Evolution of Circumstellar Disks and Planet Formation

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Jet Propulsion Laboratory

Funding

Exoplanet Research Program XRP - 2018

NRAO 2017

XRP - 2016

HST Cycle 24, 2016

Sagan Program, 2012

NSF AST 2010

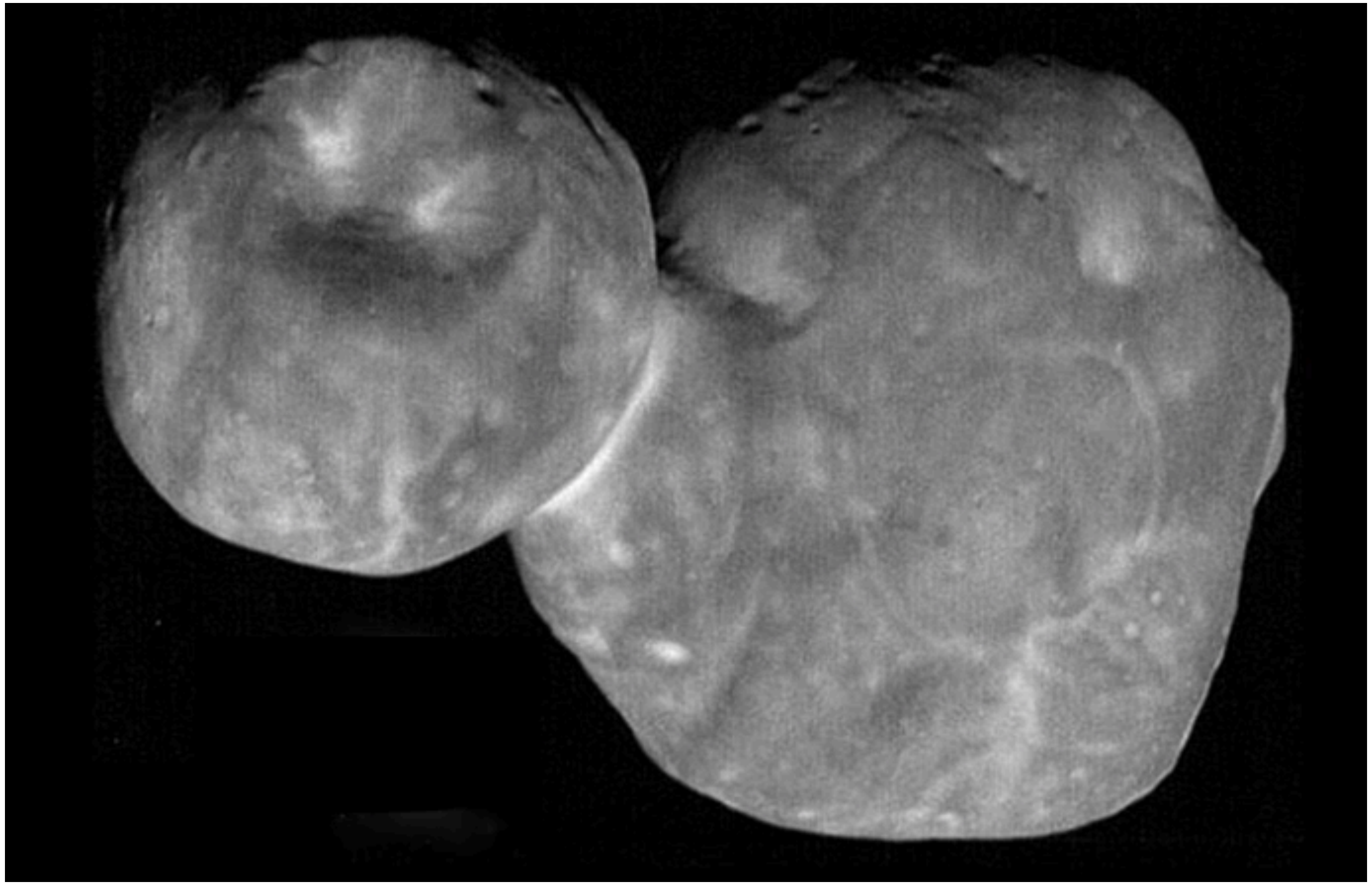
Computational Facilities

