Planet formation in the ALMA era

Giuseppe Lodato - Università degli Studi di Milano

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Menu

Appetizer

Protostellar discs: dust, gas and their tracers

1st course

Spiral structures in protostellar discs, their origin and appearance

2nd course

Gaps and planets, dust and gas

Dessert

Horseshoes in transition discs

The different components of discs and their tracers

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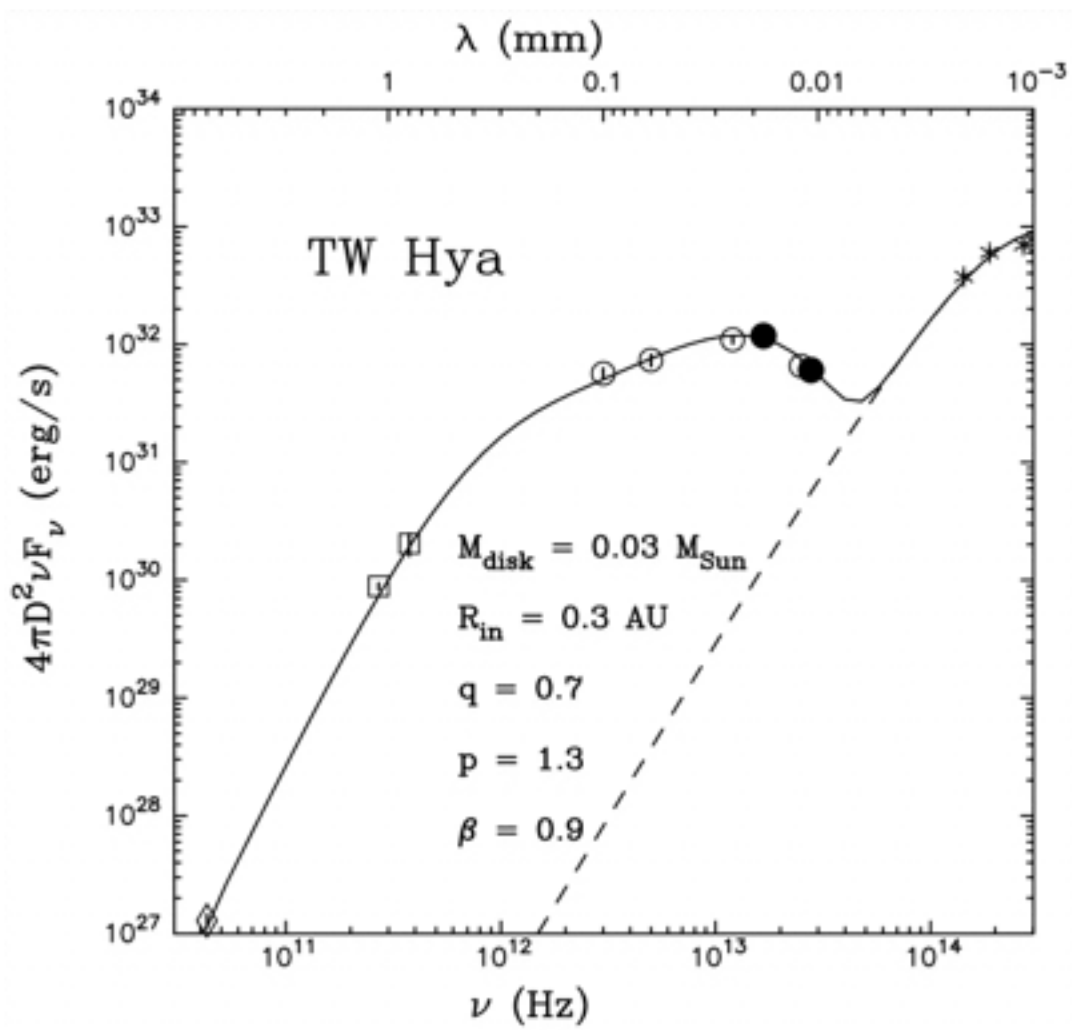

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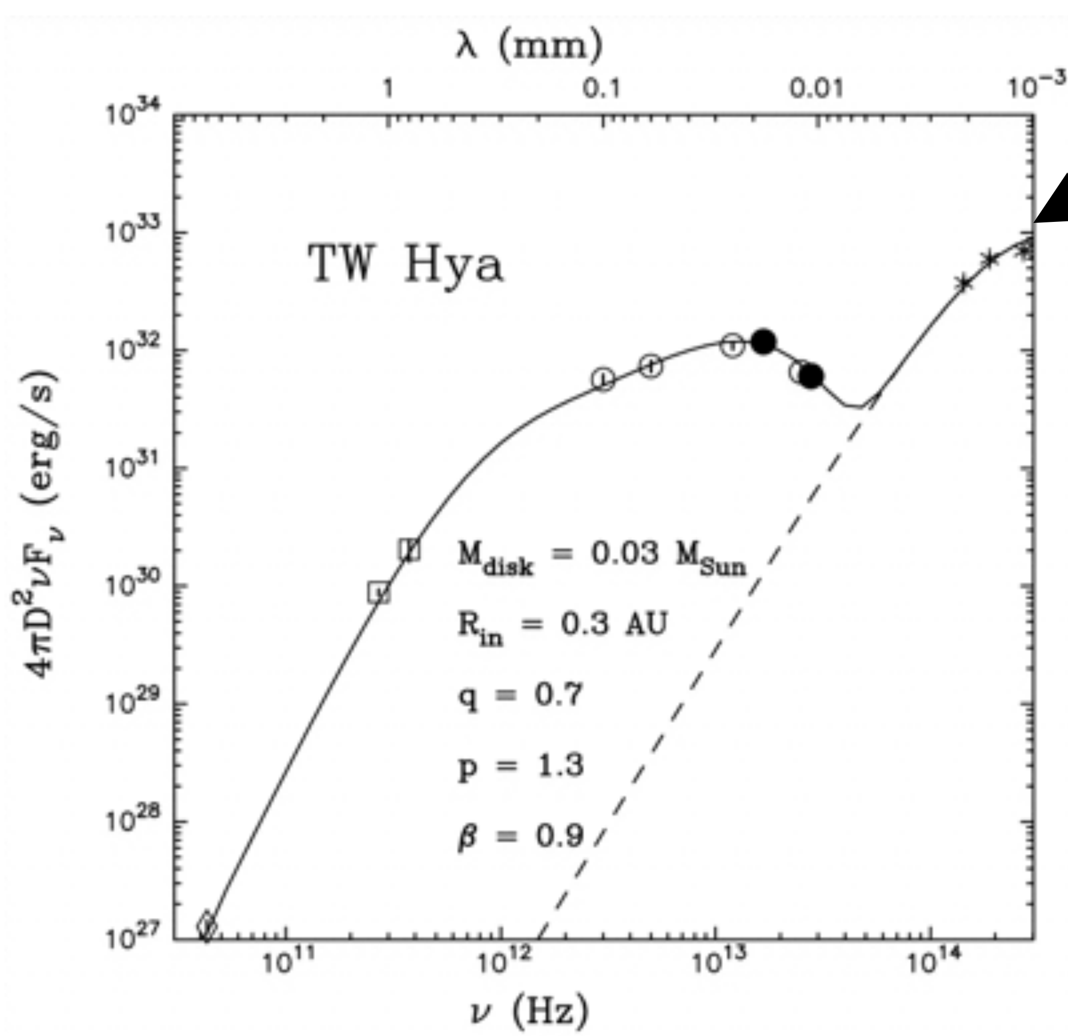

Optical: stellar photosphere

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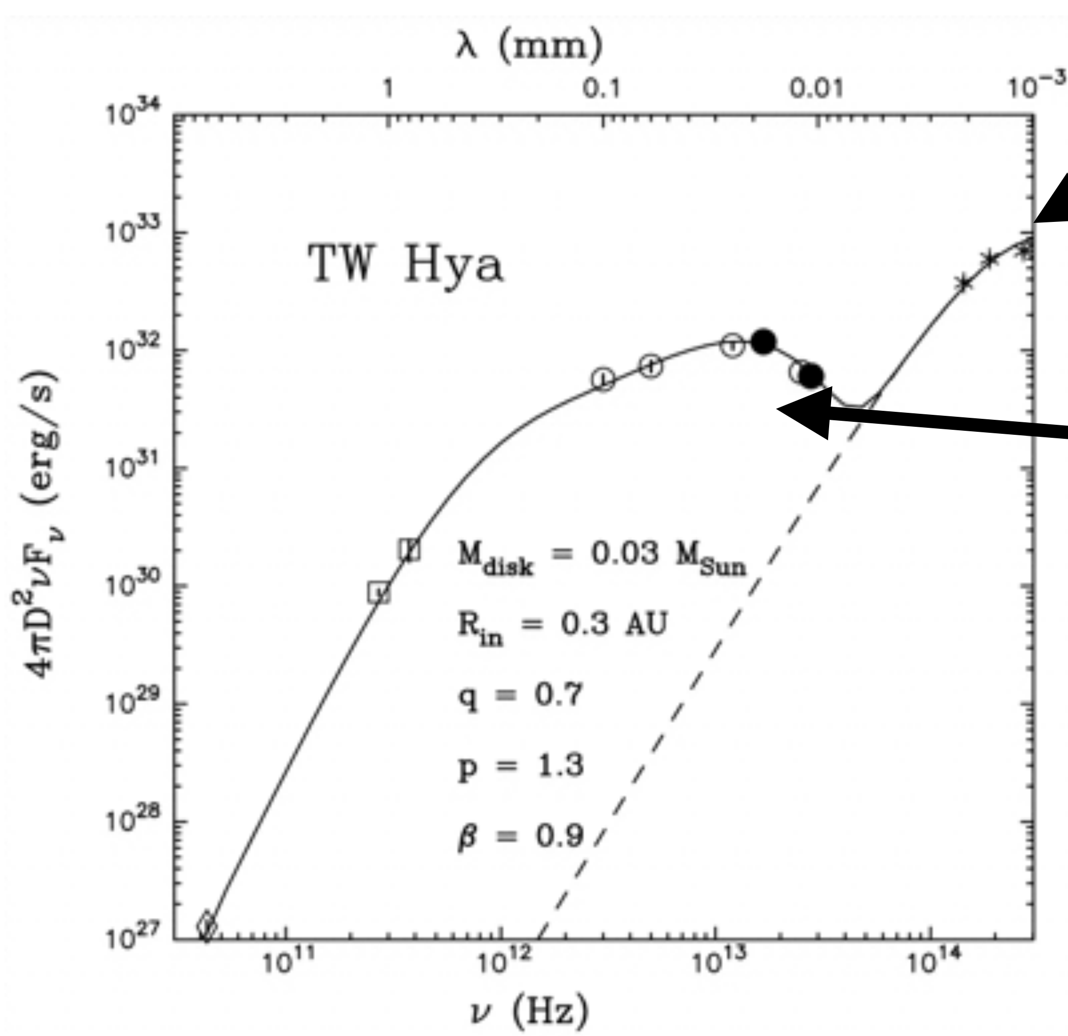

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Near-mid IR: warm, optically thick dust at ~ AU scales

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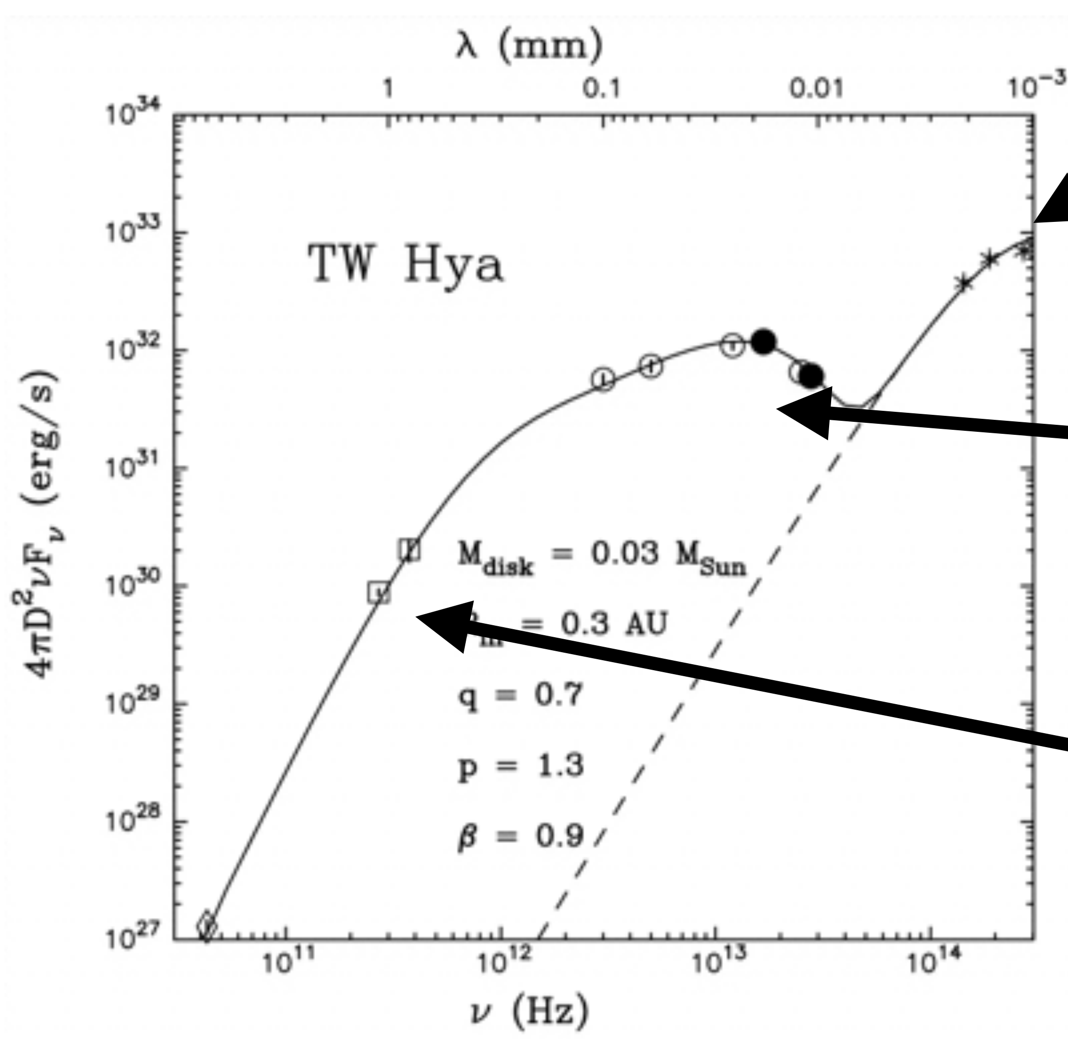

Optical: stellar photosphere

Near-mid IR: warm, optically thick dust at ~ AU scales

sub-mm: cold, optically thin mm sized dust in the outer disc

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  - H_2 molecule very hard to observe, have to rely on other less abudant tracers (CO, HCO+,…) **AND assume** abudance ratios

The revolution is happening now

- With every new instrument, emphatic statements on the revolution it will bring
- Disc imaging across the years

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TW Hya - d~50pc

2000 2016

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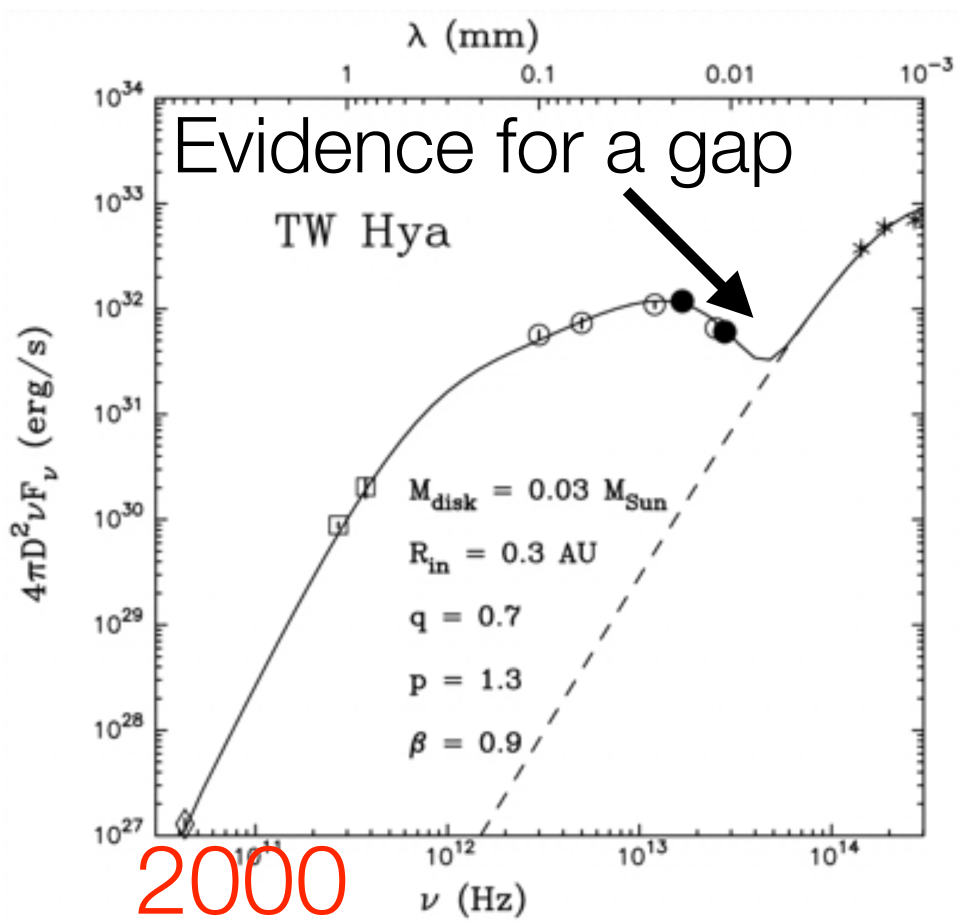

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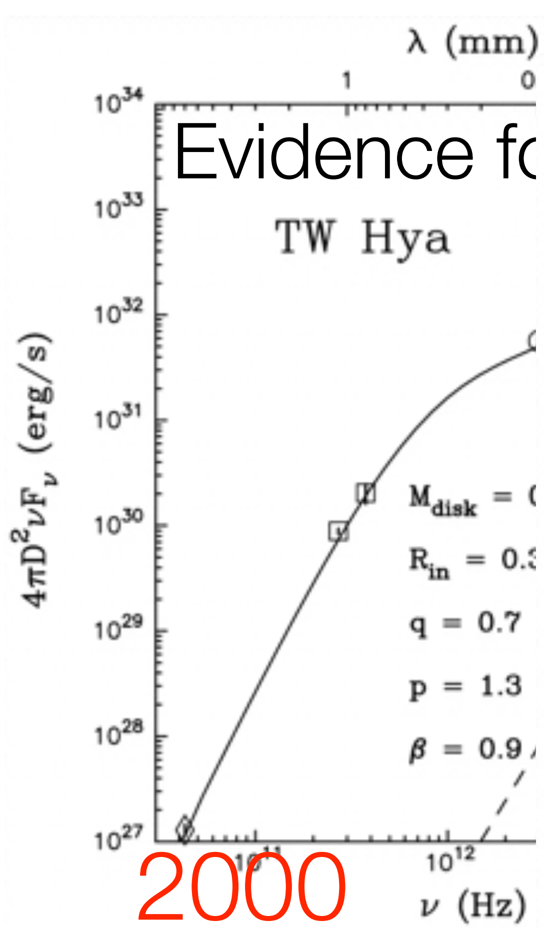

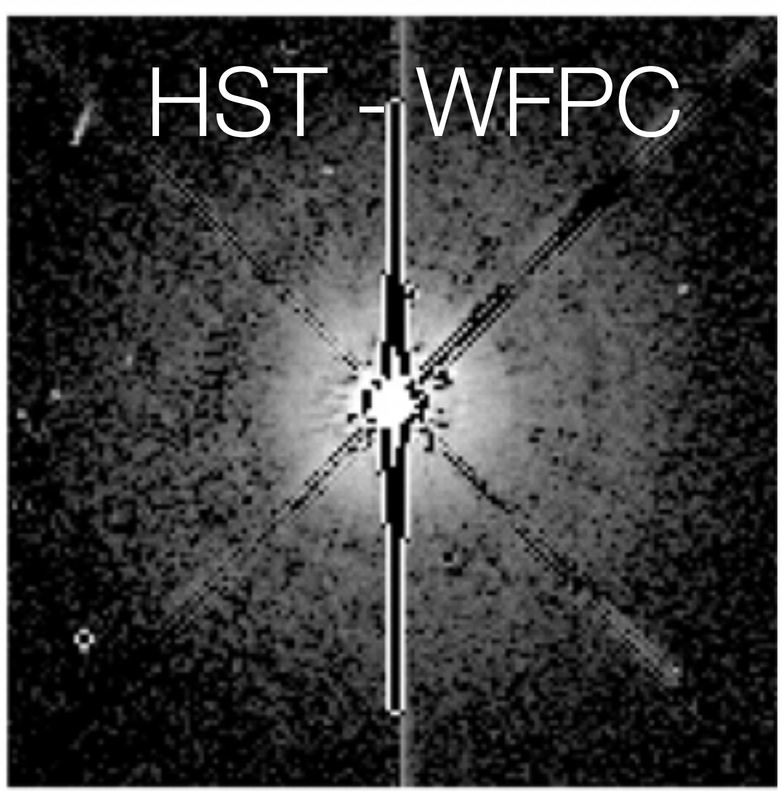

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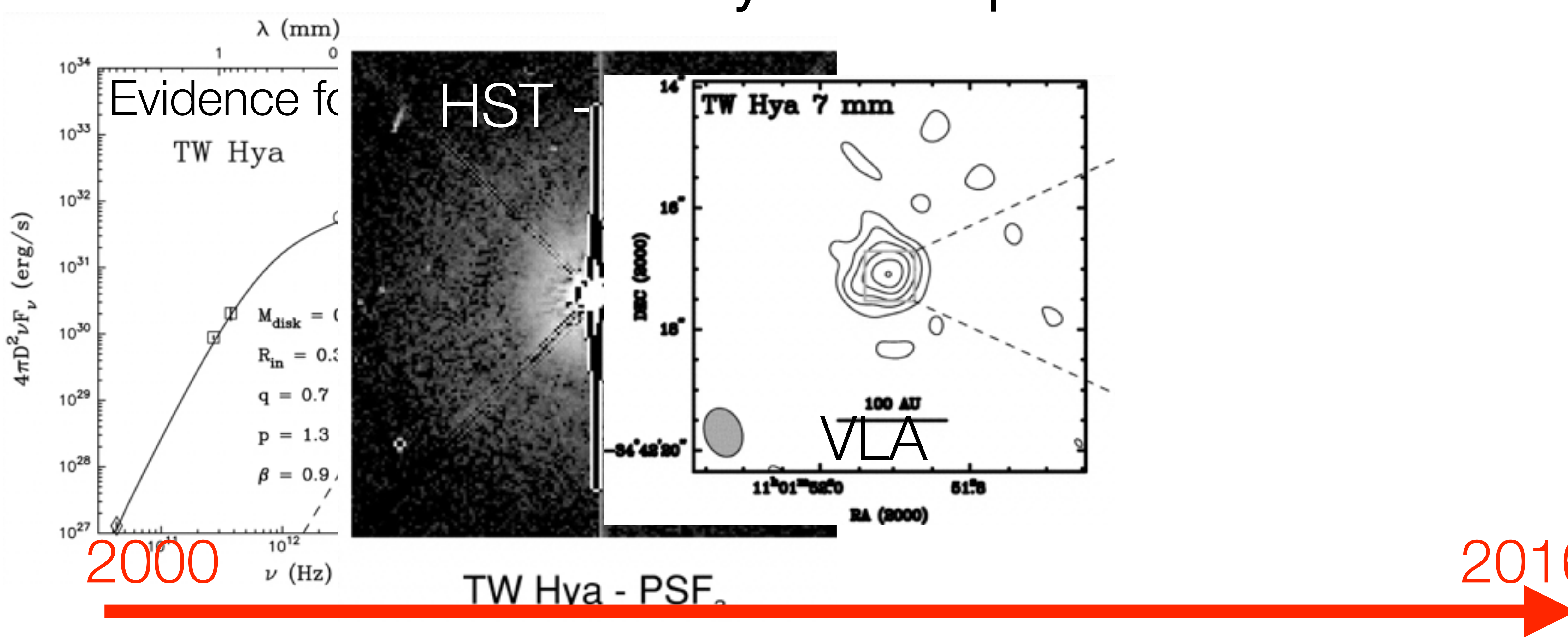

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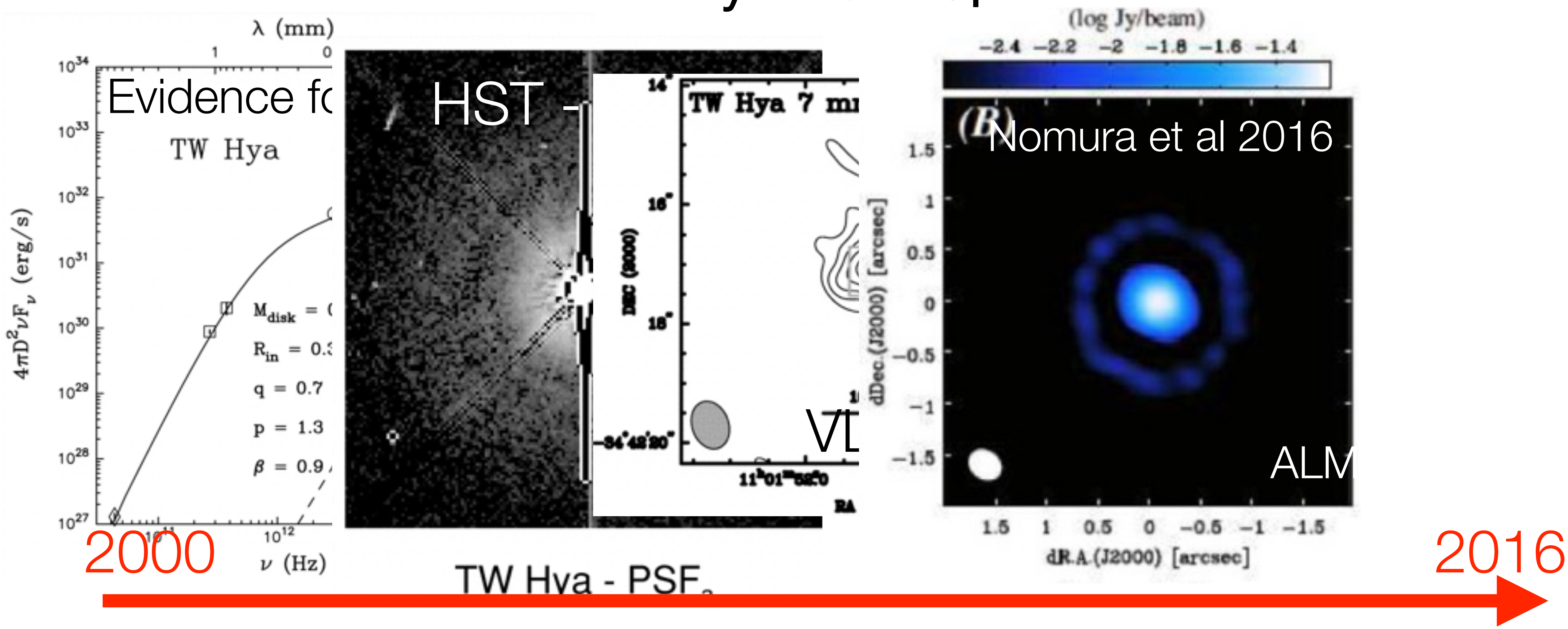

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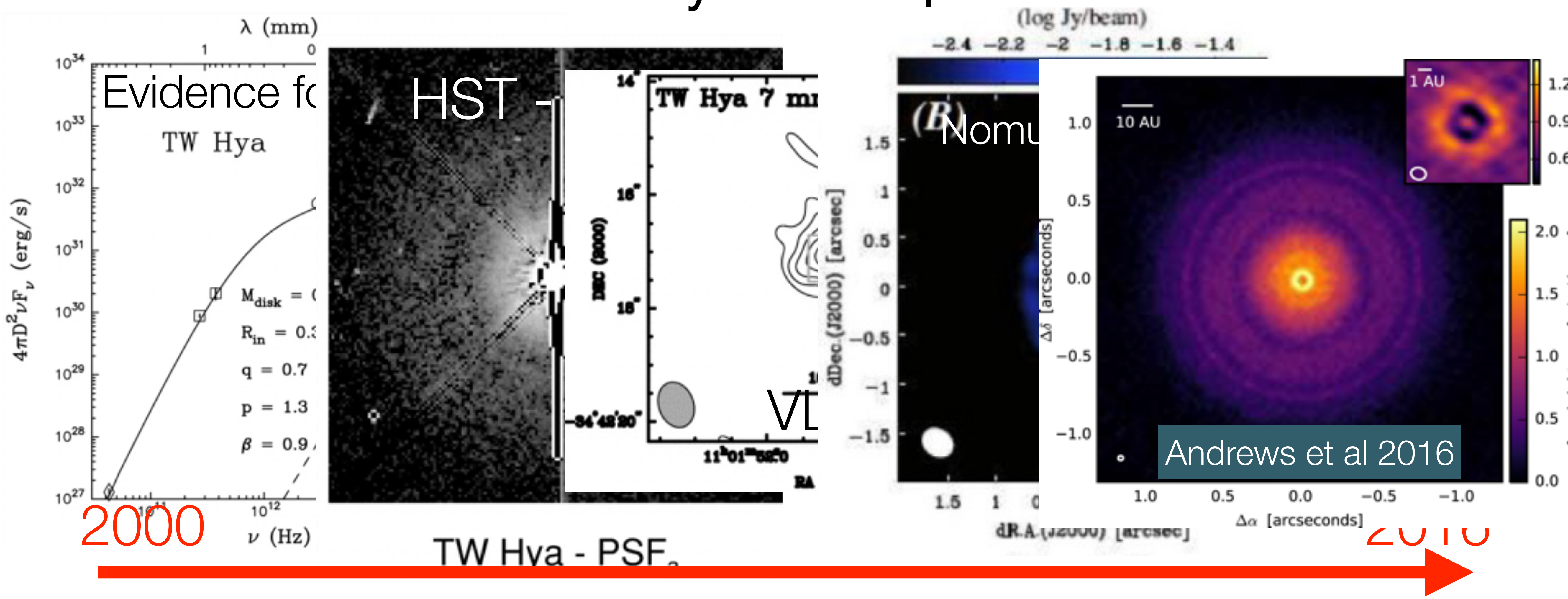

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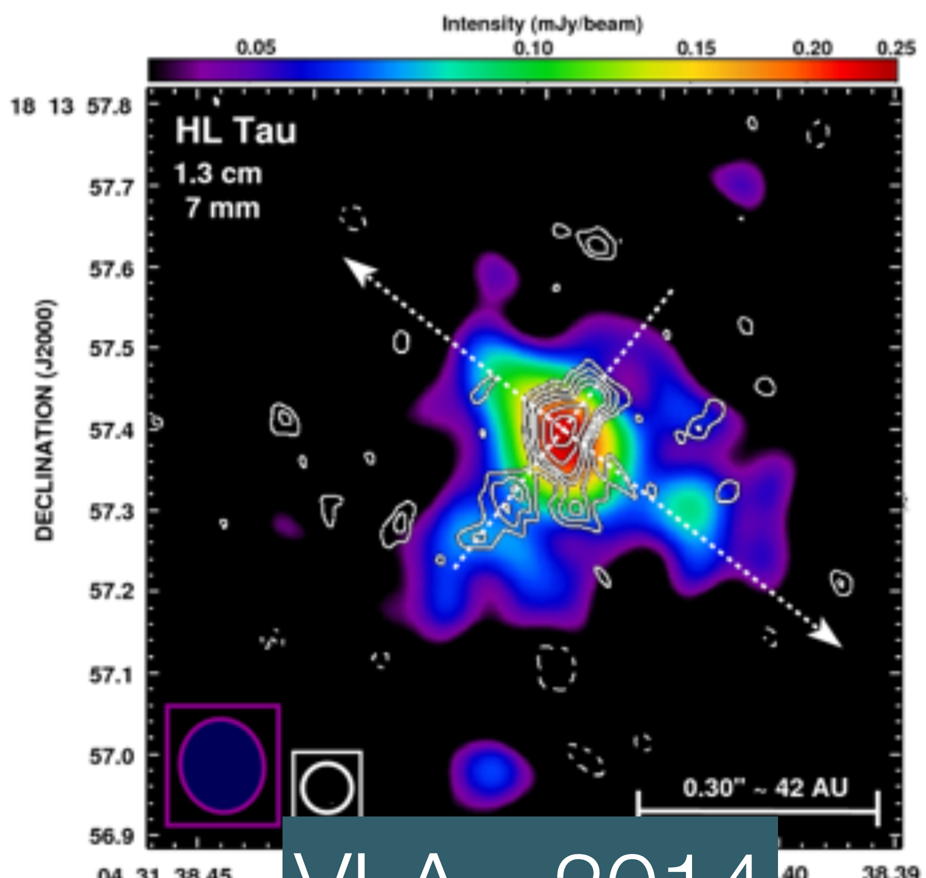

VLA - 2014

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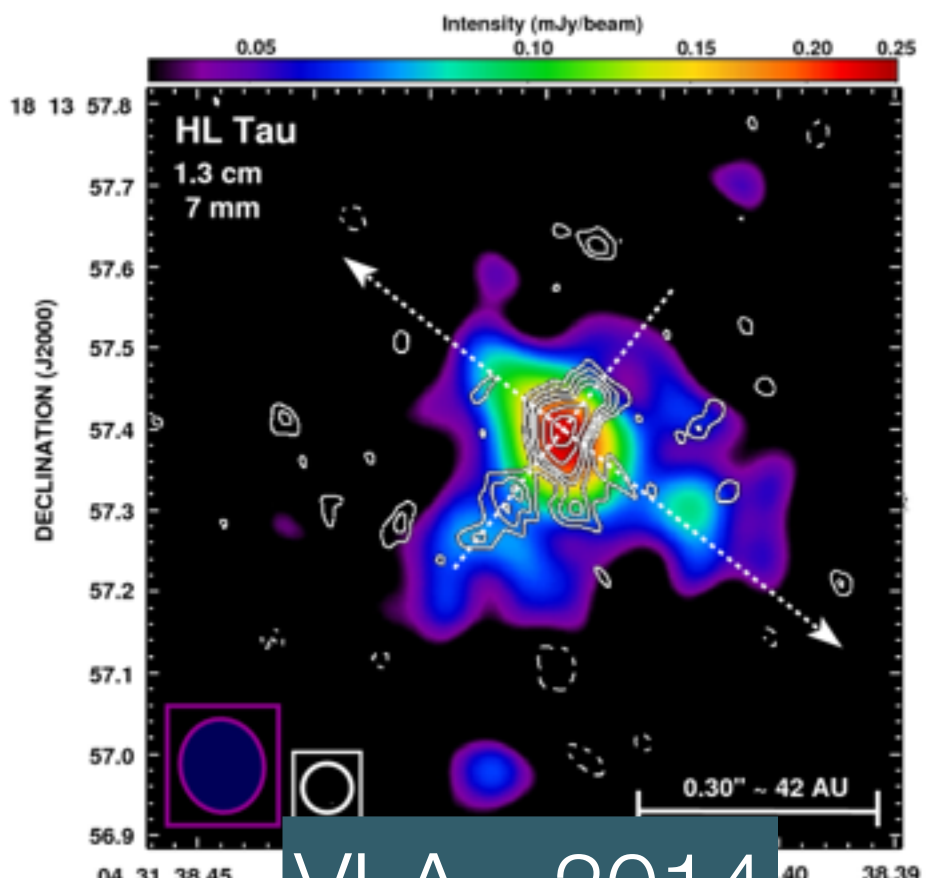

