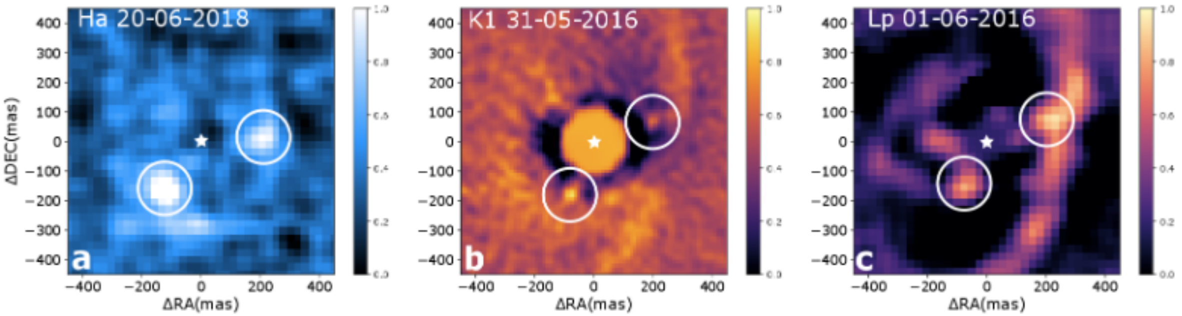
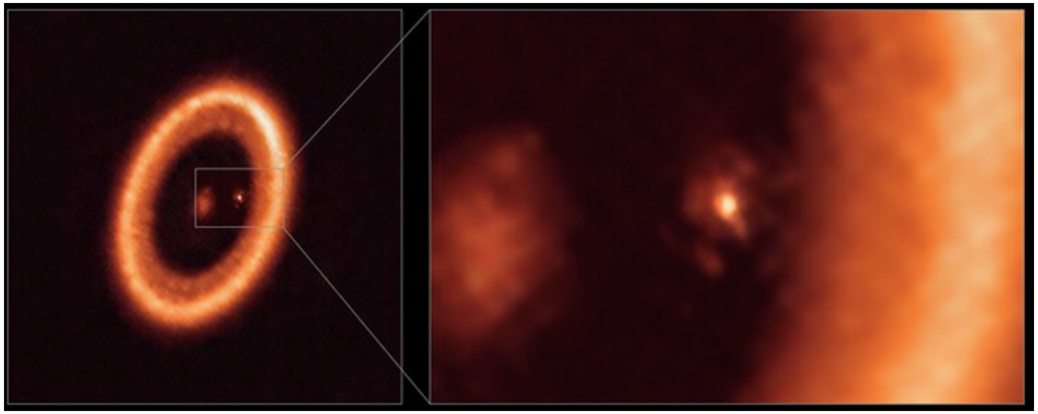


MUSE/VLT

SPHERE/VLT

NACO/VLT

Haffert et al.(2019)



ALMA

Dust continuum emission at 855 μm

Benisty et al. (2021)

Transit method

K2-33

5-10 Myr old star

Upper-Sco SFR

K2-33 b

Neptune-size planet

R=1.48±0.16 R_{Nep}

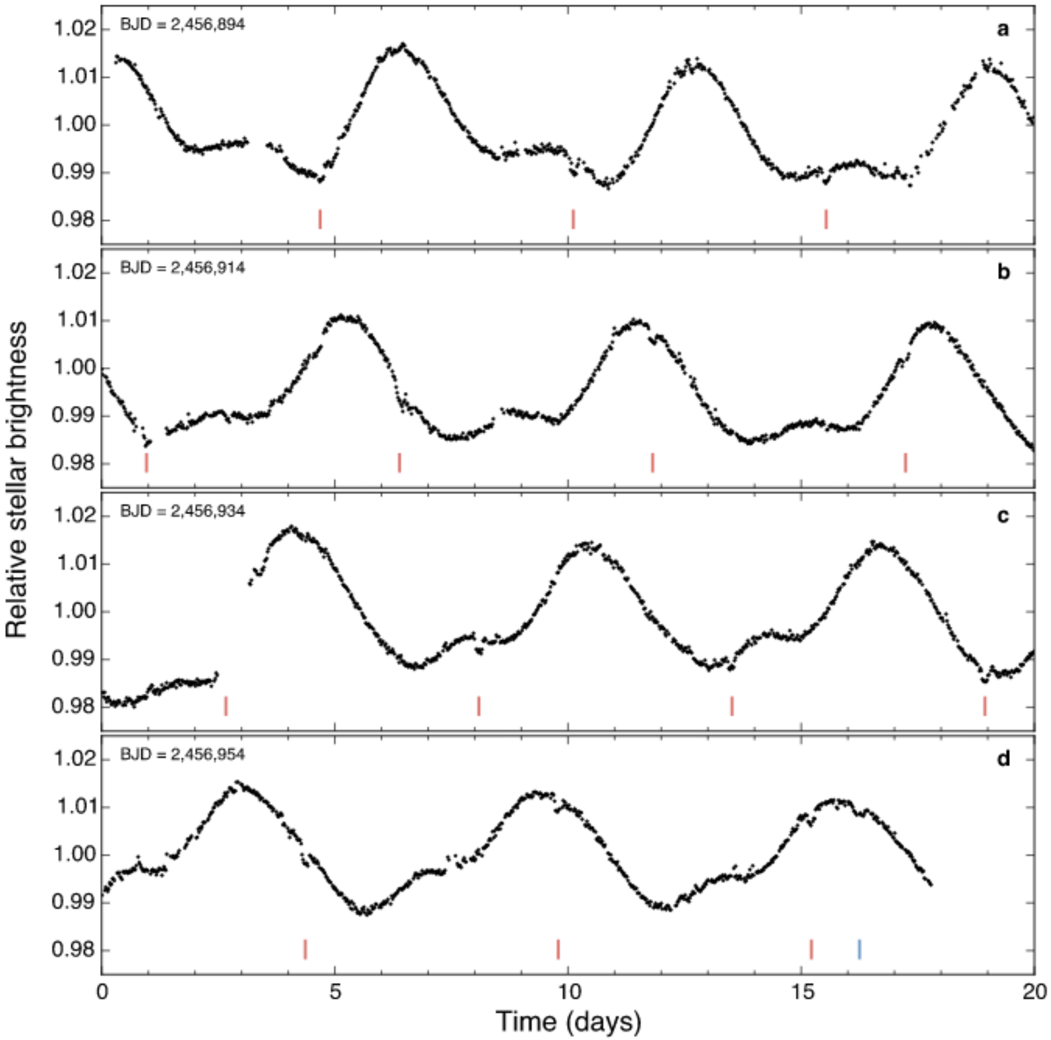
M < 3.6 M_{Jup}

P=5.42 days

a=0.041±0.002 au

Migration or in situ formation?

David et al. (2016)



Transit method

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5-10 Myr old star
Upper-Sco SFR

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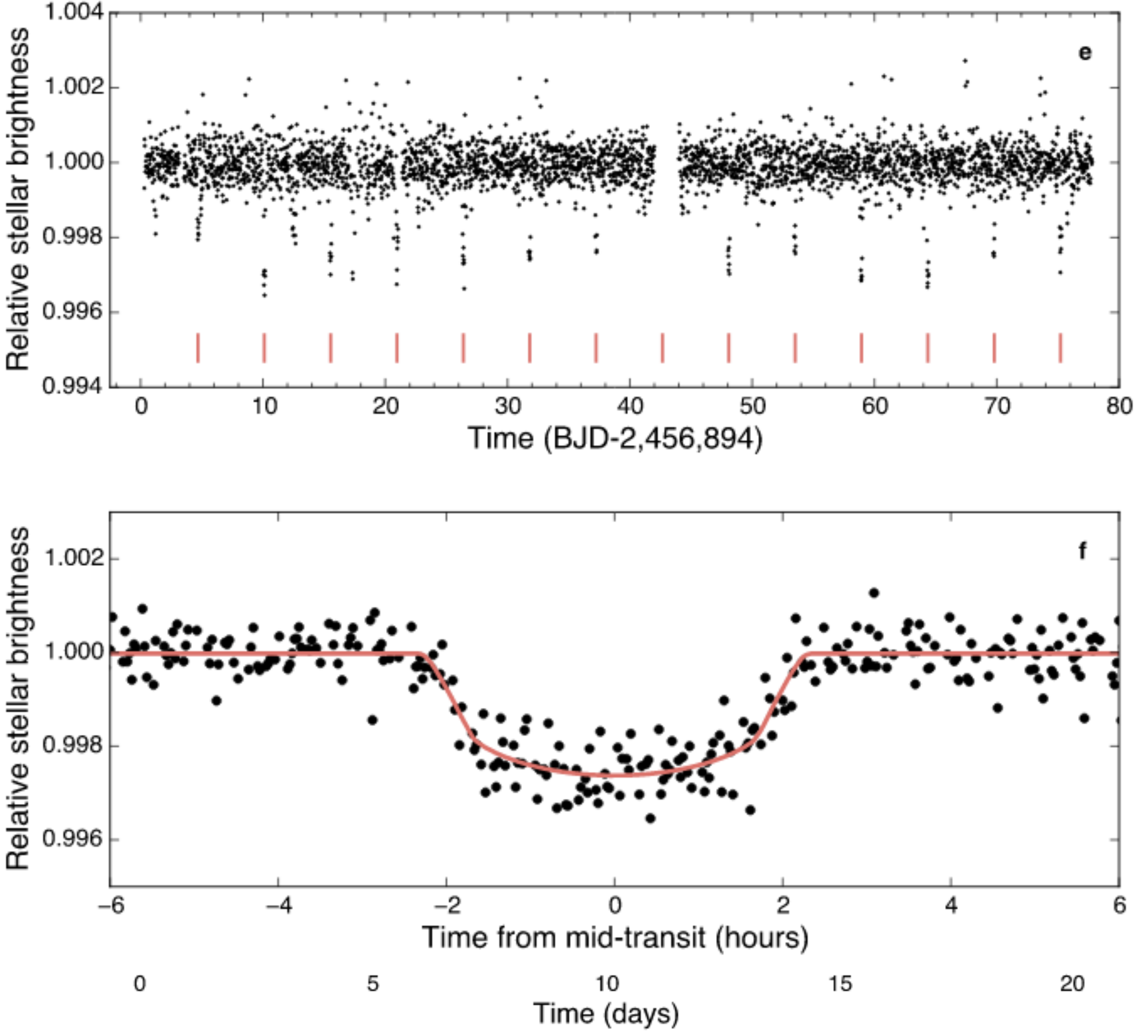
Migration or in situ formation?

