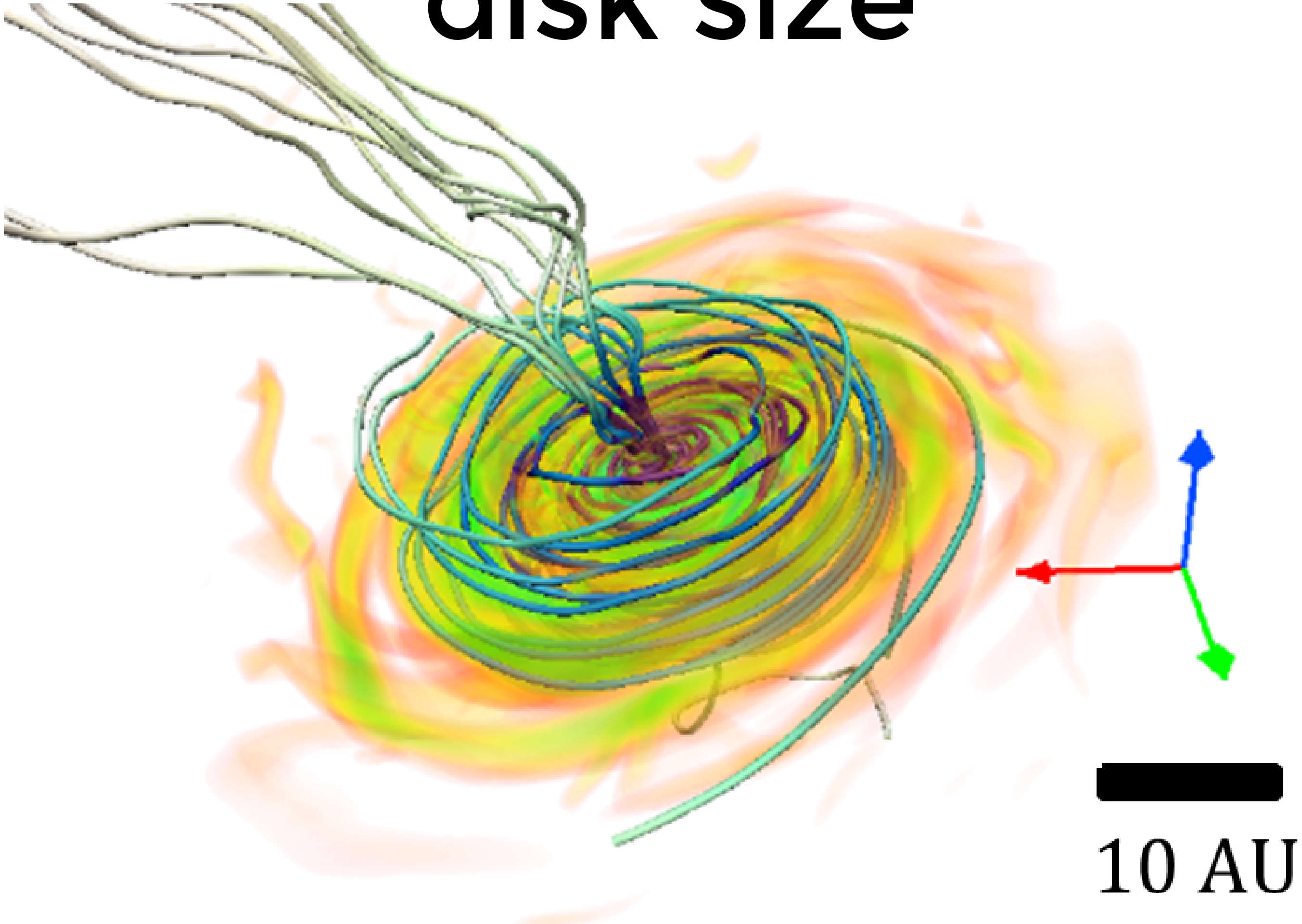
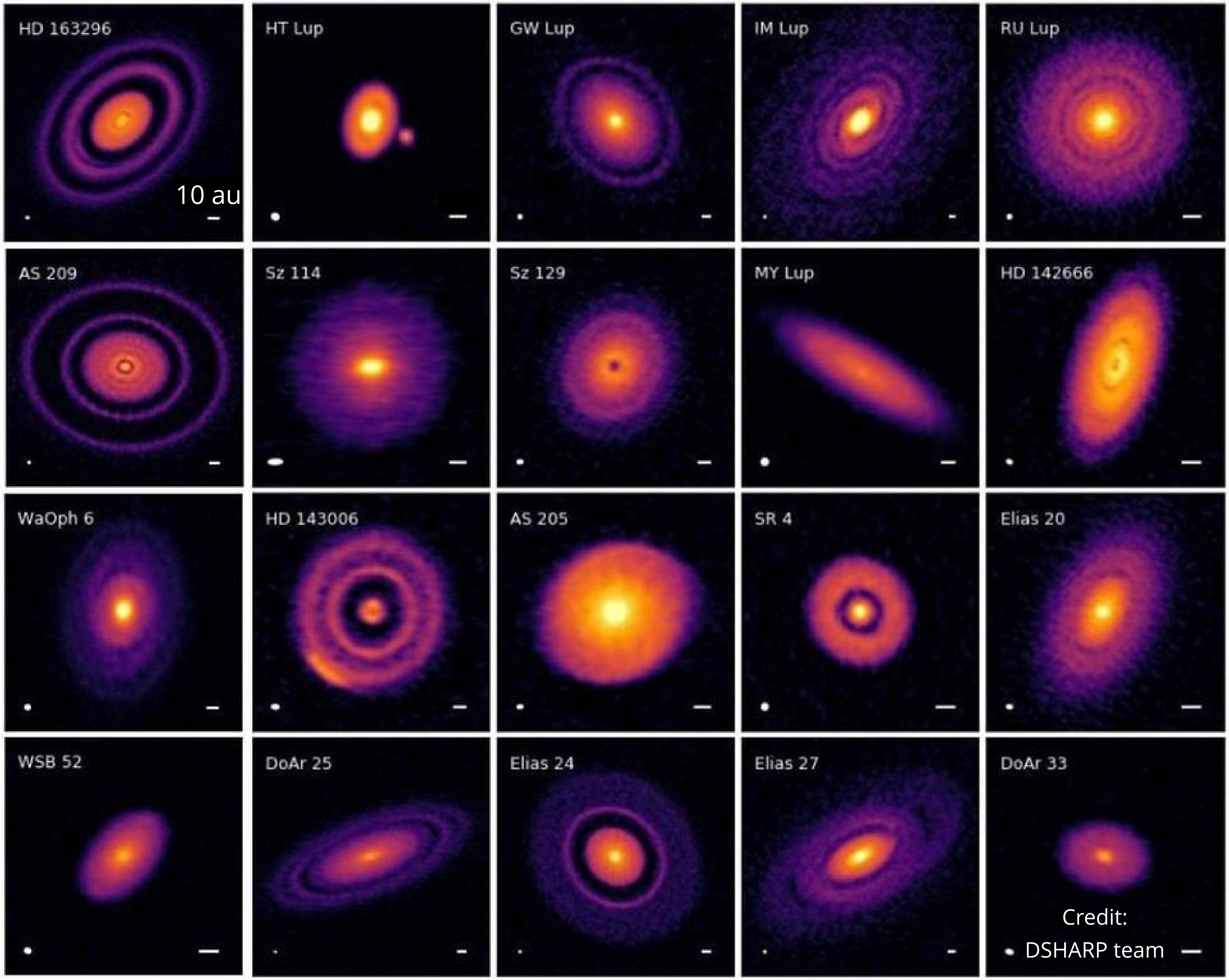
# Cosmic rays as a regulator of disk size



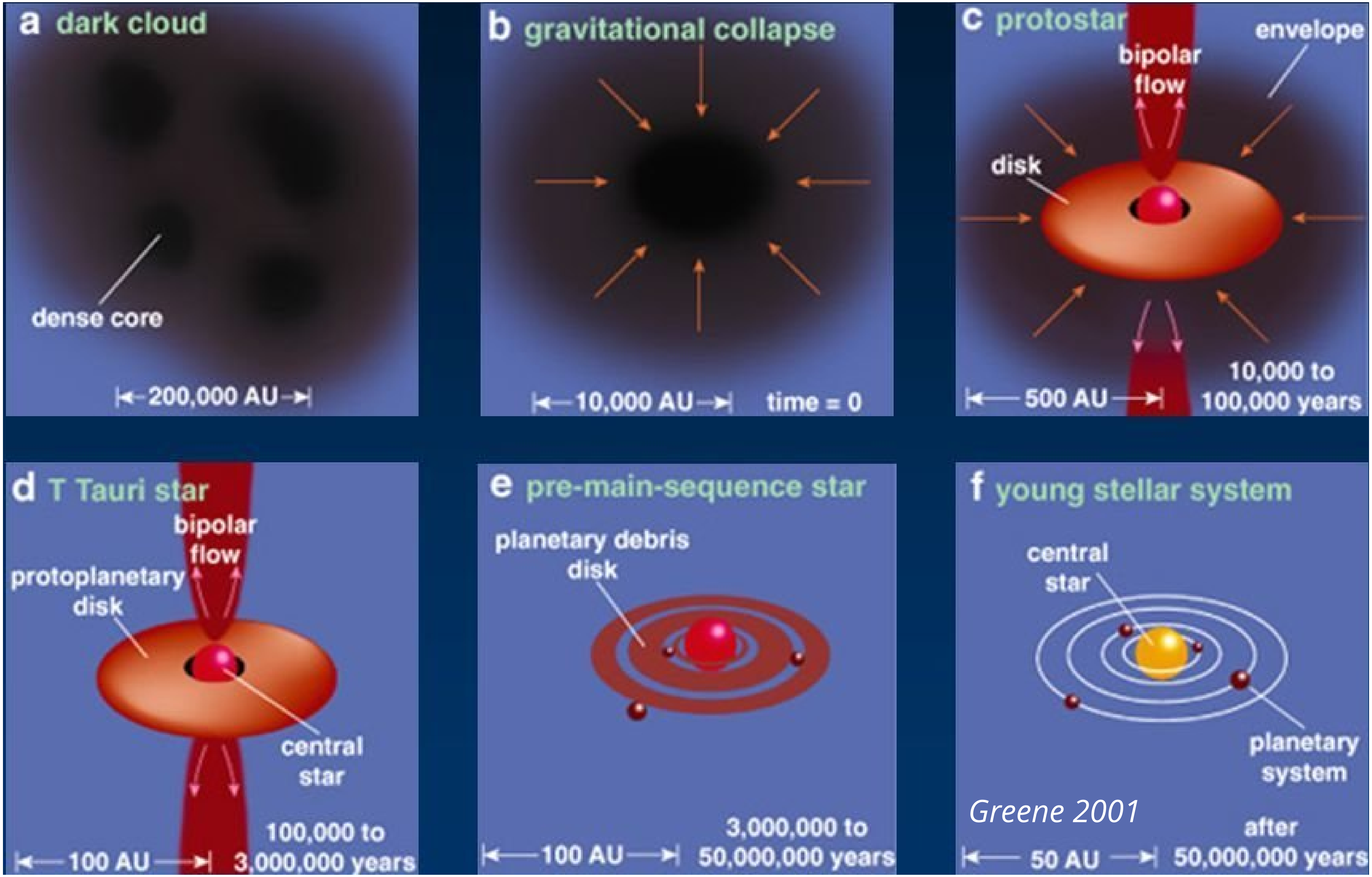

Michael Küffmeier

*Marie Skłodowska-Curie global fellow*

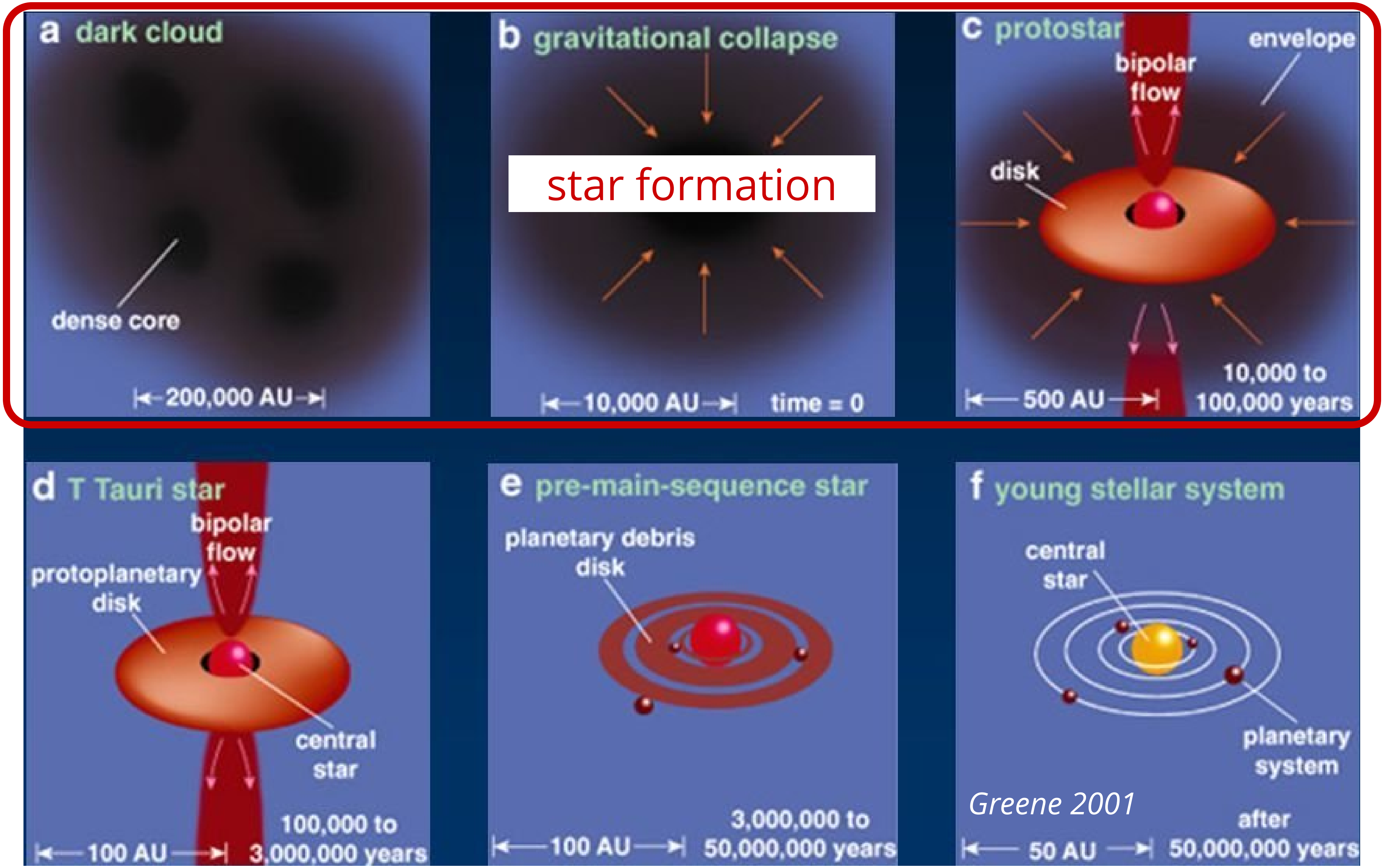

ESCHER
20 OTTOBRE 2022 - 26 MARZO 2023
FIRENZE,
MUSEO DEGLI INNOCENTI
WWW.MOSTRAESCHER.IT
MUSEO DEGLI INNOCENTI FIRENZE
Maurits
IN YOUR EVENT
COMUNE DI FIRENZE
Kingdom of the Netherlands
ARTHEMISIA
GENERALI
Valore Cultura
Ricola
CENTRALE
Designer Outlet
unicoopfirenze
QN LA NAZIONE
LABA
sky arte


HD 163296
10 au
HT Lup
GW Lup
IM Lup
RU Lup
AS 209
Sz 114
Sz 129
MY Lup
HD 142666
WaOph 6
HD 143006
AS 205
SR 4
Elias 20
WSB 52
DoAr 25
Elias 24
Elias 27
DoAr 33
Credit:
DSHARP team

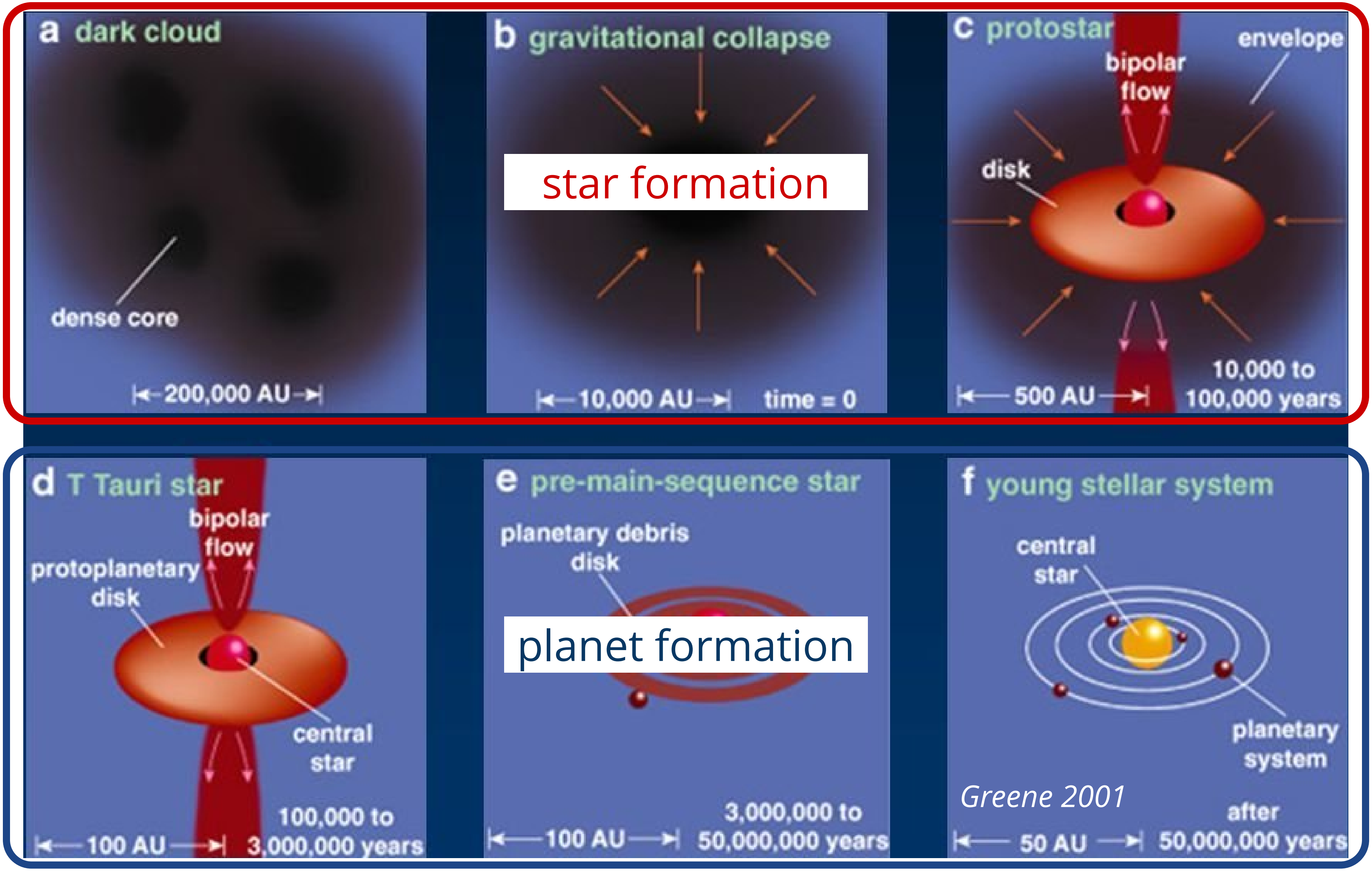
# The classical picture



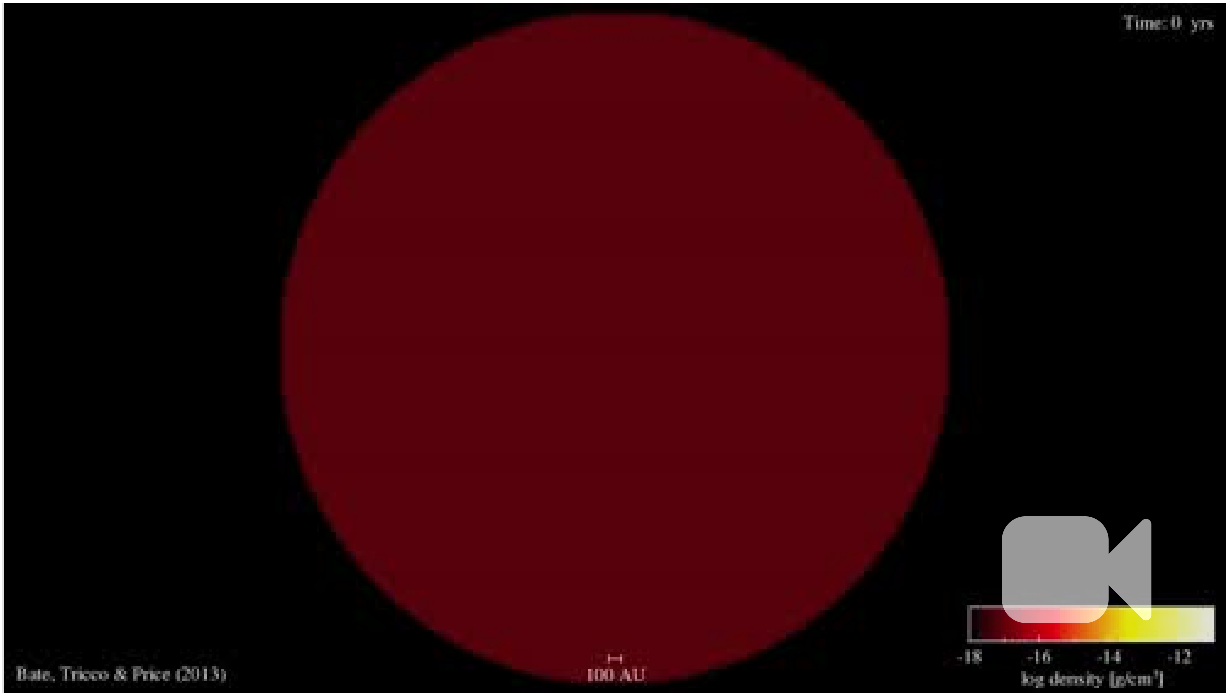
# The classical picture



# The classical picture



# History of modeling disk formation




**spherical core collapse:**

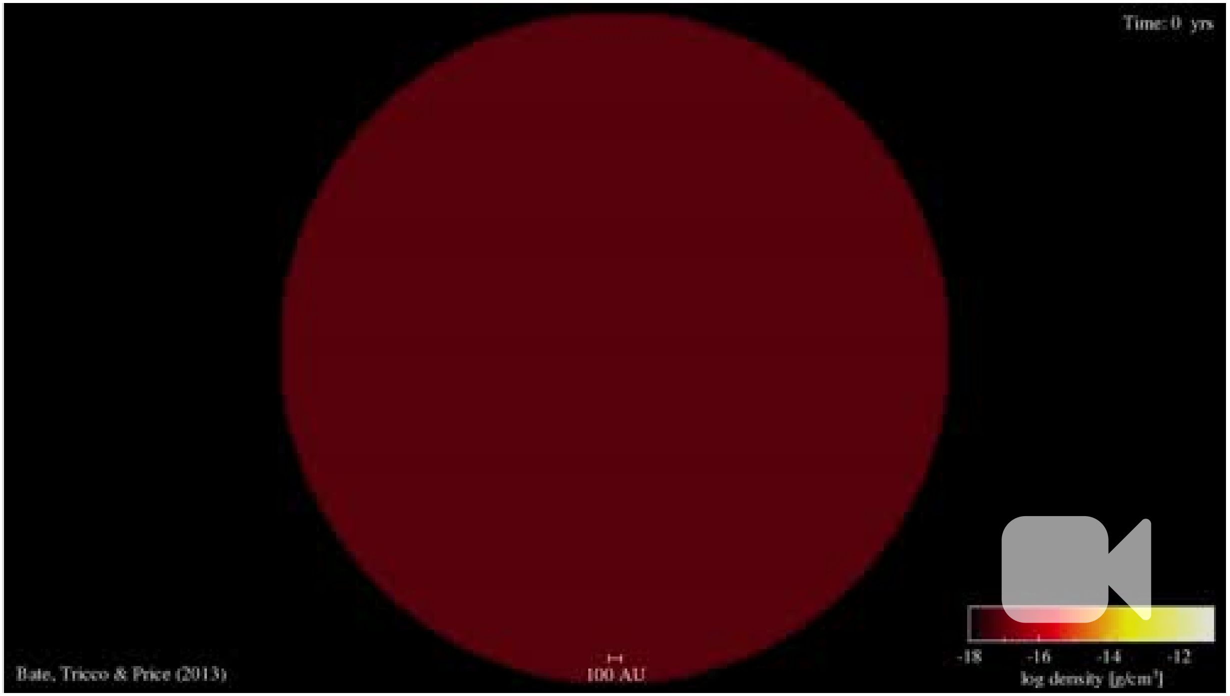
Bonnor-Ebert sphere

$$\rho(r) = \frac{\rho_c R_c^2}{R_c^2 + r^2}$$

or uniform density

$$\rho(r) = \rho_0$$

# History of modeling disk formation




**spherical core collapse:**

Bonnor-Ebert sphere

$$\rho(r) = \frac{\rho_c R_c^2}{R_c^2 + r^2}$$

or uniform density

$$\rho(r) = \rho_0$$

**useful for parameter studies**

rotation

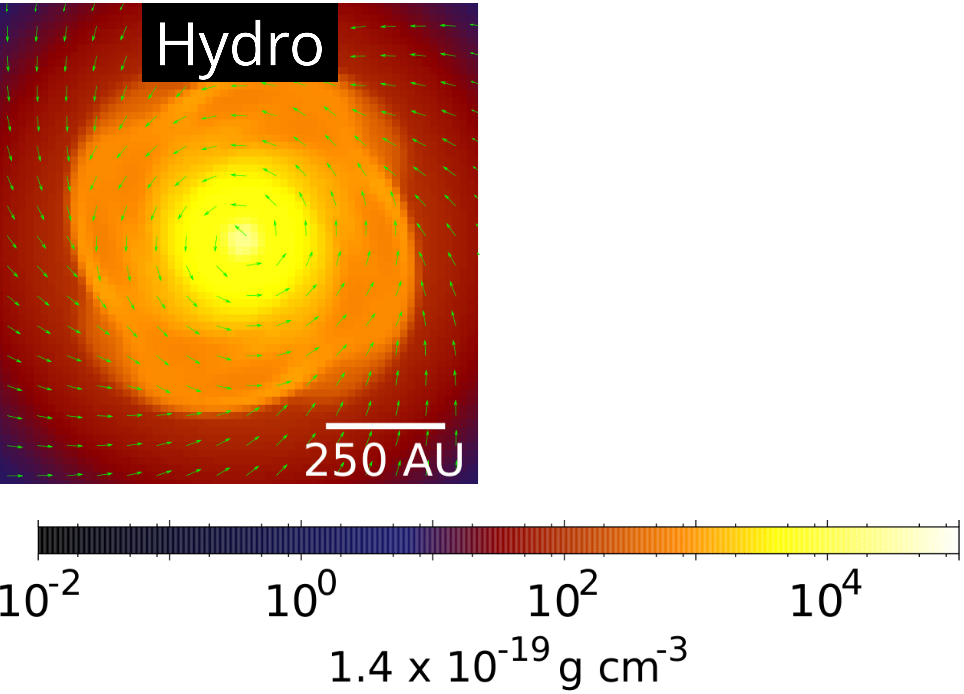
magnetization (mass-to-flux ratio)

non-ideal MHD effects

dust evolution

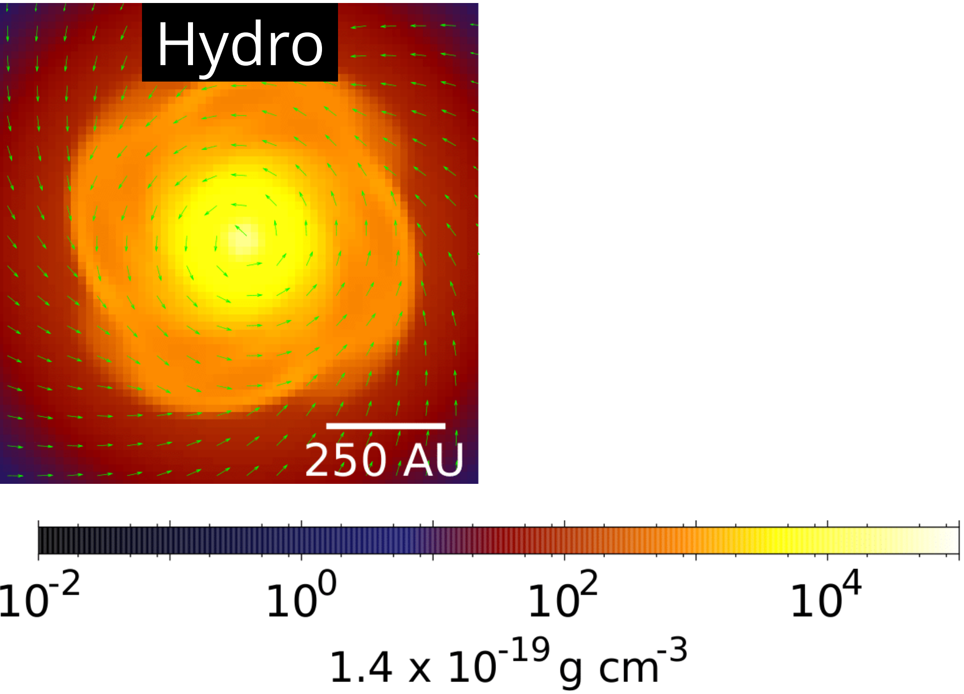
turbulence

# History of modeling disk formation



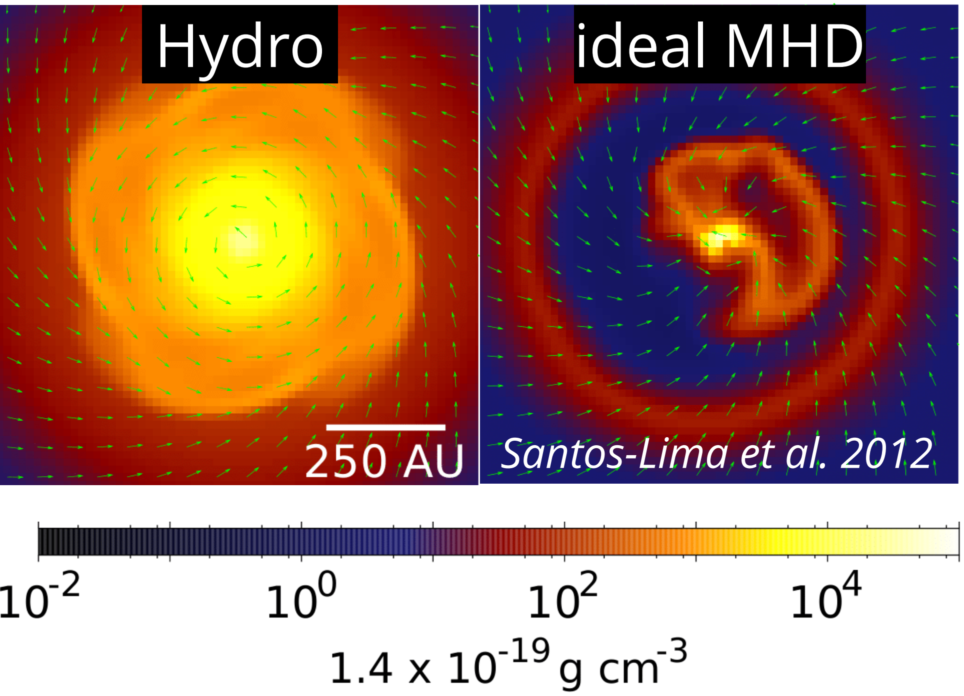
# History of modeling disk formation

What about magnetic fields?



