Osservatorio Astrofisico di Arcetri (INAF-OAA)

The Fifth National Workshop on the SKA Project - Bologna, 24-28 November 2025
From precursors to SKAO: shaping the future of Italian radio astronomy

Jets and outflows in young stellar objects in the SKAO Era

Giovanni Sabatini (INAF - OAA)

The team: Busquet G., Carrasco-González C., Rodríguez-Kamenetzky A., **Codella** C., **Podio** L., Martínez-Henares A., Girart J. M., De Simone M., Cacciapuoti L., Tychoniec L., **Giani** L., Puravankara M., Anglada G., **Bacciotti** F., Bachiller R., **Bianchi** E., Bourke T., **Bovino** S., Caselli P., **Cavallaro** F., Ceccarelli C., Diaz-Marquez E., Facchini S., **Garufi** A., Guidi G., Hirota T., Ilee J., **Ingallinera** A., Jiménez-Serra I., Lattanzi V., Lee C.-F., **Lippi** M., Lupi A., Majumdar L., Narang M., Osorio M., **Padovani** M., Pineda J., Radley I., Riaz B., Rodríguez L. F., Sánchez-Monge Á., **Sanna** A., Spezzano S., **Testi** L., Toci C., **Traficante** A., Tyagi H., & **Umana** G. M.

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cost European Cooperation in Science & Technology
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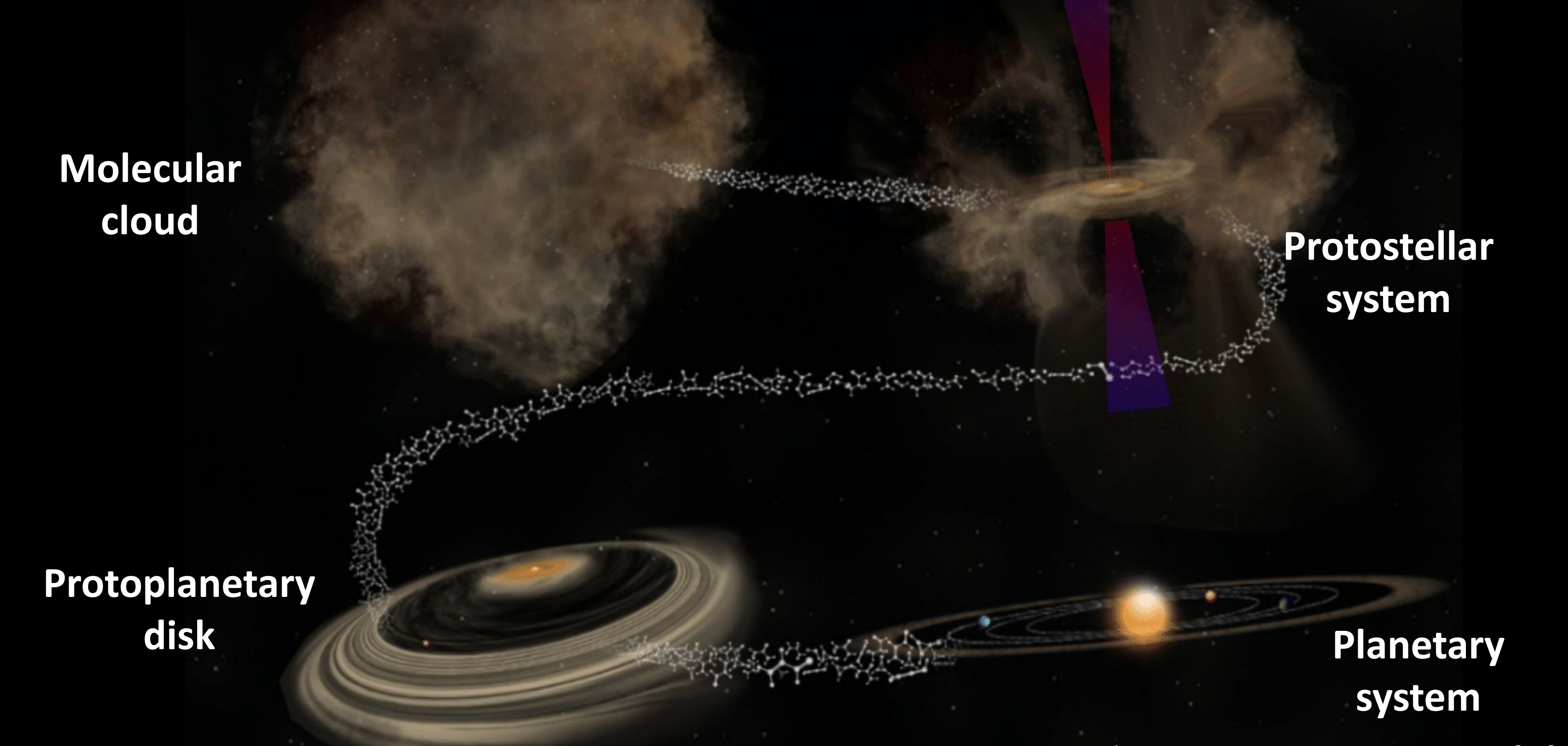
Context: Star & Planet formation

