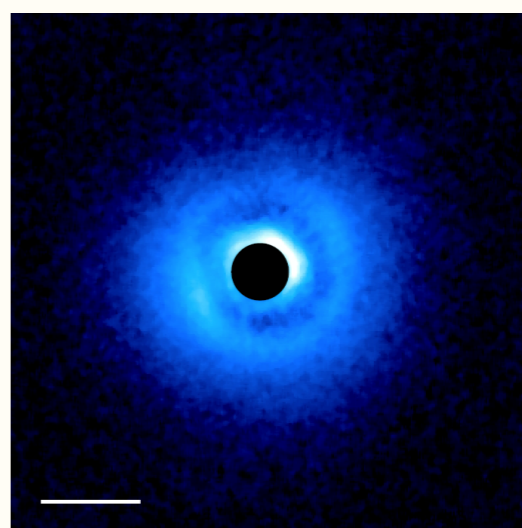
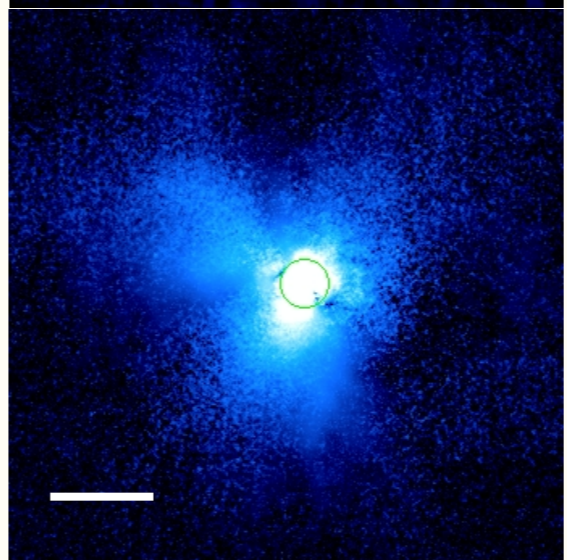
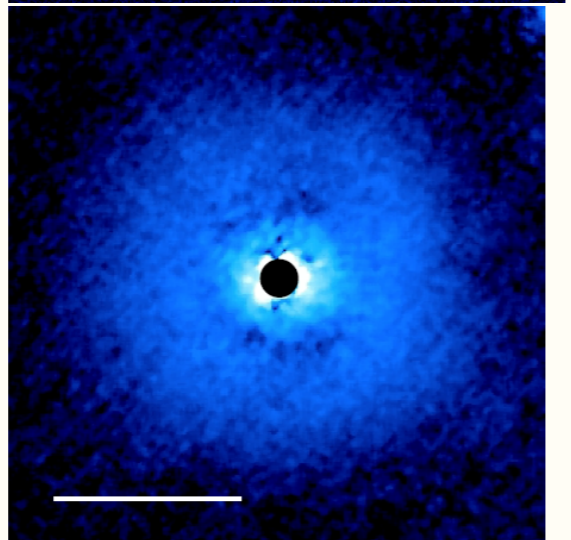
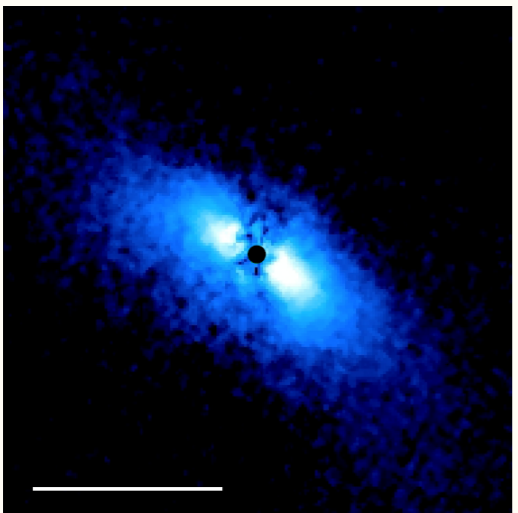
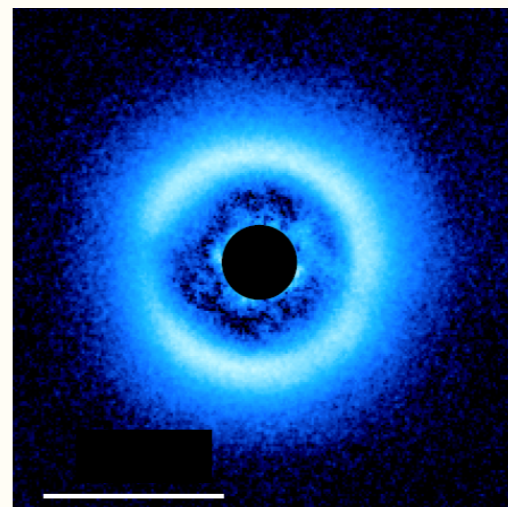
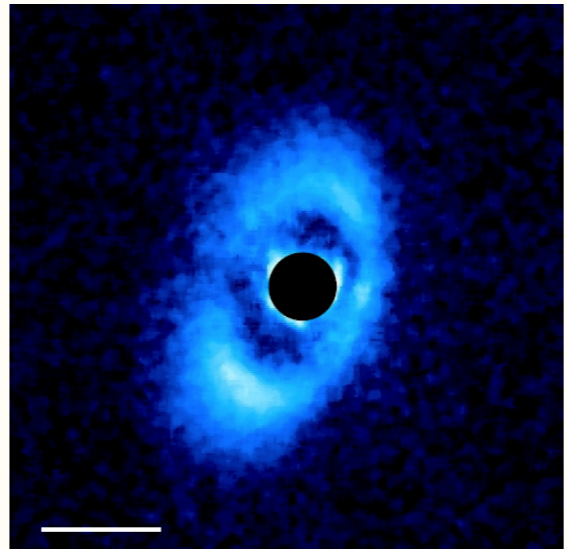
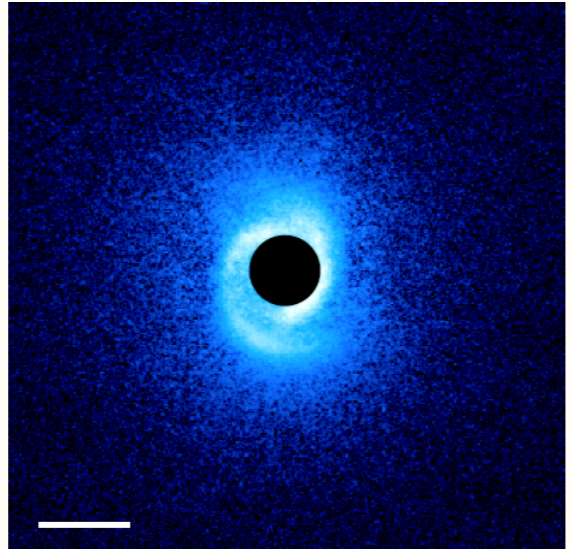
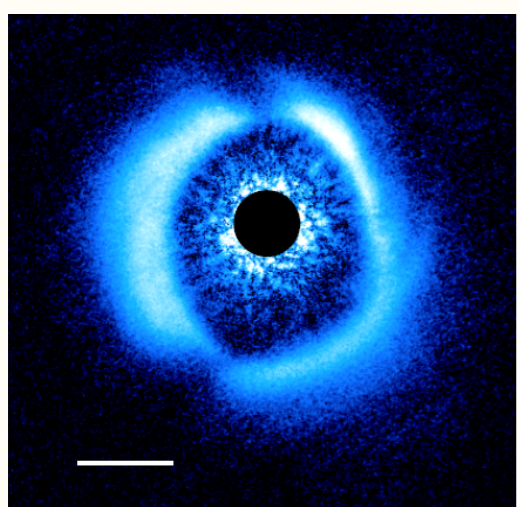
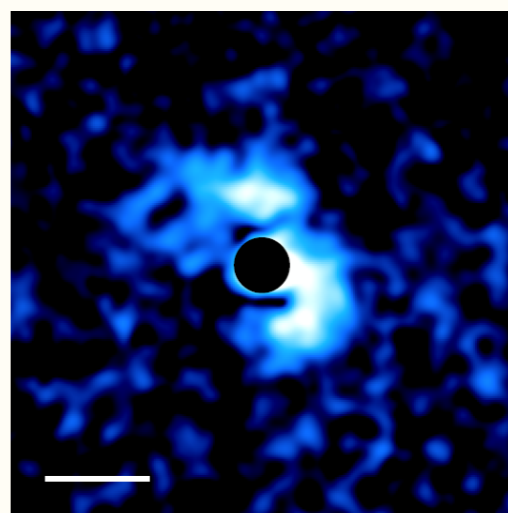
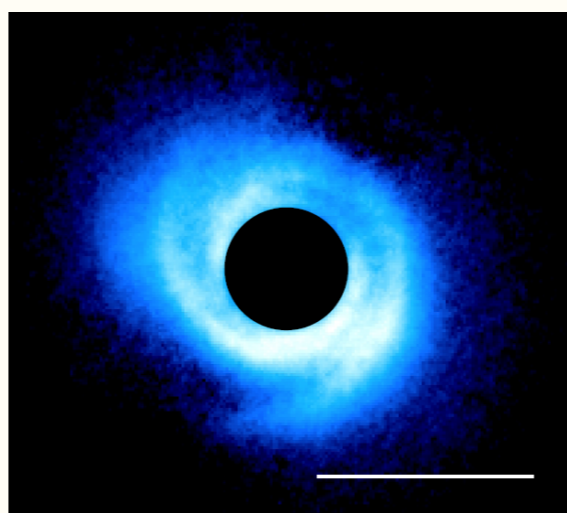
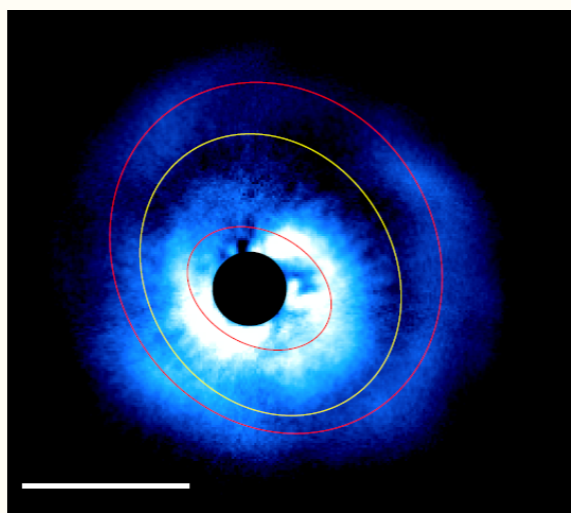
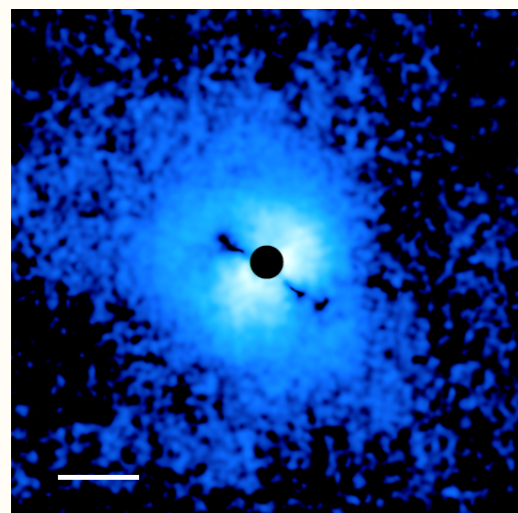


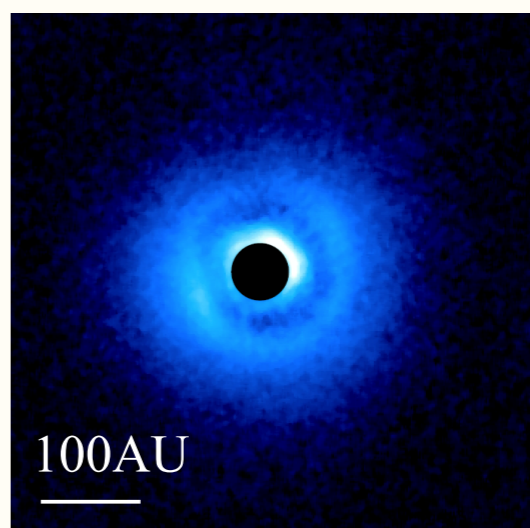
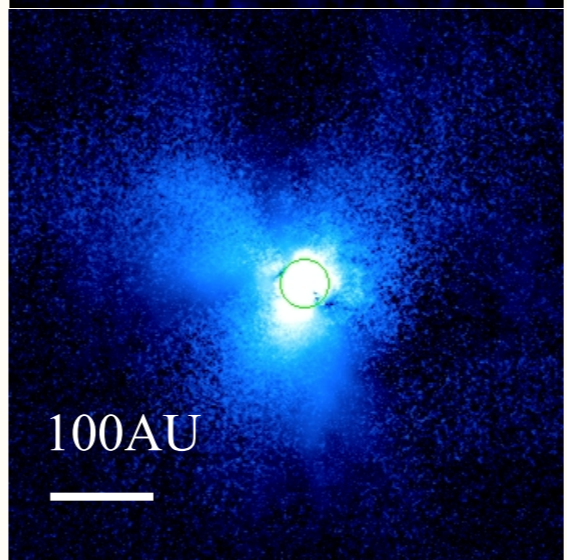
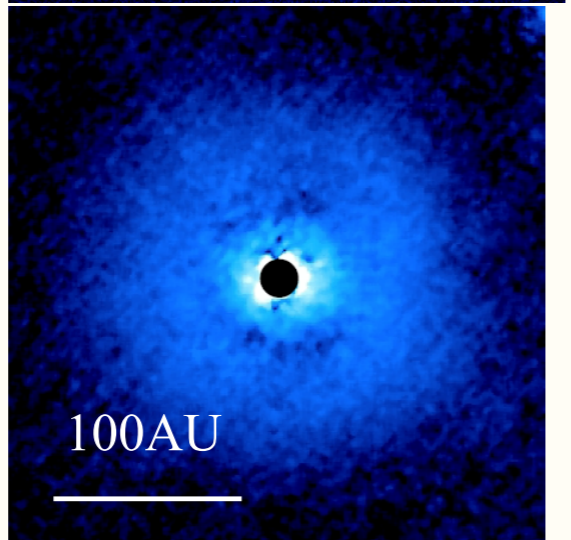
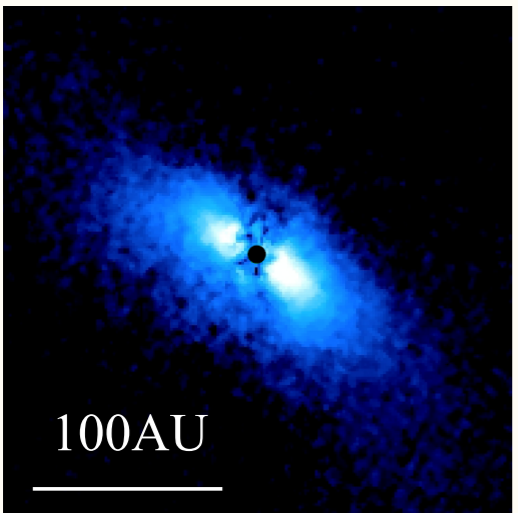
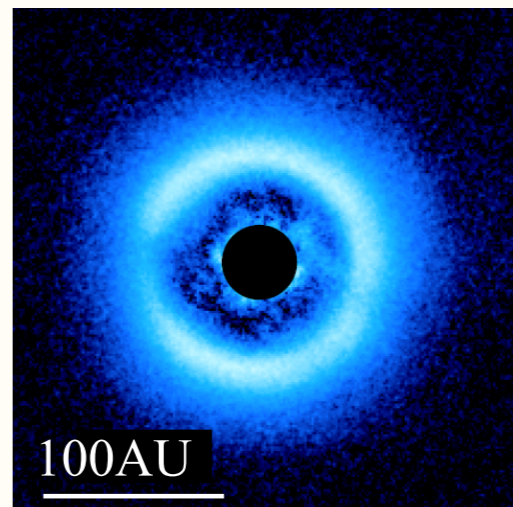
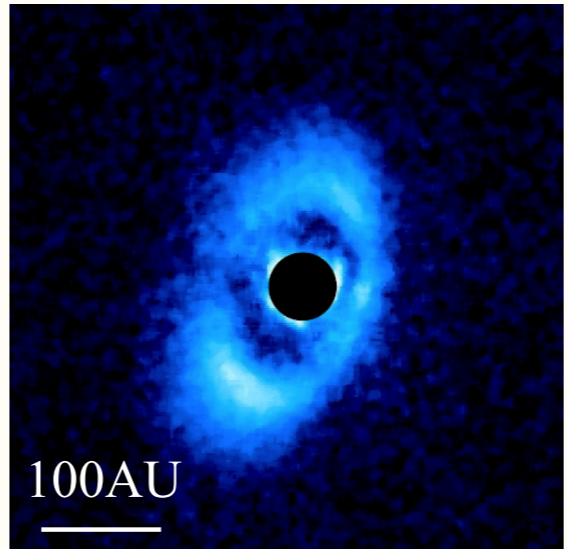
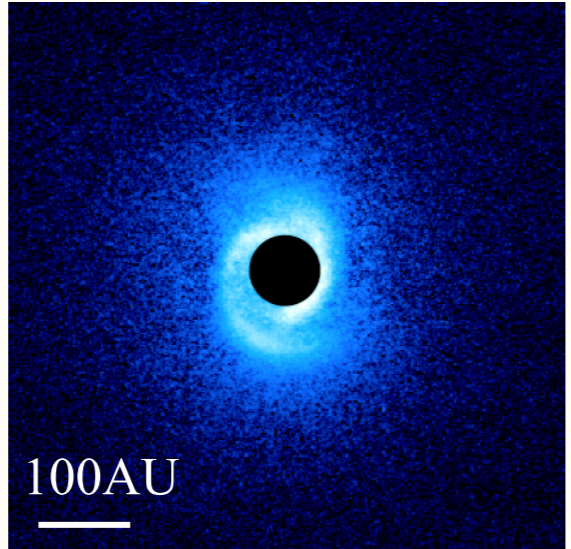
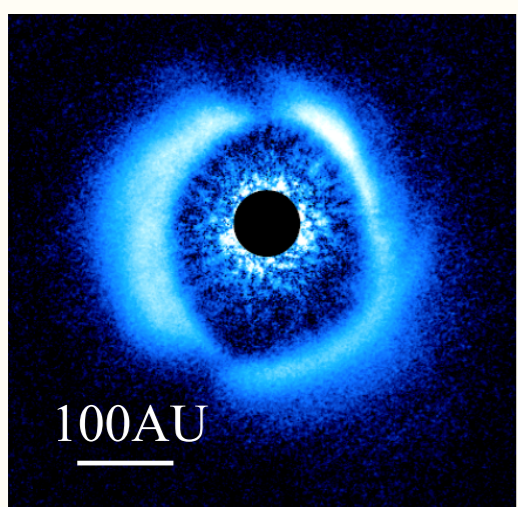
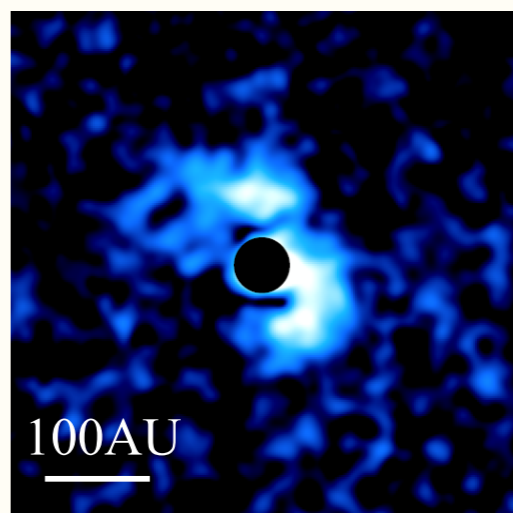
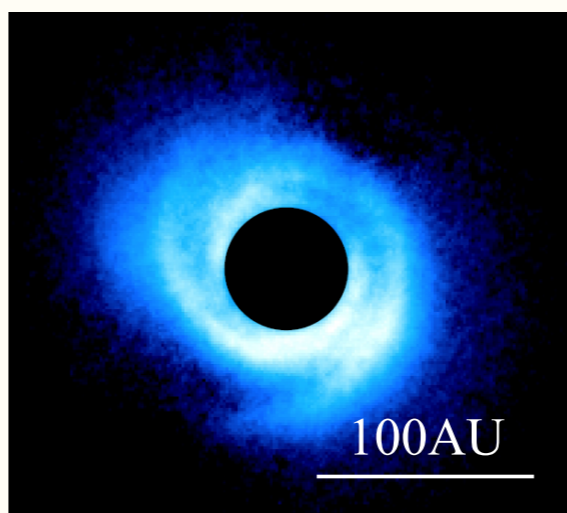
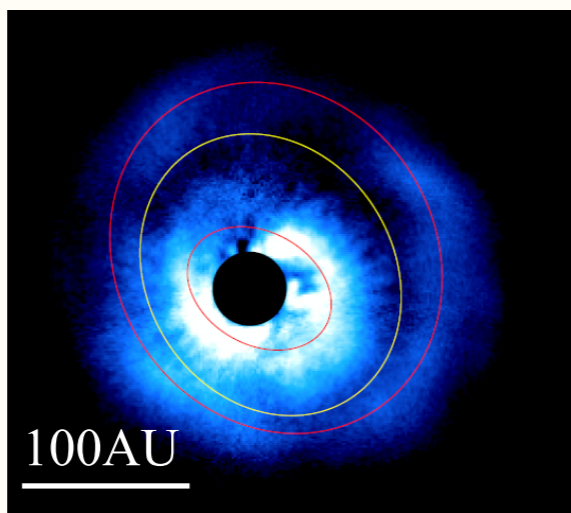
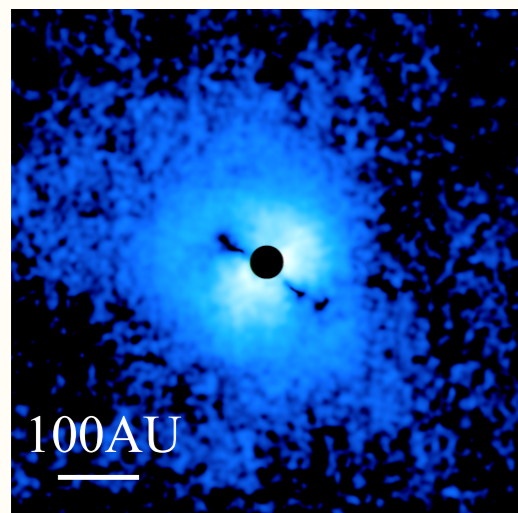
Using Density Wave Theory as a Tool to Find Young Planets in Birth

Zhaohuan Zhu 朱照寰

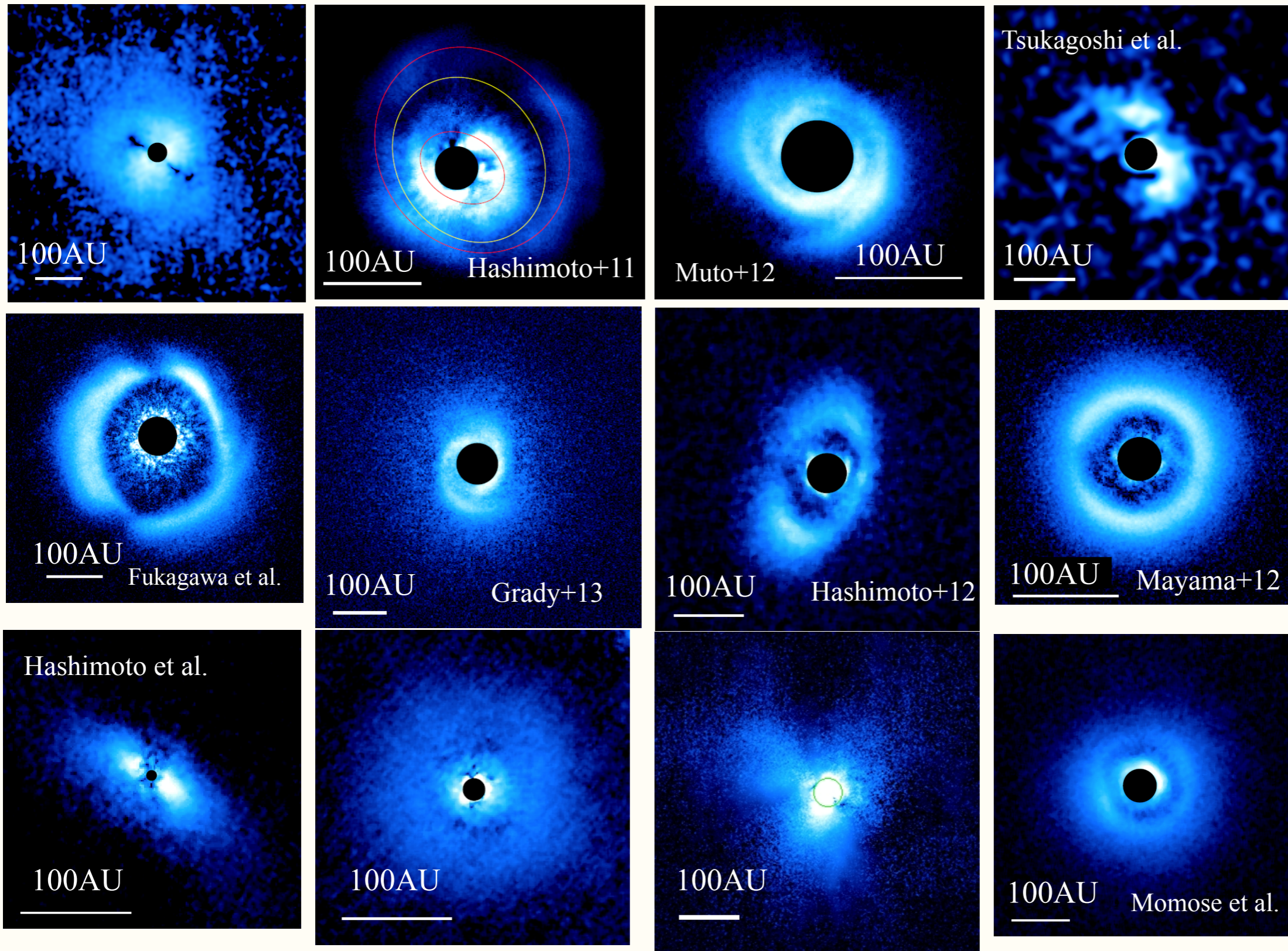
Princeton

Jim Stone, Roman Rafikov, Ruobing Dong (Princeton),
Subo Dong (IAS), Steve Lubow (Stsci), Xuening Bai (CfA),
Lee Hartmann, Nuria Calvet (Umich), Richard
Nelson(QMUL), Catherine Espaillat(CfA),
SEEDS collaboration

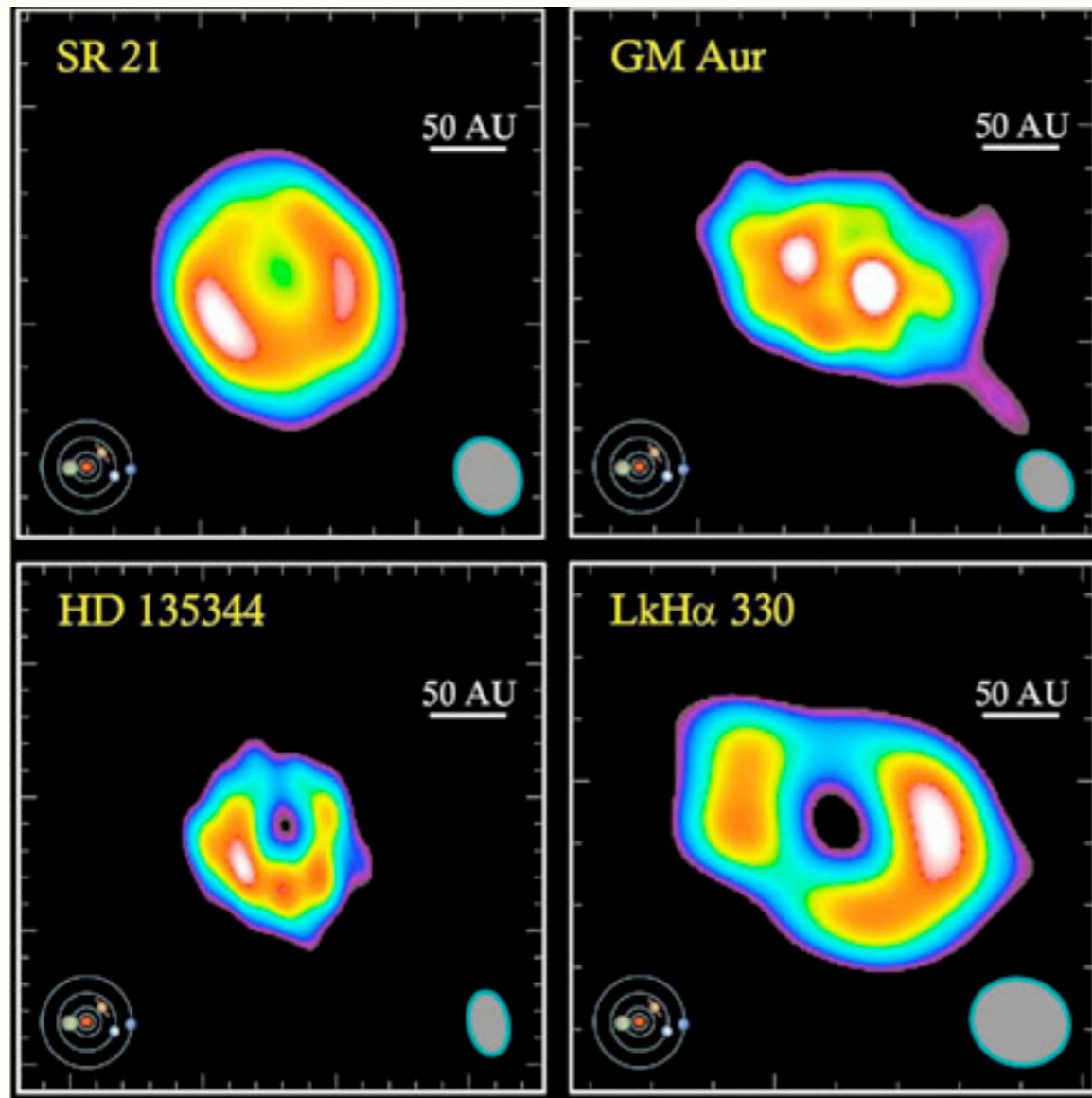




Protoplanetary Disks in SEEDS

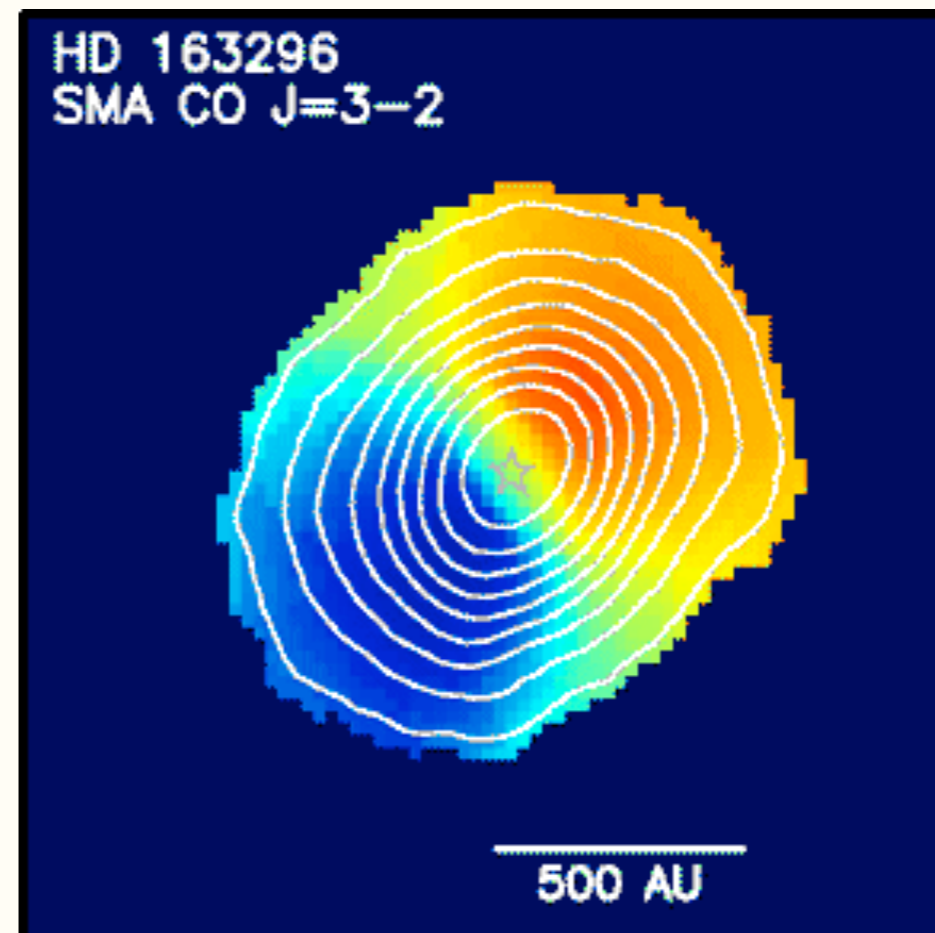
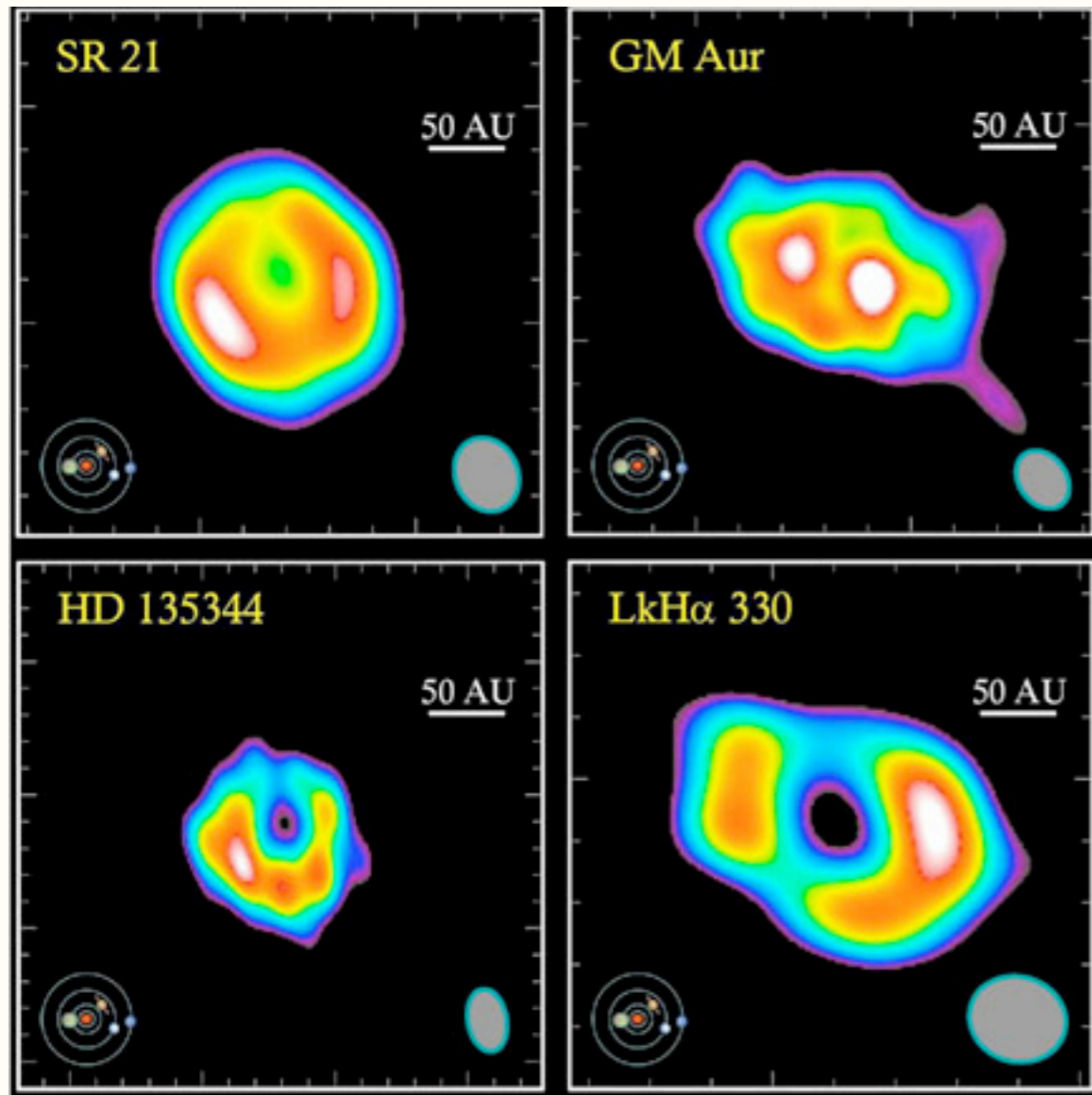


Protoplanetary Disks in Sub-mm



(Courtesy of D. Wilner)

Protoplanetary Disks in Sub-mm



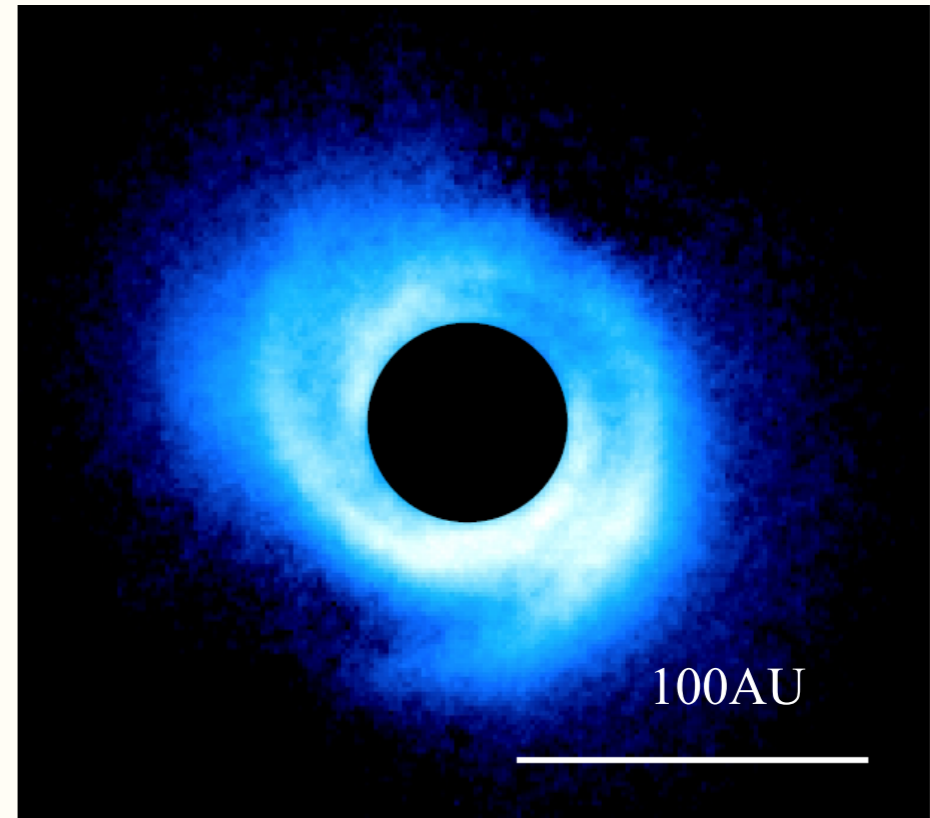
(Courtesy of D. Wilner)

“Grand” Design



100AU

“Grand” Design



Protoplanetary Disks

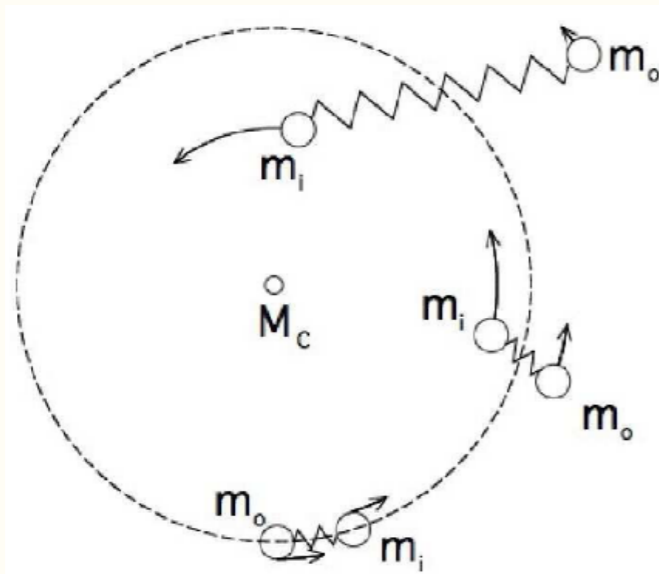
Protoplanetary Disks

Protoplanetary Disks:

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Protoplanetary Disks:

Turbulent => Accretion



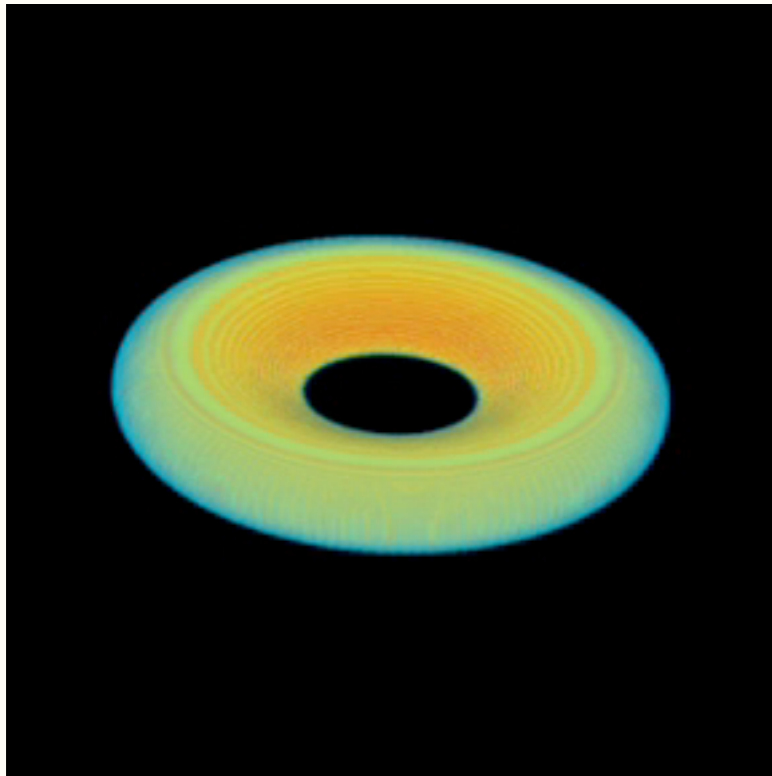
MRI: Magnetorotational
Instability

(Balbus&Hawley 1991)

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Turbulent \Rightarrow Accretion



(Credit: Hawley)

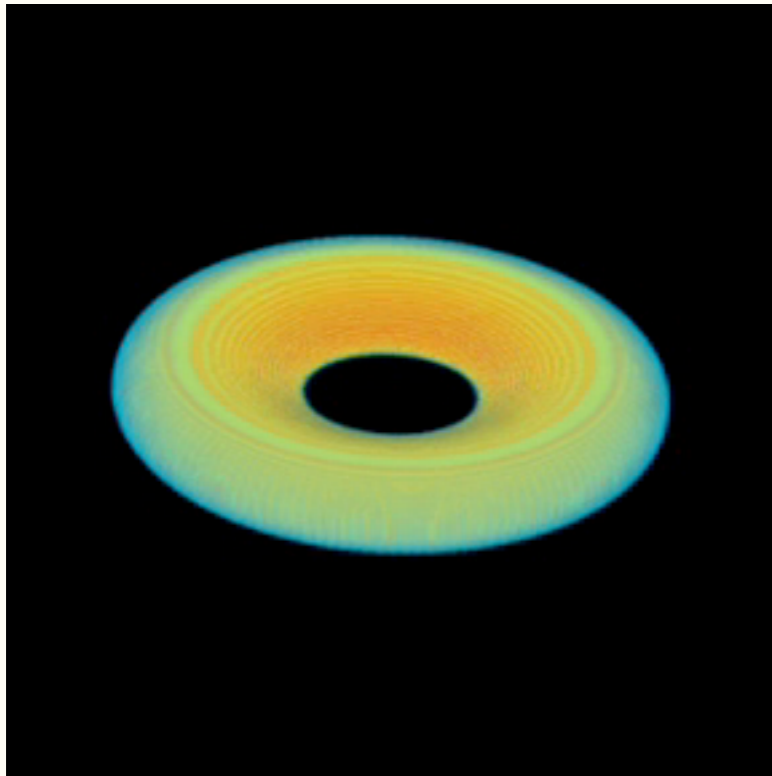
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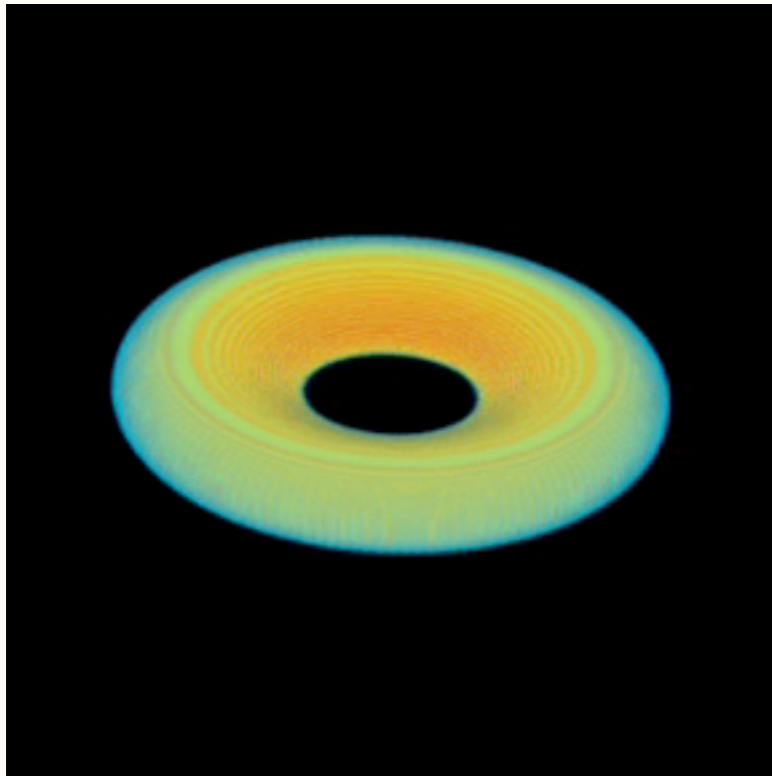
$$\alpha = \frac{\langle\langle \rho v_x v'_y \rangle\rangle}{\rho_0 c_s^2} - \frac{\langle\langle B_x B_y \rangle\rangle}{4\pi \rho_0 c_s^2}$$

Protoplanetary Disks

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Turbulent => Accretion

Layered



(Credit: Hawley)

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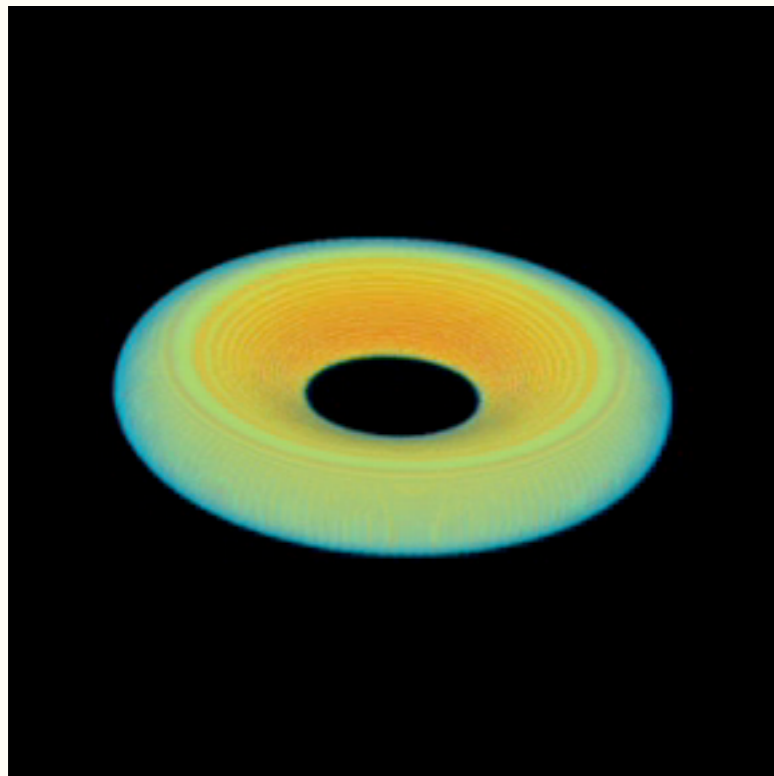
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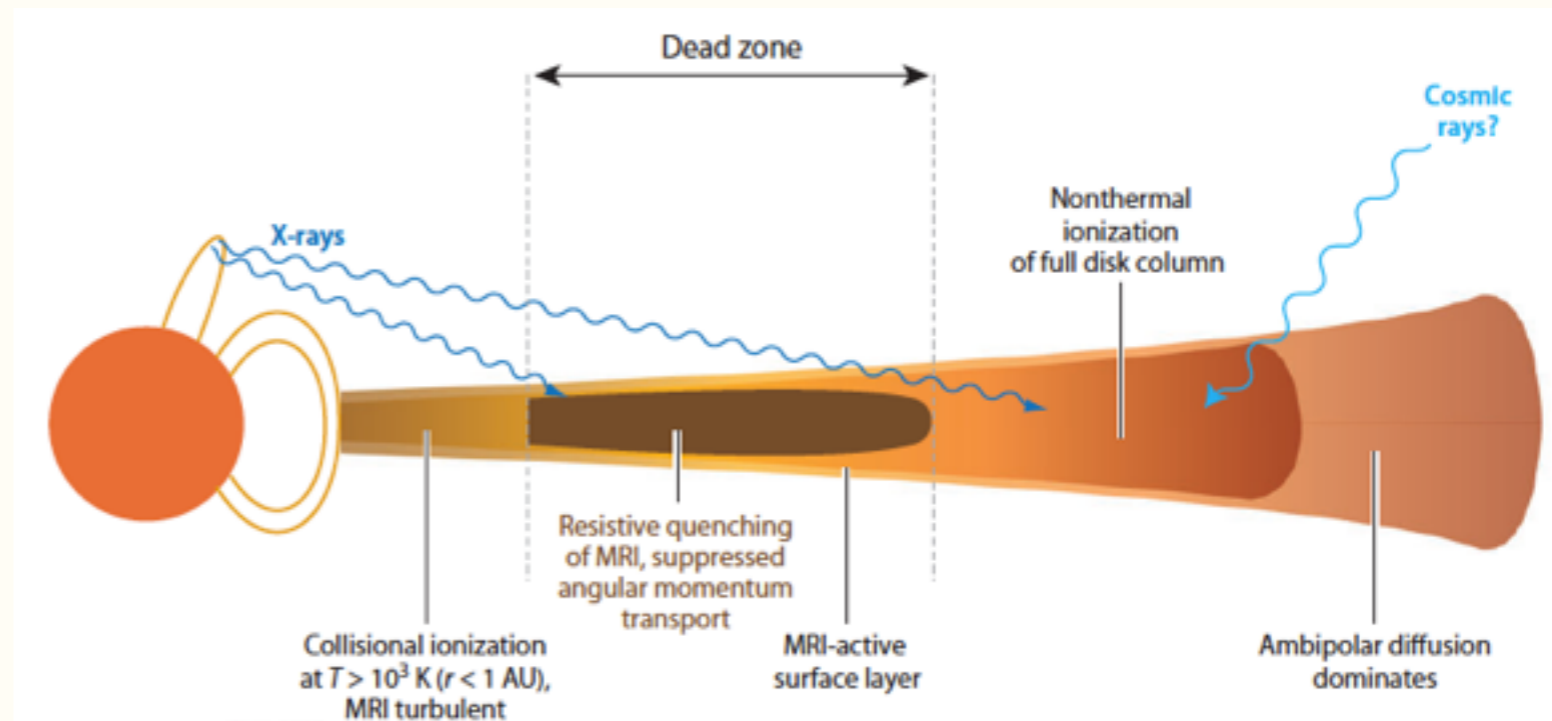
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Layered



Gammie 1996
Turner et al. 2007
Armitage 2011 ARAA

Why do protoplanetary disks have features?

The disk is gravitationally unstable? The dust layer is gravitationally unstable? MRI turbulence leads to spiral arms?

