Jets and Outflows: origin and feedback

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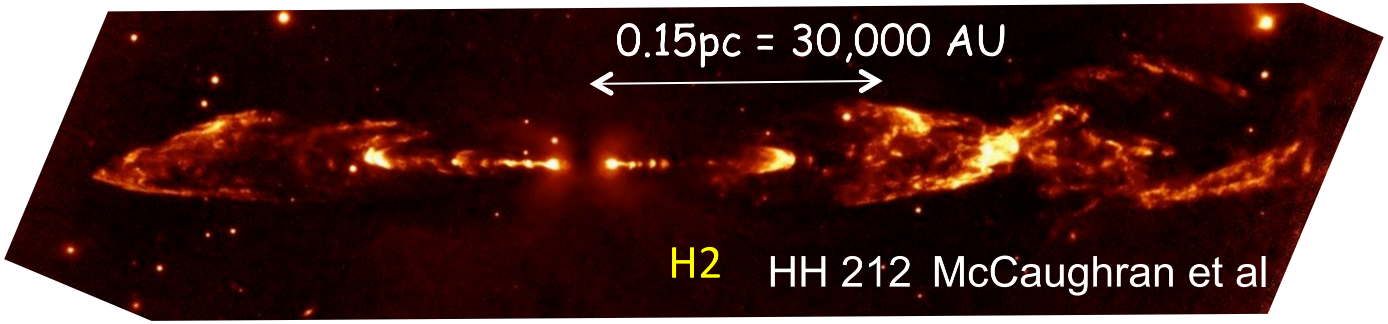
Why Do Jets & Outflows Matter ?

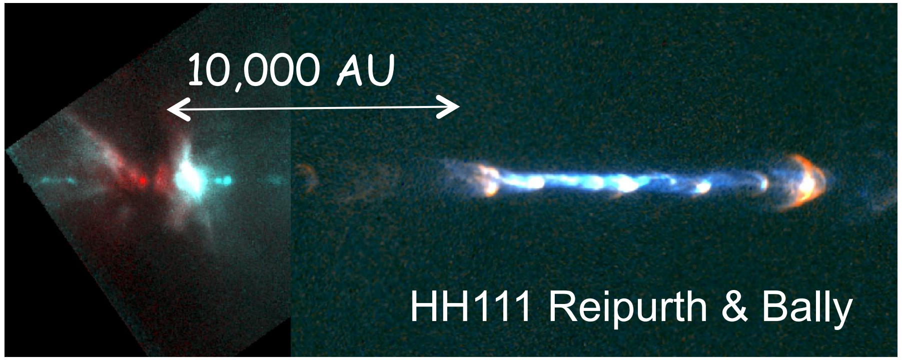
- Invoked to solve several major issues in SF:
  - Low SFE and SFR in turbulent clouds
  - 30% Core to Star efficiency
  - Removal of angular momentum to allow accretion from disk to star (2nd Larson's core ~ 10^{-3} $M_{\odot}$)
- Also:
  - Unique record on source binarity, disk precession, accretion outbursts, *cf. talk by Bo Reipurth*
  - May affect planet formation and disk dissipation

(See review in Frank et al. 2014 - PPVI + refs therein)

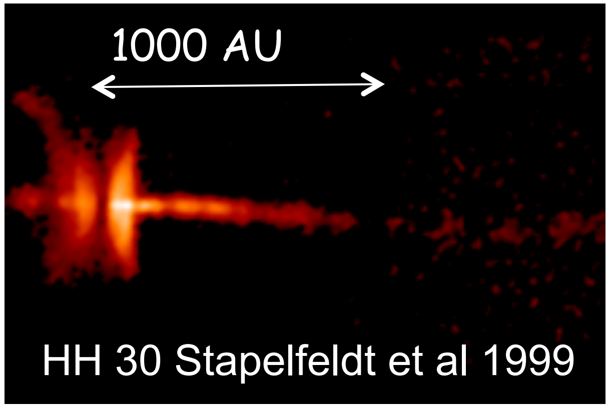
Universality of jets across YSO stages



Class 0 Protostars
~ 10^4 yr



Evolved Class 1 Protostars
~ 10^5 yr



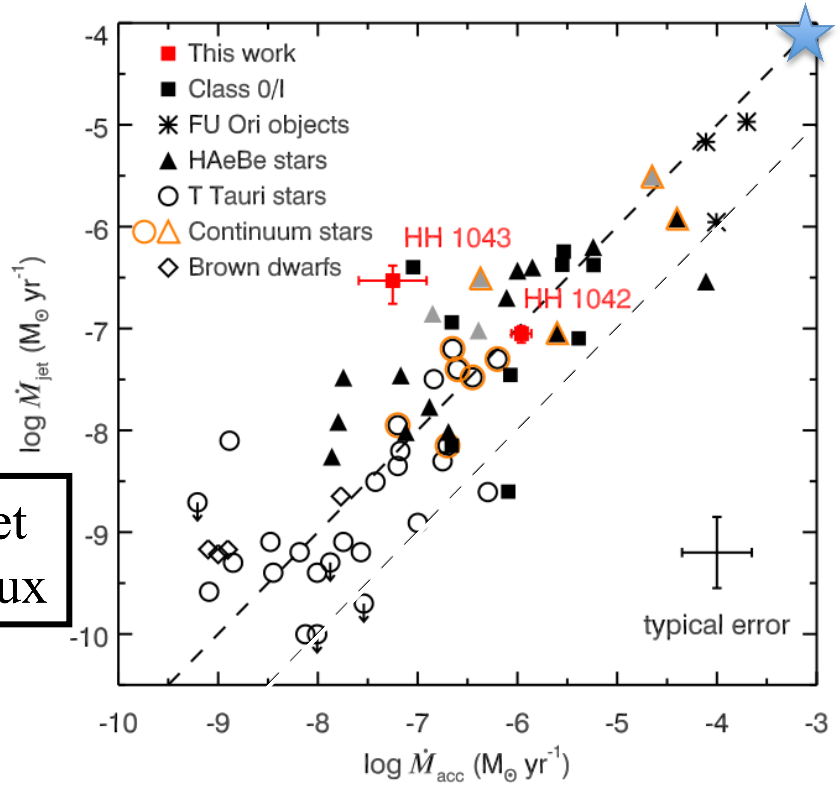
Class 2 (Disk only)
~ 10^6 yr

Accretion and ejection are correlated

✧ Universal across stages and stellar masses:

✧ independent of stellar B and Ω ?

Axial Jet Mass flux



Disk accretion rate

Mjet/Macc ~ 0.1

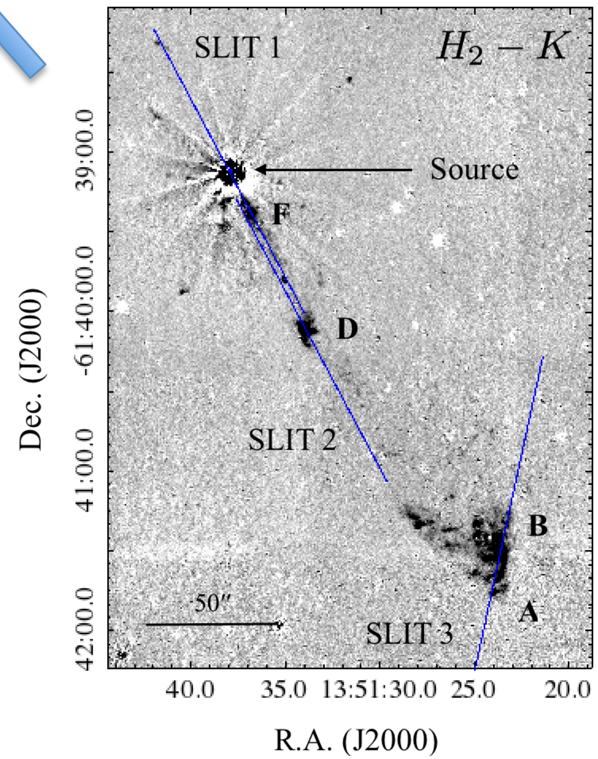
Elllerbroek+13

Antoniucci+08

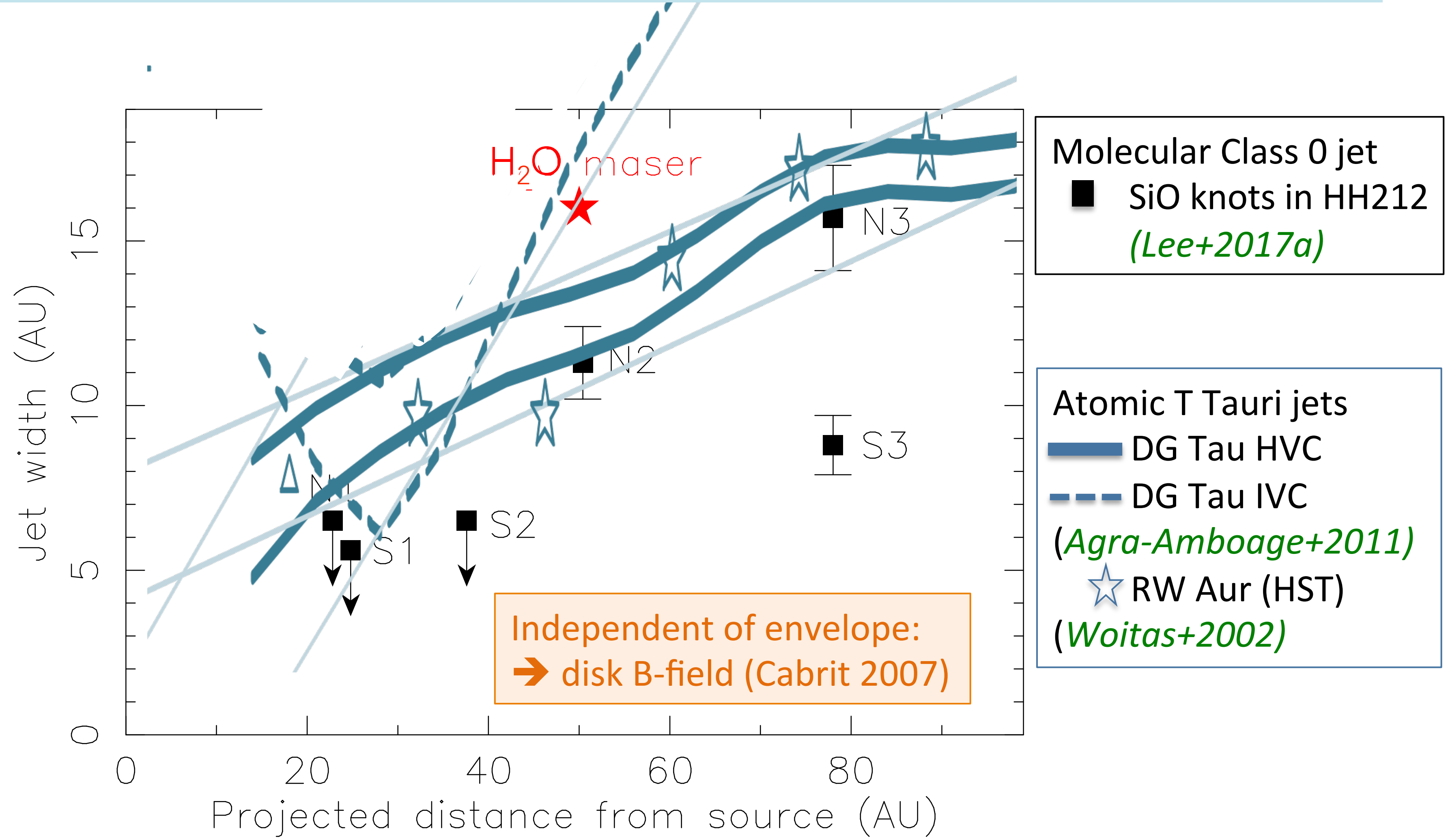
Nisini+18 …

20 $M_\odot$ protostar

Fedriani et al. 2018



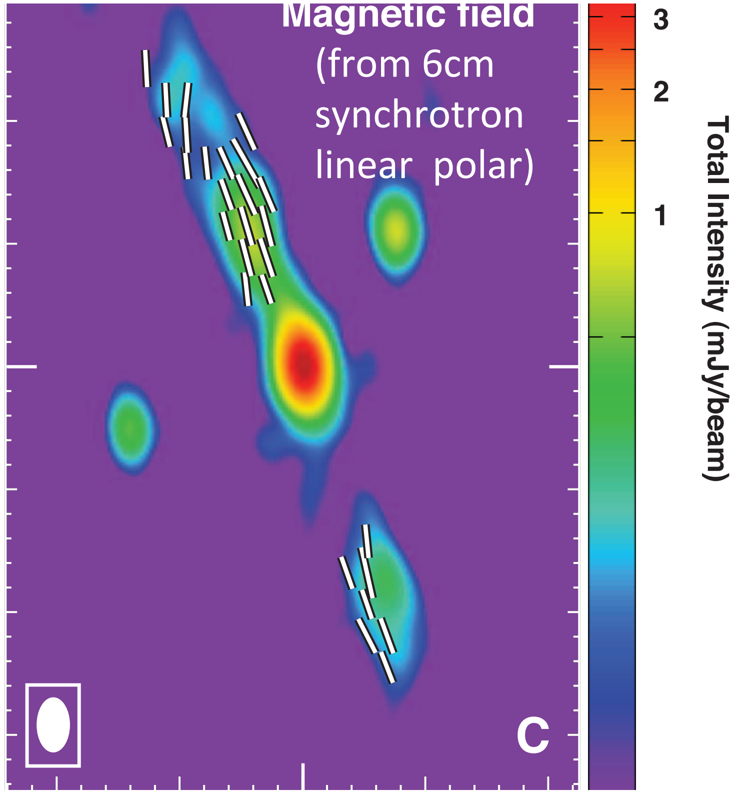
Universal jet collimation on AU scale



Jet magnetic field

- Synchrotron linear polarisation:
  - B aligned with jet in HH80-81
  - Hint of toroidal

- see also **poster 1D by A. Feeney-Johansson et al.** (Synchrotron knots in DG Tau with LOFAR and eVLA)

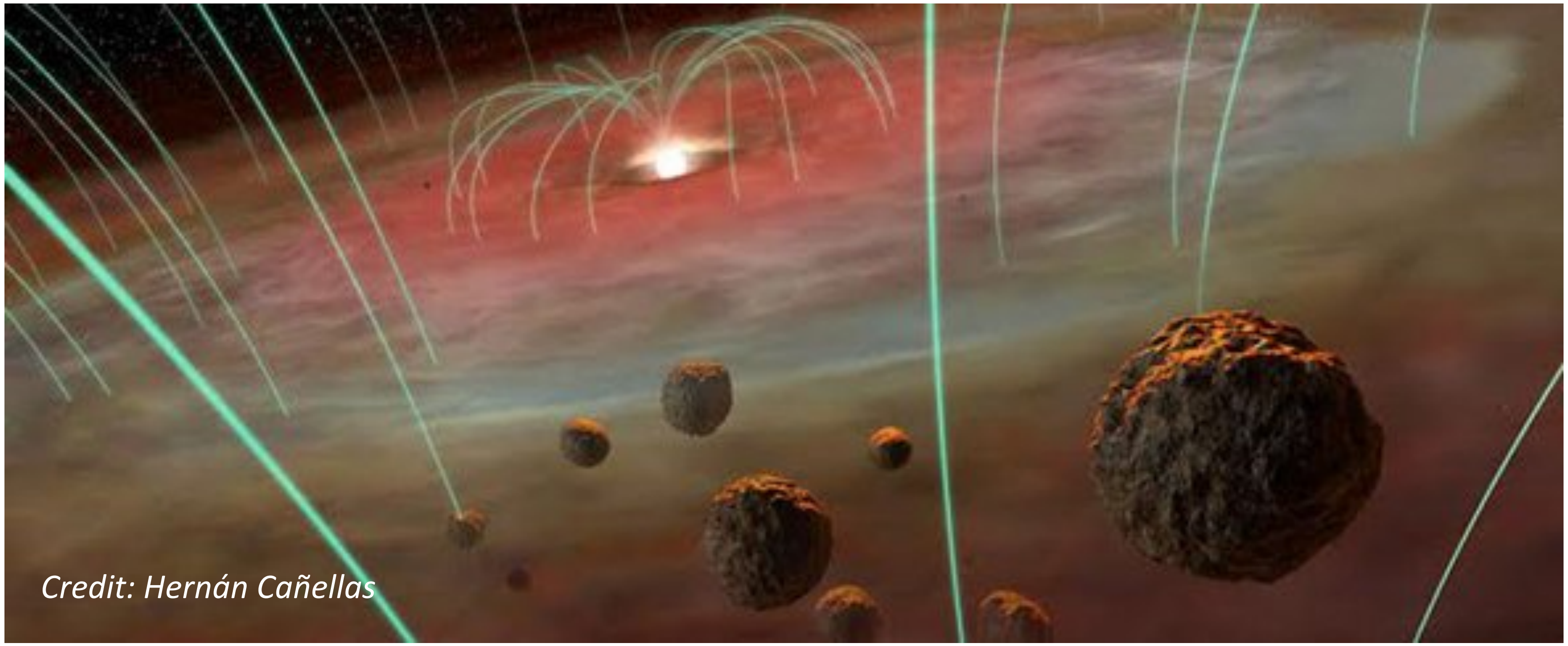


Carrasco-Gonzalez et al 2010, *Science* **330**, 1209 (2010)