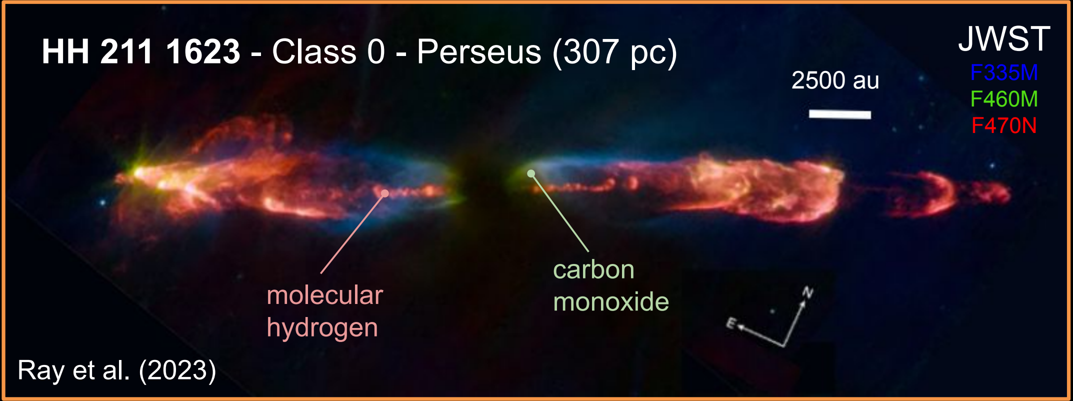


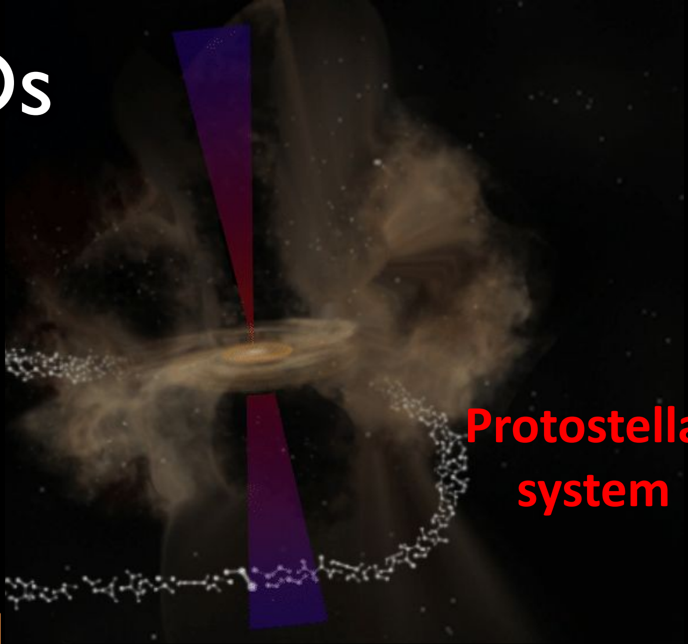
Jet and Outflows in YSOs

Ubiquitous in accreting YSOs of
all evolutionary phases

Optical jet
high velocity (~100 km s-1)
well-collimated structures

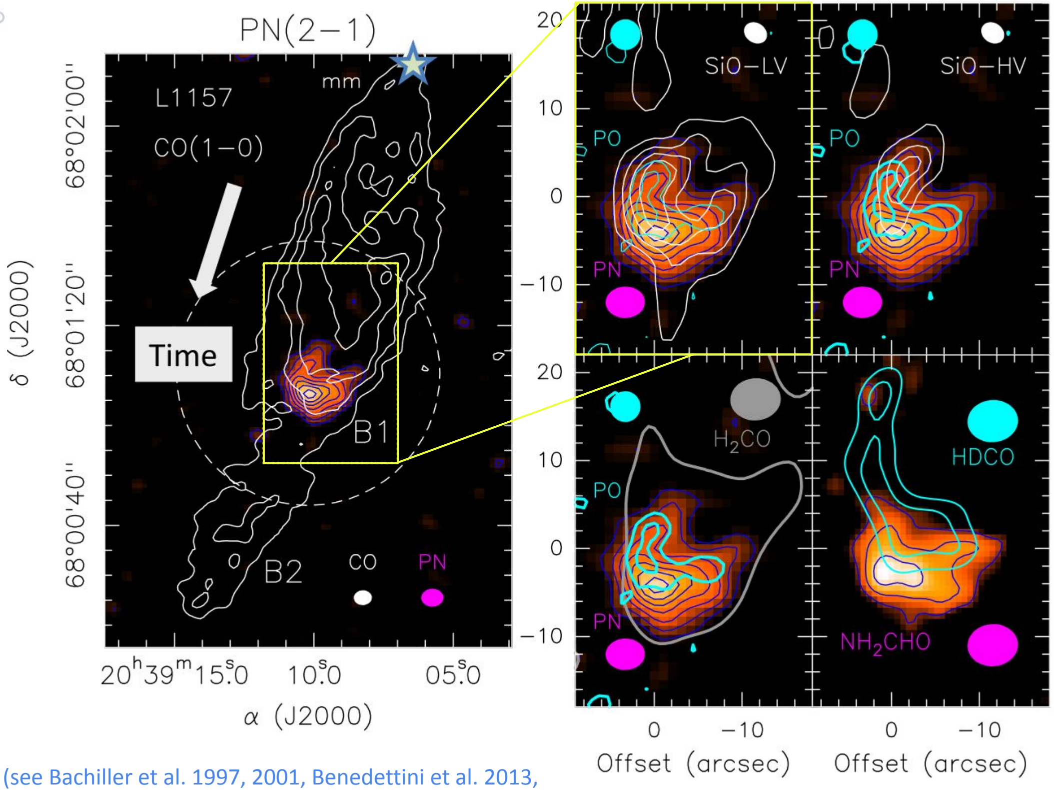
Molecular outflow
low velocity (~10 km s-1)
wide opening angle

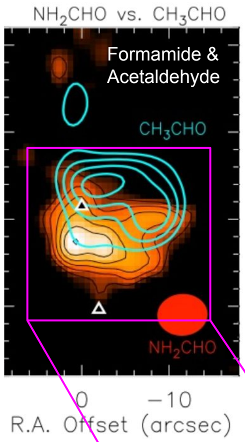


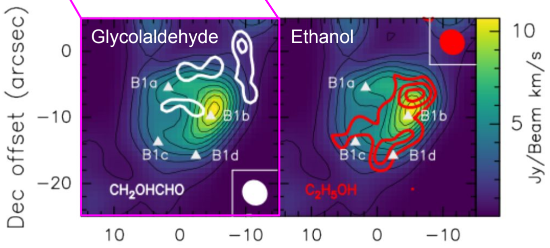


- **Remove angular momentum** from the disc→allow disc-protostar accretion
- Bring **chemically "*rich*" material into the envelope**
- **Outflow-envelope interaction**: shocks →grains sputtering/shattering envelope dispersion → final stellar mass
- **Dust recycling**

Chemical complexity in shocks by Codella, De Simone et al.