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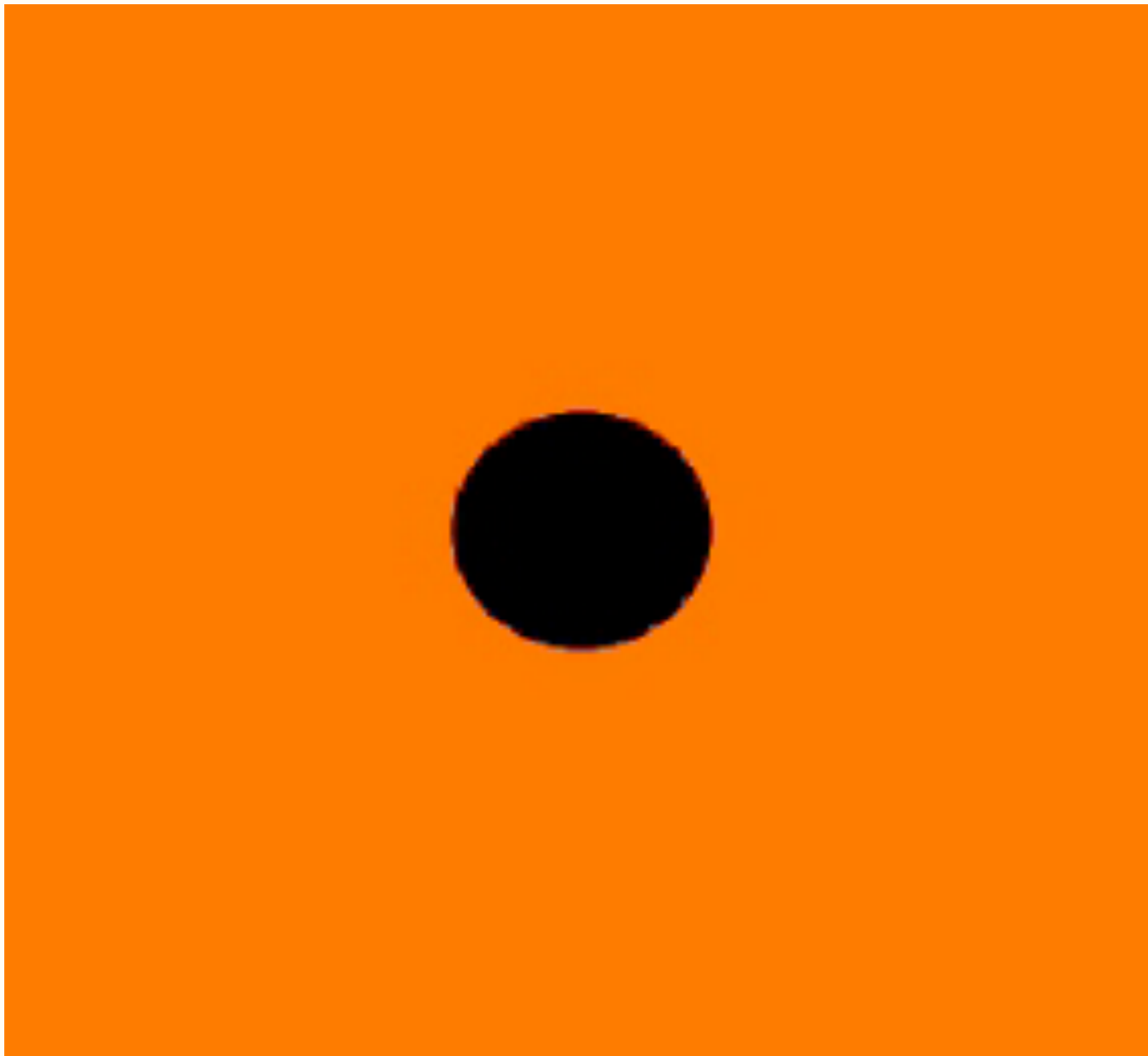
(Goldreich & Tremaine 1979,1980)

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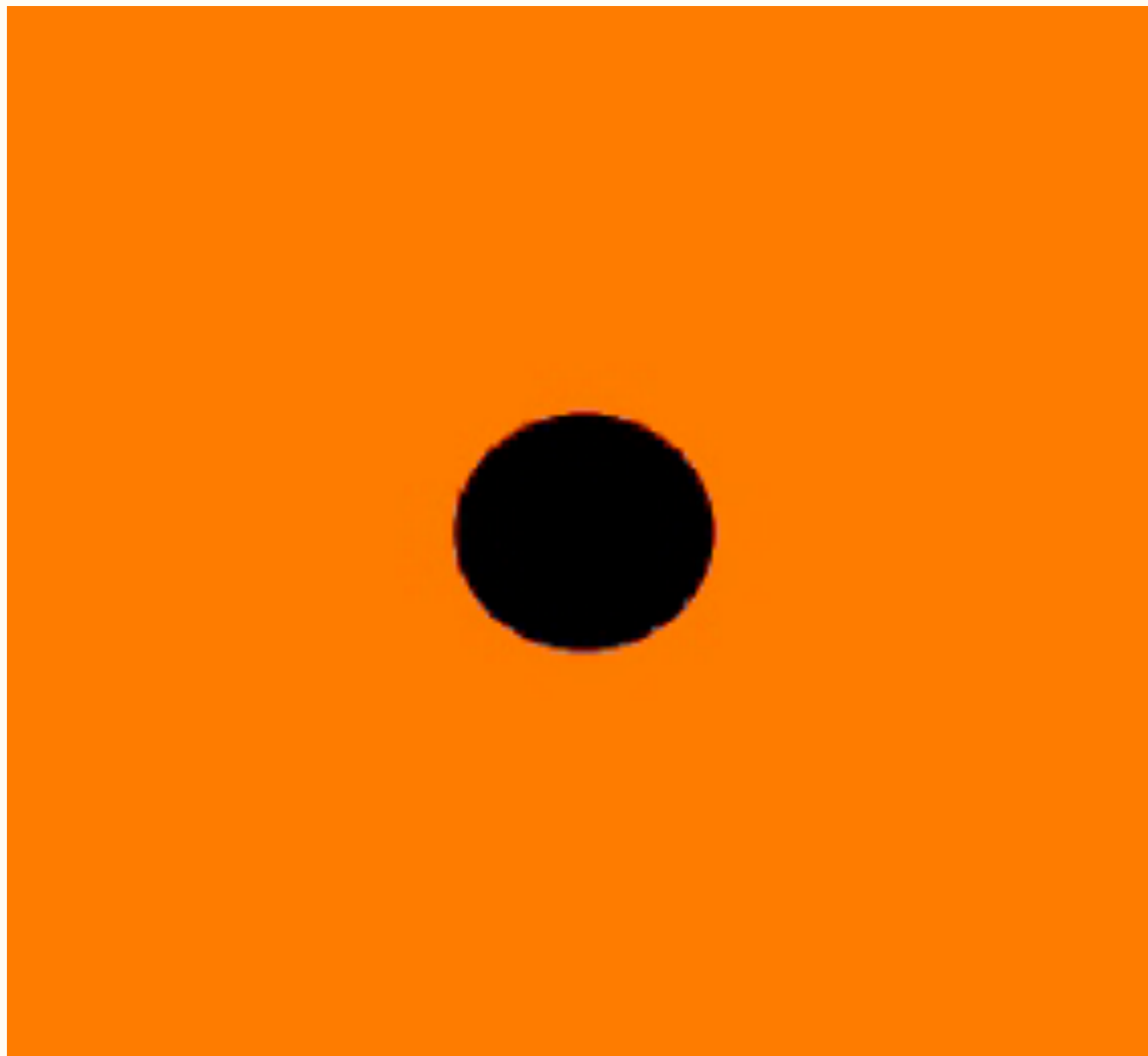


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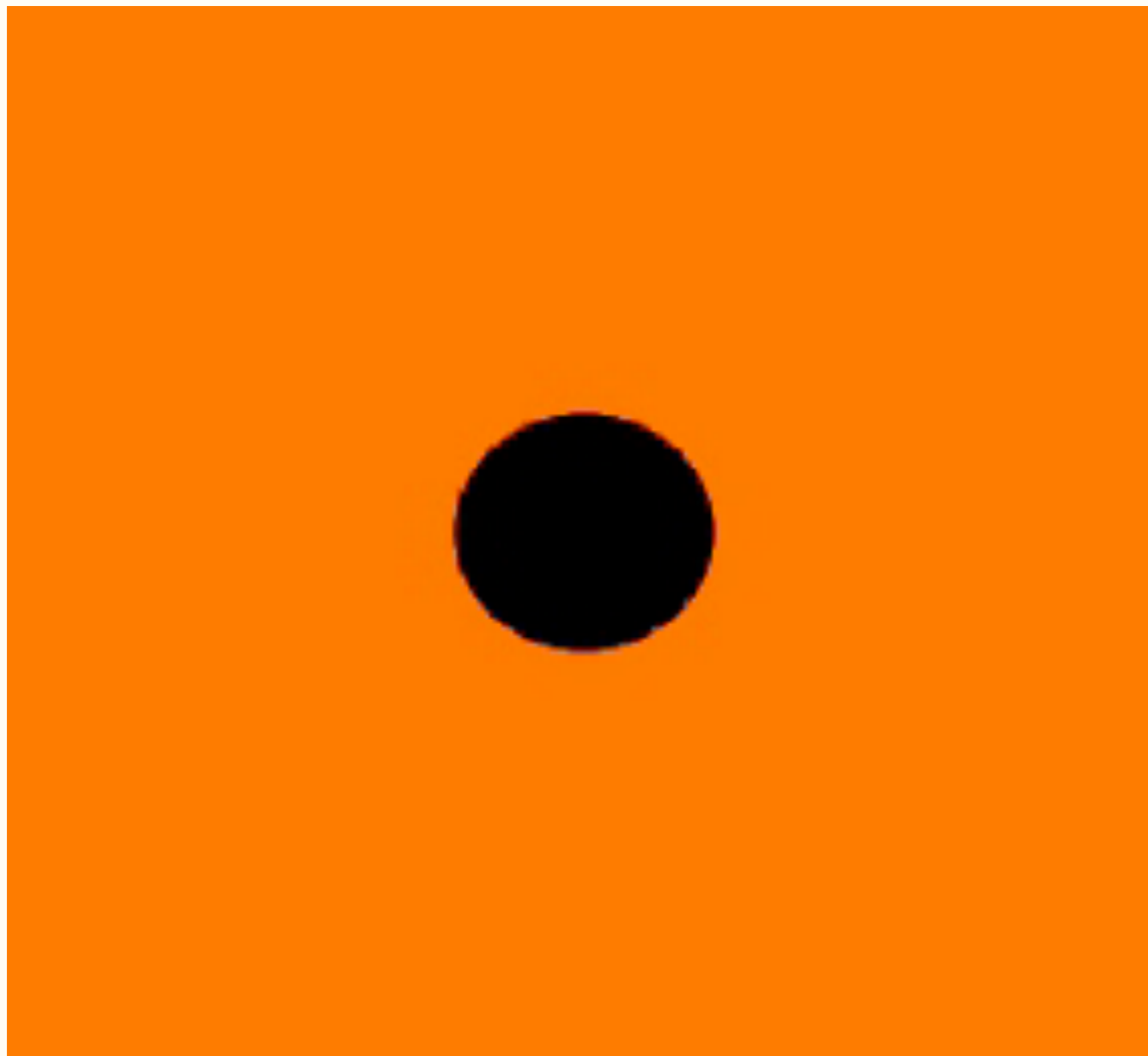
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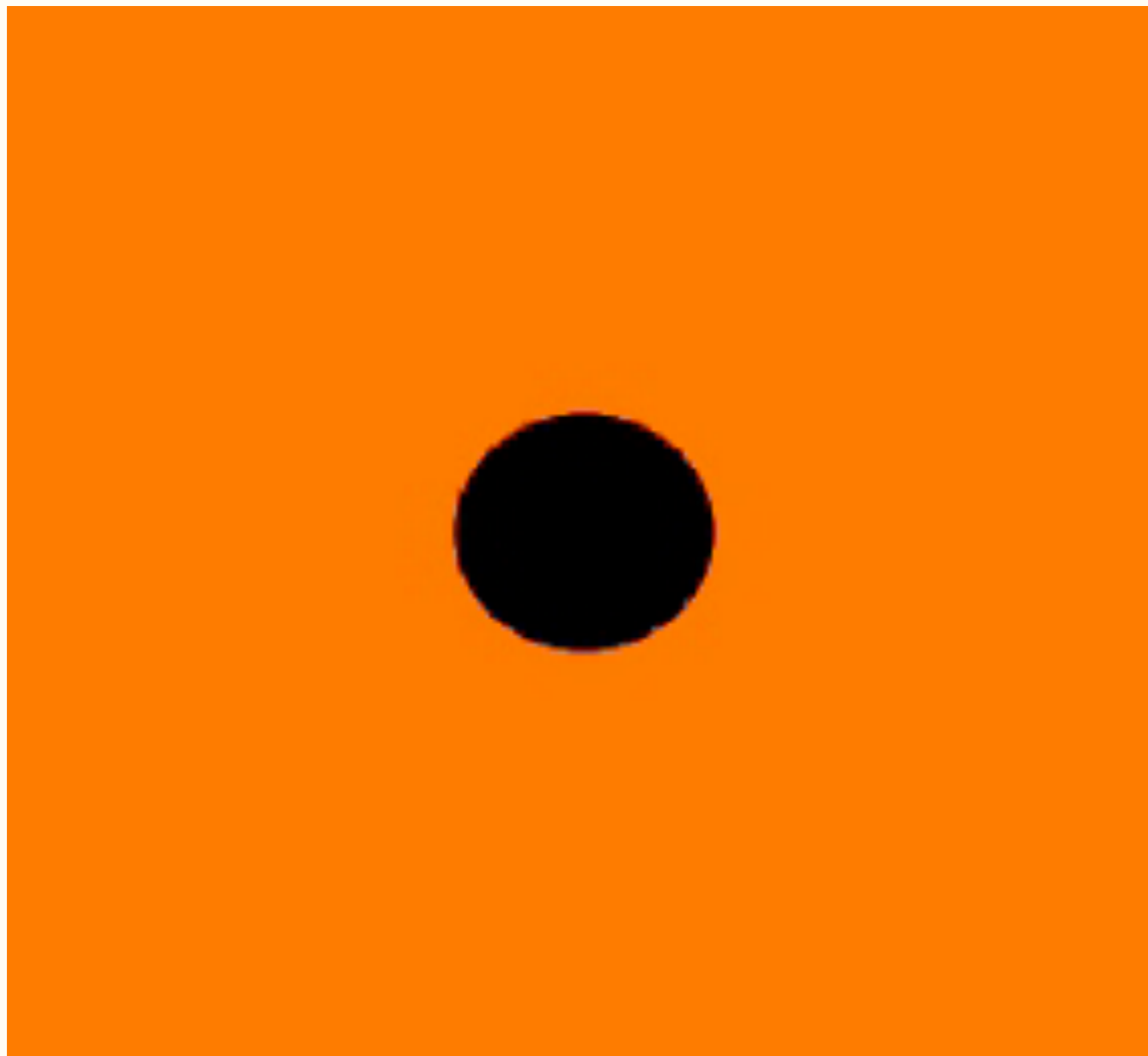
1. Spiral wakes

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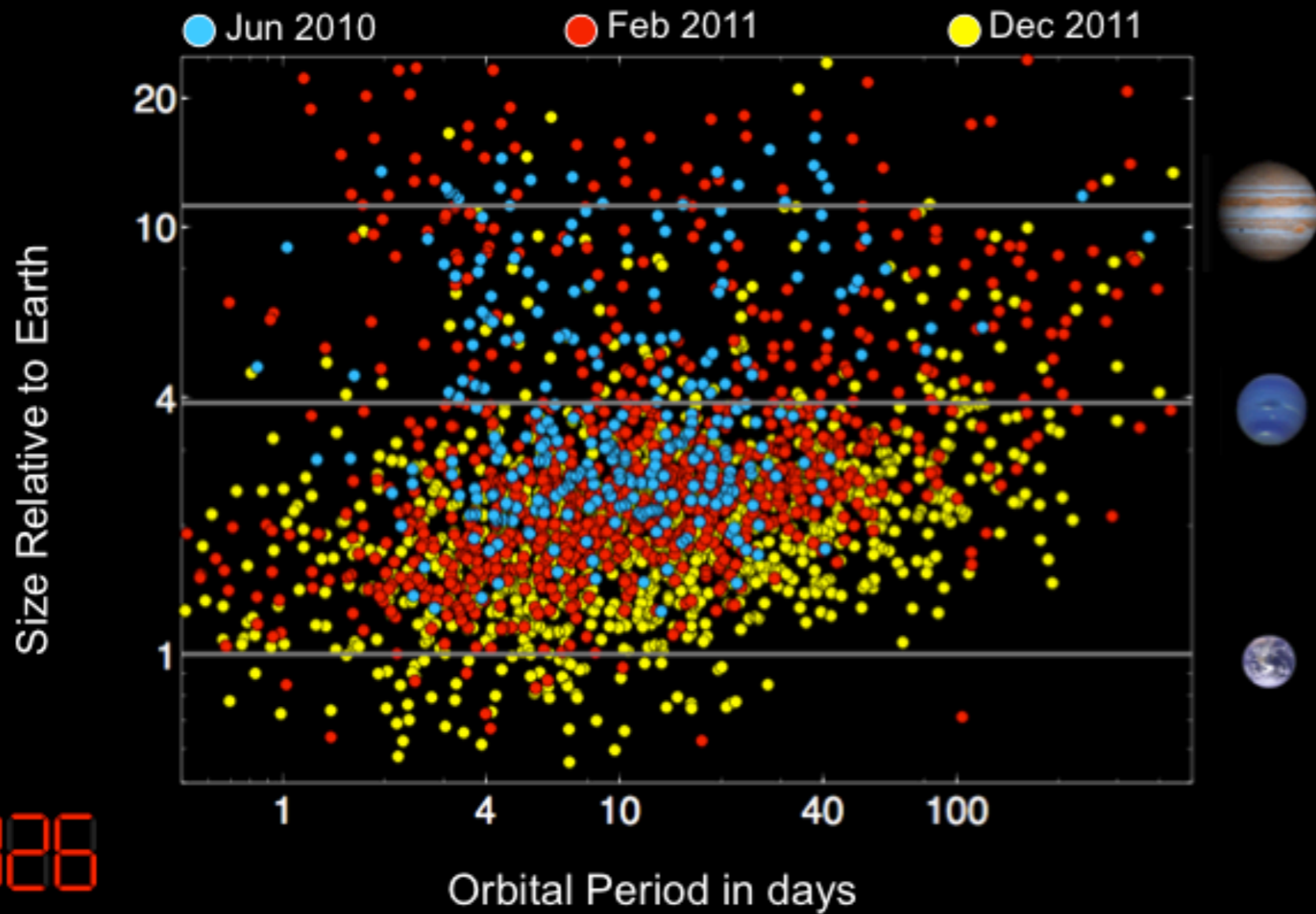
Prominent Features:

1. Spiral wakes
2. Gaps

Planets Are Common

Candidates as of Dec 2011

Q0-Q6: May 2009 - Sep 2010

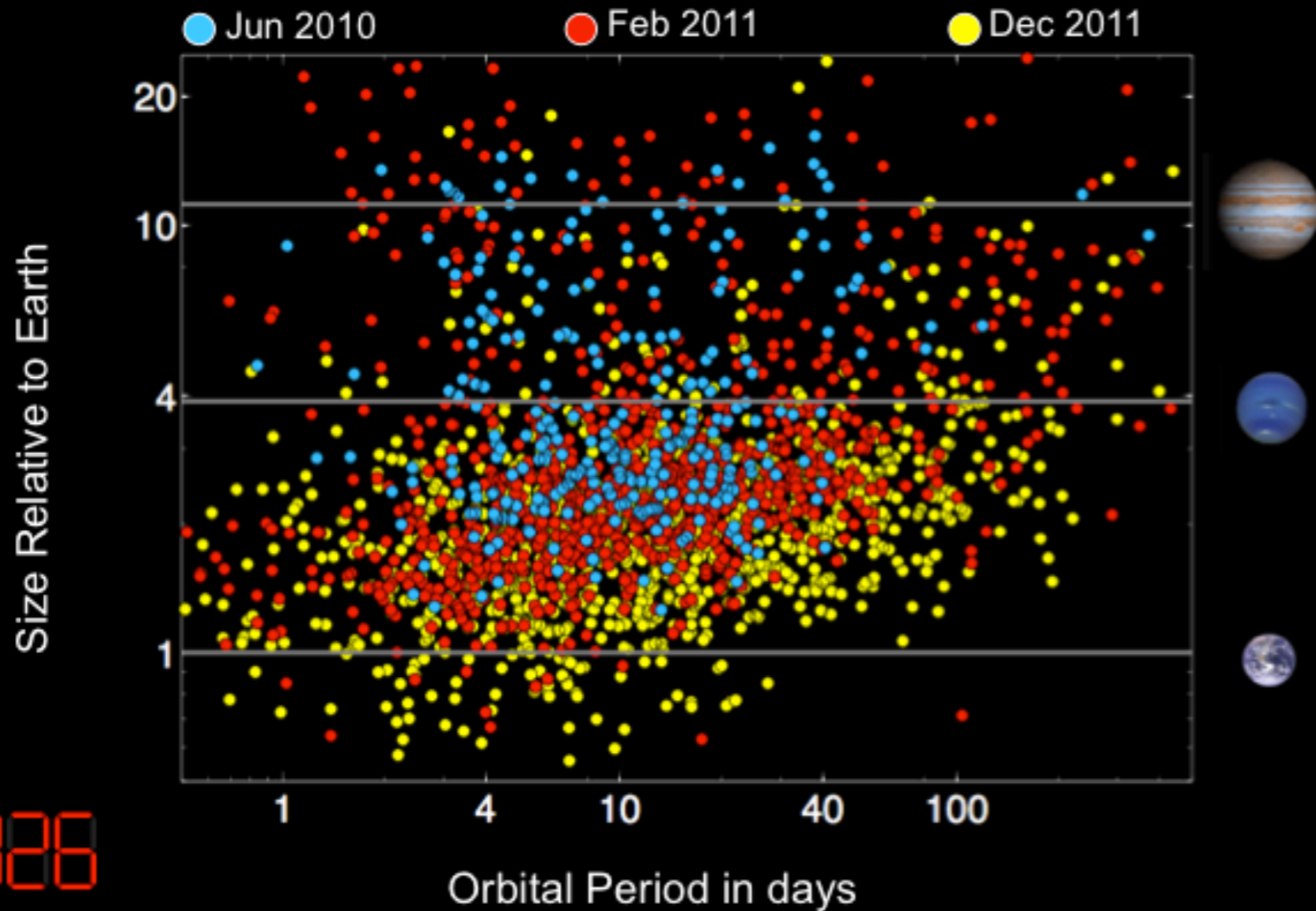


(Source: Kepler website, Credit: Natalie Batalha)

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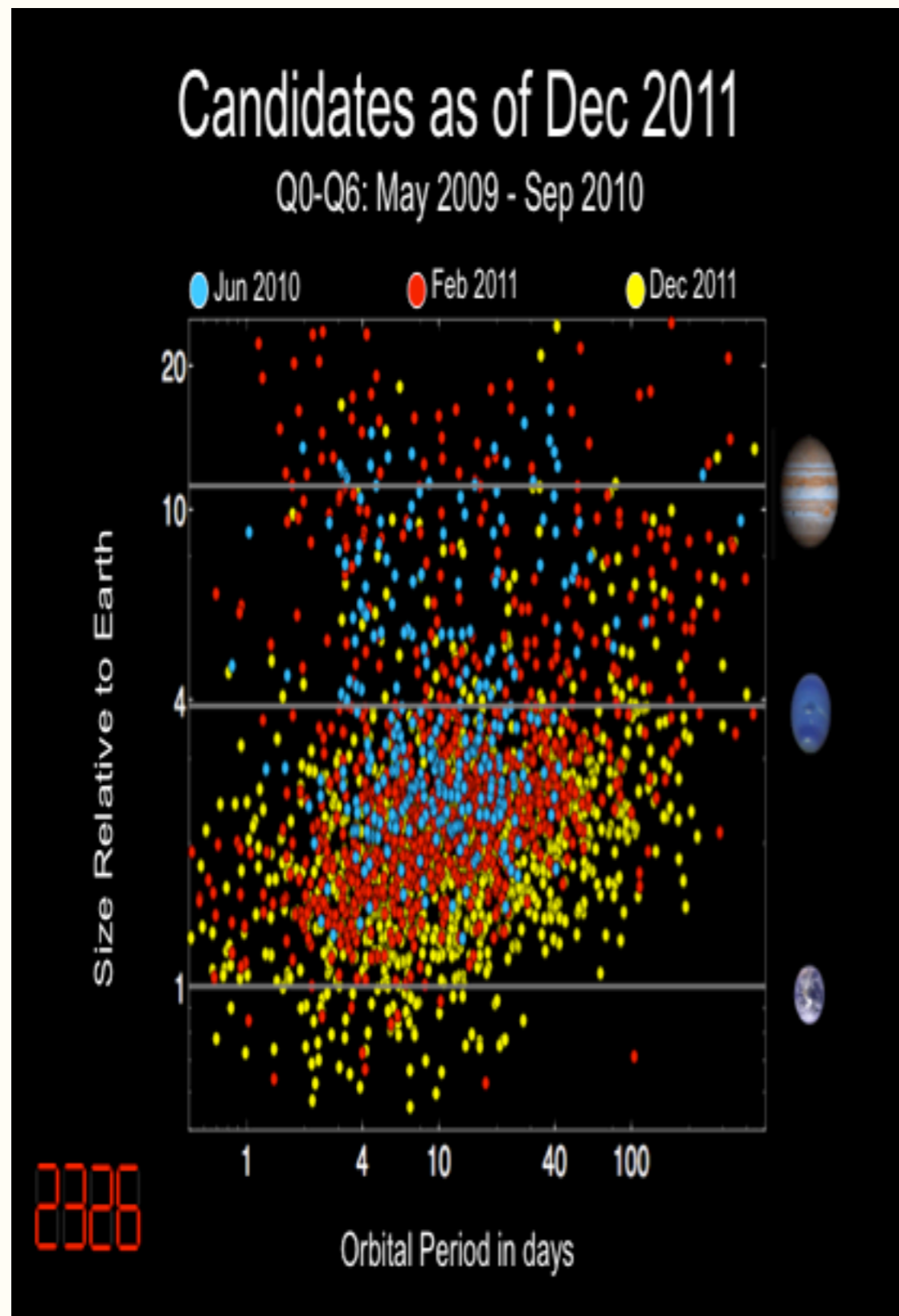


more than 60%
of solar type
stars have a
1-16 R_E planet
within 250 days
(S. Dong & Zhu 2012)

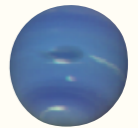
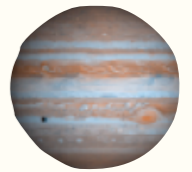
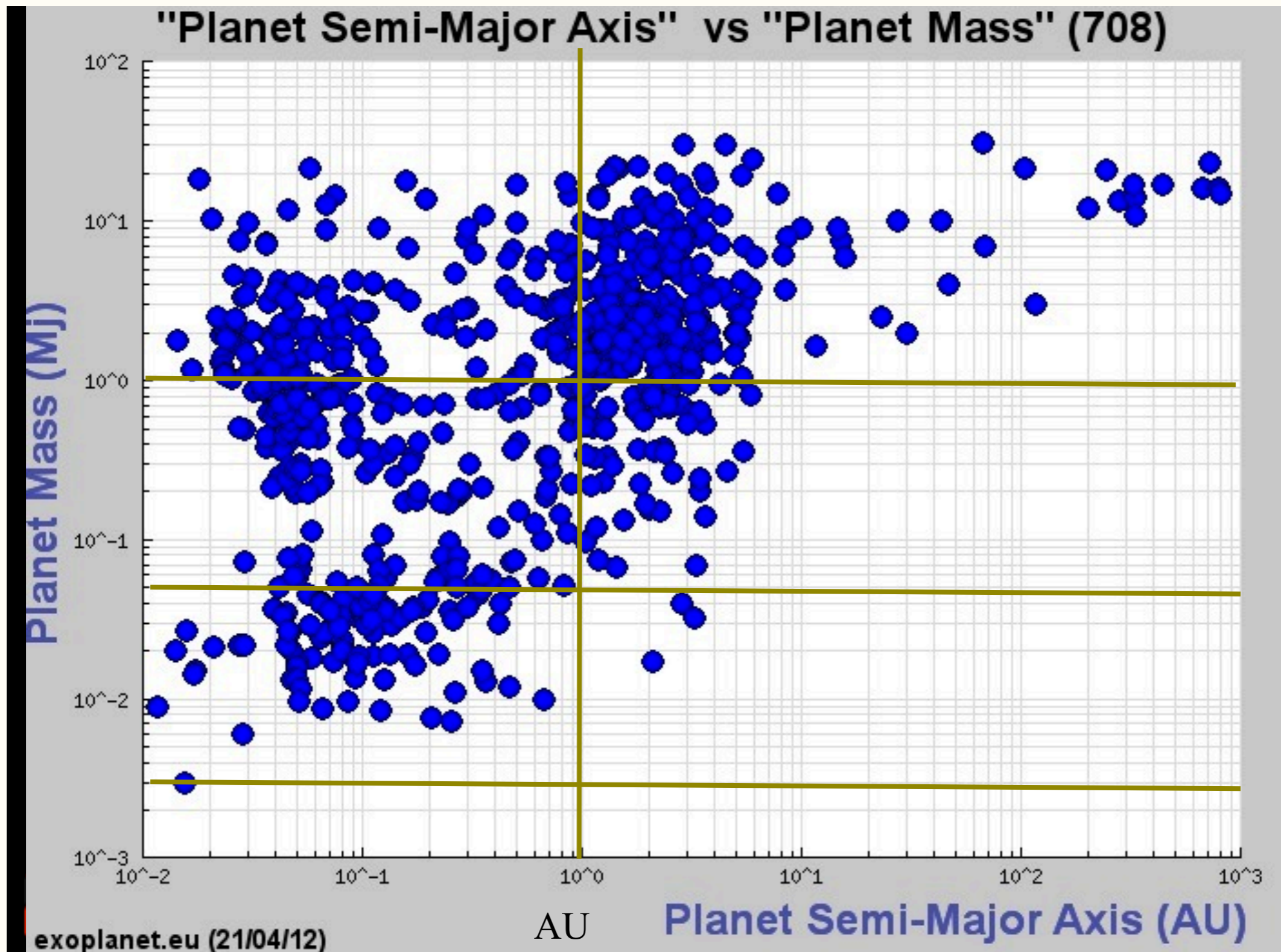
Howard et al. 2012
Fressin et al. 2013

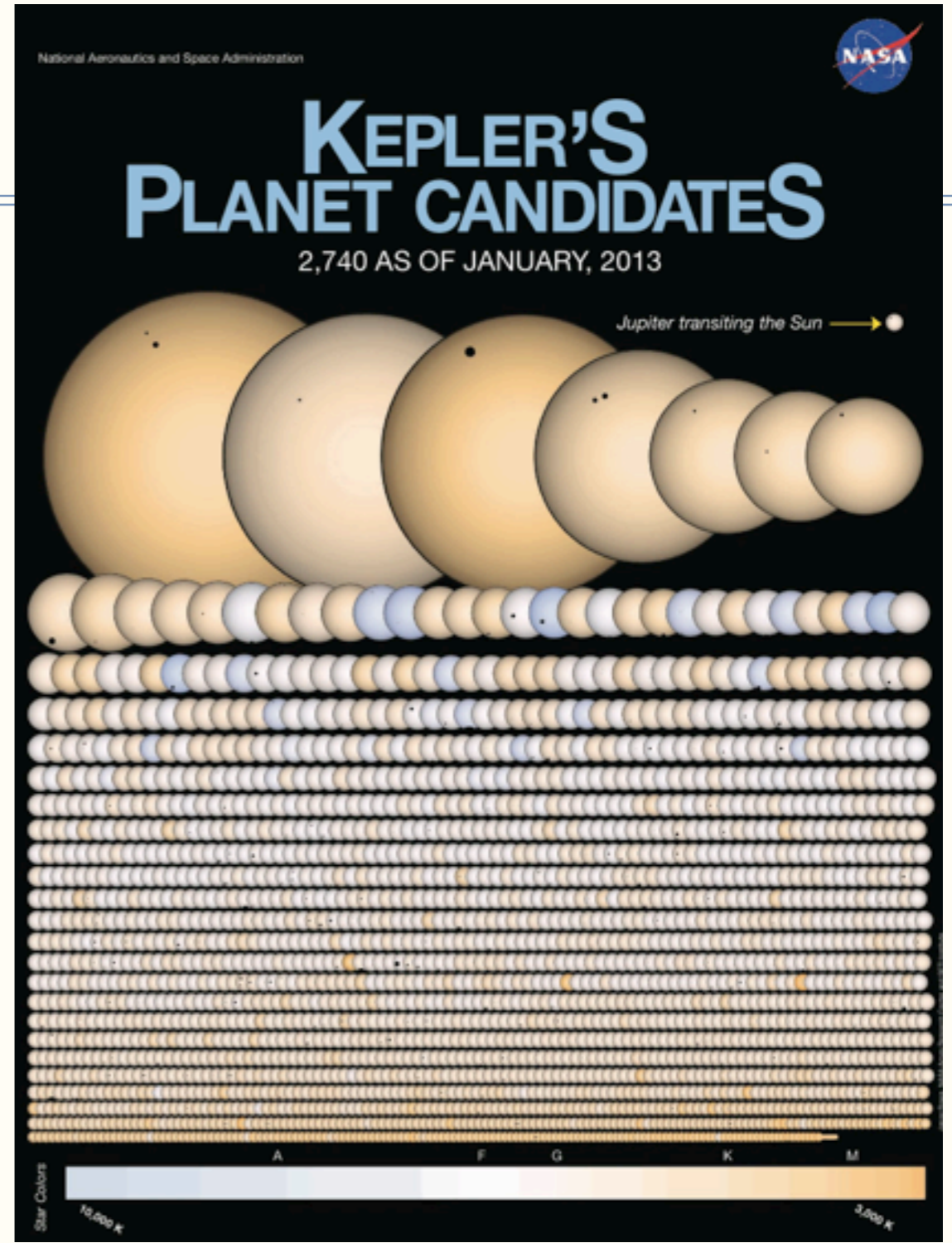
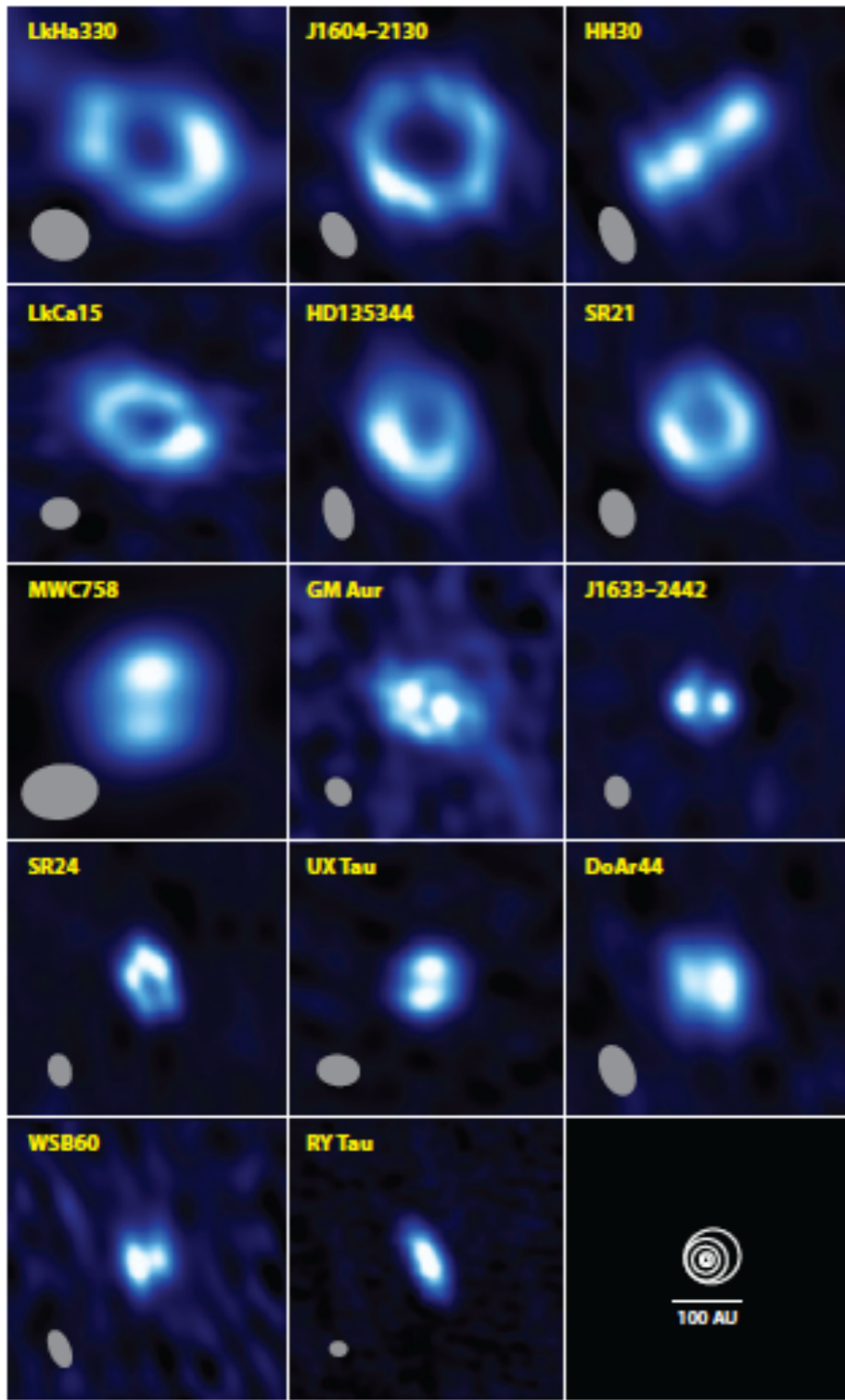
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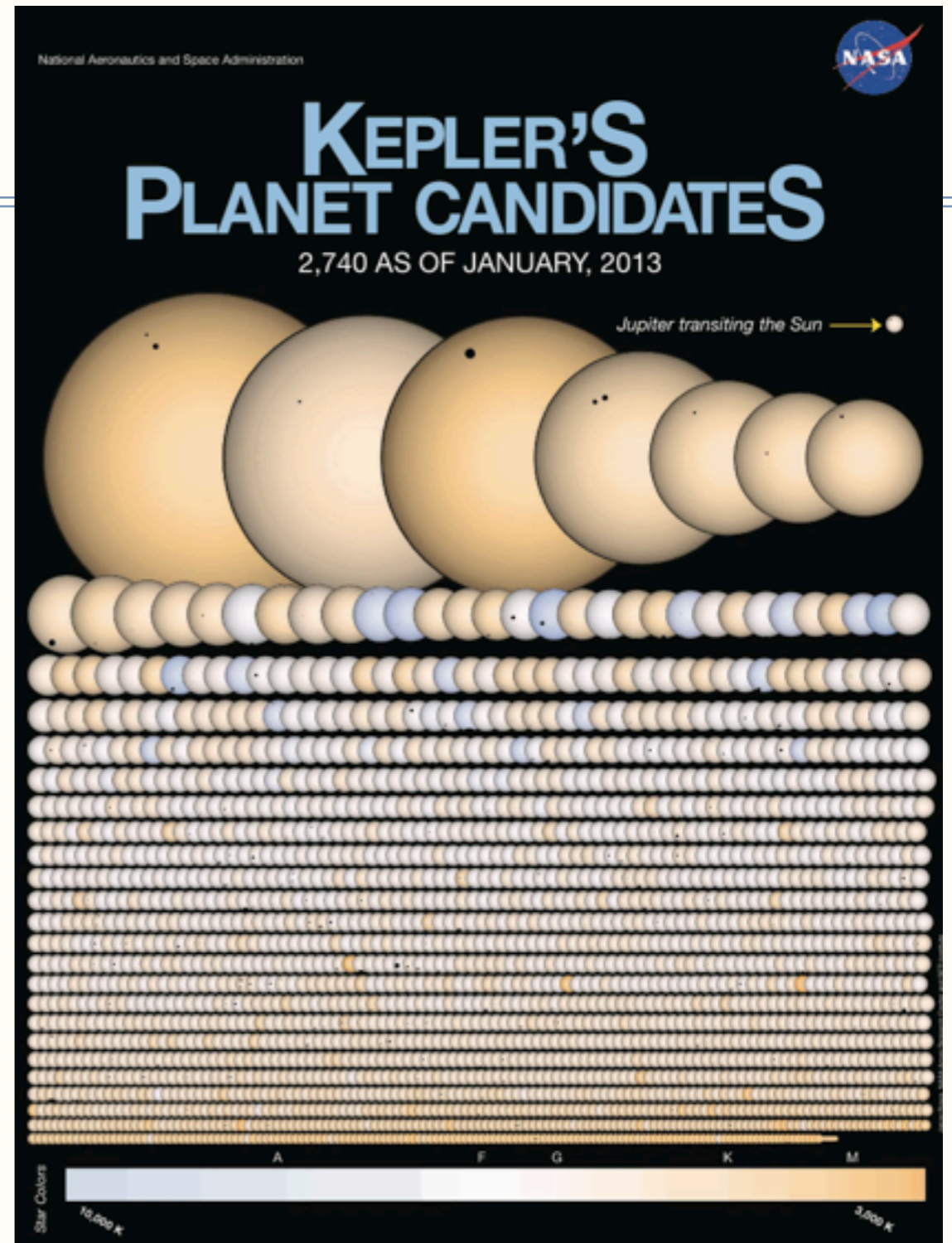
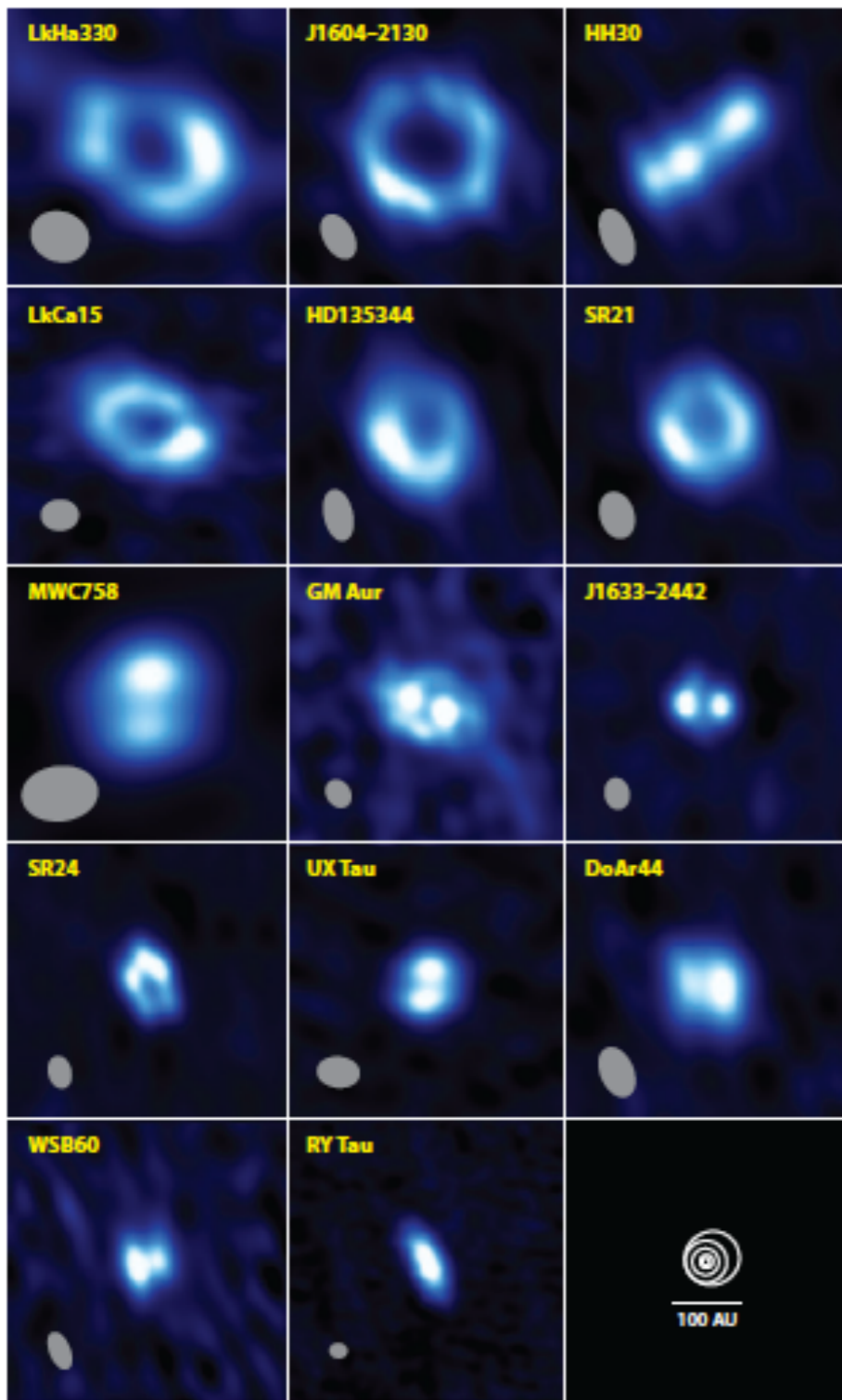
Confirmed planets with all techniques



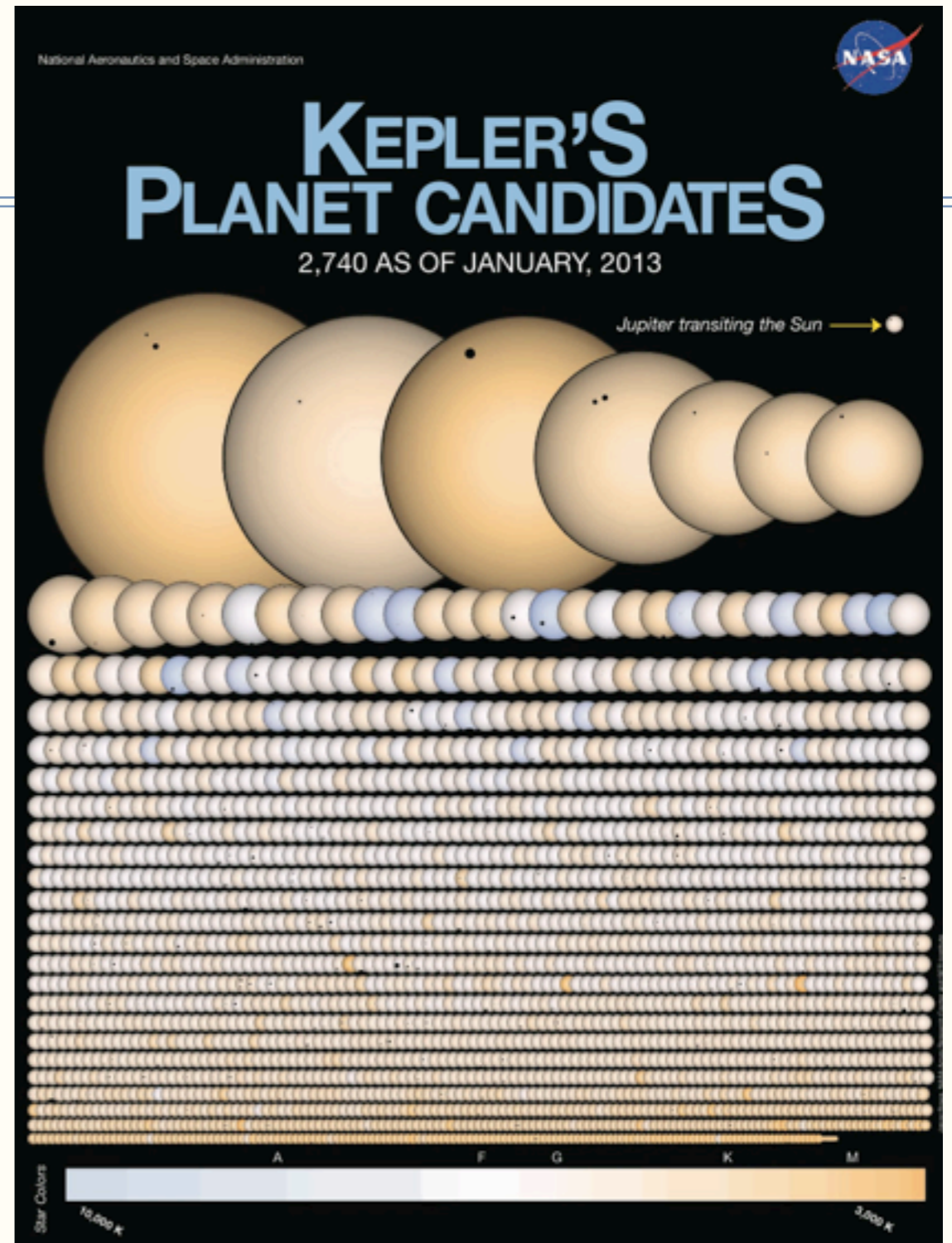
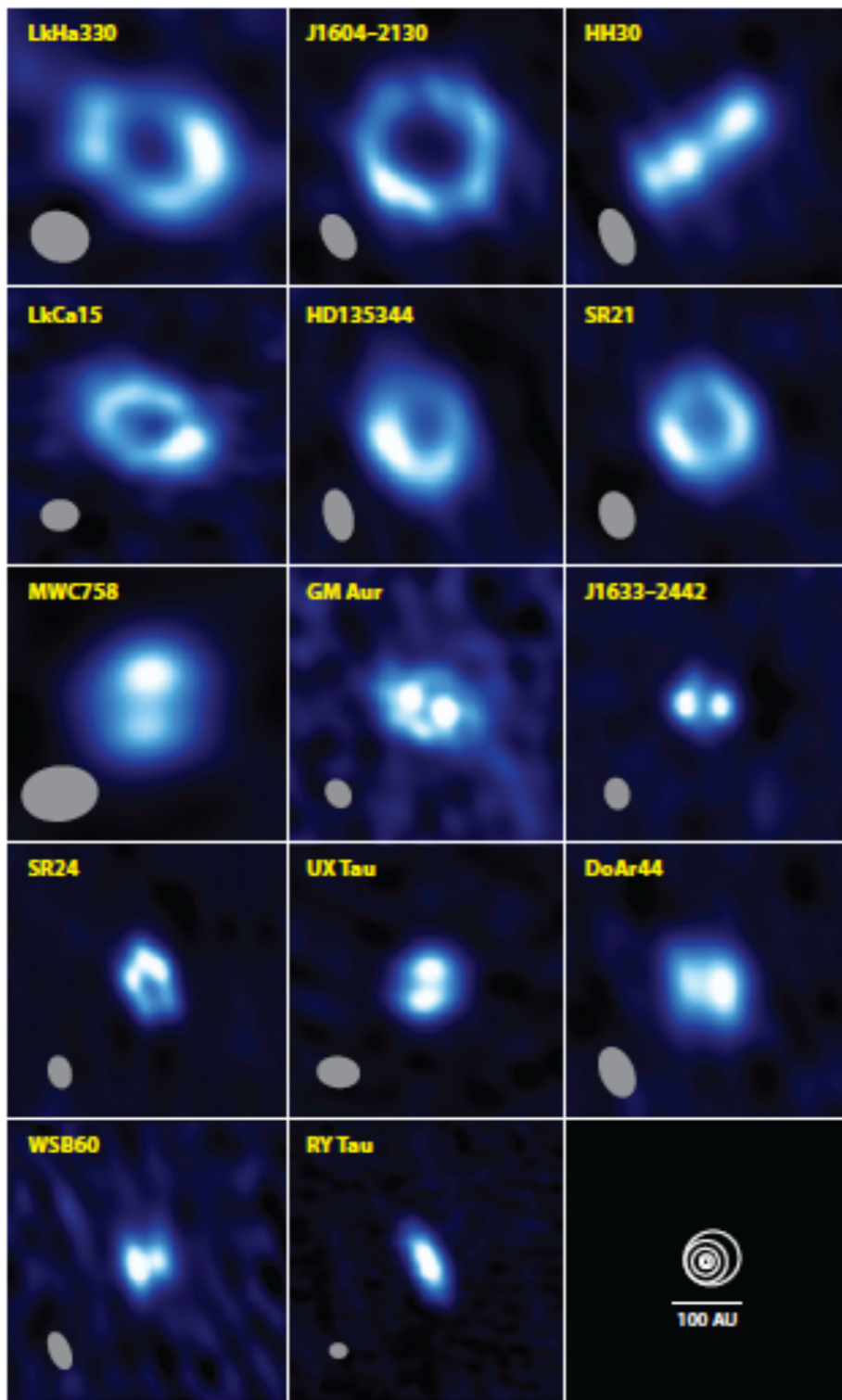
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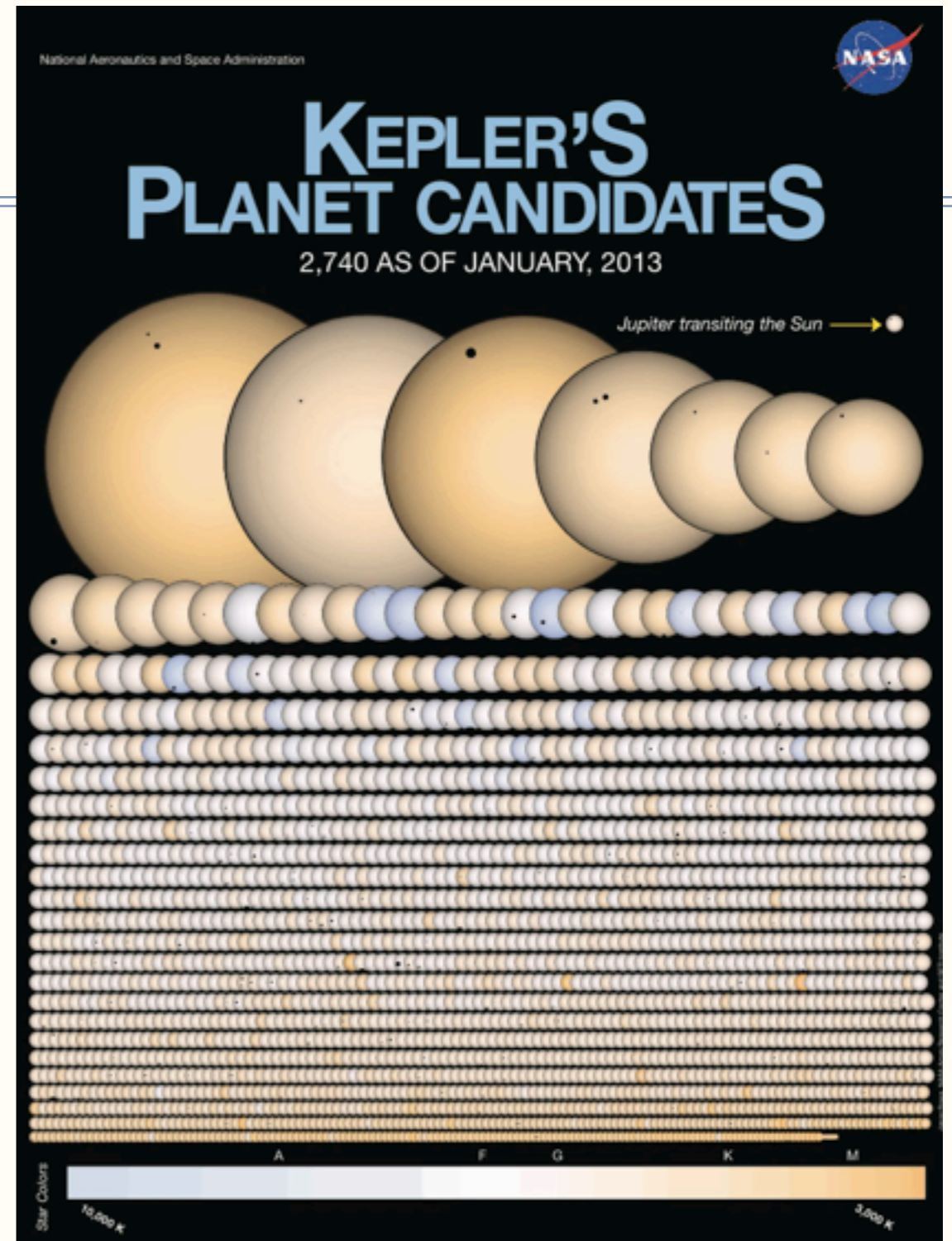
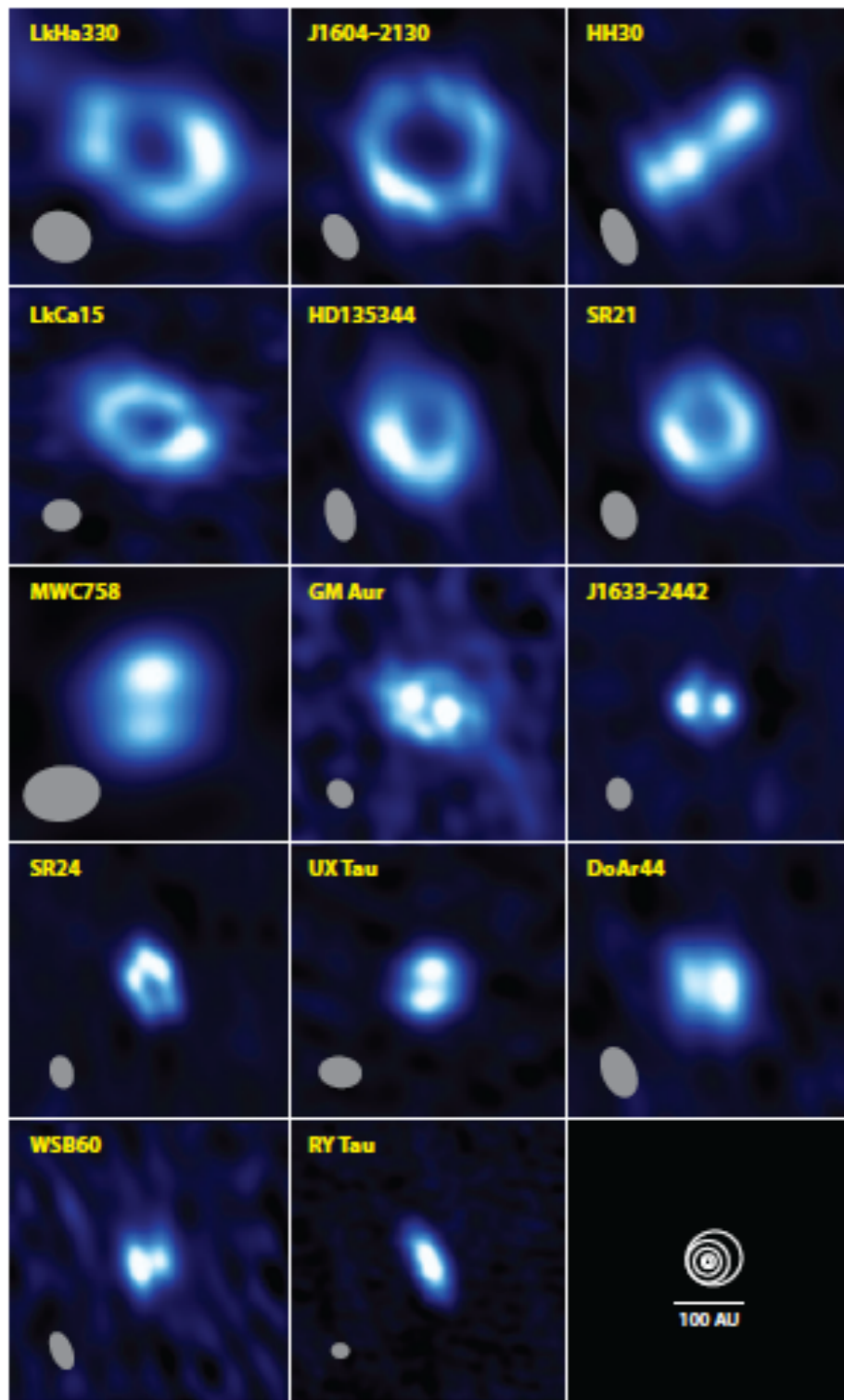




Any Connections?



Any Connections?
 How easy to carve out a gap by a planet?



Any Connections?

How easy to carve out a gap by a planet?

Within 250 days: $>1 M_E$: 60% $>8 M_E$: 35% $>0.2 M_J$: 2.5%

Outlines

- Planets are Common
- Gap opening process
 - Gap opening in inviscid disks.
 - Gap opening in MRI-turbulent disks.
- Transitional disks are candidates for harboring young planets and they start to reveal rich physics.
- Dust particle dynamics during planet-disk interaction is essential for connecting with observations to find young planets.

Gap opening

- Gap opening criteria:

1. Thermal Criterion

Density waves are nonlinear when they are excited by the planet

Critical mass for gap opening

$$M_{th} = \frac{c_s^3}{G\Omega_p} \approx 0.13 M_J \sim 41 M_E$$

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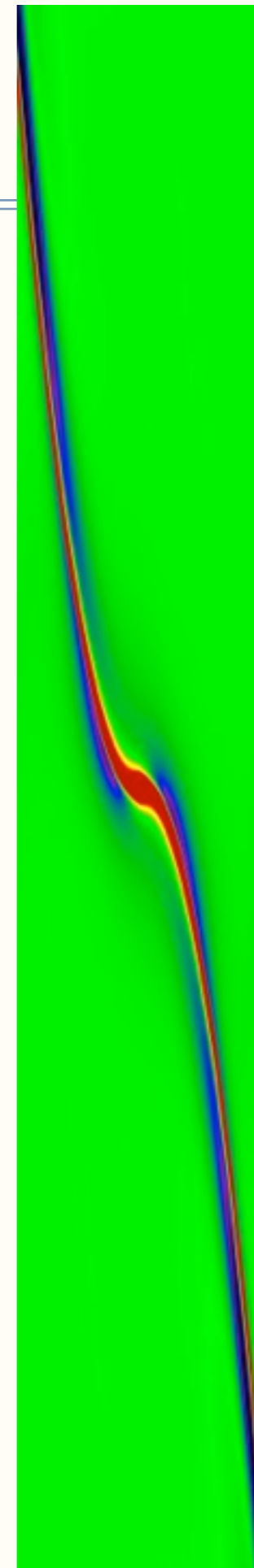
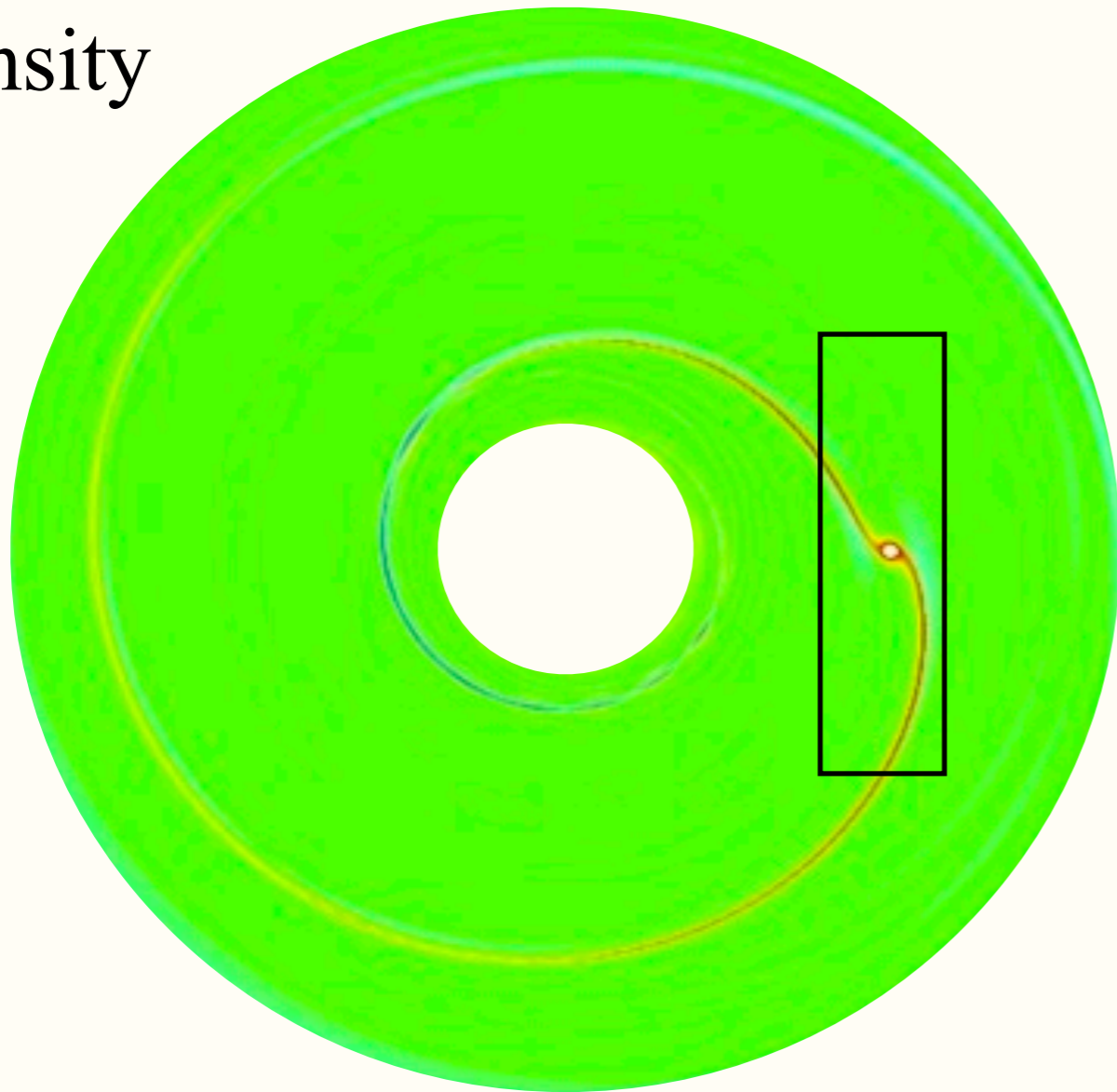
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2. Viscous Criterion

The planetary torque is larger than the viscous stress (α model)

Shearing Sheet

Surface
Density



Code: Athena

y/θ
 x/R

R. Dong et al. 2011ab

Thermal Criterion may be inaccurate

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Non-linear Density Wave Theory:

A low mass planet can excite linear density waves initially. When the spiral wake propagates in disks, they will gradually steepen to shocks, leading to gap opening.