# History of modeling disk formation

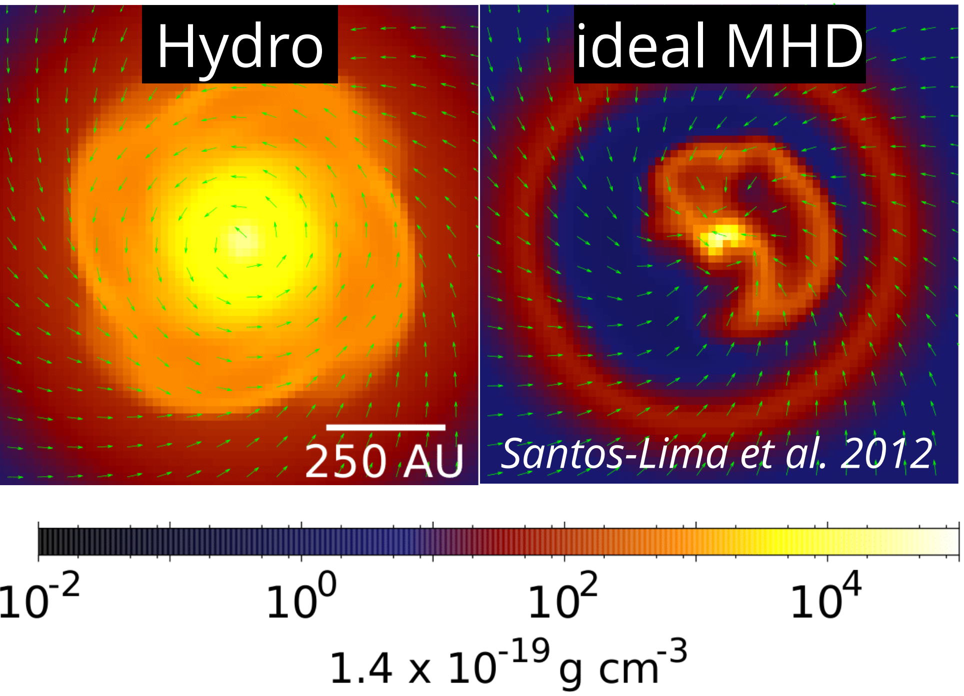
What about magnetic fields?



# History of modeling disk formation

What about magnetic fields?

Help! Where is the disk?!




**Magnetic braking catastrophe**

Angular momentum is transported too efficiently away from the disk

$$L_{\mathrm{mag}} = \int_{t_c}^{t} \int^{V} r(\mathbf{J} \times \mathbf{B})_{\phi} \mathrm{d}V \mathrm{d}t$$

# magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

# Non-ideal magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B})$$

# Non-ideal magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Ohmic dissipation

$$-\nabla \times [\eta_{\mathrm{O}}(\nabla \times \mathbf{B})]$$

# Non-ideal magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Ohmic dissipation

$$-\boldsymbol{\nabla} \times [\eta_{\mathrm{O}} (\boldsymbol{\nabla} \times \mathbf{B})]$$

Hall

$$-\boldsymbol{\nabla} \times \{\eta_{\mathrm{H}} [(\boldsymbol{\nabla} \times \mathbf{B}) \times \mathbf{B}/B]\}$$

# Non-ideal magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Ohmic dissipation

$$-\nabla \times [\eta_{\rm O}(\nabla \times \mathbf{B})]$$

Hall

$$-\nabla \times \{\eta_{\rm H}[(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\}$$

ambipolar diffusion

$$-\nabla \times \{\eta_{\rm AD}\mathbf{B}/B \times [(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\}$$

# Non-ideal magnetohydrodynamics

ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Ohmic dissipation

$$-\nabla \times \left[\eta_{\mathrm{O}} \; \textit{something} \right]$$

Hall

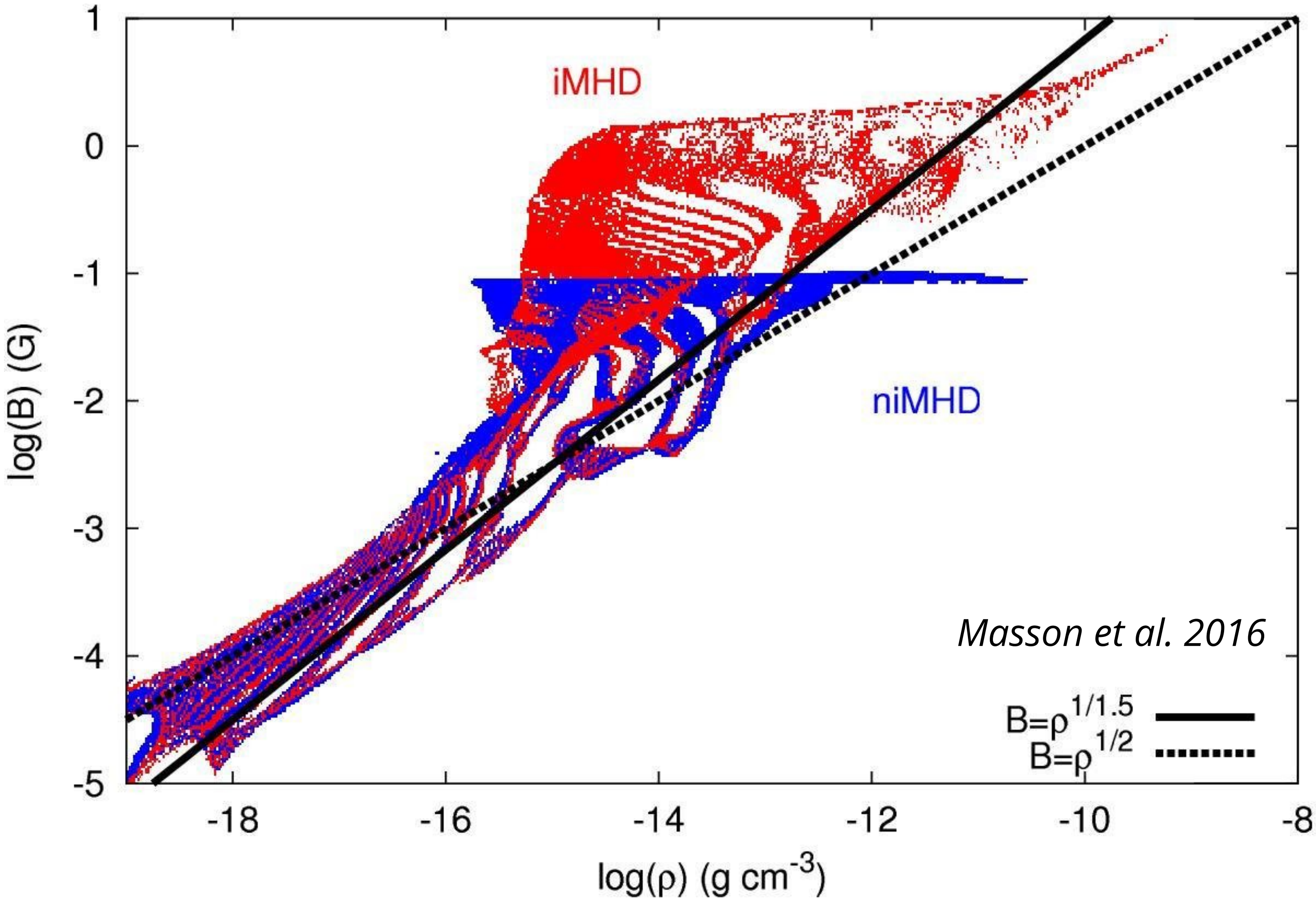
$$-\nabla \times \left\{\eta_{\mathrm{H}} \left[ \textit{something else with } \boldsymbol{B}\textit{s} \right] \right\}$$

ambipolar diffusion

$$-\nabla \times \left\{\eta_{\mathrm{AD}} \; \textit{something else with more } \boldsymbol{B}\textit{s} \right\}$$

# Non-ideal MHD

resistivities quench pile-up of magnetic field




*see Hennebelle et al. 2016 or Lee et al. 2021 for analytical studies*

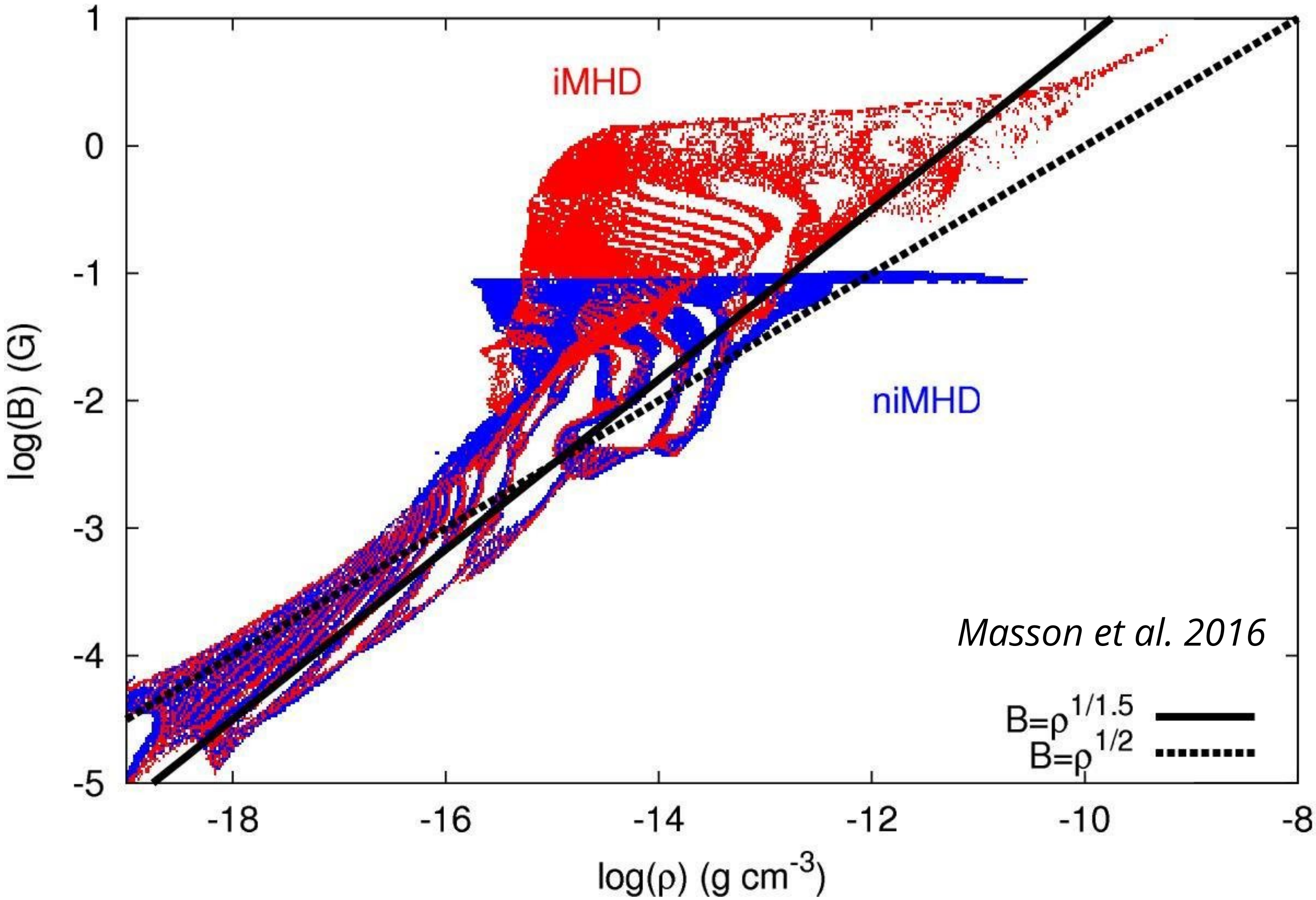
*for more references see Wurster & Li 2018 (review)*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$-\nabla \times [\eta_{\mathrm{O}}(\nabla \times \mathbf{B})] \; -\nabla \times \{\eta_{\mathrm{H}}[(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\} -\nabla \times \{\eta_{\mathrm{AD}}\mathbf{B}/B \times [(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\}$$

# Non-ideal MHD

resistivities quench pile-up of magnetic field




*see Hennebelle et al. 2016 or Lee et al. 2021 for analytical studies*

*for more references see Wurster & Li 2018 (review)*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

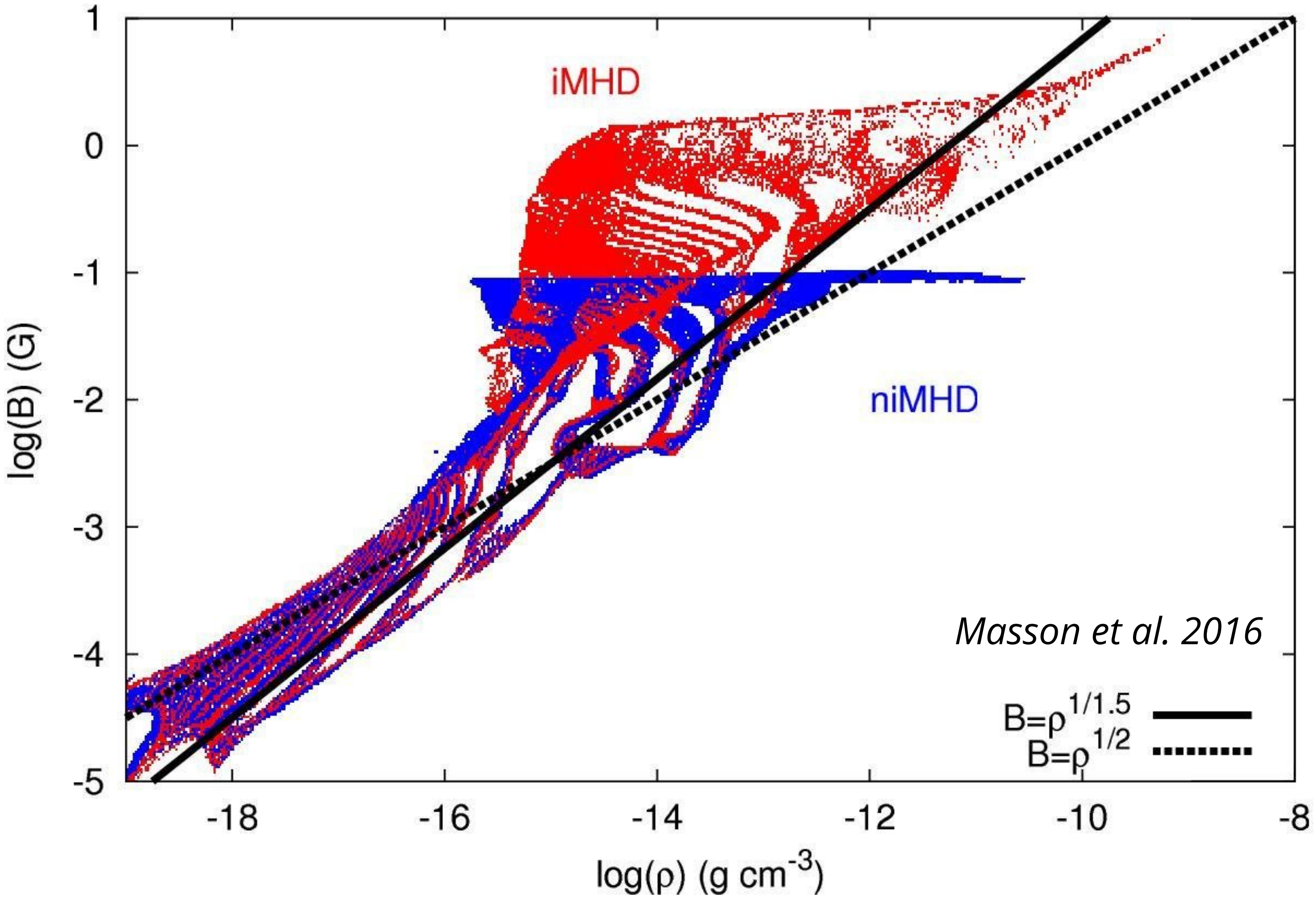
$-\nabla \times [\eta_{\rm O}$ *something* $]$ $-\nabla \times \{\eta_{\rm H} [$ *something else with* ***B****s* $\}$ $-\nabla \times \{\eta_{\rm AD}$ *something else with more* ***B****s* $\}$

# Non-ideal MHD

resistivities quench pile-up of magnetic field

↓

avoids magnetic braking catastrophe




*see Hennebelle et al. 2016 or Lee et al. 2021 for analytical studies*

*for more references see Wurster & Li 2018 (review)*

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

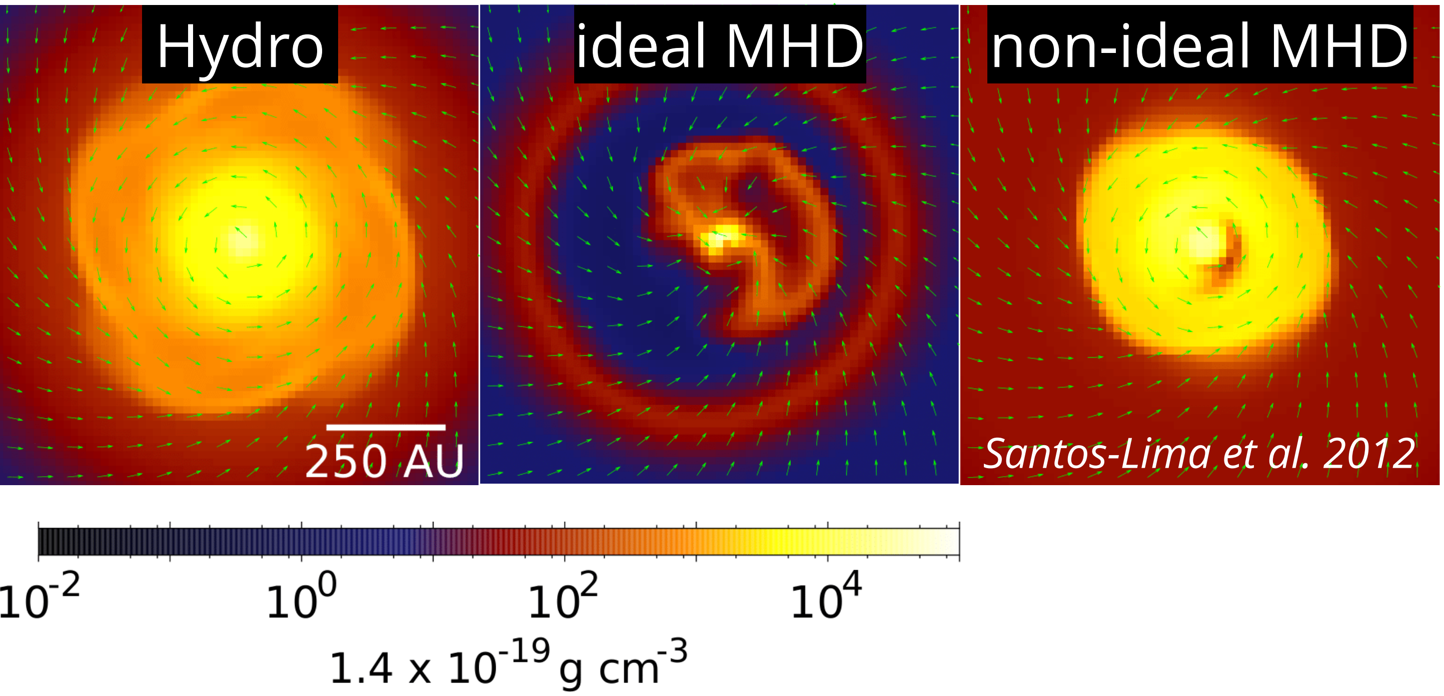
$$-\nabla \times [\eta_{\mathrm{O}} \text{ something } ] - \nabla \times \{\eta_{\mathrm{H}} [ \text{ something else with } \mathbf{B}\text{s} \} - \nabla \times \{\eta_{\mathrm{AD}} \text{ something else with more } \mathbf{B}\text{s} \}$$

# History of modeling disk formation

What about magnetic fields?

Help! Where is the disk?!

Ohmic, Ambipolar, Hall



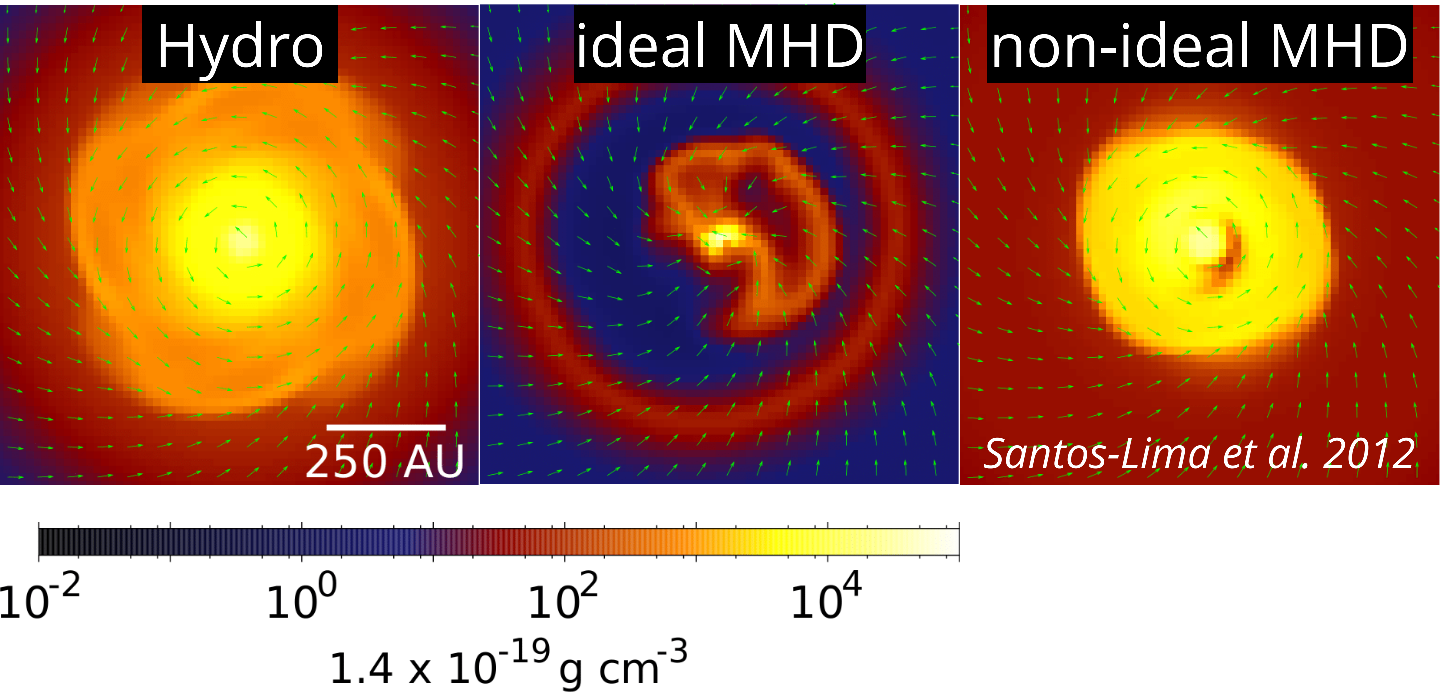
# History of modeling disk formation

What about magnetic fields?

Help! Where is the disk?!

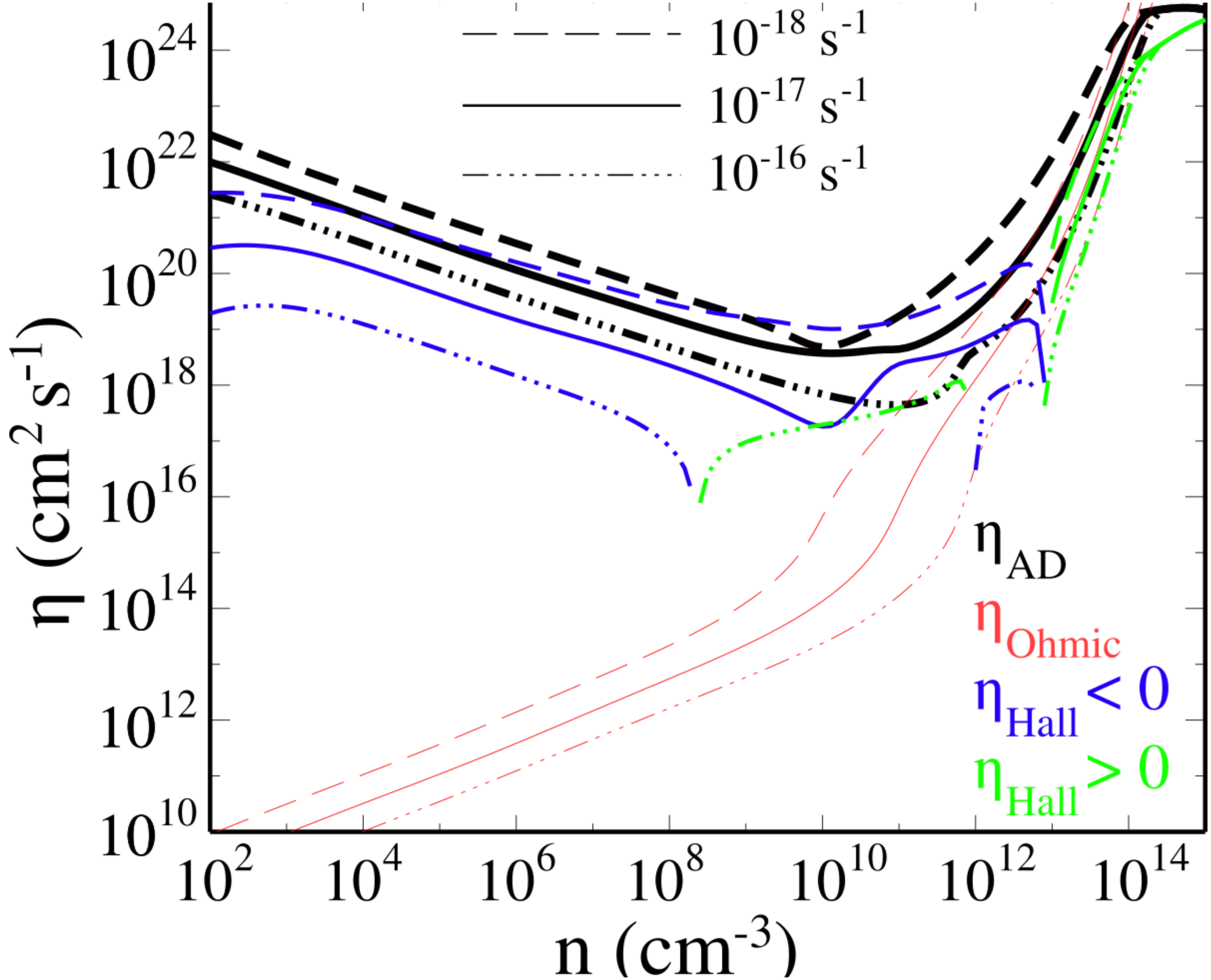
Ohmic, Ambipolar, Hall

**Achtung!**




non-ideal MHD is not a single parameter that is turned on or off

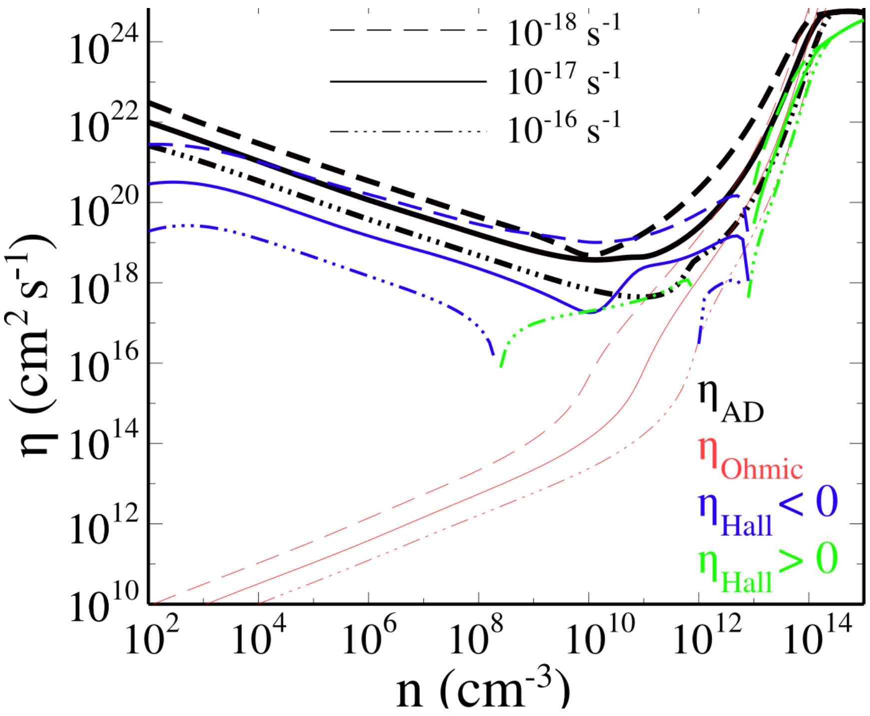
# Resistivity depends on ionization rate



