AO-assisted high angular resolution observations of protostellar jets

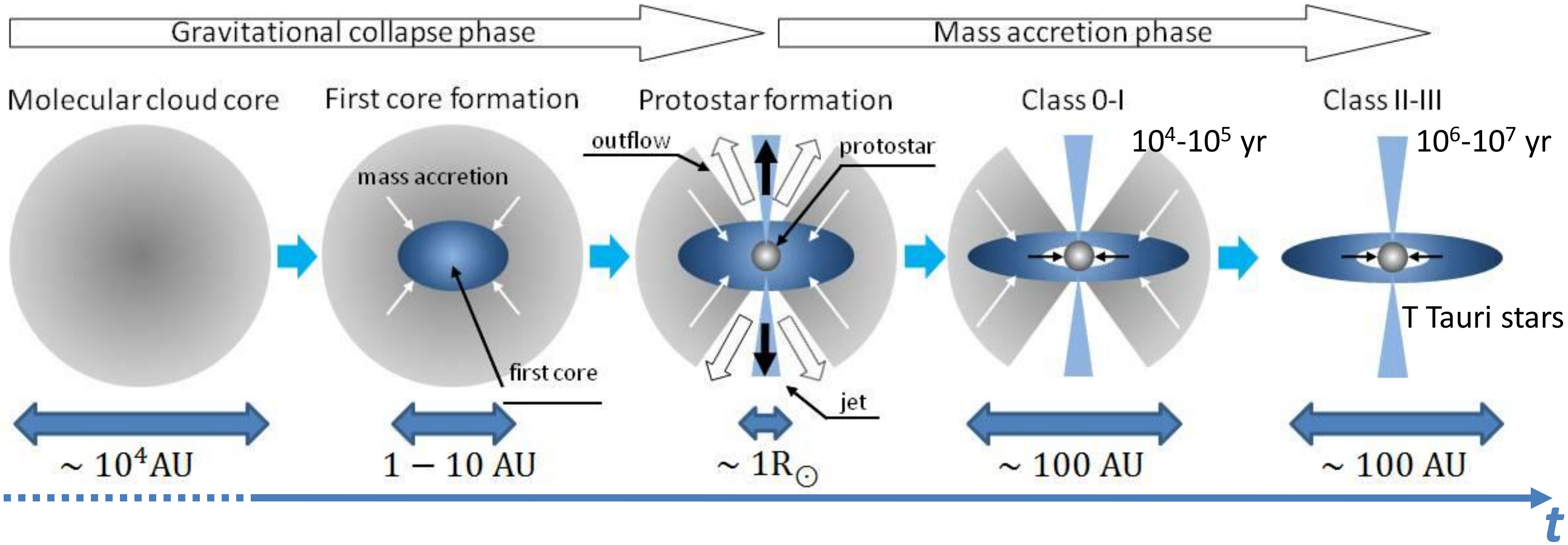
Sub-0.1arcsec optical observations of the young binary Z CMa with SPHERE

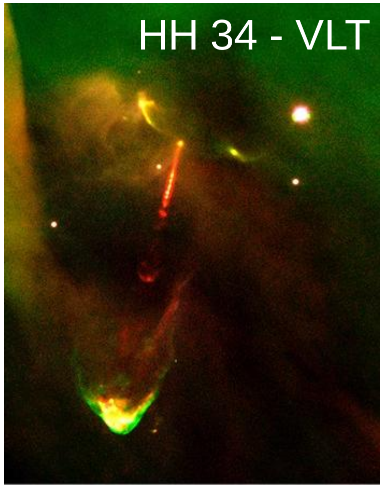
Simone Antoniucci (INAF – OARoma)

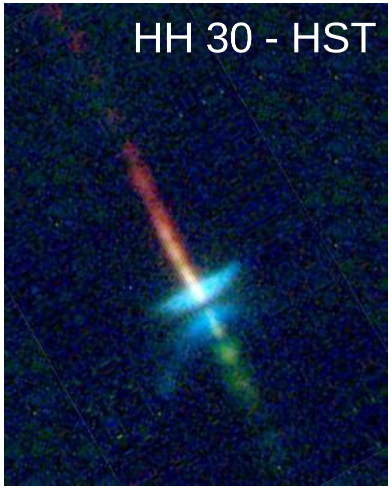
Collaborators:

L. Podio, F. Bacciotti (INAF-Arcetri), B. Nisini, T. Giannini (INAF- OARoma),
E. Sissa, R. Gratton, M. Turatto, S. Desidera (INAF-OAPd),
A. La Camera (DIBRIS – UniGe), E. Lagadec (Côte d'Azur),
B. H.M. Schmid , A. Bazzon (ETH Zurich),
C. G. Chauvin, M. Bonnefoy, C. Dougados (IPAG-Grenoble),
D. and the SPHERE Consortium

