The dispersal of the protoplanetary disc

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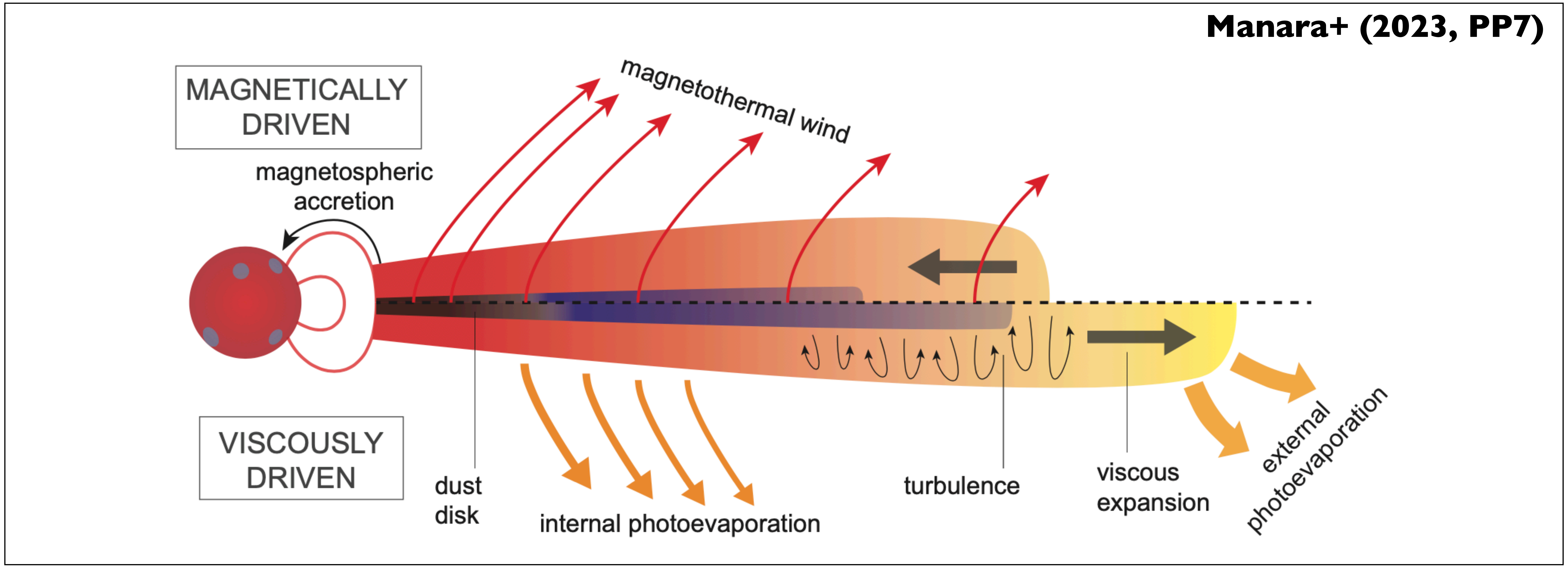
Formation of the protosolar disk and of its planetesimals
Collège de France, 26th-27th June 2024

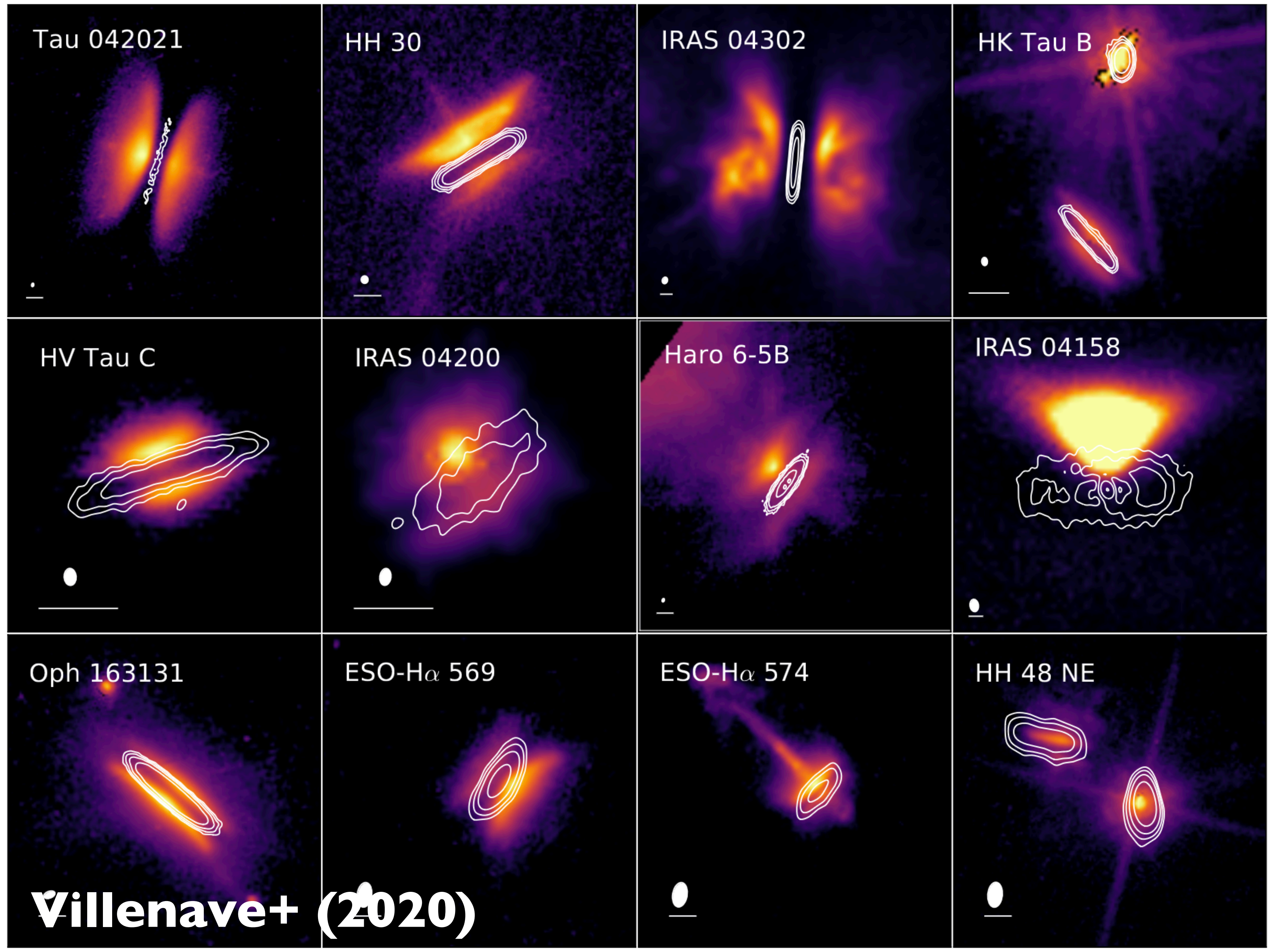


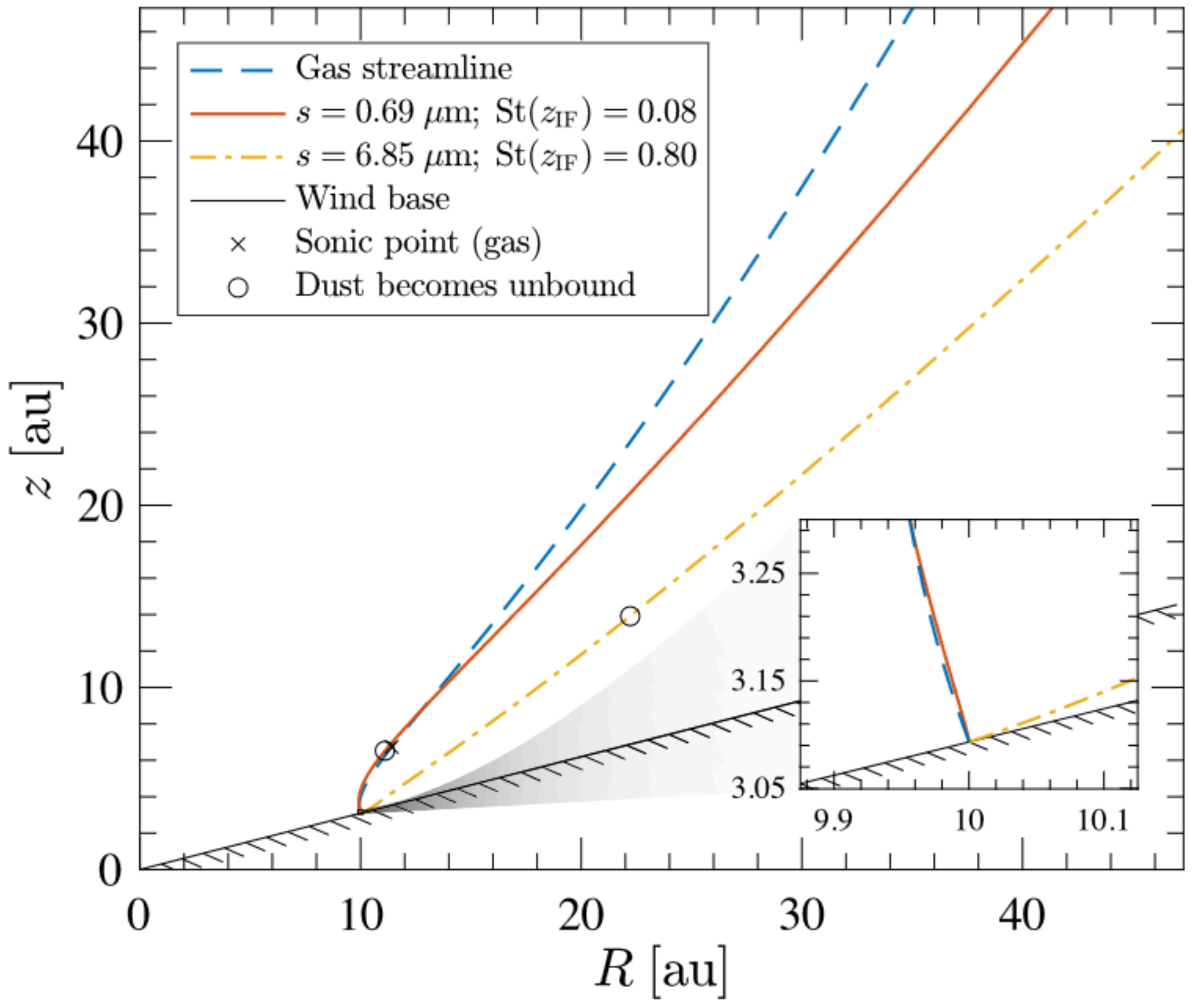
Disc evolution is driven by accretion & mass-loss.

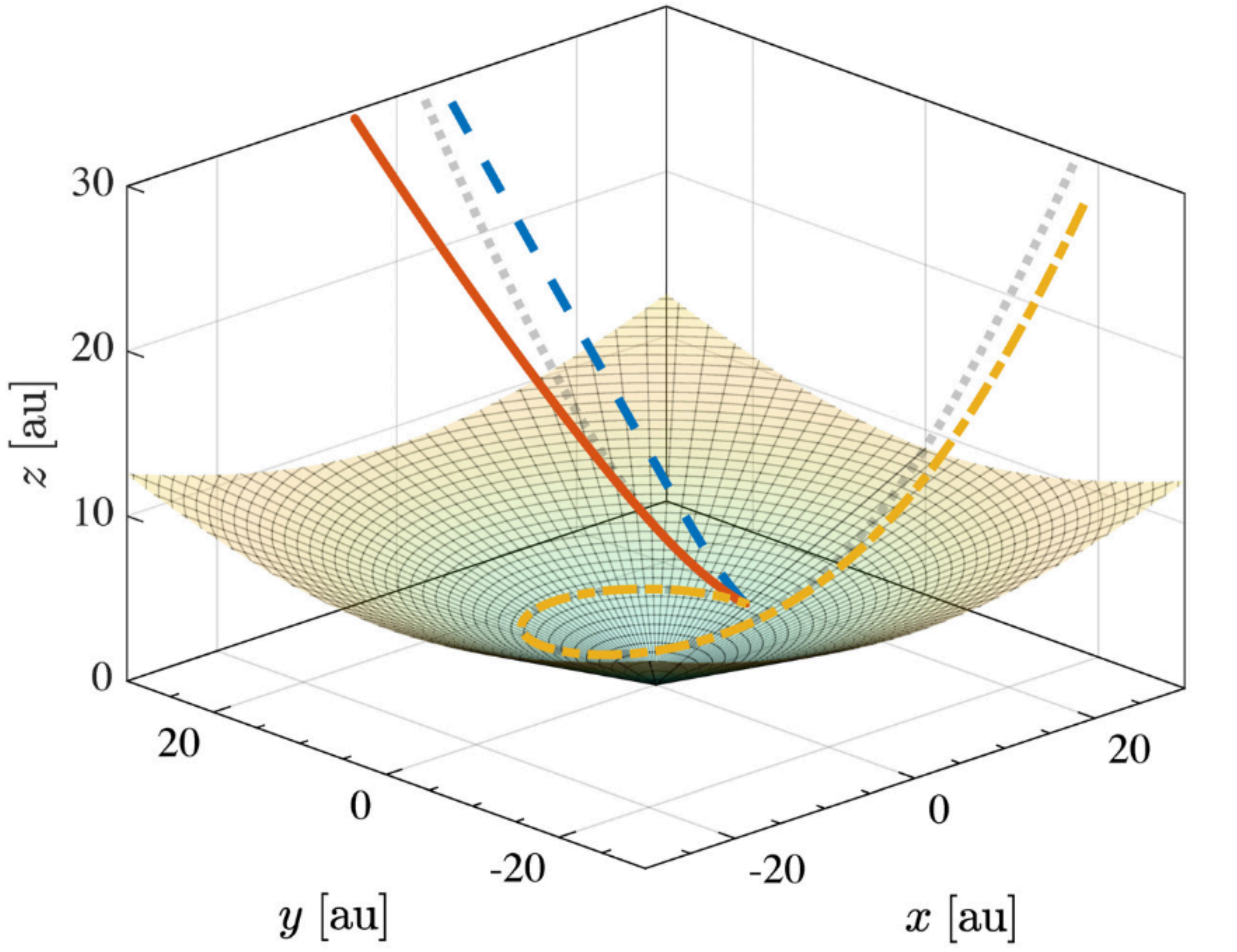
Accretion can be due to transport (turbulence) or loss (winds) of angular momentum.

Mass-loss can be via magnetised or thermal (photoevaporative) disc winds.

Mass-loss is important for planetesimal formation



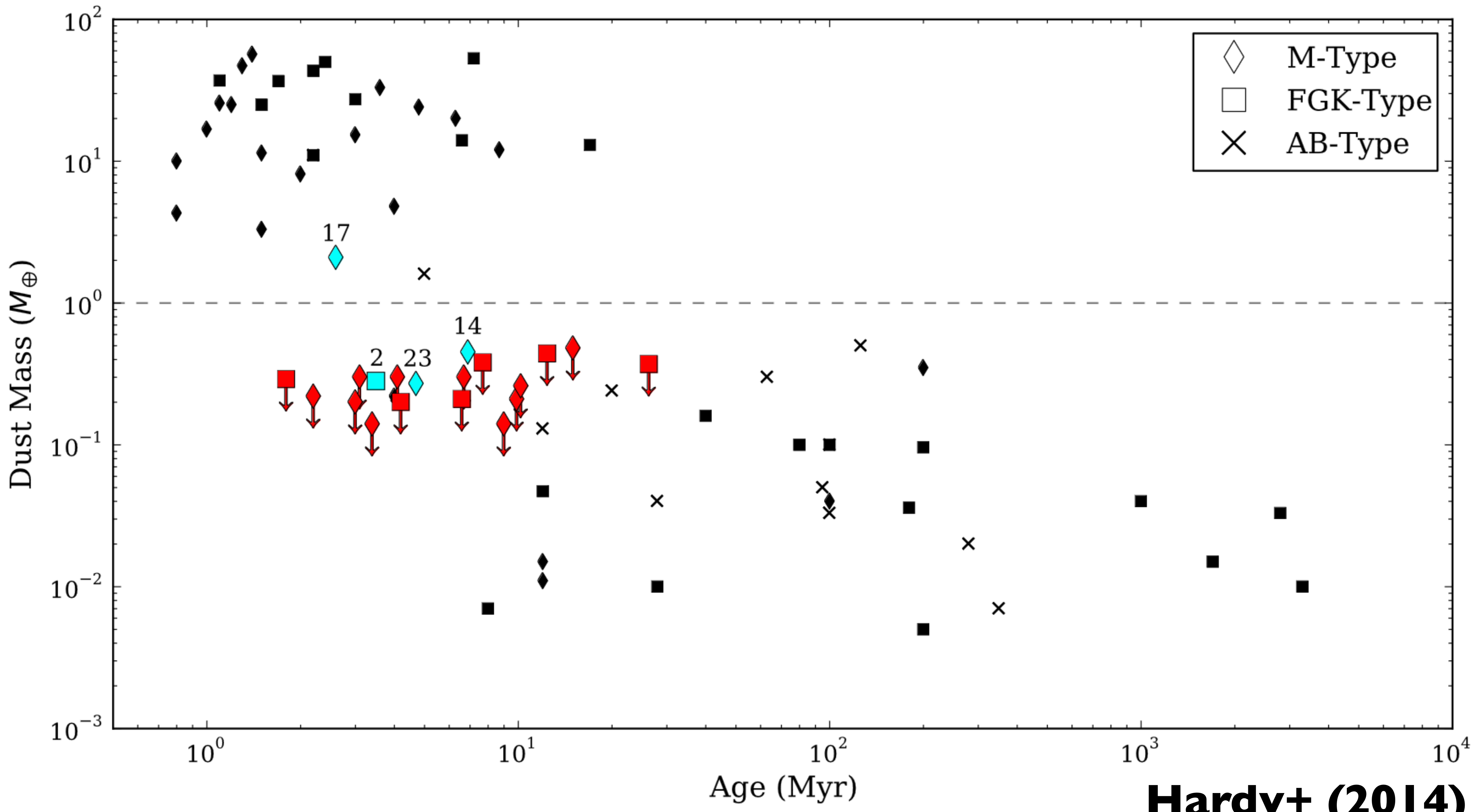




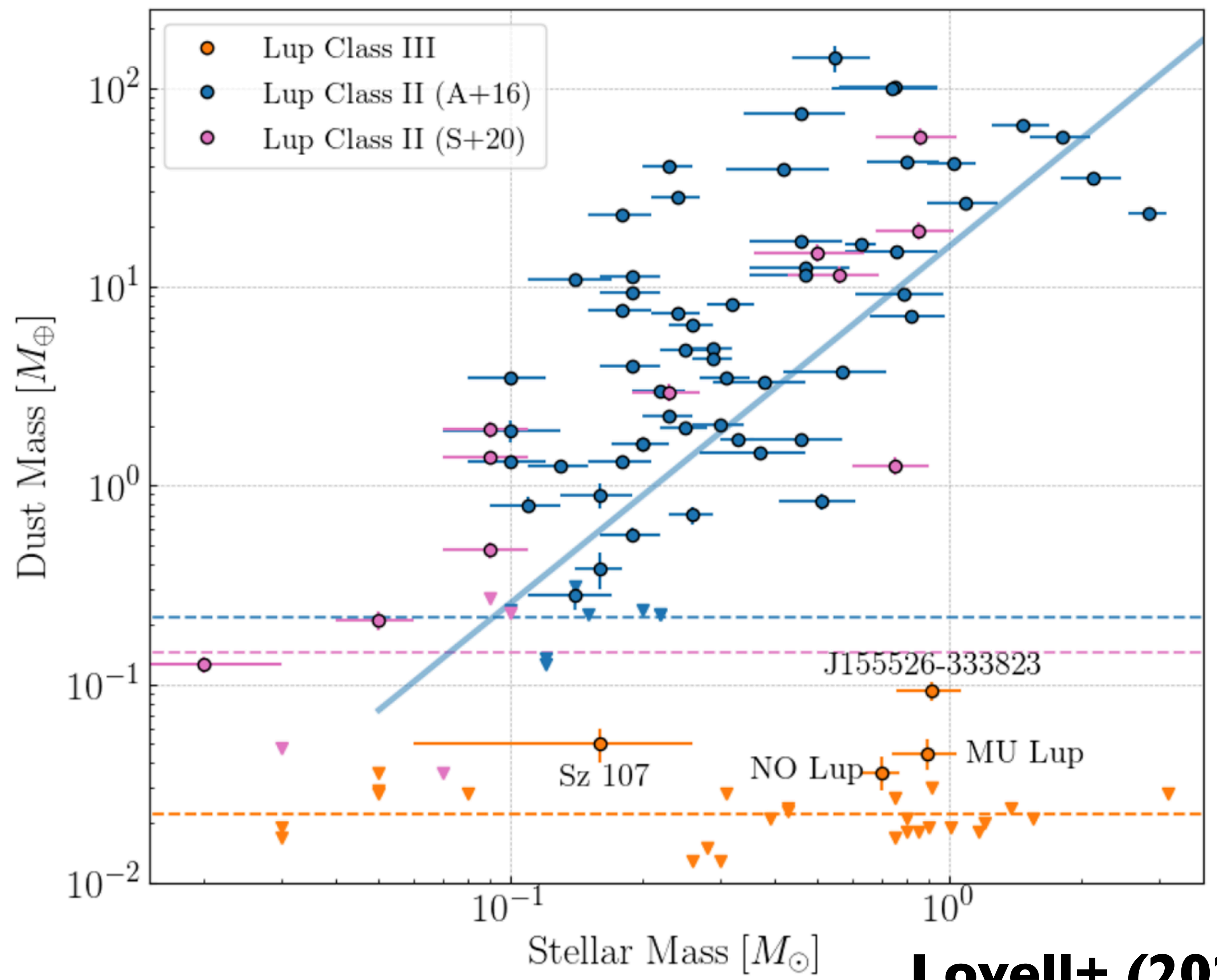
Hutchison & Clarke (2021)

- Winds (both magnetic and photoevaporative) are launched from the upper layers of the disc, which are depleted of (large) dust (e.g., Throop & Bally 2005).
- Gas density in winds is low, and flow velocities are modest, so only small grains (≲10μm) can be entrained in disc winds.
- Disc winds preferentially remove gas, so winds ***<u>increase the dust/gas ratio</u>***.

