Image: Giant proplyds in Cygnus OB2? HST/ACS —
Wright+ 2012, Levay & Frattare STScI

ZENTRUM FÜR
ASTRONOMIE

External photoevaporation in different environments

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Threats From The Surroundings — 11/11/2020

Alexander von Humboldt
Stiftung / Foundation

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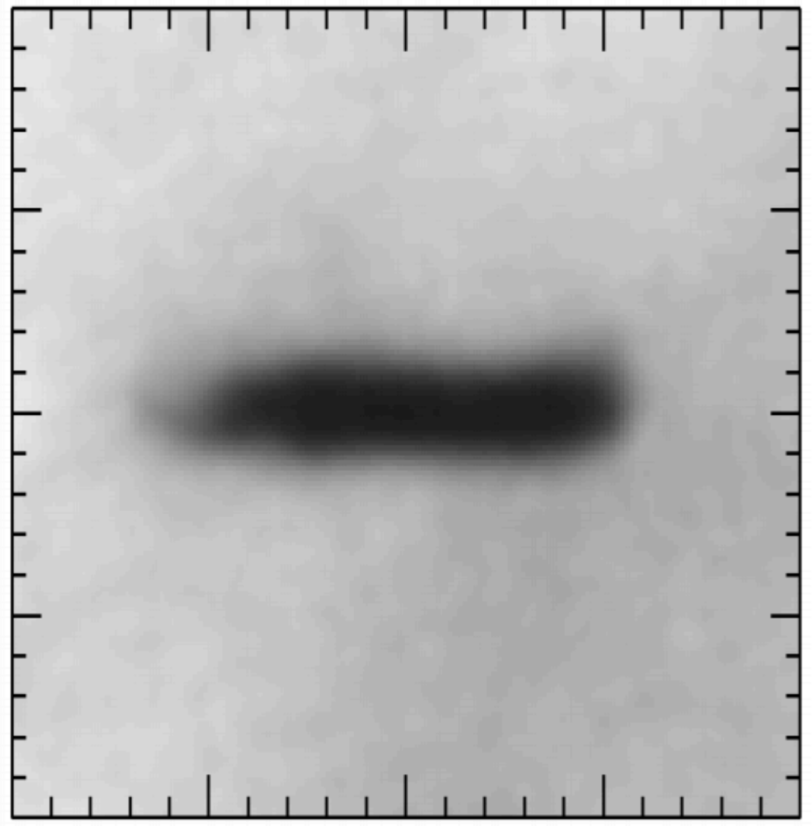
‘Classical proplyds’ of the Orion Nebula Cluster

- ‘Proplyd’: PROtoPLanetarY Disc… Now usually mean an ionised ‘cocoon’ around a PPD
- First images of PPDs with HST - silhouettes on the ionised background
- The original proplyds experience FUV fluxes of >~ 5×10^4 G_0, within ~0.3 pc of θ^1C



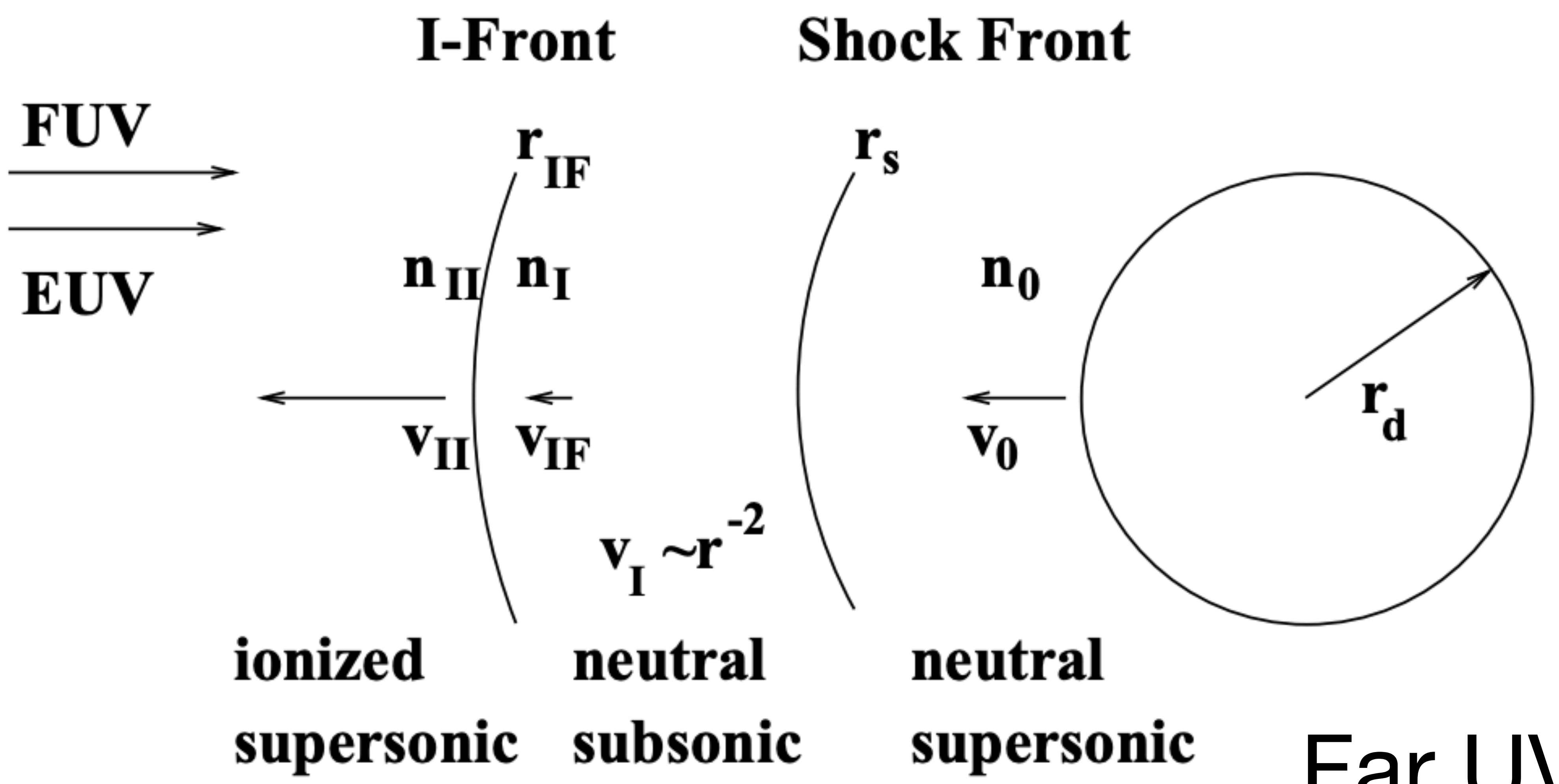
(a) F656N: Hα

Silhouette disc — McCaughrean+98

O’Dell & Wen 94

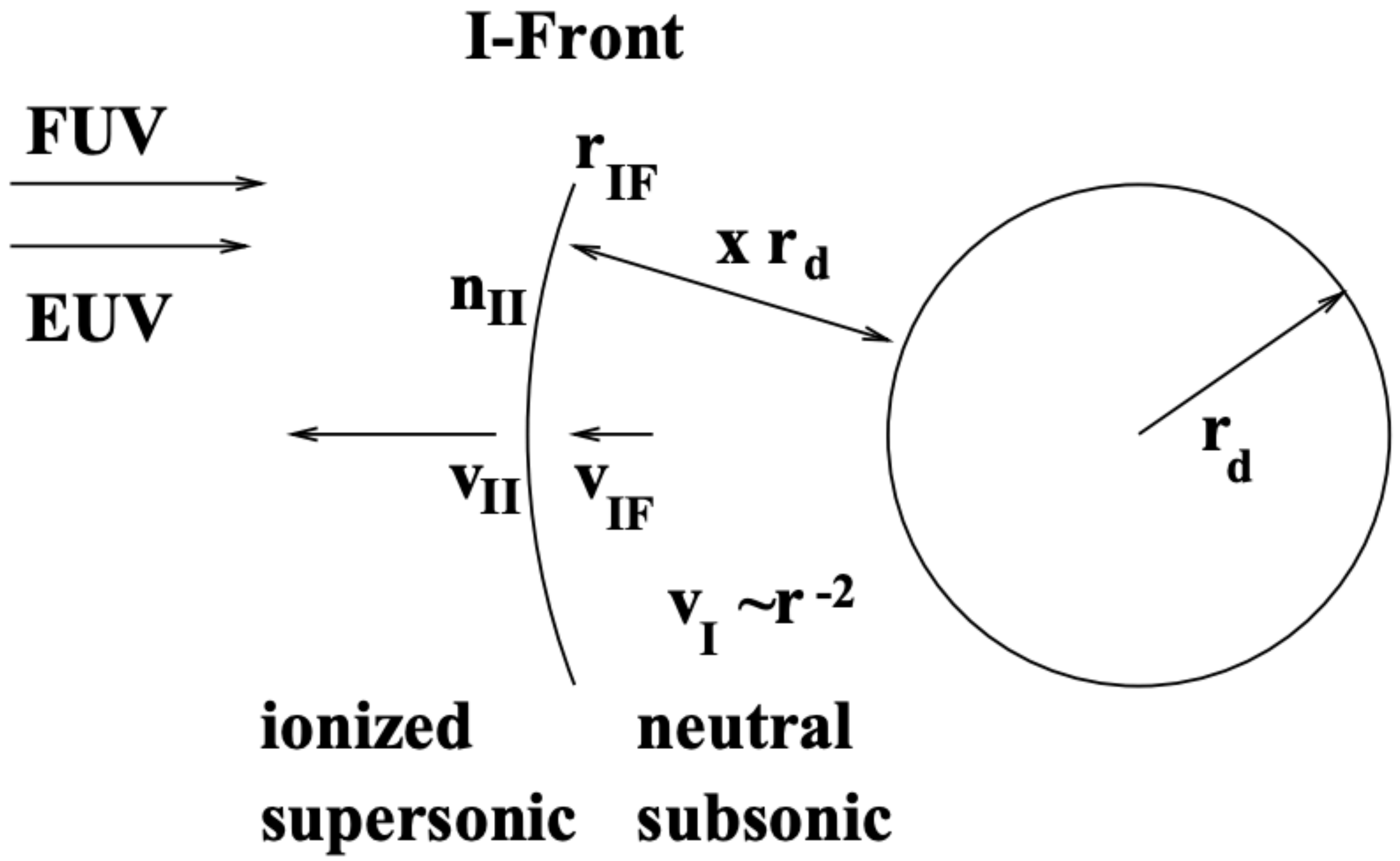
Theory

Drivers of thermal winds



Far UV driven

Extreme UV driven

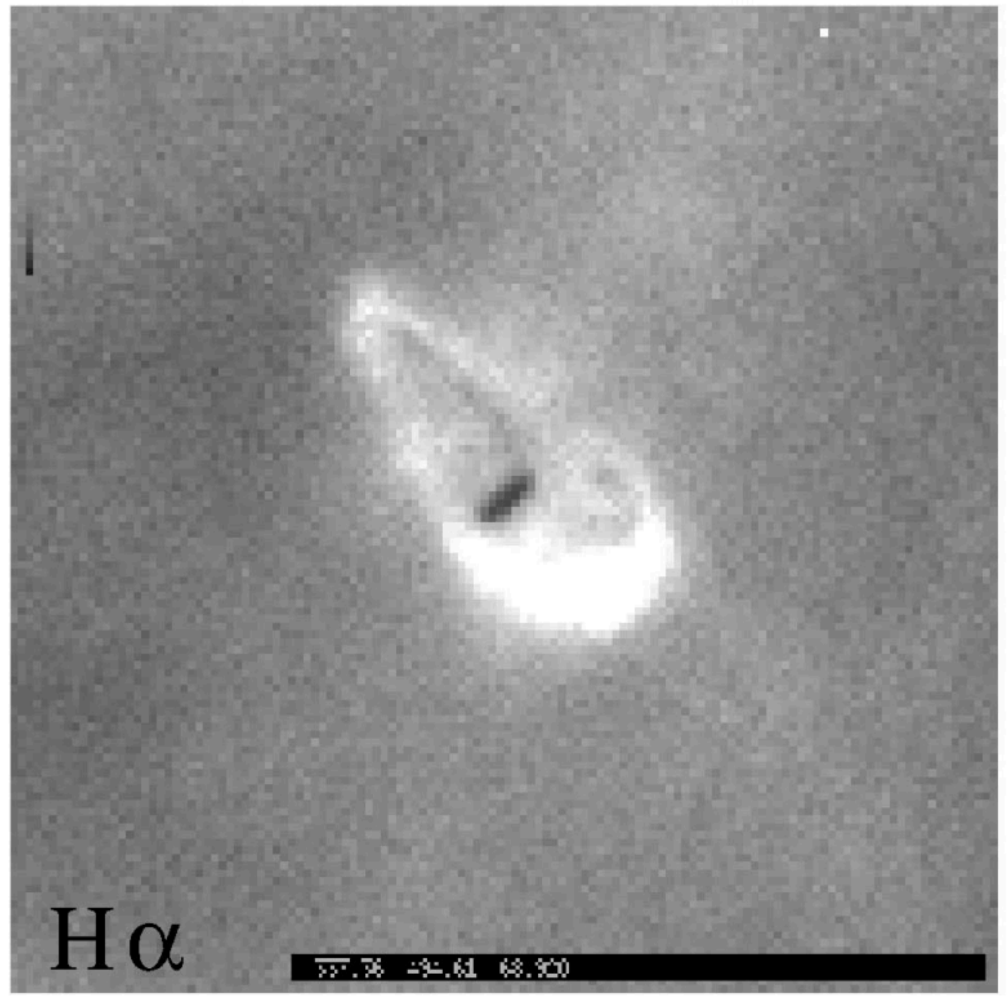


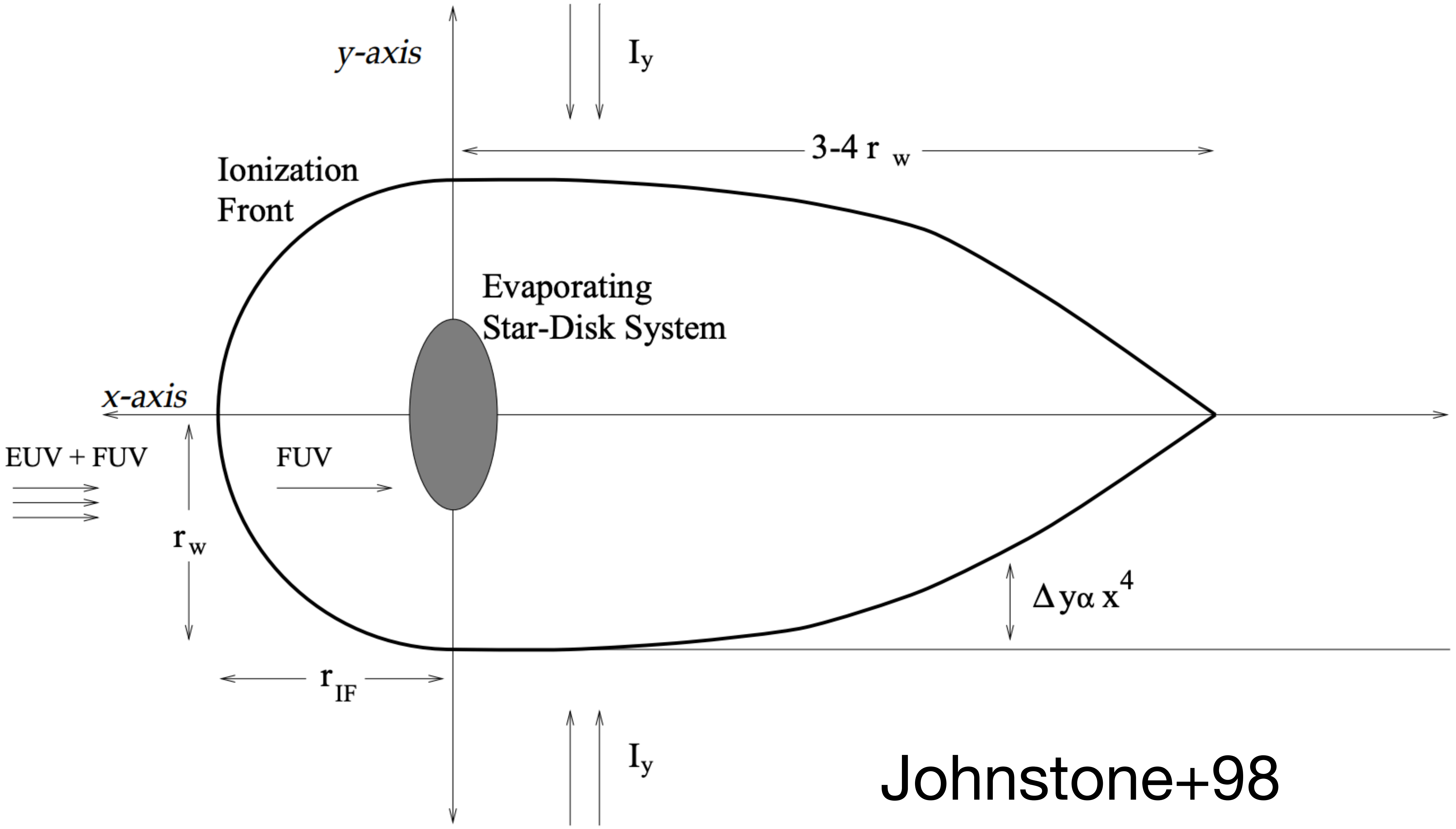
Johnstone+98

- Can be driven by EUV (ionising), or FUV (photodissociating) photons
- FUV driven - supersonic wind driven inside the photodissociation region (PDR), optically thick to EUV
- EUV driven - thin PDR, ionised winds launched close to the disc surface