Protostellar jets



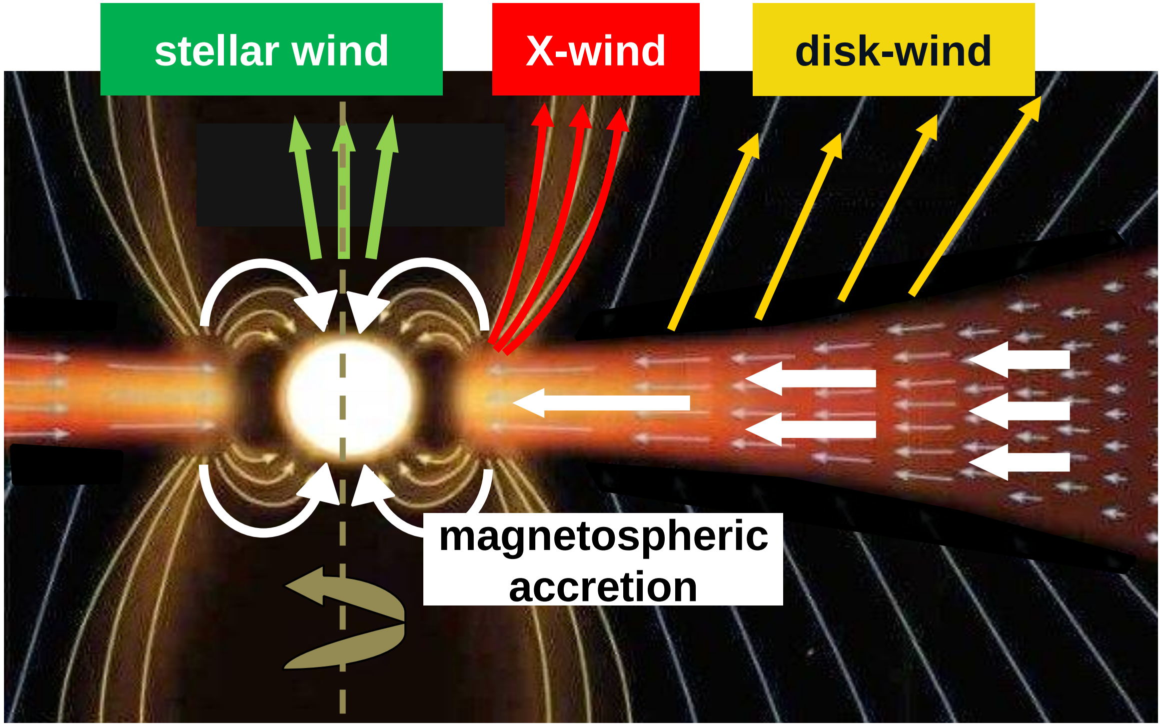




- fundamental for angular momentum removal
- excavate and disperse parental envelope
- likely affect disk structure and composition (and indirectly planet formation)

Jet-disk connection

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



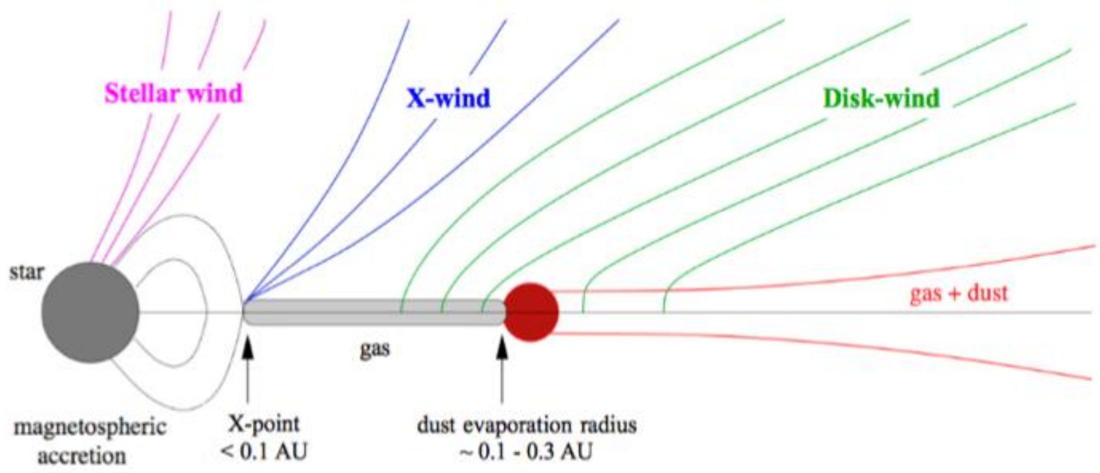
STELLAR WIND
Sauty+ 2002

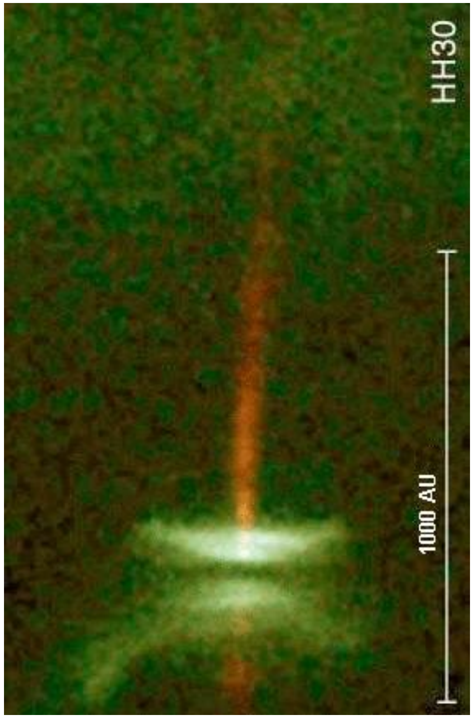
X-WIND
Shu+ 1994, 2000
< 0.1 AU

DISK WIND
Konigl & Pudritz 2007
1-10 AU

Open questions:
- What is the jet launching mechanism?
- What is the jet feedback on the disk?

Jets: scientific aims





Goals

- Understand **HOW** the jet is launched
- Understand **IF** and **HOW** the jet affects the disk structure
- Find direct evidence for **accretion and ejection events connection**

→ can we identify emission knots launched during enhanced accretion phases (outbursts?)