Disc evolution is slow, but disc dispersal is fast



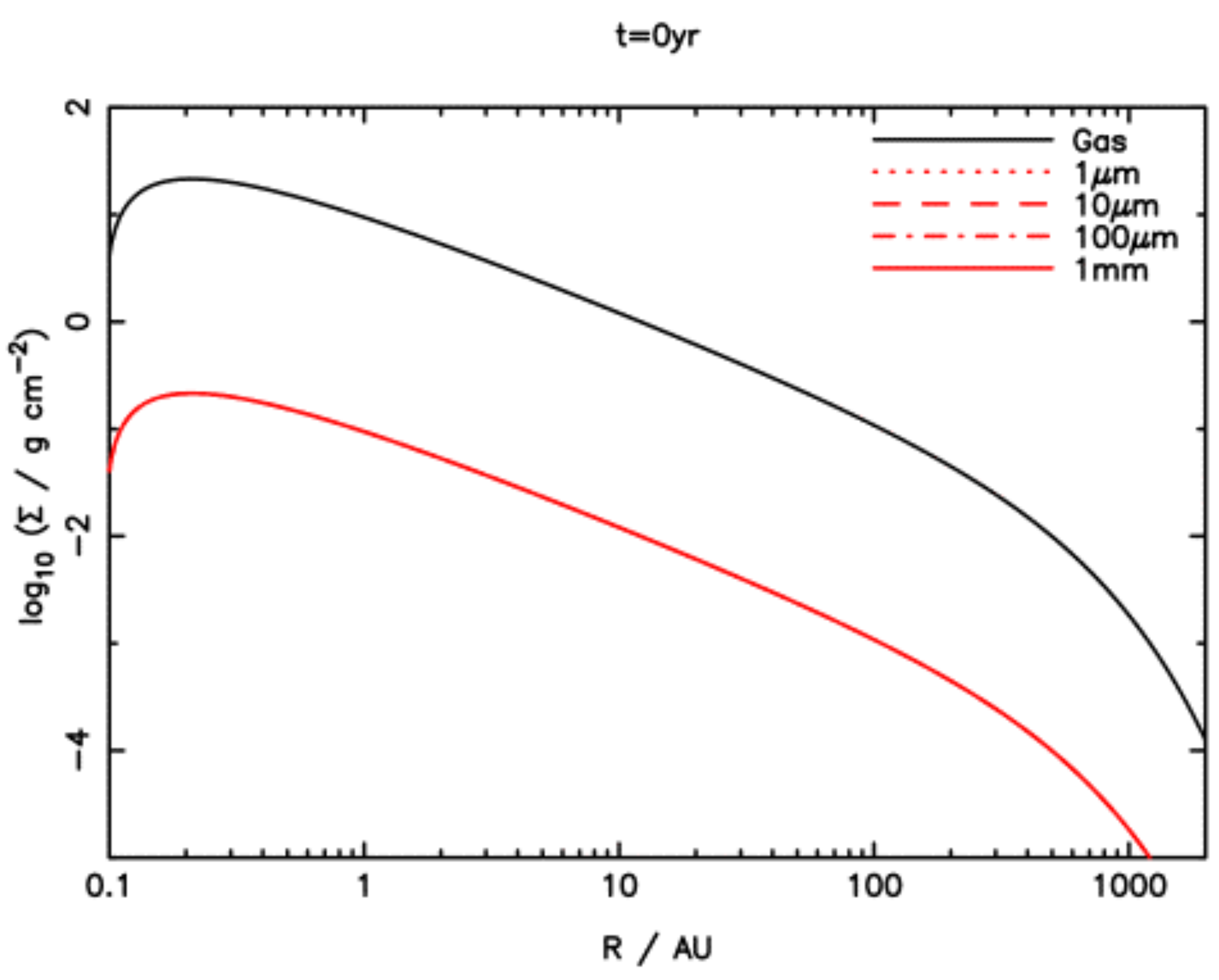
Hardy+ (2014)



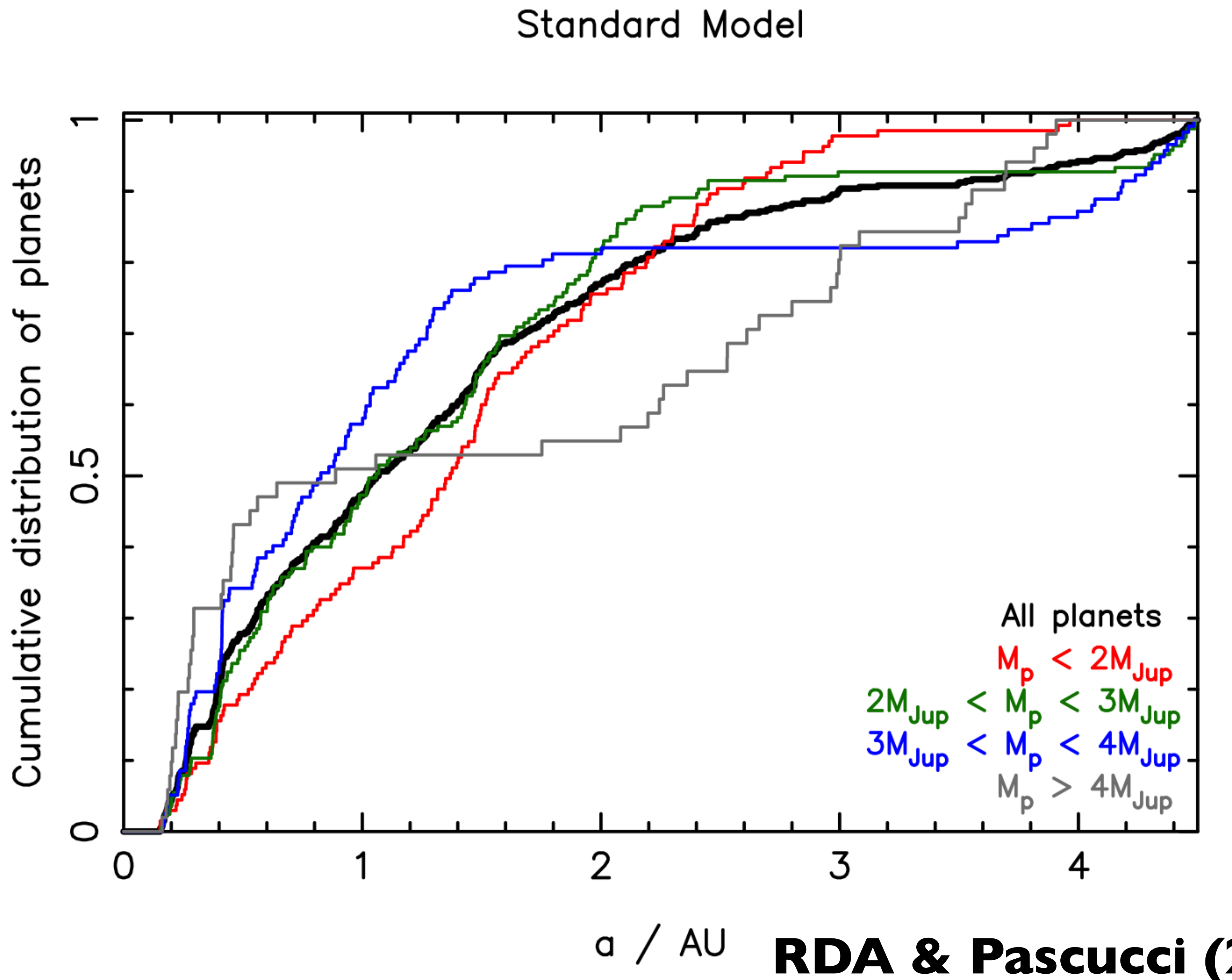
Lovell+ (2021)

- Large body of observational work (back to Strom+ 1989) shows that the final "transition" from disc-bearing to disc-less young stars is rapid.
- Final stage of evolution is ***discontinuous***: upper limits on both gas and dust in Class IIIs are orders of magnitude below disc masses in the Class II phase.
- ***Two time-scales***: rapid disc clearing (at all radii!) after lifetime of ~Myr.

How the gas disc is dispersed matters



RDA & Armitage (2007)

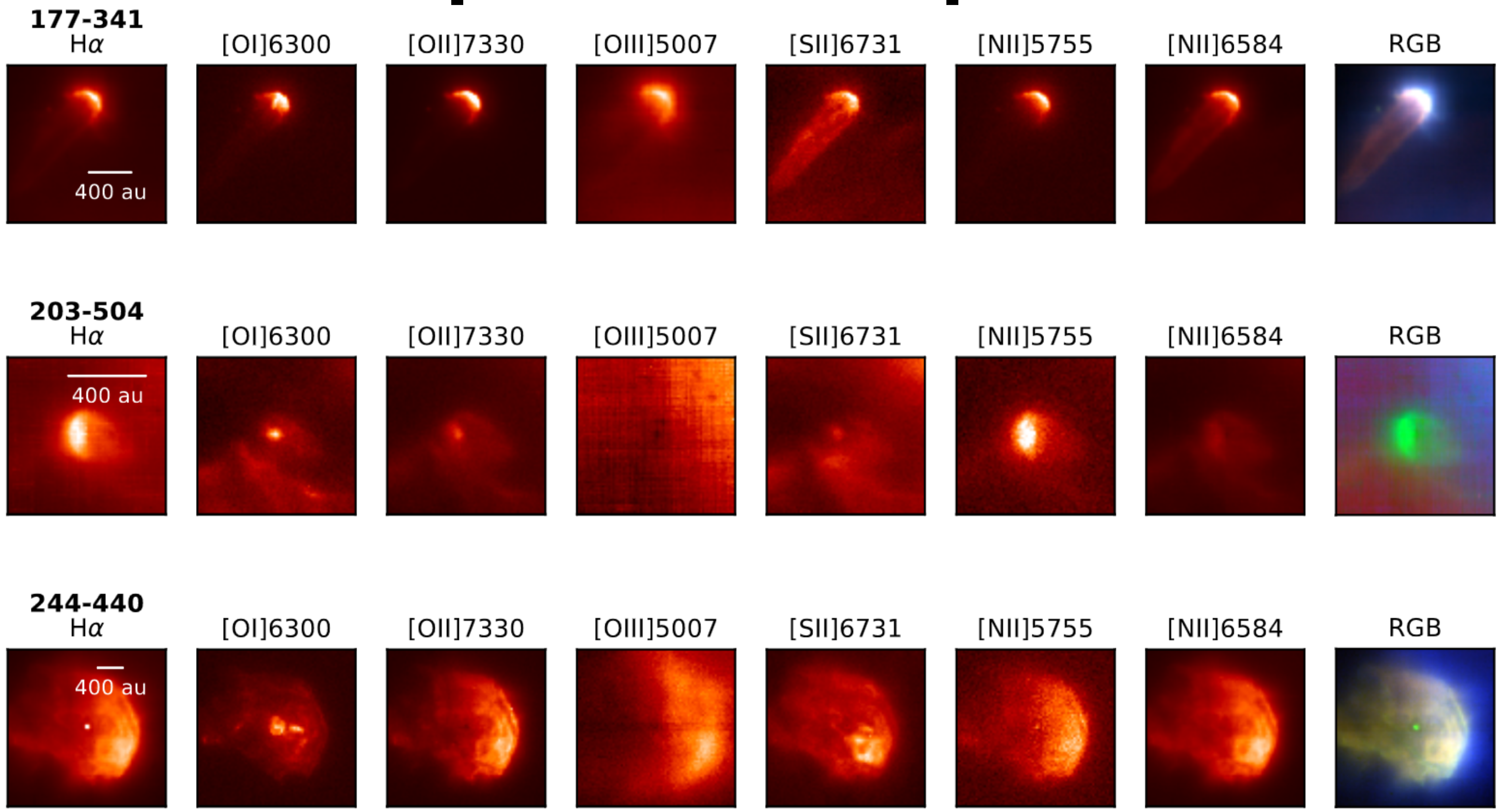


RDA & Pascucci (2012)

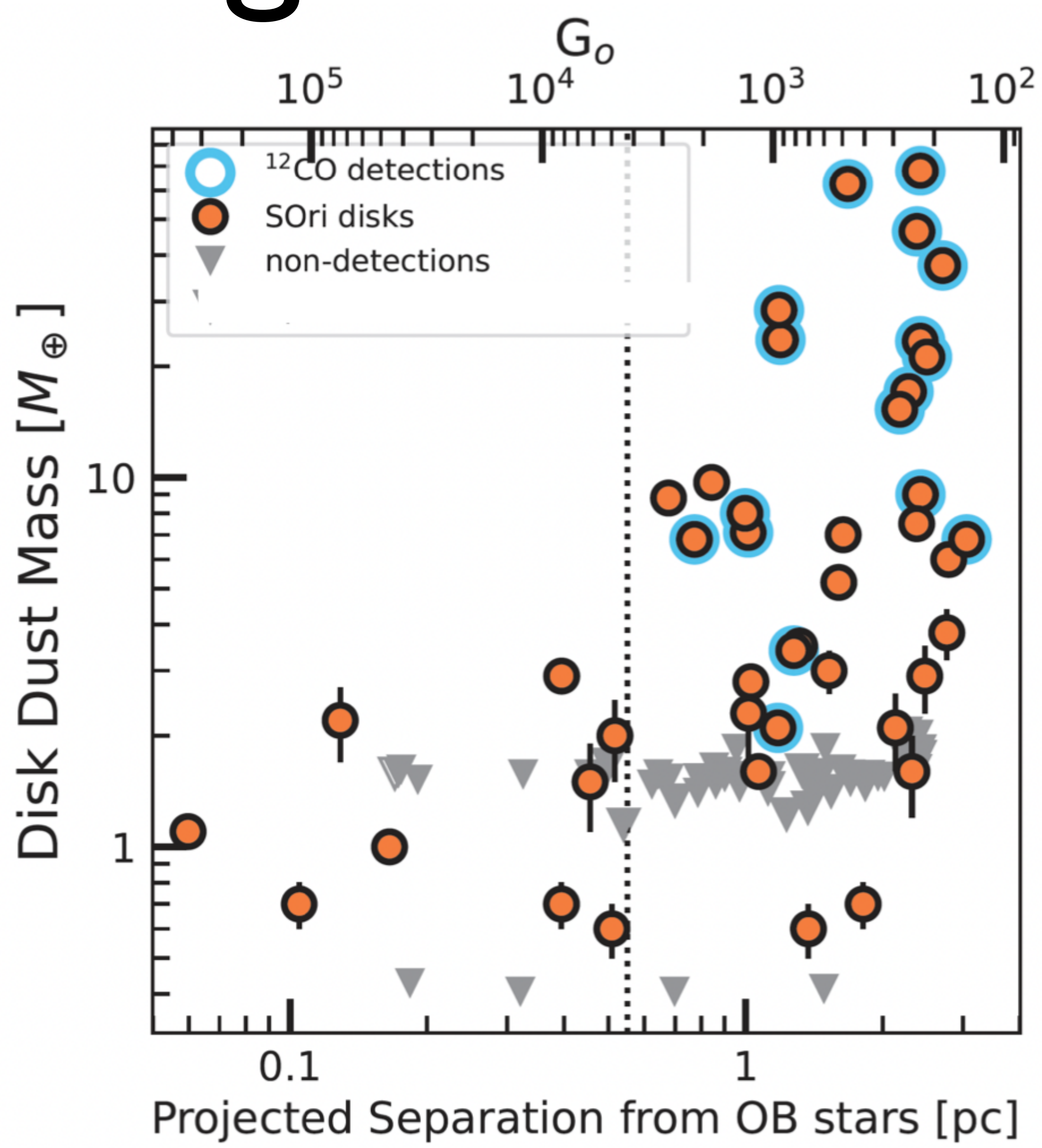
- **Dust dynamics:** inside-out disc clearing "sweeps up" dust. Dispersal can create structures in the dust and planetesimals. (Initial conditions for debris discs?)
- **Planet migration:** disc dispersal halts migration, and the mode of dispersal can create features in the radial distribution of planets.
- Toy models of disc dispersal (e.g., exponential decay) can give you the wrong answers.

So, how ***do*** discs get dispersed?