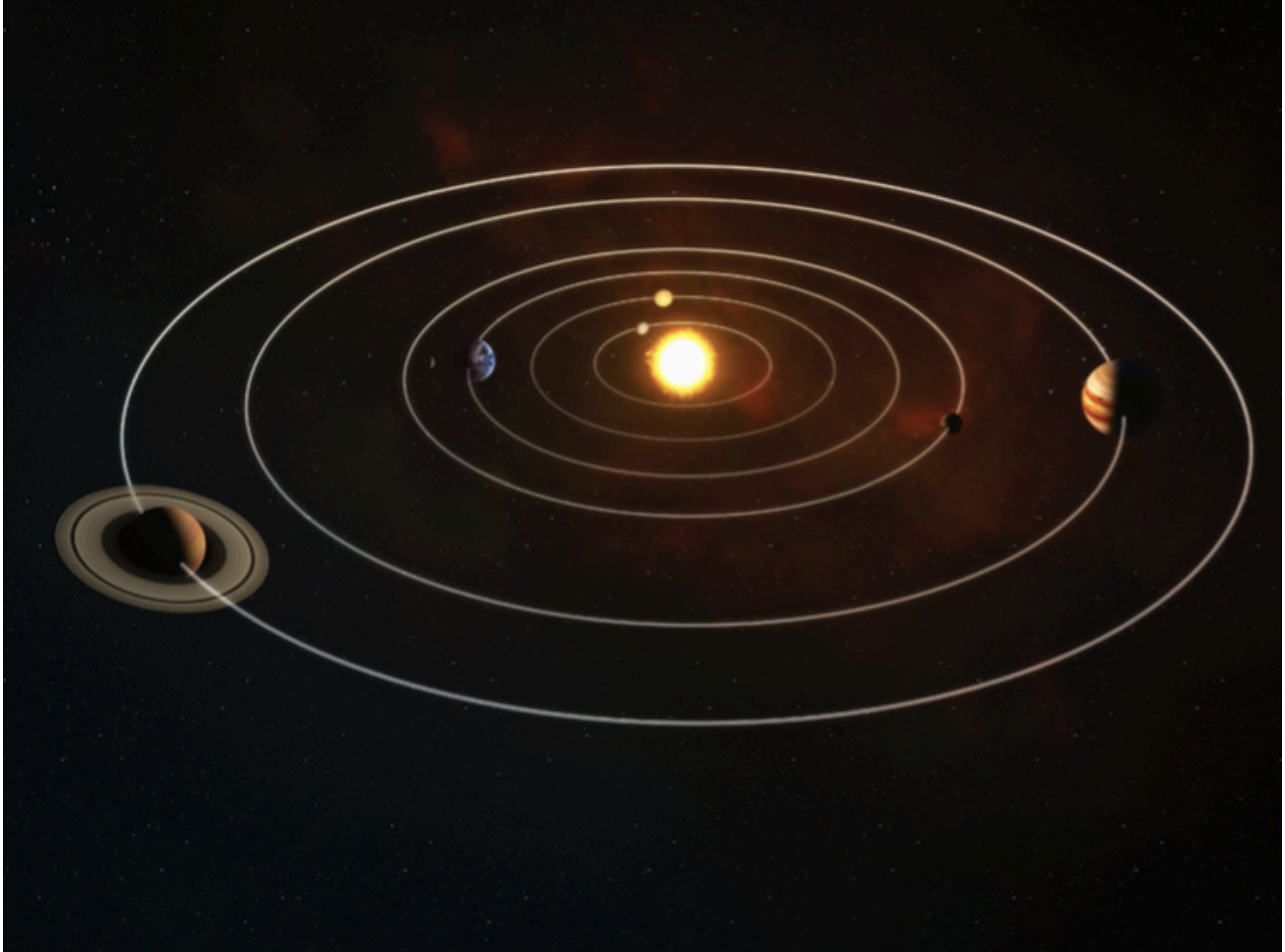
NMSU, Mar 22th, 2019

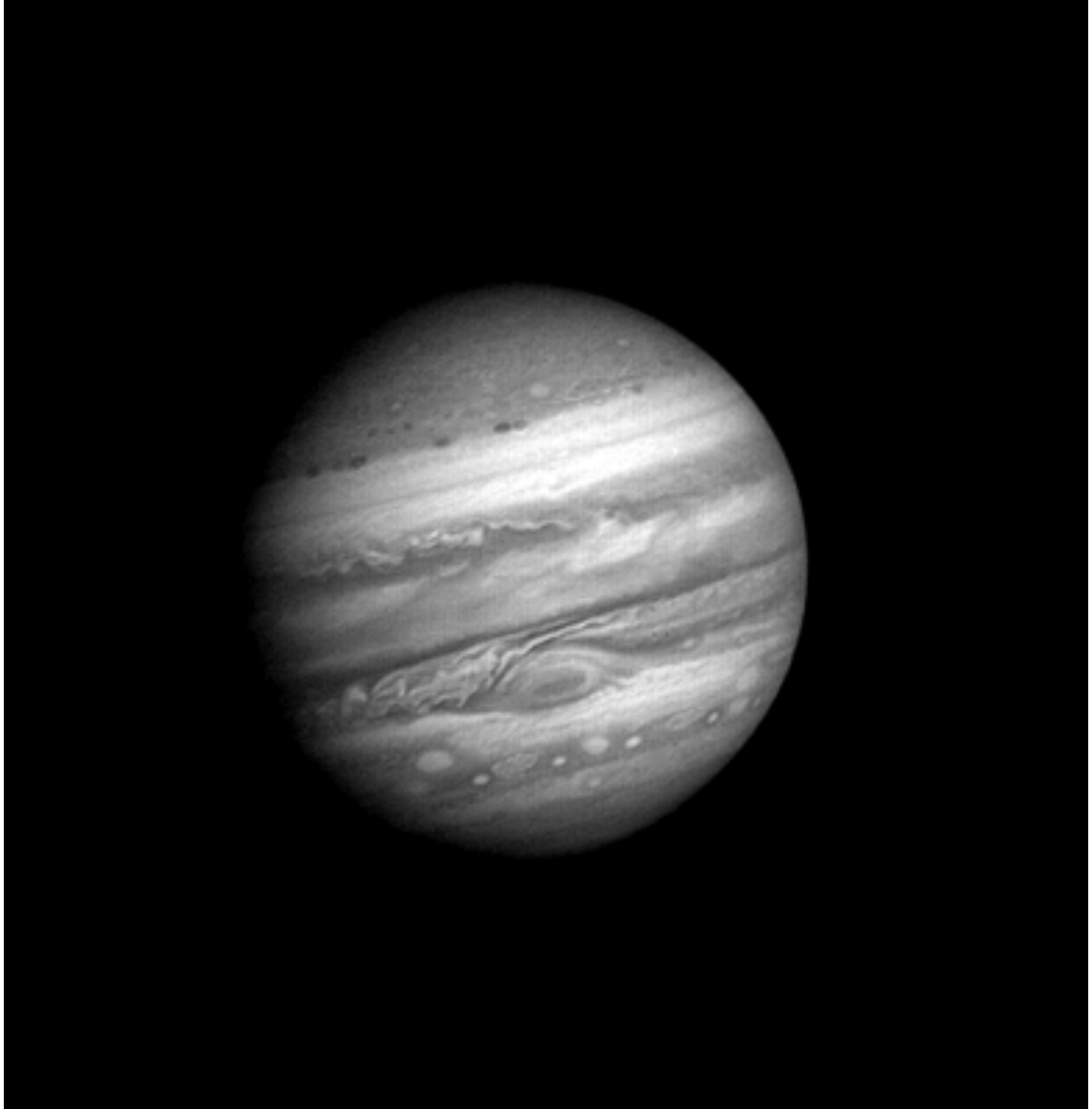
Outline

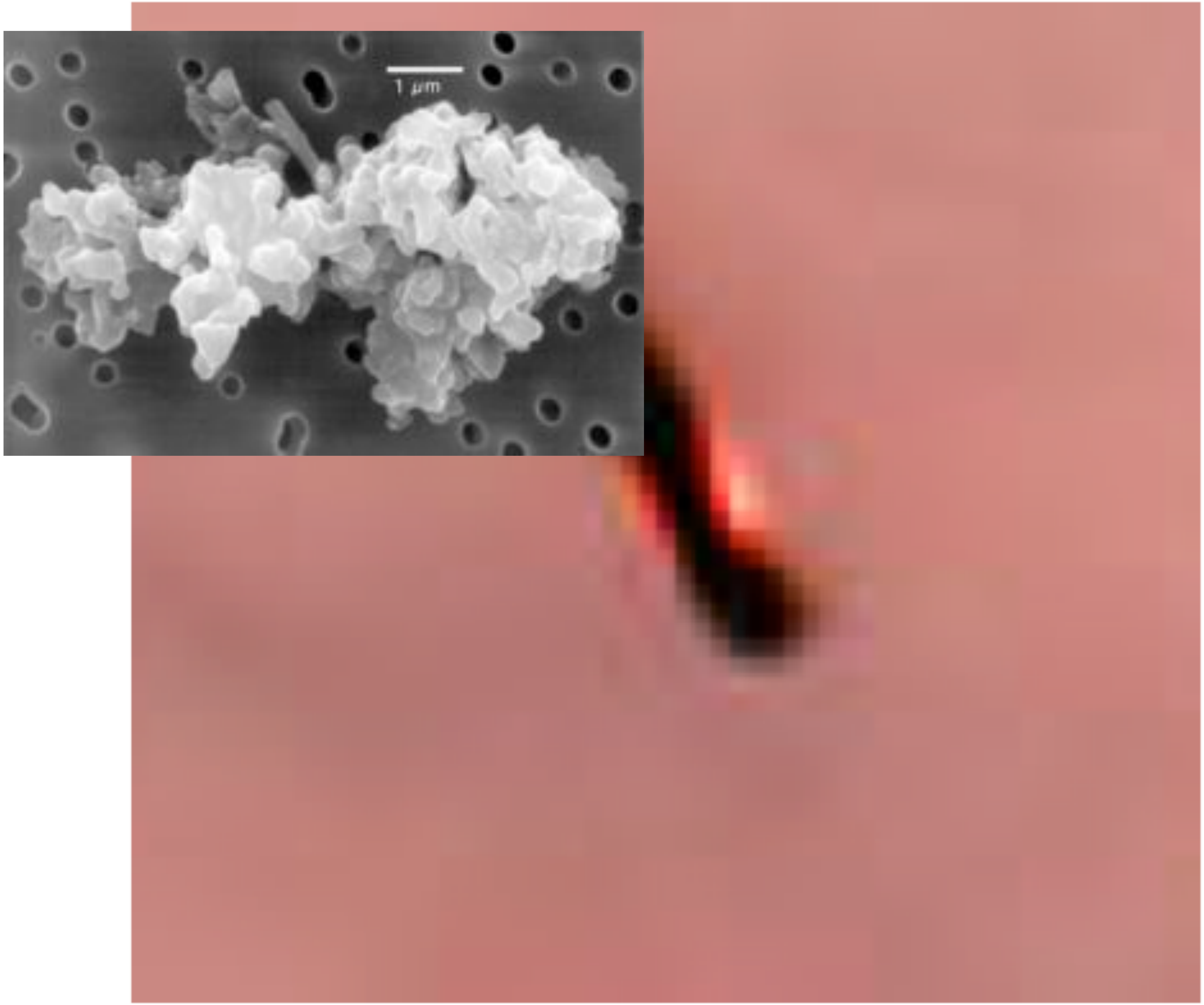
- Planet Formation
- Disk Observations
- The ALMA Revolution
- Planet signatures in disks
- Black hole mergers in AGN disks
- Ice Convection in Europa