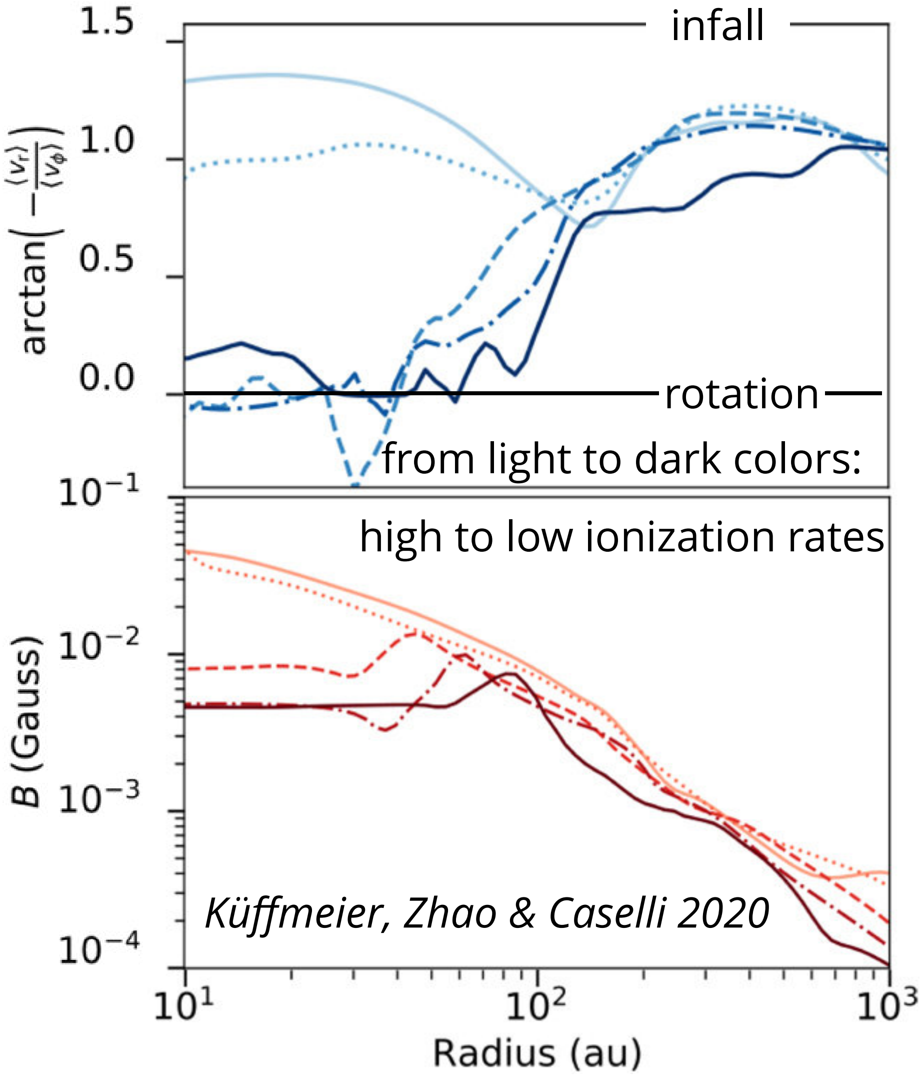

**Question:** What is the effect on disk formation when differing the ionization rate?

*Küffmeier, Zhao & Caselli 2020*

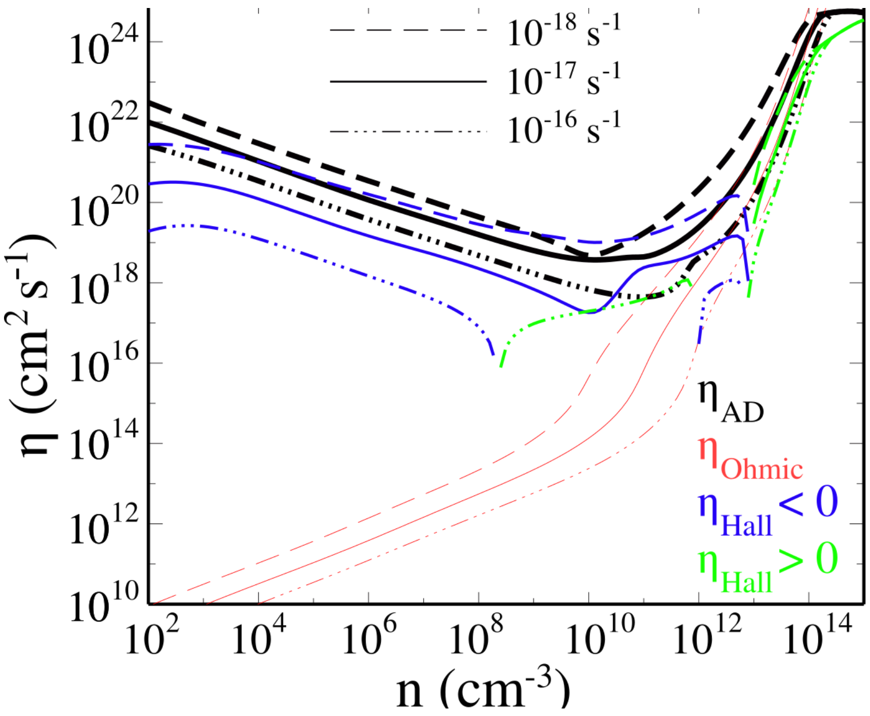
# Effect of ionization on disk size



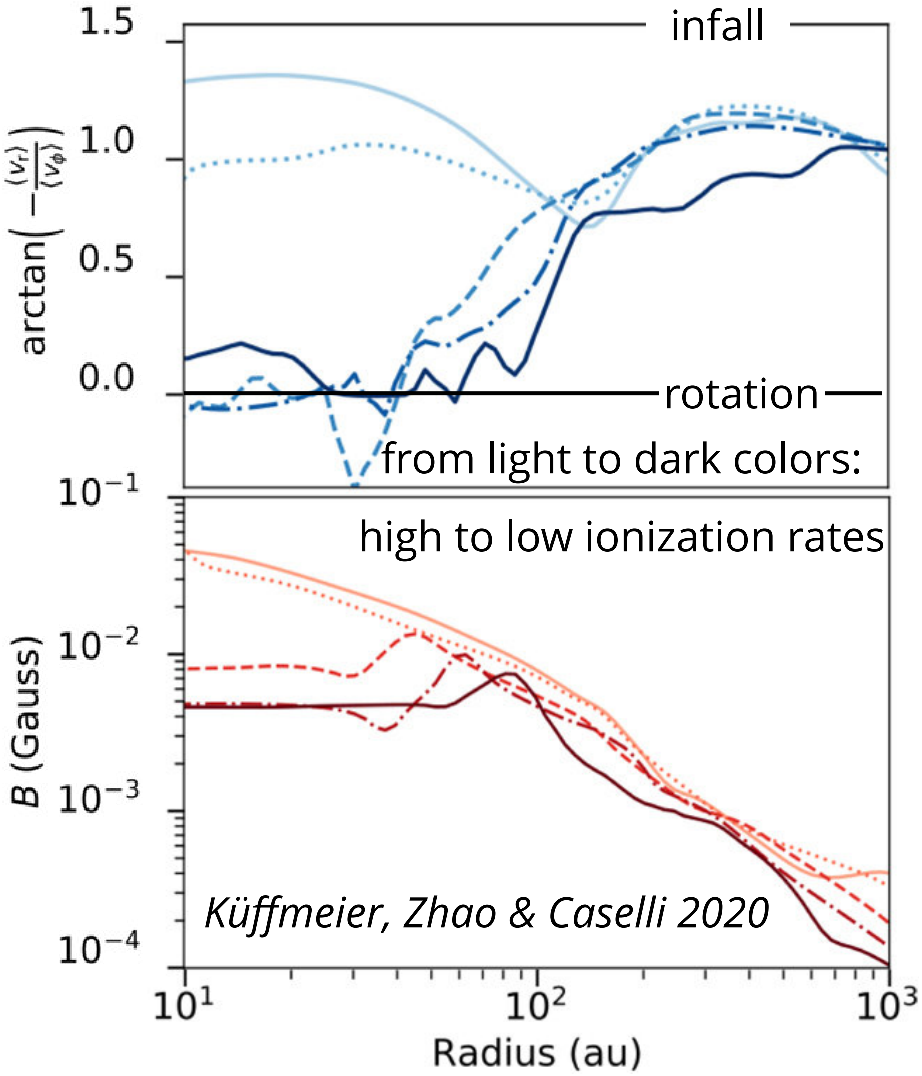

*see also Wurster et al. 2018*



# Effect of ionization on disk size

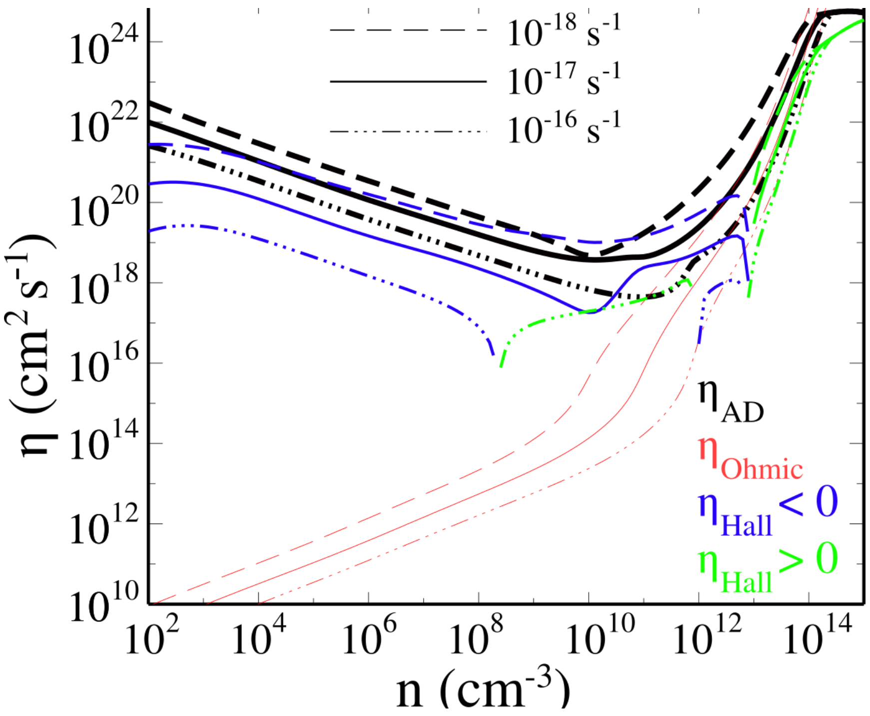



*see also Wurster et al. 2018*

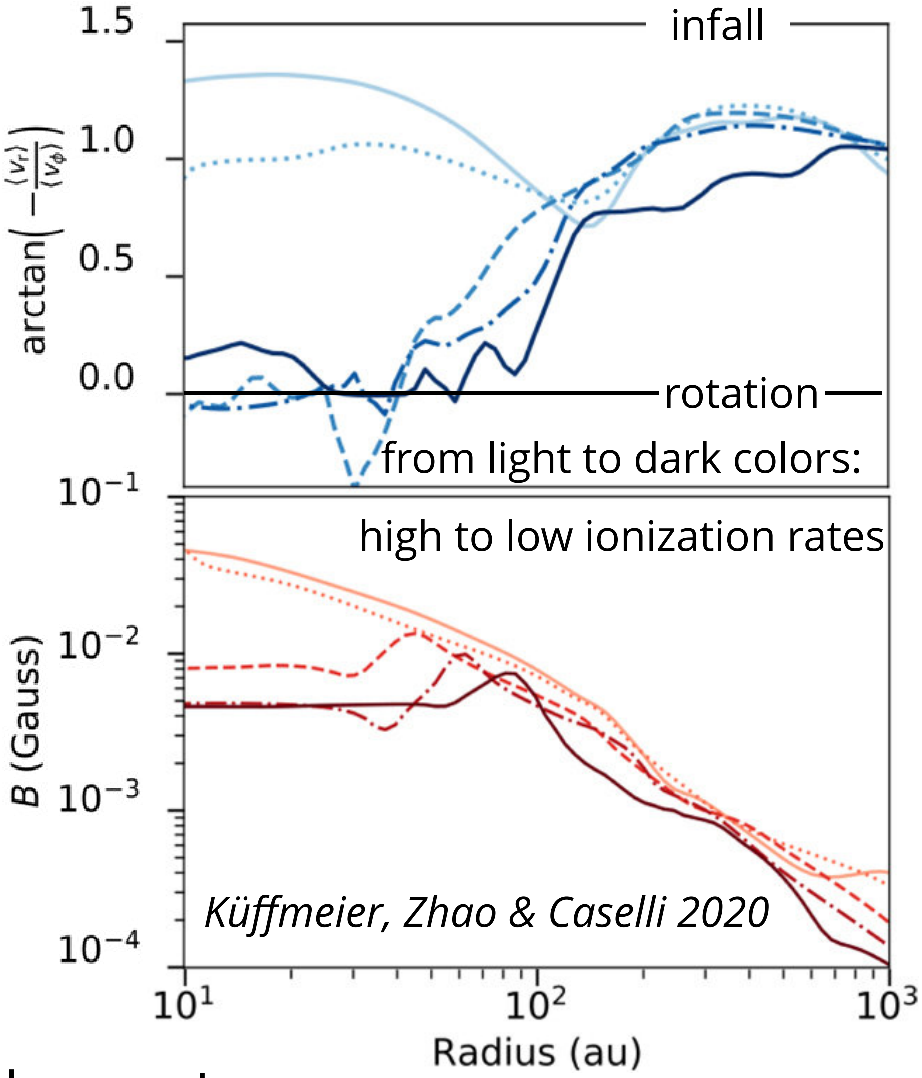



increasing
ionization rate

# Effect of ionization on disk size

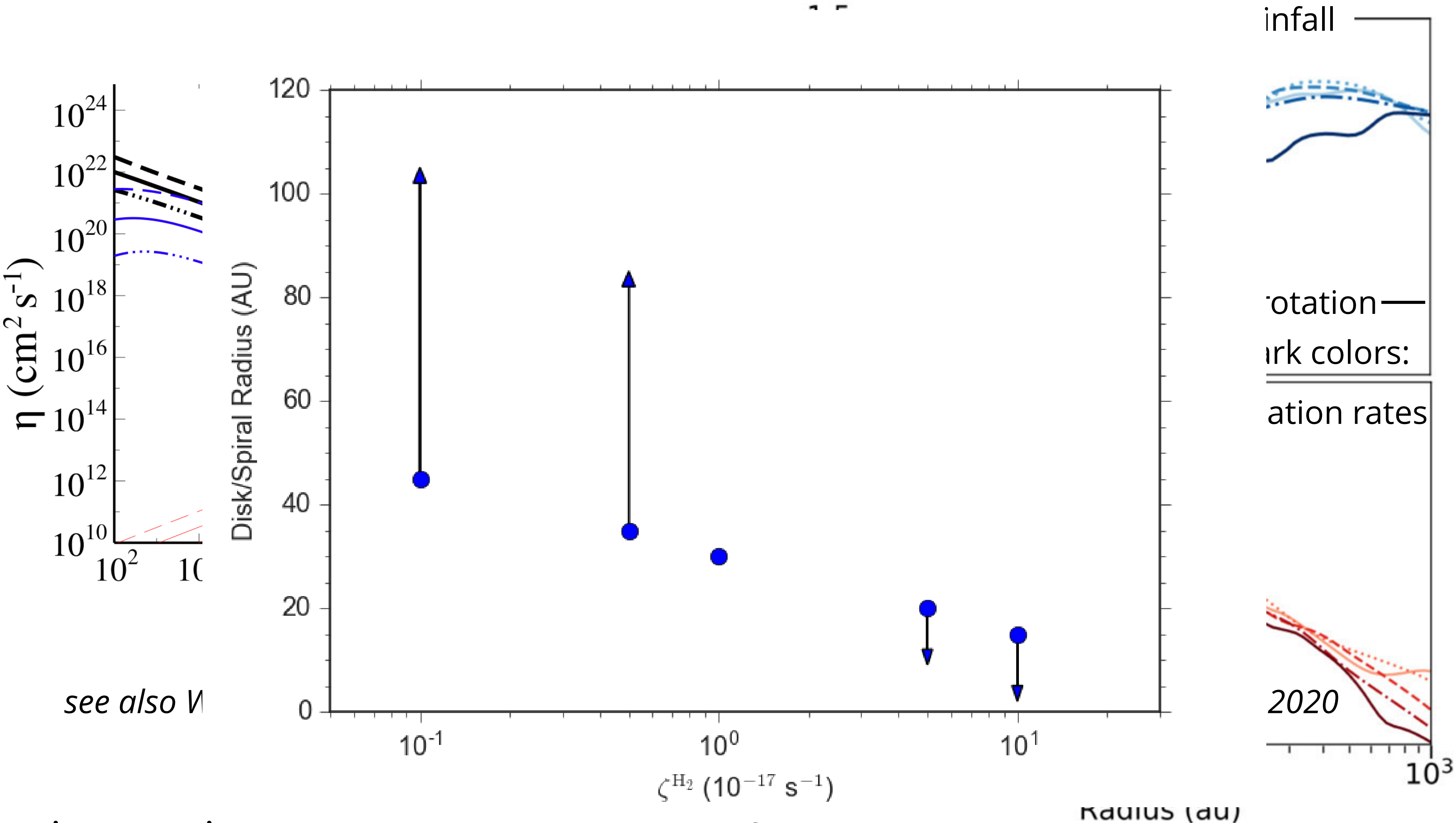



*see also Wurster et al. 2018*



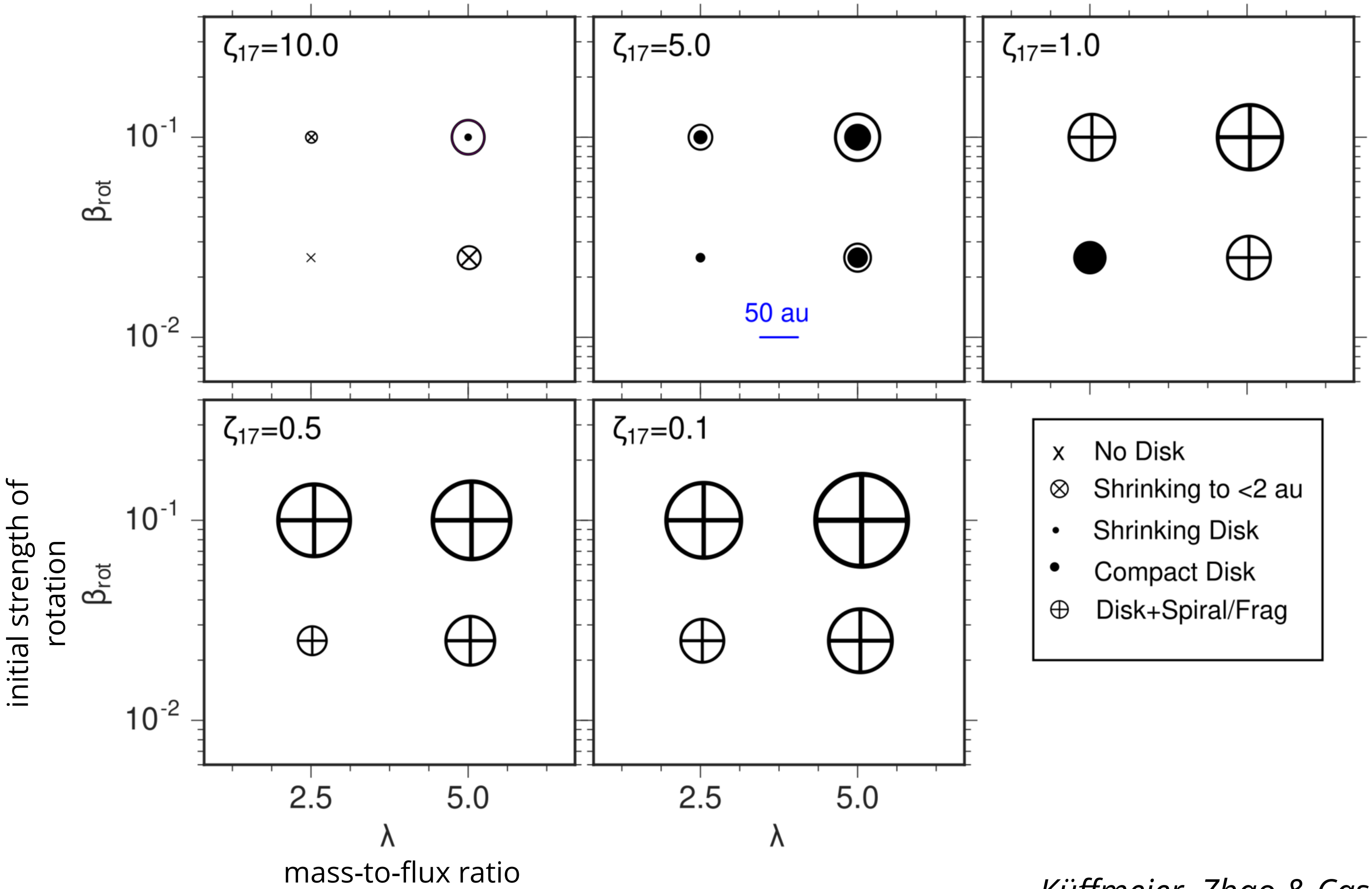

increasing ionization rate → enhanced magnetic braking

# Effect of ionization on disk size



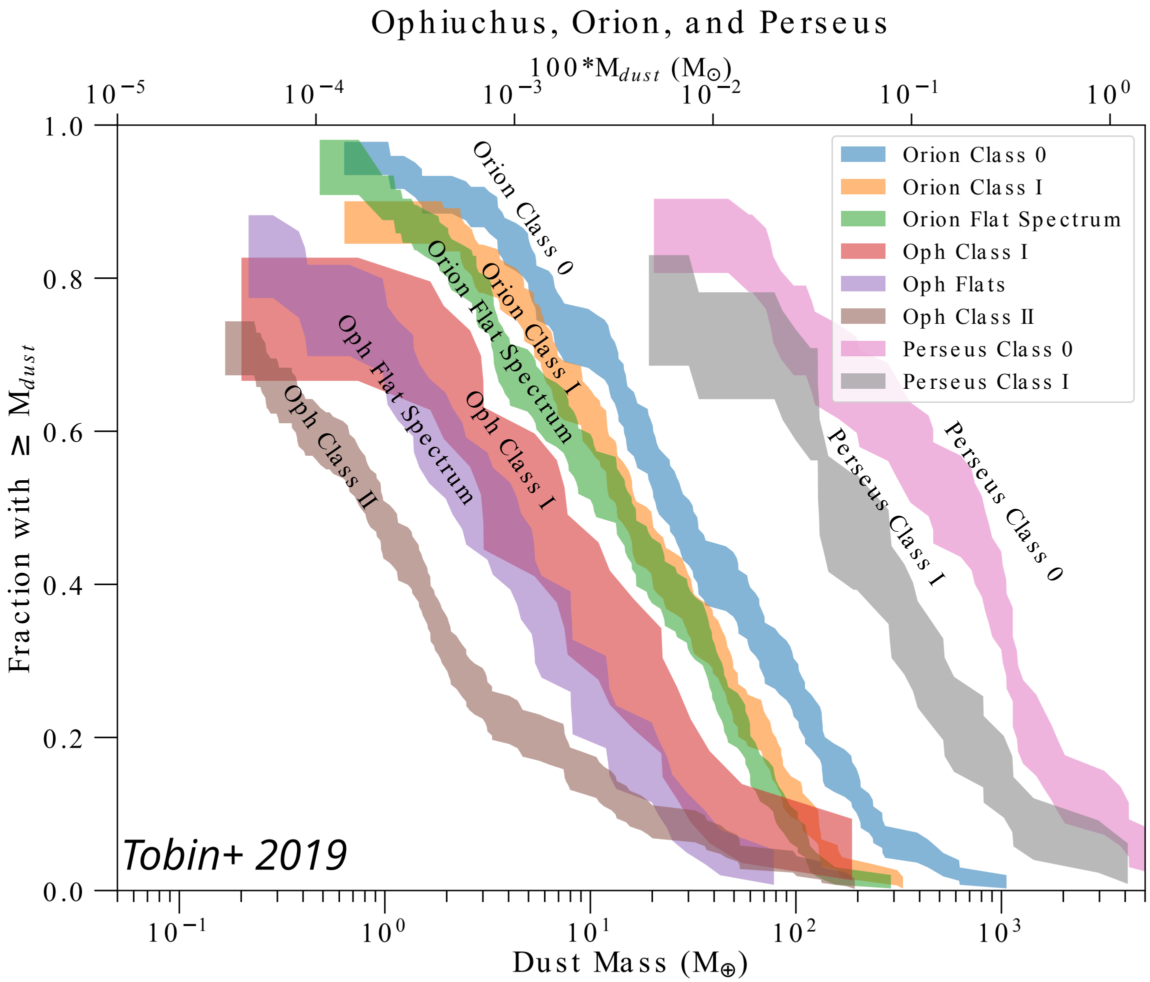

increasing ionization rate → enhanced magnetic braking → smaller disks

# Disk size distribution

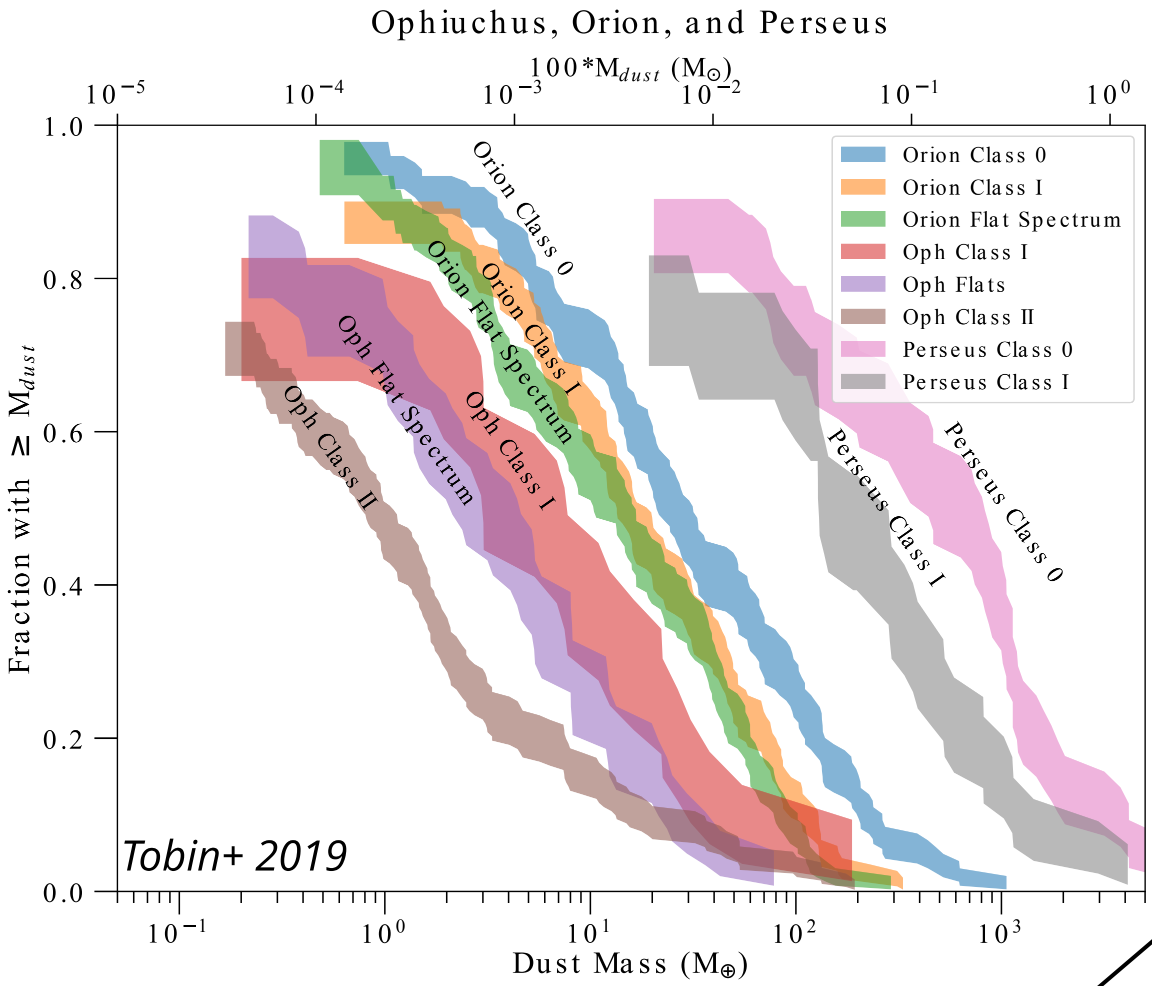



*Küffmeier, Zhao & Caselli 2020*

# Disk size distribution



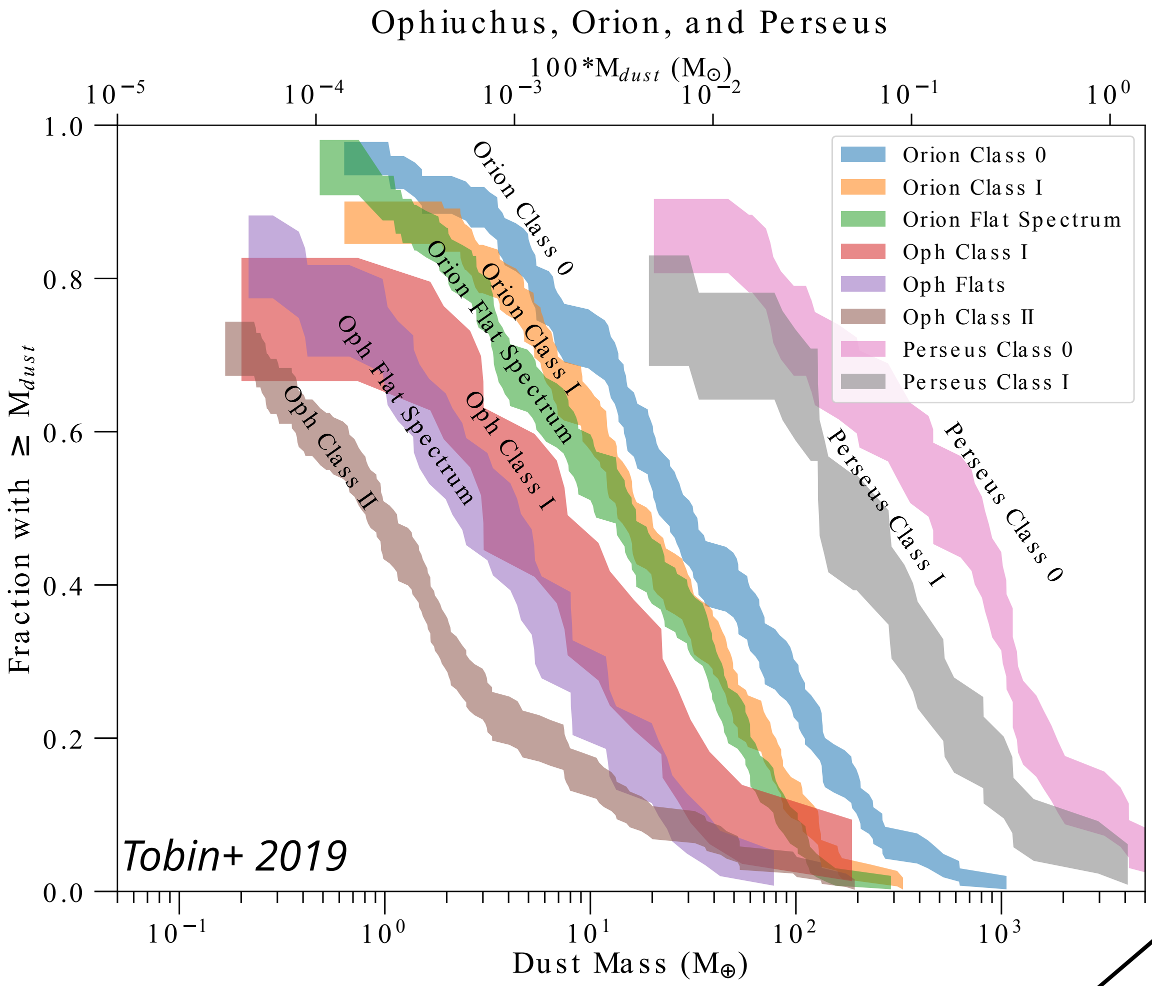
# Disk size distribution




*see A. Maury's talk*

**Are disks already born small** in some (all?) regions?

# Disk size distribution

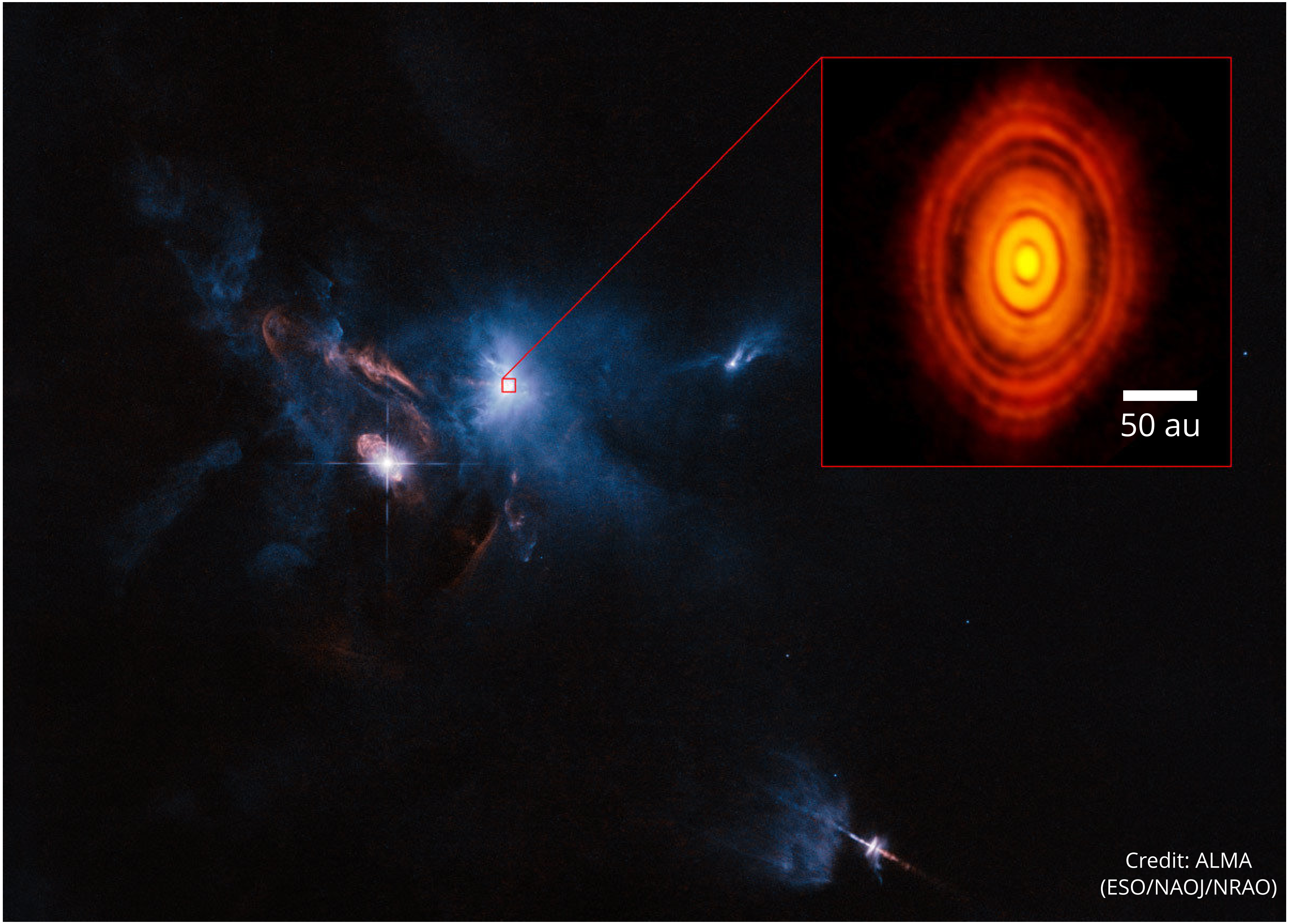


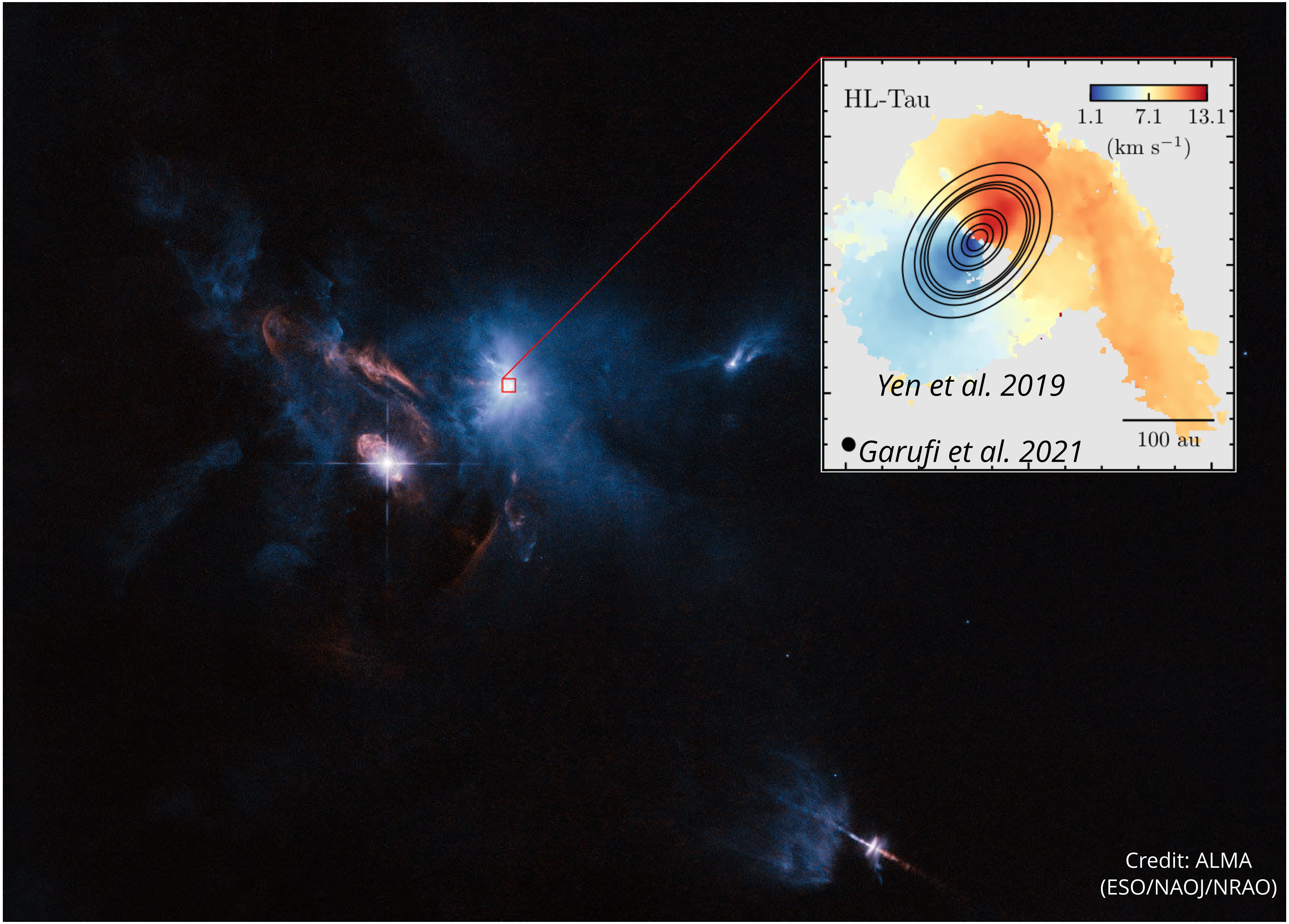

*see A. Maury's talk*

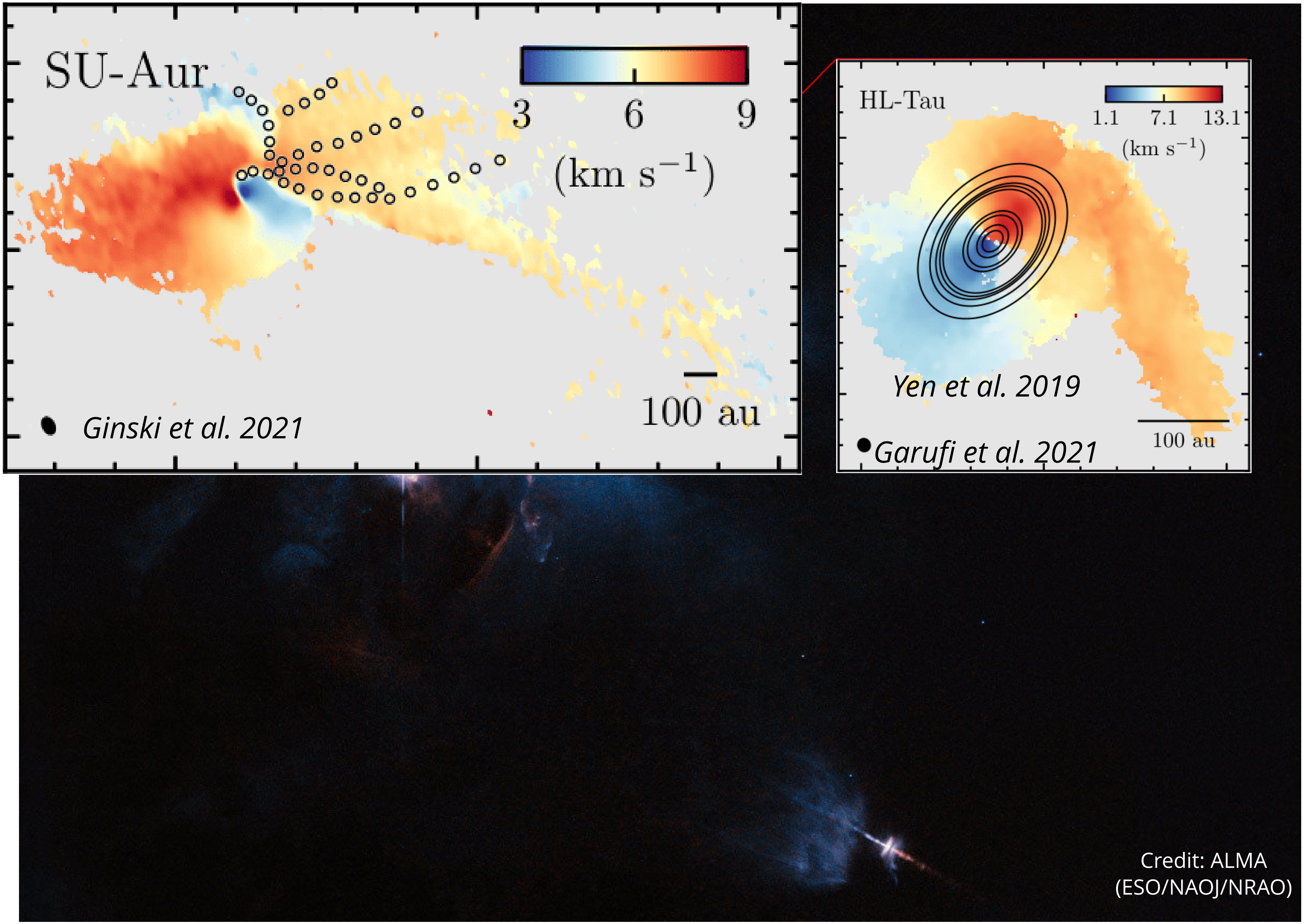
**Are disks already born small** in some (all?) regions?

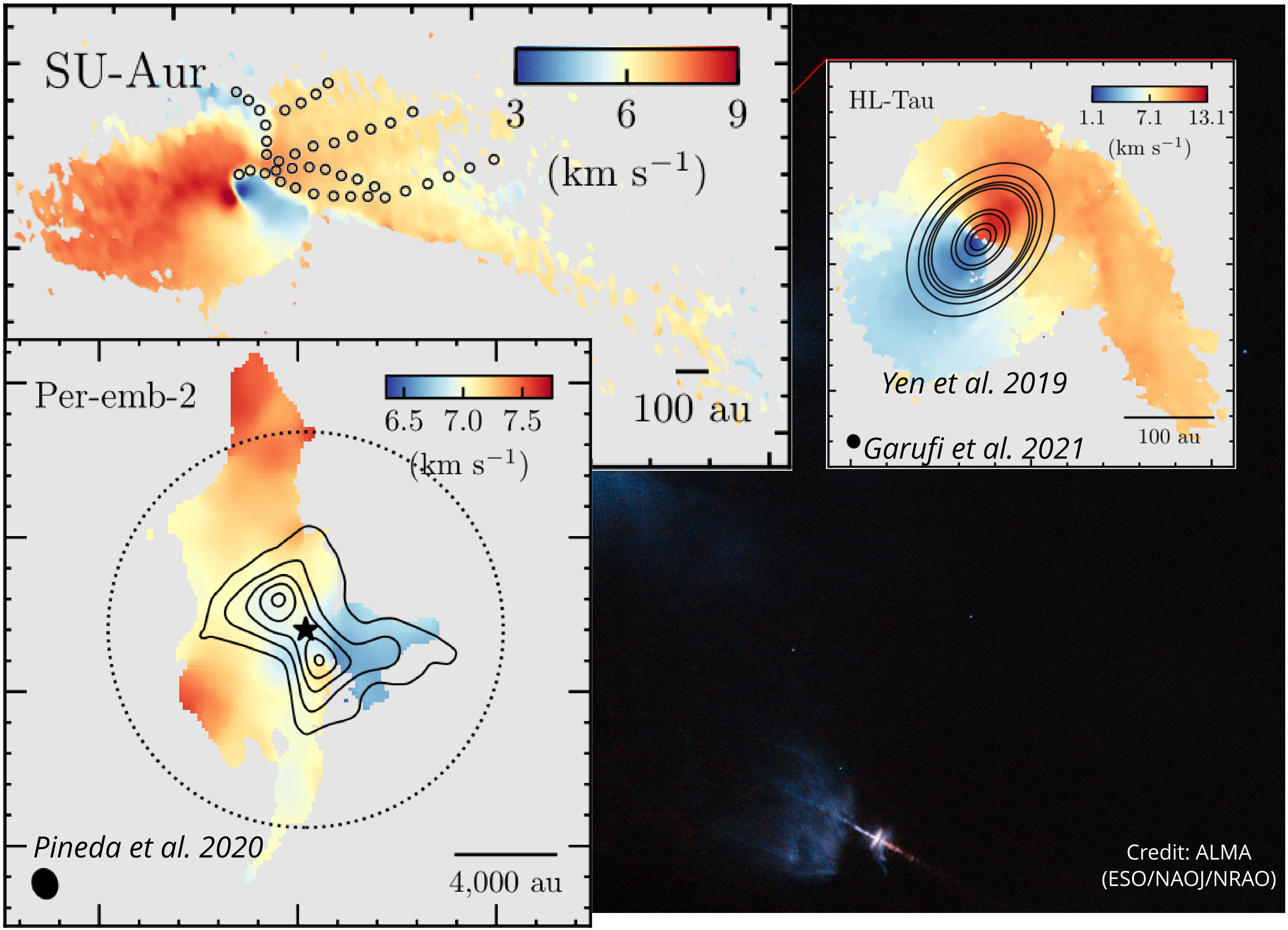
**Does cosmic-ray ionization play a crucial role?**

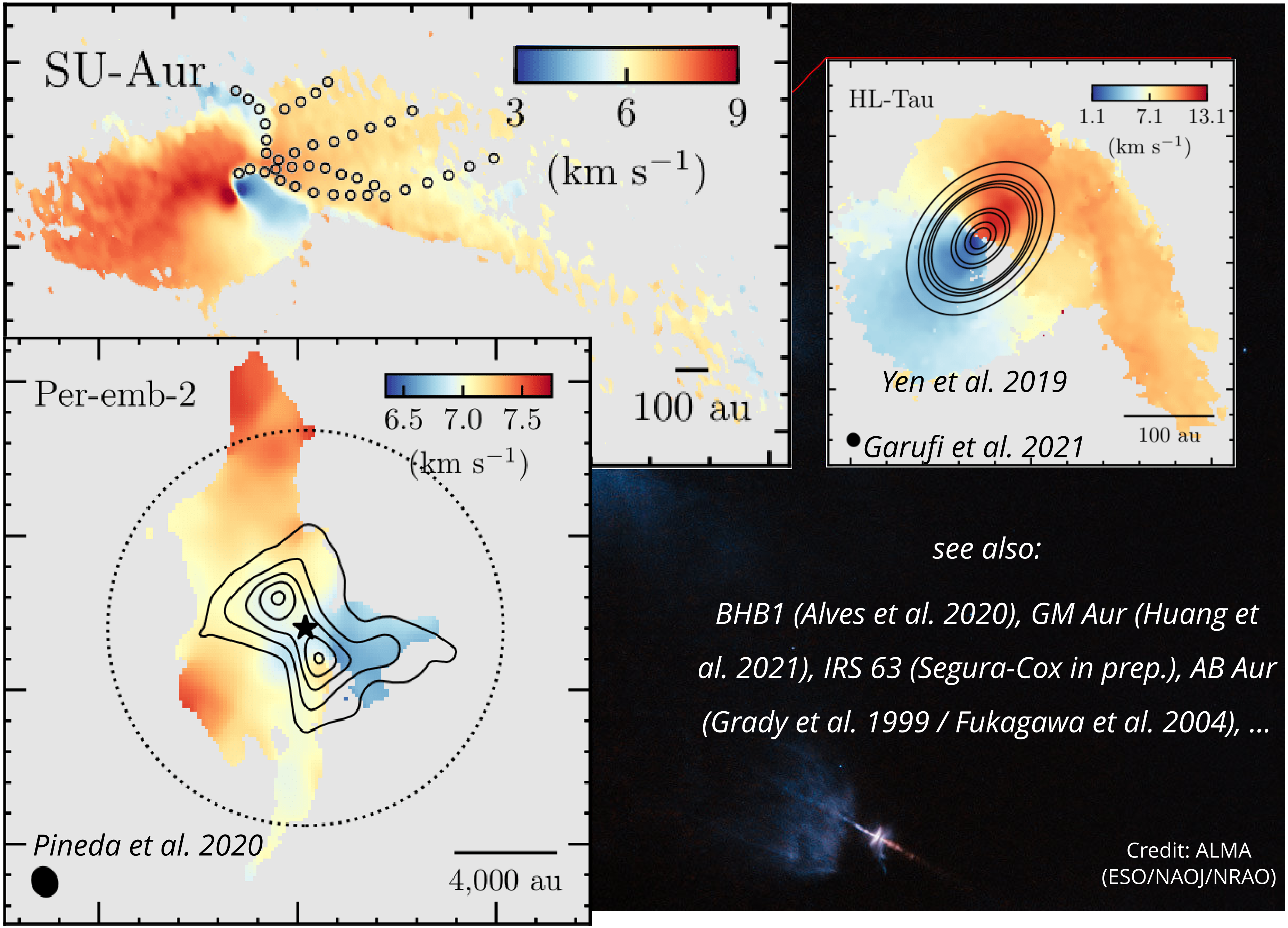
