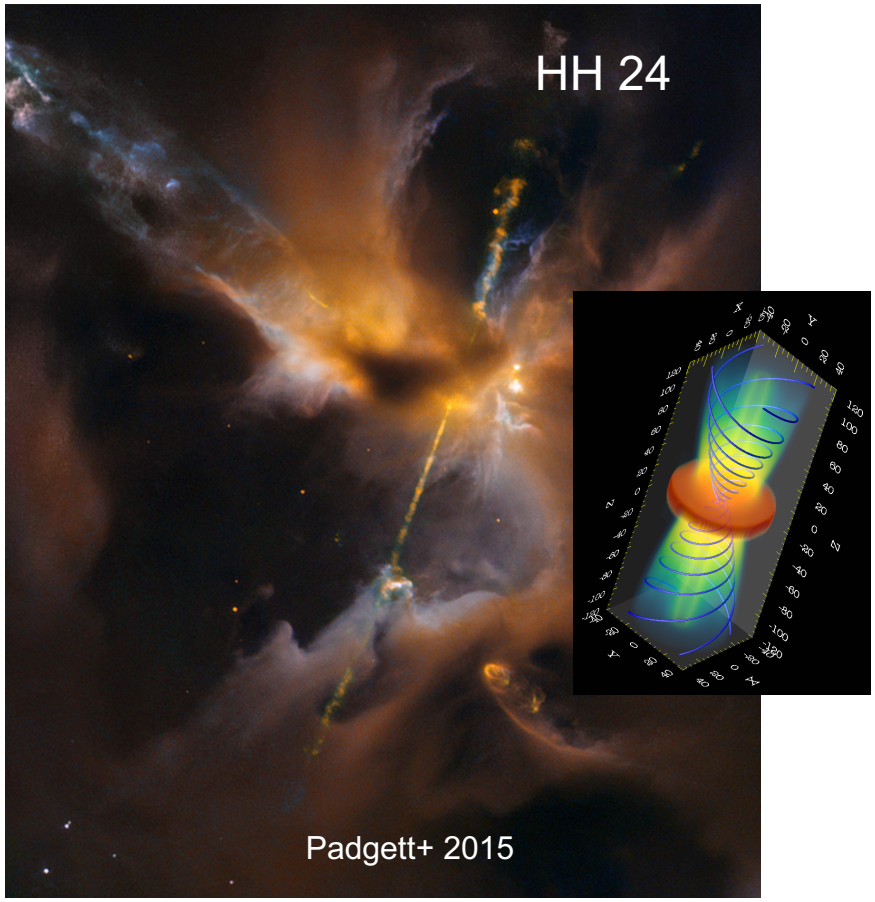
The origin of Jets & Outflows

and their (possible?) impact on planet formation



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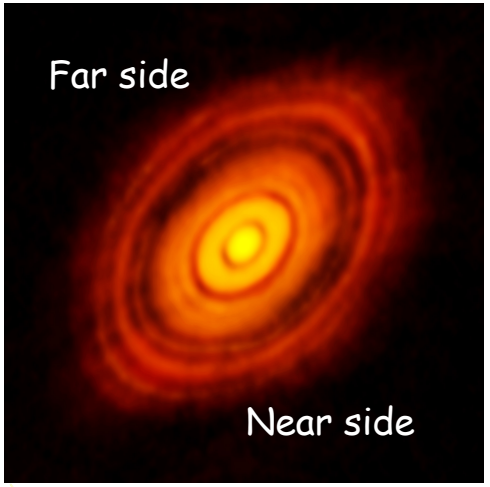
With special acknowledgments to:

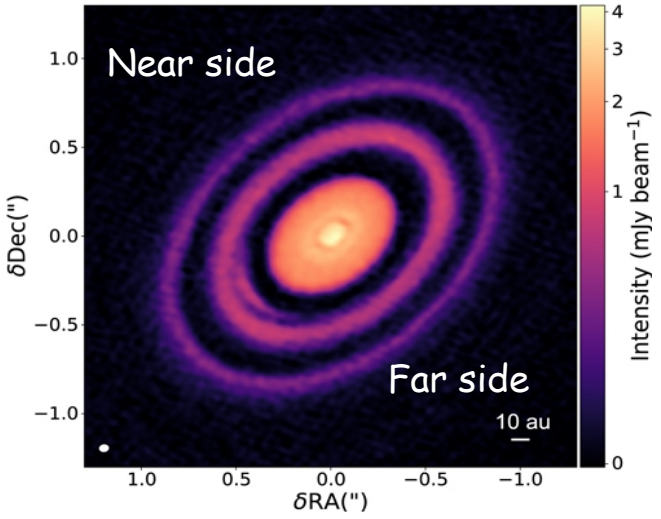
Francesca Bacciotti (INAF-Arcetri)
Sylvie Cabrit (Obs. Paris)
Fabien Louvet (Univ.Chile)

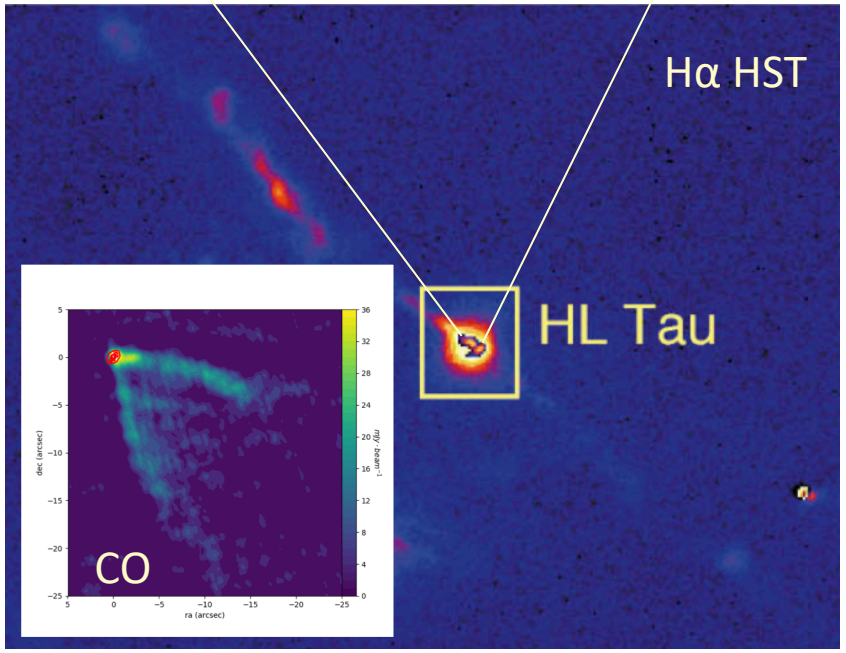
Jets/Outflows co-exist with planet formation signatures

