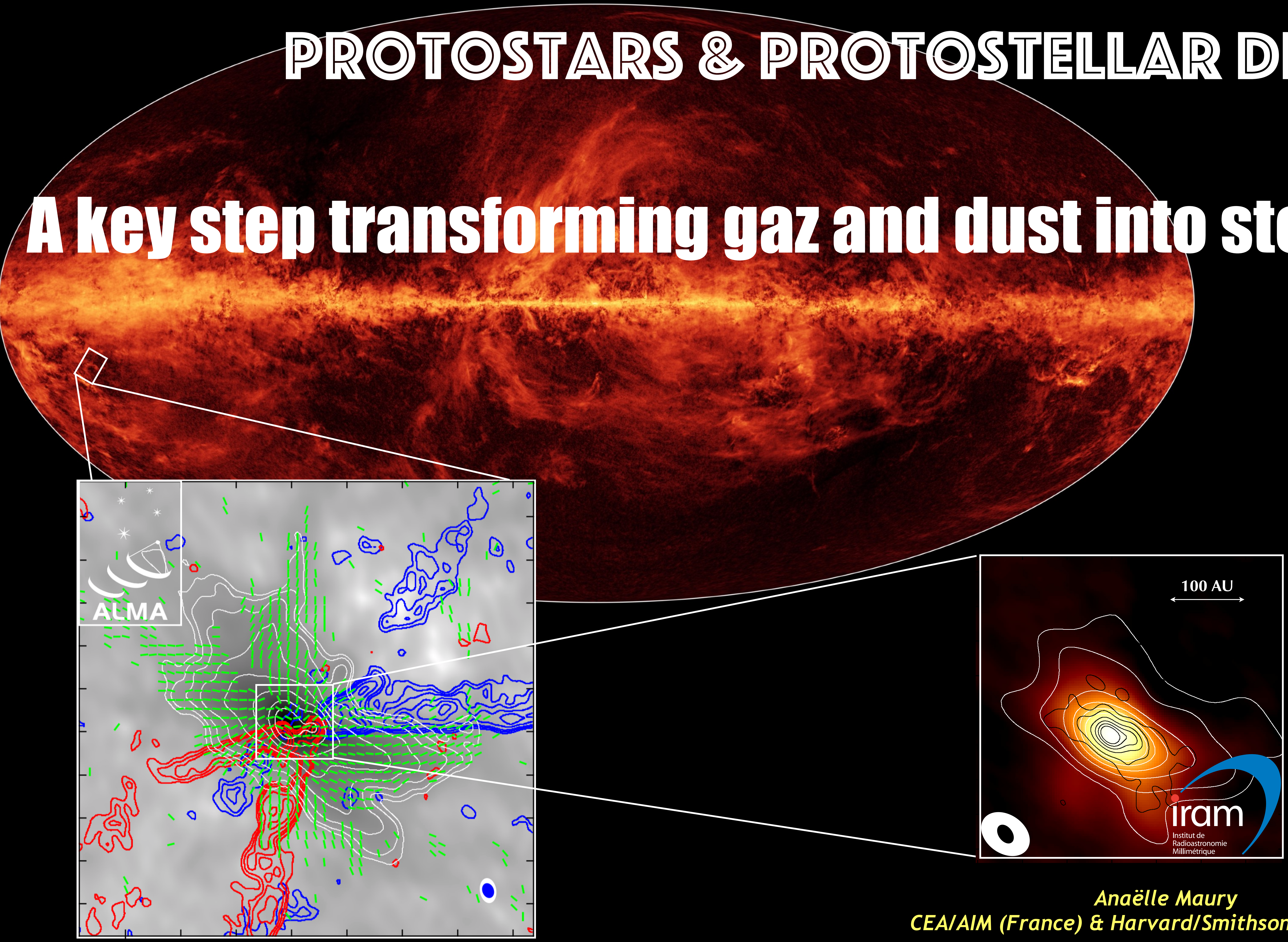
PROTOSTARS & PROTOSTELLAR DISKS

A key step transforming gaz and dust into stellar systems



Anaëlle Maury
CEA/AIM (France) & Harvard/Smithsonian CfA (USA)

I. Protostars

Yesterday

From starless cores to protostars: triggering of gravitational instability

Population studies & typical timescales

Transporting material from large to small scales: infall, accretion & the luminosity problem

« *And yet, it rotates* » …. angular momentum problem & the physics of the formation of disks

Observations: statistical properties of protostellar disks: sizes (& masses)

II. Disks and dust

Today

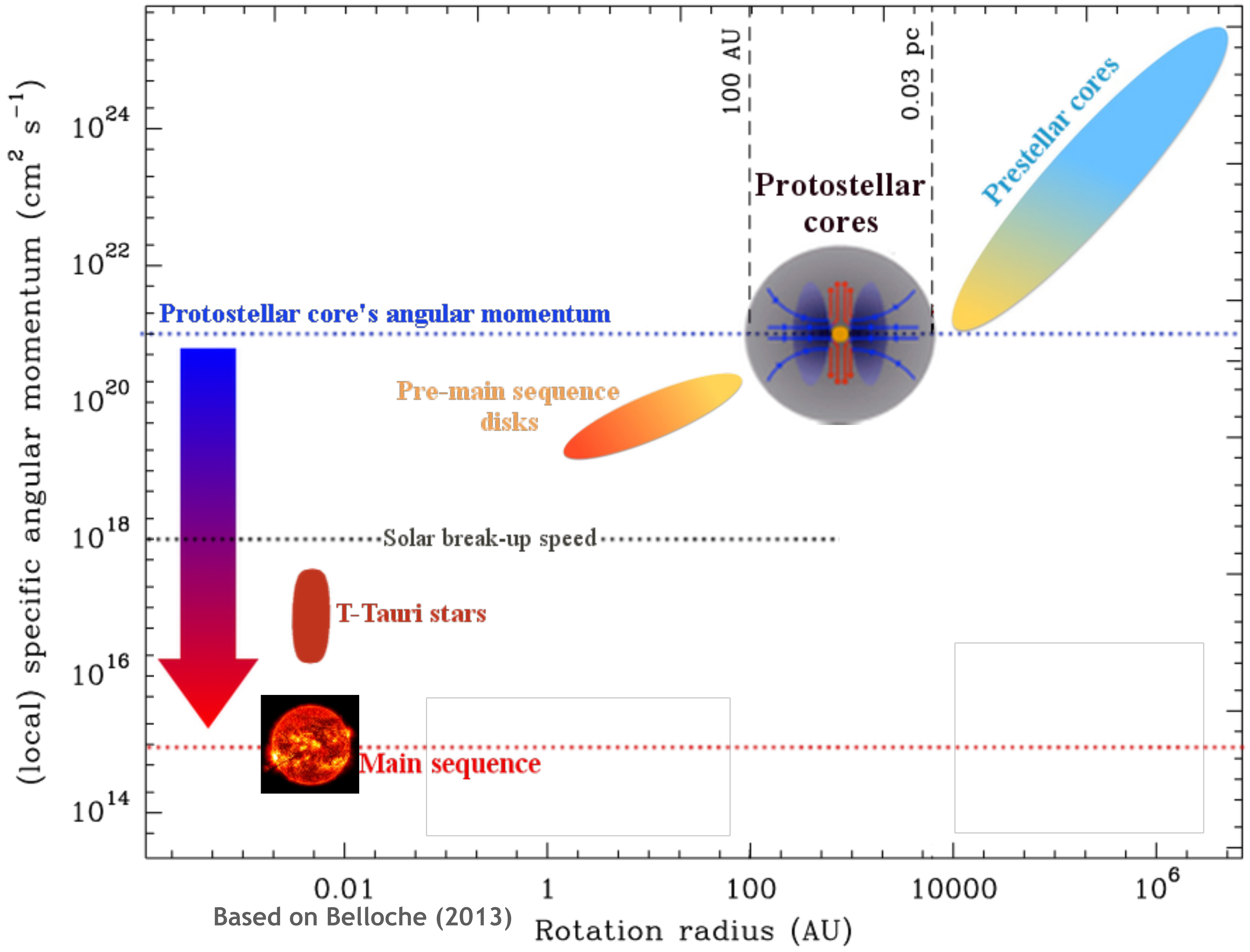
What sets the properties of the most pristine disks ?

Cabinet de curiosités: structures and sneak peaks at individual objects

What do we know of dust evolution while the star-disk system is built ?

Which instruments for the future (if time allows …) ?

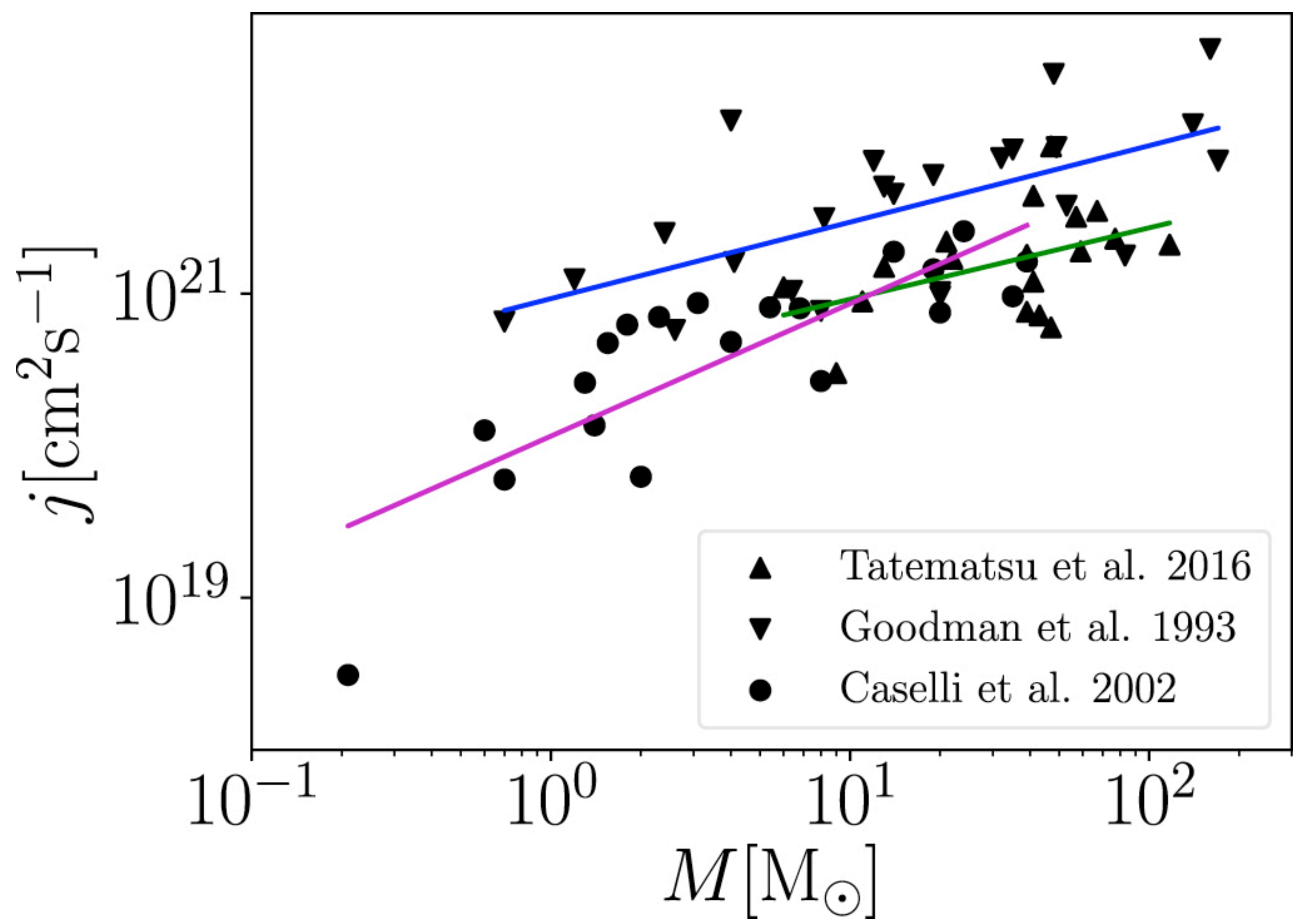
The infamous angular momentum problem



Based on Belloche (2013)

See also Maury, Hennebelle, Girart 2022 for a recent review

Observations of angular momentum content in star-forming clumps



From Misugi, Inutsuka, Arzoumanian (2019)

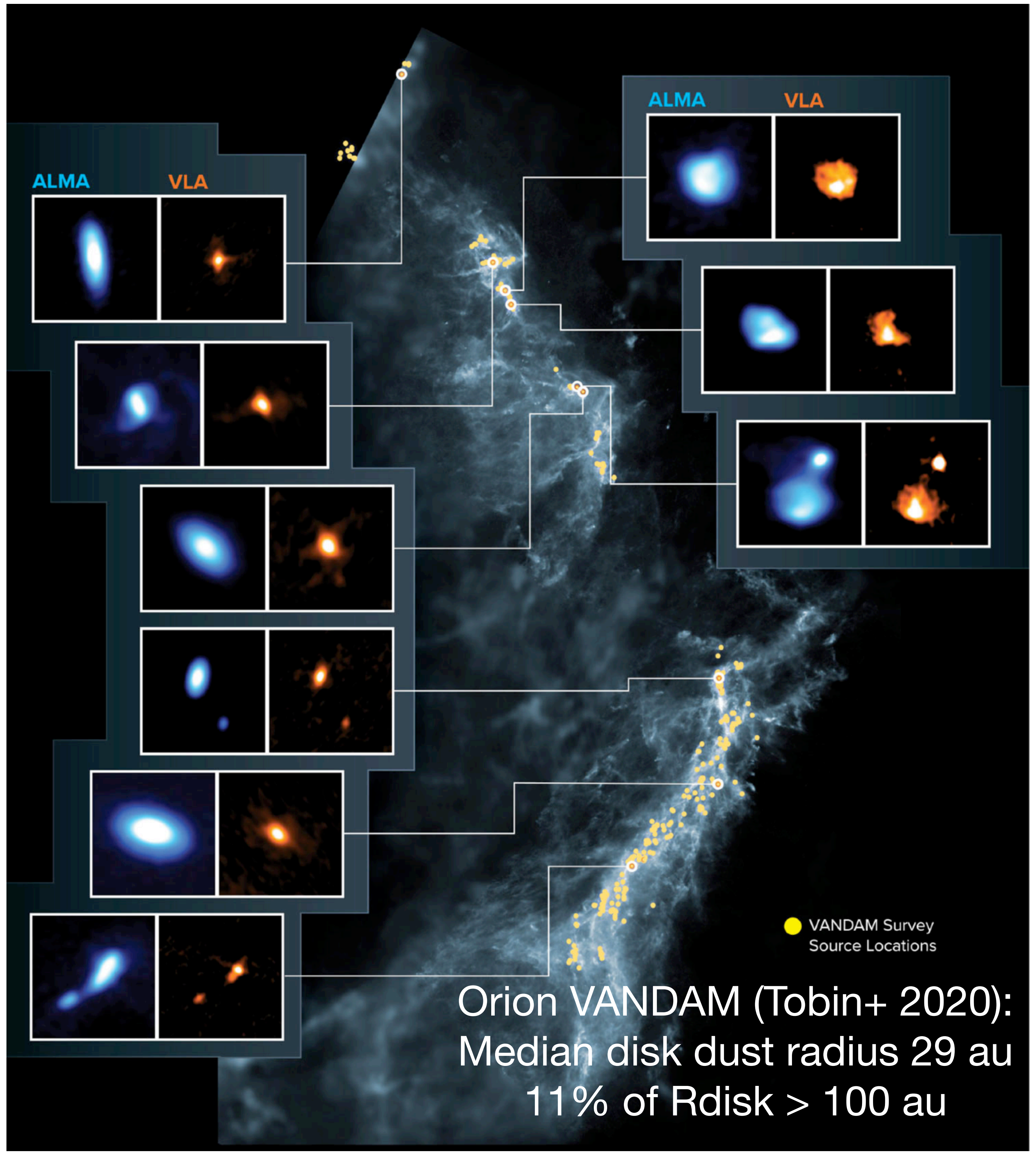
Assuming conservation of angular momentum, a gas particle of specific angular momentum j located at envelope radius r should reach a centrifugal radius at:

$$R_{cent} = \frac{< j_r >^2}{G \times M(R_{cent})}$$

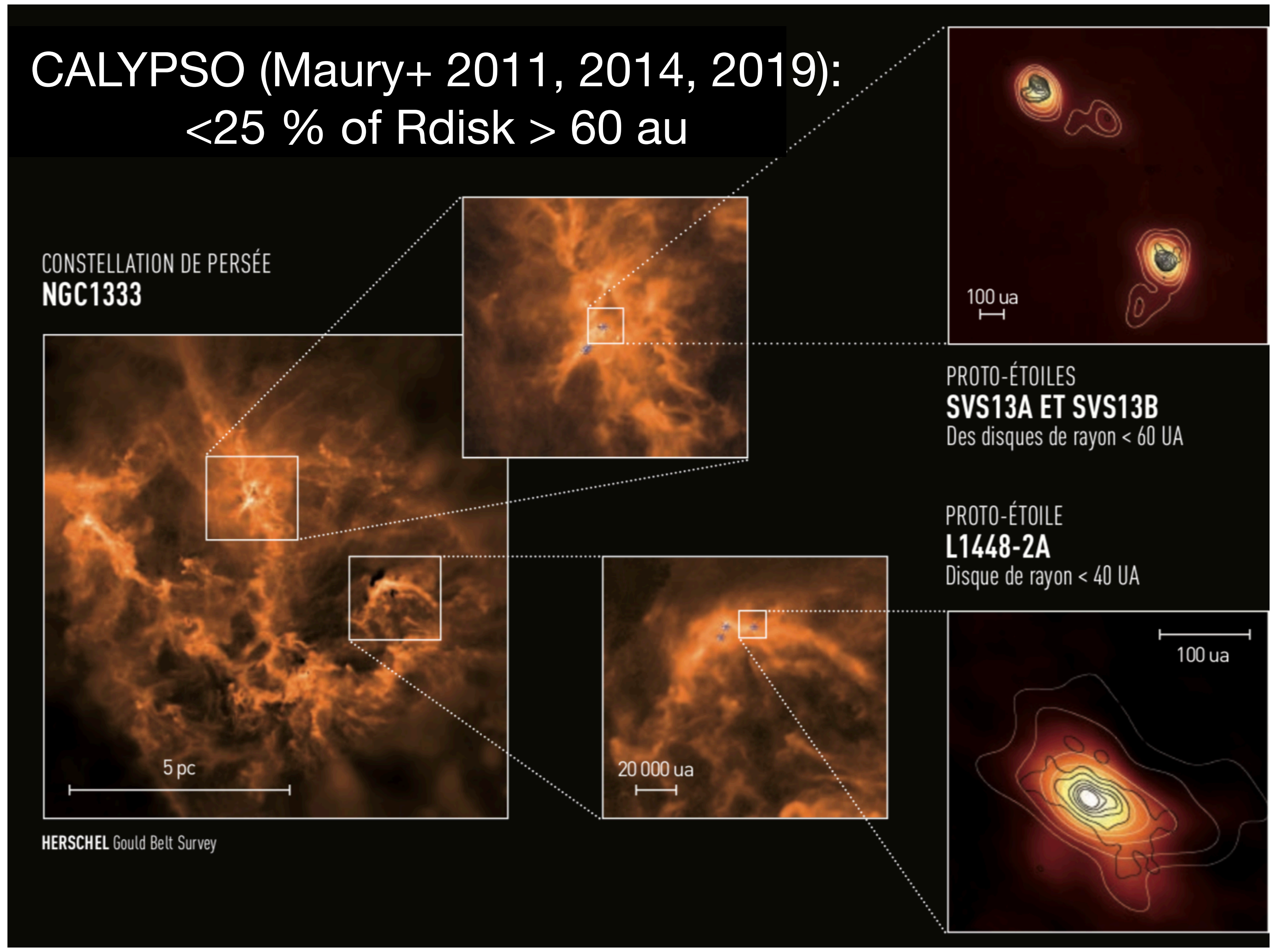
j_{1000au} ~ 10^{21} cm^2 s^{-1}
~ 3×10^{-3} km s^{-1} pc

Class 0: $M_{star} + M_{disk} < 0.3\ M_{sun}$

> 500 au disk radius

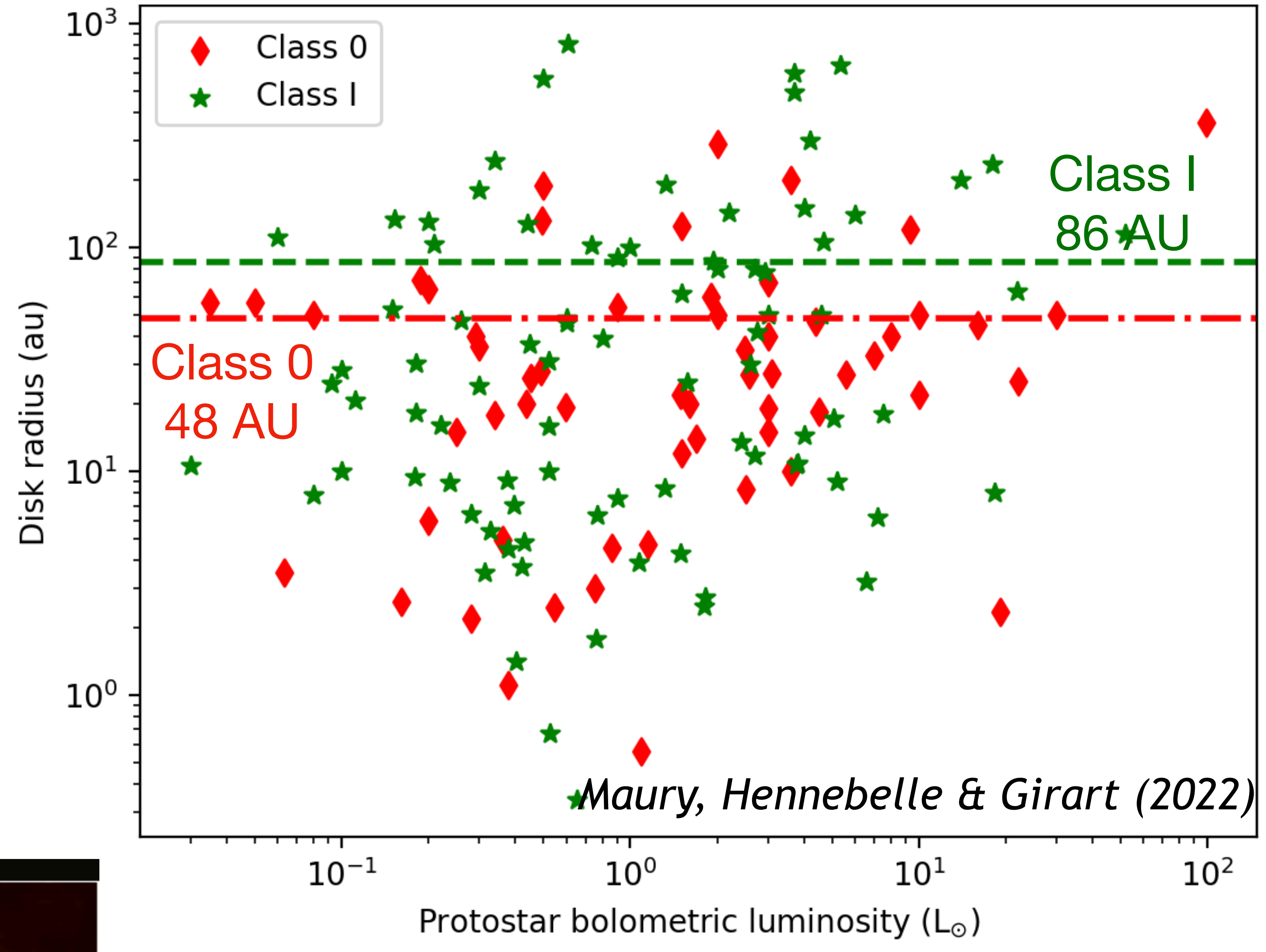


Orion VANDAM (Tobin+ 2020):
Median disk dust radius 29 au
11% of Rdisk > 100 au



CALYPSO (Maury+ 2011, 2014, 2019):
<25 % of Rdisk > 60 au

Class 0 and Class I protostellar disk radii,
observed from the dust continuum emission at < 2.7mm

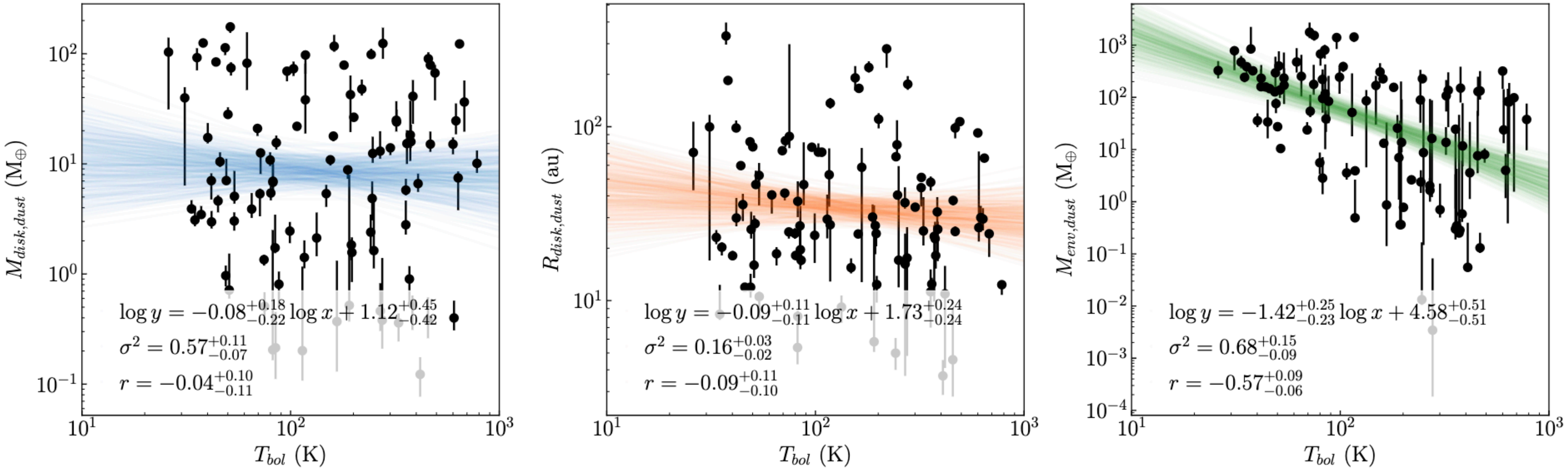


Two complete & recent reviews :

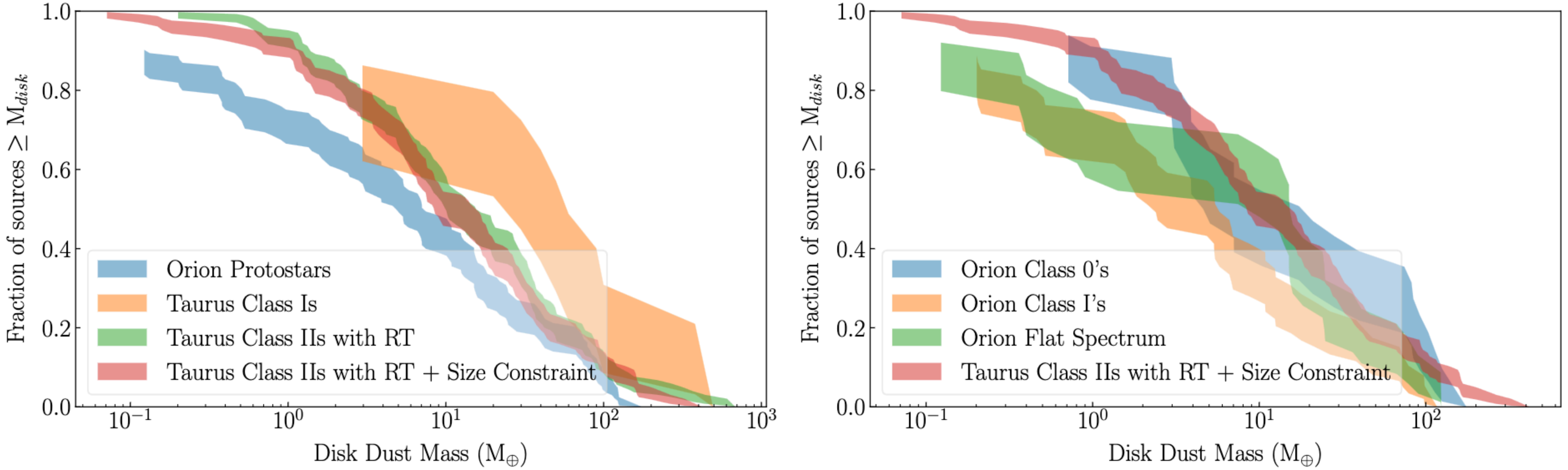
https://ui.adsabs.harvard.edu/abs/2022FrASS...9.9223M/abstract
https://arxiv.org/pdf/2209.13765.pdf

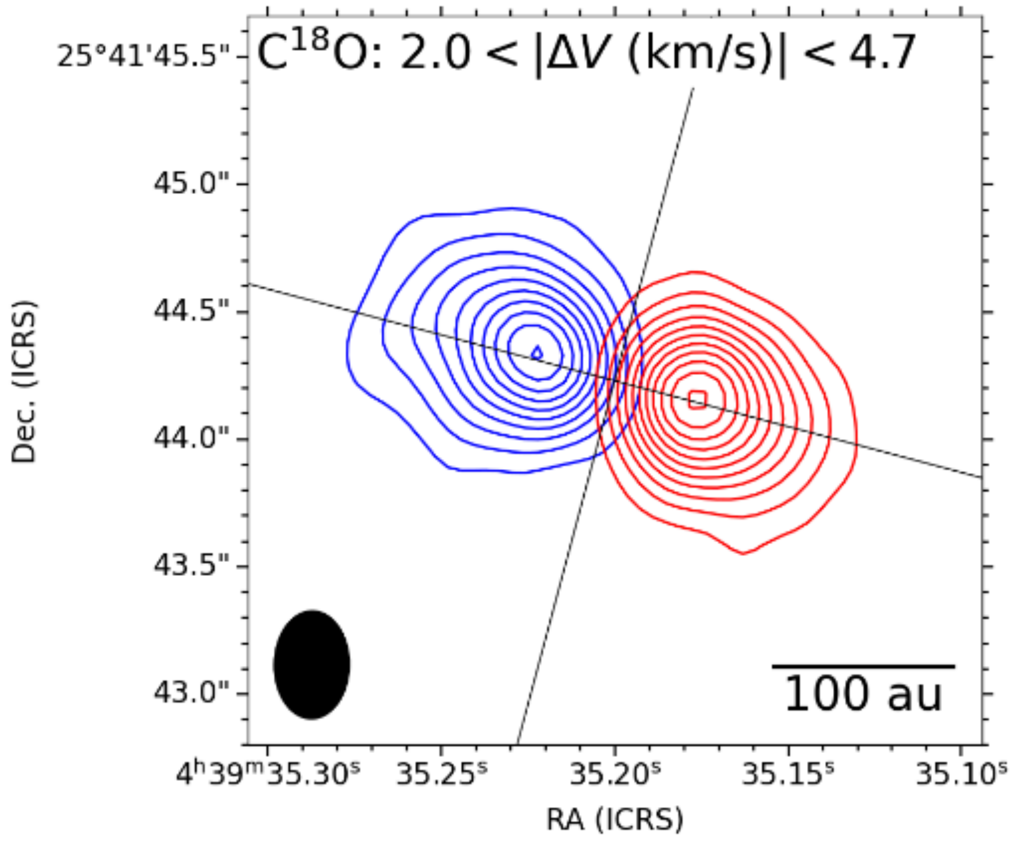
The envelope masses decreases with increasing T_{bol} (evolution):
BUT dust disk radii seem insensitive ....
dust drift drives dust disk sizes ? => kinematics needed

Sheehan+ (2022) from VANDAM survey



The disks are a few Earth masses, but beware of unconstrained dust properties
=> kinematics needed





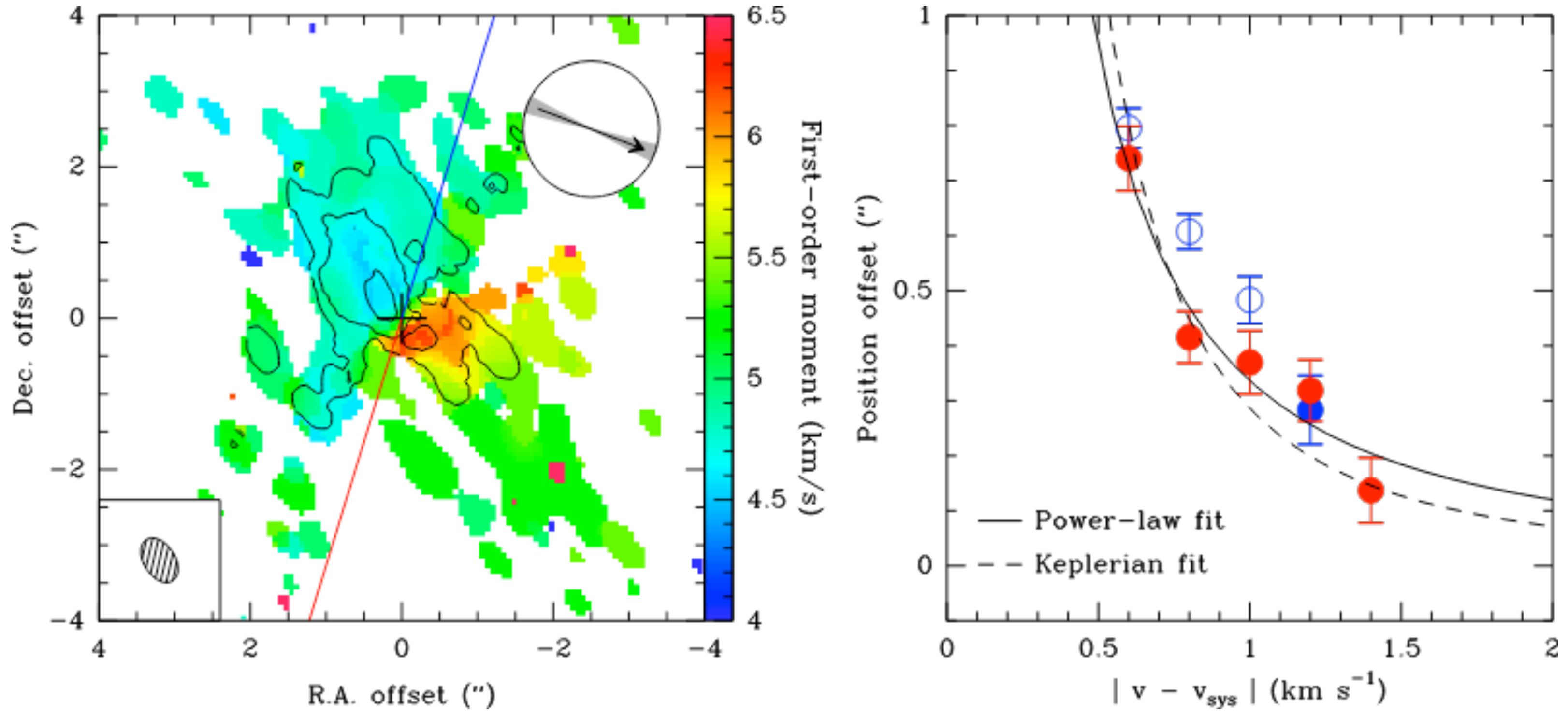
Aso et al. (2021)