External photoevaporation drives significant mass-loss



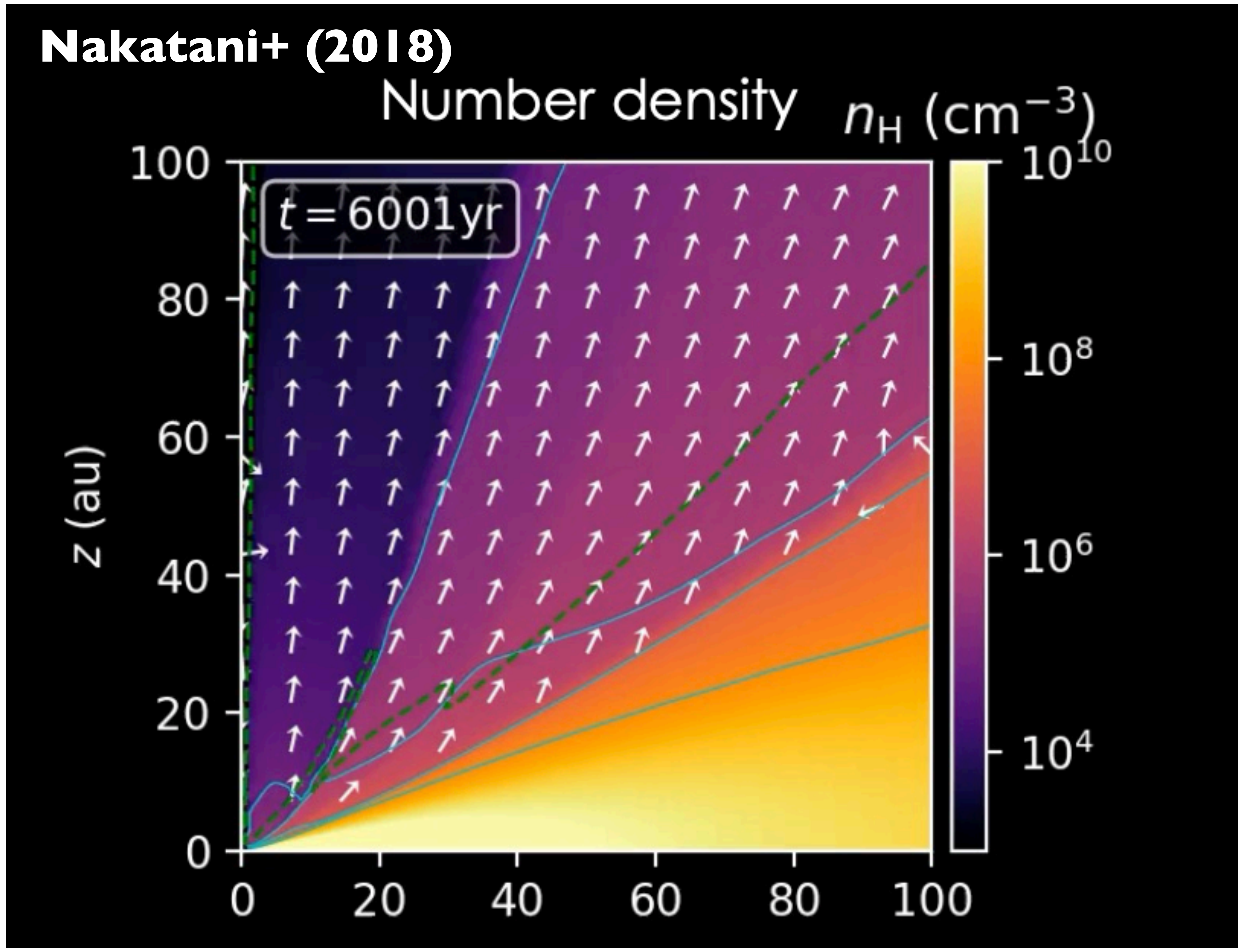
Aru+ (2024) - Orion Nebula Cluster

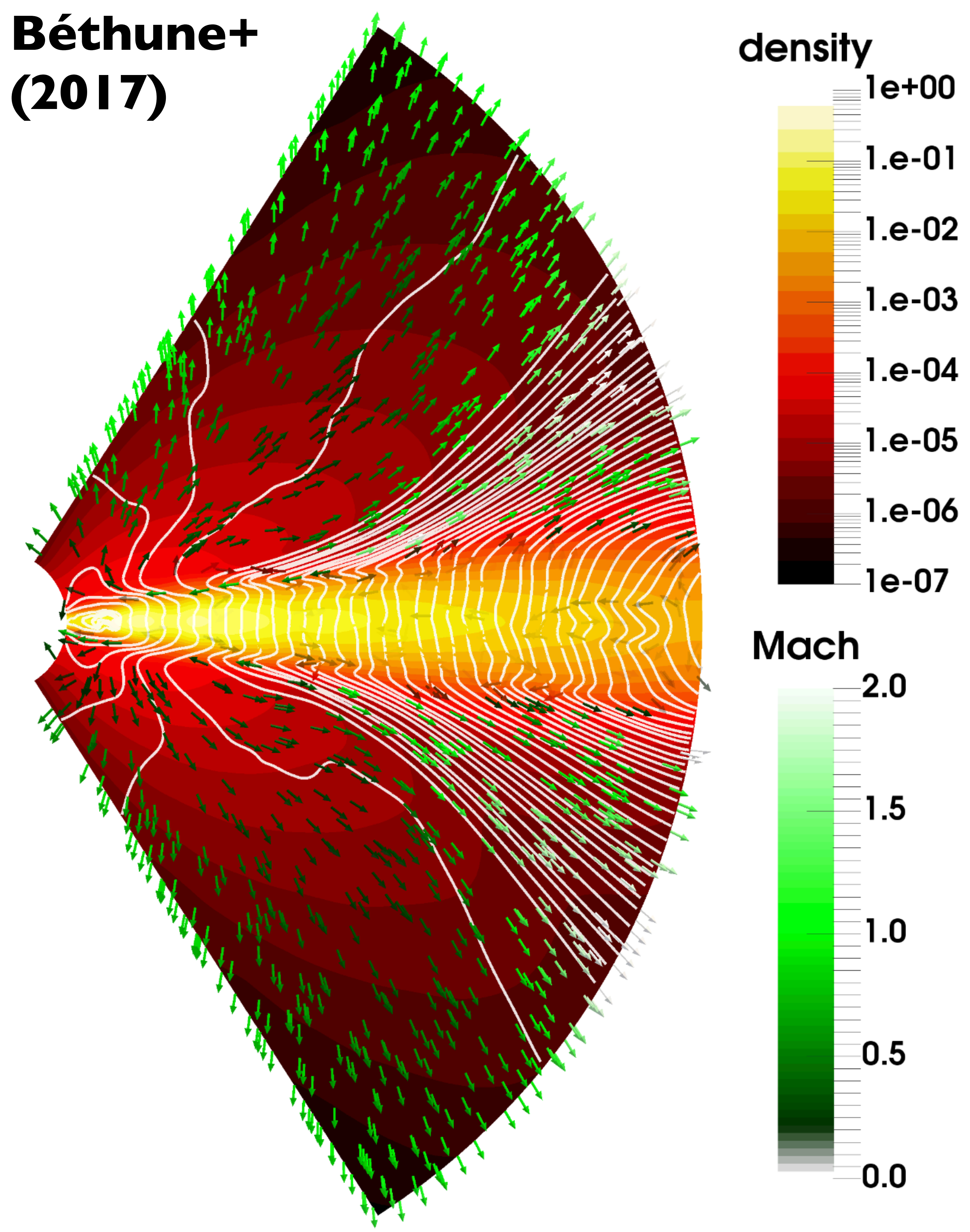


Mauco+ (2023)
σ Orionis

- Long understood that discs in high-UV environments (e.g., the Orion nebula) are dominated by external photoevaporation (e.g., O'Dell+ 1993; Johnstone+ 1998).
- Recently it has become clear that mass-loss rates are significant even in smaller clusters (e.g., Haworth+ 2018, 2023; Winter+ 2022).
- Many (most?) planetary systems form in clusters, with relatively high UV fluxes.

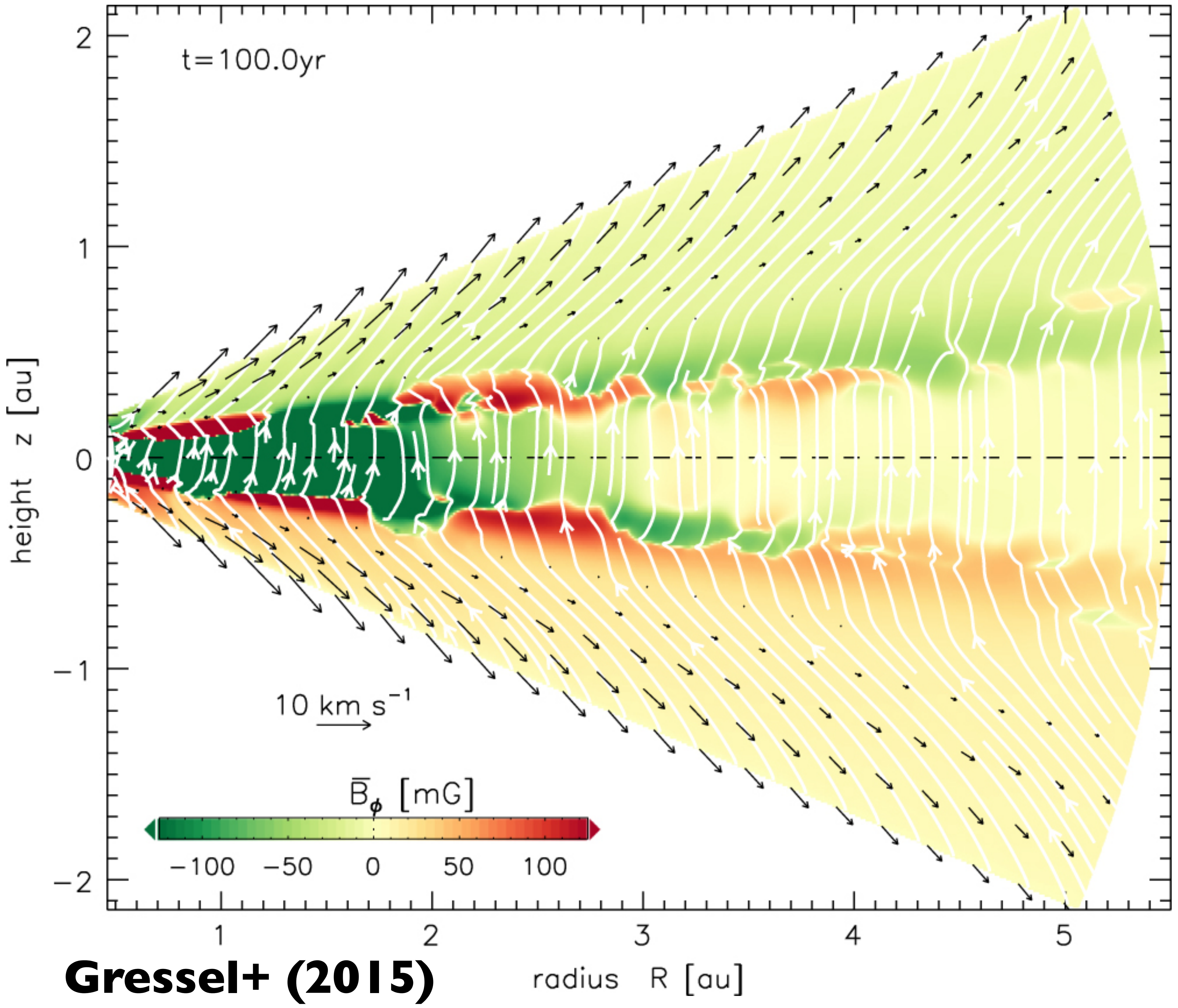
Mass-loss = disc winds



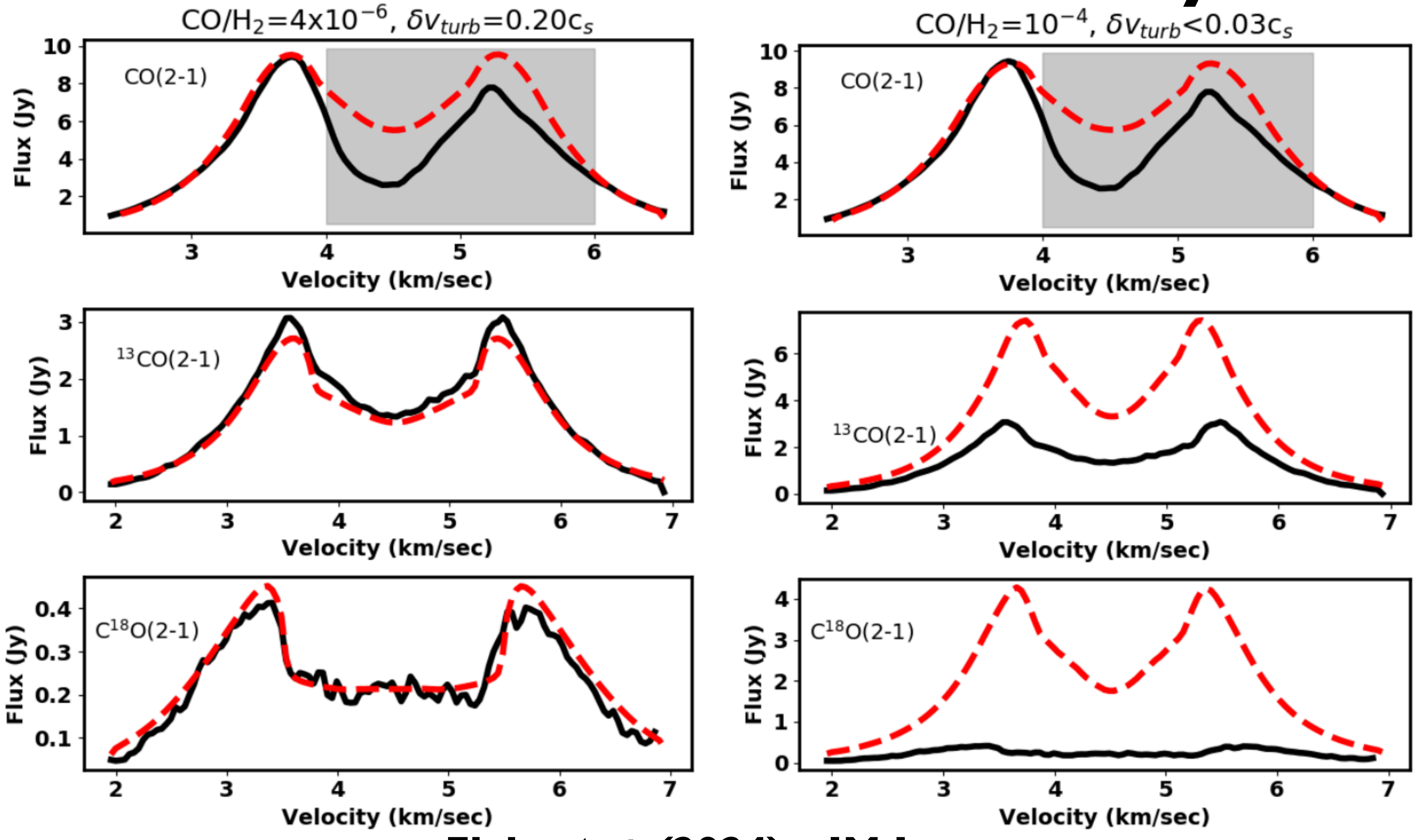


- Two ways to launch a wind from a disc:
  - thermal energy input (“evaporation”)
  - magnetic energy input (“MHD winds”)
- Thermal winds are “pure” mass loss, but magnetised winds also remove angular momentum (and thus drive accretion).

Accretion remains the dominant uncertainty



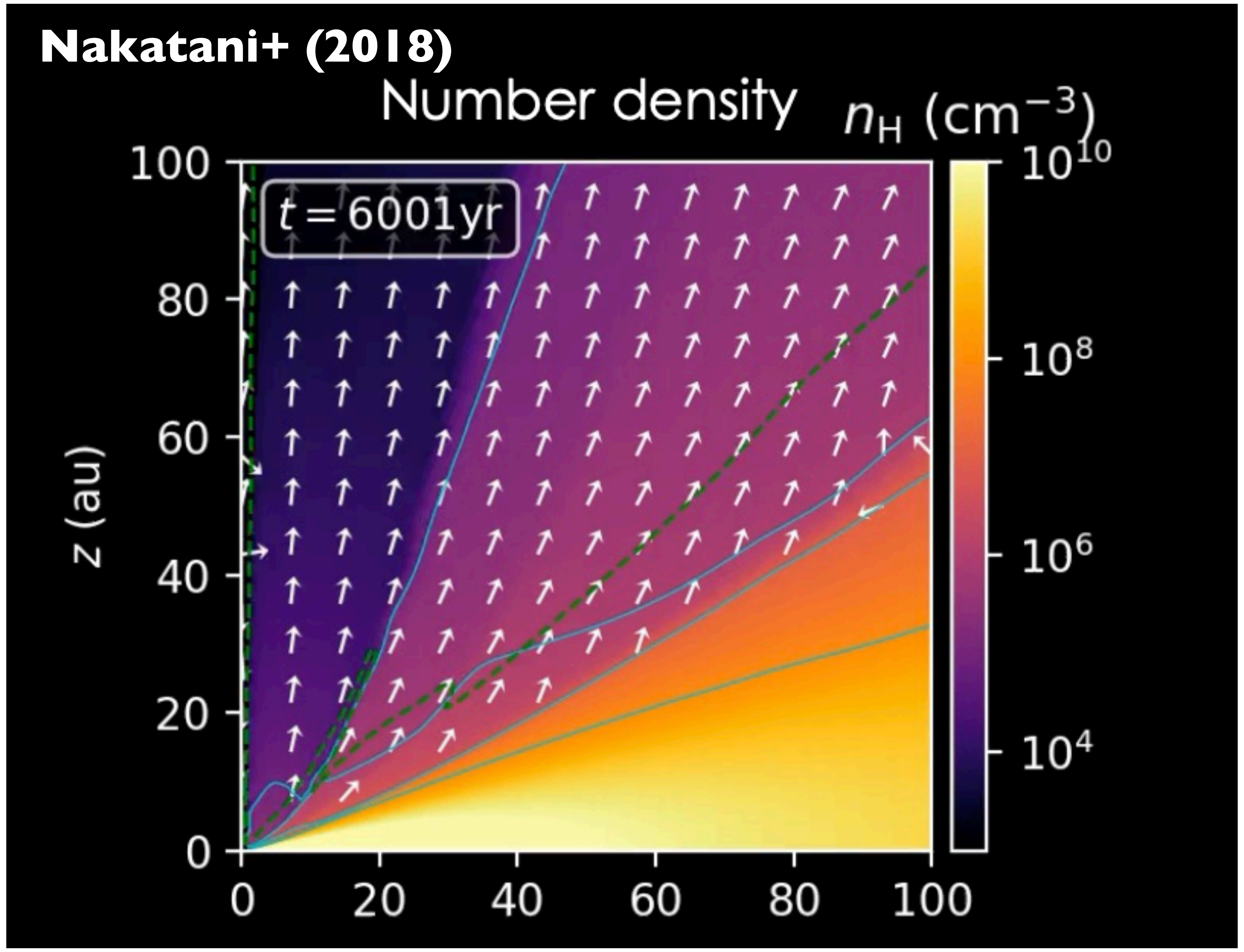
Gressel+ (2015)

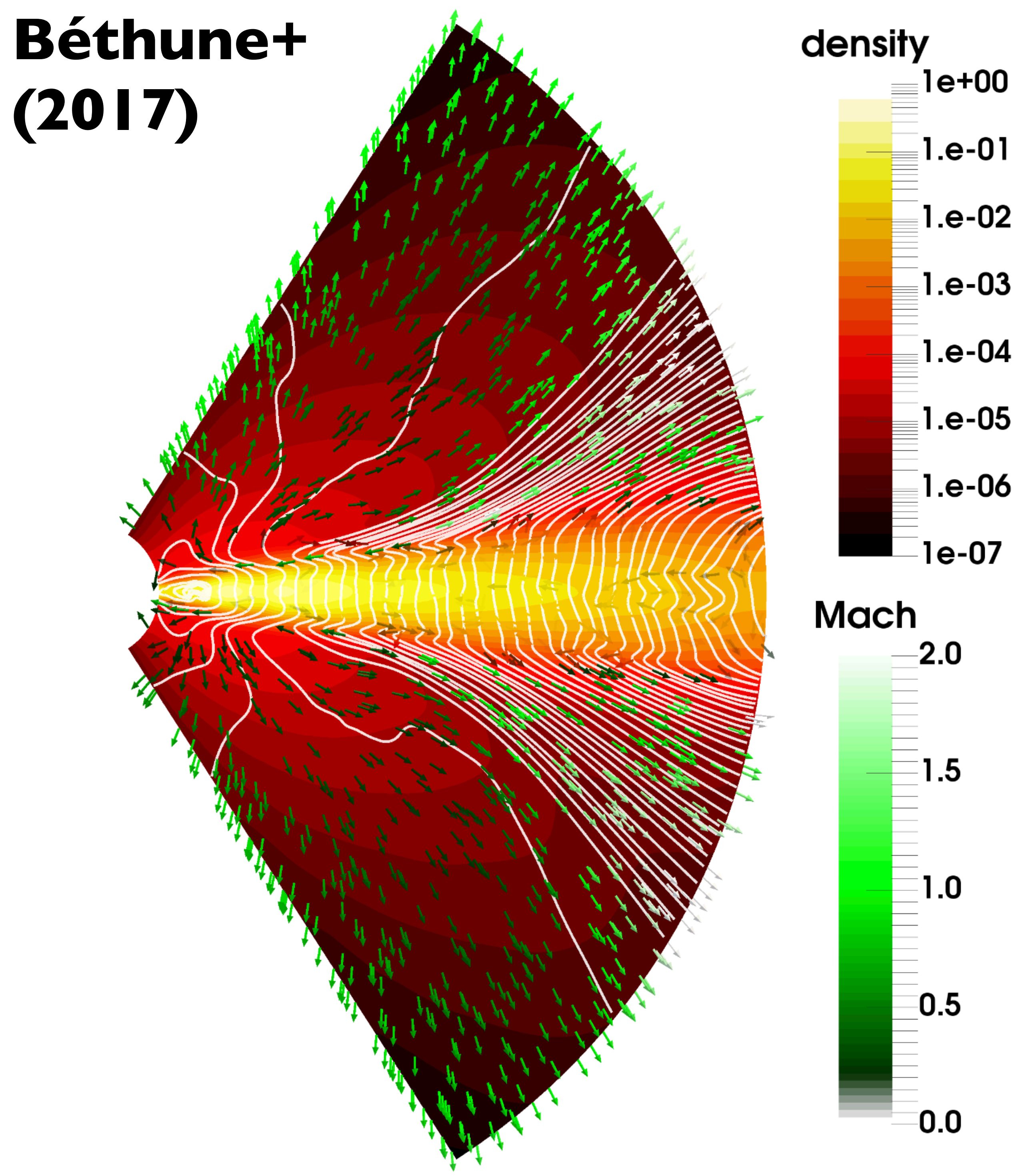


Flaherty+ (2024) - IM Lup

- Simulations now suggest that protoplanetary disc accretion is mainly wind-driven.
- Observationally, there is evidence for both turbulent and wind-driven accretion.
- Accretion alone cannot drive rapid disc dispersal; mass-loss in winds (either MHD or photoevaporative) is required.

