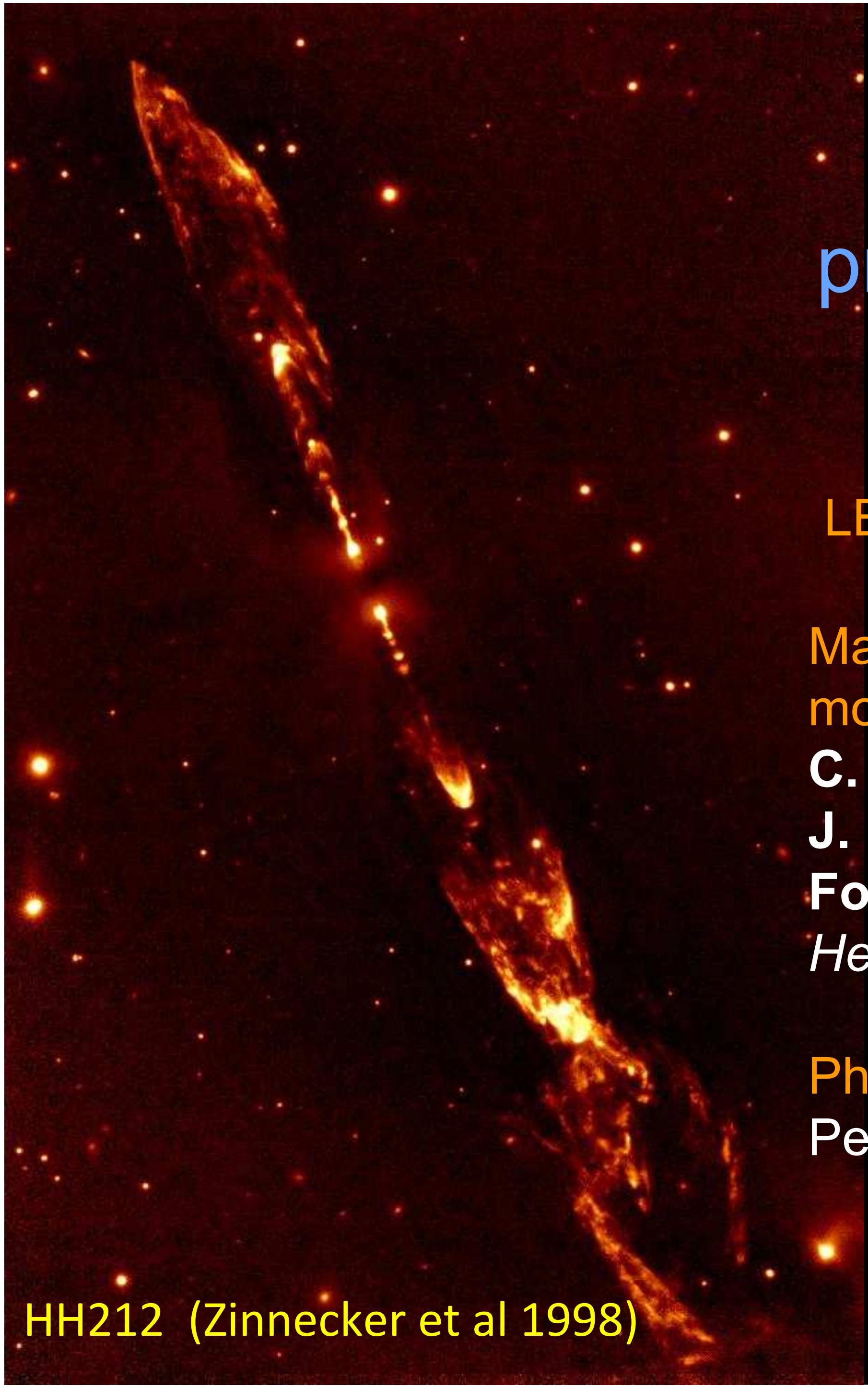
Accretion-ejection in protostars: Observational constraints

Sylvie Cabrit [1]

1 : LERMA, UMR CNRS 8112, Observatoire de Paris, École Normale Supérieure

61 Av. de l'Observatoire, 75014, Paris France



HH212 (Zinnecker et al 1998)

Accretion-Ejection in protostars: Observational constraints

Sylvie Cabrit
LERMA, Observatoire de Paris, France

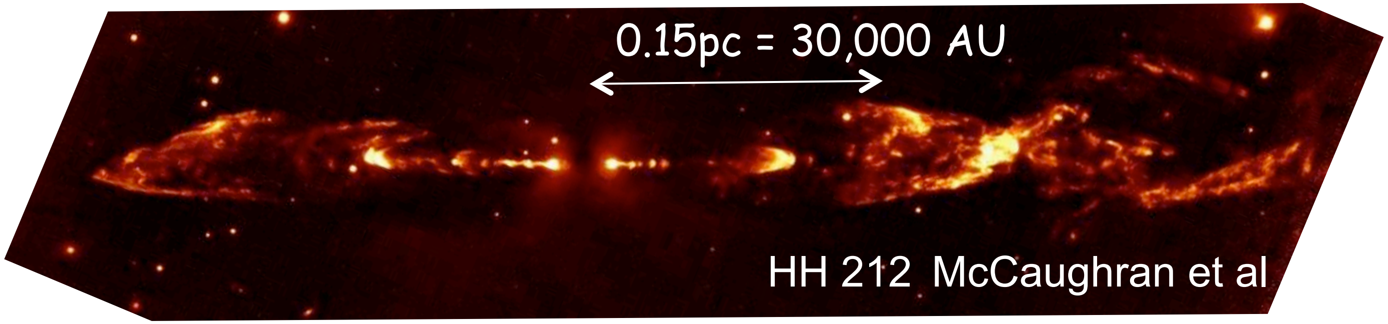
Main collaborators on observations and modeling:
C. Codella (Firenze), F. Gueth (IRAM), J. Ferreira (Grenoble), G. Pineau des Forêts (Orsay) + WISH and CHESS *Herschel* teams

PhD students: V. Agra-Amboage, N. Pesenti, D. Panoglou, W. Yvart, B. Tabone

Outline

- Introduction
- Global correlation with accretion power
- Collimation scale and mechanism
- Magnetic field in / around protostellar outflows
- Variability in speed and angle
- Constraints on r_launch: Rotation and chemistry
- The ALMA revolution: the example of HH212 and L1527
- Summary

Universality of jets across ages

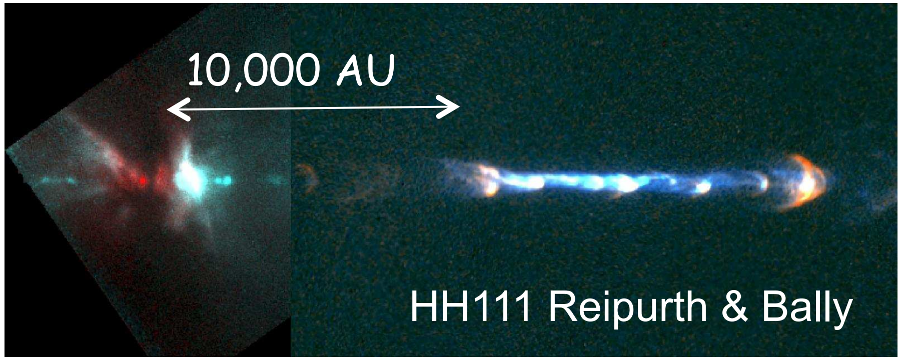


HH 212 McCaughran et al

Class 0 Protostars

10^3-10^4 yr

Main infall phase

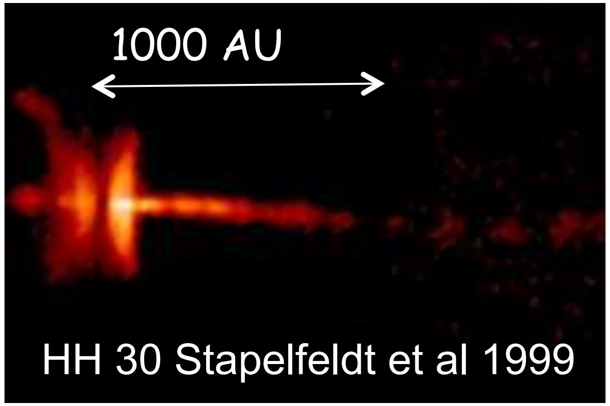


HH111 Reipurth & Bally

Evolved Class 1 Protostars

10^5 yr

Residual infall, M* > Menv



HH 30 Stapelfeldt et al 1999

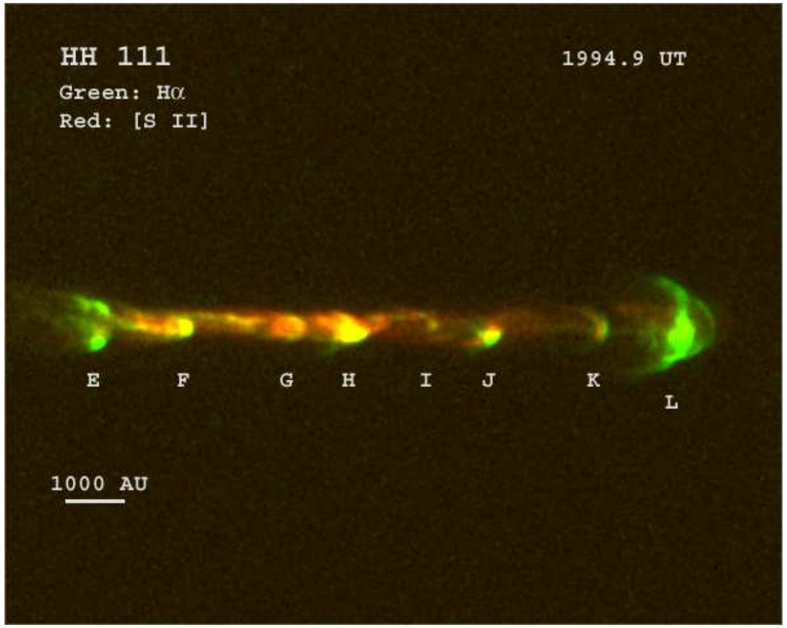
Class 2 : 10^5 yr, **Accretion Disk**

- Accretion-powered Mjet/Macc ≈ 0.1 (Edwards+2006, Antoniucci+2008)

- ***Universal in M* : from 24 Mjup to 10 $M_\odot$***
- ***Universal in Macc*** (10^{-10} - 10^{-5} $M_\odot$/yr)

Similarity in average jet speeds at all stages

- From proper motions and radial velocities
  - Class 0 (HH212 jet):
    - H_2O masers : 60 km/s
    - H_2 knots : 150 – 200 km/s
  - Class 1 protostars
    - HH34: 150 – 400 km/s
    - HH111: 220 - 300 km/s
  - Class 2 (T Tauri stars)
    - DG Tau: V ~ 300 km/s
    - HH30: 100 – 150 km/s



(Hartigan et al. 2001)