Mix of infall and Keplerian motions

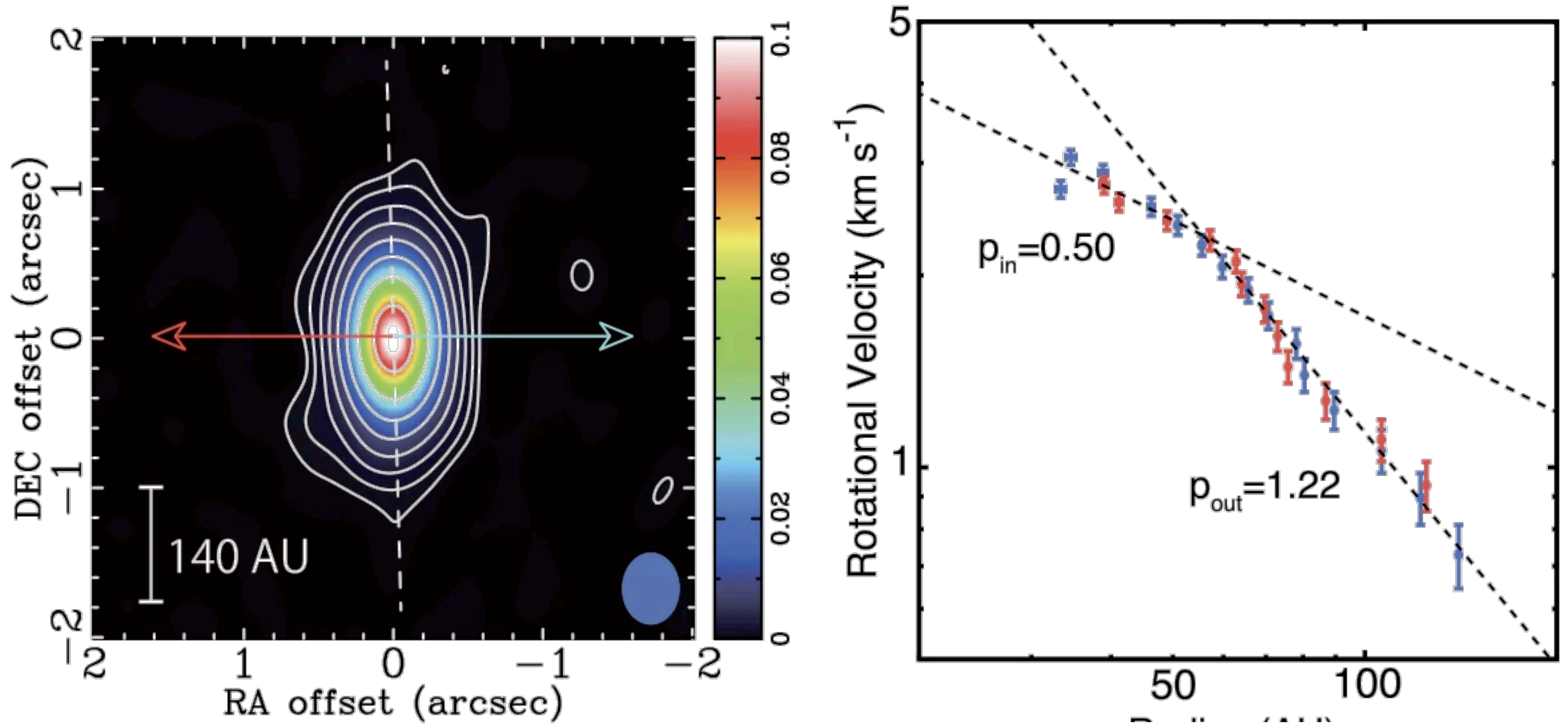
-

150 au disk in Class I TMC1-A

Maret & CALYPSO collab. 2020: 1/15 Class 0 Keplerian disk spatially resolved at scales ~50 au (L1448-C)



Aso et al. (2017)



Class 0/I L1527 disk resolved from gas kinematics obtained with ALMA

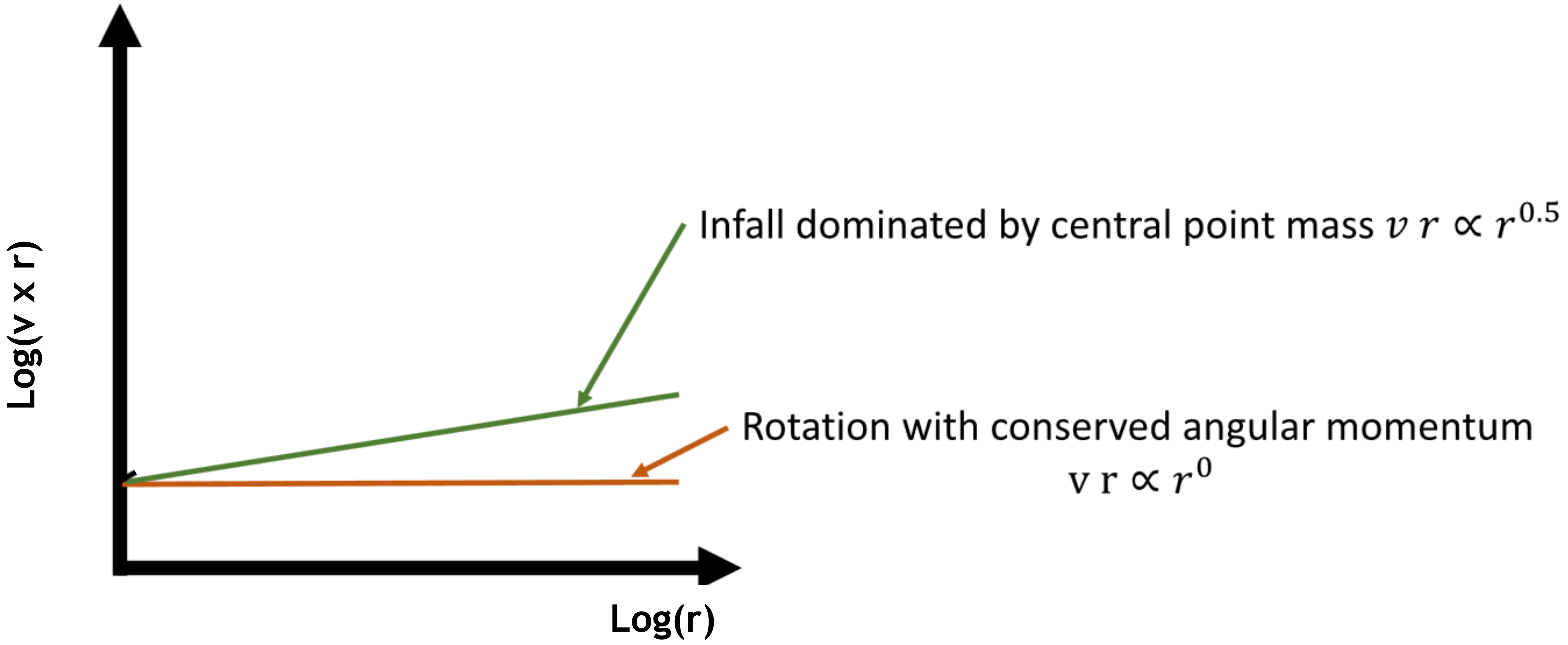
- Keplerian radius 74 au

Gas in Keplerian motions observed in the largest disks (spatially resolved) - few of them
=> disk radii mostly consistent with dusty radii in the current small samples

Where are the >500 au Class 0 disks predicted by conservation of AM during core collapse ?

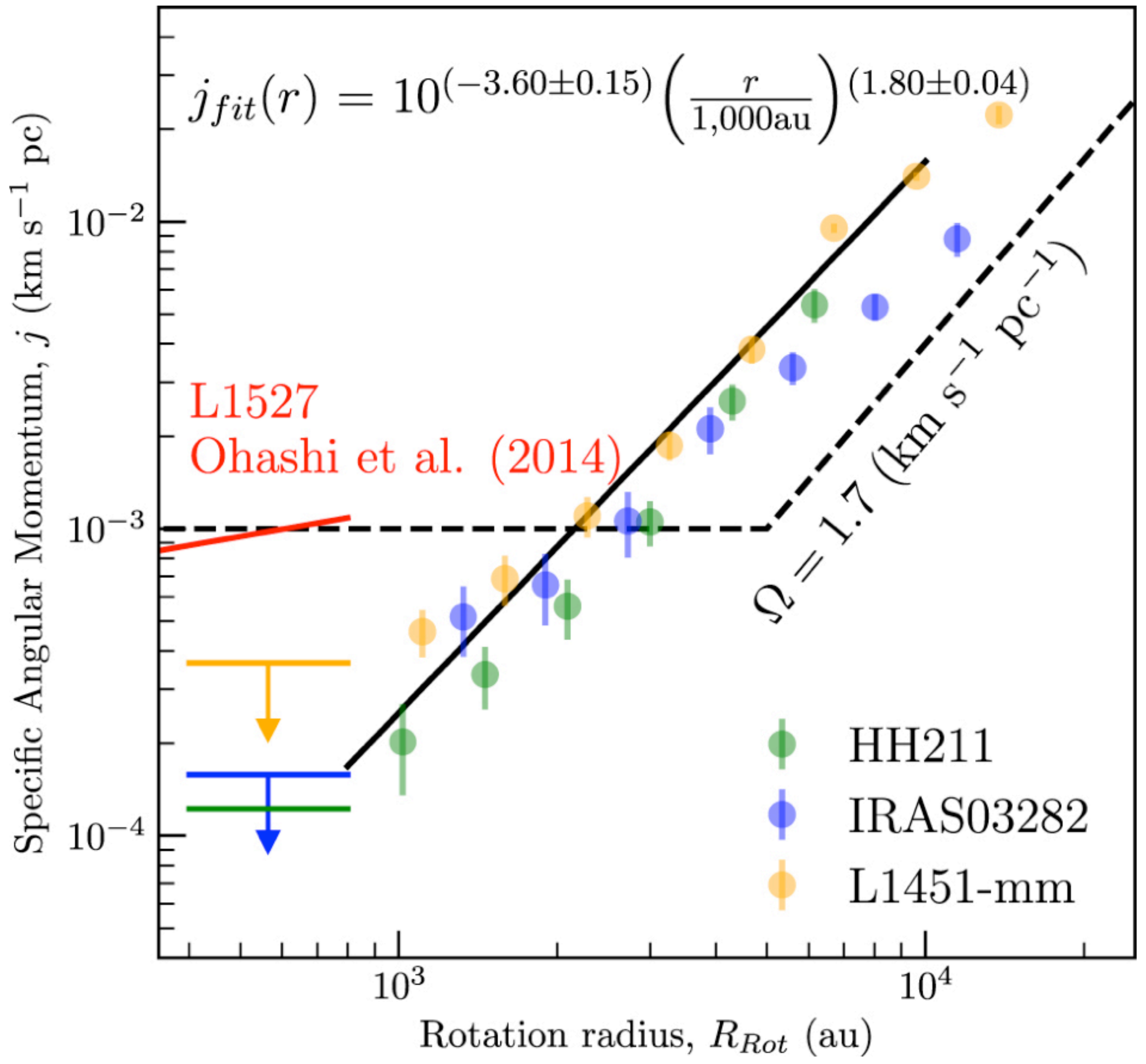
Don't count your chickens before they are hatched….

=> Measure the angular momentum due to rotational motions inside protostellar envelopes, at smaller radii than values found in the literature



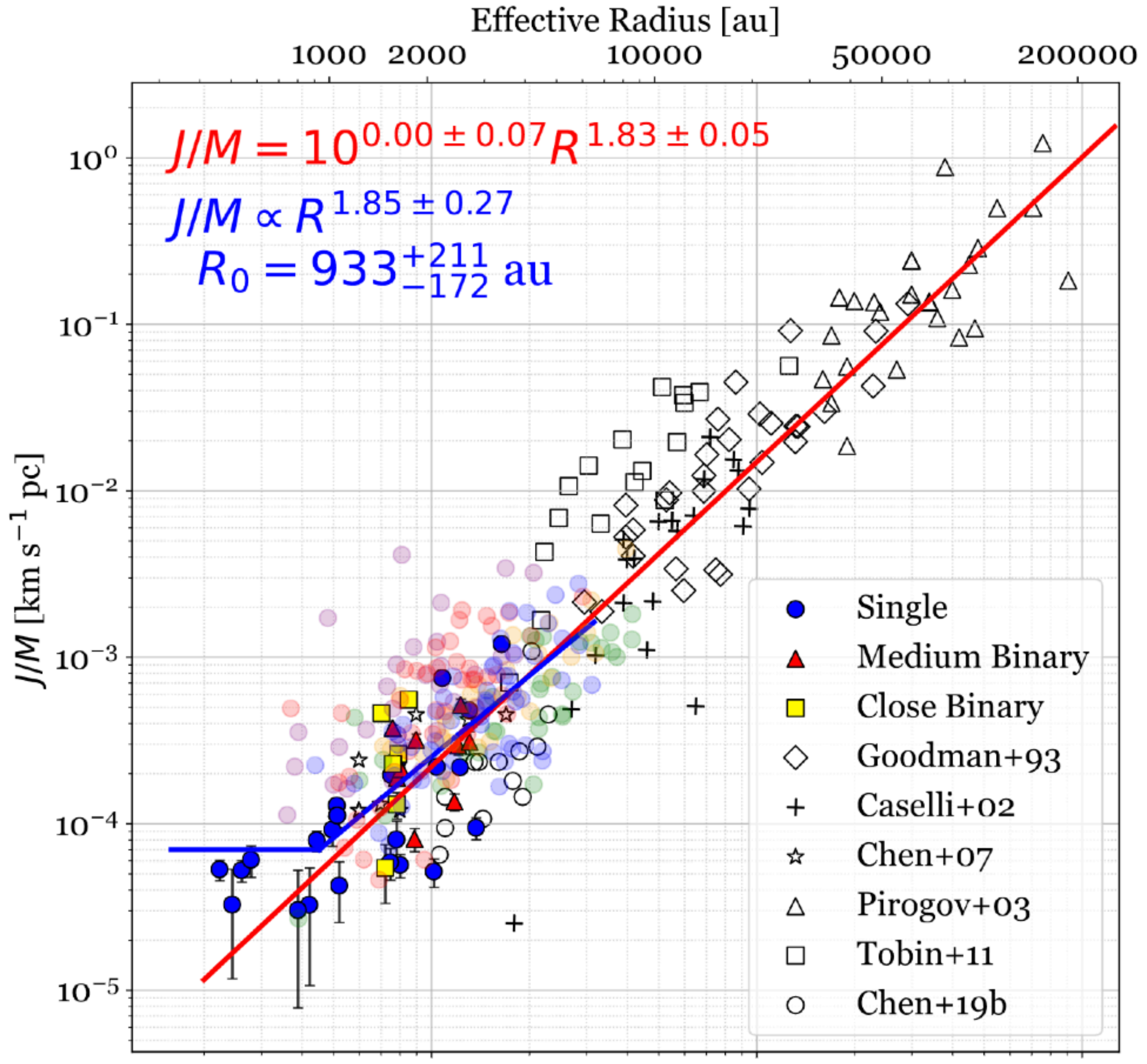
It is difficult to measure AM evolution in protostellar envelopes !

Large envelope scales:



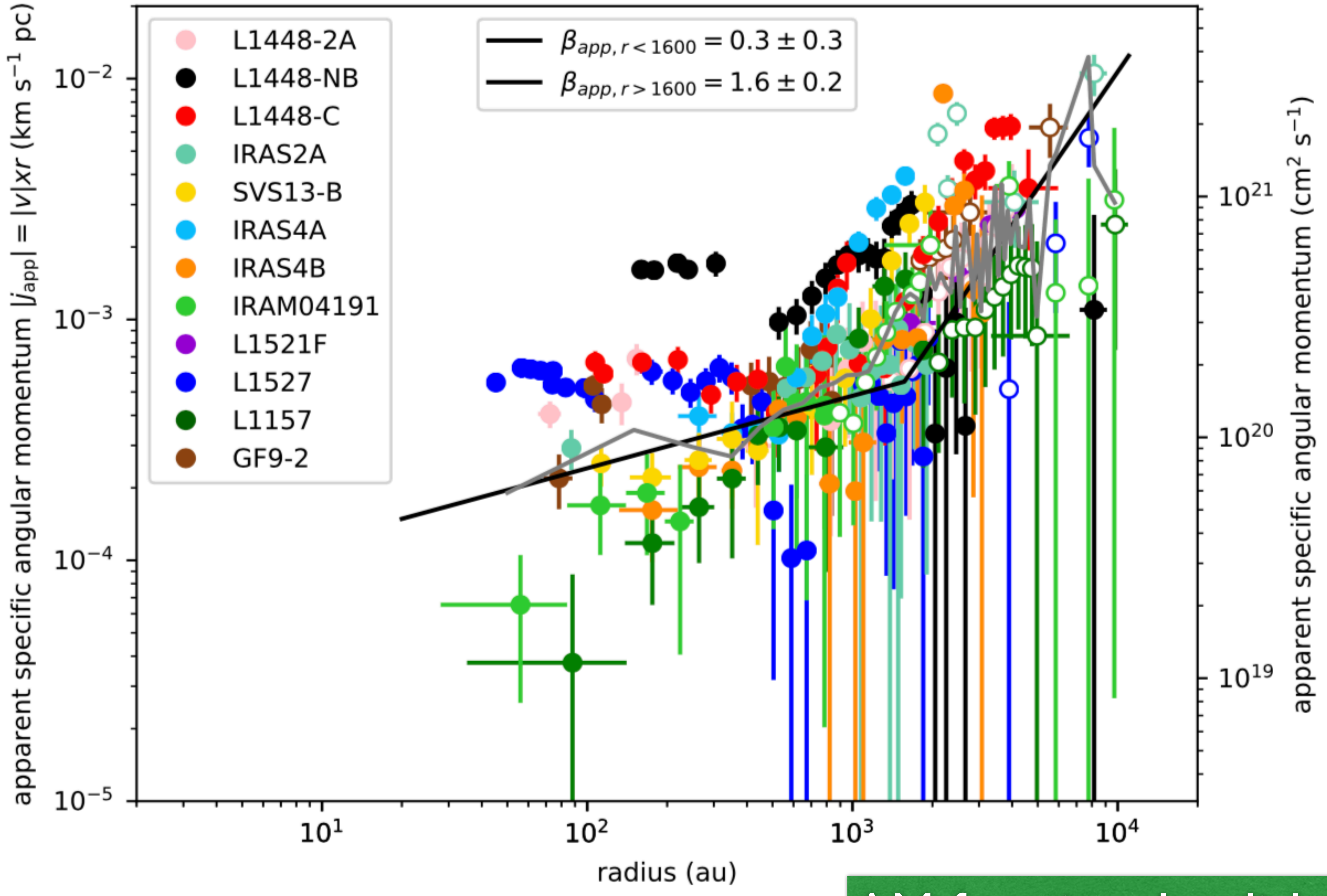
Pineda et al. (2019)
Heimsoth et al. (2021)

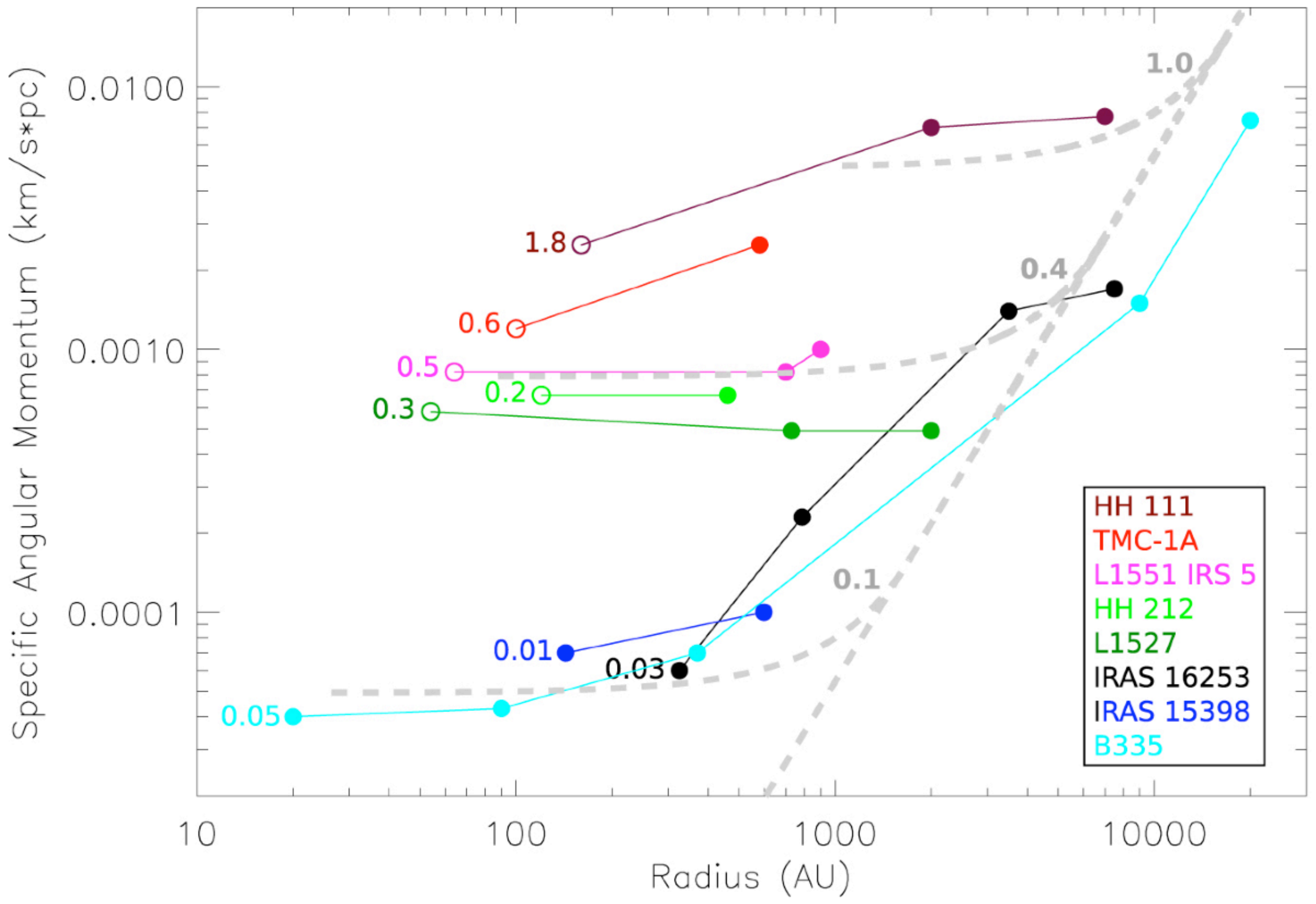
External envelopes show decreasing j(r)



Small envelope scales:

CALYPSO Class 0 protostars: Gaudel et al. (2020)
Break in angular momentum radial profiles





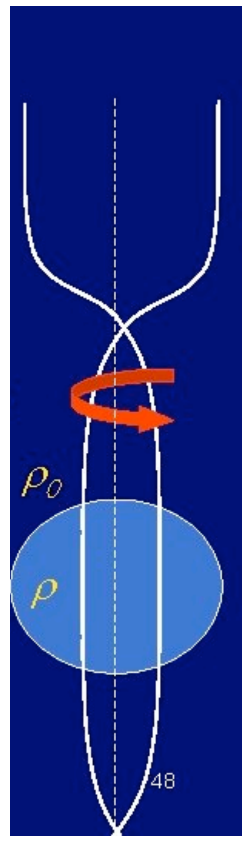
Class 0 & Class I protostars : Yen et al. (2017)
Conserved angular momentum at <1000 au ?

AM forming the disks has a LOCAL origin

Another possible scenario is that AM in envelopes is not transmitted down to disk scales if envelopes are subject to MAGNETIC BRAKING

Magnetic fields can redistribute angular momentum
away from a collapsing region thanks to torsional Alfvèn waves
(Mouschovias & Paleologou 1979, 1980)

Timescale for magnetic braking: $t_b = \rho R (2\rho_0 \times V_A)$



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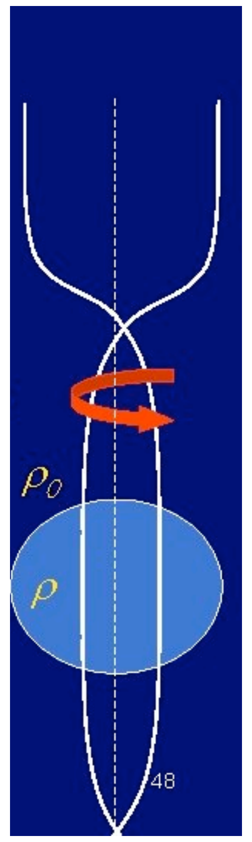

Hennebelle+ 2016 : Analytical non-ideal MHD collapse leads to self-regulation of disks to small (20-50 au radii)

Typical radius is:

$$r_{\rm d,AD} \simeq 18\,{\rm AU} \times \delta^{2/9} \left(\frac{\eta_{\rm AD}}{0.1\,{\rm s}}\right)^{2/9} \left(\frac{B_z}{0.1\,{\rm G}}\right)^{-4/9} \left(\frac{M_{\rm d}+M_*}{0.1\,{\rm M}_\odot}\right)^{1/3}.$$

By contrast hydro would lead to:

$$r_{\rm d,hydro} \simeq 106\,{\rm AU}\,\frac{\beta}{0.02}\left(\frac{M}{0.1\,{\rm M}_\odot}\right)^{1/3}\left(\frac{\rho_0}{10^{-18}{\rm g\,cm^{-3}}}\right)^{-1/3}$$

=> Early disk formation is magnetically *self-regulated* !

Another possible scenario is that AM in envelopes is not transmitted down to disk scales if envelopes are subject to MAGNETIC BRAKING

SEE HENNEBELLE'S LECTURE

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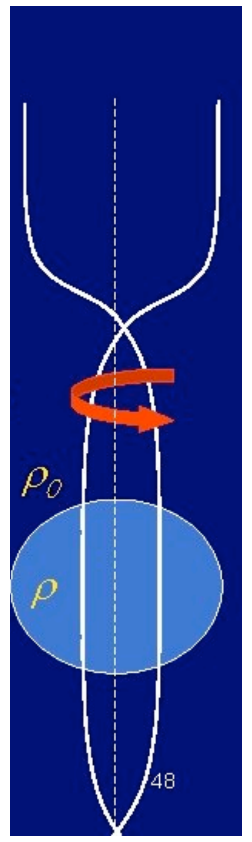

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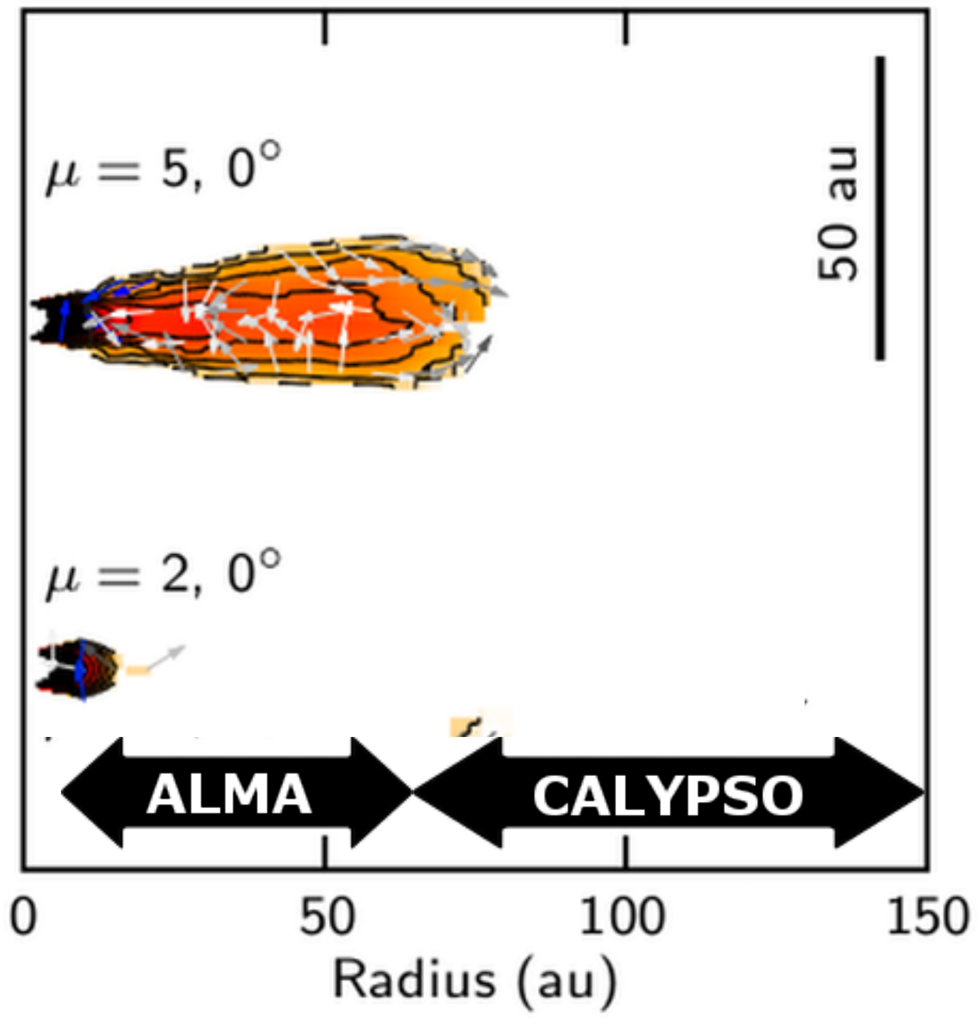
=> Early disk formation is magnetically *self-regulated* !

See our review in Maury, Hennebelle, Girart 2022

Non-ideal MHD Class 0 disks:
sizes and shapes
under various local conditions

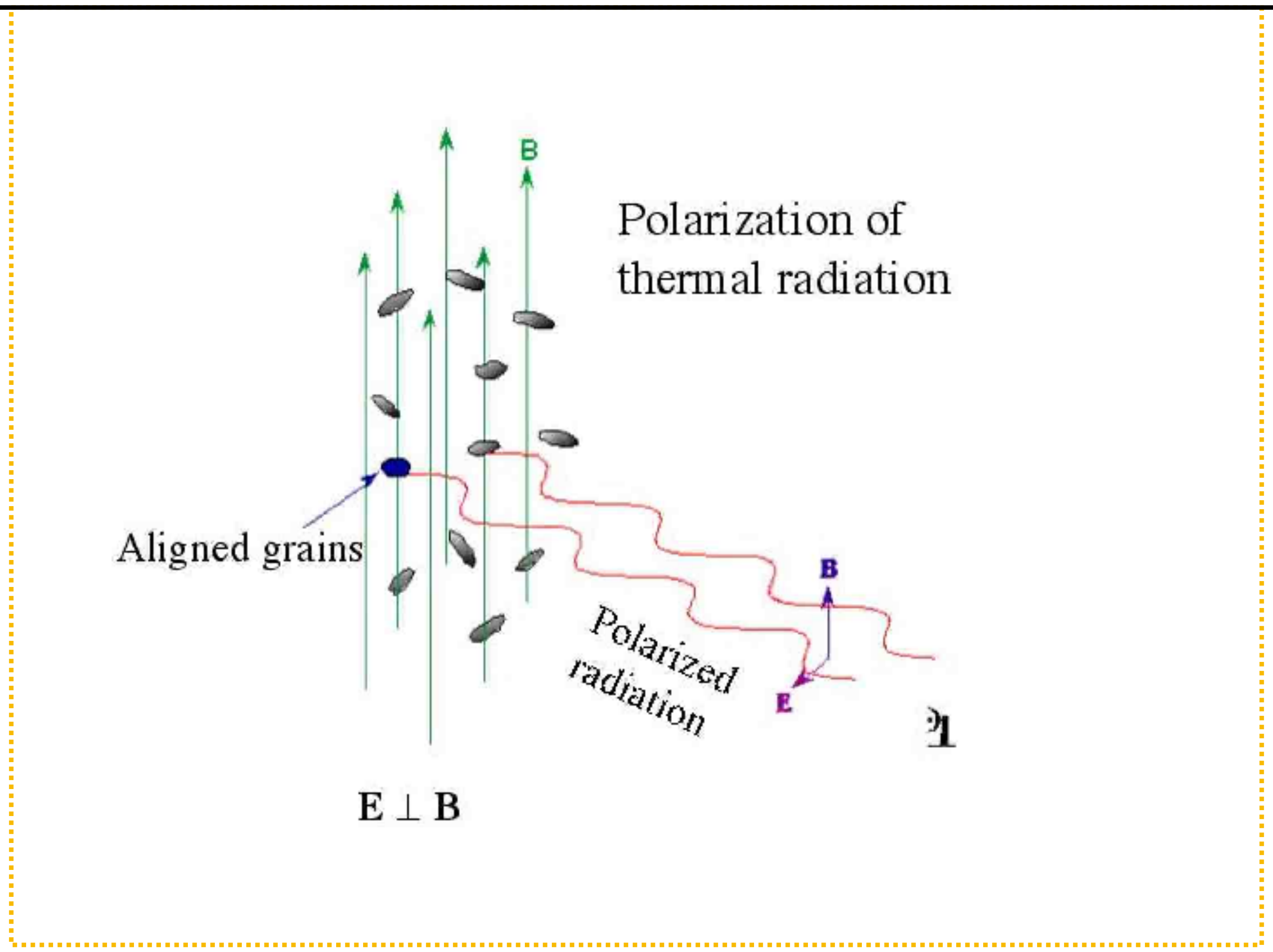


Masson+ 2015

Where are the >500 au Class 0 disks predicted by conservation of AM during core collapse ?

Don’t count your chickens before they are hatched….

=> Measure the magnetic fields in protostellar envelopes, and check predictions of magnetized models



It is difficult to measure magnetic fields in dense cores and disks !

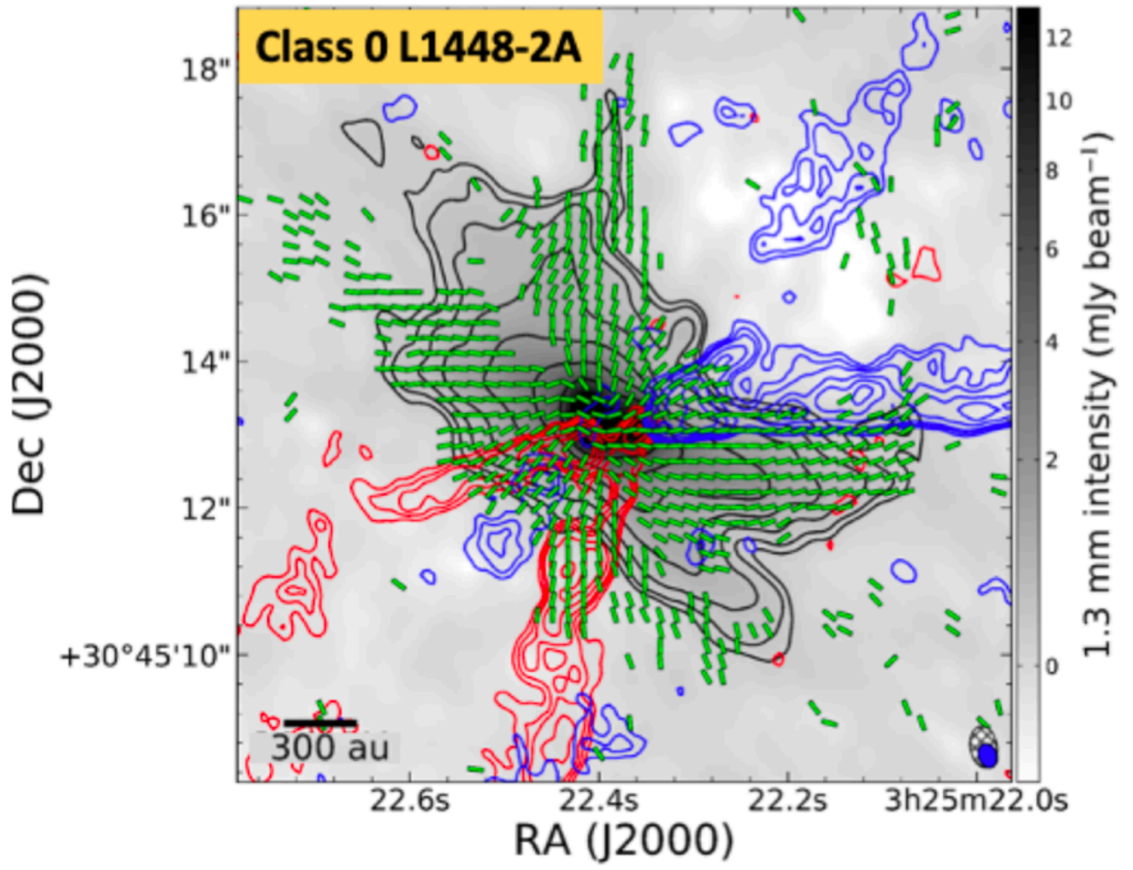
If you want to know more on how to measure B in star-forming environments:

attend Thursday evening short talks !

