Disc evolution processes: a phenomenological view

Giovanni Rosotti (NWO Veni fellow)
Richard Booth, Marco Tazzari, Cathie Clarke (Cambridge)
Giuseppe Lodato (Milan), Stefano Facchini, Carlo Manara,
Leonardo Testi (ESO)

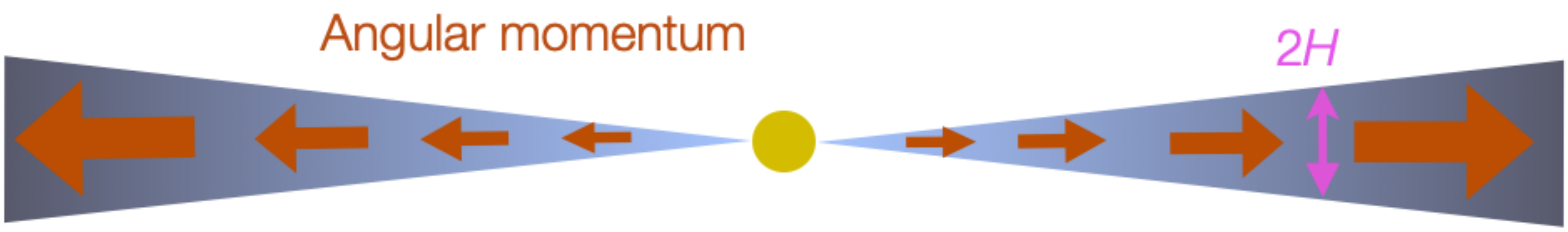
Universiteit Leiden
The Netherlands

NWO
Veni, Vidi, Vici

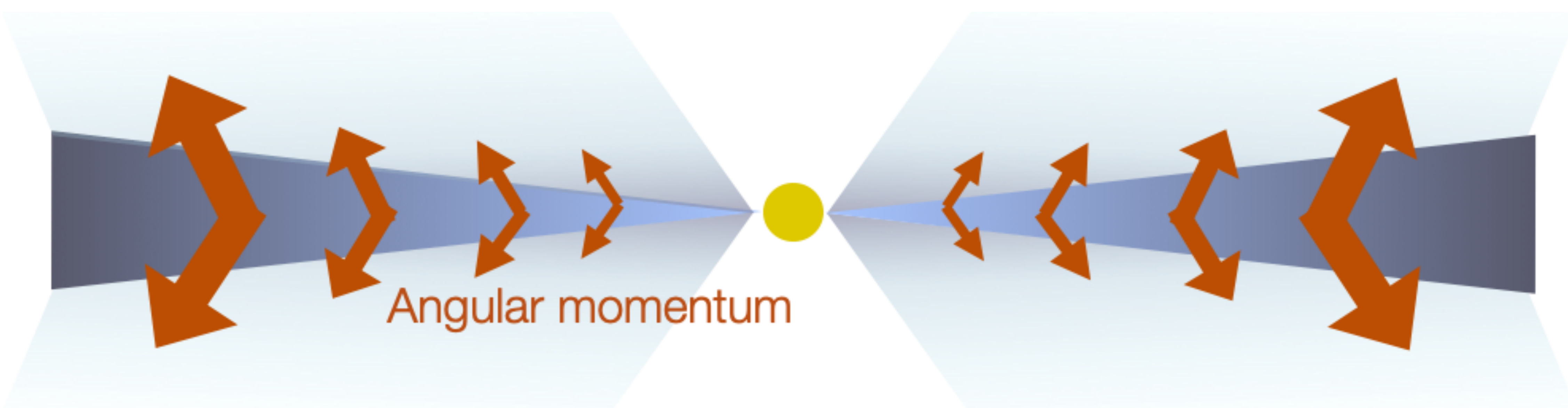
Disc evolution drivers

- Photo-evaporation **Talk B. Ercolano**
- Accretion processes
- Giant planet formation
- Radial drift and other dust processes

Why do discs accrete?



Viscosity



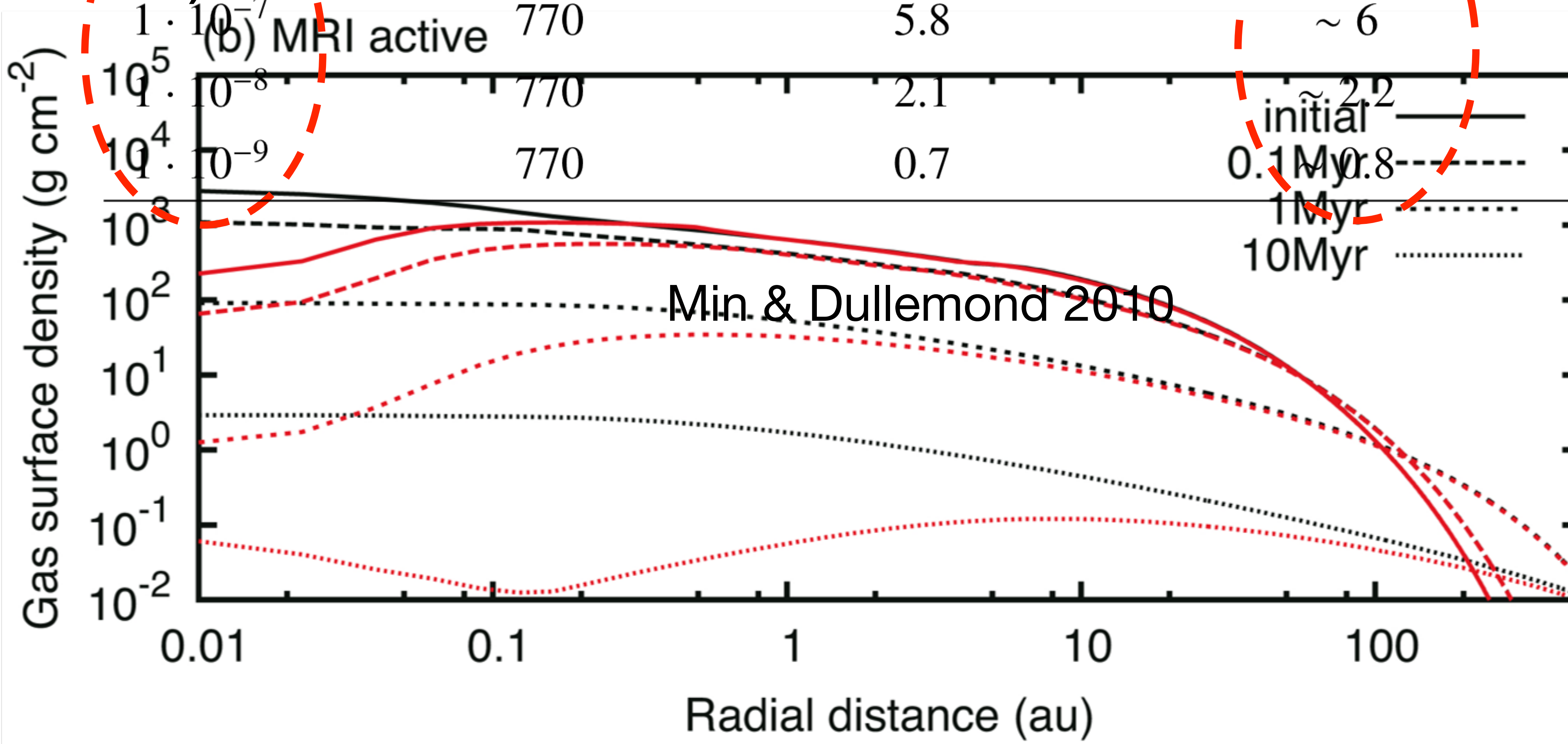
Disc winds

Should you care?

- No viscous heating in wind scenario (e.g., **Mori+ 2019**). Water snowline significantly closer in
- Different surface density profiles in the inner disc (though this depends on wind lever arm, see **Armitage 2014, Bai 2016**)

$\dot{M}$ [$M_\odot$/yr]	$\kappa_R/(f\bar{a})$ [cm^2/g]	R_{ice} [AU] (Eq. 11)	R_{ice} [AU] (numerical)
This study ($\mu = 0.5, \alpha = 0.01$)			
$1 \cdot 10^{-6}$	770	16.1	~ 16
$1 \cdot 10^{-7}$	770	5.8	~ 6
$1 \cdot 10^{-8}$	770	2.1	~ 2.2
$1 \cdot 10^{-9}$	770	0.7	~ 0.8

Min & Dullemond 2010



Ogihara 2017

Accretion Approaches

Local detailed studies

Evolution of macroscopic quantities on secular timescales

Accretion Approaches

Local detailed studies

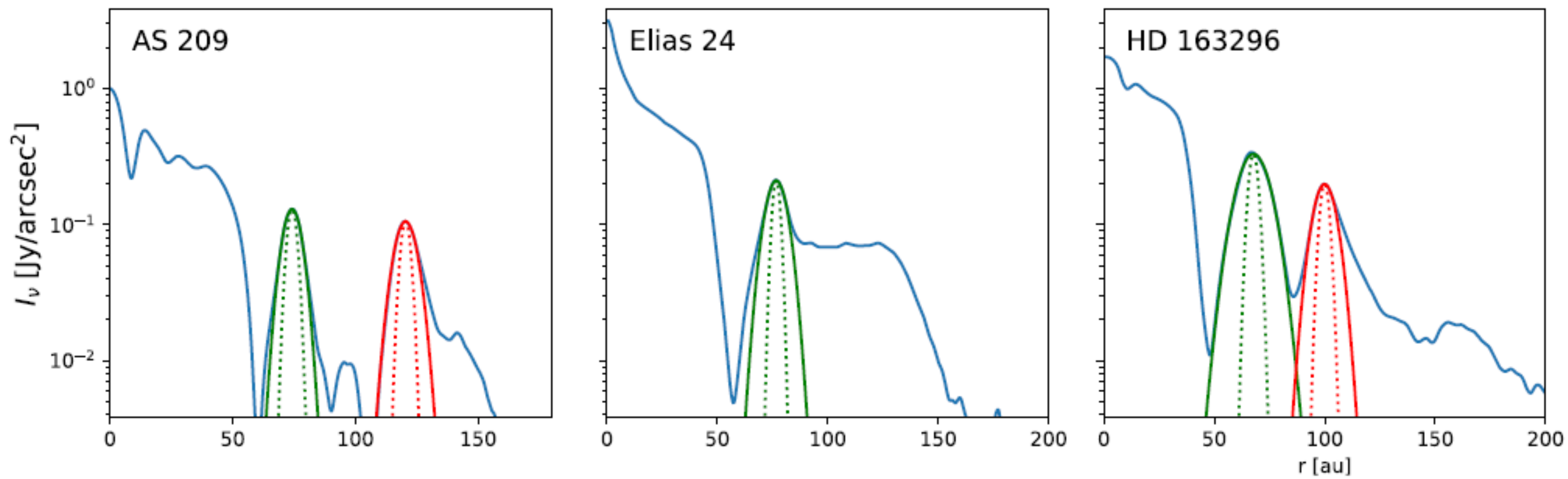
Evolution of macroscopic quantities on secular timescales

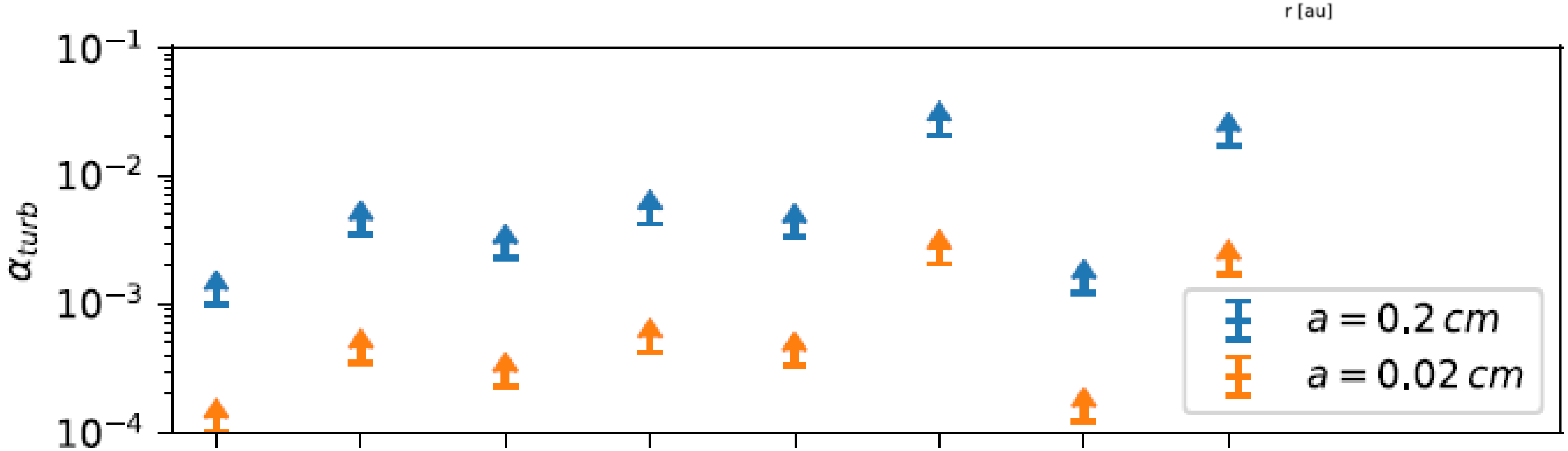
Different approaches

- Theory: MHD simulations

Talk M. Flock

- Vertical/radial extent of dust structures **(Pinte 2016, Dullemond 2018)**



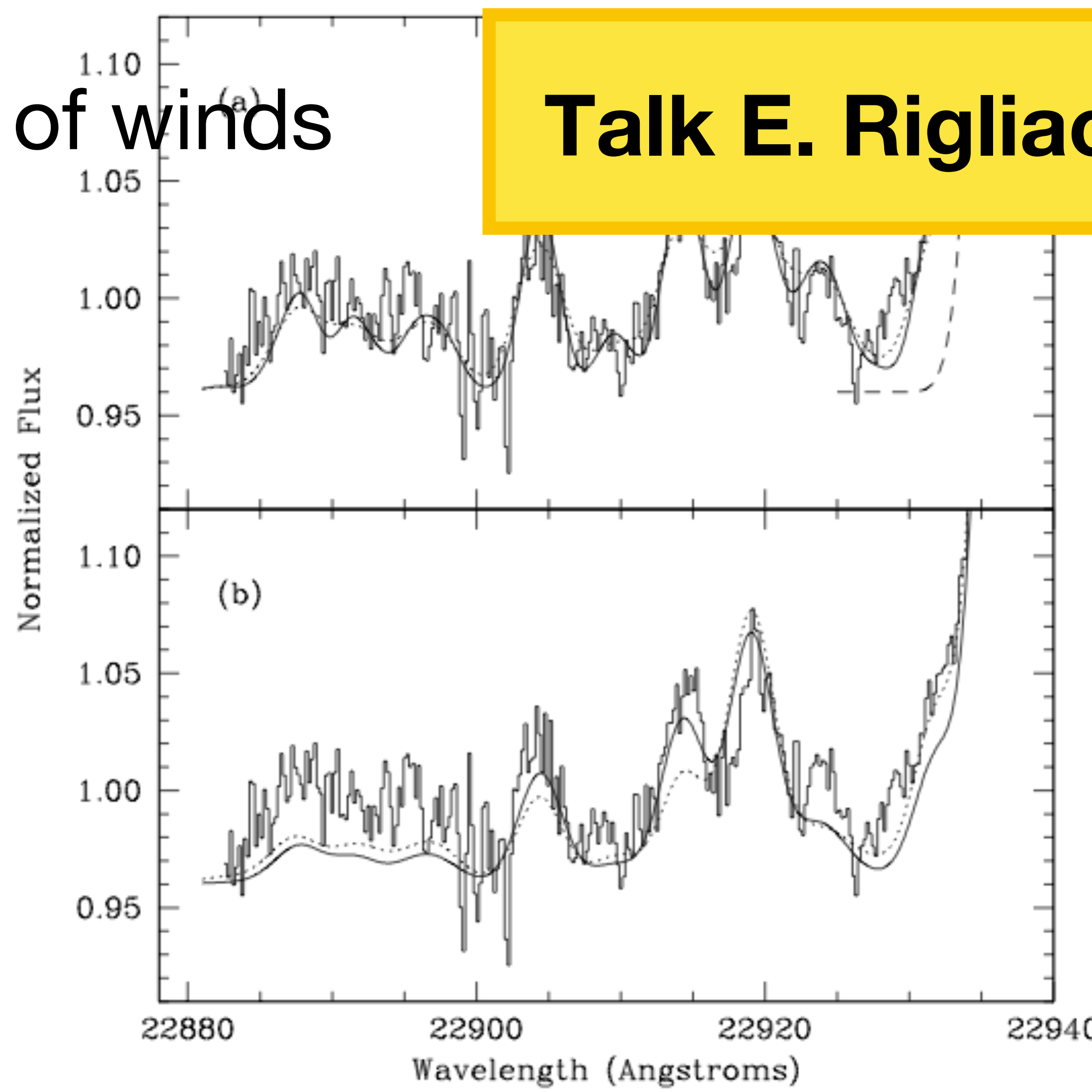


Different approaches

- Direct evidence of turbulence in outer **(Flaherty 2015,17,18, Teague 2016,18)** and inner disc **(Carr et al. 2004; Najita et al. 1996; 2009; Doppmann et al. 2008)**

