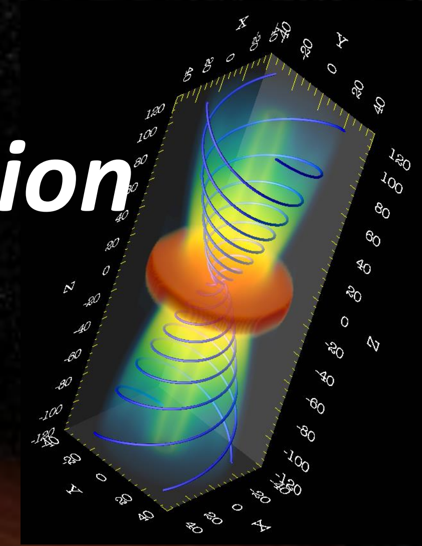
The accretion-ejection connection
in Young solar type stars



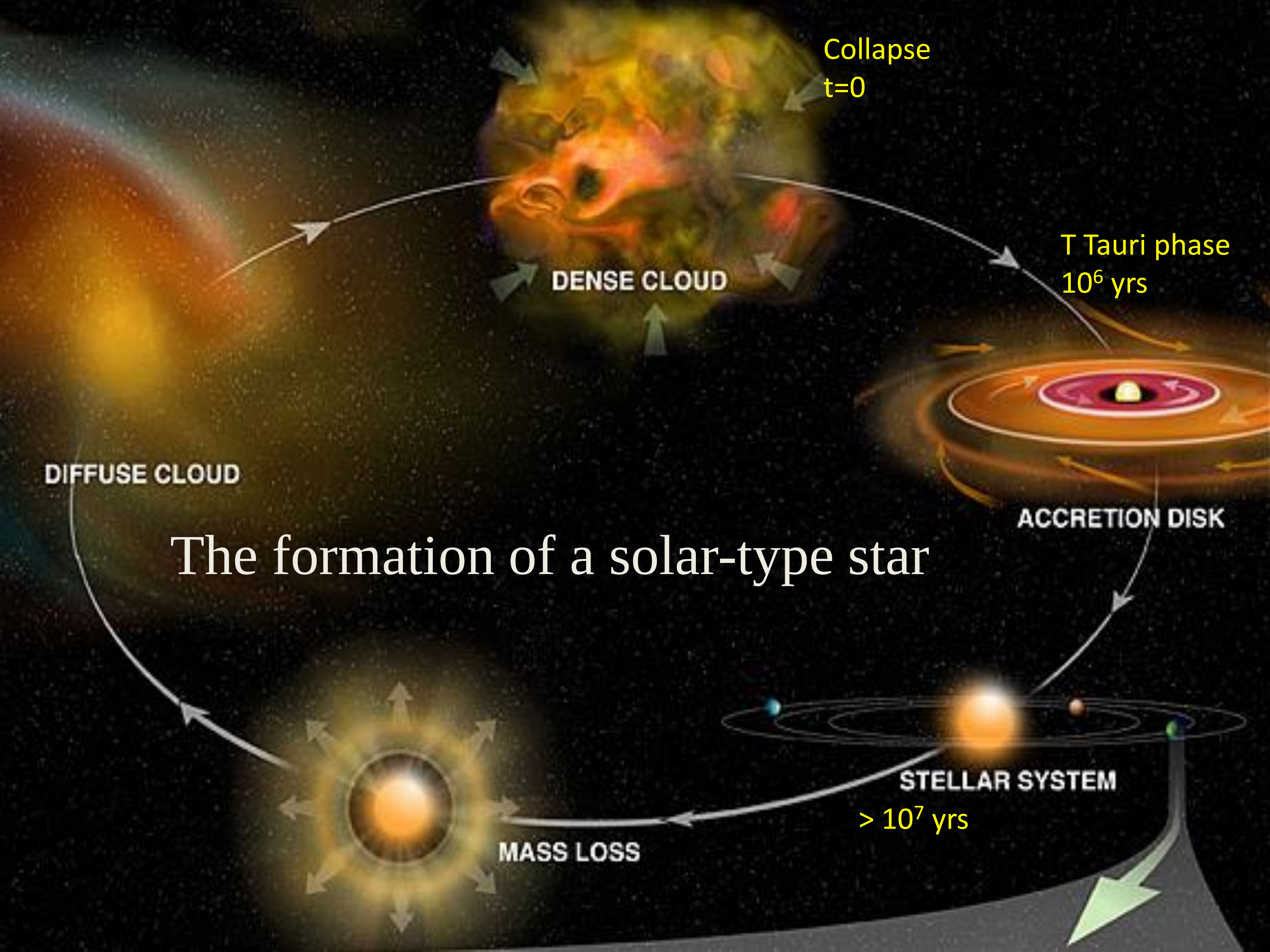
Catherine Dougados

Institut de Planétologie et d'Astrophysique de Grenoble

team

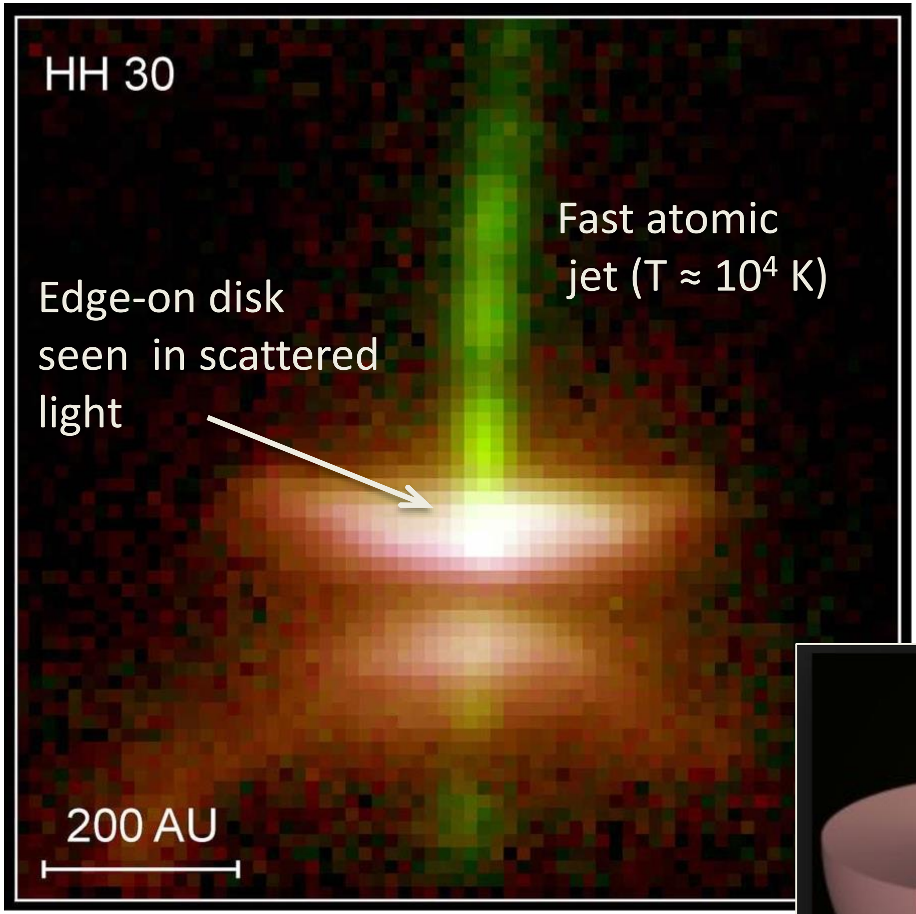
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

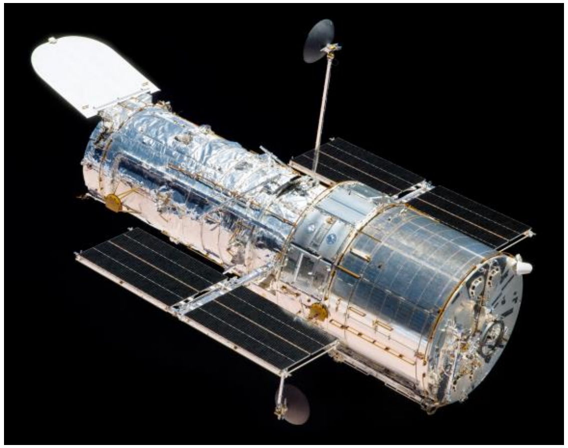
The formation of a solar-type star

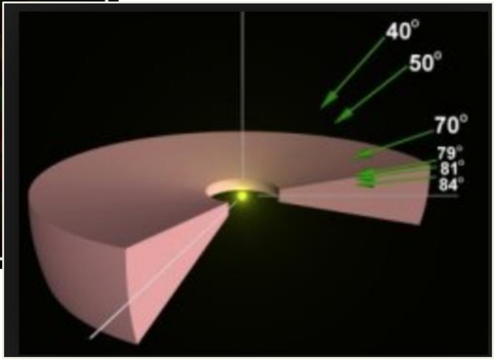


First images of a forming Sun

Optical Image from Hubble Space Telescope (HST)