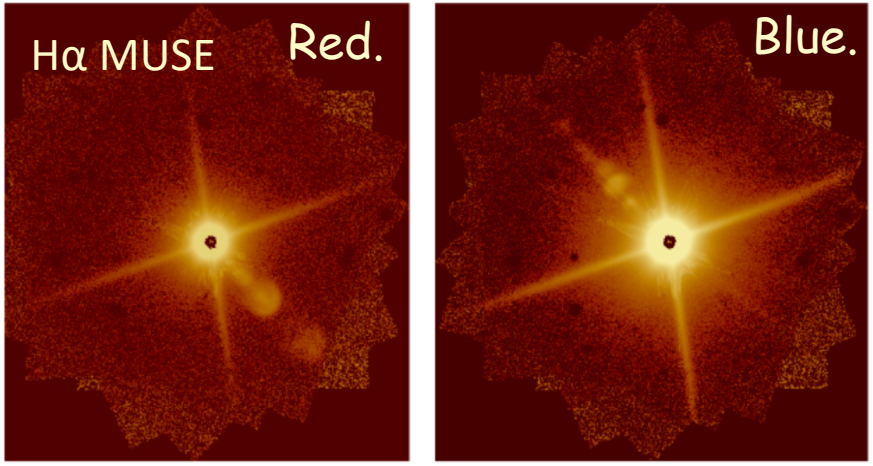
HL Tau Brogan.+2015



HD 163296 Isella+ 2018

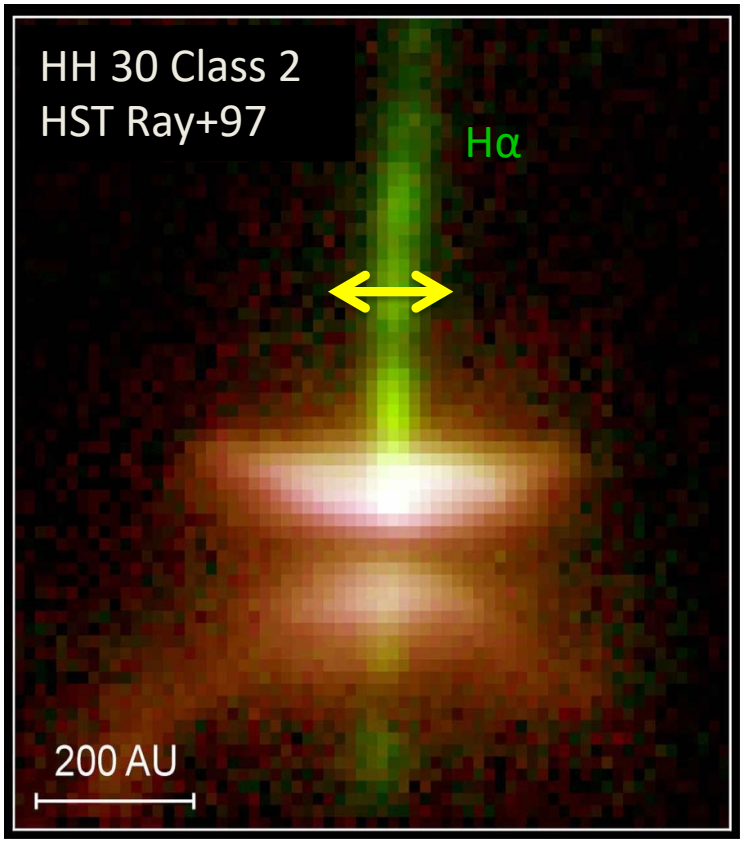


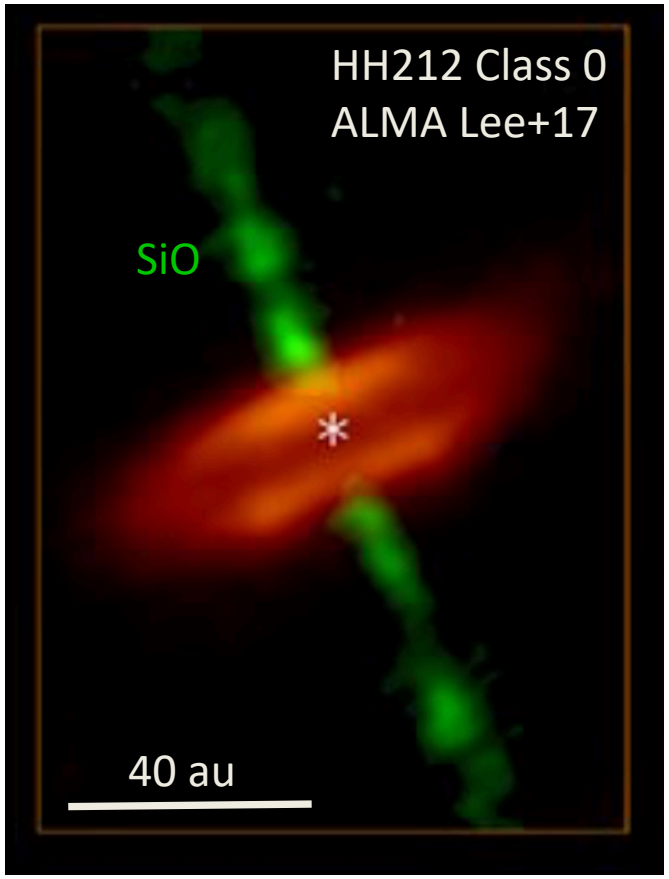




Hα MUSE observations Miller+ in prep
also X-SHOOTER Ellerbroek+ 2014

Collimation properties of jets



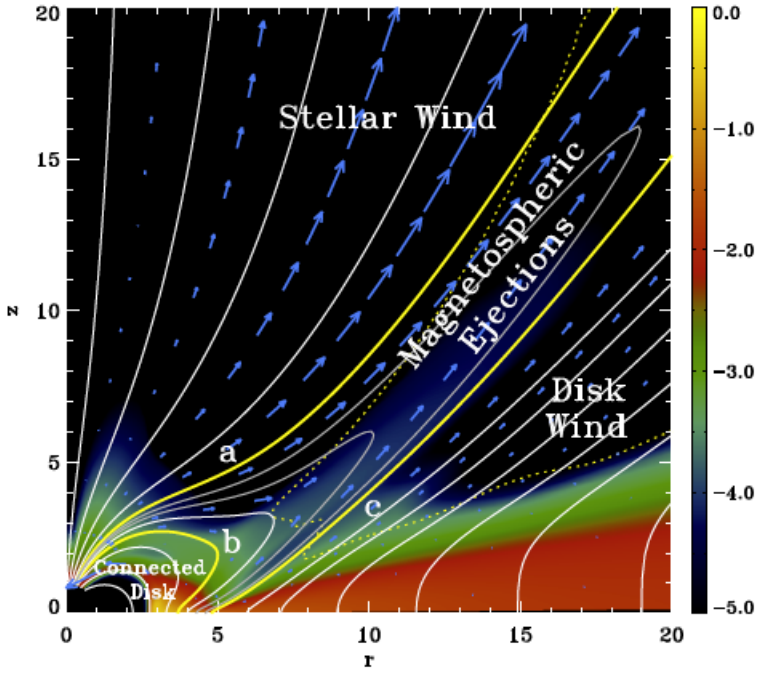


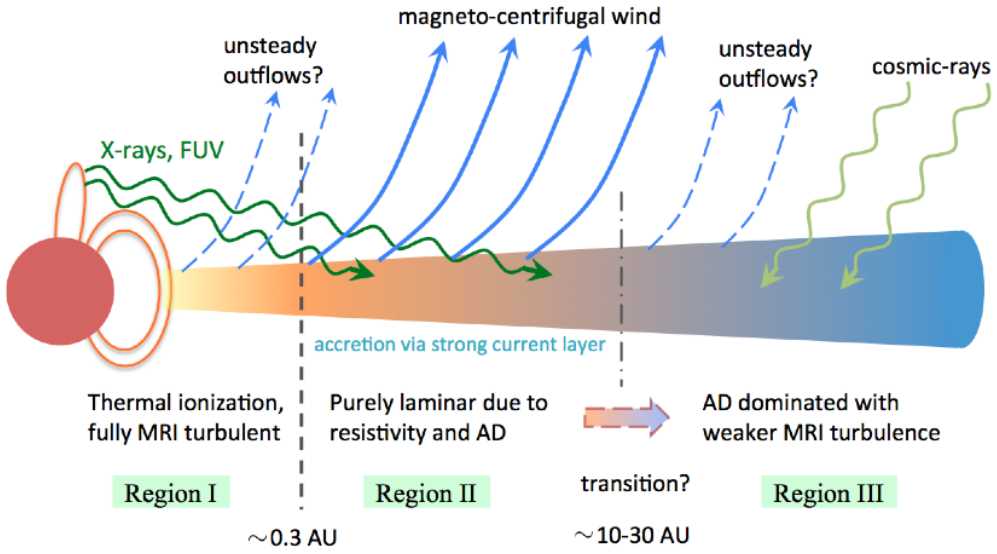
- ✓ Quasi-cylindrical collimation achieved at z <= 20-30 au
- ✓ Collimation independent of environment

  Jet FWHM = 5-15 au for z =20-30 au Ray+07 PPV Cabrit+07 Lee+17
- ✓ dMjet/dt ≈ 0.1 dMacc,star/dt

Magnetic ejection processes ?