David et al. (2016)

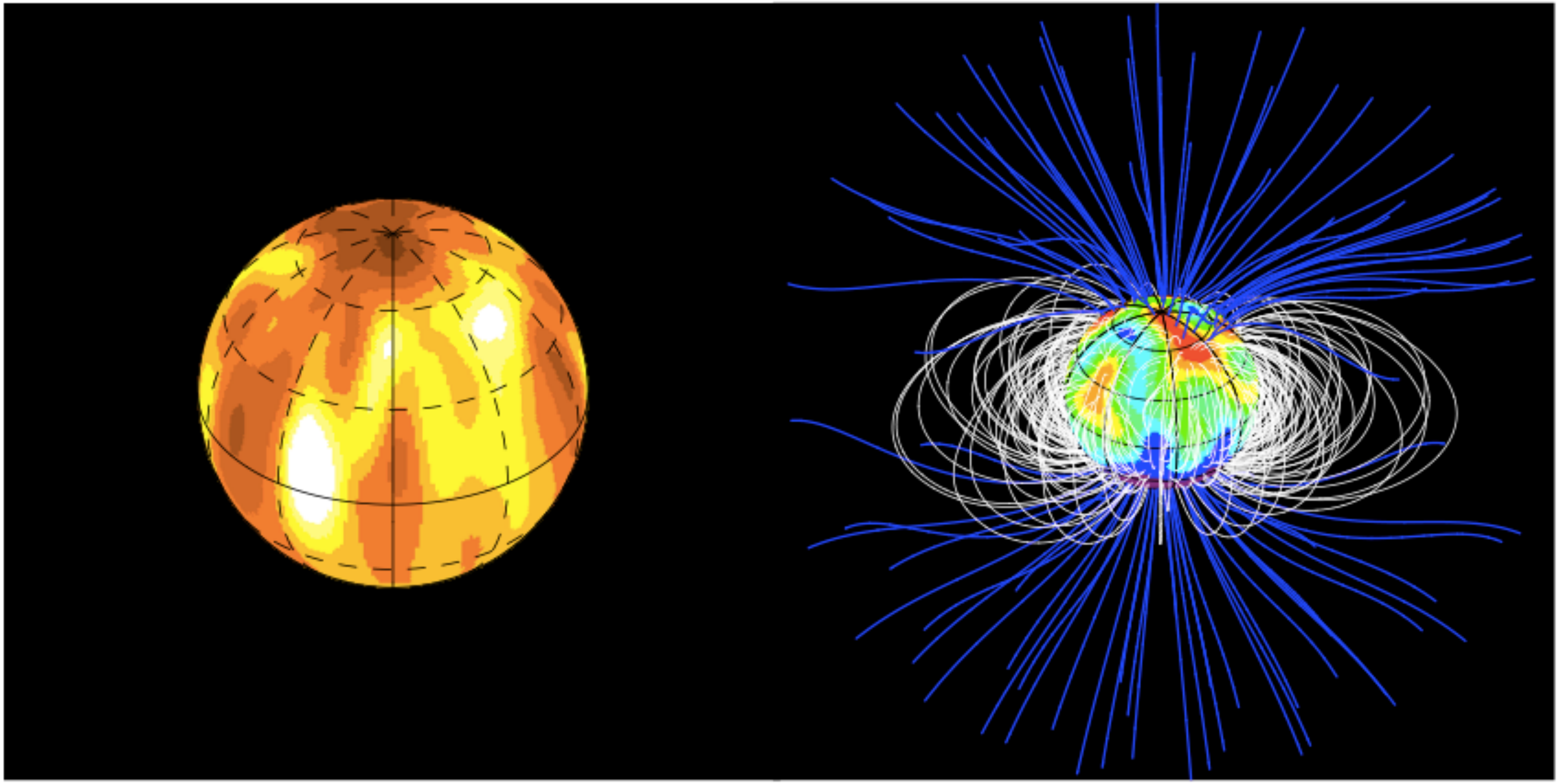
K2 light curve corrected from stellar variability



Radial velocity method

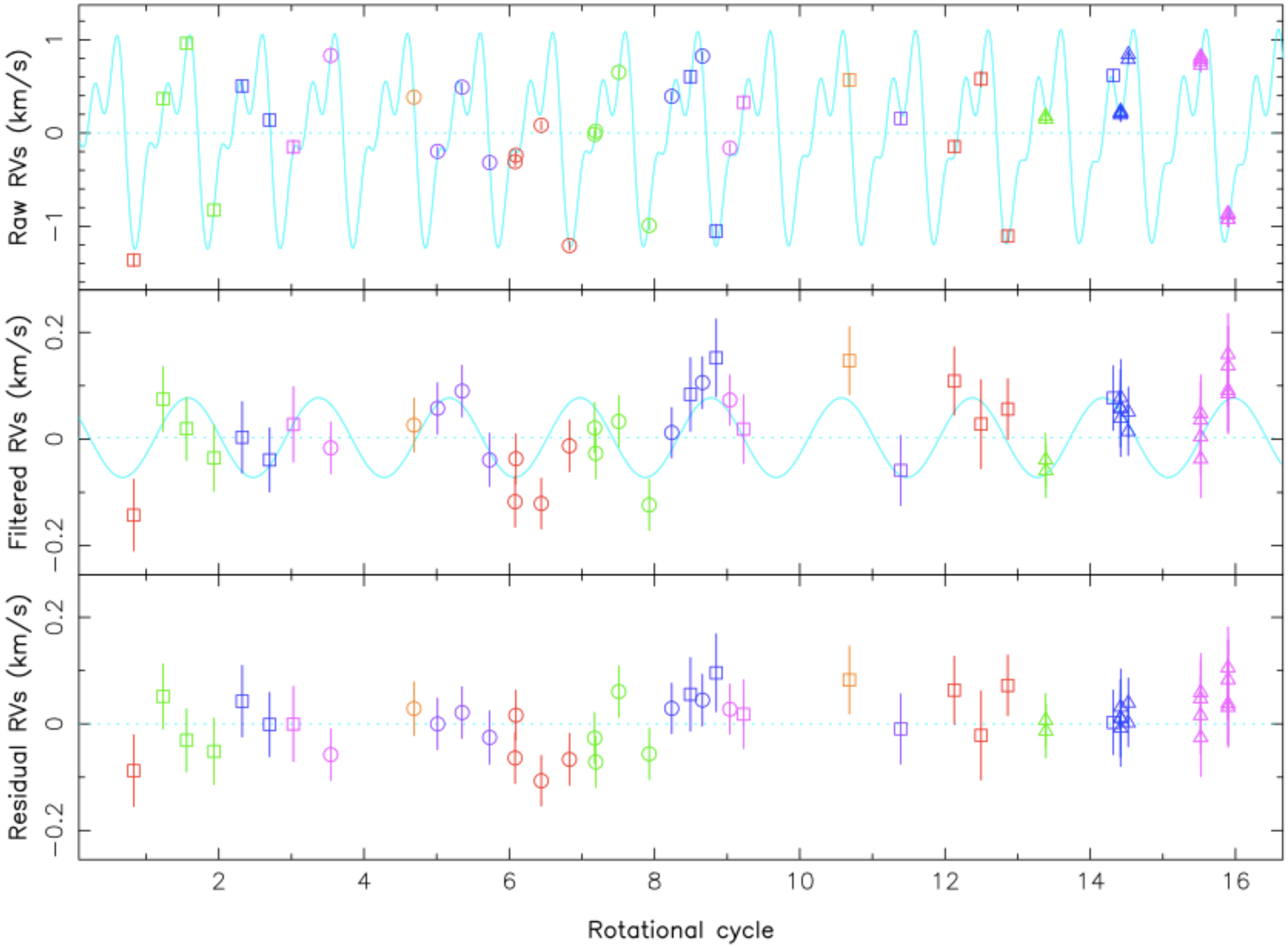
ESPaDOnS at CFHT and HARPS-Pol at ESO

V830 Tau – 2 Myr, WTTS



Donati et al. (2016)

V830 Tau radial velocity



Measured Vrad
P=2.74 days

Spot model

Residuals
P=4.93 days

Sine-wave fit

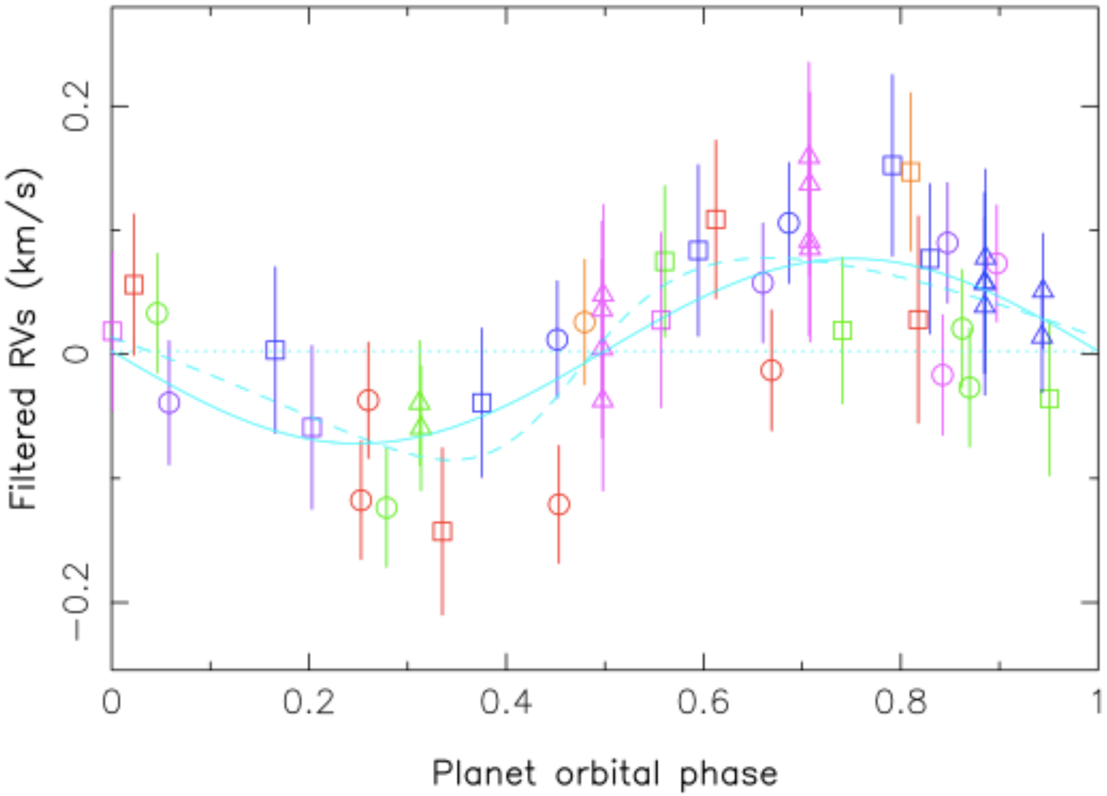
New residuals
No periodicity

Donati et al. (2016)