Theory

Geometry





Johnstone+98

- Wind driven mass-loss from the outer disc — photodissociation region 'shielding' from EUV

- Ionisation front radius, r_{IF}, connected to EUV flux and mass-loss by ionisation/recombination balance arguments:

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

- Hα surface brightness dependent on EUV flux: (O'Dell 98):

$$\langle S(\mathrm{H}\alpha) \rangle \approx 7 \times 10^{11} \frac{\alpha^{\mathrm{eff}}_{\mathrm{H}\alpha}}{\alpha_B} \frac{\Phi}{10^{49}\, \mathrm{s}^{-1}} \left(\frac{d}{0.1\, \mathrm{pc}} \right)^{-2} \mathrm{s}^{-1}\, \mathrm{cm}^{-2}\, \mathrm{s.r}^{-1}$$

Theory

Mass-loss rates in EUV driven winds (Johnstone+98)

- Subsonic flow through the PDR with ~constant density n_{I}, sound speed a_{I} - use mass and momentum conservation across IF

- For PDR of thickness xr_{d}, disc radius r_{d}, mass loss rate is ($\epsilon \sim 1$):

$$\dot{M} = 4\pi(1+x)^2 r_d^2\, n_{\mathrm{I}} m_{\mathrm{I}} \left(\frac{a_{\mathrm{I}}^2}{2a_{\mathrm{II}}}\right) . \qquad n_{\mathrm{I}} = \frac{N_D}{x r_d} . \quad \longrightarrow \quad \dot{M} = 2.0 \times 10^{-9}\, \frac{(1+x)^2}{x}\, \epsilon r_{d14}\ M_\odot\ \mathrm{yr}^{-1}$$

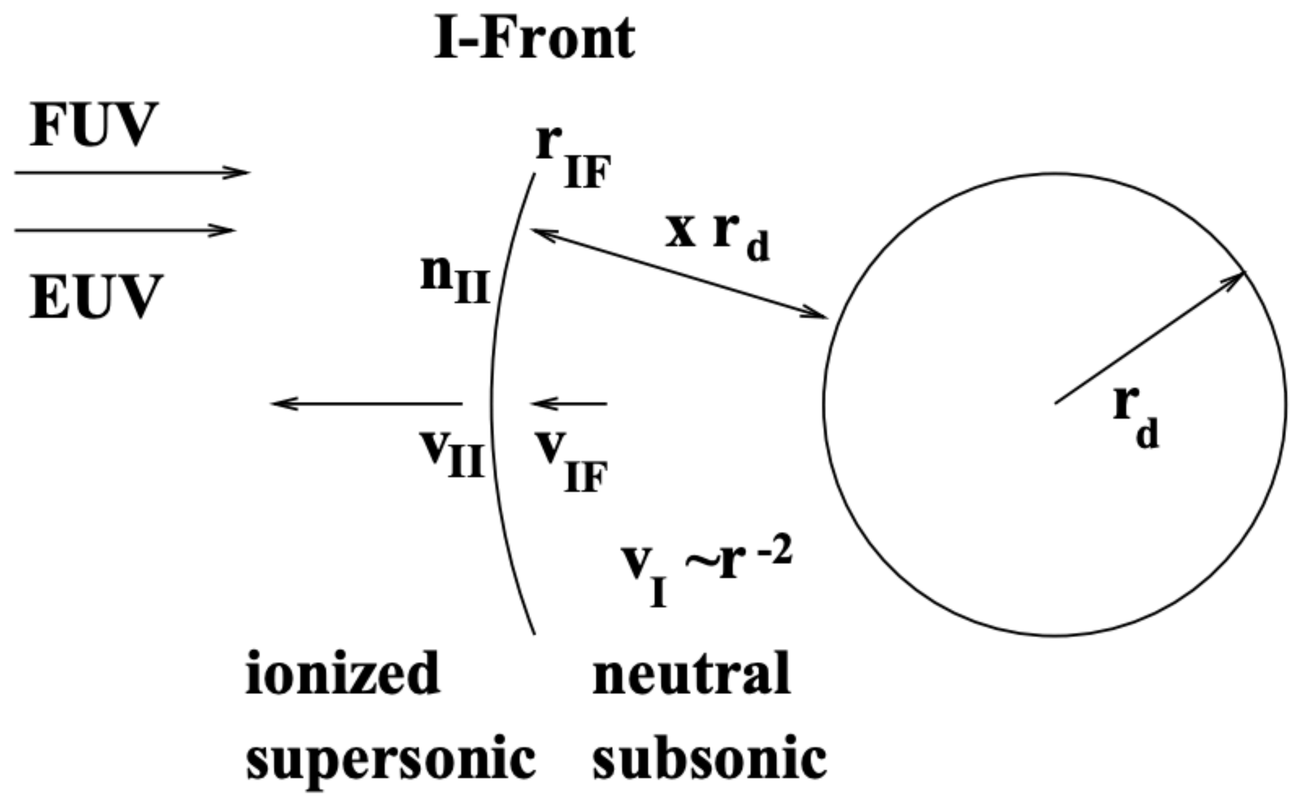
- In the limit of the thin PDR, mass-loss diverges.. but x is set by ionisation balance:

$$\frac{f_r \Phi_i}{4\pi d^2} = \int_{r_{\mathrm{IF}}}^{\infty} \alpha_r\, n_{\mathrm{II}}^2(r)\, dr \quad \longrightarrow \quad \frac{x}{(1+x)^{1/2}} = 0.21 \left(\frac{\epsilon^2}{f_r \Phi_{49}}\right)^{1/2} \left(\frac{d_{17}^2}{r_{d14}}\right)^{1/2}$$

- For extended discs or strong EUV flux, small x yields:

$$\dot{M} = 9.5 \times 10^{-9} f_r^{1/2} \Phi_{49}^{1/2} d_{17}^{-1} r_{d14}^{3/2}\ M_\odot\ \mathrm{yr}^{-1}$$

Which is the solution for a photoevaporating sphere.



Theory

Mass-loss rates in FUV driven winds

- Analytic estimate for FUV mass-loss rates - assume launching velocity $v_0 \approx a_\mathrm{I} \approx 3\,\mathrm{km\,s^{-1}}$, impose optical depth of dust in the PDR $\tau_\mathrm{FUV} \sim 1$ for column density $N_\mathrm{D} \sim 10^{21}\,\mathrm{cm^{-2}}$, dominated by base of flow:

$$\dot{M} = 4\pi r_d^2\, v_0\, n_0\, m_\mathrm{I} \qquad N_D \simeq n_0\, r_d \qquad \longrightarrow \qquad \dot{M} = 1.3 \times 10^{-8} \epsilon r_{d14}\; M_\odot/\mathrm{yr} \qquad \epsilon = \left(\frac{N_D}{10^{21}\ \mathrm{cm}^{-2}}\right)\left(\frac{v_0}{3\ \mathrm{km\ s}^{-1}}\right)$$

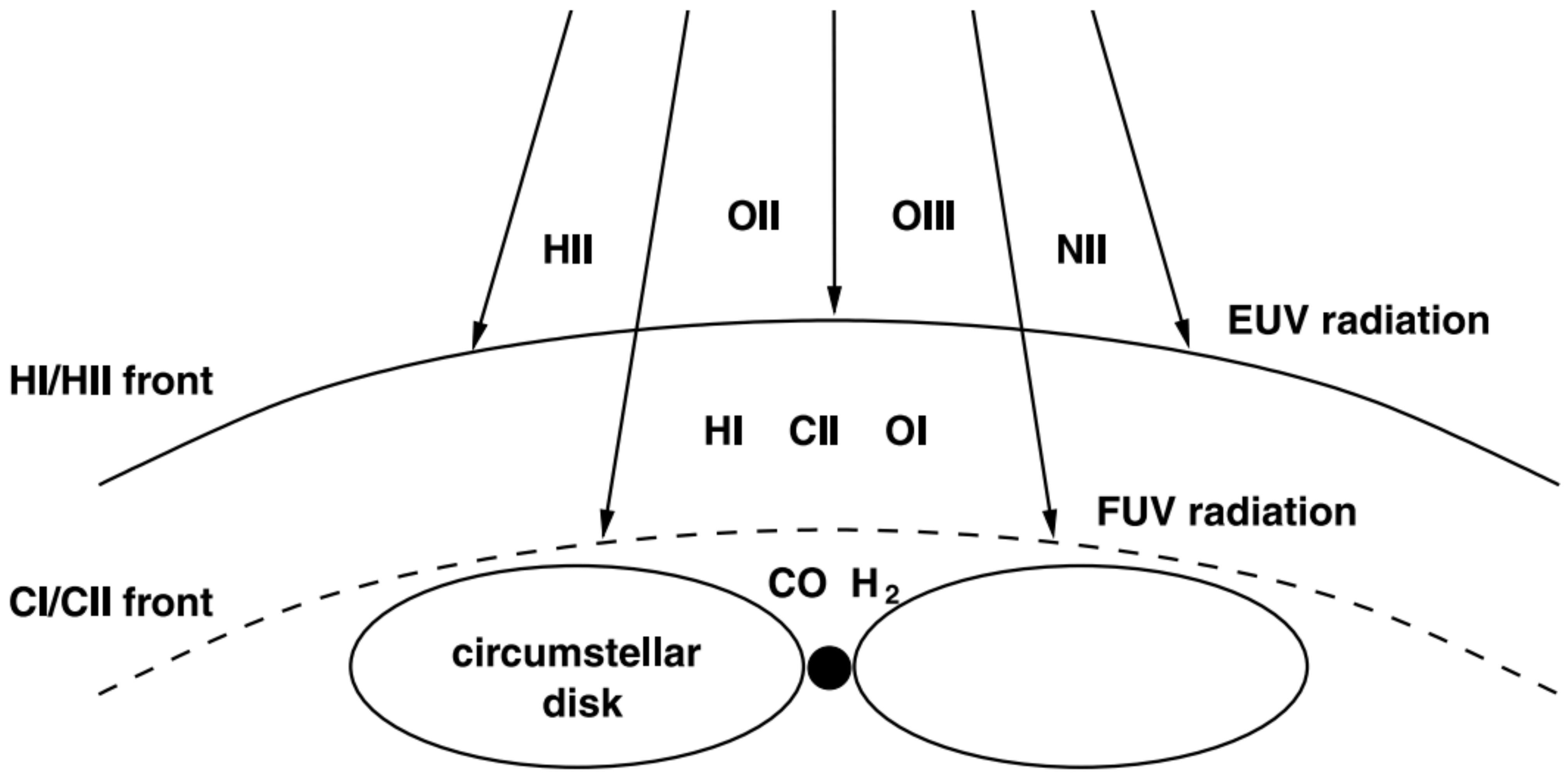
- Ignores changes in the thermal structure of the PDR, e.g. with UV flux and r_d
- Recently, PDR codes have been coupled with wind solutions to obtain mass-loss rates (Adams+04, Facchini+16, Haworth+18 - 'FRIED grid' is publicly available)
- Weaker dependence on flux and disc radius for FUV driven flows in strong UV flux limit