# Is this the full picture?


50 au
Credit: ALMA
(ESO/NAOJ/NRAO)

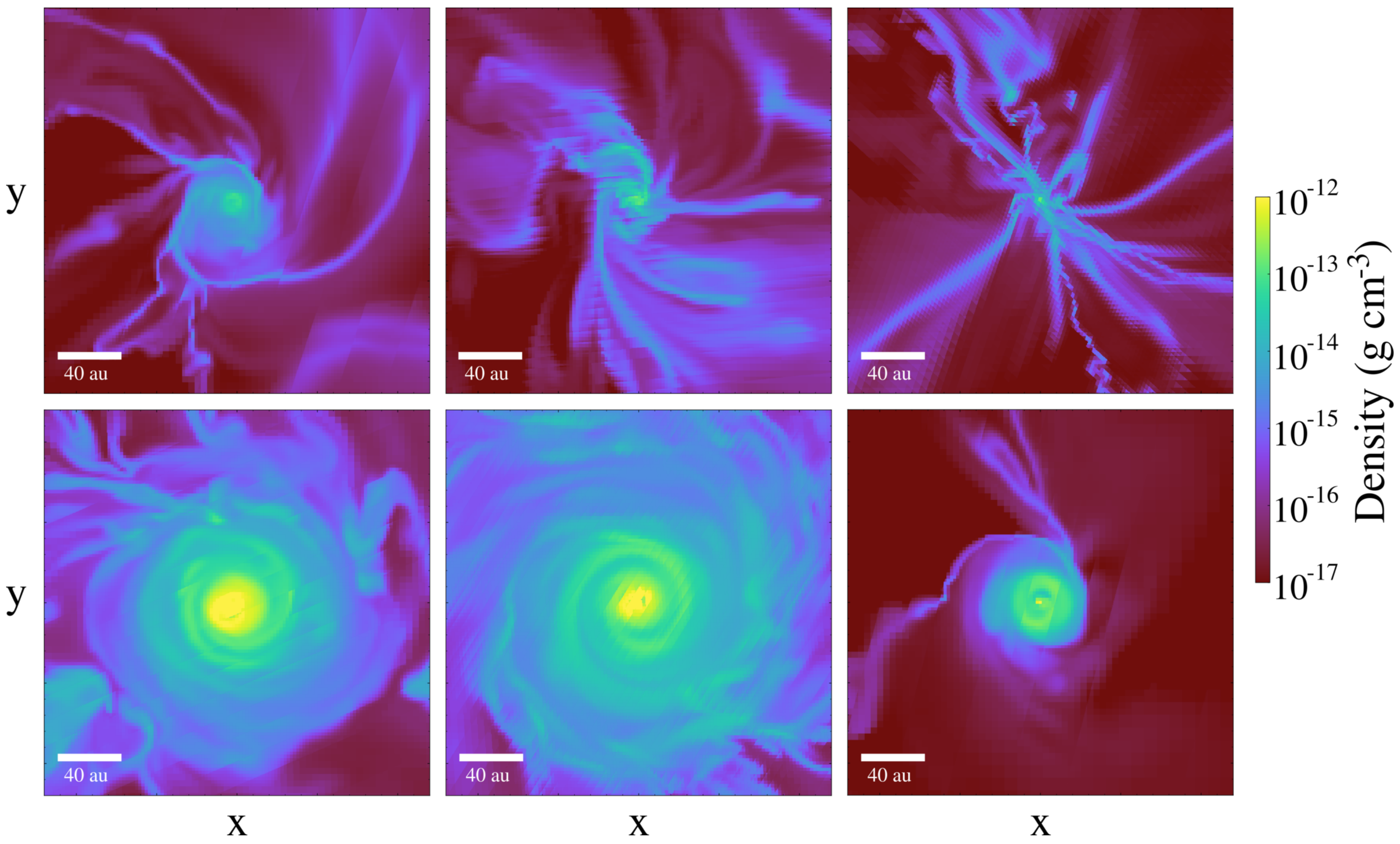

HL-Tau
1.1
7.1
13.1
(km s$^{-1}$)
Yen et al. 2019
Garufi et al. 2021
100 au
Credit: ALMA
(ESO/NAOJ/NRAO)


SU-Aur
3
6
9
(km s$^{-1}$)
100 au
Ginski et al. 2021
HL-Tau
1.1
7.1
13.1
(km s$^{-1}$)
Yen et al. 2019
100 au
Garufi et al. 2021
Credit: ALMA
(ESO/NAOJ/NRAO)


SU-Aur
3 6 9
(km s$^{-1}$)
100 au
HL-Tau
1.1 7.1 13.1
(km s$^{-1}$)
Yen et al. 2019
100 au
Garufi et al. 2021
Per-emb-2
6.5 7.0 7.5
(km s$^{-1}$)
Pineda et al. 2020
4,000 au
Credit: ALMA
(ESO/NAOJ/NRAO)


SU-Aur
3
6
9
(km s⁻¹)
100 au
Per-emb-2
6.5
7.0
7.5
(km s⁻¹)
Pineda et al. 2020
4,000 au
HL-Tau
1.1
7.1
13.1
(km s⁻¹)
Yen et al. 2019
100 au
Garufi et al. 2021
see also:
BHB1 (Alves et al. 2020), GM Aur (Huang et al. 2021), IRS 63 (Segura-Cox in prep.), AB Aur (Grady et al. 1999 / Fukagawa et al. 2004), ...
Credit: ALMA (ESO/NAOJ/NRAO)

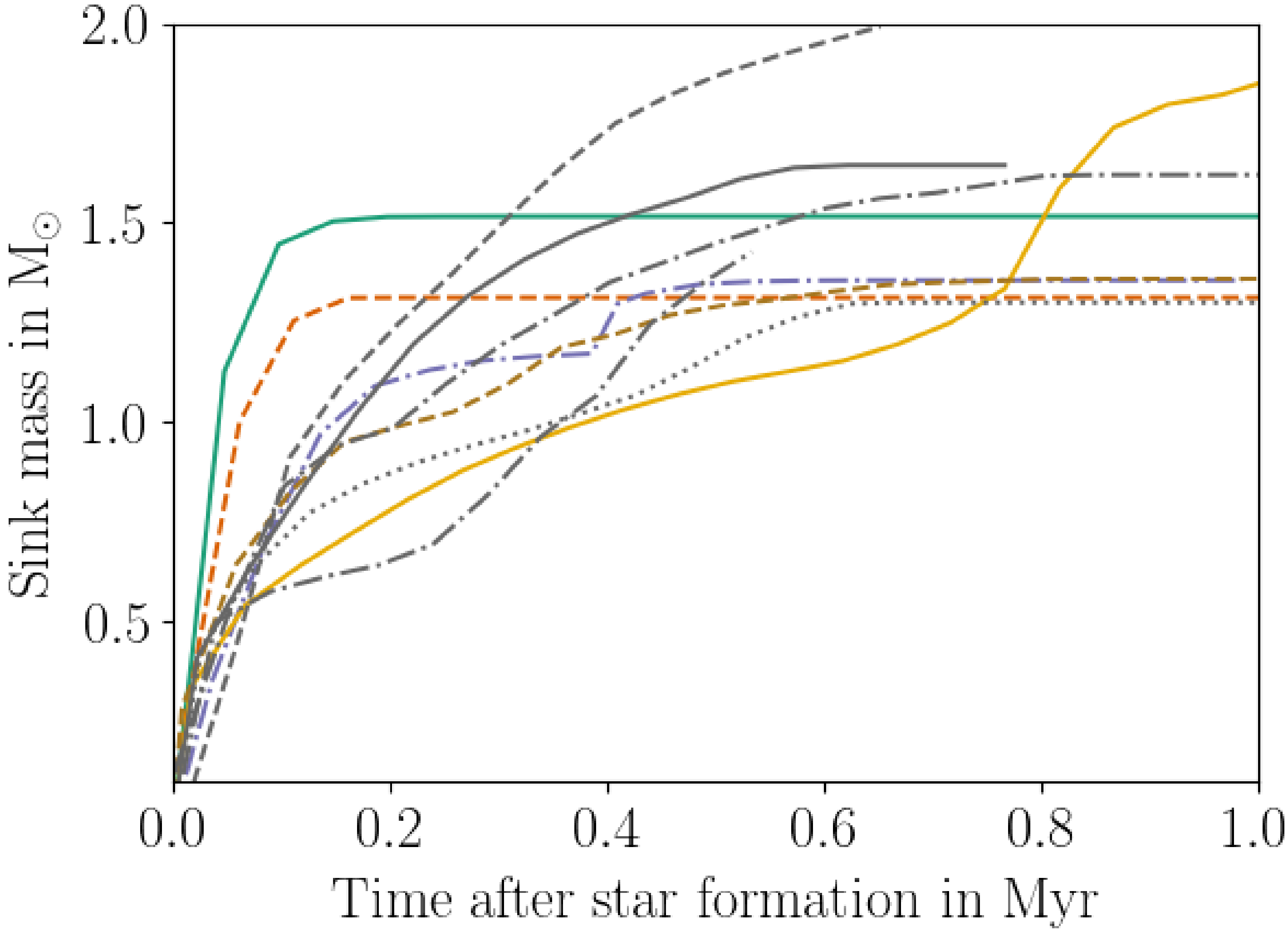
# The connection to the larger scales




*Küffmeier, Haugbølle & Nordlund 2017*

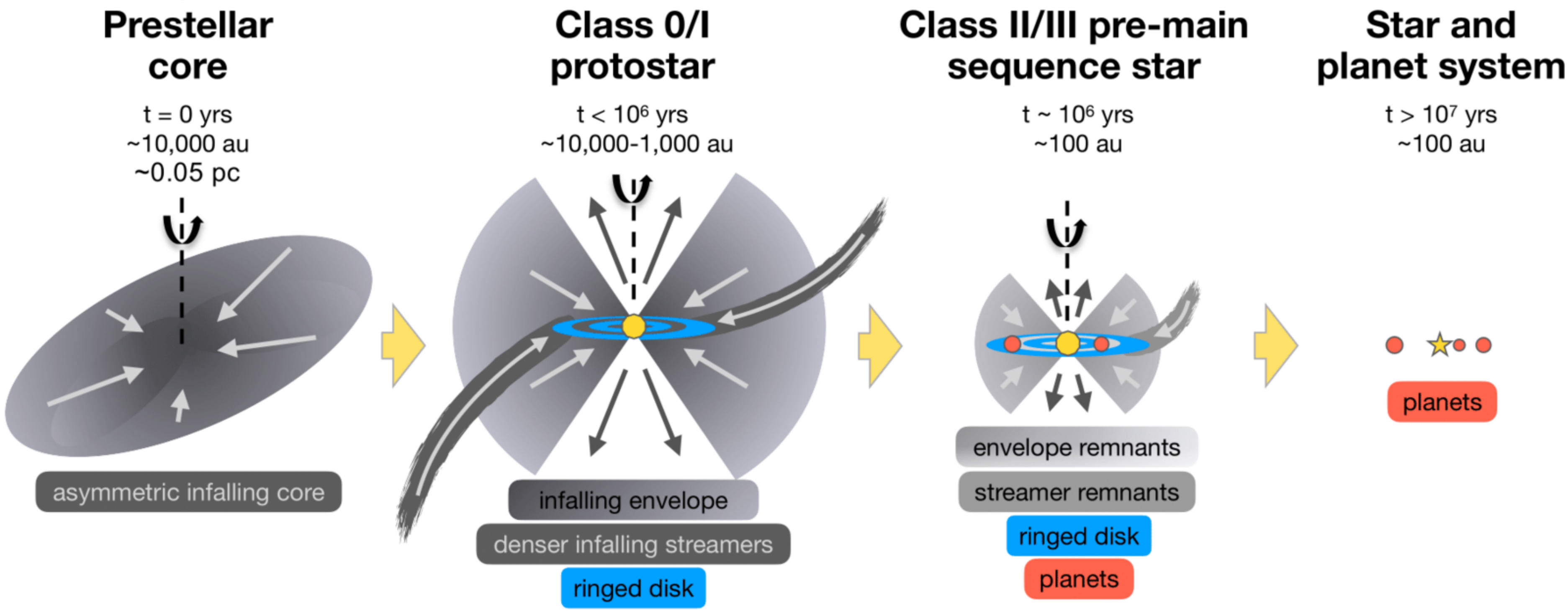
# Accretion is heterogeneous

Observational indication: **luminosity bursts**




*Küffmeier, Haugbølle & Nordlund 2017*

# Revised picture



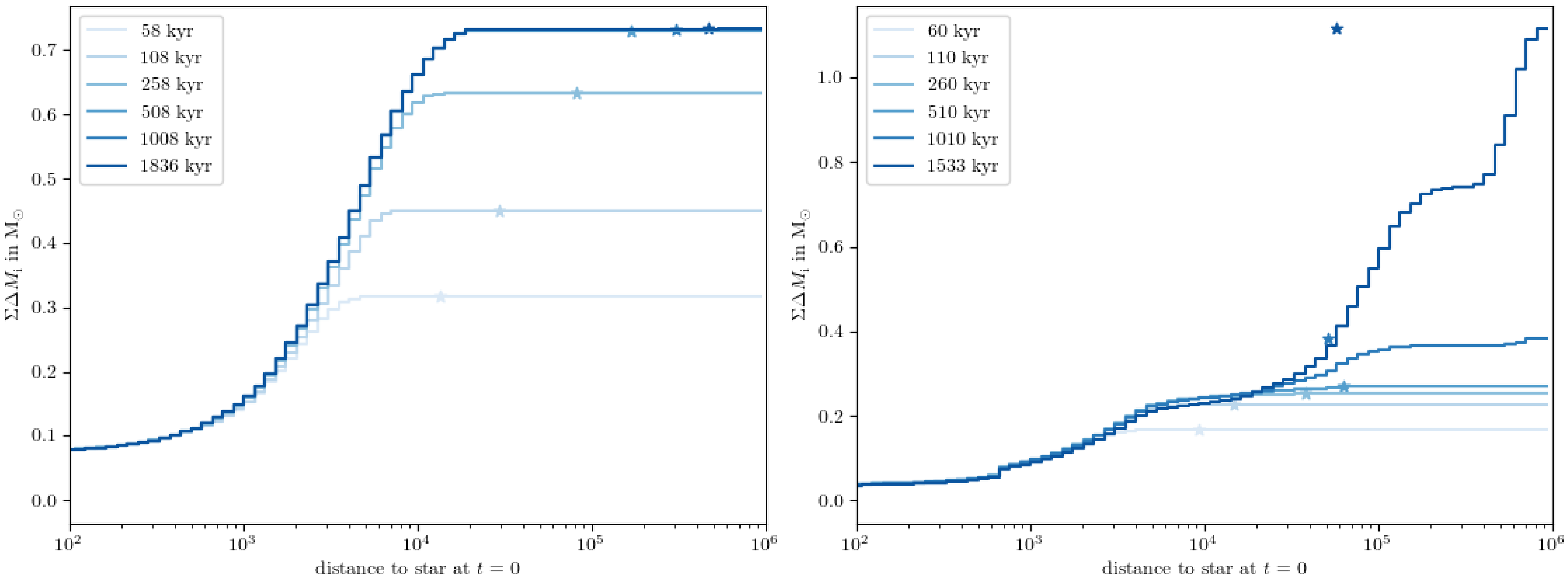

*Segura-Cox et al. in prep.*

*Pineda ... Küffmeier et al. 'Protostars and Planets VII'*

Star and planet formation are two sides of the same medal

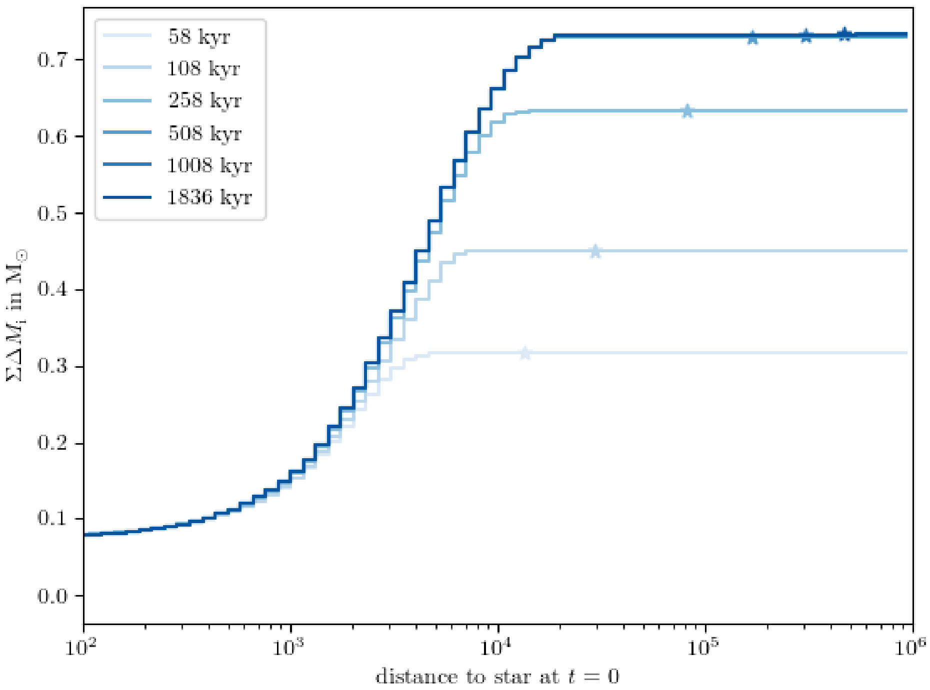
The disk is not a static entity, but rather a buffer zone