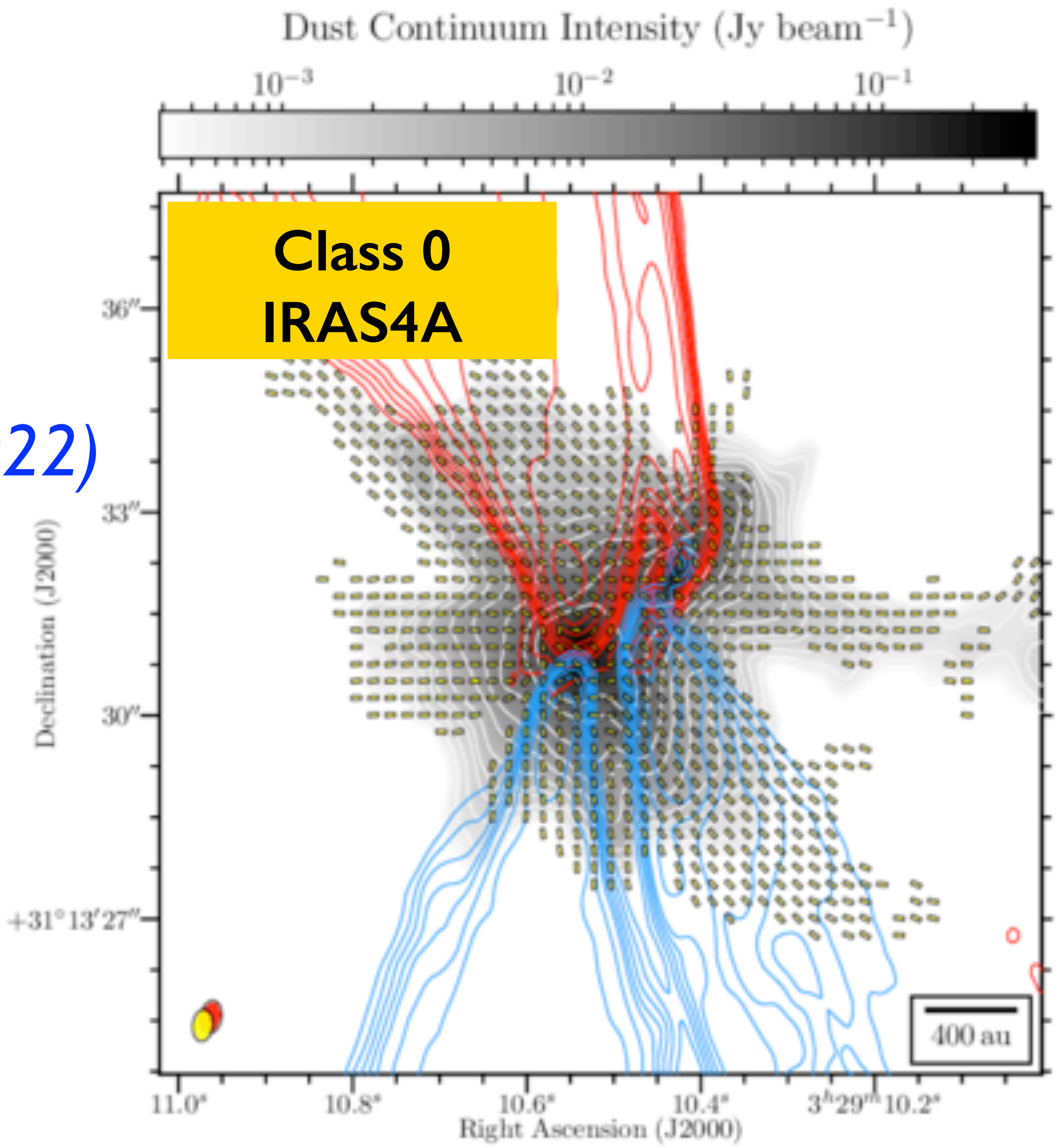
Dust polarized emission is widely used to trace the B fields in ISM

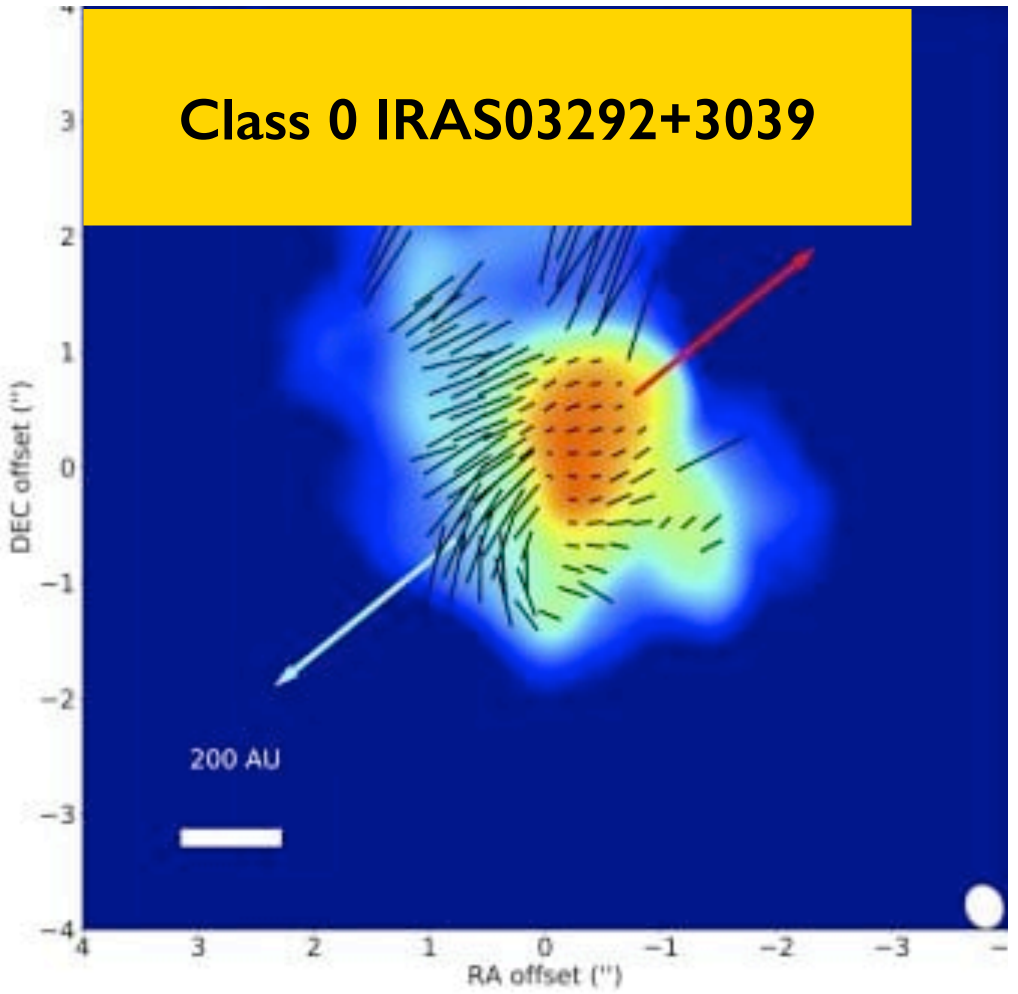
Is magnetic field ubiquitous ?

Kwon et al. (2019)

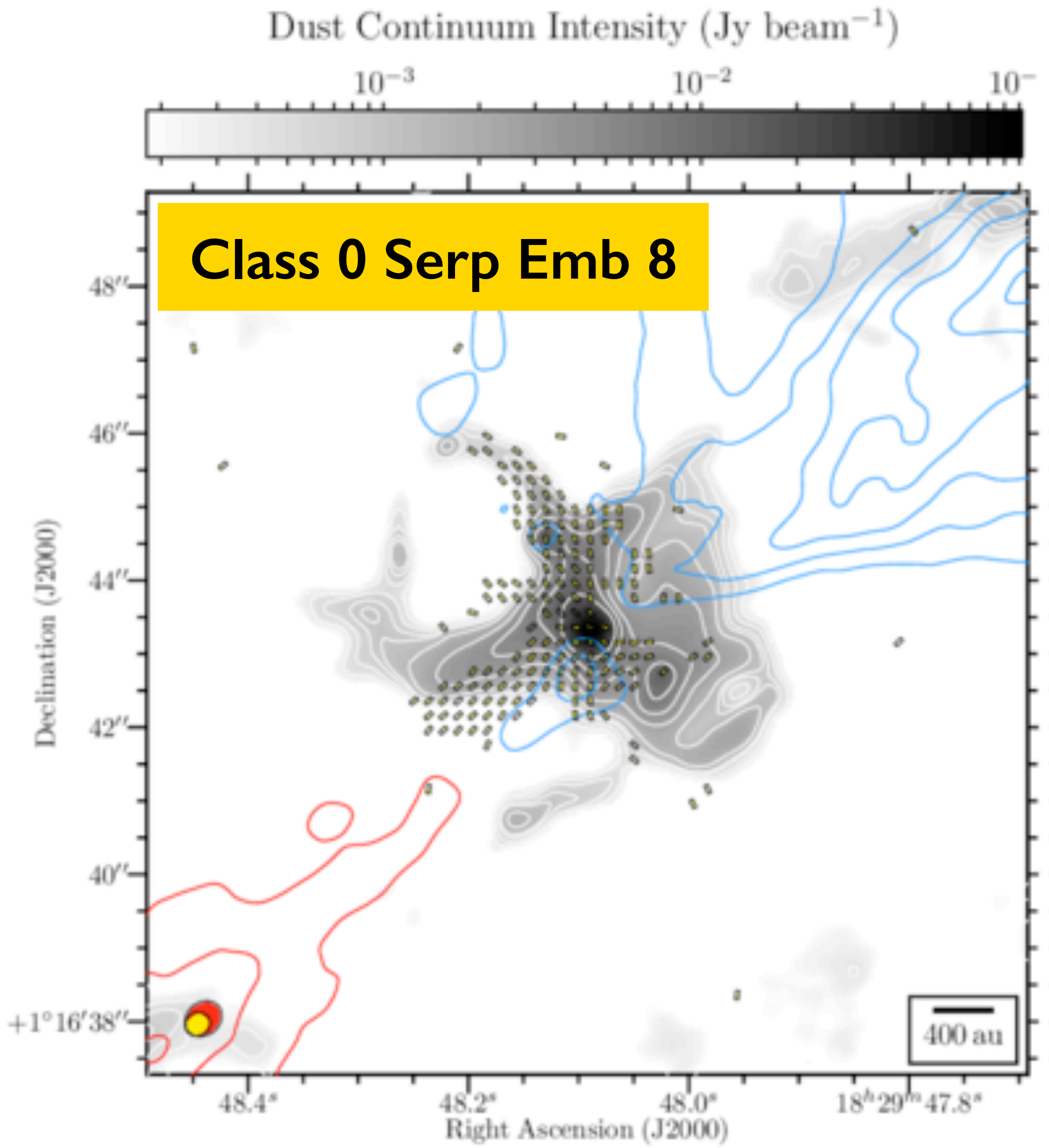


Ko et al. (2020)
Le Gouellec et al. (2022)

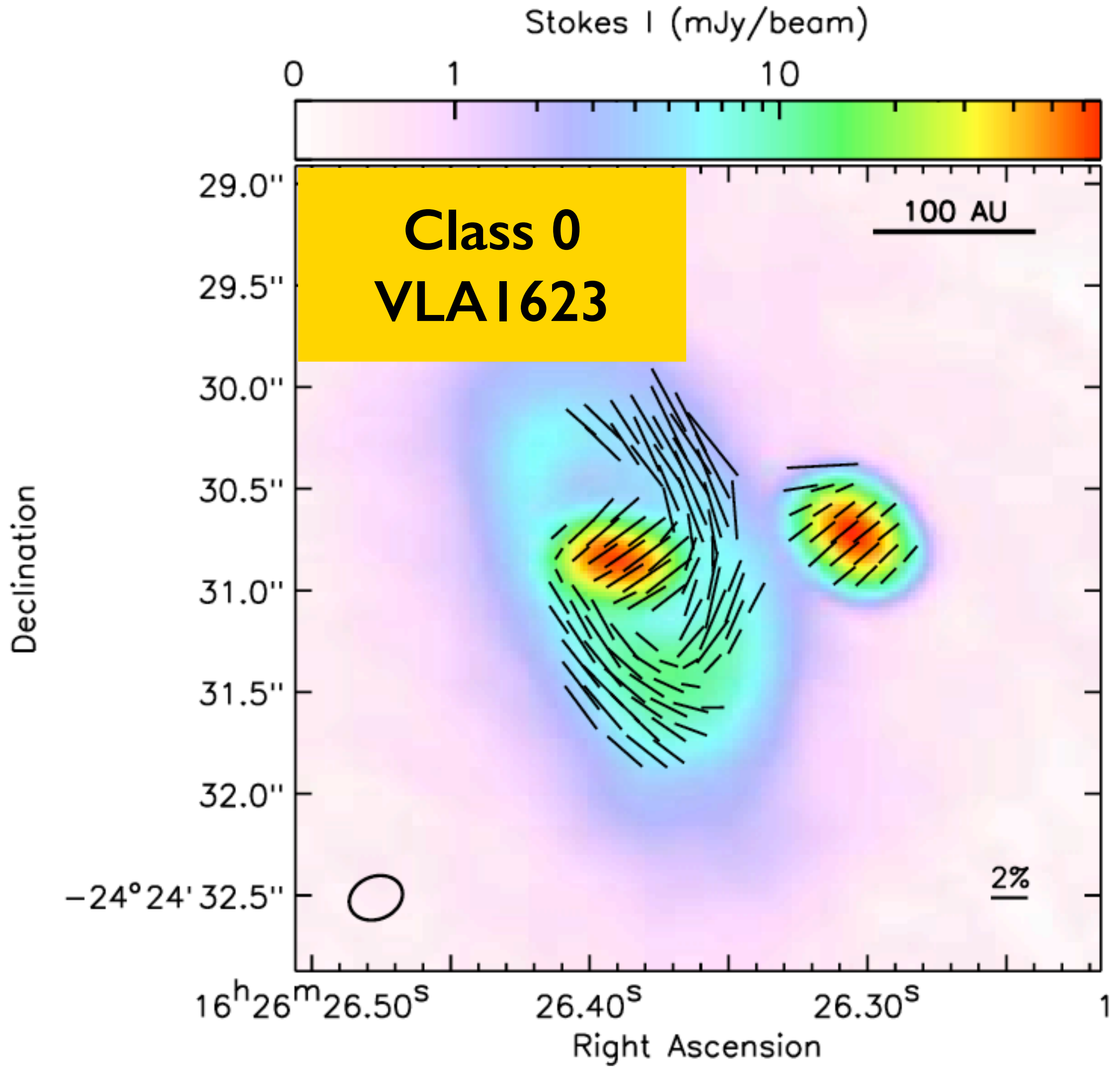




Cox et al. (2018)



Le Gouellec et al. (2020)



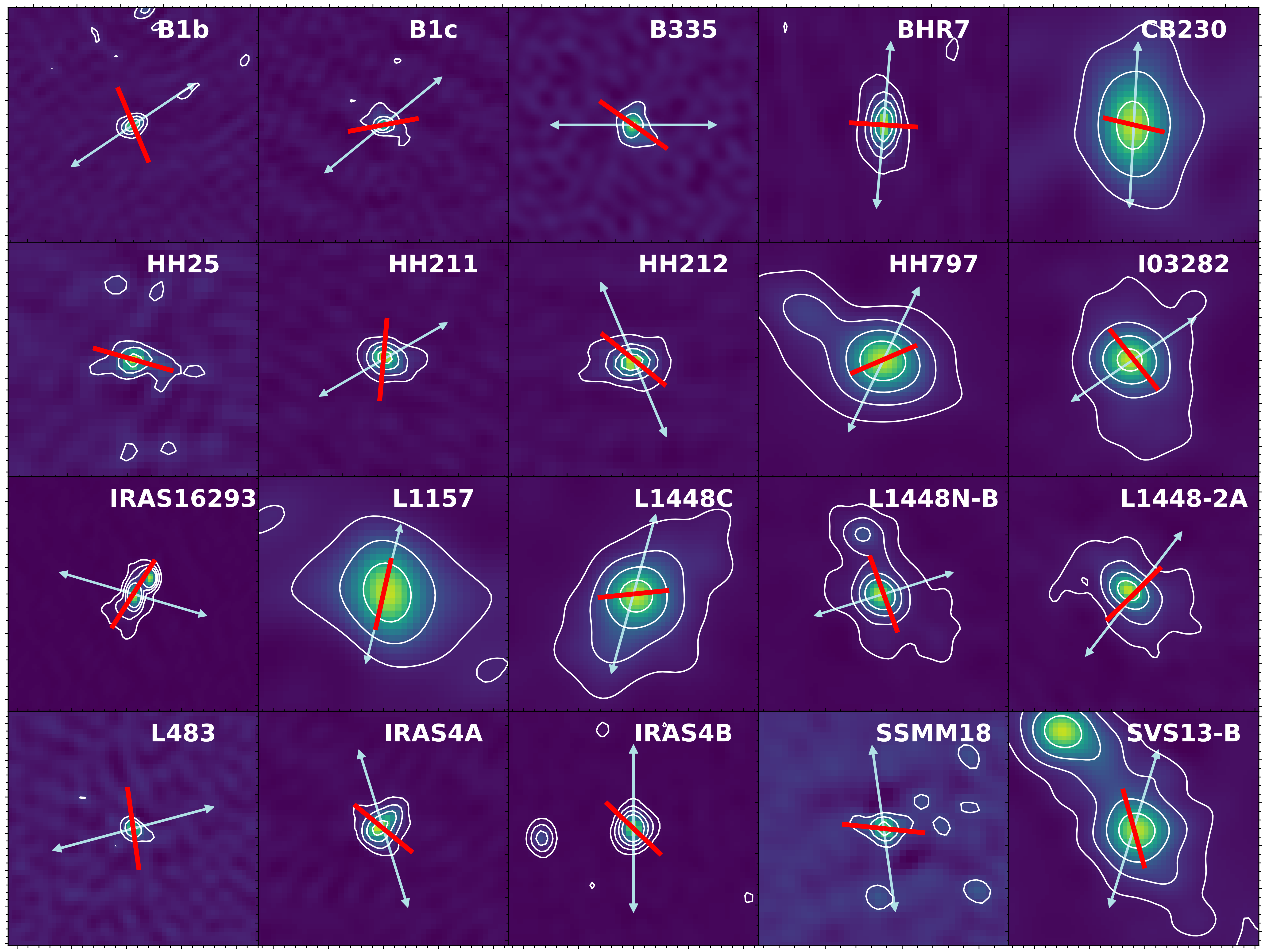
Sadavoy et al. (2019)

B-fields are detected in ALL protostars where they are looked for
+ remain largely organized in low-mass cores
(Less in massive cores ? Lack of statistics)

Many others in the literature !

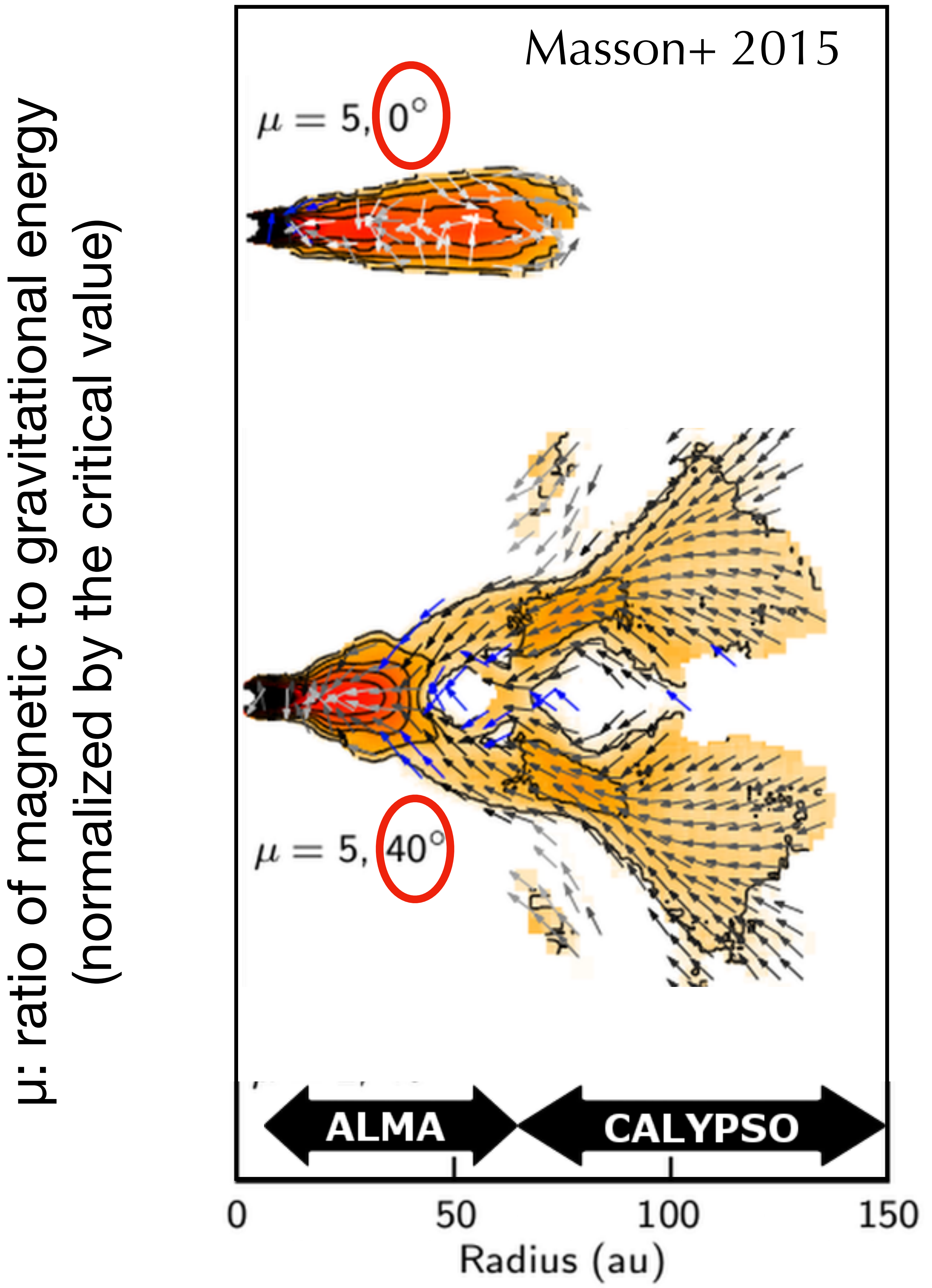
Is magnetic field ubiquitous ?

Galametz, Maury + (2018, 2020):
observations of polarized dust emission from an unprecedentedly large sample of Class 0 protostars
B fields detected in all of them at scales 2000 au !

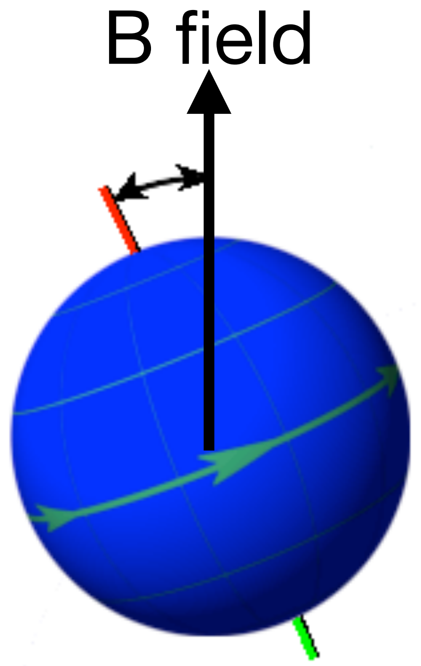


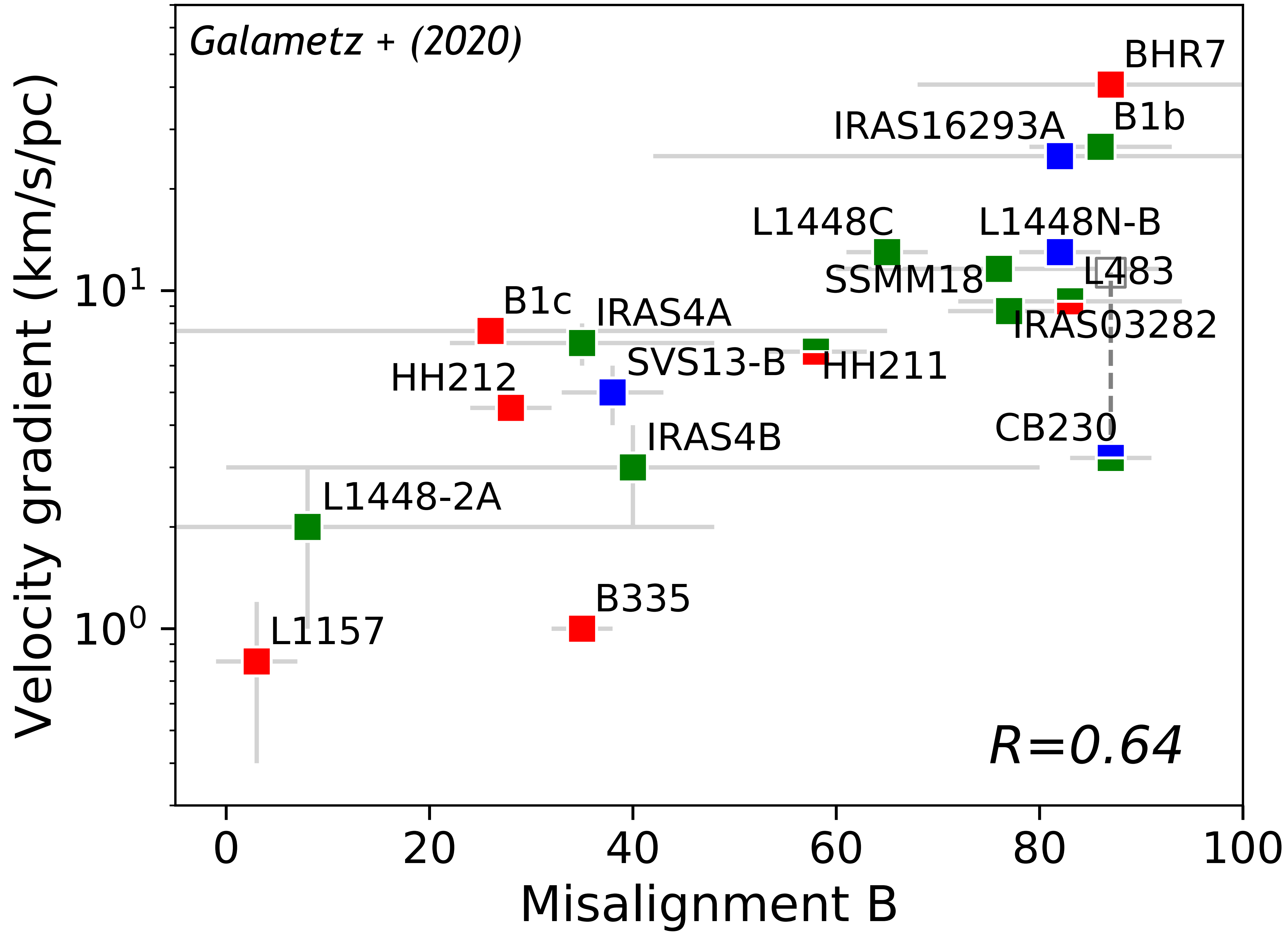
+ Keep tuned for results from the ALMA BOPS survey (Ian Stephens)

Can magnetic braking be inferred from gas kinematics ?



See also Hirano+ (2020) and many others

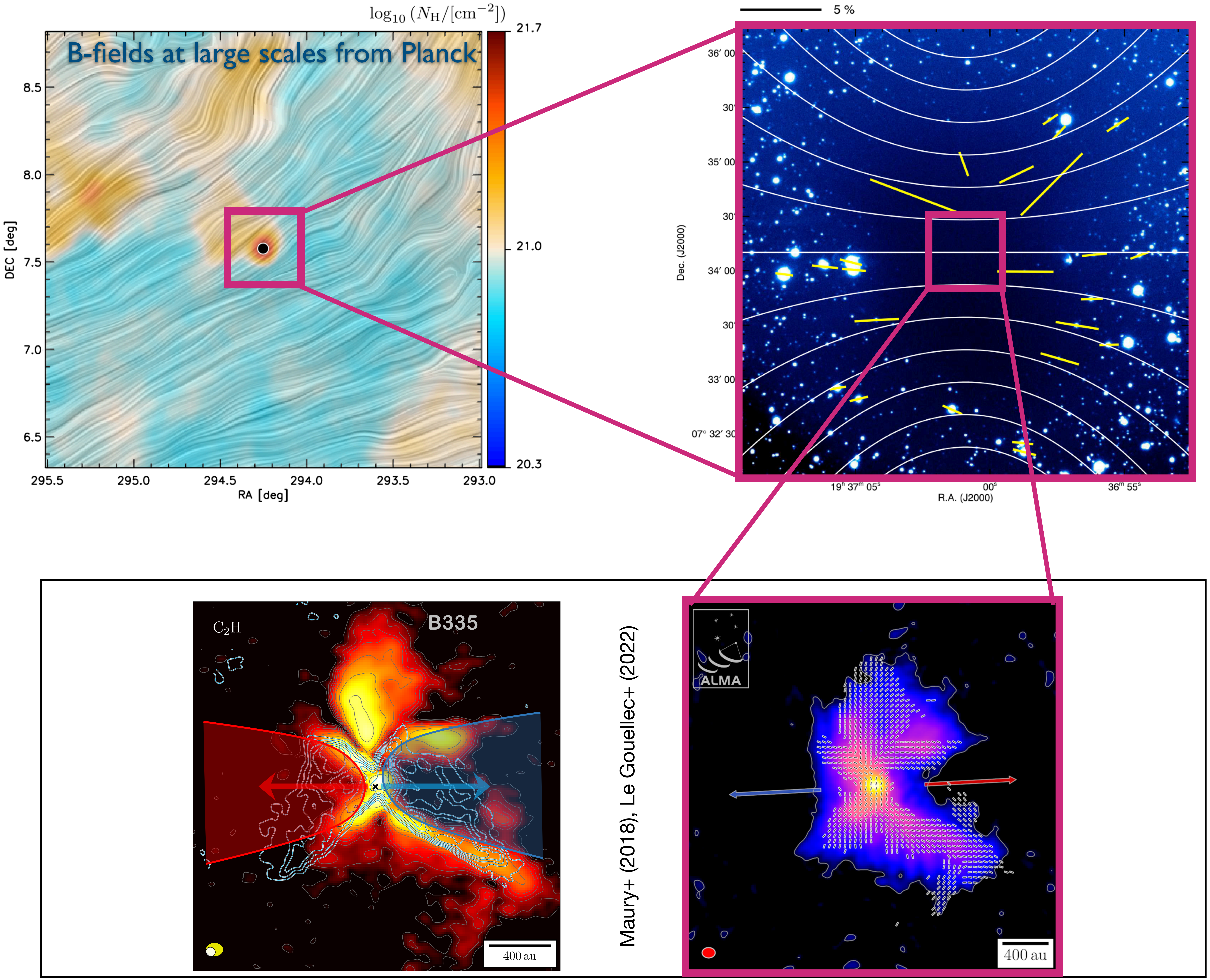




Protostars with aligned B configurations show :
less kinetic energy from rotation in their inner envelopes + less multiple systems

=> an expected outcome of more efficient magnetic braking ? Still a VERY disputed result !


10 arcsec
N
E
B335 seen in optical
E
D
C
B
A
F
G
100 km/s
B335 seen by JWST (NIRSpec)
IR 5
IR 3
IR 4

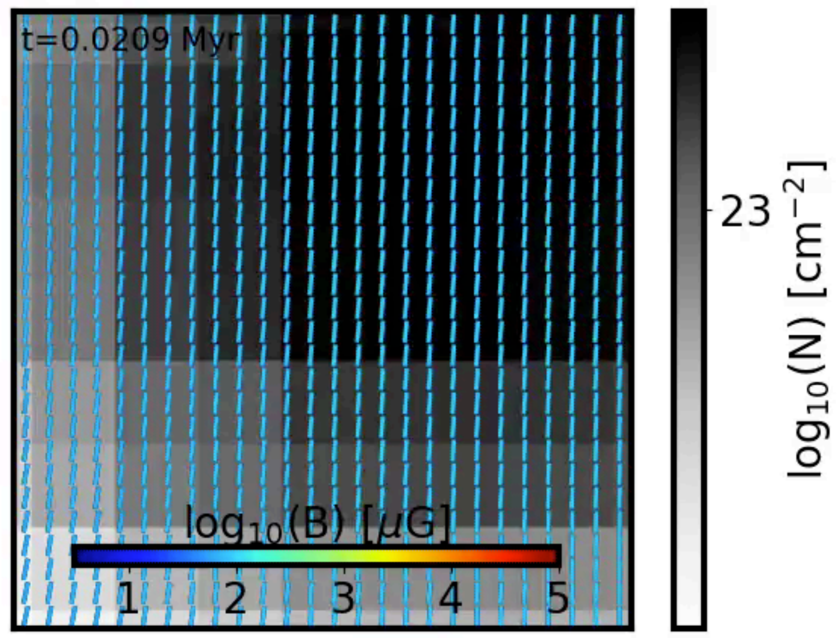


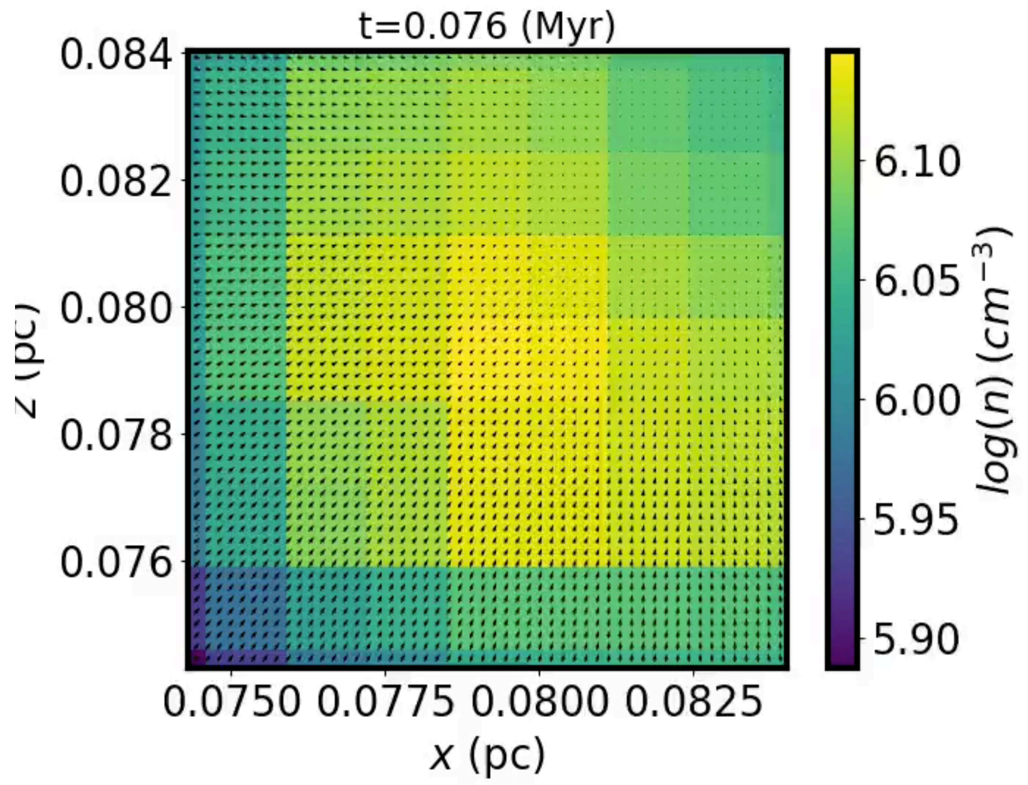
Kandori+ (2020)

Maury+ (2018), Le Gouellec+ (2022)

Comparing data to physical MHD models of protostellar disk formation

- ❖ **Numerical simulations** performed with the RAMSES code (Teyssier 2002, Fromang+2006)
  - Adaptive Mesh refinement (AMR)
  - Non-ideal MHD





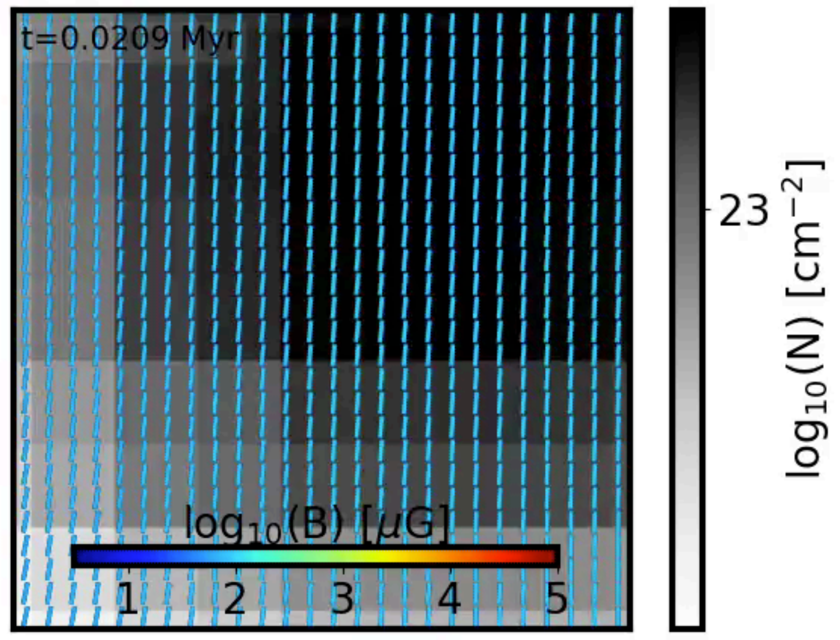
POLARIS

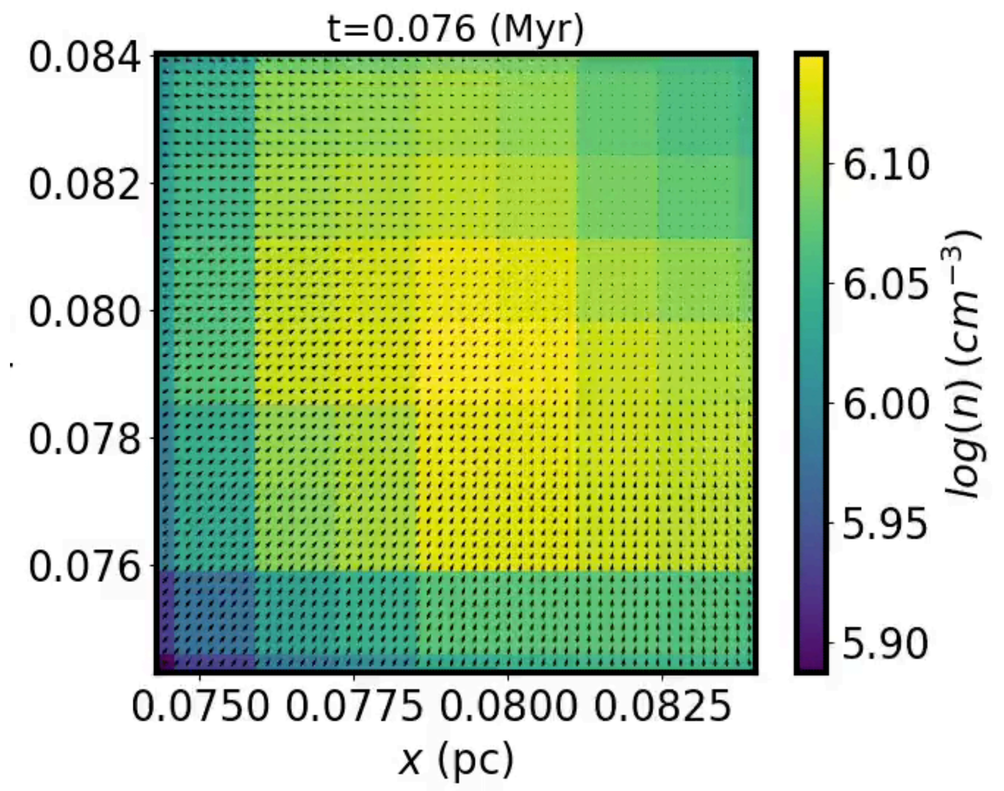
- ❖ **3D Monte-Carlo** continuum radiative transfer code
- ❖ Simulate **intensity** and **polarization** of light
- ❖ Dust heating & **dust grain alignment**