- Direct evidence of winds

Talk E. Rigliaco



Accretion Approaches

Local detailed studies

Evolution of macroscopic quantities on secular timescales

Macroscopic quantities

- Mass accretion rate
- Disc masses (gas and dust)
- Disc radii (gas and dust)
- Age

Talk C. Manara

Optical

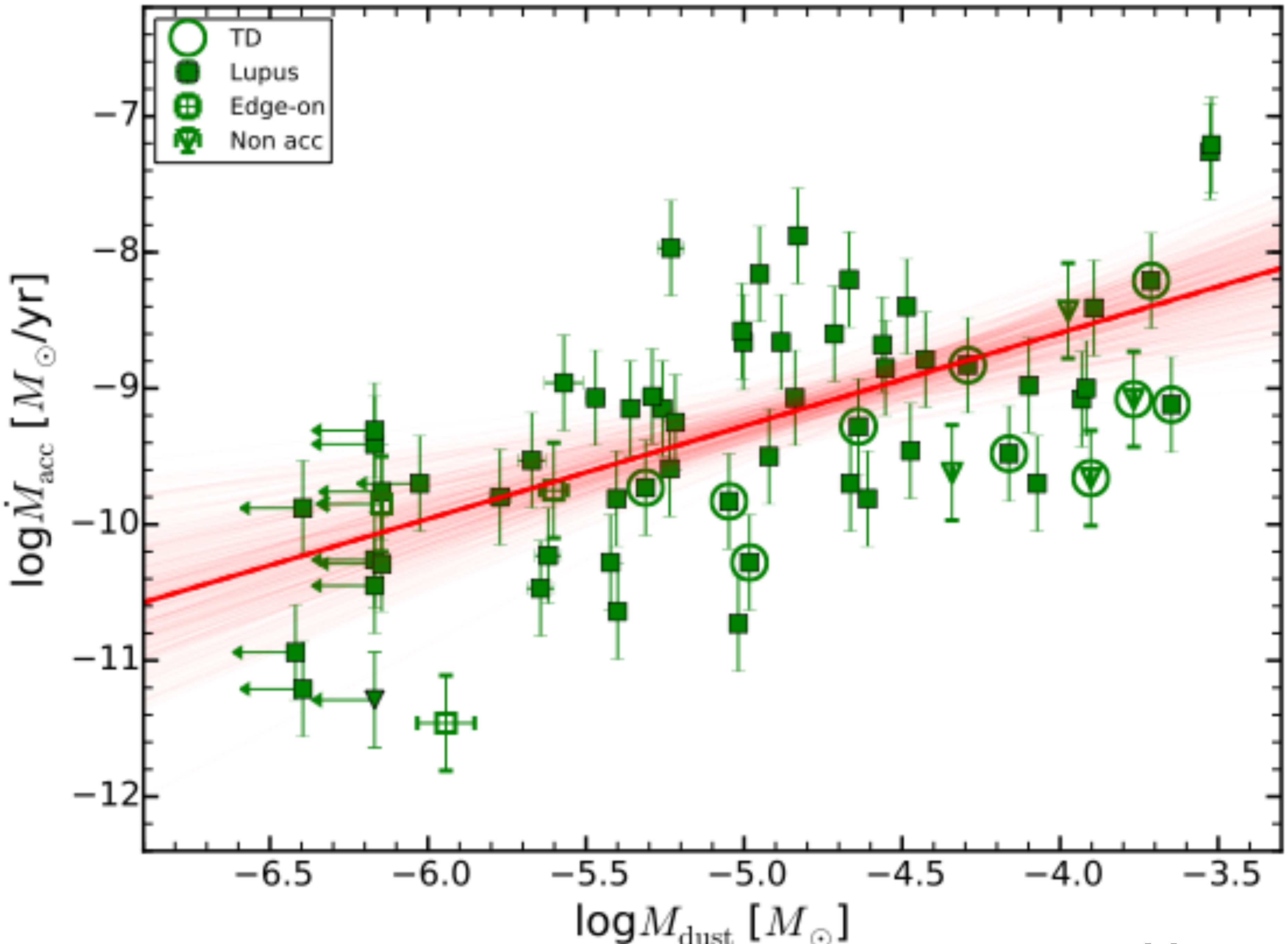
Sub-mm

Talk A. Miotello, M. Tazzari

Textbook case: evolution accretion rate with time

Accretion rate – disc mass

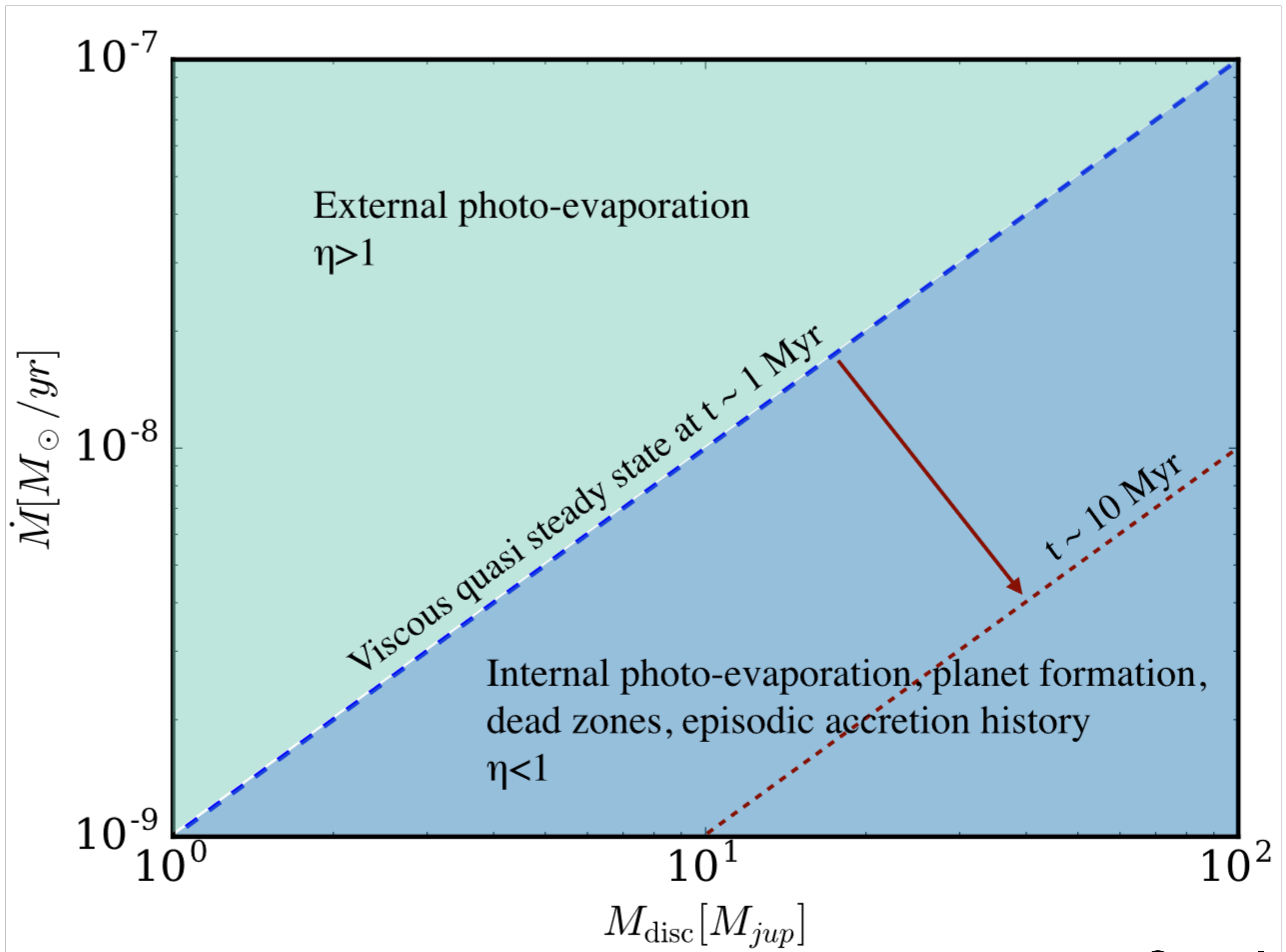
Observational evidence



Manara, GR + 2016
See also Mulders+ 2017

Theoretical expectations

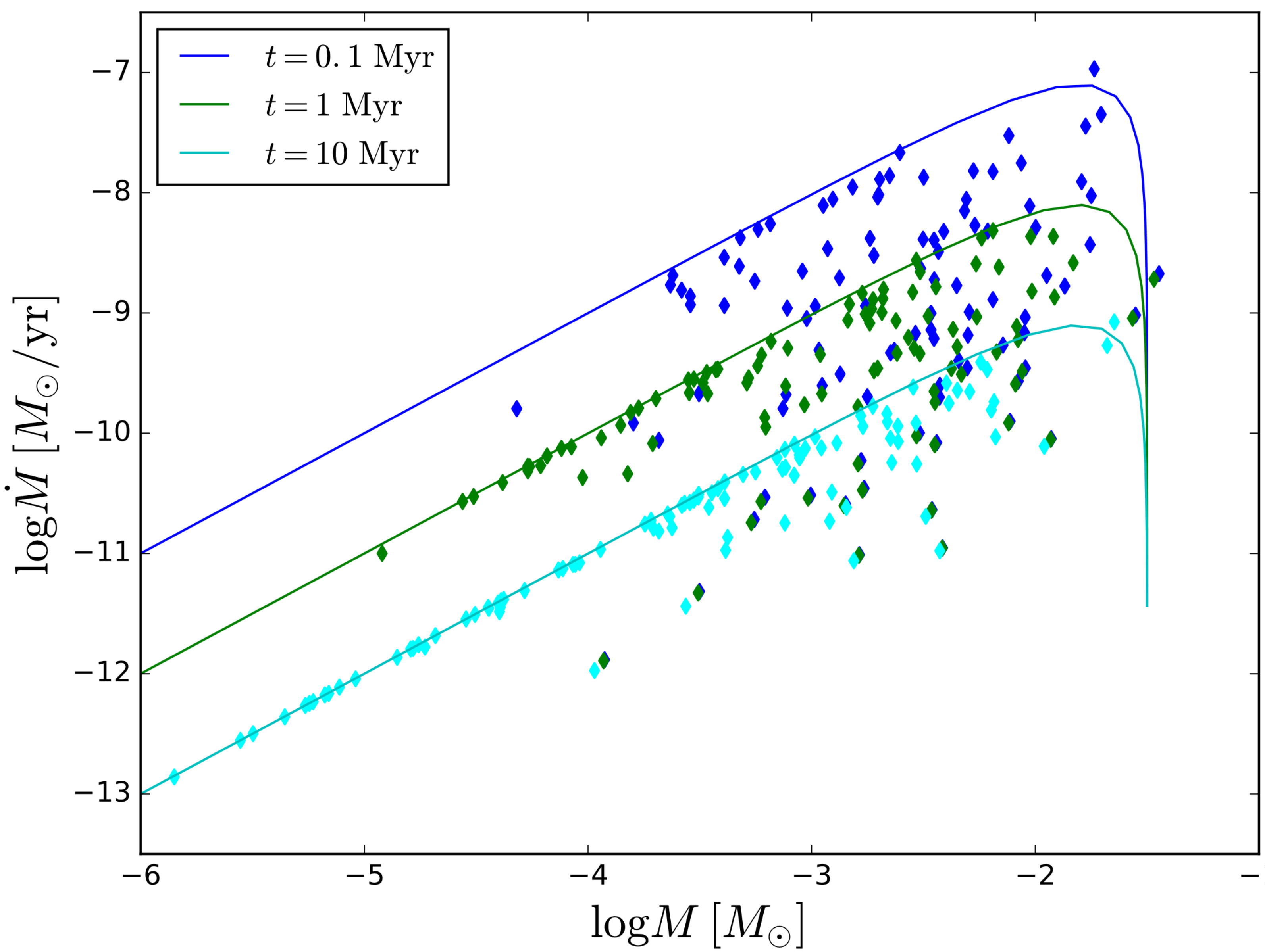
$$\eta = \tau \dot{M} / M_{\rm disc}$$



GR+ 17;
See also Jones+ 2012

In broad agreement with observed values

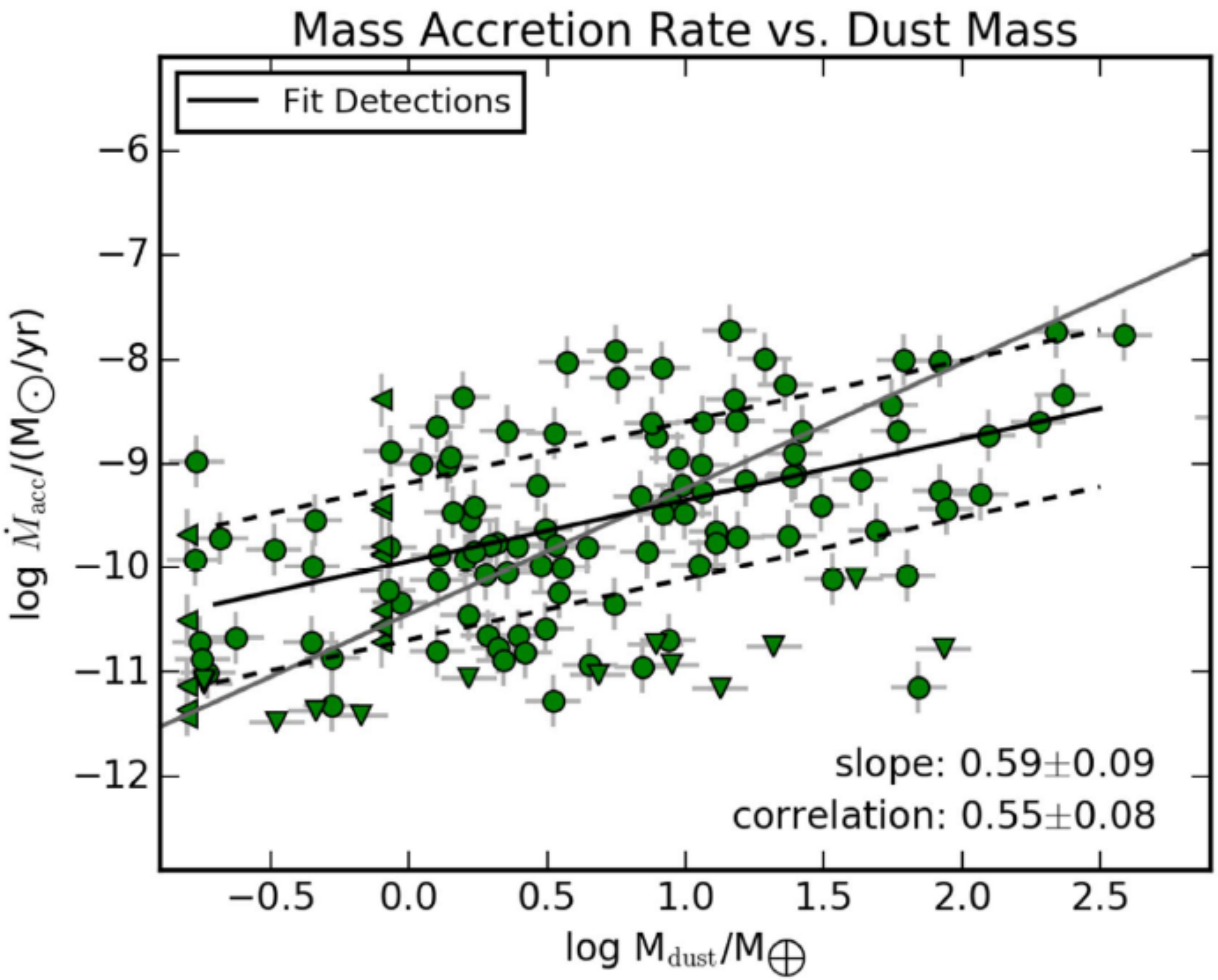
Spread of the correlation depends on time



Lodato+ 17;
See also Mulders+ 17

Points to relatively long viscous times

Does it rule out winds?