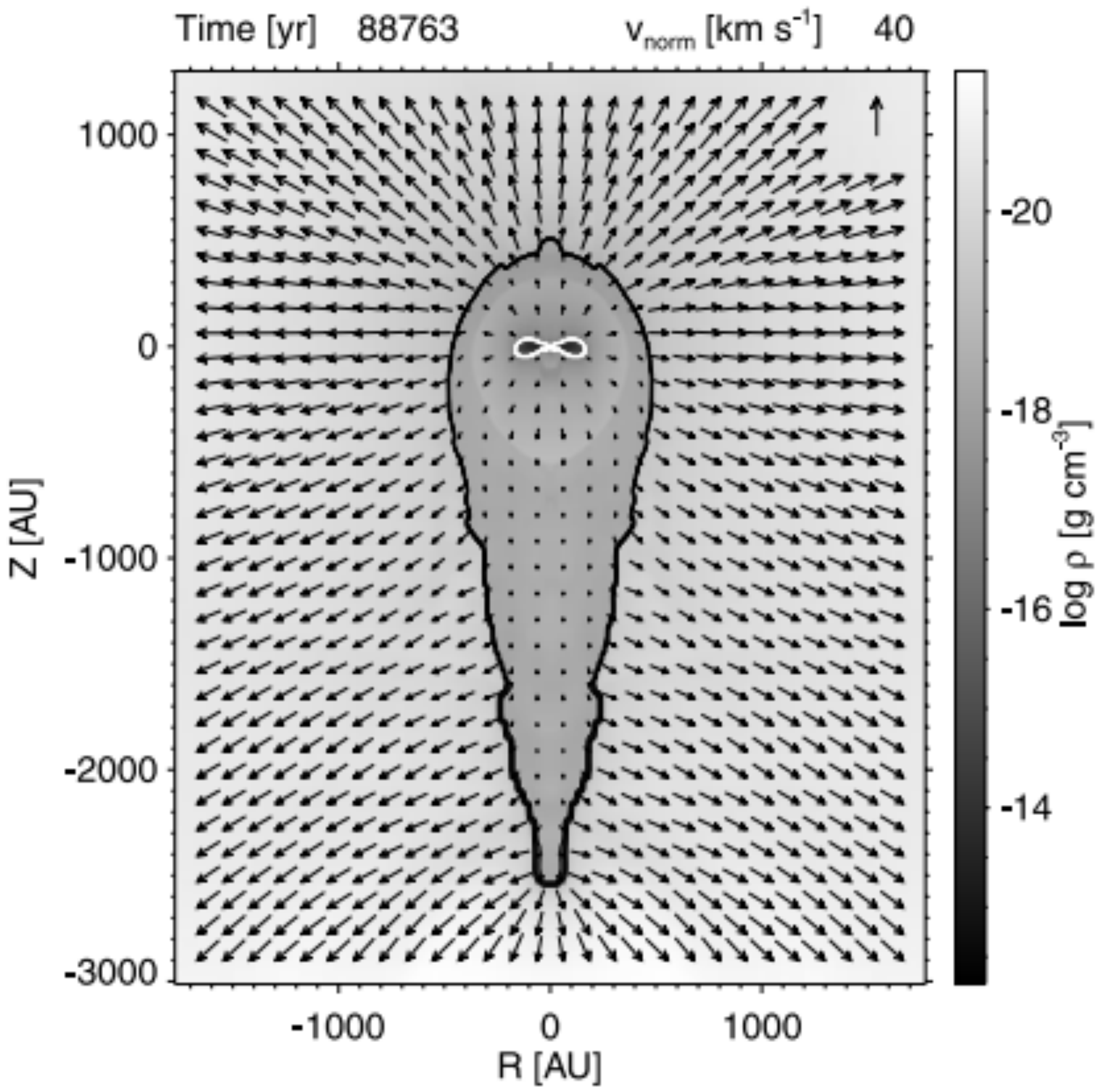
Observational diagnostics

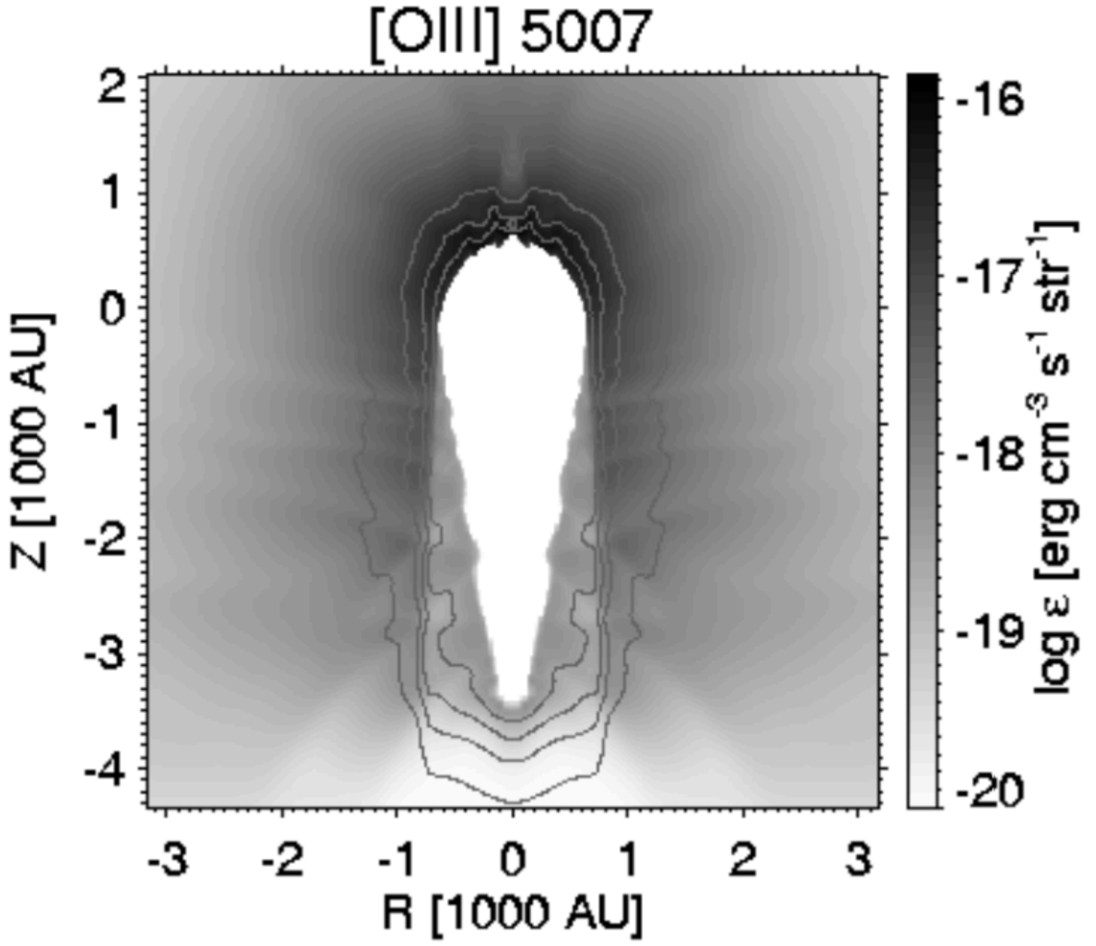
Proplyds and winds

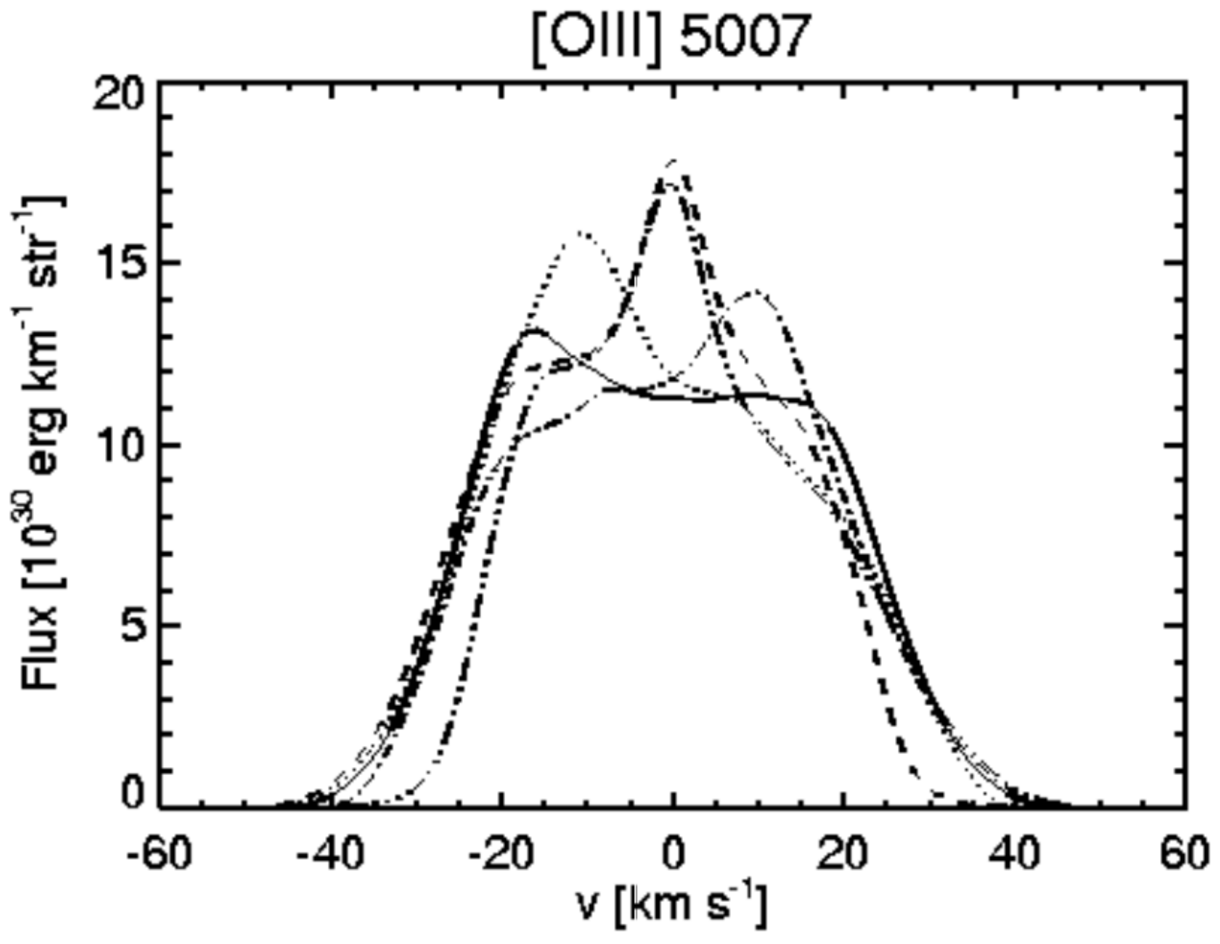
- PDR models including hydro and chemistry by Richling & Yorke 00
- Can trace e.g. SII, OII [III], NII lines at the HI/HII ionisation front
- Density from doublet line flux ratios **if excitation is collisional,** or directly by Hα surface brightness with extinction/background correction

Richling & Yorke 00





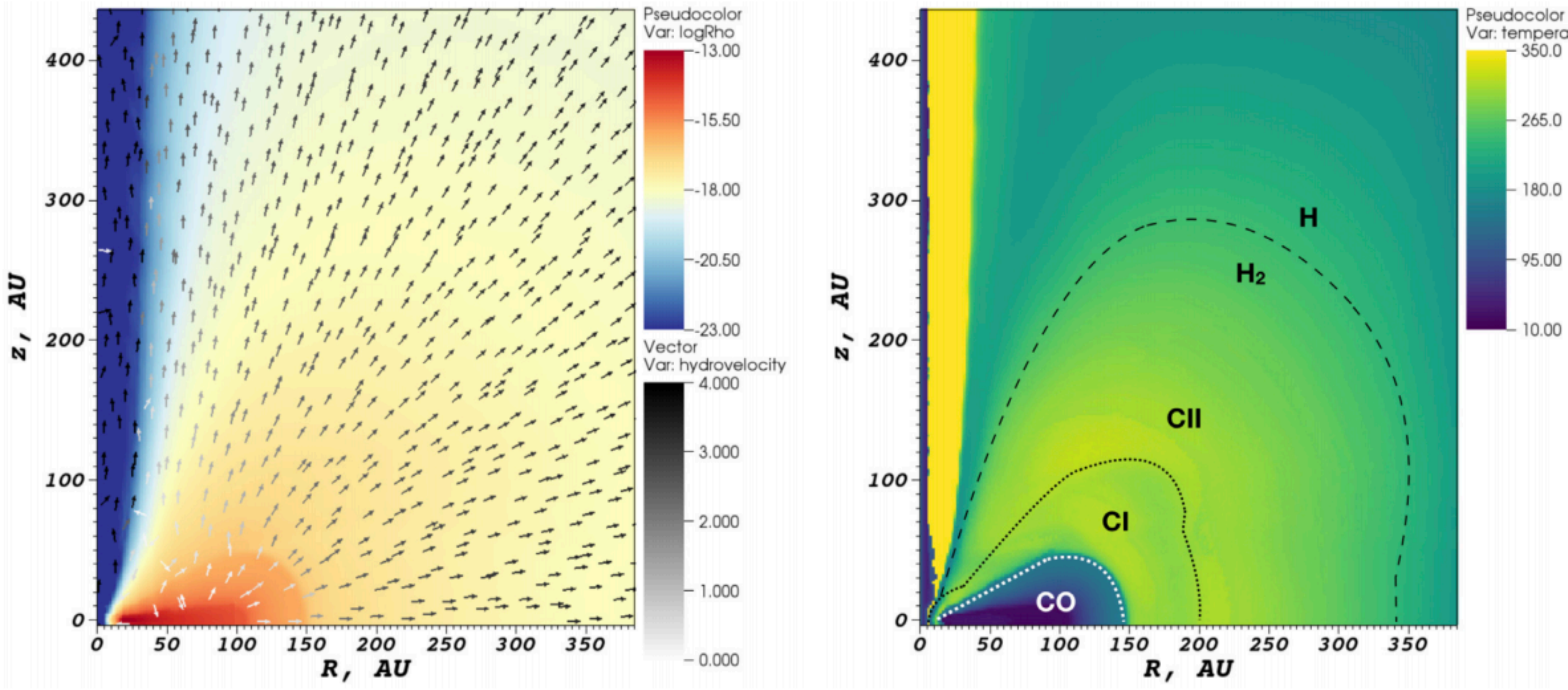




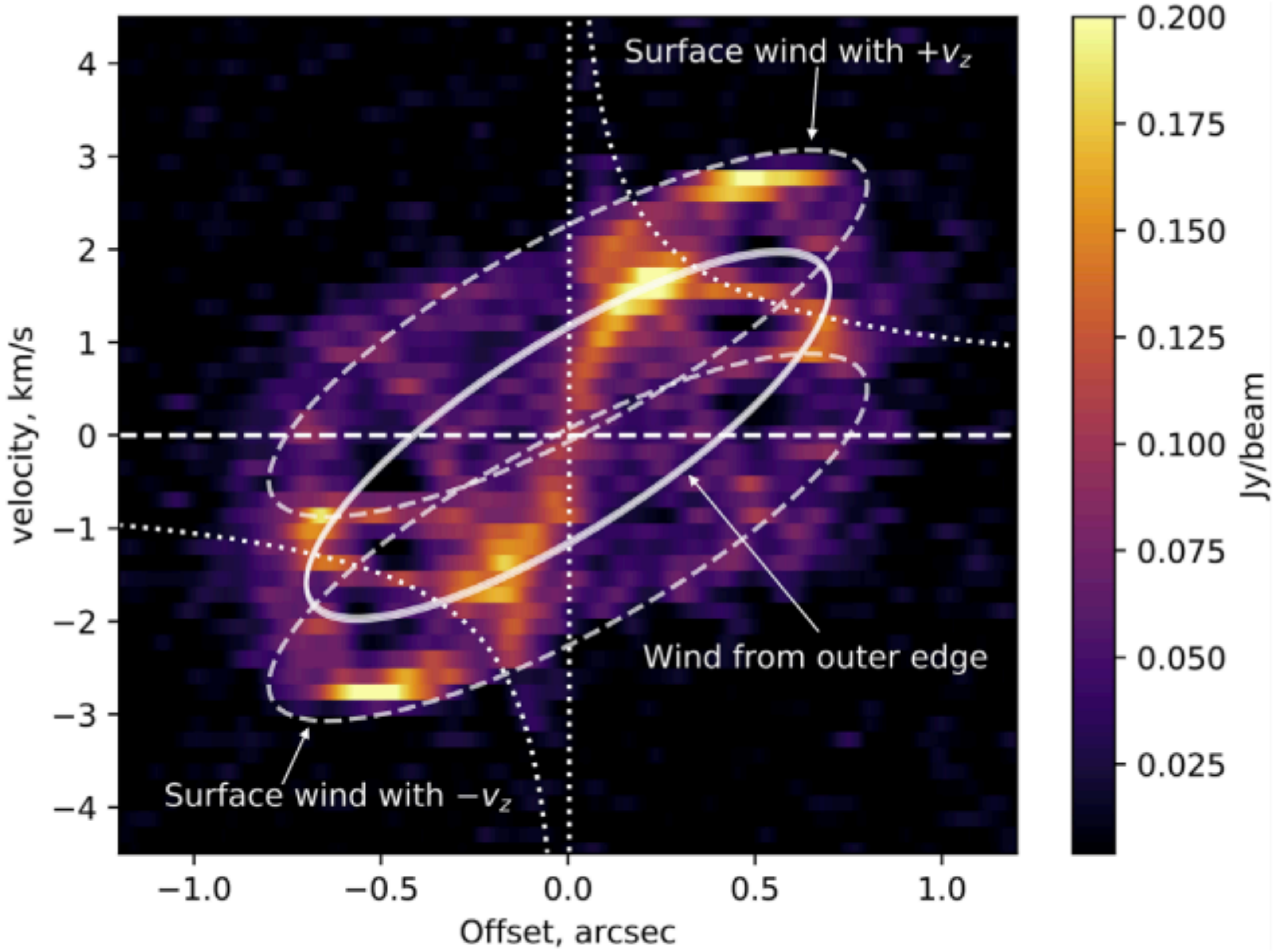
Observational diagnostics

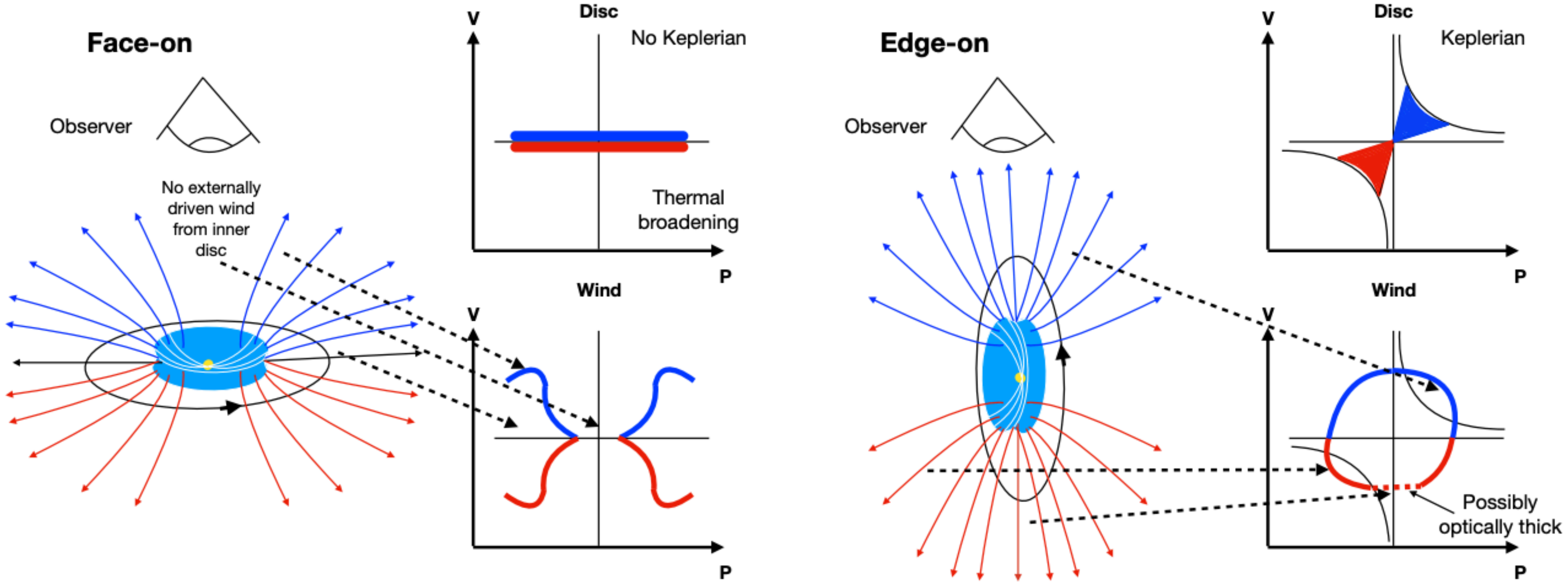
Proplyds and winds

- Haworth & Owen 19 showed how externally driven winds manifest in position-velocity space for CI
- Promising diagnostic for weaker FUV environments