Needs

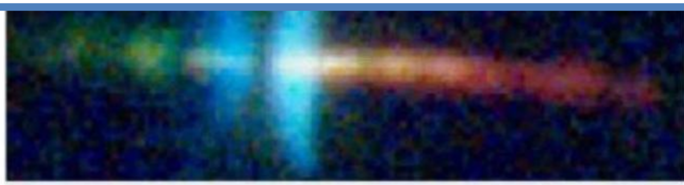
- Image the jet down to few AUs from the source (closest objects at ~150 pc)

→ **high spatial resolution** (< 0.1arcsec), **high contrast** (10^2 –10^5) images

Previous high-angular-resolution observations of jets

Typical limitations of previous high-angular-resolution observations:

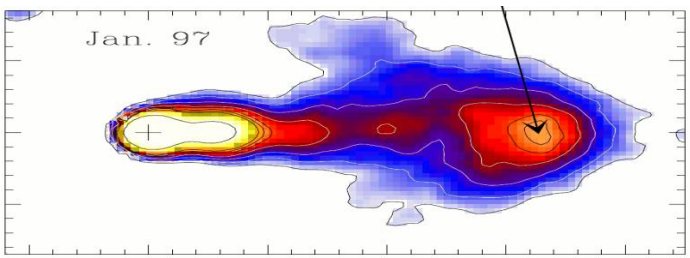
- Angular resolution ≥ 0.1 arcsec
- Poor contrast for bright sources, e.g. Herbigs
- Coronagraphs ≥ 0.3 arcsec



Narrow-band imaging

HH 30 with HST
~ 0.1”

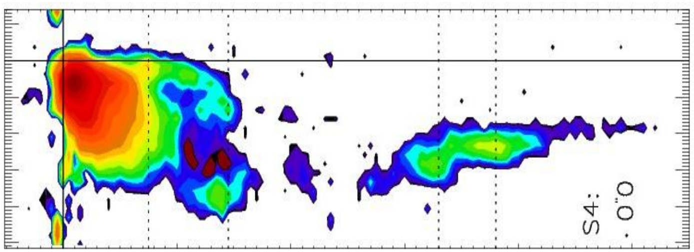
Ray+ 1996, Bacciotti+ 1999



AO imaging
[S II] 6731 A

DG TAU with CFHT
~ 0.1”

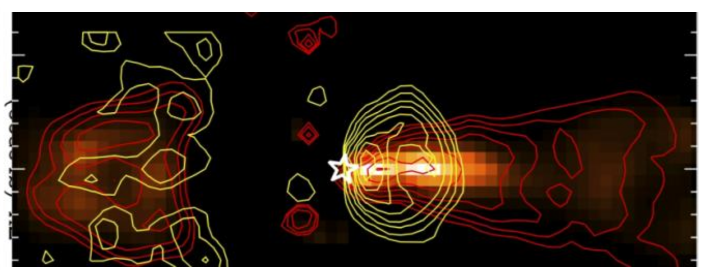
Dougados+ 2000



long-slit spectrum
[S II] 6731 A

DG TAU with STIS/HST
~ 0.1” - R=6000

Maurri+ 2014

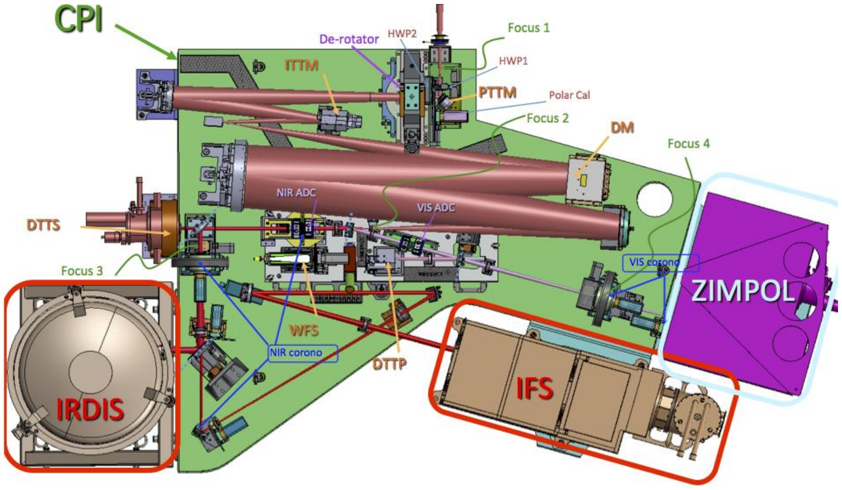


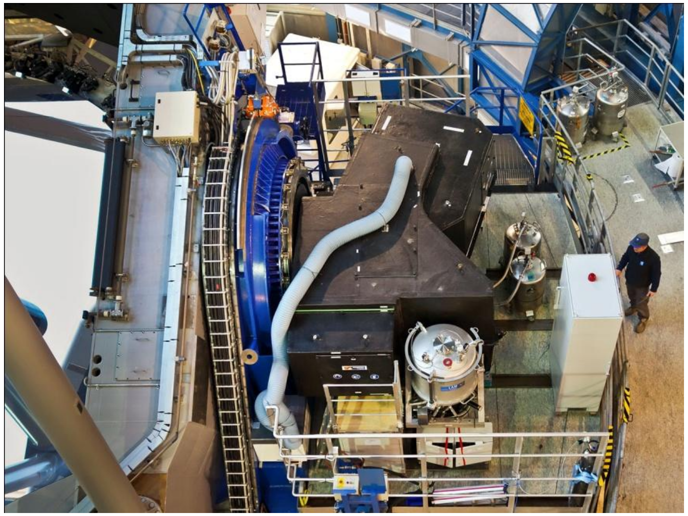
IFU image
[Fe II] + H_2

DG TAU with SINFONI
~ 0.2” - R=3000

Agra-Amboage+ 2014

SPHERE@VLT





- Extreme AO system and coronagraphic facility of the VLT.

