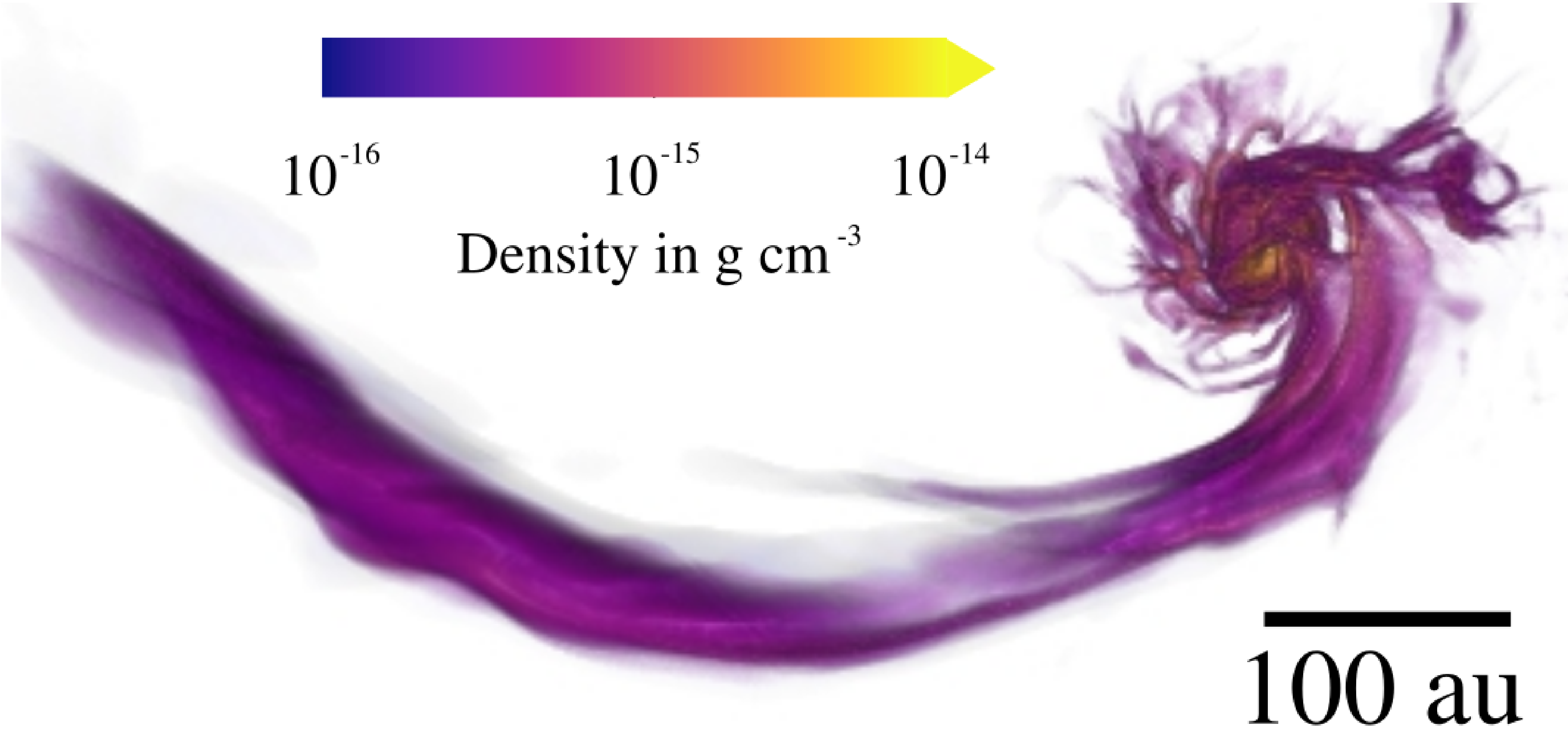
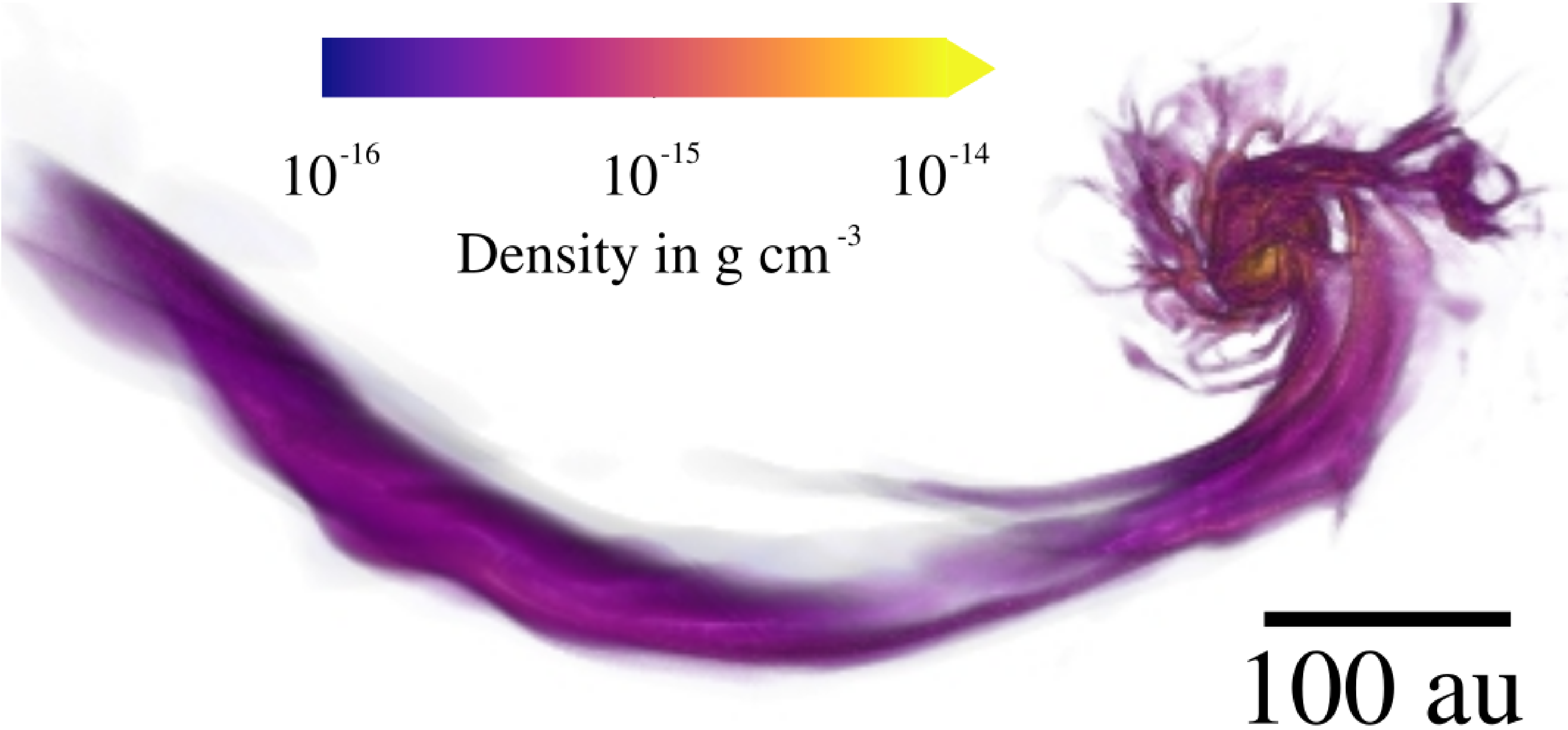
What we know, think to know, and don't know about disk formation?



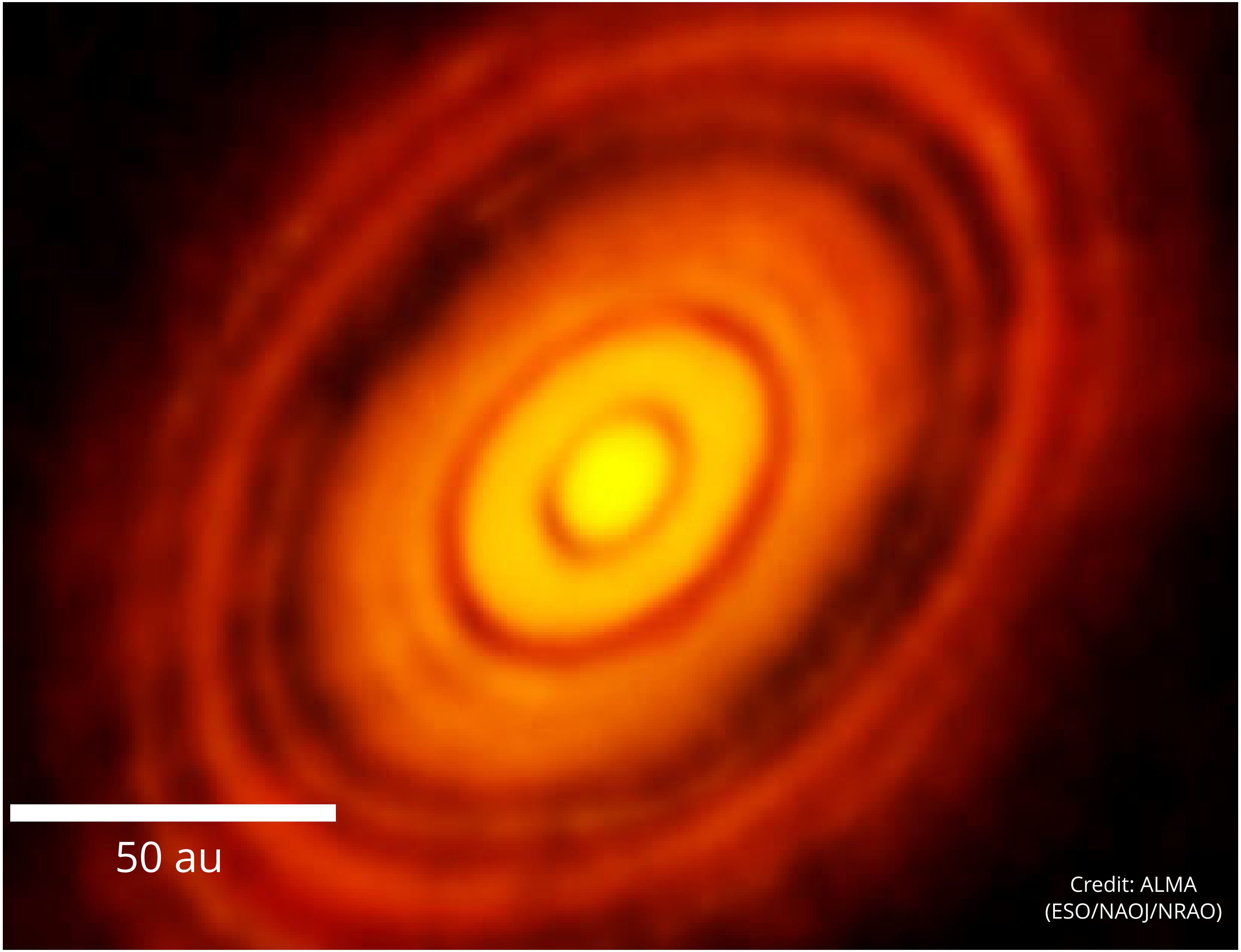
Michael Küffmeier

How did it begin?

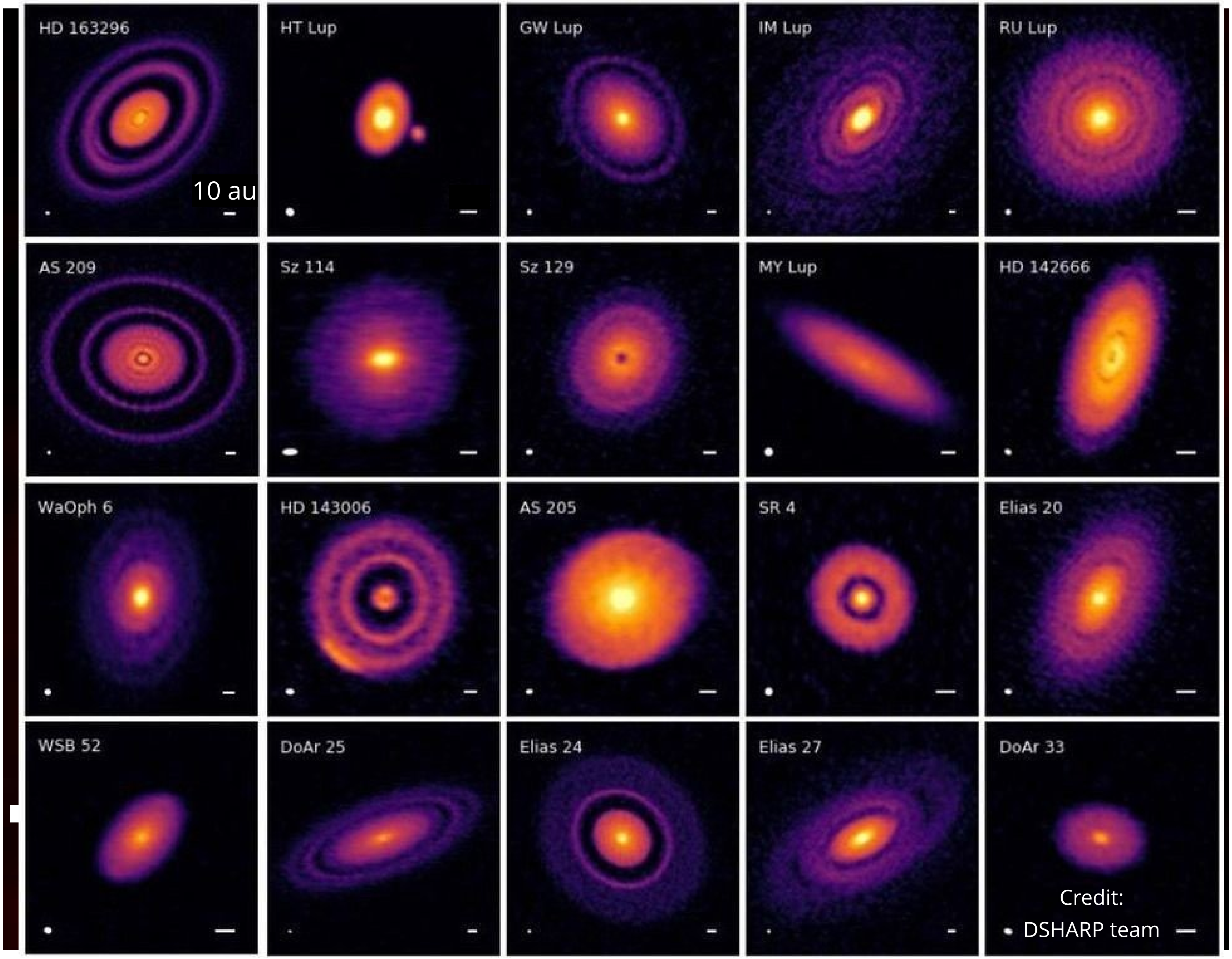


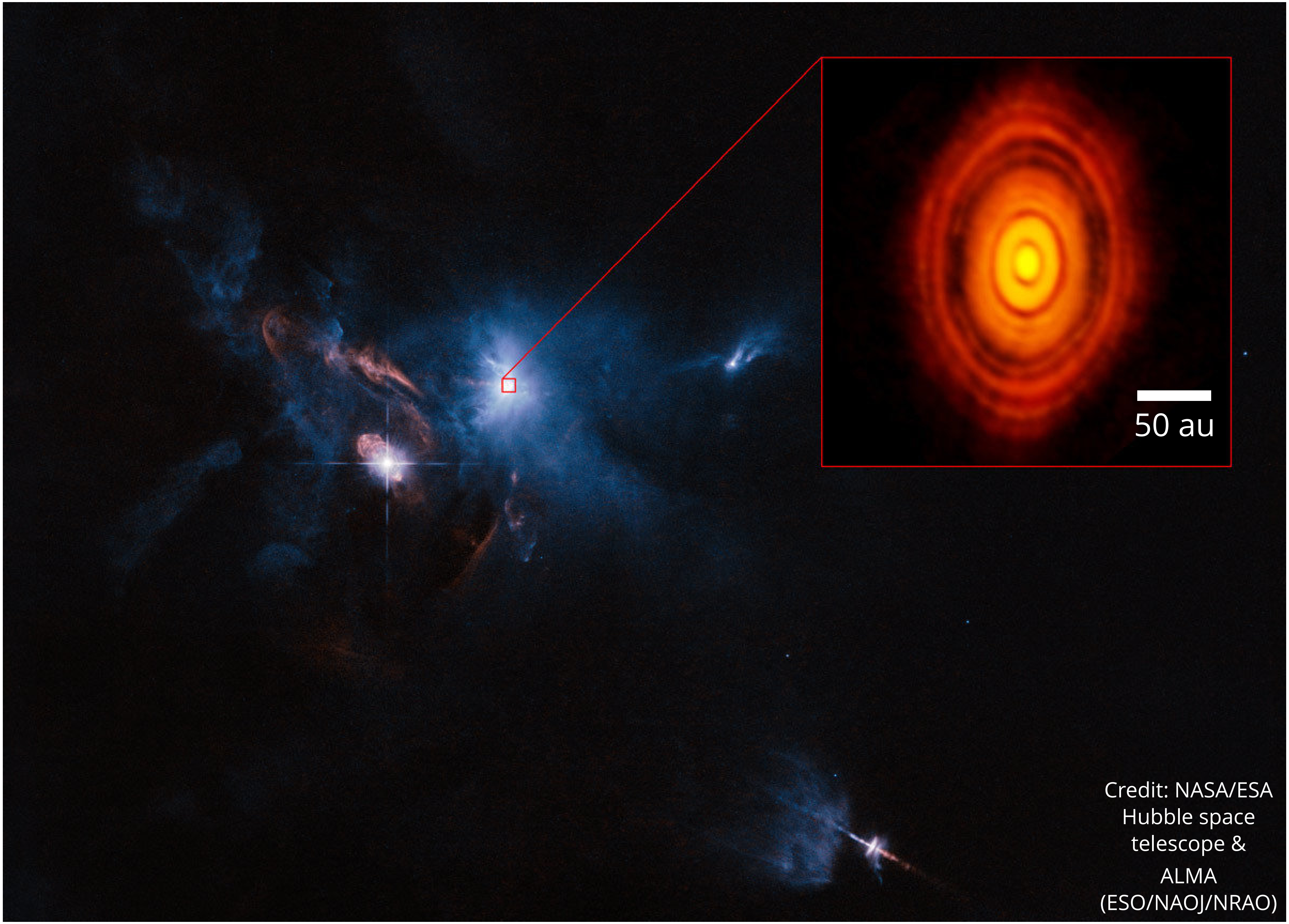
Michael Küffmeier

Let's go 7 years back in time to the year 2014

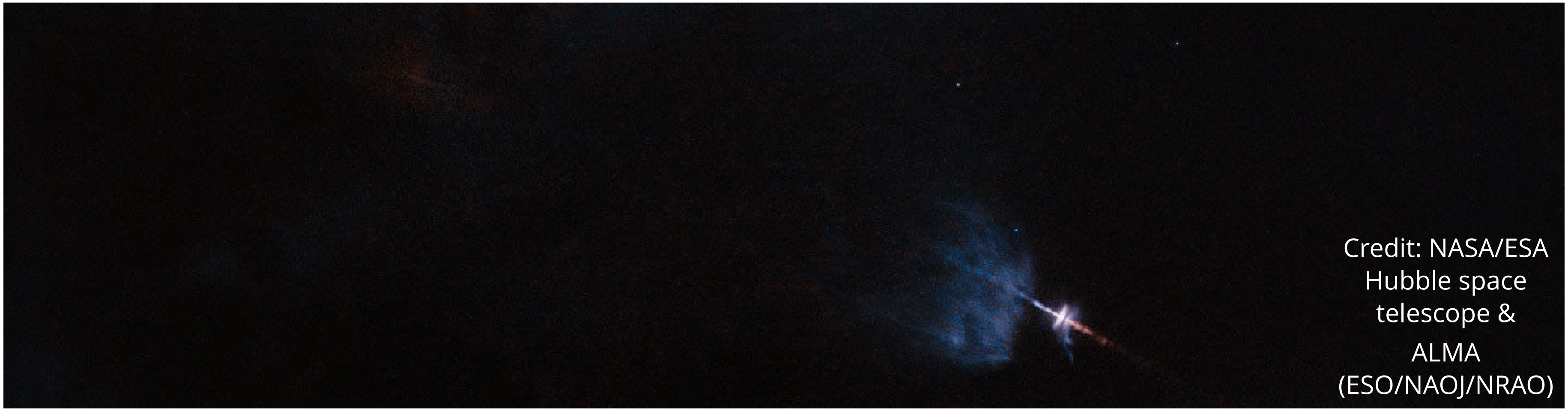

50 au
Credit: ALMA (ESO/NAOJ/NRAO)


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


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


50 au
Credit: NASA/ESA Hubble space telescope & ALMA (ESO/NAOJ/NRAO)

The big challenge:



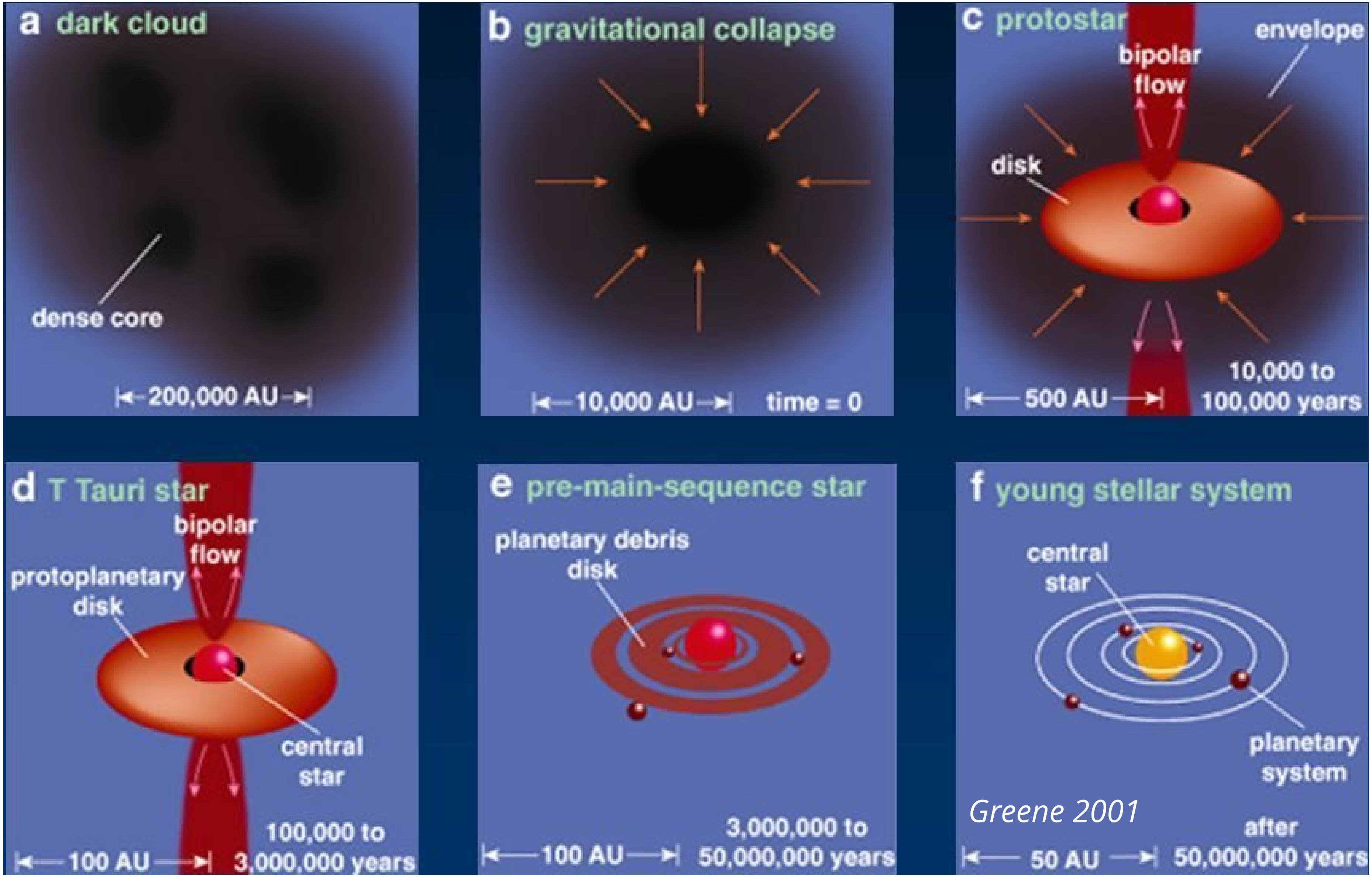
link planet

to star

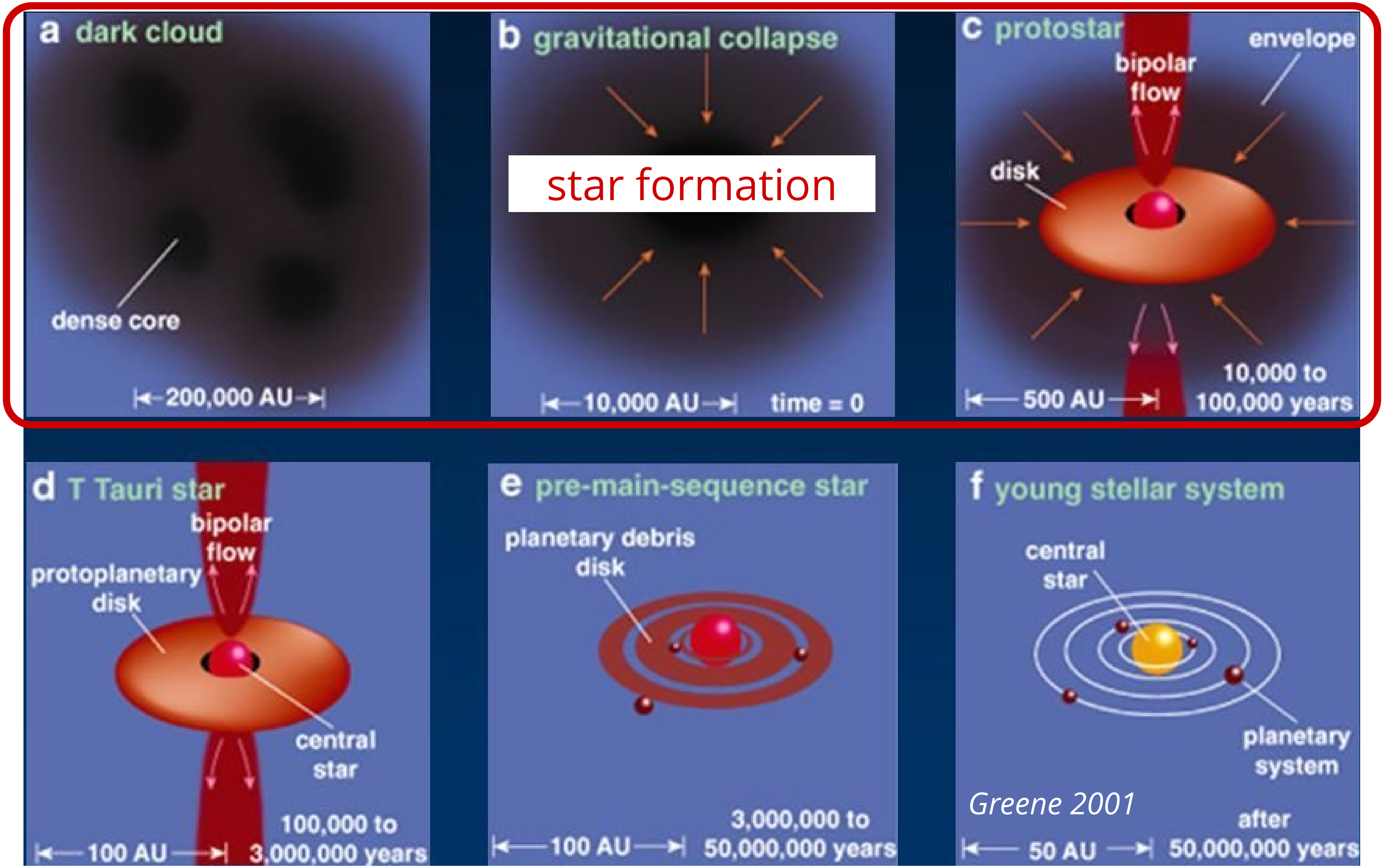
formation

ALMA
(ESO/NAOJ/NRAO)

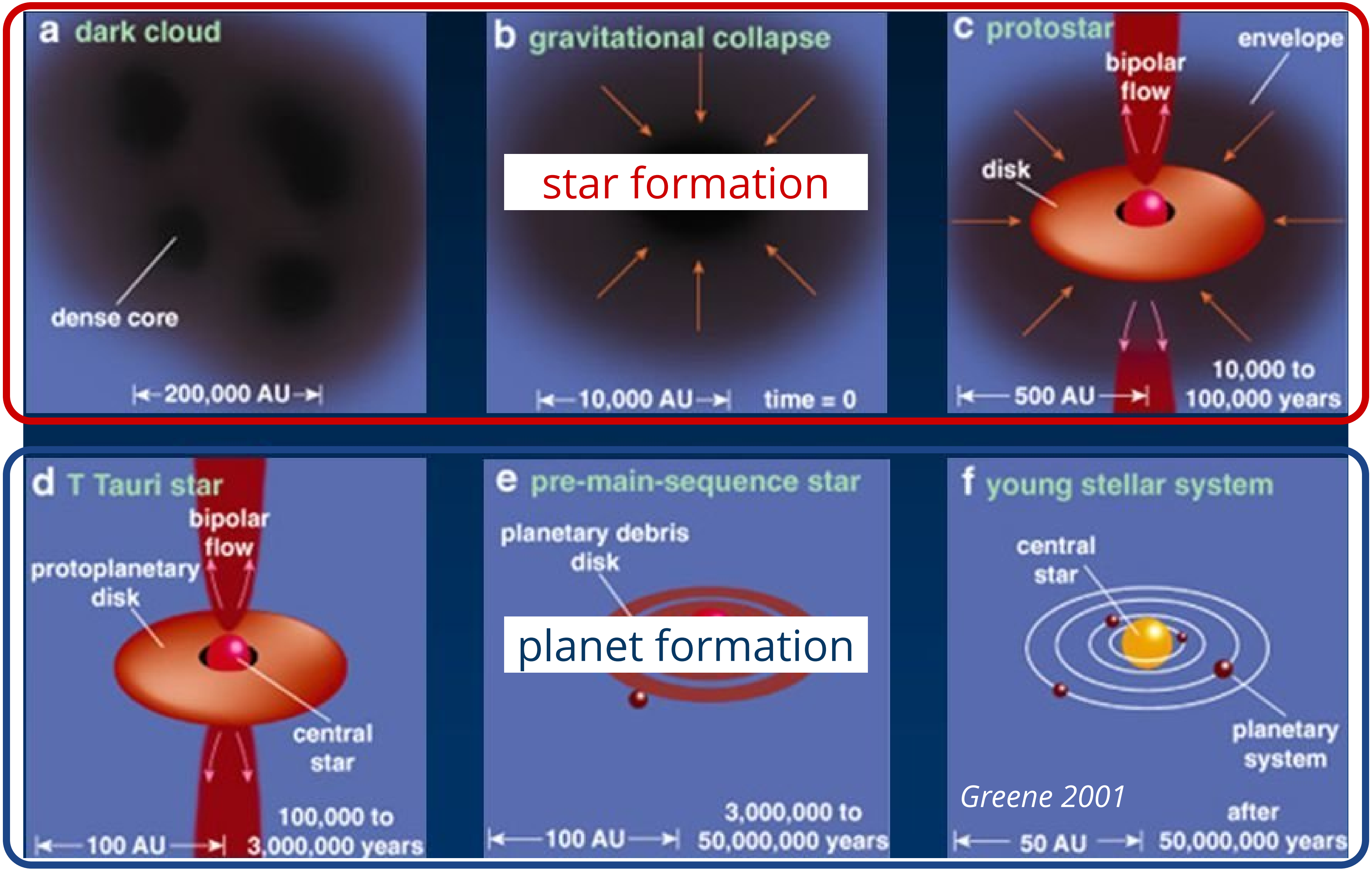
The classical picture



The classical picture

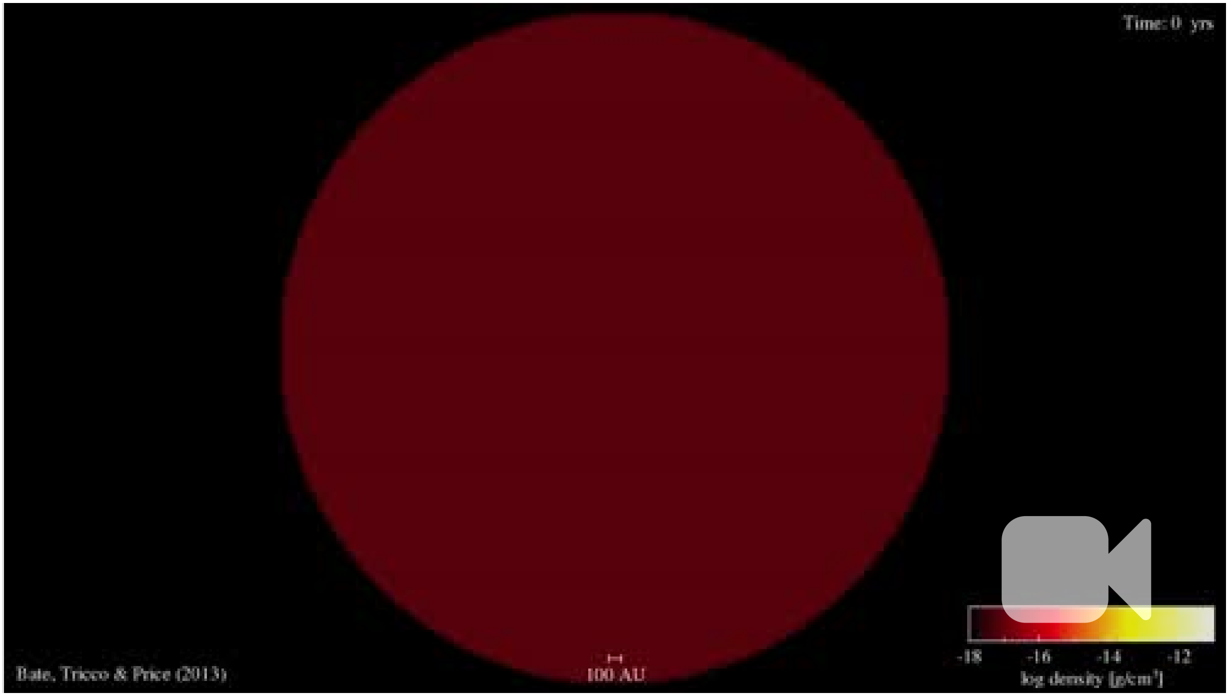


The classical picture



Greene 2001

History of modeling disk formation



spherical core collapse:

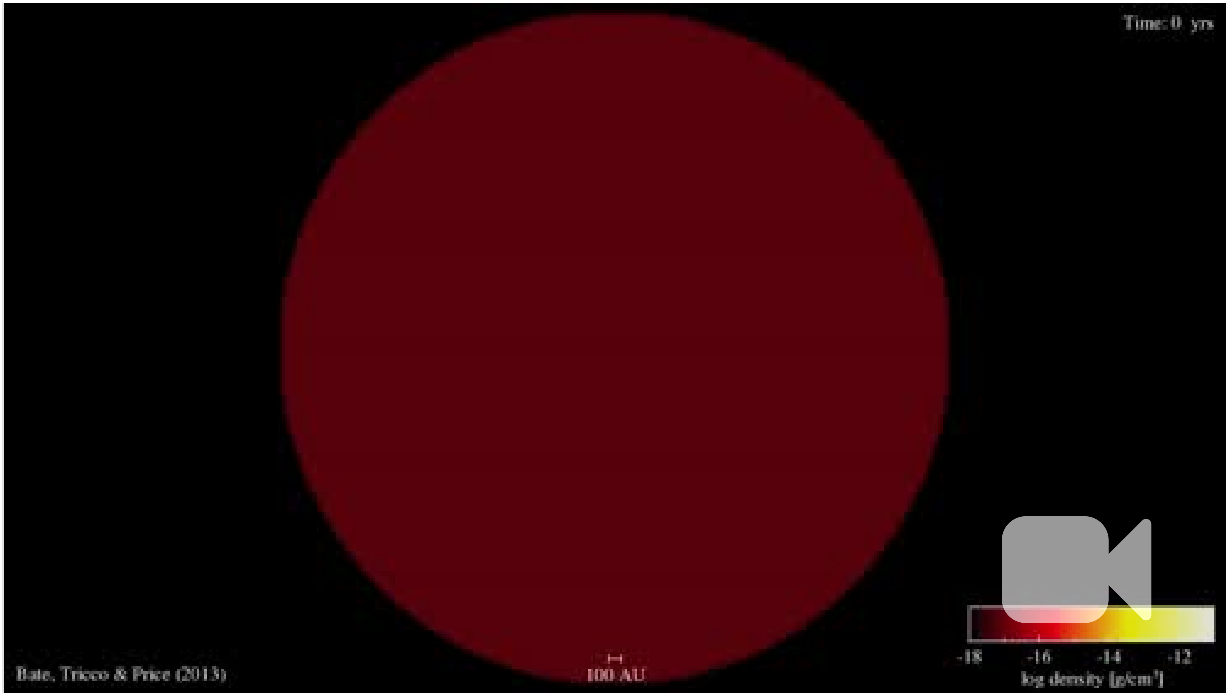
Bonnor-Ebert sphere

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

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

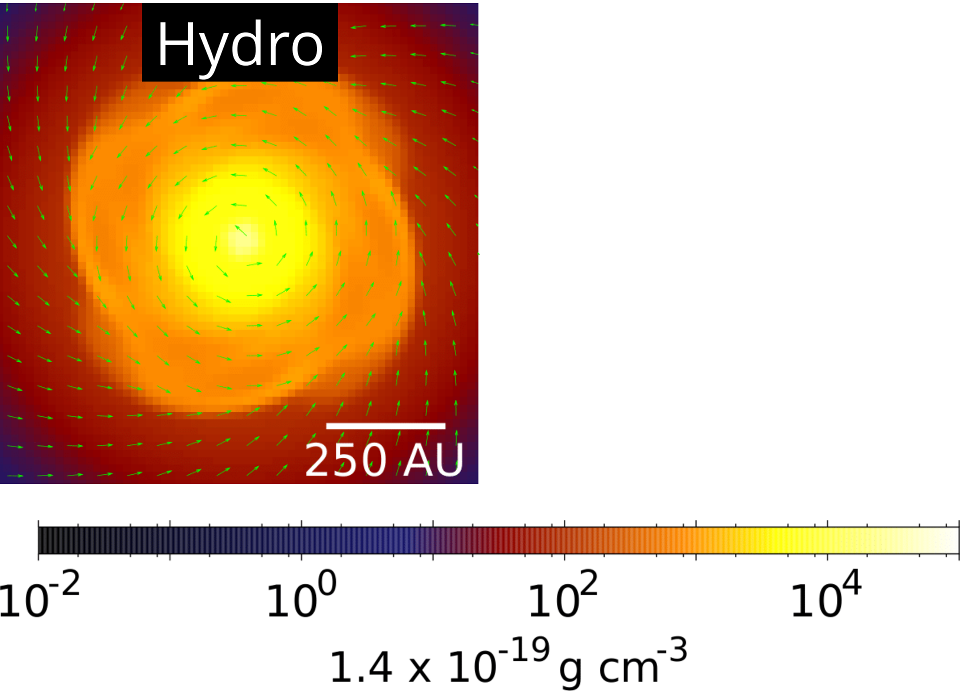
magnetization (mass-to-flux ratio)

non-ideal MHD effects

dust evolution

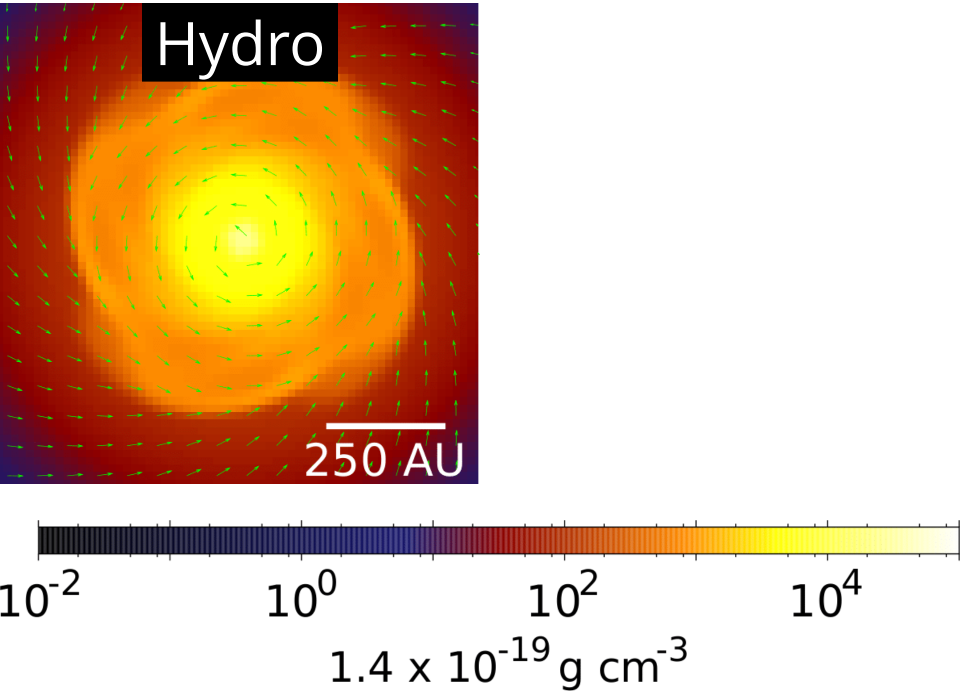
turbulence

History of modeling disk formation



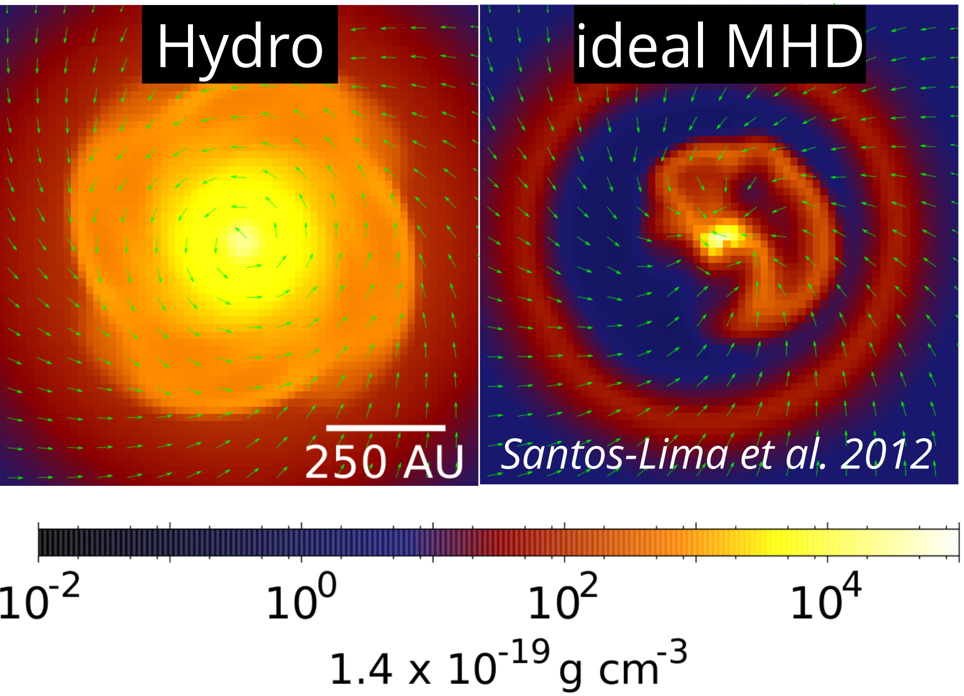
History of modeling disk formation

What about magnetic fields?



History of modeling disk formation

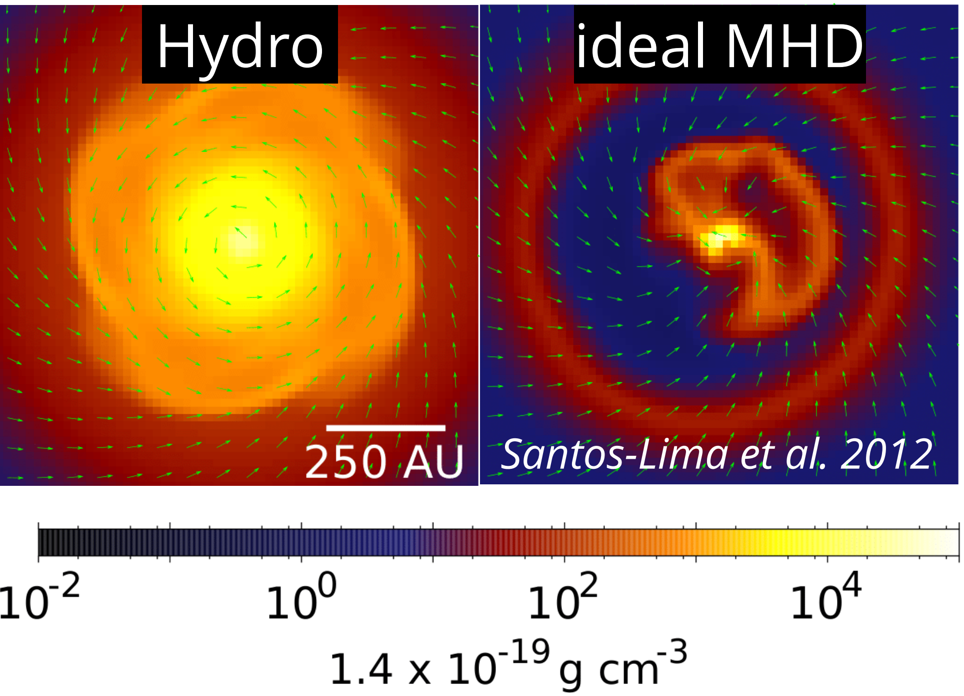
What about magnetic fields?