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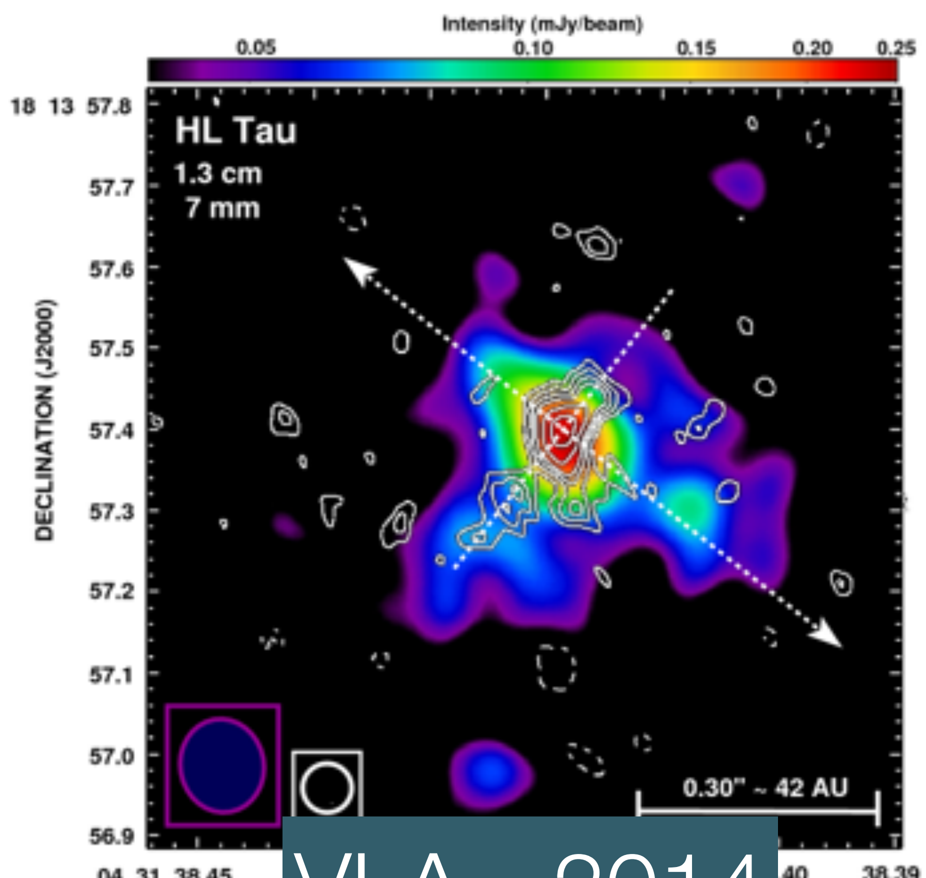

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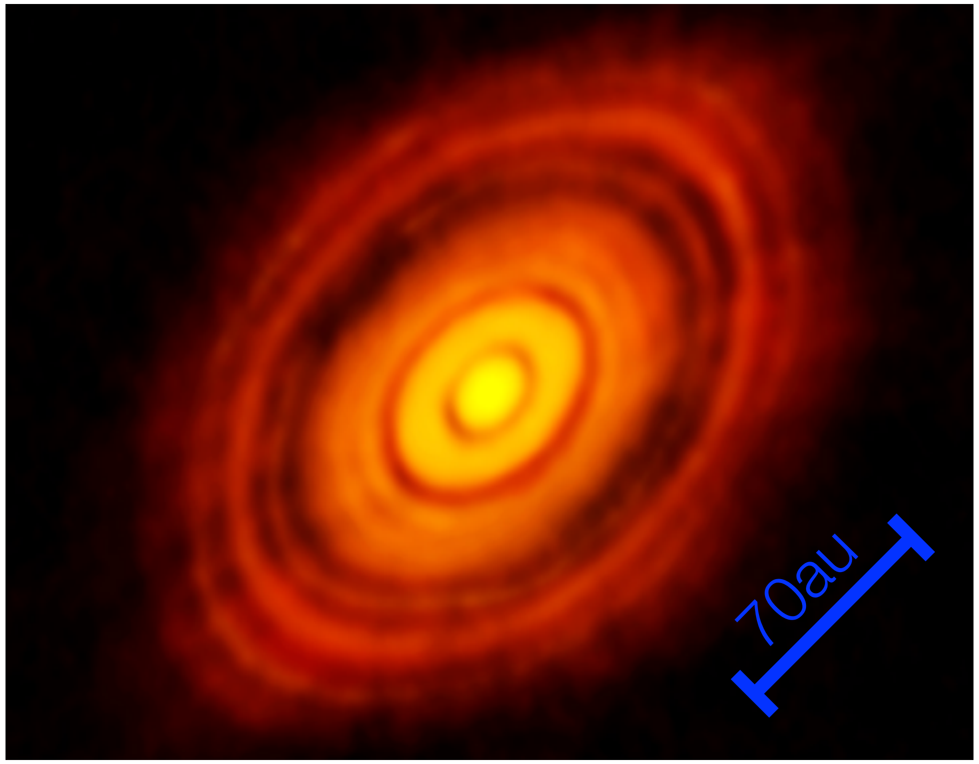

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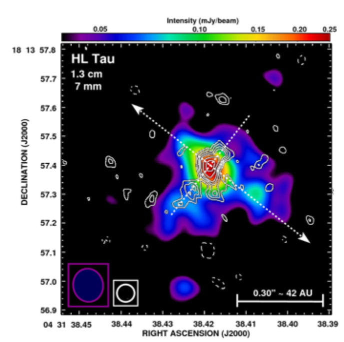

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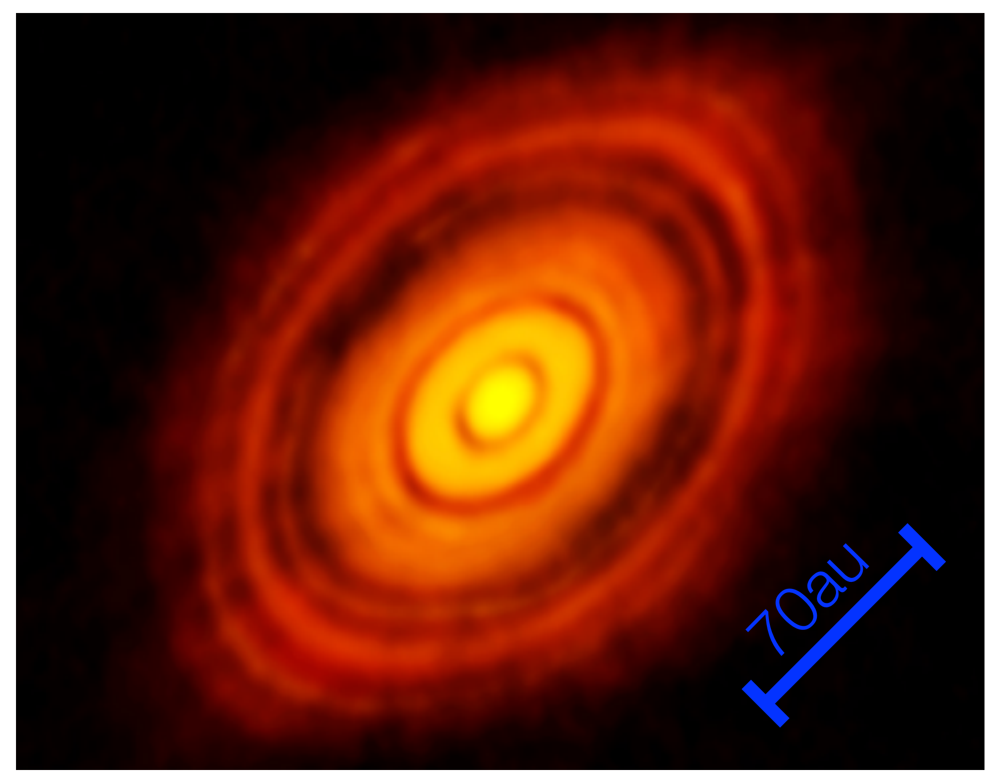

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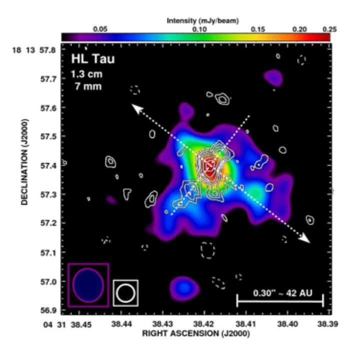

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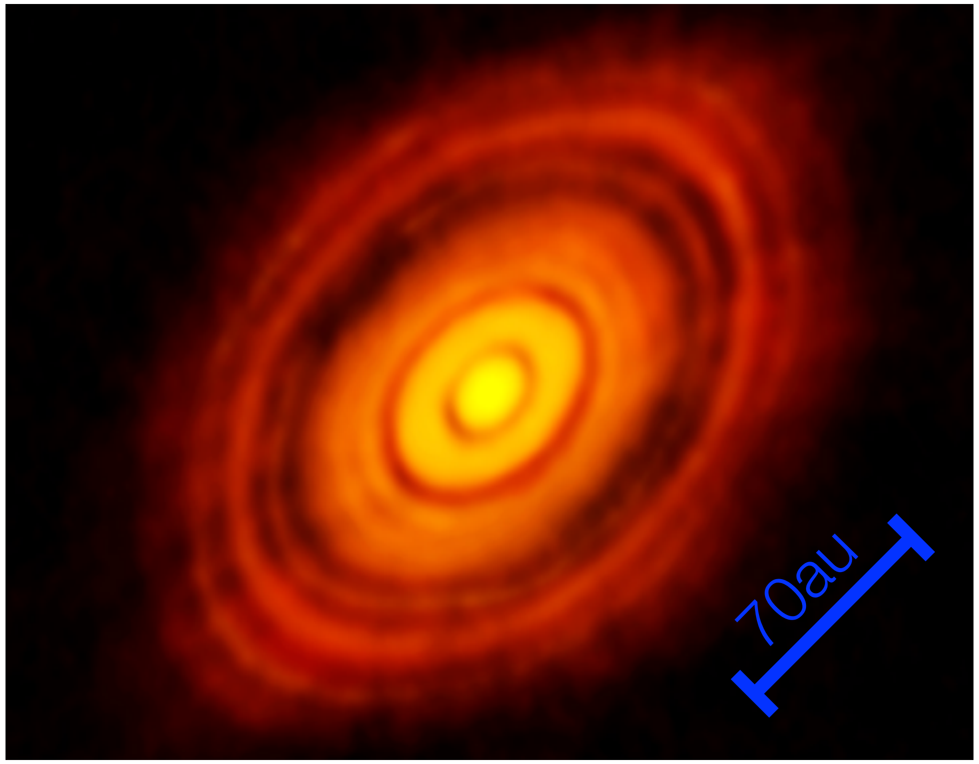

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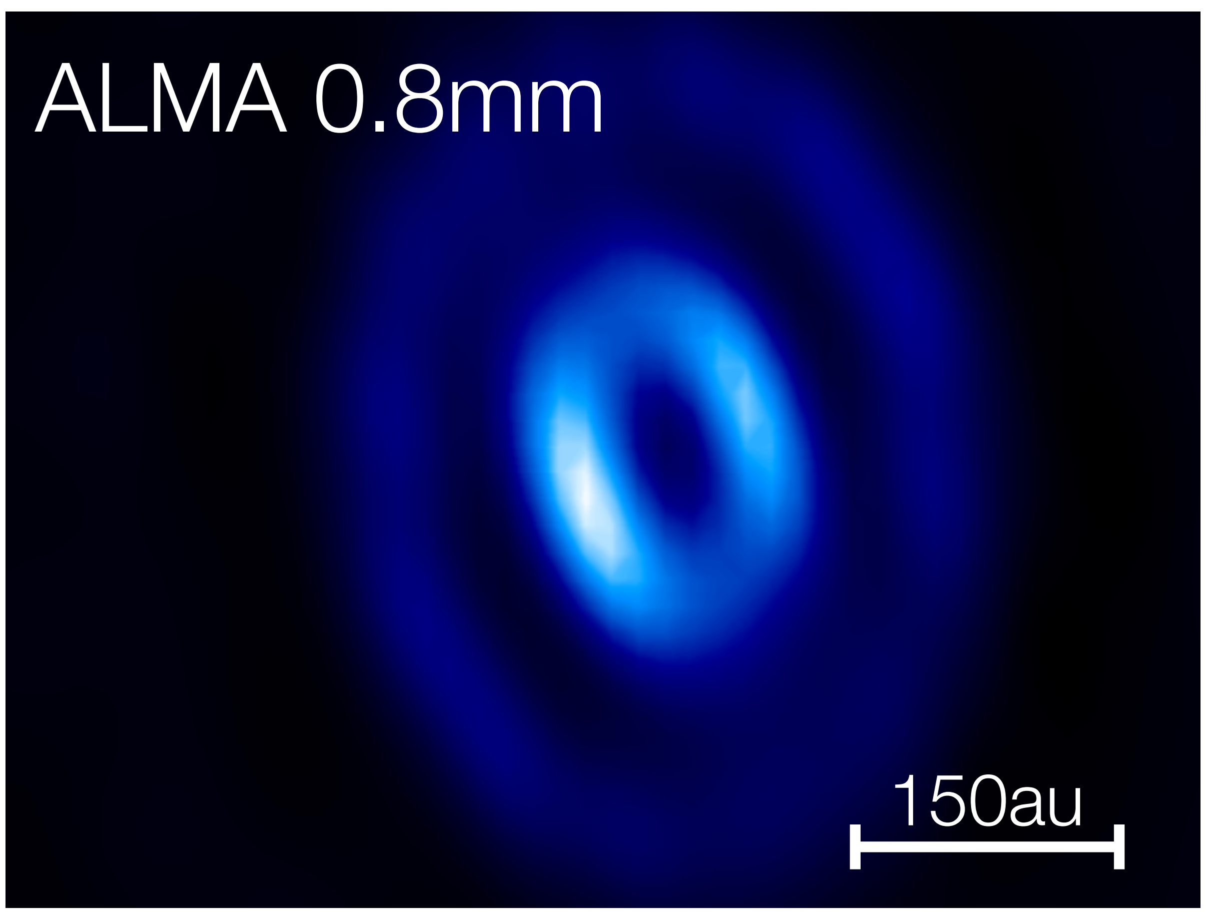
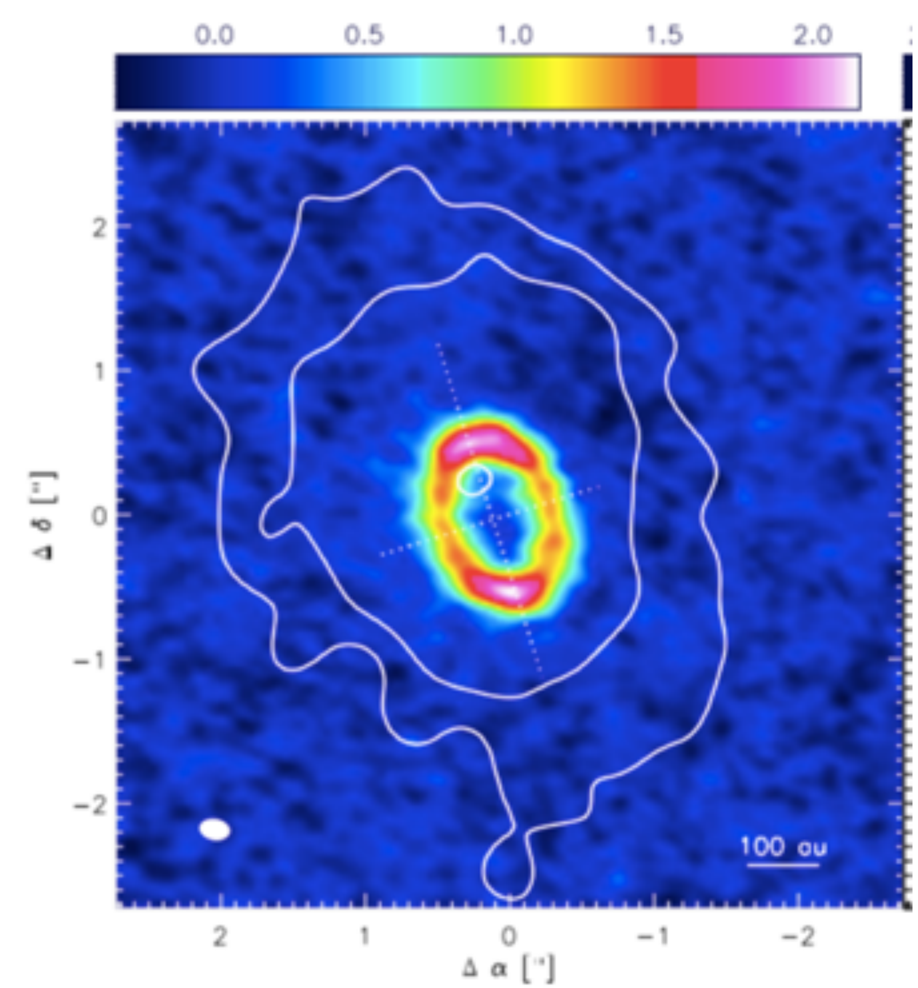
HD97048 - van der Plas in prep



Sz91 - Canovas et al 2016



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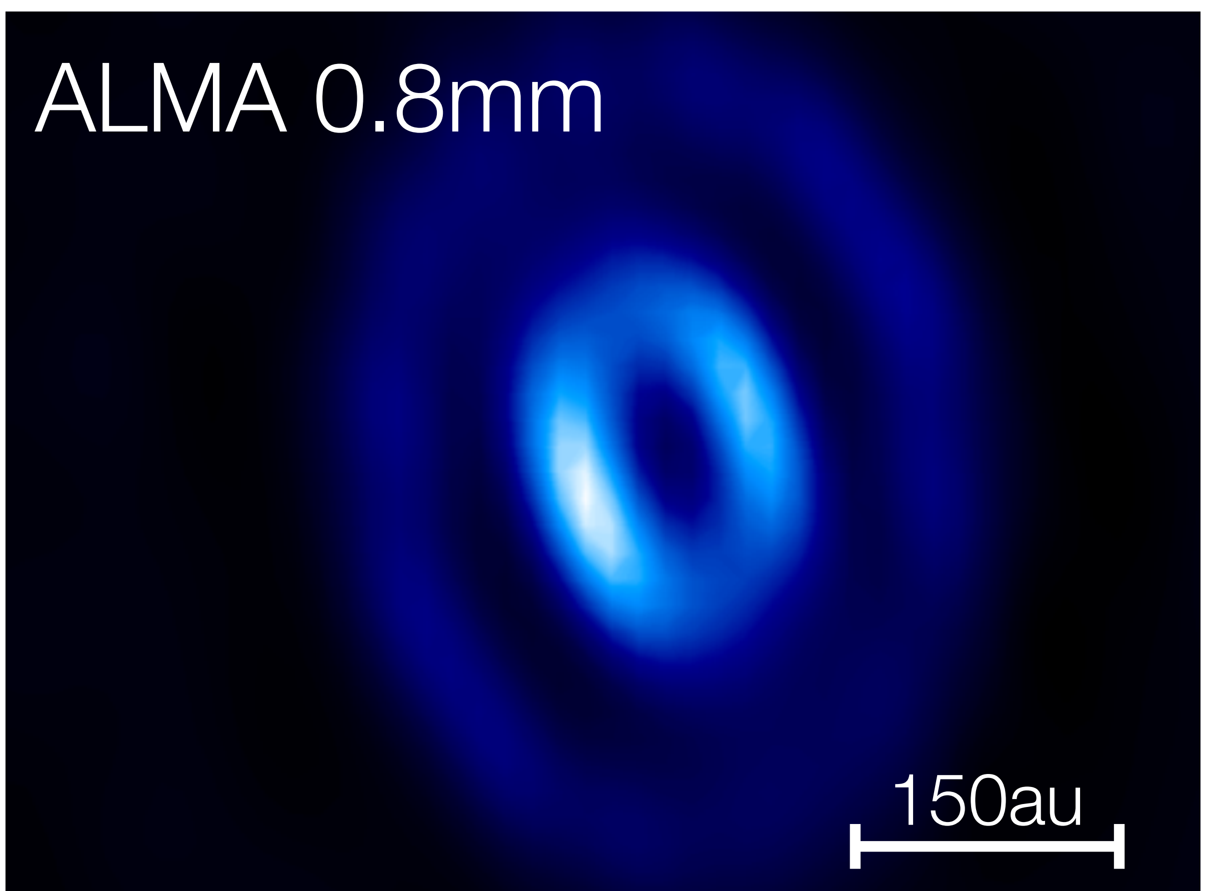

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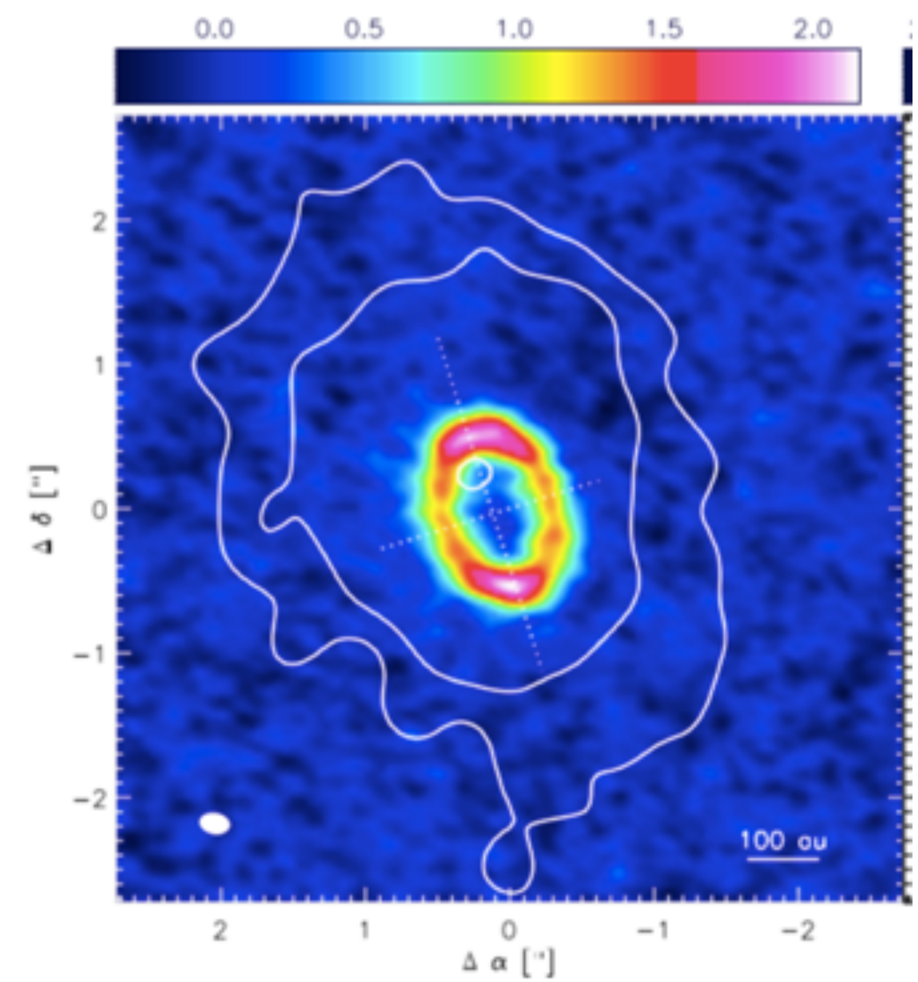

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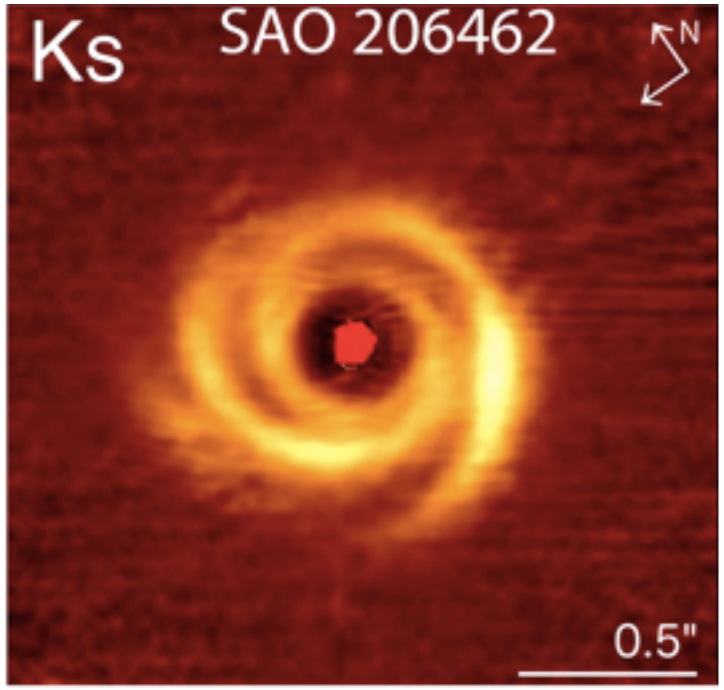
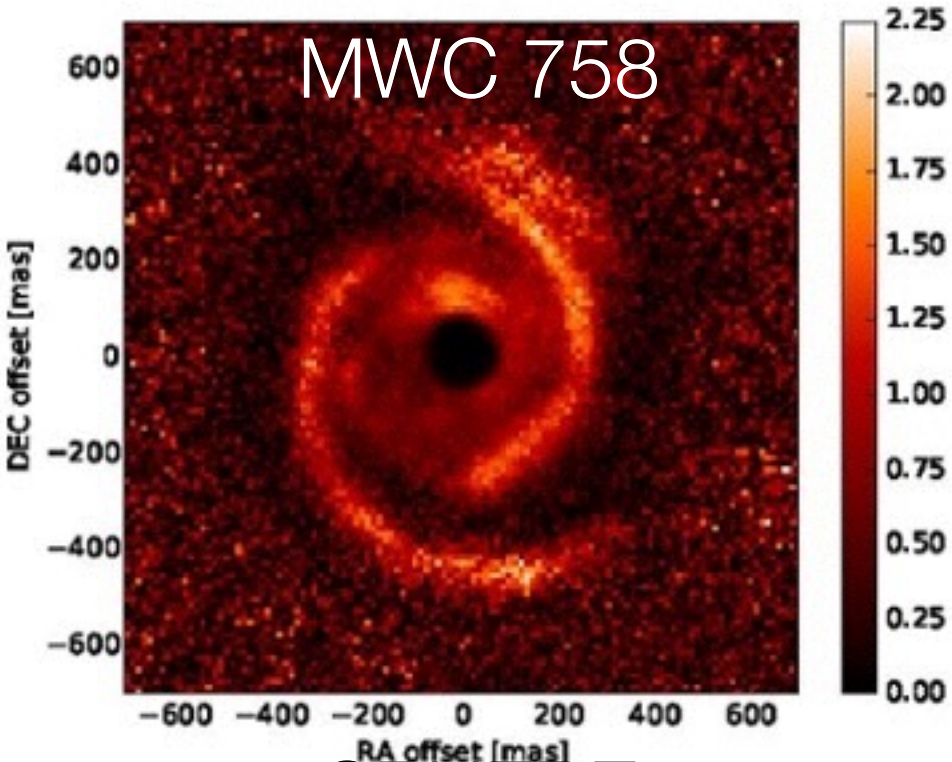
Scattered light with extreme AO (eg. SPHERE, HiCiao)

Garufi et al 2013



VLT/NACO

Benisty et al 2015



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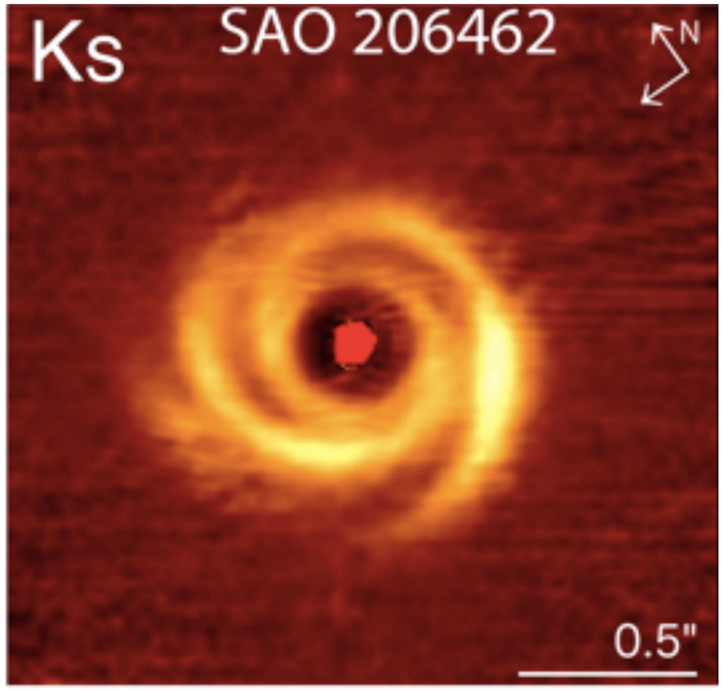

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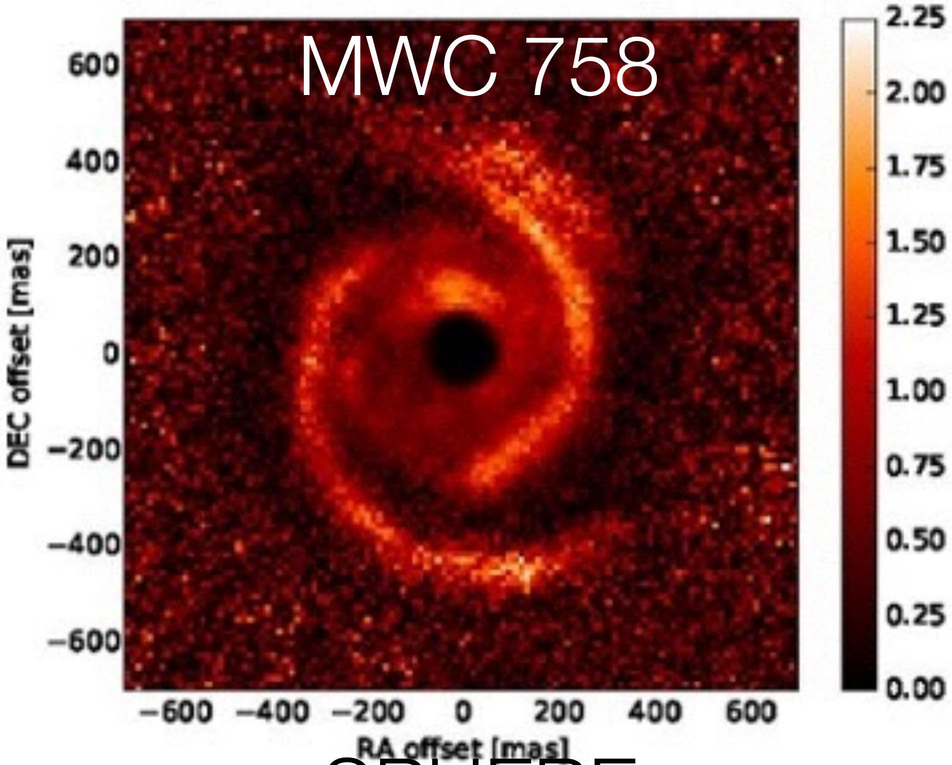

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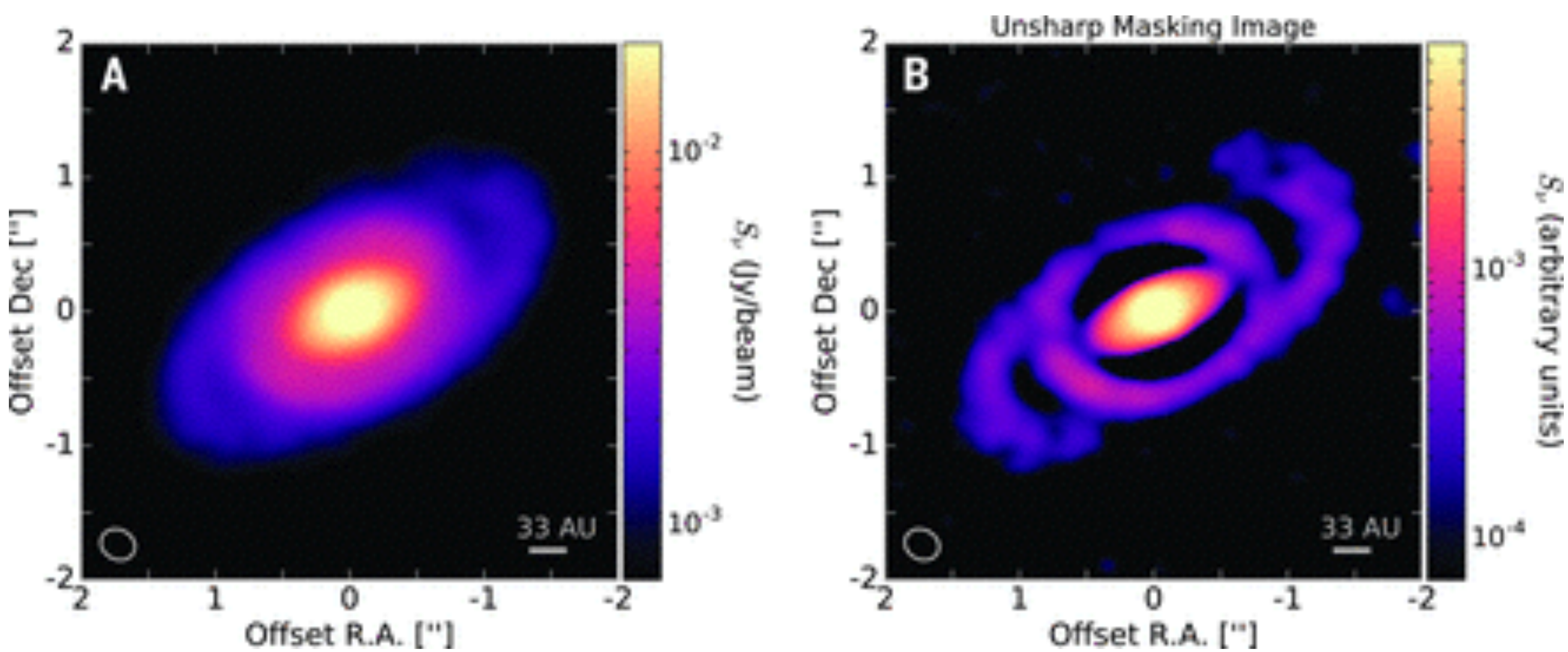
Spectacular spirals with ALMA



Perez et al 2016, Science

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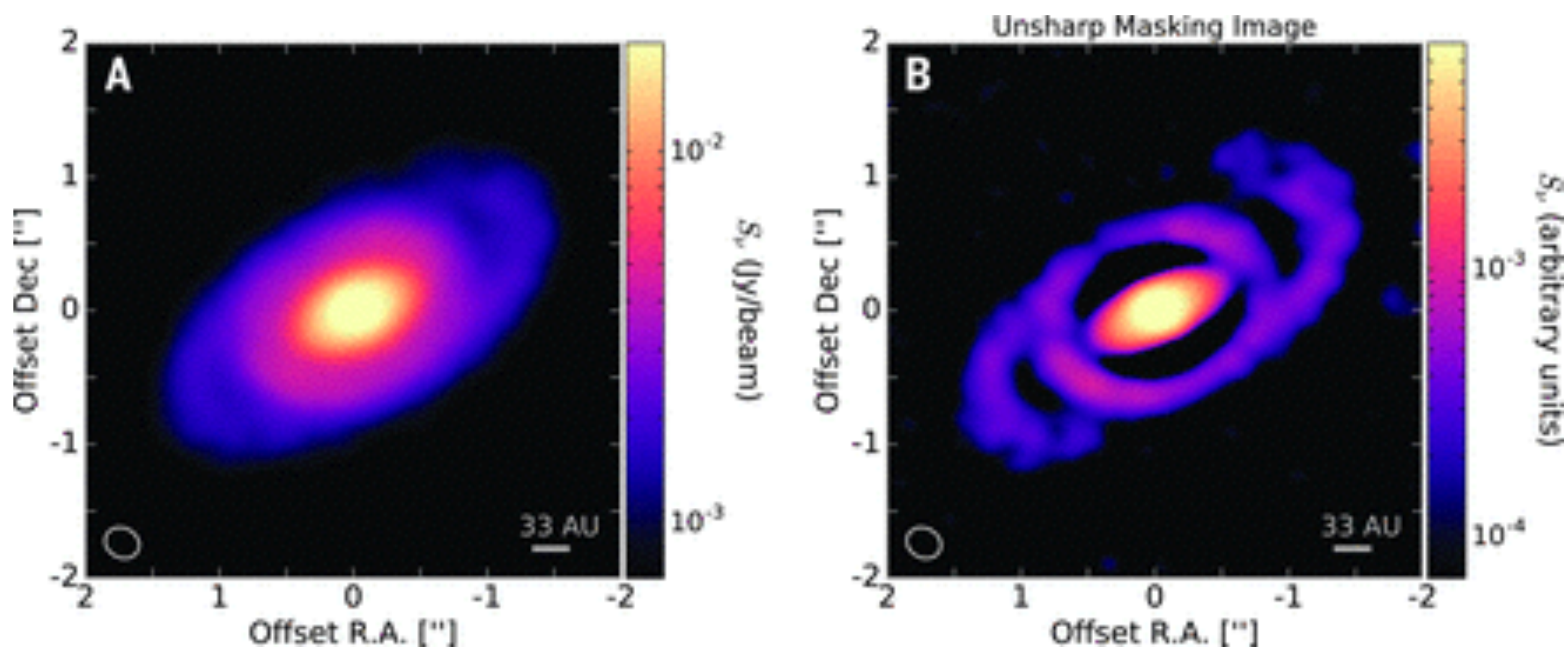

Perez et al 2016, Science

What should modelers do?

