Dynamics of Dust-Gas Interactions in Protoplanetary Disks and Implications for Planetesimal Formation

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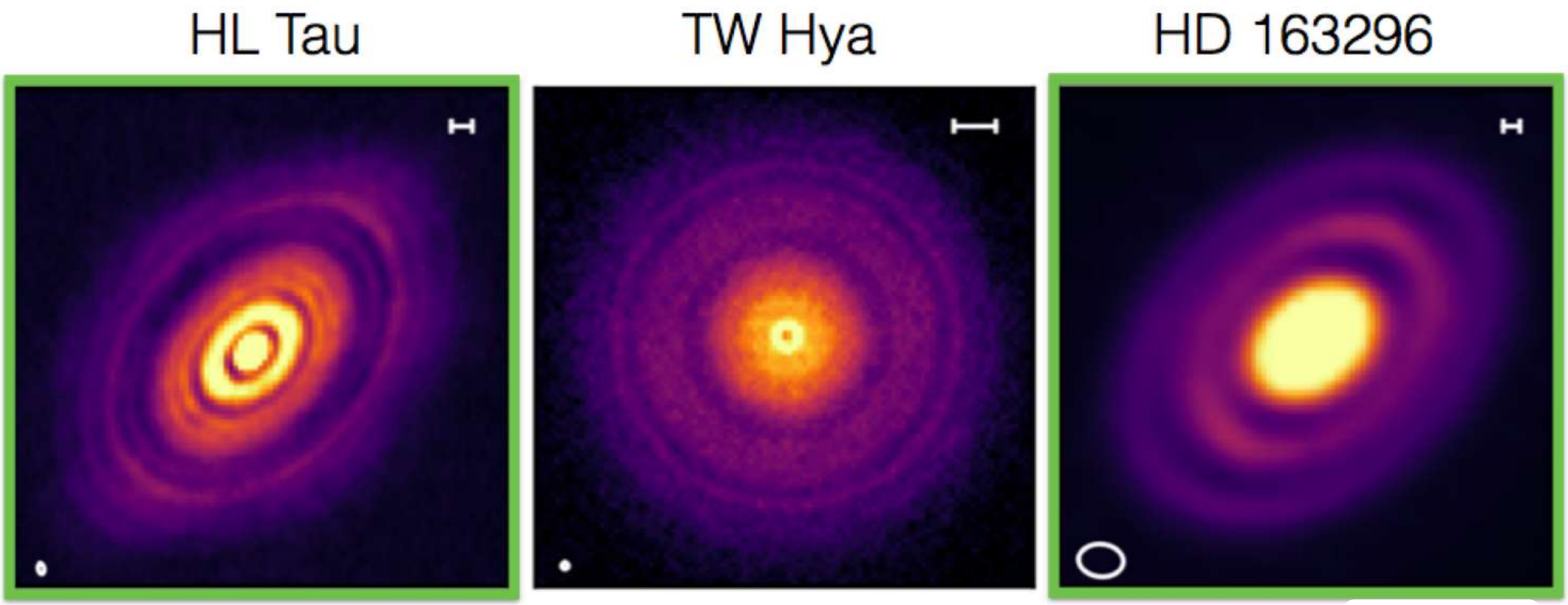
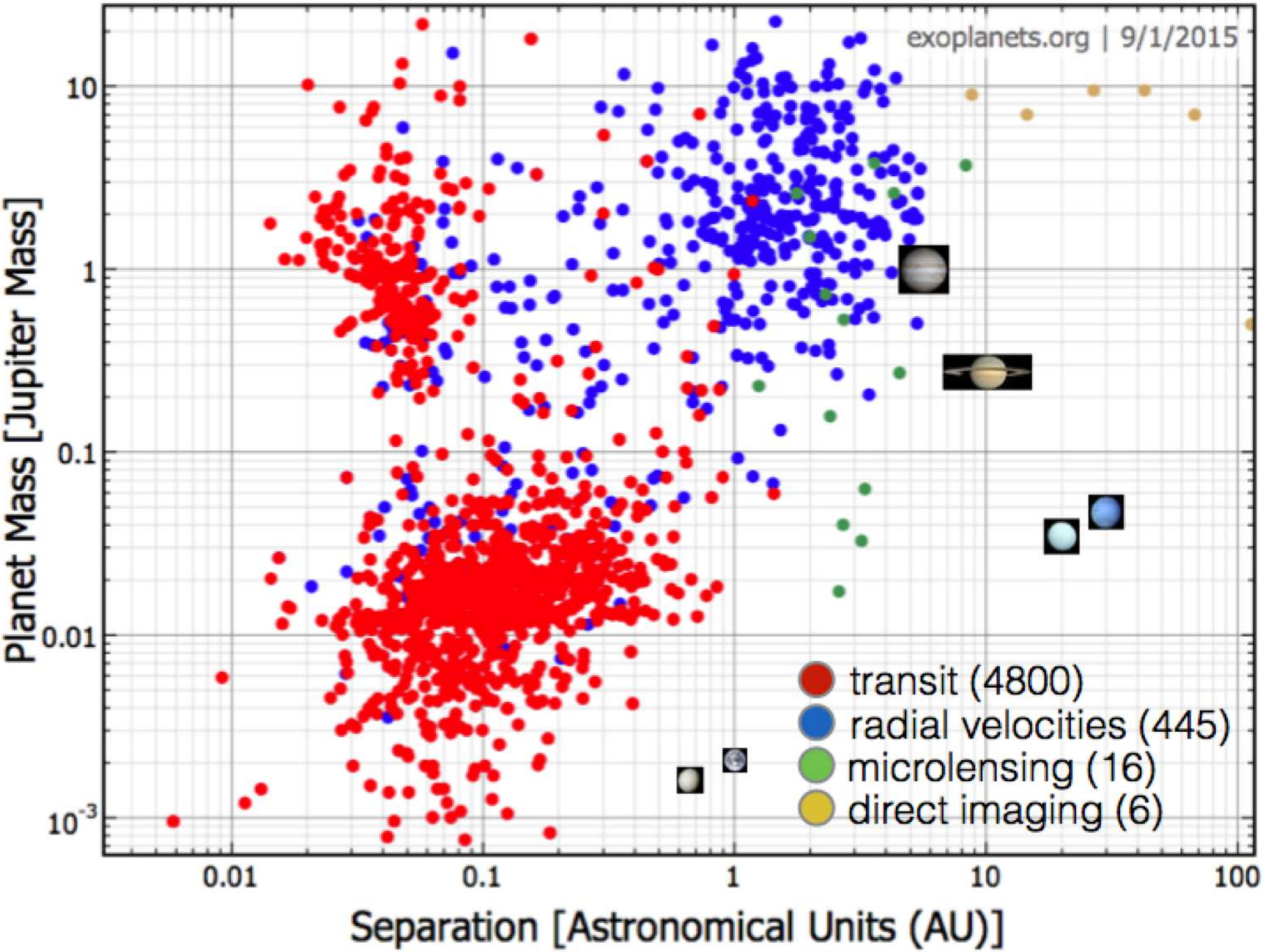
Students/Postdocs: Ryan Miranda (Cornell); Ruobing Dong (UA)
Sheng Jin (PMO-previously)

Observers: Andrea Isella (Rice) & collaborators

Simulations: Shengtai Li (LANL)



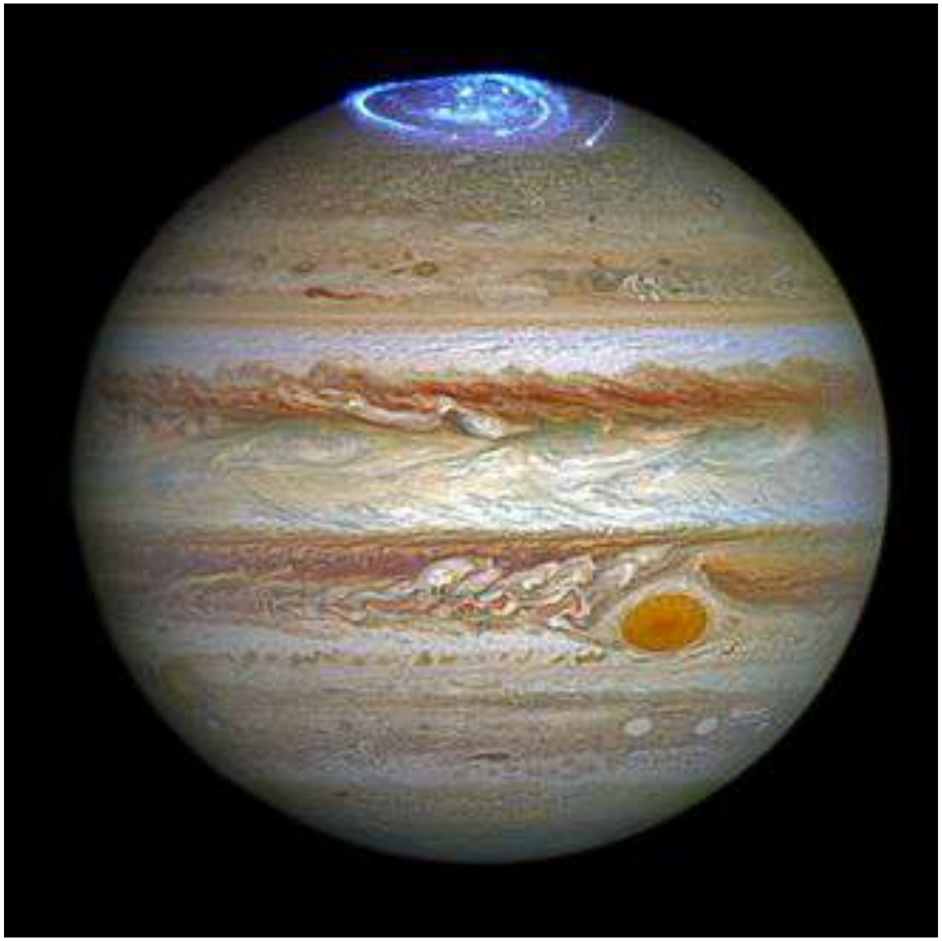
ALMA partnership (2015) | Andrews et al. (2016) | Isella et al. (2016, PRL)


exoplanets.org | 9/1/2015
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]
transit (4800)
radial velocities (445)
microlensing (16)
direct imaging (6)

