Protostellar Jets: the revolution with ALMA

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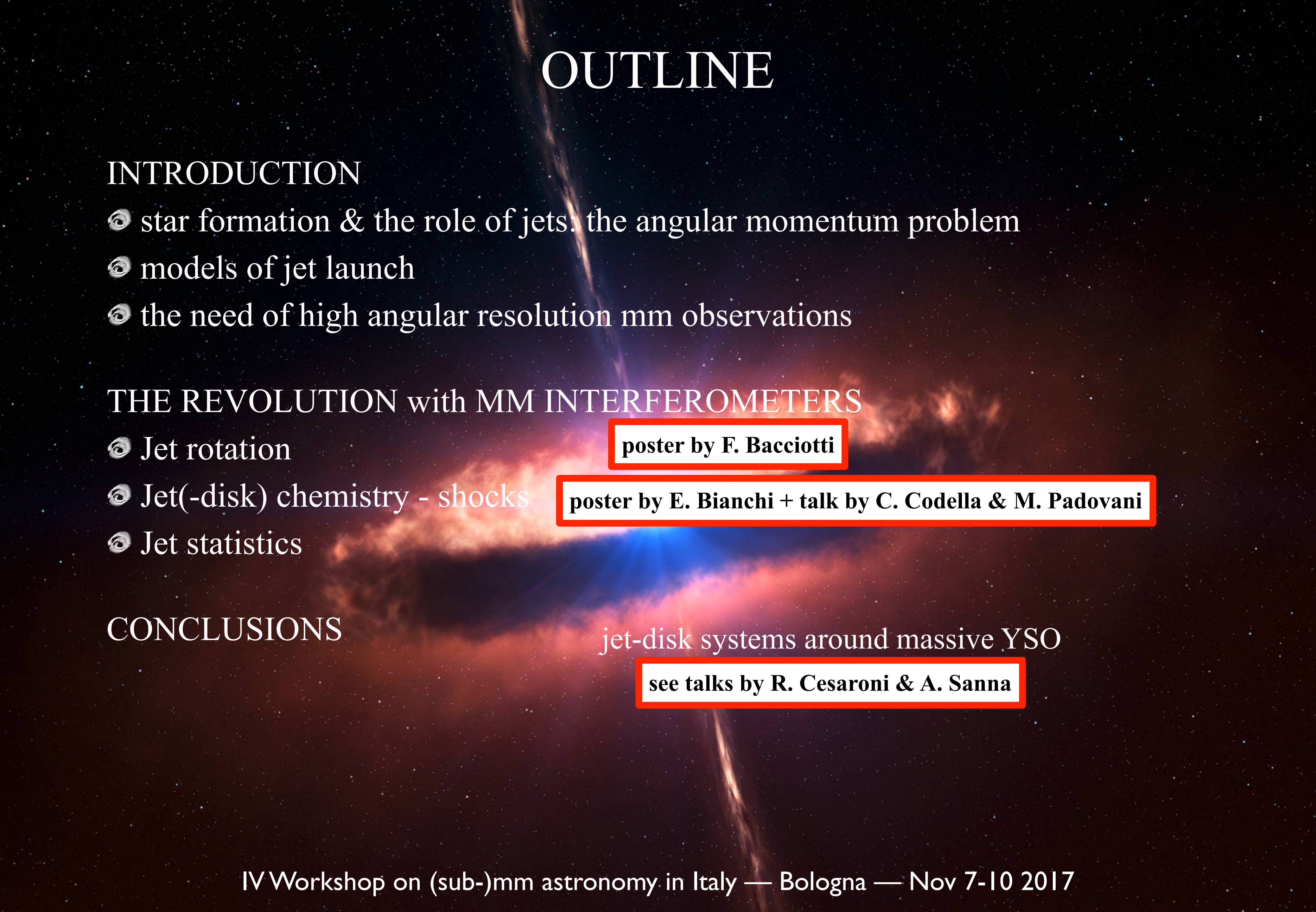
INAF - Osservatorio Astrofisico di Arcetri

IV Workshop on (sub-)mm astronomy in Italy — Bologna — Nov 7-10 2017



OUTLINE

INTRODUCTION

- star formation & the role of jets: the angular momentum problem
- models of jet launch
- the need of high angular resolution mm observations

THE REVOLUTION with MM INTERFEROMETERS

- Jet rotation
- Jet(-disk) chemistry - shocks
- Jet statistics

poster by F. Bacciotti

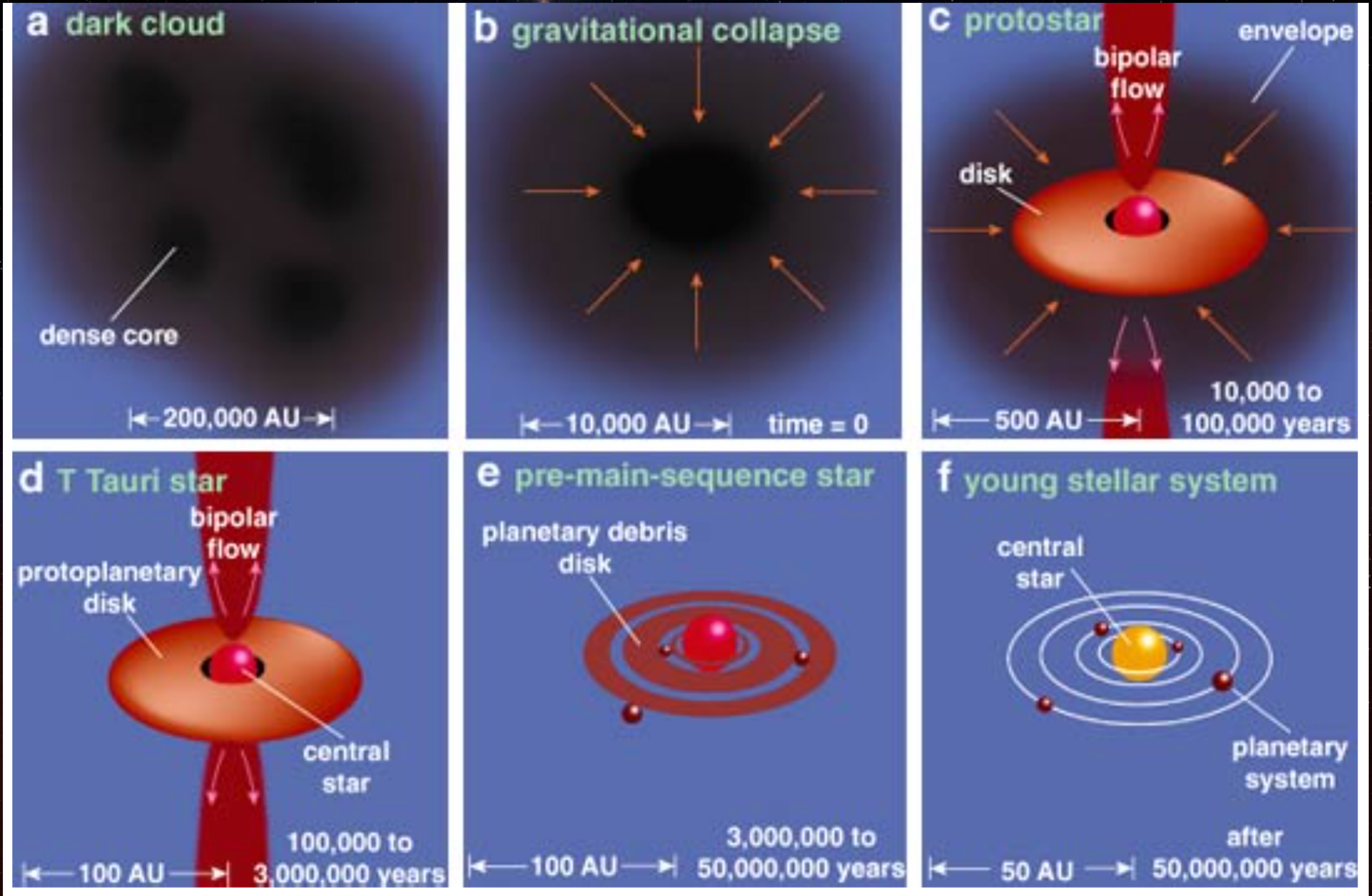
poster by E. Bianchi + talk by C. Codella & M. Padovani

CONCLUSIONS

jet-disk systems around massive YSO

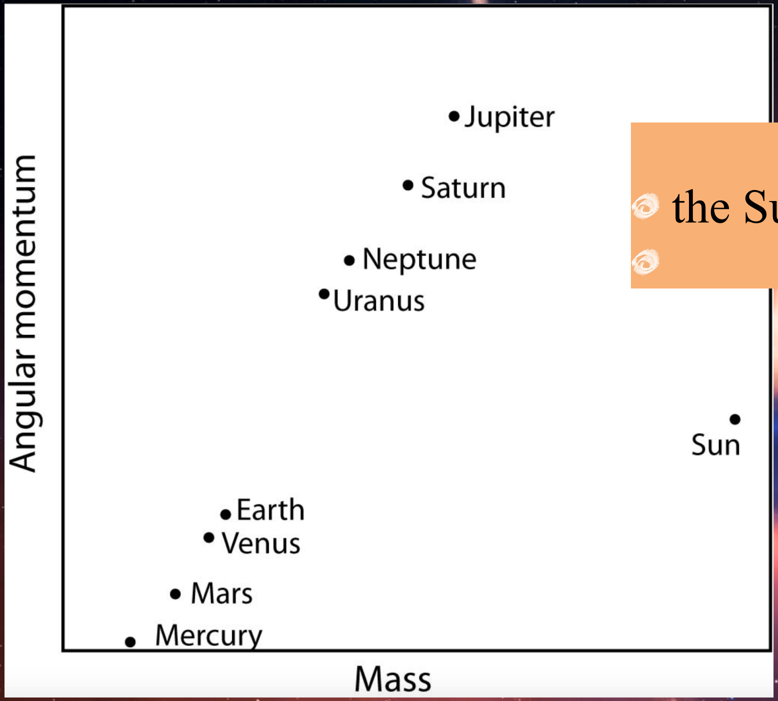
see talks by R. Cesaroni & A. Sanna

The star formation process & the birth of planets



The angular momentum problem

As the core contracts to form a star —> its rotation should speed up to conserve angular momentum
the region with the fastest rotation should be at the center …