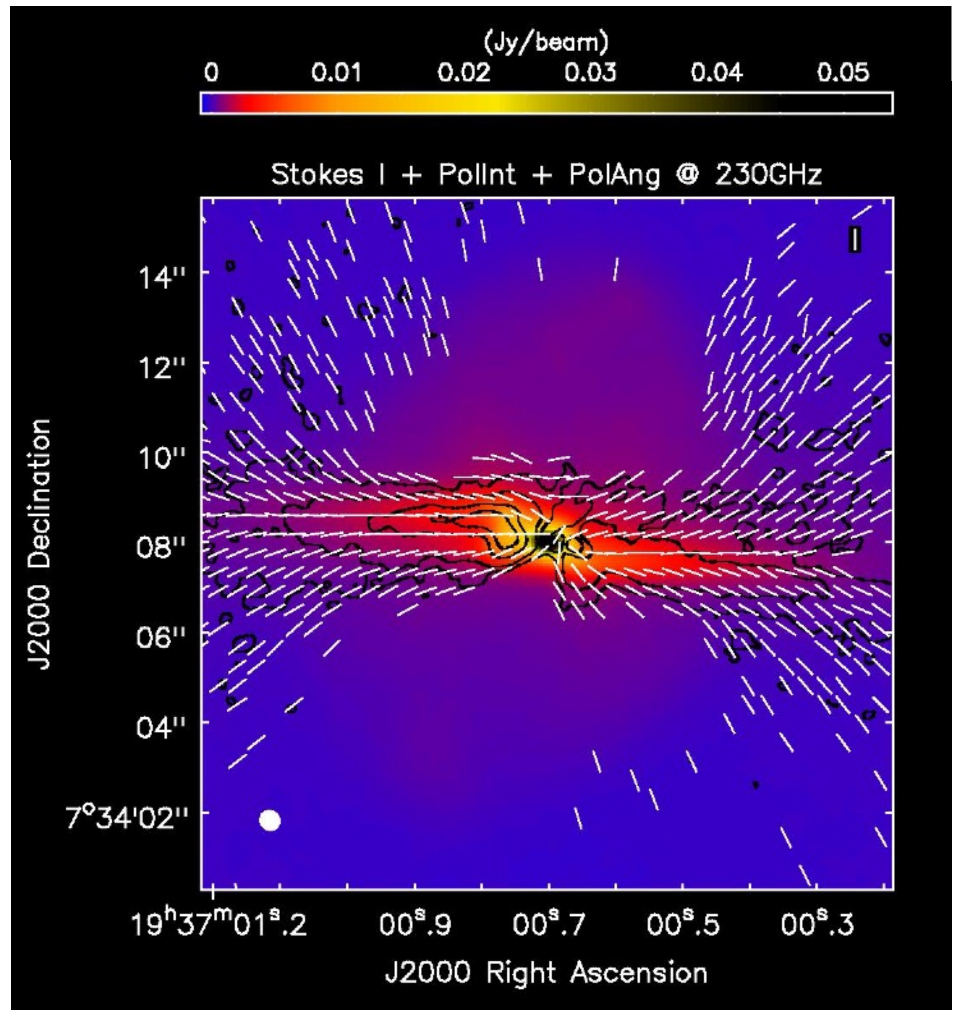
- ❖ Dust assumptions:
  - a_{min} = 5 nm to a_{max}= 1 to 50 μm
  - MRN distribution: $\mathrm{d}n(a) \propto a^{-3.5}\mathrm{d}a$
  - Composition: 62.5% astrosilicates + 37.5% carbonaceous grains

- ❖ Alignment mechanisms:
- Perfect alignment approach (not a physical mechanism!!!)
- Radiative Torques (RAT) (+ Imperfect Internal alignment+ Imperfect Davis-Greenstein)

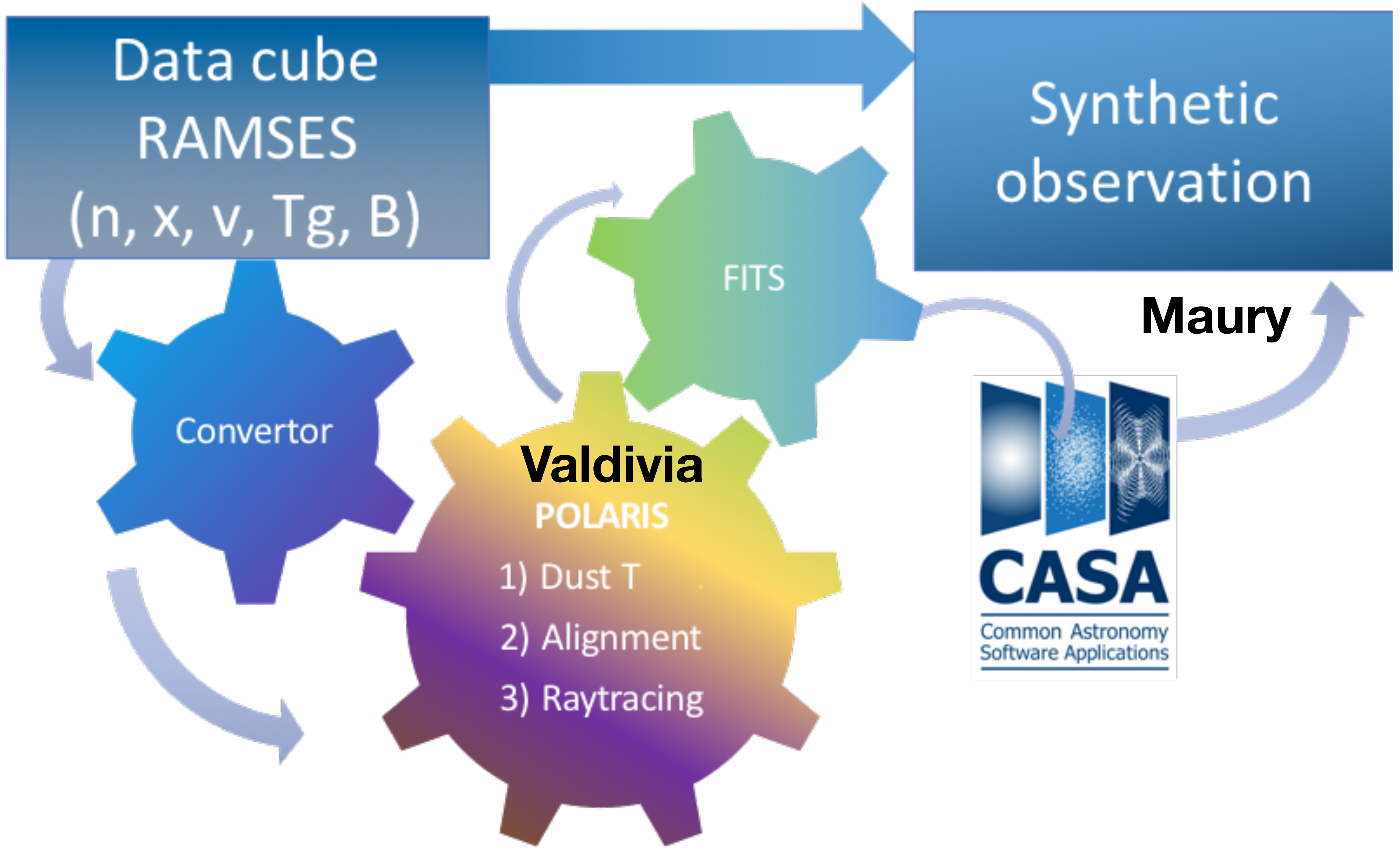
Comparing data to physical MHD models of protostellar disk formation







Hennebelle



Data cube
RAMSES
(n, x, v, Tg, B)

Synthetic observation

Convertor

FITS

Valdivia

POLARIS

1) Dust T
2) Alignment
3) Raytracing

Maury

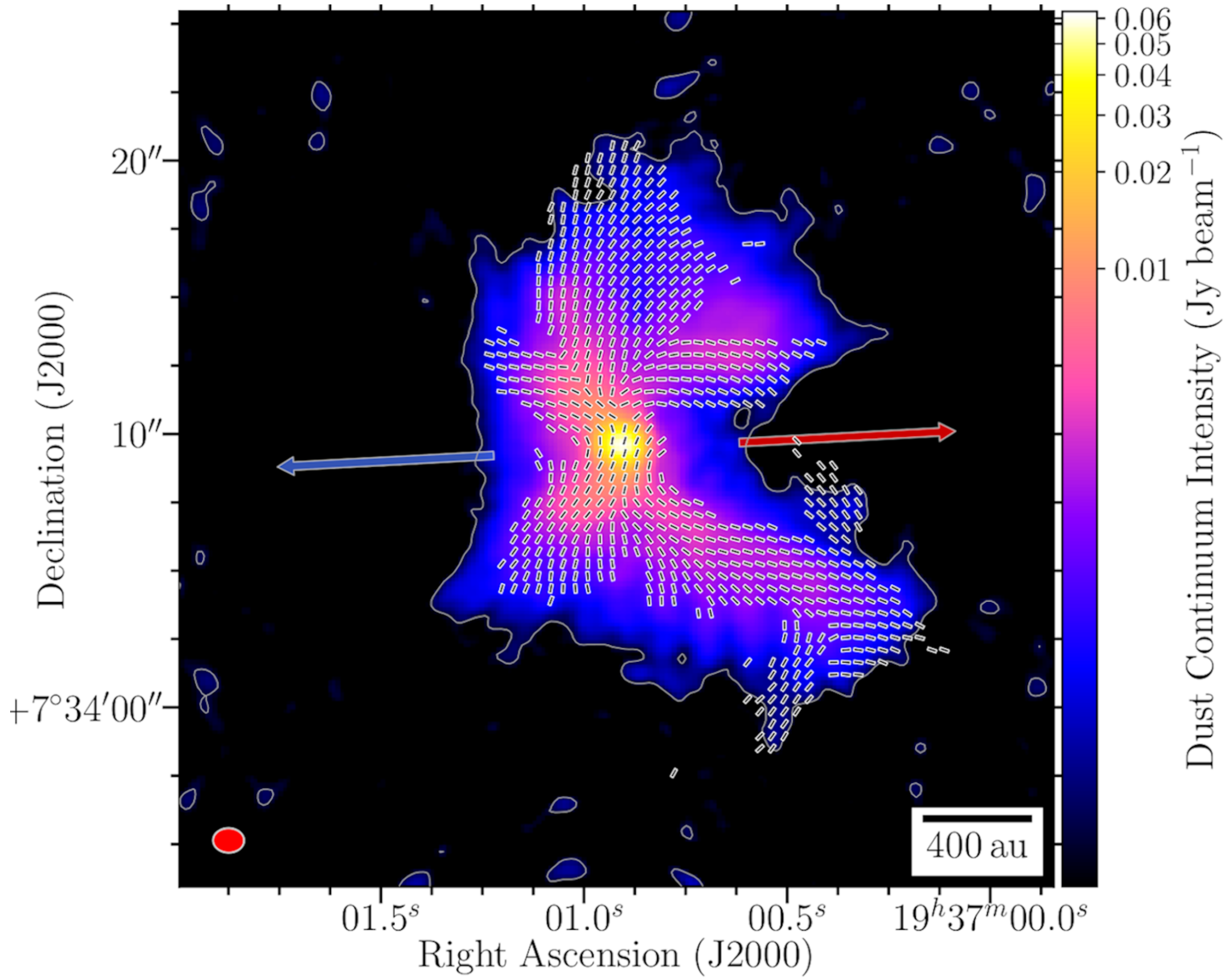
CASA
Common Astronomy Software Applications

A magnetically-regulated disk formation in B335 ?

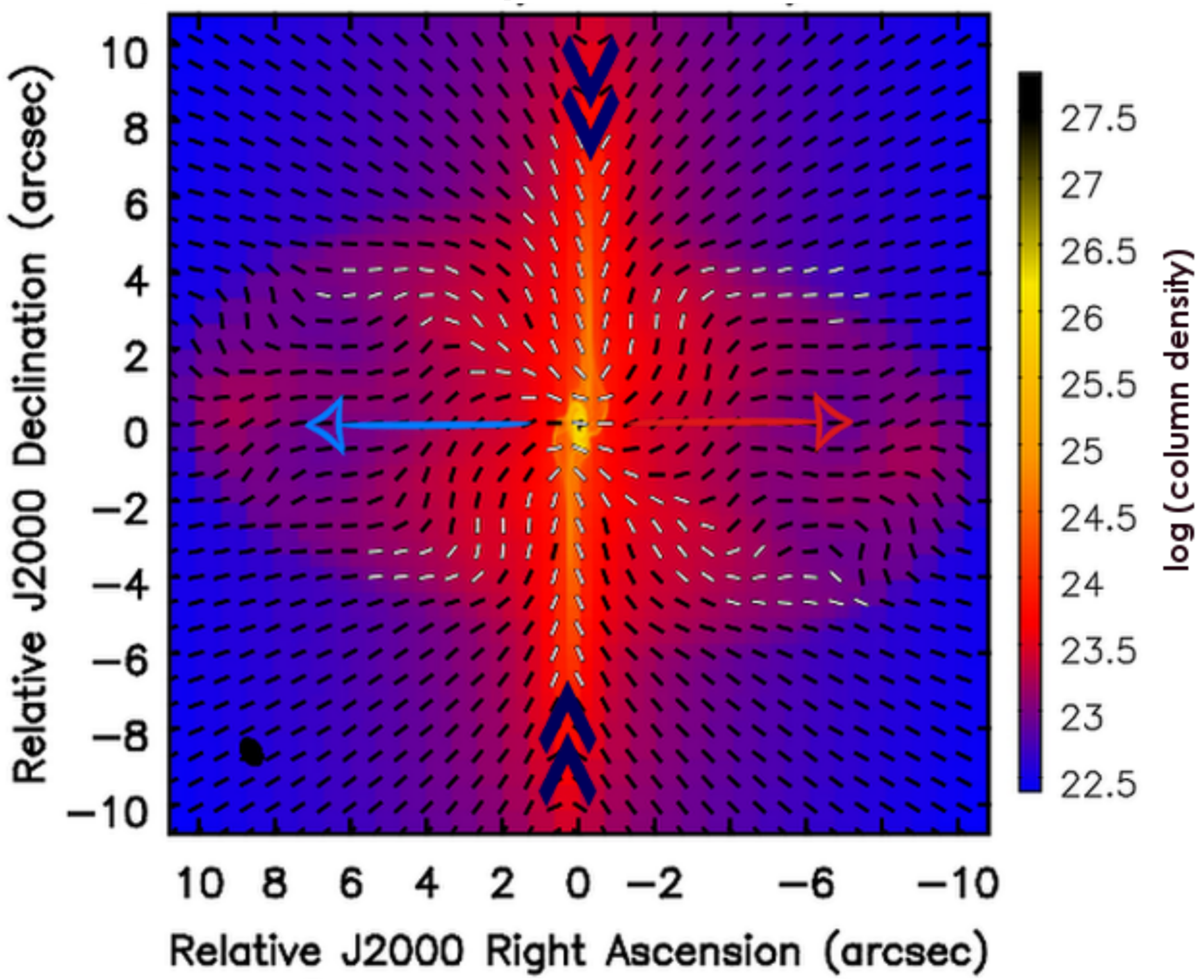
Our ALMA map of the polarized dust emission at 230 GHz

RAMSES MHD models parameter space:
Core: 2.5 Msun
Times: 0.07, 0.14 and 0.2 Myrs
Mass-to-flux ratio mu : 3, 5, 6, 10
Rotational energy beta 0.1% 1% 10%
Turbulent energy: Mach 0.01 0.2 0.5 1.0

B335: observed dust emission & B-field



MHD model: synthetic N_H & B-field



Only models with dynamically relevant B-field match the data (best model μ~6)

=> B regulates the early properties of the protostellar disk in B335

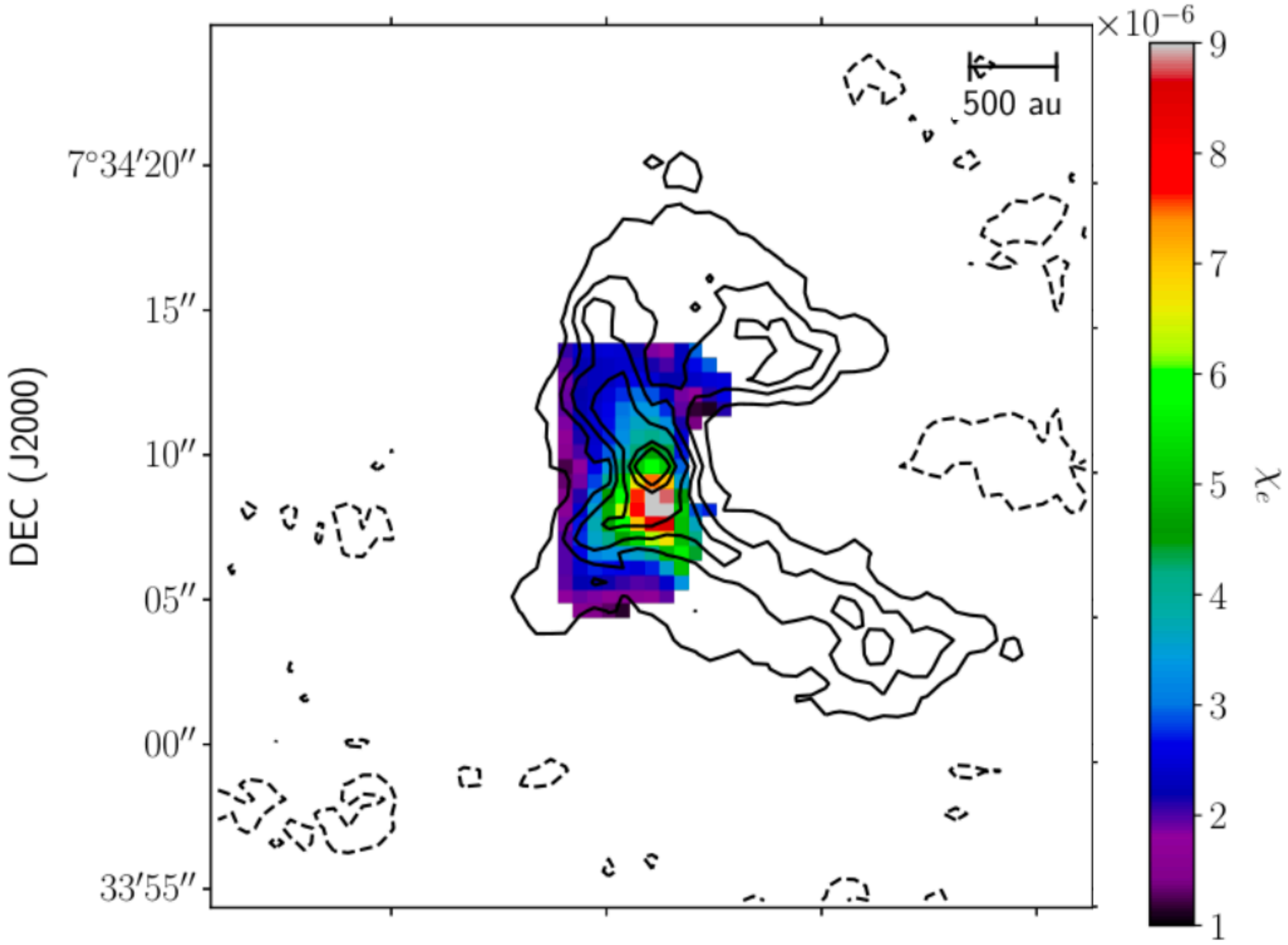
Maury+ (2018)

Coupling of B to star/disk forming material

First measurement of the ionization fraction of the gaz at disk-forming scales

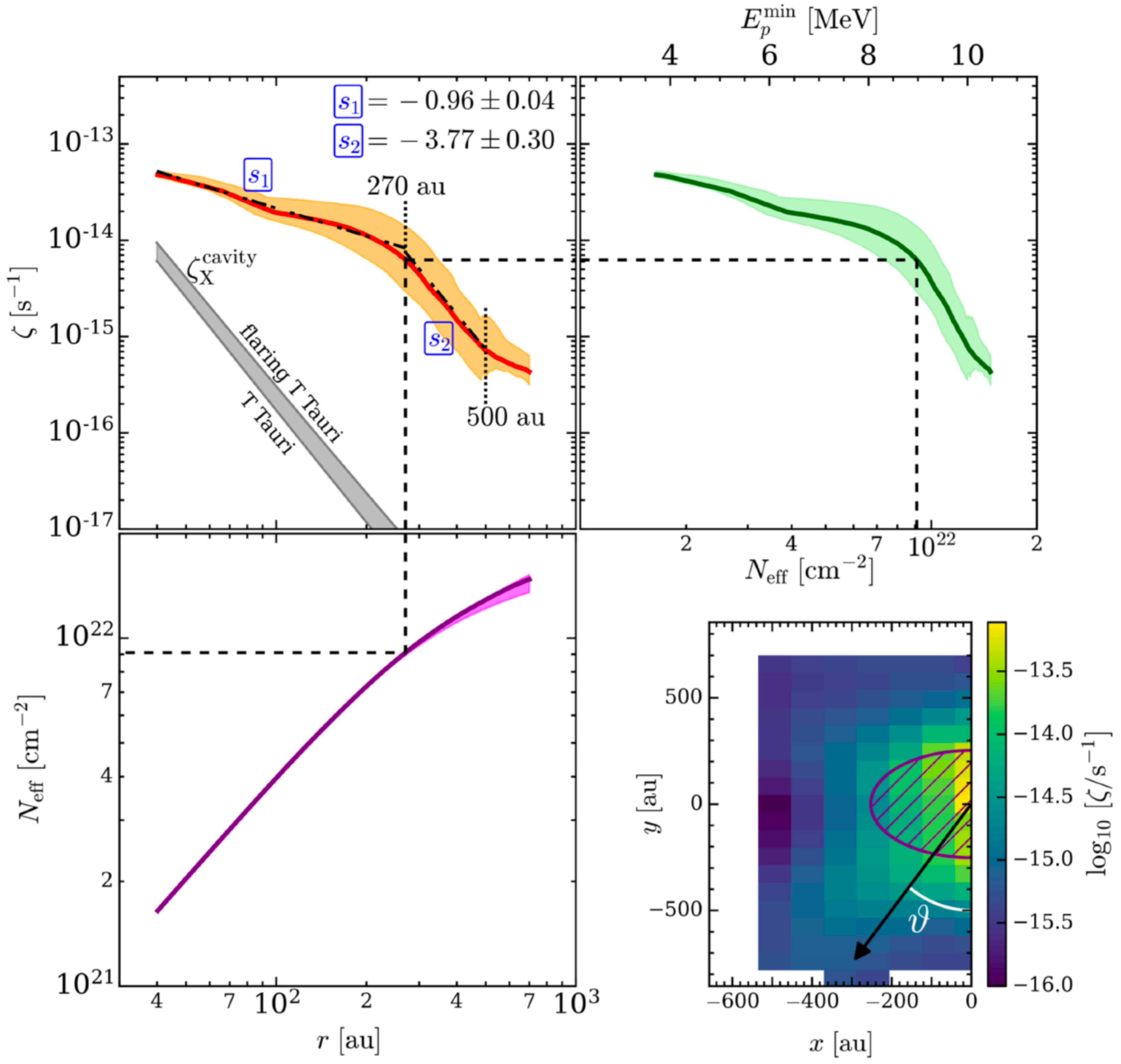
Cabedo et al. (2022)

Ionization fraction is one order of magnitude larger than expected from simple external Cosmic Rays propagation models



A break in propagation slope at 300 au

Requires CR of > a few MeVs



Observations consistent with production of cosmic rays LOCALLY

=> at disk-forming scales (r<500 au), almost quasi ideal MHD conditions ?

Ionization from protostellar CRs ?

First measurement of the ionization fraction of the gaz at disk-forming scales

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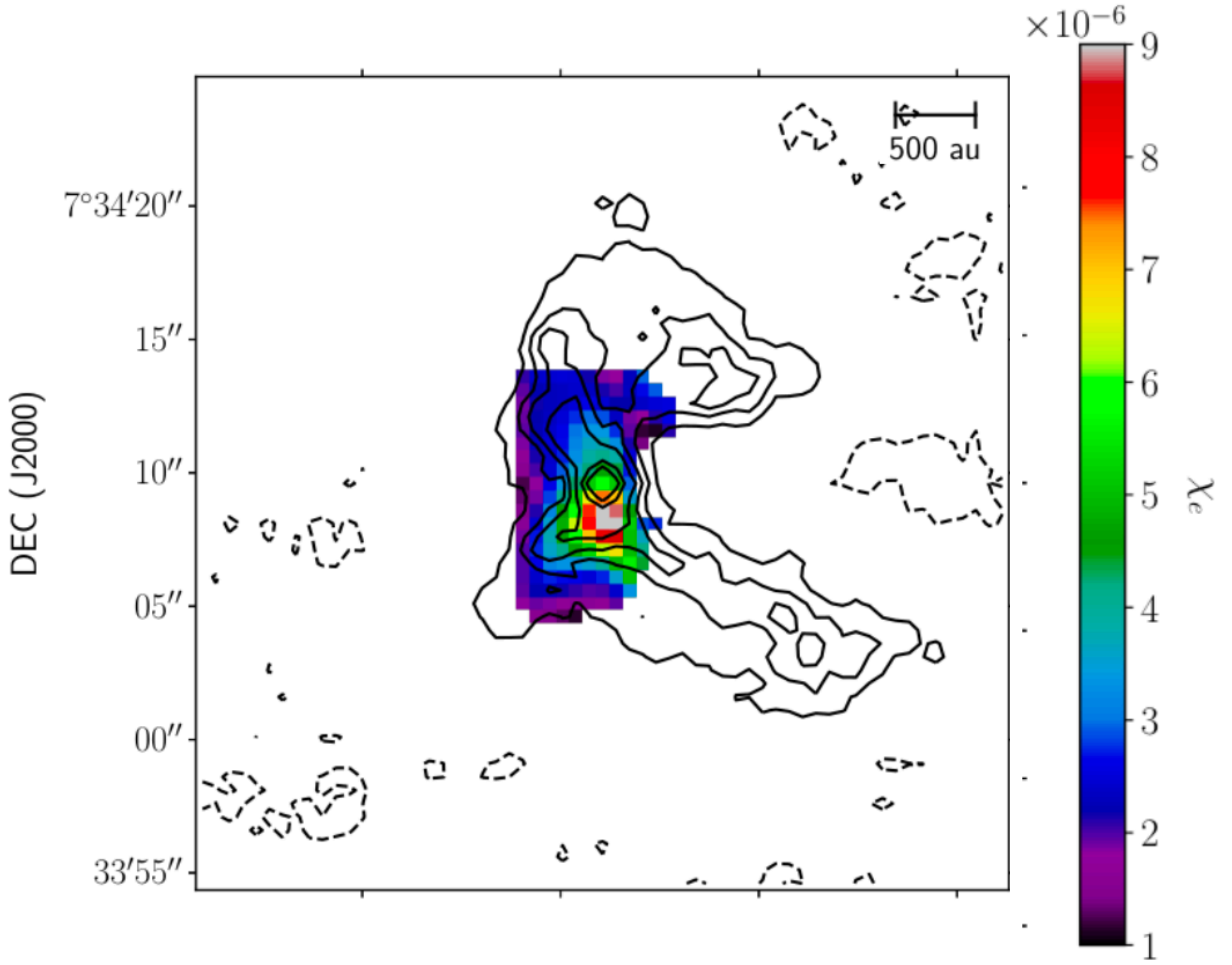

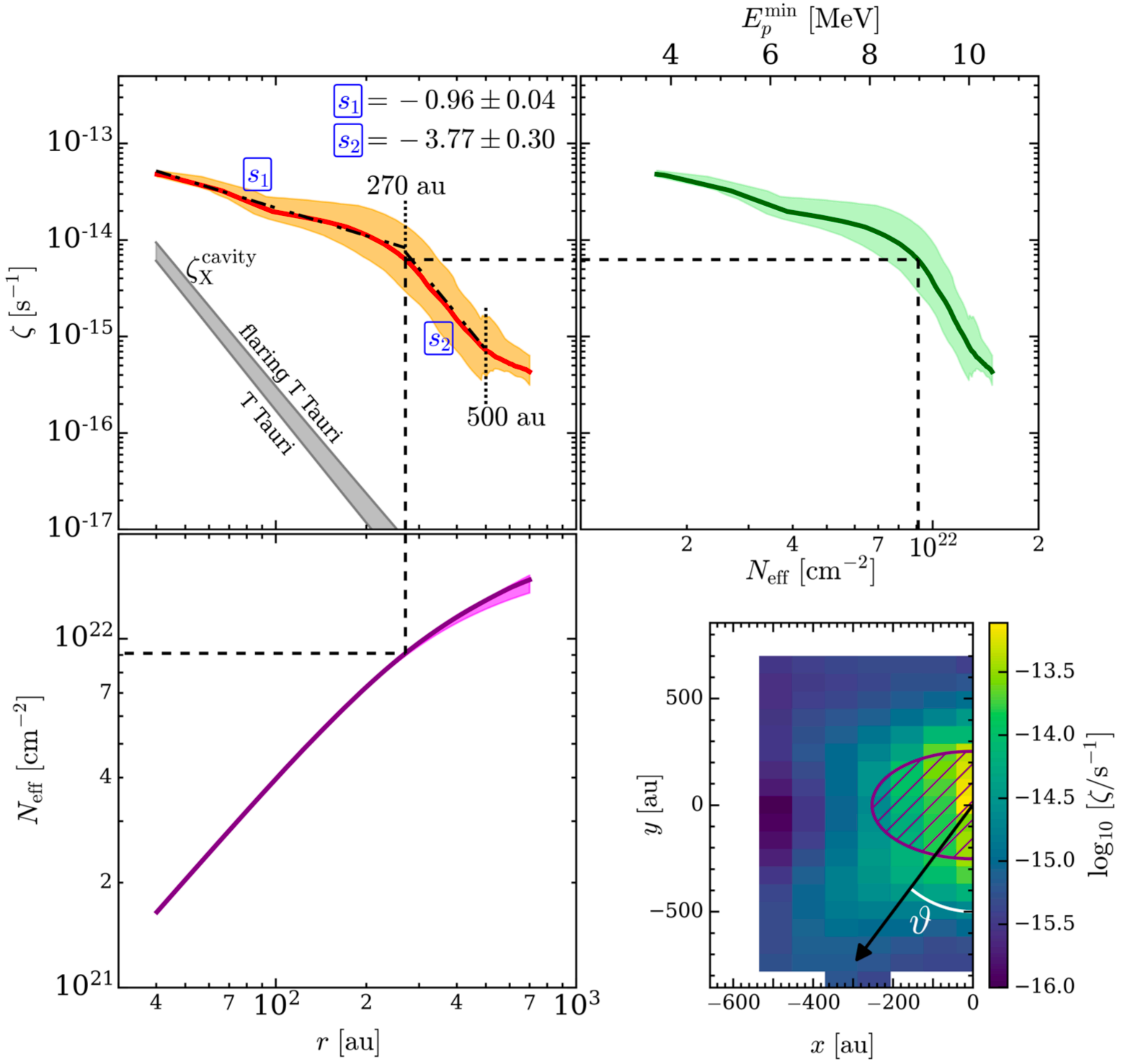

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=> at disk-forming scales (r<500 au), almost quasi ideal MHD conditions ?

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From starless cores to protostars: triggering of gravitational instability

Population studies & typical timescales

Transporting material from large to small scales: infall, accretion & the luminosity problem

« *And yet, it rotates* » …. angular momentum problem & the physics of the formation of disks

Observations: statistical properties of protostellar disks: sizes (& masses)

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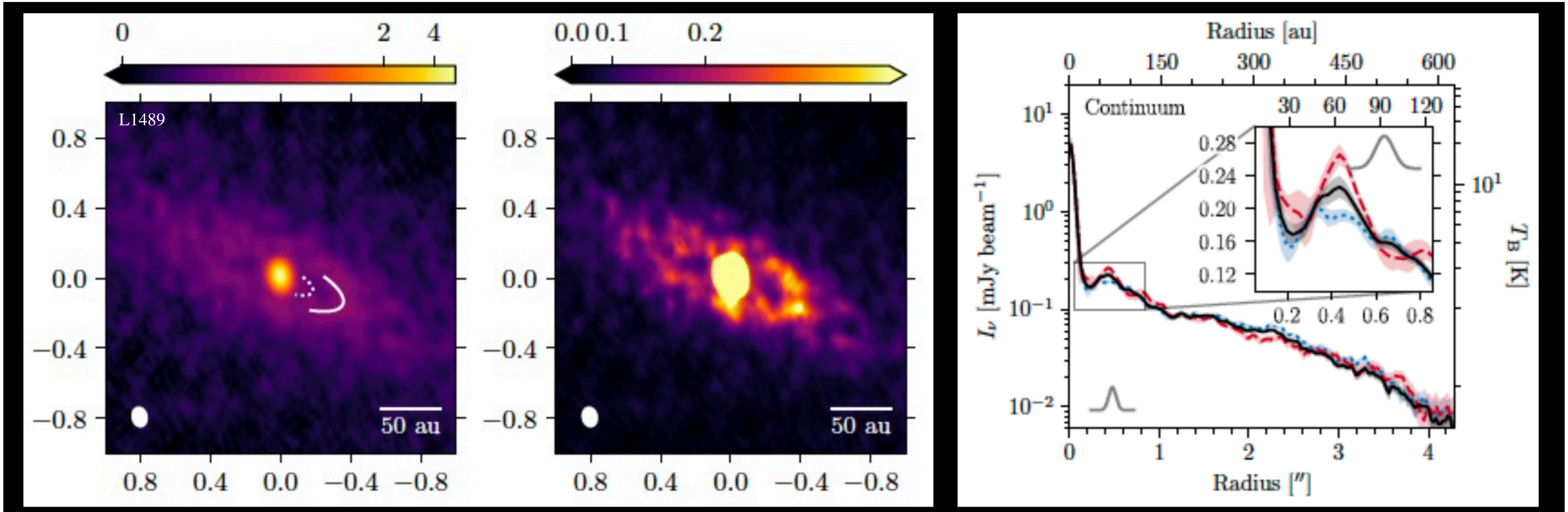
Cabinet de curiosités: structures and sneak peaks at individual objects

What do we know of dust evolution while the star-disk system is built ?

Which instruments for the future (if time allows …) ?