Phased radial velocity

After the subtraction of spot contributions

Donati et al. (2016)



Consistent with a 0,77 ± 0,15 M_{Jup} planet, orbiting the star with p=4.93 ± 0.05 days at 0,057 ± 0,001 au

Transit + Radial velocity

AU Mic

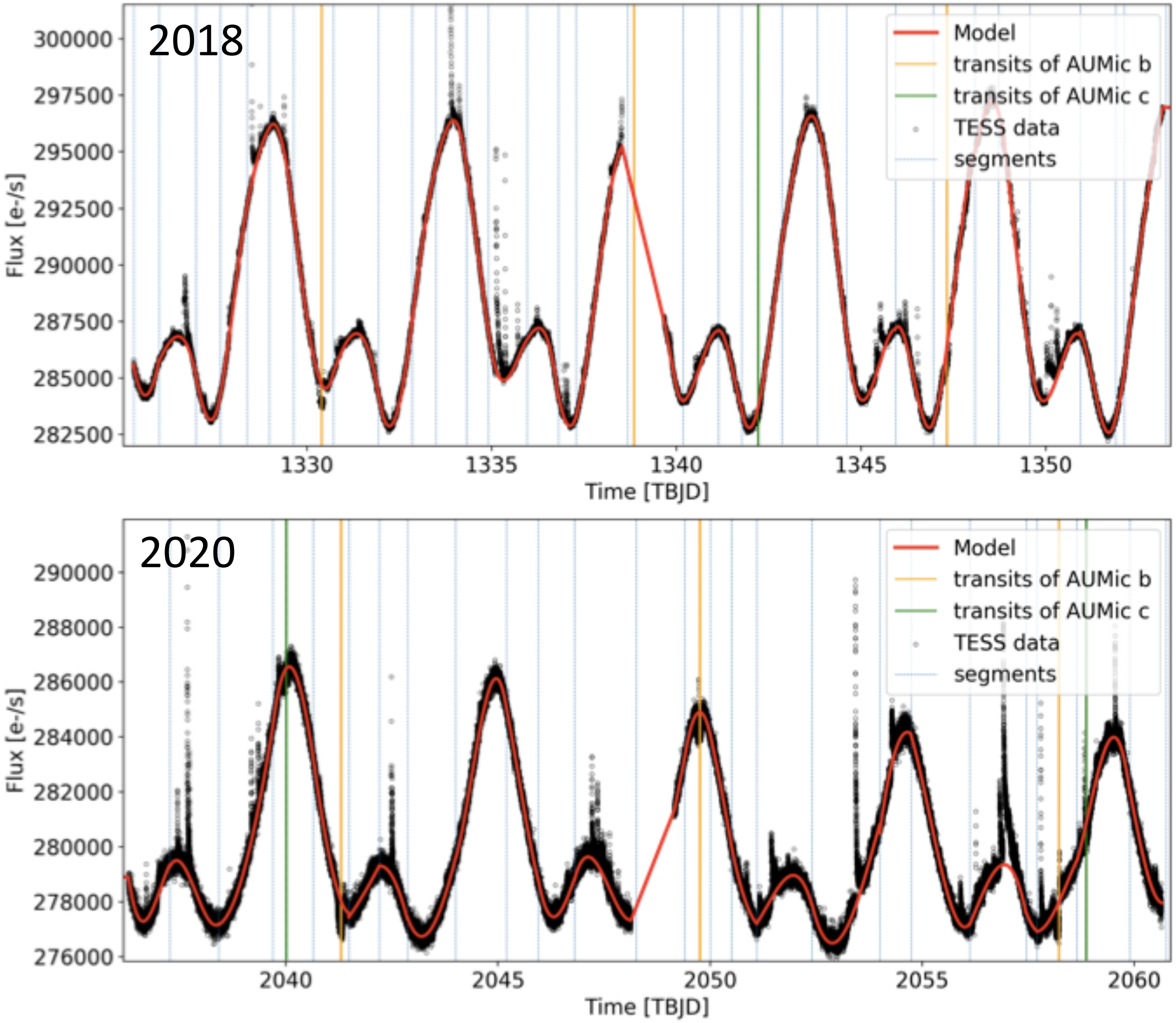
M1, 22 Myr
b Pic moving group
d = 9.72 pc
P_{rot}=4.86±0.01 d
Edge-on debris disk

AU Mic b
M=1.00 ± 0.27 M_{Nep}
R=1.05±0.04 R_{Nep}
p=8.46321 d

AU Mic c
0.13 M_{Nep} < M < 1.46 M_{Nep}
R=0.84 ± 0.04 R_{Nep}
p= 18.8590 d

Plavchan et al. (2020)
Klein et al. (2021)
Martioli et al. (2021)

TESS light curve



Martioli et al. (2021)

Transit + Radial velocity

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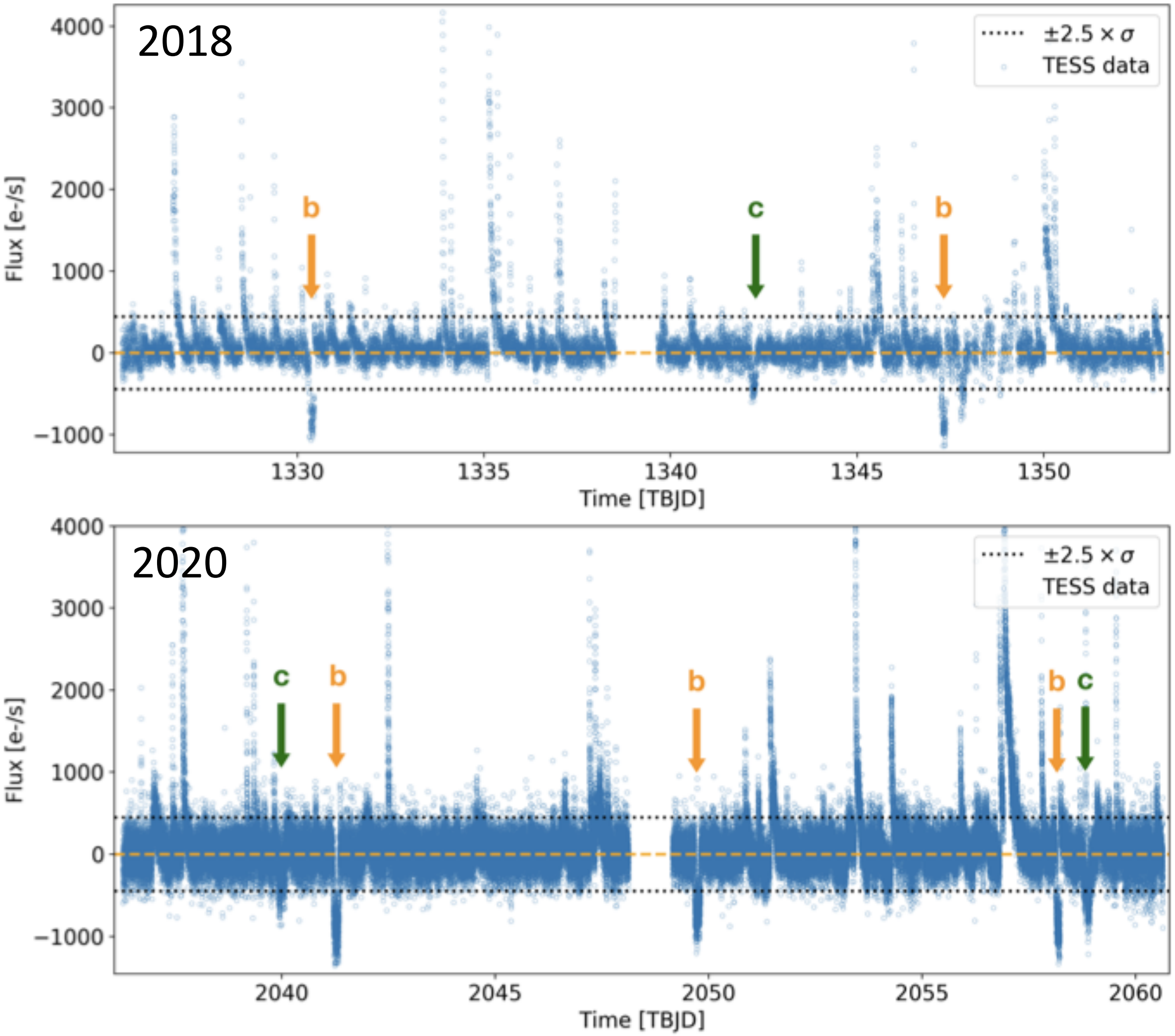
Plavchan et al. (2020)
Klein et al. (2021)
Martioli et al. (2021)

TESS light curve after subtracting the starspot model



Martioli et al. (2021)

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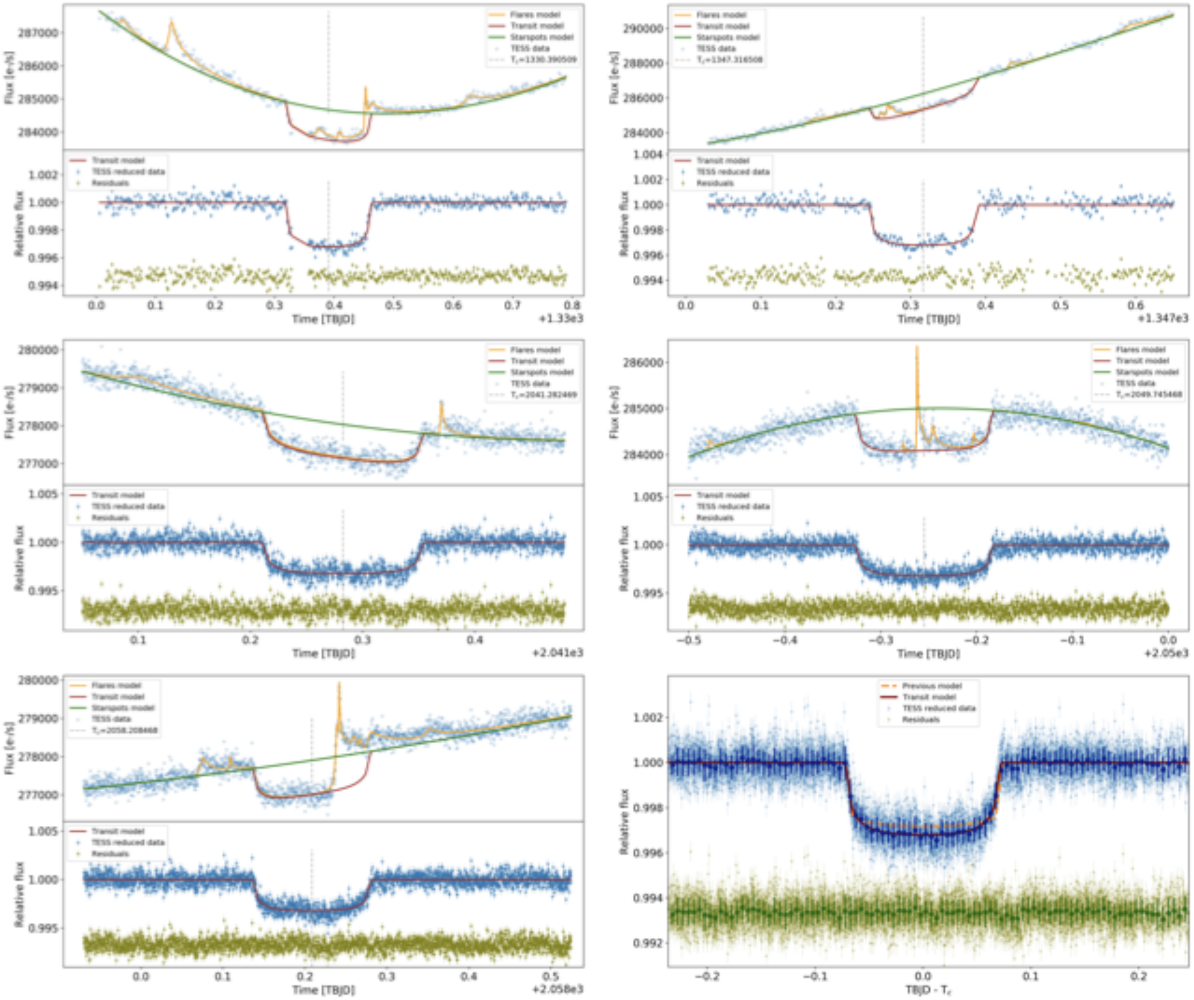
Plavchan et al. (2020)
Klein et al. (2021)
Martioli et al. (2021)

