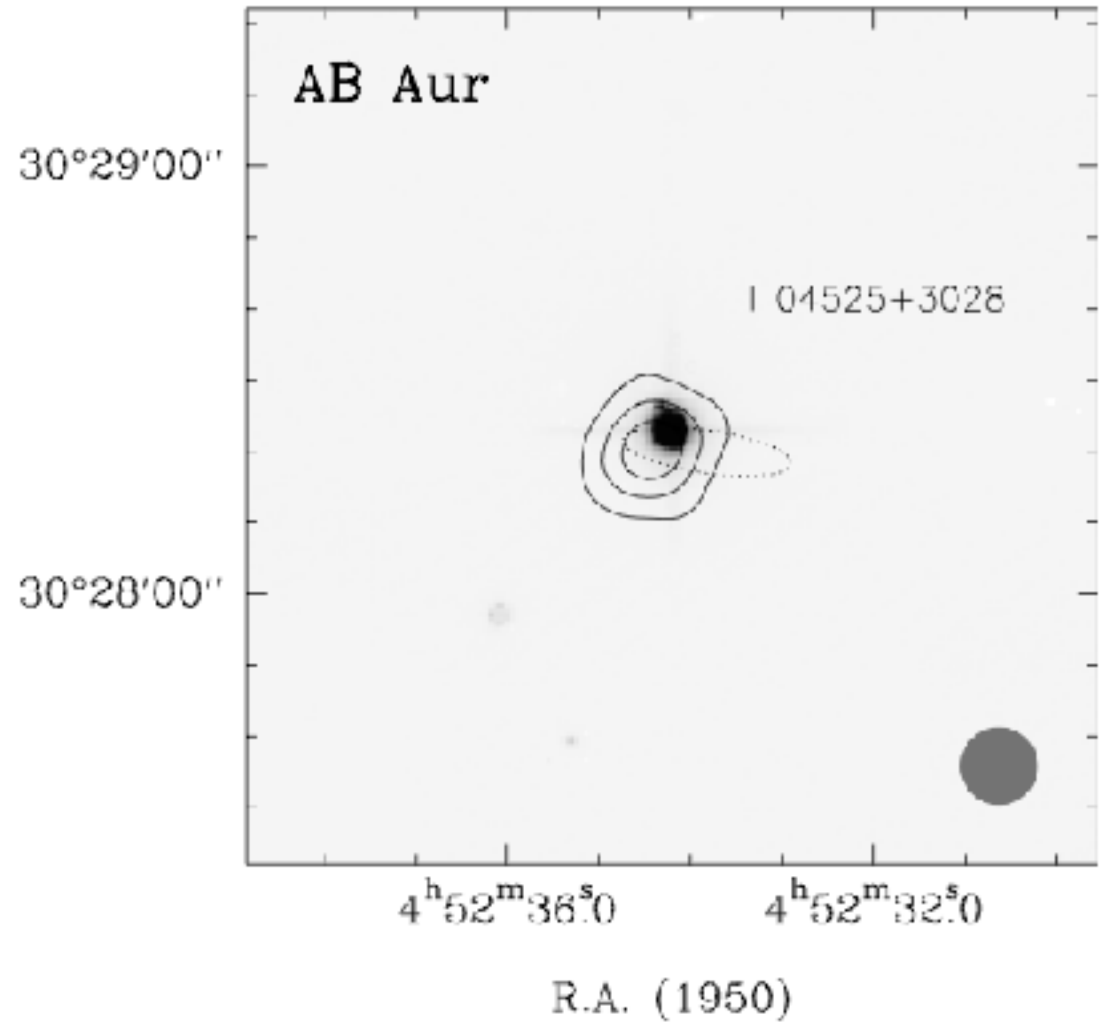
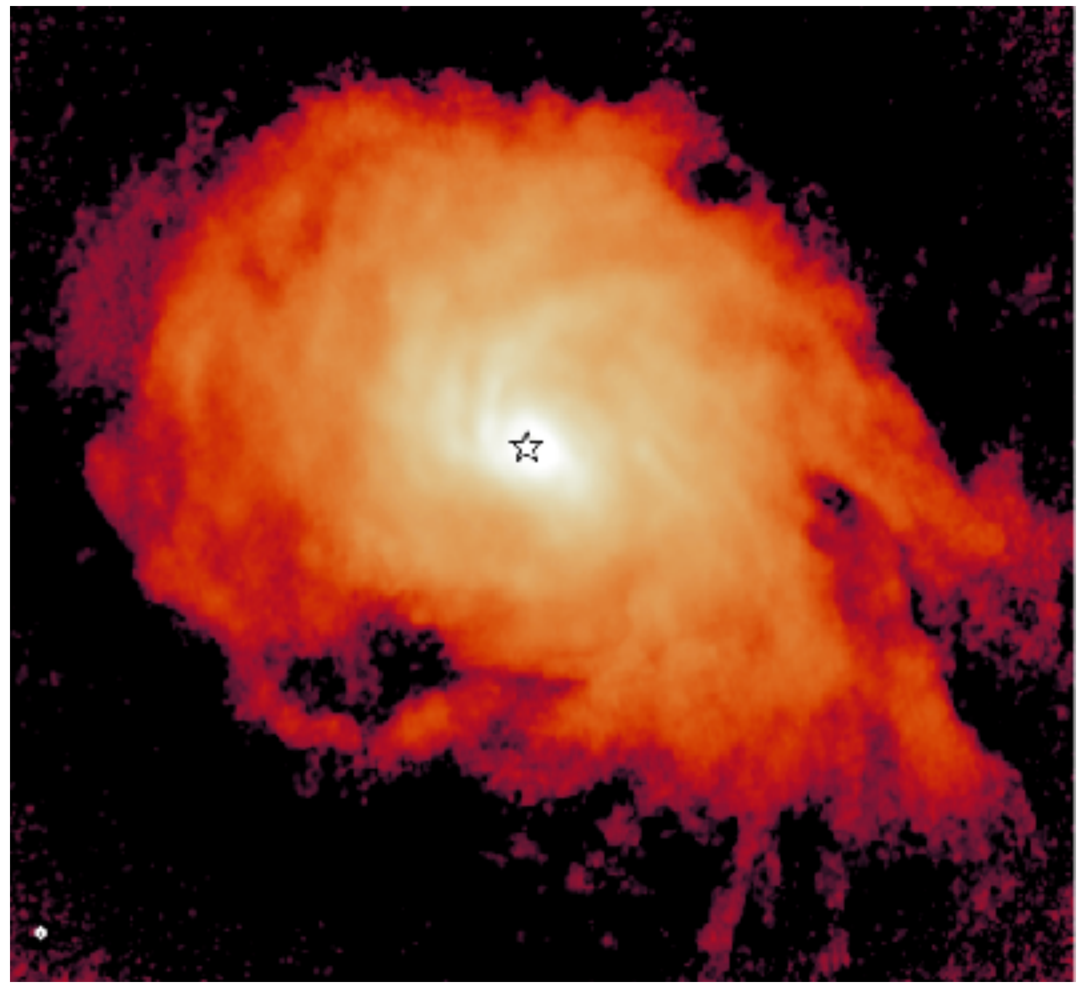
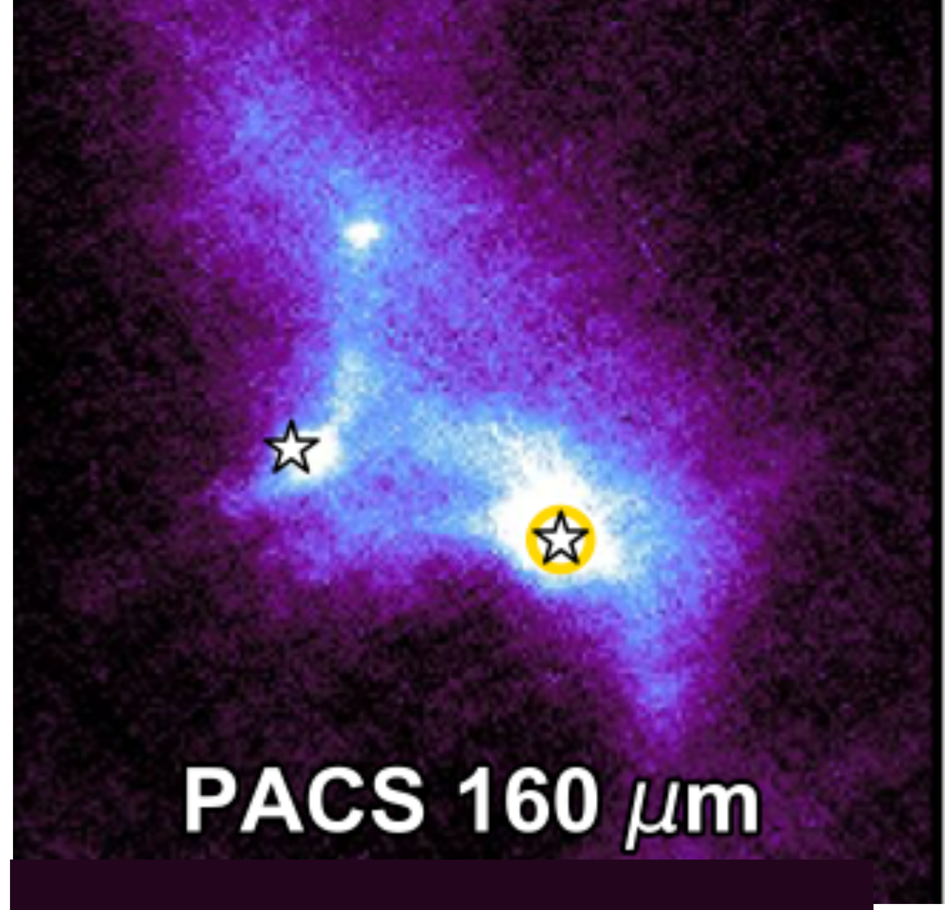
# Getting Herbigger?