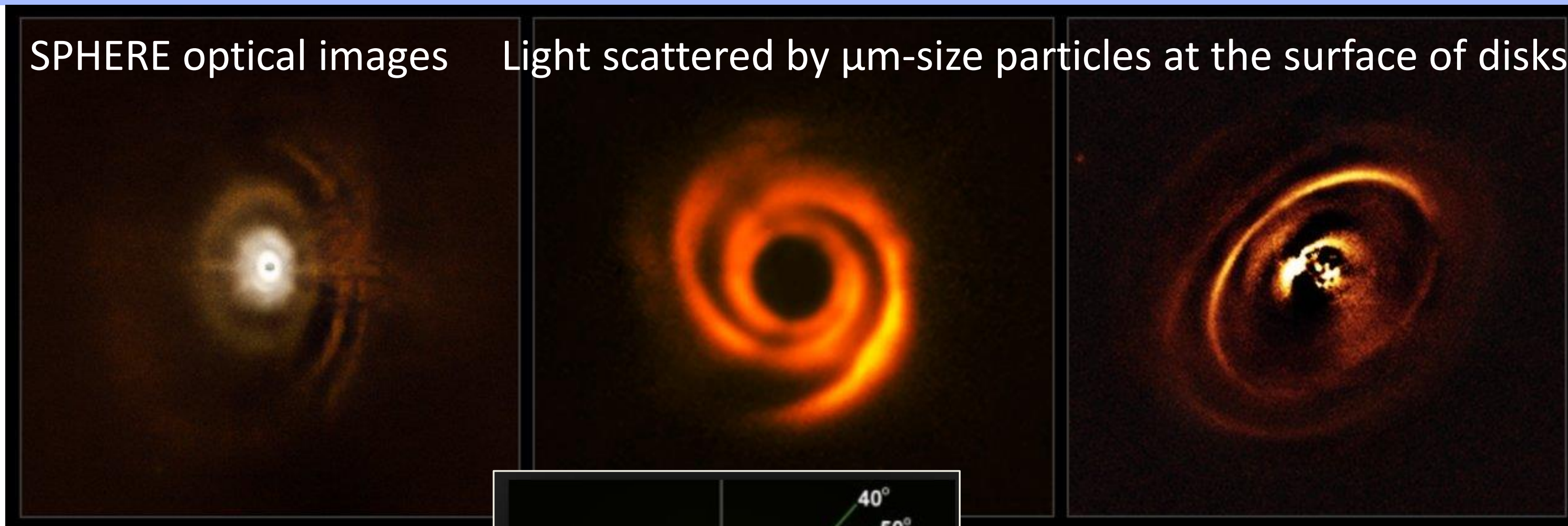


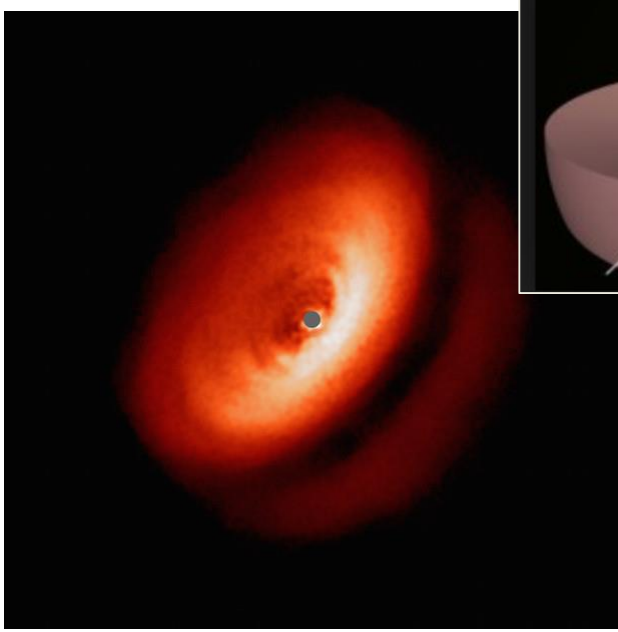


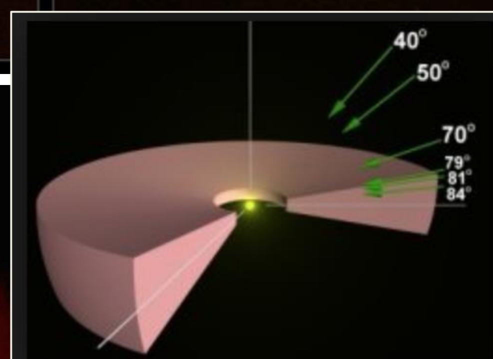


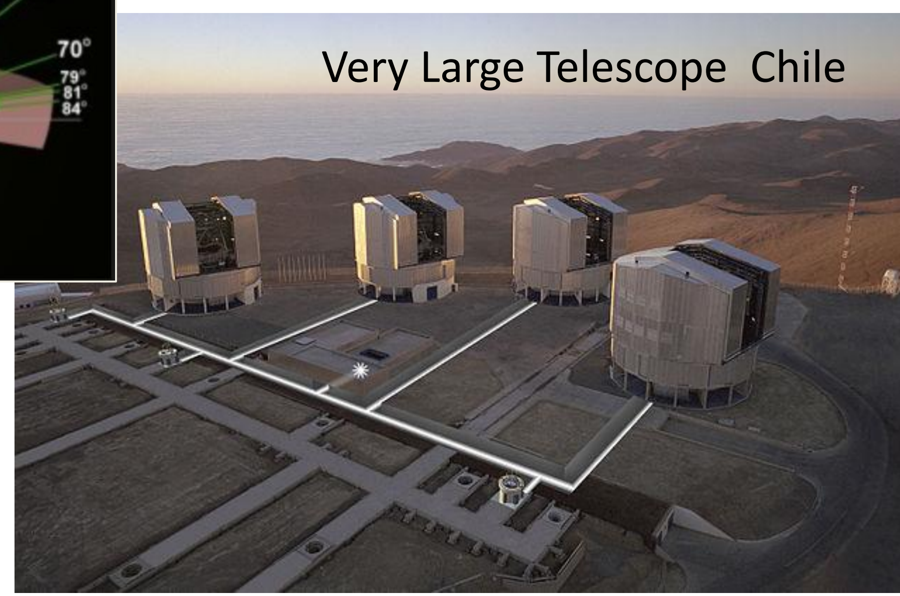
Ray et al. 1997, Burrows et al. 1996

20 years later: The SPHERE and ALMA revolution
Images of planet forming disks









20 years later: The SPHERE + ALMA revolution
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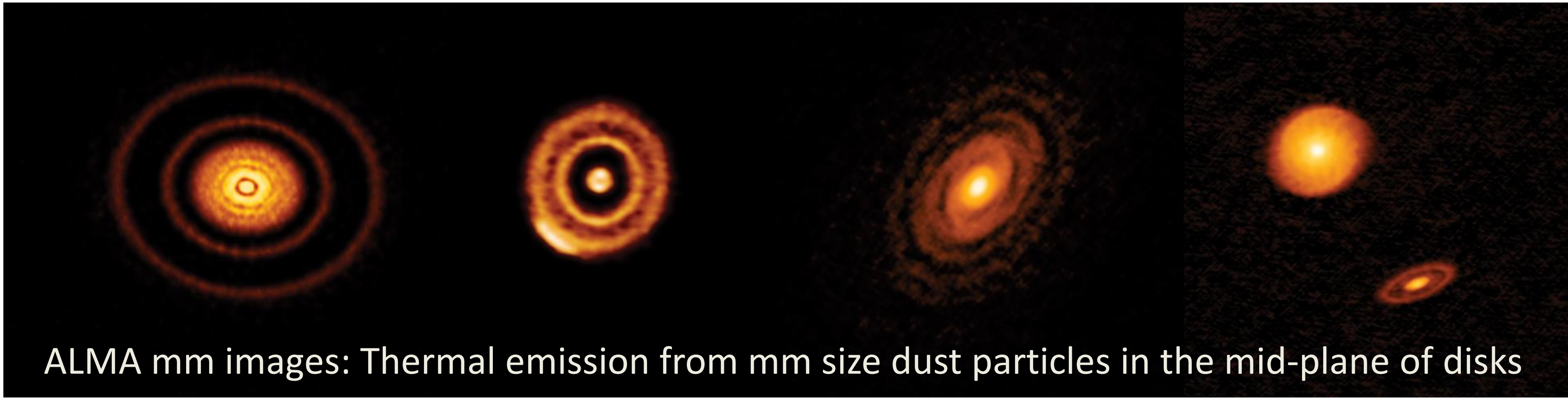
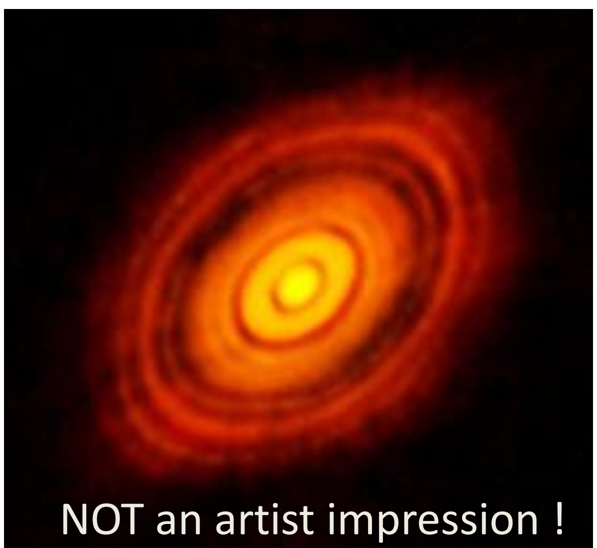
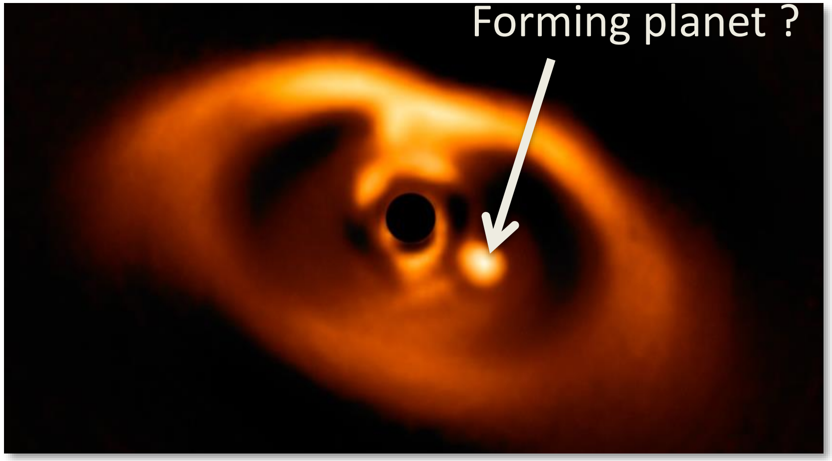


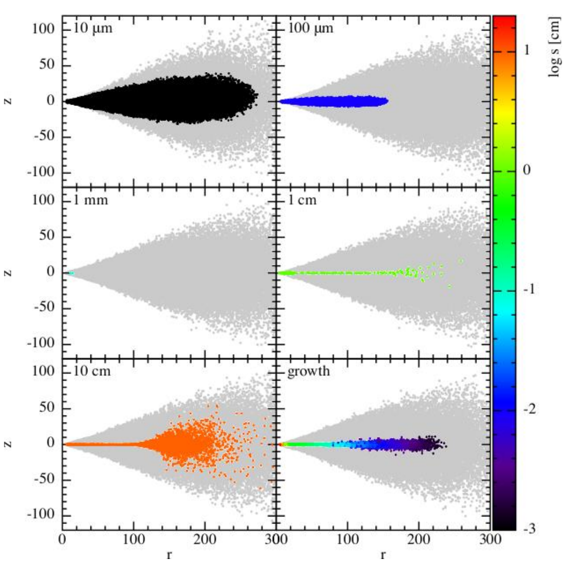


ANR Planet Forming Disk, PI F. Ménard

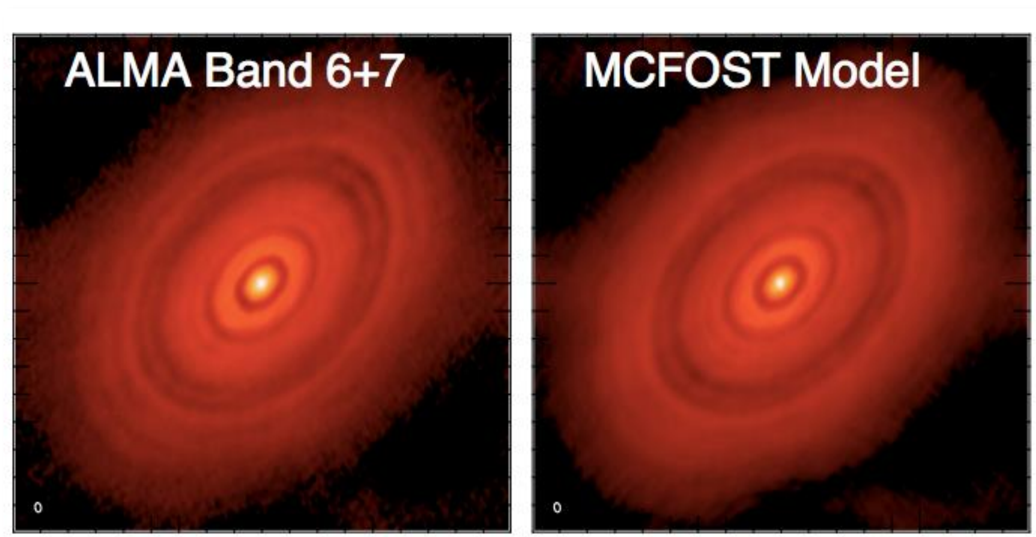


Kepler,Benisty et al. 2018

Goal:
- ✧ Understand observed structures in disks
- ✧ Identify planetary formation signatures

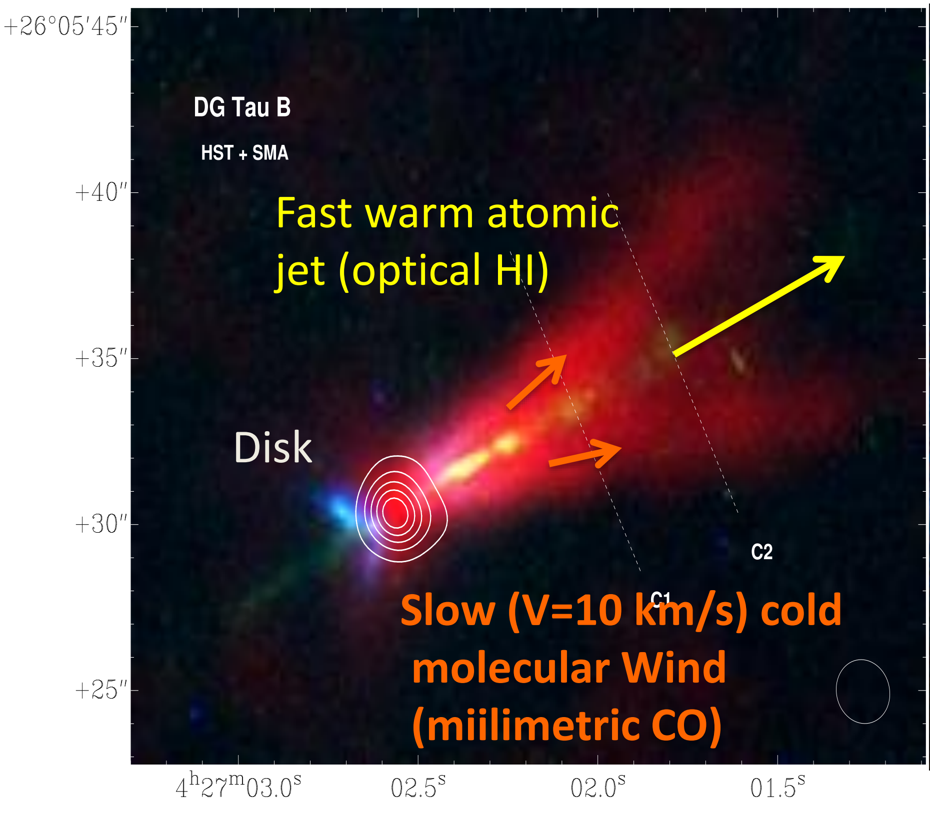


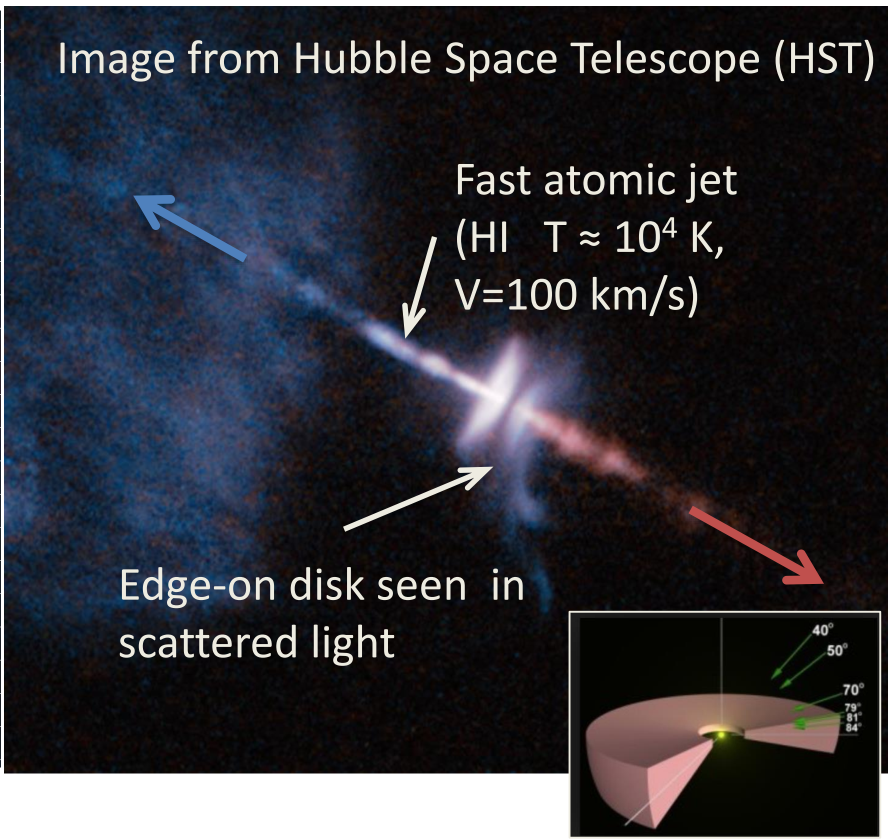
Pinte,Ménard et al. 2017



Accretion and ejection are inter-related

- Supersonic Jets and outflows observed at all stages of active accretion onto the star (ages ≤ 10^6 years)

