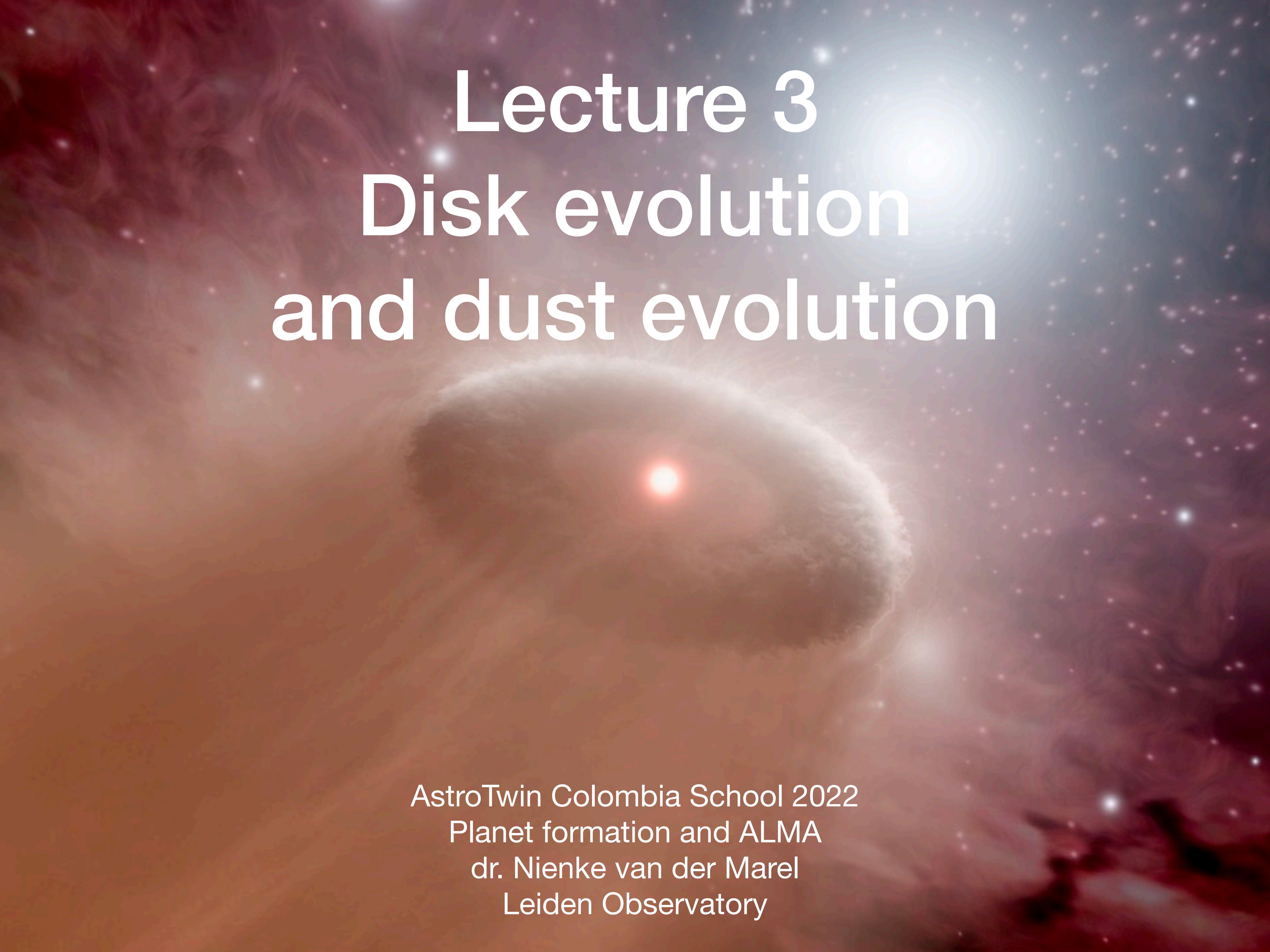


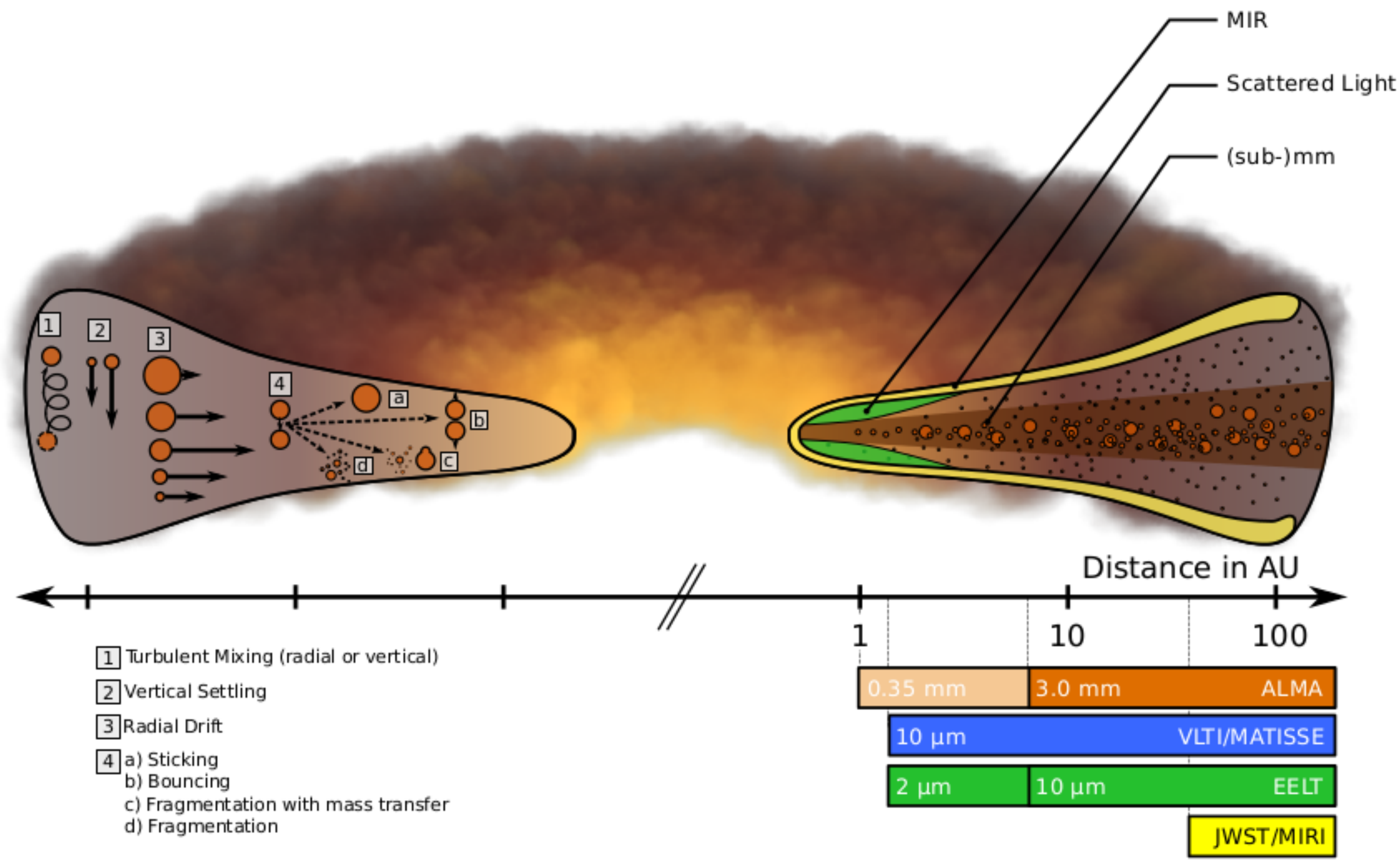
Lecture 3
Disk evolution
and dust evolution

AstroTwin Colombia School 2022
Planet formation and ALMA
dr. Nienke van der Marel
Leiden Observatory

Contents

- General picture: gas vs dust
- Gas disk evolution:
  - Accretion
  - Viscous disk model
  - Photoevaporation
  - Disk lifetime
  - Turbulence
  - Disk winds
- Dust disk evolution:
  - Dust growth
  - Settling
  - Radial drift
  - Dust trapping
  - Observational evidence
- Different evolutionary pictures

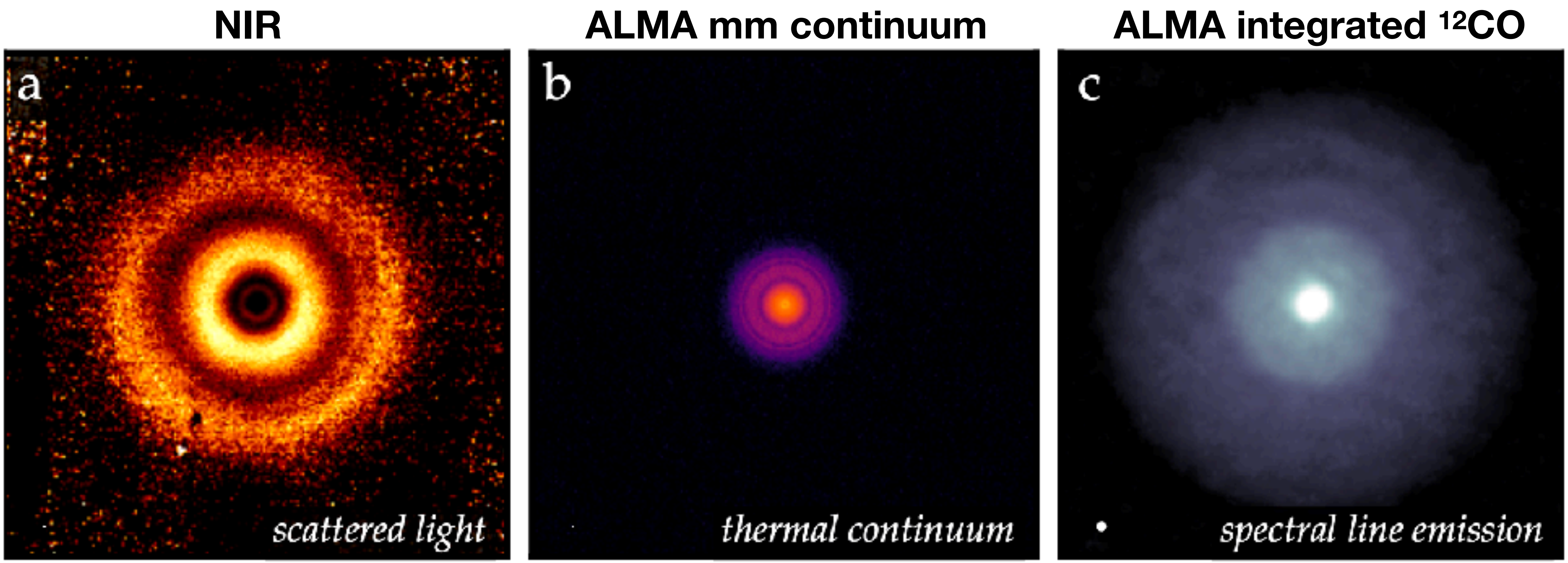
General picture



Dust structure disk: ISM ratio gas/dust = 100/1

Testi et al. 2015

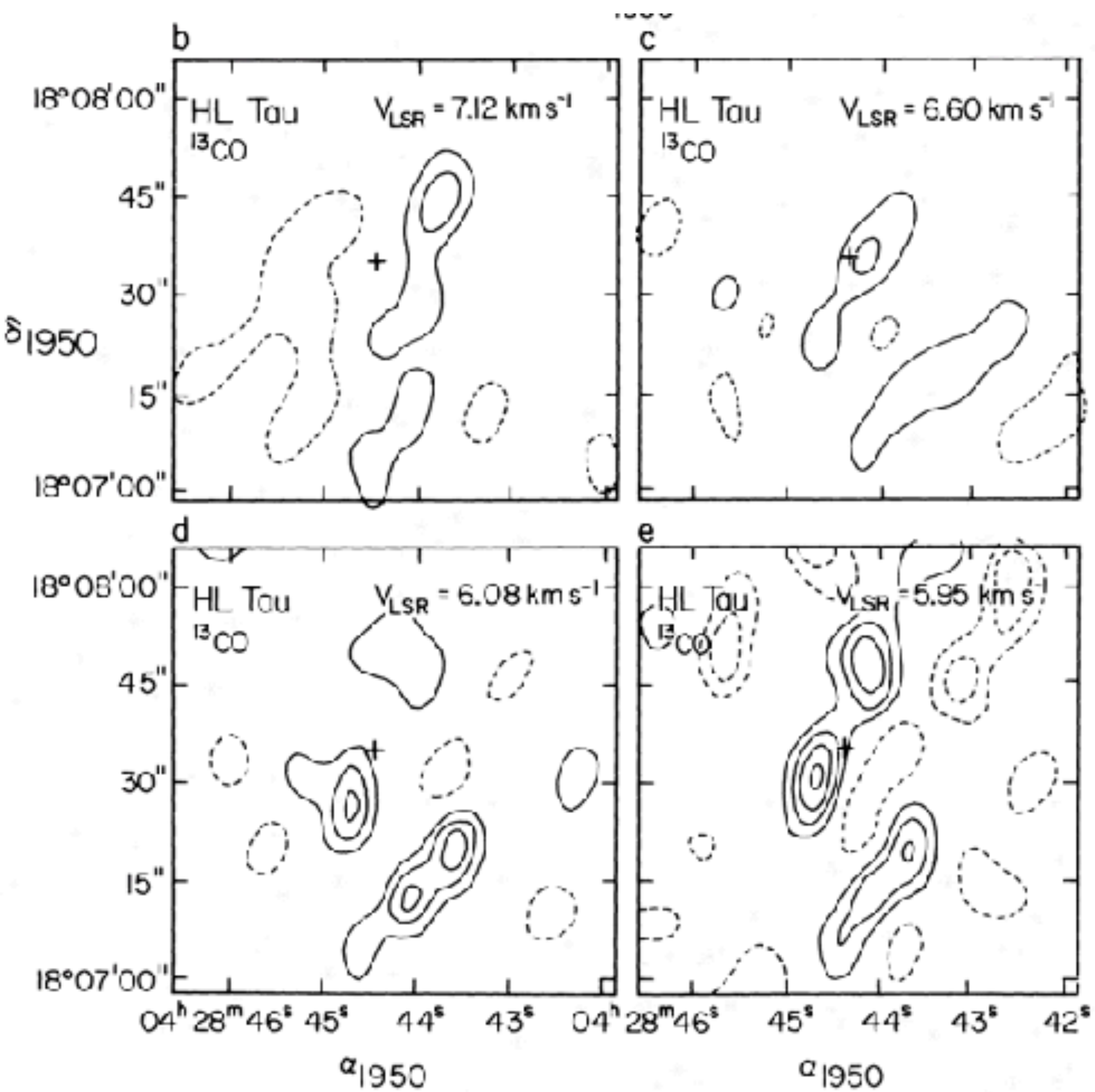
General picture

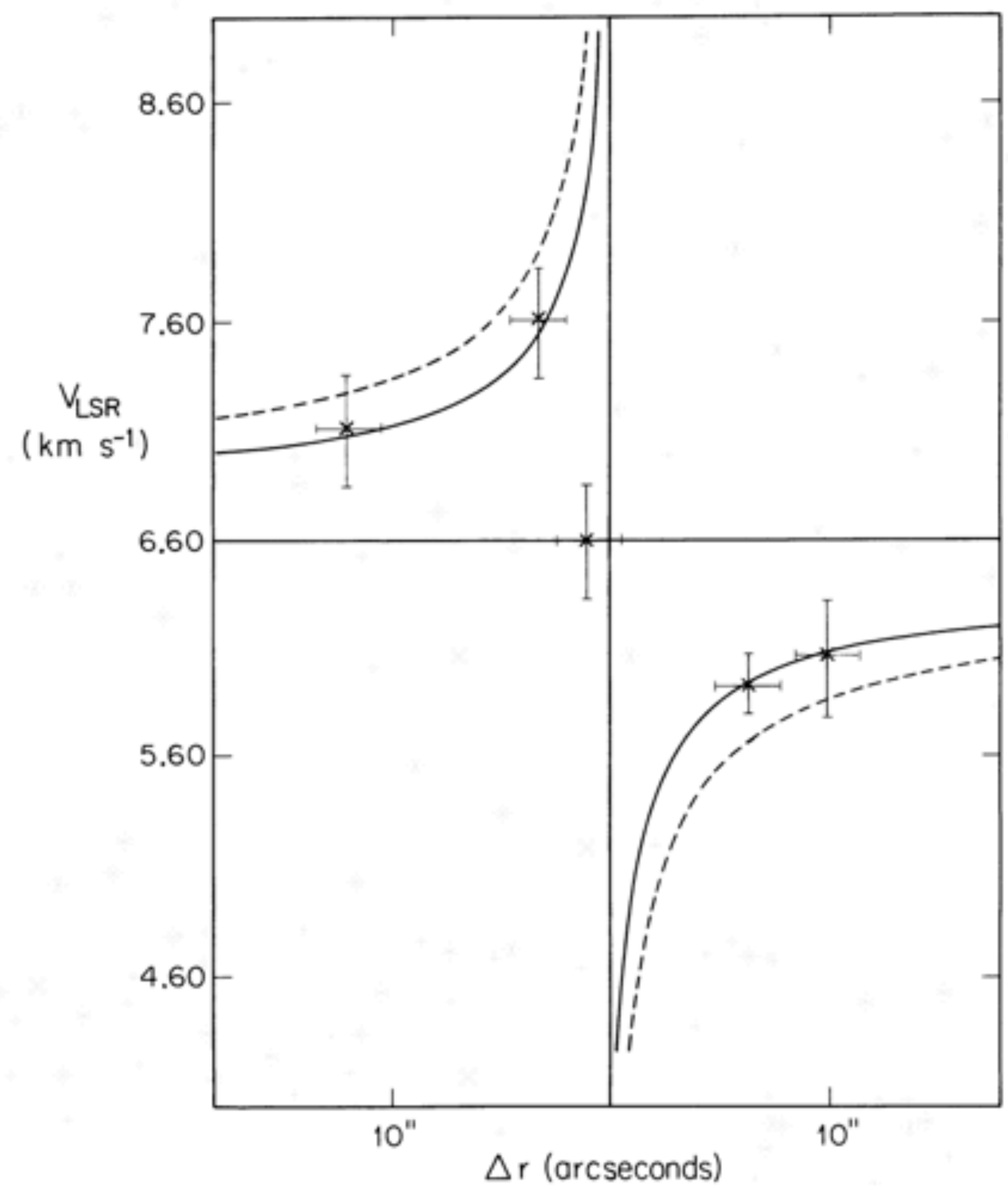


Gas and millimeter dust show very different distributions, and gas is the bulk component of the disk

Andrews 2020

How did we know gas is present?

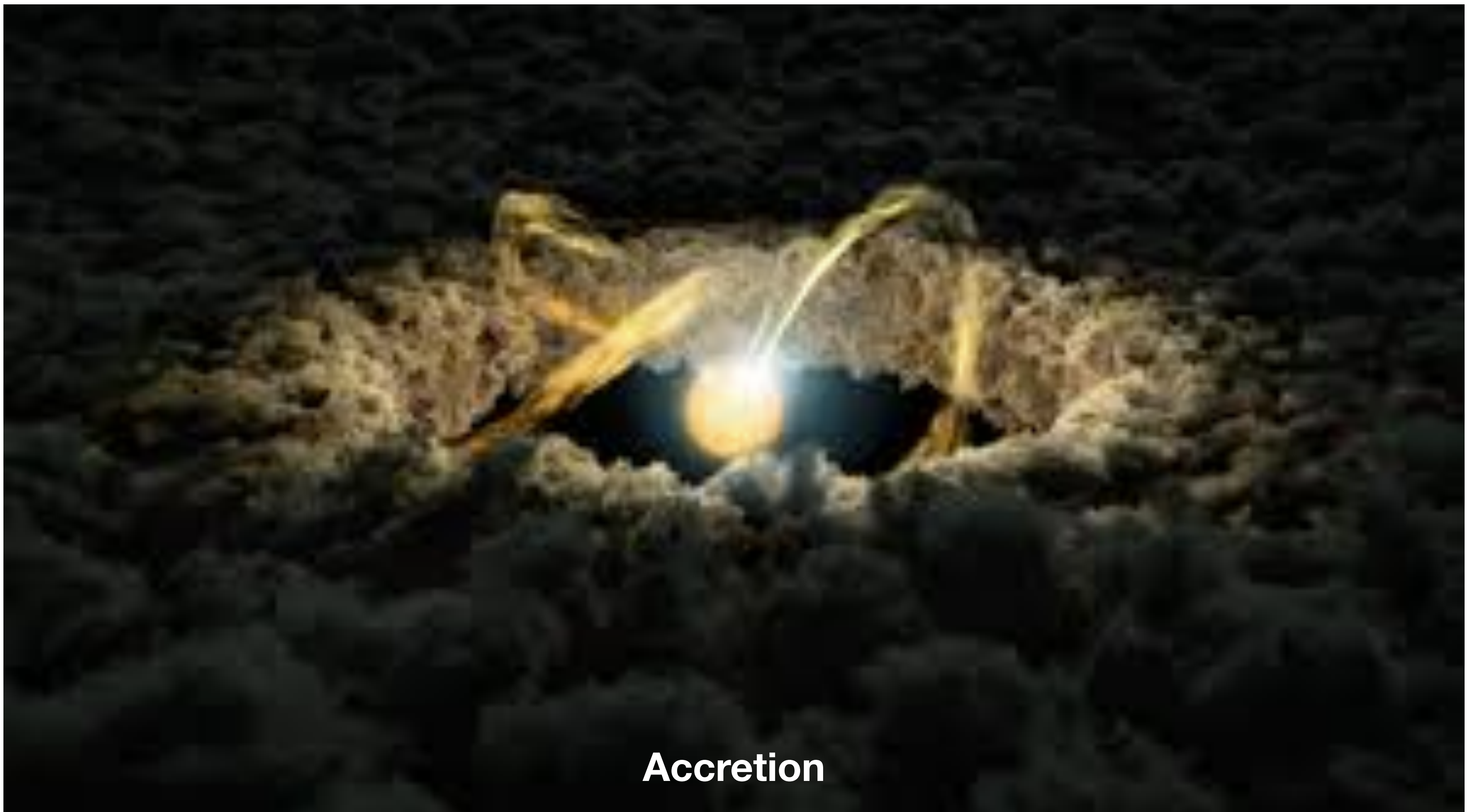




Spatially resolved ^{13}CO 1-0 emission around HL Tau in 1987: Keplerian!

Sargent & Beckwith 1987

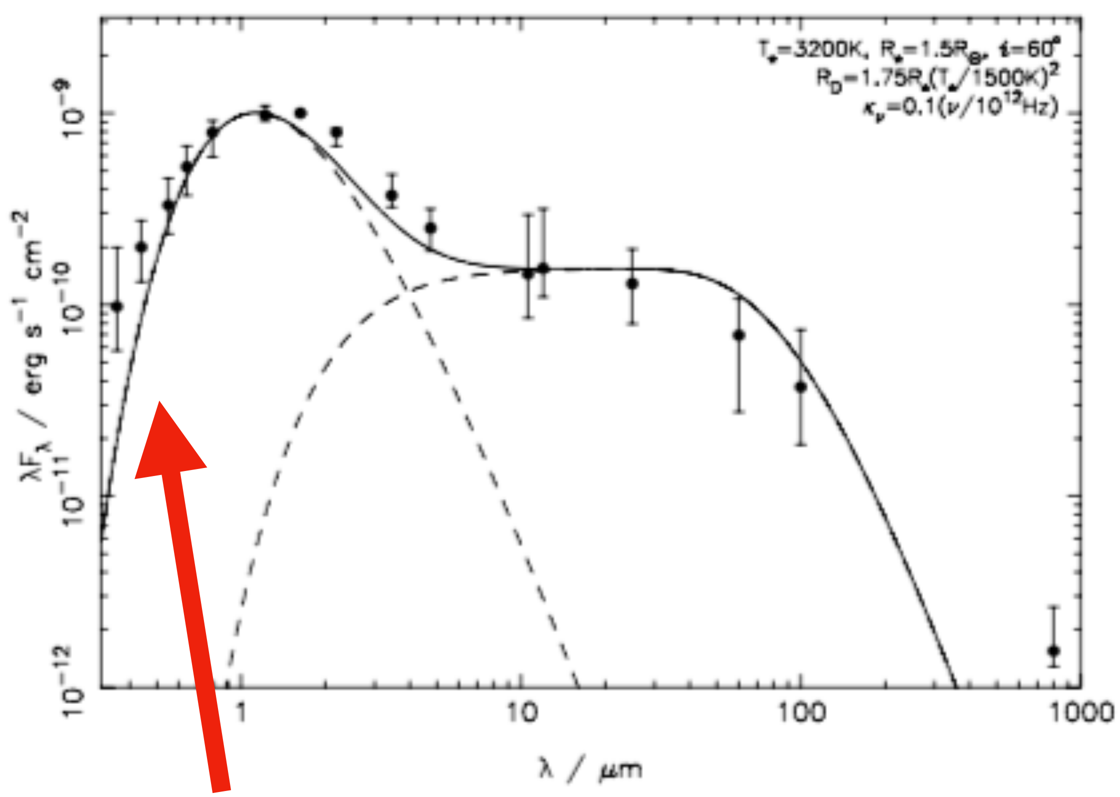
How do we know gas is present?



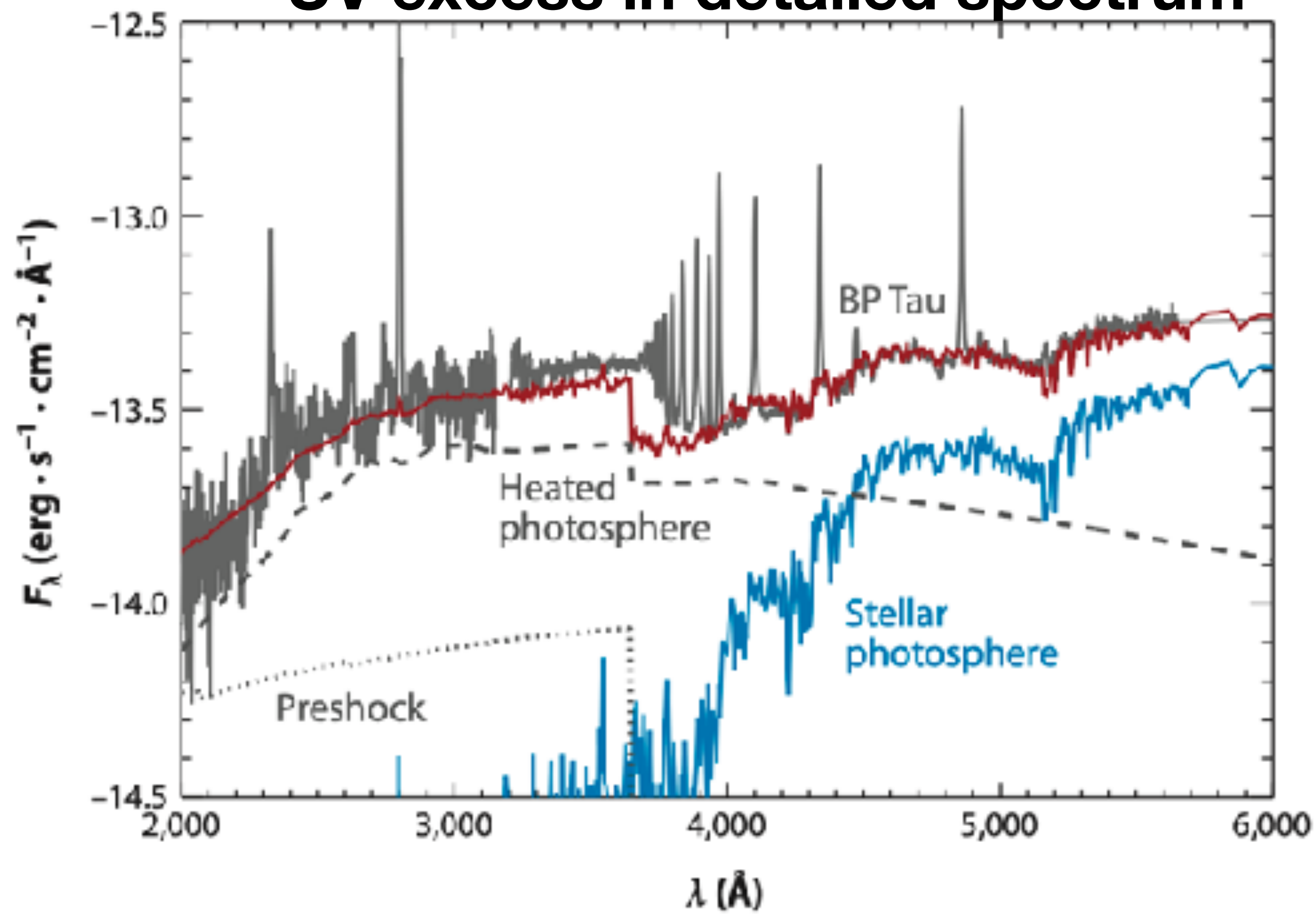
How did we know gas is present?

=> **Accretion**

UV excess in SED



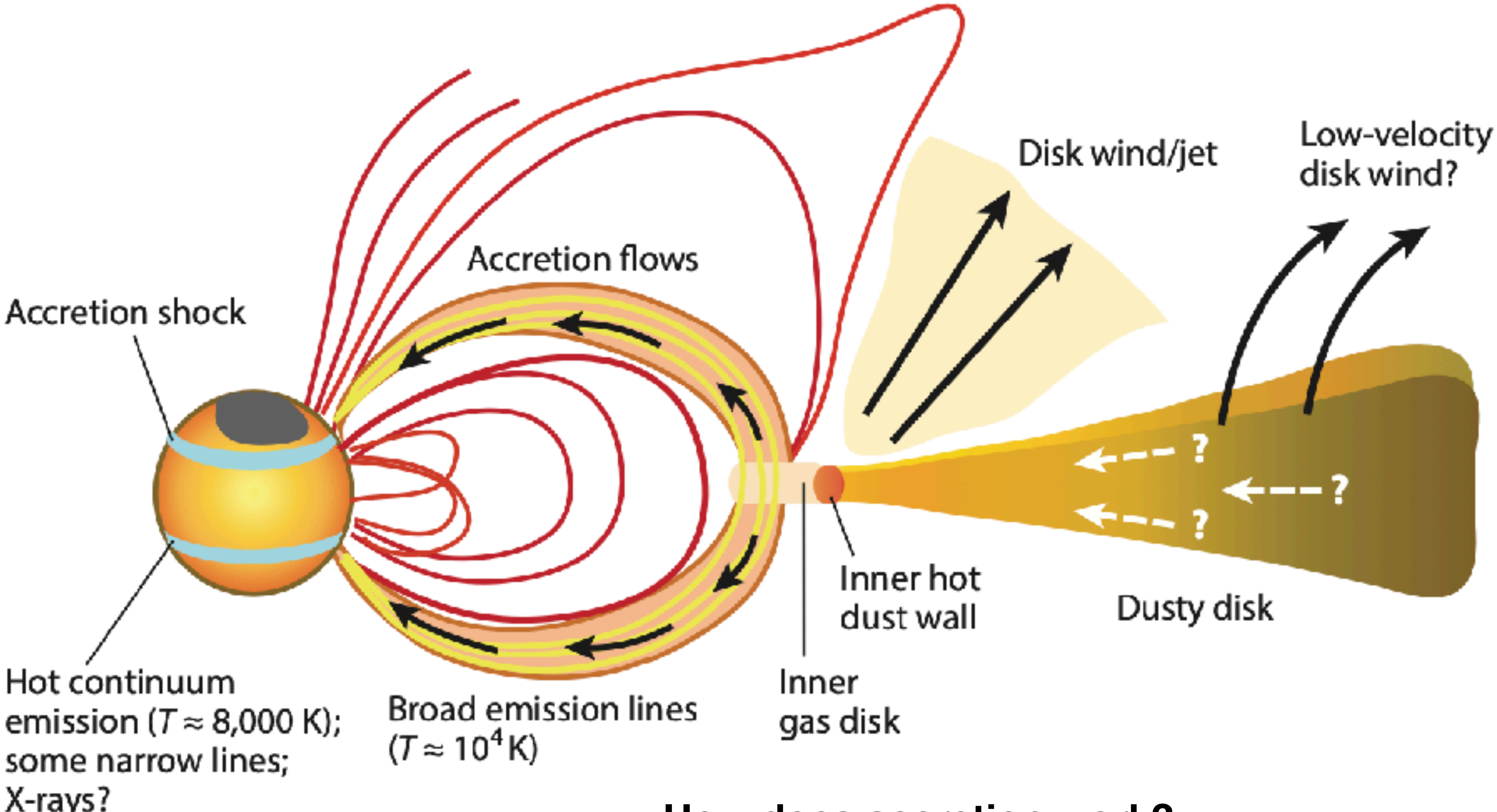
UV excess in detailed spectrum



UV accretion luminosity L_{acc} can be converted to accretion rate M_{acc} (M_{o} yr^{-1}).

Alexander et al. 2006
Hartmann et al. 2016

Accretion



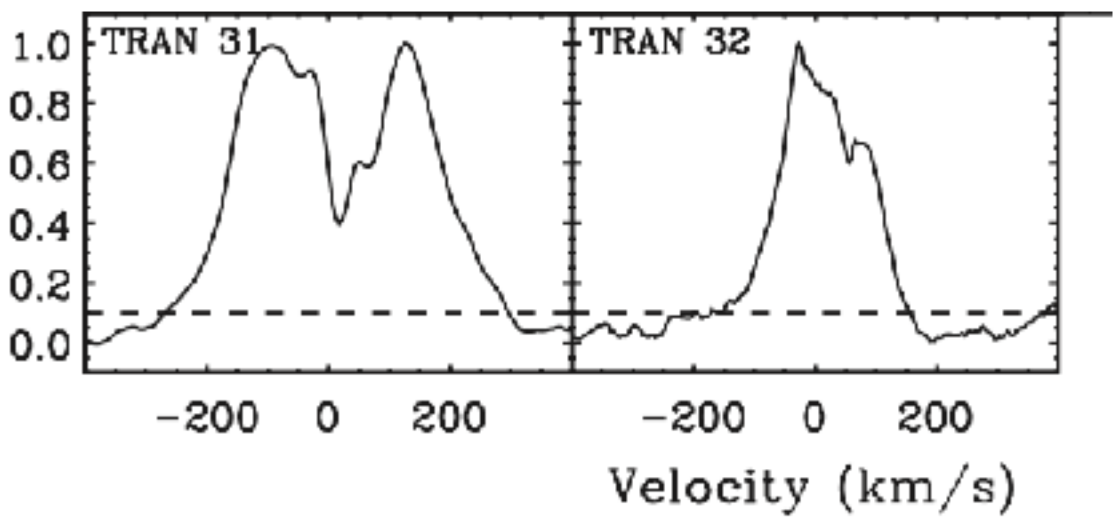
How does accretion work?

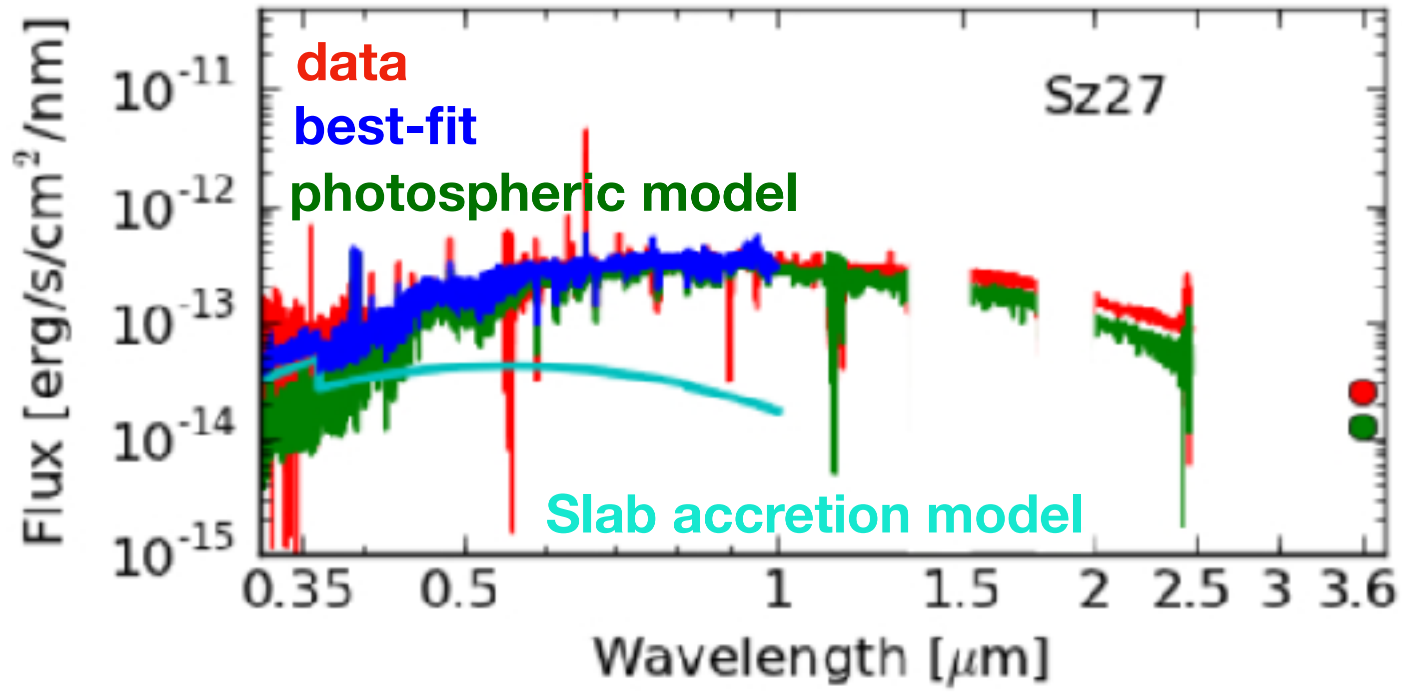
How do we measure accretion?

Hartmann et al. 2016

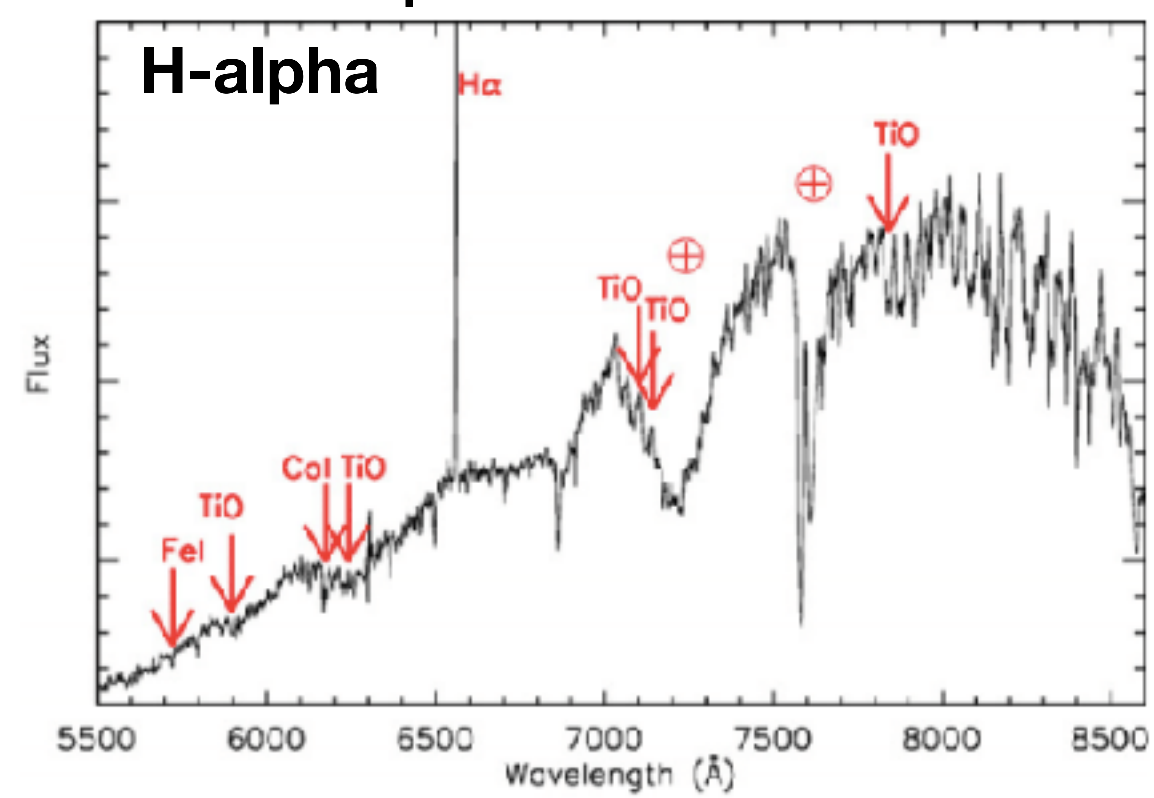
How do we measure accretion?

Measure accretion by combination of UV excess and width of H-alpha line





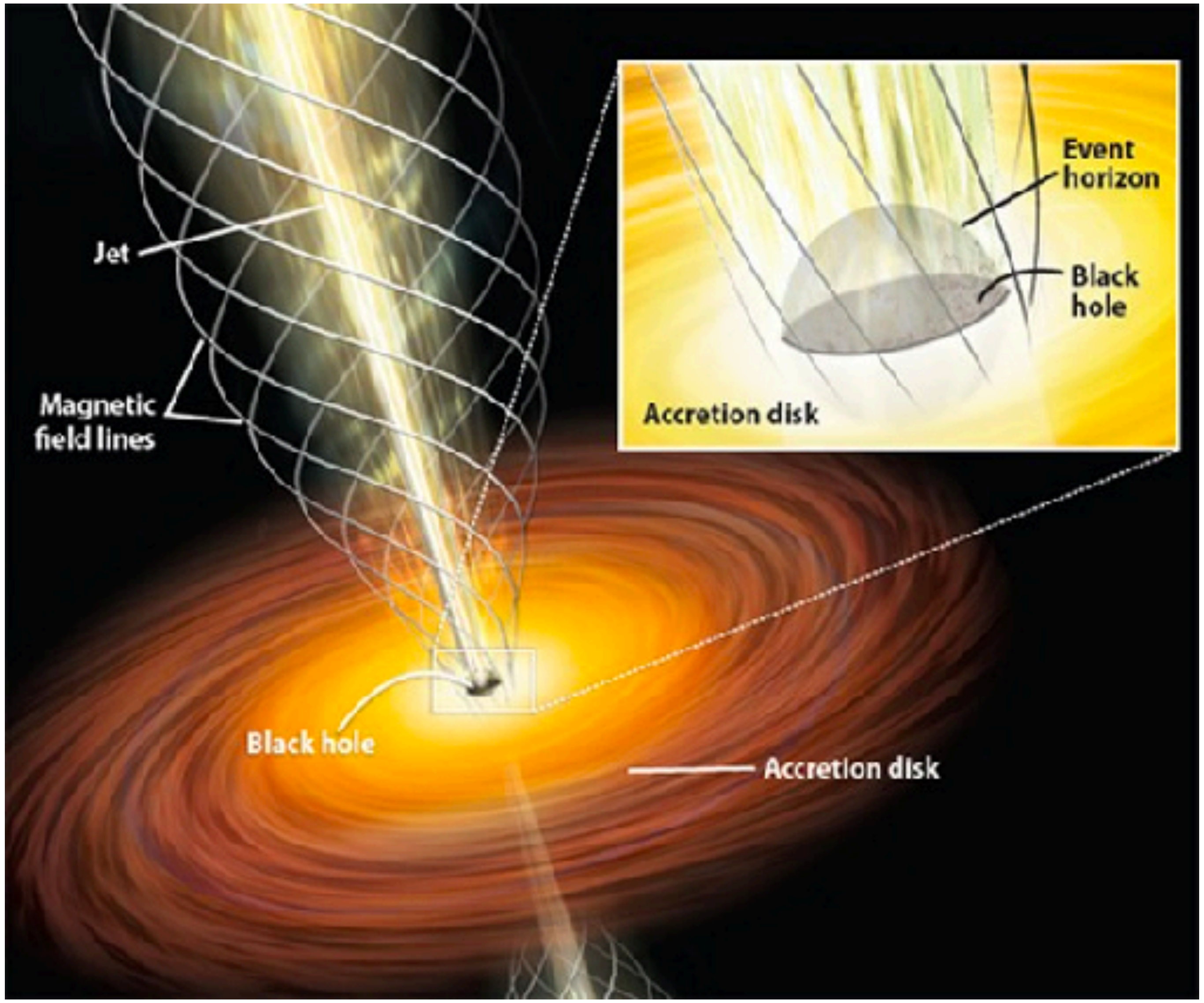
Derivation accretion in optical spectroscopy often together with fitting the spectral type based on various spectral features



Careful: in several papers in 90s and 00s, the width of the H-alpha line (equivalent width, 10%width) is converted to M_{acc} as well. Don't trust these values as these lines also have contributions from disk winds and chromospheric activity. Proper analysis requires full spectra from UV to NIR (X-shooter)

Manara et al. 2014
Alcala et al. 2014
Cieza et al. 2010

If material falls inwards onto star

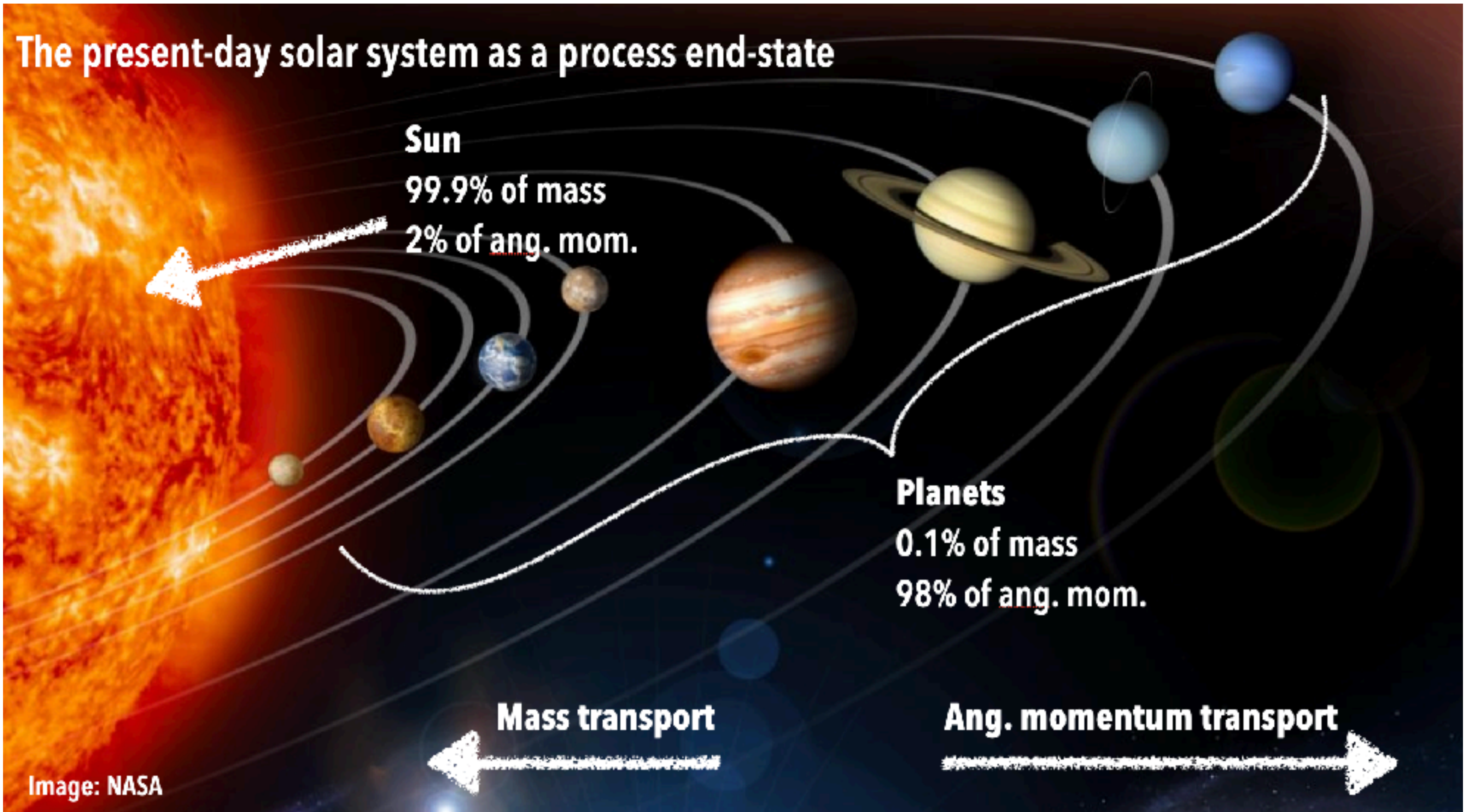


Classical accretion disk model:

material moving inwards:
angular momentum must be preserved somehow

Similar physics as for black hole accretion disks

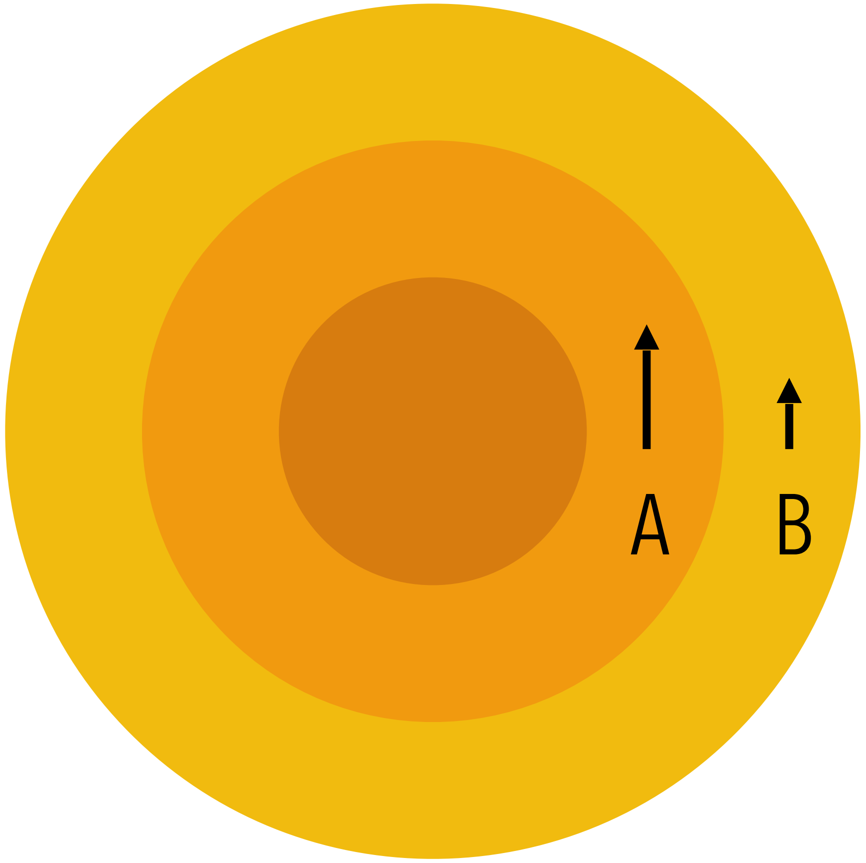
Angular momentum transport: the Solar System



Angular momentum transport

- Ring A moves faster than ring B.
- Friction between A & B slows A down, speeds B up. Therefore ang. mom. transferred from A to B.
- Specific angular momentum for a Keplerian disk:

$$l = r v_\phi = r^2 \Omega_K = \sqrt{G M_* r}$$



- So if ring A looses angular momentum (but forced to keep Kepler orbit), it must move inward!
- Ring B moves outward (unless there are additional external rings C, D, etc.).