## What can we learn from the Herbig lifetime problem

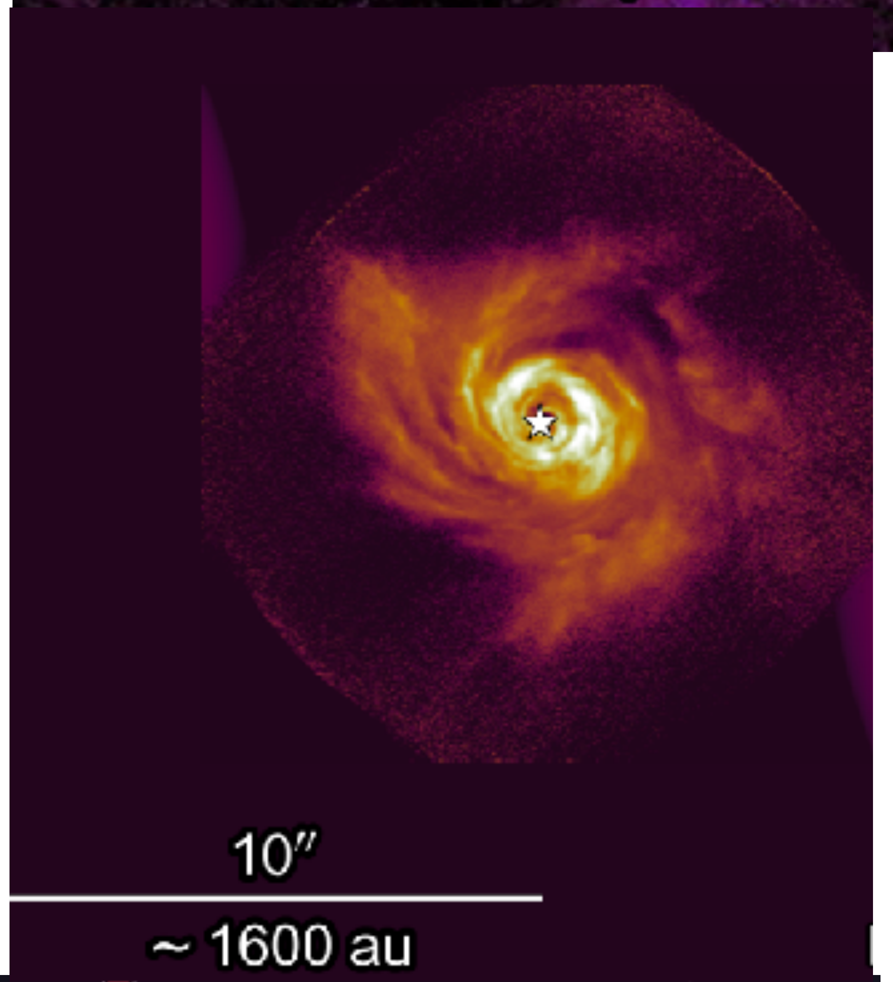


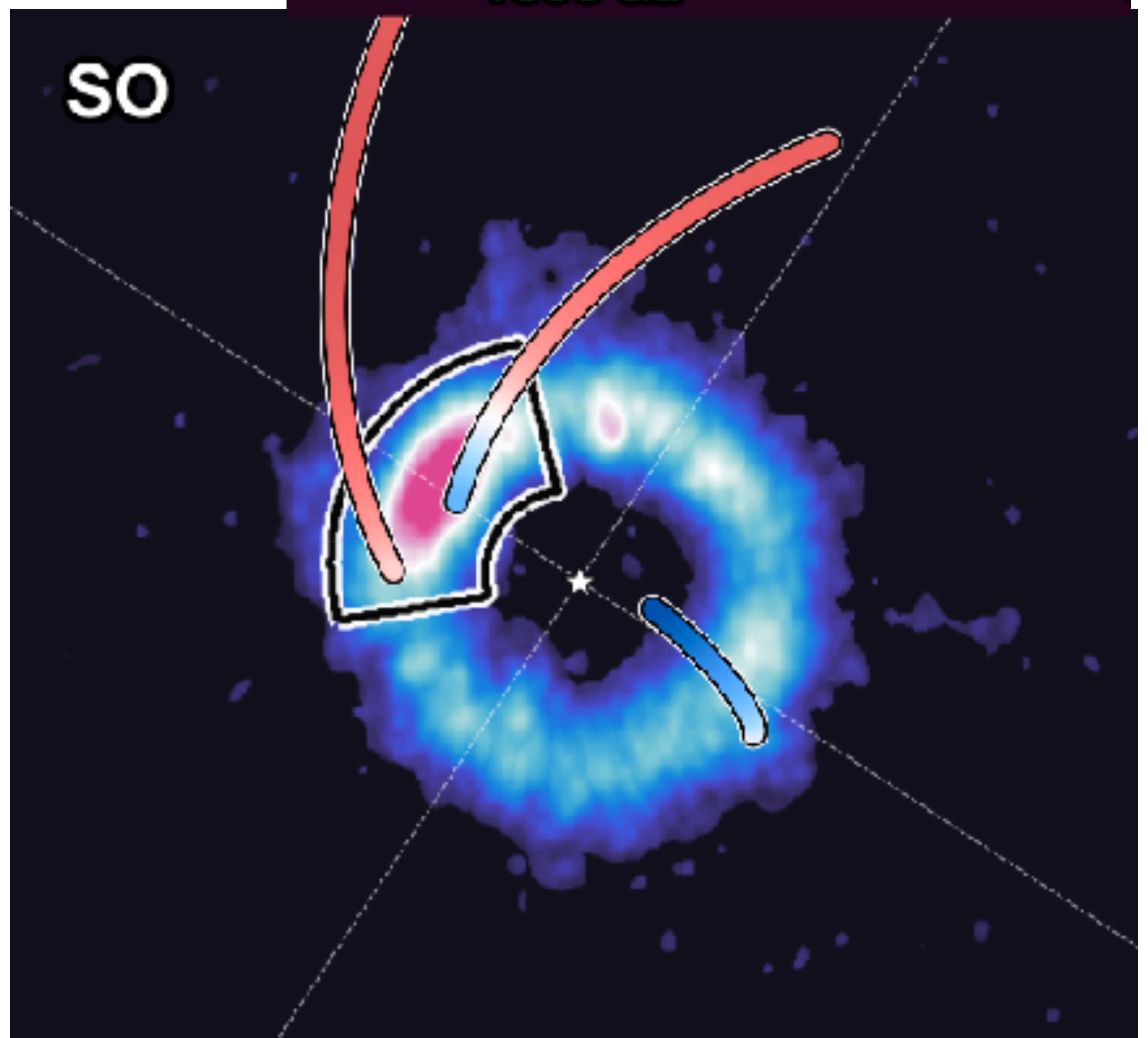



Speedie et al. 2024/2025




Bocalletti et al. 2020




**Infrared imaging and millimetre continuum mapping of Herbig Ae/Be and FU Orionis stars***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We found two different morphologies of the dust envelopes: 6 regions show a compact structure, whereas 12 regions are characterized by a core/envelope structure. The "disk" objects AB Aur and HD 163296 show only a compact core and are not surrounded by an extended envelope. We did not detect

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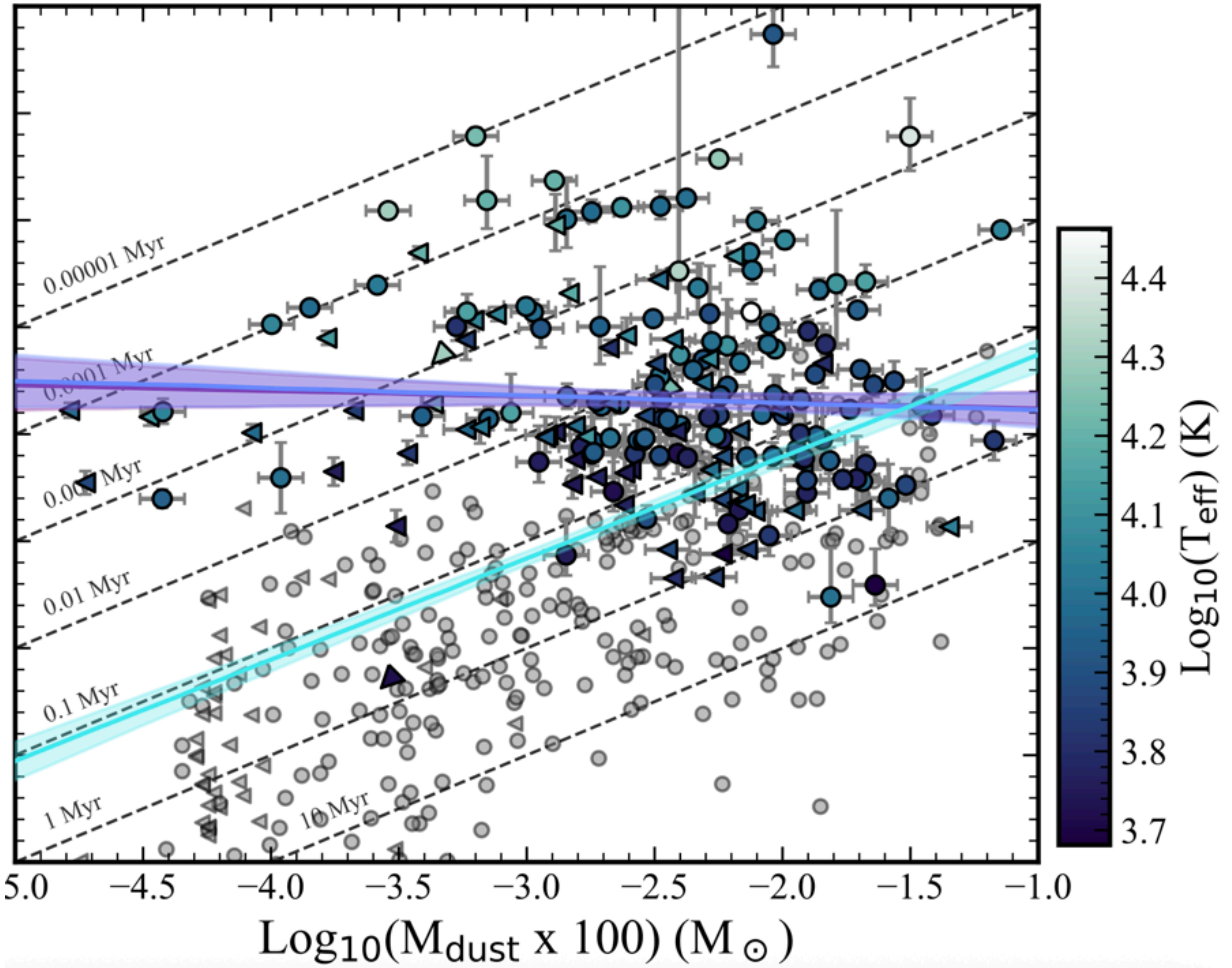
# An Herbig Lifetime Problem

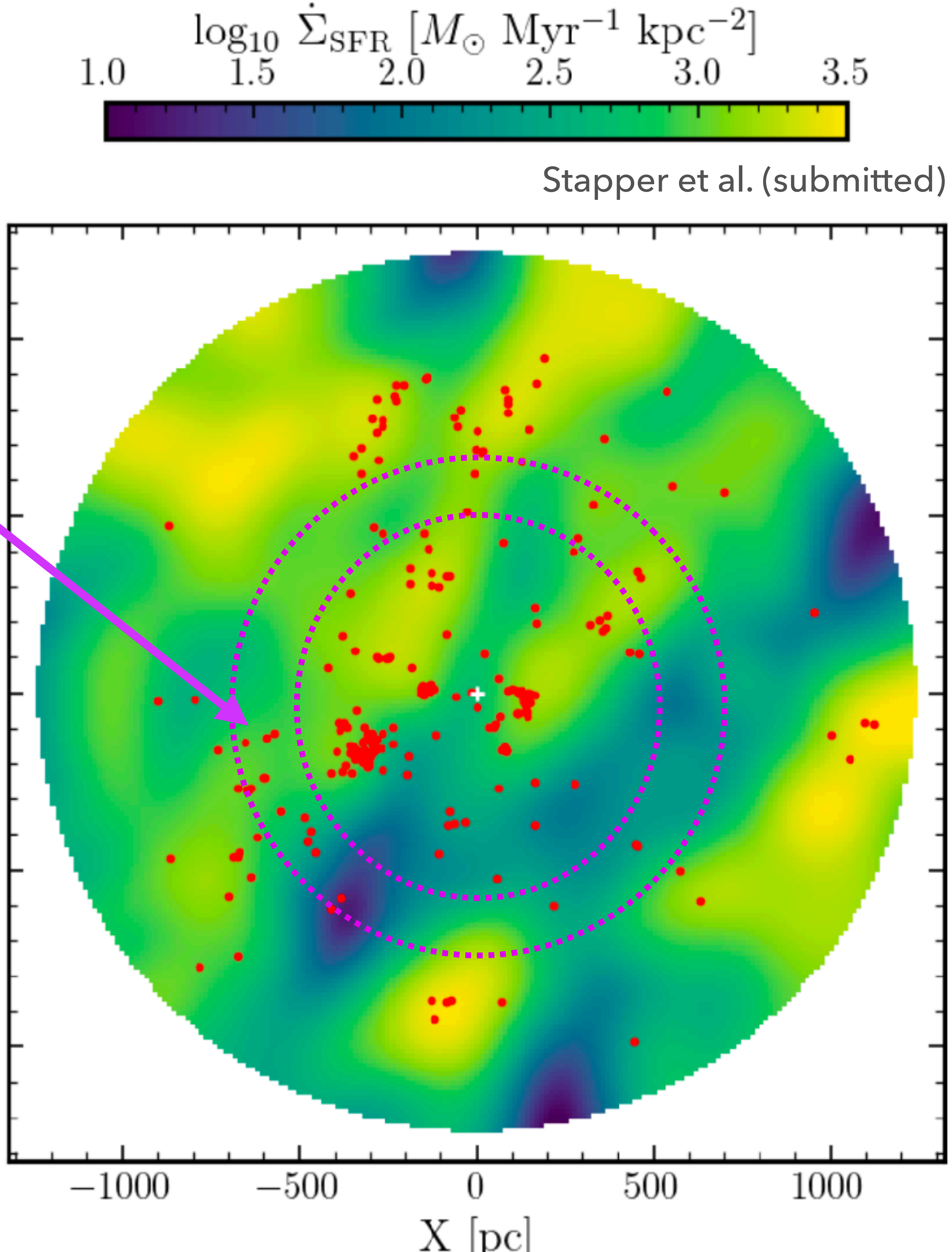
- With standard assumptions, the disc mass / accretion rate time-scale very small
- How long do these Herbig discs live for?



