MONASH University

MoCA Monash Centre for Astrophysics

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DUST BUSTERS

STAR FORMATION AND THE ROLE OF MAGNETIC FIELDS AND TURBULENCE

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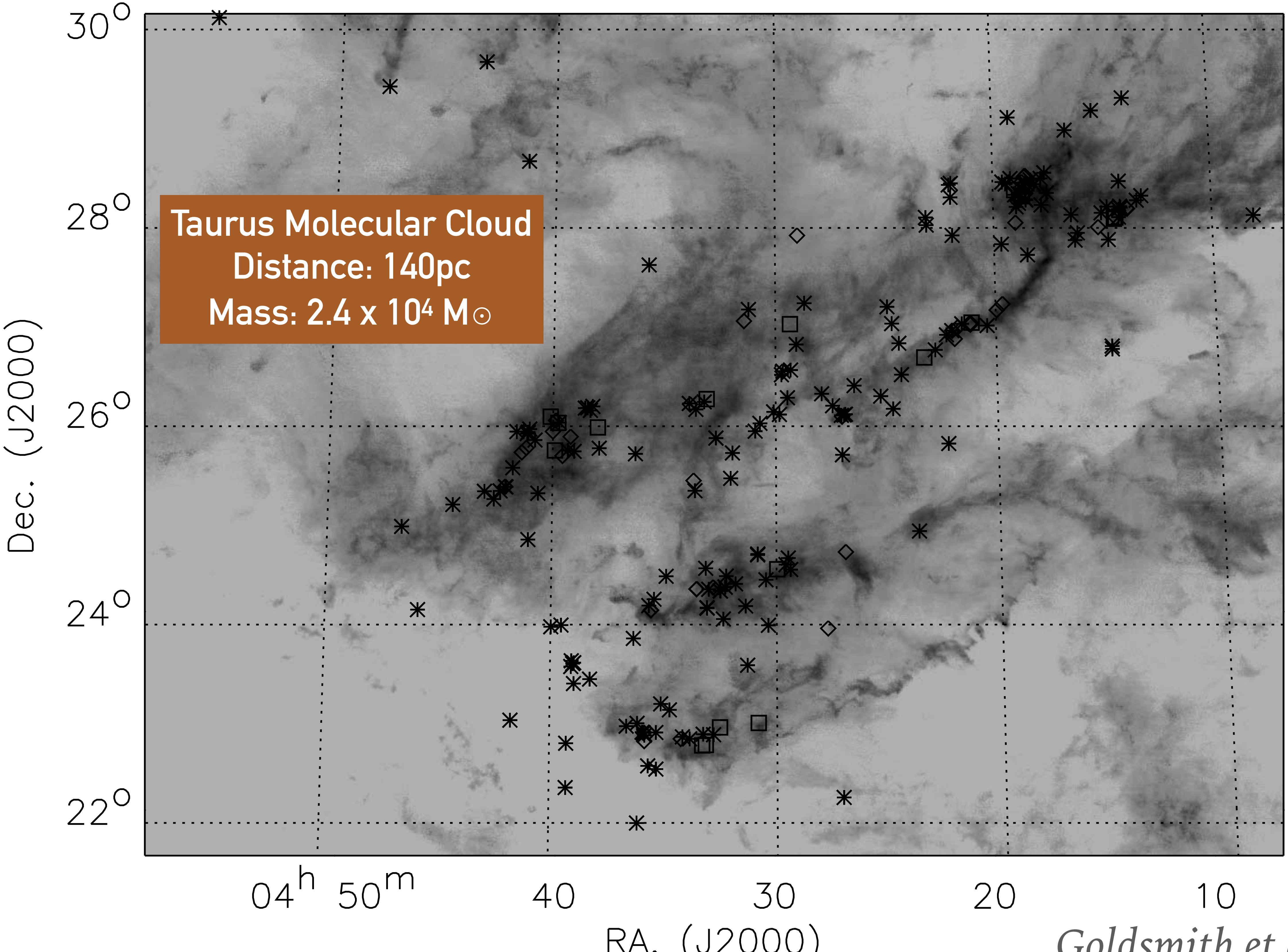
Stars, Planets & Galaxies, Berlin, April 13th-18th 2018

QUESTIONS

- Star formation: slow or fast?
- Planet formation: slow or fast?


The night sky near my house
Credit: Alex Cherney, terrastro.com

STAR FORMATION IN NEARBY MOLECULAR CLOUDS



Goldsmith et al. (2008)

TRADITIONAL VIEW

MAGNETICALLY CONTROLLED (SLOW) STAR FORMATION

72 SHU, ADAMS & LIZANO

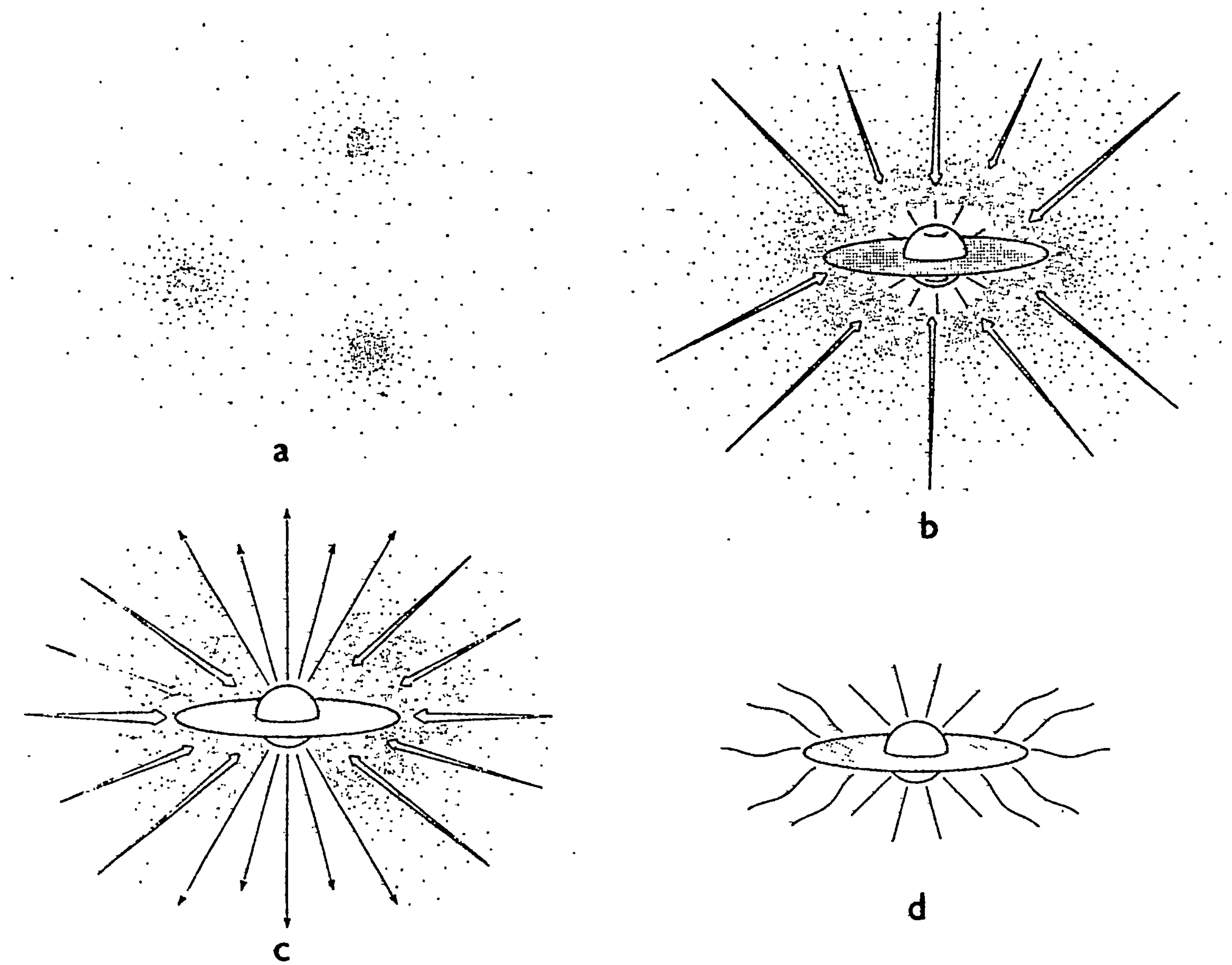
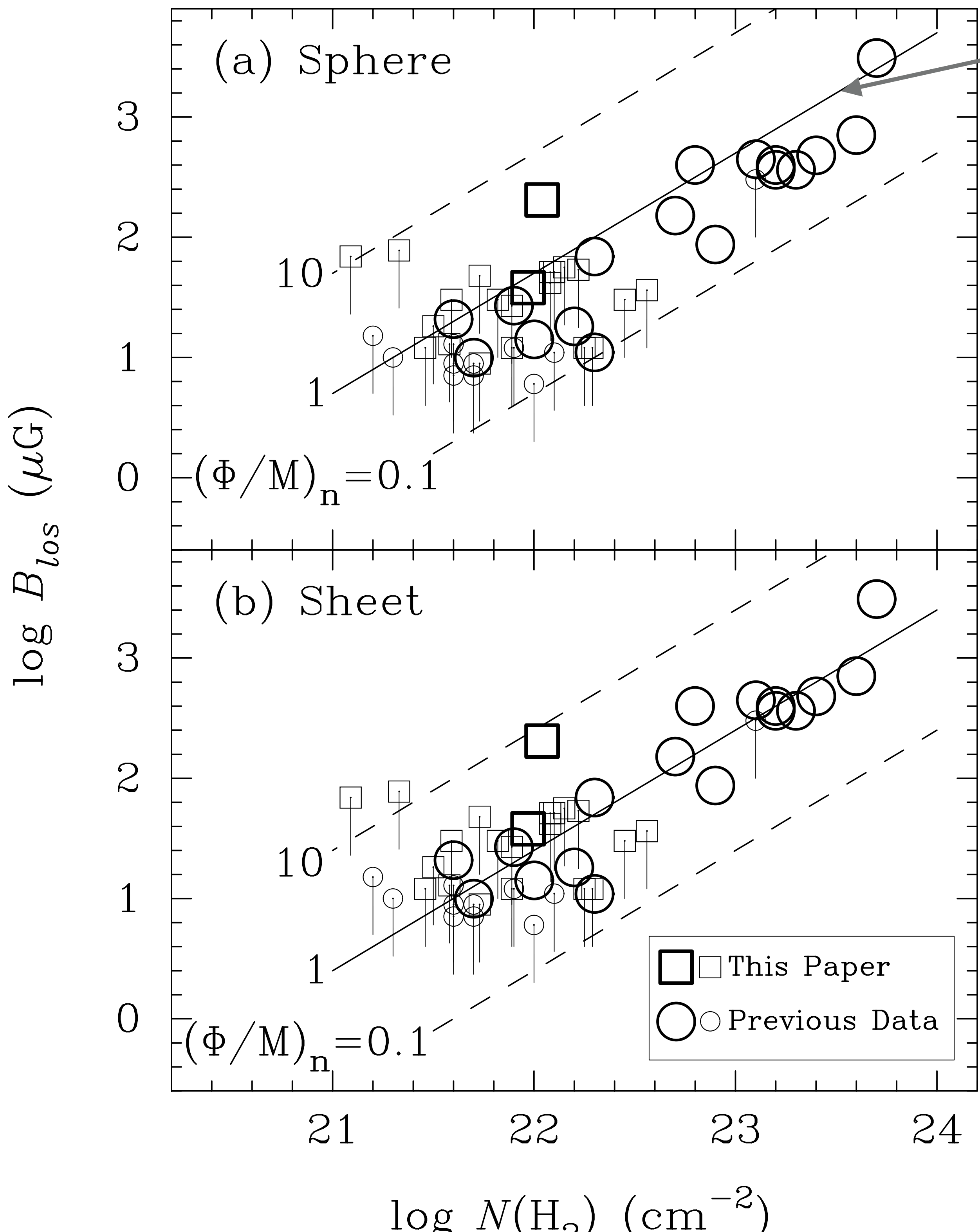


Figure 7 The four stages of star formation. (*a*) Cores form within molecular clouds as magnetic and turbulent support is lost through ambipolar diffusion. (*b*) A protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (*c*) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (*d*) The infall terminates, revealing a newly formed star with a circumstellar disk.

Shu, Adams & Lizano (1987)

MAGNETIC FIELDS

e.g. Crutcher (1999, 2012), Bourke et al. (2001), Heiles & Crutcher (2005), Crutcher et al. (2010)



Critical mass to flux ratio to prevent gravitational collapse

Field strengths too small to prevent collapse!

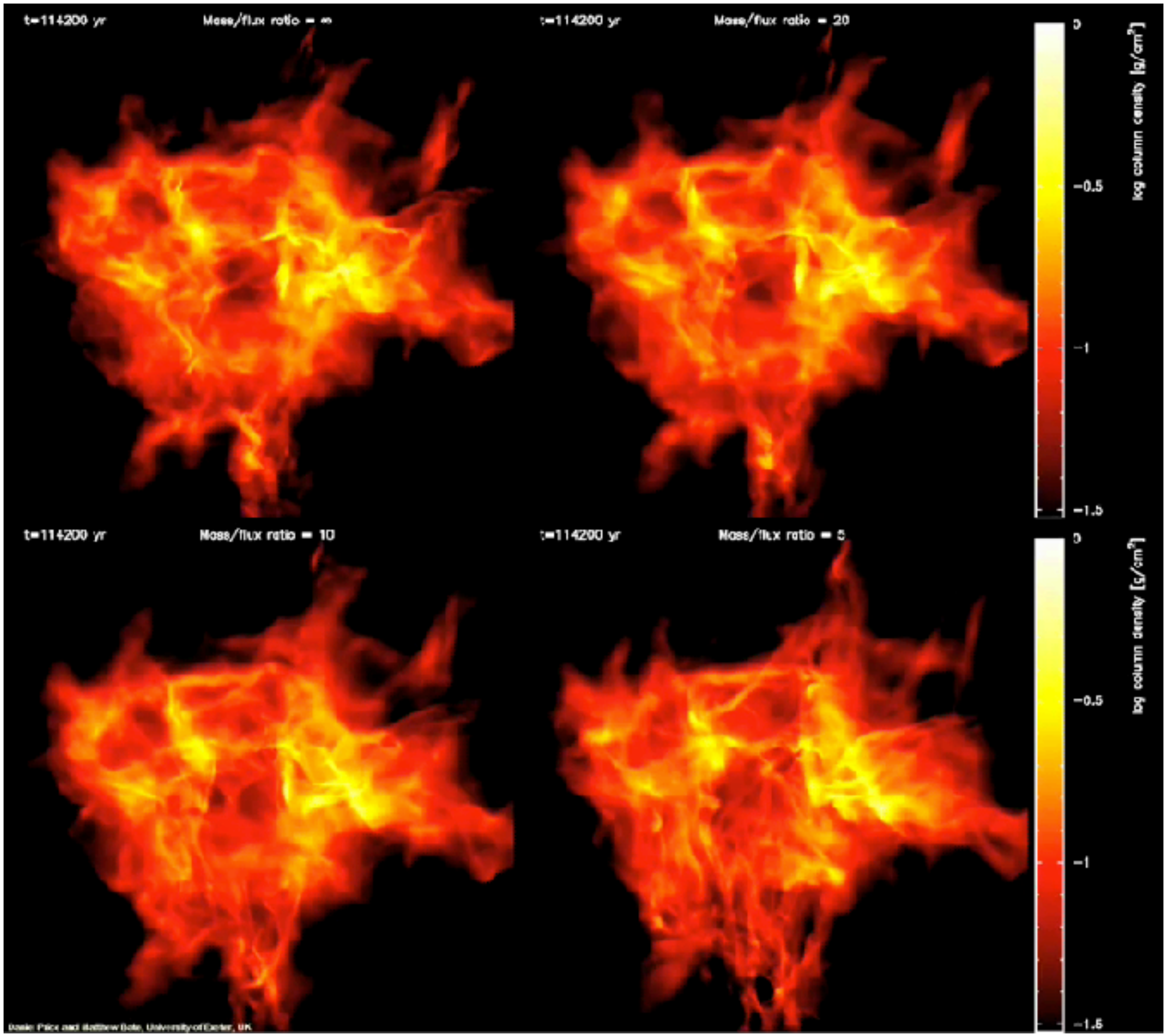
Lots of other arguments against slow star formation (see review by Mac Low & Klessen 2004)