Modern disc wind models





- Calculations are now relatively mature: different groups agree (more or less!?!) on wind properties ***for a given set of inputs***.
- Key physical uncertainties are ***irradiation*** and ***B-fields***.
- *These (probably) need to be determined observationally.*

Forthcoming papers from Nakatani+ & Sellek+

Disc winds: open questions

Photoevaporation

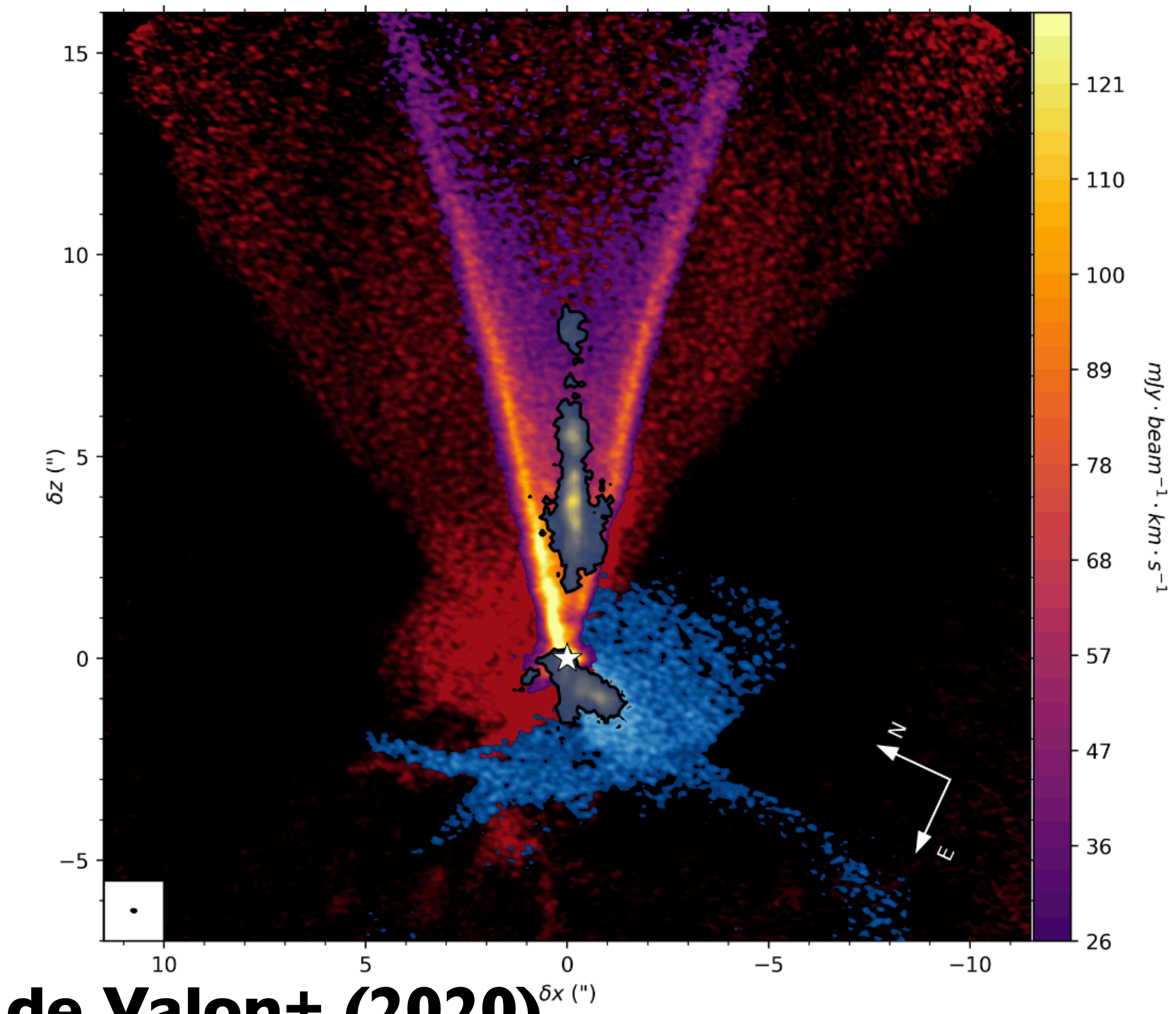
- What high-energy radiation field actually reaches the disc? (Flux and spectrum)
- Relative importance of internal vs external irradiation.
- How do these factors change with time? (Do we always have significant photoevaporation, or does it mainly occur at late times / in evolved discs?)

MHD winds

- What should the input B-field be? (Geometry; zero vs non-zero net flux; boundary conditions)
- What is the typical lever arm?
- How does the B-field change as the disc evolves / dissipates?
- Impact of environment?

Two time-scales = two ways to observe

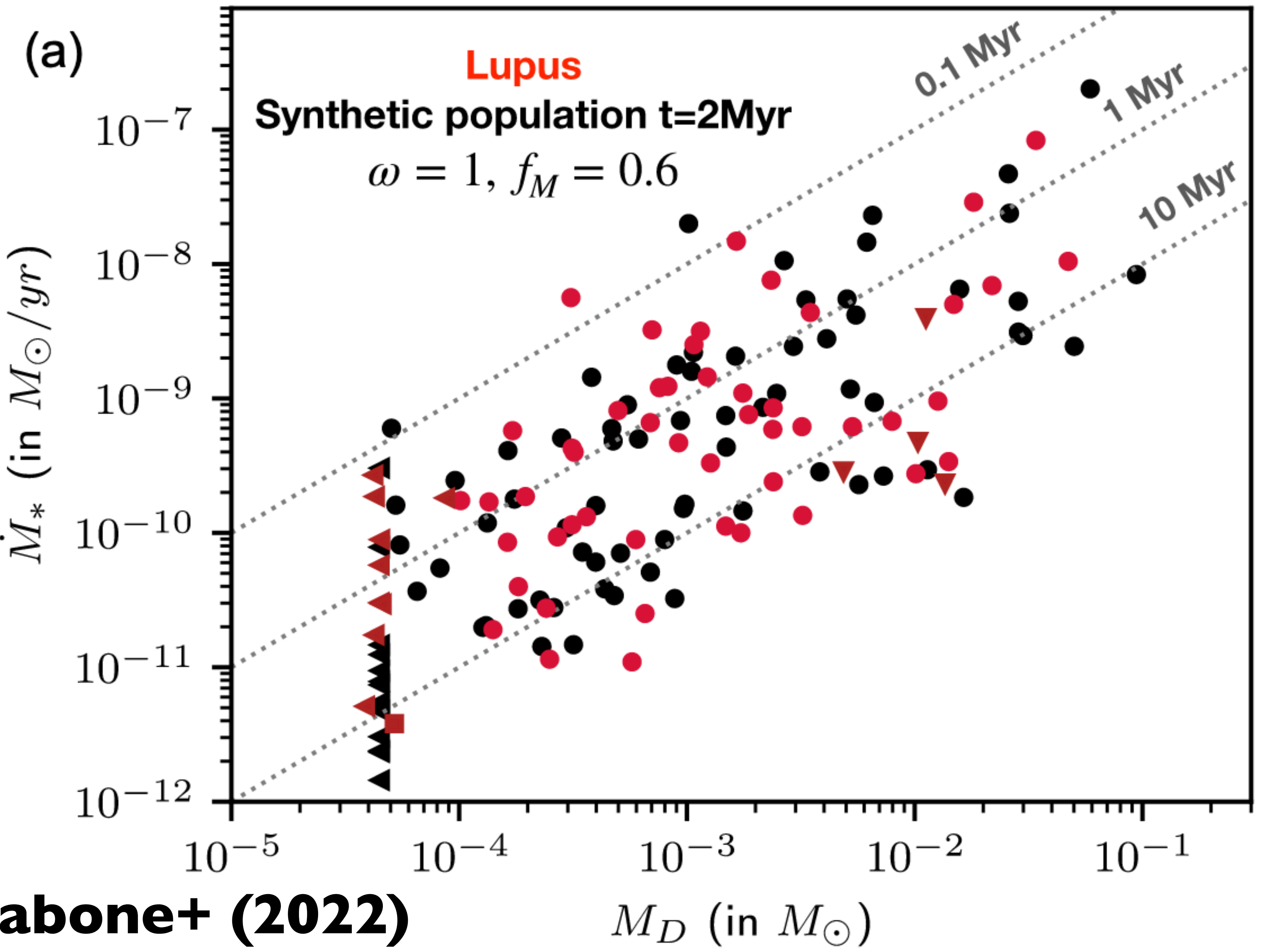
Instantaneous



de Valon+ (2020)

- Emission lines provide kinematic probes of disc & wind structure.
- Measure wind density, temperature & velocity directly.

Evolutionary



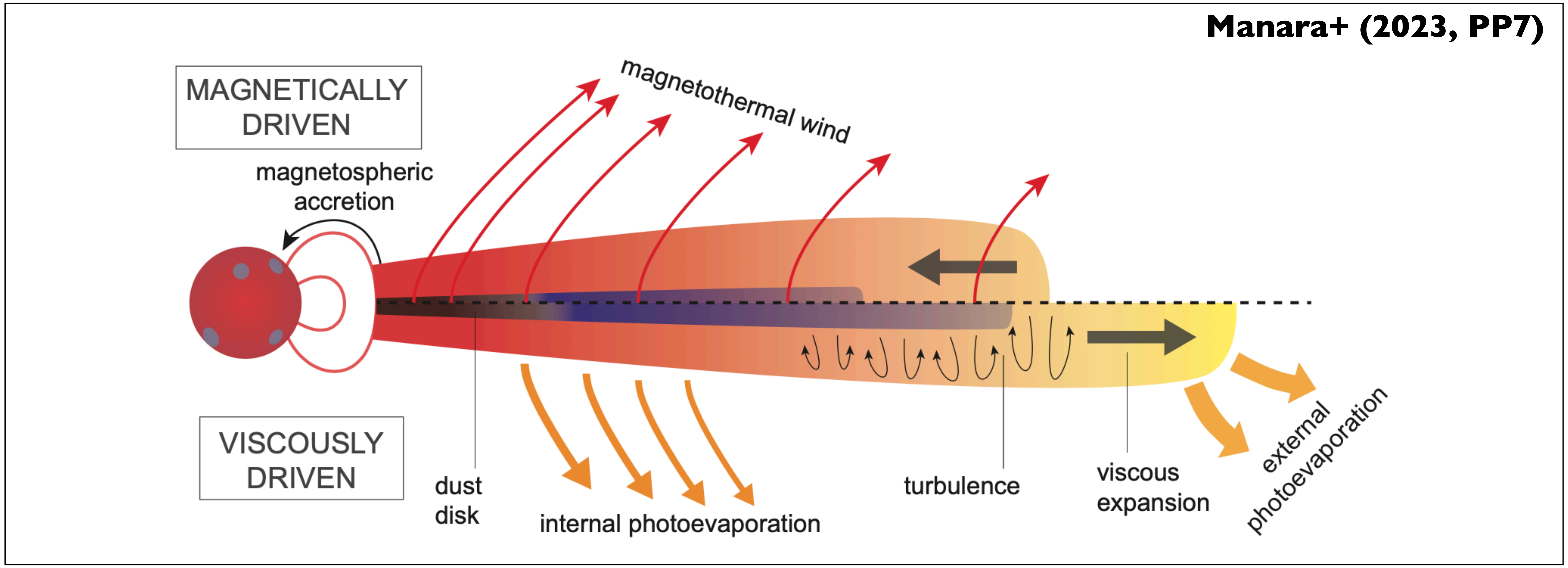
Tabone+ (2022)

- Demographics probe disc evolution on Myr timescales.
- Measure (sort of) time-averaged rates of mass and ang. mom loss.

[See also Benoît's talk!]

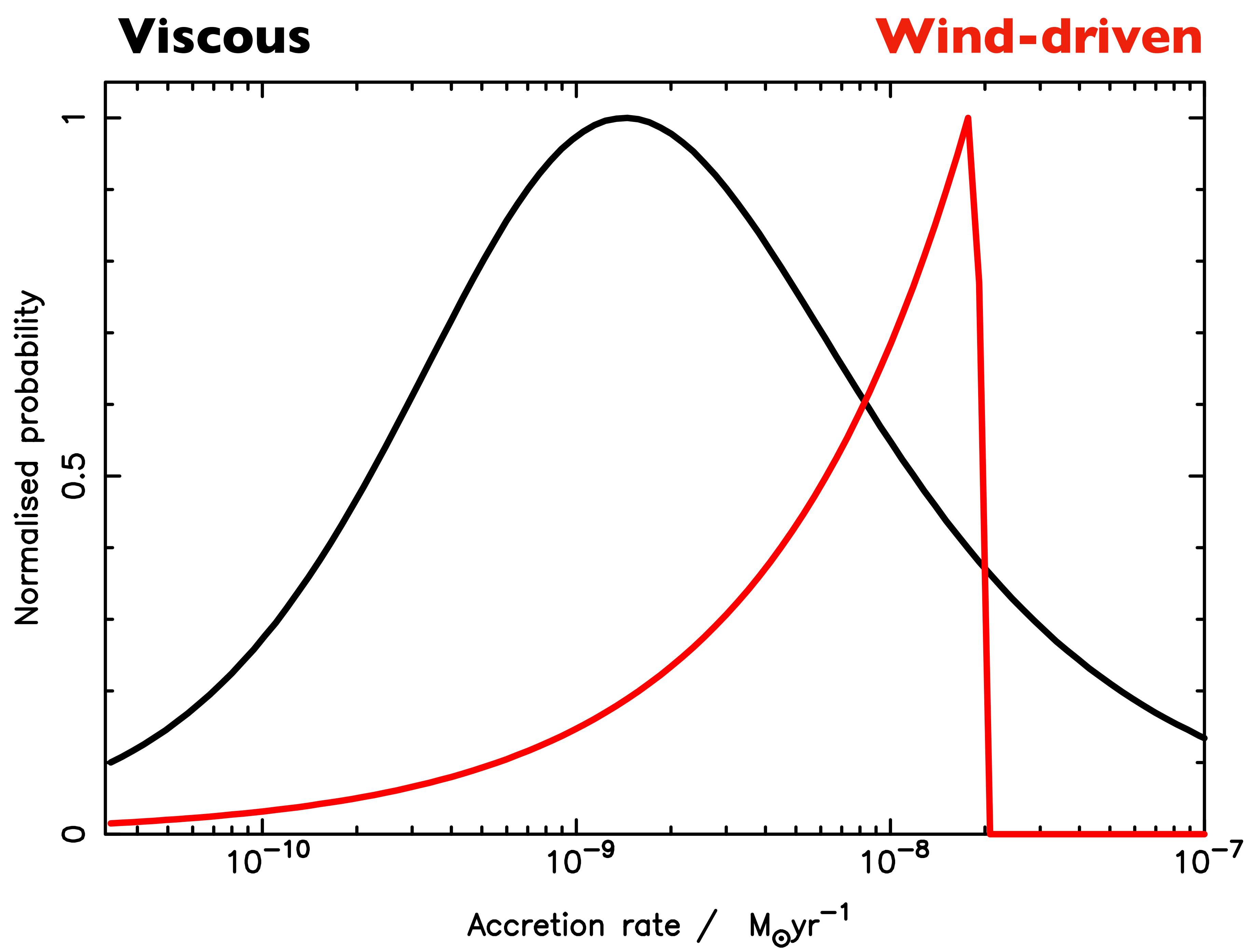
Accretion demographics

How do discs accrete?



- Two competing pictures of protoplanetary discs: turbulent vs wind-driven accretion.
- Still the dominant uncertainty in understanding disc dispersal.
- Observational evidence for both processes; in reality both may occur in different regions (or at different times) in the same disc.
- Can we tell which (if any) is the dominant mode of accretion?