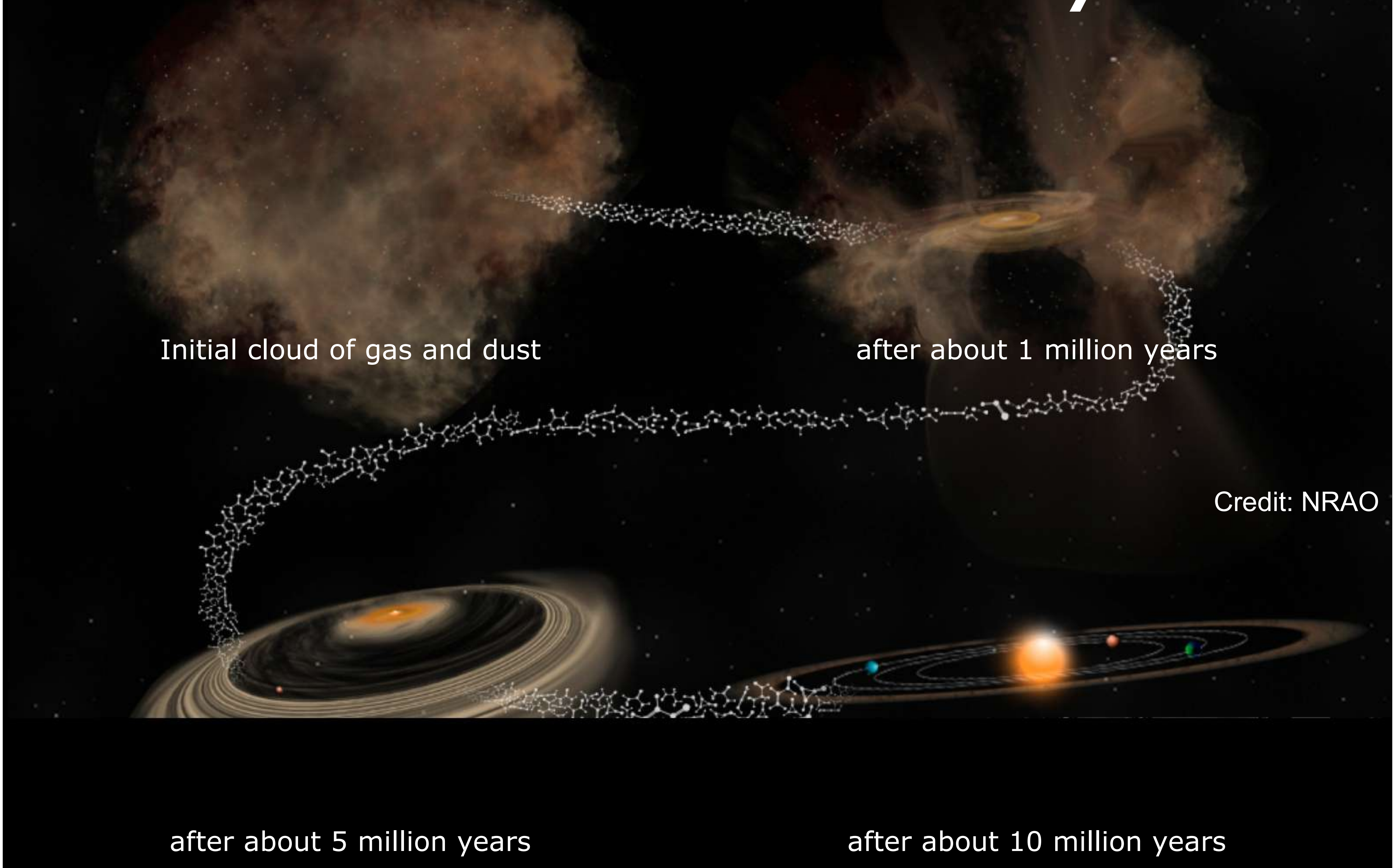
Lots of Gas, Dust, and Rocks

Mars
”Rock” mass dominate

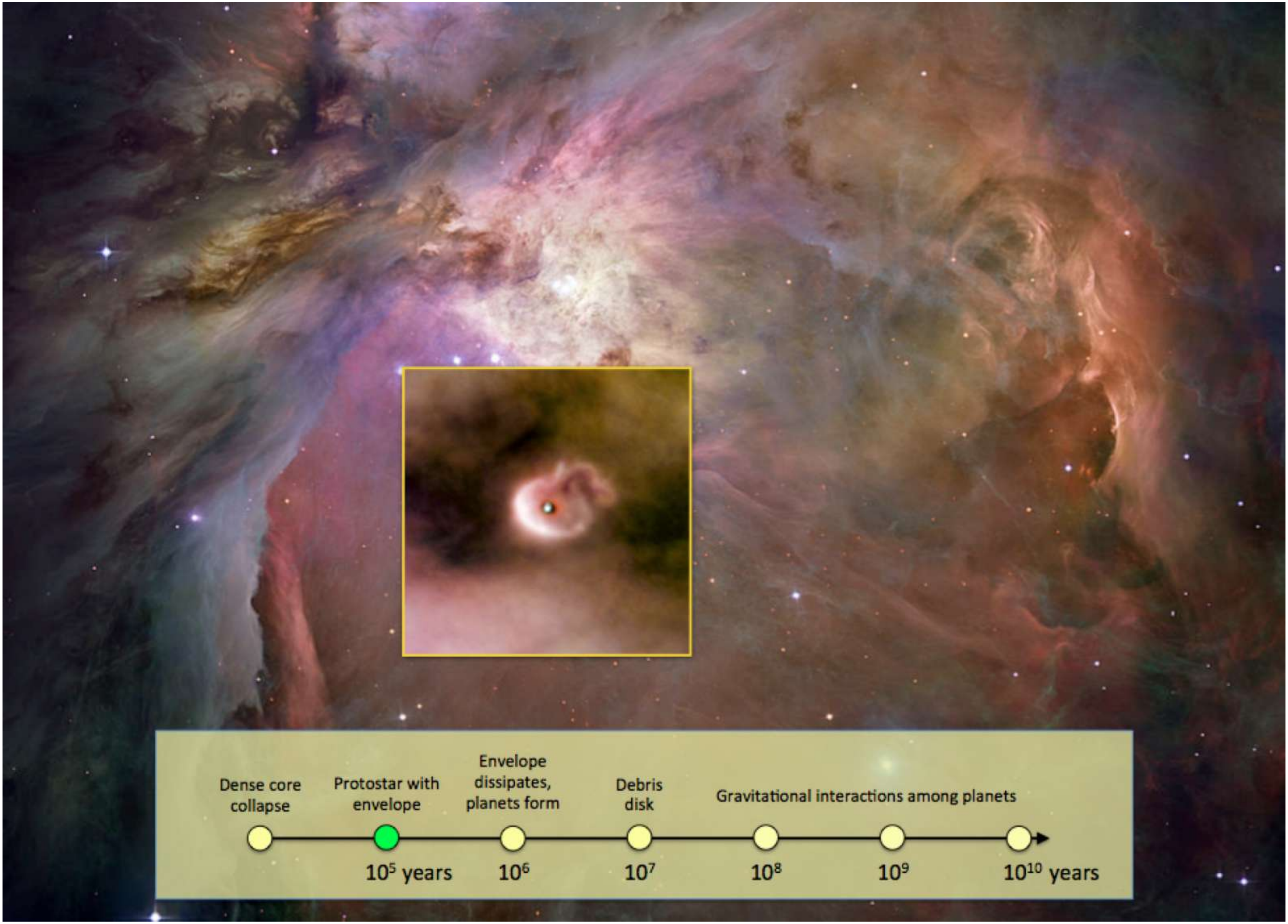
Jupiter
Gas mass dominate

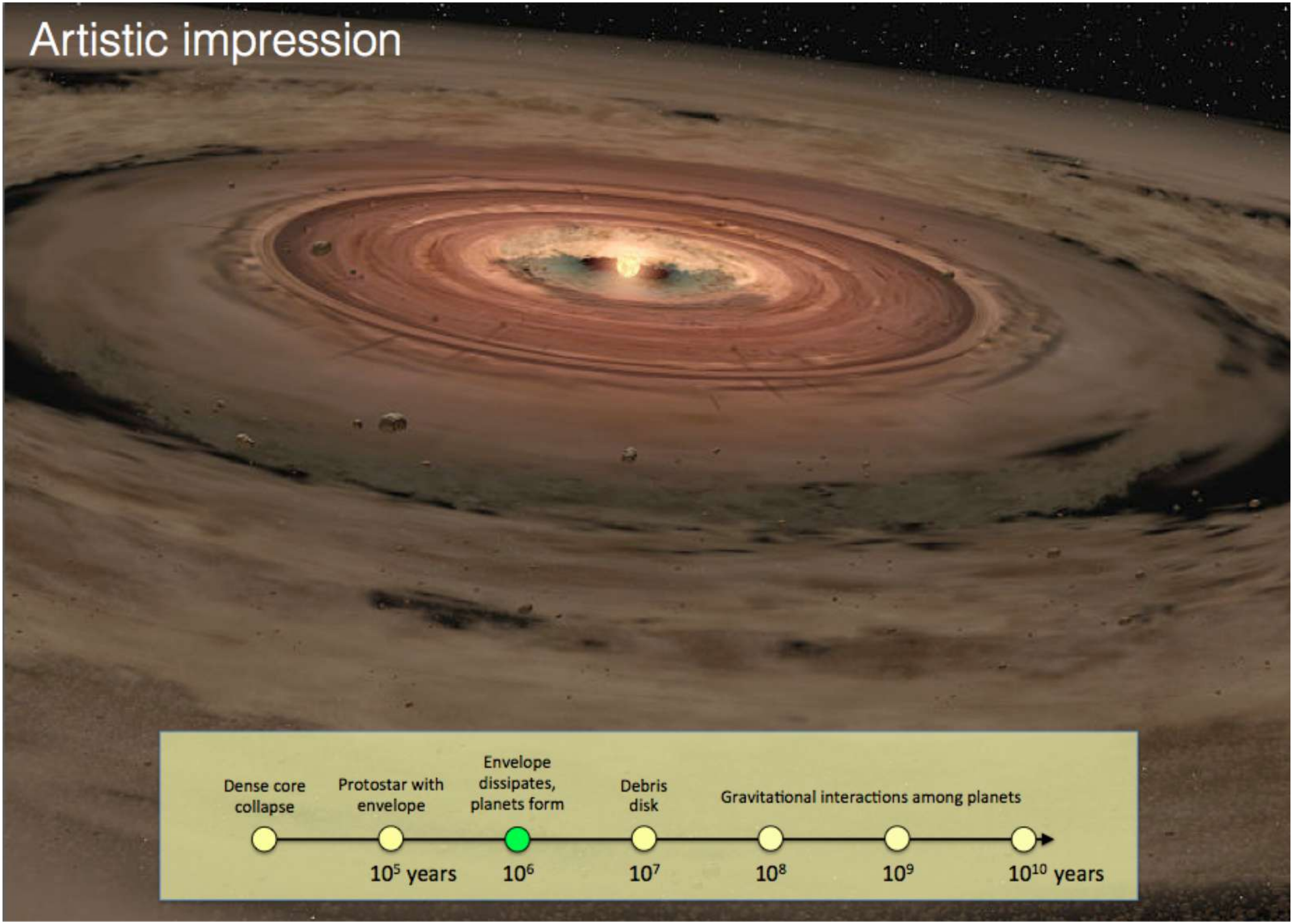


Star formation history

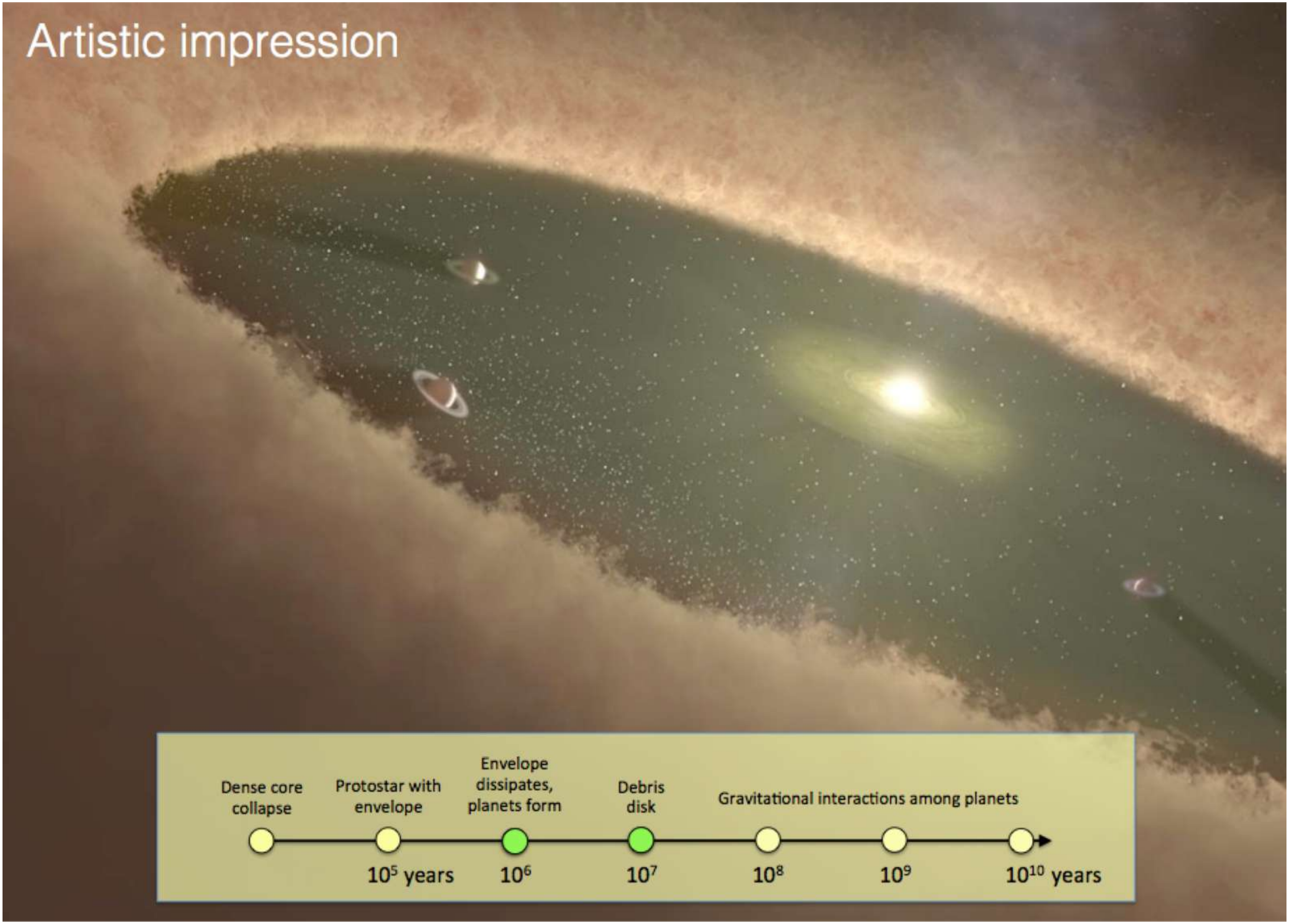


Slide from Andrea Isella


Dense core collapse
Protostar with envelope
Envelope dissipates, planets form
Debris disk
Gravitational interactions among planets
10^5 years
10^6
10^7
10^8
10^9
10^{10} years



Artistic impression
Dense core collapse
Protostar with envelope
Envelope dissipates, planets form
Debris disk
Gravitational interactions among planets
10^5 years
10^6
10^7
10^8
10^9
10^10 years



Artistic impression
Dense core collapse
Protostar with envelope
Envelope dissipates, planets form
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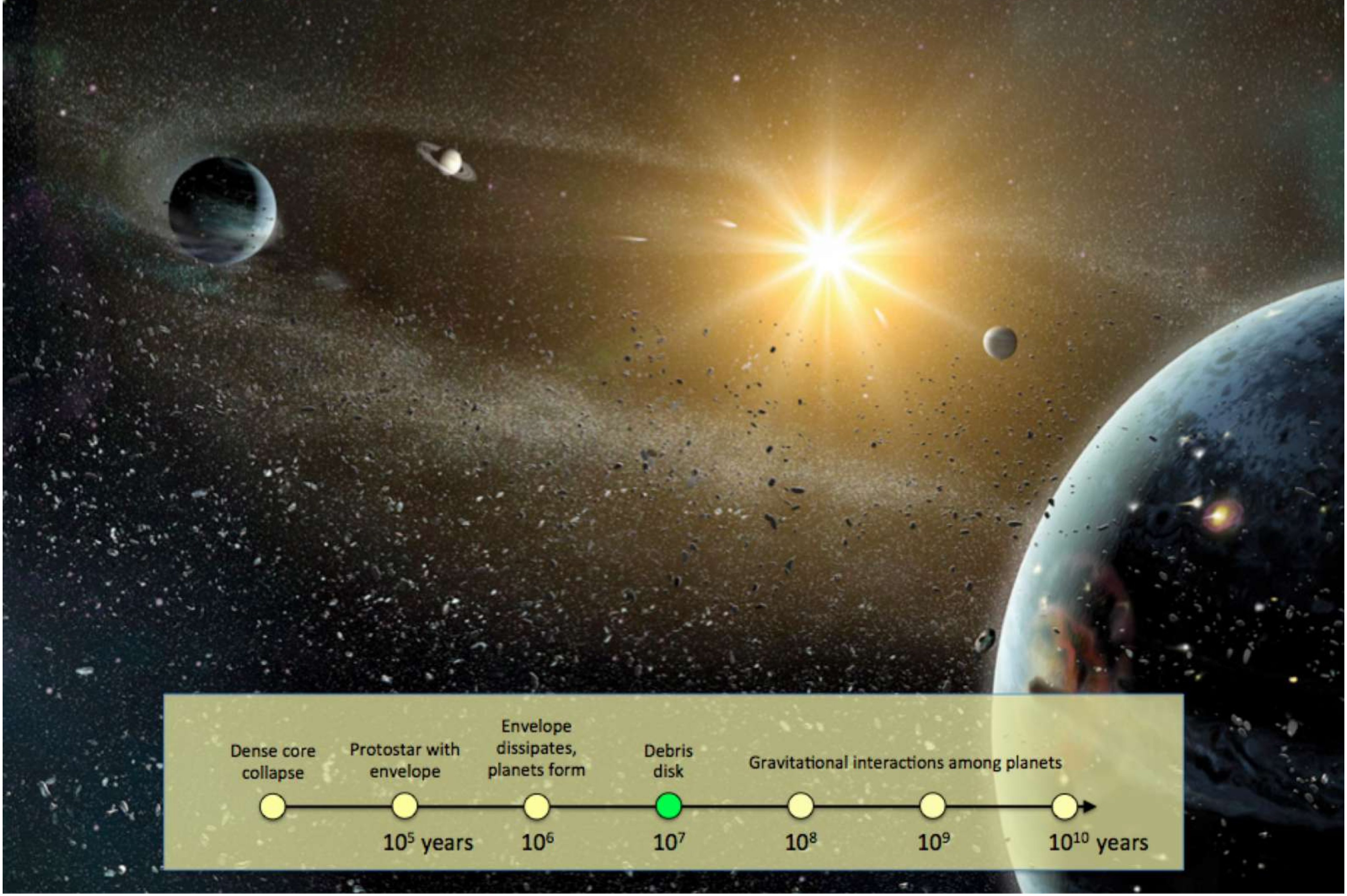
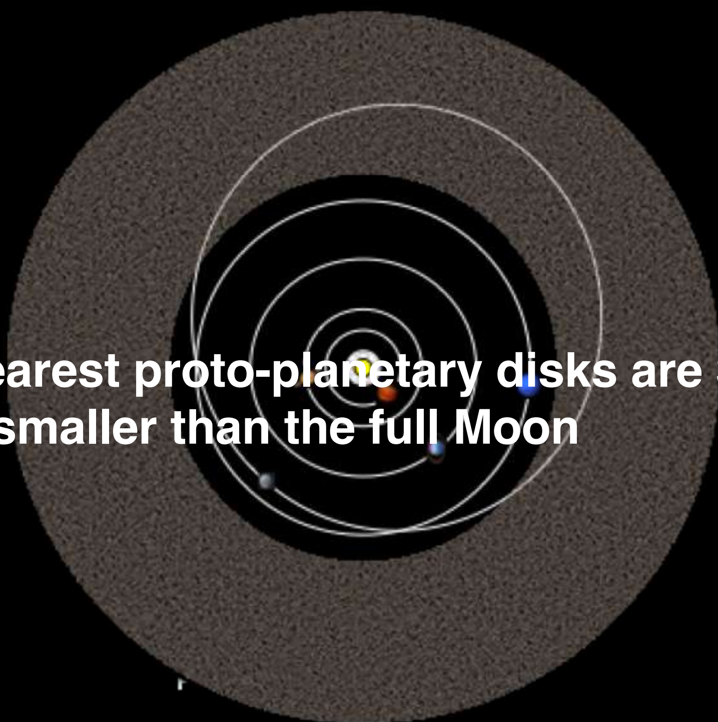
Gravitational interactions among planets
10^5 years
10^6
10^7
10^8
10^9
10^{10} years

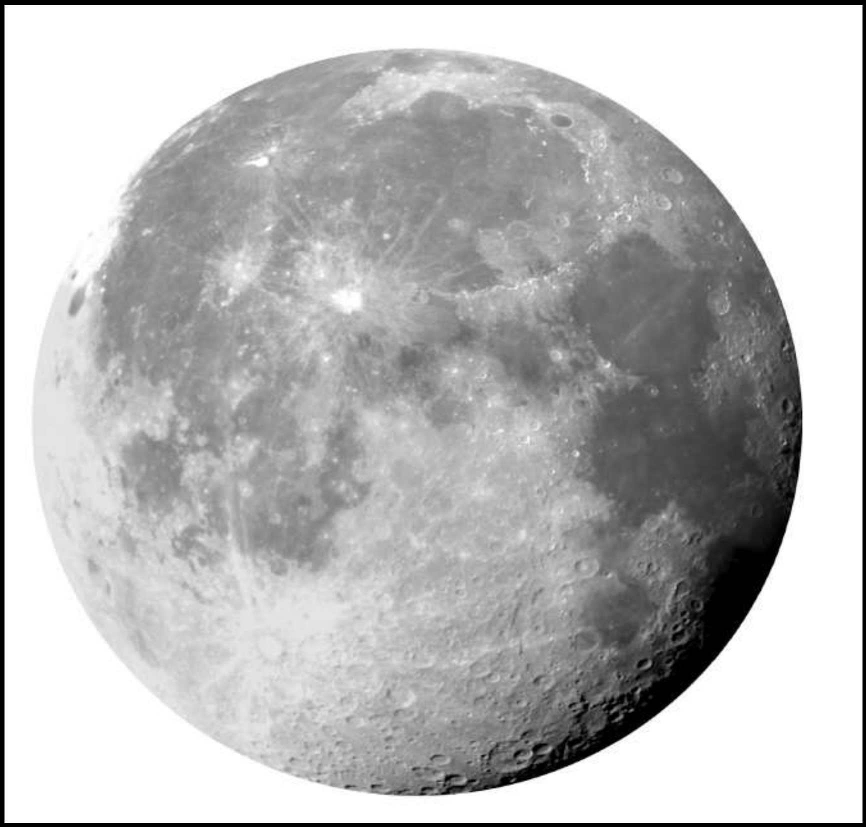
Artistic impression



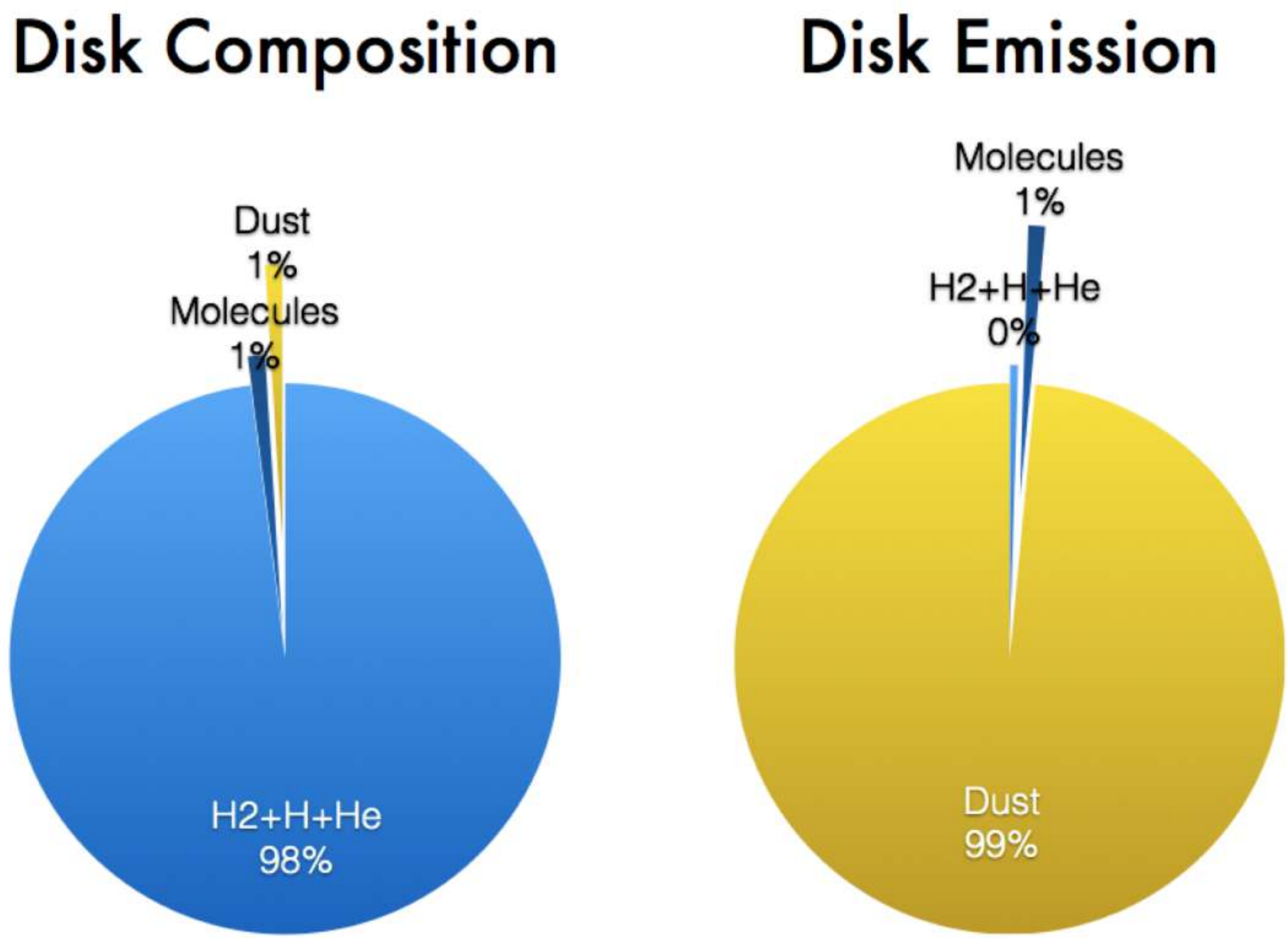
Planetary Systems are Tiny



The nearest proto-planetary disks are 3000 times smaller than the full Moon



Some Basics



1) Perform 2D/3D two-fluid (dust+gas) hydro with+w/o planets
2) Use micro-size dust to calculate disk temperature
3) Use mm-size dust to calculate continuum, also line emission
4) Fold them through ALMA “response func.” to get images

