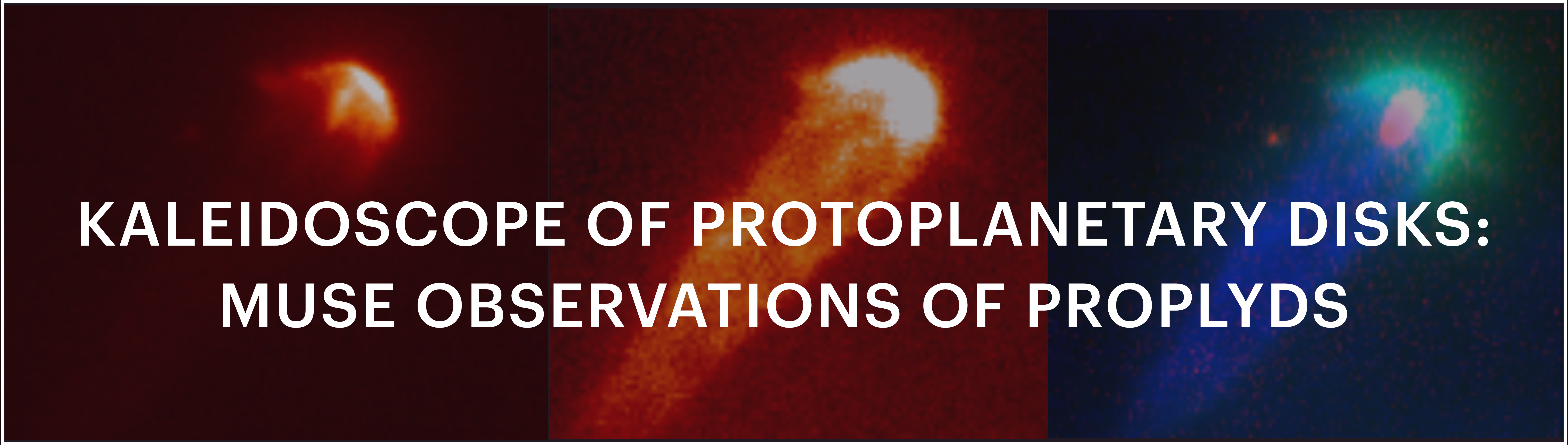
A Decade of Discoveries With MUSE and Beyond



KALEIDOSCOPE OF PROTOPLANETARY DISKS: MUSE OBSERVATIONS OF PROPLYDS

Mari-Liis Aru

With ***Carlo F. Manara (ESO), Karina Maucó,*** *T. Haworth, S. Facchini, G. Rosotti, A. Winter, N. Ballering, R. Boyden, J. Campbell-White et al.*

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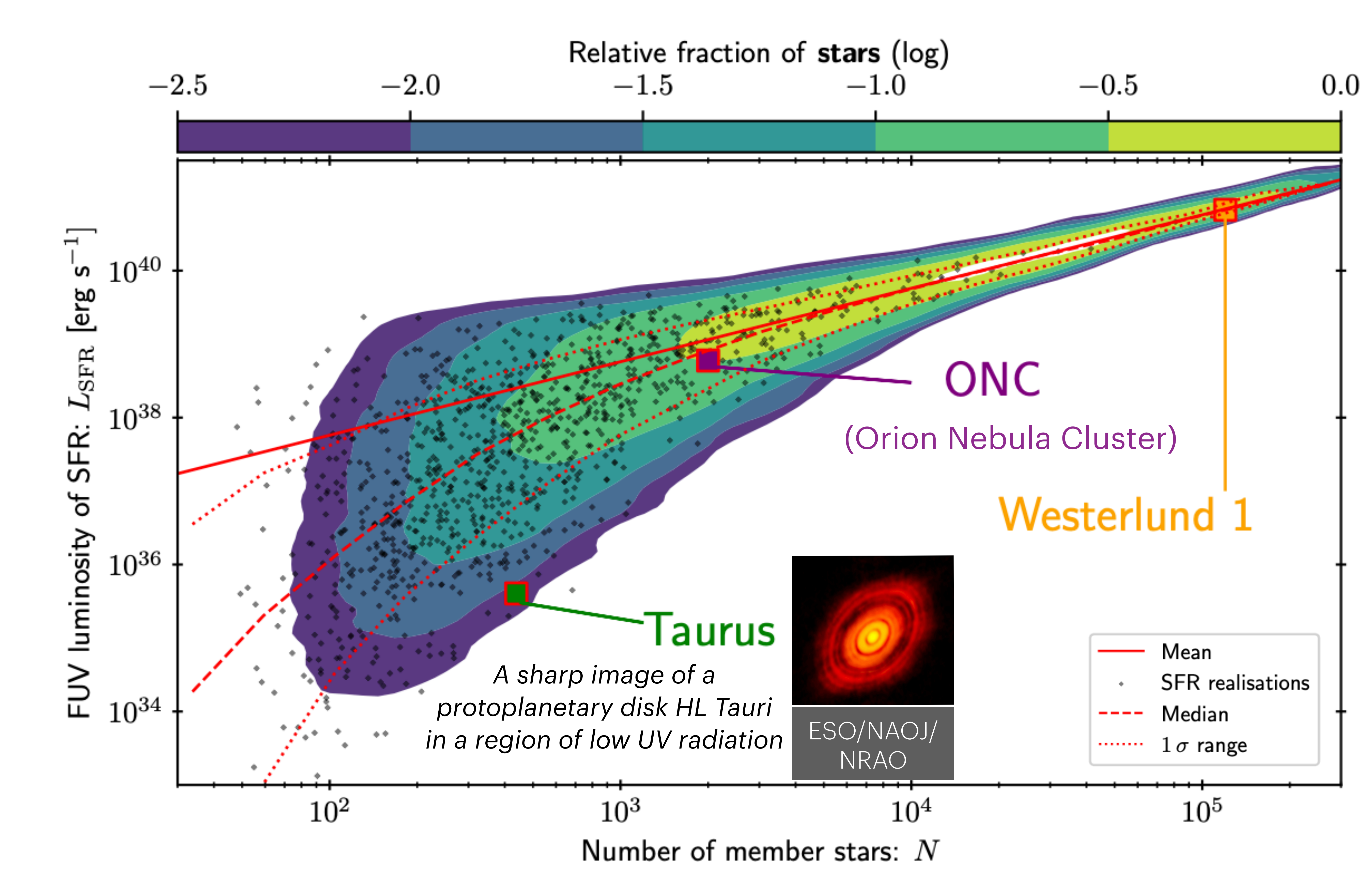
NOV. 2024

THE BIRTH ENVIRONMENTS OF PLANETARY SYSTEMS

Figure: UV luminosity of star forming regions vs their stellar density

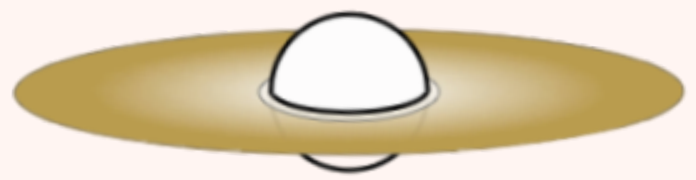
- The majority of stars (and exoplanets) form in dense clusters with strong UV radiation