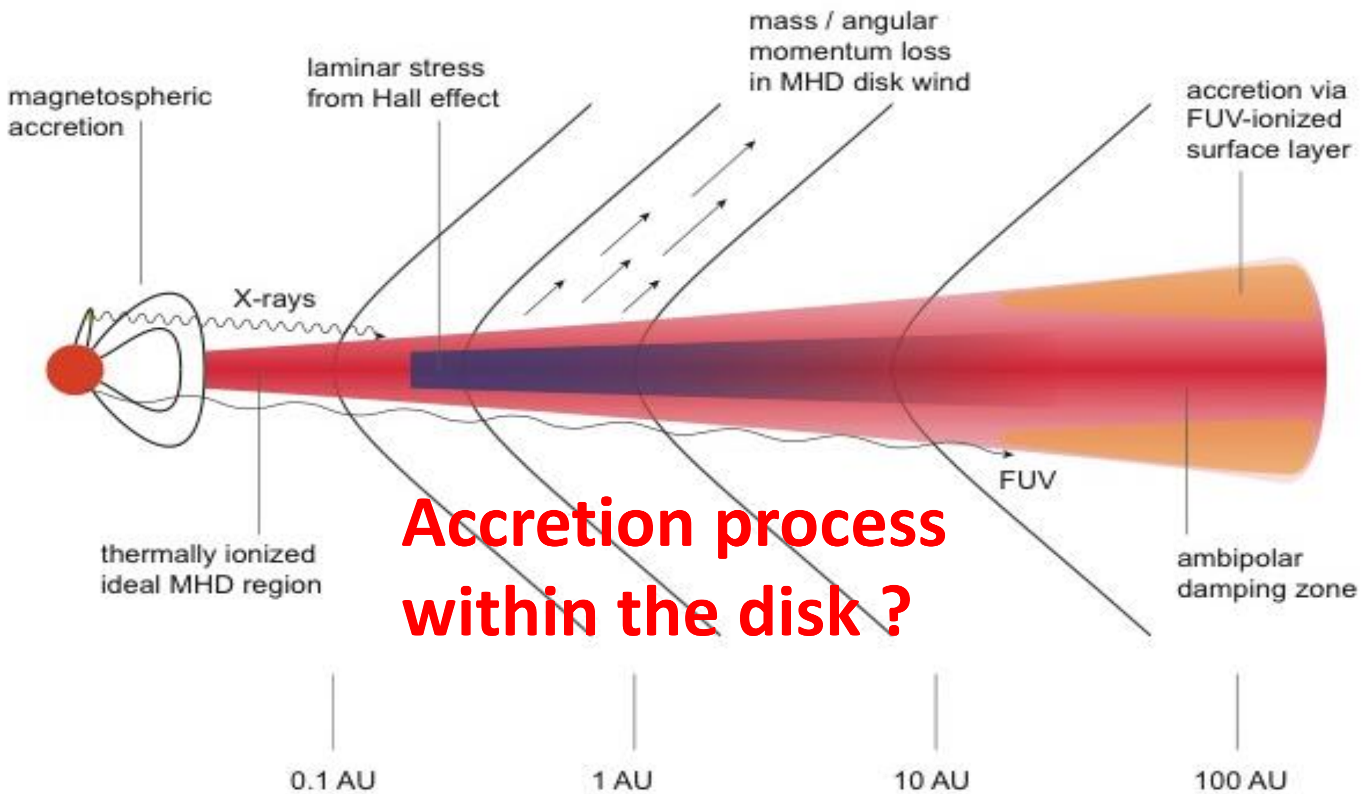




Key role of the magnetic field

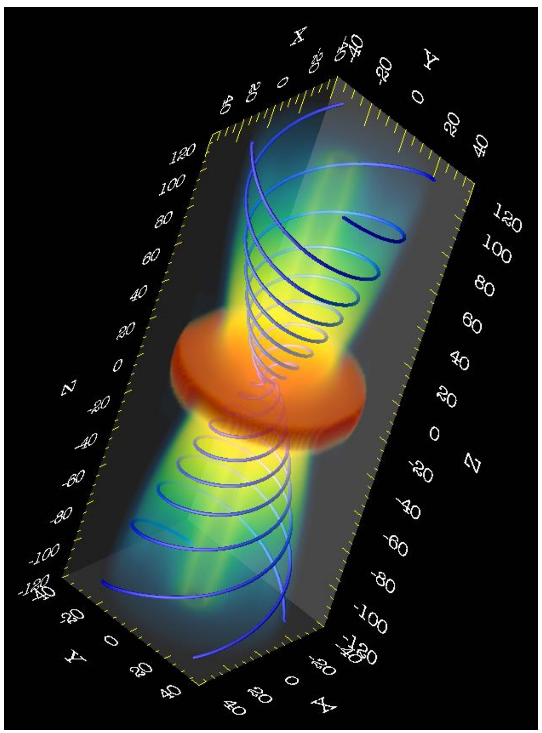
Star-disk interaction

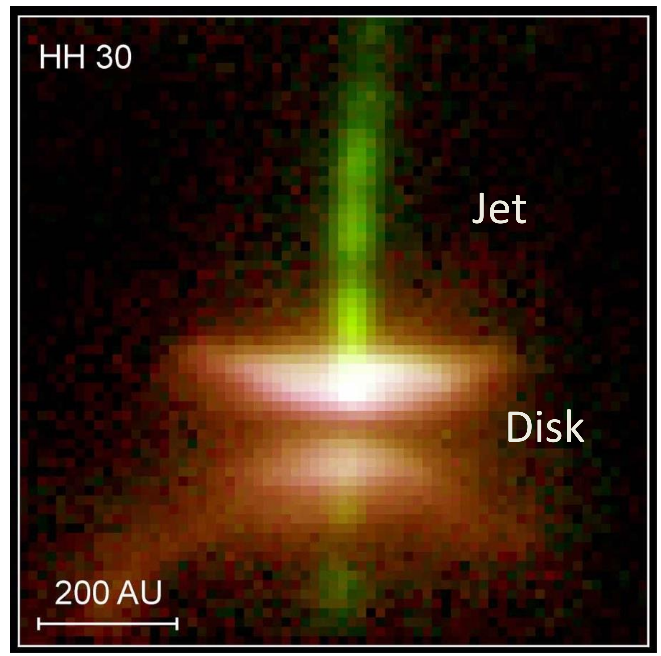
Origin of jets/winds ?



Accretion process within the disk ?

I. Jets and Outflows





Why do we need B ?

- Small collimation scale ($z < 30$ au)

  independent of environment

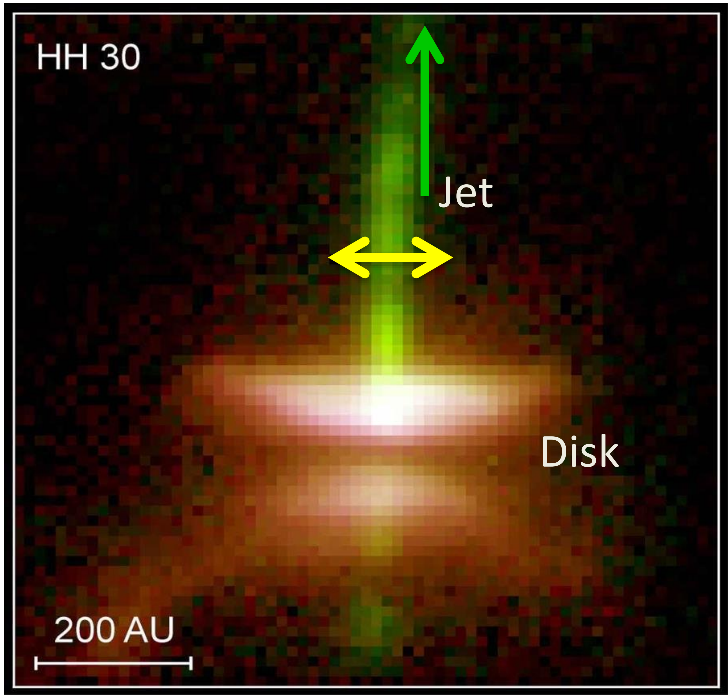
  Launching point < 5 au

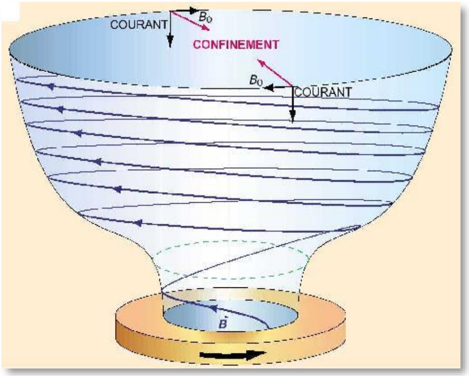
- Supersonic ejection velocities

  $V_{jet} \approx$ 200-400 km/s ($V_{esc,*} \approx$ 100 km/s)

  Mach number= $V_{jet}/C_s \approx 30$

- High efficiencies: $(dM/dt)_{jet} \approx 0.1\ (dM/dt)_{acc}$





-> magneto-centrifugal ejection

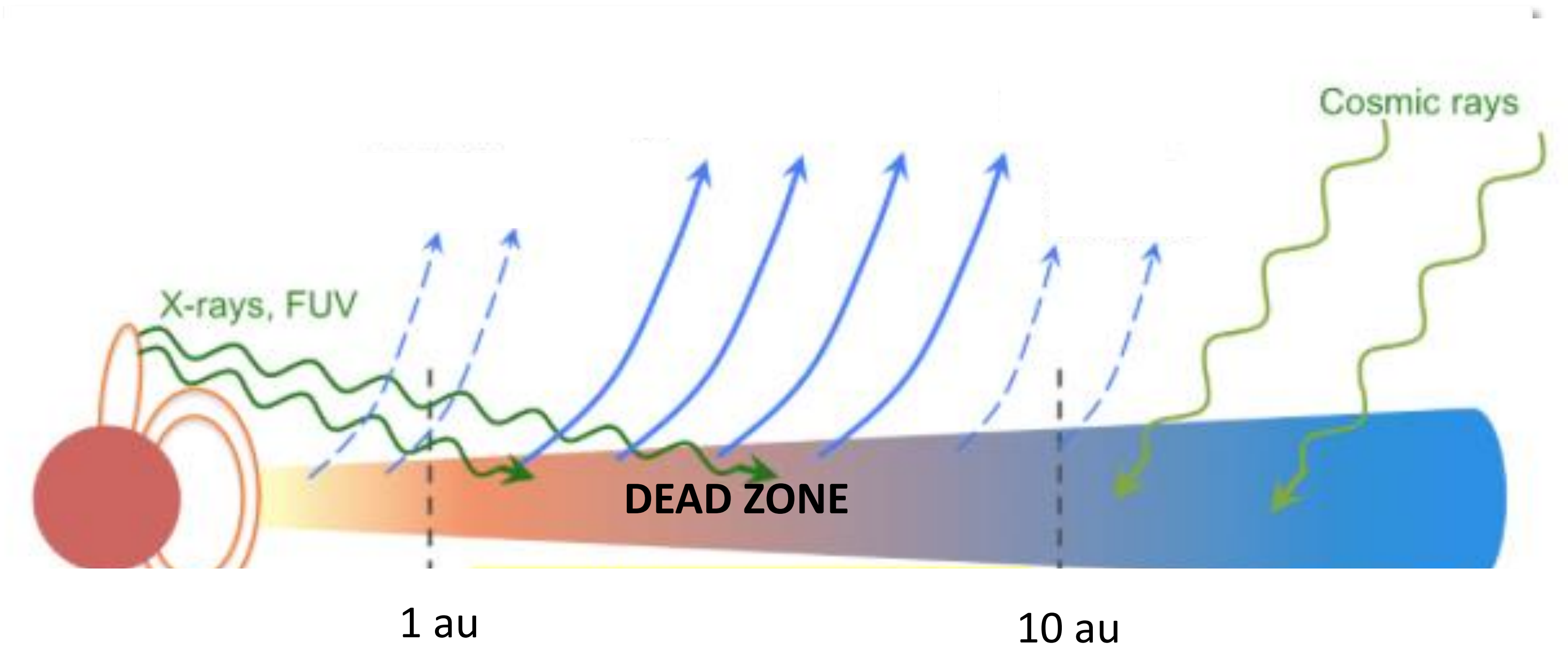
$J_z \times B_\varphi$: self-collimation

Blandford & Payne 1982

Magnetic disk winds

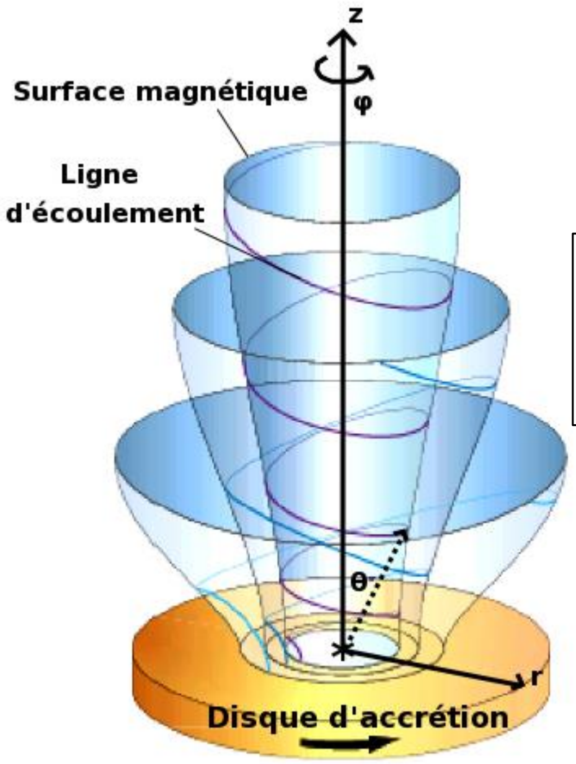
May solve the problem of angular momentum transport in disks

Traditional models: transport by abnormal viscosity due to turbulence but
no identified mechanism to sustain enough turbulence !

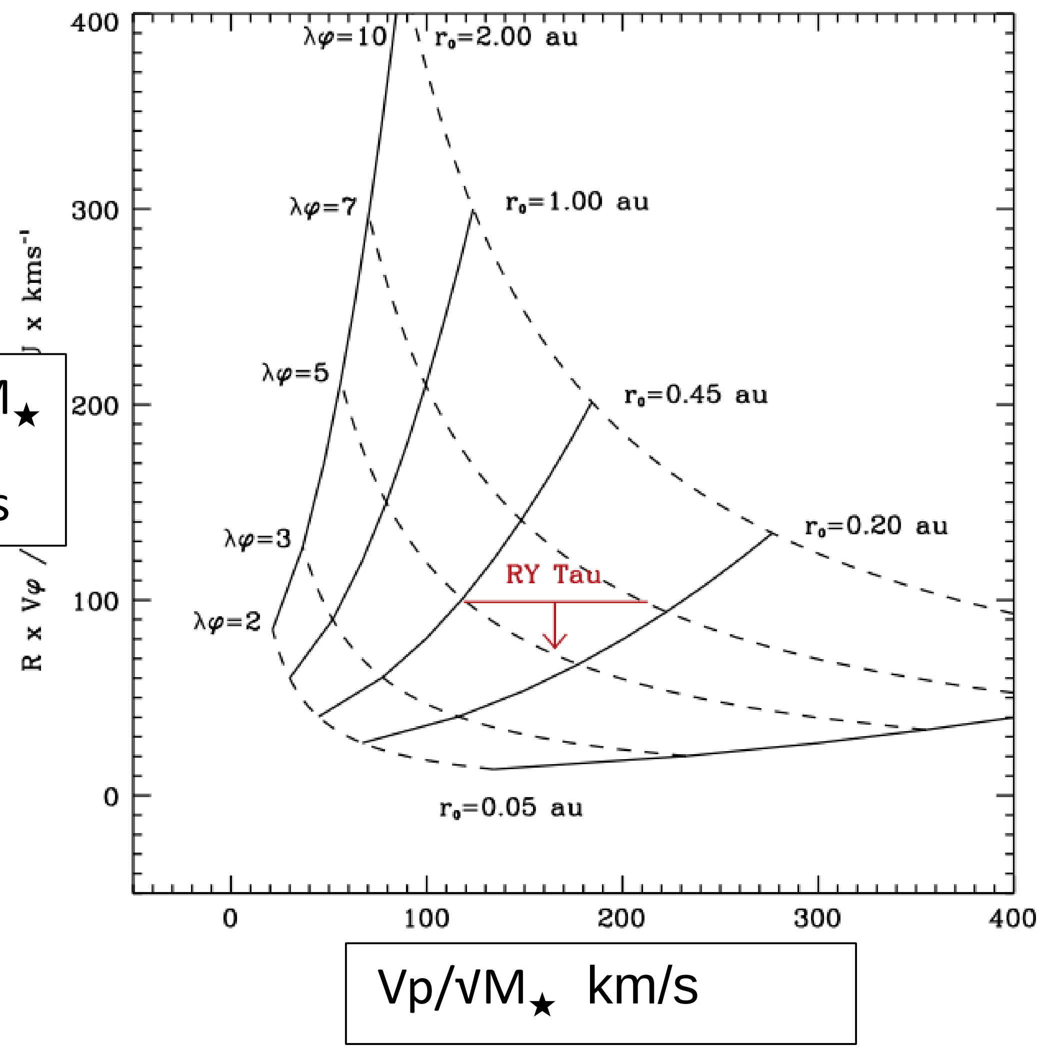


ERC G. Lesur Global Numerical simulations of disks including non ideal MHD effects