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

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

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

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

Hall

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

Non-ideal magnetohydrodynamics

ideal MHD

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

Ohmic dissipation

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

Hall

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

ambipolar diffusion

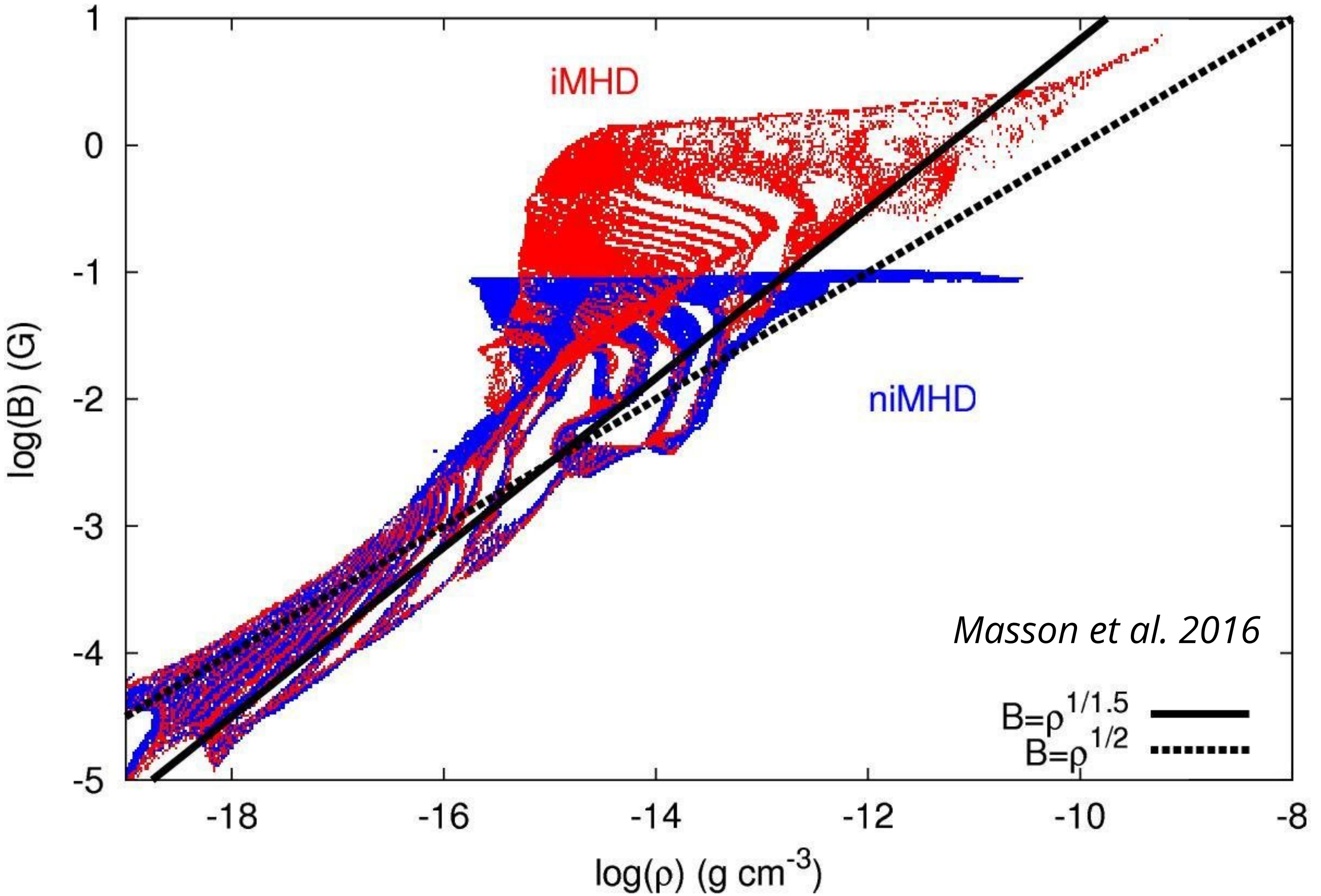
$$-\boldsymbol{\nabla} \times \{\eta_{\mathrm{AD}}\mathbf{B}/B \times [(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\}$$

Non-ideal MHD

resistivities quench pile-up of magnetic field

↓

avoids magnetic braking catastrophe



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

more references in Wurster & Li 2018 (review)

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

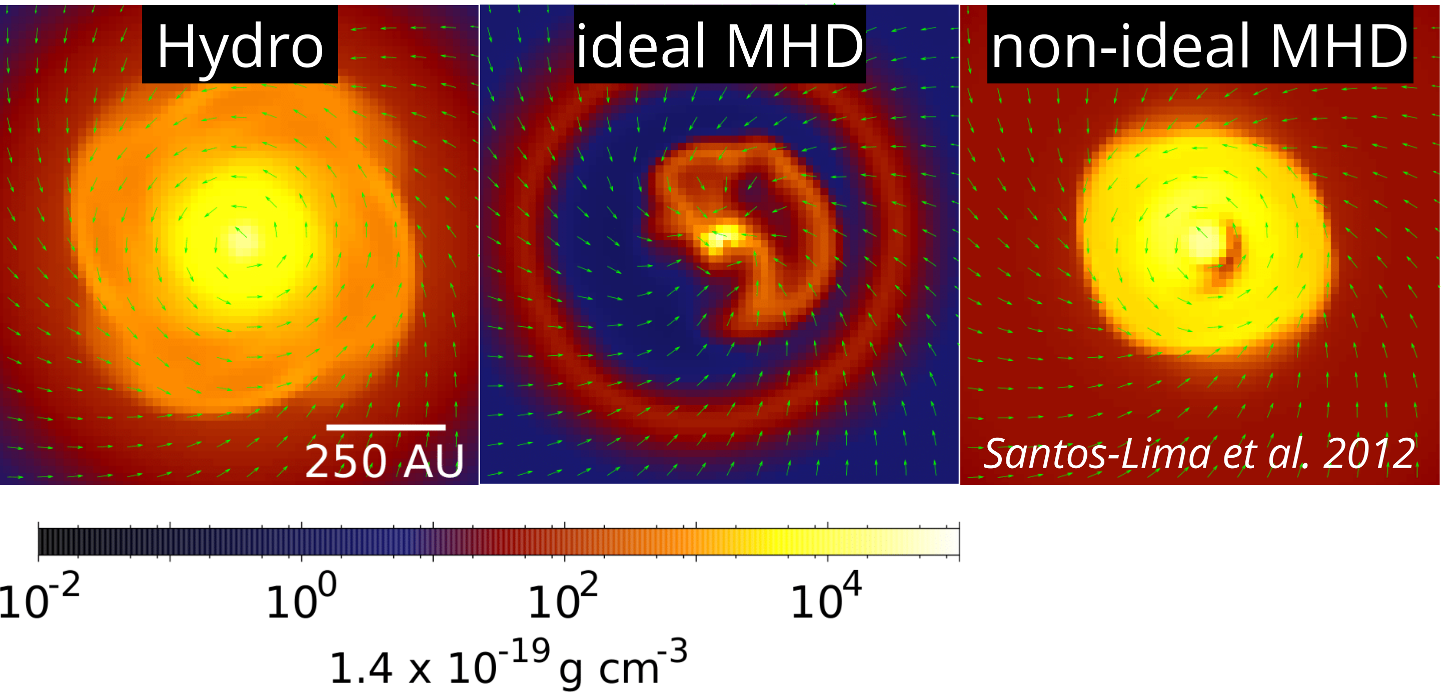
$$-\nabla \times [\eta_{\rm O}(\nabla \times \mathbf{B})] \; -\nabla \times \{\eta_{\rm H}[(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\} -\nabla \times \{\eta_{\rm AD}\mathbf{B}/B \times [(\nabla \times \mathbf{B}) \times \mathbf{B}/B]\}$$

History of modeling disk formation

What about magnetic fields?

Help! Where is the disk?!

Ohmic, Ambipolar, Hall



History of modeling disk formation

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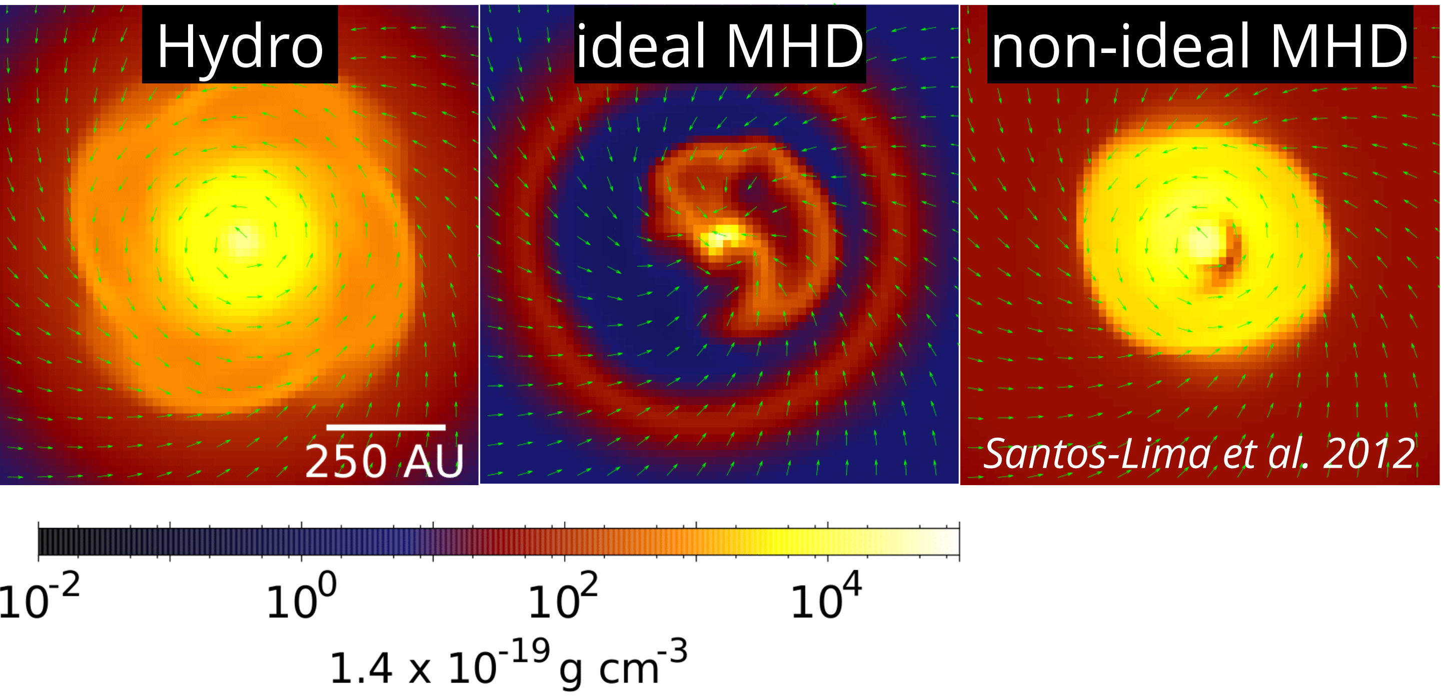
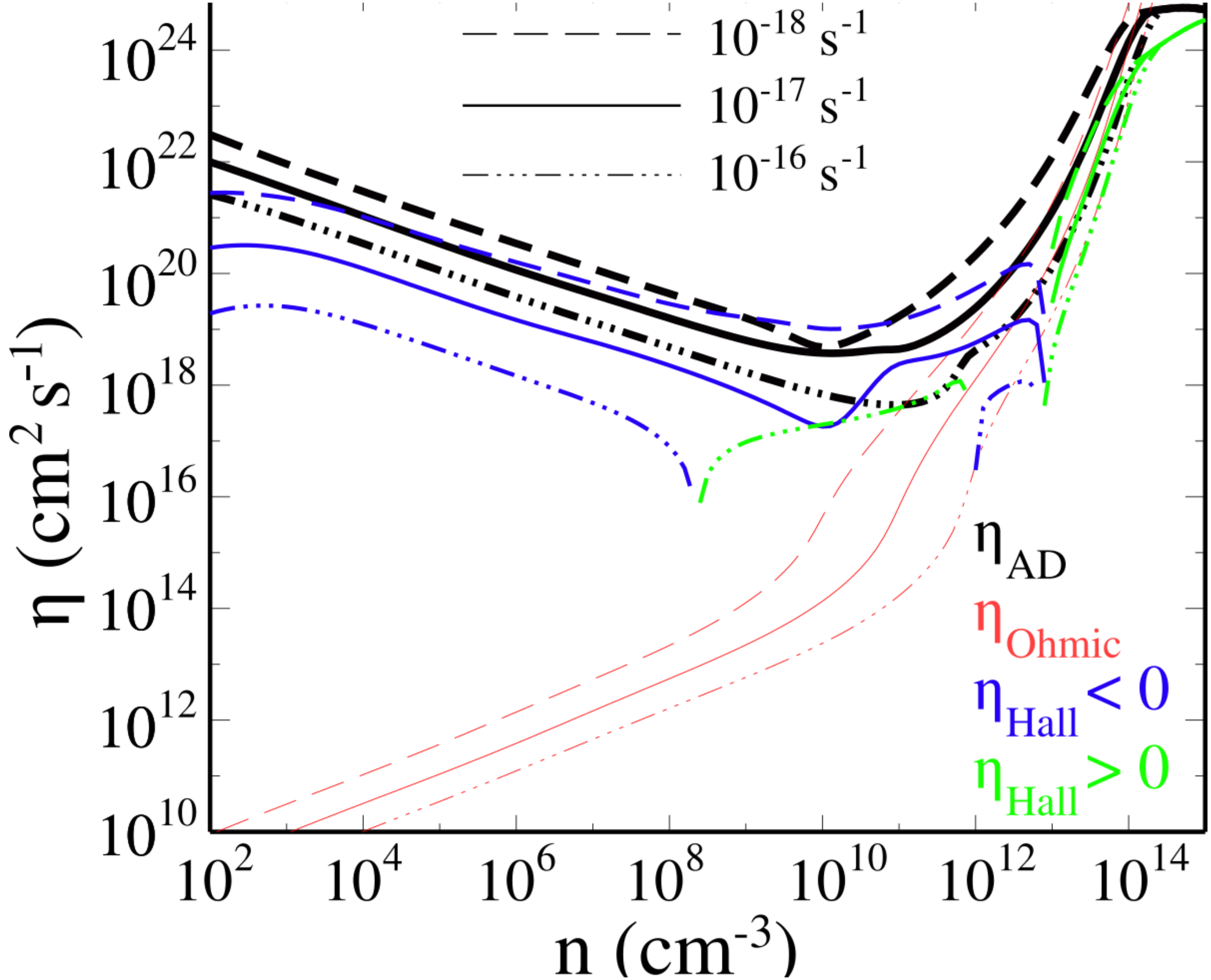


Achtung!

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

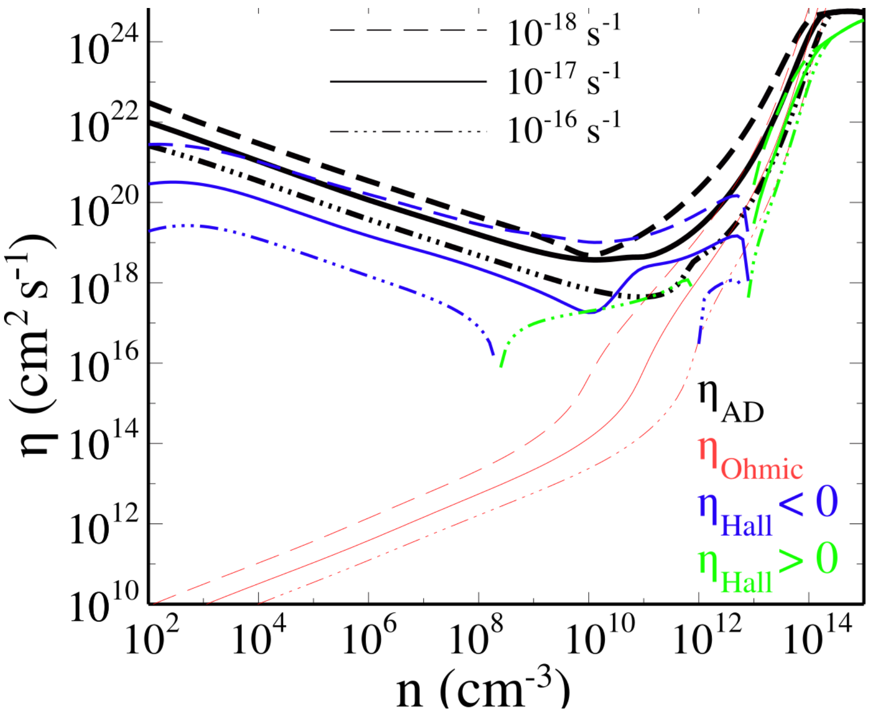
Resistivity depends on ionization rate



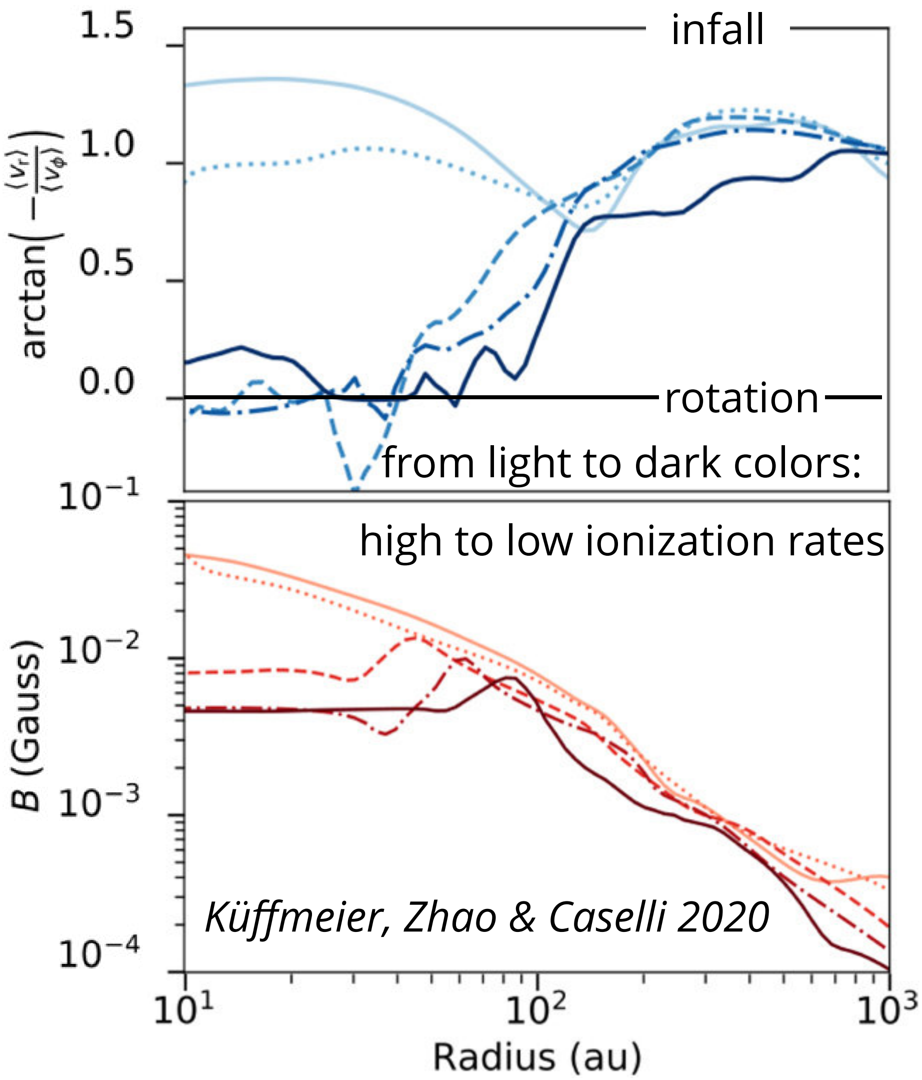
Question: What is the effect on disk formation when differing the ionization rate?

Küffmeier, Zhao & Caselli 2020

Effect of ionization on disk size

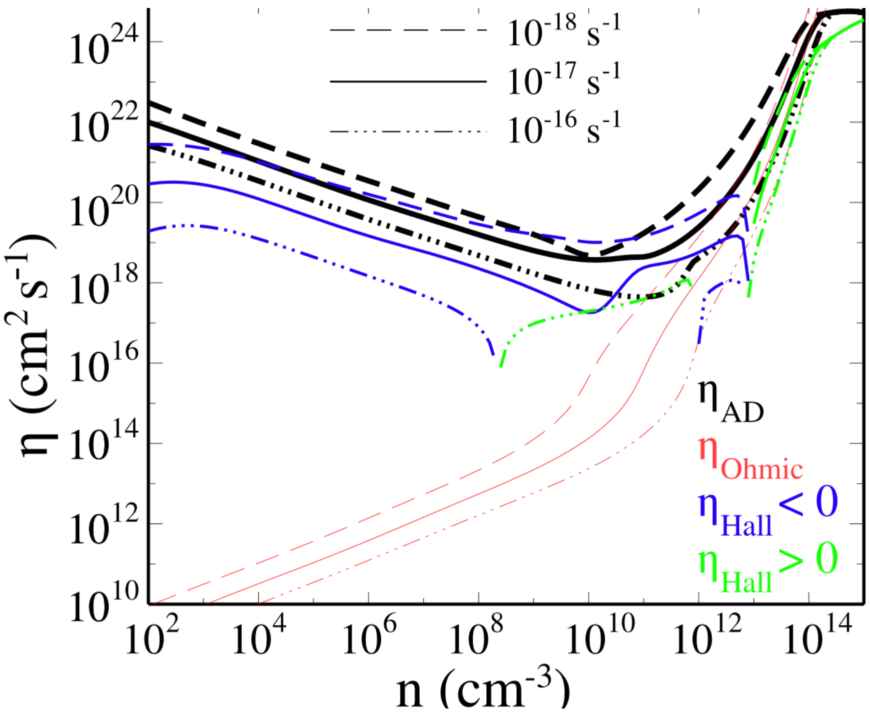


see also Wurster et al. 2018



Küffmeier, Zhao & Caselli 2020

Effect of ionization on disk size



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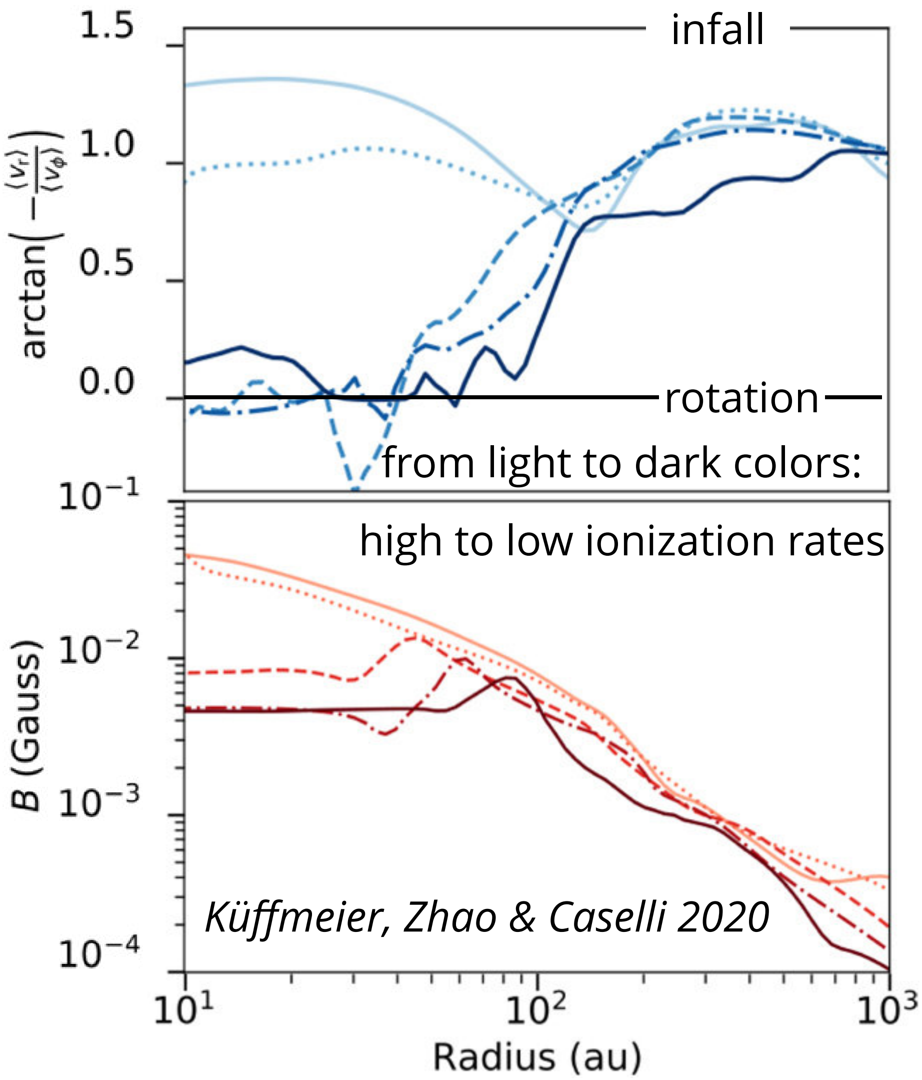
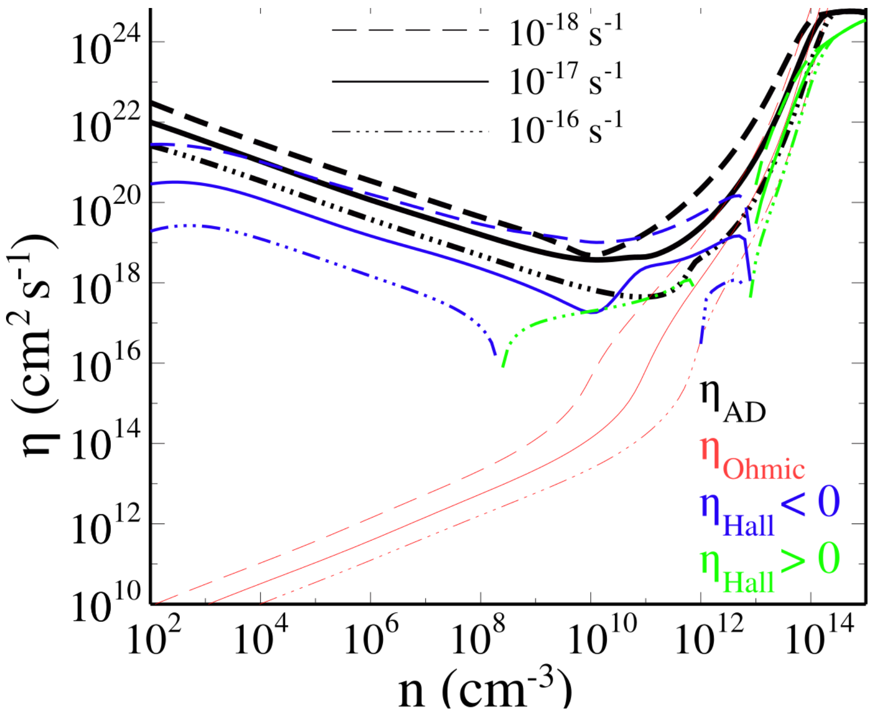
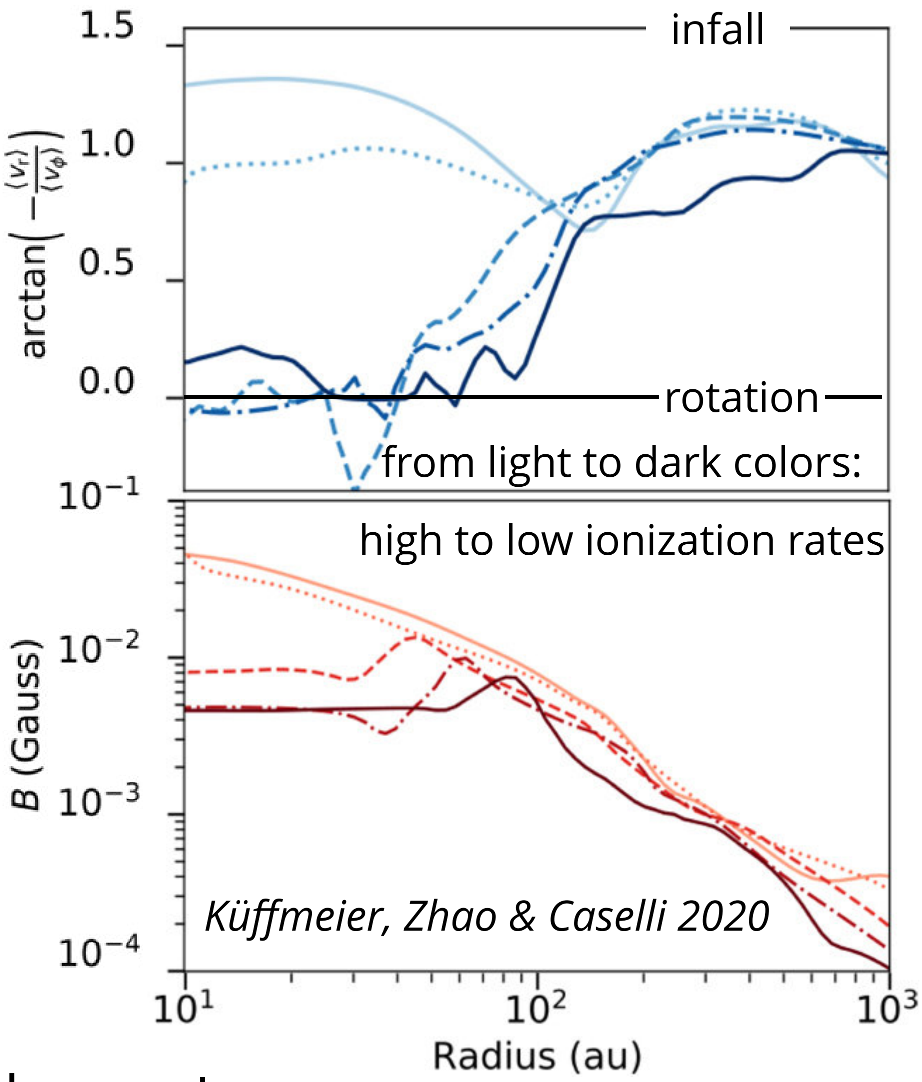