Thermal Criterion may be inaccurate

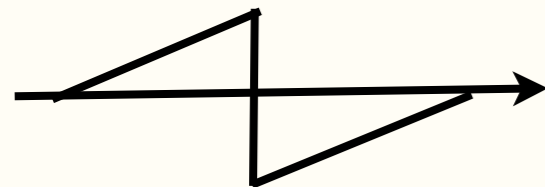
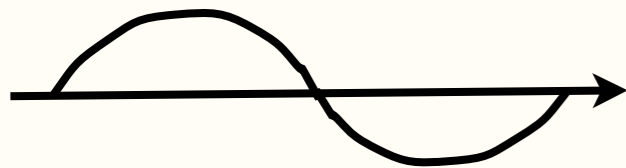
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1-D Gas Flow

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial x} + v \frac{\partial \rho}{\partial x} = 0,$$

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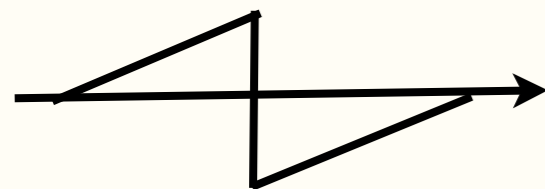
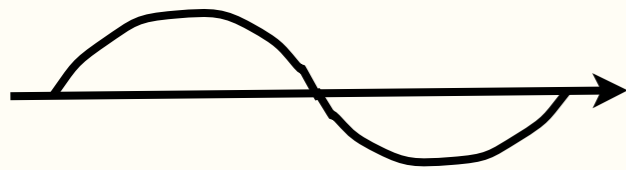
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2-D Steady Flow in Disks

$$\partial_y \ll \partial_x \text{ and } v \ll u \quad \xi \equiv Ax^2$$

$$\partial_y \Sigma + u \partial_\xi \Sigma + \Sigma \partial_\xi u = 0$$

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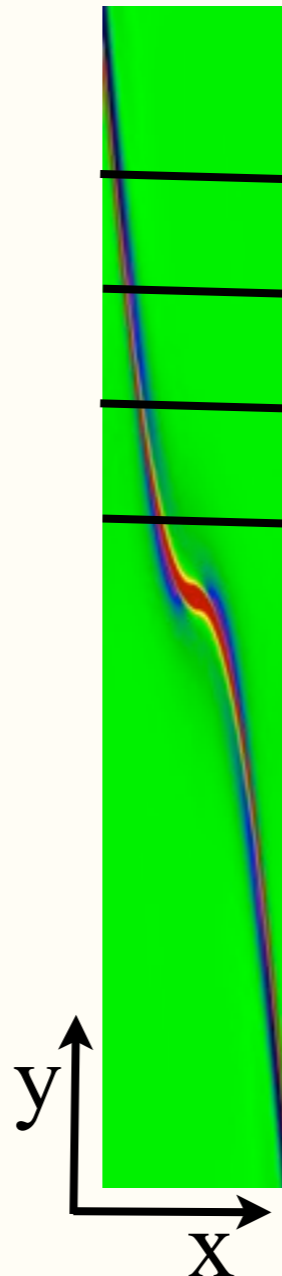
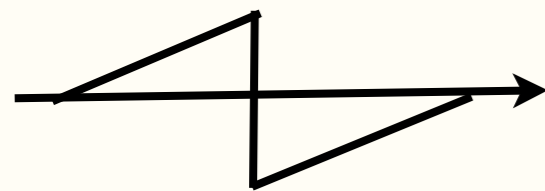
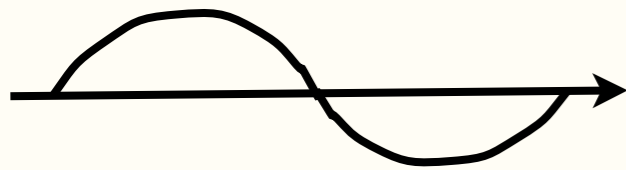
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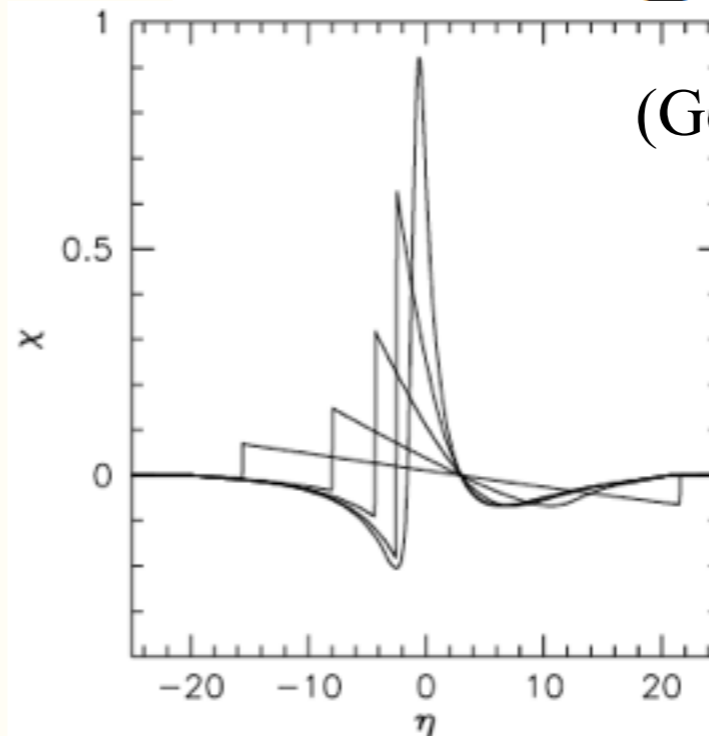


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(Goodman & Rafikov 2001,
Dong et al 2009)

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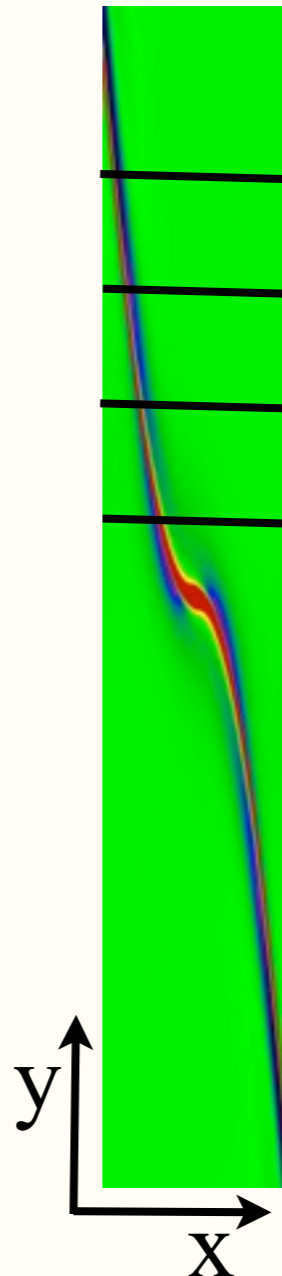
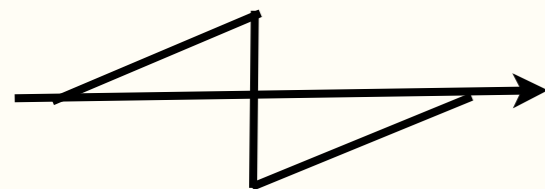
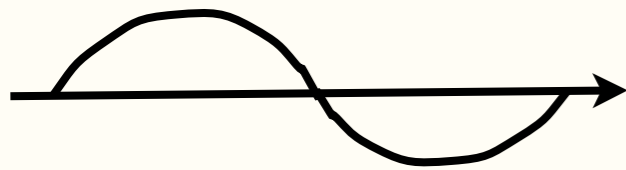
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$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x};$$

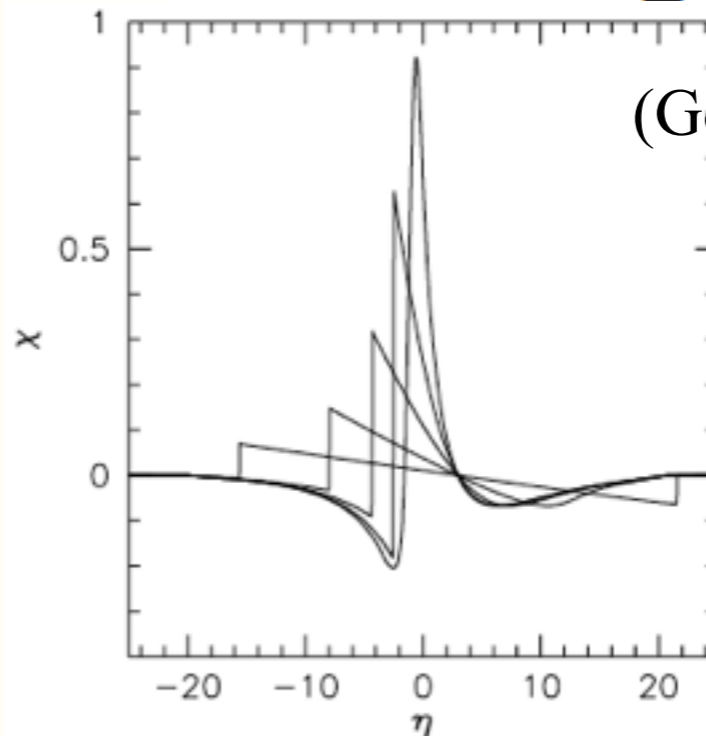


2-D Steady Flow in Disks

$$\partial_y \ll \partial_x \text{ and } v \ll u \quad \xi \equiv Ax^2$$

$$\partial_y \Sigma + u \partial_\xi \Sigma + \Sigma \partial_\xi u = 0$$

$$\partial_y u + u \partial_\xi u + \frac{c^2(\Sigma)}{\Sigma} \partial_\xi \Sigma = 0$$



(Goodman & Rafikov 2001,
Dong et al 2009)

Shocking distance: $|x| \approx 0.93 \left(\frac{\gamma + 1}{12/5} \frac{M_p}{M_t} \right)^{-2/5} H$

Gap opening in 2-D inviscid disks

$0.1 M_t$

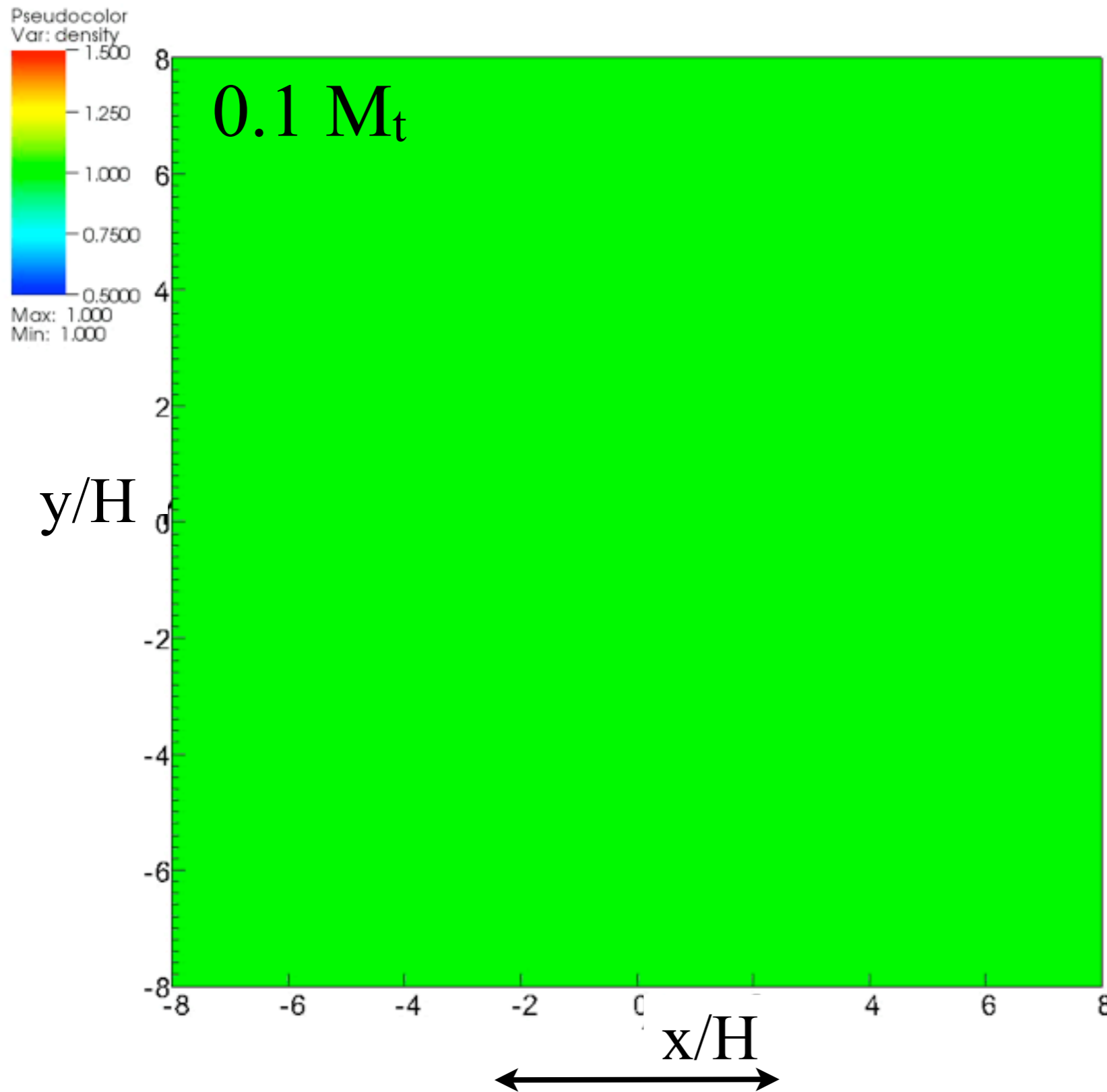
y/H

x/H



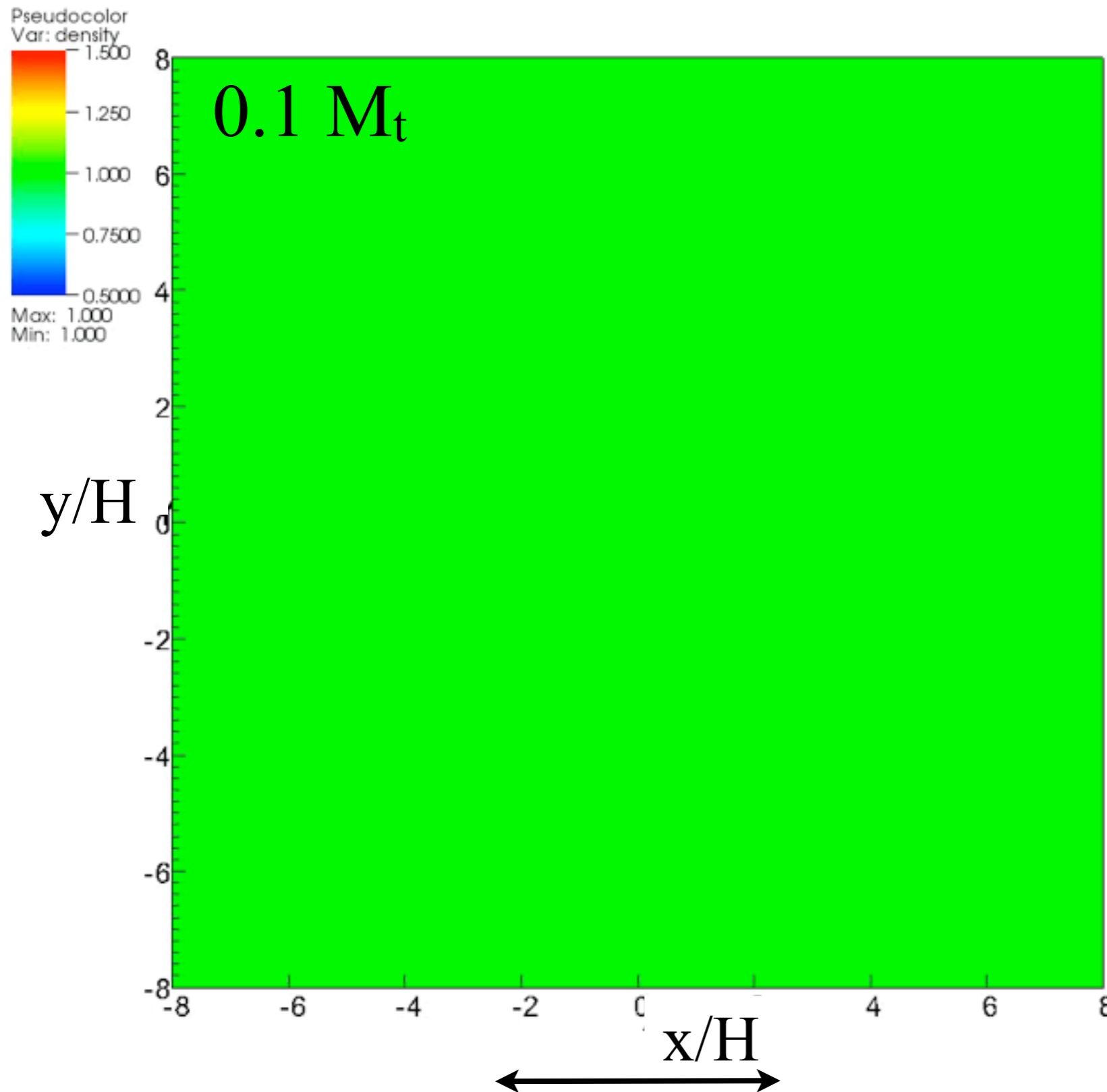
Zhu, Stone, Rafikov 2013

Gap opening in 2-D inviscid disks



Zhu, Stone, Rafikov 2013

Gap opening in 2-D inviscid disks

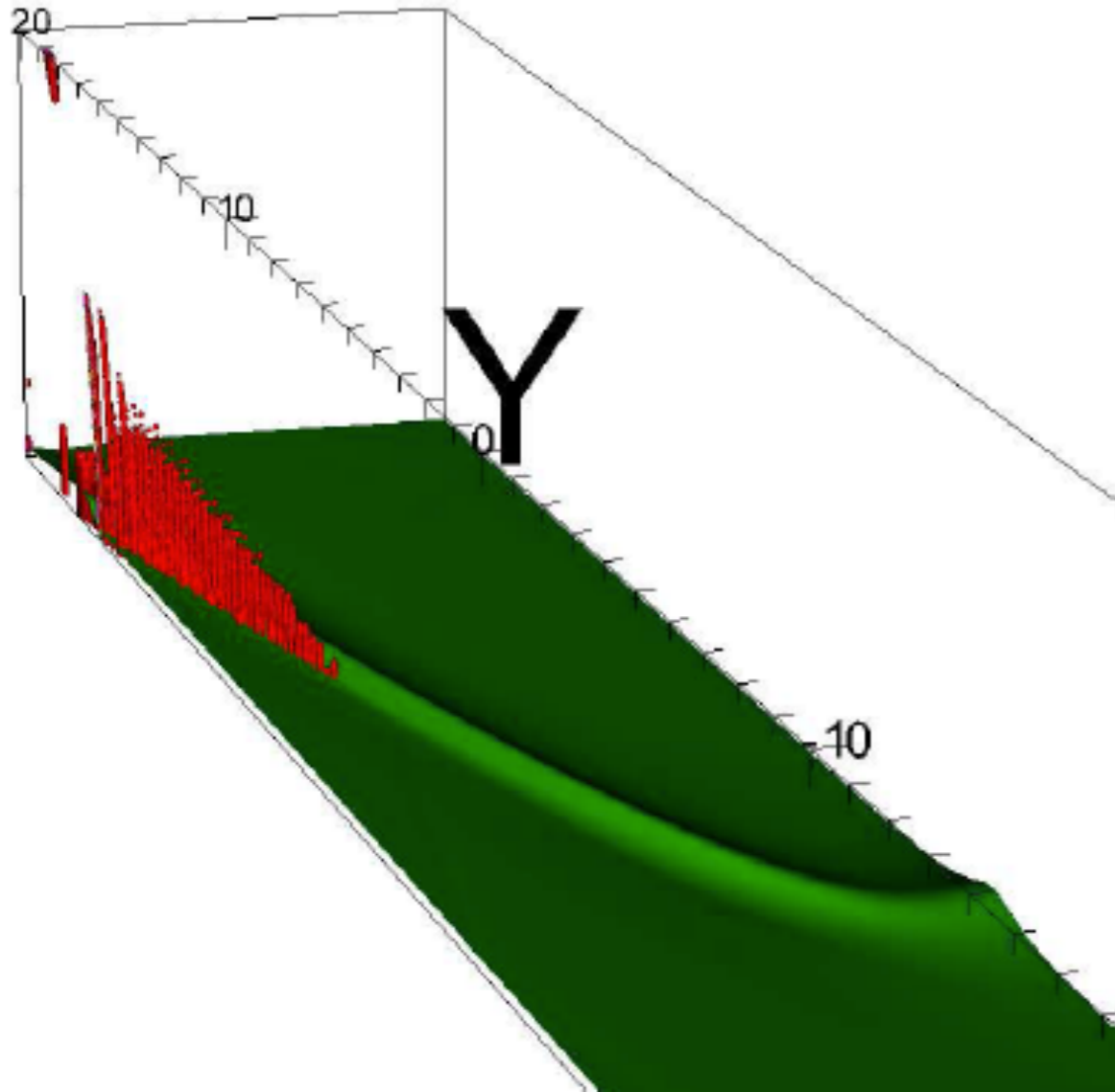


A low mass planet can
also open a gaseous
gap!
(Li et al. 2009, Muto et al. 2010)

Zhu, Stone, Rafikov 2013

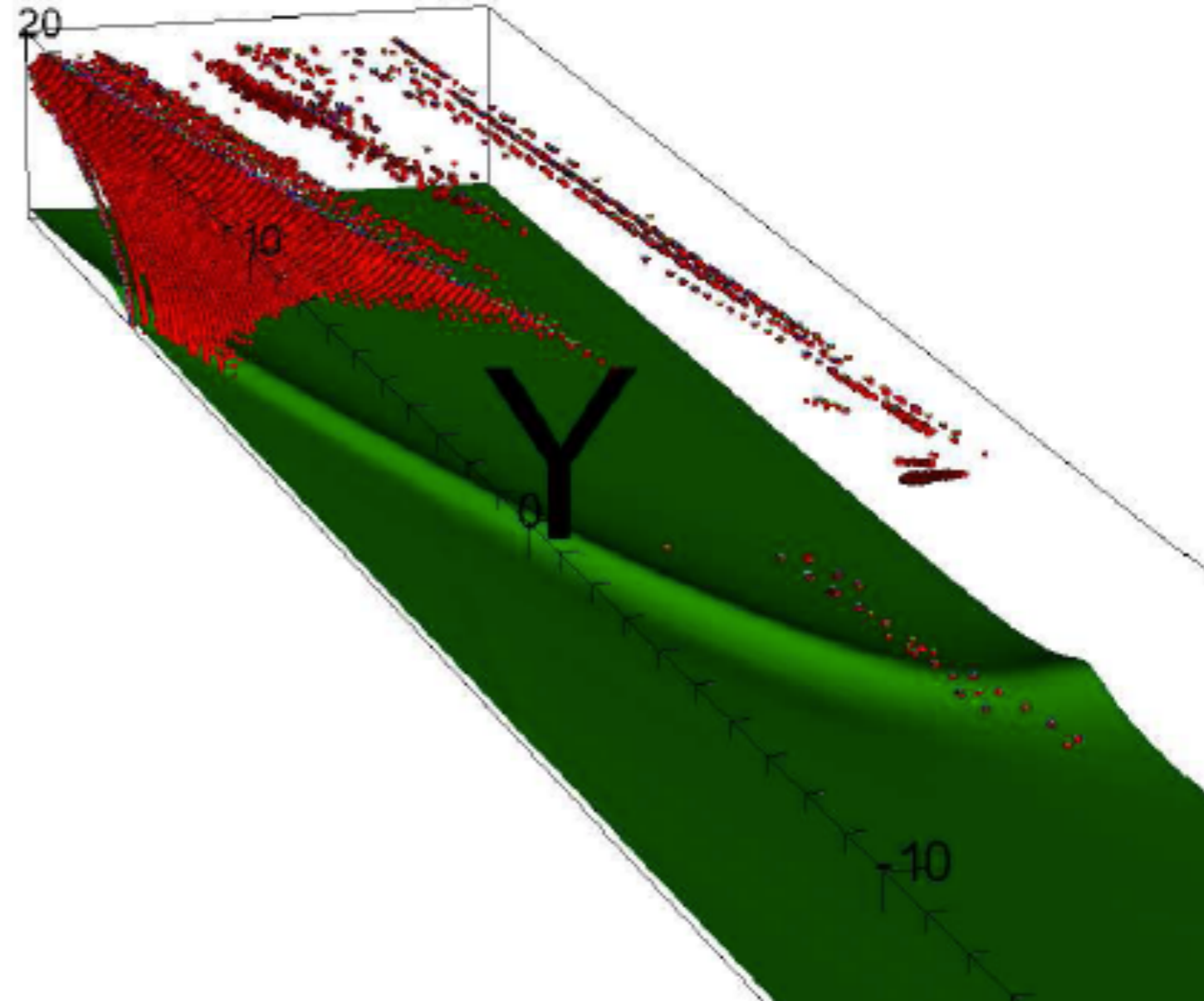
Gap opening in 3-D disks

Iso+Iso



2-D waves

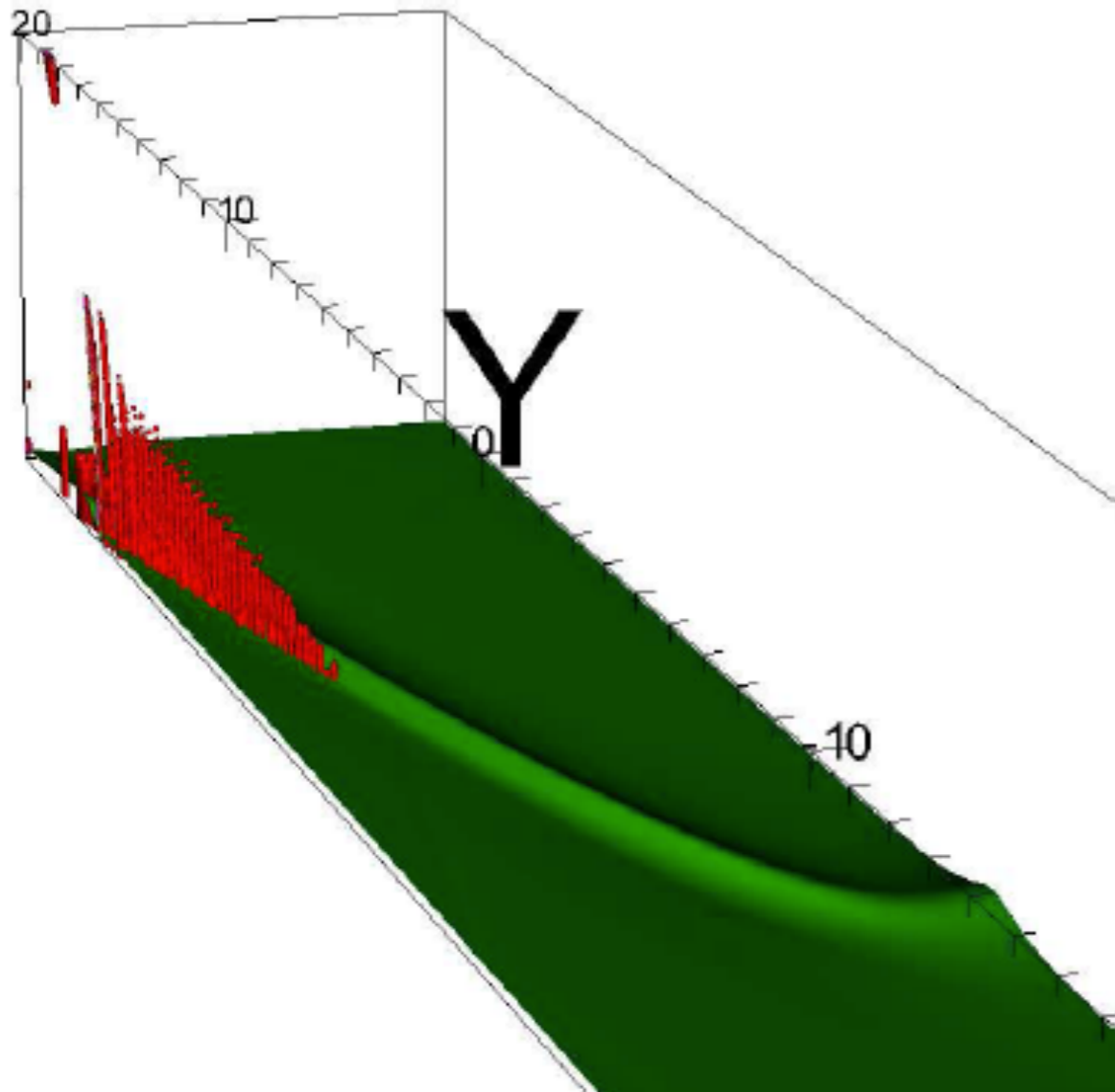
Adi+Adi



3-D waves

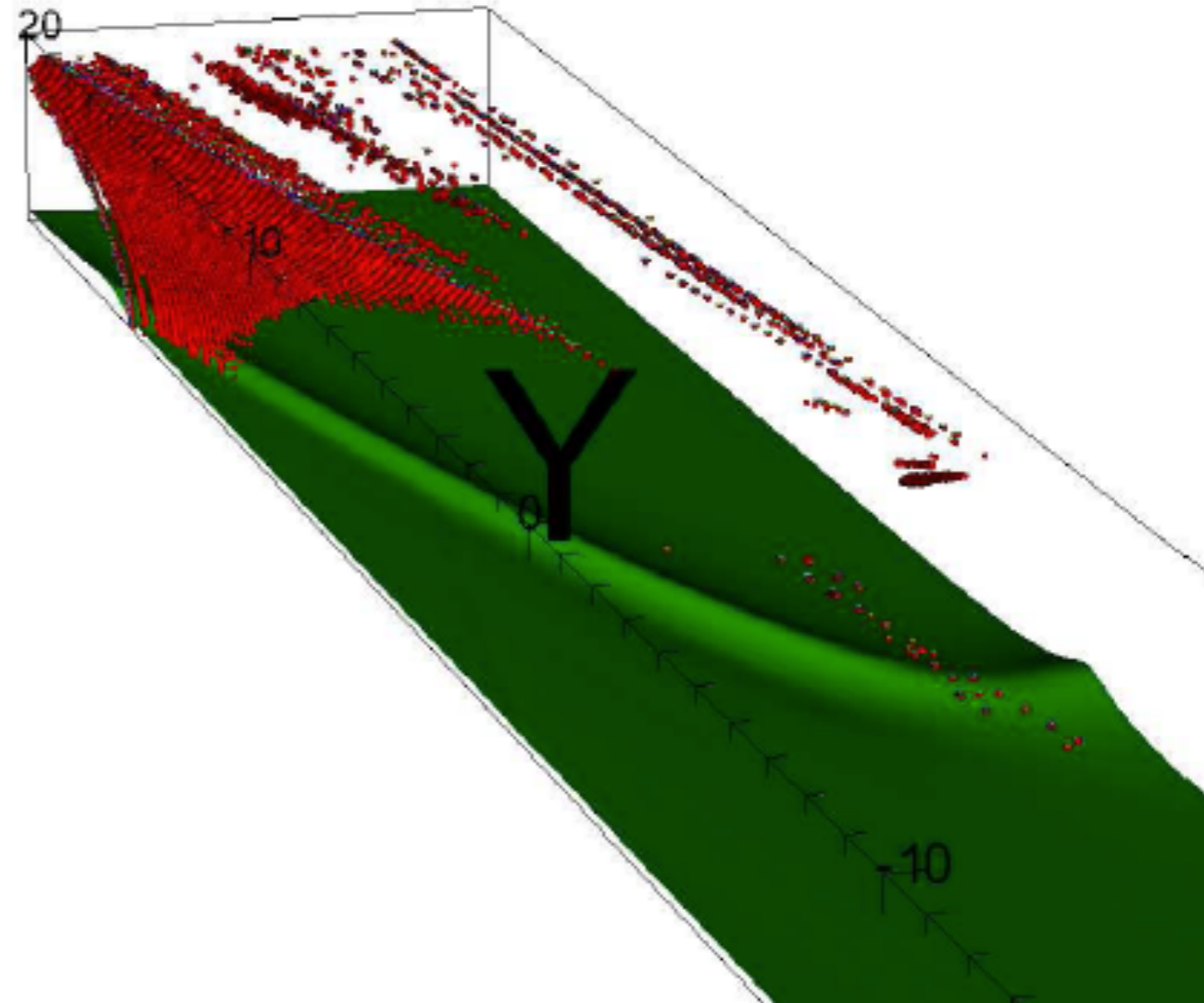
Gap opening in 3-D disks

Iso+Iso



2-D waves

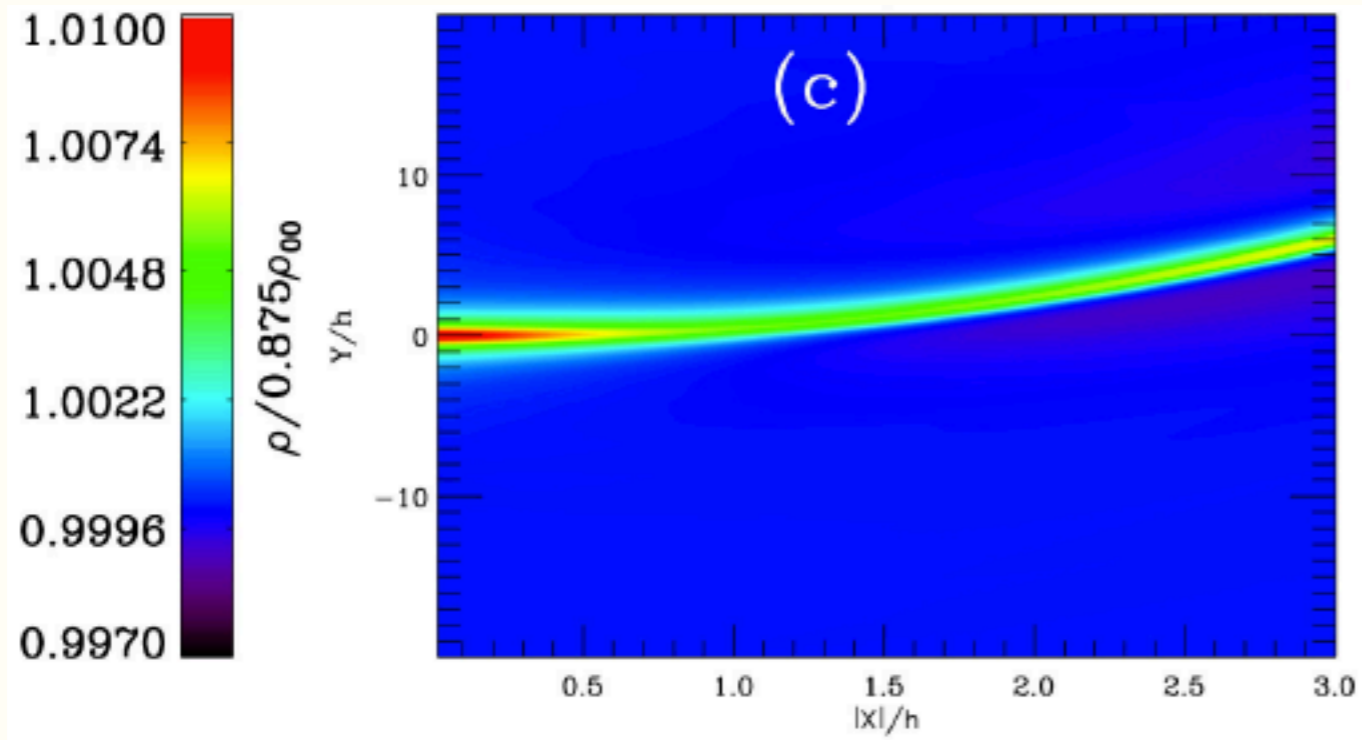
Adi+Adi



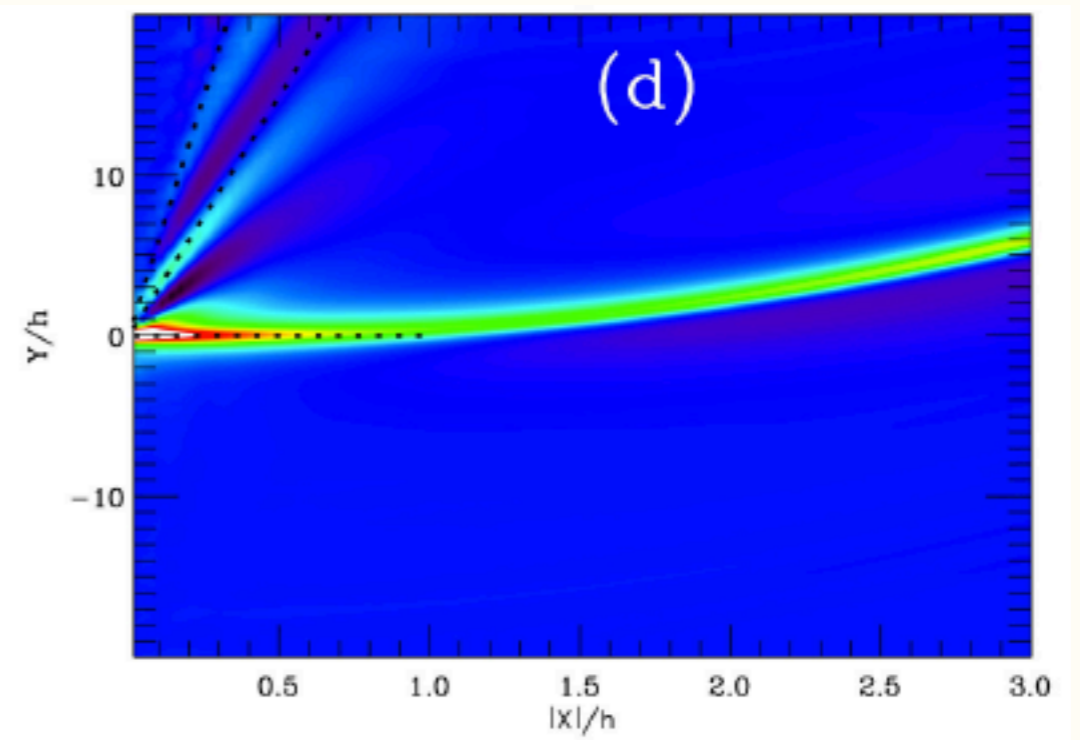
3-D waves

In 3-D disks, a low mass planet can also open gaseous gaps due to the non-linear wave theory

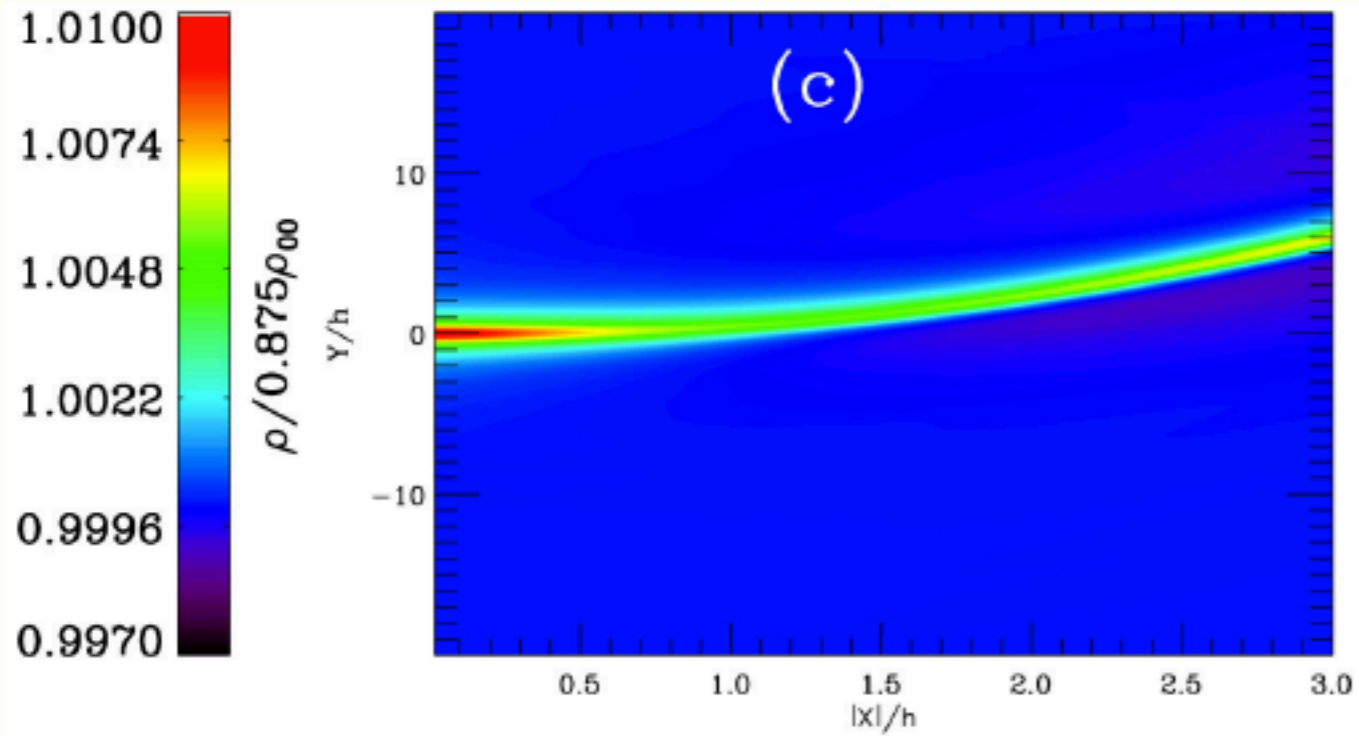
iso+iso



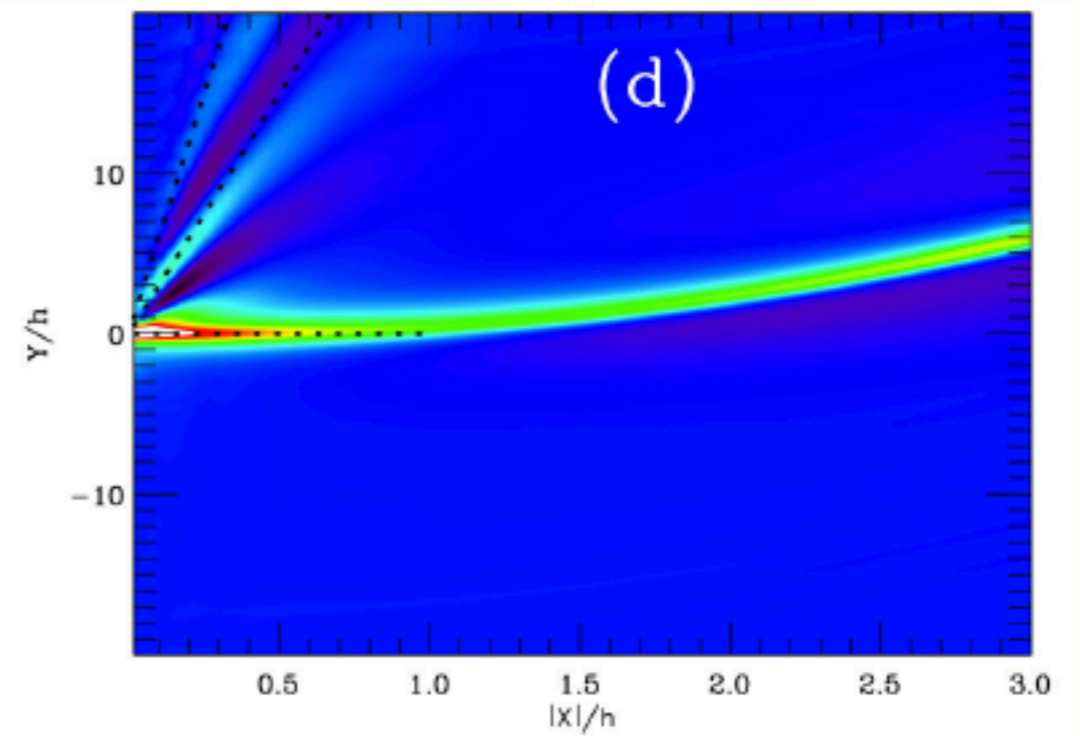
iso+adi



iso+iso



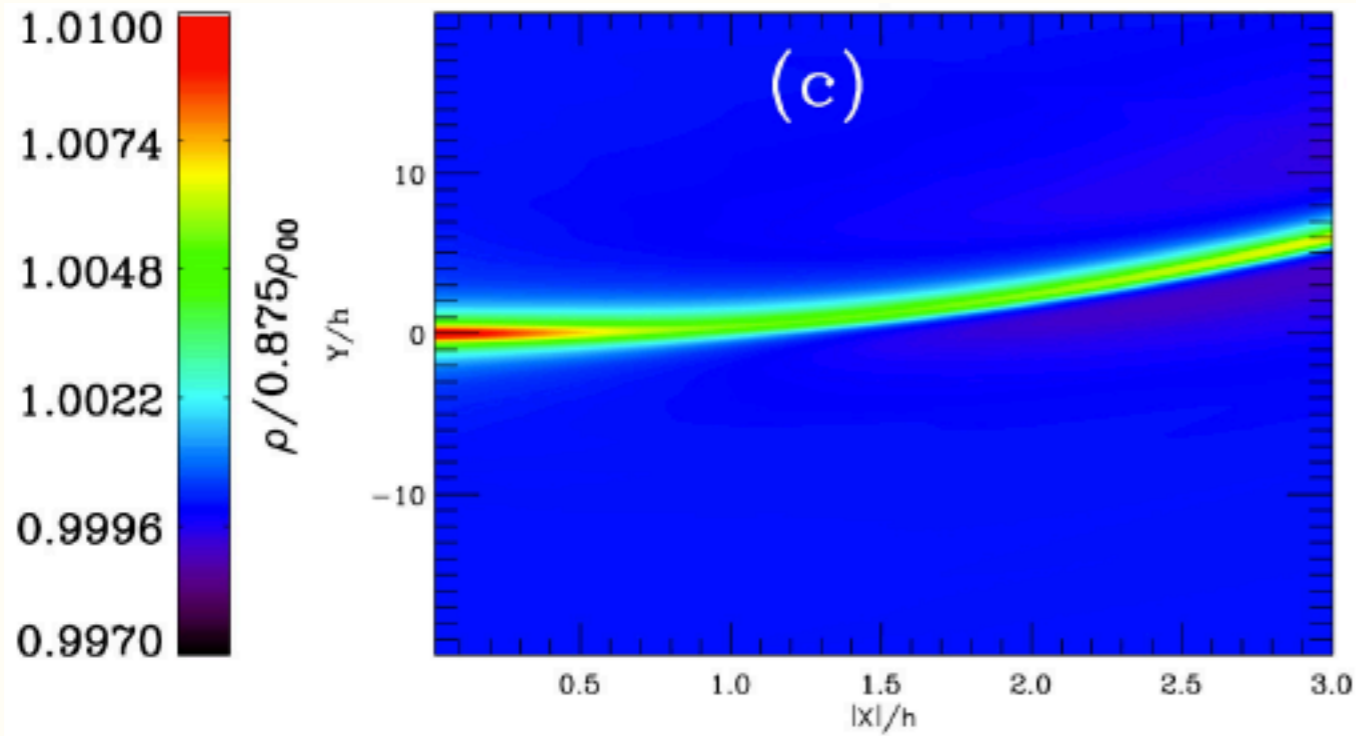
iso+adi



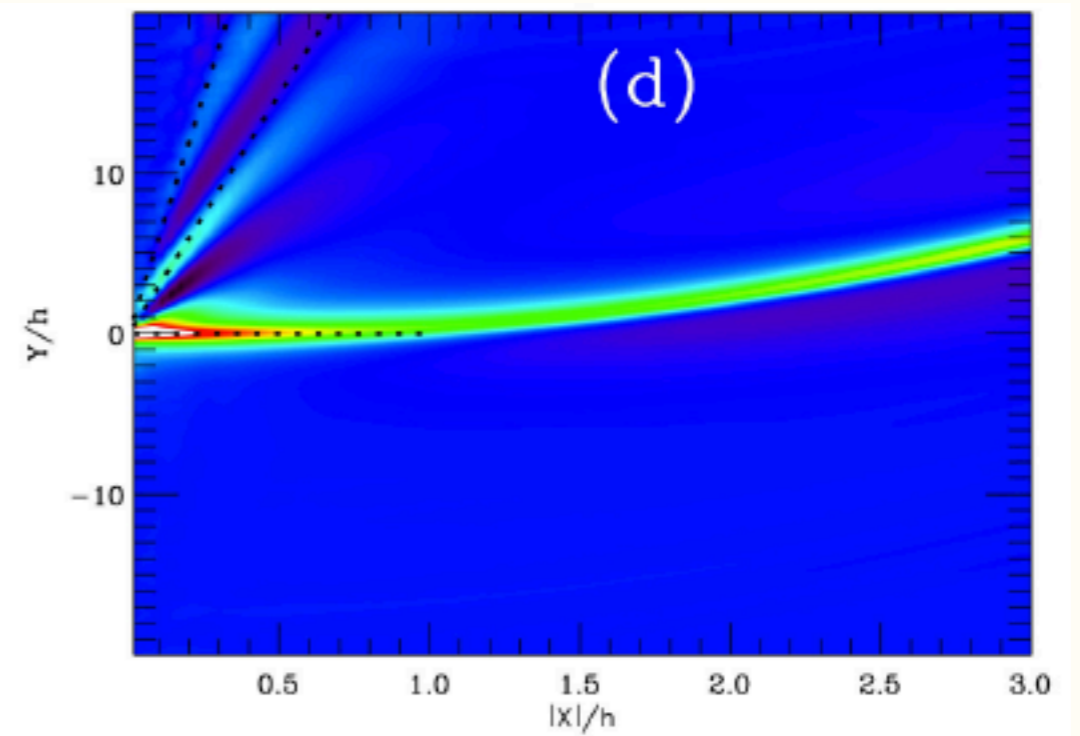
Lindblad resonance:

$$2Ak_y x = \pm \kappa$$

iso+iso



iso+adi

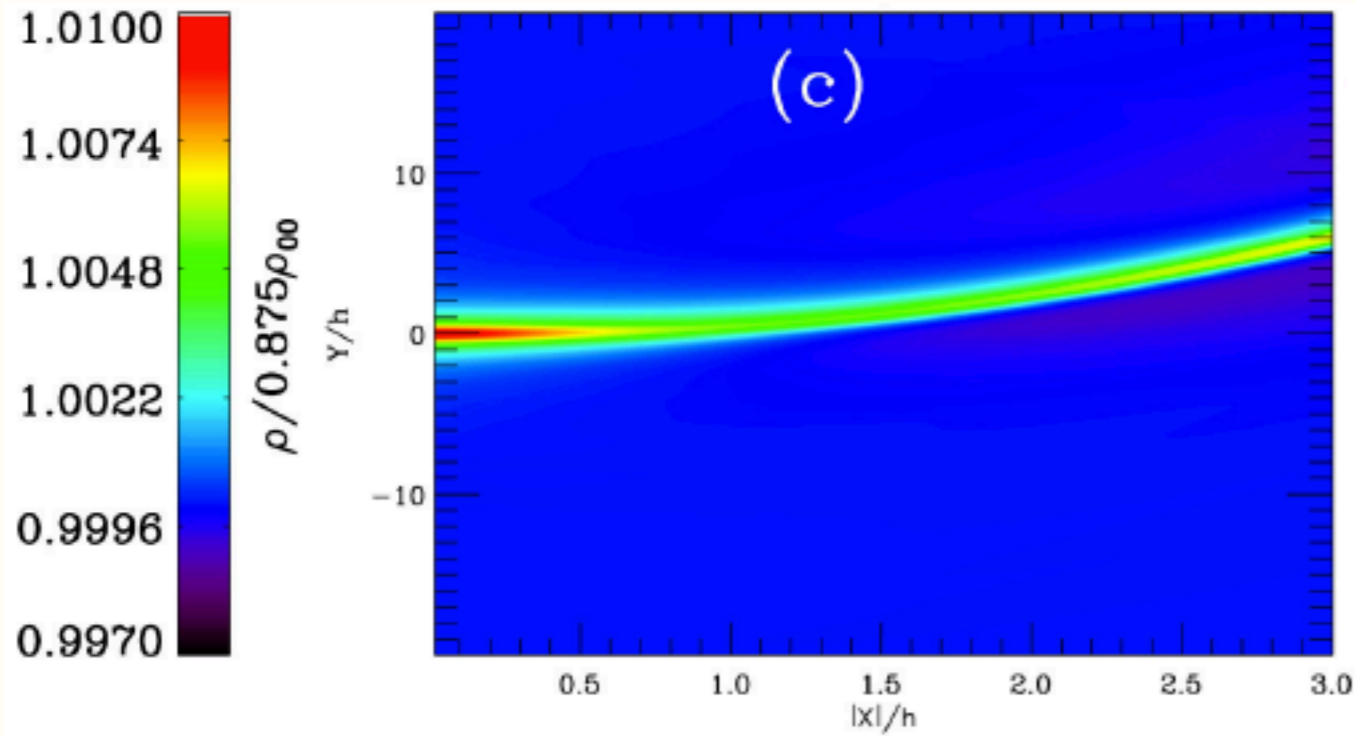


Lindblad resonance:

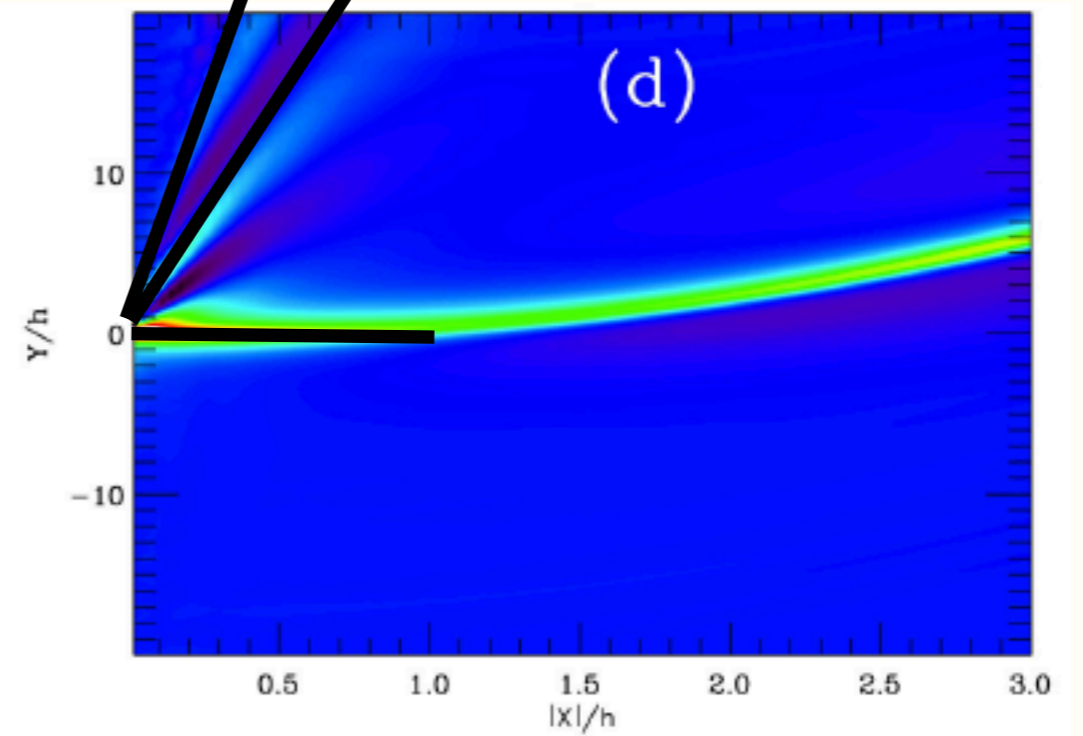
$$2Ak_y x = \pm \kappa$$

$$2Ak_y x = N$$

iso+iso



iso+adi



Lindblad resonance:

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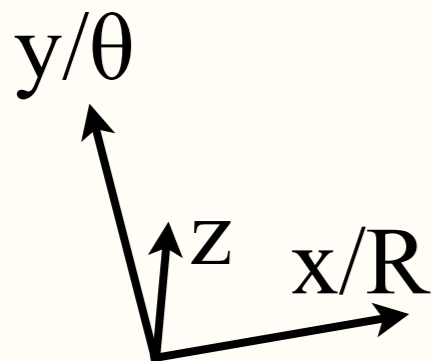
$$2Ak_y x = N$$

Outlines

- Planets are Common
- Gap opening process
 - Gap opening in inviscid disks.
 - Gap opening in MRI-turbulent disks.
- Transitional disks are candidates for harboring young planets and they start to reveal rich physics.
- Dust particle dynamics during planet-disk interaction is essential for connecting with observations to find young planets.