Viscous evolution: diffusion equation

Excess ang. mom. infalling material

Mass flux infalling material

Disk surface density (g cm^{-2})

$$\frac{\partial \Sigma}{\partial t} - \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\,\frac{\partial}{\partial r}(\Sigma \nu r^{1/2}) - \frac{2\,S(r,t)\,J(r,t)}{\Omega}\right] - S(r,t) = 0$$

Viscosity of disk material

Angular momentum

Manara et al. 2022 (PPVII)

Viscous evolution: diffusion equation

$$\frac{\partial \Sigma}{\partial t} - \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}(\Sigma \nu r^{1/2}) - \frac{2\, S(r,t)\, J(r,t)}{\Omega}\right] - S(r,t) = 0$$

- *S(r,t)* initially large, but becomes negligible by T Tauri phase.
- Therefore the viscous term dominates diffusion equation at these later times.

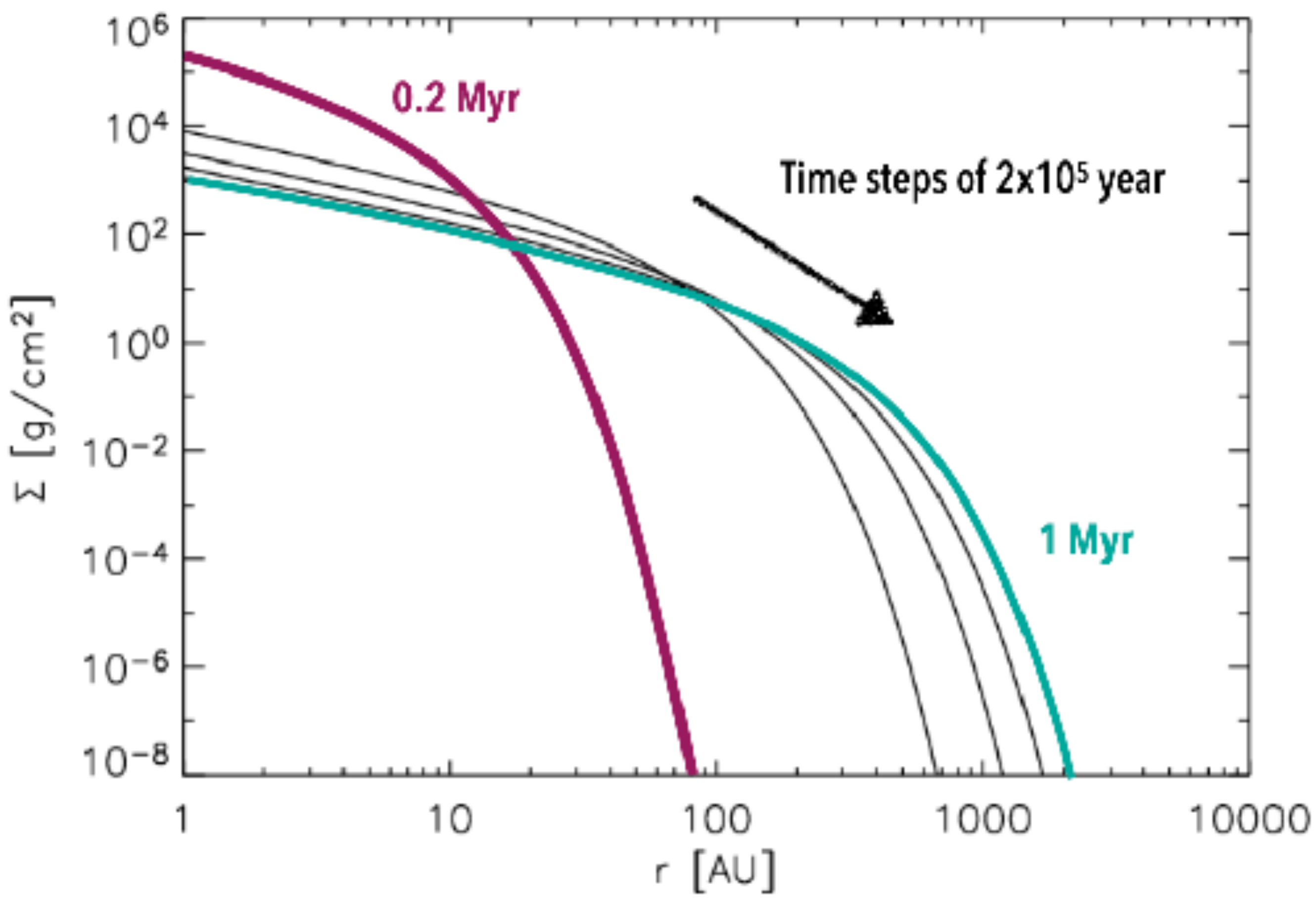
Self-similar solution (Lynden-Bell & Pringle 1974):

$$\Sigma(R,t) = \frac{M_0}{2\pi R_c^2}(2-\gamma)\left(\frac{R}{R_c}\right)^{-\gamma} T^{-\eta} \exp\left(-\frac{(R/R_c)^{(2-\gamma)}}{T}\right)$$

$T = 1 + t/t_\nu$, $\eta = (5/2-\gamma)/(2-\gamma)$, $t_\nu = R_c^2/3(2-\gamma)\nu(R_c)$.

Manara et al. 2022 (PPVII)

Viscous evolution



- Mass flow requires both:
    - angular momentum transport
    - energy dissipation

∴ **Need viscous stress**

- <u>What is origin of viscosity?</u>

Lynden-Bell & Pringle (1974)
Hartmann et al. (1998)

Origin viscosity

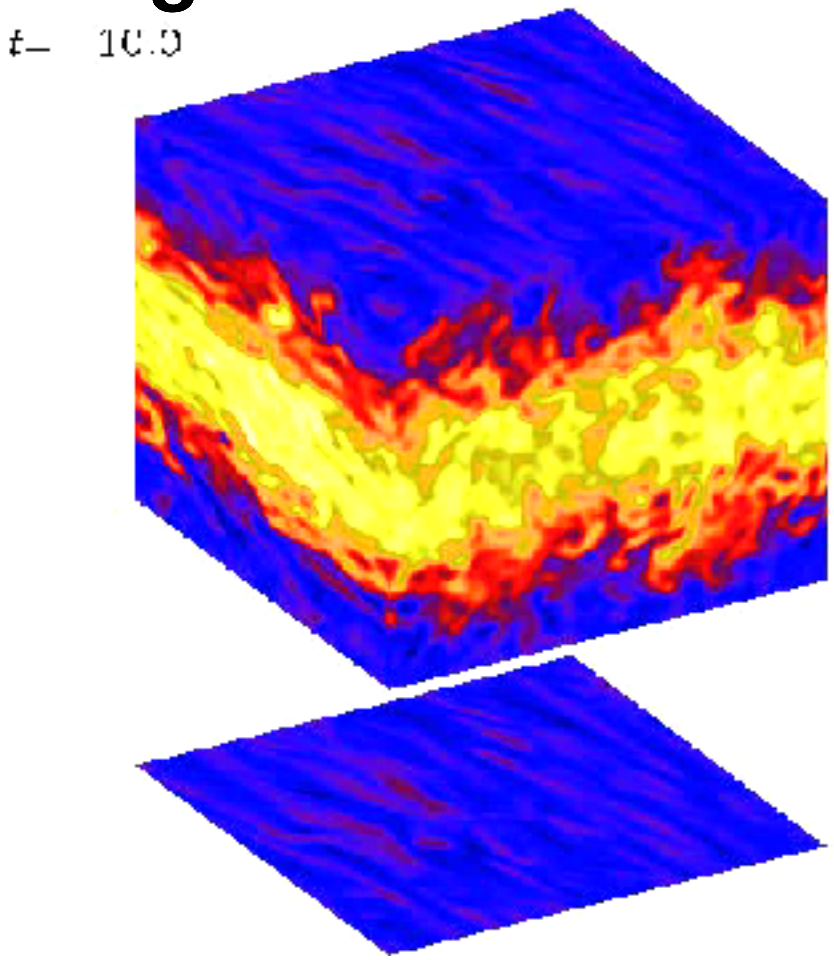
- Molecular viscosity: much too small
- Turbulent viscosity → introduce effective viscosity
  - **$\nu_{eff} = 2/3\ \alpha_s\ c_s\ H$**
    - c_s=sound speed
    - H=pressure scale height disk ≈ half thickness ≈ c_s/Ω
    - α_s= dimensionless efficiency factor
  - *Goal theories*: calculate α_s a priori
  - *In practice*: some value of α_s is assumed which satisfies observations

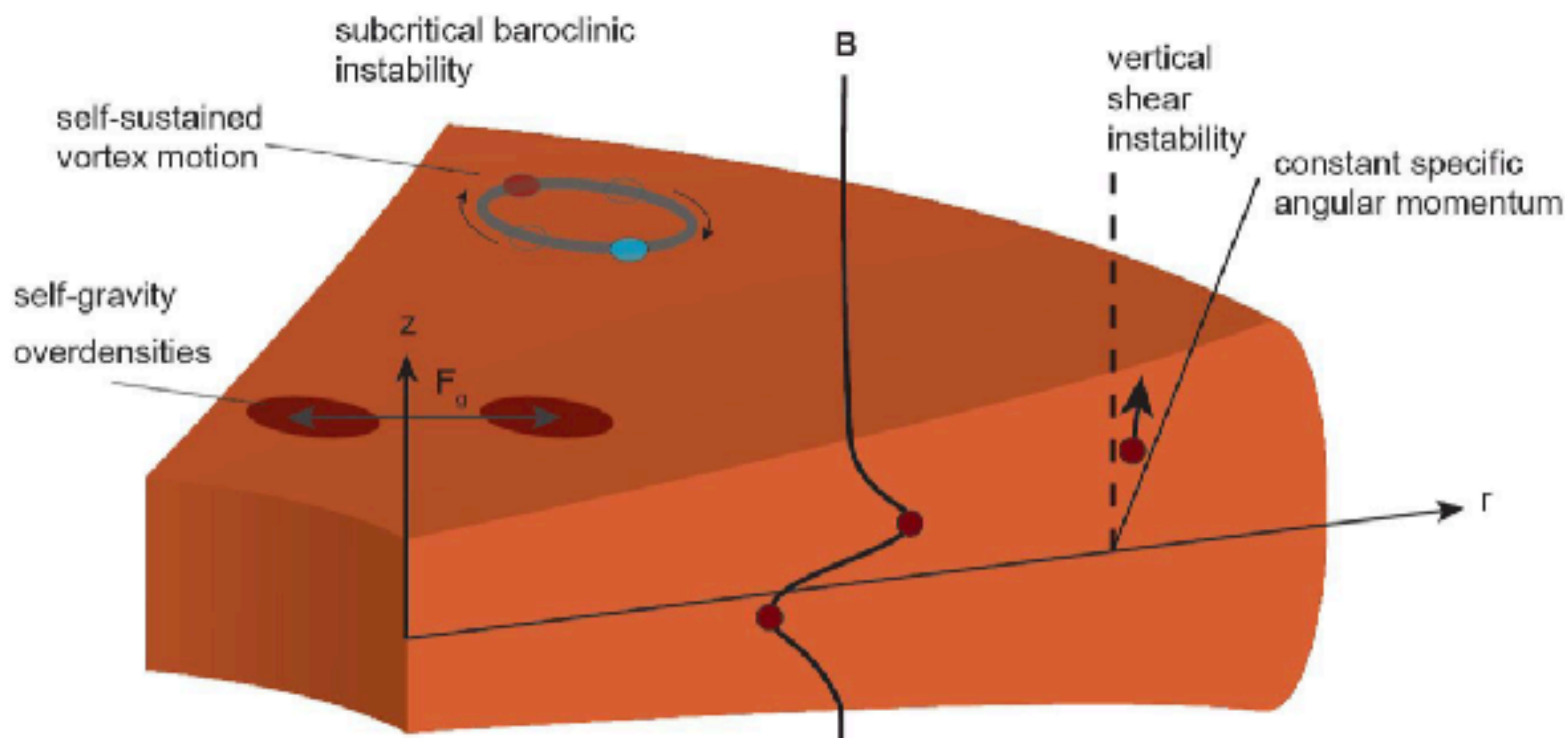
α -disk theory

Shakura & Sunyaev 1973

Origin viscosity: turbulence

Various processes can generate turbulence in disks.





Simulation
small box in disk

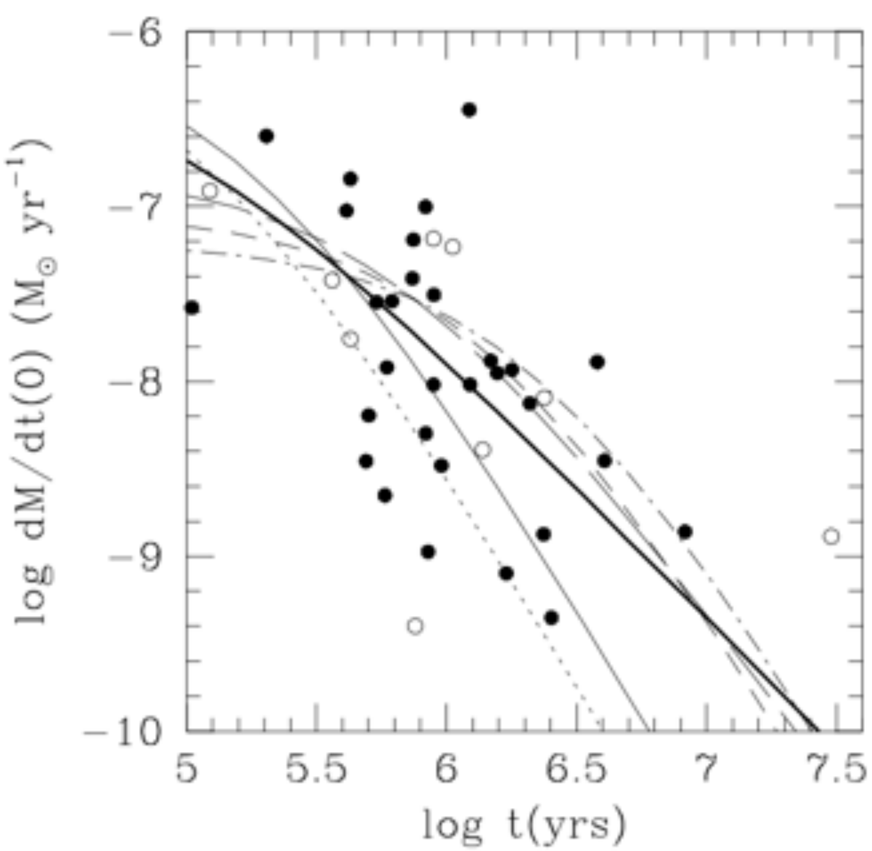
<u>Most popular</u>:
MRI (magneto-rotational instability):
assumes gas disk material to be ionised (radiation/collision) and therefore tied to magnetic field in ideal MHD: displacement through circular motion (orbiting) results in destabilising force (fluid instability) => turbulence

Johansen & Klahr

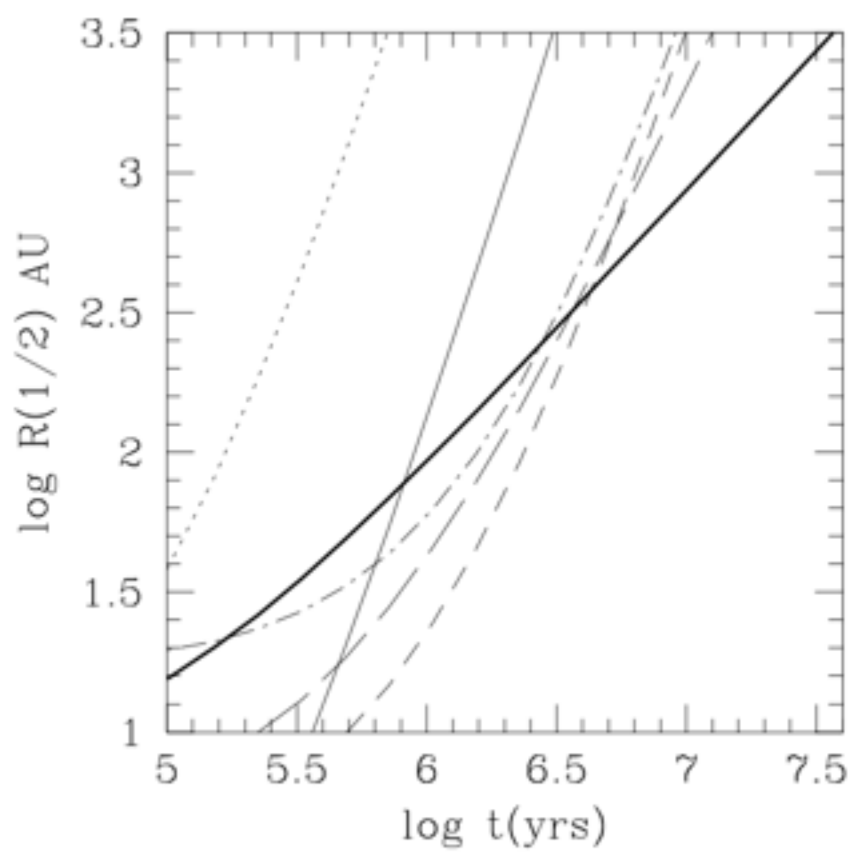
e.g. Bai & Stone 2013

Viscous disk model

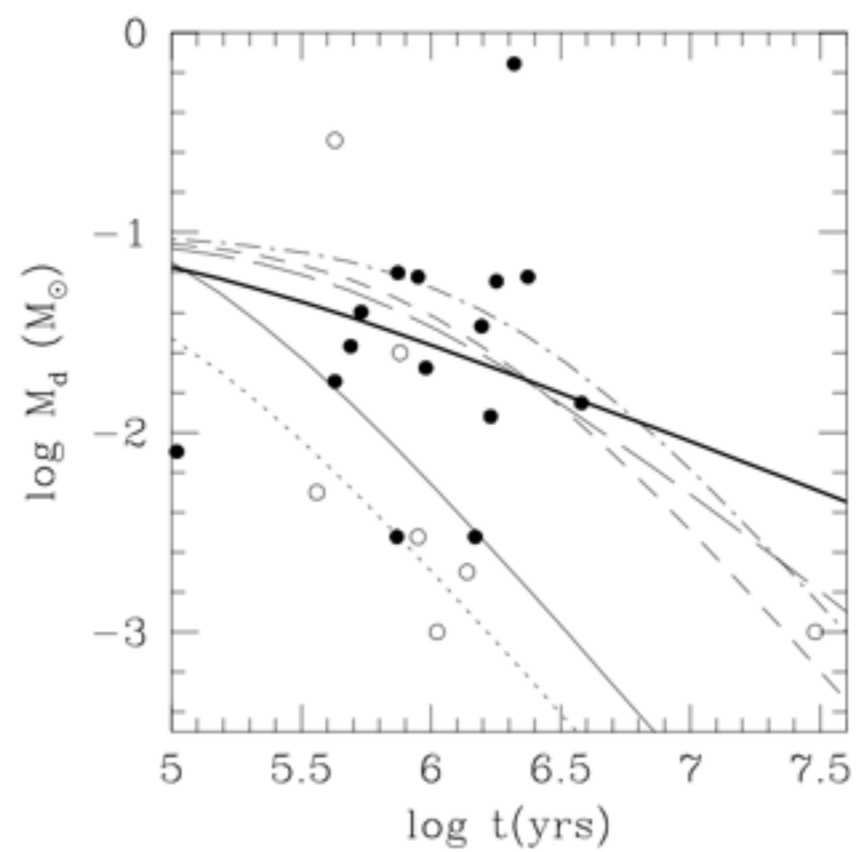
Predictions compared with observations (1998)



Accretion rate drops



Disk radius rises

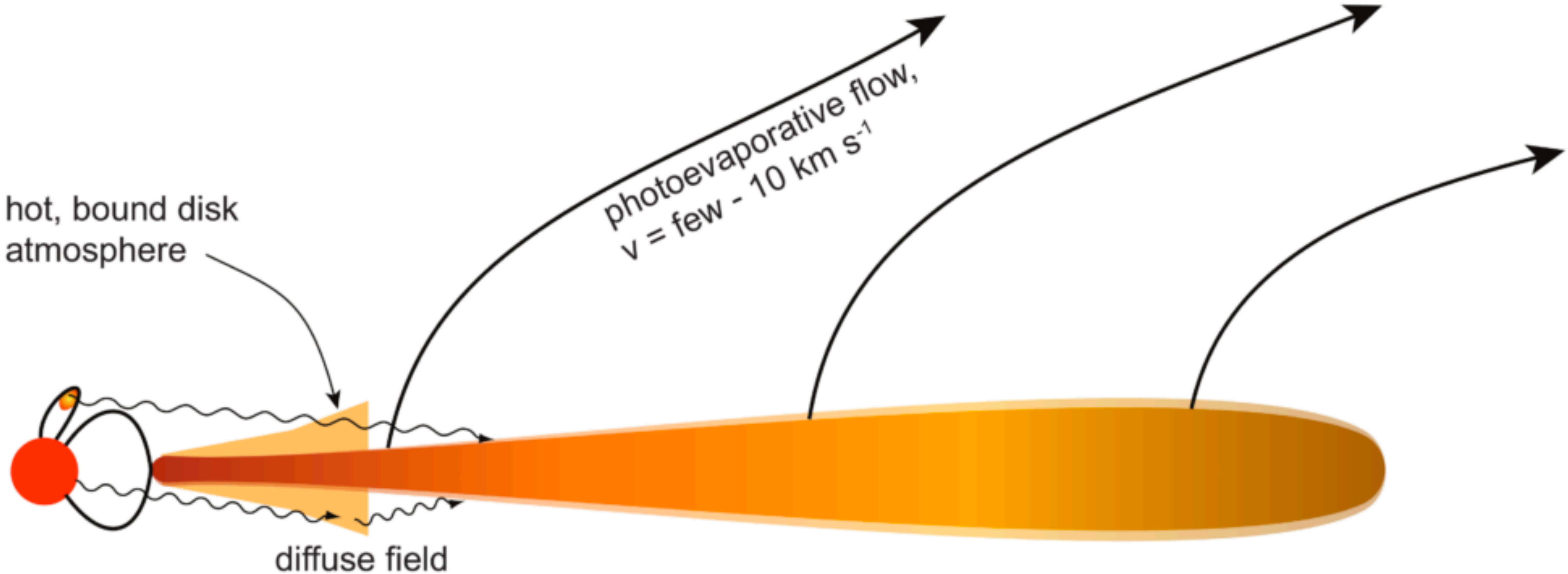


Disk mass drops

Consistent with
α_s ~10^{-2} and
disk lifetime of 2-3 Myr

Hartmann et al. 1998

Photoevaporation

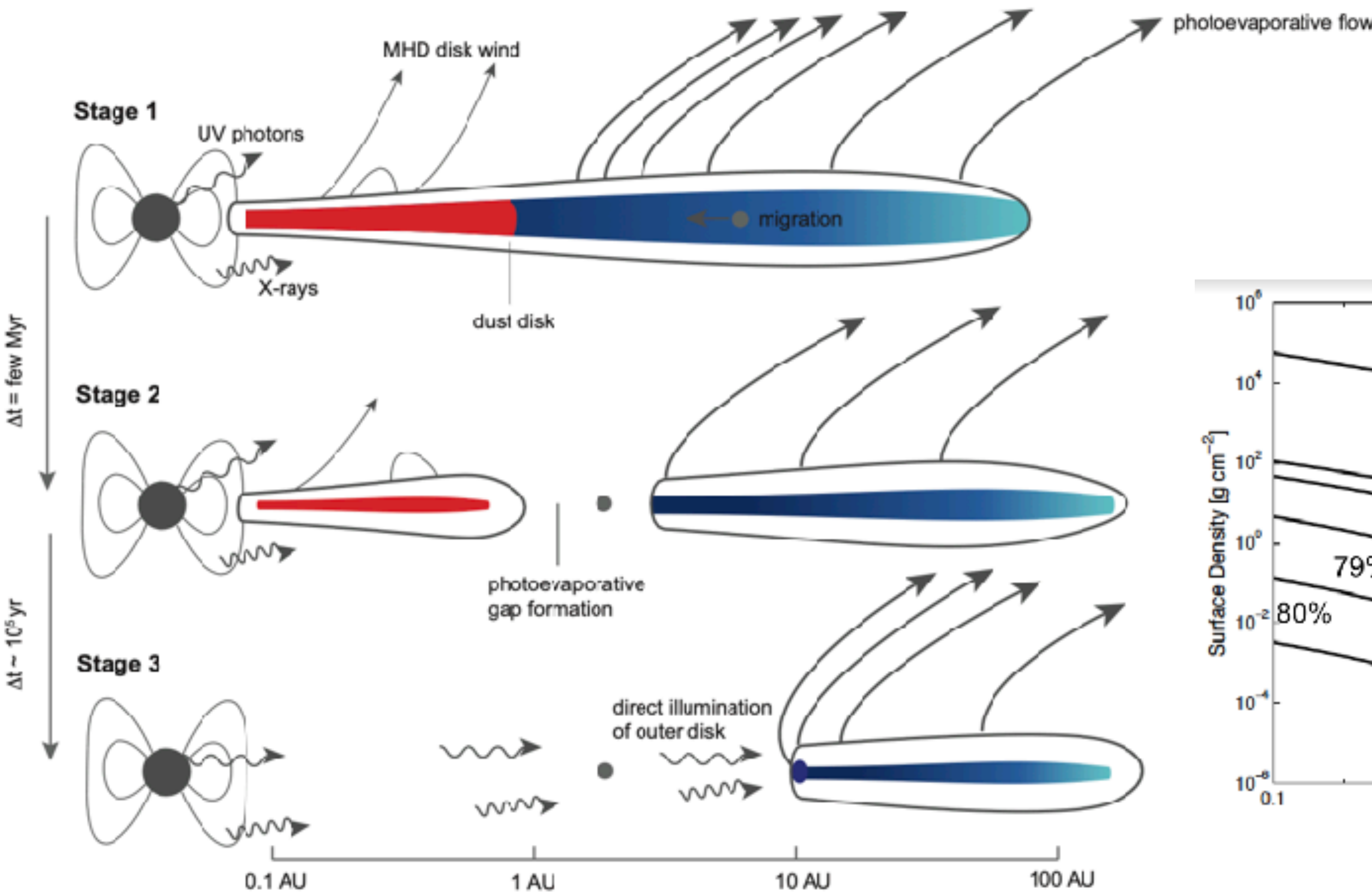


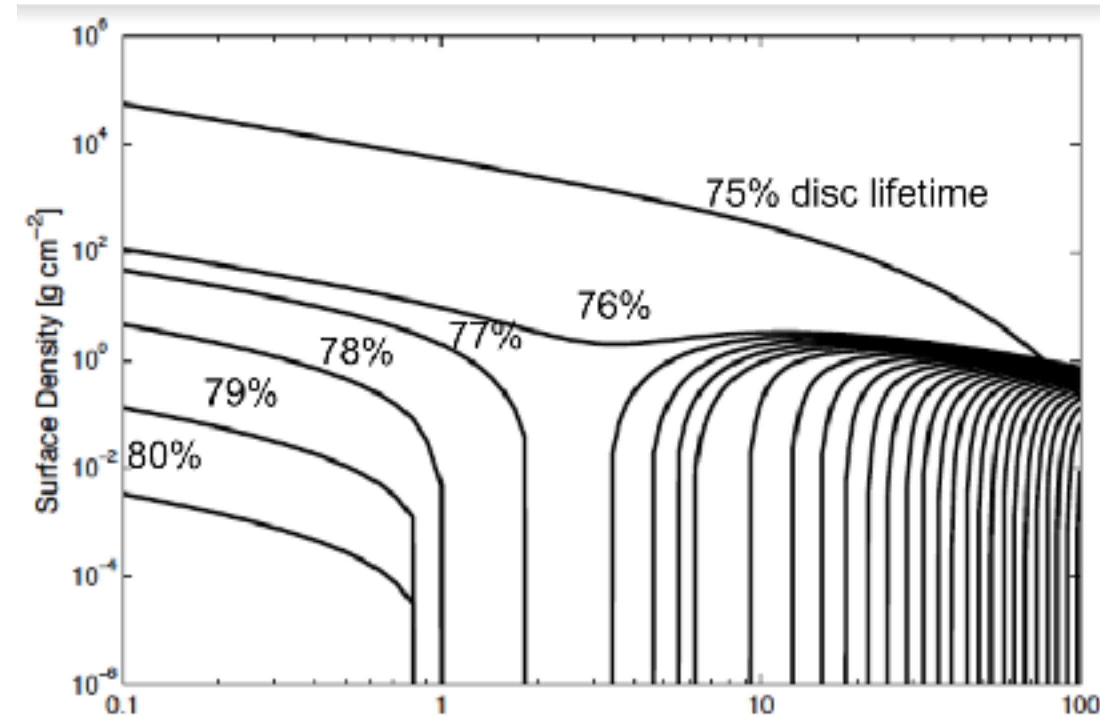
UV radiation from the star heats up the surface layers of the disk: when above the escape velocity: material blown away as photo evaporative wind

As long as accretion rate is high, material is continuously replenished, but when accretion rate has dropped too much…

Clarke et al. 2001
Owen et al. 2015

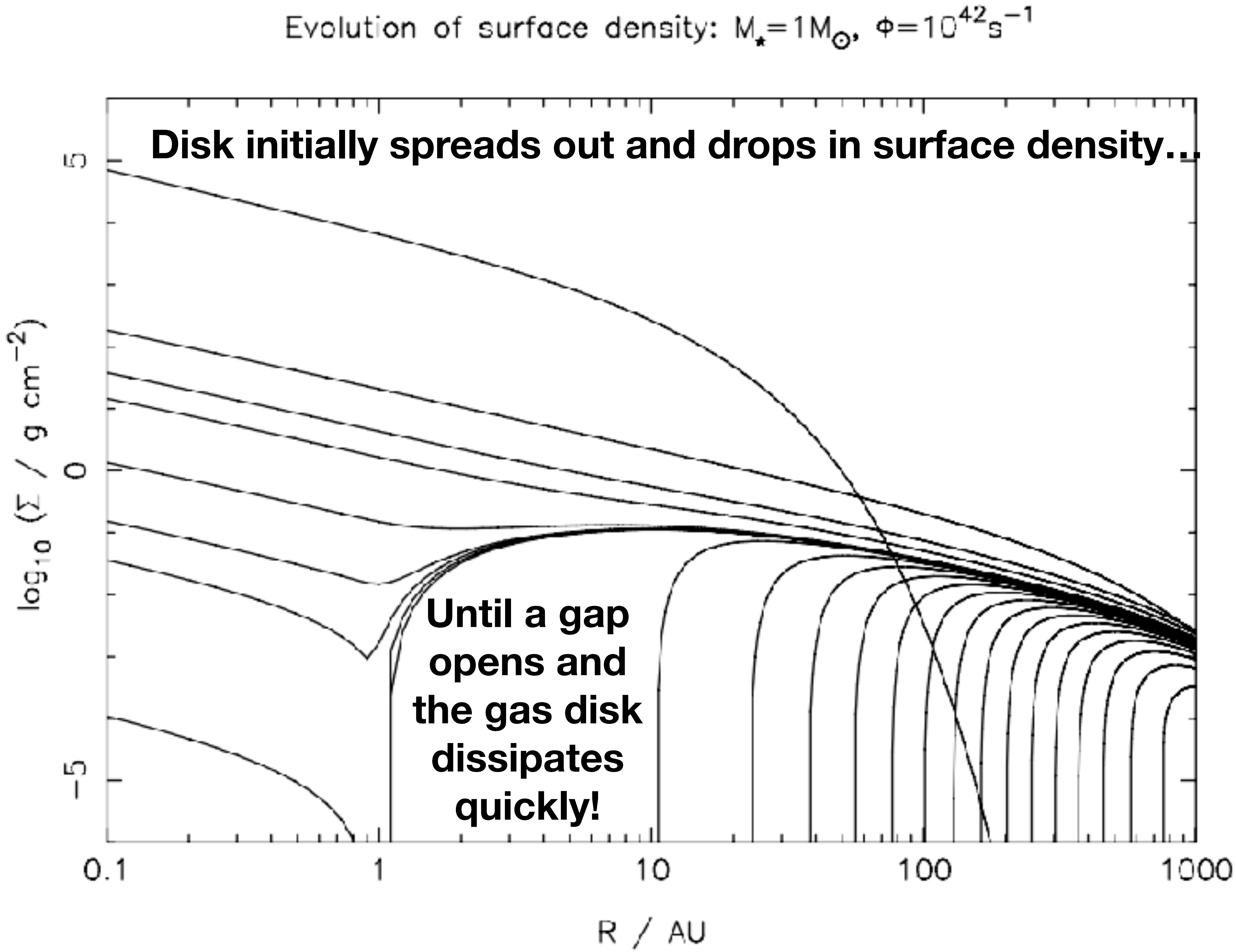
Photoevaporation





Ercolano & Pascucci 2017
Owen et al. 2015

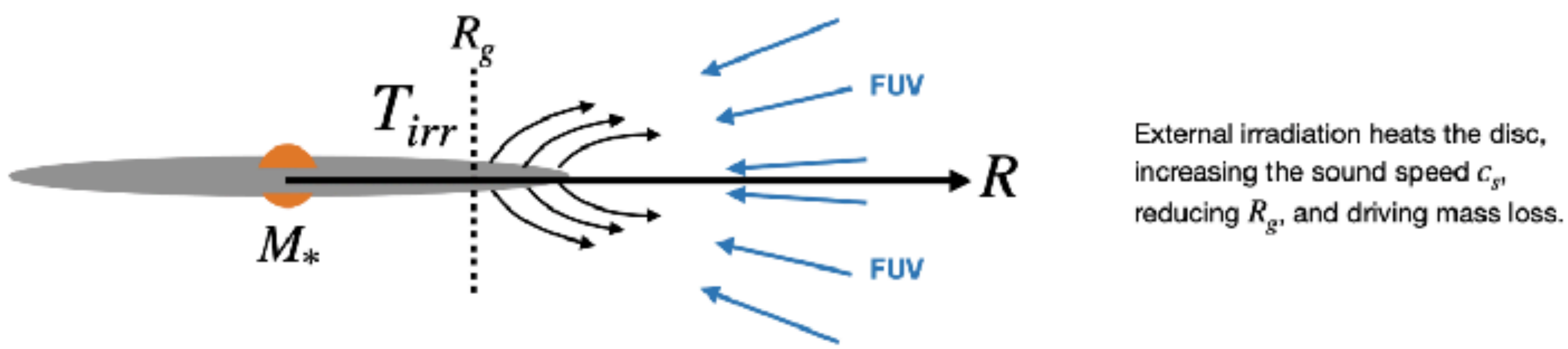
Photoevaporation and disk evolution



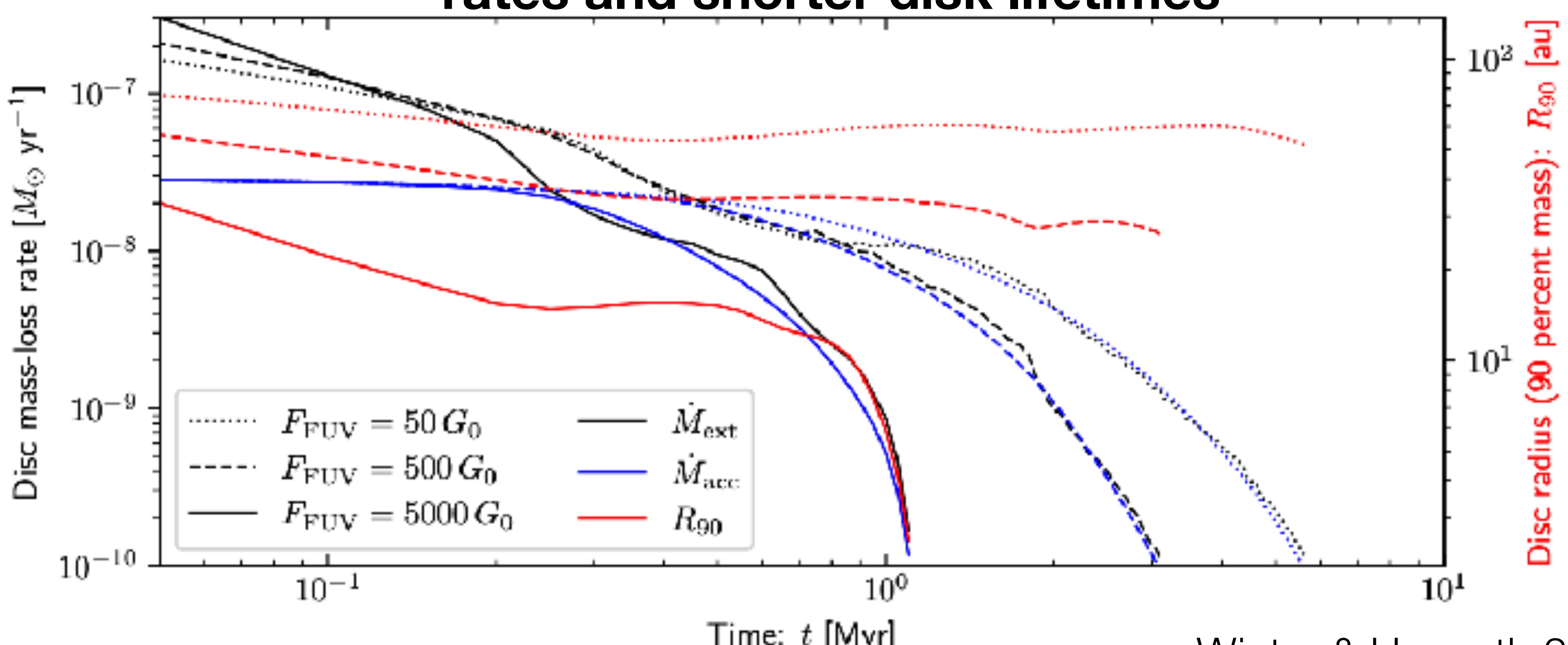
Alexander et al. 2013 (PPVI)

External photo evaporation

External UV radiation fields (nearby OB-stars!) can also lead to photo evaporation, but then in the outer disk



Stronger UV-fields lead to faster mass-loss rates and shorter disk lifetimes

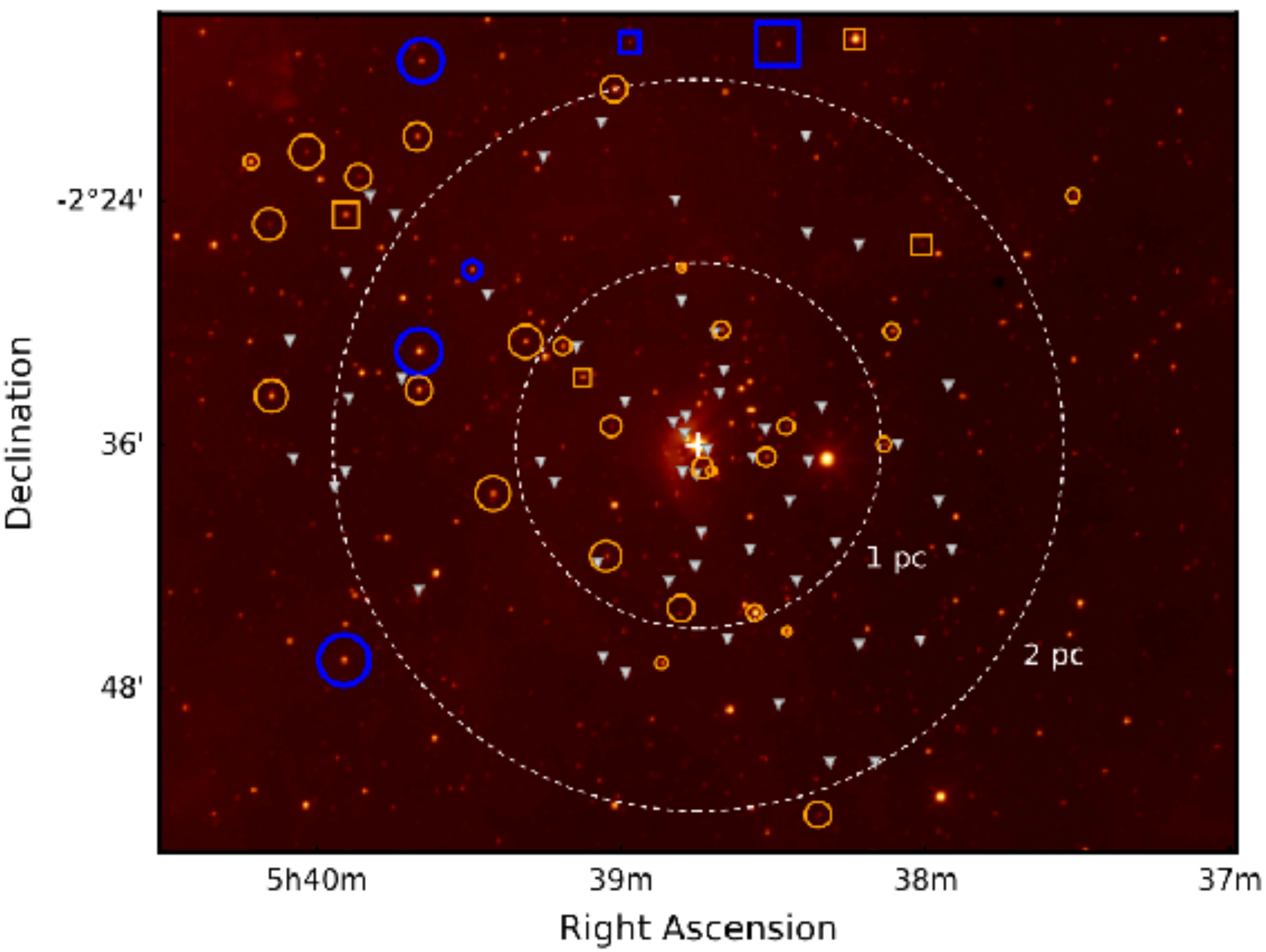


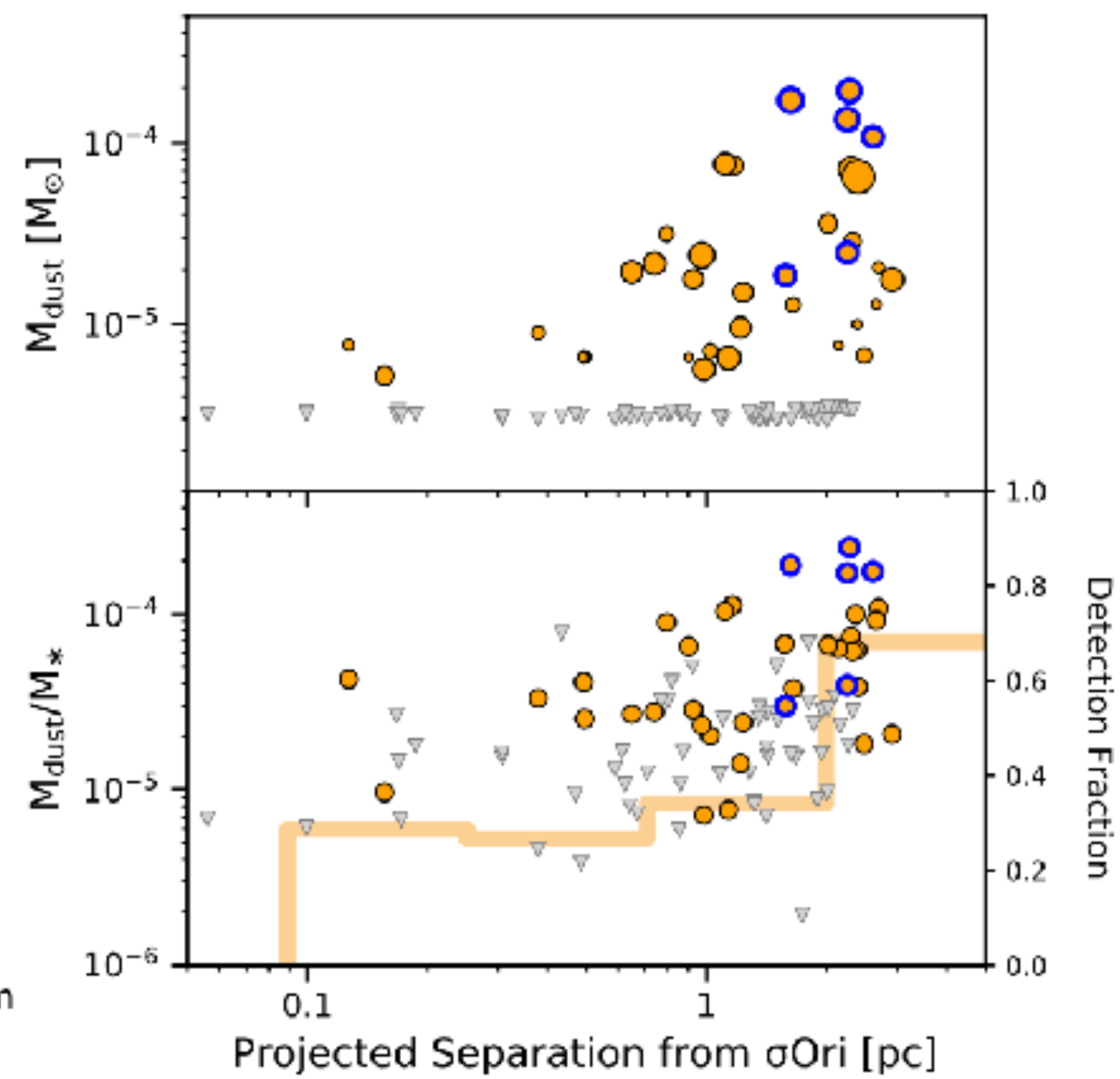
Winter & Haworth 2022 (review)

Observational evidence external photo evaporation

ALMA protoplanetary disk study in sigma Orionis region: O star

Gas detections **Dust detections**



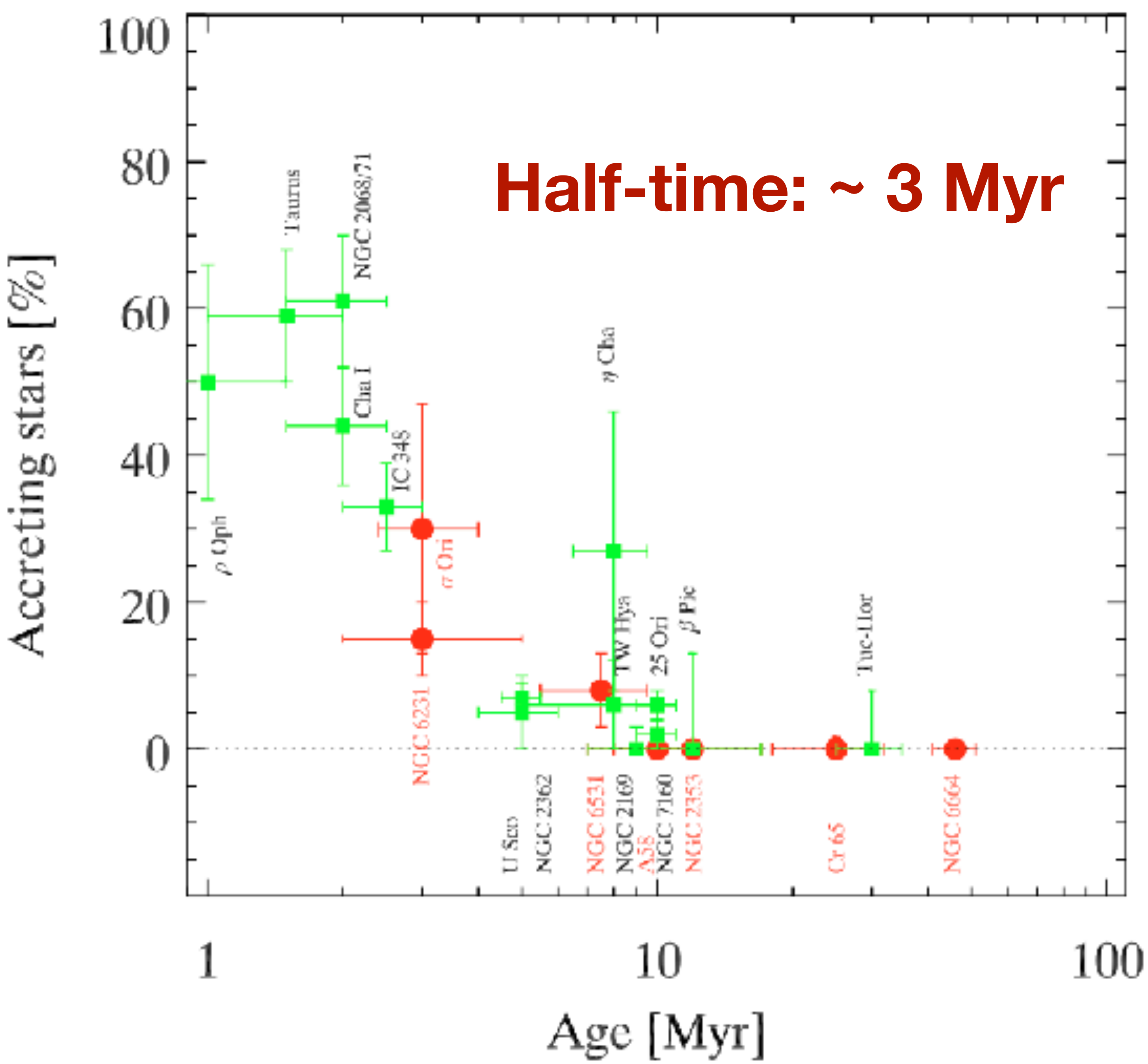


Gas-rich disks further away from O star and also massive dust disks are lacking at small separation

Ansdell et al. 2017

Disk lifetime: how long are stars accreting?