TURBULENCE AND MAGNETIC FIELDS

Goldsmith et al. (2008)

Motions aligned with magnetic field (Heyer et al. 2008)

TURBULENCE-CONTROLLED STAR CLUSTER FORMATION



Price & Bate (2008, 2008)

Effect of magnetic fields:

Slower star formation rate:

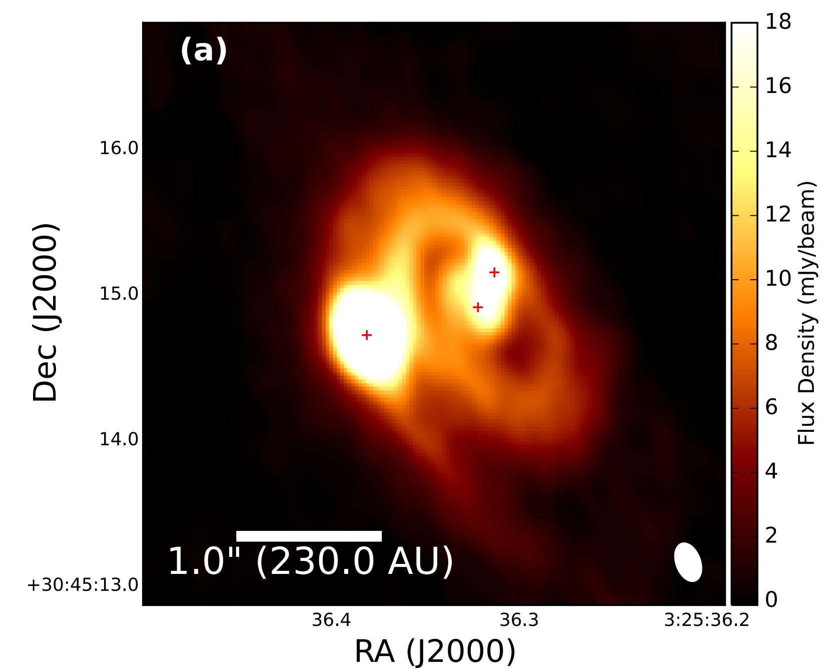
Star formation less inefficient

Supercritical mass-to-flux ratios: magnetic fields do not prevent collapse

CHARACTERISTICS OF TURBULENCE-CONTROLLED STAR FORMATION

- Fast, occurs on dynamical time(~1-2Myr)
- Chaotic; dynamical interactions common
- Initial mass function arises from competition for mass
- Binary and multiple stars usual outcome
- Massive, gravitationally unstable discs in early phase
- Filaments! (c.f. Philippe André's talk)

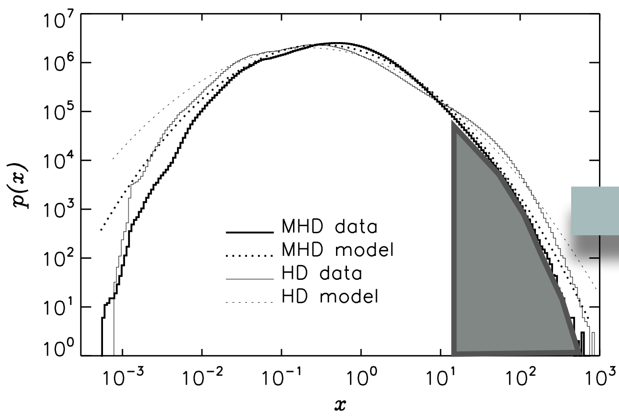
e.g. Larson (1978, 1981), Pringle (1989), Bate & Bonnell (1994a,b), Mac Low et al. (1999), Stone et al. (1998), Klessen et al. (2000), Bate et al. (2003), Elmegreen (2000), Mac Low & Klessen (2004), Bate & Bonnell (2005), Bonnell & Bate (2006), Bate (2009, 2012), Bate, Lodato & Pringle (2010)

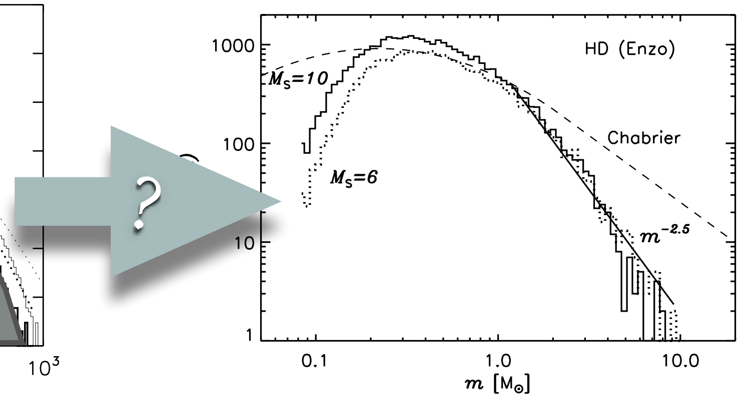


Tobin et al. (2016)

DOES TURBULENCE DETERMINE THE INITIAL MASS FUNCTION?

Liptai et al. (2017), see also Bertelli-Motta et al. (2016)



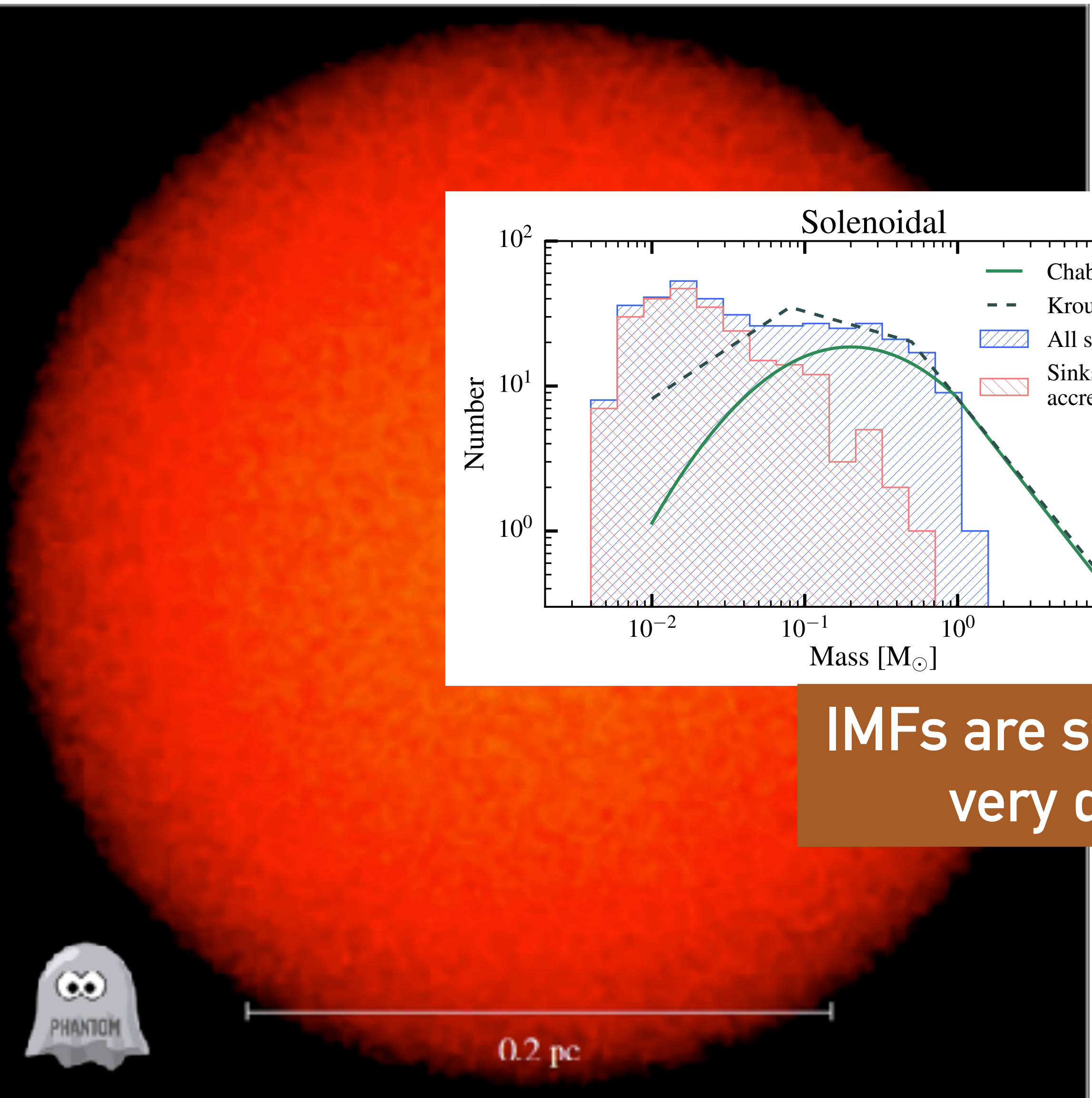


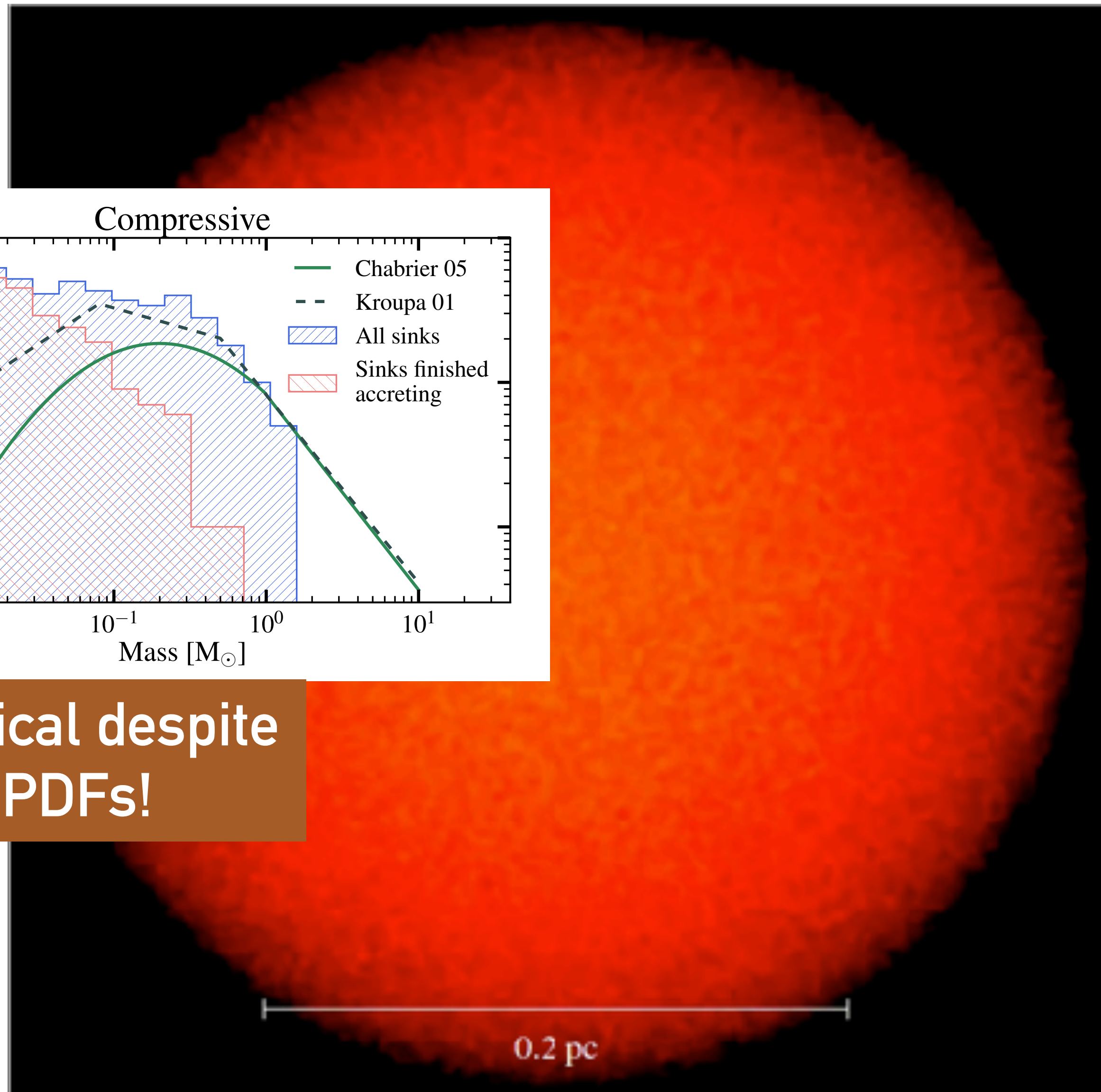
$$N(m)d\log m \propto m^{-3/(4-\beta)}\left[\int_0^m p(m_J)dm_J\right]d\log m\,.$$

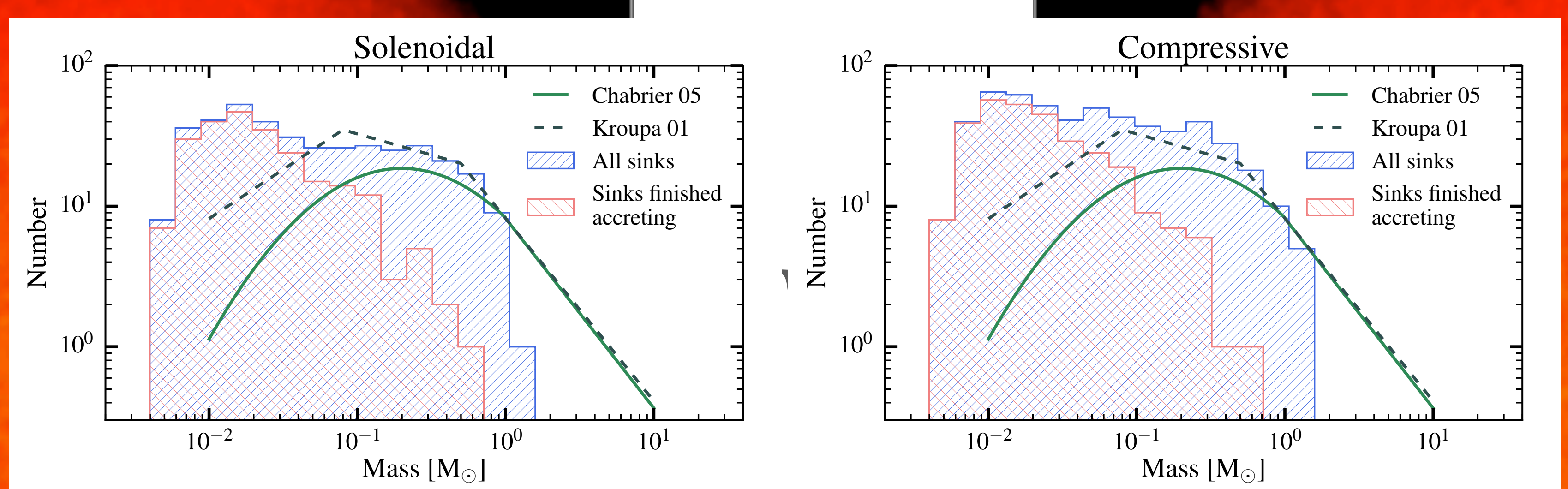
Can we map the PDF to the IMF?

e.g. Padoan and Nordlund (2002), Hennebelle & Chabrier (2008,2009), Hopkins (2012)

See Simon White's talk!