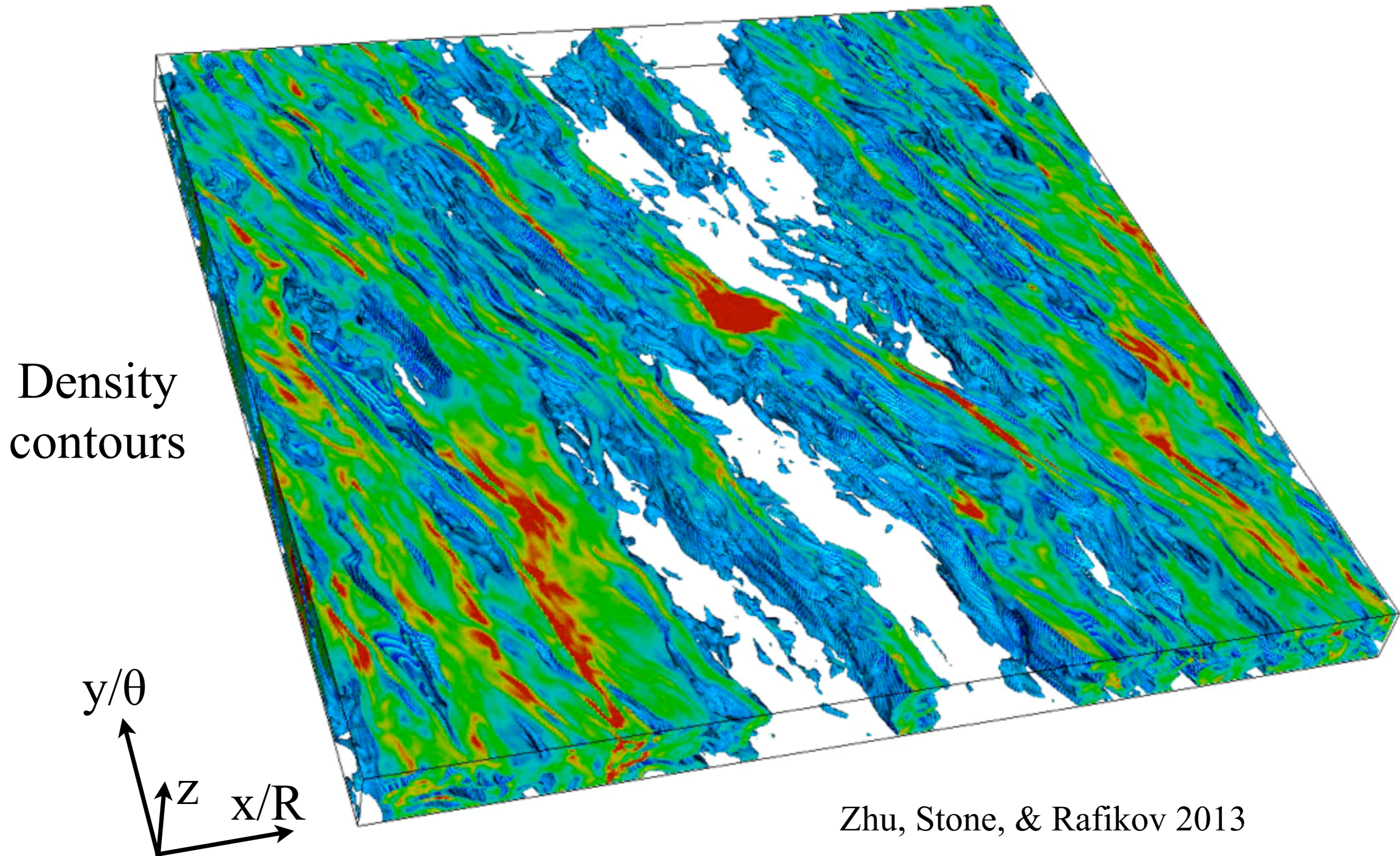
Gap opening in MRI turbulent disks

Density
contours



Zhu, Stone, & Rafikov 2013

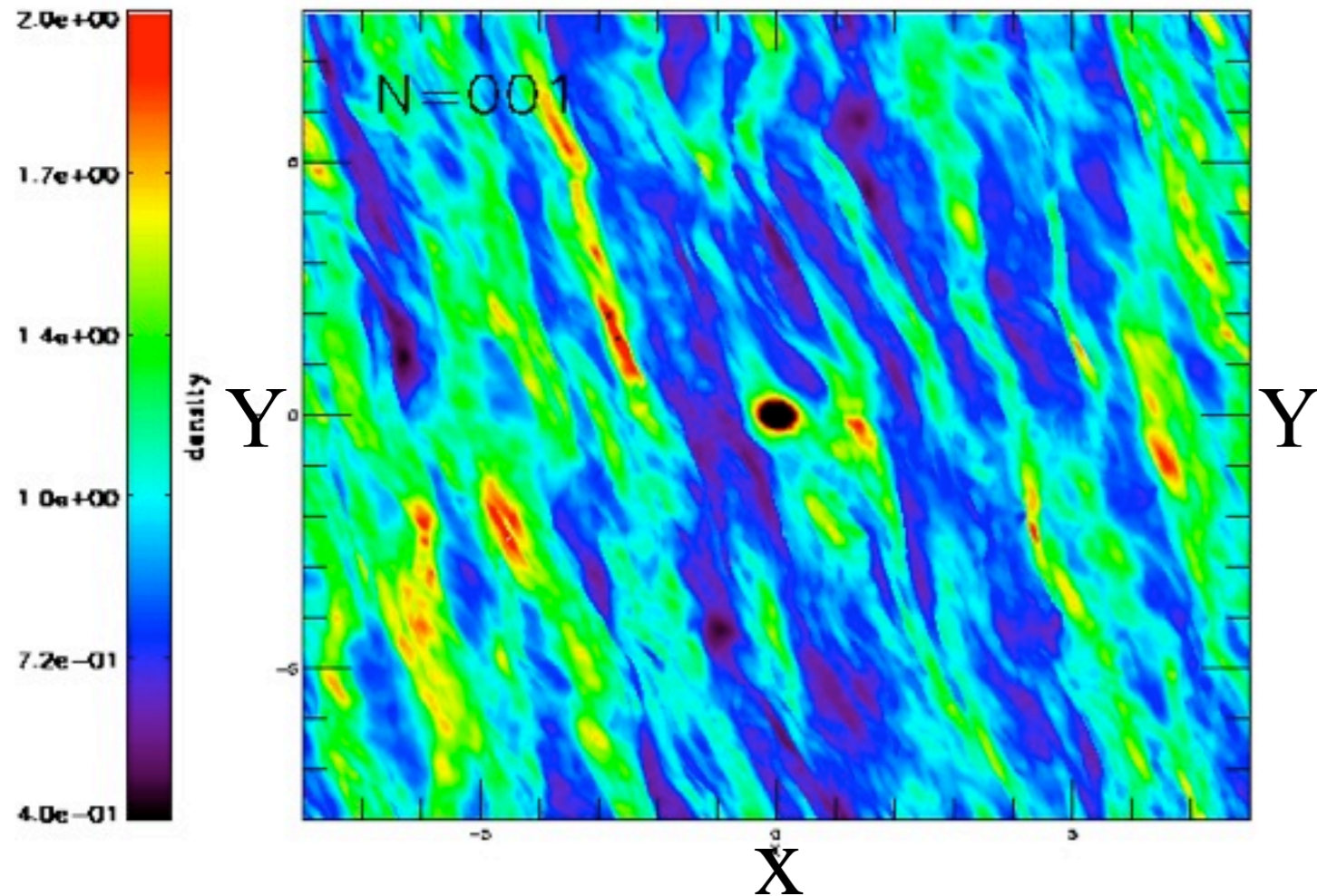
Gap opening in MRI turbulent disks



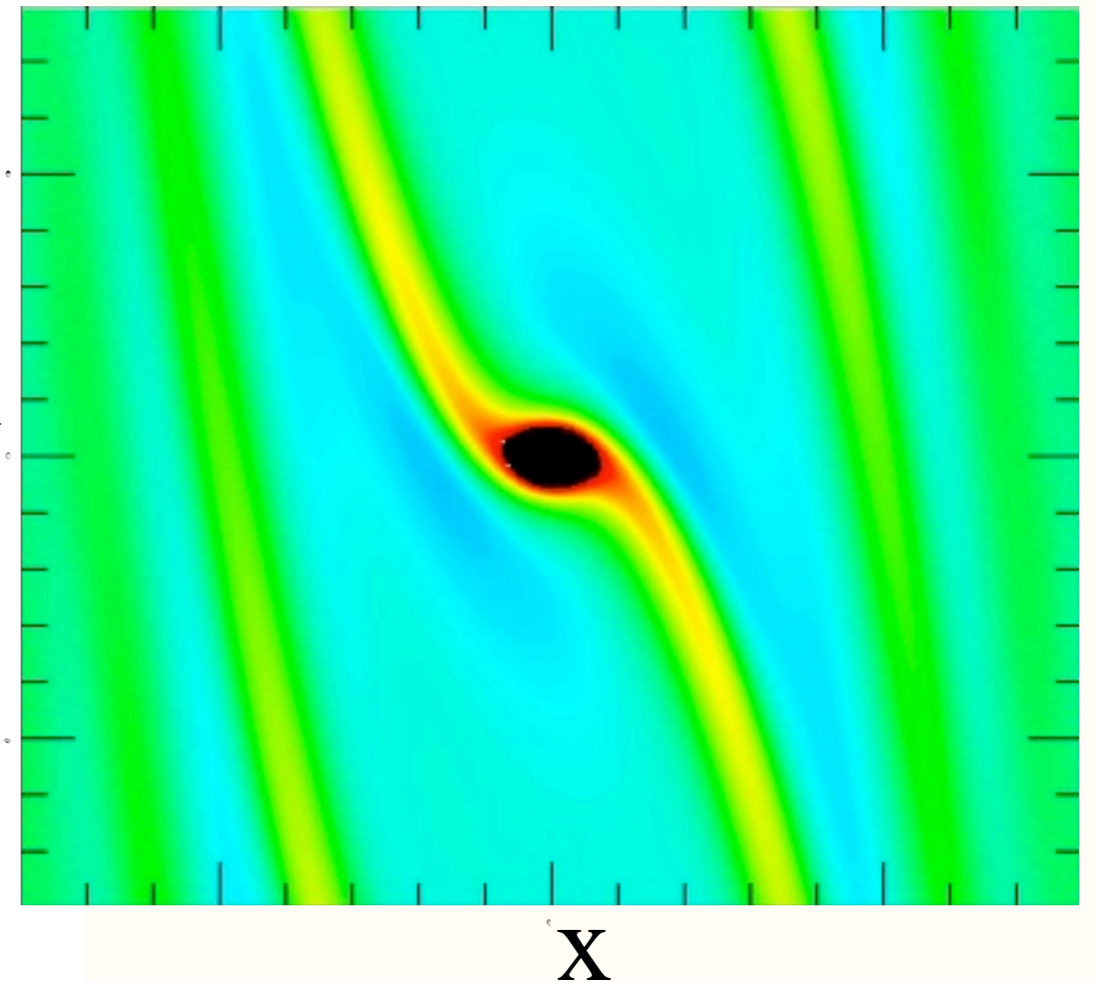
Density waves interact with turbulence

Density contours

MHD



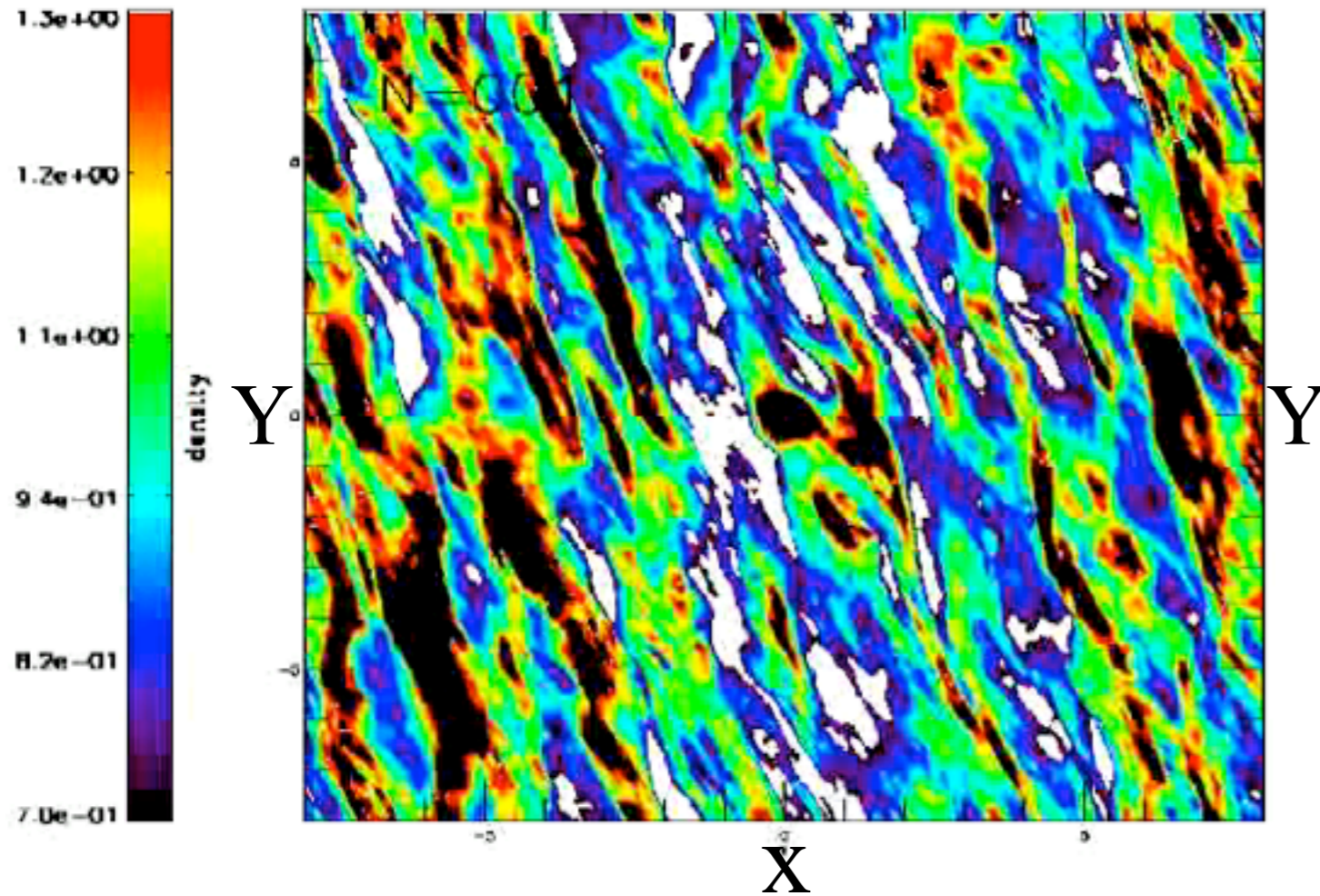
viscous disk



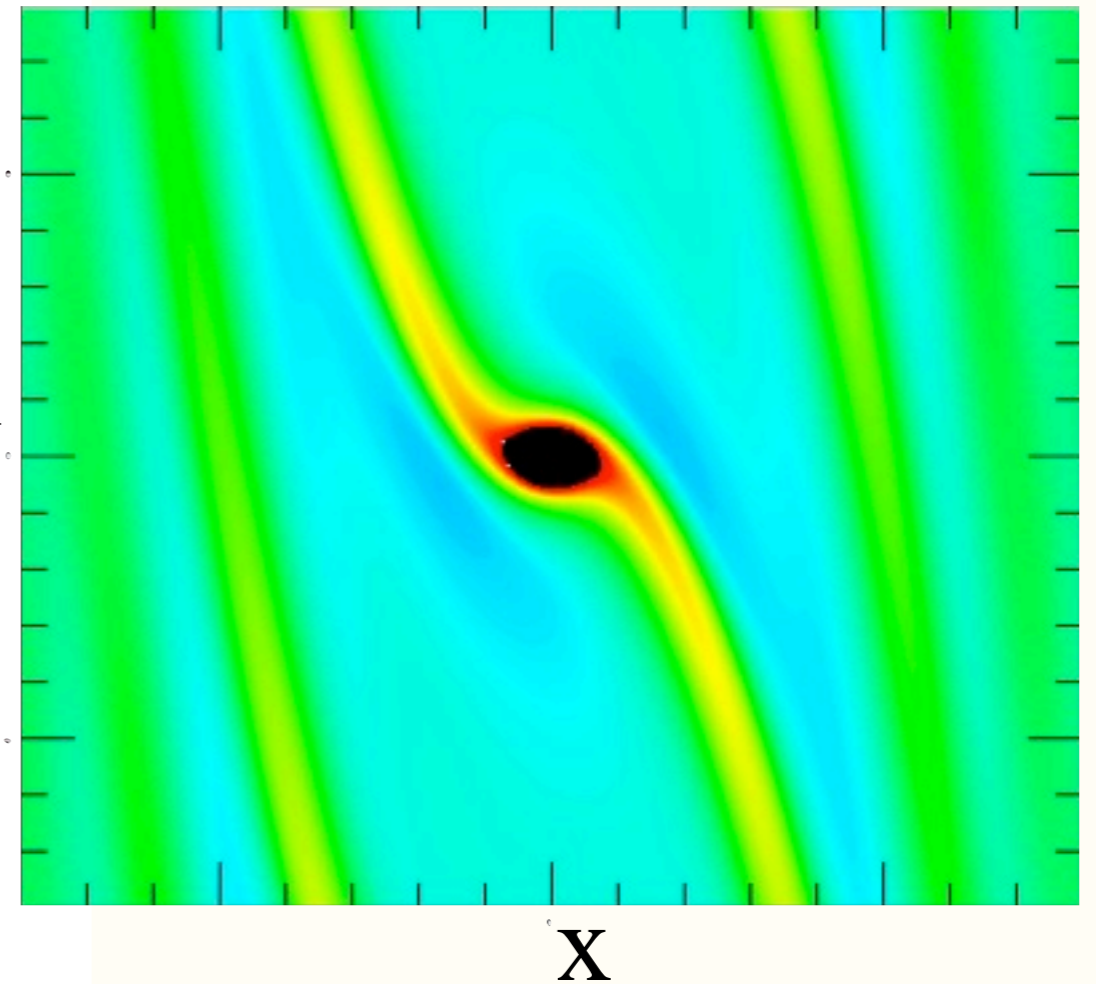
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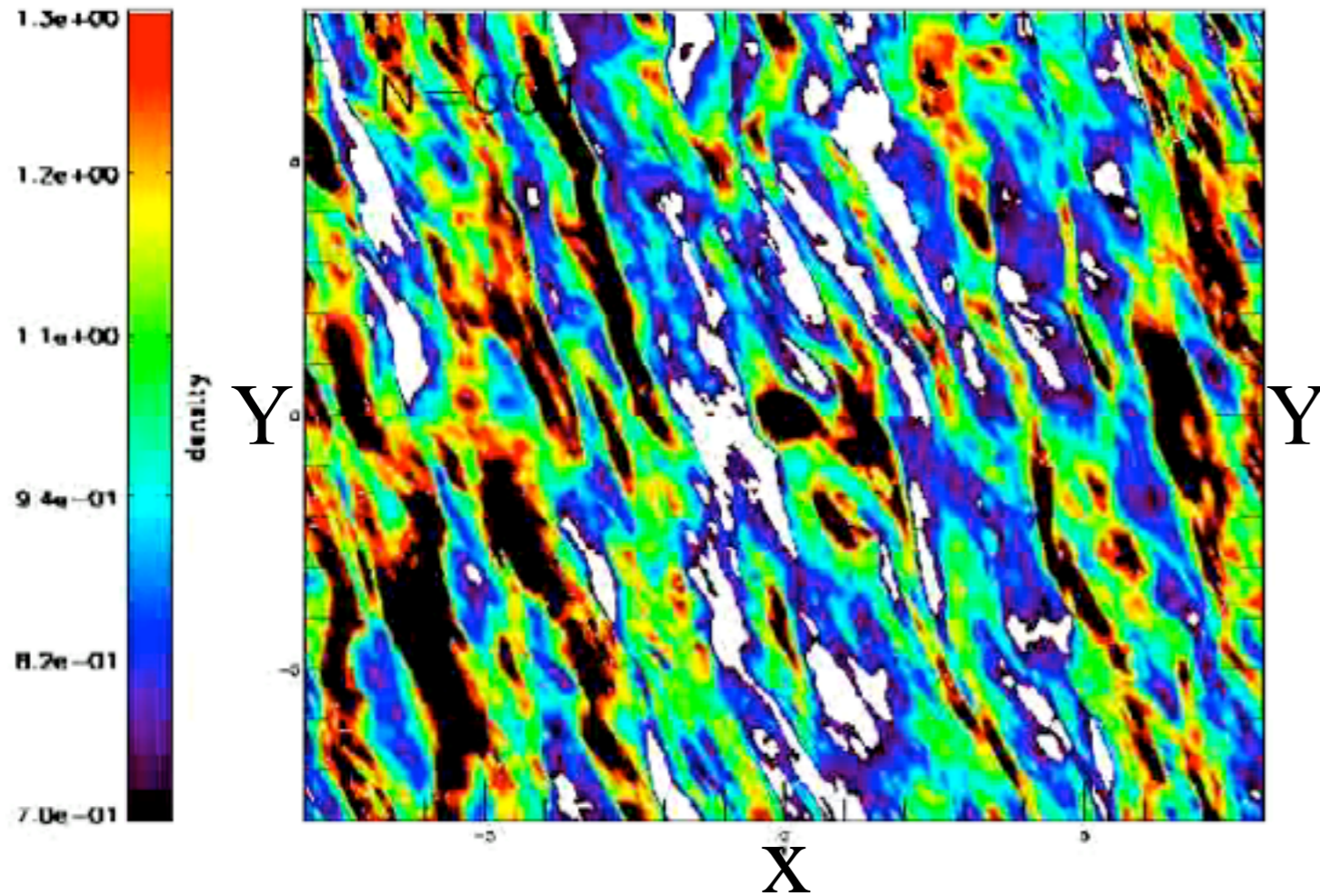
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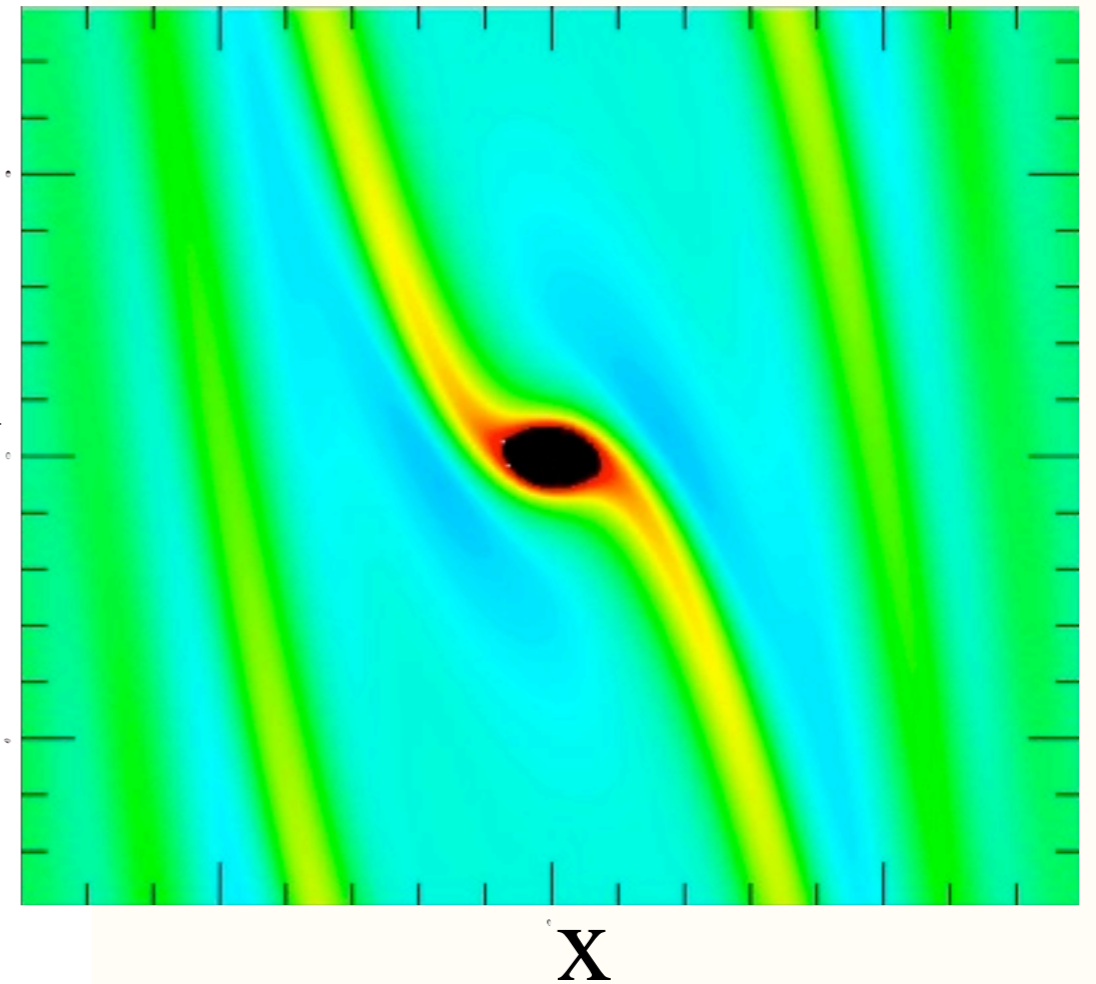
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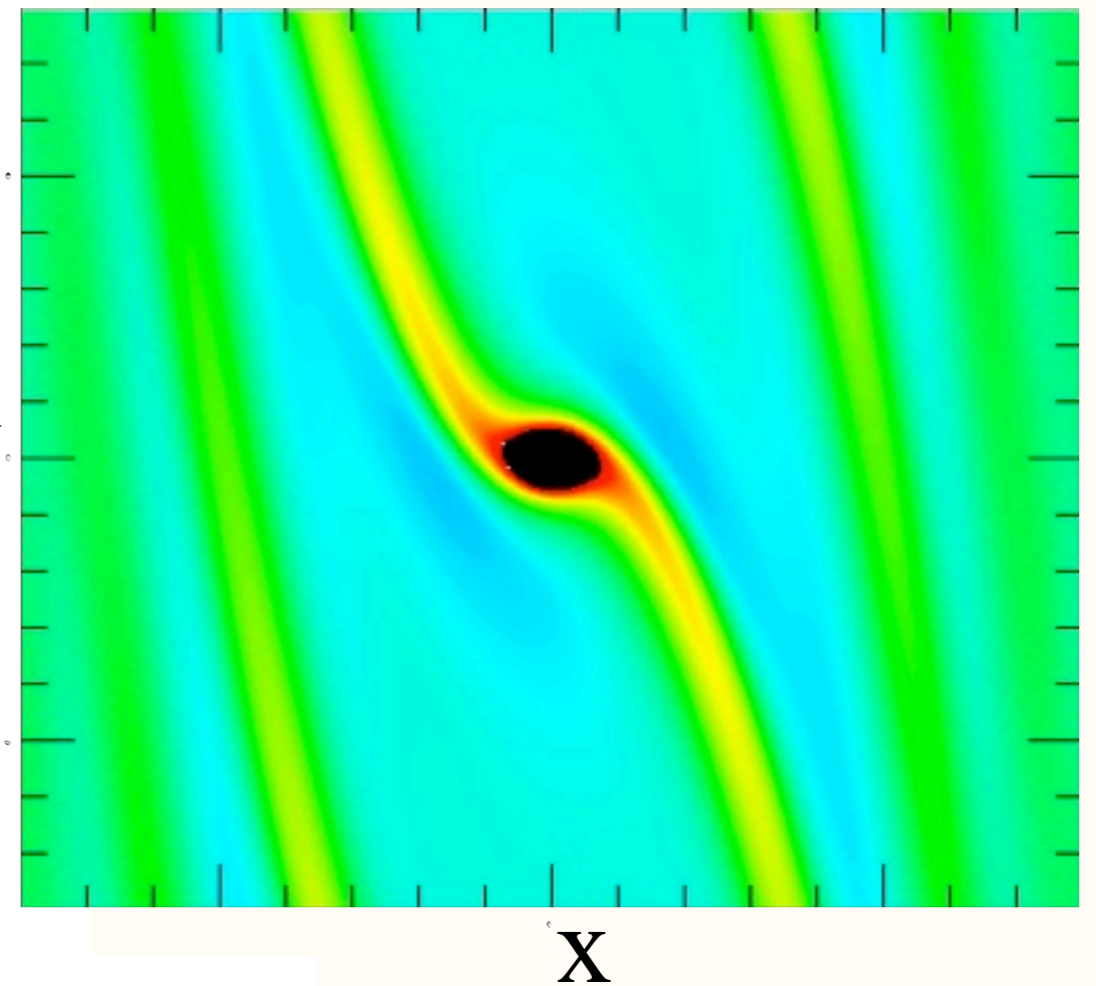
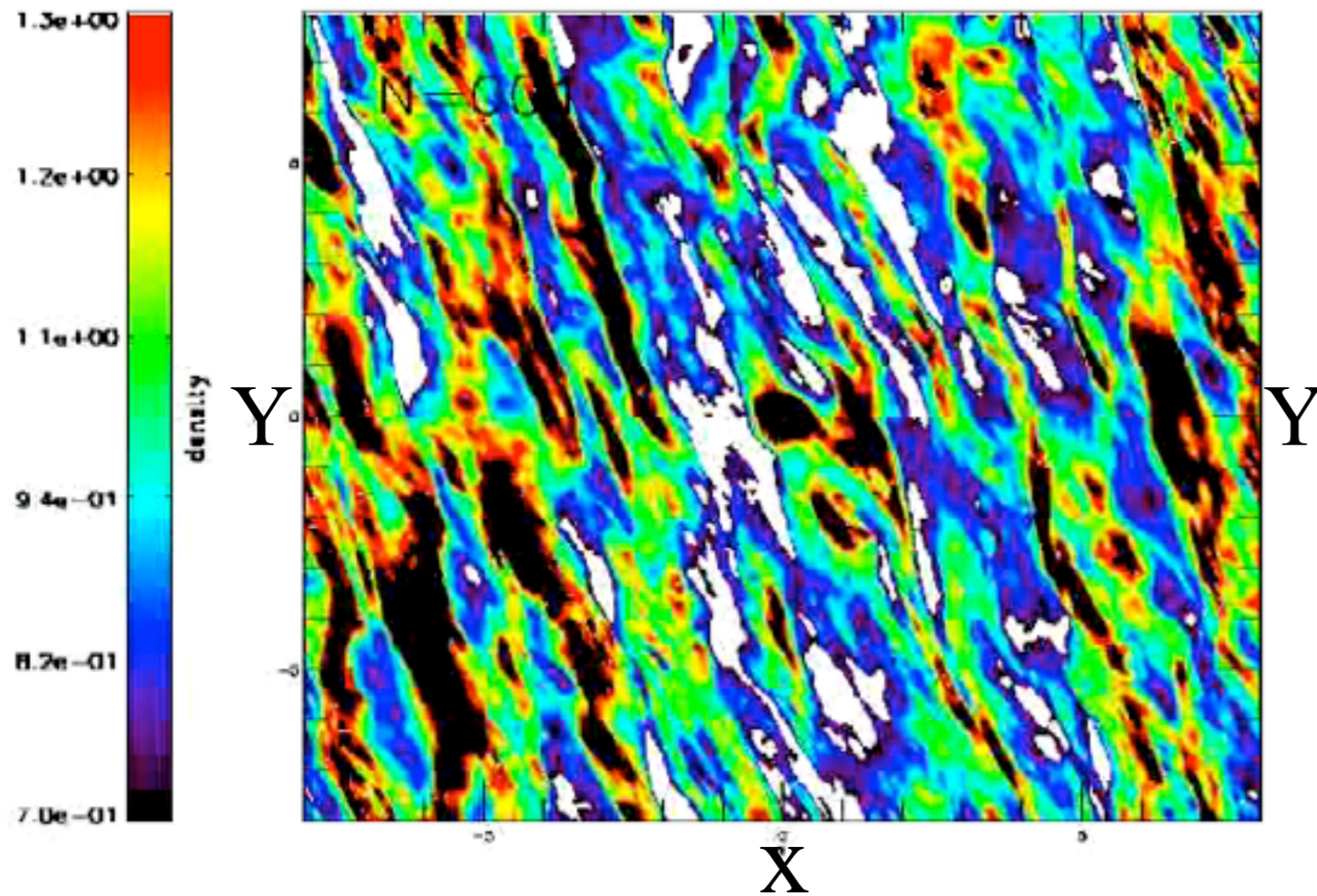


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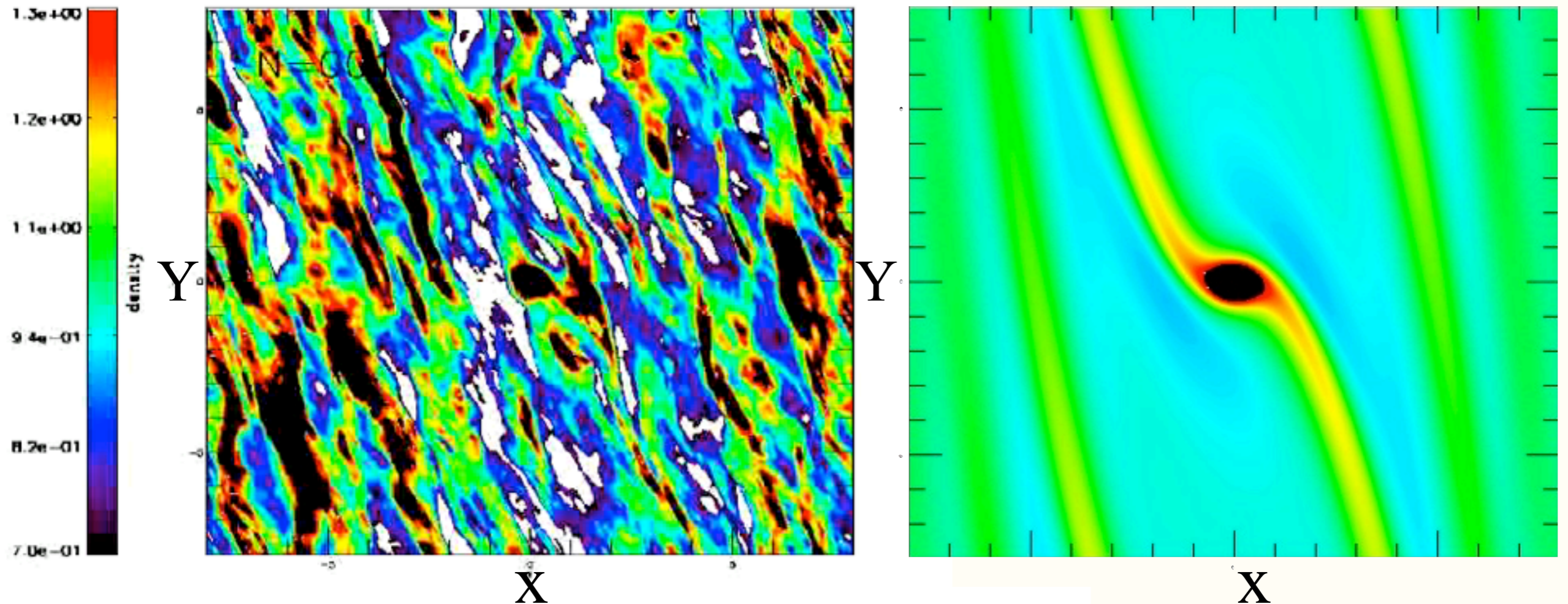
Gaps are different!

Density waves interact with turbulence

Density contours

MHD

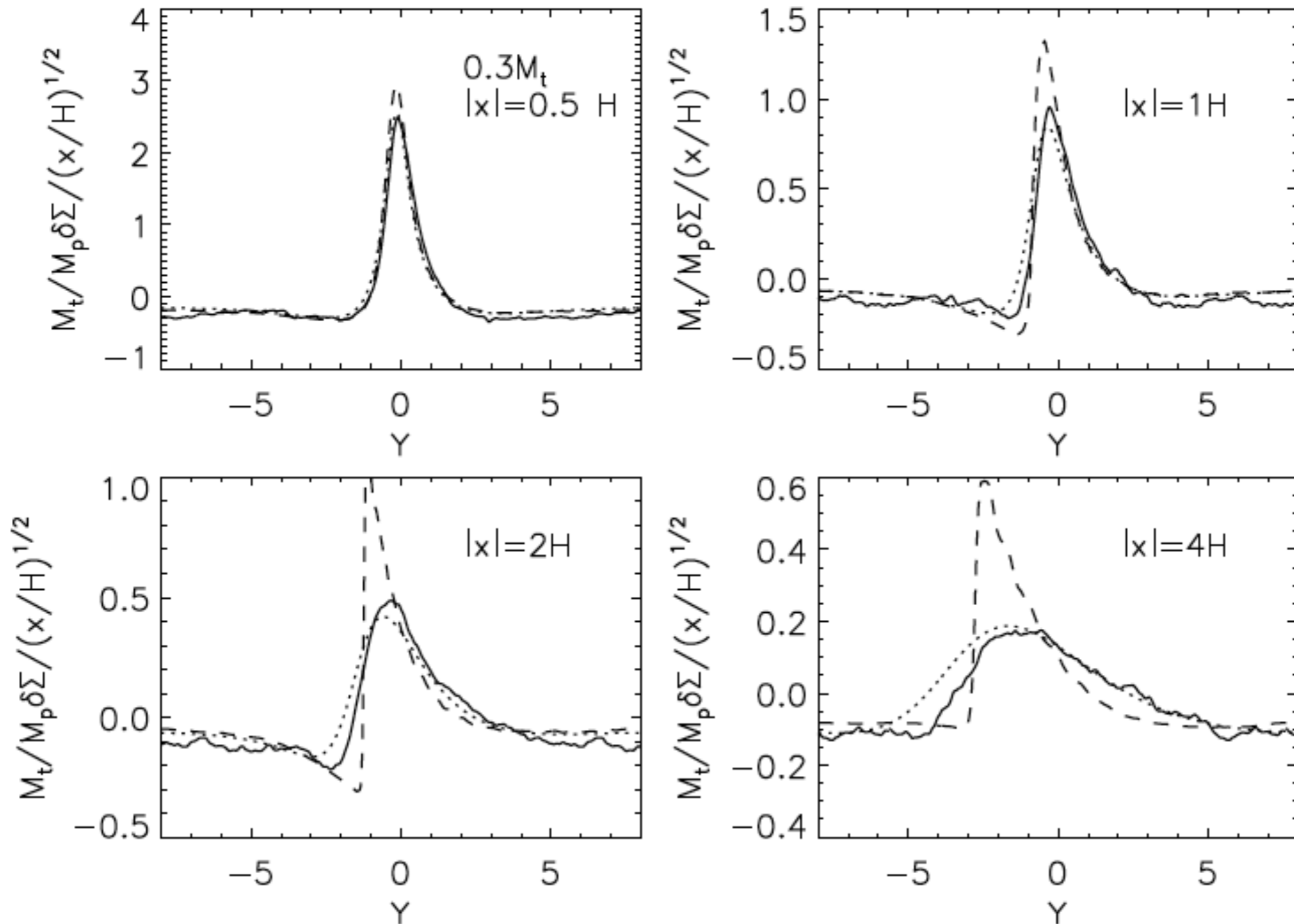
viscous disk



Gaps are different!

Damped Ang. Mom. = dT_{xy}/dx

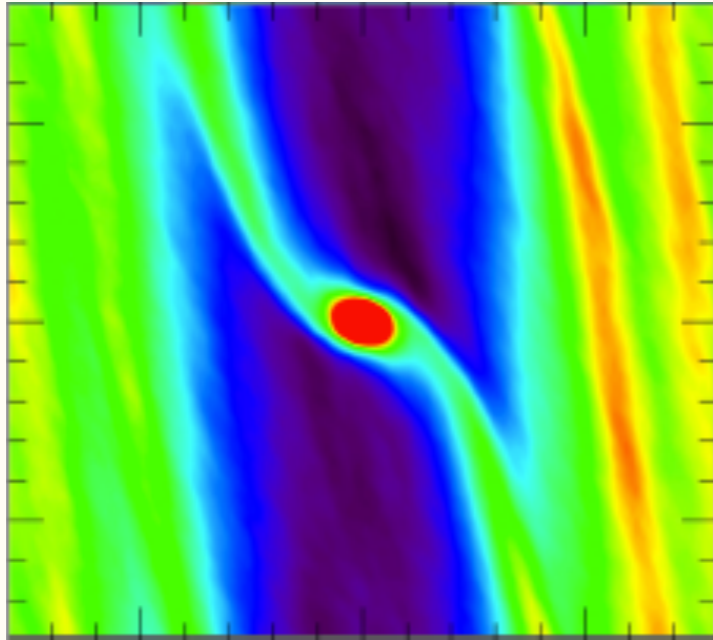
Gap opening ability = Gap closing ability



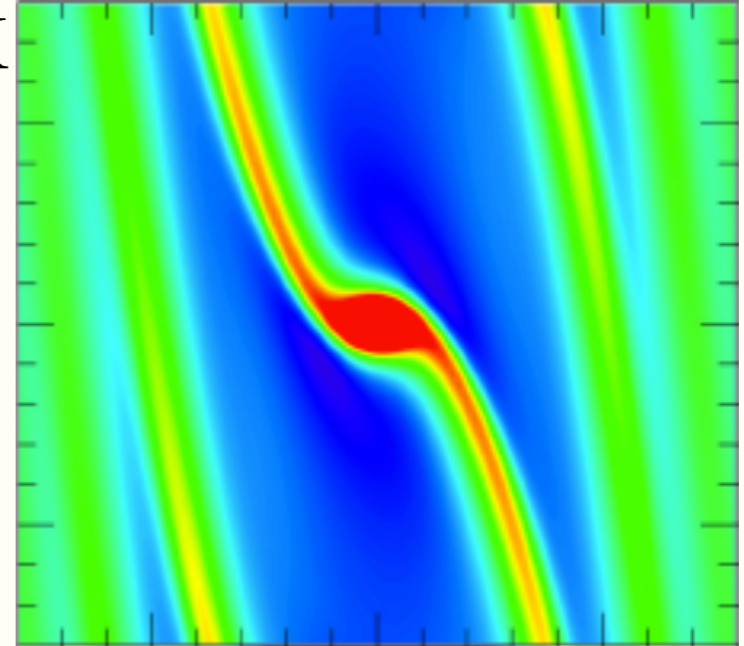
From a statistical sense, shock damping in MRI turbulence has similar effects as the viscous damping with the same stress.

Gap difference?

MHD

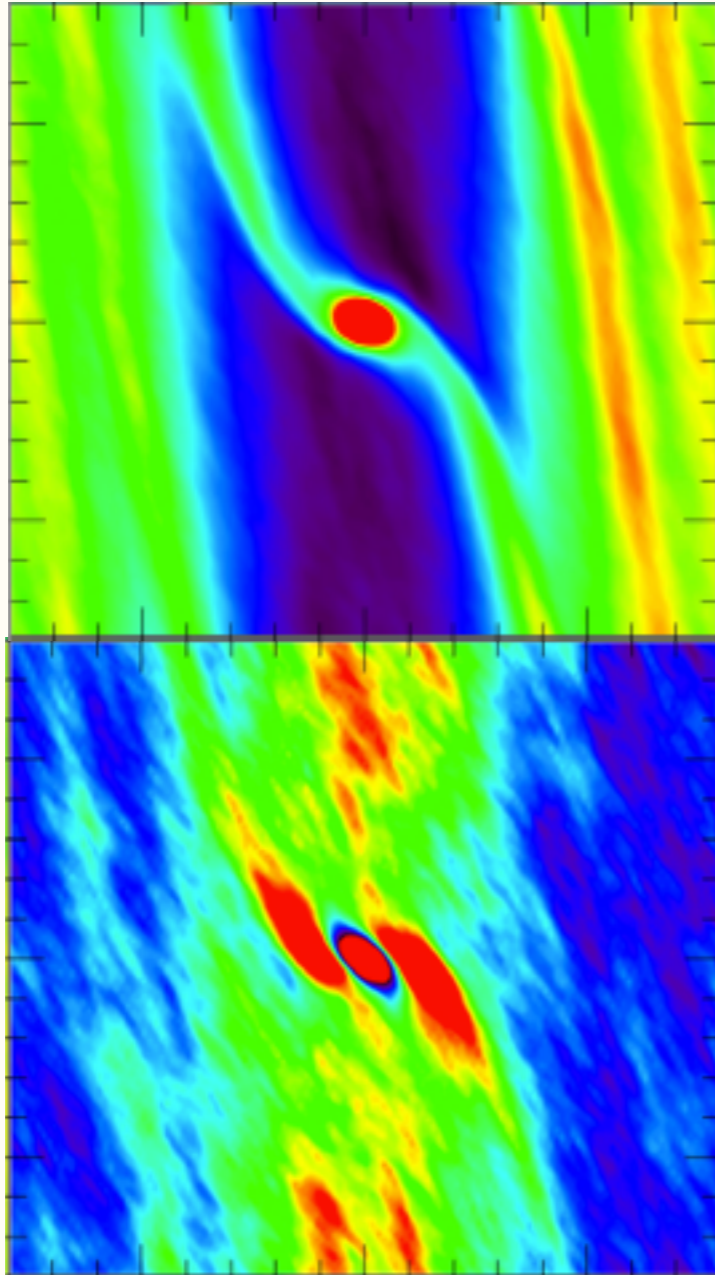


viscous disk



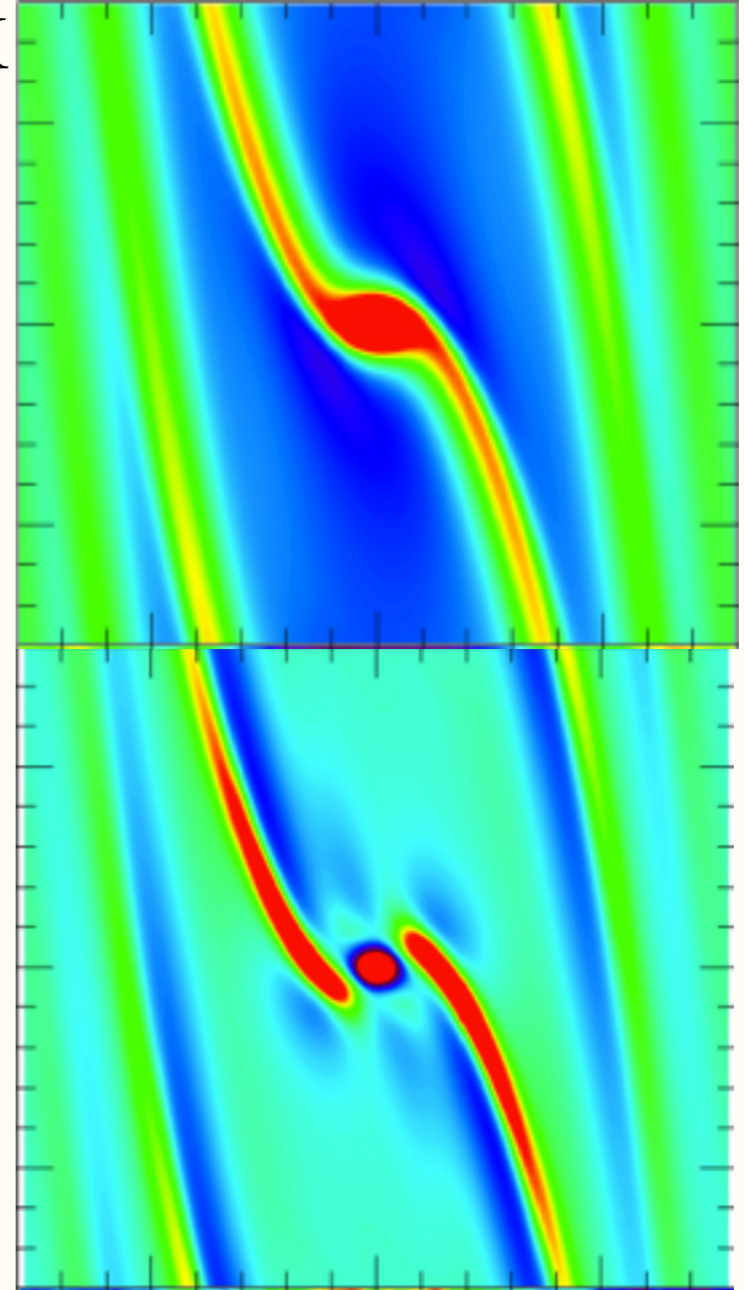
Gap difference?

MHD



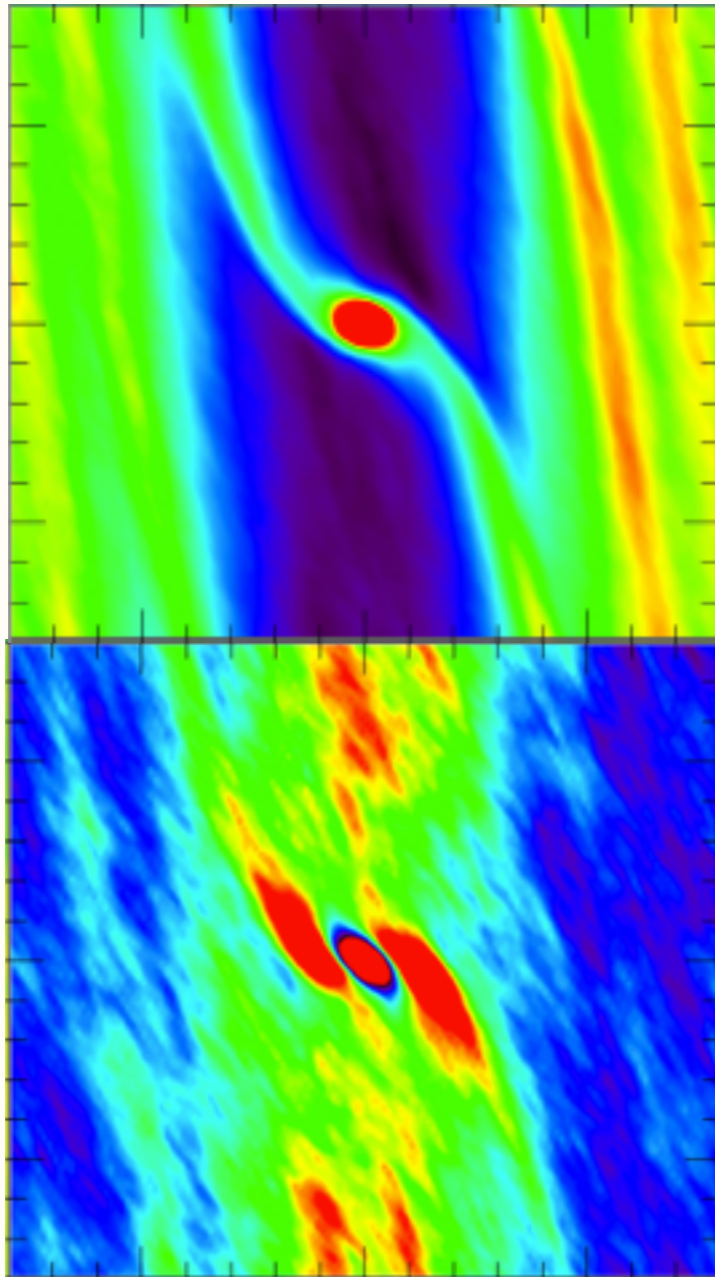
α

viscous disk



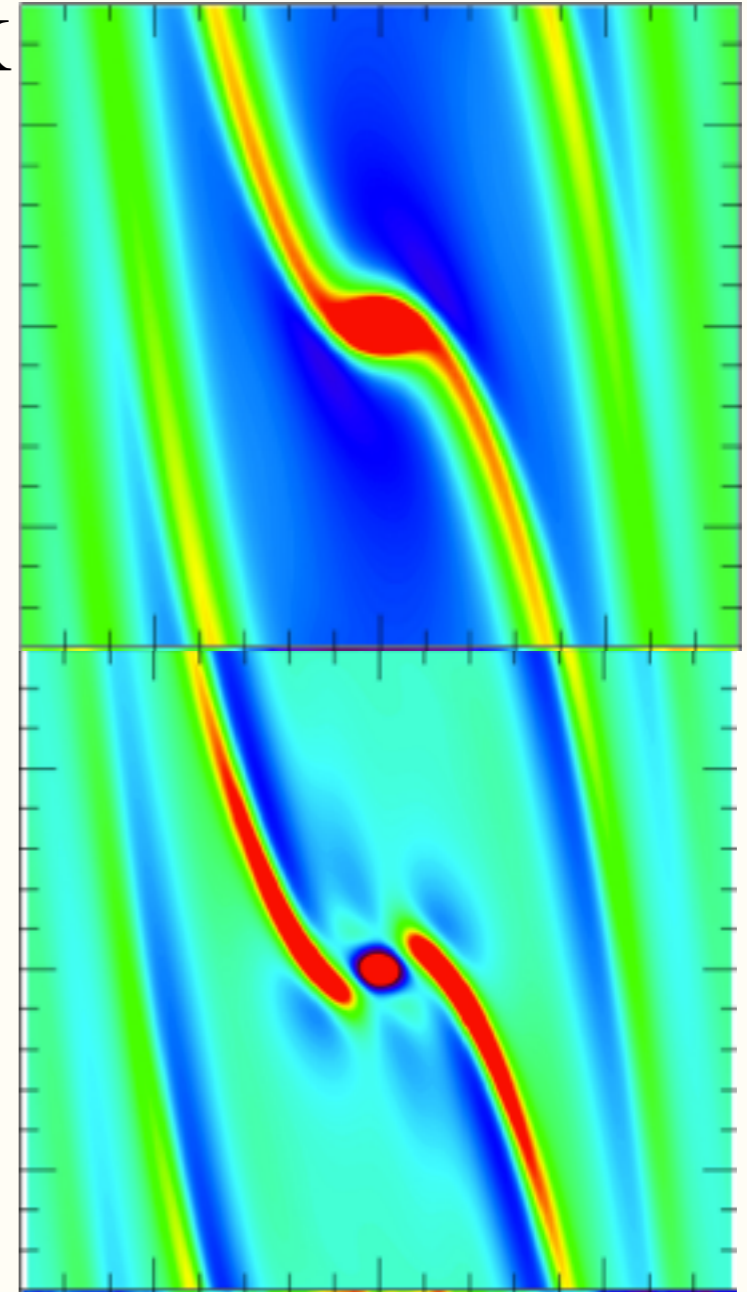
Gap difference?

MHD



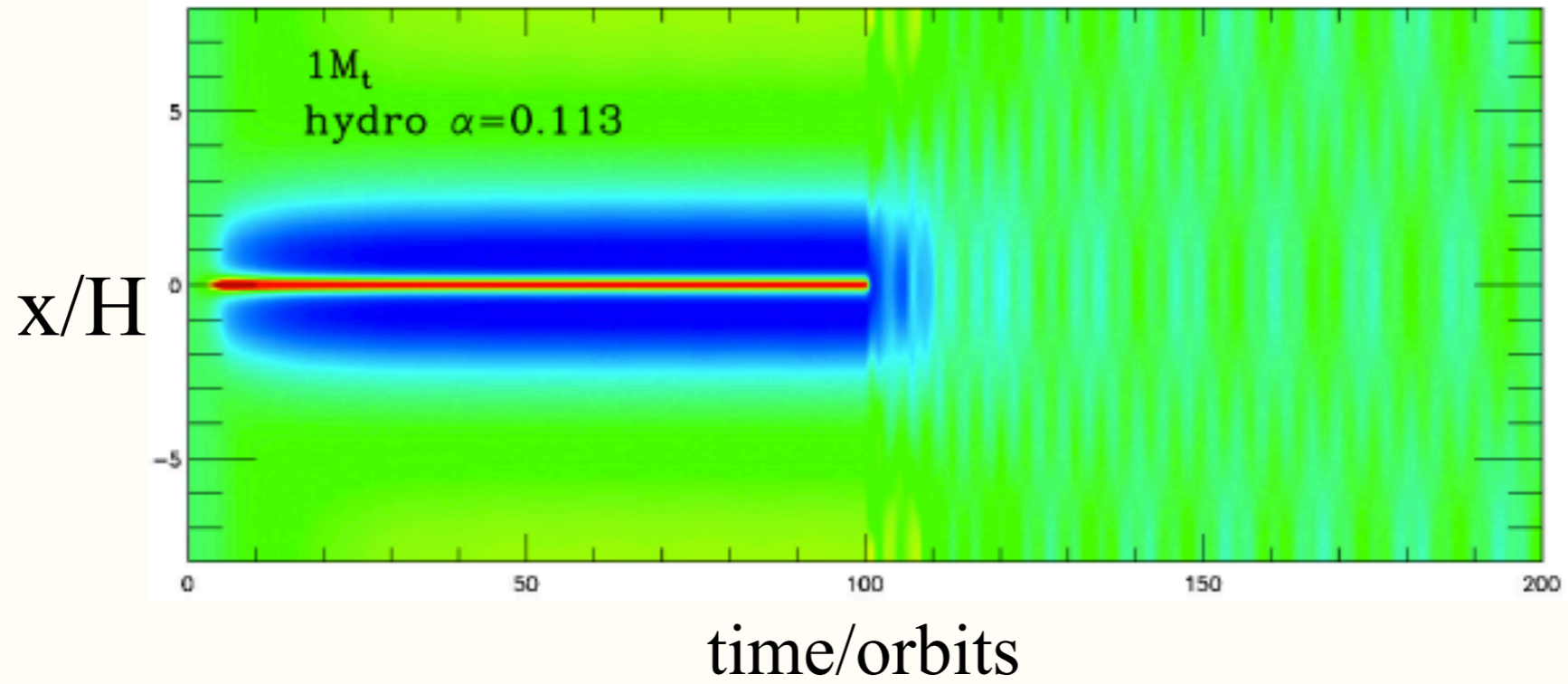
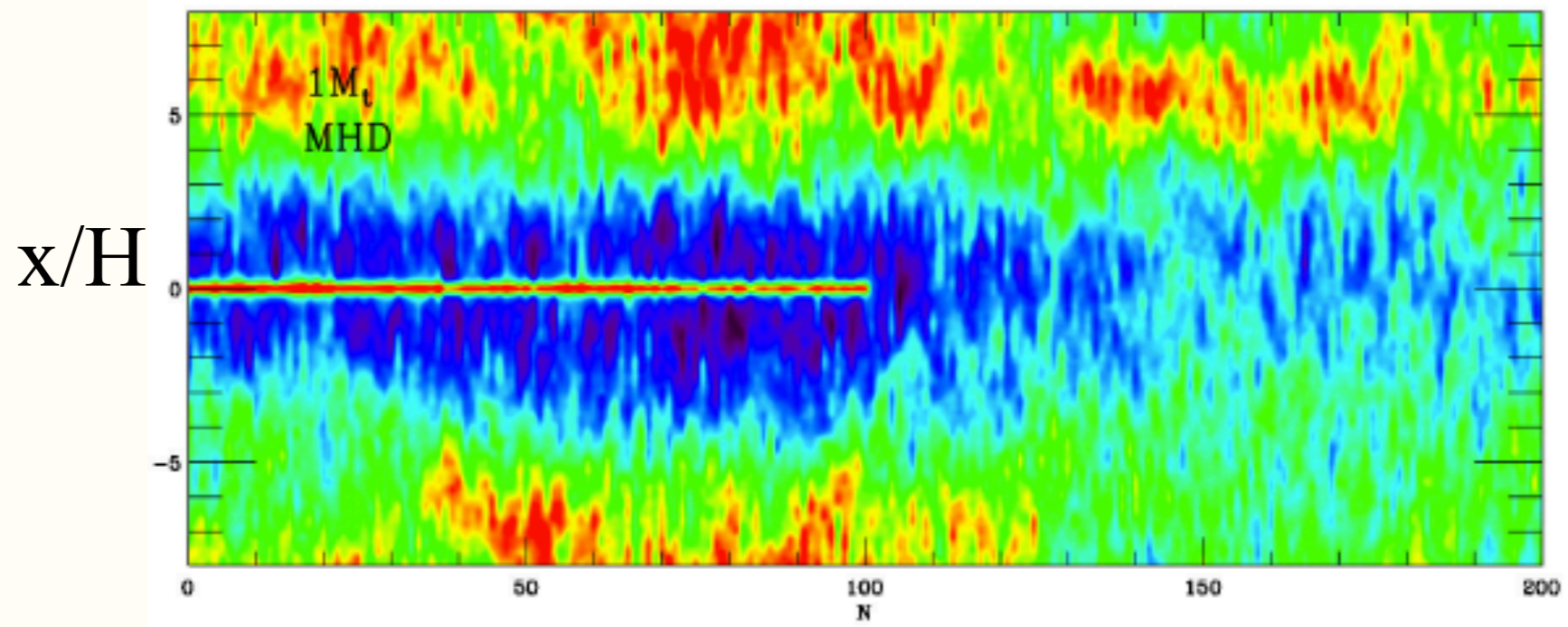
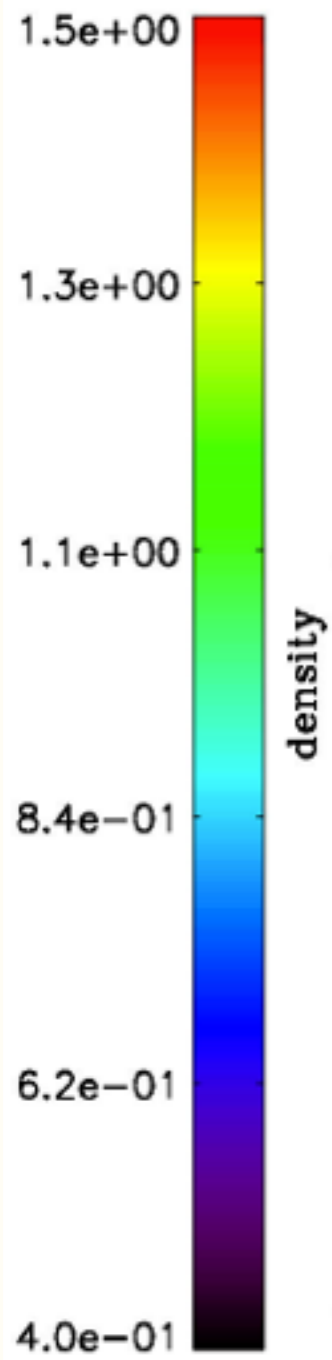
α

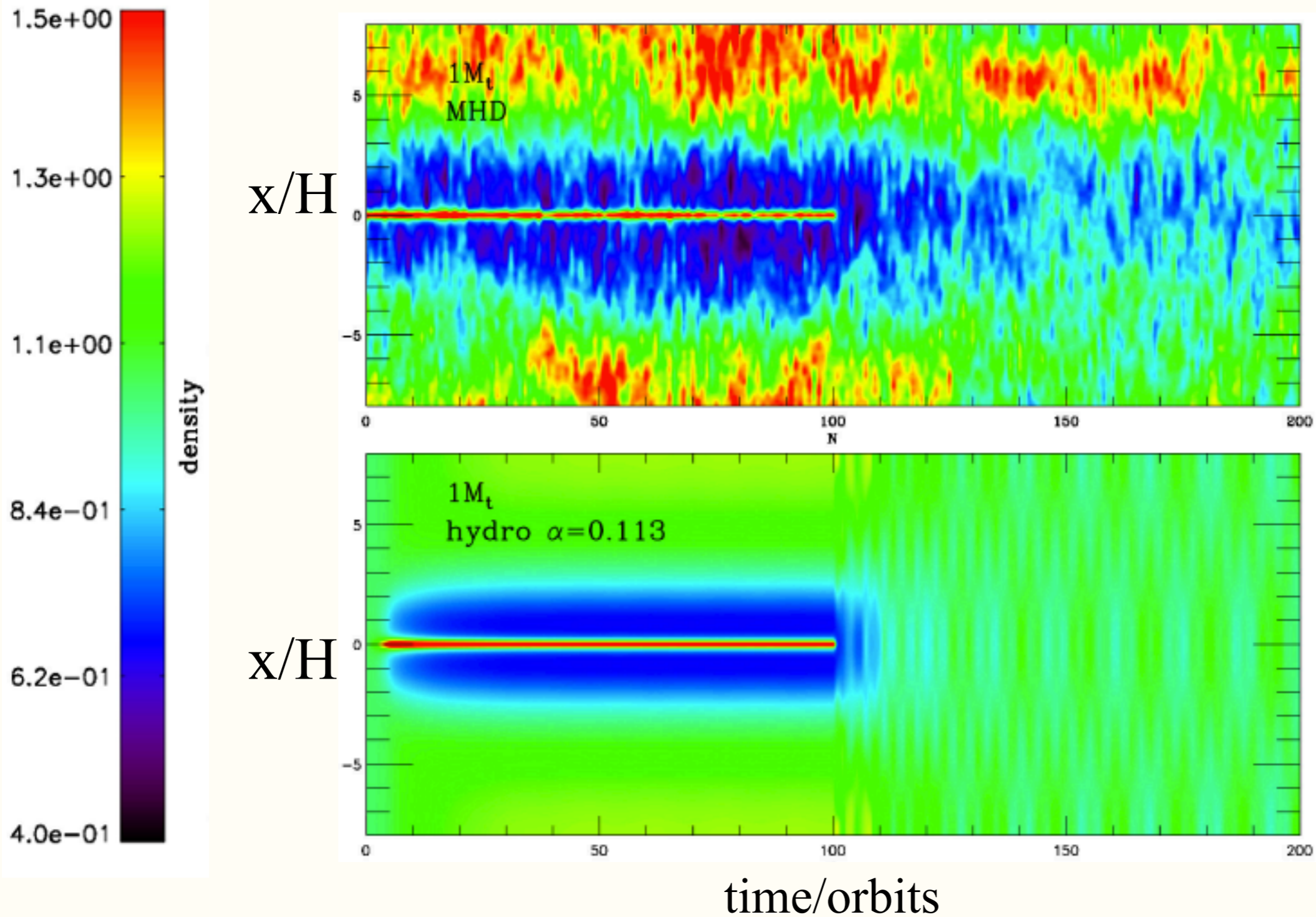
viscous disk



α is not a constant.

