Star Formation and JWST Observations

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With contributions from:
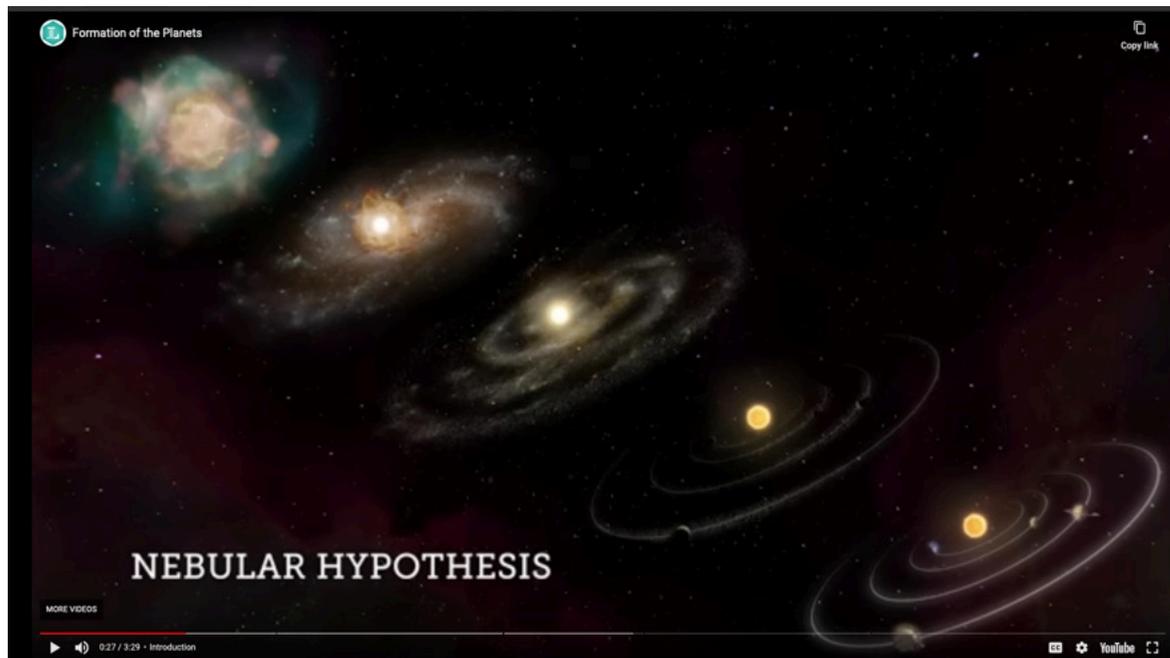S. Cabrit & V. Delabrosse

Why study star formation ?

- Key process in galaxy evolution:
    - Initial Mass Function (IMF)
    - Feedback processes
    - Chemical evolution

Why study star formation ?
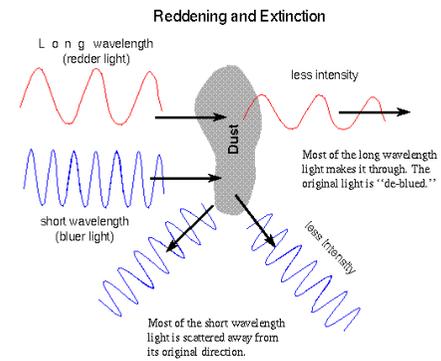
- Star and planet formation are linked

postulated by Kant (1755) & Laplace (1796)
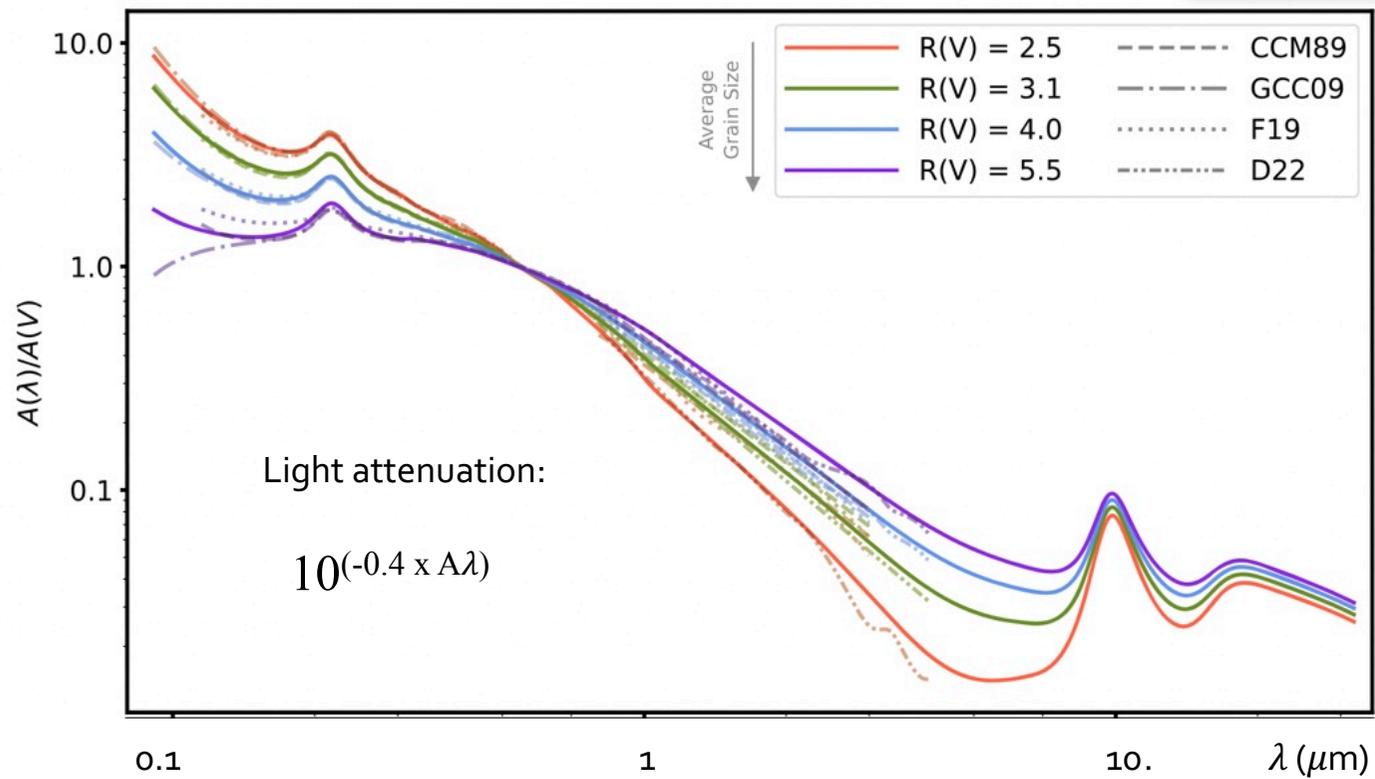
Stars form in cold and dense clouds

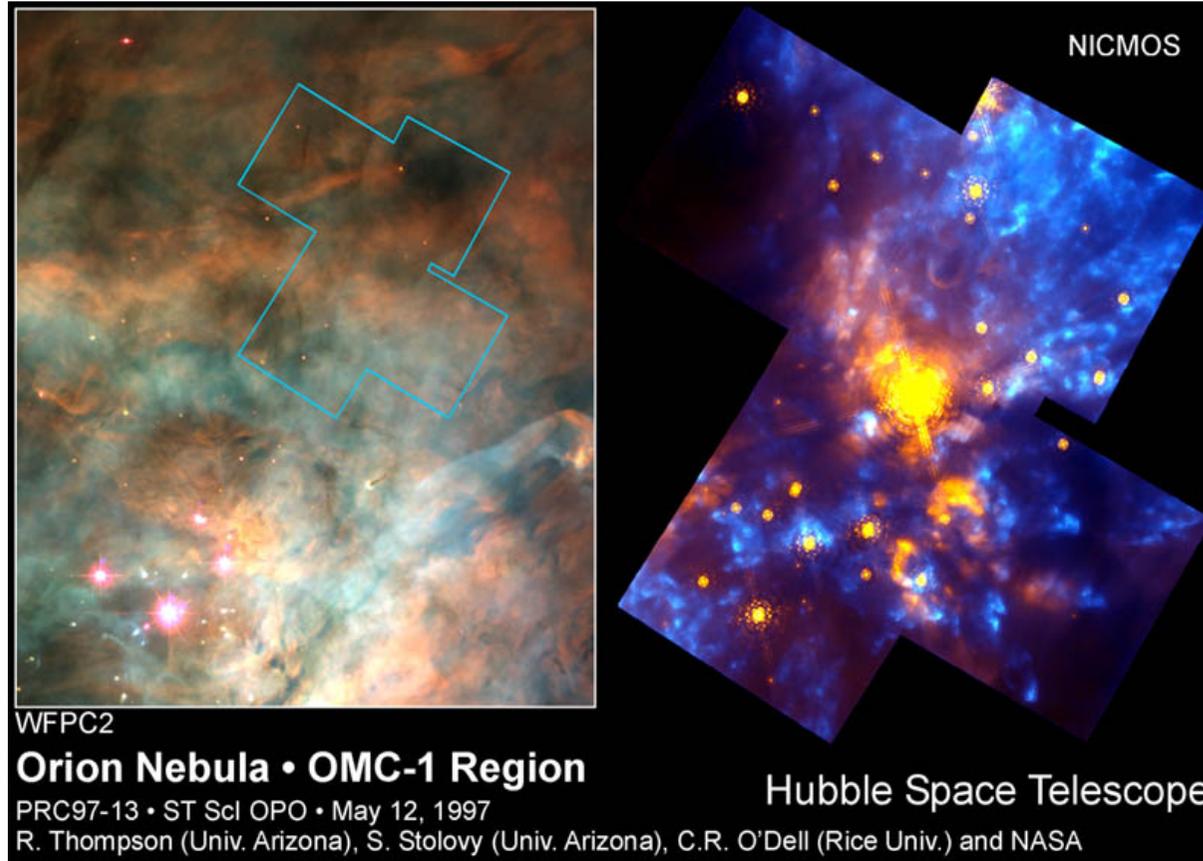Hubble Space Telescope
optical wavelength

Interstellar dust

Reddening and Extinction

L o n g wavelength
(redder light)

less intensity

Dust

Most of the long wavelength
light makes it through. The
original light is ''de-blued.''

short wavelength
(bluer light)

less intensity

Most of the short wavelength
light is scattered away from
its original direction.

Dust in clouds attenuates and redden starlight

Interstellar extinction curve

Light attenuation:

$$10^{(-0.4 \times A\lambda)}$$

from Gordon+2023

Infrared domain is key for star formation

WFPC2
Orion Nebula • OMC-1 Region
PRC97-13 • ST ScI OPO • May 12, 1997
R. Thompson (Univ. Arizona), S. Stolovy (Univ. Arizona), C.R. O'Dell (Rice Univ.) and NASA

NICMOS

Hubble Space Telescope

The need for good angular resolution

- Angular resolution set by

  λ/D (= 0.1 arcsec for a 2.4m telescope at 1 μm)

- On the ground limited by seeing

  0.5 arcsec at 1 μm

- Angular size on sky of solar system at 140 pc (closest star forming region)_

  50 au at 140 pc = 0.35 arcsec
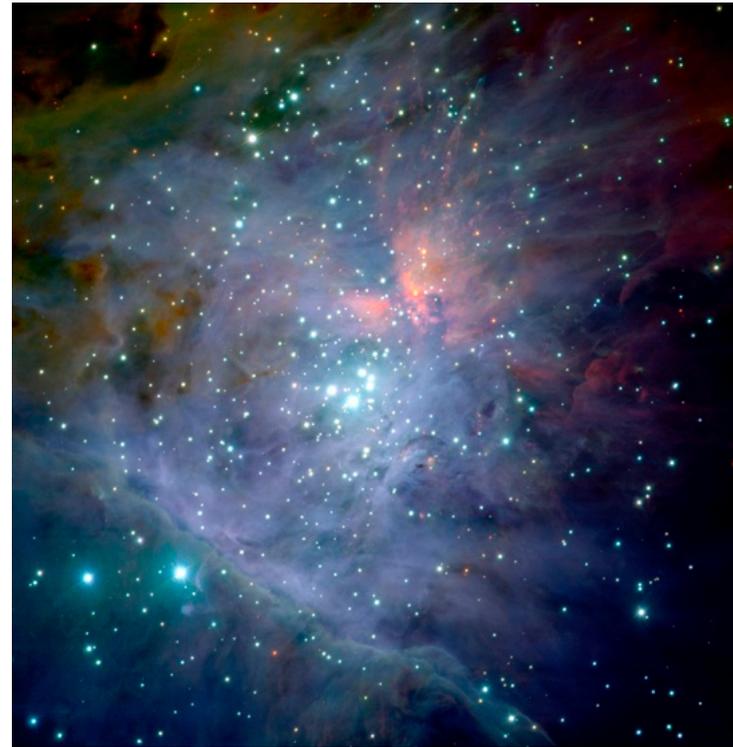
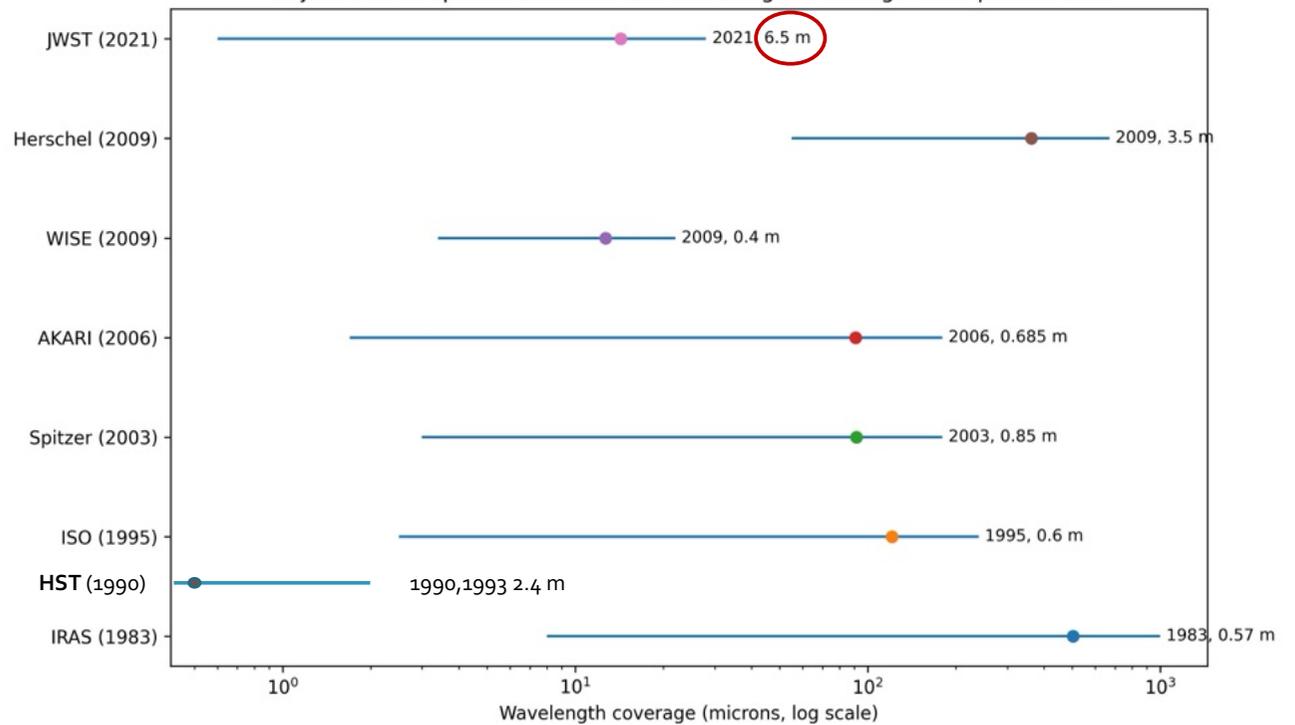The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)   © European Southern Observatory