Disk Gas Dynamics

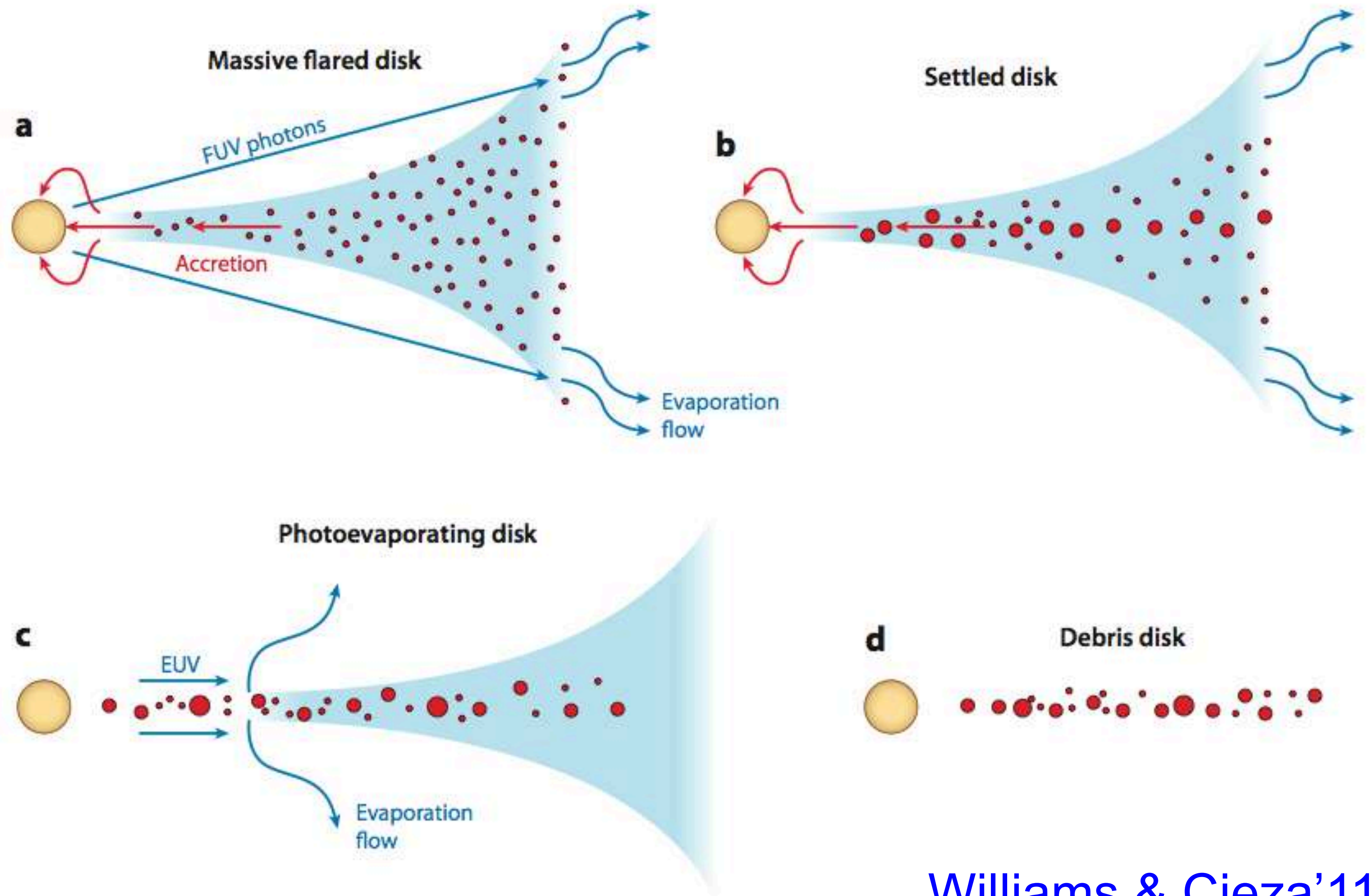
$$v_\varphi^2 = \frac{GM}{r} + \frac{r}{\Sigma}\frac{\partial p}{\partial r}$$

Keplerian velocity

Correction for pressure gradient

- For negative radial pressure gradient (as expected), the gas orbital velocity is sub-Keplerian
- Leads to gas-dust interaction
- Dust experiences a head-wind: loss of angular momentum leading to inward drift (meter-size problem)

Evolution of a Typical Disk



Williams & Cieza’11

Issue #1:

Do we expect to have any large-scale structures in PPD?

Accretion Disk Are Believed to Be Very Stable

Rayleigh Criterion:

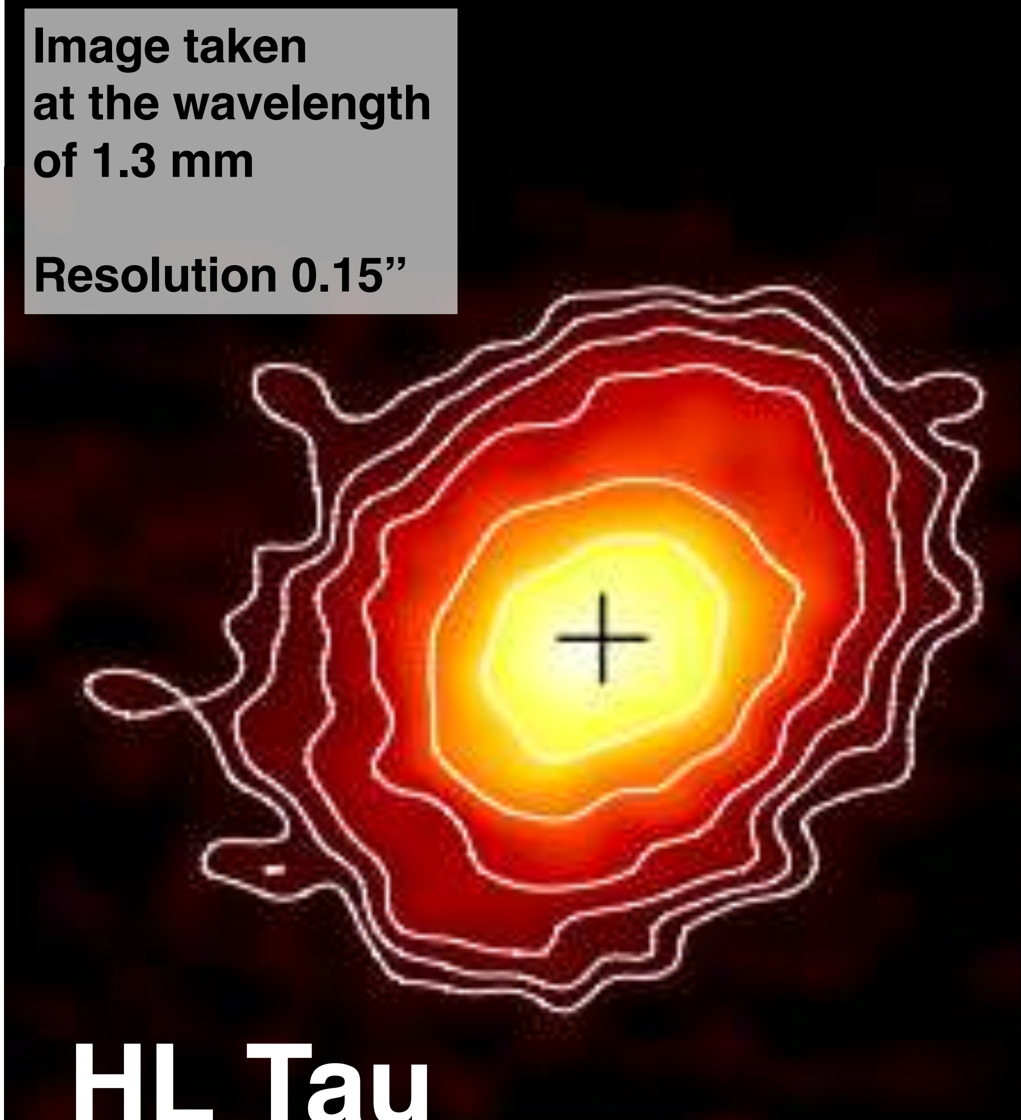
$$\kappa^2 \equiv \frac{1}{r^3}\frac{d(r^4\Omega^2)}{dr} > 0 \quad \text{i.e., stable}$$

There might be turbulence (e.g., MRI), depending on ionization level and coupling between magnetic field and gas, but no large-scale features were expected.

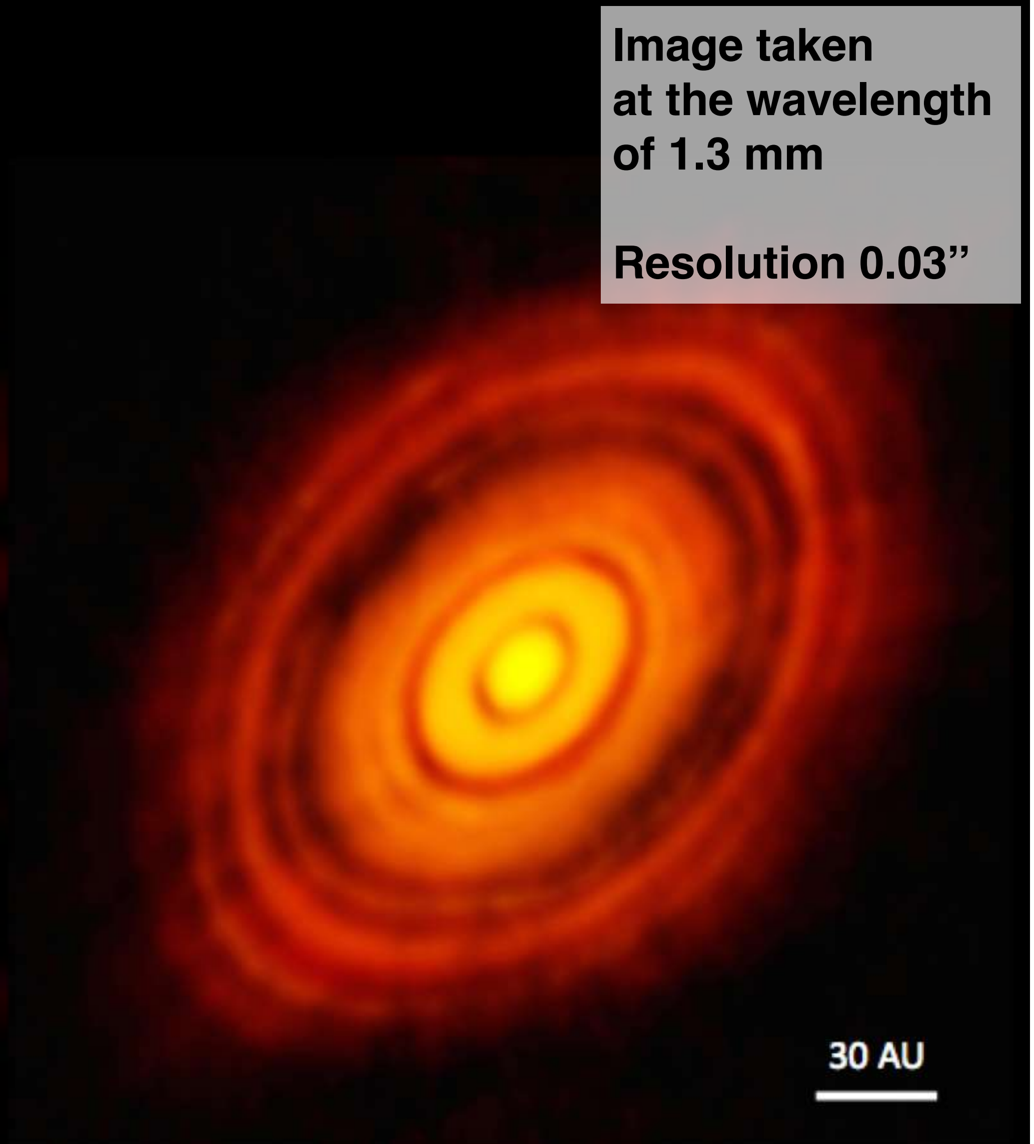
Exciting Observations

ALMA

PPD before and after ALMA



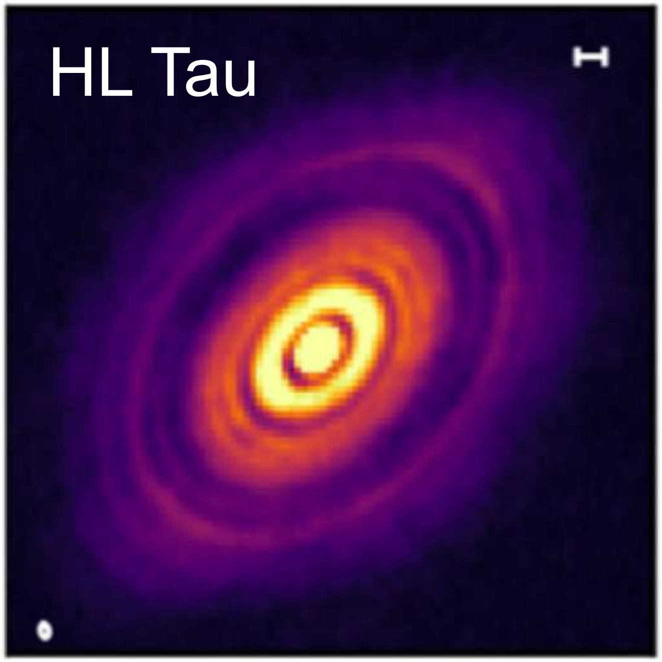
Kwon et al. (2011)



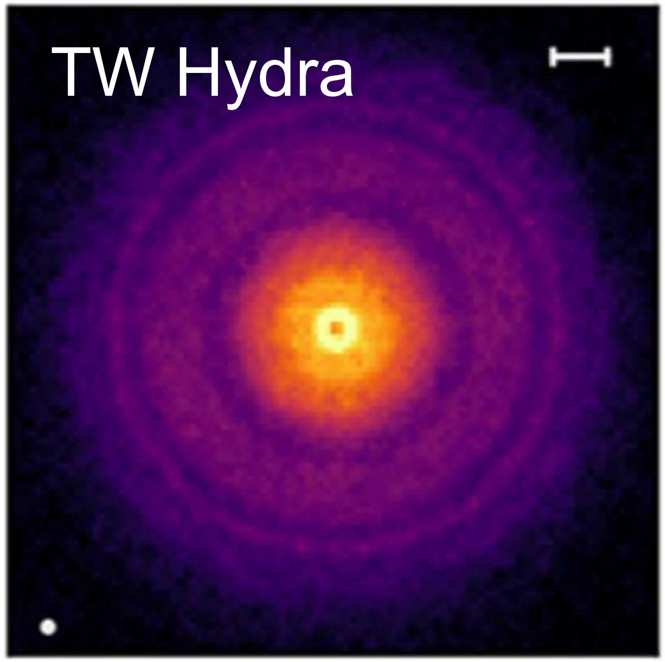
ALMA Partnership (2015)

Slide from Andrea Isella

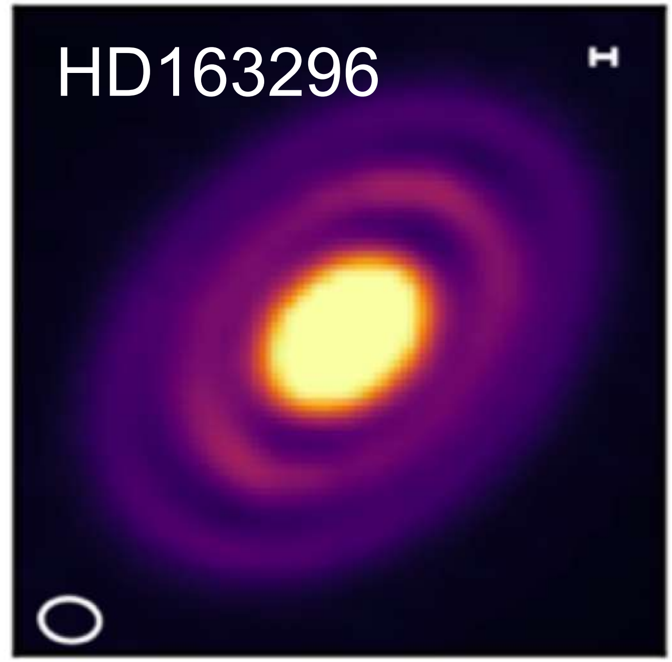
Disks with “Dust Rings”



ALMA ‘15



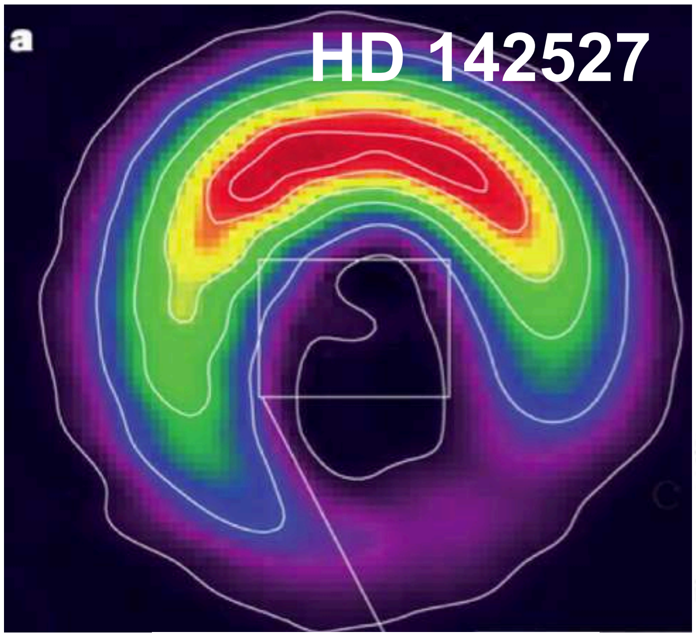
Andrews ‘16



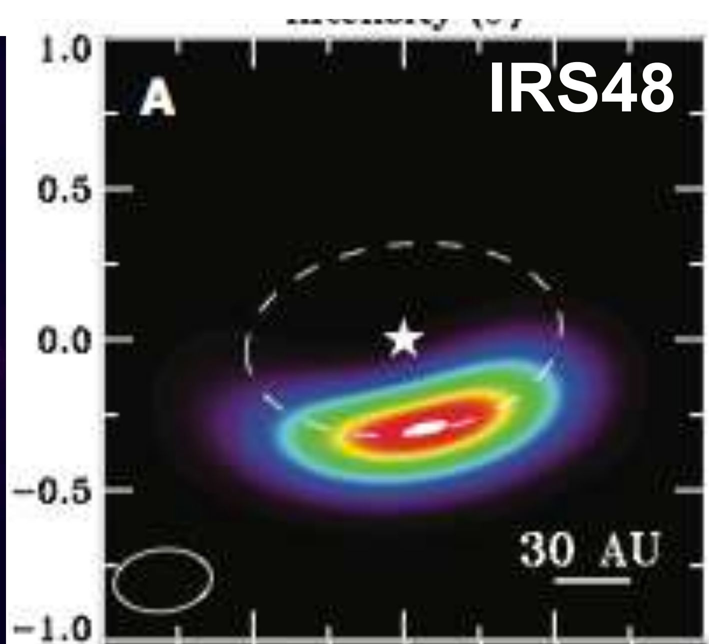
Isella ‘16

How are these rings made and what is their implication for planet formation?