Evidence for disk B-field

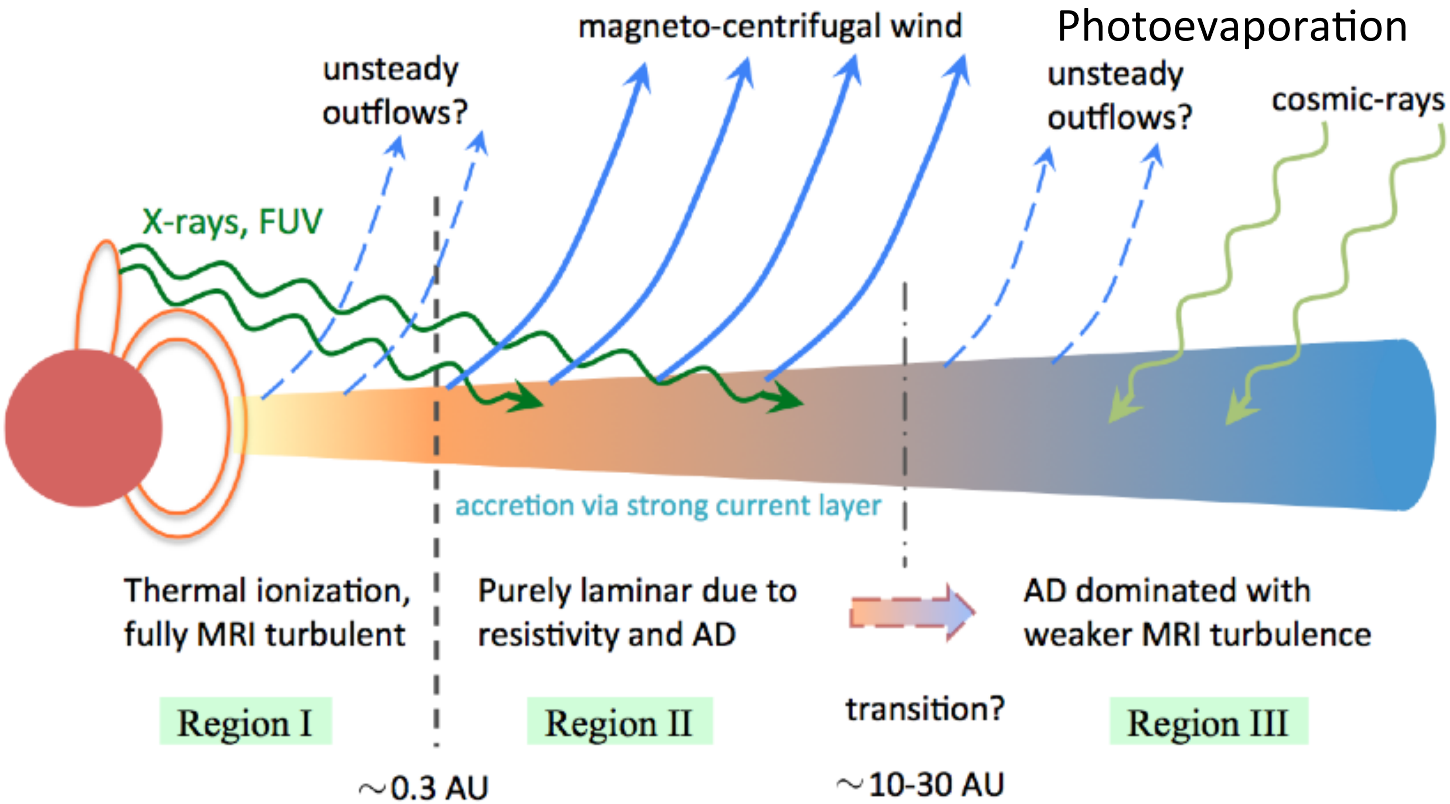
Meteoretic measurements: B ~1G at 1 au (Fu et al. 2017)

- Sufficient for jet collimation.
- angular momentum extraction through MHD disk wind ?

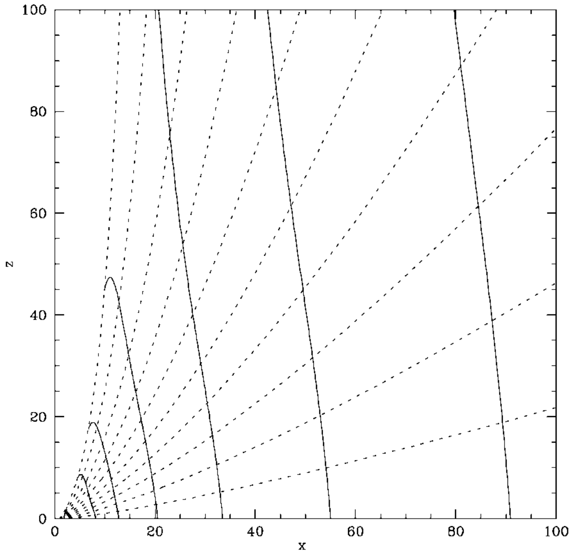


Magnetic disk winds

Magneto-centrifugal disk winds may solve the problem of angular momentum transport in « dead zones » of accretion disks Bai & Stone 2011 (see Turner et al. 2014 PPVI for a review)

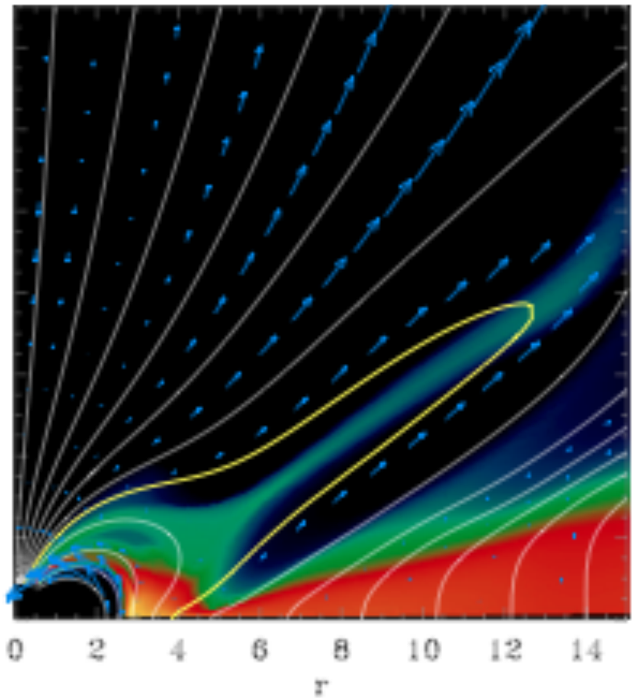


Ejection from star-disk interaction



X-wind (Shu+94, Shang+00 PPV):

- MHD DW from Rcorot ~ 0.05 au
- Fan-like: fast wide-angle wind with denser axial spine



Magnetospheric Ejections :
Cyclic inflation/reconnection
(Goodson et al. 1999, Zanni & Ferreira 2013)
Collimated by disk B / disk wind

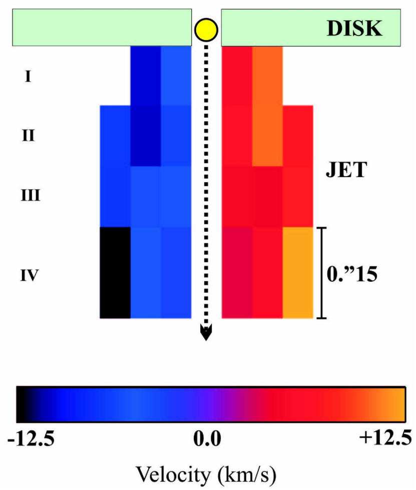
Jet / wind rotation

OBSERVATIONS

- If MHD disk wind is **steady, axisymmetric, cold** (magneto-centrifugal >> thermal), predict ***(Anderson+03):***

$$r V_\phi \Omega_0 = \frac{V^2}{2} + \frac{3}{2}(G M_\star \Omega_0)^{2/3}$$

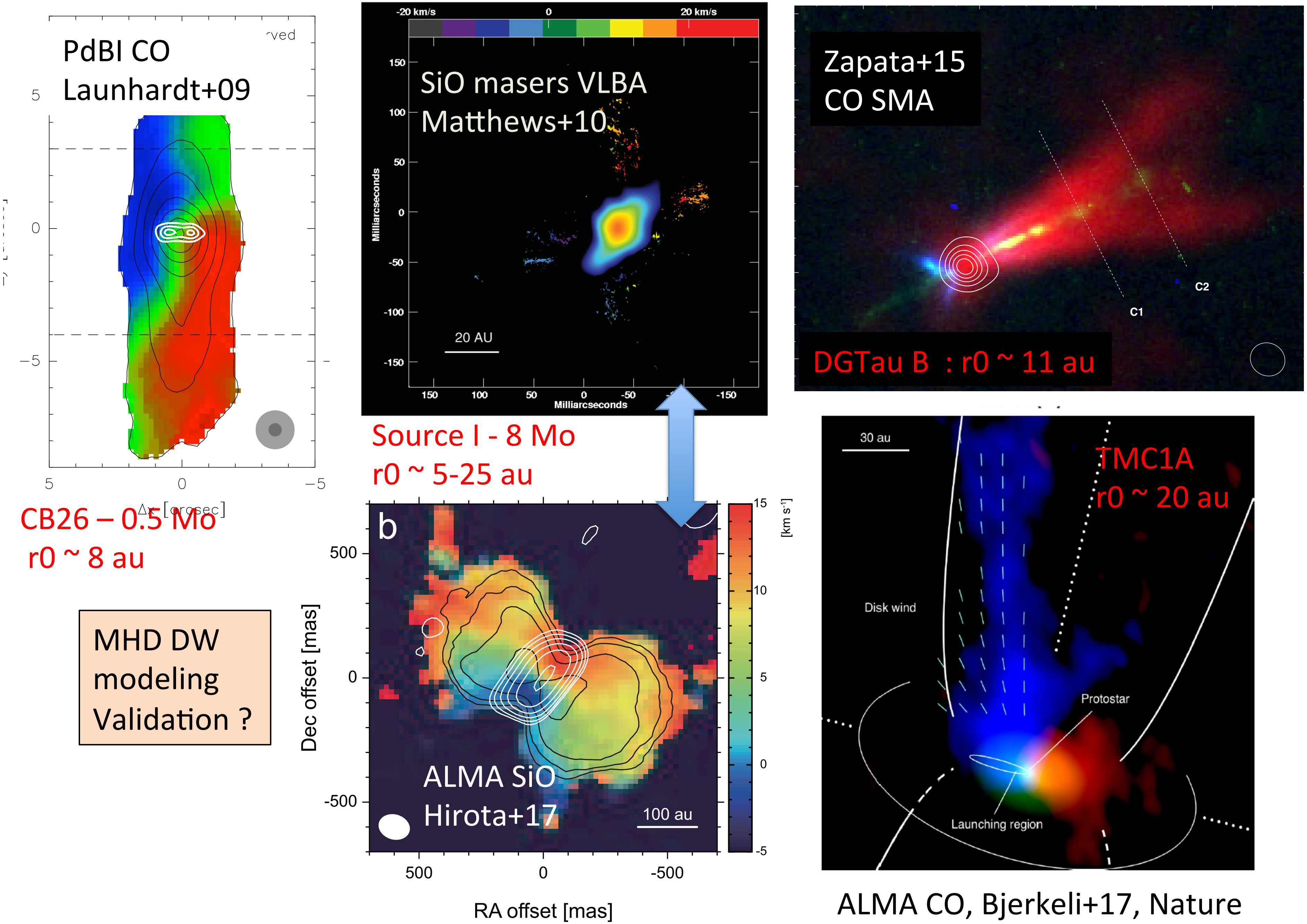
$$\Rightarrow r_0 \approx 0.7\ \mathrm{AU} \left(\frac{\varpi_\infty}{10\ \mathrm{AU}}\right)^{2/3} \left(\frac{v_{\phi,\infty}}{10\ \mathrm{km\ s^{-1}}}\right)^{2/3} \times \left(\frac{v_{p,\infty}}{100\ \mathrm{km\ s^{-1}}}\right)^{-4/3} \left(\frac{M_*}{1\ M_\odot}\right)^{1/3},$$



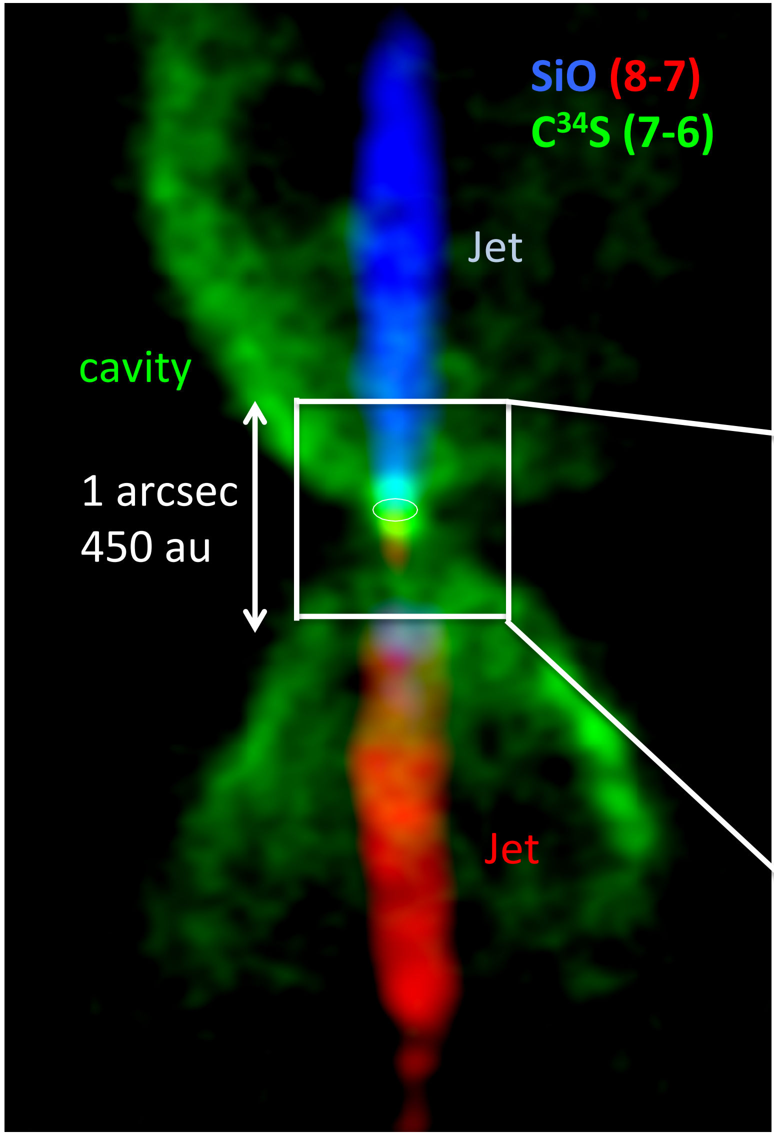
HST/STIS
DG Tau
(***Bacciotti+2002***)

- DG Tau model MHD DW with rout ~ 3 au, $\lambda = (r_A/r_0)^2 = 13$ (*Pesenti+04*) *BUT:*
- beam-diluted Vshift when Rjet < HST beam (Pesenti+2004)
- counter-rotating jet / disk in RW Aur (Cabrit+2006) and Th28 (Louvet+2016)

  ➔ **go to radio wavelengths to increase velocity resolution !**


PdBI CO
Launhardt+09
5
0
−5
5
0
−5
CB26 – 0.5 Mo
r0 ~ 8 au
MHD DW
modeling
Validation ?
-20 km/s
0
20 km/s
SiO masers VLBA
Matthews+10
150
100
50
0
-50
-100
-150
Milliarcseconds
20 AU
Source I - 8 Mo
r0 ~ 5-25 au
b
500
0
-500
Dec offset [mas]
RA offset [mas]
ALMA SiO
Hirota+17
100 au
15
10
5
0
-5
[km s-1]
Zapata+15
CO SMA
C1
C2
DGTau B : r0 ~ 11 au
30 au
TMC1A
r0 ~ 20 au
Disk wind
Protostar
Launching region
ALMA CO, Bjerkeli+17, Nature

HH212 as a test case for MHD-DW models

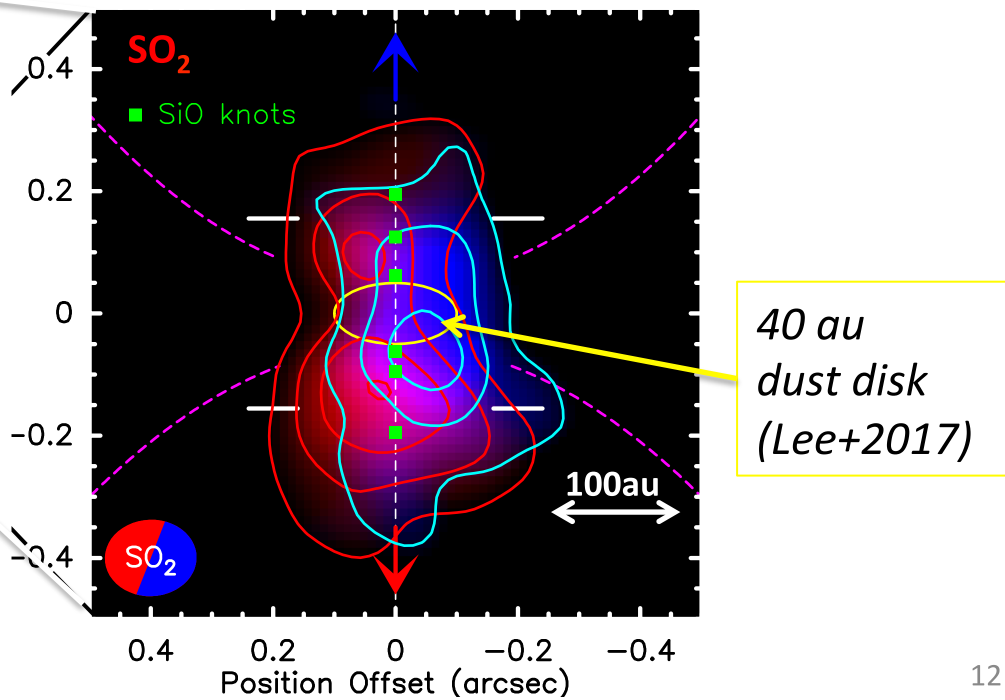


ALMA @0.15'' = 70 au in SO_2 / SO

(Tabone+2017, A&A Letters)