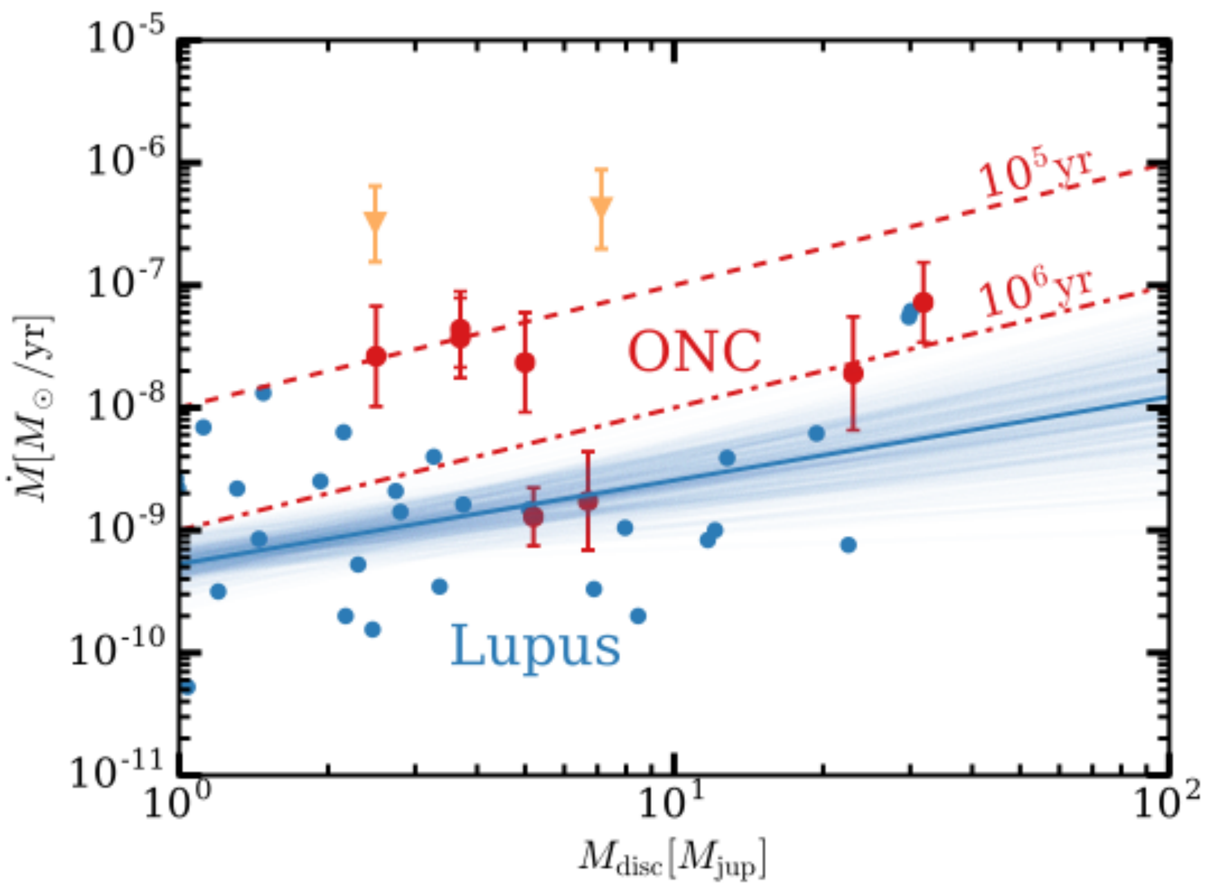


Mulders+ 17

Can be explained with *ad-hoc* initial conditions (where the correlation is already present)

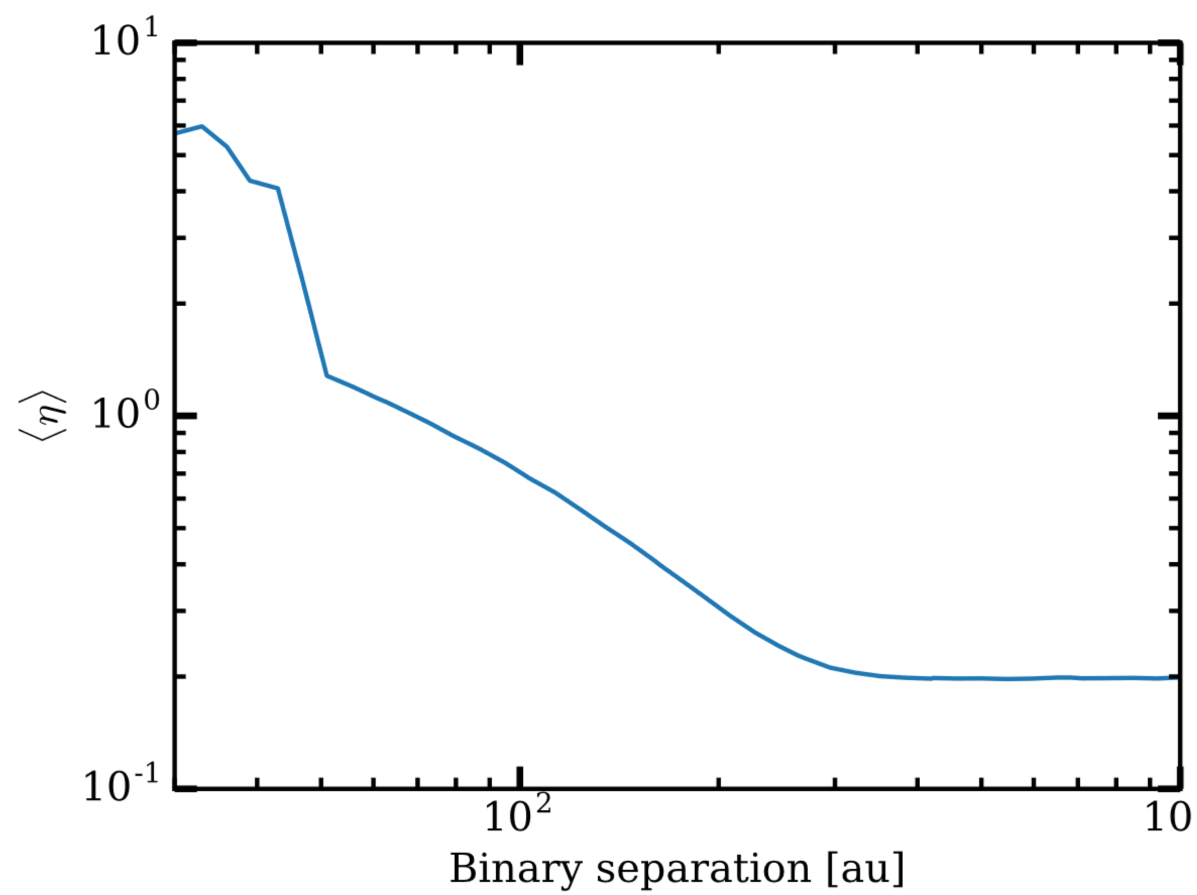
Different environments

High UV irradiation



GR+ 17

Binaries



GR & Clarke 18

Evolution of disc radii

Proto-planetary disc radii

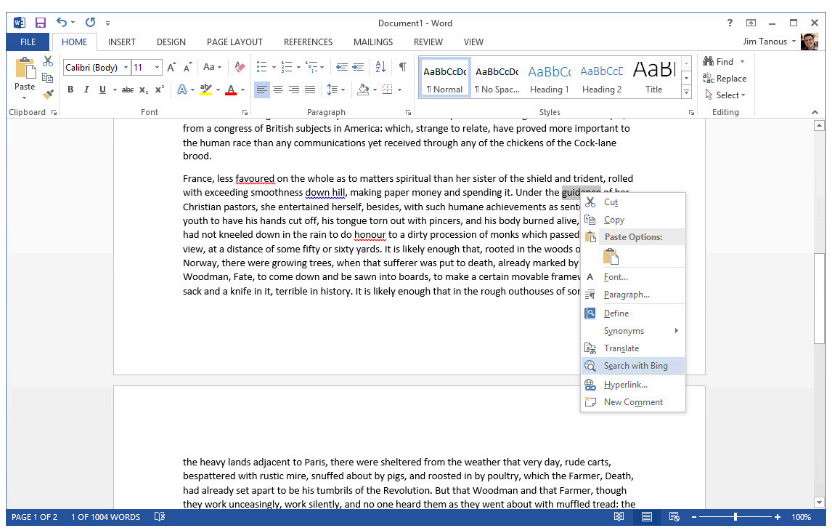
- Viscous spreading is smoking gun signature: mass goes in, angular momentum goes out
- No large sample of radii measured from optically *thin* gas lines (though see Najita & Bergin 2018 for an attempt)
- Possible to do it using *dust* radii?

Viscosity moves things outwards, radial drift inwards. Is the time evolution of dust disc radii set by viscous expansion or radial drift?

One has to be careful…

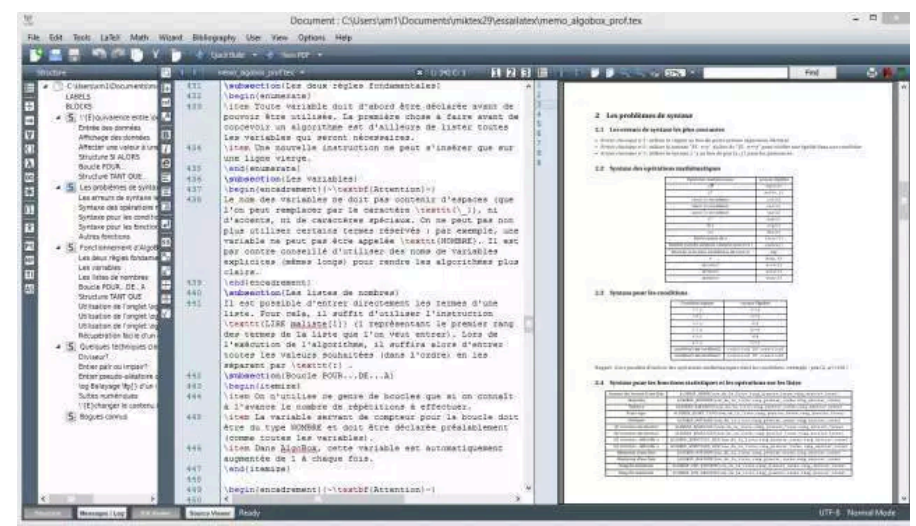
WYSIWYG

What you see is what you get



WYSINWYG

What you see is NOT what you get



LaTeX

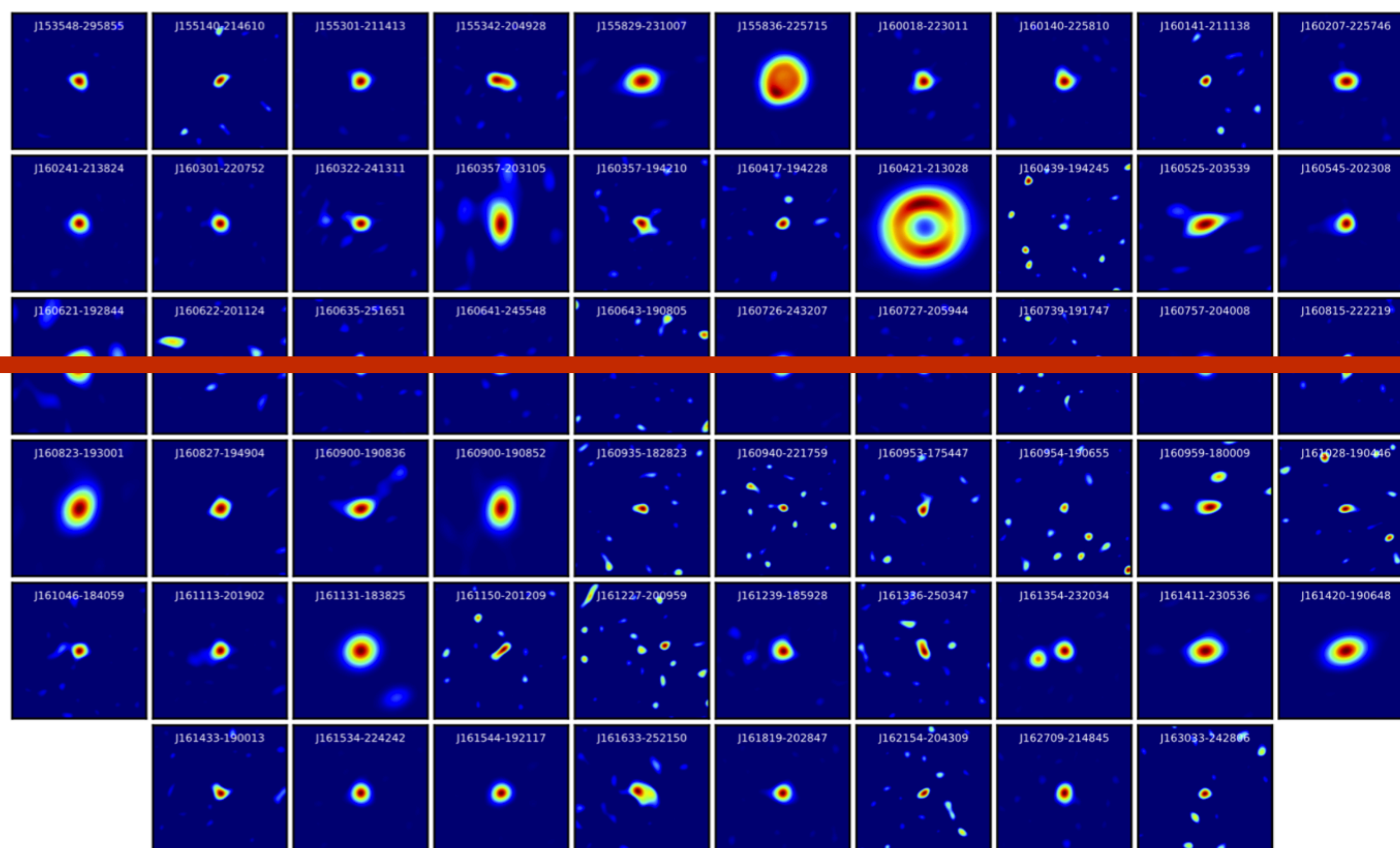
Proto-planetary disc radii

- Important to build statistics of disc properties to feed into planet formation models

- Can be measured efficiently in the sub-mm with ALMA

Ansdell (2016), Barenfeld (2016), Pascucci (2016), …

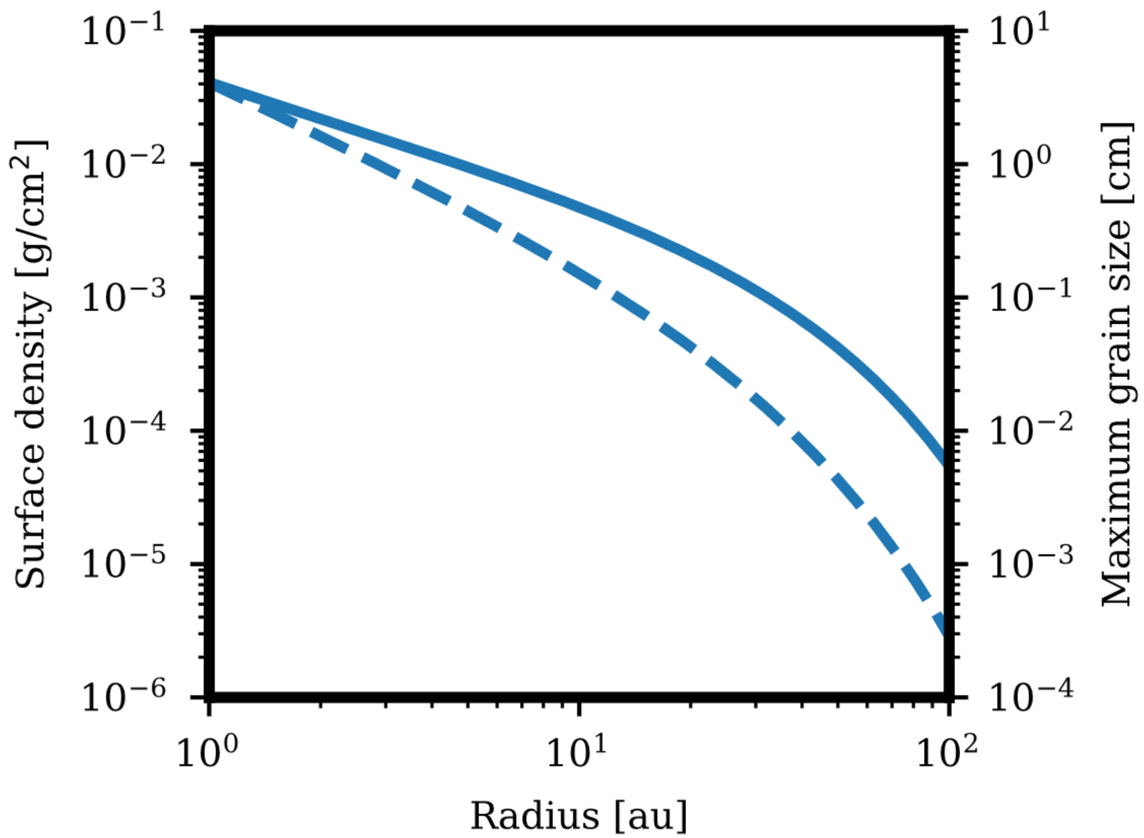
- Importar operating
in proto- ad, *radial*
drift shri