Jet variability record

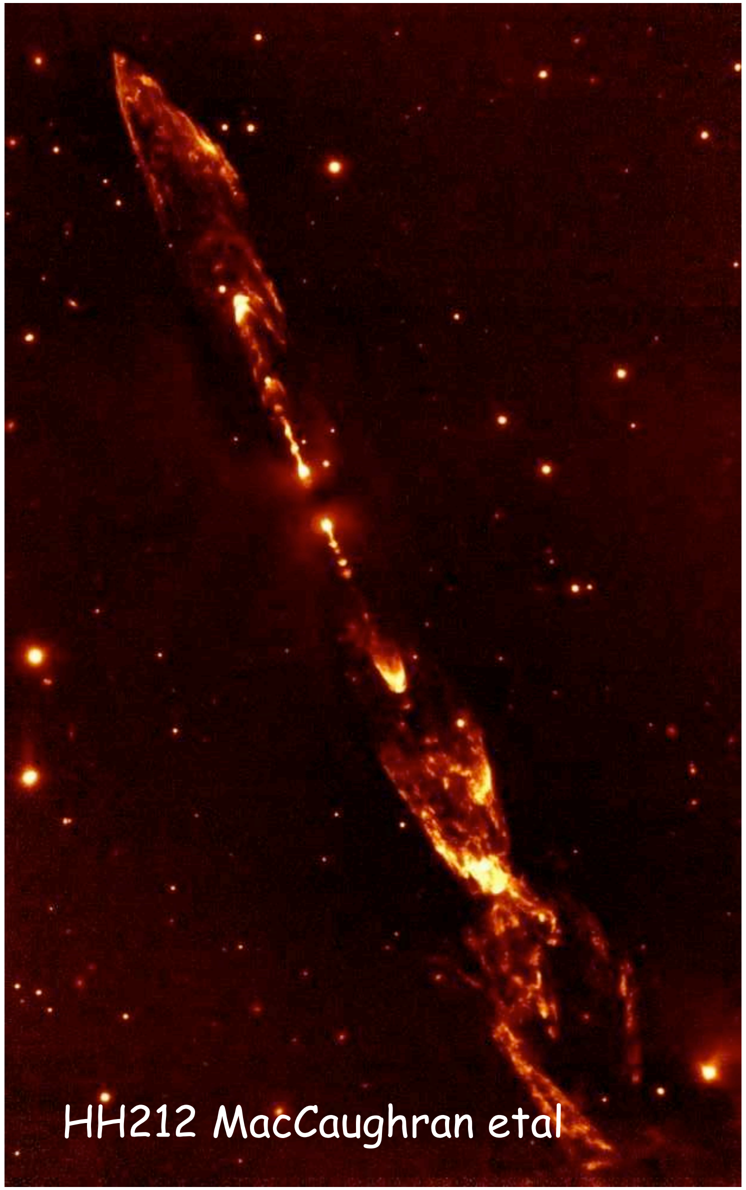
- 3 preferred time scales

  ≈3-10yrs, ≈100yrs, ≈1000 yrs

  Shock ΔV of 20-140 km/s

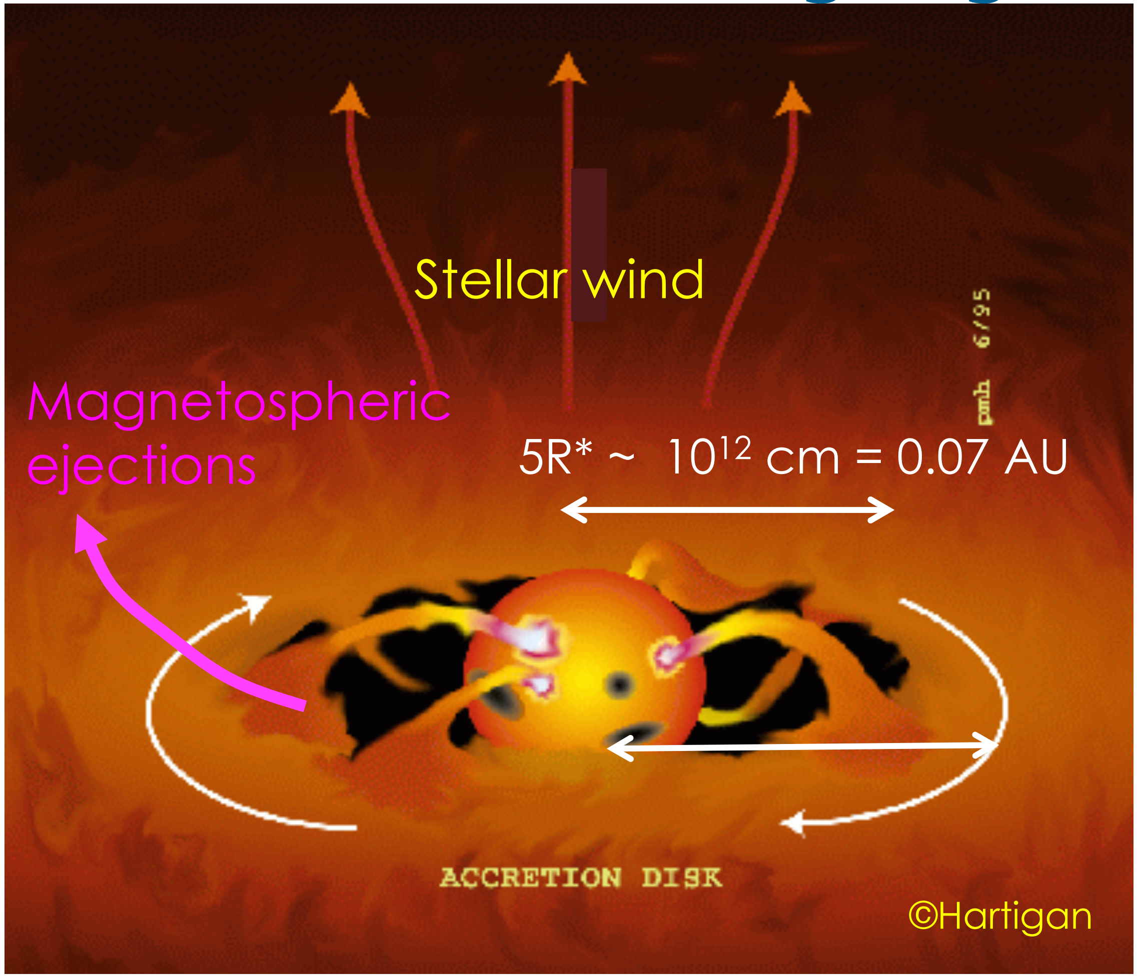
  Raga+2002,2011; Hartigan+2007; Agra-Amboage+2011…

- May probe
  - Stellar or disk dynamo cycles (cf Fendt)
  - perturbations by companions
  - link with EX Or / FU Or outbursts ? (cf. Audard etal. PPVI)



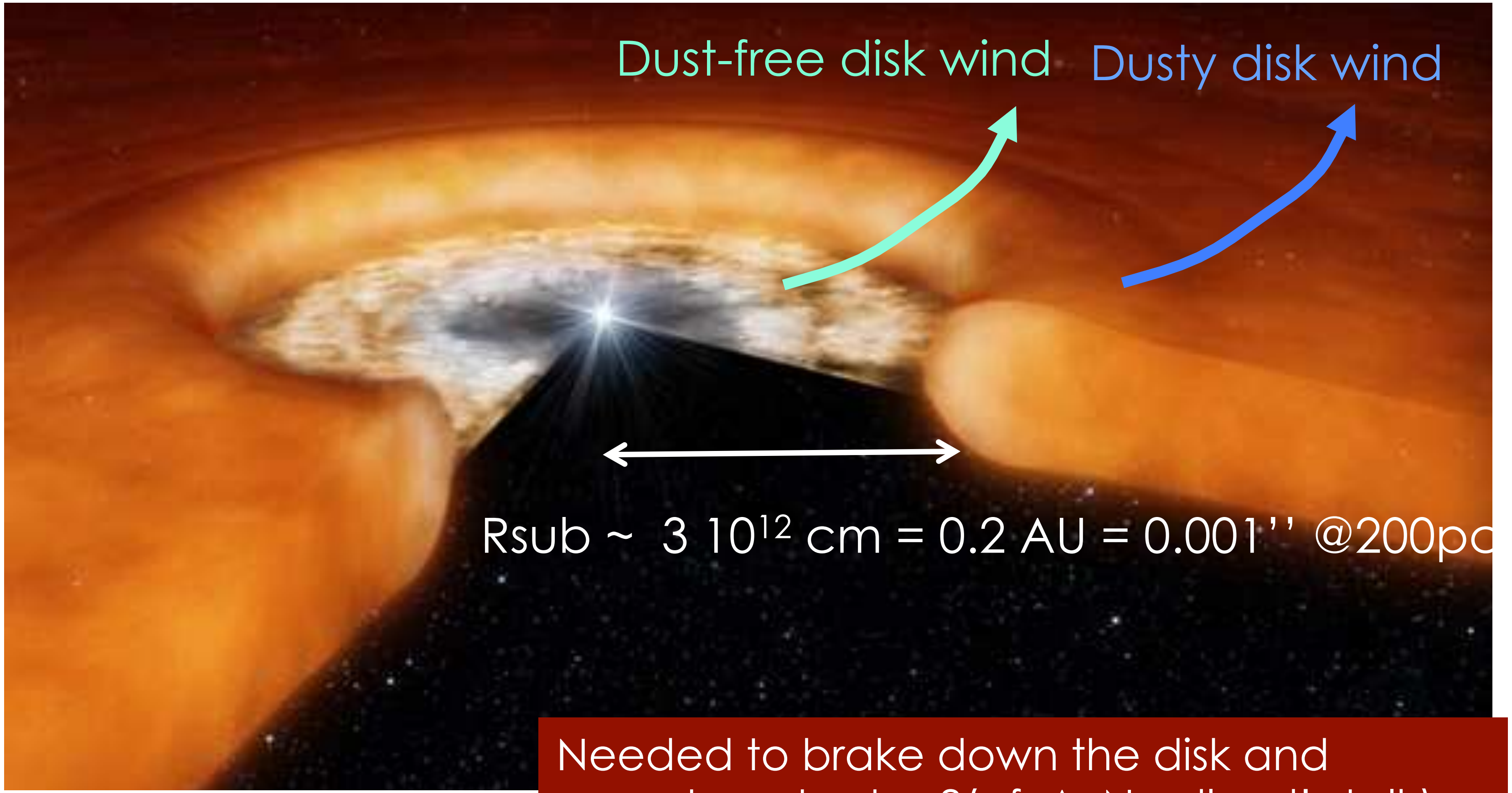
HH212 MacCaughran etal

Jet launching region(s)



Needed to brake down the star
(cf S. Matt's talk)

Jet launching region(s)



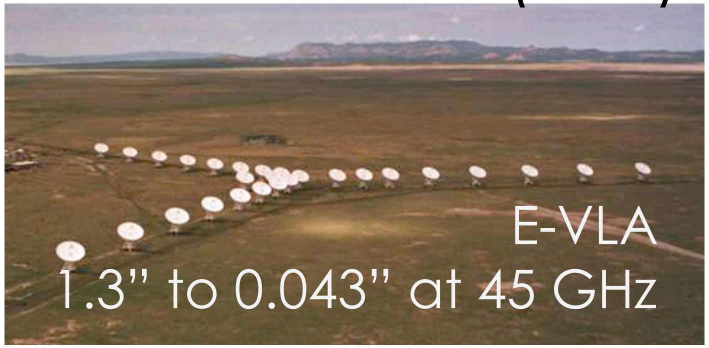
Rsub ~ 3 10^{12} cm = 0.2 AU = 0.001'' @200pc

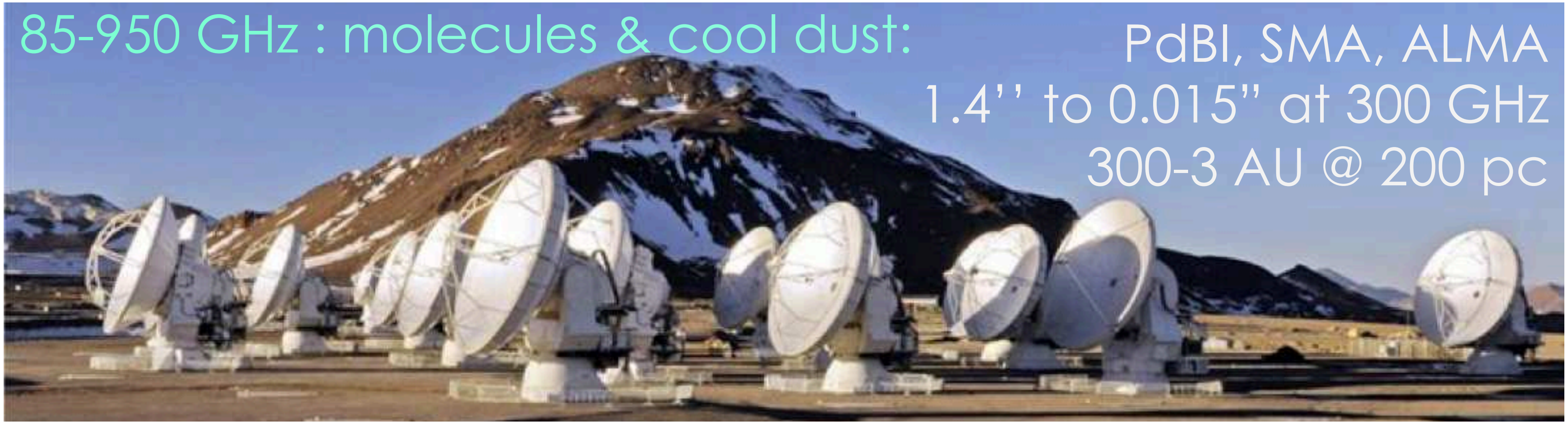
Needed to brake down the disk and accrete onto star ?(cf A. Nordlund's talk)

Observing Class 0 jets

- High dust extinction: go to longer wavelengths
- Ions and warm H_2 in mid/far-IR (*Spitzer, Herschel)* with 1"-10" and no velocity information
- cm/mm interferometers: Start to rival HST, with much better velocity resolution..