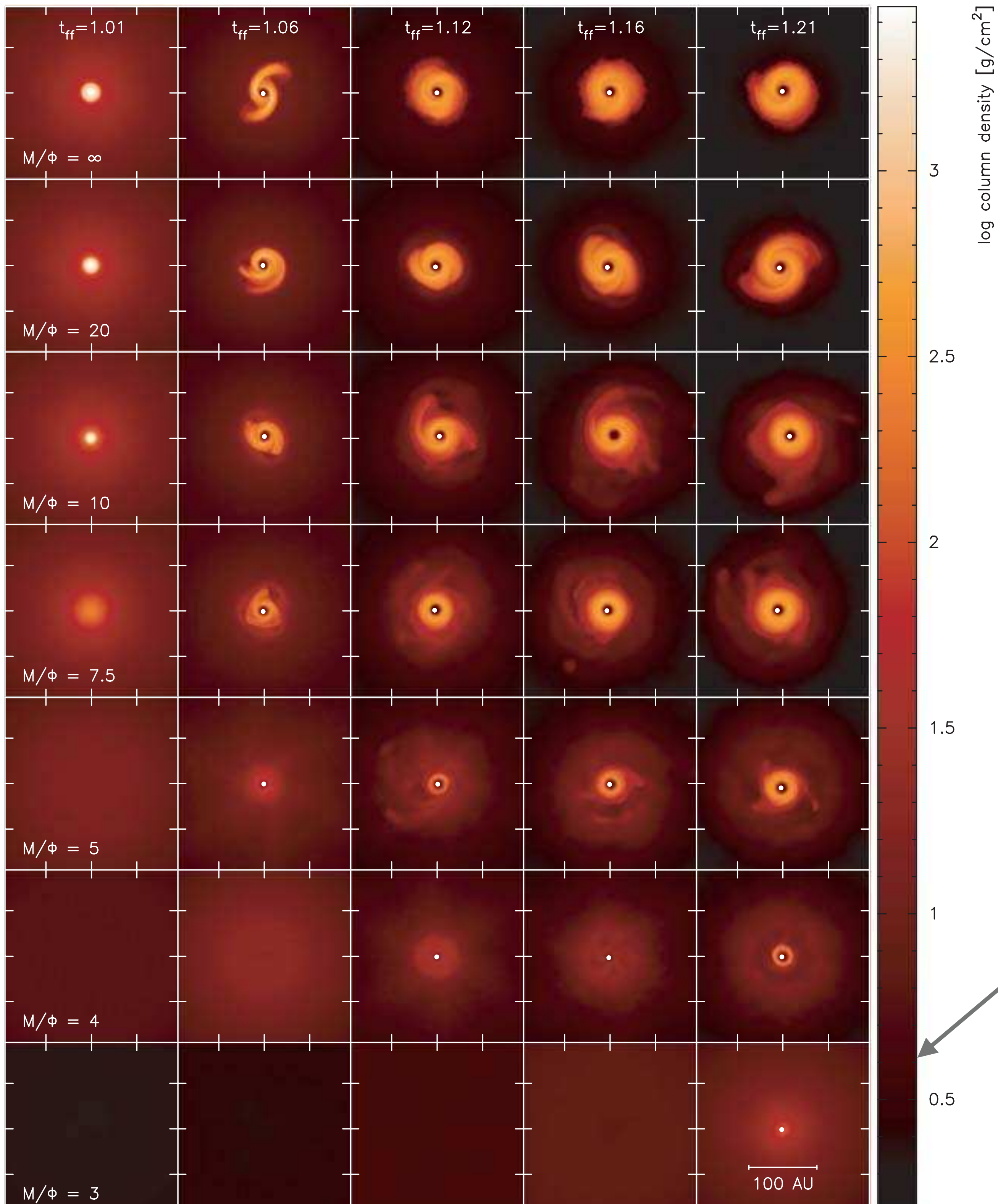






IMFs are statistically identical despite very different density PDFs!

SMALL SCALES: MAGNETIC BRAKING CATASTROPHE



Price & Bate (2007)

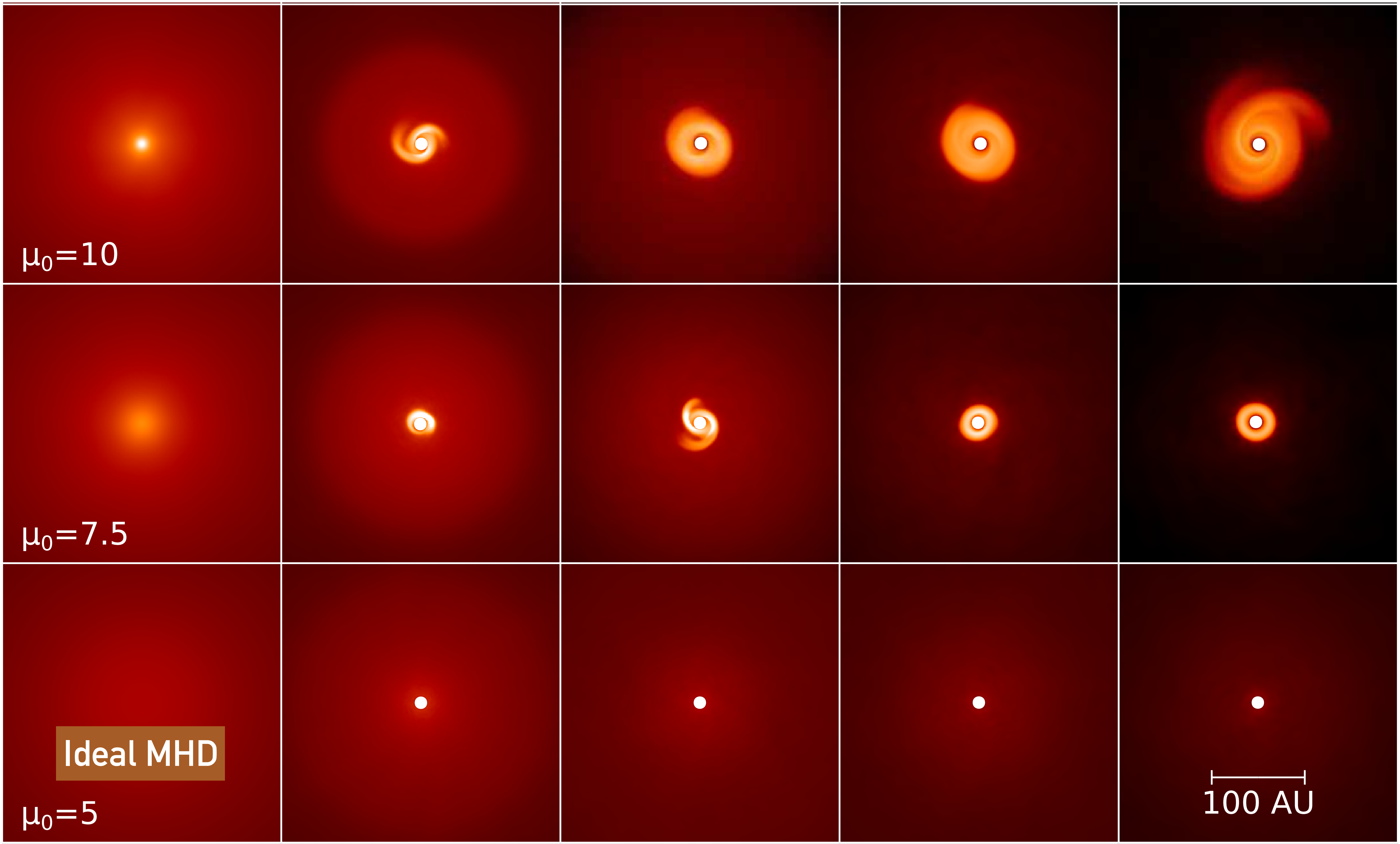
see Allen et al. (2003), Galli et al. (2006), Price & Bate (2007), Mellon & Li (2008), Hennebelle & Fromang (2008), Commerçon et al. (2010), Krasnopolsky et al. (2010), Seifried et al. (2012), Santos-Lima et al. (2012), Joos et al. (2013) and many others

No discs in models with realistic magnetic field strengths

But assumed ideal MHD!

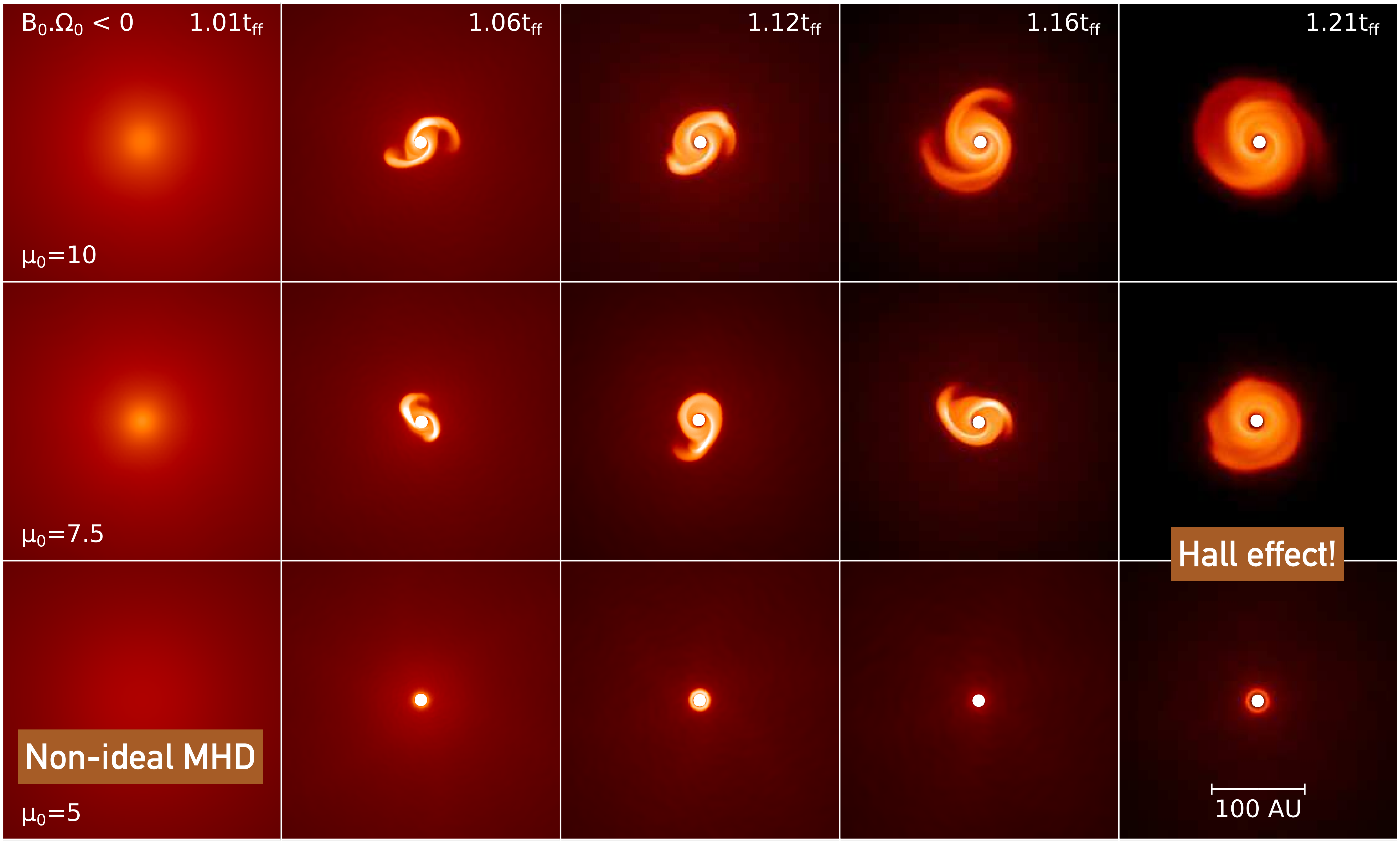
CAN NON-IDEAL MHD SOLVE THE MAGNETIC BRAKING CATASTROPHE?

Wurster, Price & Bate (2016)



CAN NON-IDEAL MHD SOLVE THE MAGNETIC BRAKING CATASTROPHE?