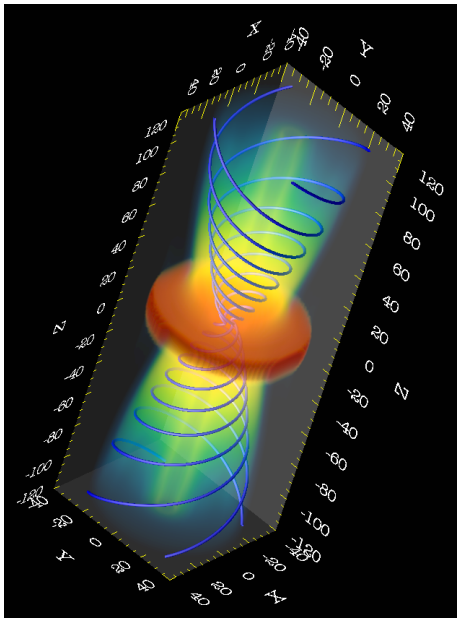
Zanni & Ferreira 2013

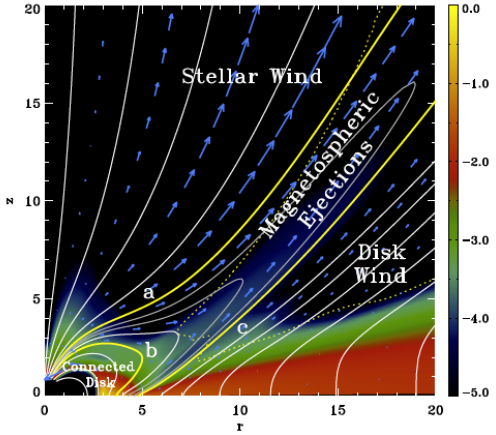




- ✧ Transport of angular momentum by MHD disk winds ?
- ✧ Impact of disk B-field on migration & planetary formation ?

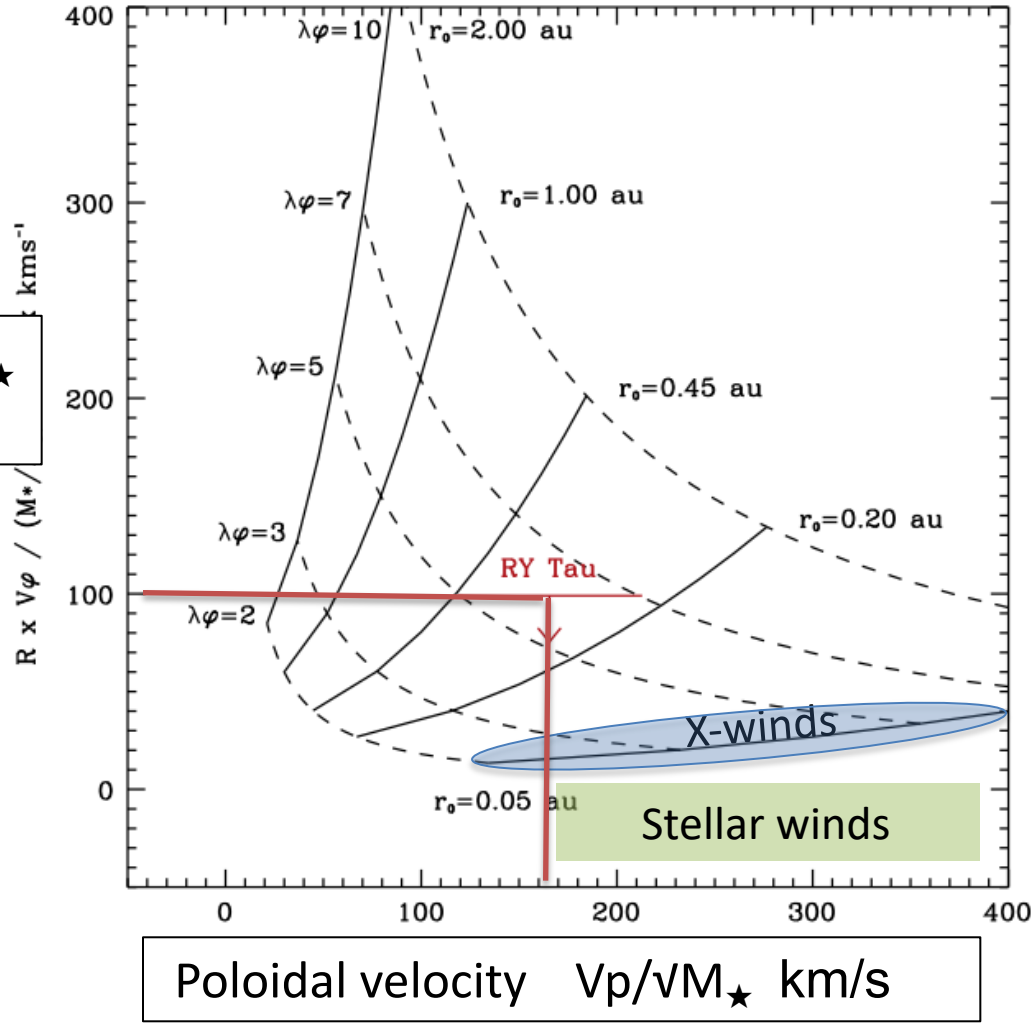
In search of rotation signatures





RxVϕ/√M★ au km/s

STEADY MHD wind models

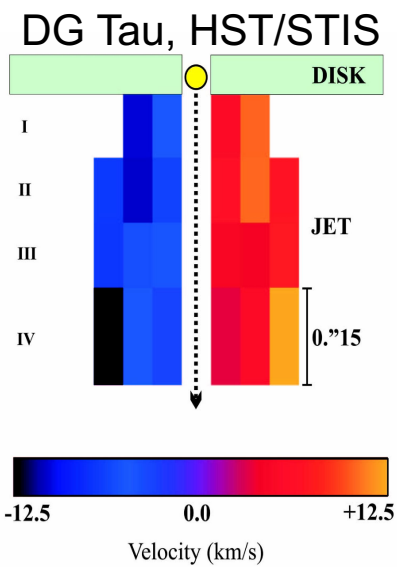


Ferreira, Dougados,Cabrit 2006 (also Anderson+03 Bacciotti+02)