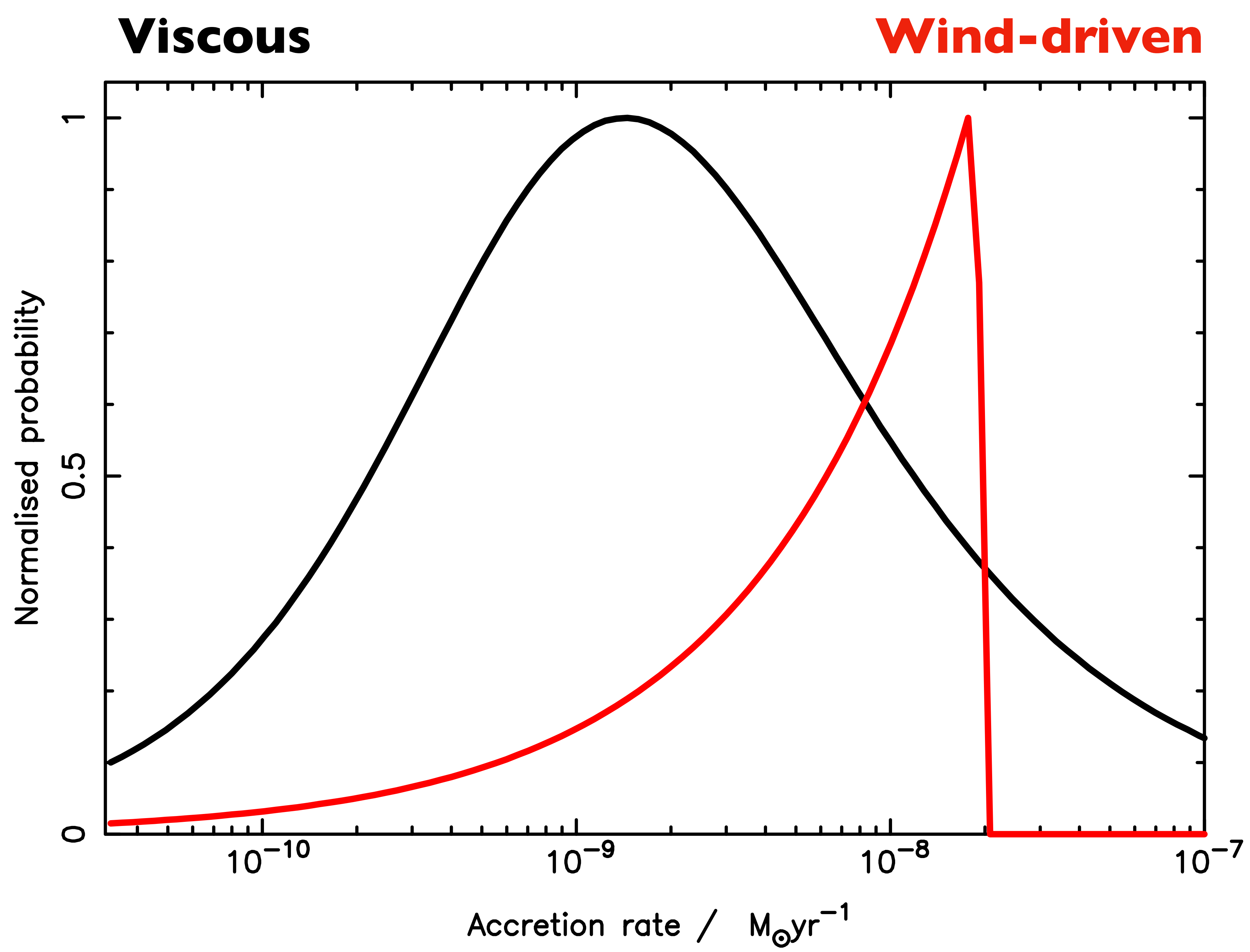
A statistical look at accretion rates

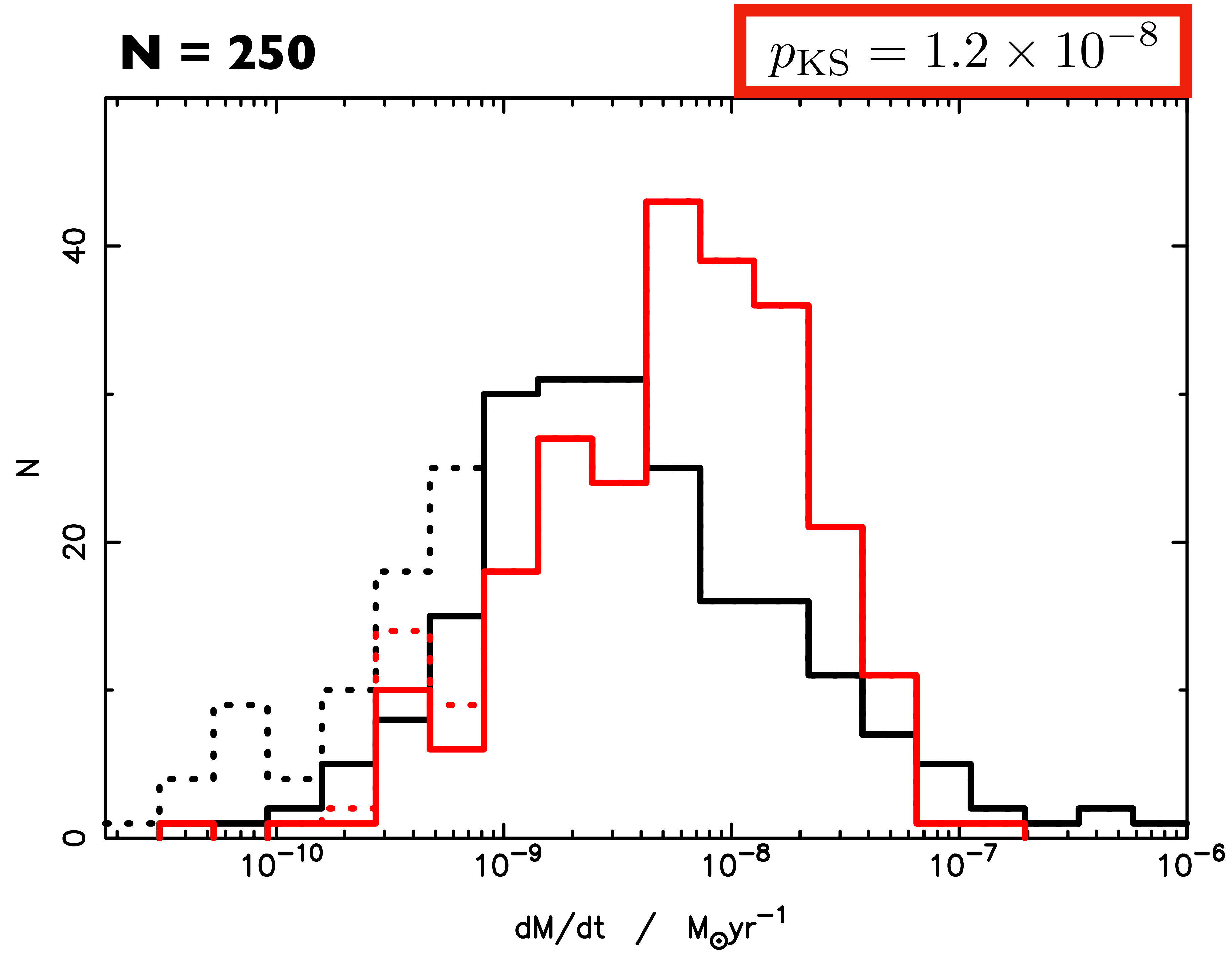


See also Somigliana+ (2023); Weder+ (2023), etc.

RDA+ (2023)

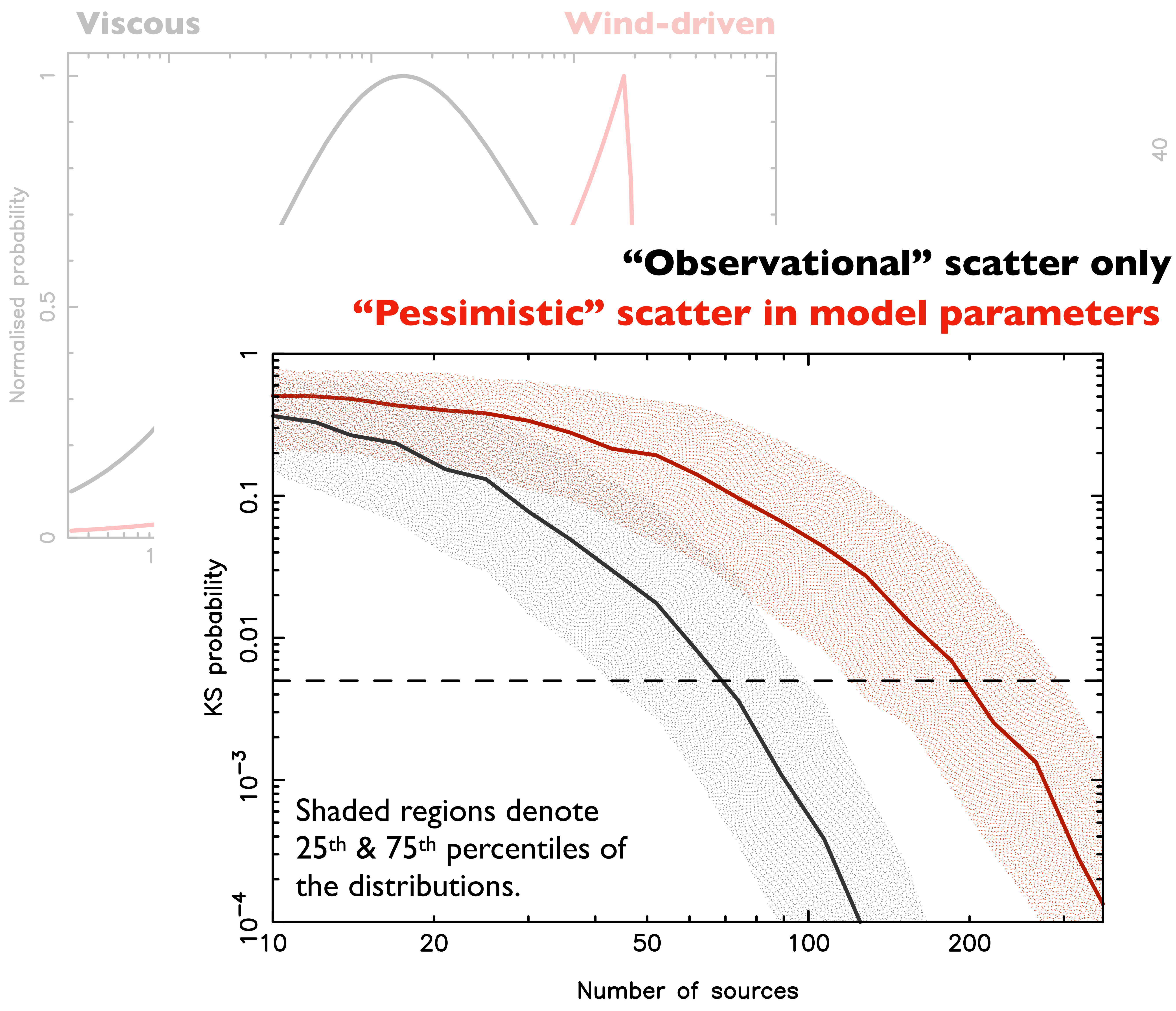
A statistical look at accretion rates

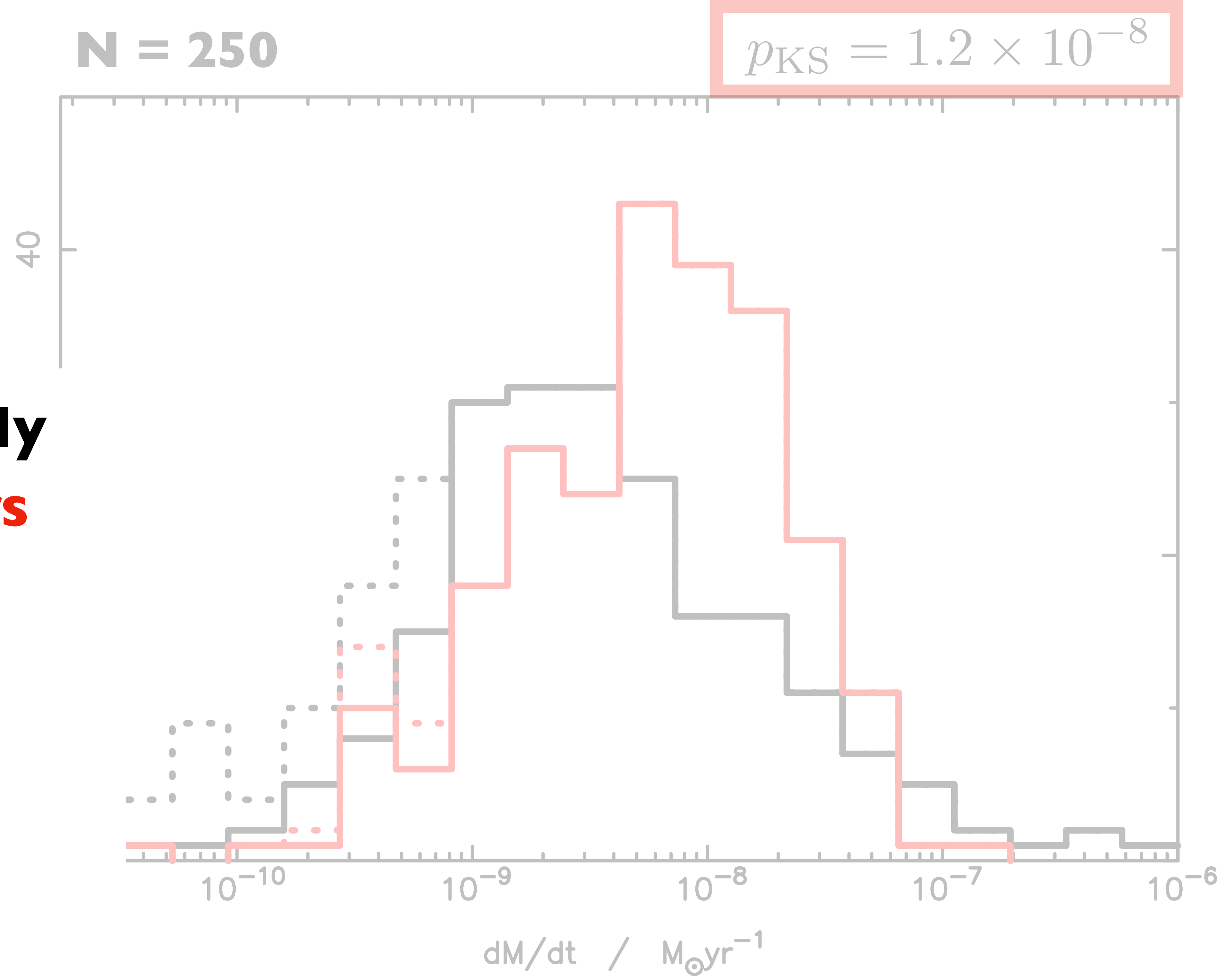




RDA+ (2023)

A statistical look at accretion rates

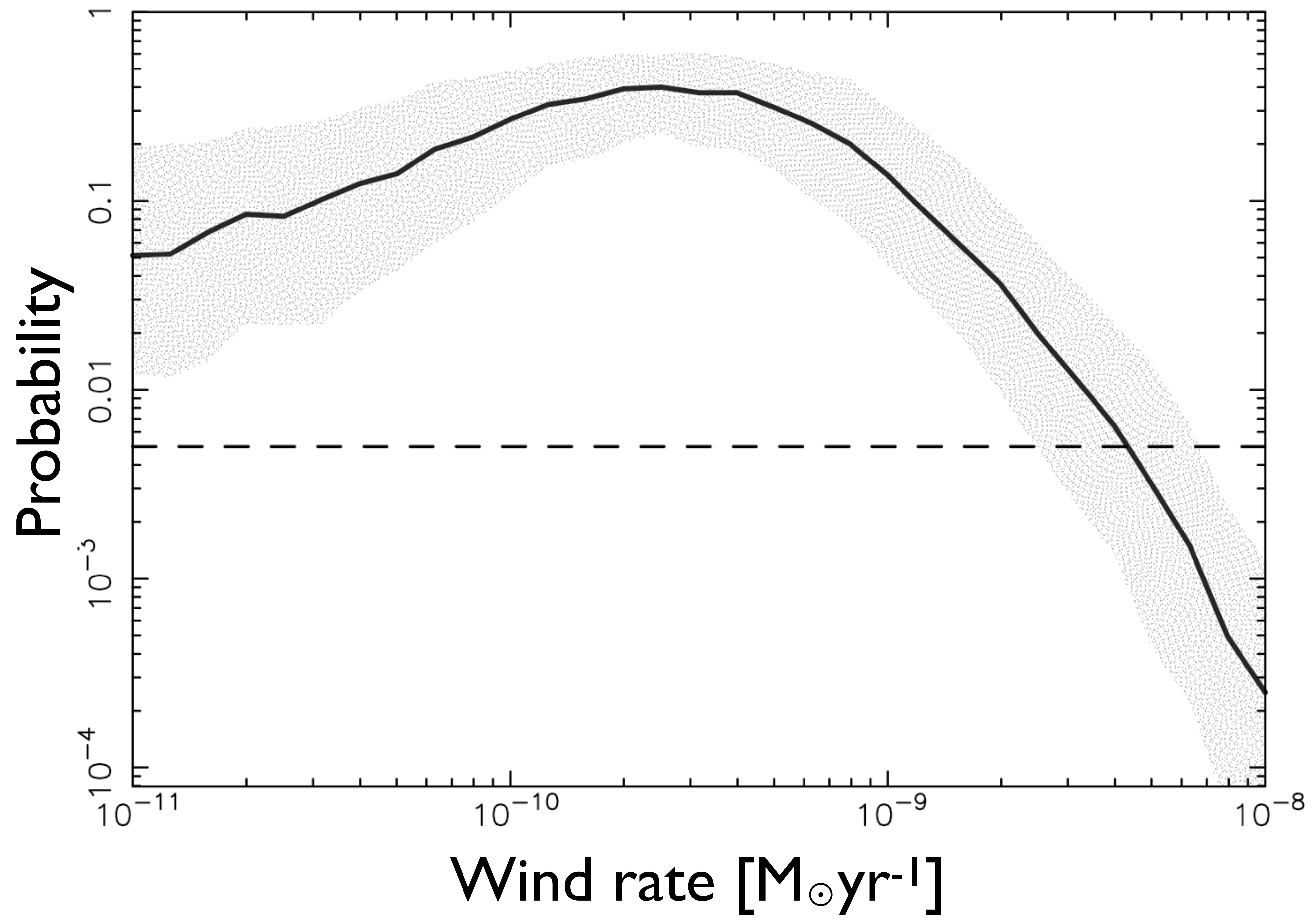


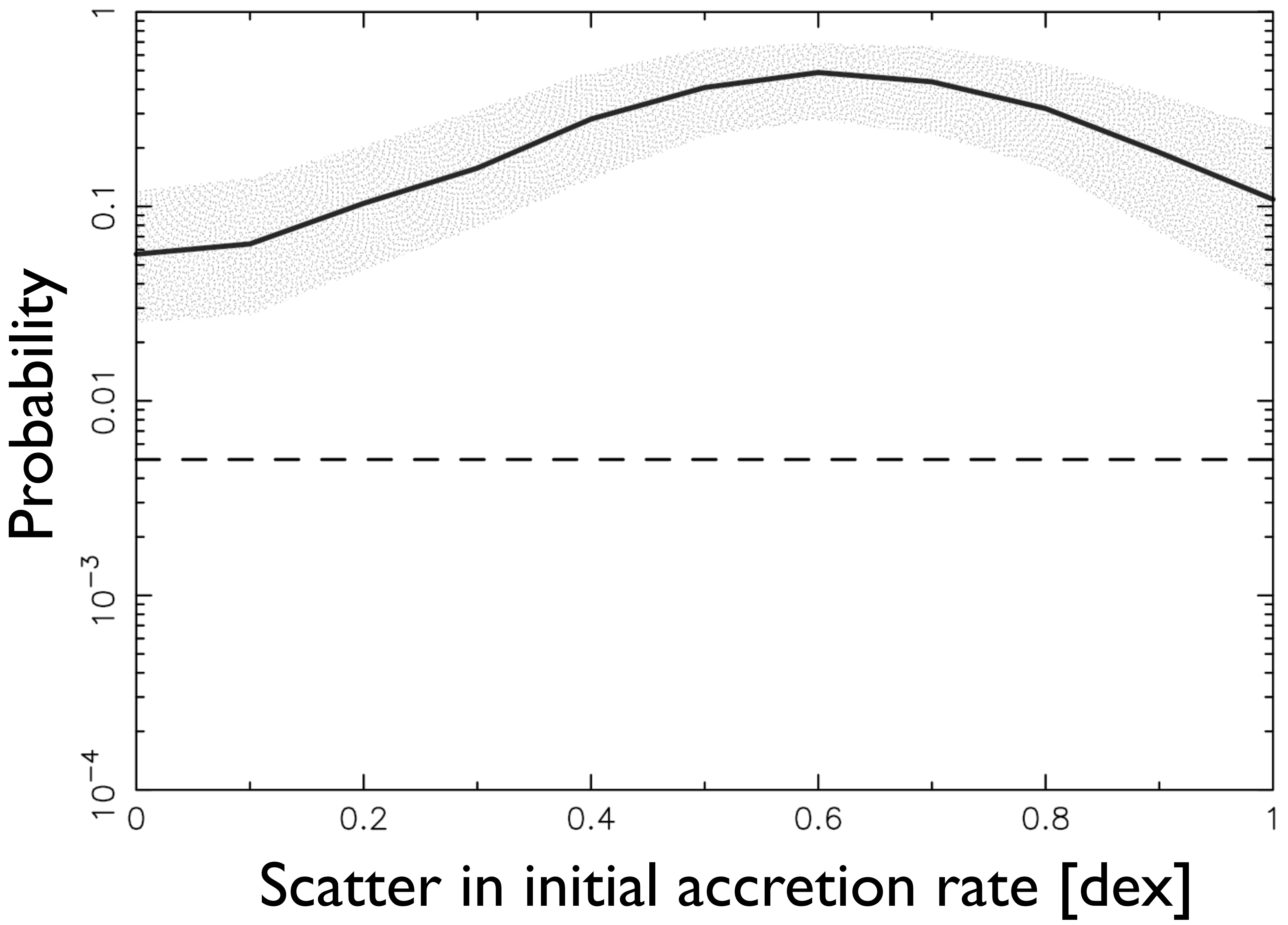


~300 objects with measured accretion rates should be(!) enough to distinguish between these models.