AU Mic b transits after removing starspots and flare signals



Martioli et al. (2021)

Transit + Radial velocity

AU Mic

M1, 22 Myr
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P_{rot}=4.86±0.01 d
Edge-on debris disk

AU Mic b
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p=8.46321 d

AU Mic c
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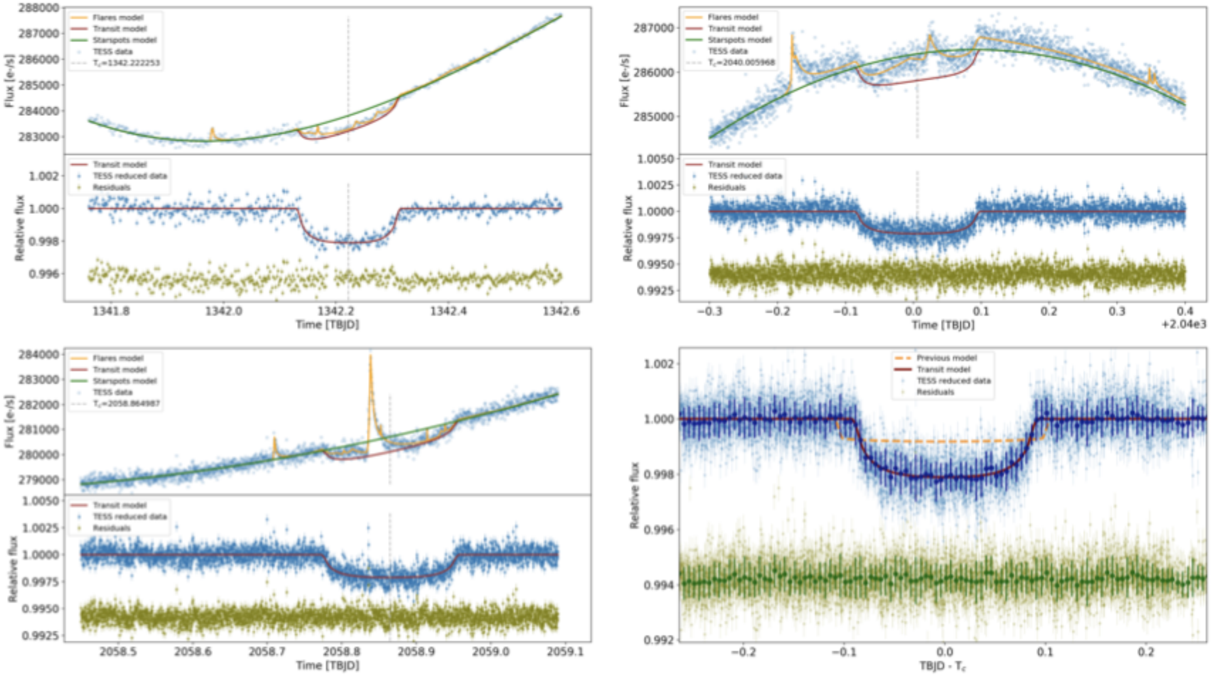
R=0.84 ± 0.04 R_{Nep}
p= 18.8590 d

Plavchan et al. (2020)
Klein et al. (2021)
Martioli et al. (2021)

AU Mic c transits after removing starspots and flares signals



Martioli et al. (2021)

AU Mic

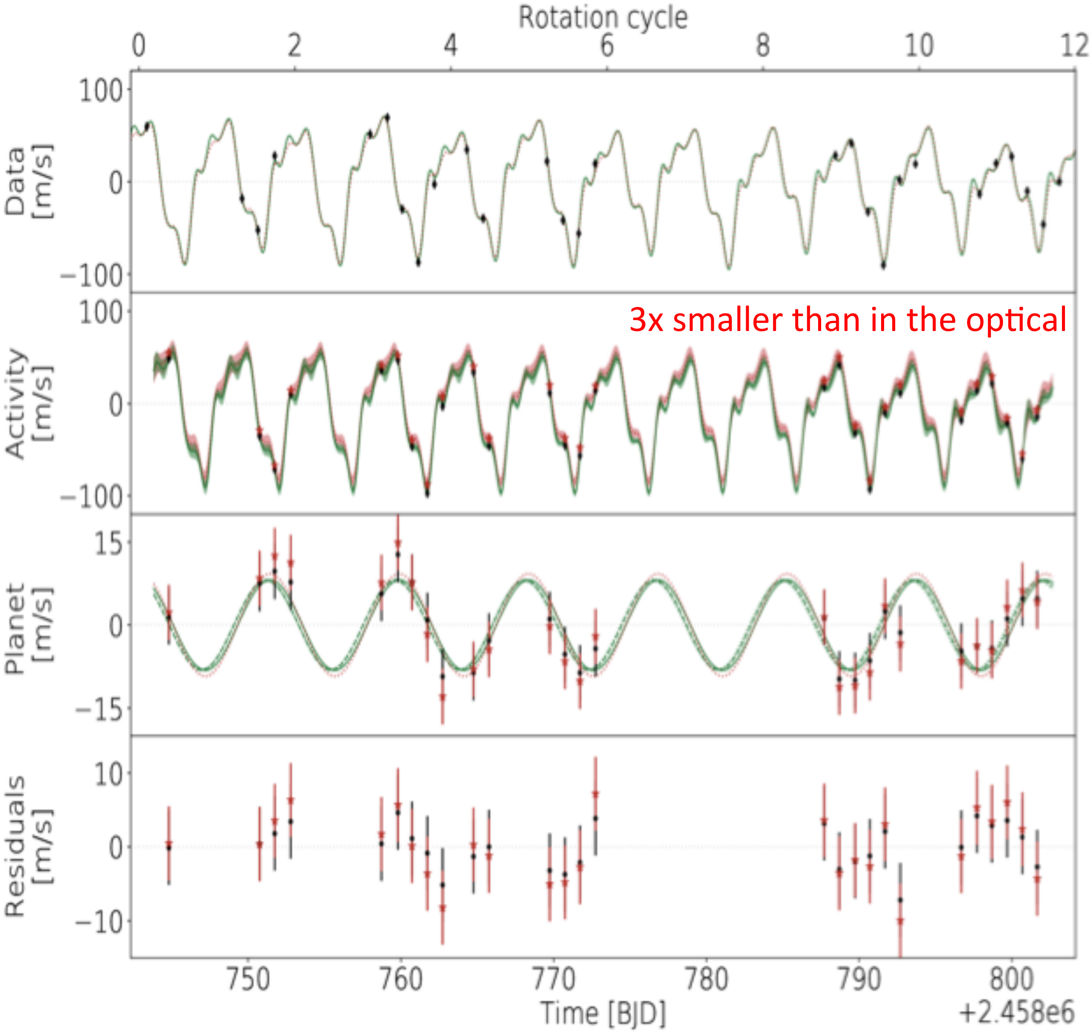
M1, 22 Myr
β Pic moving group
d = 9.72 pc
P_{rot}=4.86±0.01 d
Edge-on debris disk

AU Mic b
M=1.00 ± 0.27 M_{Nep}
R=1.05±0.04 R_{Nep}
density=1.3 ± 0.4 g cm^{-3}
p=8.46321 d

AU Mic c
0.13 M_{Nep} < M < 1.46 M_{Nep}
R=0.84 ± 0.04 R_{Nep}
p= 18.8590 d

Plavchan et al. (2020)
Klein et al. (2021)
Martioli et al. (2021)

SPIRou data



The v_{rad} analysis constrained the mass of AU Mic b

Klein et al. (2021)

AU Mic

SPIRou data

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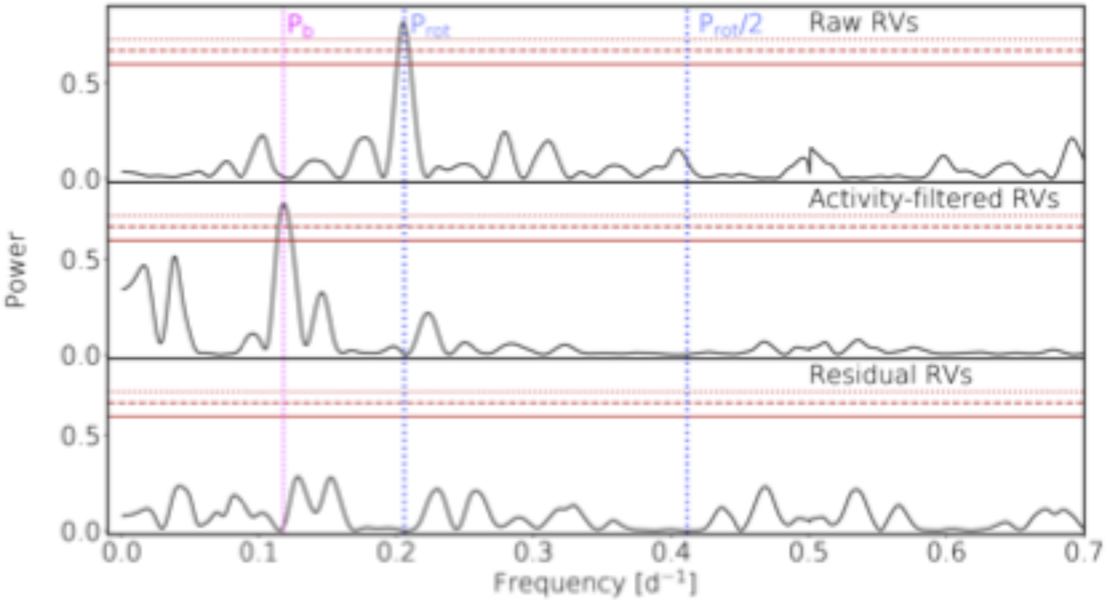