Disks in Class I protostars: some show structures

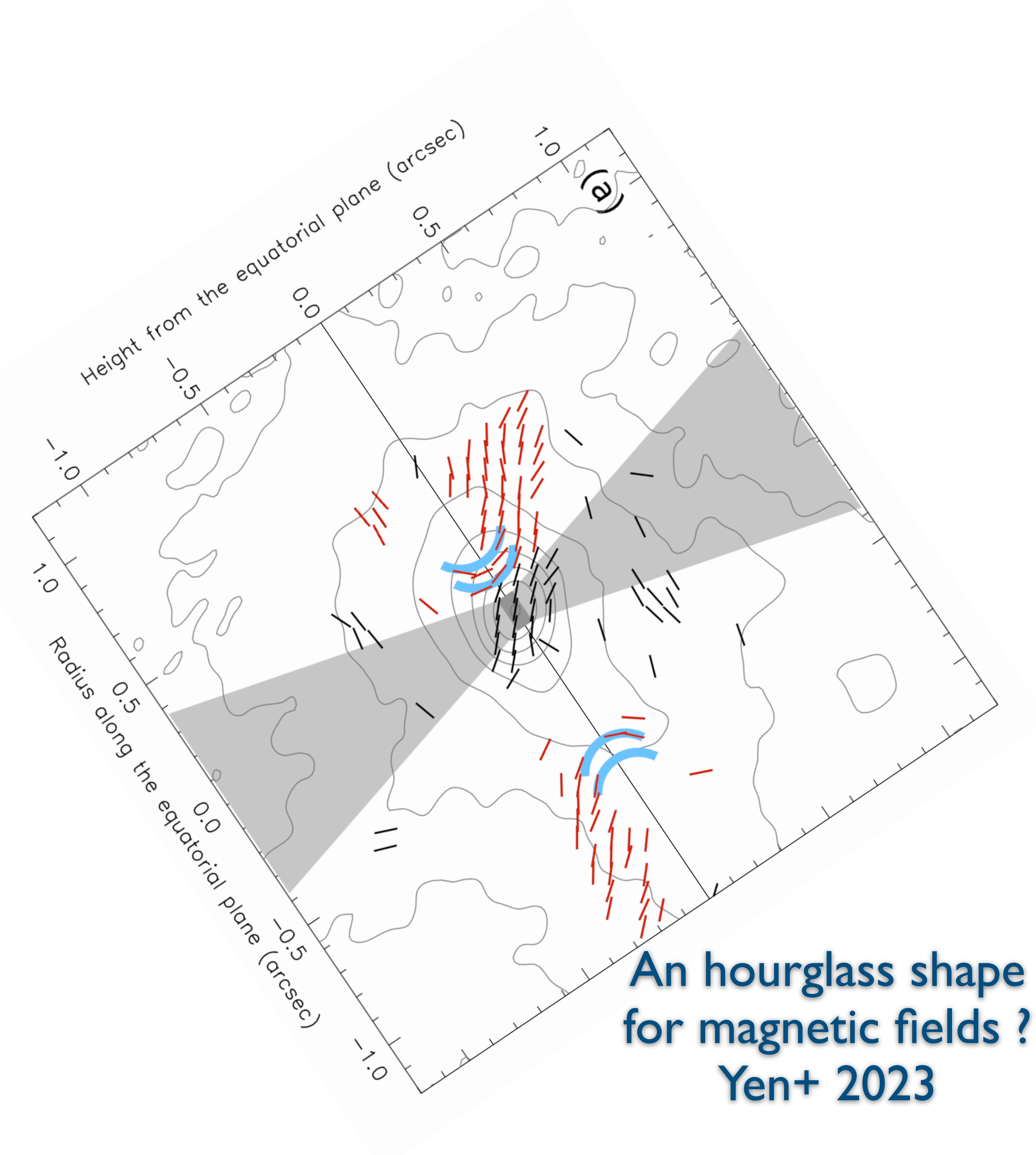


Yamato et al. (2023)

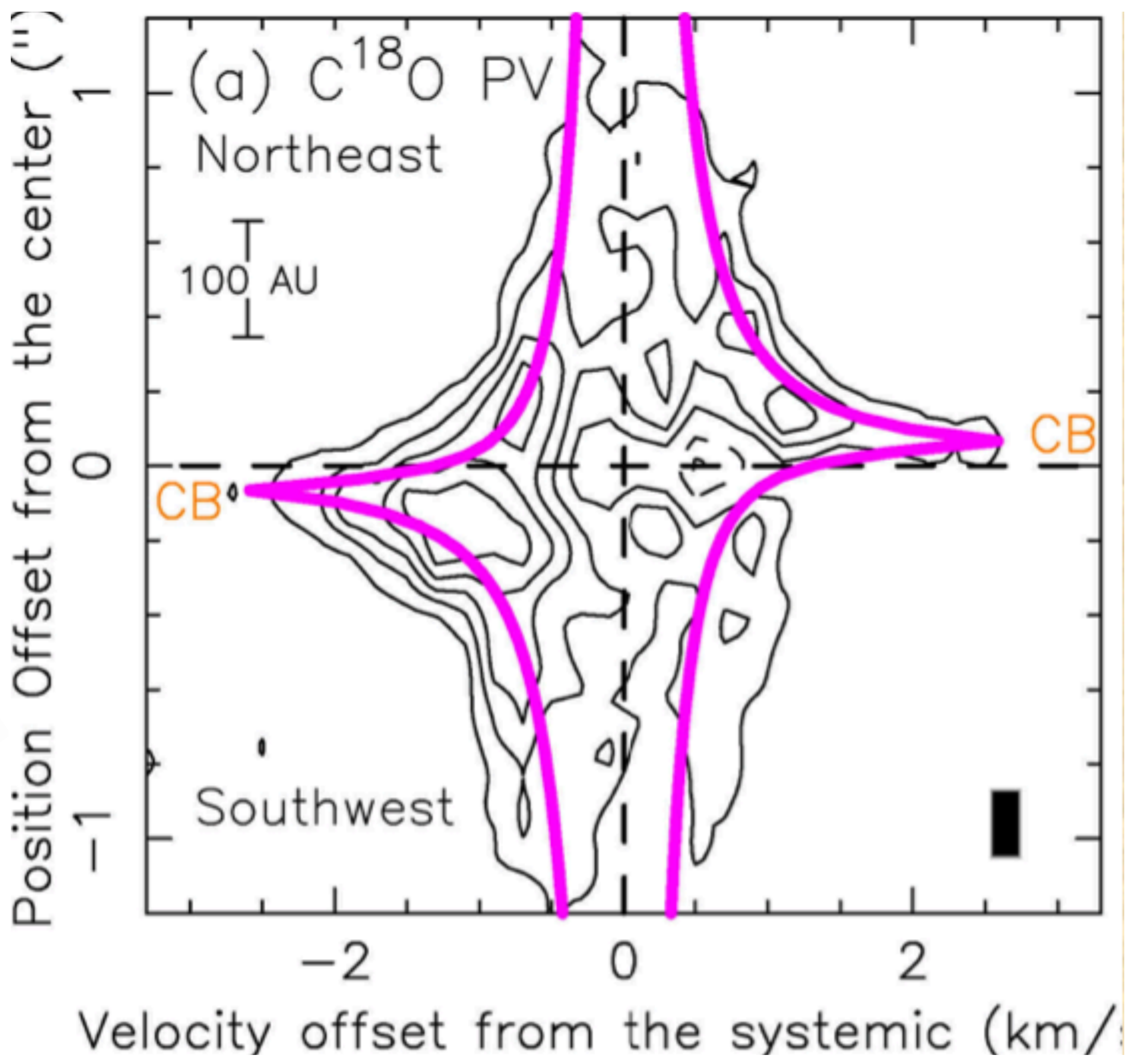
HH211: Class 0/I protostar

Flattened Envelope
= Pseudo-Disk (infall > rotation):
r ~ 400 au

Gas disk : 20 au

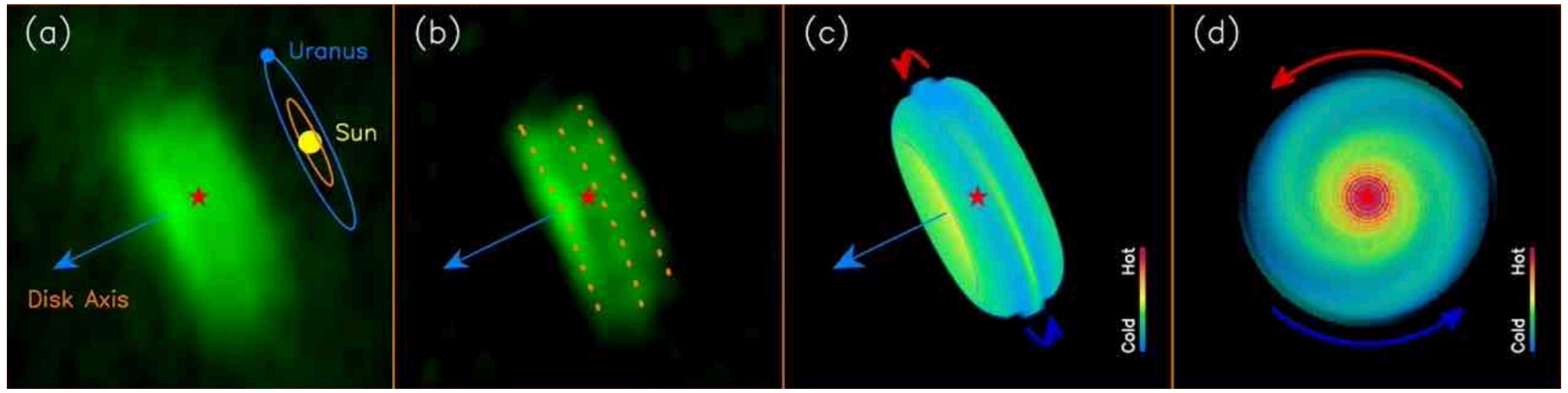


An hourglass shape
for magnetic fields ?
Yen+ 2023

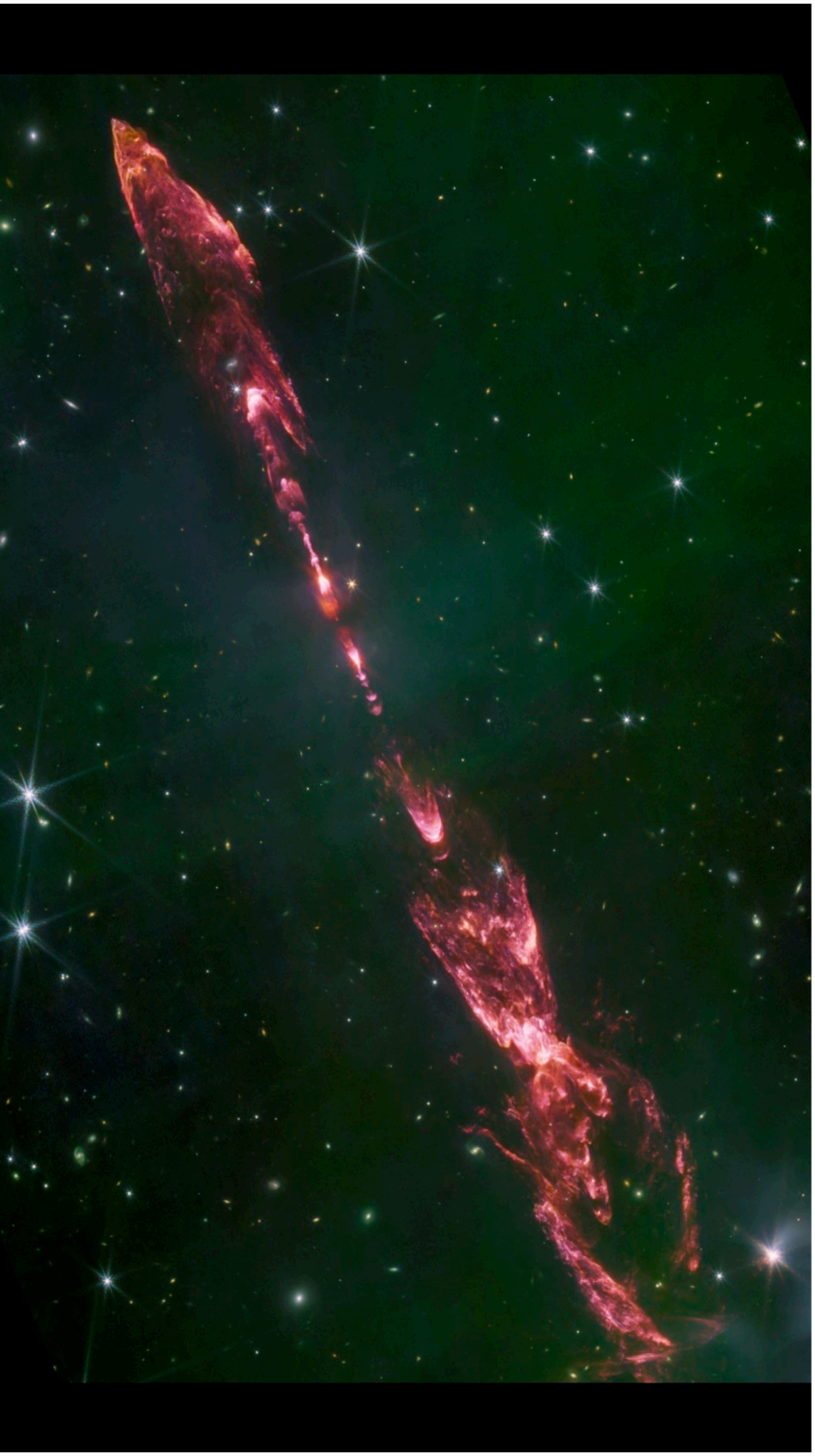


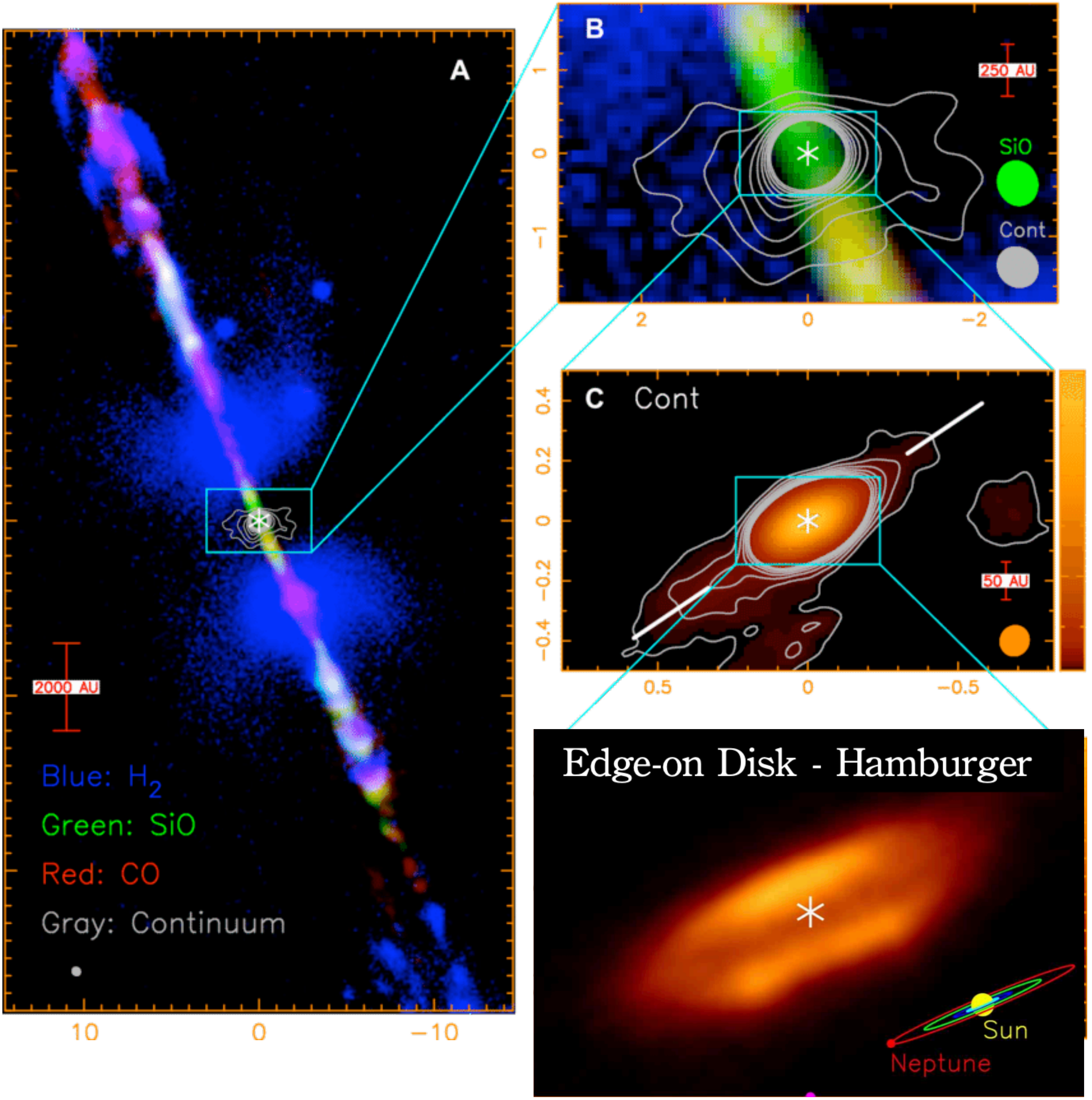
A shadow
due to a spiral ?

Lee+ 2023



HH212: Class 0 protostar

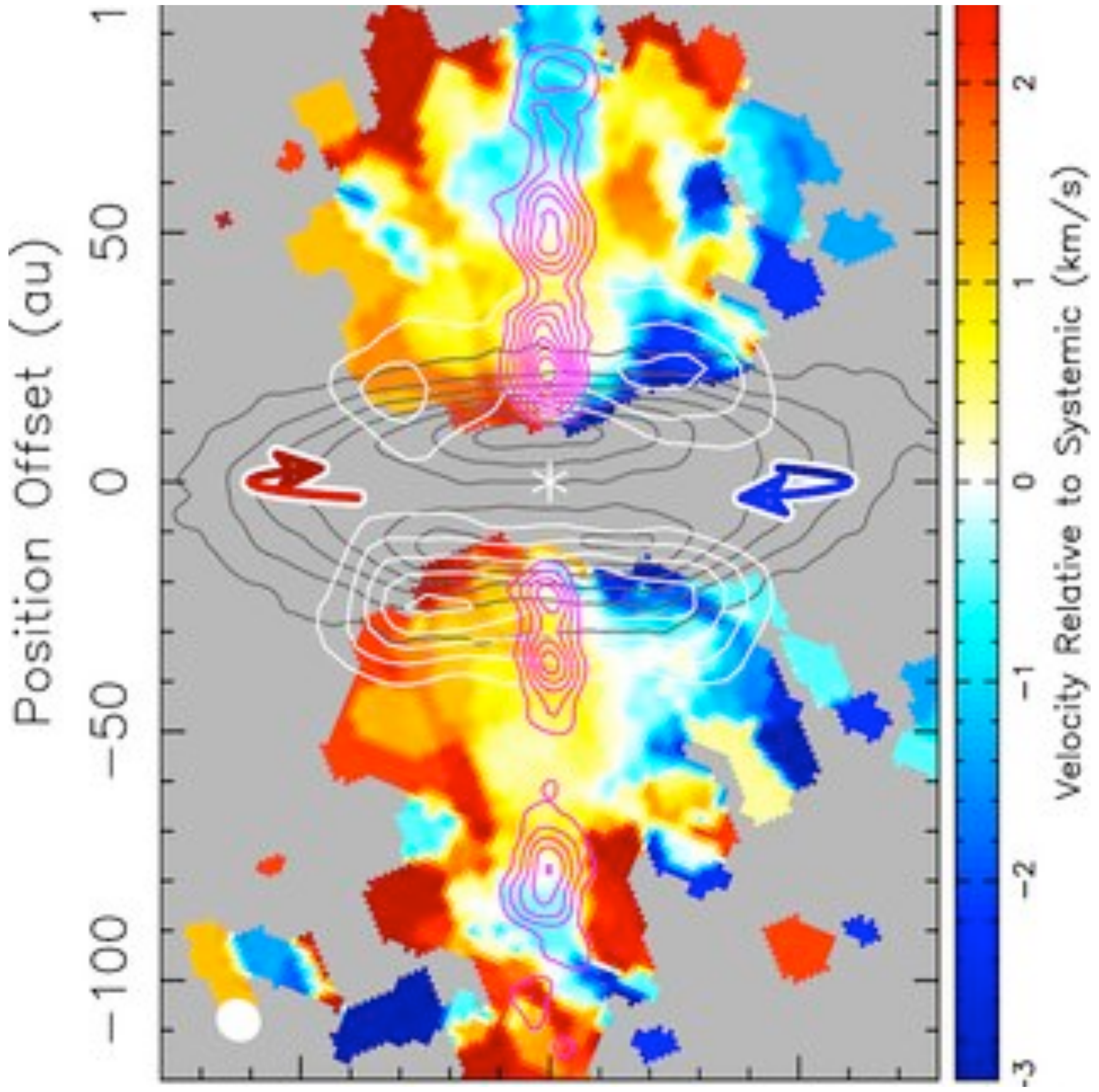




Gas disk radius : 45 au

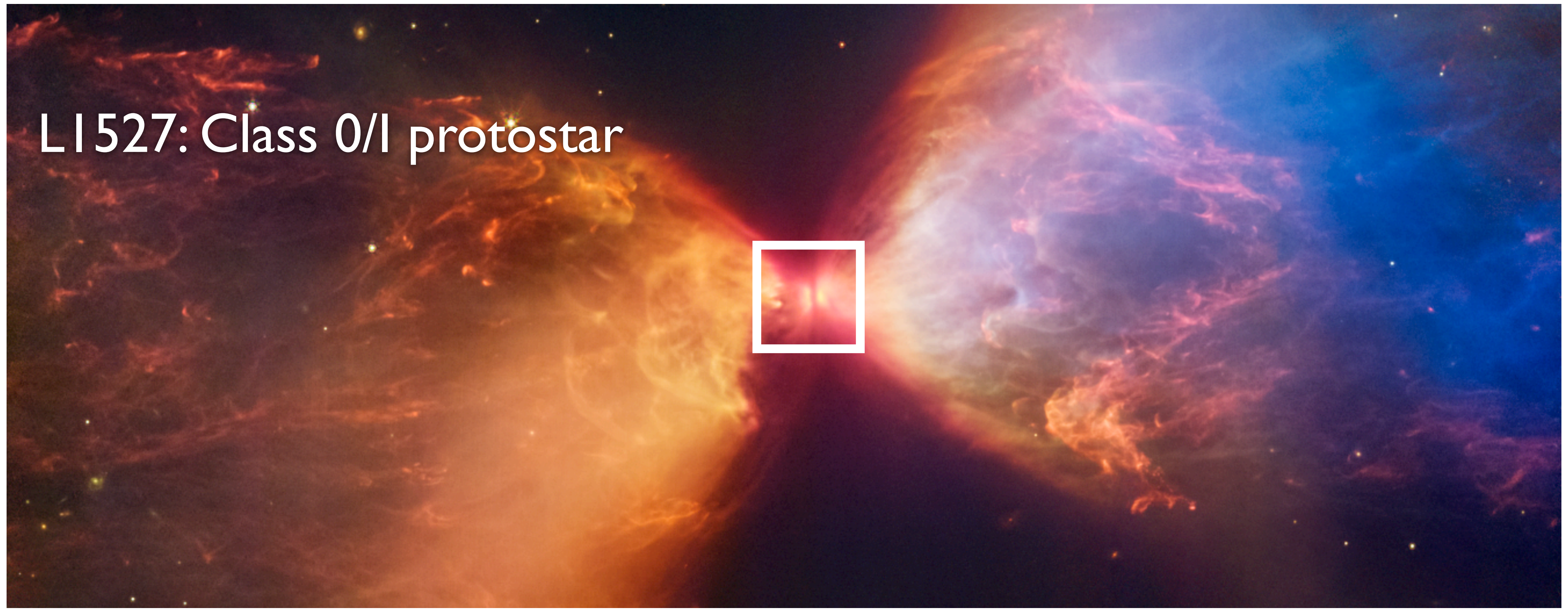
$M_* + M_{disk} \sim 0.25\ M_\odot$

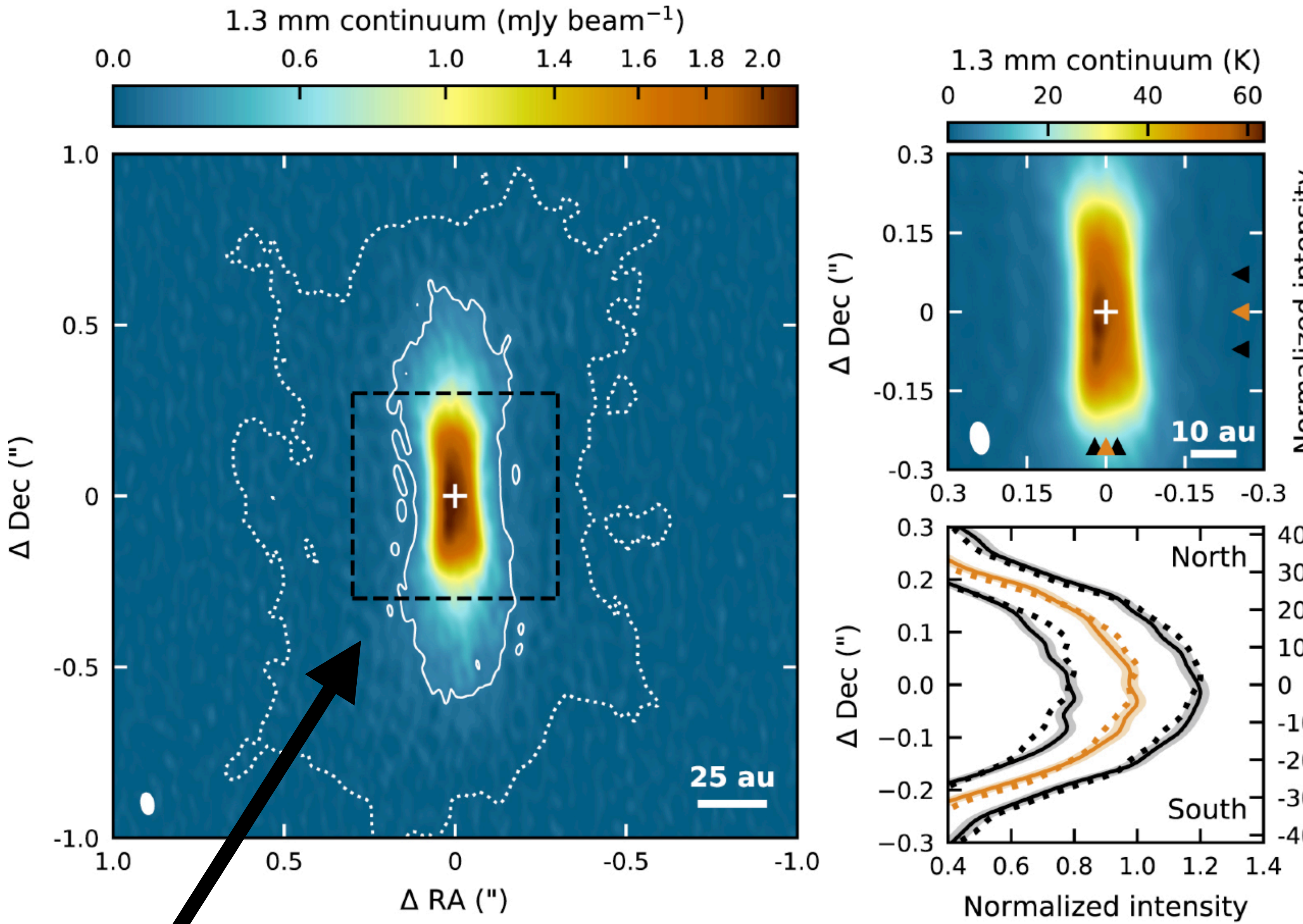
observations of MHD disk-wind ?



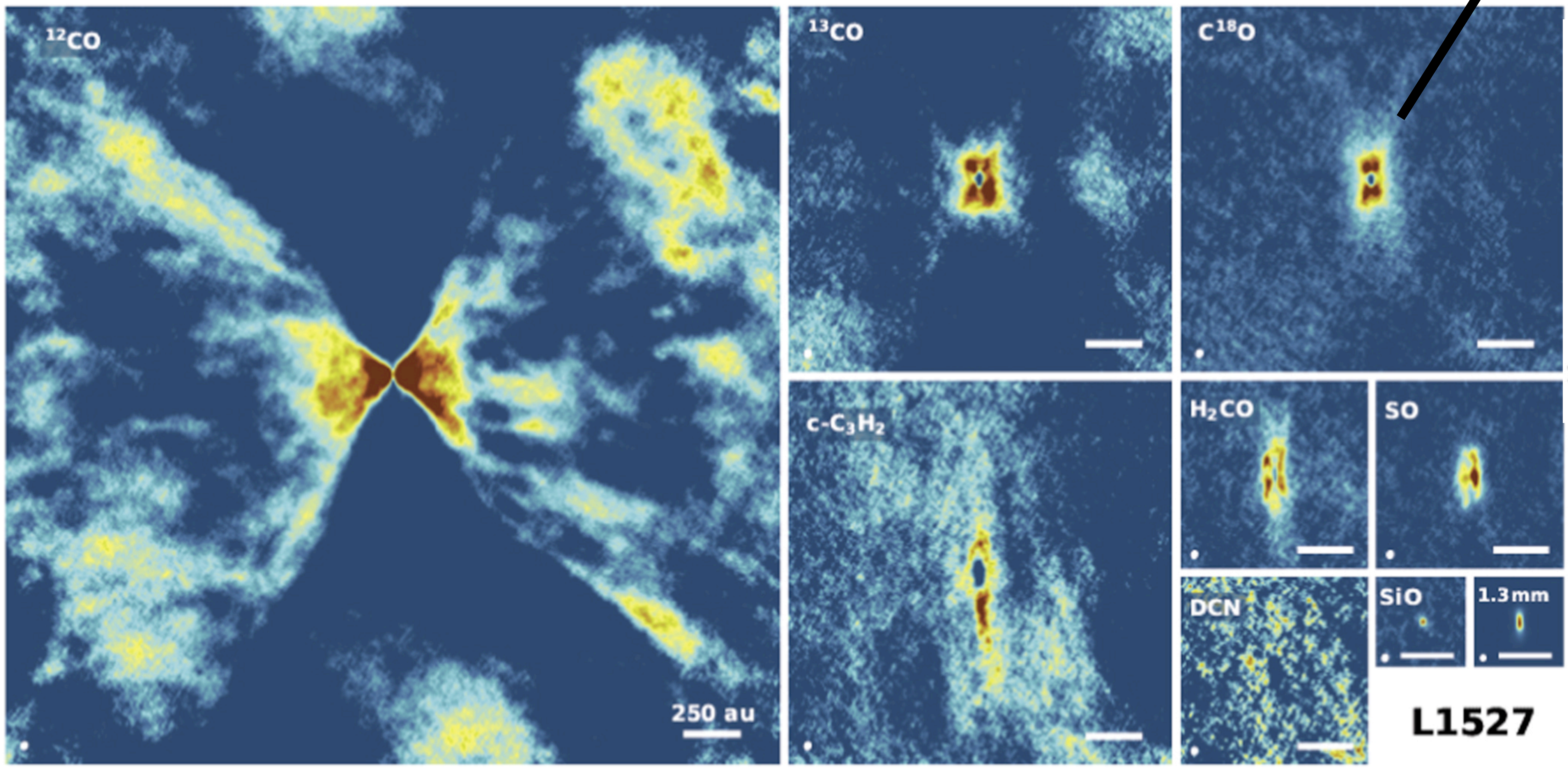
MHD DW dominates the AM extraction out to 40 au,
but not inside <4 au (MRI?)

Lee+ 2021

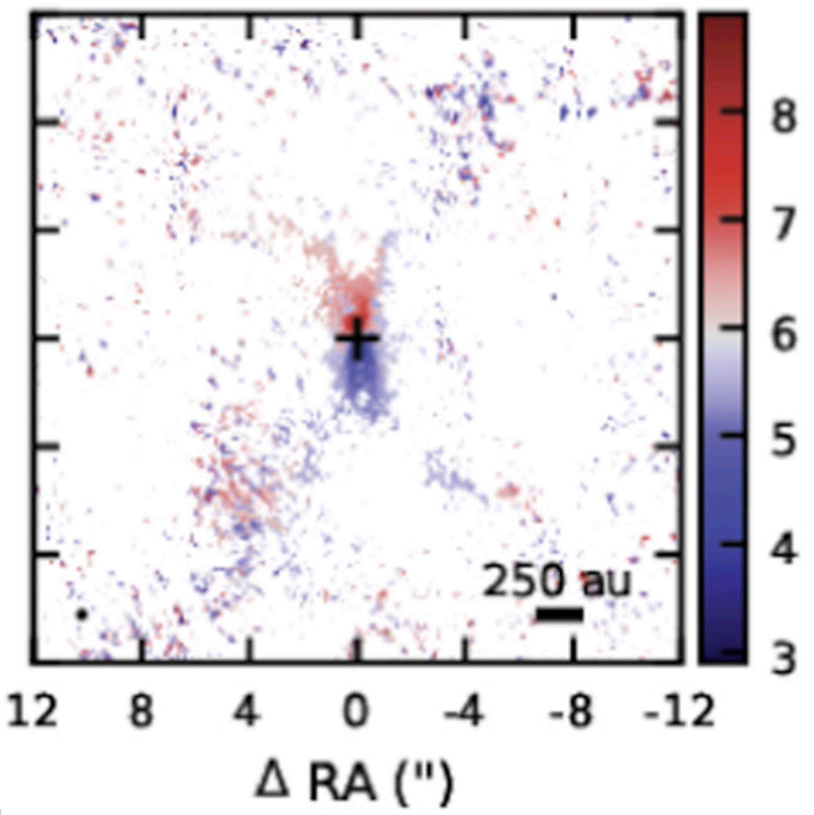




Van't Hoff+ 2023

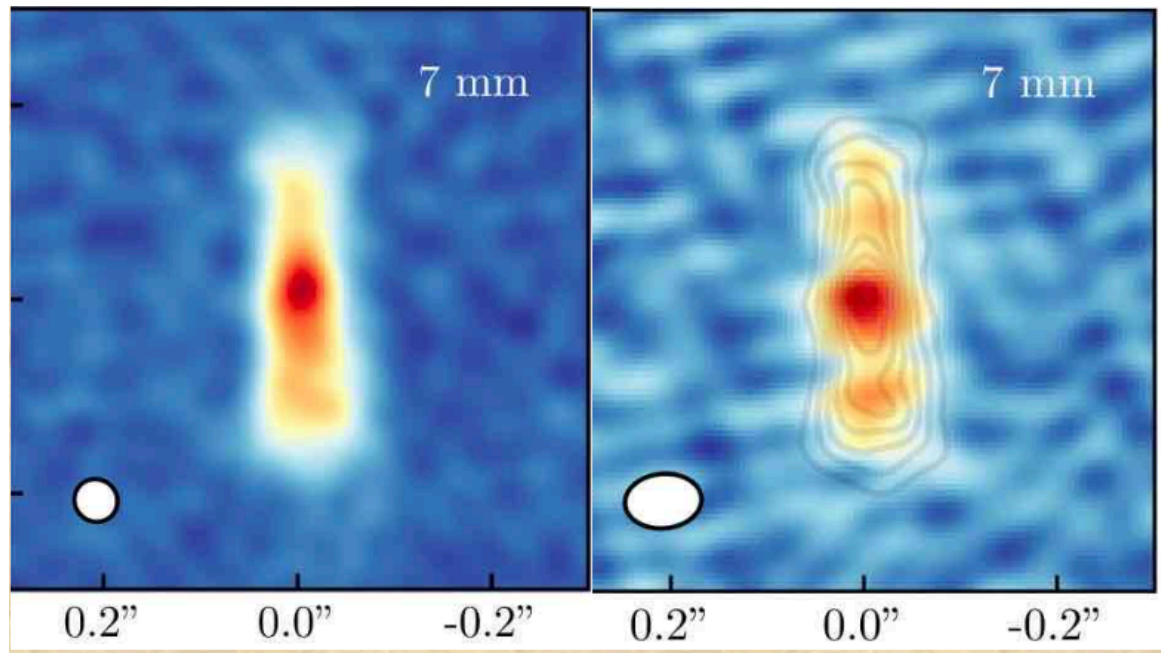


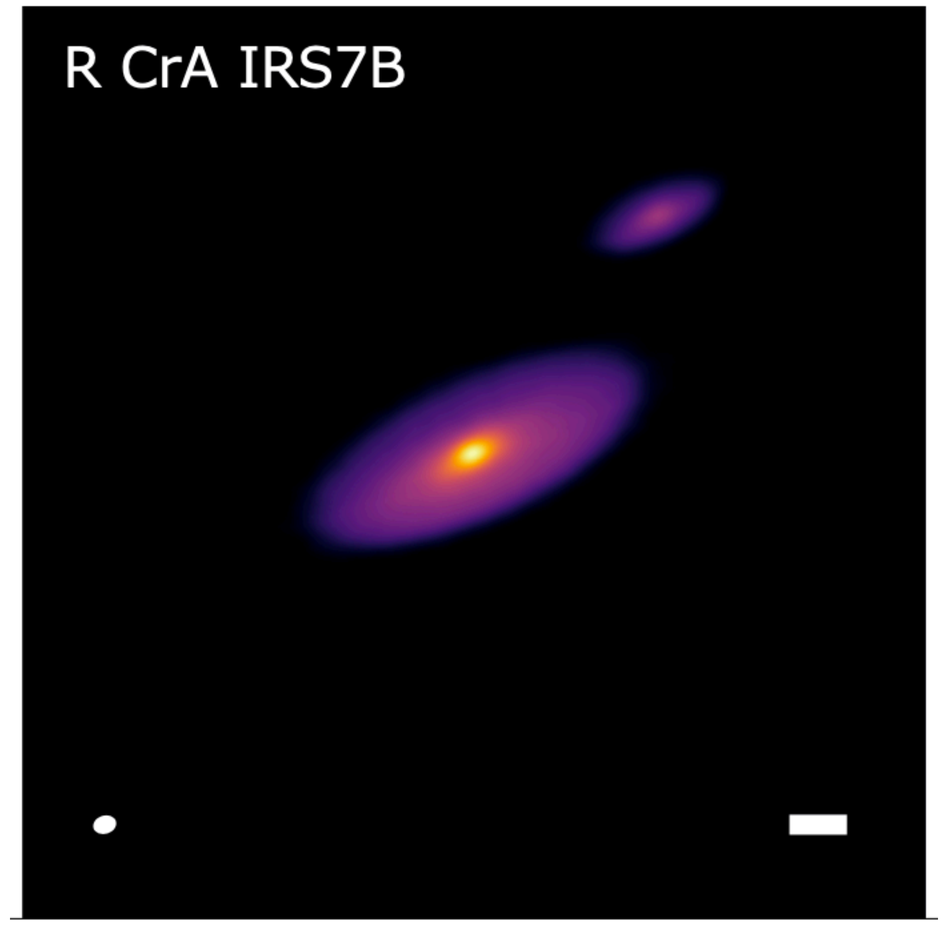
L1527



C^{18}O 2-1

Sheehan+ 2022





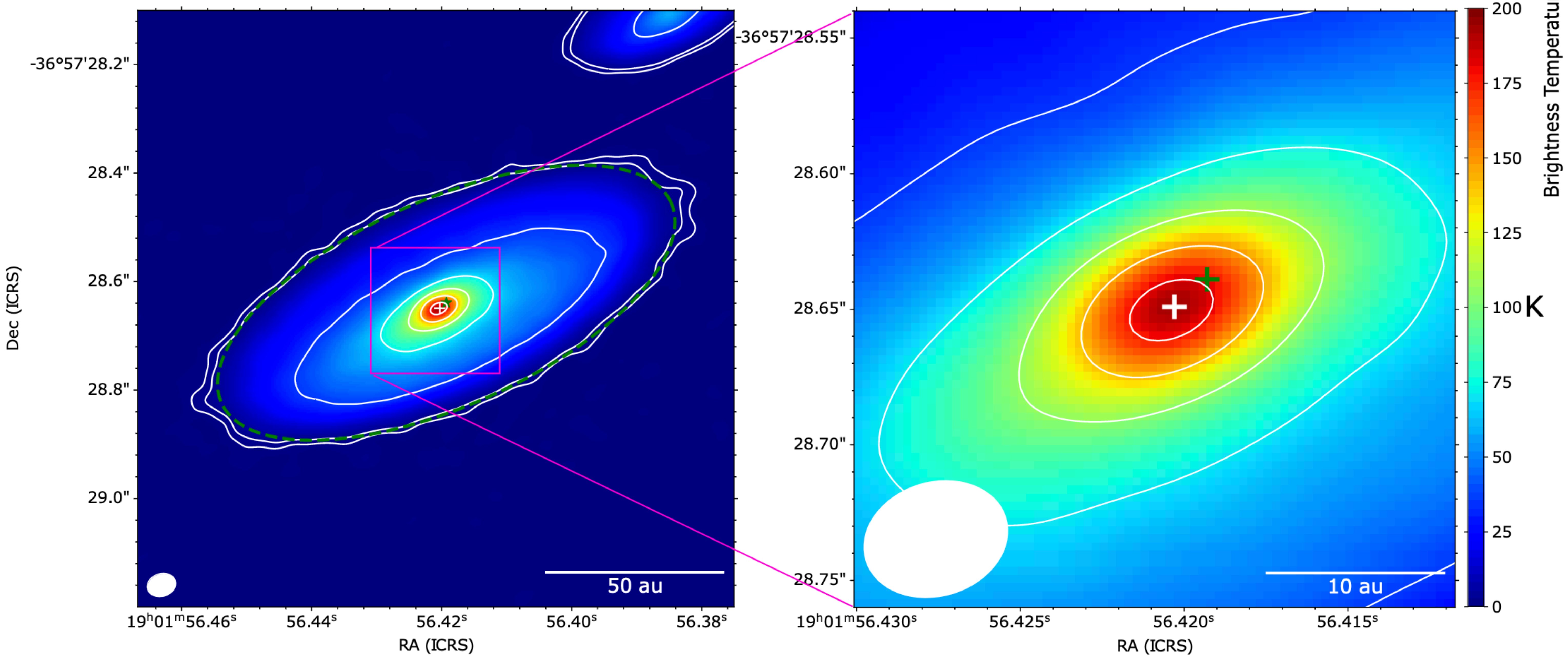
Class I protostar R CrA IRS7B-a

Ohashi+ 2023: Keplerian rotation in the disk => central protostellar mass of 2–3 $M_\odot$