Wurster, Price & Bate (2016)

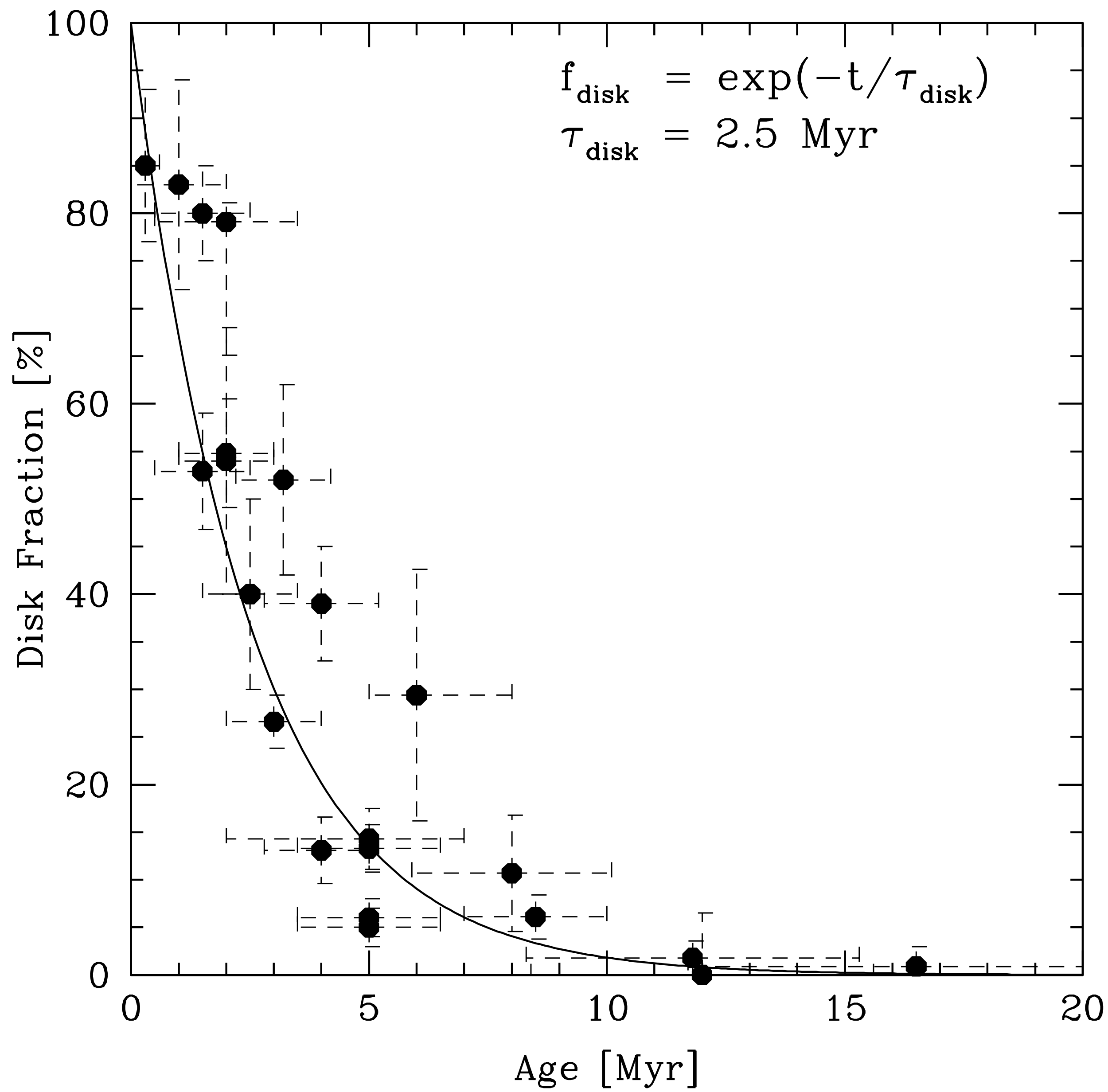


Likely answer is combination of non-ideal MHD and turbulence

STAR FORMATION: SUMMARY

- Star formation is fast: Governed by turbulence on large scales (pc)
- Magnetic fields do not prevent gravitational collapse, but may help set star formation rate
- Magnetic braking catastrophe on small scales (~100 au) can be solved with turbulence + non-ideal MHD
- Dynamical interactions, radiation + non-ideal MHD dominate on scales < 100 au
- No fossil fields in stars (embargoed)

PLANET FORMATION – FAST OR SLOW?

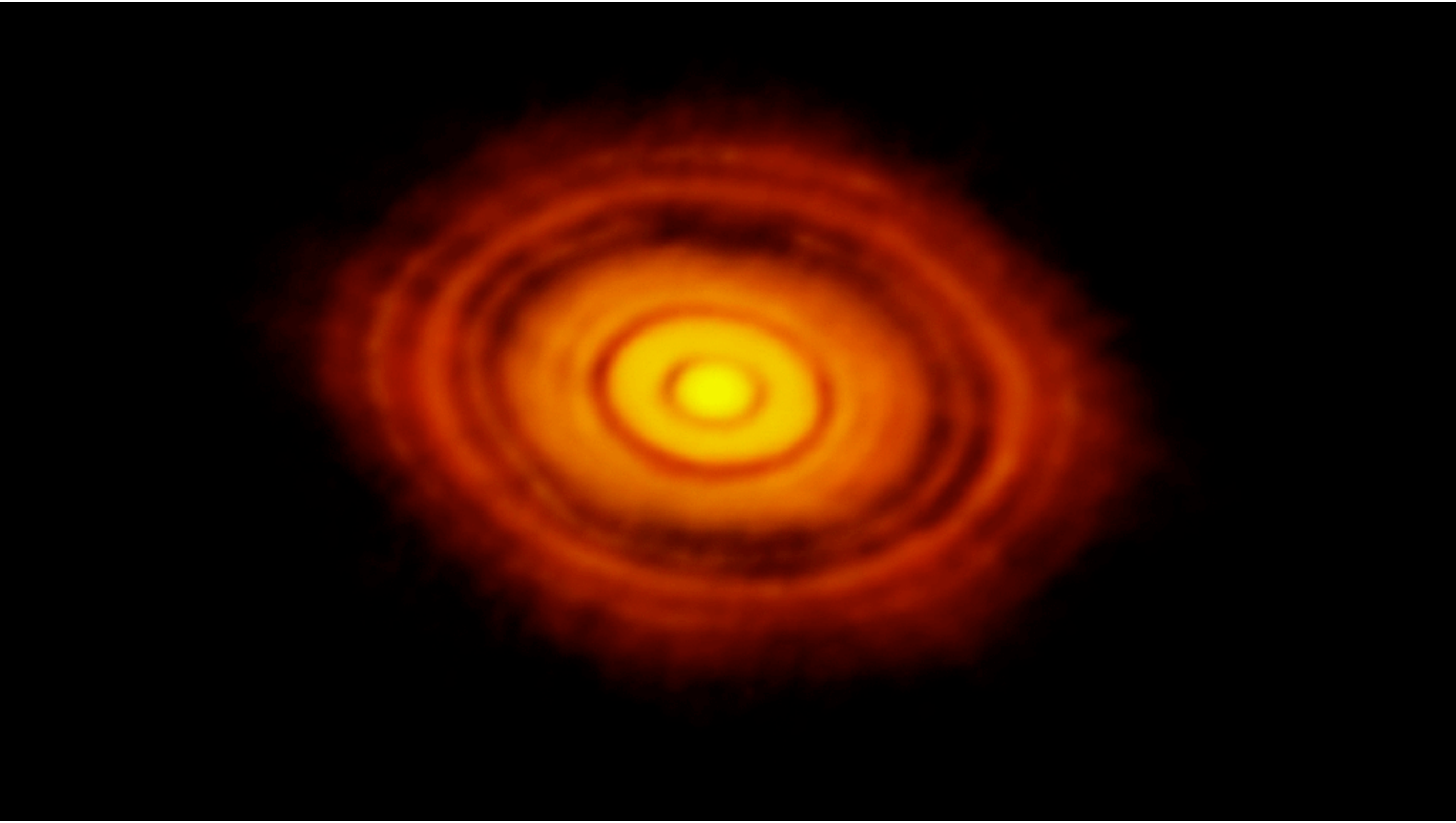


Mamajek (2009)

Lifetime of protoplanetary disc ~ 10 Myr

TRADITIONAL VIEW

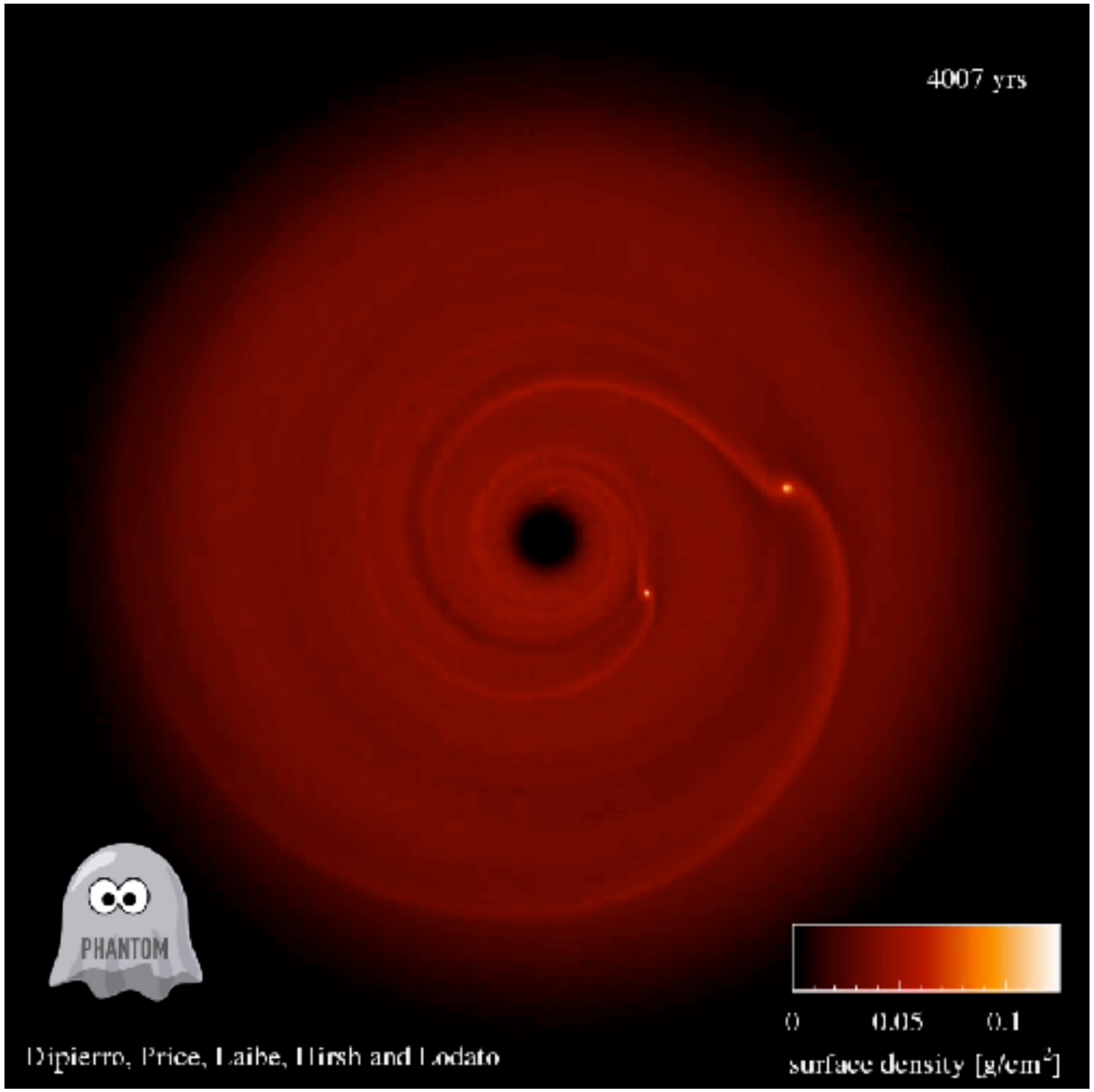
PLANET FORMATION IN THE TAURUS MOLECULAR CLOUD



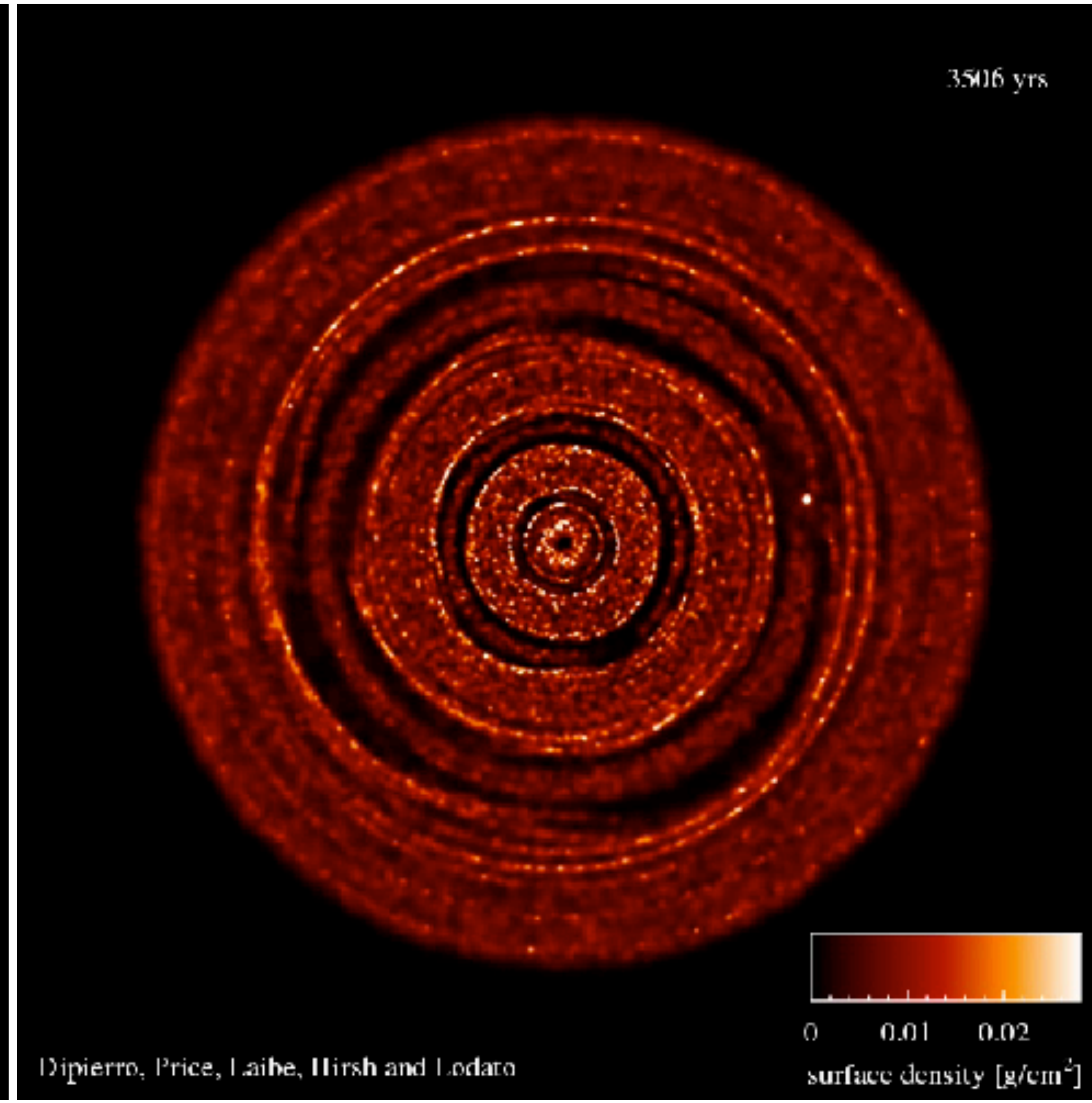
ALMA collaboration et al. (2015)

DUST, GAS AND PLANETS IN HL TAU

Dipierro et al. (2015)