increasing
ionization rate

Effect of ionization on disk size

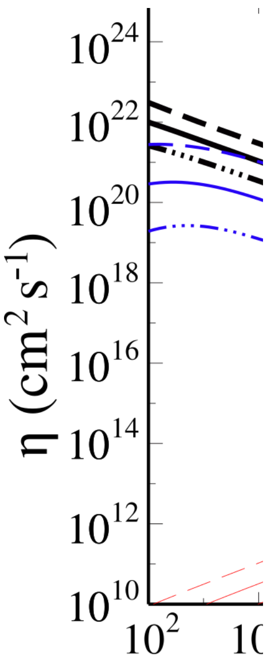


see also Wurster et al. 2018

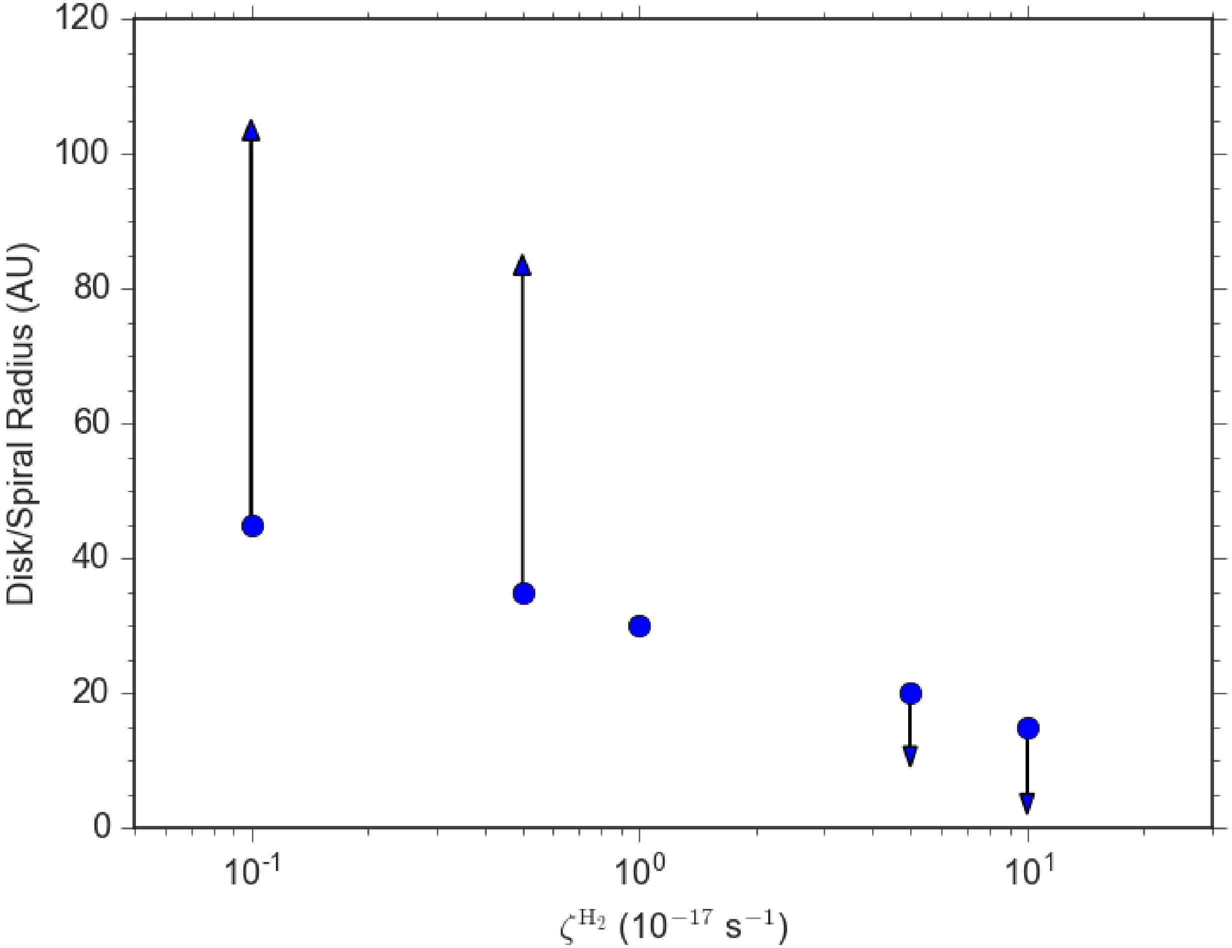


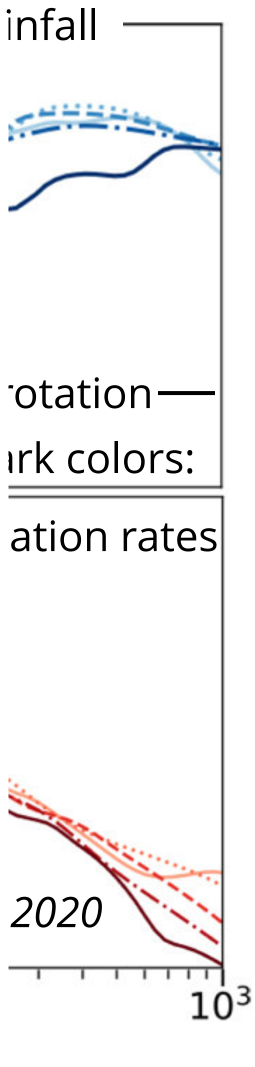
increasing ionization rate → enhanced magnetic braking

Effect of ionization on disk size



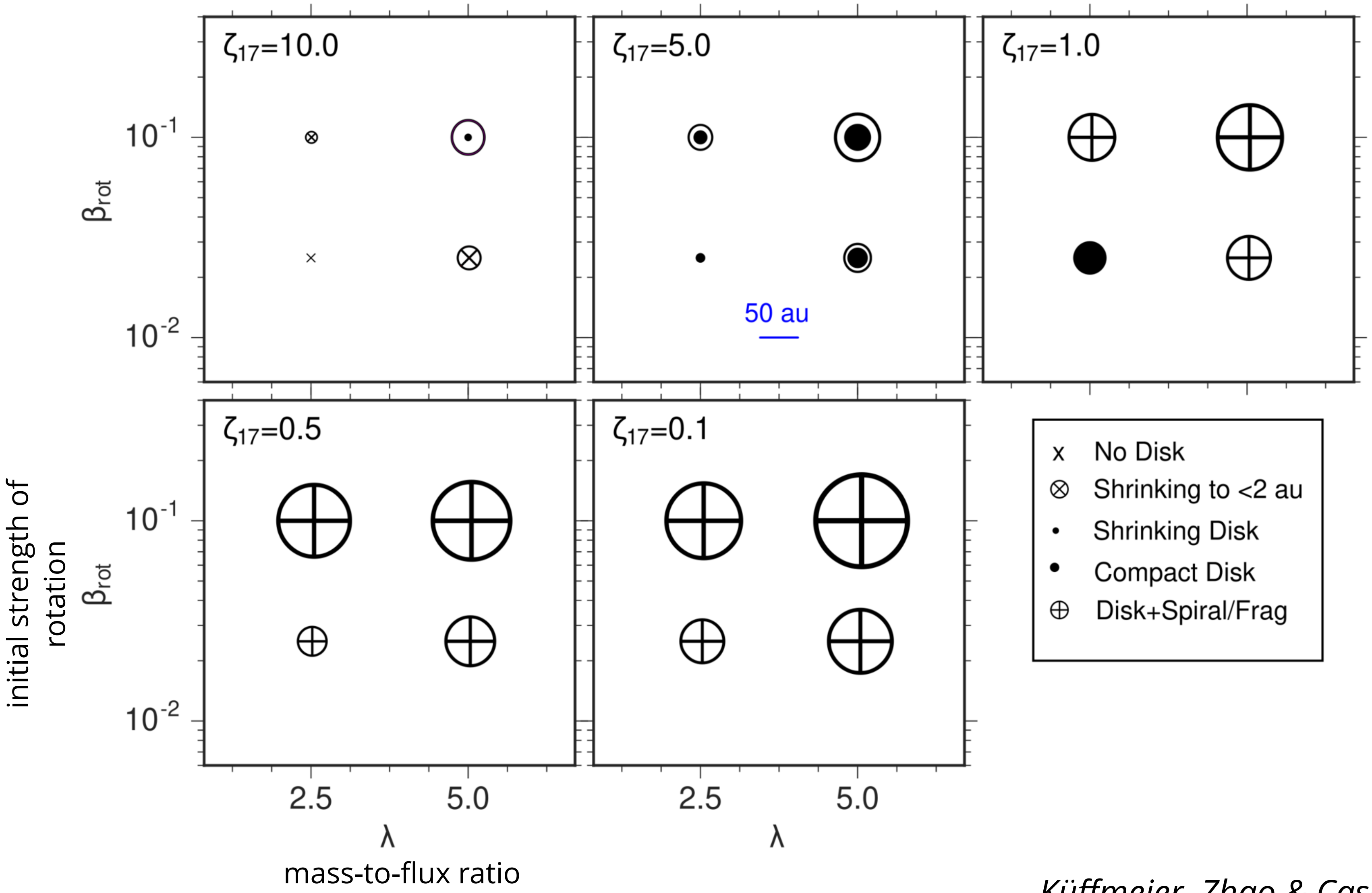
see also W





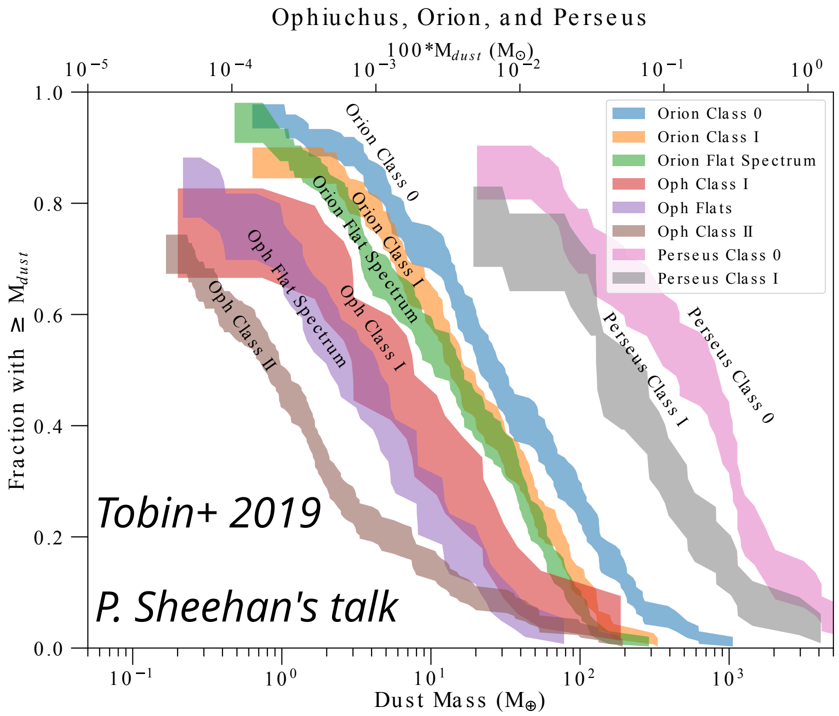
increasing ionization rate ⟶ enhanced magnetic braking ⟶ smaller disks

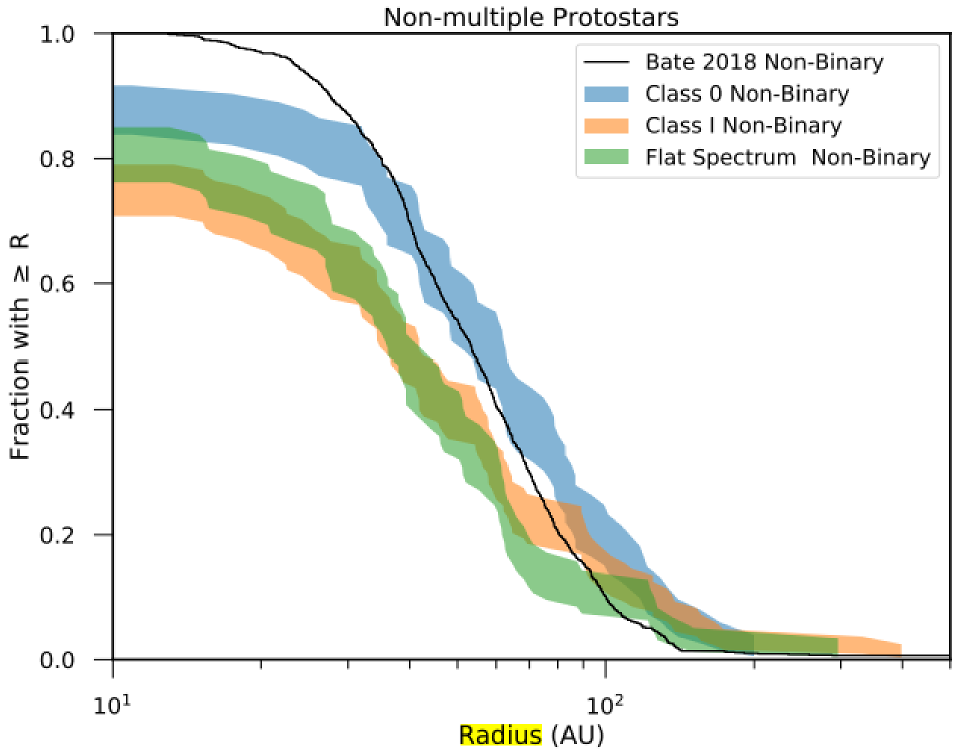
Disk size distribution



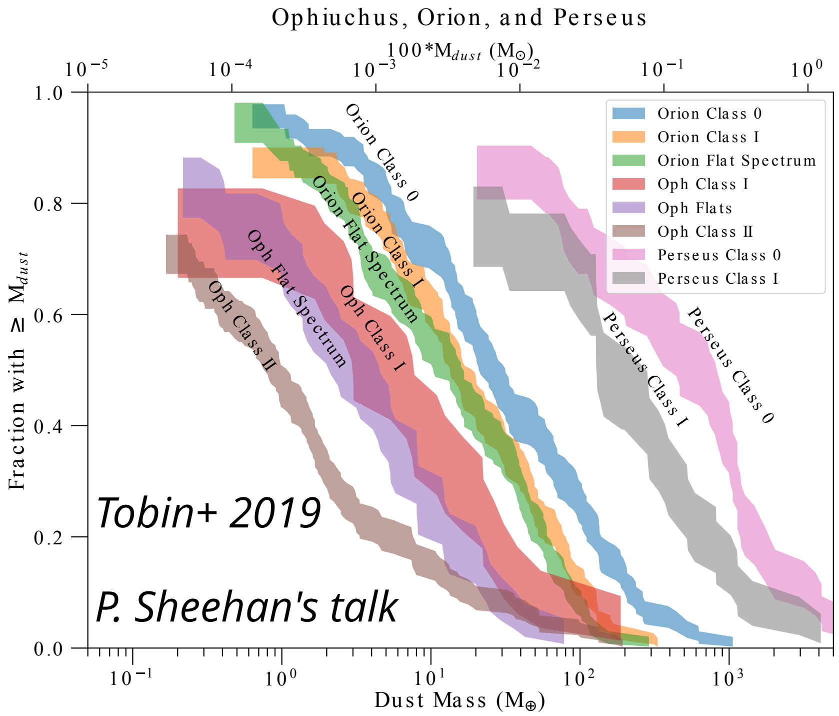
Küffmeier, Zhao & Caselli 2020

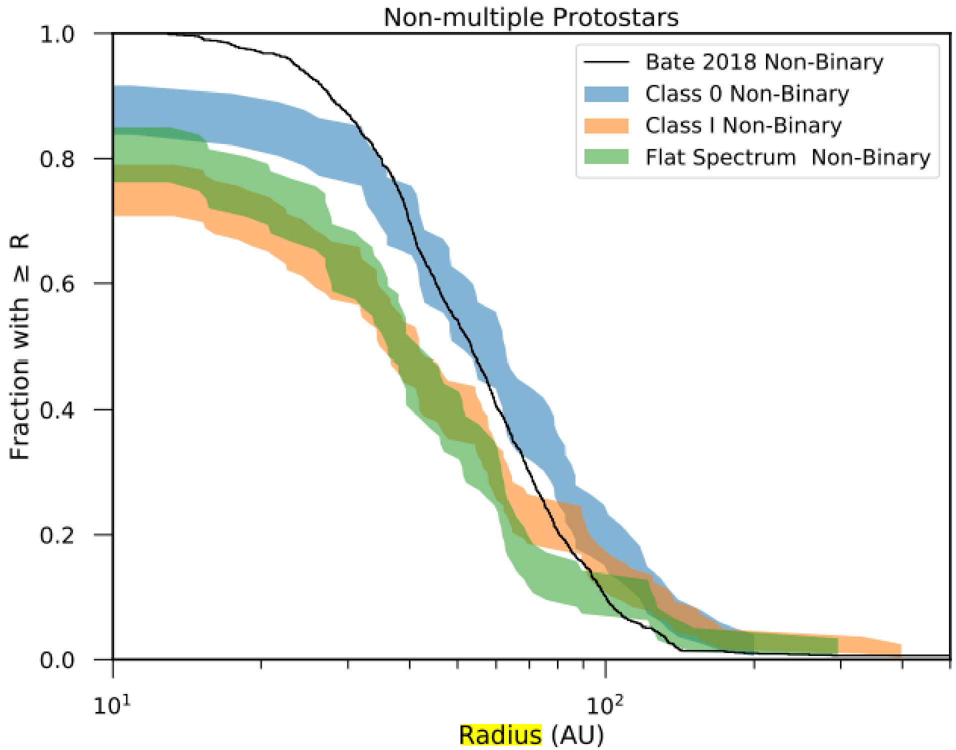
Disk size distribution





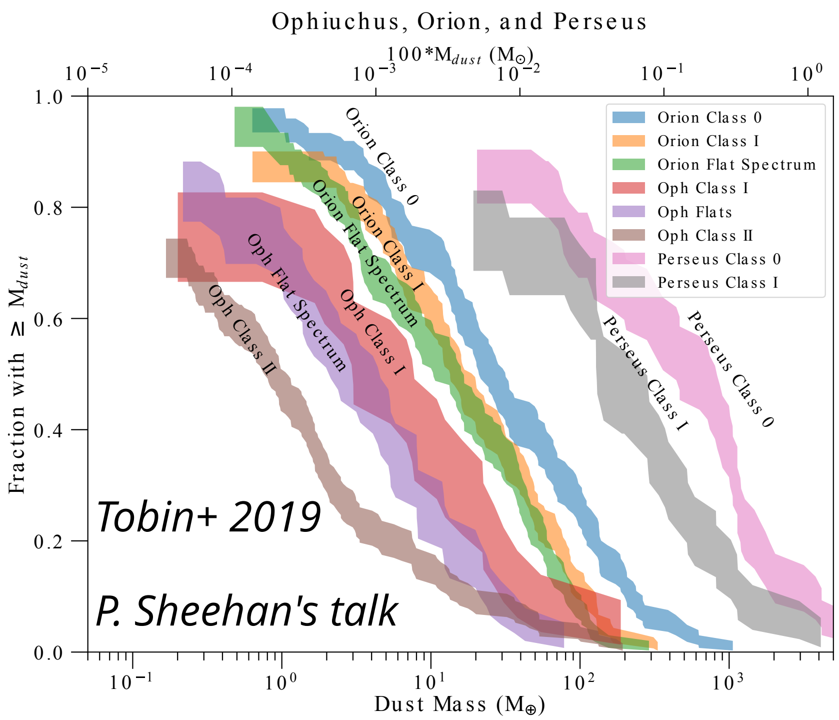
Disk size distribution

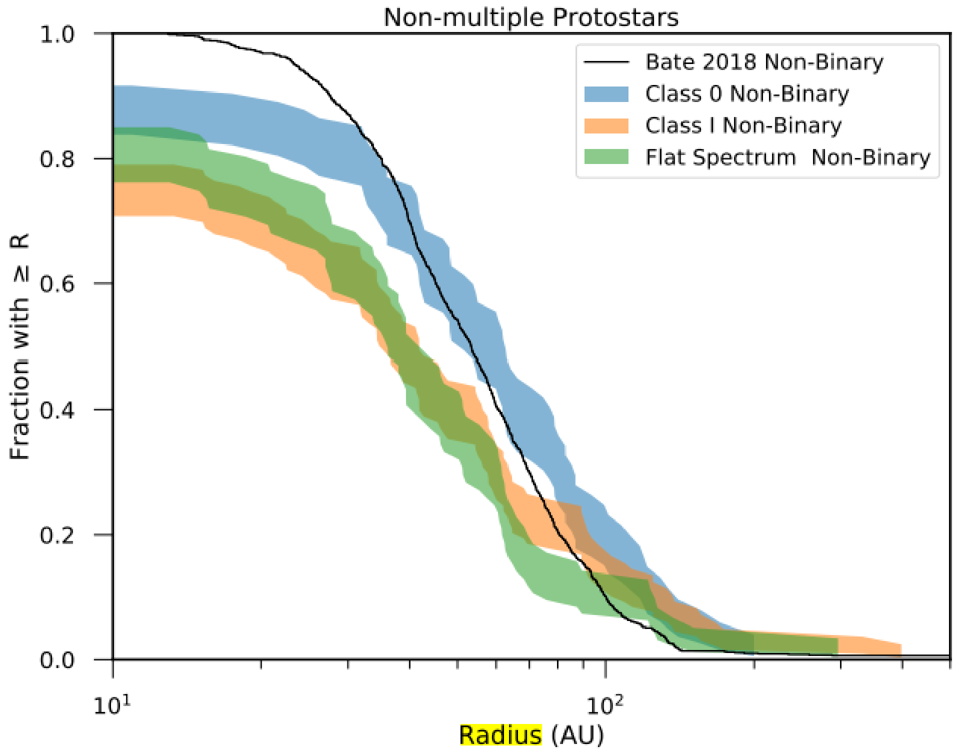




Are disks already born small in some regions?