Infrared space astronomy

Earth atmosphere extinction
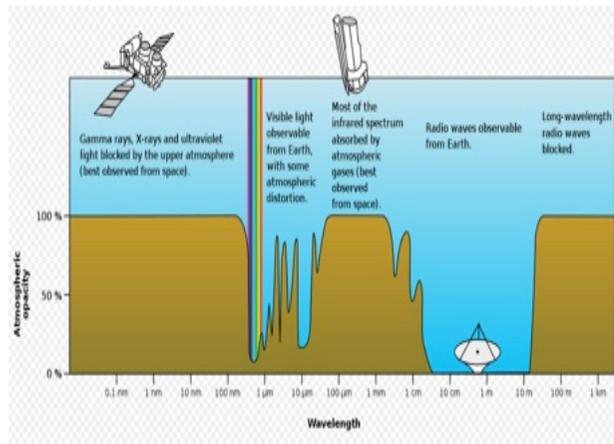
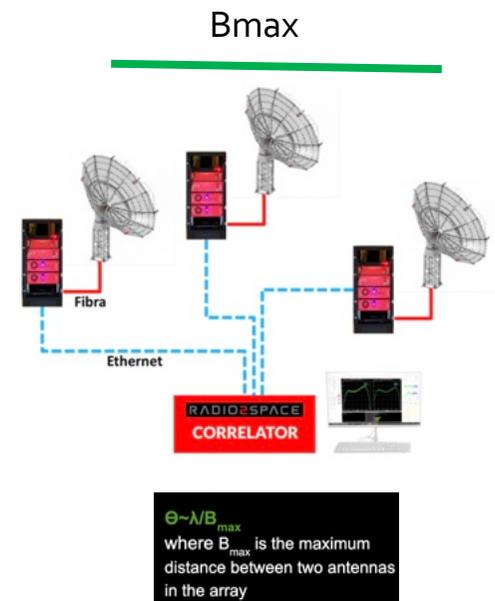Telescope diameter D sets:
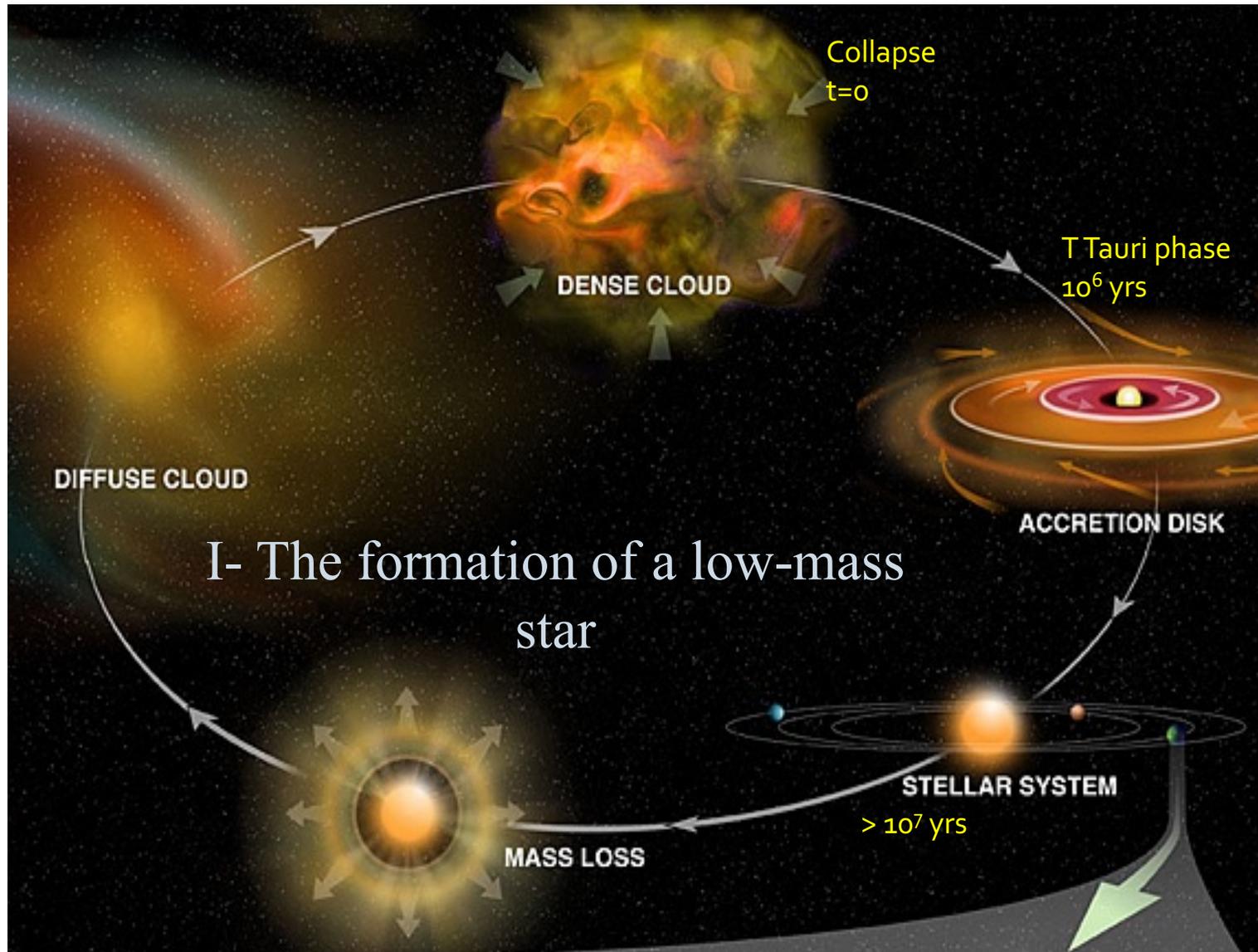- Sensitivity: D^2
- Angular resolution: λ/D

The ALMA radio (sub-)mm interferometer

o Sub-millimeter interferometer: 400 μm − 4mm.

o Reconfigurable metwork of 50 x 12m diameter antennas + 12 x 7 m antennas

o angular resolution down to 5 au

o Probes cold medium: T a few 10 K   thermal emission from cold dust,   molecular emission (e.g. CO)
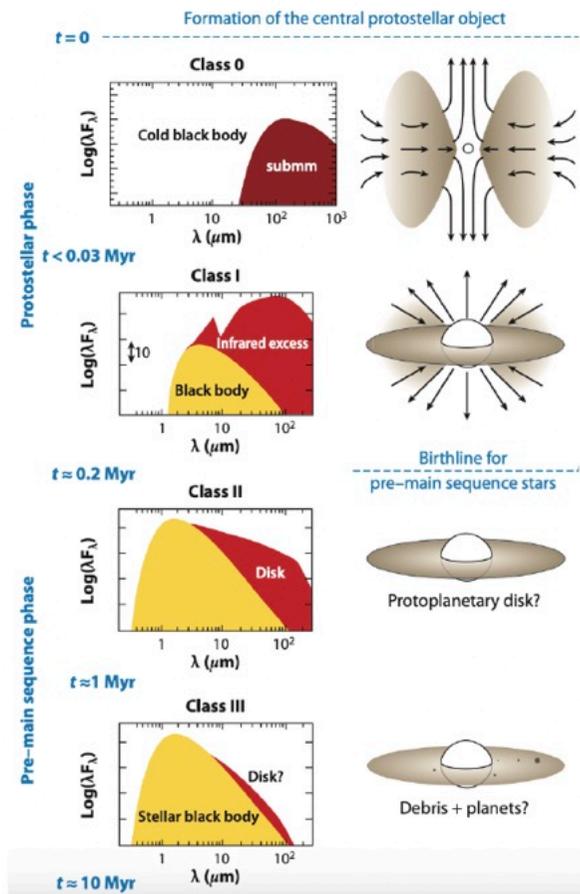
ALMA radio interferometer Chile 5000m altitude

Bmax

$\theta \sim \lambda / B_{max}$
where B_{max} is the maximum distance between two antennas in the array

I- The general picture of low-mass star formation

I- The formation of a low-mass star

Collapse
t=o

DENSE CLOUD

T Tauri phase
10^6 yrs

DIFFUSE CLOUD

ACCRETION DISK

MASS LOSS

STELLAR SYSTEM
> 10^7 yrs

I – Low mass Protostellar evolution
Spectral Energy Distribution Classes

Sub-millimeter Protostar. a few 10^4 yrs
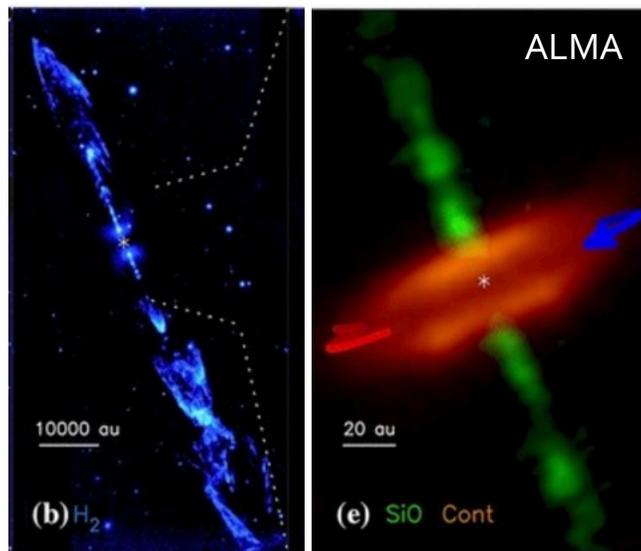
Infrared Protostar. A few 10^5 yrs

T Tauri star, a few 10^6 yrs
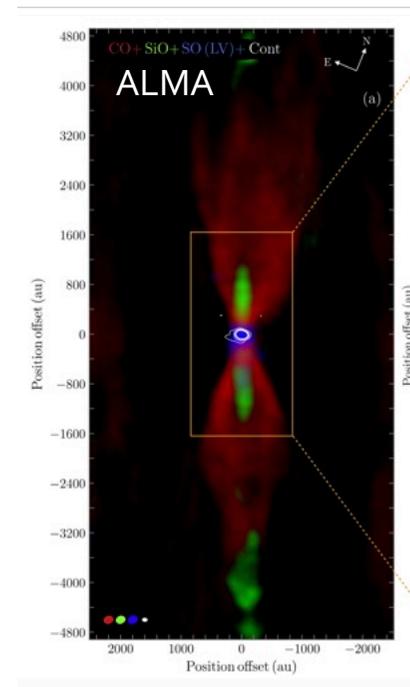IR emssion disk dominated

Evolved T Tauri star,   a few 10^7 yrs

Adapted from Lada 1987,
André, 2002

I - Jets and Outflows at all stages of active accretion

Class 0   HH 212   Jet H2 & SiO (CO)

Outflow CO

- Fast (v a few 100 km/s) collimated **jets** detected up to parsec scales   impact on cloud scales
- Low velocity (v=10 km/s) wider molecular **outflows:** trace entrained matter on large scales (jet = primary ejection)