- For many years, disc models where 1D, axi-symmetric, power-law structures for density and temperature
- Going beyond such models is essential not only to explain observations, but also to understand dynamics
- Two component modeling (gas/dust) is crucial (CRUCIAL!)

What do we (in Milano) do?

- We start from a hydrodynamical SPH simulation with
  - Two components: **gas and dust** coupled though drag
  - Several point masses: **star(s), planets**
  - **Self-gravity** (of both gas and dust)

PHANTOM code
Price et al 2017?

- We use a Monte-Carlo ray tracing code to get dust temperatures from irradiation
- We compute synthetic images either in scattered light or in dust continuum assuming a given instrumental response (ALMA, HiCIAO, SPHERE, etc…)
- What we do NOT do (yet):
  - Chemistry: chemical network needed to get molecular species and produce gas intensity maps
  - Radiative transfer: to have temperature self-consistently during hydro simulation

Dust/gas dynamics

- Dust dynamics depends on dust size
- Drag force (Stokes or Epstein drag) couples gas and dust motion

$$St = t_{\rm stop}\Omega \propto a$$

- Gas motion: slightly sub-Keplerian azimuthally (due to pressure gradients), small radial velocity due to viscosity (accretion)

$$v_{{\rm g},\phi} = \sqrt{1 + \frac{{\rm d}\log\Sigma}{{\rm d}\log R}\left(\frac{H}{R}\right)^2} v_{\rm K} \approx v_{\rm K} + \Delta v$$

$$v_{{\rm g},R} = \alpha(H/R)^2 v_{\rm K}$$

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- Dust radial drift

$$v_{{\rm d},R} = \frac{\Delta v}{St + St^{-1}} + \frac{v_{{\rm g},R}}{1 + St^2}$$

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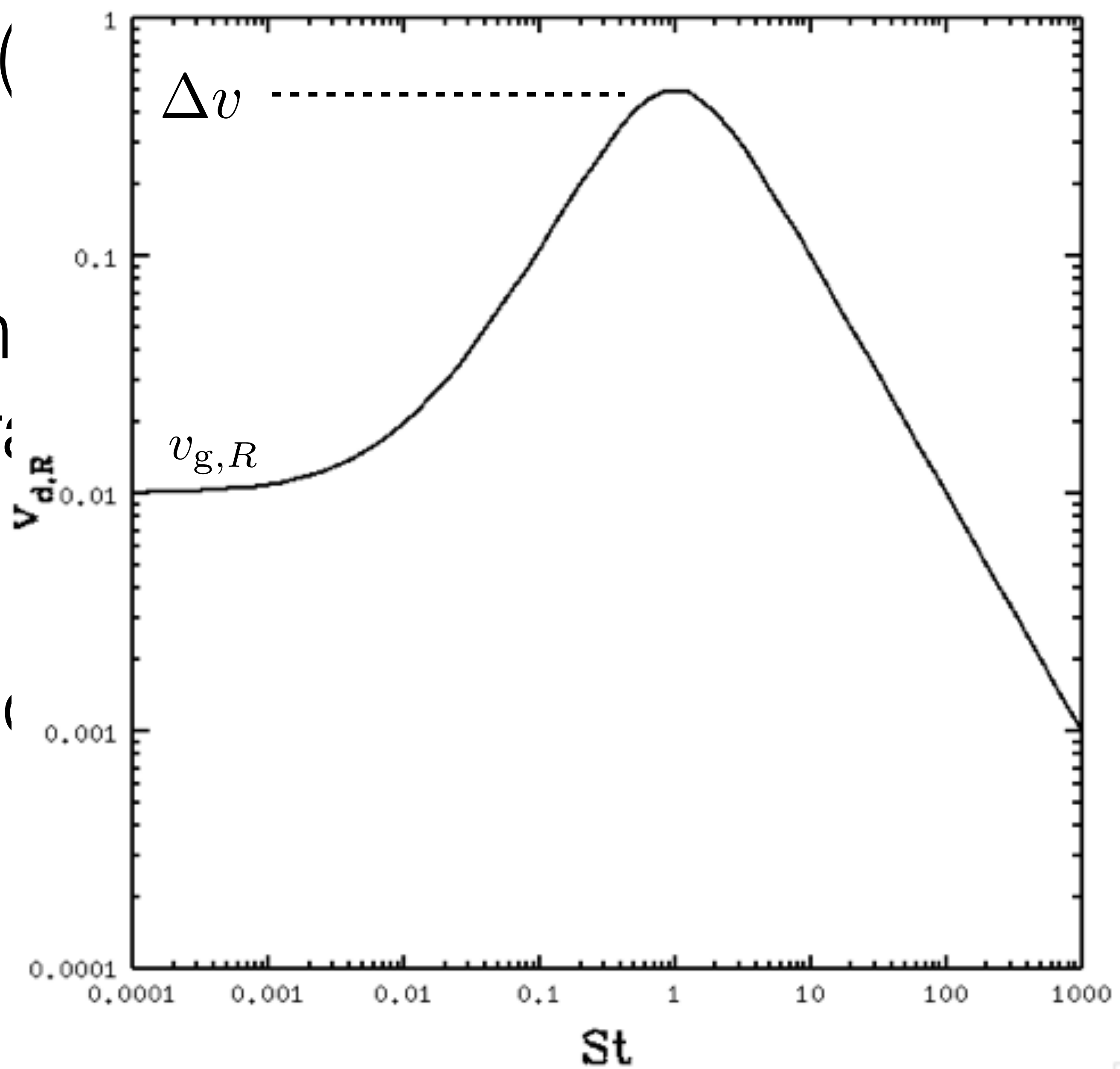
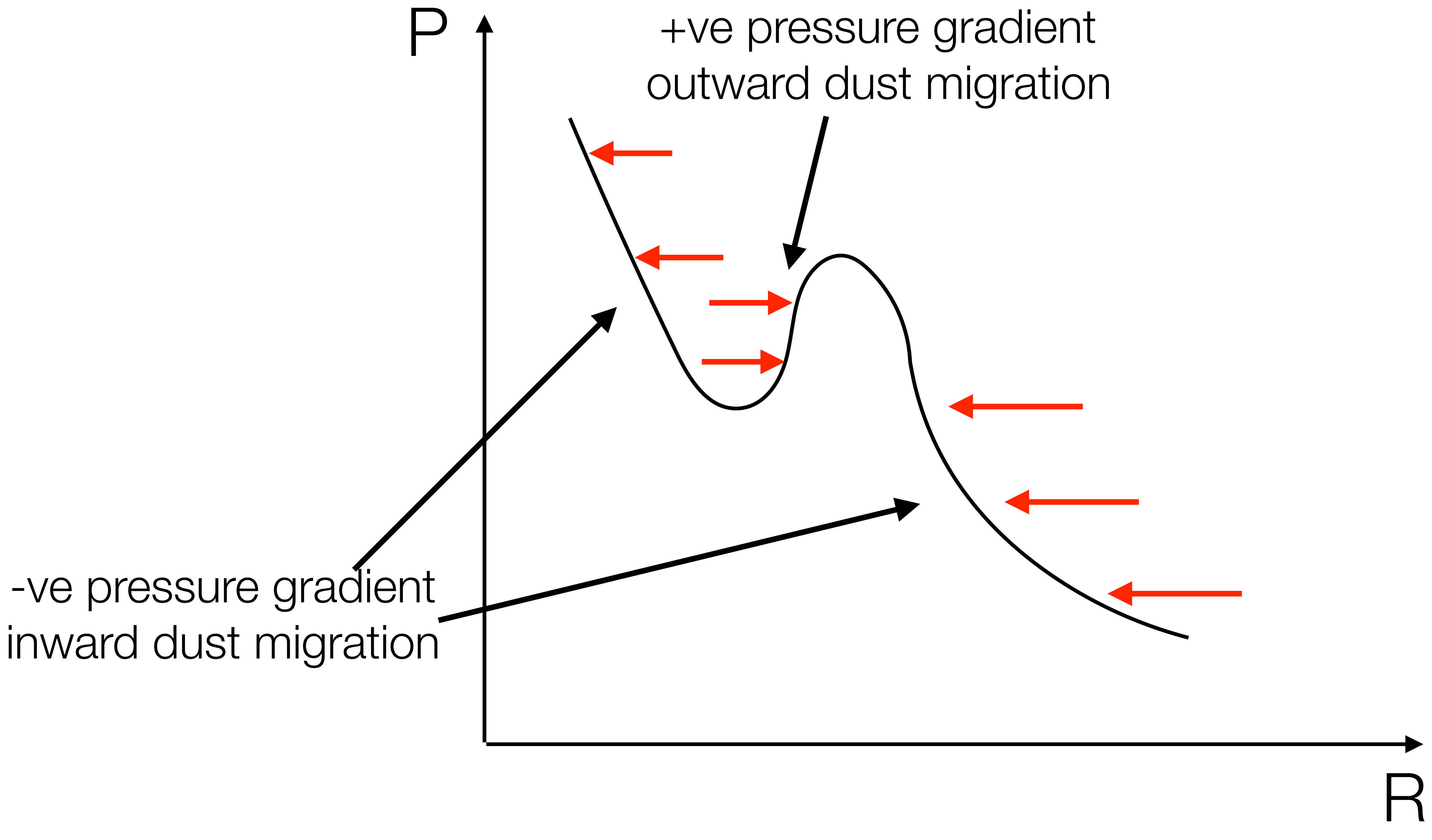


Dust traps

- Dust with *St~1* is trapped at gas pressure maxima



1st Course: Spirals

- Spirals can be induced by
    - Self-gravity
    - Planets
- In both cases they are density waves
- A little advertisment: Kratter & Lodato, ARA&A, 2016 (ArXiv: 1603.01280)

Gravitational Instabilities in Circumstellar Disks

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Keywords

star and planet formation, accretion disks, hydrodynamics

Abstract

Star and planet formation are the complex outcomes of gravitational collapse and angular momentum transport mediated by protostellar and protoplanetary disks. In this review we focus on the role of gravitational instability in this process. We begin with a brief overview of the observational evidence for massive disks that might be subject to gravitational instability, and then highlight the diverse ways in which the instability manifests itself in protostellar and protoplanetary disks: the generation of spiral arms, small scale turbulence-like density fluctuations, and fragmentation of the disk itself. We present the analytic theory that describes the linear growth phase of the instability, supplemented with a survey of numerical simulations that aim to capture the non-linear evolution. We emphasize the role of thermodynamics and large scale infall in controlling the outcome of the instability. Despite apparent controversies in the literature, we show a remarkable level of agreement between analytic predictions and numerical results. In the next part of our review, we focus on the astrophysical consequences of the instability. We show that the disks most likely to be gravitationally unstable are young and relatively massive compared to their host star,

Linear stability criterion

- Linear dispersion relation

$$(\omega - m\Omega)^2 = c_{\rm s}^2 k^2 - 2\pi G \Sigma |k| + \kappa^2$$

Lin & Shu (1964)

- Well known axisymmetric instability criterion:

$$Q = \frac{c_{\rm s}\kappa}{\pi G \Sigma} < \bar{Q} \approx 1$$

- Equivalent form of the instability criterion

$$\frac{M_{\rm disc}(R)}{M_\star} \gtrsim \frac{H}{R}$$

- Need the disc to be cold and/or massive

- What are the masses and aspect ratio in actual protostellar discs?

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Are protostellar discs linearly unstable?

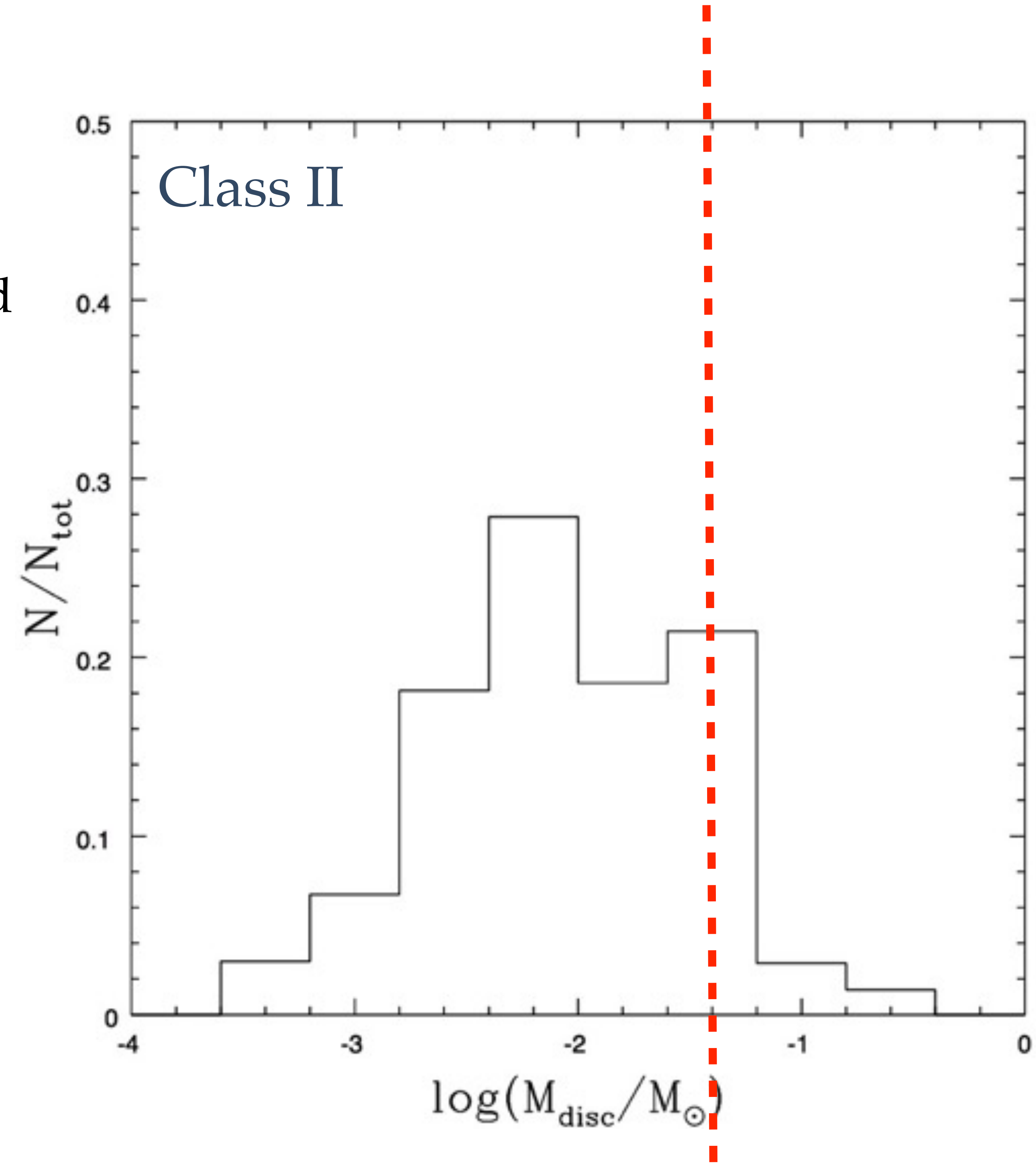
- Midplane temperature for irradiated discs (Chiang & Goldreich 1997, Chiang & Youdin 2009) gives:

$$\frac{H}{R} \simeq 0.02 \left(\frac{R}{\mathrm{AU}} \right)^{2/7}$$

- Therefore *H/R* varies from **0.02** at 1AU to **0.06** at 100 AU
- Need disc masses of order 5% of the stellar mass to be unstable
- Protostellar disc masses difficult to measure (see Hartmann et al 2006)

Are protostellar discs linearly unstable?

- Disc masses in Taurus and Ophiucus by Andrews and Williams (2005, 2007)
- Disc masses might be underestimated significantly (Hartmann et al 2006)
- Uncertainties in dust opacities
- If density profile steep, most of the mass might be hidden in optically thick inner parts (Hartmann 2009)



Are protostellar discs linearly unstable?

- Class II (T Tauri) discs are relatively evolved. Can we infer the masses at early stages?
- Simple (simplistic?) approach:
- Take all objects with measured M and Mdot
- Apply similarity solutions (Lynden-Bell & Pringle 1973)
- Find “initial’ disc mass and evolutionary timescale

$$M_0 = M_{\rm d}(t)\left(\frac{t_{\rm d}}{t_{\rm d}-t}\right)^{1/2(2-\gamma)}$$

$$t_{\rm d} = \frac{M_{\rm d}(t)}{2(2-\gamma)\dot{M}(t)}$$

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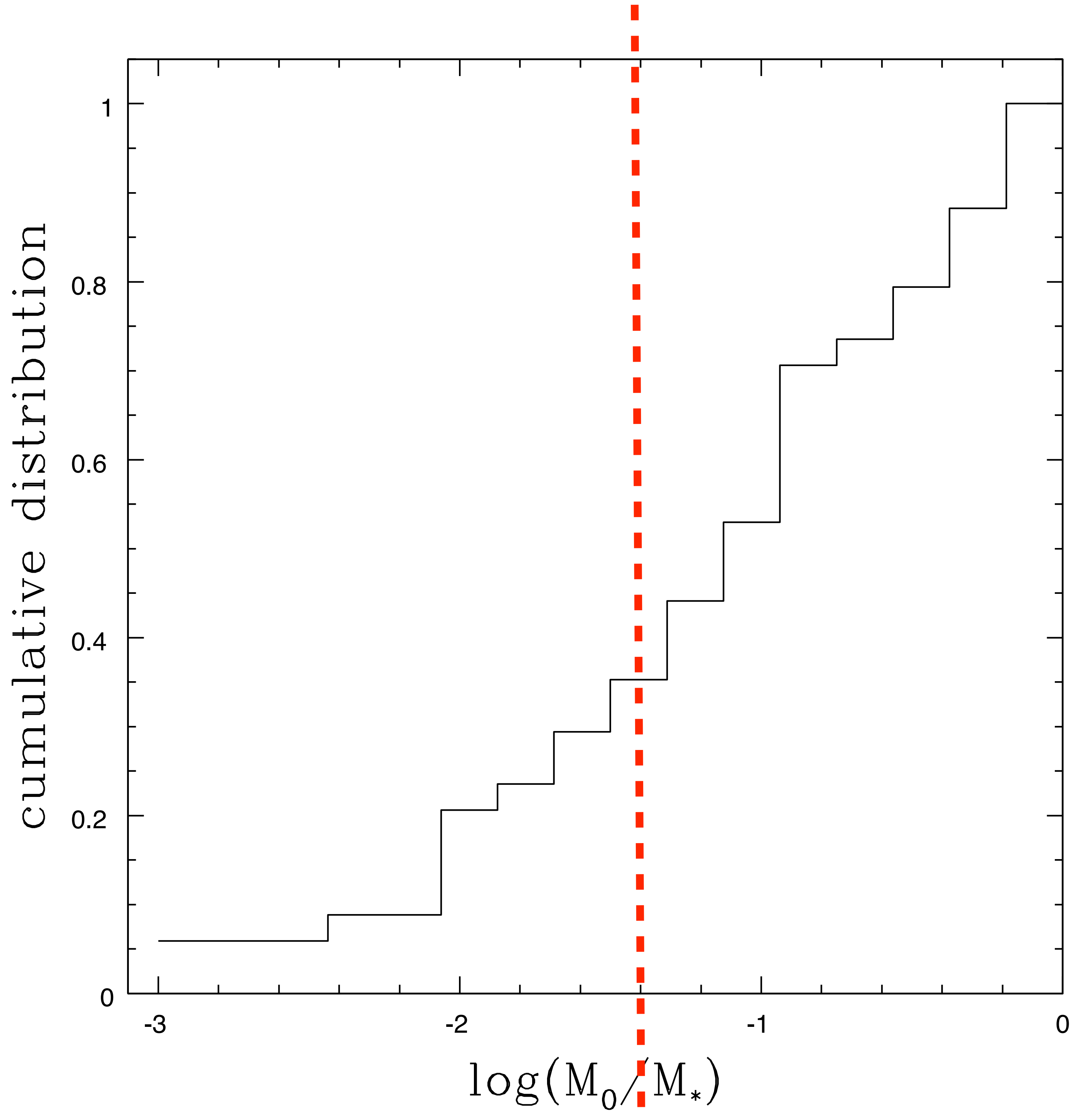
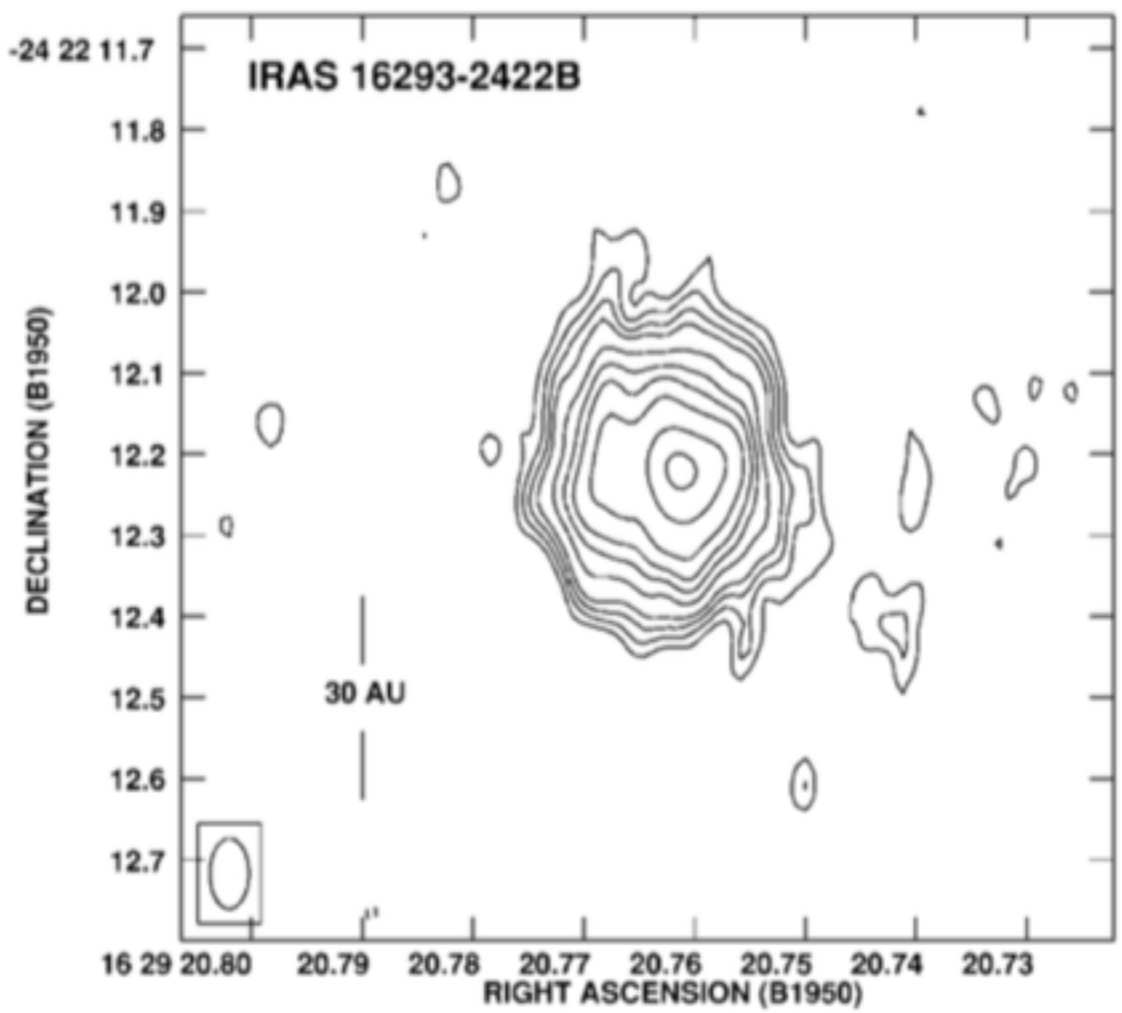
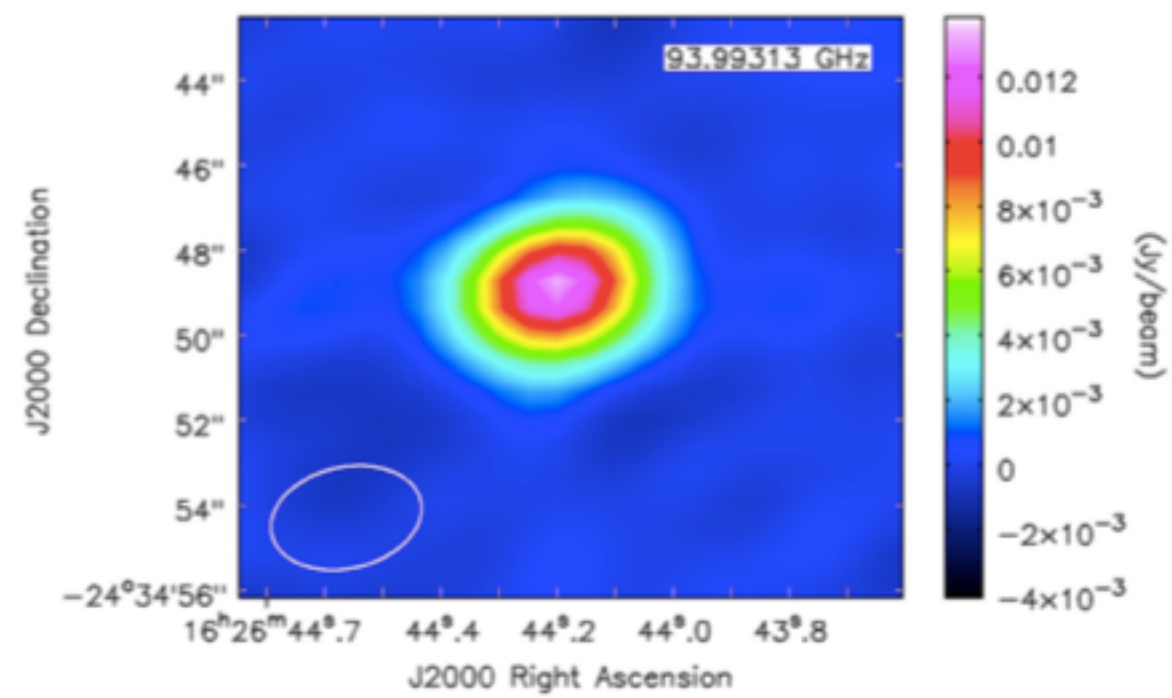


A couple of interesting examples

- Class 0/I objects



Rodriguez et al (2005)
R_{out} ~ 26 au
M_* ~ 0.8M_{sun} - M_{disc} ~ 0.4M_{sun}

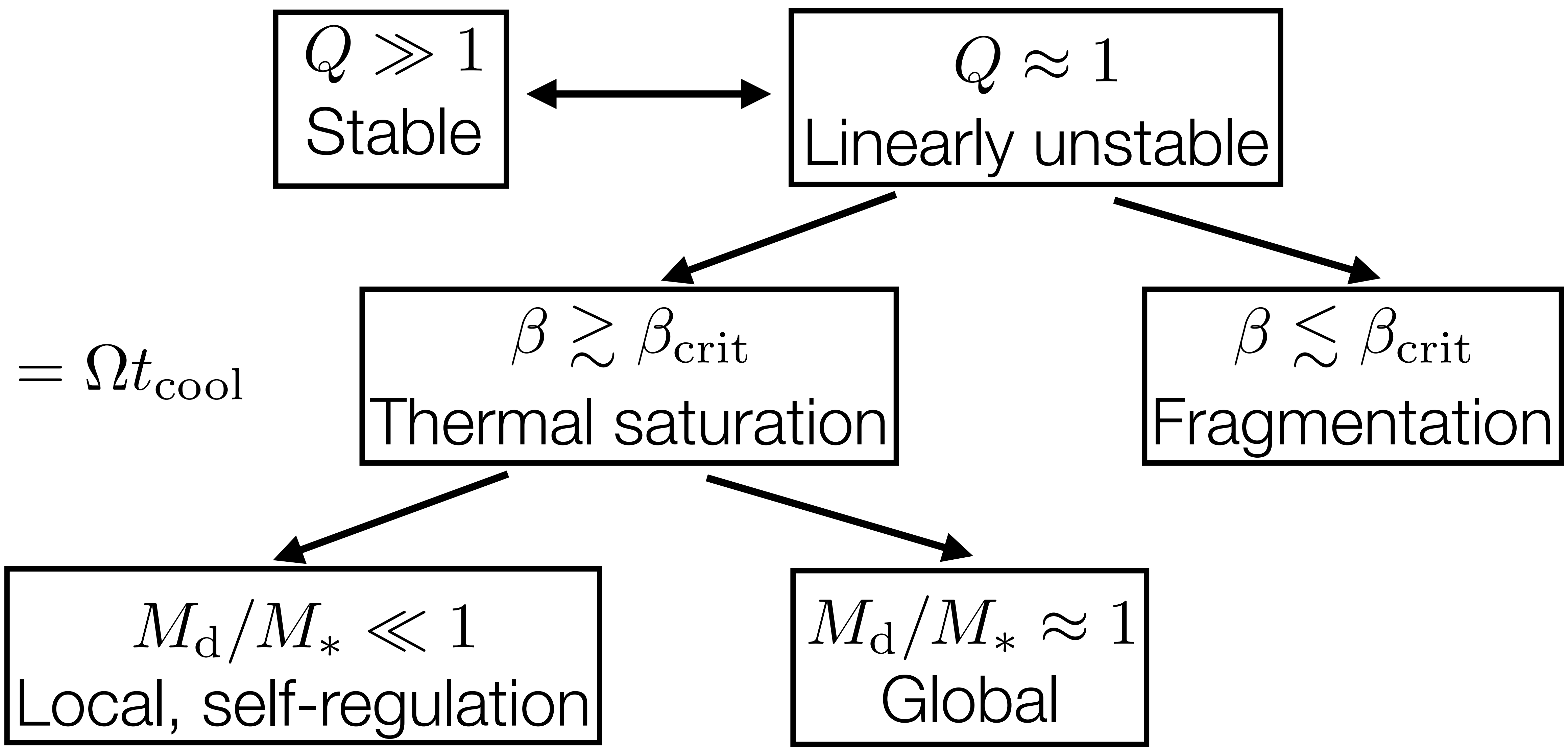


Miotello et al (2014)
R_{out} ~ 30 au
M_* ~ 0.6M_{sun} - M_{disc} ~ 0.3M_{sun}

The “standard” picture of self-gravitating disc dynamics: thermal saturation

- Start from a disc characterized by (Σ, T, R)
- Compute three dimensionless parameters $(Q, \beta, M_\mathrm{d}/M_*)$

$\beta = \Omega t_\mathrm{cool}$



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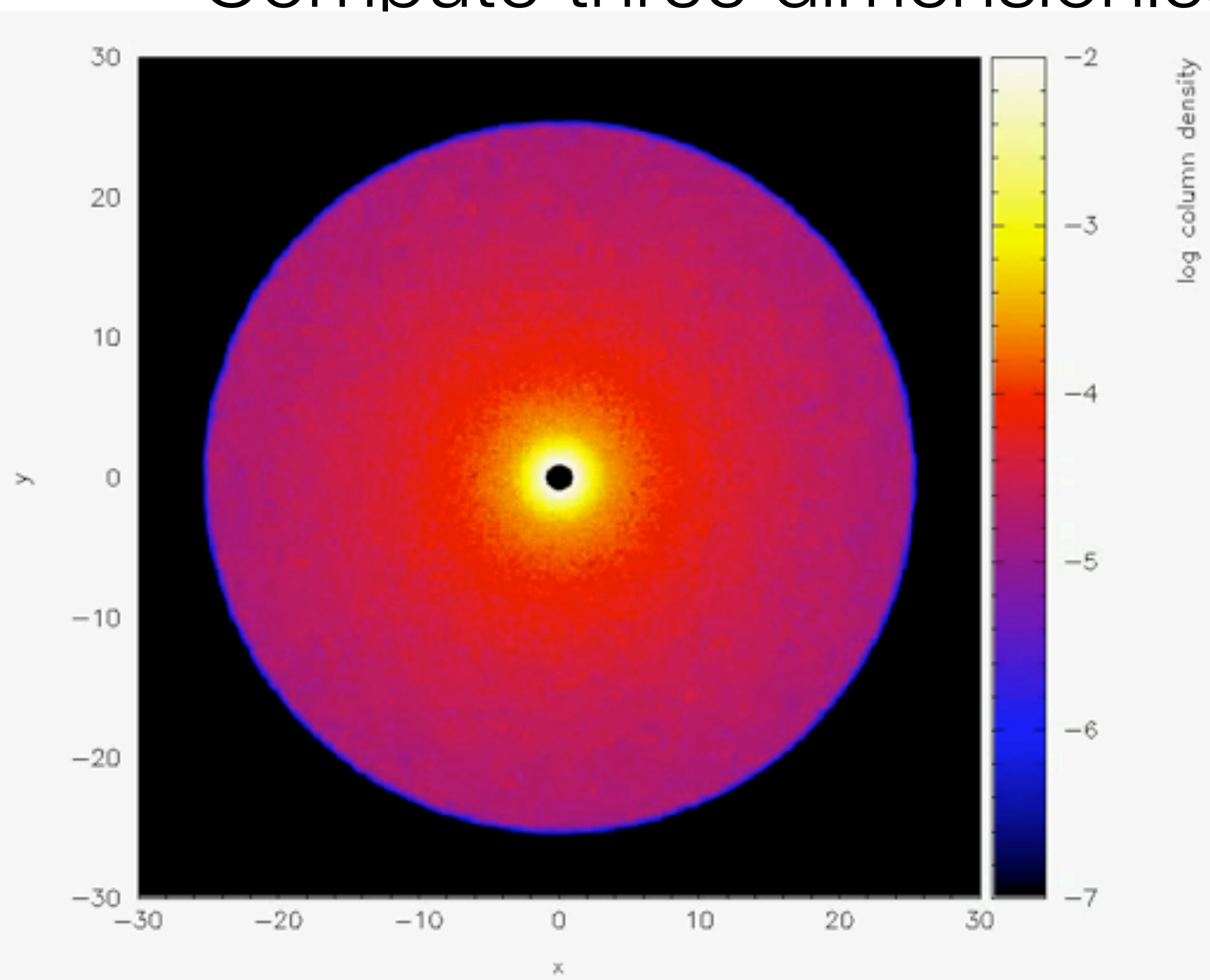