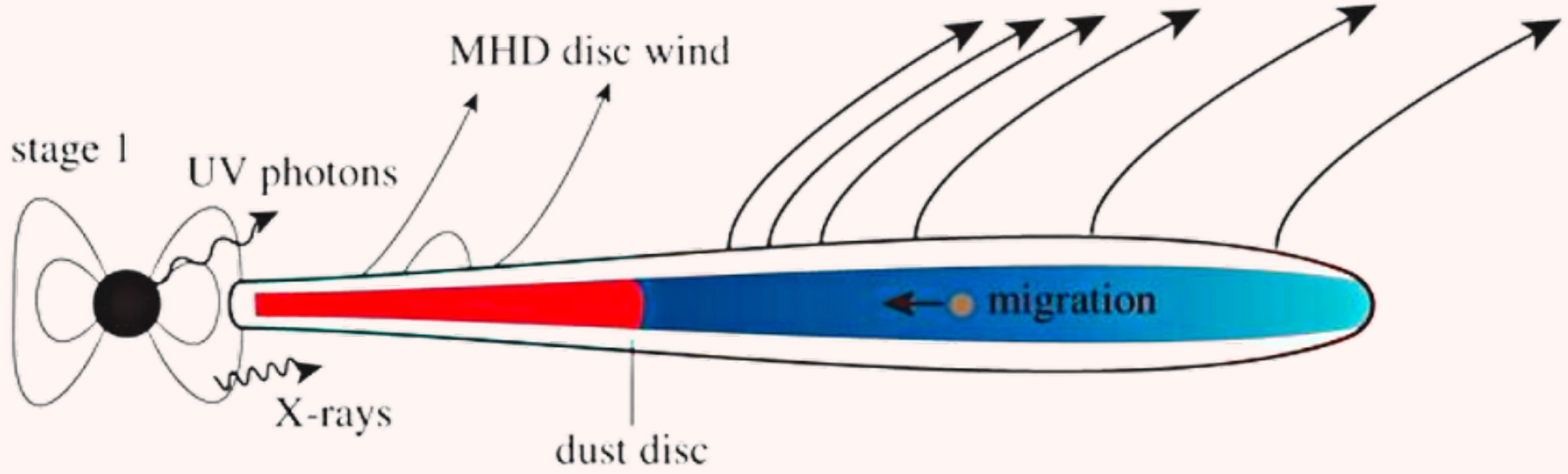
WINTER & HAWORTH 2022

THE BIRTH ENVIRONMENTS OF PLANETARY SYSTEMS: LOW UV

Isolated disk



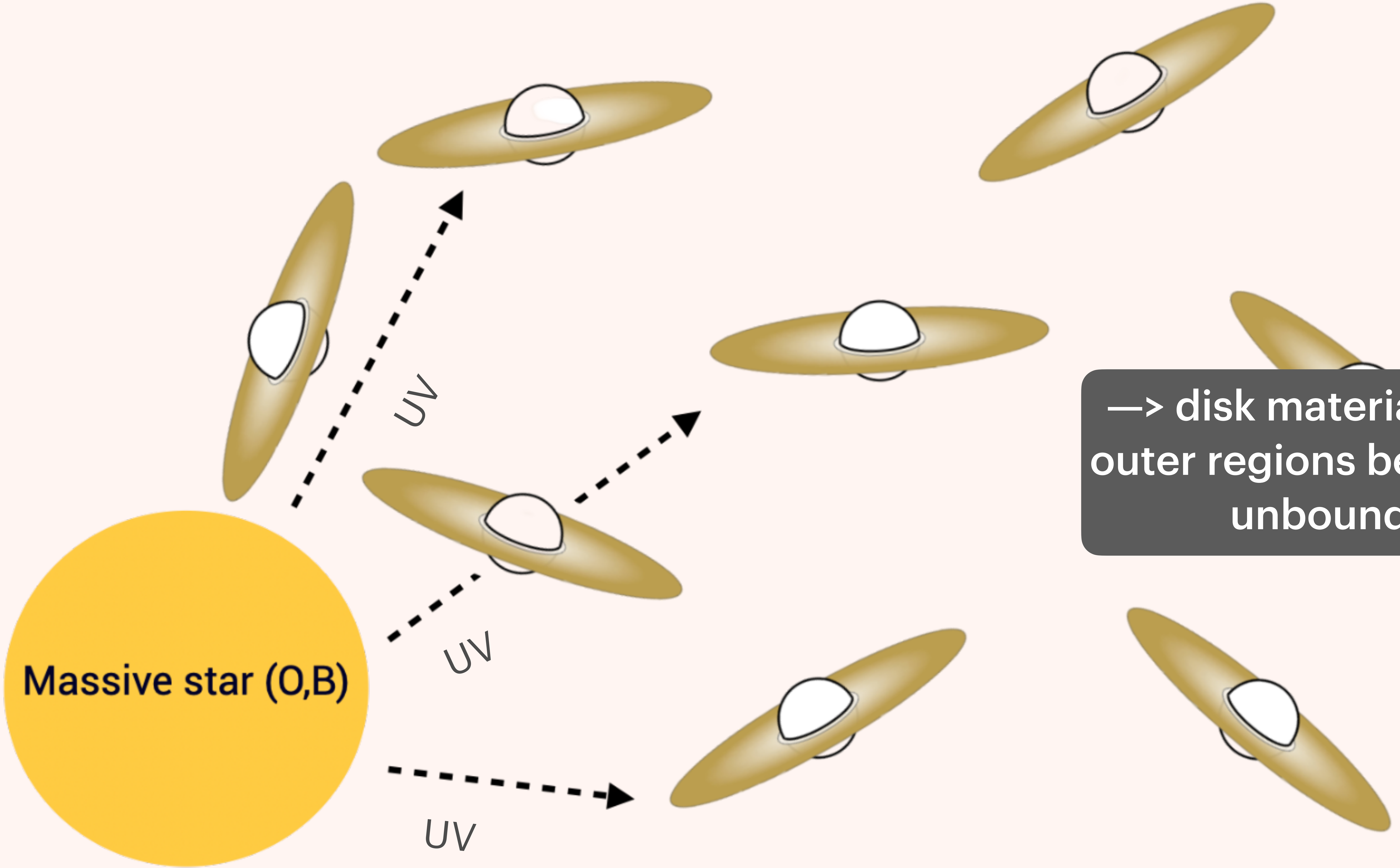
(INTERNAL) PHOTOEVAPORATION, MHD WINDS



ERCOLANO & PASCUCCI (2017)

- Internal photoevaporation: inside-out depletion. Driven by photons from the central host star (e.g., Ercolano+ 2008; Picogna+ 2019)
- *Method: forbidden line emission*

THE BIRTH ENVIRONMENTS OF PLANETARY SYSTEMS: HIGH UV



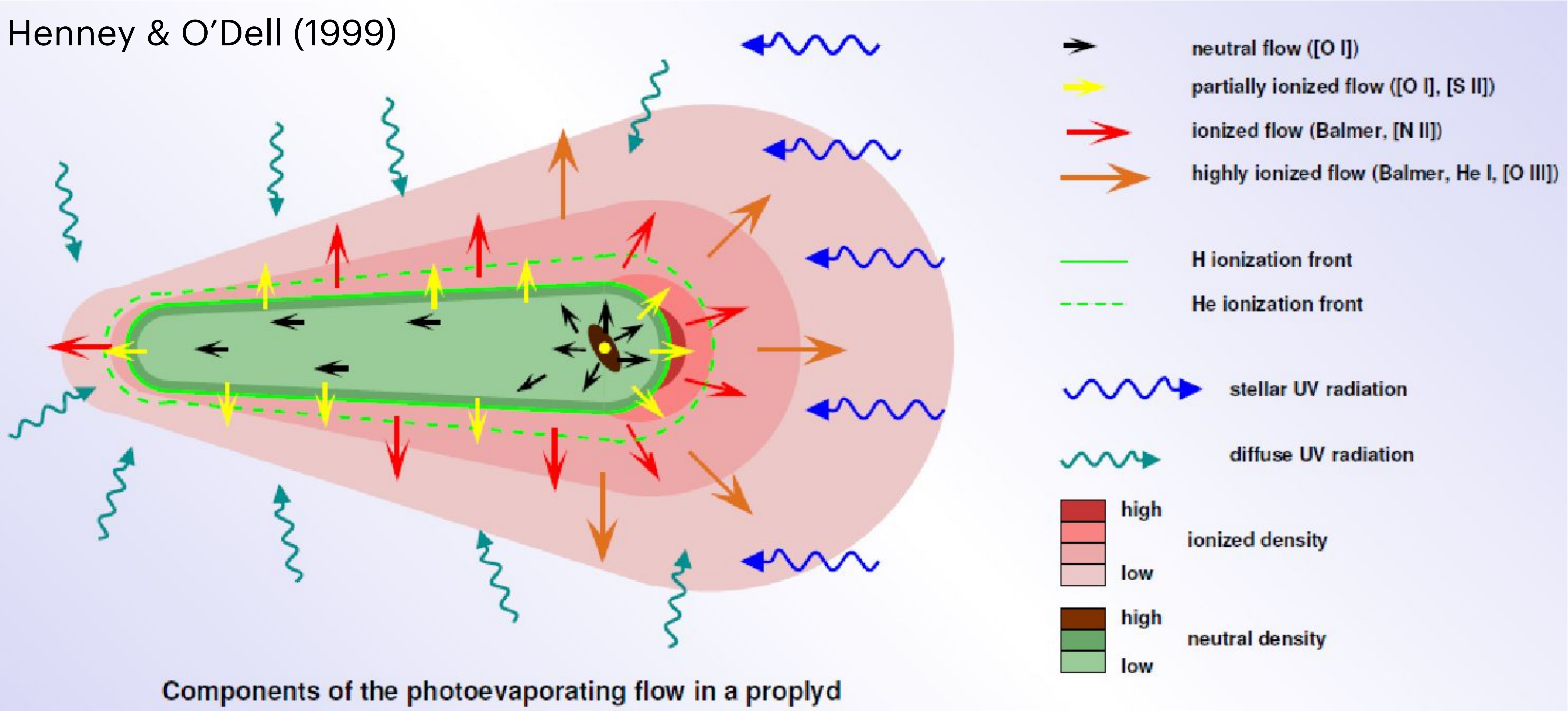
—> disk material in its outer regions becomes unbound

UV photons heat the disk material externally.

ILLUSTRATION: C. F. MANARA

—> comet-shaped cloud of ionized gas with an ionization front

—> dispersal of the disk, reduction of its lifetime



Such systems, called **proplyds**, allow us to study how the **surrounding environment** affects the evolution of disks and their ability to form planets.

Observed in various forbidden lines.

HOW TO DISENTANGLE THE TWO EFFECTS?

INTERNAL PHOTOEVAPORATION

in both low mass and massive SFRs

EXTERNAL PHOTOEVAPORATION

in massive SFRs

↓

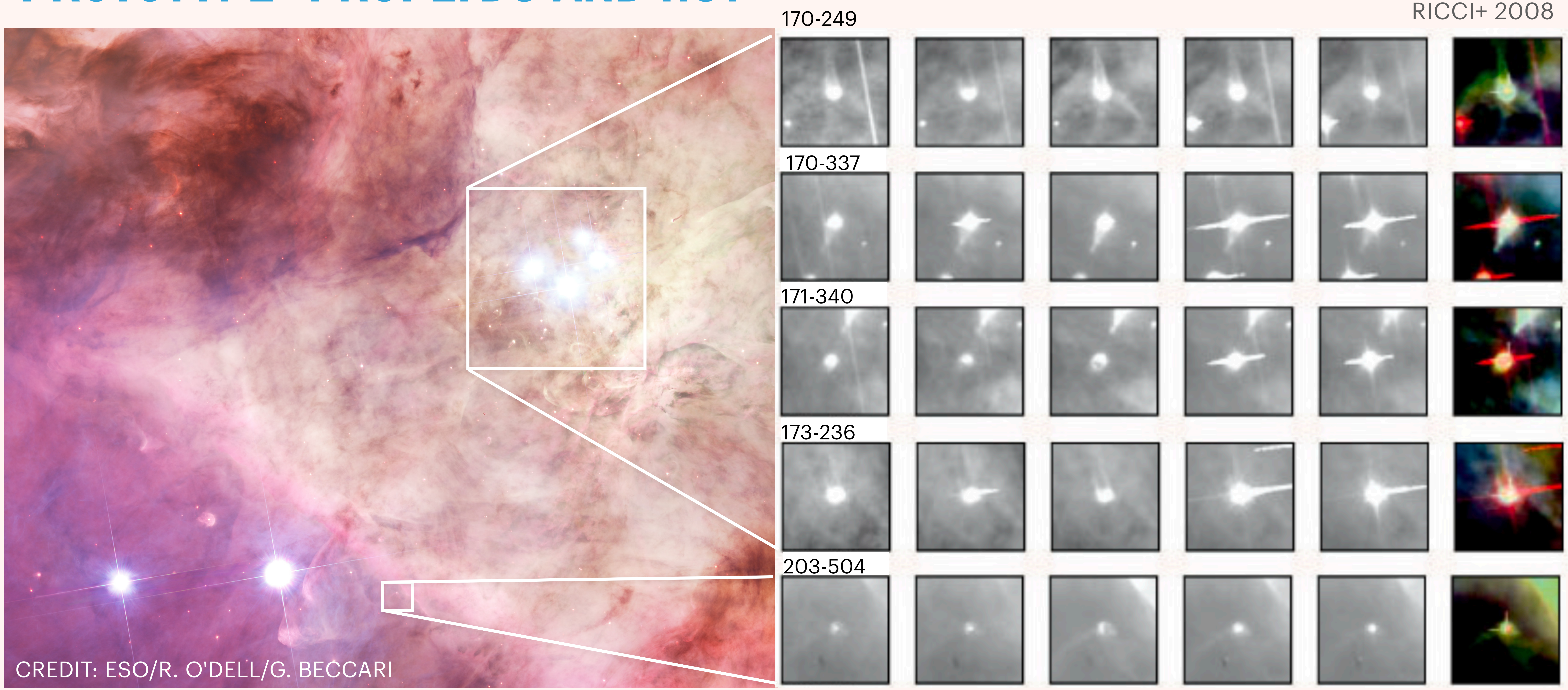
forbidden line emission

Which lines or line ratios allow us to disentangle the two?
Let's look at proplyds in depth.