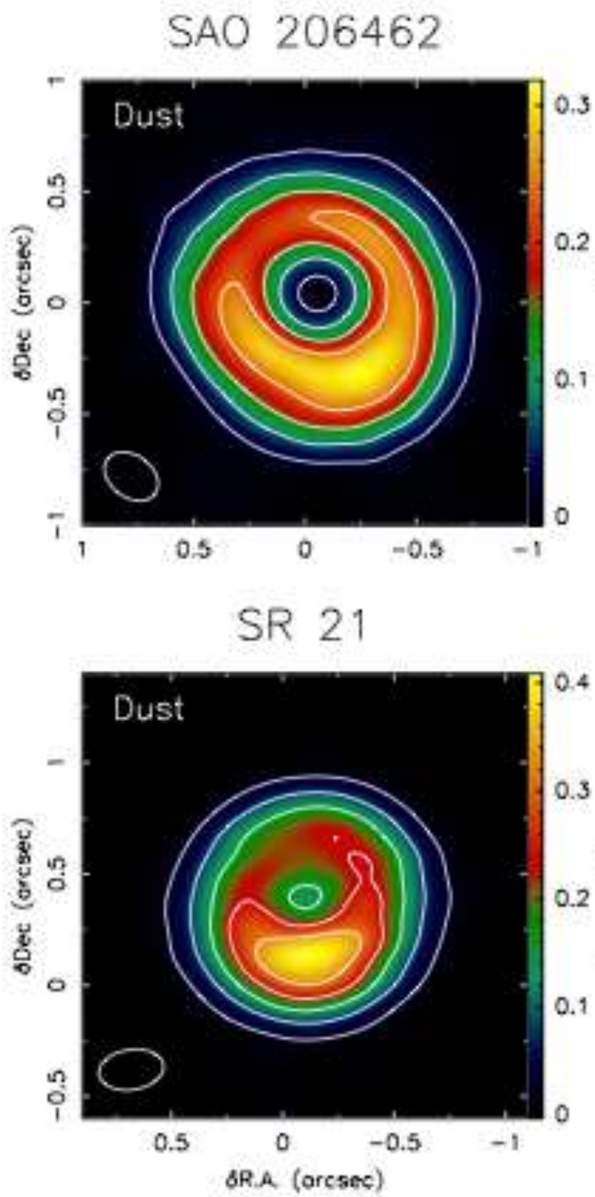
Disks with Dust Asymmetries: "Vortices" ?



Casassus et al.,
Nature, 2013

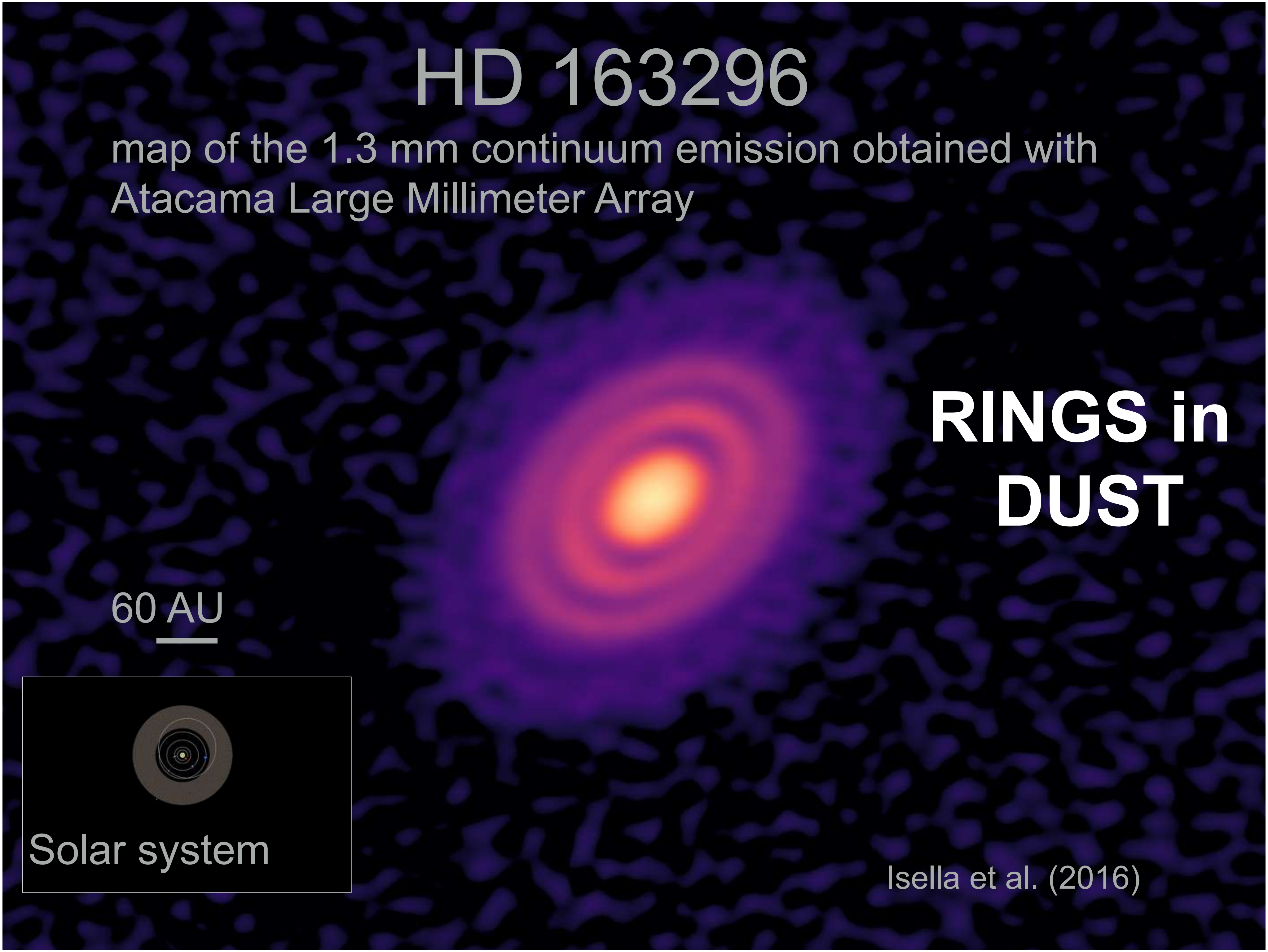


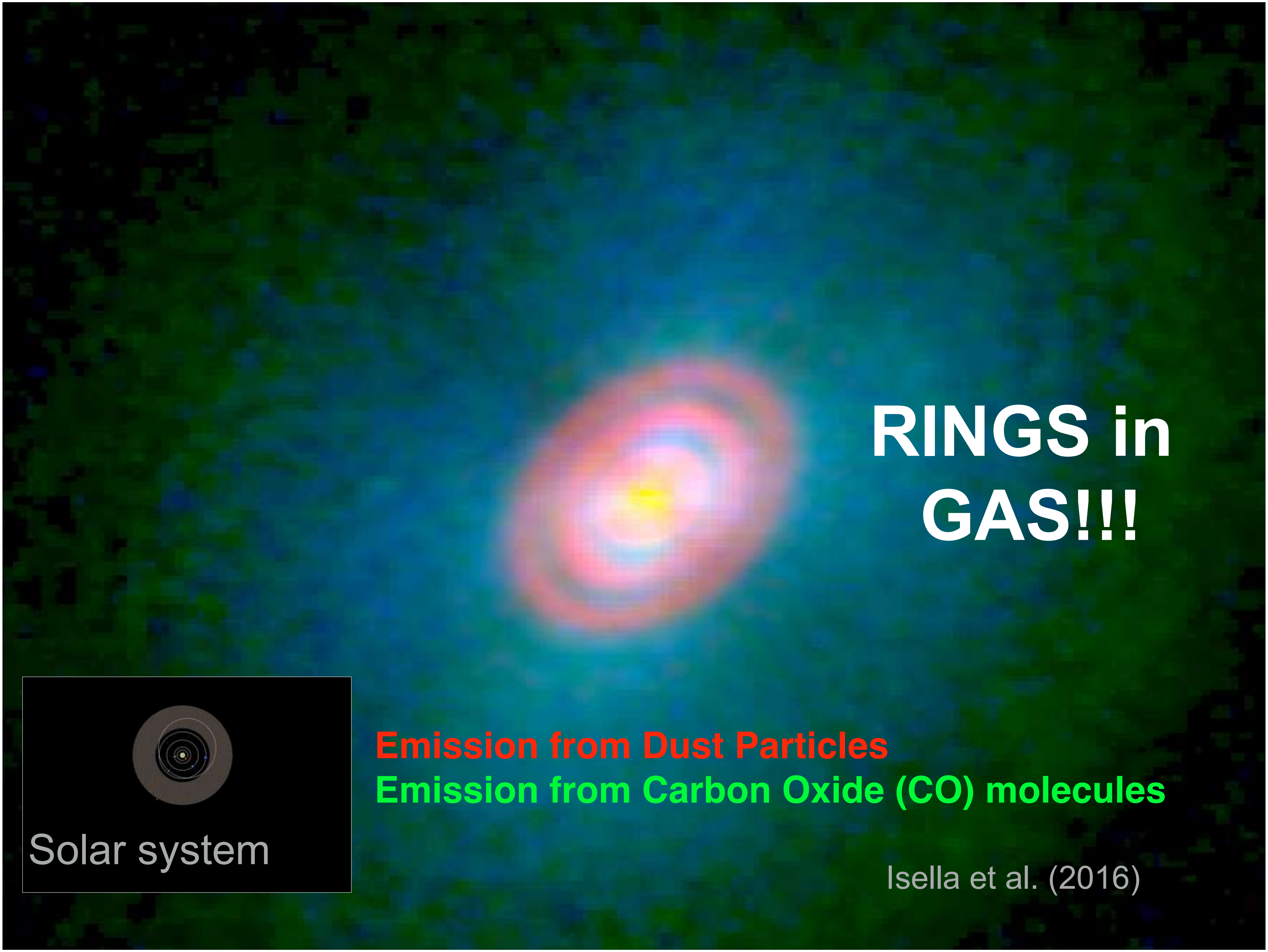
van der Marel et al.,
Science, 2013



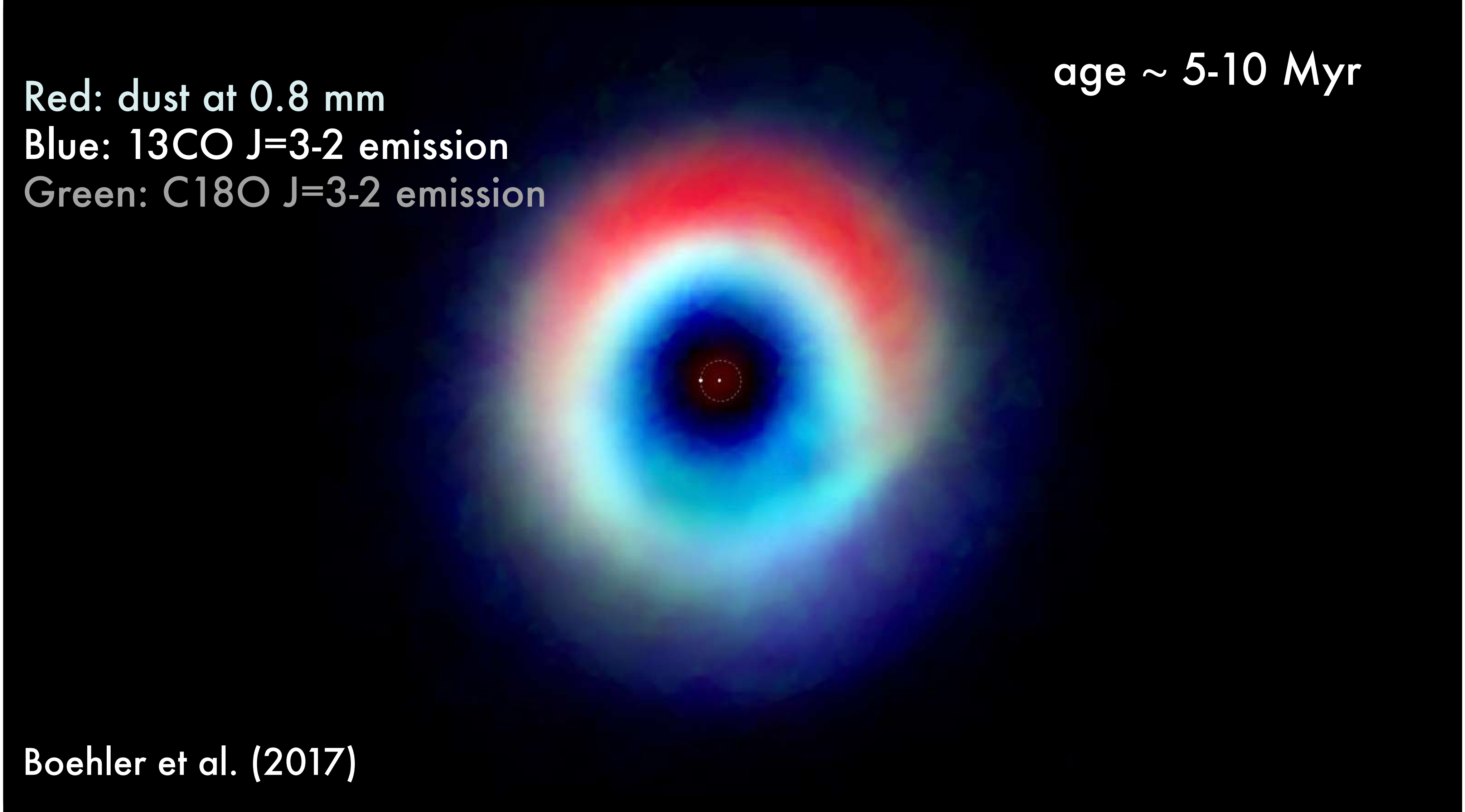
Perez et al. '14

Disks are not boringly axisymmetric as one might naively imagine.


HD 163296
map of the 1.3 mm continuum emission obtained with
Atacama Large Millimeter Array
RINGS in
DUST
60 AU
Solar system
Isella et al. (2016)


RINGS in GAS!!!
Solar system
Emission from Dust Particles
Emission from Carbon Oxide (CO) molecules
Isella et al. (2016)

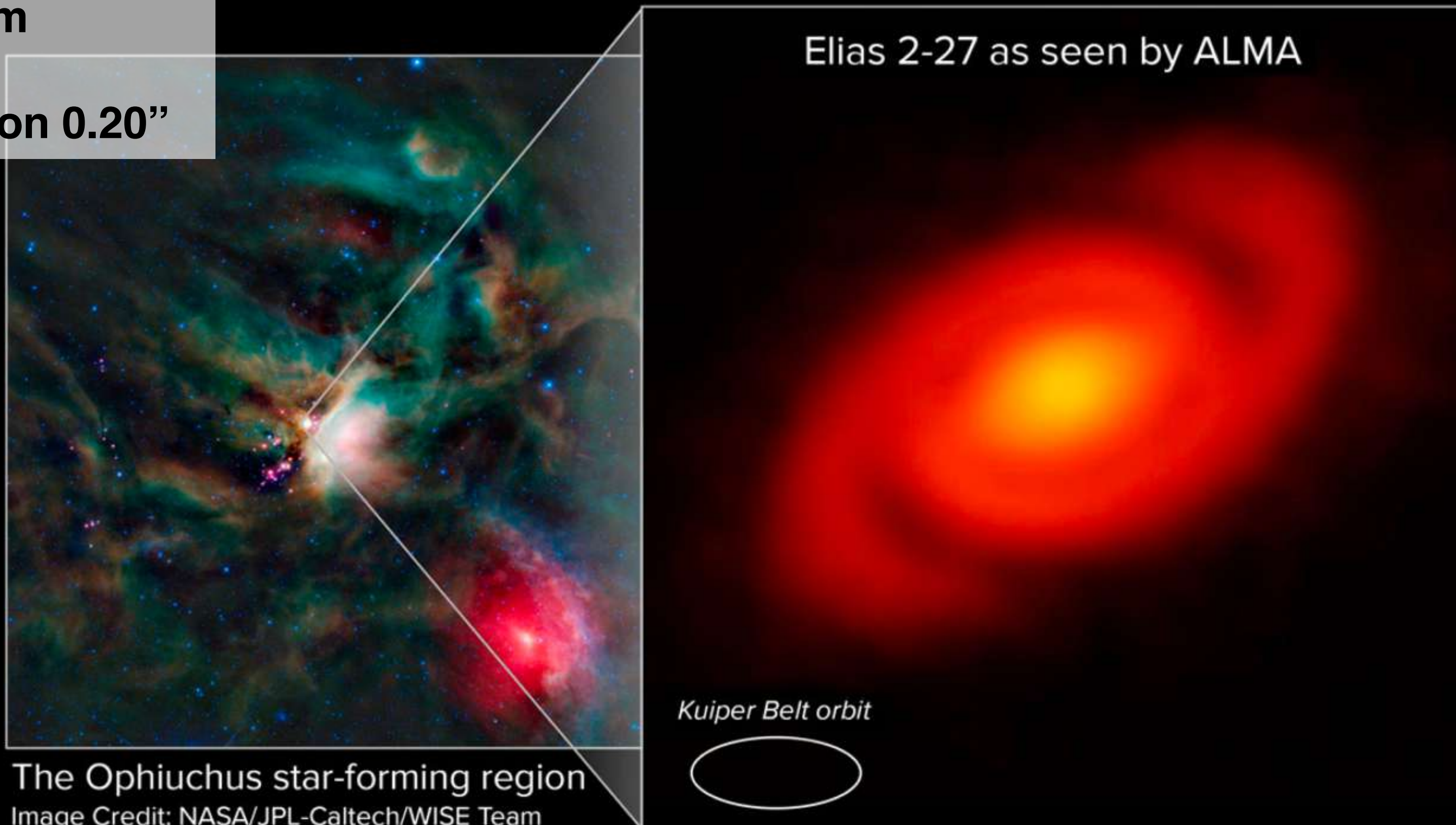
Not only rings: crescents



Not only rings: spirals

Image taken at the wavelength of 1.3 mm

Resolution 0.20”