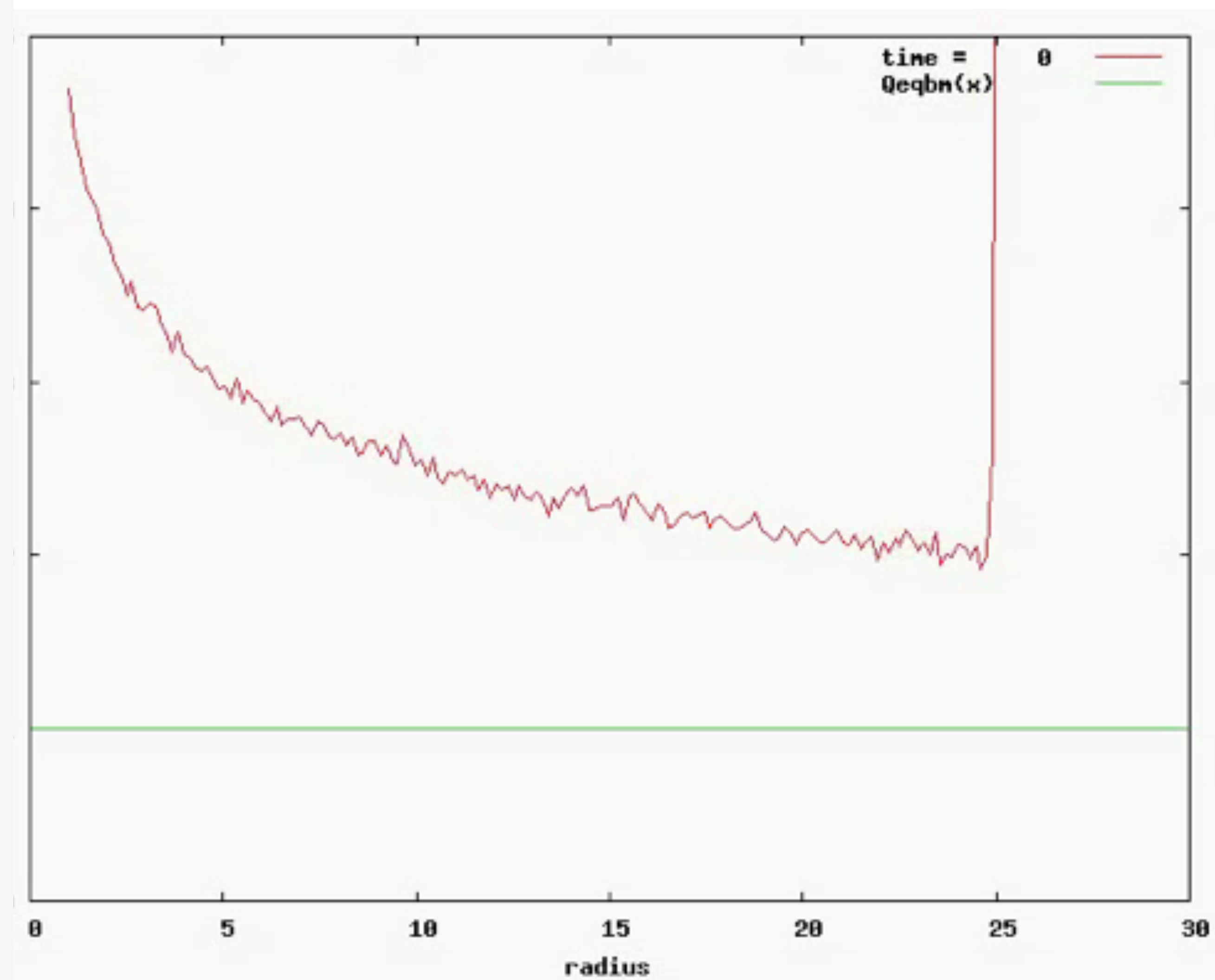

Cossins, Lodato & Clarke 2009

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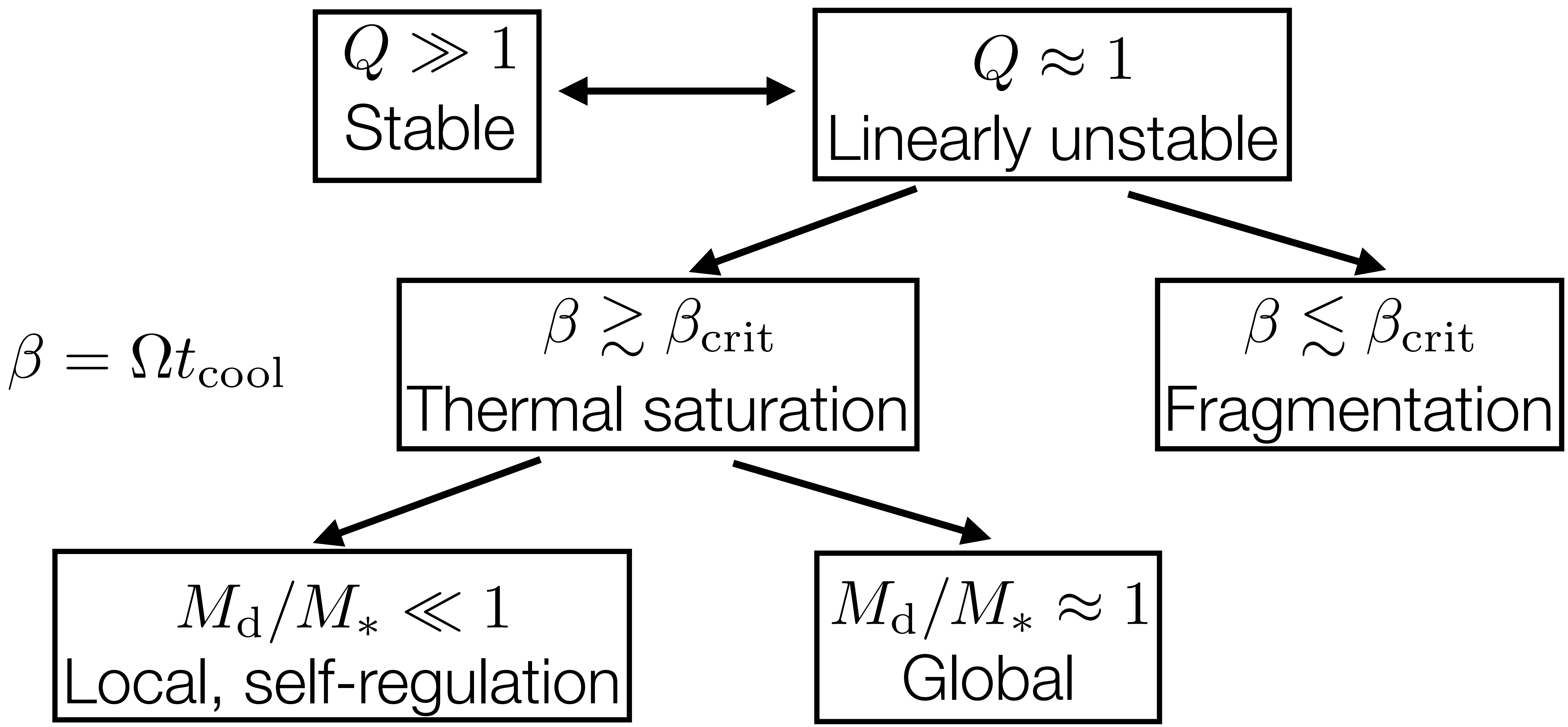

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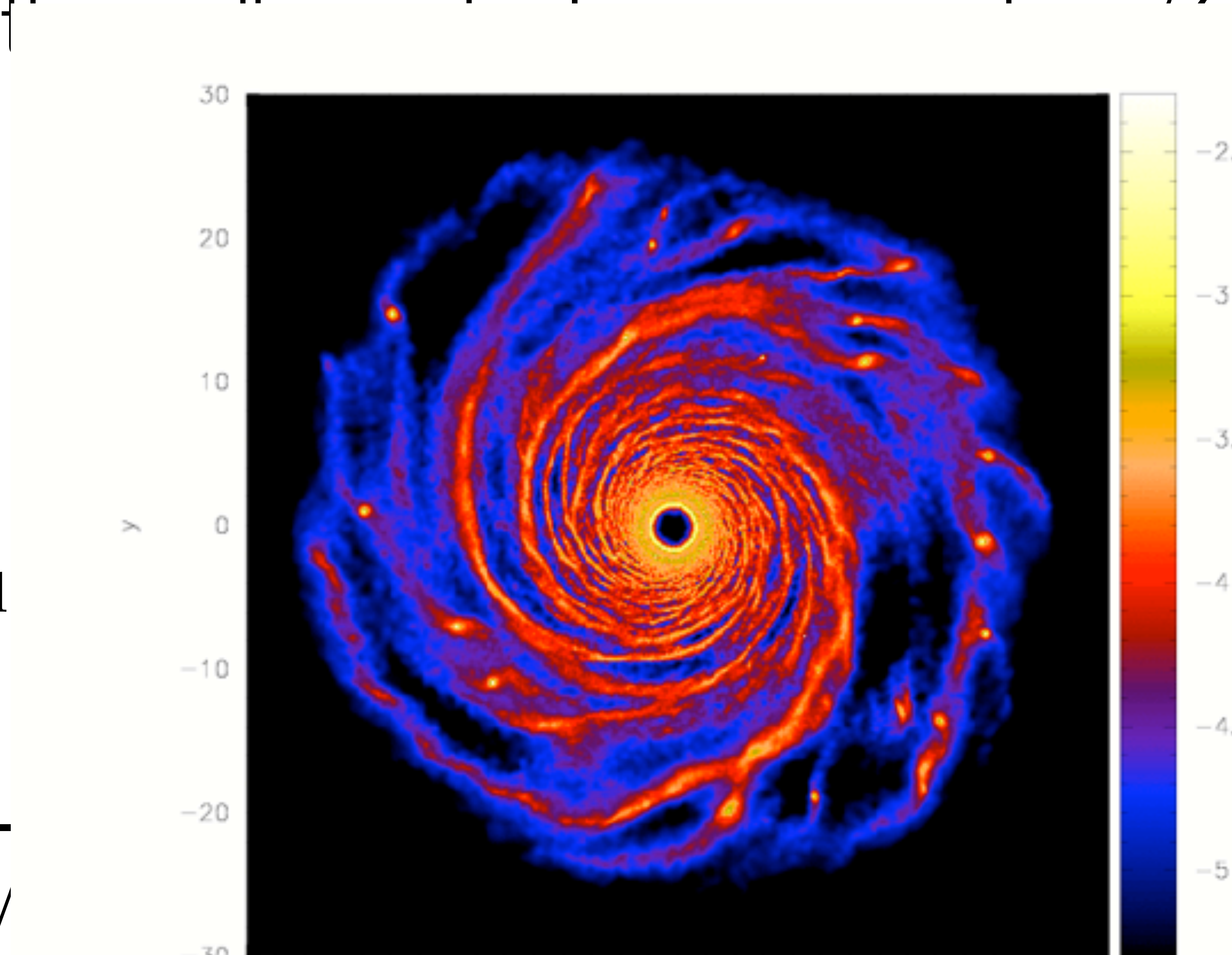


ble

$\beta \lesssim \beta_{\rm crit}$
agmentation

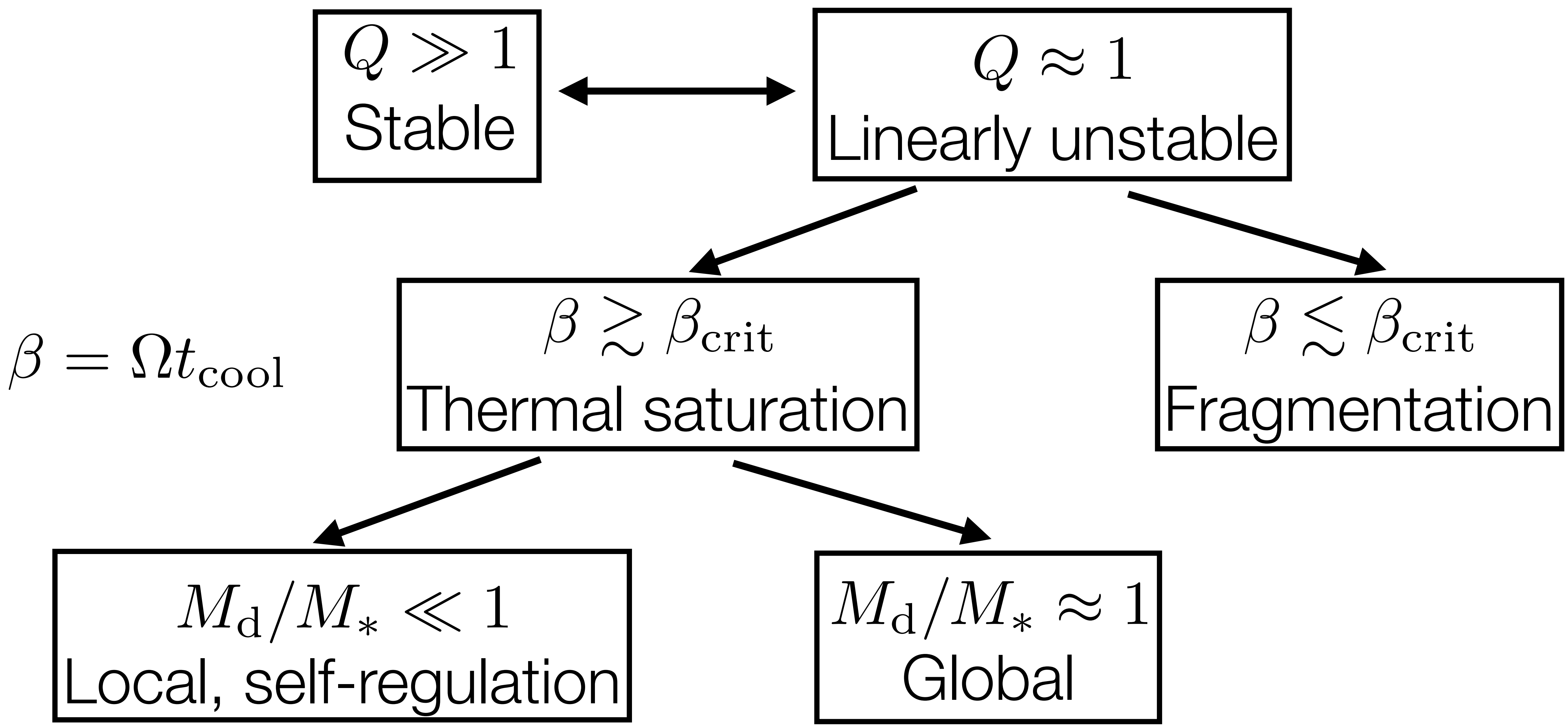
$\beta = \Omega t_{\rm cool}$

$M_{\rm d}/$
Local, self-regulation

Global

The “standard” picture of self-gravitating disc dynamics: thermal saturation

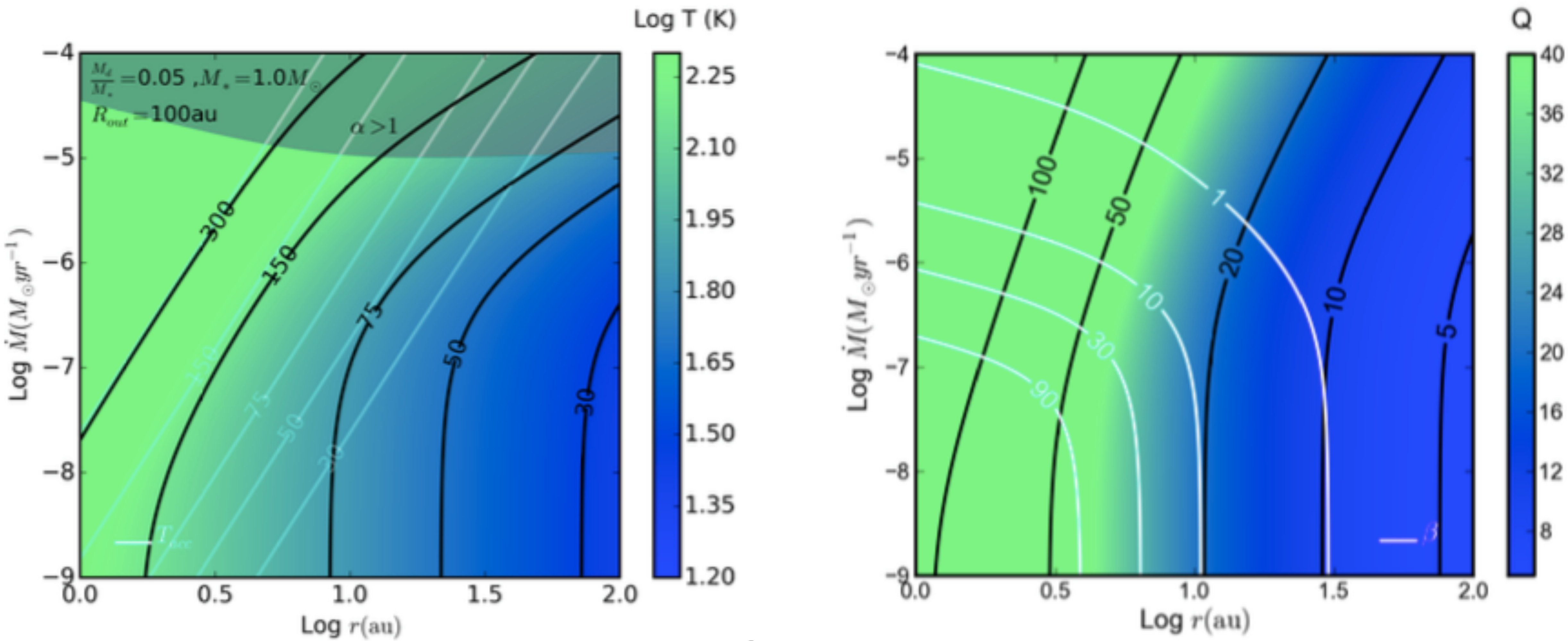
- Start from a disc characterized by (Σ, T, R)
- Compute three dimensionless parameters $(Q, \beta, M_\mathrm{d}/M_*)$



In which parameter range do we expect actual protostellar discs?

Kratter & Lodato (2016)

- Compute (Σ, T, R) based on a given total mass, outer radius, and accretion rate, assuming thermal equilibrium including irradiation and viscous heating.



A typical Class II object

$$M_\mathrm{d}/M_* = 0.05, R_\mathrm{out} = 100\mathrm{au}, M_* = 1M_\odot$$

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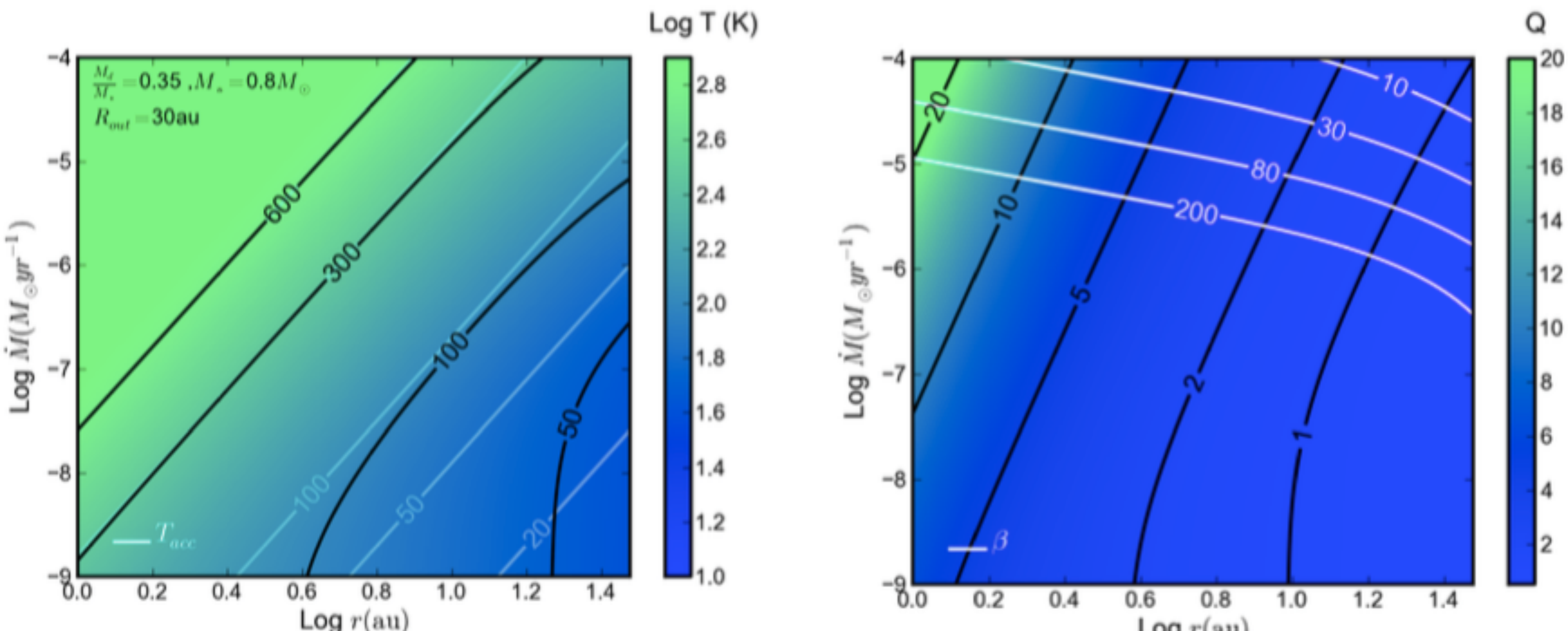

A compact disc around a Class I source, after Rodriguez et al 2005

$$M_{\rm d}/M_* = 0.35, R_{\rm out} = 30{\rm au}, M_* = 0.8 M_\odot$$

See also the case of WL12 Miotello et al 2015

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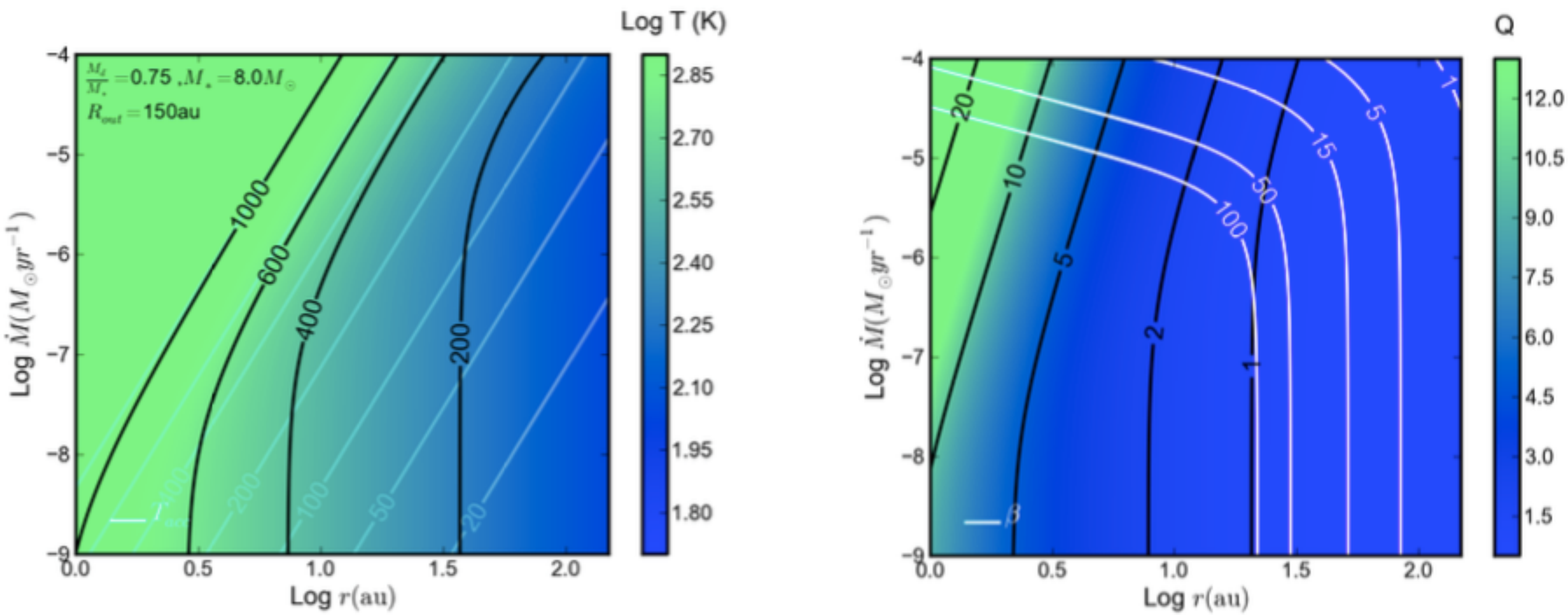
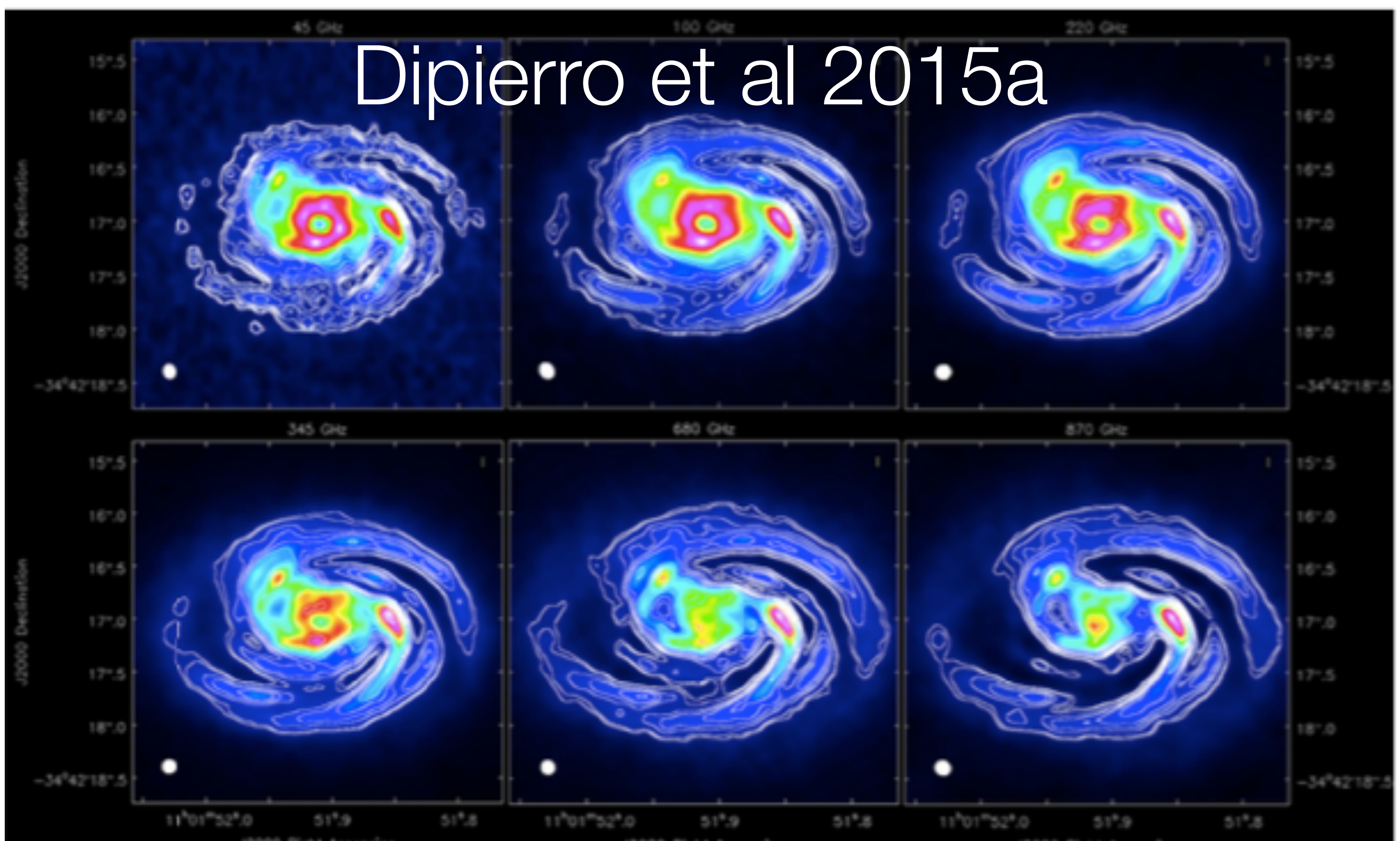


A disc around a massive star

$$M_{\rm d}/M_* = 0.75, R_{\rm out} = 150{\rm au}, M_* = 8M_\odot$$

Is there a way to observationally distinguish GI spirals from planet spirals?

- We know that both GI and planets produce spirals
- Planetary spirals are typically tightly wound while GI might have open spirals. Is this true?



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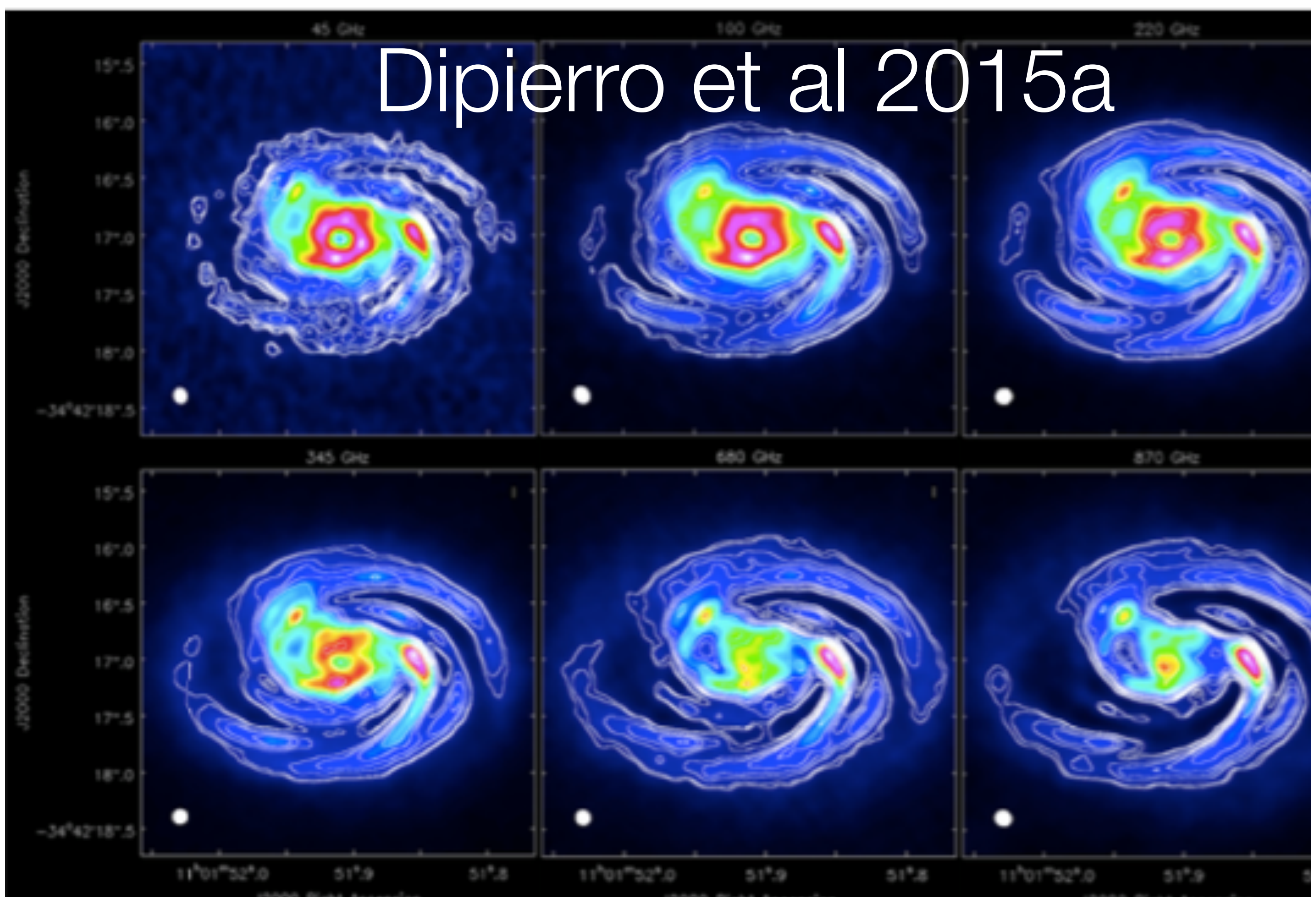
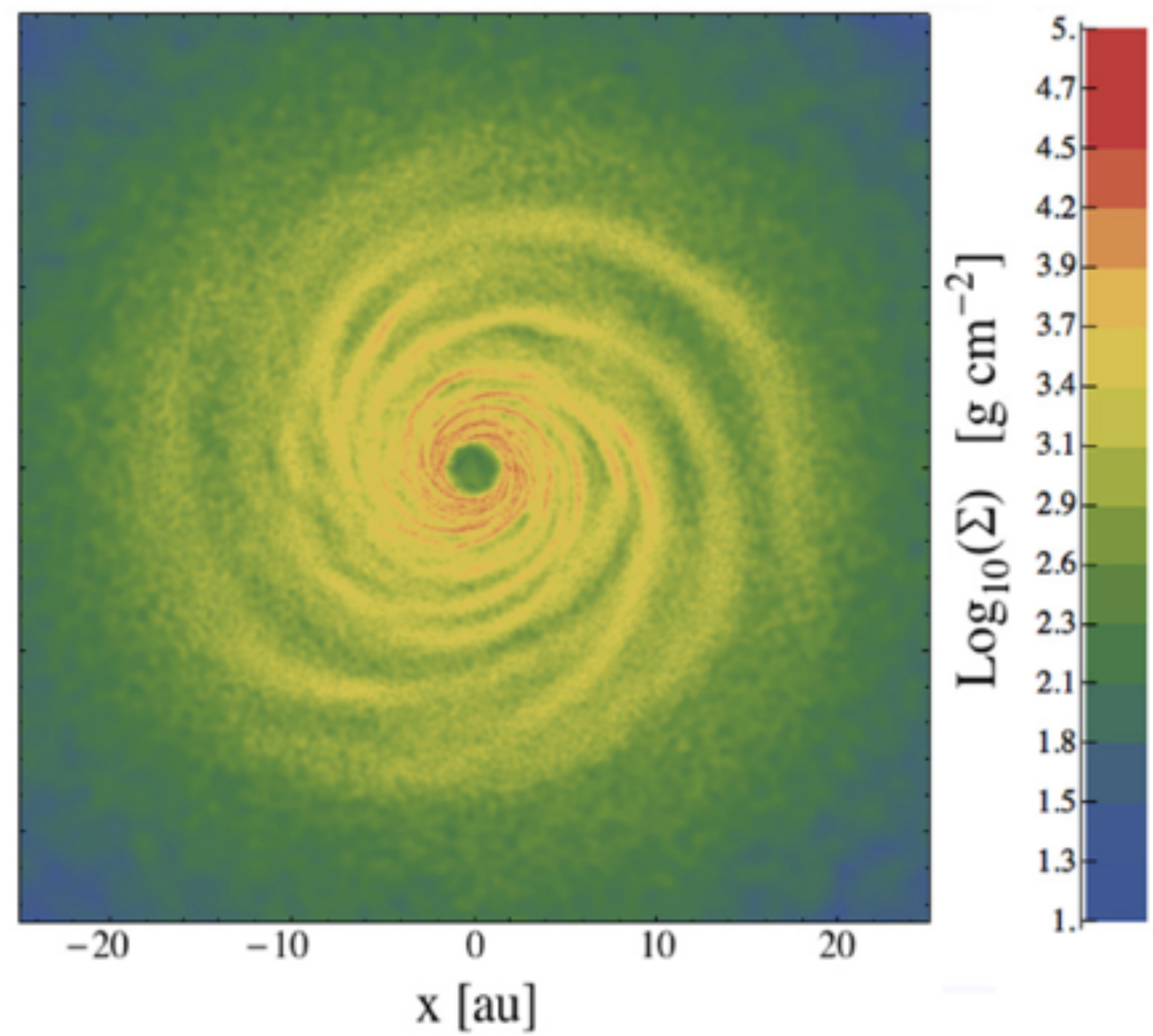