Rotation signatures

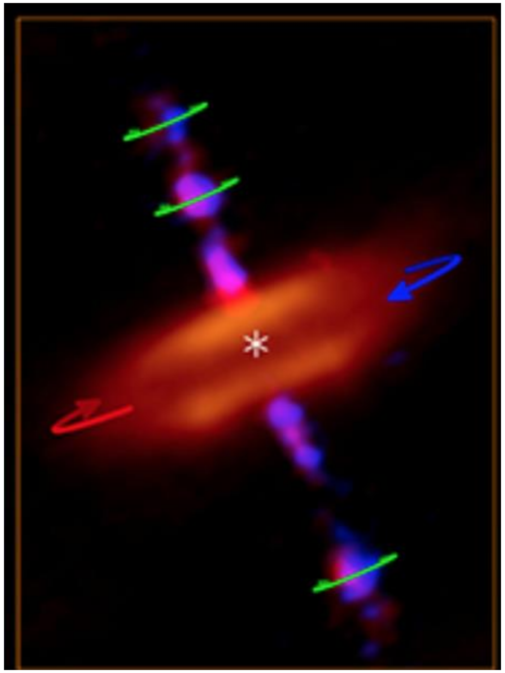


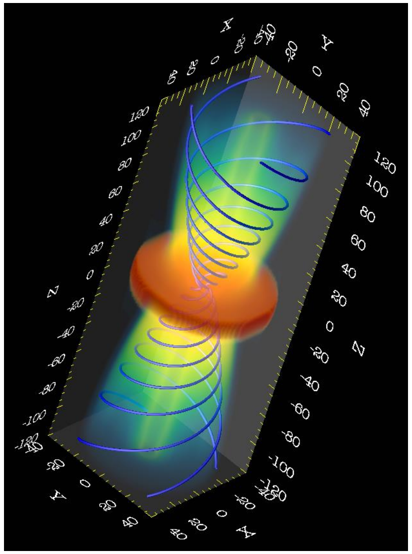
STEADY MHD disk wind models



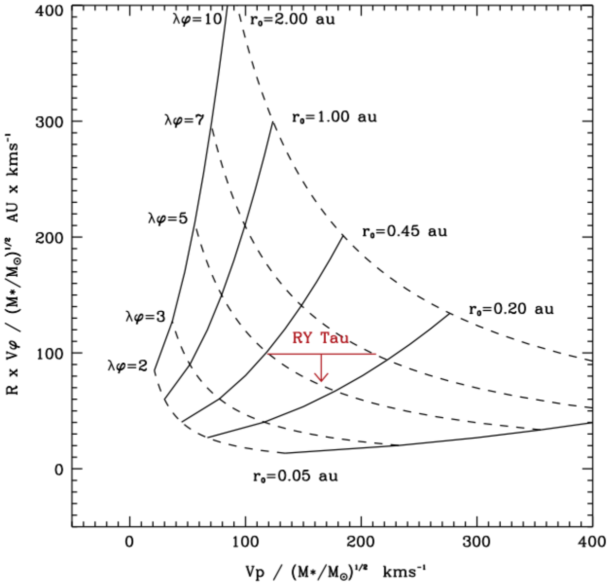
Ferreira, Dougados & Cabrit 2006 (also Anderson+02 Bacciotti+02)

Atomic jets: rotation signatures





DISK WIND MODELS



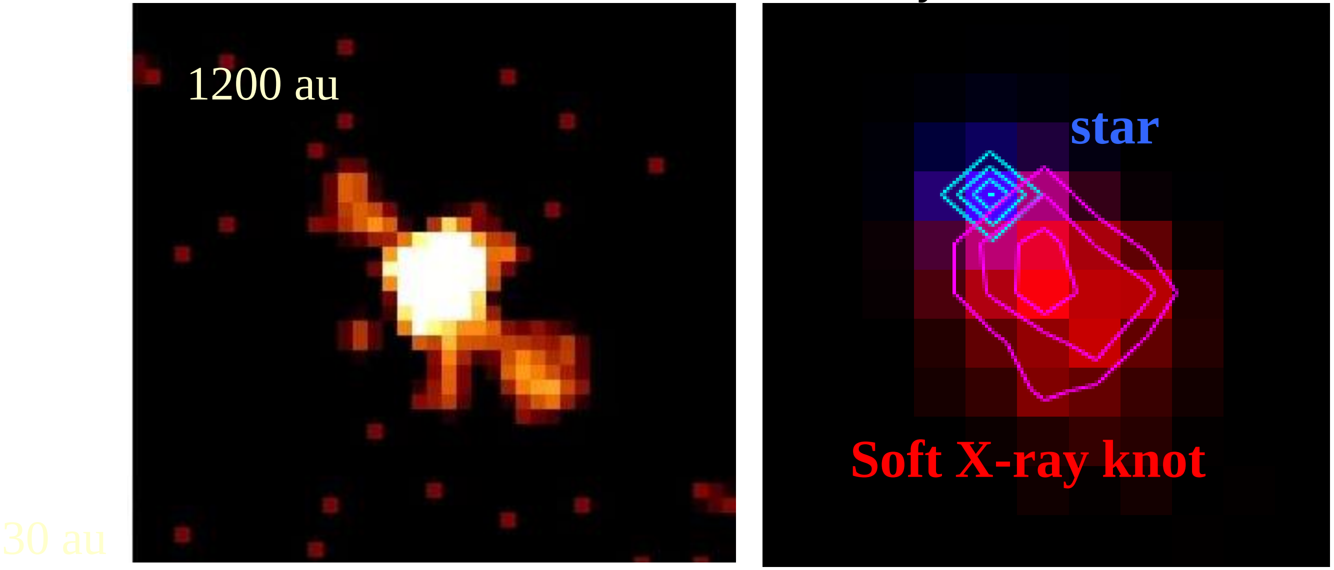
- Transverse ΔV = 10-15 km/s in 6 T Tauri jets

  Bacciotti+02 Coffey+04,07,11,12 Woitas+03 Lee+17

- ➔ suggests rlaunch ≈ 0.1 – 5 au for all candidates so far

Inner jet X-ray emission ?

DG tau Jet in X-rays



Gudel+08,12

- Soft X-ray along jet axis (40-1200 au)

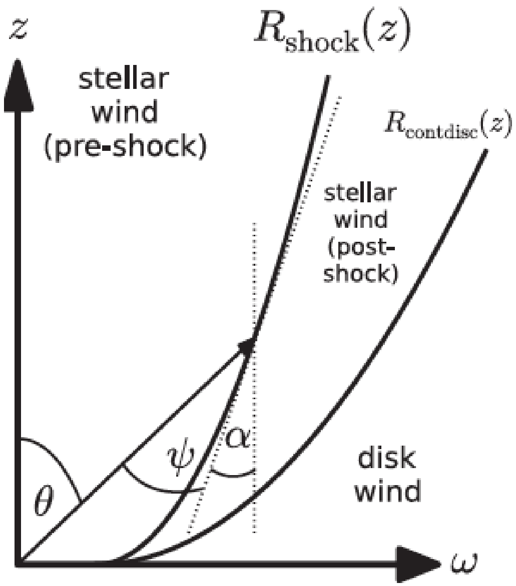
  Gudel+08 Skinner&Gudel14 Skinner+11 Favata+02

- Tx= 3-4 x10^6 K → **If shocks: Vs > 450 km/s**
  - ✓ dM/dt ≈10^{-10} Msun/yr reproduces Lx Gunther+09
  - ✓ Other heating processes: magnetic heating ?

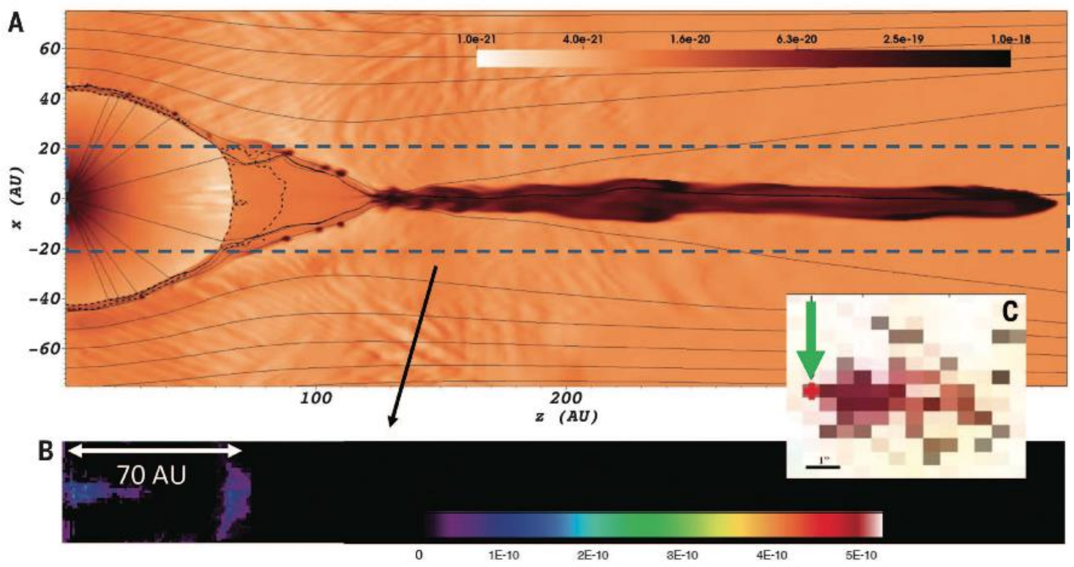
- Inner X-ray knot stationary: recollimation shock ?

The inner X-ray emission

Recollimation shock in an inner tenuous fast stellar wind ? Bonito+10



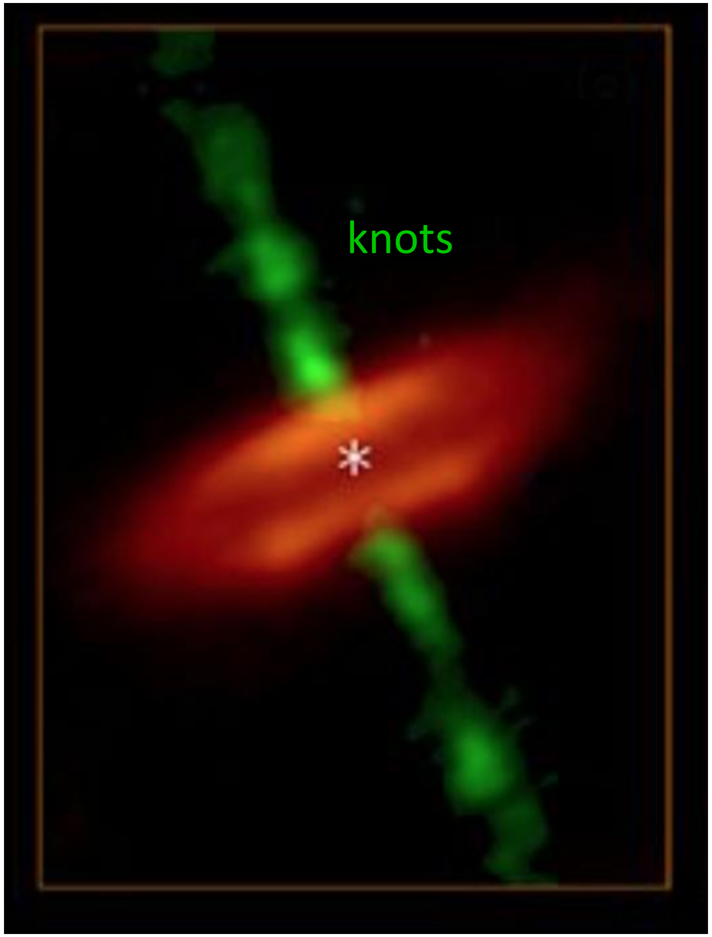
Gunther+14



Albertazzi+14

Link with spectroscopic unresolved signatures of stellar winds ?

Jet asymetries and variability ?



- Velocity asymetries(x2) between 2 sides

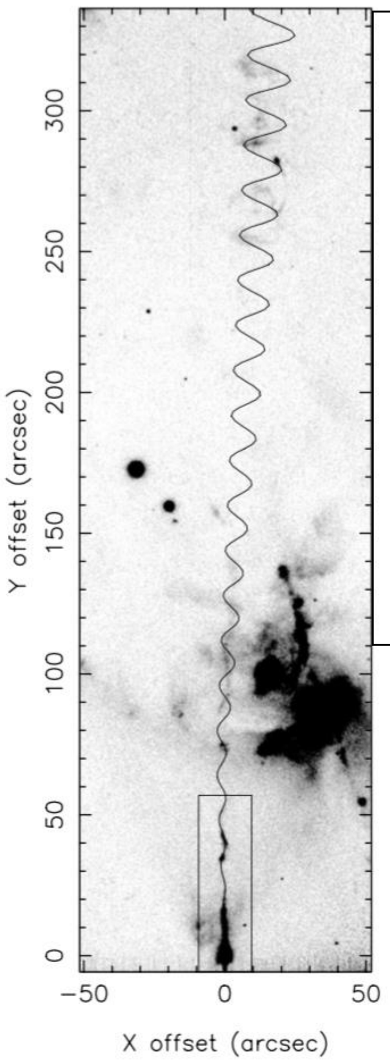
  Melnikov+09 Podio+11 Ellerbroek+14

  → ≠ momentum flux and kinetic energy flux

- Emission knots: Internal shocks due to time variable ejection with Δt a few years. Origin of such timescales ?
  - Variability in stellar B ?
  - Dynamical perturbations by companions in disks ?