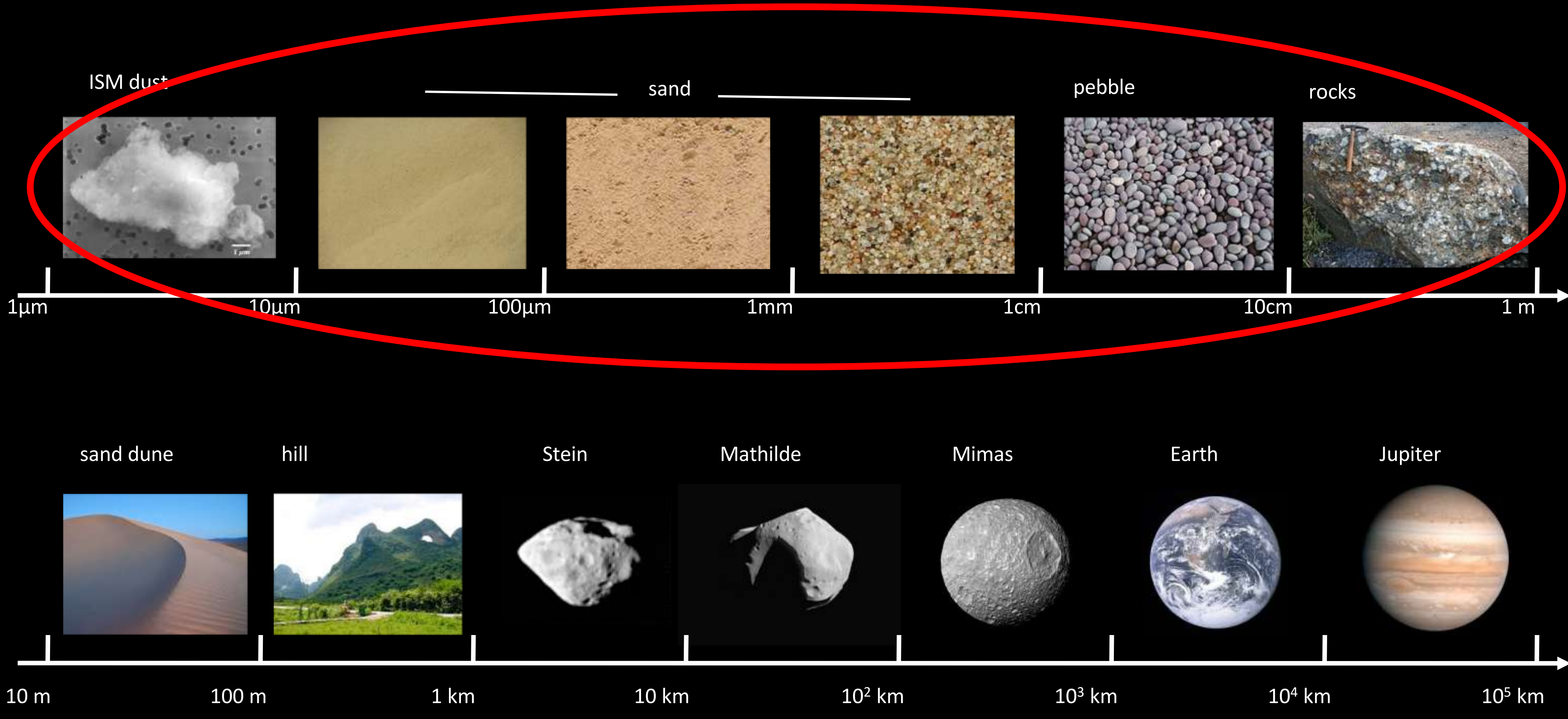


The Ophiuchus star-forming region
Image Credit: NASA/JPL-Caltech/WISE Team

Credit: B. Saxton (NRAO/AUI/NSF);
ALMA (ESO/NAOJ/NRAO), L. Pérez (MPIfR)

Pérez et al. 2016, Science, 353, 6307

Evolution of Solids

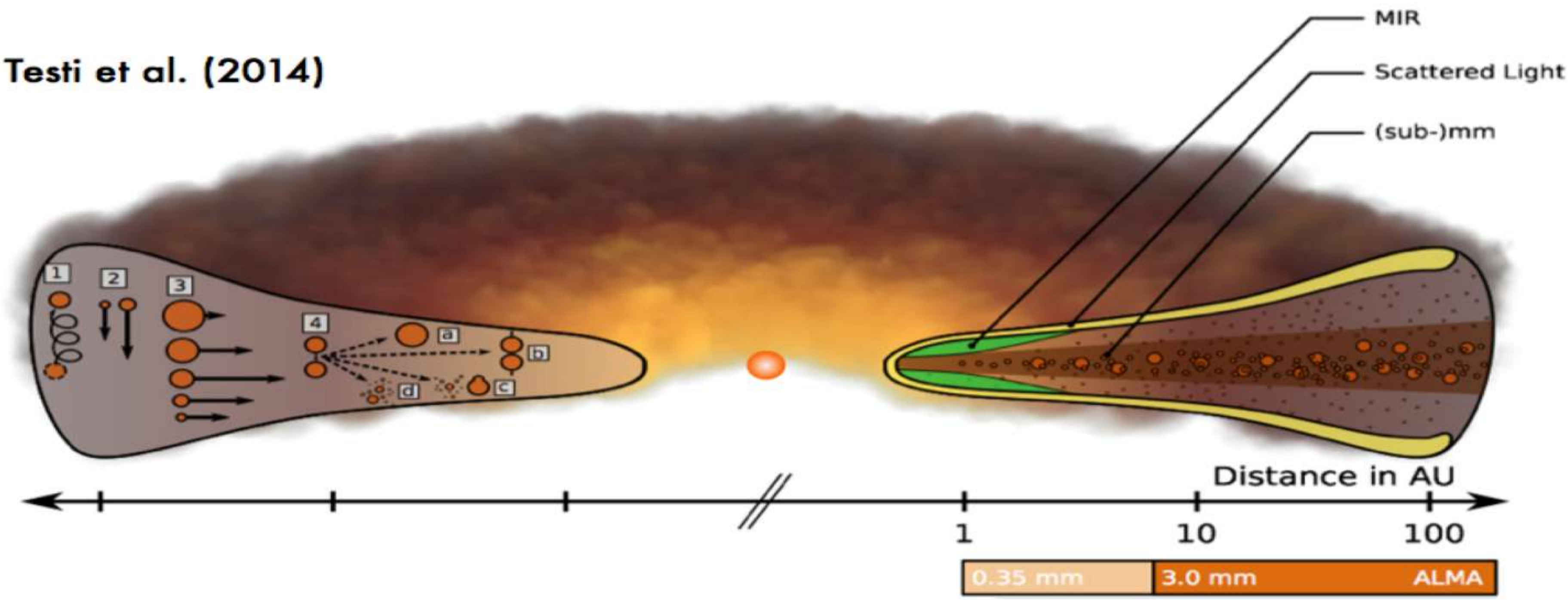


Core accretion model (Safranov 1976, Pollack 1996)

Issue #2:

Dust Dynamics

Some Disk Physics: Dust



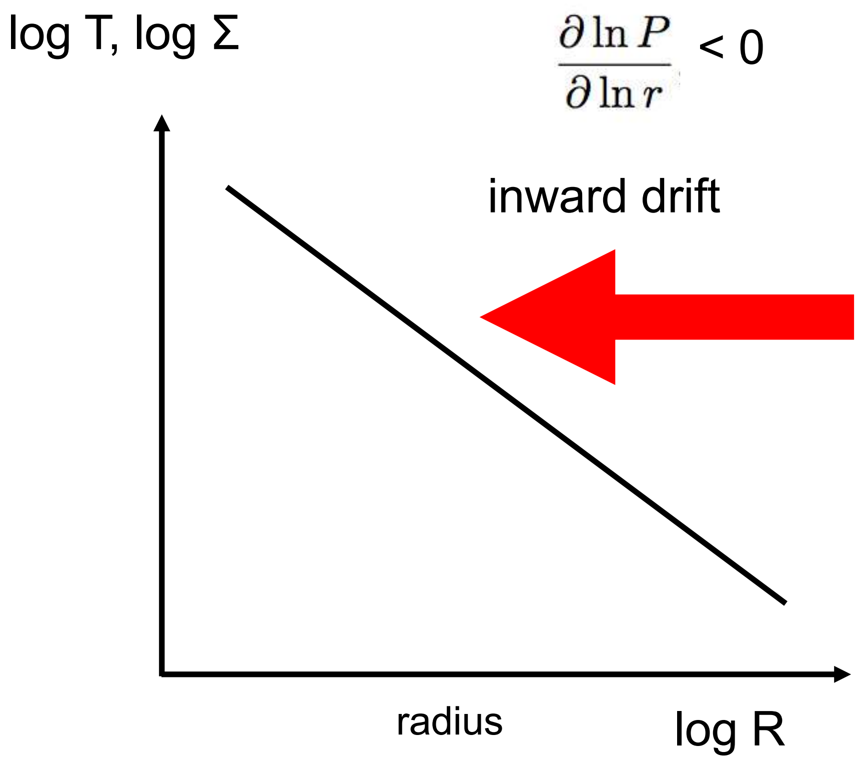
$$u_{\rm drift} = \frac{1}{{\rm St} + {\rm St}^{-1}(1+\epsilon)^2} \frac{c_{\rm s}^2}{V_{\rm K}} \frac{\partial \ln P}{\partial \ln r},$$

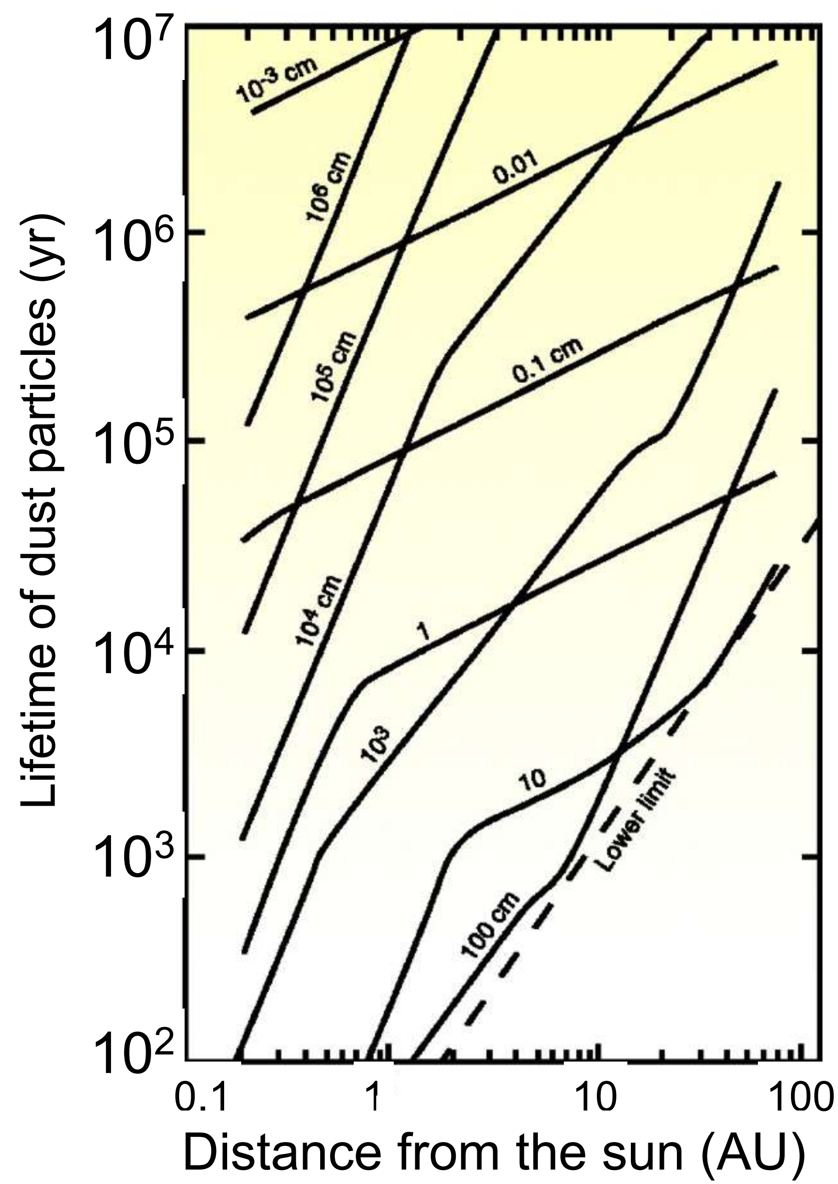
$$\mathrm{St} = \frac{\rho_{\rm s}\, a}{\rho_{\rm g}\, c_{\rm s}\, \sqrt{8/\pi}}\, \Omega_{\rm k},$$

Dust Radial Drift Problem

$$u_{\rm drift} = \frac{1}{\mathrm{St} + \mathrm{St}^{-1}(1+\epsilon)^2} \frac{c_s^2}{V_K} \frac{\partial \ln P}{\partial \ln r},$$

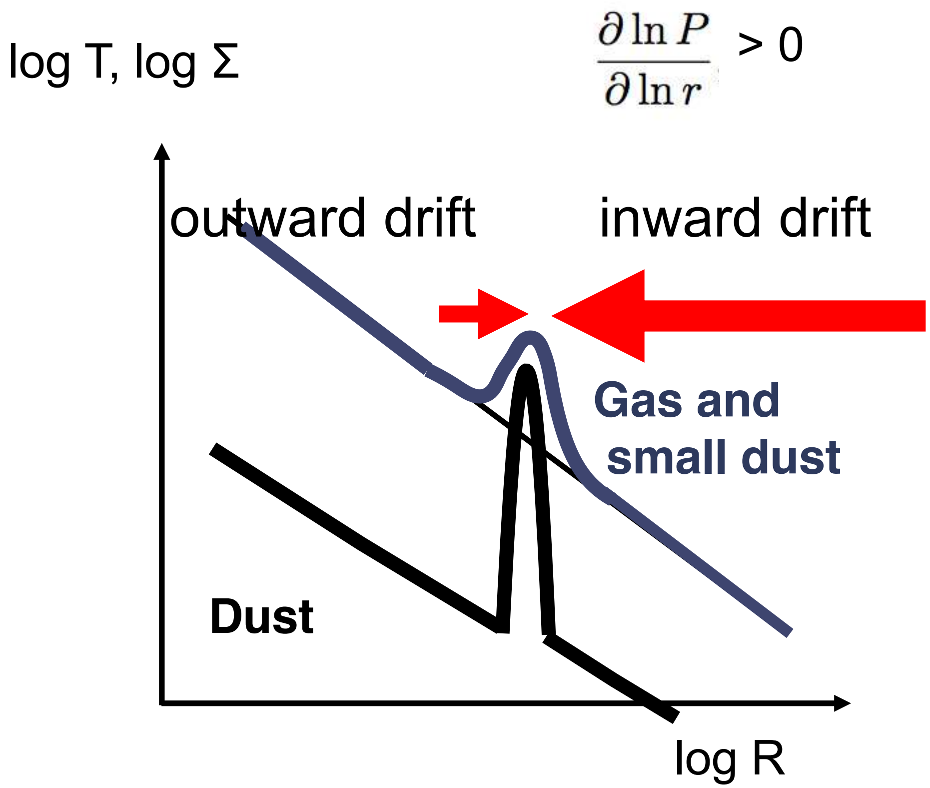
$$\frac{\partial \ln P}{\partial \ln r} < 0$$





Weidenschilling (1977)

A possible solution



Whipple (1972)

Local bumps in the gas pressure can trap dust particles, slowing down or halting the inward radial drift.

Dust traps lead to grain size segregation.

Dust traps lead to enhanced dust-to-gas ratio.

Issue #3:

Instabilities: Global and Local

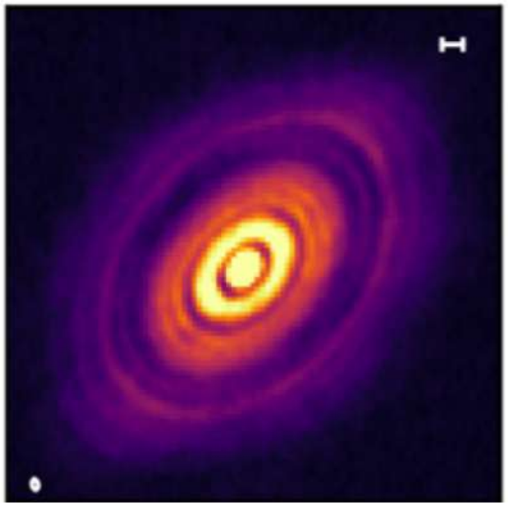
Mechanisms for Producing Non-Axisymmetric Features and Rings

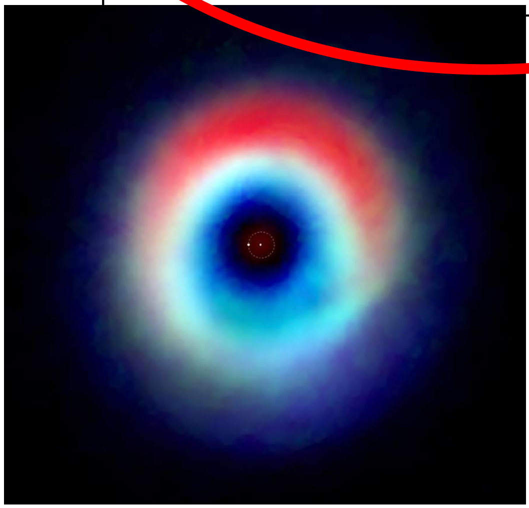
With protoplanets

Without protoplanets

Protoplanet – disk (gas+dust) interaction is the main driver

disk (gas+dust) dynamics is the main driver

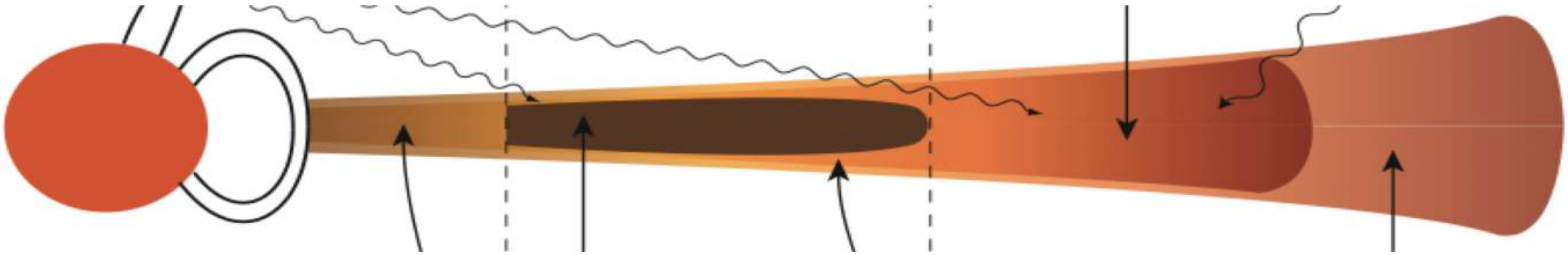


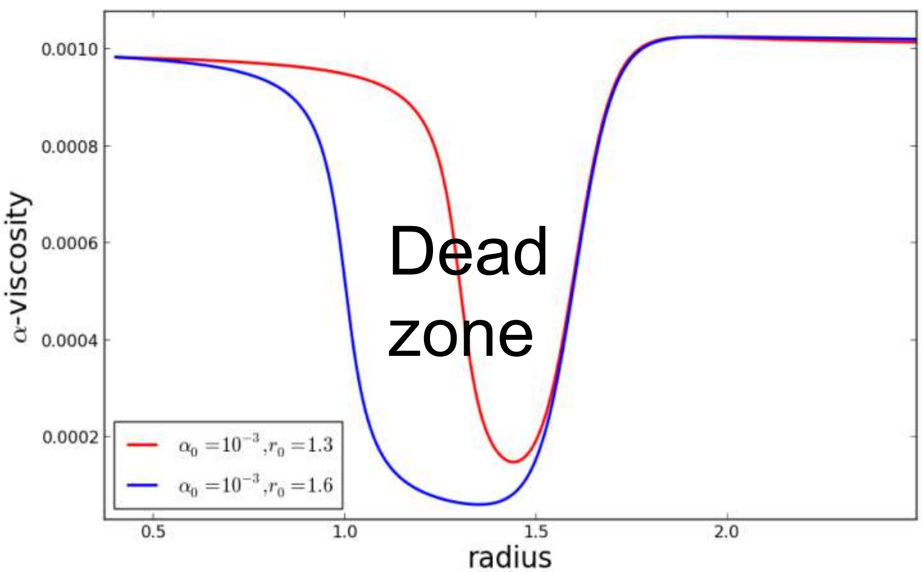


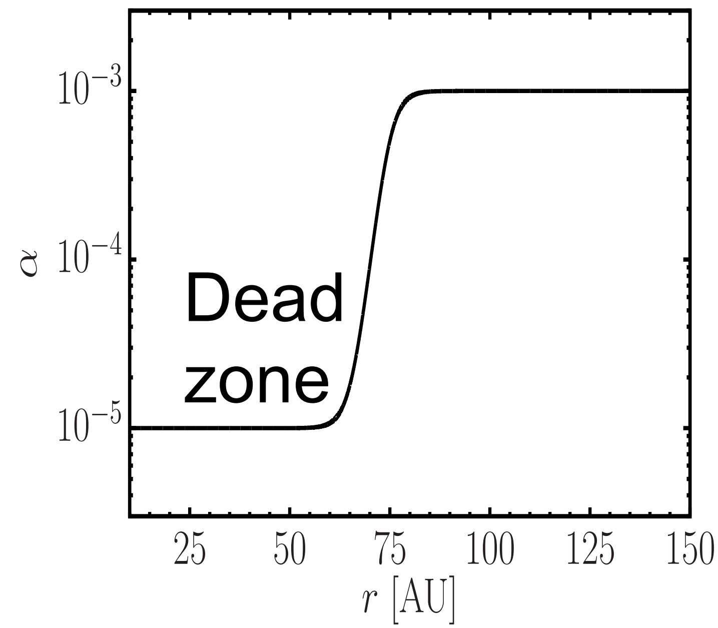
Case 1: Global Rossby Wave Instability excited by viscosity transition