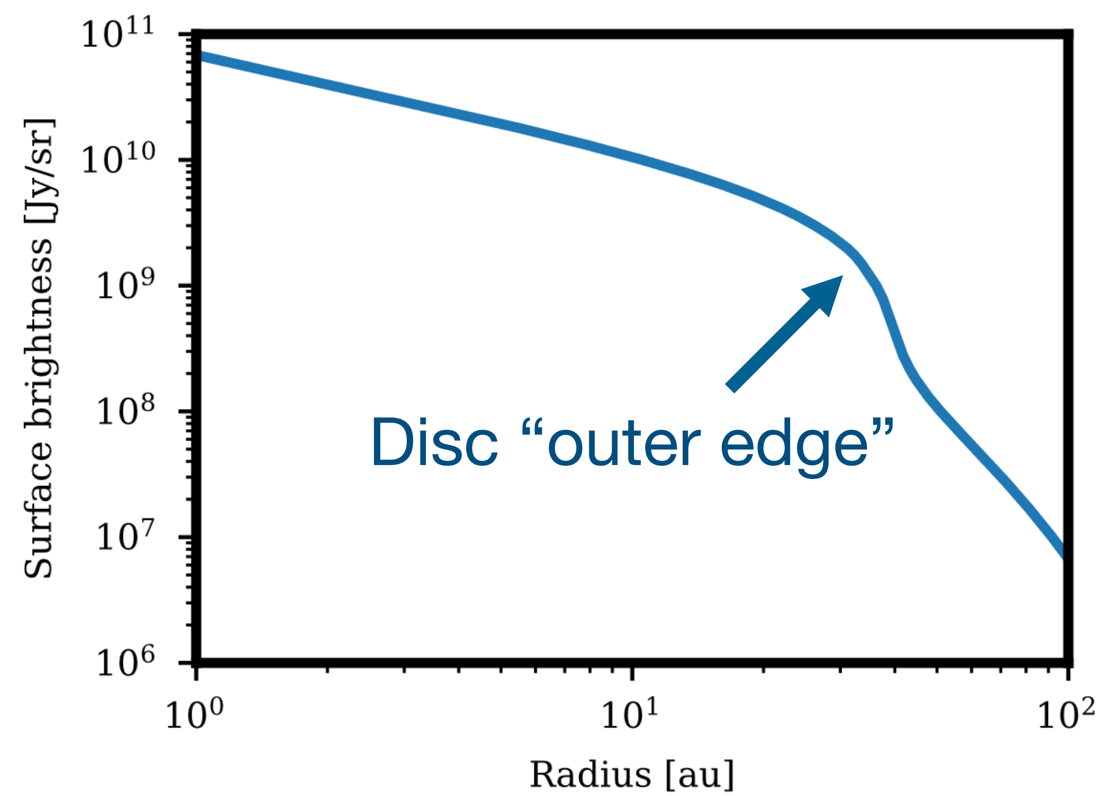


Proto-planetary discs are more like LaTex than Word!

A simple example

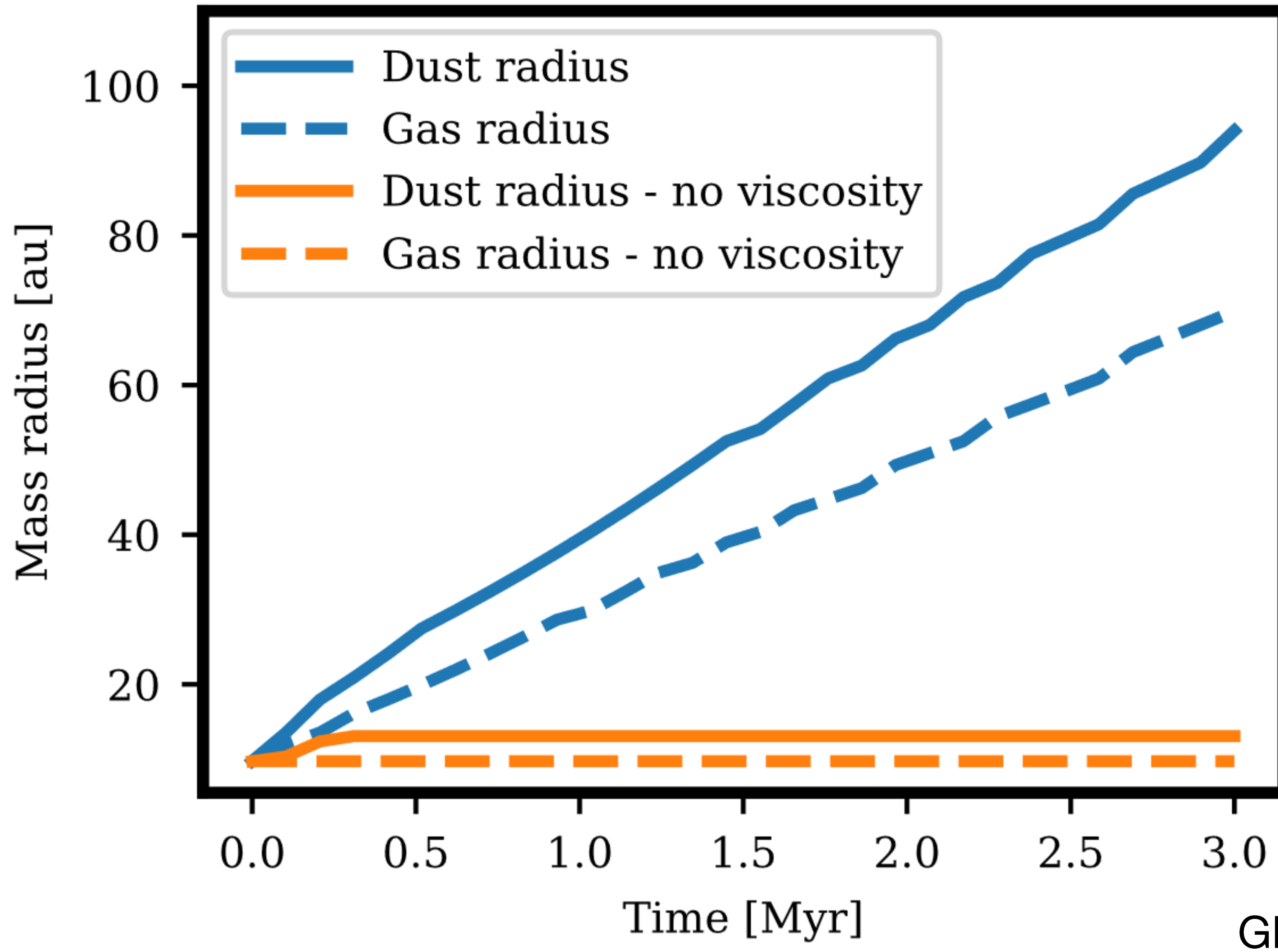
$$S_b(R) \sim T(R)\kappa_\nu \Sigma_{\rm dust}$$