1-50 GHz: free-free +synchrotron +NH_3 + H_2O and SiO masers (VLBI)

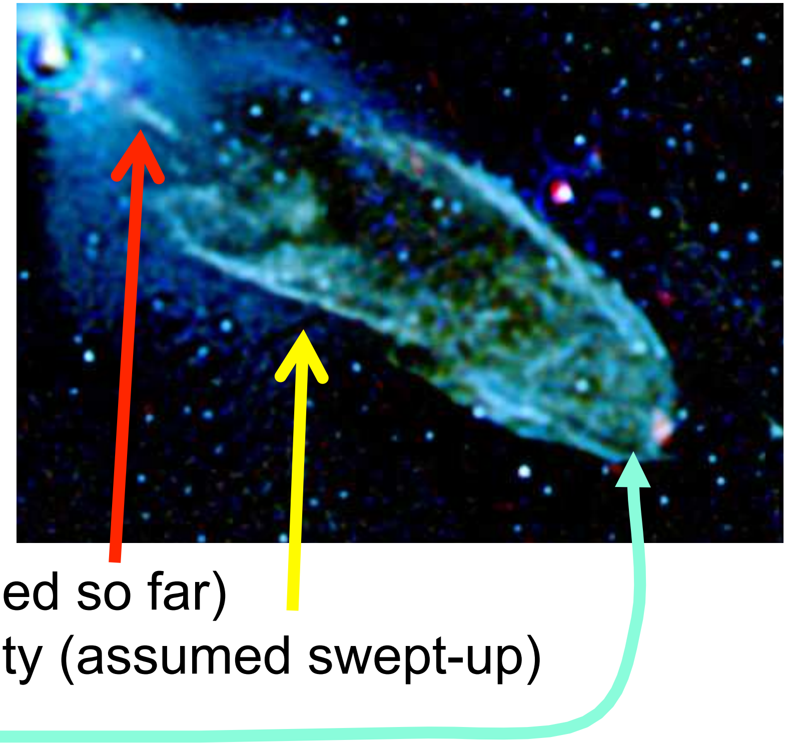

E-VLA
1.3" to 0.043" at 45 GHz


85-950 GHz : molecules & cool dust:

PdBI, SMA, ALMA
1.4'' to 0.015" at 300 GHz
300-3 AU @ 200 pc

Ejection to accretion ratio in Class 0 sources

- Accretion rate proxies: deeply embedded : No detectable UV excess from accretion shock. Use instead
  - Lbol = Lacc + L* ≈ Lacc
  - Menv ≈ Macc x 1e5 yrs (Bontemps et al 96)
  - Minfall (from envelope kinematics)

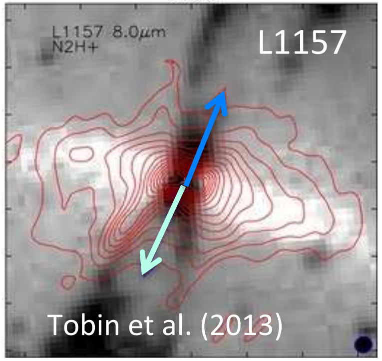


- Ejection rate proxies:
  - Mass-flux in fast CO jet (very few mapped so far)
  - Momentum flux in slow CO outflow cavity (assumed swept-up)
  - [OI]63mic from Mach disk α Mdot(jet)
- All give similar results : Mej/Macc ≈0.1

Outflow-Envelope Interactions:
widening of outflow cavity with time

Time

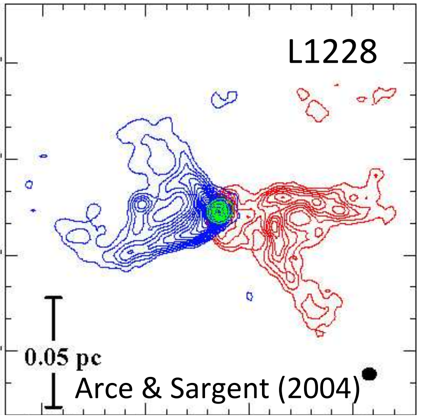
Class 0



Tobin et al. (2013)

Cavity o.a. ~ 20-50°.
Outflow starts entraining dense envelope

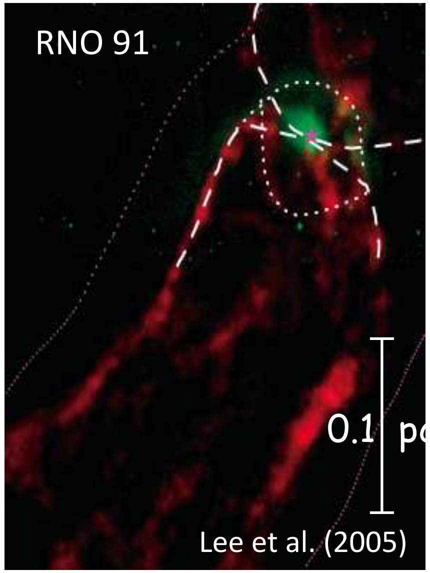
Class I



Arce & Sargent (2004)

Cavity o.a. ~ 80-120°.

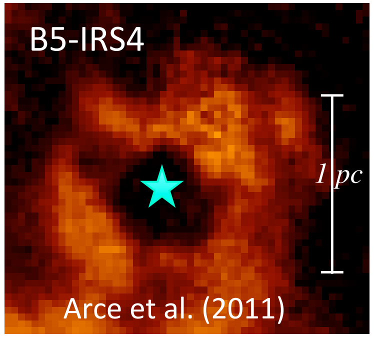
early Class II



Lee et al. (2005)

Very wide cavity
o.a. > 100 -130 °.
Low-density (or no) envelope left

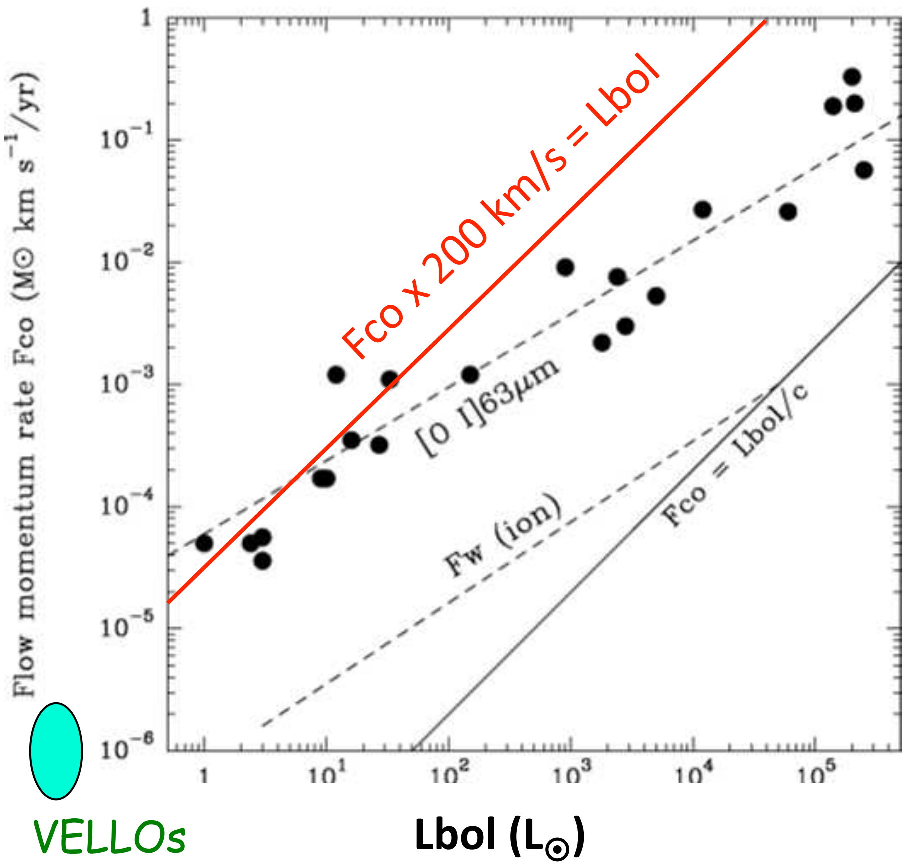
late Class II



Arce et al. (2011)

Quasi-spherical shell
Not clear how common this is.

Momentum flux in CO outflows vs Lbol



See: Richer et al. (2002, PPIV), Downes & Cabrit (2007)

- Fco correlated with Lbol over 5 orders of magnitude
  - ➢ Universal mechanism?
- Momentum-conservation:

Fw ~Fco ~ 10-1000 x Lbol/c

Agrees with Mdot from [OI] shock if Vw ~ 200 km/s

- If CO cavity swept-up by ~ 200 km/s wind :

➔ Lj ~ ½ Vj Fco ~ 0.5%-50% Lbol

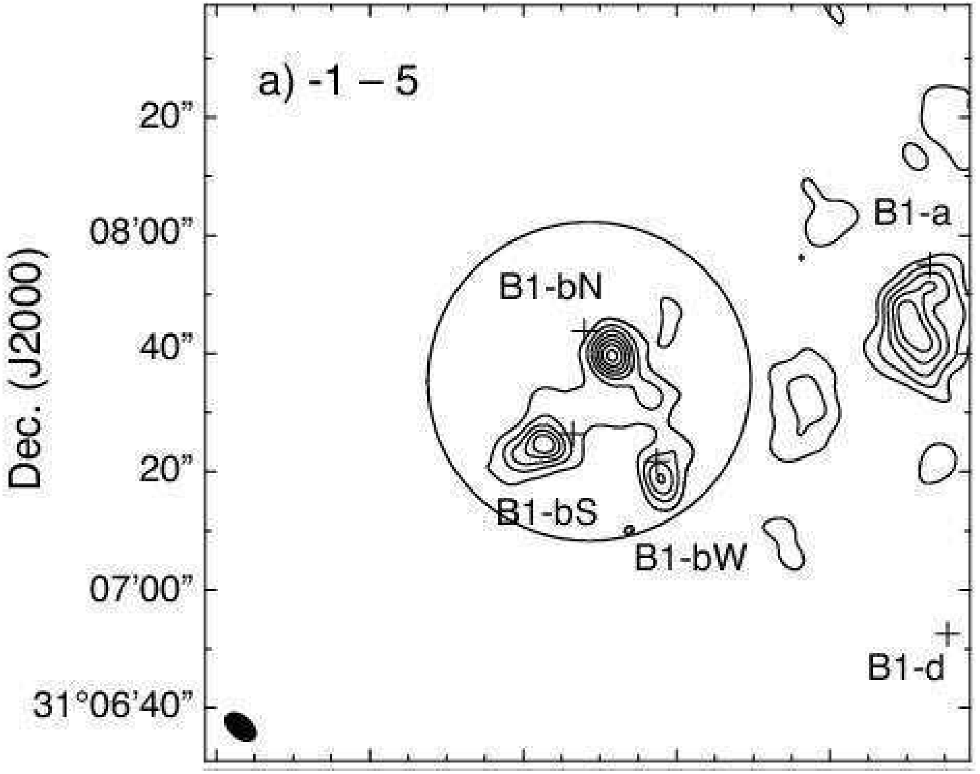
  - ➢ Very efficient ejection mechanism at low Lbol !
  - ➢ Major role in disk angular momentum extraction

Outflows from VELLOs - first hydrostatic cores?