The v_{rad} analysis constrained the mass of AU Mic b

Klein et al. (2021)

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Some observational perspectives

Ongoing surveys and facilities

Gaia (full DR3 in mid-2022)
TESS
ALMA programs
VLT/SPHERE programs
GRAVITY programs
ULLYSES (HST) & ODYSSEUS
SPIRou Legacy Survey

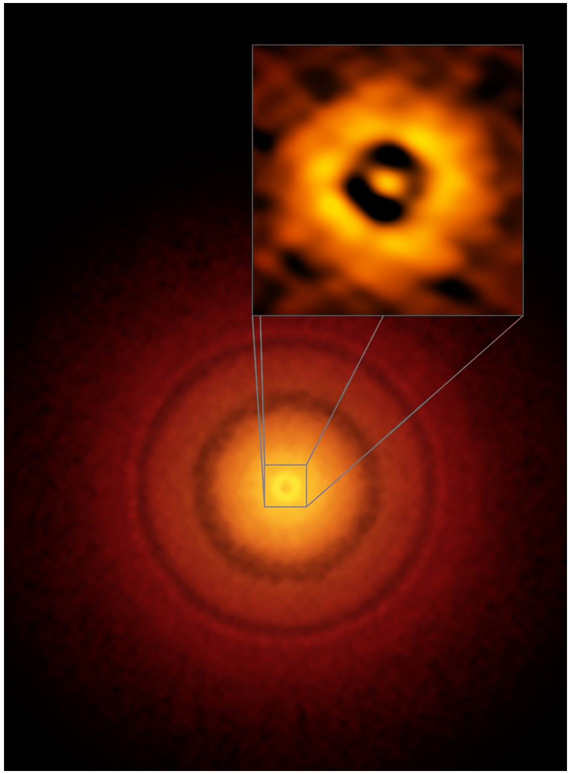
Upcoming facilities

James Webb Space Telescope (JWST) – launch in 2021
Nancy Grace Roman Space Telescope (Roman) – launch in mid-2020s
PLAnetary Transits and Oscillations of stars (PLATO) – launch in 2026

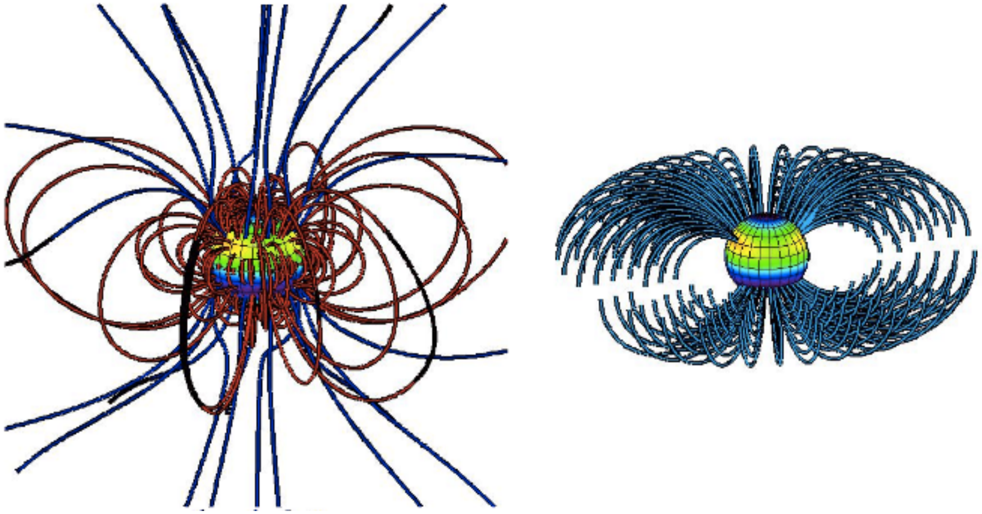
TW Hya

K7, Classical T Tauri star, 10 Myr
i ~ 7^o (Wilner, 2003)
d = 52 ± 1 pc (Mamajek, 2010)
2.8 kG octupole + 0.7 kG dipole (Donati et al. 2011)

ALMA



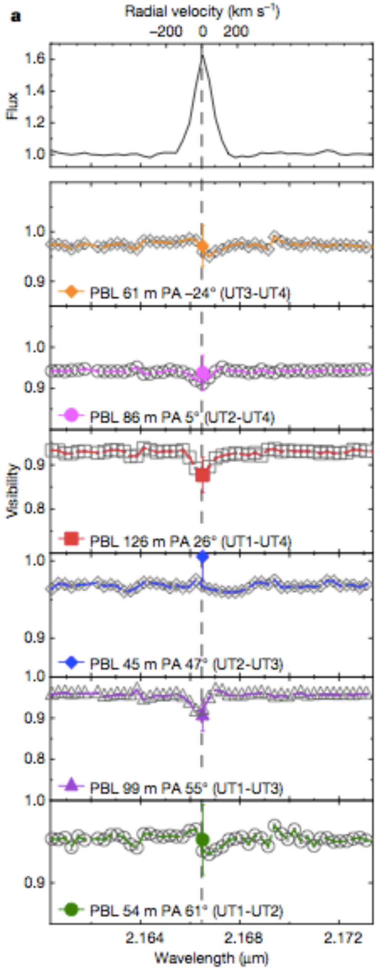
Andrews et al. (2016)



Johnstone et al. (2013)

TW Hya with VLTI-GRAVITY (ESO)

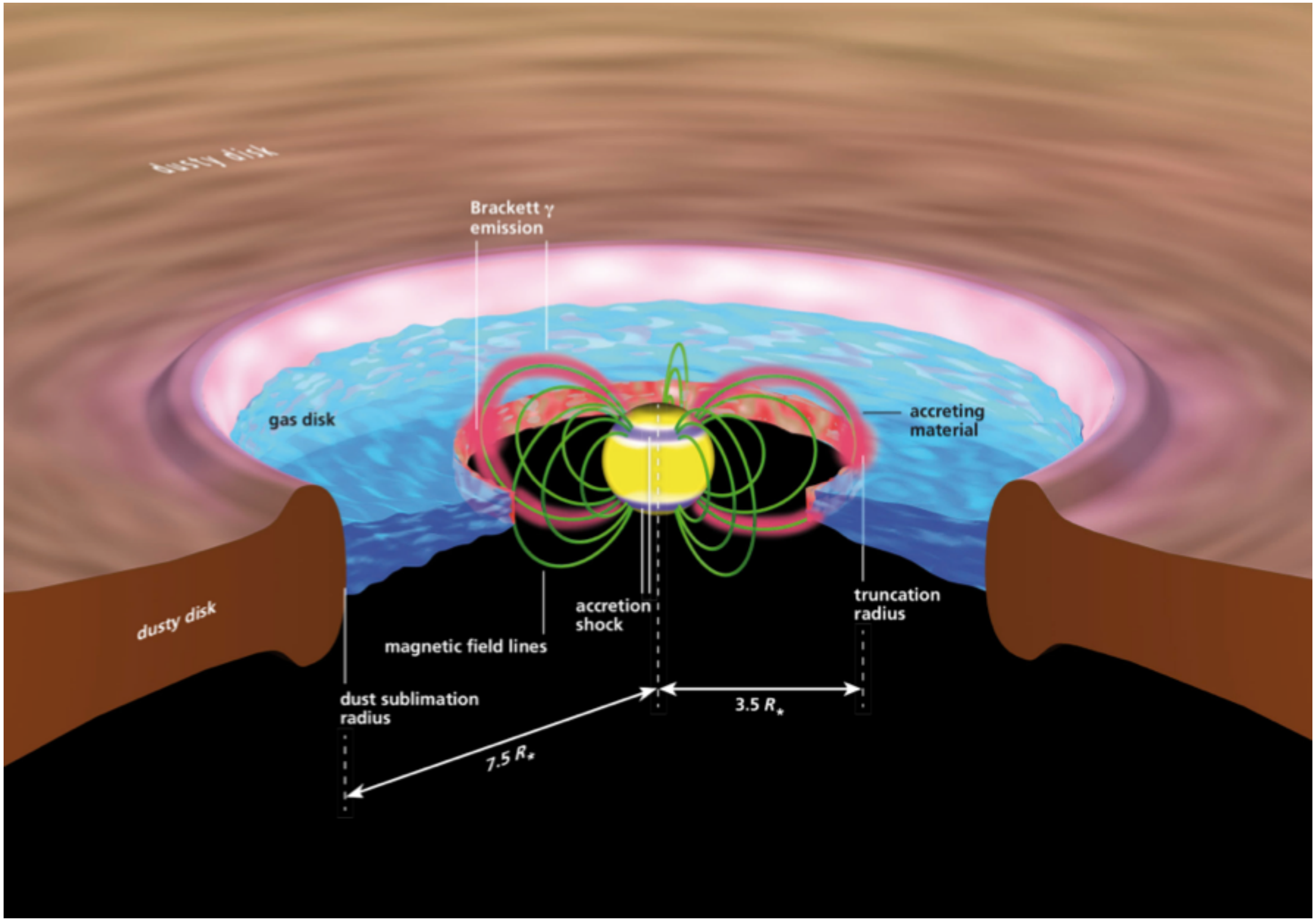
High-angular resolution observations of the hydrogen Brγ line in TW Hya using the Very Large Telescope Interferometer (VLTI) instrument GRAVITY with the four 8-m Unit Telescopes



- Nominal angular resolutions of around 4 mas to 10 mas. Size of the magnetosphere: a few tenths of mas
- Inner edge of the dusty disk at (6.50 ± 0.16) R⁎, from K band continuum excess
- The Brγ line emitting region is very compact $R_{\mathrm{Br\gamma}}$ = (3.49 ± 0.20) R⁎ , and marginally resolved for the longest projected baselines
- Magnetospheric radius of 3 R⁎–4 R⁎, assuming 700 G measured dipole field

GRAVITY Collaboration (2020)

TW Hya and VLTI-GRAVITY (ESO)