# Herbig lifetimes

$$\frac{d\dot{N}_{\rm SFR}}{dm_*} = \xi(m_*)\frac{\dot{\Sigma}_{\rm SFR}}{\langle m_* \rangle}$$

- Assume complete very nearby
- Calculate how many formed from star formation rate
- Calculate required lifetime to give number : $d\dot{N}(m_*) = 0 = d\dot{N}_{\rm SFR} - dN_{\rm SFR}(m_*)/\tau_{\rm lifetime}(m_*)$
- Fit mass dependent completeness and lifetime

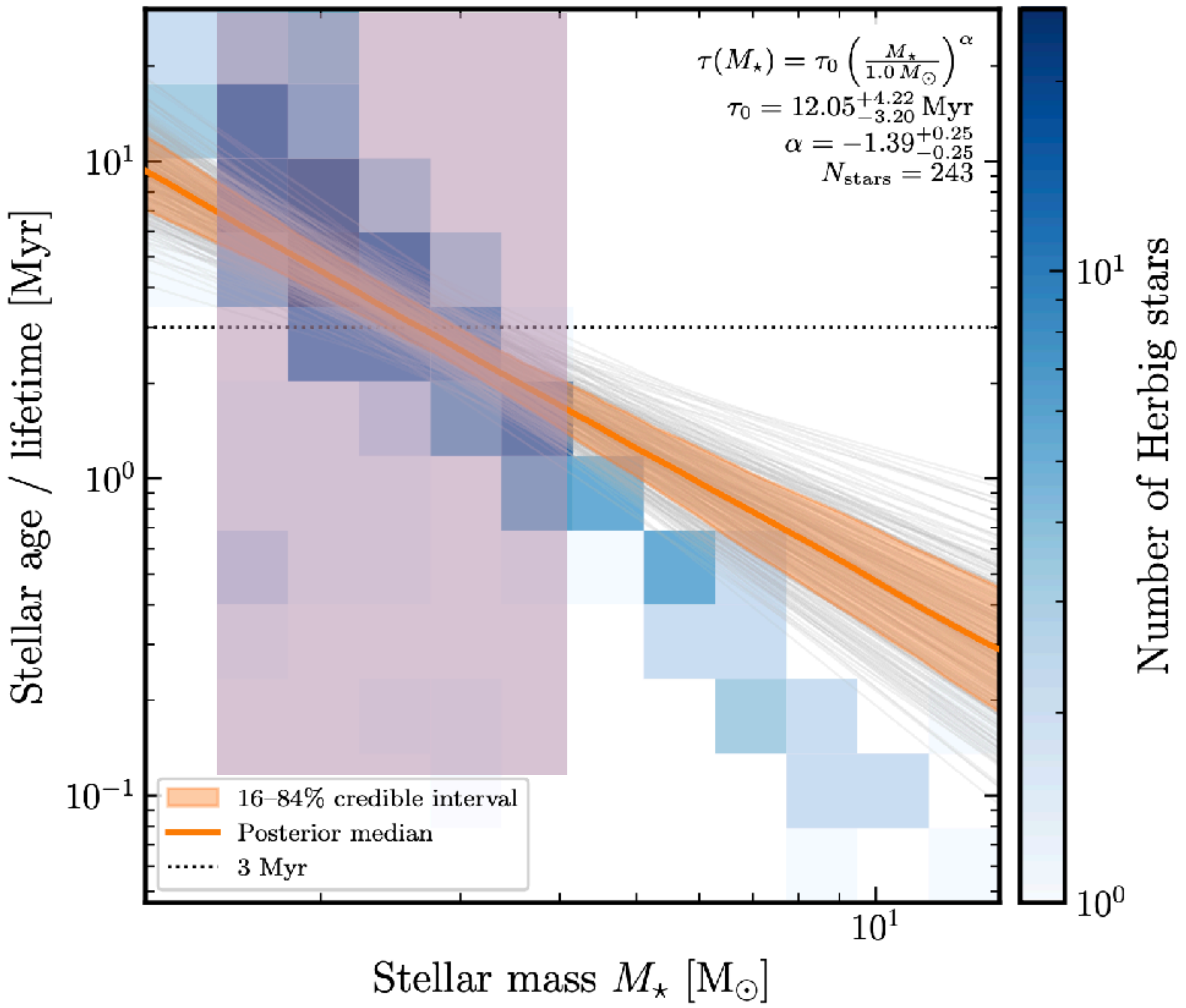



Stapper et al. (submitted)

# Lifetime vs. H—R fit

- Counting predicts ~ 5 Myr disc lifetime for ~ 2 solar mass stars
- (Surprisingly?) good agreement between HR fit and lifetime from counting

Stapper et al. (submitted)



# Model? Principles

- ***"All models are wrong, some are useful"*** — George Box

- Population synthesis — we learn more from what we cannot fit than what we can!

- *Herbig sample: can assume* ***uniform age distribution*** *,* ***know lifetime****,* ***~close to complete within 500 pc***

# Canonical models

= distribution

= single value

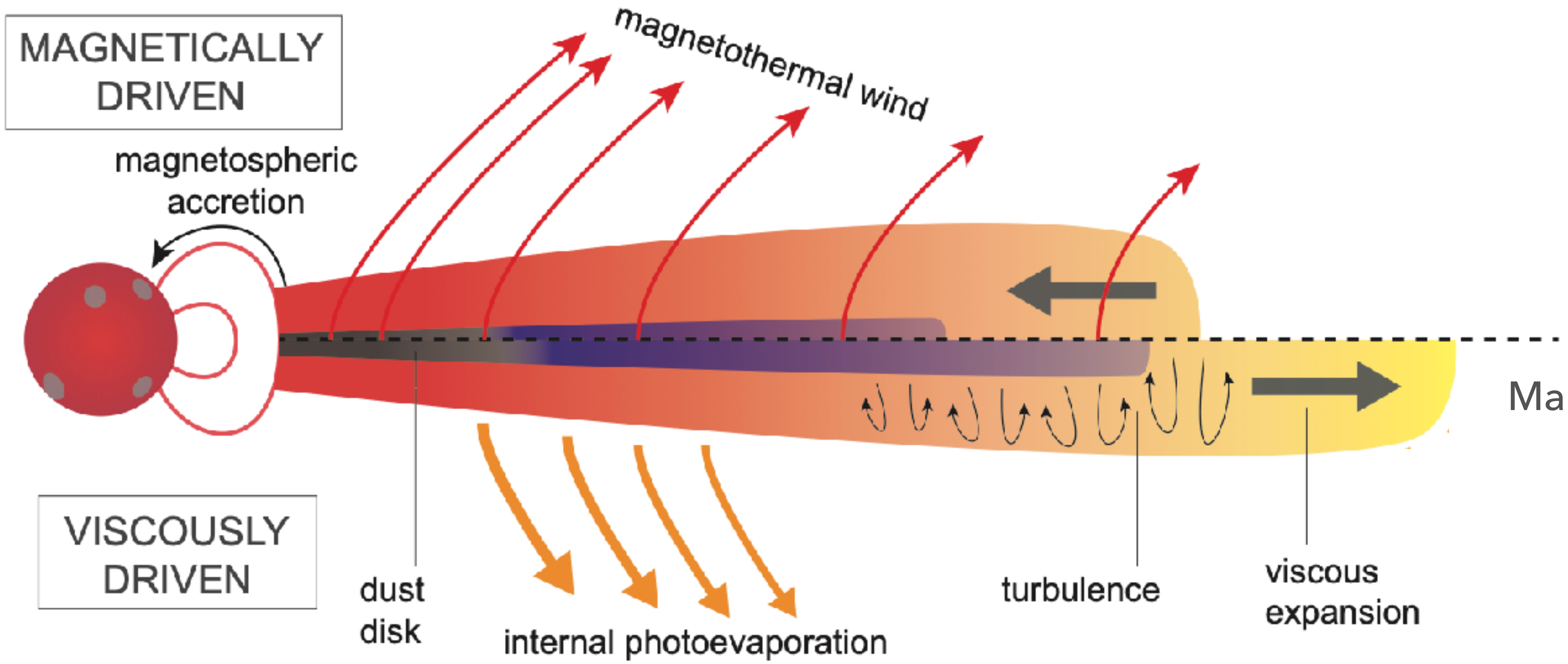
$$\frac{dM}{dt} = -\frac{M}{2(t_\nu + t)} - \dot{M}_{\rm wind}$$

$$M(t_1) = \frac{M(t_0)\sqrt{t_\nu + t_0} - \frac{2}{3}\dot{M}_{\rm wind}\left[(t_\nu + t_1)^{3/2} - (t_\nu + t_0)^{3/2}\right]}{\sqrt{t_\nu + t_1}}$$

$$\dot{M}_* = M/[2(t_\nu + t)]$$

$$M(t) = M_0\left[1 - \frac{\omega t}{2t_{\rm acc}}\right]^{1/\omega}$$

$$\dot{M}_* = M/[(1 + f_M) \cdot 2t_{\rm acc}]$$

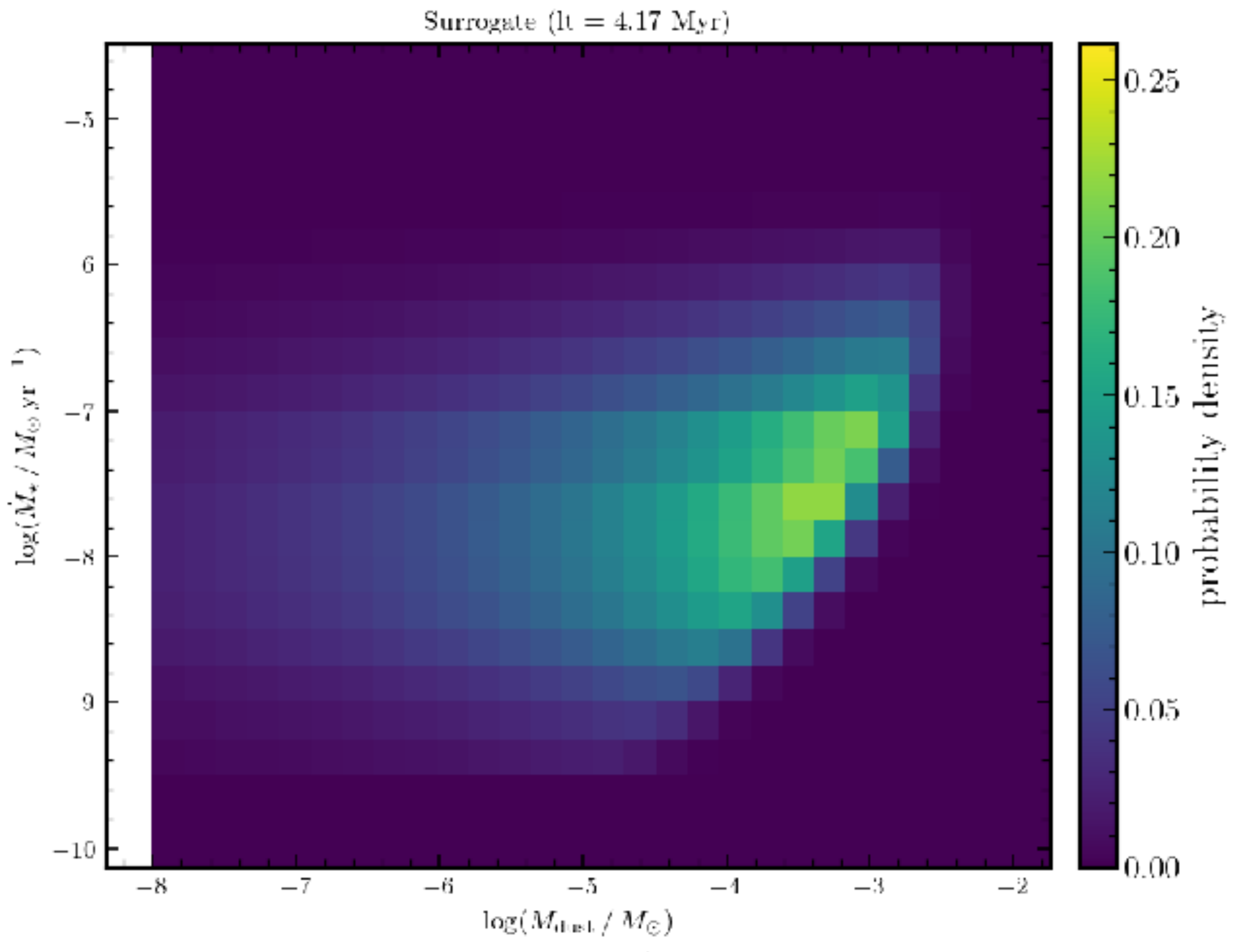


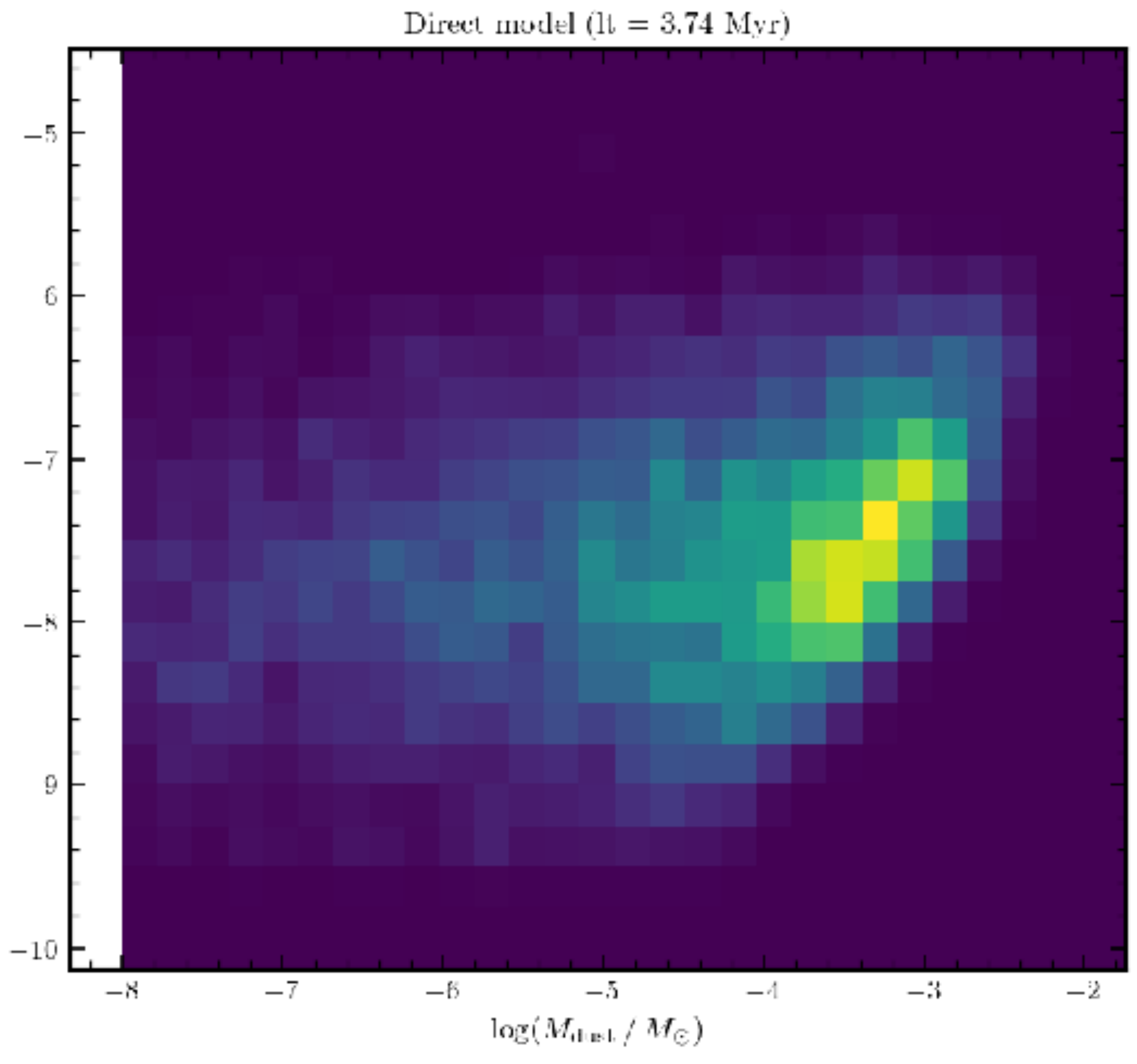

Manara et al. 2023 (PPVII)