→ Rotating slow outflow from disk, surrounding fast SiO jet

→ Onion-like velocity structure



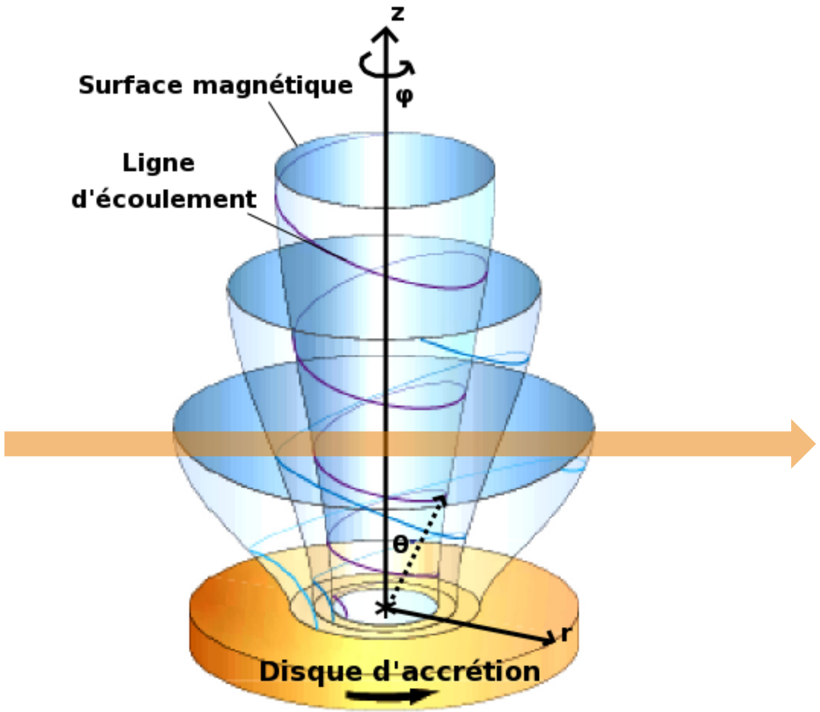
HH212 as a test case for MHD-DW models
Part 1: SO_2 @ 70 au (0.15'')

Synthetic data cubes for self-similar MHD D-winds (Casse & Ferreira 2000b)

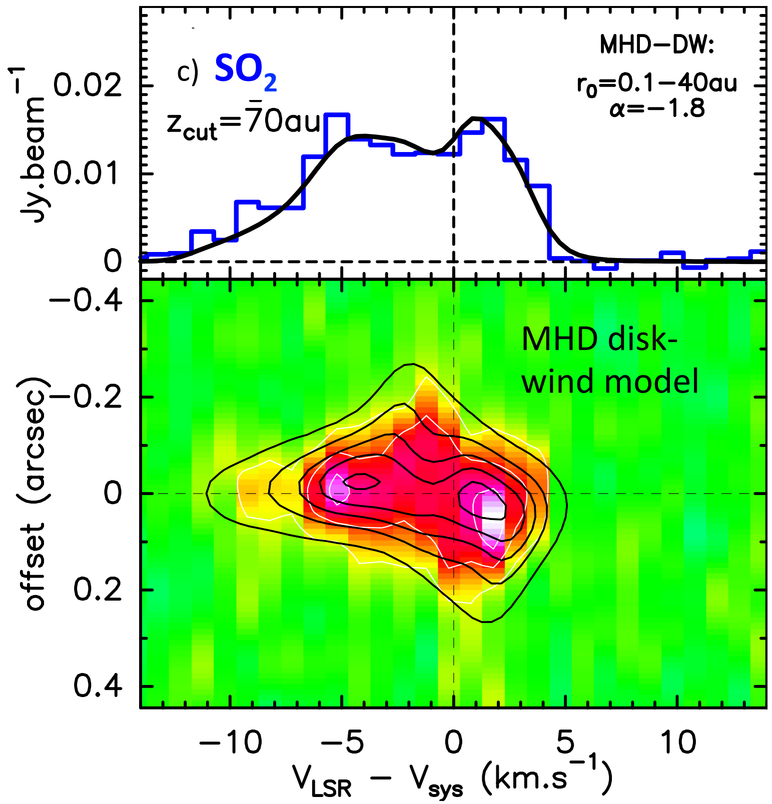
- $M_\star$ = 0.2 $M_\odot$ (Lee et al. 2017), i = 87° (Claussen et al. 1998)

→ Good fit for λ = 5.5 (Tabone+2017)

→ Rout = 40 au >> Anderson's formula : observational bias in Jobs (Tabone+2018,

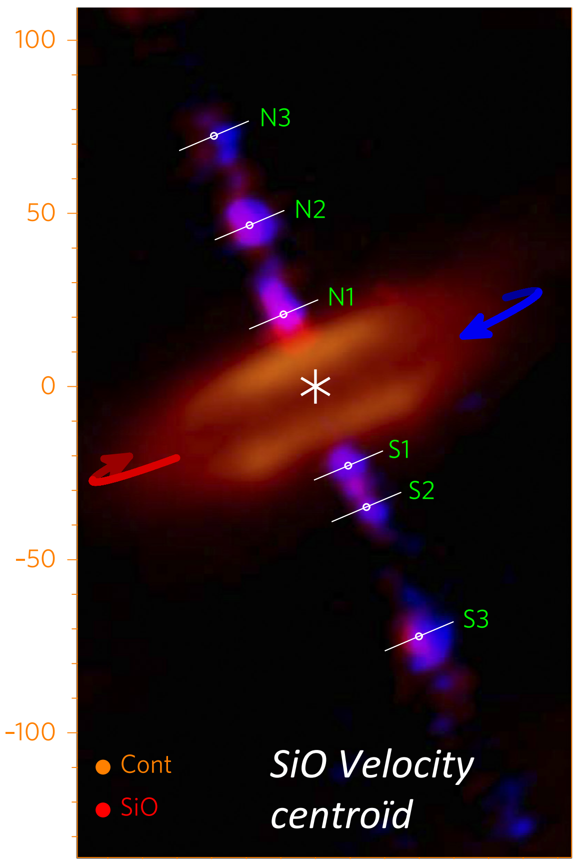


Ferreira 1997



SiOHH212 as a test case for MHD-DW models
Part 2: SiO @ 8au (0.02'')

Lee et al. 2017, Nature astronomy



Tabone et al. 2017 A&A Letters

same MHD DW solution as for SO / SO_2 :

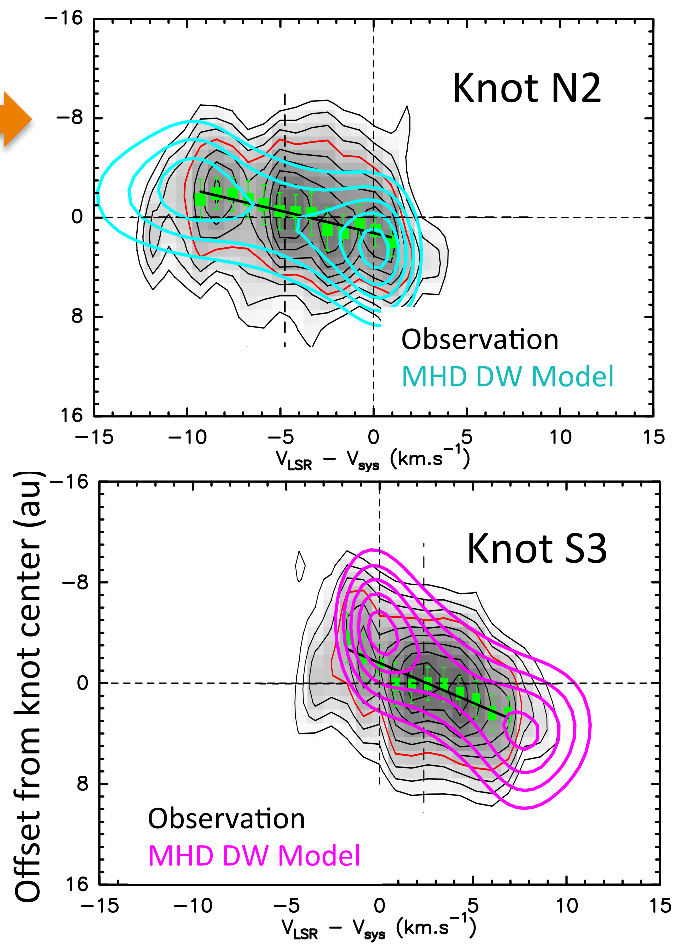
➔ r_0=0.05-0.2 au (N2)

➔ r_0=0.1-0.3 au (S3)

>> Lee+2017 (0.05au)

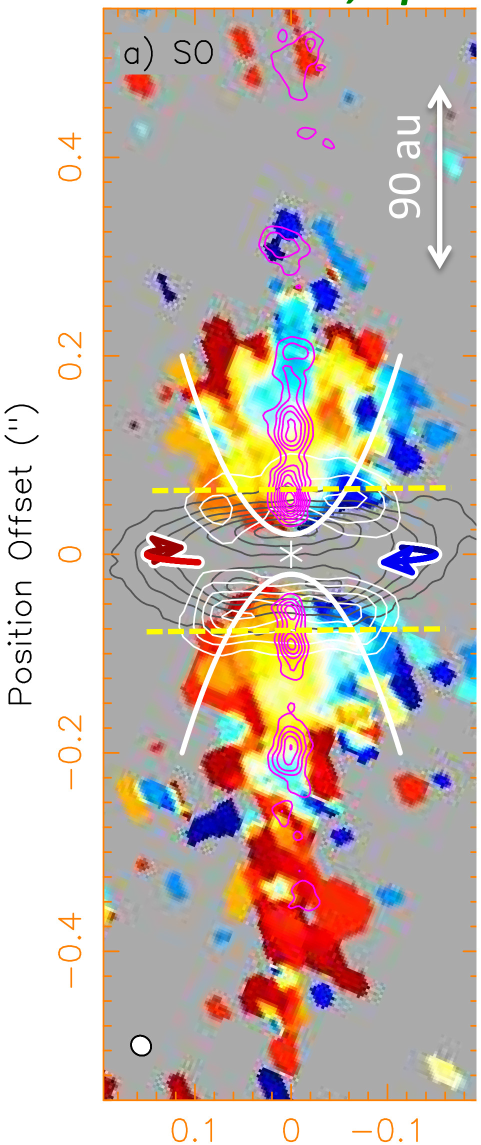
➔ SiO jets would trace only dust-free streamlines (Rsub ~ 0.2 au):

➔ Chemical tomography



SiOHH212 as a test case for MHD-DW models
Part 3: SO@20 au (0.04'')

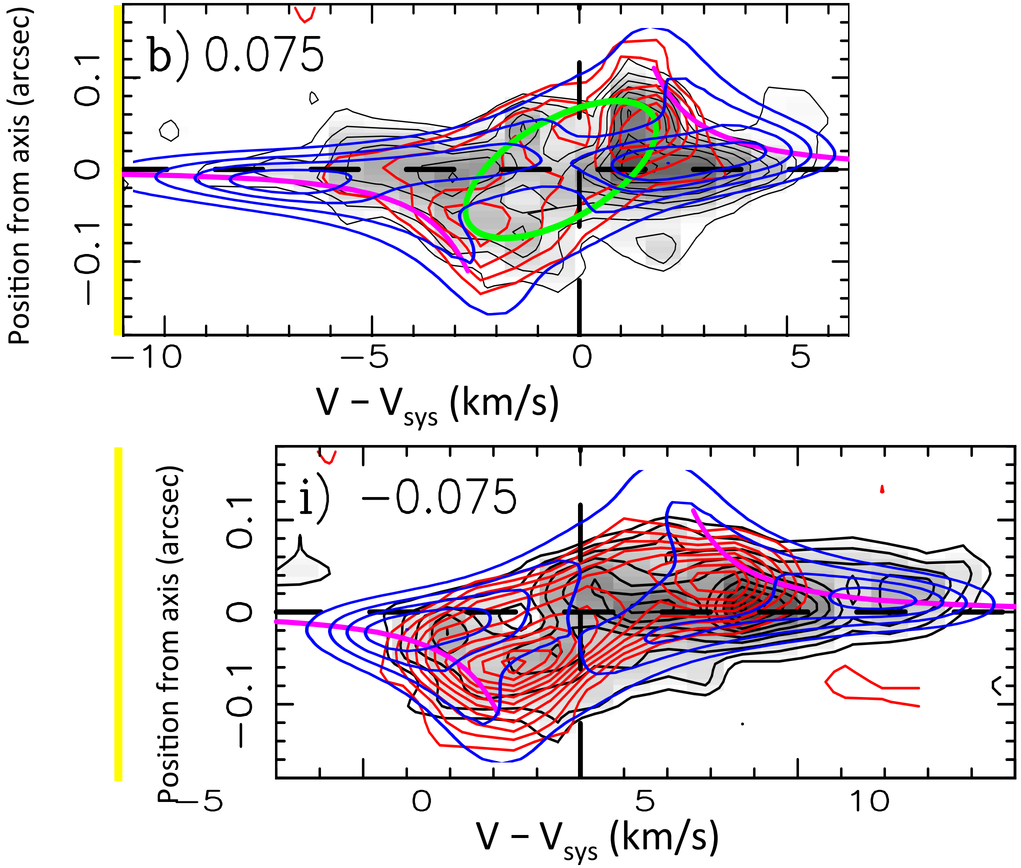
Lee+2018, ApJ



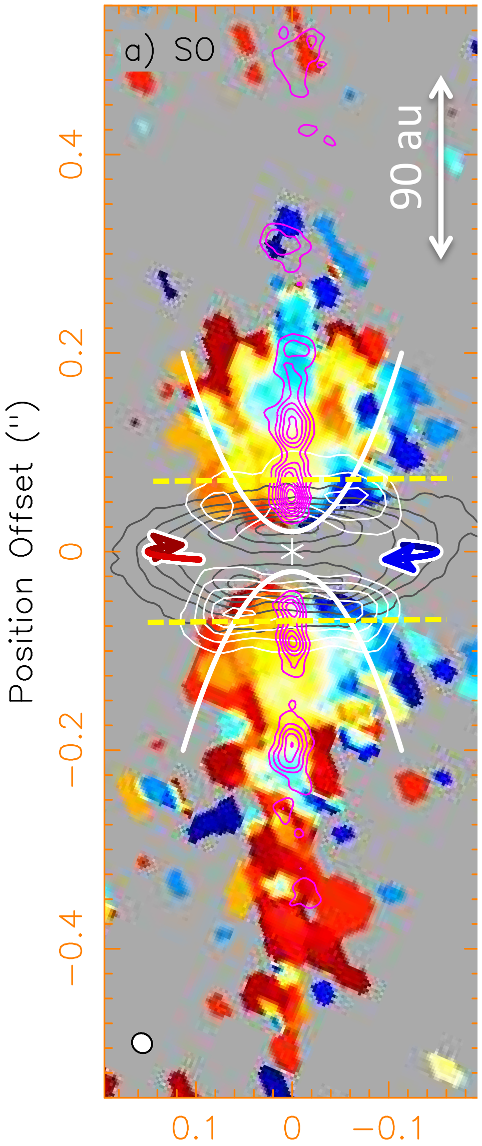
→ confirm SO/SO_2 rotating outflow from disk

→ DW model of Tabone et al. 2017

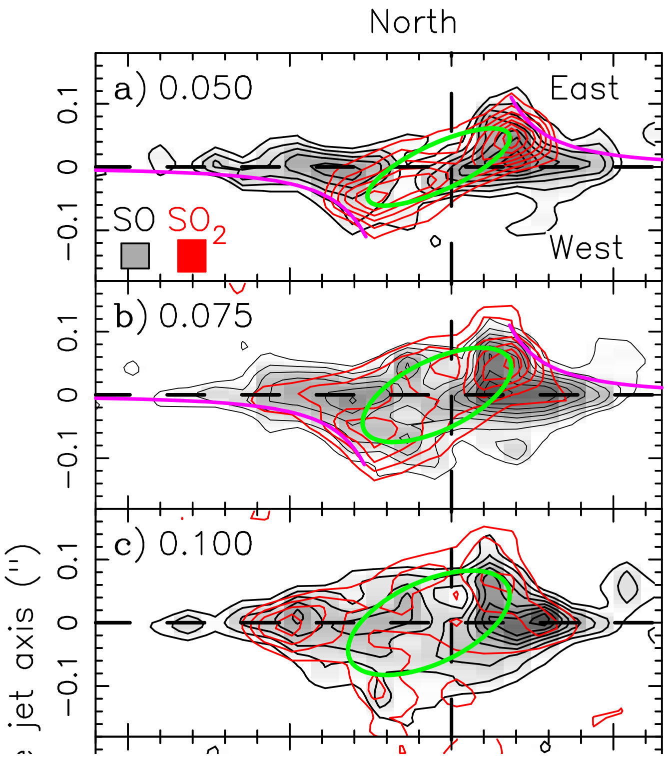
still works at z = +/- 30 au:

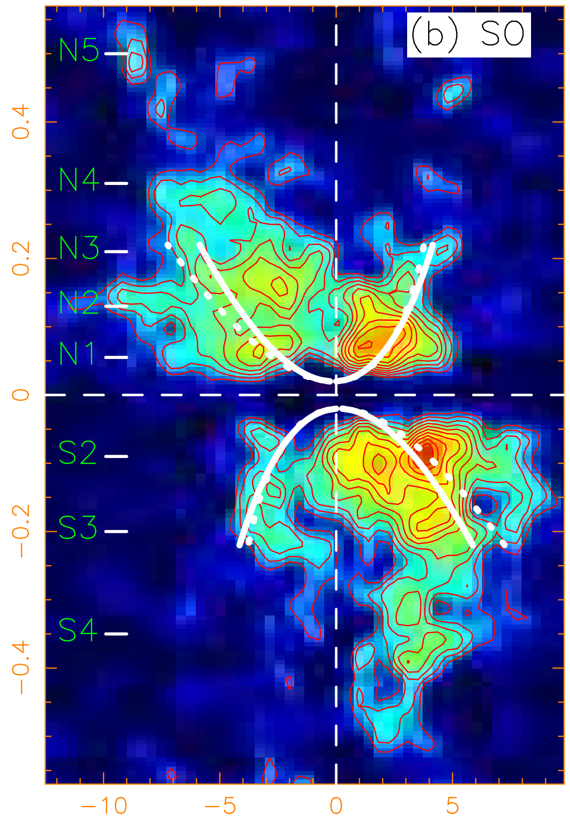


Alternative interpretation



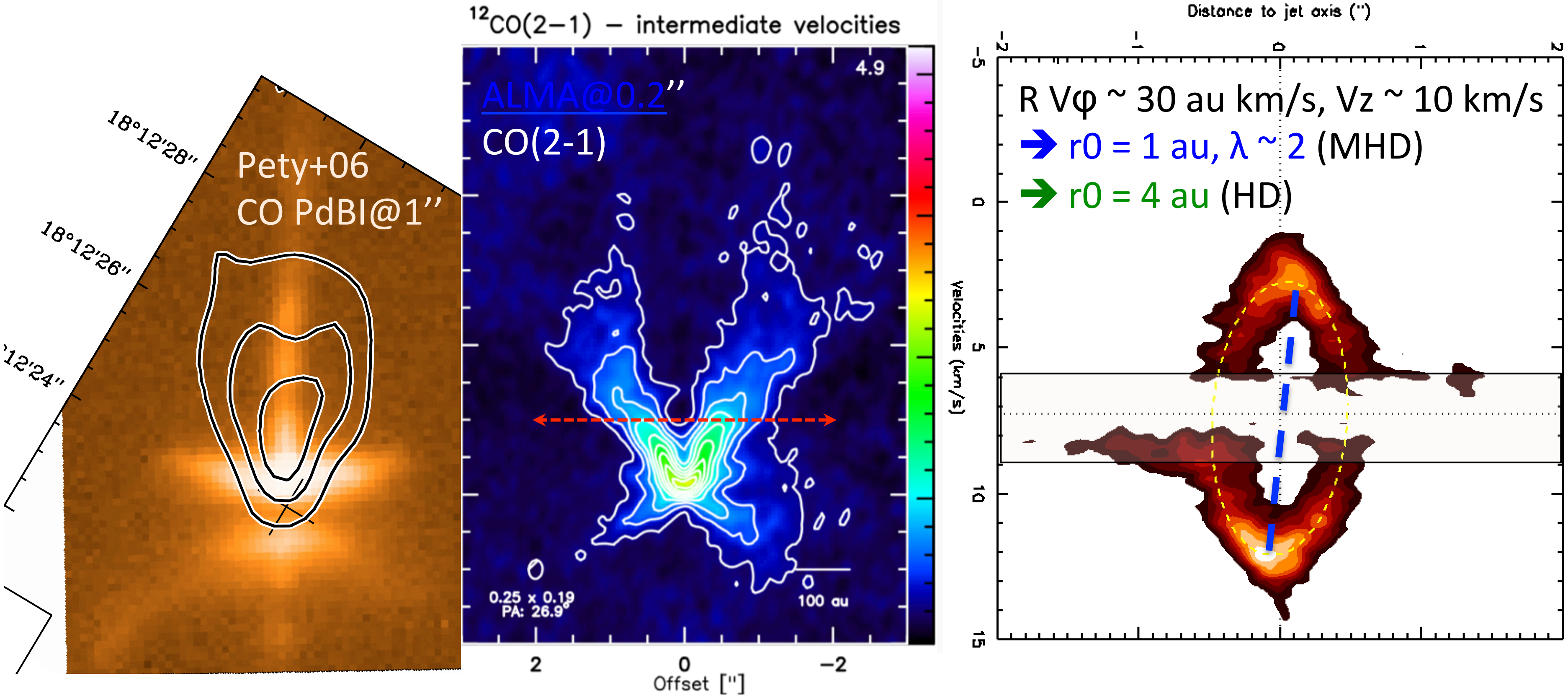
➔ **Lee+2018** Propose thin rotating shell driven by (invisible) wide-angle wind





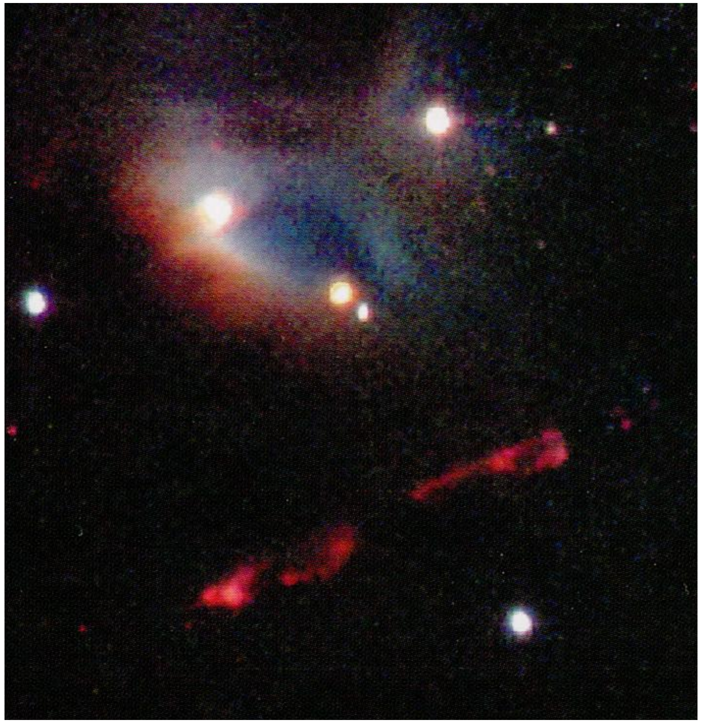
Not as clear in southern lobe…

Rotating CO cavity in HH30 – Class 2 (Louvet et al. 2018)

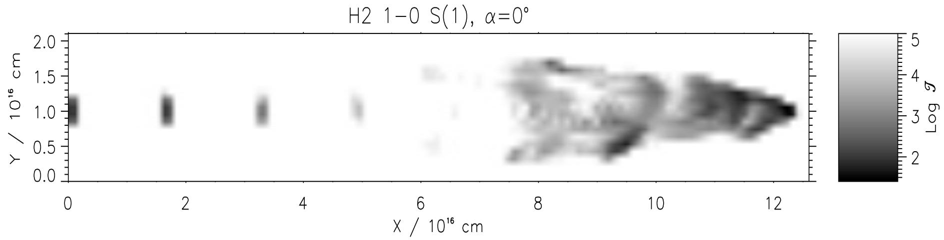


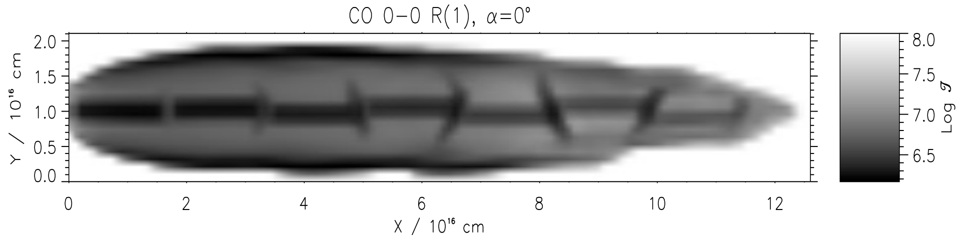
Very massive ! If steady-state flow along cone: Mdot(CO) ~ 10^{-7} $M_{\odot}$/yr
~ 50 x Mdot (atomic jet) > Macc(rin) ➔ **disk dissipation** ?

Insight from HH211



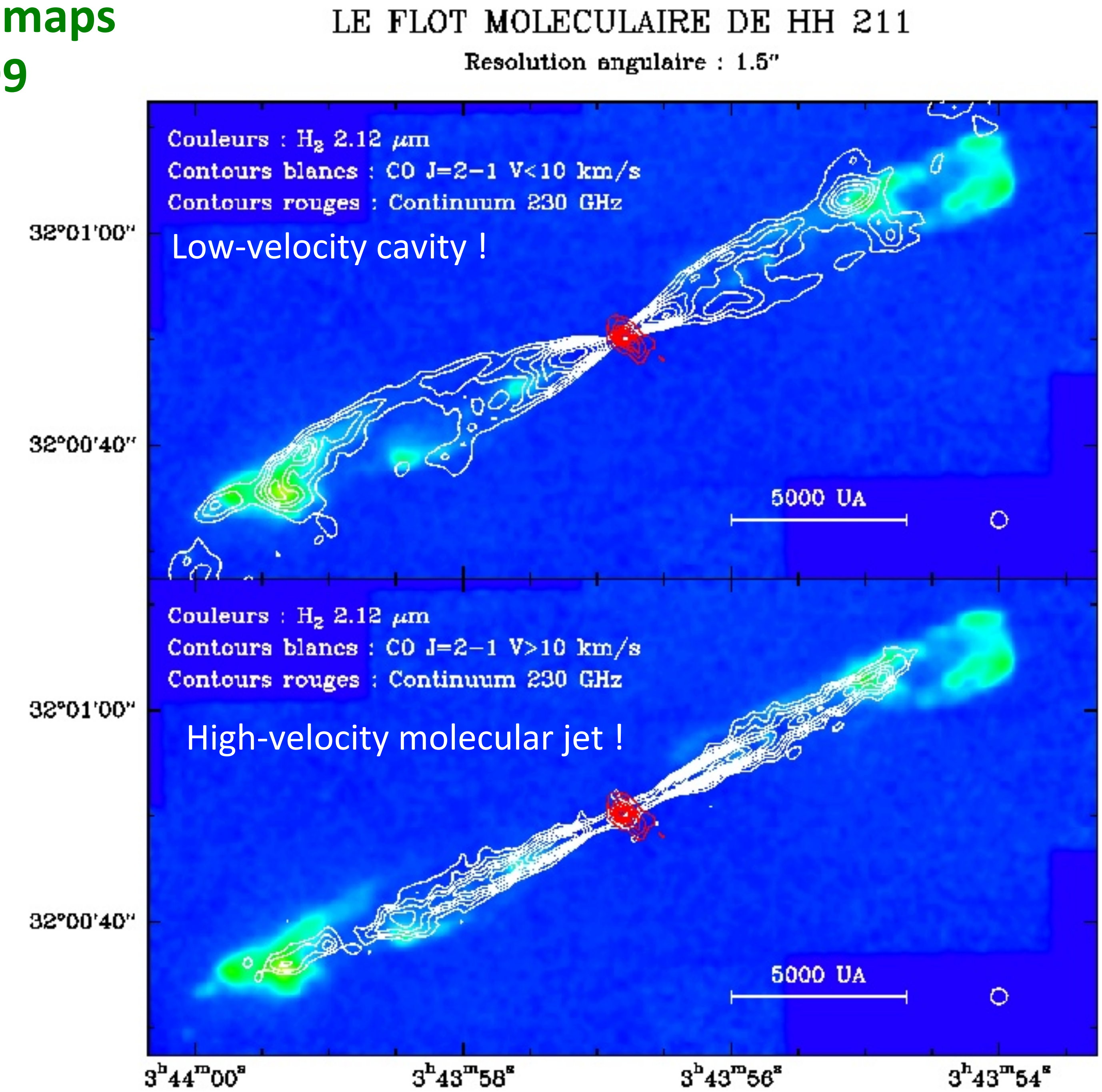
Suttner, Smith, Yorke, Zinnecker 1997 (A&A)
First 3D jet simulations, including H_2 chemistry, with initially molecular jet





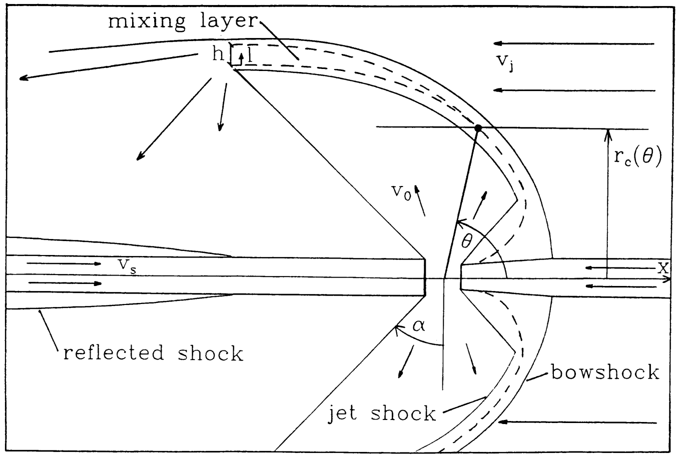
McCaughrean, Rayner, Zinnecker 1994
« First system of jet, molecular outflow,
and embedded source discovered by nIR imaging »

PdBI CO maps
Gueth+99

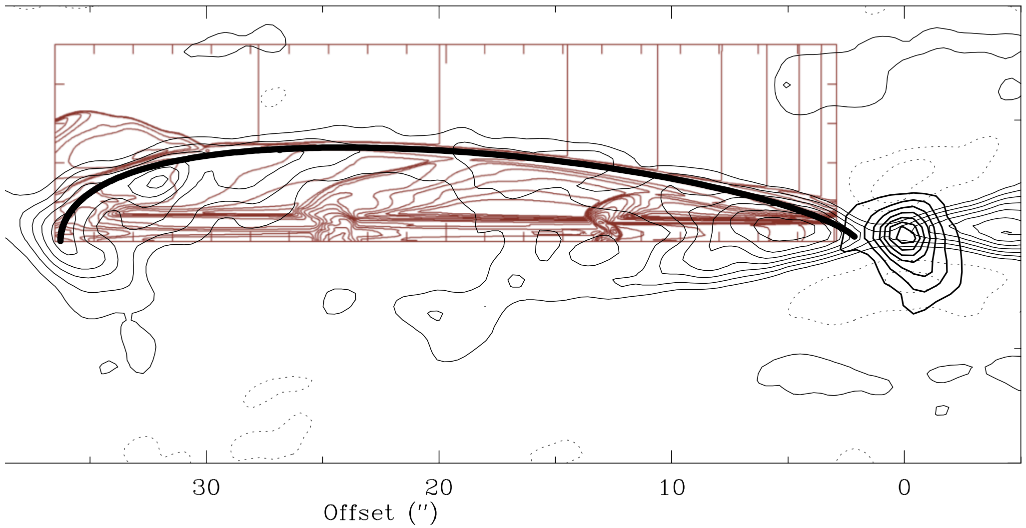


HH211: archetype of jet-driven outflow

Raga & Cabrit 1993



Simulation from Cabrit, Raga, Gueth 97



Gueth+99 could fit cavity by Raga & Cabrit93 model
with n_amb ~ r^{-2} and

$$\dot{m} \sim 3\,10^{-6}\ M_\odot/\text{year}\left(\frac{R_0}{380\,\text{AU}}\right)^2\left(\frac{n_{H_2}}{10^4\,\text{cm}^{-3}}\right)\times\left(\frac{V_S}{80\,\text{km}\,\text{s}^{-1}}\right)^2\left(\frac{V_0}{50\,\text{km}\,\text{s}^{-1}}\right)^{-1}$$