Magnetic fields can globally transport into the gap region.





In net vertical B disks, the rearrangement of B makes the disk to ``lose'' the ability to change the disk features

In inviscid disks, gaps can be opened by a low mass planet

In MRI disks with net vertical B , gaps are easier to open by planets

In inviscid disks, gaps can be opened by a low mass planet

In MRI disks with net vertical B , gaps are easier to open by planets



Gaps can be common!

Outlines

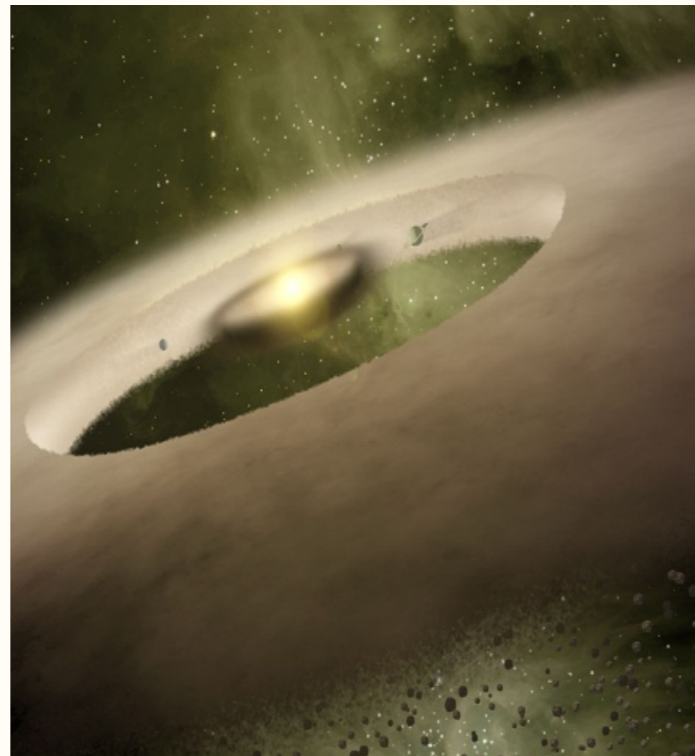
- Planets are Common
- Gap opening process
 - Gap opening in inviscid disks.
 - Gap opening in MRI-turbulent disks.
- **Transitional disks are candidates for harboring young planets and they start to reveal rich physics.**
- Dust particle dynamics during planet-disk interaction is essential for connecting with observations to find young planets.

Gaps are observed? Transitional Disks

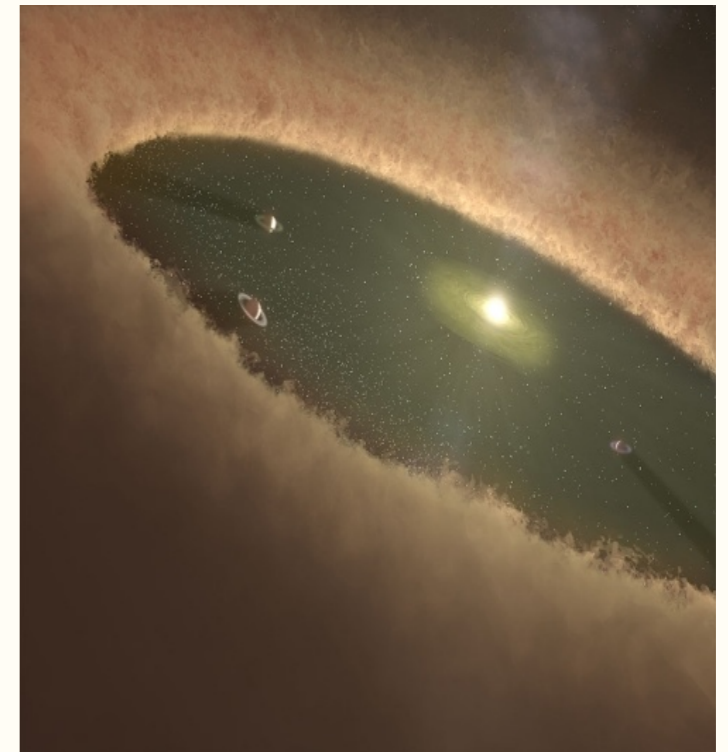
“Full” disks



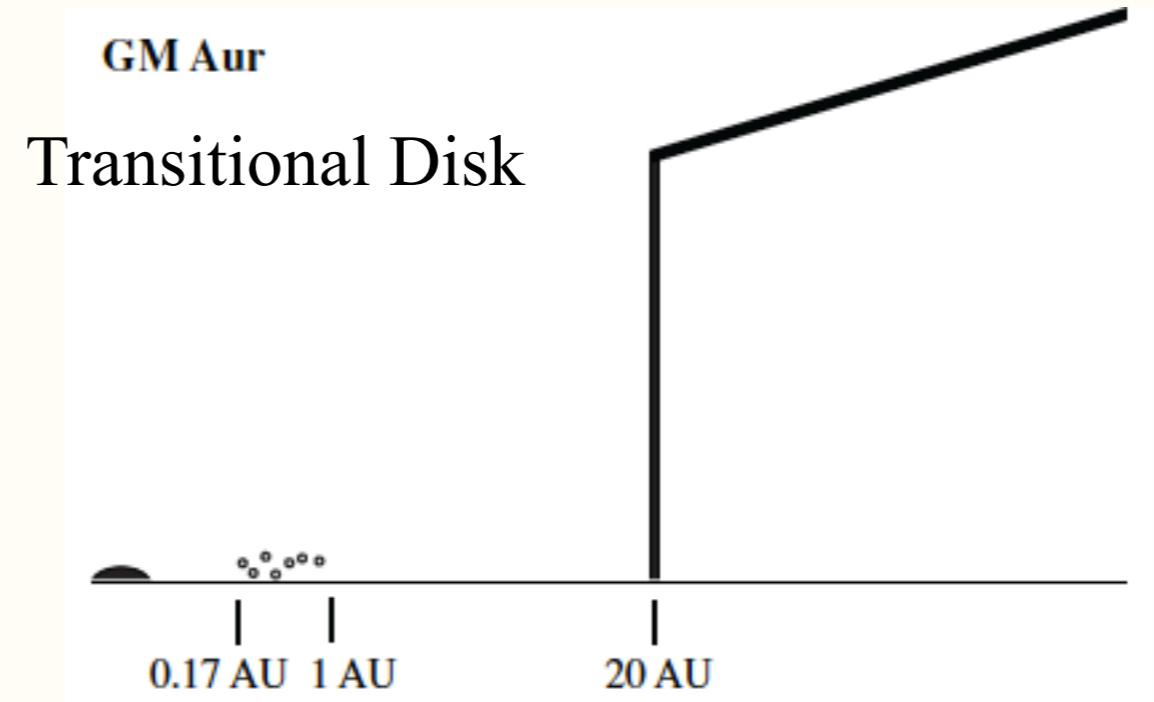
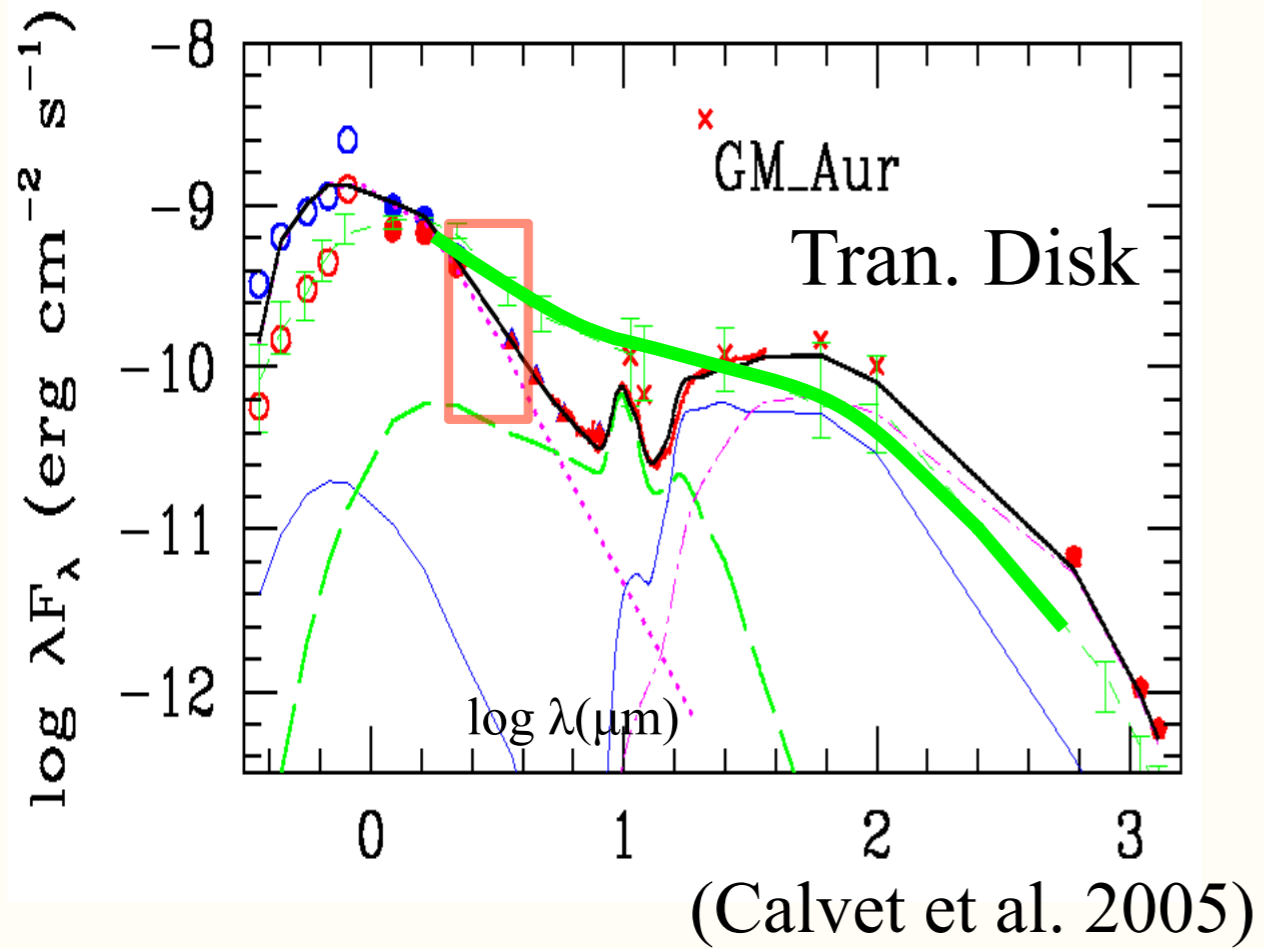
Disk Gaps: Pre-transitional disks



Inner Disk Holes: Transitional disks

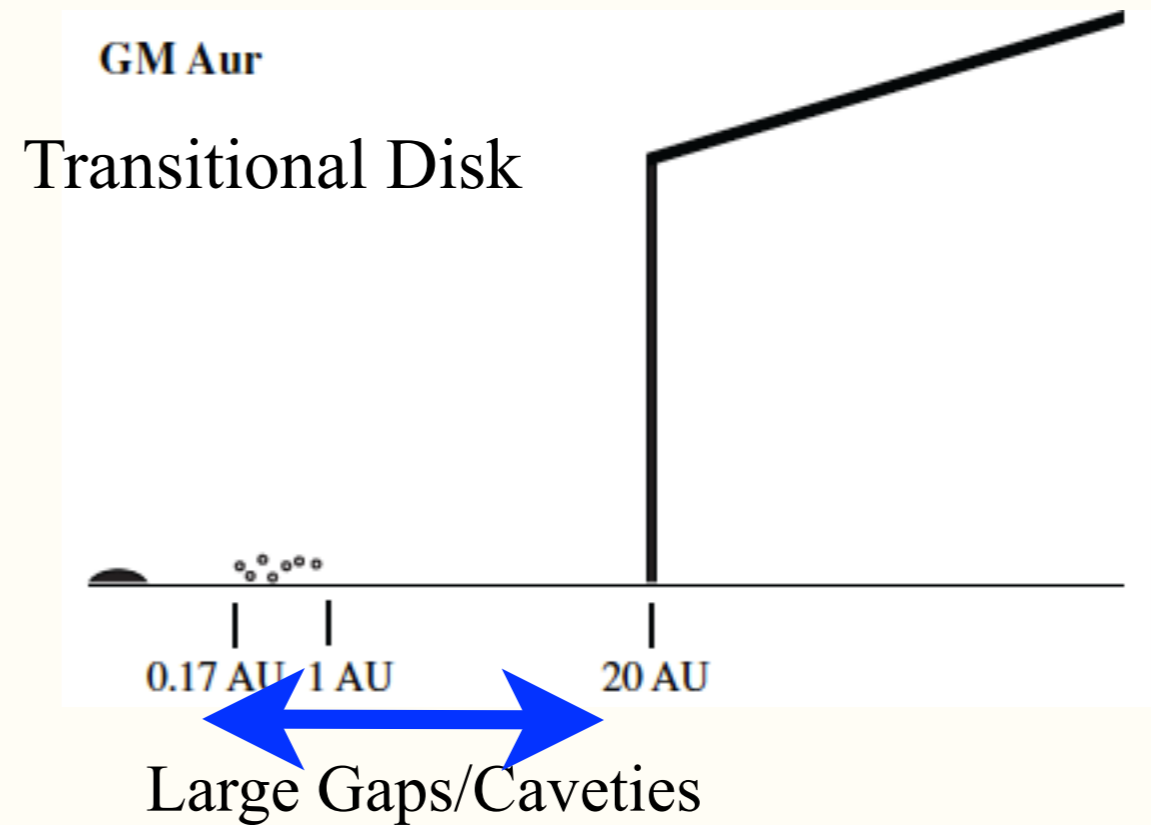
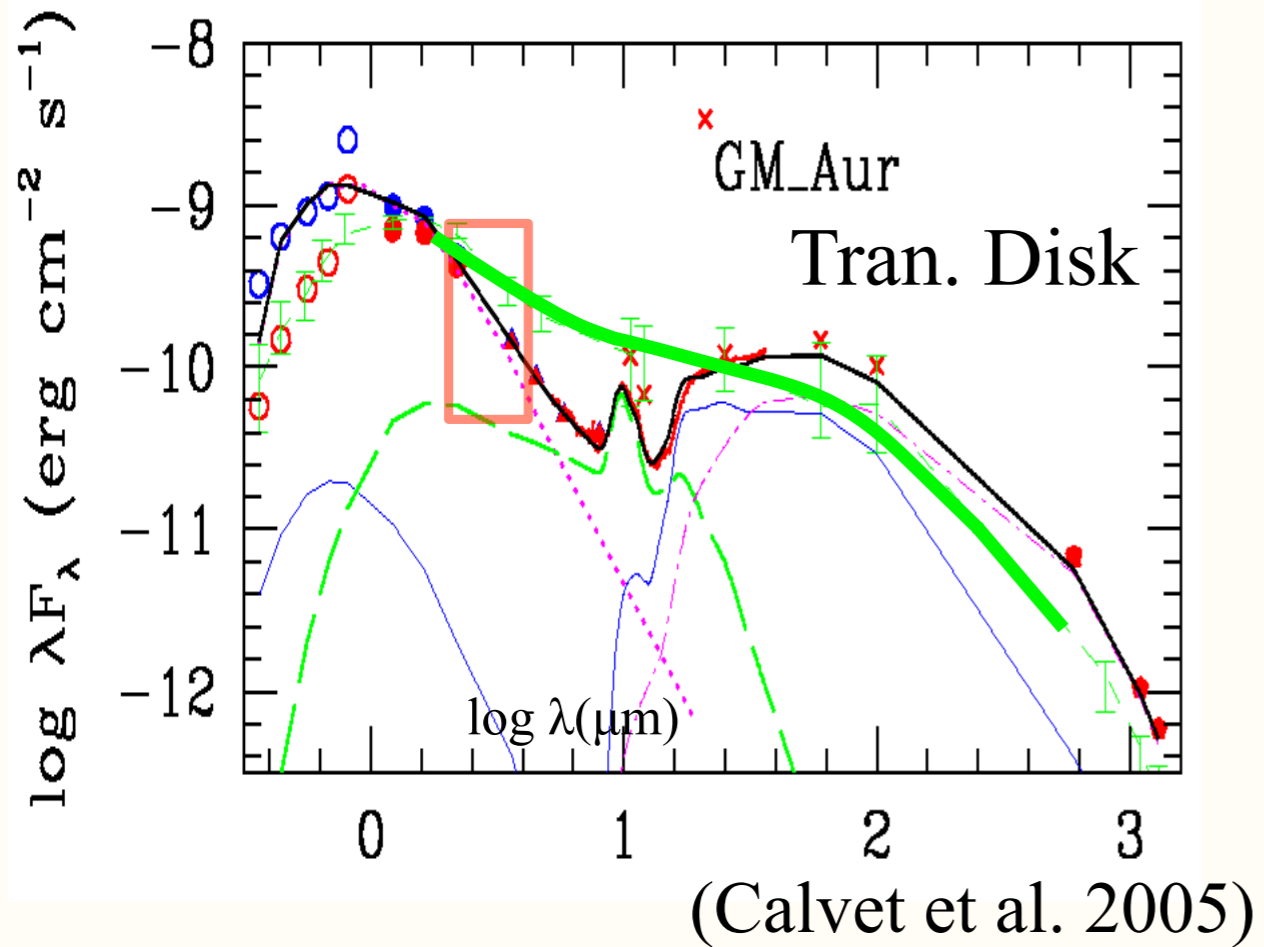


Transitional Disks: SED



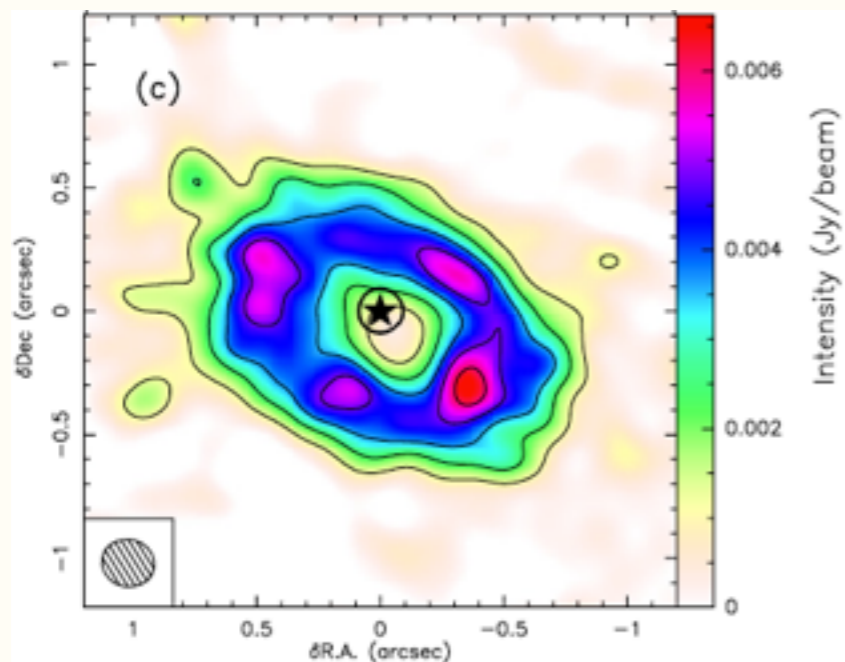
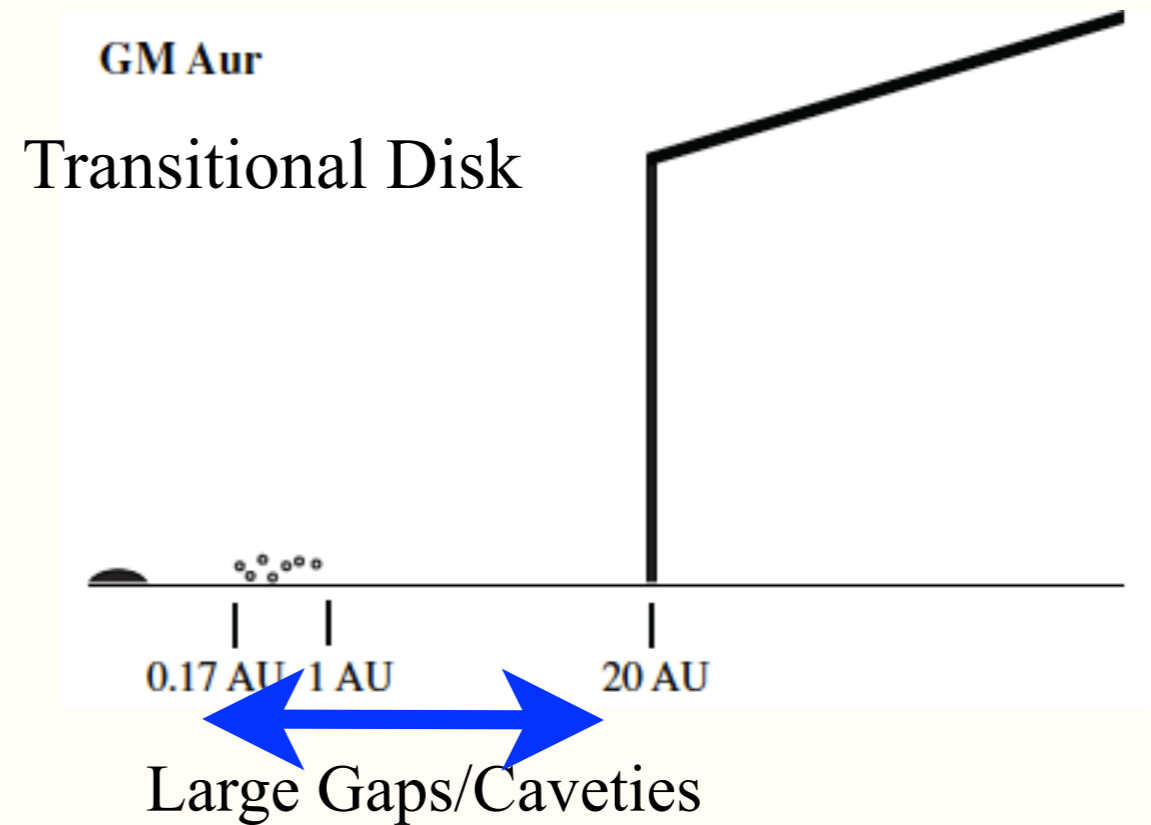
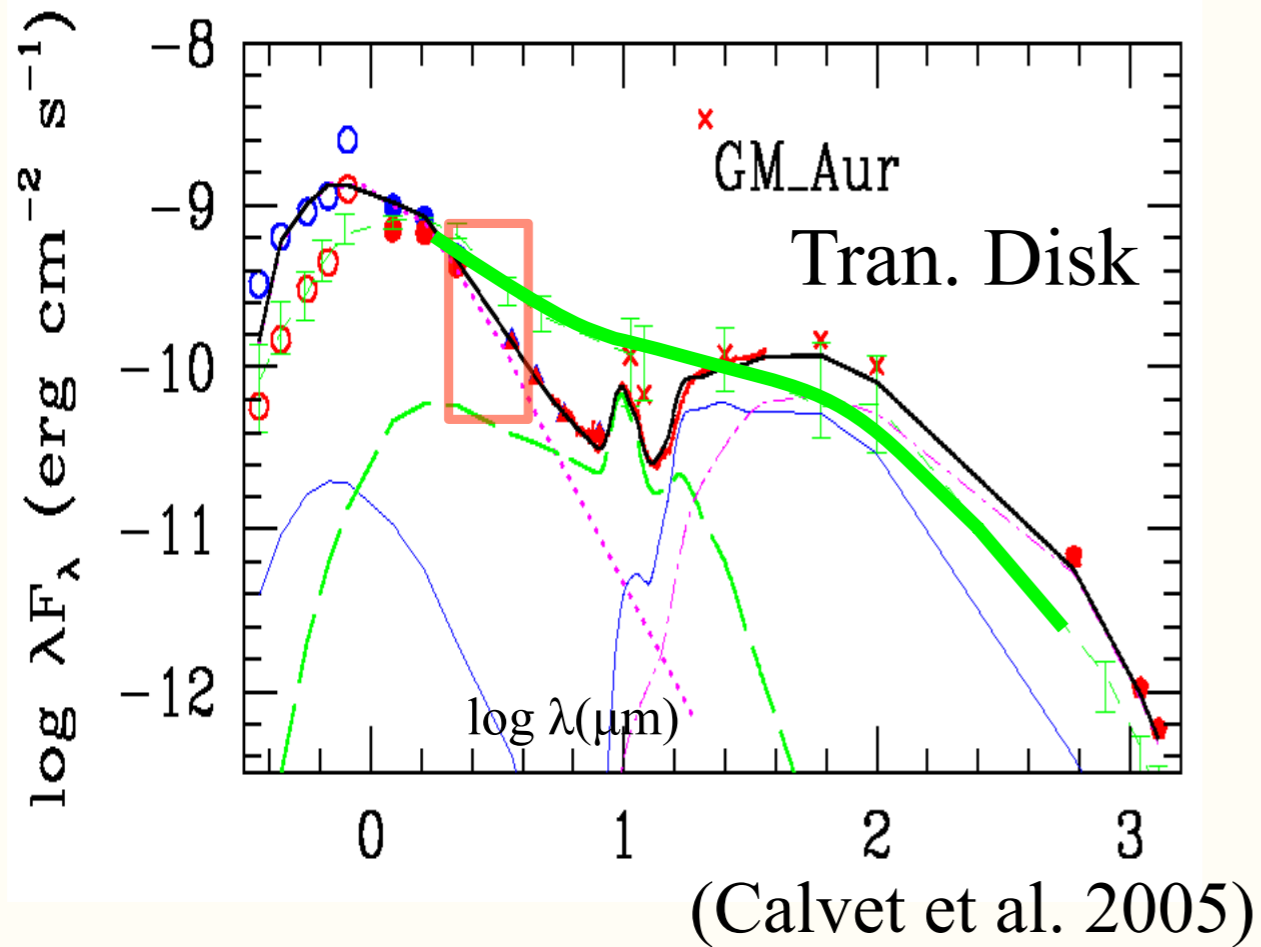
(Espaillat et al. 2010)

Transitional Disks: SED



(Espaillat et al. 2010)

Transitional Disks: SED



(Isella, Perez & Carpenter 2012)

Can planet-induced gaps explain observations?

- Three observational constraints:
- Accretion rate onto the star $\geq 10^{-9} M_{\text{sun}}/\text{yr}$
- Large, <1 AU to ~ 10 's AUs, gaps/holes
- Low optical depth <10 AU, despite having gas flowing through it

Can planet-induced gaps explain observations?

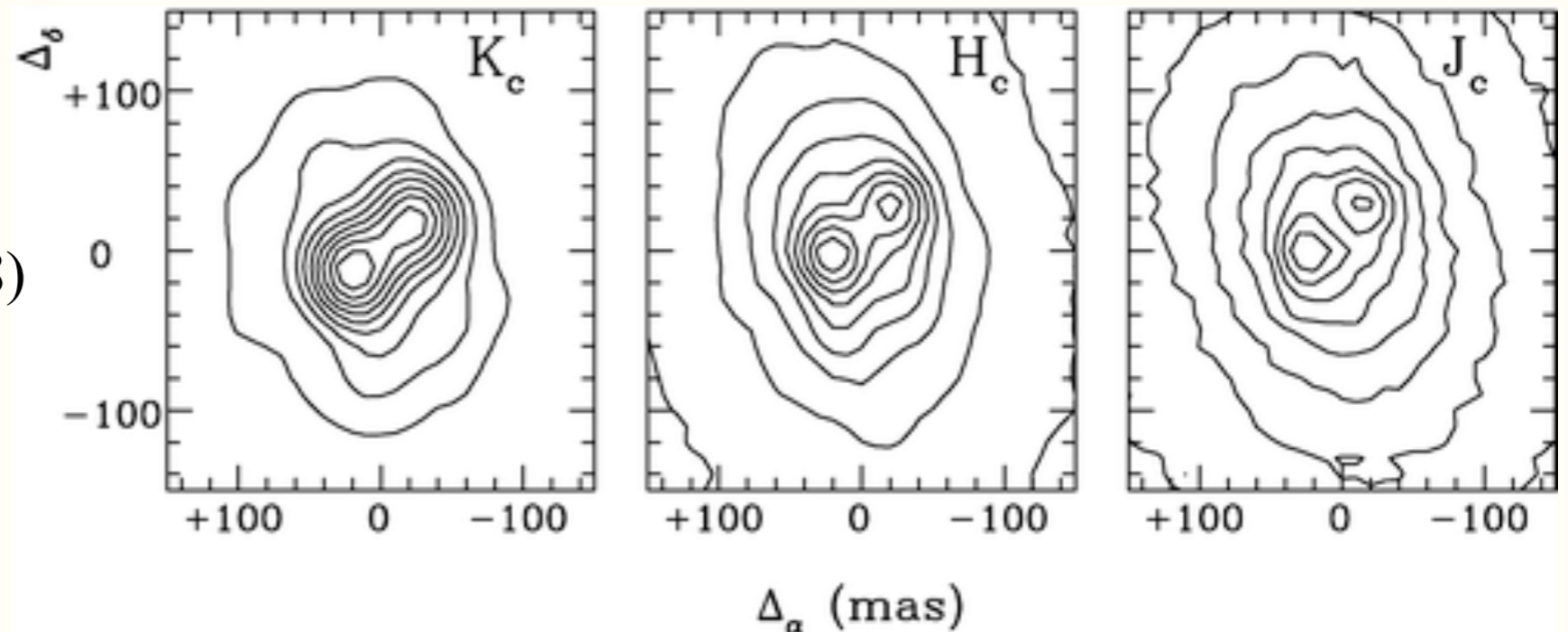
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- Binary clearing
CoKu Tau/4
(Ireland & Kraus 2008)

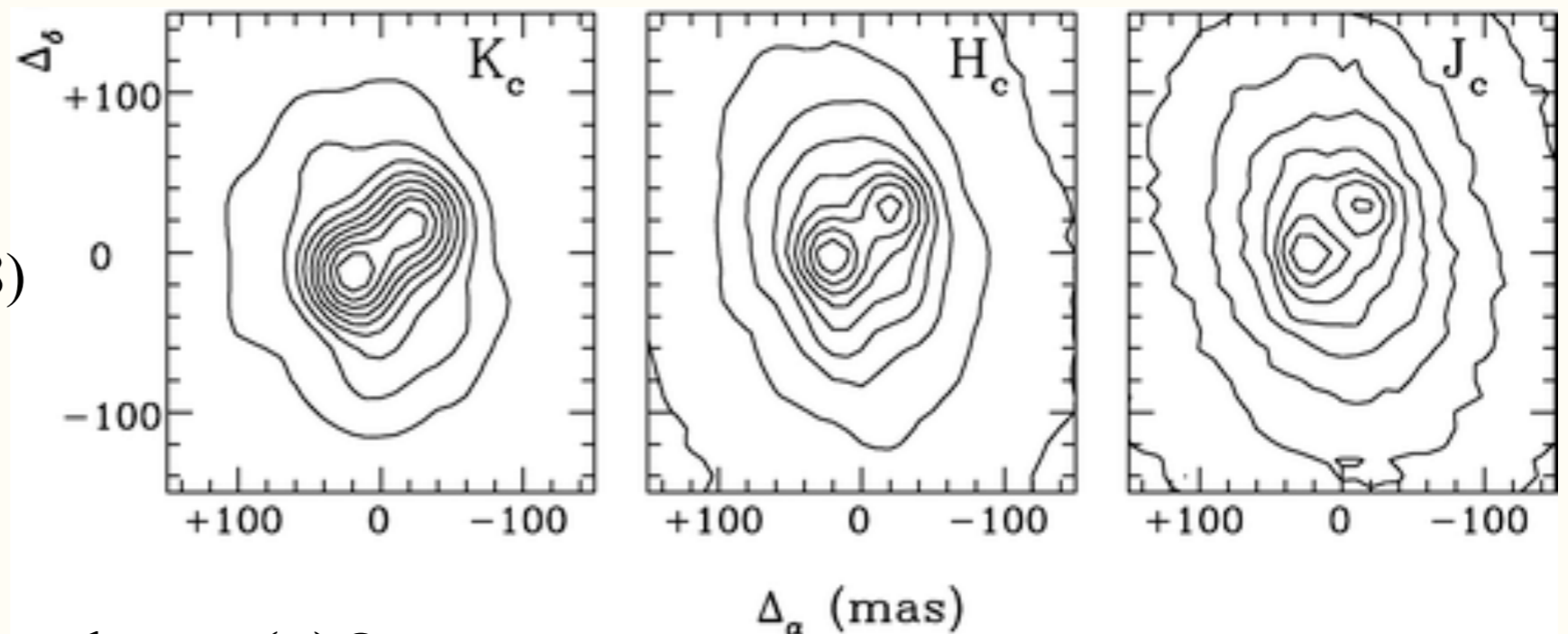


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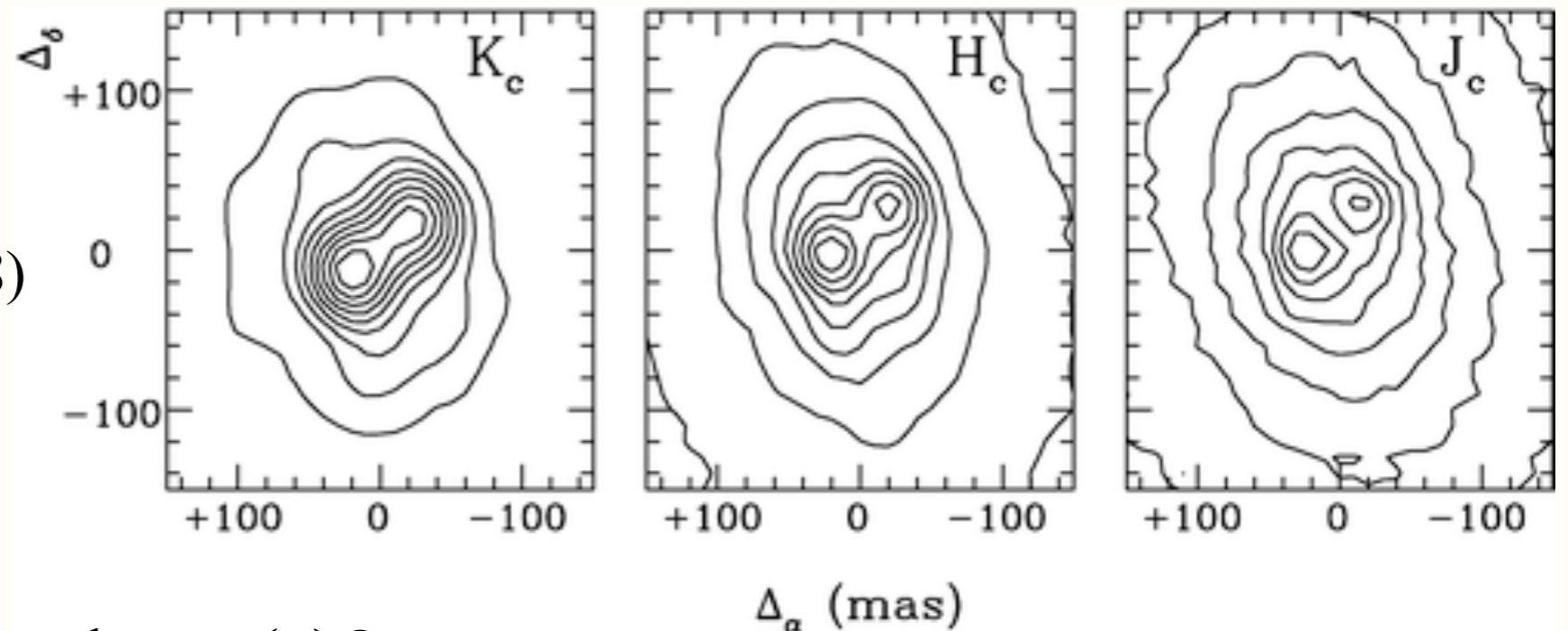
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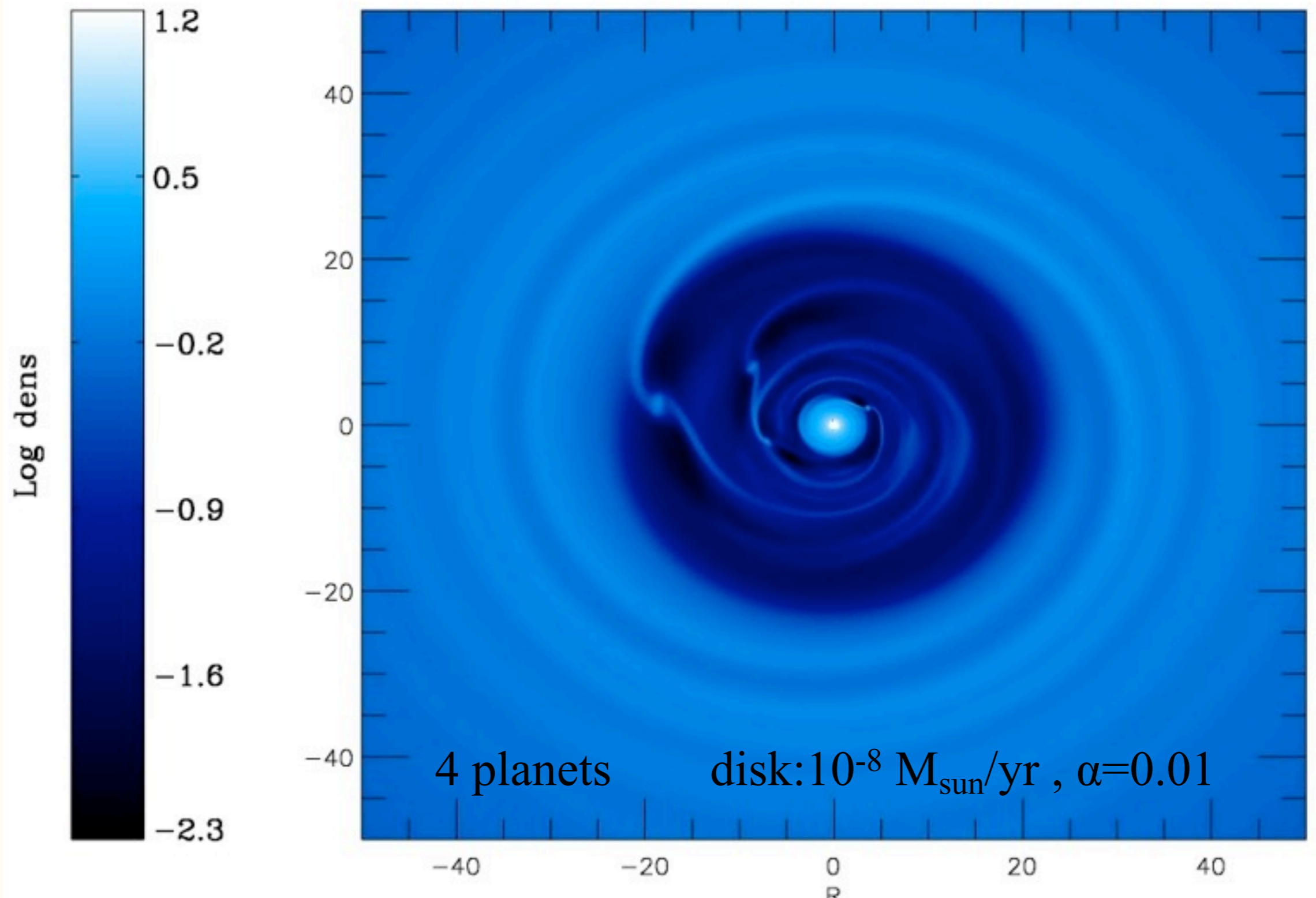
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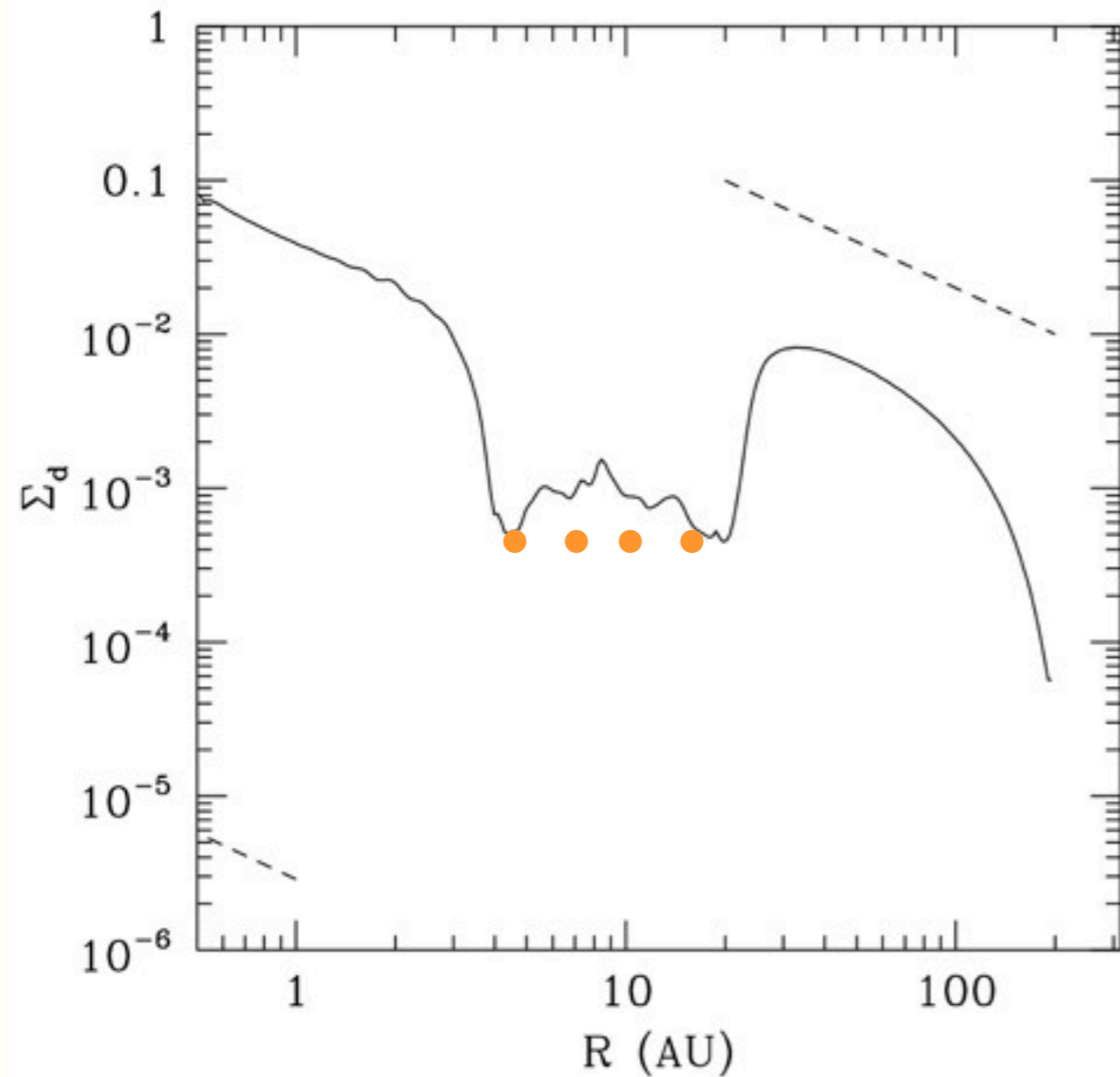


- Gap opening by planet(s)? **There are problems!**

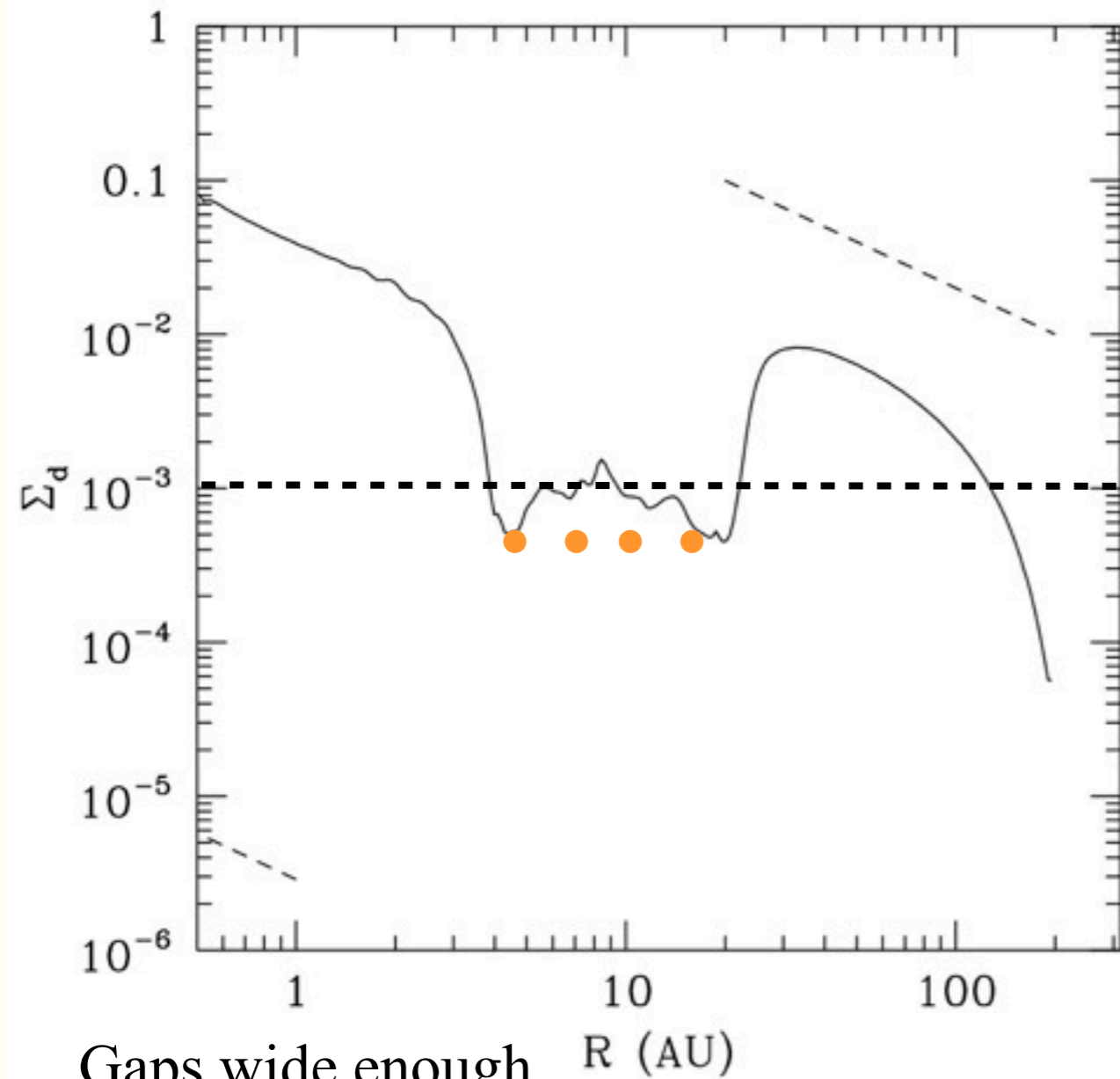
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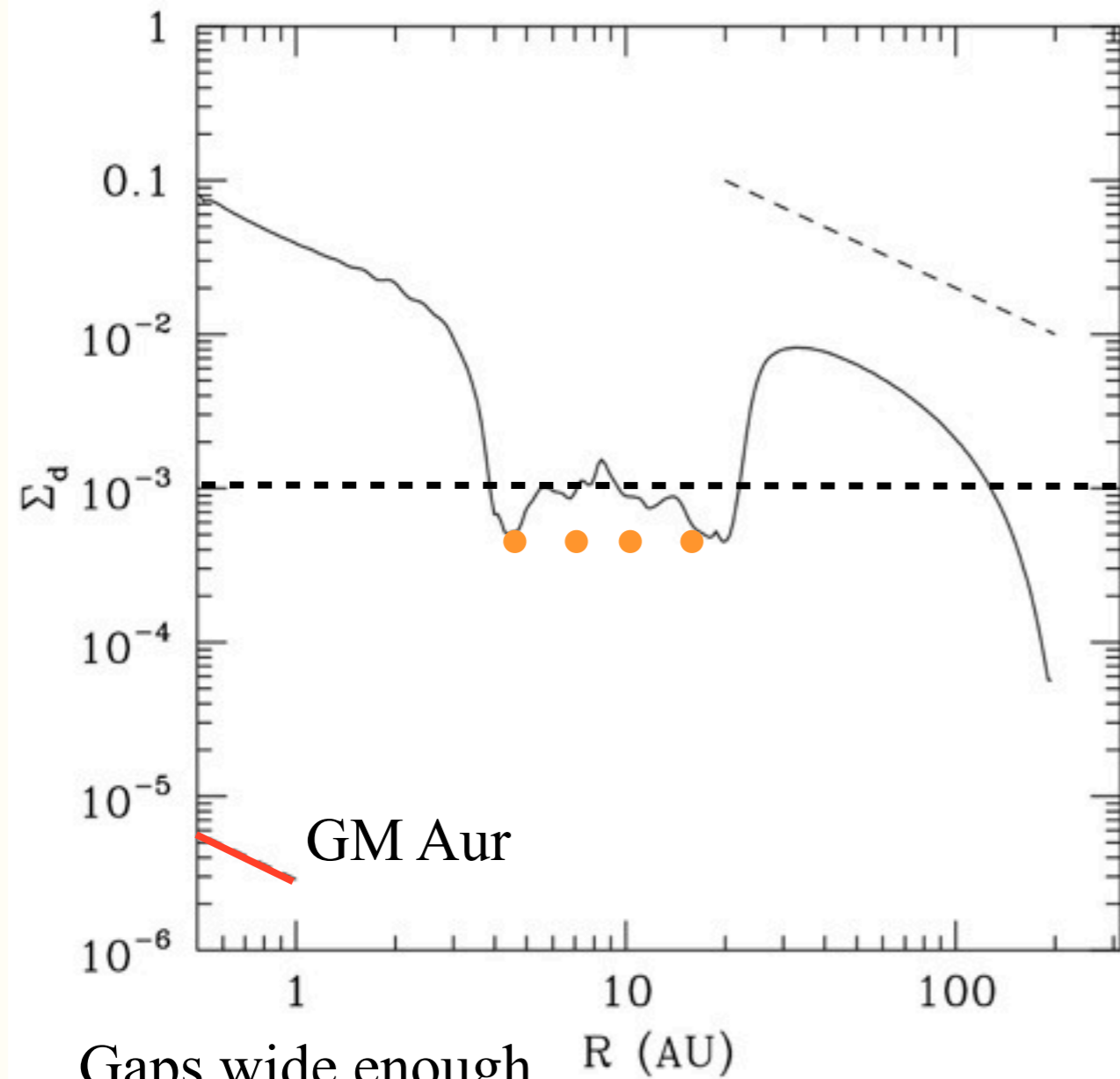
Can planet-induced gaps explain observations?



Gaps wide enough

However, they cannot affect the inner disk (Consider $\kappa_{10\ \mu\text{m}} = 10\ \text{cm}^2/\text{g}$, the inner disk is optically thick).