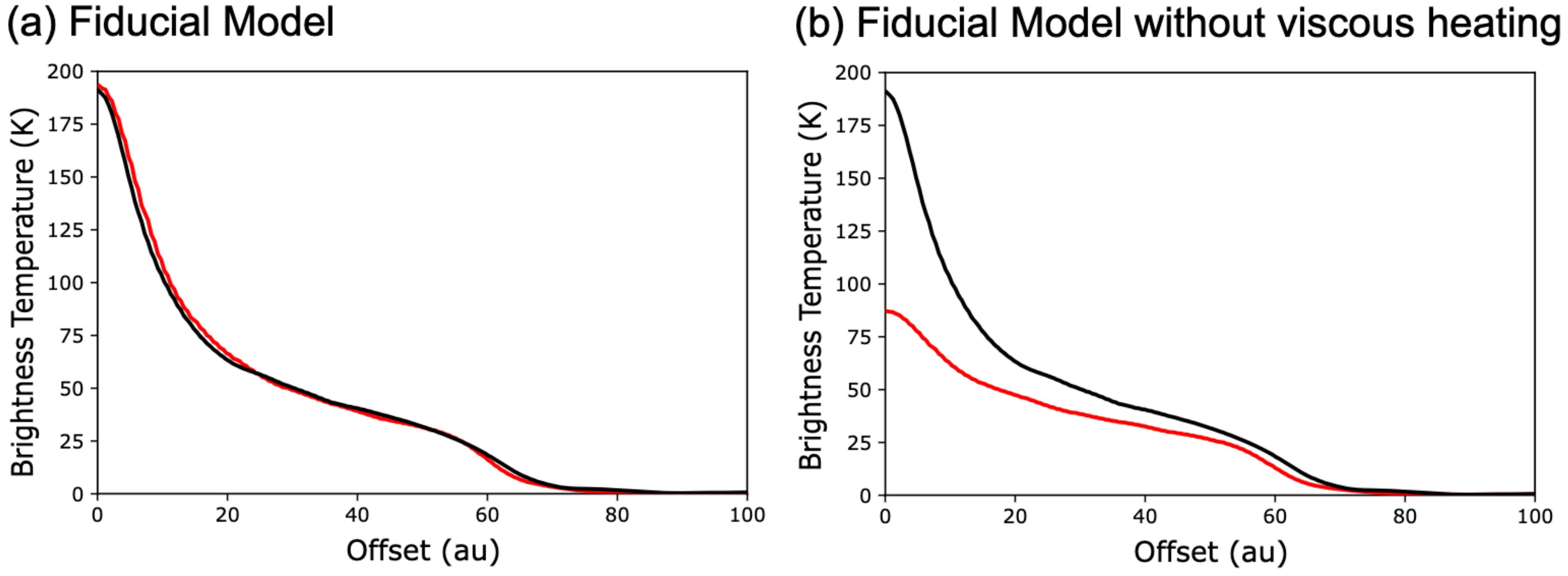
Disk gas mass : 0.41 $M_\odot$
Core mass : 1.9 $M_\odot$

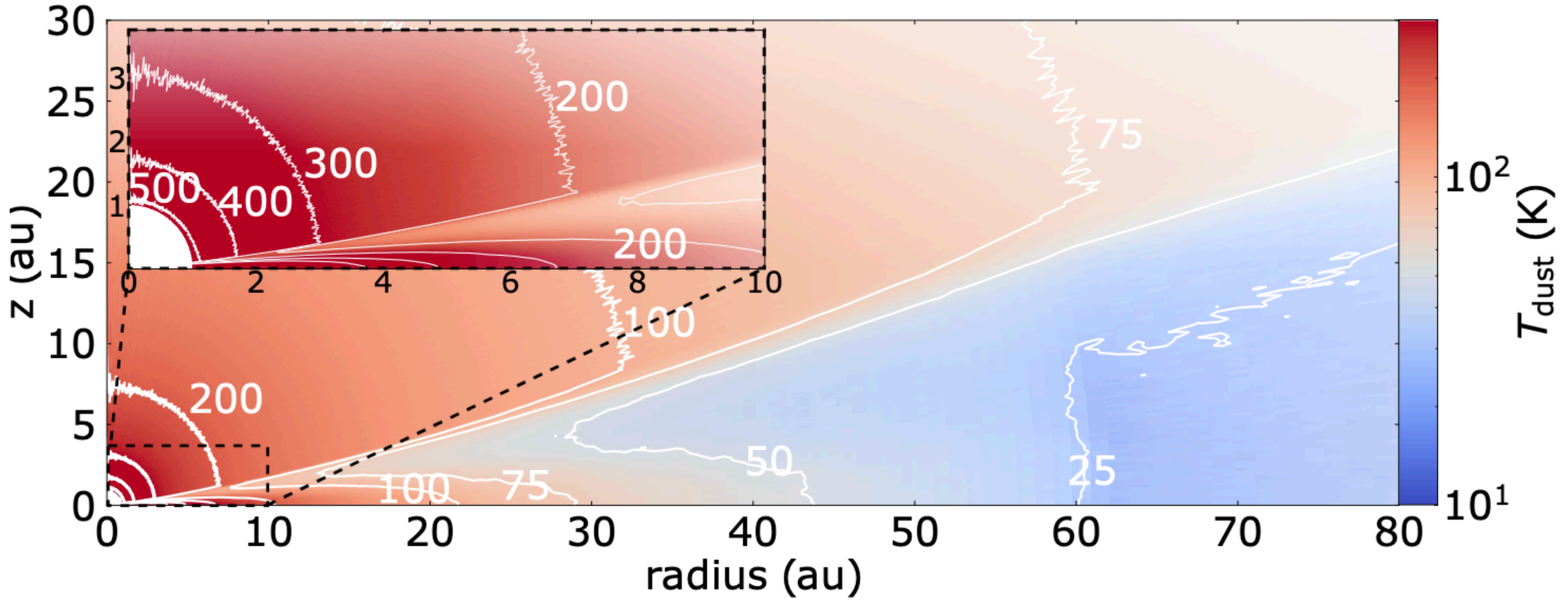
Dust disk radius : 62 au
Gas disk radius : 80 au

Takakuwa+ 2024



Viscously heated disk ?





I. Protostars

Yesterday

From starless cores to protostars: triggering of gravitational instability

Population studies & typical timescales

Transporting material from large to small scales: infall, accretion & the luminosity problem

« *And yet, it rotates* » …. angular momentum problem & the physics of the formation of disks

Observations: statistical properties of protostellar disks: sizes (& masses)

II. Disks and dust

Today

What sets the properties of the most pristine disks ?

Cabinet de curiosités: structures and sneak peaks at individual objects

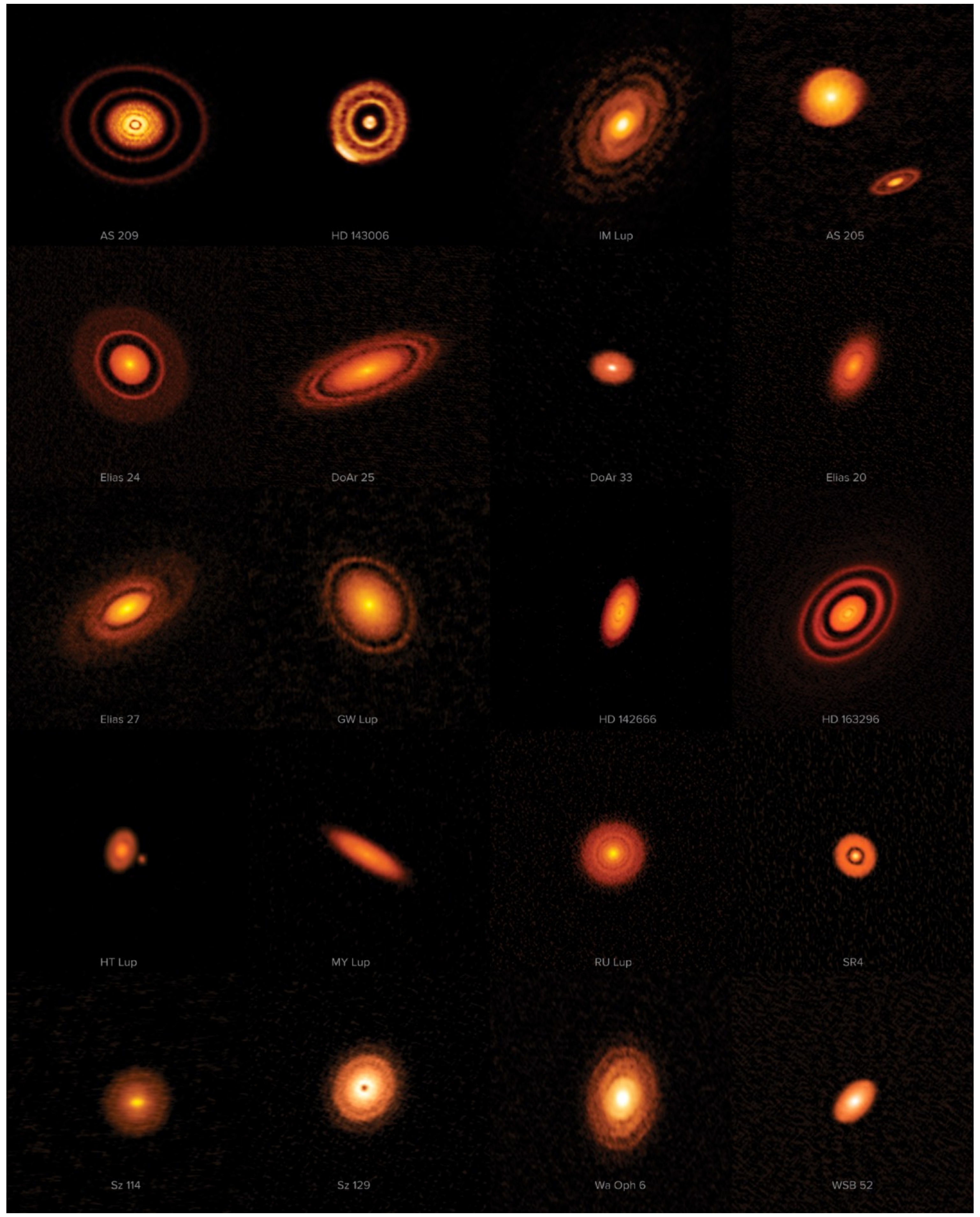
What do we know of dust evolution while the star-disk system is built ?

Which instruments for the future (if time allows …) ?

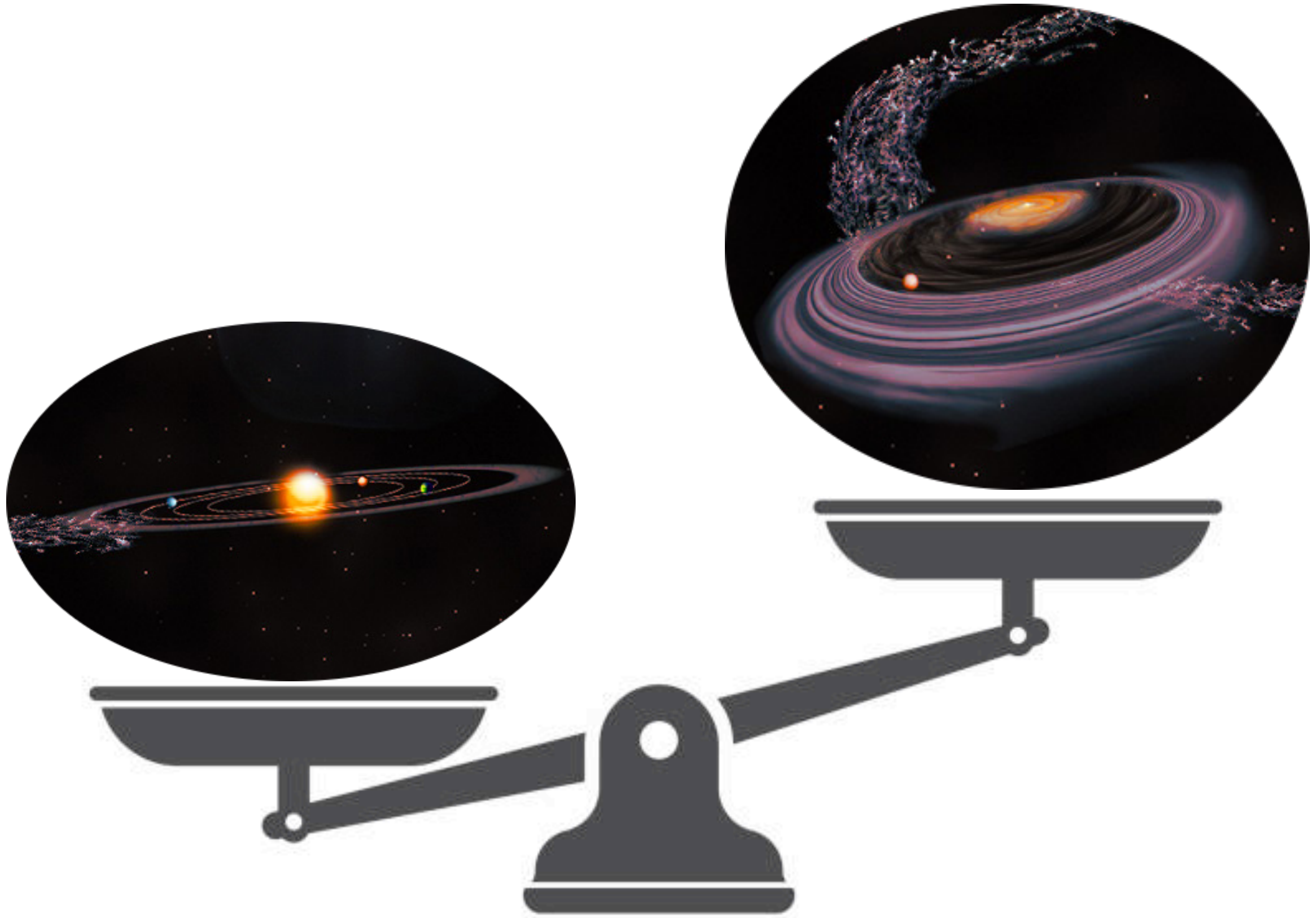
Why is dust evolution in early stages important for planet formation ?

Challenging the current paradigm leading for disk evolution:

recent observations of 1-5 Myrs T-Tauri disks: more structured & less massive than expected / required ?



T-Tauri disks observed with ALMA (DSHARP survey, dust seen at 1mm)
Andrews+ 2020



2-Myr old disks : less mass (dust and gas) than required for minimum mass of the solar nebula ?
(Cieza+ 2015, Miotello+ 2016, Sturm+ 2022, Manara+ 2022) - highly debated in community

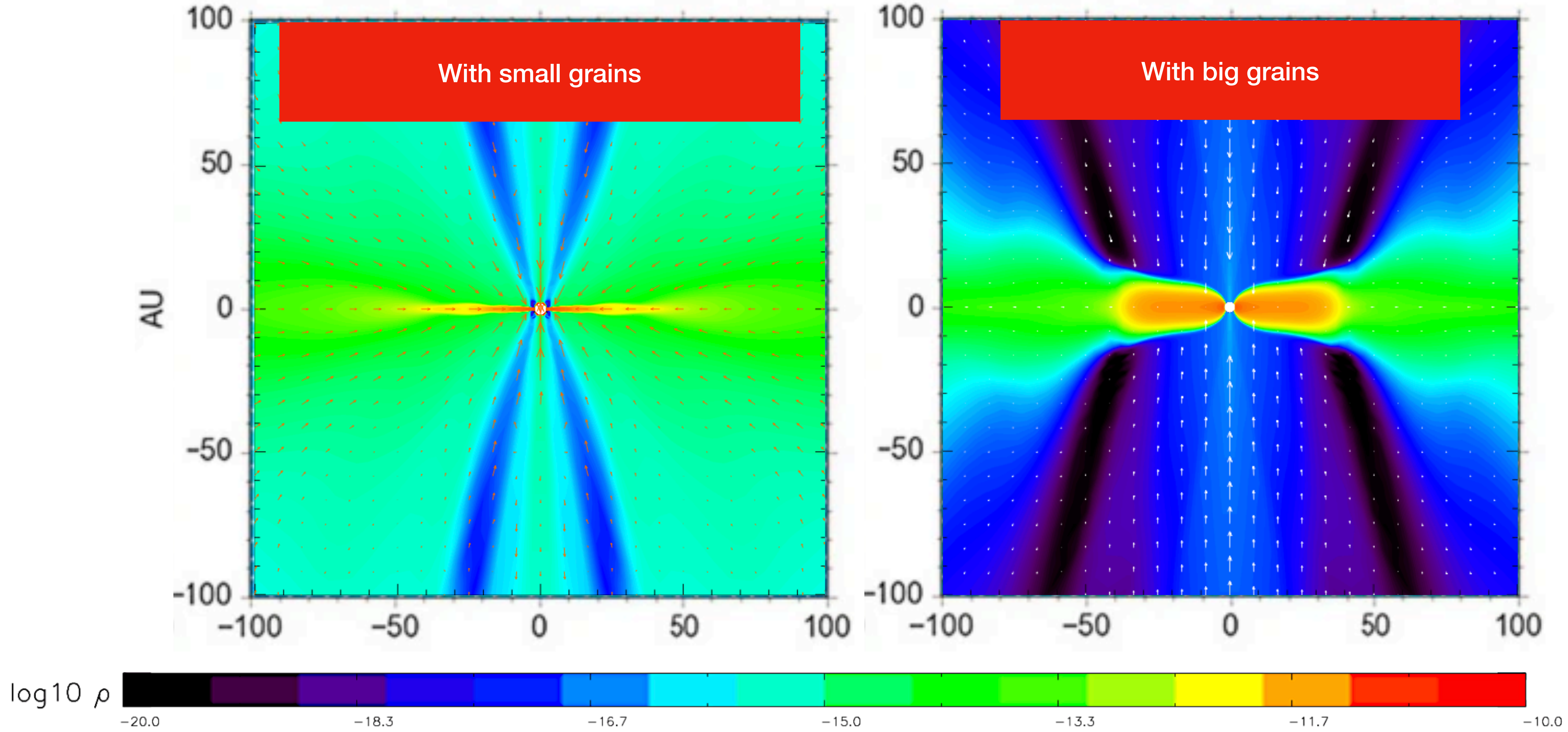
SEE TESTI'S LECTURE

Why is dust important beyond planet formation ?

Dust: a key parameter of magnetic field coupling to the star-disk forming material !

See Guillet+ 2020, Zhao+ 2020, Lebreuilly+ 2024

The sizes and masses of protostellar disks depends on the dust size distribution in the envelope !



Protostellar disk models from Zhao+ (2020)

Dust grain sizes affects the MHD resistivities and the role of the magnetic field

SEE LEBREUILLY'S LECTURE

Why is dust important beyond planet formation ?

- **Dust is an indirect tracer of mass**

Used from Galaxies, to clouds, cores, disks etc

- **Mass deduced from mm observations if optically thin :**

$$M_{\mathrm{obj}} \propto \frac{\mathrm{Flux}}{\kappa_{\mathrm{abs}}(\nu)\, \mathrm{B}(\nu, T_{\mathrm{obj}})}$$

Masses of astrophysical structures measured from dust emission depends much on the dust optical constants …
…. which vary with dust composition, size etc ….

SEE TESTI'S & DEMYK'S LECTURE

Measuring dust properties: spectral dependance of dust emissivity from thermal emission

THERMAL EMISSION

➡ Solution of the radiative transfer equation for a medium with optical depth $\tau\nu$ and for a source function constituted by the Planck blackbody Bν at temperature T is:

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu}) \quad \text{where} \quad B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT} - 1}$$

➡ Assuming Iν being uniform over the solid angle Ω, the corresponding flux is:

$$F_\nu = \Omega(1 - e^{-\tau_\nu})\,B_\nu(T)$$

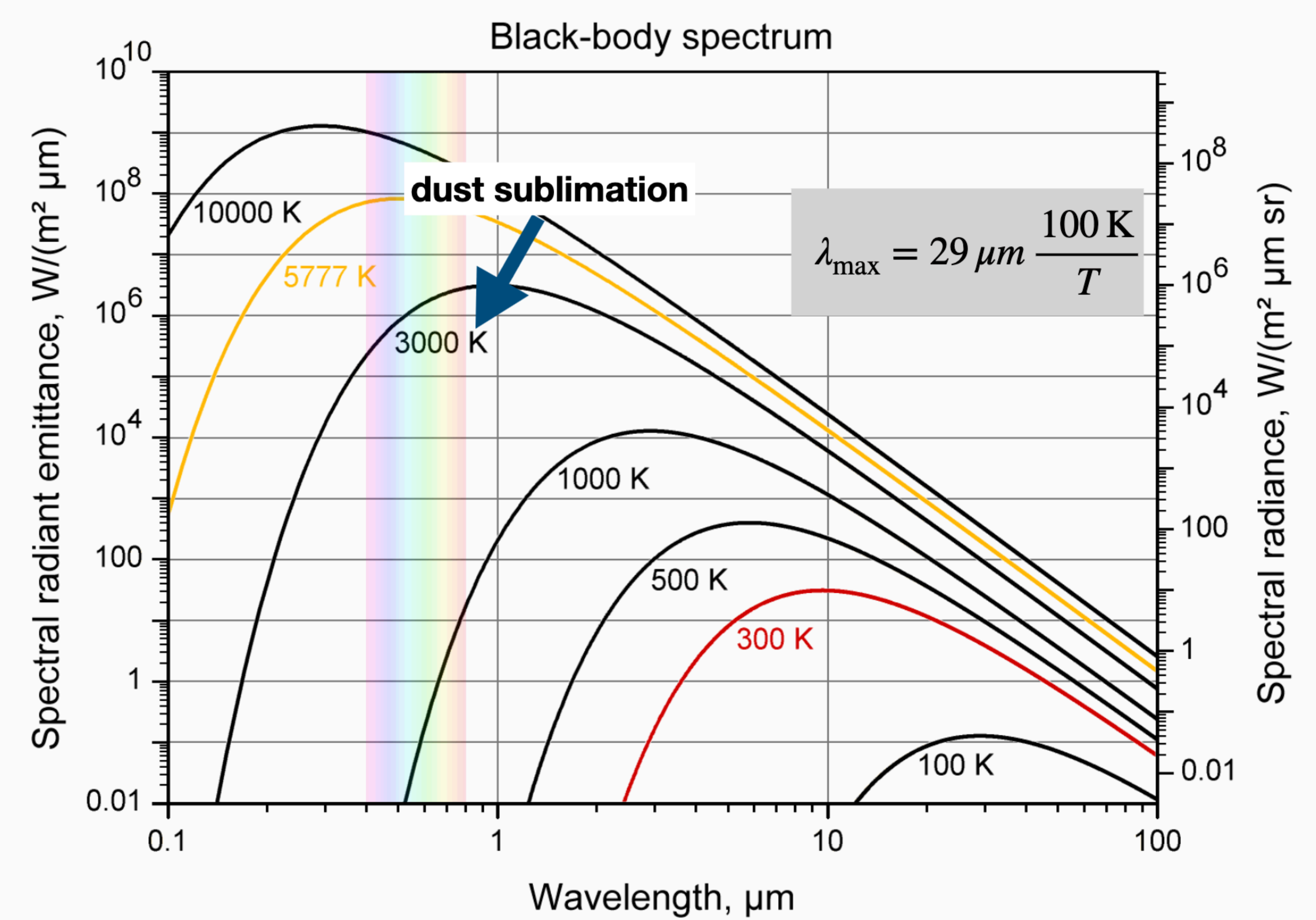
➡ Empirical behaviour of $\tau\nu$ as a function of ν for large interstellar dust grains is modelled as a power law: $\tau_\nu = \left(\frac{\nu}{\nu_0}\right)^\beta$ where the cut-off frequency $\nu_0 = c/\lambda_0$ is such that $\tau_{\nu_0} = 1$

➡ In the limit of $\nu << \nu_0$: $(1 - e^{-\tau_\nu}) = \tau_\nu$ $\Longrightarrow$ $I_\nu \approx \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$

Observations at three or more wavelengths this simple model can be used to determine both **T** and **β**

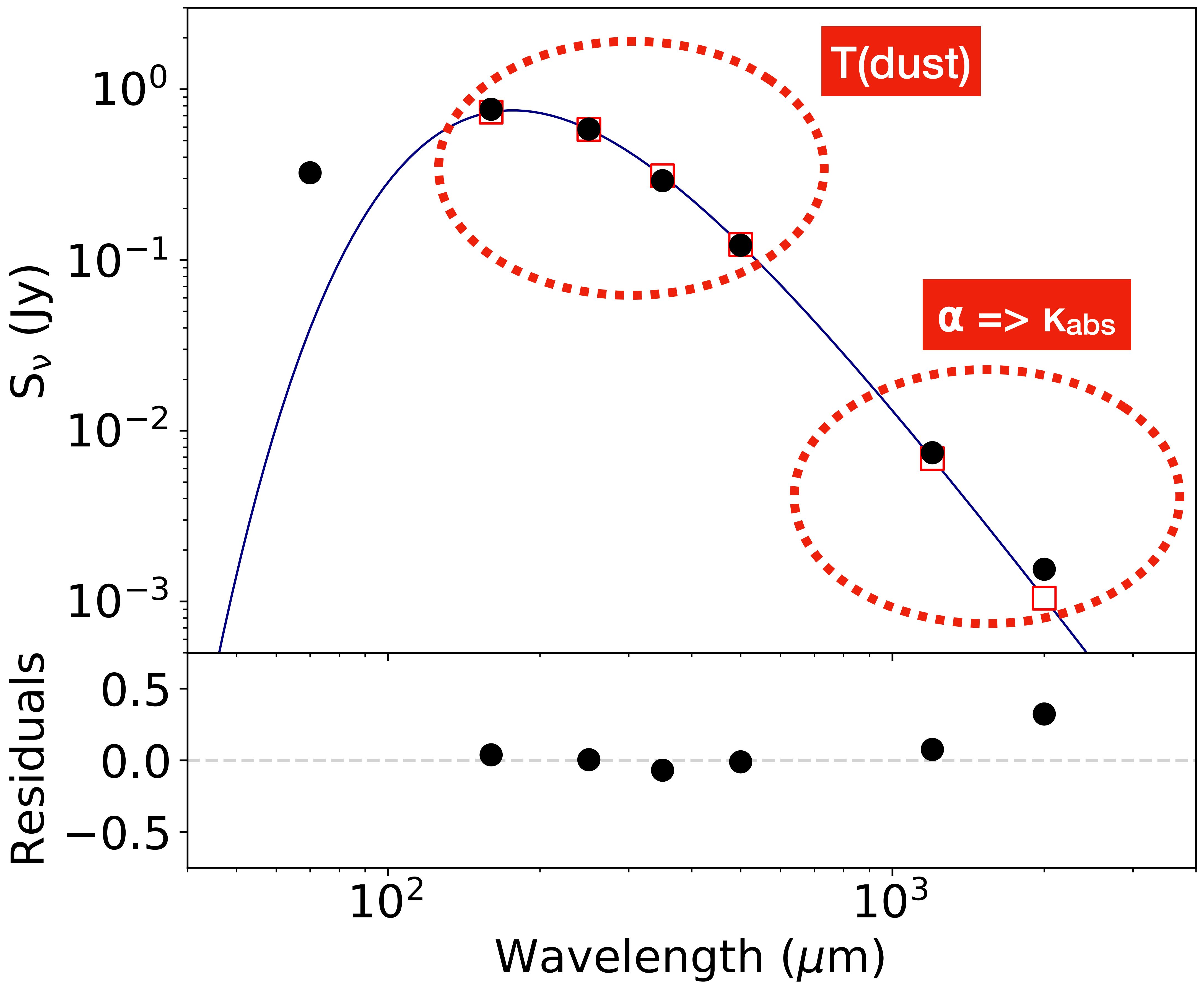
Measuring dust properties: spectral dependance of dust emissivity from thermal emission

THERMAL EMISSION



$$\lambda_{\rm max} = 29\,\mu m\,\frac{100\,{\rm K}}{T}$$

Measuring dust properties: spectral dependance of dust emissivity from thermal emission



Dust temperature and spectral index in RJ regime are usually obtained from SEDs of dust thermal emission from 70μm to 3mm

Measuring dust properties: spectral dependance of dust emissivity from thermal emission

We can measure the spectral index of the SED as α

$$\alpha_{1-2\mathrm{mm}} = \frac{log(F(\nu_1)/F(\nu_2))}{log(\nu_1/\nu_2)}$$

Assuming optically thin emission at mm wavelengths,
this informs on β as being α-2 in RJ approximation

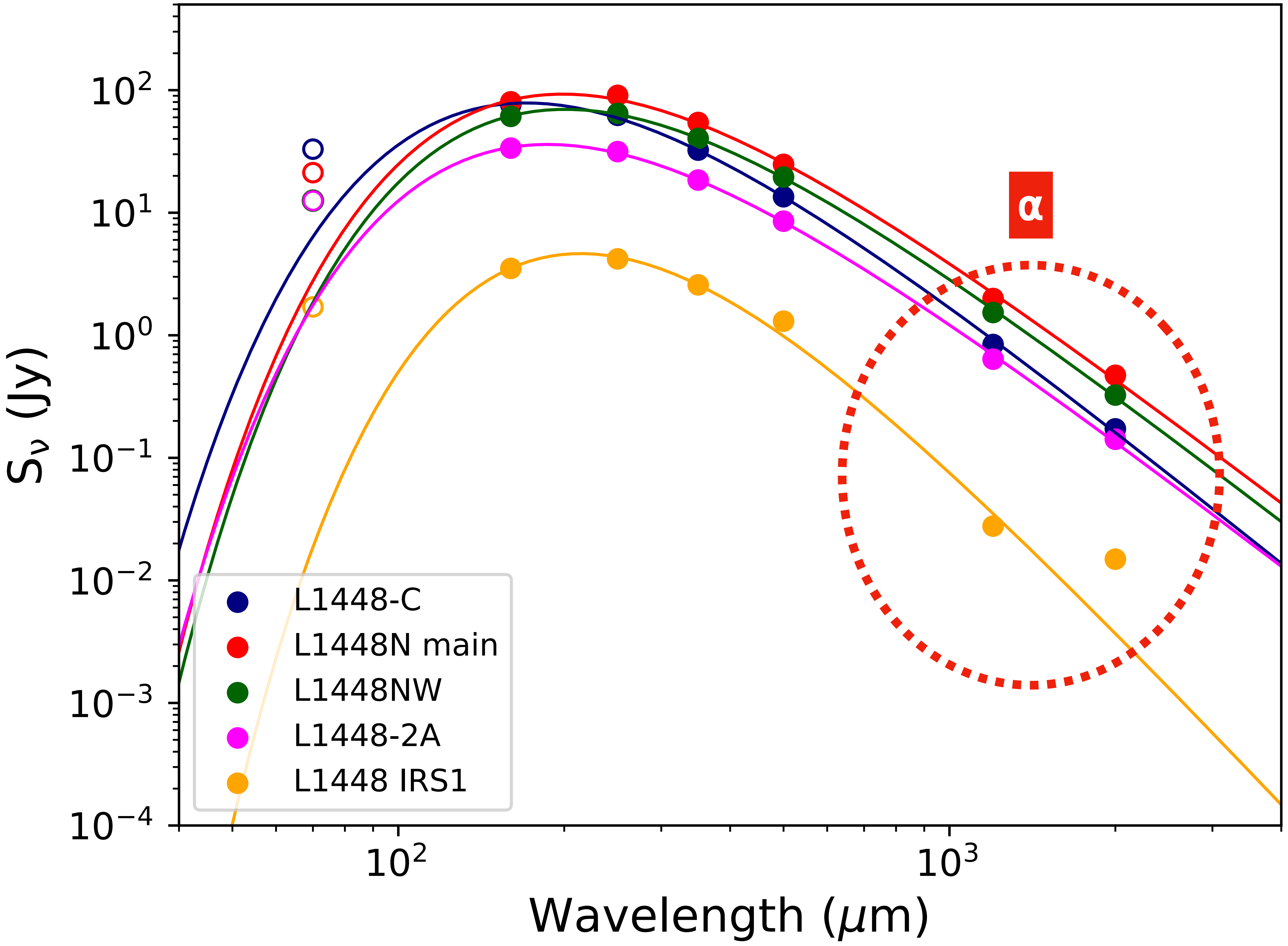
$$\kappa_{1.2\mathrm{mm}} = \kappa_{250\mu m} \left(\frac{\nu_{1.2\mathrm{mm}}}{\nu_{250\mu m}}\right)^{\beta}.$$

BUT

Protostellar envelopes are **COLD**: the **Rayleigh-Jeans approximation does not hold** because of their low dust temperatures

=> need to know T(dust) to get the Planck law correctly

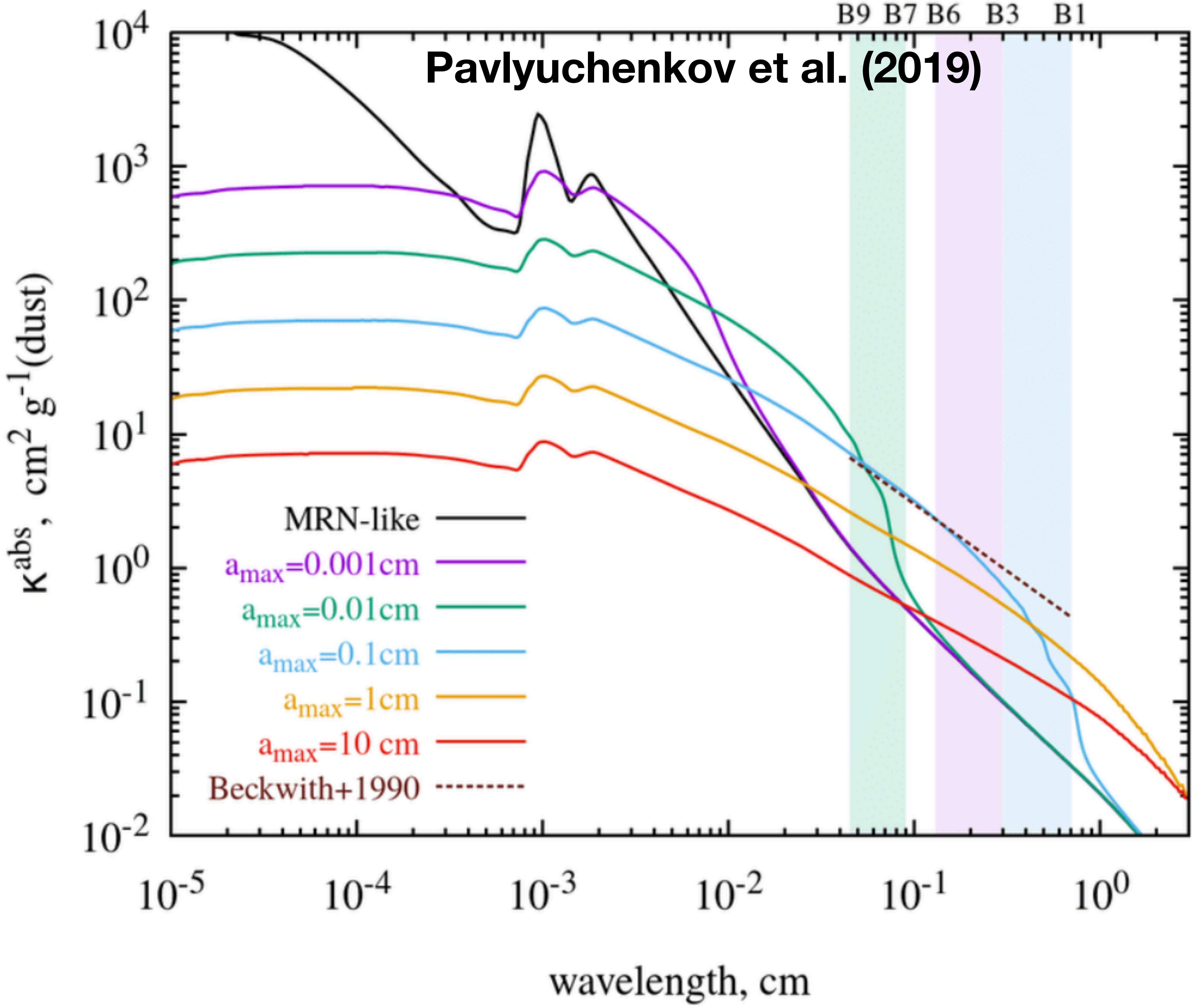
$$\beta = \frac{\log \frac{S_{1.2\mathrm{mm}}}{S_{2\mathrm{mm}}} - \log \frac{B_{1.2\mathrm{mm}}(T_\mathrm{d})}{B_{2\mathrm{mm}}(T_\mathrm{d})}}{\log \frac{\nu_{1.2\mathrm{mm}}}{\nu_{2\mathrm{mm}}}}.$$



How do we measure dust properties ?