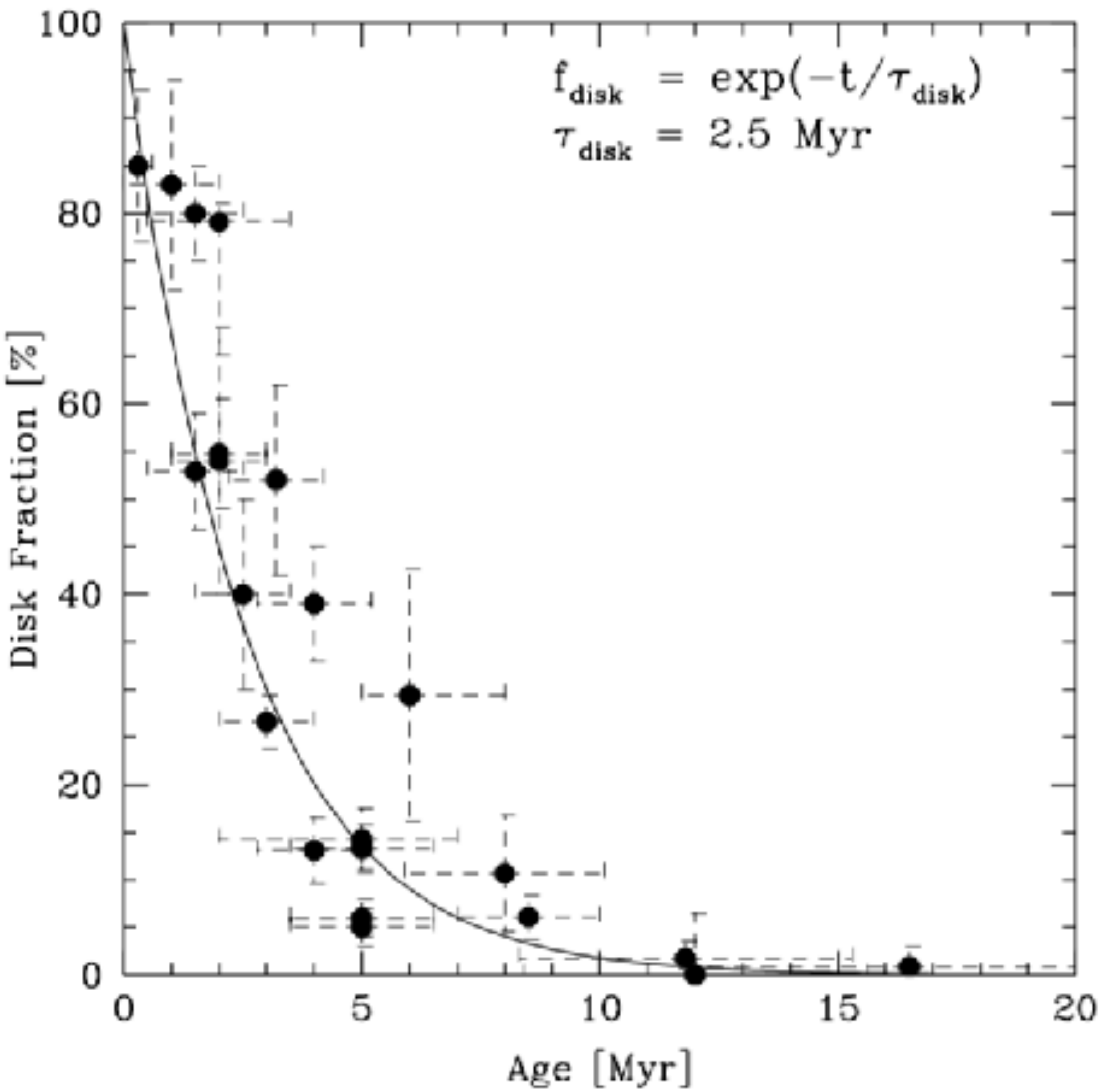
Approach: compute fraction of stars in a cluster that are still accreting and plot them as function of age



Fedele et al. 2010

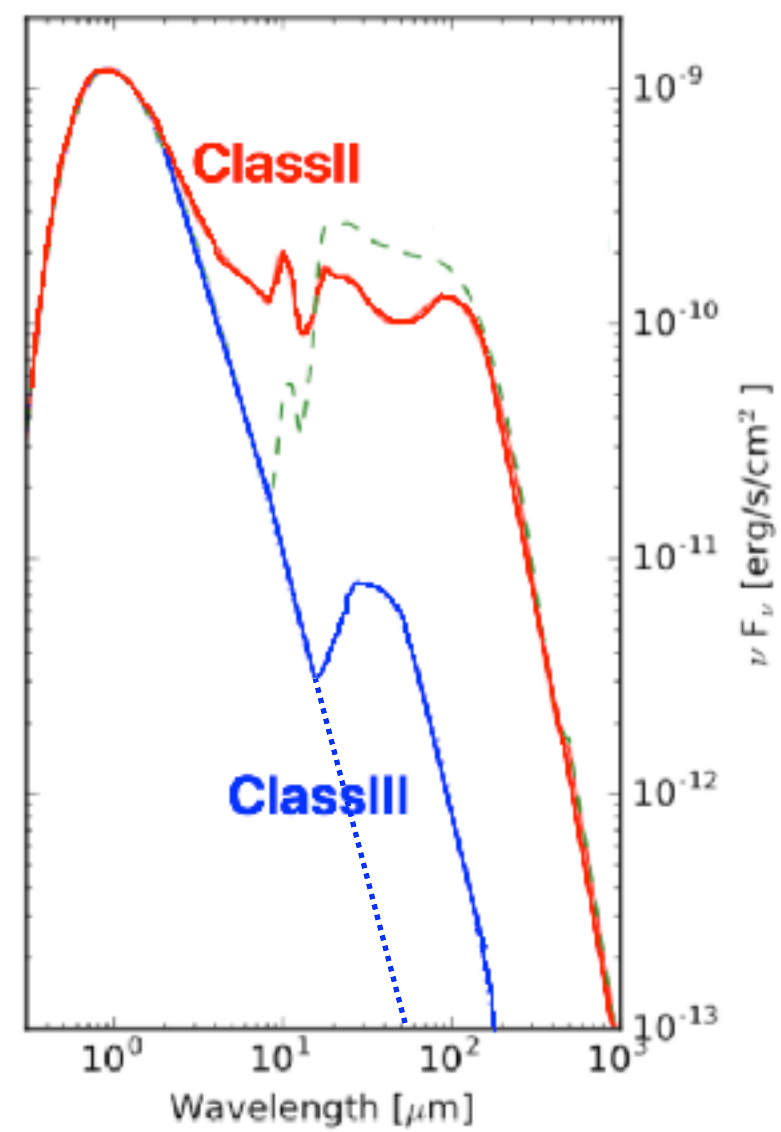
Disk lifetime: alternative (IR)

Approach: compute fraction of stars in a cluster that have a dusty disk (strong IR excess) and plot them as function of age



SED with strong IR excess: disk

SED with weak/ no IR excess: disk-less

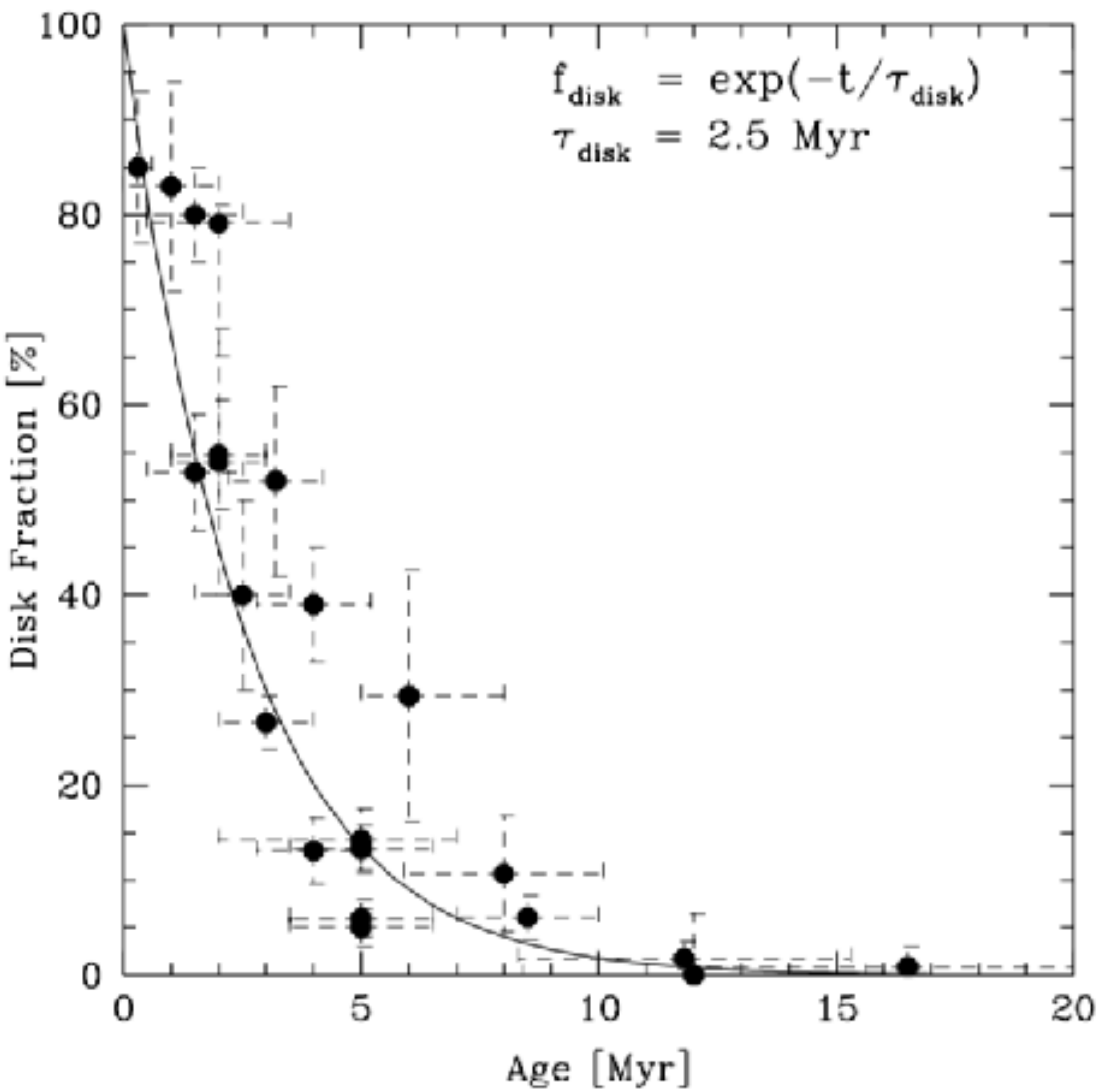


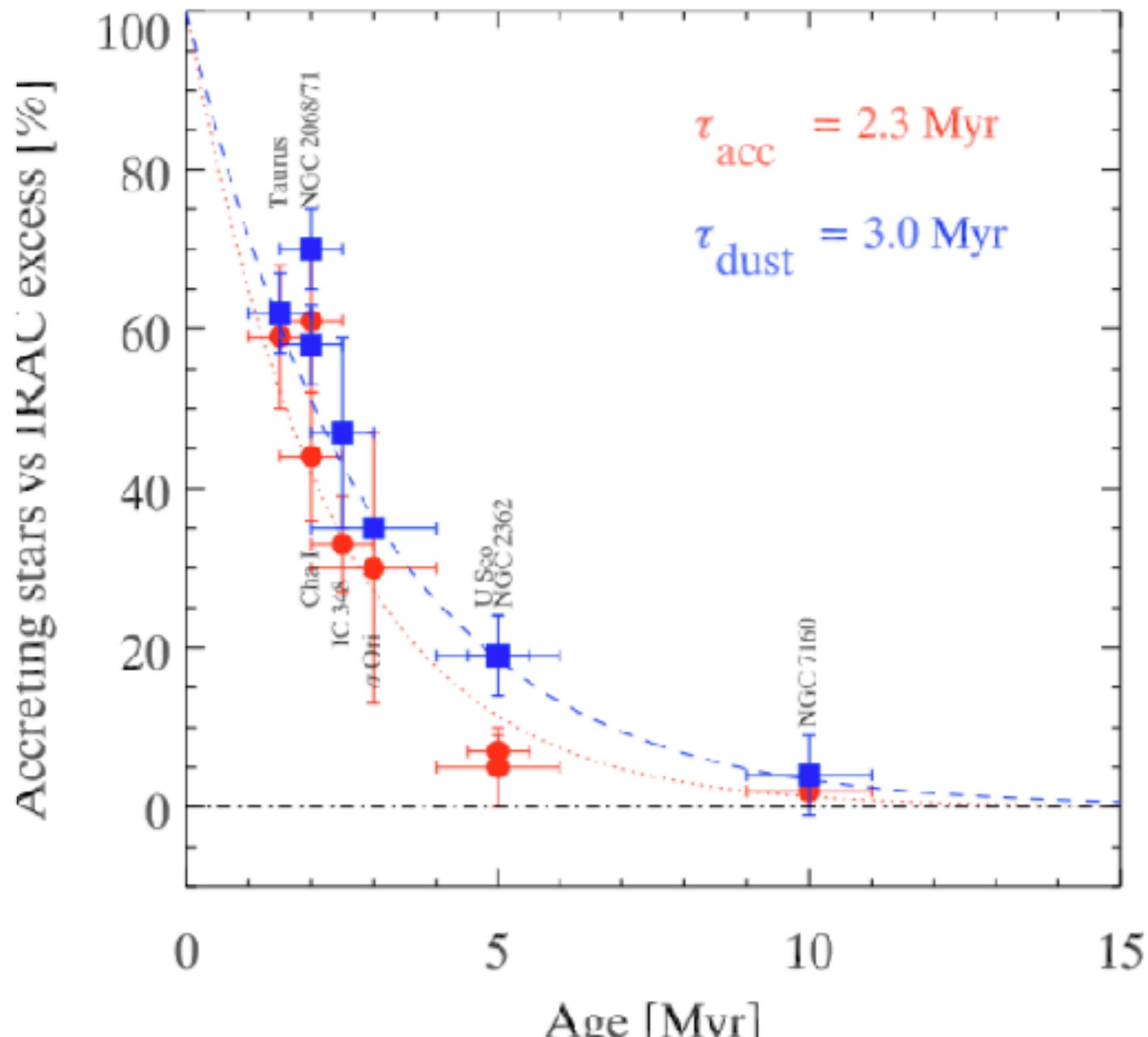
Hernandez et al. 2007
Mamajek 2009

Disk lifetime

Basically a match! So accretion and IR excess both trace the presence of a gas disk

Fedele et al. 2010





The lifetime of 2-3 Myr matches well with the predictions of the viscous disk model for alpha ~ 10^{-2} and is still used as the disk lifetime in most disk evolution and planet formation models

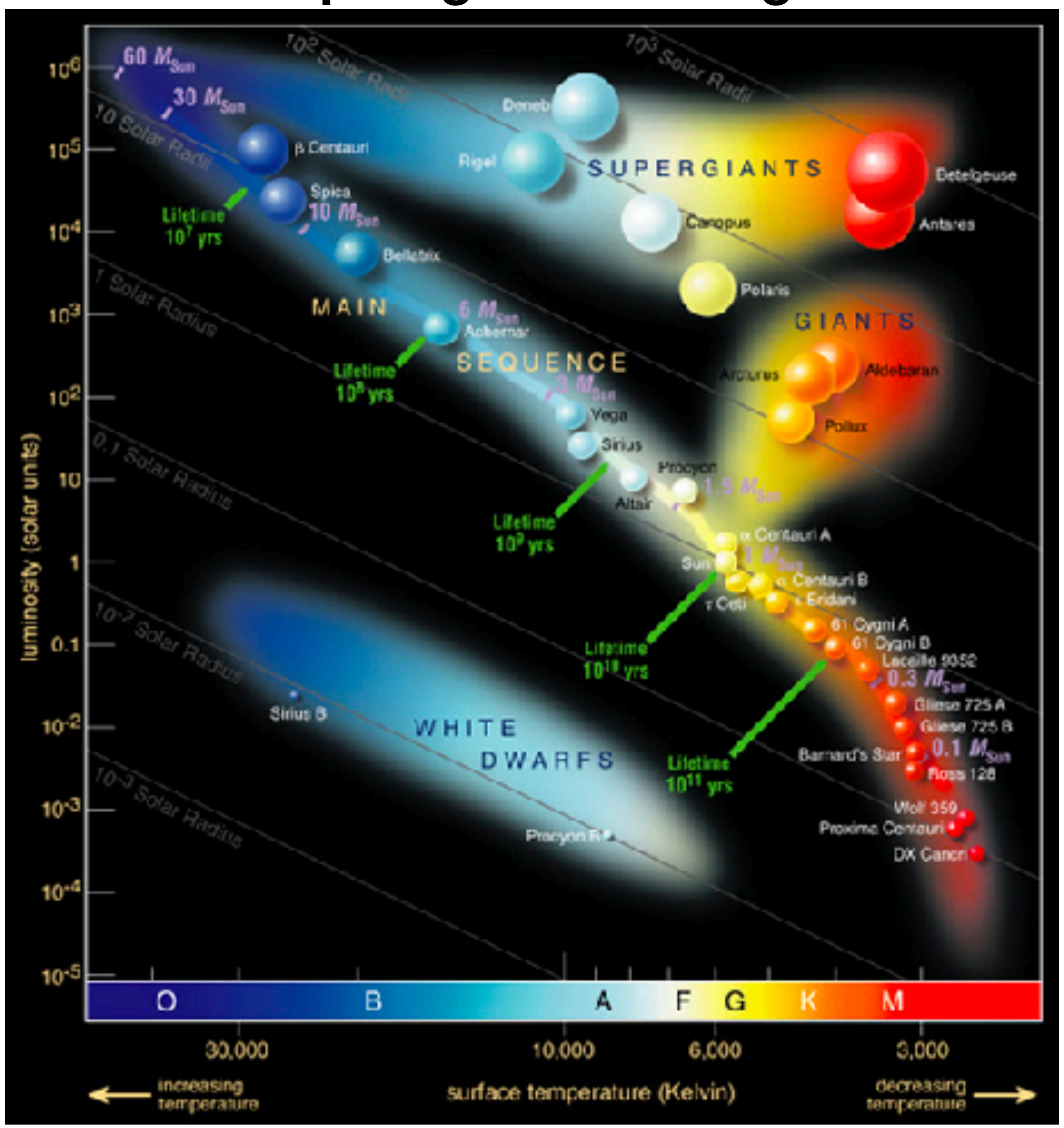
Large uncertainties on age, cluster membership and environment!

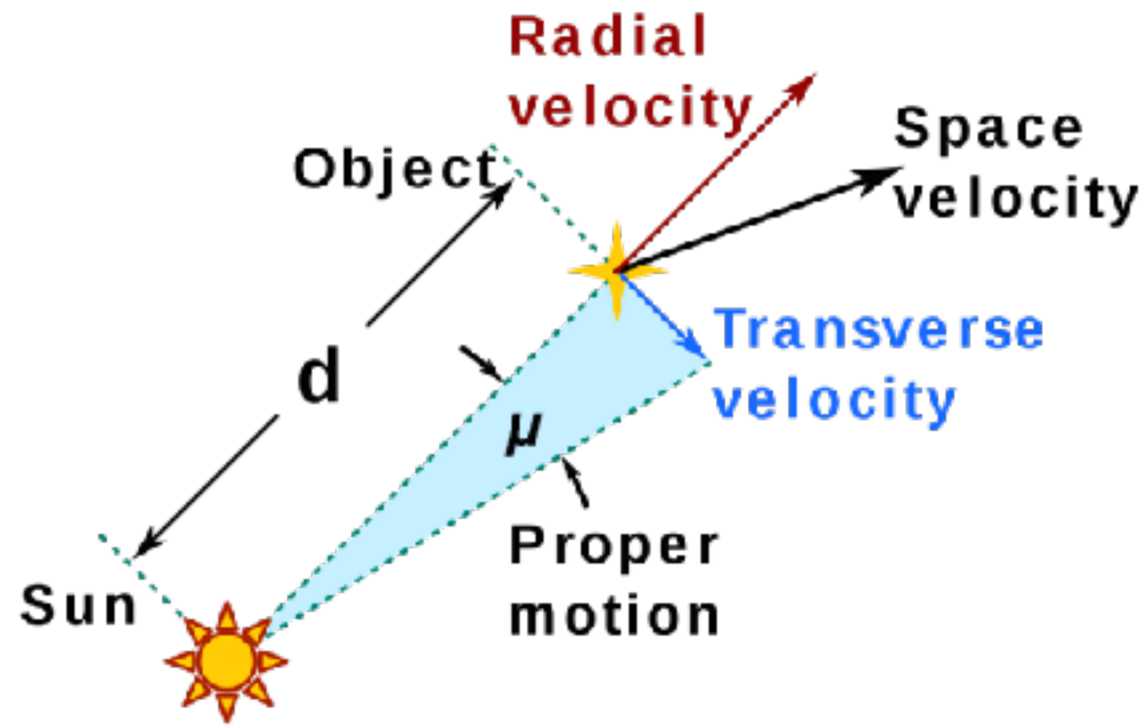
How do you measure the age of a group of stars?

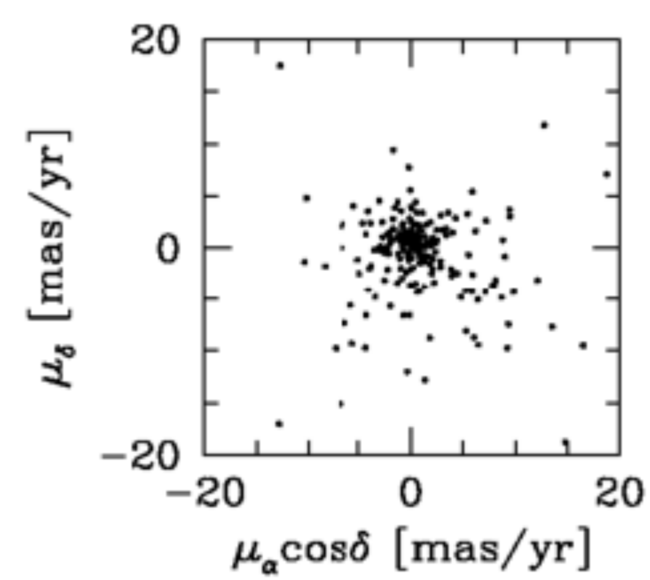
How do you measure the cluster membership of a group of stars?

Large uncertainties on age, cluster membership and environment!

Herzsprung Russel diagram

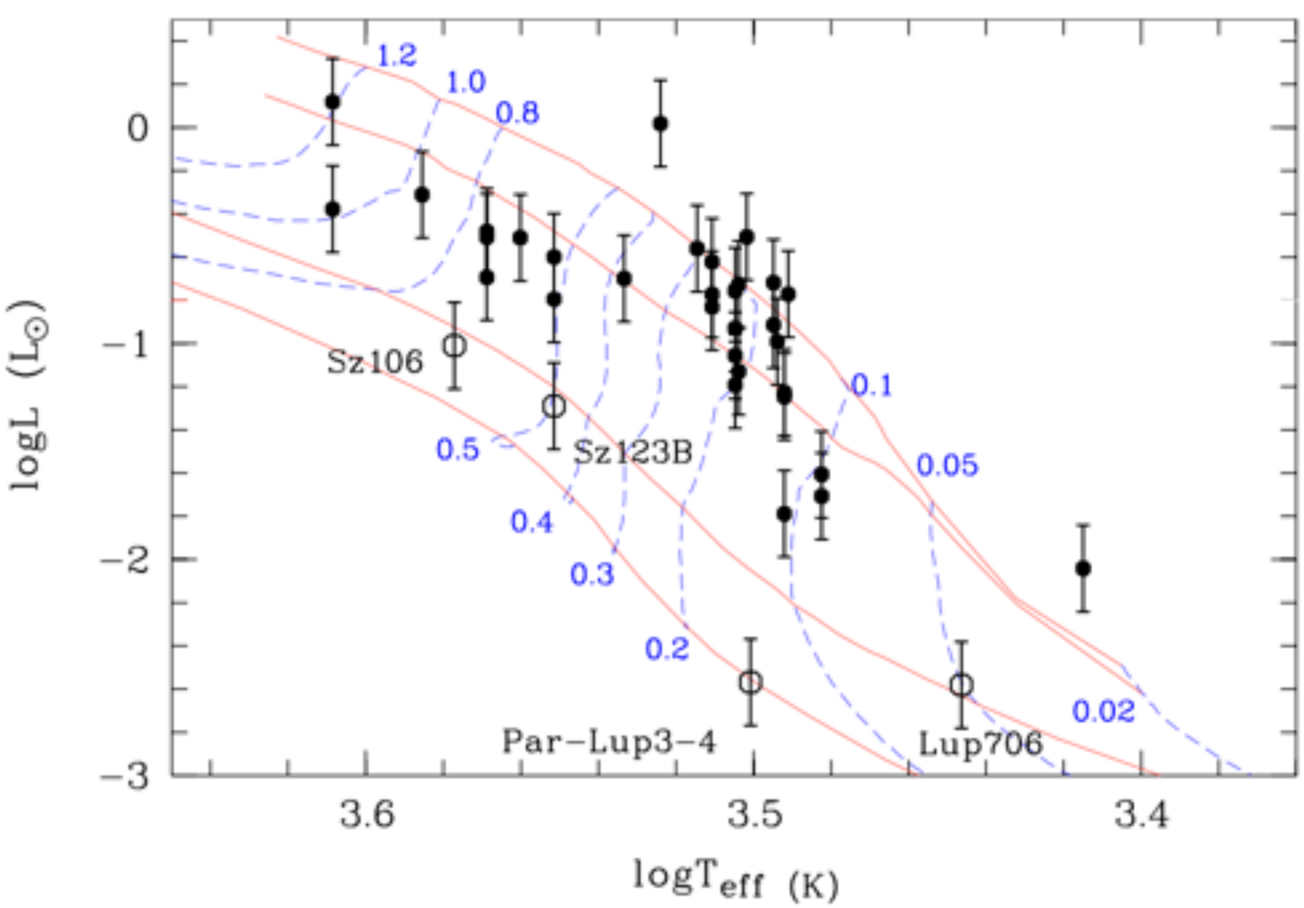






Large uncertainties on age, cluster membership and environment!

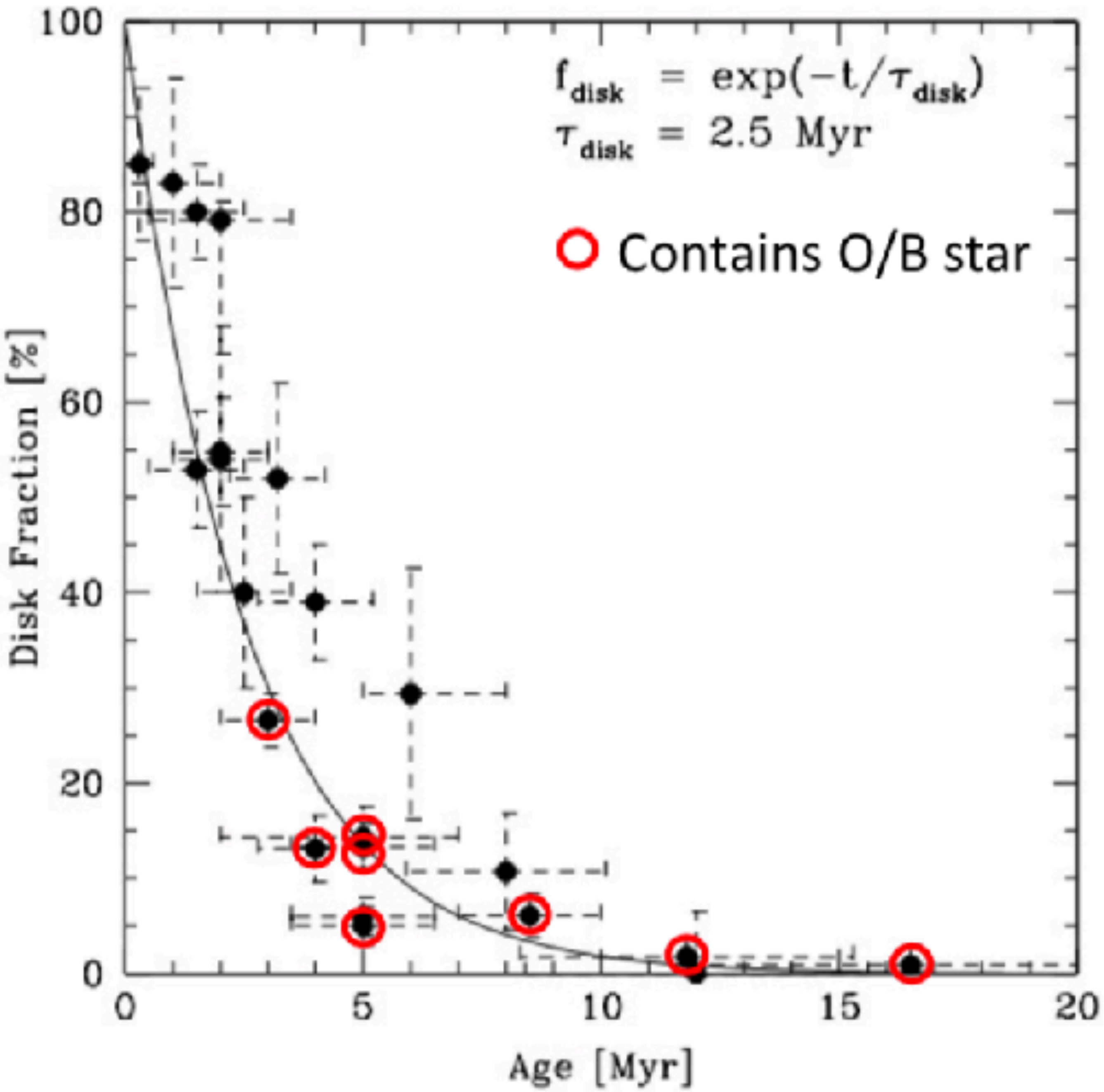
Isochrones of Lupus stars

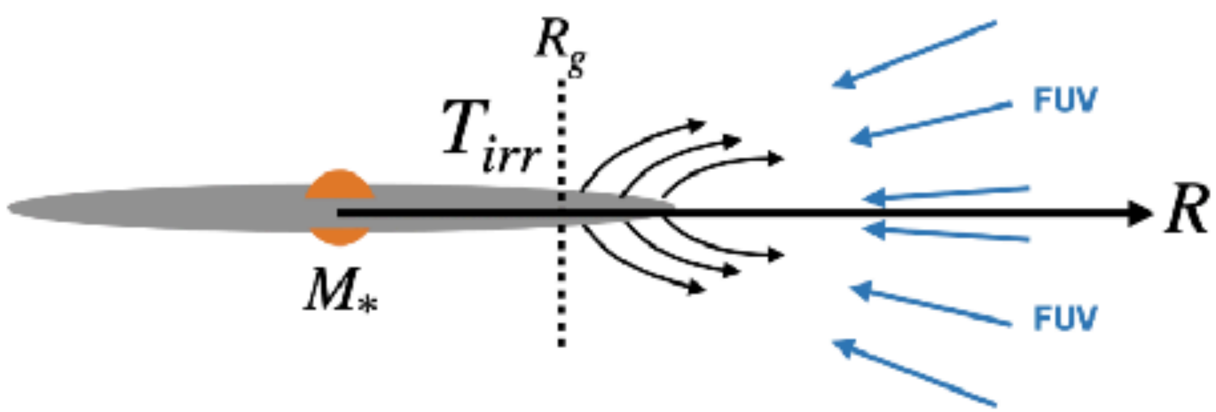


Gaia DR2 (2018): individual parallax and proper motion of young stars in nearby clusters

Alcala et al. 2014
Gaia consortium et al. 2018

Environment?

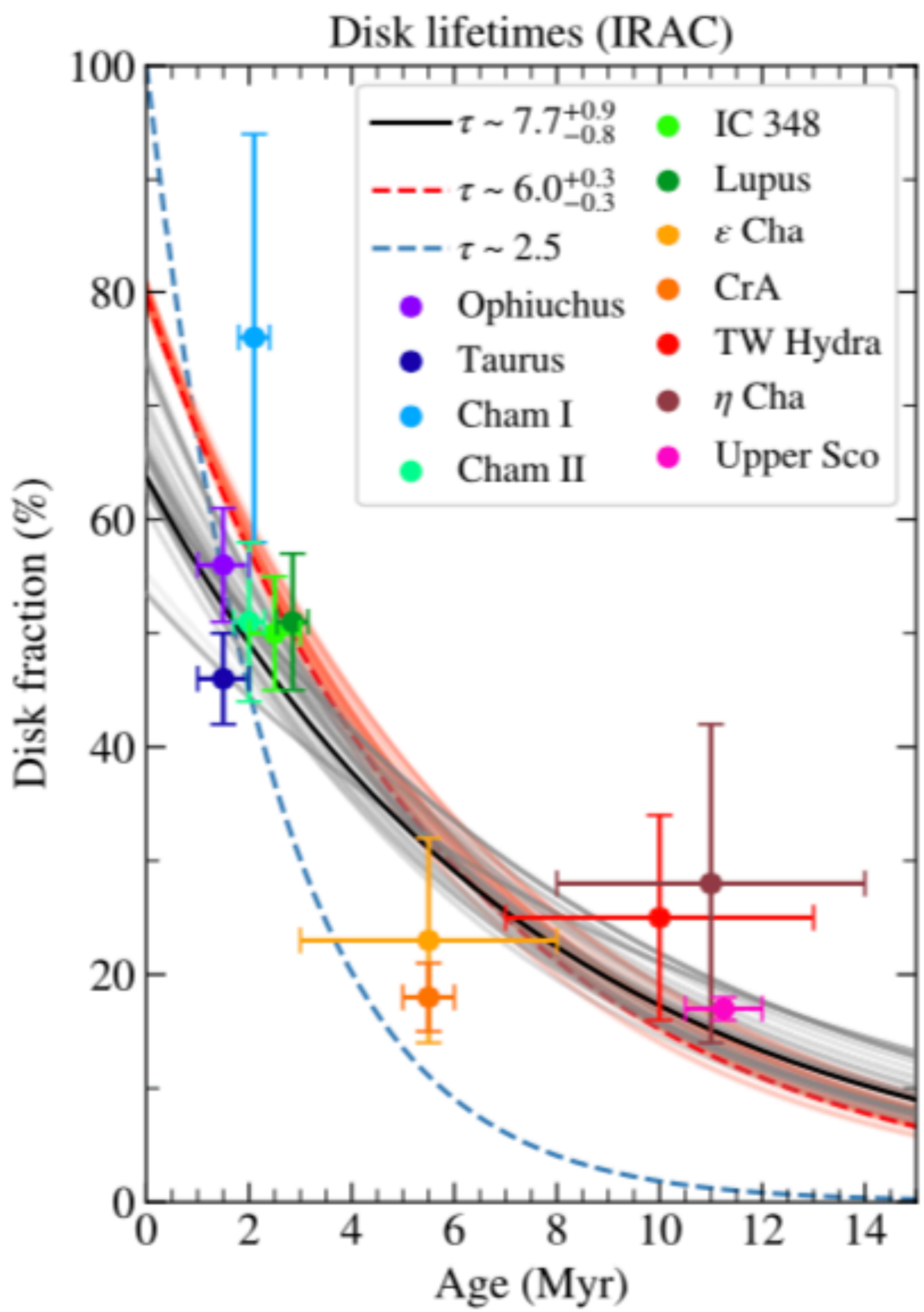


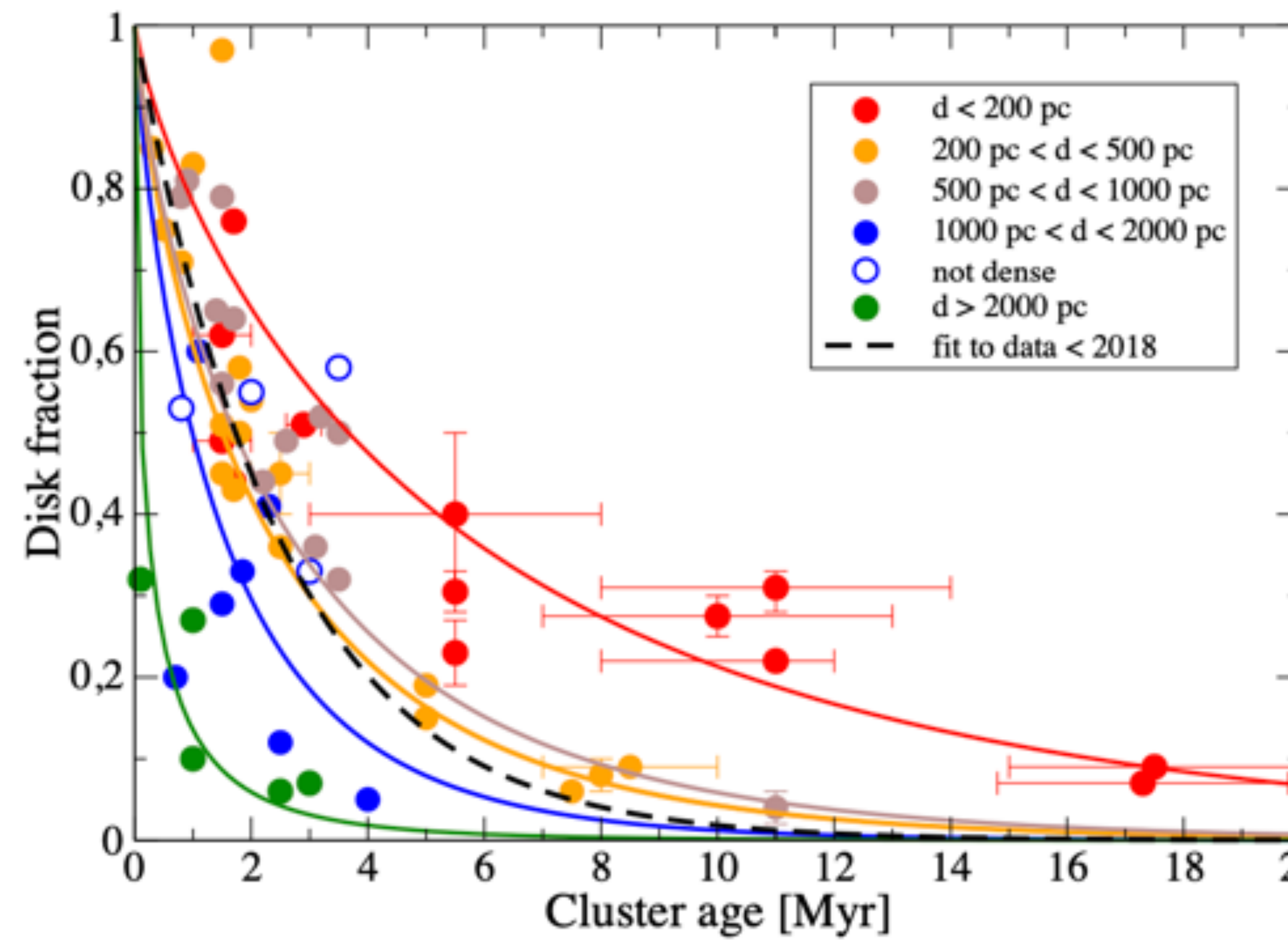


Many of the clusters in these early studies contain an OB star, and their disk lifetime is thus affected by their environment

Michel et al. 2021

New disk lifetime





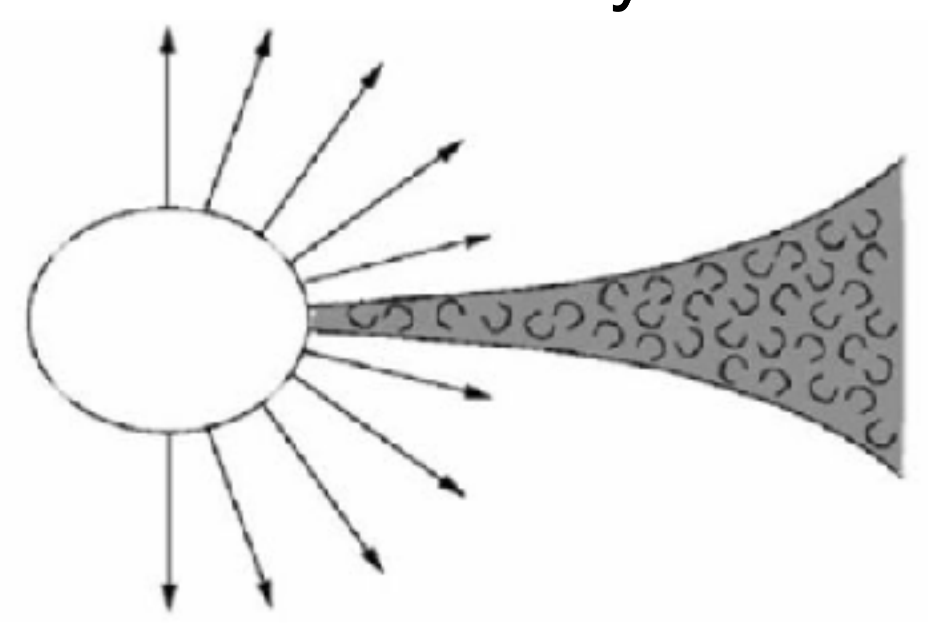
When only including the clusters without OB-stars, the disk lifetime is closer to 8 Myr!

RECENT RESULT!