Part 1. Planet Formation








1 μm

Circumstellar/Protoplanetary Disks

PP disk fact sheet

Density: $10^{13} – 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

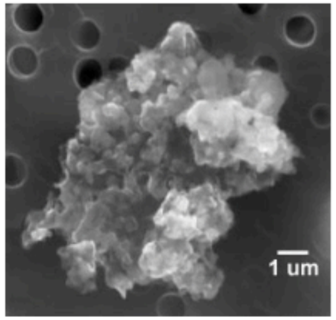
Temperature: 10-1000 K

Scale: 0.1-100AU

Mass: $10^{-3} – 10^{-1}$ M_{sun}

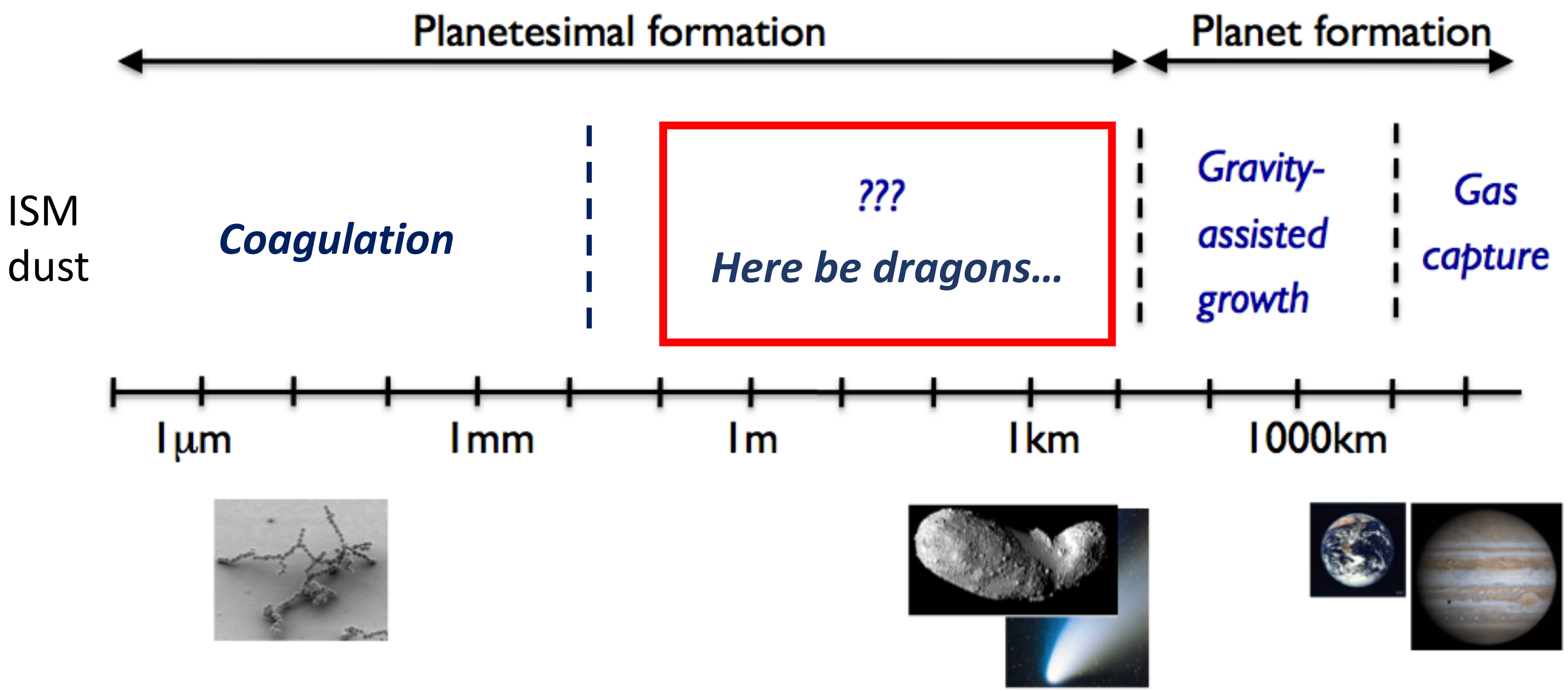
Planet Formation

“Planets form in disks of gas and dust”