45˚ viewing angle, CI emission computed from a PDR model





Observational diagnostics

Proplyds and winds: Advantages and disadvantages

Advantages:

- Direct evidence of thermal winds driven by neighbouring star
- Can measure/estimate instantaneous mass-loss rates
- Proplyds appear to exist in most (young) regions with OB stars
- Nice pictures…

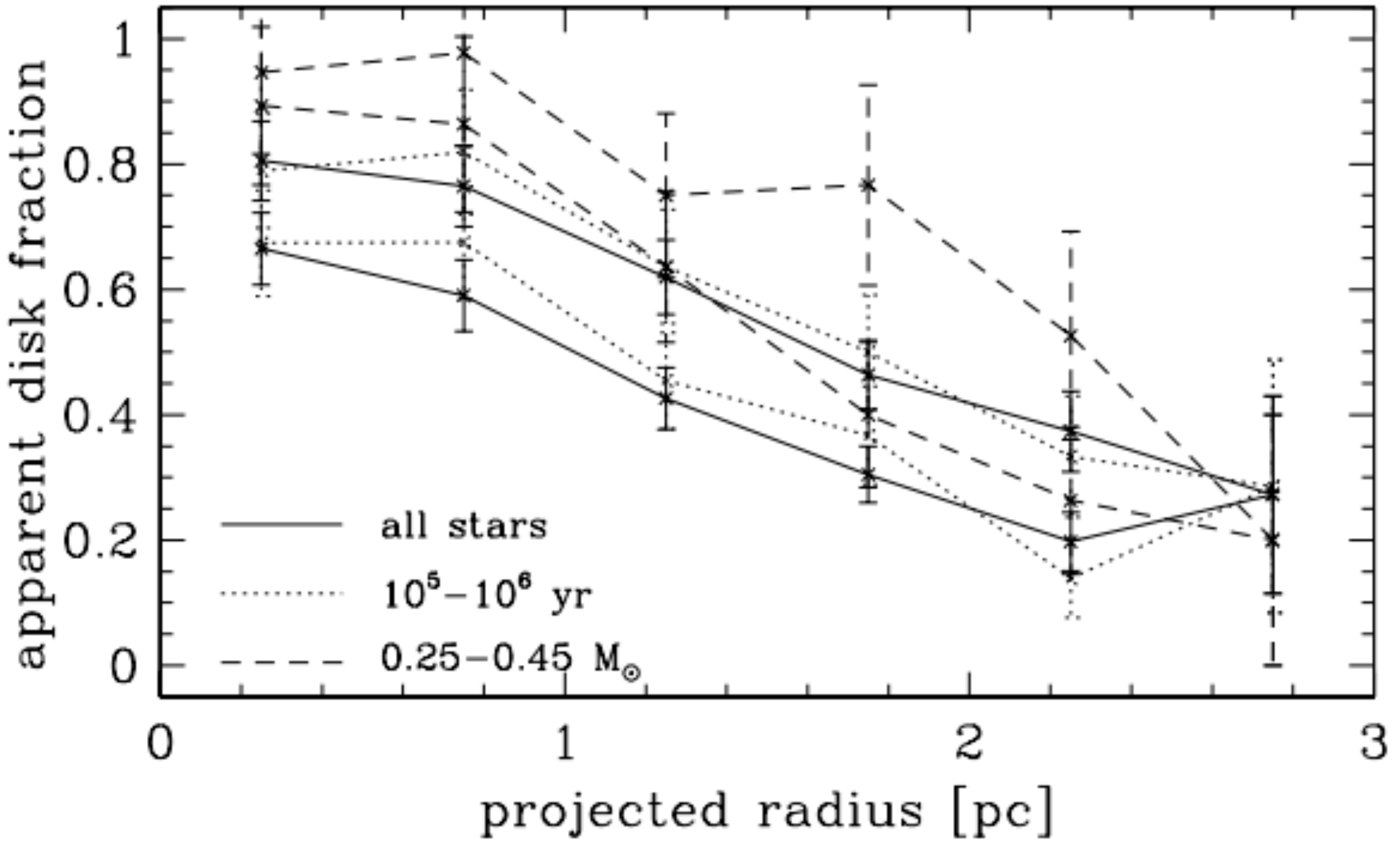
Disadvantages:

- Bright proplyds may be a short lived phase in life of the PPD
- Can only be easily detected for discs exposed to strong EUV fields (bright ionisation front)
- Can only be easily resolved when mass-loss rate is high/distant from ionising source

Observational diagnostics

Inner disc depletion

- Detection of NIR excess + census of YSOs to obtain inner disc fraction
- Either compared across different regions, or search for spatial gradients within a single region
- No obvious depletion in the ONC - high disc fraction in the core (Hillenbrand+ 98 - see also Lada+00)
- External photoevaporation does not alter disc lifetime…? Also Richert+15 - similar results in multiple star forming regions



Hillenbrand+ 98

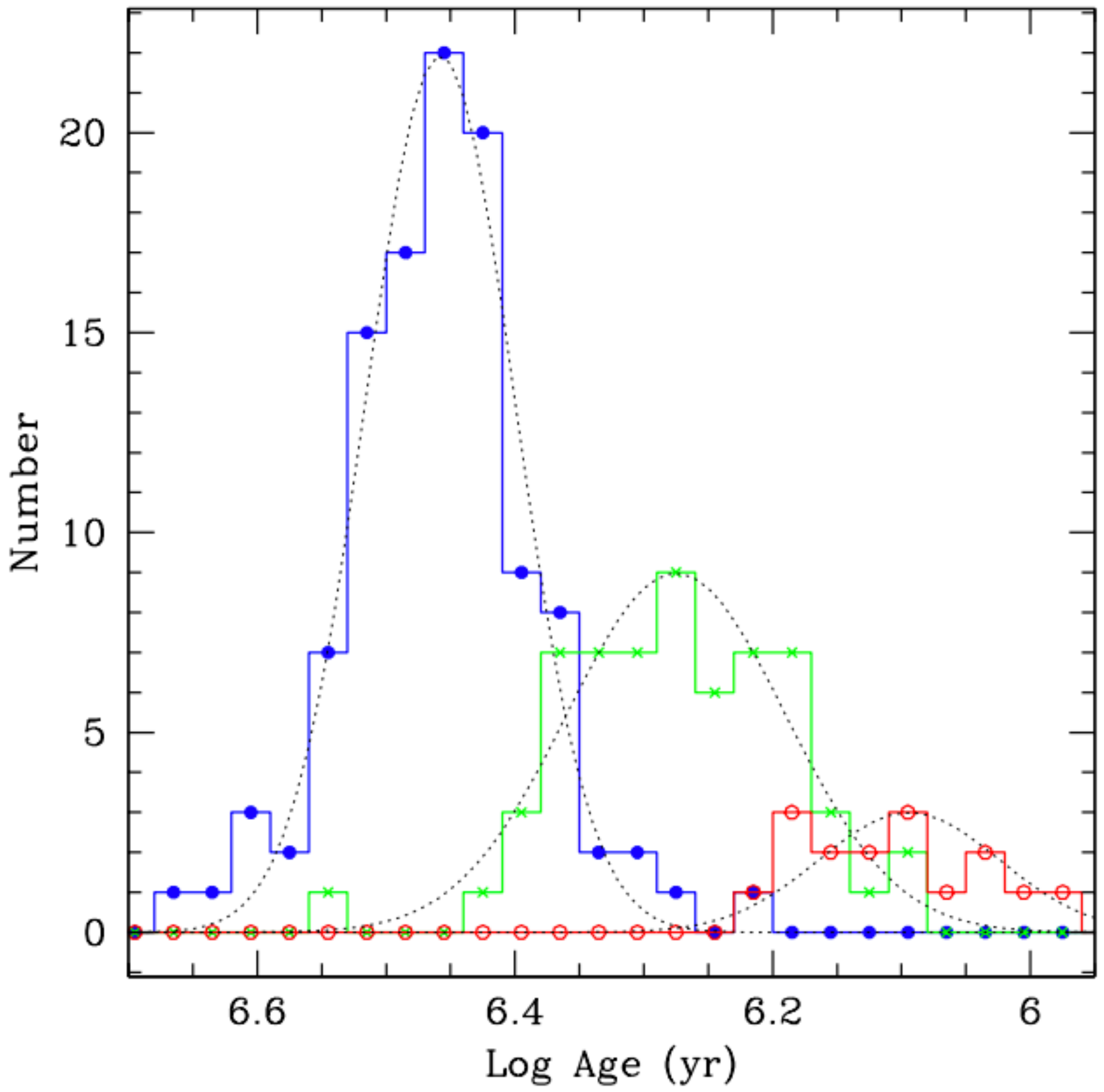
The ONC: A proplyd lifetime problem?

- Age gradient (Hillenbrand+97, Getman+18) and possibly multiple stellar populations (Beccari+17) in the ONC - youngest stars in the centre

- Would expect more OB stars - strange IMF? Dynamical ejection of massive stars (Poveda+05, Kroupa+18)?

- Extended epoch of star formation can help to explain disc survival and mass distribution (Eisner+18) in the core of ONC (Winter+19)

- **Need to look at other regions**



3 populations in the ONC?
Beccari+ 17

Observational diagnostics

Inner disc depletion: Advantages and disadvantages

Advantages:

- Probe what the long term influence of photoevaporation is on PPD
- ‘Simple’ metric for comparison with disc evolution models

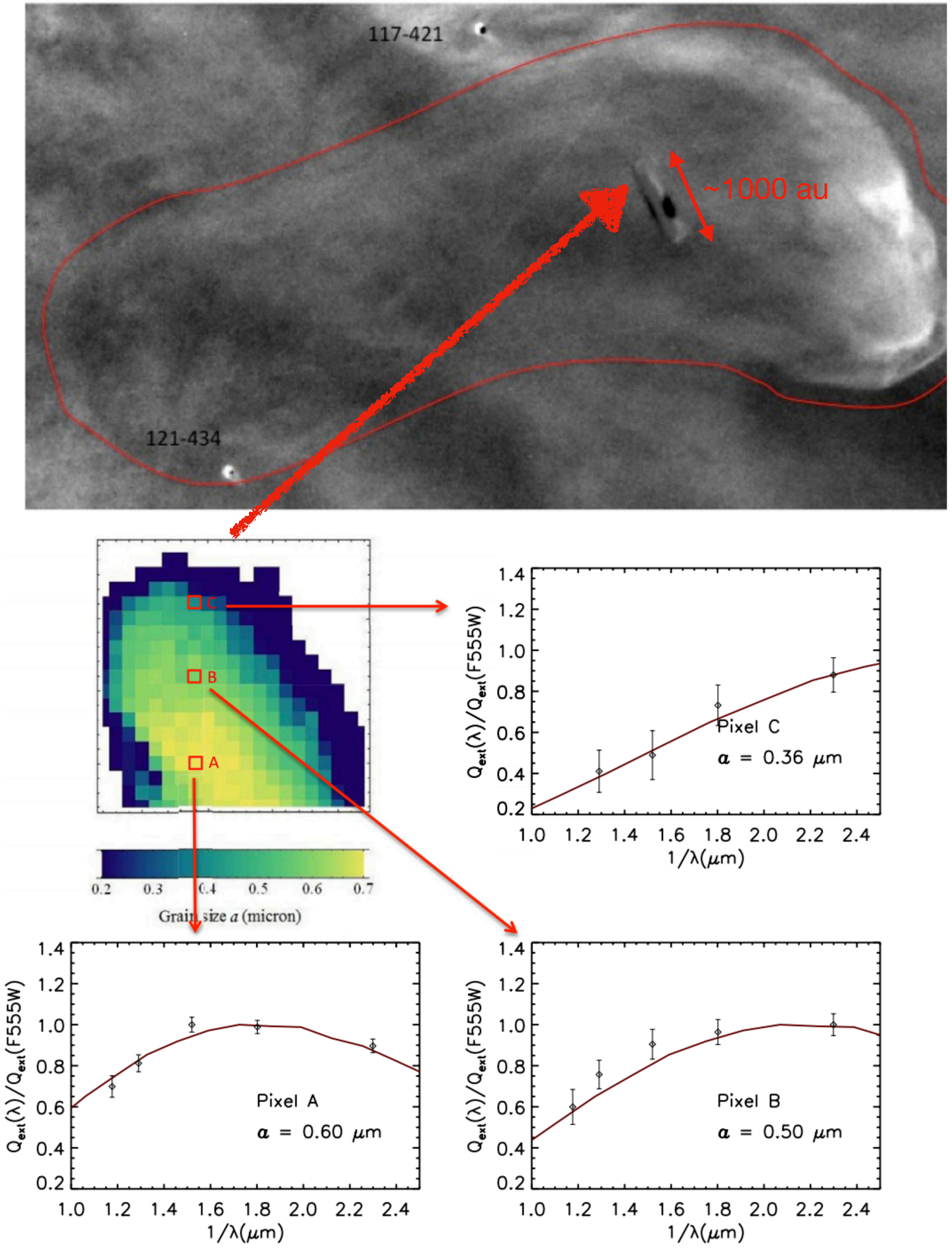
Disadvantages:

- Inner disc least strongly influenced by photoevaporation
- Requires YSO census, e.g. from X-ray
- Ambiguous: dynamical mixing, age gradients and uncertainties, other dispersal mechanisms

Observational diagnostics

Dust depletion

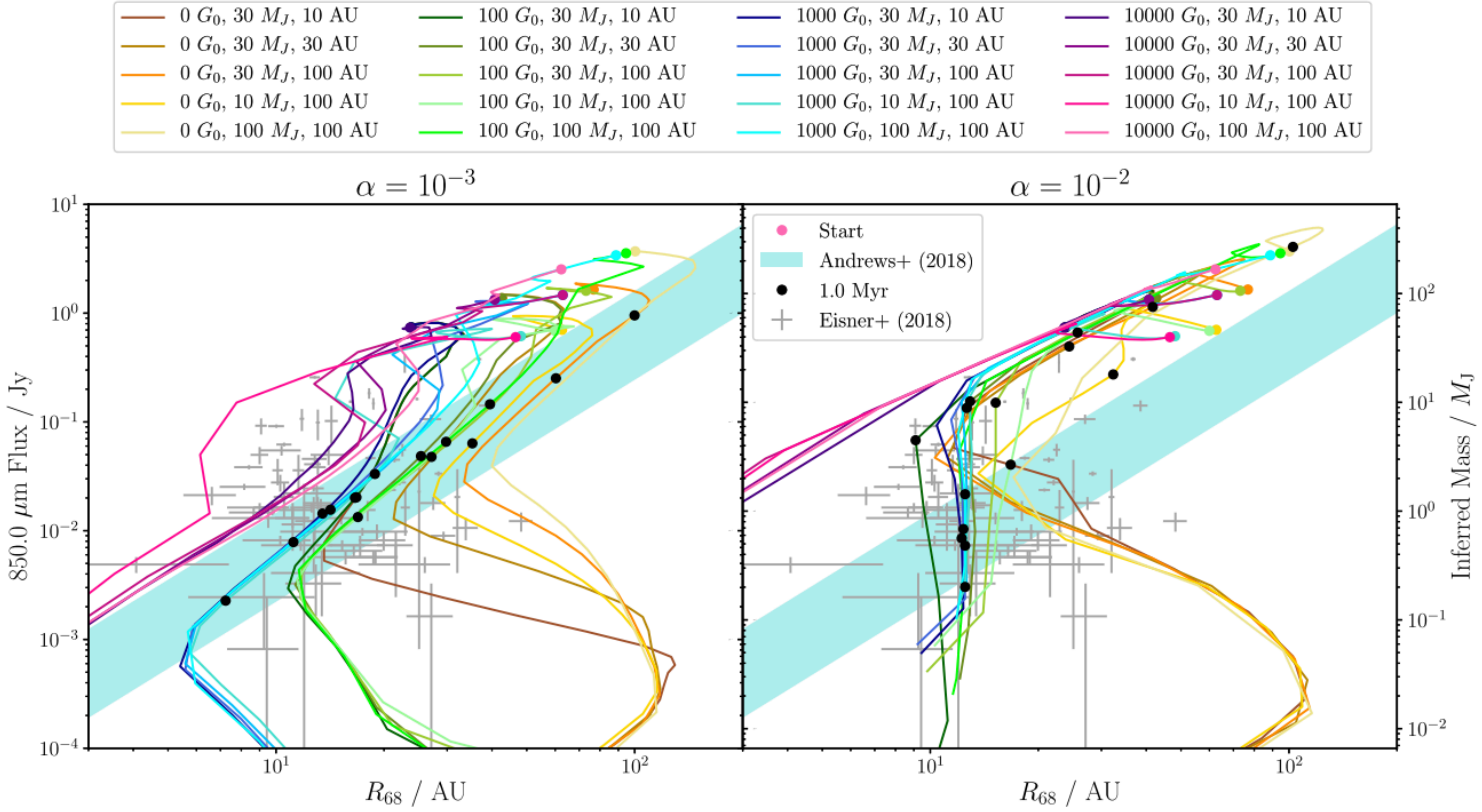
- Is solid material efficiently photoevaporated? Stokes number? Sublimation?
- Miotello+12: Evidence for dust entrained in the flow for proplyd 114-426 in the ONC
- Gradient in dust grain sizes: decrease with increasing distance in the northern flow region
- Using (sub-)mm fluxes can probe dust depletion near OB stars…



Observational diagnostics

Dust depletion

- Need to understand evolution of dust with respect to gas (e.g. Sellek+ 20)
- Depletion of dust in outer disc + radial drift lead to rapid depletion?