Jet/flow axis wiggling

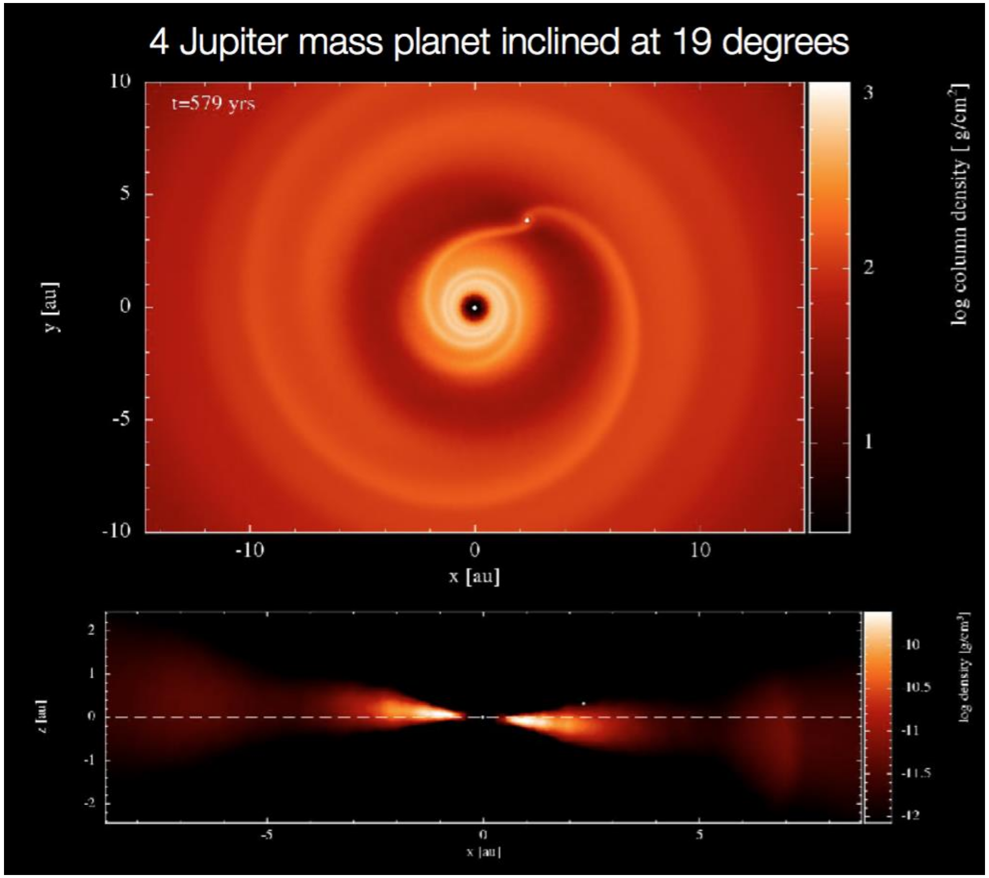
Atomic jet wiggling



✧ Orbital motion in 18 au sep binary

✧ Disk precession
tprec=100 yrs
ϑ =1.3°

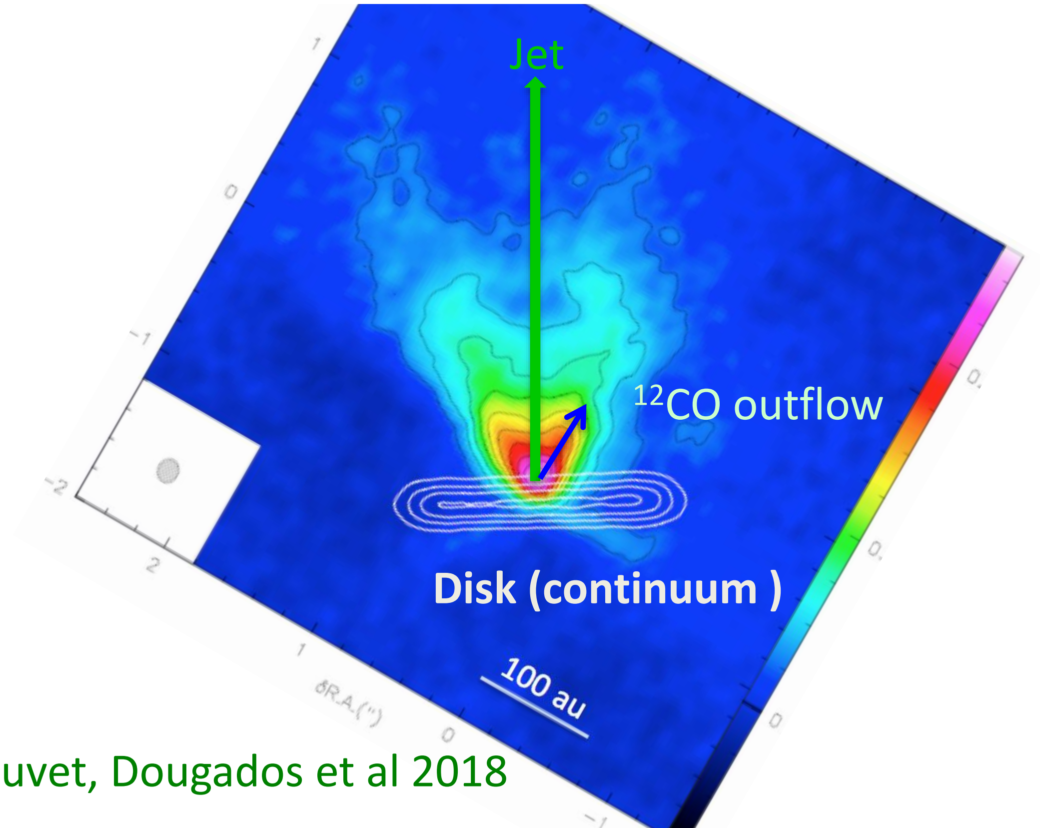
Anglada+2007
Estallela+2012



Precession induced by companion/massive planet ?
Nealon+18 Sheikhnezami+18

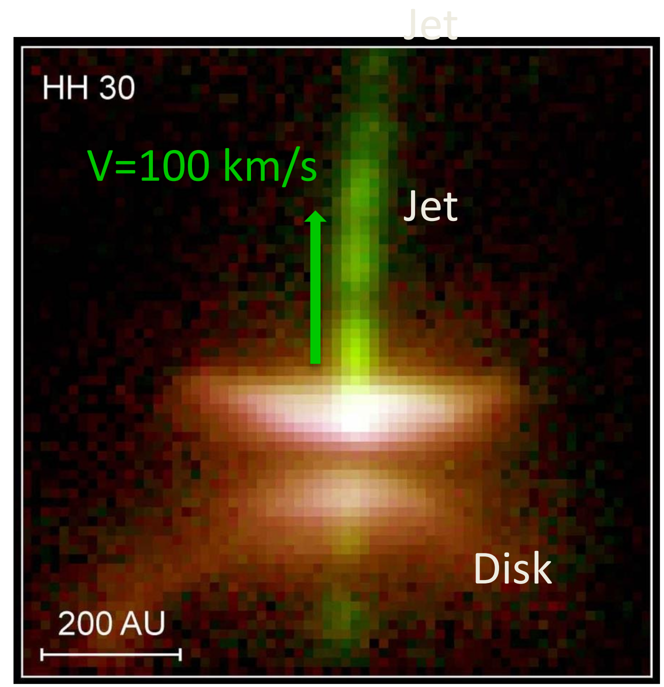
Small scale molecular outflows

Image at millimetric wavelengths



Louvet, Dougados et al 2018

Image at optical wavelengths



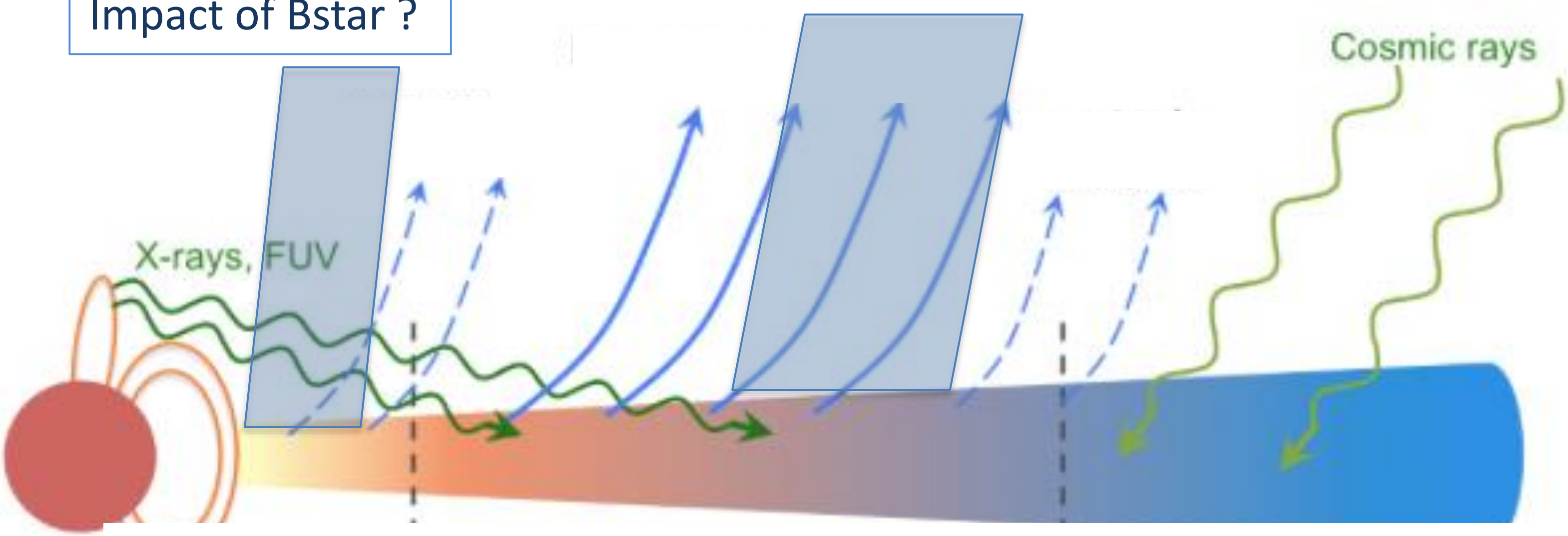
Slow rotating conical molecular flow around fast axial jet

- Kinematics consistent with expectations from MHD disk winds
- Mdot(CO) ~ 50 x Mdot (atomic jet) > Macc(star) ➔ **strong disk impact** ?

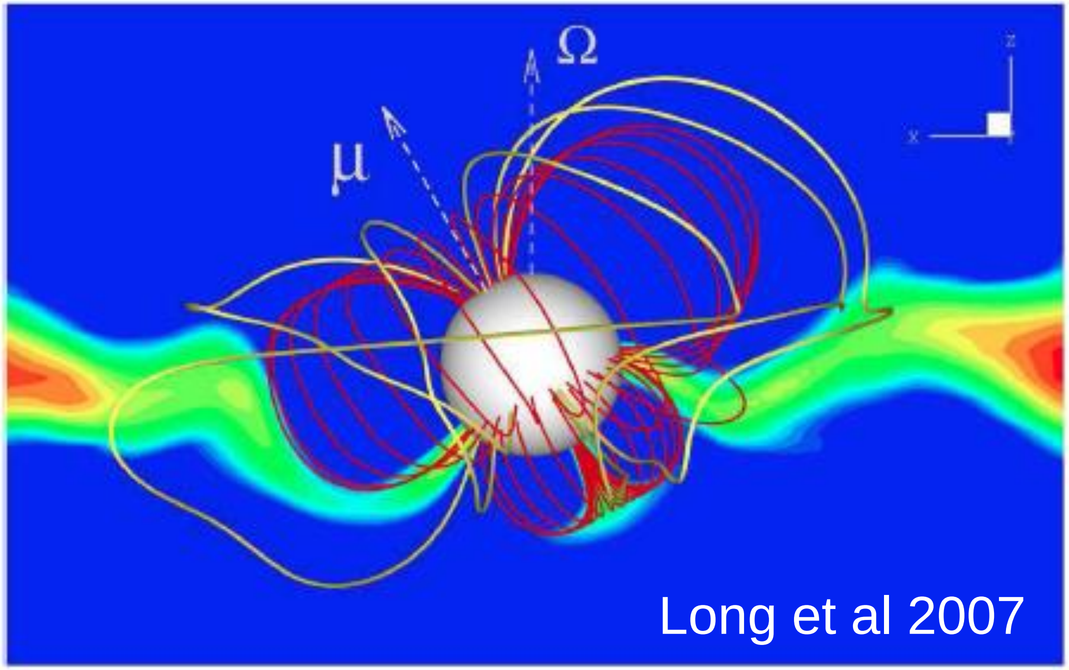
Global view

Optical Jets trace inner streamlines
Tgas=10^4 K
Impact of Bstar ?

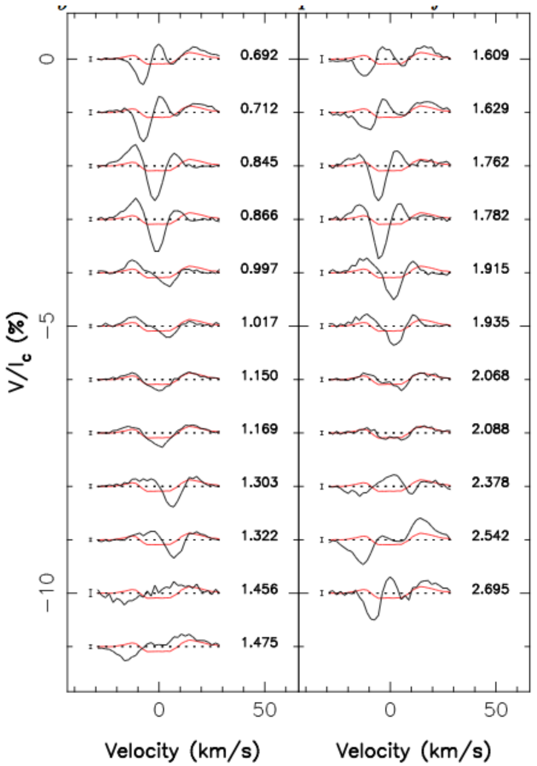
Slow (CO) winds, Tgaz= 10 K
streamlines at 1-10 au