Jet/flow origin: rotation

Jets from T Tauri stars

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



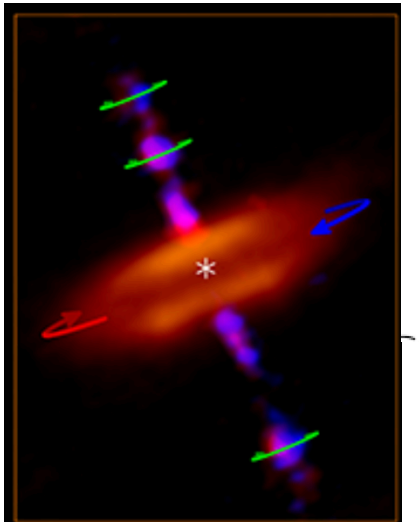
Pesenti+04

r_0=0.05-3 au
Lambda=13

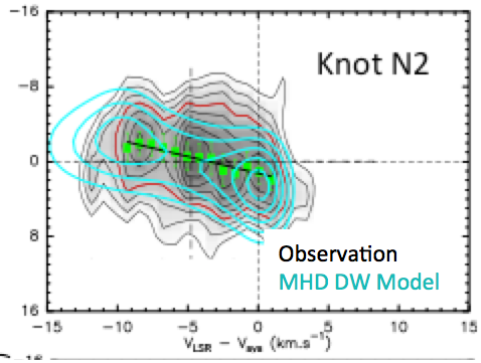
Jets from Class 0

HH 212 ALMA

Lee+2017



Tabone,Cabrit+2017



MHD DW solution:
➔ r_0=0.05-0.3 au
➔ Lambda=5.5

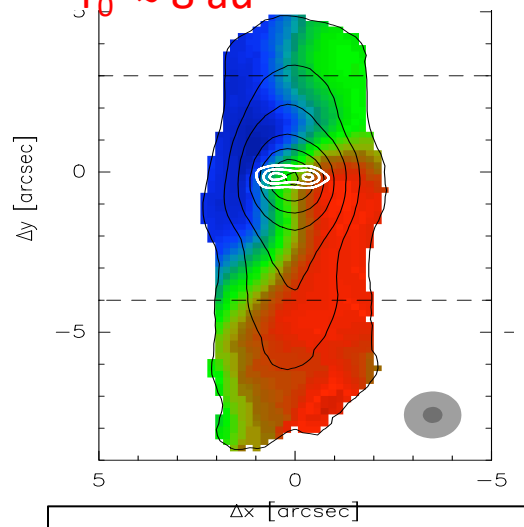
✧ Footpoint radius r_0 = 0.05-**3 au** ➔ **origin in inner MHD disk wind**