Dipierro et al 2015a



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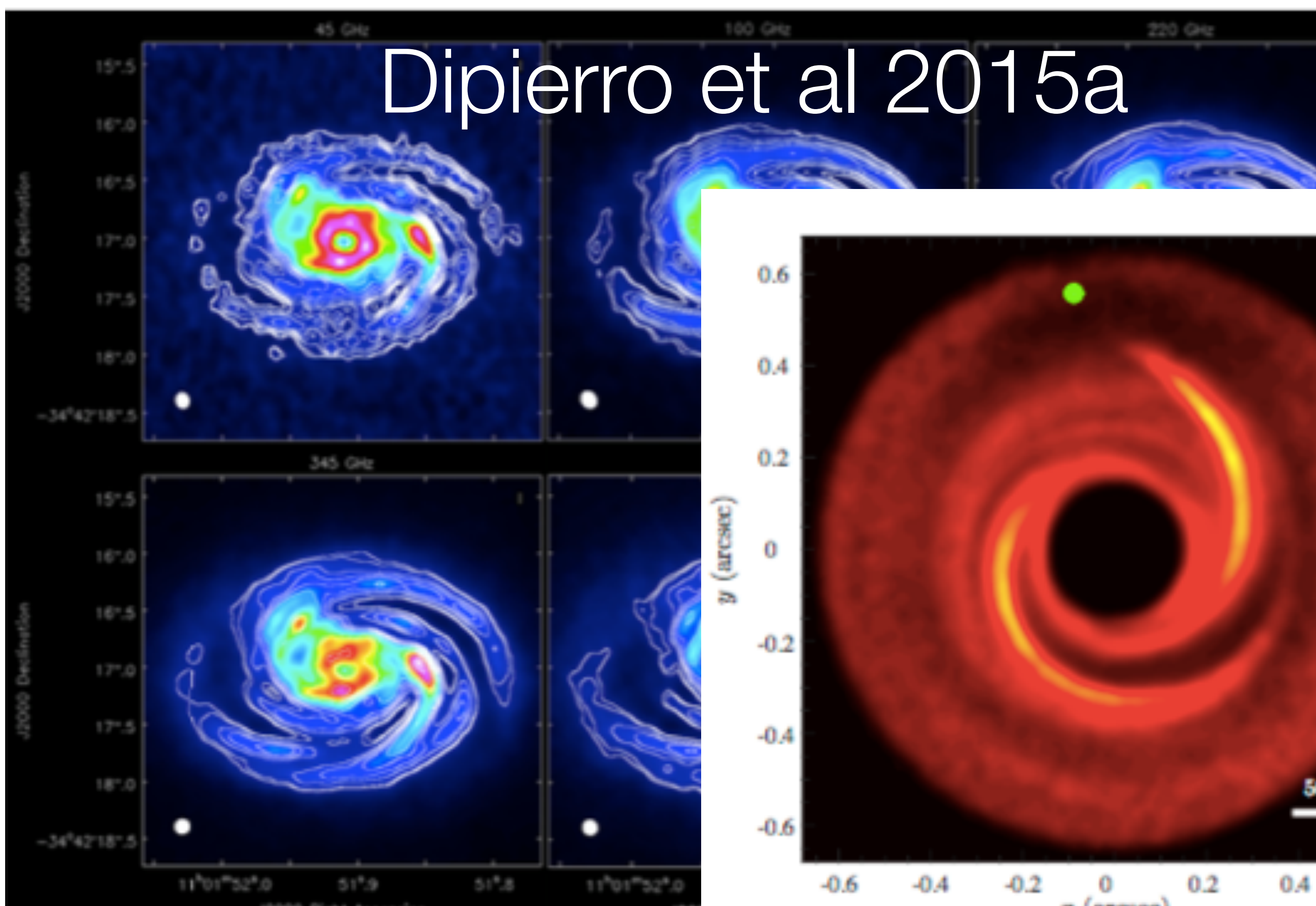

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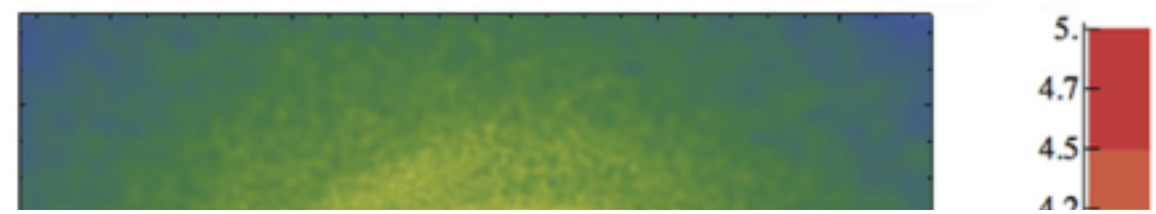

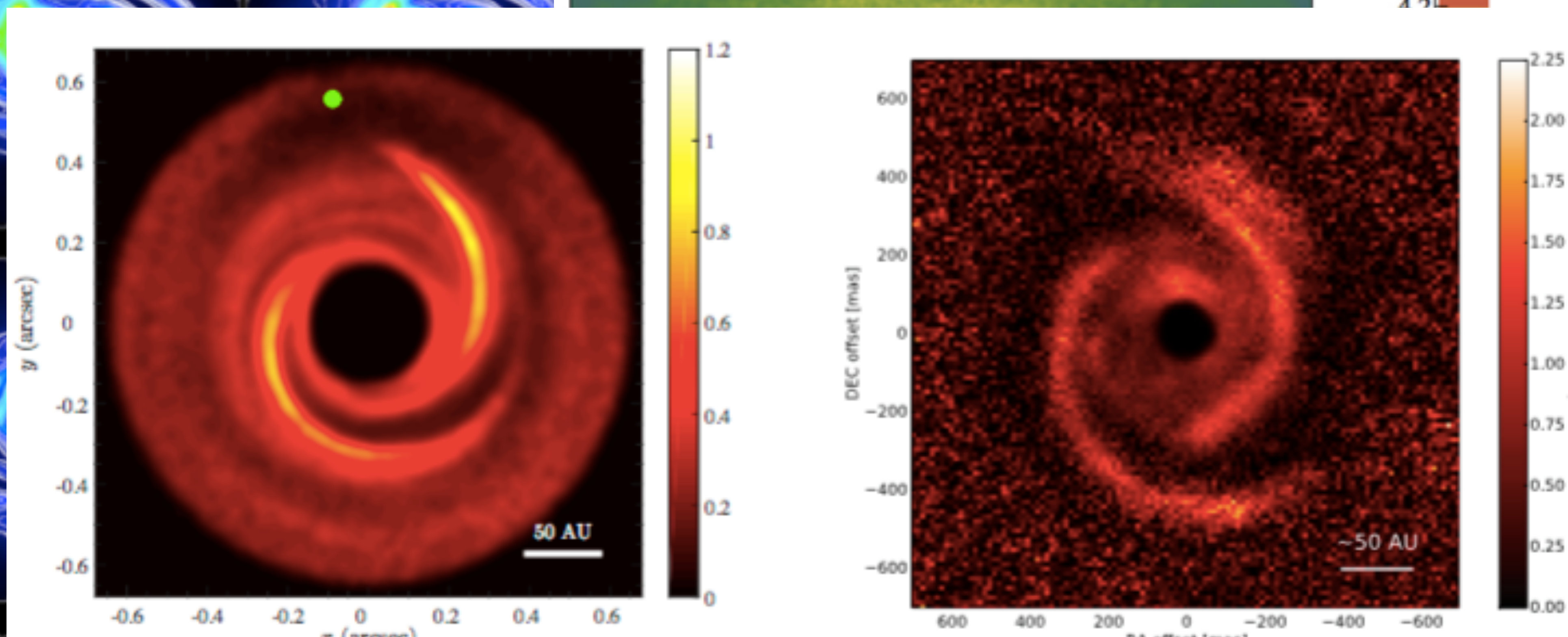

Dong et al 2015, Benisty et al 2015

Outstanding questions on the gravitational instability

- A lot has been understood in the last ~10 years on the thermal saturation of gravitational instability
- **Very little progress on other saturation mechanisms that are more relevant for irradiated, high-mass discs**
- Discs in this regime might be the most common to develop GI
- **How to observationally distinguish planet induced spirals from GI induced spirals?**

2nd Course: Gaps and planets

- By far the most significant novelty coming from disc imaging is the widespread presence of gaps (e.g. HL Tau)
- Many mechanisms proposed to create gaps (chemistry, dead zones in the MRI, etc.)
- The most natural explanation is associated with the presence of young planets
- The gravitational torque of the planet is able to carve a gaps in the disc

2nd Course: Gaps and planets

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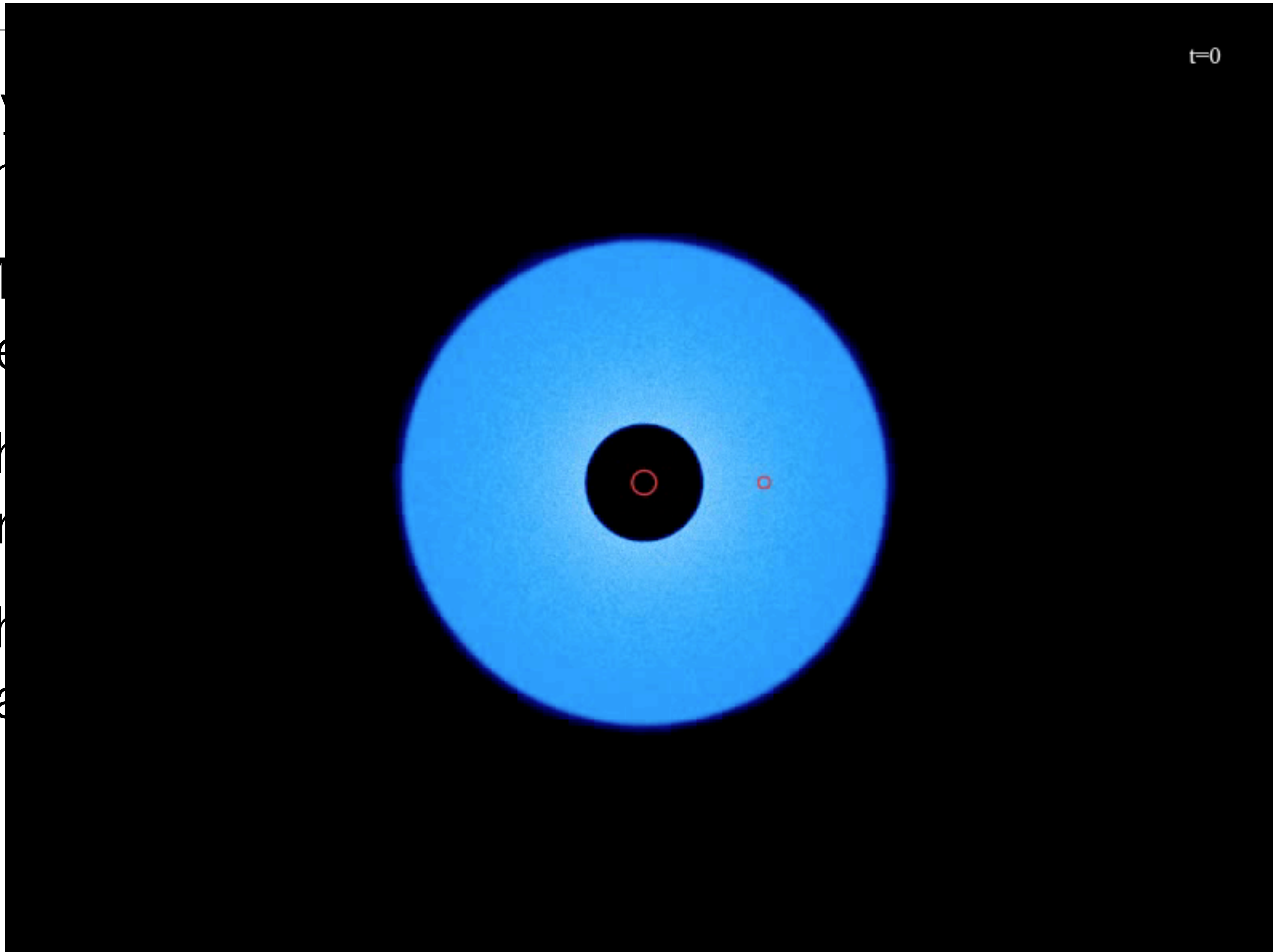

Gap opening criteria: the gas disc

- For a gas disc it can be shown that to open a gap

$$\frac{3H}{3R_{\mathrm{H}}} + \frac{50\Omega R^2}{q\nu} \lesssim 1$$

Crida et al 2006

- The gap width is given by

$$\left(\frac{\Delta_{\mathrm{gas}}}{R}\right)^3 = f q^2 \frac{\Omega R^2}{\nu}$$

- A gap produces a pressure maximum
- For thick-ish discs (H/R~0.1), gap opening does not prevent accretion (Artymowicz & Lubow 1994)

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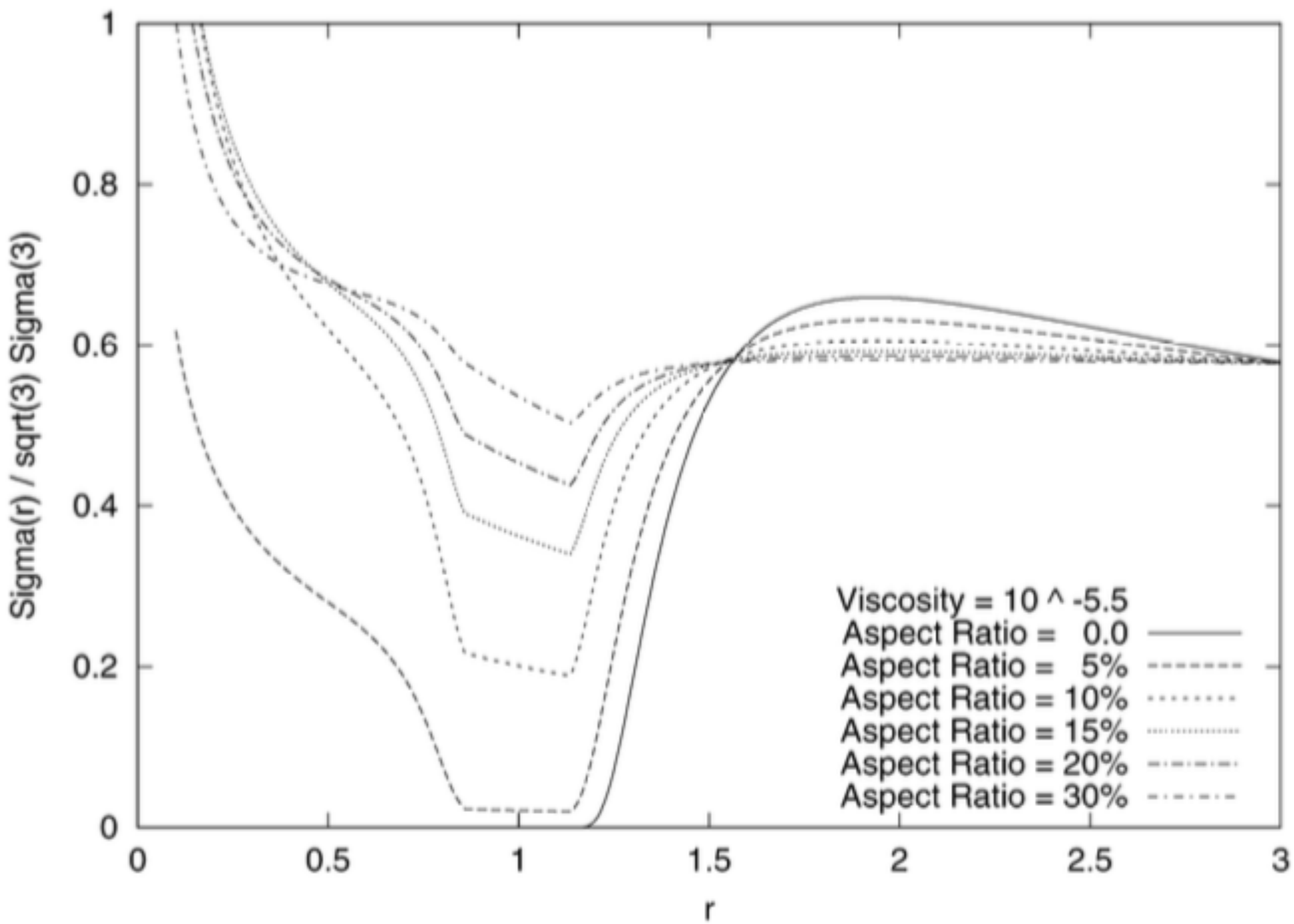

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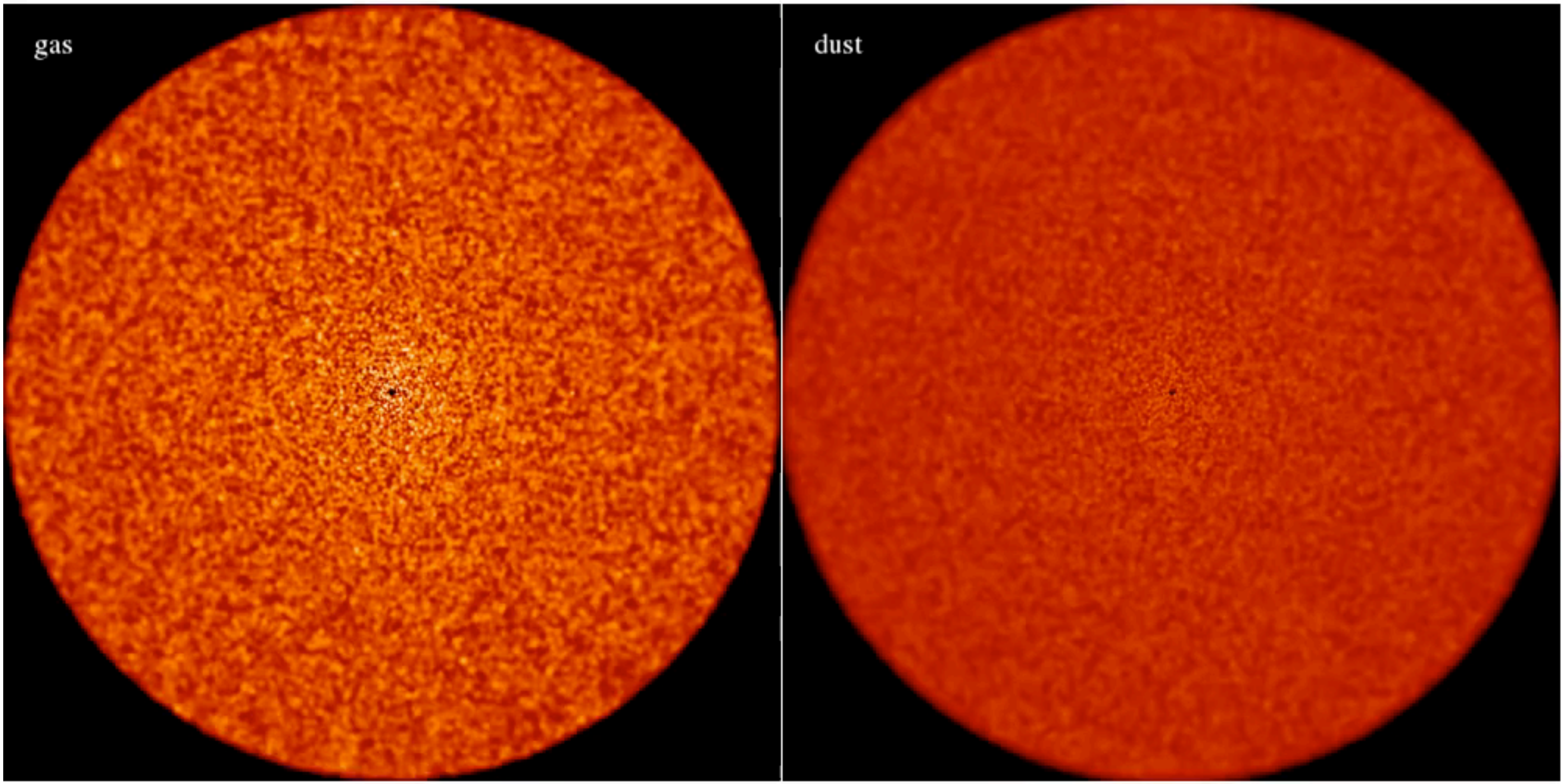
Gap opening in a dust disc

(Dipierro et al 2016)

- Several possible mechanisms, depending on planet mass and Stokes number
  - **Large planet** (satisfies gas gap opening)
    - Small dust (*St<<1*): follows the gas
    - For *St~1*: dust trapping at the gap edge (Pardekooper & Mellema 2004)
    - Dust filtration at the gap edge (Rice et al 2006)
    - This is likely to create narrow rings in dust
  - **Small planet** (does not open a gap in the gas)
    - For *St>~1*, a gap can *still* be opened in the dust
    - Here, drag *resists* rather than *assists* gap opening

Gap opening in a dust disc
(Dipierro et al 2016)



$M_p = 1 M_{Jup}$ - $St = 10$

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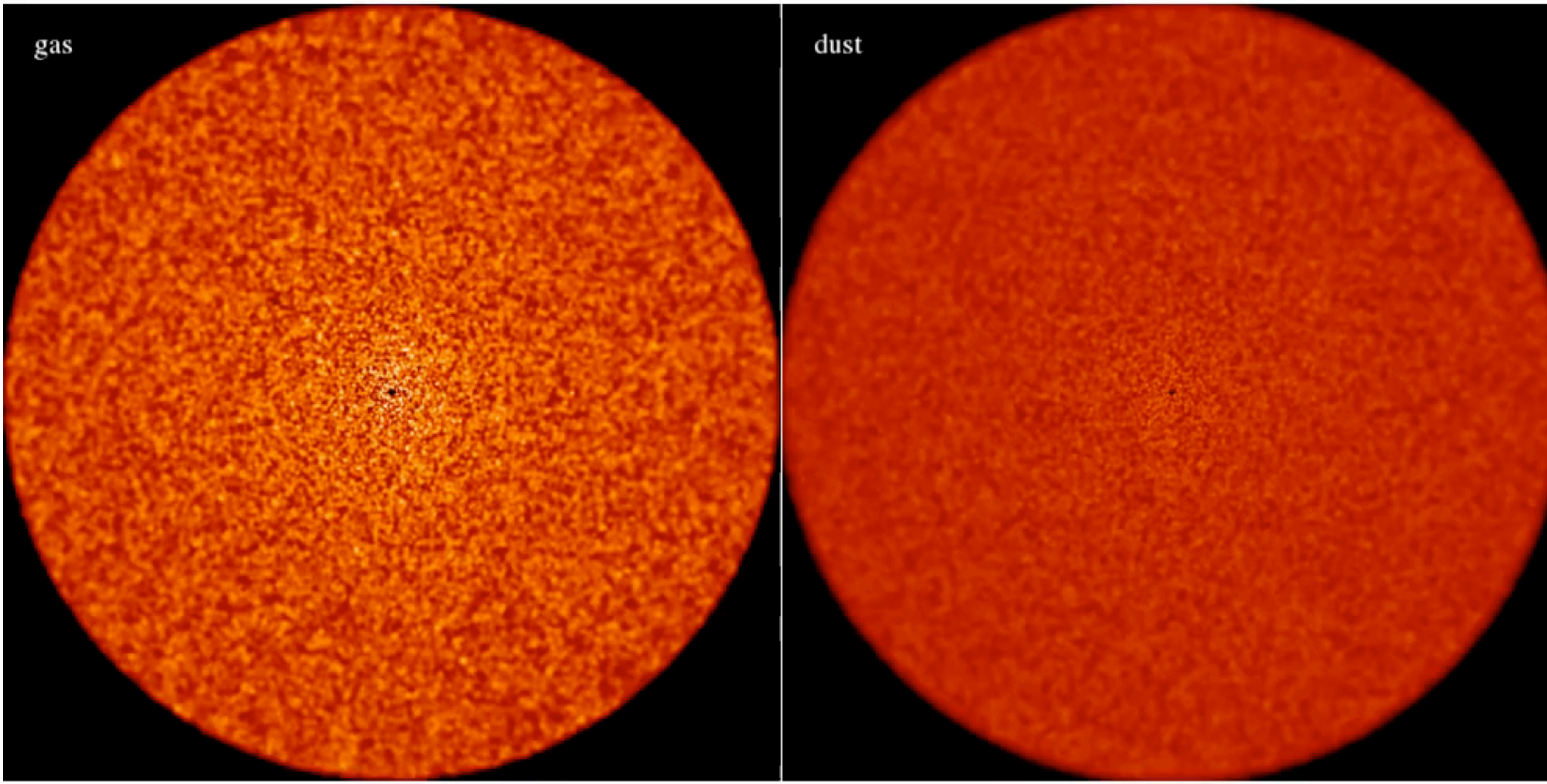

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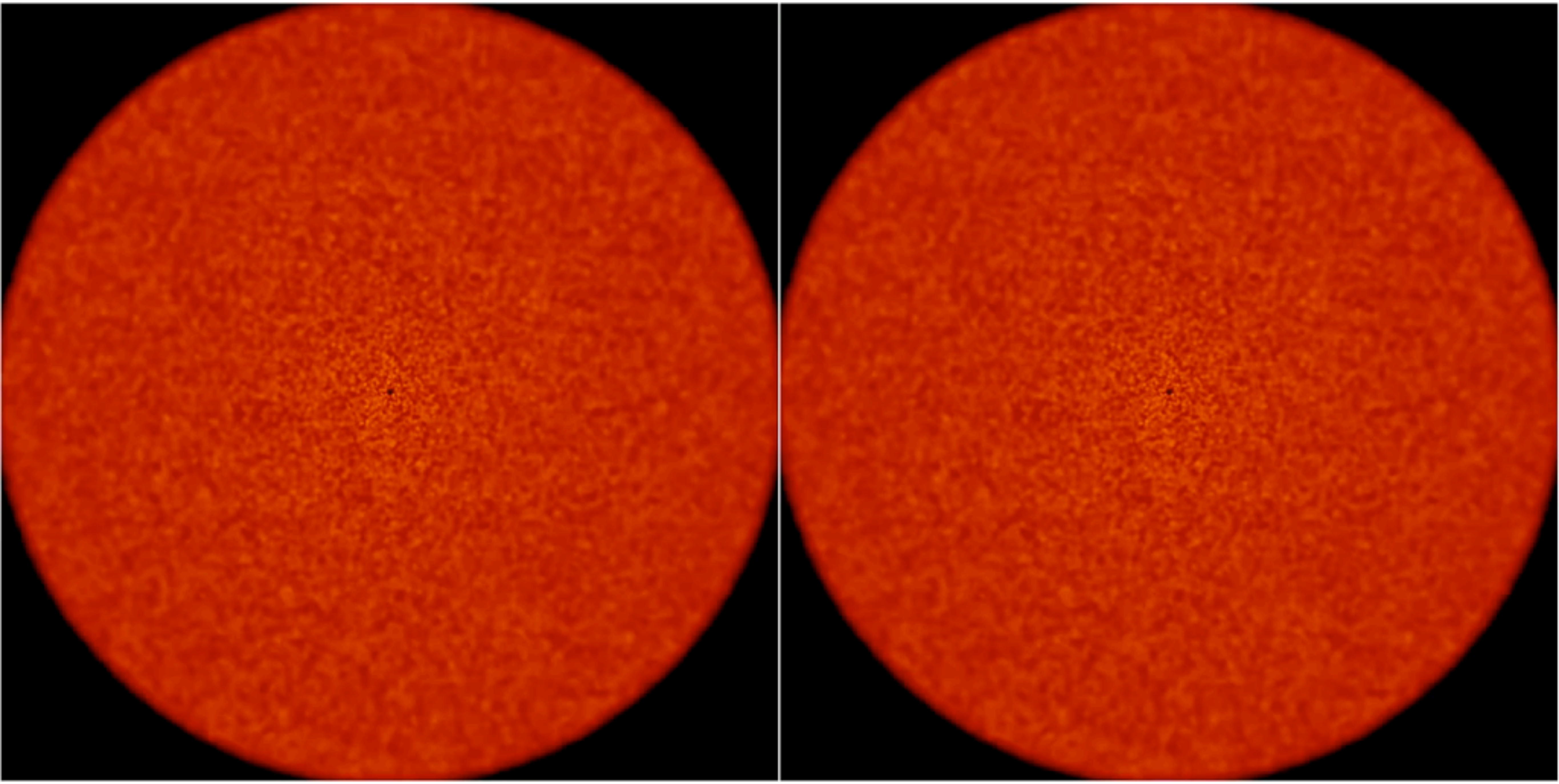

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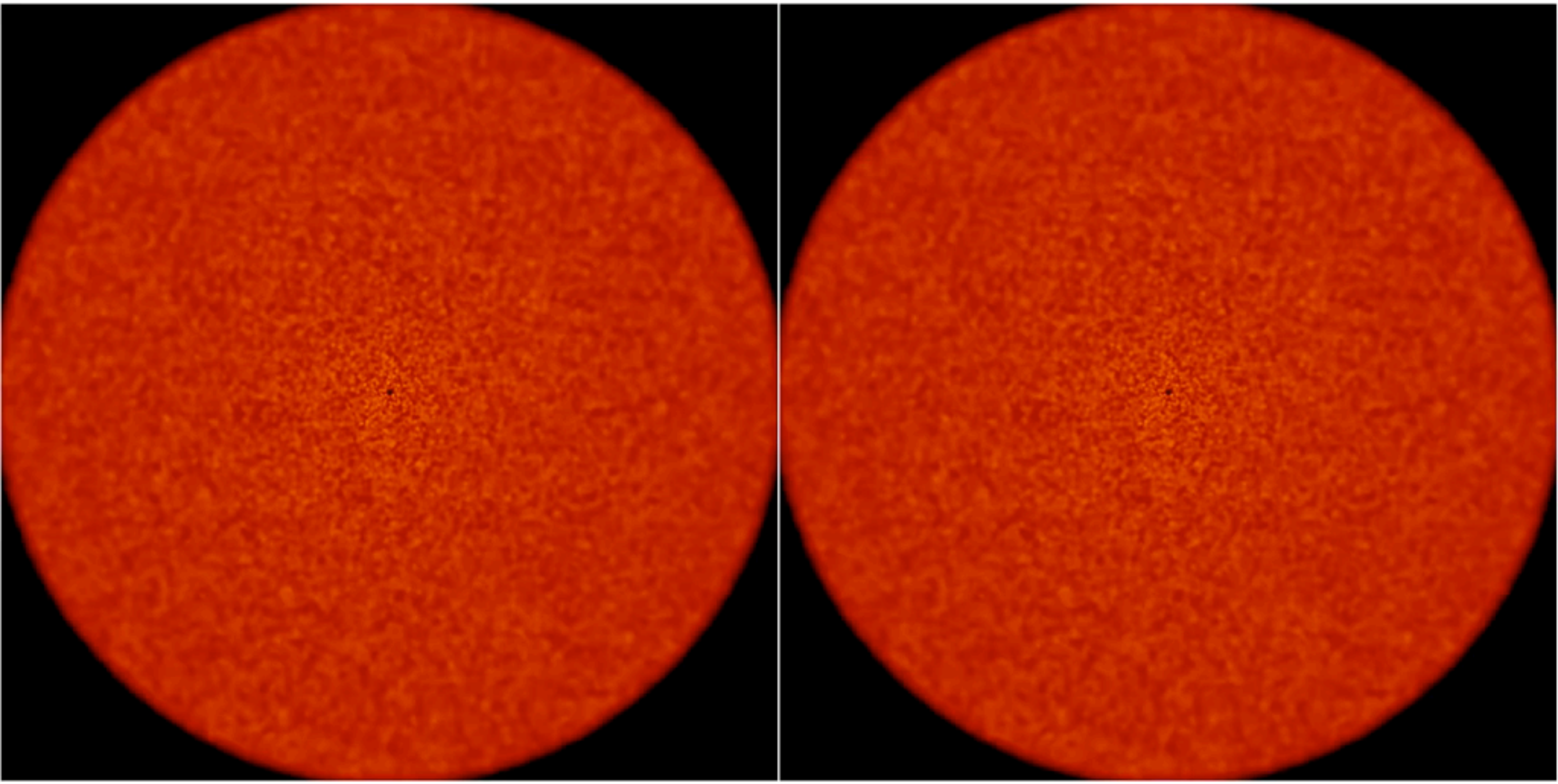

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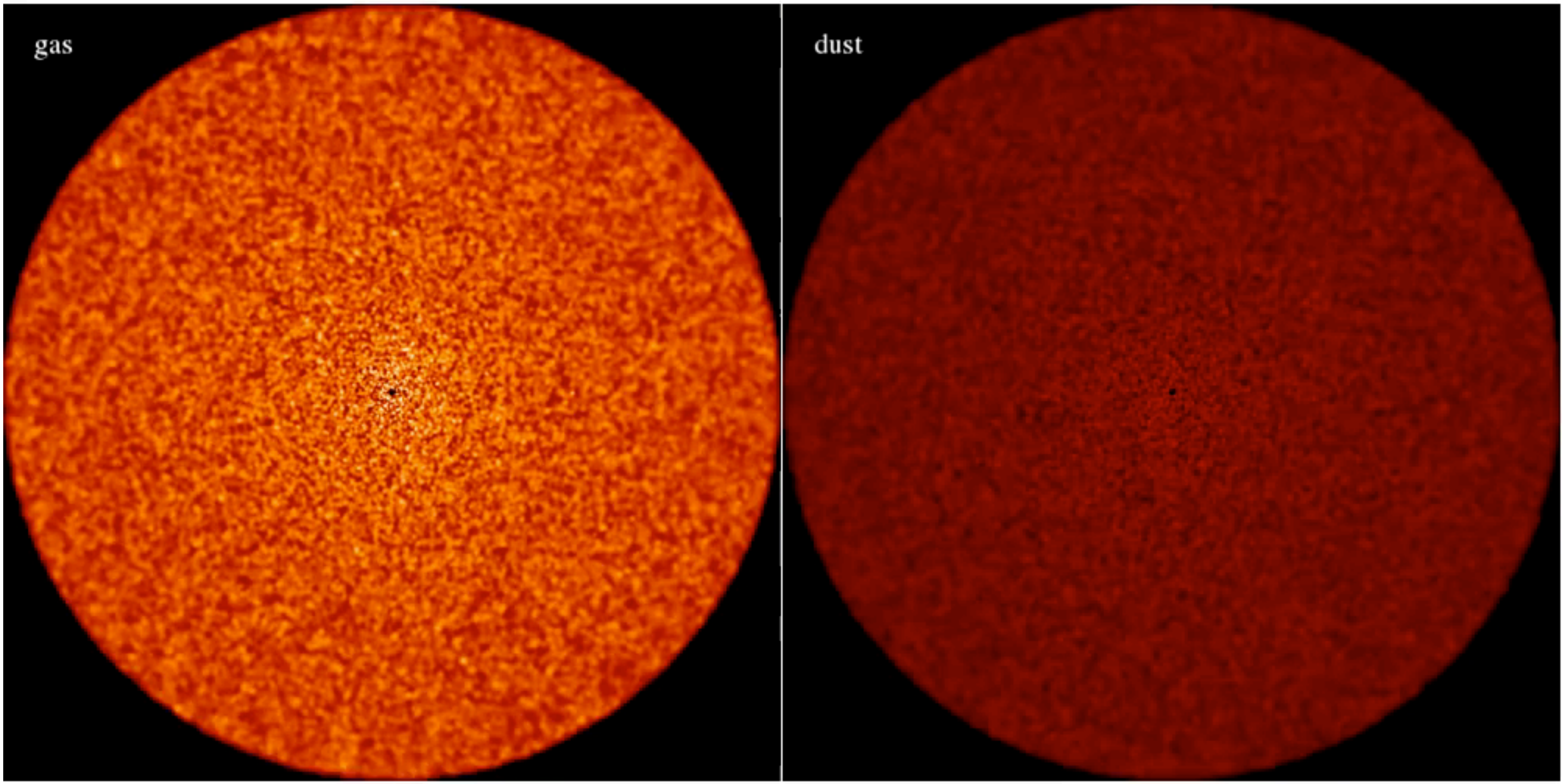