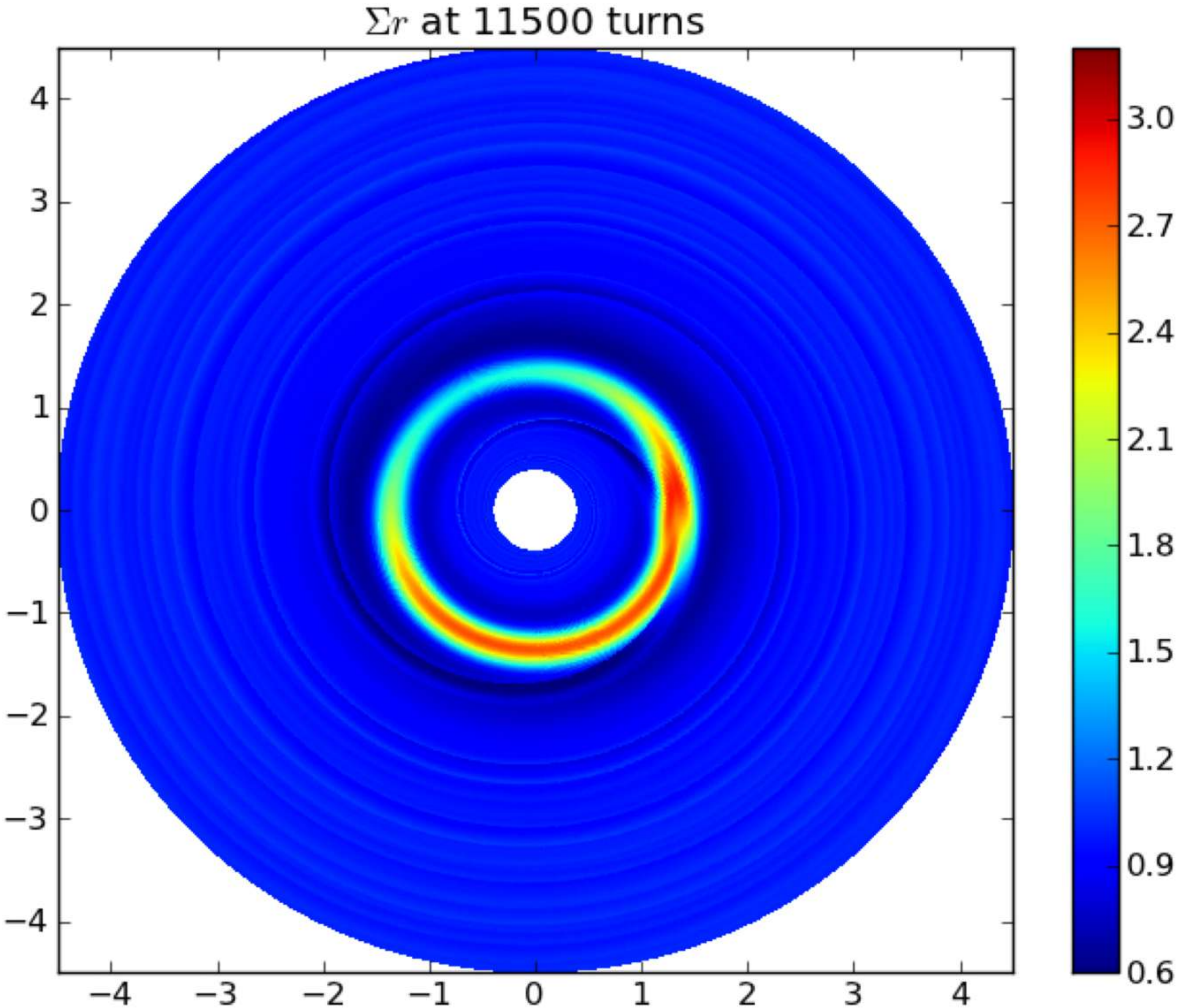
Without proto-planet:

Viscosity Transition



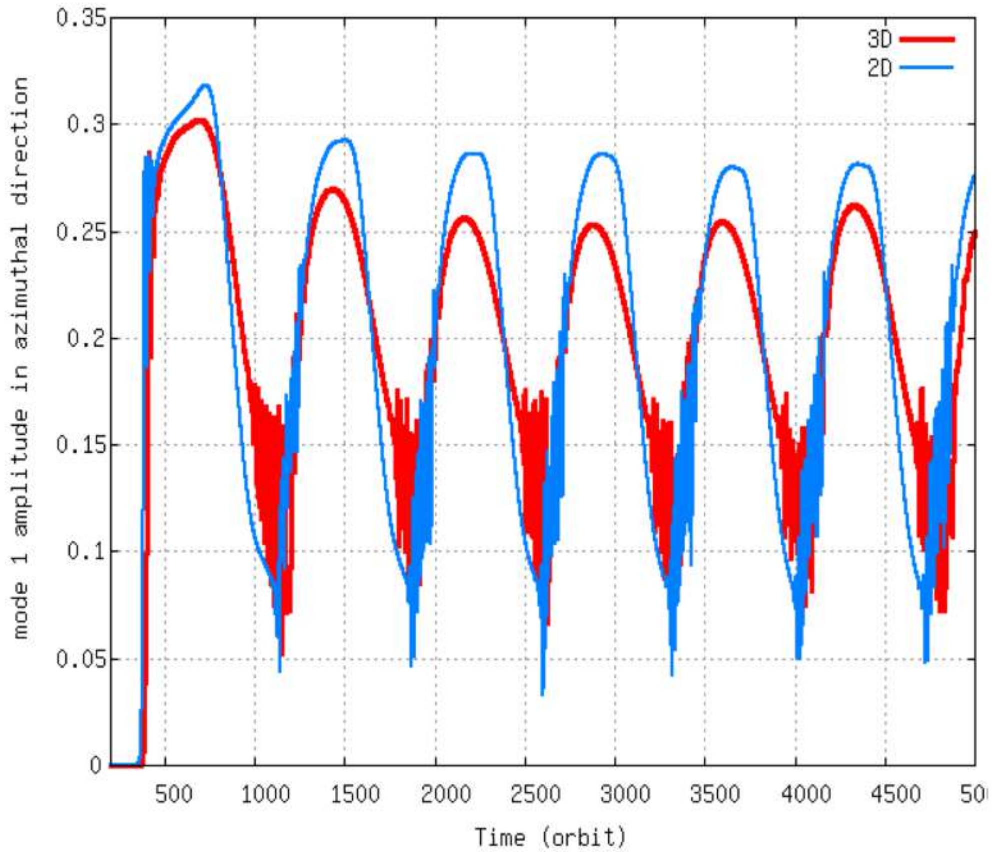




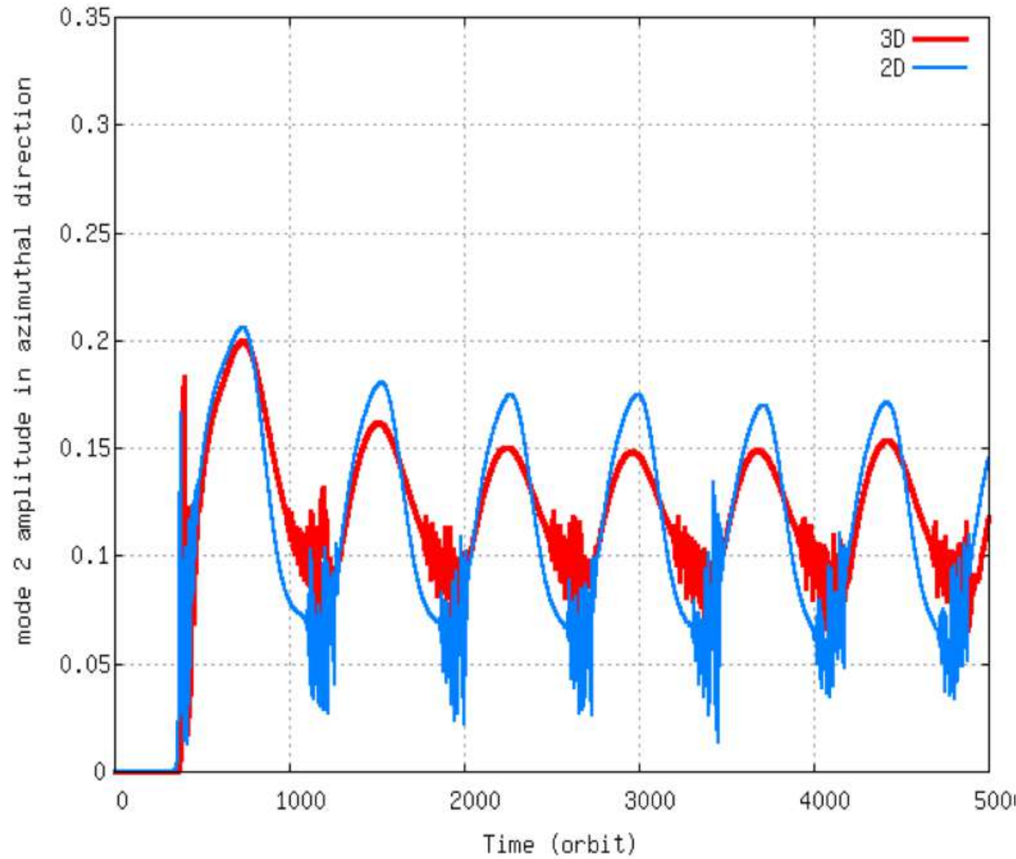


Σr at 11500 turns
4
3
2
1
0
−1
−2
−3
−4
−4
−3
−2
−1
0
1
2
3
4
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6

Evolution of m=1 and m=2 modes in 2D vs. 3D



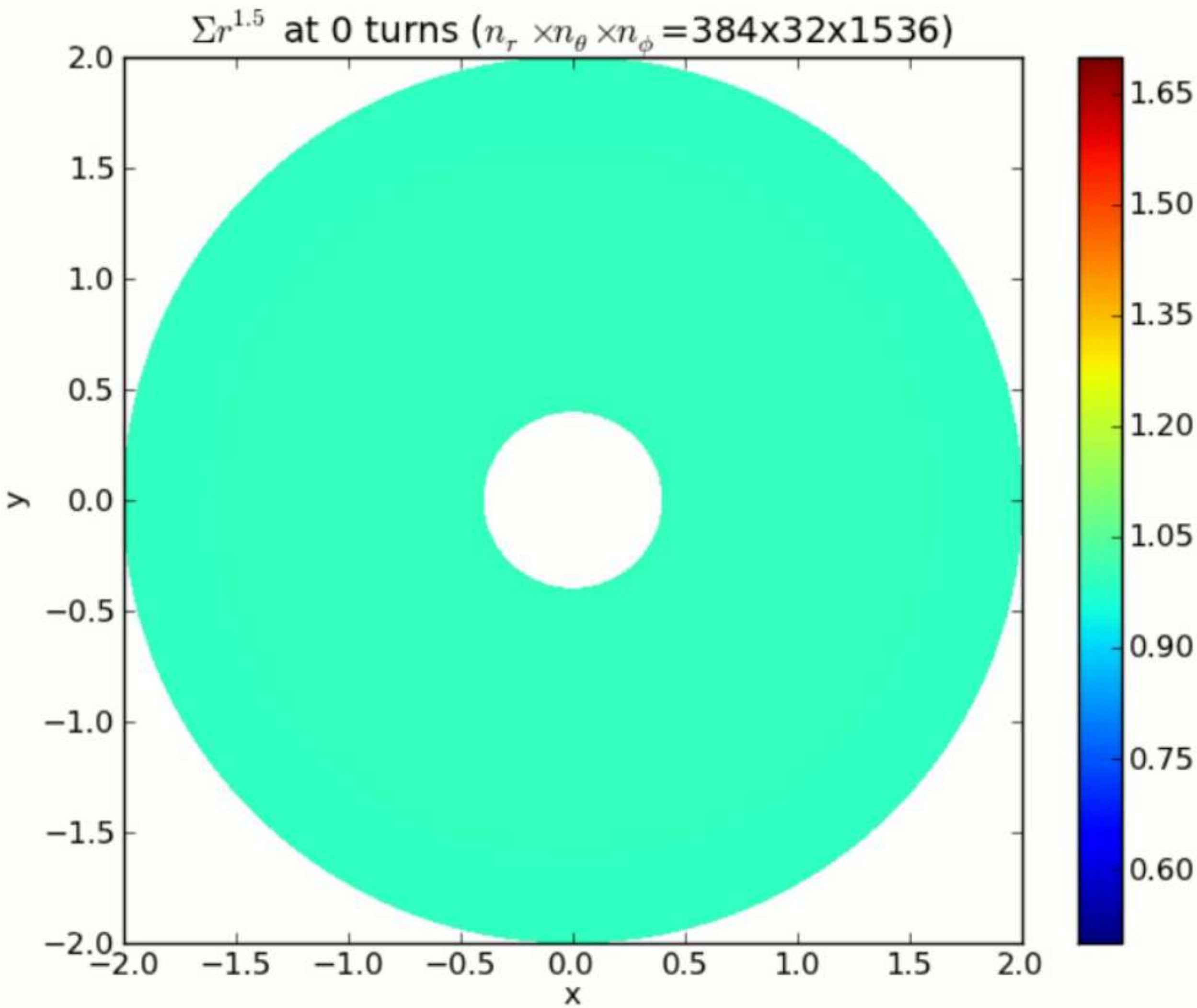
m = 1



m = 2

Case 2: Global Rossby Wave Instability excited by planet-disk interaction

If there is a protoplanet already, planet-disk interaction can excite Rossby Wave Instability