Disk size distribution

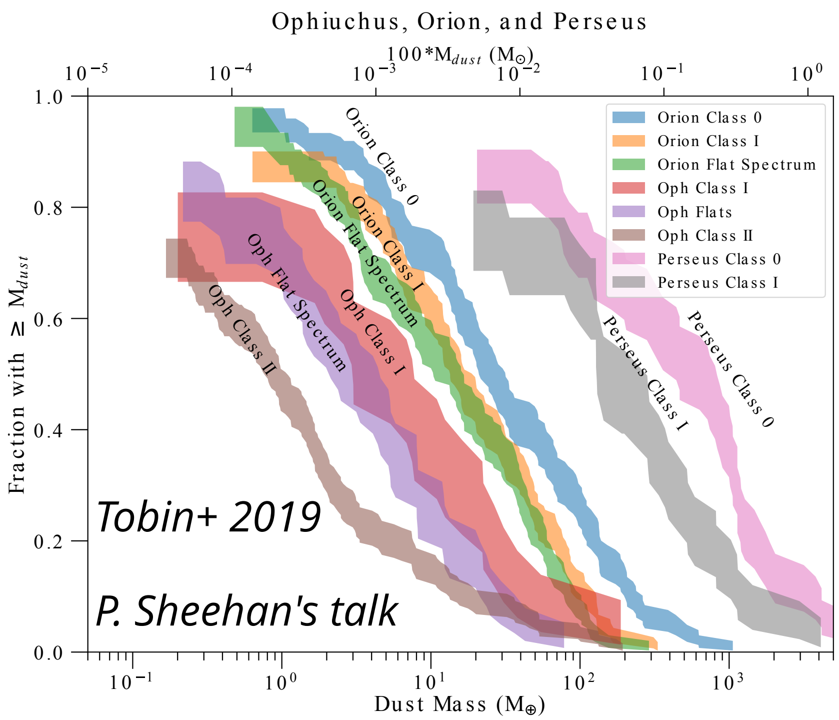


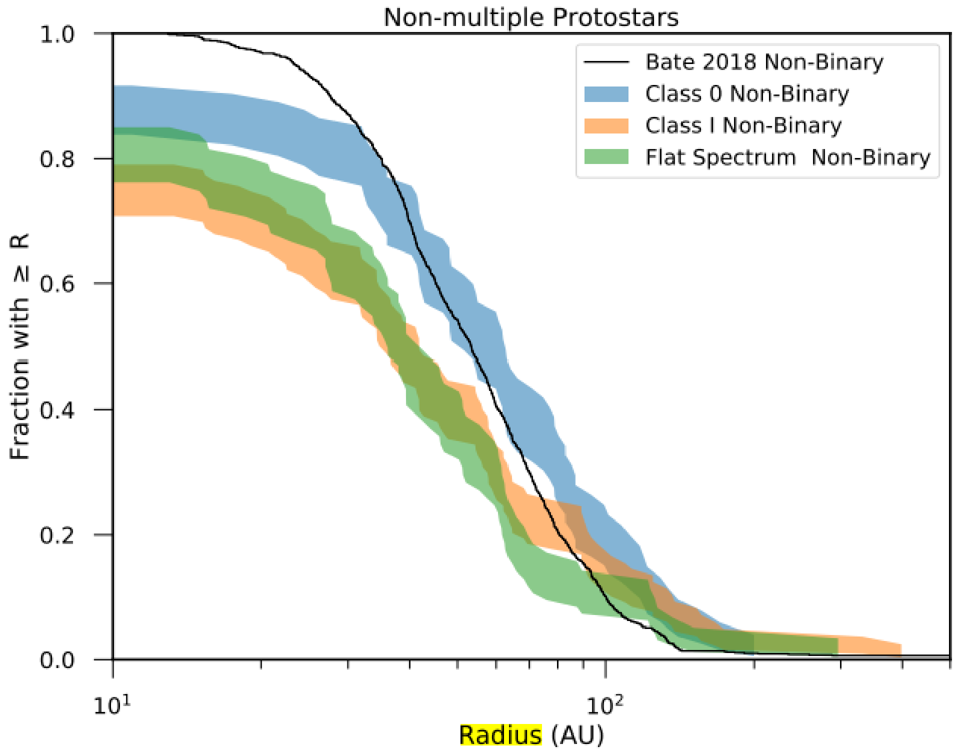


Are disks already born small in some regions?

What is the effect of local ionization rates?

Disk size distribution





Are disks already born small in some regions?

What is the effect of local ionization rates?

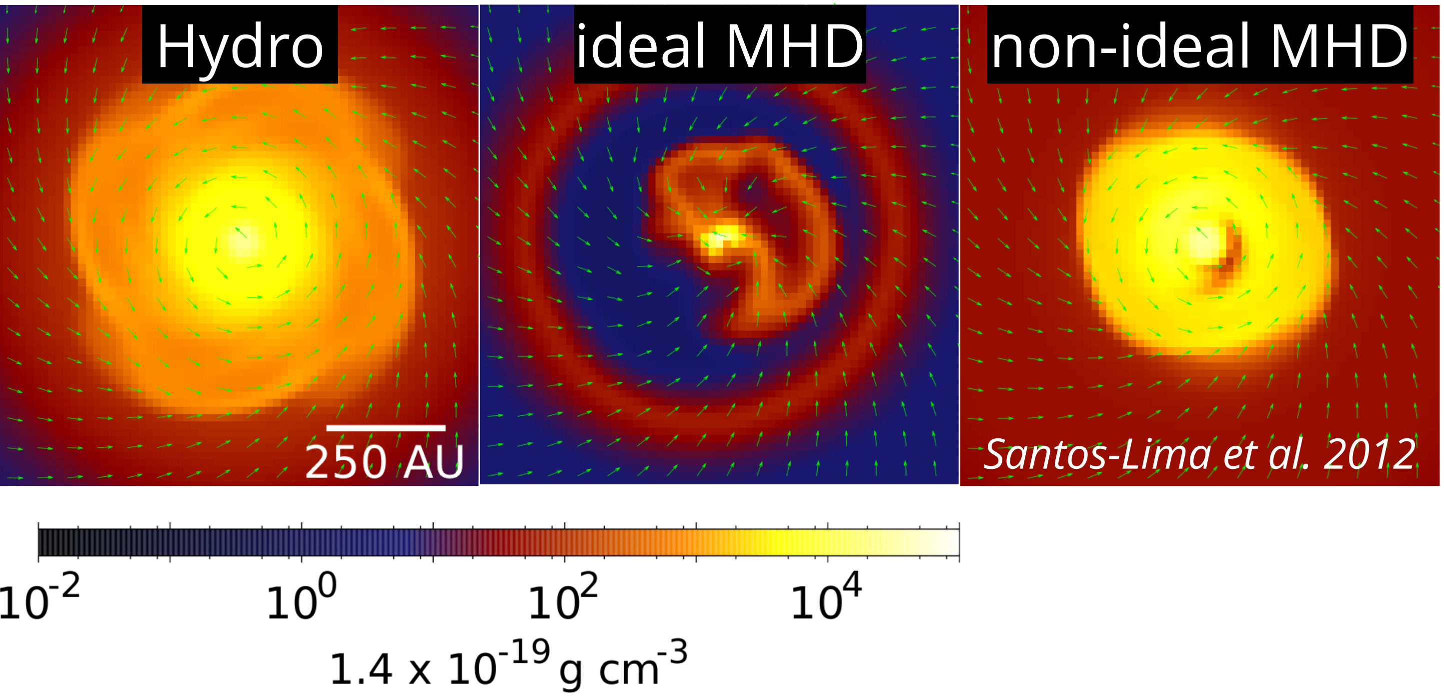
Cosmic-ray ionization rate (or even Al-26)?

What about the dust?

What about magnetic fields?

Help! Where is the disk?!

Ohmic, Ambipolar, Hall



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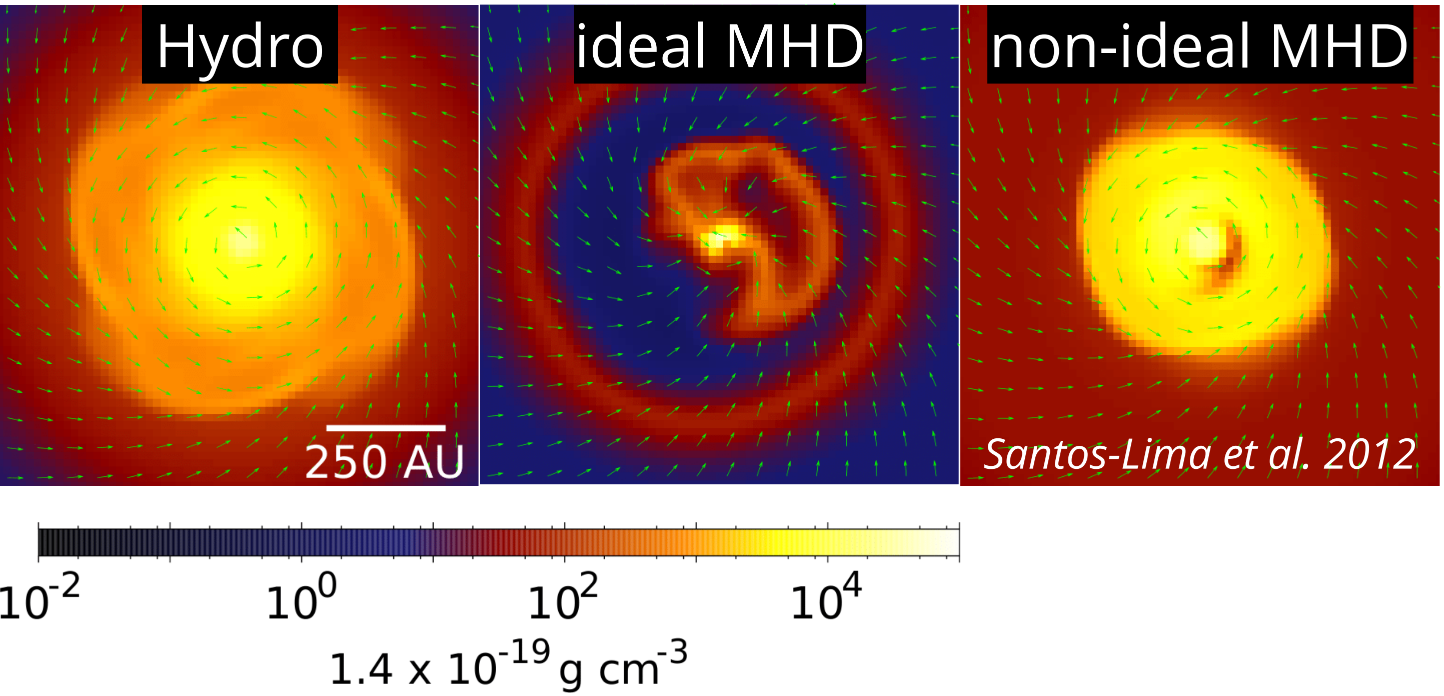
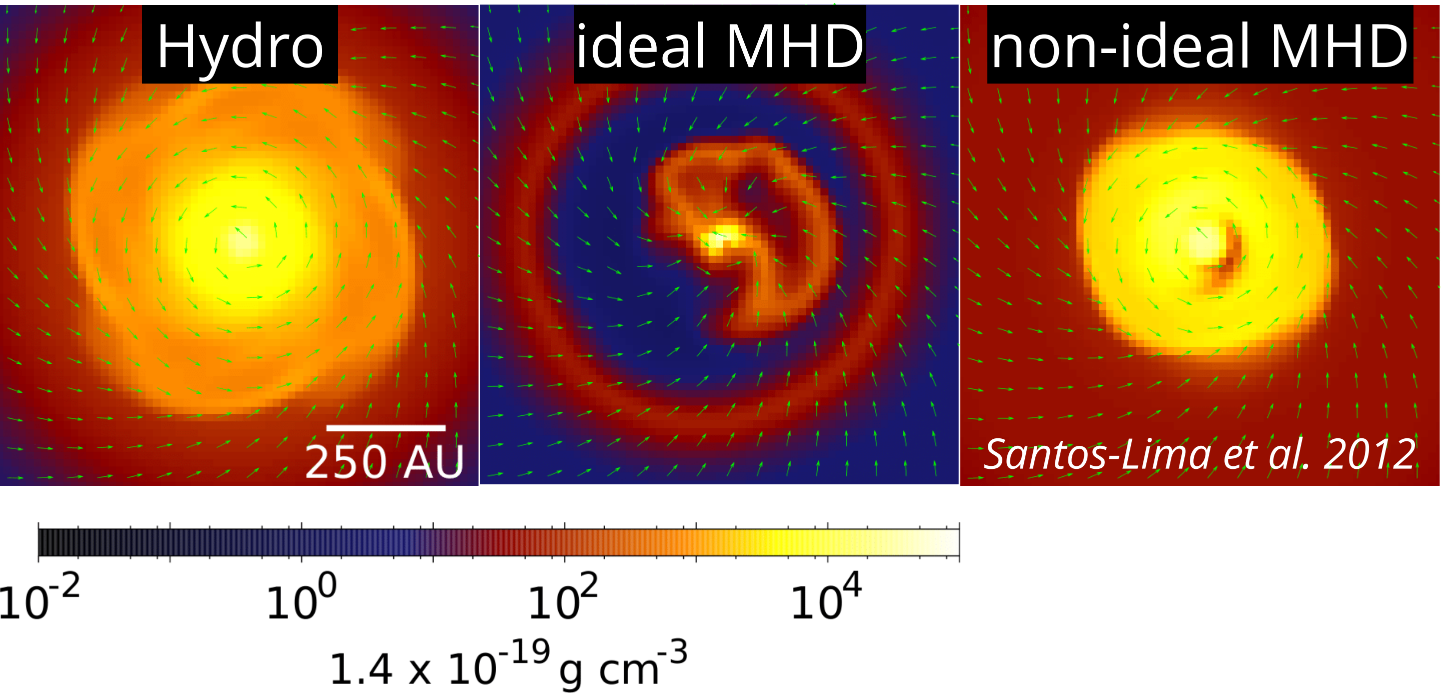


dust growth weakens magnetic braking => larger disks

Zhao et al. 2018, Marchand et al. 2020

What about the dust?

What about magnetic fields? | Help! Where is the disk?! | Ohmic, Ambipolar, Hall



dust growth weakens magnetic braking => larger disks

Zhao et al. 2018, Marchand et al. 2020

dust-rich disks from collapse

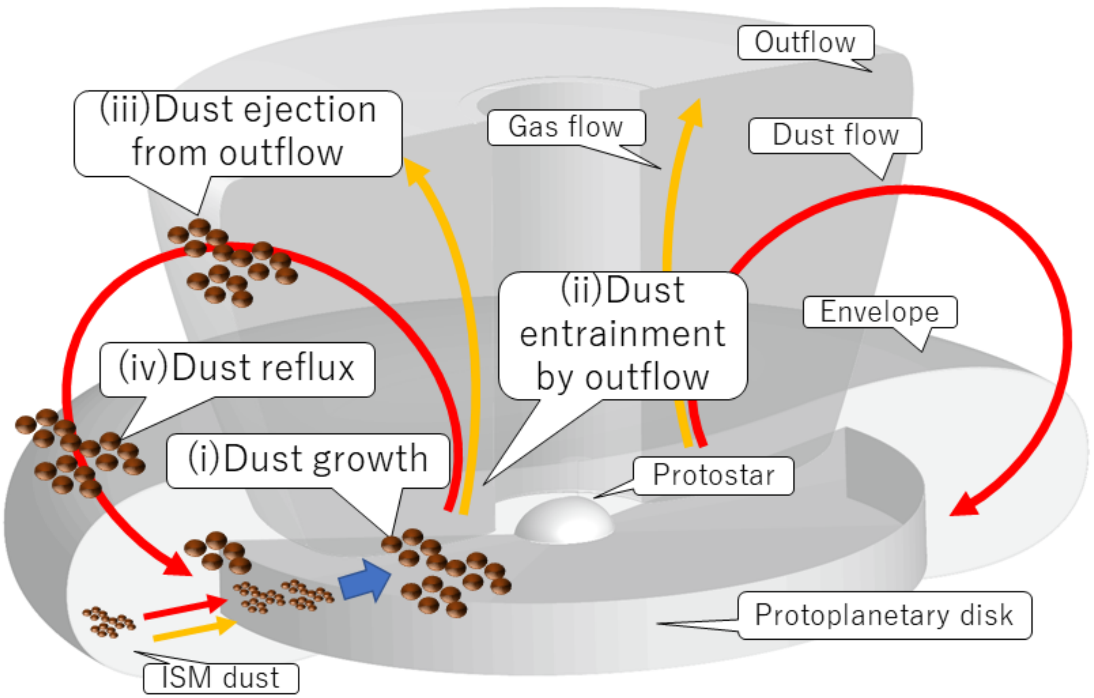
dust accumulates

Lebreuilly et al. 2020

"ash-fall" scenario

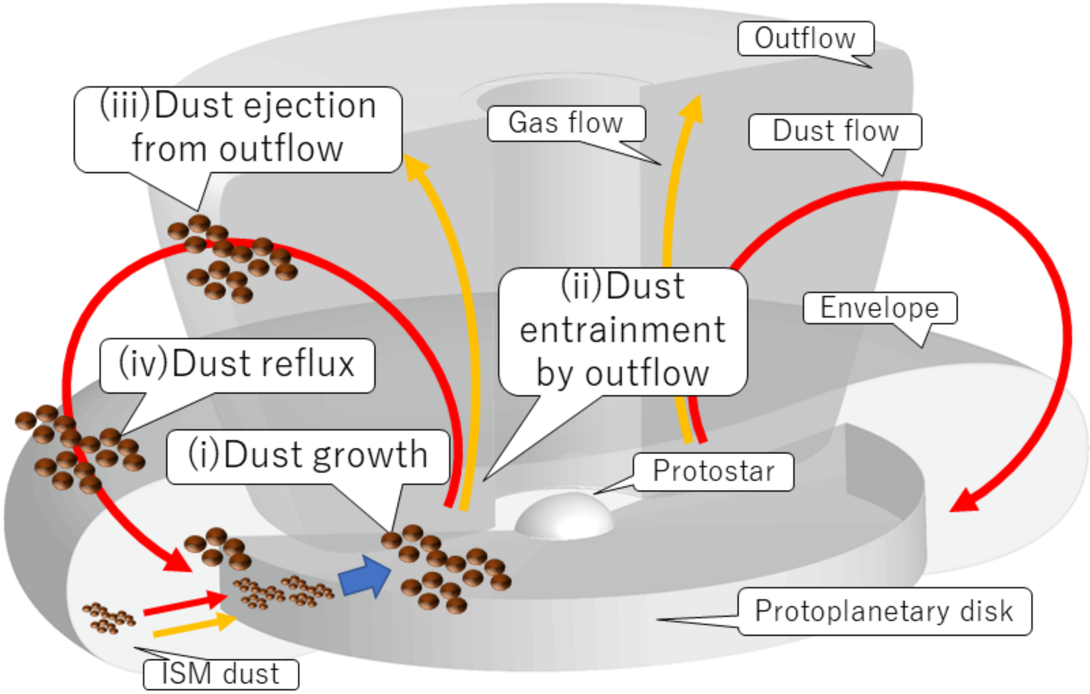
Tsukamoto et al. 2021

"Ash-fall" scenario aka conveyor belt



Credit: Tsukamoto et al. 2021

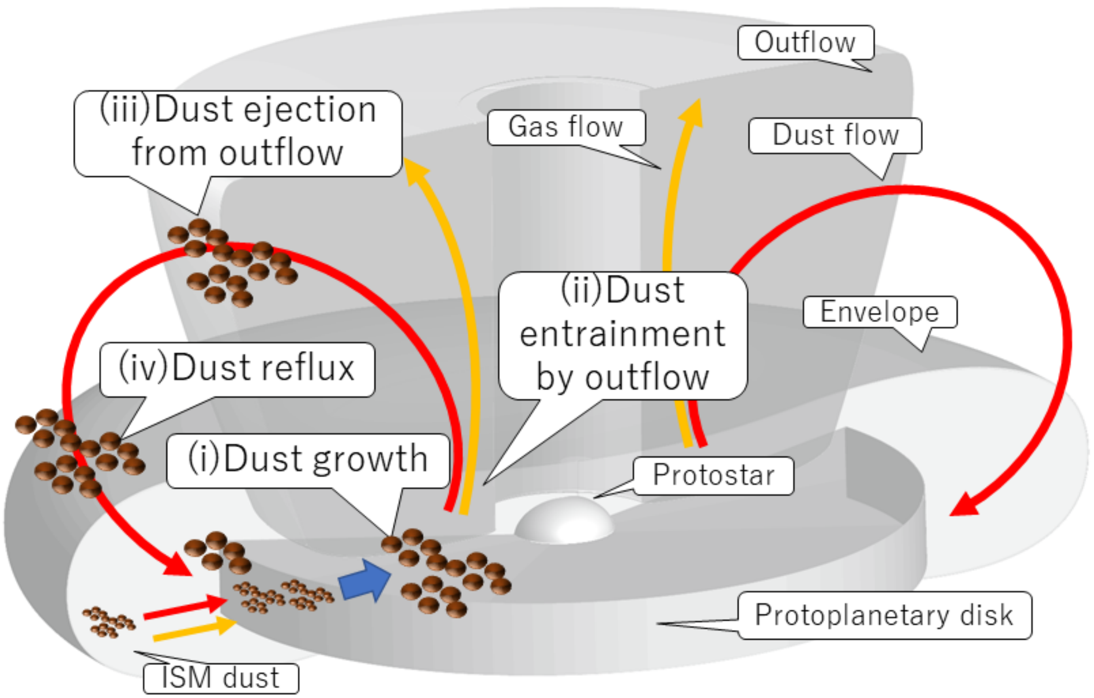
"Ash-fall" scenario aka conveyor belt



Key question

Credit: Tsukamoto et al. 2021

"Ash-fall" scenario aka conveyor belt

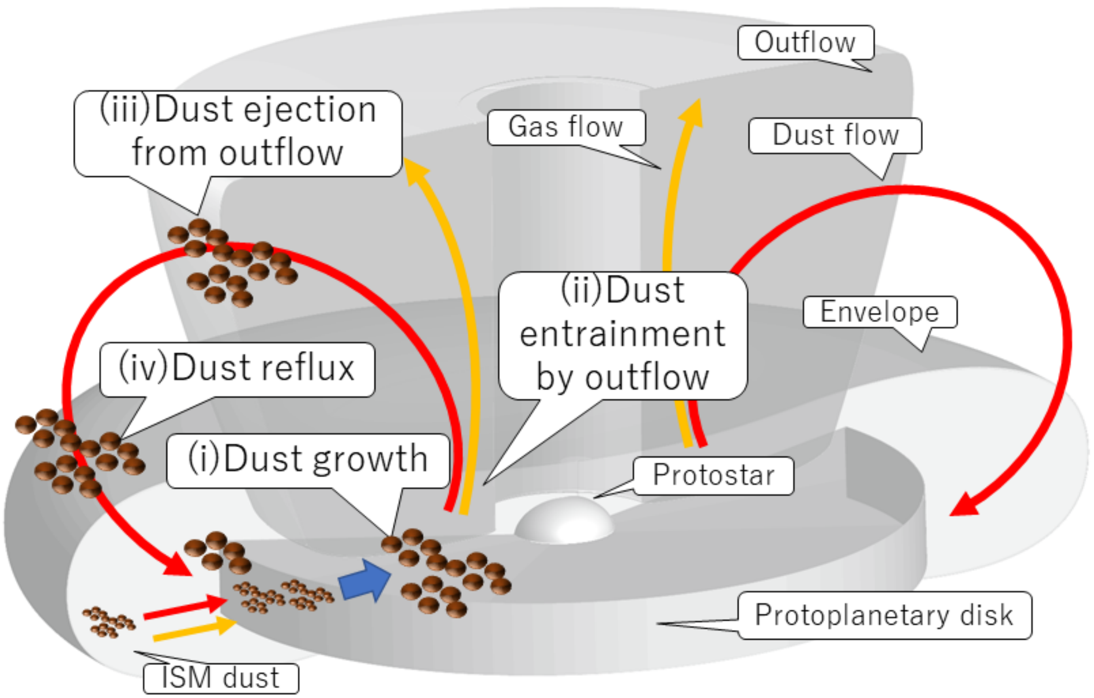


Credit: *Tsukamoto et al. 2021*

Key question

What fraction of the **gas and dust returns** to the disk after being ejected by an outflow?