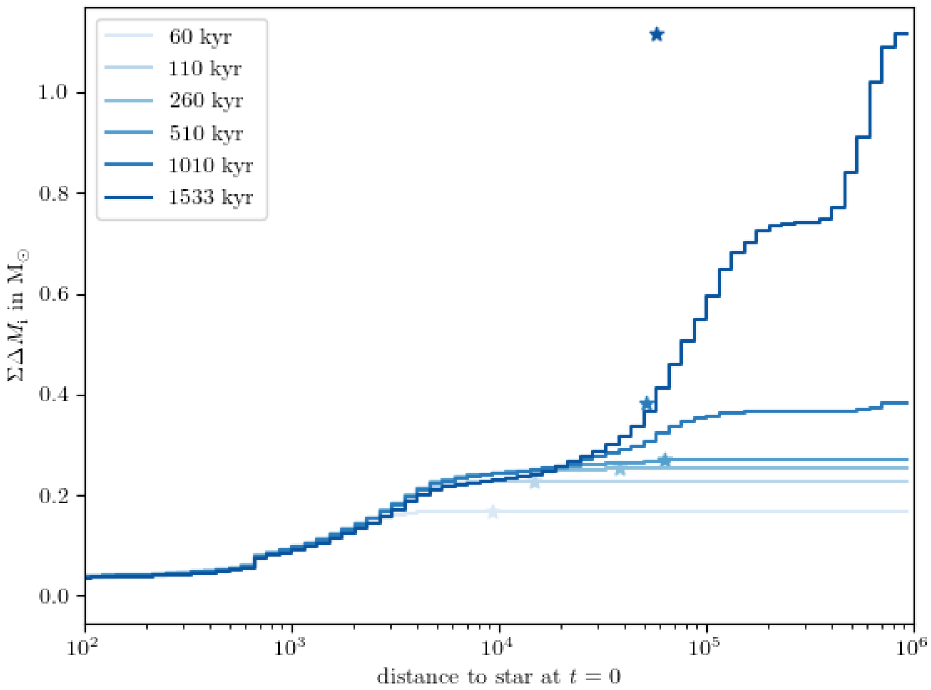
# Late infall happens more often than assumed




*Küffmeier et al. 2022 in prep*

# Late infall happens more often than assumed

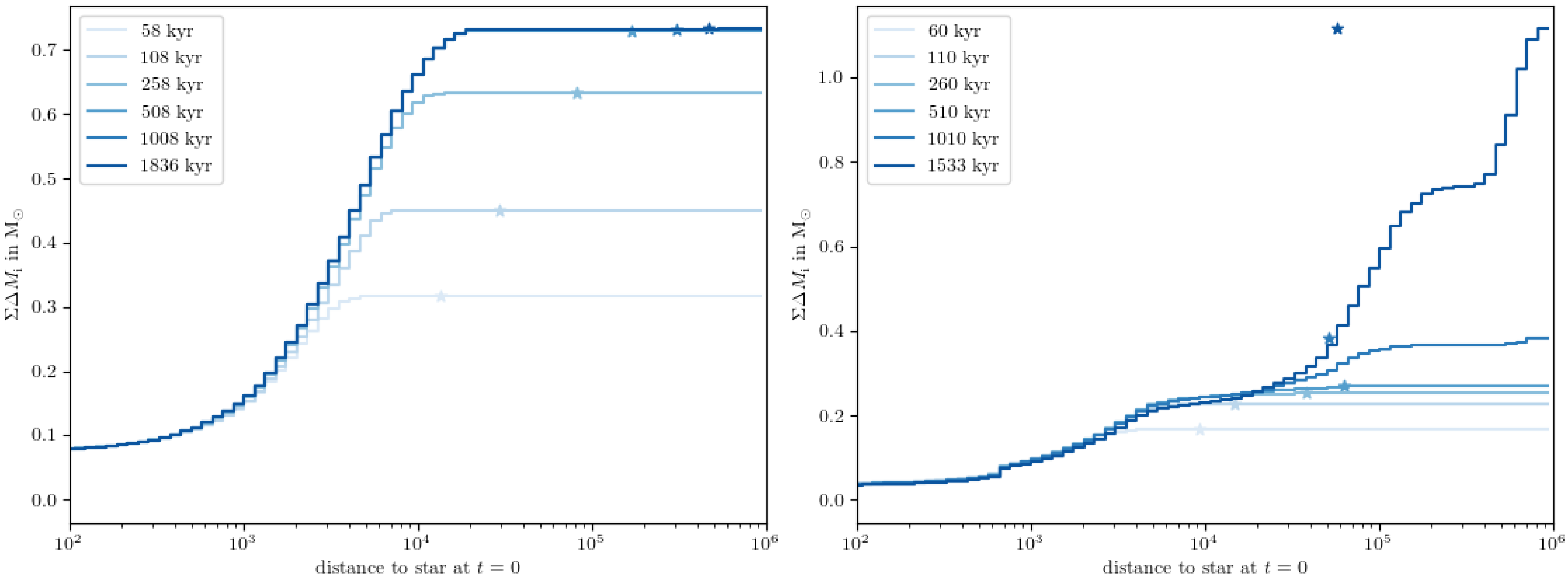



*Küffmeier et al. 2022 in prep*

For solar mass stars ~50 % of final mass from beyond prestellar core! *(Pelkonen et al. 2021)*

# Late infall happens more often than assumed

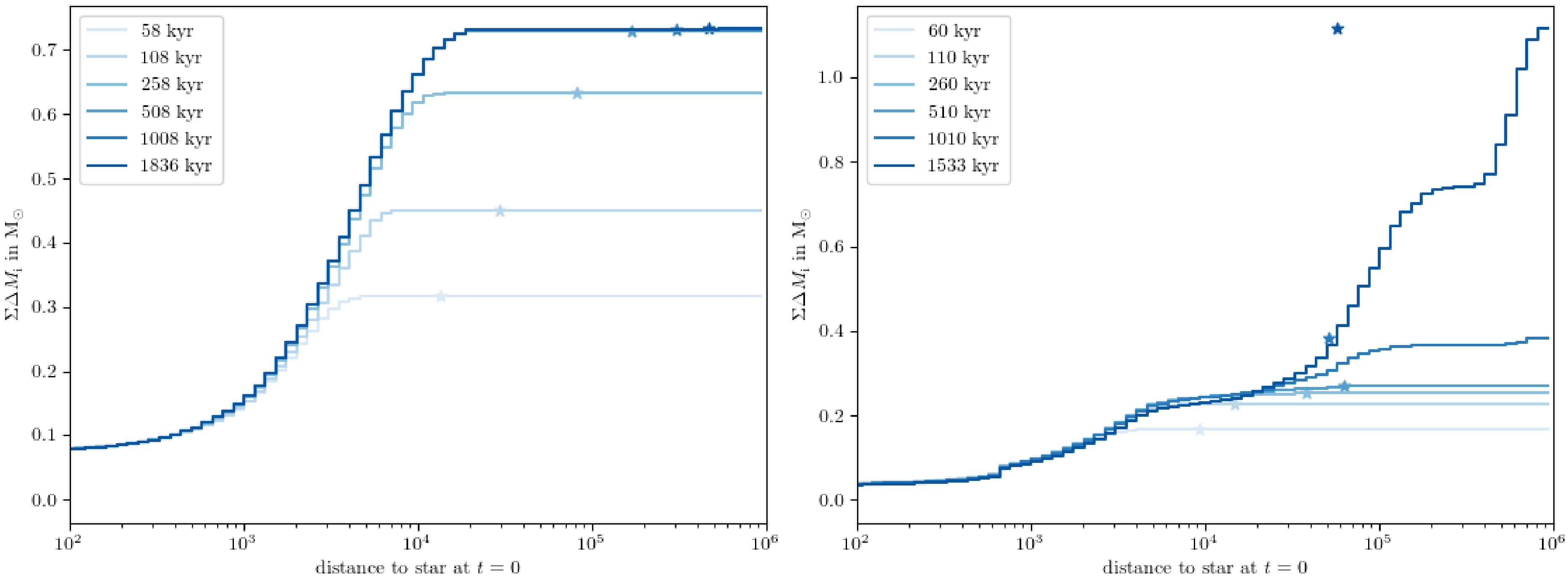



*Küffmeier et al. 2022 in prep*

For solar mass stars ~50 % of final mass from beyond prestellar core! *(Pelkonen et al. 2021)*

Possibility of replenishing and refreshing the mass and *chemical* budget

# Late infall happens more often than assumed




*Küffmeier et al. 2022 in prep*

For solar mass stars ~50 % of final mass from beyond prestellar core! *(Pelkonen et al. 2021)*

Possibility of replenishing and refreshing the mass and *chemical* budget

**Can disks be rejuvenated?**

# Does cosmic-ray ionization play a crucial role in disk formation?

# Does cosmic-ray ionization play a crucial role in disk formation?

# Does cosmic-ray ionization play a crucial role in disk formation?

*It's fun to work on cosmic rays,*

*instead of catching Covid waves.*

# The big uncertainty

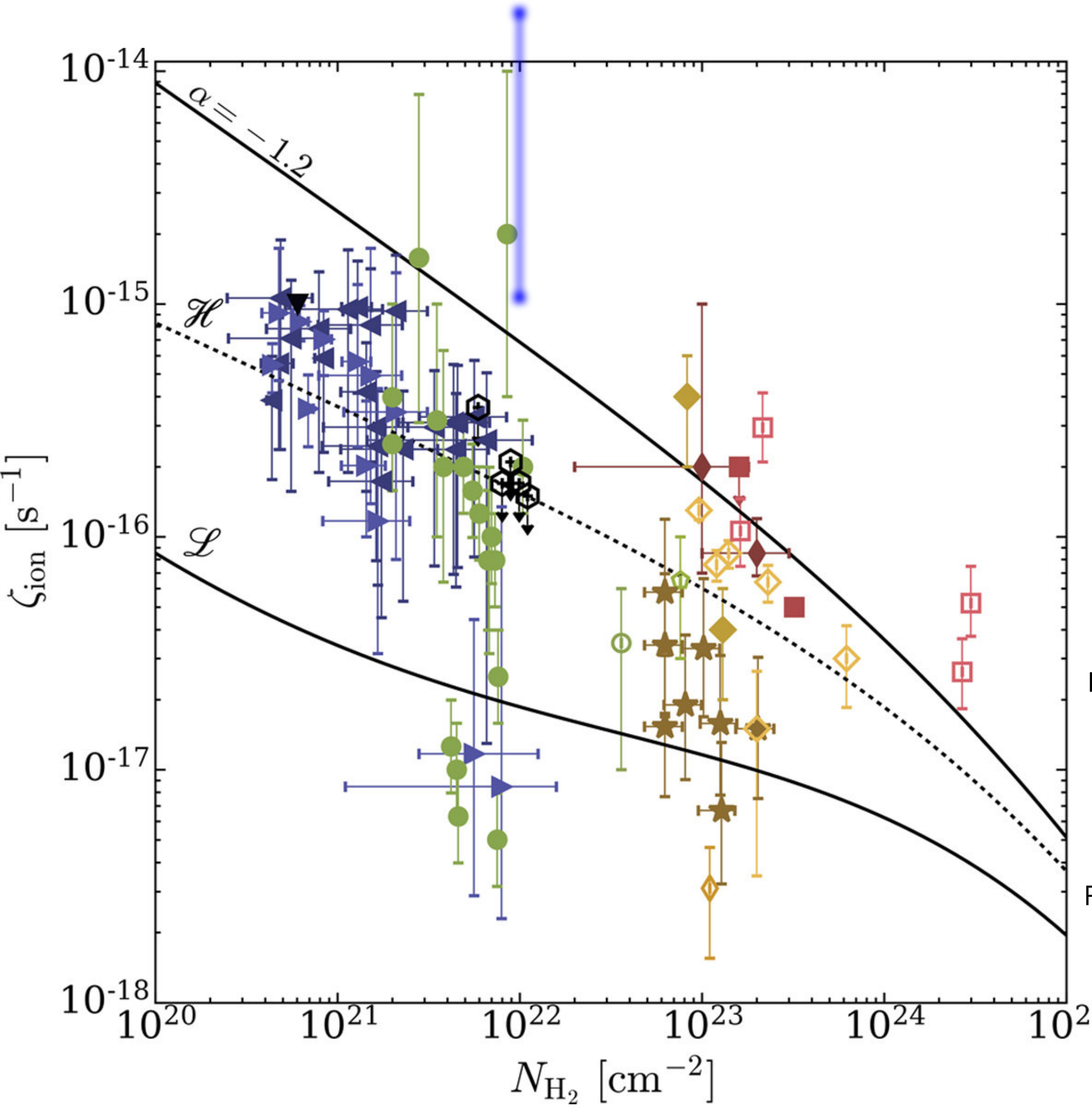
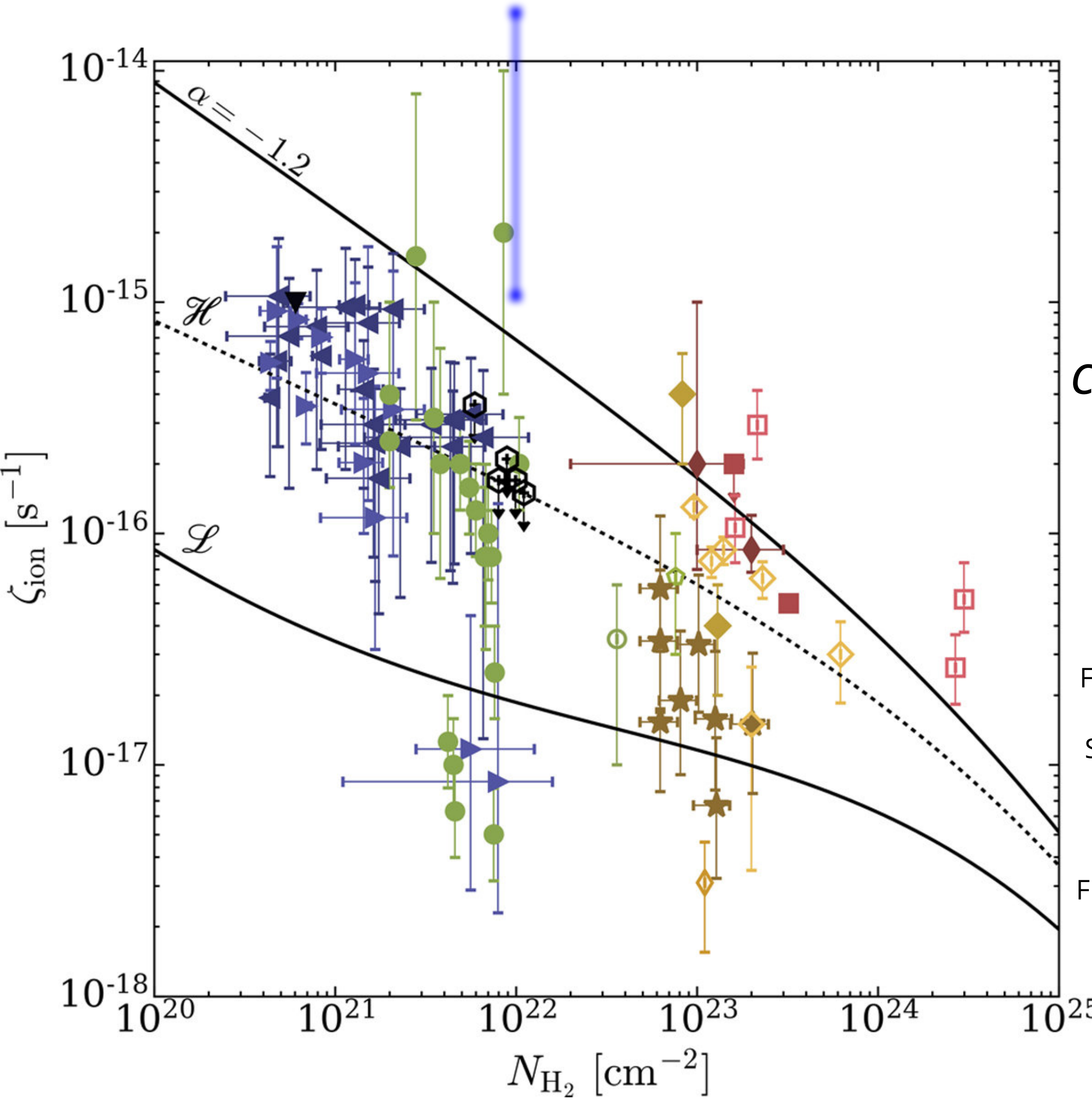



Figure from Padovani+'22 showing observations by Shaw+'08, Indriolo & McCall '12, Neufeld & Wolfire '17, Caselli+'98, Bialy+'22, Maret & Bergin '07, Fuente+'16, Sabatini+'20, de Boisanger+'16, van der Tak+'00, Hezareh+'08, Morales Ortiz+'14, Ceccarelli+'04, Barger & Garrod'20 *(in addition: results by Cabedo+'22 [blue line])*

# The big uncertainty




## Current state-of-the-art in MHD models:

*constant* rate independent of densities

Figure from Padovani+'22 showing observations by Shaw+'08, Indriolo & McCall '12, Neufeld & Wolfire '17, Caselli+'98, Bialy+'22, Maret & Bergin '07, Fuente+'16, Sabatini+'20, de Boisanger+'16, van der Tak+'00, Hezareh+'08, Morales Ortiz+'14, Ceccarelli+'04, Barger & Garrod'20 *(in addition: results by Cabedo+'22 [blue line])*

# External vs. internal

# External vs. internal

Competition between *external* and *internal* cosmic rays

Do *externally* or *internally* produced cosmic rays dominate disk formation process?

Self-regulation during disk formation? *(Offner, Gaches & Holdship'19)*

# External vs. internal

Competition between *external* and *internal* cosmic rays

Do *externally* or *internally* produced cosmic rays dominate disk formation process?

Self-regulation during disk formation? *(Offner, Gaches & Holdship'19)*

Are cosmic ray rates **environment** dependent or independent?

*(Küffmeier, Zhao & Caselli+'20)* *(Cabedo, Maury+'22)*

# External vs. internal

Competition between *external* and *internal* cosmic rays

Do *externally* or *internally* produced cosmic rays dominate disk formation process?

Self-regulation during disk formation? *(Offner, Gaches & Holdship'19)*

Are cosmic ray rates **environment** dependent or independent?

*(Küffmeier, Zhao & Caselli+'20)* *(Cabedo, Maury+'22)*

**We need**

a better handle on CR propagation

talks by Offner, Owen, Grassi, Gaches

# External vs. internal

Competition between *external* and *internal* cosmic rays

Do *externally* or *internally* produced cosmic rays dominate disk formation process?

Self-regulation during disk formation? *(Offner, Gaches & Holdship'19)*

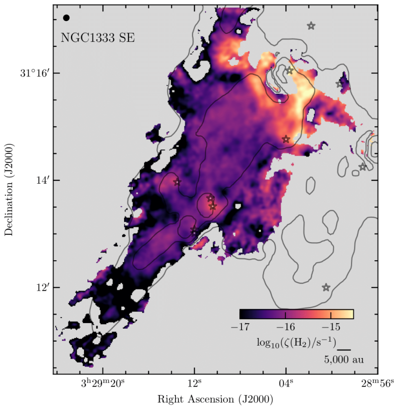
Are cosmic ray rates **environment** dependent or independent?

*(Küffmeier, Zhao & Caselli+'20)* *(Cabedo, Maury+'22)*

**We need**

a better handle on CR propagation

talks by Offner, Owen, Grassi, Gaches




measurements/maps of CR rates

talks by Redaelli (L1544), **Pineda (NGC1333)**, Cabedo & Maury (B335), Sanna (G035.02+0.35), Sabatini

# Summary

# Summary

under otherwise identical initial conditions:

# Summary

under otherwise identical initial conditions:

increasing
ionization rate

# Summary

under otherwise identical initial conditions:

increasing ionization rate ⟶ enhanced magnetic braking

# Summary

under otherwise identical initial conditions:

increasing ionization rate ⟶ enhanced magnetic braking ⟶ smaller disks

# Summary

under otherwise identical initial conditions:

increasing ionization rate ⟶ enhanced magnetic braking ⟶ smaller disks

but disk formation depends on many parameters!

# Summary

under otherwise identical initial conditions:

increasing ionization rate → enhanced magnetic braking → smaller disks

but disk formation depends on many parameters!

**Cosmic ray ionization** during disk formation **depends on density, space and time.**

# Summary

under otherwise identical initial conditions:

increasing ionization rate ⟶ enhanced magnetic braking ⟶ smaller disks

but disk formation depends on many parameters!

**Cosmic ray ionization** during disk formation **depends on density, space and time.**

The ultimate modeling challenge is

to (self-consistently) account for cosmic-ray variations in multi-scale non-ideal MHD models.

# Summary


under otherwise identical initial conditions:

increasing ionization rate → enhanced magnetic braking → smaller disks

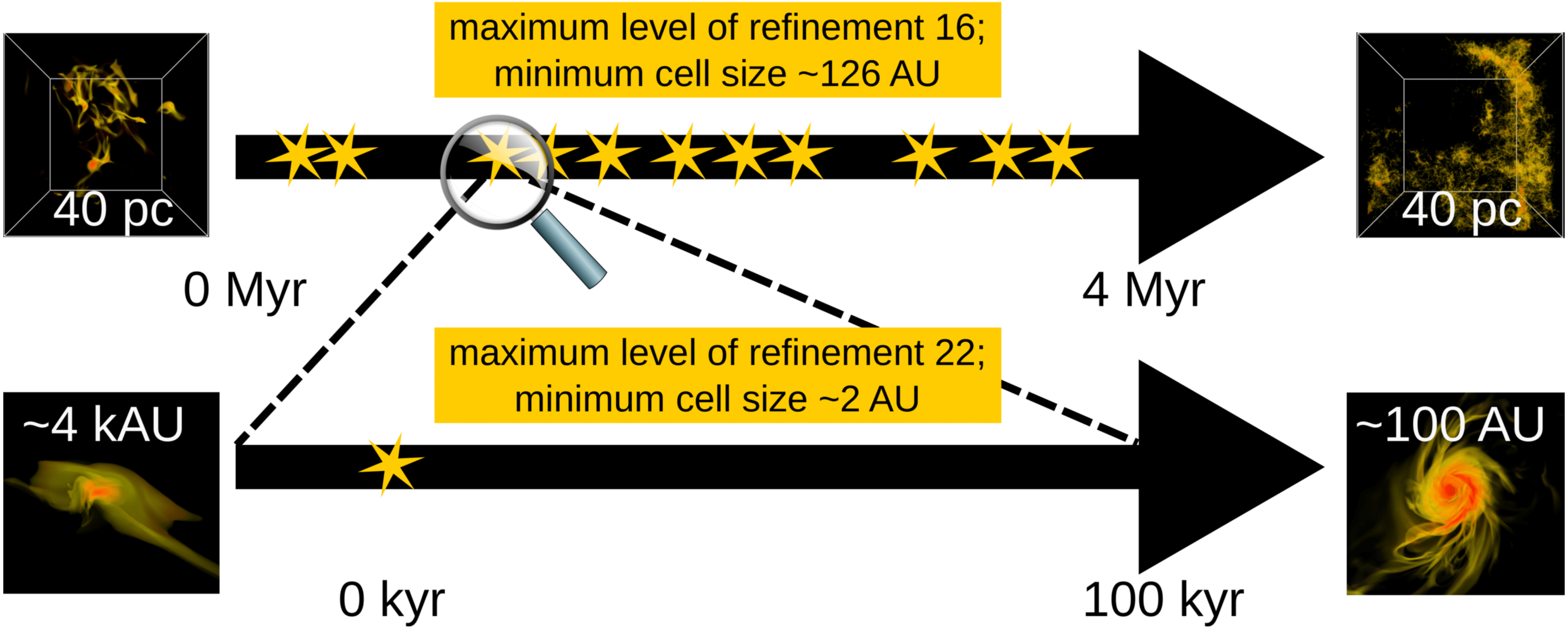
but disk formation depends on many parameters!

**Cosmic ray ionization** during disk formation **depends on density, space and time.**

The ultimate modeling challenge is

**to (self-consistently) account for cosmic-ray variations in multi-scale non-ideal MHD models.**

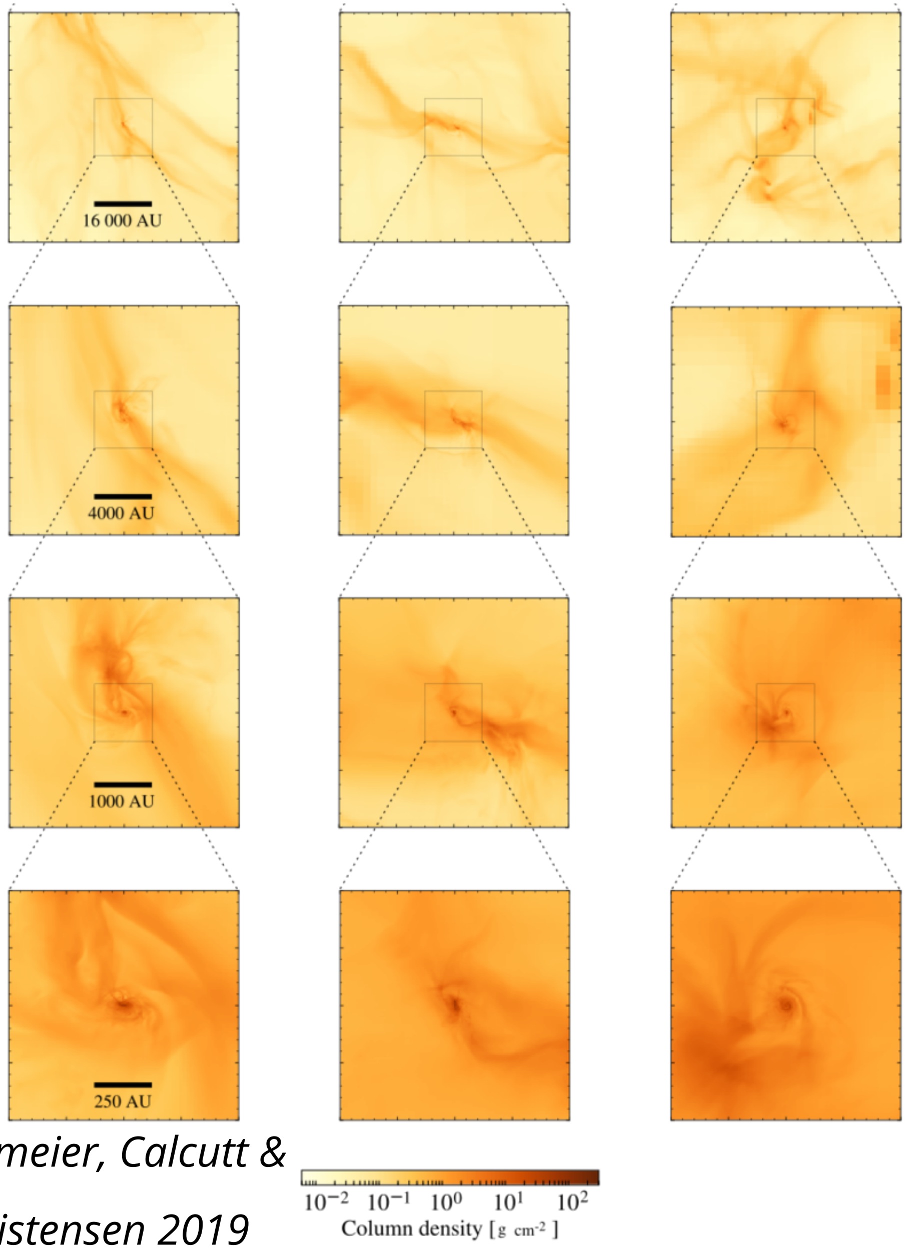
# Zoom-in method




*Küffmeier et al. 2017*

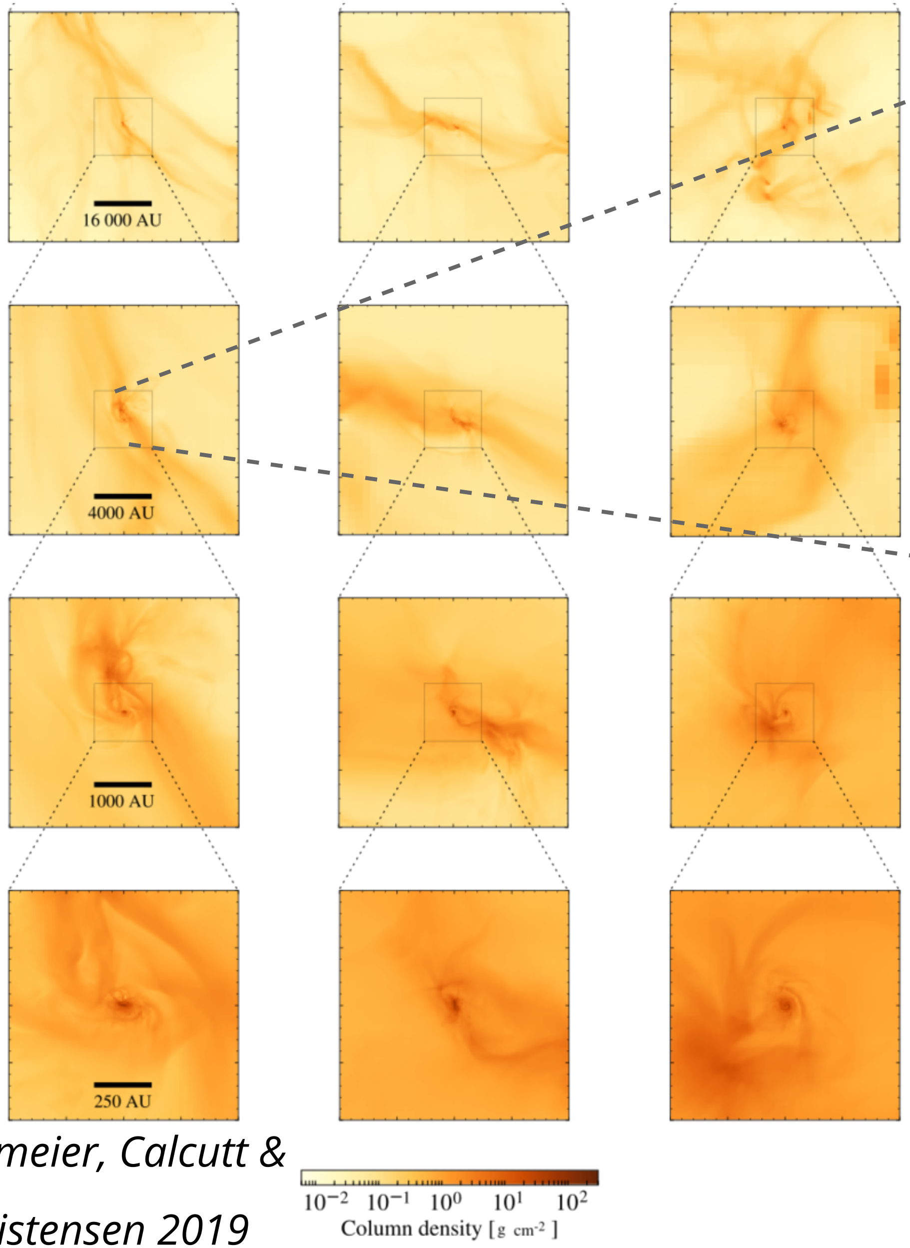
- adaptive mesh refinement
- ideal magnetohydrodynamics
- turbulence driven by supernovae
- stars modelled as sink particles