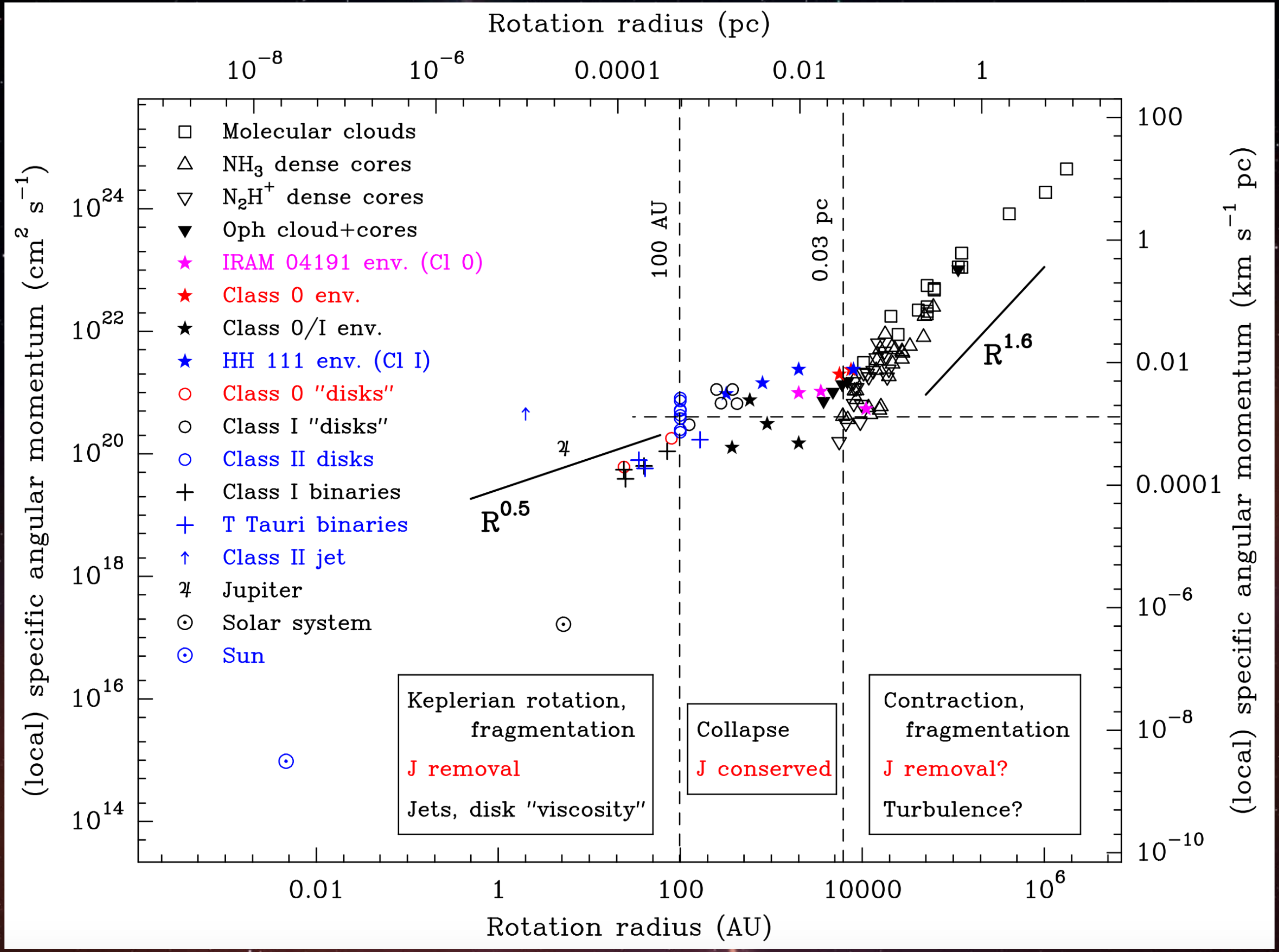
<u>in our Solar System</u>

- the Sun rotates much more slowly than it should
- most of AM is in the external planets

the initial angular momentum in the core
has to be redistributed during the star/planet formation process

slide by A. Maury

The angular momentum problem

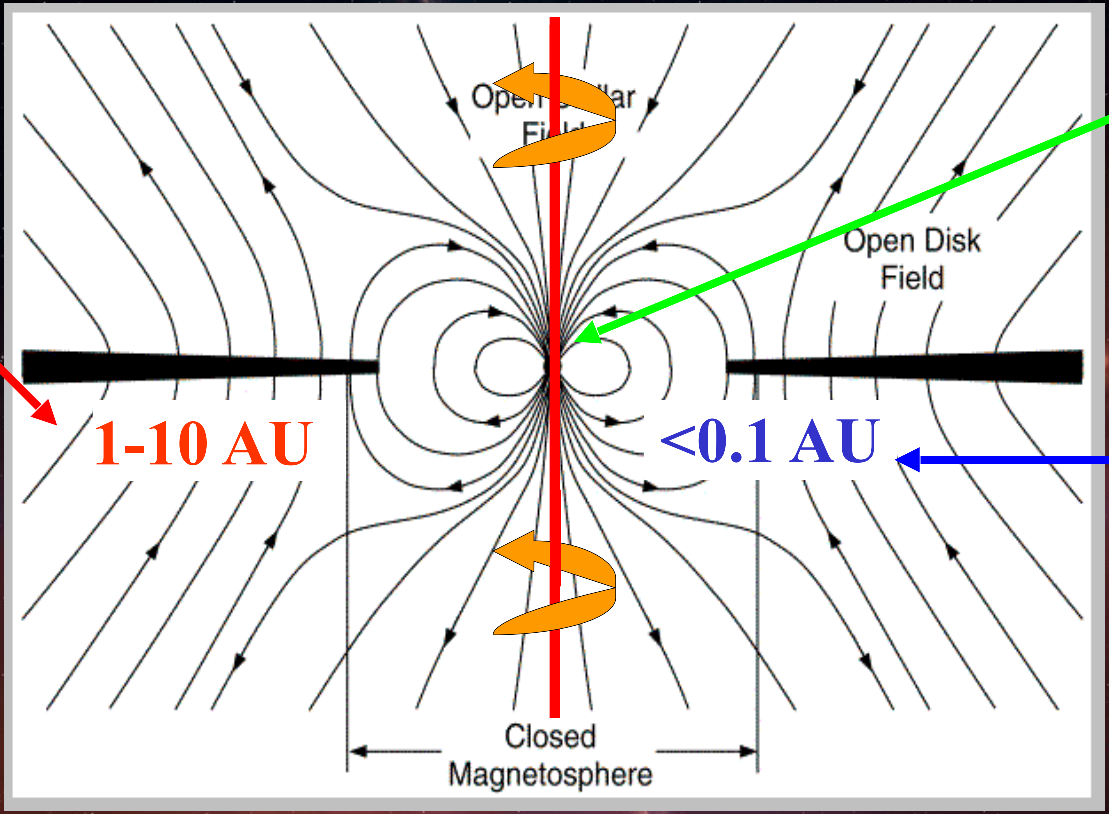


Belloche+ 2013

most of the mass (and associated angular momentum) —> already accreted at the TTauri phase —> need to investigate the ***YSO dynamics at the protostellar stage & on <100 AU scale***

THEORY: jets & disks are tightly connected !

MHD models: the jet is launched & accelerated by magneto-centrifugal forces
Jets may remove angular momentum from the disk !



DISK WIND
Konigl & Pudritz 2007

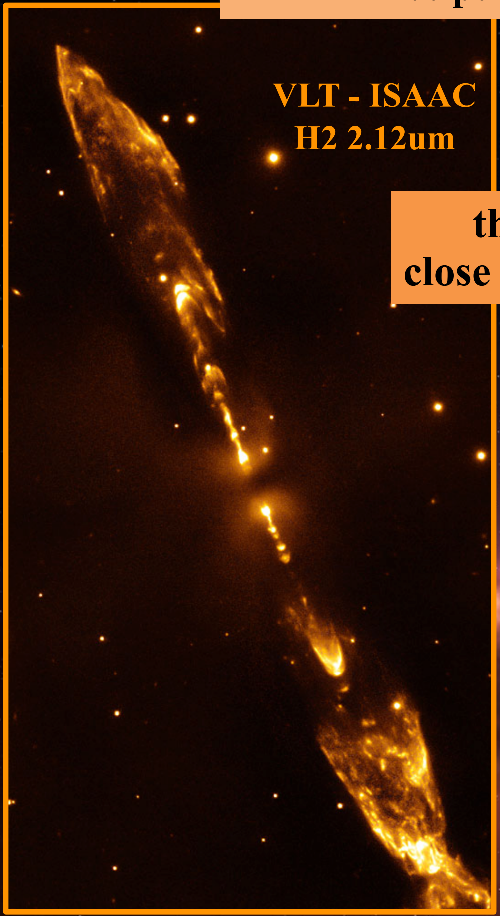
STELLAR WIND
Sauty et al. 2002

X-WIND
Shu et al. 1994, 2000

What is the jet launching mechanism ?
What is the jet feedback on the disk in the region of planet formation ?

OBSERVATIONS: the need of high-angular resolution & mm

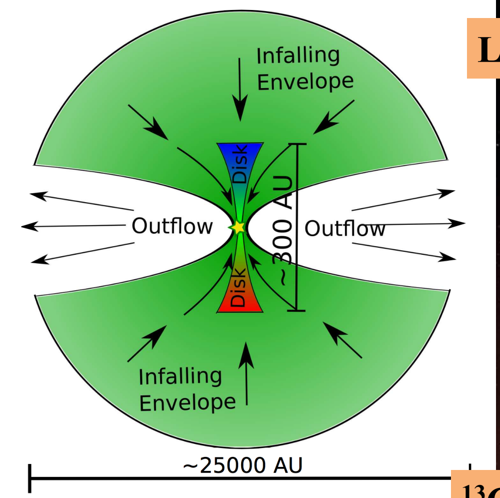
HH 212 - 400 pc



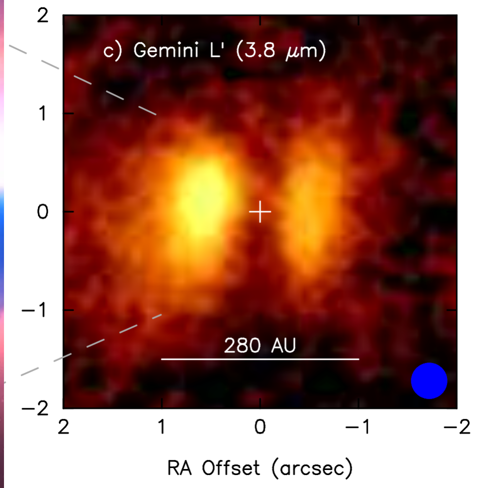
the jet is extincted close to the driving source

Zinnecker+ ***Nature*** 1998
McCaughrean+ 2002

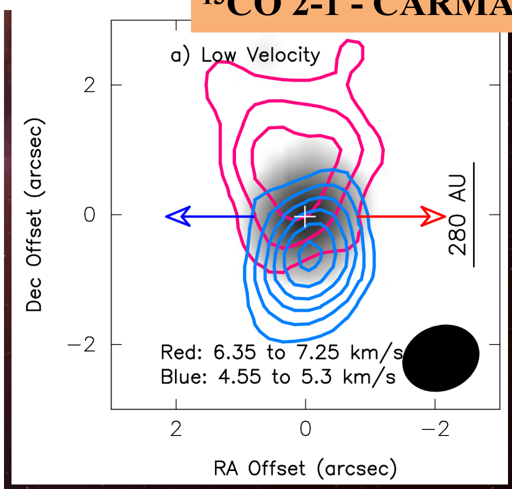
L1527 - 140 pc



Tobin+ 2012



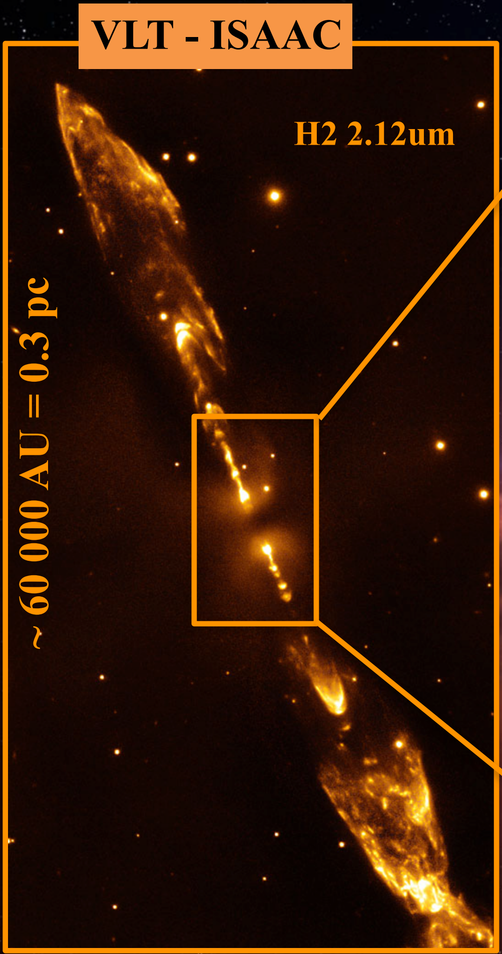
^{13}CO 2-1 - CARMA



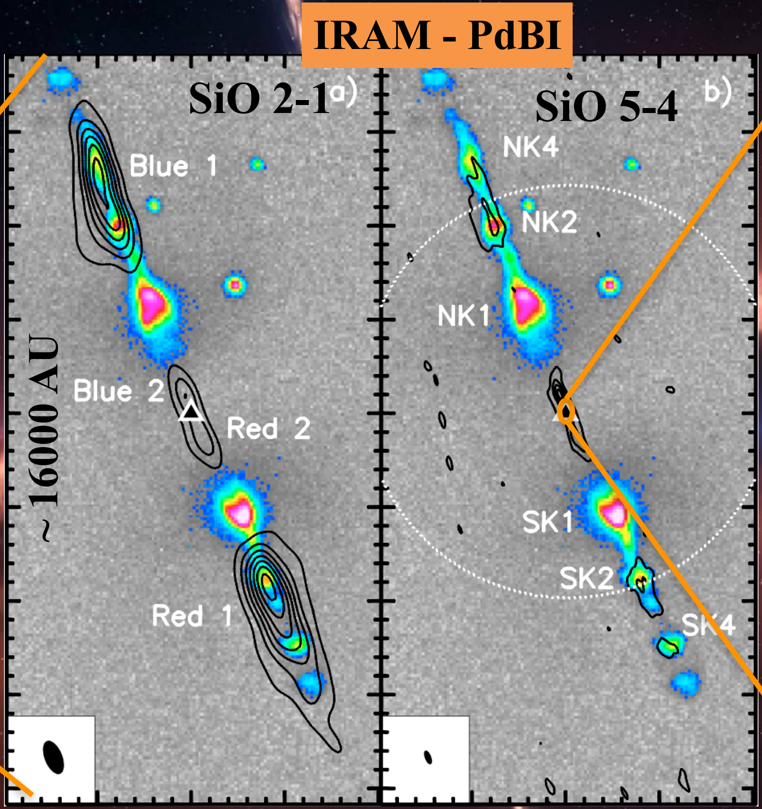
many kinematical components (jet, outflow, disk, infalling envelope, accretion shocks, …) on 100 au scale