M_p=0.1M_{Jup} - St=10

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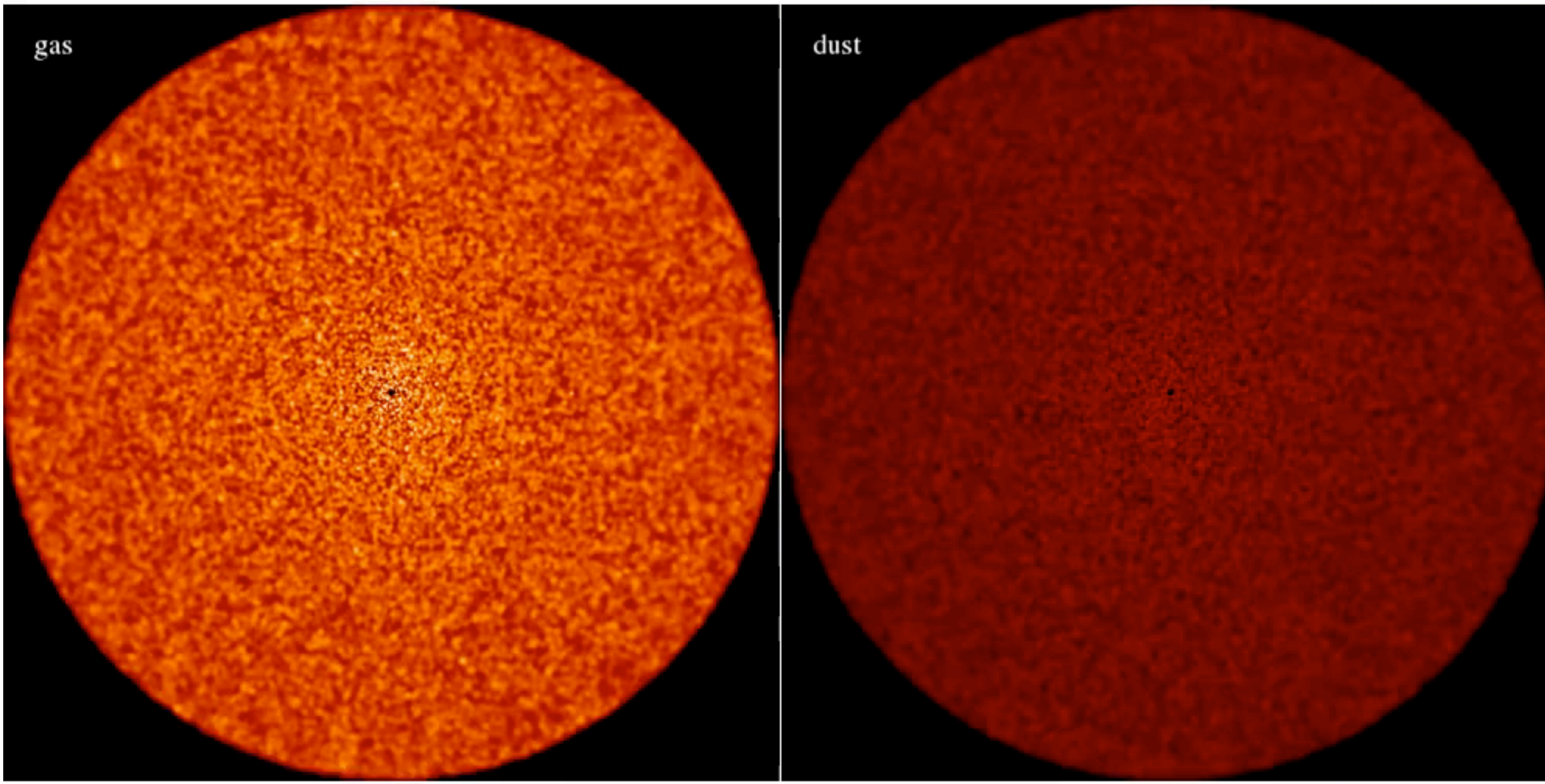

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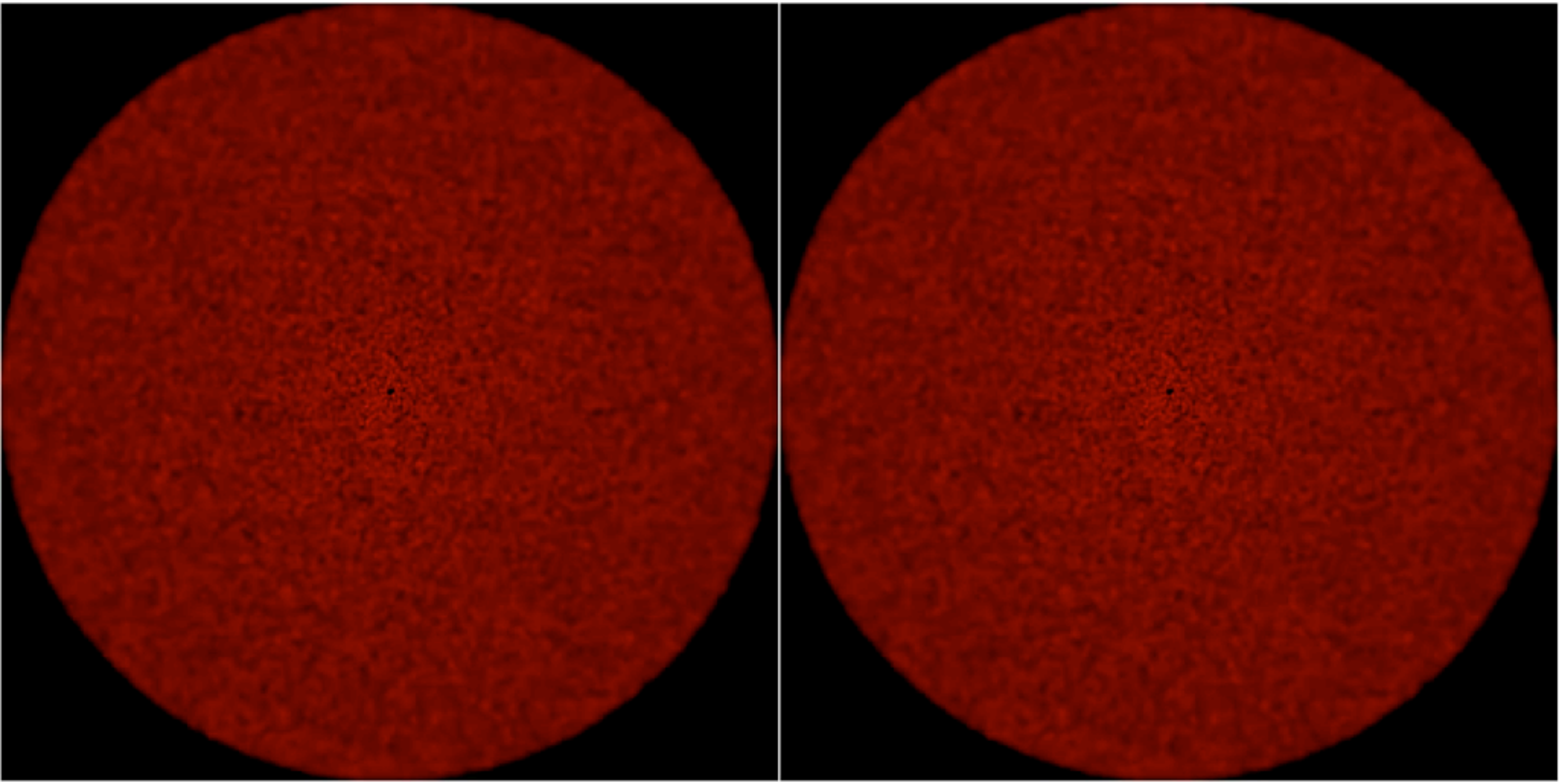

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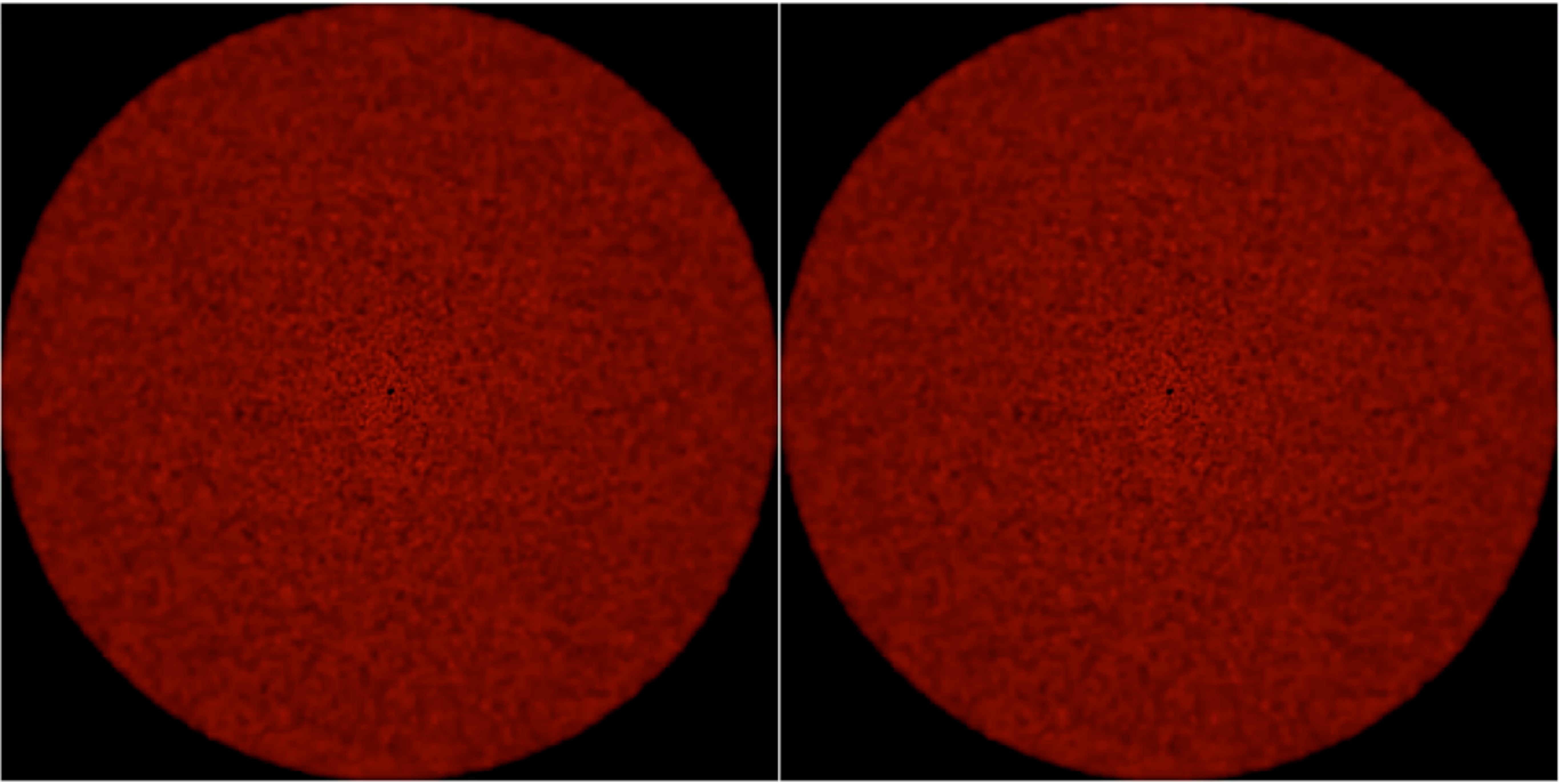
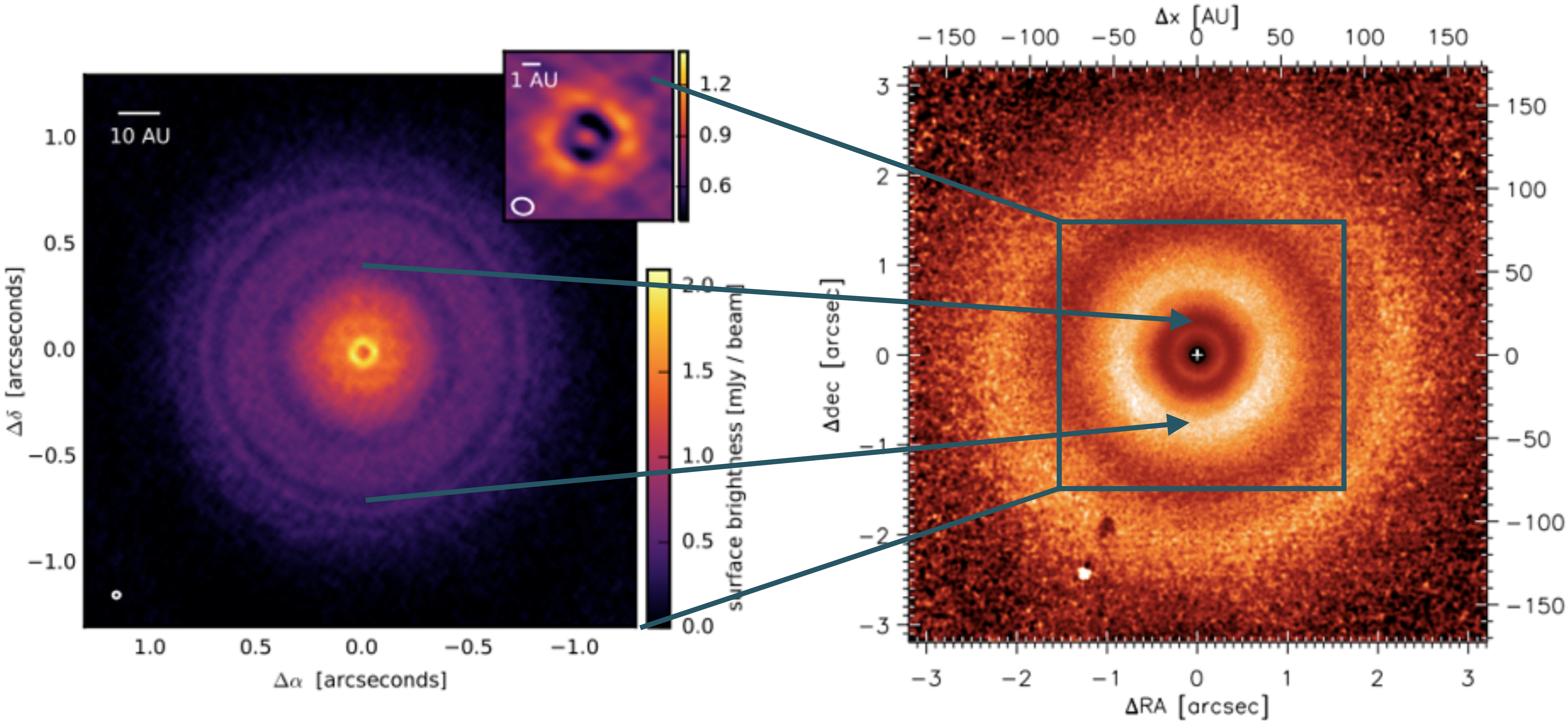


M_p=0.1M_{Jup} - St=10

Dust gaps do not necessarily correspond to gas gaps

- TW Hya

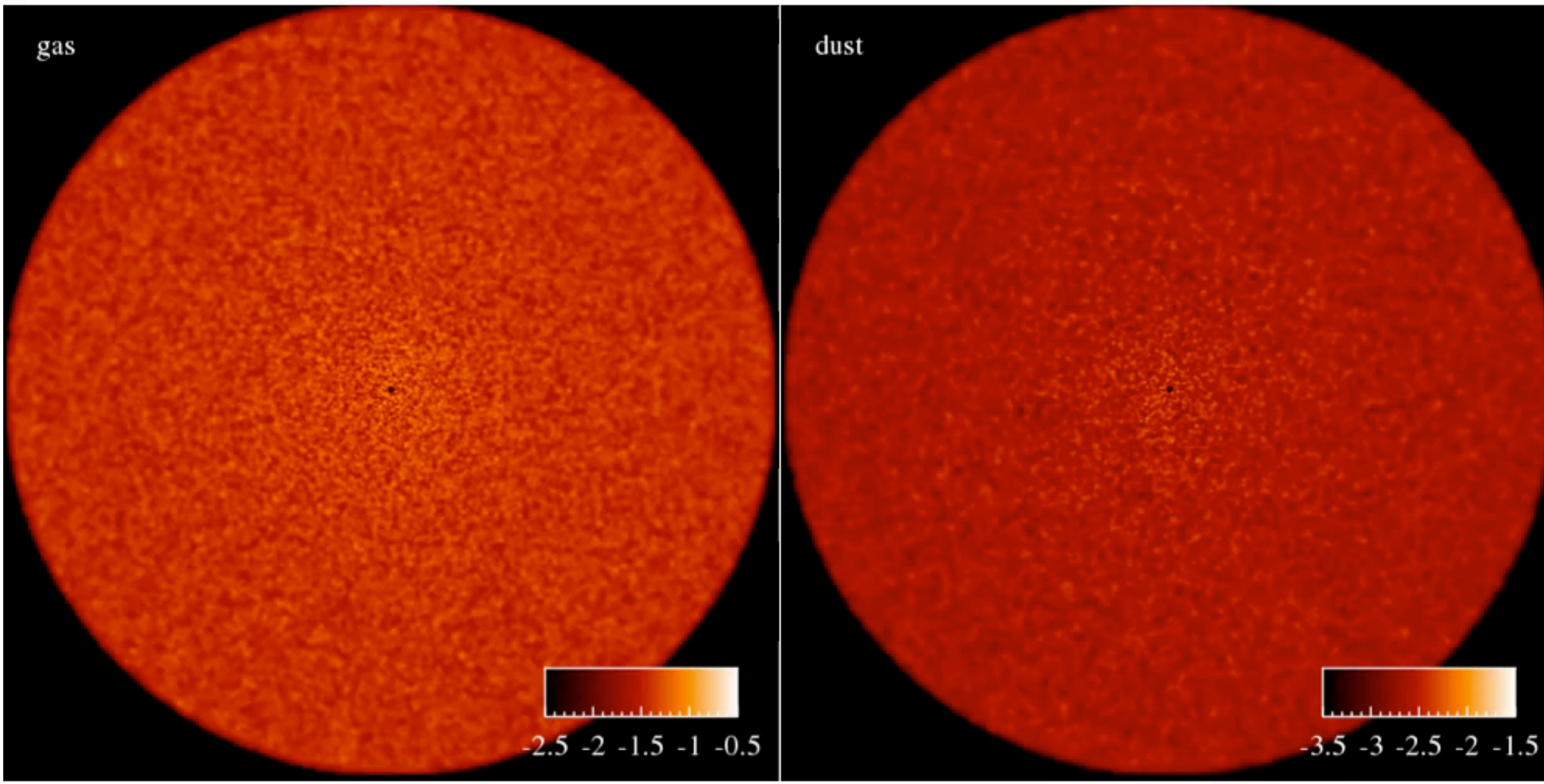


ALMA dust continuum
Andrews et al 2016

SPHERE scattered light image
van Boeckel et al 2016

Explaining the HL Tau disc

(Dipierro et al 2015b)



Three planets: *0.2*M_{Jup} (*@13.2au*), *0.27*M_{Jup} (*@32.3au*), *0.55*M_{Jup} (*@68.8au*)

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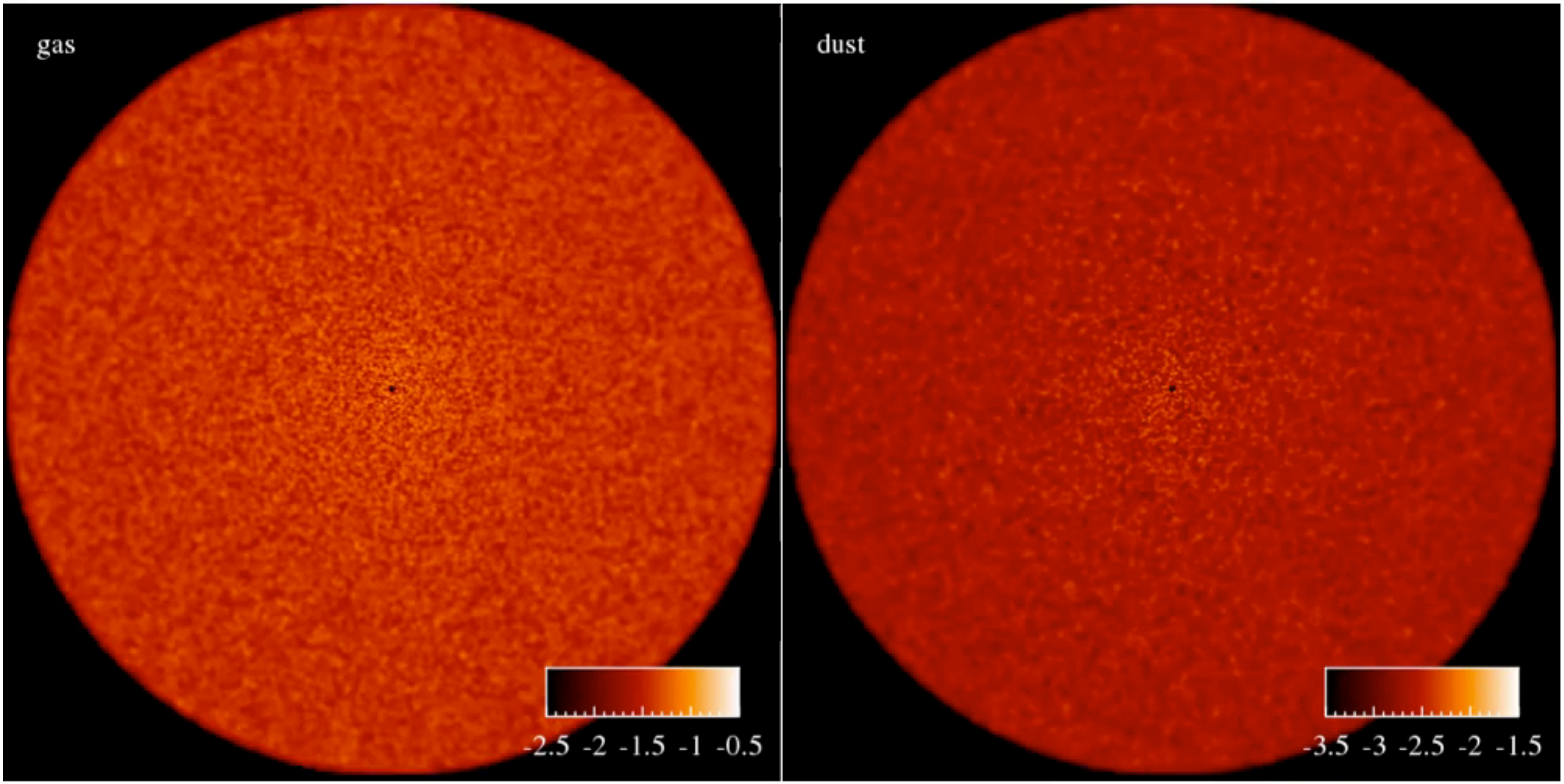

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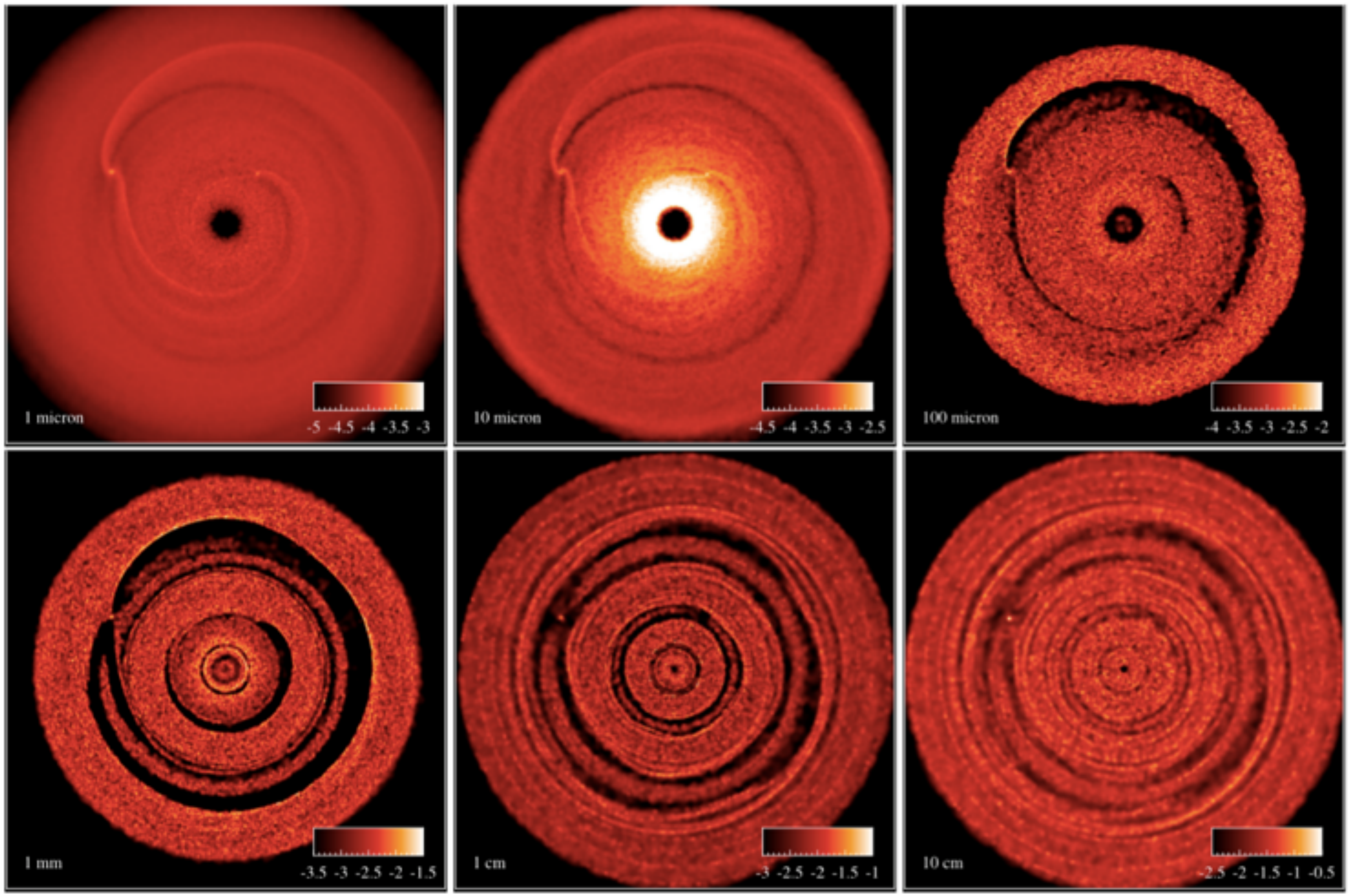
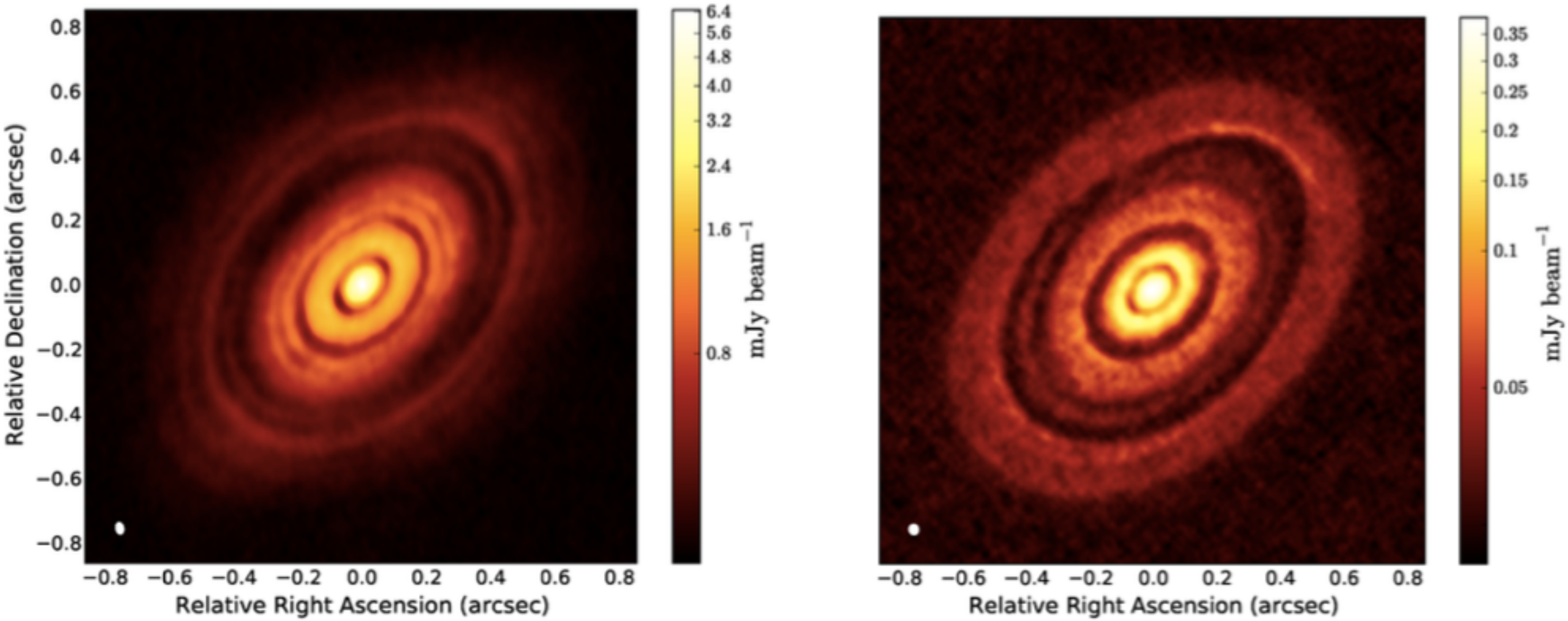


Simulate 6 different sizes, assume a dust size distribution and a gas/dust ratio —> compute synthetic images

Explaining the HL Tau disc
(Dipierro et al 2015b)



ALMA Partnership (2015)

Dipierro et al (2015)

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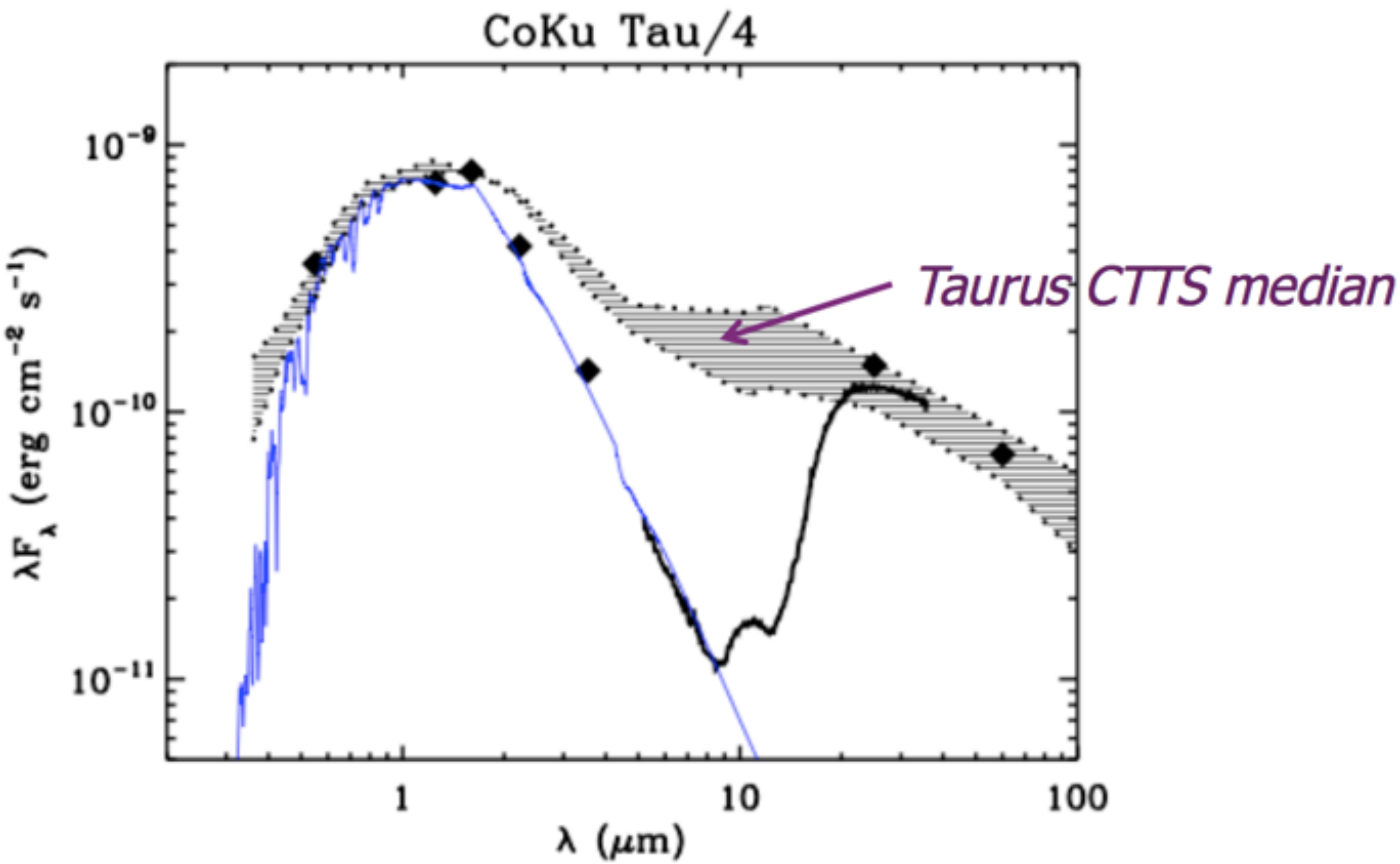
Dessert: Horseshoes in transition discs

- Transition discs are discs displaying a large inner cavity
- Originally discovered from SED modeling



Muzerolle et al 2015

Dessert: Horseshoes in transition discs

- Transition discs are discs displaying a large inner cavity
- Originally discovered from SED modeling
- Many possible sources of inner clearing:
  - A massive planet
  - Photoevaporation
- Imaging of transition discs sometimes show non-axisymmetric structures (van der marel et al 2016, Casassus et al 2015)

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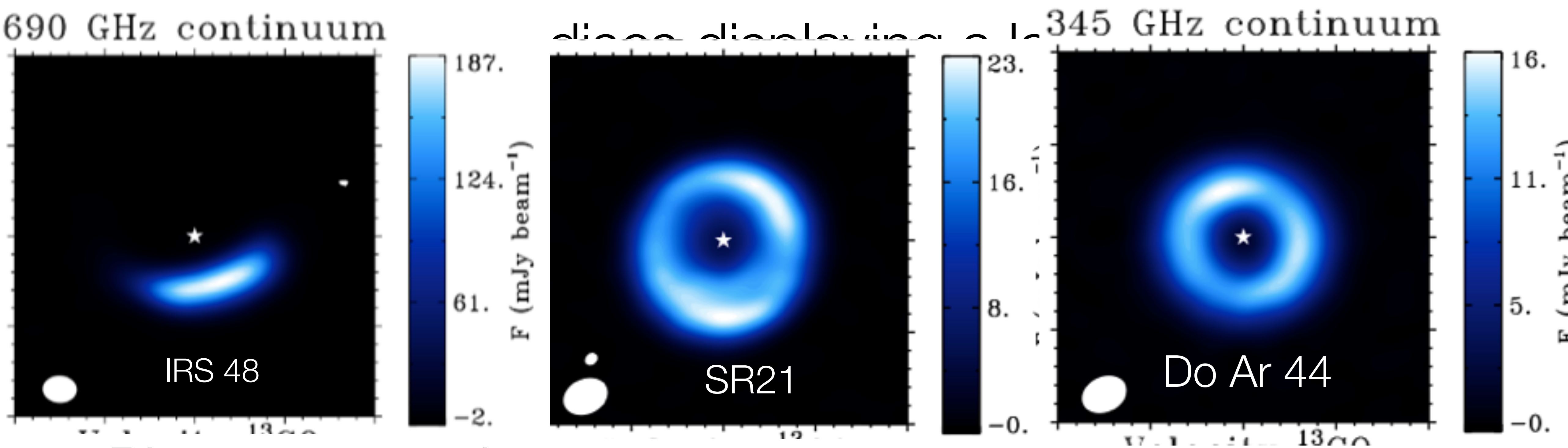