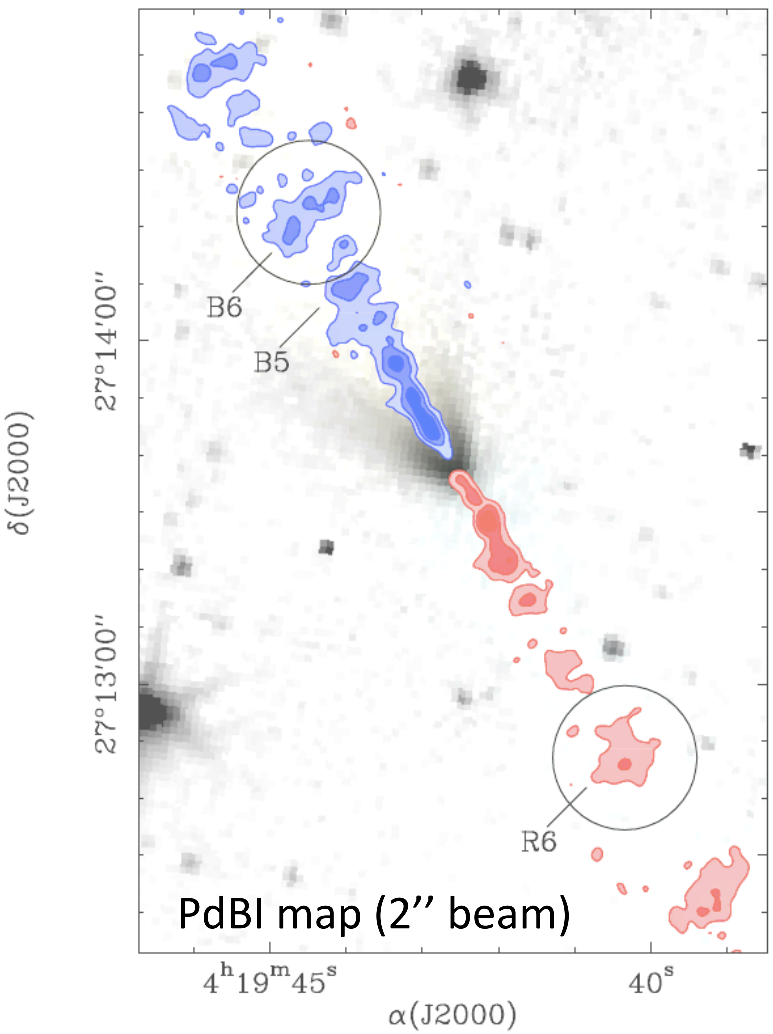
consistent with

Mjet (CO) ~ 2.5 10^{-3} Mo

T_{dyn} (jet) ~ 750 yr (V_s / 80 km/s)$^{-1}$

PdBI observations of IRAS 04166

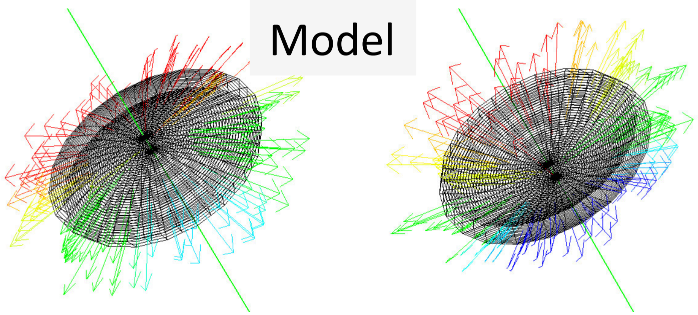
Santiago-Garcia, Tafalla, Johnstone, Bachiller 2009 (A&A)



Slide courtesy of M. Tafalla

ALMA observations of IRAS 04166

Tafalla, Su, Shang, Johnstone, Zhang, Santiago-García, Lee, Hirano, & Wang (2017, A&A, 597, A119)

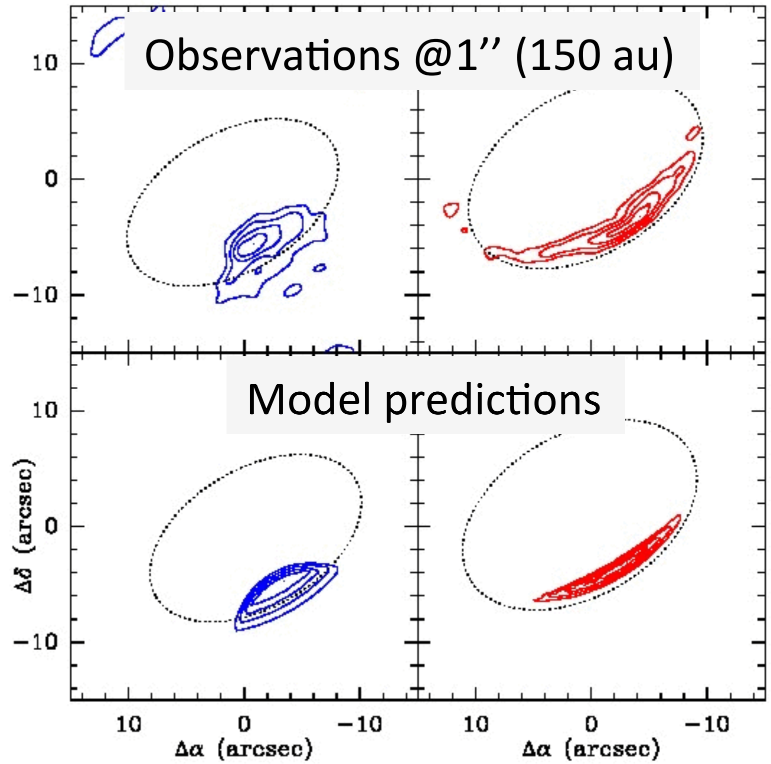


Parabolic shell model:

- Sideways expansion along shell from 0 to 13 km/s

- gas ejected laterally: jet shock, not wind-shock !

- Ejected sideways momentum + knot frequency (150 yr) sufficient to push aside cavity mass over outflow age



Slide courtesy of M. Tafalla

ALMA observations of L1448

Tafalla et al., in prep.

- Cycle 3 CO(2-1), SiO(5-4). Resol. ~ 0”.3 (~75 au)

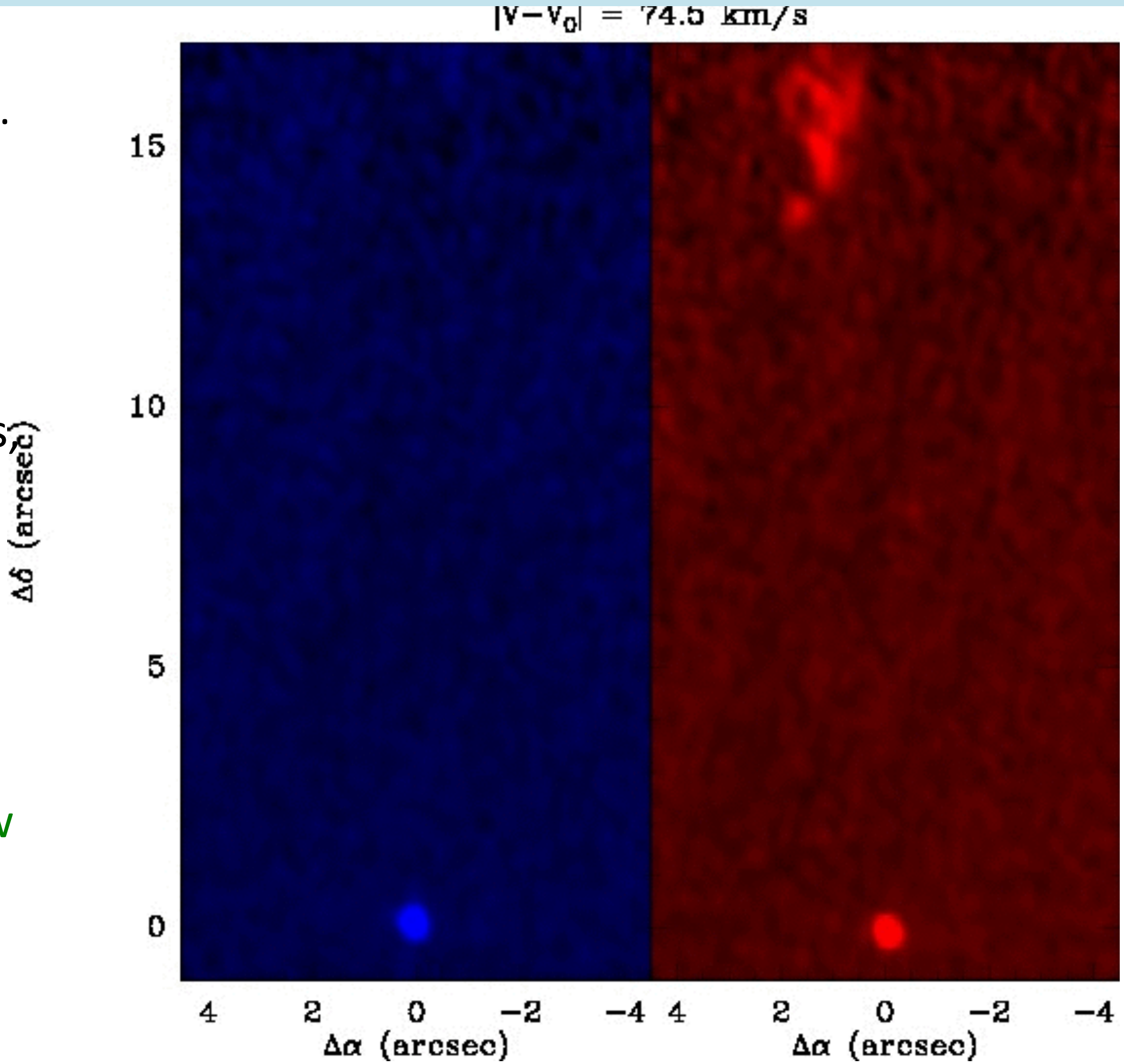
+ IRAM 30m zero spacing

- Modeling in progress
  - Preliminary results!

– Nested conical cavities ➔ outflow driven by Multiple Bowshocks

  (cf. Hammer jet of Volker+99)

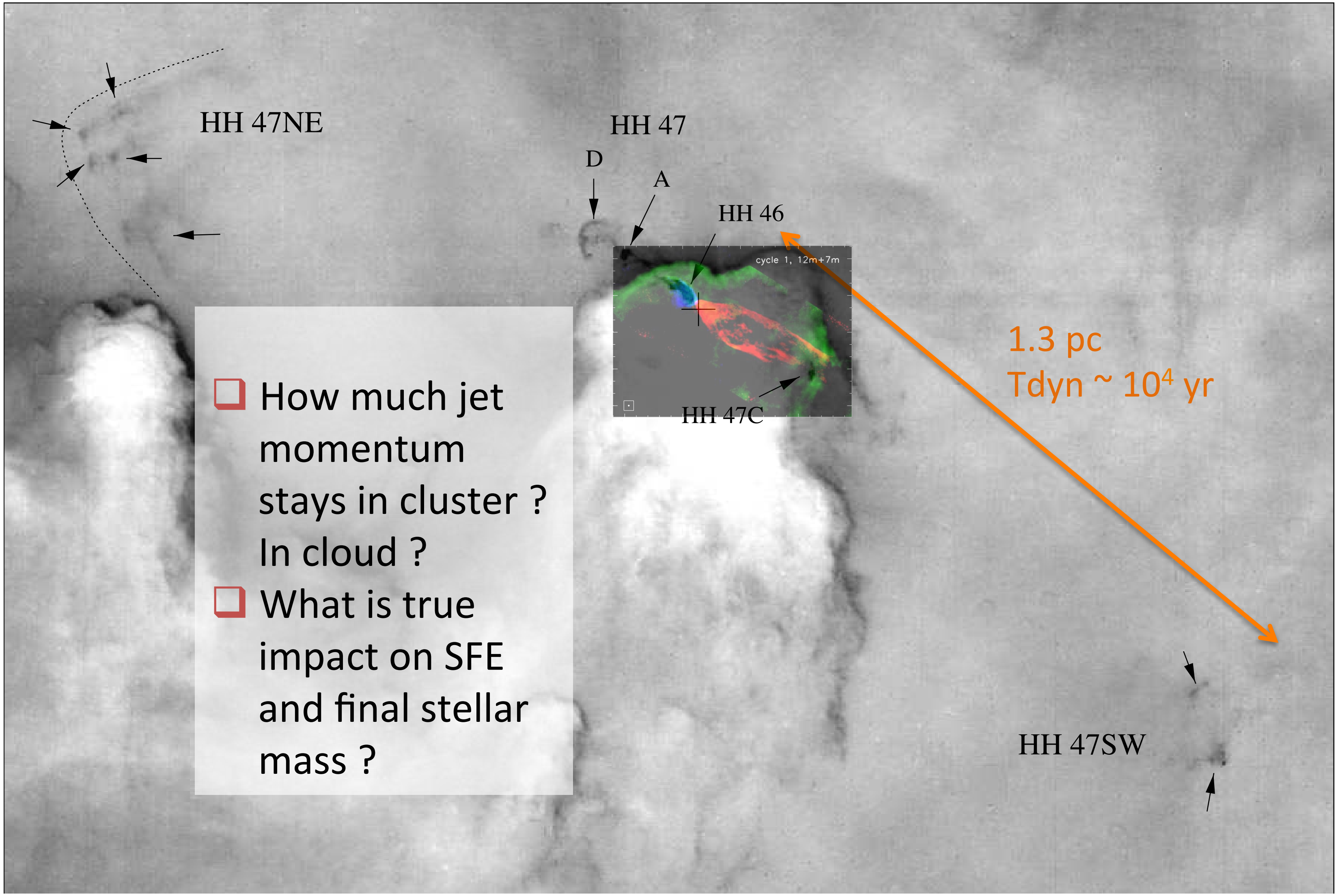
- update P(θ) in simulations of outflow feedback
- Biases in flow age (Downes & Cabrit 07)



Slide courtesy of M. Tafalla

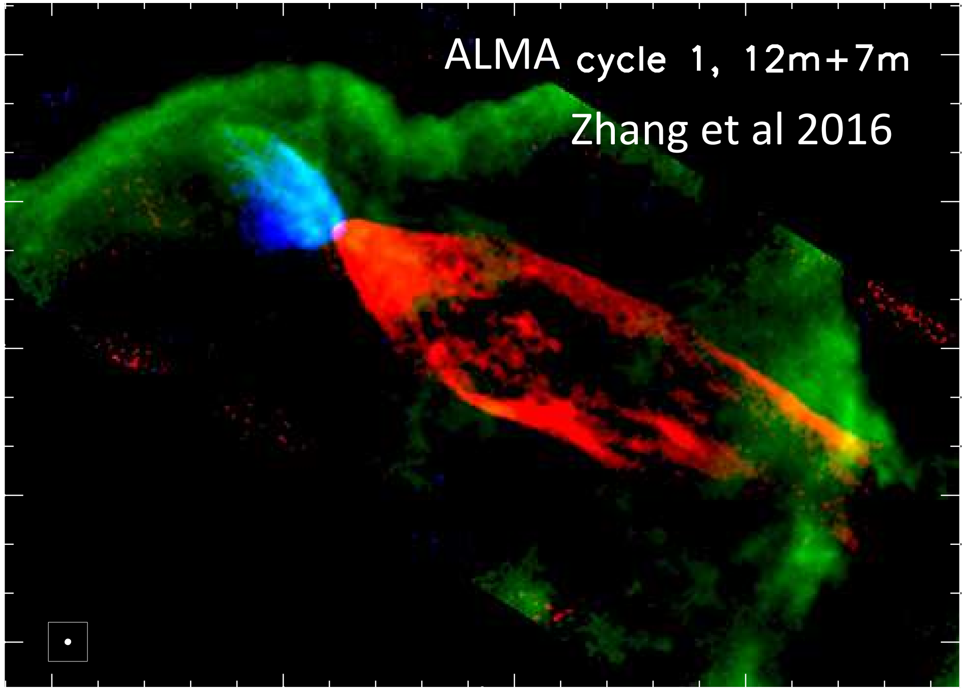
HH46-47: also a pc scale flow

Stanke, McCaughrean, Zinnecker 1999

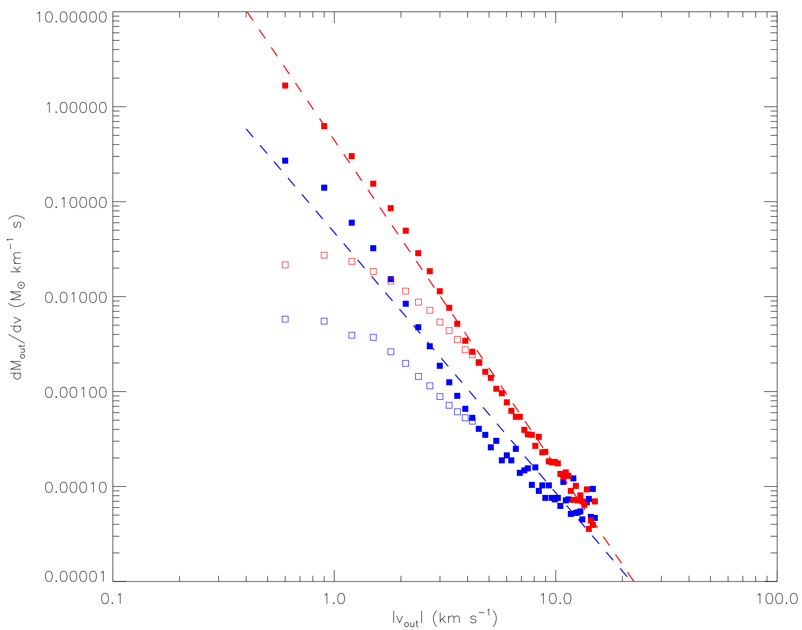


- How much jet momentum stays in cluster ? In cloud ?
- What is true impact on SFE and final stellar mass ?