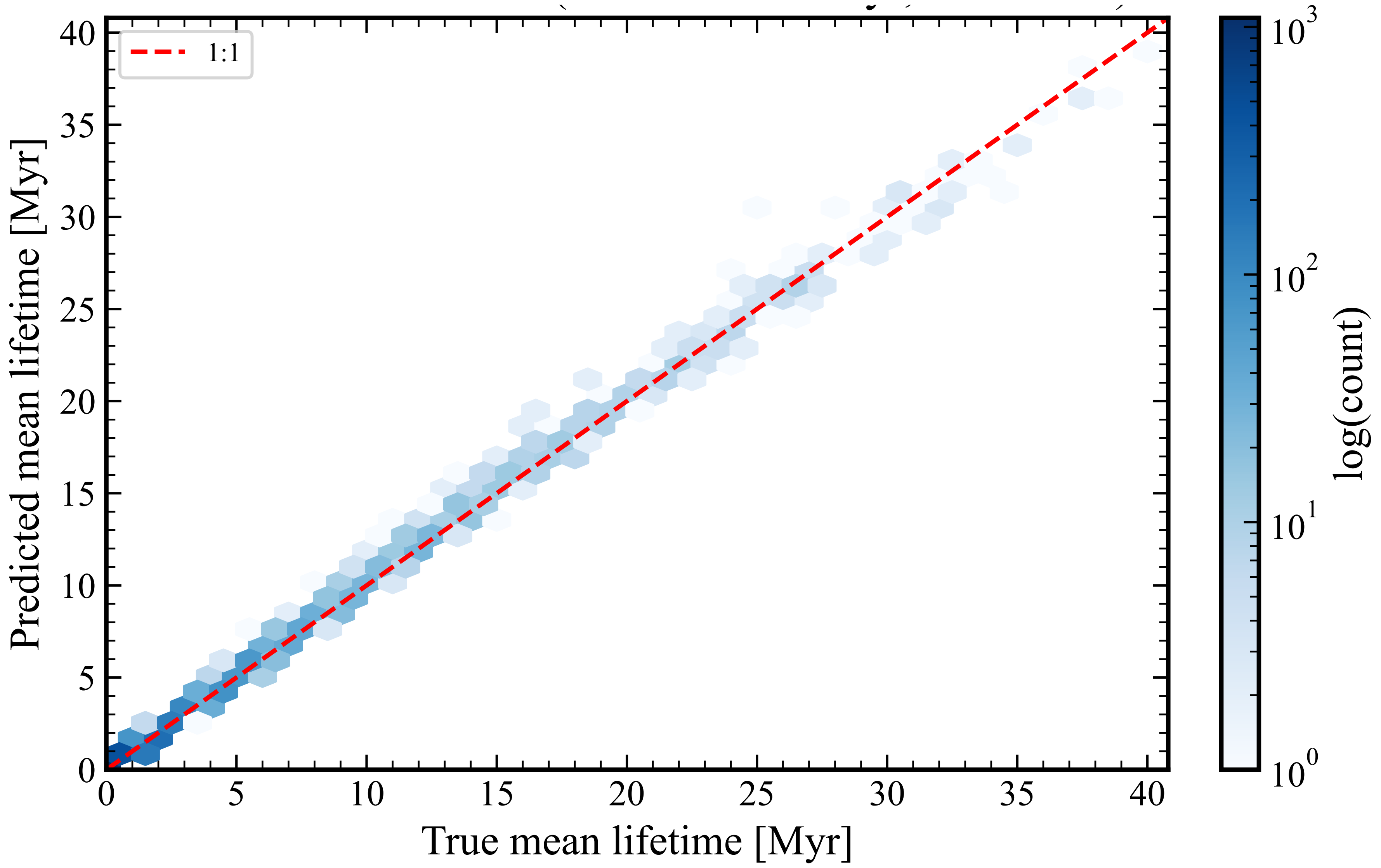
# Strategy

Problem: *large number of parameters, high dimensionality, multi-modal likelihood space,* ***stochasticity*** *—> Need a deterministic function —> NN Surrogate*

Grid of parameters — $2^{15}$ ➔ Draw populations — $2 \times 10^4$ ➔ Train CNN surrogate ➔ Nested sampling

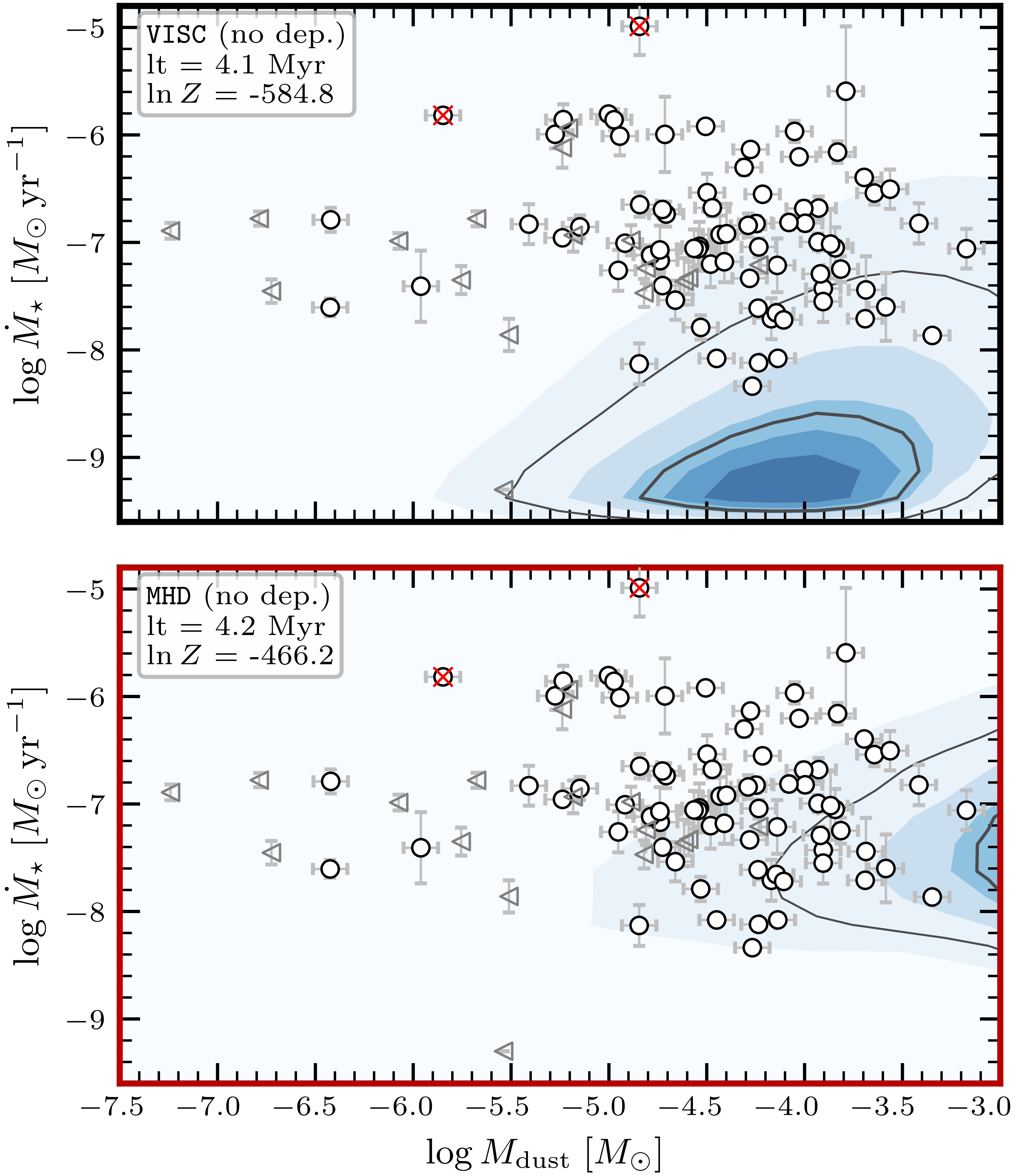


# Canonical models

- Impossible!