- IRS2E in L1448 cloud *(Chen+ 2010)* < 0.1 $L_\odot$
- L1521F-IRS *(Takahashi+2013)* 0.05 $L_\odot$
- B1-bN and B1-bS *(Hirano et al 2014)* 0.15-0.3 $L_\odot$

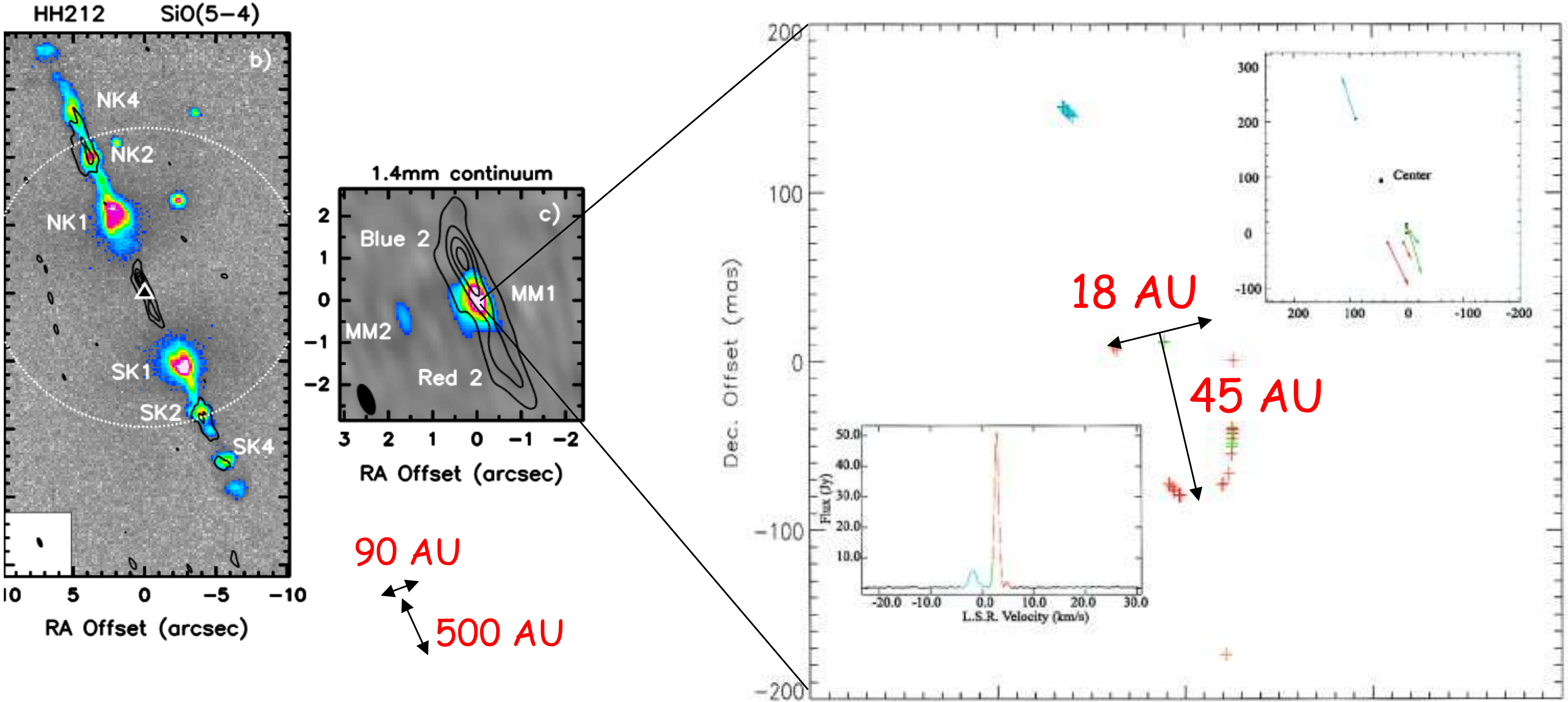
- In all cases:
  - Vmax = 3-8 km/s to 25 km/s
  - Age ≥ 2000 yr
  - Mdot(CO) ≈10^{-6} $M_\odot$/yr
  - Exceeds accretion rate?

  Or Luminosity problem ?



(Hirano et al 2014)

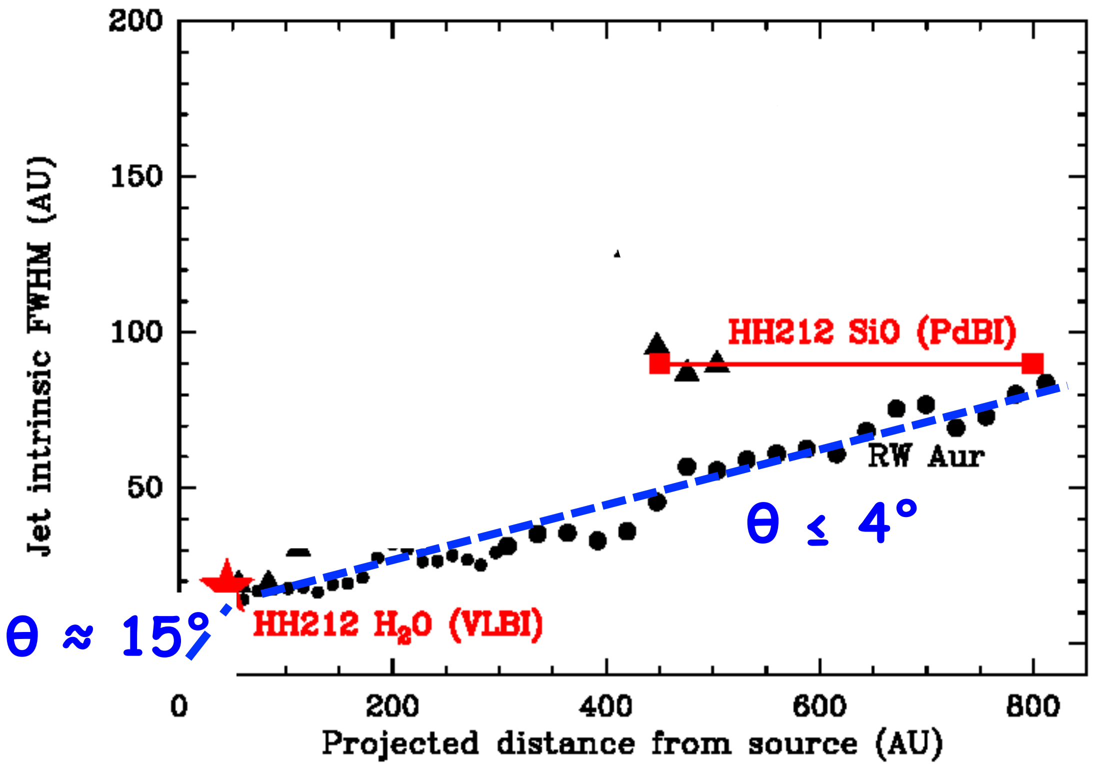
Jet collimation in Class 0 protostars
HH212 in Orion



SiO « microjet »
IRAM/PdBI 0.34'' x 0.78'' beam
(Codella et al. 2007, A&A Lett.)

Water maser spots (VLBI)
(Claussen et al. 1998, ApJ)

Universal jet collimation scale



Apparent collimation scale Z ~ 50 AU, R ~10 AU

(Cabrit et al. 2007 A&A)

- Same jet widths in Class 0 jet and in Class 2 **T Tauri jets**

- Hydro collimation is ruled out in T Tauri stars (ambient nH too low; Cabrit 2007, LNP)

➔ ***Argues for universal magnetic** jet collimation at R ~ 10 AU = **disk scales***

➔ *Strong constraint for MHD models ?*

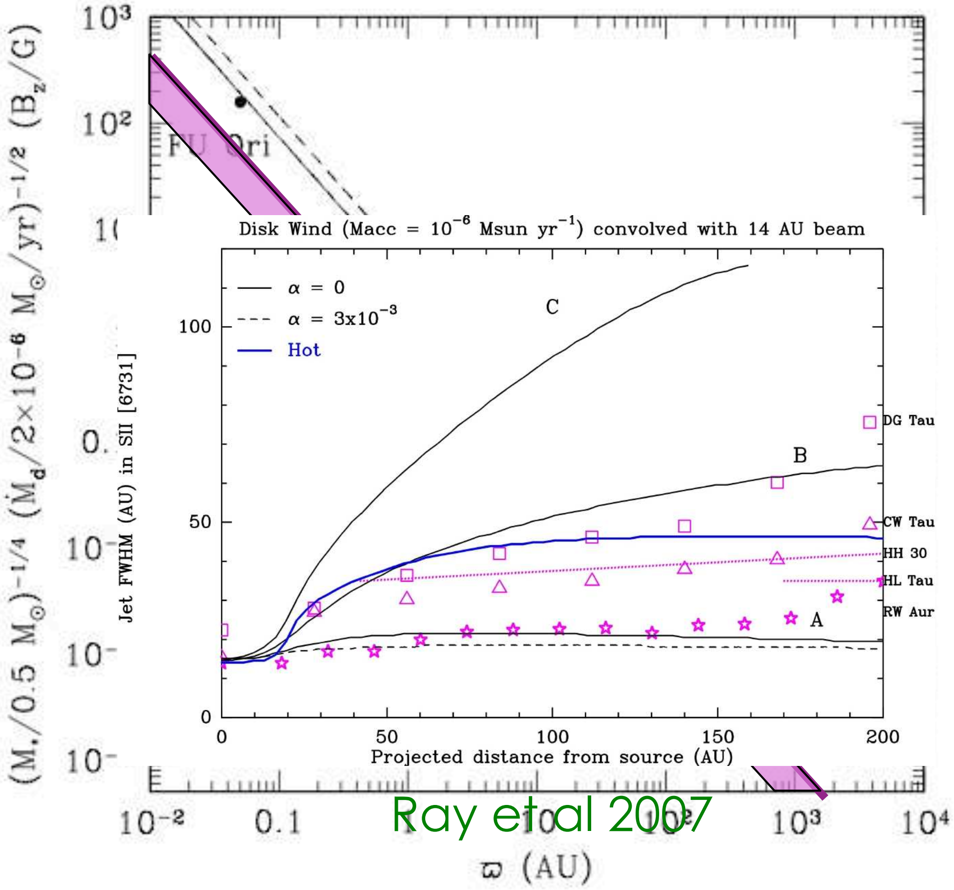
Magnetic fields in YSO disks

- External collimation by disk Bz
  - Bcoll ≈ 10mG $\sqrt{\text{Macc}/10^{-7}M_\odot/\text{yr}}$
  - Agree with few measurements and passive advection model of Shu etal (2007)
  - Φ_{coll}(100 AU) ~ 2% $\Phi_{crit}(1M_\odot)$

(Cabrit 2007, LNP)

- Self-collimated MHD disk winds ?
  - Same Bz scaling but **$B^2/8\pi P$** ~ 0.5 (Ferreira 97)
  - Could confine inner stellar + magnetospheric winds (Meliani+2006)
  - Can reproduce observed jet widths
- How to distinguish between the 2 ? Recollimation shock ?

Shu et al. (2007, IAU 243)



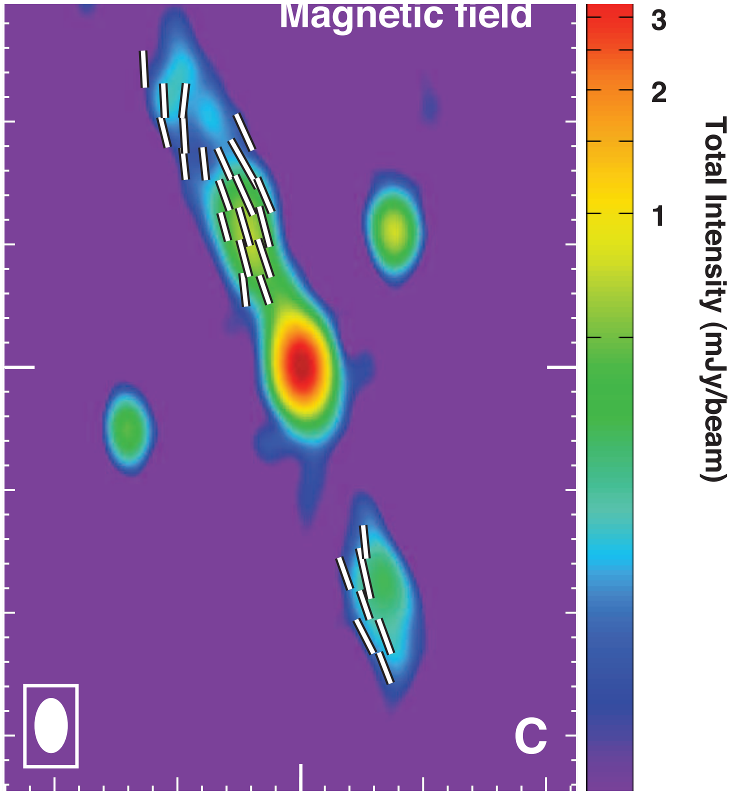
Ray et al 2007

Magnetic field in Class 0 jets

- Synchrotron linear polarisation in HH80-81 jet *(Carrasco-Gonzales+ 2010)*
  - Helical B aligned with jet