The origin of large scale molecular outflows

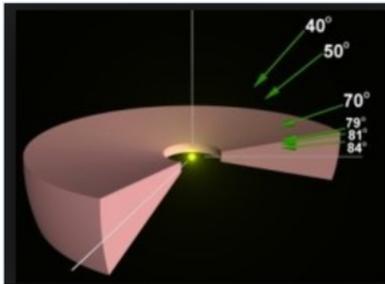- Trace interaction of inner variable jet with infalling enveloppe ? Cavity interpretation

o Jet emission is structured:
Emission **knots**

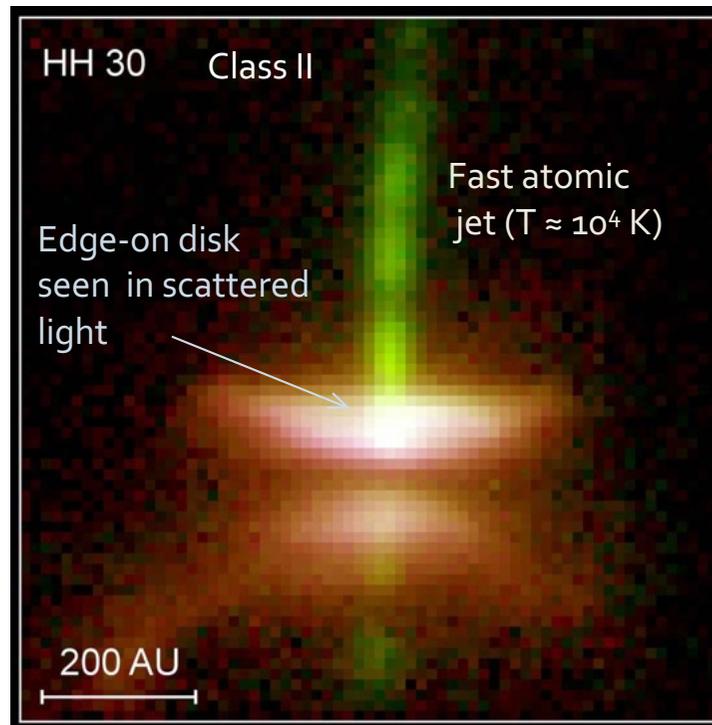o Jet knots: **inner shocks** due
to ejection variability
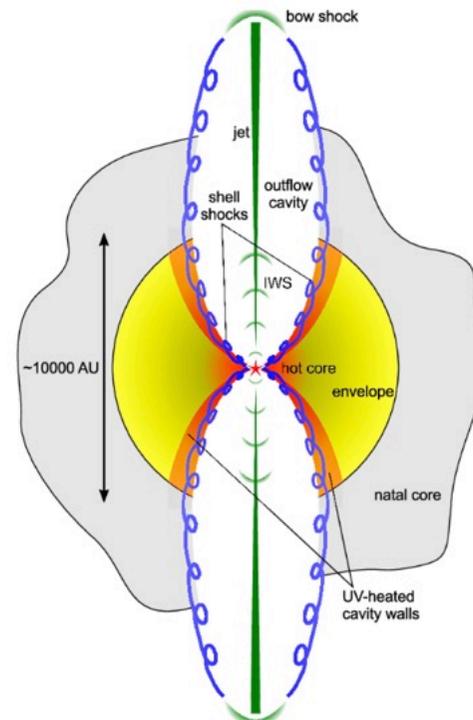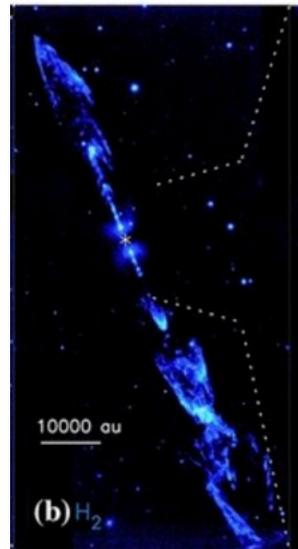
I- Jets and Outflows at all stages of active accretion

Class I – II atomic jets
HI + Low ionisation
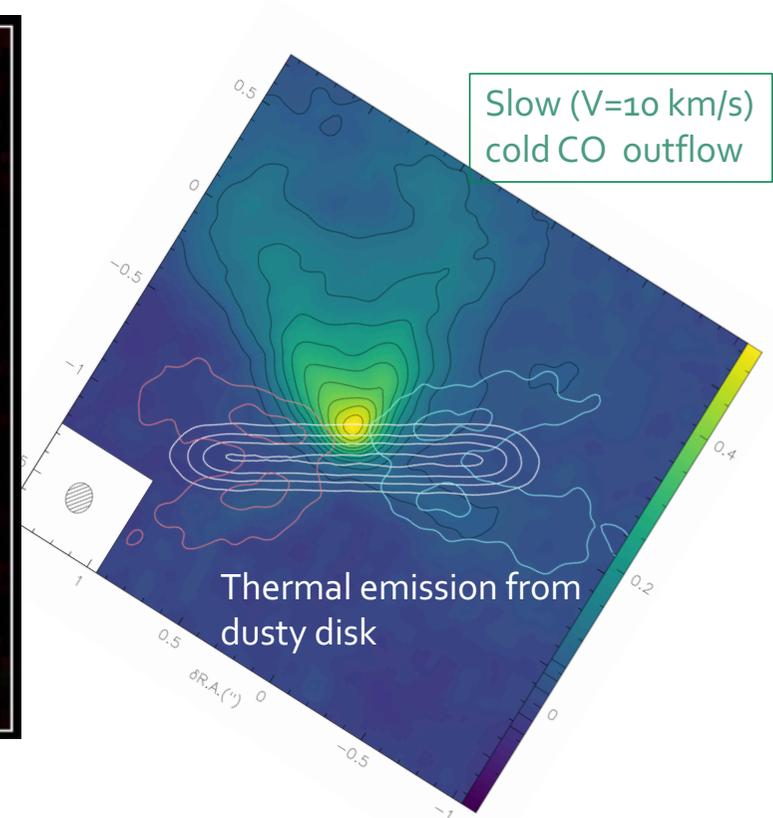forbidden emission lines
[OI], [S II], [N II]
{Fe II]

M_{jet} = 10 % M_{acc} (star)

Optical Image from HST

HH 30   Class II

Fast atomic
jet (T ≈ 10^4 K)
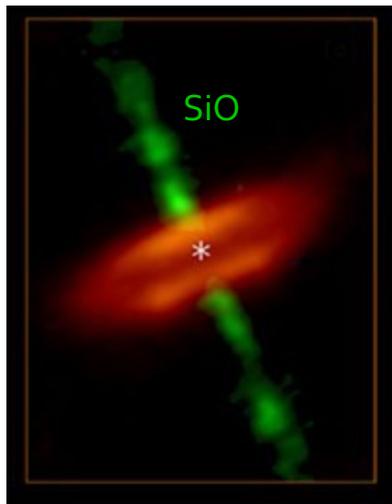
Edge-on disk
seen in scattered
light

200 AU

Ray et al. 1997,   Burrows et al. 1996

Radio Image from ALMA

Slow (V=10 km/s)
cold CO outflow

Thermal emission from
dusty disk

Jets require magnetic acceleration & collimation

Short collimation and acceleration scales → **magneto-centrifugal ejection processes**

see Cabrit 2007

HH212 Class 0 - ALMA   HH30 Class II -HST
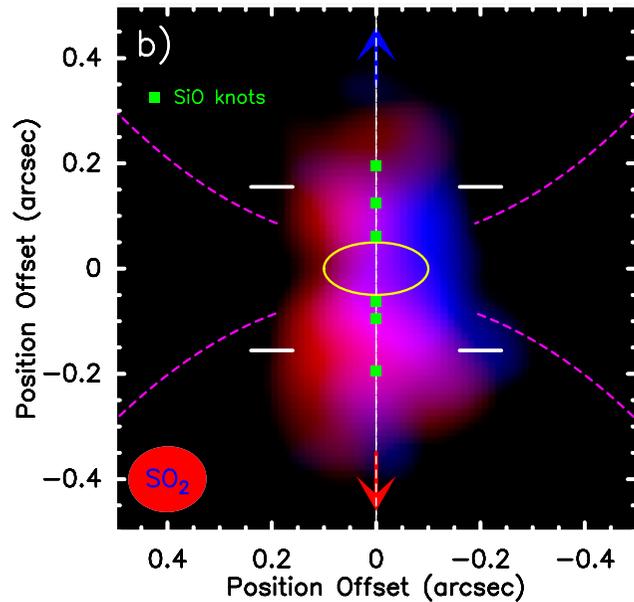

SiO

HH 30

Hα

200 AU
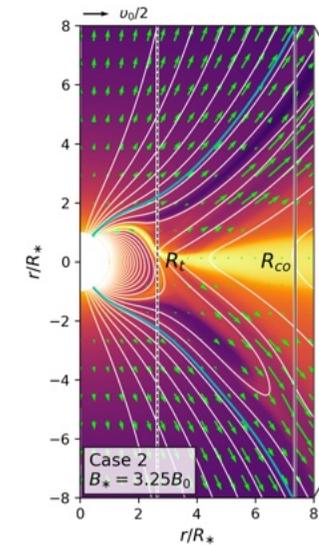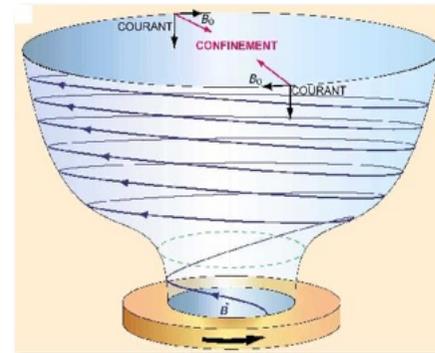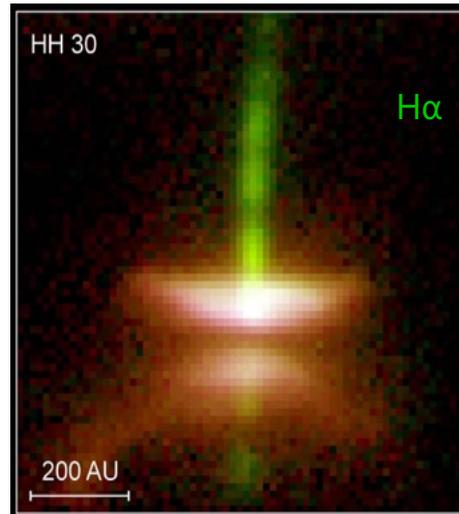
Jet radius < 5 au   for z =20 au

Ray+2007   Lee ARAA2020
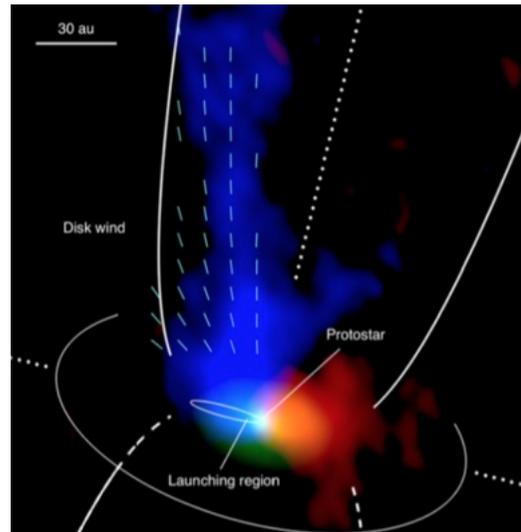

Zanni & Ferreira 2013
Pantolmos+2020

Molecular outflows at disk scales

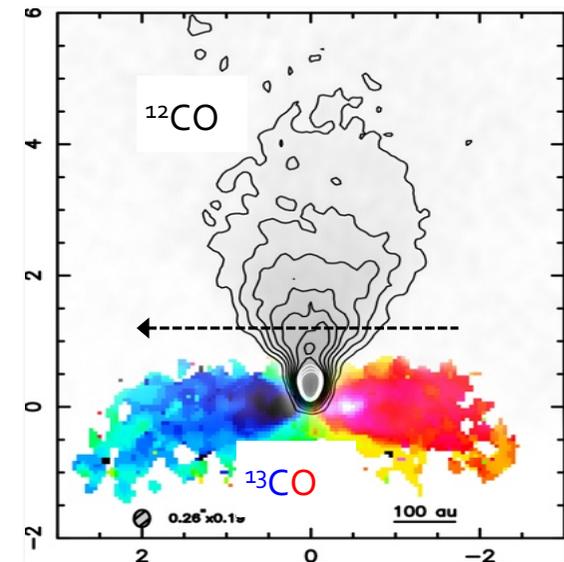Rotating outflows originate from within the disk and reside **inside** of the envelope cavity

Class 0 HH 212 SO/SO$_2$
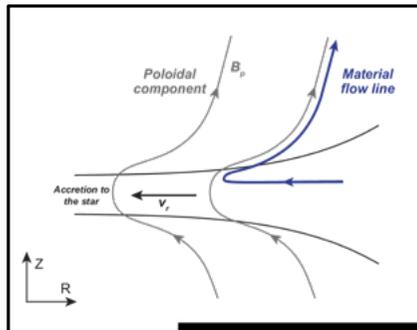Tabone+17, Lee+18