(Ceccarelli et al. 2017)

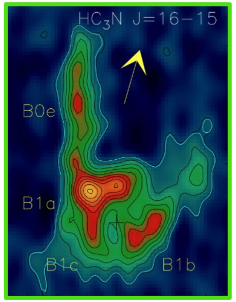
Shock regions are astrochemical laboratories!!

iCOMs → released from the grain or formed in gas phase?

(see Bachiller et al. 1997, 2001, Benedettini et al. 2013, Codella et al. 2017, 2020, Lefloch et al. 2024, Lopez-Sepulcre et al. 2024, and Robuschi et al. 2025)

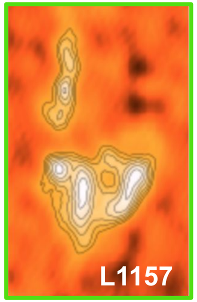
Carbon-chains and rings by Sabatini, Bianchi, Giani et al.

HC_3N (16-15)



(Benedettini et al. 2013)

CCH lines

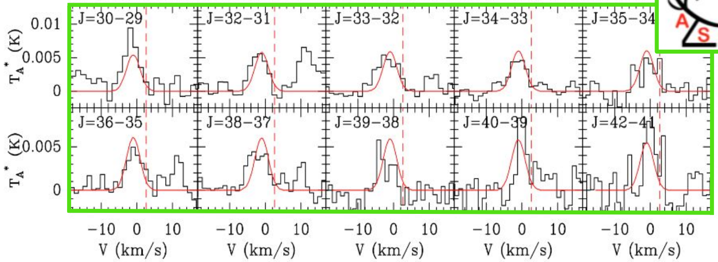


(Codella et SOLIS in prep)

Cyanopolyynes probe gas-phase chemistry & dust grain sputtering in shocks

Key role in setting the chemistry of planet-forming regions

HC_5N lines (IRAM-30m @3mm)



HC_5N is detected with the IRAM-30m but never imaged.

(Mendoza et al. 2018)

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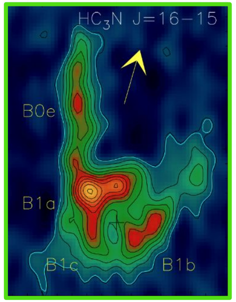

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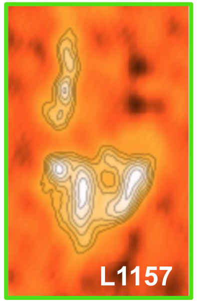

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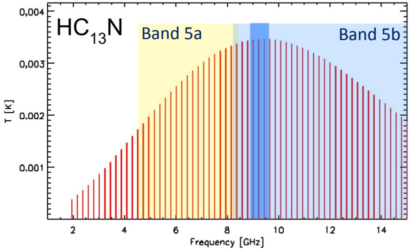
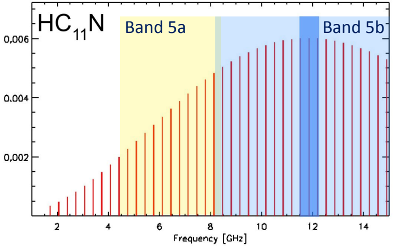
Cyanopolyynes probe gas-phase chemistry & dust grain sputtering in shocks

Large molecules peak at lower frequencies





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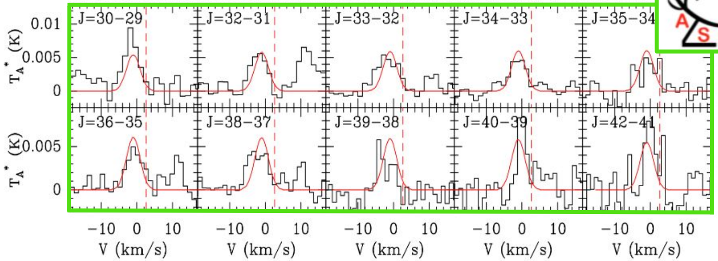

HC_5N is detected with the IRAM-30m but never imaged.

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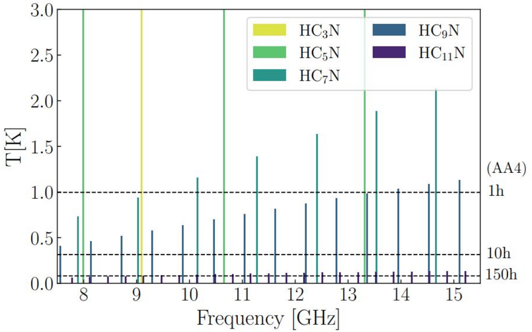
SKA-Mid Band 5b (AA4)



1st imaging > HC_5N with the SKAO

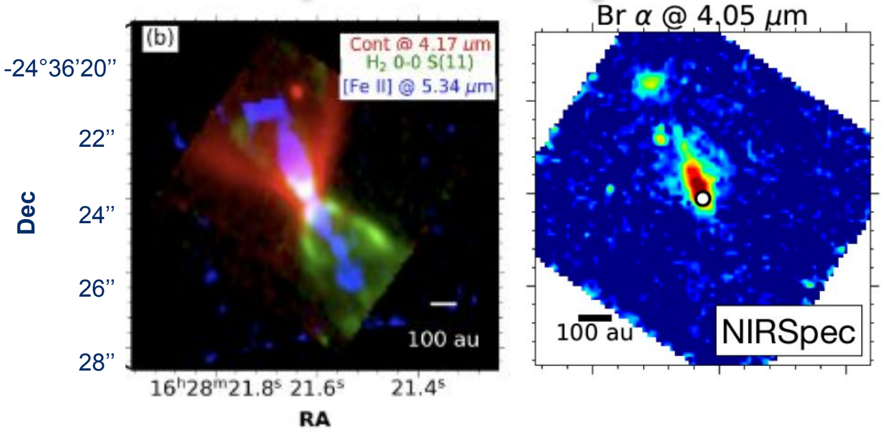
Spectral resolution:
13.44 kHz
(smoothed @1.5 km/s)

θ_{beam}~2.5"

Sensitivity
(3σ; @12GHz):
~1 K, ~0.3 K and ~0.09 K

LTE simulation with T=20 K, FWHM=4 km/s and extended source size
N(HC_3N)=1e16 cm^{-2}, N(HC_5N)=3e15 cm^{-2}, N(HC_7N)=8e14 cm^{-2}, N(HC_9N)=3e14 cm^{-2}, N($HC_{11}N$)=3e13 cm^{-2}

Ionised jet component (RRL) by Martínez-Henares, Tychoniec, Jiénez-Serra et al.