The revolution with mm interferometry

1997- 2002	2007	2017
~0.7" / 300 AU	~0.8x0.35" / 320 x140 AU	~0.02" / 8 AU

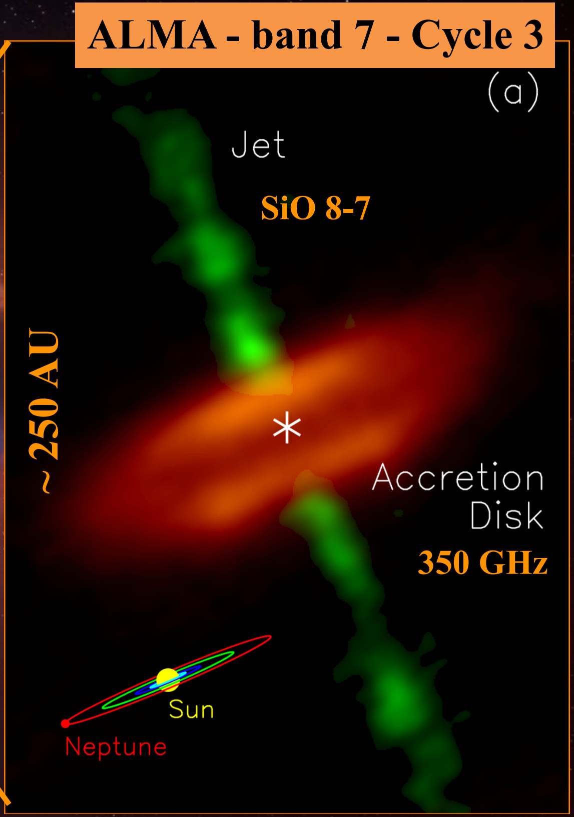


Zinnecker+ ***Nature*** 1998
McCaughrean+ 2002



Codella+2007

similar images with SMA: Lee+ 2007, 2008, 2009



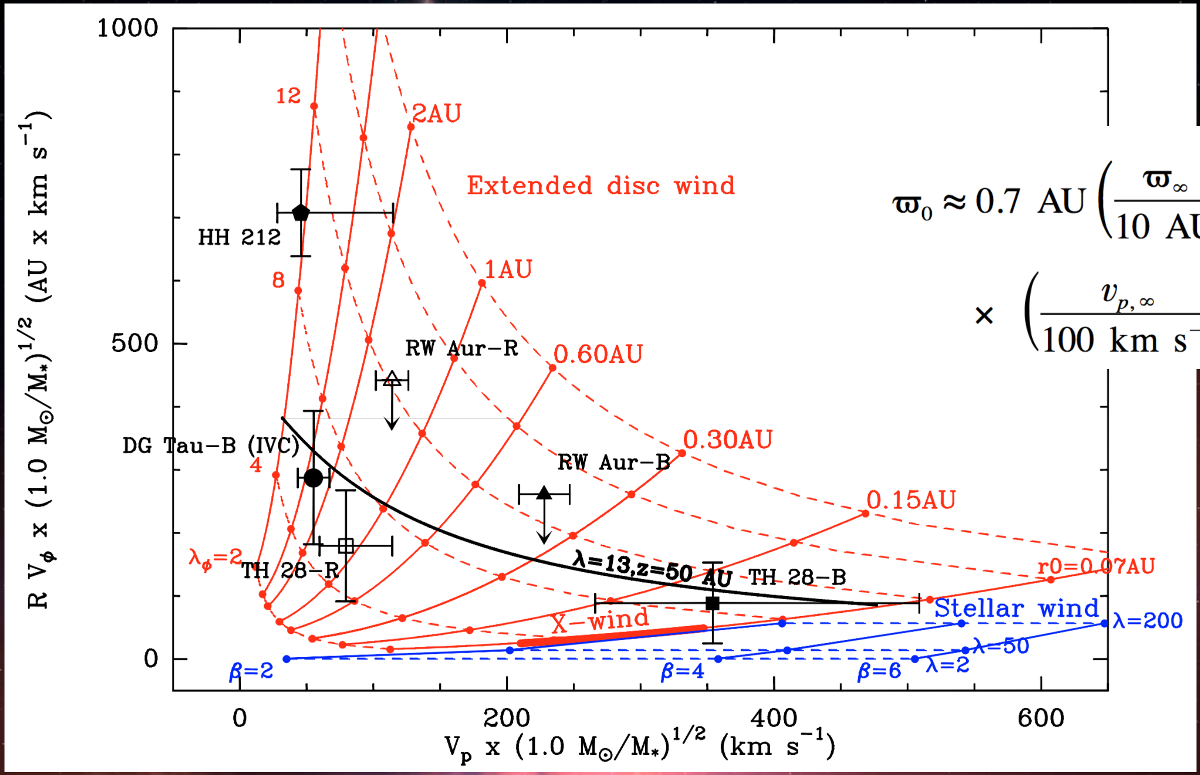
Lee+ ***Science*** 2017a

Lee+ ***Nature*** 2017b

THE REVOLUTION with MM INTERFEROMETERS

JET ROTATION

Validating magneto-centrifugal launch: JET ROTATION



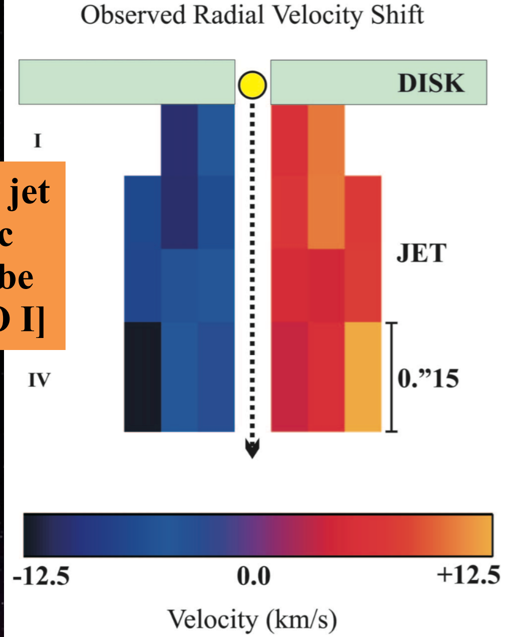
$$\varpi_0 \approx 0.7\ \mathrm{AU} \left(\frac{\varpi_\infty}{10\ \mathrm{AU}}\right)^{2/3} \left(\frac{v_{\phi,\infty}}{10\ \mathrm{km\ s^{-1}}}\right)^{2/3} \times \left(\frac{v_{p,\infty}}{100\ \mathrm{km\ s^{-1}}}\right)^{-4/3} \left(\frac{M_*}{1\ M_\odot}\right)^{1/3},$$

from the jet poloidal velocity along its axis (Vp) + jet rotation velocity around its axis (V**φ**)
—> we can recover the jet launching radius & removed angular momentum

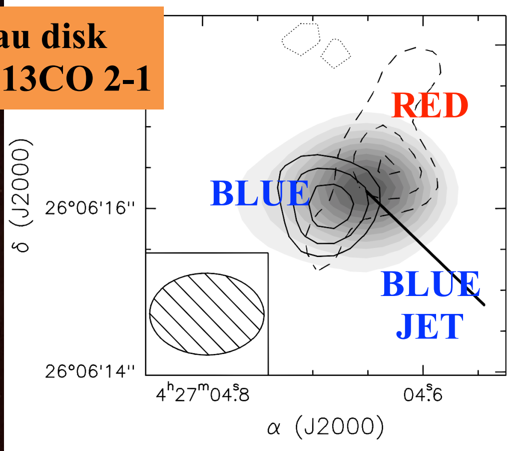
JET ROTATION I: pioneering studies with HST on Class II jets

Bacciotti+ 2002

DG Tau jet
140 pc
blue lobe
[SII], [O I]



DG Tau disk
OVRO - 13CO 2-1



Testi+ 2003

Bacciotti+2002, Coffey+ 2004, 2007, Woitas+ 2005

The Radius from the Star on the Disk Plane of the Jet Footpoint (or Launch Point), ϖ_0, Calculated for Targets in the Optical and NUV Using the Method Described in Anderson et al. (2003)

Target	Emission Line	ϖ_∞ (arcsec)	ϖ_∞ (AU)	$\Delta v_{\rm rad}$ (km s^{-1})	$\overline{v_{\rm rad}}$ (km s^{-1})	$v_{\phi,\infty}$ (km s^{-1})	$v_{p,\infty}$ (km s^{-1})	ϖ_0 (AU)
DG Tau approaching jet	λ6300	0.15	21	26 (18)	195 (60)	21 (15)	248 (76)	0.5 (1.9)
	λ6583	0.15	21	7	165	6	209	0.3
	λ2796	0.116	16	8	193	6	244	0.2
CW Tau approaching jet	λ6300	0.15	21	12	108	8	164	0.6
	λ6583	0.10	14	15	102	10	155	0.5
TH 28 receding jet	λ6300	0.20	34	16	8	8	46	3.9
	λ6583	0.20	34	24	27	12	155	1.0
	λ2796	0.20	34	6	13	3	75	1.0

RESULTS

- radial velocity asymmetries across the jet width: DVrad~5-25 km/s at 15-50 AU from axis & <100 AU from source
- if due to rotation —> the jet is launched at Rlaunch = 0.5 - 5 AU
- the jet removes Ljet ~1e5 Msun/yr AU km/s ~ 70% excess angular momentum to allow accretion at the observed Macc