Michel et al. 2021
Pfalzner et al. 2022

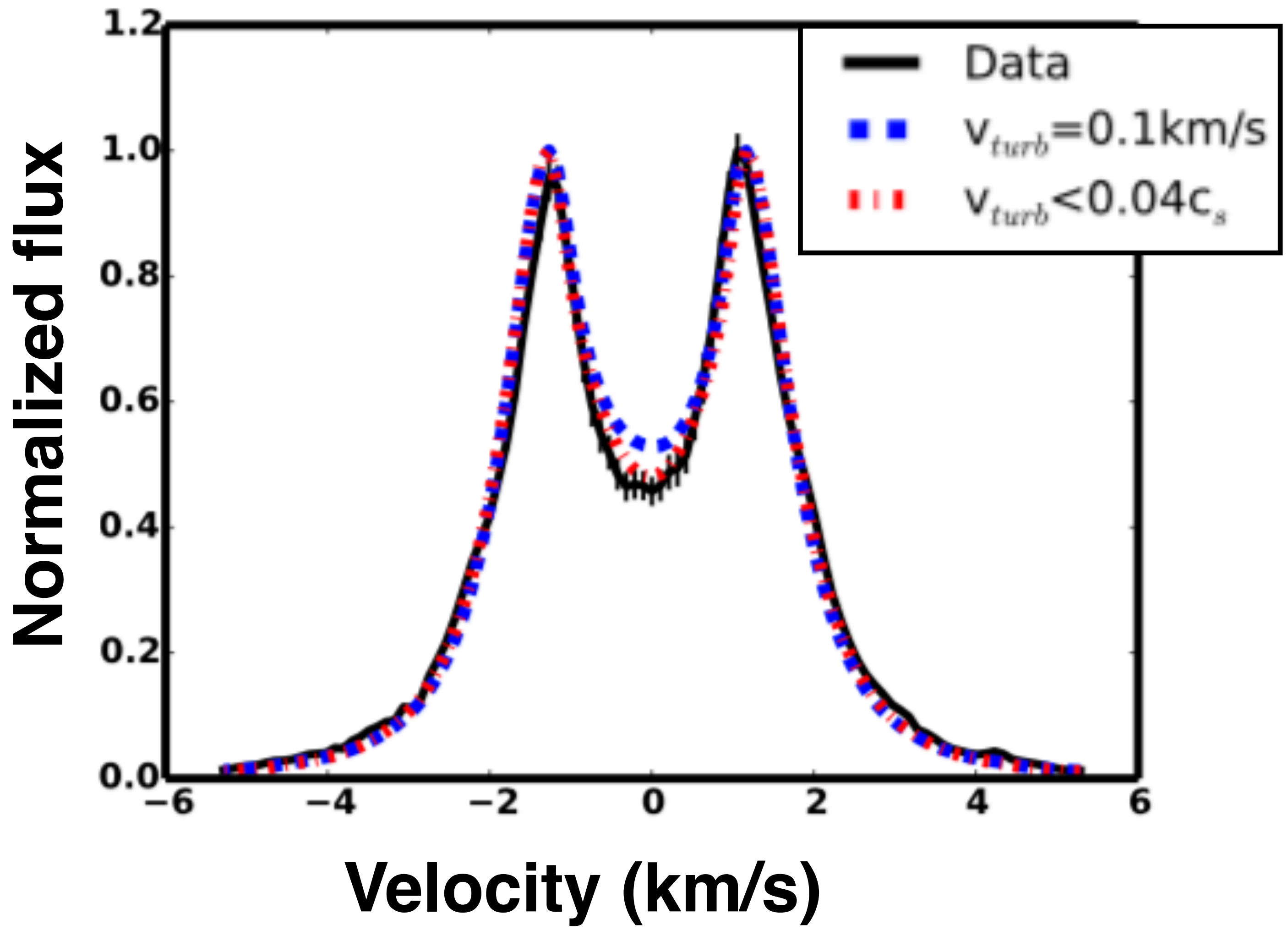
Turbulence

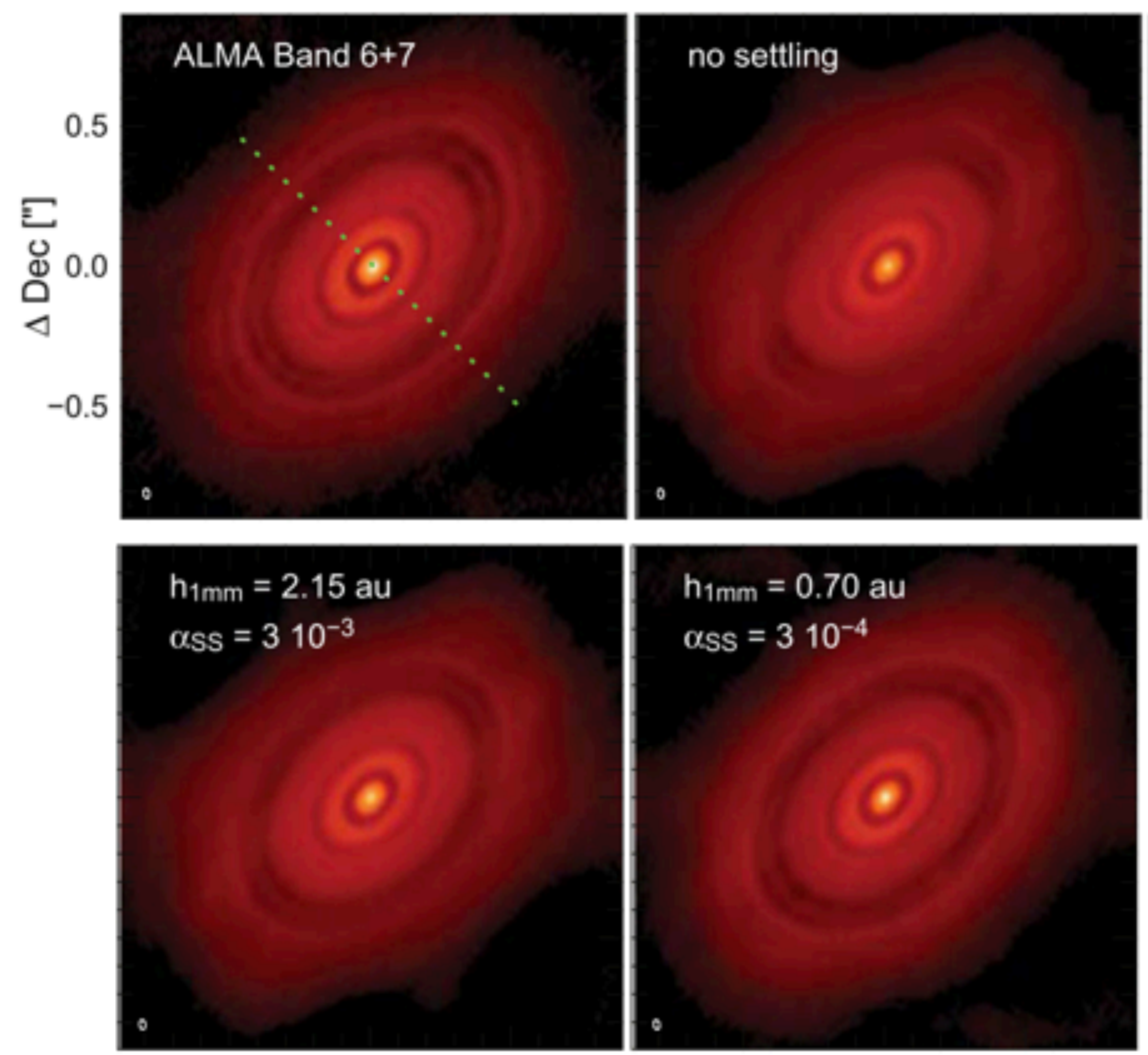
- Recall: parameter α_s (viscosity) used to parametrize the turbulence in the disk
- Hartmann et al. 1998: $\alpha_s \sim 10^{-2}$ consistent with observations.
- Turbulence parameter is important in many hydrodynamic and dust processes in the disk: many indirect constraints from observations



Line broadening and extreme dust settling

CO line profile: very little pressure broadening



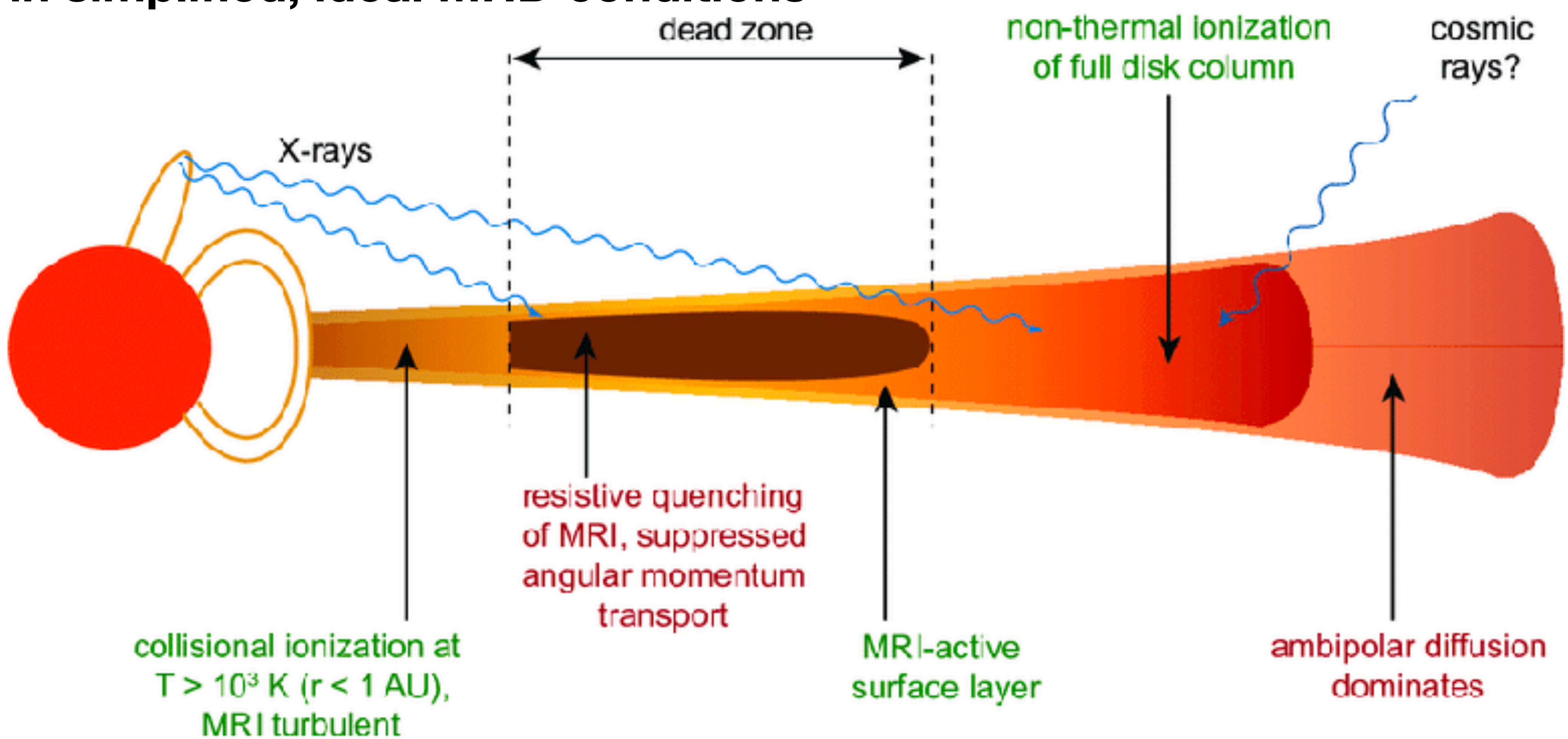


Vertical height of mm grains: very settled => very low vertical turbulence

Flaherty et al. 2015
Pinte et al. 2016

MRI efficiency?

Lower turbulence when including non-ideal MHD effects in disks: MRI only efficient in simplified, ideal MHD conditions



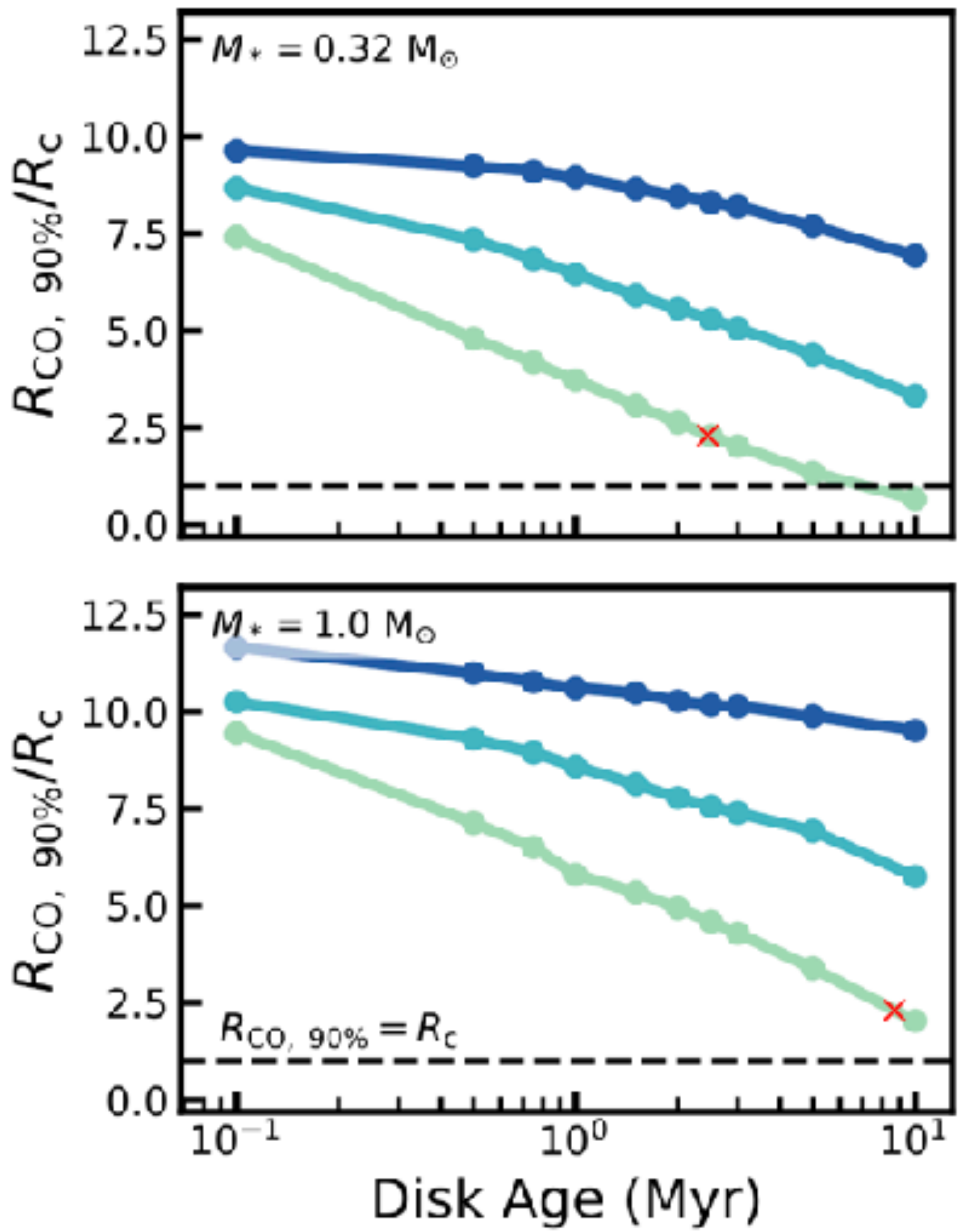
If MRI is suppressed, the turbulence is naturally very low and cannot transport angular momentum

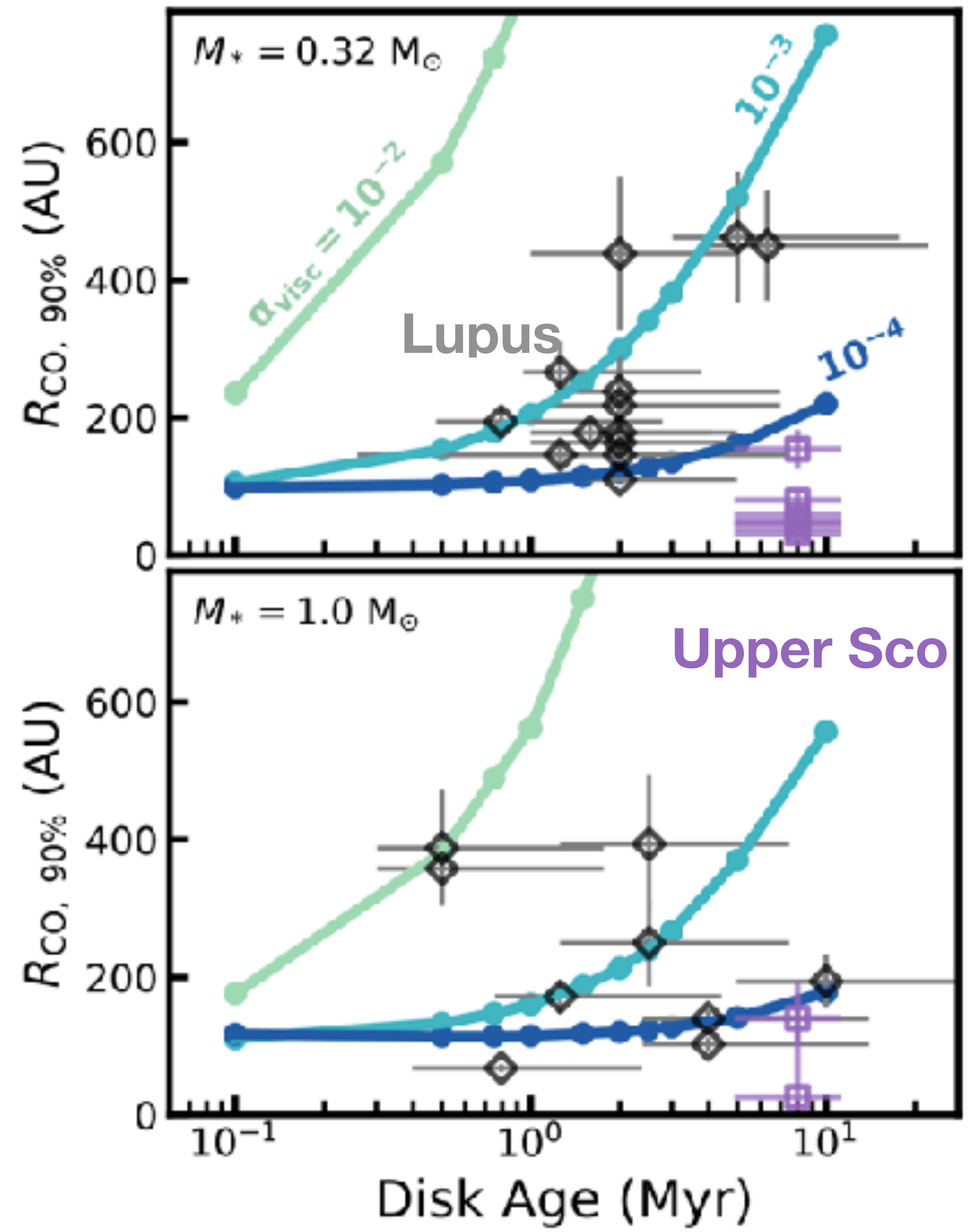
Armitage 2011
Bai & Stone 2013

More on CO analysis in Lecture 5

Evidence viscous spreading?

Using a viscous disk model to compute ^{12}CO emission (observable in disks with ALMA as gas disk size tracer)

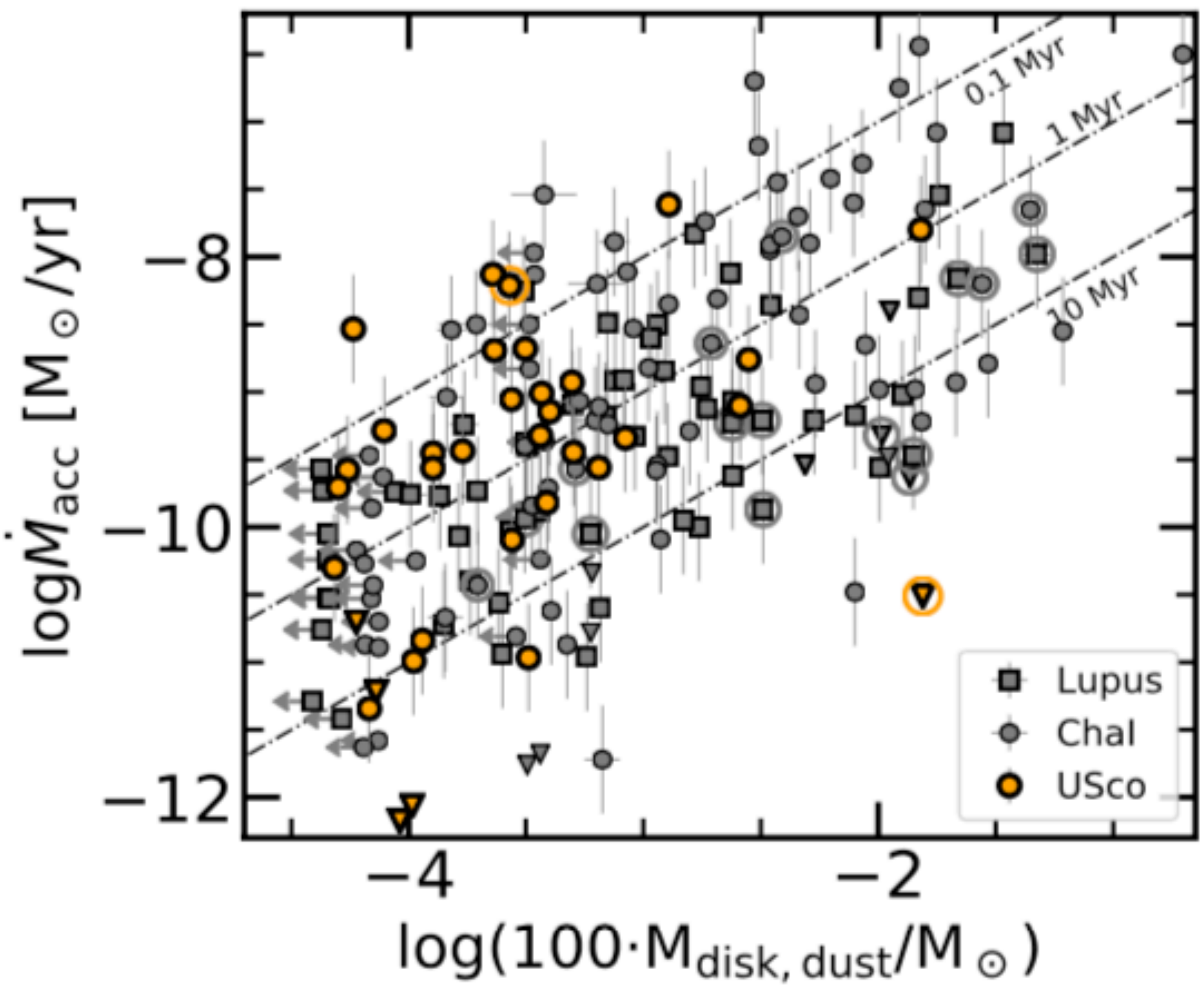




CO observations appear to be consistent with alpha <~10^{-3}

Trapman et al. 2020

Accretion rates over time



Accretion rates in young stars in Upper Sco region (10 Myr) are similar and equally scattered as those in Lupus: NO strong decrease over time as expected from viscous model?

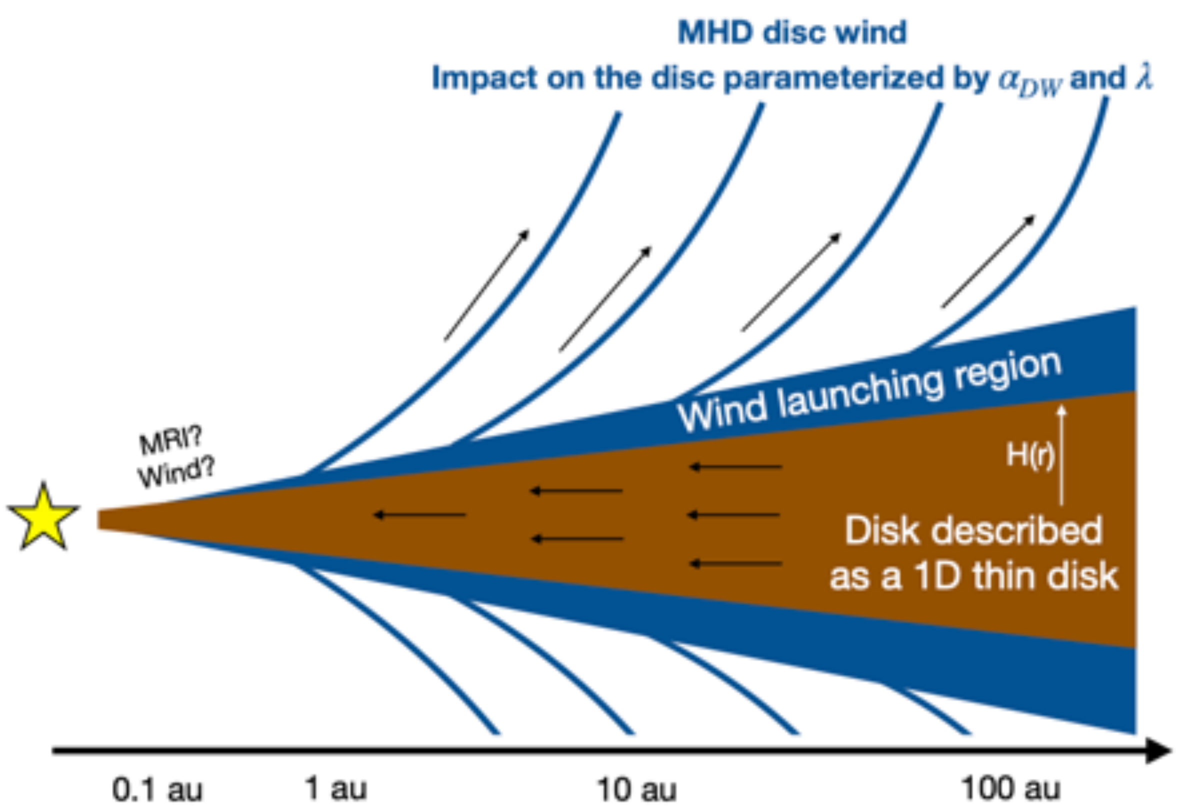
(2 Myr)

(10 Myr)

Is there an alternative way to get rid of angular momentum?

Mulders et al. 2017
Manara et al. 2020

Alternative: MHD disk wind model



Old viscous model:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}(\Sigma \nu r^{1/2})\right]$$

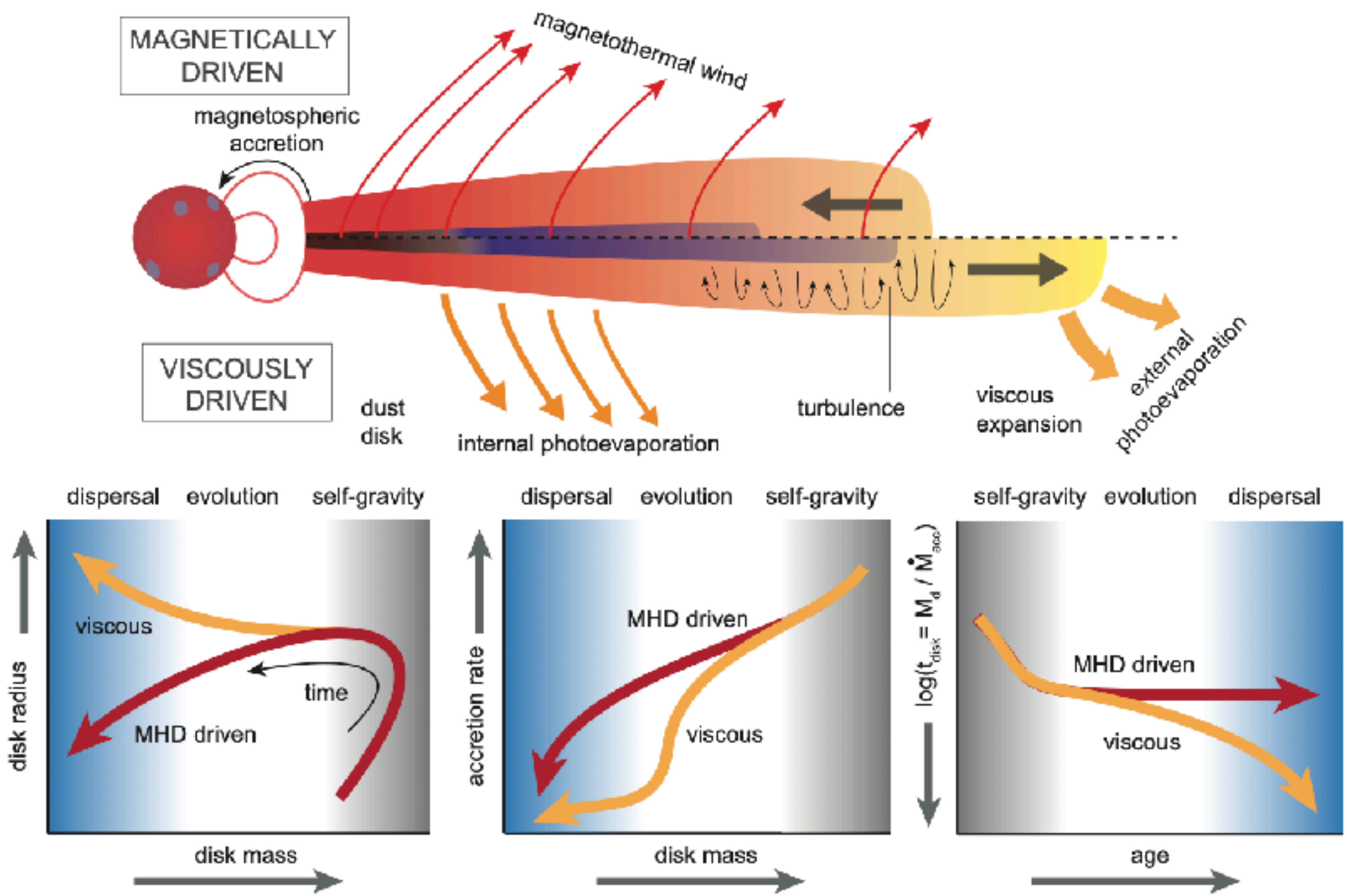
New terms:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{2r}\frac{\partial}{\partial R}\left(\frac{\alpha_{\rm DW}\Sigma c_s^2}{\Omega}\right) - \frac{3\alpha_{\rm DW}\Sigma c_s^2}{4(\lambda-1)r^2\Omega}.$$

$$\lambda \equiv \frac{L}{r\Omega(r)}$$

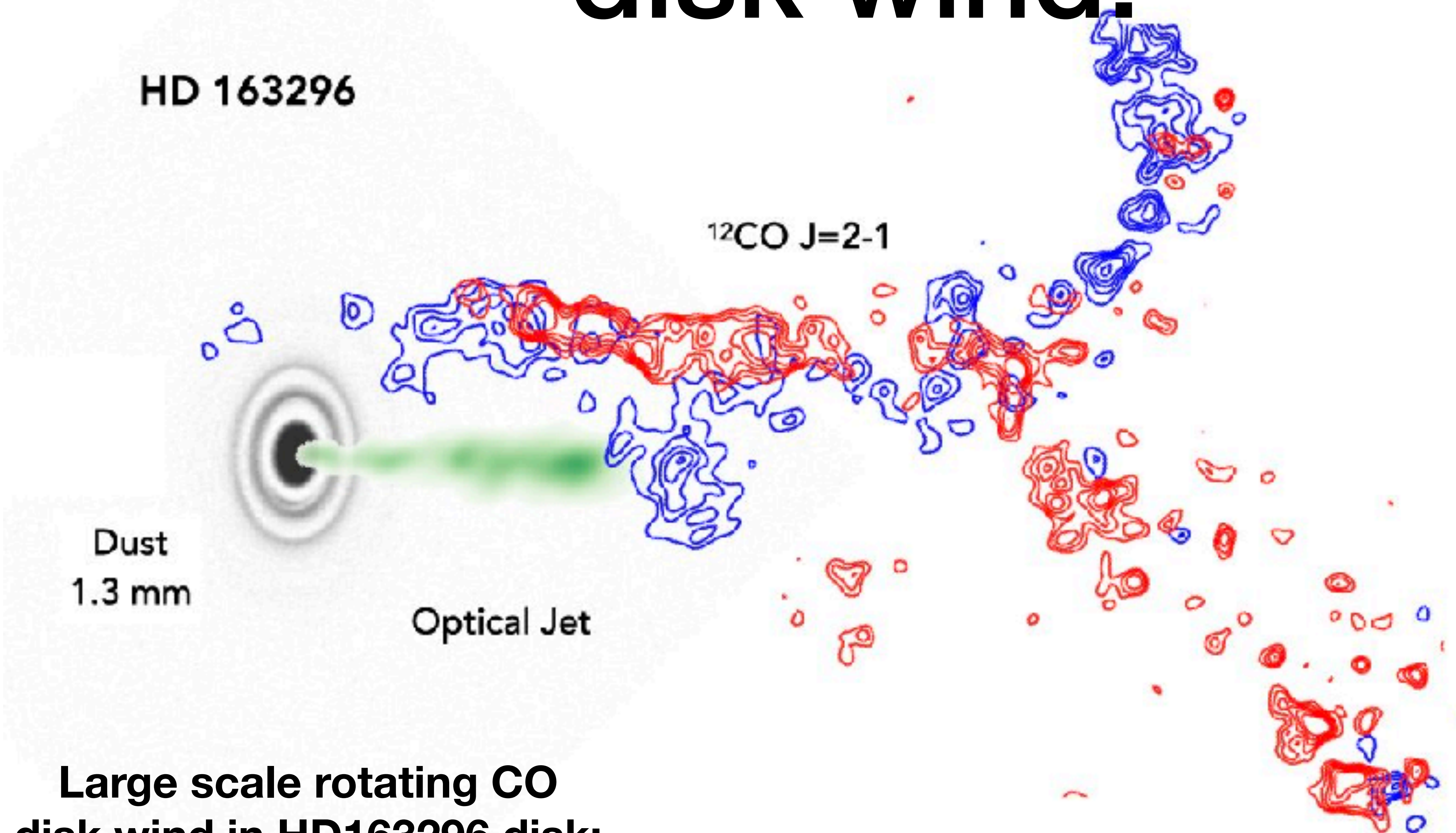
Bai & Stone 2013
Tabone et al. 2021

Differences between viscous and MHD wind



Manara et al. 2022 (PPVII)

Observational evidence disk wind!

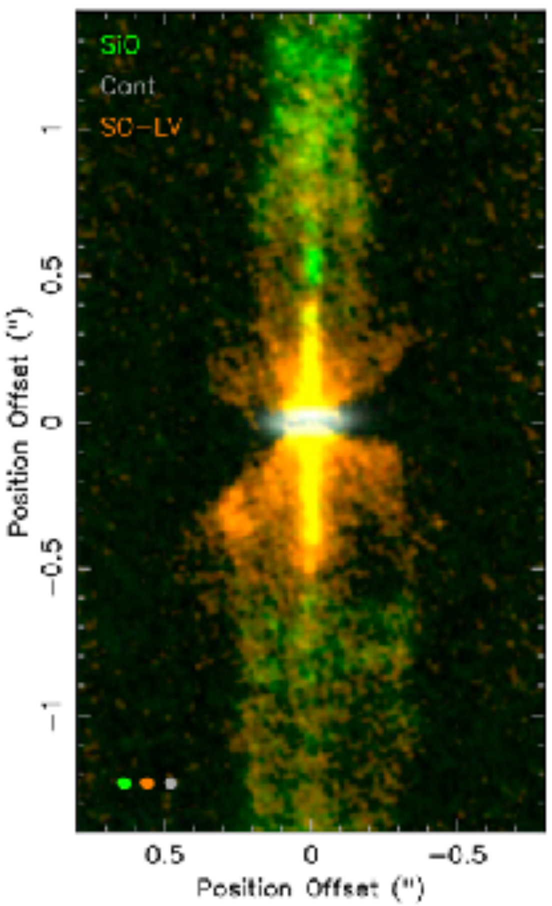


Large scale rotating CO disk wind in HD163296 disk: Mass-loss rate is ~ 10^{-6} M_{sun} yr^{-1}, 5-50 times the accretion rate: Such a large ratio is consistent with MHD disk wind, not photo evaporative wind

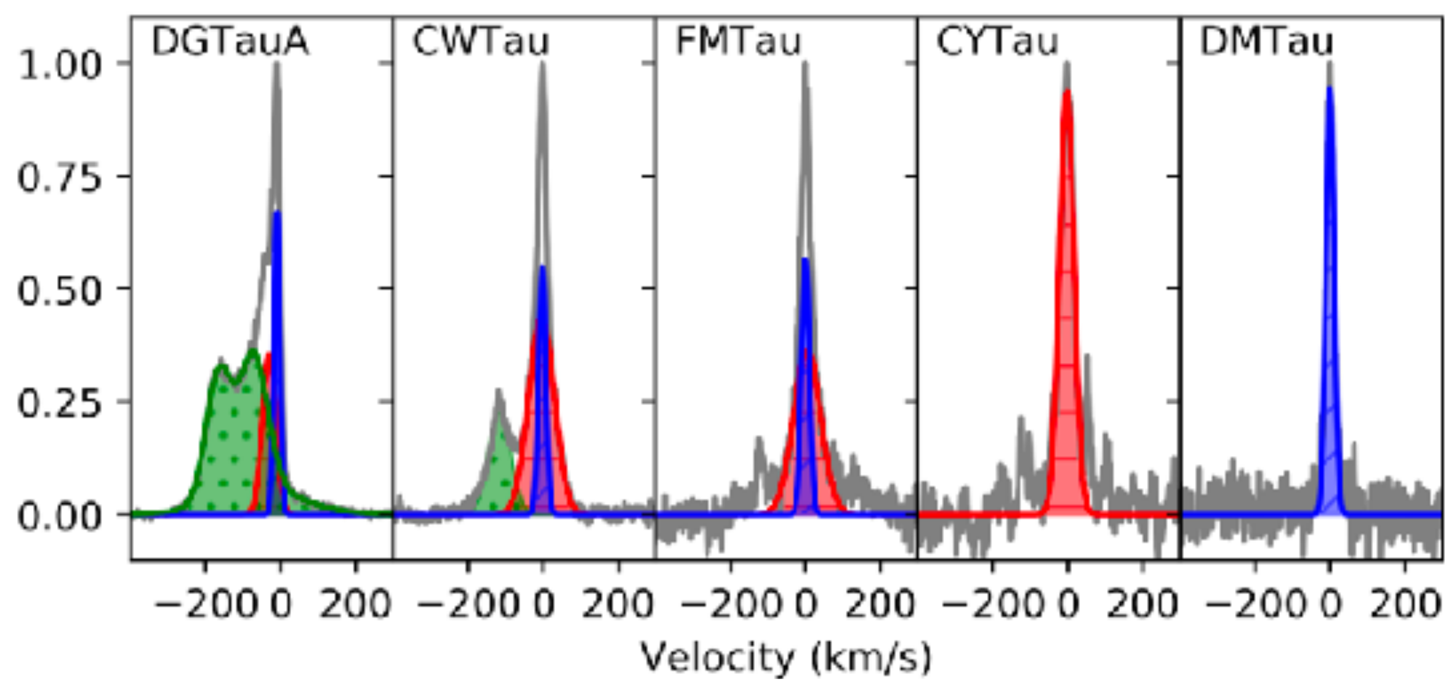
So far, this is the only one, but this is the brightest protoplanetary disk by far with such deep CO observations…

Booth et al. 2021

Disk winds



Spectrally resolved [OI]λ6300 profiles



Property	Class 0	Class I	Class II
$\dot{M}_{acc}$ ($M_\odot$/yr)	$\sim 10^{-5} - 10^{-6}$	$\sim 10^{-6} - 10^{-9}$	$\sim 10^{-6} - 10^{-12}$
R_{gas} (au)	$\lesssim 50 - 300$	$\lesssim 50 - 700$	$\lesssim 20 - 600$
Jets (HVC)			
molecular tracers	CO, SiO, SO, H_2	H_2	H_2
atomic tracers	[S II], [Fe II]	Hα, [O I], [S II], [Fe II]	Hα, [O I], [S II], [Fe II]
semi-opening angle (°)	$\sim 1 - 4$	$\sim 1 - 4$	$\sim 1 - 5$
$\dot{M}_{jet}$ ($M_\odot$/yr)	$\sim 10^{-6} - 10^{-7}$	$\sim 10^{-6} - 10^{-8}$	$\sim 10^{-7} - 10^{-10}$
$\dot{M}_{jet}/\dot{M}_{acc}$	~ 0.2	$\sim 0.2 - 0.1$	~ 0.1
Winds (LVC)			
molecular tracers	SO, SO_2	H_2, CO	H_2, CO
atomic tracers	unknown	[O I], [S II]	[O I], [S II]
semi-opening angle (°)	$\sim 20 - 45$	$\sim 20 - 40$	$\sim 25 - 35$
$\dot{M}_{wind}$ ($M_\odot$/yr)	$\sim 10^{-5} - 10^{-7}$	$\sim 10^{-6} - 10^{-7}$	$\sim 10^{-8} - 10^{-11}$
$\dot{M}_{wind}/\dot{M}_{acc}$	~ 1	~ 1	$\sim 0.1 - 1$
Specific AM* (au km/s)	20-100	40-250	20-300
r_{geom}* (au)	20-120	7-40	5-10
r_{MCW}* (au)	0.3-40	0.8-32	0.5-3

Many detections of winds, both low- and high-velocity in many different lines: no clear picture yet on origin

Pascucci et al. 2022 (PPVII)

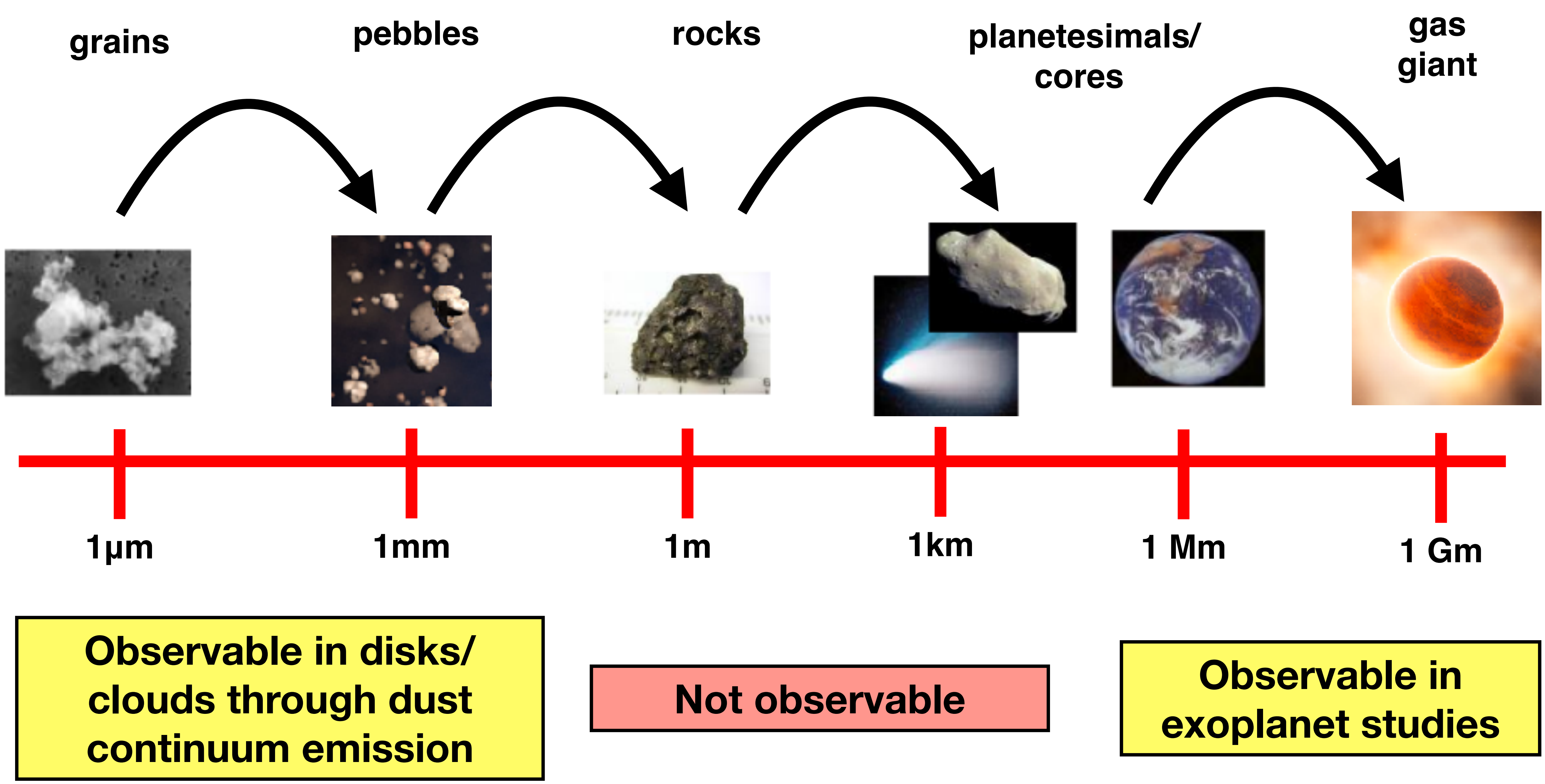
Summary gas evolution

- Gas disk difficult to trace and disk evolution still poorly understood
- Many studies use the classical viscous disk model with high alpha and longer disk lifetimes, which may not be valid
- Important to remember that mm-dust does not follow the gas as the result of dust evolution (coming up…)


Dust evolution

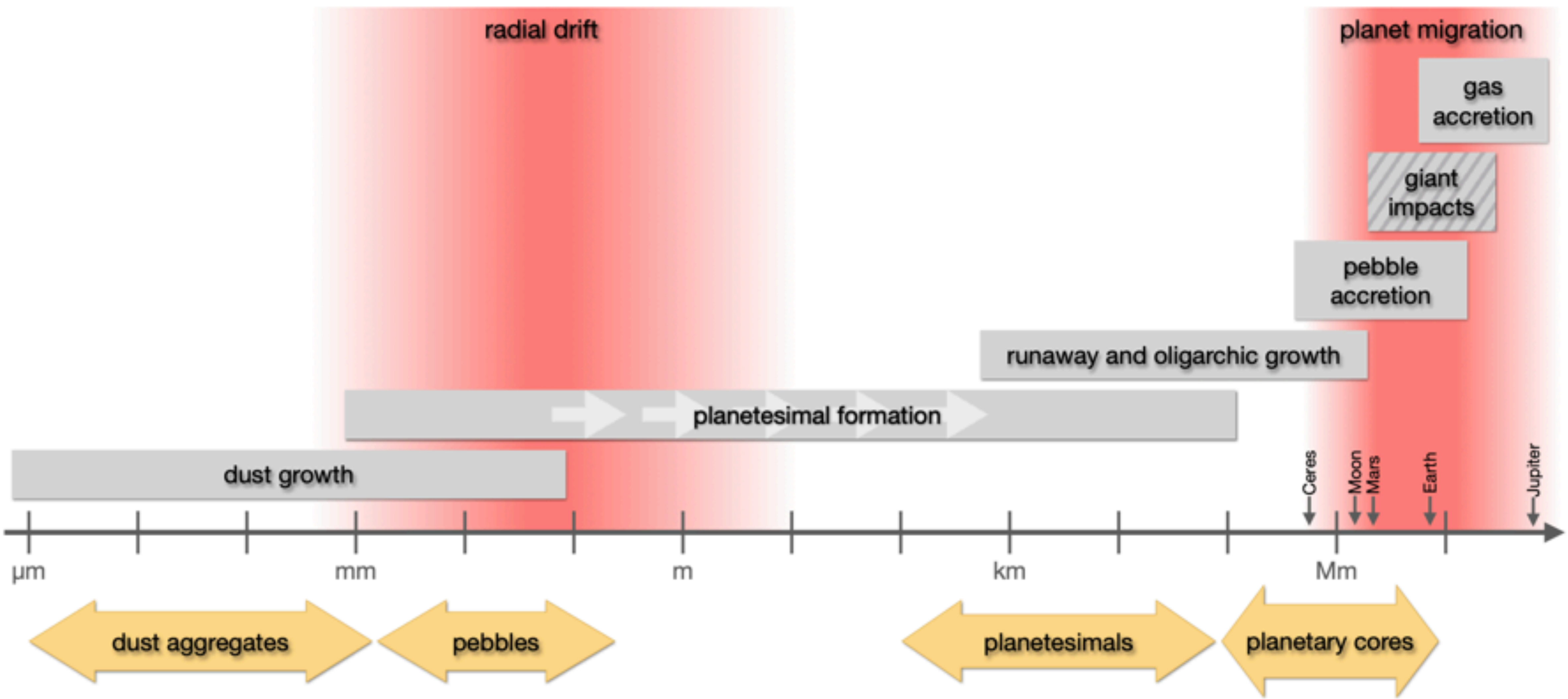
Dust growth

In order to form planets you have to grow many orders of magnitude....



Planet formation process

…and growth happens in many steps which are often analysed separately



Today we just focus on the growth of pebbles in disks: next steps towards planet formation on Friday!

Drazkowska et al. 2022 (PPVII)

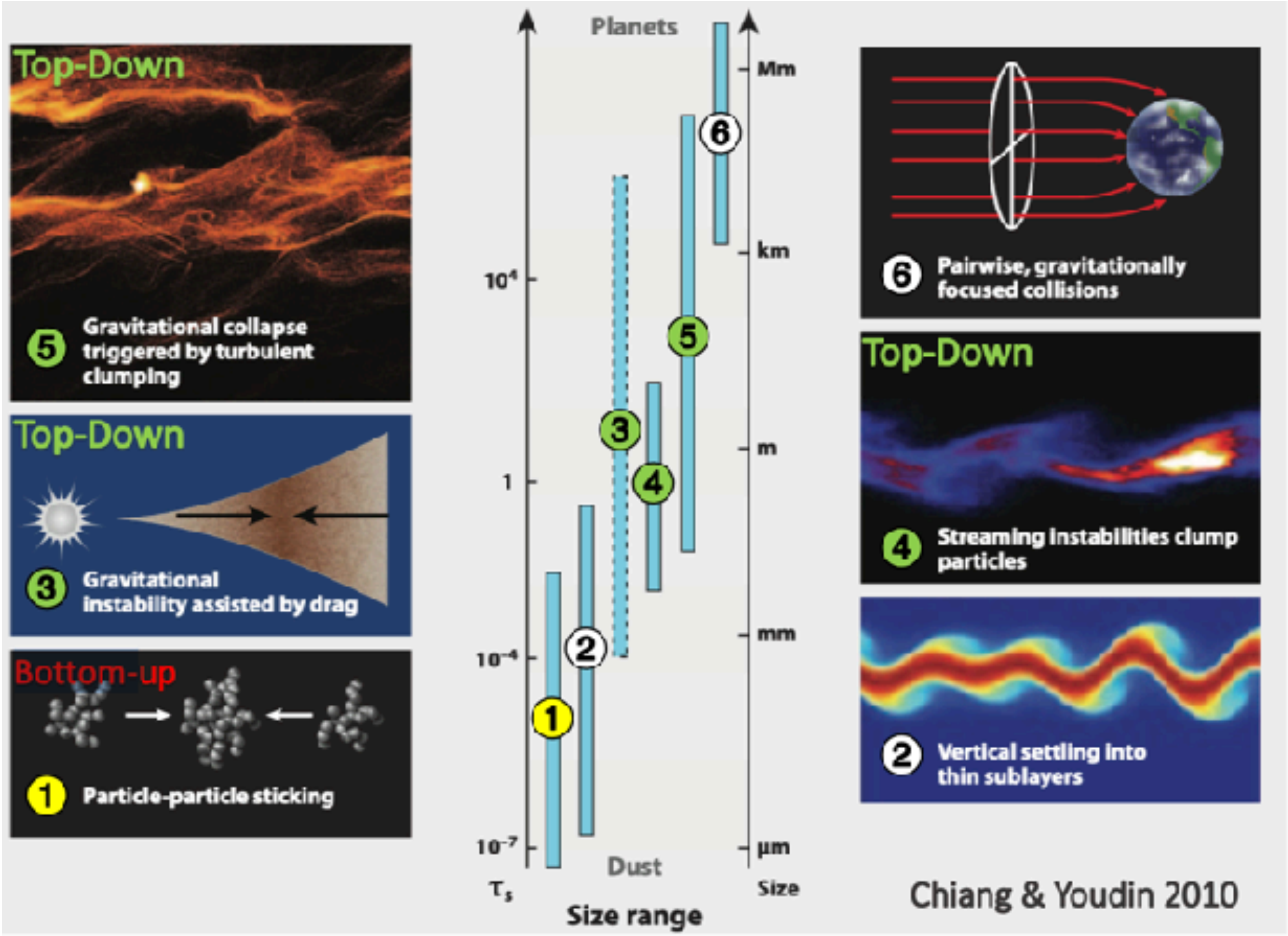
Dust growth

Bottom-up:

Dust evolution (coagulation, fragmentation,...,with several barriers incl. drift, fragmentation, bouncing, ...)