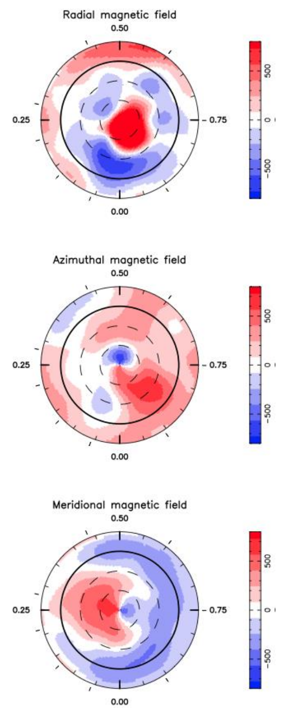


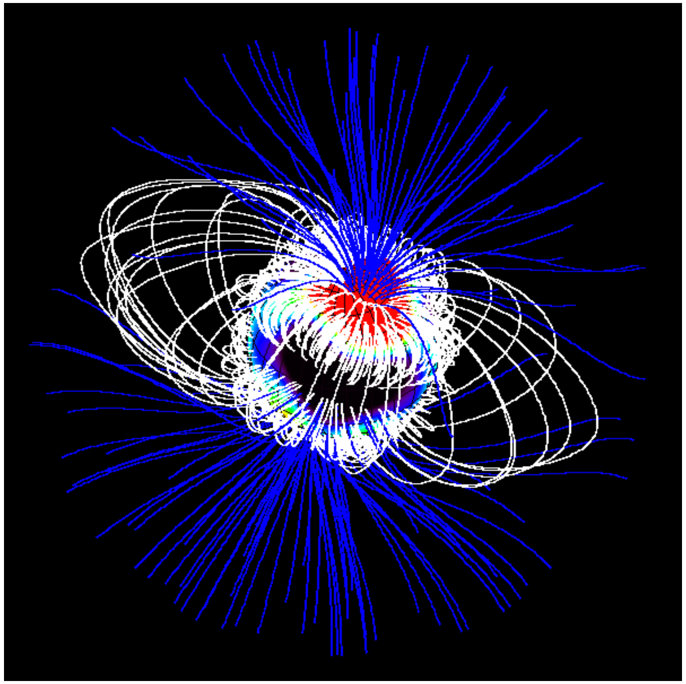
II- The impact of the stellar B-field



Young suns are magnetic



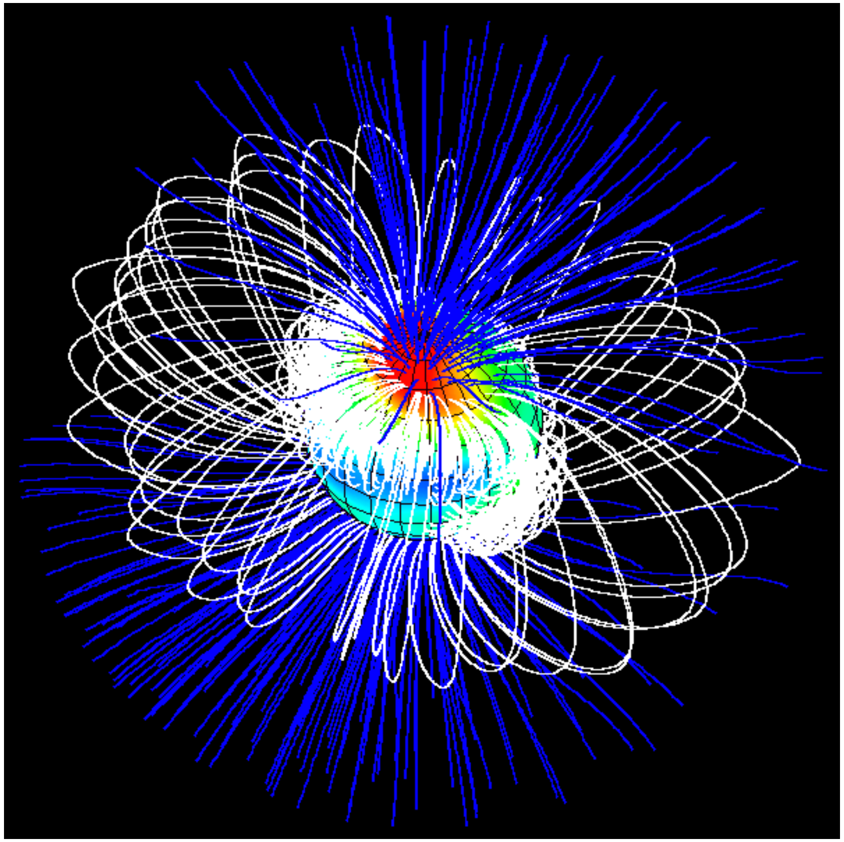


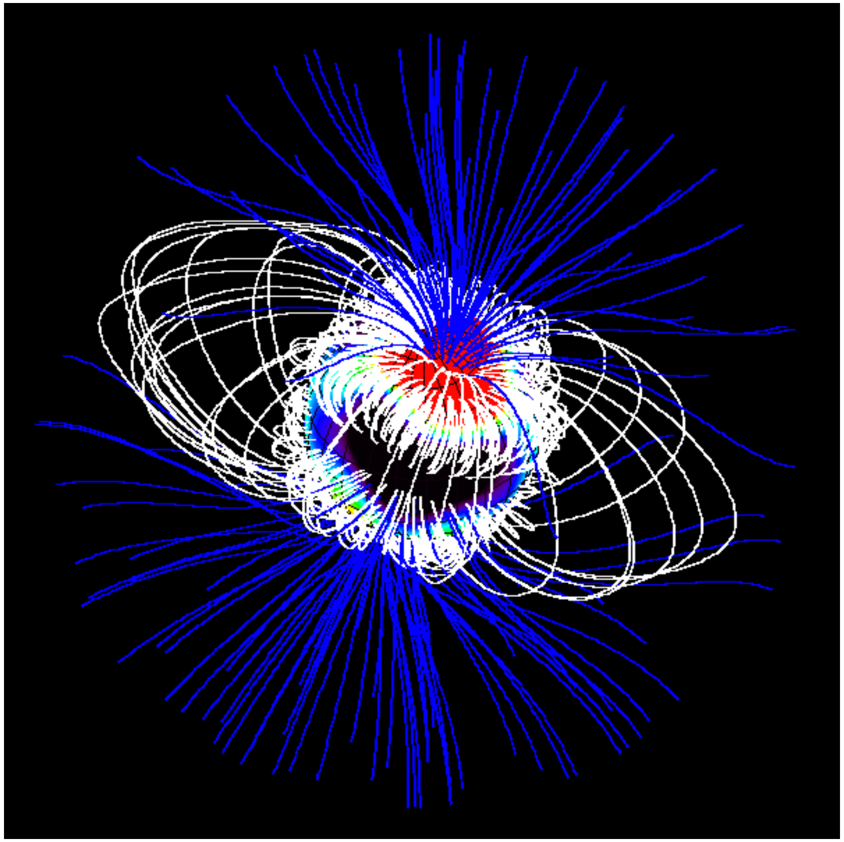


Donati et al. 2012, Gregory et al. 2012 Johnstone et al. 2014

- On-going magnetic surveys of young stars with optical/near-infrared spectropolarimeters (ESPADONS-SPIROU at CFHT PI J.F. Donati)

The magnetosphere of T Tauri stars





BP Tau (Donati et al. 2008)

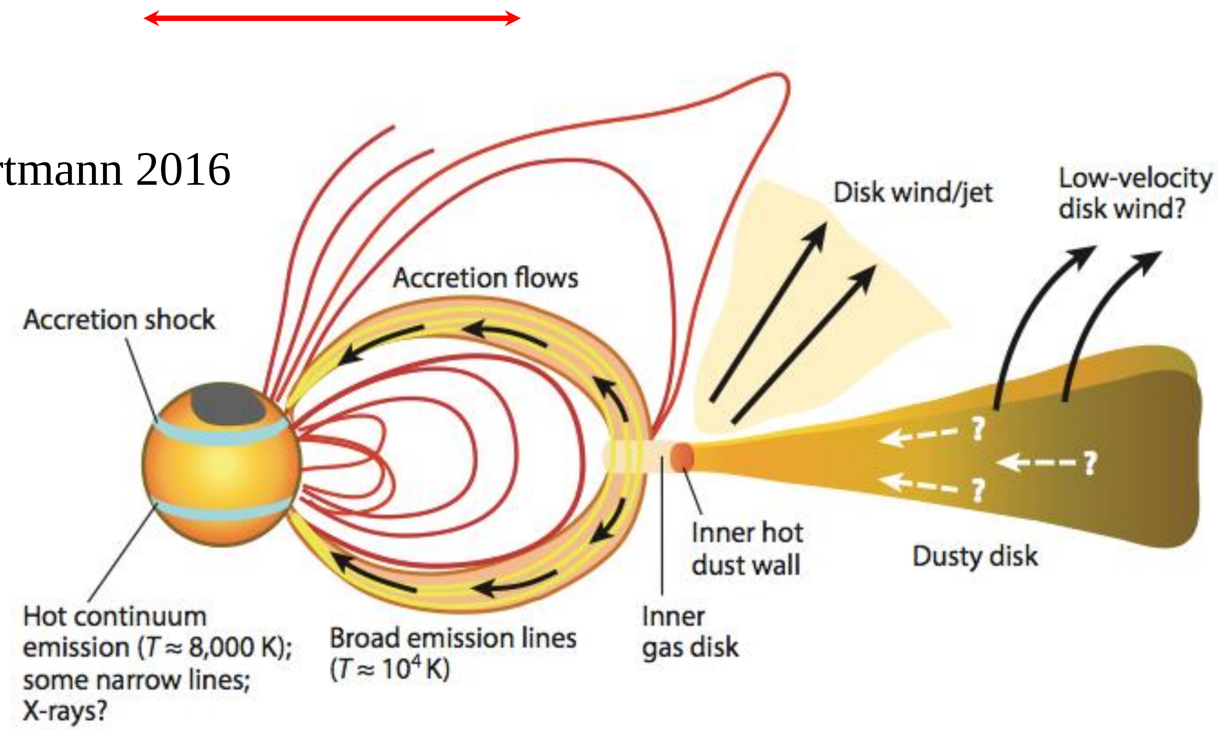
V2129 Oph (Donati et al. 2007)

Magnetic field strength ~ a few 100 Gauss to a few kG, (1 Gauss = 10^{-4} Tesla)

dipole+octupole in 50 %

The magnetospheric accretion paradigm

Magnetospheric cavity: a few Rstar < 0.1 AU

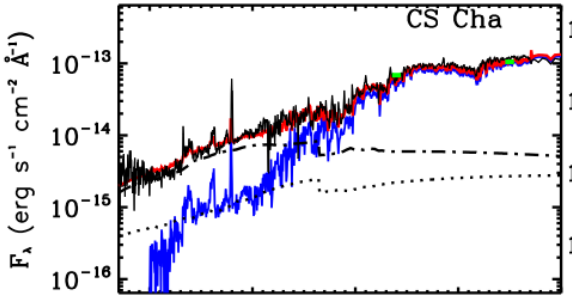


Rtrunc = f(Bstar,Macc) ≈ Rcor

Camenzind 1990
Edwards et al. 1994
Hartmann et al. 1994

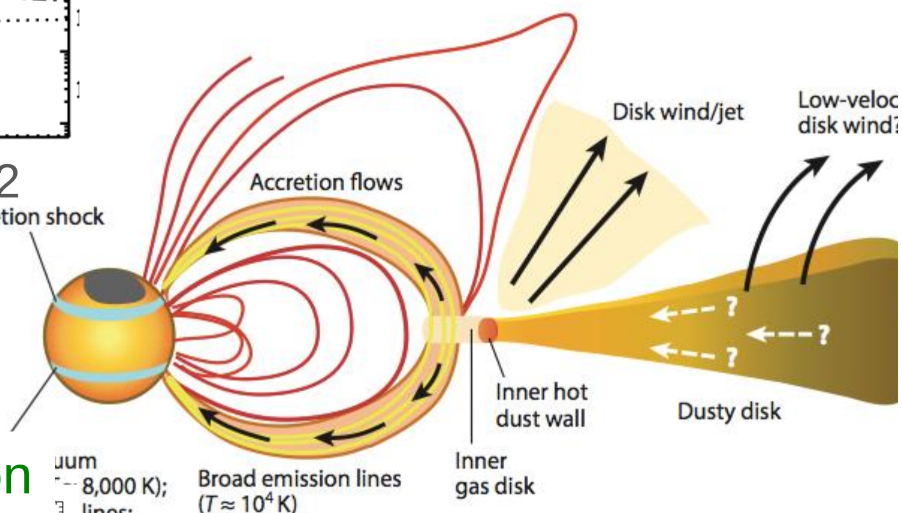
Signatures of accretion shocks

UV excess emission

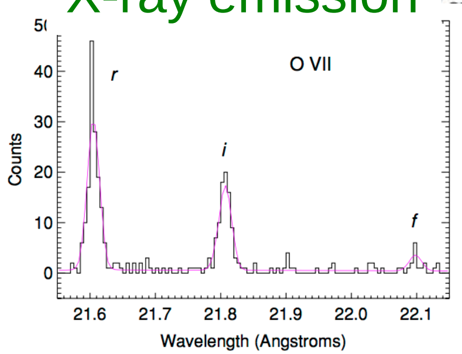


Ingleby et al. 2012

L. Hartmann 2016



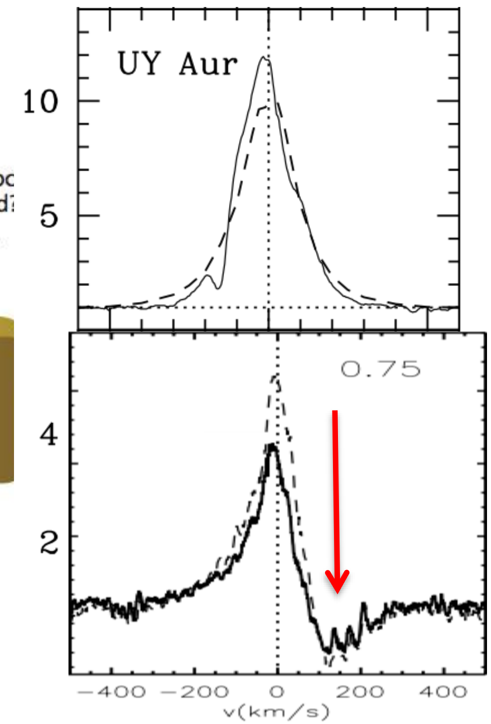
X-ray emission



Brickhouse et al. 2010

V_{ff} = 200-300 km/s

HI line profiles

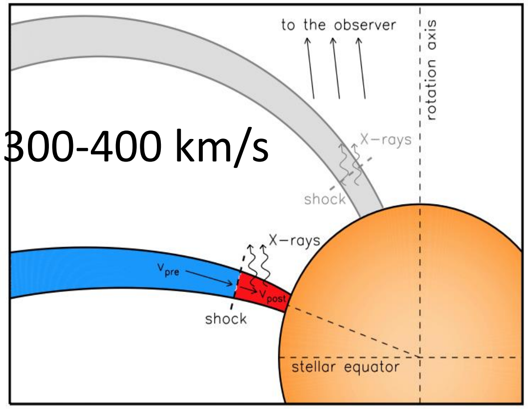


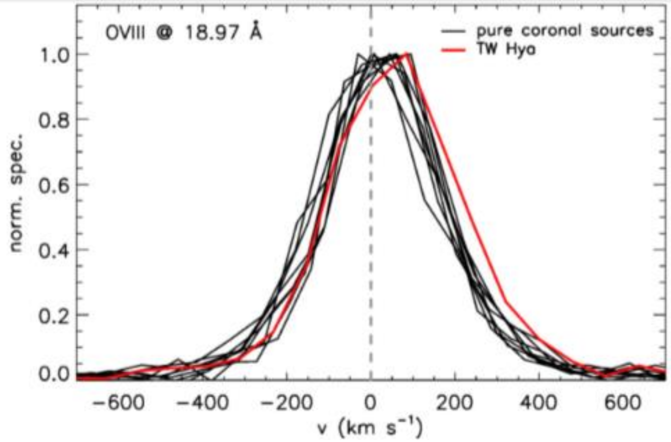
Edwards et al. 1994
Muzerolle et al 2001