"PROTOTYPE" PROPLYDS AND HST

- 1990s: first proplyds (and protoplanetary disks in general) discovered in the ONC, Orion Nebula Cluster.
- The closest massive region of star formation, ~400 pc.

"PROTOTYPE" PROPLYDS AND HST



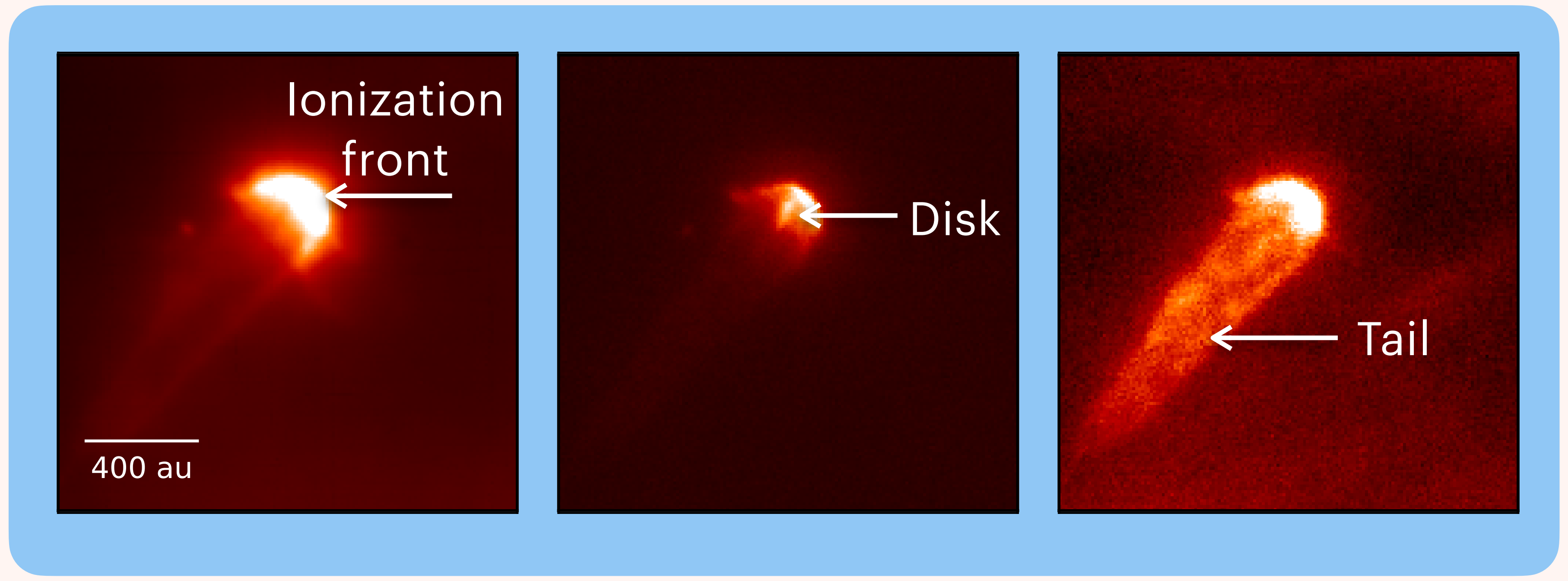
- Observational properties of proplyds studied in a limited number of filters: O'Dell et al. 1993; O'Dell & Wen 1994; McCaughrean & O'Dell 1996; Ricci et al. 2008

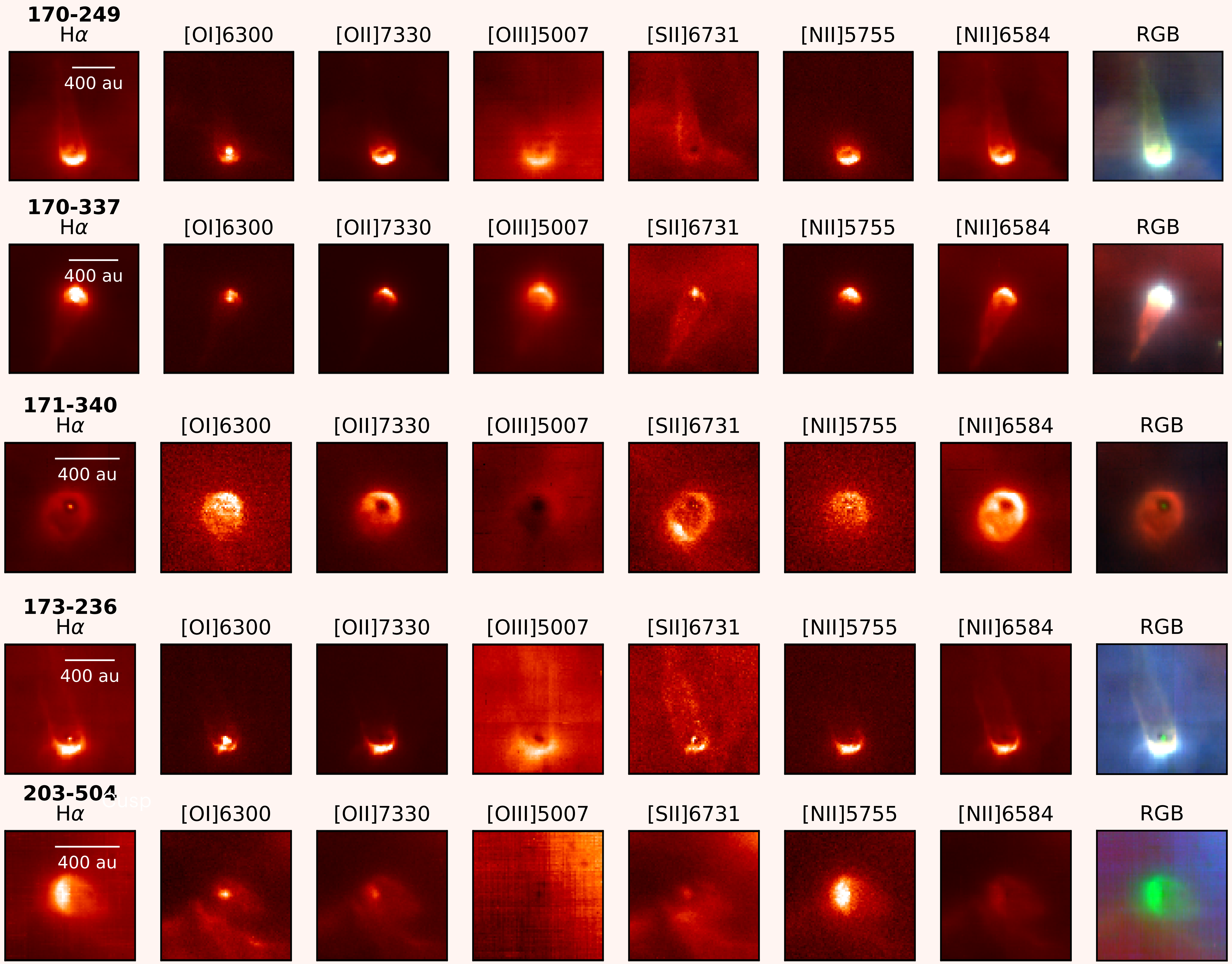
MUSE

Aru+ 2024a (first PhD project: sample presentation)

- A wealth of forbidden emission lines detected
- FWHM ~ 0.07″ (28 au)

—> Spatially distinguish different parts of the system

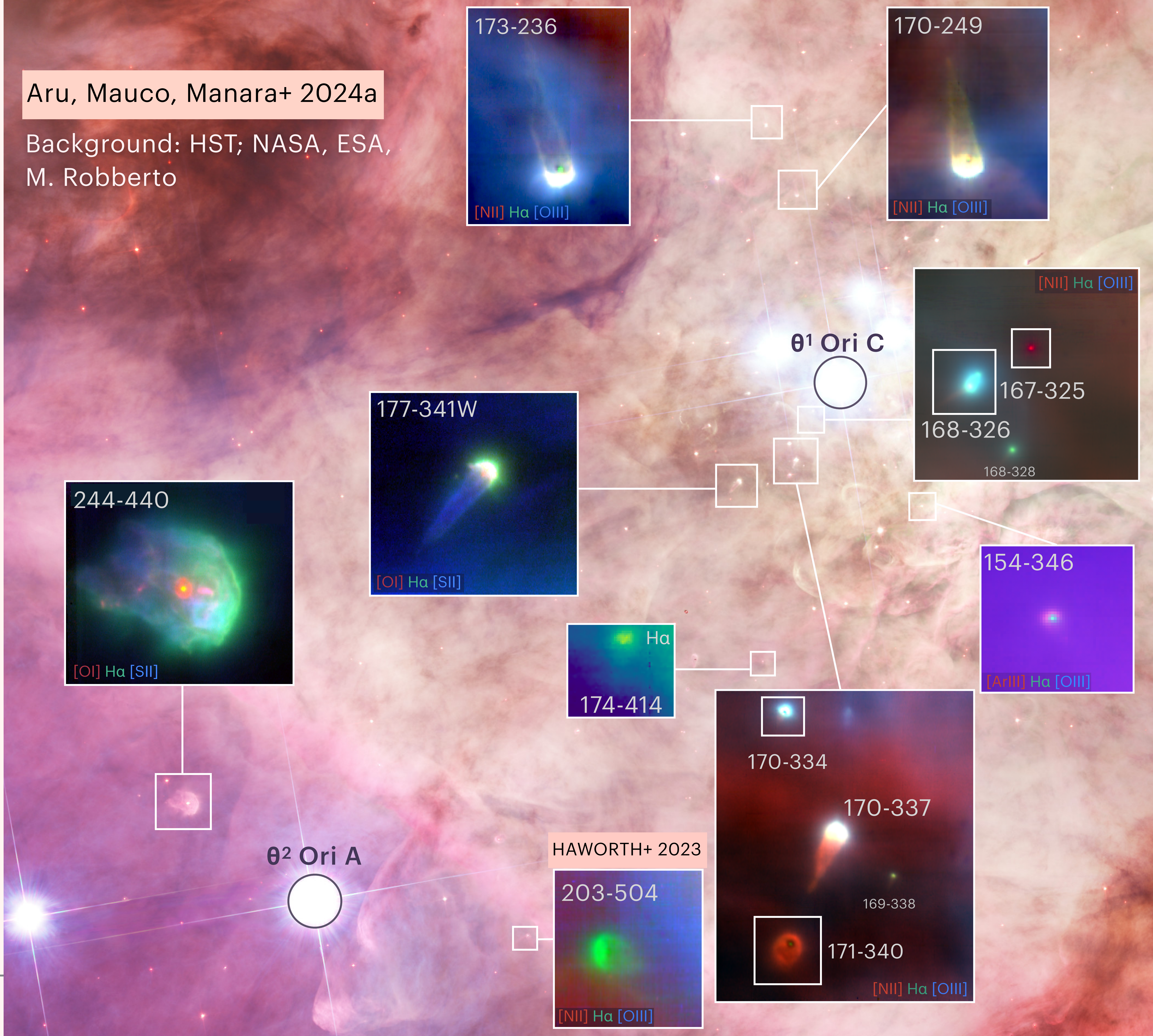




OUR SAMPLE

- MUSE NFM observations of 12 proplyds in the ONC (insets)
- Different distances from the main UV source θ^1 Ori C