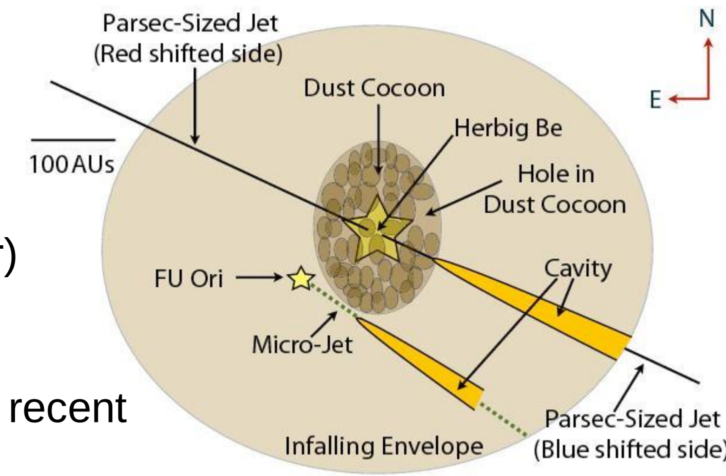
- Common AO infrastructure (CPI+SAXO) feeding 3 instruments:
  > ZIMPOL (optical imager and polarimeter)
  > IRDIS (NIR imager and spectrograph)
  > IFS (NIR integral field spectrograph)

- Mainly devoted to exoplanet search.
- Observations of jets included in GTO “other science” (PI Antoniucci & Podio)

First target: Z CMa and its twin jets

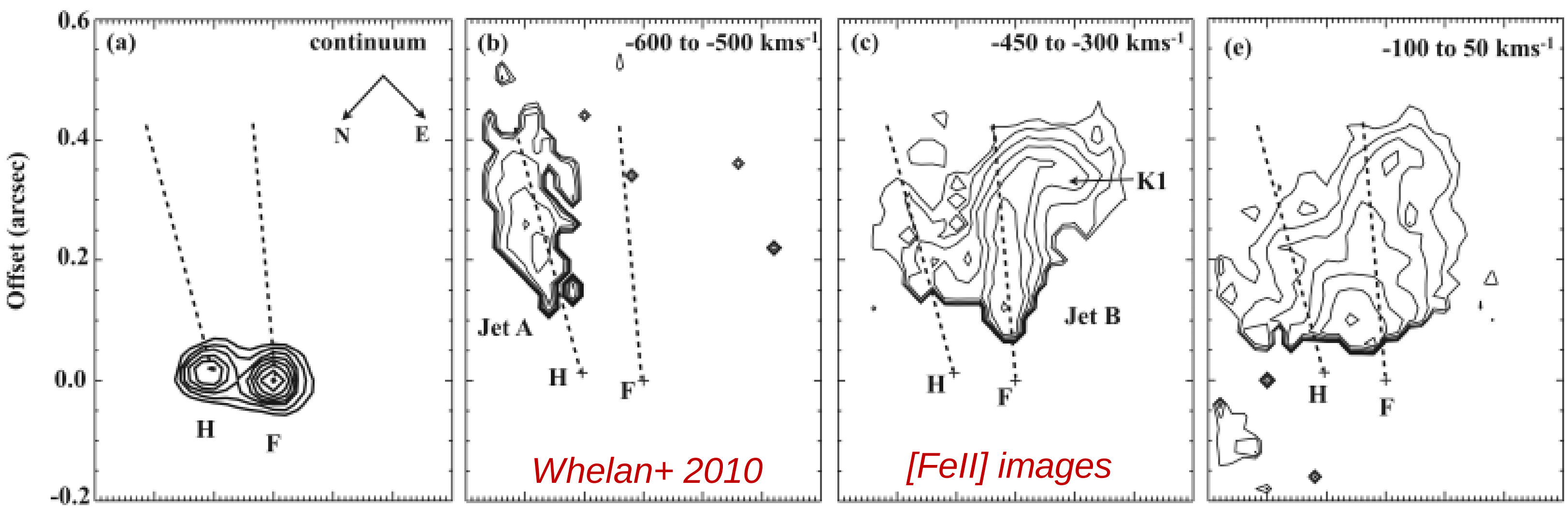
- V = 8.8 mag, K = 4.5 mag, d~1150 pc
- Binary system (0.1” sep)

1 - **Herbig Be star** (intermediate mass young star)
2 - **FU Ori star** (young eruptive star with massive disk, undergoing strong accretion outburts (~10^4-10^5 M_{sun}/yr) with duration ~10^2 yr)



Canovas+ 2012

- The Herbig component has recurrent outbursts: most recent ones in 2008, 2010, 2015 (enhanced accretion events)
- **Each component drives a jet** detected in optical and NIR lines



Whelan+ 2010

[FeII] images

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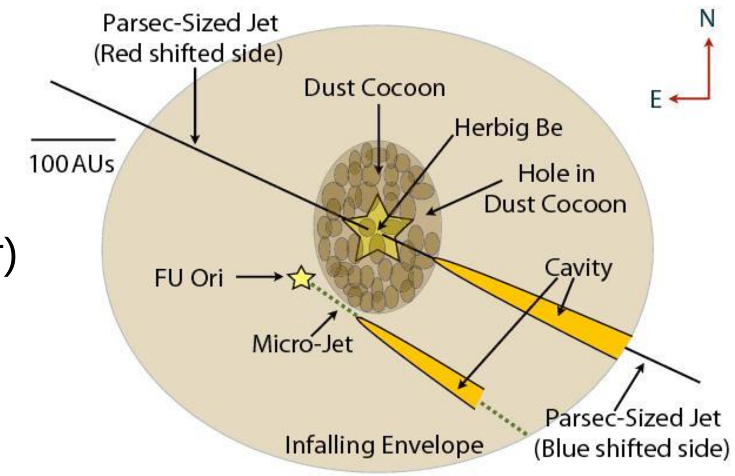