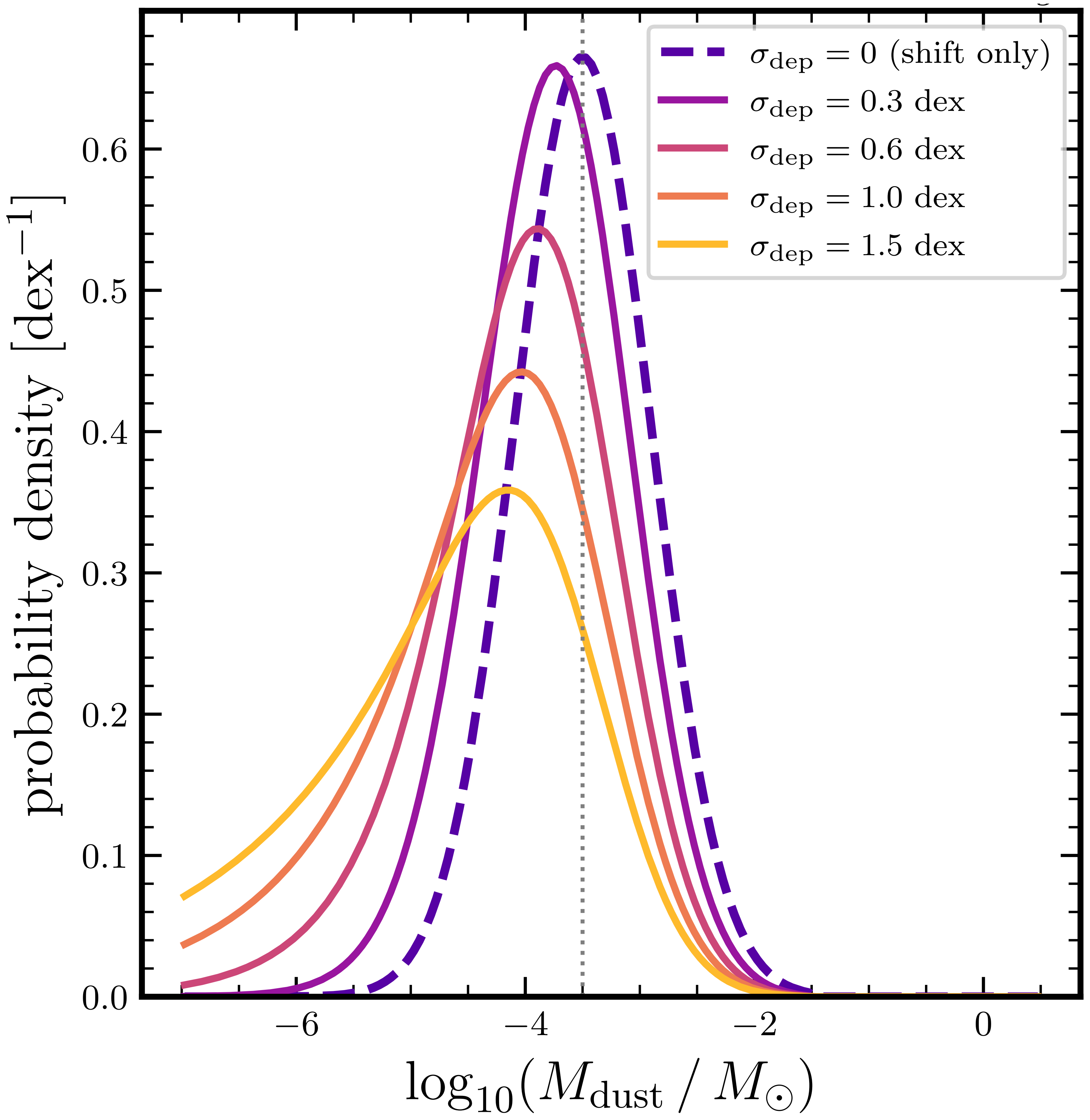


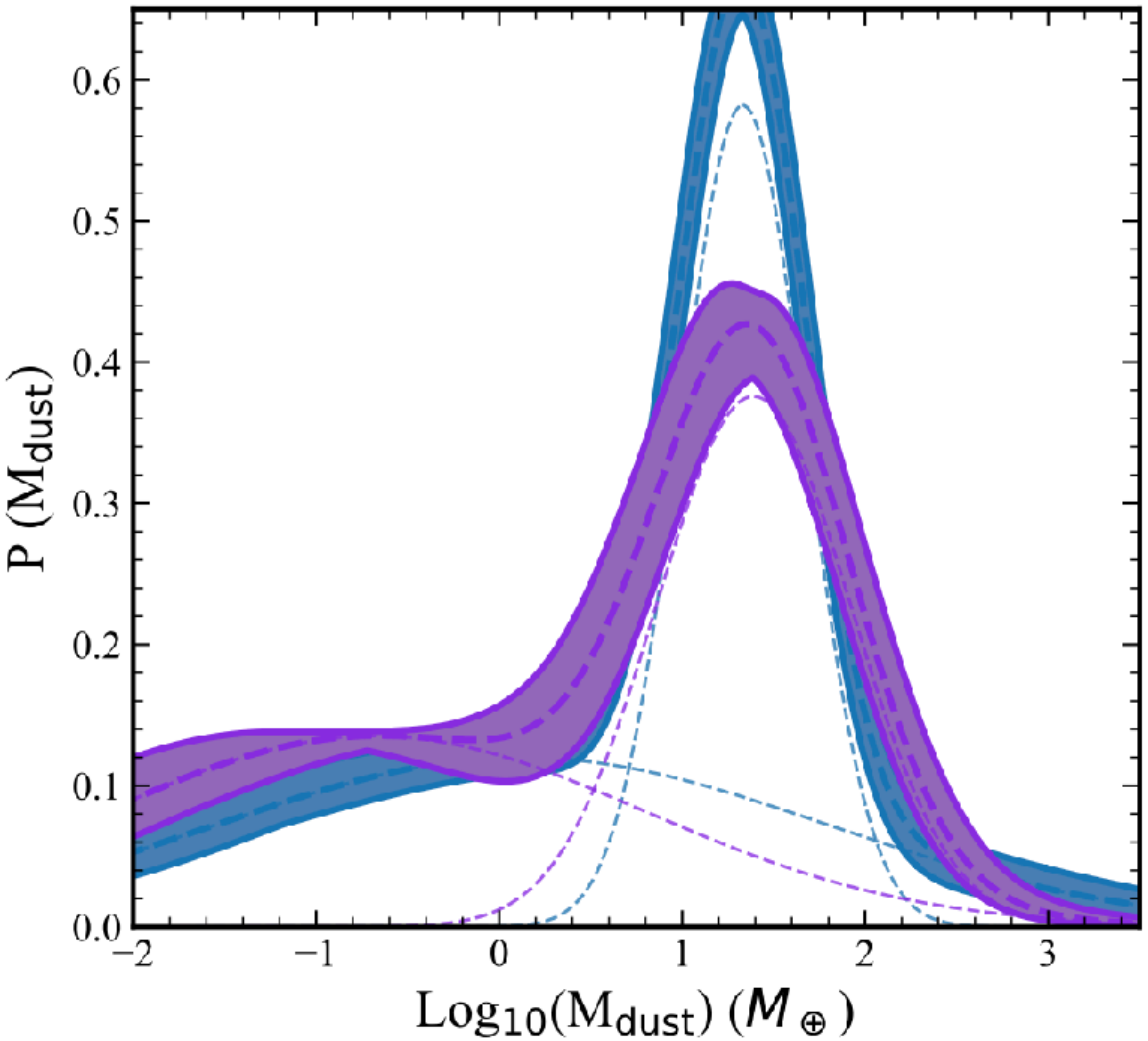
# Dust depletion?

- Apparent depletion of dust in a fraction of the Herbig discs… $\sigma_{\rm dep} \in [0,2]$

$$M_{\rm dust} = \delta_{\rm dtg}\, M_{\rm gas}\, 10^{-\delta}$$

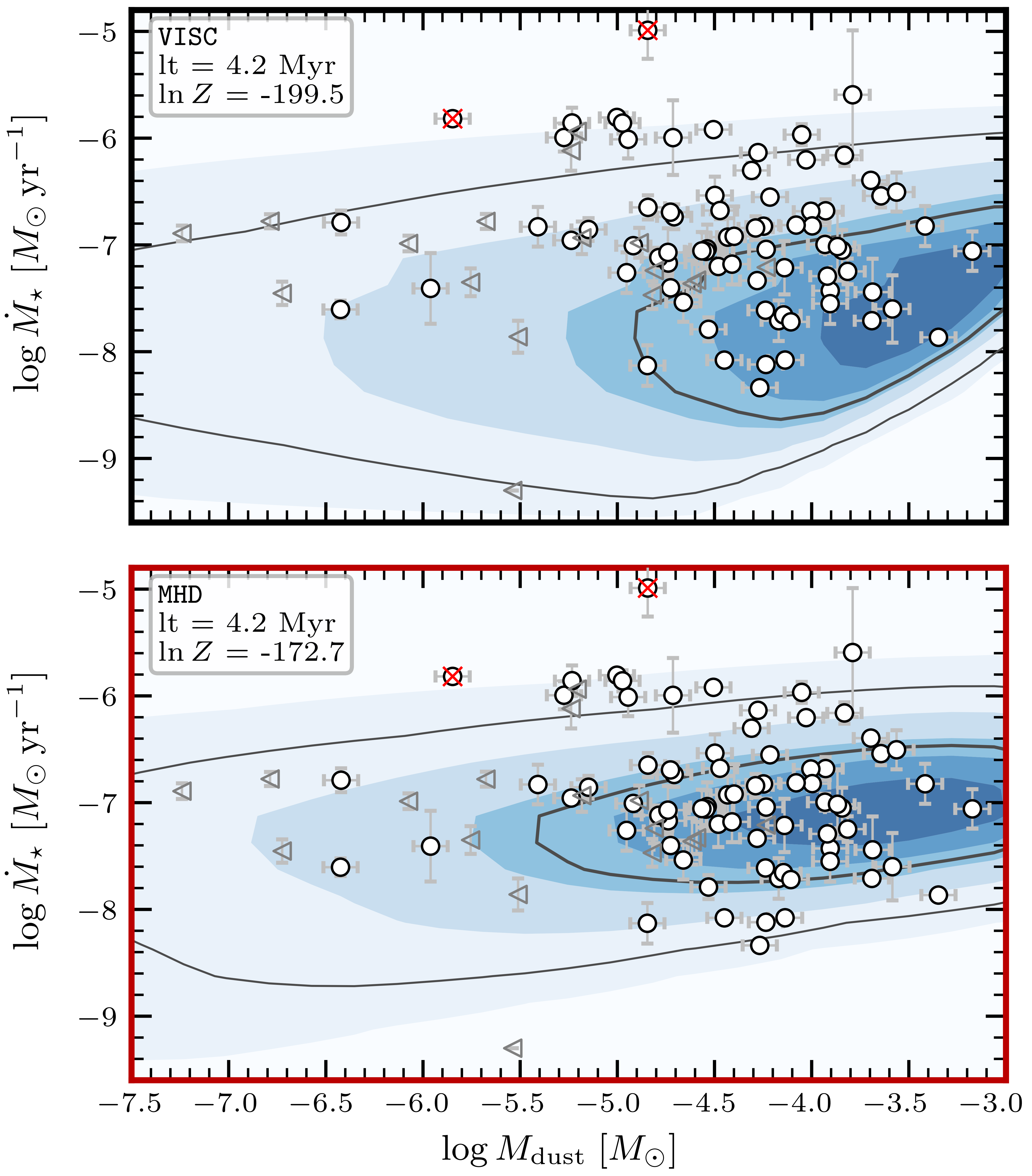
$$\delta \sim \mathrm{Exp}(\sigma_\delta)$$



# Dust depletion

- With dust depletion, models immediately improved but...
- Maxes out $\sigma_{\text{dep}} \approx 2$, still predicts too much dust
- Requires extremely massive discs
- Misses high accretors
- **Keep dust depletion in all models**



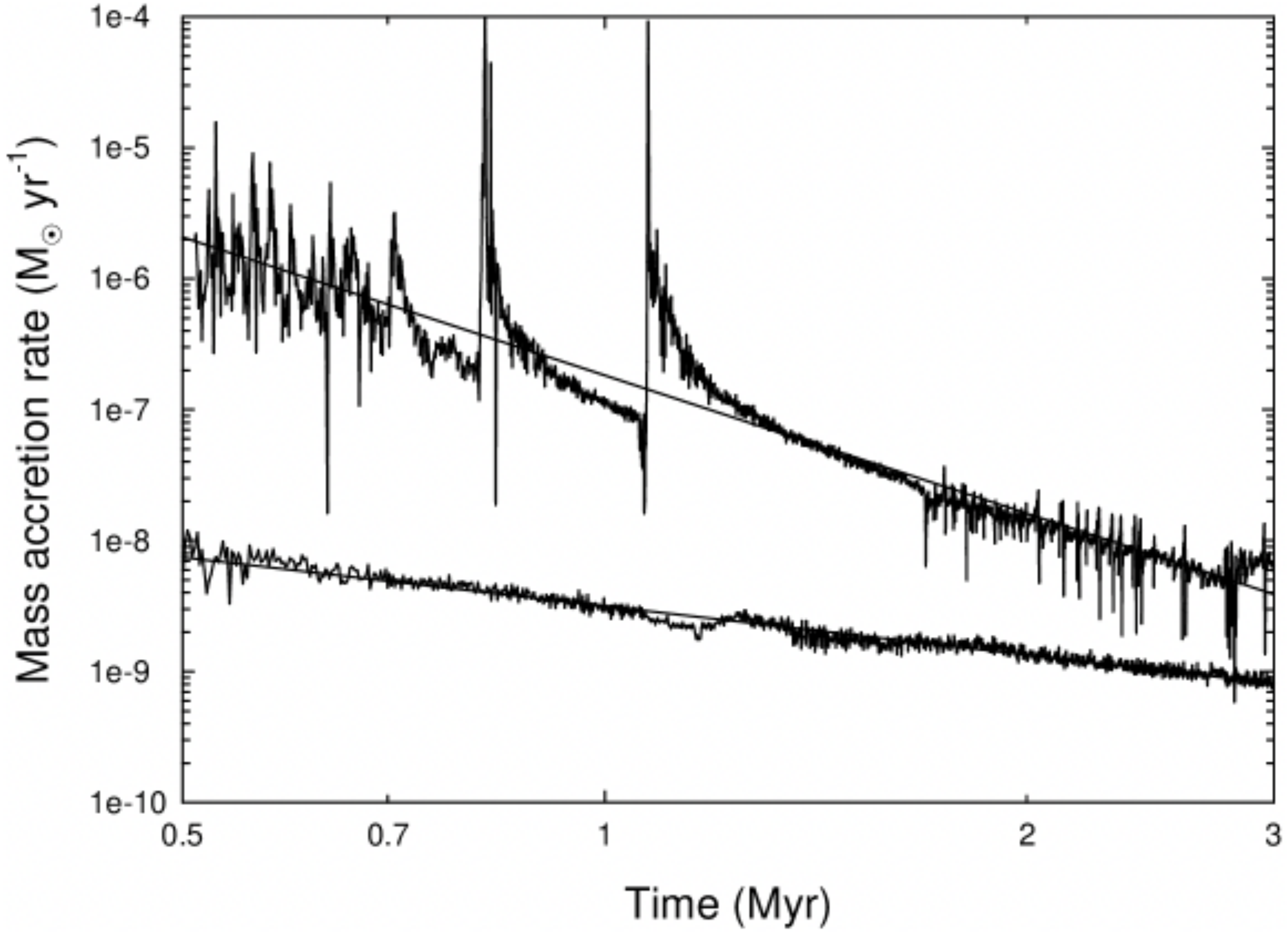
# A simple variability model

Vorobyov & Basu 2008

$$\lambda(t) = \frac{1}{\tau_{\mathrm{rep},0}} \exp\left(-\frac{t}{\tau_{\mathrm{SF}}}\right)$$

$$\log_{10} \Delta M_k = \log_{10}\langle \Delta M_0 \rangle - \frac{t_k}{\tau_{\mathrm{SF}} \ln 10} + \sigma_{\Delta M} \mathcal{N}(0,1)$$

$$\dot{M}_{\mathrm{burst}}(t) = \dot{M}_{\mathrm{burst}}(t_{\mathrm{prev}}) \exp(-\Delta t / \tau_{\mathrm{burst}})$$




Viscous

$$t_{\mathrm{eff}} = \max\left(0,\ t_\nu \left[\left(\frac{M_0}{M_{\mathrm{new}}}\right)^2 - 1\right]\right)$$