- H_2O masers in IRAS16293 with VLA *(Alves+ 2013)*

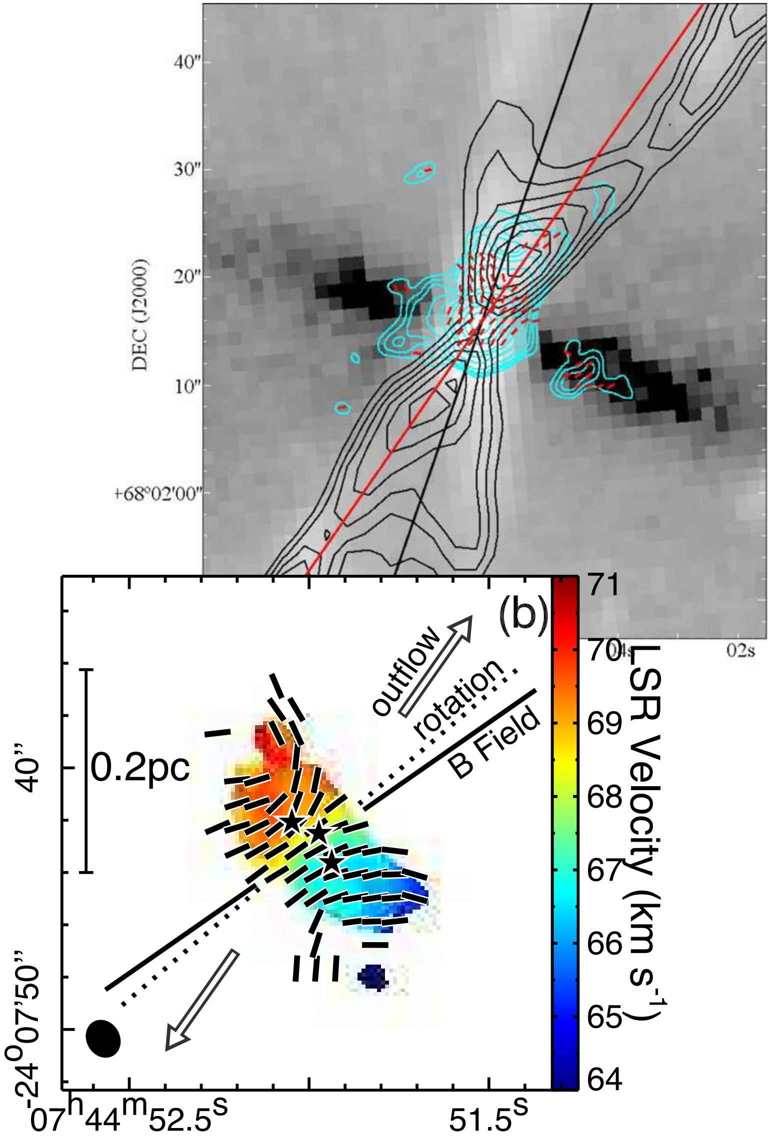
- Zeeman circular polarisation:
  - B_{los} = 110 mG after shock
  - $V_A = 20$ km/s $(n_H/10^8 cm^{-3})^{-0.5}$
  - upper limit on V_A(preshock) but unknown Vjet…



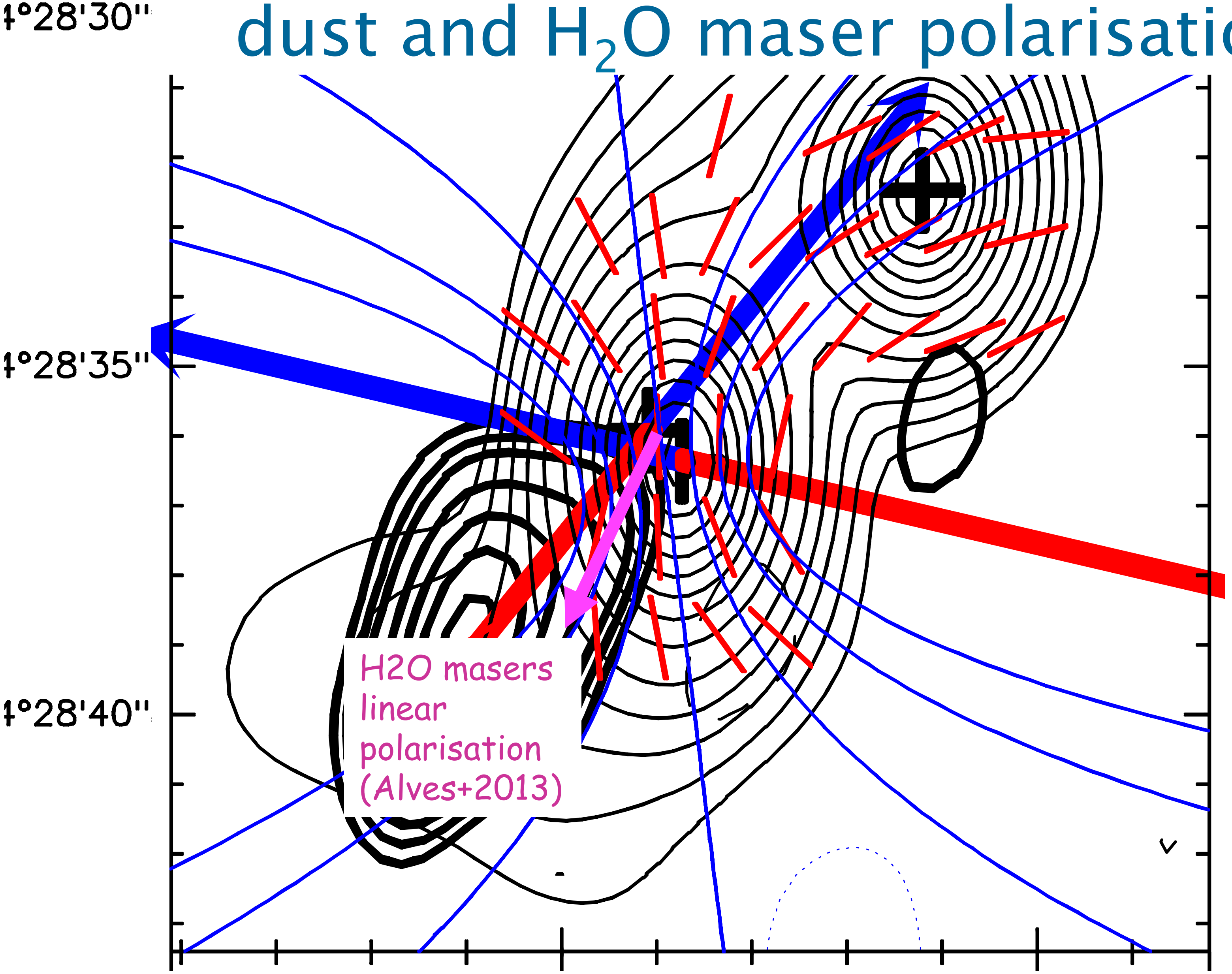
Carrasco-Gonzalez et al 2010, *Science* **330**, 1209

Jet alignment with magnetic field of dusty parental core ?

- Alignement seems random on > 1000 AU scales
- Better, but not perfect, alignement in cases where dust polarisation shows hourglass geometry < 500 AU
  - L1157: low-mass single protostar *(Stephens+2013)*
  - G240.31: massive cluster forming core *(Qiu+2014)*



IRAS16293-A flow axes vs B from dust and H_2O maser polarisation



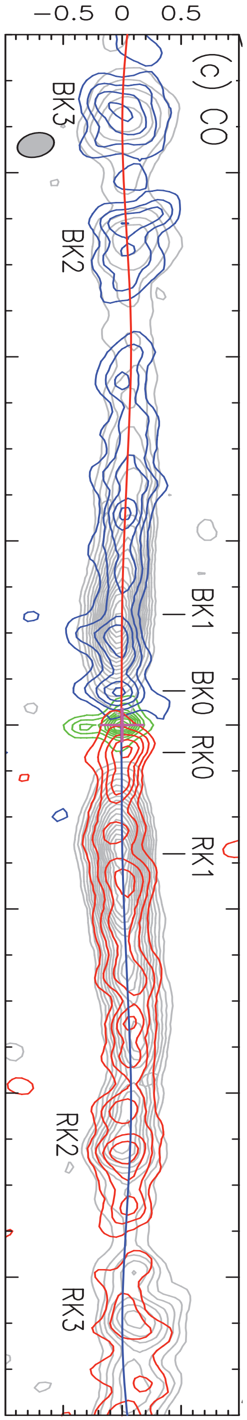
H2O masers linear polarisation (Alves+2013)

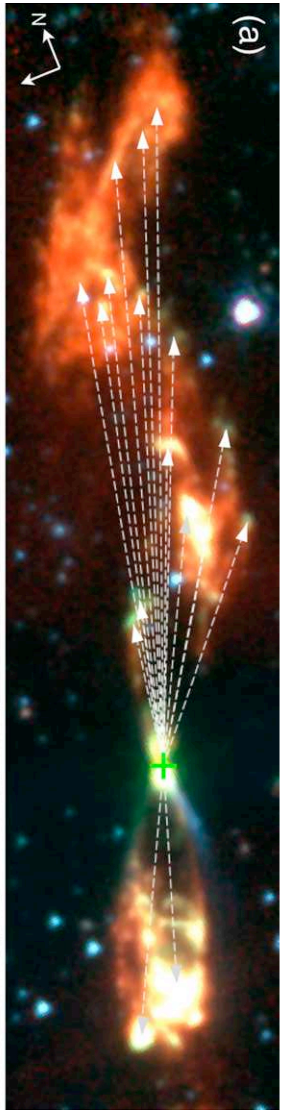
Rao+ 2009

Jet angle variations

- **W-shaped : orbital motion:** *HH211, P=43yrs; HH111, P=1800 yrs* *Lee+2010, Noriega-Crespo+2011*
  - constrain binary mass and separation
- **S-shaped : precession** 3000-50,000 yrs (eg Devine+97,Takami 2011)

due to disk precession?

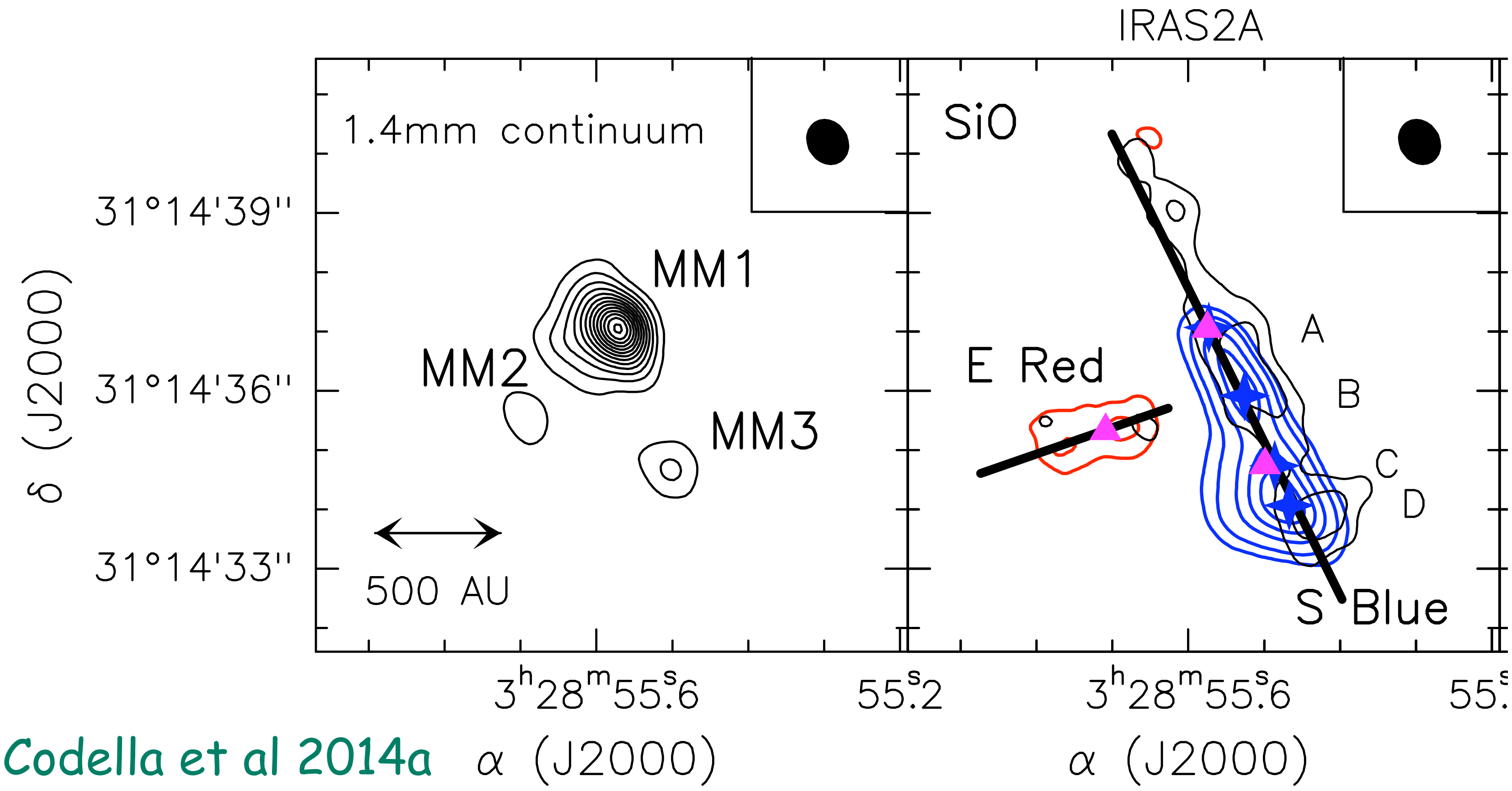




Monopolar Class 0 jets

SiO and SO jets cqn be one-sided over inner 1000 AU despite bipolarity on larger scale

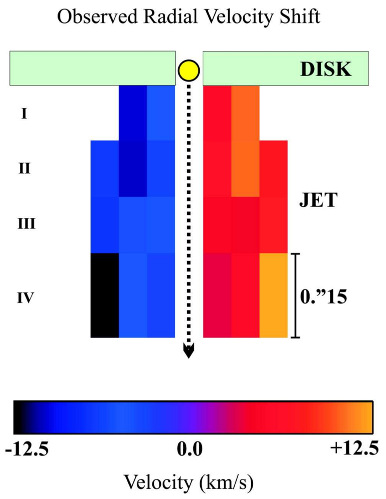
➔ intrinsically monopolar ejection over last 90 yrs ?