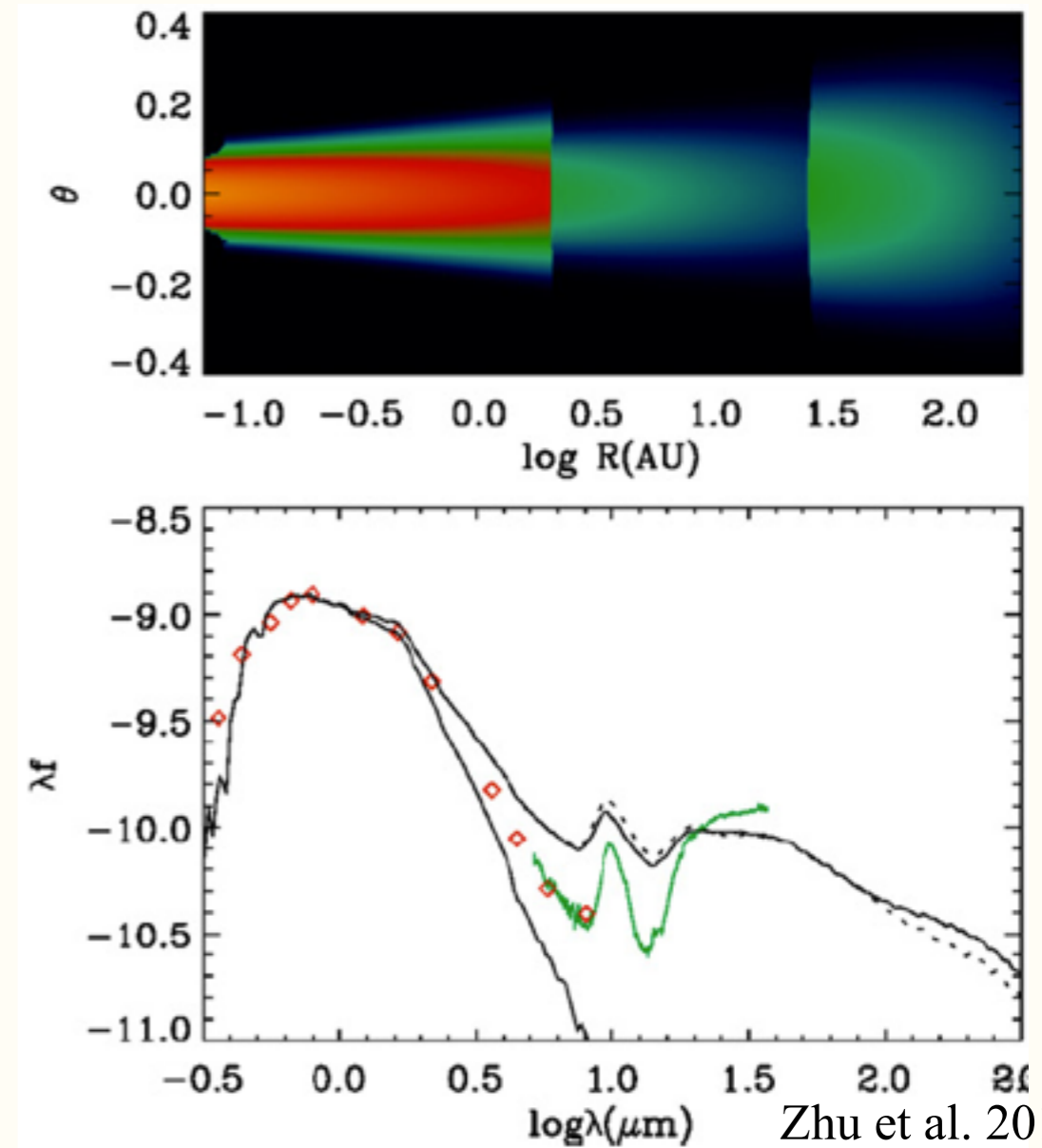
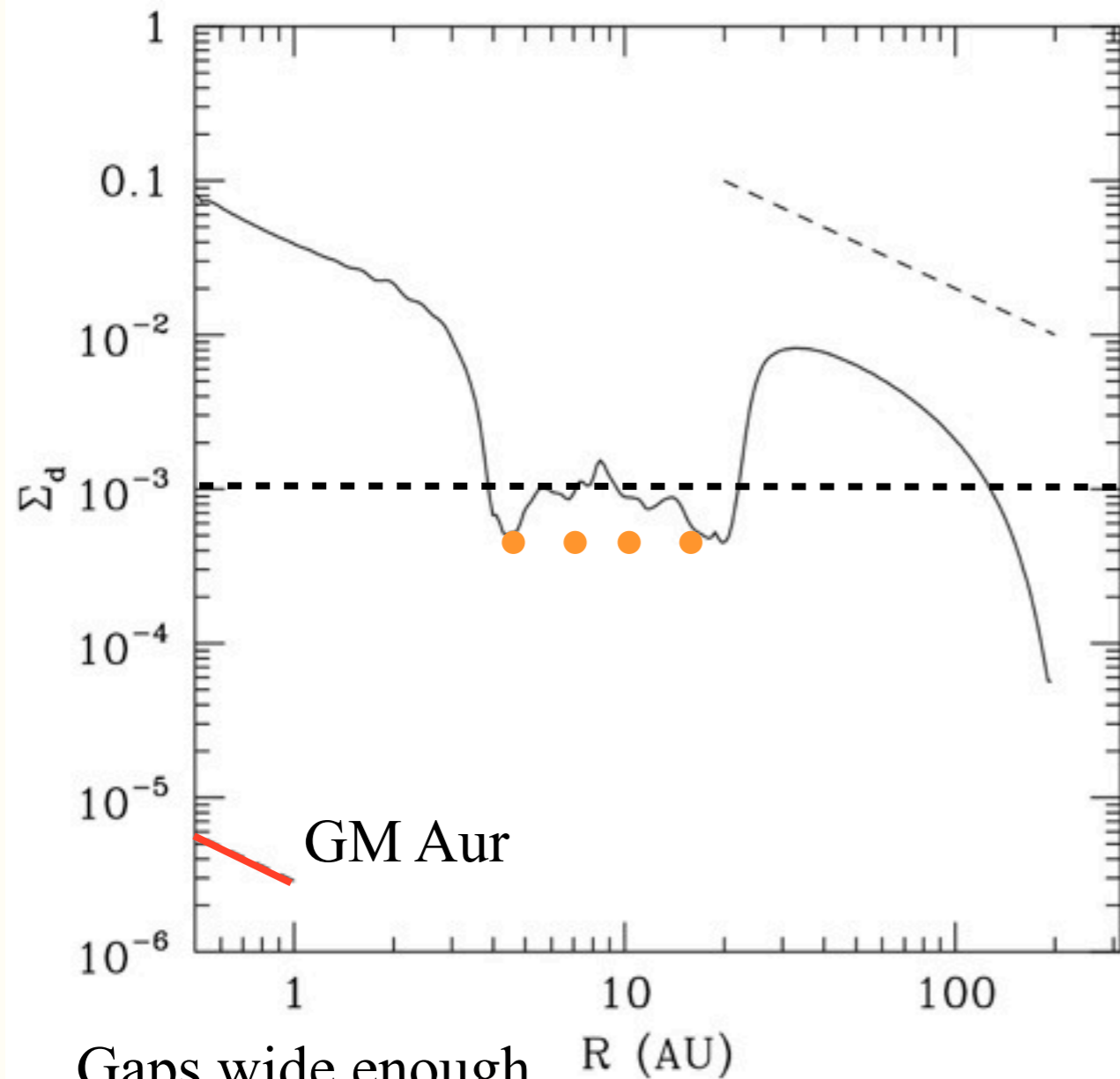
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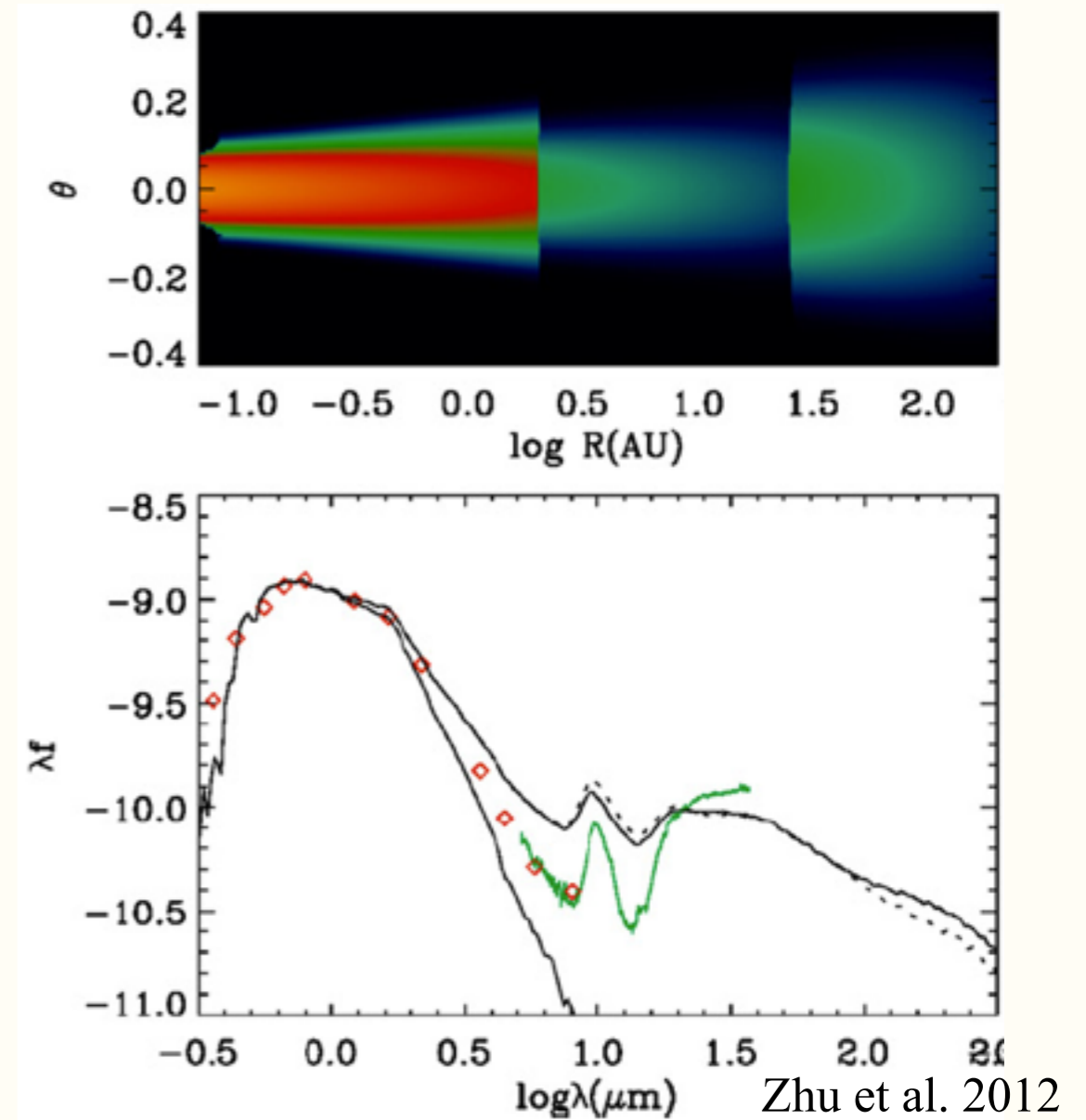
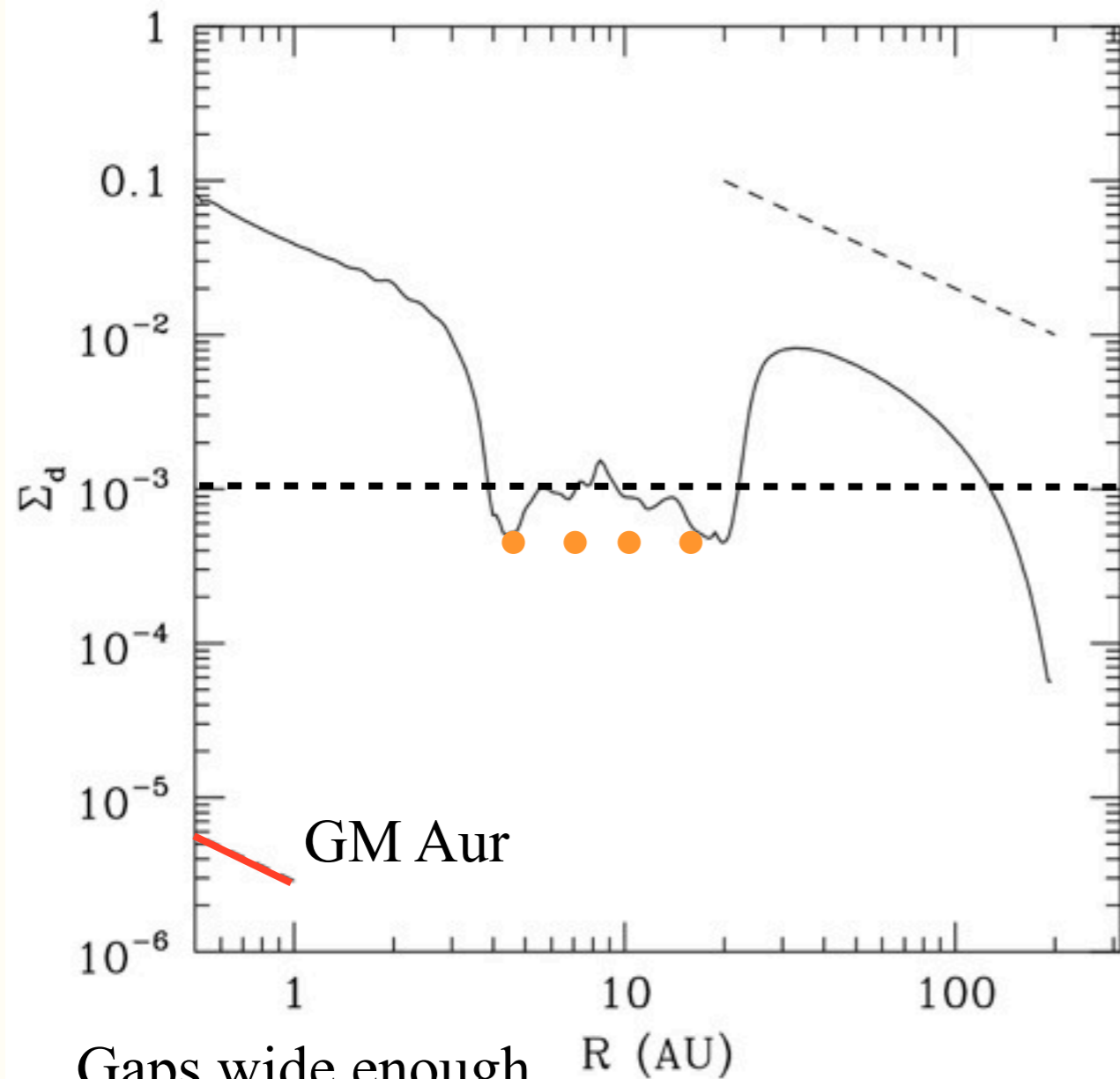
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Can planet-induced gaps explain observations?



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Significant **dust depletion** is required at the inner disk
(Depletion factor $\sim 10^3$ - 10^5)

Zhu et al. 2011

Problems

Accretion: $10^{-8} M_{\text{sun}}/\text{yr}$

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$\Sigma_{\text{g}}=100 \text{ g/cm}^2$ at 0.1 AU if $\alpha=0.01$

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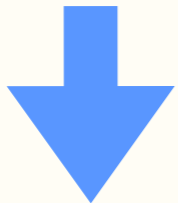
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$\tau_{10\mu\text{m}}=1000$

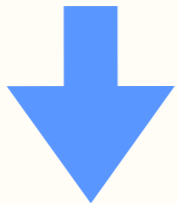
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$\tau_{10\mu\text{m}}=1000$

Transitional Disk $\tau_{\text{Near-IR}}<1$, GM Aur $\tau_{\text{Near-IR}}\sim 0.01$

Dust opacity decreases by 10^3 to 10^5

Abstract/conclusion

- Planets are Common
- How to find young planets? Using density wave theory (spiral wakes, gaps).
 - Non-linear density wave theory and gap opening.
 - Density waves interact with MRI turbulence.
- Transitional disks are candidates for harboring young planets and they start to reveal rich physics.
- Dust particle dynamics during planet-disk interaction is essential for connecting with observations to find young planets.

Gas and Dust Particles decouple

Dust particle systems are collisionless systems.

=> Collisionless Boltzmann equation (similar to stars)

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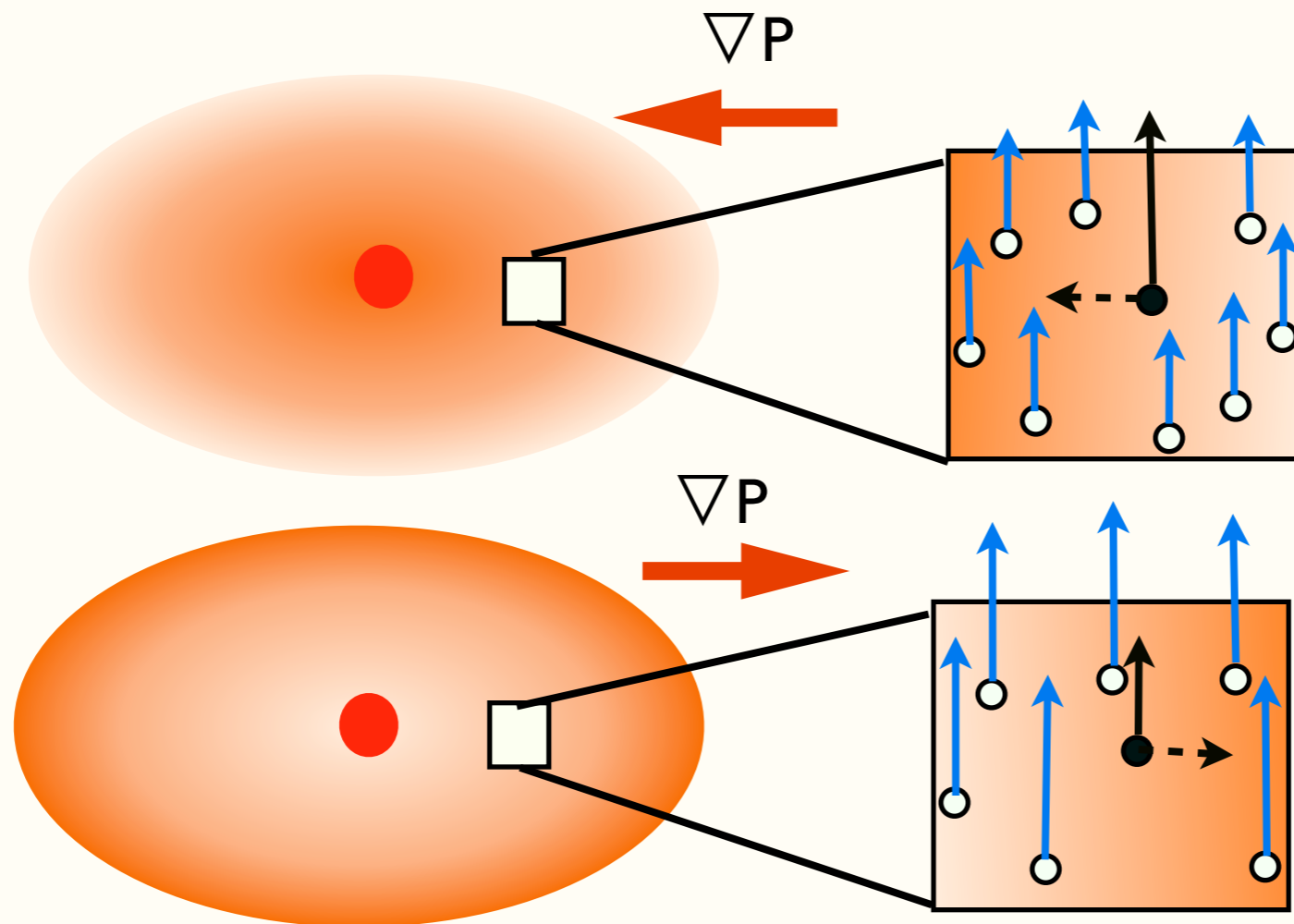
Particle-Gas Interaction: Gas Drag

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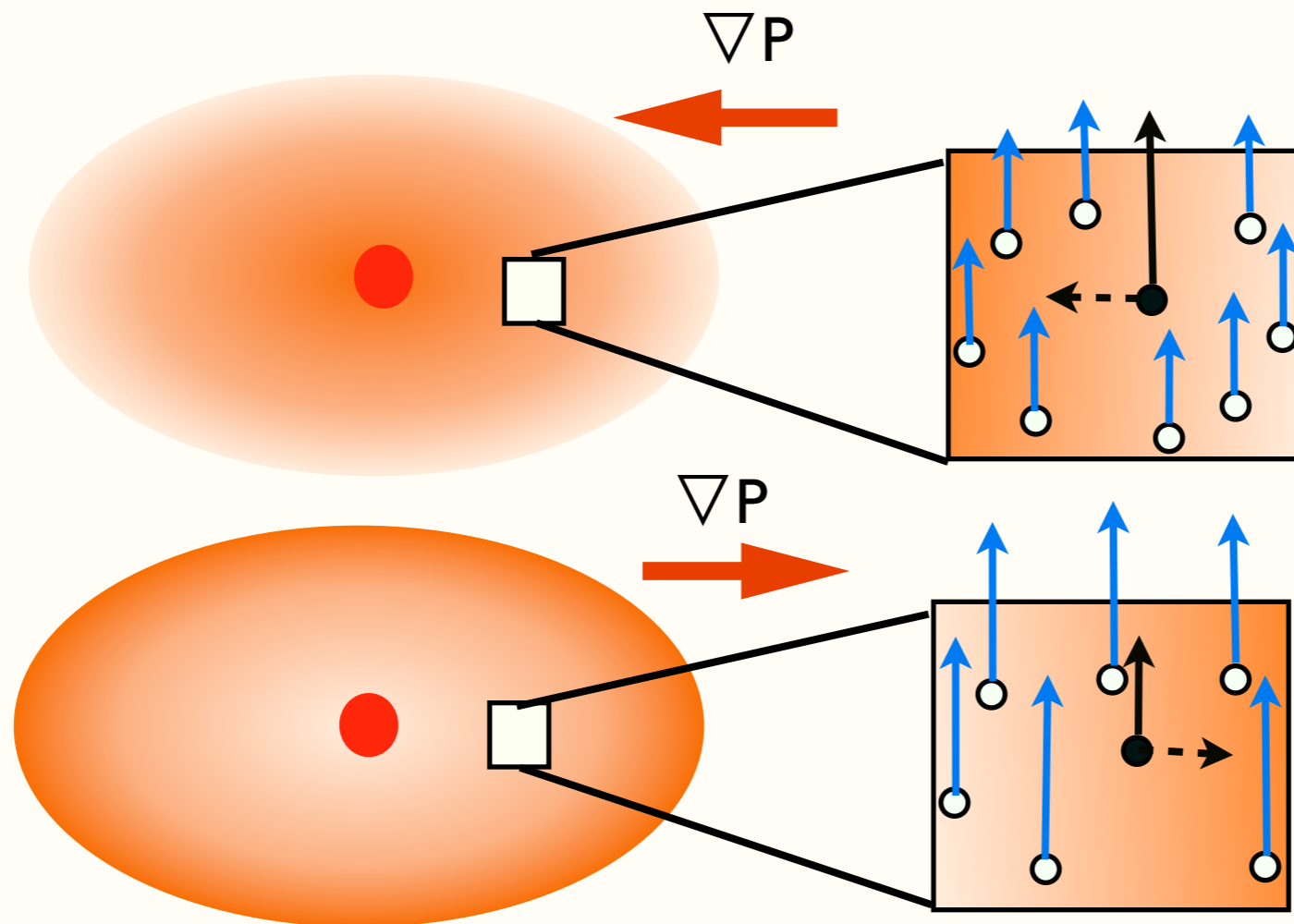


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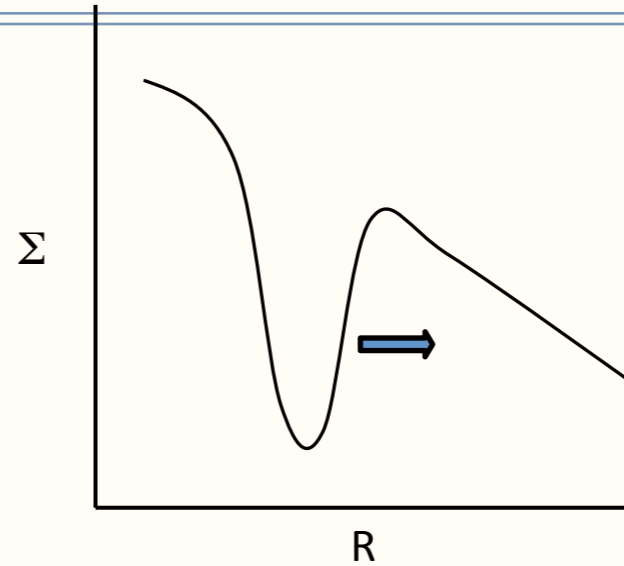


Drag force is related to the particle size
Intermediate sized particles drift fastest

Planets affect particle distribution

1) Drift outwards at the gap edge

(Rice et al. 2006, Paardekooper & Mellema 2006)

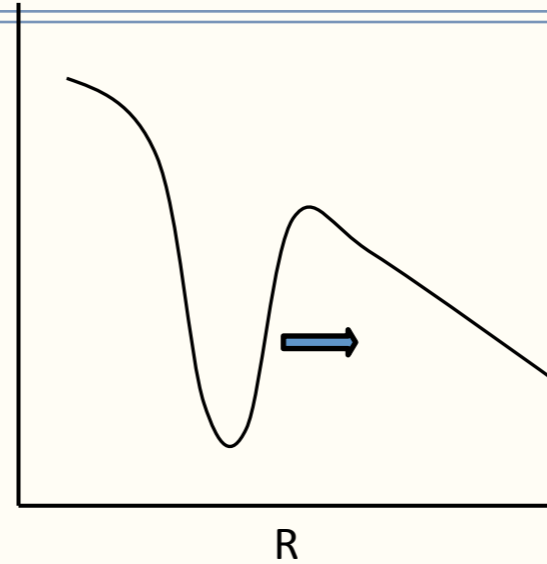


Planets affect particle distribution

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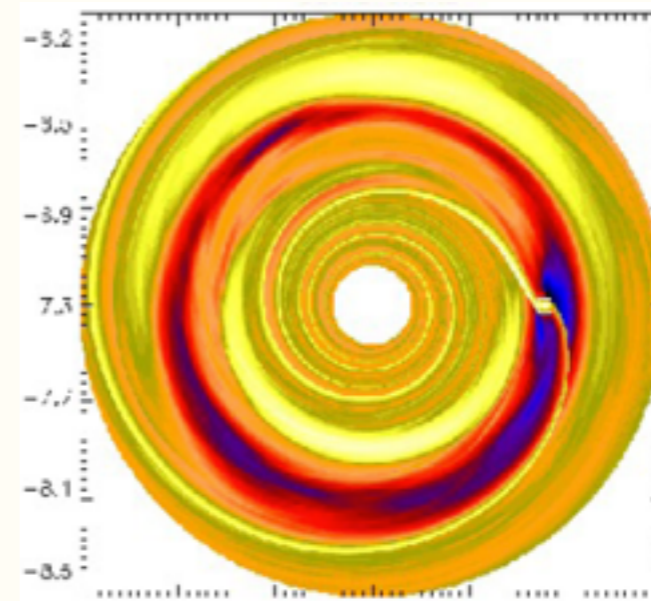
(Rice et al. 2006, Paardekooper & Mellema 2006)

Σ



2) Vortex trapping particles (inviscid disks)

(Lin & Papaloizou 2010)

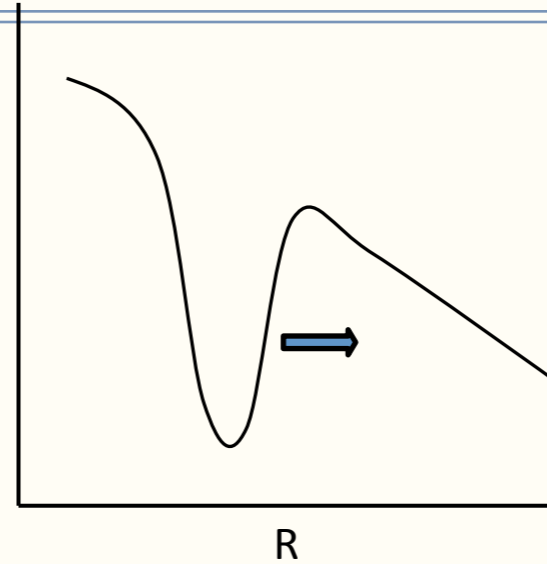


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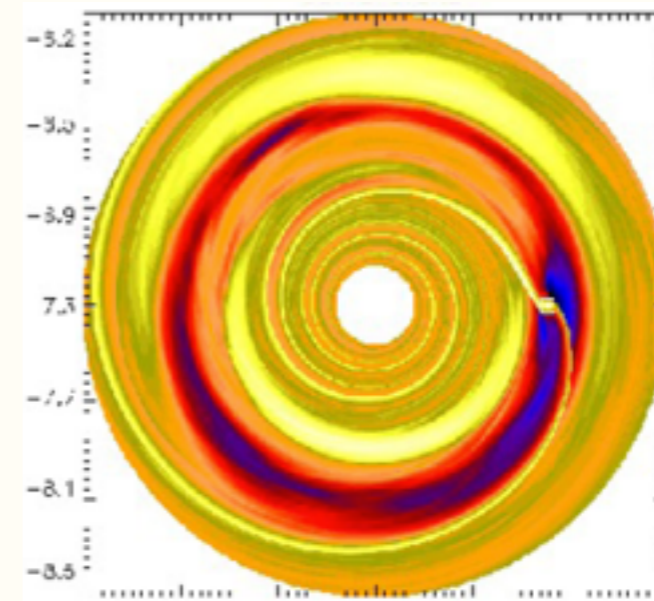
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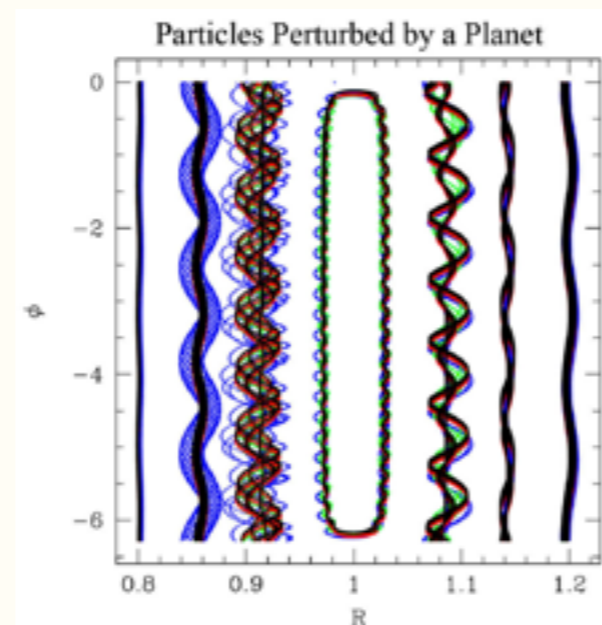


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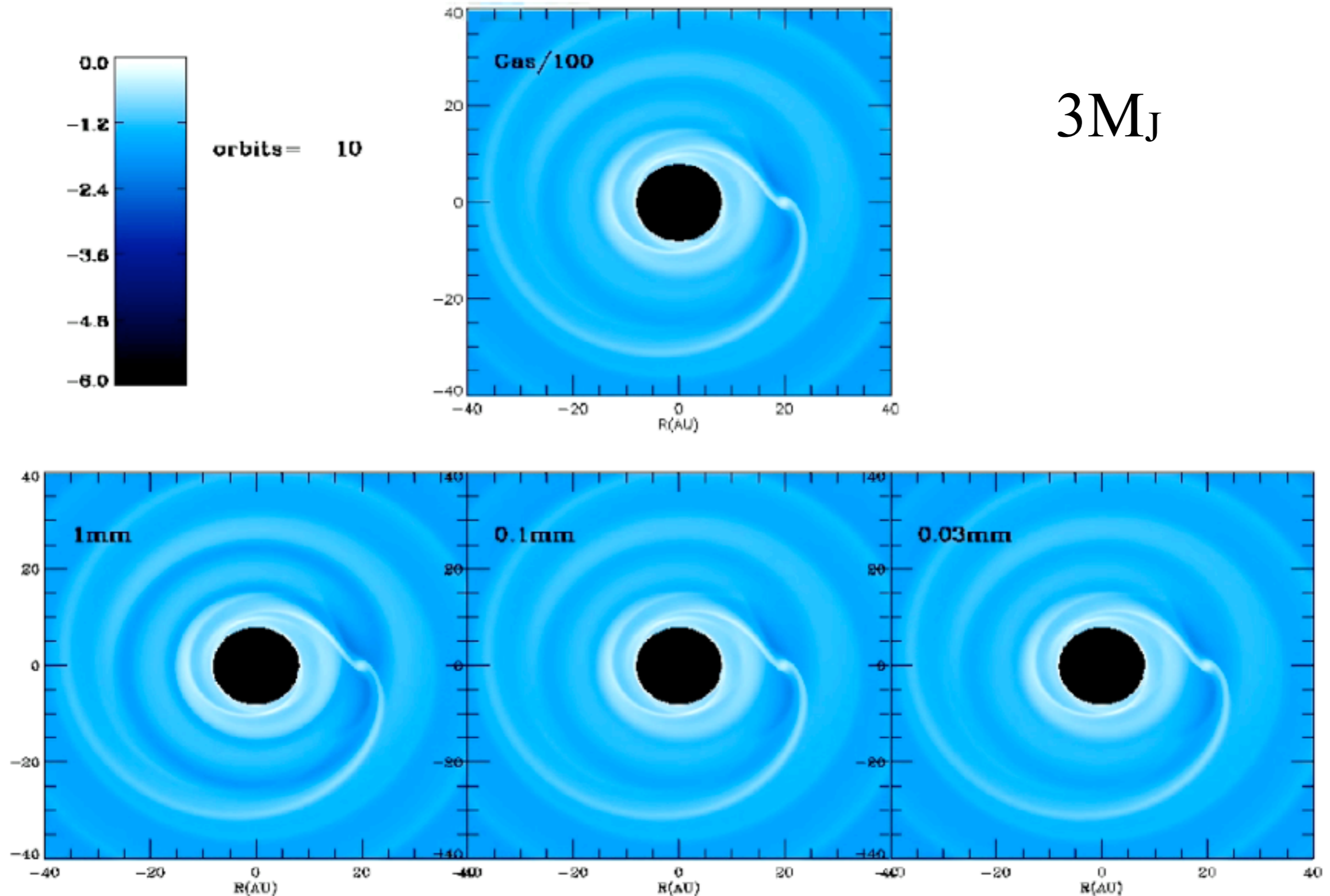
3) Excite eccentricity



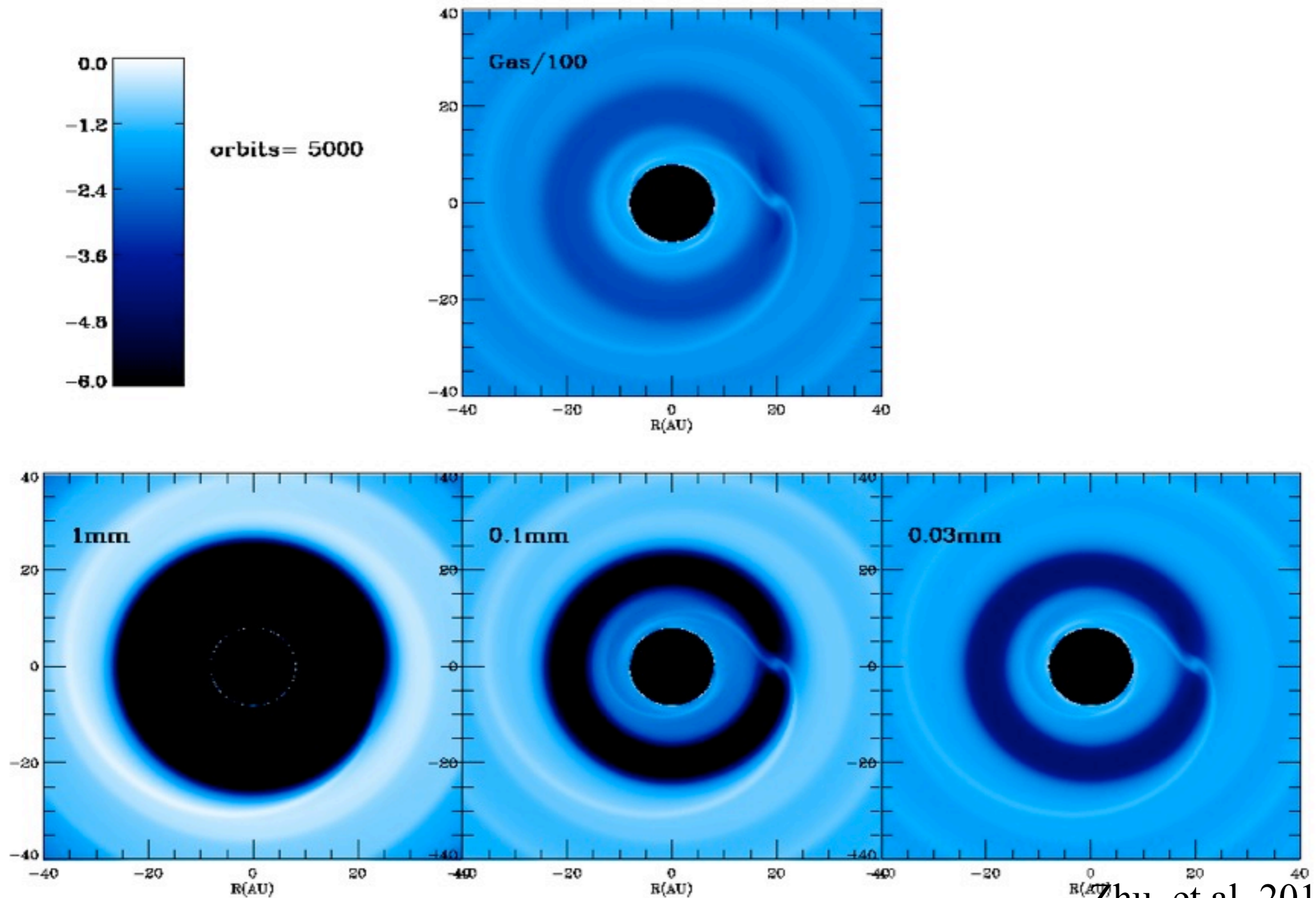
Two-fluid (Dust/Gas) viscous simulations

$3M_J$

Two-fluid (Dust/Gas) viscous simulations



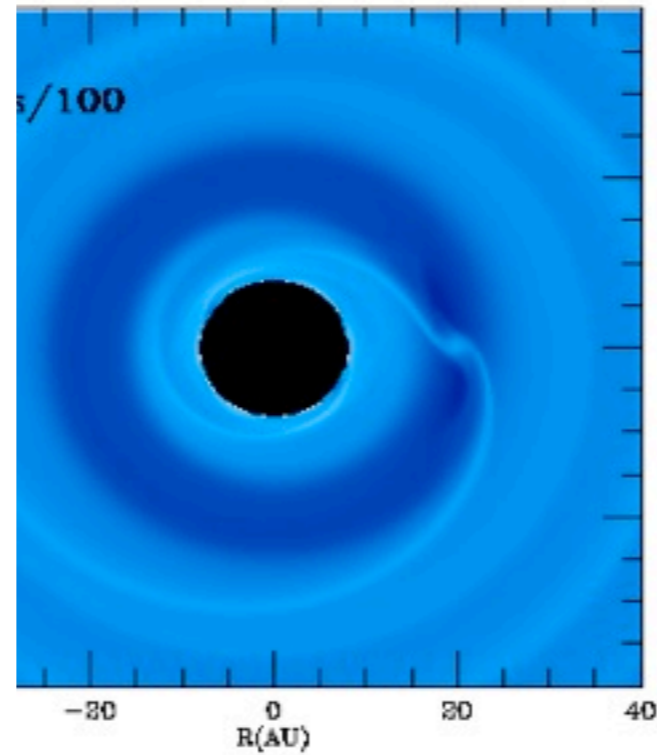
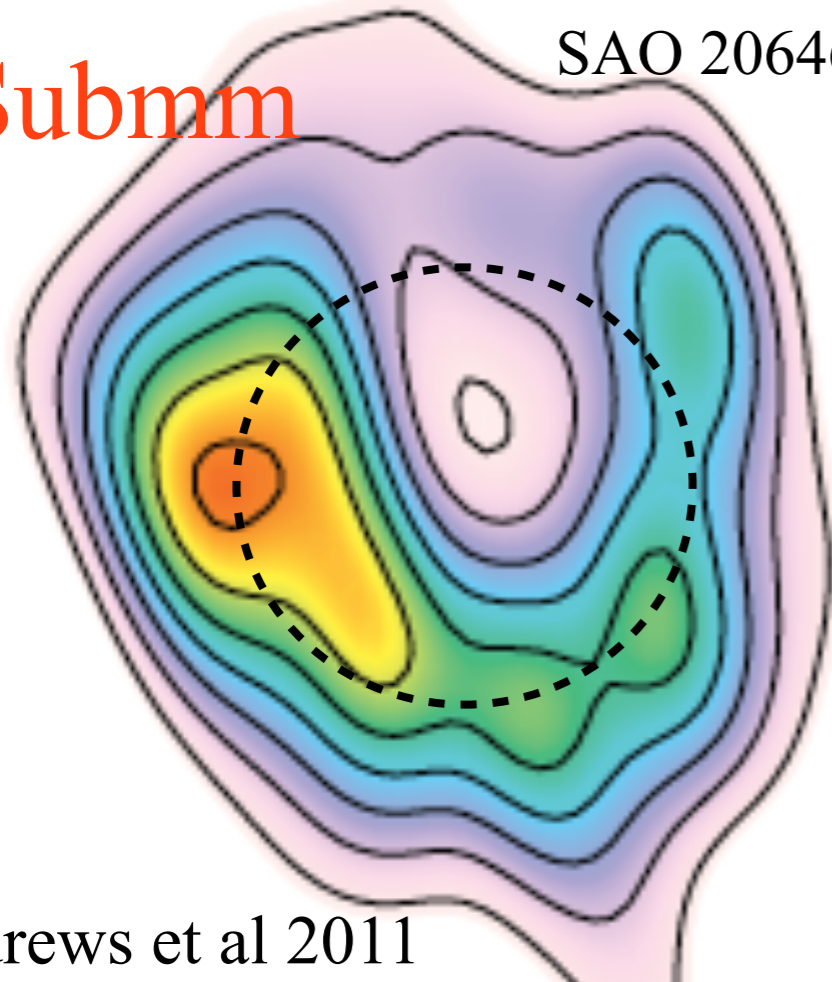
Dust Filtration: Submm vs Near-IR



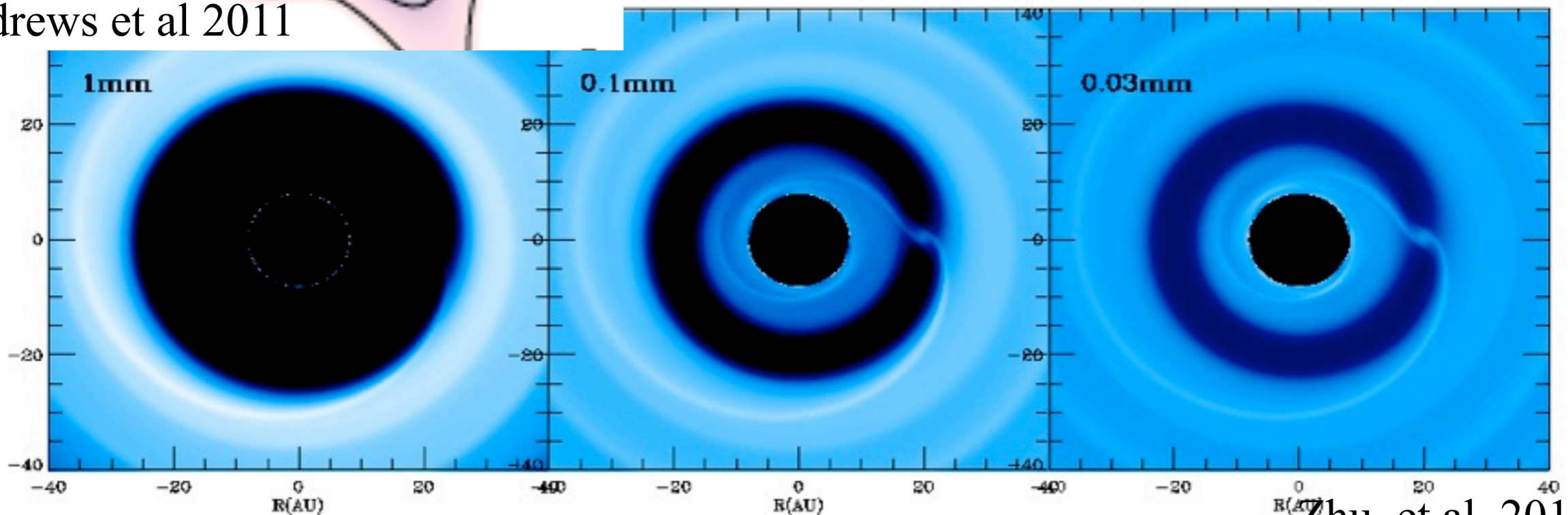
Dust Filtration: Submm vs Near-IR

Submm

SAO 206462



Andrews et al 2011

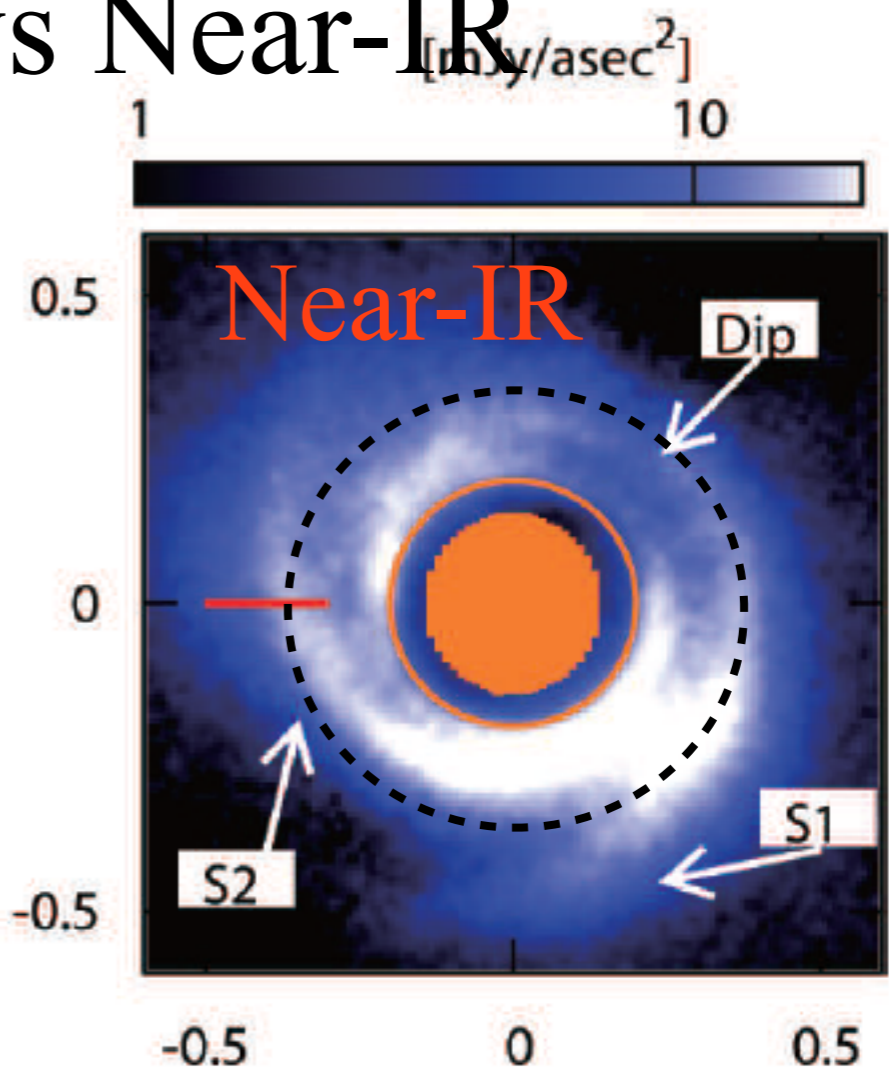
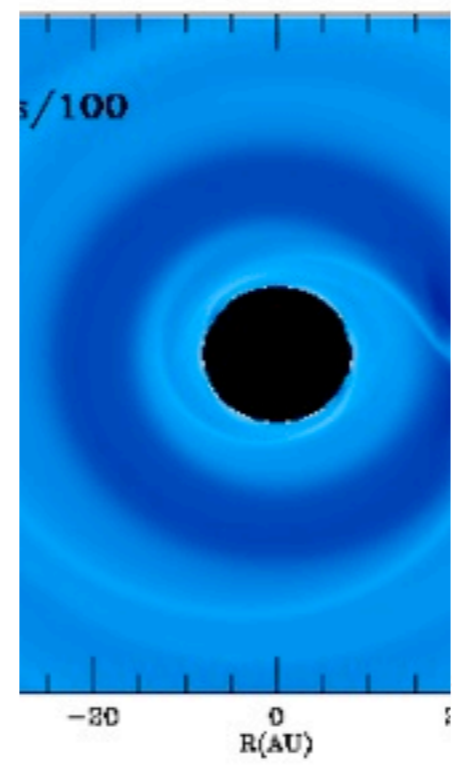
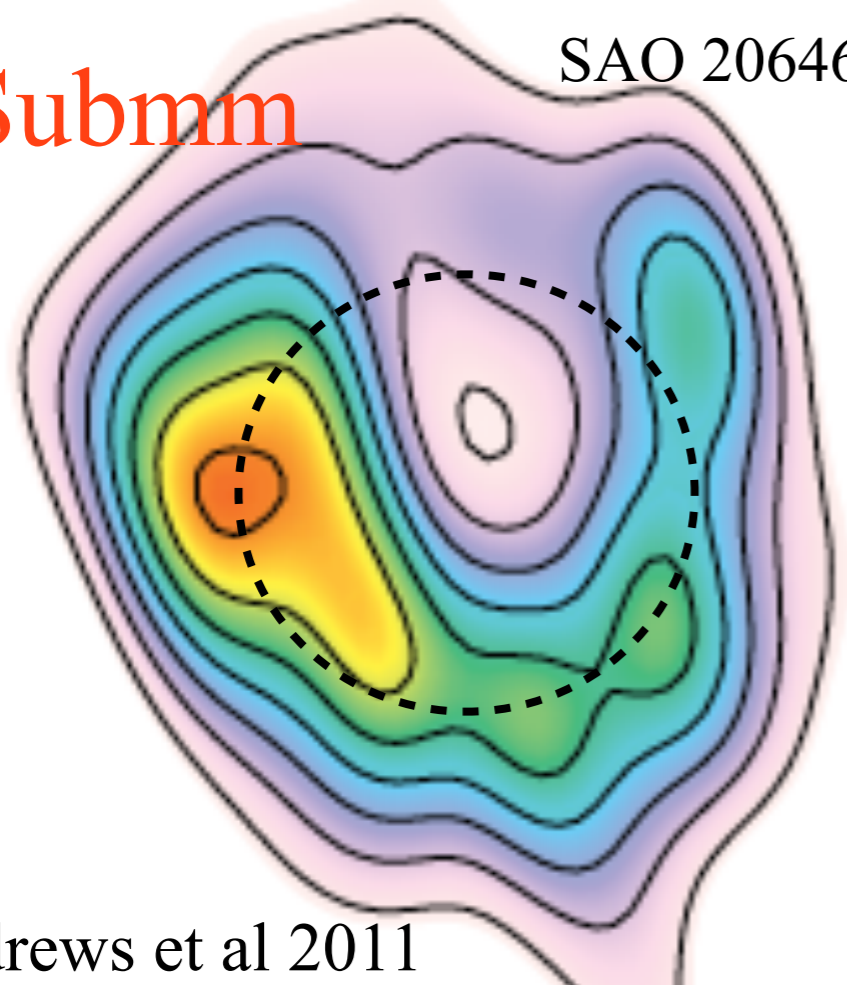


Zhu et al. 2012

Dust Filtration: Submm vs Near-IR

Submm

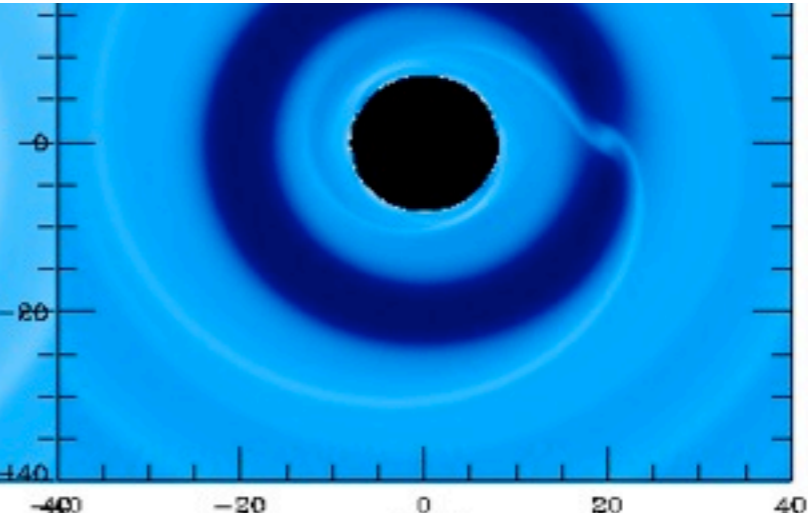
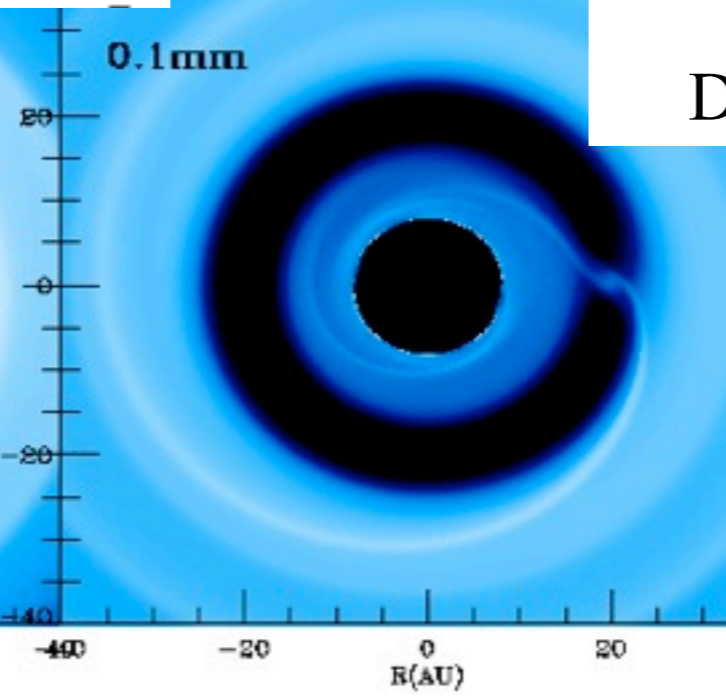
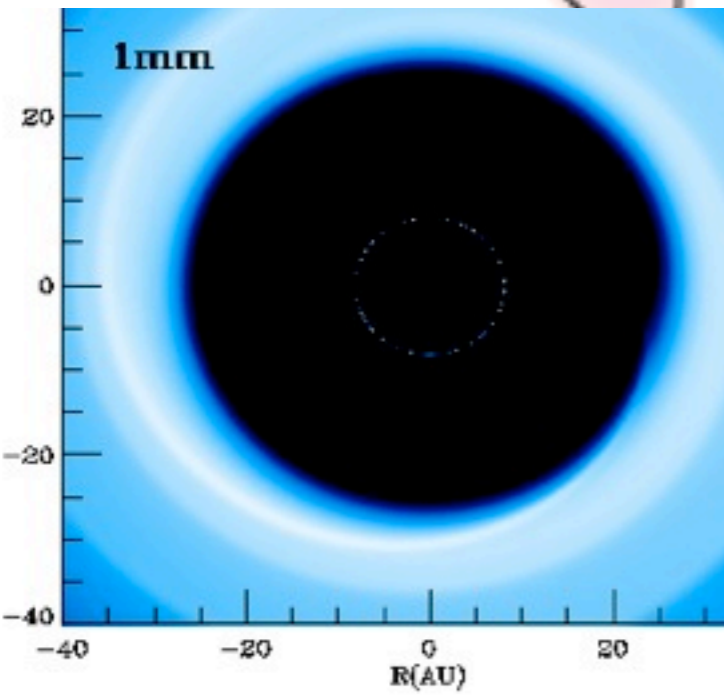
SAO 206462



Andrews et al 2011

Muto et al 2012

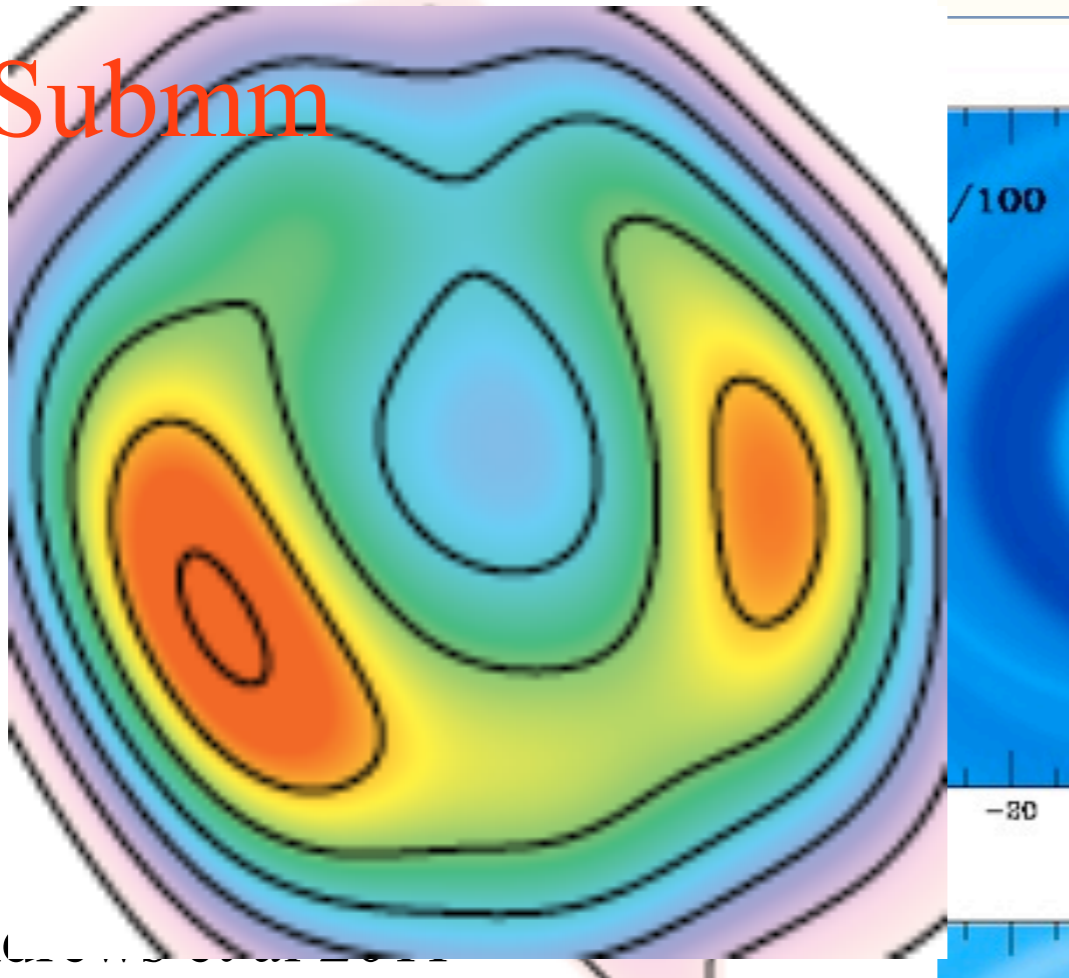
Dong, Rafikov, Zhu et al. 2012



Zhu et al. 2012

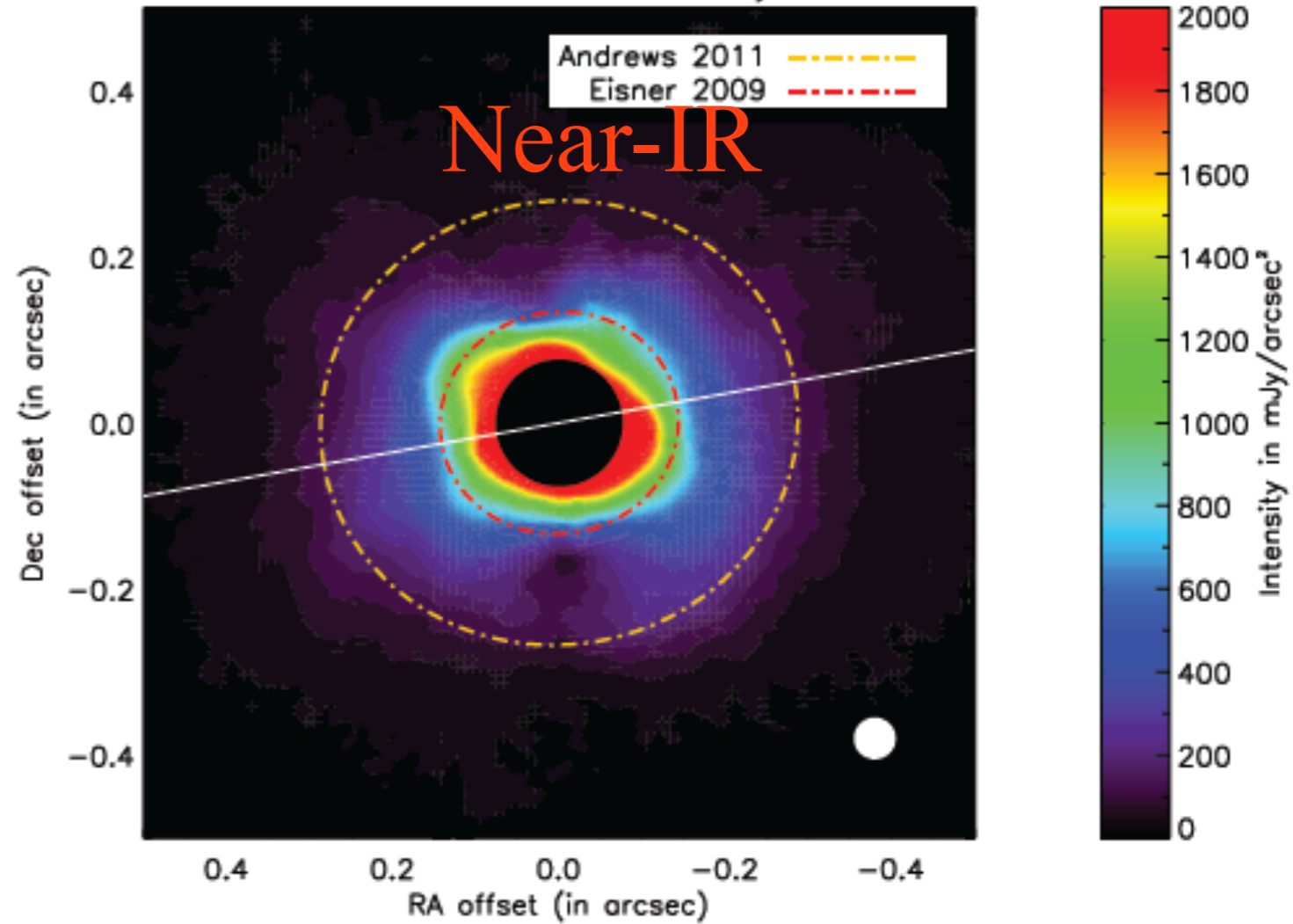
Dust Filtration: Submm vs Near-IR

Submm



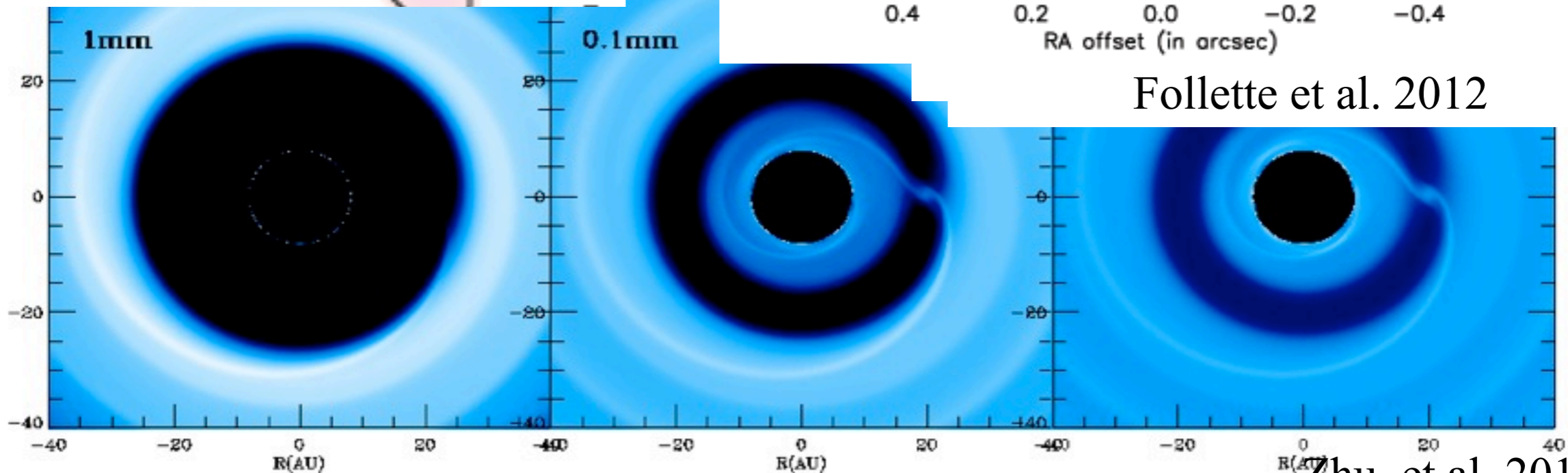
Andrews

SR21 Polarized Intensity



Near-IR

Follette et al. 2012



Zhu et al. 2012

Particle Approach:

Implementing the Particle Integrator into Athena:

$$\frac{d\mathbf{v}_i}{dt} = \mathbf{f}_i$$

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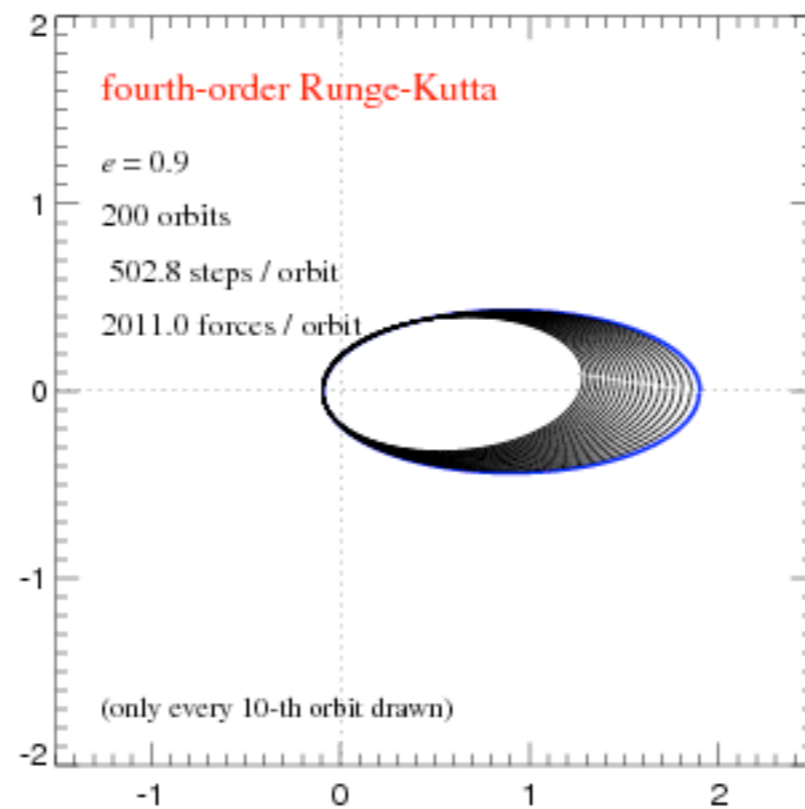
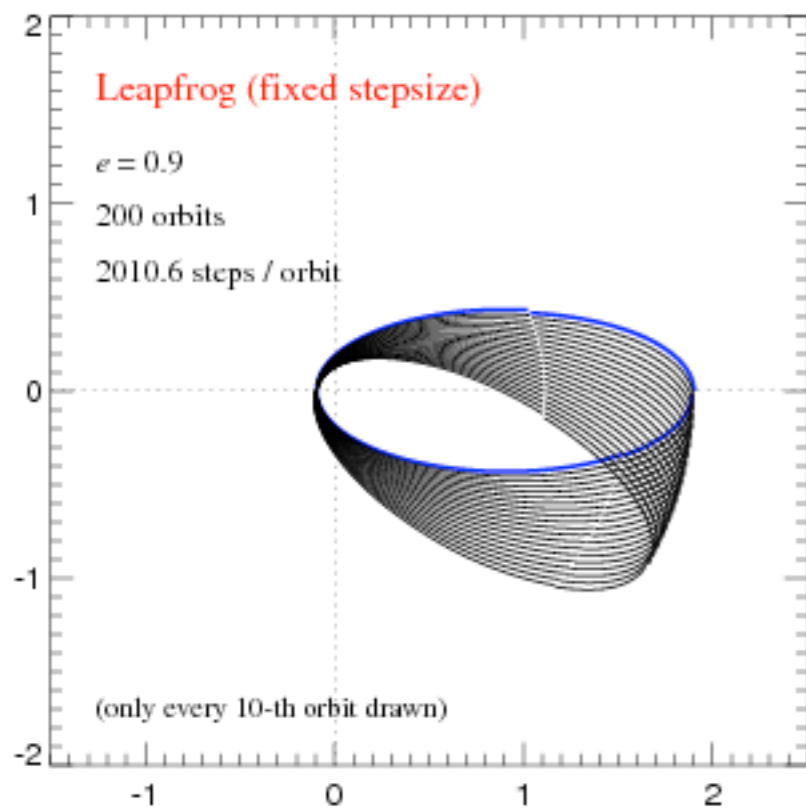
Preserving the geometric properties of an orbit !!!