Local outflow Feedback on IMF



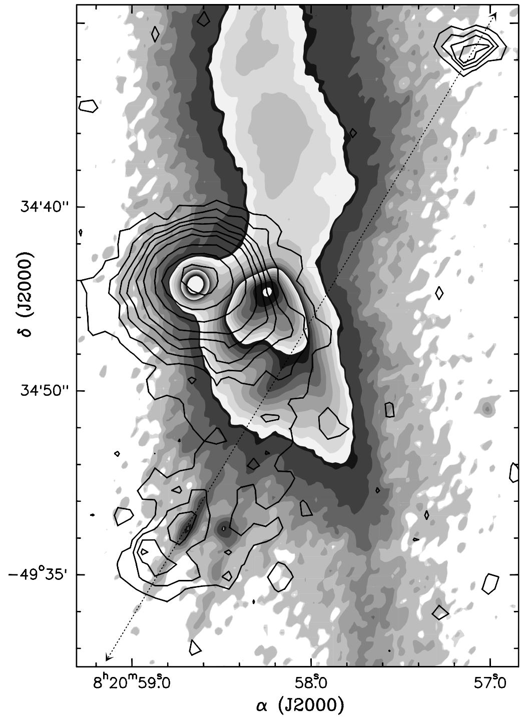
- Correcting for optical depth at low V using ^{12}CO, ^{13}CO and $C^{18}O$ increases Mflow by factor 14



Mass-loading rate within 15'':
Mdot(CO > Vesc) ~ 3 x Mdot(infall)
Outflow currently removes ¾ of infalling mass
➔ SFE ~25% locally

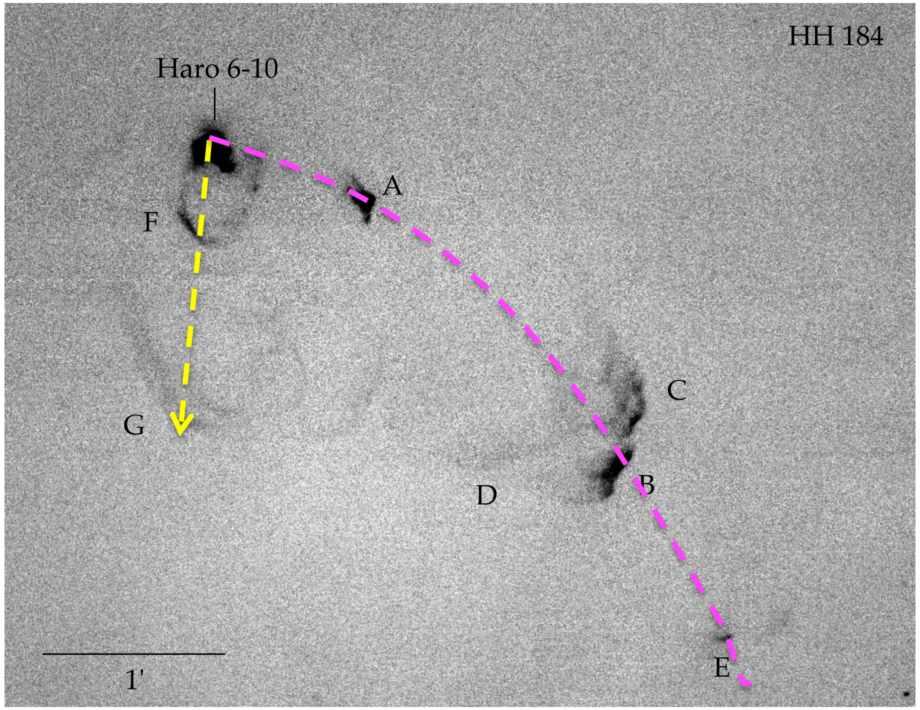
Twin jets with synchronous outbursts: first hints

Re 4 IRS



*K-band **Zinnecker+ 1999***

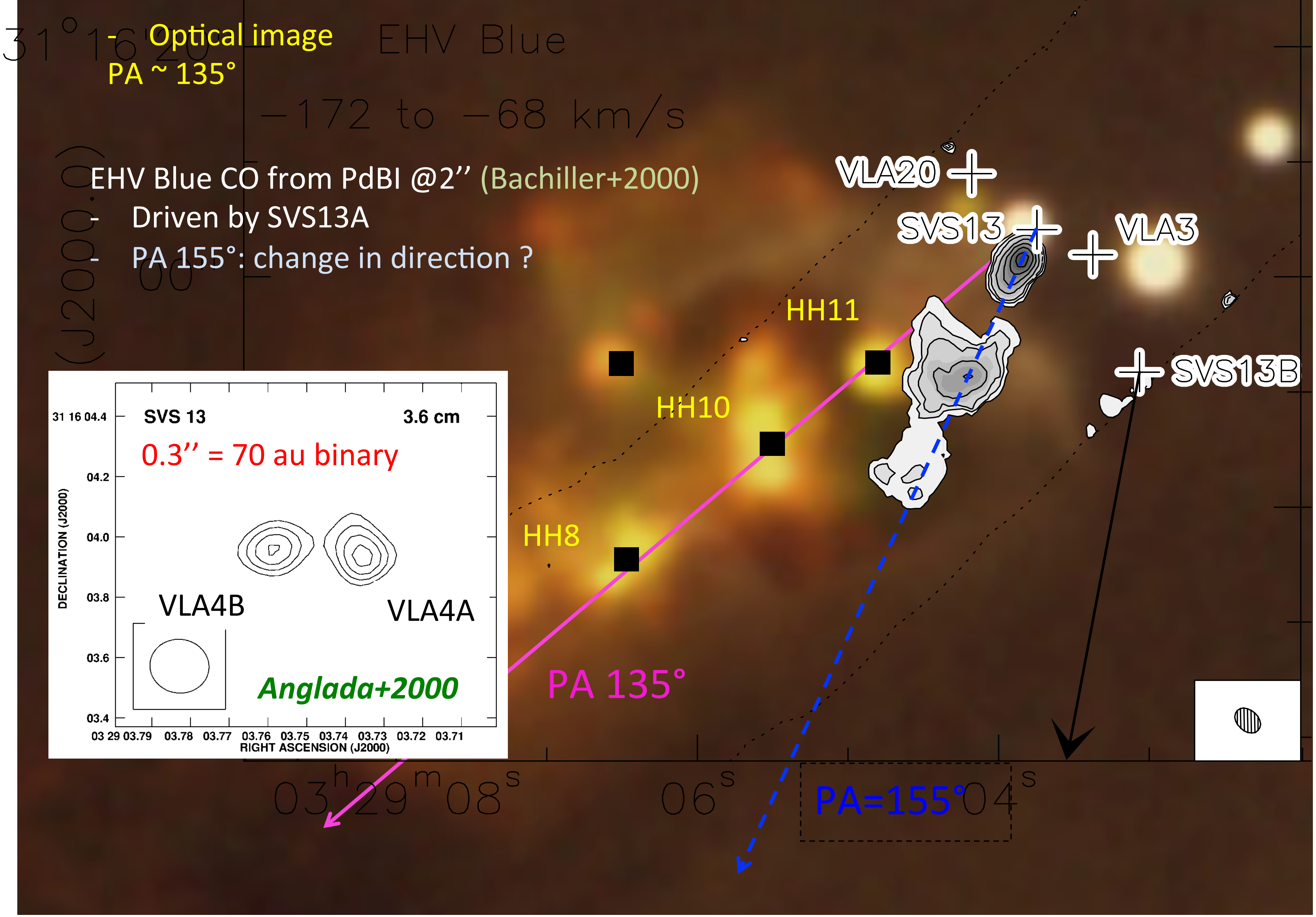
Haro 6-10 = 175 AU binary



F/G = A/B: synchronous outbursts ?

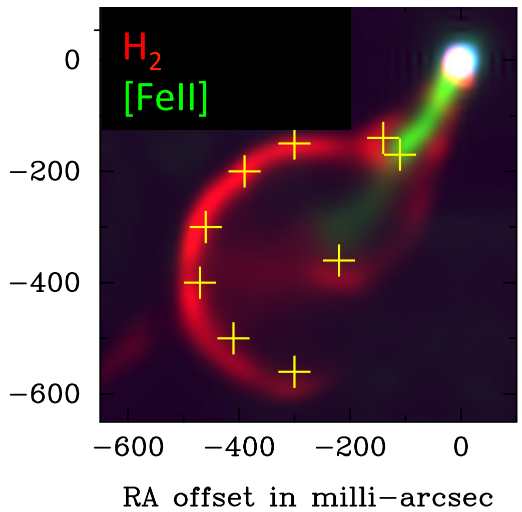
Devine, Reipurth, Bally, Balonek 1999

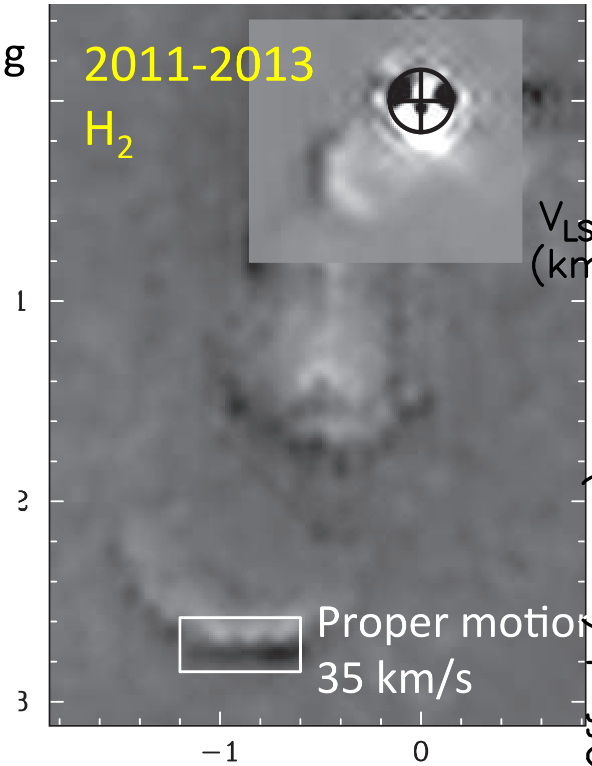
The case of HH7-11



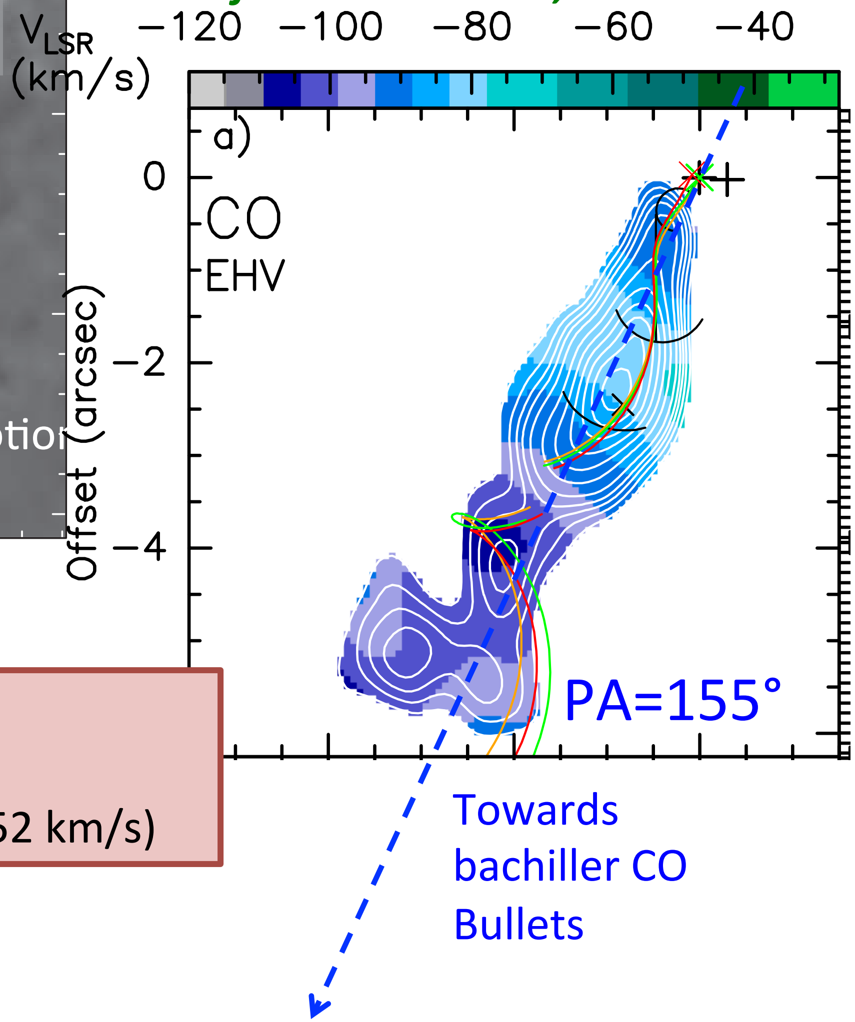
The molecular micro-jet of SVS13A

Near-IR spectro-imaging
Keck OSIRIS + LGS
20 – 100mas spaxels
Hodapp & Chini 2014





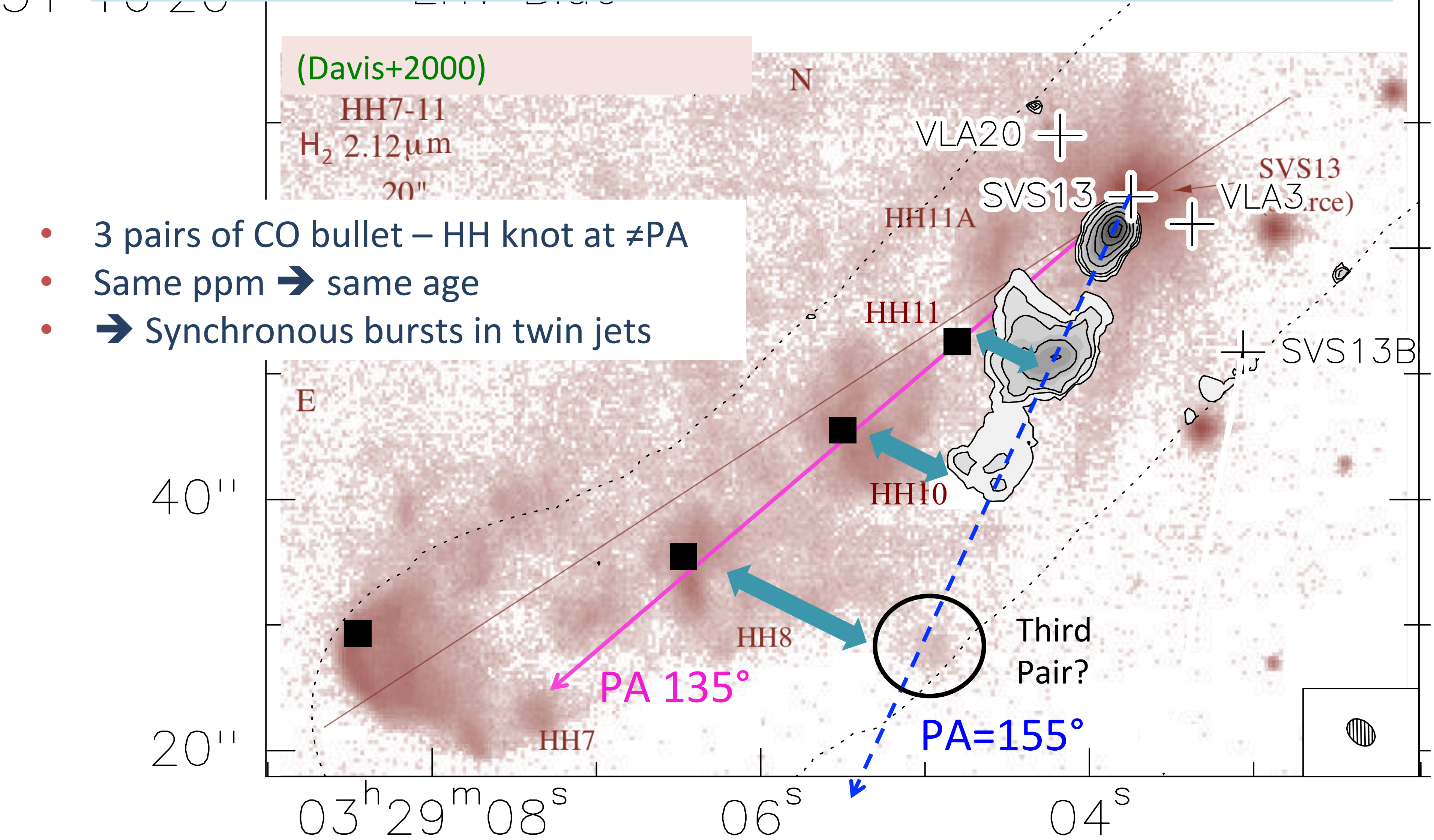
CALYPSO @ PdBI (0.5'' x 0.8'')
Counterpart in CO, SO, SiO
Lefèvre et al. 2017, A&A



Lefèvre: Vrad(CO) = Vrad(H_2) from Takami+06
➔ Closely associated tracers (shock fronts)
➔ **ppm (CO) ~ ppm (H2) ~ ppm(HH10-HH11)** (26-52 km/s)

Twin jets with synchronous bursts

- 3 pairs of CO bullet – HH knot at ≠PA
- Same ppm ➔ same age
- ➔ Synchronous bursts in twin jets



How can we have synchronous outbursts in twin jets ?