RDA+ (2023)

A statistical look at accretion rates



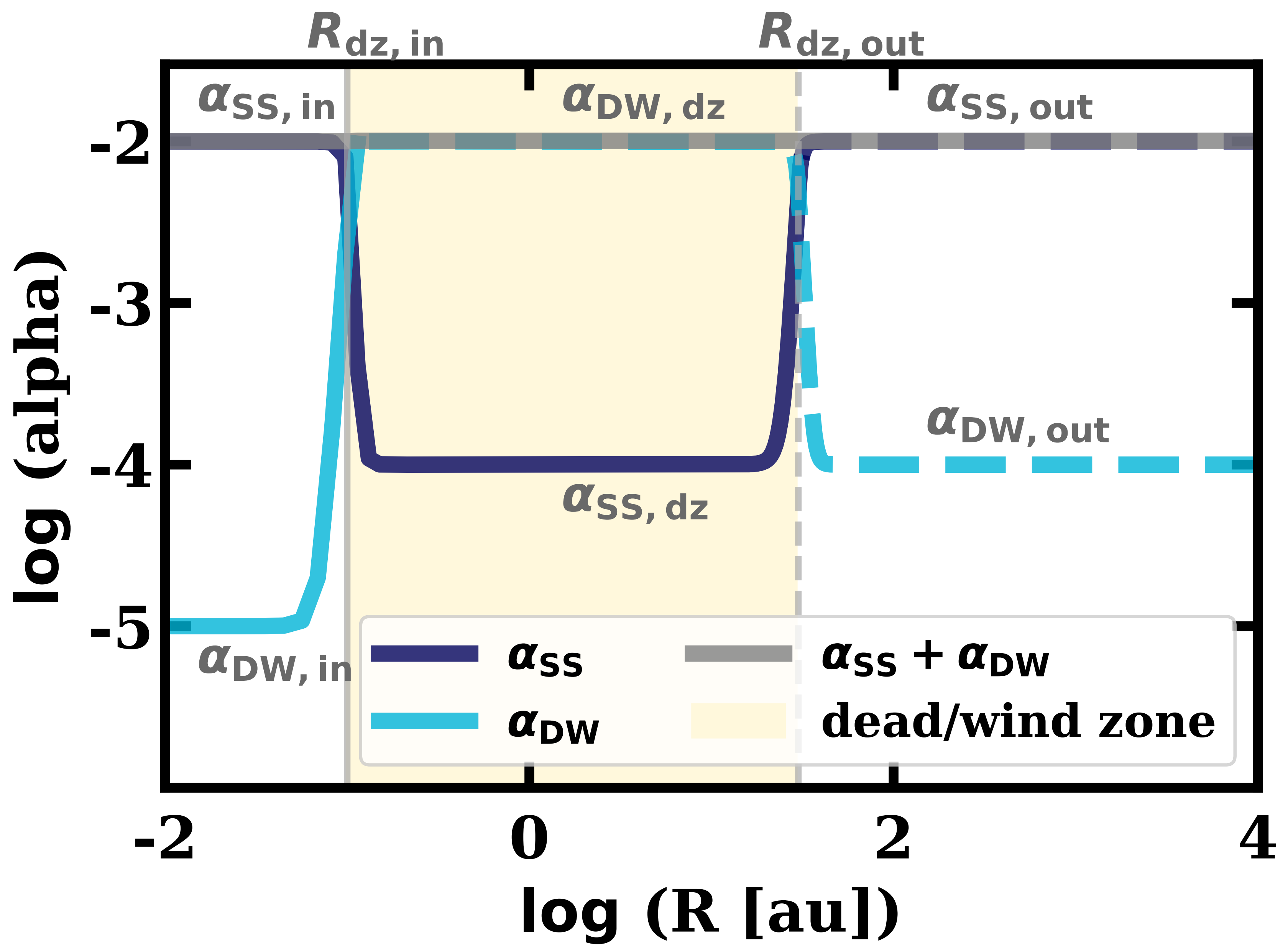


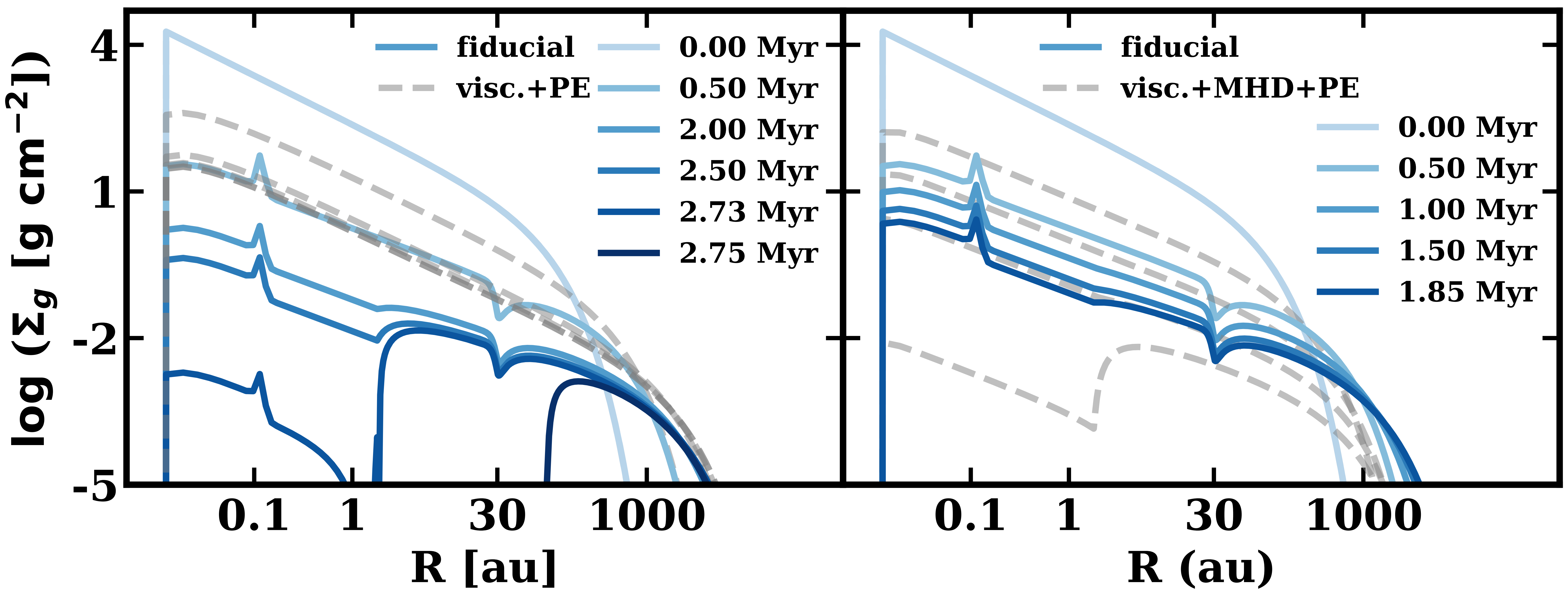
- Current sample sizes are ~100 objects, so accretion rate observations do not (yet) distinguish between wind-driven and viscous accretion (both models fit).
- Statistically significant preference for lower photoevaporation rates.
- Additional observables can break degeneracies (e.g., AGE-PRO & DECO surveys), but also introduce more systematics (disc masses, etc.).

RDA+ (2023)

Turbulent ~~or~~ ***and*** wind-driven accretion

Tong+ (submitted)

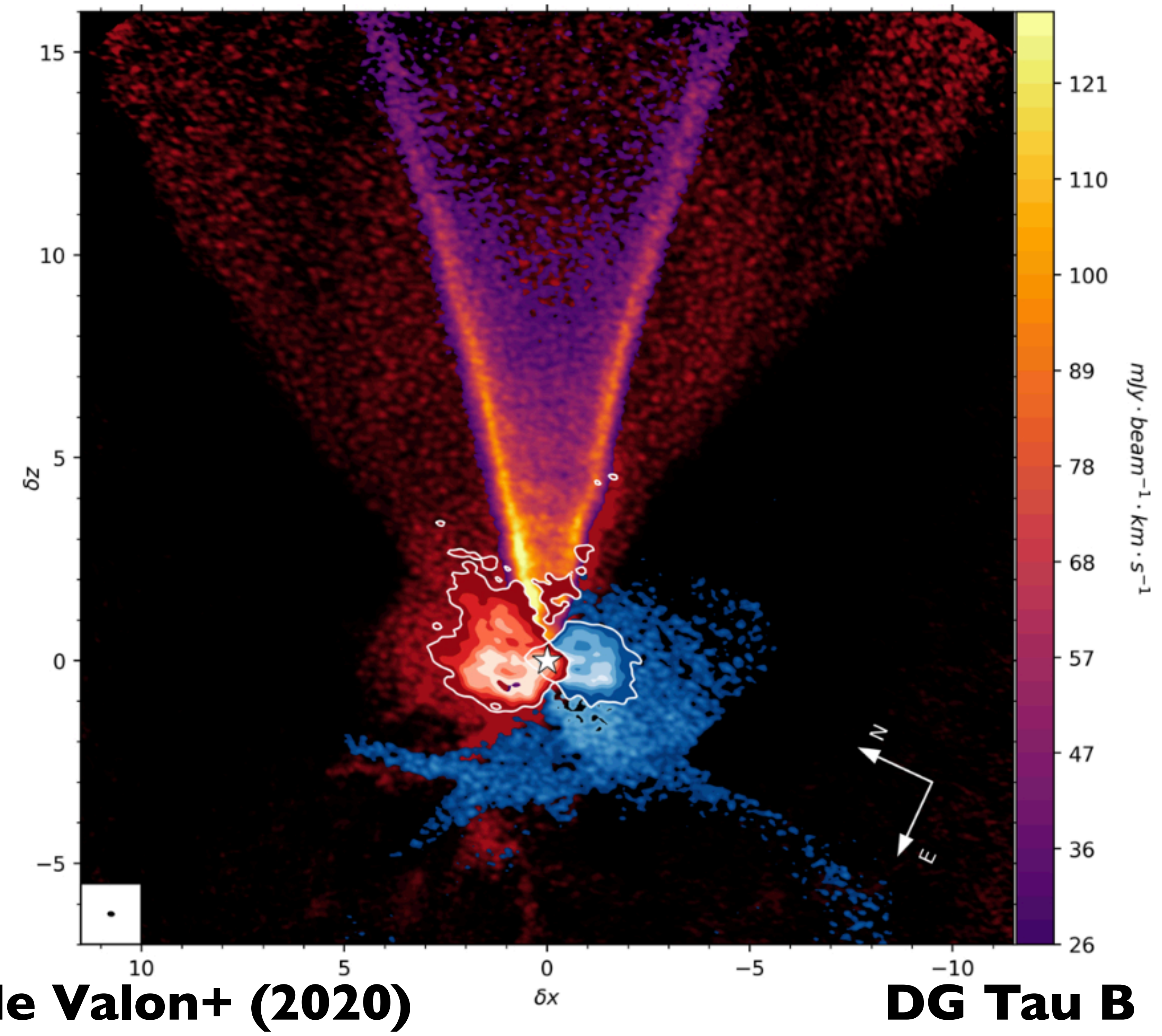




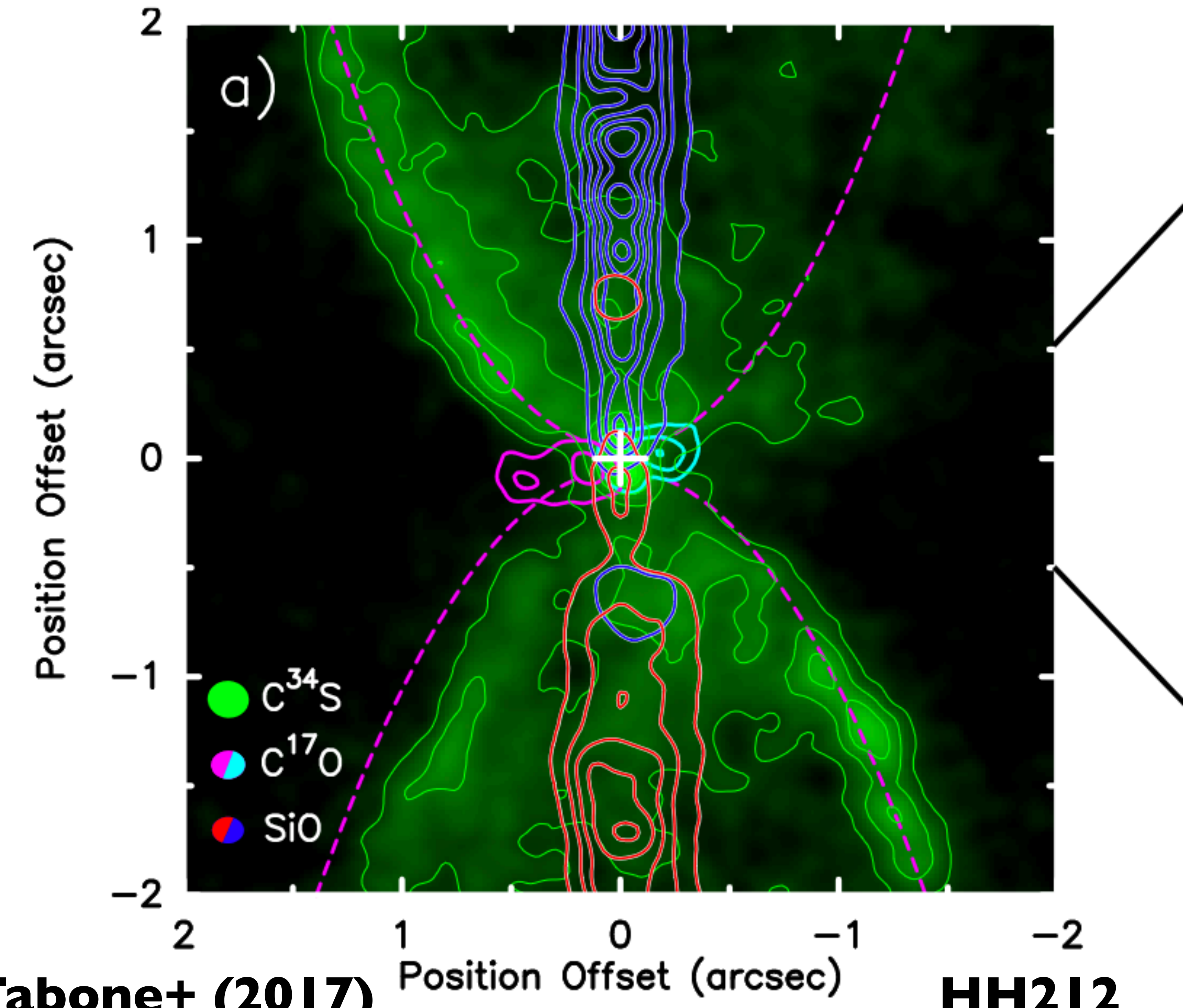
- New "hybrid" disc evolution models, which incorporate viscous accretion, MHD winds, and photoevaporation in different regions of the disc.
- Interplay is complex, with some surprising results - paper will be on arXiv soon!

Observations of disc winds

Resolved winds/outflows in CO



de Valon+ (2020) **DG Tau B**



Tabone+ (2017) **HH212**

- ALMA allows us to map molecular jets/outflows: measure density, velocity / rotation profiles, etc.
- Must be magnetically launched, and mass loss rates are ***high***.
- Thus far the well-characterised sample is mostly Class 0/I discs; not many Class IIs yet…

Blue-shifted emission in atomic lines…

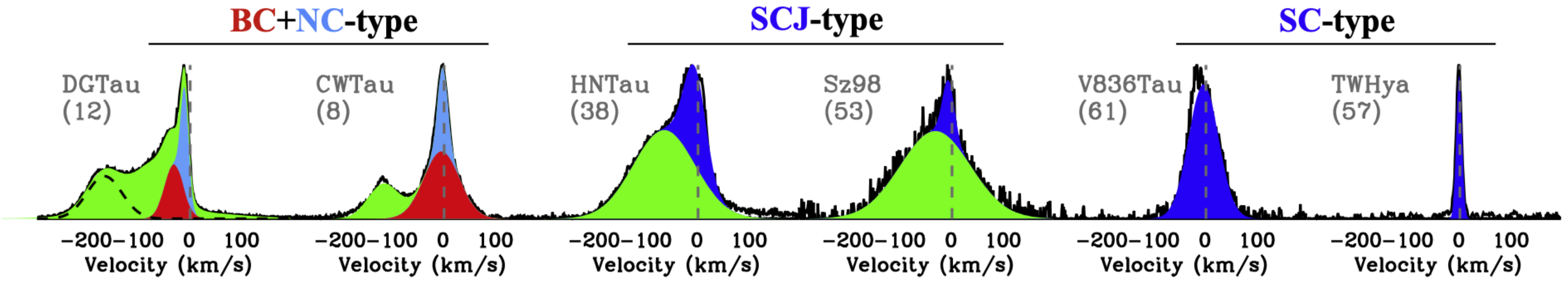
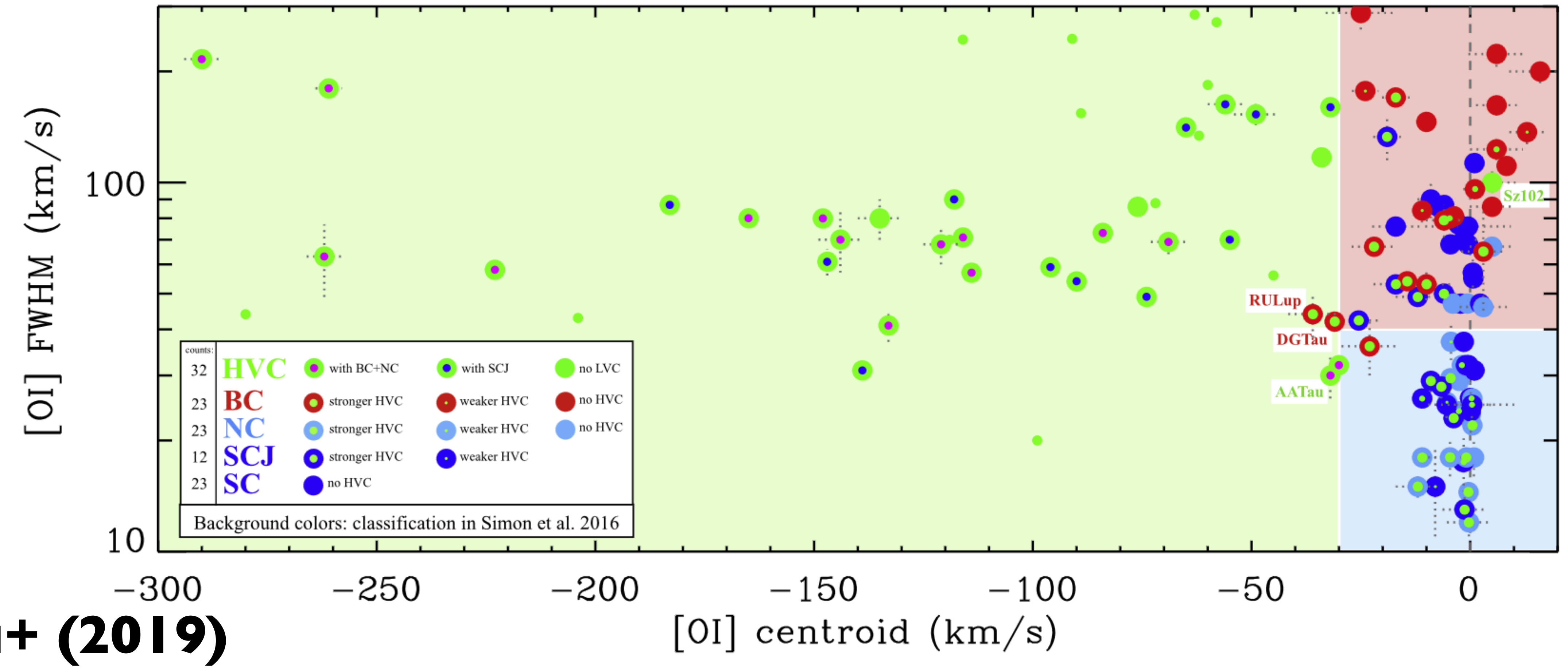