Codella et al 2014a

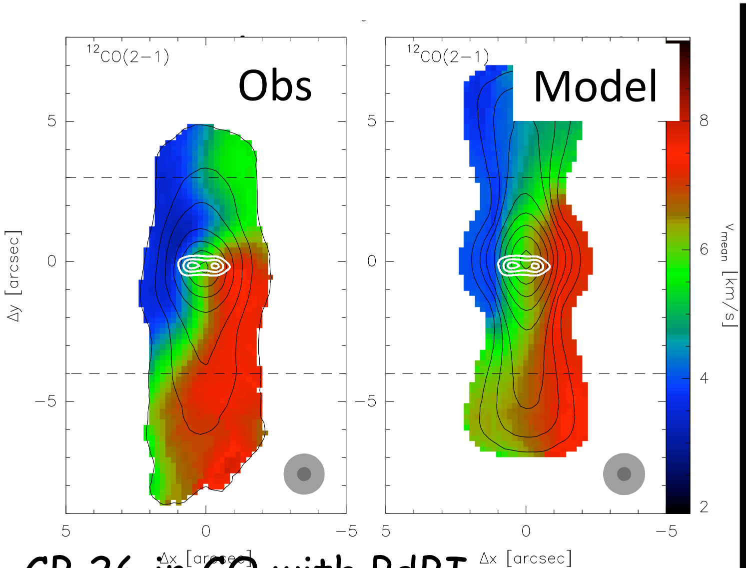
Jet / wind rotation

Class 2



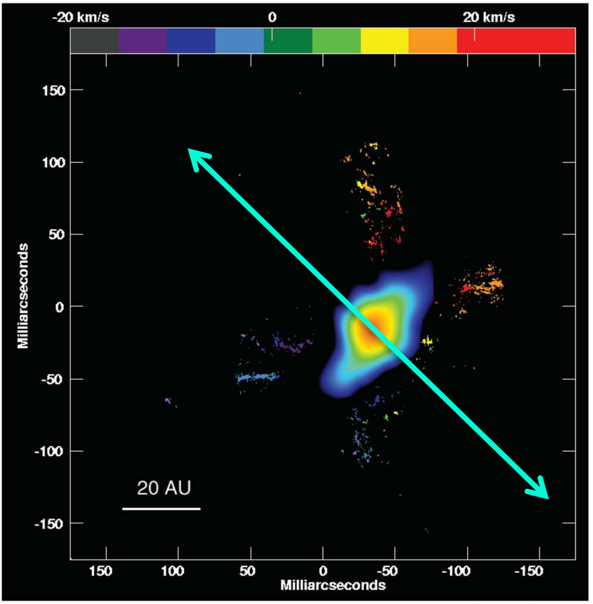
DG Tau with HST (Bacciotti+2002, Coffey+2007)

Class 1



CB 26 in CO with PdBI (Launhardt et al 2009)

Class 0



Massive protostar Source I SiO maser VLBA (Matthews et al 2010, Vaidya etal 2013)

Stationary MHD disk winds predict (Anderson+03. Ferreira+06)

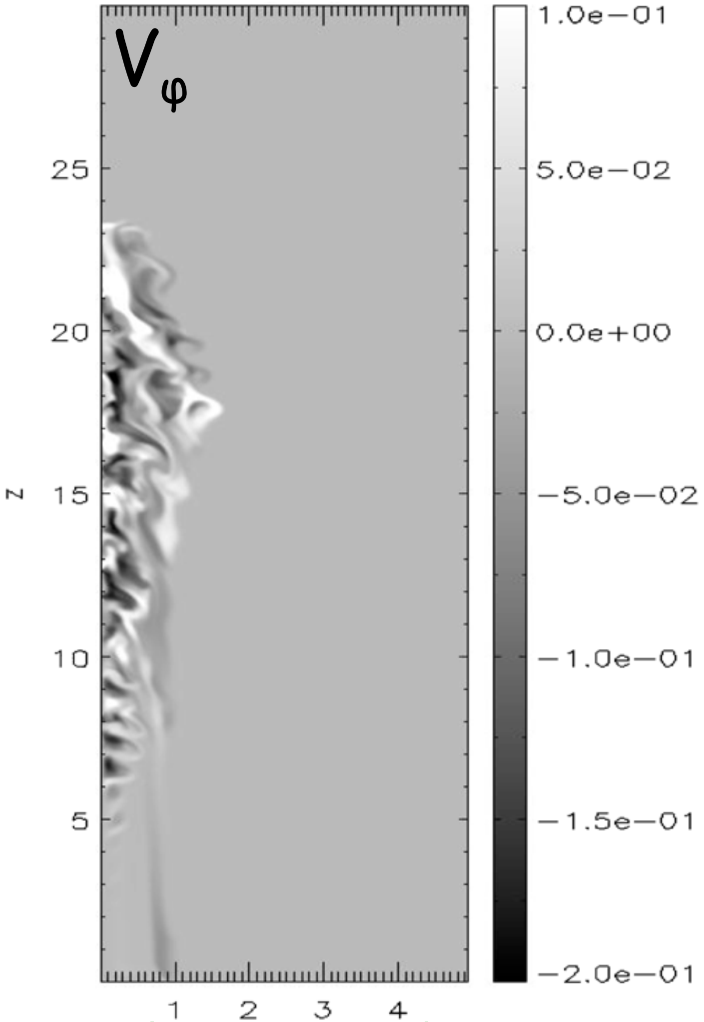
$$2rV_\phi\Omega_0 = V_p^2 + 3\Omega_0^2 r_0^2$$

➔ suggests r0 ≈ 0.1 - 5 AU, rA/r0 < 4 for all candidates so far

Feedback on disk structure in the region of formation of terrestrial planets?

Questioning Jet Rotation

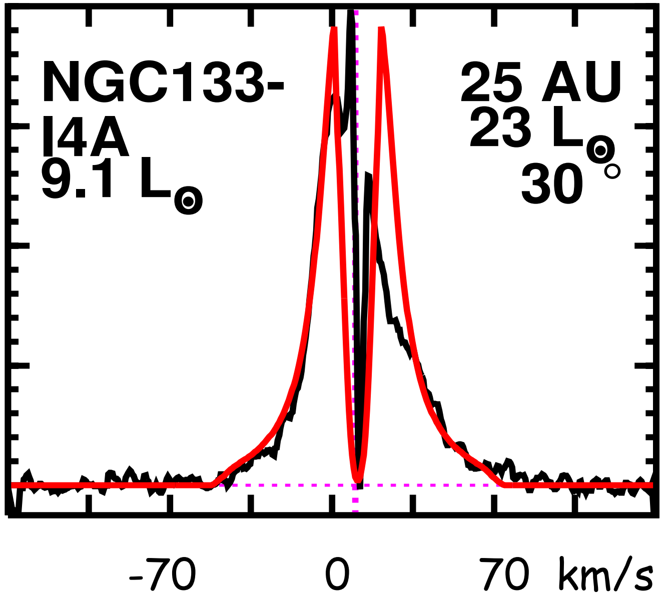
- Puzzling observations in optical jets
  - Opposite rotation of Disk / Jet or Jet / Counterjet + variable (RW Aur, HH212)
- Proposed interpretations
  - Jet precession, orbital motion, asymmetric shocks
  - Transfer btw matter rotation and B-field torsion in shocks (Fendt 2011, Sauty 2012): unsteady flow where r0 cannot be inferred
  - Beam dilution of true jet rotation signatures (Pesenti et al 2004)



(Fendt 2011)

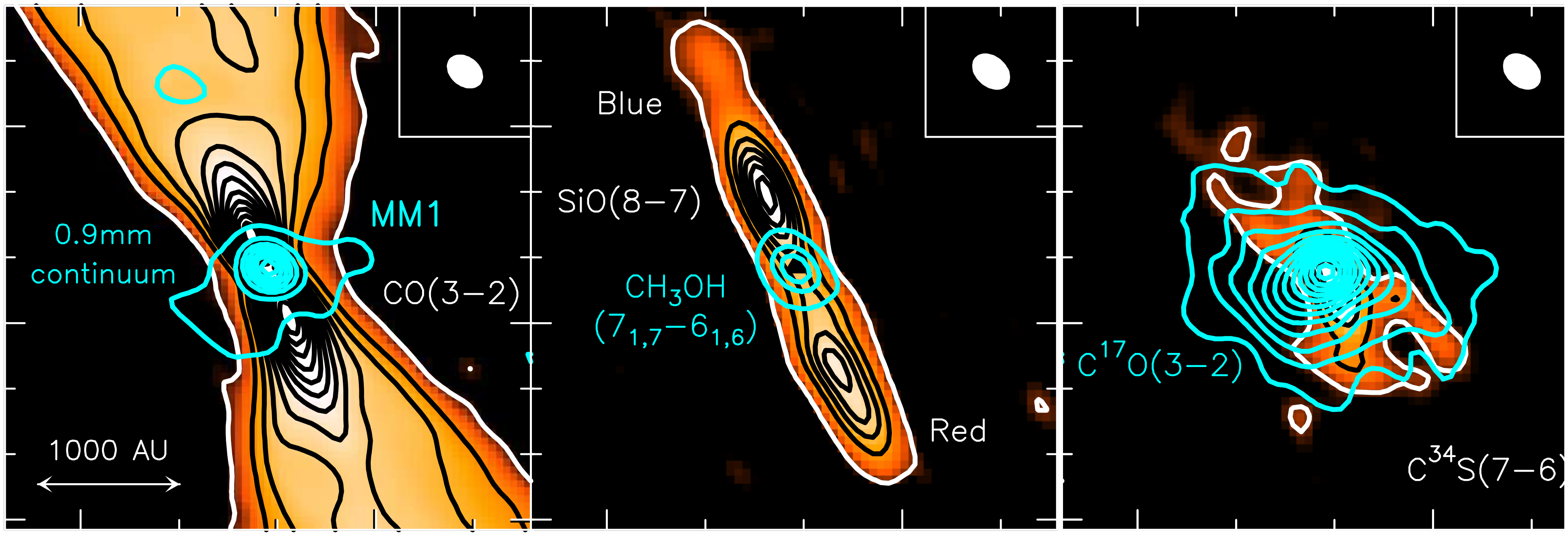
Molecular diagnostics of R_{launch}

- Non-equilibrium thermo-chemical models of dusty MHD disk winds (Panoglou et al 2012)
  - Molecules can survive against heating by ion-neutral drag and UV-Xrays from source
- Predicted H_2O line profiles (Yvart, PhD thesis)
  - Range of Rlaunch from 0.2 to 6-25 AU can explain broad H_2O wings seen by *Herschel* in all Class 0 sources



Models: W. Yvart
Data: Kristensen et al. 2012

ALMA Cycle 0 observations of HH212: a different behavior in each molecule !