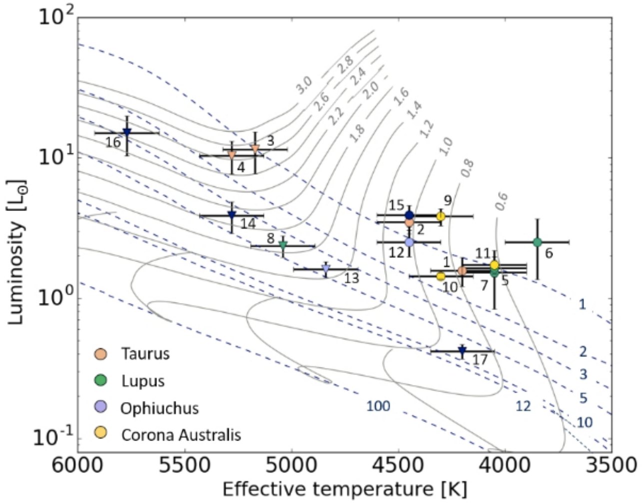


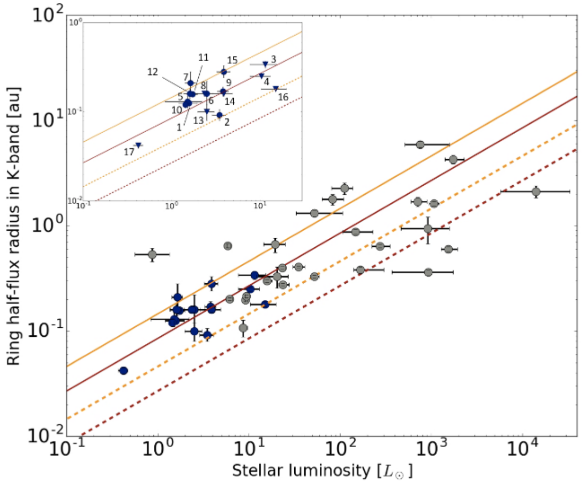
GRAVITY Collaboration (2020)

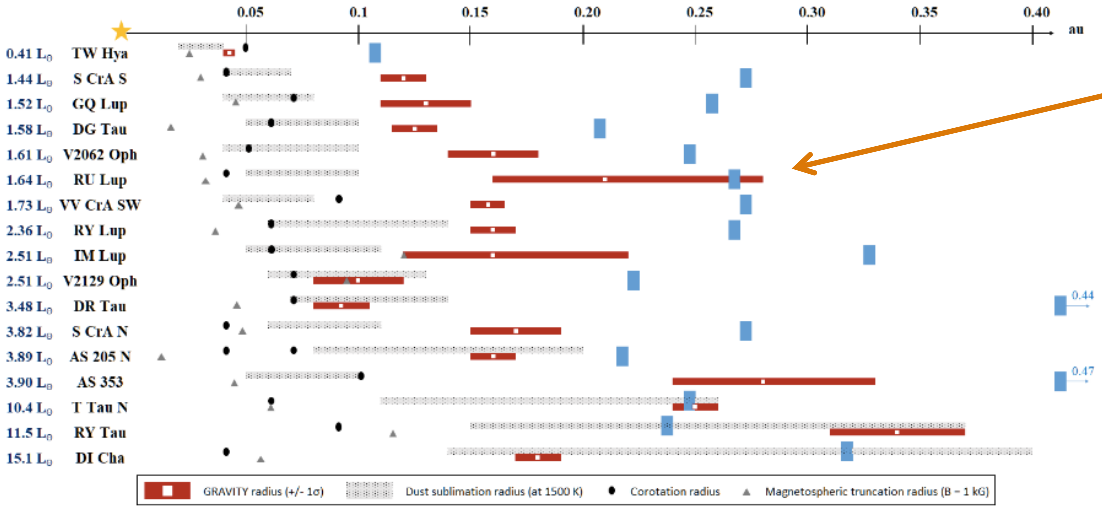
The GRAVITY YSO survey

Inner dusty disks of T Tauri stars

K band continuum emission appears as wide rings





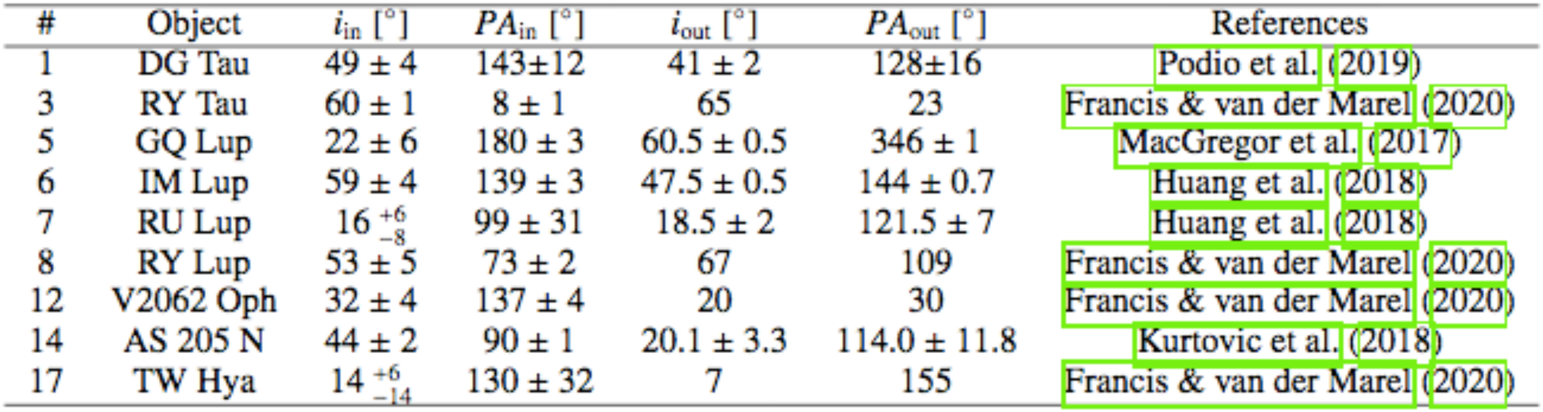


Sub-au half-flux radius of the ring model

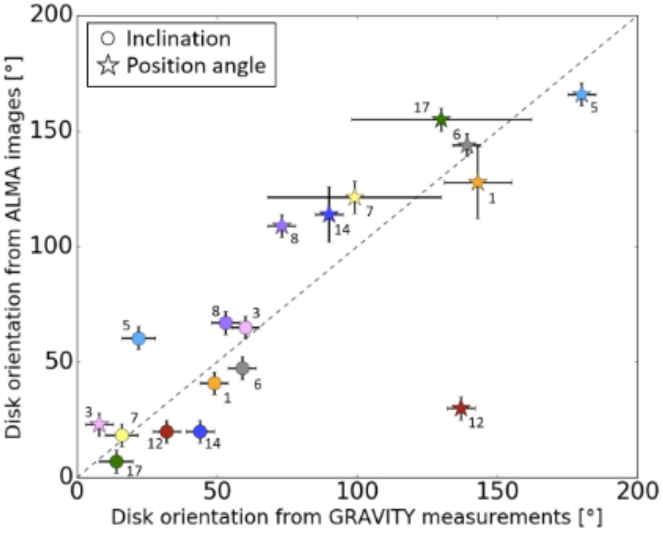
Perraut et al. (2021)

GRAVITY and ALMA

Linking the inner and outer disk scales



		GRAVITY inner disk		ALMA outer disk		
#	Object	i_{in} [°]	PA_{in} [°]	i_{out} [°]	PA_{out} [°]	References
1	DG Tau	49 ± 4	143 ± 12	41 ± 2	128 ± 16	Podio et al. (2019)
3	RY Tau	60 ± 1	8 ± 1	65	23	Francis & van der Marel (2020)
5	GQ Lup	22 ± 6	180 ± 3	60.5 ± 0.5	346 ± 1	MacGregor et al. (2017)
6	IM Lup	59 ± 4	139 ± 3	47.5 ± 0.5	144 ± 0.7	Huang et al. (2018)
7	RU Lup	16^{+6}_{-8}	99 ± 31	18.5 ± 2	121.5 ± 7	Huang et al. (2018)
8	RY Lup	53 ± 5	73 ± 2	67	109	Francis & van der Marel (2020)
12	V2062 Oph	32 ± 4	137 ± 4	20	30	Francis & van der Marel (2020)
14	AS 205 N	44 ± 2	90 ± 1	20.1 ± 3.3	114.0 ± 11.8	Kurtovic et al. (2018)
17	TW Hya	14^{+6}_{-14}	130 ± 32	7	155	Francis & van der Marel (2020)



Perraut et al. (2021)

Many CTTSs have misaligned inner disks with respect to the outer disks

Hubble UV Legacy Library of Young Stars as Essential Standards (ULLYSES)

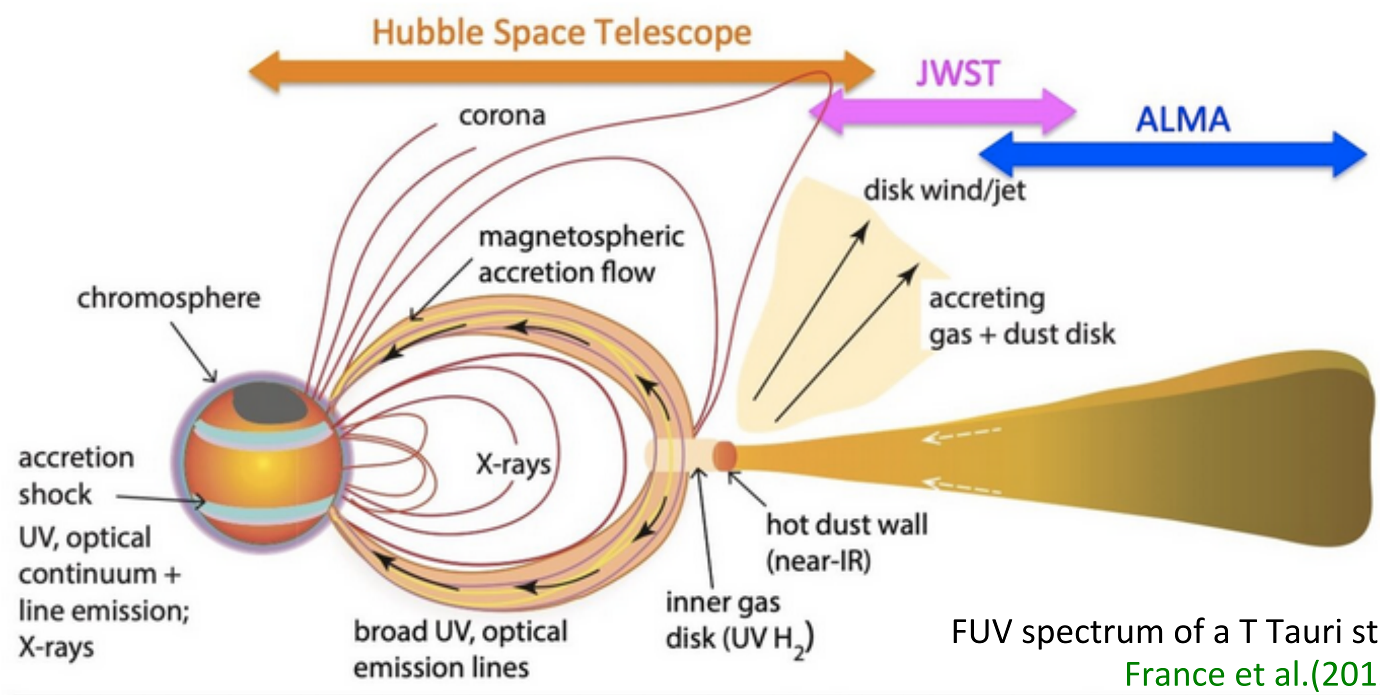
Director’s Discretionary Program to observe low-mass pre-main-sequence stars, during 500 orbits in 2020-2022.