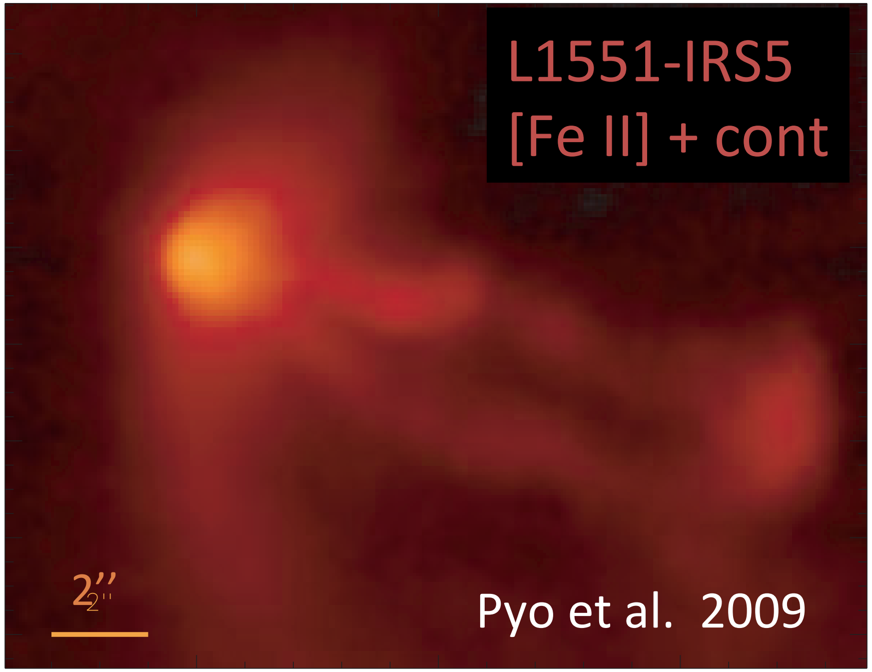
- requires **external** triggering
- Outburst period ~ 300 yr: consistent with VLA 4A-4B close encounters

$$a \simeq 45\,(M_{\rm tot}/M_{\odot})^{1/3}(P/300\ \ {\rm yr})^{2/3}\ {\rm au}$$

Current AB Sep = 70 au ➔ e ~ 0.5 periastron ~ 20au

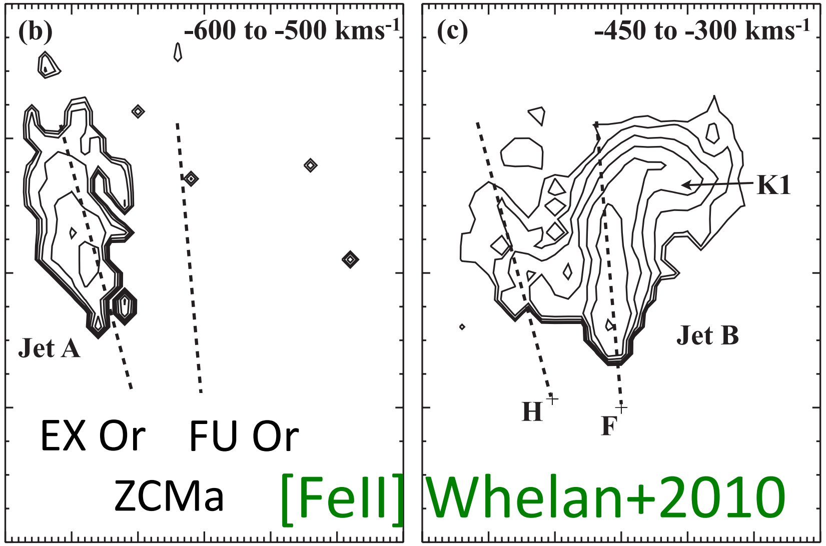
- twin accretion bursts from tidal disk perturbations at periastron? (see Bo Reipurth's talk)

Twin jets from other eruptive sources



- 50 au binary, FU Or -like

Quasi-coplanar disks and jets +
3rd source at 15 au (Lim+2006)



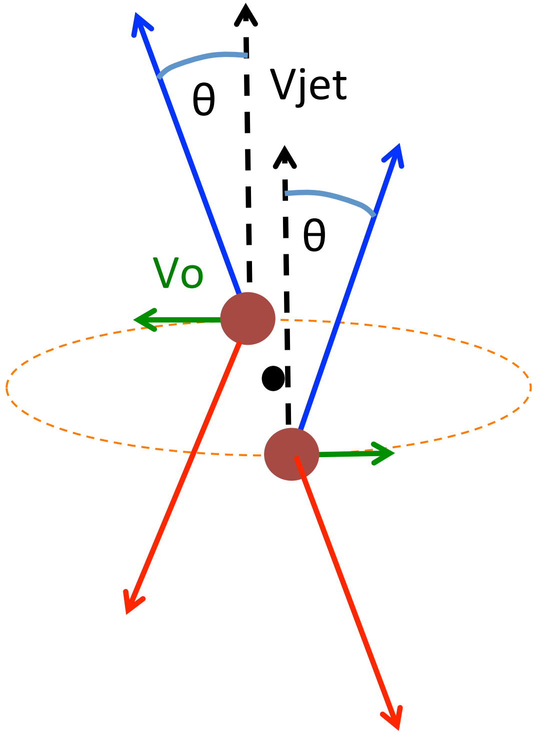
- 115 au binary : FU Or + EX Or
- Quasi-parallel jets
- Wiggling P ~ 4-40 yr ~ EX Or outburst
  ➔ 3rd source ?

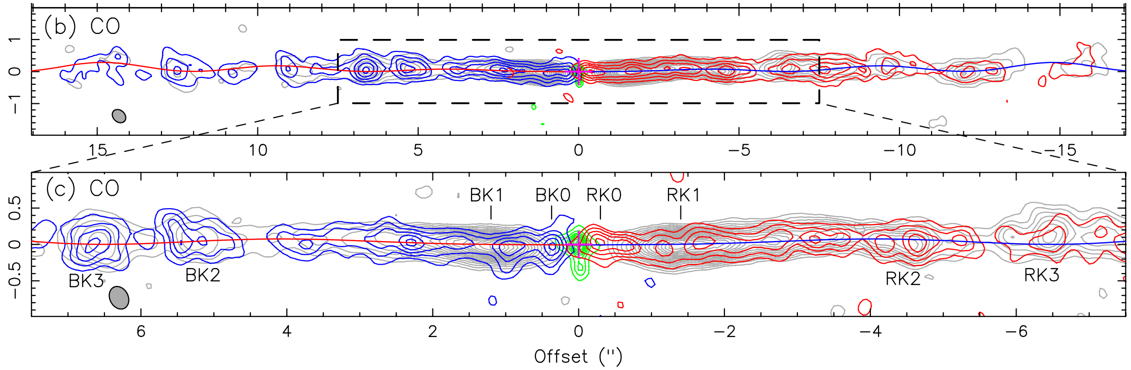
(see also Antoniucci+2016)

Jet bending by orbital motion (Fendt & Zinnecker 1998)

Masciadri & Raga 2002

- W-type symmetry
- $\tan\theta = V_o / V_{jet}$
- $\lambda = V_{jet} \times \text{Period}$
- ➔ $R_o = \lambda \tan\theta / 2\pi$





HH211 Lee et al. 2010, SMA map

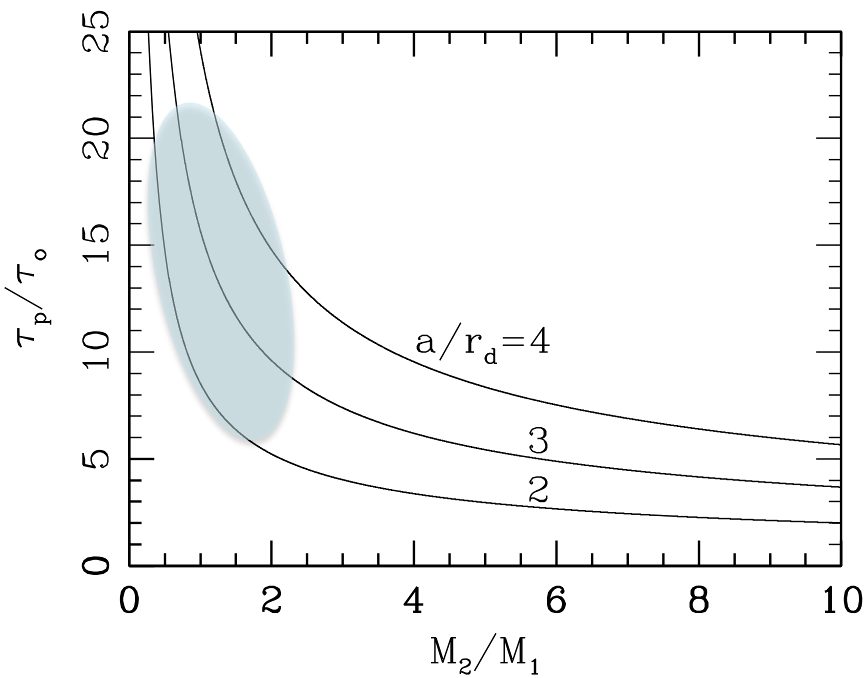
➔ R0 = 2.3 Au

- Vjet = 170 km/s ➔ Period 43 yr, Mtot ~ 60 Mjup !?

Precession period vs. orbital period

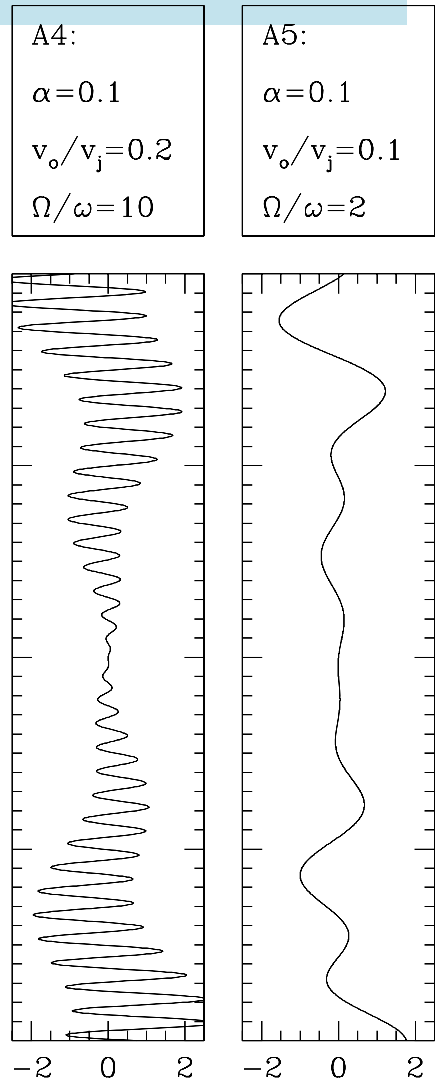
- solid (retrograde) precession driven by inclined companion (Terquem 1999)

$$\frac{\tau_p}{\tau_o} = \frac{\Omega}{\omega} = \frac{32}{15\cos\alpha}\left(\frac{a}{r_d}\right)^{3/2}\left(1+\frac{M_2}{M_1}\right)^{1/2}\left(\frac{M_1}{M_2}\right)$$

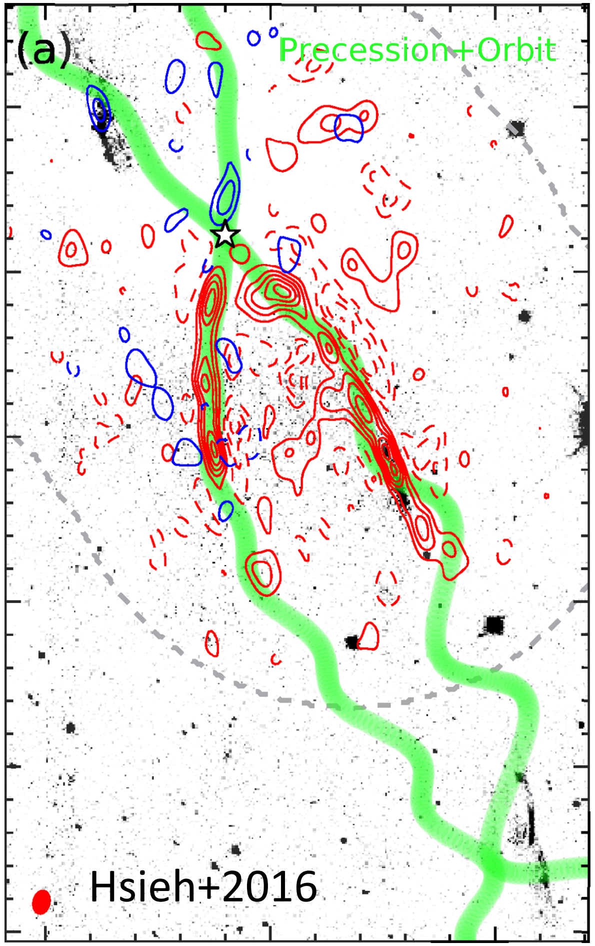


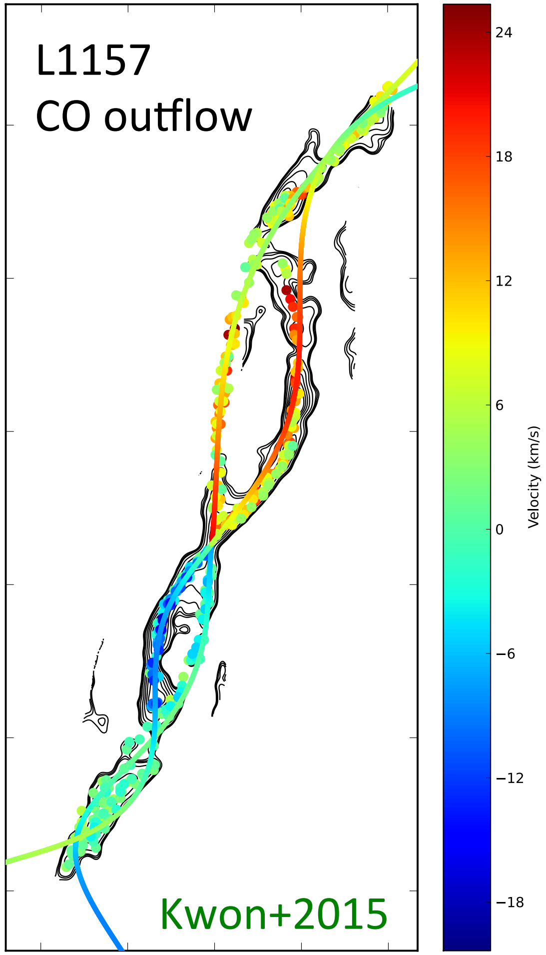
Raga+2009

Expect
Tau_p >> tau_orbit



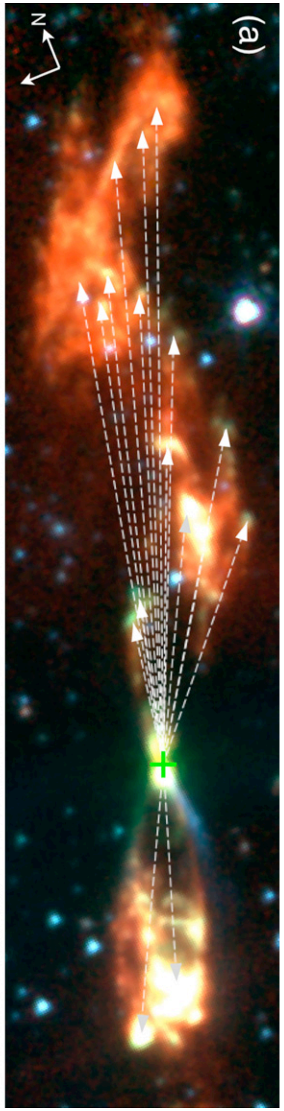
CO cavity walls are not twin precessing jets…

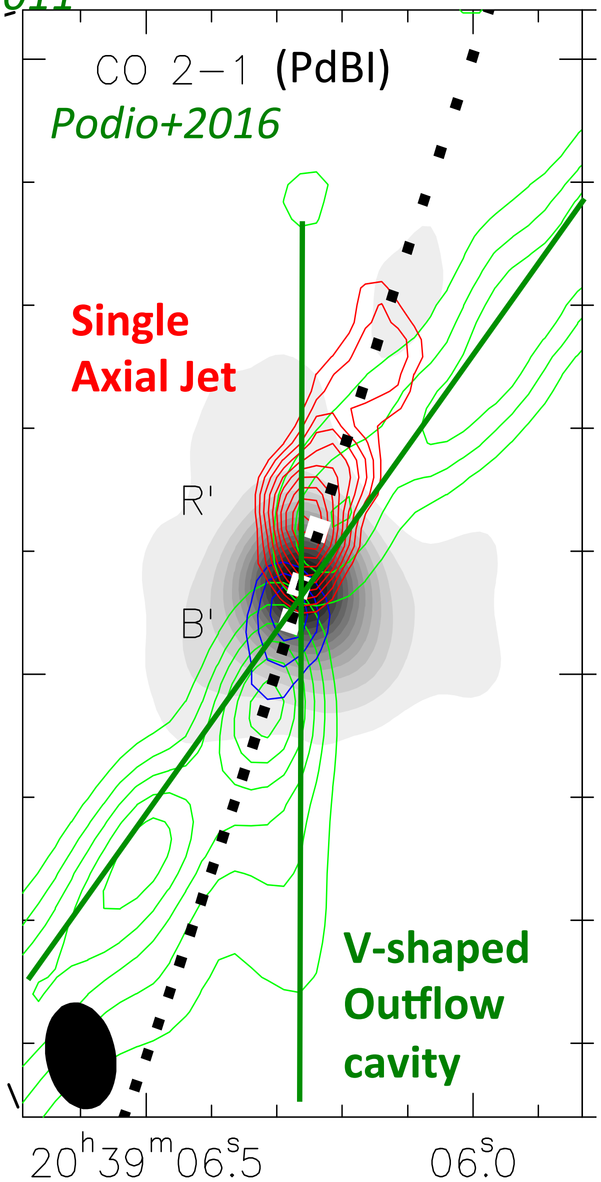


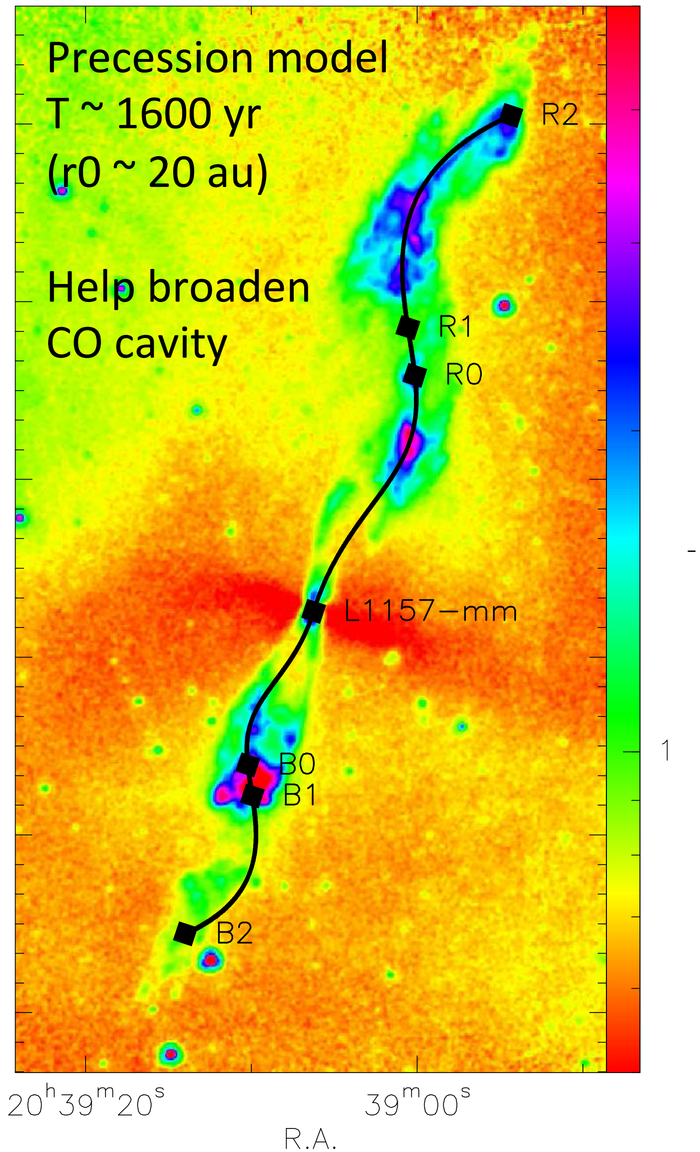


Jet precession in L1157 (S-shaped)