JWST revealed that even very low-mass and young sources can power an ionized jet

(e.g. Narang et al. 2023, van Dishoeck et al. 2025)

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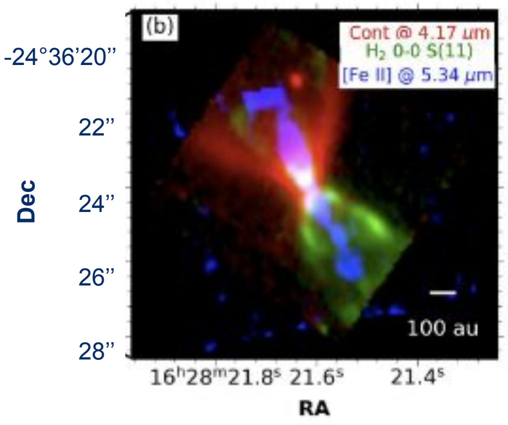

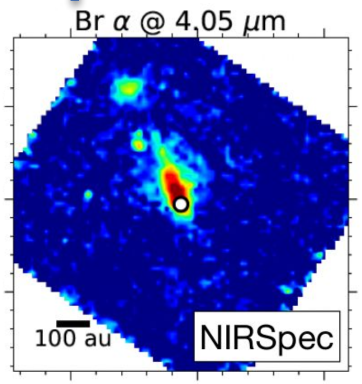

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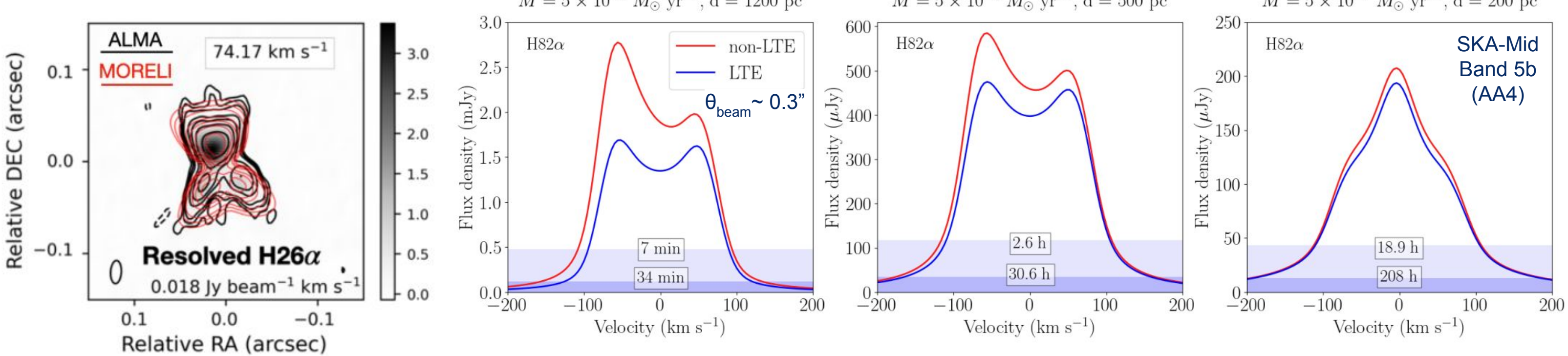
SKA-Mid B5b AA4 will push the detection of these lines closer to the source in < 3 hrs

(Martínez-Henares et al. 2023, 2024)



Hydrogen RRL predictions for SKA-AA4 by MORELLI-code

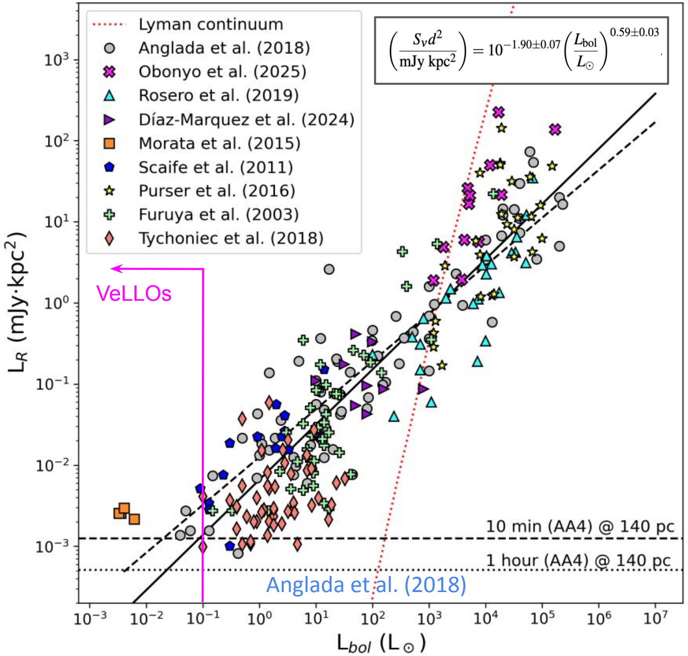
Thermal radio jets by Busquet, Carrasco-González et al.

Winds & jets are present across the full range of stellar masses

(also Anglada et al. 1995, 2015, Furuya et al. 2003, Kavak et al. 2021, Purser et al. 2021, Tychoniec et al. 2018)

Uncertain if launching-collimating mechanism is the same across different stellar masses and evolutionary stages.

SKA-Mid B5b-AA4 provides ~4 au resolution @200 pc:
characterization of faint jets and winds across the full mass spectrum (up to 1 kpc!!!)