The program will uniformly sample the parameter space in the mass, age, and accretion rate for 71 low-mass T Tauri stars in nine young Galactic associations.

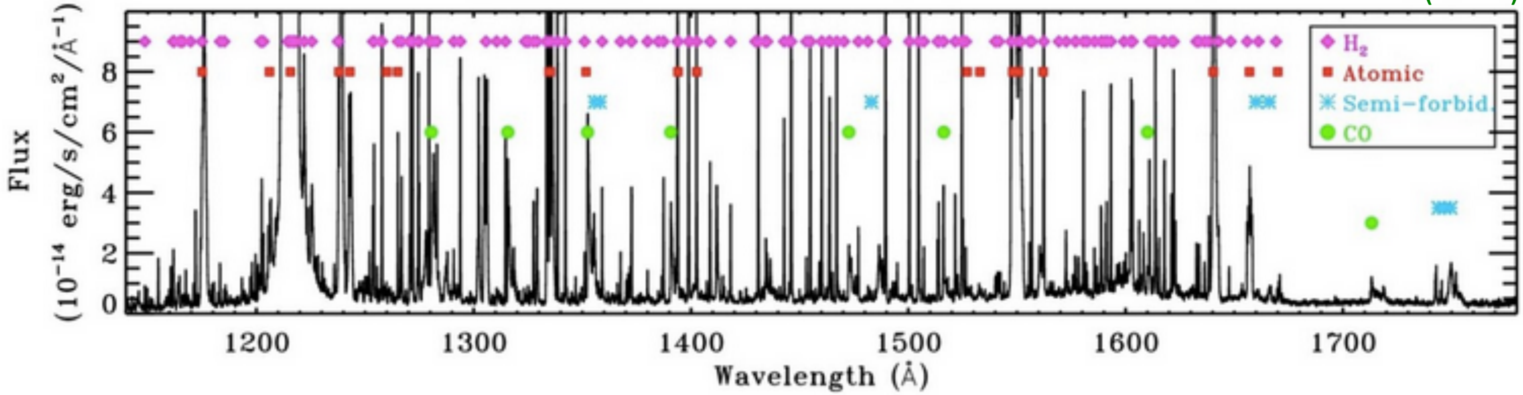
Monitoring of four chosen targets (TW Hya, RU Lup, GM Aur, BP Tau).

Synergy with ALMA and JWST data.

A comprehensive evaluation of the physics of disk evolution and planet formation requires understanding the intricate relationships between mass accretion, mass outflow, and disk structure.

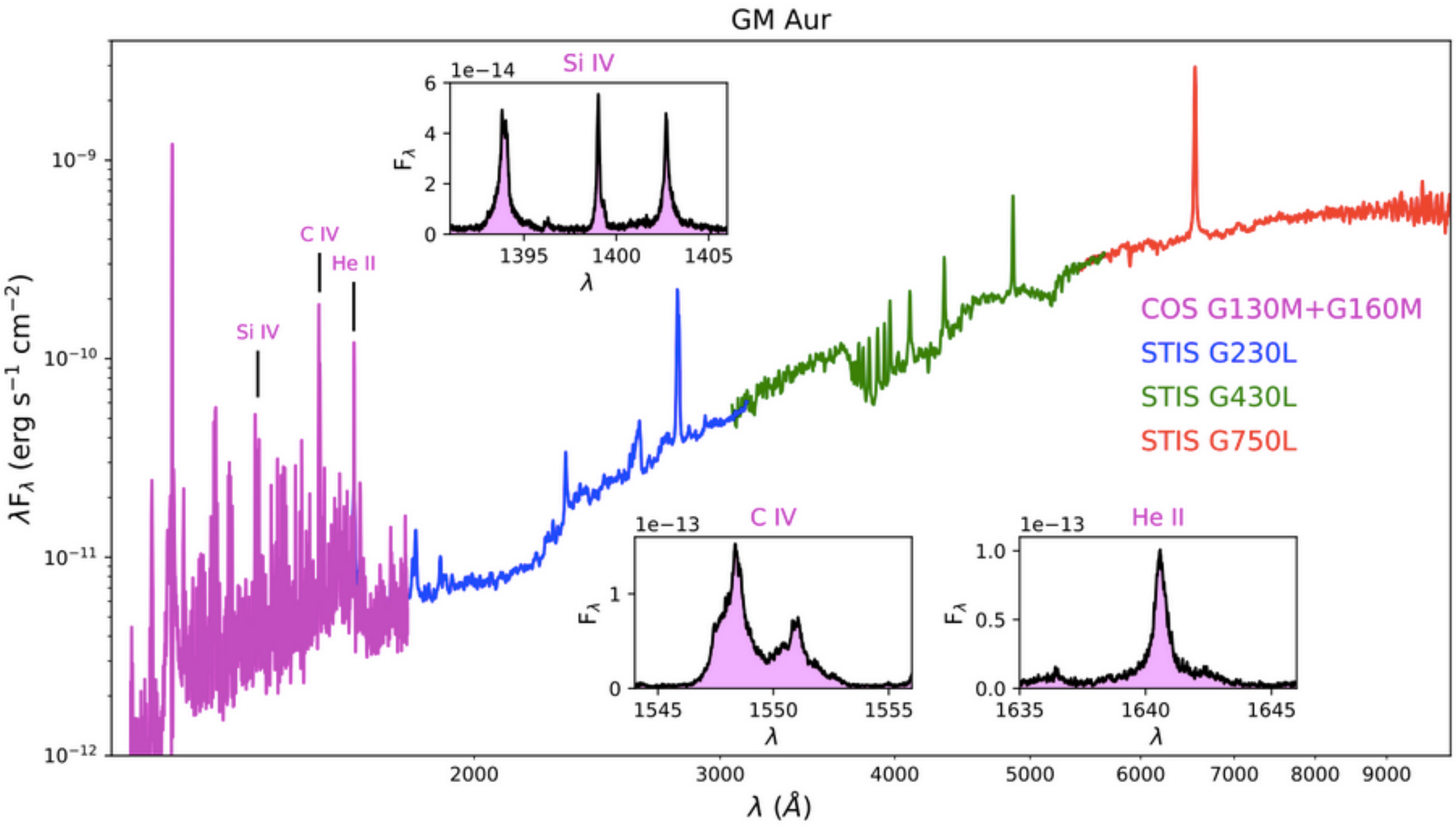


FUV spectrum of a T Tauri star
France et al.(2012)



ULLYSES FUV/NUV spectra will provide access to powerful spectral diagnostics of the young star and innermost disk, from which we can extract fundamental accretion, outflow, and disk properties, crucial information necessary to interpret the disk chemistry revealed by ALMA and soon by JWST. Top figure from Hartmann et al. (2016)

Hubble UV Legacy Library of Young Stars as Essential Standards (ULLYSES)



Full spectral coverage that will be obtained for the 67 survey targets.
The four monitoring targets will consist of COS G160M (FUV) and G230L (NUV).

Outflows and Disks around Young Stars: Synergies for the Exploration of ULLYSES Spectra (ODYSSEUS)

- Measure how the accretion flow depends on the accretion rate and magnetic structures
- Determine where winds and jets are launched and how mass loss rates compare to accretion
- Establish the influence of FUV radiation on the chemistry of the warm inner regions of planet-forming disks.

Contemporaneous observations:
X-ray spectra for select targets
VLT optical/NIR with X-Shooter and ESPRESSO/UVES spectra (PENELLOPE project)
NOIR- Lab/CHIRON optical spectra
IR spectra with TNG/GIARPS
SPIRou spectropolarimetry for the monitoring targets

SPIRou Legacy Survey

300 nights in 4 years (2019-2022)

Work Package 3 – Magnetic PMS star/planet exploration

Impact of stellar and disc magnetic fields on

Accretion and outflows
Internal structure and rotation
Formation, migration and survival of planets

Goals

Detect and map magnetic topology of protostars and accretion discs
Constrain accretion, outflows, dynamos
Origin and evolution of the stellar magnetic field
Angular momentum evolution
Model activity and activity jitter of WTTSs and search for hot Jupiters

SPIRou Legacy Survey

Star and planet formation

WP3 main questions

What are the magnetic topologies of class-I, II and III stars ?

How do they correlate with the evolutionary status?

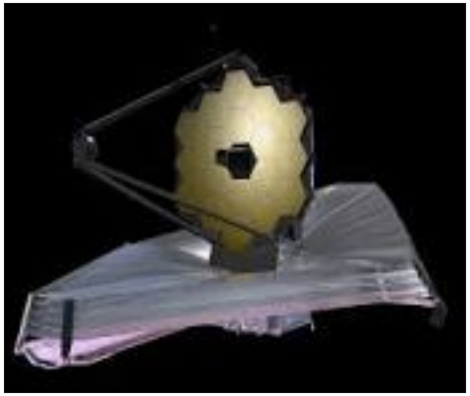
What are the fields in the innermost discs regions of accreting PMS stars?

How frequent are hot Jupiters around PMS stars?

Can we progress in our understanding of magnetospheric accretion?

Can we improve the description of the earliest phases of angular momentum evolution ?

James Webb Space Telescope - JWST (NASA, ESA, CSA)



- JWST is a 6.5 m telescope
- High spatial resolution
- Four instruments: Mid-Infrared Instrument (MIRI), Near-Infrared Spectrograph (NIRSpec), Near-Infrared Camera (NIRCam), Fine Guidance Sensor/Near Infrared Imager and Slitless Spectrograph (FGS-NIRISS)

- JWST is set to launch in December 18, 2021.