Canovas+ 2012

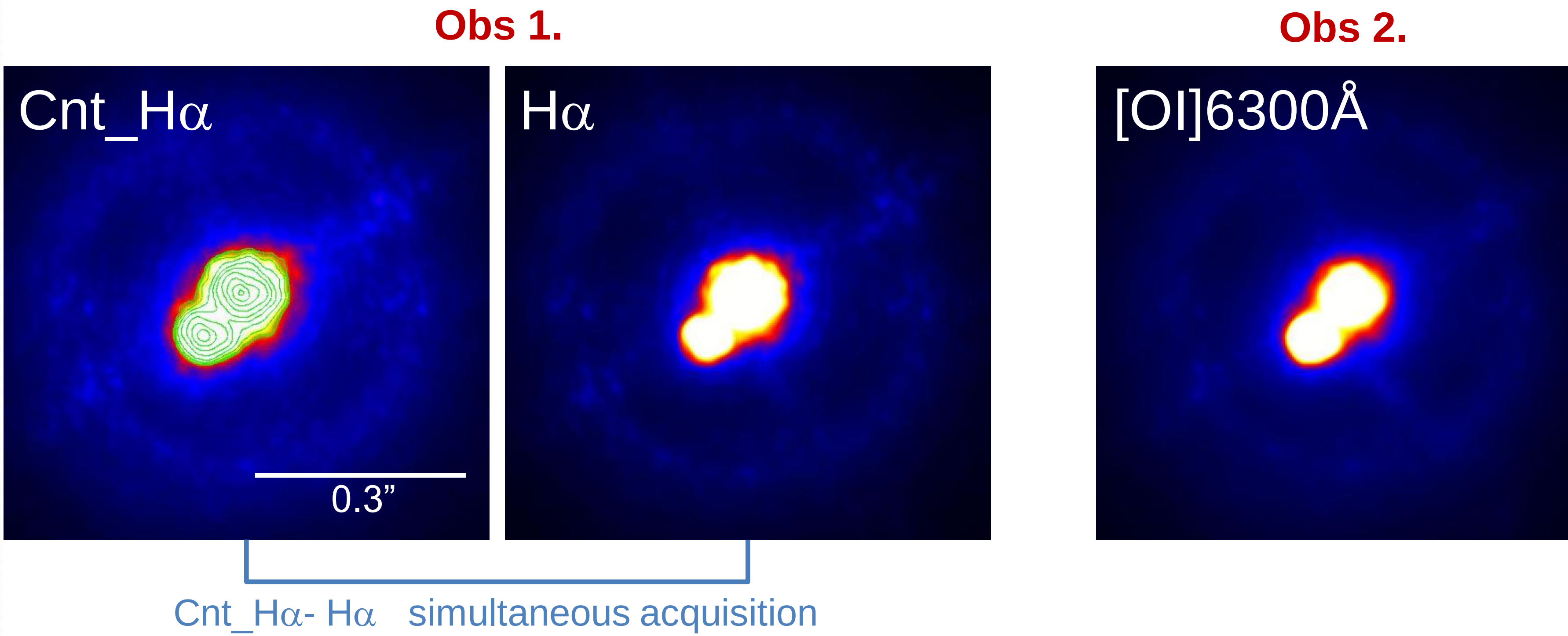
Despite distance Z CMa is a unique laboratory to:

• investigate **connection between accretion and ejection** events

• test the magneto-centrifugal scenario and universality of MHD models for intermediate mass stars and FU Ori objects:
→ by measuring **collimation** and **accretion/ejection efficiency** (M_{loss}/M_{acc}) and from comparison with jets from low-mass stars (T Tauri stars)

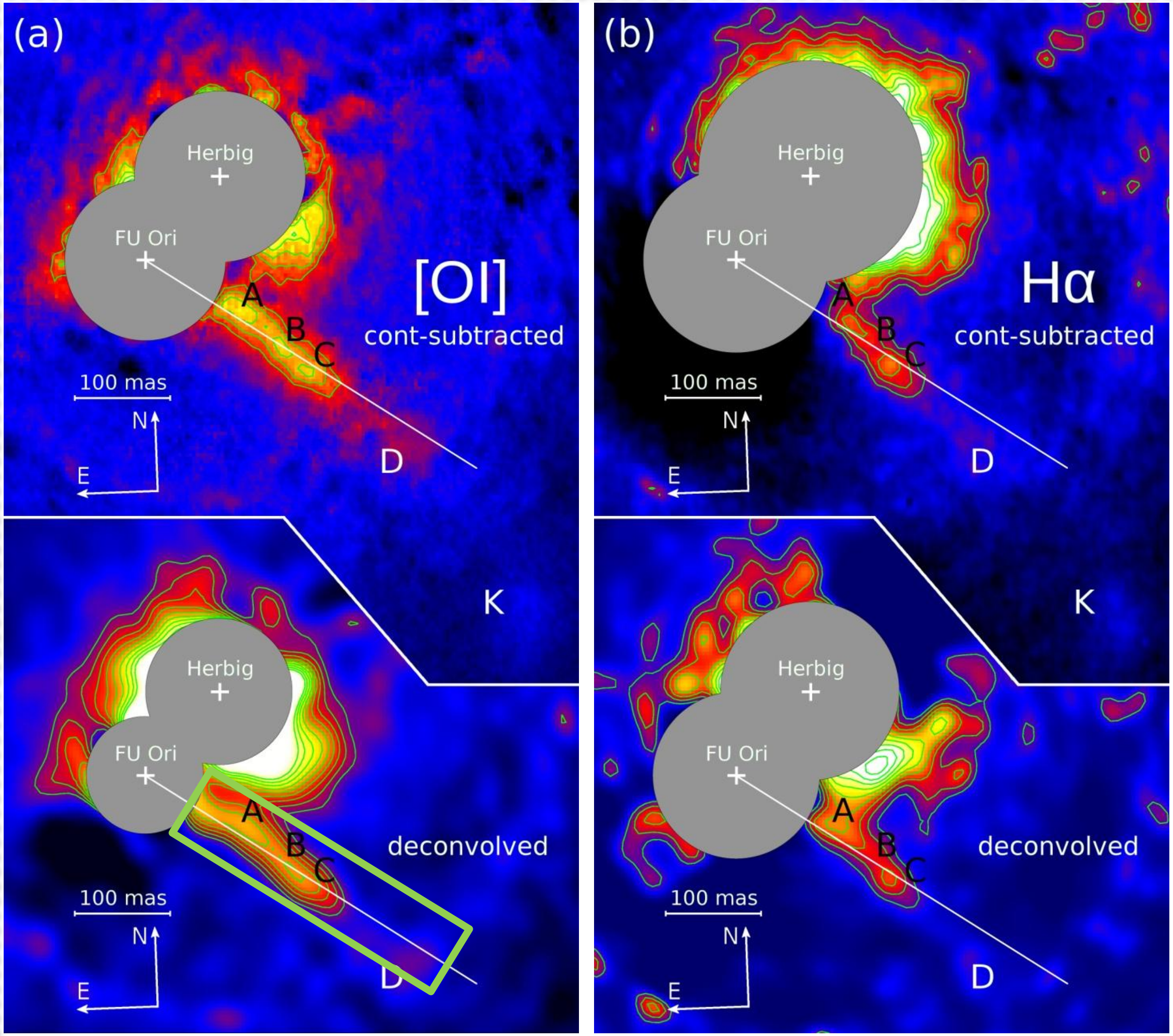
• study **ejection in FU Ori objects** (no direct M_{loss} determinations from jets observed close to the source)