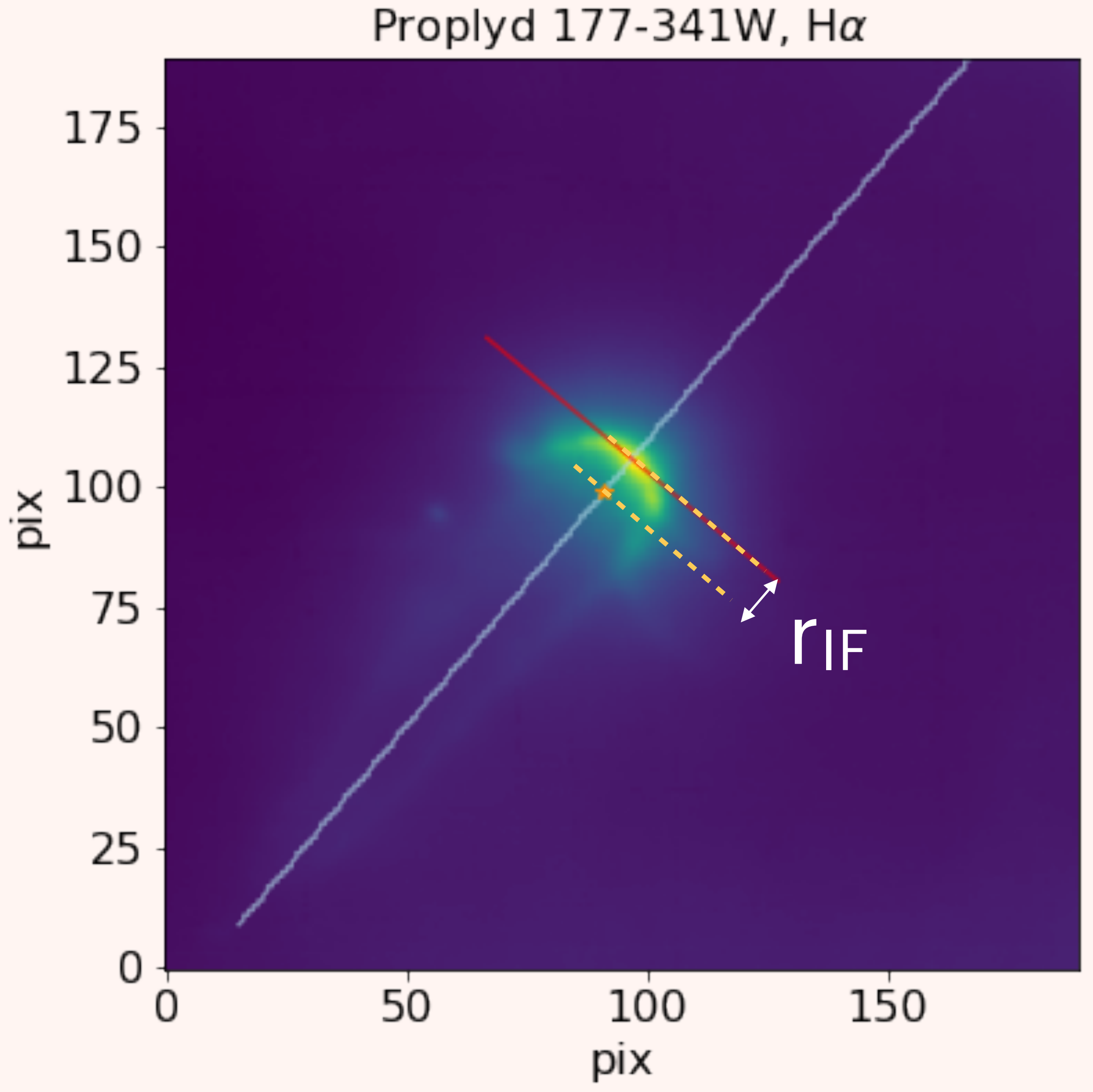
Insets: MUSE, continuum-subtracted single-line integrated flux images

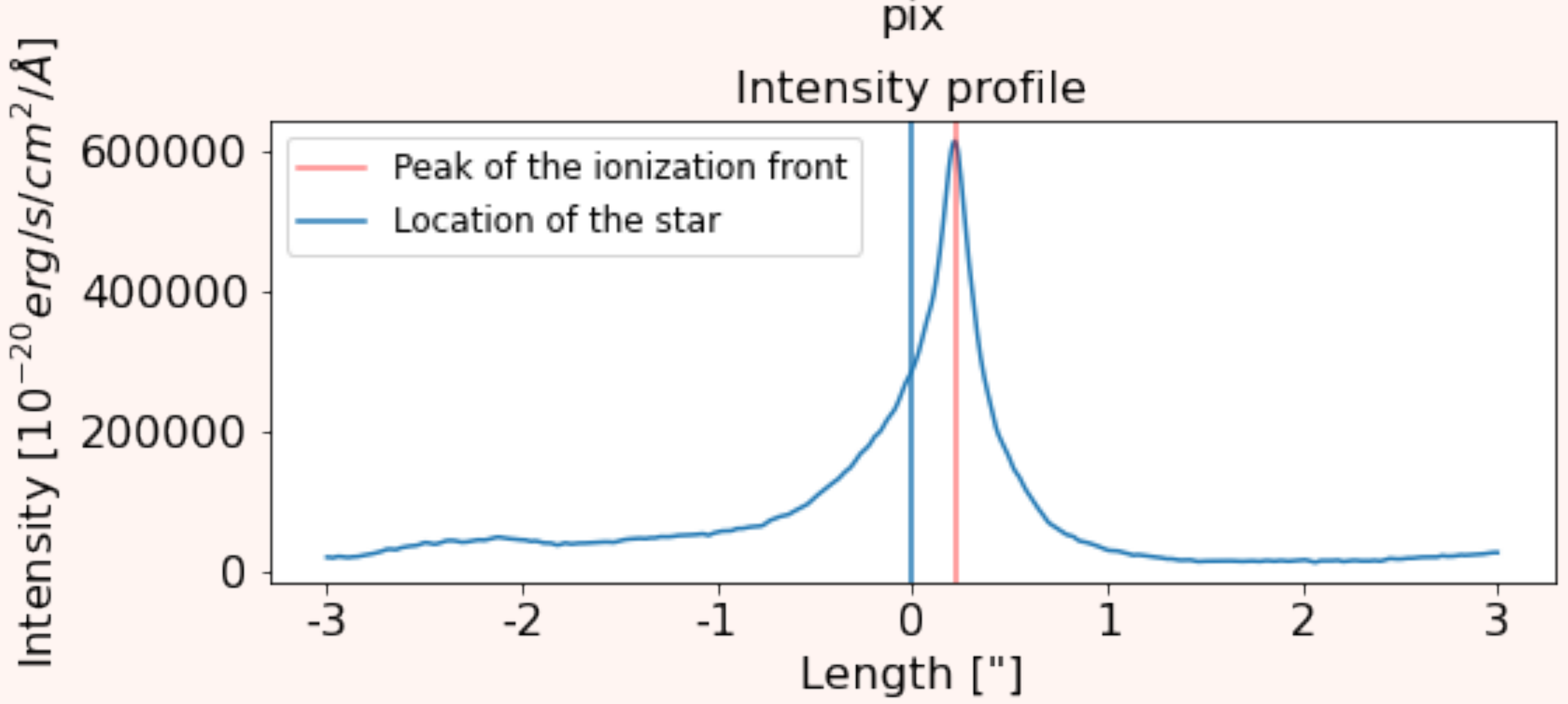


IONIZATION FRONT RADIUS

Aru+ 2024a

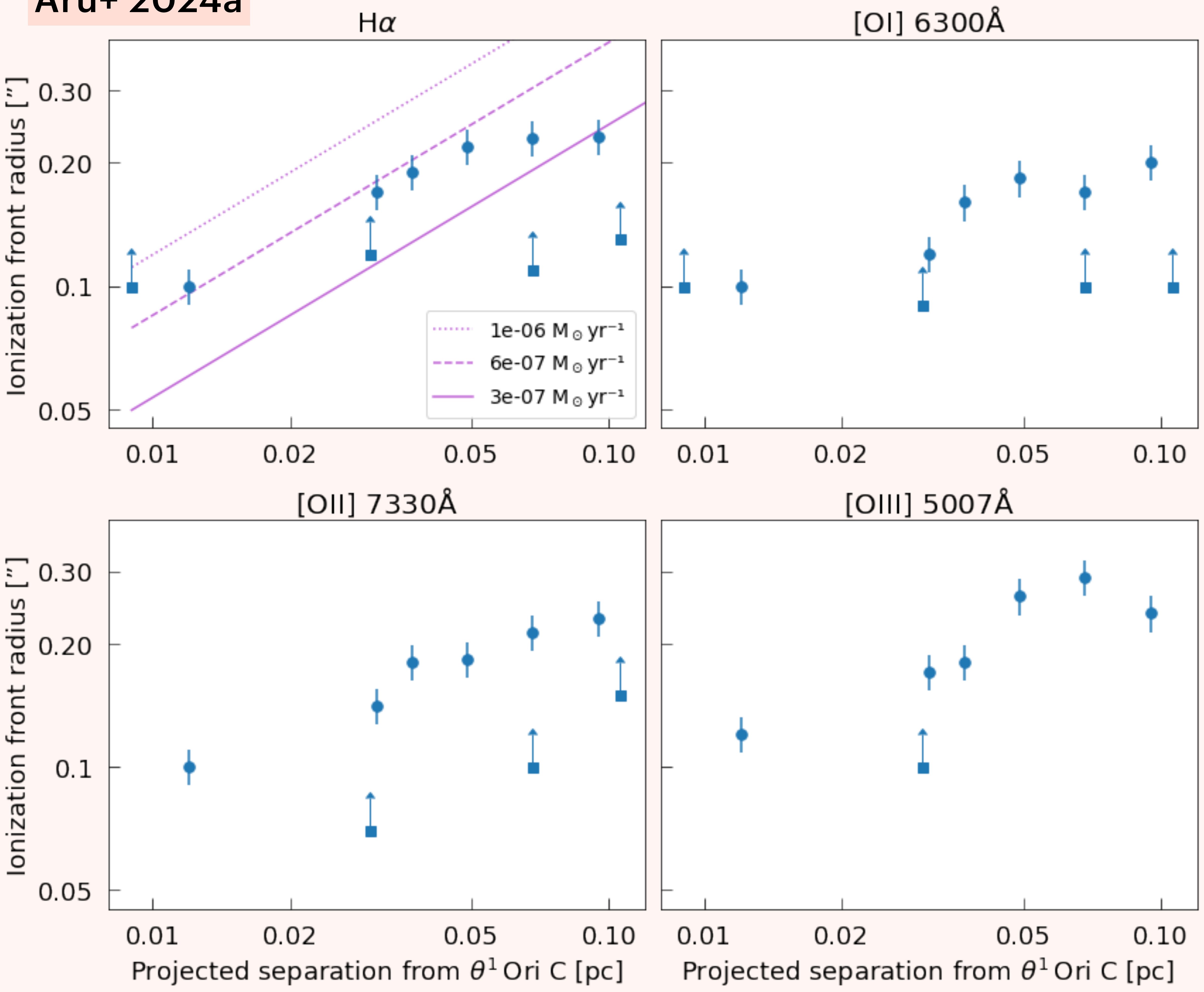
- We can measure the ionization front radius (r_{IF}) in different levels of ionization