The accretion shock

- Soft X-ray emission from shocked infalling material

V_{ff} = 300-400 km/s

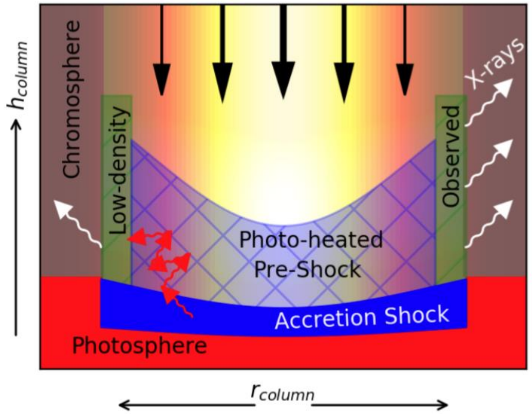




Argiroffi et al. 2017

- *Missing* X-ray flux

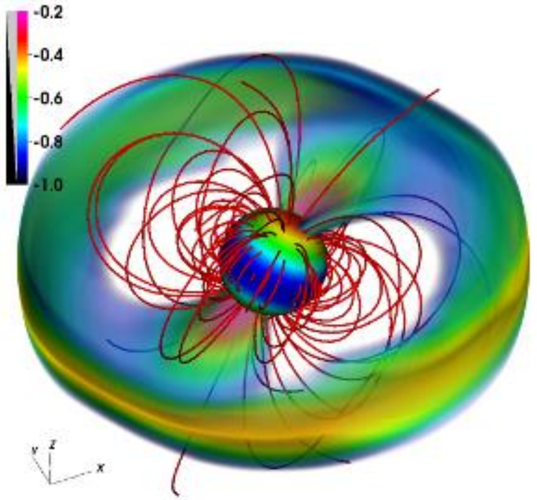
Schneider et al. 2018

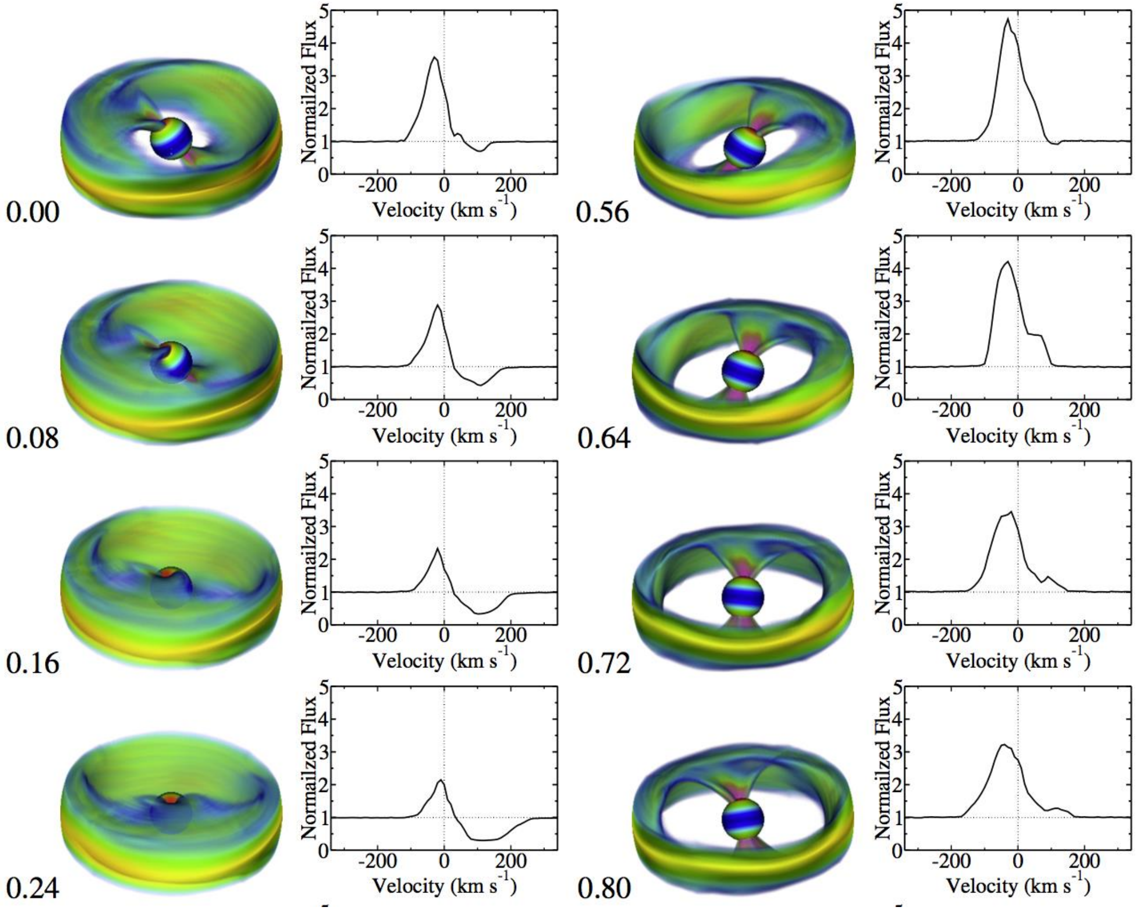


Spectroscopic modulation

Stellar rotation periods 2-8 days

MHD 3D numerical simulation of tilted dipole disk interaction

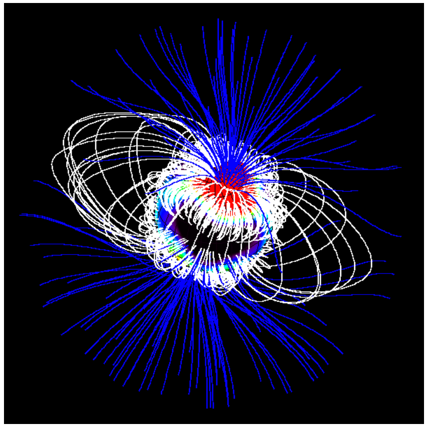


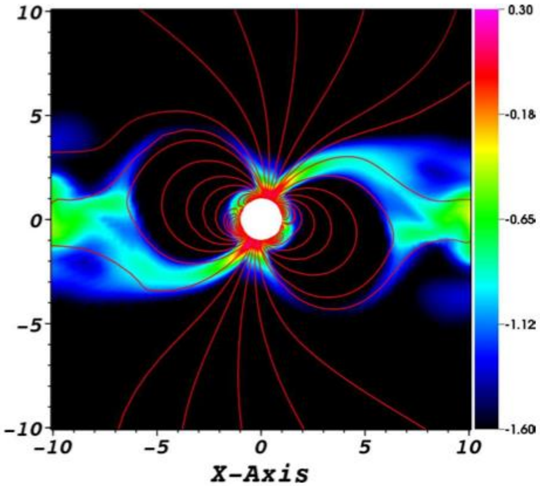


Kurosawa & Romanova 2013

Spectroscopic modulation: observations meet models

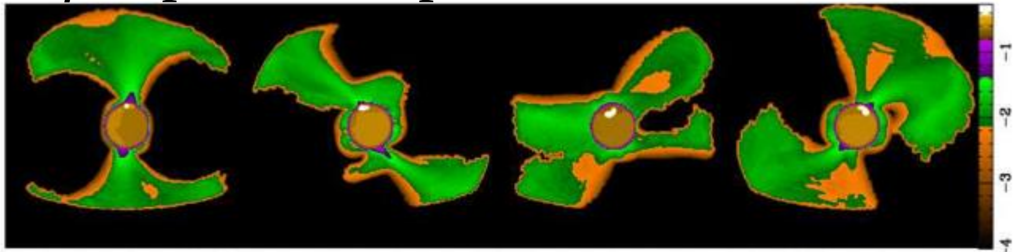
Stellar B field
mapped



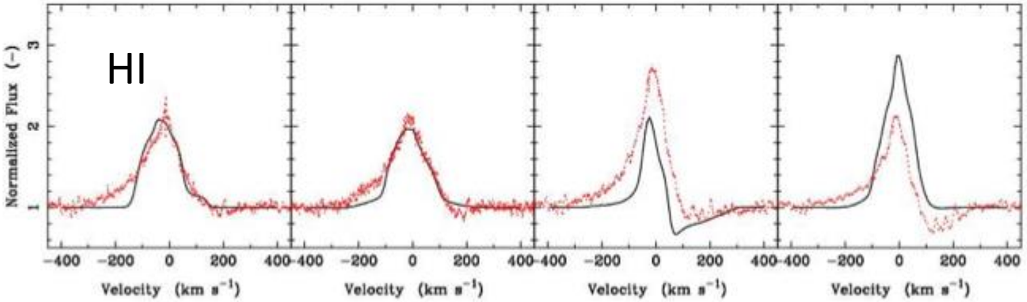


Stellar B field
Input to numerical
Simulation

Hβ dipole+octupole



Predicted HI maps
and profiles as
Function of rotation
phase



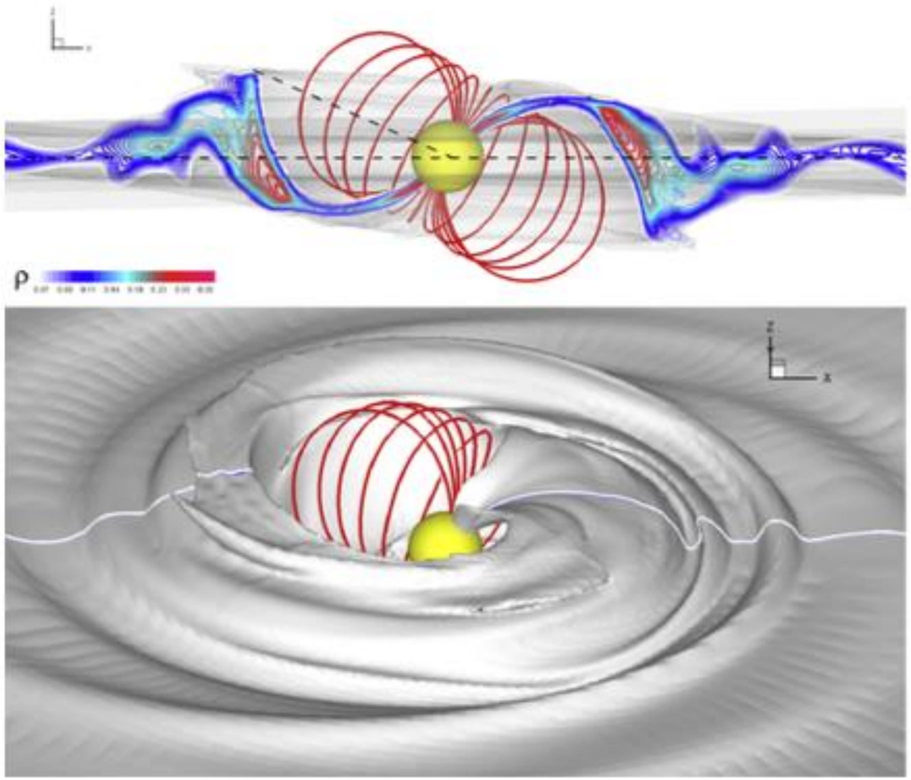
model

data

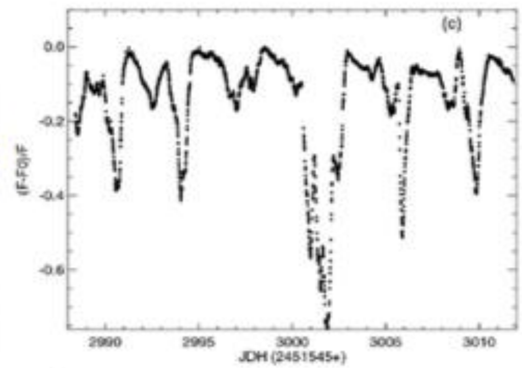
Alencar et al. (2012)

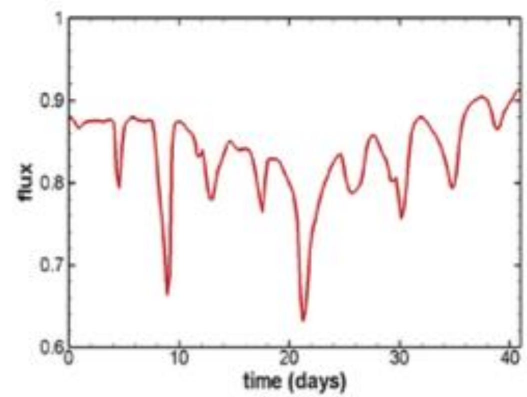
Photometric modulation

Time monitoring of stellar flux in the optical



Romanova et al. (2013)



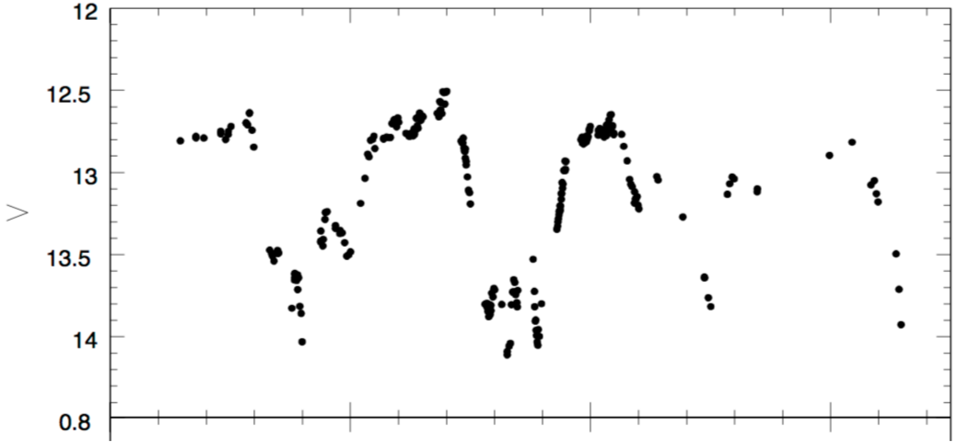


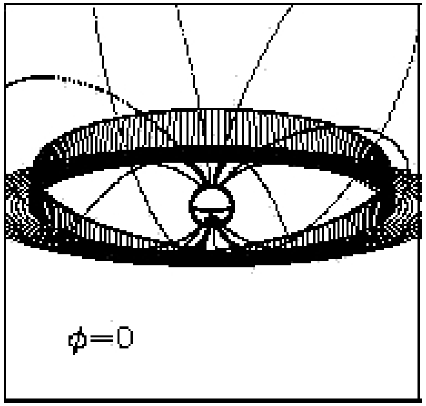
‘Dippers’