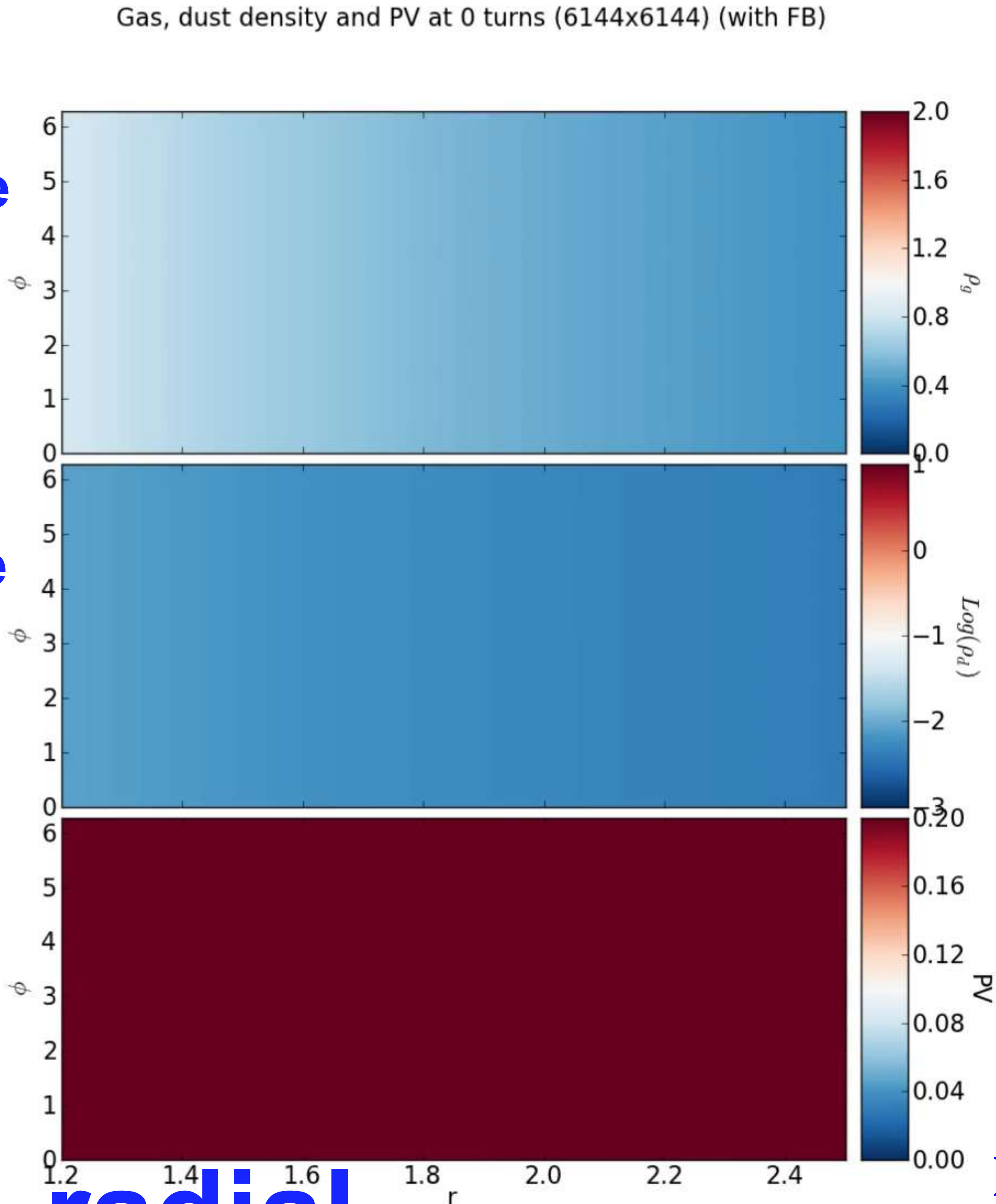


2D Global Simulations of gas-dust dynamics

Gas Surface density

Dust Surface density

PV



ϕ

radial

1 mm dust
d/g = 0.01
With feedback

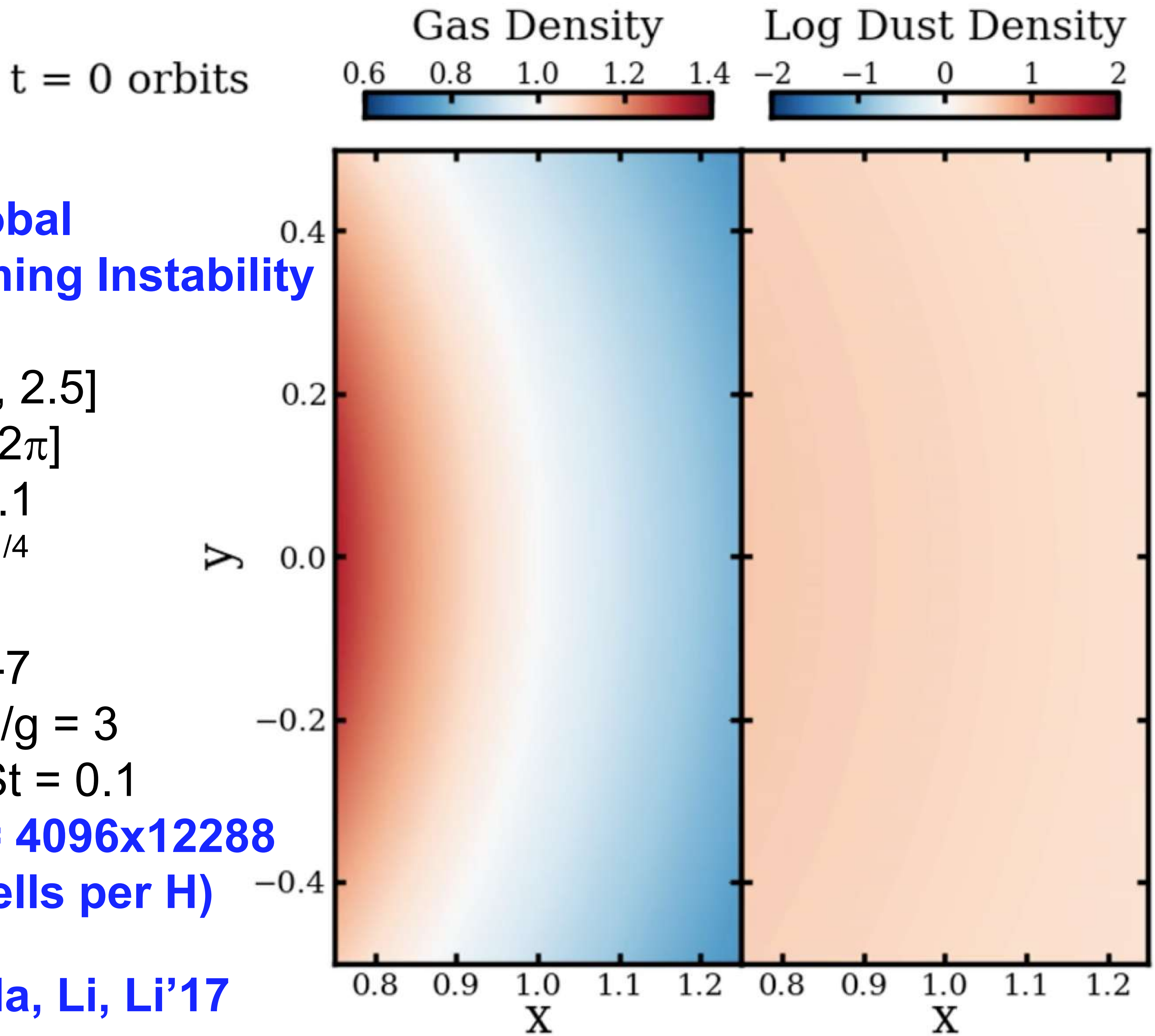
Vortex can "suck in" all the dust from the outer disk

Fu, Li et al. 2014b

Case 3: Local Shearing Instability excited gas-dust interaction (when dust/gas ratio exceeds unity)

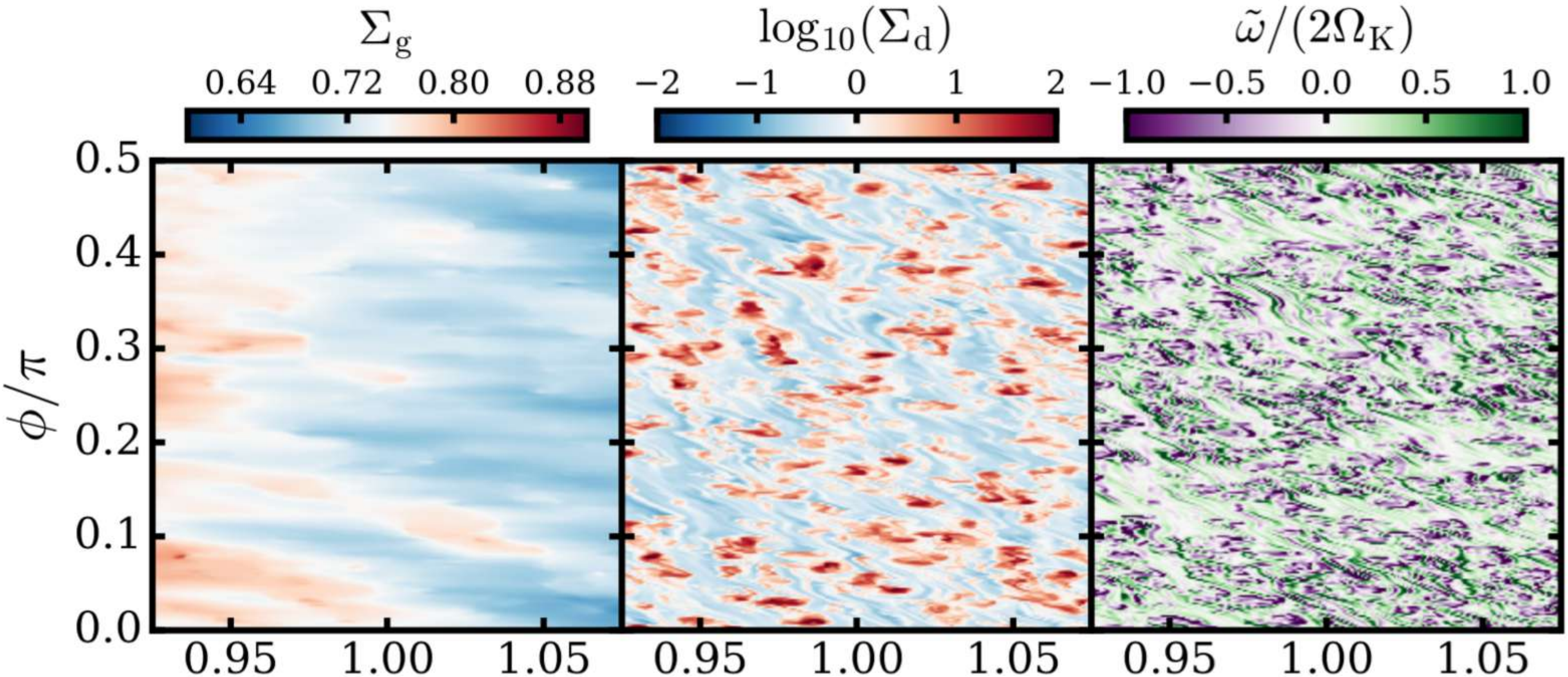
2D Global Streaming Instability

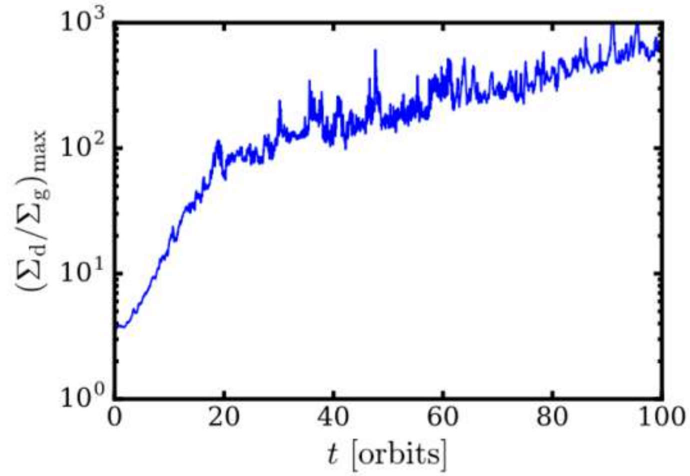
R=[0.4, 2.5]
ϕ = [0, 2π]
H/r = 0.1
$c_s \sim r^{-1/4}$
$\Sigma \sim r^{-1}$
α = 1e-7
initial d/g = 3
Initial St = 0.1
$n_r x n_\phi$ = 4096x12288
(196 cells per H)