- CO: cavity+jet
- Continuum: cool dust

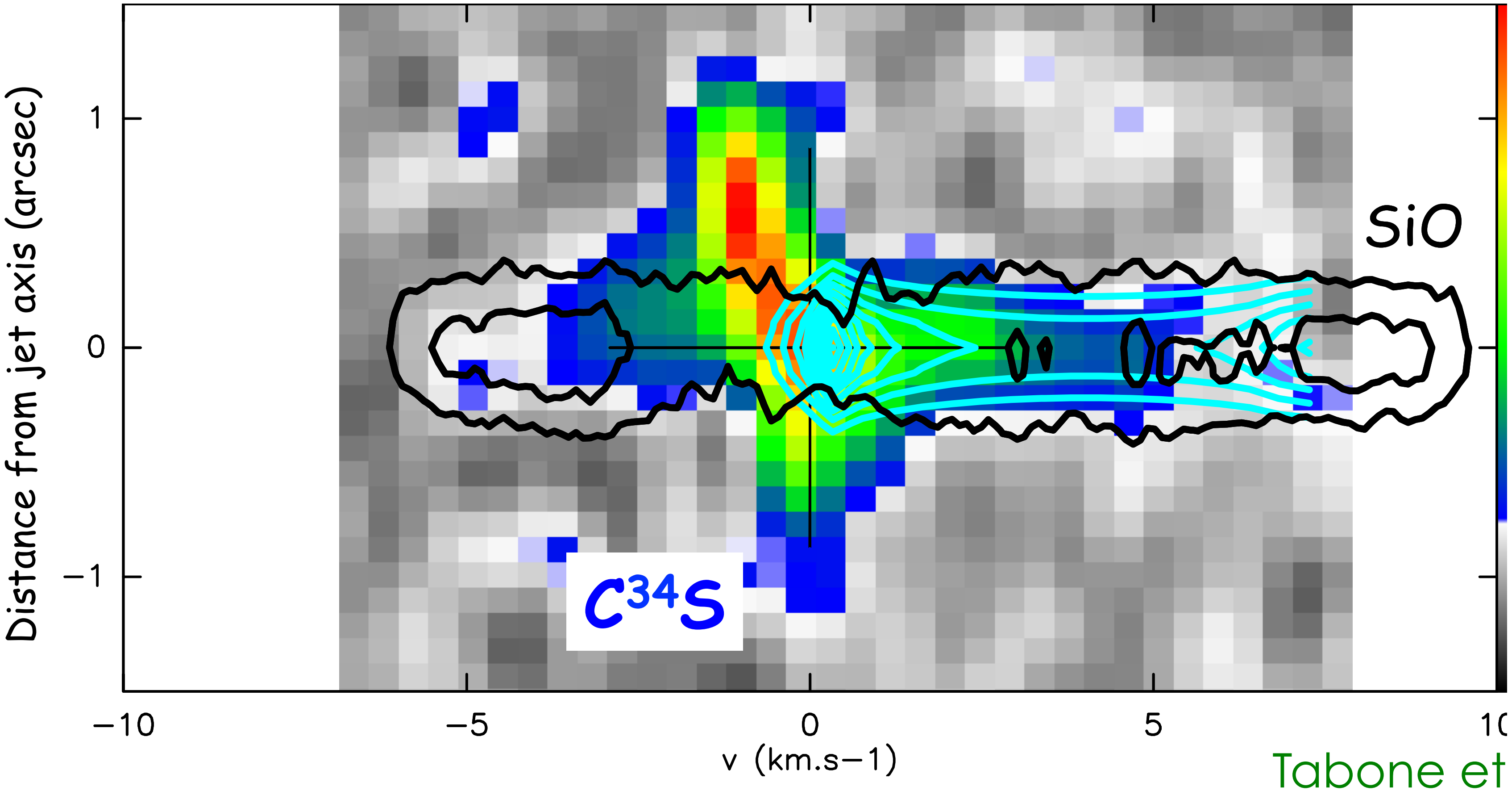
- SiO: jet only
- CH_3OH: hot dust > 100 K

- $C^{34}S$: cavity walls + jet
- $C^{17}O$: envelope+disk

Codella et al 2014b

Testing for jet rotation in SiO

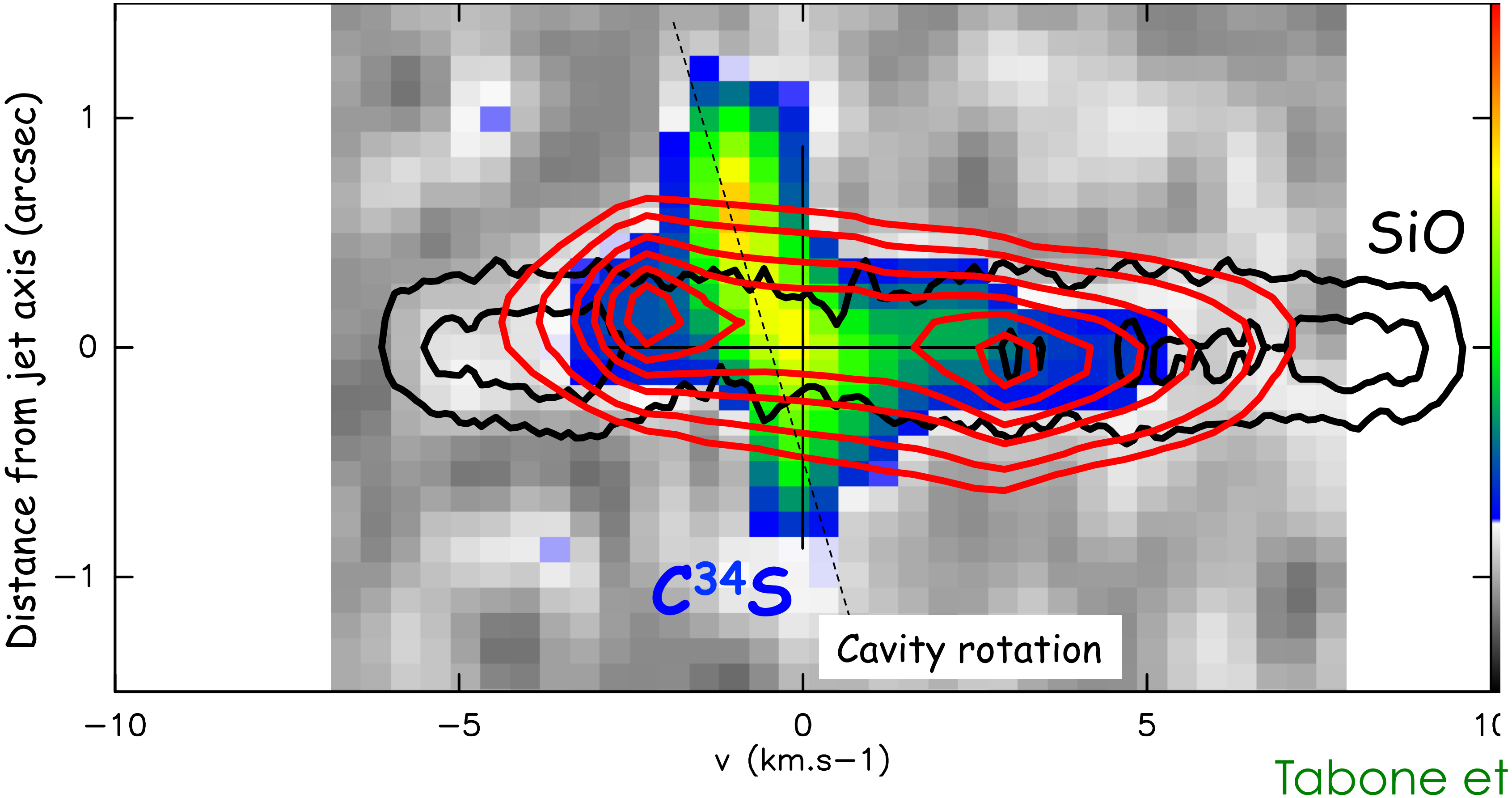
Transverse Position-velocity cut across jet axis at z= 0.6''= 250 AU Compared with **MHD disk wind model from 0.2 to 0.6 AU** (Casse & Ferreira 2007)**: compatible with no detectable rotation in SiO**



Tabone et al 2014

Testing for jet rotation in CS

Transverse Position-velocity cut across jet axis at z= 0.6''= 250 AU Compared with MHD disk wind model from 0.6 to 25 AU (Casse & Ferreira 2007): **compatible with CS jet feature**



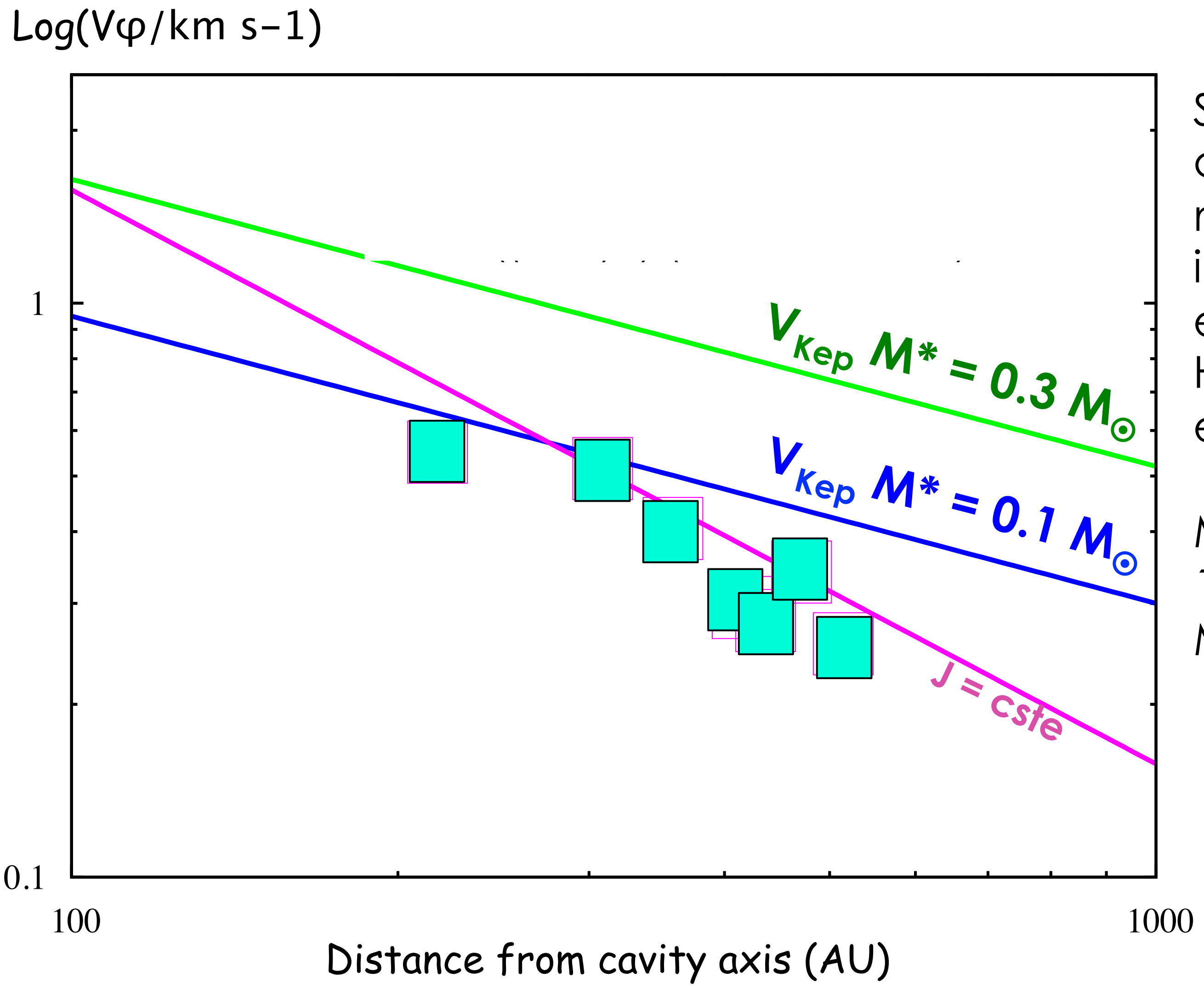
Tabone et al 2014

The cavity walls

ALMA Cycle 0 data
Codella et al 2014

$C^{34}S$ highlights the cavity walls without confusion by the extended envelope seen in $C^{18}O$ and HCO^+: CS released from grain mantles in shock ?