Compact disc even if *dust* disc is larger

Time evolution - mass

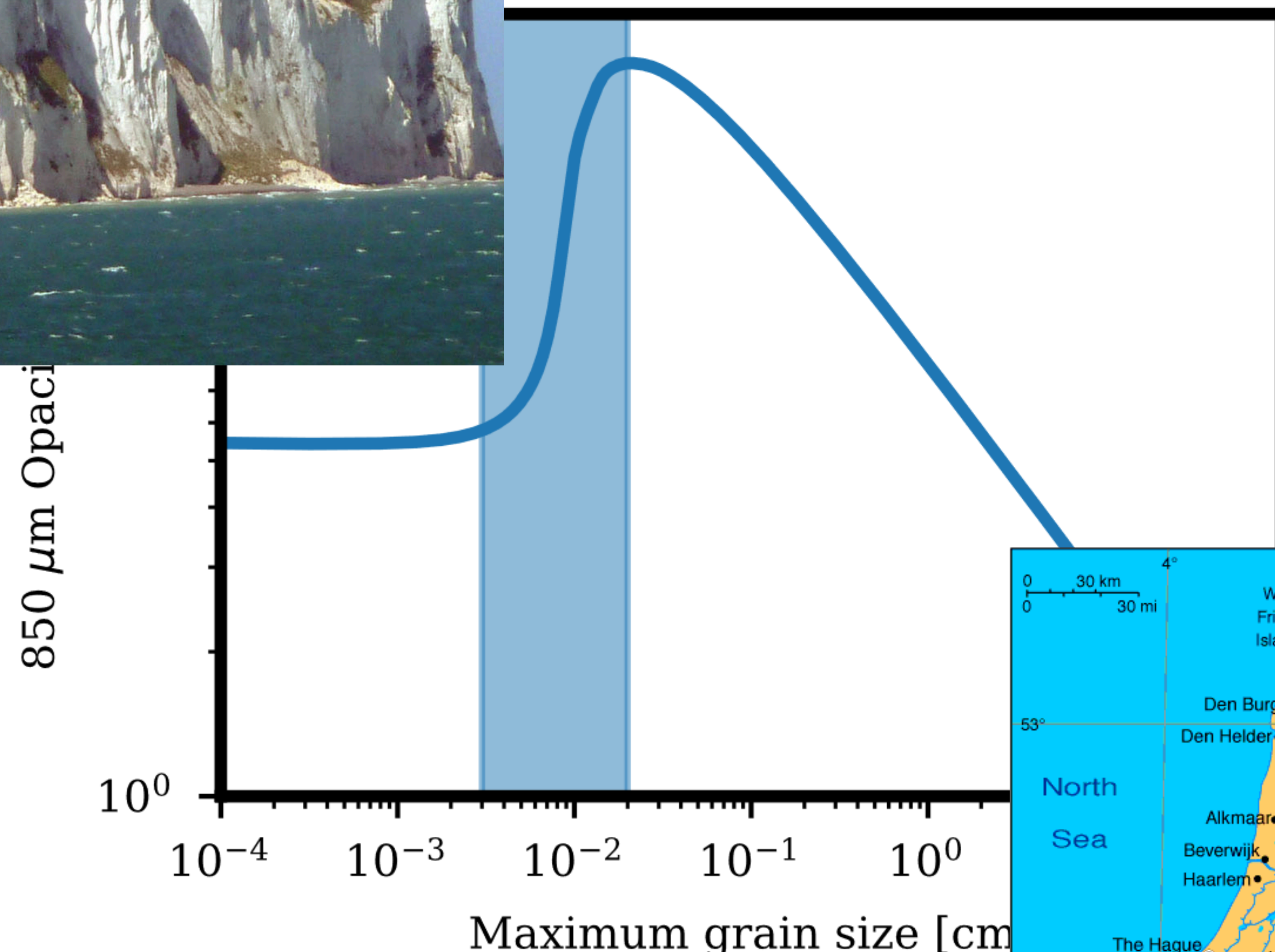


GR+ (2019a), submitted

Mass radius contains 63% of disc mass

Viscosity wins: dust disc expands

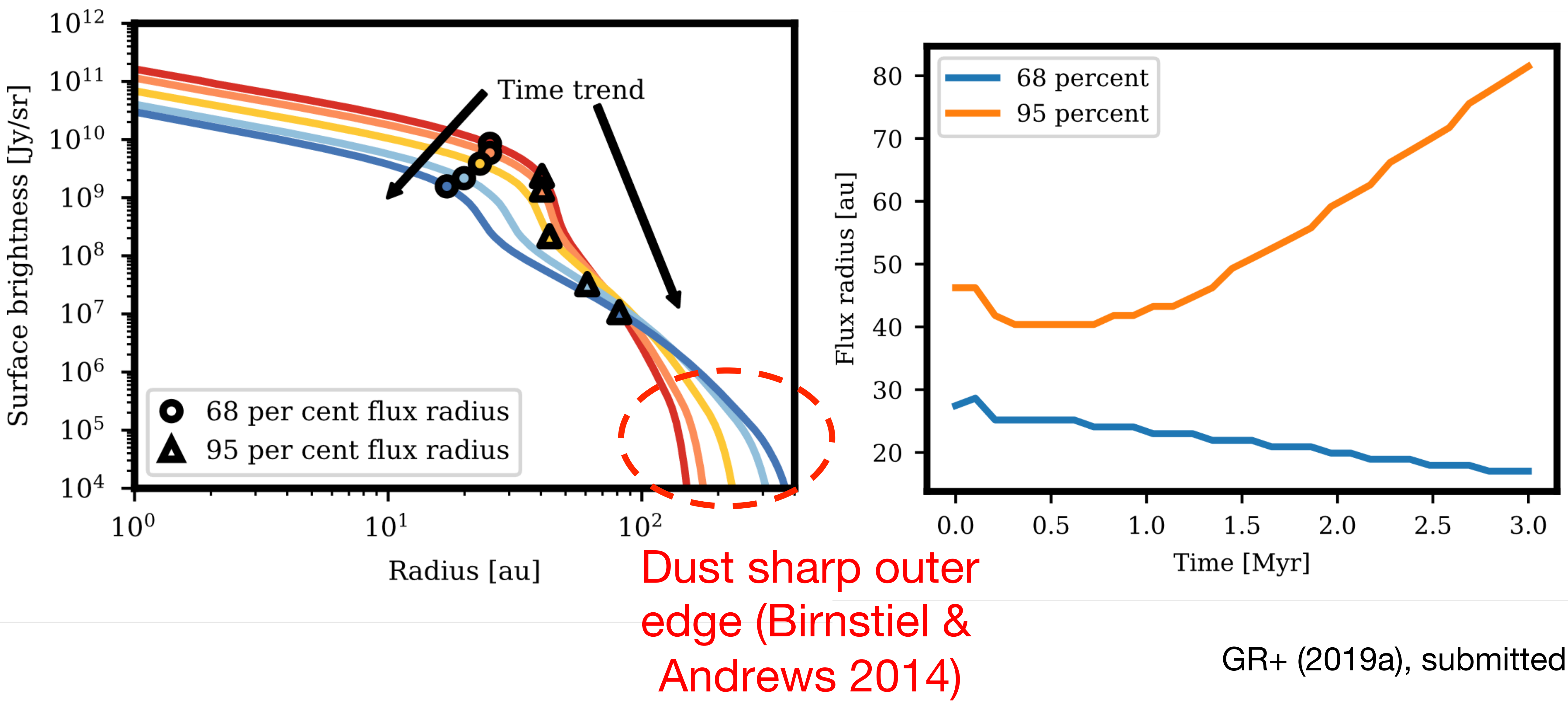
of the issue



Large drop in opacity ove

range of grain size

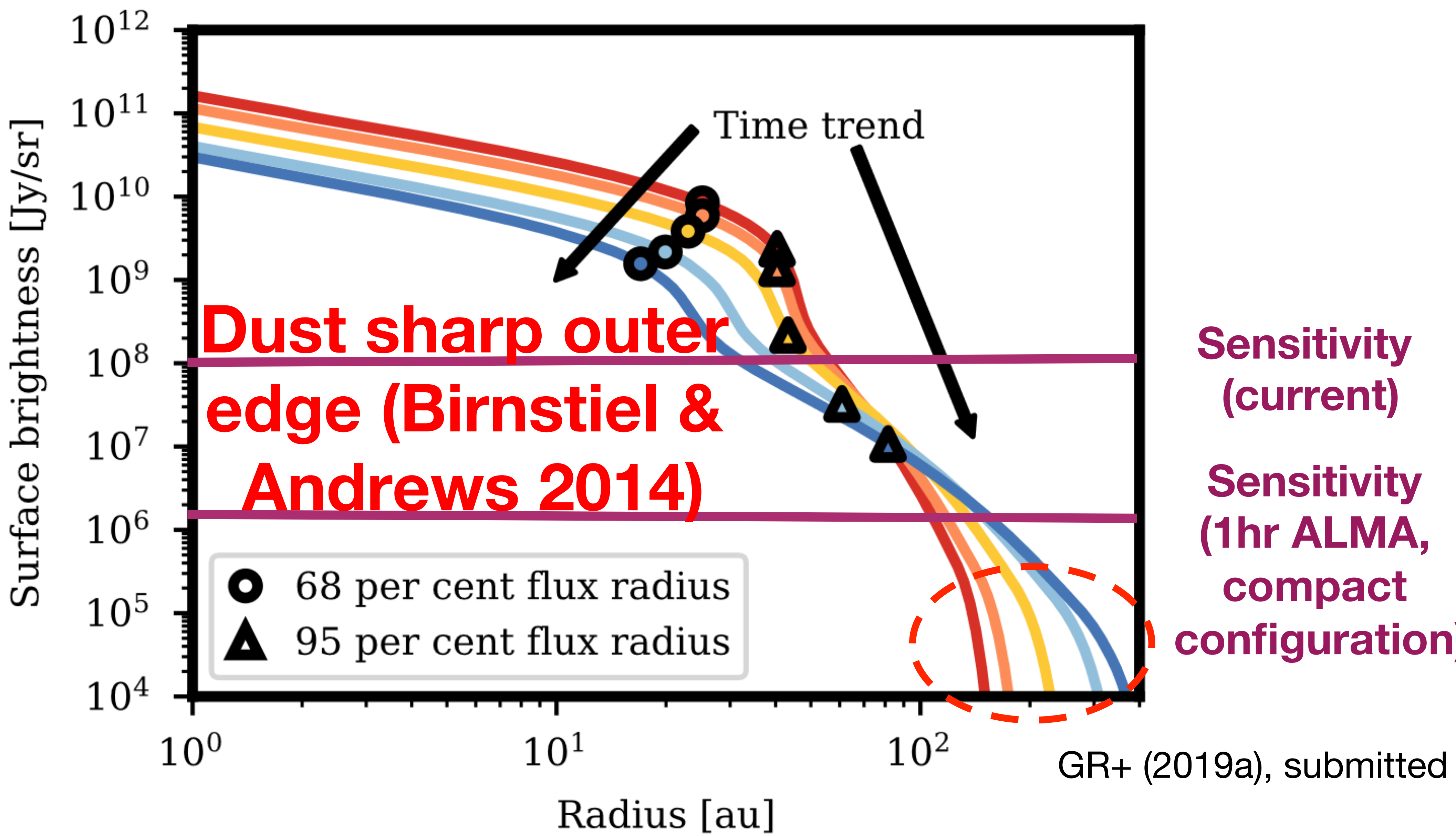
Time evolution - flux



GR+ (2019a), submitted

68 per cent radii *decrease*
95 per cent radii *increase*

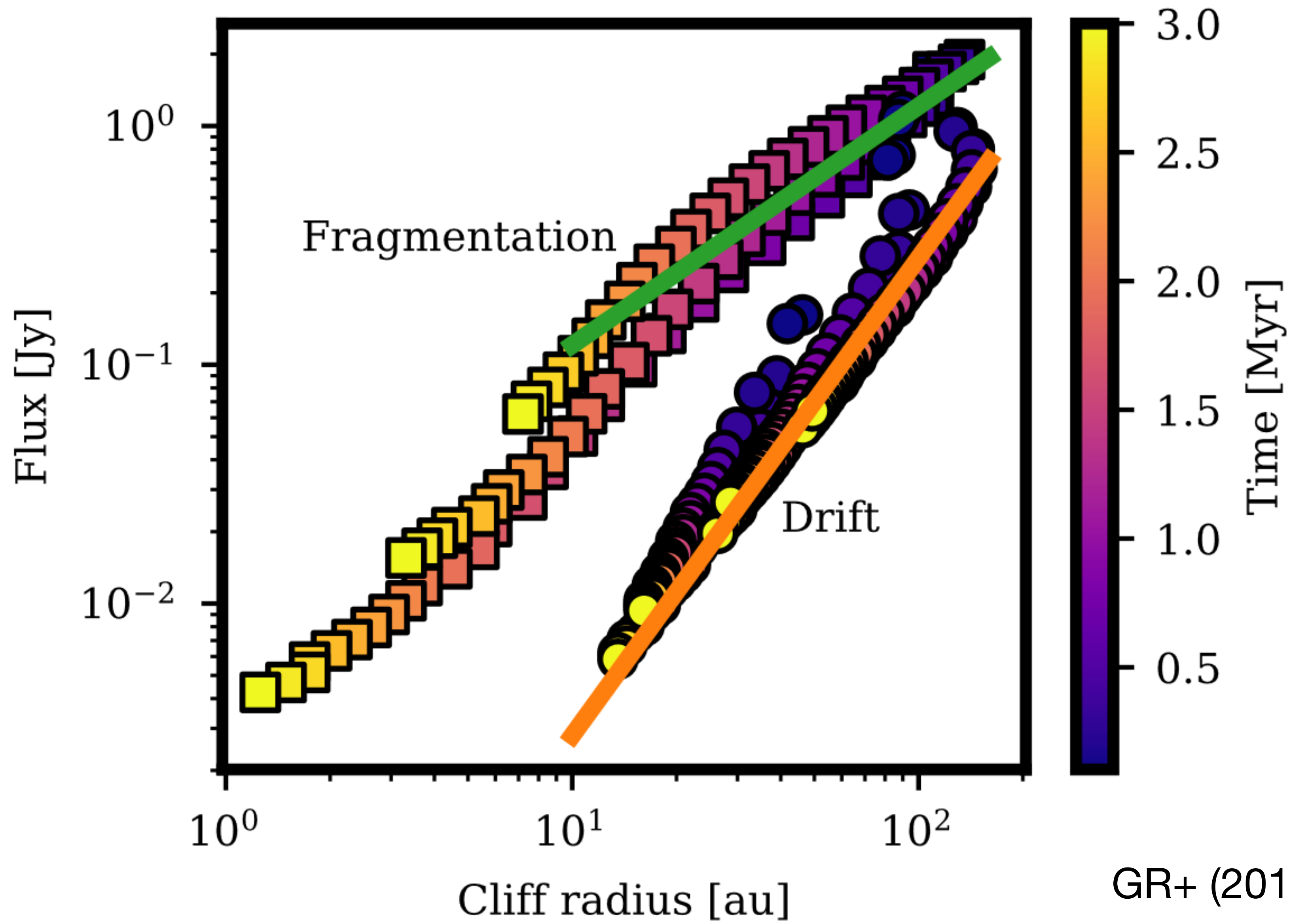
Time evolution - flux



GR+ (2019a), submitted

Current ALMA surveys are sensitive only to the cliff radius rather than to the viscous expansion

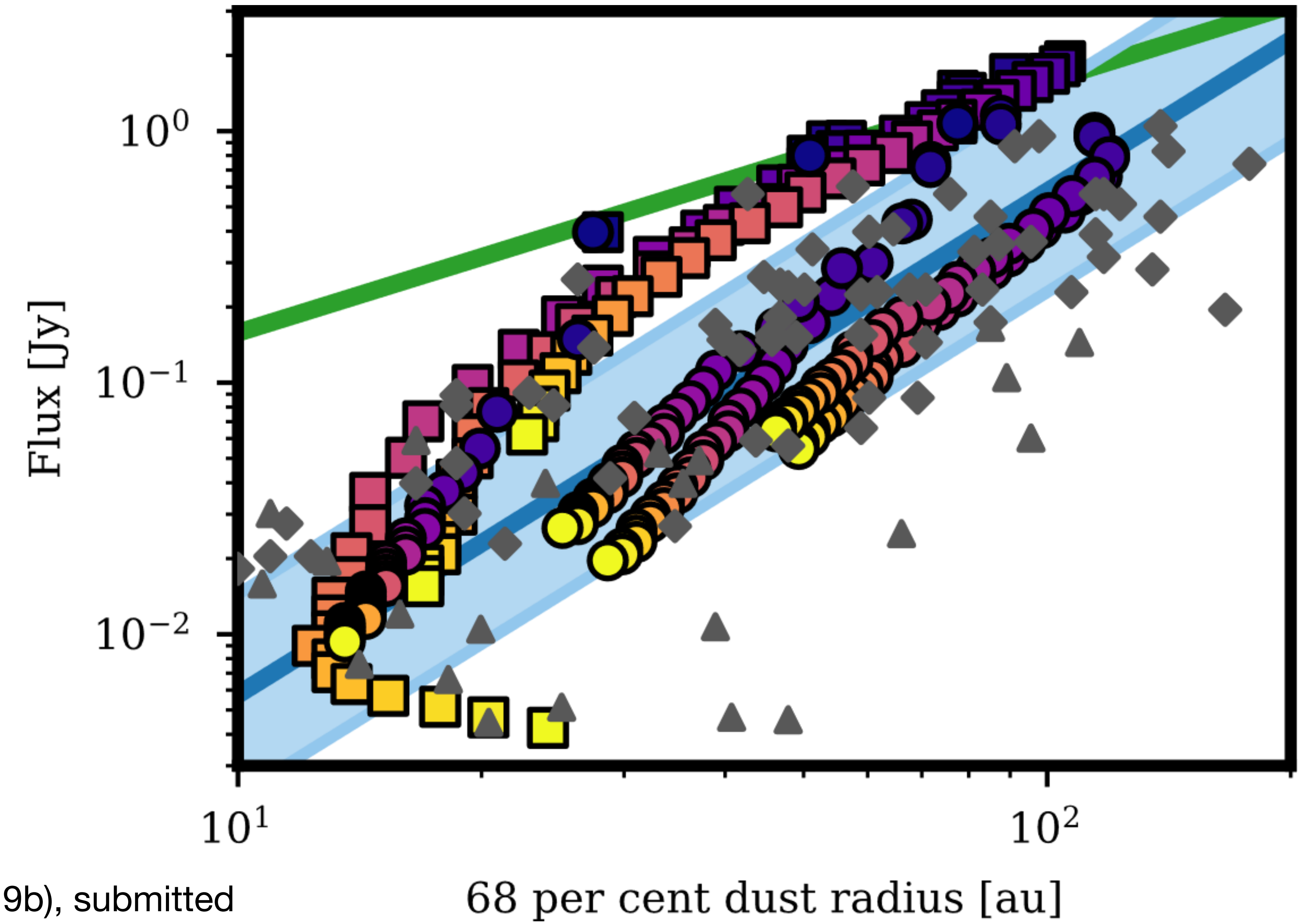
Are the measured radii useless?



GR+ (2019b), submitted

Different flux-radius relation depending on grain growth regime

Flux-radius relation

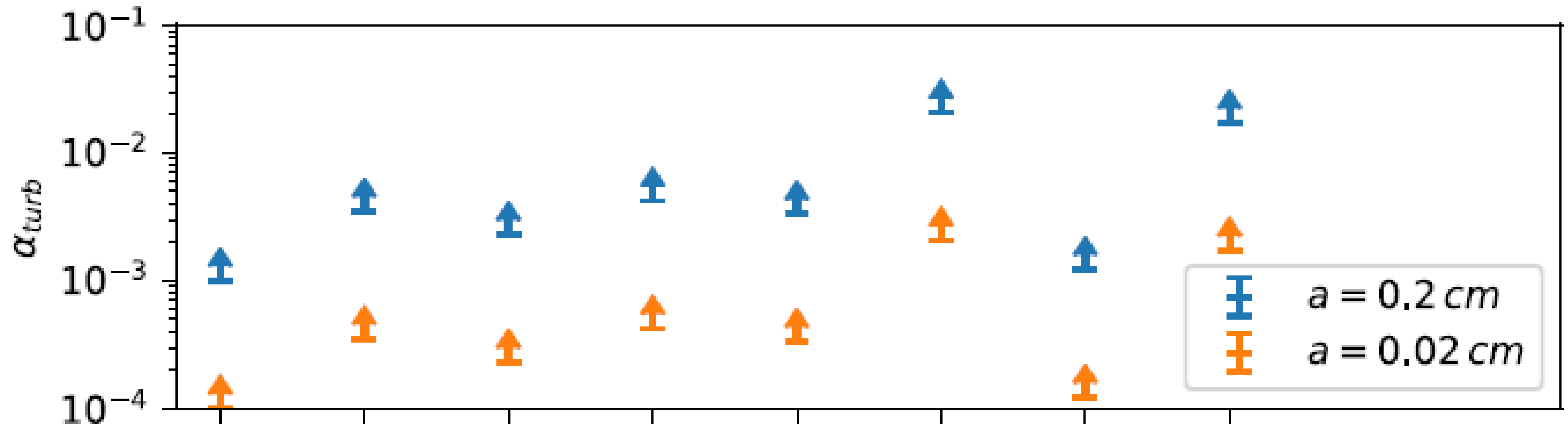


GR+ (2019b), submitted

Data from Tripathi (2017), Andrews (2018)

Data points to drift-dominated regime

Summary



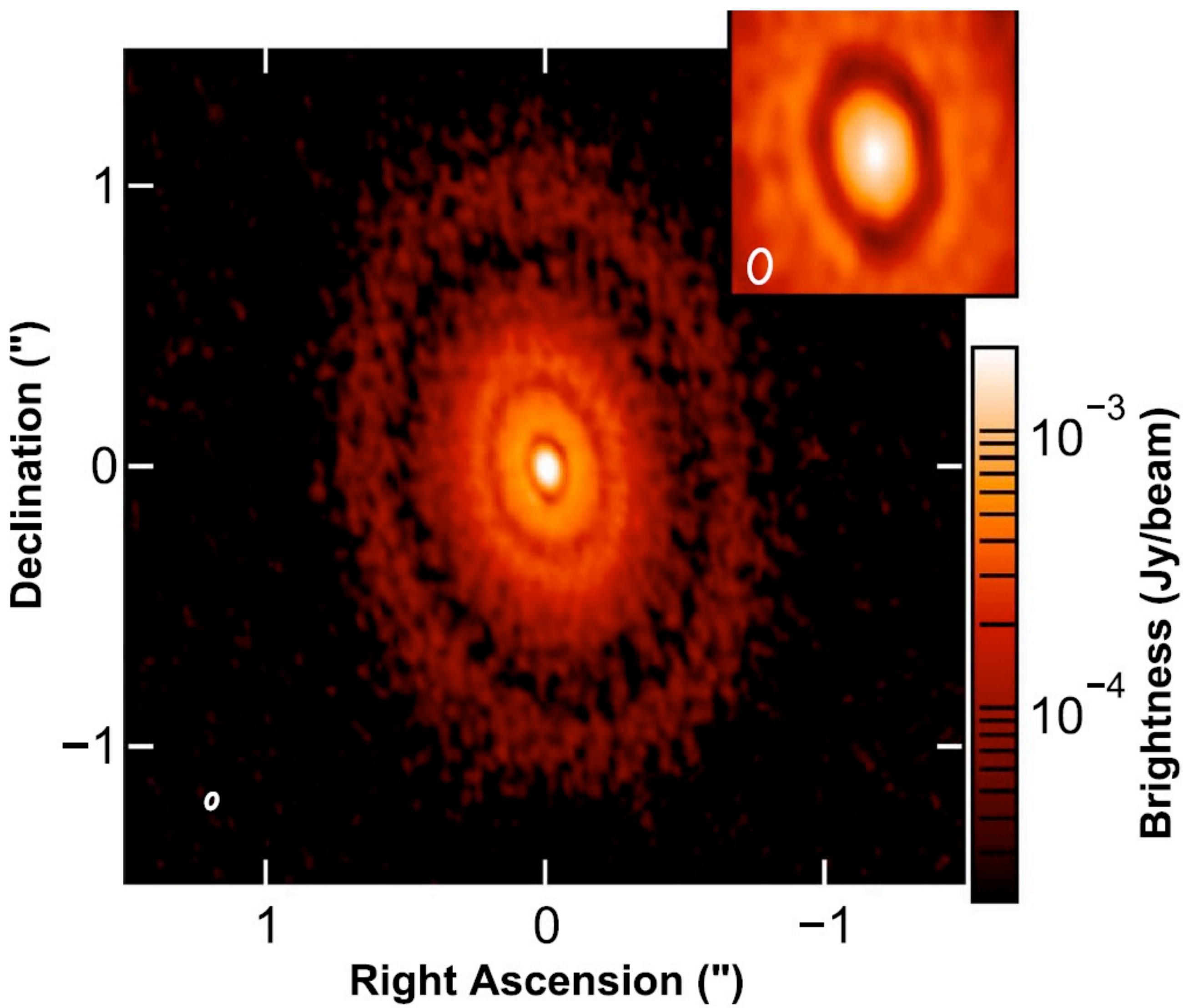
Method	Alpha value
Disc radii	<~10^{-3}
Spread accretion rate – disc mass	~10^{-3}
Lack of turbulence from CO rotational transitions	<10^{-2}
Dust settling	10^{-4}