Miranda, Li, Li'17

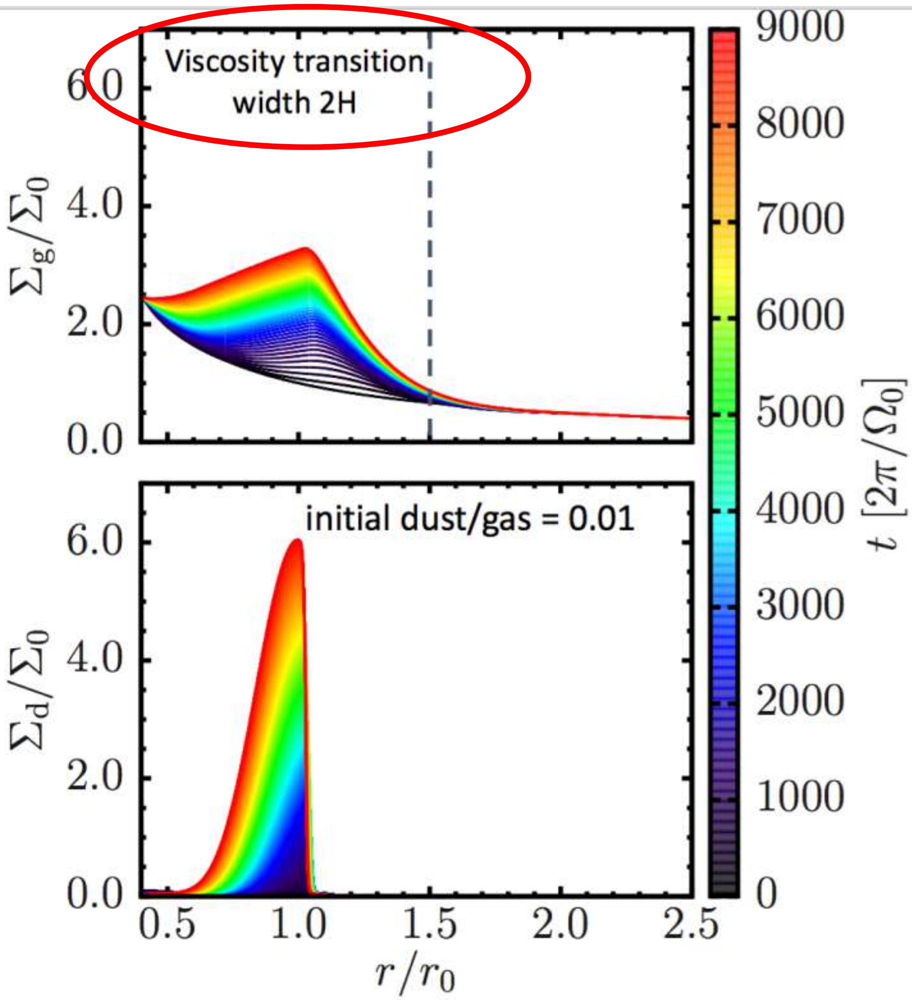
2D Global Streaming Instability



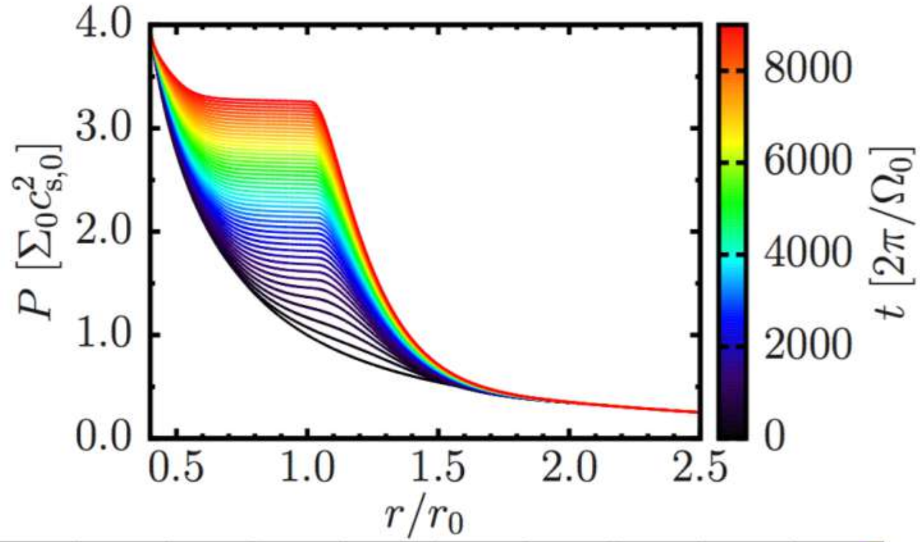


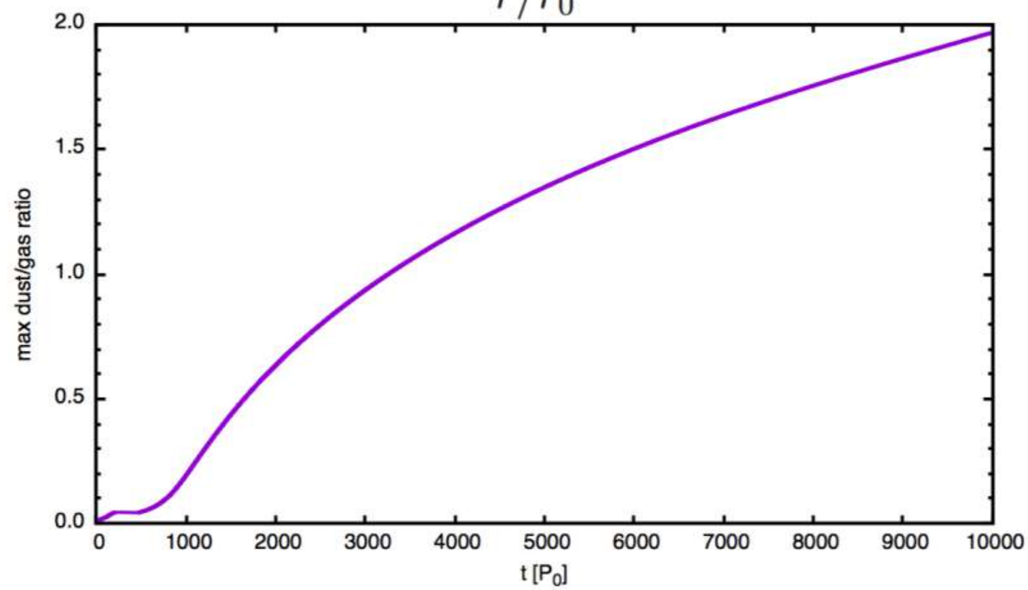
Miranda, Li, Li'17

1D (axisymmetric) Results



1D Evolution

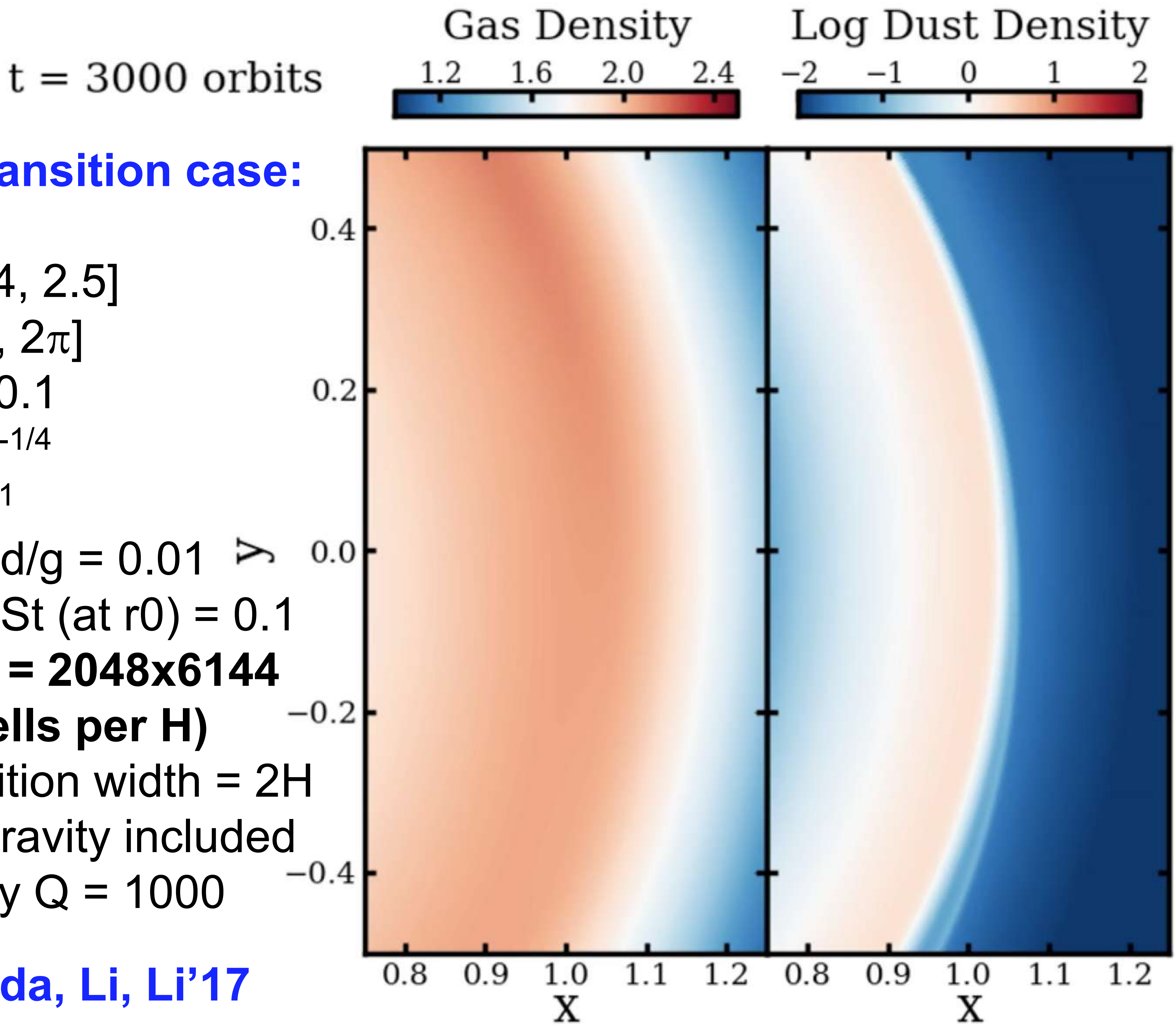




Miranda, Li, Li’17

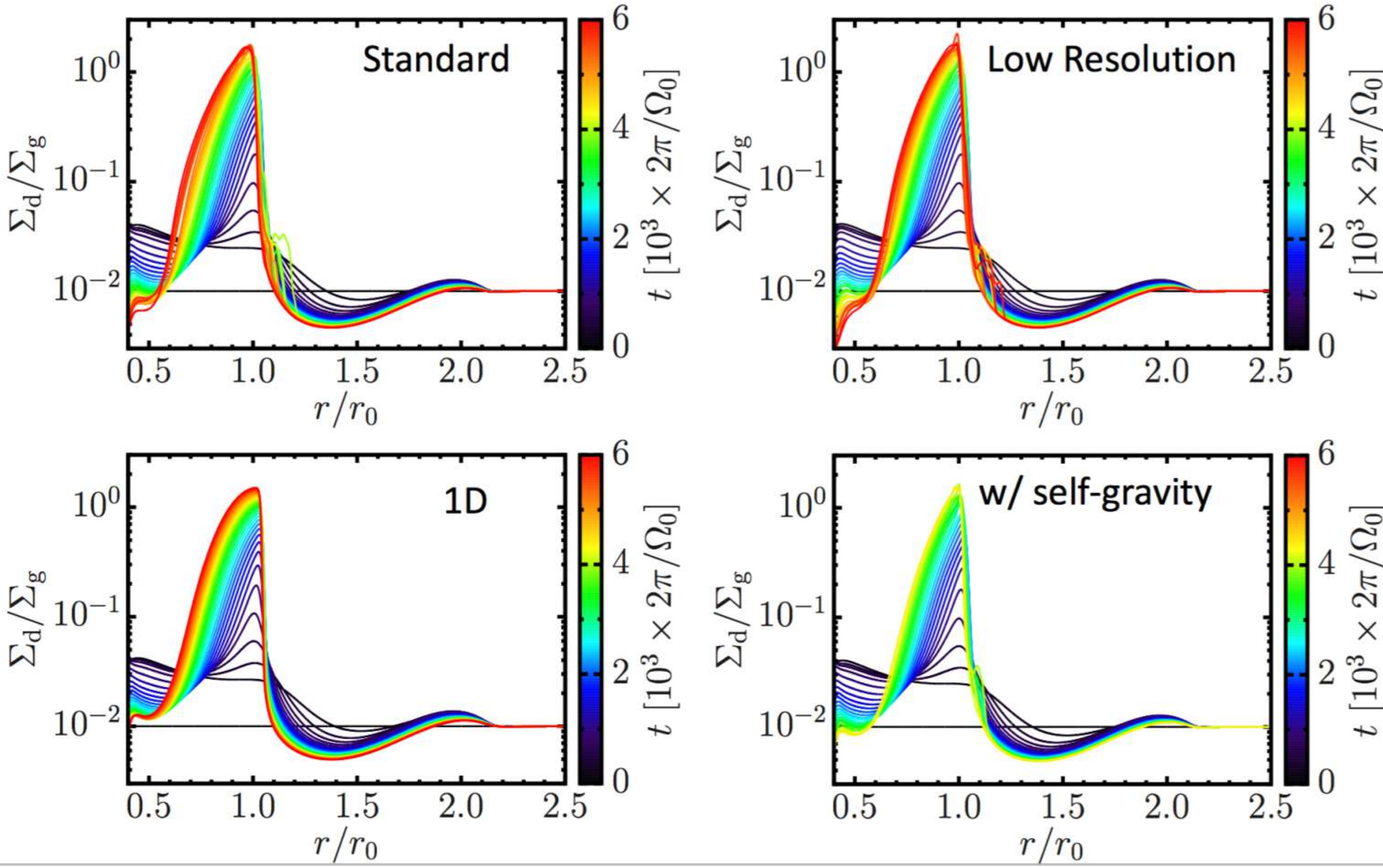
2D Transition case:

R=[0.4, 2.5]
ϕ = [0, 2π]
H/r = 0.1
$c_s \sim r^{-1/4}$
$\Sigma \sim r^{-1}$
Initial d/g = 0.01
Initial St (at r0) = 0.1
nrxnf = 2048x6144
(98 cells per H)
Transition width = 2H
Self-gravity included
Initially Q = 1000



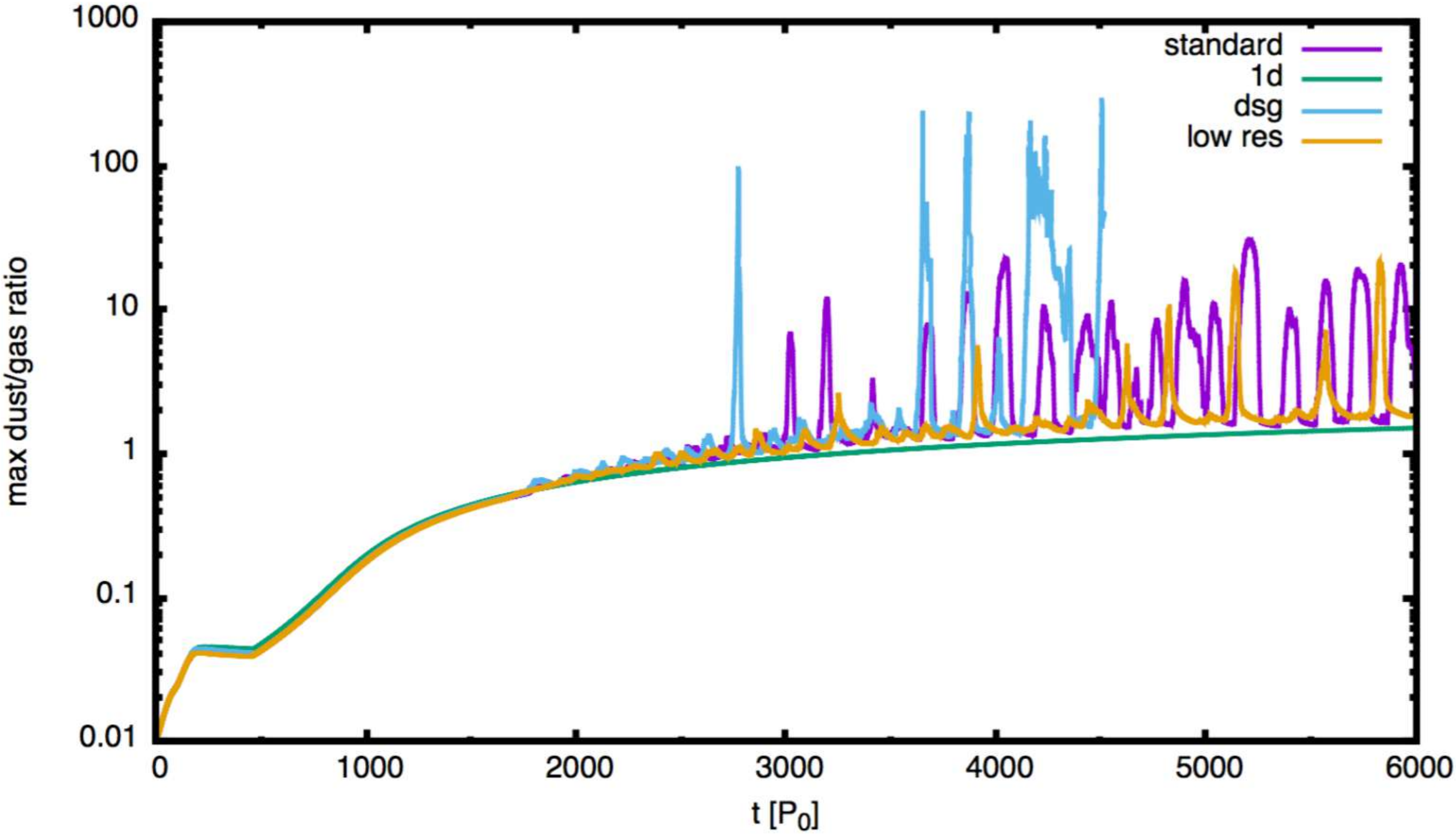
Miranda, Li, Li'17

Averaged Quantities (from 2D)



Miranda, Li, Li'17

Maximum dust/gas ratio (2D runs)



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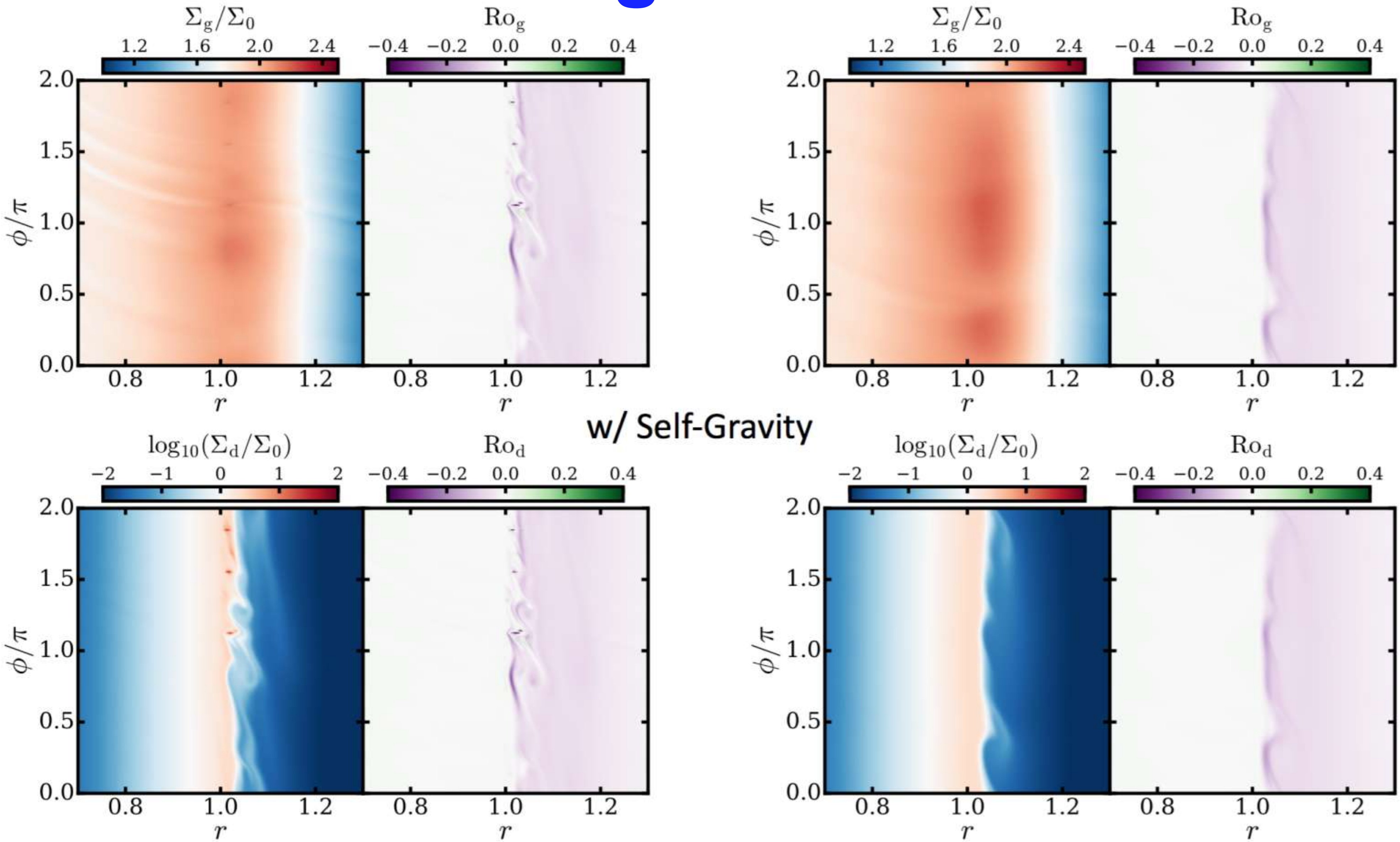
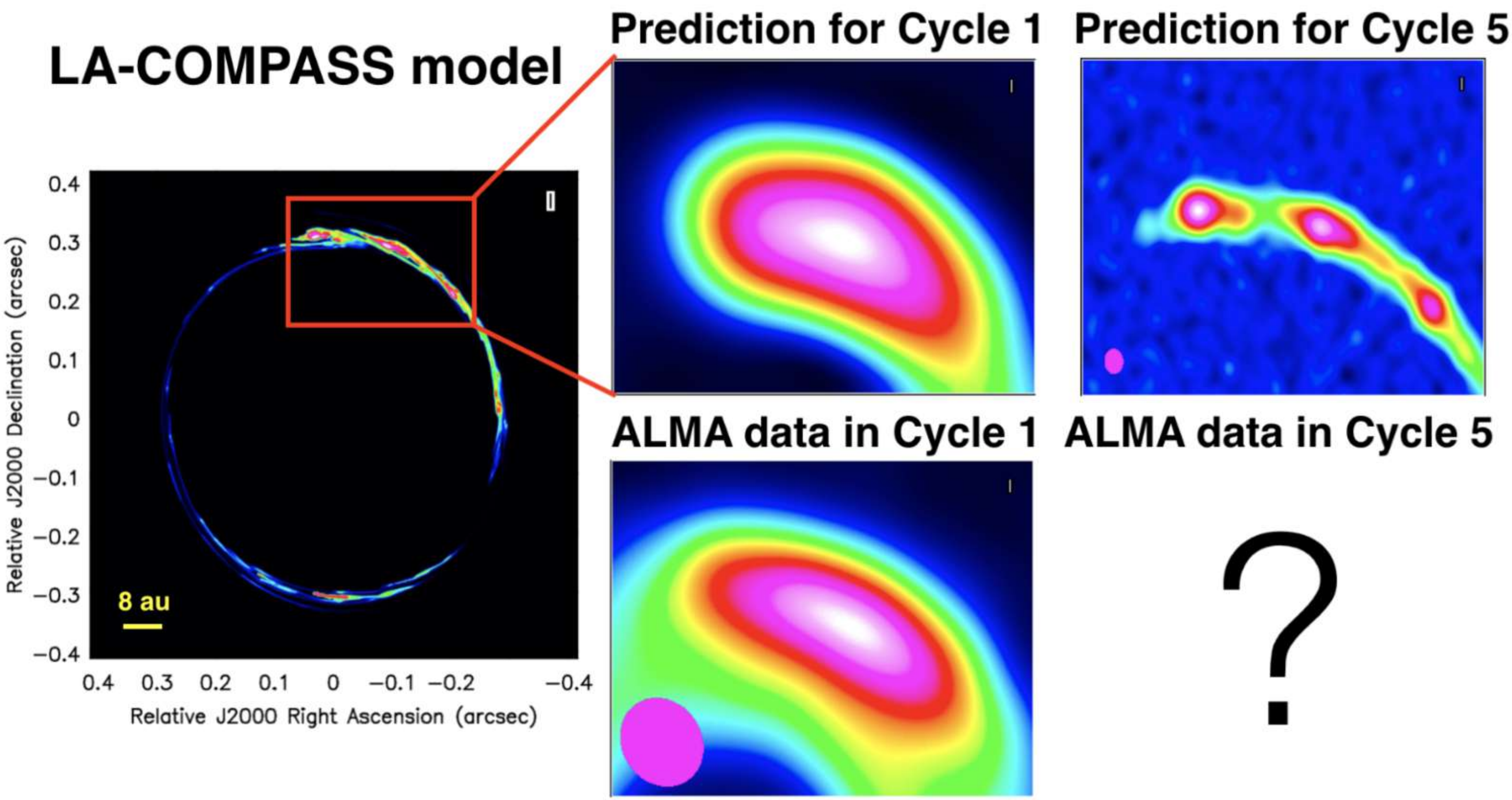
Dust Ring is unstable



Miranda, Li, Li'17

High Resolution ALMA should reveal finer features

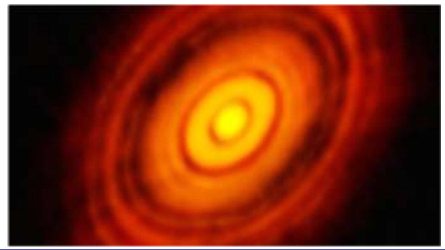


Ricci, Isella, Li et al.

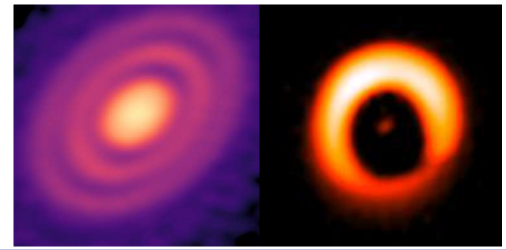
Summary

very young disks might be sufficiently massive to be unstable

some structures might be primordial



some structures might develop from fluid instabilities (e.g. Rossby waves and streaming instability)



Dust and solid particles decouples.
Concentration of particles leads to enhanced dust-to-gas ratio

Formation of planetary rocky cores

accretion of gas = formation of giant planets

Los Alamos National Laboratory

search

Center for Space and Earth Science

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In collaboration with Universities, the Center for Space and Earth Science (CSES) focuses on scientific understanding of fundamental physical processes that are critical to maintenance of habitat earth homeostasis with a long-term objective of achieving sufficient knowledge to identify the tipping points that can push habitat earth out of its homeostatic equilibrium, homeostatic imbalance.

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cses.lanl.gov

Student Fellows (3 yr)
Postdoc Fellows (2 yr)

PlanetFormation@Rice

planetformation.rice.edu

@ LANL

Postdoctoral Scholars

Yann Boehler

Luca Ricci

Shangfei Liu

Grads

Erik Weaver

Jason Ling

LANL collaboration

Hui Li

Shengtai Li (LANL)

Yaping Li (SHAO)

Pinghui Huang (PMO)

Ruobing Dong (U Arizona)