Top-Down:

Gravitational collapse of pebble clouds to form planetesimals



Coagulation through collisions

- Coagulation/sticking:
  - Van der Waals forces
  - Electrostatic/magnetic forces
  - Hysteresis (low-velocity)
- What determines outcome collision?
  - Composition (incl. ices)
  - Monomer size distribution
  - Structure (porous, compact, fractal)
  - Impact velocity
- What determines collision frequency?
  - Cross section
  - Number density
  - Relative velocities

=> many of these efficiencies figured out by lab experiments!

Possible outcomes of collisions

Collisions do not always lead to growth

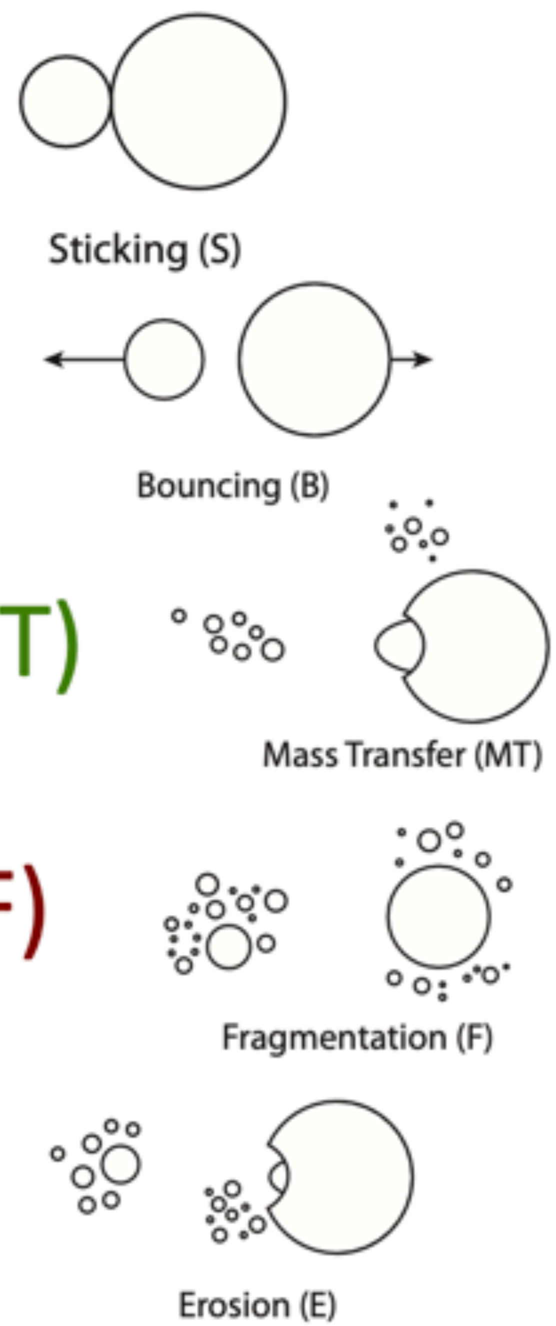
Sticking (S)

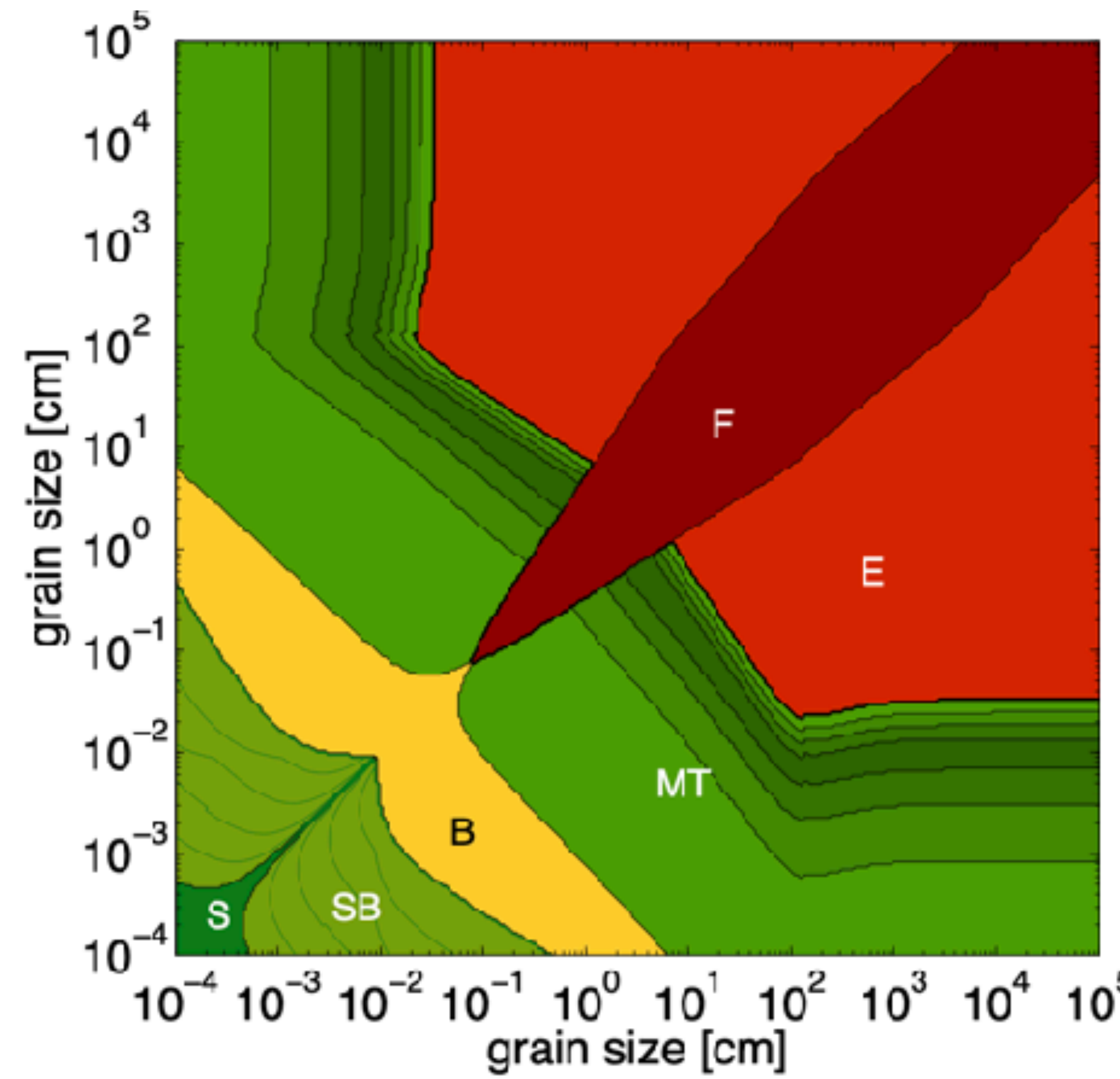
Bouncing (B)

Mass Transfer (MT)

Fragmentation (F)

Erosion (E)

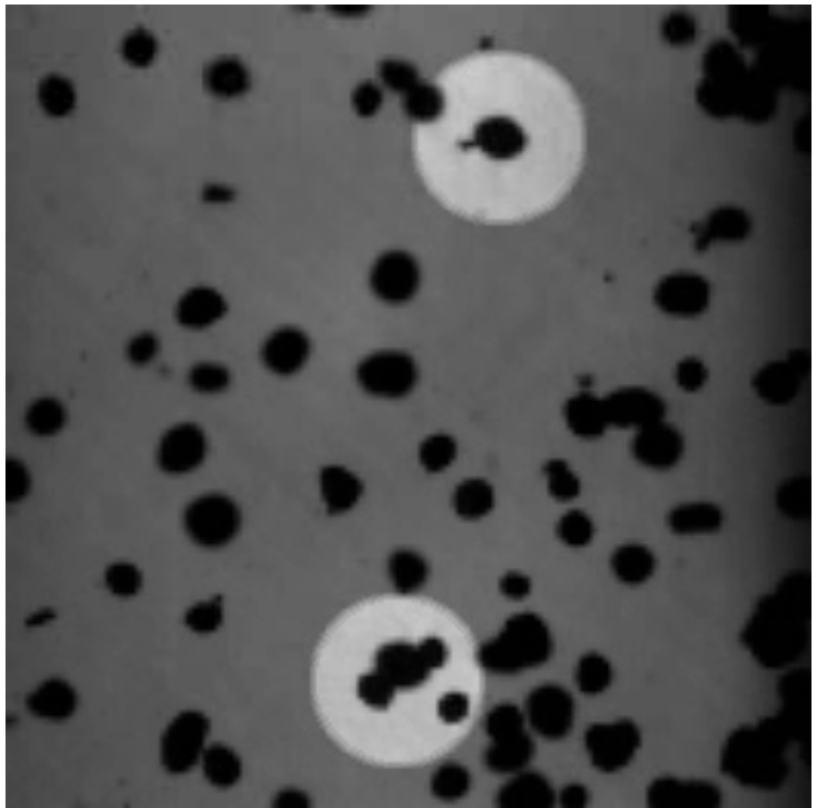




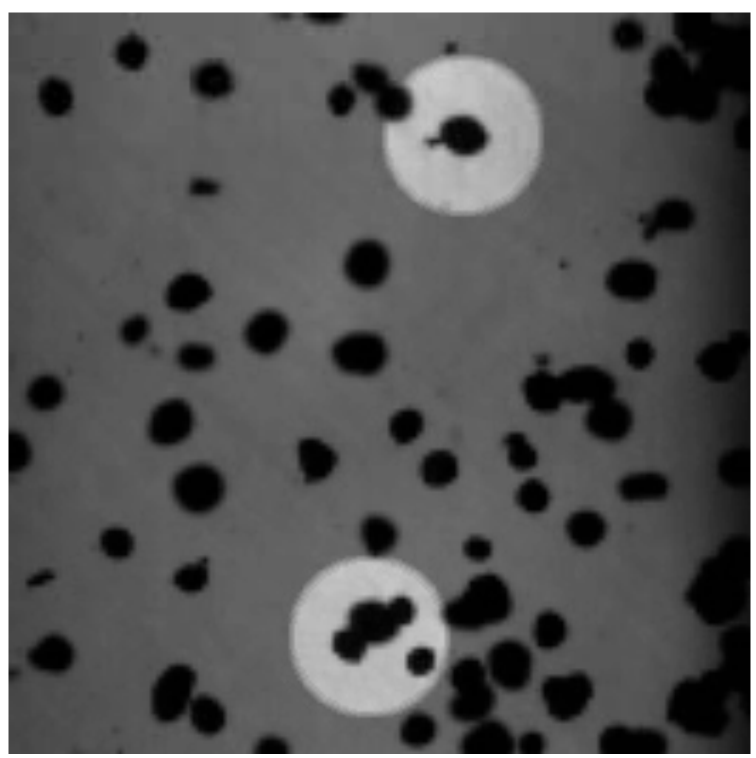
Windmark et al. (2012)

Collision outcome

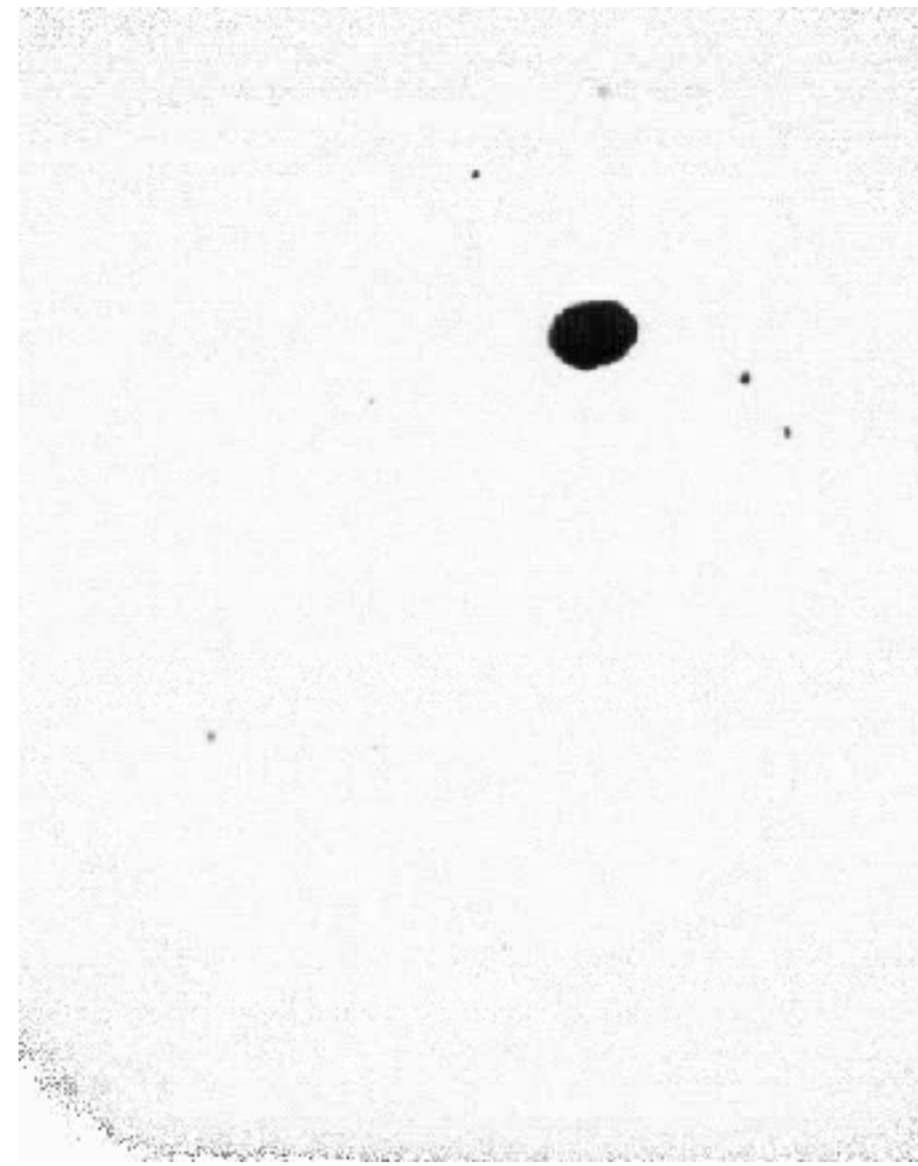
Sticking



Bouncing



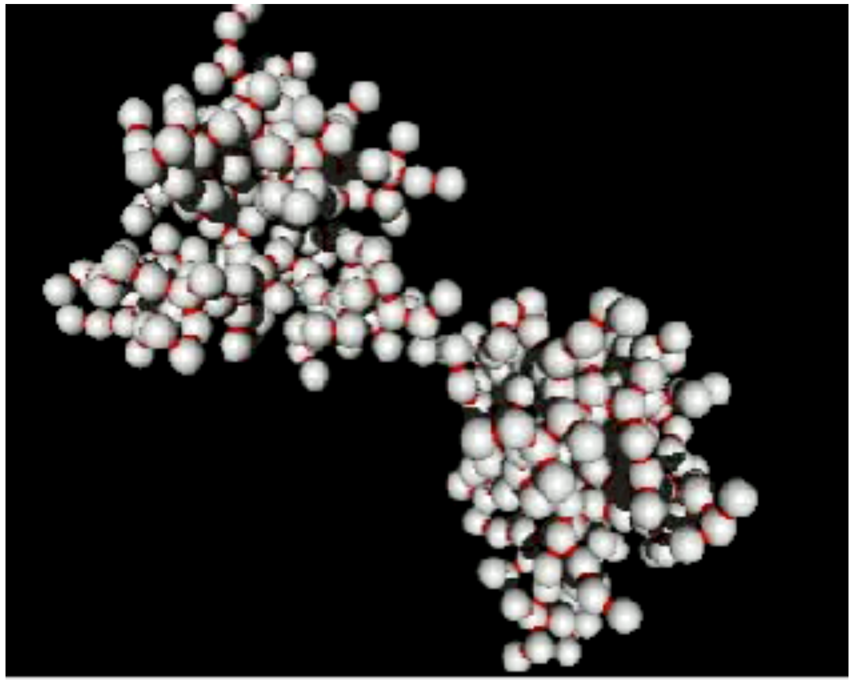
Fragmentation



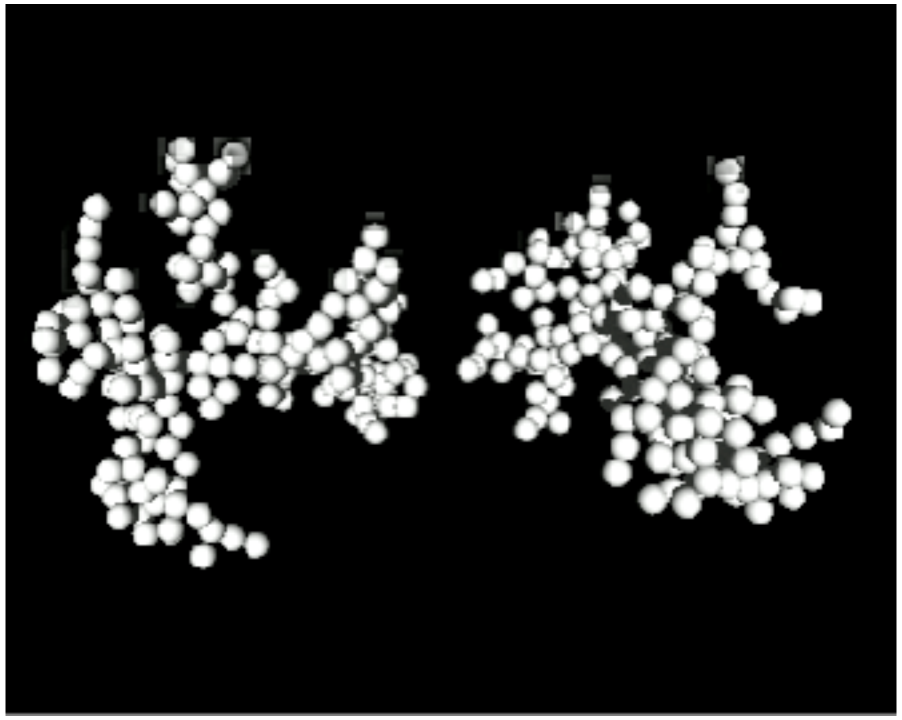
Courtesy of Paola Pinilla

Collision outcome

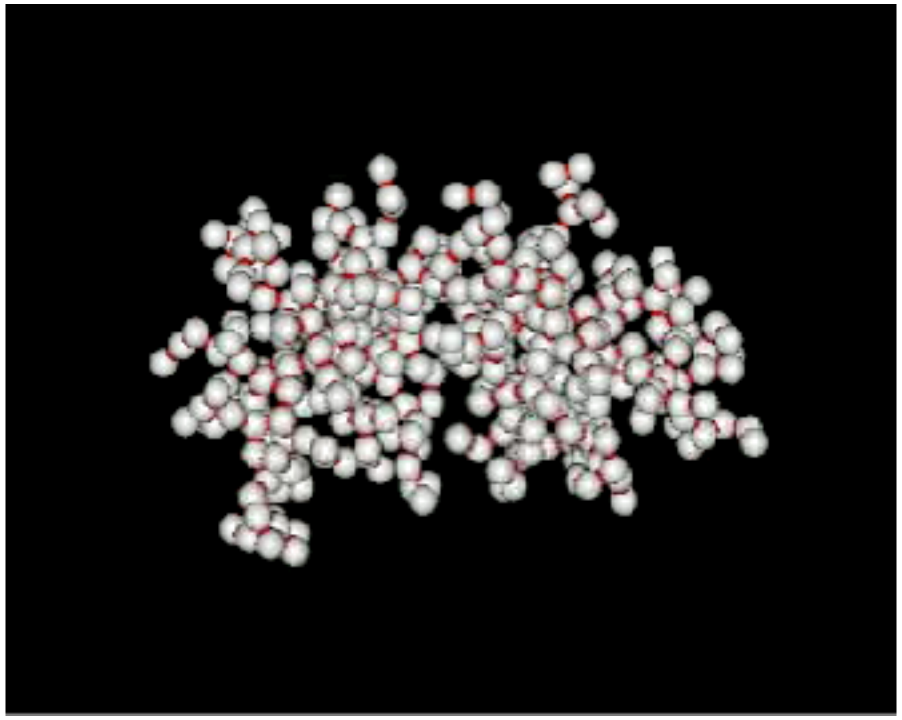
Also numerical work, particularly of fractal structures!



Coagulation & compactification



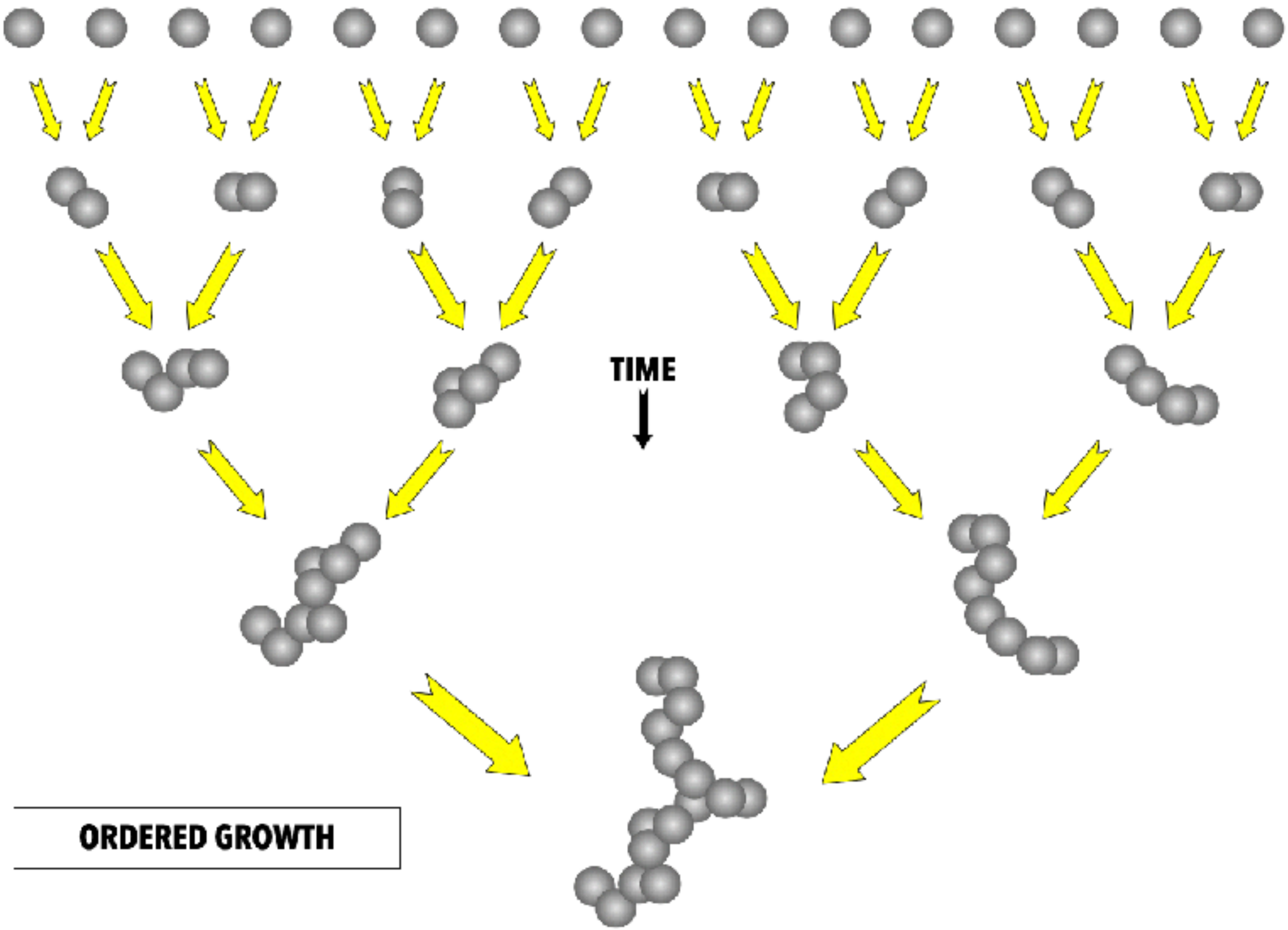
Fragmentation



Courtesy of Paola Pinilla

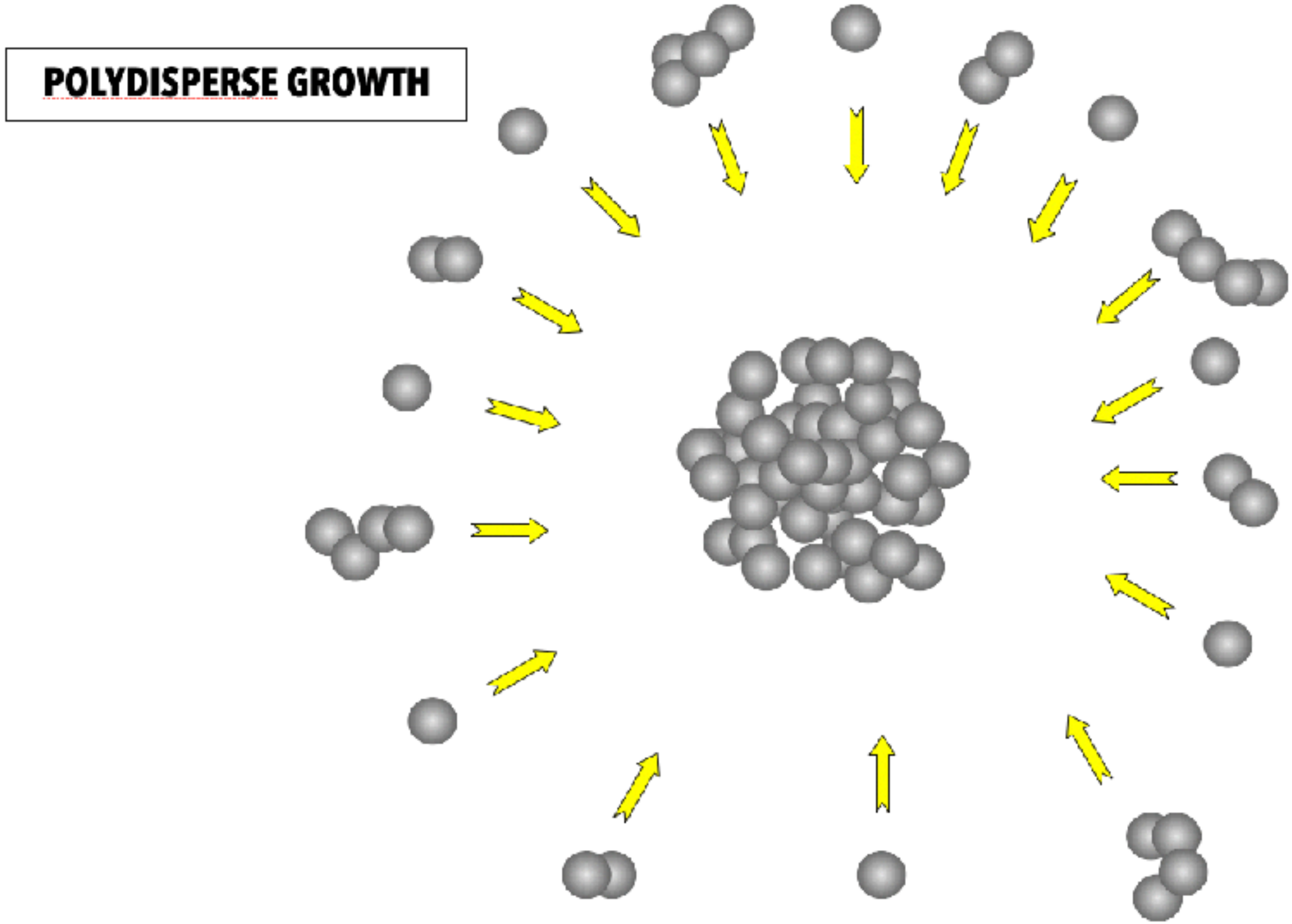
Dust growth

Small dust grains: ordered growth



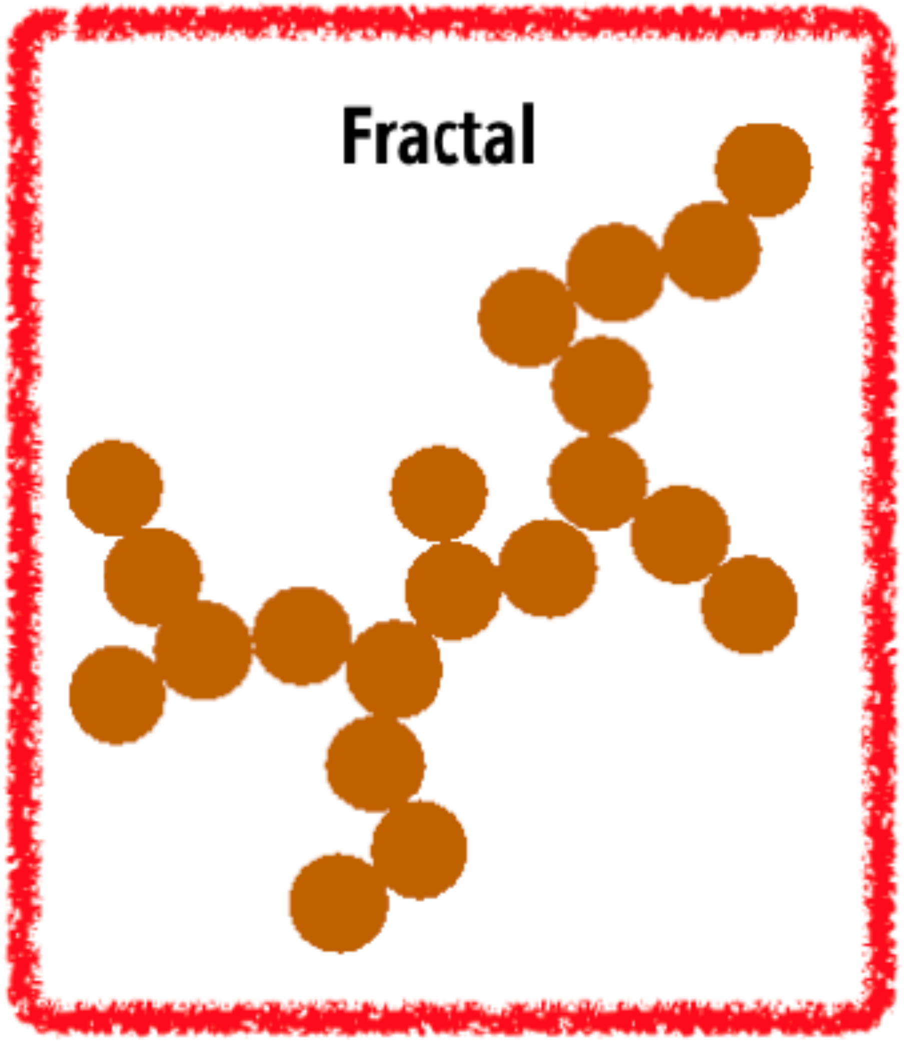
Dust growth

As soon as you have some larger dusty embryos: polydisperse growth



Dust growth

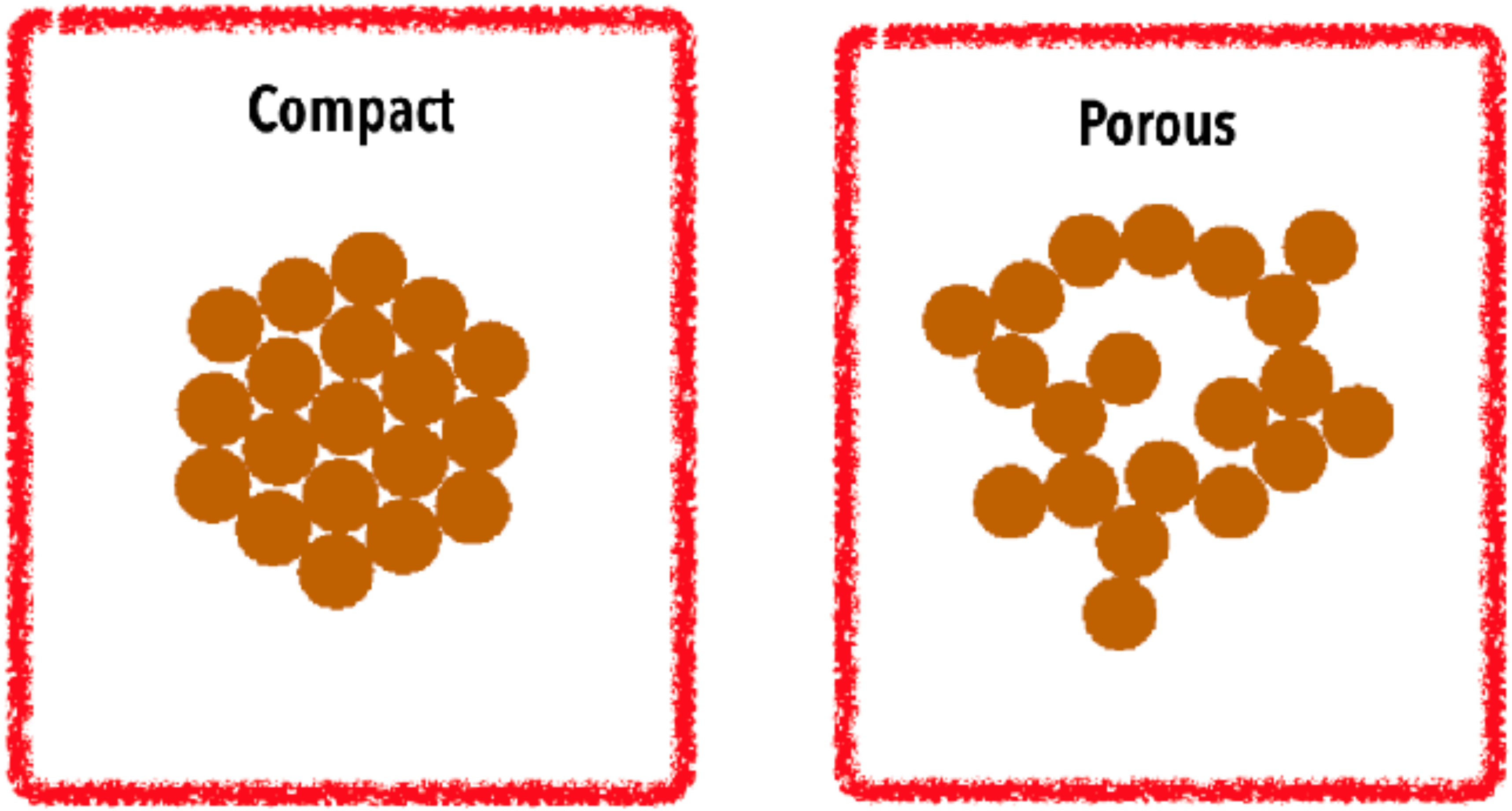
Lab experiments show that fractal dust is most easily produced by low-velocity (hit-and-stick) collisions



- Produced by cluster-cluster aggregation (ordered growth)
- Very high d/m, i.e. very slow settling
- $d/m \propto m^{\alpha}$ with $-1/3<\alpha<0$

Higher velocity (impact) results in either compactification or (highest velocity) fragmentation

Dust growth

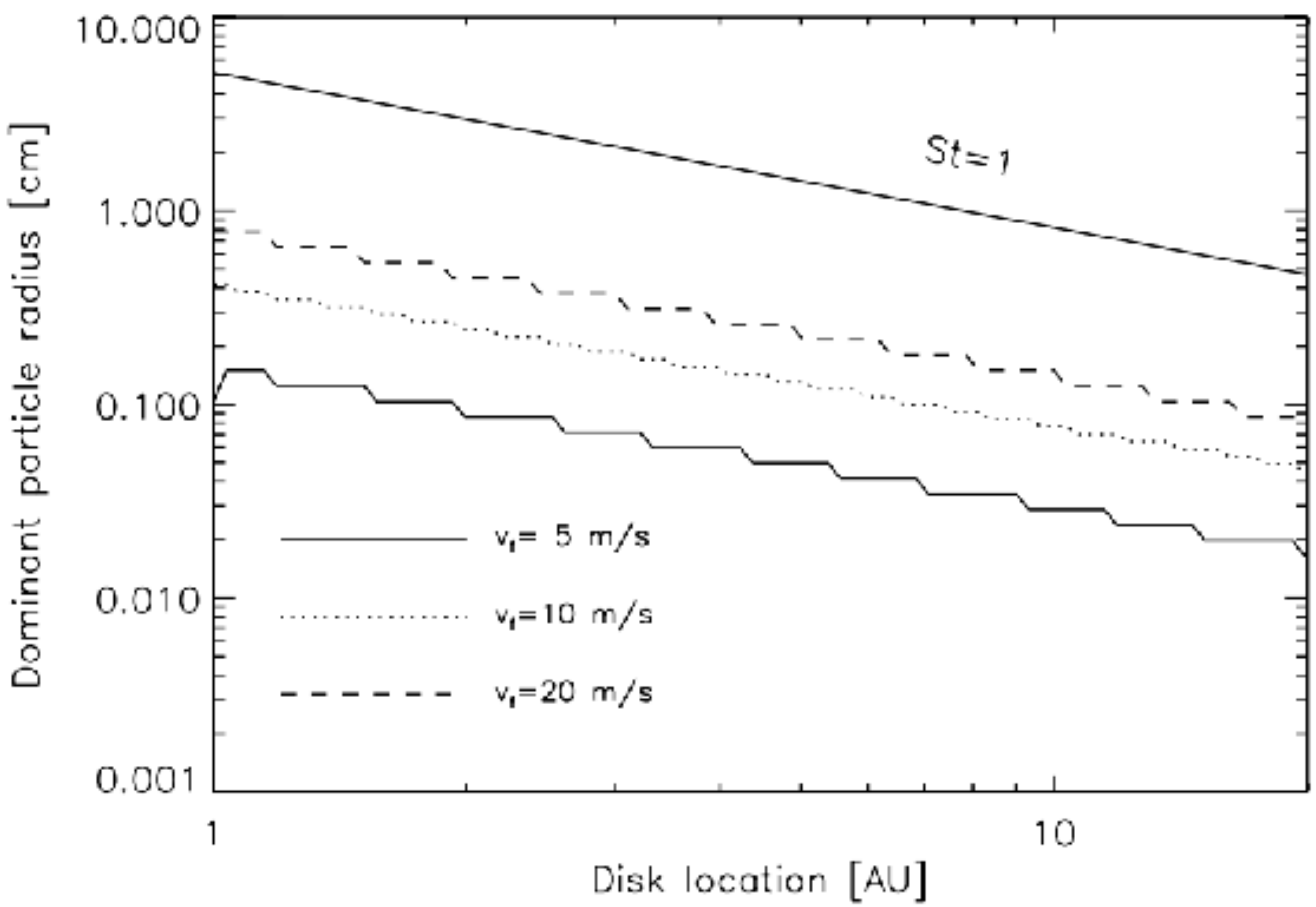


- Produced by particle-cluster aggregation (polydisperse growth), if anything
- Lowest possible d/m, i.e. fastest settling velocity
- $d/m \propto m^{-1/3}$ (but slightly higher for porous)

Fragmentation barrier

- In a balance of coagulation and fragmentation, there is a maximum particle size depending on the local conditions:

$$a_{\max} \simeq \frac{4\Sigma_g}{3\pi\alpha\rho_s}\frac{v_f^2}{c_s^2},$$



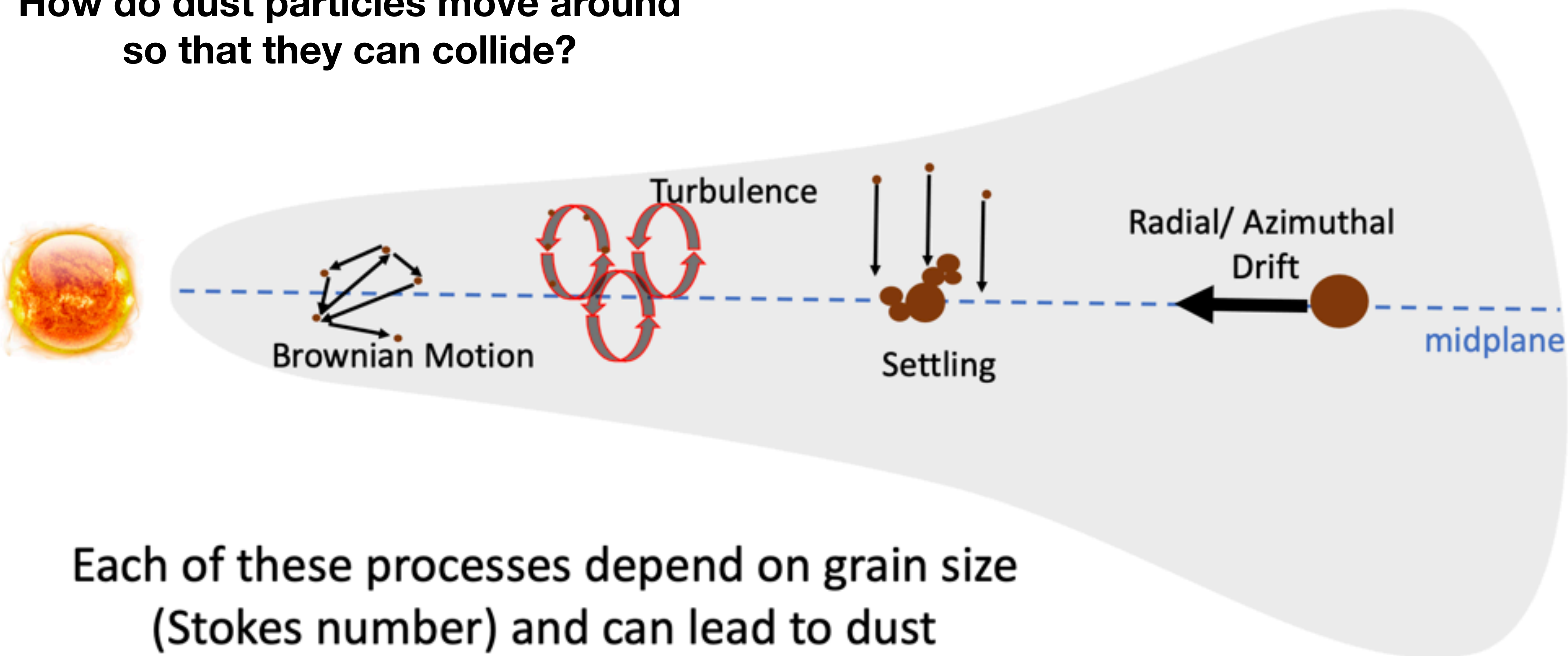
Fragmentation velocity usually taken as 10 m/s in the outer disk based on lab experiments, but can be lower in presence of ices: often assumed as 1 m/s inside H_2O snowline

Why is it lower for icy dust grains?

Brauer et al. 2008
Birnstiel et al. 2010

Dust movement in a disk

How do dust particles move around so that they can collide?



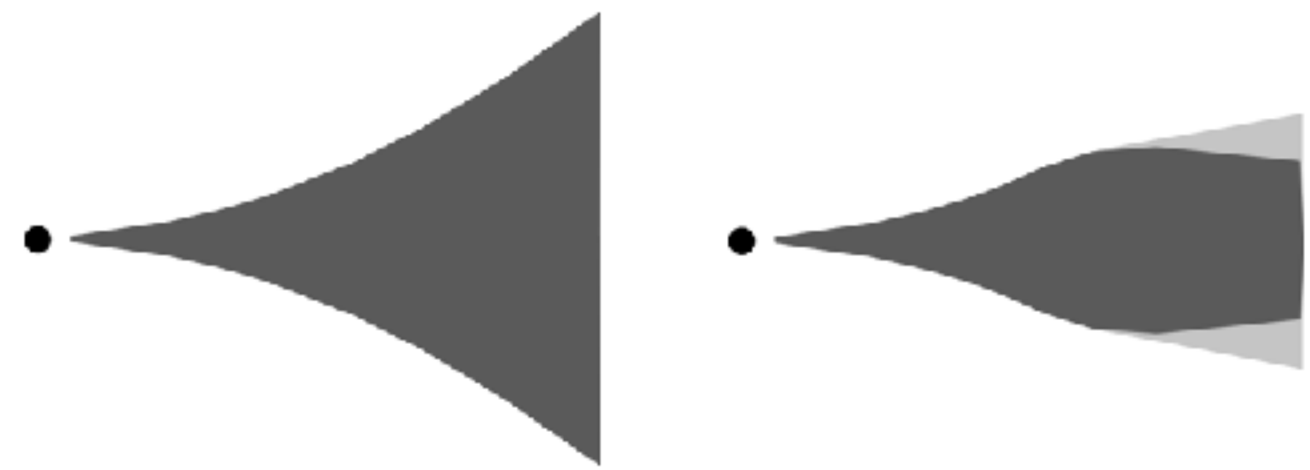
Each of these processes depend on grain size (Stokes number) and can lead to dust collisions

Settling

Settling of large grains:

$$v_{\rm sett} = -z\Omega_{\rm K}{}^2 t_{\rm fric} = -\frac{3\Omega_{\rm K}{}^2 z}{4\rho c_{\rm s}}\frac{m}{\sigma},$$

$$t_{\rm sett} = \frac{z}{v_{\rm sett}} = \frac{4}{3}\frac{\sigma}{m}\frac{\rho c_{\rm s}}{\Omega_{\rm K}{}^2}.$$



Balance between settling and stirring

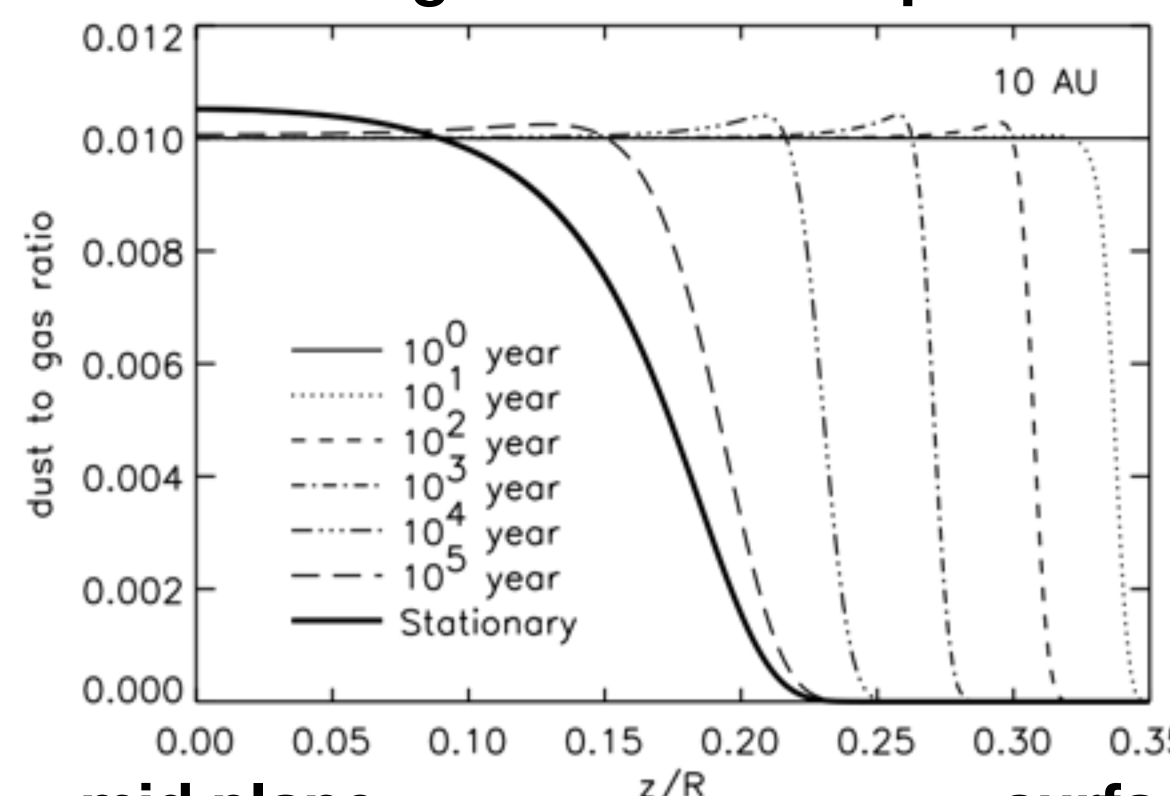
$$t_{\rm stir} = \frac{z^2}{D_{\rm d}} \cdot = \frac{\rm Sc}{\alpha\Omega_K}\frac{z^2}{H_p^2}.$$

$${\rm Sc} = (1 + {\rm St}),$$

Result: large grains settle to midplane, small grains remain in the surface

Also, large grains grow further through settling through sedimentation

Increase dust-to-gas ratio in mid plane

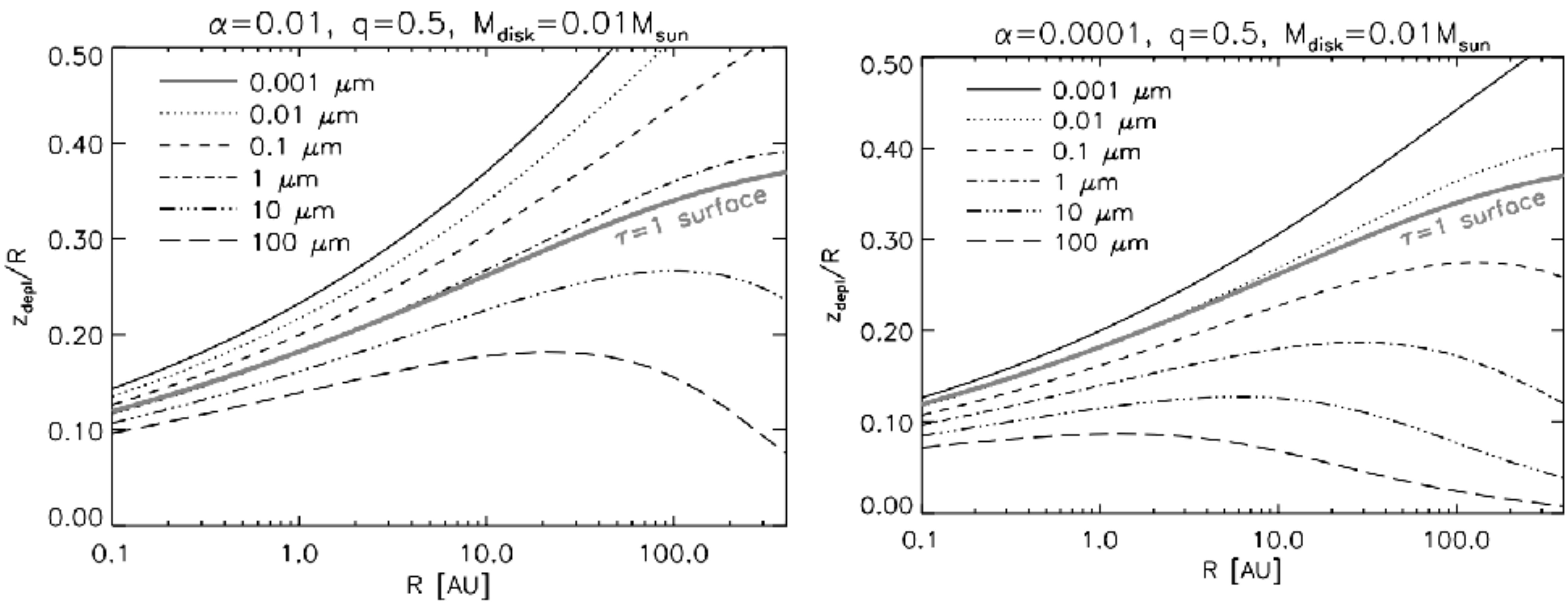


mid plane **surface**

Dullemond & Dominik 2004

Settling

Strong dependence on turbulence (alpha) in the disk!