Class I TMC-1A CO
Bjerkeli+16, Harsono+19

Class II HH30 Louvet+2018

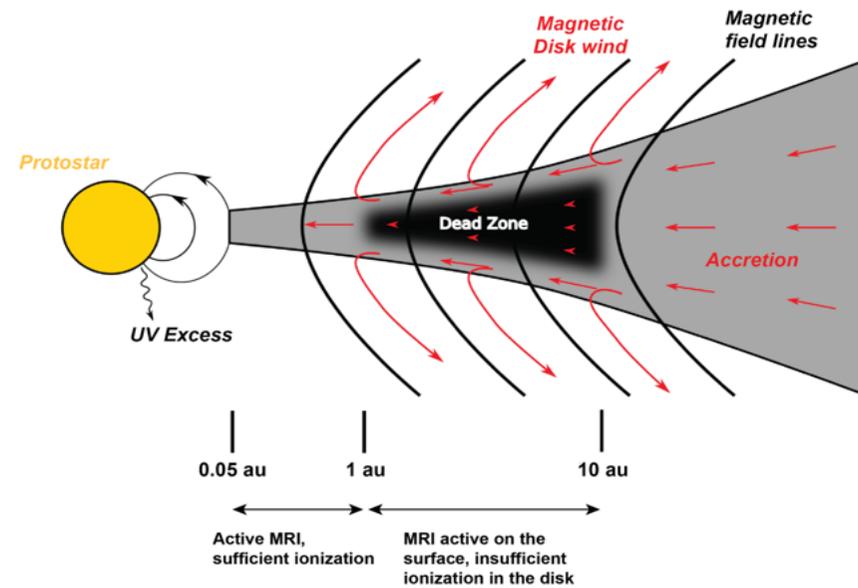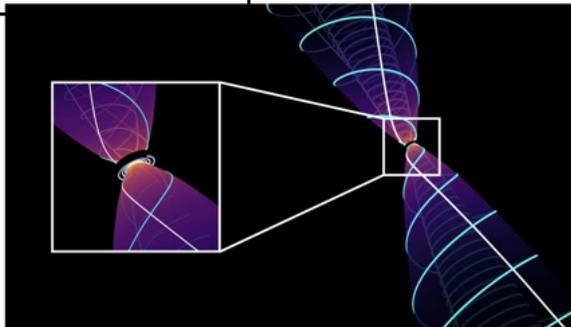- **high M$_w$** ($M_{out} \simeq M_{acc}$) => large impact on final stellar mass

The origin of small scale molecular outflows

- Magneto-centrifugal ejection process: requires large scale B in the disk
- Solves angular momentum extraction in dead zone of disks

(e.g. Blandford & Payne 1982, Ferreira 1997, Jacquemin-Ide+2019, Zimniak+2024)

II- JWST Key diagnostics and scientific results

II- The JWST revolution

- 0.6-28.5 microns,   6m diameter telescope, launched 25 dec 2021

- **Sensitivity improvement: x10 over HST at optical, x 60 over Spitzer**

- angular resolution: 0.1 arcsec

- Imaging and Spectroscopic capabilities: IFS R=3000

Integral field Spectroscopy
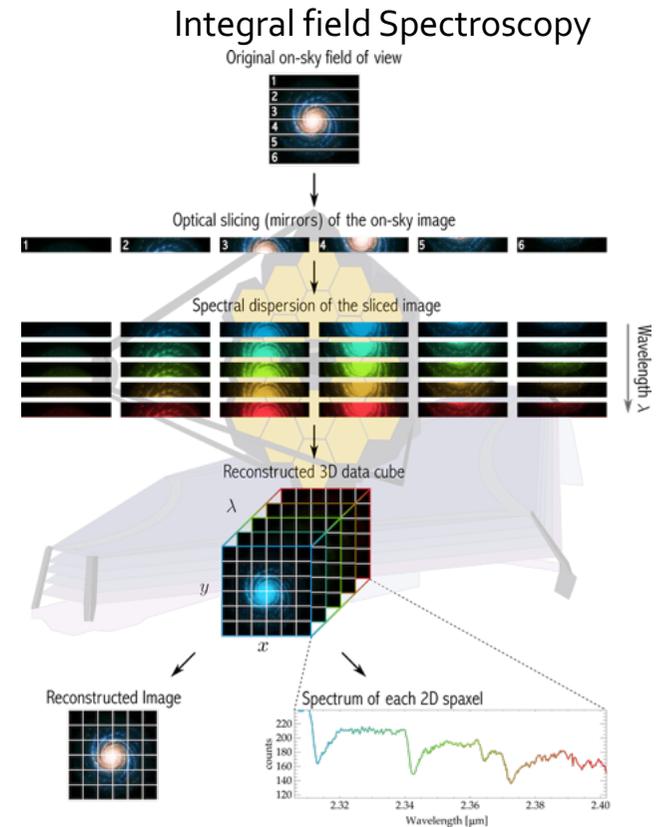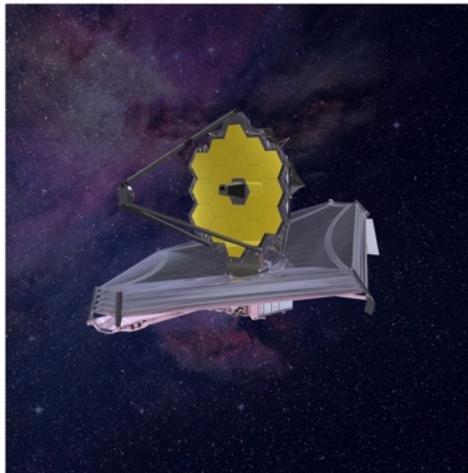
Peering into dark clouds with JWST

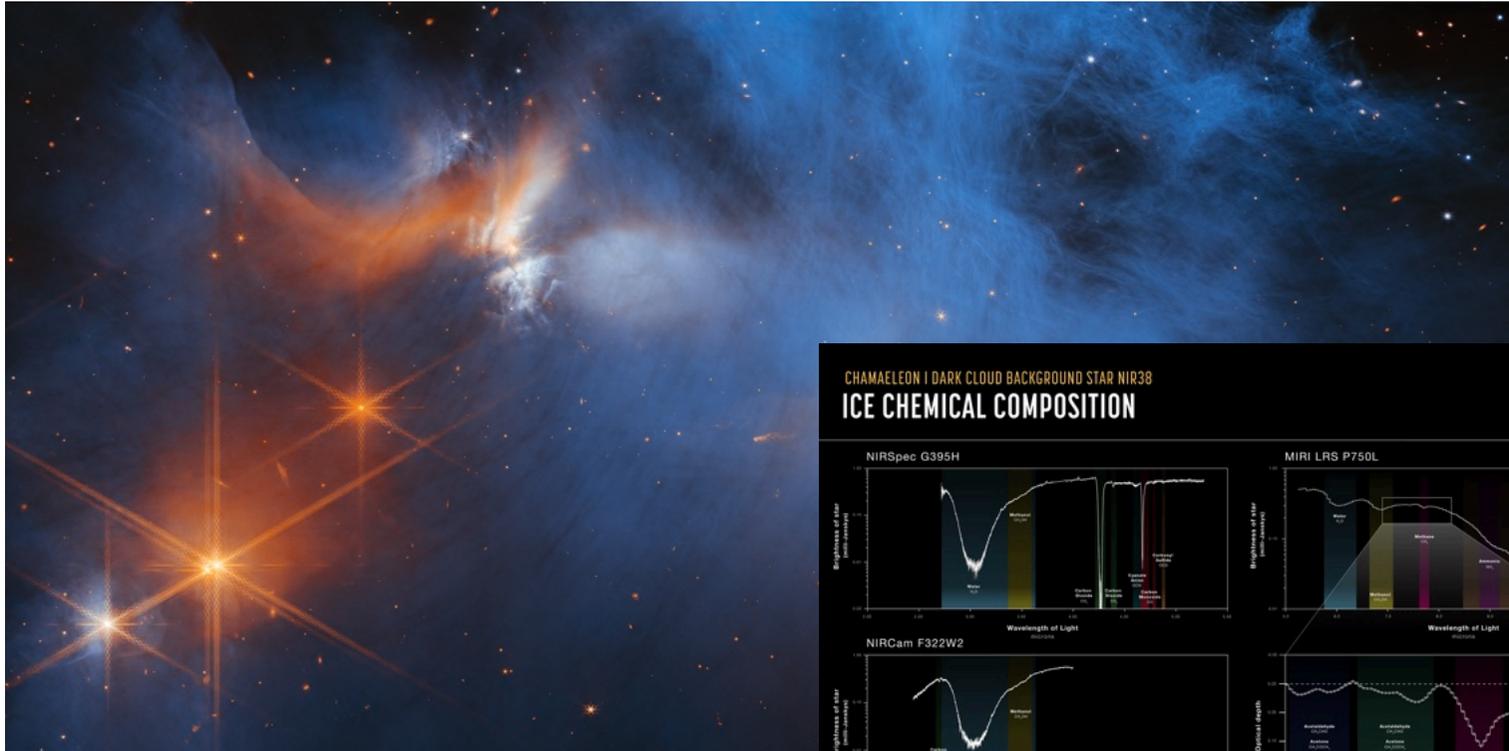# Peering into stellar nurseries with JWST
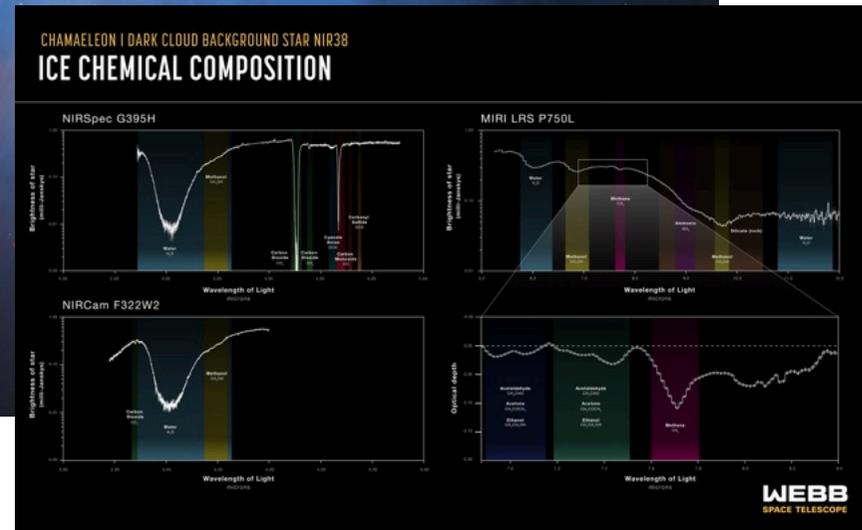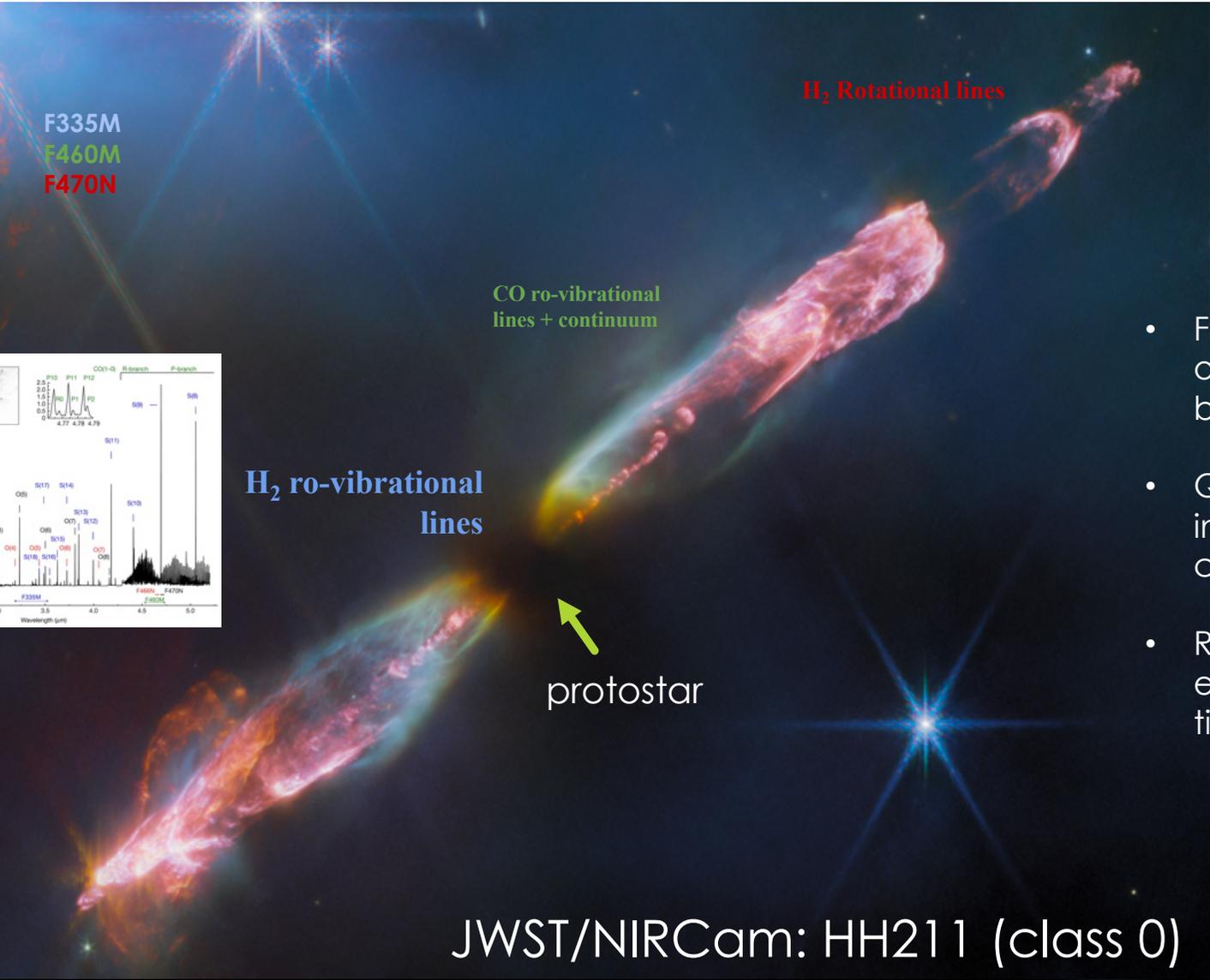