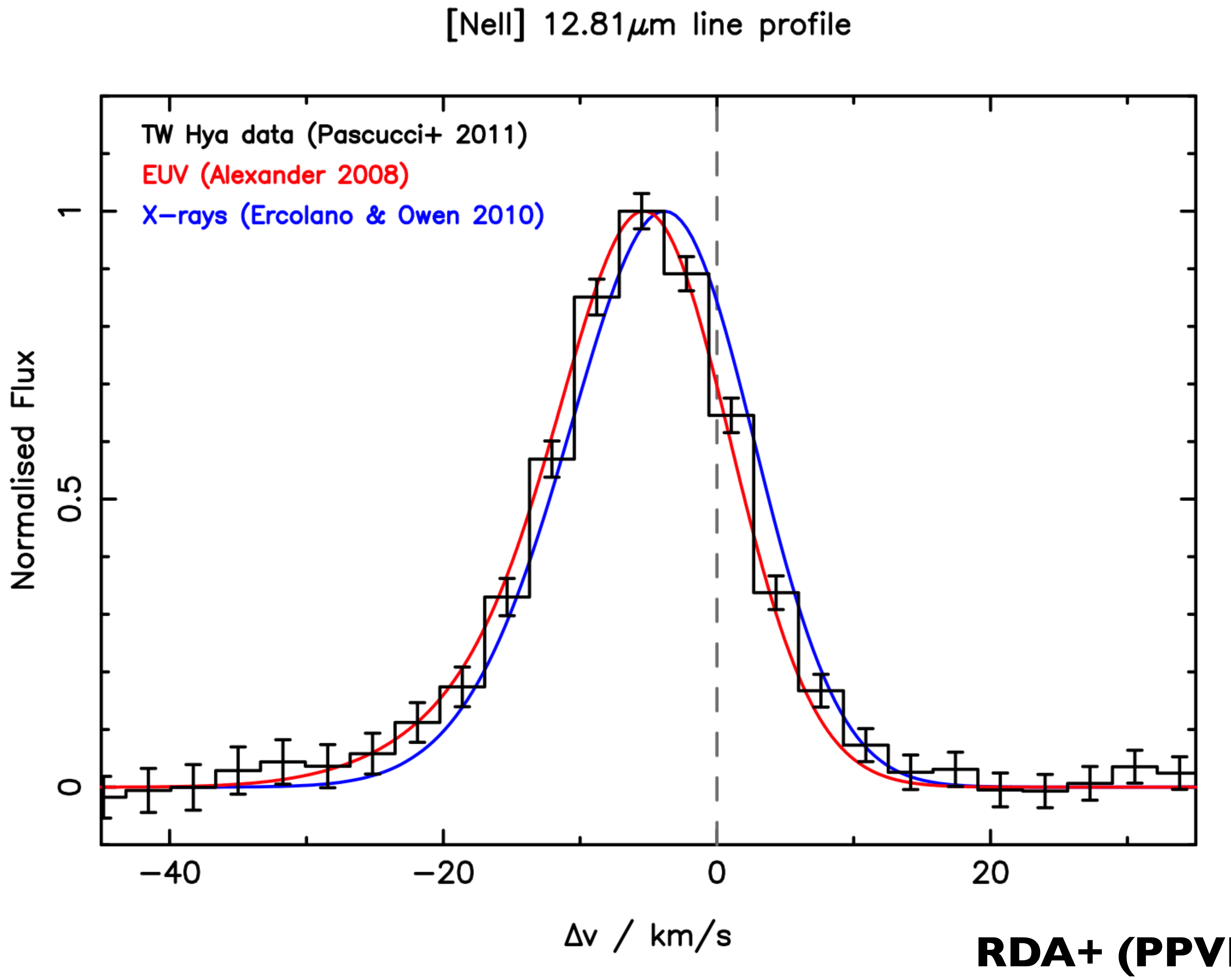
Figure 2. Representative examples of [O I] line profiles, showing “BC+NC”-type LVC (DG Tau and CW Tau), “SCJ”-type LVC (HN Tau and Sz 98), and “SC”-type LVC (V836 Tau and TW Hya) by color-coding their HVC and LVC components as described in Section 3.3: HVCs are in green, LVC-BC are in red, LVC-NC in light blue, and LVC-SC and SCJ in dark blue. Line profiles for the entire sample are shown in Appendix A. Where multiple are present, we mark with a dashed black line the most blueshifted HVC component used in the analysis.



Banzatti+ (2019)

- Large samples of spatially unresolved observations (e.g., in [OI]).
- Low-velocity components (LVCs) divide into broad and narrow components.
- Broad LVCs probably magnetic origin; narrow LVCs uncertain.

…and in ionized lines

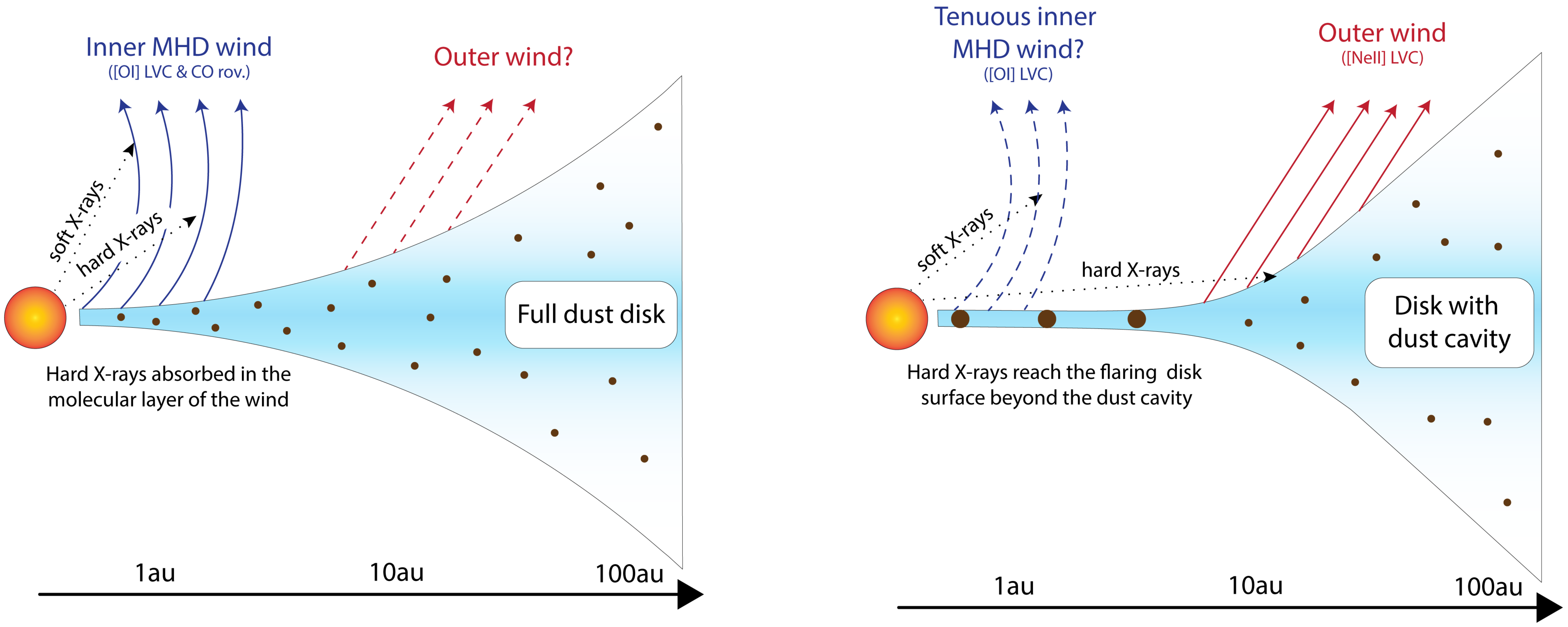


RDA+ (PPVI)

- Blue-shifted [NeII] emission ($\Delta v \sim 10\,\mathrm{km\,s^{-1}}$) observed from several nearby discs (e.g., Pascucci+ 2009; Sacco+ 2012).
- Unambiguous detection of a slow, ionized wind.

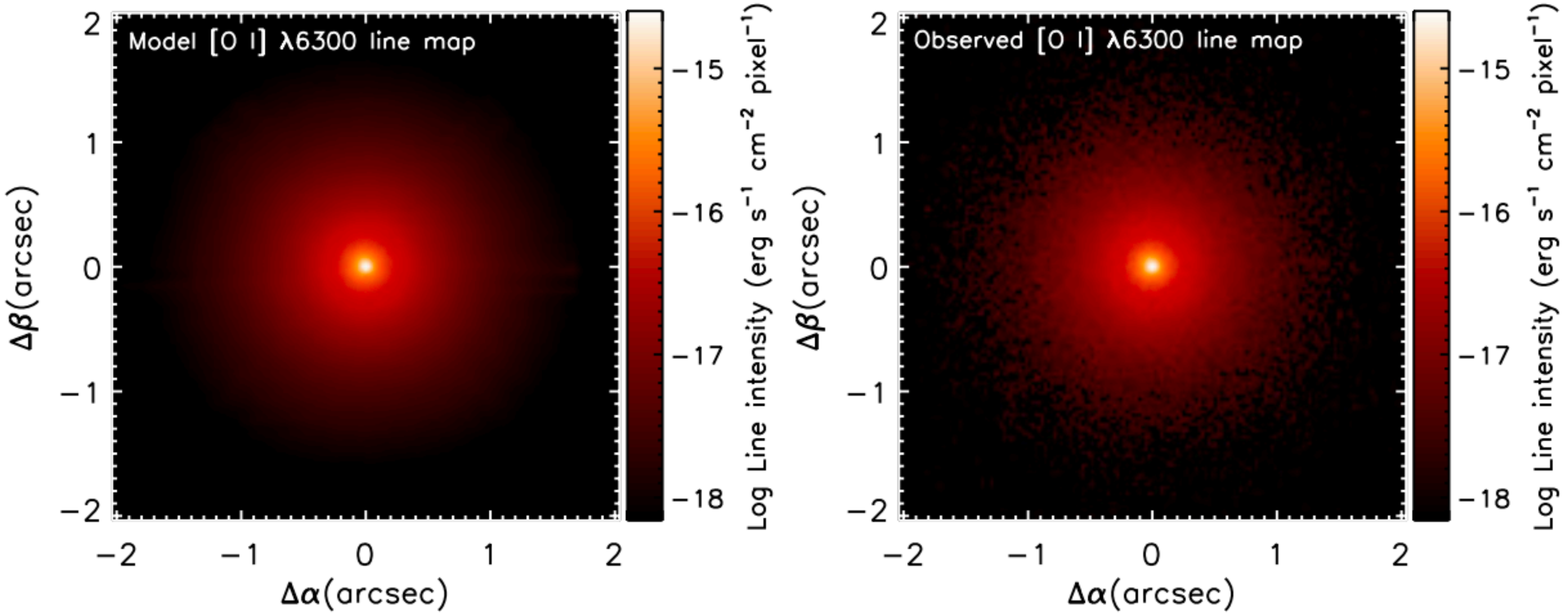
An evolutionary sequence(?)

Pascucci+ (2020)



Spatially-resolved line emission

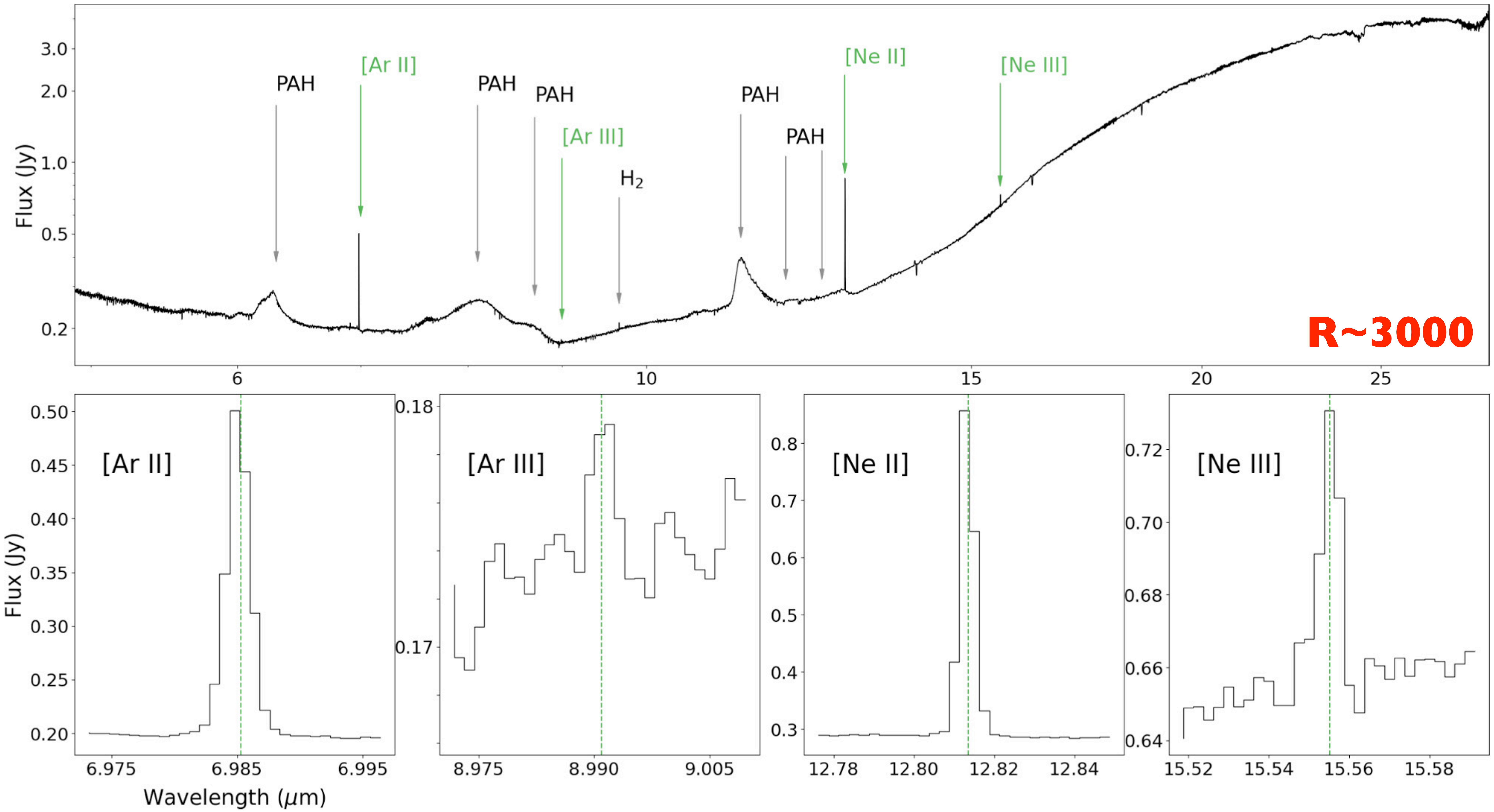
Fang+ (2023)



- VLT-MUSE IFU observation of [OI] 6300Å line in TW Hya.
- Line shows a small blue-shift (0.8km/s), and 80% of the [OI] flux comes from within 1AU of the star.
- Consistent with a simple magnetothermal wind model; difficult to reconcile with photoevaporation (but see Rab+ 2023).