Sellek+ 20

Observational diagnostics

Dust depletion: Advantages and disadvantages

Advantages:

- Probe the outer disc material most strongly influenced by winds
- Can estimate both PPD mass and outer radius in many cases
- Measure differences in the solid mass budget for planets due to photoevaporation

Disadvantages:

- Dependent on dust grain growth, entrainment in wind and opacity models
- Possible contamination by free-free emission around high mass star forming regions
- Ambiguous: dynamical mixing & other mechanisms

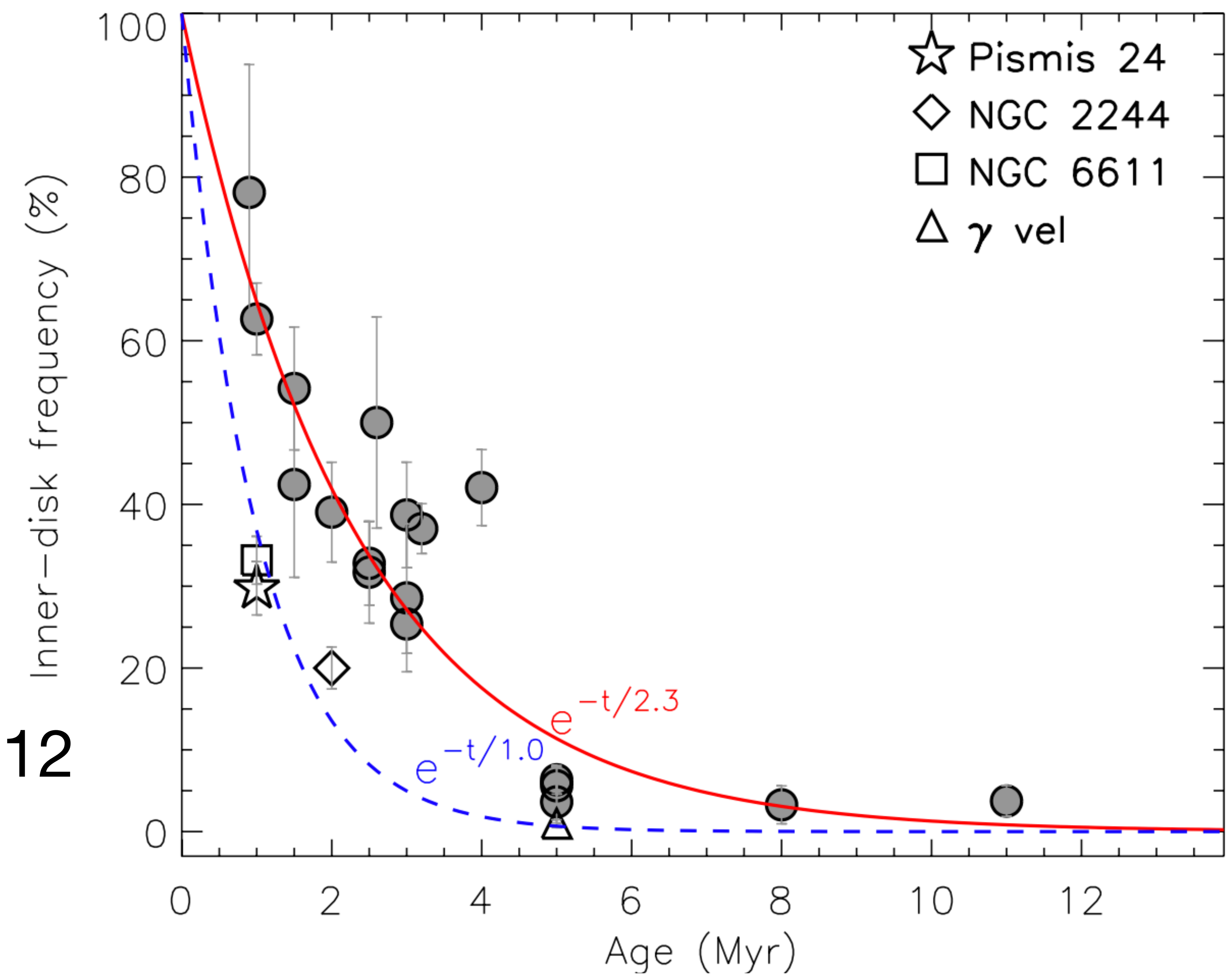
Looking beyond the ONC…

Region	Proplyds/ Winds	Inner disc dispersal	Dust depletion	Log M (Msol)	Log Rho0 (Msol/pc^3)	Age (Myr)	E.g. Refs.
NGC 2024	Y	-	Y	2.1	~3	~1	Van Terwisga+20, Haworth+ sub.
NGC 1977	Y	-	-	~2	~1.6	~1	J.S. Kim+16
σ **Orionis**	Y	-	Y	2.2	2.7	3-5	Rigliaco+09, Maucó+16, Ansdell+17
ONC	Y	-	Y	3.6	4.3	1-3	O'dell & Wen 93, Henney & O'Dell 90, Vicente & Alves 05, Mann+15, Eisner+18, Van Terwisga+19
Cygnus OB2	Y(?)	Y	-	4.2	~1.3	3-5	Wright+12, Guarcello+16
Pismis 24	Y(?)	Y	-	~4	-	~1	Fang+12
Arches	-	Y	-	4.3	5.1	2-3	Stolte+10,15
NGC 3603	Y	Y	-	4.1	5.0	~1	Brandner+00, Stolte+04

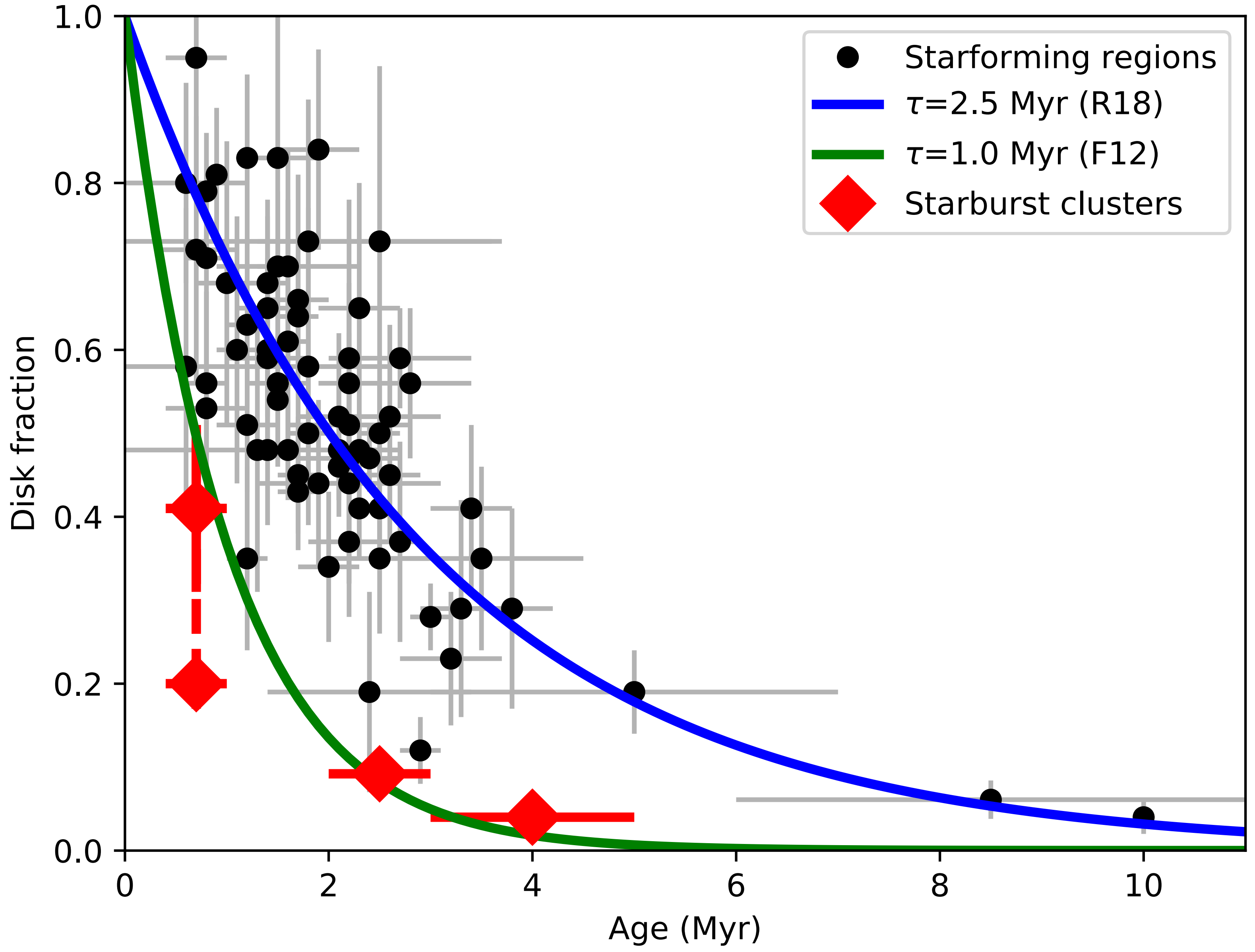
Local star forming regions

Disc lifetimes

- Inner disc life-times appear shorter at the highest FUV fluxes (‘starburst clusters’)
- So far no strong evidence for inner disc depletion rate gradient across lower mass regions… age uncertainties?
- Disc fraction gradients also only found in highest mass regions… c.f. Nicholson+19
- Threshold UV flux to disperse inner disc?