Hubble Space Telescope
optical light

James Webb Space Telescope
infrared light

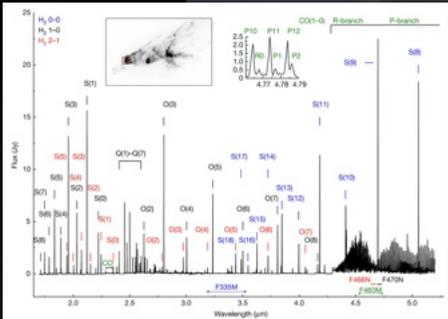# The evolution of solid ice

JWST image of Chamaleon I dark cloud

JWST/NIRCam: HH211 (class 0) *Ray+2023*

Introduction

First CO outflow discovery Snell et al. 1980
FCRAO @2.3 arcmin beam
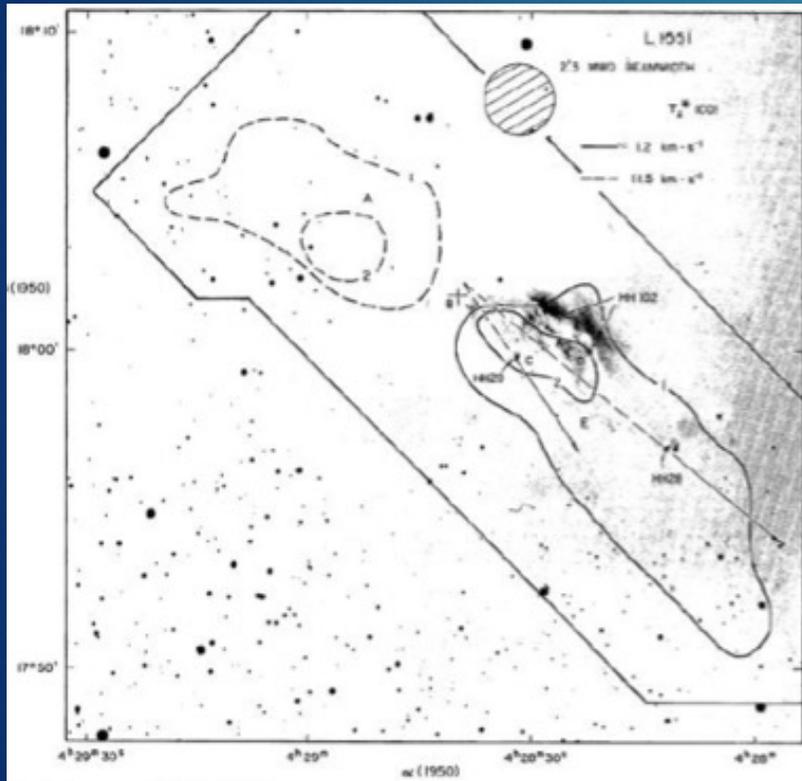
CO (blue,green,red) ALMA@1'' Arce
[SII] [OIII] ESO/NTT Reipurth

JWST HH46-47 (Class 1)

Wiggling jet: signature of binarity

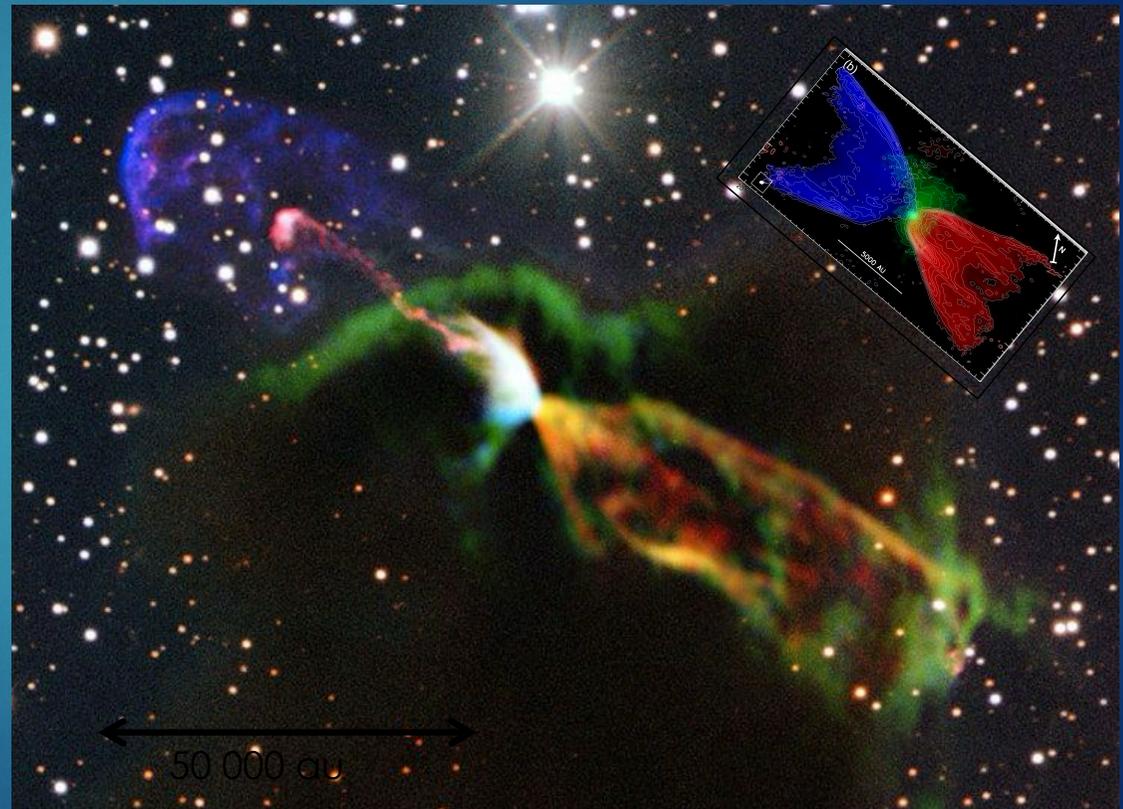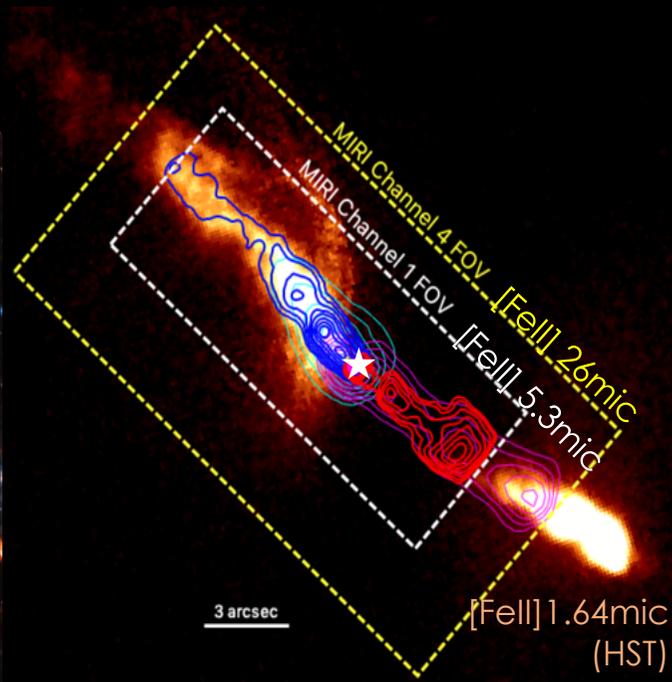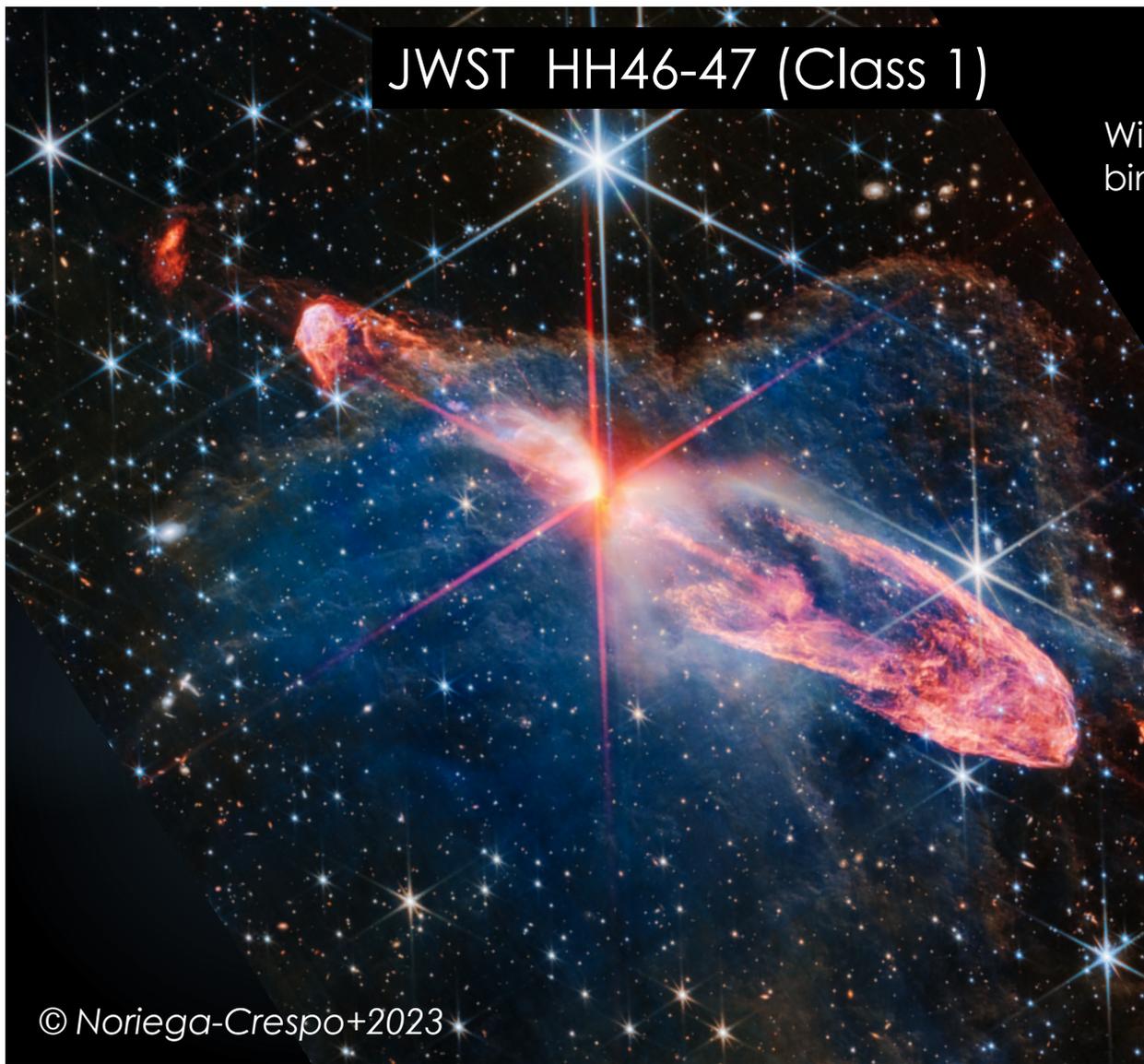MIRI Channel 4 FOV

MIRI Channel 1 FOV

[FeII] 26mic

[FeII] 5.3mic

[FeII]1.64mic (HST)

3 arcsec

Nisini+2014

© *Noriega-Crespo+2023*

JWST reveals nested H2 low velocity winds

Delabrosse+2024. Class I

Federmann+2024 Class o

Pascucci+2024. Class II

IRAS 16253

5 μm continuum
[FeII] 4.889μm
H₂ (0-0) S(11)

DG Tau B   Class I

HH 30

[FeII] (JWST)
H₂ (JWST)
CO (ALMA)
CO trace (JWST)
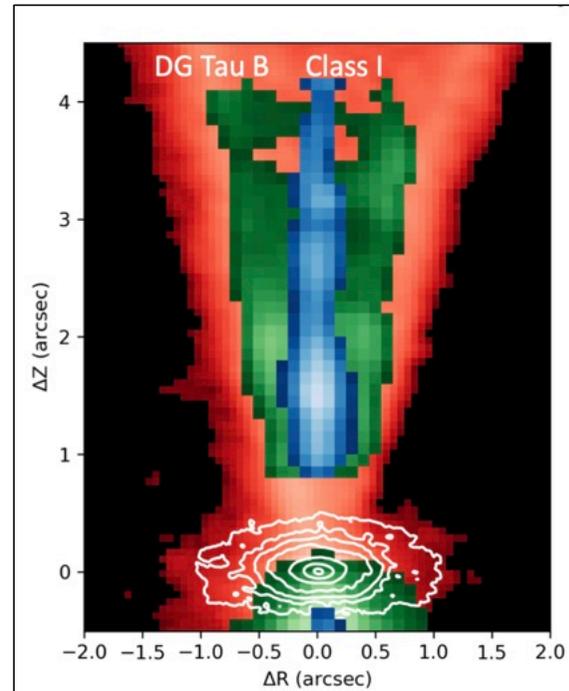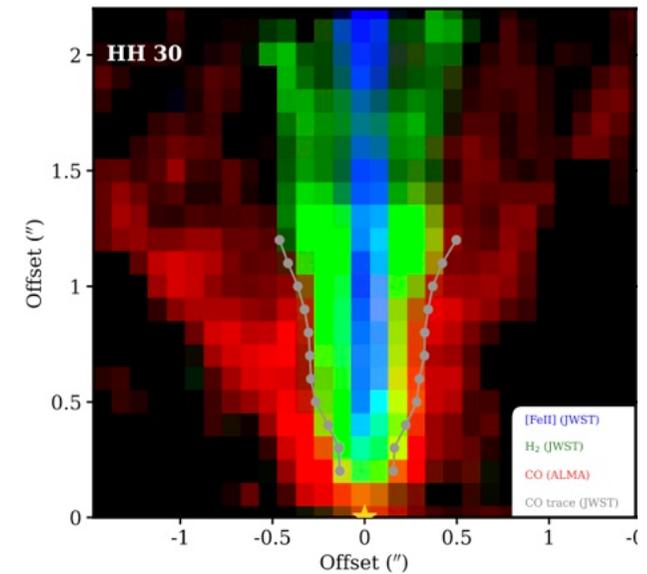
see also Tychoniec+2024 , Arulanantham+2024, Harsono+2023, Issani+2024   and more to come !