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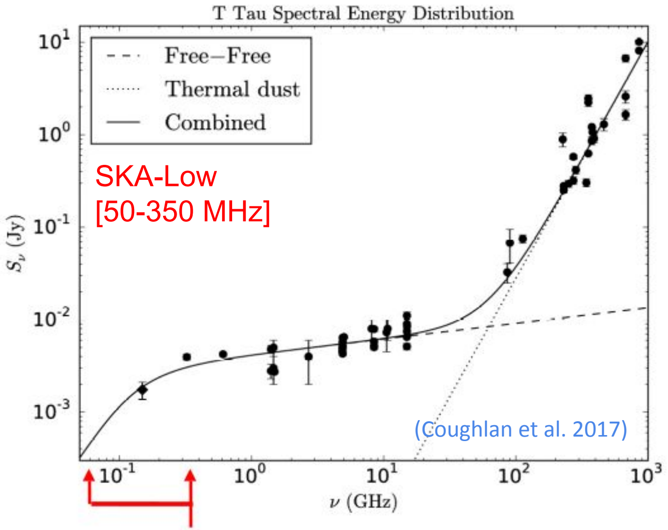
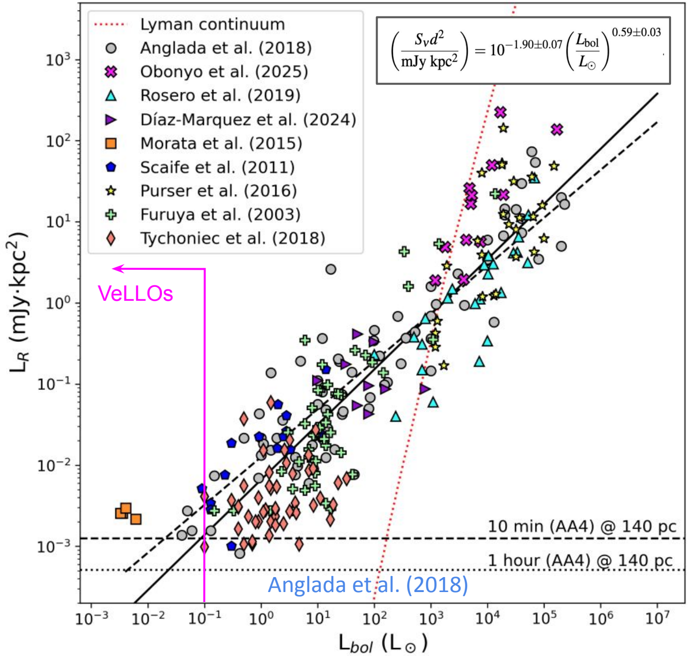


Turnover to constrain the X(e) and ionized gas-mass



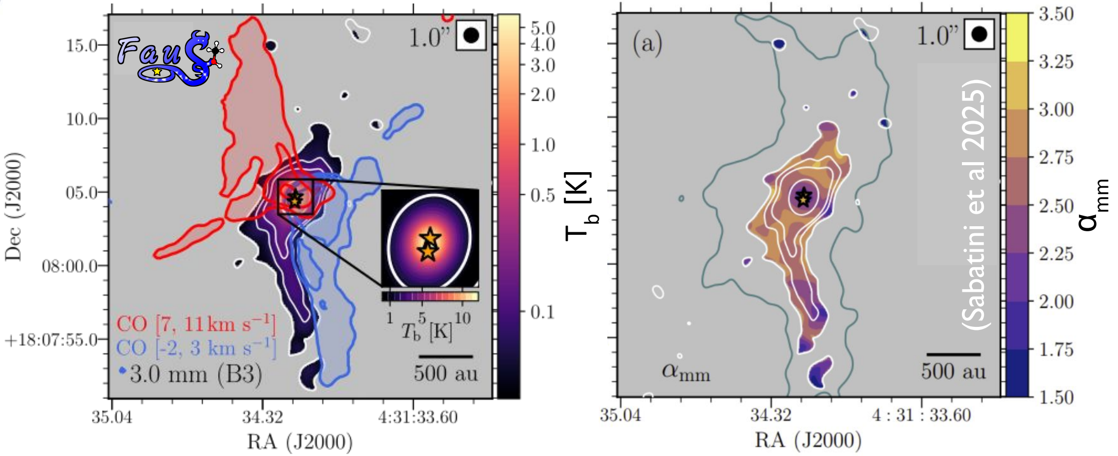
SKA-Low @ 200 MHz - 5 hrs ($L_{bol} > 1\ L_\odot$)

AA4 (512 stations) ⟶11✕sensitivity than LOFAR (beam <3.5”)

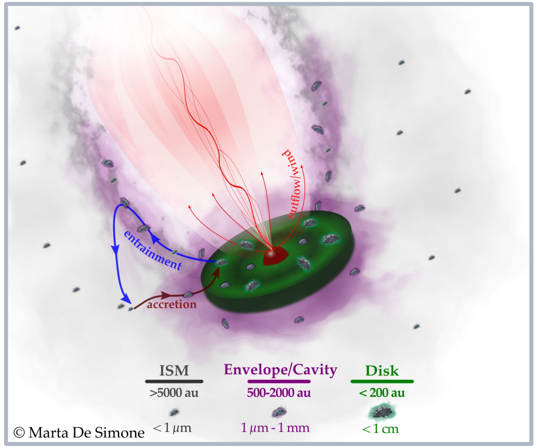
AA* (307 stations)⟶8✕ sensitivity than LOFAR (beam <5”)

Outflow dusty cavity walls by Sabatini, Cacciapuoti, Podio et al.