Fang+12

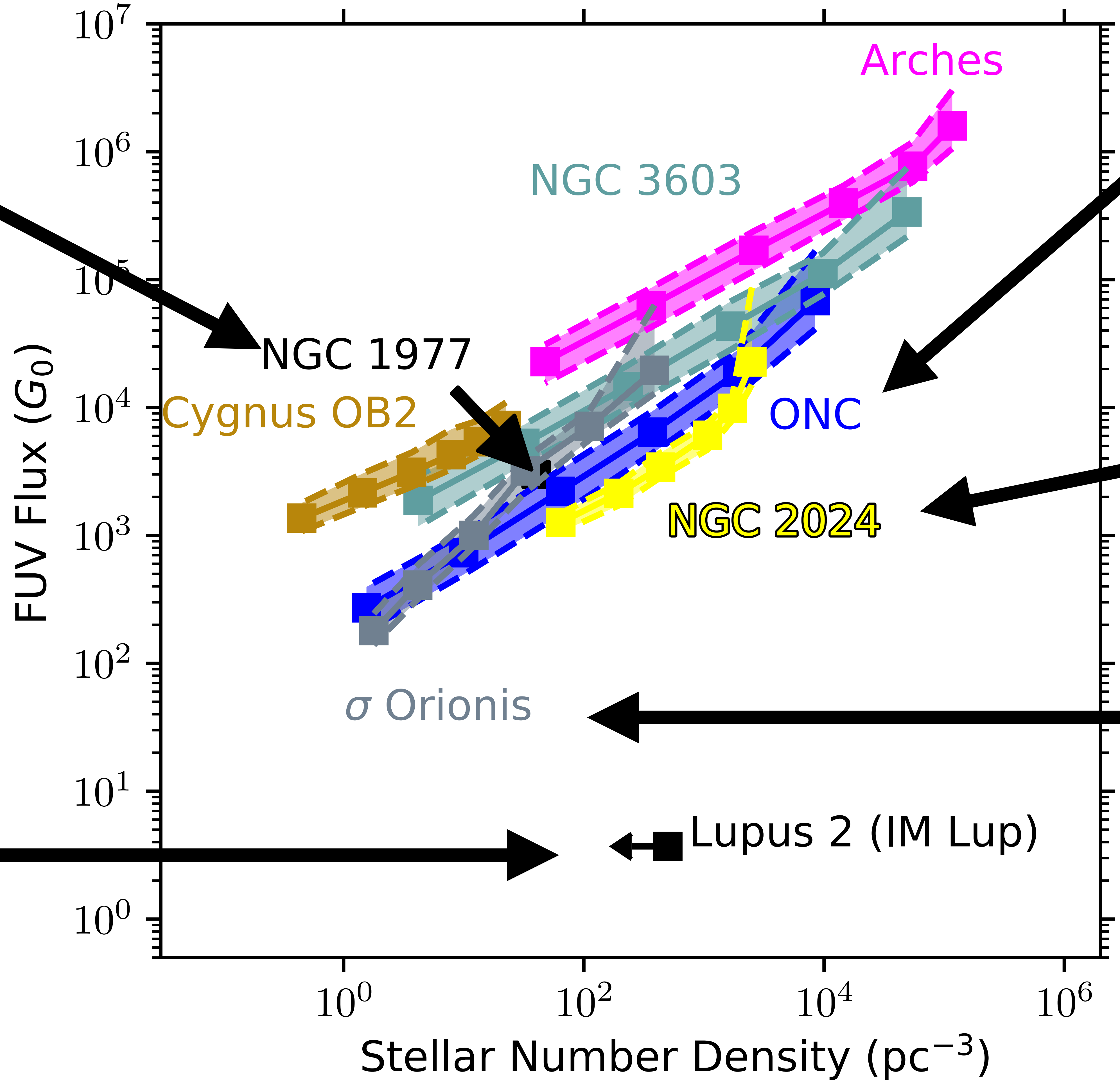


More recent version courtesy of Arjan Bik

Local star forming regions

FUV flux

Serena Kim's talk



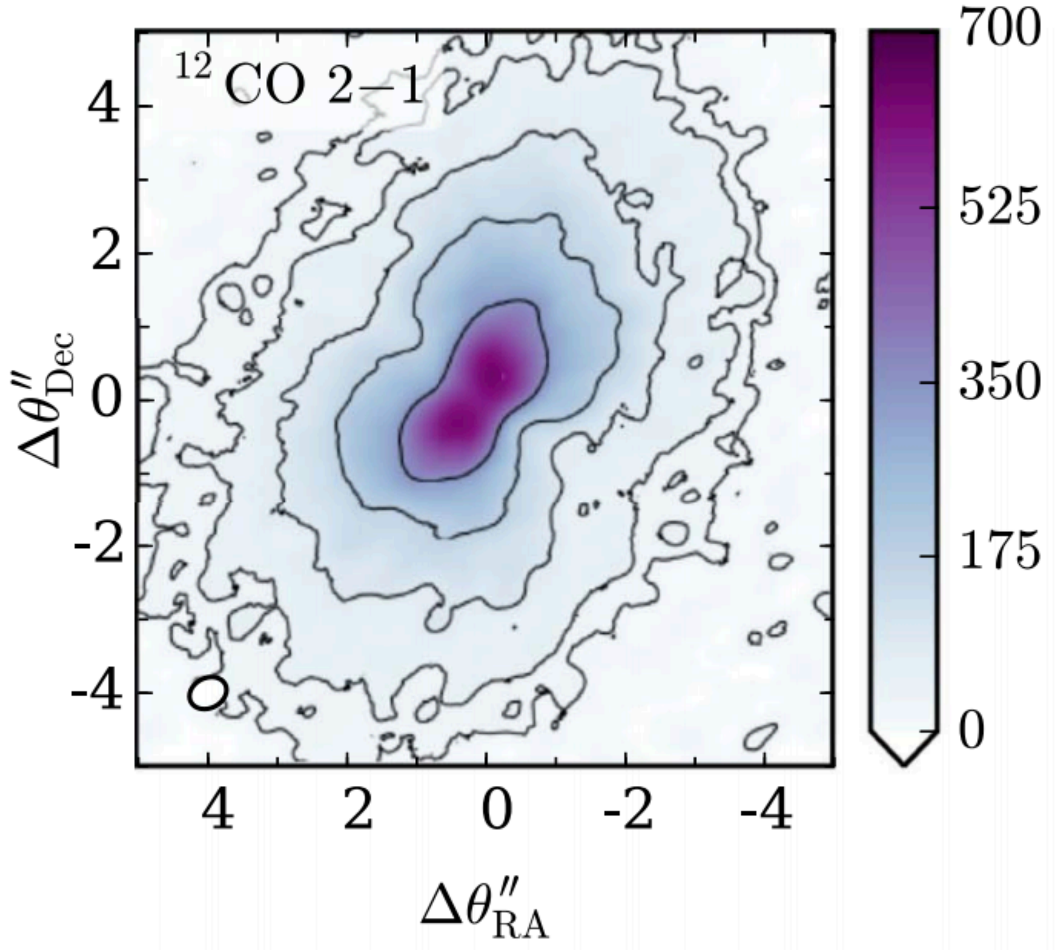
Adapted from Winter+18

Ryan Boyden's poster

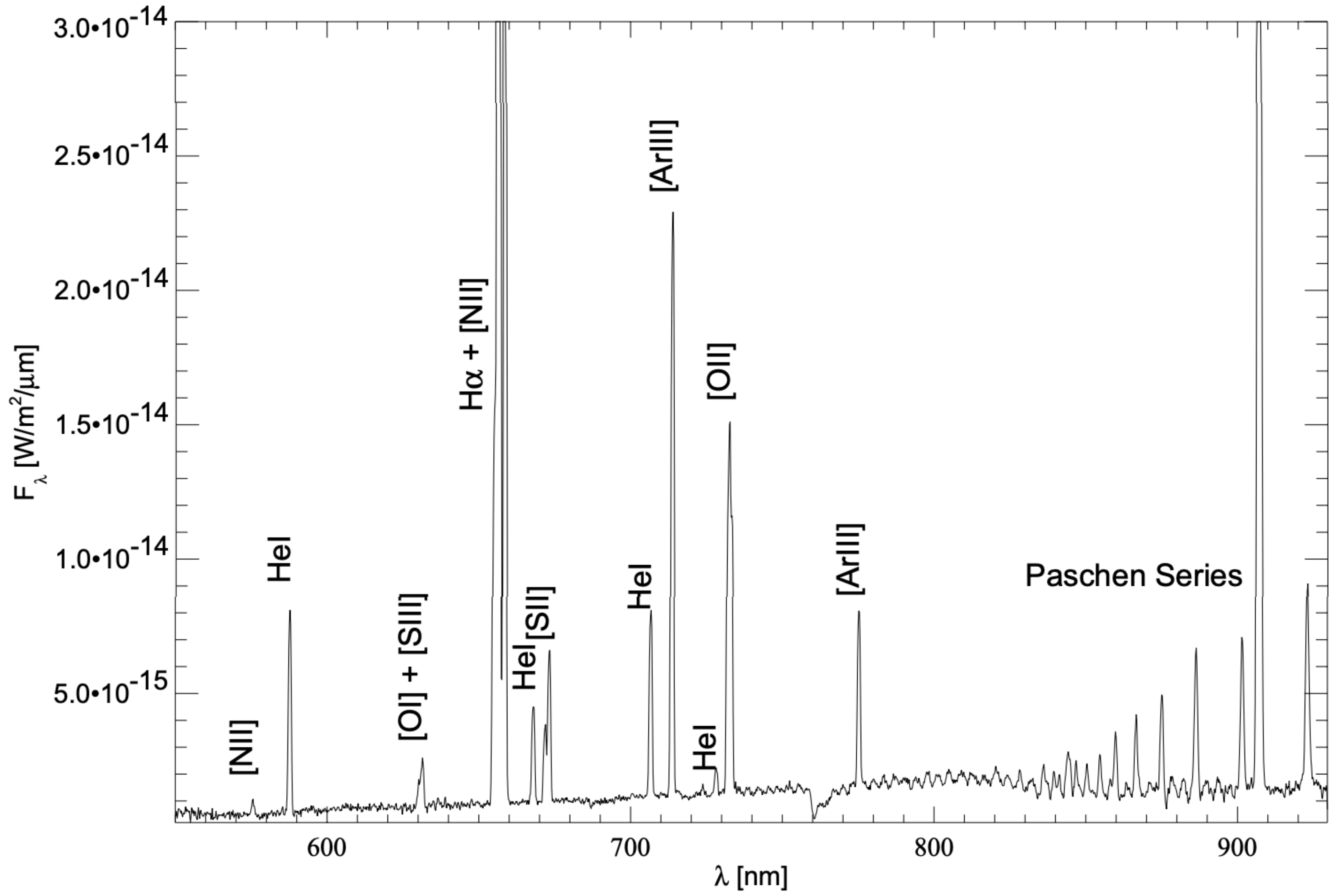
Tom Haworth's poster

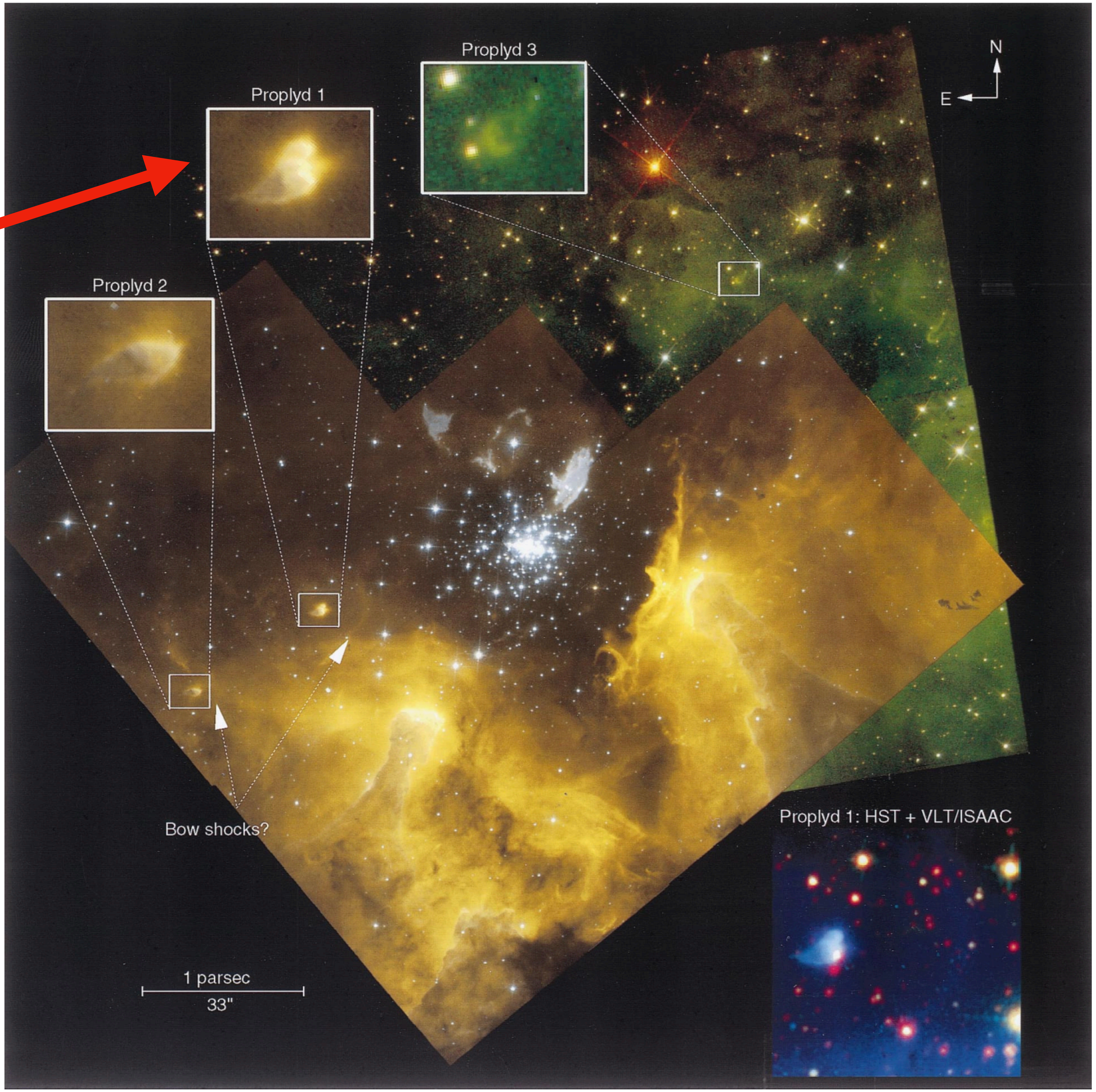
Karina Maucó's poster

IM Lup: ~900 au disc
mildly irradiated by FUV
Cleeves+16, Haworth+17



NGC 3603



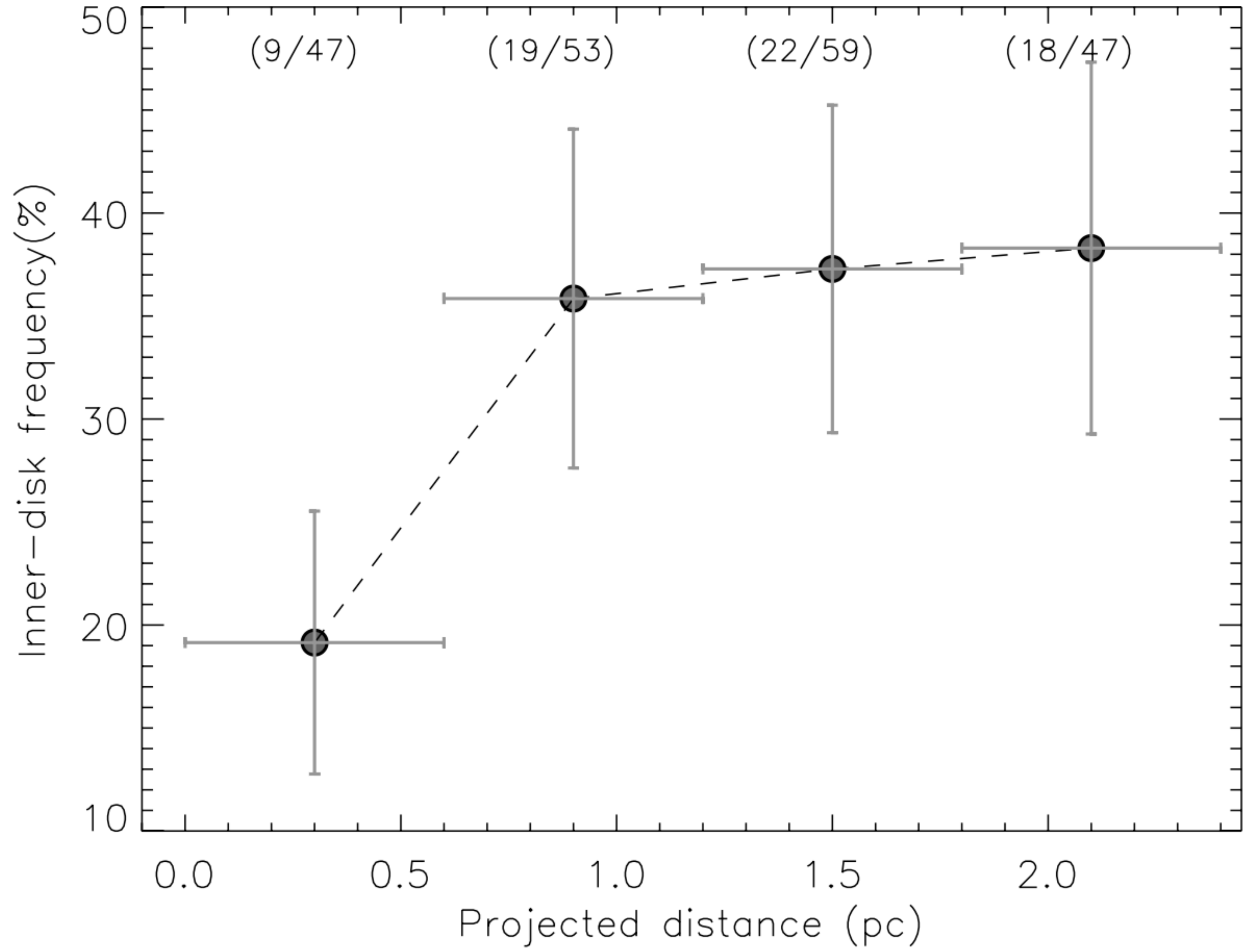


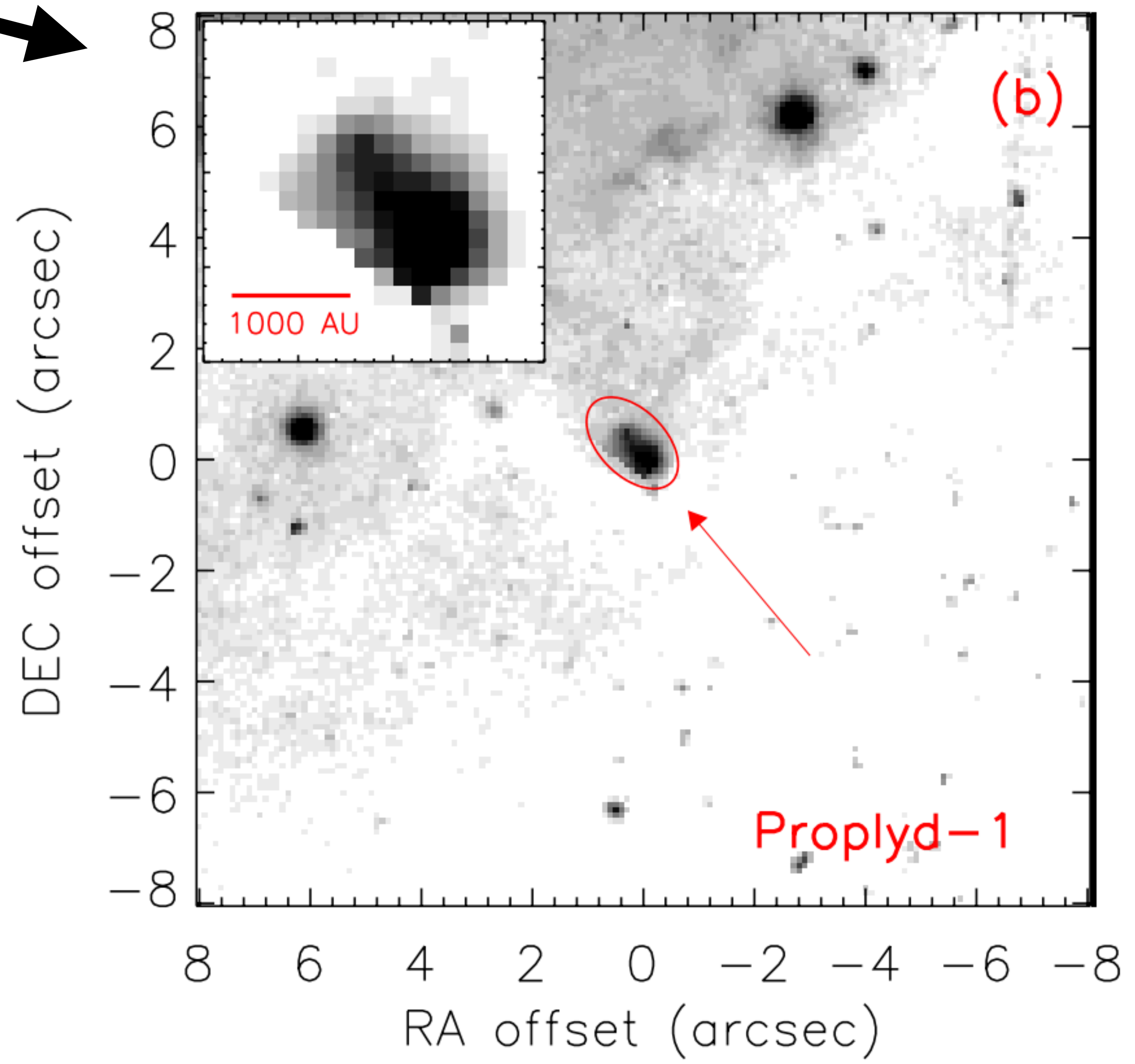
- Proplyds in NGC 3603 found by Brandner+00
- Large scale (~10 000 au): $\dot{M}_{\rm wind} \sim 10^{-5} \, M_\odot \, {\rm yr}^{-1}$
- Gradient in disc fraction from 20% to 40% with distance from centre (Stolte+04)