Z CMa ZIMPOL observations



- narrow-band imaging ($\Delta\lambda \sim 5$ nm), pixel-scale = 3.6 mas/pix
- exposure time = 30 min (frames with DIT of 30s)
- field-stabilized mode
- average seeing during observations ~ 1.0 arcsec, fairly stable conditions

[OI] and Hα images



Antoniucci+ 2016

Tech 1.

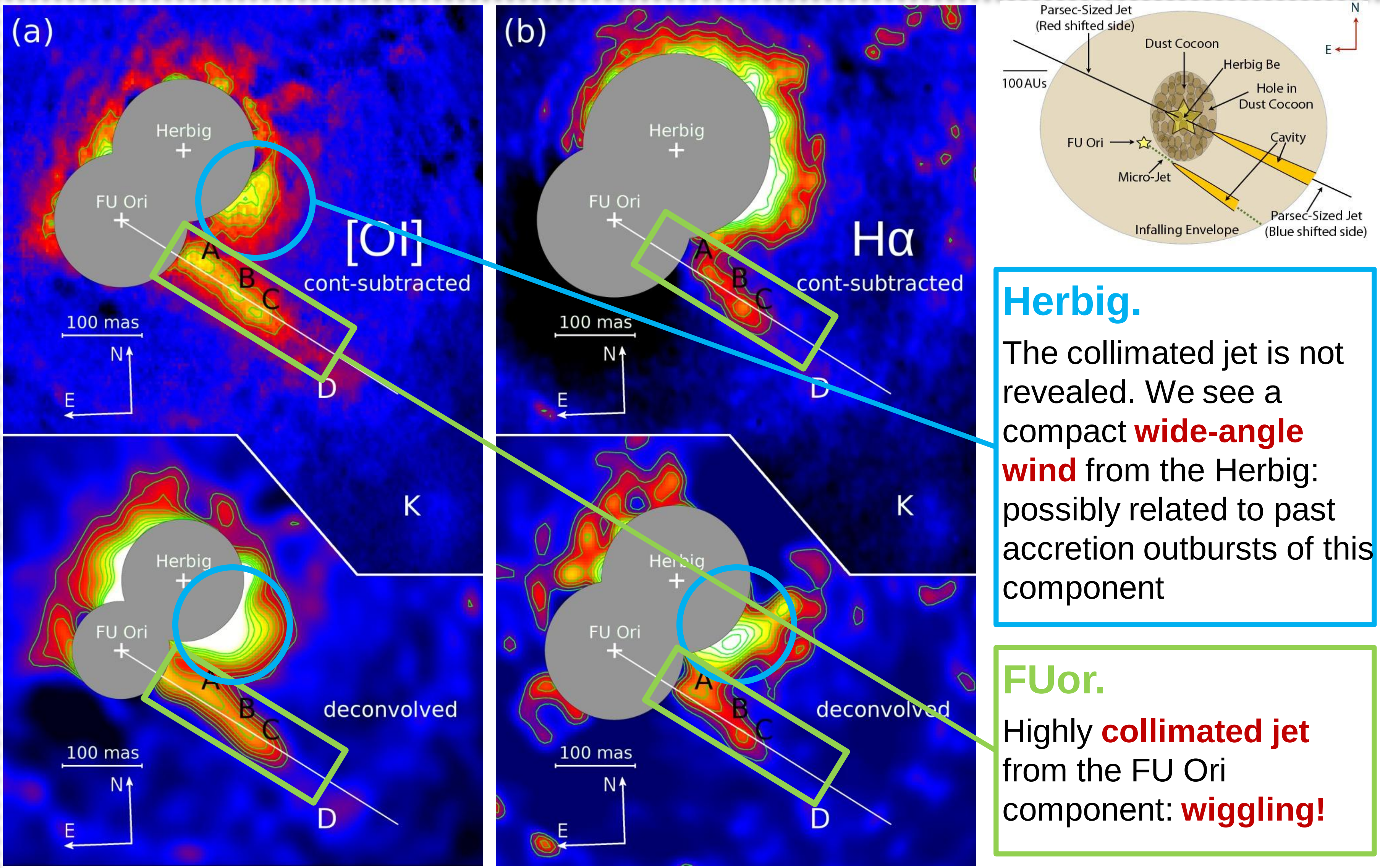
Subtraction of the Cnt_Hα exposure to remove stellar continua

Tech 2.