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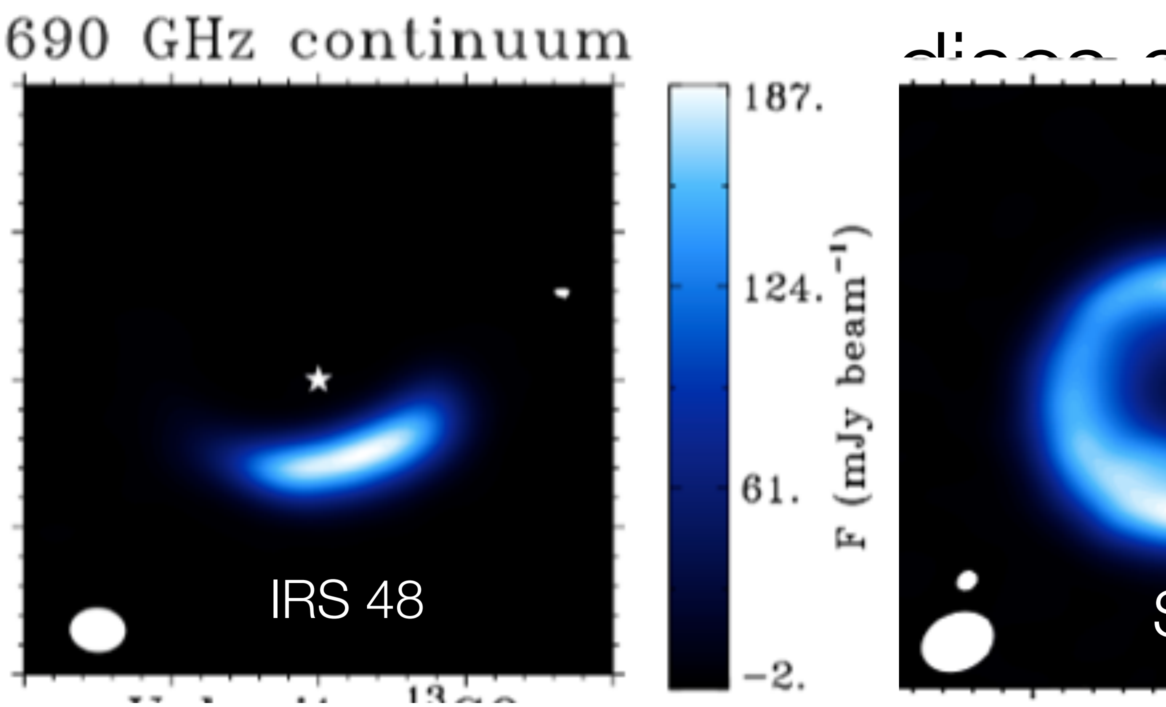

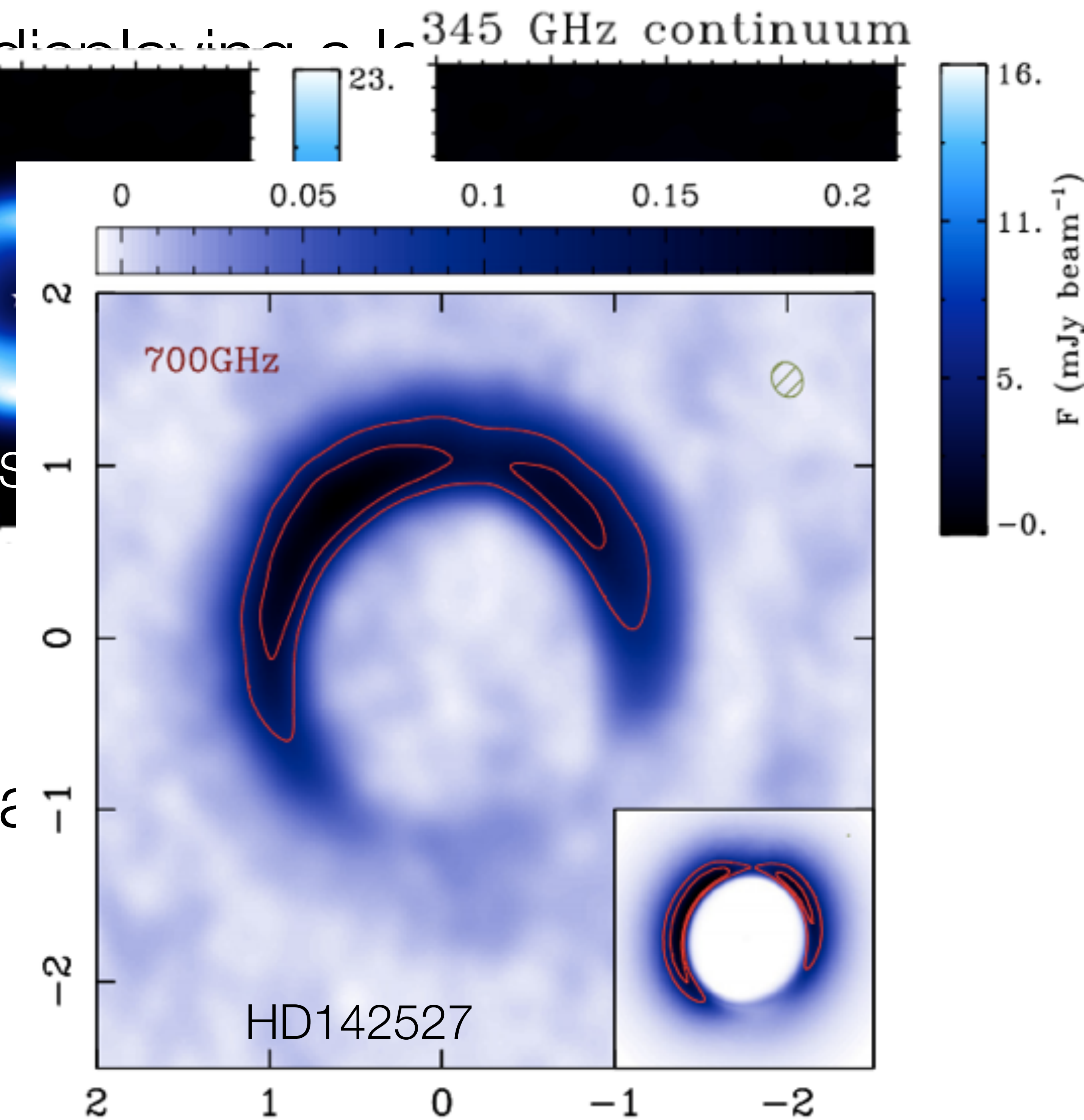

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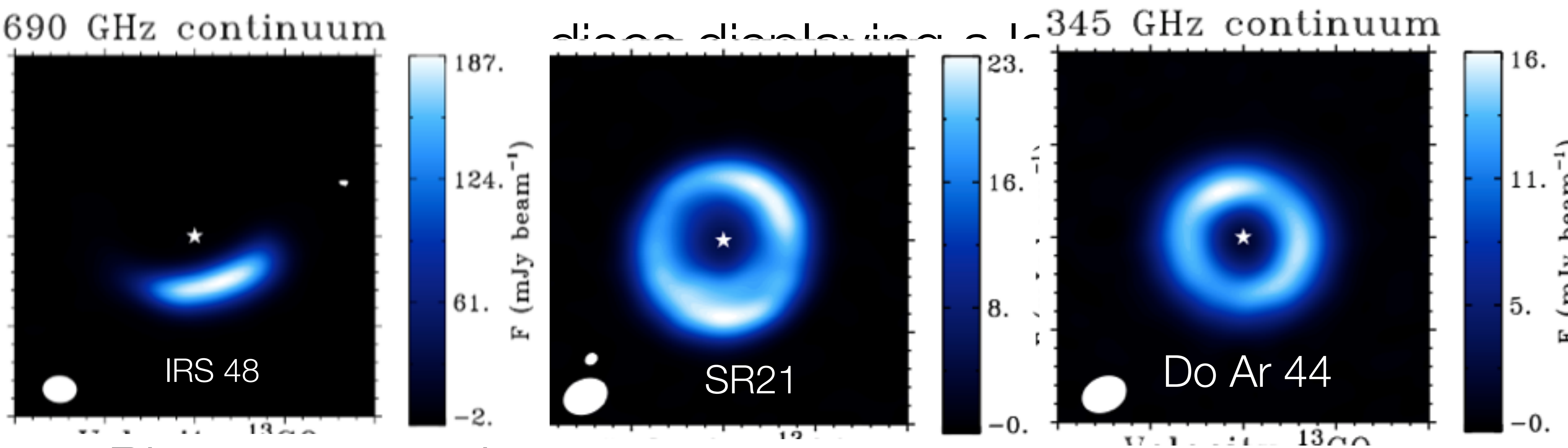

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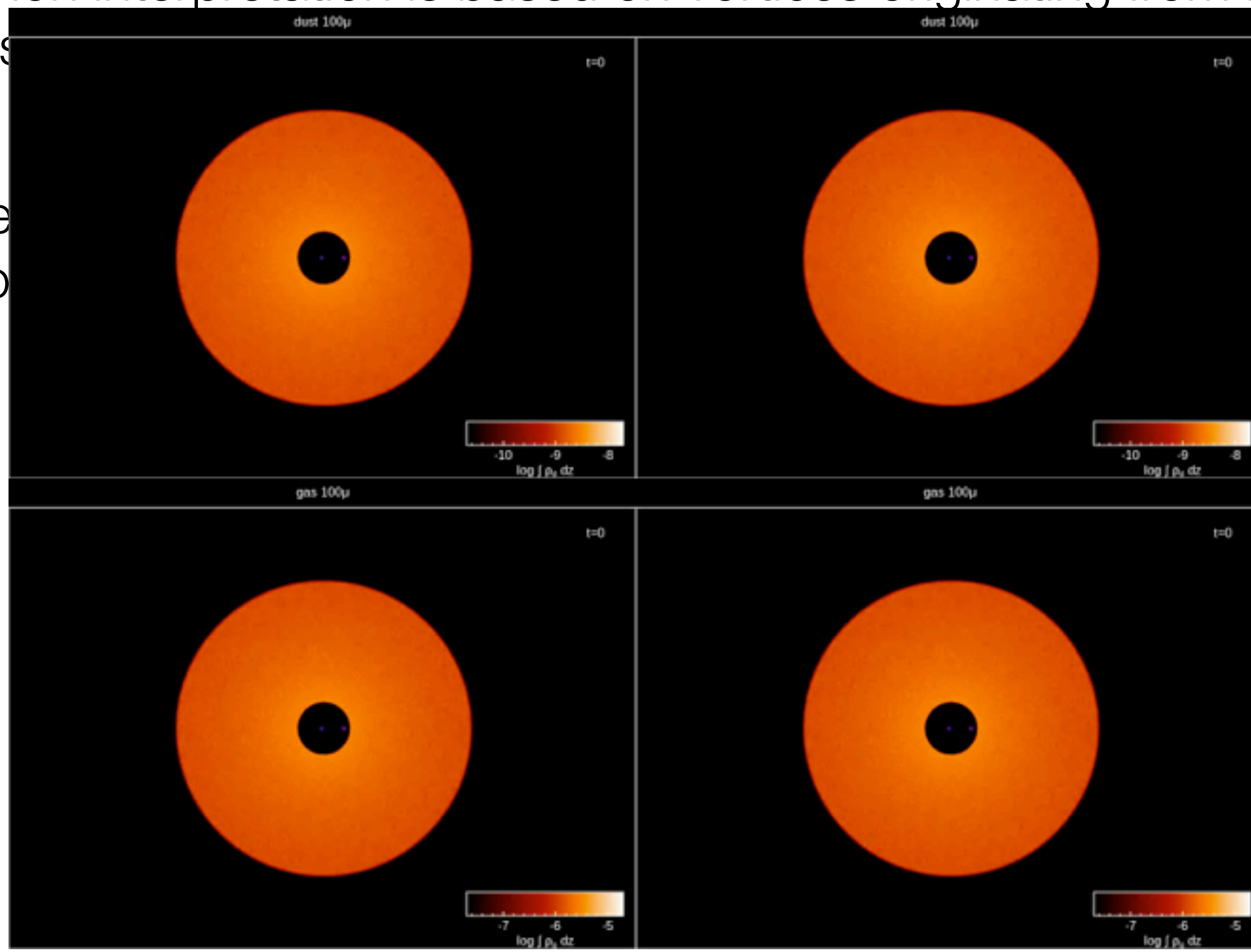

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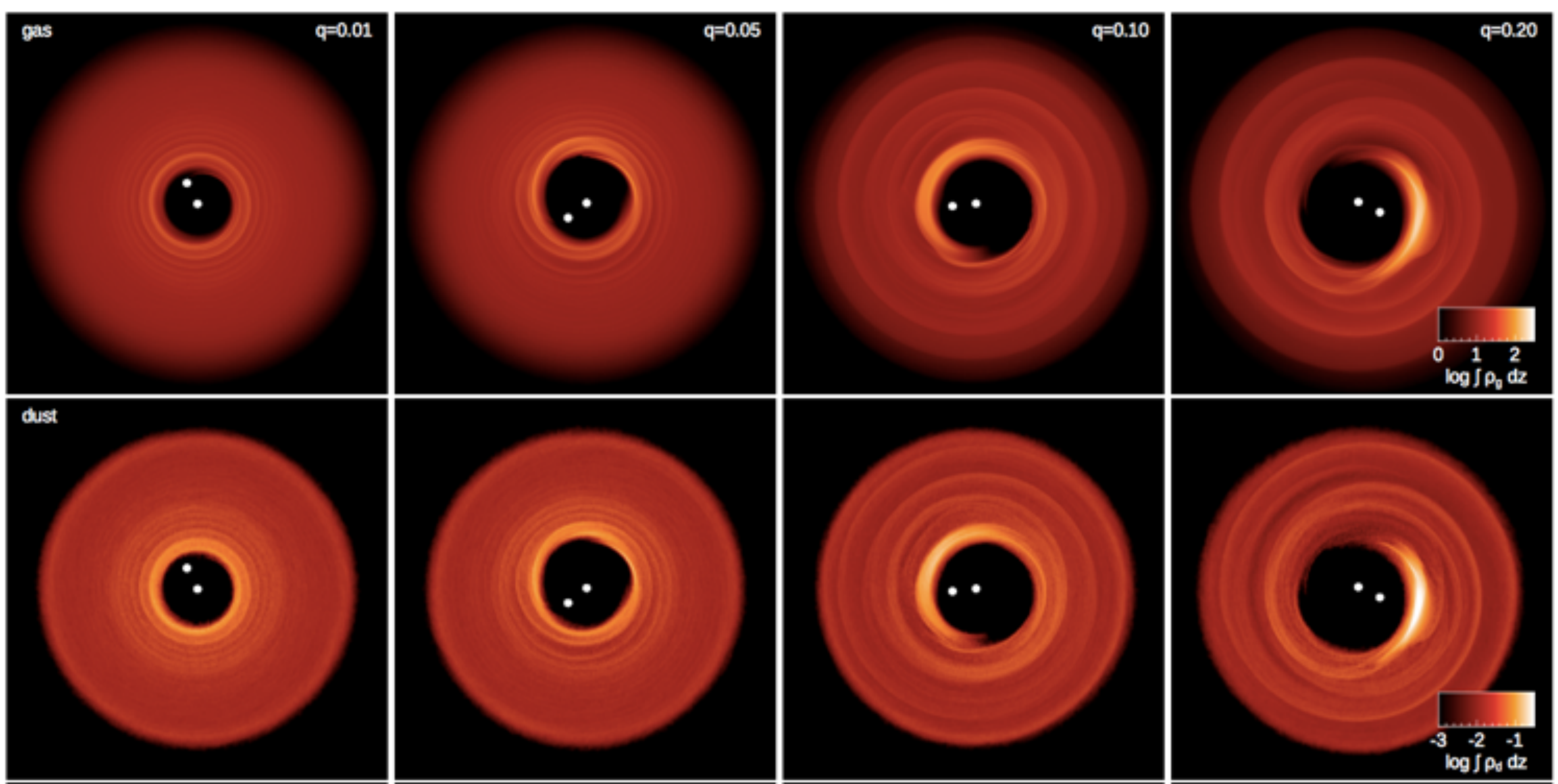

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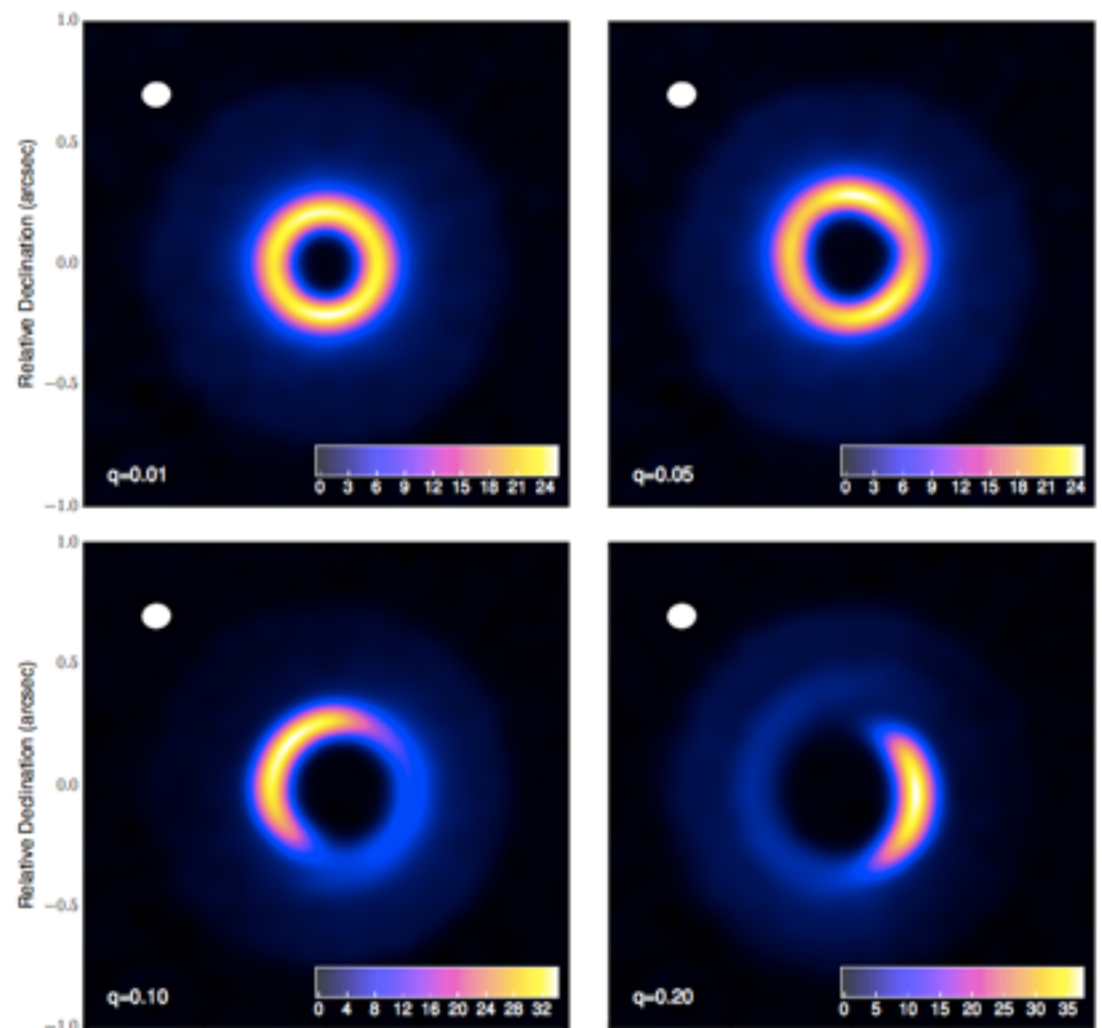

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Name	Contrast	Dust trapping	Companion	Consistency
HD135344B	$\lesssim 10$	No	Strong indication	Yes
SR 21	$\lesssim 10$	No	Indication	Yes
DoAr 44	$\lesssim 10$	?	?	Yes
IRS 48	$\gtrsim 100$	Yes	?	No
HD142527	~ 30	cm grains?	Yes	Yes
Lk Hα 330	$\lesssim 10$	?	Indication	Yes

Asymmetric cavities: binaries vs vortices

- This model only produces asymmetries at the cavity edge
- Require relatively massive companion
- Does not require low viscosity
- Structure depends on coupling with gas: strong coupling results in more concentrated “clump”
- If St $>\sim 1$, just produce an eccentric ring
- Expect structures to become wider azimuthally with increasing wavelength

Modeling HD142527

Price et al, in prep

- Very well studied object
- Lots of observational constraints
- **Large cavity**: inner edge at ~ 90au

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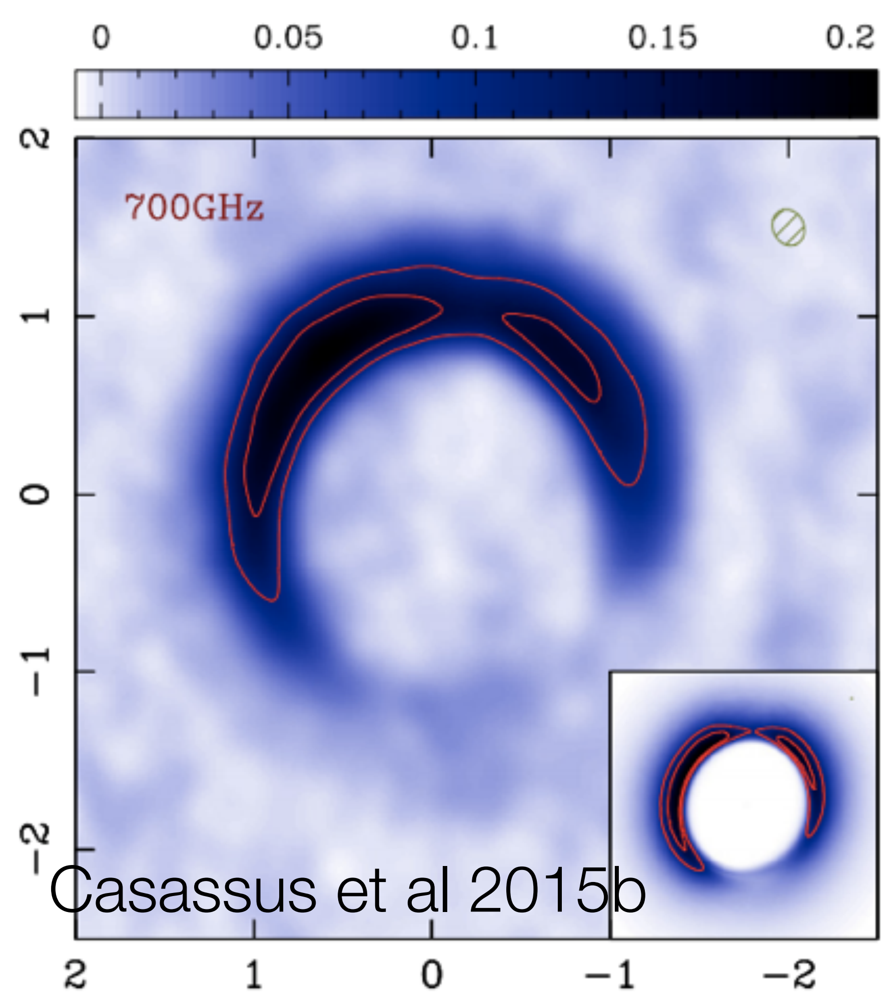

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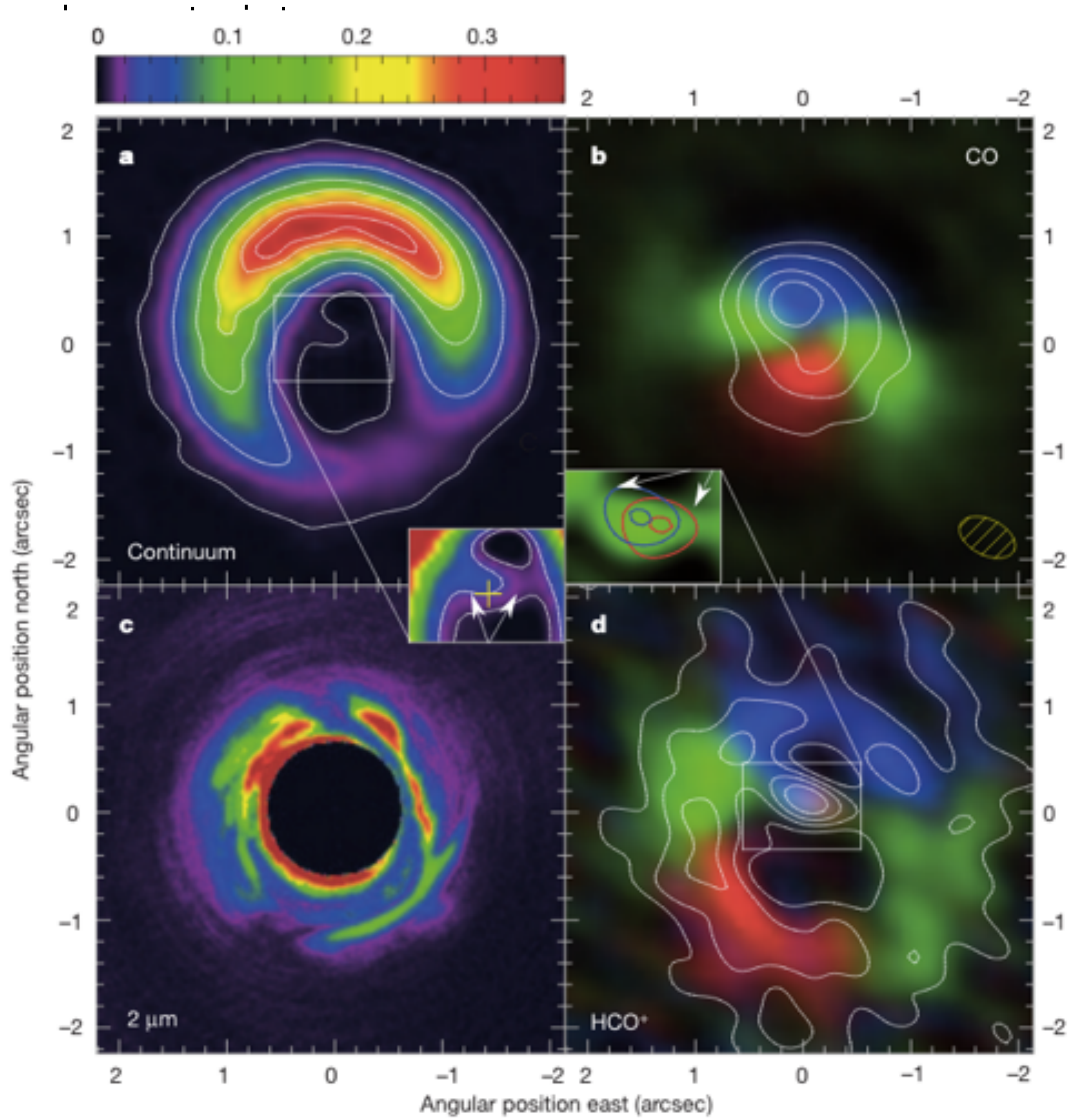

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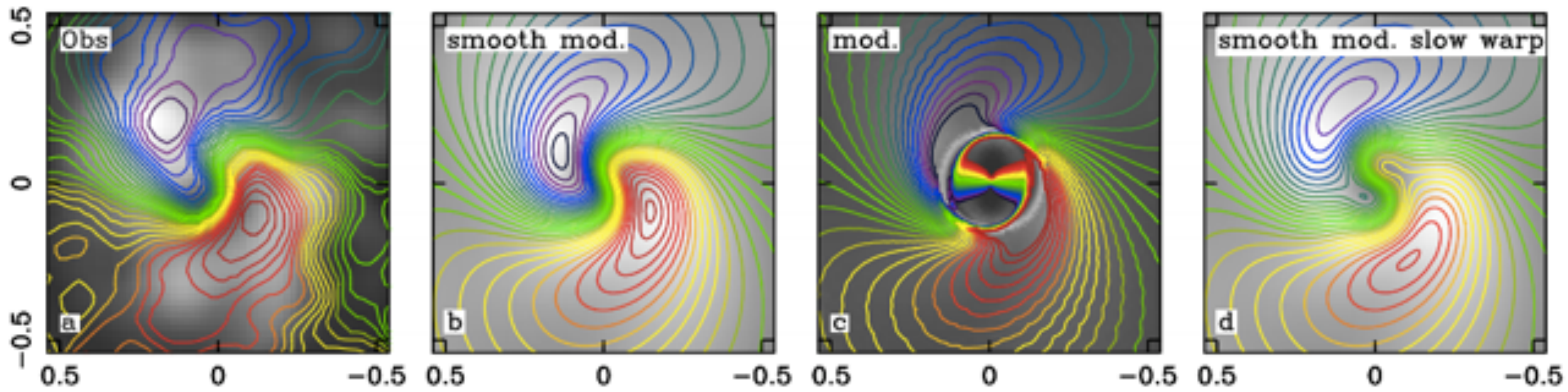

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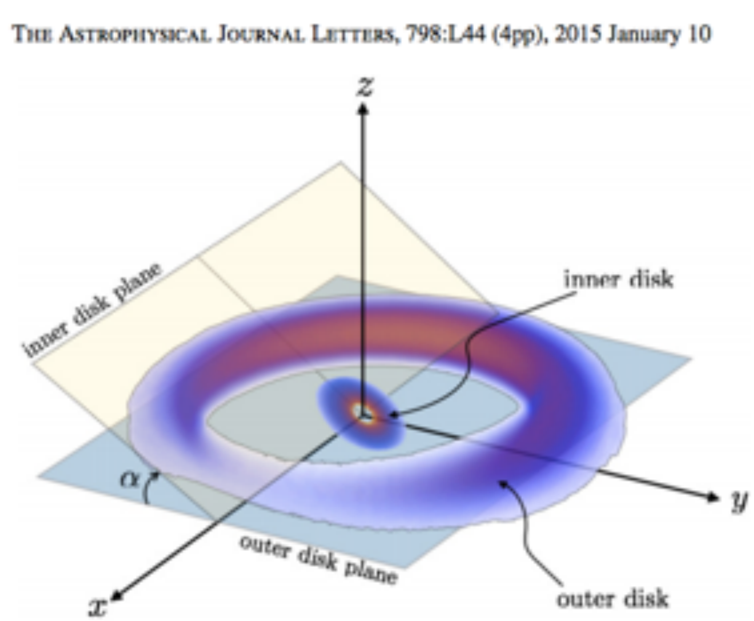

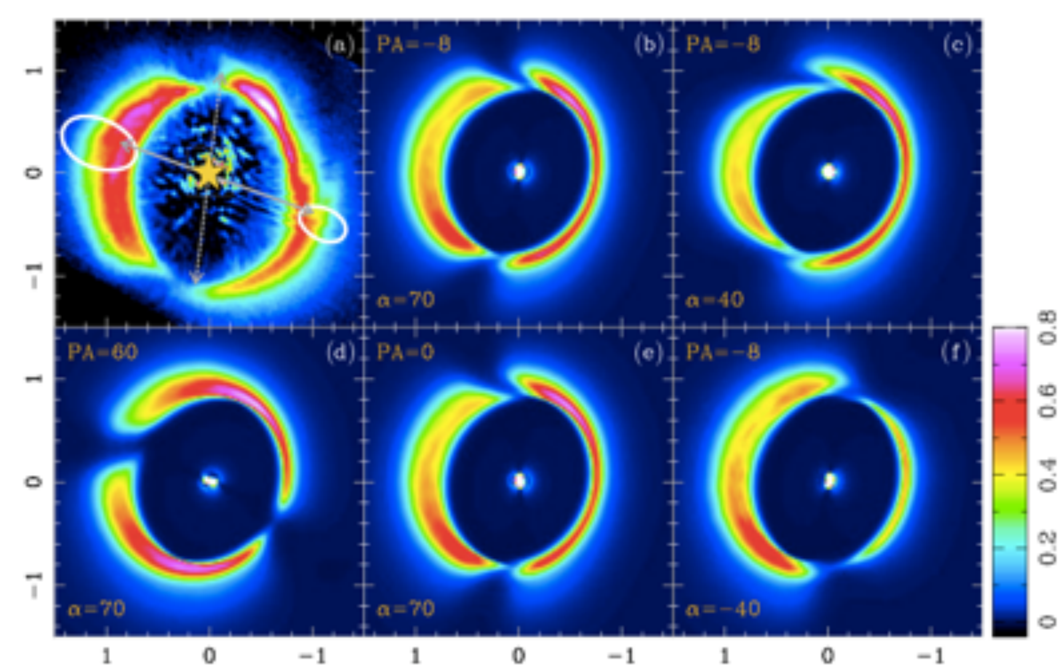

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- **Spirals** observed in scattered light and ALMA (Fukagawa et al 2006, Christiaens et al 2014)

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- **Large cavity**: inner edge at ~ 90au
- Cavity shows **fast filamentary flows** (Casassus et al. 2013), with M_{dot} ~ $10^{-(7-8)}$ M_{sun}/yr
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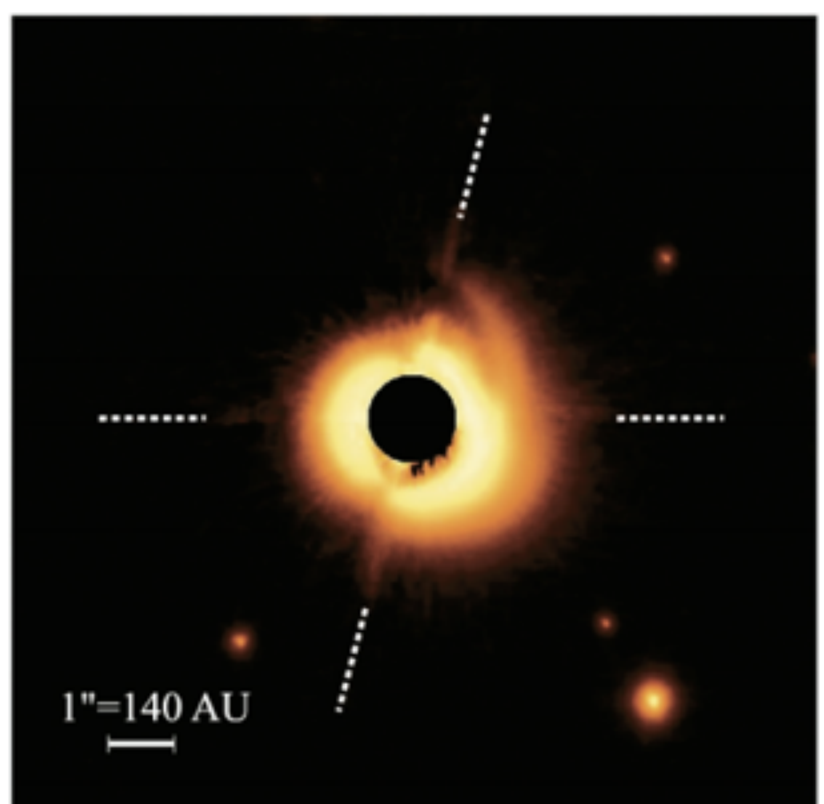

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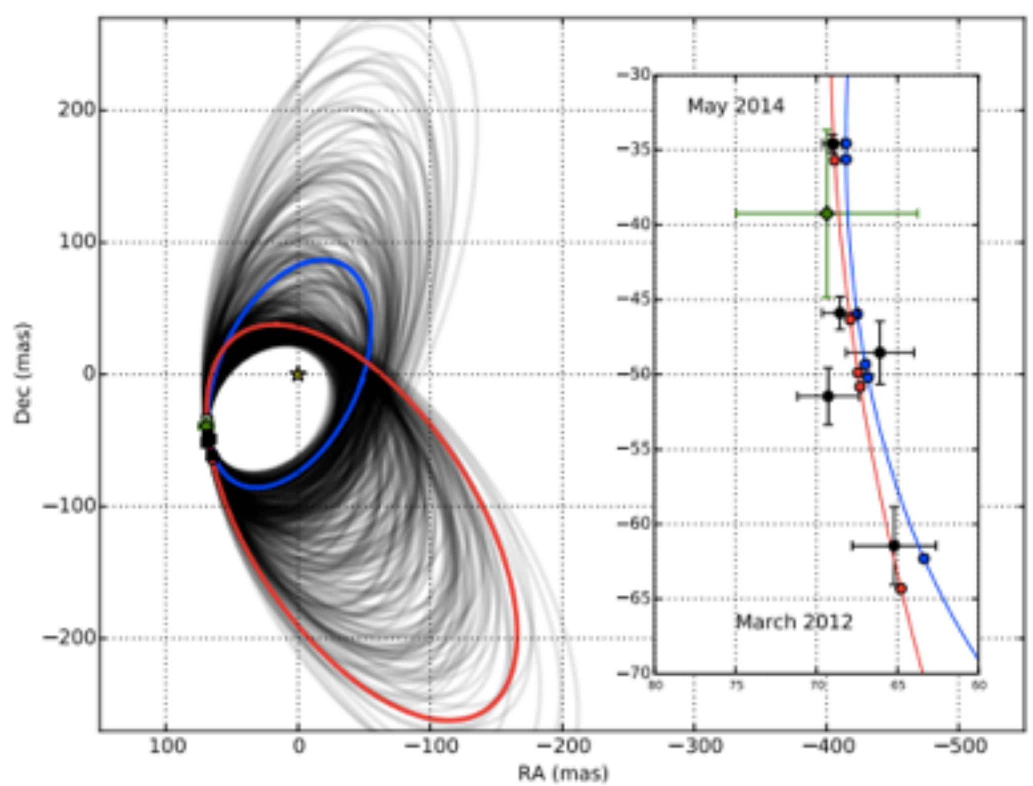