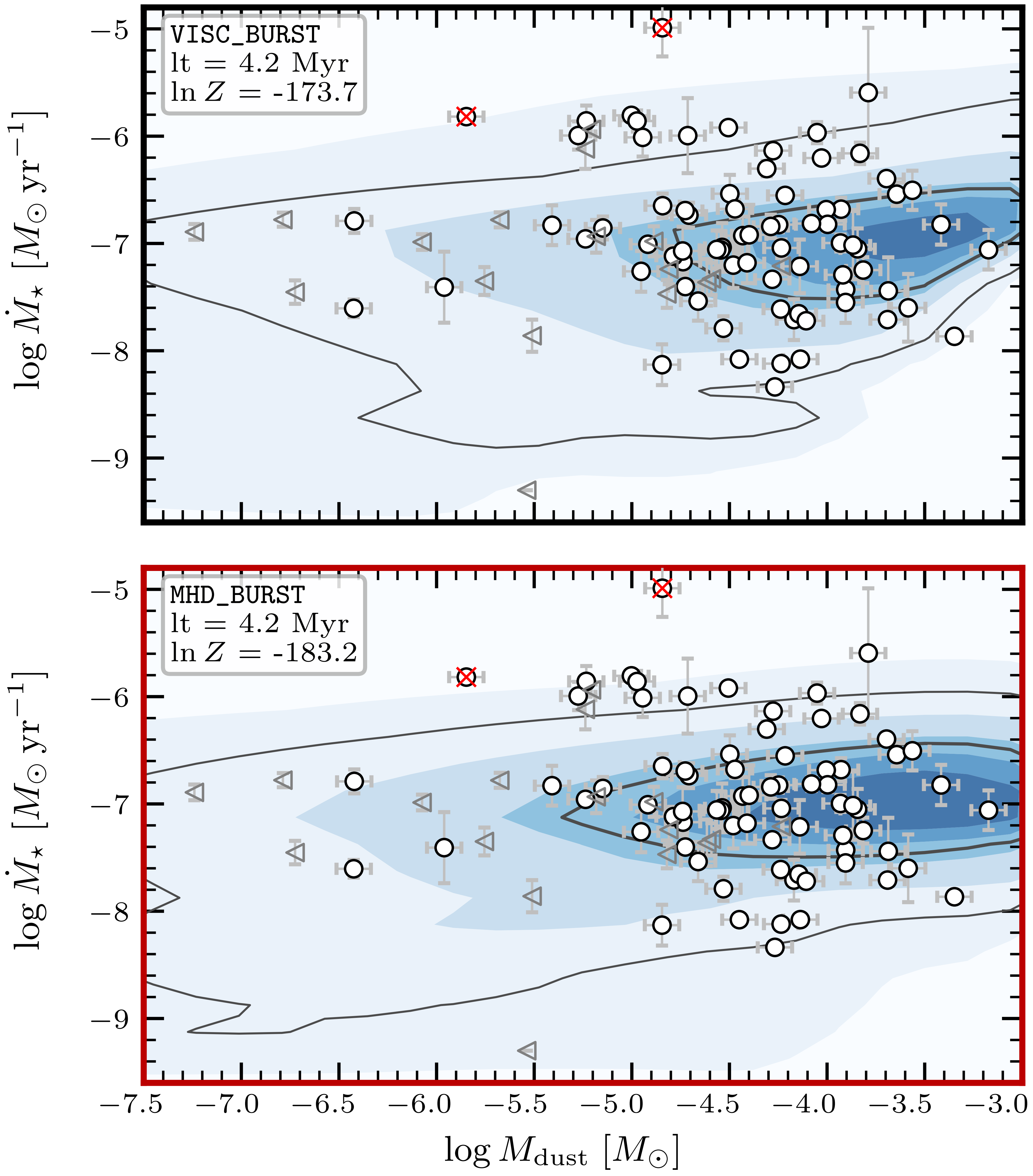
MHD

$$\dot{M}_*(t) = \frac{M(t)}{(1+f_M)\cdot 2t_{\mathrm{acc}}}, \quad \text{so} \quad \frac{\dot{M}_*}{M} = \frac{1}{(1+f_M)\cdot 2t_{\mathrm{acc}}} = \text{const.}$$

# Variable accretion

- Variable accretion with dust depletion, models slightly better for high accretors

- Bulk population — very high average accretion rates/low time-scales, difficult to fit



# A simple replenishment model

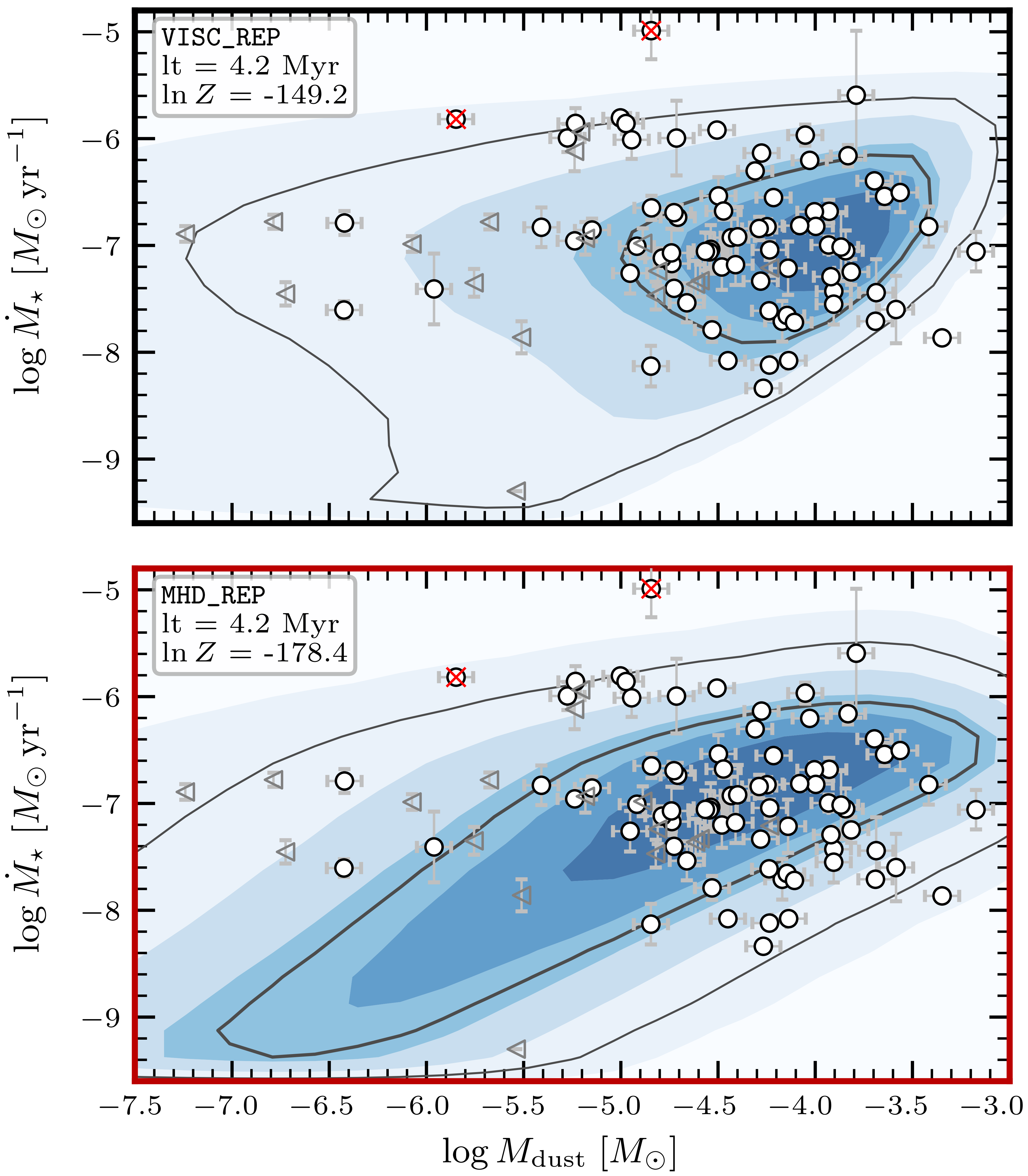
Same as variable accretion but **add** mass, and do not have burst period

$$\lambda(t) = \frac{1}{\tau_{\mathrm{rep},0}} \exp\left(-\frac{t}{\tau_{\mathrm{SF}}}\right)$$

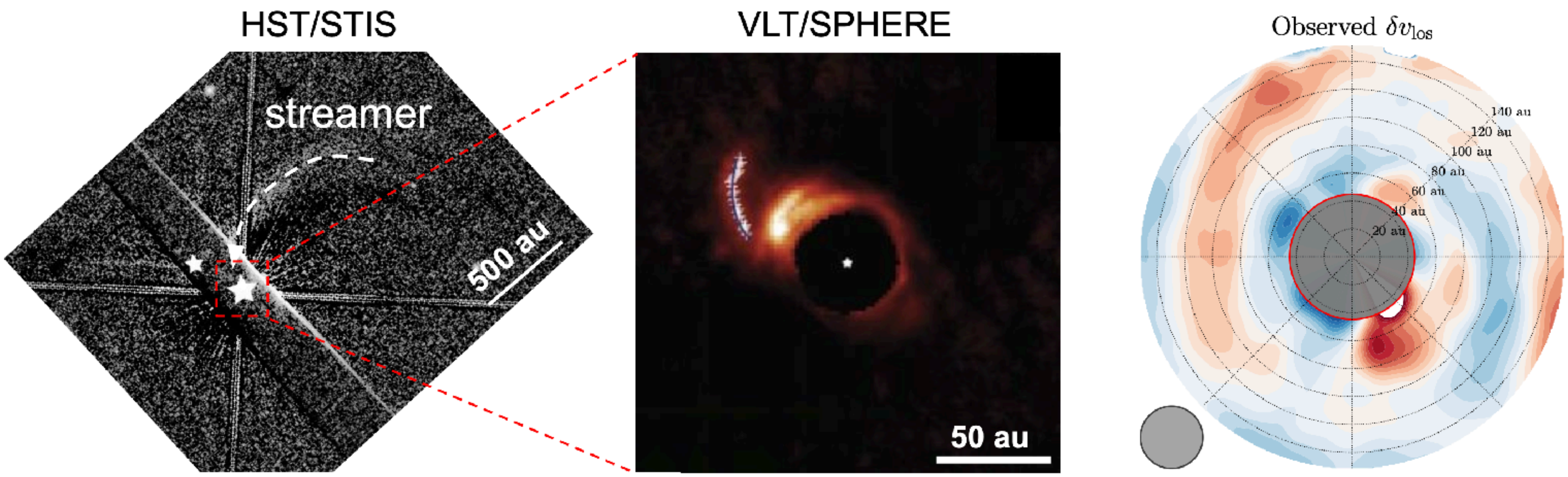
$$\log_{10} \Delta M_k = \log_{10}\langle \Delta M_0 \rangle - \frac{t_k}{\tau_{\mathrm{SF}} \ln 10} + \sigma_{\Delta M} \mathcal{N}(0,1)$$

# With replenishment

- Improves both models
- MHD models do not have photoevaporative wind — over predict low accretors
- Initially infall at $\sim 10^{-6}\,M_\odot\,\mathrm{yr}$, decays over $\sim 3\,\mathrm{Myr}$



# CQ Tau




Optical (large scale streamer)

Grady et al. 2005

IR (scattered light)