# Zoom-in on embedded protostars

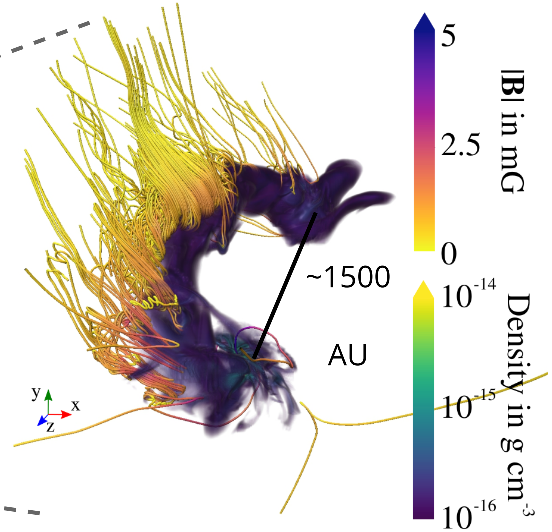



*Küffmeier, Calcutt & Kristensen 2019*

# Zoom-in on embedded protostars



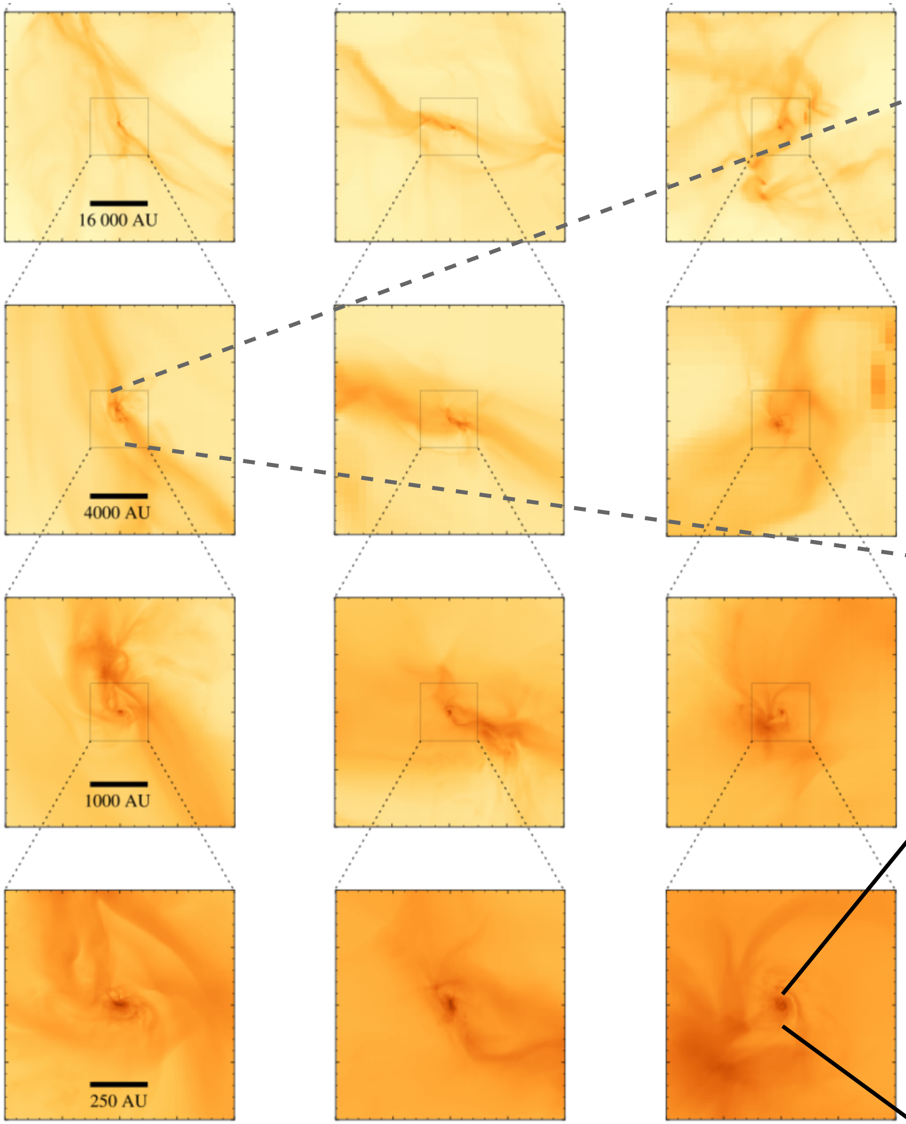

*Küffmeier, Calcutt & Kristensen 2019*

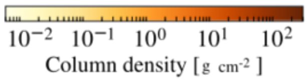



*Küffmeier, Reißl et al. 2020*

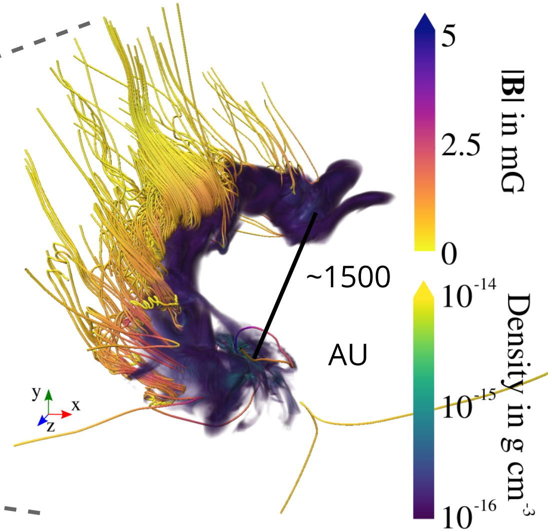
bridge structure similar to IRAS 16293--2422 *(e.g. Sadavoy+ 2018, van der Wiel+ 2019, Maureira+ 2020)*

# Zoom-in on embedded protostars



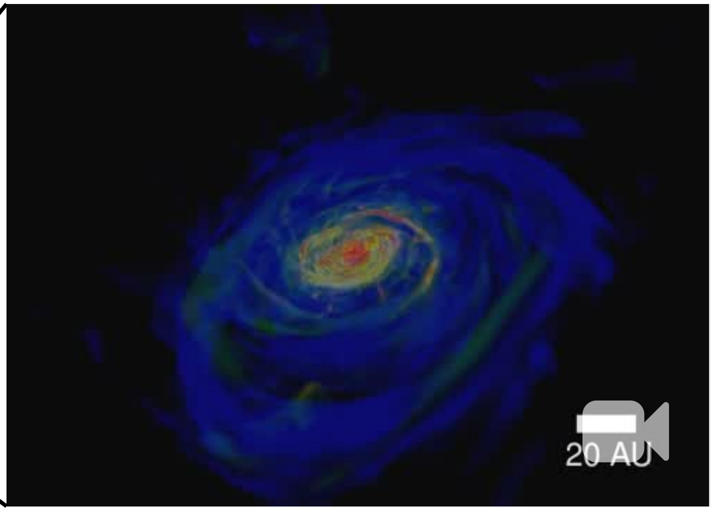




*Küffmeier, Calcutt & Kristensen 2019*




*Küffmeier, Reißl et al. 2020*

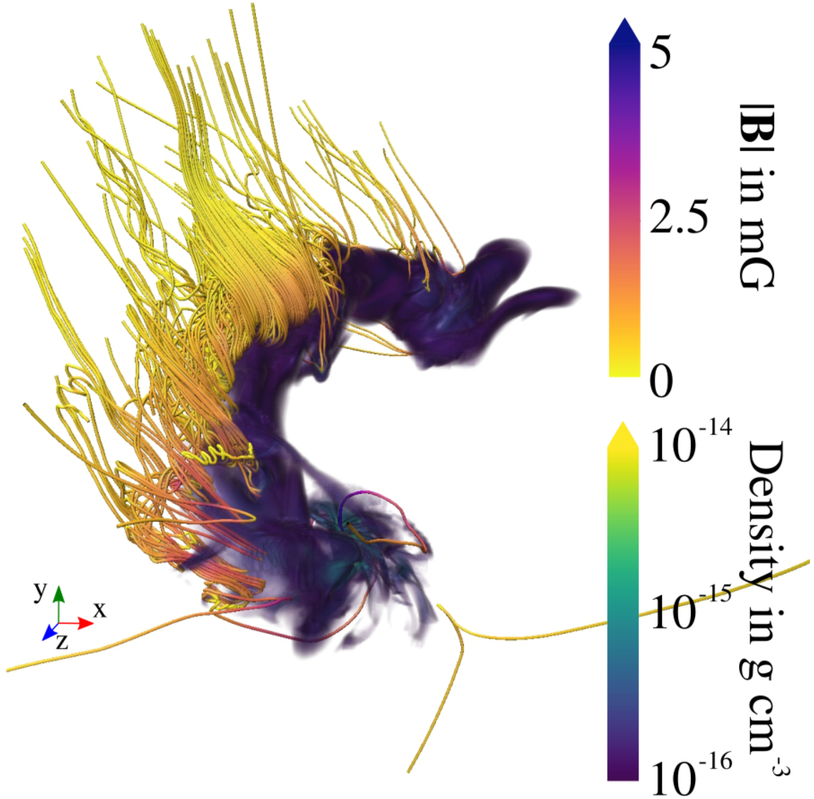
bridge structure similar to IRAS 16293--2422 *(e.g. Sadavoy+ 2018, van der Wiel+ 2019, Maureira+ 2020)*



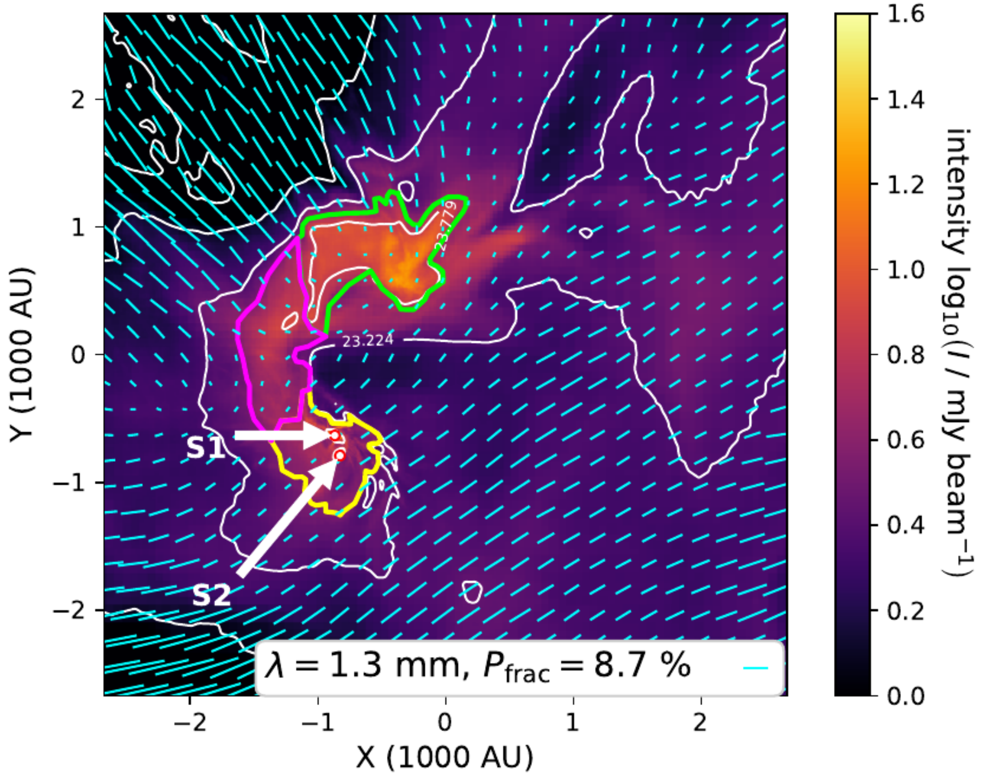

*Küffmeier et al. 2018*

# Formation of embedded protostellar multiple

Magnetic field in bridge




Synthetic observation with POLARIS



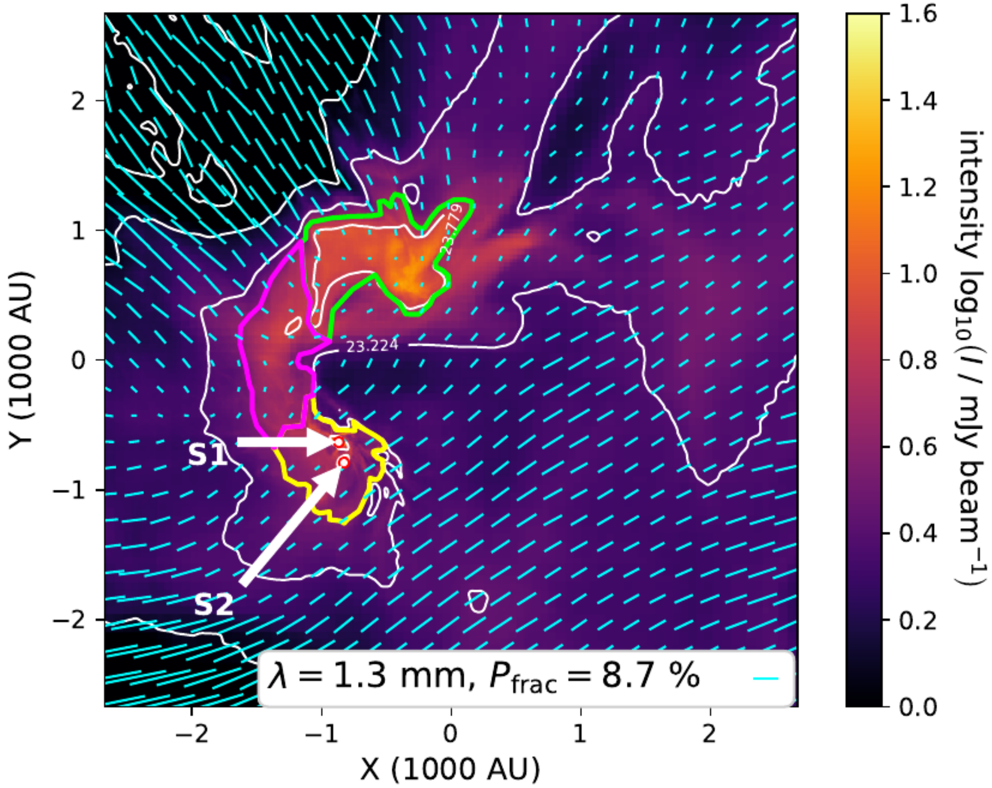

Field strength in bridge:
about **1 to 2 mG**

Polarization fraction in bridge:
**a few %**

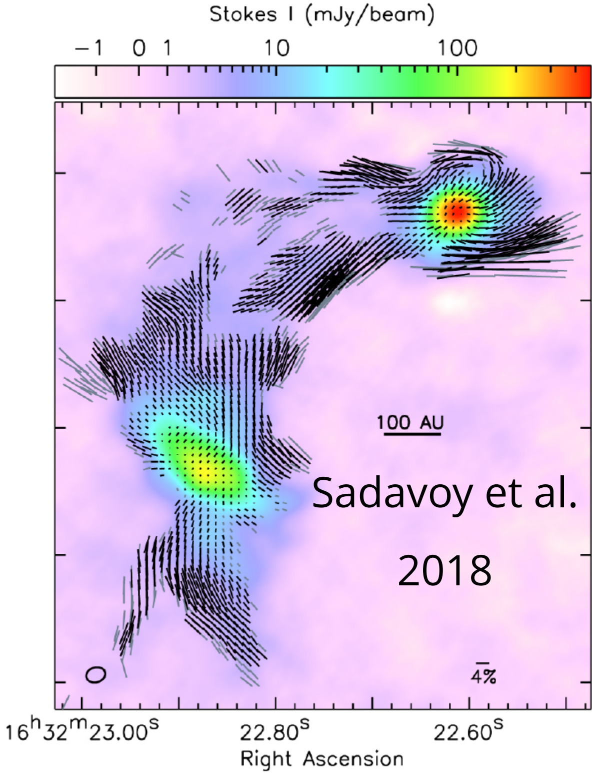
Küffmeier, Reißl et al. 2020

# Synthetic dust polarization maps at 1.3 mm

Emitted radiation




IRAS 16293--2422




Polarization fraction in bridge:

**a few %**

Polarization fraction in bridge:

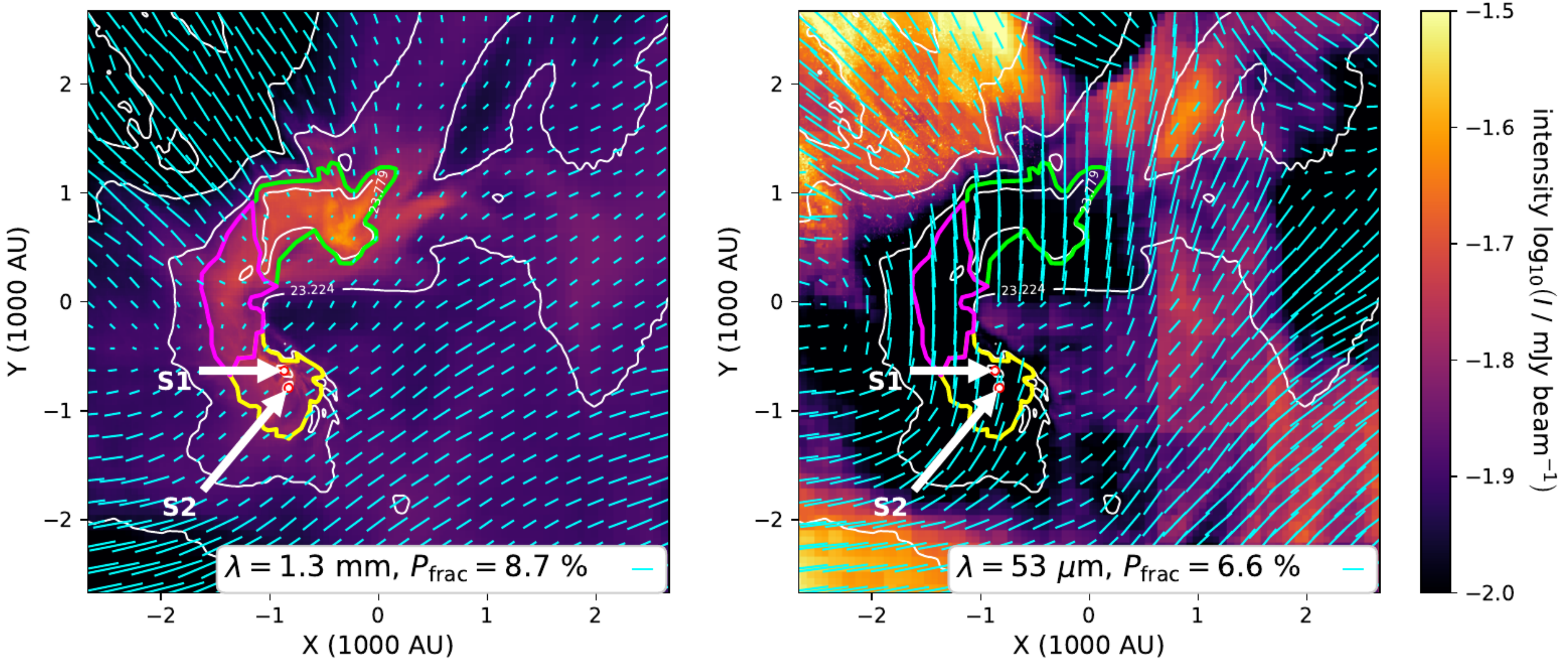
**up to 20 %**

=> IRAS 16293-2422 is strongly magnetized

Küffmeier, Reißl et al. 2020

# Wavelength dependence: 1.3 mm vs 53 micron

Emitted radiation



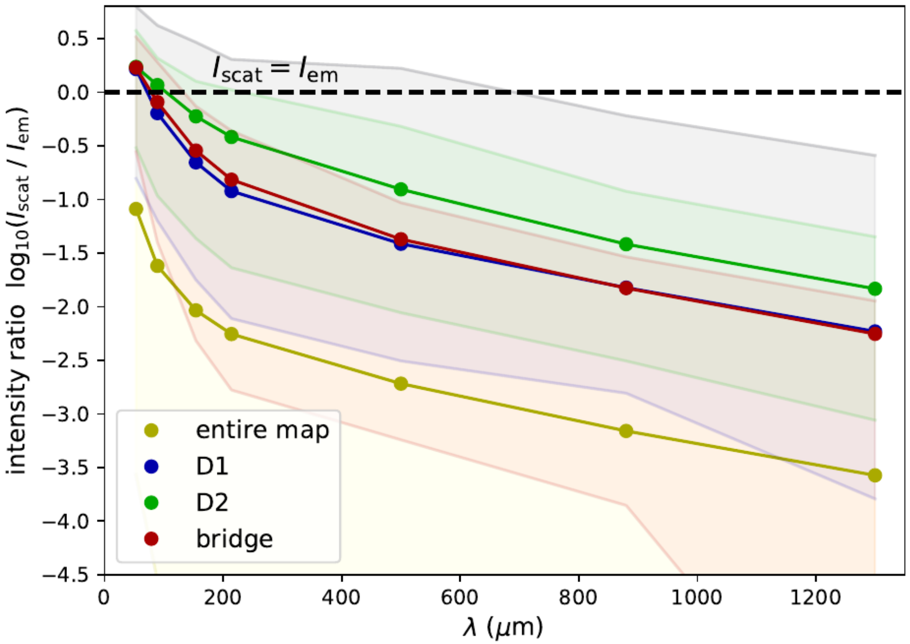

1.3 mm: good tracer of magnetic field

53 micron: poor tracer of magnetic field

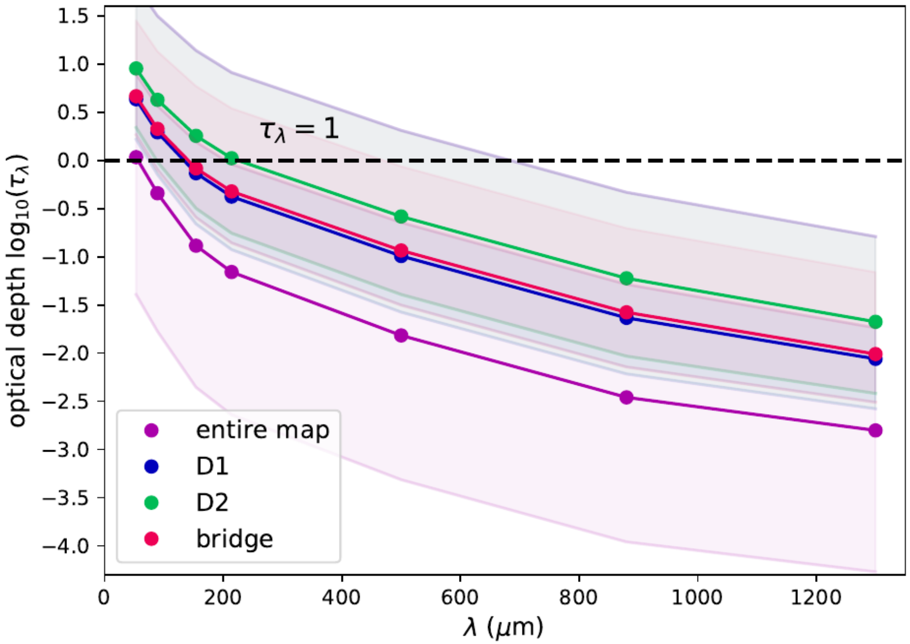
Küffmeier, Reißl et al. 2020

# Two reasons for wavelength dependence

## Self-scattering




## Dichroic extinction



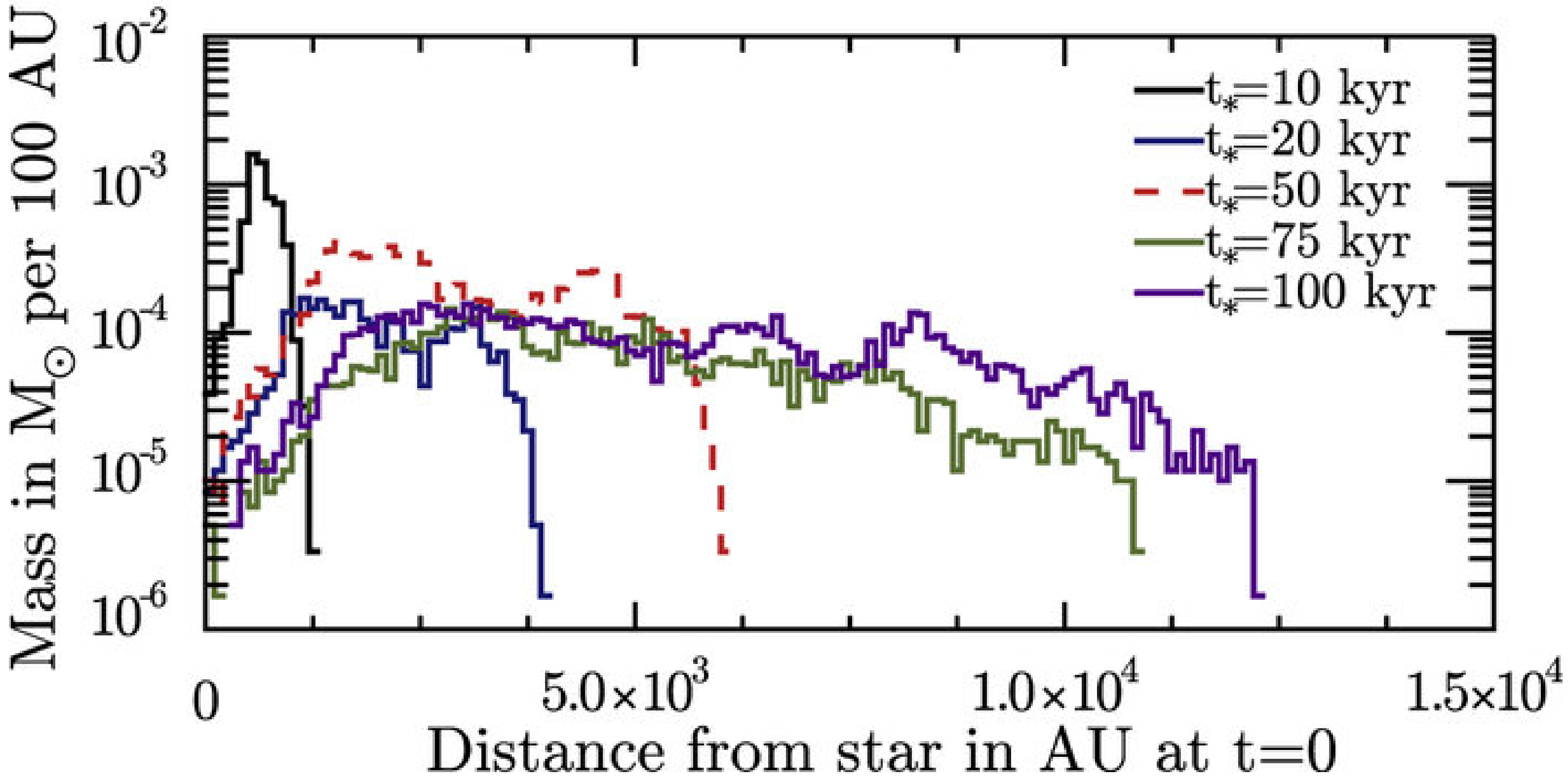

# Take-away for scales beyond >100 au

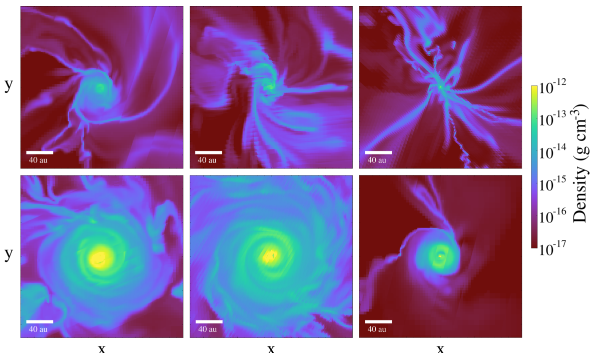
< 200 micron: dichroic extinction and self-scattering; no trace of **B**