JWST **NIRCam**

NIRCam/JWST
[FeII] 1.64μm
H₂ 2.12μm
H₂ 3.23μm

Atomic jet

H₂ Conical outflow

Disk occultation gap

Scattering Nebula

1.4"
200 au

E
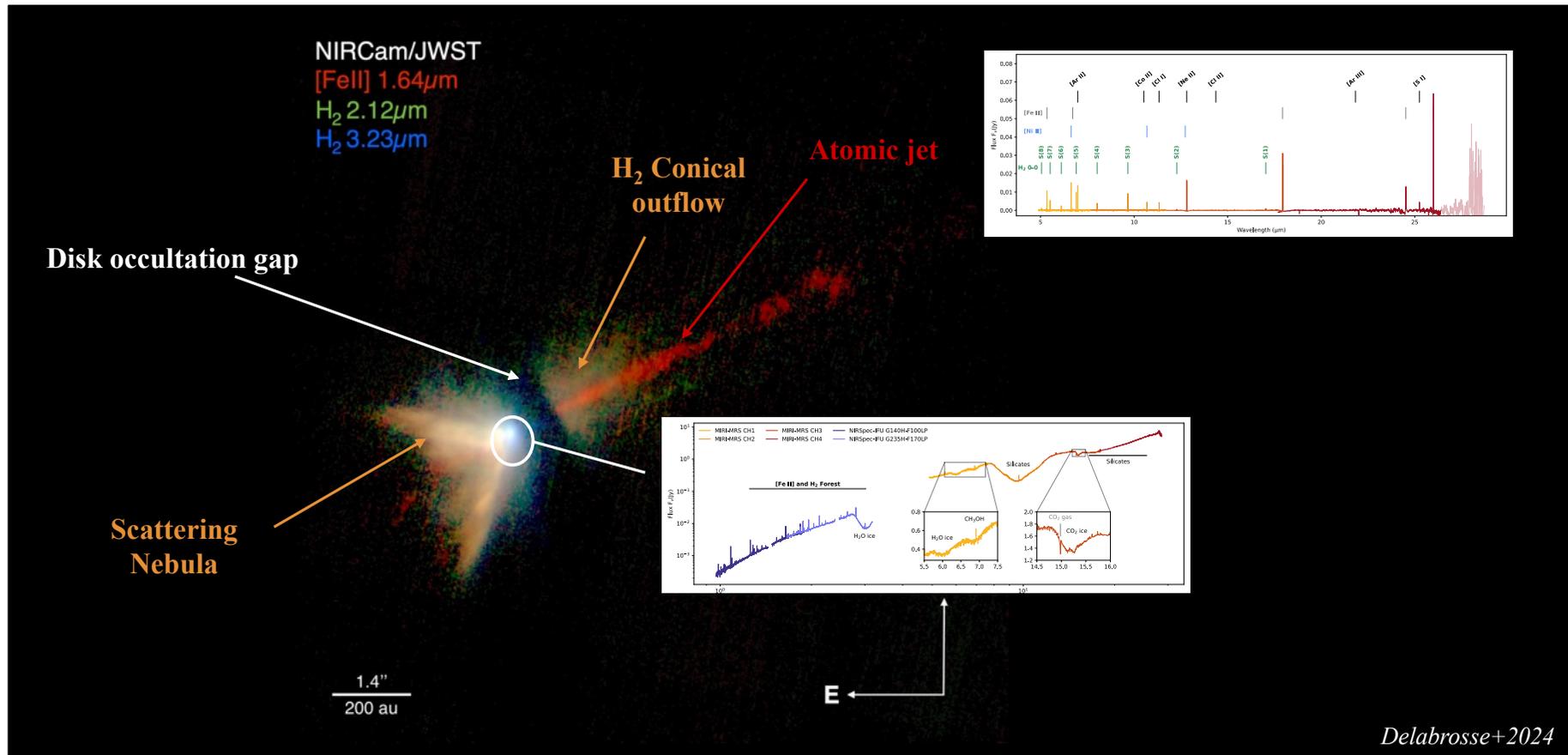
Delabrosse+2024

Nested outflows in the Class I DG Tau B

NIRCam /JWST

1.64μ
2.12μ
3.23μ

Warm H2 wind (T=2000 K)

Hot atomic jet (10⁴ K)
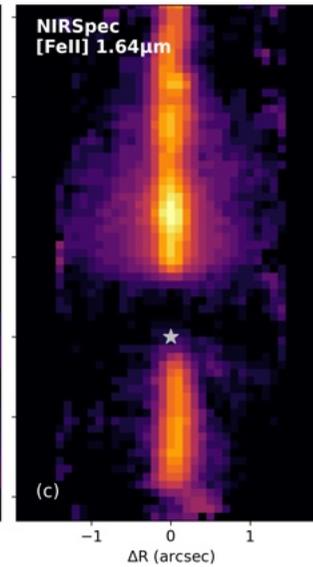
Cold CO wind (50 K) ALMA
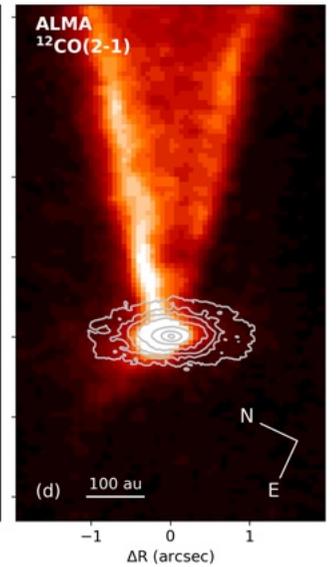
Delabrosse+2024

H$_2$ excitation diagram: Wind mass-flux
ex: DG Tau B (class 1)

T ~ 830 K
N$_{tot}$ ~ 2 x 10^{18} cm^{-2}
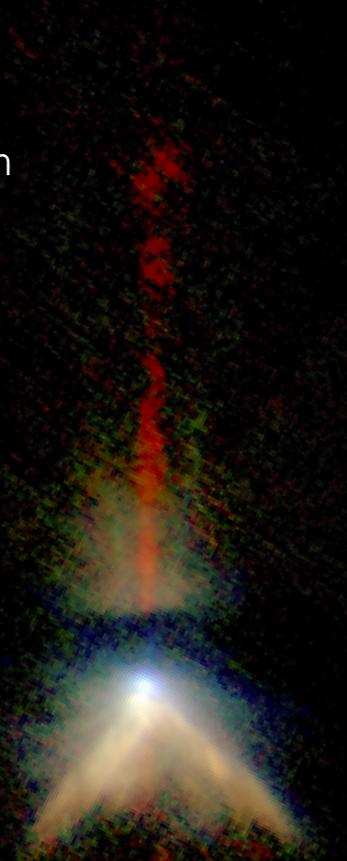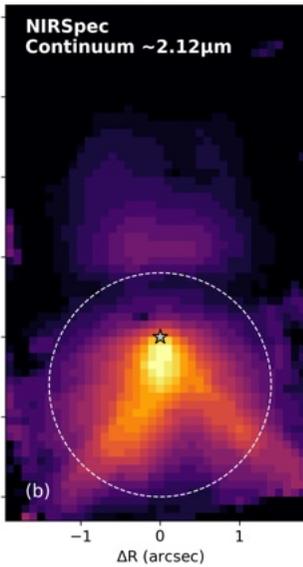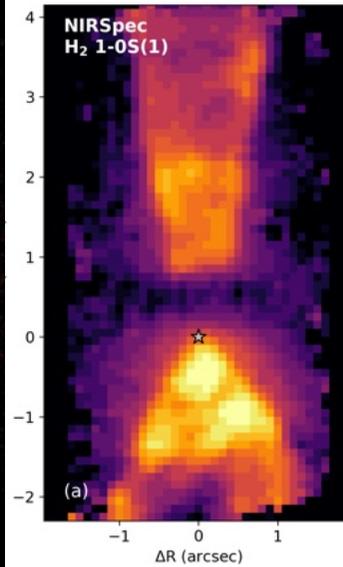
Slope = 1/T

T ~ 2000 K
N$_{tot}$ ~ 10^{17} cm^{-2}

T ~ 2700 K
N$_{tot}$ ~ 2 x10^{16} cm^{-2}

ln(N$_{up}$/g$_{up}$)

Upper level energy E$_{up}$/k (K)
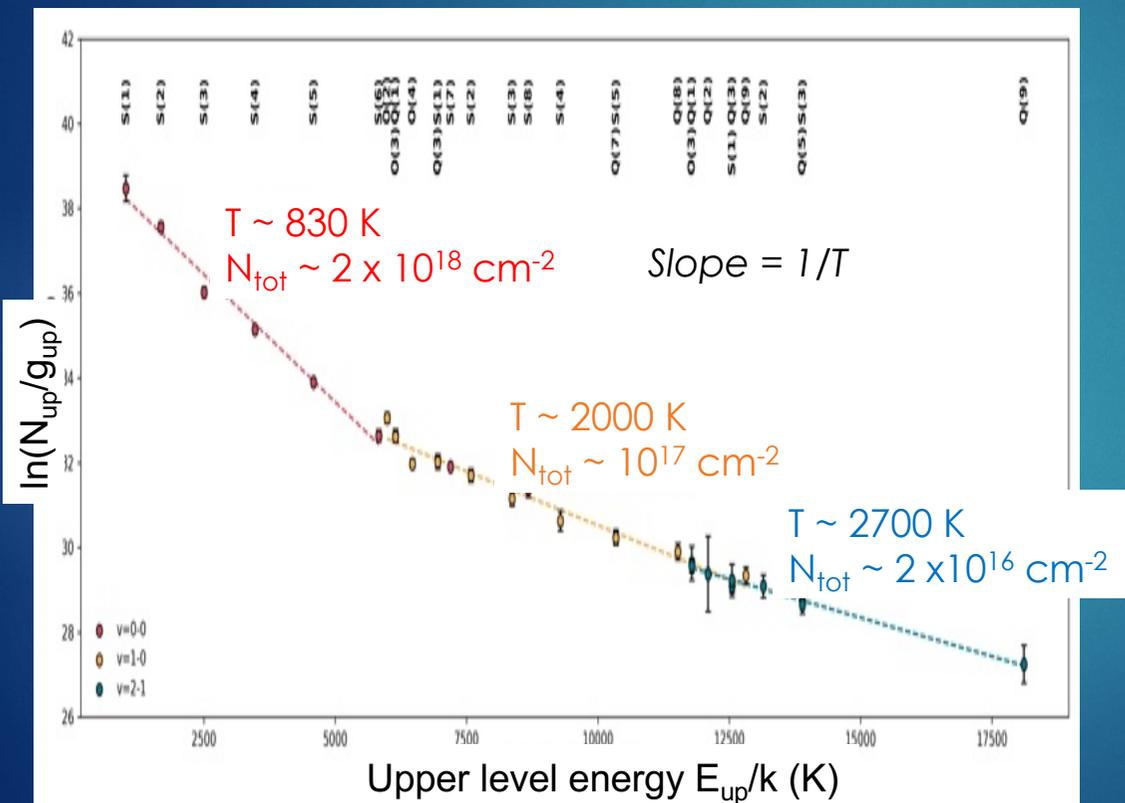
Delabrosse+ in prep.

▶ Optically thin emission:

  Line flux = N$_{up}$ (hν A$_{ul}$ / 4π)

▶ Boltzmann distribution:

  N$_{up}$ = N$_0$ g$_{up}$ exp(-E$_{up}$/kT)

▶ « Excitation diagram » :

  slope = 1/ T

  Intercept = N$_0$

  N$_{tot}$ = N$_0$ x Z(T) (partition function)

  Caveat: unknown H$_2$ abundance !