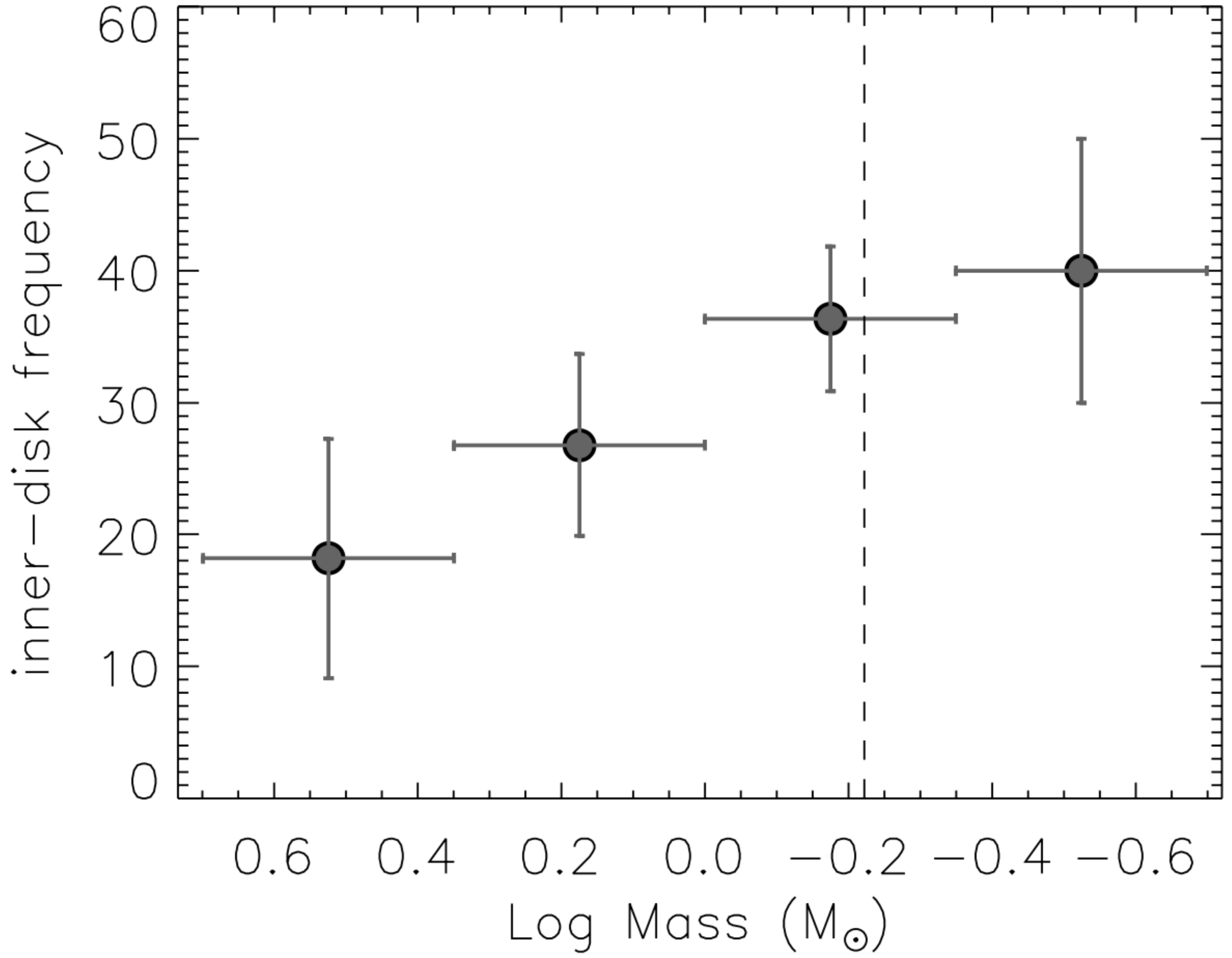
Pismis 24

Disc fraction & proplyd candidates

- Fang+12 found declining disc fraction with separation from Pis24-1 and evidence of proplyds
- Evidence of quicker dispersal for higher mass stellar hosts..?







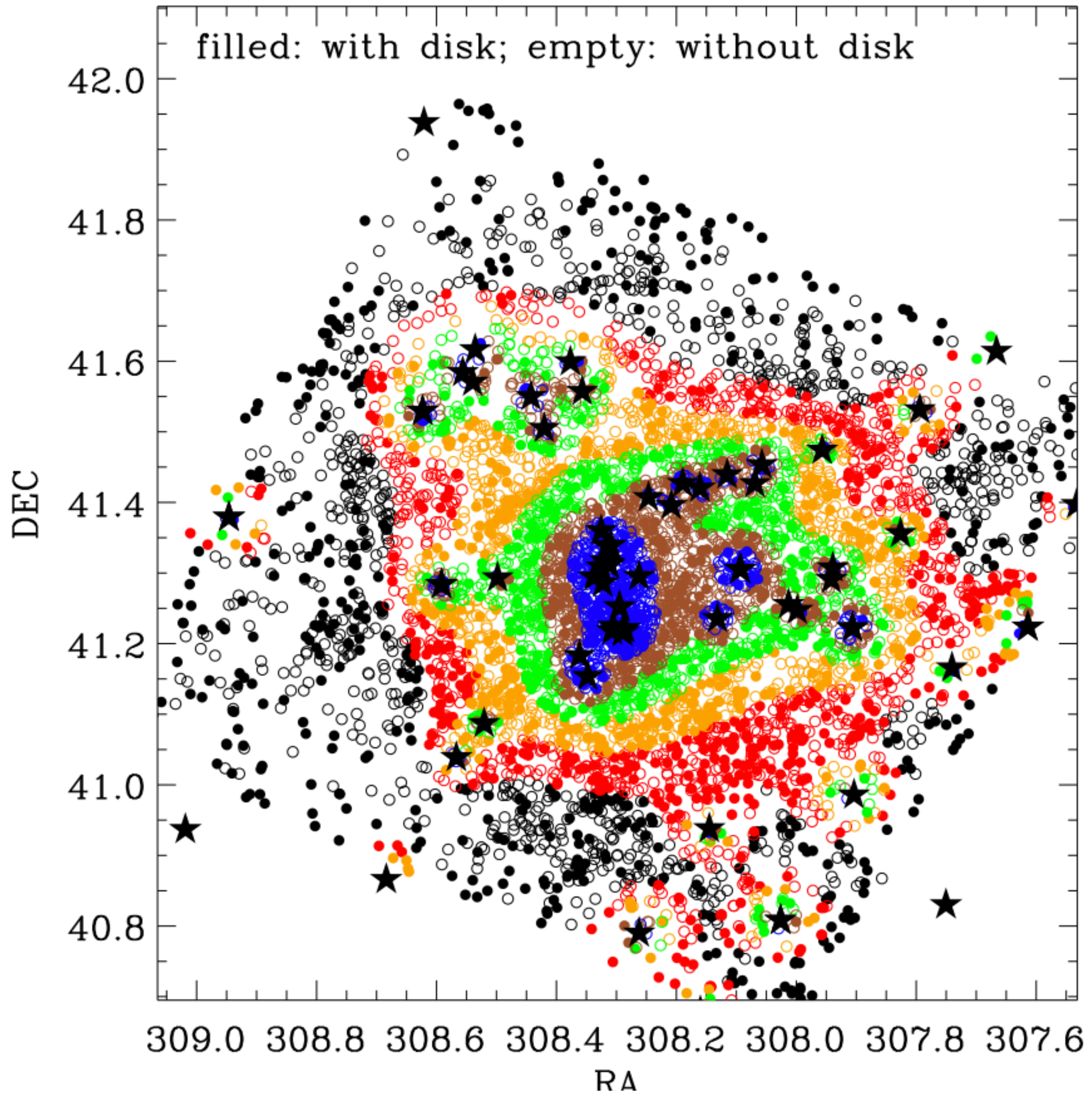
Cygnus OB2

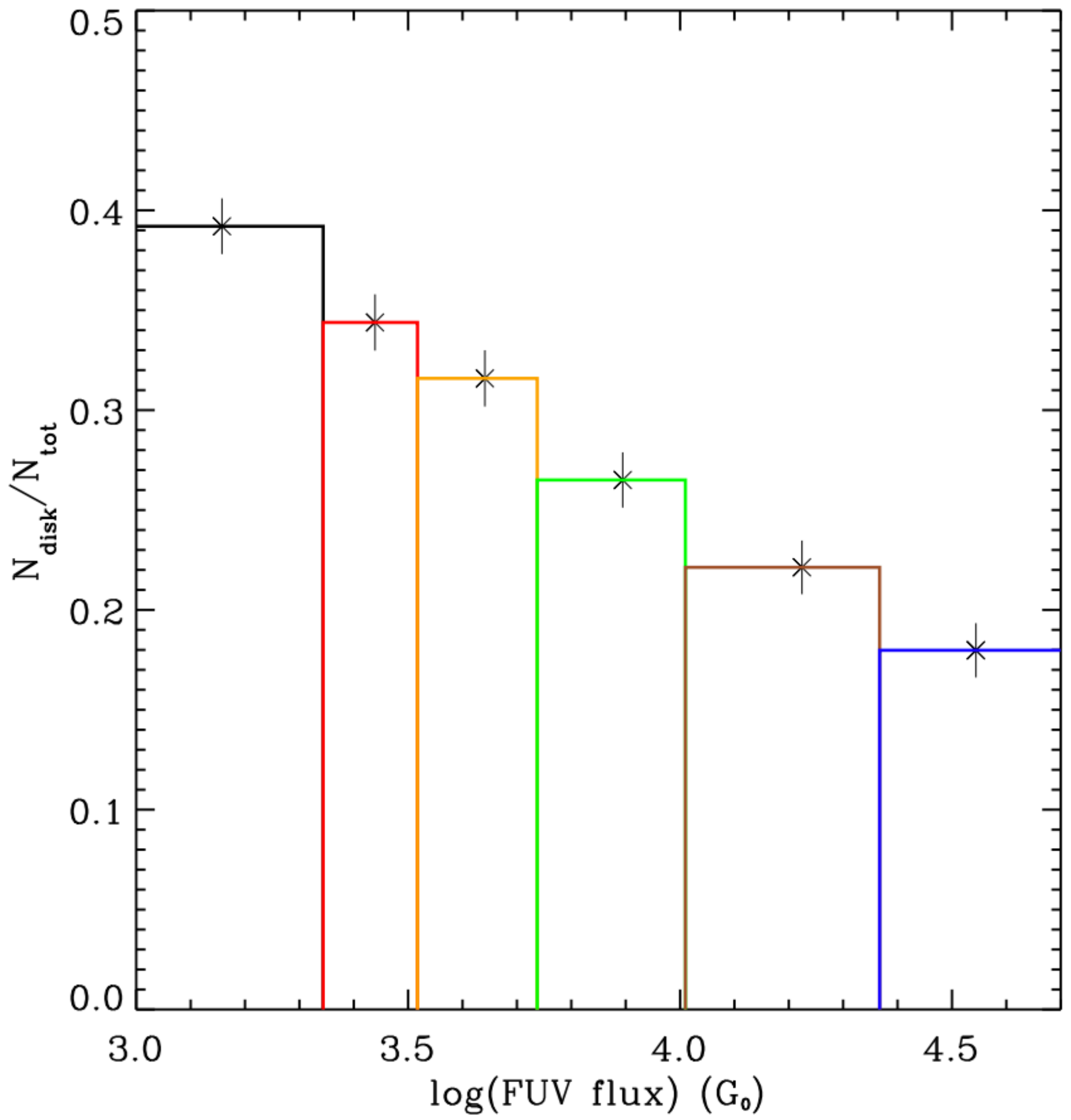
Disc fraction

- Cygnus OB2 is one of the closest massive OB associations $d \sim 1400\,\mathrm{pc}$: mass $\sim 1.6 \times 10^4\, M_\odot$, age ~ 3-5 Myr, low density $\sim 20\,\mathrm{stars\,pc^{-3}}$

- Guarcello+16 used a Chandra X-ray survey of Cygnus OB2 coupled with optical and IR photometry (Guarcello+13,14)

- Obtained clear correlation between disc fraction and (projected) FUV flux — see also Mario's poster!

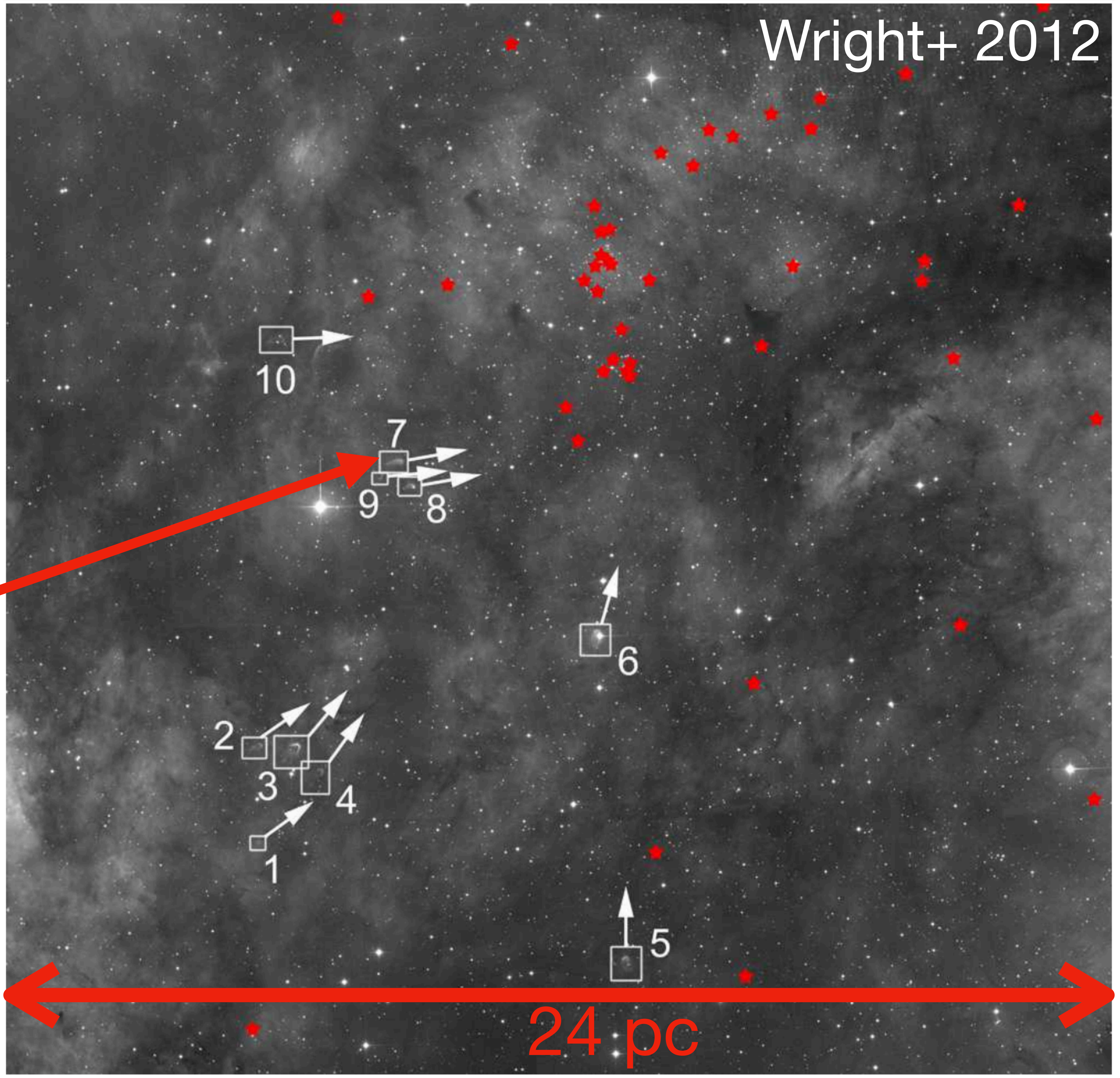




Cygnus OB2

Proplyds?