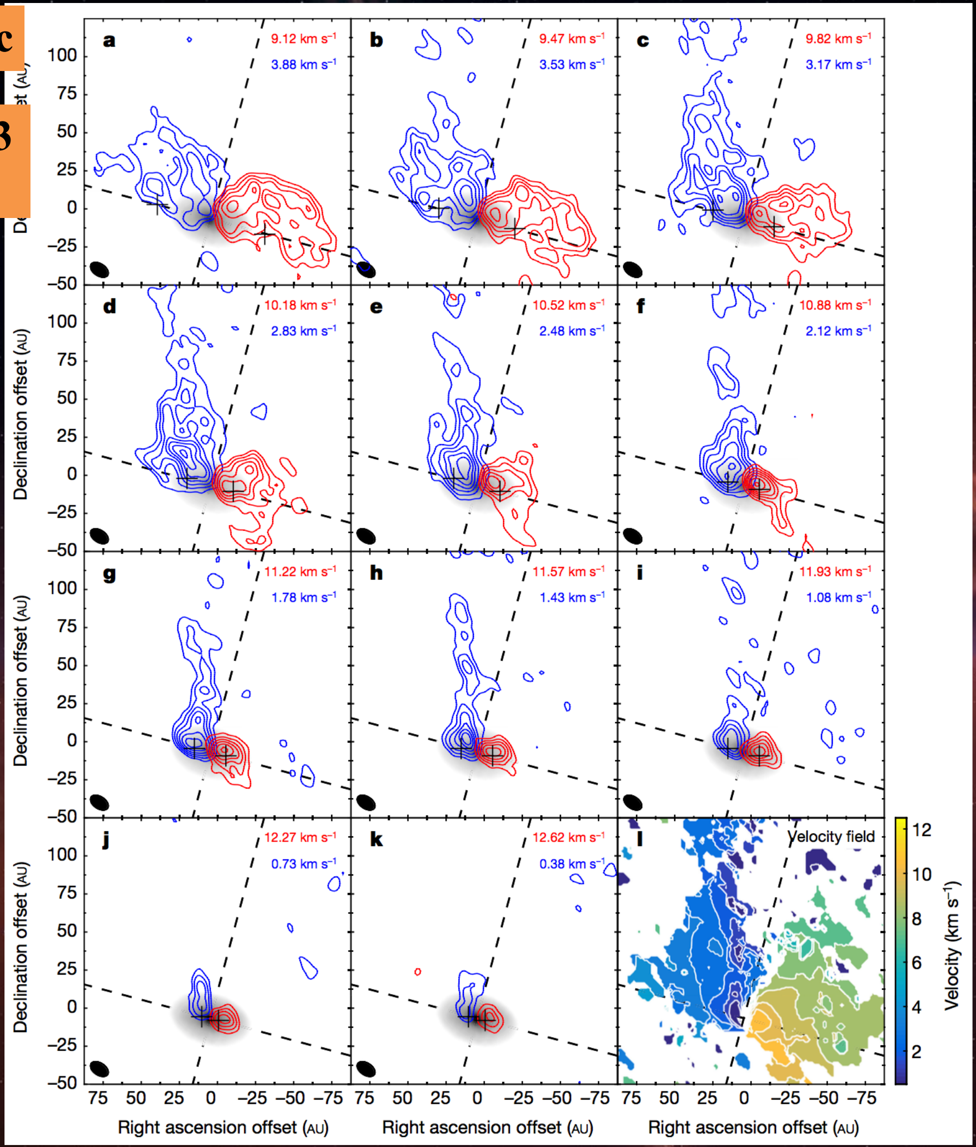
CRITISMIS

- are radial velocity asymmetries due to jet rotation ?Alternatives: jet wiggling, jet precession, interaction with a warped disk, asymmetric shocks (Cerqueira et al. 2006, Stoker et al.,)
- disagreement btw disk & jet rotation (e.g., Cabrit et al. 2006)
- HST limited spectral resolution (~50 km/s)

JET ROTATION II: first detection of rotation with ALMA

TMC1A - 140 pc

ALMA band 6 - Cycle 3
0.4” = 60 au



Bjerkeli+ Nature 2016

$M_* \sim 0.4\ M_{sun}$

$V_\varphi < 5$ km/s

$l < 200$ au km/s

$R_{launch} \sim 2\text{-}\ 25$ au

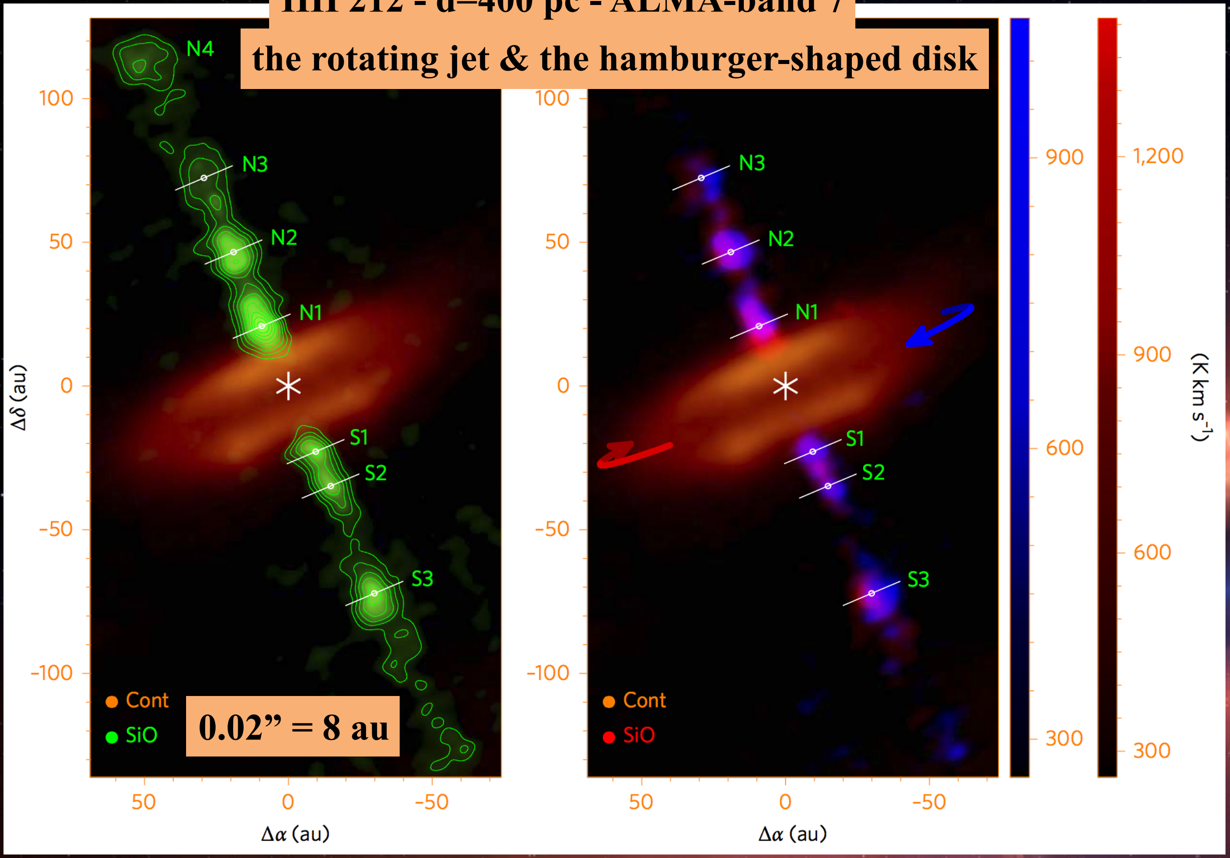
suggest a
D-wind scenario

JET ROTATION III: the HH 212 collimated SiO jet

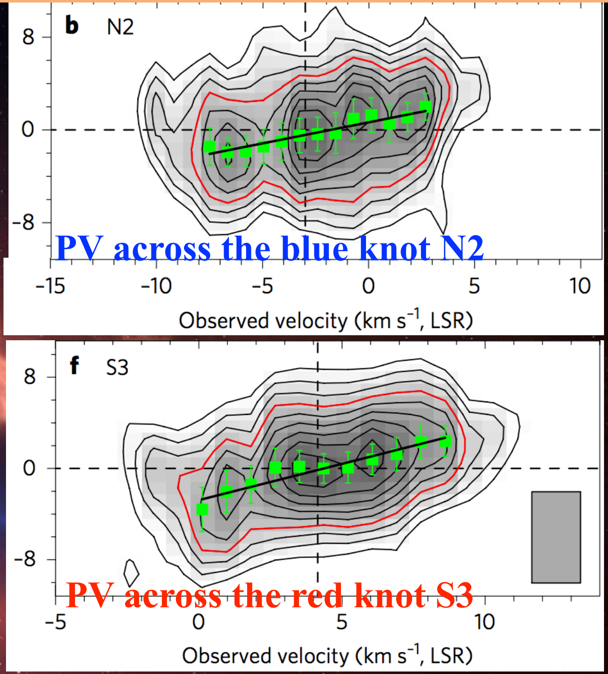
Lee+ Nature 2017b

HH 212 - d=400 pc - ALMA-band 7

the rotating jet & the hamburger-shaped disk



velocity gradient across the ~20 au wide jet



$M_* \sim 0.25\ M_{sun}$

$V_p \sim 115$ km/s

$l \sim 10$ au km/s

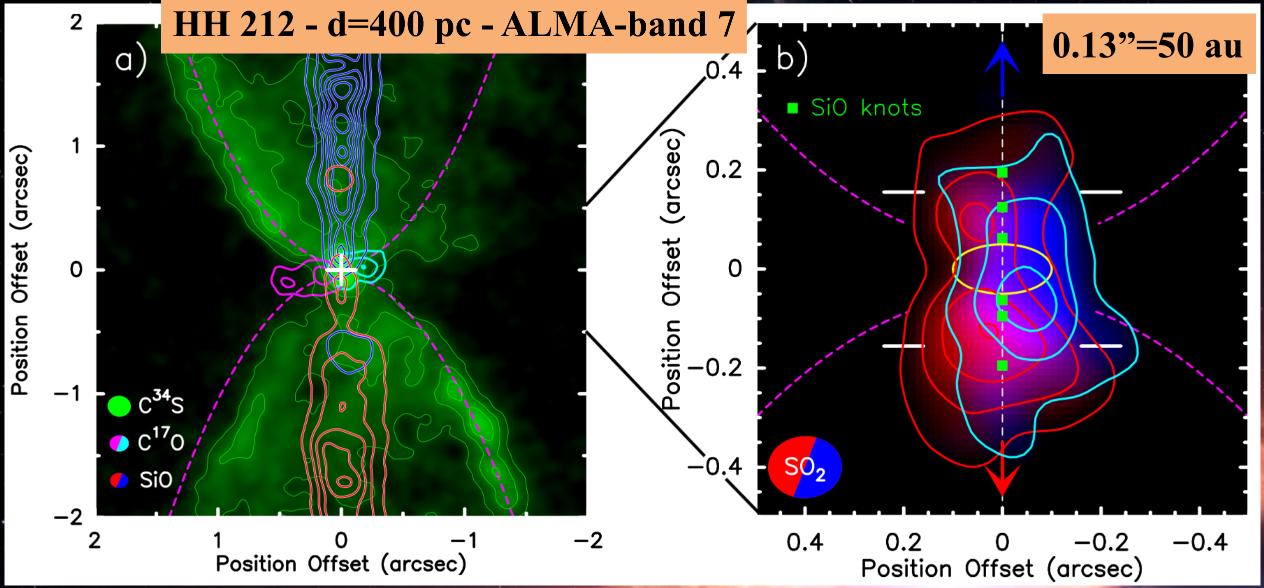
→ $R_{launch} \sim 0.05 - 0.3$ au

the highly collimated SiO jet removes AM in the innermost disk region enabling material to accrete onto the protostar

X-wind or inner layer of D-wind ?

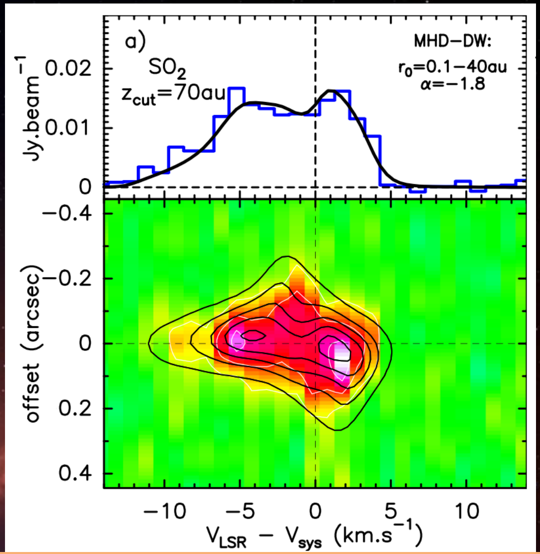
JET ROTATION IV: the HH 212 extended Disk-wind

Tabone+ 2017

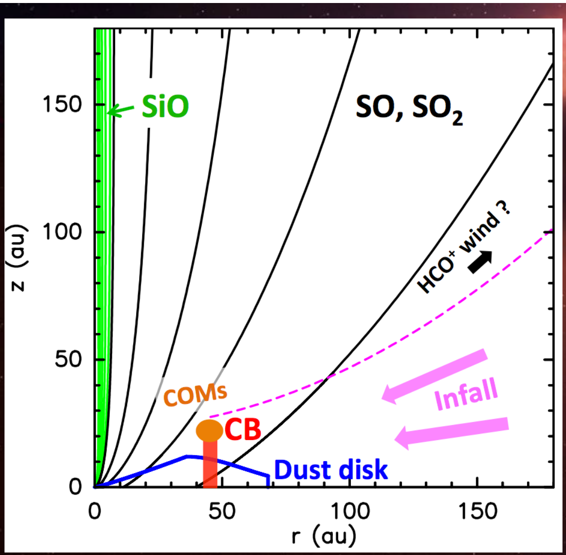


HH 212 - d=400 pc - ALMA-band 7

0.13”=50 au



velocity gradient across the jet is well reproduced by a D-wind with magnetic lever arm $\lambda = (r_A/r_0)^2 = 5.5$ widening $W = r_{max}/r_0 = 30$