✧ Magnetic lever arm $\lambda = 5 - 13$ ➔ **Efficient Magnetic Braking**

Candidate (rotating) outer disk winds

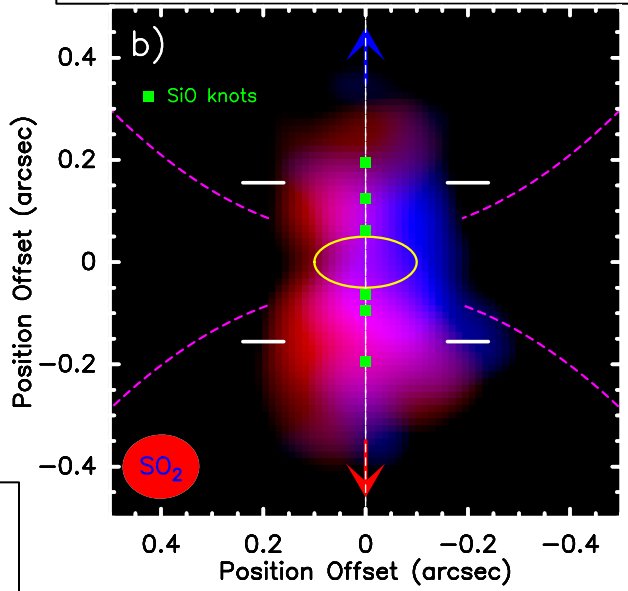
CB 26 Launhardt+09

r_0 ≈ 8 au



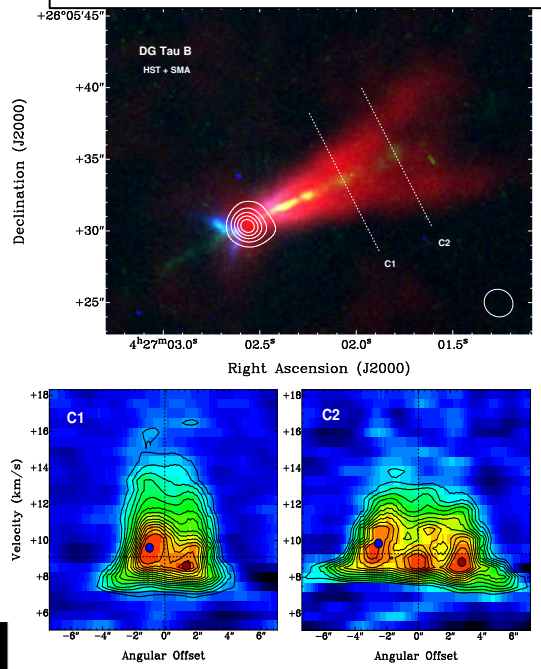
HH 212 Tabone+17, Lee+18

SO/SO_2 r_0=0.2- 40 au, λ=5.5



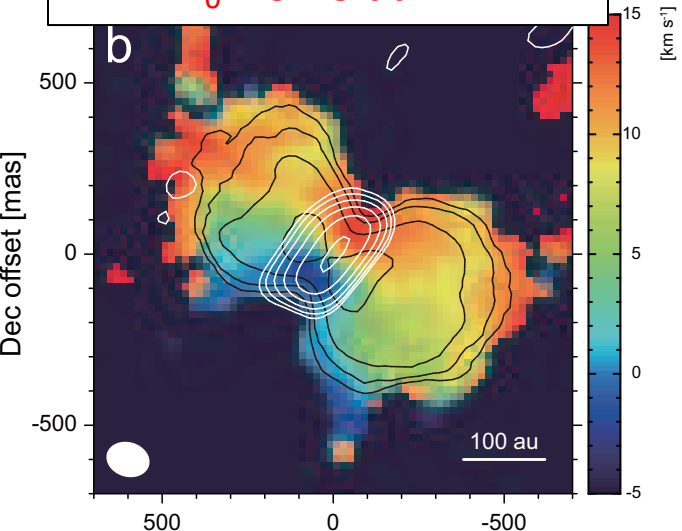
DG Tau B Zapata+14

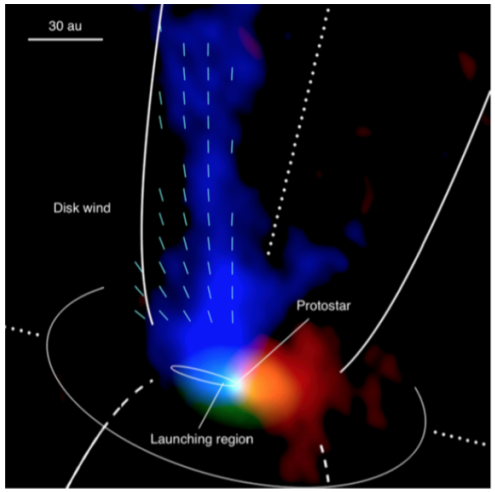
r_0 ~ 5-25 au



Source i Orion Hirota+17

r_0 ~ 5-25 au



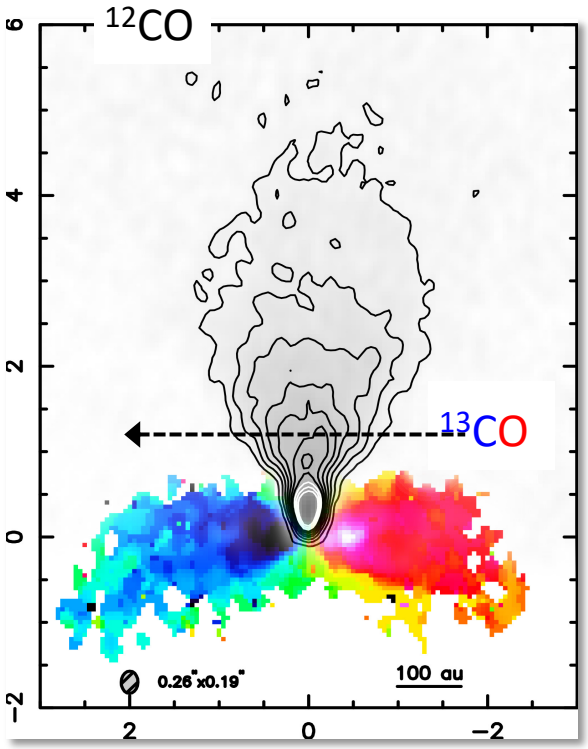


TMC-1A Bjerkeli+16

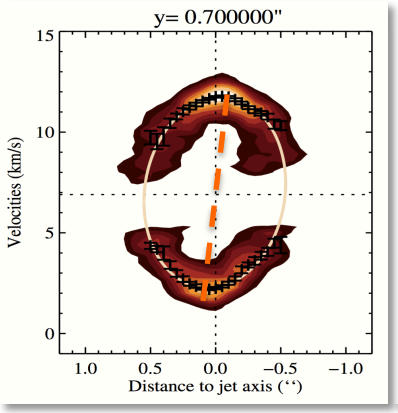
r_0 ≈ 20 au

ALMA observations of HH30

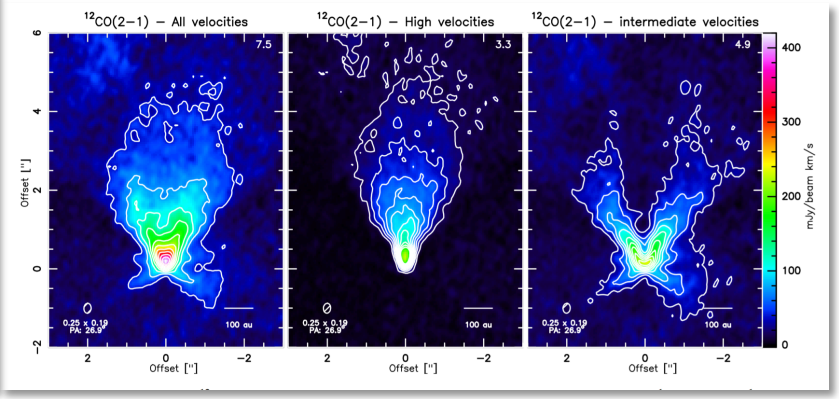
^{12}CO HV & ^{13}CO mom 1



Transverse PV diagrams



^{12}CO channel maps



Conical rotating V=10 km/s outflow

✧ RVϕ = 40 au km/s → r_0 < 7 au

✧ dMCO/dt = 10^{-7} Msun/yr ≈ 50 x dMjet /dt

Louvet, Dougados, Cabrit+ A&A 2018

Origin of the HH 30 rotating CO conical flow

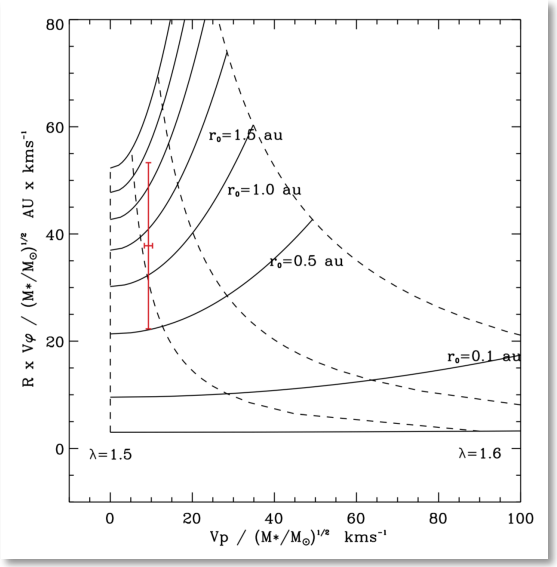
❖ Photo-evaporated disk wind: r_0=1-7 au

but challenge for:

- CO survival (T ≈ 2000 K in launching regions) ?

Wang & Goodman 2017

- mass flux



❖ Magneto-thermal ejection (e.g. Wang,Bai+2019)

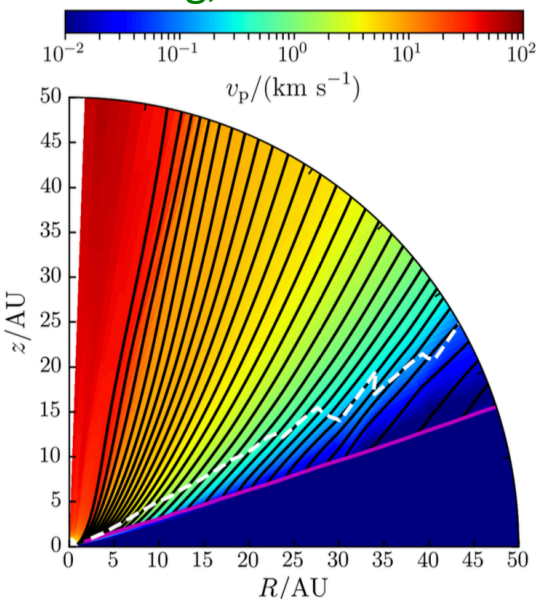
λ < 1.6 r_0= 0.5-2.5 au

reproduces mass-flux but implies

dMacc,rin/dt ≈ dMCO/dt

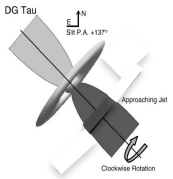
Observational predictions required !

Wang,Bai+2019

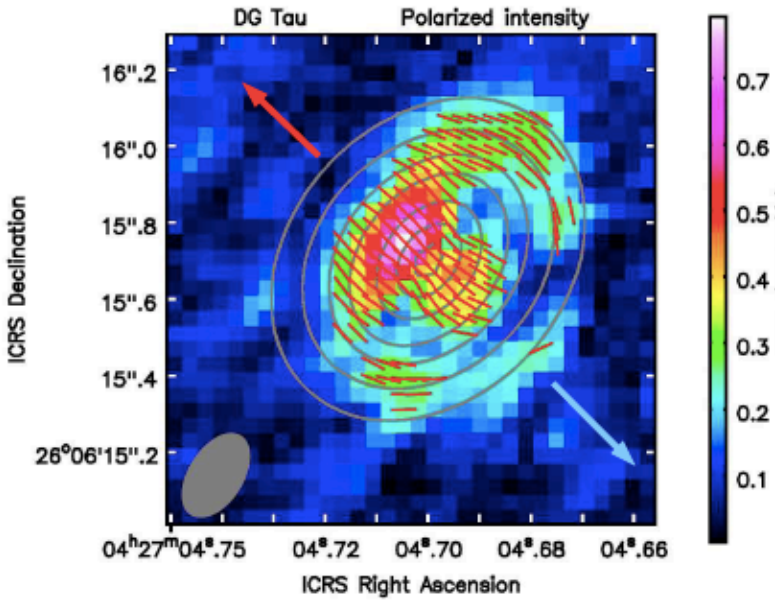


MHD origin: desperately seeking $\vec{B}$

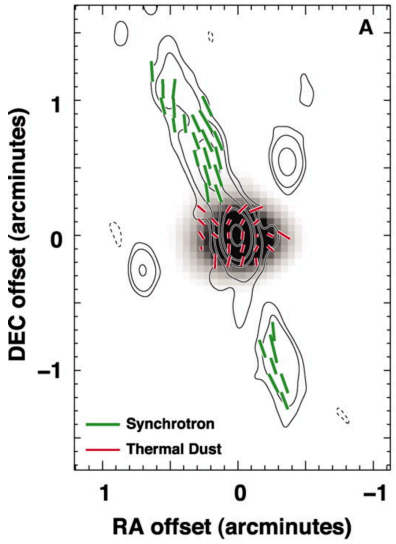
in the disk ?