Dust absorption coefficient (also called dust opacity, and dust emissivity ….):

$\kappa_{abs} \propto \nu^{\beta}$



Pavlyuchenkov et al. (2019)

Rayleigh regime (a << λ):

$Q_{abs} \sim a \Rightarrow \sigma\, Q_{abs} \sim a^3 \sim$ grain (total) volume

=> when grain size is << λ, impossible to derive a from the dust SED of grains emitting at thermal equilibrium

In the Mie regime (a ~ λ):

Q_{abs} strong function of a/λ, so β is affected

=>

The dust emissivity spectral index ONLY gives indication on Q_{abs} cross sections when a ~ λ

It can be measured in absorption, or in emission

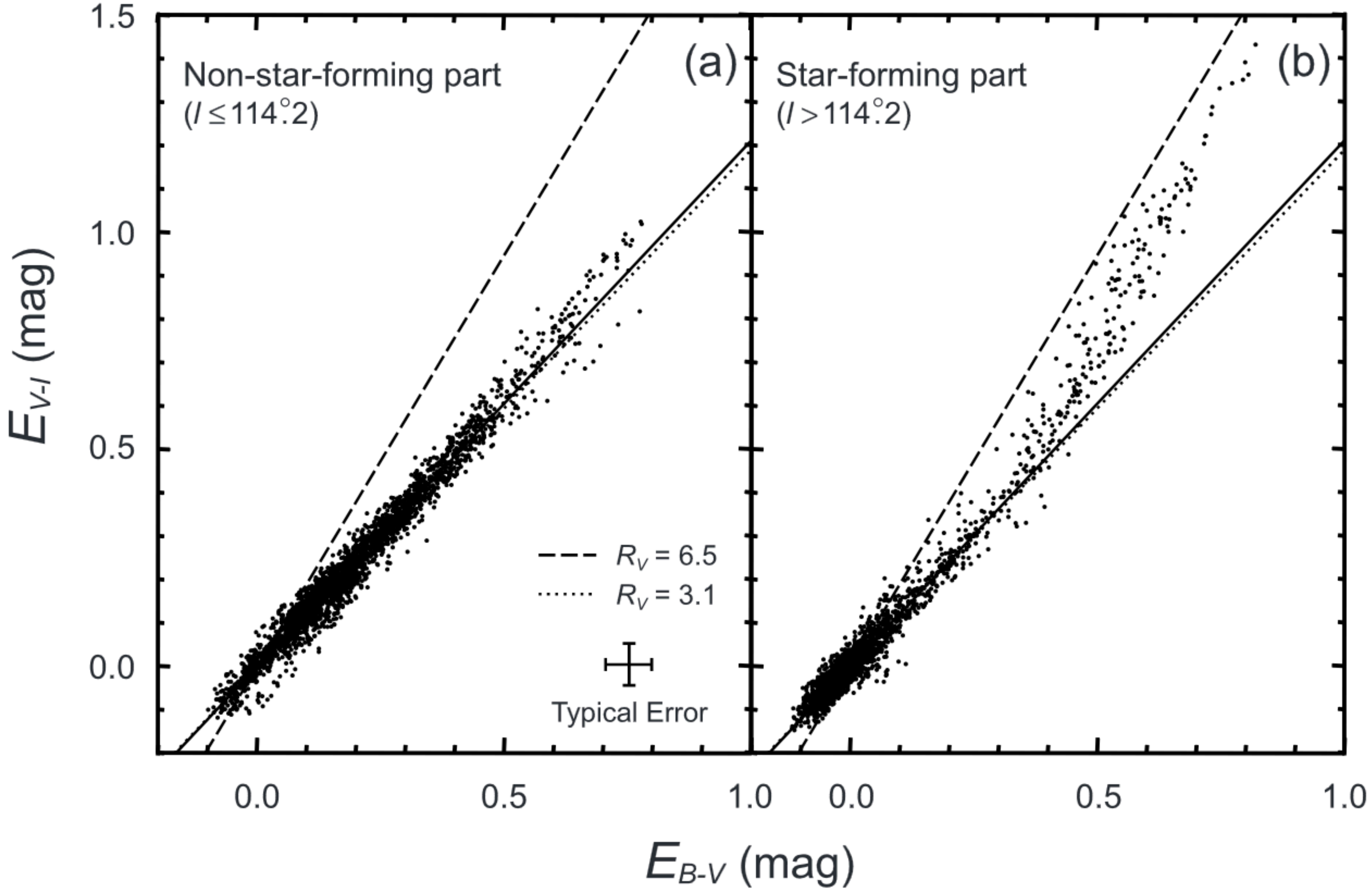
SEE DEMYK'S LECTURE

DENSE ISM

- Extinction = Absorption + Scattering
- Scattering efficiency is a strong function of *a*/λ, and peaks when 2π*a* ~ λ.
- A dust model is needed: a_{max} ~ 0.3 - 0.5 μm for the diffuse ISM (Rv = 3.1)
- The polarization curve in extinction can also be used.

$R_V = A_V / E_{B-V}$ the color excess

A measure of wavelength dependence of the interstellar extinction



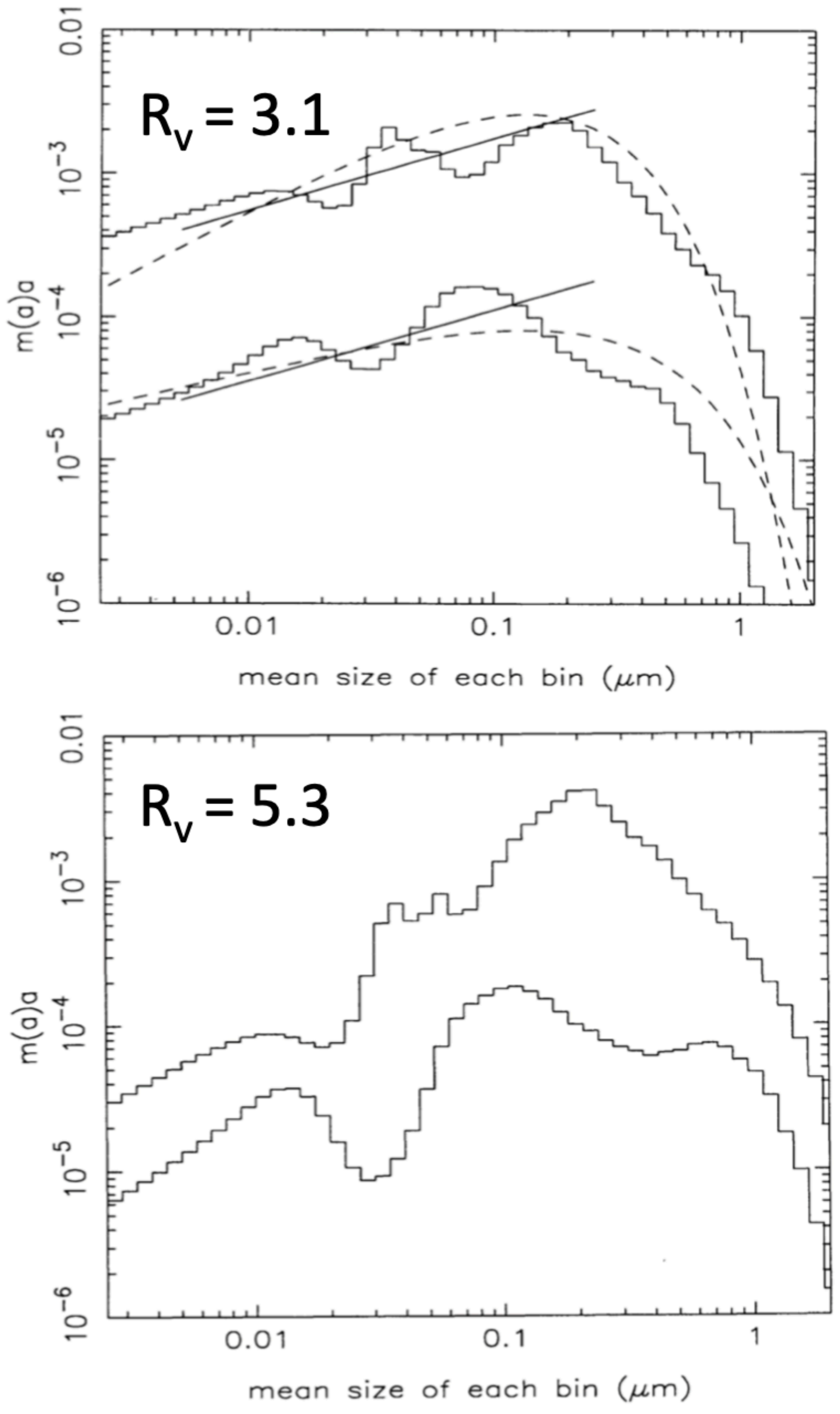
Kandori et al. (2003) in L1251

the non-star-forming part of the cloud has a typical interstellar value R_V=3.1,

while in the denser part of the cloud experiencing star formation has R_V = 6.5

DENSE ISM

$R_V = A_V / E_{B-V}$ color excess
changes in regions experiencing star formation

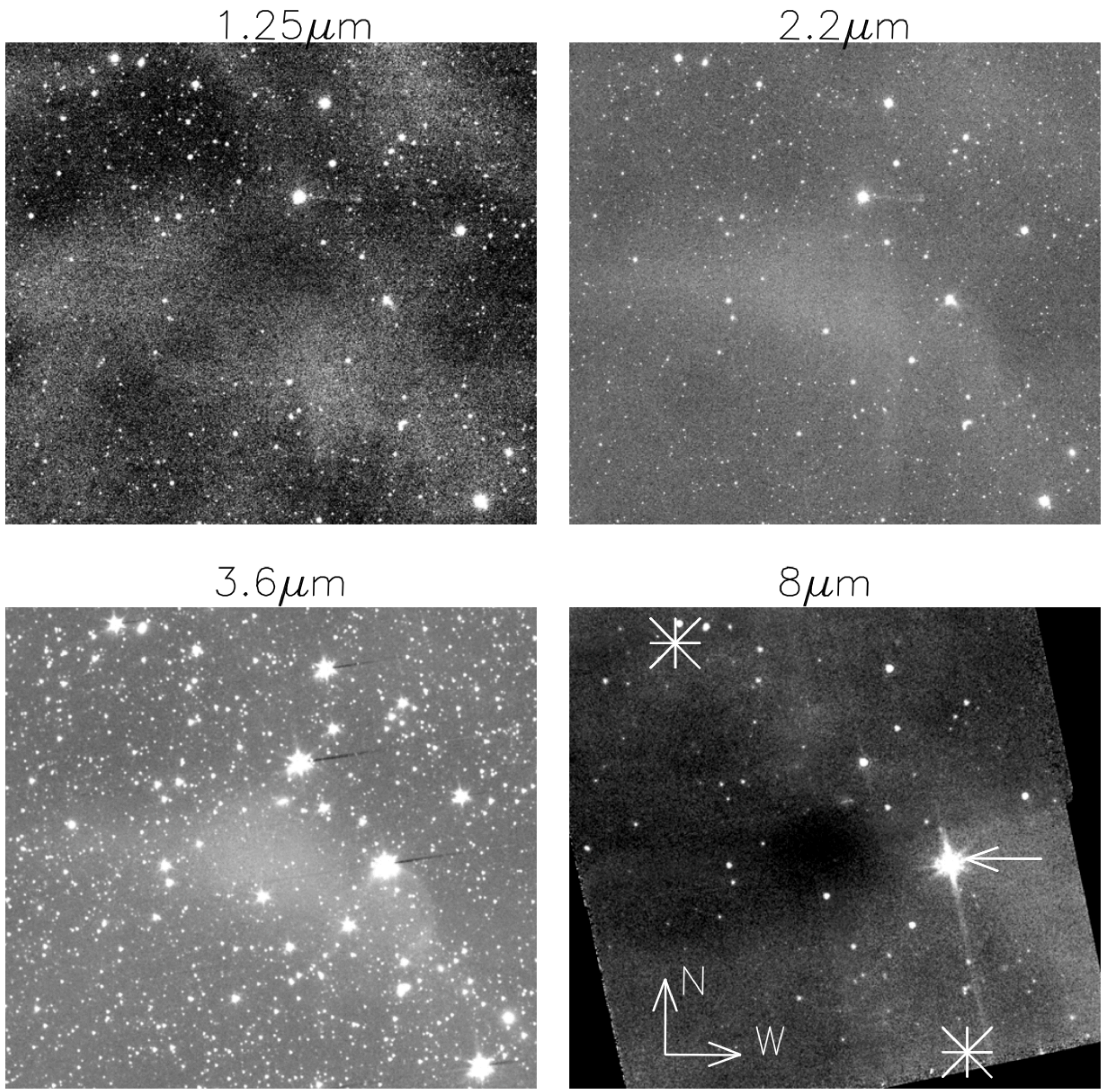


The abundance of small grains is very different !!!

Important for disk formation ! What do you start with ?

- MRN from diffuse ISM (R_V=3.1)?
- Already evolved (R_V = 5.3)?

PRESTELLAR CORES



Coreshine: grains in low-mass cores scatter mid-infrared (3.6–4.5 μm) light efficiently

Pagani et al. (2010b) reported on the detection of **coreshine** for about half of 110 investigated prestellar cores

To fit simultaneously the near-IR extinction and FIR Herschel emission profiles: the grain opacity has to increase

- Requires a = 0.5 – 1.5 μm (Steinaecker+2015) with astrosilicates.
- Requires a ~ 0.7 μm and fluffy grains (Ysard+2015, THEMIS) through the accretion of aliphatic-rich C-H mantles.

See K. Demyk’s lecture for more clues on dust evolution in clouds/cores with **coreshine** effect and **scattered light excess** in JWST spectra !

PRESTELLAR CORES

➡ Solution of the radiative transfer equation for a medium with optical depth τ_ν and for a source function constituted by the Planck blackbody B_ν at temperature T is:

$I_\nu = B_\nu(T)(1-e^{-\tau_\nu})$ where $B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT}-1}$

➡ Assuming I_ν being uniform over the solid angle Ω, the corresponding flux is:

$$F_\nu = \Omega(1-e^{-\tau_\nu})B_\nu(T)$$

➡ Empirical behaviour of τ_ν as a function of ν for large interstellar dust grains is modelled as a power law: $\tau_\nu = \left(\frac{\nu}{\nu_0}\right)^\beta$ where the cut-off frequency $\nu_0 = c/\lambda_0$ is such that $\tau_{\nu_0} = 1$

➡ In the limit of $\nu << \nu_0$: $(1-e^{-\tau_\nu}) = \tau_\nu$ ➡ $I_\nu \approx \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$

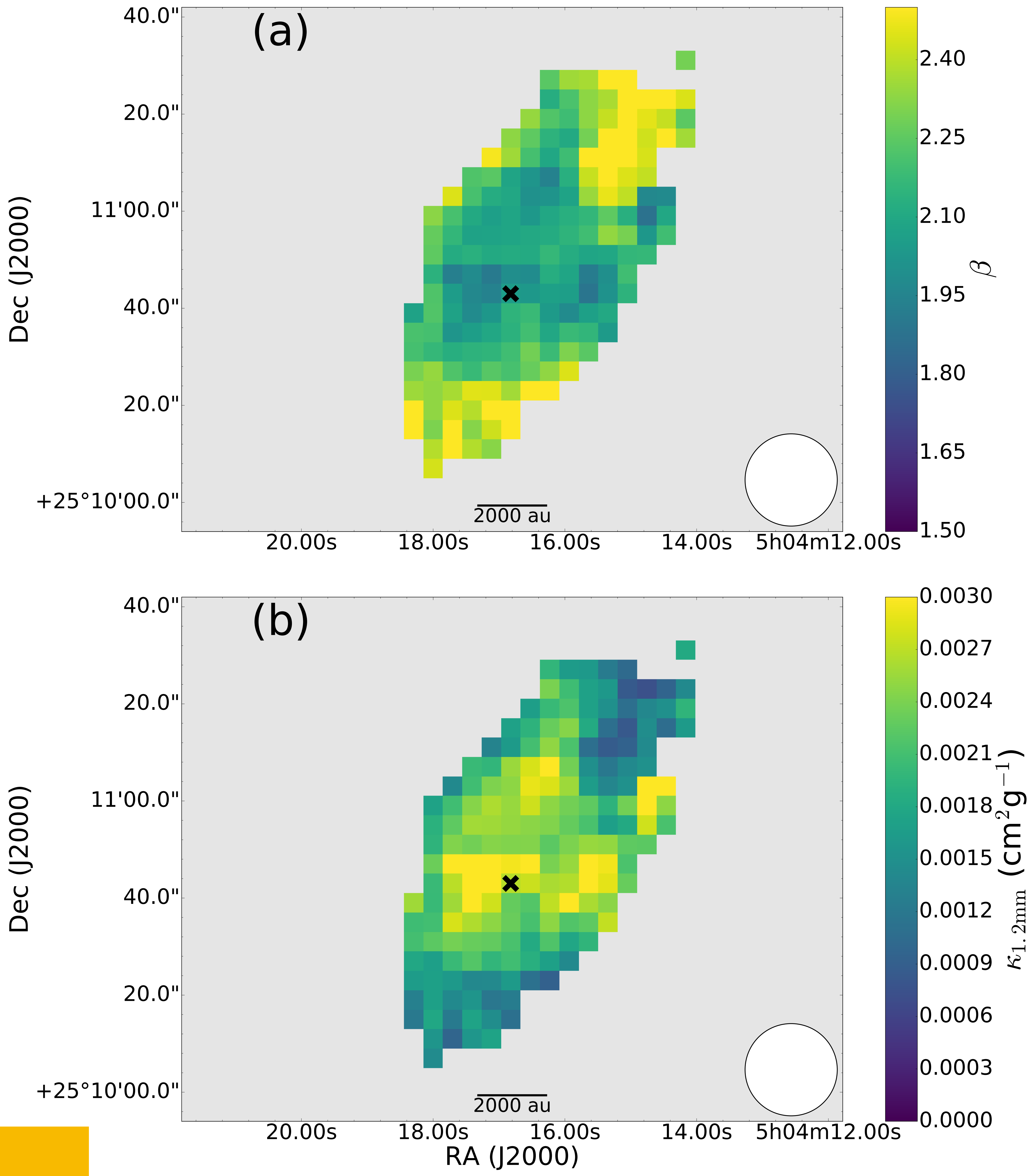
Observations at three or more wavelengths this simple model can be used to determine both **T** and **β**

Using longer wavelengths allows to probe for larger grains

$$\kappa_{1.2\mathrm{mm}} = \kappa_{250\mu\mathrm{m}}\left(\frac{\nu_{1.2\mathrm{mm}}}{\nu_{250\mu\mathrm{m}}}\right)^\beta.$$

$$\beta = \frac{\log\frac{S_{1.2\mathrm{mm}}}{S_{2\mathrm{mm}}} - \log\frac{B_{1.2\mathrm{mm}}(T_\mathrm{d})}{B_{2\mathrm{mm}}(T_\mathrm{d})}}{\log\frac{\nu_{1.2\mathrm{mm}}}{\nu_{2\mathrm{mm}}}}.$$

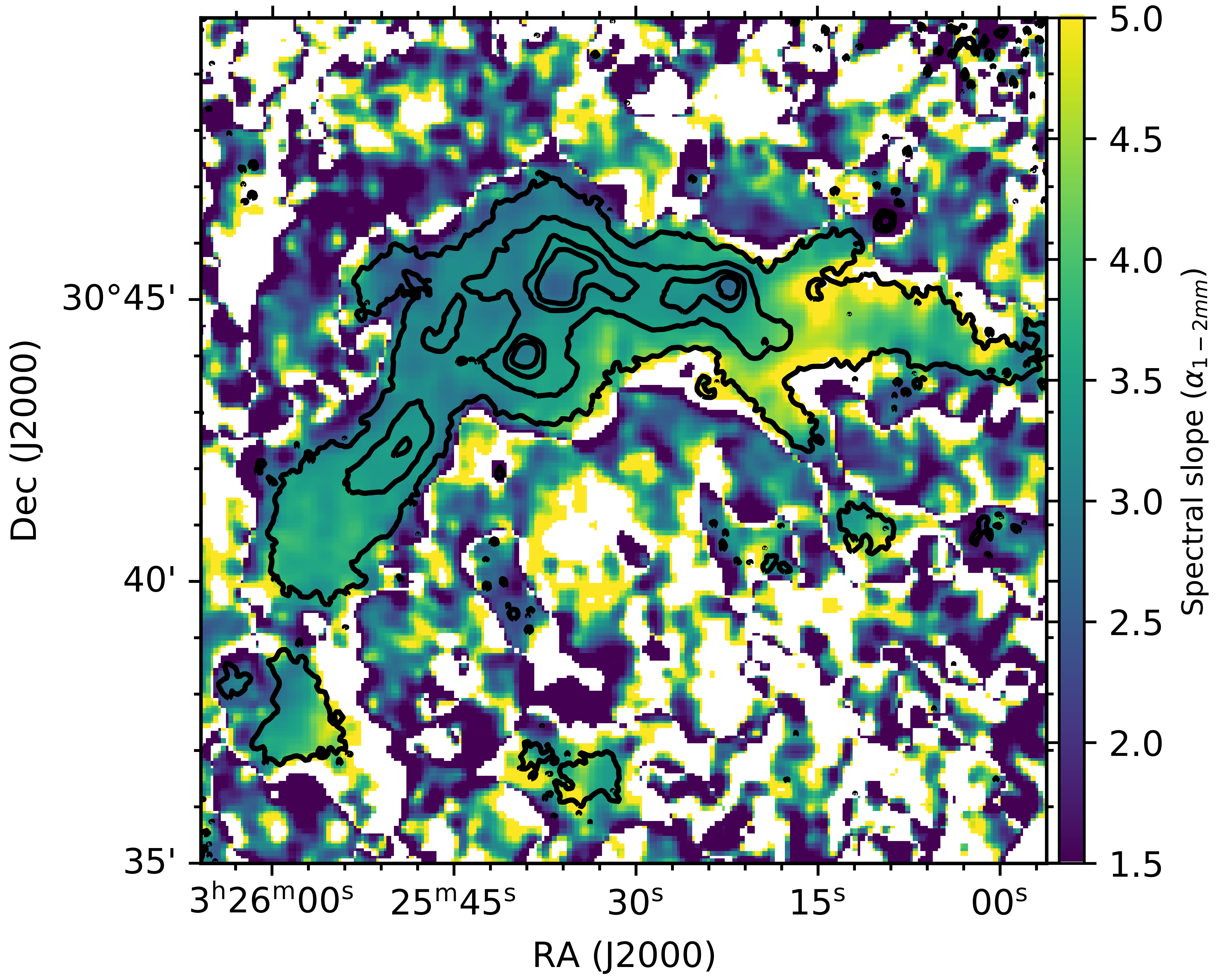
No indication of change in the mm dust opacities of pre stellar cores ?
=> no grains larger than > 20 µm

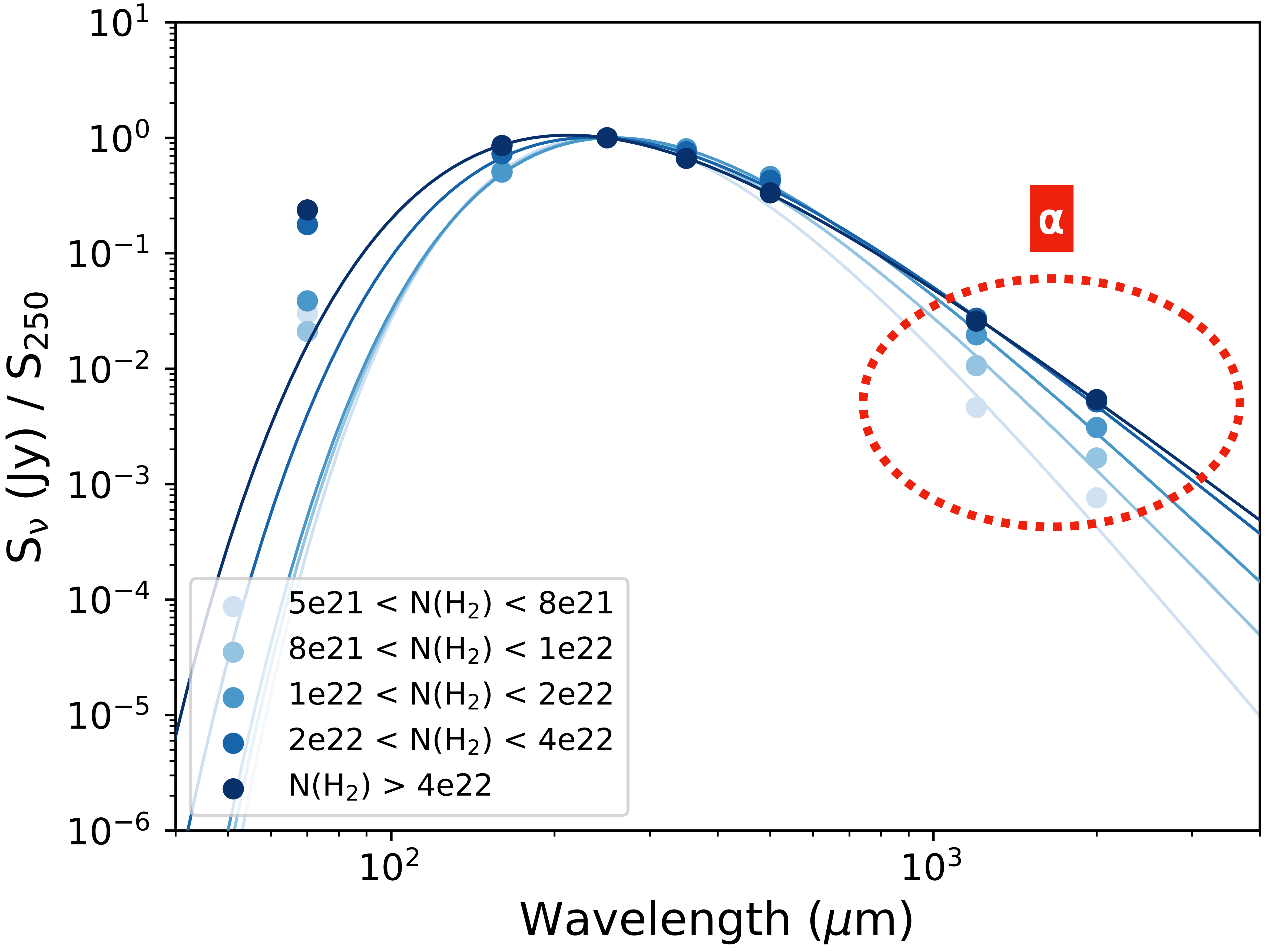


Chacon-Tanarro et al. (2019)

PROTOSTELLAR ENVIRONMENTS

Protostars embedded in the Perseus L1448 clump: observations with IRAM/NIKA2



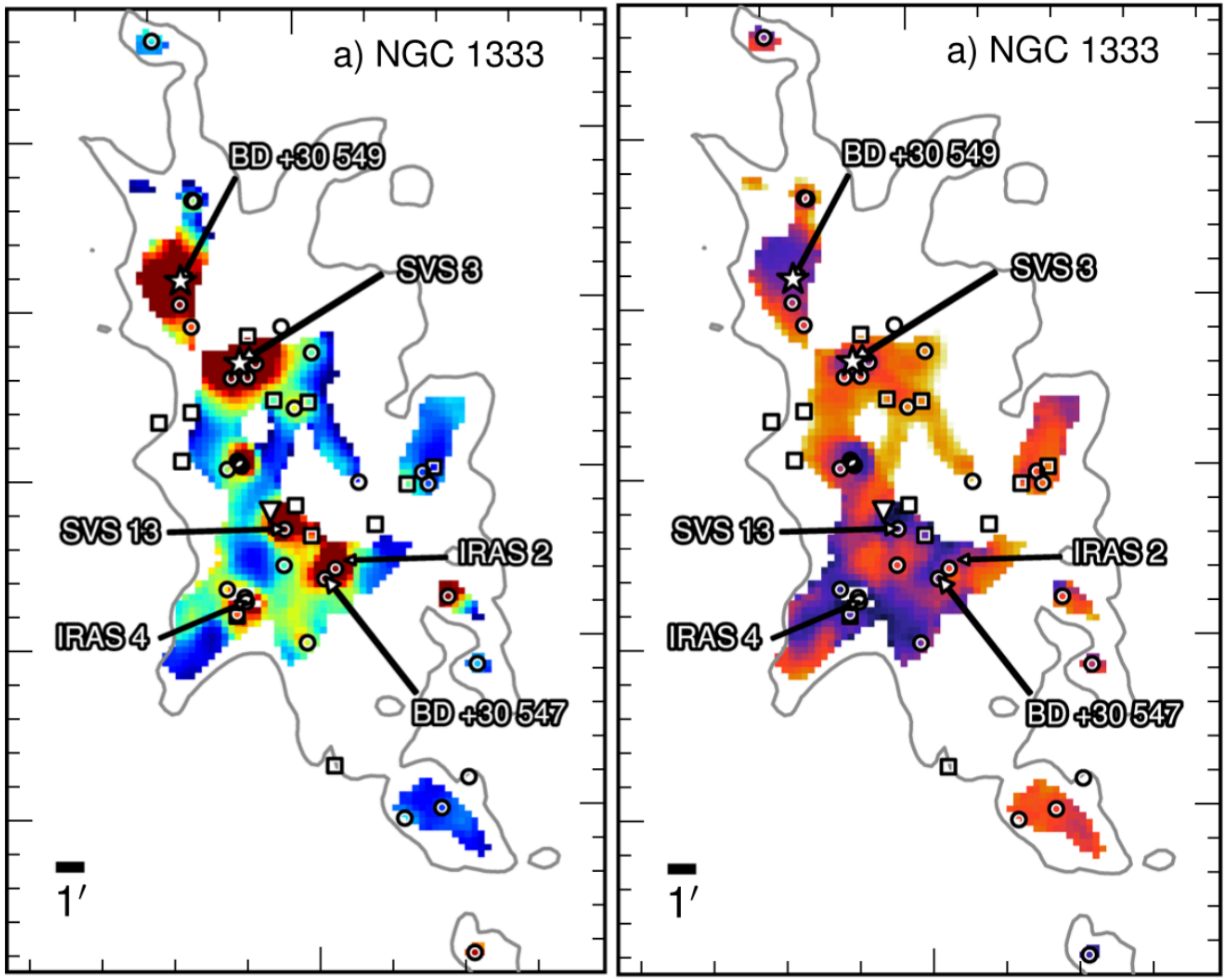


Observations show flattening of α when probing larger column densities

NGC1333 star-forming region in Perseus cloud

Temperature map:

[9-18 K]



Chen et al. (2016)

β map: ranges from 1 to 3

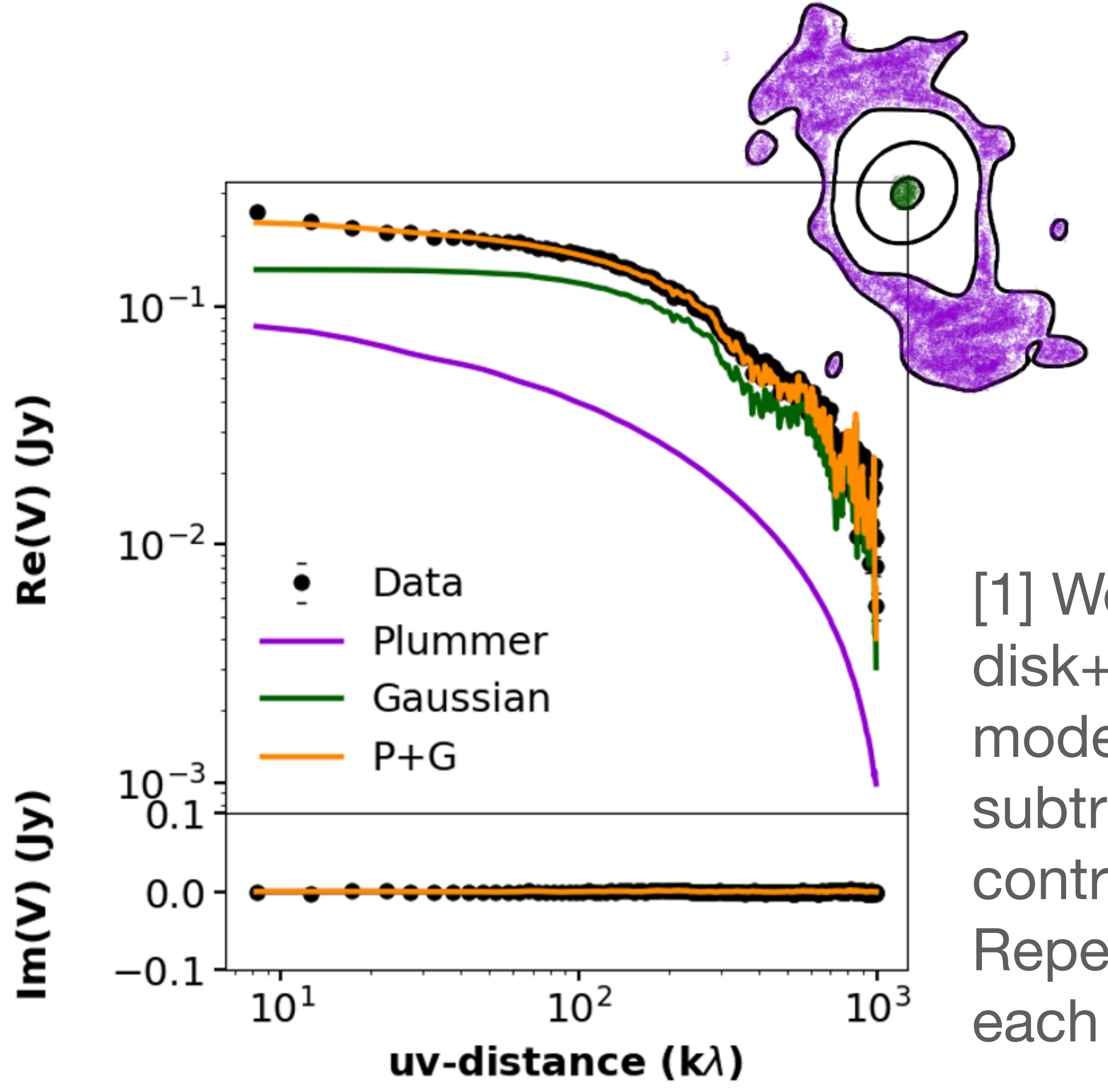
➡ Low values tend to correlate with T_d peaks