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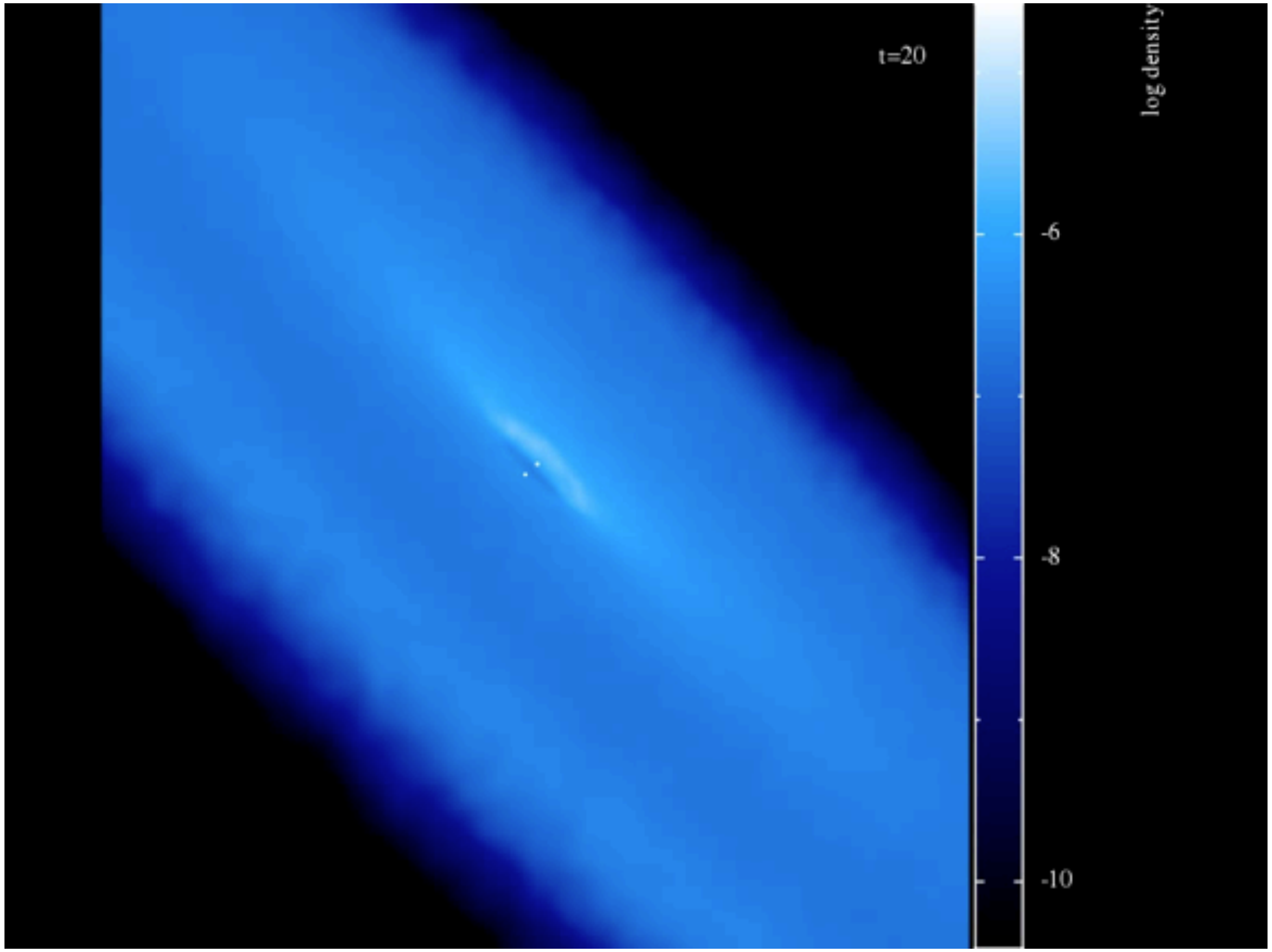

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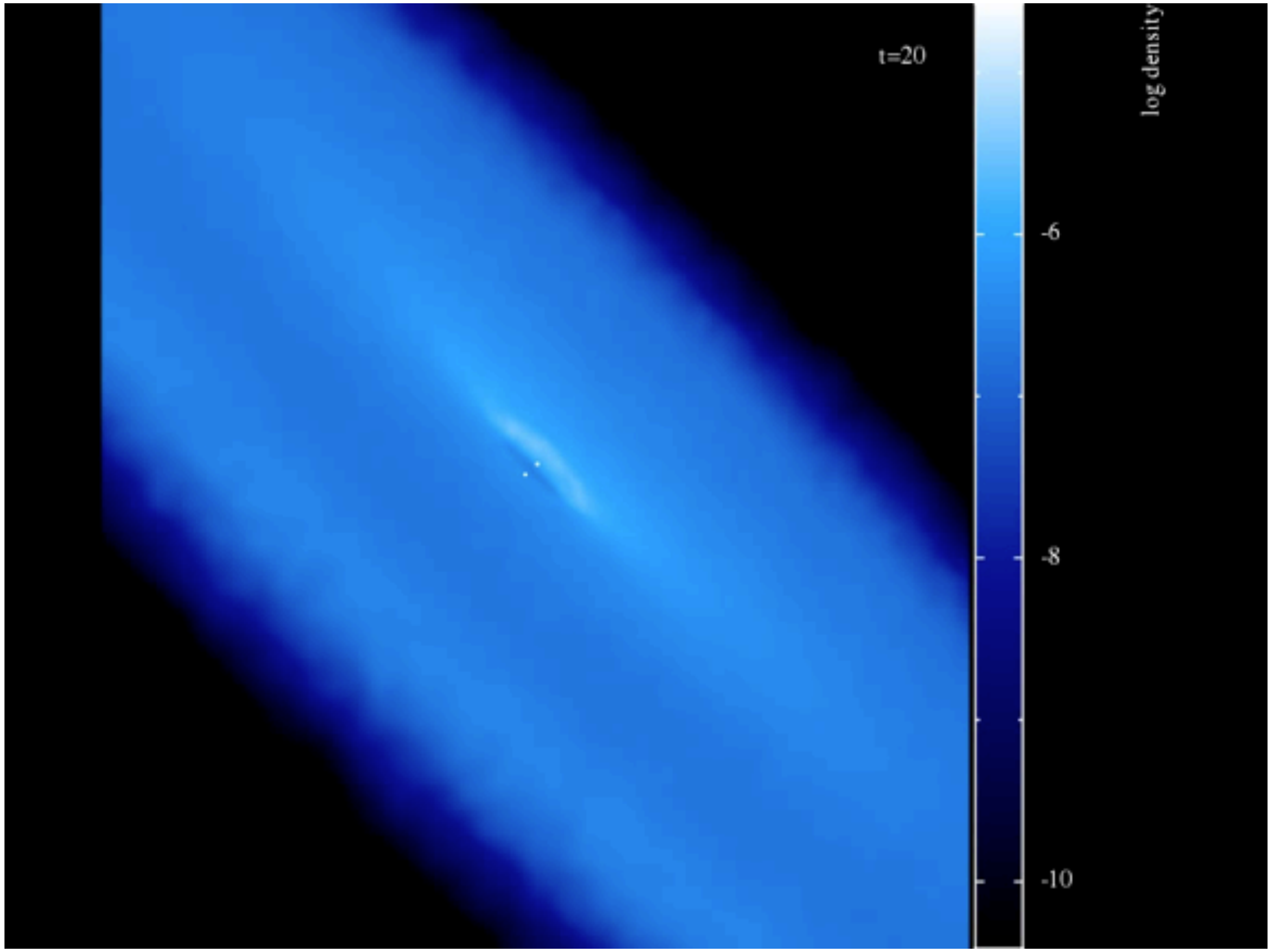

Modeling HD142527

- First attempt at modeling this
- Stellar mass: $1.8M_{sun}$
- Companion mass: $0.3M_{sun}$, a=25au, e=0.5
- Disc: R_{in}=30au, R_{out}=300au, inclined by 70deg wrt companion, 1M particles

Modeling HD142527

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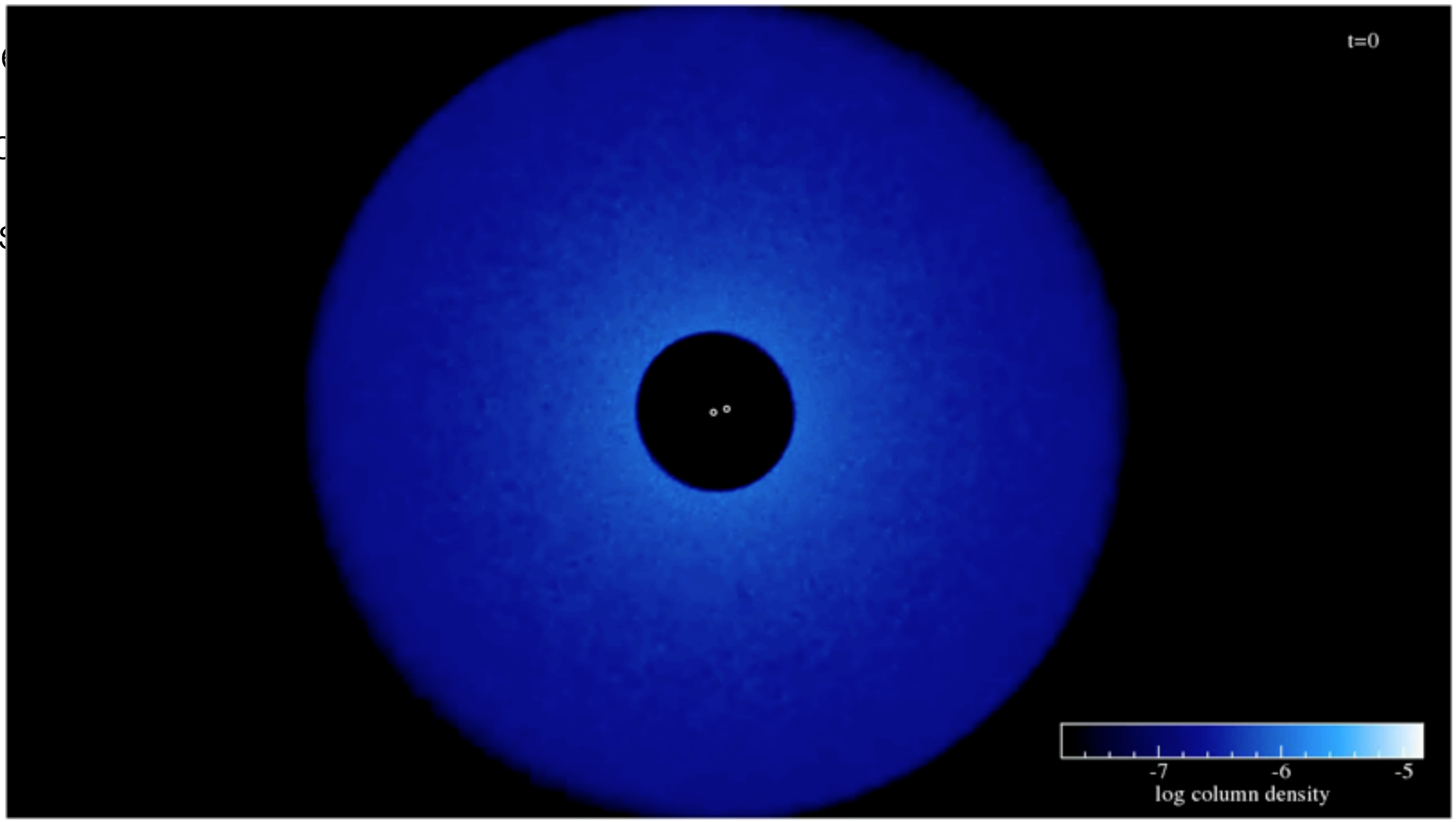
- Co
- Dis



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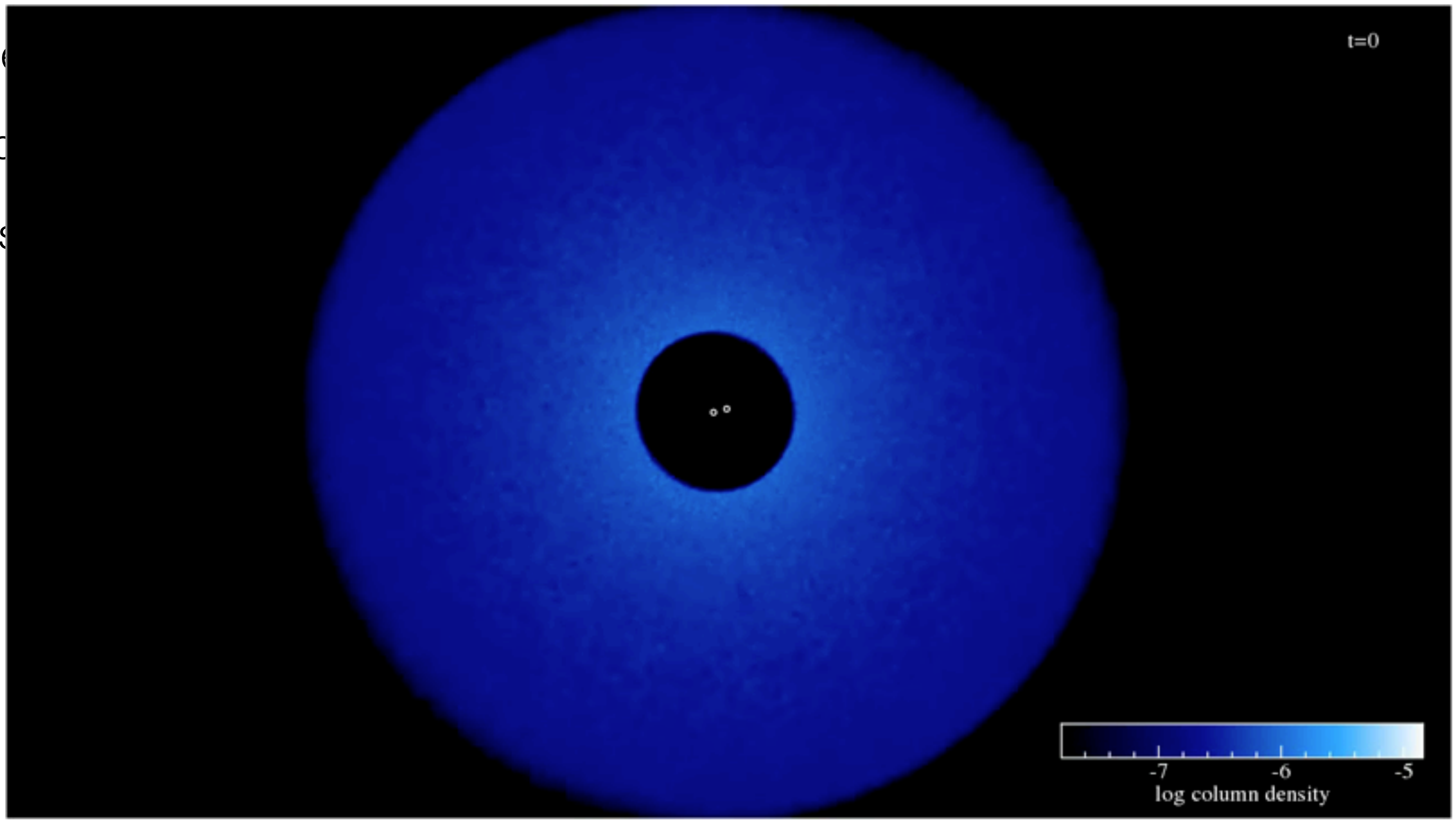


How rare is HD142527?

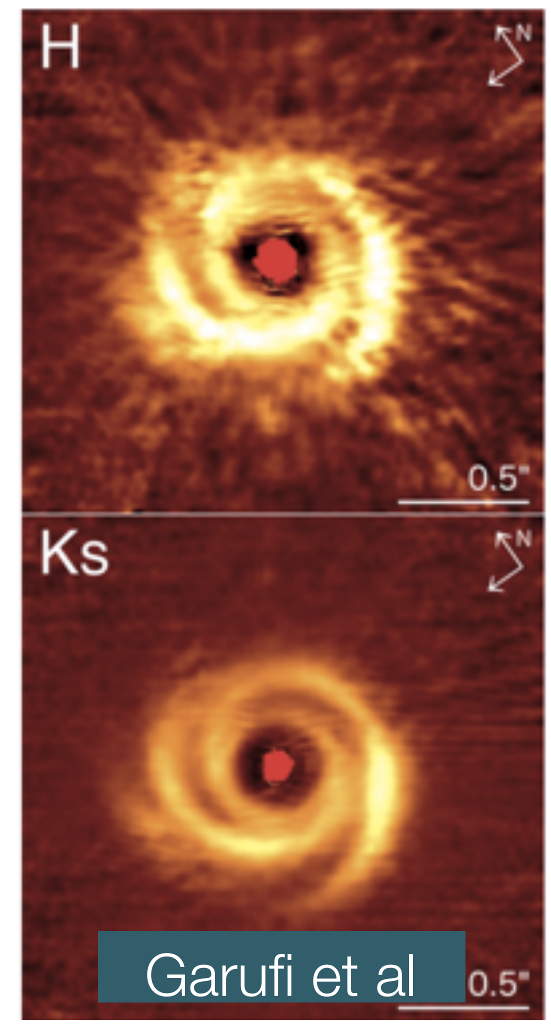
- HD135344B: shows shadows, possibly a warped inner disc, spirals, and a dust asymmetric structure

Shadows cast on the transition disk of HD 135344B ⋆,⋆⋆

Multi-wavelength VLT/SPHERE polarimetric differential imaging

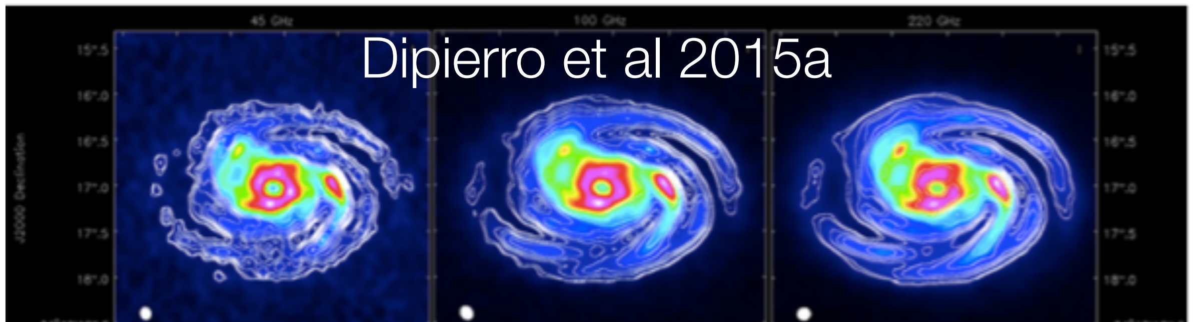
T. Stolker[1], C. Dominik[1], H. Avenhaus[2], M. Min[3,1], J. de Boer[4,5], C. Ginski[4], H.M. Schmid[6], A. Juhasz[7], A. Bazzon[6], L.B.F.M. Waters[3,1], A. Garufi[6], J.-C. Augereau[8,9], M. Benisty[8,9], A. Boccaletti[10], Th. Henning[11], A.-L. Maire[11], F. Ménard[12,2], M.R. Meyer[6], M. Langlois[13,14], C. Pinte[12,2], S.P. Quanz[6], C. Thalmann[6], J.-L. Beuzit[8,9], M. Carbillet[15], A. Costille[14], K. Dohlen[14], M. Feldt[11], D. Gisler[6], D. Mouillet[8,9], A. Pavlov[11], D. Perret[10], C. Petit[16], J. Pragt[17], S. Rochat[8,9], R. Roelfsema[17], B. Salasnich[18], C. Soenke[19], and F. Wildi[20]

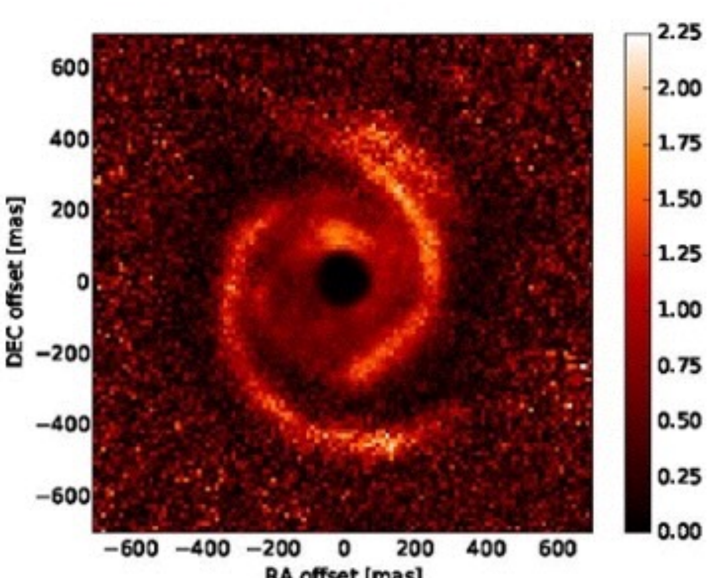
Conclusions. The shadows on the outer disk of HD 135344B could be cast by an inner dust belt which is 22° inclined with respect to the outer disk, a warped disk region which connects the inner disk with the cavity and an accretion funnel flow from the inner disk onto the star. The wide open spiral arms indicate the presence of one or multiple massive protoplanets, a local disk instability beyond the dust cavity or a combination of the two.



The Bill

The Bill

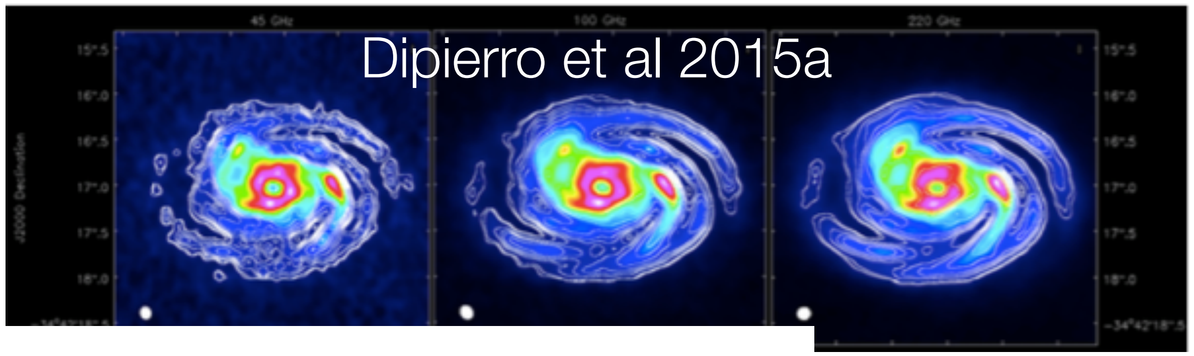

Dipierro et al 2015a



Benisty et al 2015

Everything on spirals
Kratter & Lodato, ARA&A, 2016

The Bill



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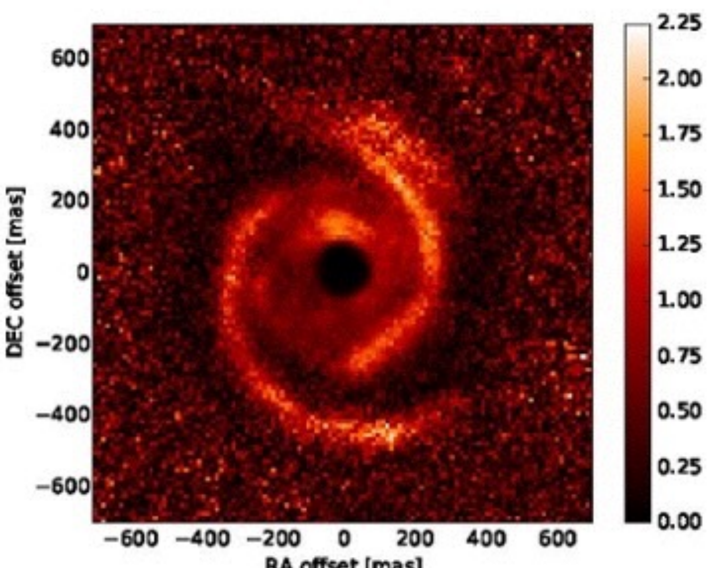

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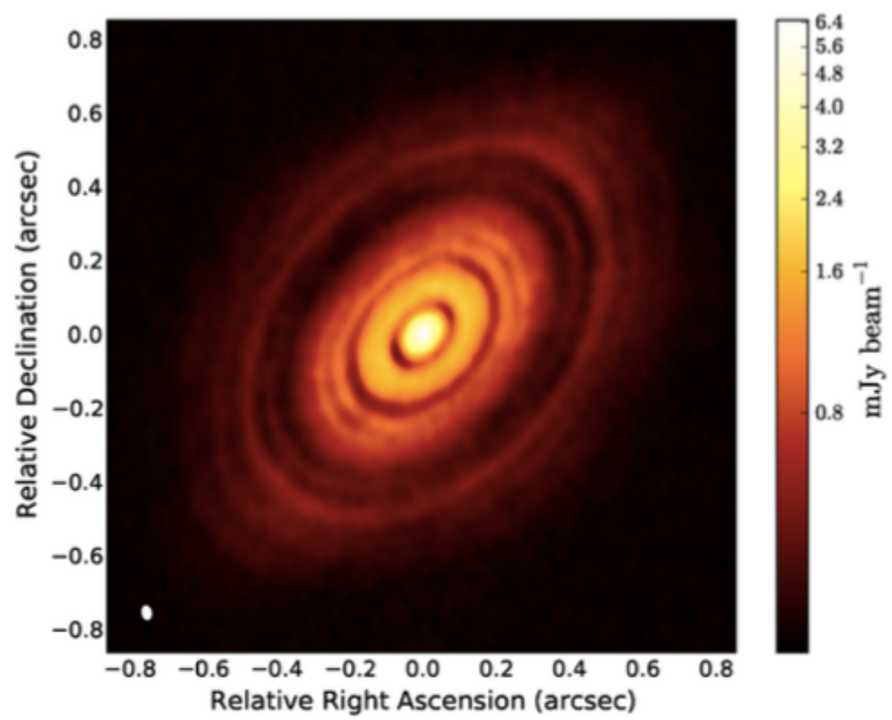
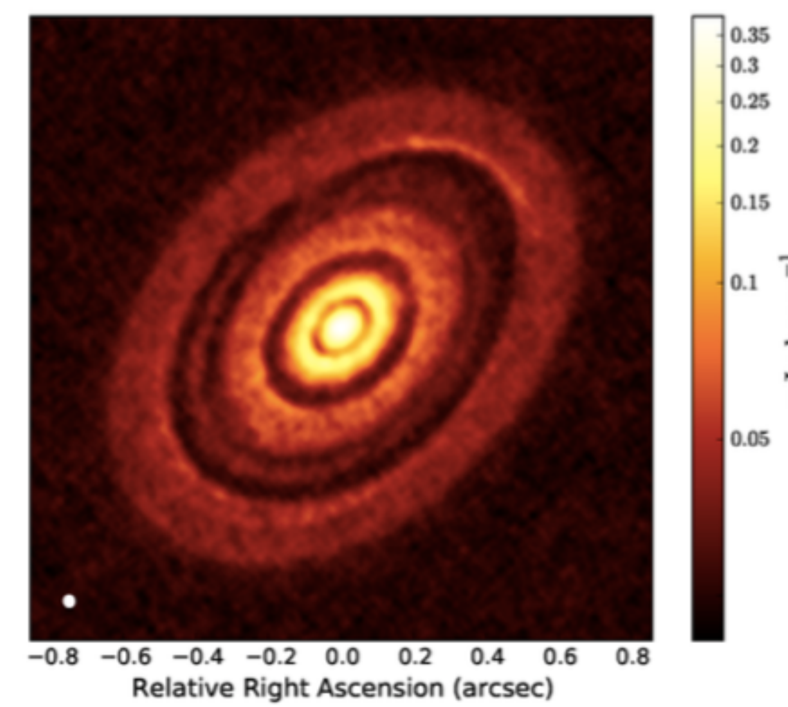


ALMA Partnership (2015)



Dipierro et al (2015)

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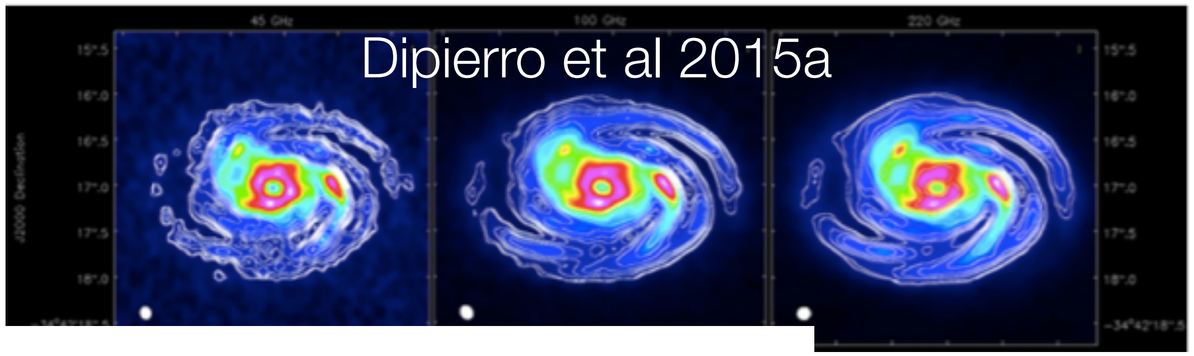

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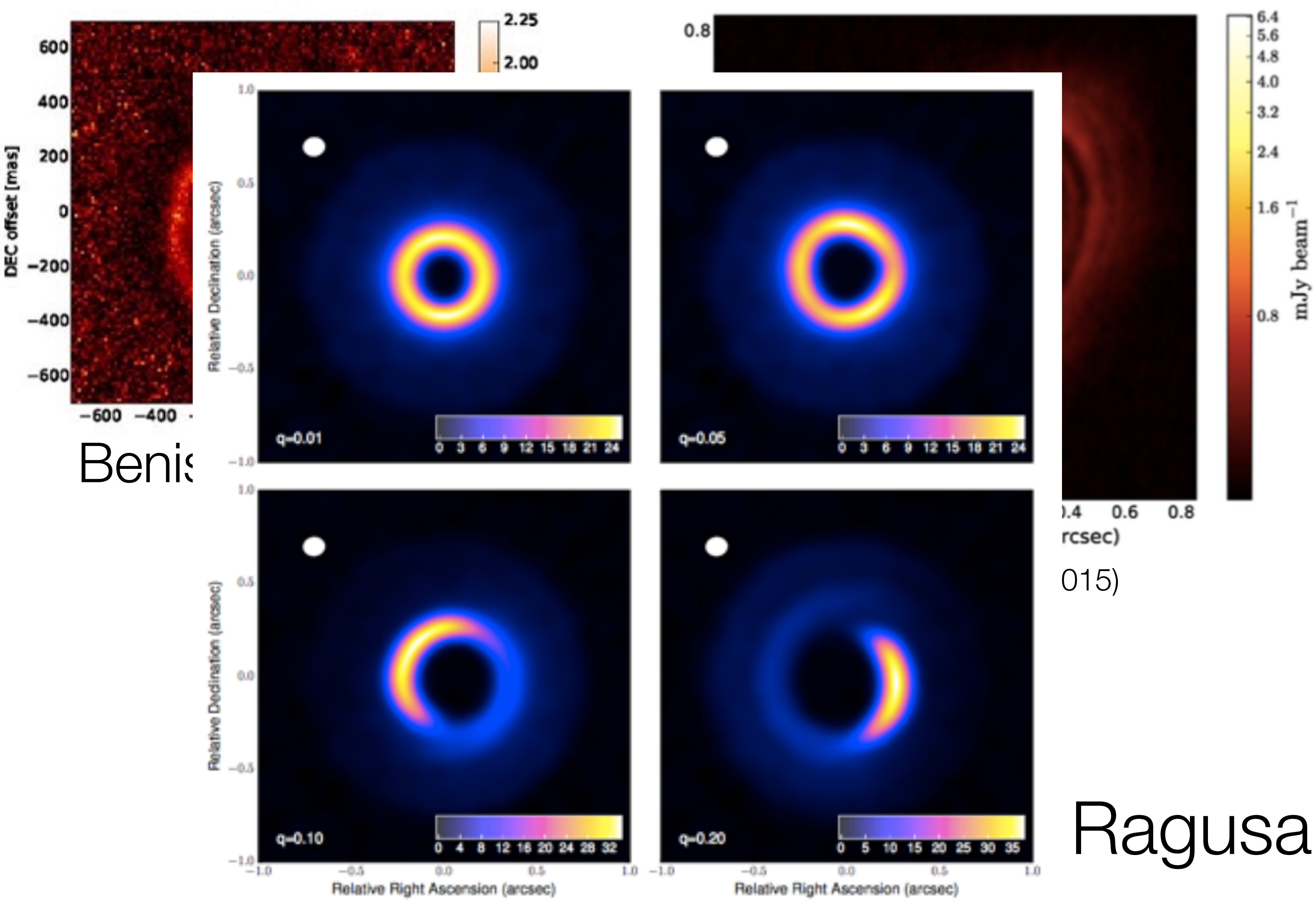

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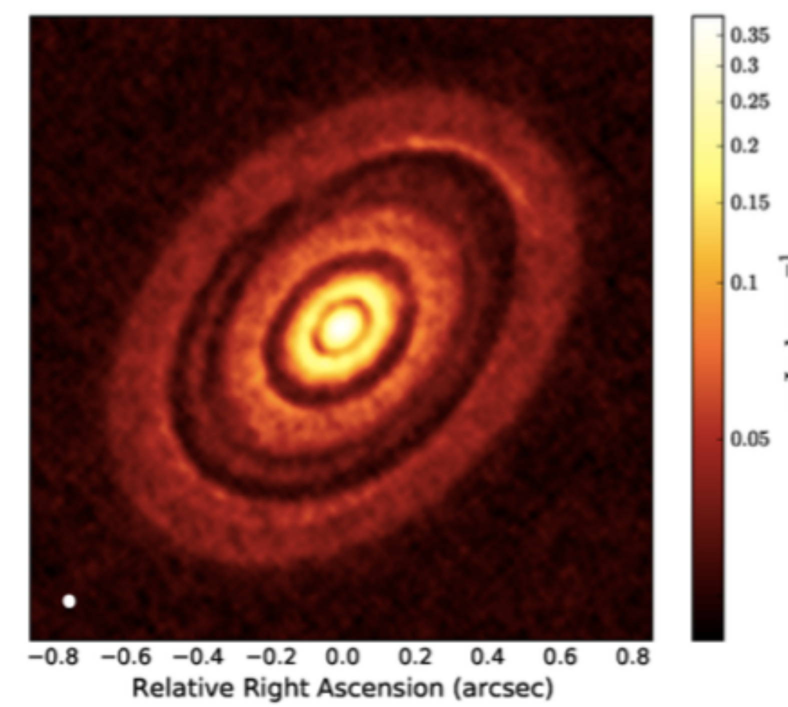

Dipierro et al (2015)

Ragusa et al 2016