- Gaseous globule or giant proplyd? Class 0 disc photoevaporating?
- Separated by ~5 pc: FUV ~ 1000 G_0

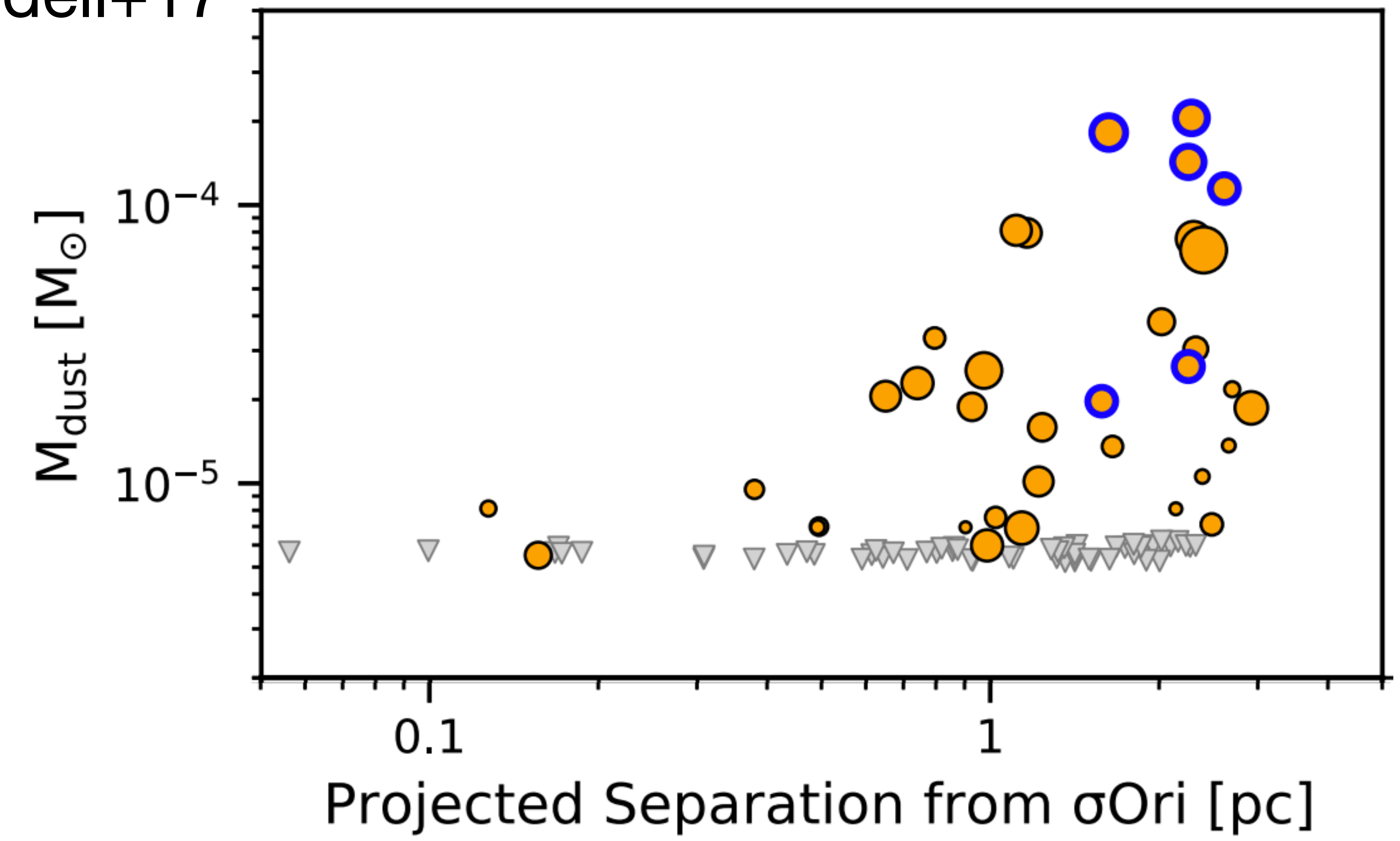

Wright+ 2012

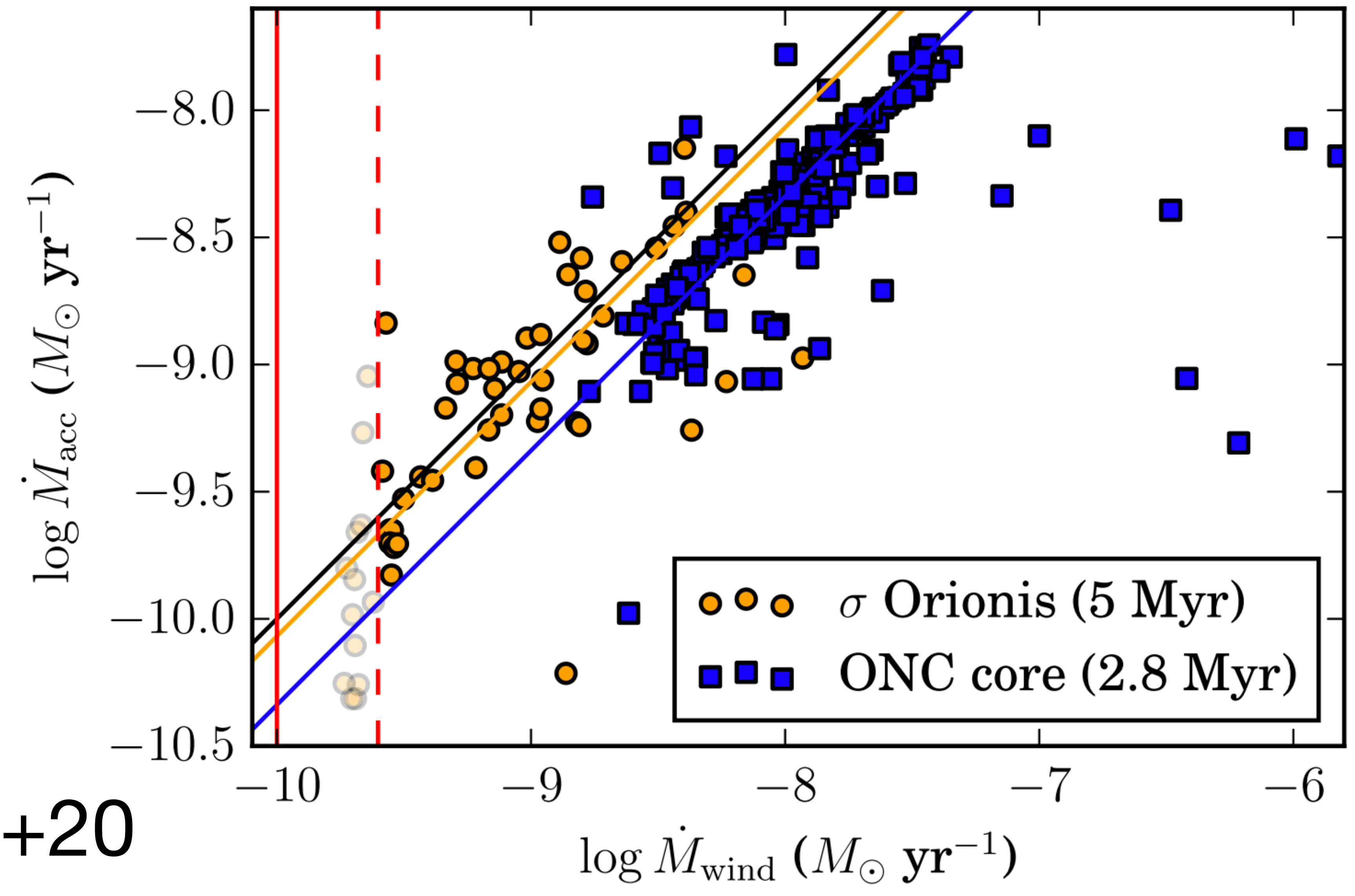
σ Orionis

Dust depletion

- Ansdell+17: Lower dust masses close to the massive star σ Ori (see also Maucó+16 & Karina's poster)
- Also evidence for photoevaporative winds (e.g. Rigliaco+09)
- In a viscous disc model, outwards mass-flux eventually balances mass-loss in the photoevaporative wind..?
- Not viscous (e.g. MHD driven accretion) - does mass-loss become inefficient for older regions?

Ansdell+17





Winter+20

What do we think we know?

External photoevaporation

- Speeds up inner-disc dispersal… *In the most massive star-forming regions*
- Depletes dust content in PPDs
- Can act on PPDs in relatively low UV environments (much lower than ‘classical’ ONC proplyds)
- Common process affecting at least ~50% of discs in the solar neighbourhood (Fatuzzo & Adams 08, Winter+ 20)
- Bright/large proplyds *seem* to be a short-lived state

Open problems

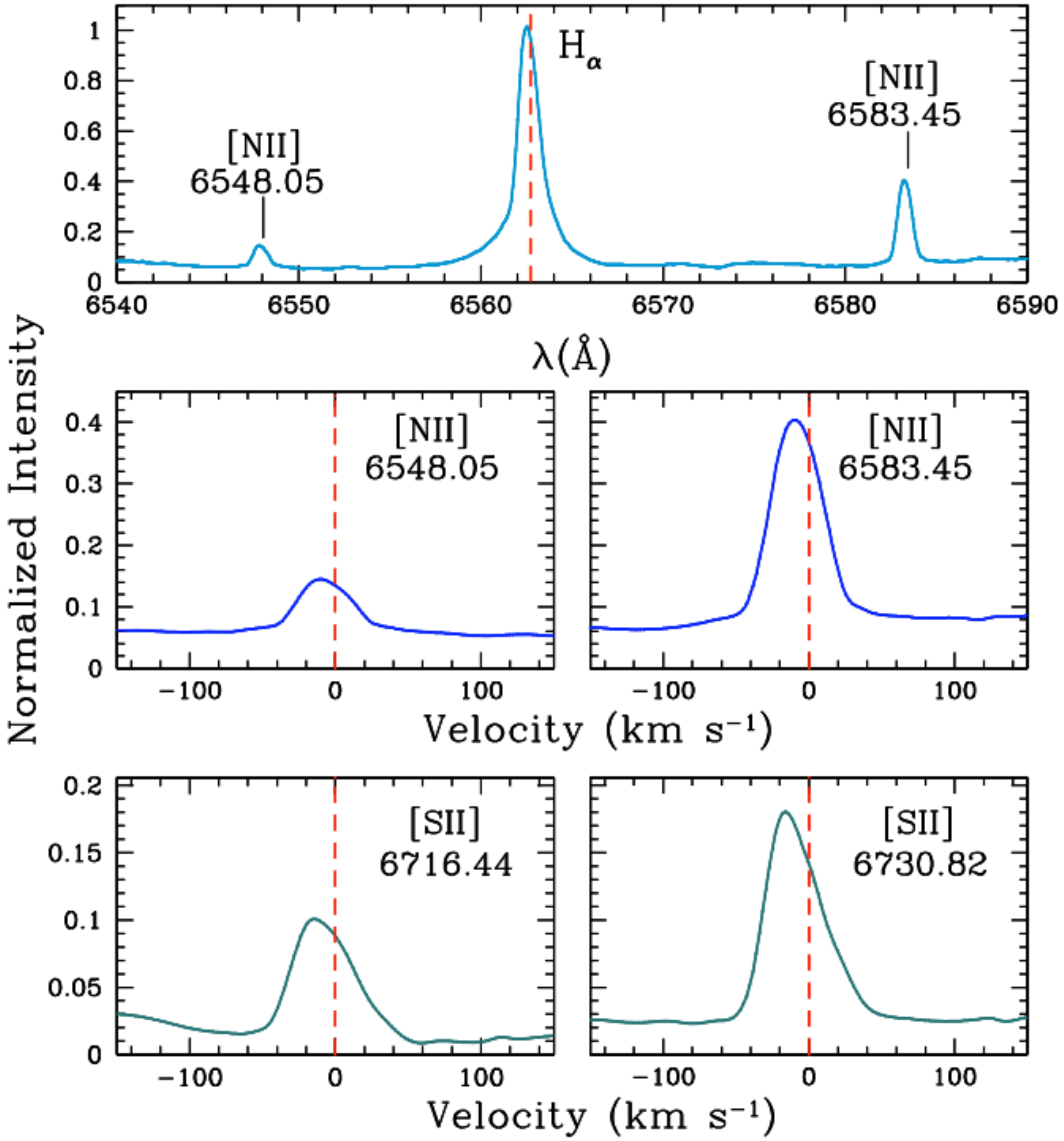
How does external photoevaporation influence planet formation?

1. Down to what radius are PPDs efficiently photoevaporated at given UV flux?
2. How much dust is entrained in thermal winds? Dust-to-gas ratio? Size?
3. Balance between externally driven wind/internal angular momentum transport?
4. Fraction PPDs/planetary systems that underwent significant photoevaporation?
5. How does external photoevaporation interact with internal processes/depletion?
6. Depletion rate variation with stellar mass?
7. Are the ‘giant proplyds’ the early phases of a photoevaporating disc?

Additional slides…

σ Orionis

Winds



Hα, NII and SII emission lines detected around the ~0.2 $M_{\odot}$, ~1 Myr star S0587 — Rigliaco+09

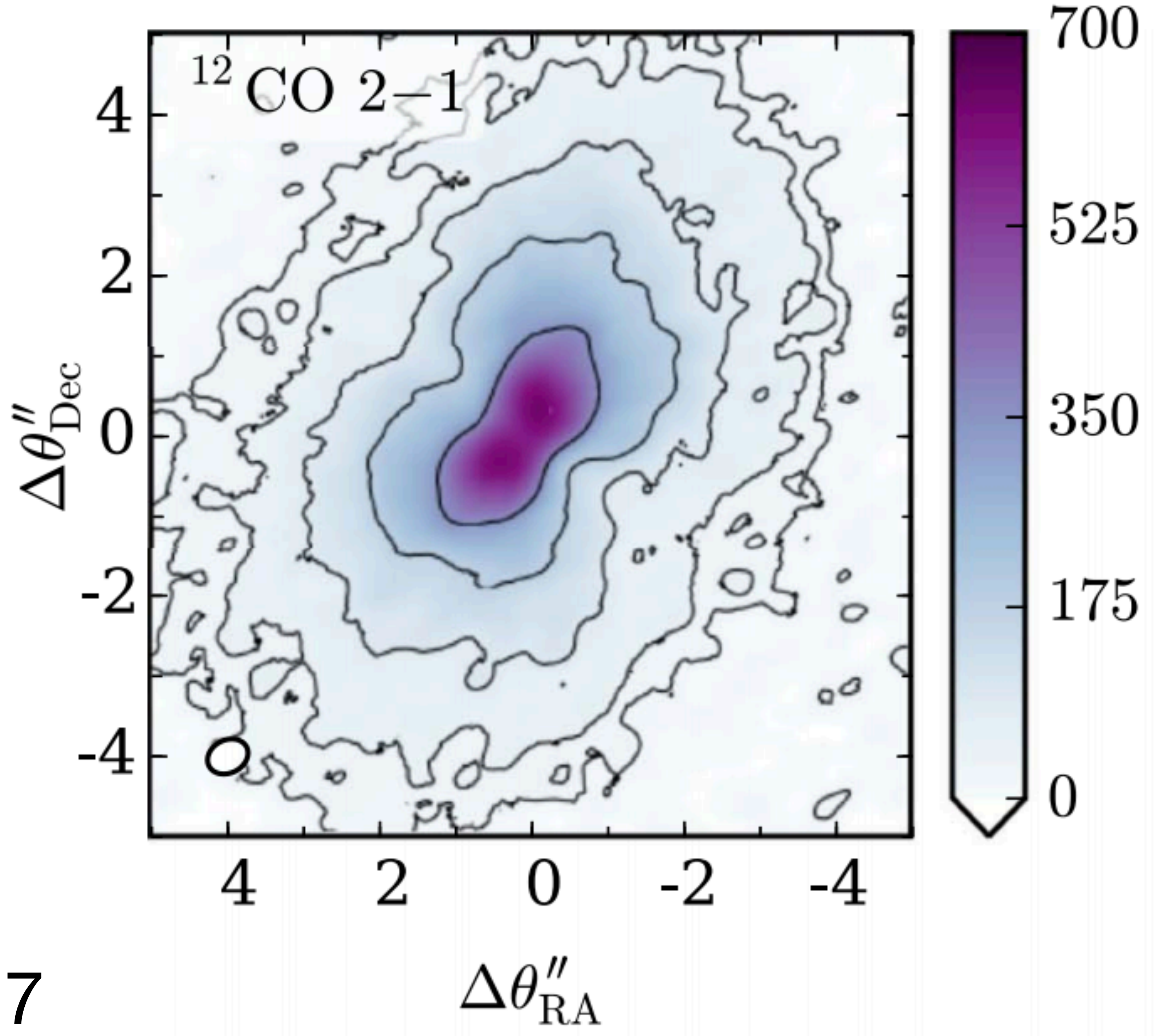
- σ Orionis: ~3 Myr old star forming region in Orion hosting a O9.5 star that irradiates the PPDs
- Rigliaco+09 found evidence of wind around T Tauri star with mass-loss rate $\dot{M}_{\mathrm{wind}} \sim 10^{-9}\, M_{\odot}\, \mathrm{yr}^{-1}$

IM Lup

Low UV winds

- IM Lup hosts a massive ($\sim 0.17\,M_\odot$) disc, detected out to ~970 au in ^{12}CO, ~ 300 au in dust
- Gas and dust properties using the TORUS code: low FUV (~4 G_0), allows gas phase CO at large separations
- Coupled with 1D hydro solution by Haworth+ 17: significant mass loss at the outer edge - halo?

Cleeves+16



Haworth+17