> 200 micron: thermal emission; linear polarization traces **B**

Küffmeier, Reißl et al. 2020

# The connection to the larger scales




Gas from beyond the prestellar core can fall onto the star-disk system

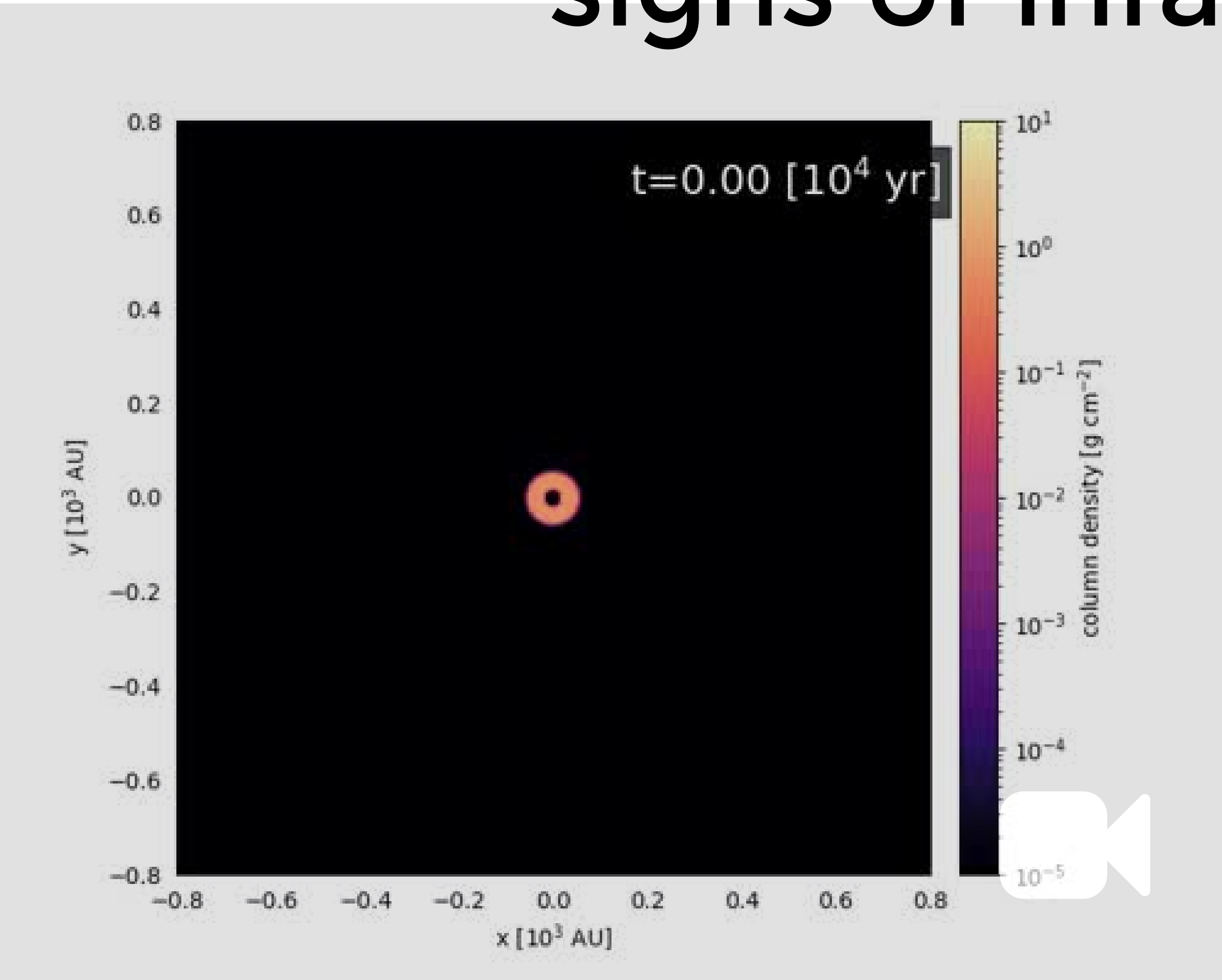
*Küffmeier et al. 2017 / 2022 in prep.*

# Streamers (and shadows?) as signs of infall

*see also Bate 2018*

*Küffmeier, Dullemond et al. 2021*

# Streamers (and shadows?) as signs of infall

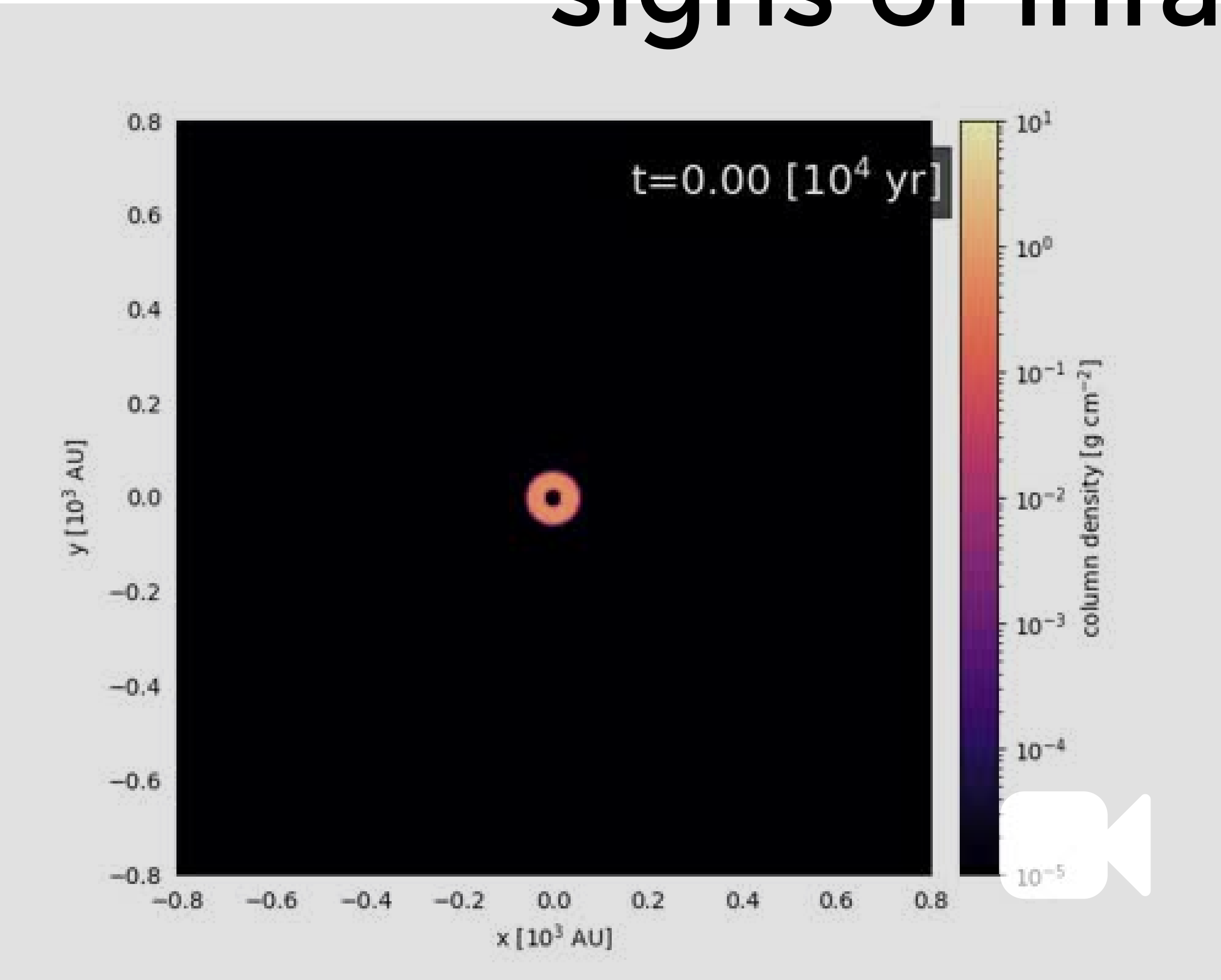



Formation of misaligned configuration

*see also Bate 2018*

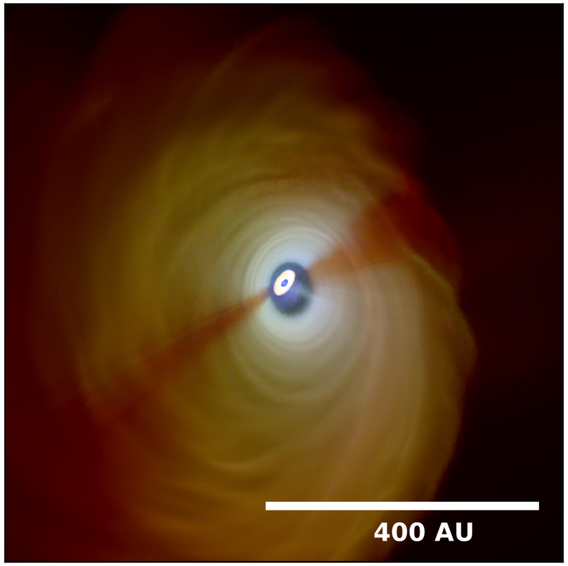
*Küffmeier, Dullemond et al. 2021*

# Streamers (and shadows?) as signs of infall




Formation of misaligned configuration

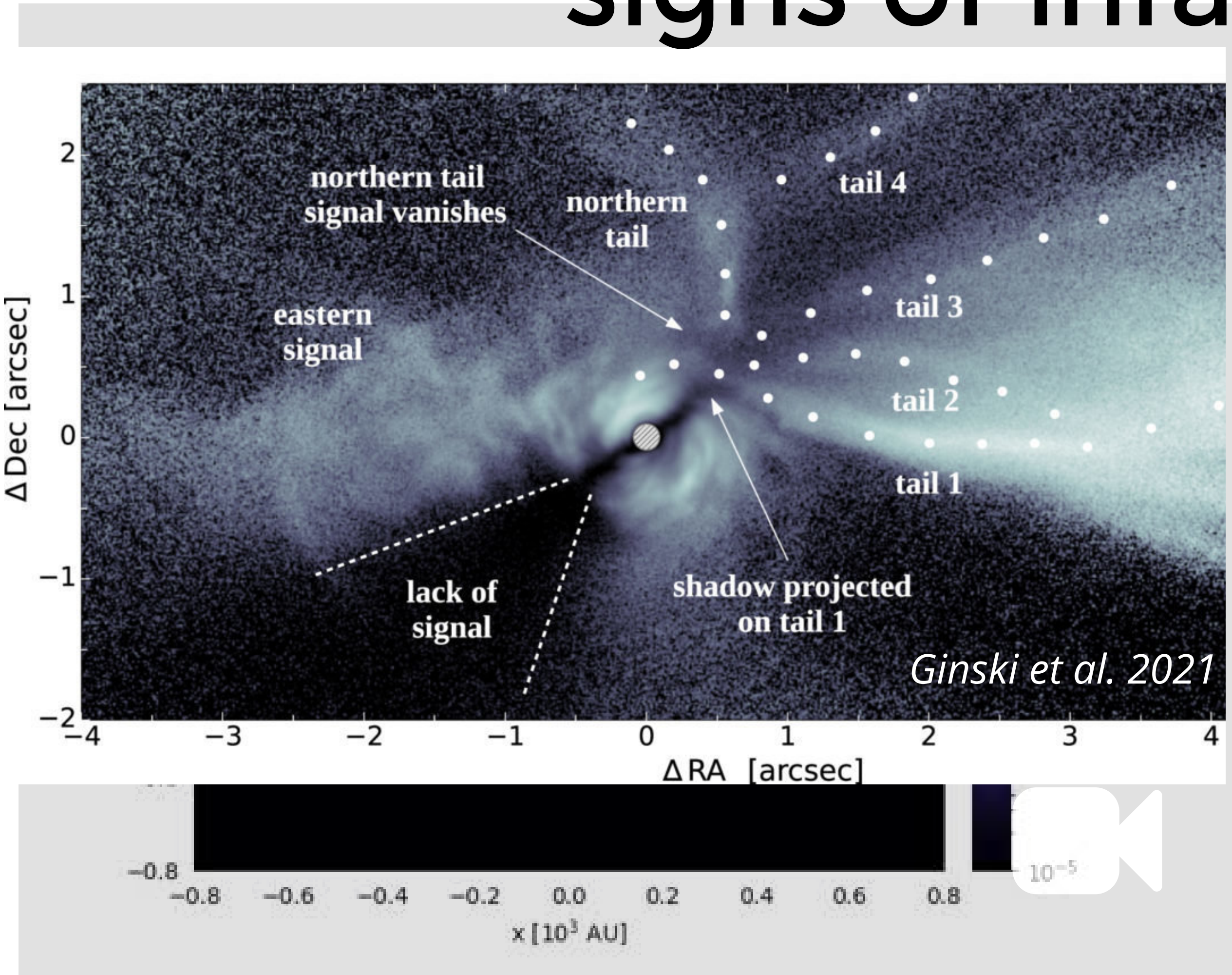
*see also Bate 2018*

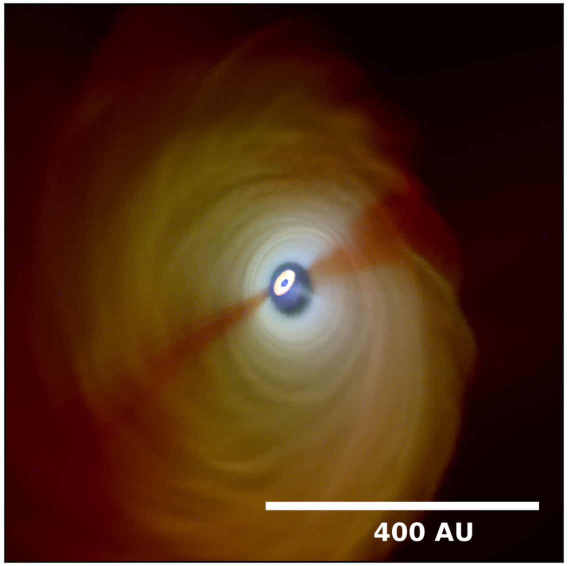



Observable as shadows in outer disk

*Küffmeier, Dullemond et al. 2021*

# Streamers (and shadows?) as signs of infall



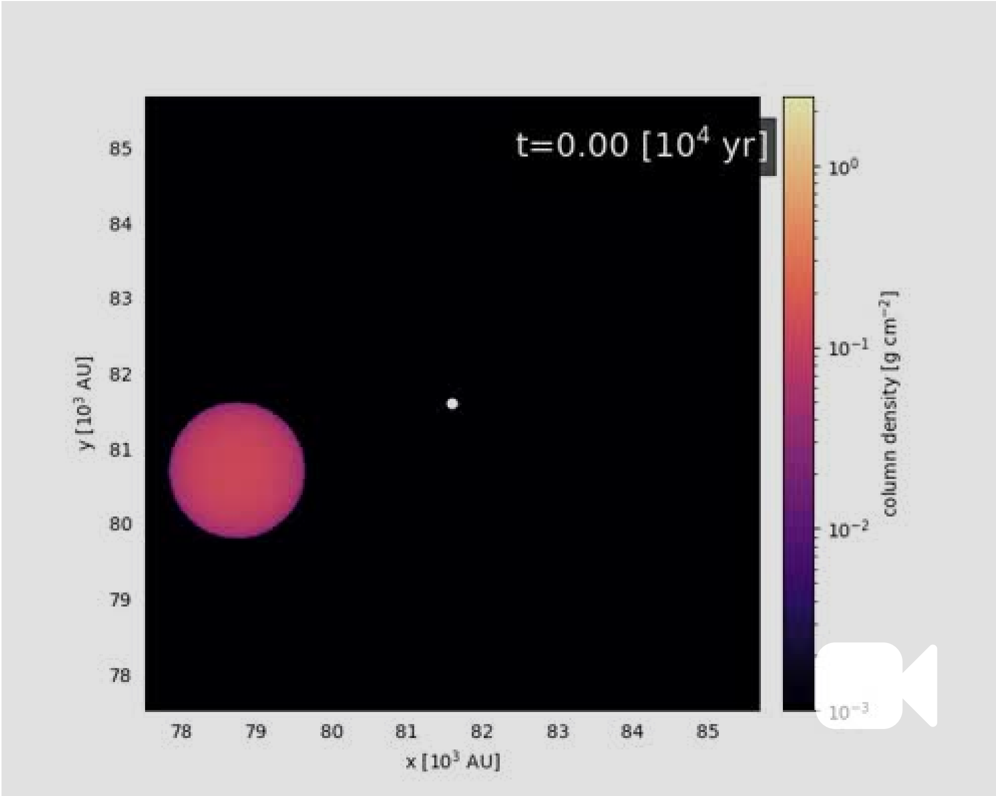

Observable as shadows in outer disk

Formation of misaligned configuration

*see also Bate 2018*

*Küffmeier, Dullemond et al. 2021*

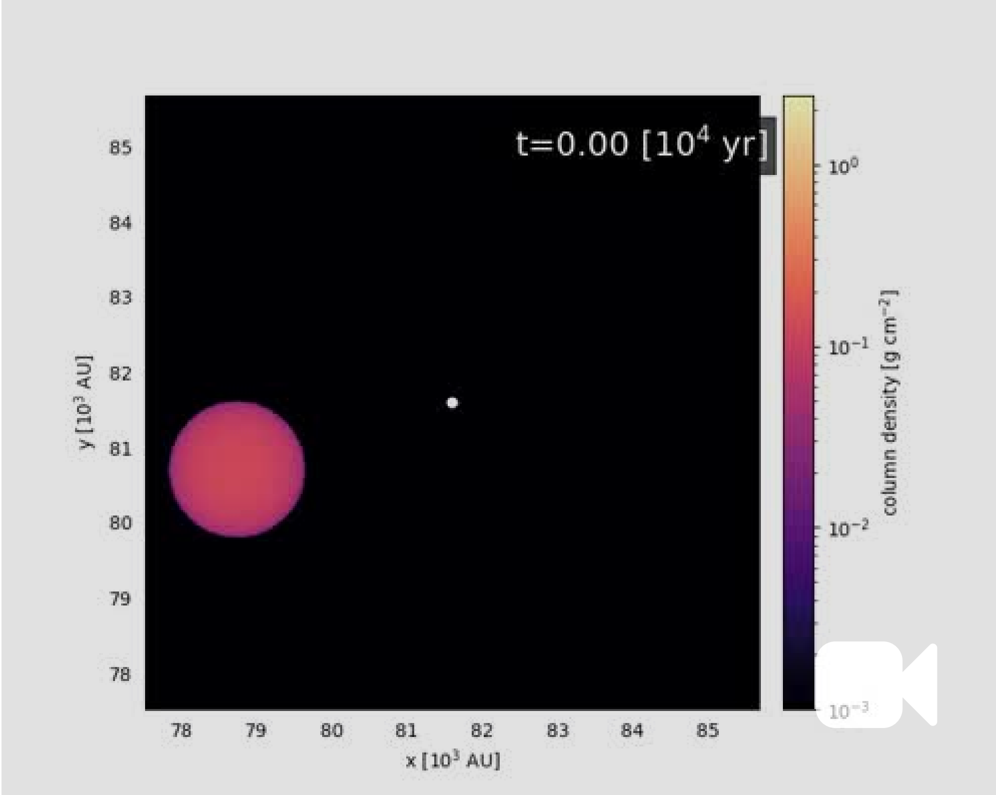
# Simulate cloudlet infall onto disk




*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

# Simulate cloudlet infall onto disk

AREPO, pure hydrodynamical

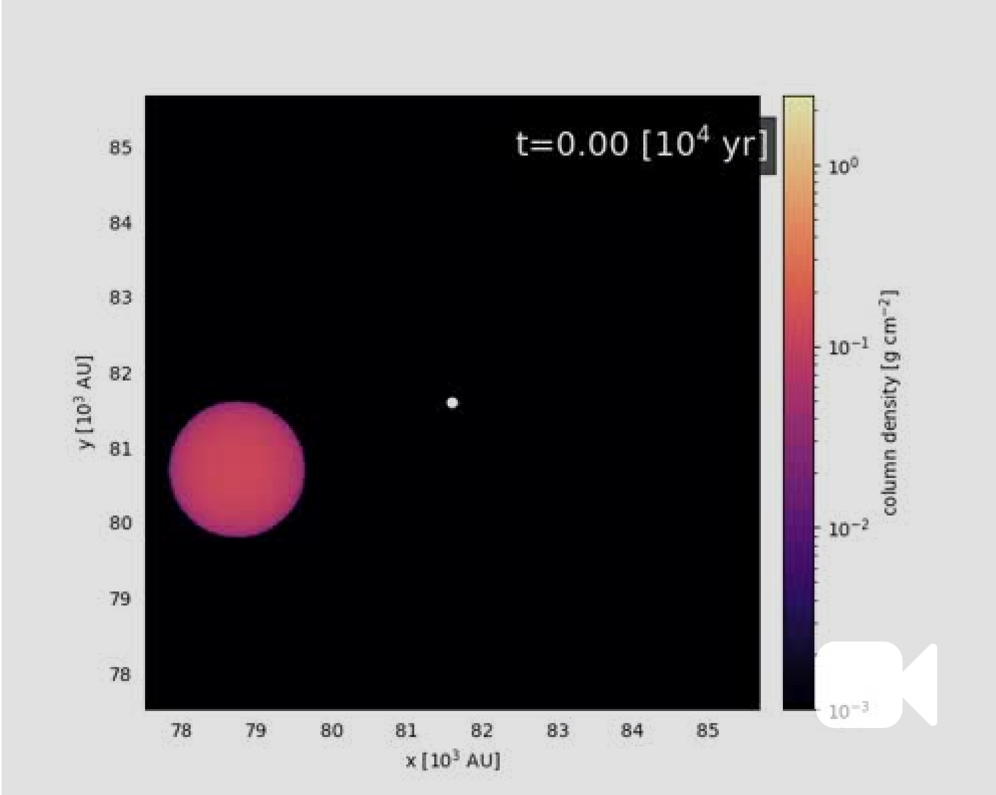



*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

# Simulate cloudlet infall onto disk

AREPO, pure hydrodynamical

isothermal gas




*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

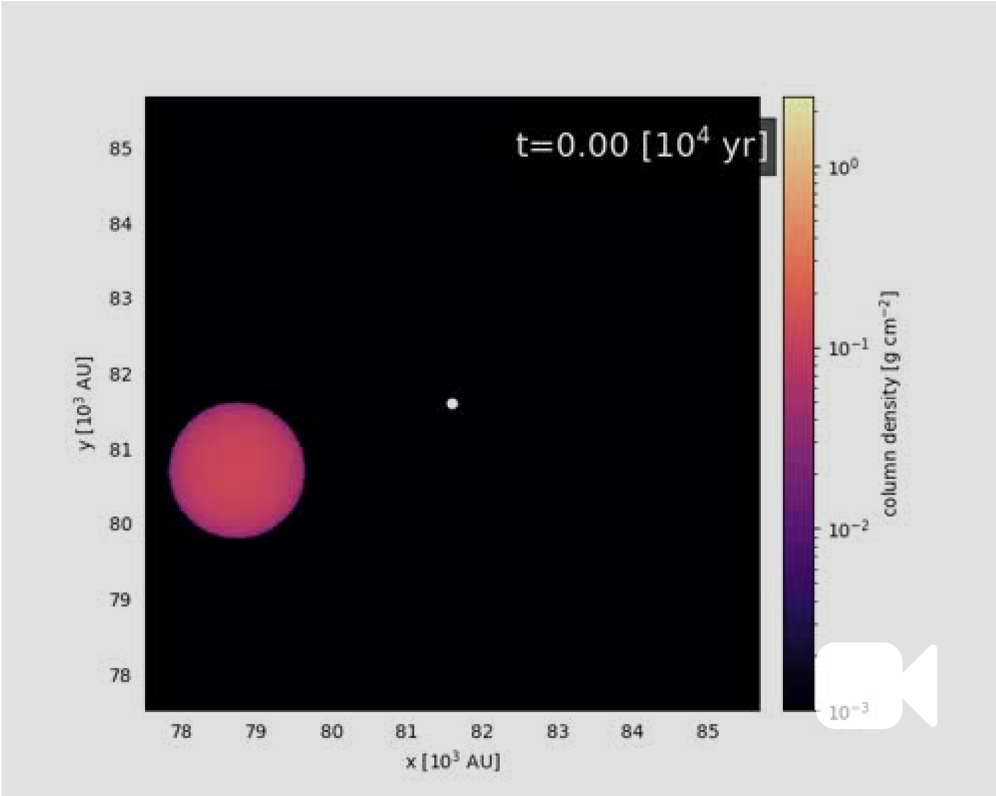
# Simulate cloudlet infall onto disk

AREPO, pure hydrodynamical

isothermal gas

vary infalling angle

$\alpha = 0^\circ (35^\circ, 60^\circ, 90^\circ)$




*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

# Simulate cloudlet infall onto disk

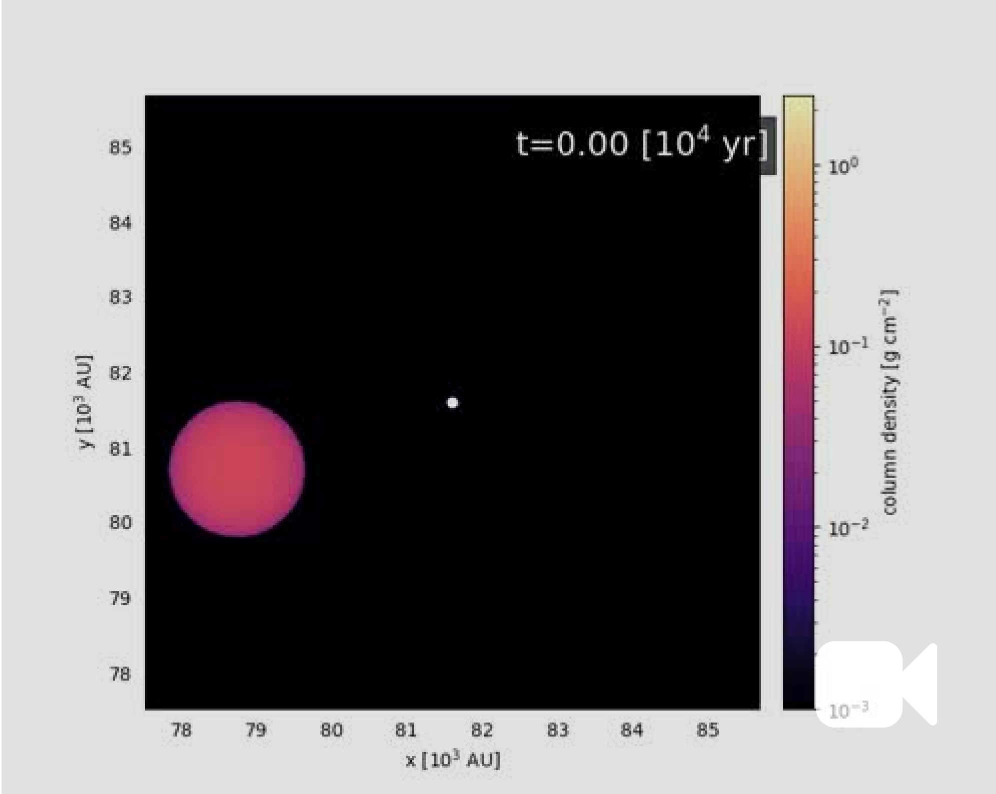
AREPO, pure hydrodynamical

isothermal gas

vary infalling angle

$\alpha = 0^\circ (35^\circ, 60^\circ, 90^\circ)$

vary rotation
(prograde, retrograde)




*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

# Simulate cloudlet infall onto disk

AREPO, pure hydrodynamical

isothermal gas

vary infalling angle

$\alpha = 0^\circ (35^\circ, 60^\circ, 90^\circ)$

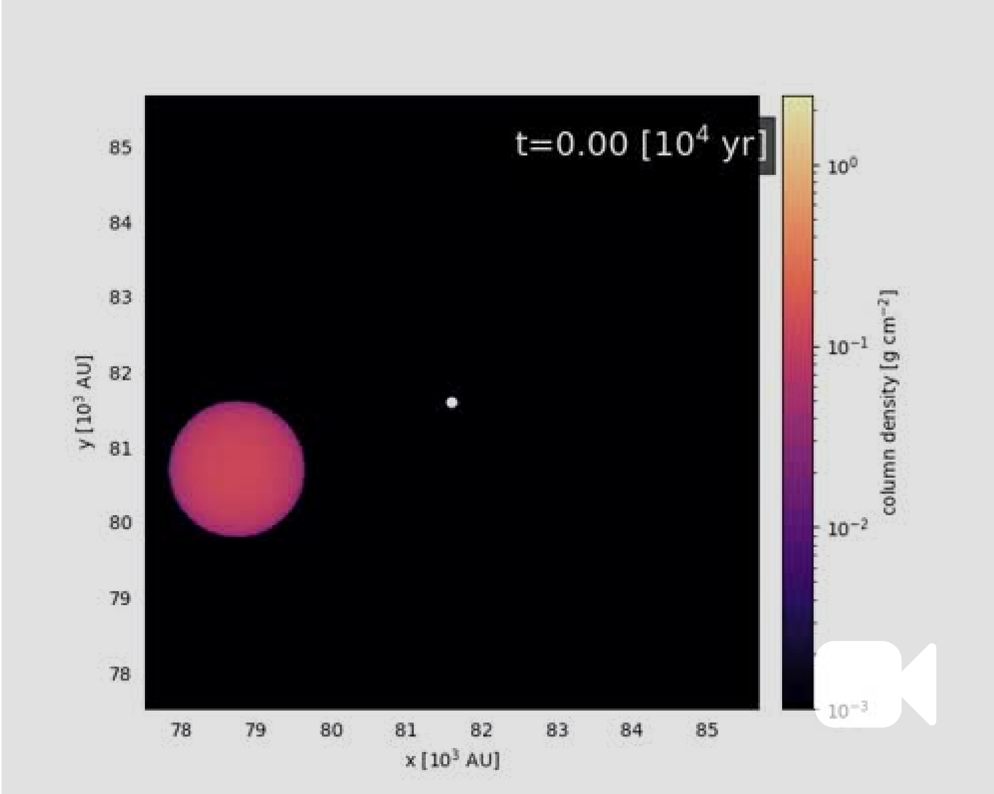
vary rotation
(prograde, retrograde)

$R_{\mathrm{i,d}} = 50\,\mathrm{au} \quad M_* = 2.5\,\mathrm{M}_\odot$

$\Sigma(r) = 170\left(\frac{\mathrm{g}}{\mathrm{cm}}\right)^2 \left(\frac{r}{1\mathrm{au}}\right)^{-3/2}$

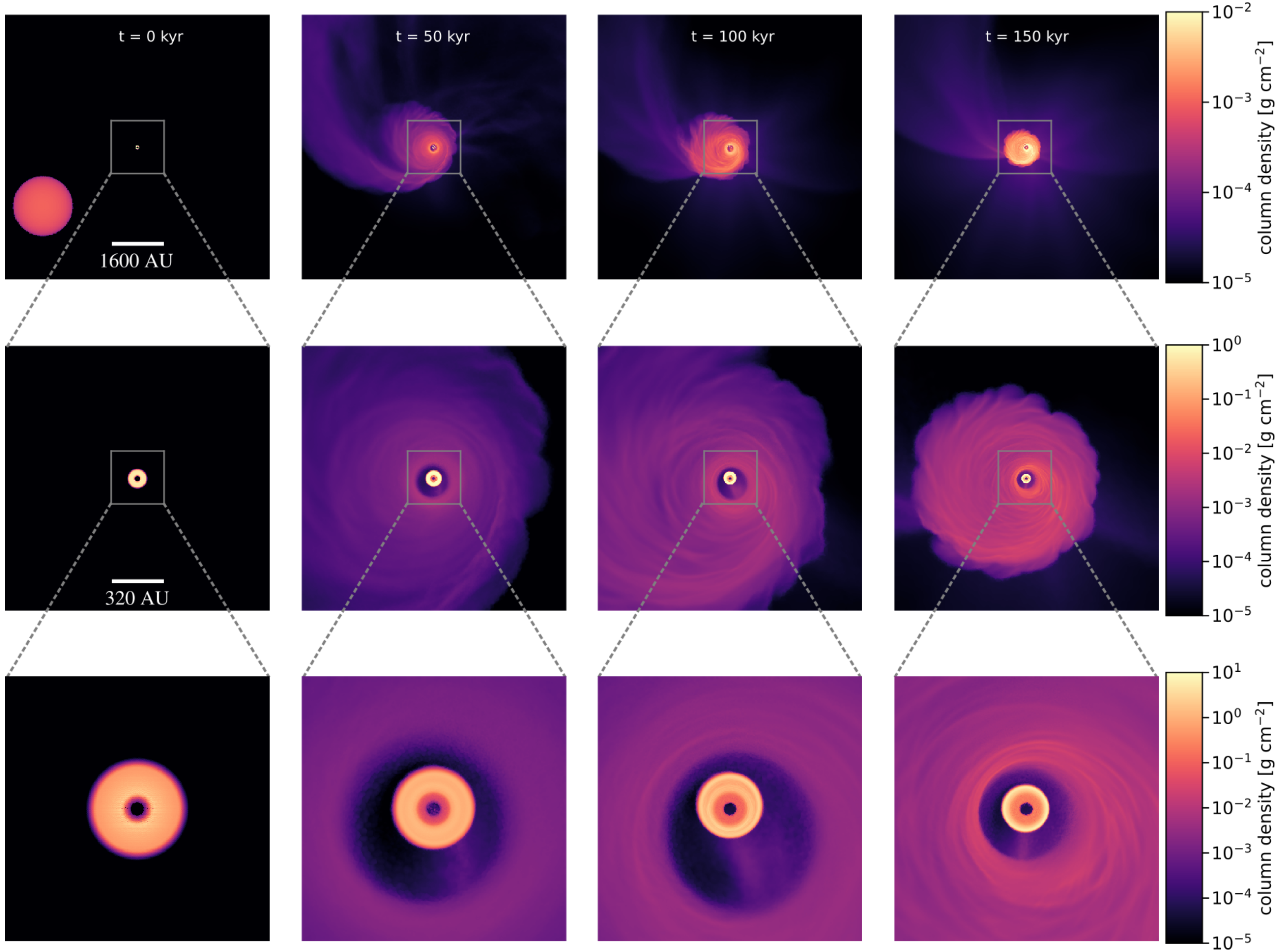
$b = 1774\,\mathrm{au}$

$R_{\mathrm{cloudlet}} = 887\,\mathrm{au} \quad M_{\mathrm{cloudlet}}(R_{\mathrm{cloudlet}}) = 0.01\mathrm{M}_\odot \left(\frac{R_{\mathrm{cloudlet}}}{5000\mathrm{au}}\right)^{2.3}$