Nested outflows : magnetic disk wind signature ?
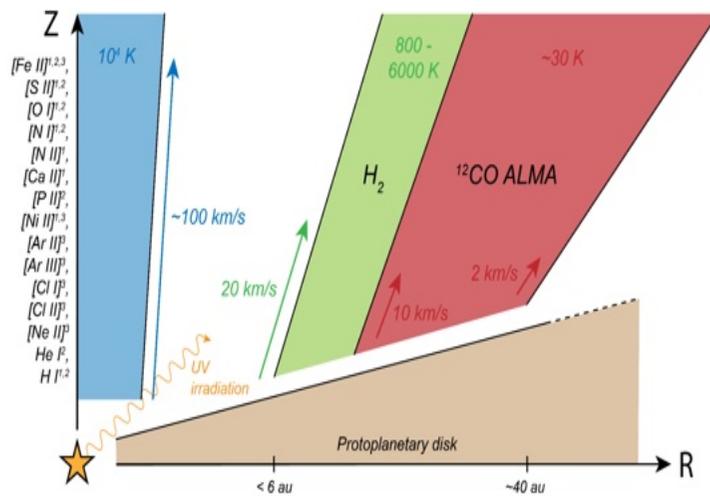
DG Tau B (Class I, 1 Msun)
JWST NIRSpec Delabrosse+2024
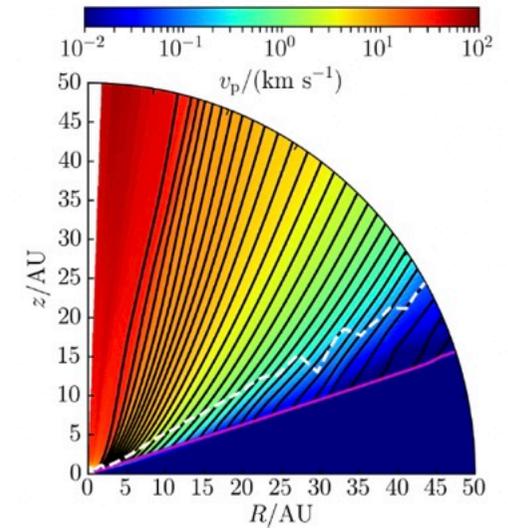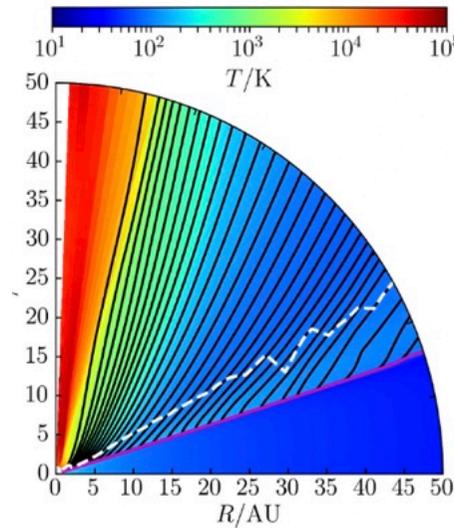
numerical simulations of MHD disk winds
Wang+2019
→ Need for detailed predictions in H₂ :
time dependent thermo-chemistry required

IV. H$_2$ Excitation mechanisms:

Irradiated shocks models

Paris Durham Shock code
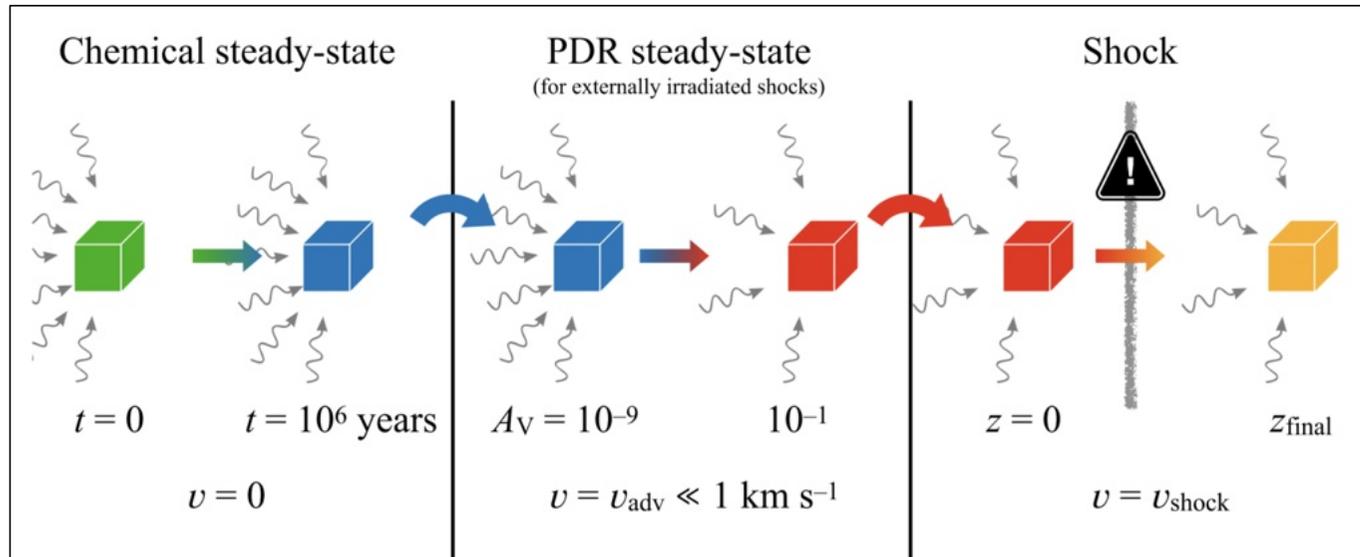
Simulates the dynamics, thermodynamics and chemistry of a gas subjected to 1D plane-parallel shock wave

Model grid, 6 parameters covered:

- Pre-shock density: **n$_H$**
- Shock speed: **v$_S$**
- Magnetic field intensity: **b**

- UV Field: **G$_0$**
- Cosmic ray H$_2$ ionisation rate: **ζ$_{H2}$**
- PAH Abondance: **X(PAH)**

(Flower+1985,2003, Godard+2019, Kristensen+2023)

II- H₂ excitation diagram: irradiated shocks ?
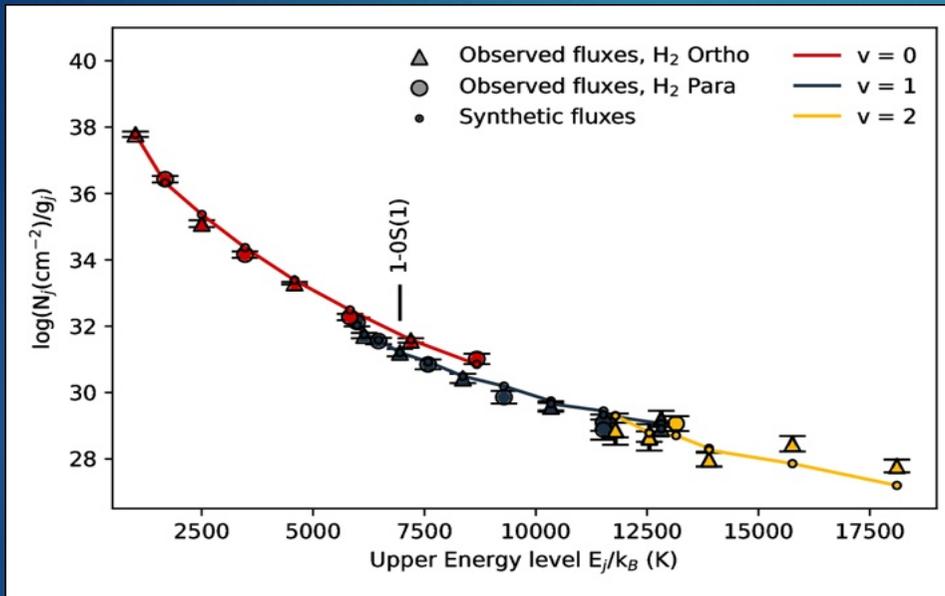
Delabrosse+ in prep.

Best Shock solutions

Chi2,r	6 — 7.2
n_H (cm^{-3})	10^4
V_S (km s^{-1})	10
G_0	10^3
b	0.1 (*10 μG*)
Type	*J*
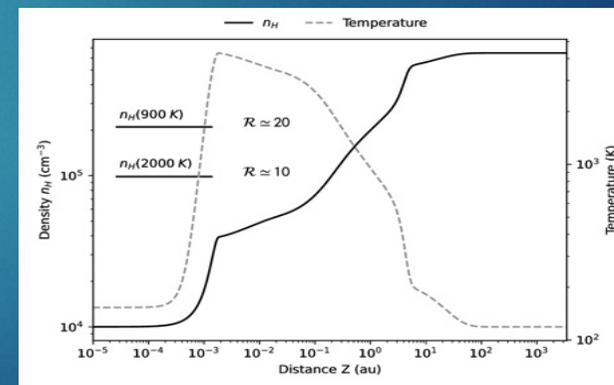
Interaction with inner pulsed jet ?
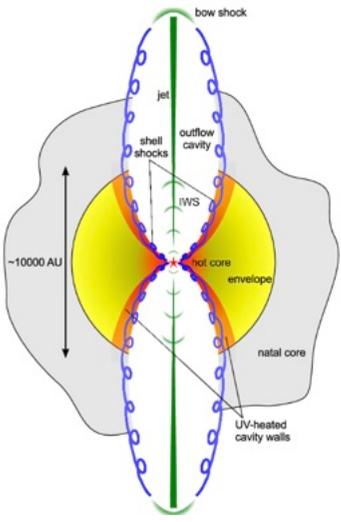
Jet propagating in static envelope

Jet propagating in disk wind
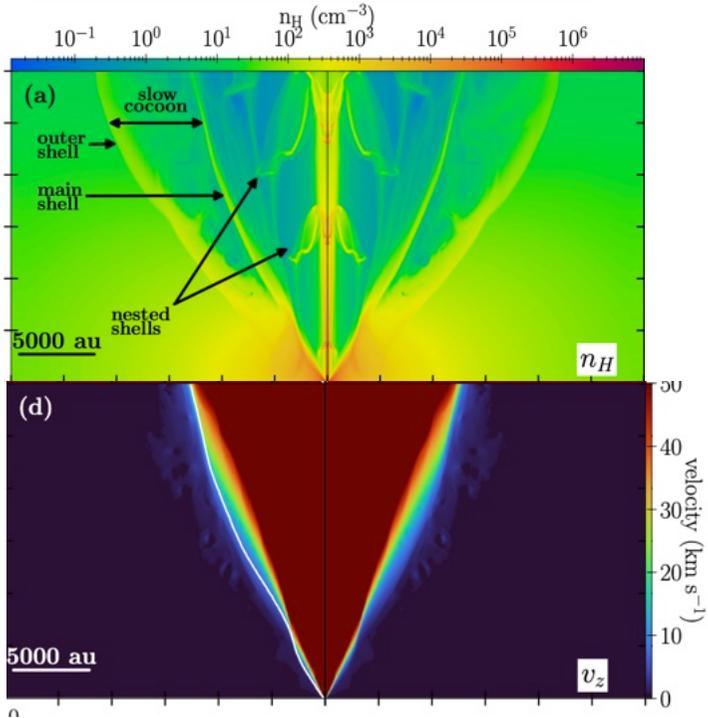
Rabenanahary+2022
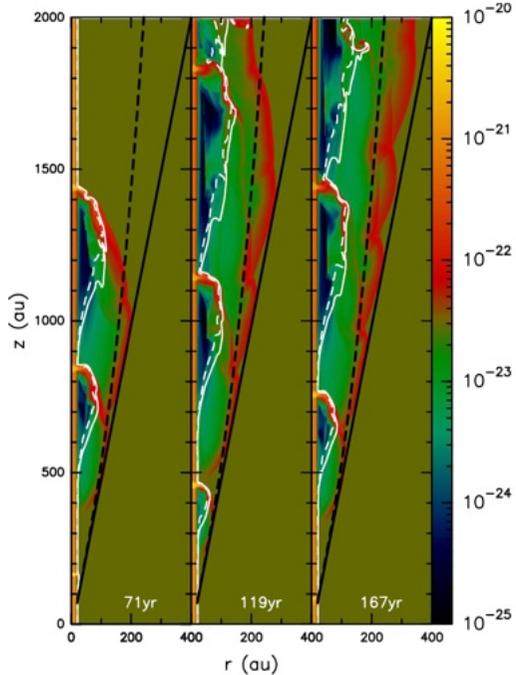
Tabone+2018

→ Need for detailed predictions in H2

34

Exctintion maps from H2 line ratios

- Optically thin emission:

$$I_v = \frac{hv}{4\pi} \times A_{ul} N_u \Delta s$$

- In the absence of extinction, the ratio of two transitions originating from the same upper level is fixed by the ratio of their Aul and frequencies.

- When affected by extinction, the observed ratio allows to derive Av (assuming the interstellar extinction law)

Extinction maps from H$_2$ line ratios
ex: DG Tau B (class 1)

▶ Constraint on envelope density profile (assuming some Av / N$_H$)
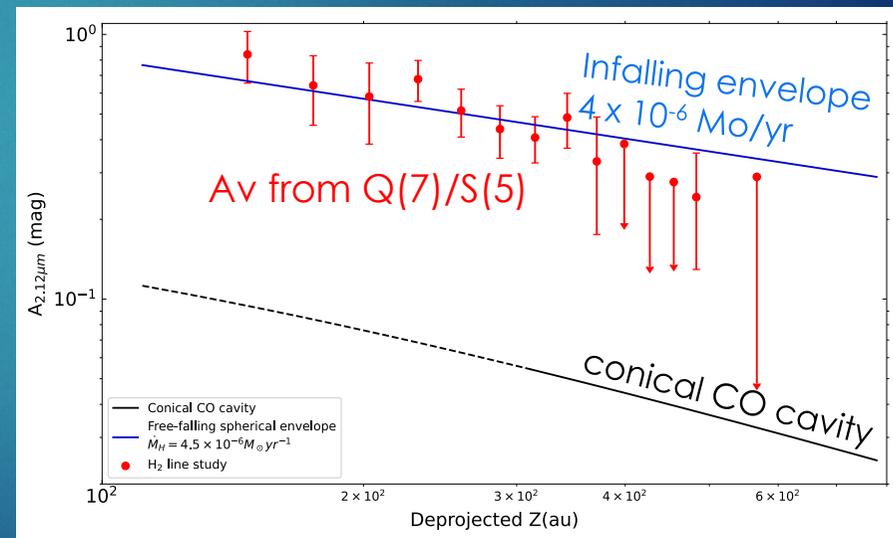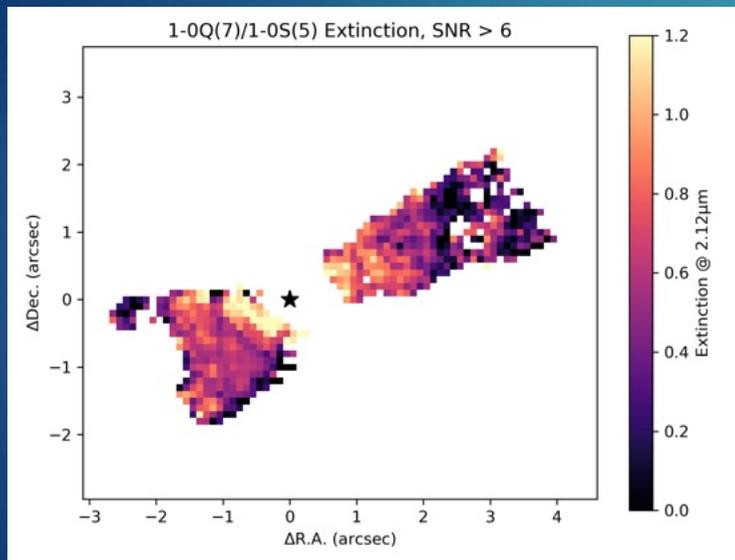
Delabrosse+2024