IONIZATION FRONT (I-FRONT) RADIUS VS PROJECTED SEPARATION FROM θ1 ORI C

Aru+ 2024a



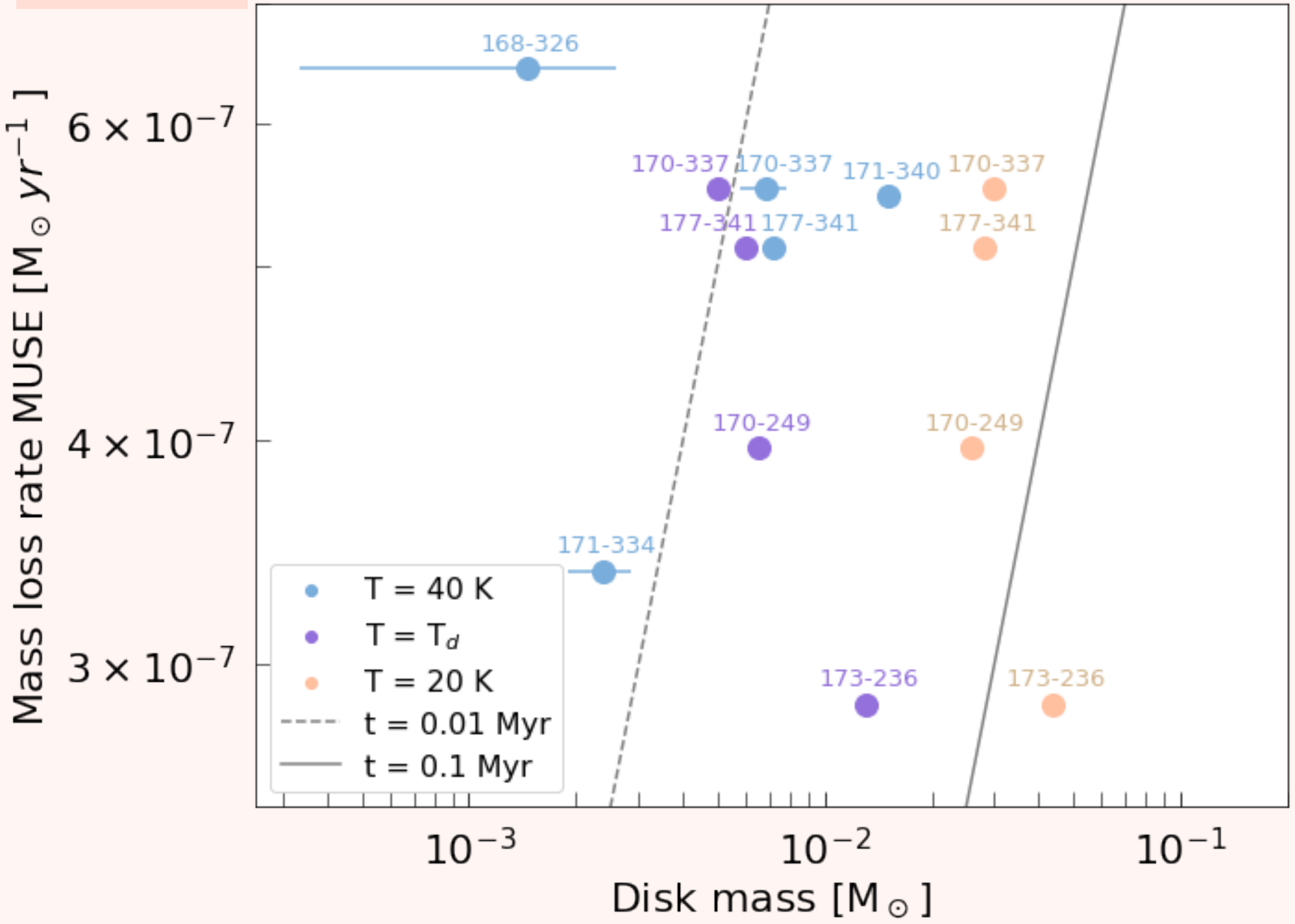
- I-front radius increases at larger projected separation from the massive star, i.e. at lower ionization rates, in all tracers used.
- r_{IF}: allows to empirically infer the **mass-loss rate of proplyds, which is a critical factor in the evolution of irradiated disks.**

$$r_{\rm IF} \approx 1200 \left(\frac{\dot{M}_{\rm loss}}{10^{-8}\, M_\odot\, {\rm yr}^{-1}} \right)^{2/3} \left(\frac{\dot{N}_{\rm Ly}}{10^{45}\, {\rm s}^{-1}} \right)^{-1/3} \left(\frac{d}{1\ {\rm pc}} \right)^{2/3} {\rm au}$$

—> UPPER LIMIT ON MASS-LOSS RATE   Winter & Haworth 2022

MASS-LOSS RATE VS DISK MASSES FROM ALMA

Aru+ 2024a



- Proplyd lifetime t=$\dot{M}/M_{disk}$
- t = 2.4 to 130 kyr
  (But ages of the ONC stars: 1-2 Myr)

- Plotted: Disk gas mass, 100 x disk dust mass
- Colors: different assumed dust temperature

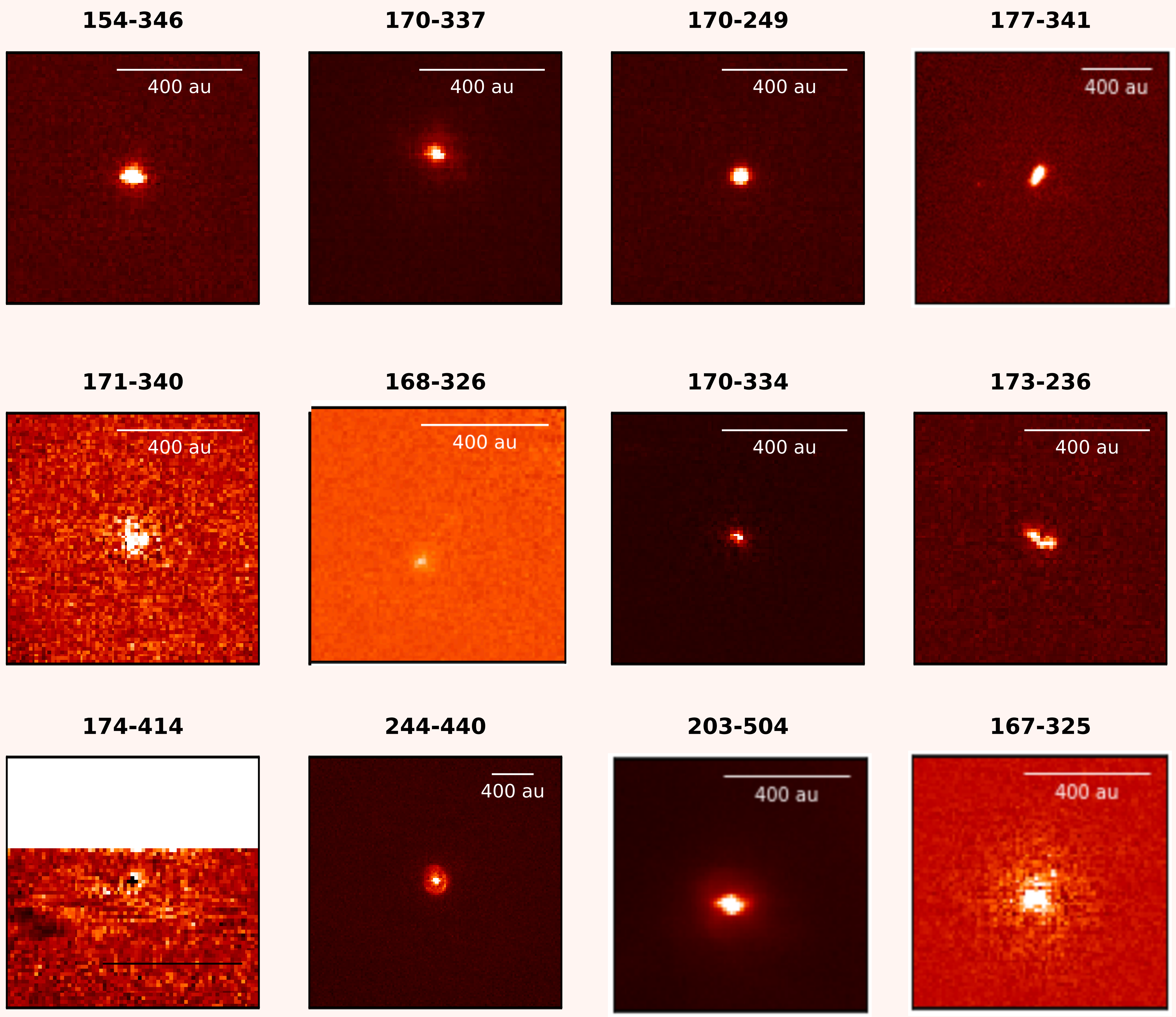
Disk masses: Mann+ 2014, T=40 K, Ballering+ 2023, T_d=62–108 K. Diagonal lines mark lifetimes.

TRACING DISKS WITH MUSE: [CI] EMISSION LINE AT 8727 Å

Aru+ 2024b (second PhD project)

- First presented in two disks by Haworth+ 2023.
- We find [CI] 8727 A detection in each 12 proplyds.