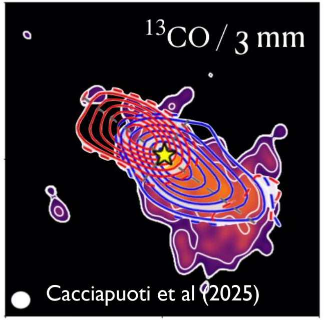
L1551-IRS5 - Class I Taurus (147 pc)

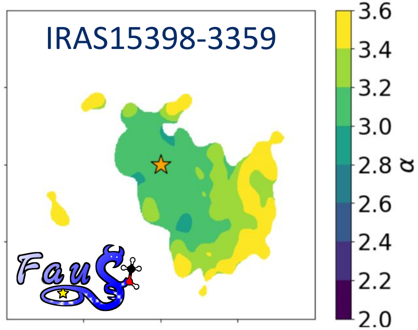


α≲ 3 ⟶ mm-sized grains



(NRAO press-release June 12th)





Alternative scenario to explain large grains in protostellar envelopes

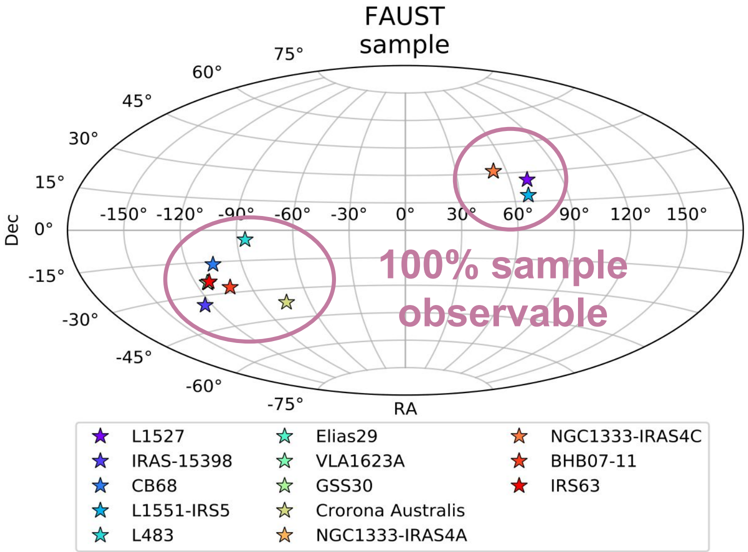
More time for the growth of grain in planetesimals

Free-free contamination @ 3mm?? (<20%)

(see Cacciapuoti et al. 2024, Giacalone et al. 2019, Tsukamoto et al. 2021, Bhandare et al. 2024, Sabatini et al. 2024, Uchimura et al. 2025)

Outflow dusty cavity walls by Sabatini, Cacciapuoti, Podio et al.

13 Sun-like star forming regions
ALMA Band 3 and 6 (x2)



≳ 50 Class 0 & I protostars

SKA-Mid (+MeerKAT) B5b AA4

Correlator: Continuum mode
Continuum Bandwidth: 5 GHz
Angular resolution: <1.0”
Sensitivity: ~0.4-0.9 μJy/beam @12 GHz
(>7-3σ from ALMA-B3, with α_{mm} ~ 2.5)
Int. time: ~10 hrs (13✕ faster than VLA!!)

SKAO TRAILS

Hun**T**ing la**R**ge-grains f**A**ctories **I**n protoste**L**lar outflow cavitie**S** with **SKAO**
(SKAO-TRAILS; PI: G. Sabatini)

Take-home messages

1. **Chemical complexity in shocks**
   - Search for heavy carbon chains
   - Full census of the chemistry in shocks revealing the refractory core components

2. **Ionised jet component**
   - SKA-Mid will push the detection of RRL closer to the YSOs

3. **Thermal radio jets**
   - Characterization of faint jets and winds across the full mass spectrum

4. **Outflow dusty cavity walls**
   - New large-grains factories!!
   - Unveil a key step in the formation of planetesimal and future planetary systems

The SKAO is positioned to play a pivotal role in leading transformative science to characterise the physico-chemical properties of jets and outflow in YSOs