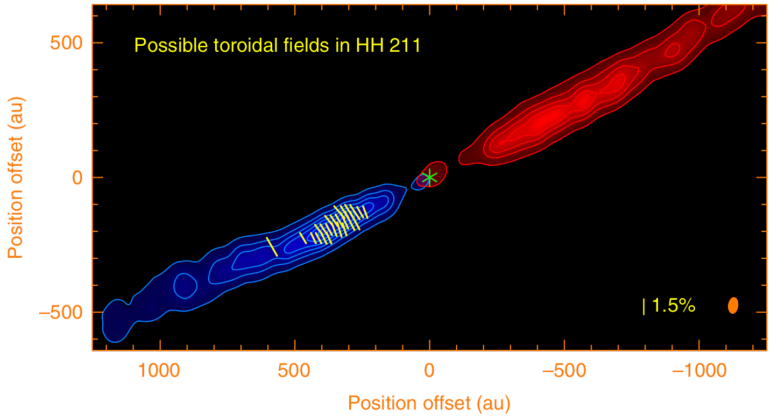
Polarization in DG Tau rotating disk/jet: Dust scattering only *Bacciotti+ 2018*



in the jet/flow ?



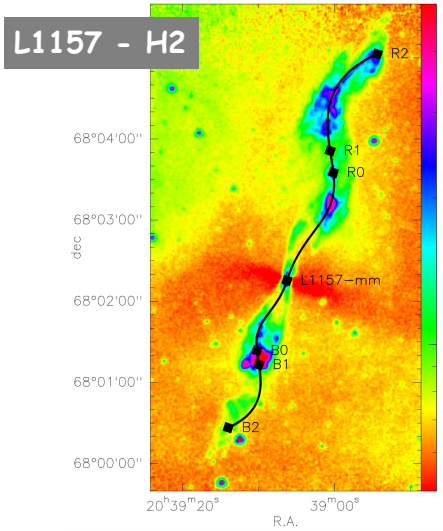
From polarized emission in HH 80 81 jet *Carrasco-Gonzales+ 2010*



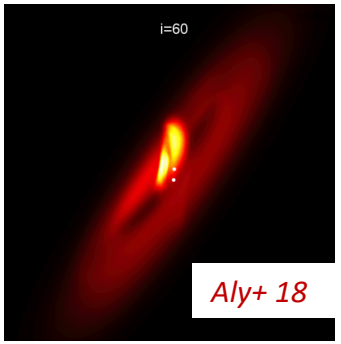
From polarized SiO emission (G-K) in HH 211 jet *Lee+ 2018*

UBIQUITOUS jet axis WIGGLING

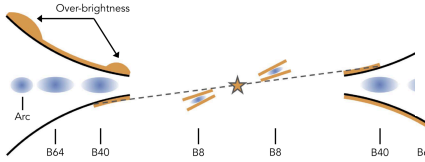
Point Symmetry: flow axis precession ?



Inner disk breaking ?
Inclined/eccentric planet ?
Nealon+18, Sheiknezami+18
(small misalignment angle)

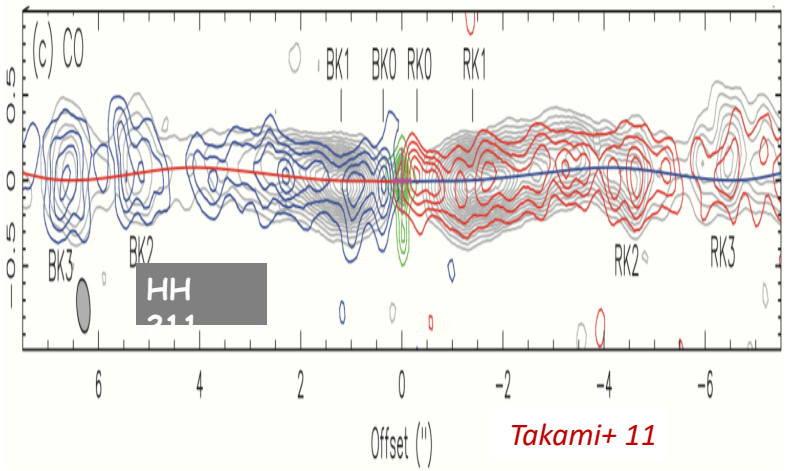


Aly+ 18

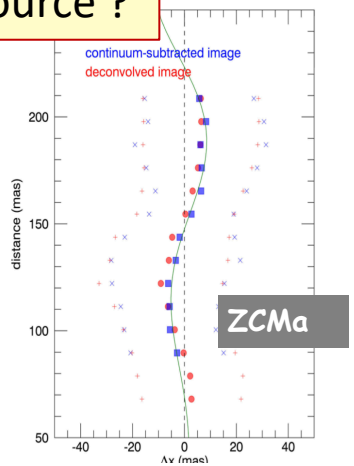


Model for HD 143006
Perez+ 18

Mirror symmetry → orbital motion of source ?