(Goicoechea+ 2024: line emitted via FUV-pumping)



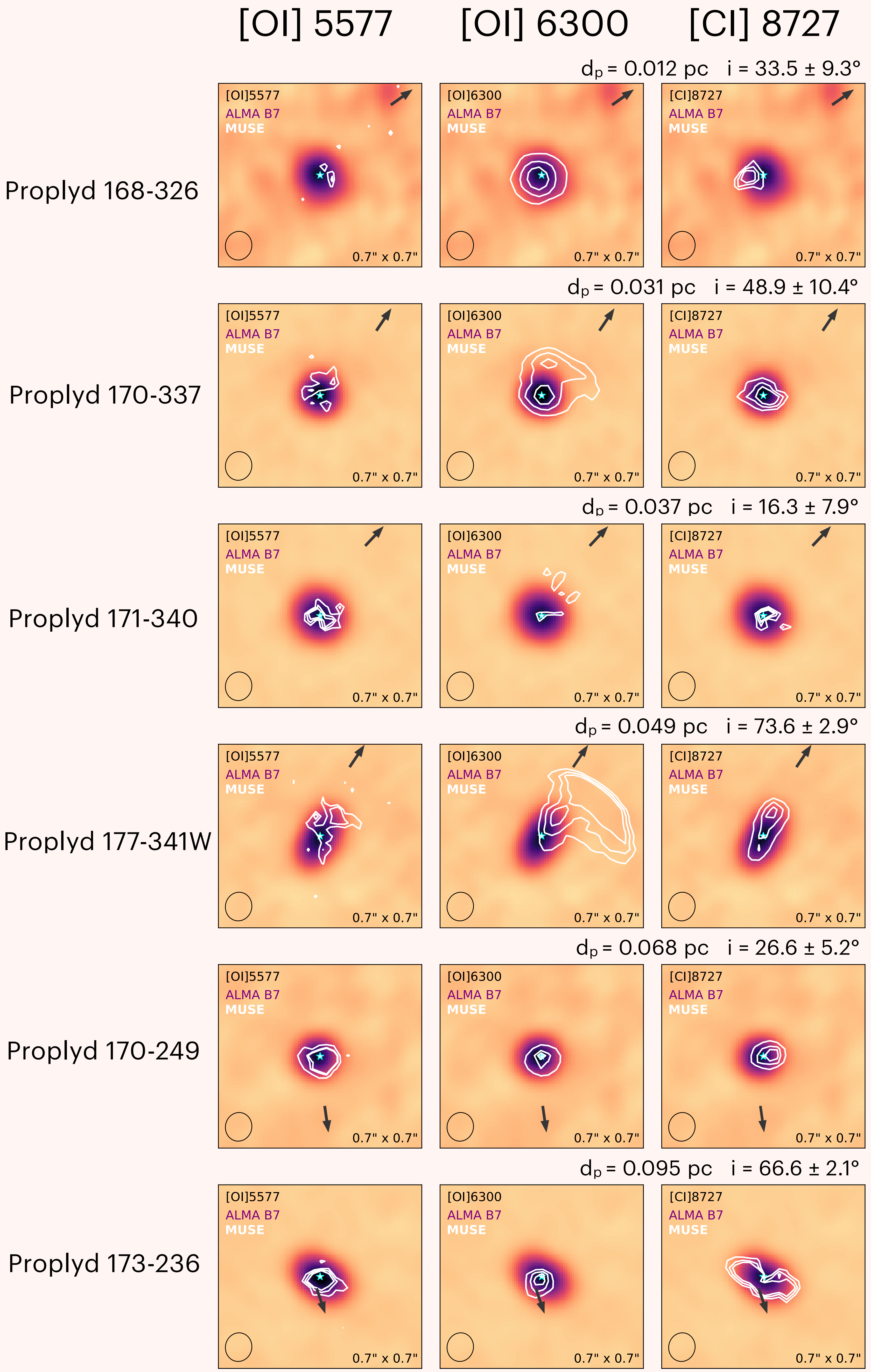
SPATIAL COMPARISON OF SIX TARGETS: MUSE + ALMA OVERLAP

Aru+ 2024b

➡Compare [CI] with [OI] lines, and compare them with ALMA.

- Colormap: ALMA disk dust emission, Band 7 (0.86 mm)

- White contours: MUSE. Comparing three emission lines close to the disk.

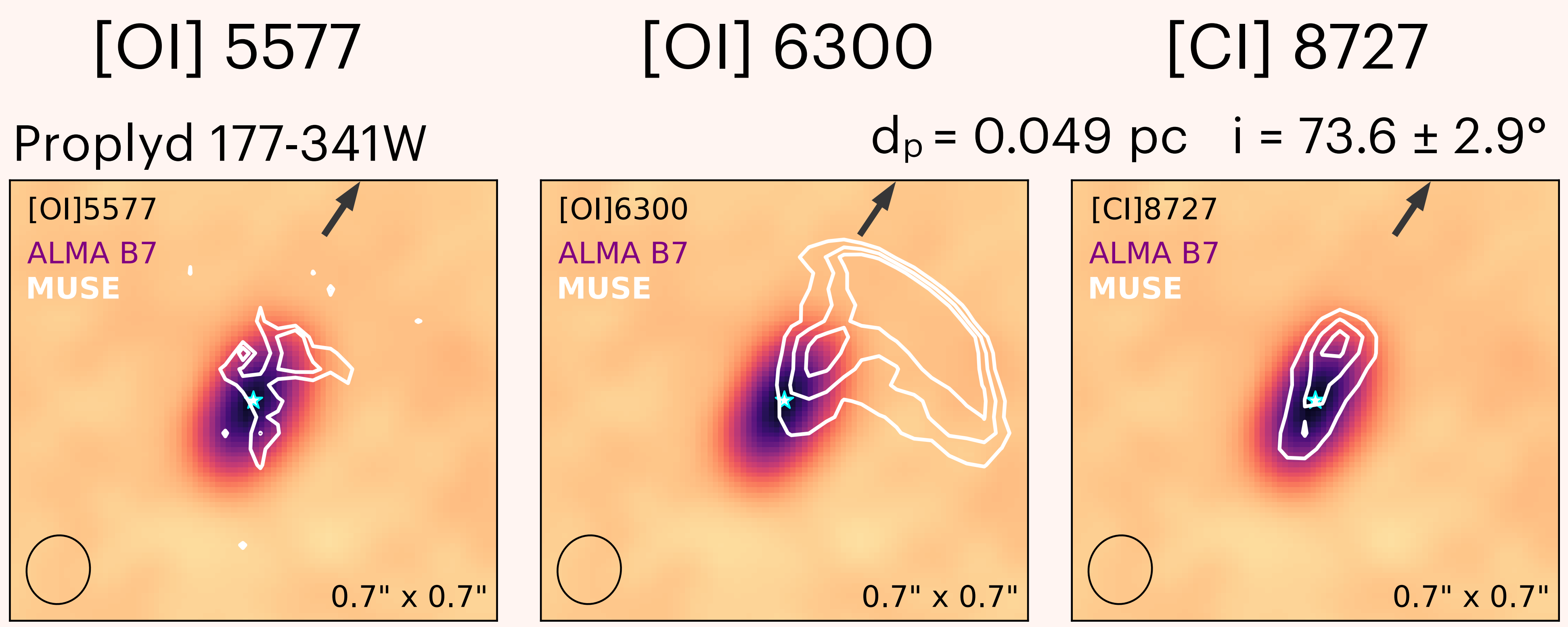


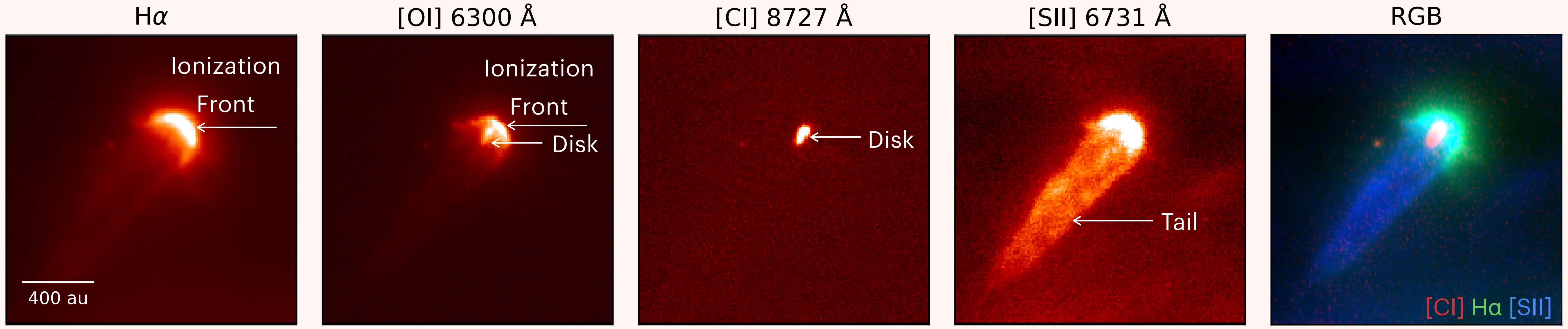
Angular resolution: MUSE ~0.07" / ALMA: 0.09"

ALMA data: Eisner+ 2018, Ballering+ 2023

Aru+ 2024b

- Compared to the oxygen lines, [CI] locates the disk most clearly.
  Its spatial location strongly suggest that this line traces the base of the externally photoevaporated wind.