Acknowledgements

The team

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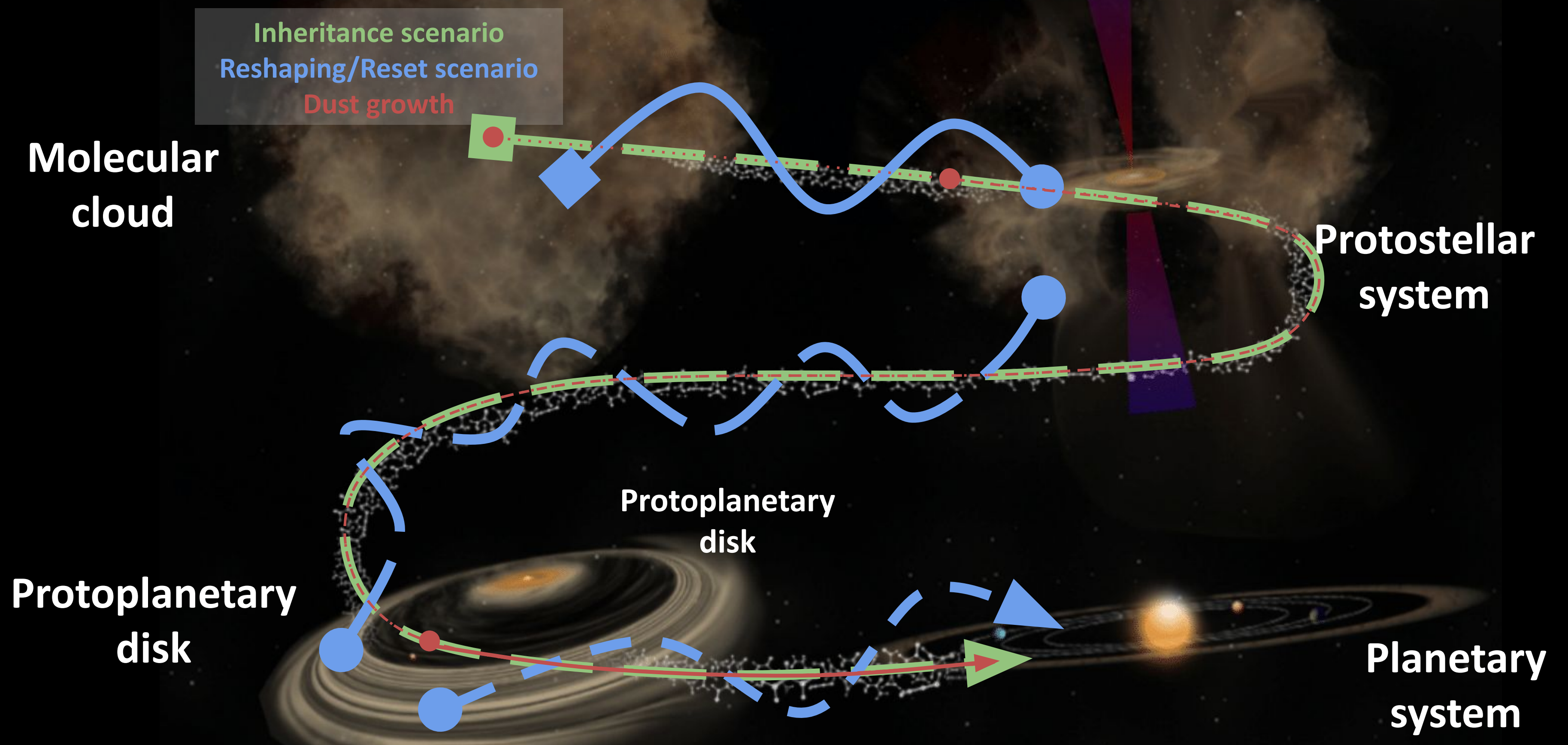
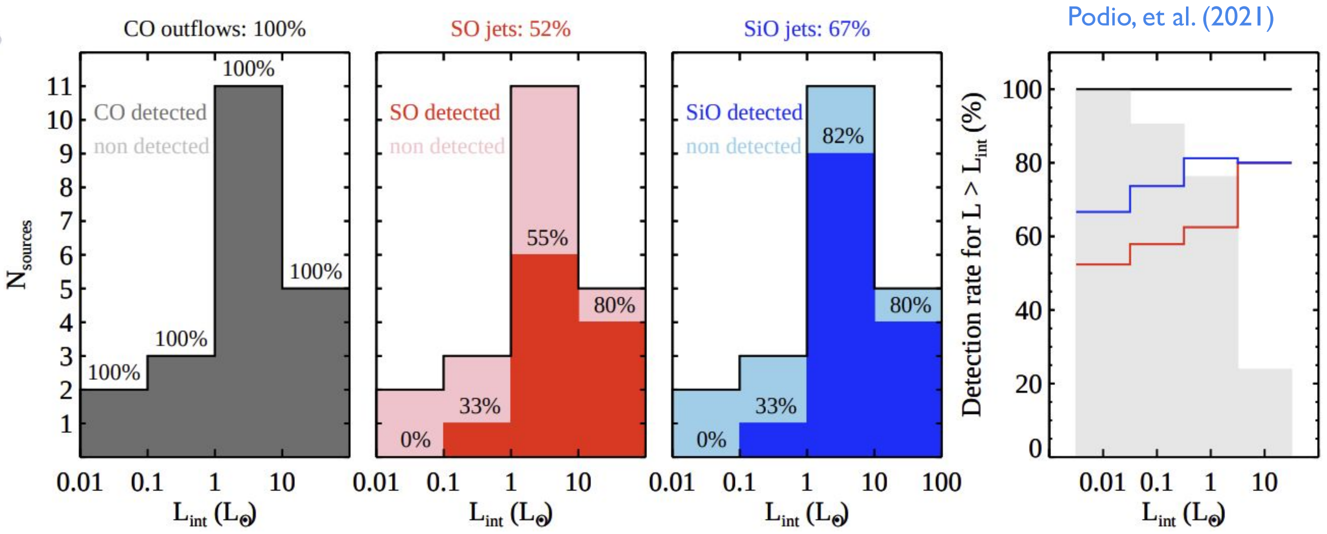


The CALYPSO IRAM-PdBI survey

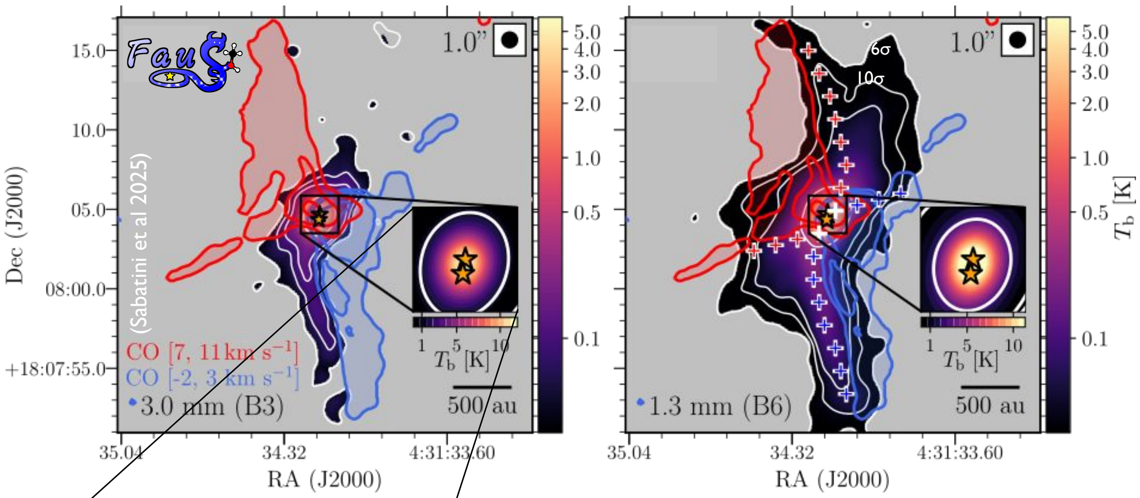


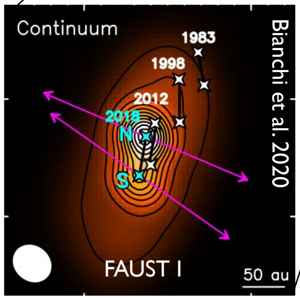
21 Class 0 objects

PI: P. André

- **100%** of the sources are associated to **outflows** detected in CO
- **67%** of the sources have **jets** detected in SiO
- **Detection rate of jet increases with L_{int}** (i.e. M_{acc})→80% SiO-jet for L_{int}> 1 $L_\odot$
- Non-detection of SiO jets in low-accreting sources could be an observational bias