JWST-MIRI observations of T Cha

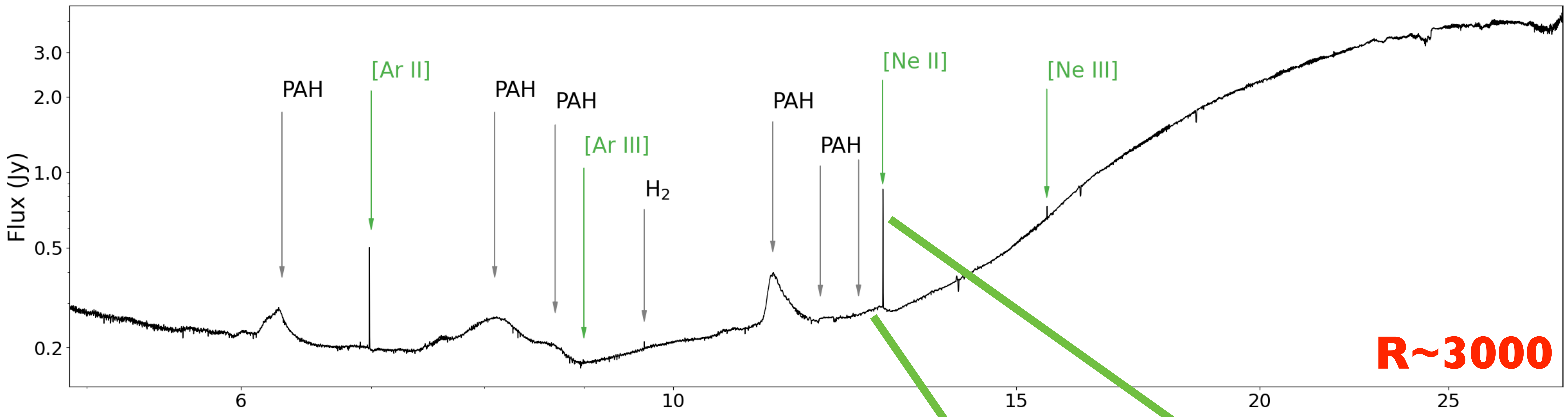
Bajaj+ (2024)

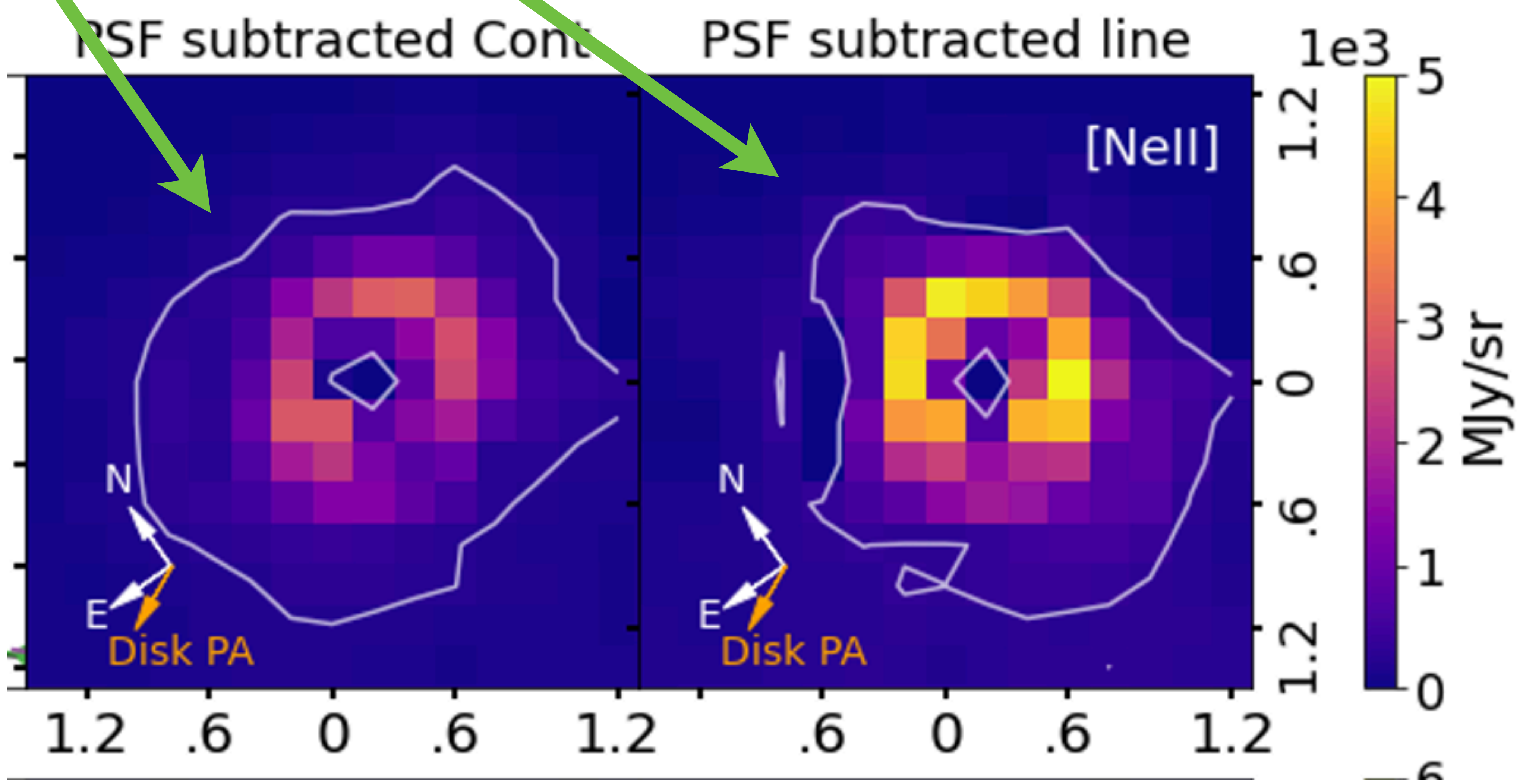


- First detection of four noble gas forbidden lines in a disc.

JWST-MIRI observations of T Cha

Bajaj+ (2024)

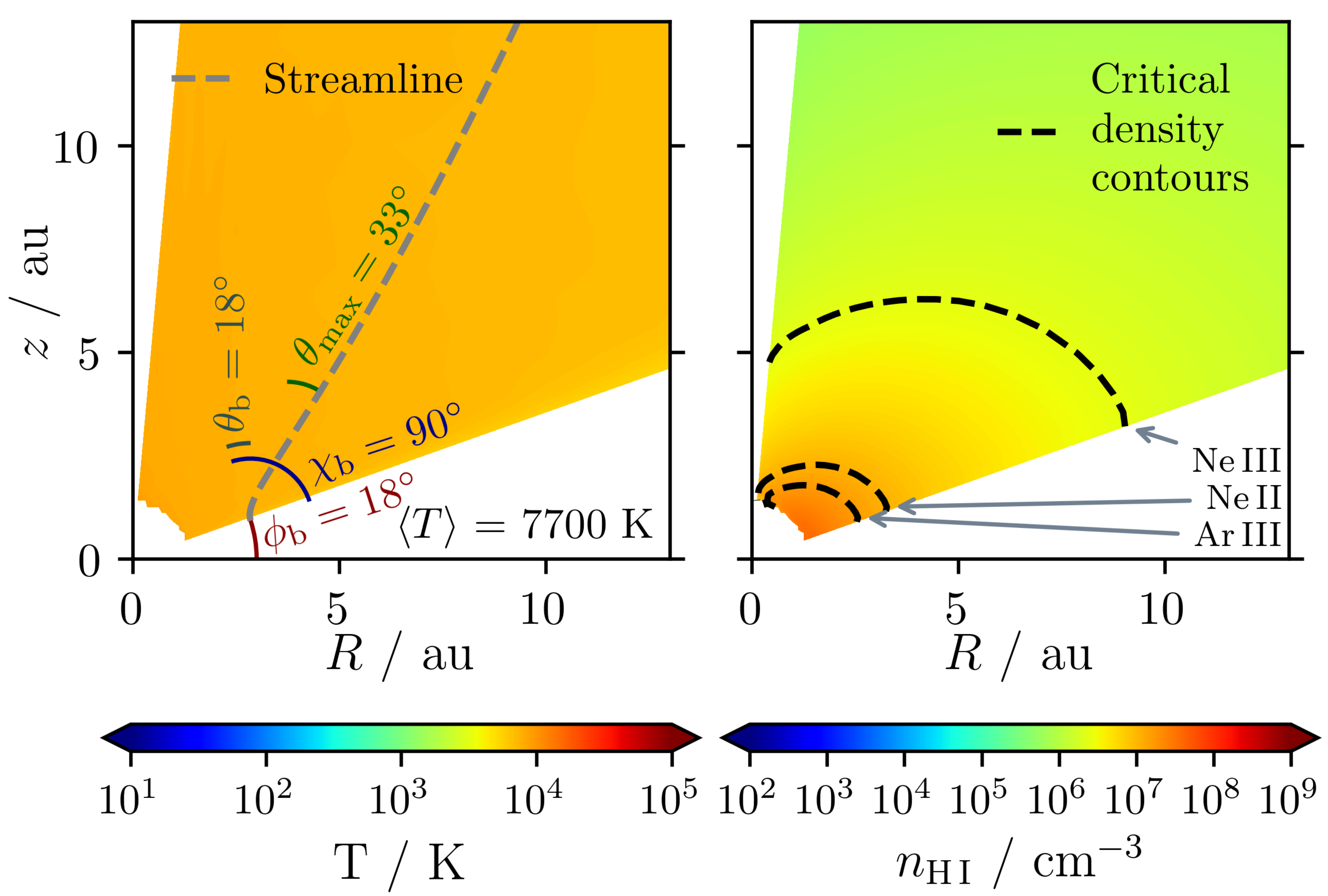


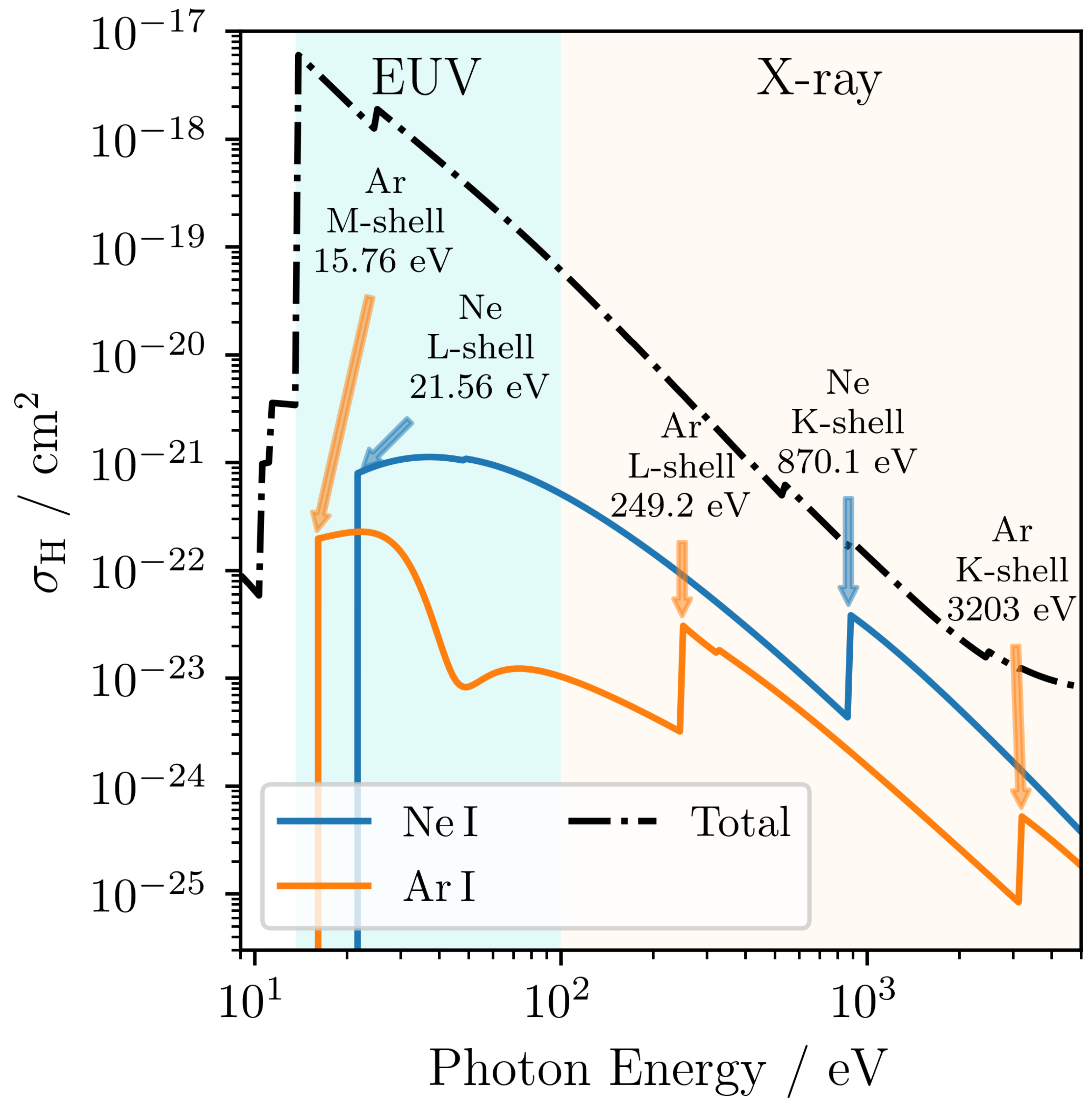


- [NeII] emission is (just!) spatially resolved with the MIRI IFU.
- Line extended in a different direction to the continuum.
- Spatial extent + multiple different lines strongly constrain density and temperature in the wind.

Modelling the line emission

Sellek+ (2024)

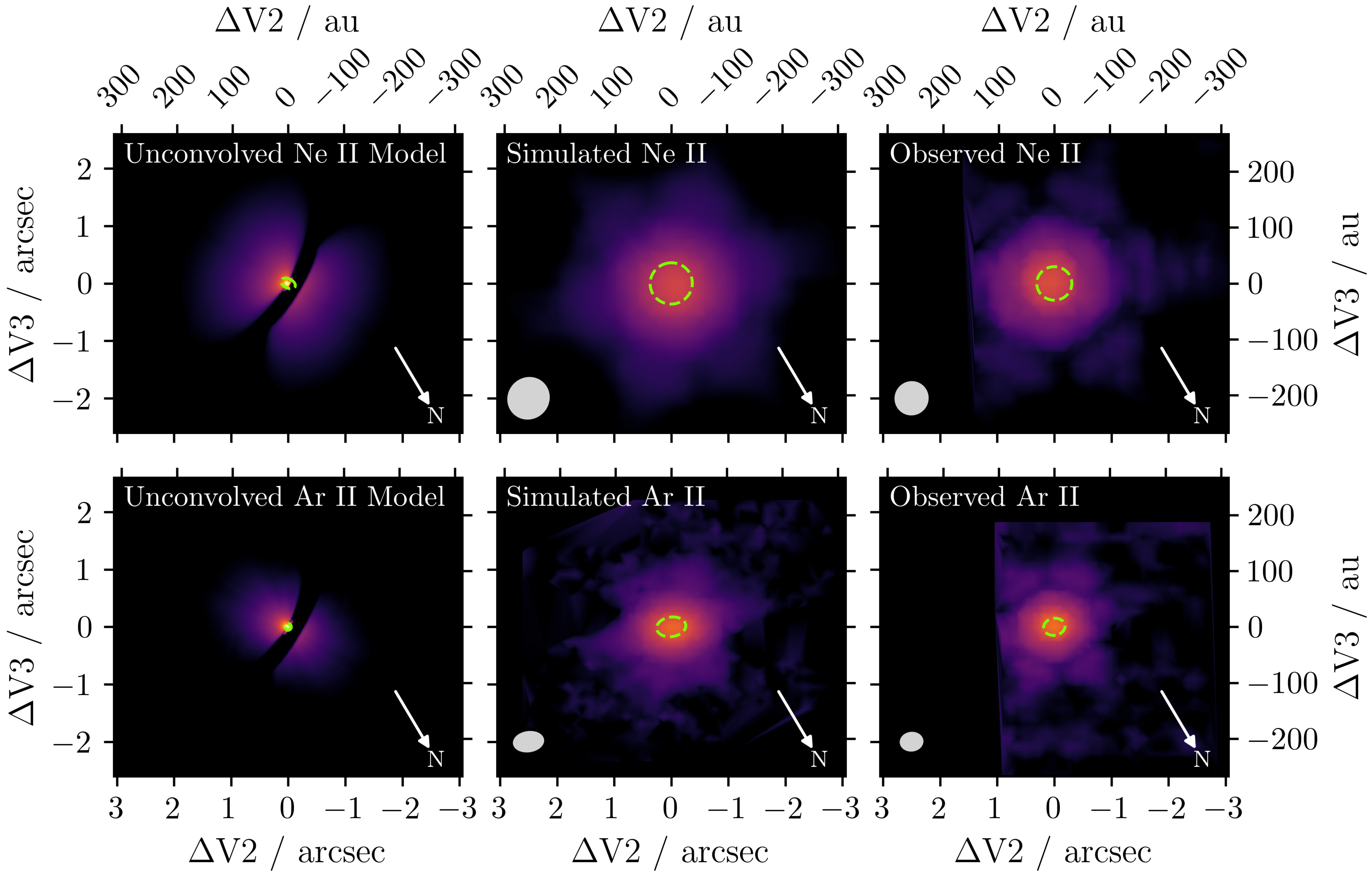




- Analytic disc wind model + Monte Carlo radiative transfer.
- Aim to match line ratios, blue-shifts ***<u>and</u>*** spatial emission maps.
- Line ratios require a hard(ish) spectrum, with more X-rays than UV.

Modelling the line emission

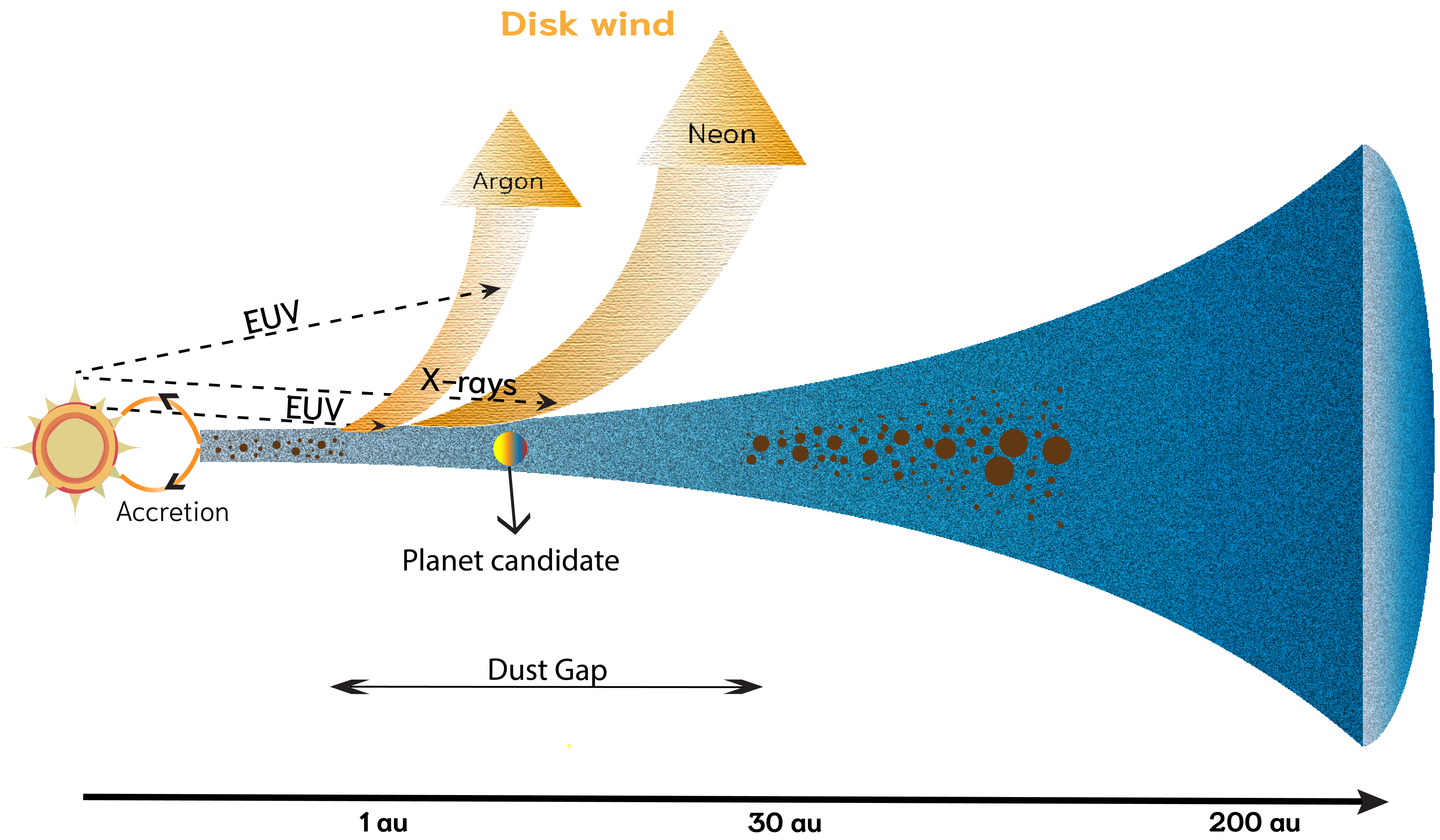
Sellek+ (2024)



- Resolving [NeII] but not [ArII] requires quite specific parameters.
- Reproducing all diagnostics simultaneously requires low ionization in the wind, inner radius ~1AU, and relatively high mass-loss rates.

T Cha: summary

Bajaj+ (2024), Sellek+ (2024)



- Measured wind properties (especially R_{in} ~ 1AU) are consistent with expectations for photoevaporation (with a fairly high wind rate).
- MHD wind not ruled out, but not required to explain the data.
- Only one disc; larger samples are coming…

Disc dispersal: summary & open questions

- **Disc dispersal has important consequences for planetesimals**
- **Accretion physics remains the dominant uncertainty**
  [If accretion is wind-driven, then many of our models of planetesimal formation (and planet migration) are incomplete, or just wrong.]
- **Disc evolution is gradual, but disc dispersal happens suddenly**
- **Disc evolution & dispersal depend on the stellar environment**
  [How much can we learn from studying nearby regions like Lupus or Taurus if most planets form in regions like Orion?]
- We are moving into an era where we can observe disc winds directly, and where we can study disc populations statistically.