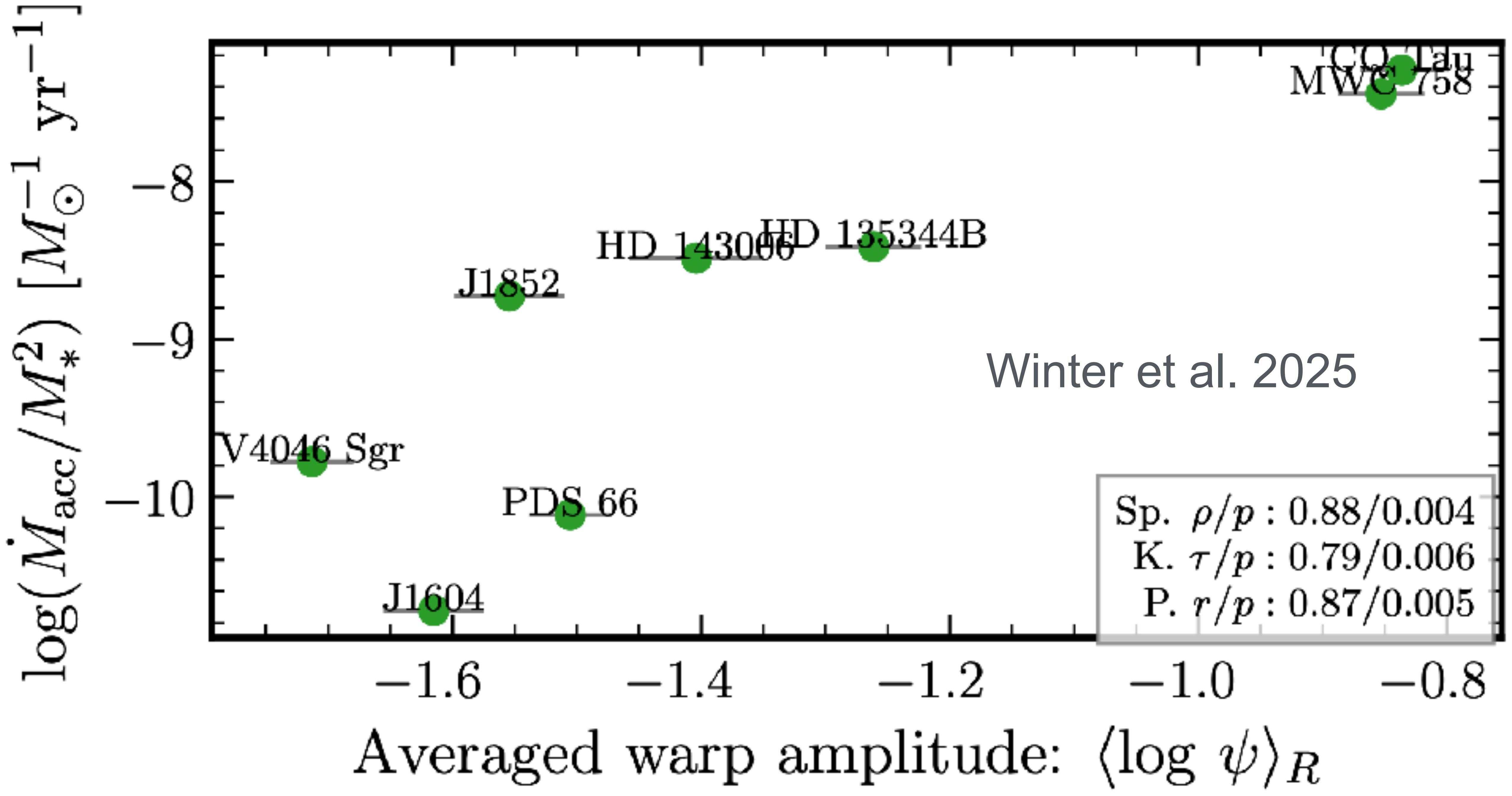
Uyama et al. 2020

mm (kinematic warping)

Winter et al. 2025

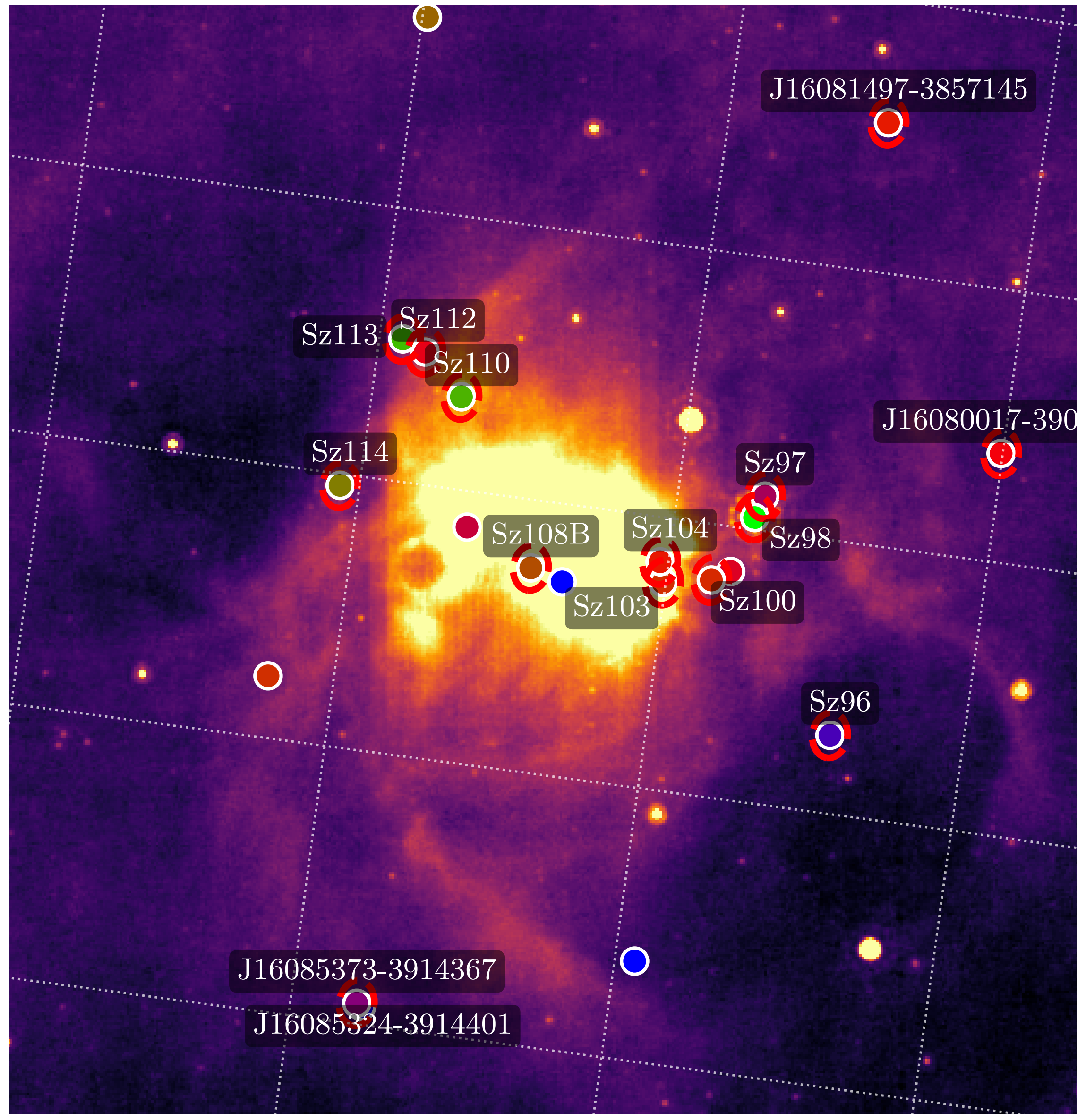
- Infall —> warp —> accretion?

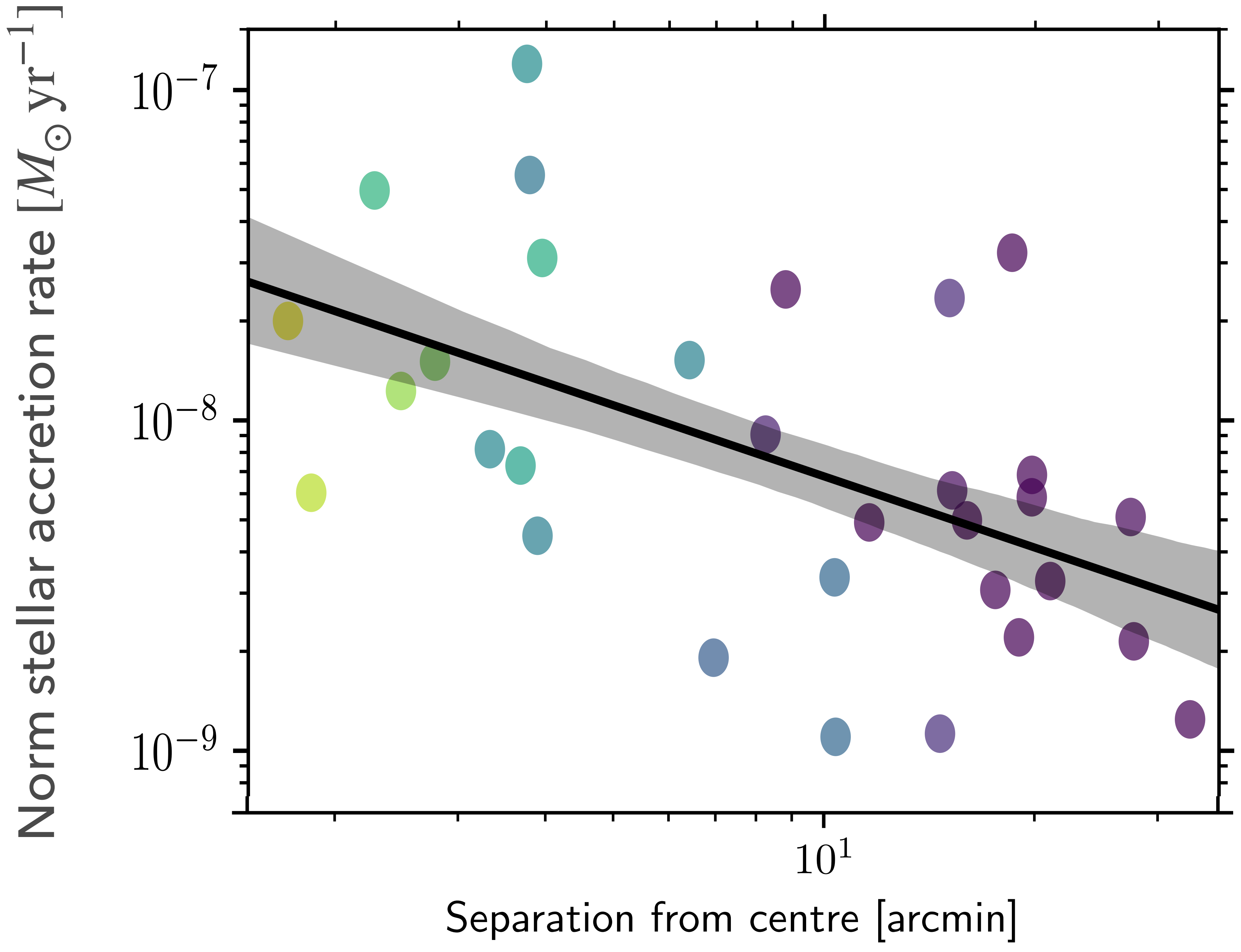
# Infall-driven accretion?