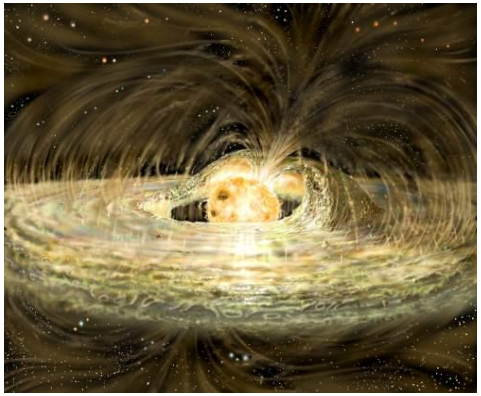
A prototype *dipper* system

The AA Tau system Bouvier et al. 1999, 2003, 2007

Optical stellar flux as a function of time







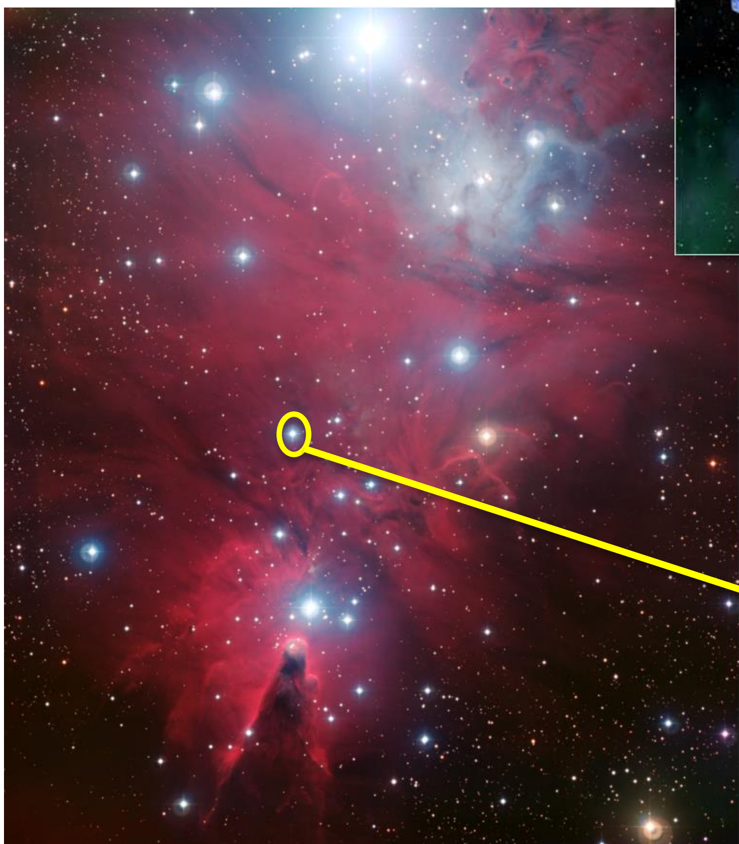
Occultation by inner disk warp resulting from inclined magnetosphere

Coordinated Synoptic Investigation by CoRoT

A revolution in space based monitoring of young stars

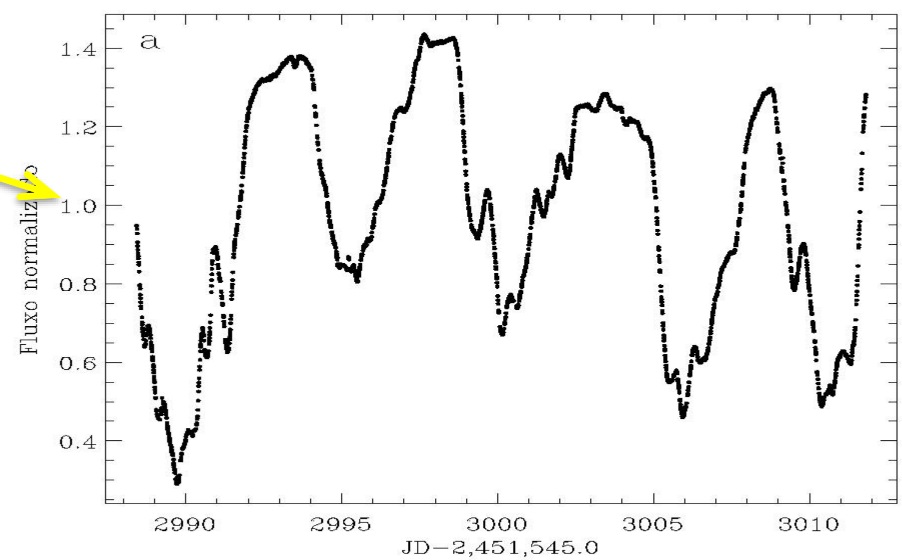
ESA- COROT satellite

NGC 2264 young cluster

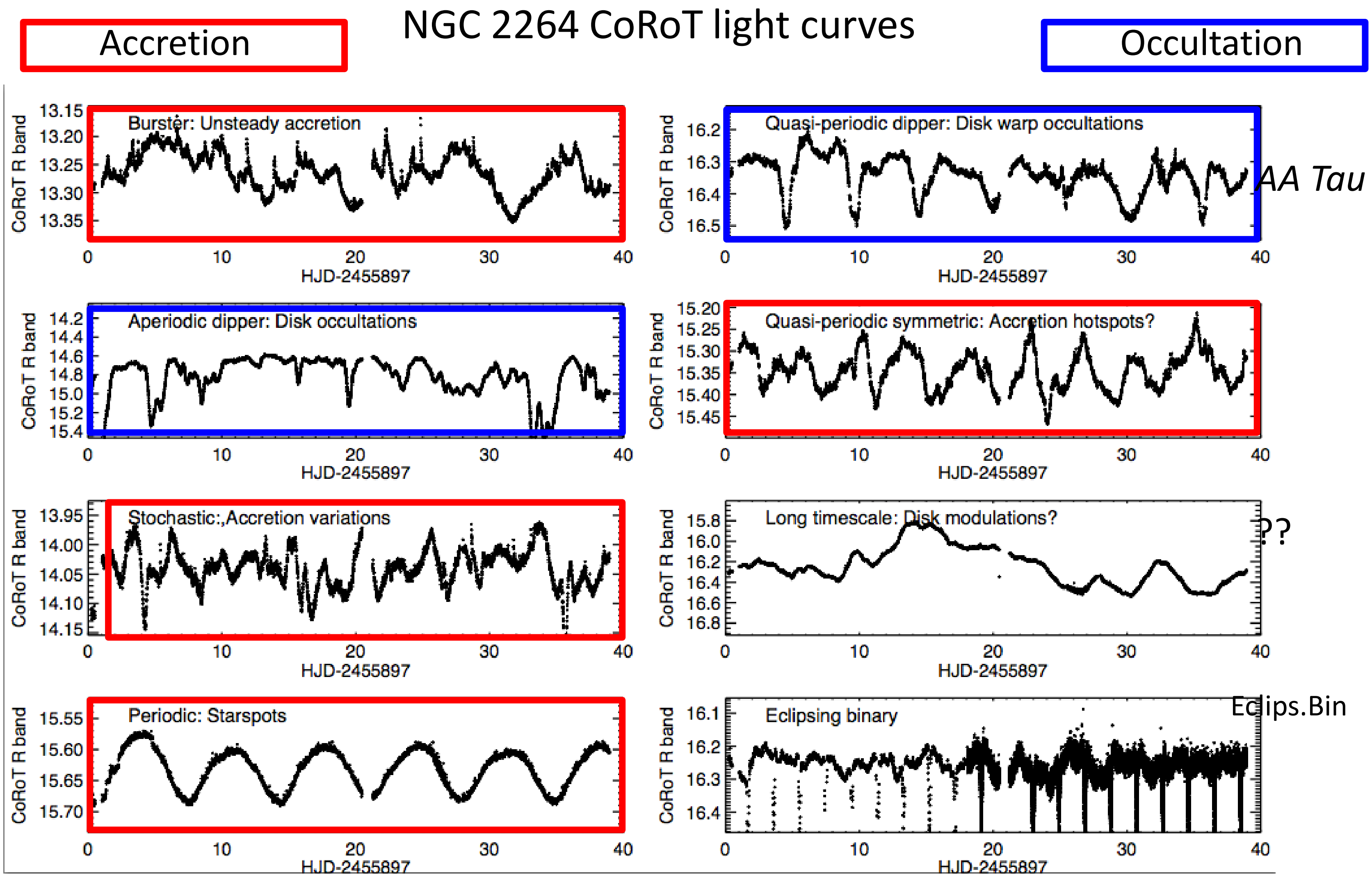


CSI NGC 2264
P.I. J. Stauffer, G. Micela
2008, 2011

Uninterrupted optical lightcurves for a few 100 stars over 40 days (≈ 5-10 stellar rotation periods)



CoRoT NGC2264 optical light curves

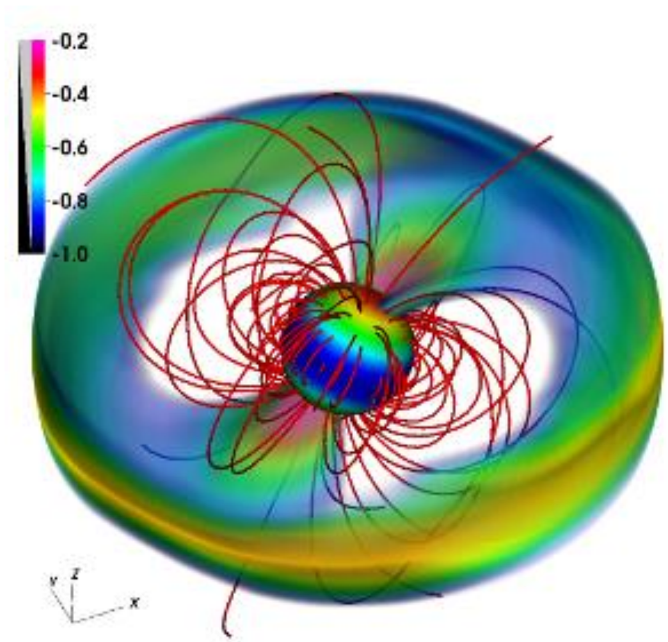


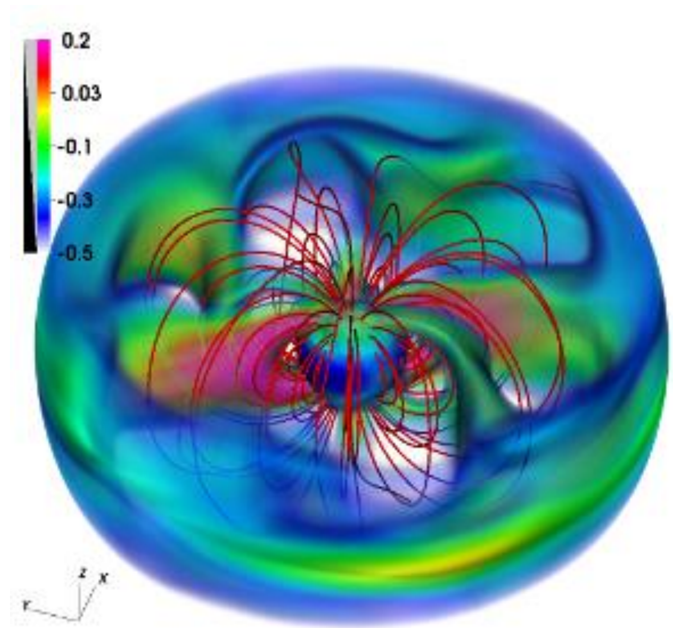
Cody+14

Different accretion regimes ?

CoRoT lightcurves: ~30% periodic; ~70% aperiodic

Stable vs. unstable accretion onto the star?





Raileigh-Taylor instability at small misalignement and $R_m \leq 0.7\ R_{co}$

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

Summary: the crucial role of B

- Atomic jets launched from inner AU regions: MHD disk winds most promising scenario but
  - requires additional observational tests (dust, molecular disk winds)
  - + more realistic modelling including inner star-disk interactions
  - Origion of variability and X-ray emission ?

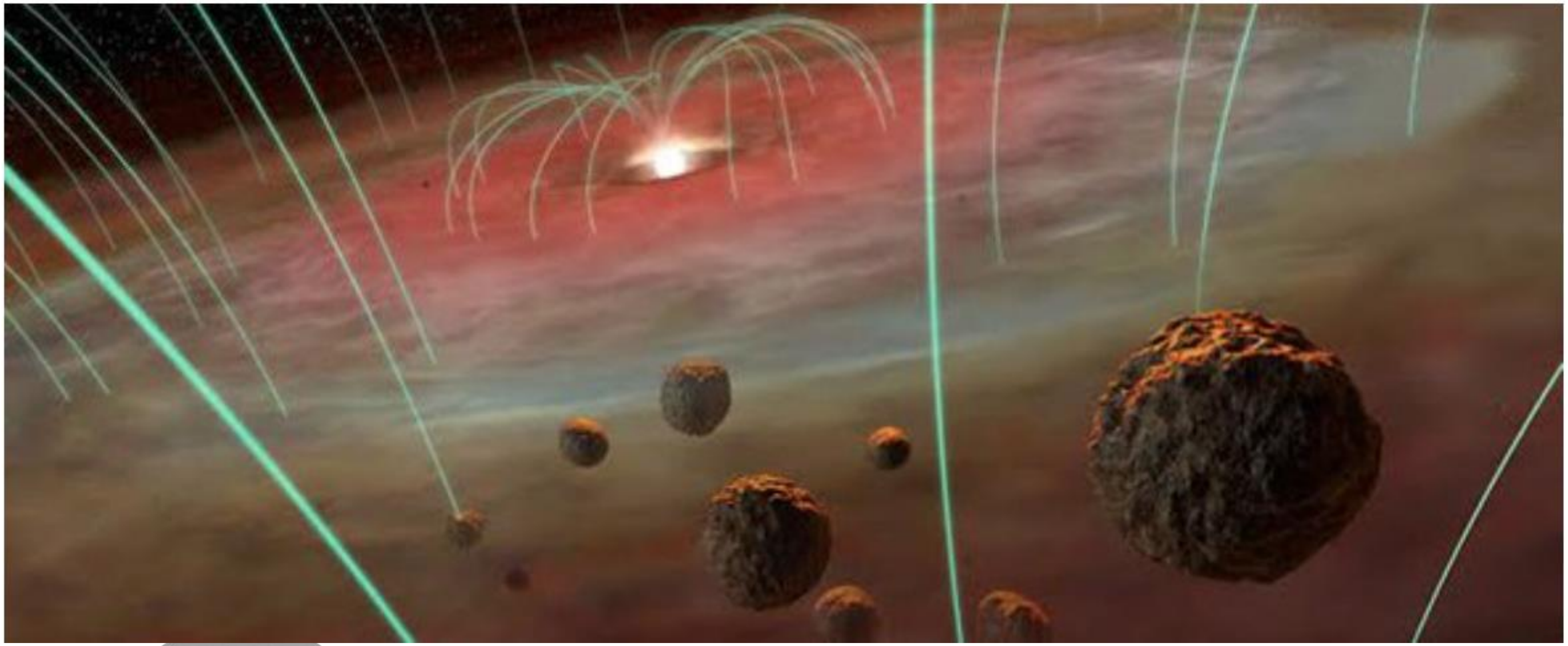
- Magnetic disk winds could operate also in the outer regions of disks: solving angular momentum disk transfer problem ?

- Strong observational/theoretical support for magnetospheric accretion in T Tauri stars but B more complex than dipole: different accretion regimes ?

- Potentially a strong impact on planetary formation

What’s next

How does planetary formation fit in the picture ?
How is it affected by Magnetic fields in the disk/star ?



SpIDI
star planets
inner disk interactions

Star-Planet- inner disk interactions
ERC project PI J. Bouvier (IPAG) 2018-2022


THANK YOU !