Gas



mm grains

COMPARISON

Dipierro, Price, et al. (2015), MNRAS 453, L73-L77

Computed using RADMC3D radiative transfer code plus ALMA simulator

in HL Tau 5

Observed

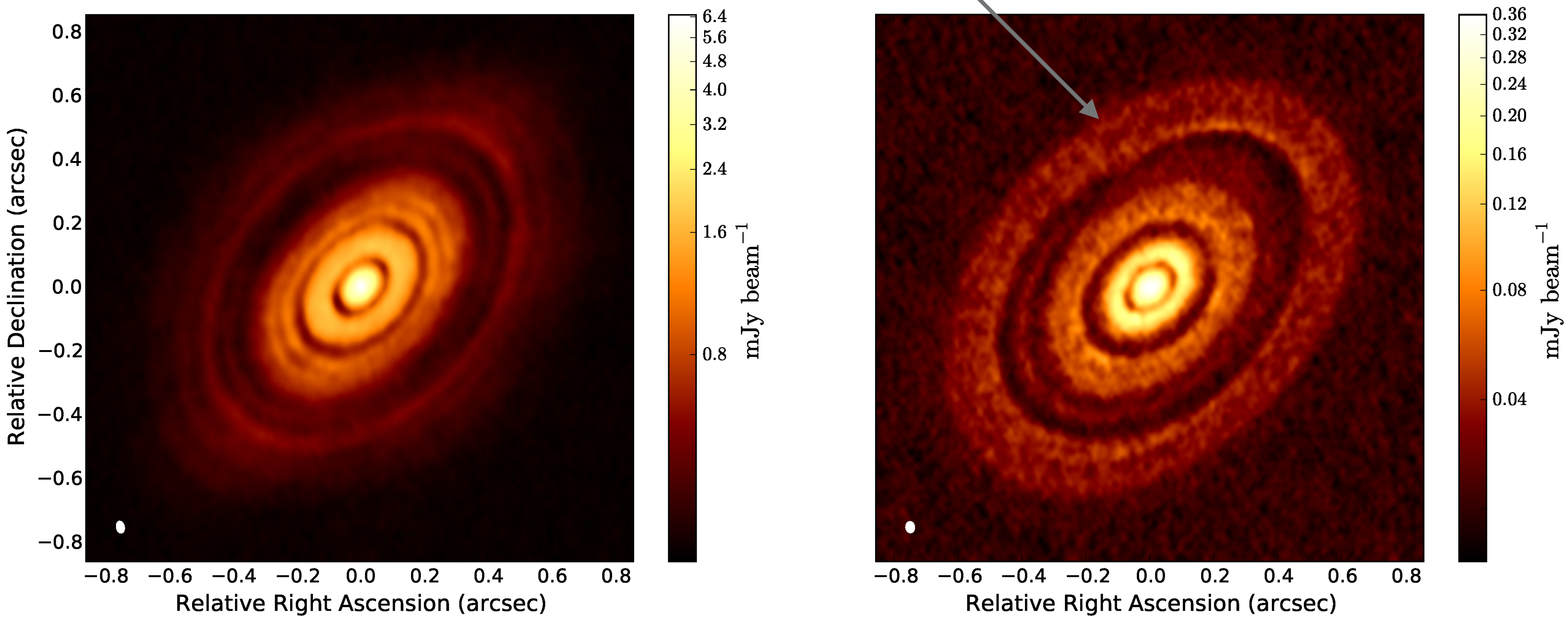


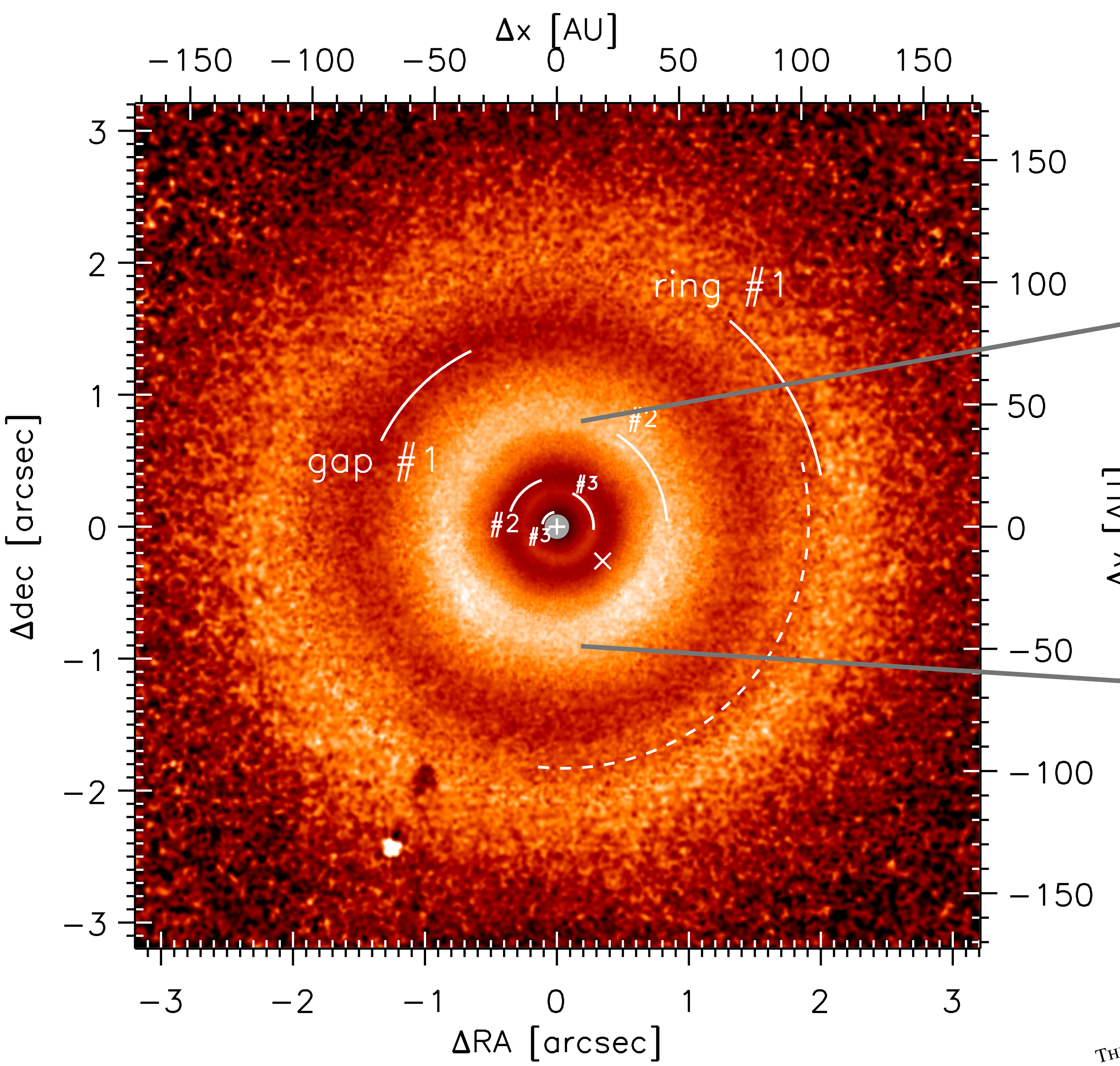
Figure 4. Comparison between the ALMA image of HL Tau (left) with simulated observations of our disc model (right) at band 6 (continuum emission at 233 GHz). The white colour in the filled ellipse in the lower left corner indicates the size of the half-power contour of the synthesized beam: (left) 0.035 arcsec × 0.022 arcsec, P.A. 11°; (right) 0.032 arcsec × 0.024 arcsec, P.A. 6°.

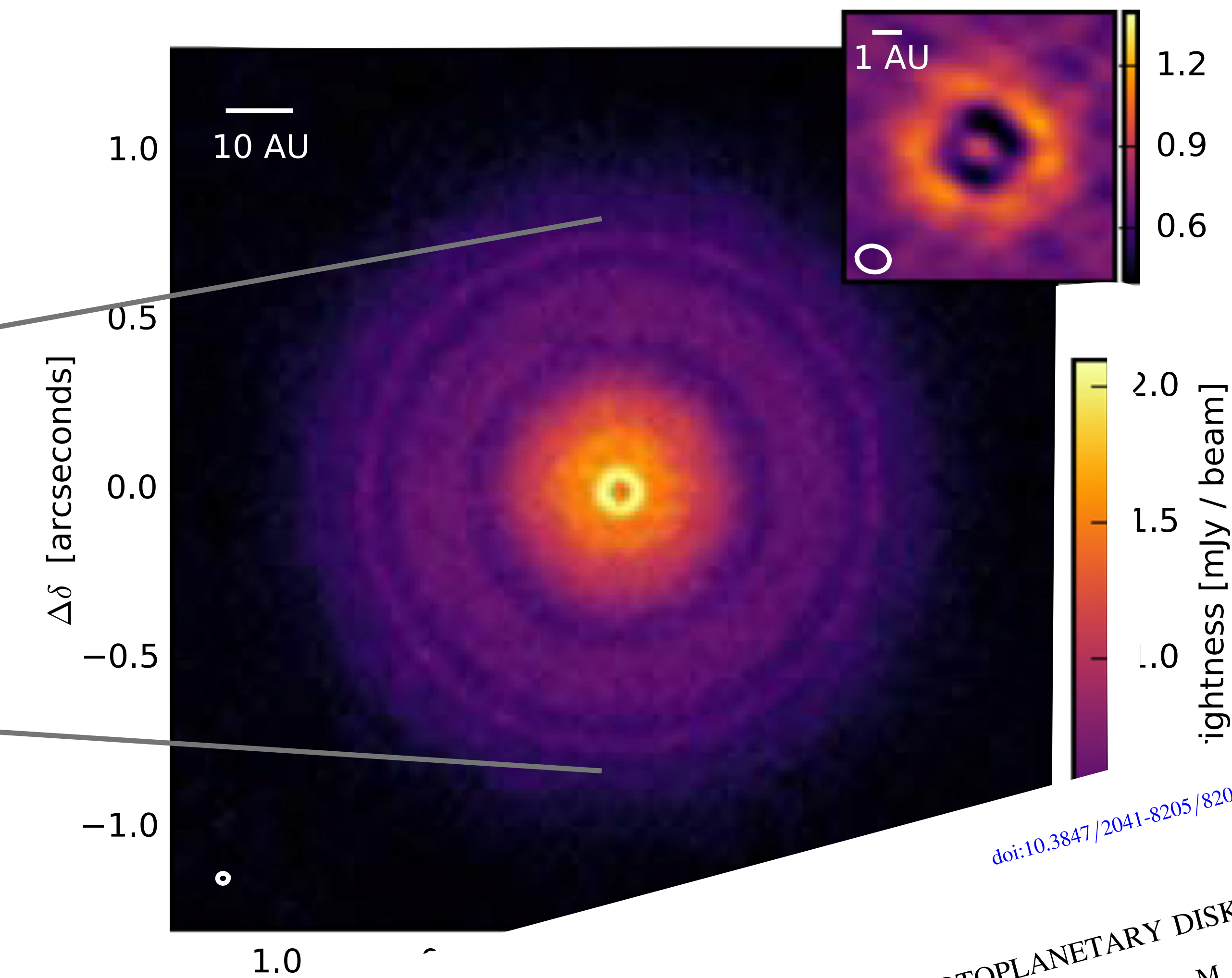
But need 3 x Saturn-mass planets in less than 1 million years!

Similar conclusions reached by Jin+(2016), Picogna+(2016)

TW HYA: OUR NEAREST PROTOPLANETARY DISC

Ask Sean Andrews!





THREE RADIAL GAPS IN THE DISK OF TW HYDRAE IMAGED WITH SPHERE

R. van Boekel[1], Th. Henning[1], J. Menu[1,2], J. de Boer[3,4], M. Langlois[5,6], A. Müller[4,1], H. Avenhaus[7], A. Boccaletti[8], H. M. Schmid[9], Ch. Thalmann[9], M. Benisty[10,11], C. Dominik[12], Ch. Ginski[3], J. H. Girard[4,10,11], D. Gisler[9,13], A. Lobo Gomes[14], F. Menard[15,7], M. Min[16,12], A. Pavlov[1] A. Pohl[1], S. P. Quanz[9], P. Rabou[10,11], R. Roelfsema[17] J.-F. Sauvage[18] R. Teague[1], F. Wildi[19], and A. Zurlo[20,6,7]

The Astrophysical Journal Letters, 820:L40 (5pp), 2016 April 1

doi:10.3847/2041-8205/820/2/L40

RINGED SUBSTRUCTURE AND A GAP AT 1 au IN THE NEAREST PROTOPLANETARY DISK

Sean M. Andrews[1], David J. Wilner[1], Zhaohuan Zhu[2], Tilman Birnstiel[3], John M. Carpenter[4], Laura M. Pérez[5], Xue-Ning Bai[1], Karin I. Öberg[1], A. Meredith Hughes[6], Andrea Isella[7], and Luca Ricci[1]
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[6] Department of Astronomy, Wesleyan University, Van Vleck Observatory, 96 Foss Hill Drive, Middletown, CT 06457, USA
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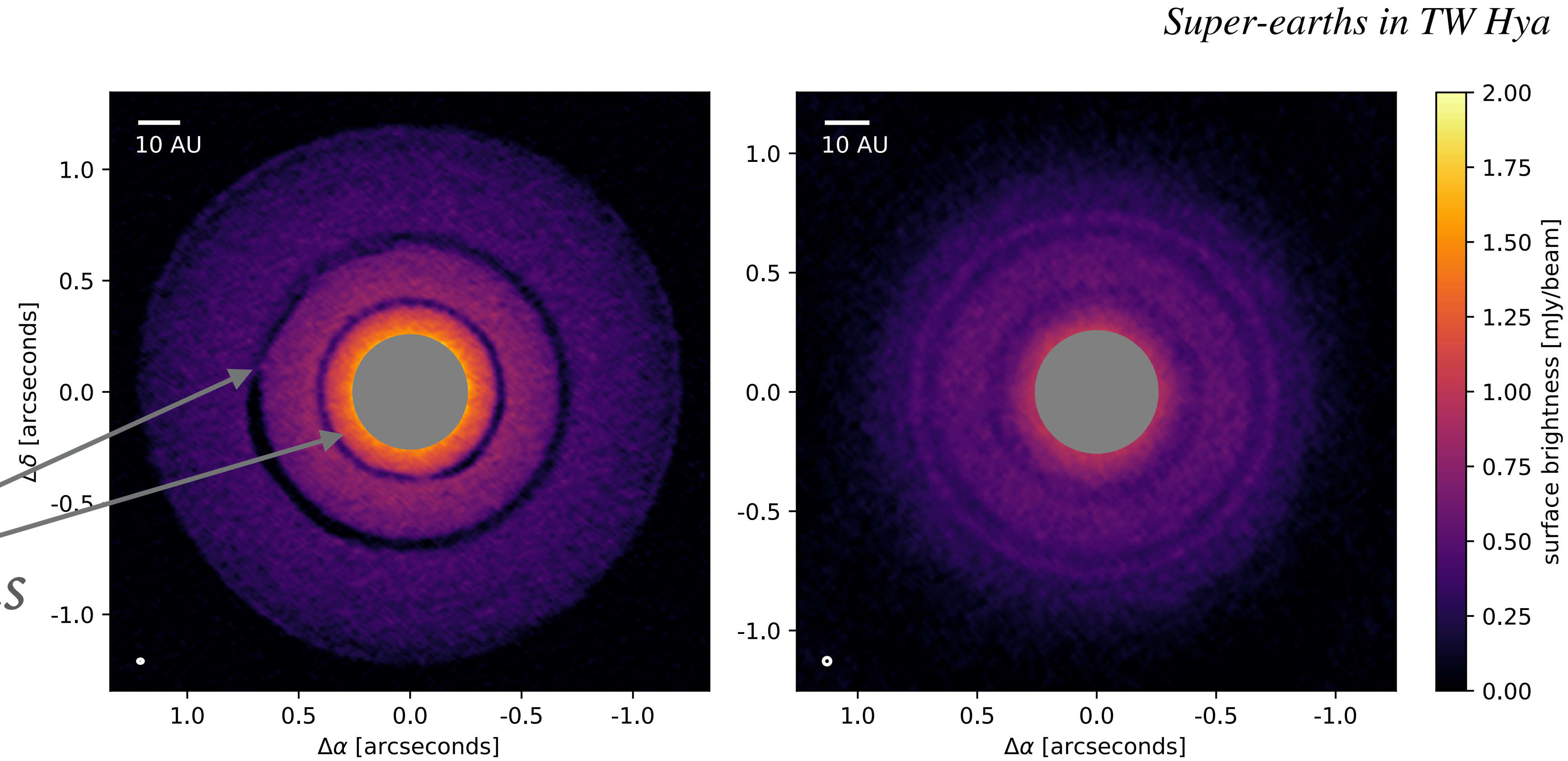
TW HYA MODELLING