New excitation diagnostics in atomic jets from NIRSpec. ex: *HH30 (class 2)*

C I 1.175　　HI 4-3　　He I 1.083　　[N I] 1.041　　[S II] 1.032　　[C I] 0.985　　[Fe II] 1.257

0.6"

HH 30

[C I]　[S II]　[N I]　[Fe II]　[Fe II]　Detector Gap　[Fe II]　[Fe II]

10^4

HH 30

Wavelength (μm)

1　1.1　1.2　1.3　1.4　1.5　1.6　1.7　1.8

Bajaj+2025
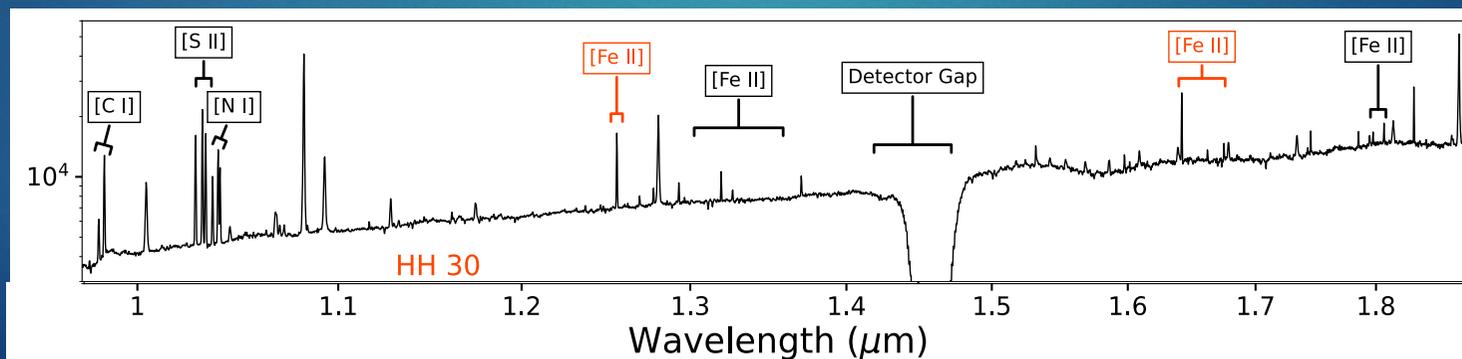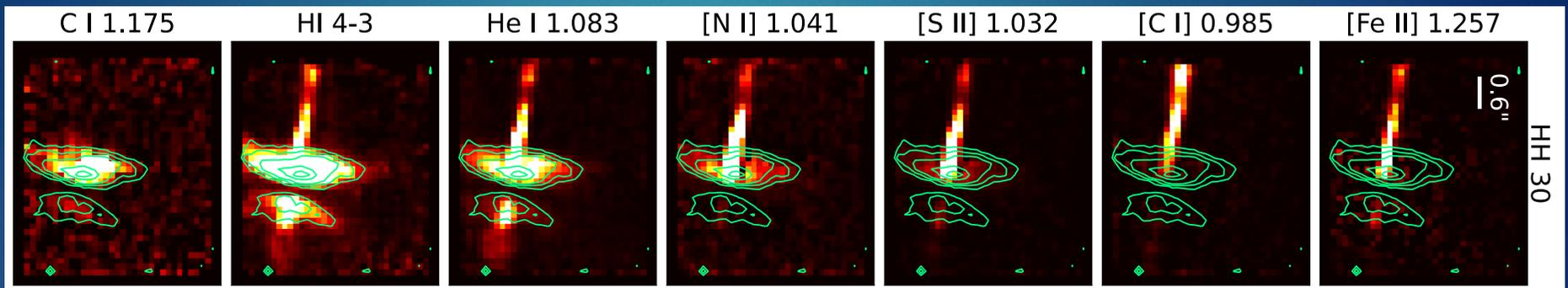
JWST excitation diagnostics in atomic jets

- Forbidden line emission: non LTE but optically thin.

- Depends on ne, xe =ne/nH, Te

- Assuming statistical equilibrium and neglecting induced radiative processes can derive ne from transitions of same element with similar excitation temperatures,

- E.g. [Fe II] 1.53 and 1.64 μm
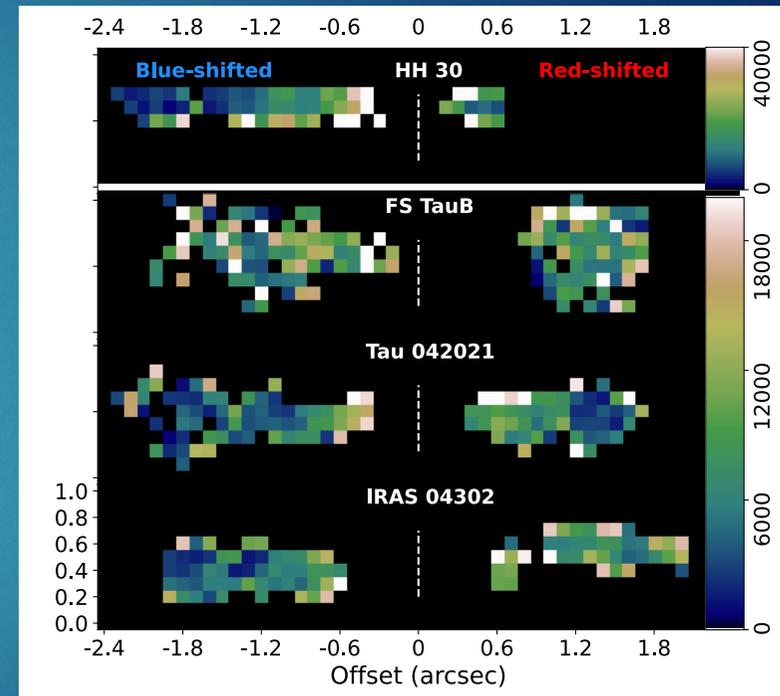
Bajaj+2025

tomic jet mass-fluxes

the ... ux from [FeII]
observations (c.f. *Agra-Amboage+2011)*

Mej/Macc is an important constraint for ejection models

▶ 1) Cross-section + e- density (assuming xe)

$$\dot{M}_J = (\mu m_H \frac{n_e}{x_e}) \times \pi r_J^2 \times v_J$$

▶ 2) Luminosity + e- density (assuming T_e)

$$\frac{\dot{M}_J}{(M_\odot \ yr^{-1})} = 1.34 \times 10^{-8} \times \left(1 + \frac{35000}{n_e(cm^{-3})}\right) \times \frac{L_J}{(10^{-4} L_\odot)}$$

$$\frac{v_J}{(km \ s^{-1})} \times \left(\frac{l_J}{au}\right)^{-1} \times \left(\frac{[Fe]/[H]}{[Fe]/[H]_\odot}\right)^{-1}$$

▶ 3) Luminosity + shock front (assuming some shock spacing)

$$\frac{\dot{M}_J}{(M_\odot \ yr^{-1})} = 9 \times 10^{-8} \ \frac{L_J}{(10^{-4} L_\odot)} \ \frac{v_J}{(50 \ km \ s^{-1})}$$

Bajaj+2025
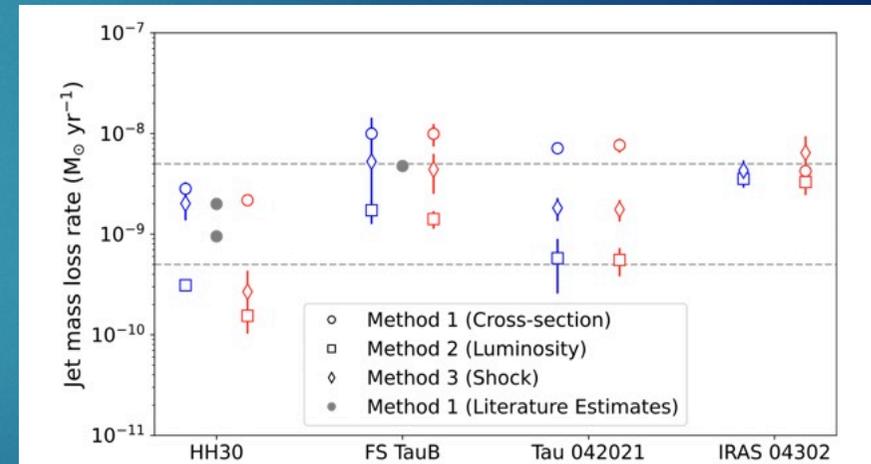
Photoevaporative winds from externally irradiated disks

Photoevaporating disk inside
Orion Bar (MIRI-MRS and
NIRSPEC)

- H_2 and OH = photoevaporative wind

- High-J Rotational OH (MIRI-MRS)
= water photodissociation

Trapezium massive stars

d203-506

Orion Bar

Jet
[Fe II]

Bright spot

OH

Extended molecular emission
H_2+OH

200 AU
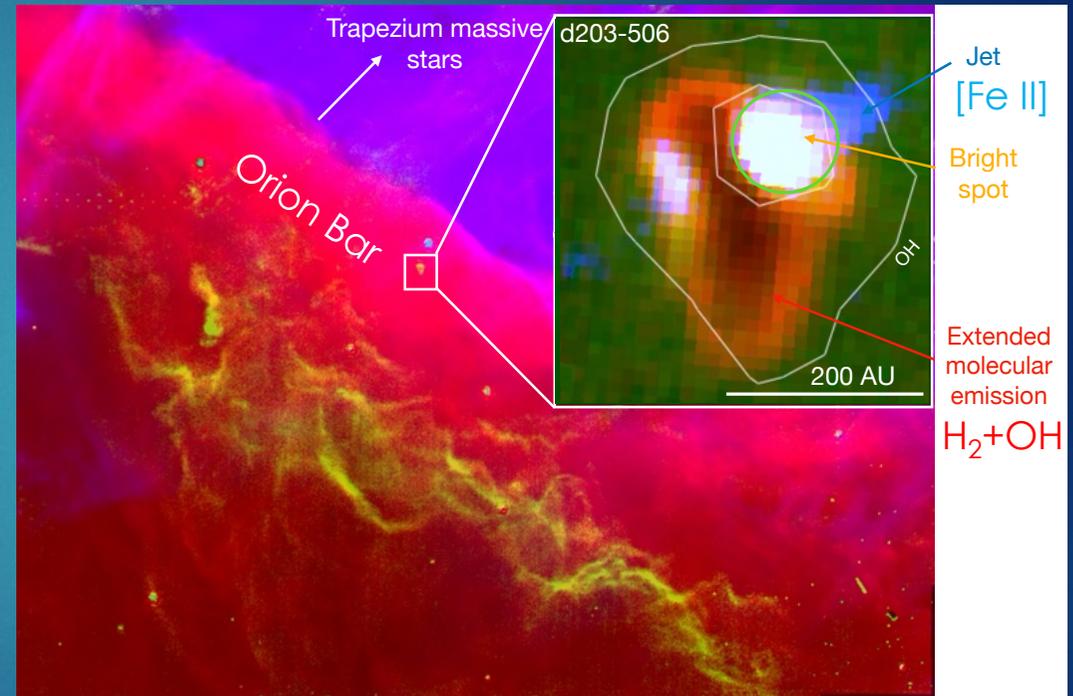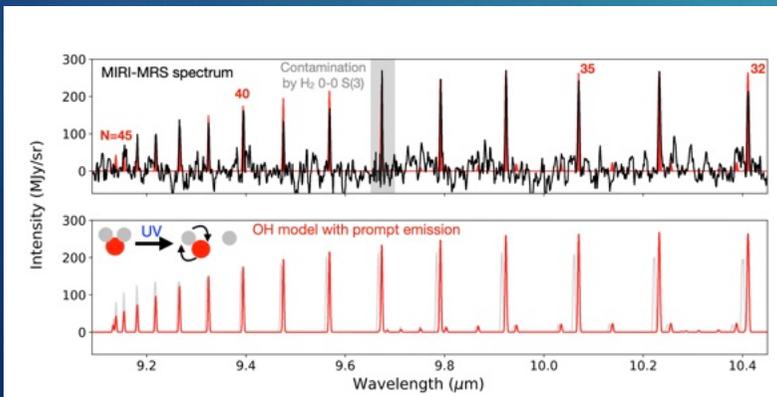
Zannese+2024, Nat.Ast.

III- Summary and open questions

Star formation: Which new info with JWST ?

- Exquisite image quality, unachievable from ground
  - reveal key morphological details (bowshocks, cavities, disk winds, binary jets…)
  - disentangle multiple shocks, constrain cooling length : more reliable modeling
- Pure rotational H_2 lines + (ro-vib CO emission), unobservable from ground (5-17mic)
  - unique probe of temperature regime 400-1000 K expected eg. in disk winds
  - Intermediate between cold CO of ALMA (30K) and rovib-H2 @2mic (2000K)
- Exquisite sensitivity, unachievable from ground
  - forest of new lines
  - New diagnostics of temperature, ionization, density➔ shock speed
  - Av maps ➔ better jet mass-flux ➔ Macc

Open questions and future directions

- ▶ Strong JWST & ALMA synergy
- ▶ Detailed comparison to model predictions now required (shock/irradiation models, mhd disk wind, collapse models)
  - ▶ Requires careful treatment of thermo-chemistry (H_2)
- ▶ New plasma diagnostics to be explored (spectral richness)
- ▶ Future directions: ELT, PRIMA

- ▶ References and Biblio:
  - ▶ JOYS summary paper van Dishoeck+ 2024

Thank you for your attention !!!