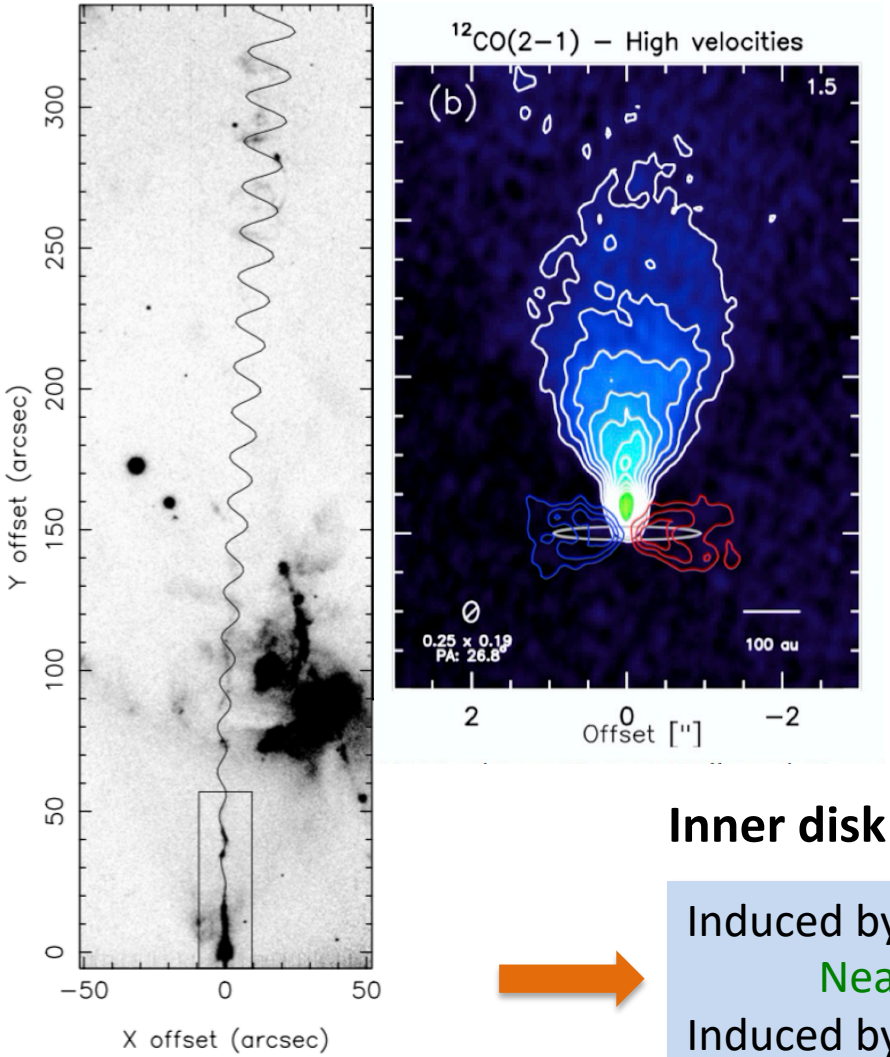
Takami+ 11



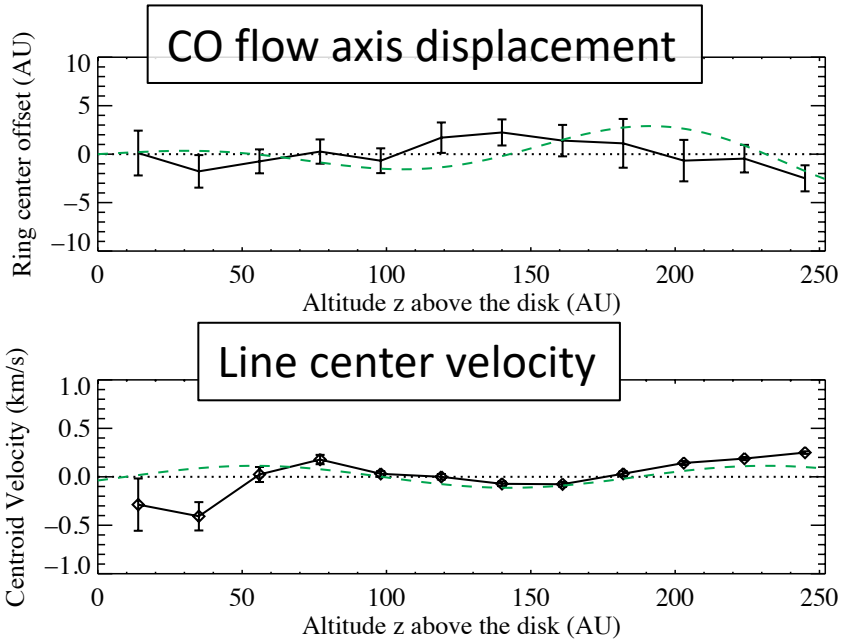
Anglada+ 07, Antonucci+ 17

HH30 Jet/CO flow axis wiggling

Atomic jet axis wiggling



CO flow axis precess with the exact same solution as atomic jet !

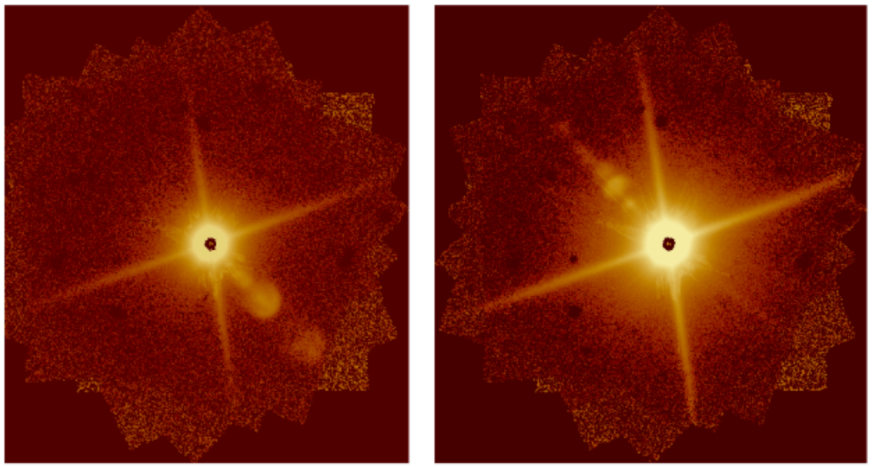


Inner disk (r=0.1- a few aus) solid body precession ?

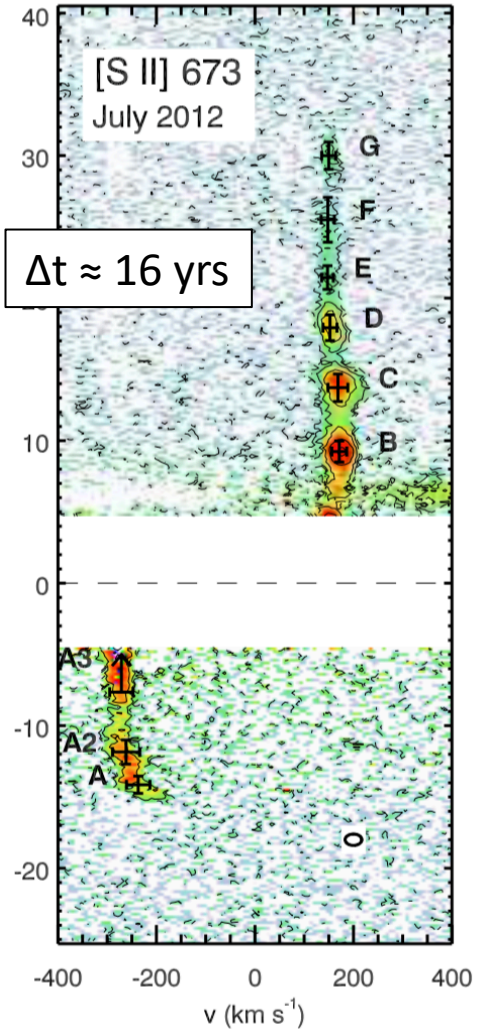
Induced by companion/massive planet ?
Nealon+18 Sheikhnezami+18
Induced by magnetic instabilities ? Bai+13

Variability: Knots , Asymmetry …

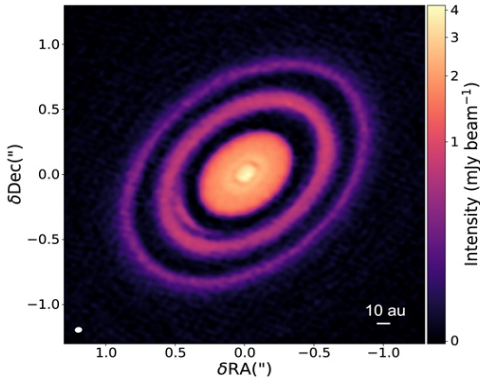
HD163296



Ellerbroek+2014



?