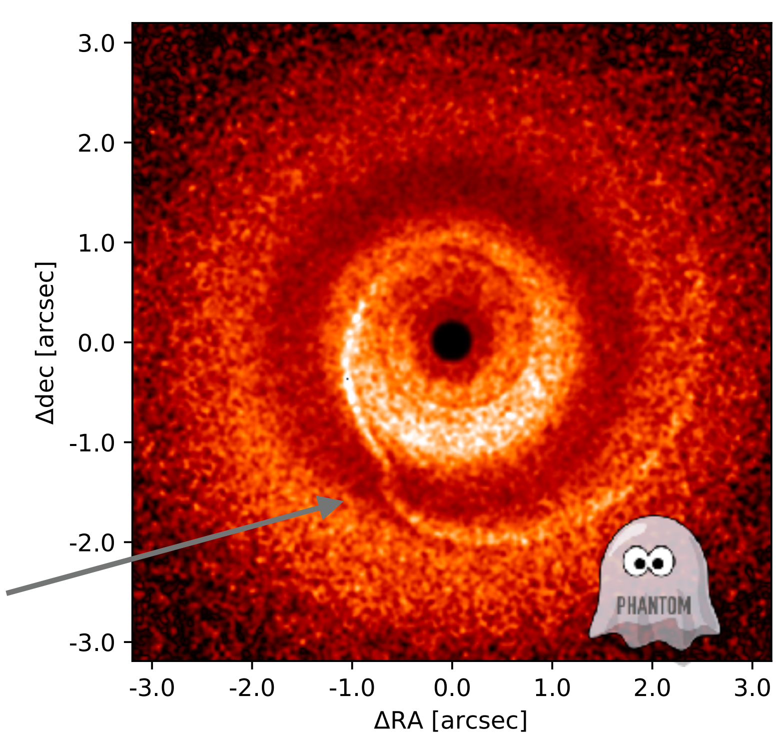
Mentiplay, Price & Pinte (in prep)



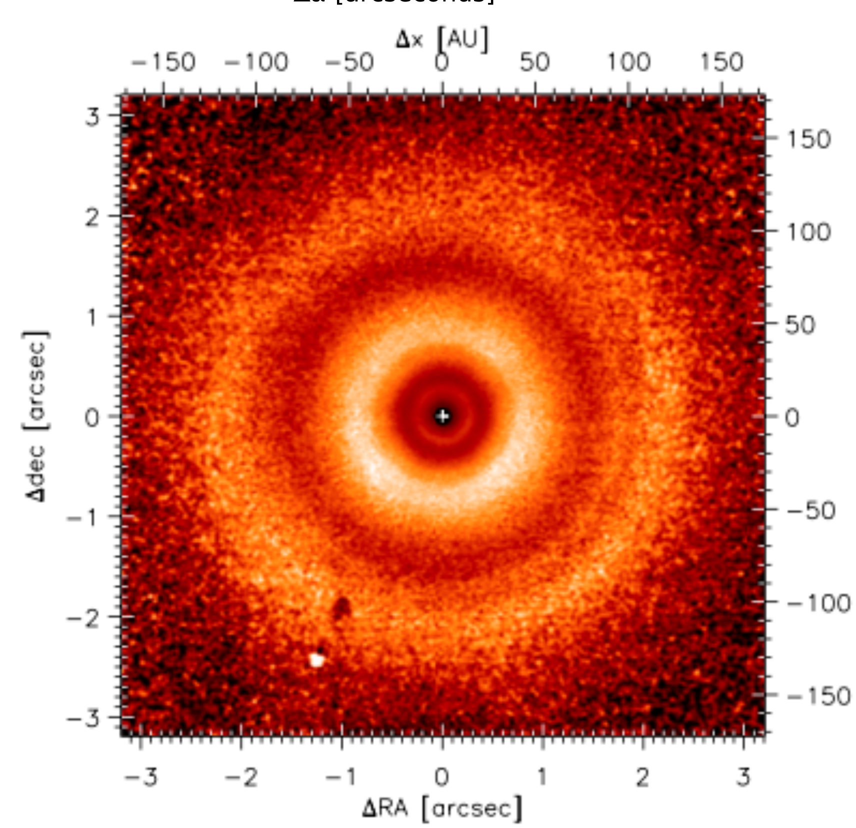
Super Earths

Left: Our simulation

Right: Andrews et al. (2016)



Saturn

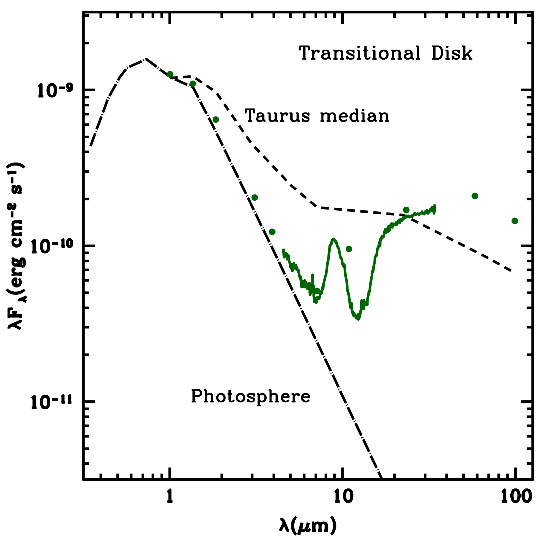


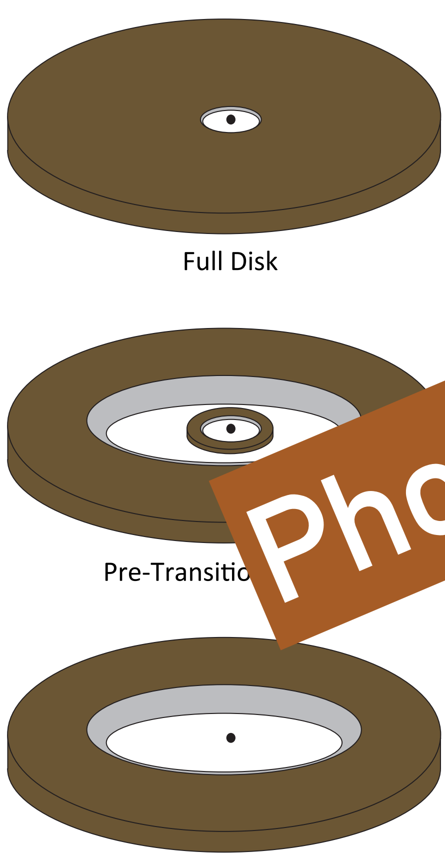
Left: Our simulation

Right: Van Boekel et al. (2017)

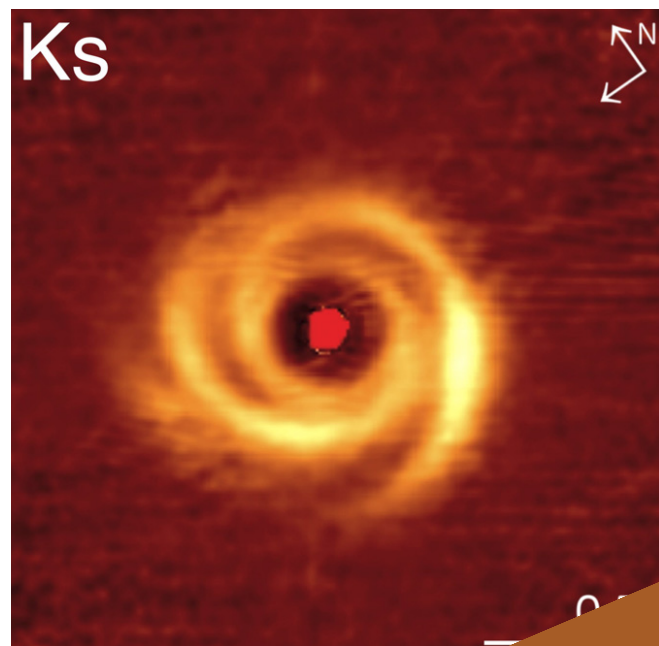
"TRANSITION" DISCS

Strom et al. (1989), Calvet et al. (2005), Espaillat et al. (2014), Casassus (2016), Owen (2016)





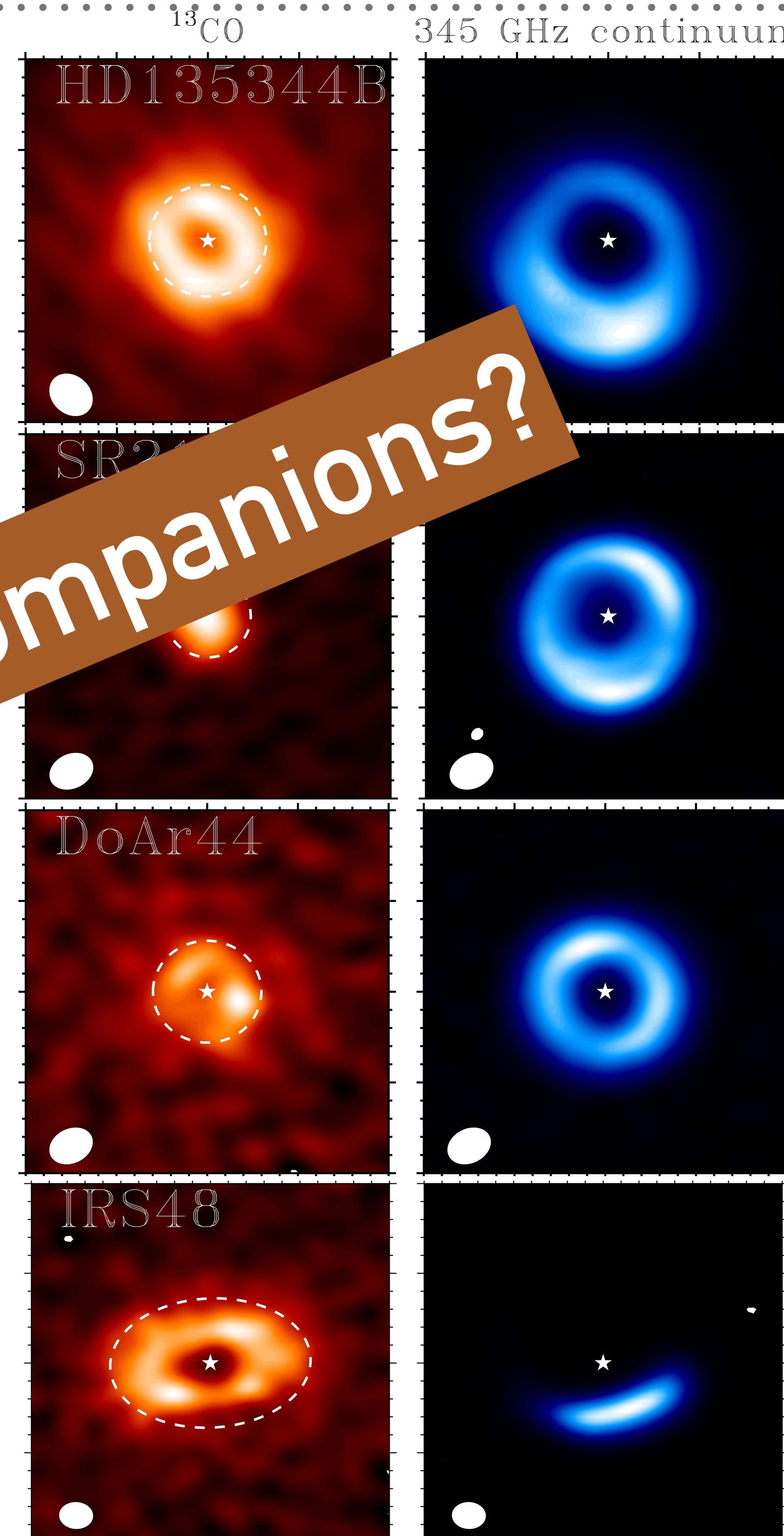
Espaillat et al. (2014)



Garufi et al

Photoevaporation or companions?