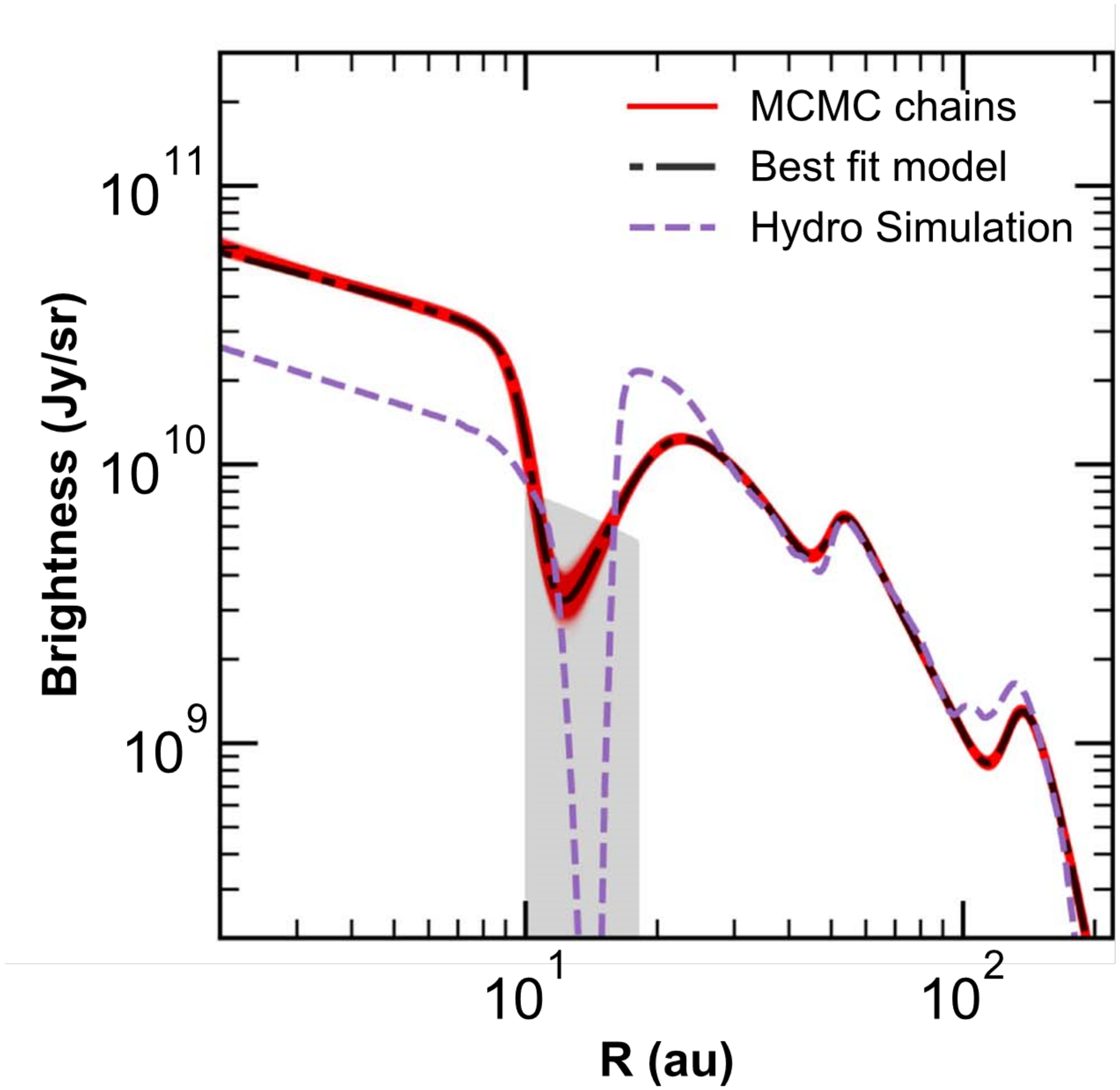
Conclusions

- Evolution of macroscopic quantities poses constraints on disc evolution processes
- General conclusion: if discs are viscous, they are unlikely to be *highly* viscous
- So far absence of evidence of viscosity/turbulence in the outer disc (but no evidence of absence)

Backup slides

An oddball?

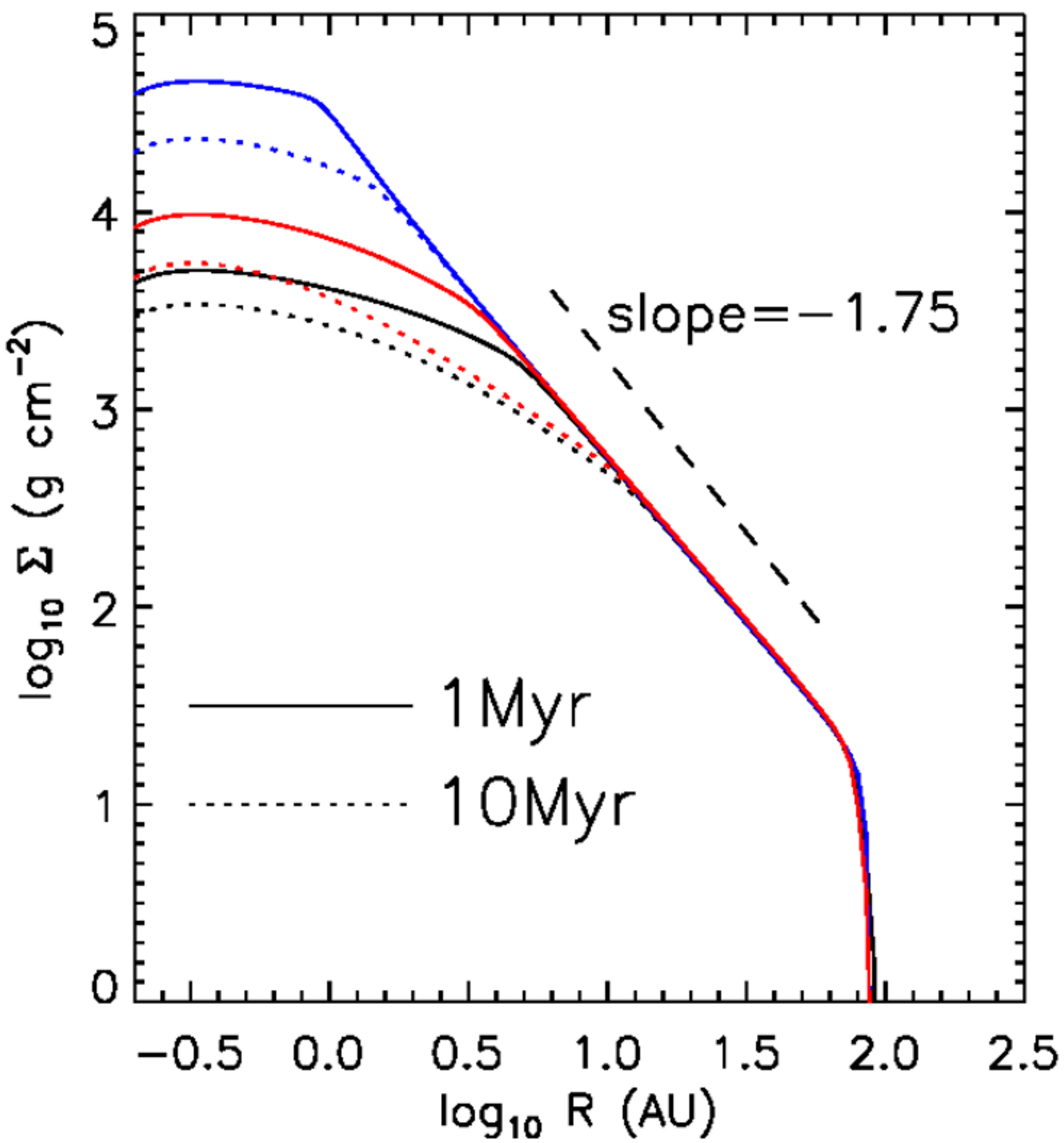




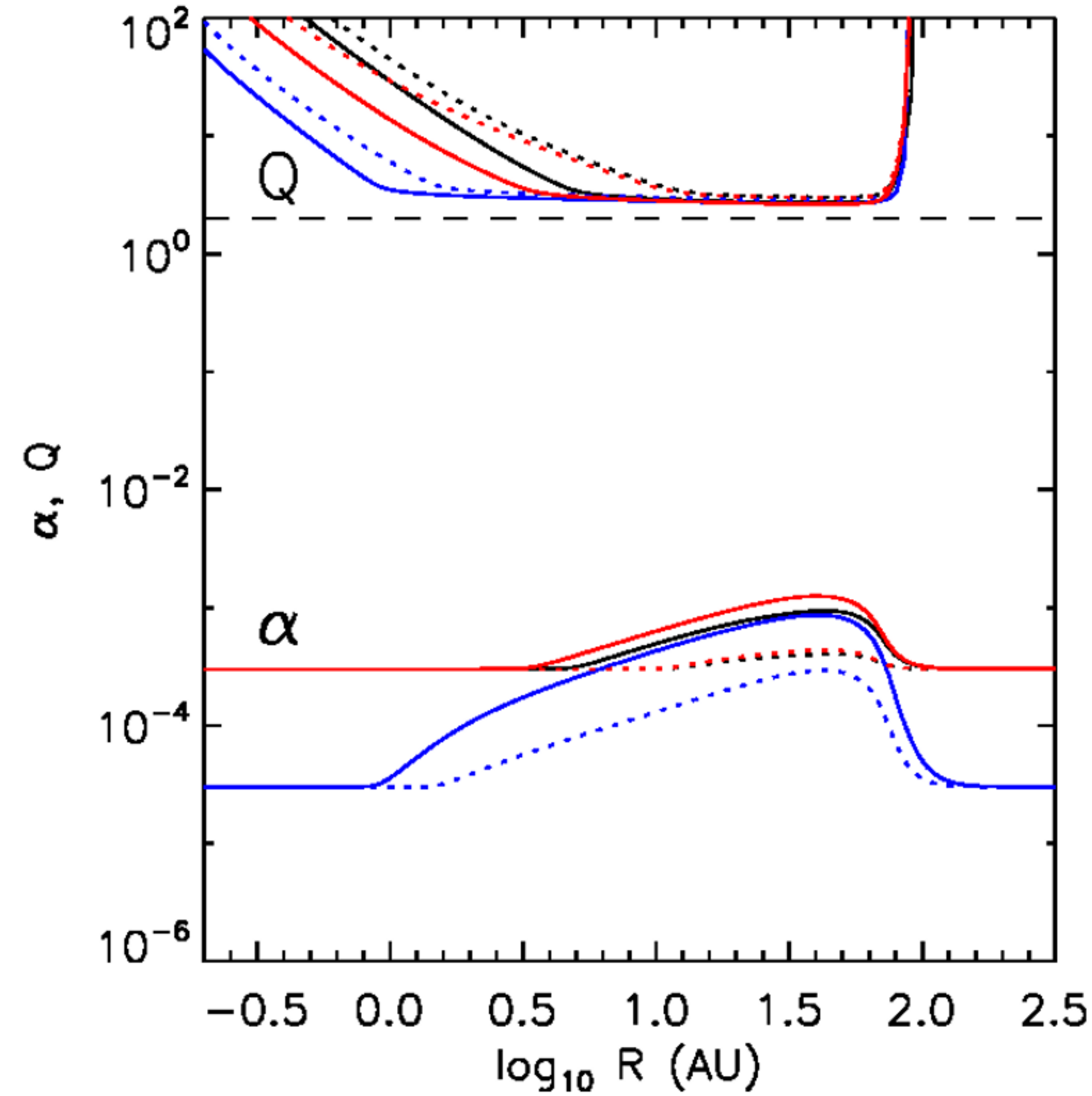
Matches all observational constraints with grains in fragmentation limit; alpha=0.012

An alternative framework

Hartmann & Bae 2018



$0.02\ M_\odot$ within 1 AU



Low levels of viscosity

Simple scaling relations

$$F_\nu \approx \pi B_\nu(T)\Sigma_d \kappa_\nu R_{\mathrm{cliff}}^2$$

Flux dominated by cliff radius

$$a_{\mathrm{frag}} = f_{\mathrm{f}} \frac{2}{3\pi} \frac{\Sigma_{\mathrm{g}}}{\rho_{\mathrm{s}}\alpha} \frac{u_{\mathrm{f}}^2}{c_s^2}$$

$$a_{\mathrm{frag}} \propto \frac{\Sigma_{\mathrm{g}}}{c_s^2} = \frac{\Sigma_{\mathrm{d}}}{\epsilon c_s^2}$$

$$\boxed{F_\nu \propto R_{\mathrm{cliff}}}$$

$$a_{\mathrm{drift}} = f_{\mathrm{d}} \frac{2\,\Sigma_{\mathrm{d}}}{\pi\,\rho_{\mathrm{s}}} \frac{V_{\mathrm{k}}^2}{c_s^2} \gamma^{-1}$$

$$a_{\mathrm{drift}} \propto \left(\frac{H}{R}\right)^{-2} \Sigma_{\mathrm{d}}$$

$$\boxed{F_\nu \propto R_{\mathrm{cliff}}^2}$$

Grain growth model

Birnstiel+ (2012)

$$a_{\mathrm{frag}} = f_{\mathrm{f}} \frac{2}{3\pi} \frac{\Sigma_{\mathrm{g}}}{\rho_{\mathrm{s}} \alpha} \frac{u_{\mathrm{f}}^2}{c_s^2}$$

Turbulence-induced fragmentation

$$a_{\mathrm{drift}} = f_{\mathrm{d}} \frac{2\,\Sigma_{\mathrm{d}}}{\pi\,\rho_{\mathrm{s}}} \frac{V_{\mathrm{k}}^2}{c_s^2} \gamma^{-1}$$

Grains grow as fast as they drift

Fiducial model: $\alpha=10^{-3}$, R=10 au, M=0.1 $M_\odot$

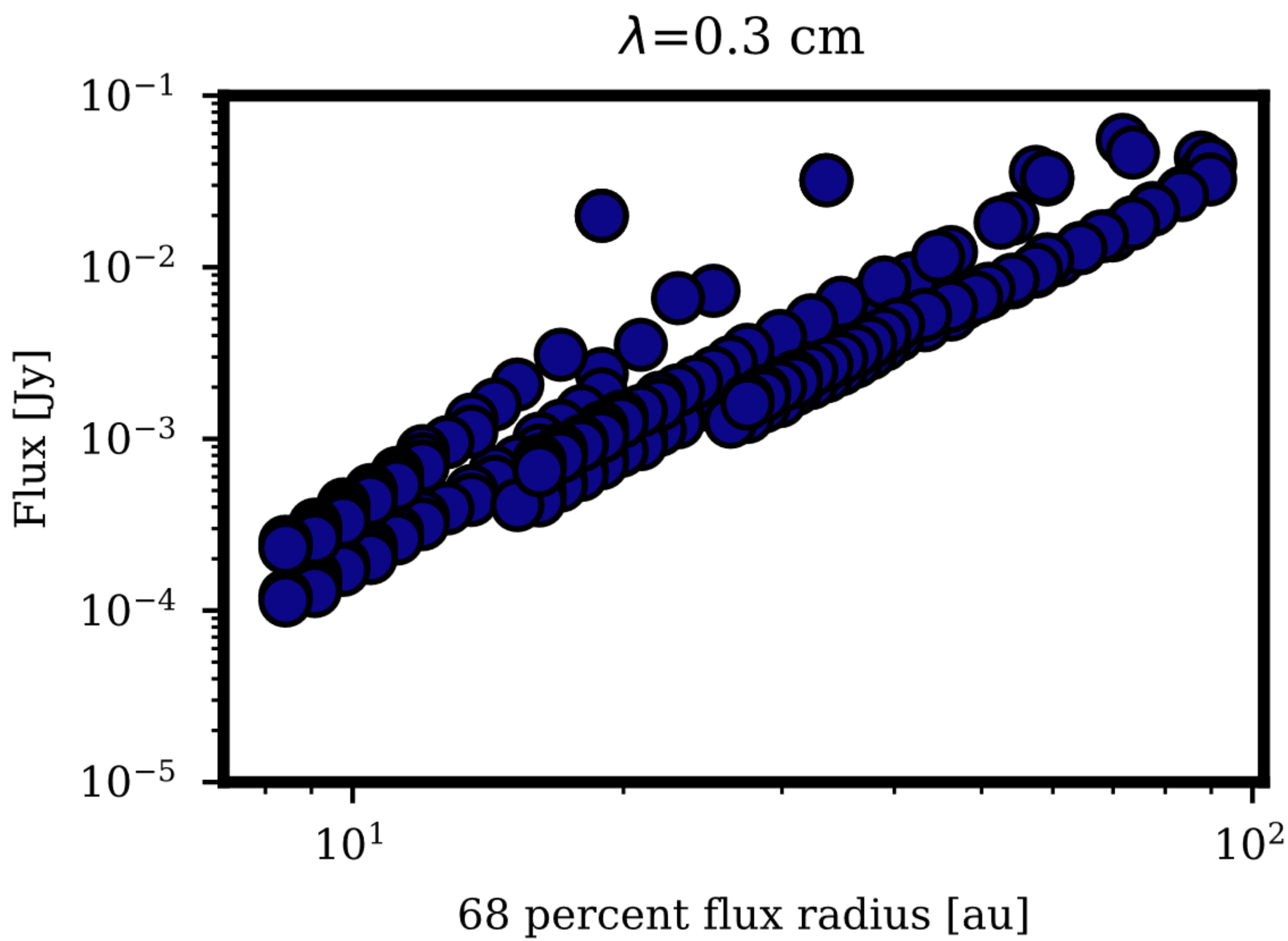
So does everything work?