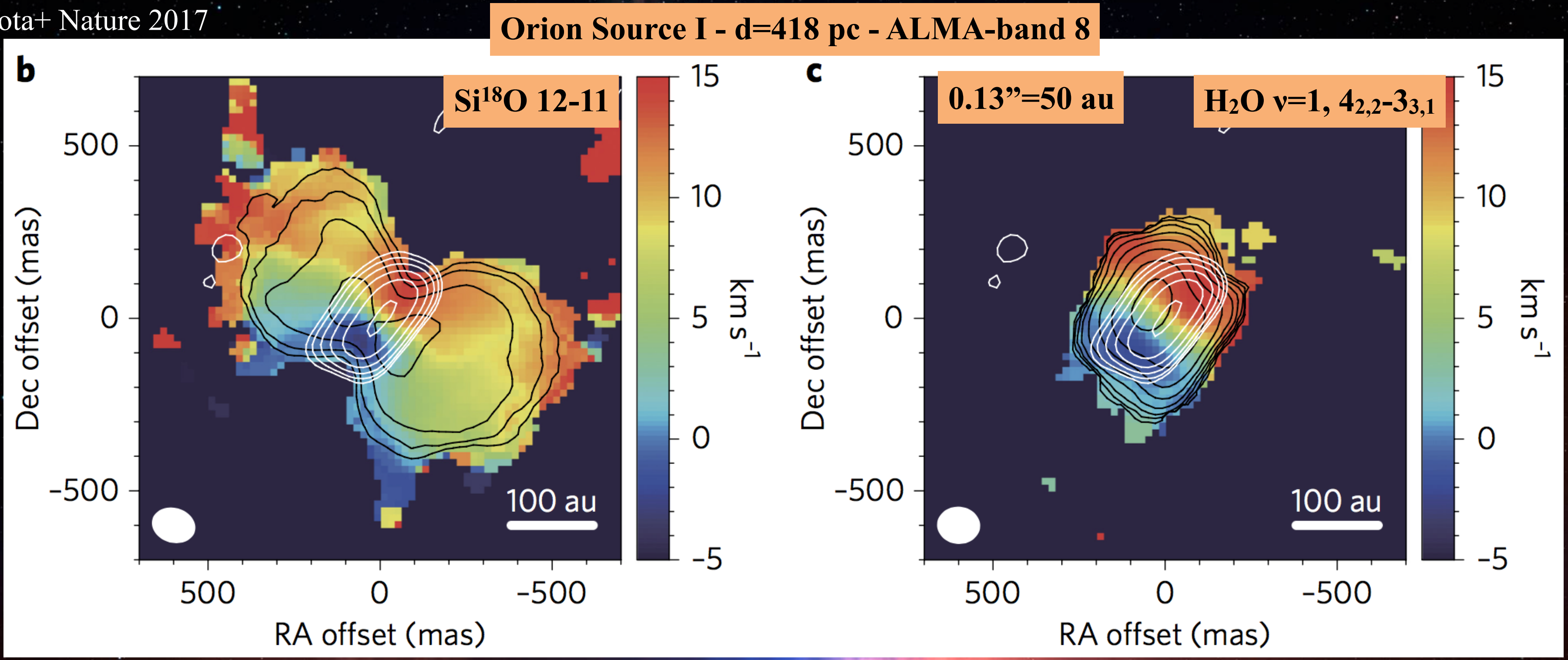
$M_* \sim 0.25\ M_{sun}$
$V_p \sim 20$-40 km/s
$l \sim 40$ au km/s

→ $R_{launch} \sim 0.1$ - 40 au

the slower SO/SO2 D-wind removes AM from the outer disk regions (up to 40 AU) allowing material to move to the inner disk

JET ROTATION V: D-wind from the high-mass YSO Orion Source I

Hirota+ Nature 2017



Orion Source I - d=418 pc - ALMA-band 8

$Si^{18}O$ 12-11

0.13”=50 au

H_2O v=1, $4_{2,2}$-$3_{3,1}$

$M_* \sim 8.7\ M_{sun}$
$V_p \sim 10$ km/s
R (z=0) ~ 25-75 au → $R_{launch} \sim 5$ - 25 au
$V_\varphi \sim 20$-5 km/s
$l \sim 400$-600 au km/s

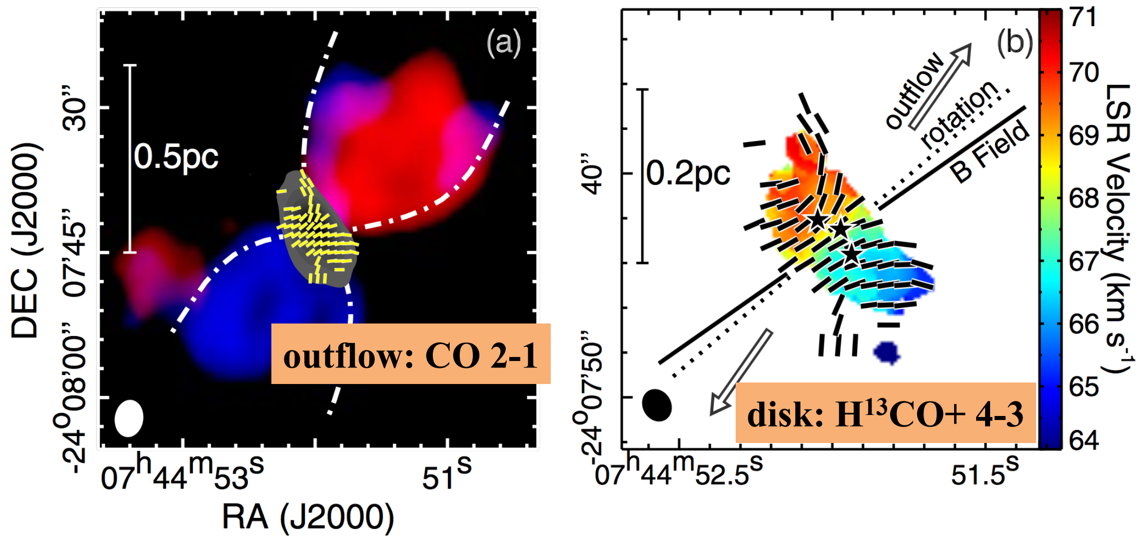
similarly to what observed in low-mass YSO: angular momentum is carried away by the magneto-centrifugal disk wind

high-mass star formation via disk-accretion ?

Validating magneto-centrifugal launch: MAGNETIC FIELD

Qiu et al. 2014

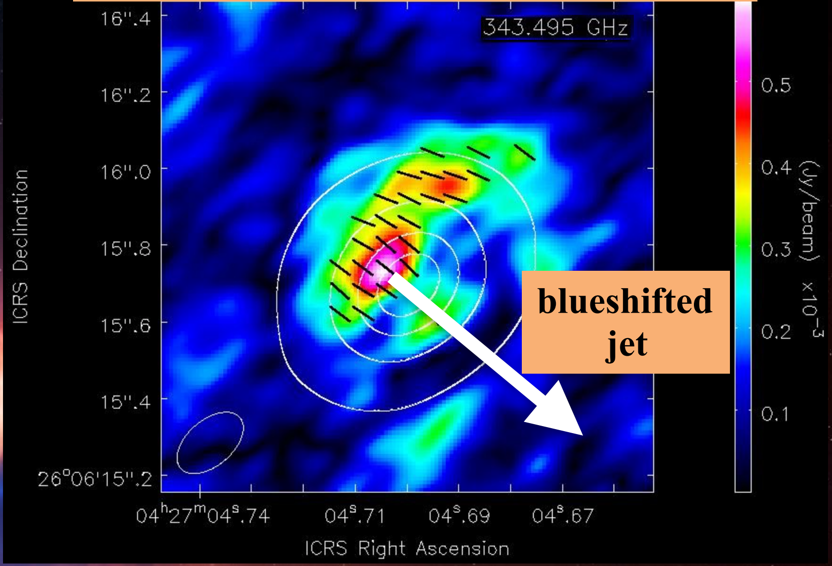
G240.31+0.07 - SMA - polarized dust emission at 0.88mm



outflow: CO 2-1

disk: $H^{13}CO+$ 4-3

DG Tau ALMA - polarized dust in band 7



blueshifted jet

the first detection of an hourglass magnetic field
aligned with an outflow rotation system
in an high-mass star forming region

searching for the magnetic field in TTSs
showing coherent disk & jet rotation

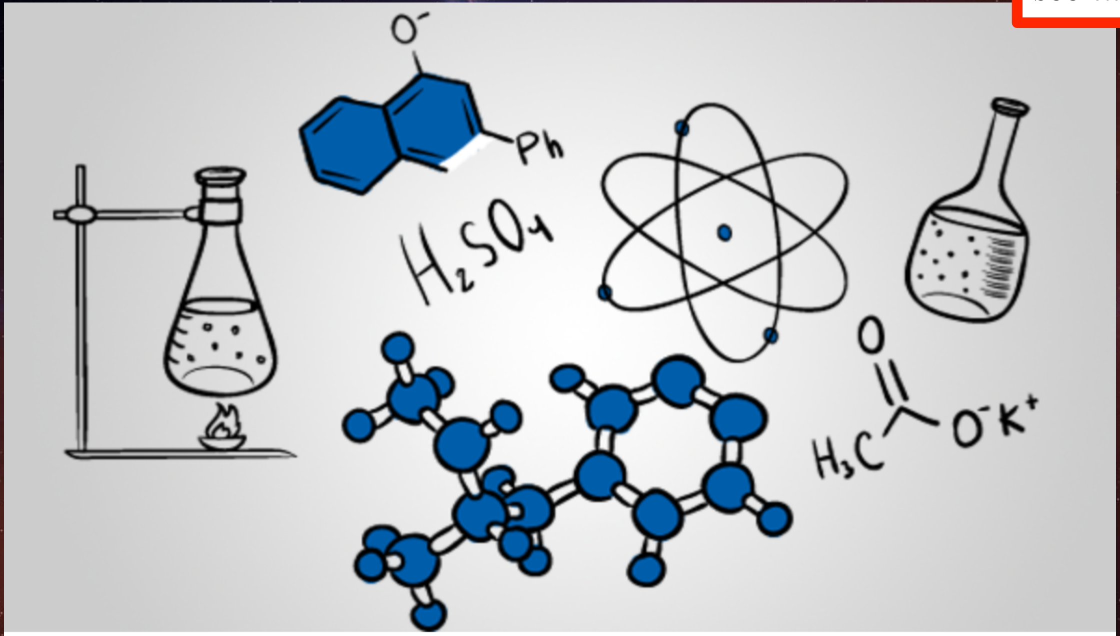
polarization: magnetic field vs scattering ?

poster by F. Bacciotti

THE REVOLUTION with MM INTERFEROMETERS

JET CHEMISTRY

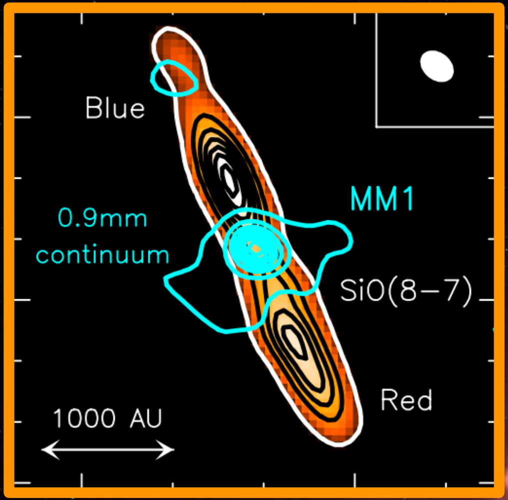
see talk by C. Codella



JET CHEMISTRY I: chemistry at the envelope-disk-jet interface

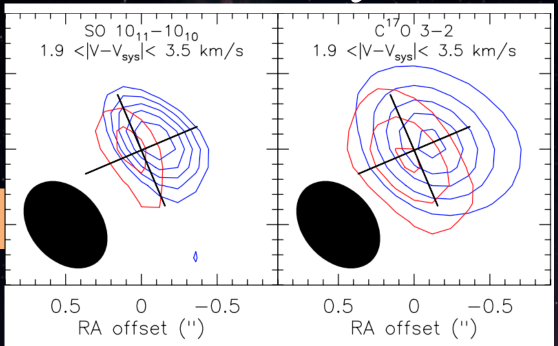
HH 212, d~400 pc

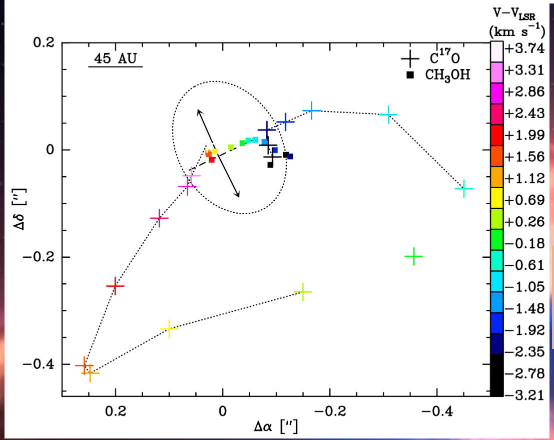
ALMA band 7 - Cycle 0 - 0.5”=200 au



Codella+ 2014

Podio+ 2015

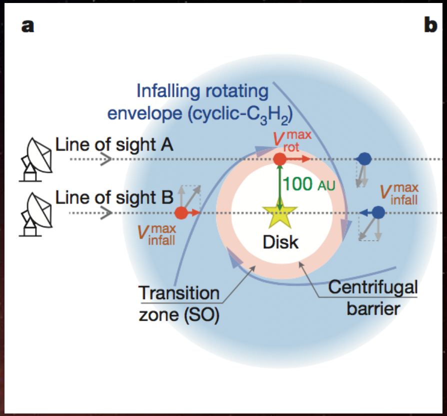




Leurini+ 2016

C^{17}O —> rotating disk/inner infalling envelope
SO —> accretion shock at the CB ?