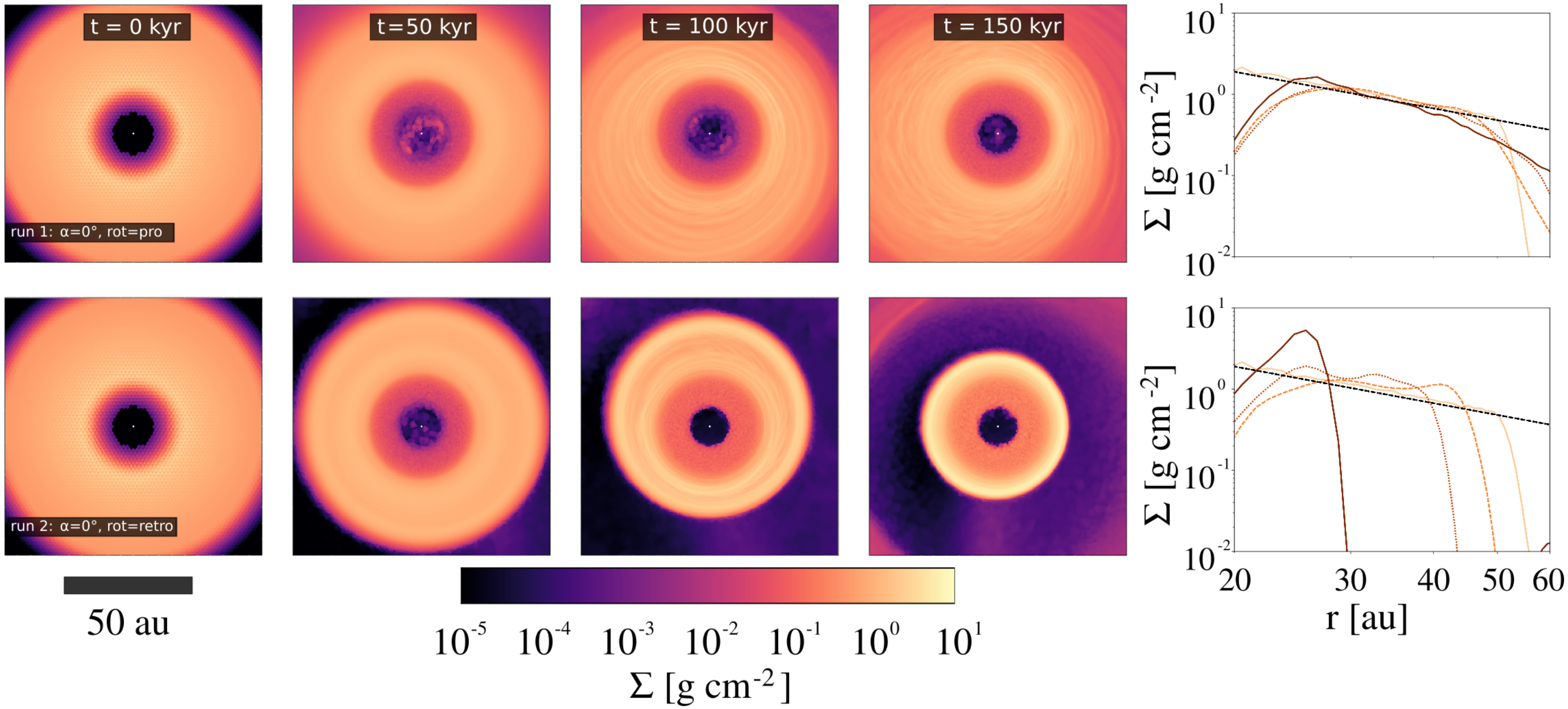

*Küffmeier, Dullemond, Reißl, Goicovic et al. 2021*

# Outer disk forms around inner disk



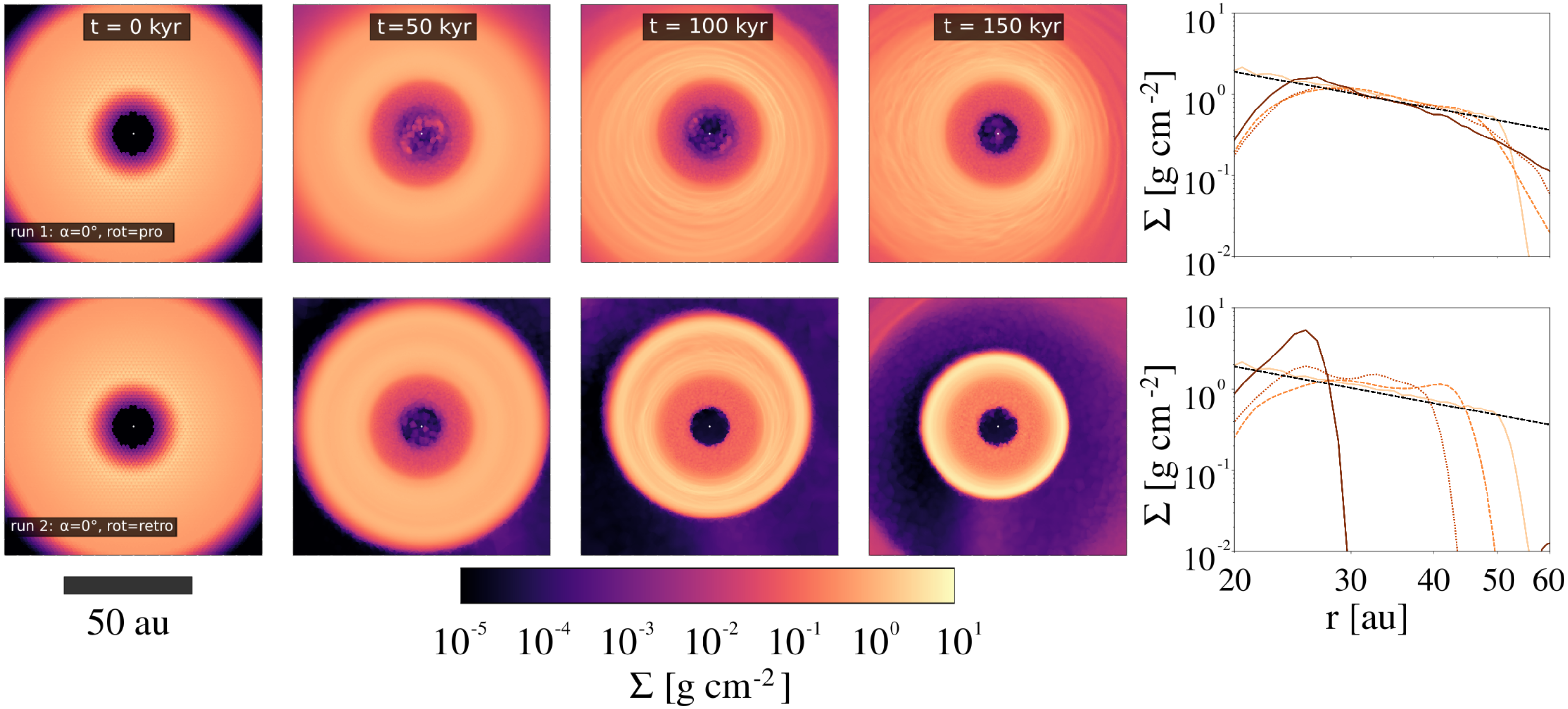

*Küffmeier et al. 2021*

# Prograde vs. retrograde infall




*Küffmeier et al. 2021*

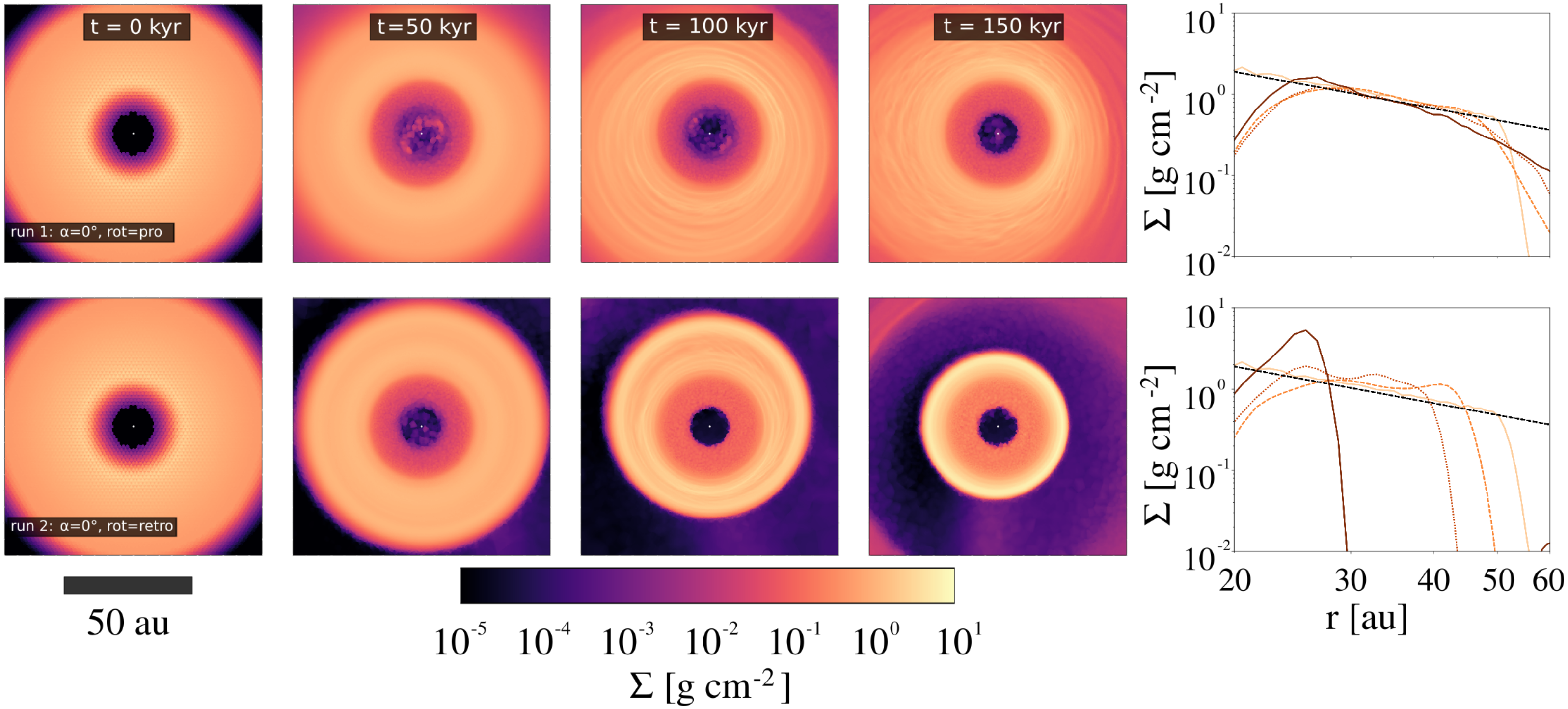
# Prograde vs. retrograde infall




**Retrograde infall causes:**

*Küffmeier et al. 2021*

# Prograde vs. retrograde infall

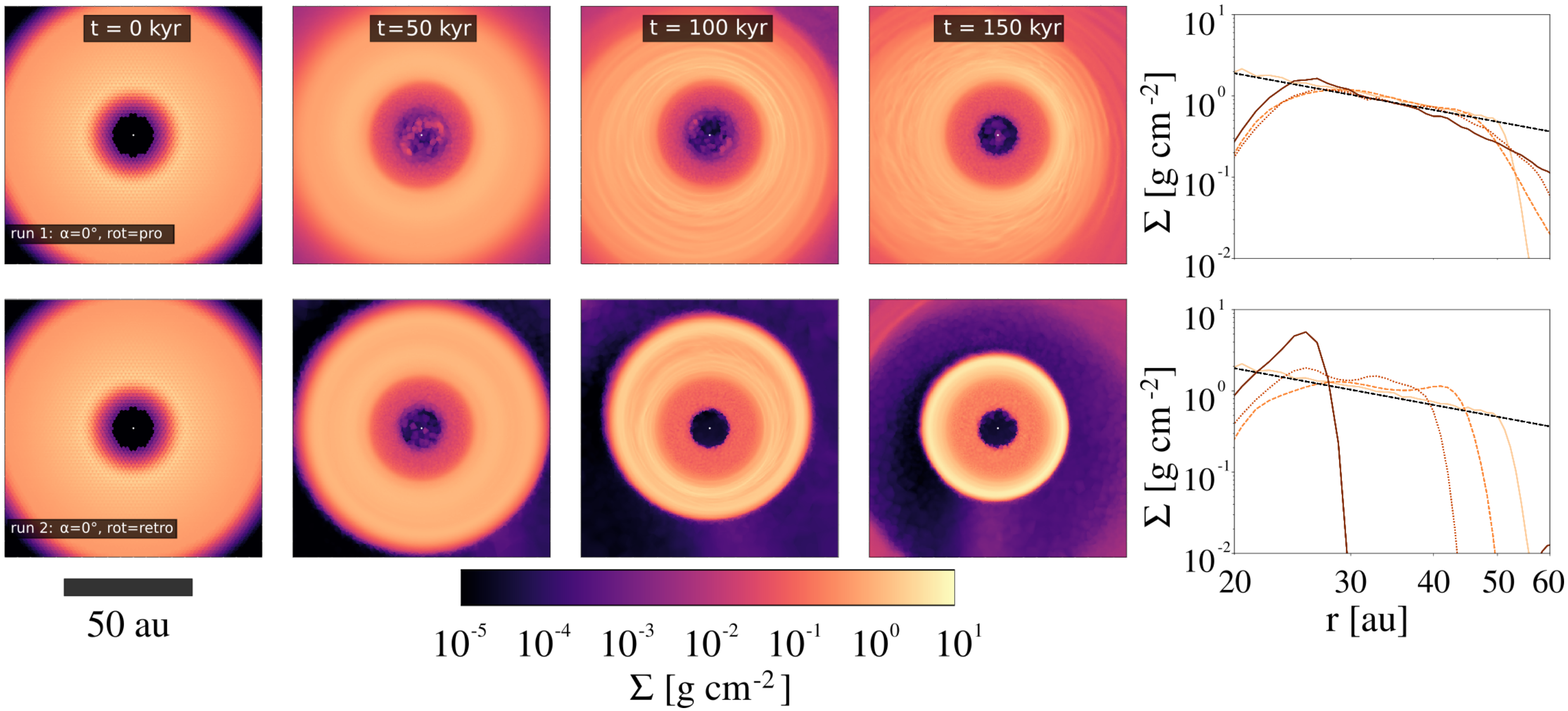



**Retrograde infall causes:**

- counter-rotating inner and outer disk

*Küffmeier et al. 2021*

# Prograde vs. retrograde infall



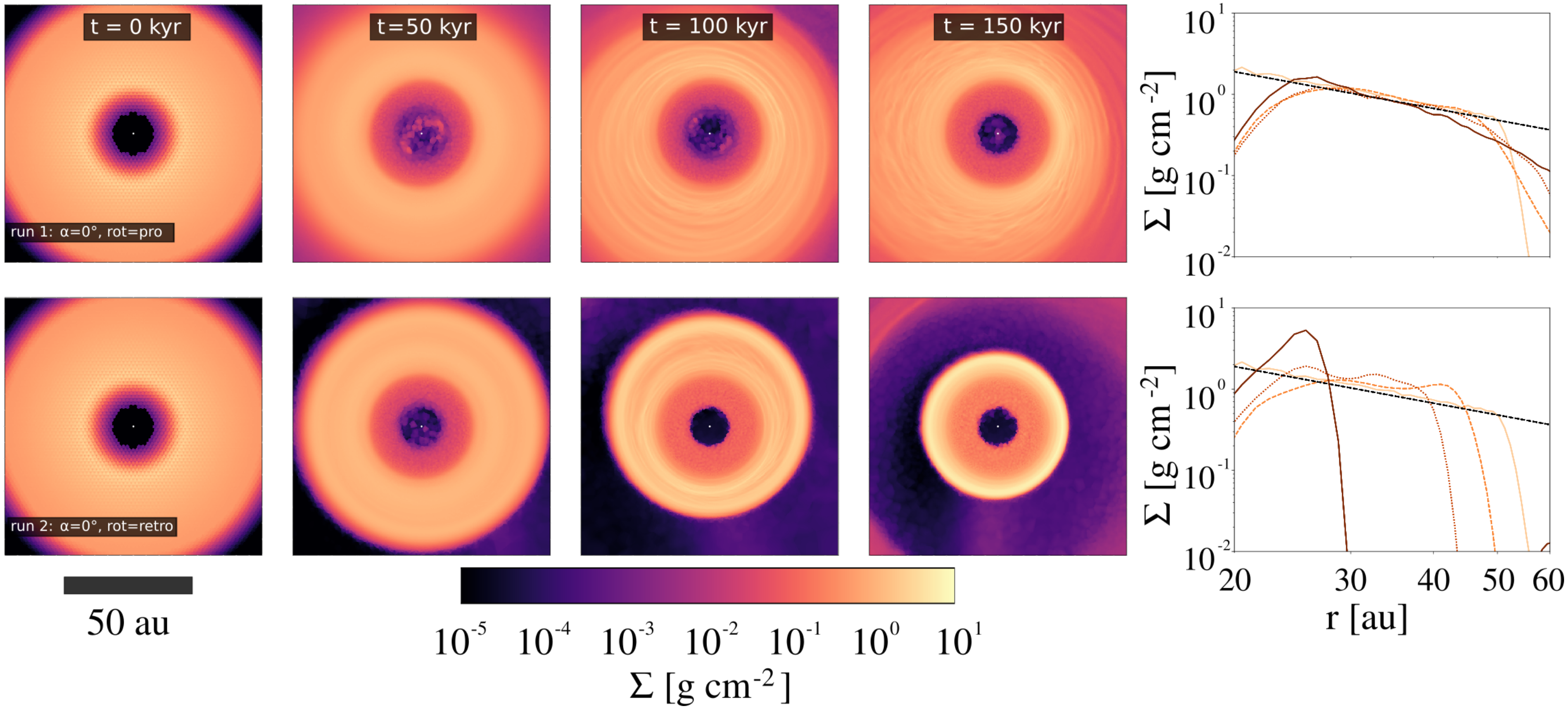

**Retrograde infall causes:**

- counter-rotating inner and outer disk
- larger and deeper gap between disks

*see also Vorobyov+ 2016*

*Küffmeier et al. 2021*

# Prograde vs. retrograde infall



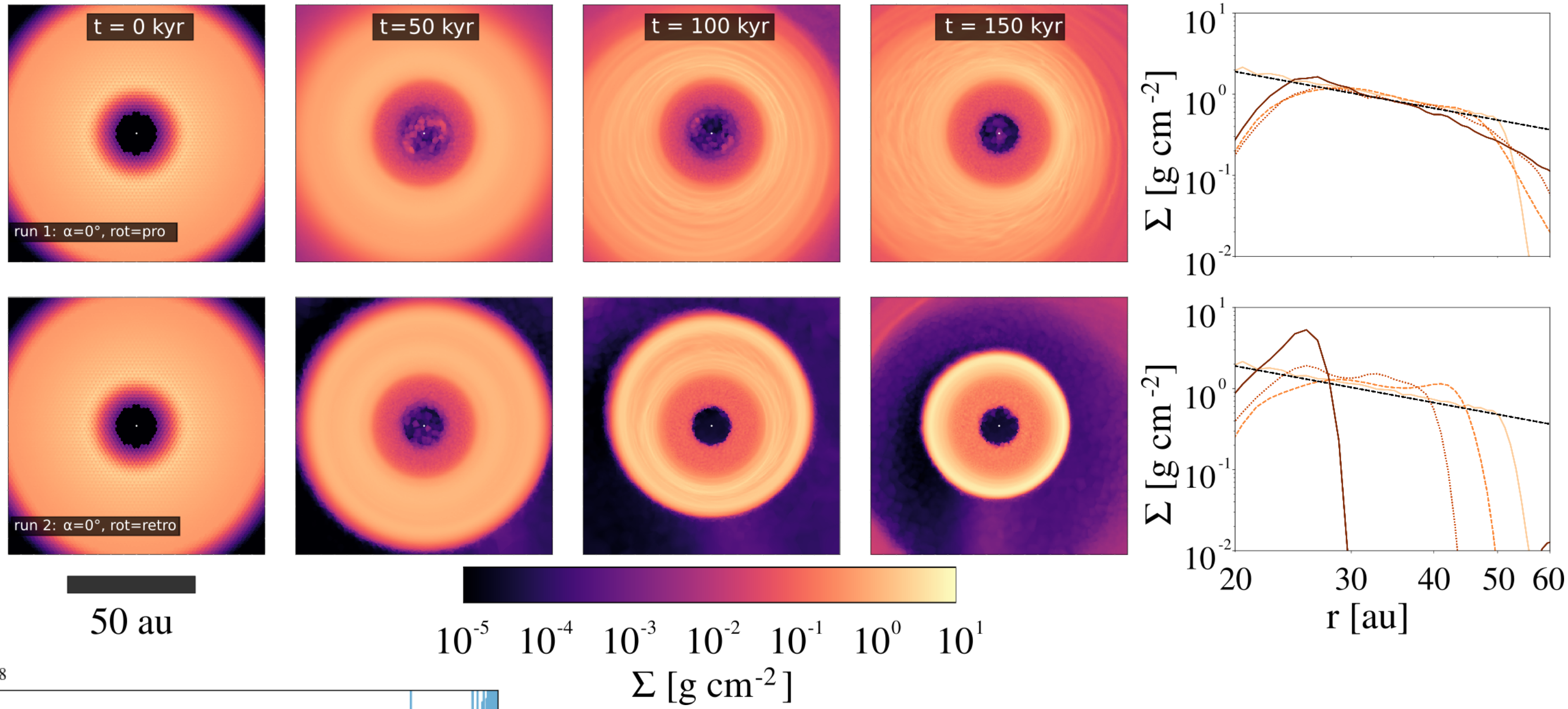

**Retrograde infall causes:**

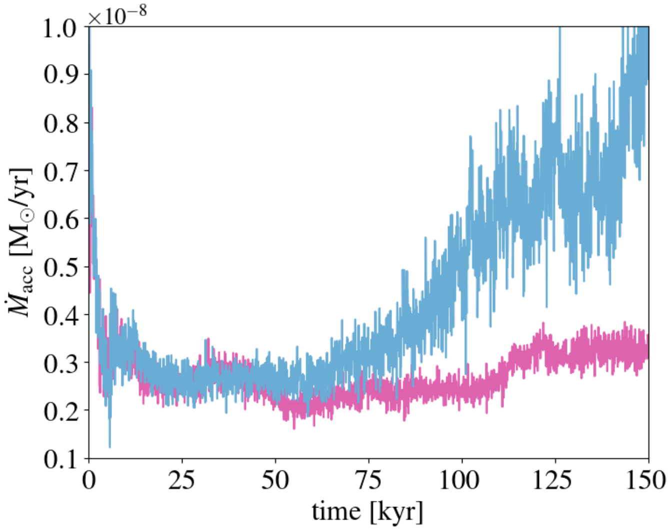
- counter-rotating inner and outer disk
- larger and deeper gap between disks
- shrinking of inner disk

*see also Vorobyov+ 2016*

*Küffmeier et al. 2021*

# Prograde vs. retrograde infall



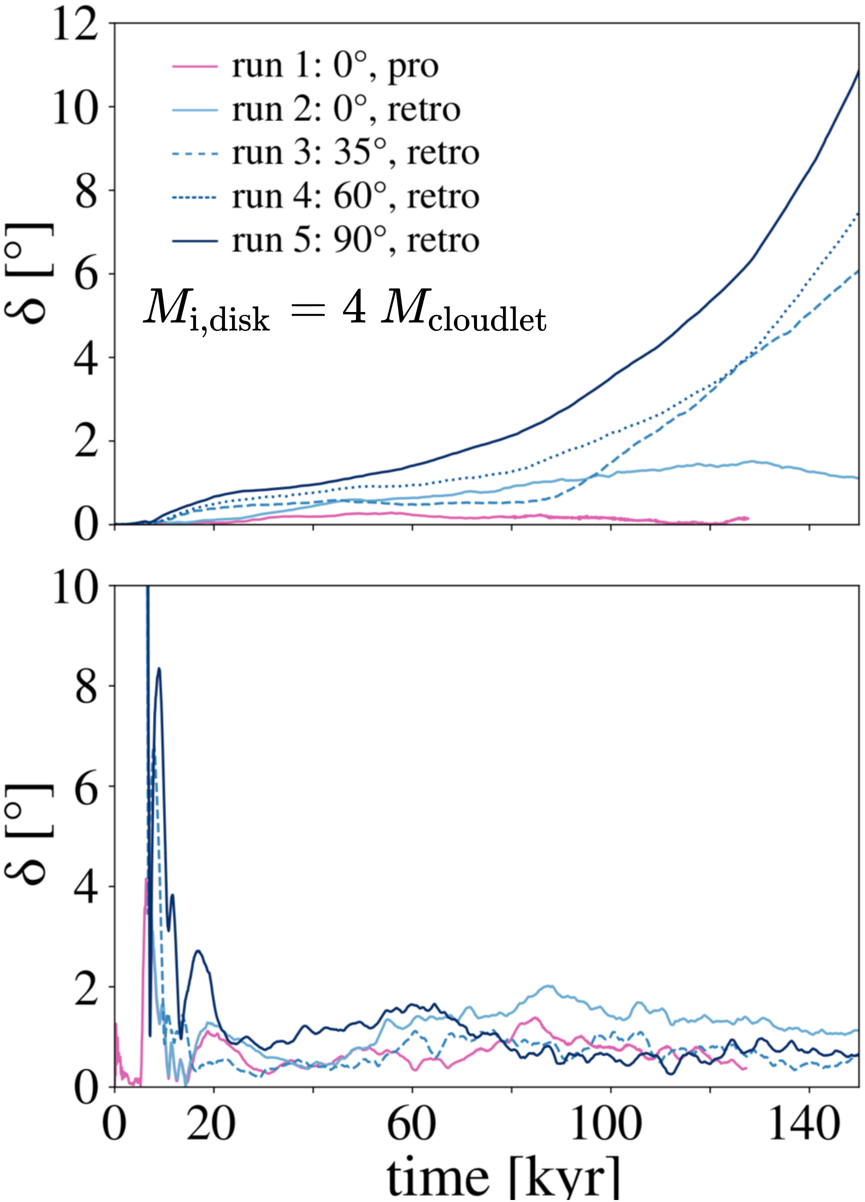




**Retrograde infall causes:**

- counter-rotating inner and outer disk
- larger and deeper gap between disks
- shrinking of inner disk *see also Vorobyov+ 2016*
- enhanced accretion

*Küffmeier et al. 2021*

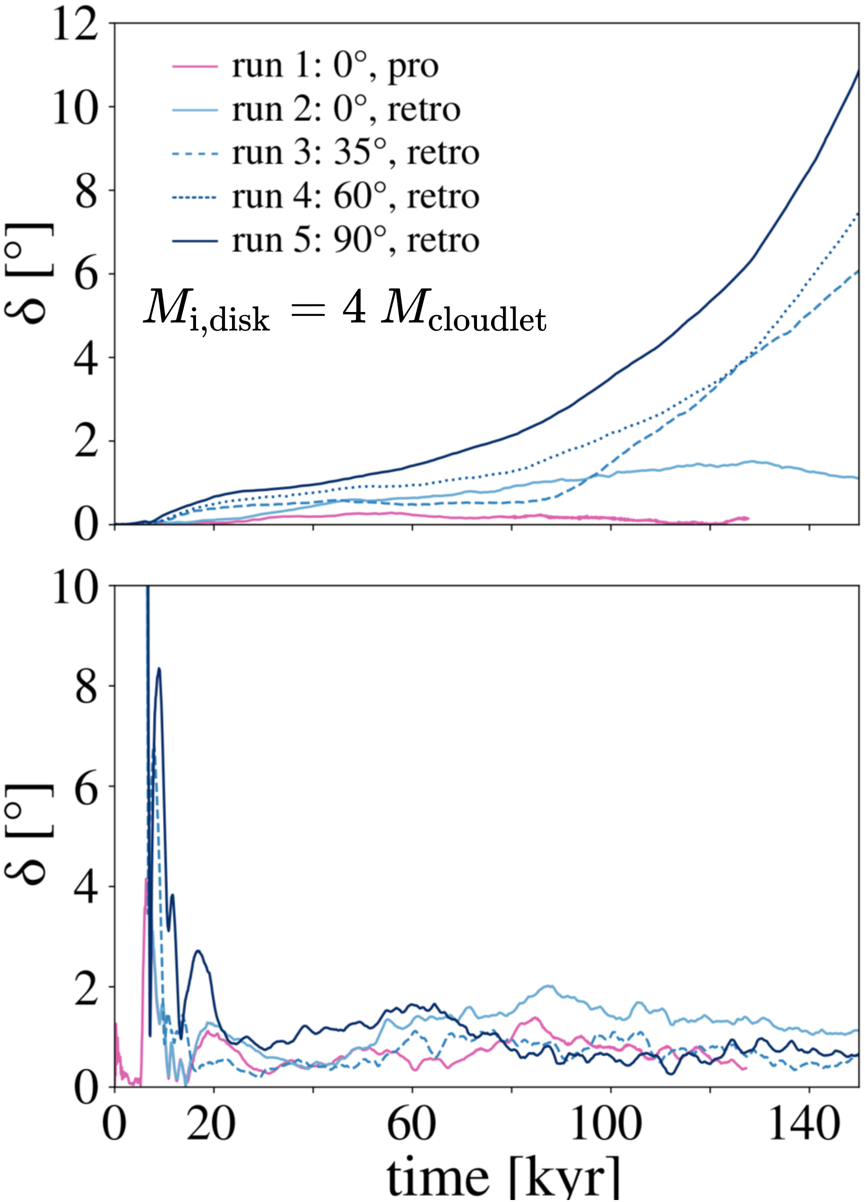
# Inner disk orientation

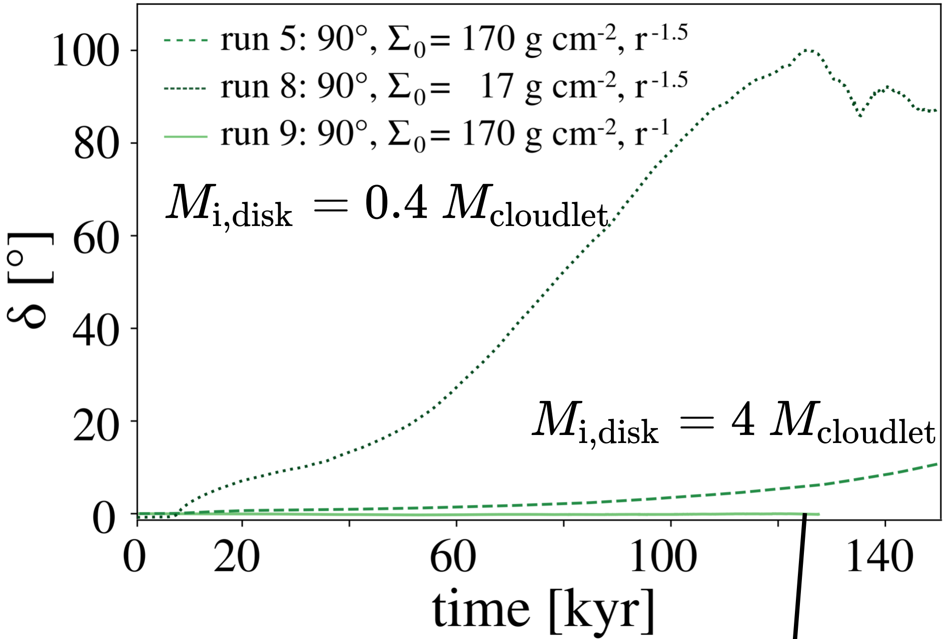



$M_{\rm cloudlet} = 1.87 \times 10^{-4}\ {\rm M}_\odot$

*Küffmeier et al. 2021*

# Inner disk orientation




$M_{\mathrm{i,disk}} = 24 M_{\mathrm{cloudlet}}$

$M_{\mathrm{cloudlet}} = 1.87 \times 10^{-4}\ \mathrm{M}_{\odot}$

*Küffmeier et al. 2021*