Origin of Knots :

Range of timescales

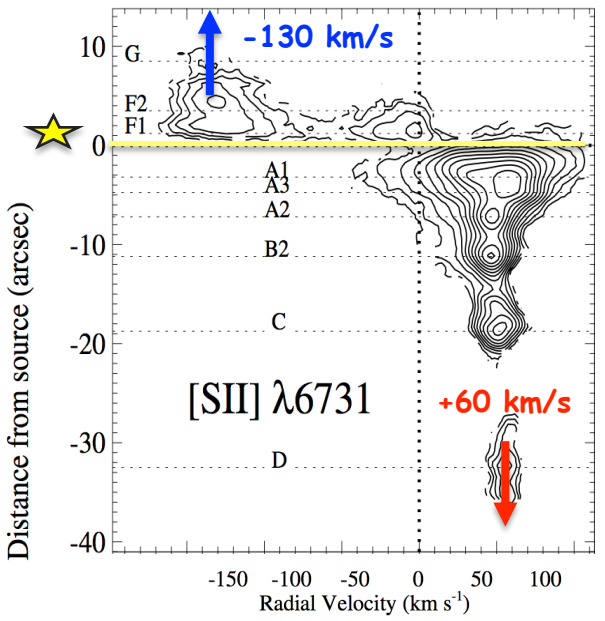
Δt ≈ a few years (inner knots)

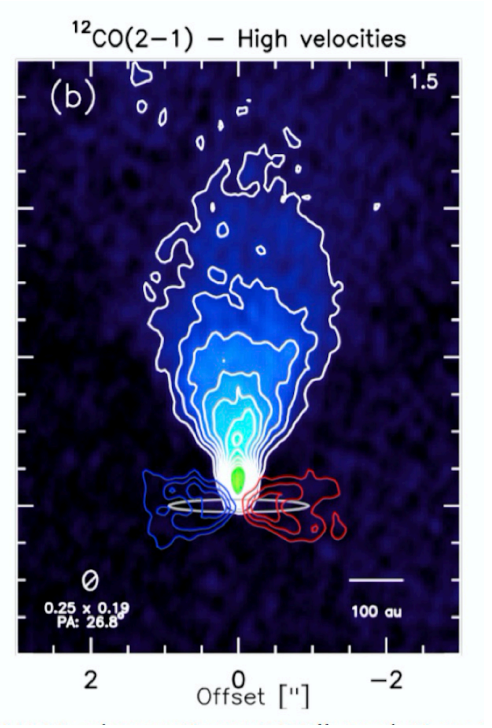
- *Instability of accretion process ?*
- *Stellar Magnetic cycles ?*
- *Dynamical perturbations in disk ?*

Variability: Knots , Asymmetry …

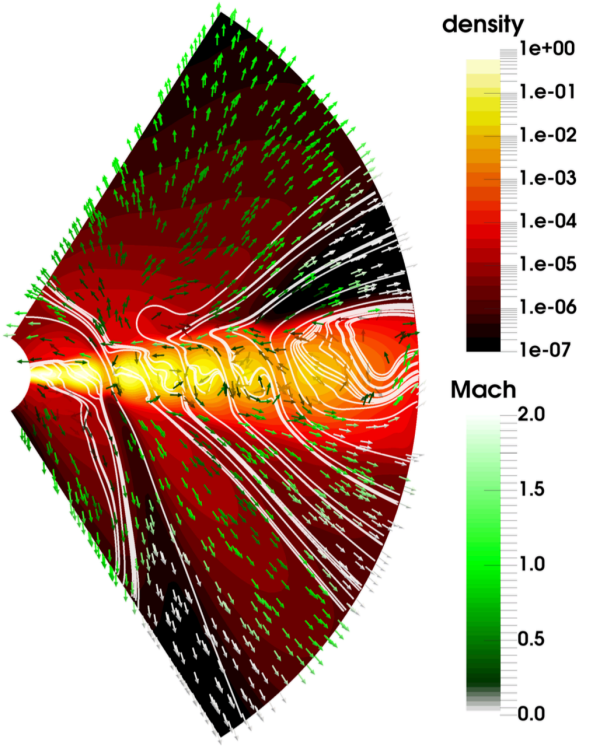
- ubiquitous **flow and velocity asymmetry**:
Natural asymmetry in magnetic configuration ?

DG Tau B Podio et al. 2011





HH 30 CO Louvet+2018

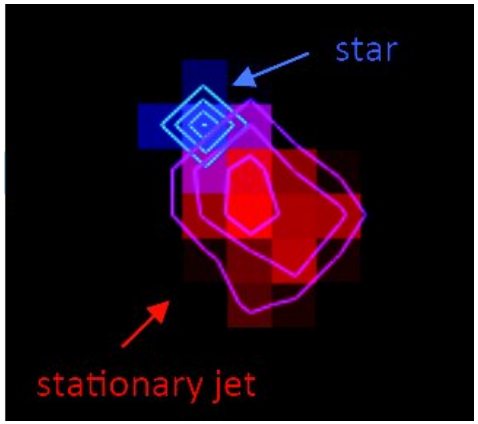


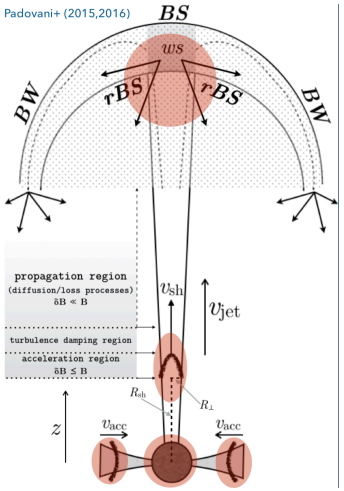
Bethune+2018 also Bai+2016

Feedback: X and UV radiation, cosmic rays, dust screening

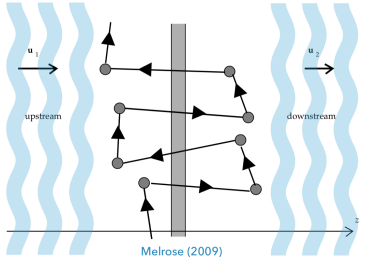
X-rays
DG Tau

Gudel+ 2009

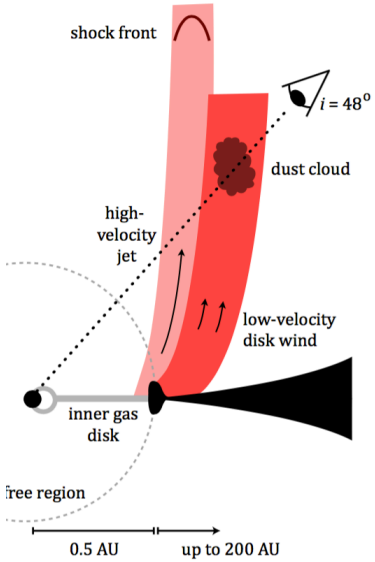




Cosmic Rays:
in situ 1st order Fermi acceleration Padovani+ 15,16



Energetic EUV, FUV, X rays and Cosmic rays produced in inner bow shocks can affect disk physics and chemistry



- Fe gas phase depletion: Podio+ 2006,2009,2011 Agra-Amboage+2011
- Occultation events: Ellerbroek+2014 Koutoulani 2019 See also poster by Franz et al.

Shielding by dusty winds : will affect photoevaporation and disk clearing

Summary – Open questions

- Some evidence for MHD disk winds operating out to r= a few 10's au
  more observations needed (ALMA, JWST, MUSE…)
  need to take into account in simulations

- Link with unresolved (spectroscopic) slow wind signatures ? Talks on Thursday

- Origin of variability, jet/flow ubiquitous asymetries and wiggling ?
  link with disk structure

- Possible important radiative feedback on disks; energetic particles from jet shocks, dust shielding …

Thank you !