Discs still there *despite* radial drift, with the right radii and fluxes

Two pending issues:

- *large* discs (>100 au) become small (~50 au) after 2 Myr. Traps?
- 3mm spectral indexes. Clearly need more observational input from ALMA. Note however that spatially integrated spectral index measures grain size *slope*, more than the *grain size*

Longer wavelengths

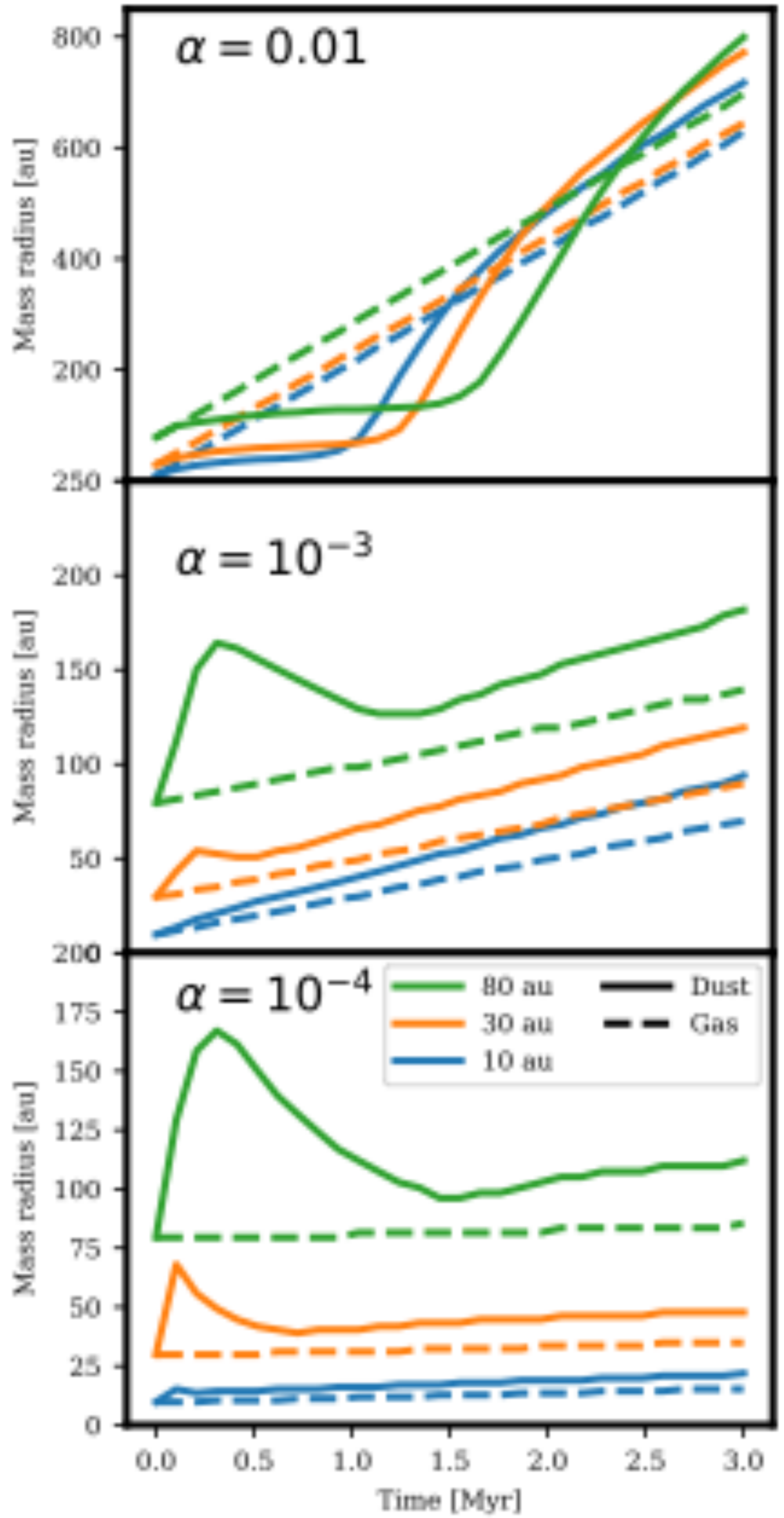


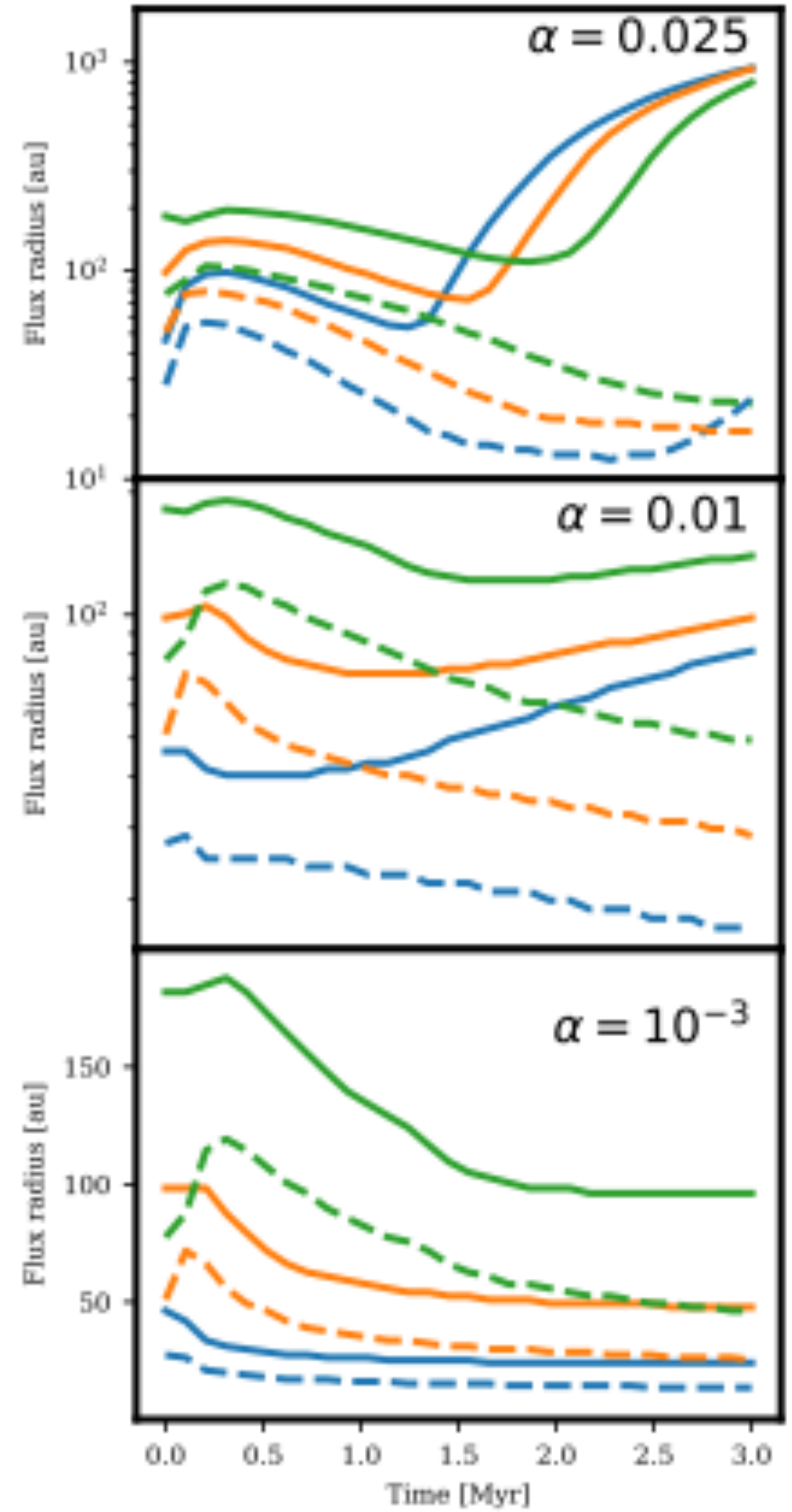
$$F_\nu \propto \kappa_\nu a_{\rm cliff} R_{\rm cliff}^2 \nu^2$$