Rotation of the red lobe cavity walls

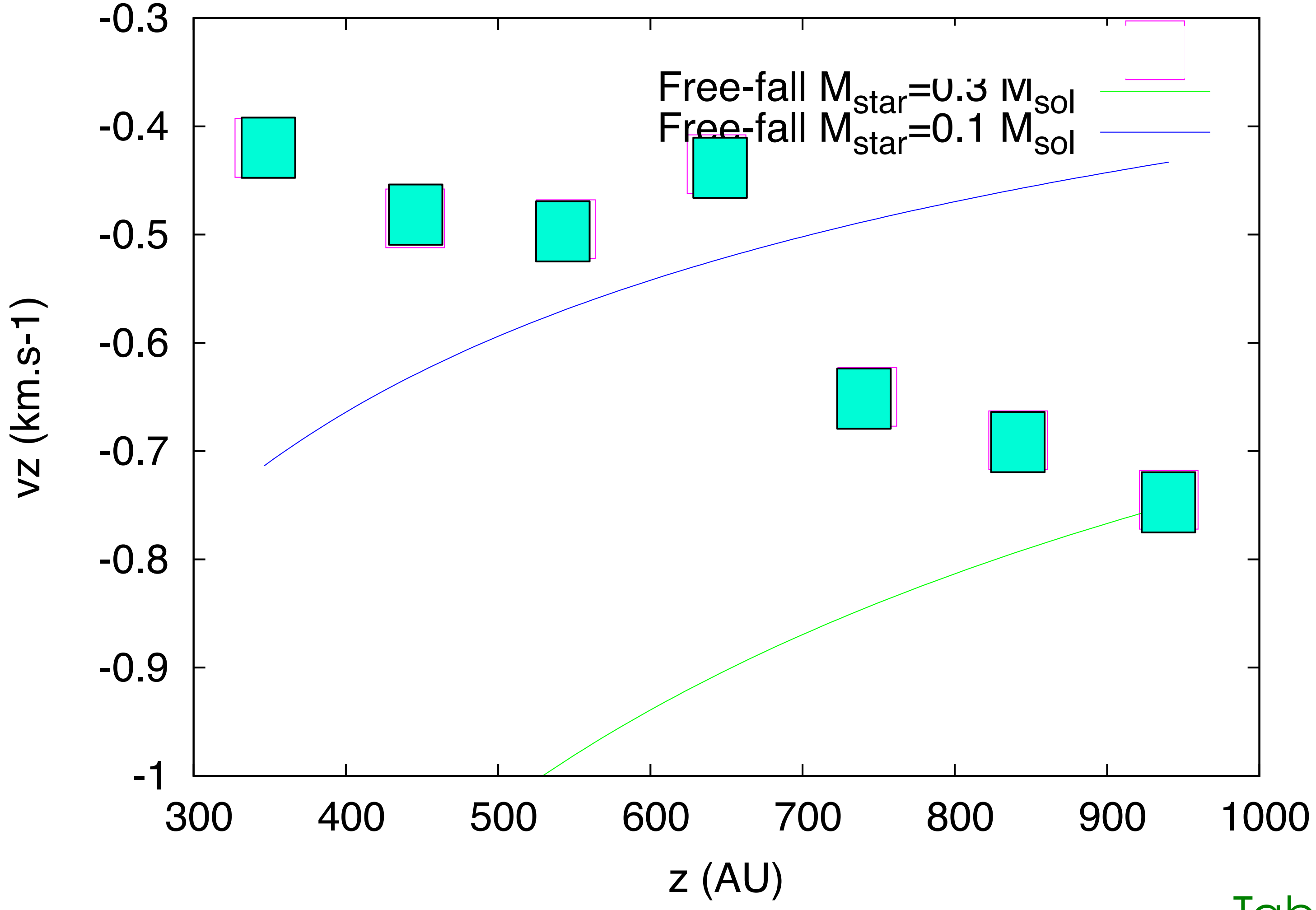


Same specific angular momentum as infalling envelope seen in HCO+ by Lee etal 2014

Mdot(infall) = 5 10^{-6} Mo/yr = 5 x Mdot(CO jet)

Tabone et al 2014

Vz of the red lobe cavity walls

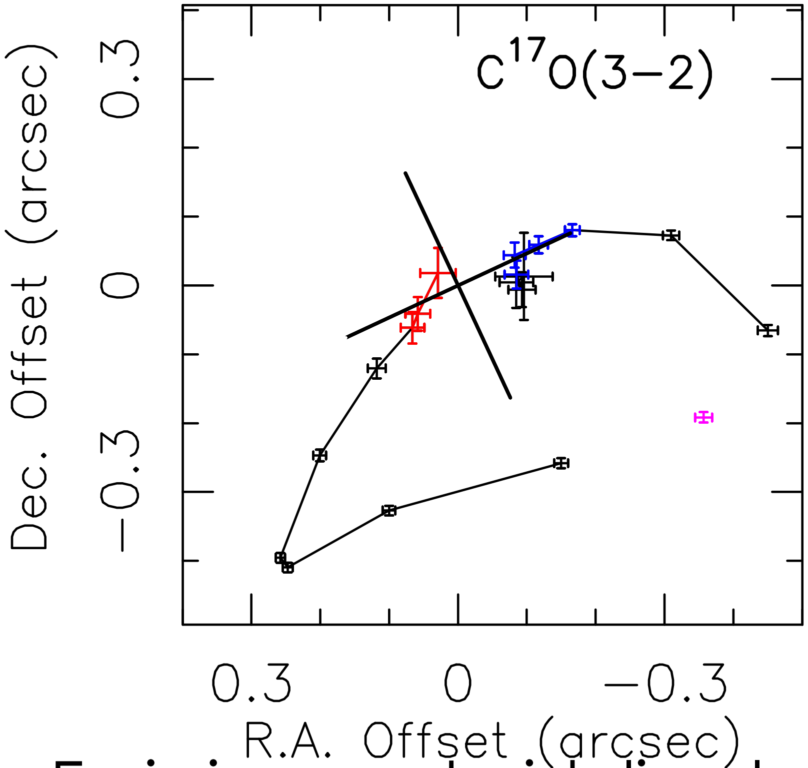


Blueshifted in red lobe : falls towards the disk ➔ **infalling rather than outflowing !**

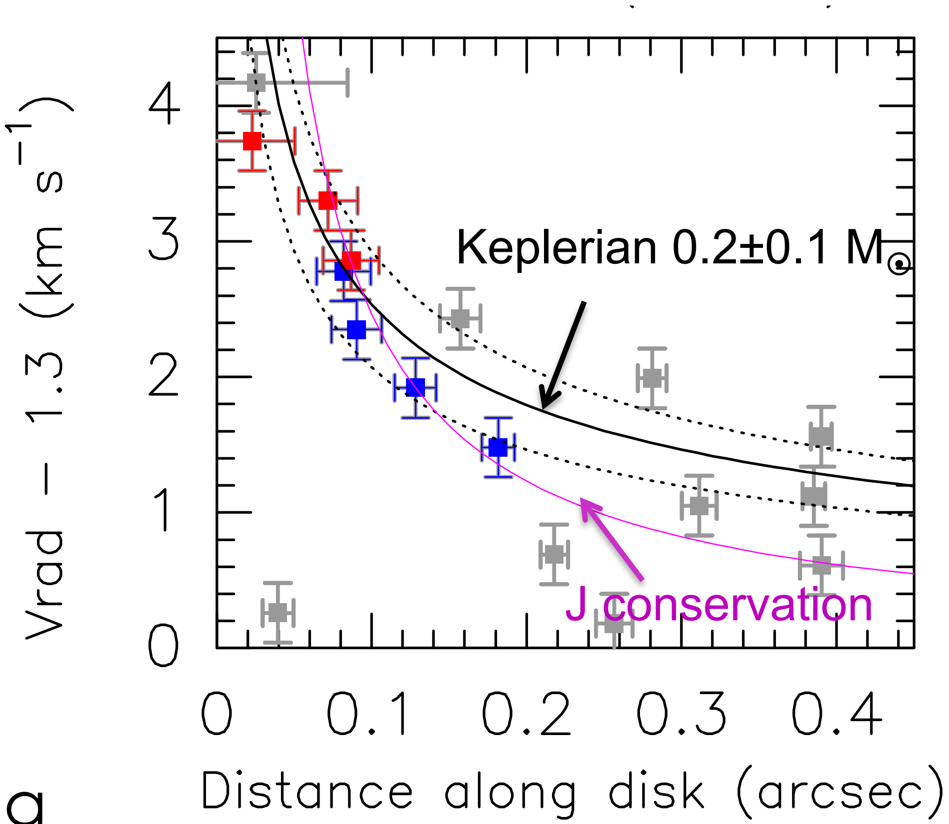
Infall slower as approaches source: ➔ opposing force?

Tabone et al 2014

C^{17}O: rotating inner disk < 80 AU



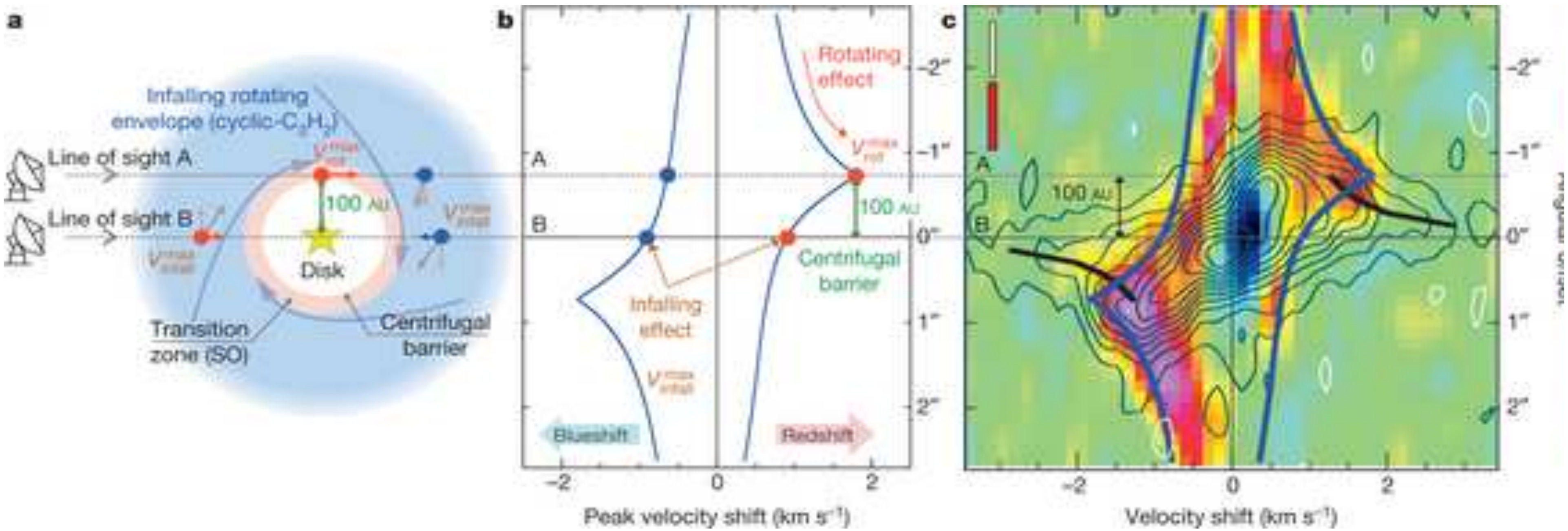
- Emission centroids lie along disk plane in high velocity channels



- Keplerian rotation at radii ≤0.2'' = 80 AU

Codella et al 2014

Digression: Centrifugal barrier in L1527 ?



C3H2 suggests rotating infall with j=cst down to centrifugal barrier (100 AU). C3H2 disappears inside while SO appears.
Chemical changes attributed to local heating.

Sakai et al, Nature, 2014

Summary

- Ejection power is 10%-100% of radiated accretion power in low-luminosity protostars, depending on Vwind
- CO outflow rate exceeds stellar accretion rate in VELLOs ➔ impact on CMF/IMF ?
- Jet speed and variability timescales surprisingly similar from Class 0 to Class 2. Observation bias ?
- Collimation at 10-50 AU independent of envelope ➔ disk B-field: Bp or Bφ ?
- Jet not perfectly aligned with hourglass B-field on 500 AU scales: precession + Orbital motion ?
- Jet rotation signatures challenging. Need both high angular **and** velocity resolution at jet base
- Current molecular obs (*Herschel*, ALMA) compatible with MHD disk winds from 0.2 to 25 AU. But more stringent tests to come !
- CO cavity appears infalling rather than outflowing: interaction between wide-angle wind and infalling envelope conserving angular momentum