H2 Spitzer, *Takami+2011*







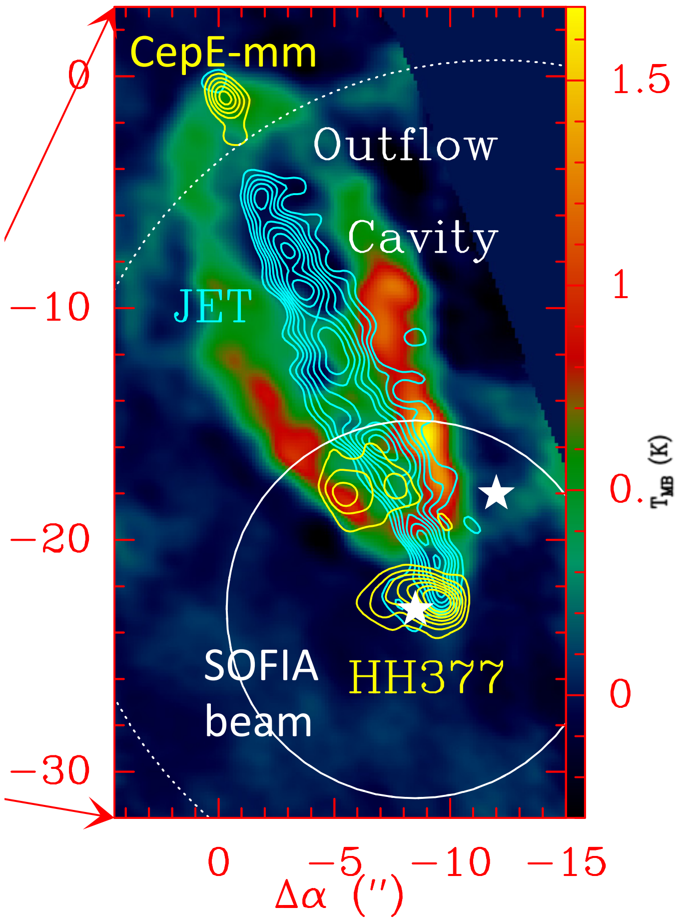
Summary (part 1)

- Striking jet universality in Mej/Macc, collimation
  - Process independent of stellar B and Ω
  - Collimation by disk B-field < 5 au
- ALMA reveals rotating slow disk winds at various stages and M★
  - Small lever arm: Magneto-rotational or Thermal ?
  - Role in disk accretion and dissipation ? Link to disk B-structure ?
  - NB: Launch radius often underestimated by Jobs
- CO outflow cavities bowshock-driven, not wind-driven
  - Broadening by internal jet shocks and jet wandering
  - Still an impact on final stellar mass (25% in HH46?)
  - May need to revise : estimates of flow age and driving power, outflow feedback prescription in simulations

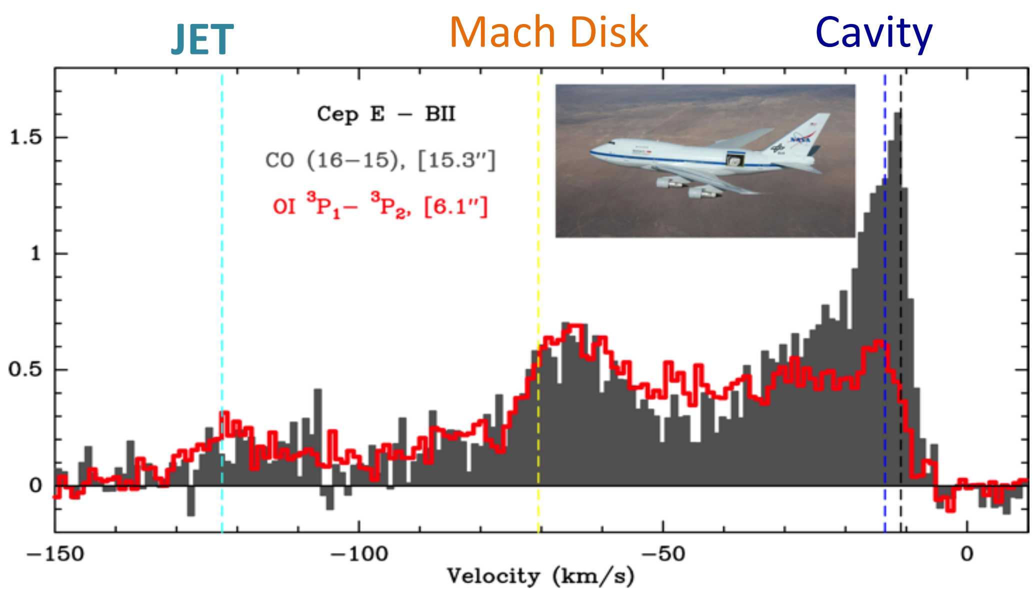
Summary (part 2)

- Synchronous outbursts in twin jets (SVS13A)
  - Favor external outburst triggered by tidal interactions
  - Implications… cf. Bo Reipurth's talk
- Jet bending offers key insight into
  - close binaries 20-300 au
  - disk precession : tidal warps ? MHD warps ? Asymmetric infall ?
- Jet / outflow chemistry
  - Strong test for MHD DW models (eg. Yvart+2016)
  - Fast jet initially atomic and dust-free (Herschel and SOFIA): molecule formation despite UV field ?
  - First Hydrostatic Core outflow tracers

SOFIA: CepE outflow



CO(2-1) map - PdBI
Lefloch+2015

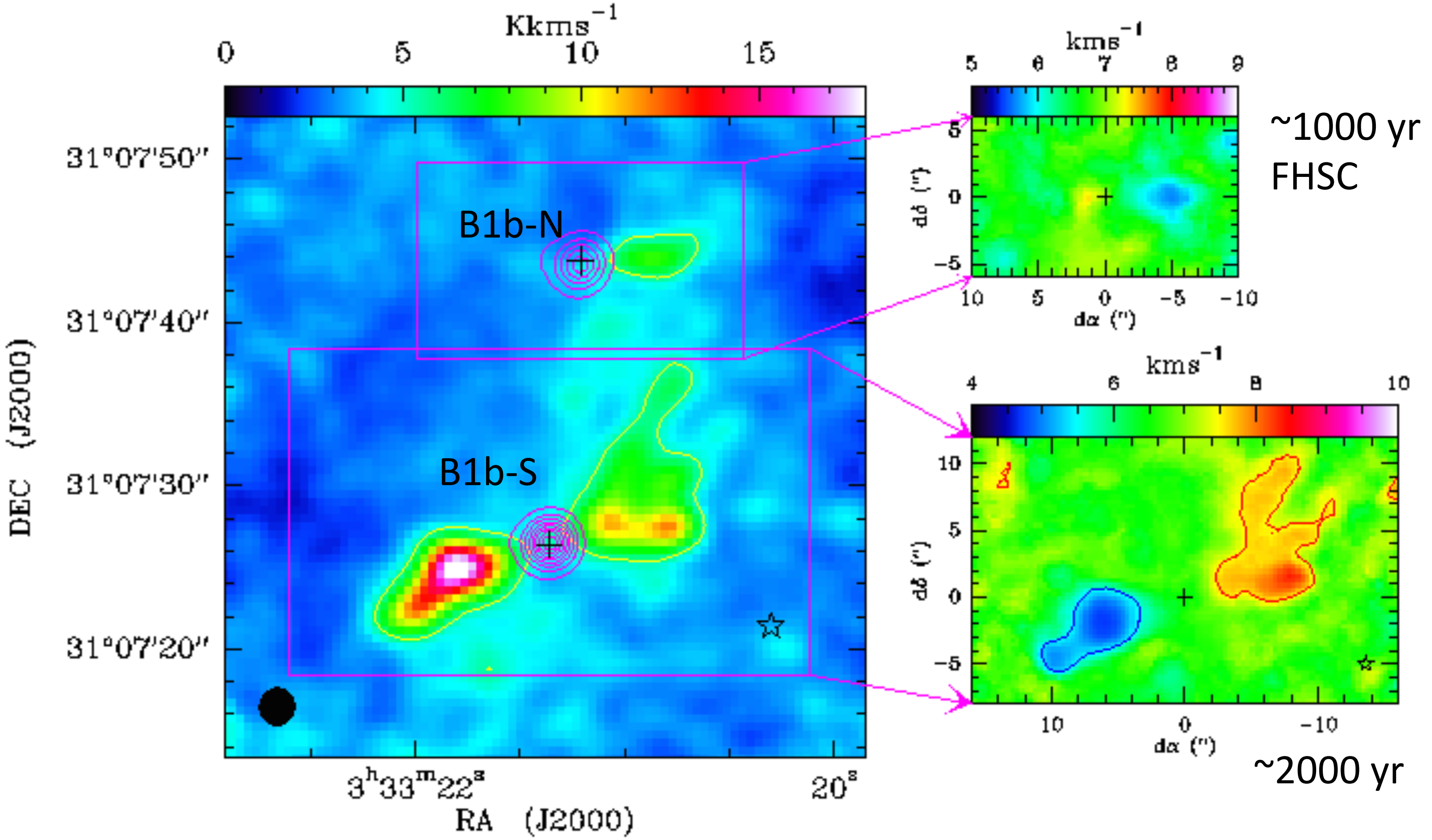


[OI] stronger than expected, in all V-components
➔ New insight on jet chemistry and shock physics !

Gusdorf+2017

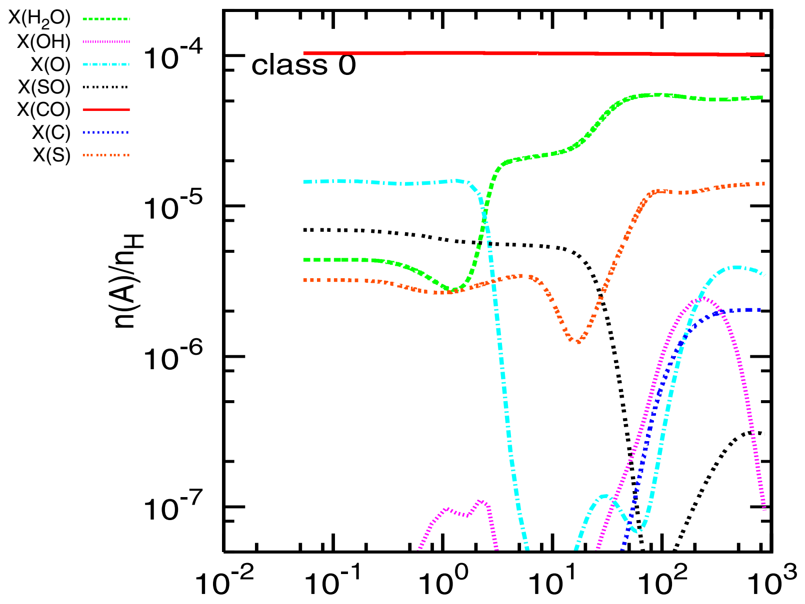
Slow outflows from First Larson cores

H_2CO PdBI map @2'' of B1b (Gerin et al. 2015)



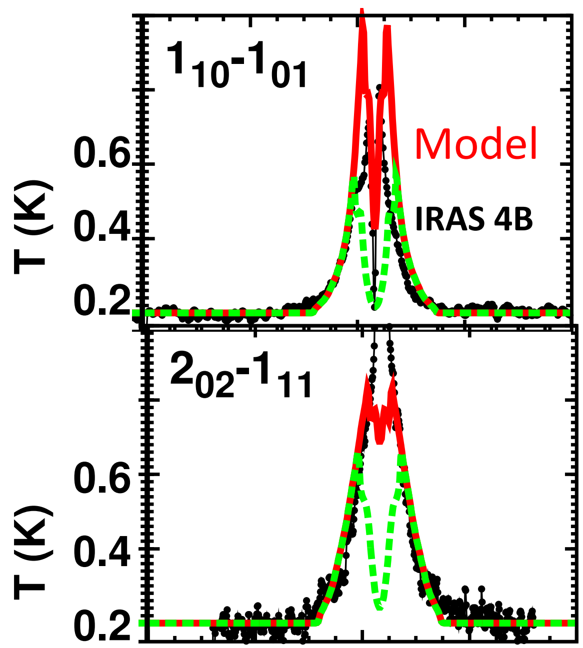
Thermochemical modelling of dusty MHD D-winds (r0 > 0.2 au)

a) Molecules survive at r0 > 0.2-1 au ***(Panoglou+ 2012)***



Panoglou+2012

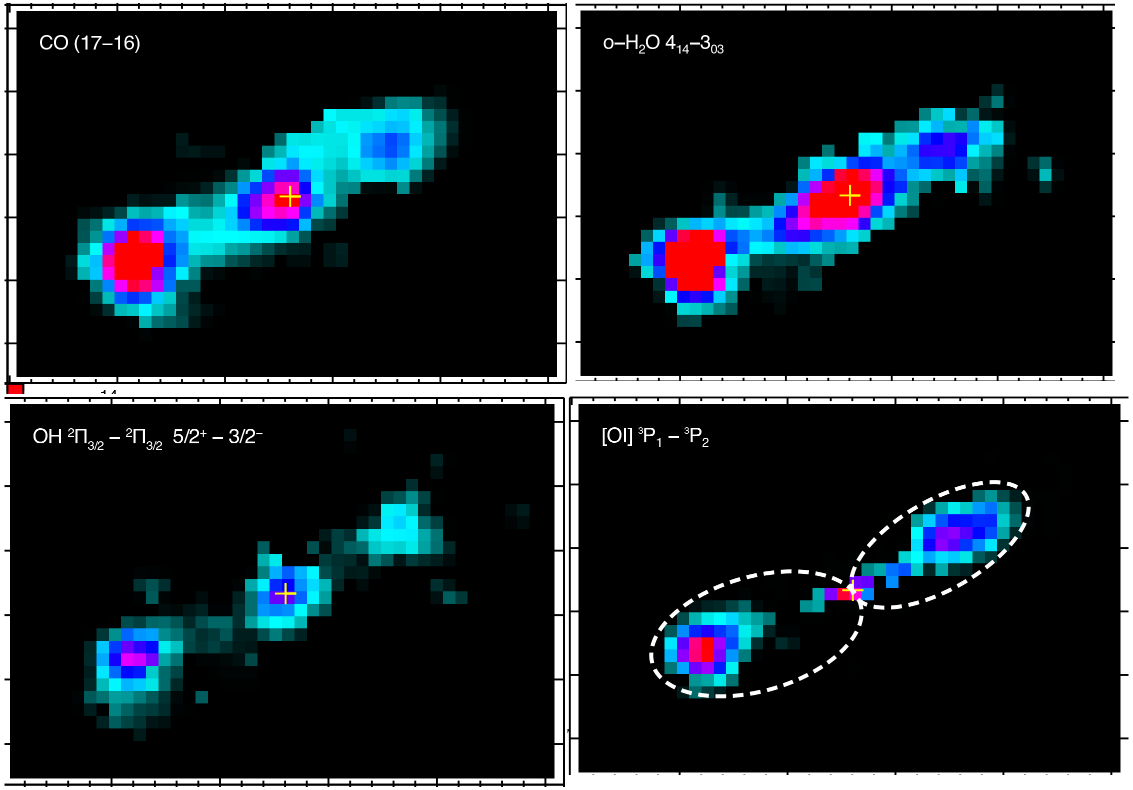
B)Can reproduce *Herschel* water lines in protostars (beam size 20''-40'') for λ~ 13 and r_{0ut} = 3-25 AU (Yvart+2016)



Models: Yvart+2016

Data: Kristensen+2012

Jet chemistry : HH211



Low X(CO)

Atomic OI jet has similar thrust as SiO jet and H2 flow

Dionatos, Ray, Gudel 2018

and Thank you Hans !

- For giving us the most beautiful jets to work with !
- For making SOFIA such a GREAT instrument for jet / outflow studies: [OI], OH, high-J CO, H_2… !
- For inspiring us to work on crucial questions, many we still can't answer today !
  - Origin of jets and jet precession ?
  - blue / red asymmetries ?