Deconvolution with the MC-RL method of *La Camera+ 2014*

(reconstructs star + diffuse emission)

[OI] and Hα images



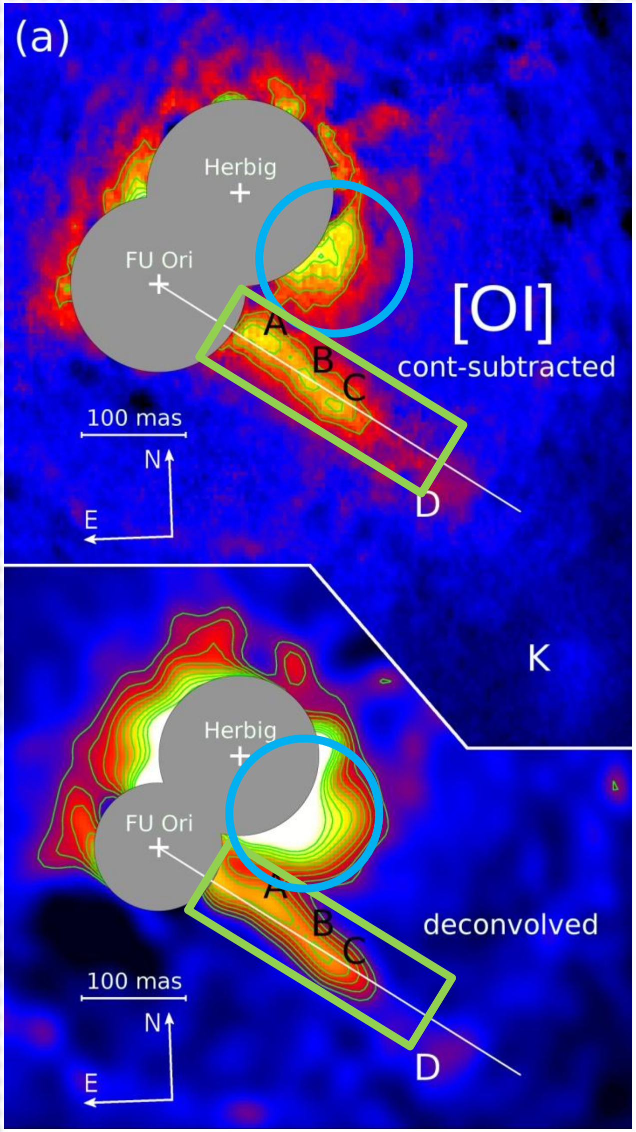
Herbig.

The collimated jet is not revealed. We see a compact **wide-angle wind** from the Herbig: possibly related to past accretion outbursts of this component

FUor.

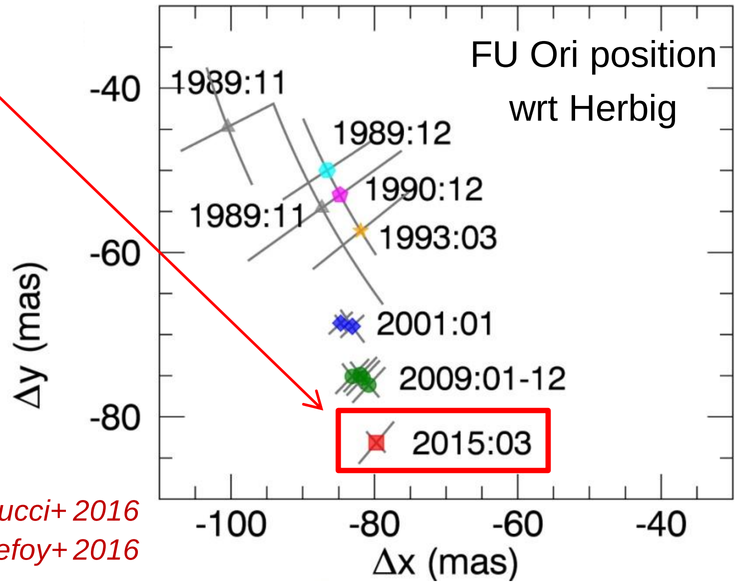
Highly **collimated jet** from the FU Ori component: **wiggling!**

ZIMPOL images



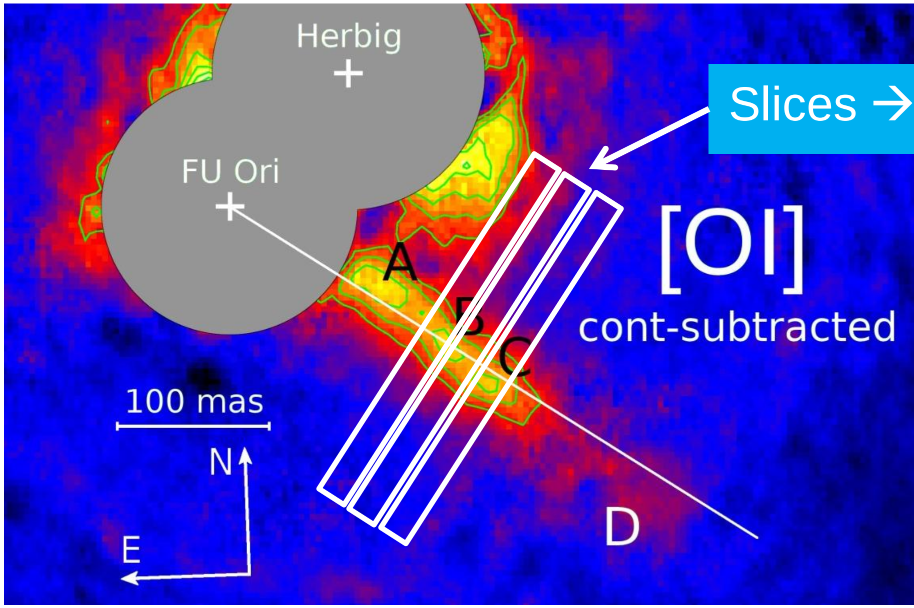
Some numbers:

- at Z CMa distance 1 mas = 1.15 AU
- effective resolution ~ 30 mas
- effective (source-jet) contrast ~ 10^3
- trace the jet down to ~70-80 mas (~80-90 AU)
- S/R (FUor jet) > 10
- <u>binary separation</u>: 114 mas, P.A. 136°