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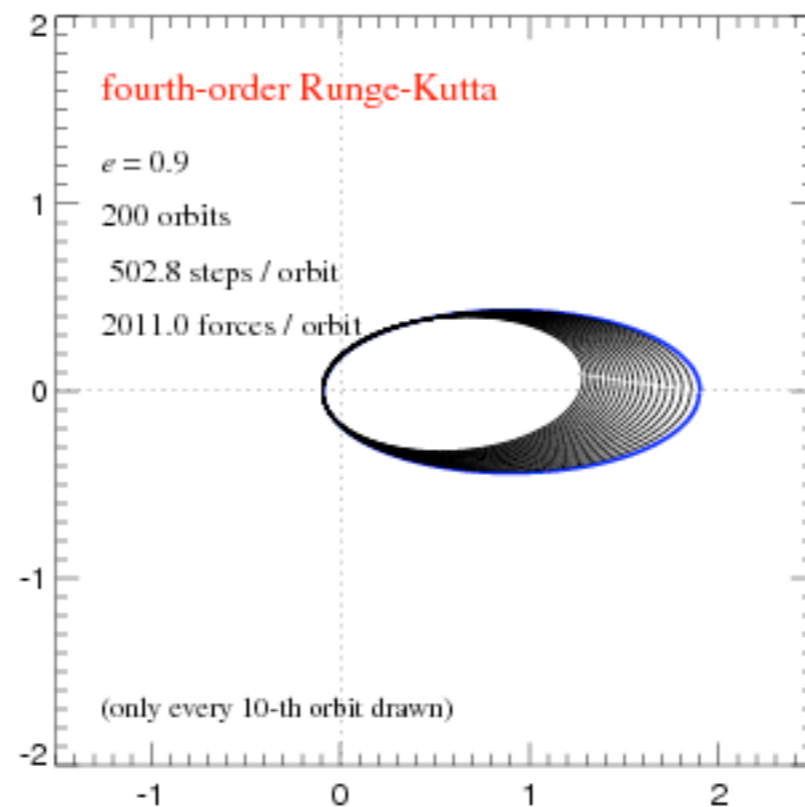
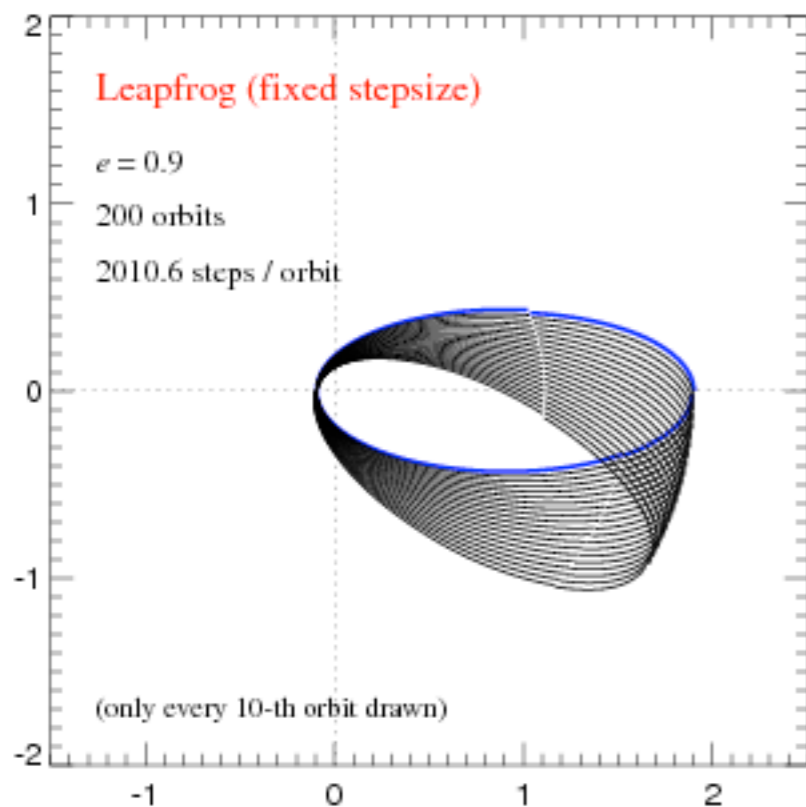
Springel 2005

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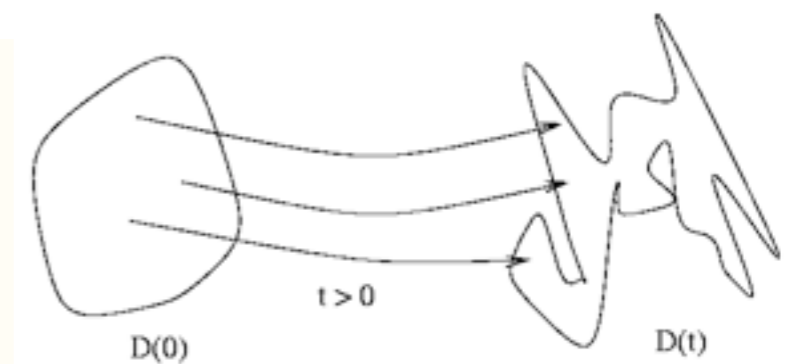
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Preserving the geometric properties of an orbit !!!



Springel 2005

Symplectic, Liouville theorem

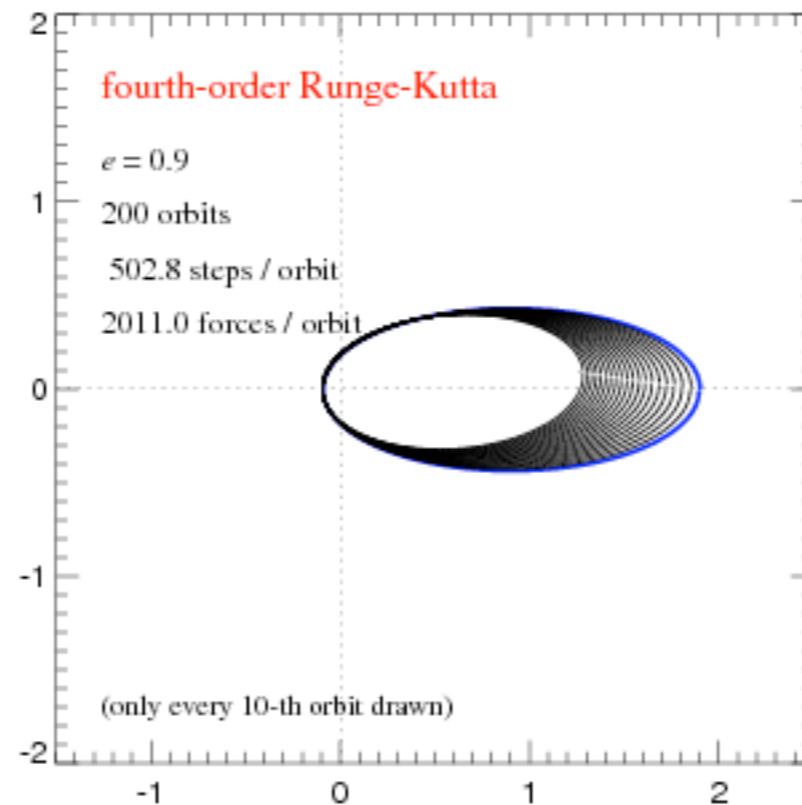
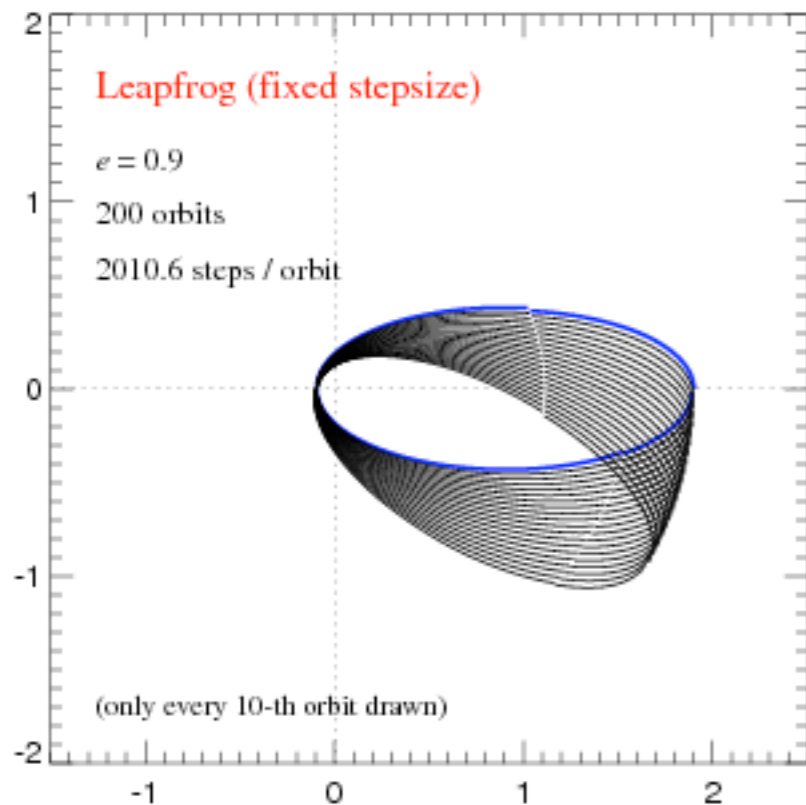


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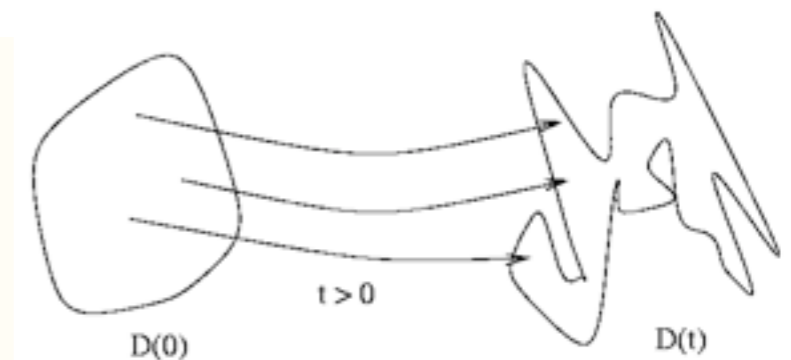
Springel 2005

Symplectic, Liouville theorem

Mapping $\{q_{n+1}, p_{n+1}\} = f(q_n, p_n)$, $dV_{n+1} = M V_n$

M: Jacobian matrix, $|M| = 1$

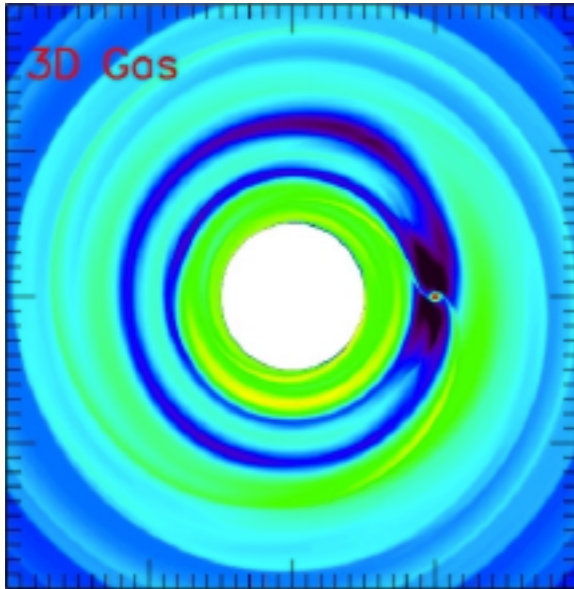
(the area in phase space is preserved)



Planet-Disk Interaction: ``4'' Dimension Simulations

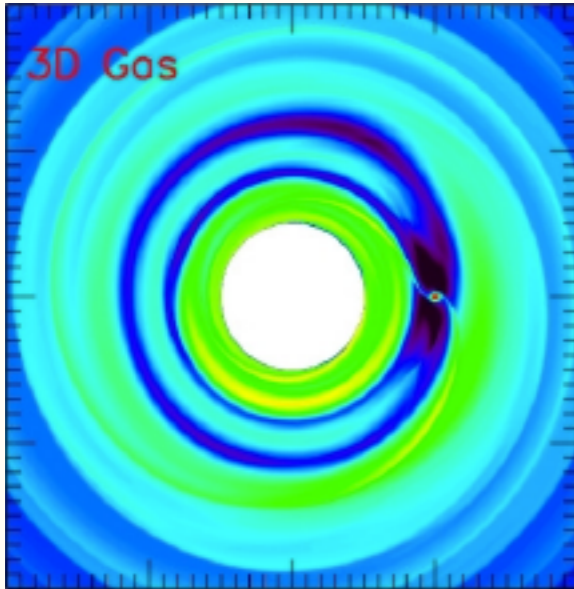
Planet-Disk Interaction: ``4'' Dimension Simulations

gas

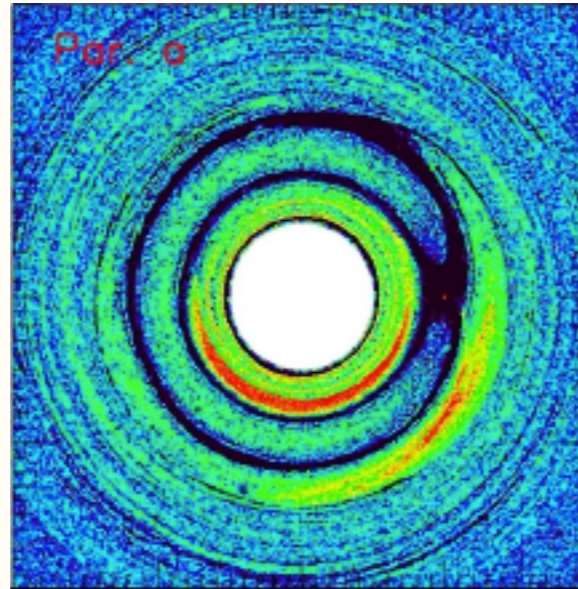


Planet-Disk Interaction: ``4'' Dimension Simulations

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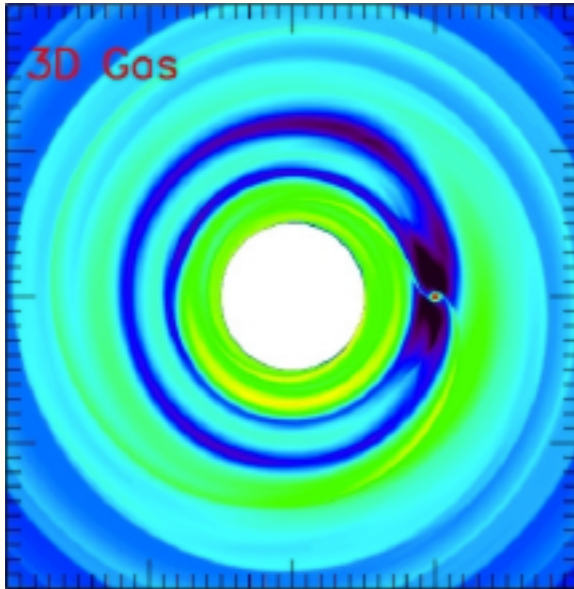


100 μm

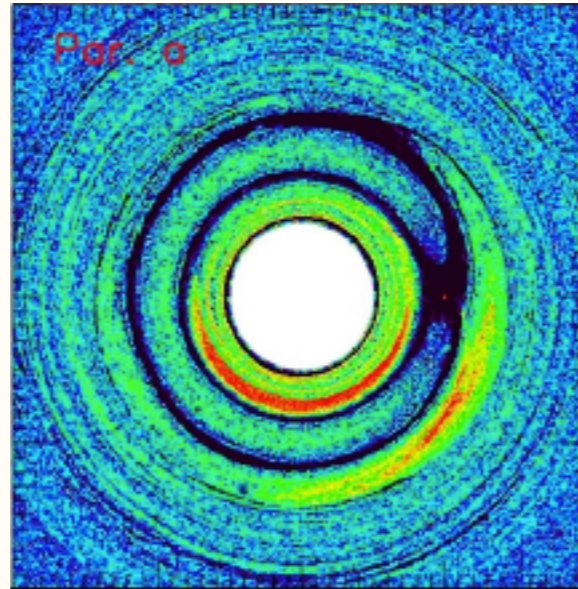


Planet-Disk Interaction: ``4'' Dimension Simulations

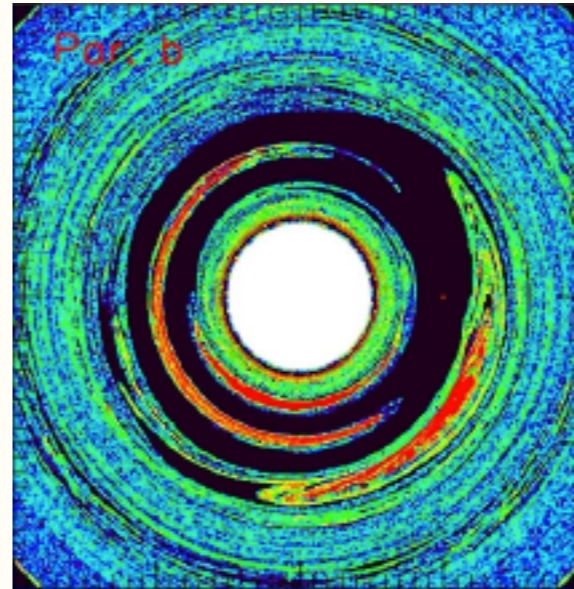
gas



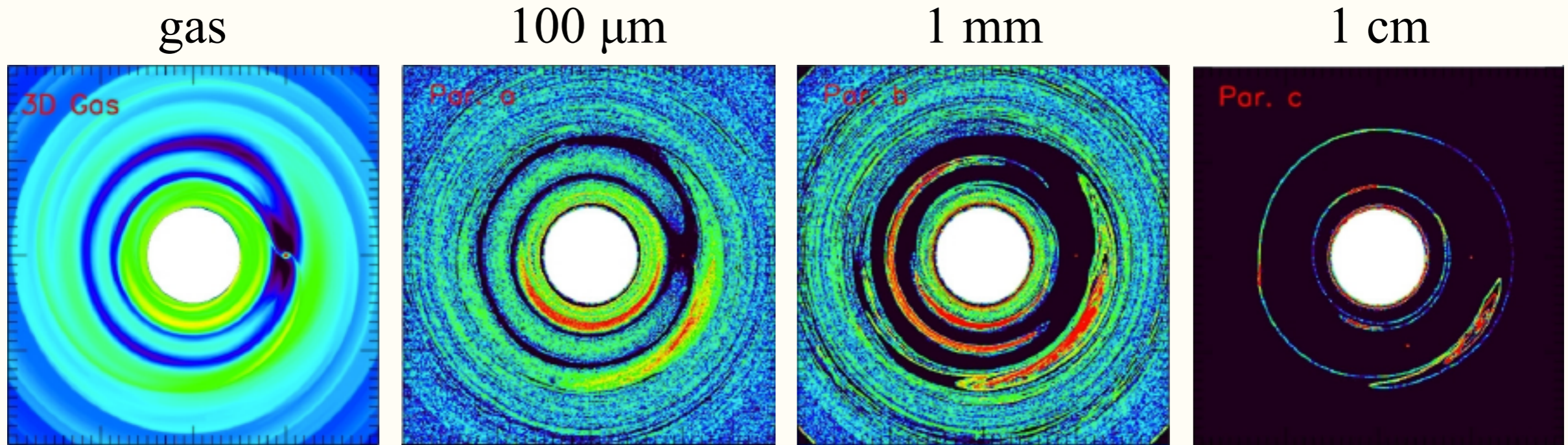
100 μm



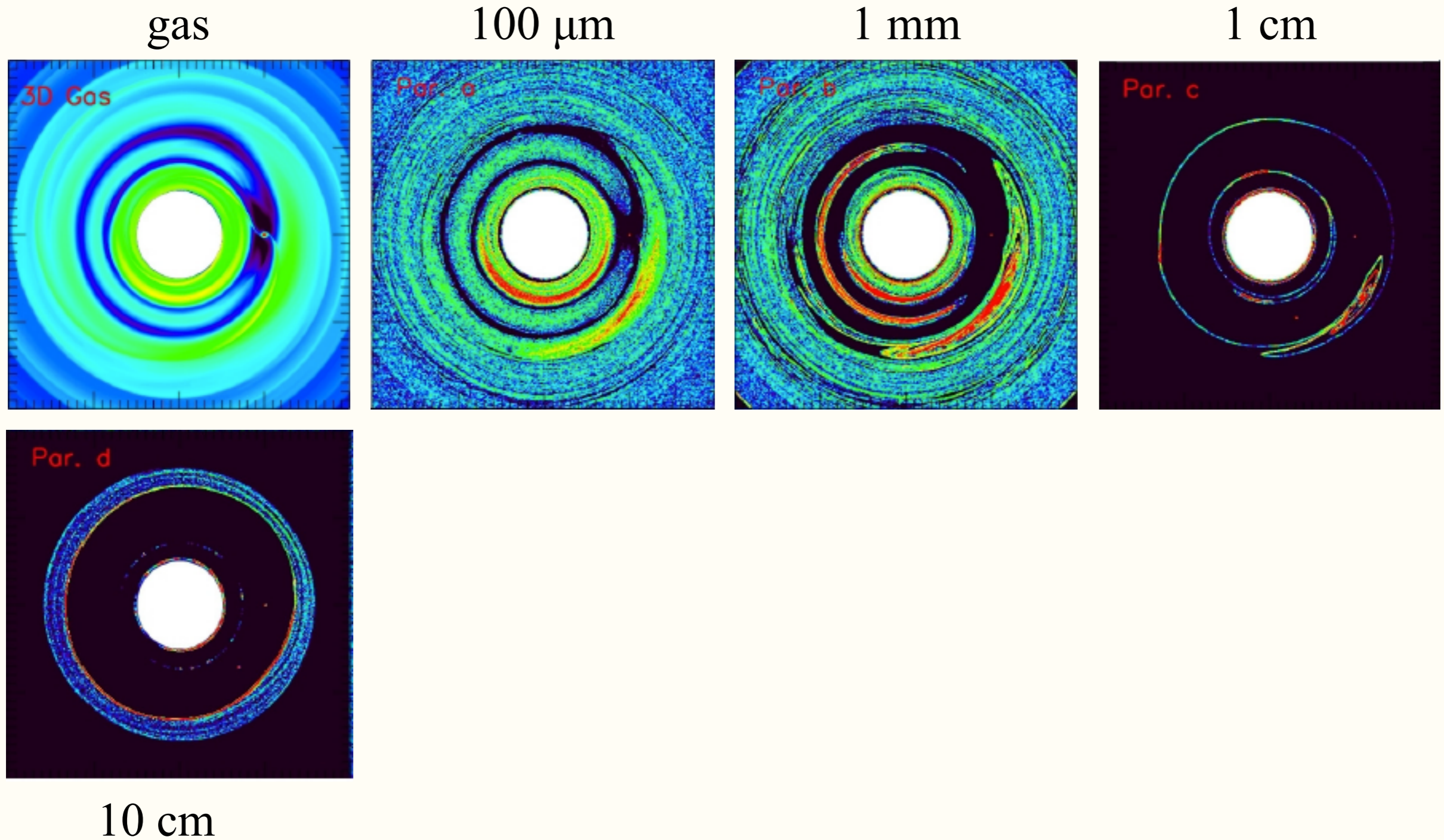
1 mm



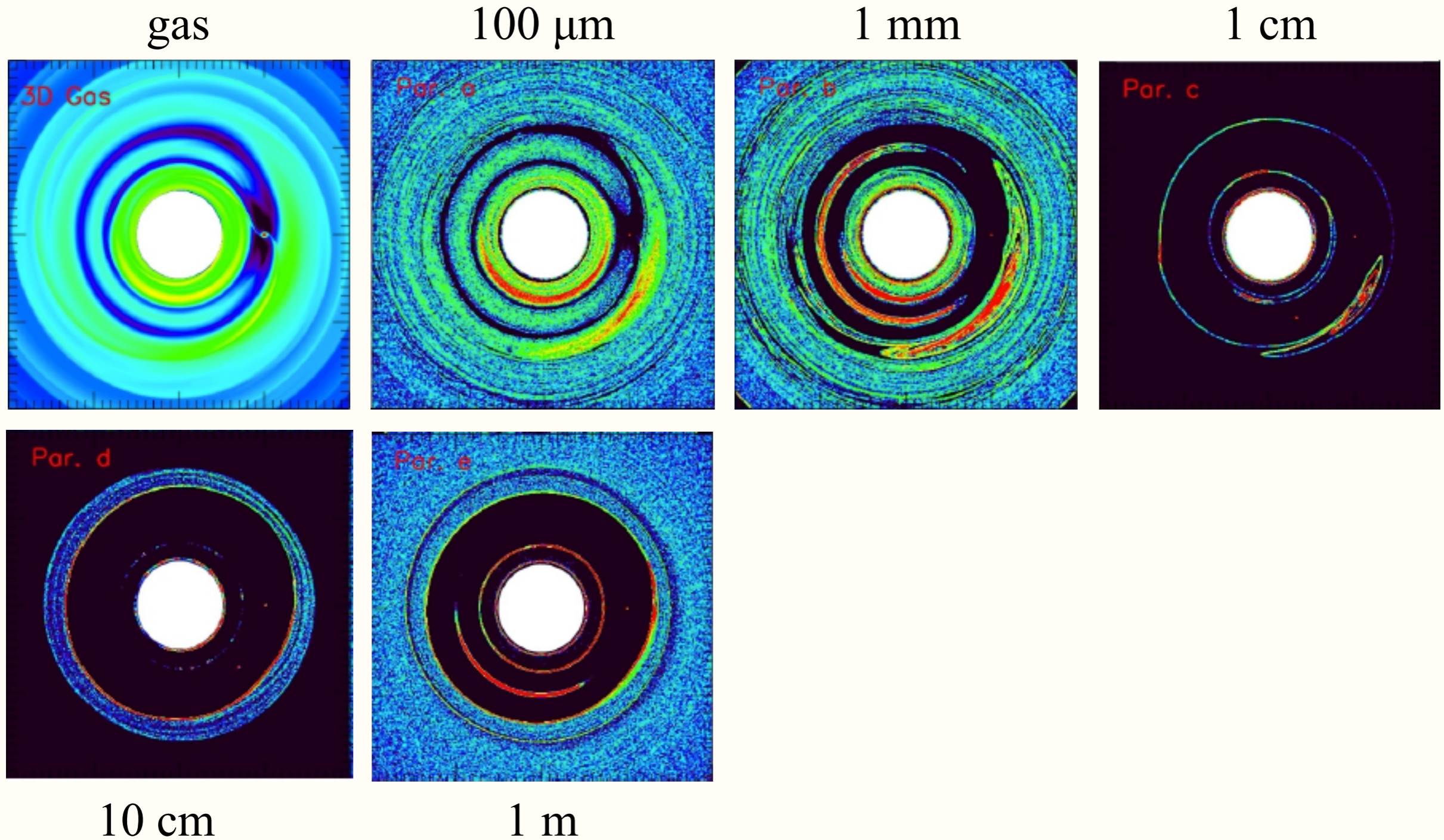
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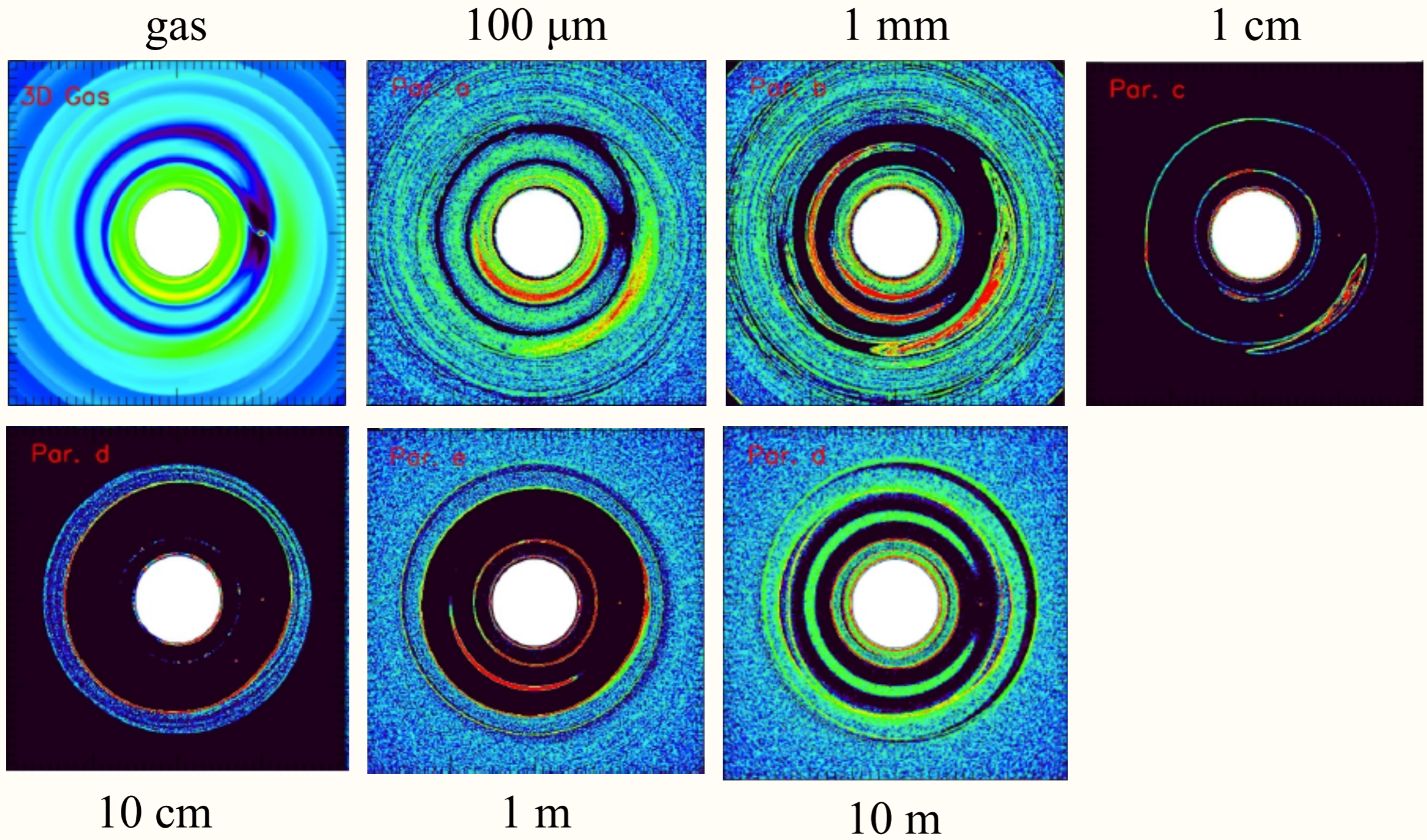
Planet-Disk Interaction: ``4'' Dimension Simulations



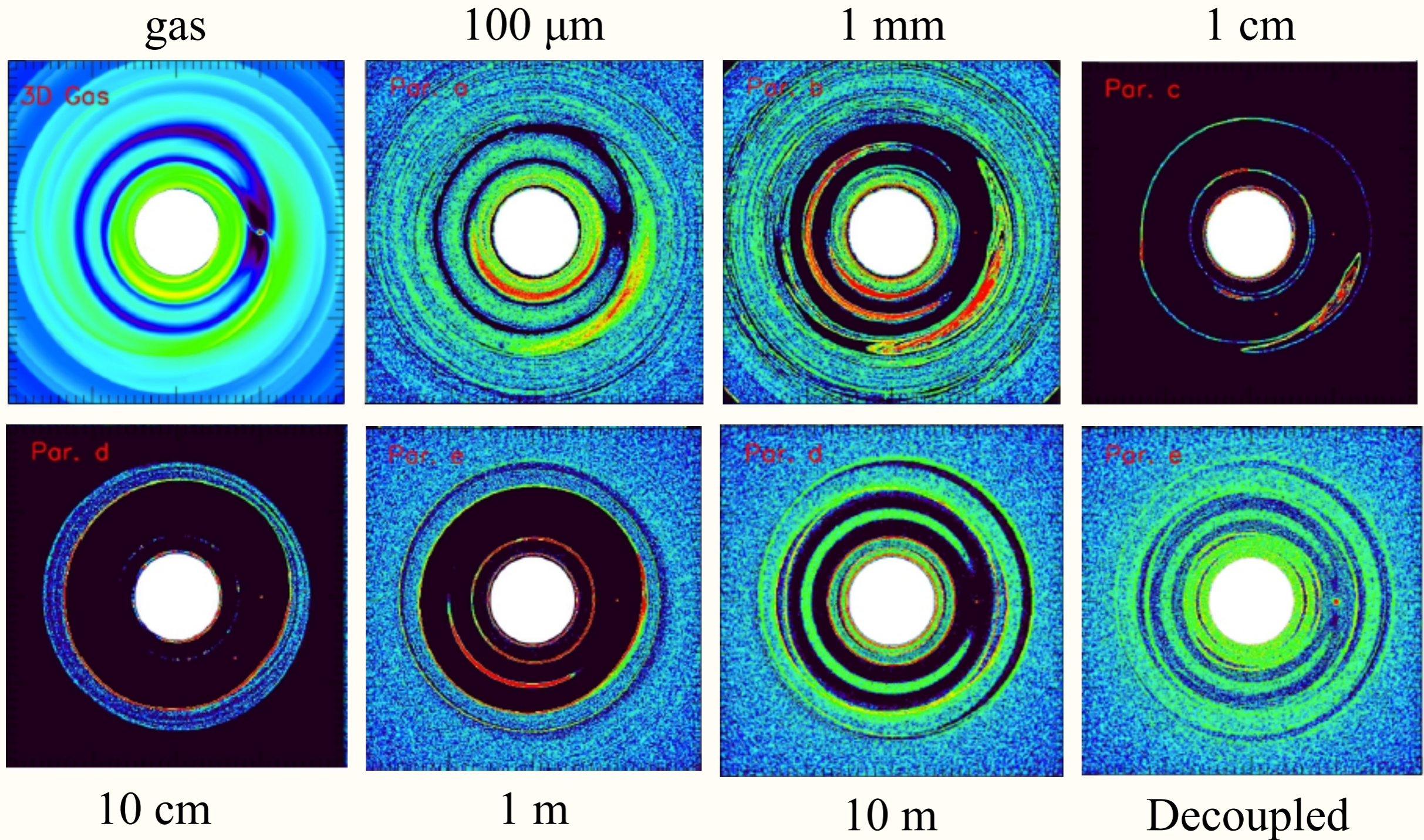
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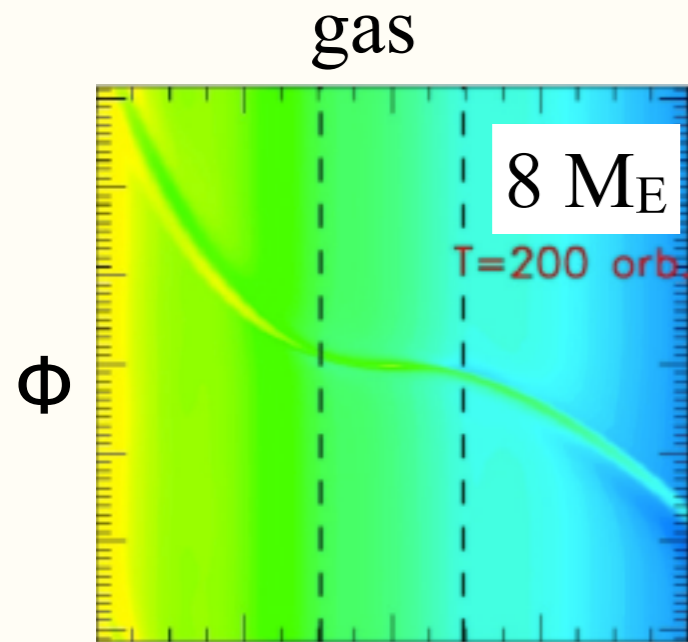


Planet-Disk Interaction: ``4'' Dimension Simulations



Shallow Gaseous Gaps but Deep Particle Gaps

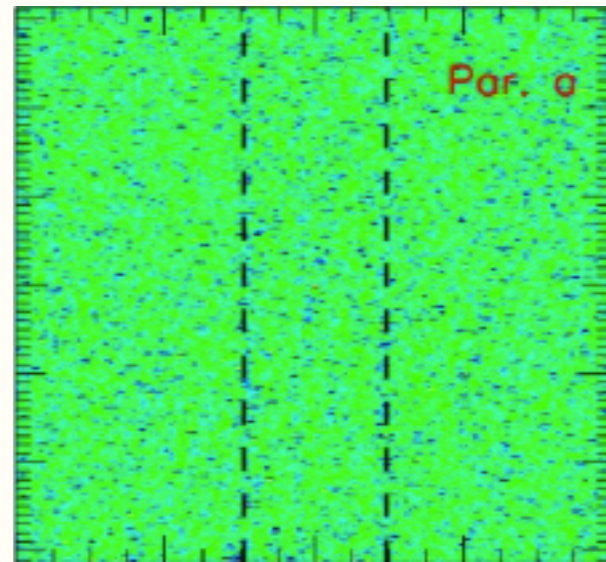
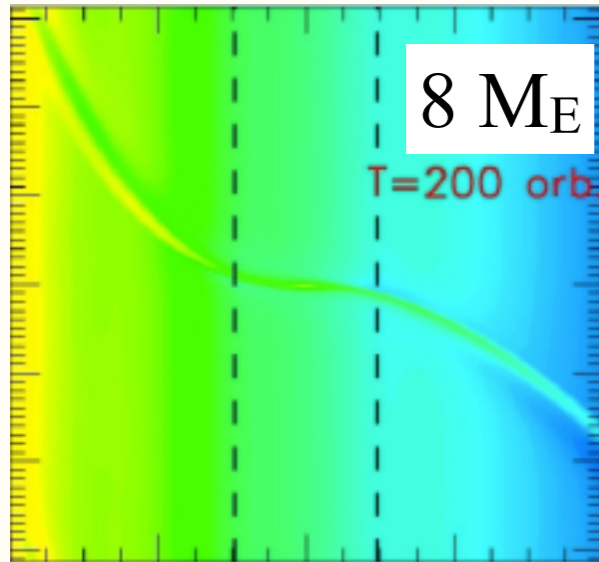
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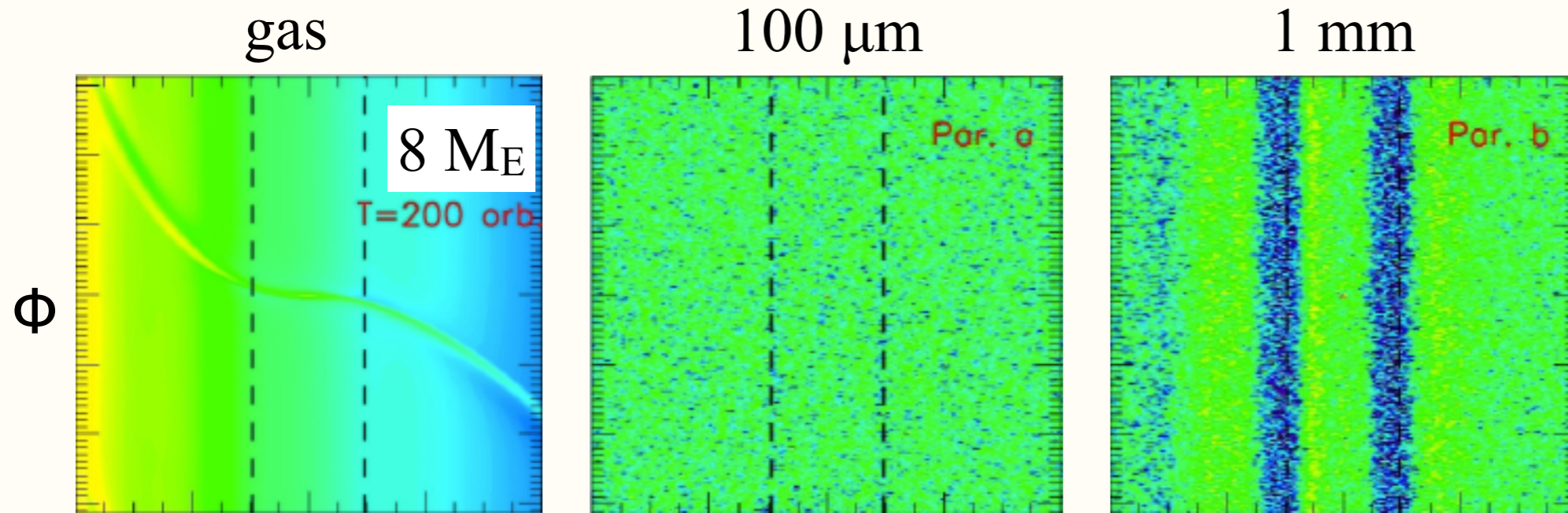
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gas

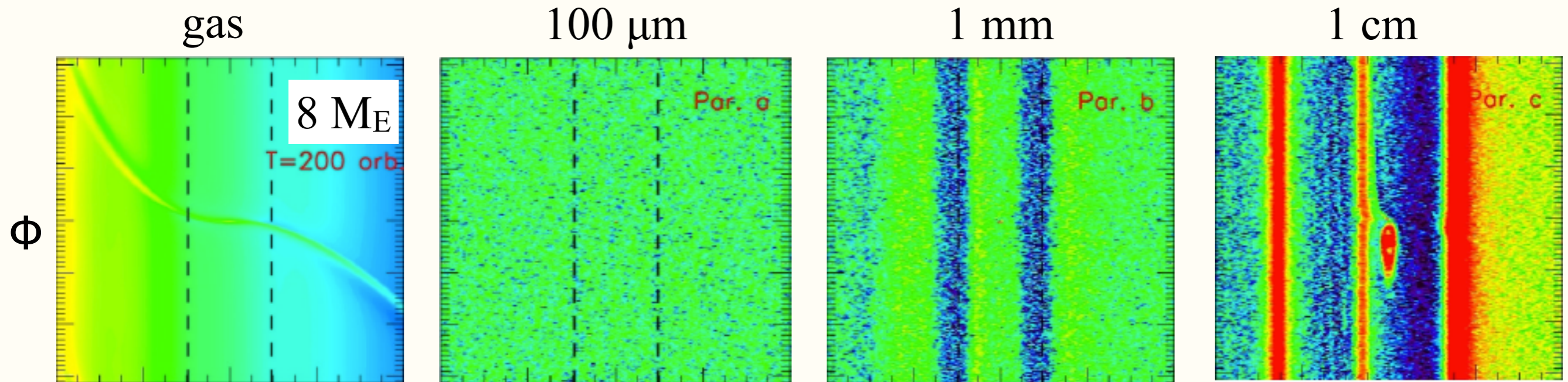
100 μm



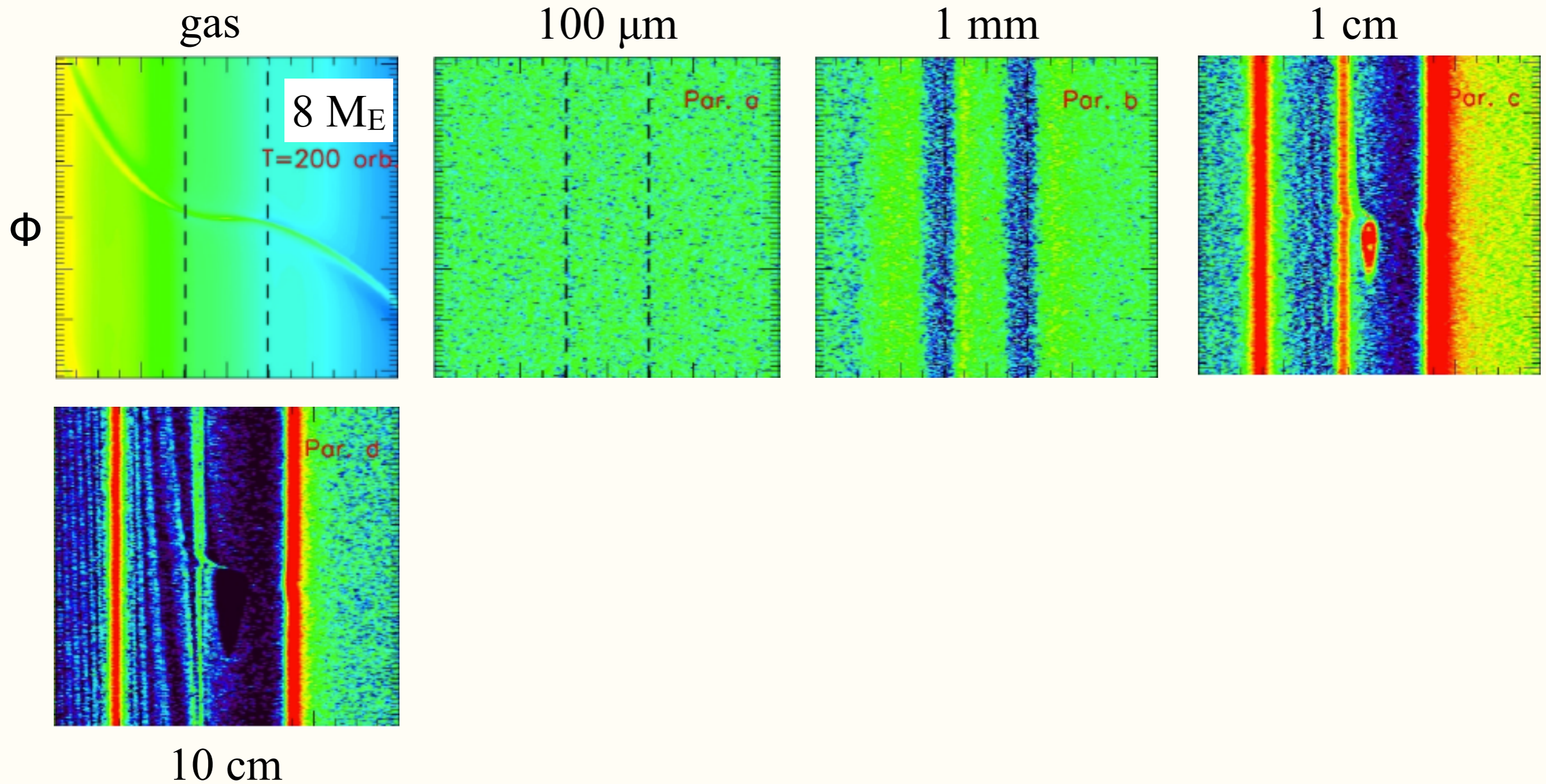
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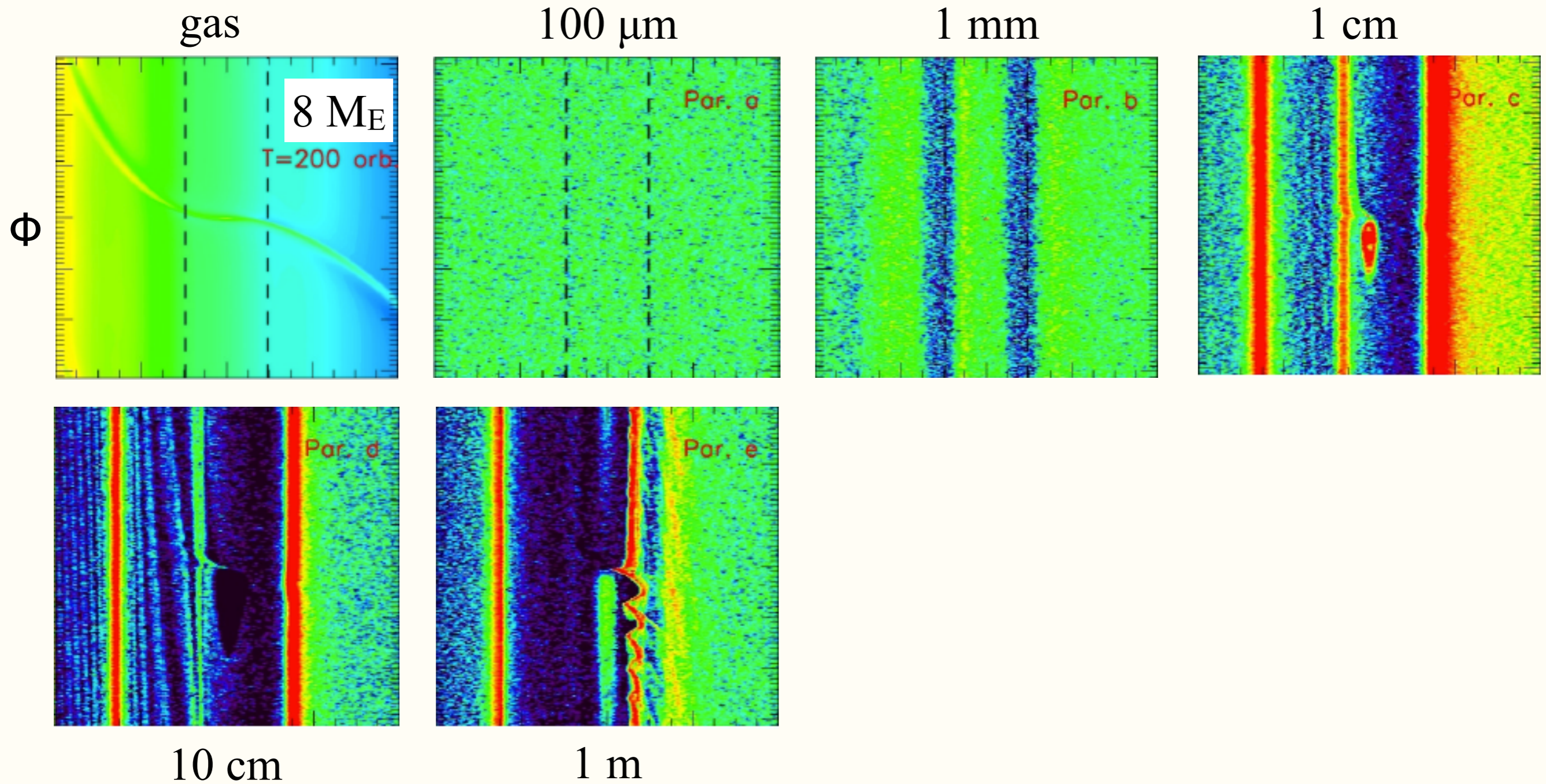
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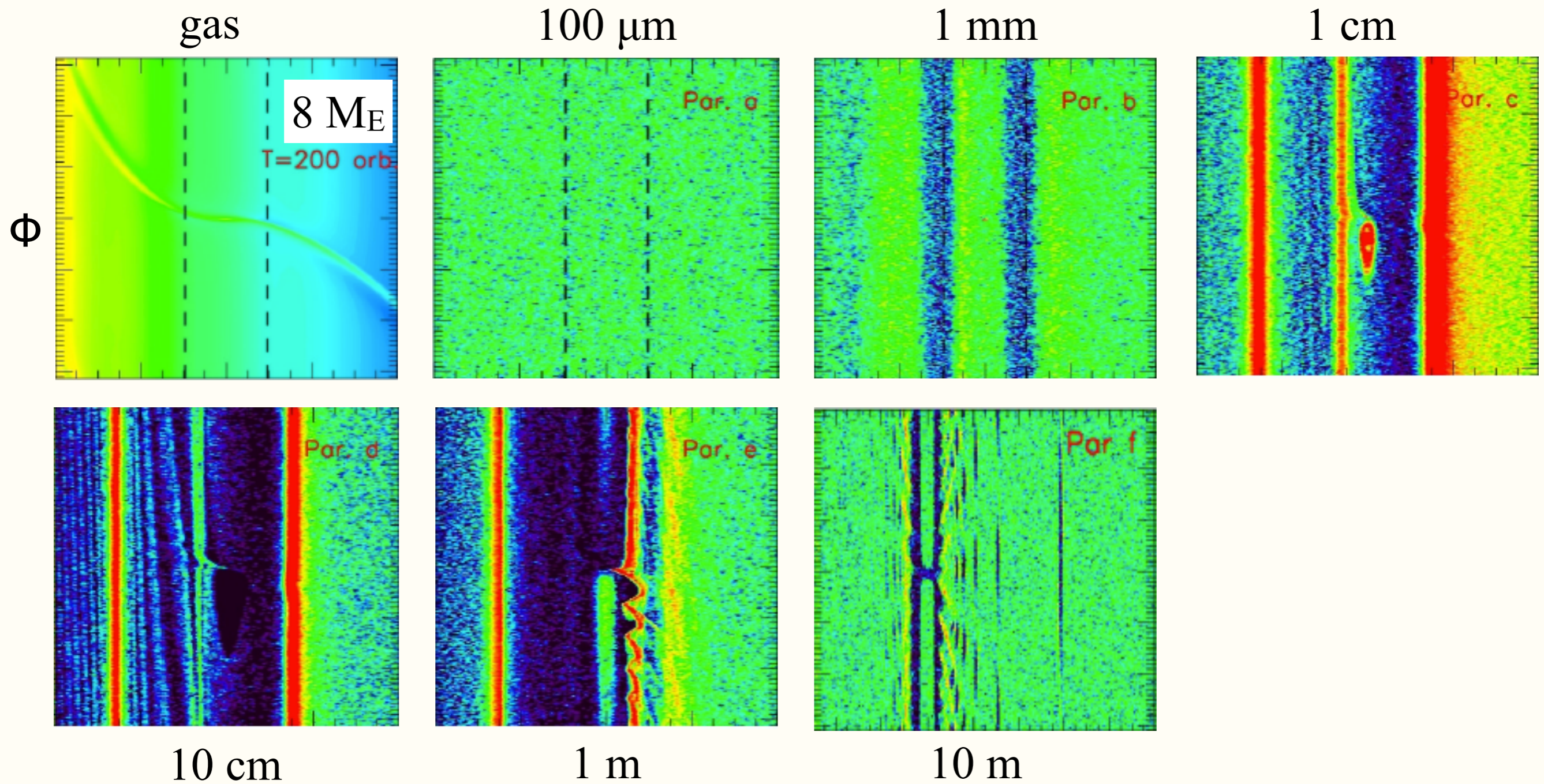
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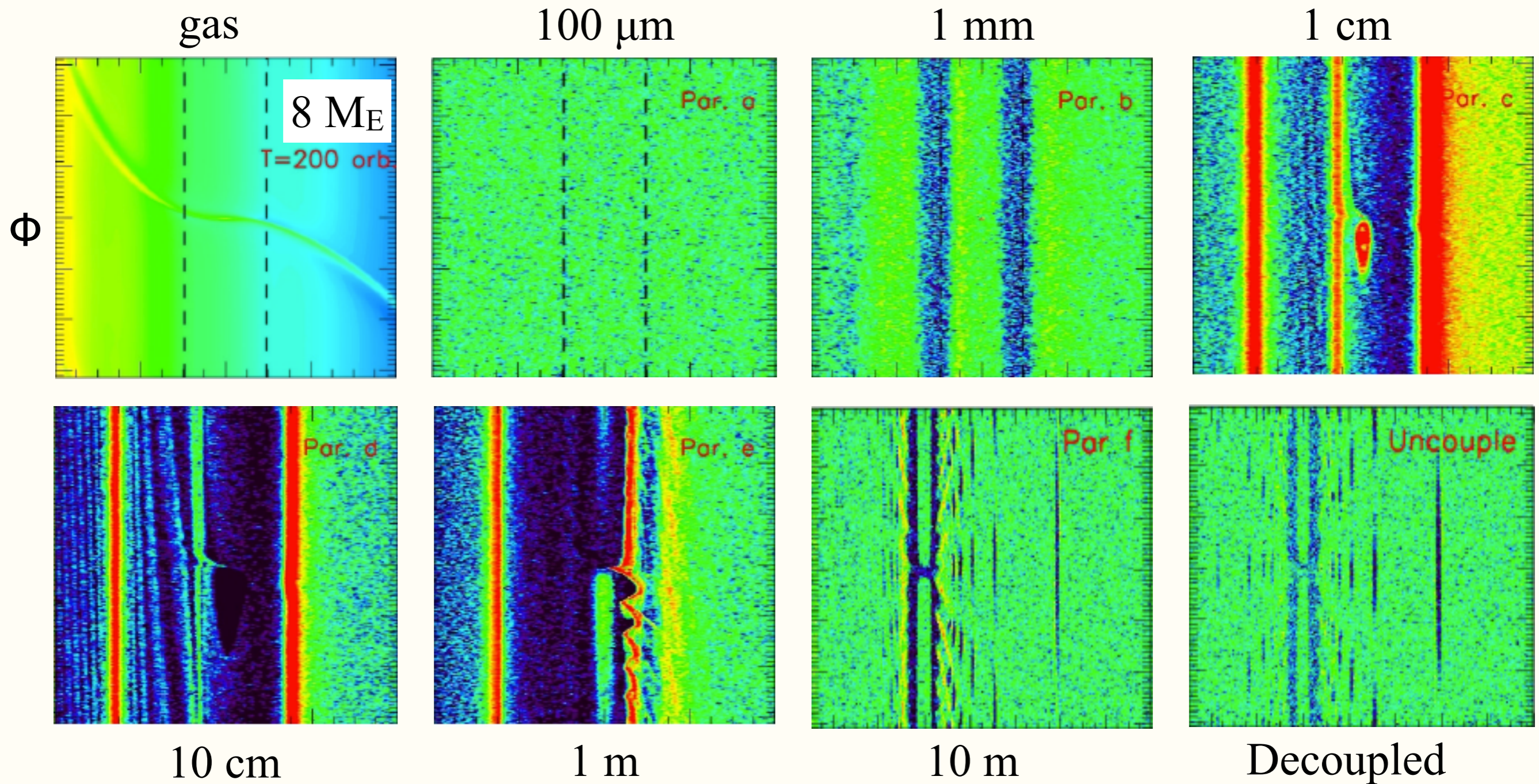
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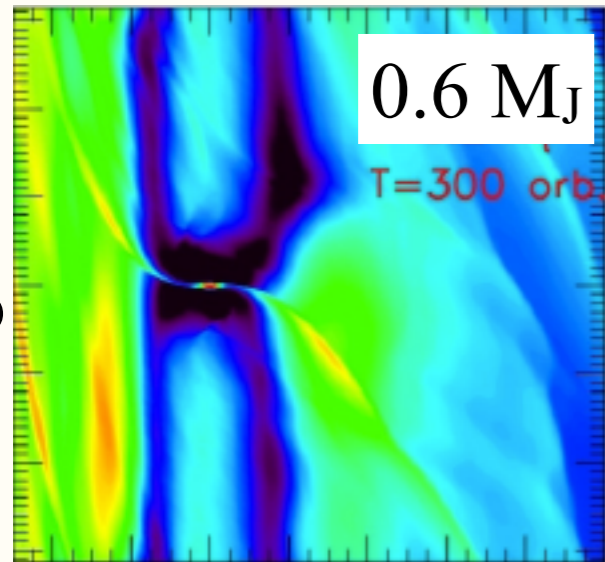