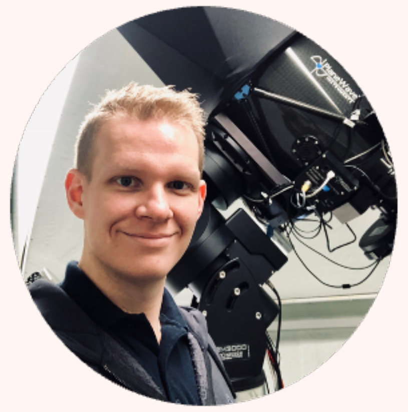
ALMA data: Eisner+ 2018, Ballering+ 2023

[CI] 8727 Å AS A SIGNATURE OF EXTERNAL PHOTOEVAPORATION

Aru+ 2024b

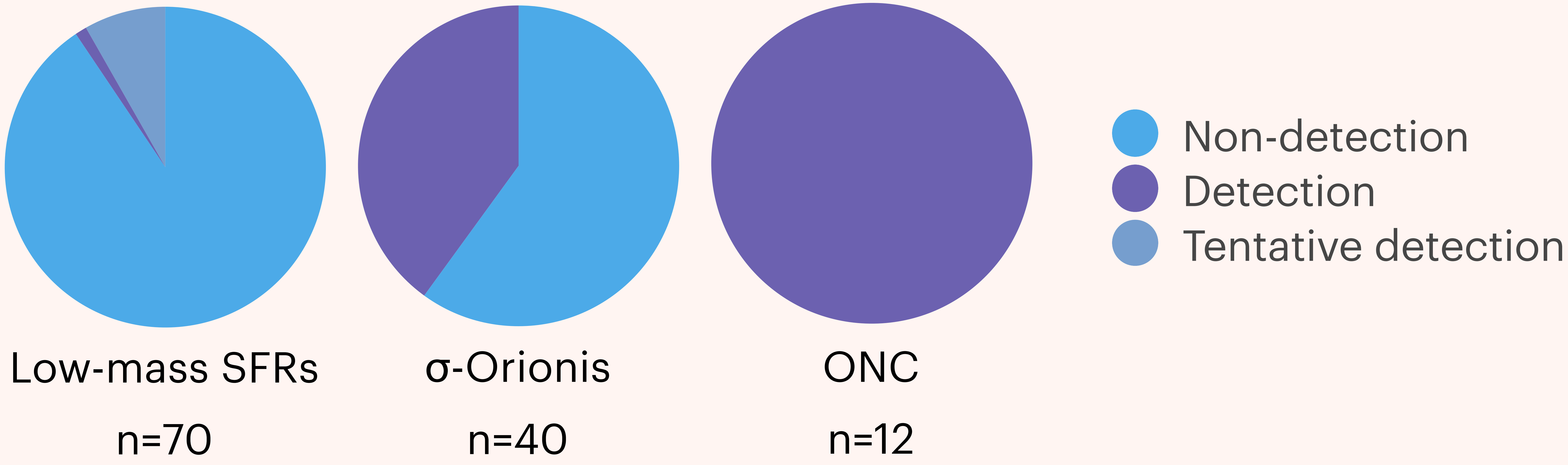
Thanks to group members:

Karina Mauco



Justyn Campbell-White

- [OI]: very common in low-UV radiation environments (internal photoevaporation)
- However, [CI] rarely detected (<10% of targets and tentative!), based on 77 X-Shooter spectra



☑ Goicoechea+ 2024: intensity of the IR carbon lines scales with UV field strength, G_0.

[CI] 8727 Å AS A SIGNATURE OF EXTERNAL PHOTOEVAPORATION

Aru+ 2024b

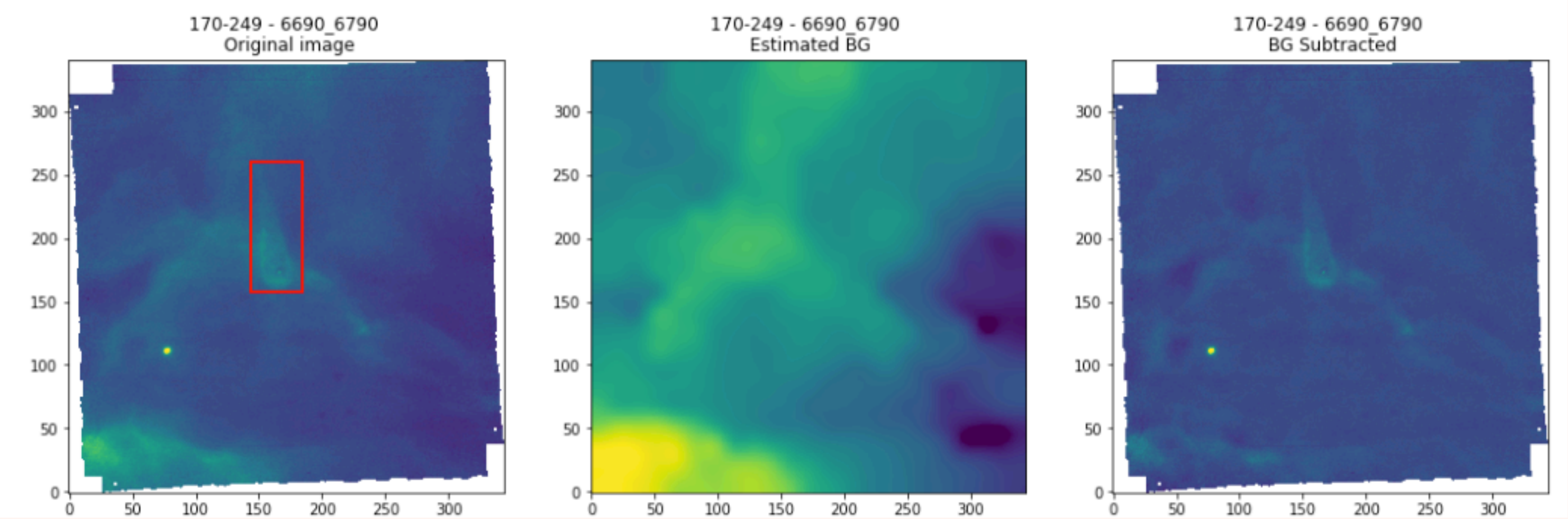
- An emission line that pinpoints to the disk and/or base of the wind.
- Emerging in the conditions of external photoevaporation: a proxy that is especially valuable in regions with unresolved proplyds.

✓ Disentangle external and internal winds.

IN PROGRESS / NEXT STEPS

- Line ratios
  -> Measure line intensities to calculate electron temperature and density
  -> A more refined value of mass-loss rate

- Background subtraction



in prep.
Using *photutils Background2D*

CONCLUSIONS

☑ MUSE allows us to characterize the morphology of proplyds at different ionization levels using a gallery of spectral line tracers.

☑ [CI] 8727 A: a tell-tale tracer for photoevaporating disks which agrees with the newest models.

▶ Next: physical properties in detail.

Aru, M.-L., Maucó, K., Manara, C. F., et al. 2024, A&A, 687, A93

Aru, M.-L., Maucó, K., Manara, C. F., et al. 2024, arXiv:2410.21018

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EXTRA SLIDES

[OI] LINES

[OI] 6300:
The **photodissociation of OH** produces an abundance of excited neutral oxygen that originates bright [O i]λ6300 emissions (Bally et al. 2000; Bally & Reipurth 2001).

I-front: where oxygen is **excited thermally** due to collisions with H, H2 and electrons (e.g., Störzer & Hollenbach 1998)

PROPLYD LIFETIME PROBLEM

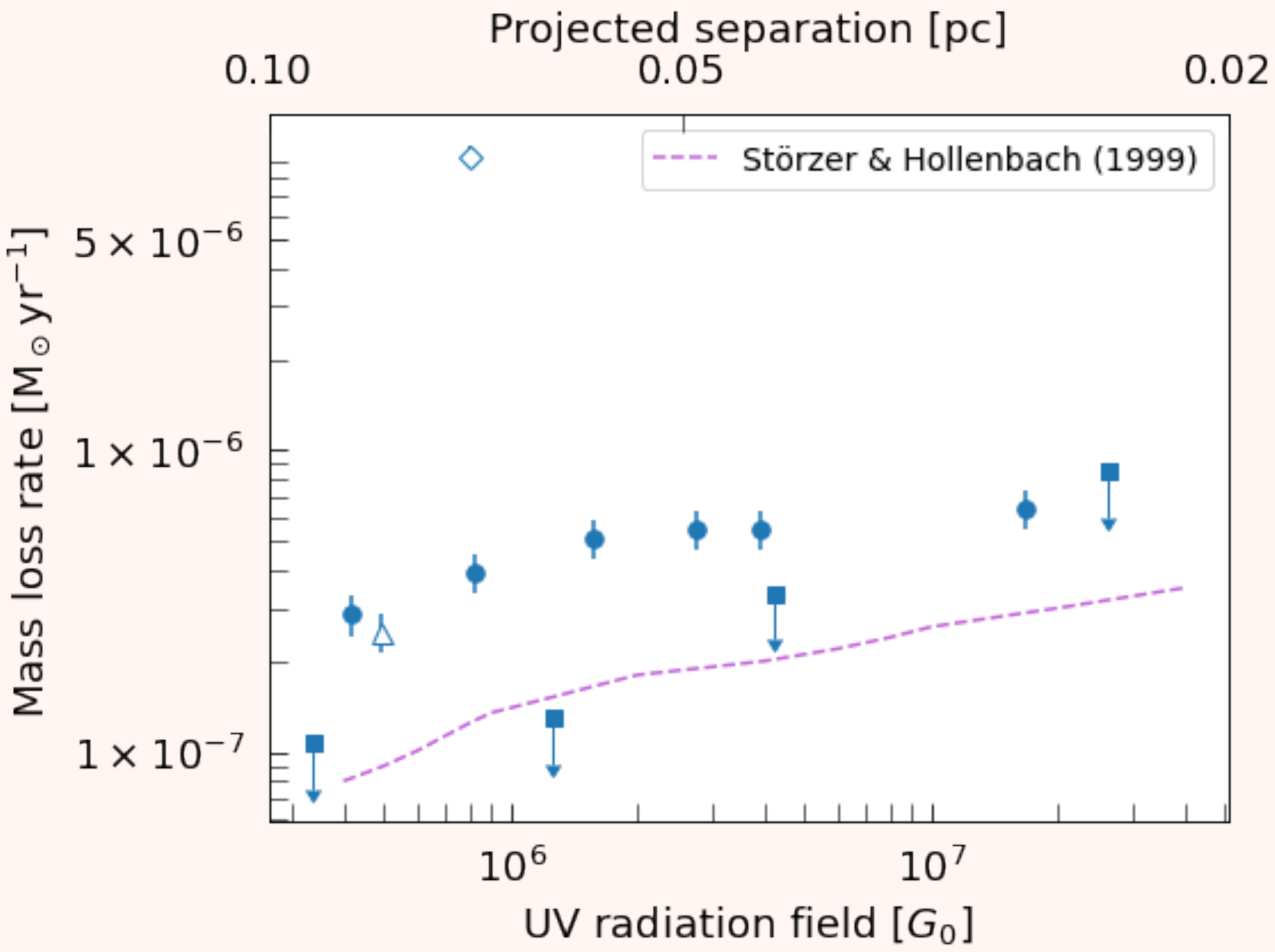
- The lifetimes are very short compared to the age of the region.

What can make the problem milder?

- Age spread in the stellar population of the ONC - episodes of star formation. (e.g., Hillenbrand 1997; Palla & Stahler 1999; Da Rio et al. 2010; Jeffries et al. 2011; Beccari et al. 2017).

- Wilhelm+ 2023: Radiation shielding by gas - the disk lifetime could be extended by an order of magnitude by such shielding.