$$\boxed{F_\nu / R_{\rm cliff}^2 \propto \nu^2}$$

Varying α

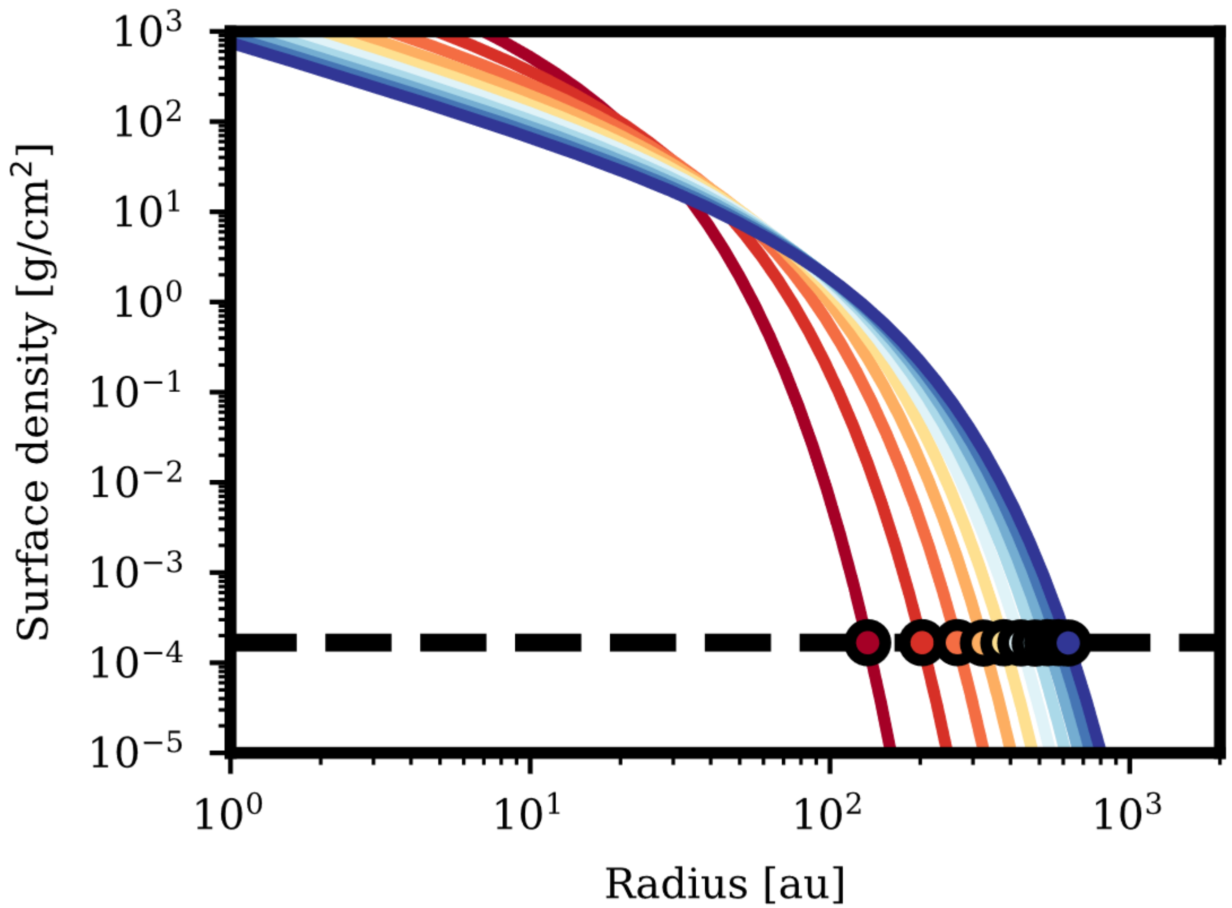
GR+ (2019a), submitted

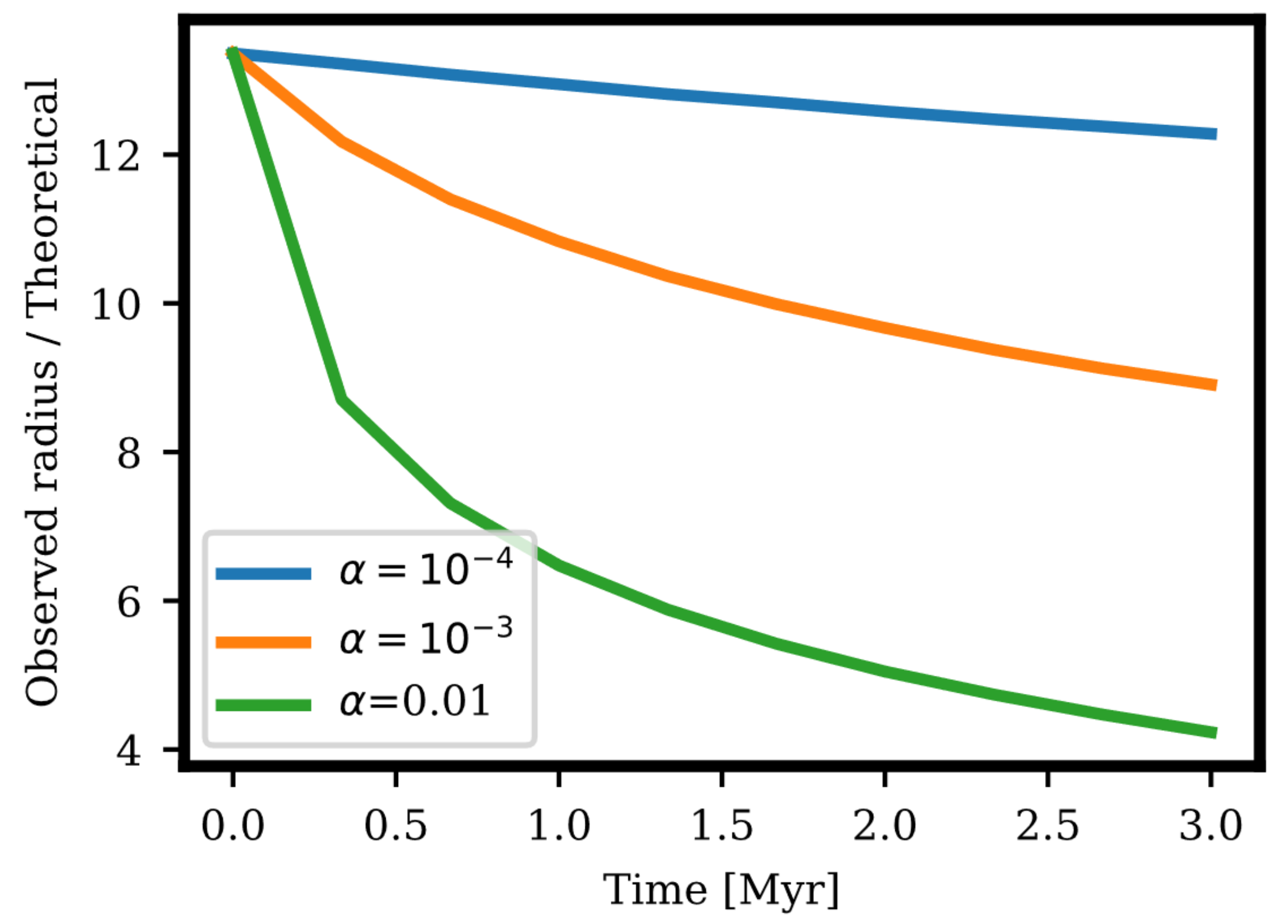




Rate of spreading increases with α

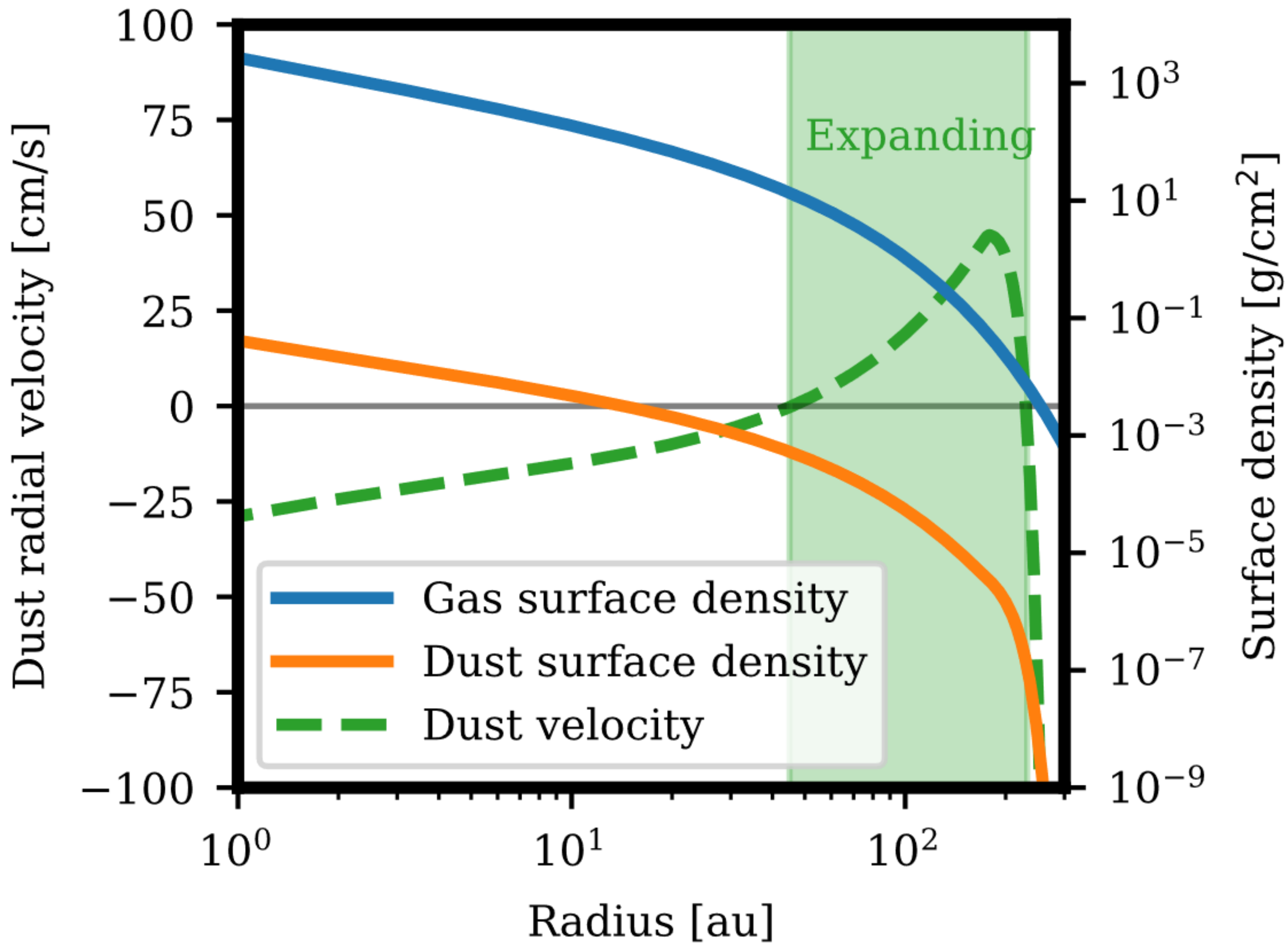
Can’t we do this in the gas?



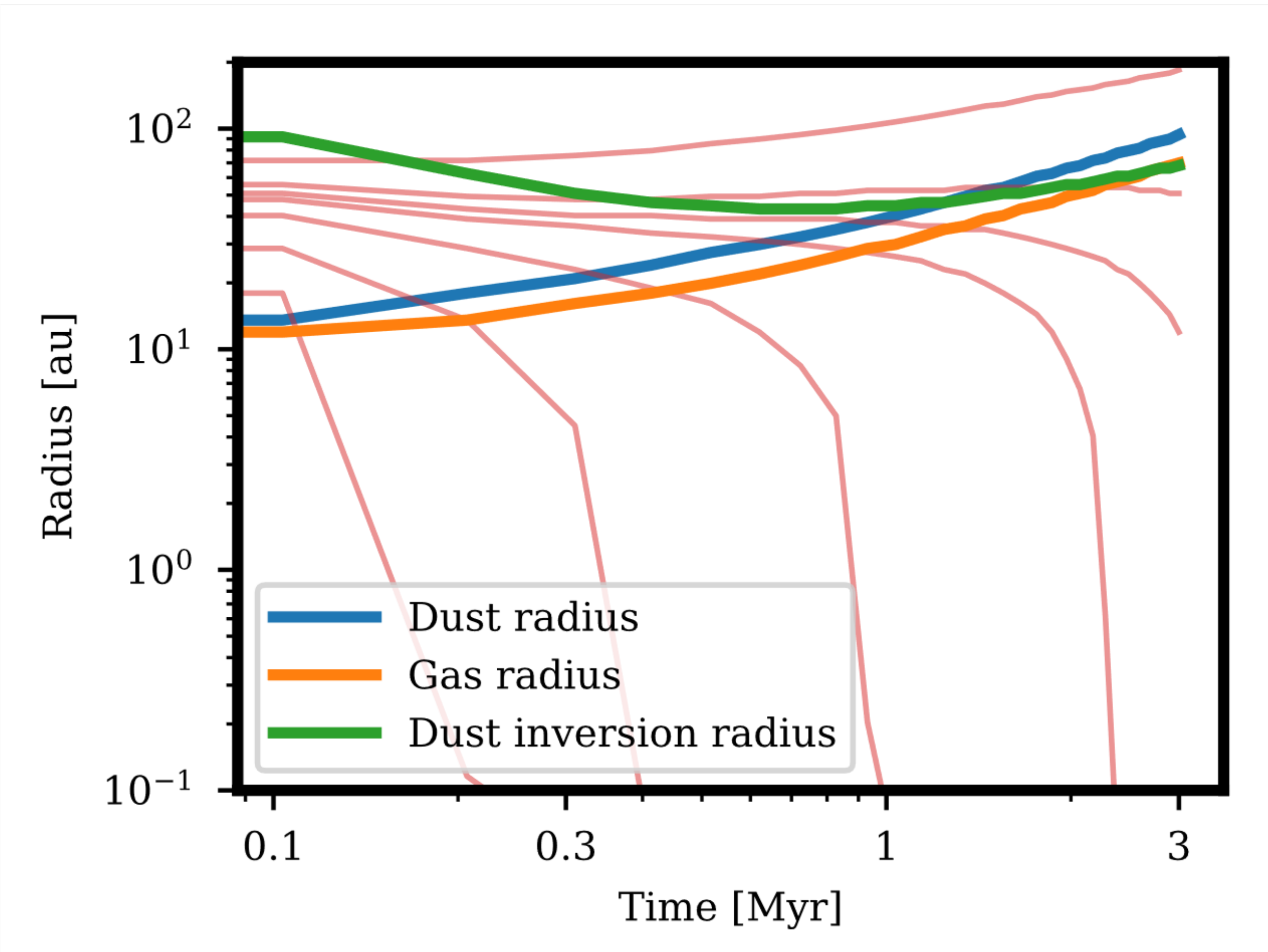


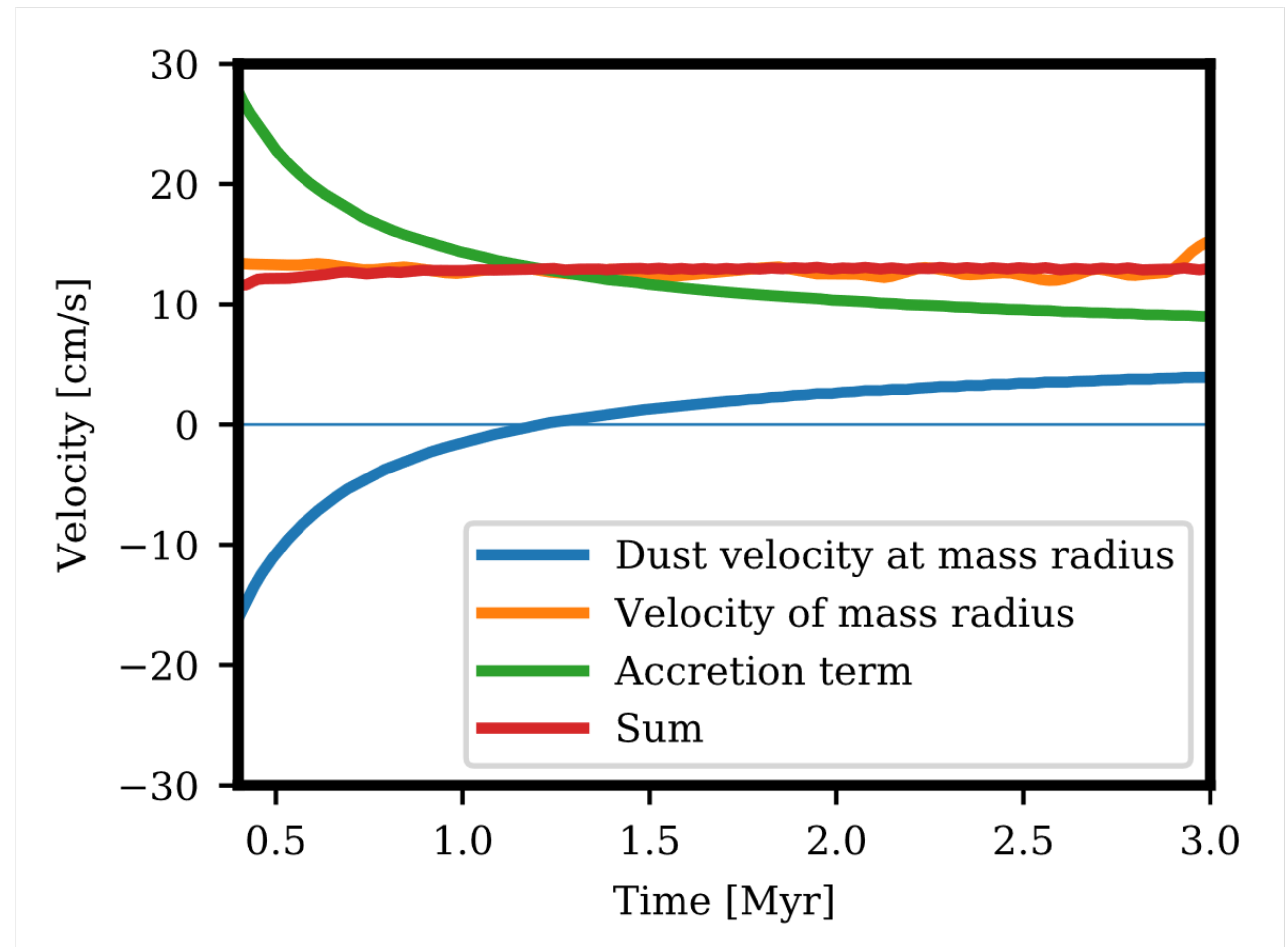
Perhaps, but not with an optically thick line like ^{12}CO
Dashed horizontal line is photo-dissociation density
(van Dishoeck & Black, 1988)

In-depth look at mass radius evolution



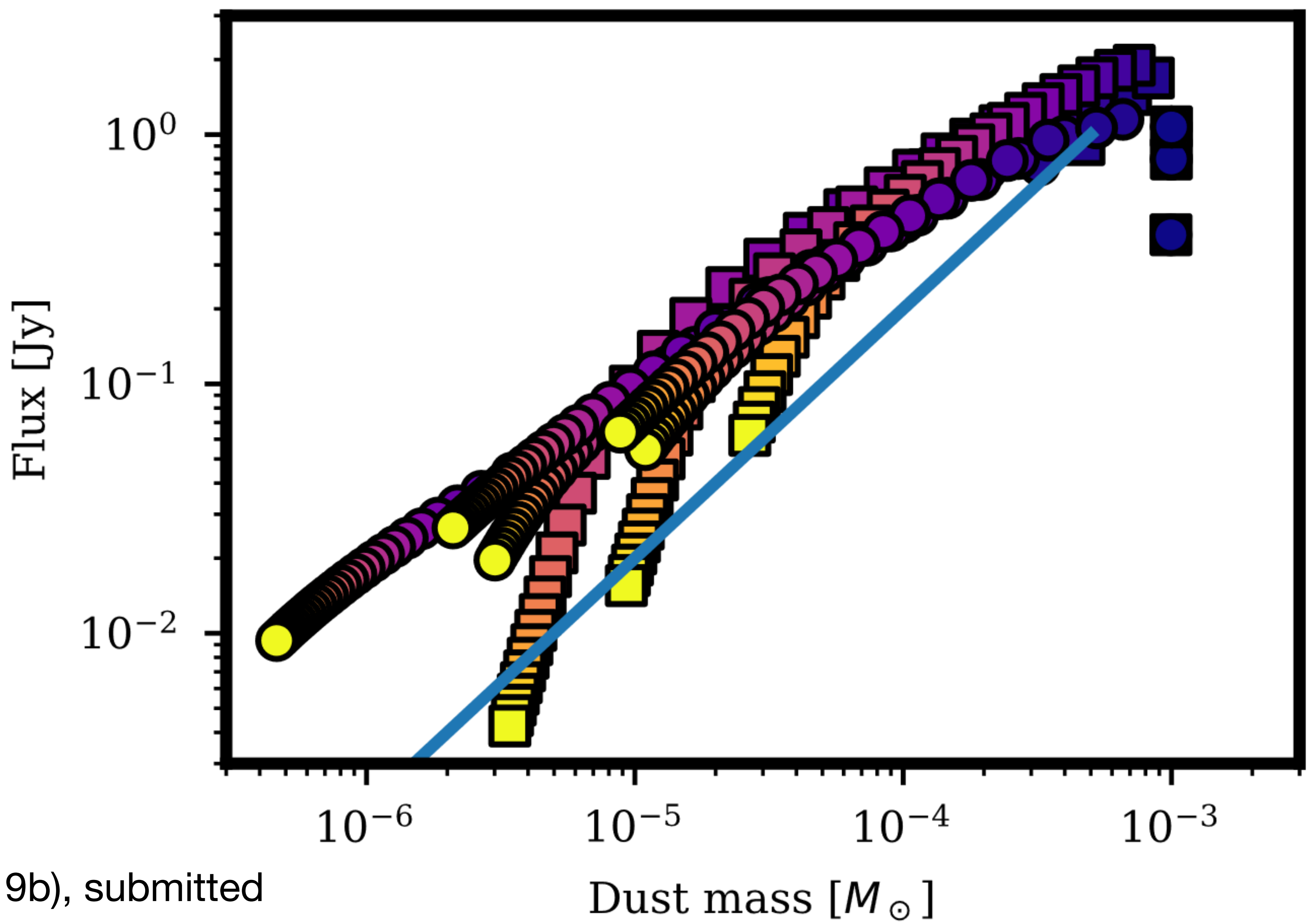
In-depth look at mass radius evolution





$$\frac{\mathrm{d}r_\mathrm{s}}{\mathrm{d}t} = \frac{-\dot{M}(r_\mathrm{s}) + (1-f)\dot{M}(r_*)}{2\pi r_\mathrm{s}\Sigma(r_\mathrm{s})}$$

Do we see all the mass?



GR+ (2019b), submitted

No. But mass actually *overestimated* using standard relations because of different opacity