"Ash-fall" scenario aka conveyor belt



Credit: Tsukamoto et al. 2021

Key question

What fraction of the **gas and dust returns** to the disk after being ejected by an outflow?

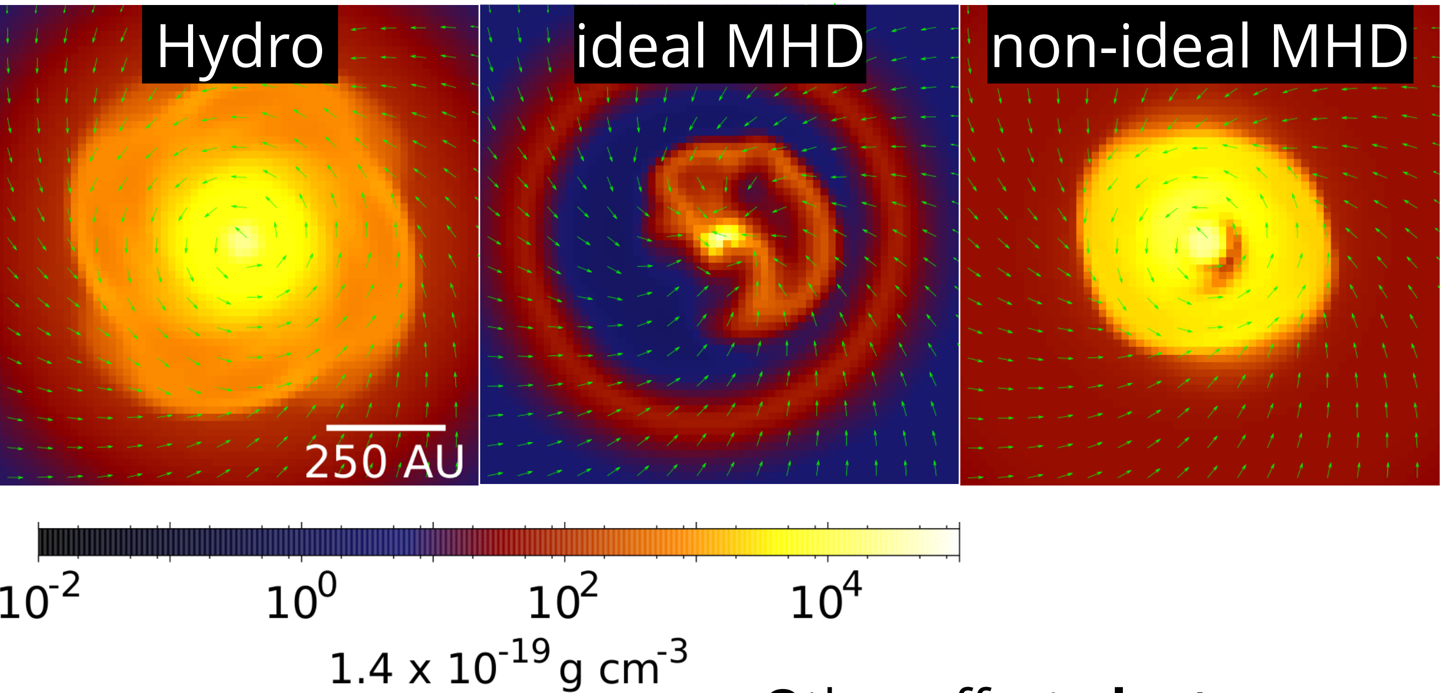
Increase in dust-to-gas ratio because dust can **grow** in disk and **return**

Tsukamoto et al. 2021

Is this the full picture?

Streamers!

What about magnetic fields? | Help! Where is the disk?! | Ohmic, Ambipolar, Hall



Santos-Lima et al. 2012

Other effect: **dust**

dust growth weakens magnetic braking => larger disks

Zhao et al. 2018, Marchand et al. 2020

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dust accumulates

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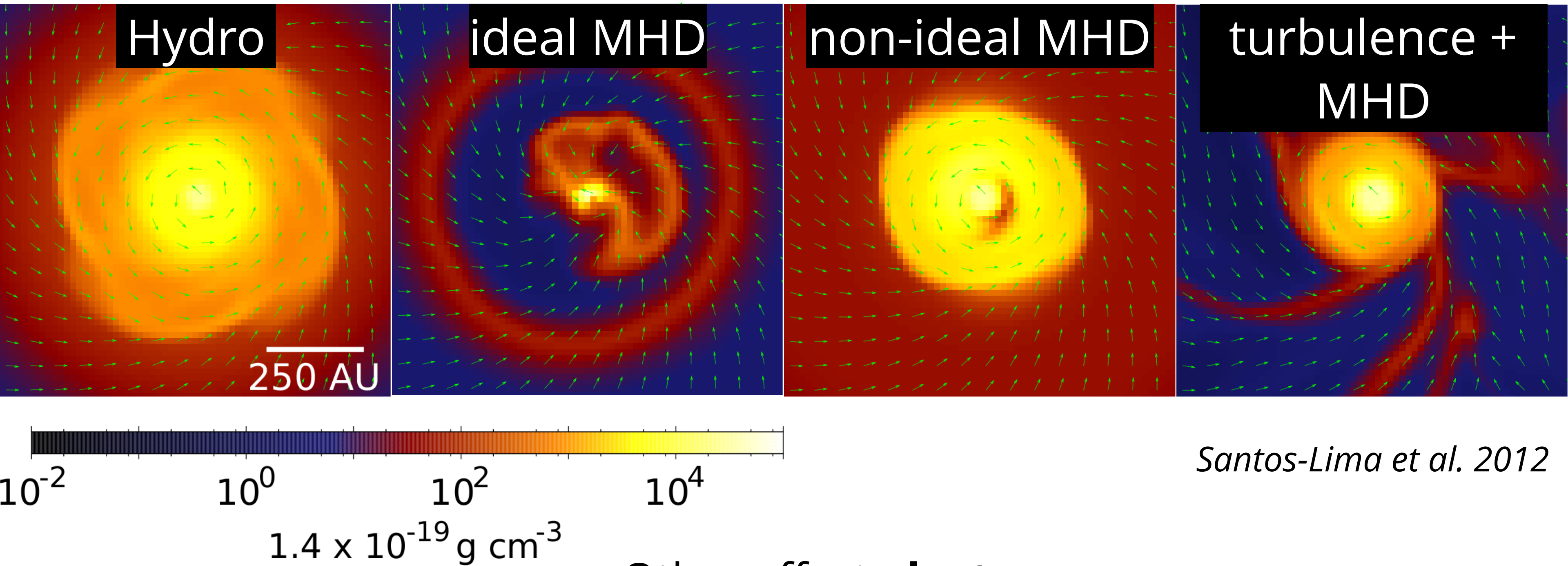
Streamers!

What about magnetic fields? | Help! Where is the disk?! | Ohmic, Ambipolar, Hall | Turbulence



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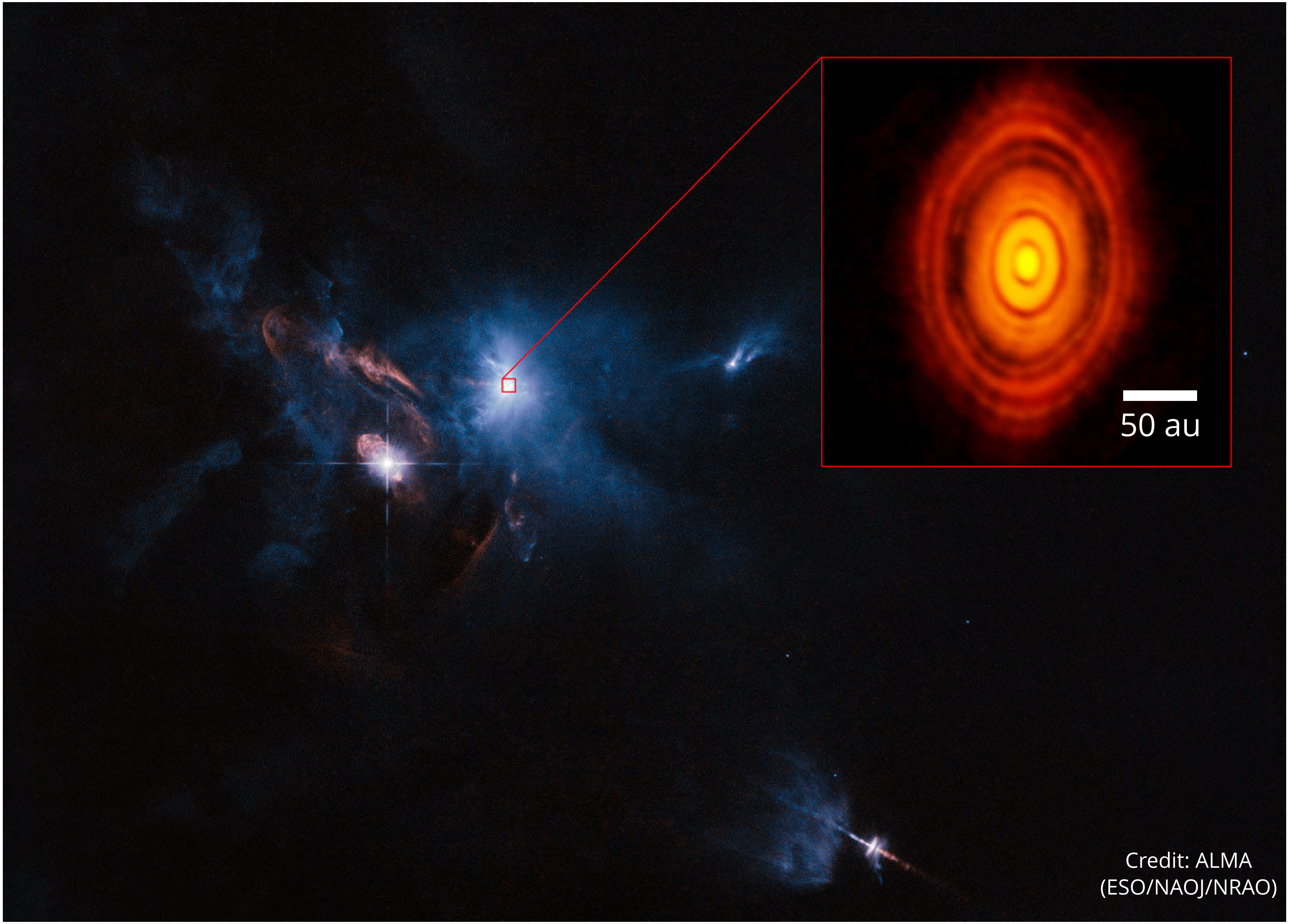
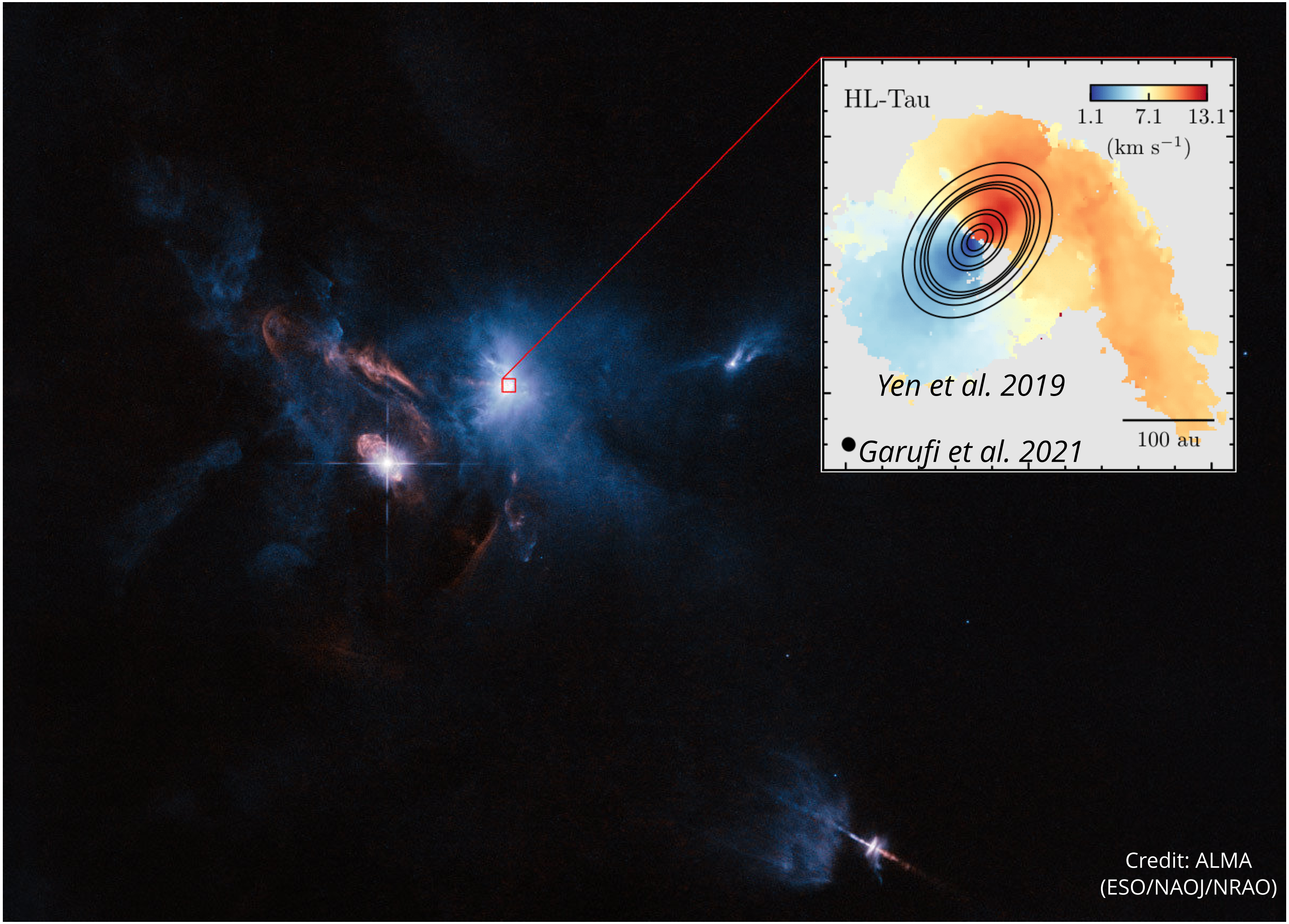
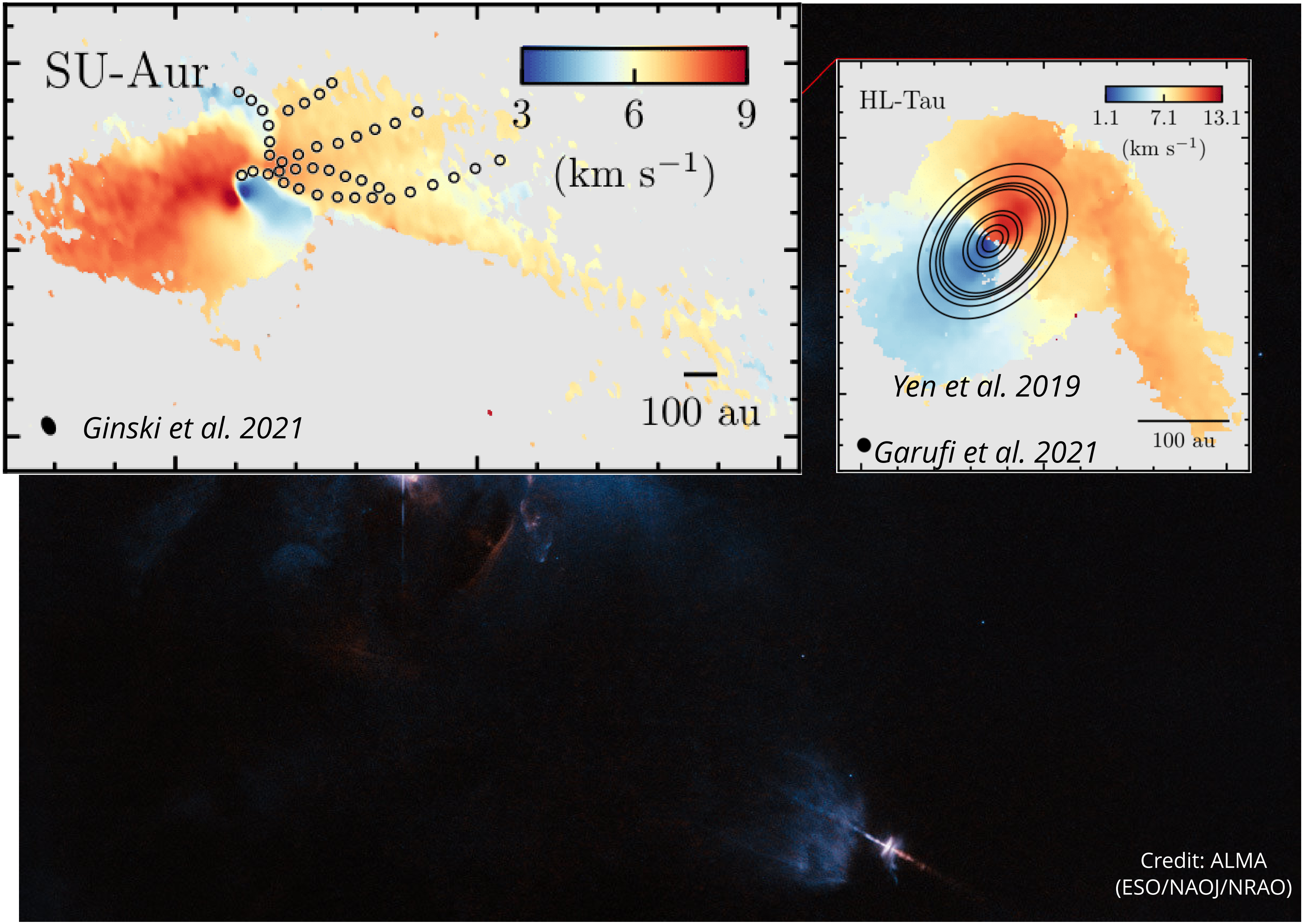
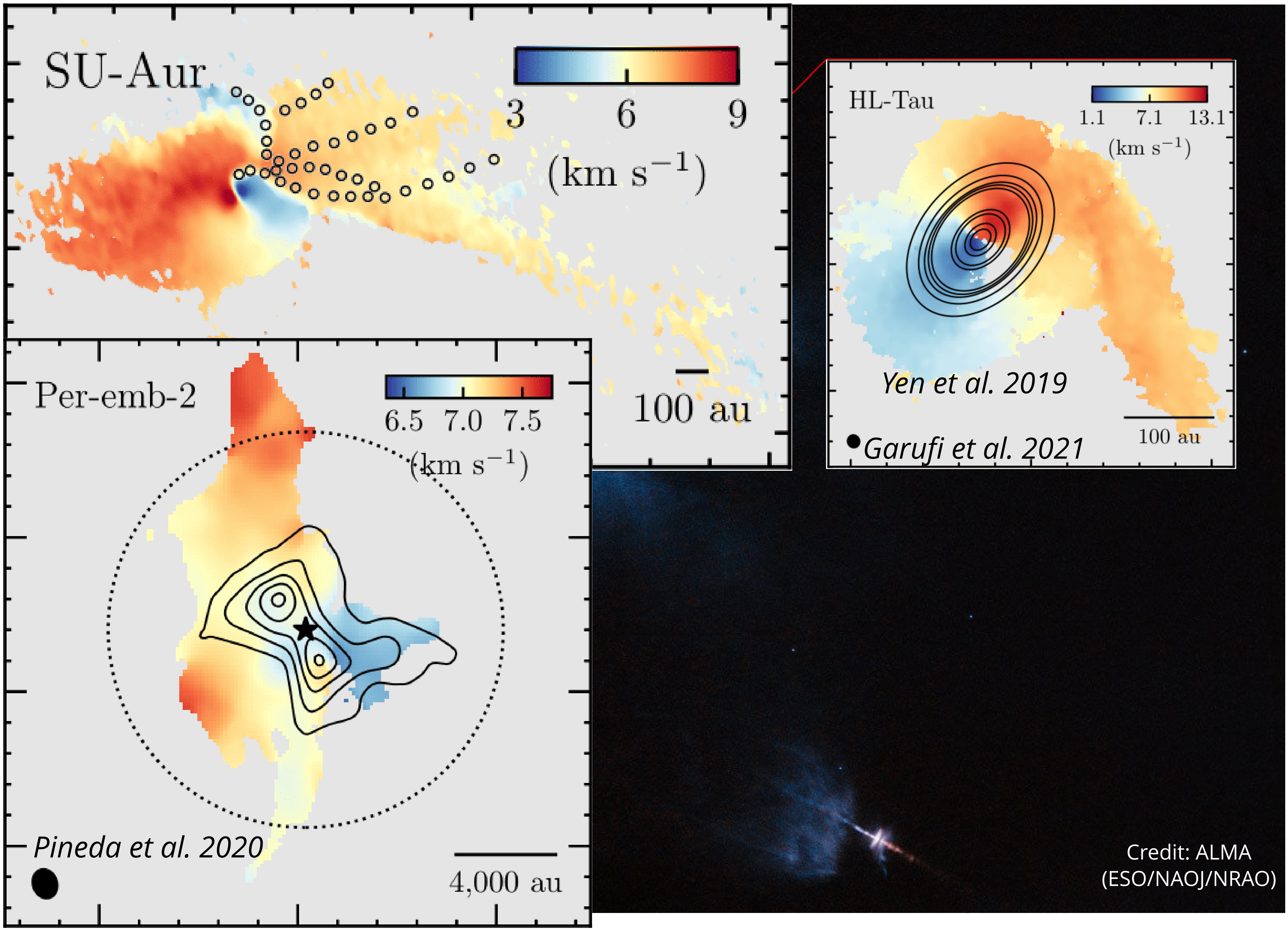
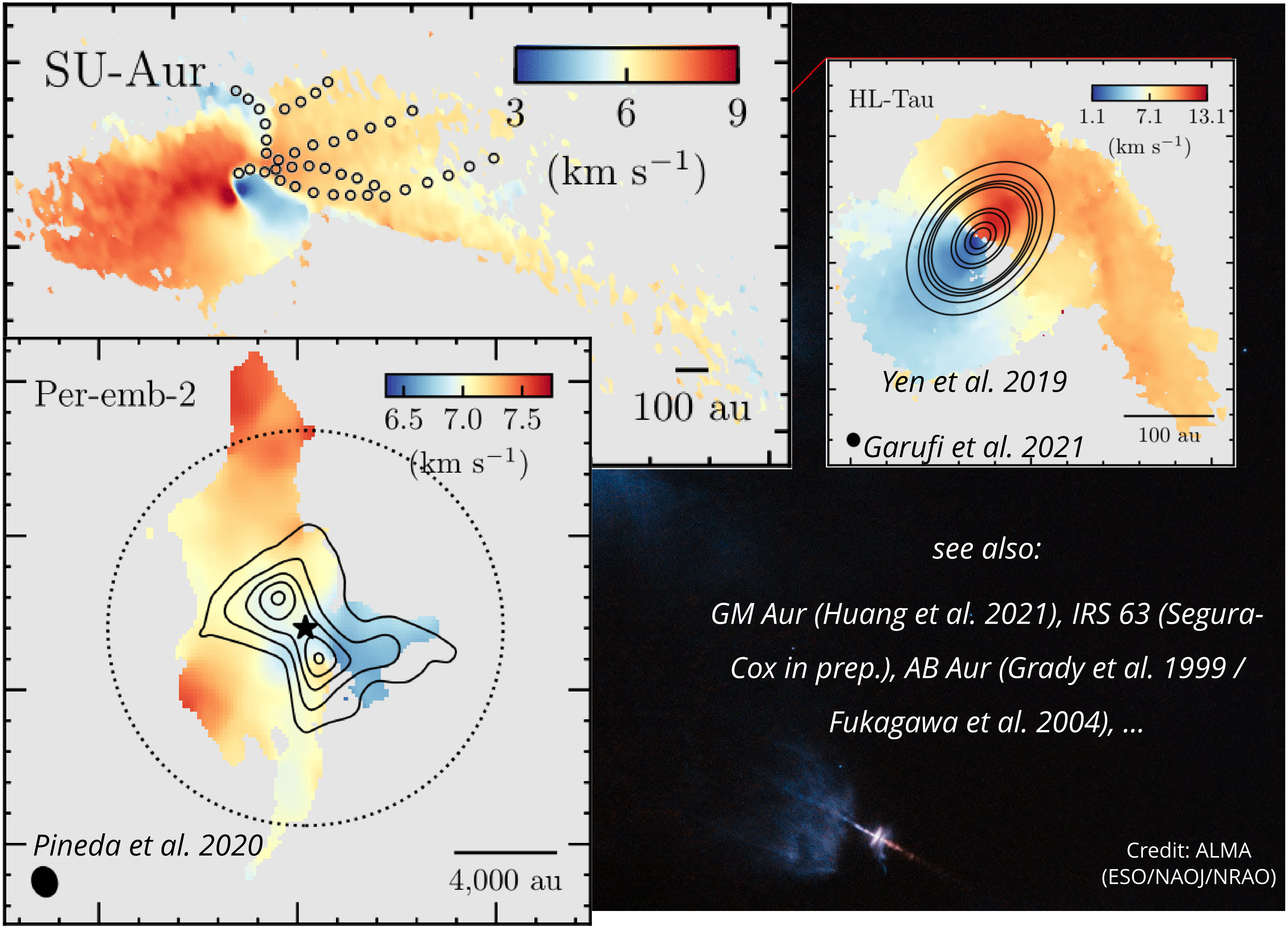