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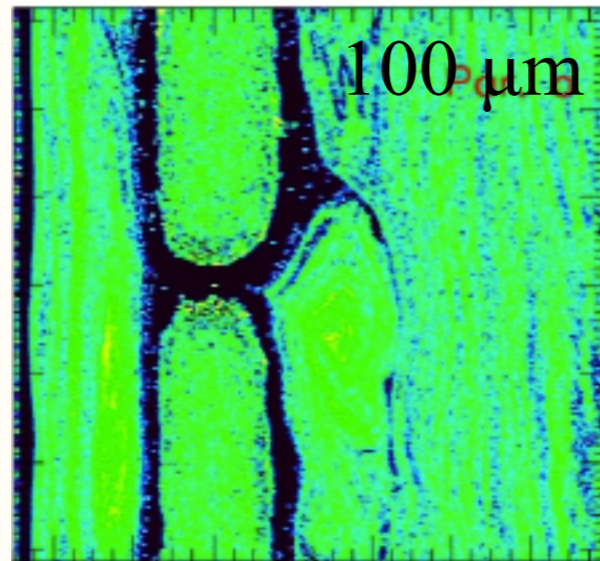
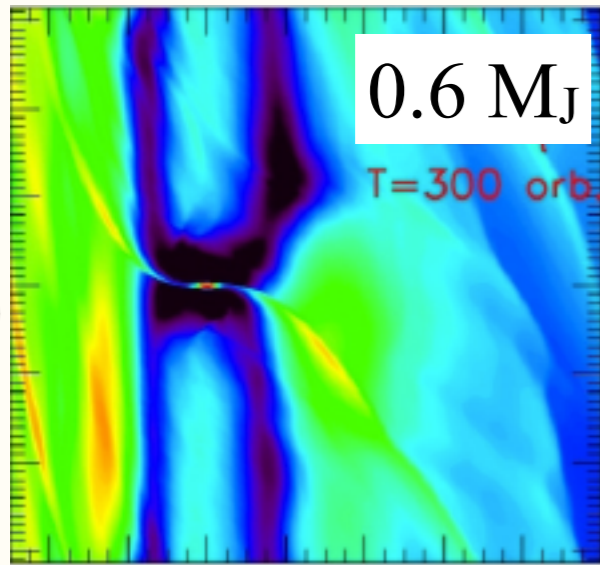


Deep Gaseous Gaps: Particles trapping in Vortex

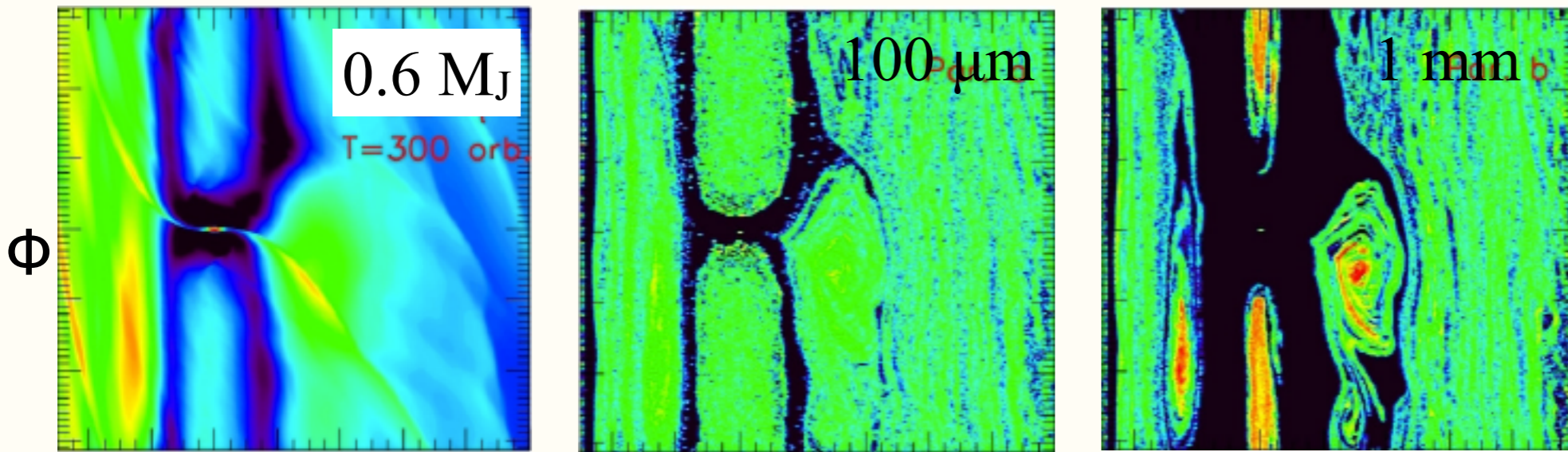
Deep Gaseous Gaps: Particles trapping in Vortex



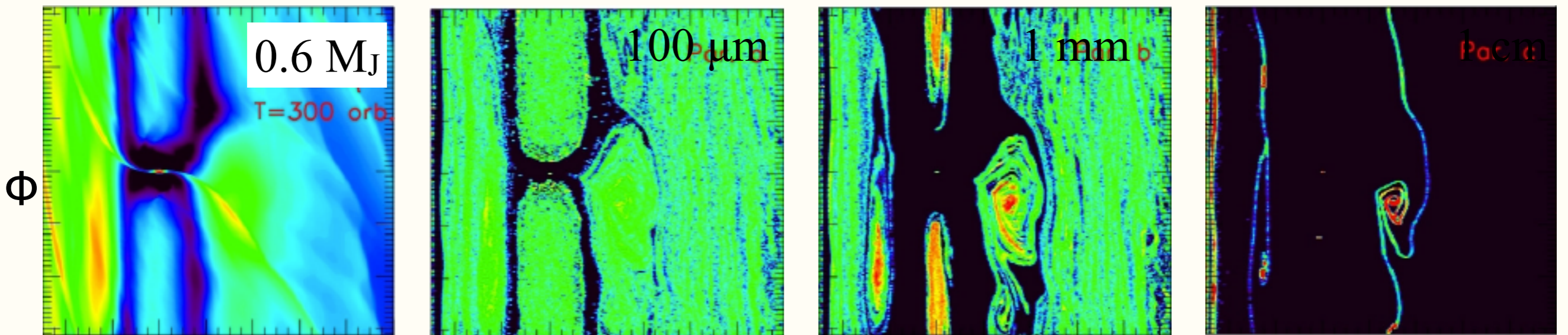
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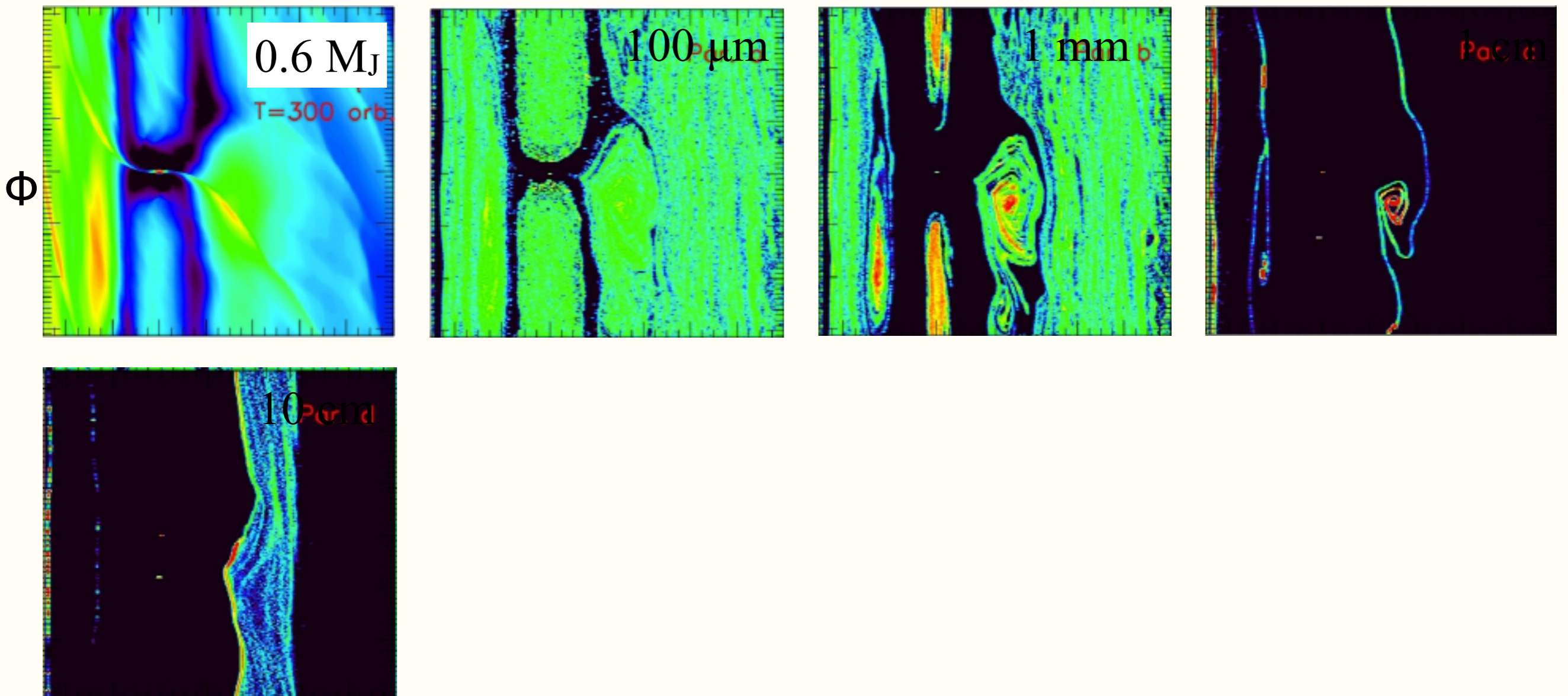
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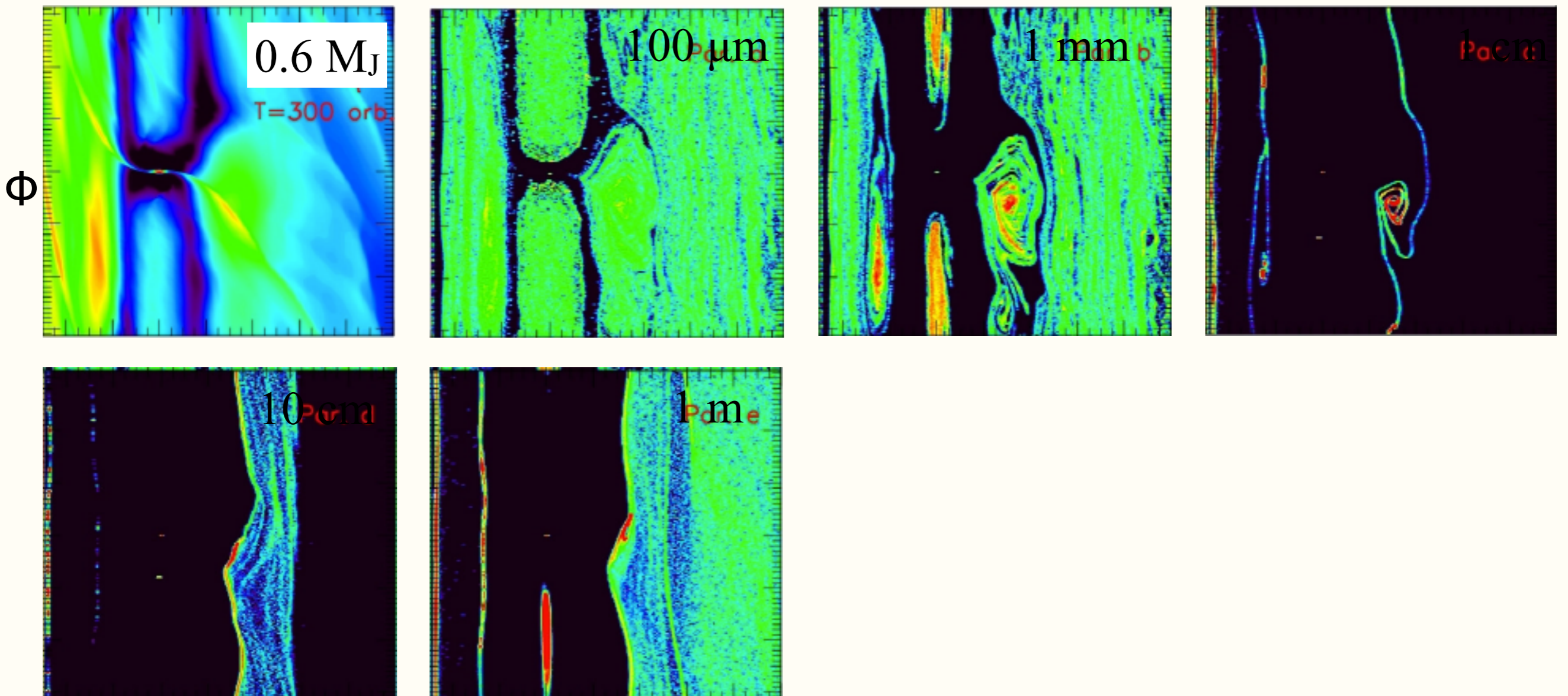
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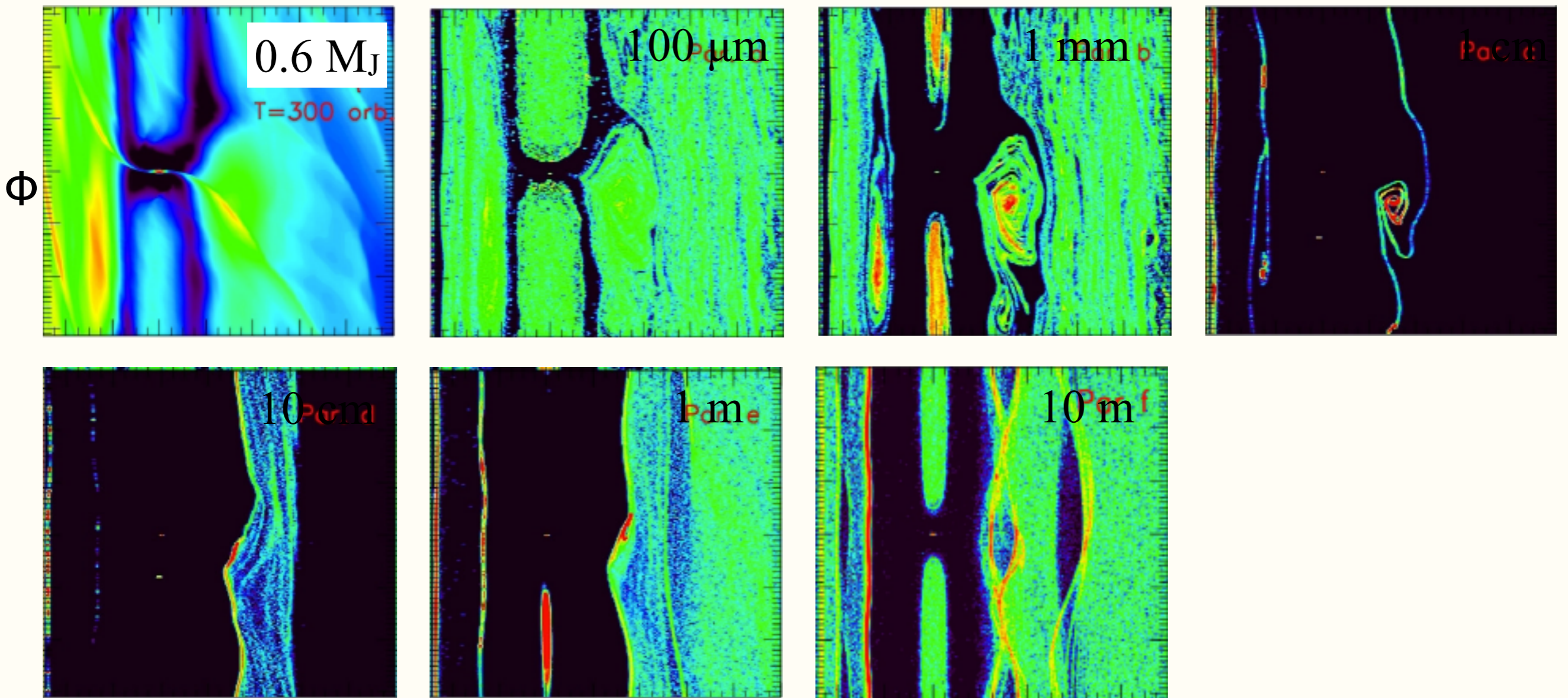
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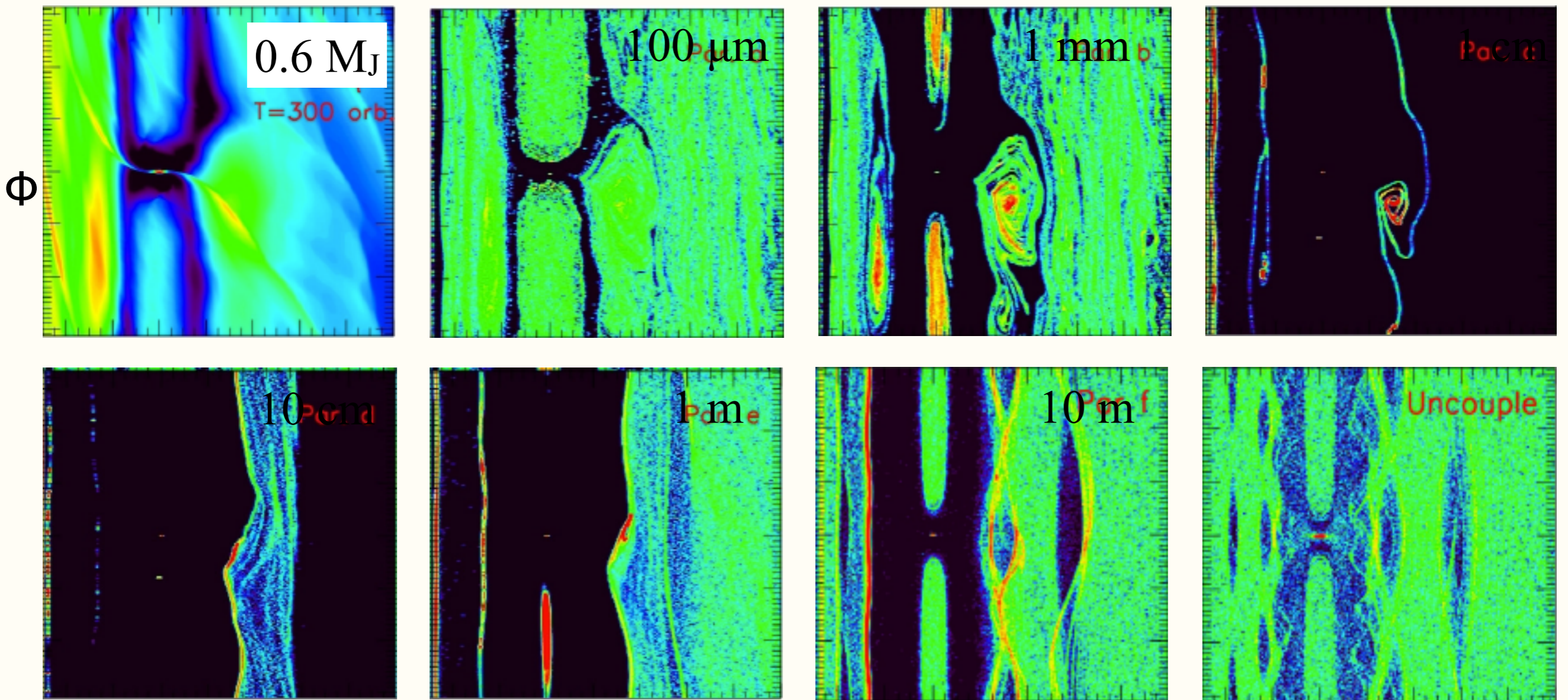
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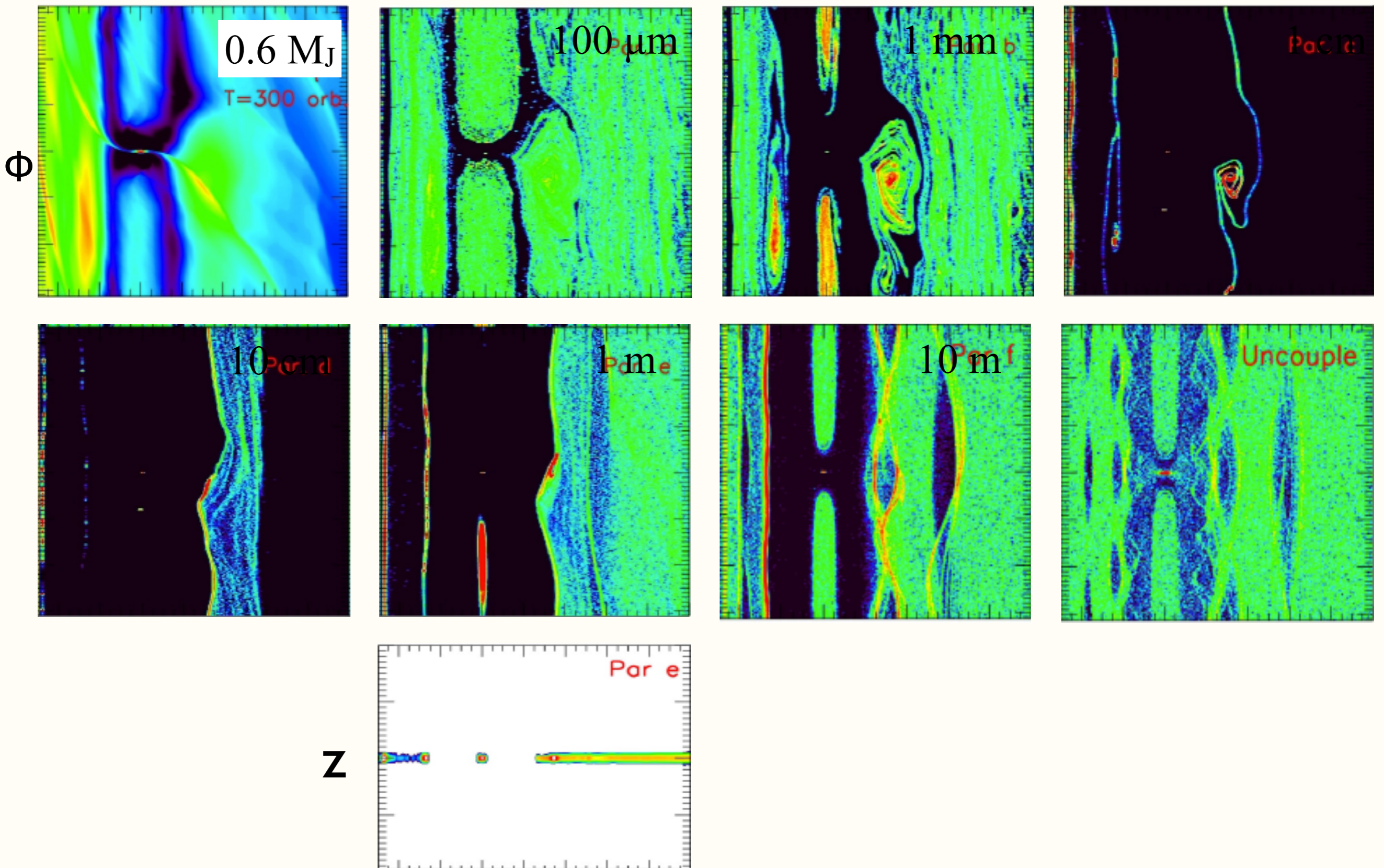
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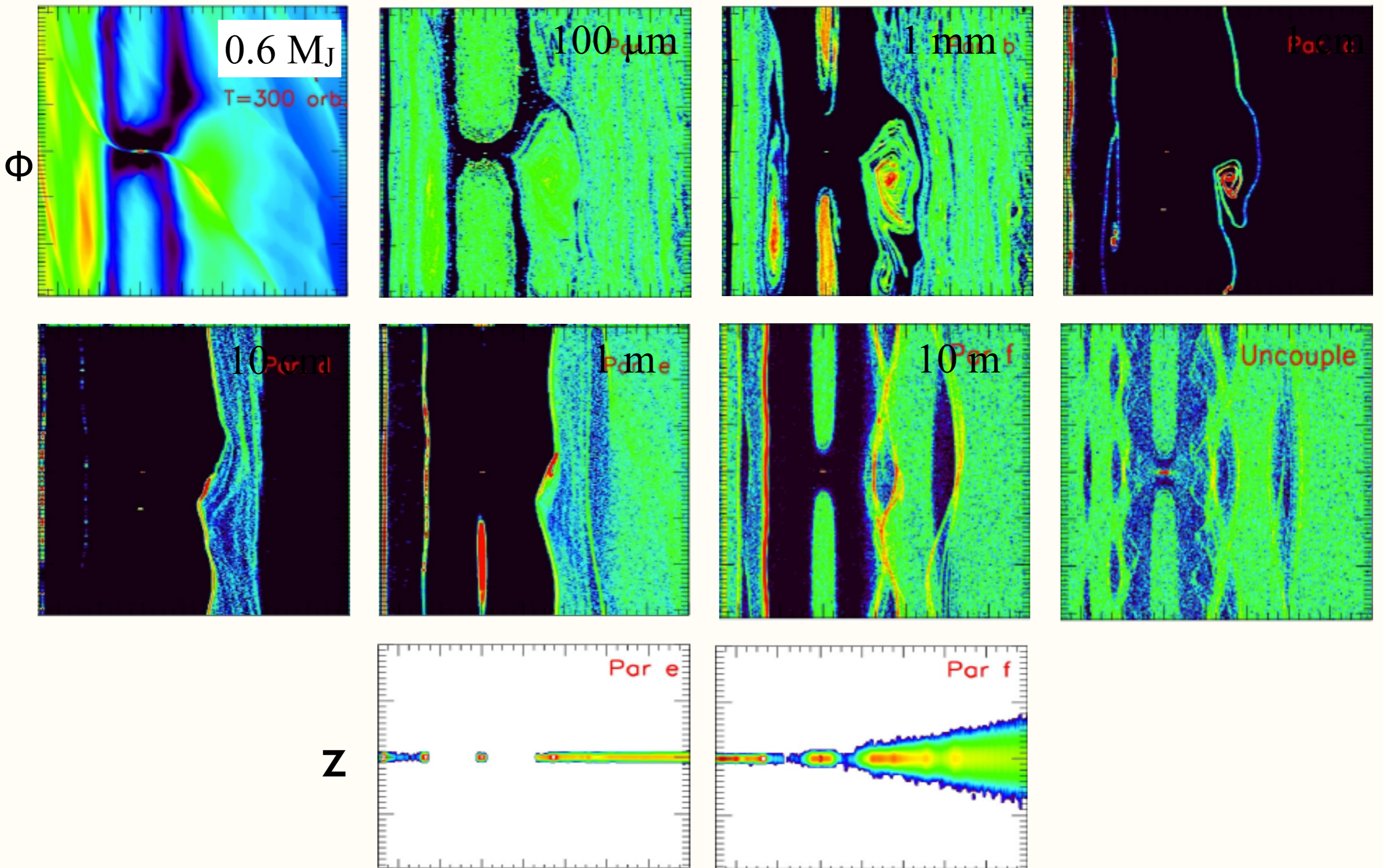
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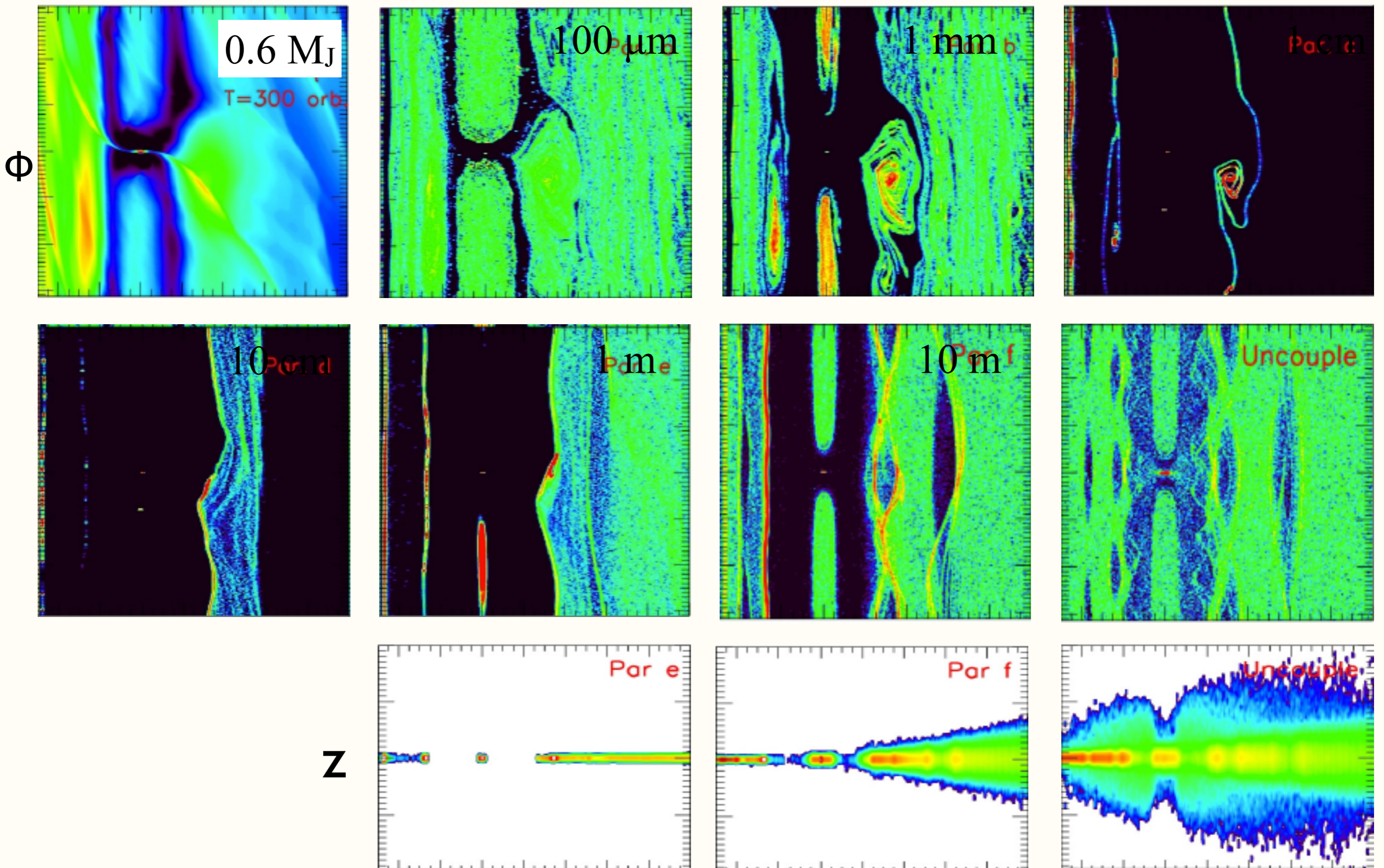
Deep Gaseous Gaps: Particles trapping in Vortex



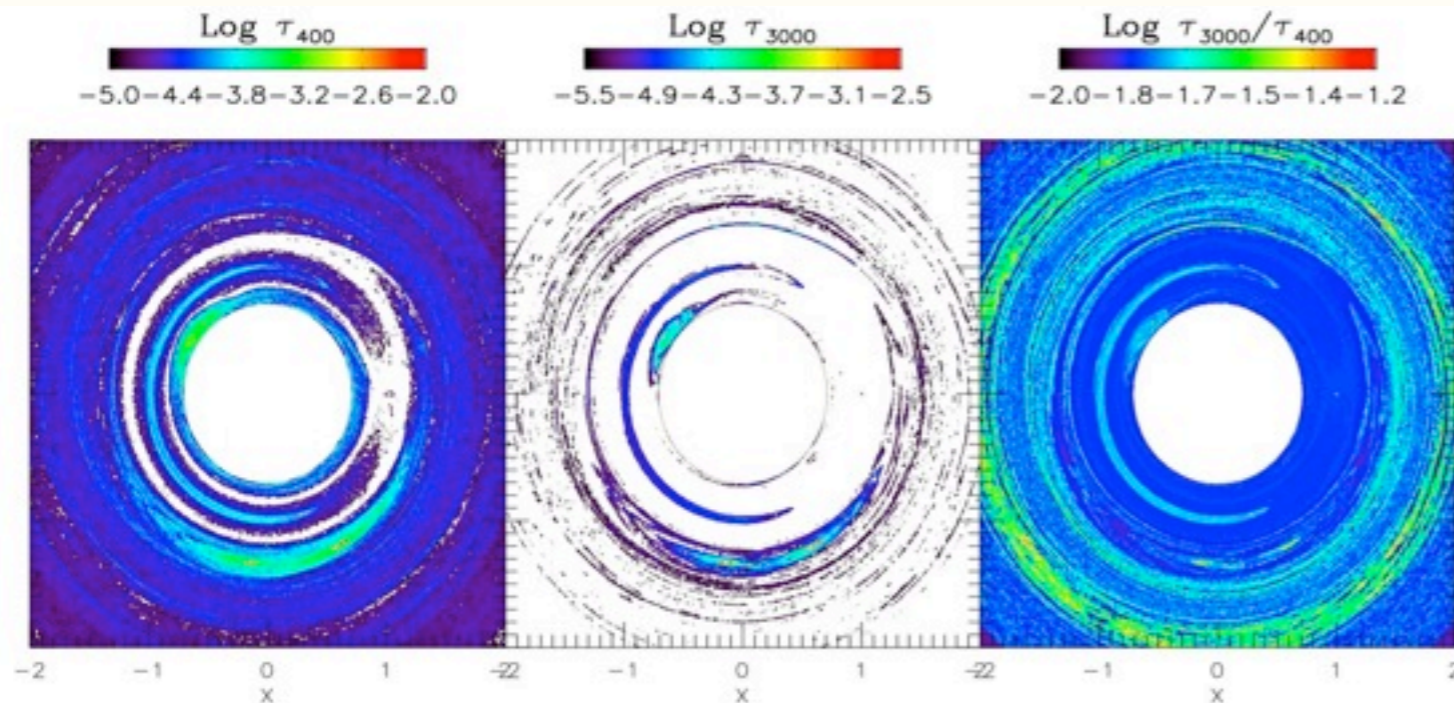
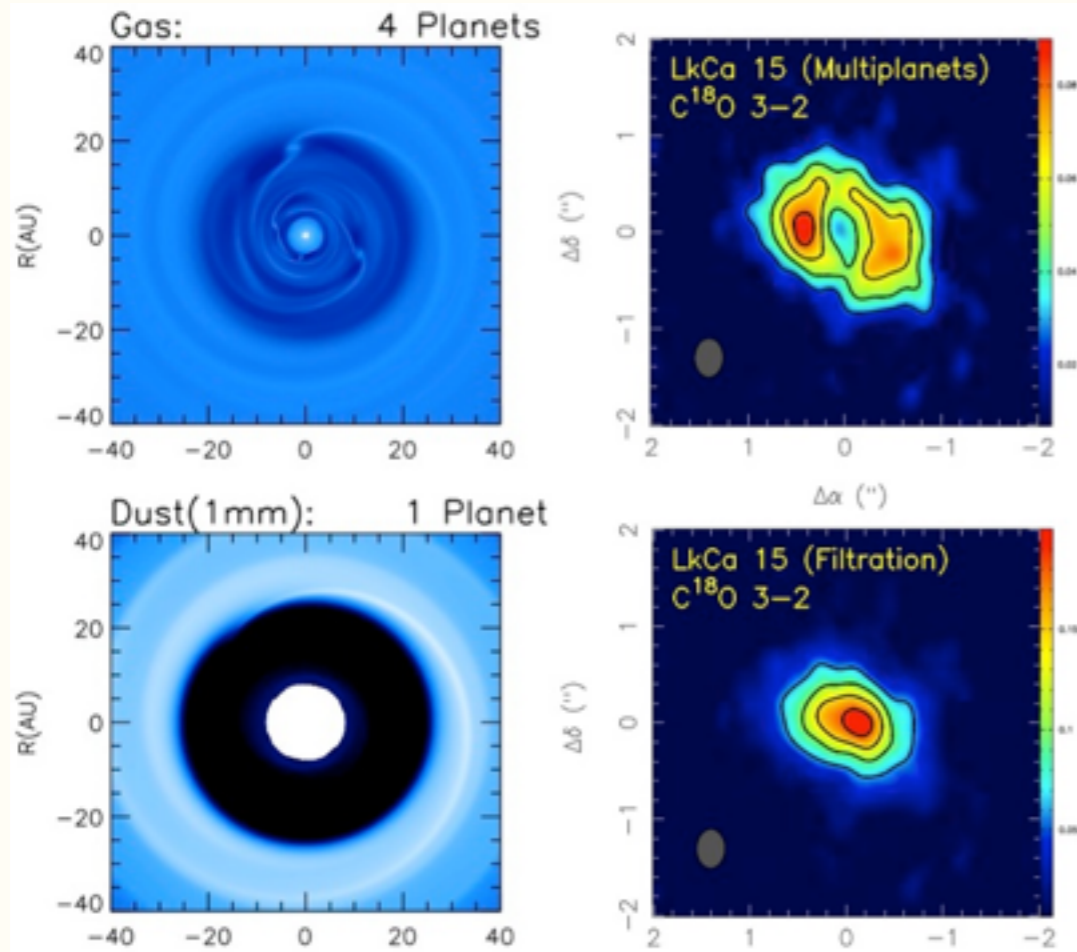
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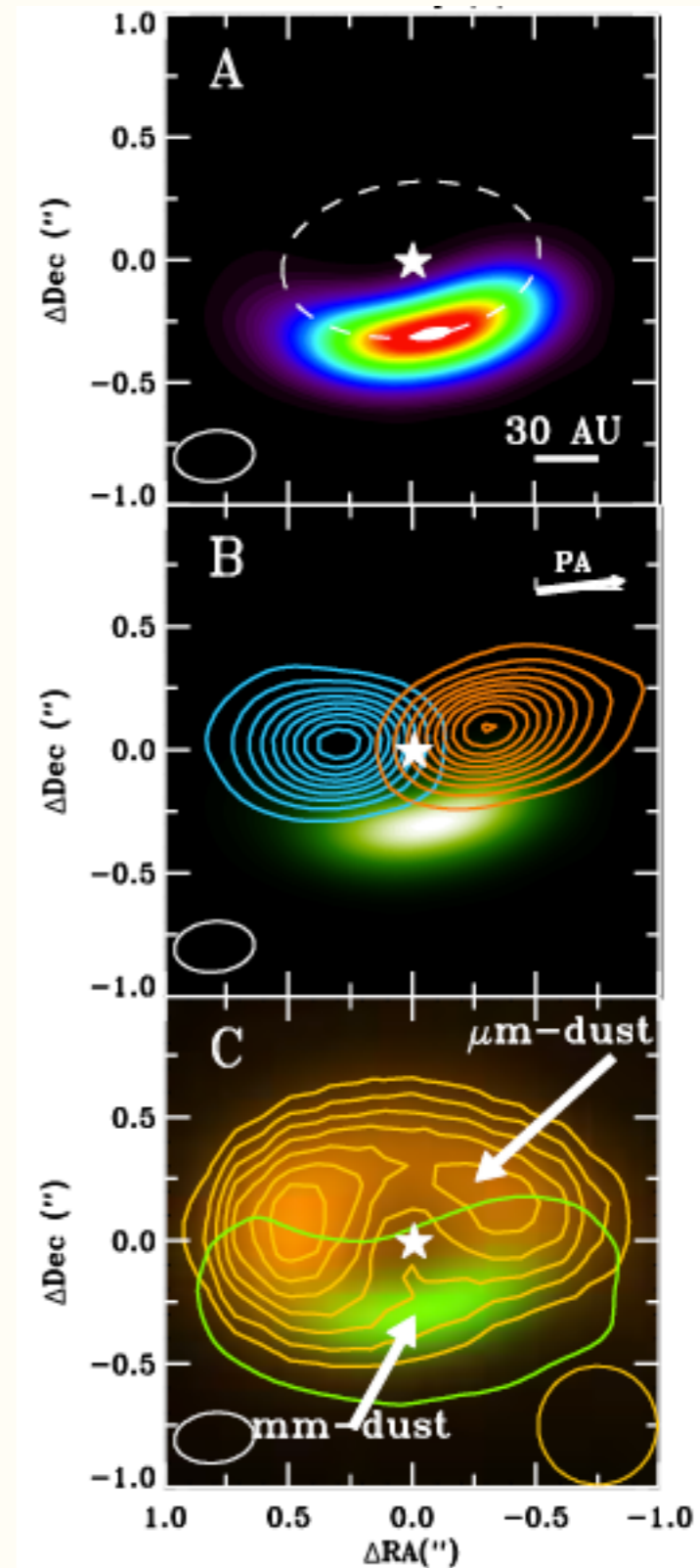
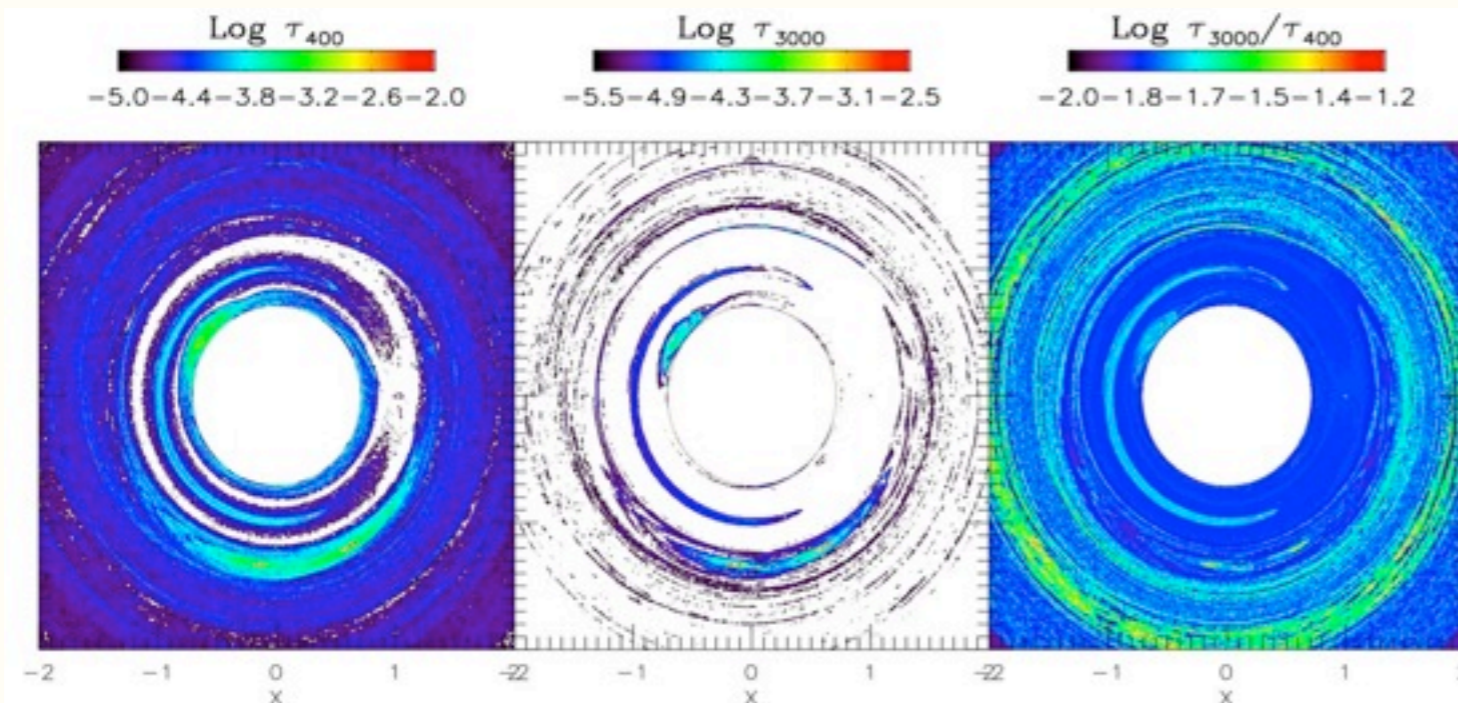
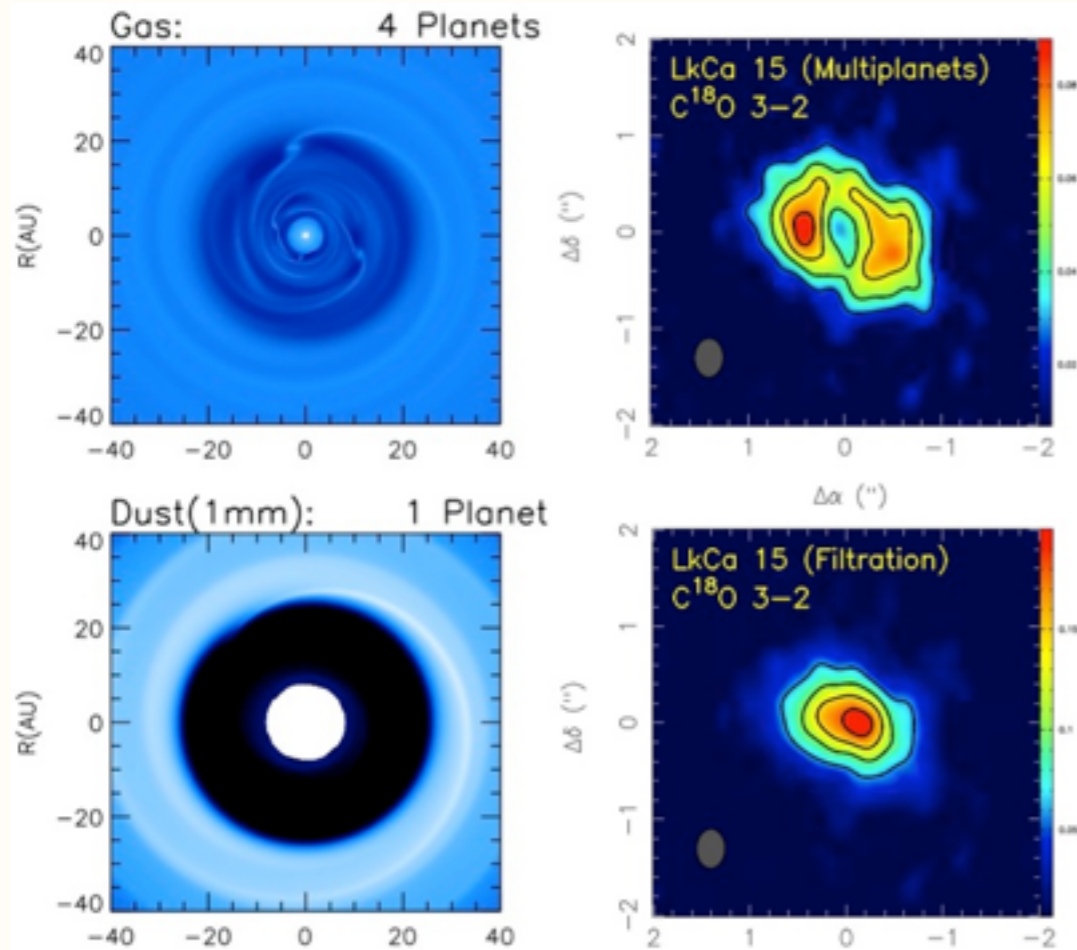
Deep Gaseous Gaps: Particles trapping in Vortex



Predictions for ALMA



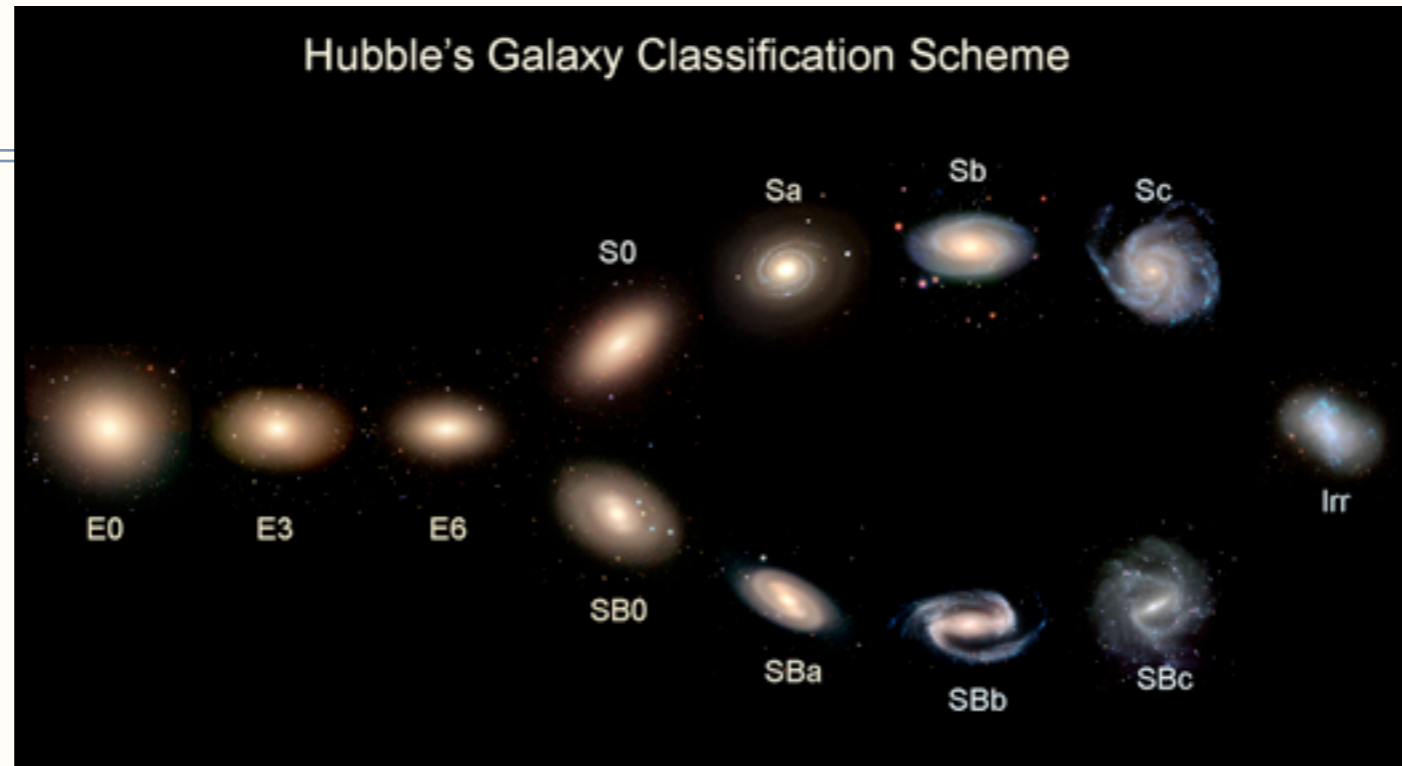
Predictions for ALMA



Outlines

- Planets are Common
- Gap opening process
 - Gap opening in inviscid disks.
 - Gap opening in MRI-turbulent disks.
- Transitional disks are candidates for harboring young planets and they start to reveal rich physics.
- Dust particle dynamics during planet-disk interaction is essential for connecting with observations to find young planets.

Future



Future