Outflow dusty cavity walls





(Adams, et al. 1987, Connelley & Reipurth 2018)

$$F(\nu) \propto \nu^{\alpha_{\rm mm}}$$

$$\alpha_{\rm mm} = \frac{\log_{10} F(\nu_{B3}) - \log_{10} F(\nu_{B6})}{\log_{10}\nu_{B3} - \log_{10}\nu_{B6}}$$

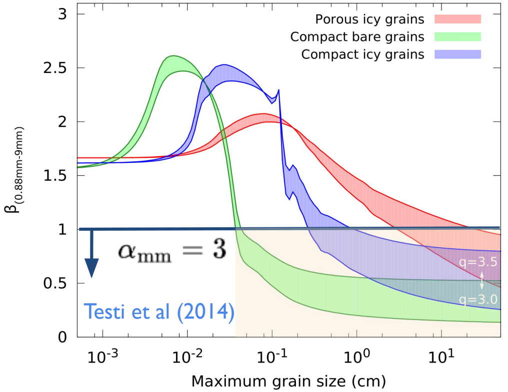
Slope of the dust sub-mmSED

$$\kappa_\nu \propto \nu^\beta$$

$$\beta = \alpha_{\rm mm} - 2$$

Dust opacity index

(RJ-approximation + optically thin emission)



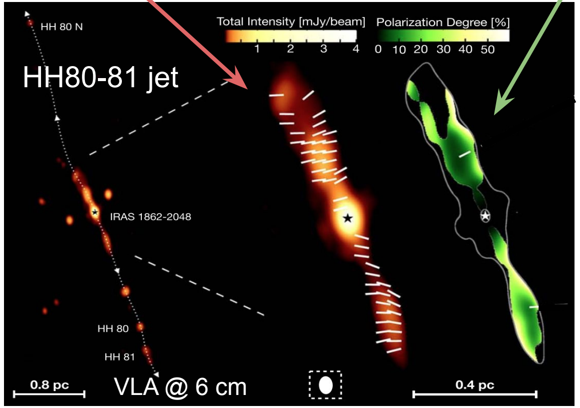
Alternative scenario to explain large grains in protostellar envelopes

(e.g. Cacciapuoti et al 2024 and Giacalone et al. 2019, Tsukamoto et al. 2021, Sabatini et al. 2024)

Non-thermal emission in jets by Rodriguez-Kamenetzky et al.

Pol. angle

Pol. degree



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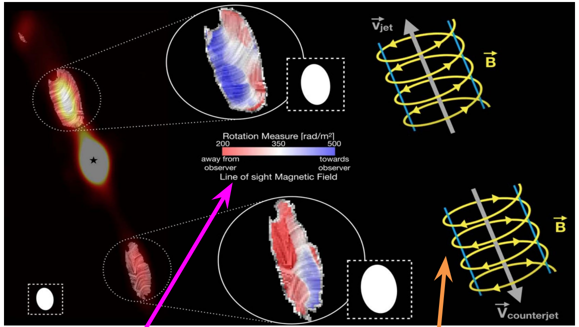

Rotation measure

3D-configuration

Key to unveiling the 3D-configuration of magnetic fields within the jet.

Rotation measure analysis + polarisation angle + polarisation degree (at different wavelengths)

VLA @ 6 GHz

Sub-bands: ~128 MHz
Resolution: 10 arcsec
Sensitivity = 10-20 μJy/beam
Total integration time = 20 hrs

SKA-Mid AA4 (B2)

Sub-bands: ~36 MHz
Resolution: 1 arcsec
Sensitivity = 3 μJy/beam
Total integration time = 1.7 hrs

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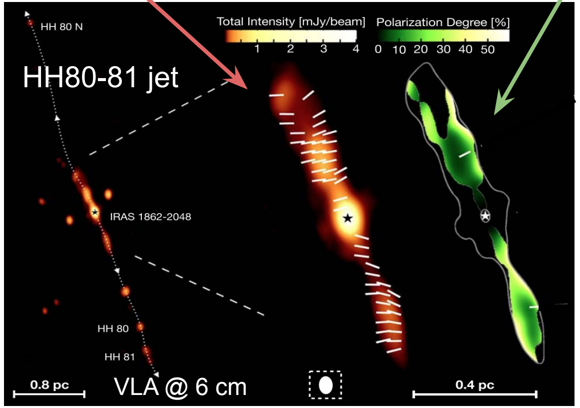

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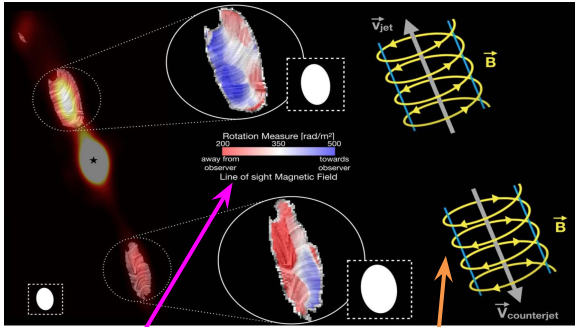

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Typical polarisation fractions from 5% to 10% in synchrotron-dominated regions

(also Purser et al. 2016, Rosero et al., 2016, Sanna 2019 & Obonyo et al. 2025)

Observations with the SKA-AA* (B1 & B2)

Expected polarised intensity:

Radio jet fluxes (@cm as a reference) ~1 mJy

rms_{SKAO}= 2 μJy/beam (α_{index} of -0.6; θ_{beam}~ 1”):

- ❑ Band 2 ⟶ Bandwidth = 720 MHz; rms in 11 min
- ❑ Band 1 ⟶ Bandwidth = 435 MHz; rms in 1.4 hrs

Polarisation studies with S/N ratio ~[25 - 50] !!!