50 au
Credit: ALMA
(ESO/NAOJ/NRAO)


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)

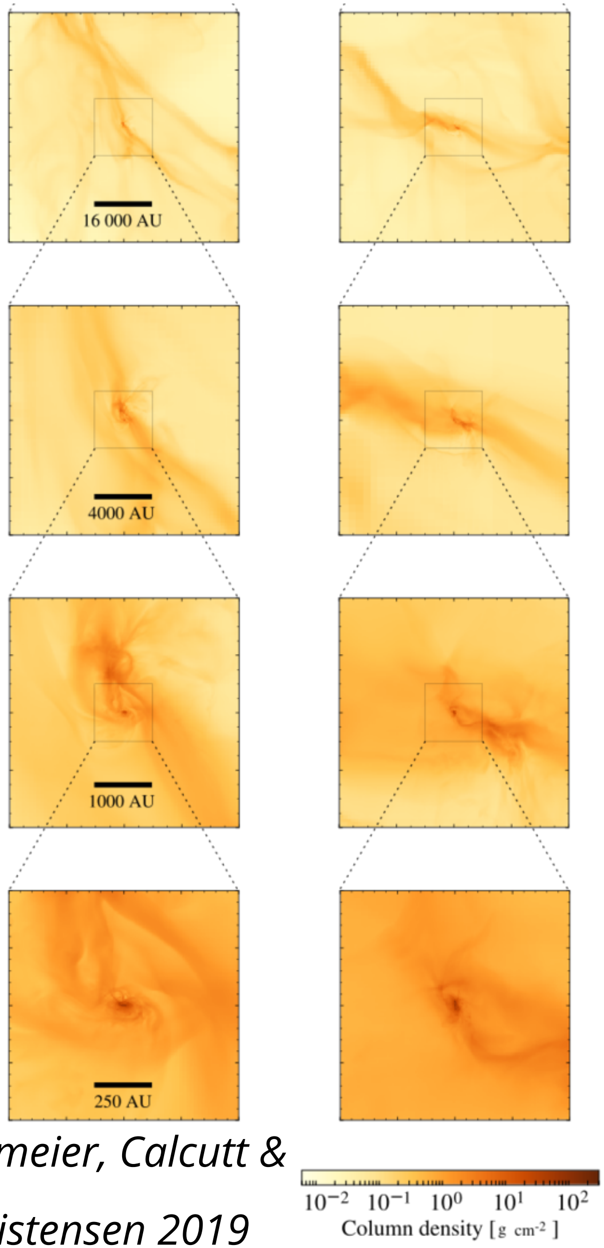

SU-Aur
3
6
9
(km s−1)
100 au
Ginski et al. 2021
HL-Tau
1.1
7.1
13.1
(km s−1)
Yen et al. 2019
100 au
Garufi et al. 2021
Credit: ALMA
(ESO/NAOJ/NRAO)



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)

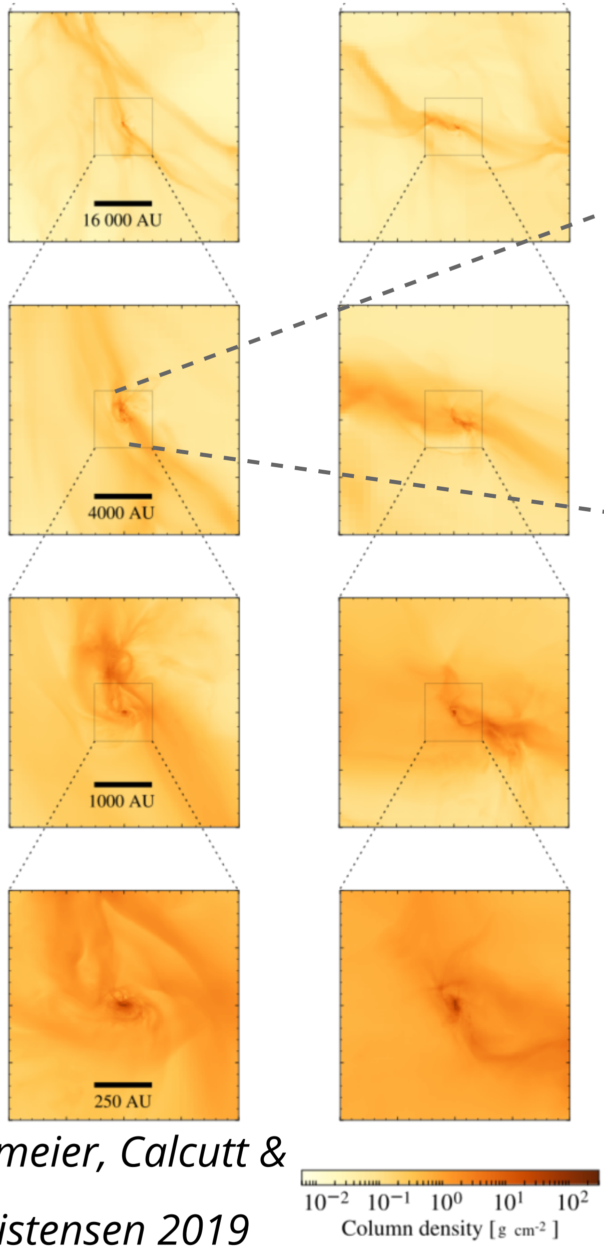

SU-Aur
3
6
9
(km s^{-1})
100 au
HL-Tau
1.1
7.1
13.1
(km s^{-1})
Yen et al. 2019
Garufi et al. 2021
100 au
Per-emb-2
6.5
7.0
7.5
(km s^{-1})
Pineda et al. 2020
4,000 au
see also:
GM Aur (Huang et al. 2021), IRS 63 (Segura-Cox in prep.), AB Aur (Grady et al. 1999 / Fukagawa et al. 2004), ...
Credit: ALMA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

Zoom-in on embedded protostars

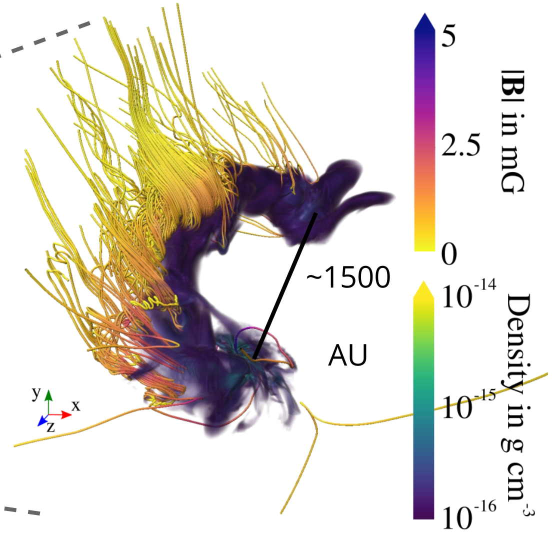


Küffmeier, Calcutt & Kristensen 2019

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)*

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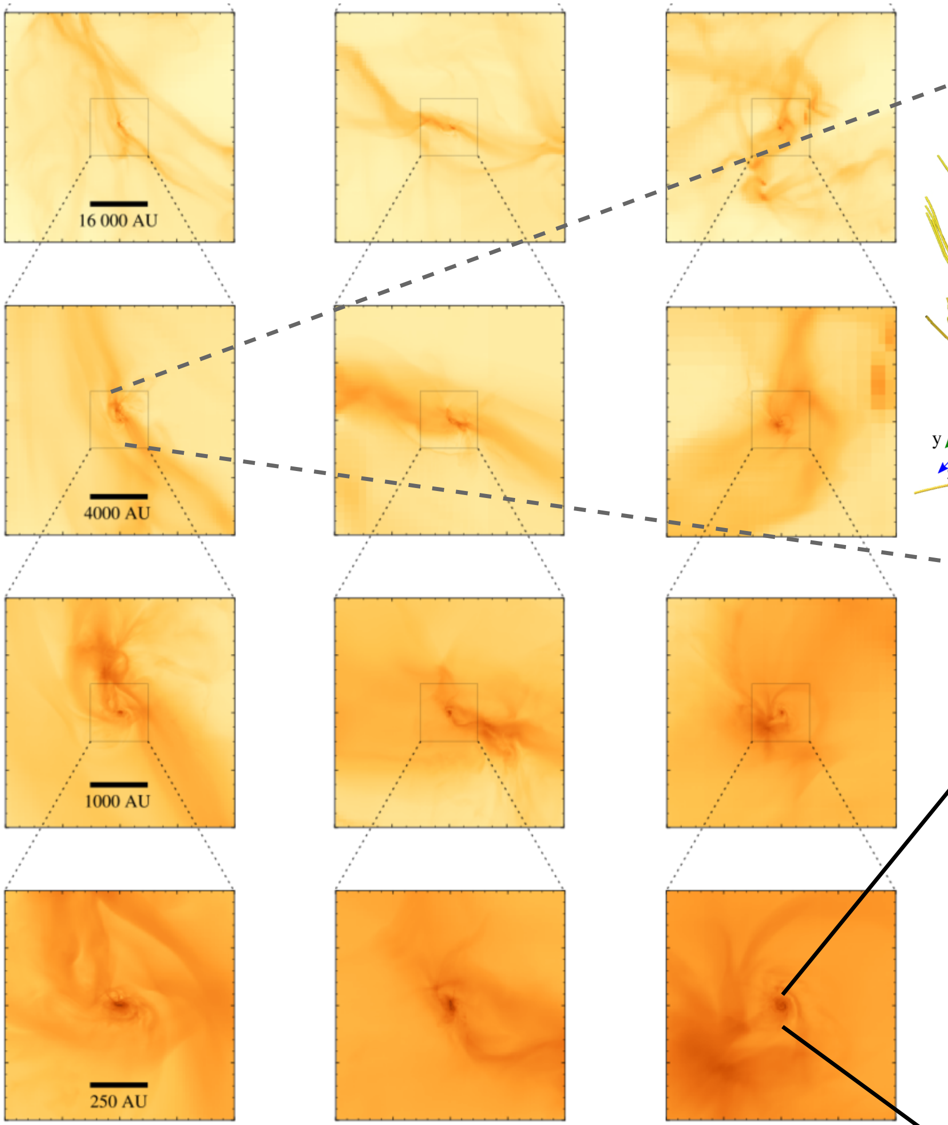
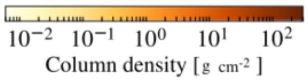
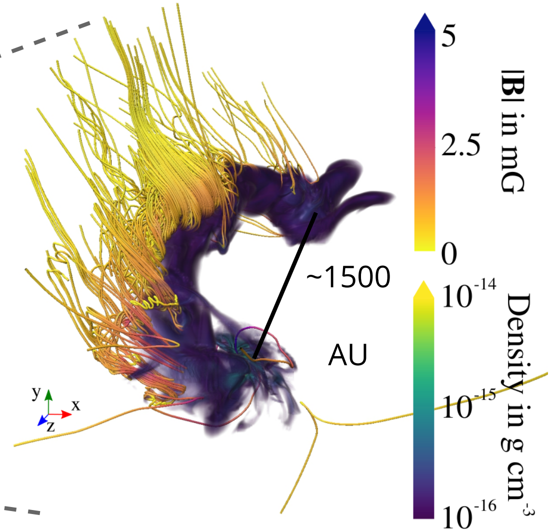




Küffmeier, Calcutt & Kristensen 2019



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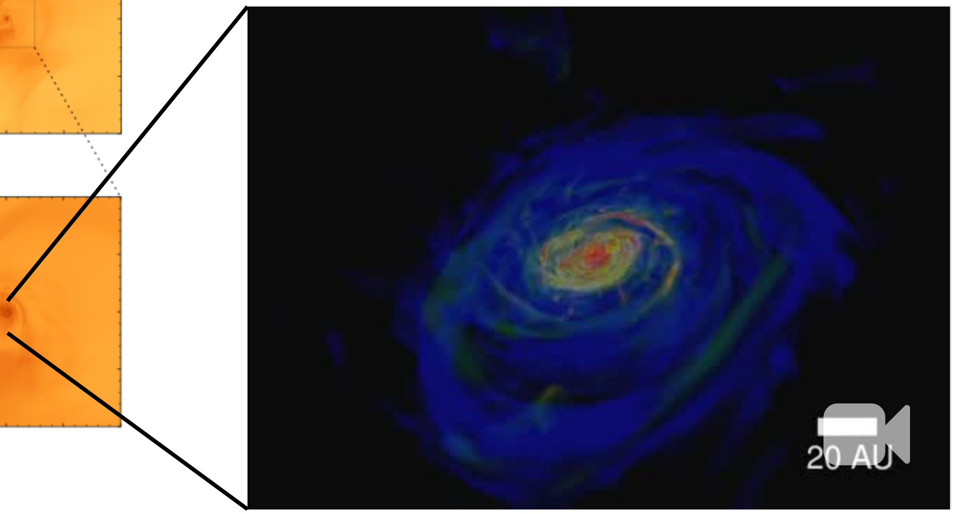
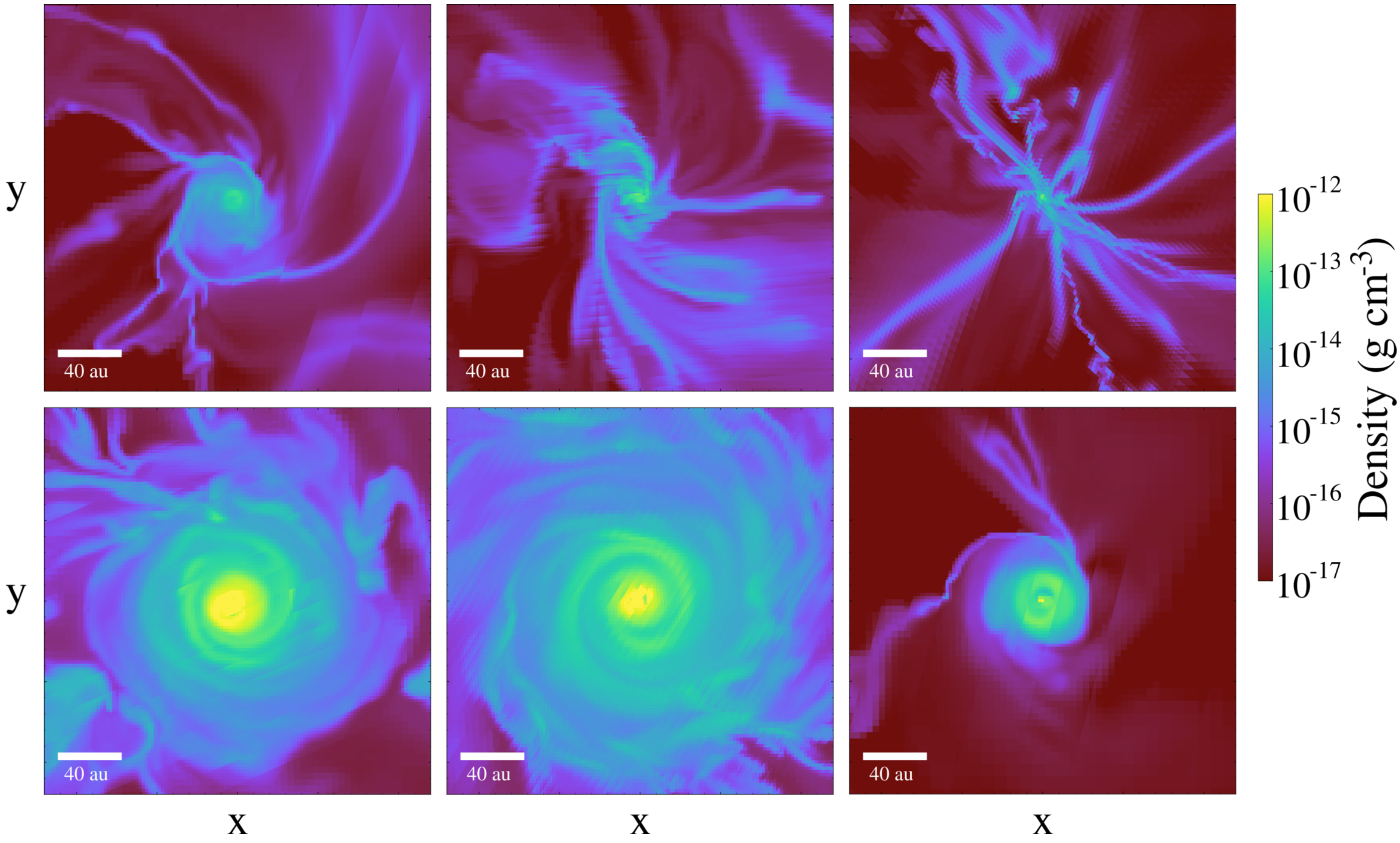