Winter et al. 2025

Lupus 3 – Spitzer/
MIPS 24 μm




Winter et al. 2024c

# Replenishment + turbulent injection

$$\alpha_{\rm turb} + \varepsilon_{\rm turb} \frac{\Delta M_e}{M_{\rm post}}$$

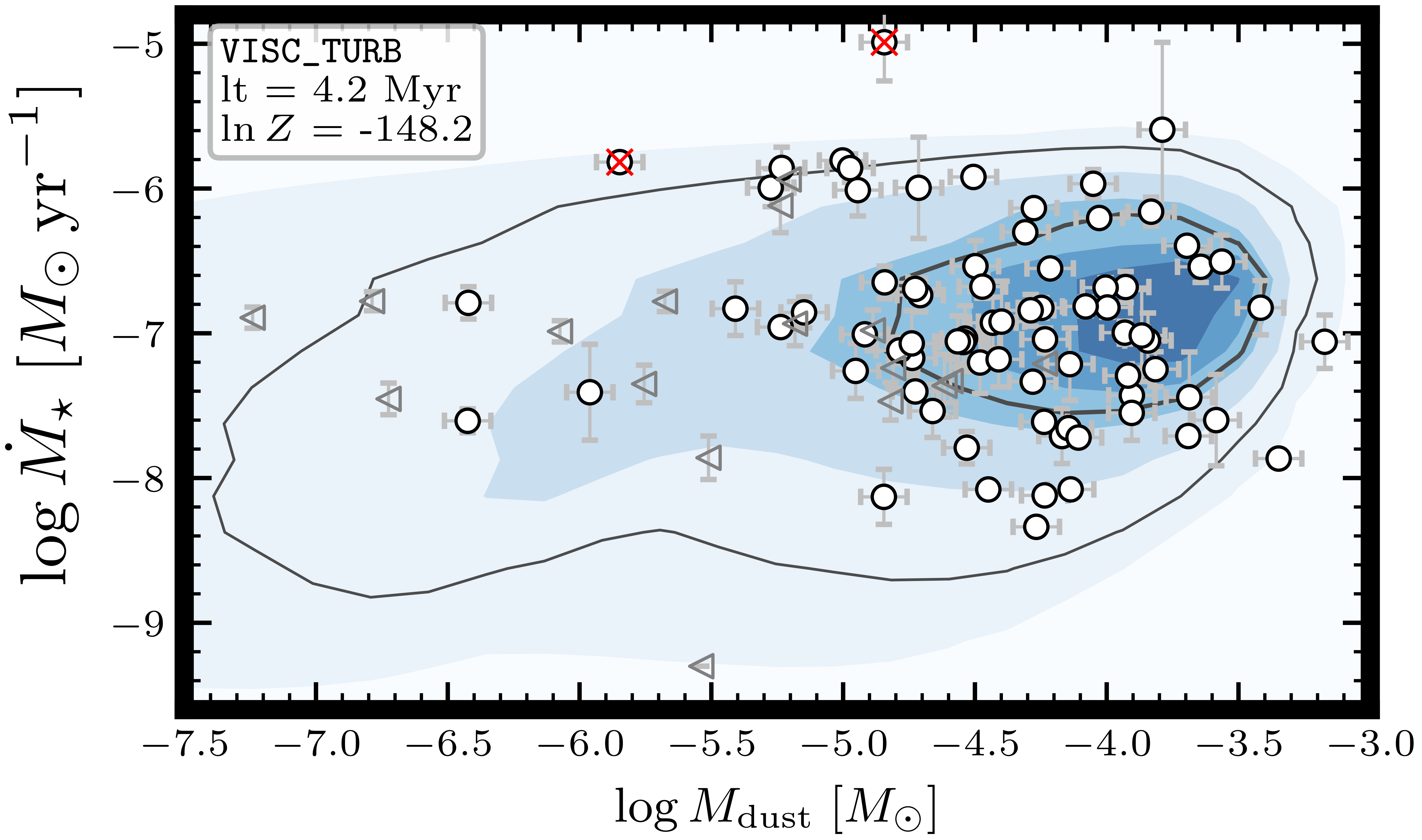
Fixed at $10^{-4}\,\mathrm{yr}^{-1}$

$$\alpha_{\rm turb}(t) = \alpha_{\rm turb}(t_0)\, e^{-\gamma(t-t_0)}$$

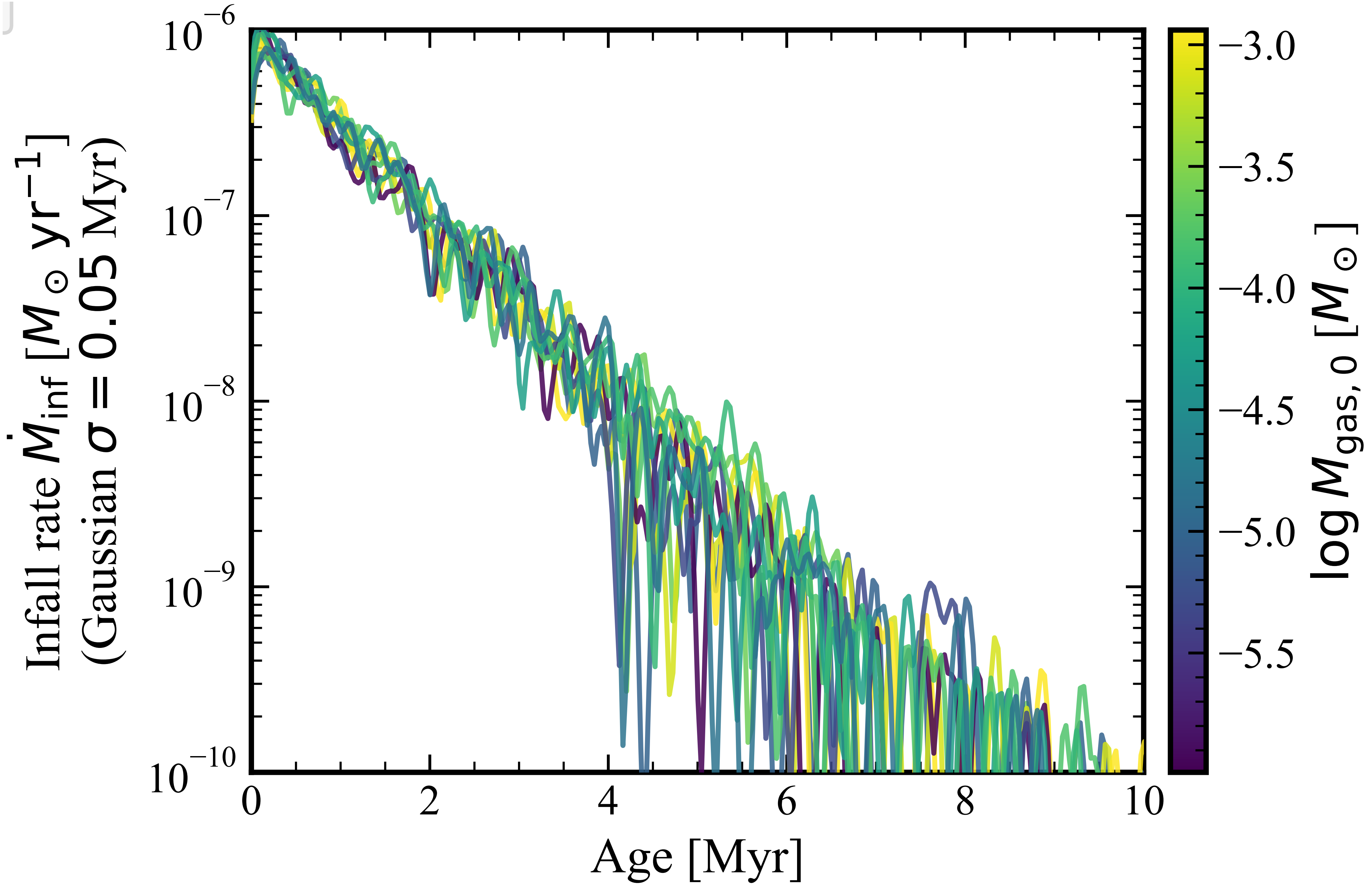
$$t_\nu = C_\alpha / \alpha_{\rm floor}.$$

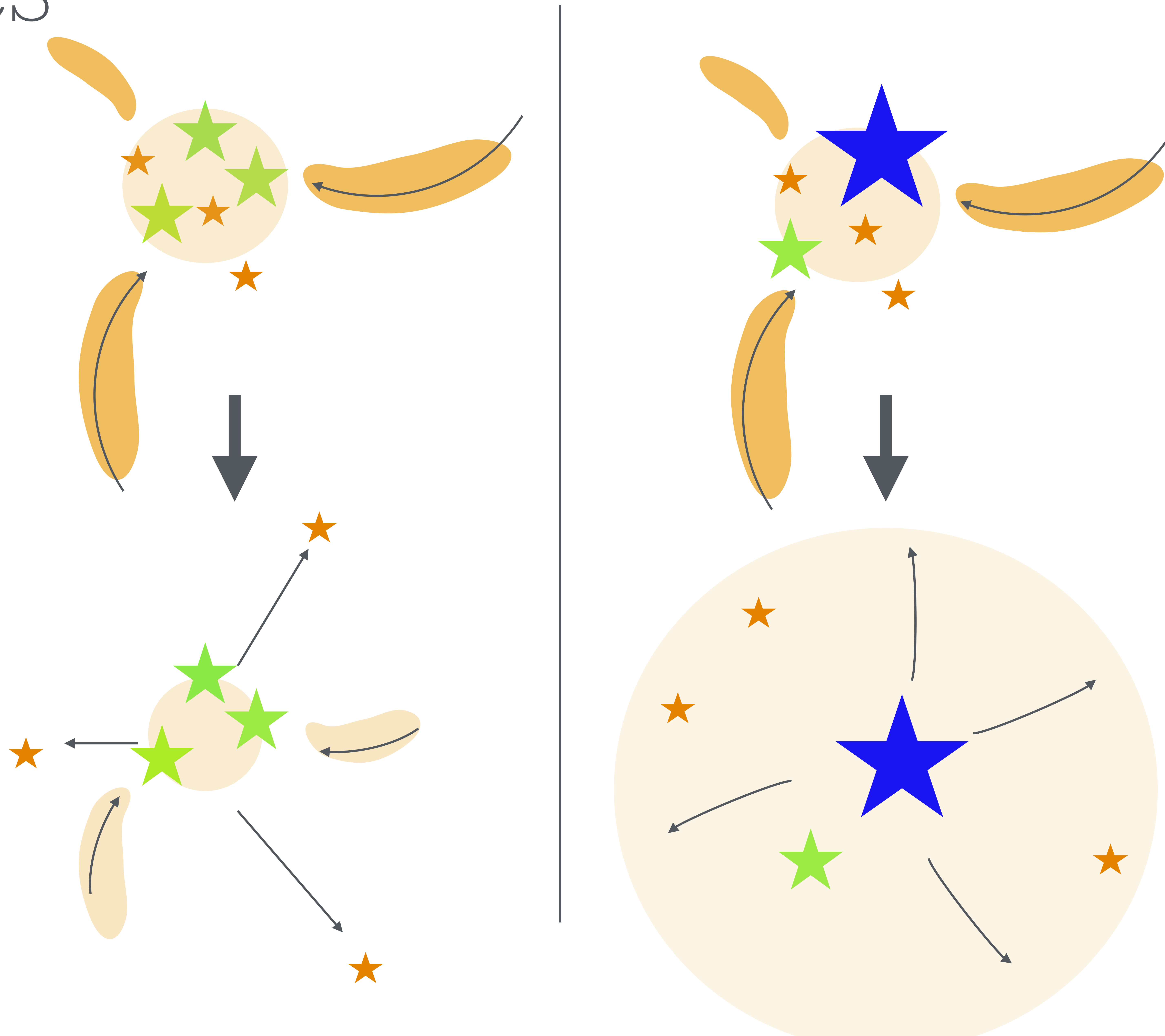
# Replenishment + injected turbulence

- Technically 'best' model
- Does infall contribute to transport?



# Feeding time-scales



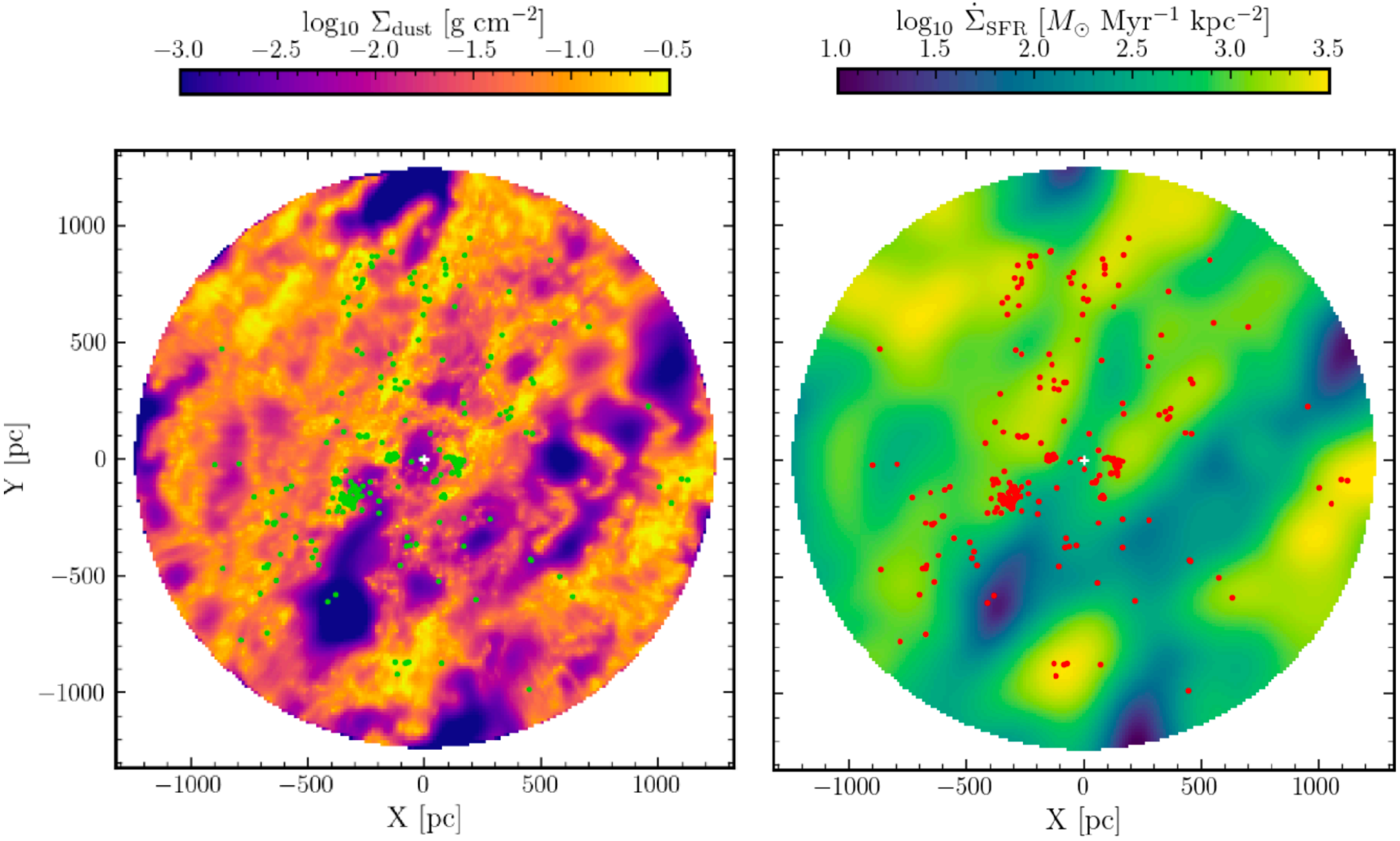
# Conclusions

- **Herbigs $1.5 - 4\,M_\odot$ are not young**...
- ... but they have short accretion lifetimes
- Requires dust depletion
- Requires replenishment at high rate
- May require variability/transport mediated by infall
- **Consequences for what we infer about evolutionary time-scales: dust trapping, planet formation time-scales...**

# How long do Herbig discs live?

- Create dust surface density from extinction map
- Convert to gas, convolve with 200 pc (galactic scale height)
- Kennicutt-Schmidt law for SFR

Stapper et al. (submitted)




Extinction maps: Edenhofer et al. 2024