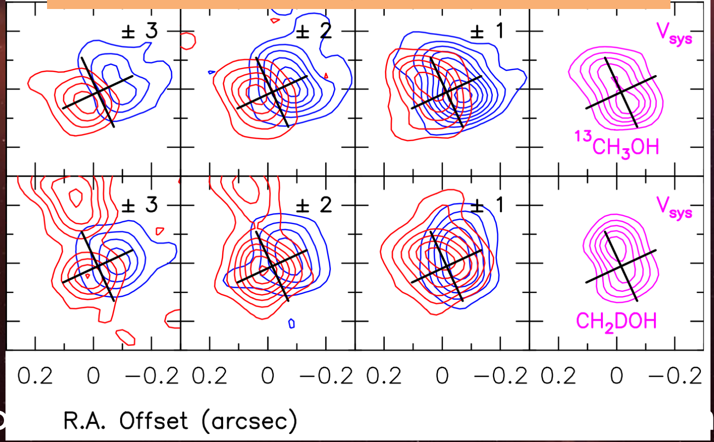
Sakai+ 2014, 2015, 2017
Oya+ 2016



CH$_3$OH probes the base of the D-wind ?
—> R$_{launch}$ ~ 1 au

ALMA band 7 - Cycle 4 - 0.13”=50 au

Bianchi+ 2017

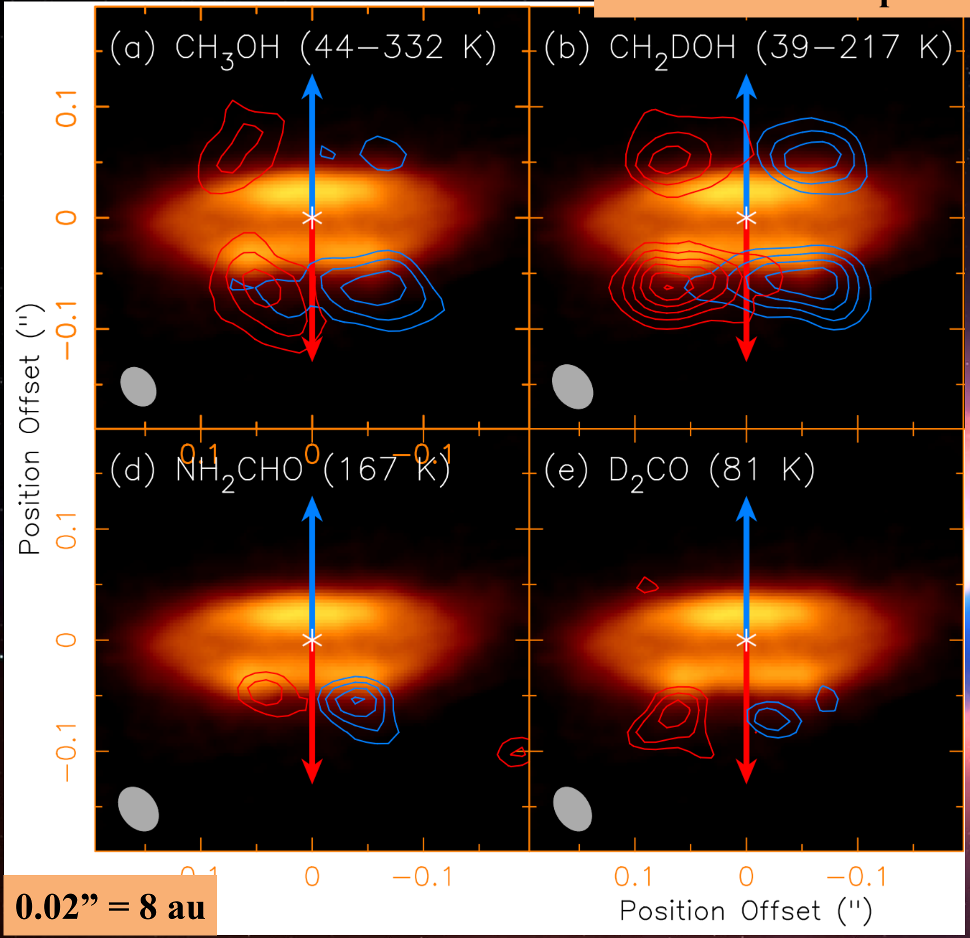


methanol deuteration on 50 au scale

poster by E. Bianchi

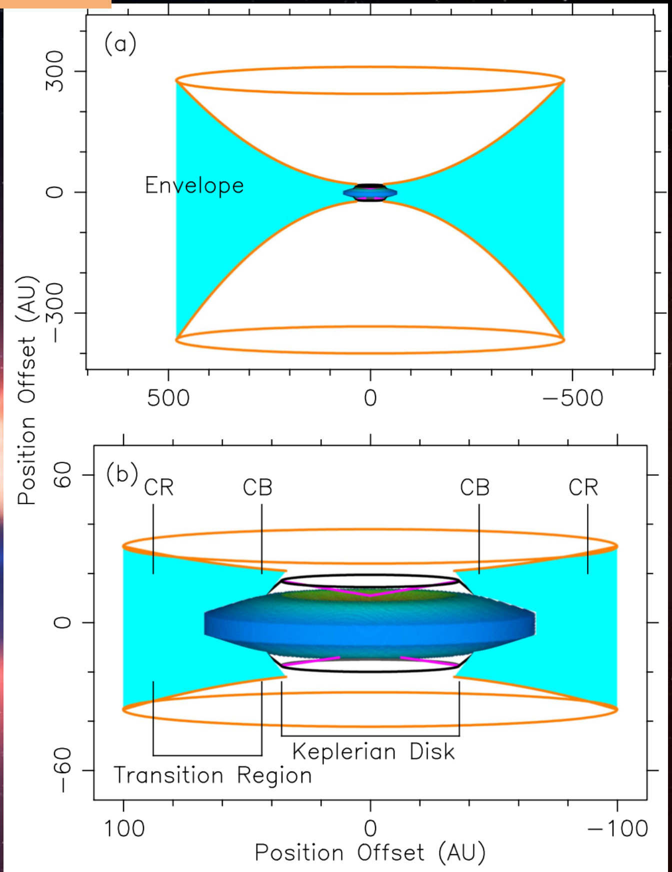
JET CHEMISTRY II: chemistry at the envelope-disk-jet interface

or the disk atmosphere within the CB ?

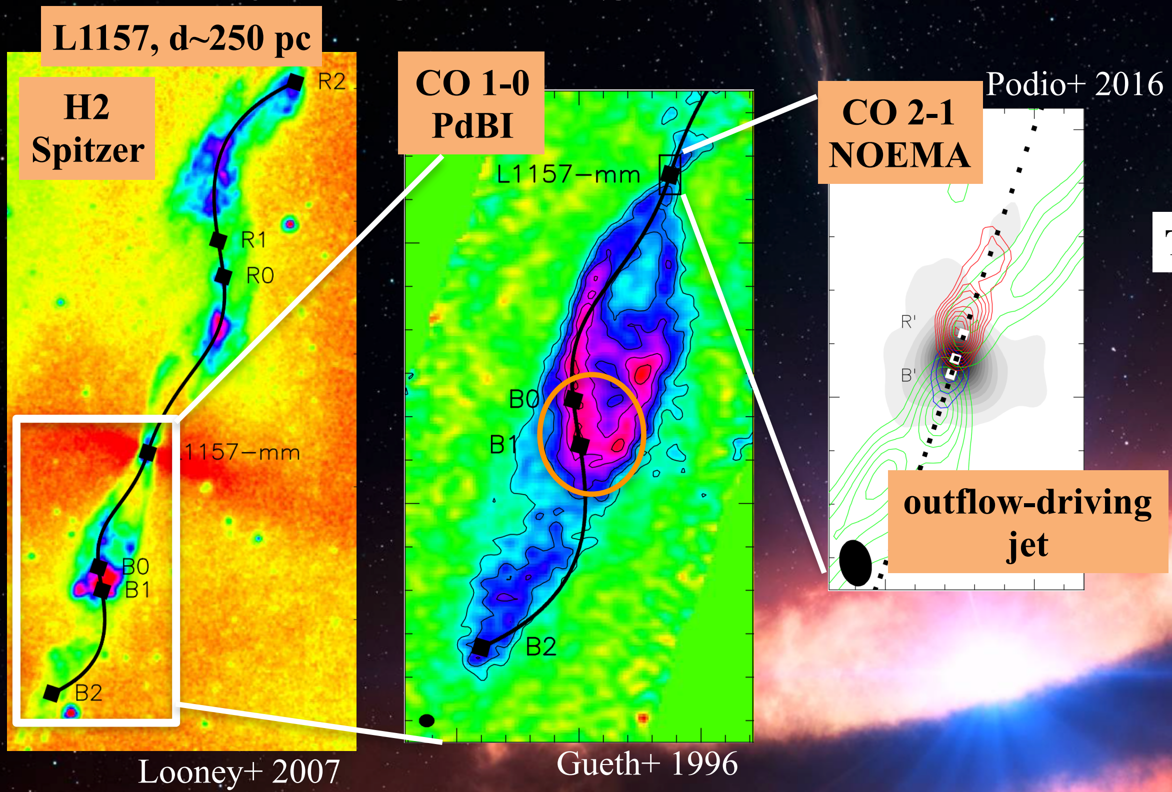


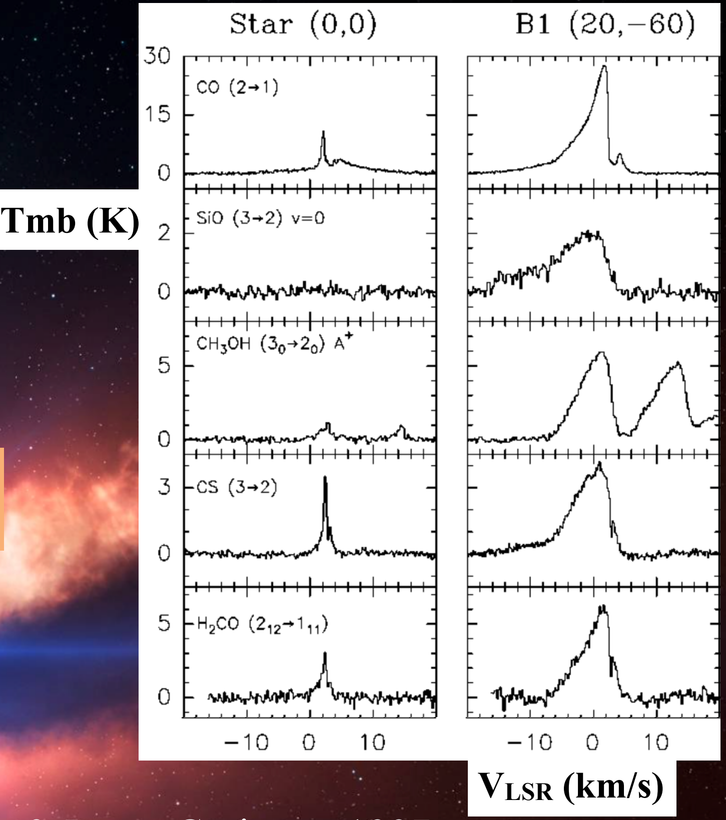
0.02” = 8 au

Lee+ 2017c



JET CHEMISTRY III: chemical complexity in shocks





The chemical richness of L1157-B1 first highlighted by Bachiller & Perez-Gutierrez 1997