Benisty et al. (2016)



Van-der-Marel et al. (2016)

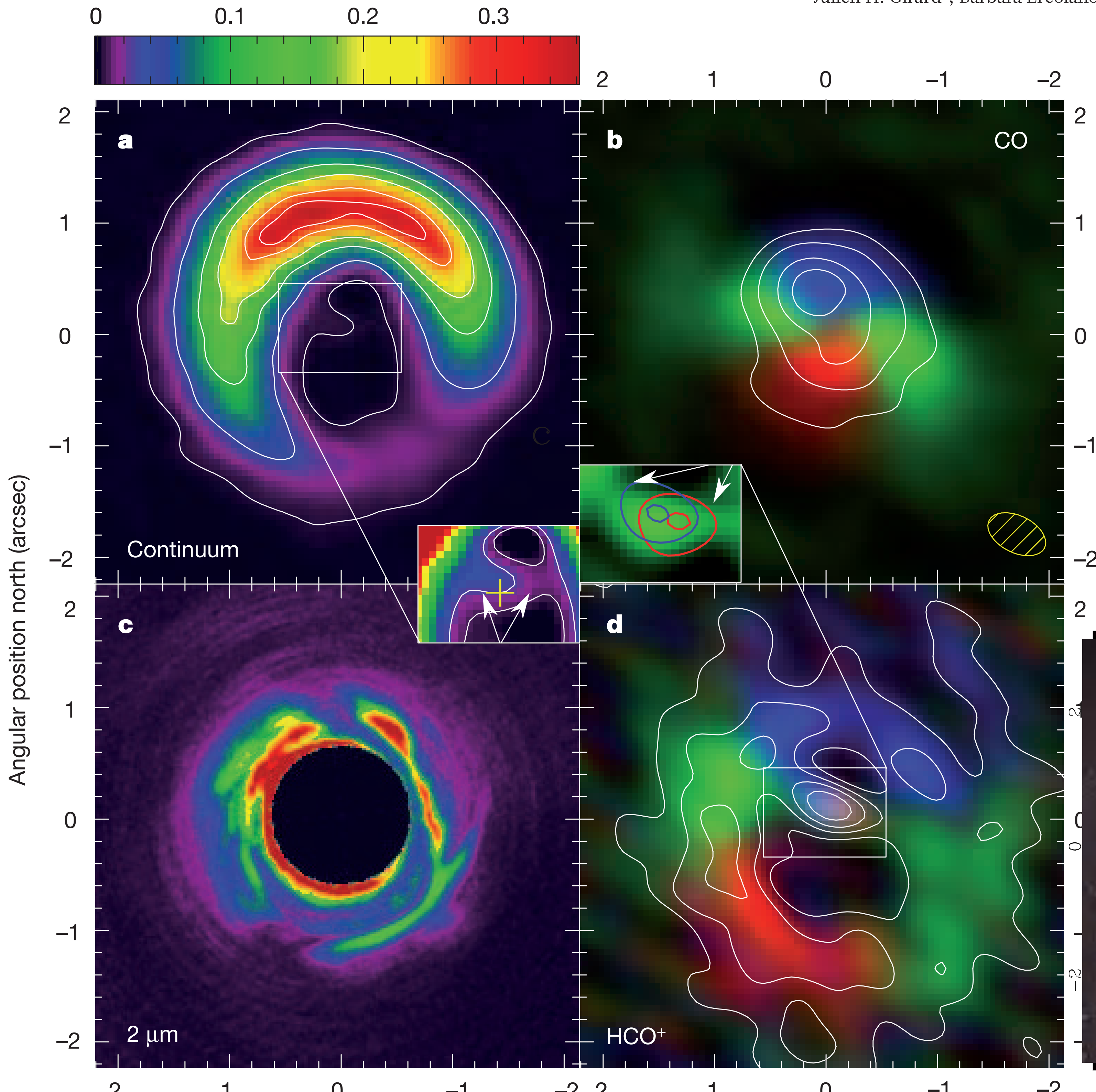
HD142527

LETTER

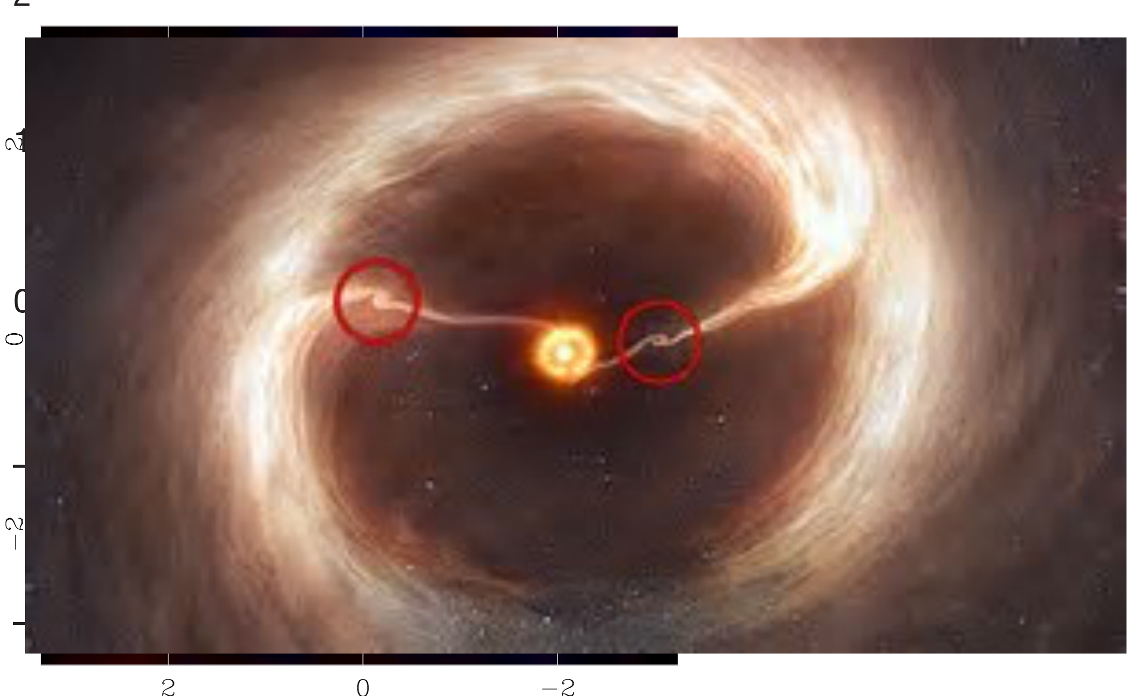
doi:10.1038/nature11769

Flows of gas through a protoplanetary gap

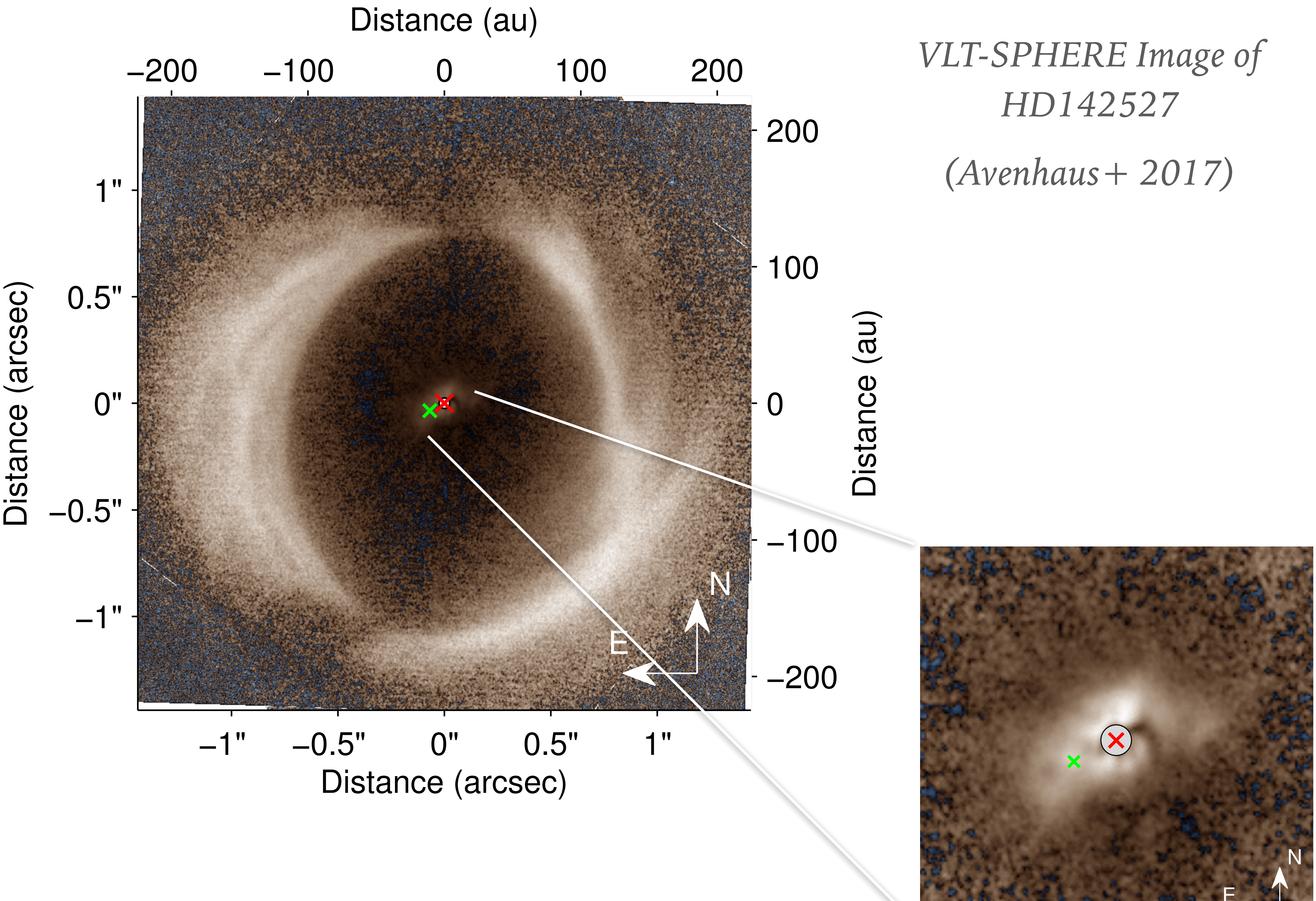
Simon Casassus[1], Gerrit van der Plas[1], Sebastian Perez M[1], William R. F. Dent[2,3], Ed Fomalont[4], Janis Hagelberg[5], Antonio Hales[2,4], Andrés Jordán[6], Dimitri Mawet[3], Francois Ménard[7,8], Al Wootten[4], David Wilner[9], A. Meredith Hughes[10], Matthias R. Schreiber[11], Julien H. Girard[3], Barbara Ercolano[12], Hector Canovas[11], Pablo E. Román[13] & Vachail Salinas[1]



- Large ~100 au cavity
- Horseshoe in mm emission
- Gap-crossing filaments?



SPIRAL ARMS

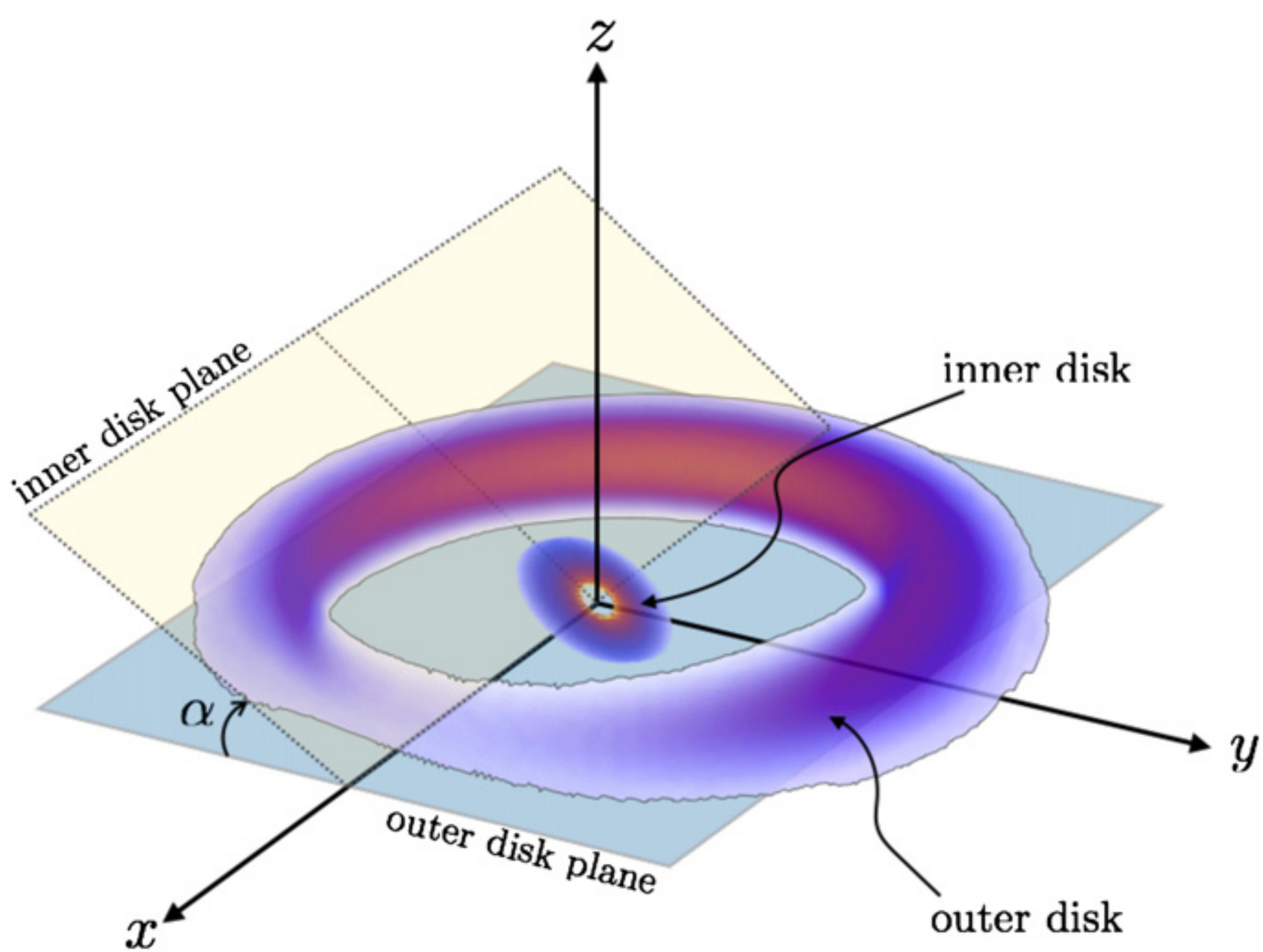


VLT-SPHERE Image of HD142527

(Avenhaus+ 2017)

SHADOWS = INCLINED INNER DISC?

The Astrophysical Journal Letters, 798:L44 (4pp), 2015 January 10



Marino, Perez & Casassus (2015)

"FAST RADIAL FLOWS" = DISC TEARING?