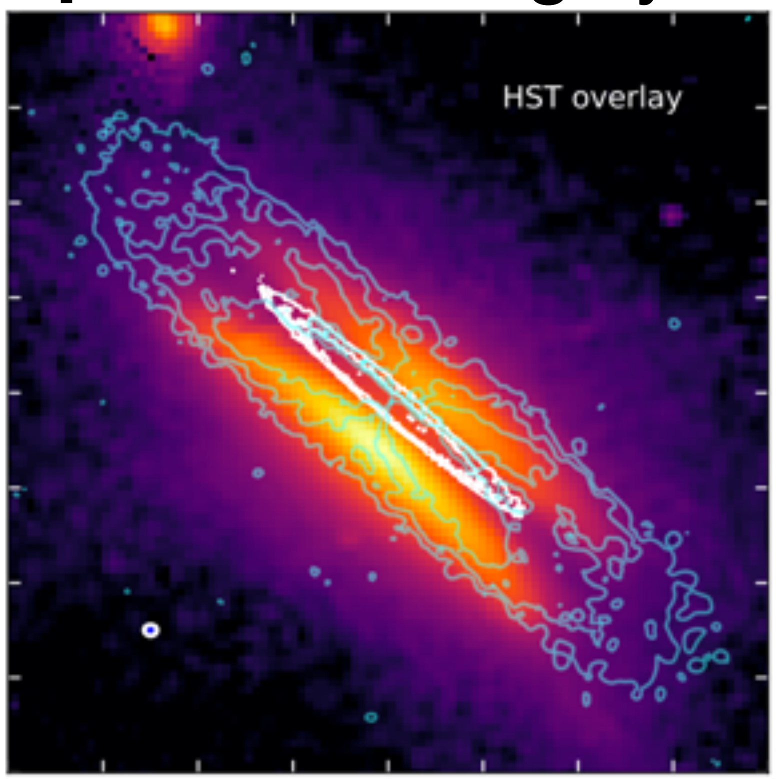


Remember how we used turbulence measurements earlier today?

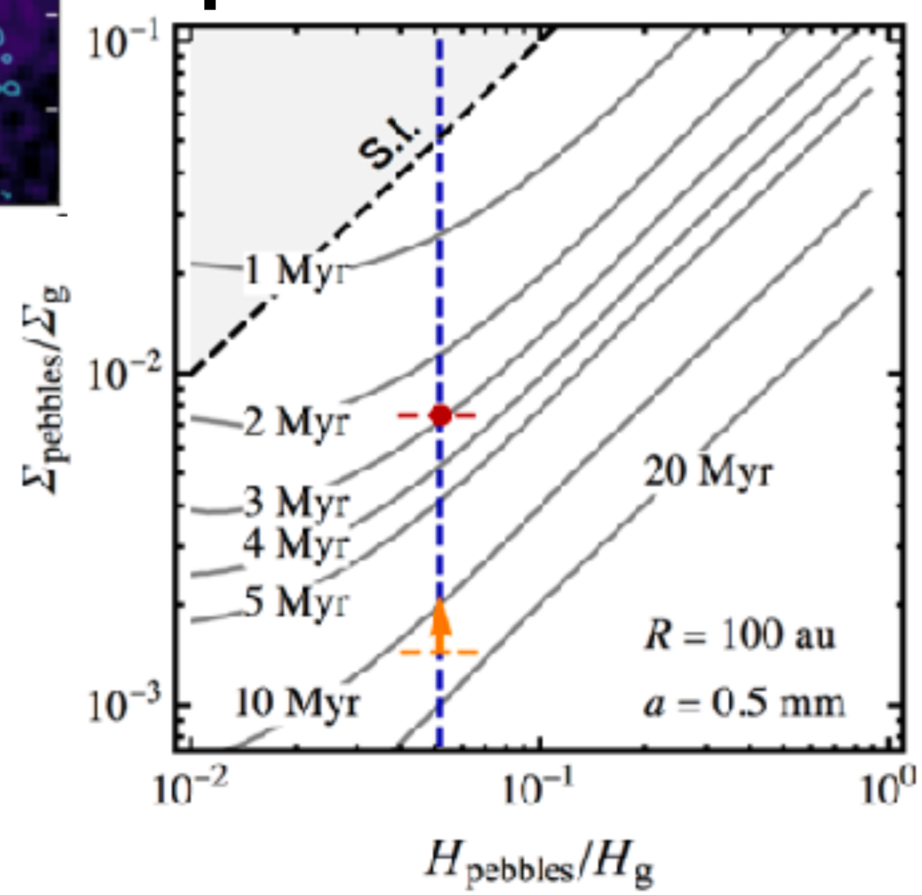
Dullemond & Dominik 2004

Settling

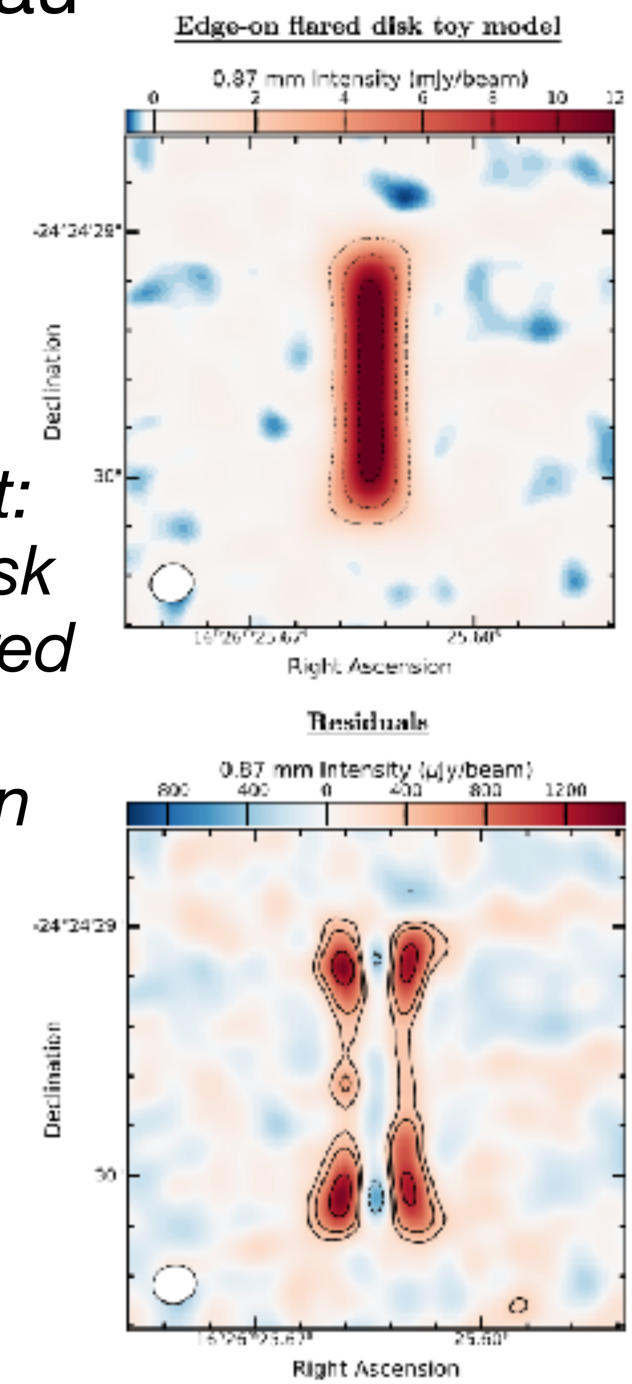
Oph163131: highly settled mm-dust disk with h=0.5/100 au



High settling: pebble accretion



In contrast: Class 0 disk shows flared mm-dust distribution



Villenave et al. 2022
Michel et al. 2022

Radial drift

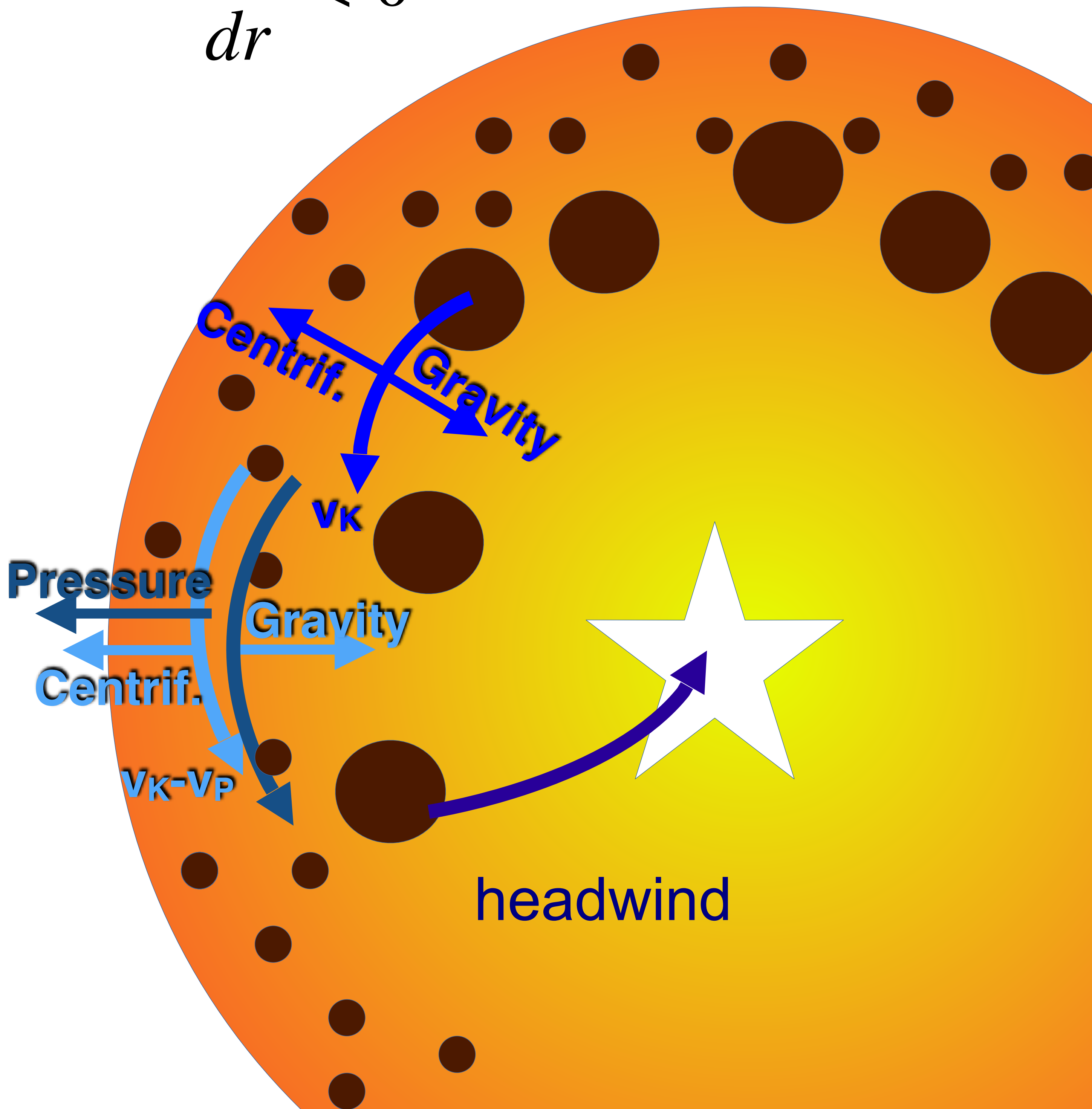
- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward <u>drift</u> dust

$$\frac{v_\phi^2}{r} = \frac{GM_\star}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

↓ pressure force

$$v_\phi \approx v_K \cdot (1 - \eta)$$

(0.5% slower than Keplerian)



Weidenschilling 1977

What sets the radial drift?

- **Stokes number: property of particle**

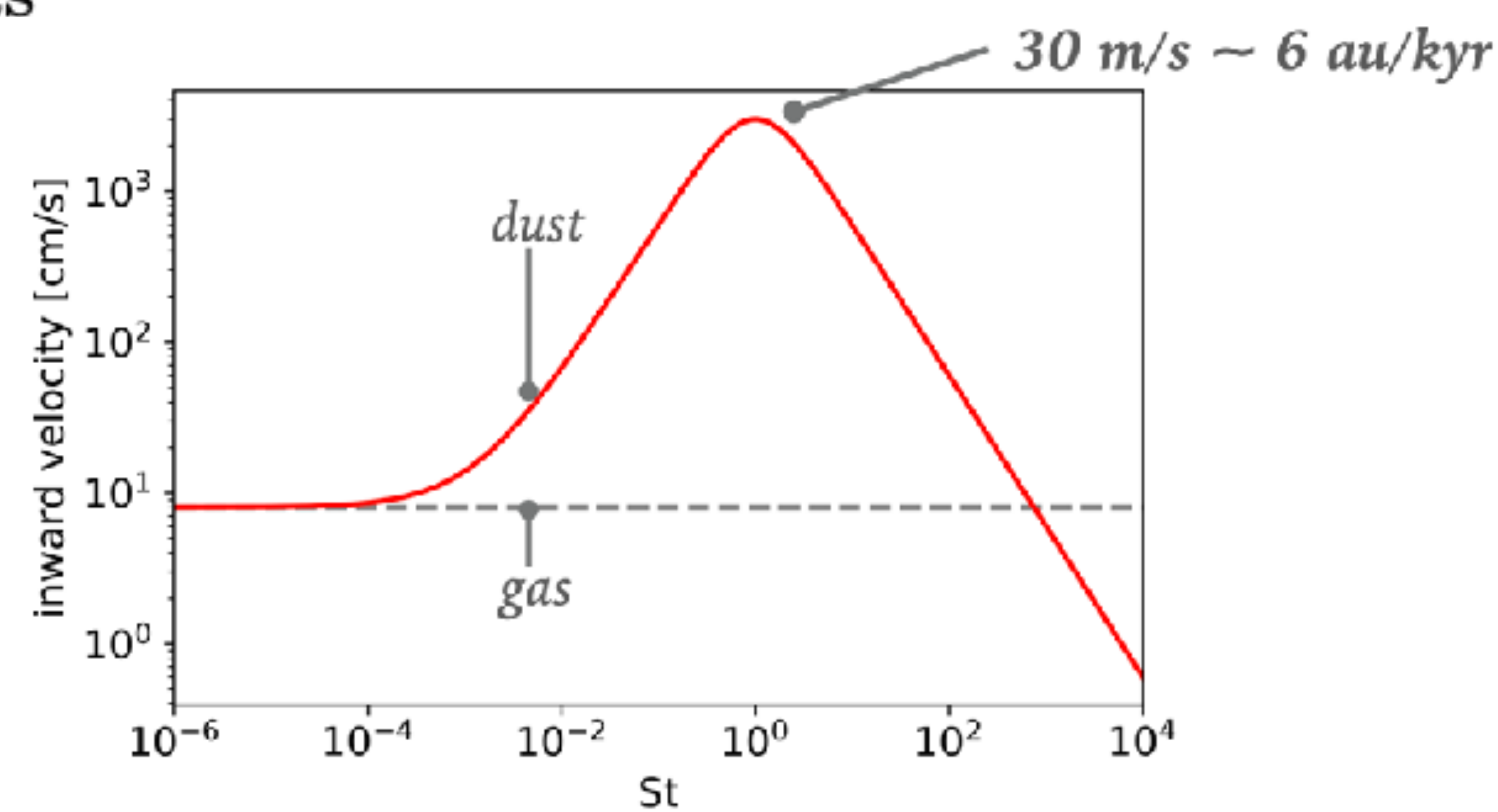
a = grain size

$$\mathrm{St} = \frac{t_{\rm stop}}{t_{\rm orb}} = \frac{\pi}{2}\frac{a\rho_\bullet}{\Sigma_{\rm gas}}$$

(`Epstein regime')

Gas surface density

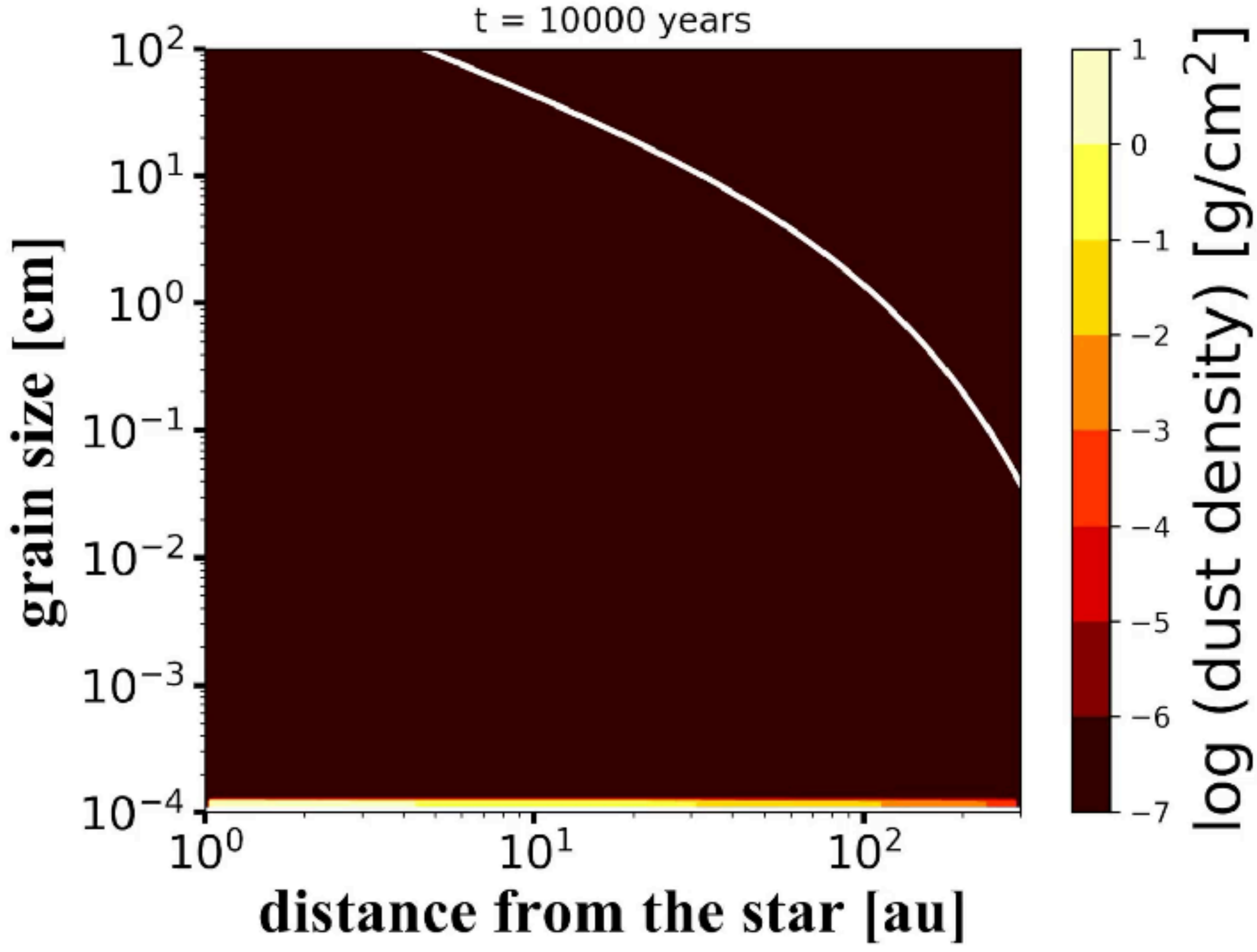
Drift velocity based on Stokes number



Drazkowska et al. 2022 (PPVII)

Dust evolution with radial drift

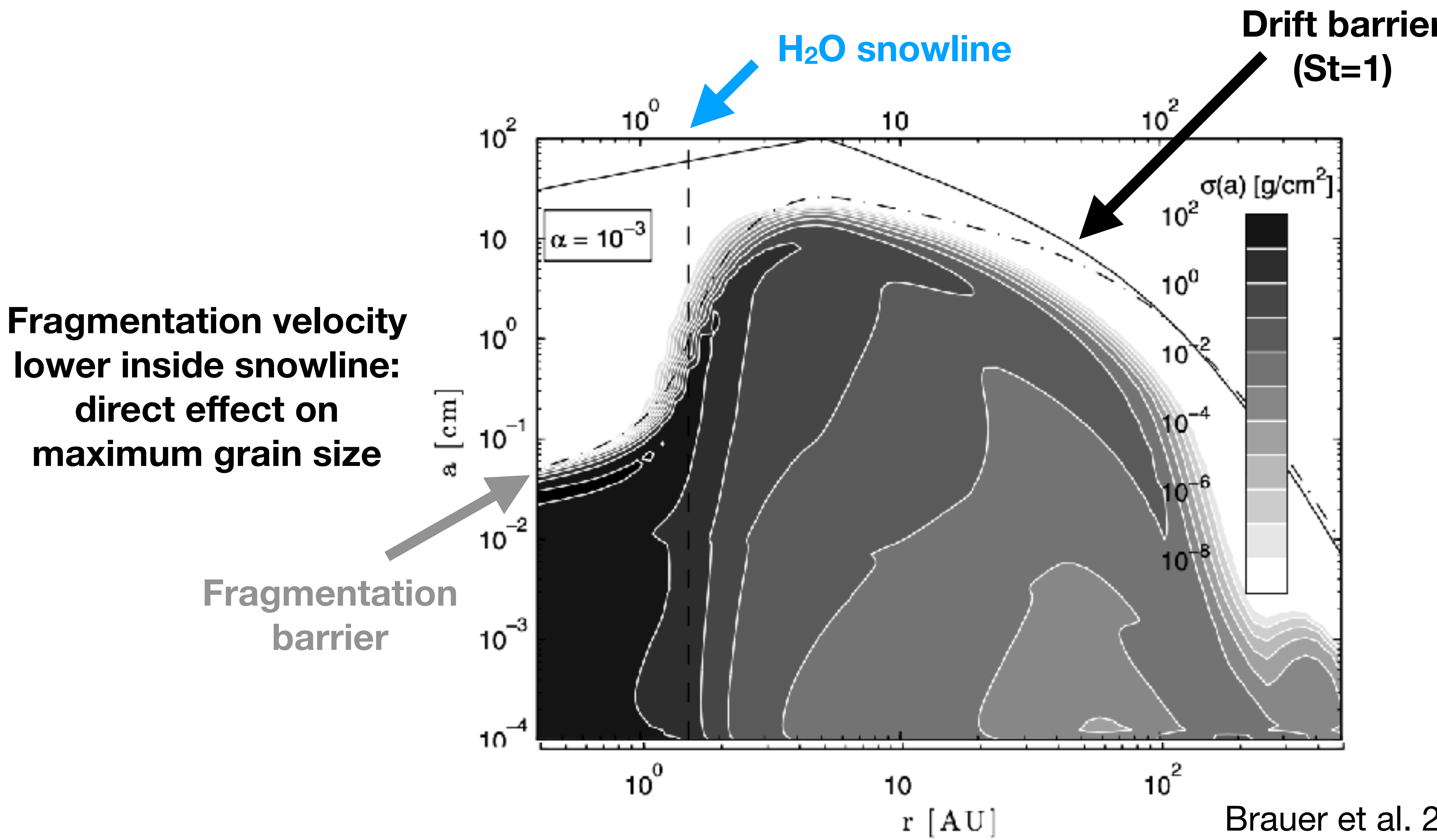
Gas disk evolution, radial drift, coagulation and fragmentation all affect each other: need for simulations combining all the effects



Check out on Github: dustpy package (Stammler & Birnstiel)

Courtesy of Paola Pinilla

Fragmentation inside the snowline



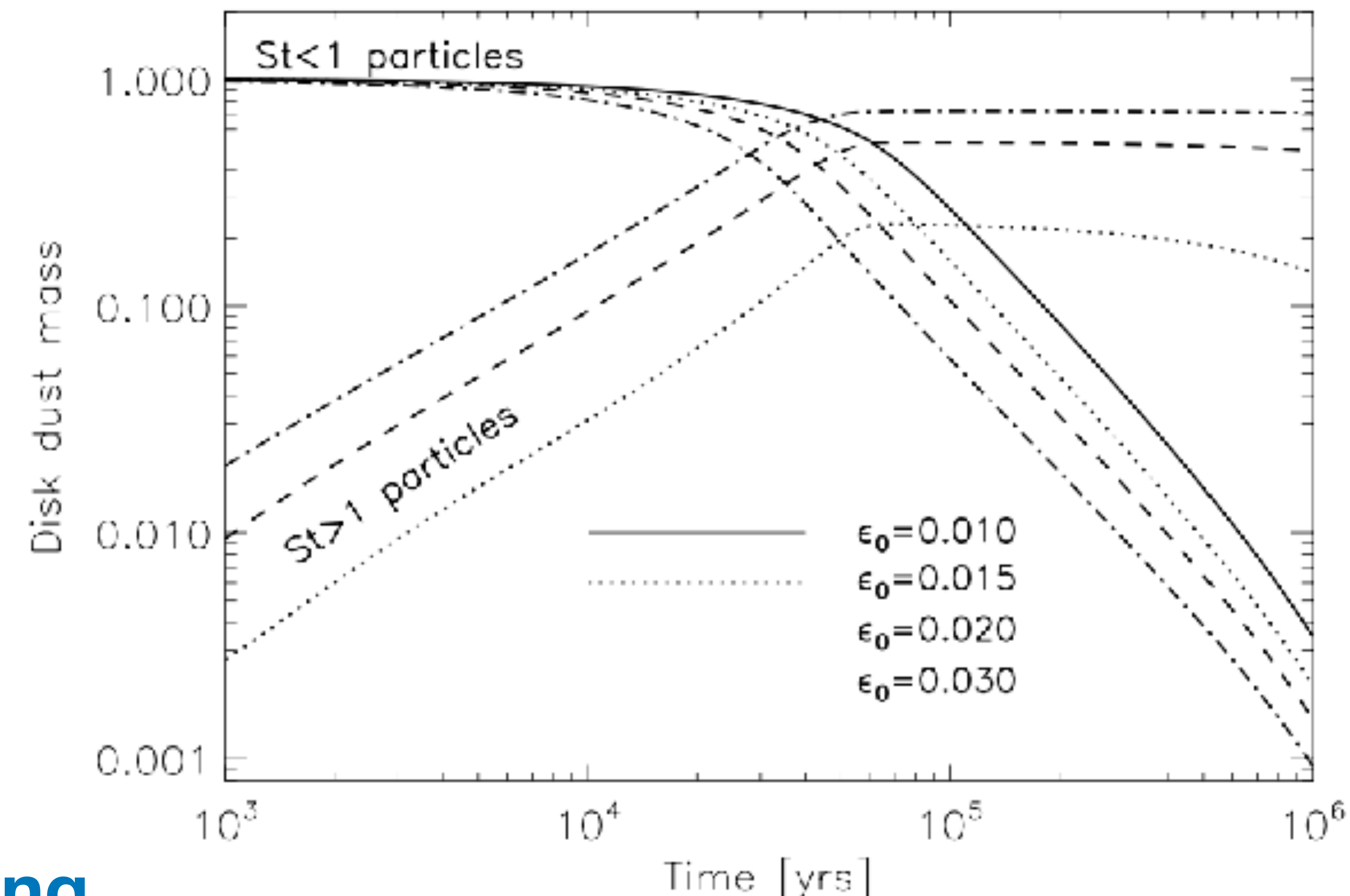
Brauer et al. 2008
Birnstiel et al. 2010

The radial drift problem

- Due to radial drift, grains cannot grow beyond millimetre sizes at 100 au: how to grow planets?
=> Radial drift problem or radial drift barrier

- Also called:
meter-size barrier:

when is radial drift affecting meter-size dust grains?

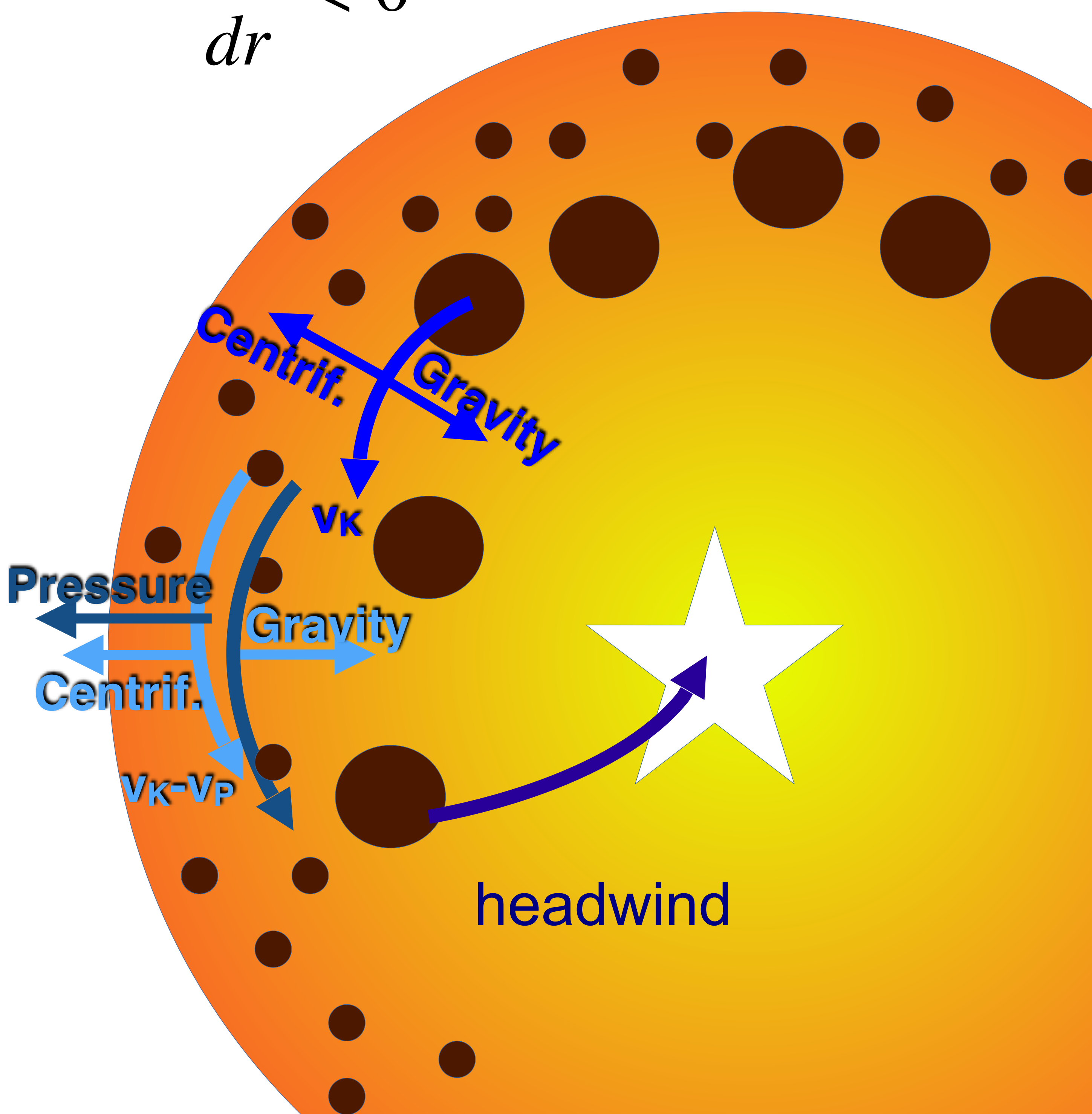


Dust mass decreases rapidly as a result of radial drift, but we still observe mm-dust emission in disks of 1-10 Myr: how?

Recall: radial drift

- Gas disk has a pressure gradient $\frac{dp}{dr} < 0$
  - Radial inward drift dust
- **Large particles move towards high pressure**

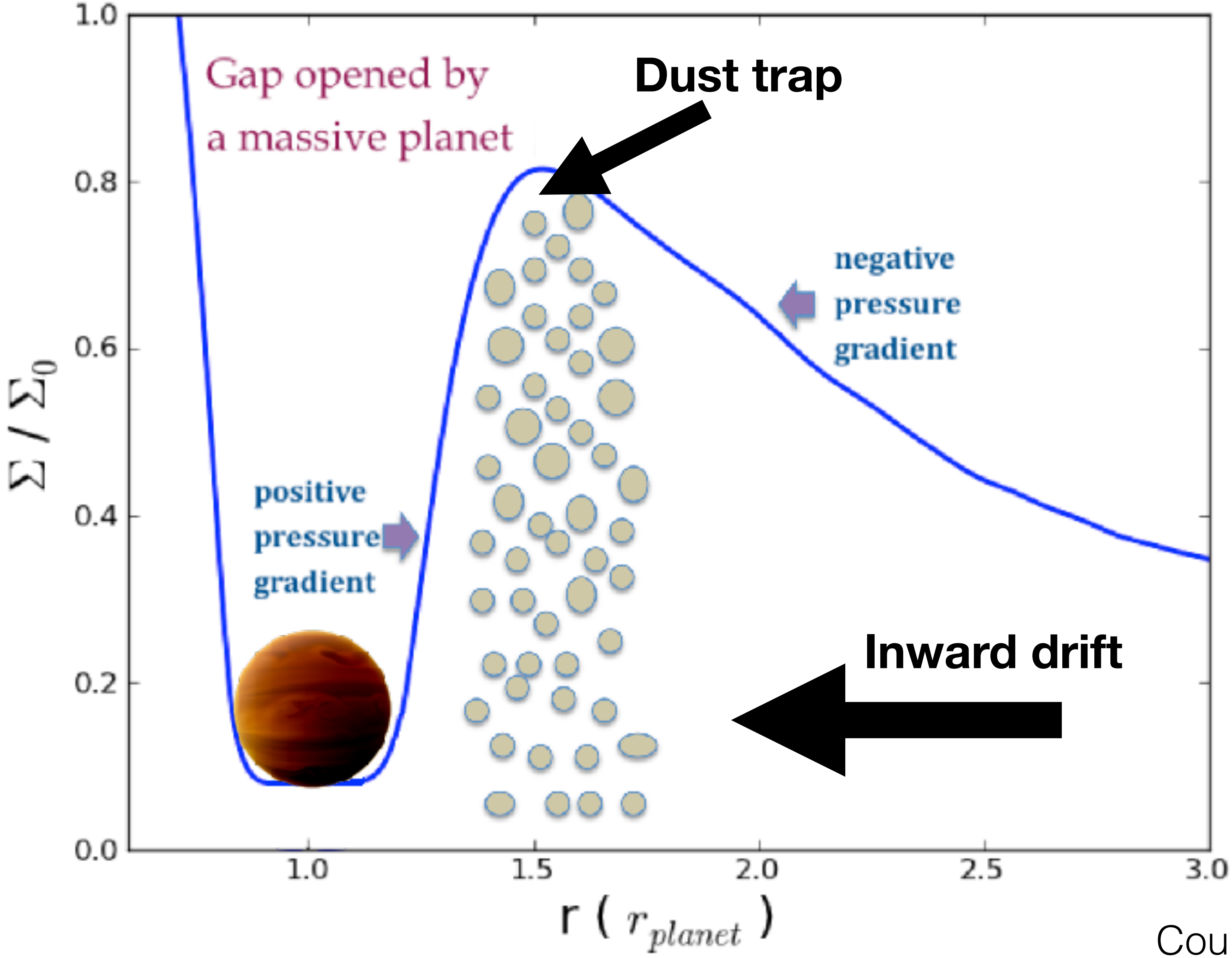
  => Need pressure bump to prevent radial drift



Weidenschilling 1977

Pressure bump/dust trap

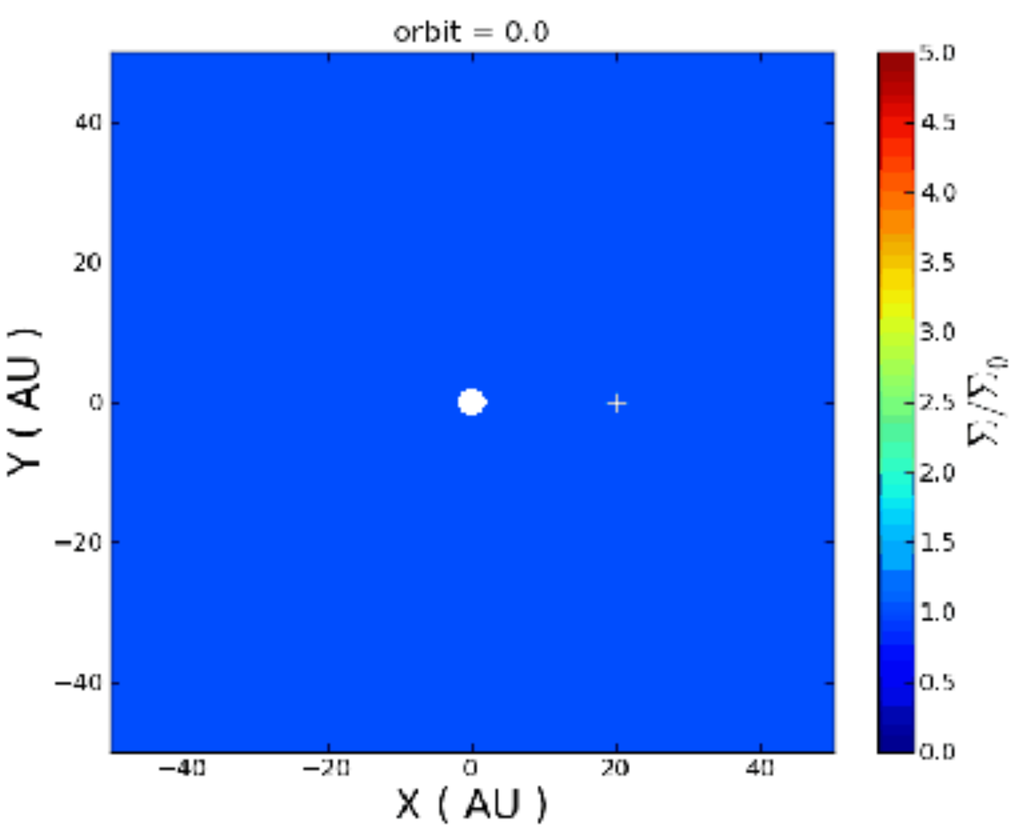
A forming planet will carve a gap in the gas distribution: at the outer edge you naturally get a pressure maximum



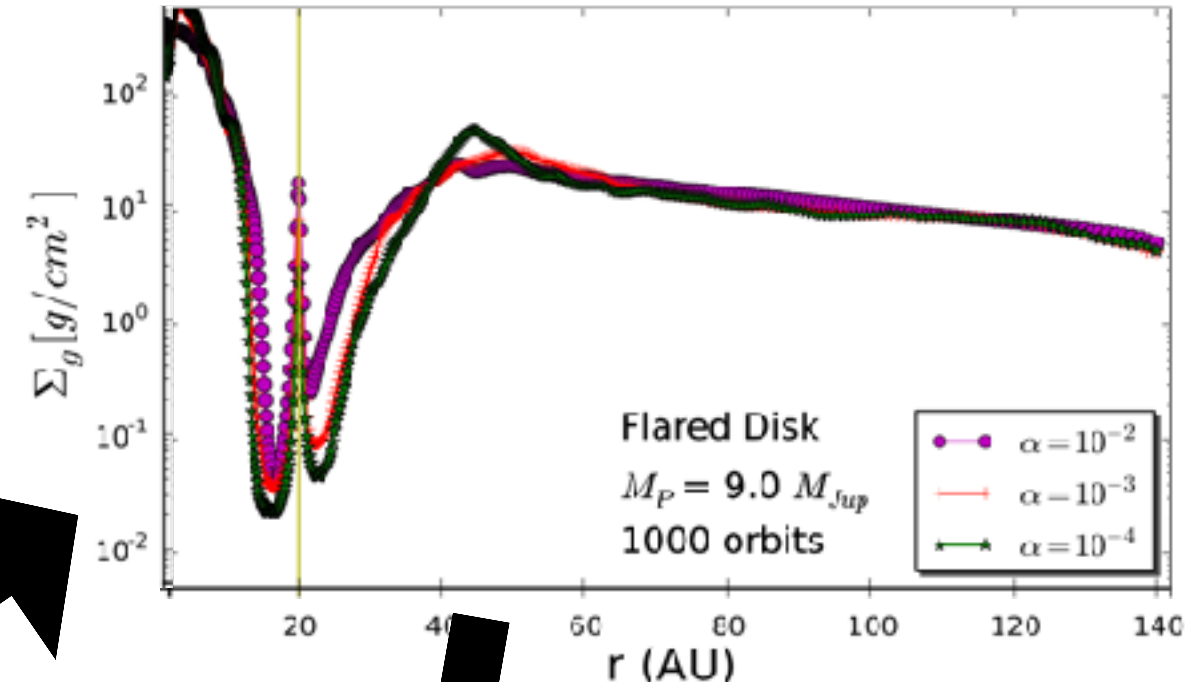
Courtesy to Paola Pinilla

Pressure bump

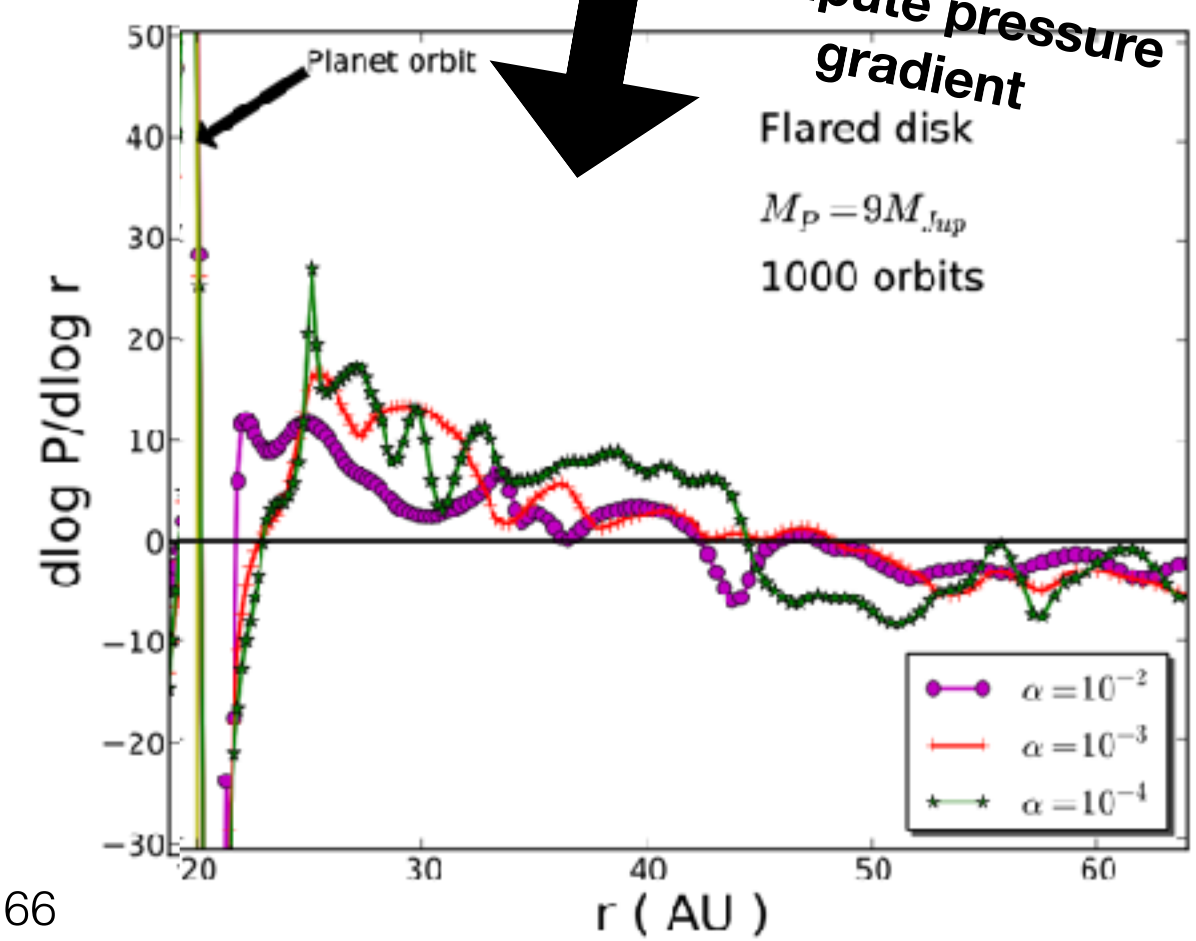
A forming planet will carve a gap in the gas distribution: at the outer edge you naturally get a pressure maximum



Azimuthally average



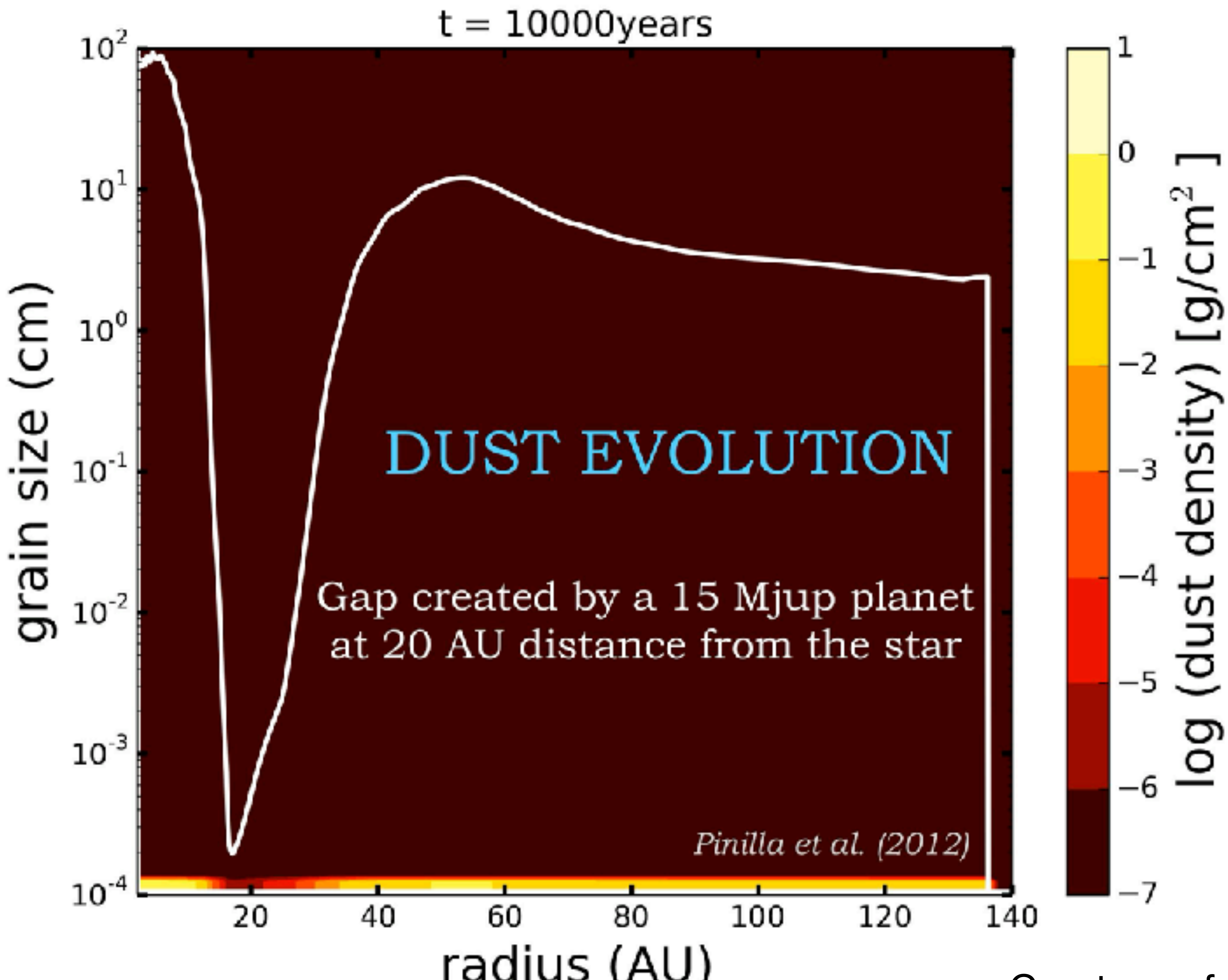
Compute pressure gradient



Pinilla et al. 2012b

Pressure bump/dust trap

Now we run the same dust evolution simulation but with a planet-carved gap



Courtesy of Paola Pinilla

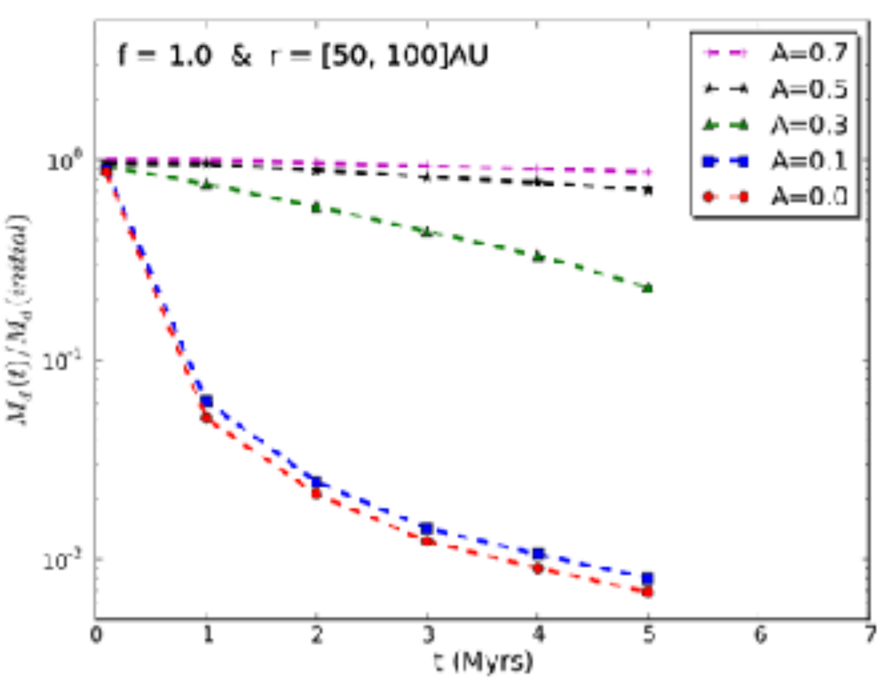
Why is this scenario not the ultimate solution for planet formation?