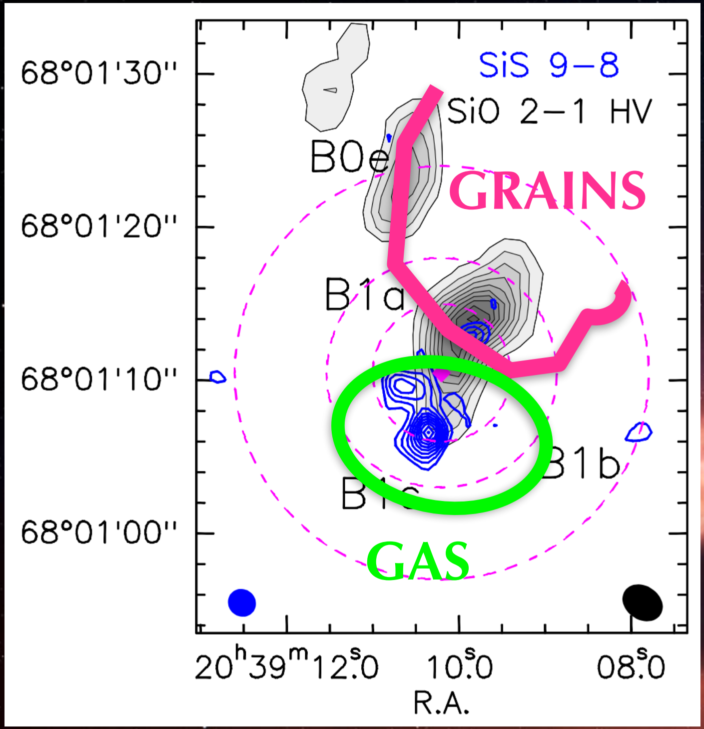
Since then L1157-B1 has been the target of several mm spectral surveys:

- S-bearing molecules (Gomez-Ruiz+ 2015, Holdship+ 2016)
- deuterated molecules (Codella+ 2010, 2012, Fontani+ 2014)
- COMs (Arce+ 2008, Lefloch+ 2017, Benedettini+ 2013, Codella+ 2015, Mendoza+ 2015)
- molecular ions (Podio+ 2014) —> shock produces CR ?
- P-bearing species (PO, PN) (Lefloch+ 2016)

talk by C. Codella & M. Padovani

JET CHEMISTRY IV: chemical complexity in SHOCKS

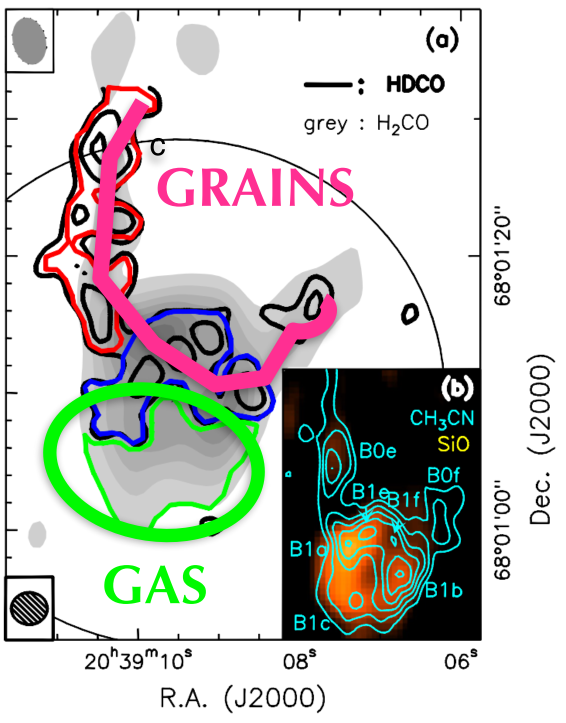
SiO vs SiS



SiO —> direct release from grains
SiS —> gas-phase chemistry

Podio et al. 2017

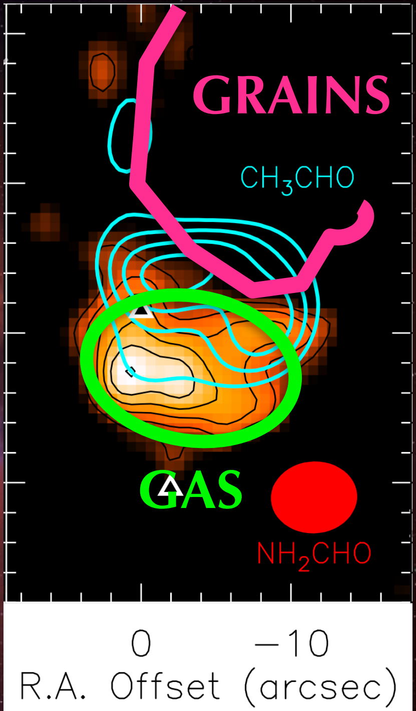
HDCO vs H_2CO



HDCO —>freshly sputtered from ices
H_2CO —> grain + gas-phase

Fontani et al. 2014

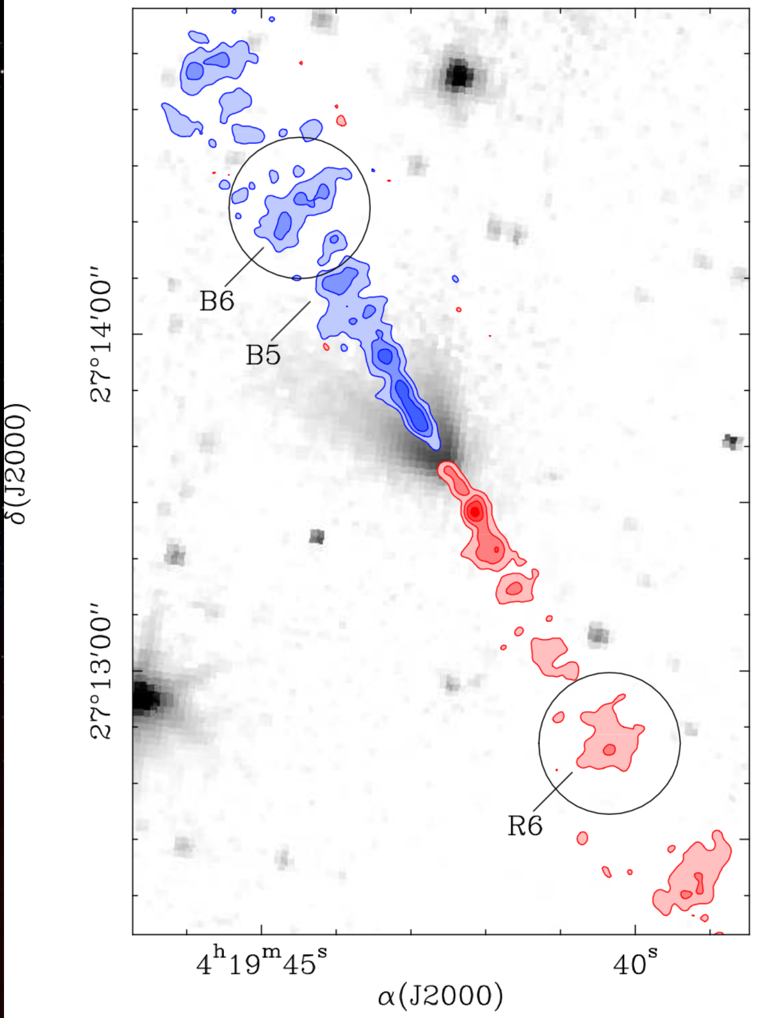
NH_2CHO vs CH_3CHO



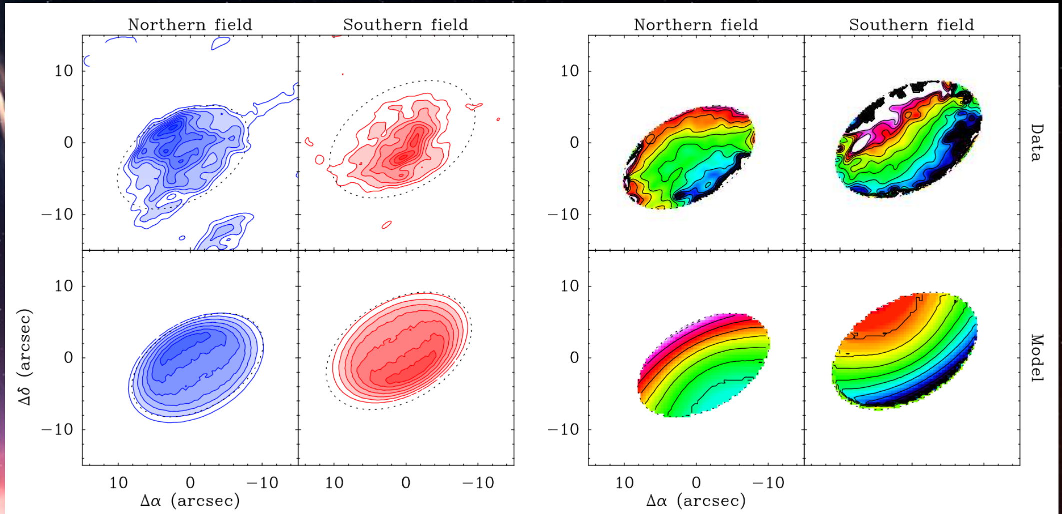
CH_3CHO—> gas-phase
NH_2CHO —> gas-phase