MASS-LOSS RATE VS G0



Aru+ 2024a

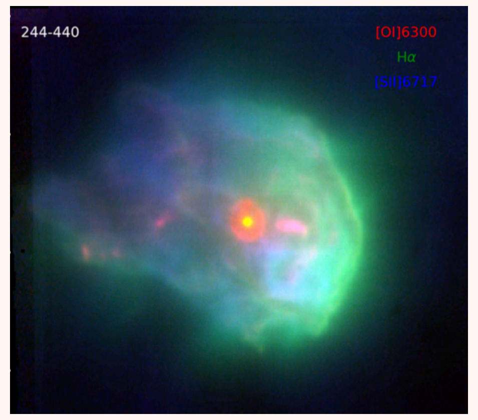
- Mass-loss rate is a slowly decreasing function of G_0; agreement with models (Störzer & Hollenbach 1999)

$$F_{FUV} = \frac{1}{G_0}\frac{L_{\rm FUV}}{4\pi r^2}$$

- Values: 10^{-7}–10^{-6} $M_\odot$/yr

- Agreement compared to other measurements:
  - higher Mloss than in NGC 1977 (G_0~3000, 10^{-9}–10^{-8} $M_\odot$/yr, Kim+ 2016, Boyden & Eisner 2024)
  - And NGC 2024 (10^{-7} $M_\odot$/yr, G_0~10^6, Haworth+ 2021).

- 244-440: an outlier. Also peculiar in terms of its shape.



[CI] EMISSION

- Escalante+ 1991: predict this line to be emitted from recombination of C+ ;
  clouds 10^5 cm-3 subject to radiation fields 10^3 – 10^6 G0.

- **Goicoechea+ 2024:**
  FUV-pumping (C atom absorbs FUV photons), followed by de-excitation cascades.

  - At 1000 K (typical T derived from JWST), n_cr(e) ~ 6e7 cm^-3.

- Very high energy level, 2.7 eV, which is much higher than the gas temperature, so one can anticipate that collisions will not be relevant.

- Line intensity only weakly dependent on n.

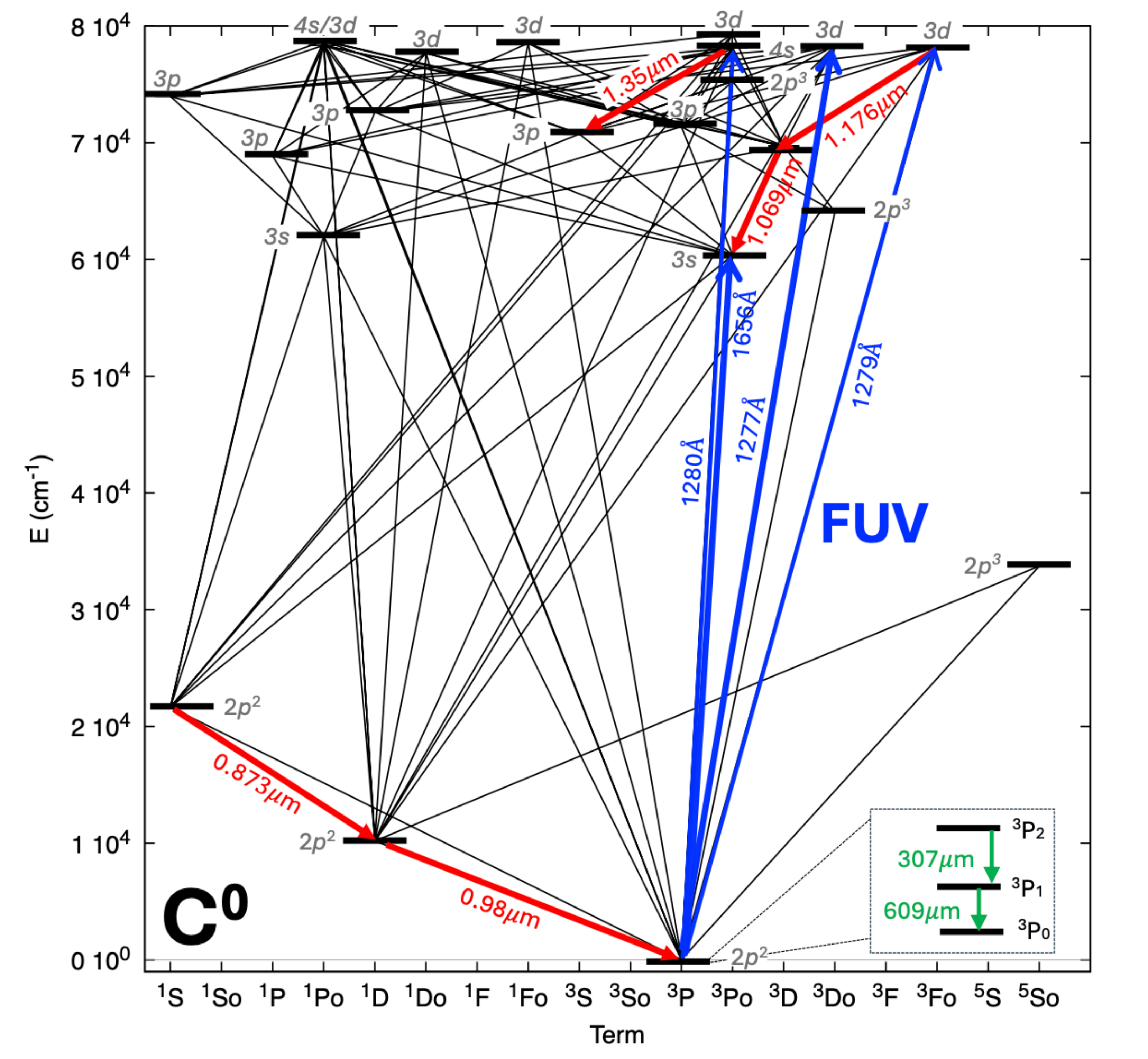
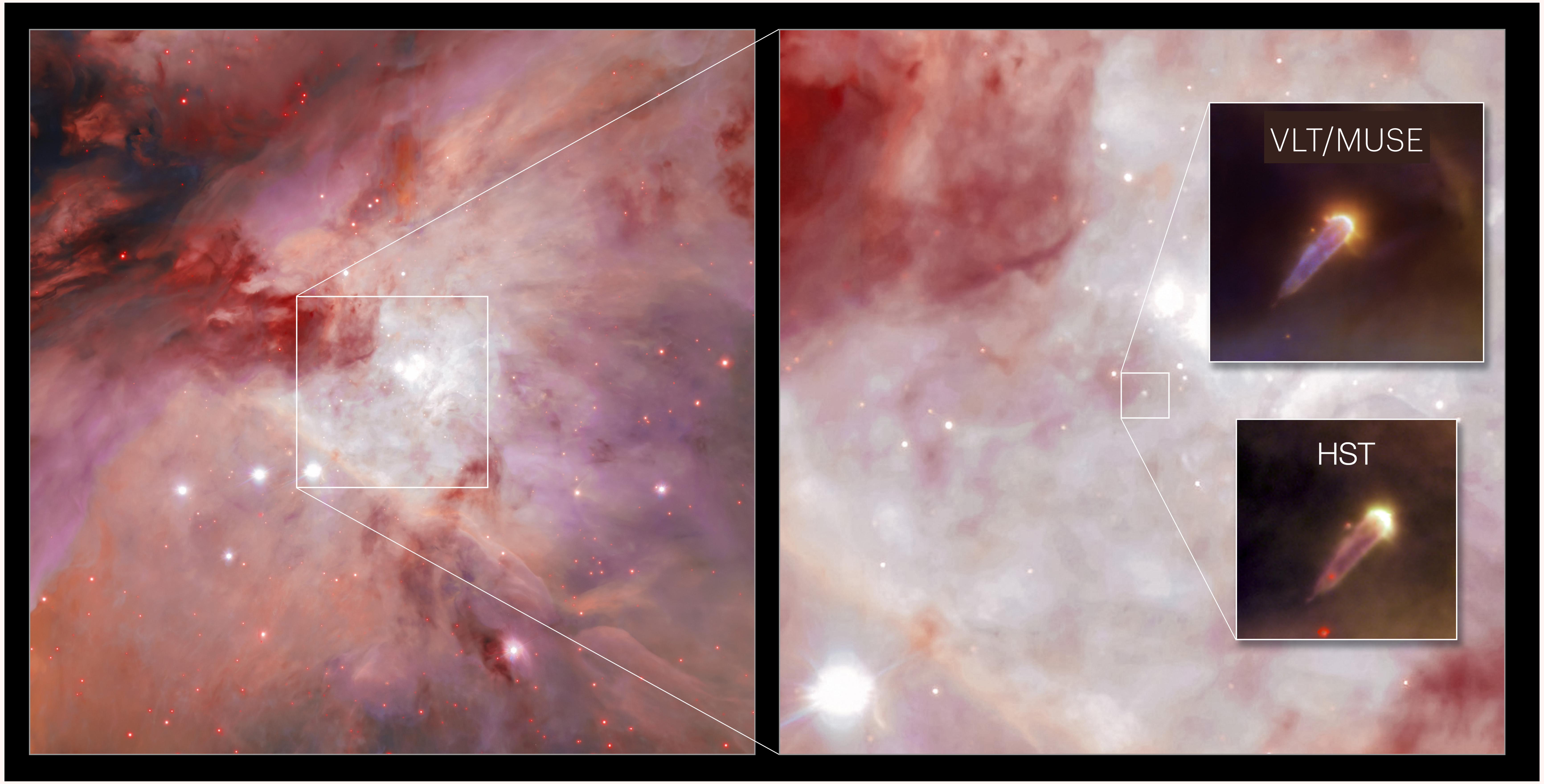


Fig. E.1. Reduced Gotrian diagram of C^0 showing up to the electronic levels associated with the NIR lines discussed in this study. The figure also includes the main FUV-pumping lines (in blue) of the detected NIR C^0 lines, as well as the submm fine-structure lines within the ground state detectable with ALMA (in green; energy level splitting is exaggerated).

PROTOTYPE PROPLYDS: ORION NEBULA CLUSTER (ONC)



CREDIT: ESO/M.-L. ARU ET AL./R. O'DELL/G. BECCARI

STELLAR PARAMETERS

- Extraction of the spectra of central stars
- SpT: Spectra compared with the set of pre-main sequence templates (Manara+ 2013, 2017)
- J-band mag (Robberto+ 2010)
- Stellar mass: evolutionary tracks (Siess+ 2000)

- The stellar parameters for 10 targets in our sample retrieved.
- One half of the sample classify as M spectral type (M0 and M5), and the other half classifies as mid-late K spectral type.

BACKGROUND SUBTRACTION

- Done slab by slab (where the line is)

  Example: 6690-6790 A ([SII] 6717)

- Photutils Python library, Background2D class

- Background 2D object: estimate of background level in each mesh as the sigma-clipped median.

- Sigma Clipping: The data will be iterated over, each time pixels that are above or below a specified sigma level from the median are discarded and the statistics are recalculated.