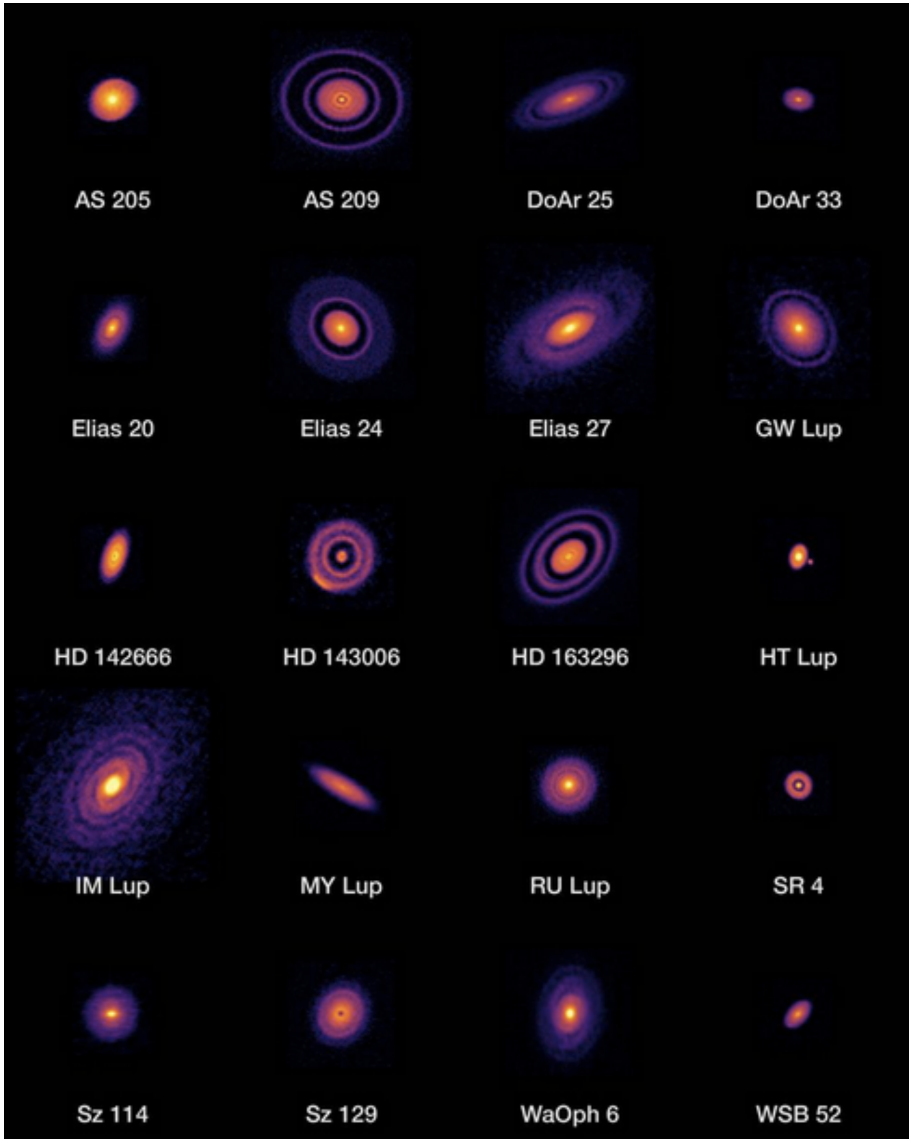
- Star formation related science

  - ✓ Core collapse
  - ✓ Deeply embedded star-disk systems
  - ✓ Complete young cluster sensus membership
  - ✓ IR imaging and spectroscopy of protoplanetary disks
  - ✓ Inner disk outflows
  - ✓ Atmospheres of exoplanets
  - ✓ Direct imaging of exoplanets

Protoplanetary disks with ALMA and JWST

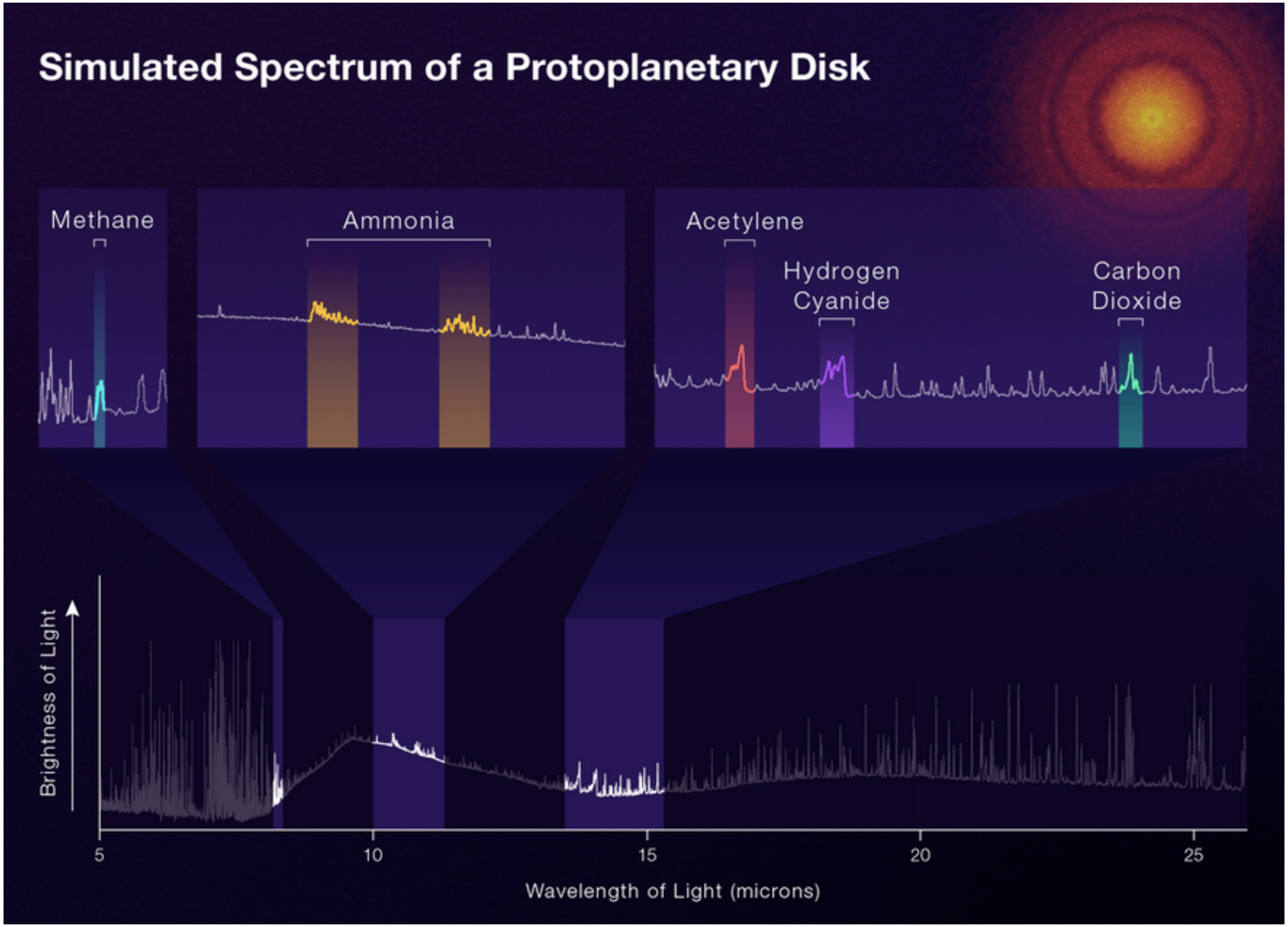
IR inventory of 17 nearby protoplanetary systems observed by ALMA for the DSHARP project.

JWST will obtain mid-IR (MIRI) molecular spectra that will reveal the chemical composition of the inner disks.



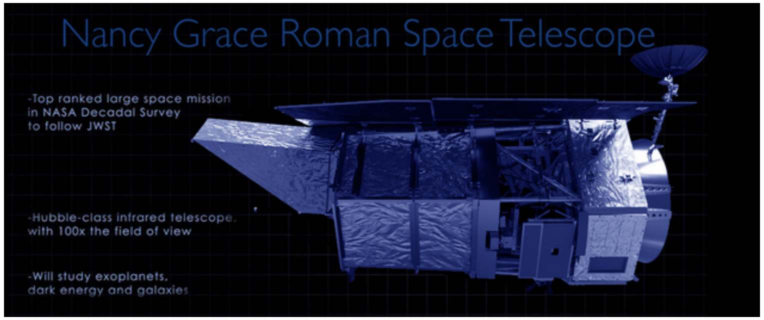
Credits: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; N. Lira

Protoplanetary disks with ALMA and JWST



Credits: NASA, ESA, CSA, Leah Hustak (STScI)

Roman Space Telescope (NASA)


Nancy Grace Roman Space Telescope

-Top ranked large space mission in NASA Decadal Survey to follow JWST

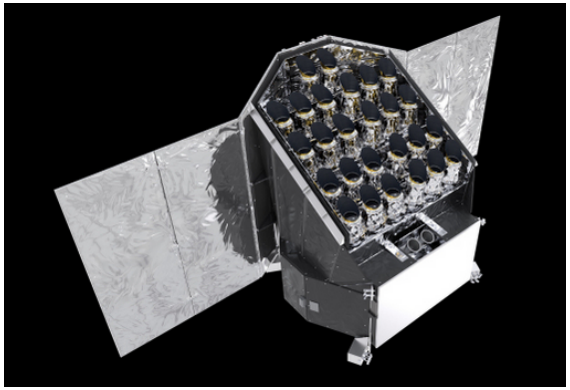
-Hubble-class infrared telescope with 100x the field of view

-Will study exoplanets, dark energy and galaxies

- Roman is a 2.4 m telescope
- Two instruments: the Wide Field Instrument, and the Coronagraph Instrument
- The Wide Field Instrument will have a field of view that is 100 times greater than the Hubble infrared instrument
- Study of stellar populations
- Microlensing survey of the inner Milky Way to find ~2,600 exoplanets
- The Coronagraph Instrument will perform high contrast imaging and spectroscopy of individual nearby exoplanets.

The Roman Space Telescope is slated to launch in the mid-2020s.

PLAnetary Transits and Oscillations of stars – PLATO (ESA)



- Detection and characterization of terrestrial exoplanets around bright solar-type stars, with emphasis on planets orbiting in the habitable zone

- Investigate seismic activity in stars, enabling the precise characterization of the planet host star, including its age.

- Complementary science includes: discoveries of circumbinary planets, moons orbiting exoplanets, exorings, comets in other systems, and planets around young and evolved stars, time-variable phenomena in various populations of the Galaxy

Ecole Evry Schatzman 2021

Formation et caractérisation des exosytèmes avec SPIRou

Roscoff, 3-8 octobre 2021

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Thank you!

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