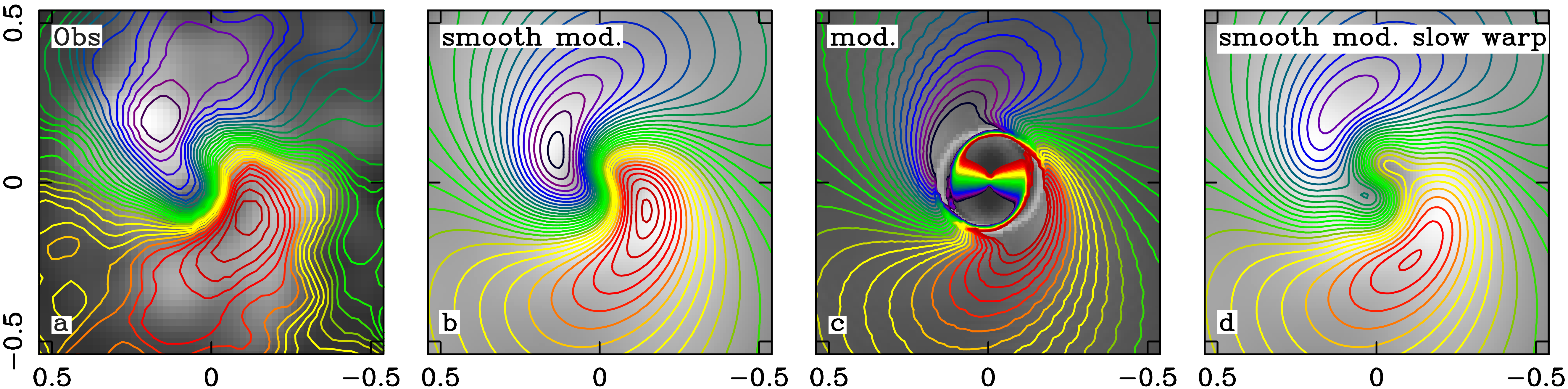
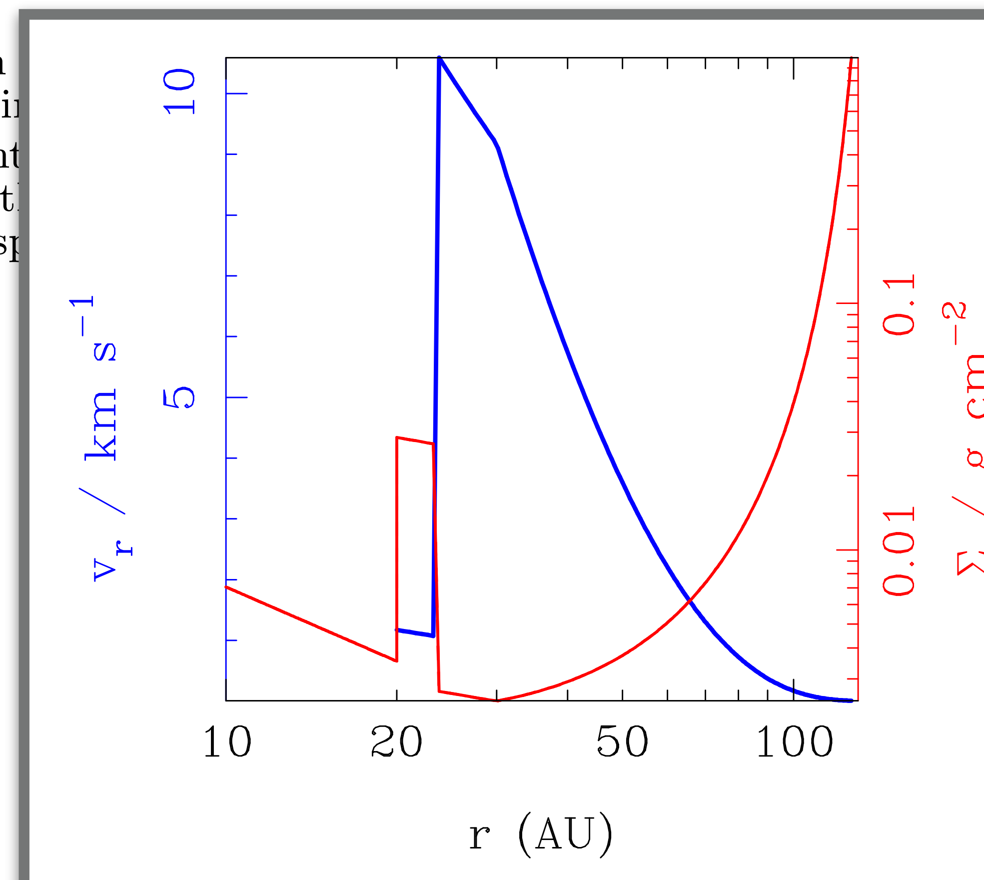


Figure 7. Comparison of observed and model CO(6-5) kinematics in … rdinates is set to
the stellar position. Velocity-integrated intensity in CO(6-5) is shown i… tant interval and
are spread over [0.21, 7.87] km s^{-1} (as in Fig. 1). **a)**: Observed moment… ents extracted on
the radiative transfer prediction, after smoothing to the resolution of t… odel resolutions,
without smoothing. Regions without contours near the origin corresp… a slow velocity
component perpendicular to the disk plane (v_{warp} in the text).

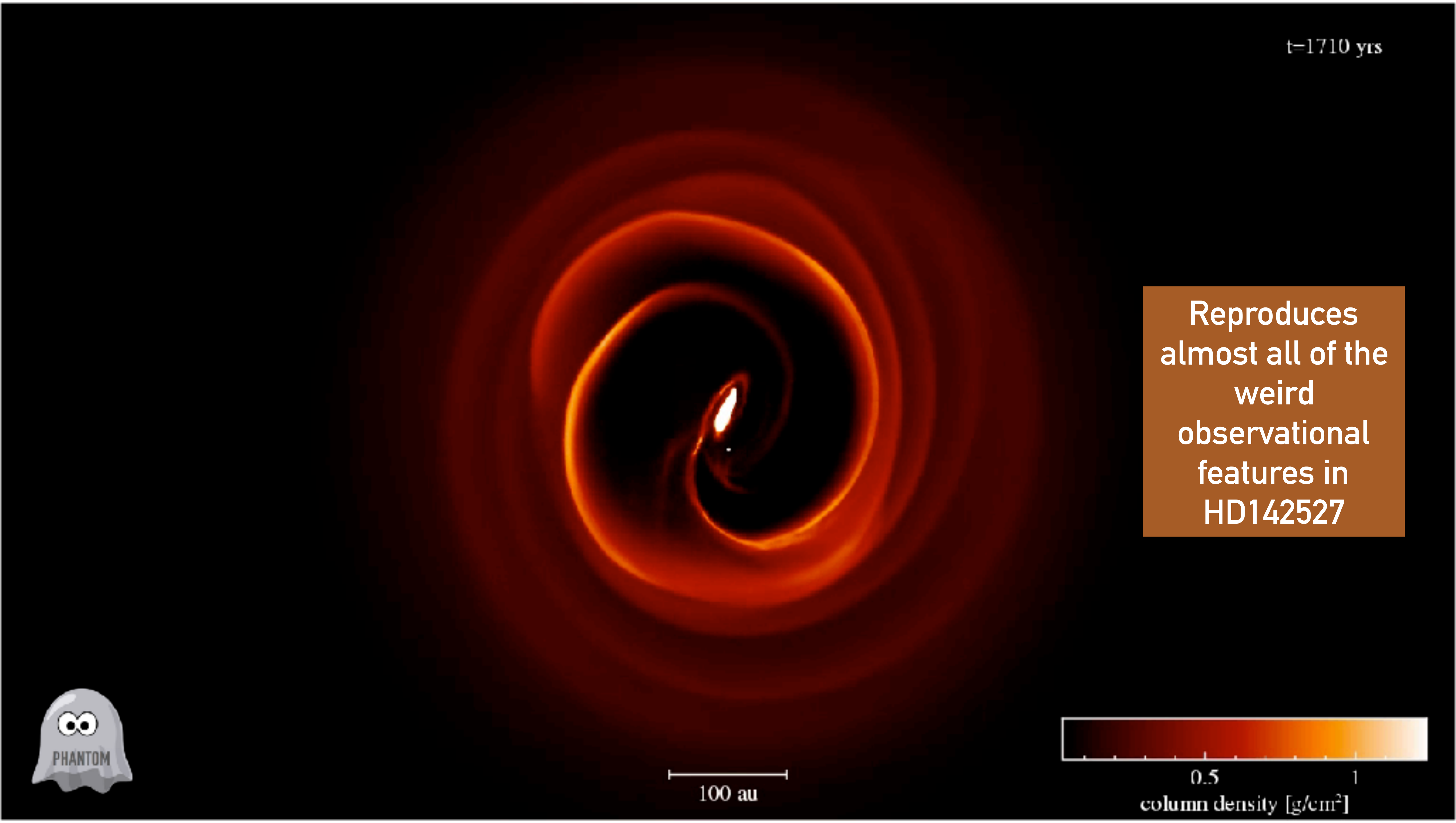
dubbed disk tearing (Nixon et al. 2013; Nealon et al. 2015; Doğan et al. 2015), where nodal precession torques induced by the binary produce a warp at the inner edge … companion on … 100 AU scale … cavity. It is

Require infall motions from cavity edge at the free-fall velocity!



MODELLING HD142527

Price et al. (2018), arXiv:1803.02484



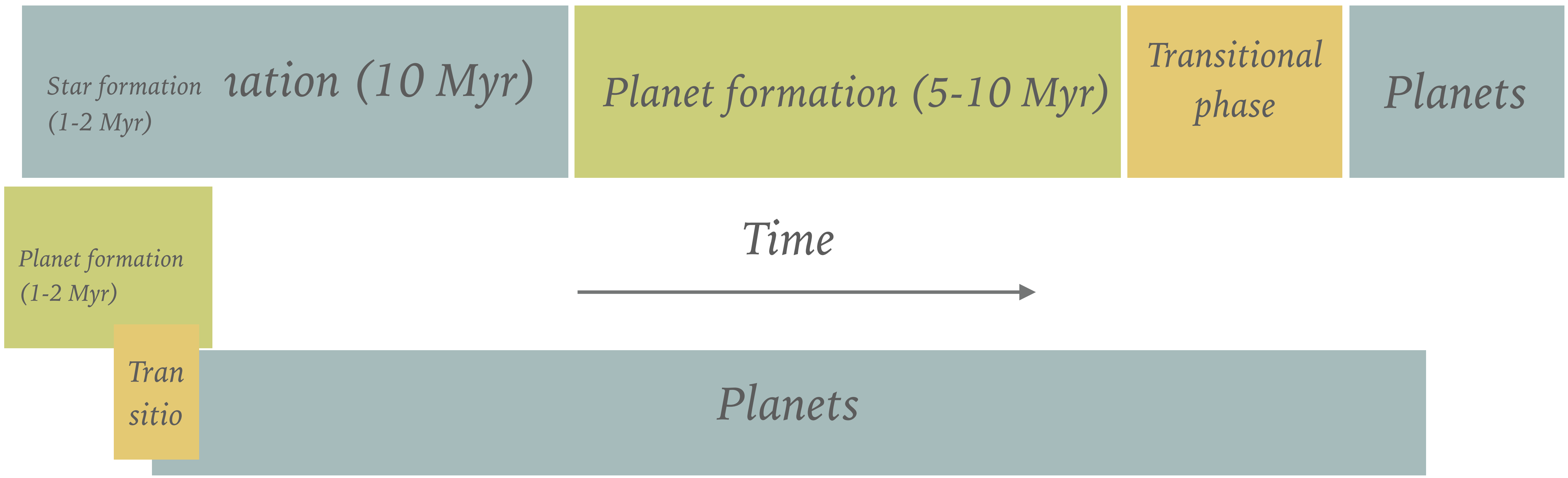
Almost polar alignment of binary to disc! c.f. Aly et al. (2015), Martin & Lubow (2017)

SUMMARY

- Every disc imaged so far shows signs of interaction with already-formed planets or low mass companions*
- Lots of discs similar to HD142527 - disturbed morphologies, asymmetries, spirals. Suggests highly misaligned, eccentric companions are common?*
- Discs with holes telling us about chaotic star formation - how discs are born - not how they die*
- Suggests planet formation is FAST not slow*

** This is controversial*

NEW VIEW?

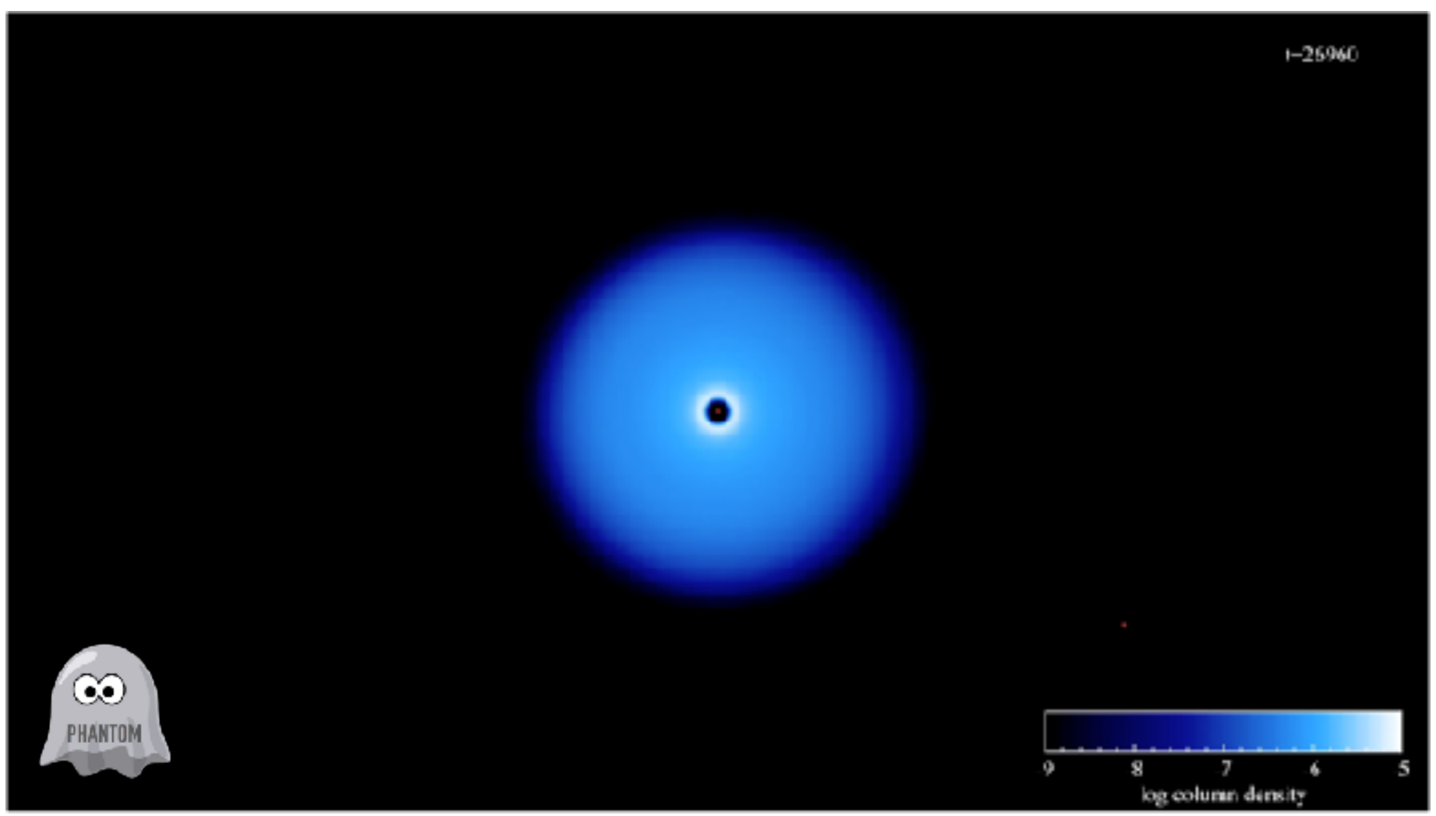


Hypothesis: Star and planet formation are both fast, dynamical processes

PREDICTIONS:

Lodato & Price (in prep)

- Expect lots more discs with companions on wild orbits
- Discs around more massive stars should be more disturbed
- Rings and gaps will be found everywhere
- Tidal encounters common!



Credit: Nicolás Cuello

Reminds us of galaxy formation!