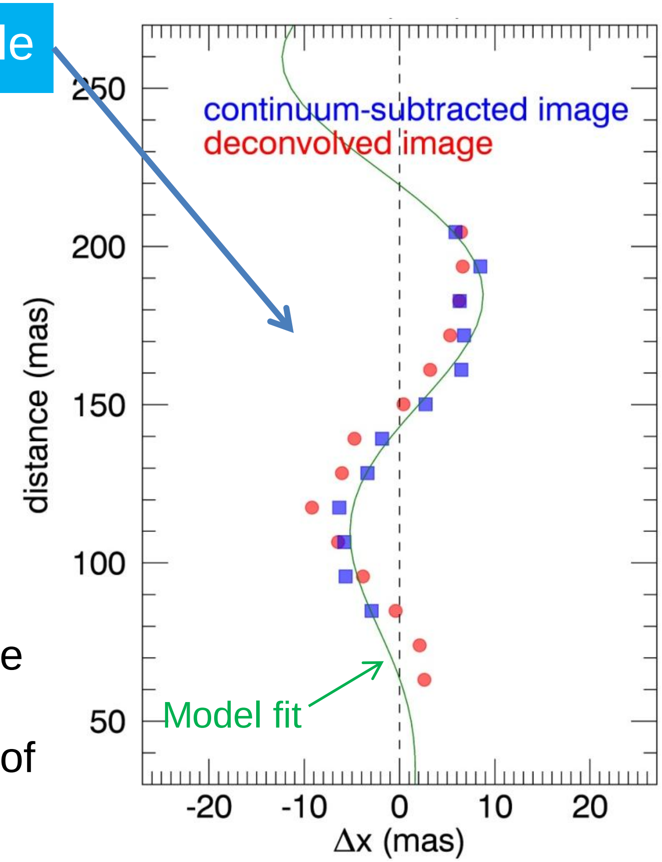
Antoniucci+ 2016
Bonnefoy+ 2016

The jet from FU Ori component



Slices → jet profile

1. Jet profile peak



Antoniucci+ 2016

Jet wiggling: likely originates from **orbital motion** of the jet source around an undetected companion. Using a simple model (*Anglada+ 2007*) we infer the parameters of the binary:

T_o= 4.5 yr, r_o=1.3 AU
with M_{tot} = 1-3 M_{sun} → a = 2.7-3.9 AU, m_1-m_2 = 0.5-0.5 M_{sun} – 2.0-1.0 M_{sun}

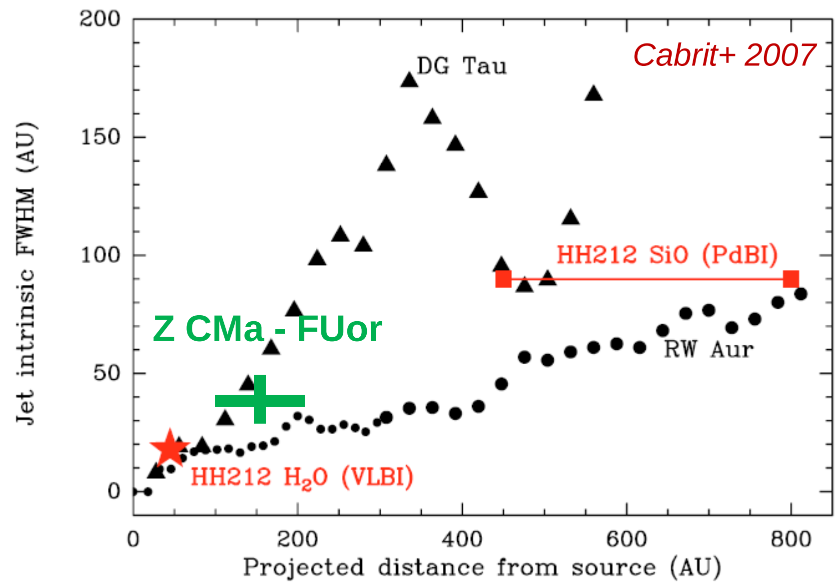
The jet from FU Ori component

2. Jet profile width (FWHM)

- FWHM of jet profile → ~30-50 mas

- **Collimation** comparable with that observed in other classes of young sources with jets (Class 0/I, T Tauri)

- Indicates **that launching mechanism is the same** (magneto-centrifugal) even in sources with massive disks like FU Ori objects!



3. M_{loss} and M_{acc}

- **First** direct **measurement of M_{loss} in FU Ori** objects!
→ from [OI] flux (*e.g. Hartigan+ 1995, Giannini+ 2015*) → M_{loss} = 5 10^{-7} M_{sun}/yr

- In MHD models expected M_{loss}/M_{acc} between 0.01-0.2 (*e.g. Ferreira+ 2006*) → indicates M_{acc} between 3 10^{-6} M_{sun}/yr (not consistent with previous estimates) and 5 10^{-5} M_{sun}/yr (consistent) → possible **indication for low ejection efficiency** in FU Ori obejcts

AO-assisted observations of jets

Jets are wonderful scientific targets for AO-assisted instruments

- **The closer we go, the better it is!** To study the base of the jet within 10 AU in closest star-forming regions (150 pc) → go **below 70 mas** angular resolution!
- With this unprecedented resolution:

→ measure jet collimation, disentangle jet formation and launching mechanism

→ probe interaction with disk

→ directly connect accretion and ejection events

- … But central star typically has **R ≥ 11-12 mag**
- Expected **contrasts 10^3 – 10^5**
- Important tracers in the optical: e.g. [OI] 6300Å, [SII] 6716Å & 6731Å, Hα
- Best scenario: couple the high-angular-resolution with high-spectral resolution!

What's next

- Observations of classical T Tauri jets with SPHERE (DG Tau, T Tau)
- Simulations of jet observations with **SHARK-VIS** and **SHARK-NIR** @LBT

Thank You