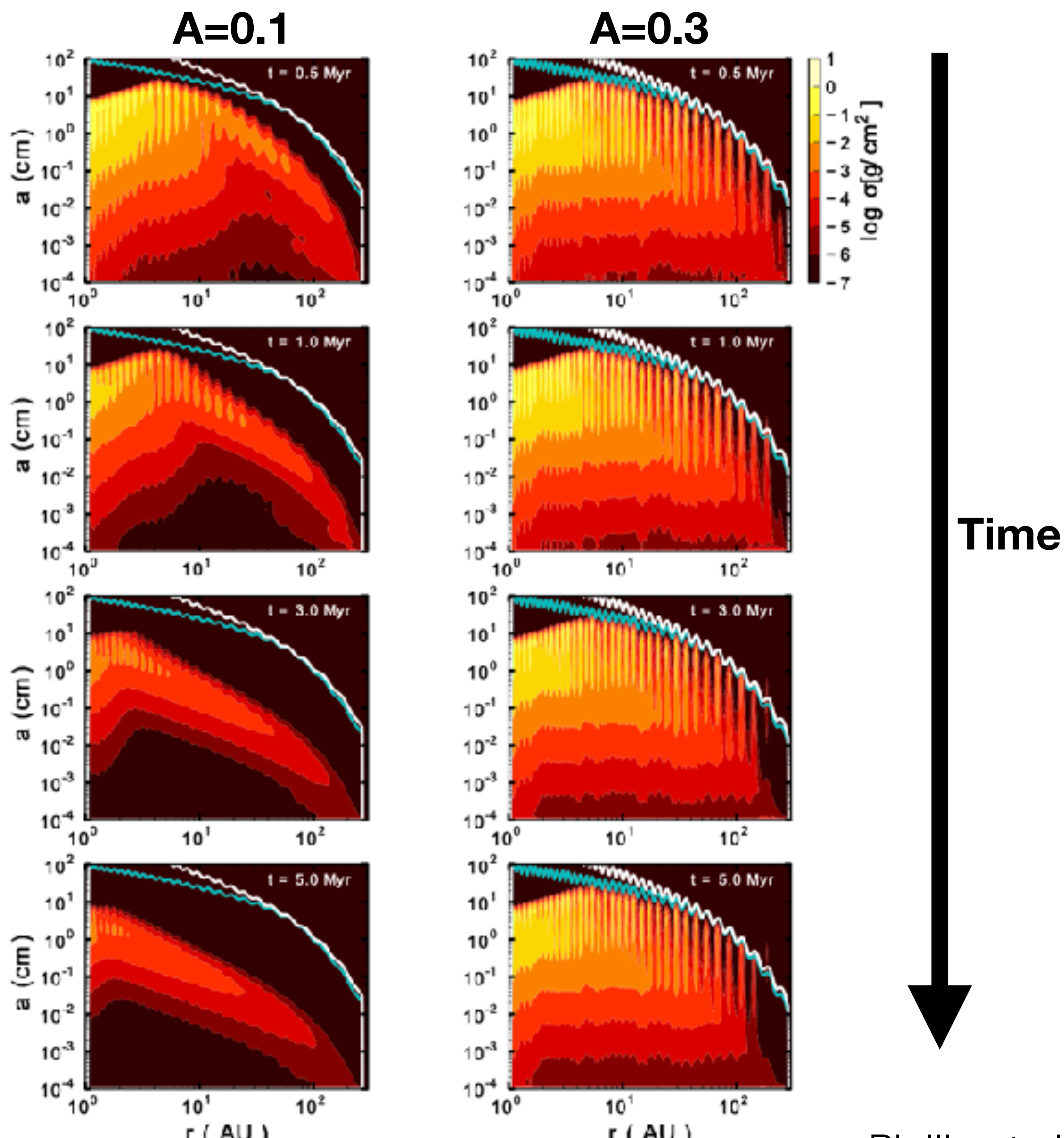
Problem:
dust traps require planets?

Dust trapping

Initially, the idea of dust traps was more general: any perturbation in the pressure profile (e.g. zonal flows) would trap dust, maintaining the mm-dust particles

See example here: effect of small-amplitude variations in gas surface density on dust particles

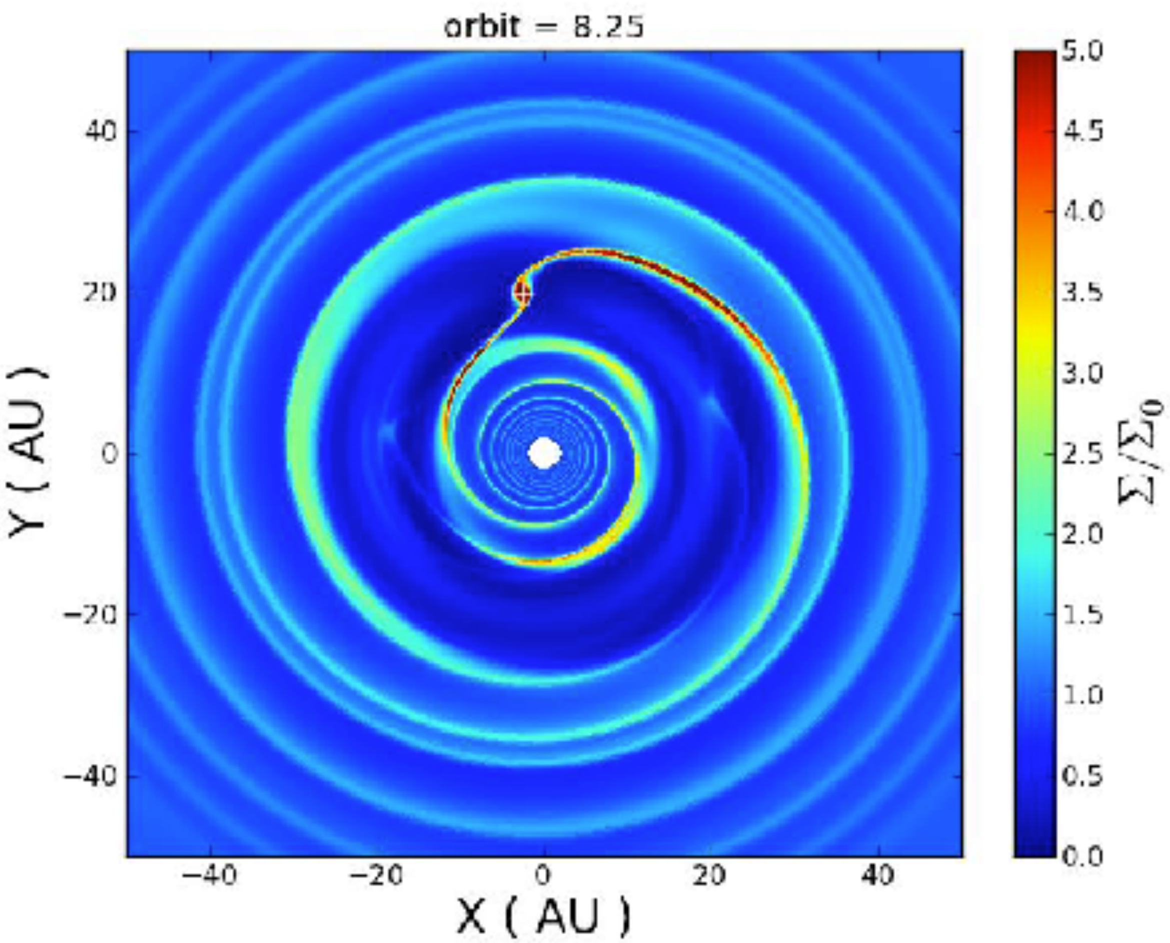




Pinilla et al. 2012a

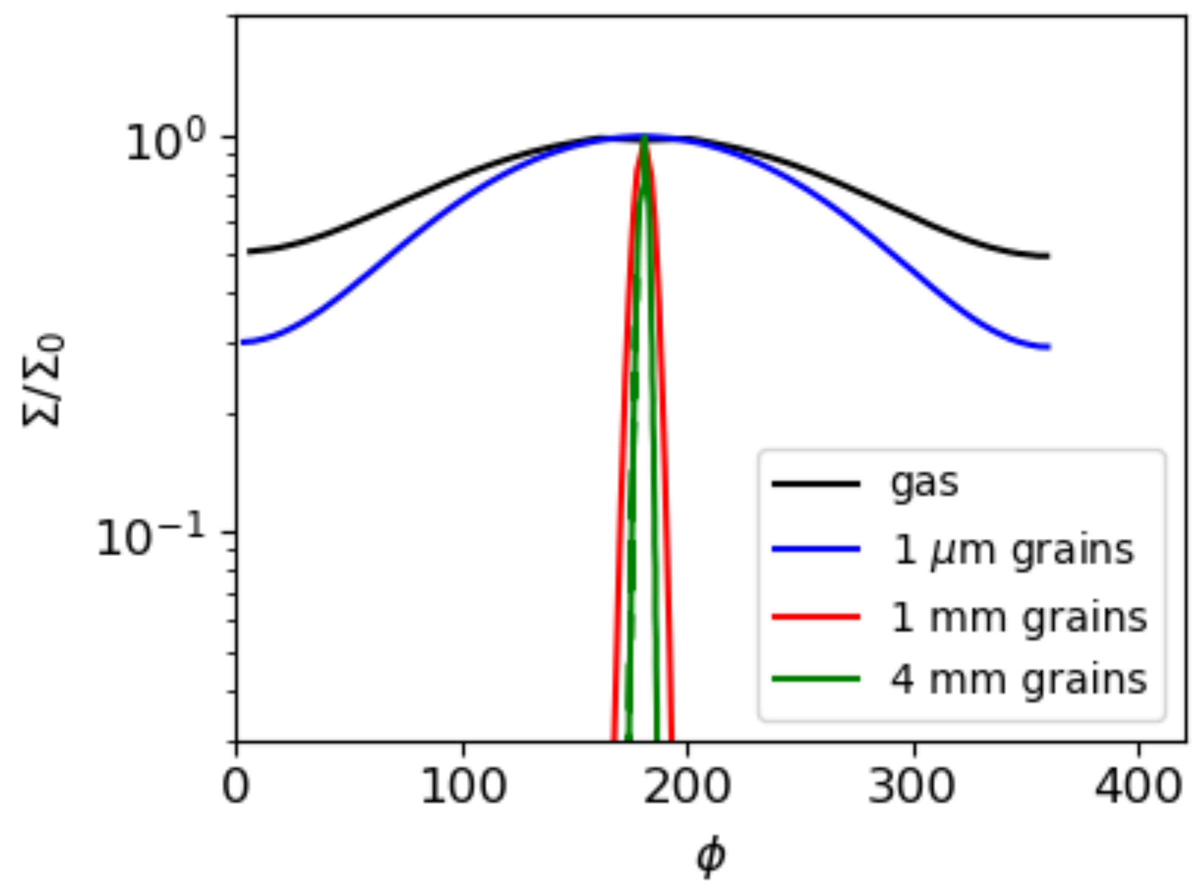
Special case of dust trapping: azimuthal overdensity

More on asymmetries in Lecture 4



Rossby Wave Instability can lead to vortices in the disk, which are azimuthal gas overdensities which trap dust

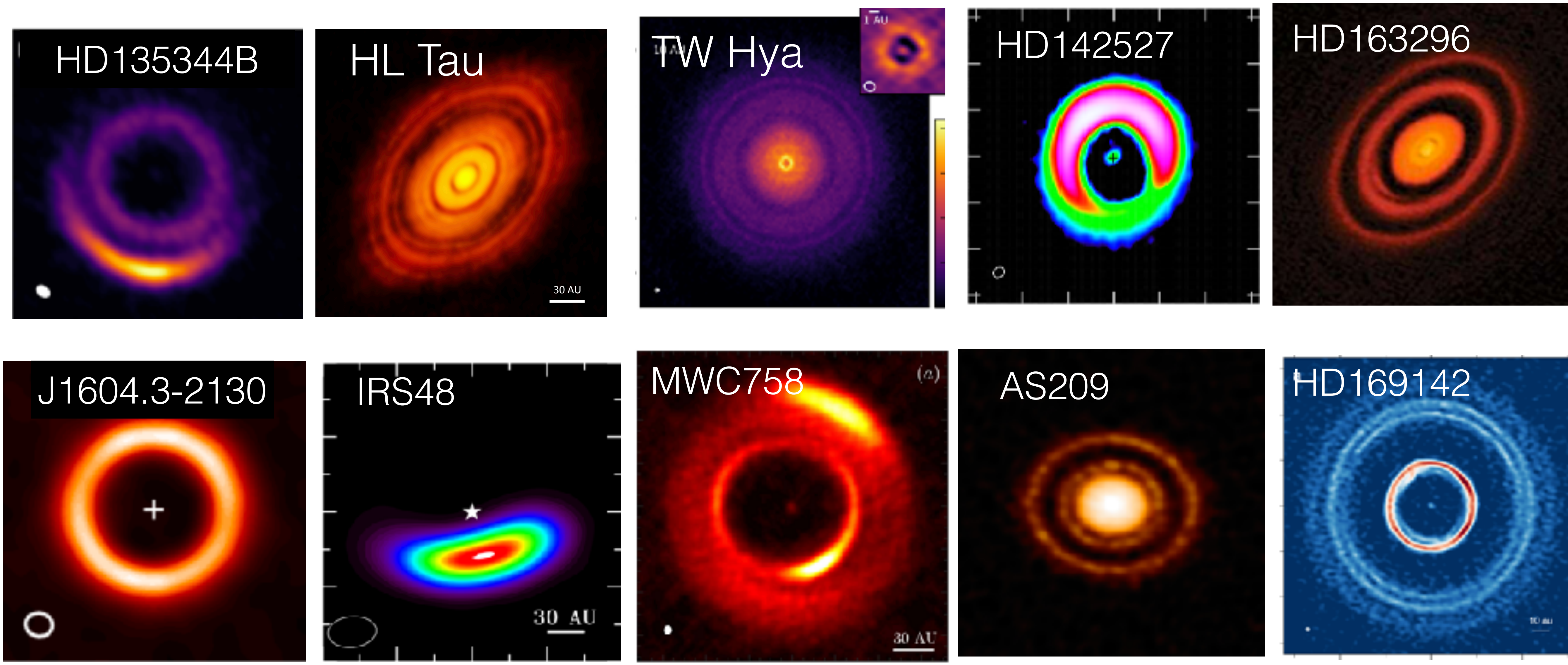
Dust evolution: small azimuthal concentration of gas leads to strong concentration of mm grains



Birnstiel et al. 2013

Many dust traps!

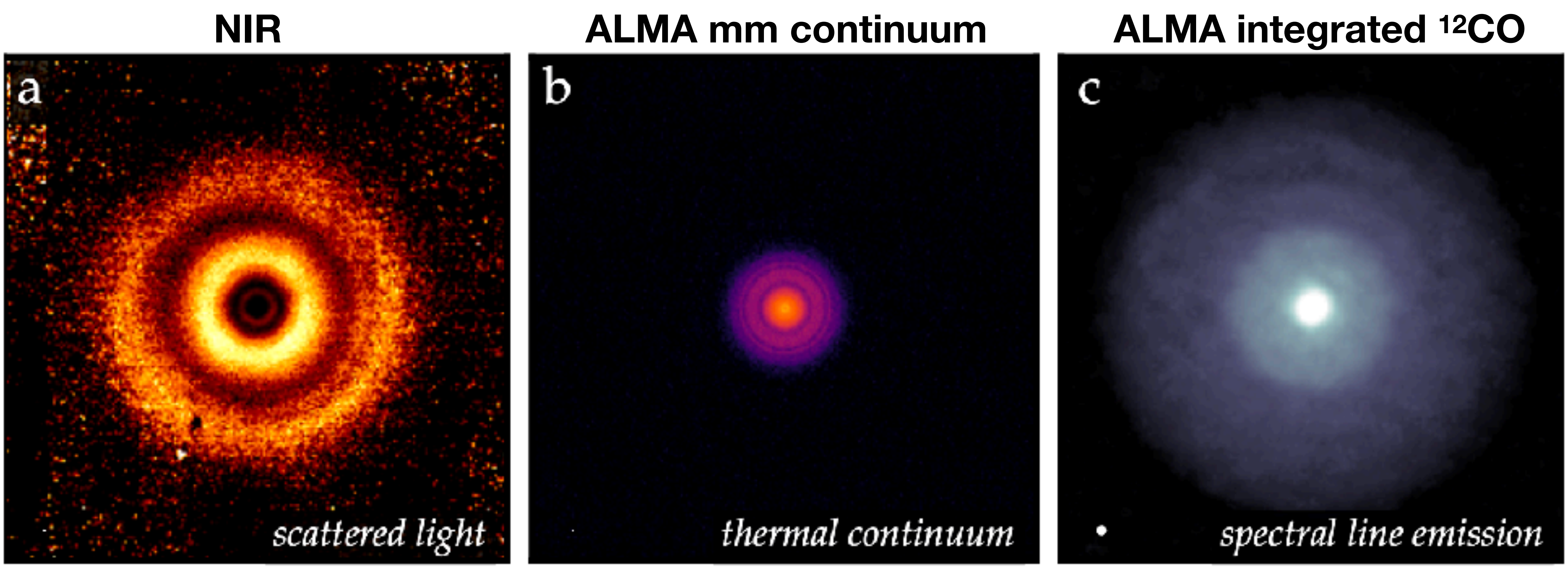
More on substructures in Lecture 4



Large diversity: unclear whether they are all caused by planet gaps or other types of pressure bumps

ALMA et al. 2015; Andrews et al. 2016, 2018; Boehler et al. 2017, Cazzoletti et al. 2018; Dong et al. 2018; Fedele et al. 2017; Isella et al. 2016; Perez et al. 2019; Van der Marel et al. 2013, 2016a & 2020

Observational evidence for dust transport

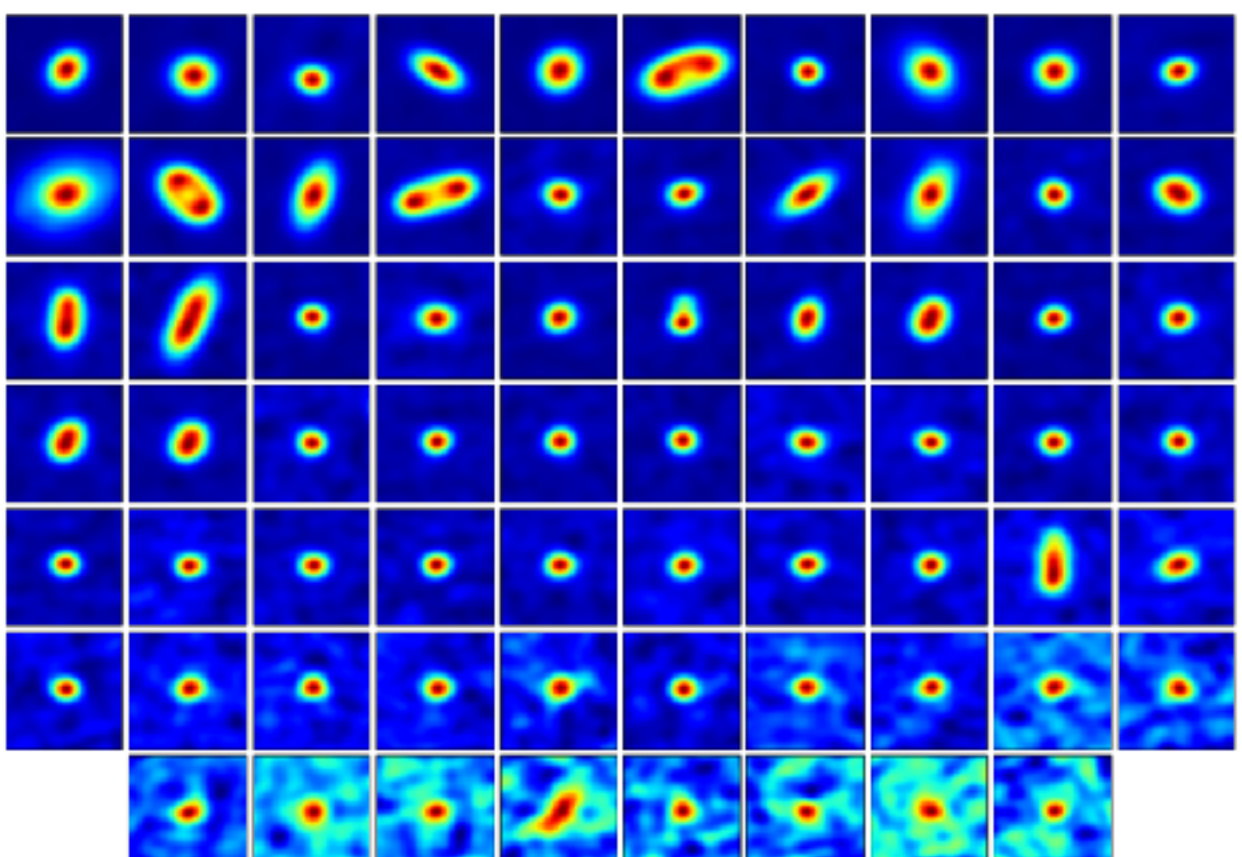


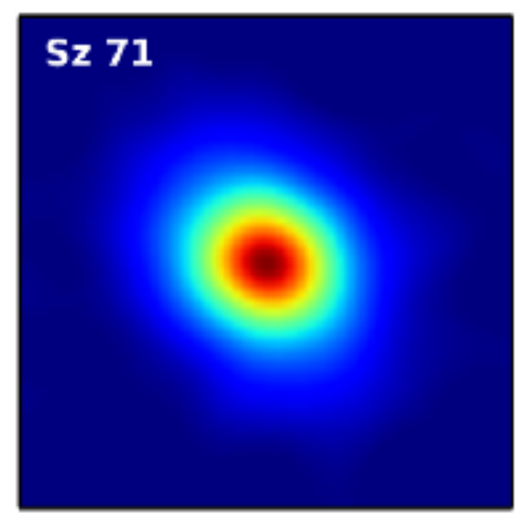
Dust has clearly drifted inwards compared to the gas!

Andrews 2020

Testing observations

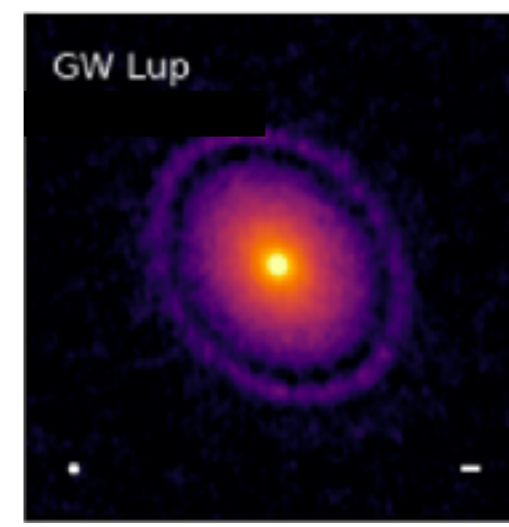
- Major issue: need high-resolution observations of disks, whereas many of the early observations (<2018) of complete surveys were done at moderate 0.25” resolution
- Low-res observations do not show dust traps, even if present
- Alternative: look at other observables such as size





(0.30”)

=

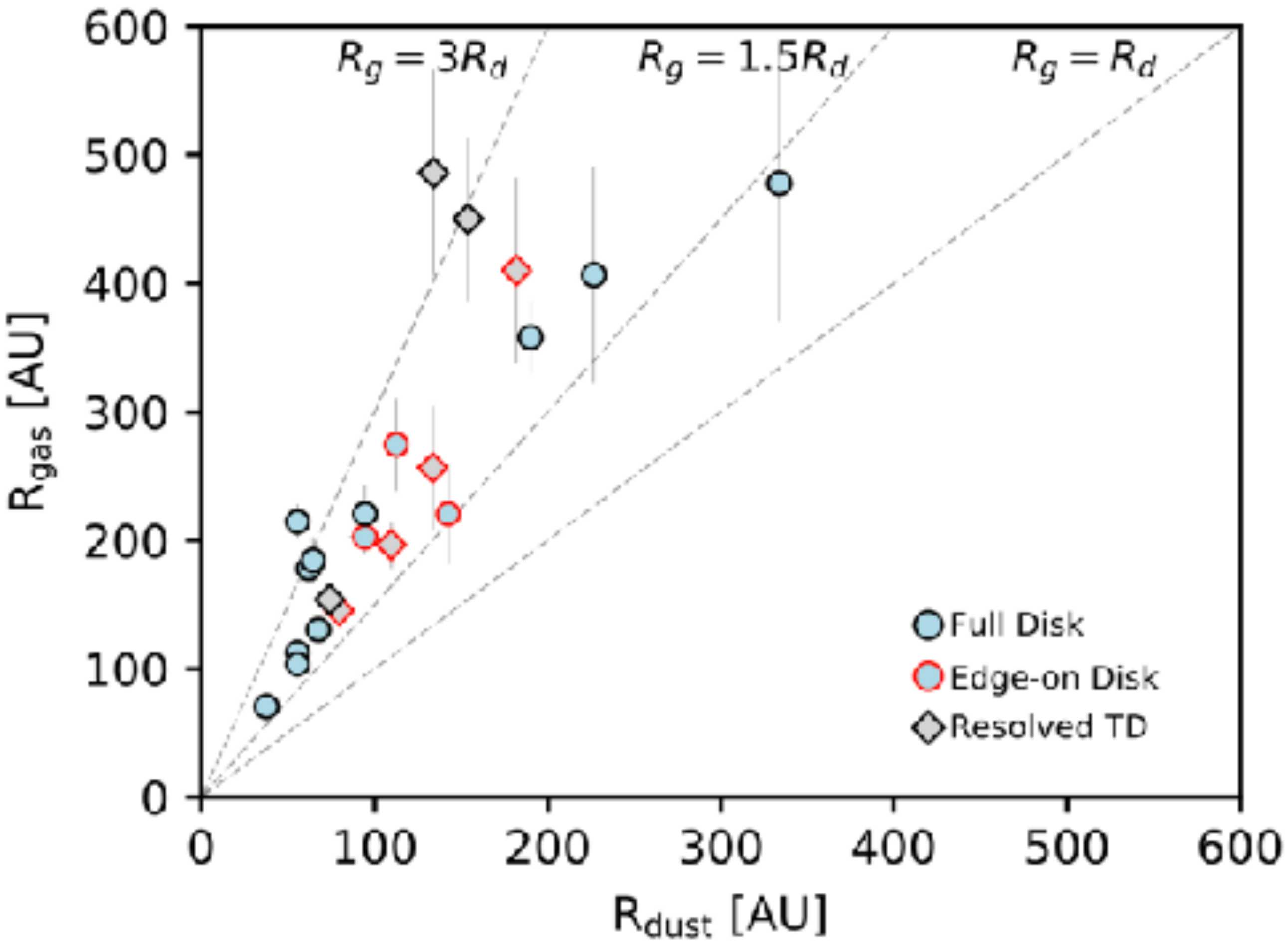


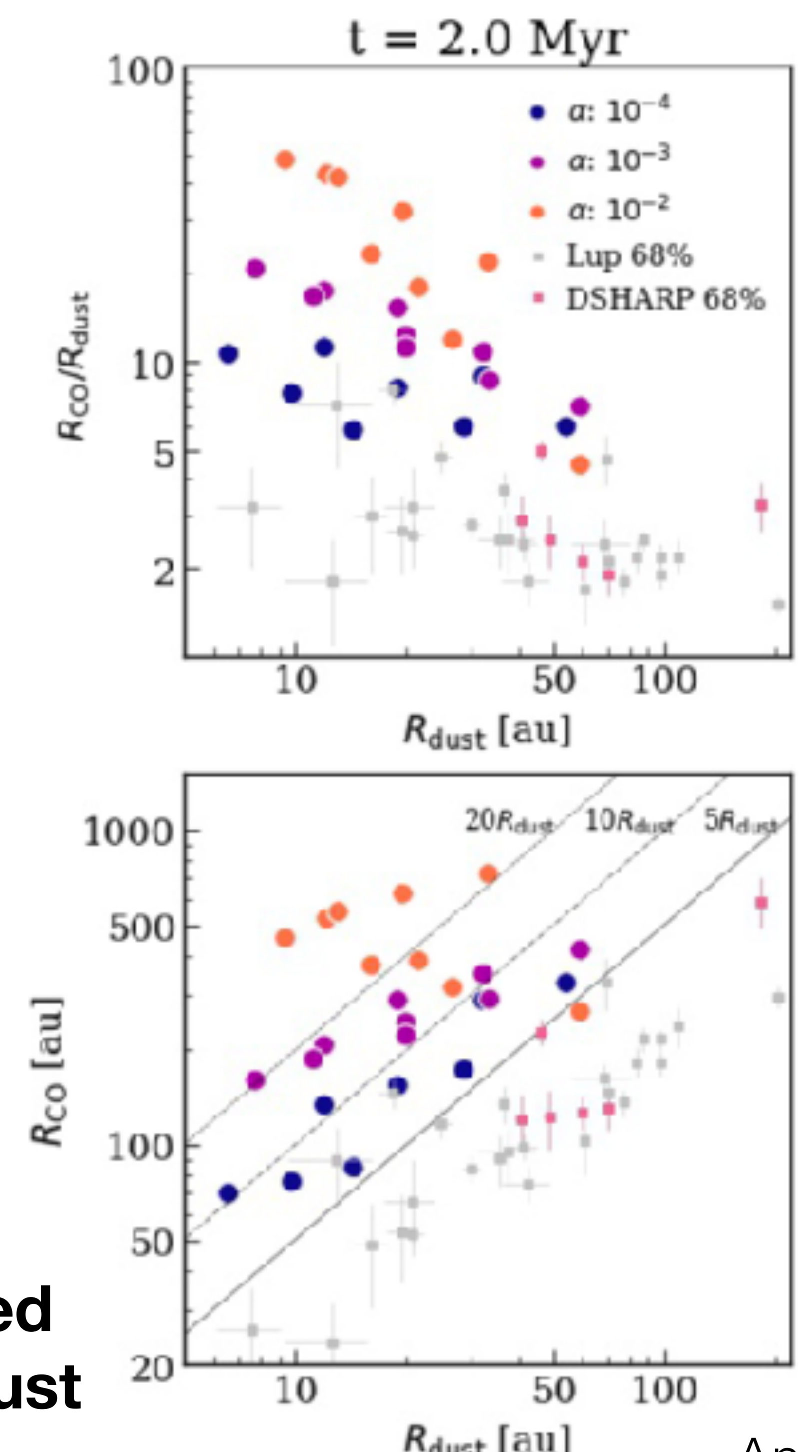
(0.04”)

Ansdell et al. 2016

Observational evidence: Gas-to-dust size ratios

Lupus disks: gas sizes from ^{12}CO, dust sizes from continuum, typically 2-3





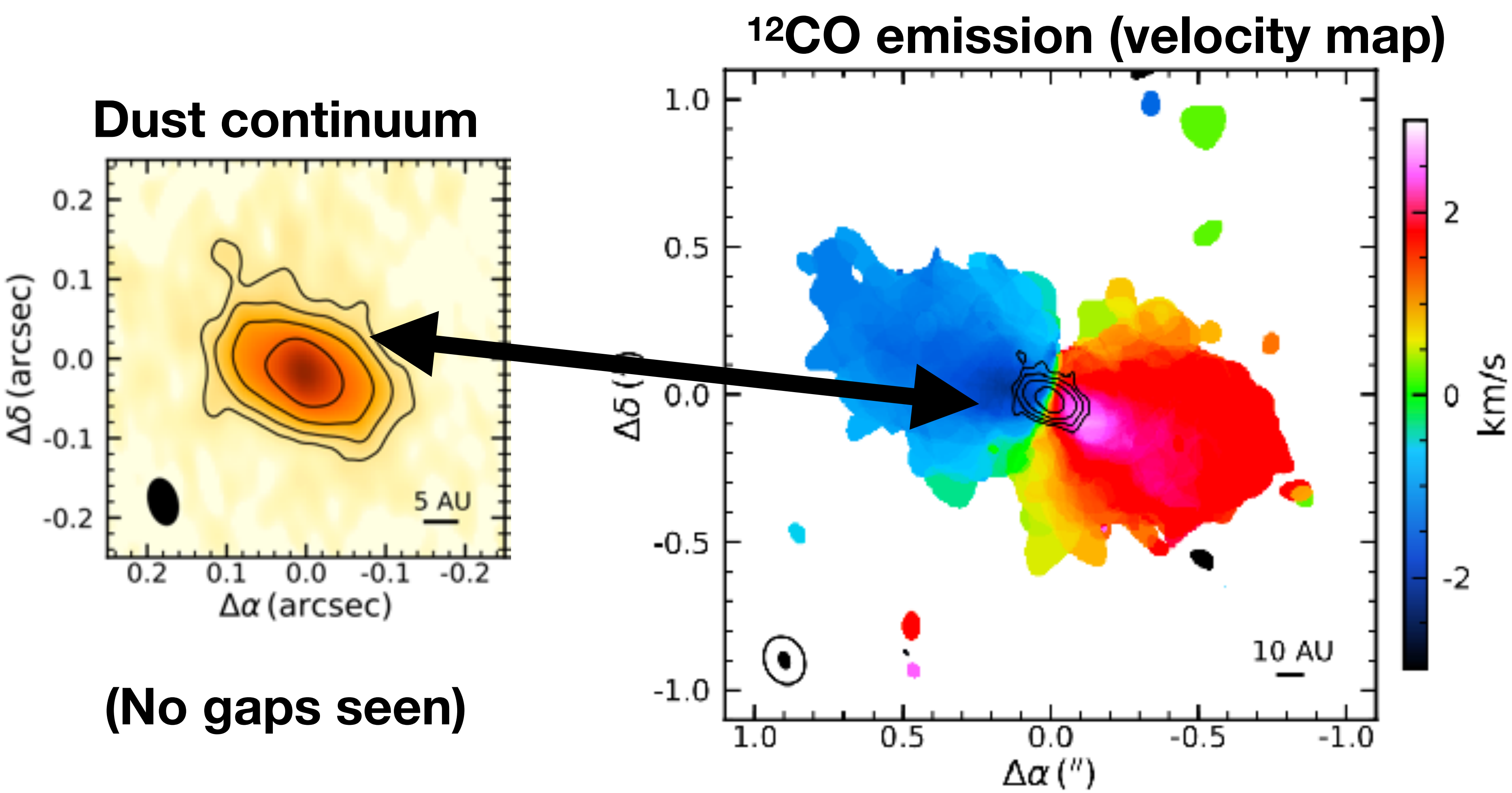
Typical dust evolution models of drift-dominated disks result in much higher ratios: dust traps must be present in these disks!

Ansdell et al. 2018
Toci et al. 2021

Gas-to-dust size ratio

Most extreme example

CX Tau (at high resolution of 0.04"!) with a ratio of >6:

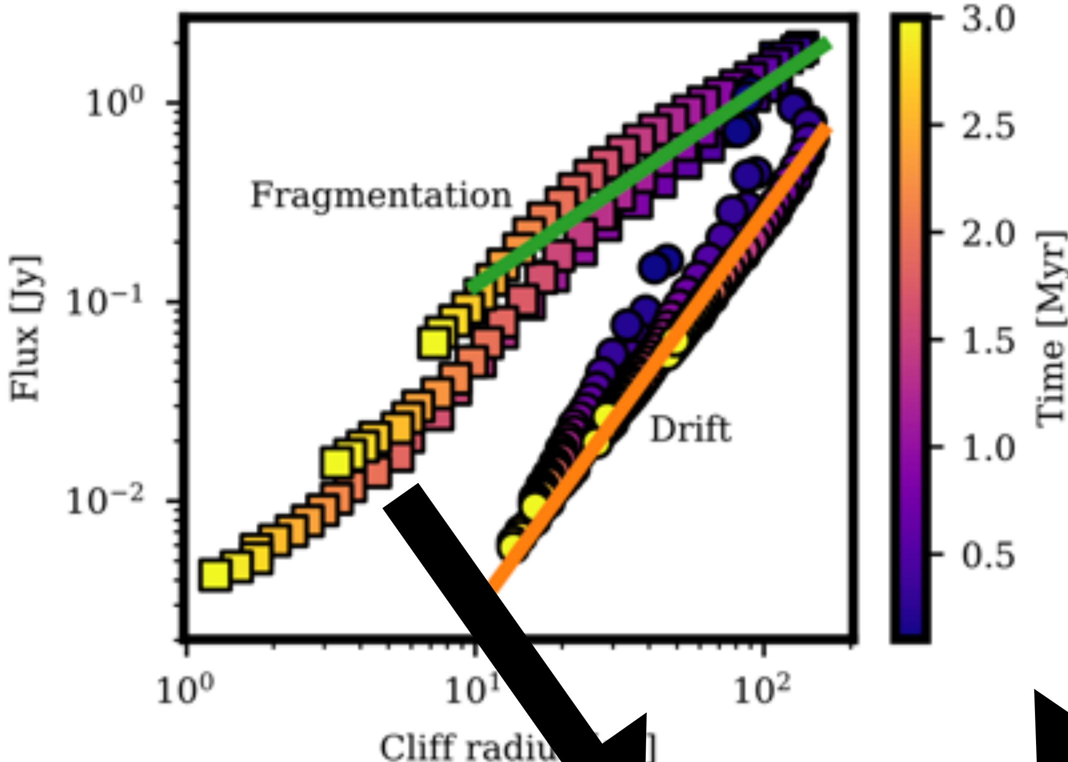


This may be a case of a drift-dominated disk, but very few small disks have been resolved at high spatial resolution

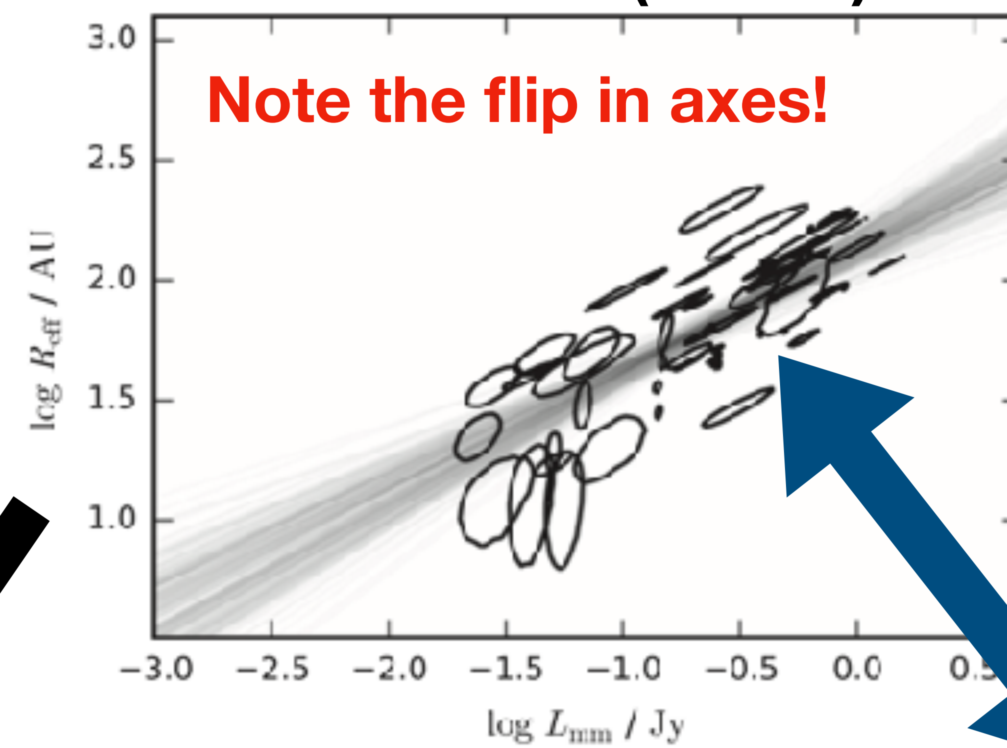
Facchini et al. 2019

Observational evidence: the size-luminosity diagram

Dust evolution models



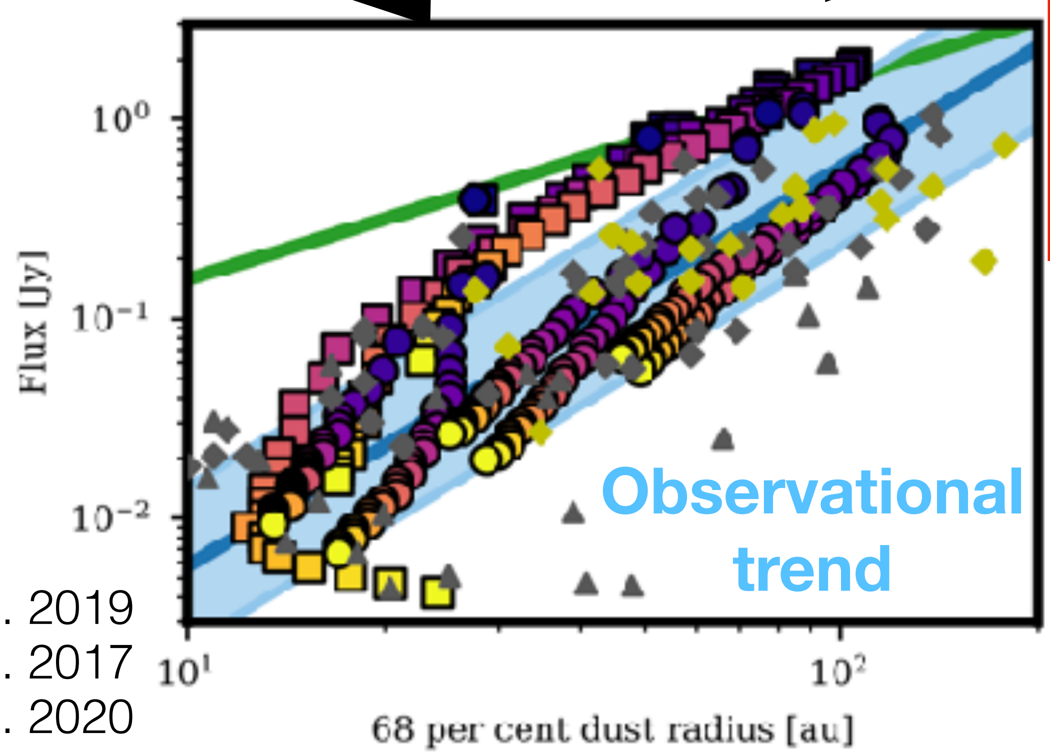
Observations (Taurus)

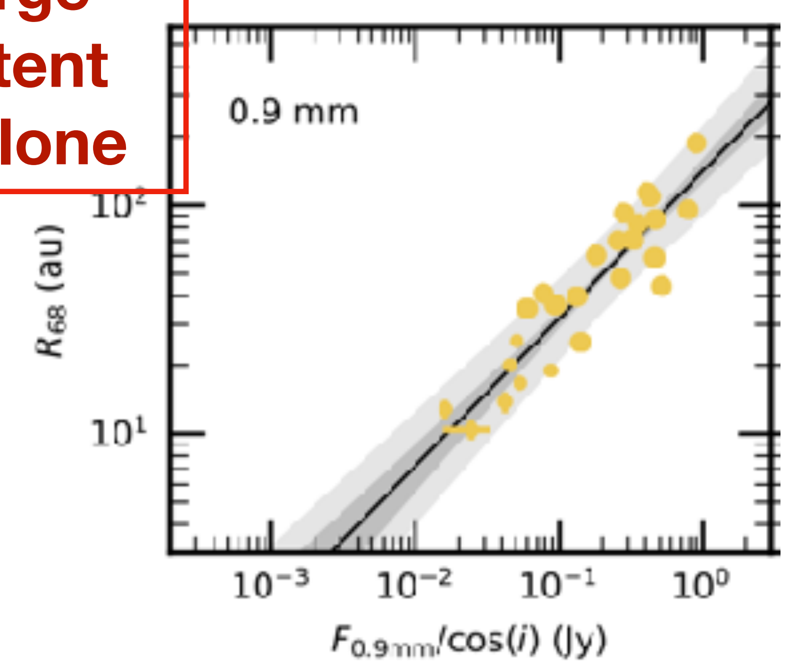


Comparable

Observations (Lupus)