Küffmeier et al. 2018

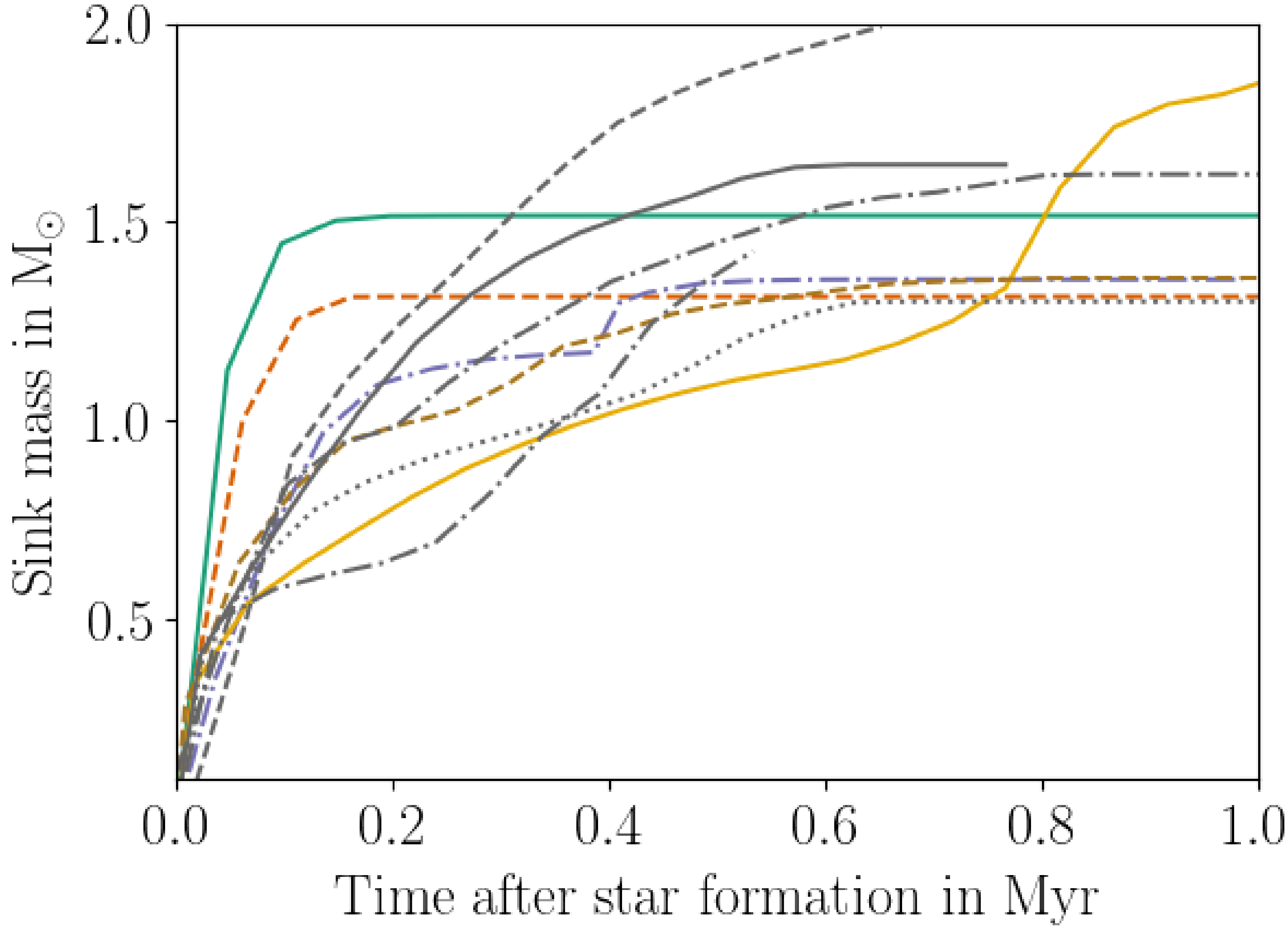
The connection to the larger scales



Küffmeier, Haugbølle & Nordlund 2017

Accretion is heterogeneous

Observational indication: **luminosity bursts**



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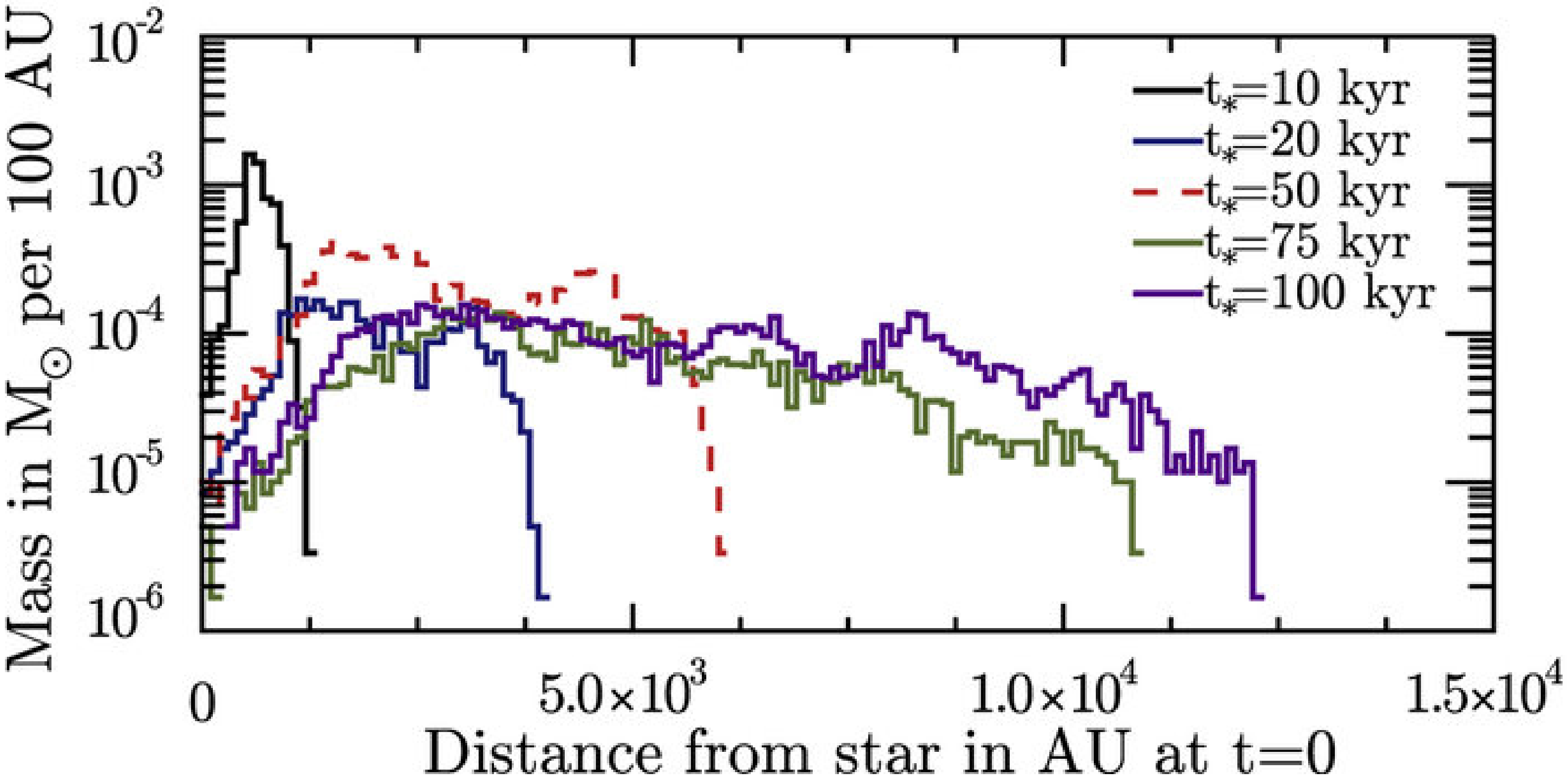
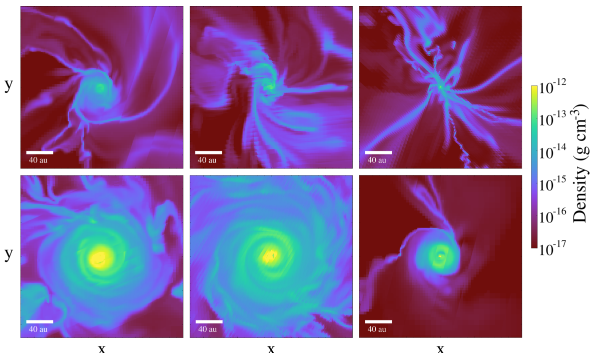
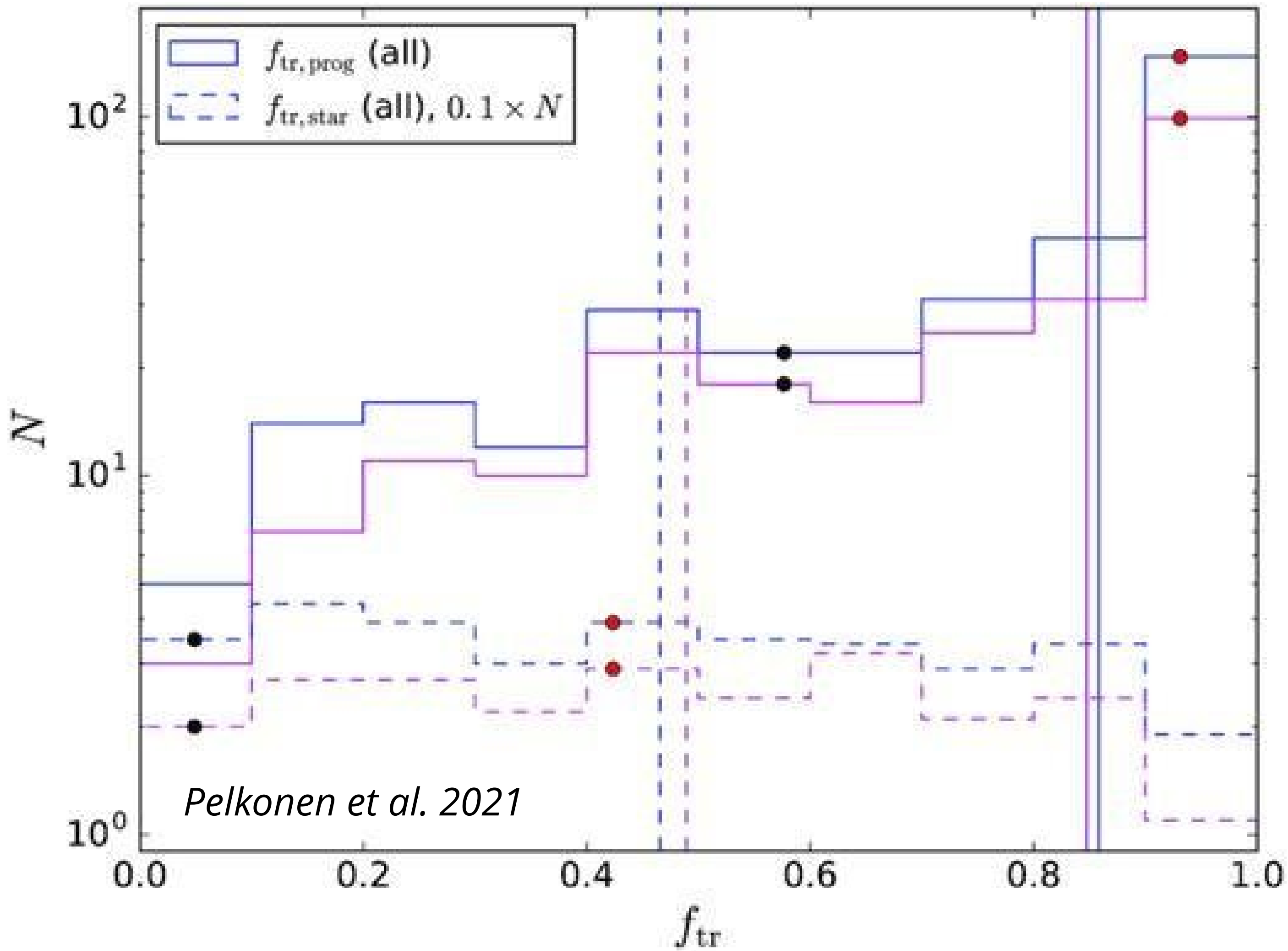




Gas from beyond the prestellar core can fall onto the star-disk system

Küffmeier, Haugbølle & Nordlund 2017

Late infall happens more often than assumed



Even for solar mass stars, up to 50 % of final mass from beyond the prestellar core!

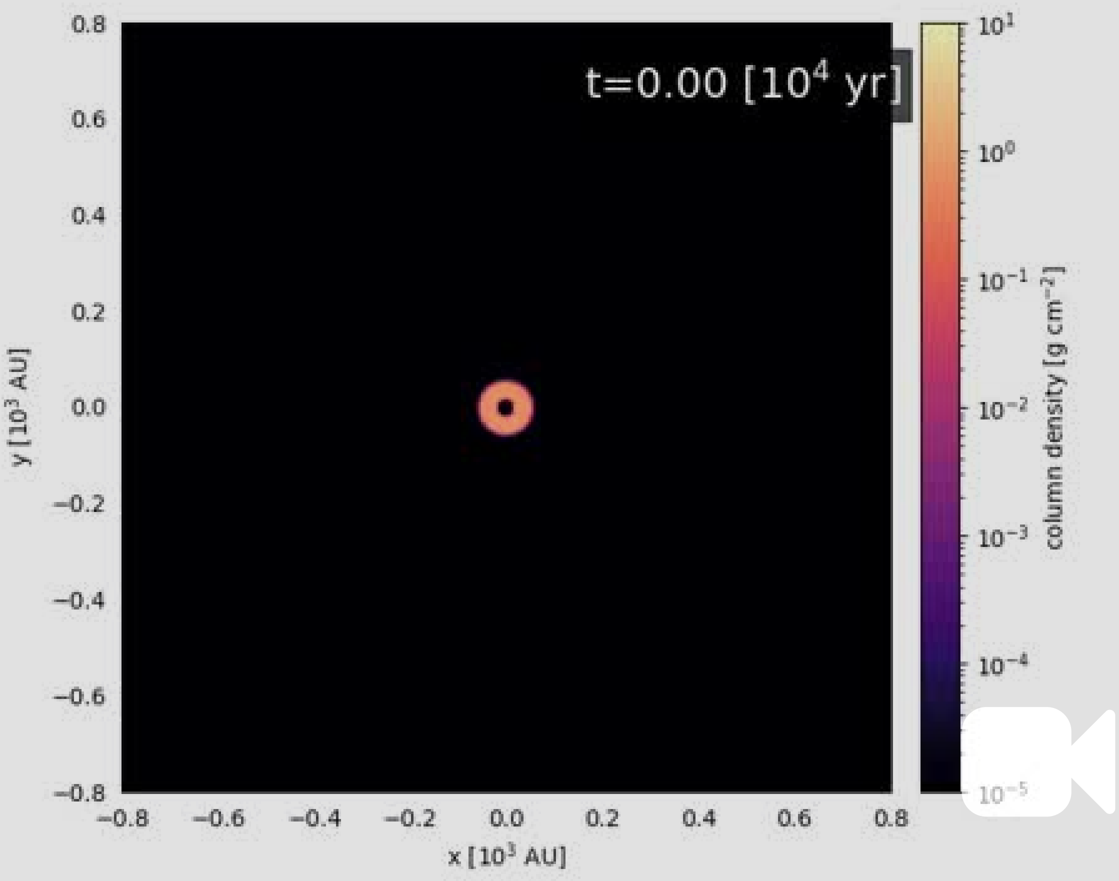
Can disks be rejuvenated?

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

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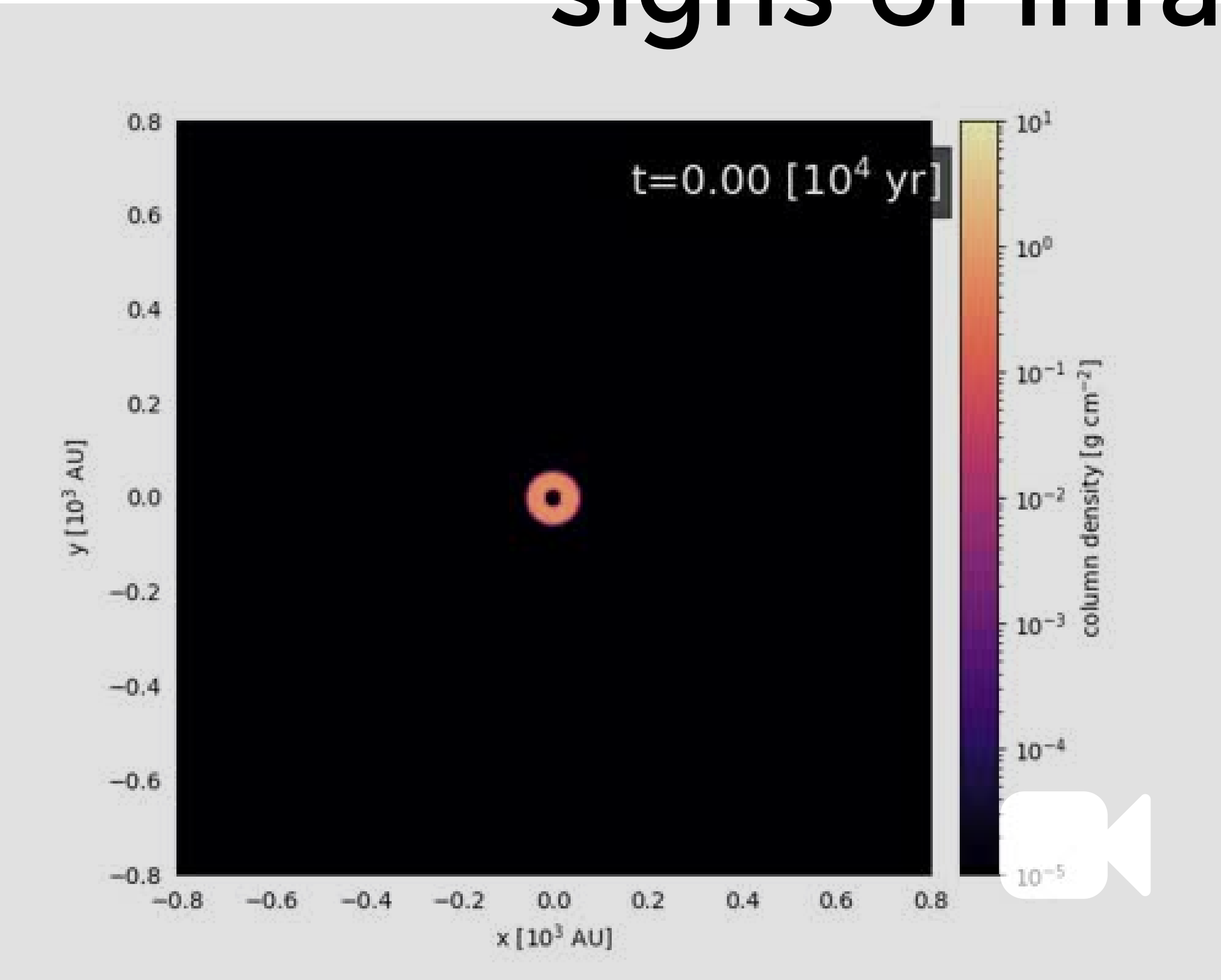

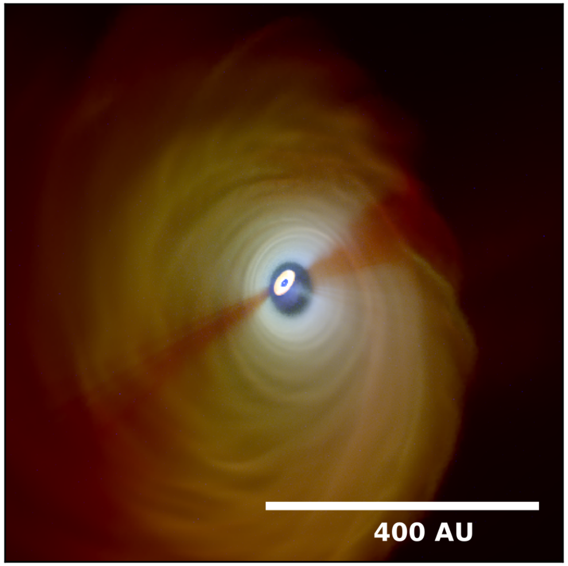

Observable as shadows in outer disk

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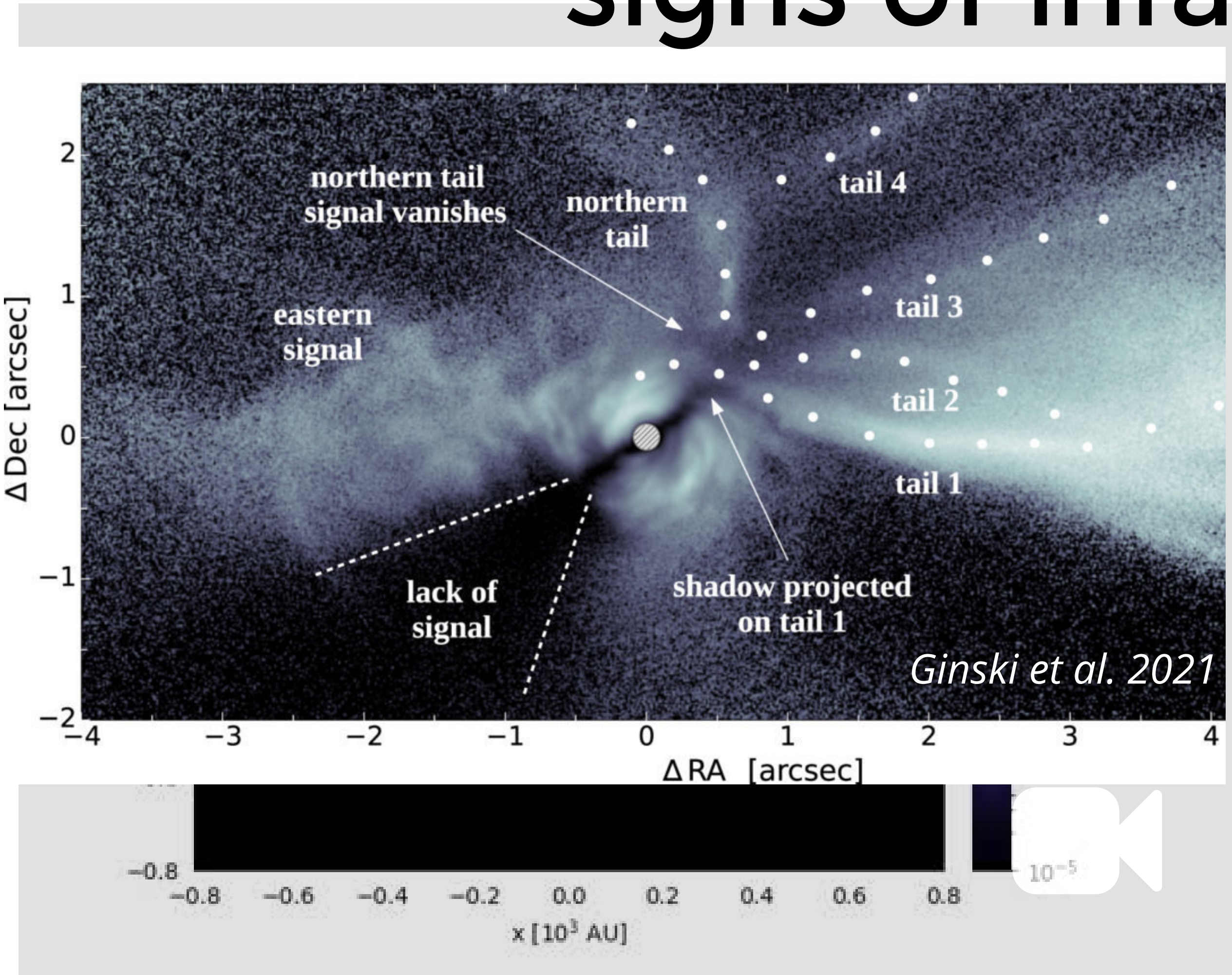

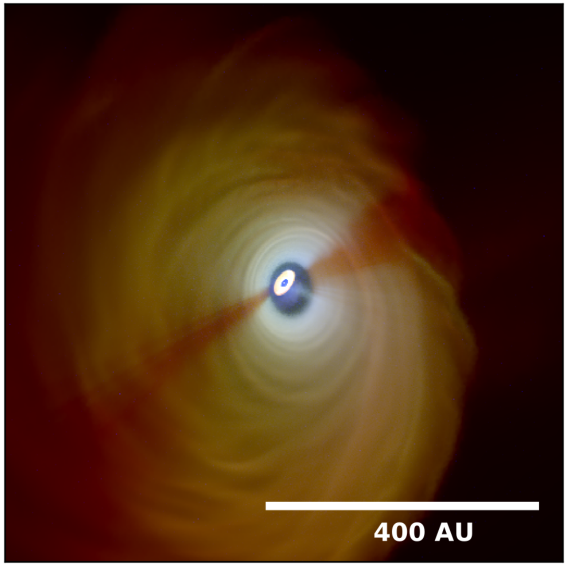

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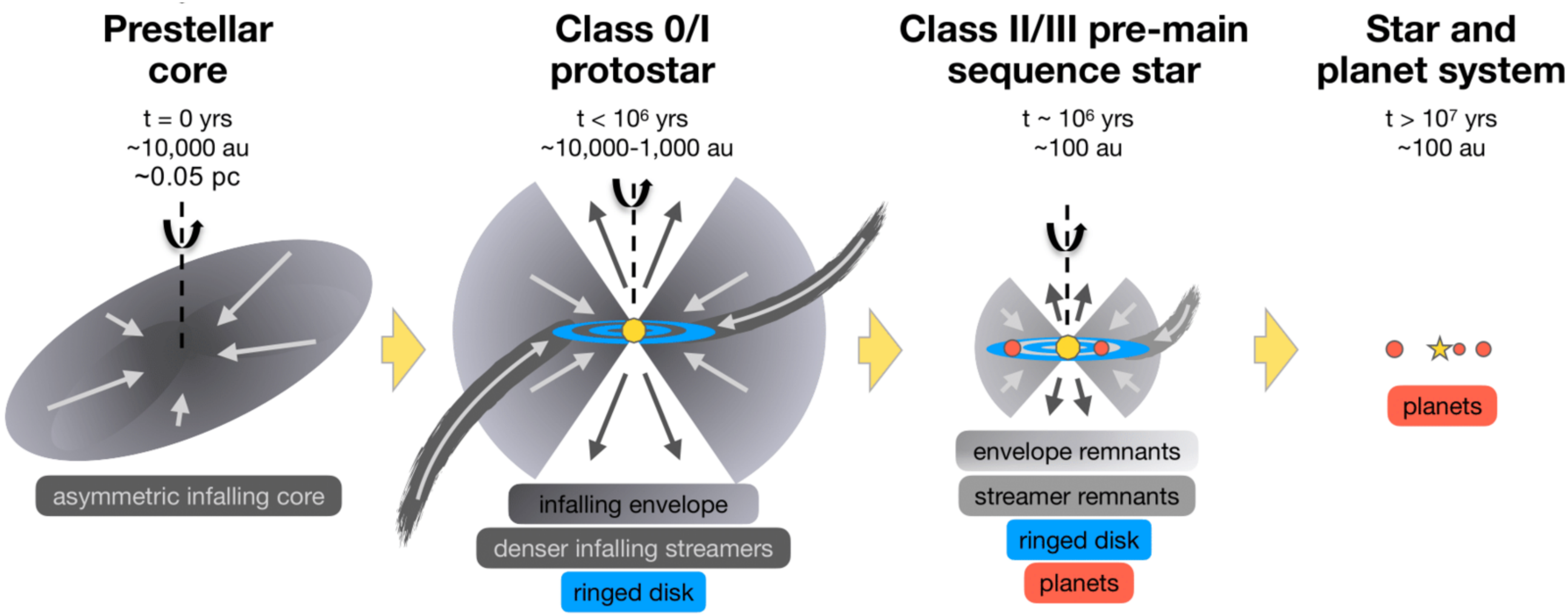
Revised picture



Segura-Cox et al. in prep.

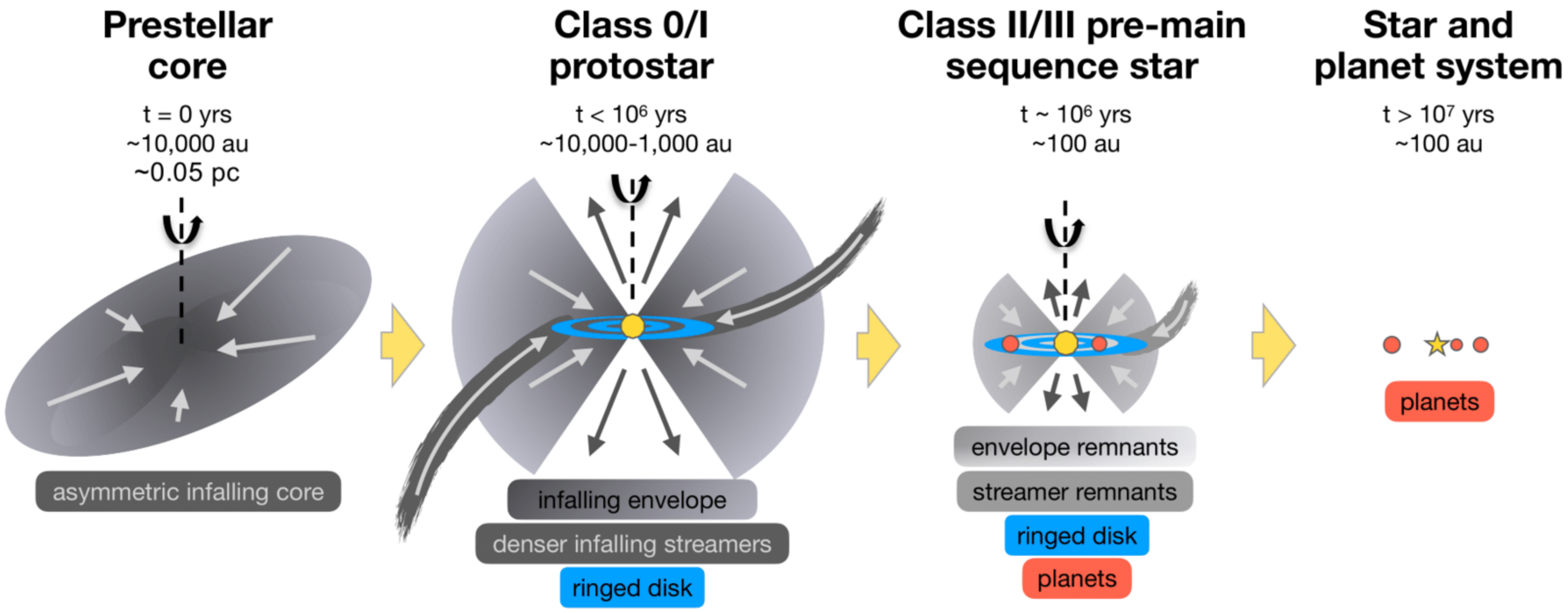
Pineda et al. 'Protostars and Planets VII'

Star and planet formation are two sides of the same medal

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

Revised picture

*we haven't even touched (proto-)stellar multiplicity



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