➡ β values can be intrinsically temperature dependent (Boudet et al. 2005)

➡ Grain growth can cause β values to decrease significantly

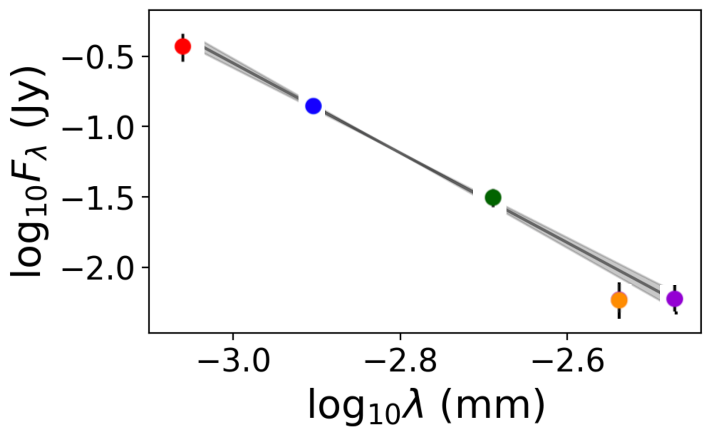
L1527 IRS in the sky

L1527 IRS in the uv-space

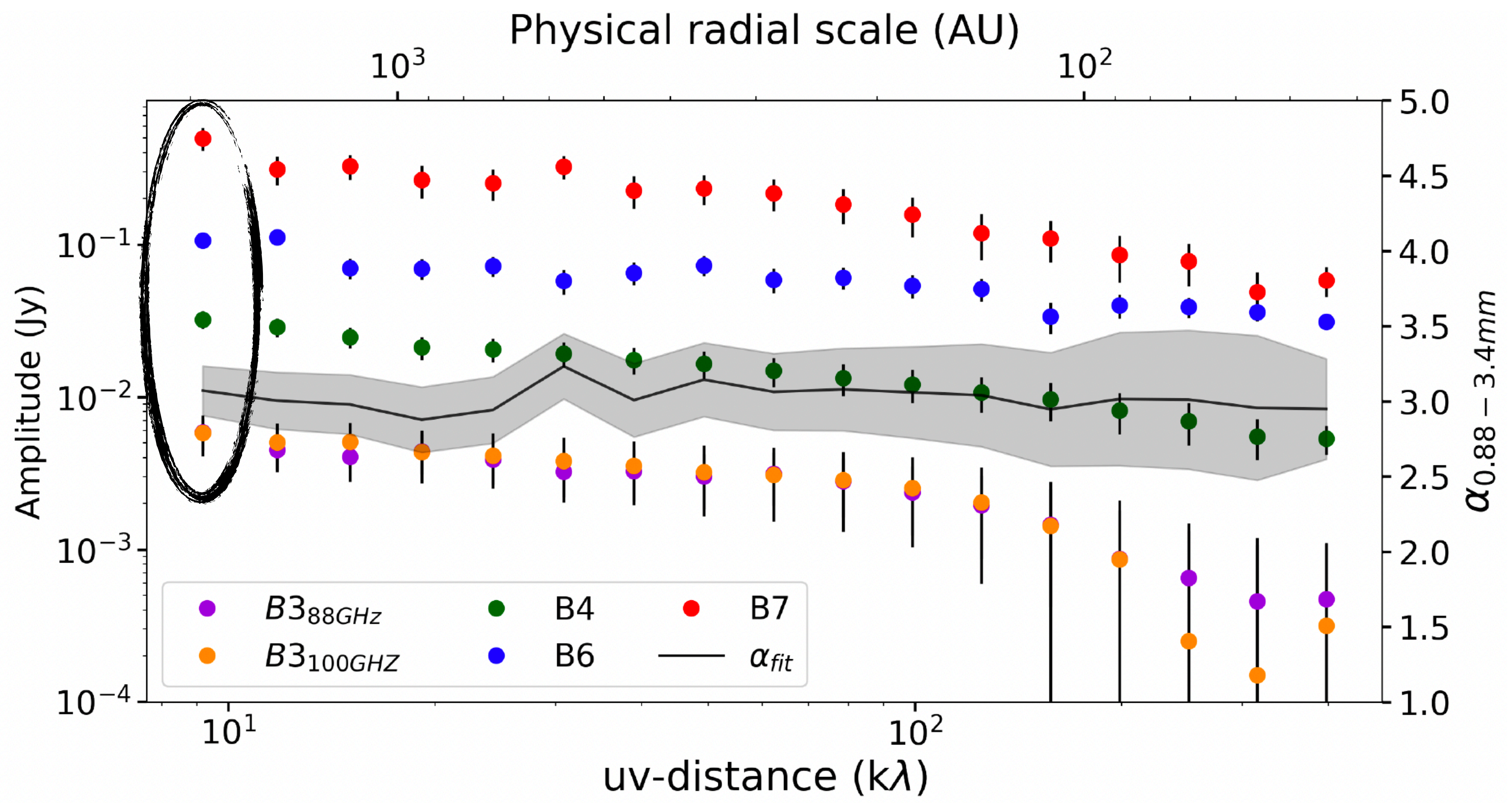


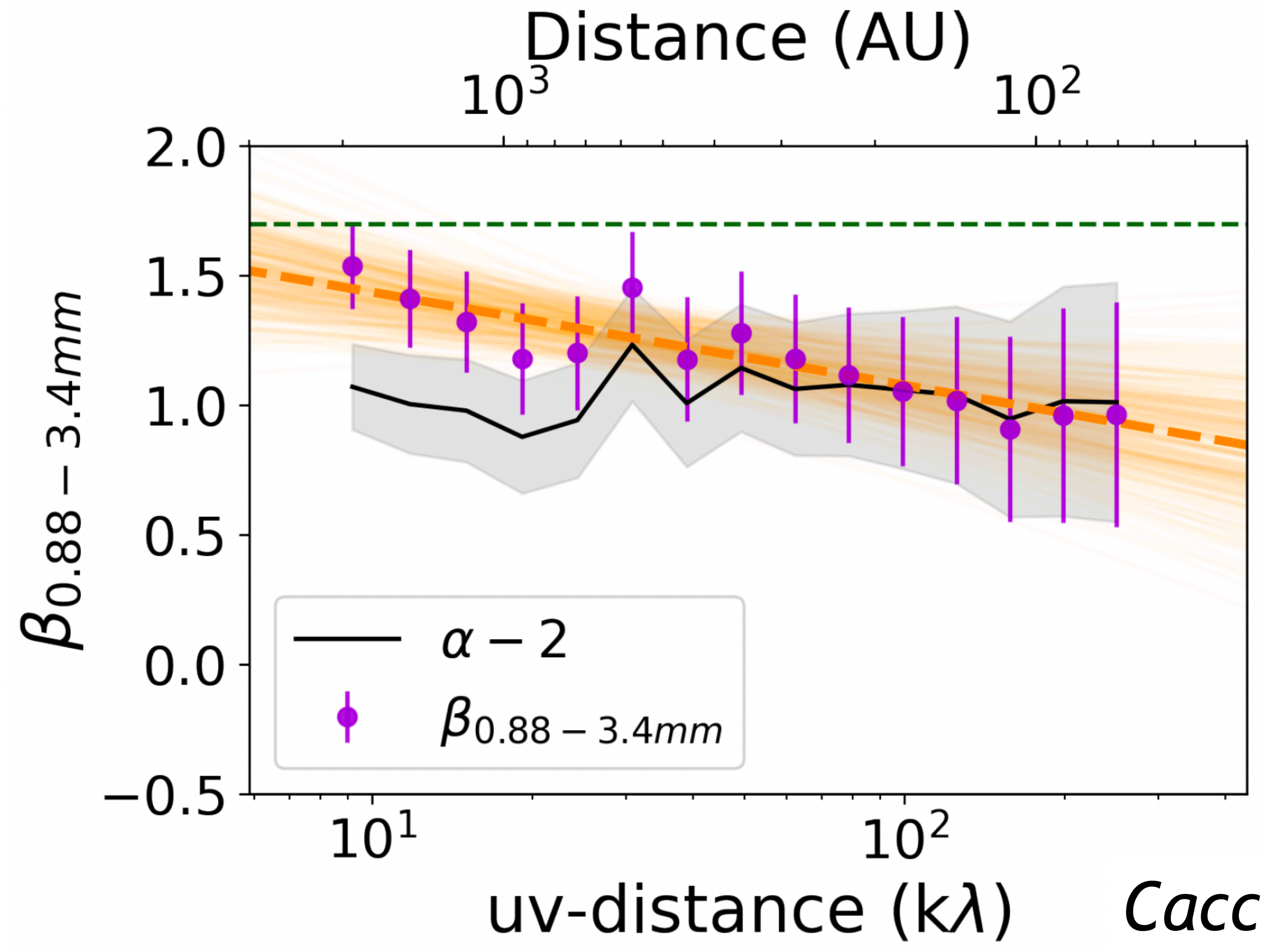
[1] We fit disk+envelope model to subtract disk contribution. Repeat for each band.

Envelope-only $\alpha(r)$, $\beta(r)$



[2] At each scale, we fit 4 bands to measure the spectral index.

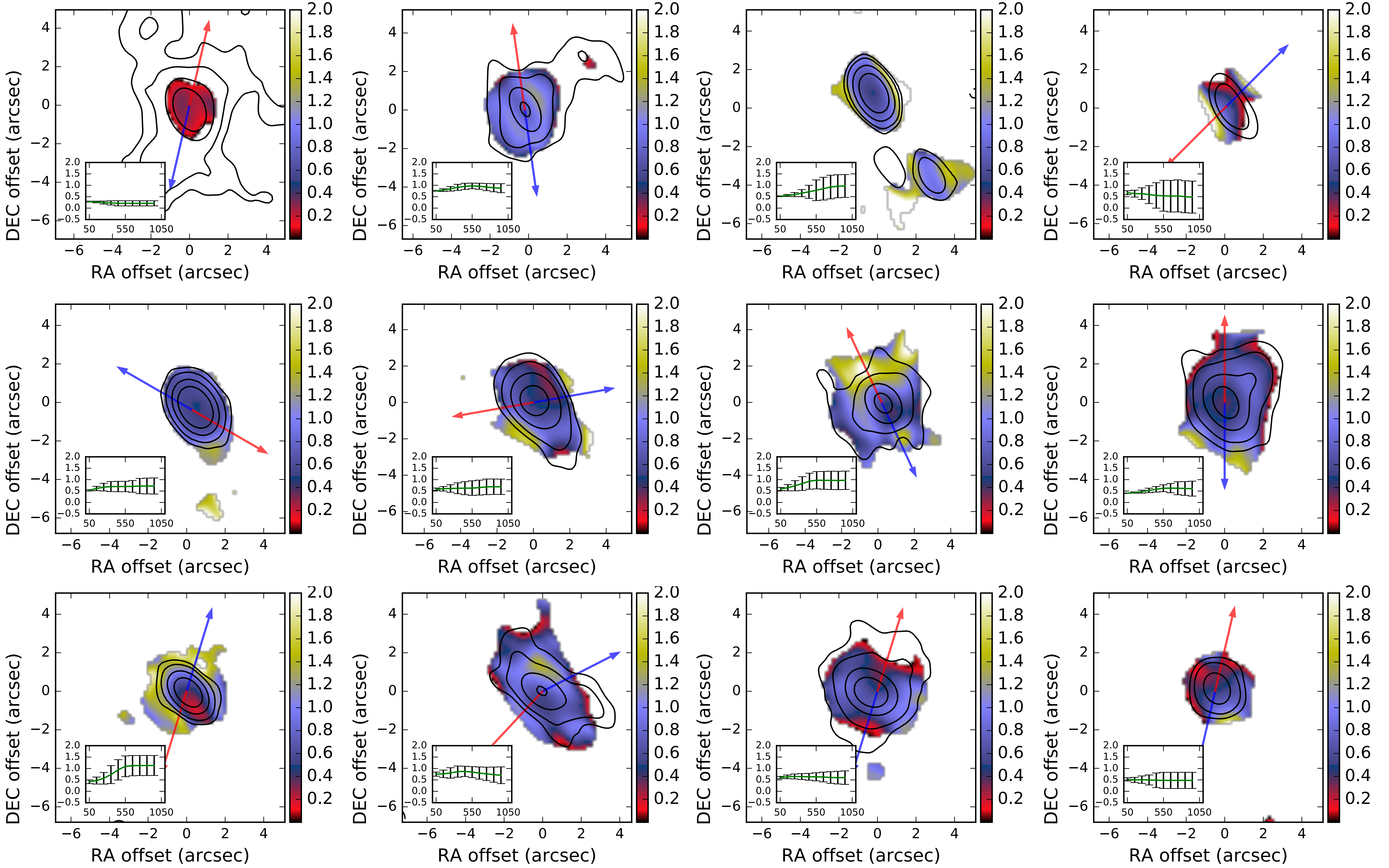




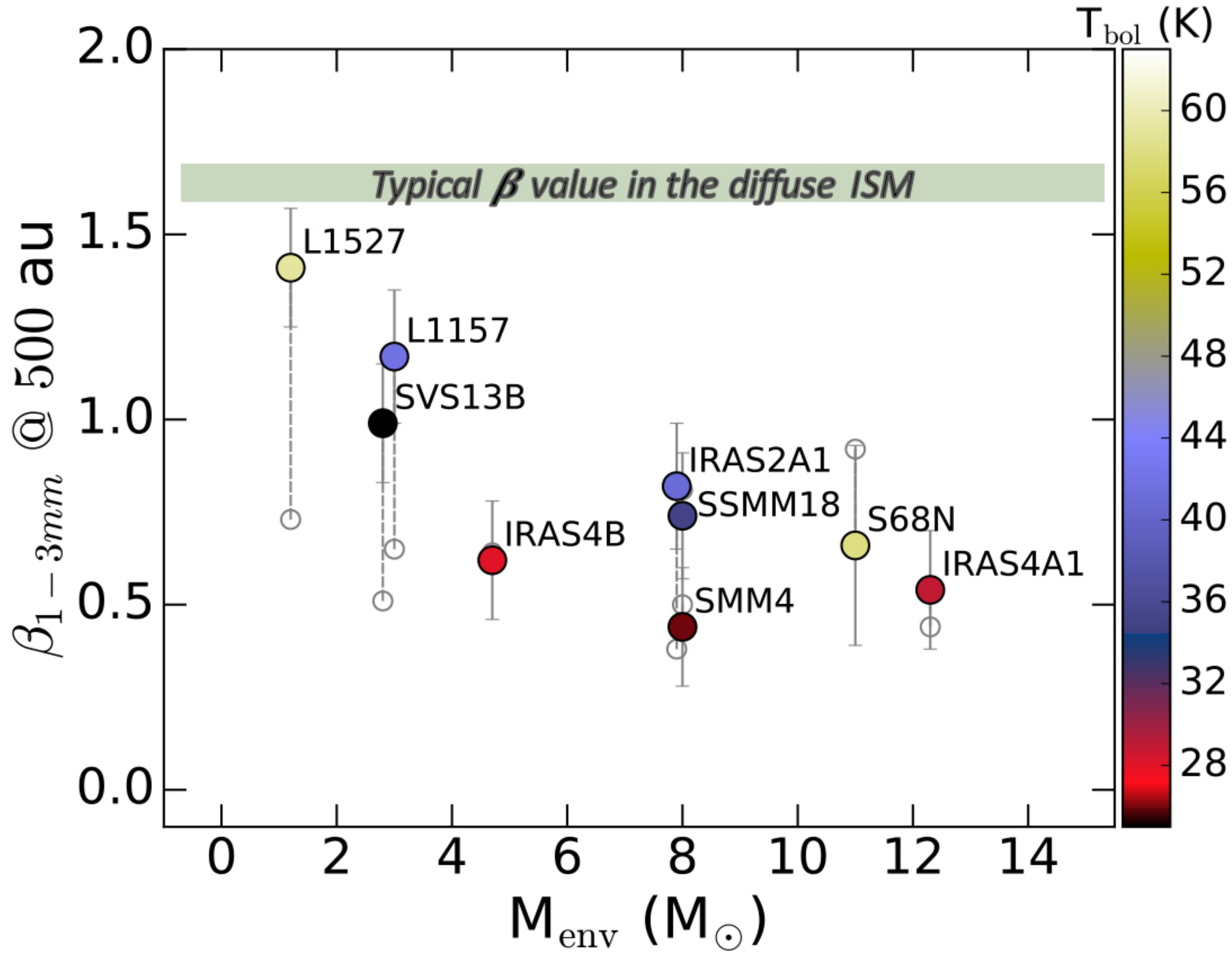
[3] We derive the dust opacity after correcting for discrepancies from RJ approximation

Cacciapuoti et al. (2023)

Very low dust emissivities in the youngest protostars (Galametz+ 2019)



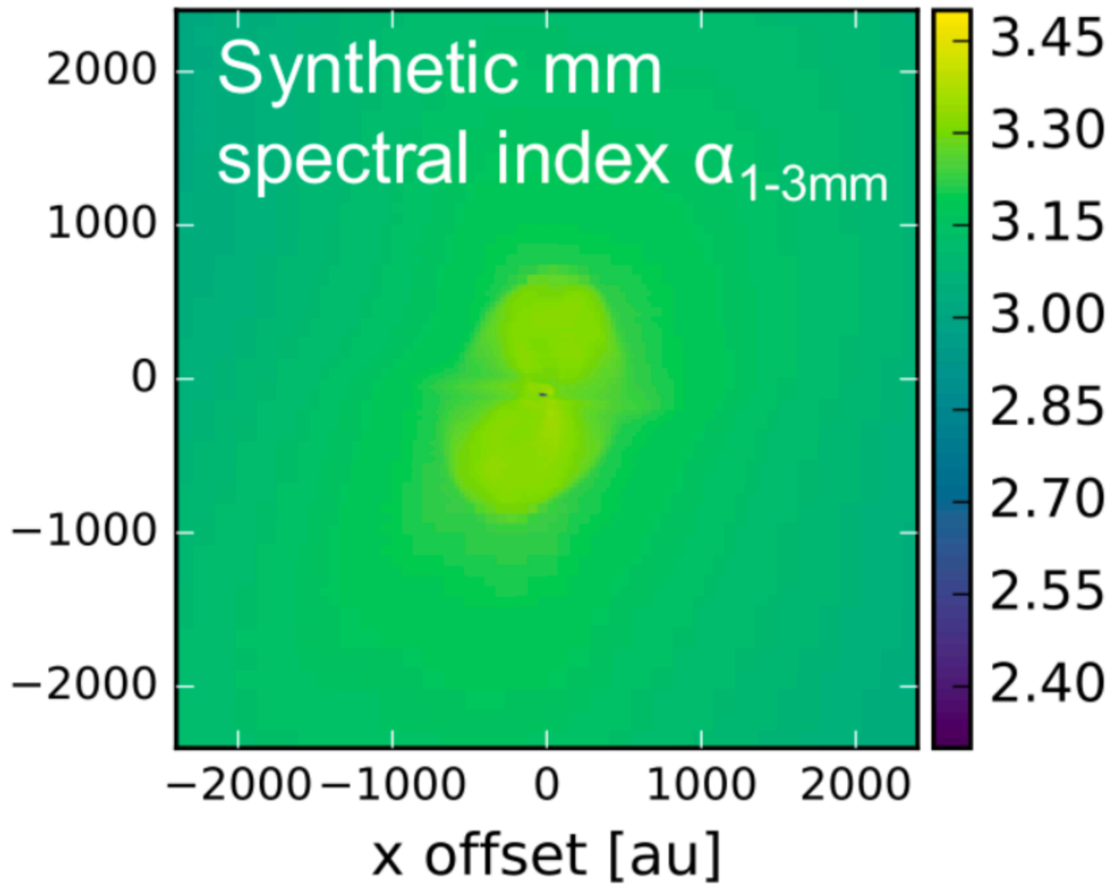
PROTOSTARS



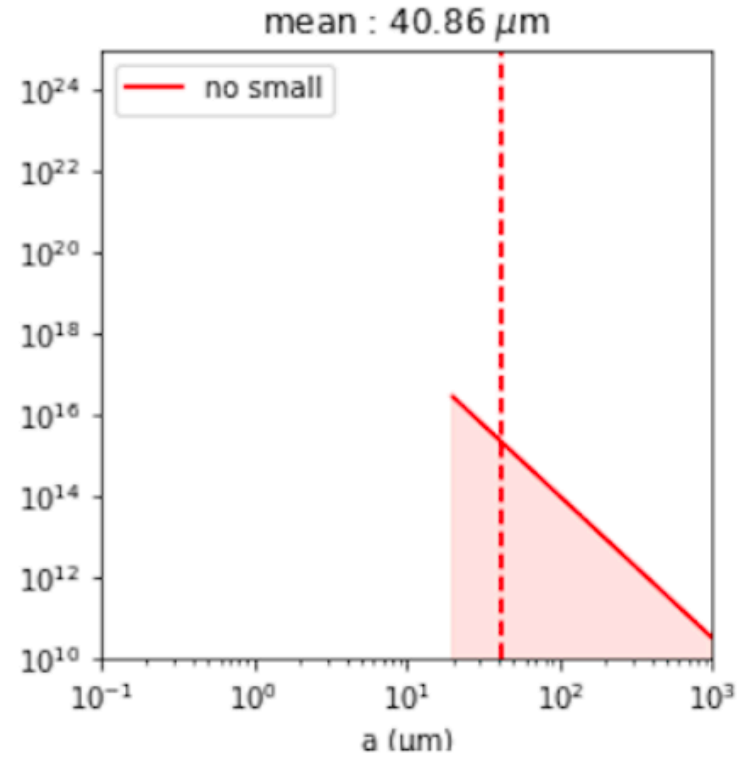
LOW dust opacity spectral indices in ALL of the observed Class 0 envelopes

Galametz, Maury, Valdivia, Testi, Belloche, André (2019)

PROTOSTARS



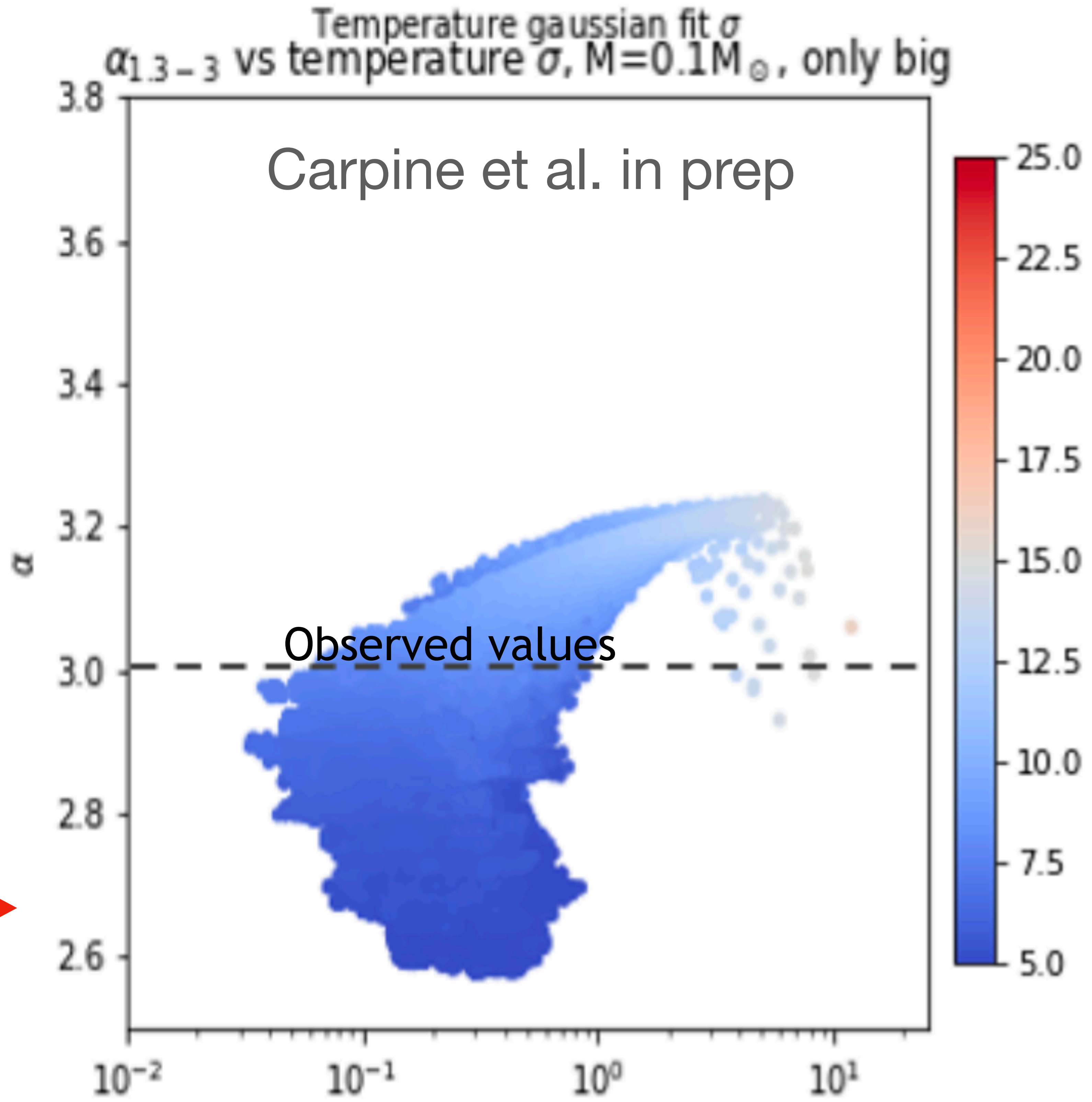
Dust grain size distribution in fiducial dust model



Millimeter spectral index of dust emissivity:
Synthetic observations at envelope scales
(in function of max temperature on the line-of-sight)

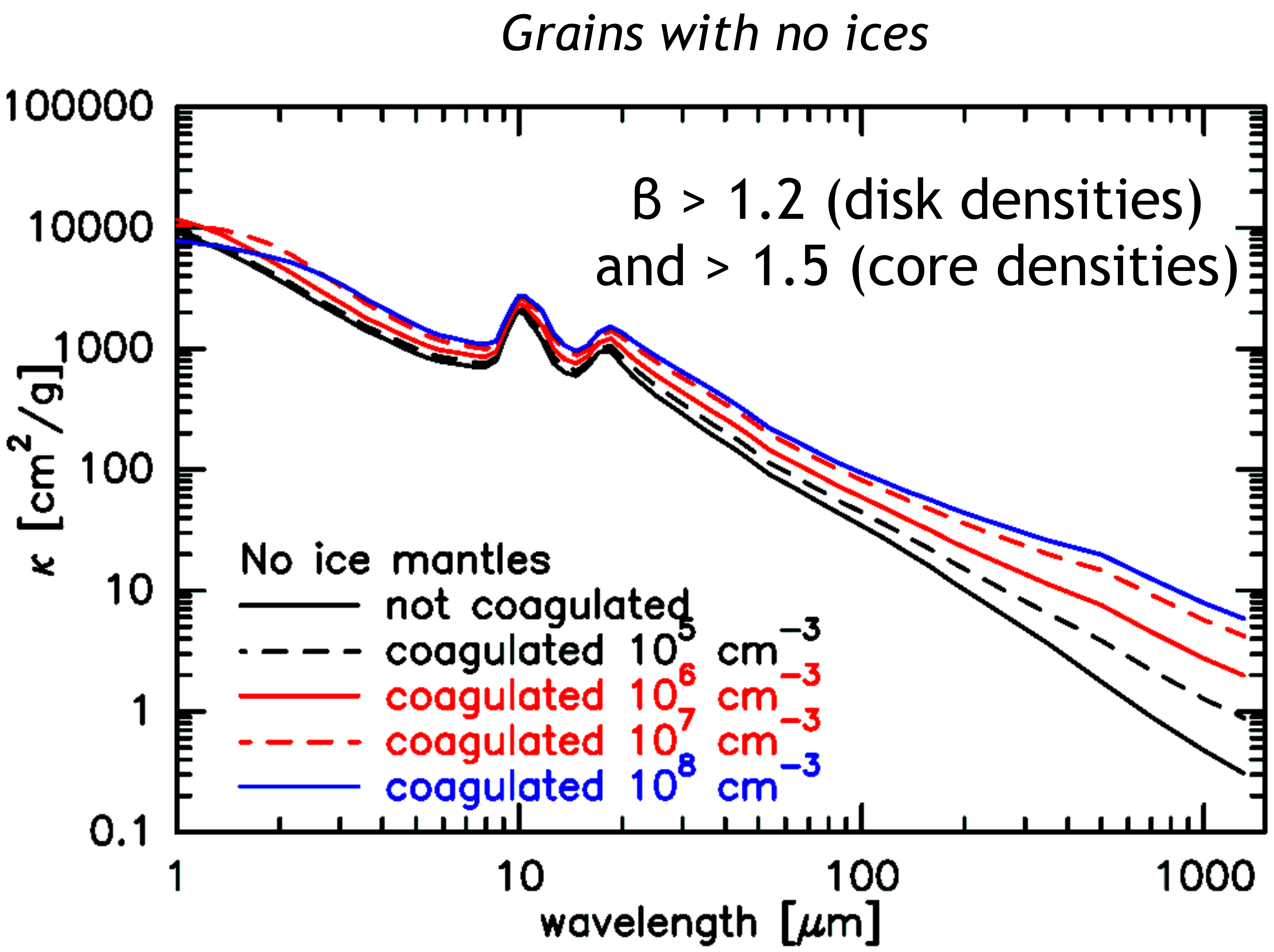
Using standard dust models:

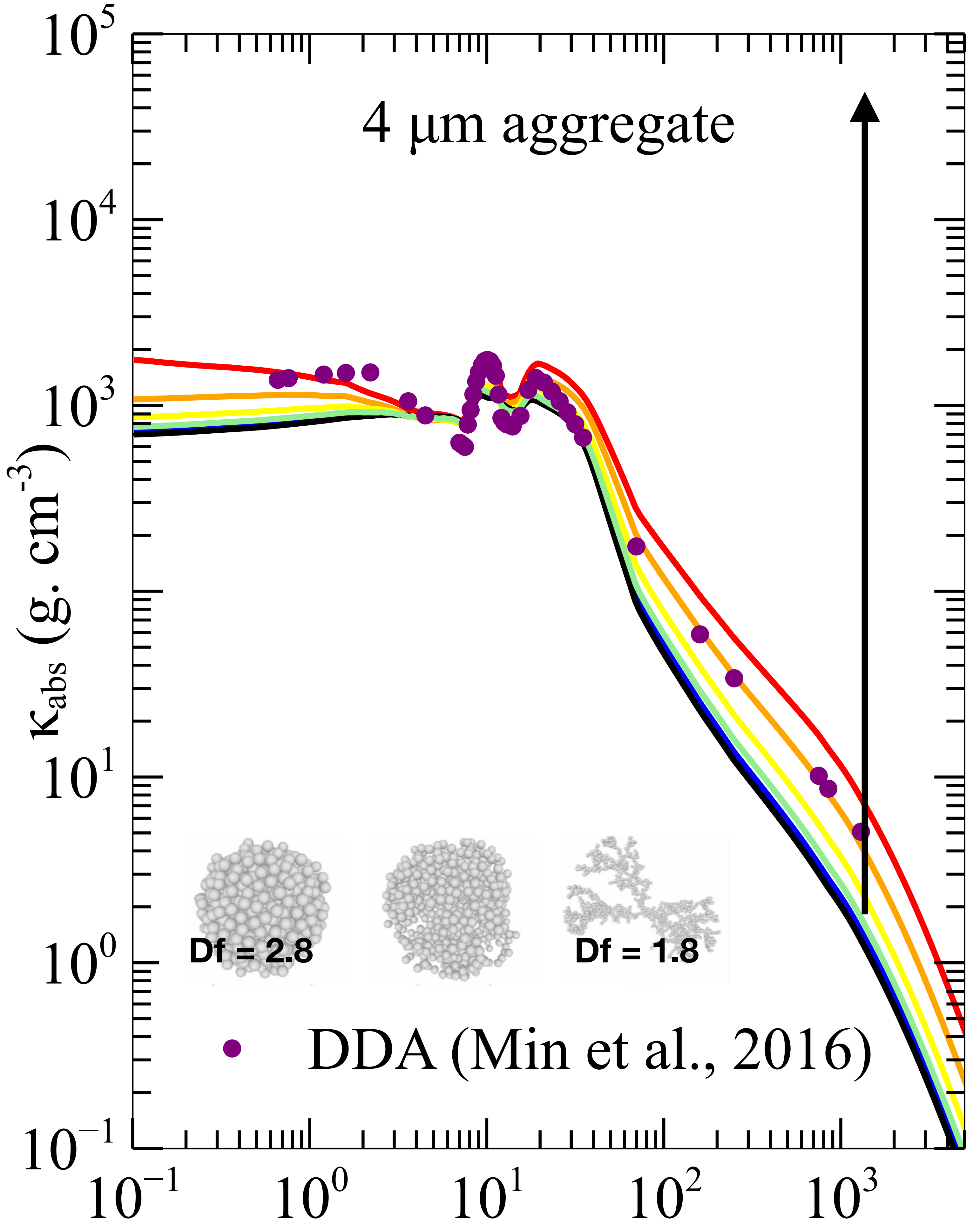
Only models with large grains
can reproduce observed spectral indices



Carpine et al. in prep

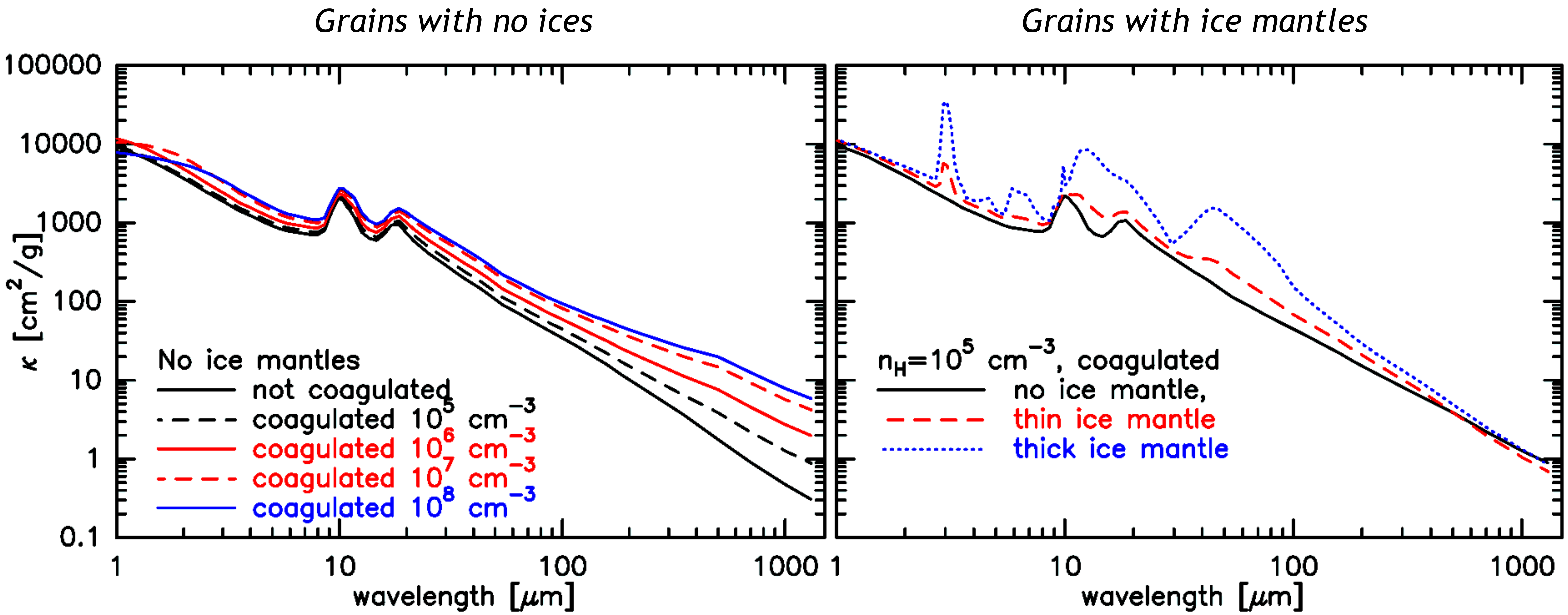
What should we do to dust to fit observations ?





Emissivity of irregular shaped grains can increase up to a few at mm
(Lefevre et al. 2019, Min et al. 2016, Ysard et al. 2023)
But not down to β < 1.0 ?

What should we do to dust to fit observations ?



Ices are not expected to significantly change dust opacity at mm (Kohler et al. 2016, Ysard et al. 2021)

TO KNOW MORE: ATTEND K. DEMYK'S LECTURE !