Inconclusive: large scatter inconsistent with radial drift alone



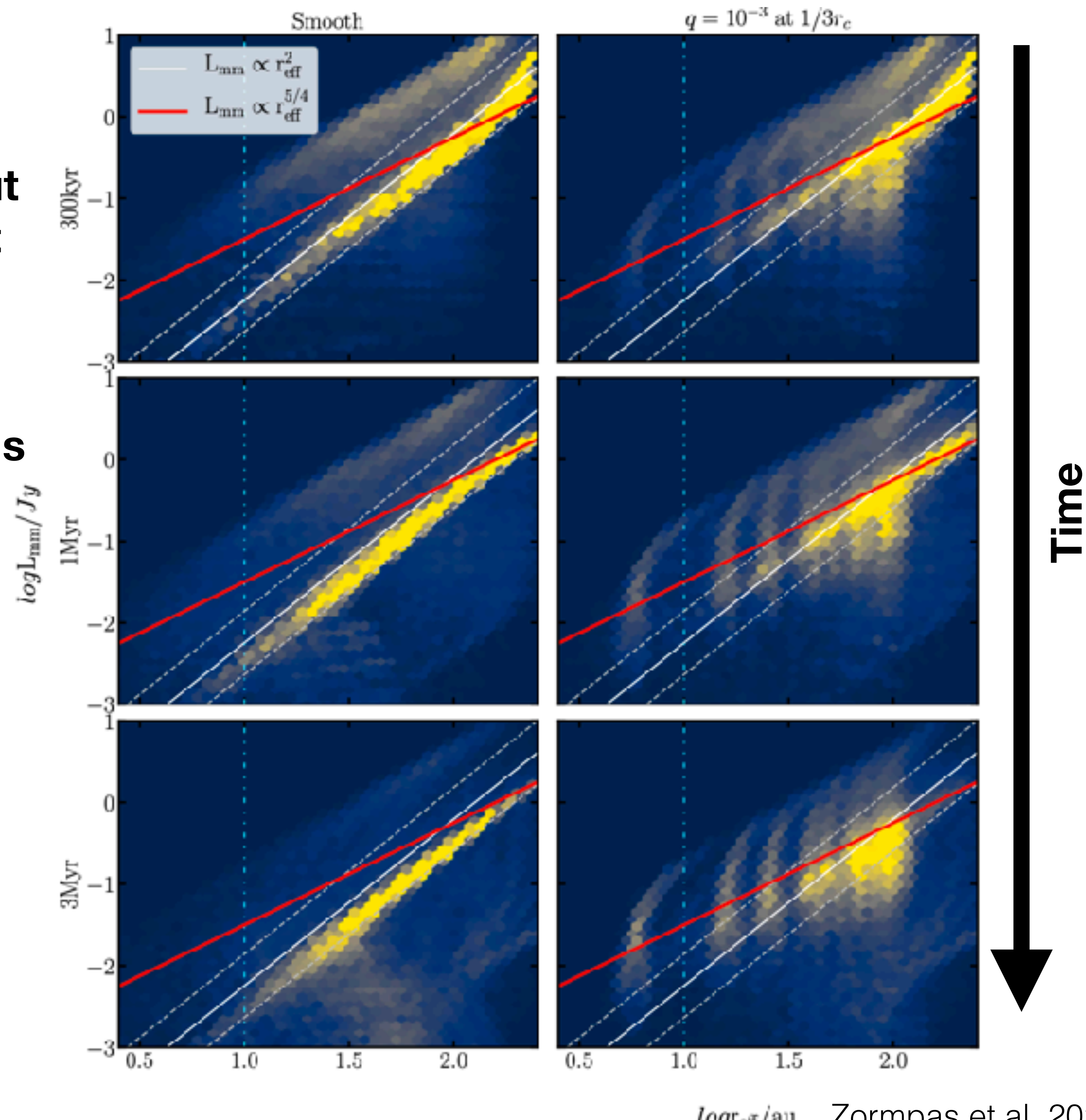


Rosotti et al. 2019
Tripathi et al. 2017
Tazzari et al. 2020

Observational evidence: the size-luminosity diagram

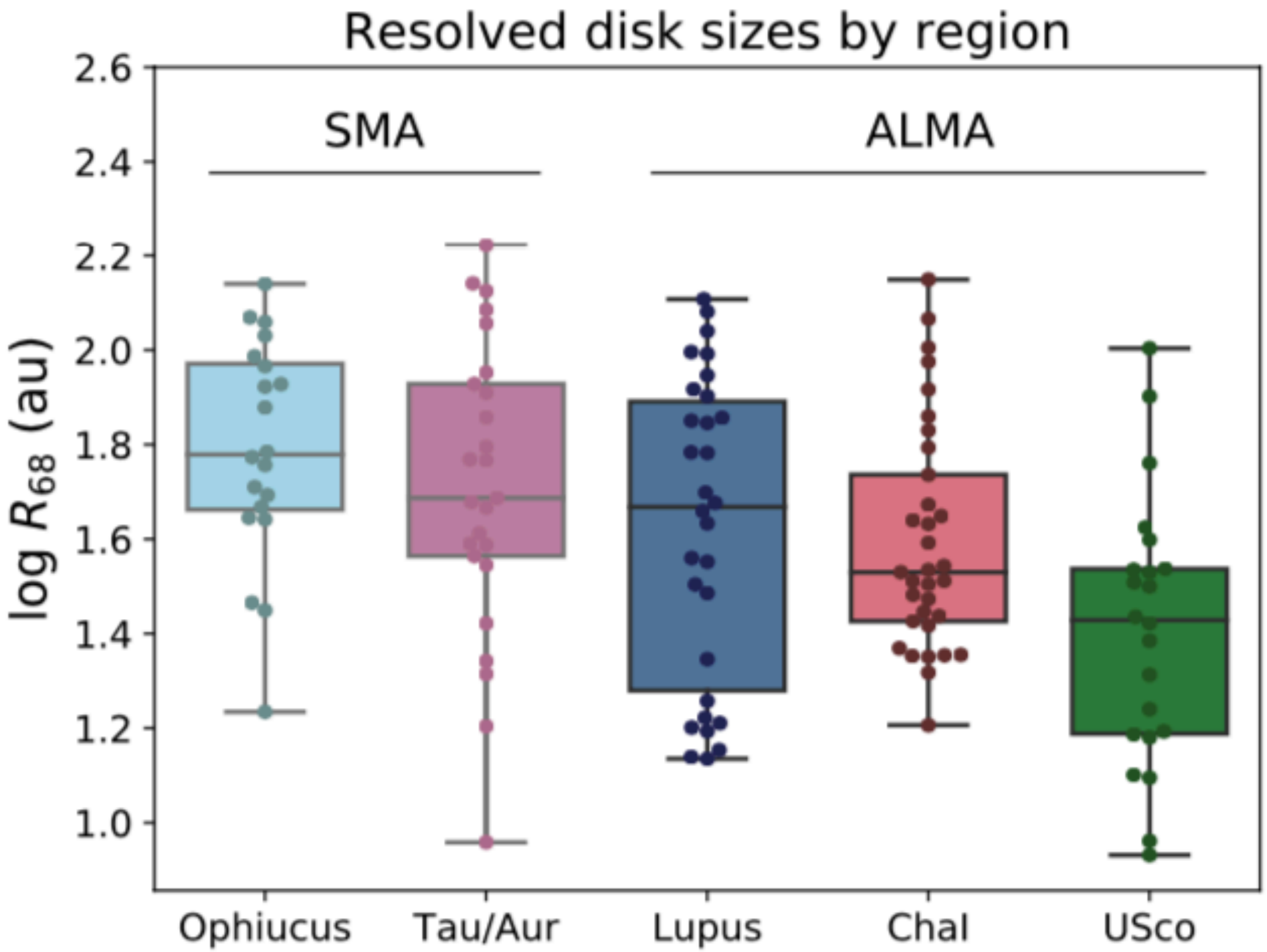
Another set of dust evolution simulations, now with and without dust traps as the result of planet gaps (q planet mass ratio)

Slope in size-luminosity diagram is different, but not distinguishable for larger disk sizes (>20 au)



Zormpas et al. 2022

R_{dust} evolution

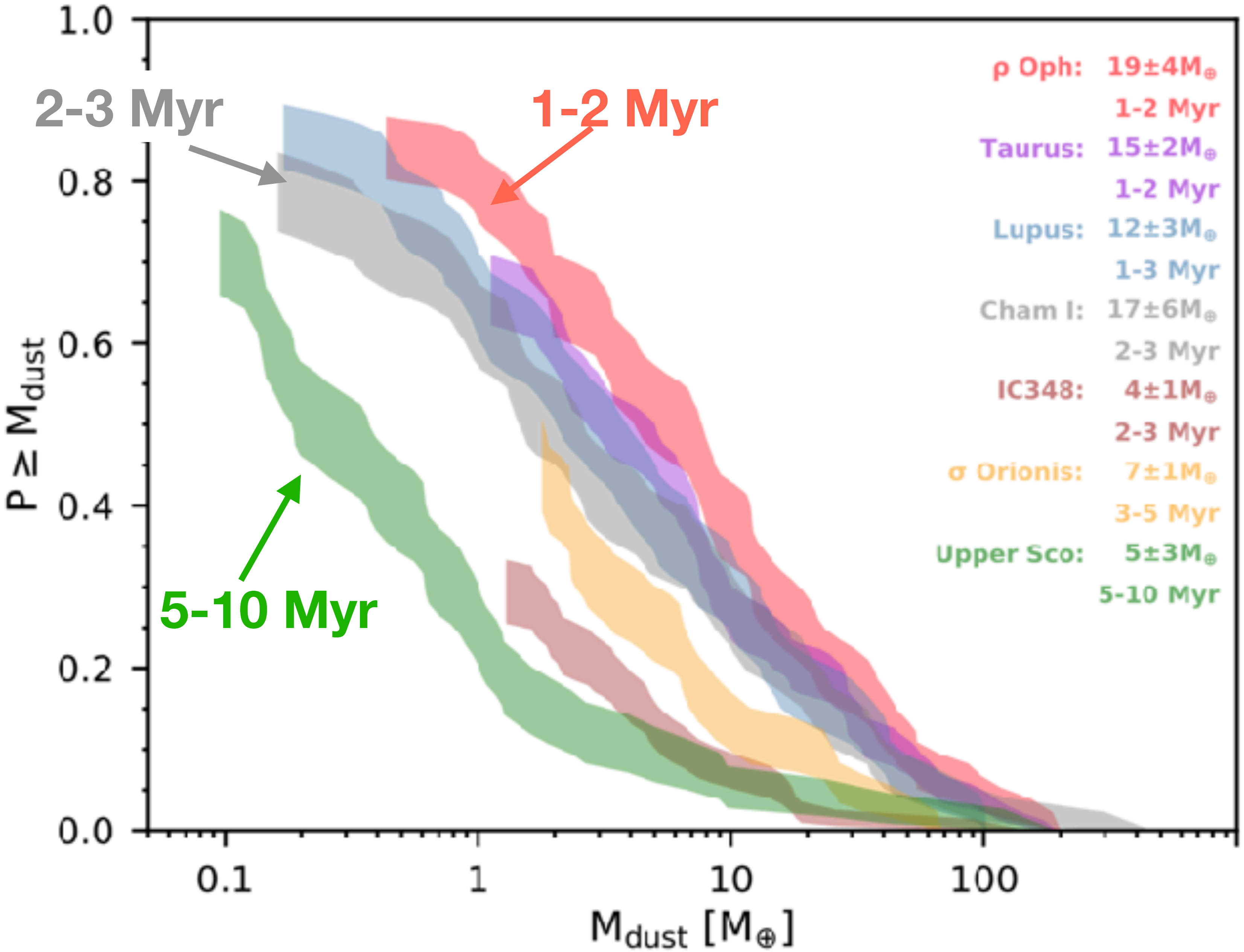


Overall, dust disk size decreases with time, but with significant scatter: consistent with radial drift?

Hendler et al. 2020

M_{dust} evolution

More on dust mass evolution in Lecture 5



$$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$

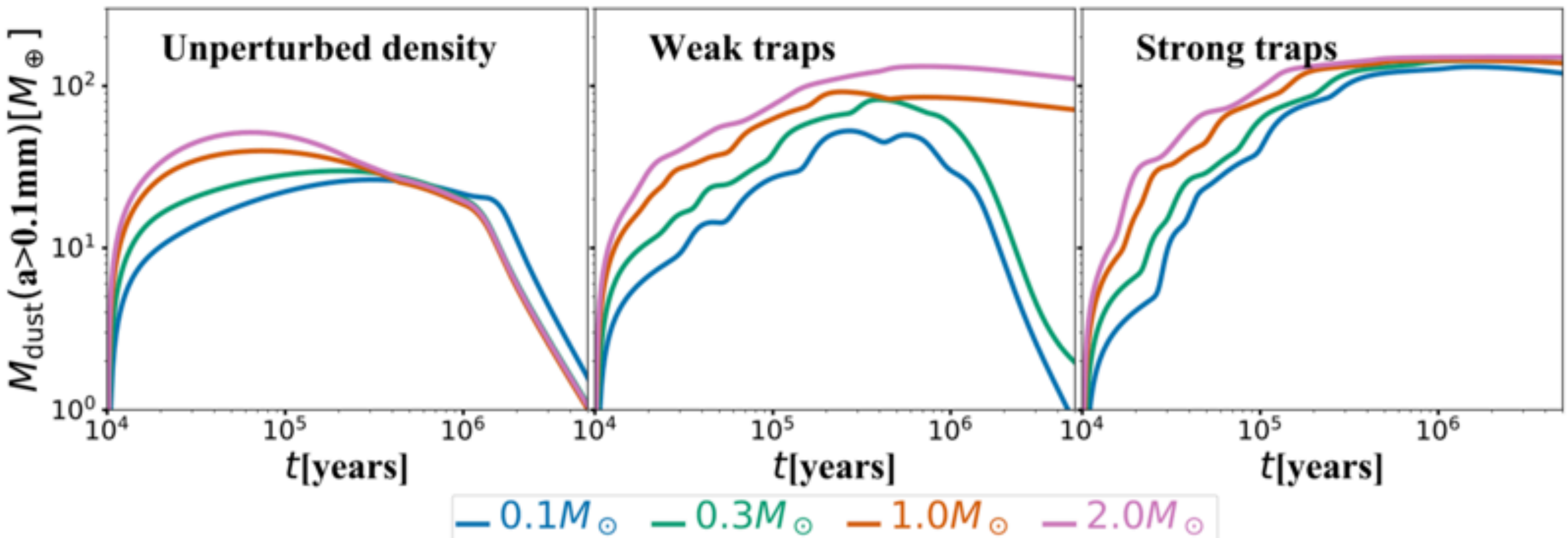
(Use kappa ~ 2.3 at 230 GHz, see Andrews et al. 2013)

Overall, disk dust mass decreases with age: consistent with radial drift?

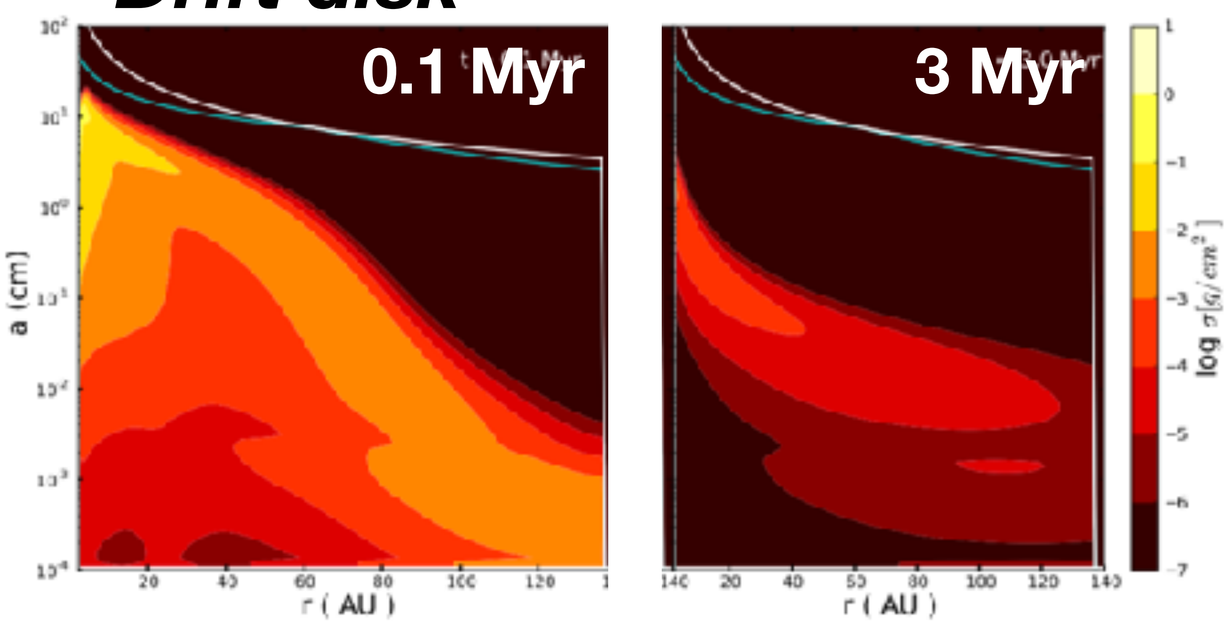
Ansdell et al. 2016, 2017
Cieza et al. 2018

M_{dust} evolution

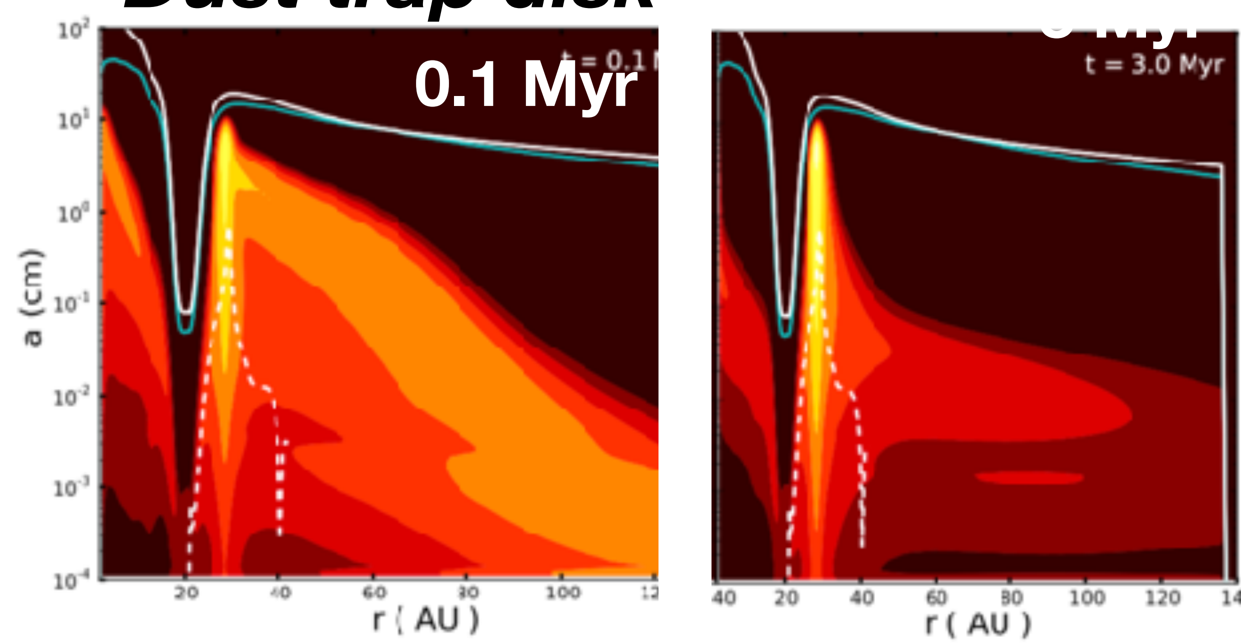
Disk dust mass decreases rapidly (factor 20 in 5 Myr) through radial drift



Drift disk



Dust trap disk



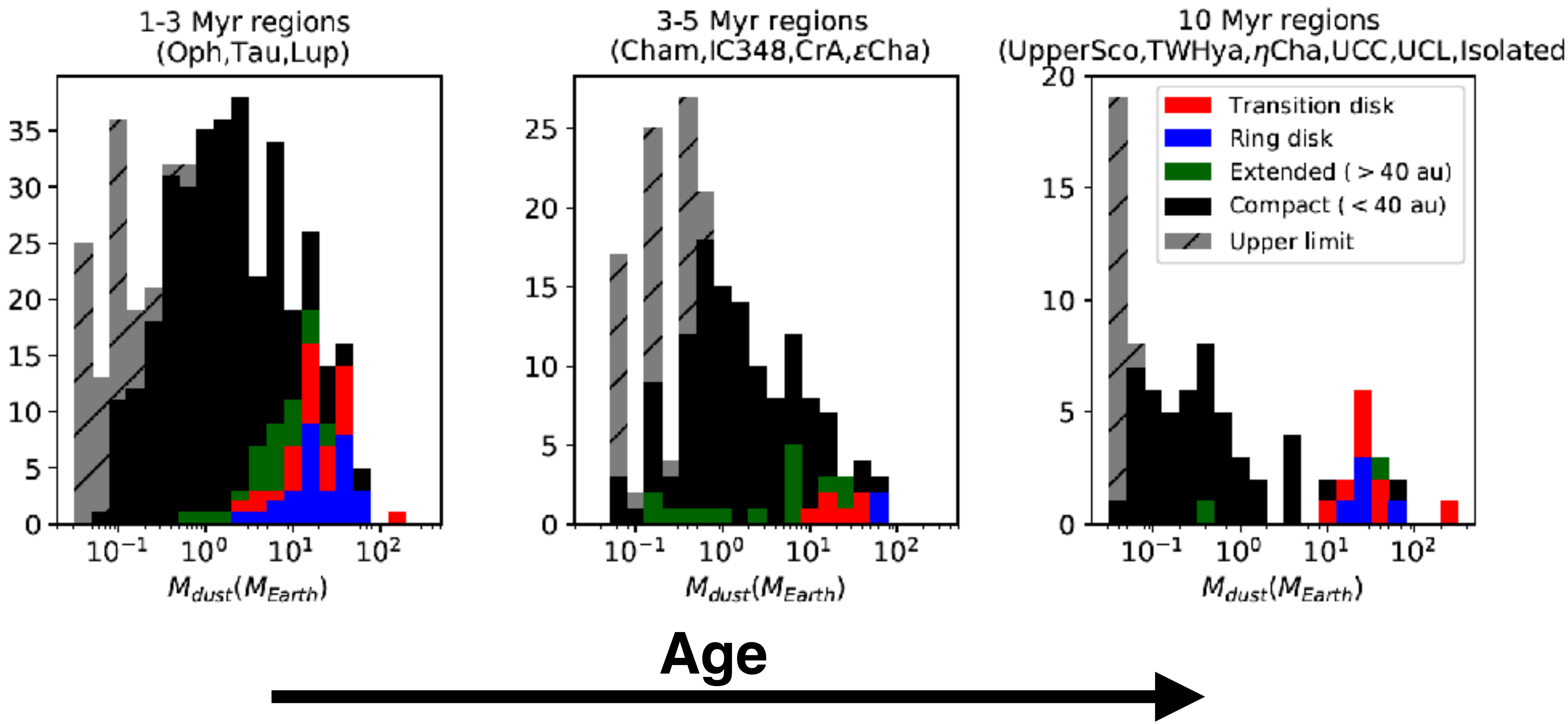
Pinilla et al. 2012, 2020

Summary

- Dust evolves separately from the gas.
- Dust evolution depends on the presence or absence of pressure bumps
- In case of radial drift, dust mass decreases much more rapidly than accretion rates and gas disk mass:
  => important argument not to use dust mass as tracer gas mass (see also Lecture 5)
- Dust evolution timescales depend on a number of unknown parameters such as fragmentation velocity, sticking efficiency and turbulence
- For proper observables, gas and dust evolution needs to be combined

Disk dust evolution

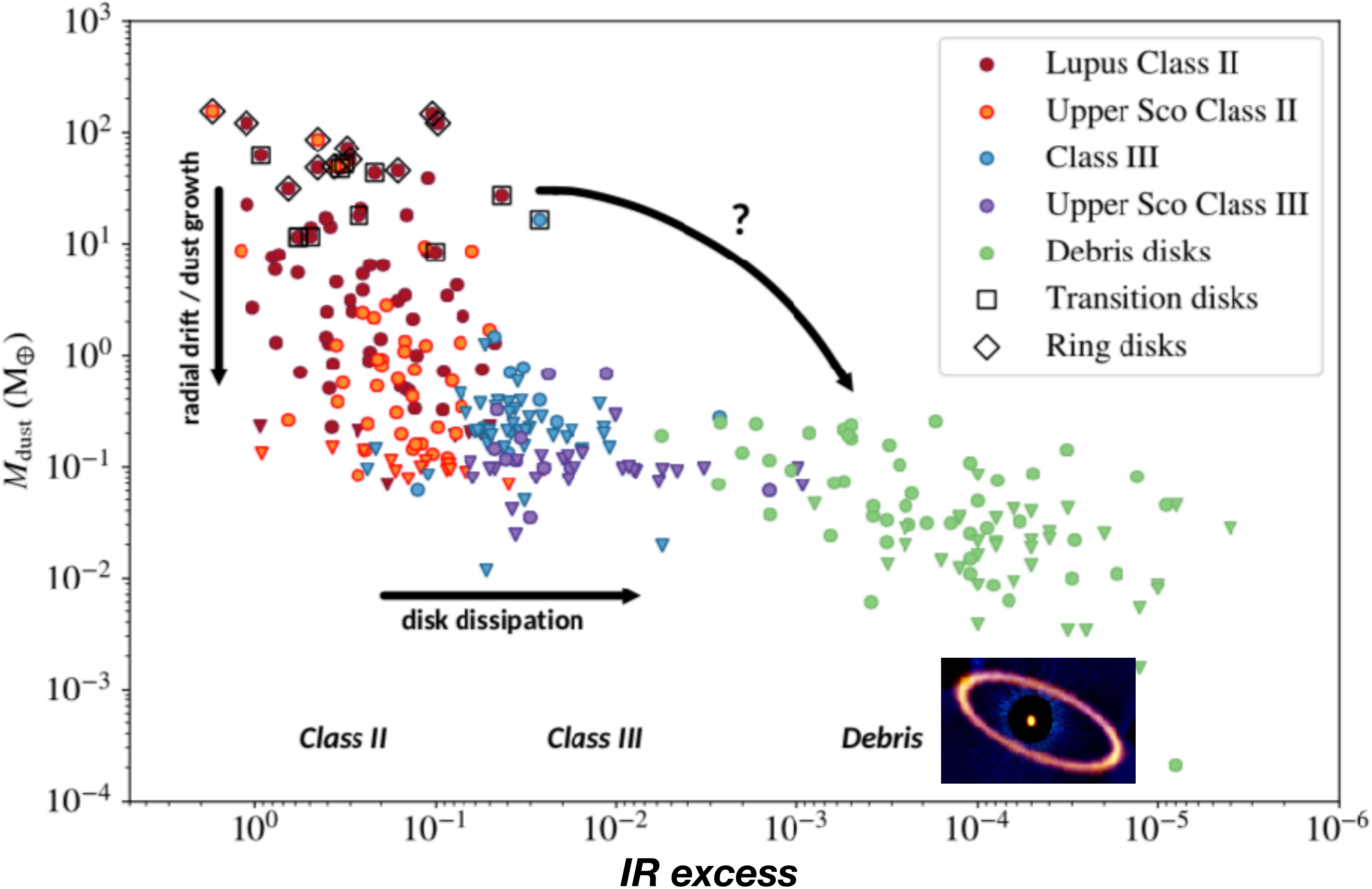
Distribution dust masses as function of age and disk type



Two separate evolutionary pathways:
the gapped disks and compact disks

Van der Marel & Mulders 2021

Disk evolution to debris disks



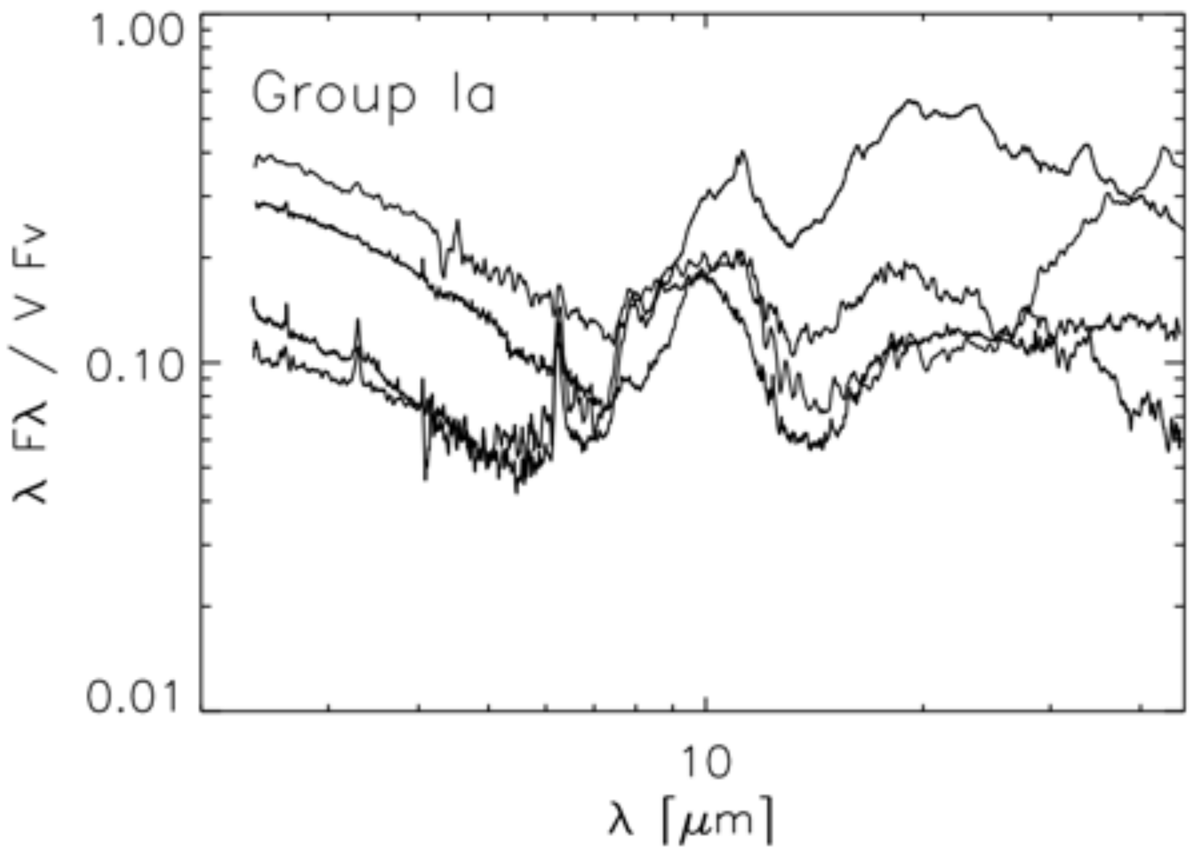
Michel, van der Marel & Matthews 2021
Najita et al. 2022

Are gapped disks progenitors of debris disks?

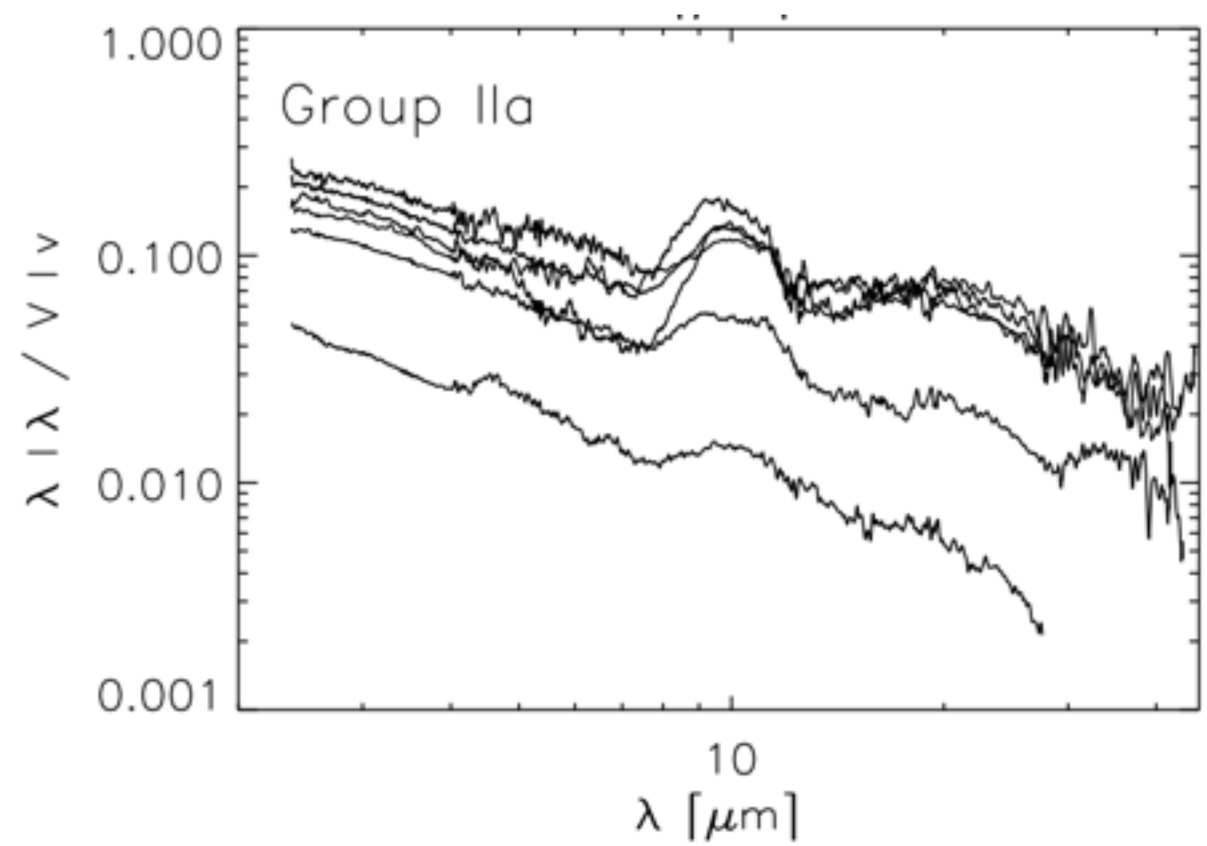
Disk evolution in Herbigs

Infrared classification:

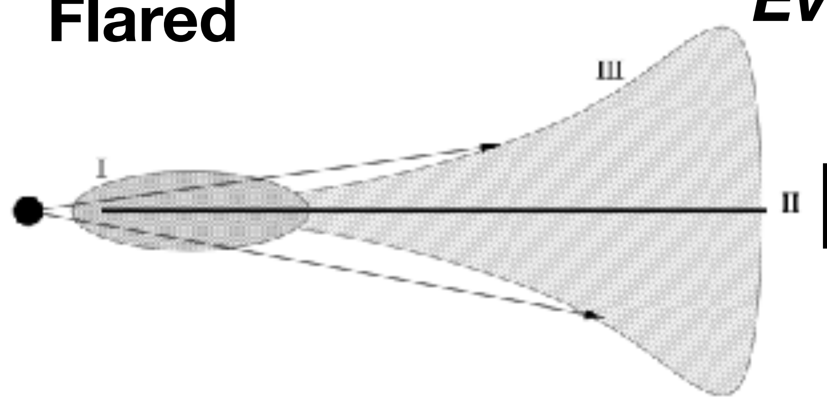
Group I



Group II

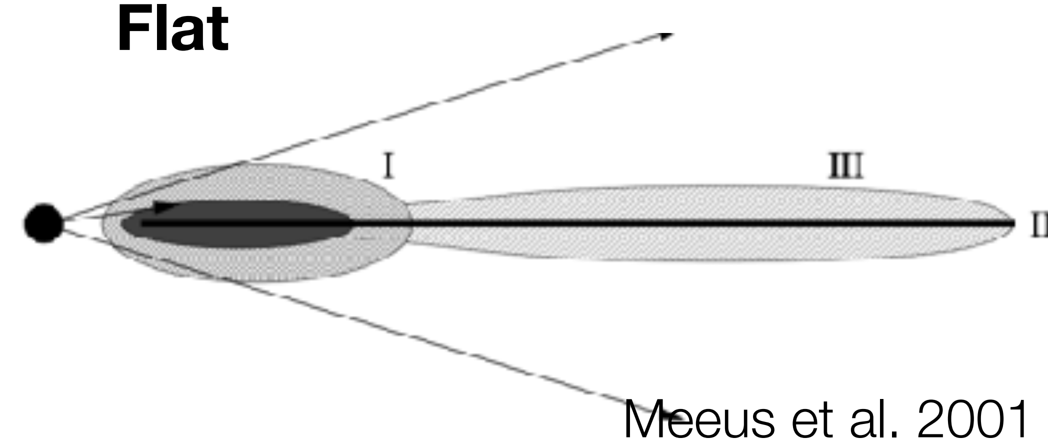


Flared



Evolutionary sequence of settling?

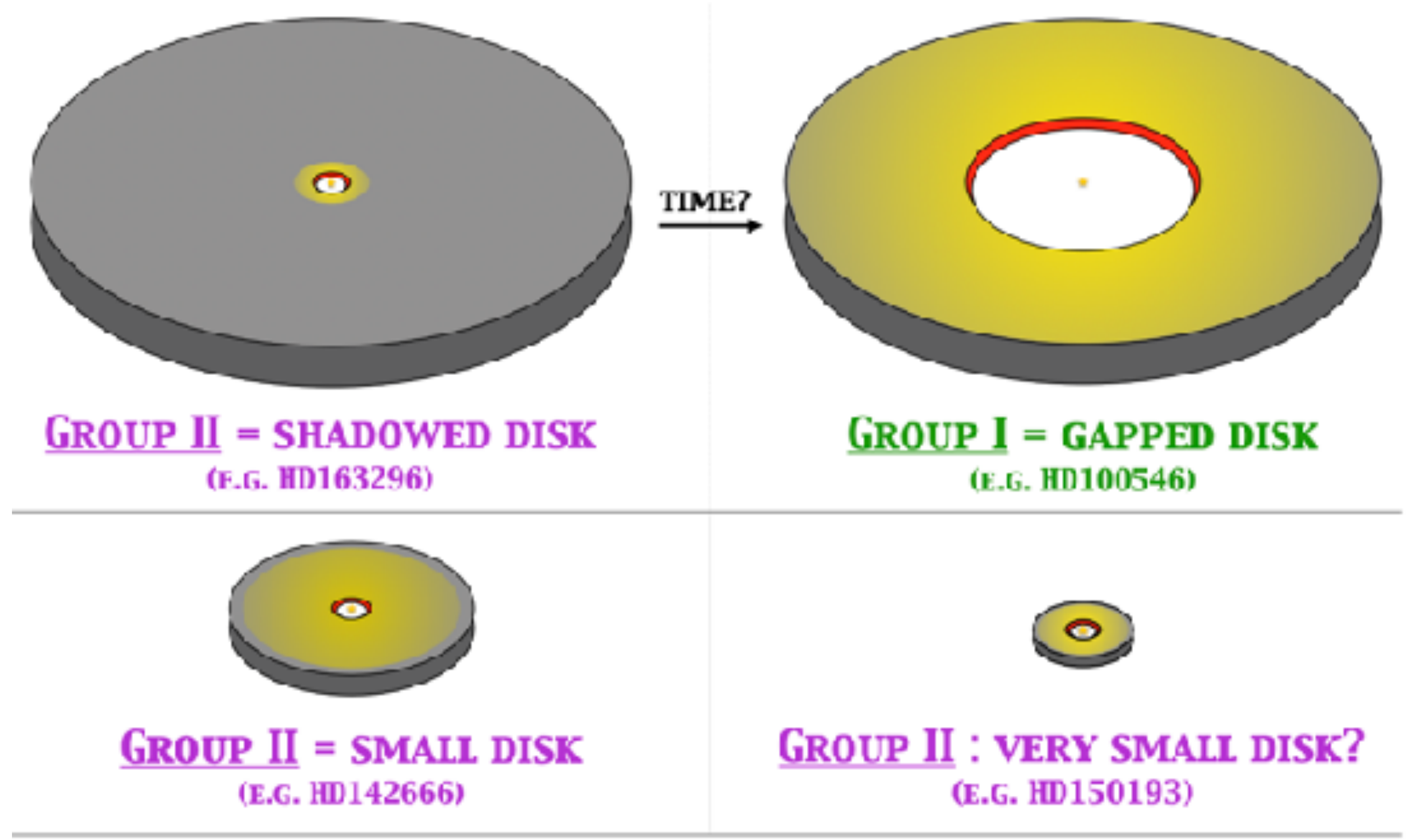
Flat



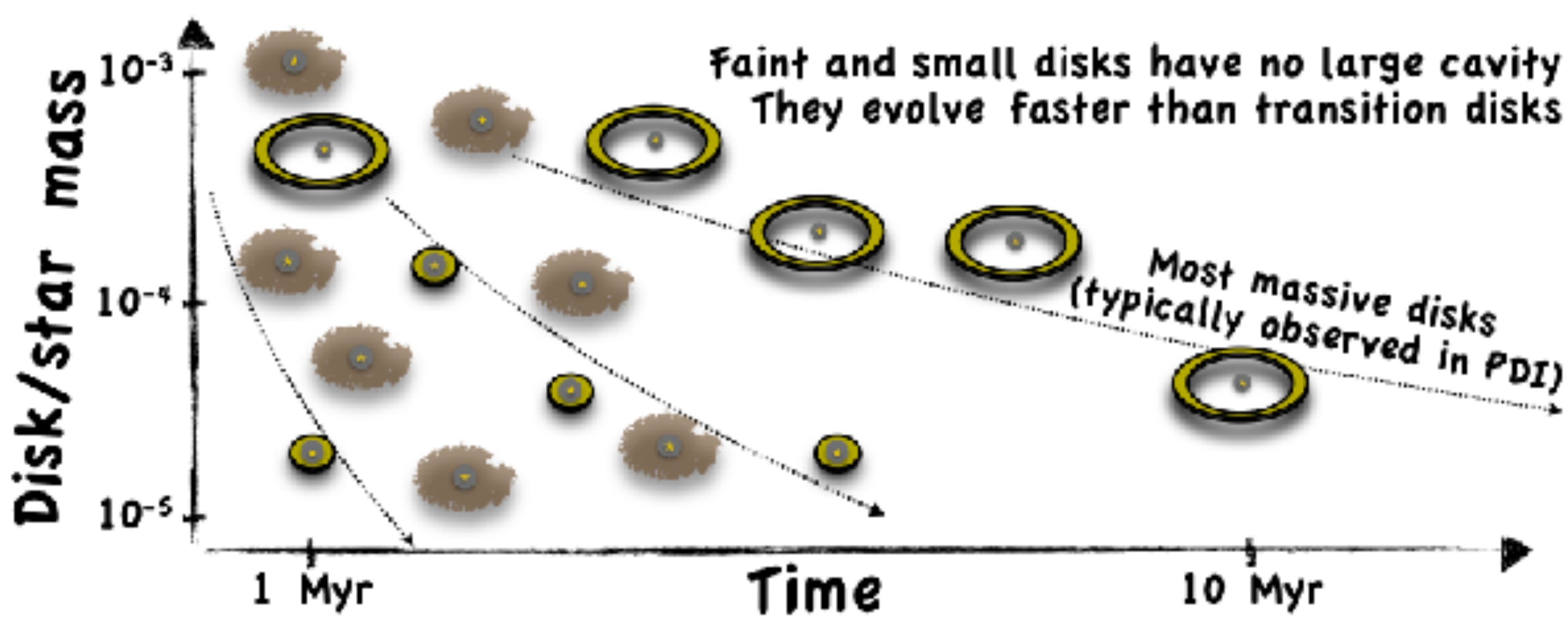
Meeus et al. 2001
Dullemond & Dominik 2004

Disk evolution in Herbigs

Group I disks all have inner cavities, while Group II disks do not: evidence against evolutionary sequence



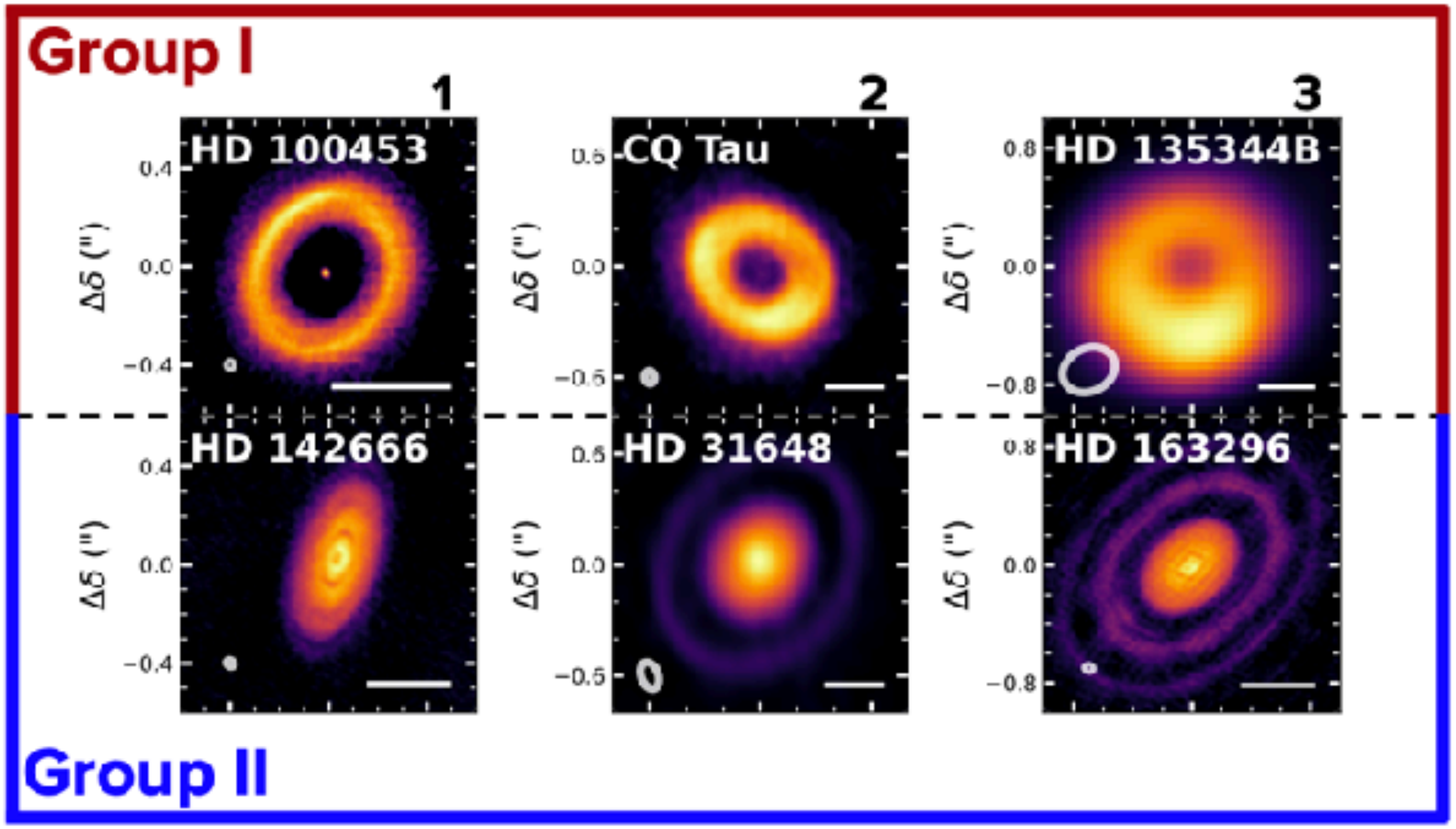
Instead: two paths of evolution!

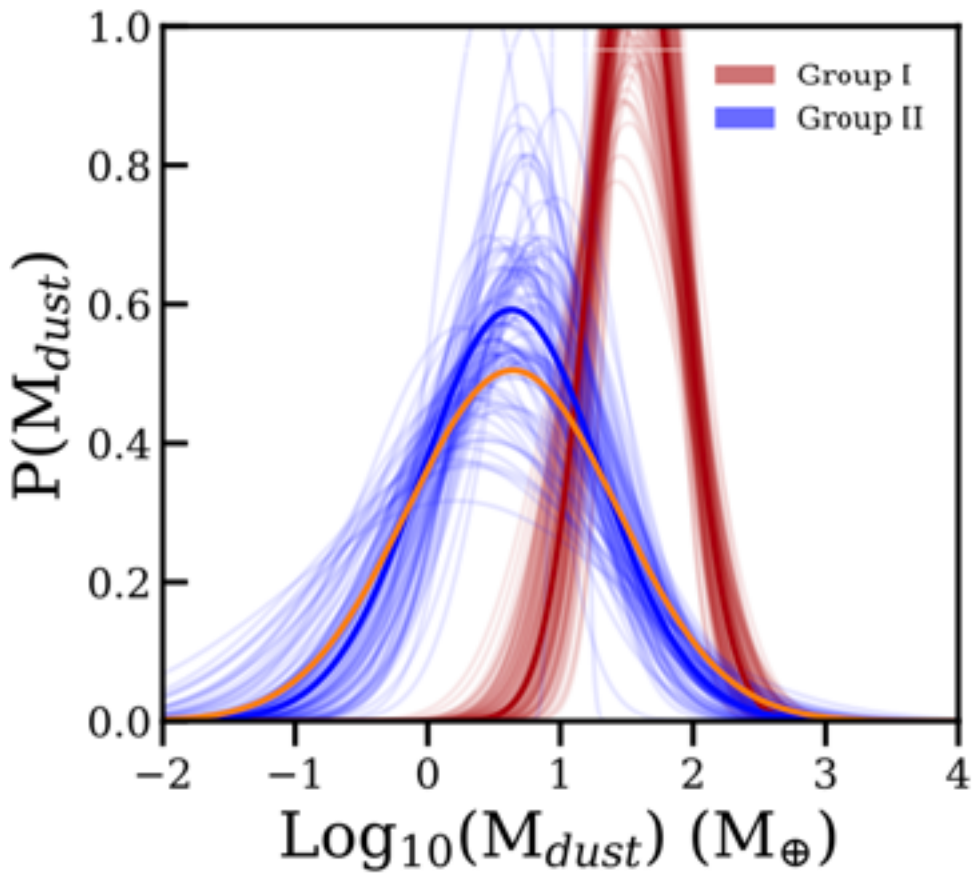


Garufi et al. 2017, 2018

Disk evolution in Herbigs

This evolutionary pathway is also seen in ALMA observations in the mm-dust distribution





Group I disks have large scale gaps and high dust mass (trap) and Group II disks are generally more compact (drift) with some outliers

Stapper et al. 2021

Questions?

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