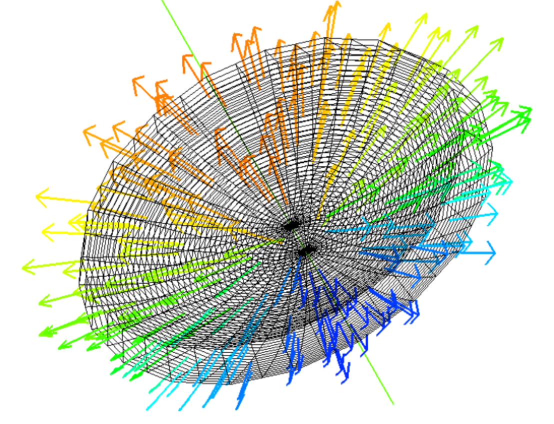
Codella et al. 2017

Anatomy of BOW-SHOCKS with ALMA



Tafalla+ 2017



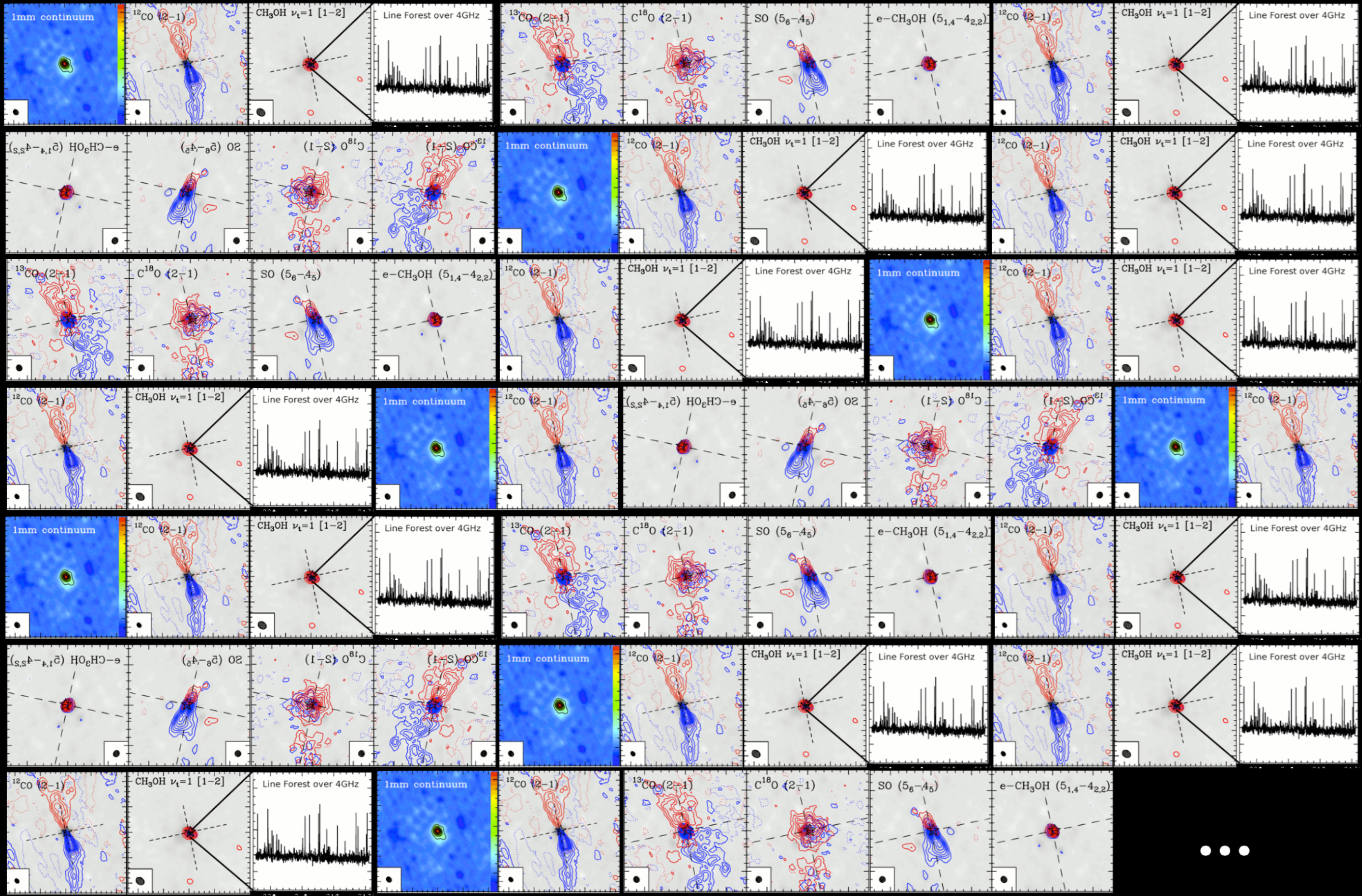


THE REVOLUTION with MM INTERFEROMETERS

JET STATISTICS

ARE jets ubiquitous at the protostellar stage ??

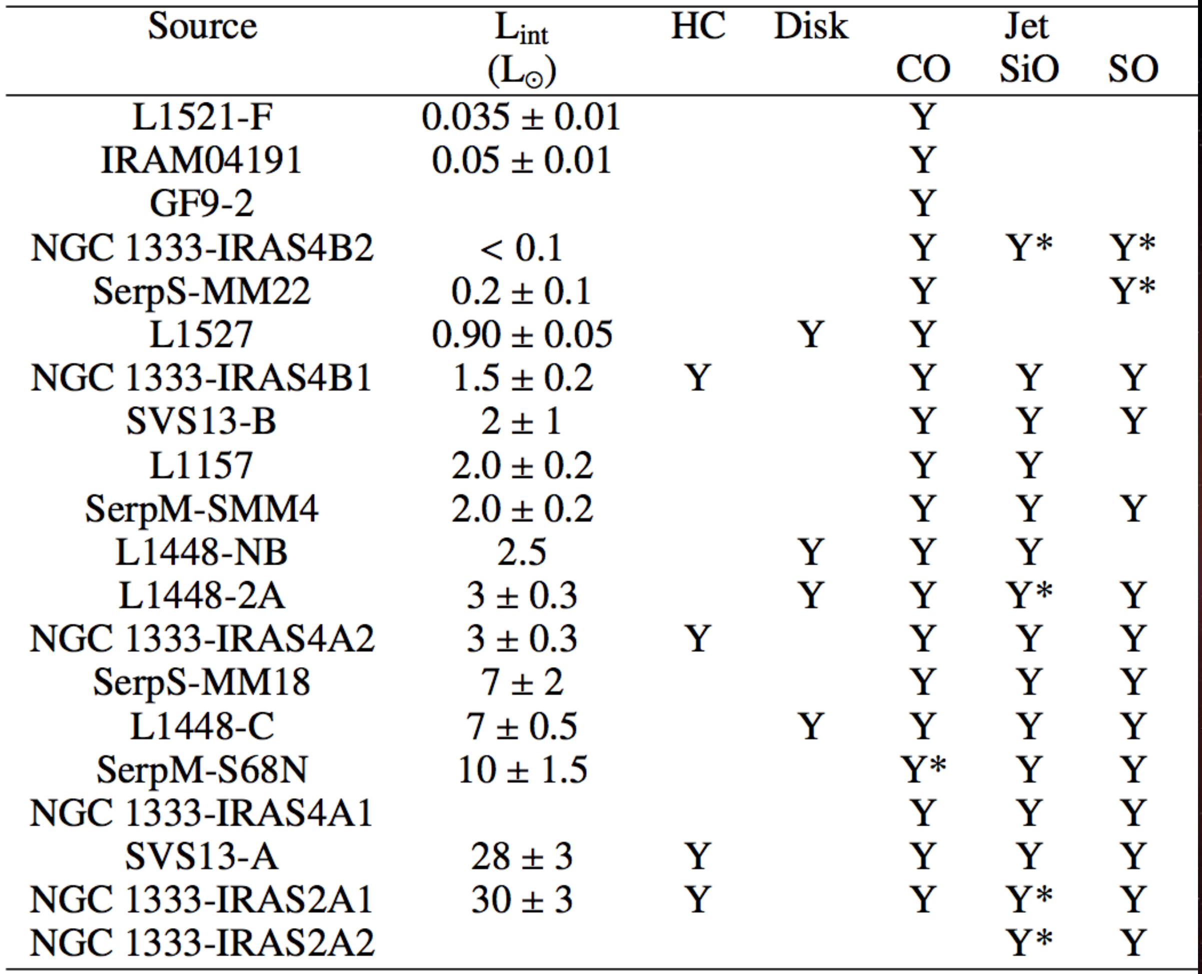
CALYPSO:
the Plateau de Bure Large Program on Class 0 protostars



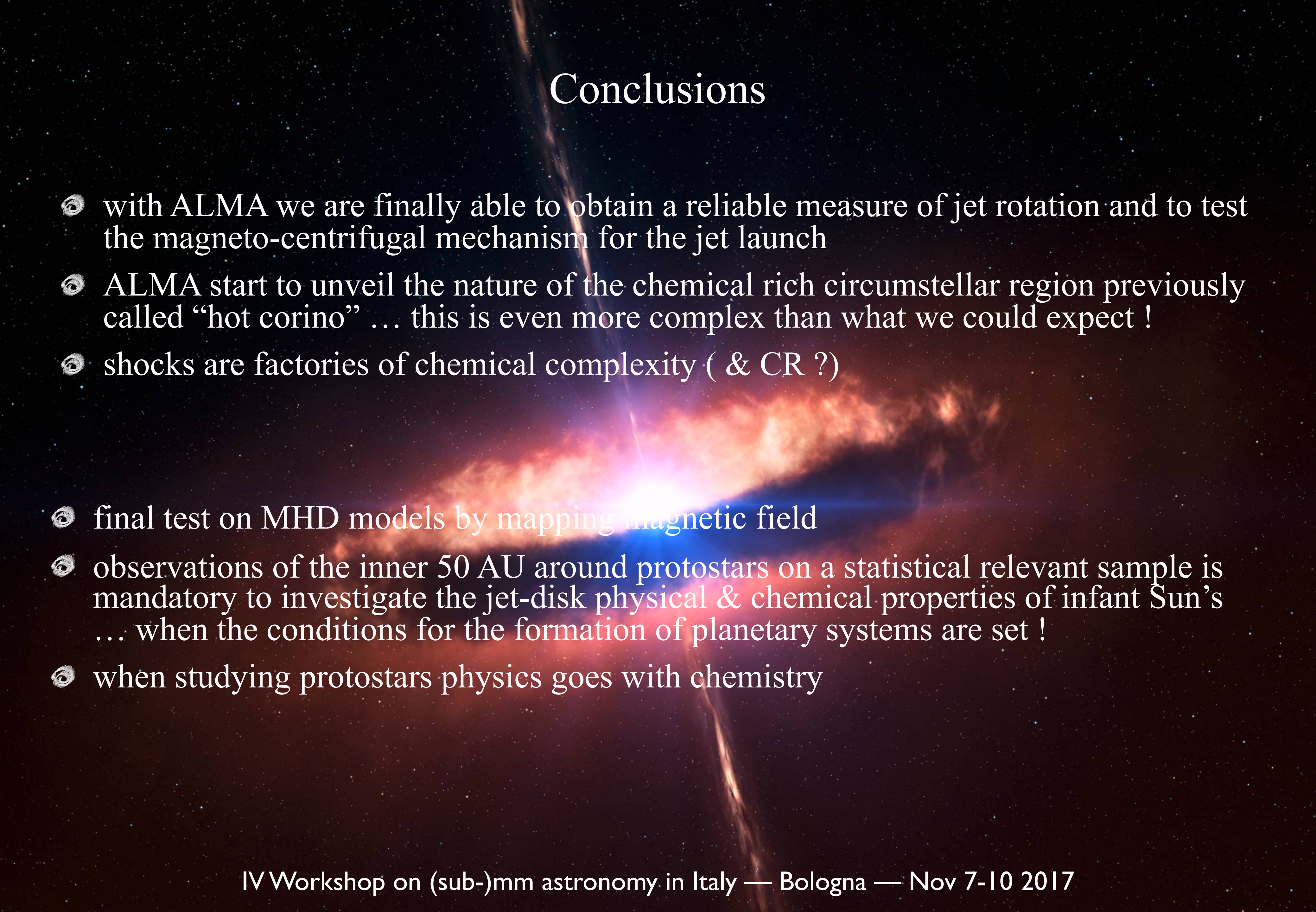
ARE jets ubiquitous at the protostellar stage ??

CALYPSO survey
Codella+ 2014
Santangelo+ 2015
Podio+ 2016

see also Tobin+ 2016
survey of CO outflows
with CARMA



Source	L_{int}	HC	Disk	Jet		
	$(L_\odot)$			CO	SiO	SO
L1521-F	0.035 ± 0.01			Y		
IRAM04191	0.05 ± 0.01			Y		
GF9-2				Y		
NGC 1333-IRAS4B2	< 0.1			Y	Y*	Y*
SerpS-MM22	0.2 ± 0.1			Y		Y*
L1527	0.90 ± 0.05		Y	Y		
NGC 1333-IRAS4B1	1.5 ± 0.2	Y		Y	Y	Y
SVS13-B	2 ± 1			Y	Y	Y
L1157	2.0 ± 0.2			Y	Y	
SerpM-SMM4	2.0 ± 0.2			Y	Y	Y
L1448-NB	2.5		Y	Y	Y	
L1448-2A	3 ± 0.3		Y	Y	Y*	Y
NGC 1333-IRAS4A2	3 ± 0.3	Y		Y	Y	Y
SerpS-MM18	7 ± 2			Y	Y	Y
L1448-C	7 ± 0.5		Y	Y	Y	Y
SerpM-S68N	10 ± 1.5			Y*	Y	Y
NGC 1333-IRAS4A1				Y	Y	Y
SVS13-A	28 ± 3	Y		Y	Y	Y
NGC 1333-IRAS2A1	30 ± 3	Y		Y	Y*	Y
NGC 1333-IRAS2A2					Y*	Y



Conclusions

- with ALMA we are finally able to obtain a reliable measure of jet rotation and to test the magneto-centrifugal mechanism for the jet launch
- ALMA start to unveil the nature of the chemical rich circumstellar region previously called “hot corino” … this is even more complex than what we could expect !
- shocks are factories of chemical complexity (& CR ?)

- final test on MHD models by mapping magnetic field
- observations of the inner 50 AU around protostars on a statistical relevant sample is mandatory to investigate the jet-disk physical & chemical properties of infant Sun’s … when the conditions for the formation of planetary systems are set !
- when studying protostars physics goes with chemistry