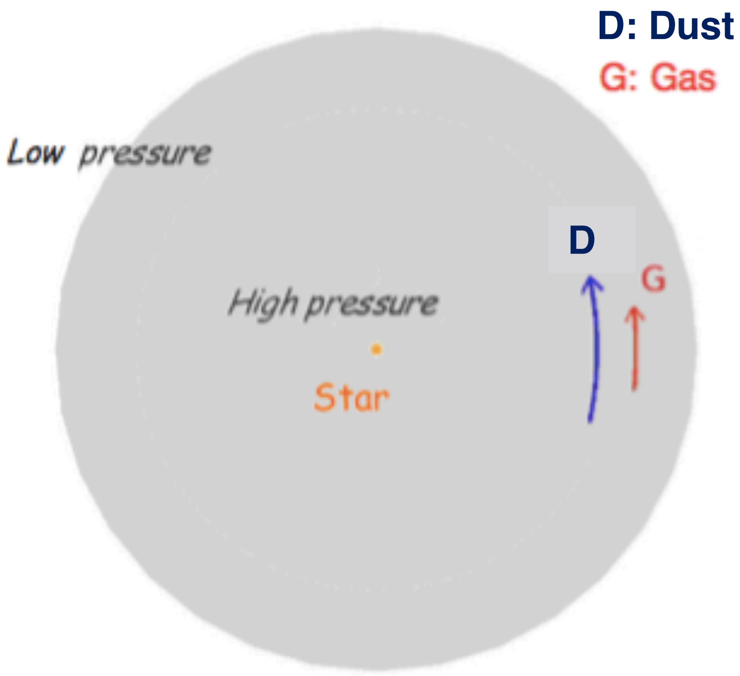


A miracle happens →

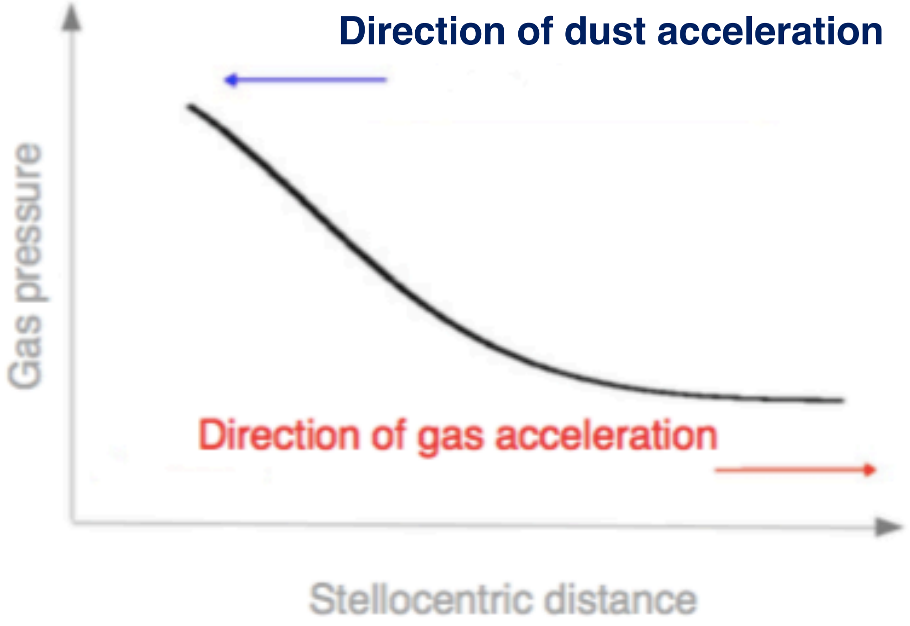
Dust evolution



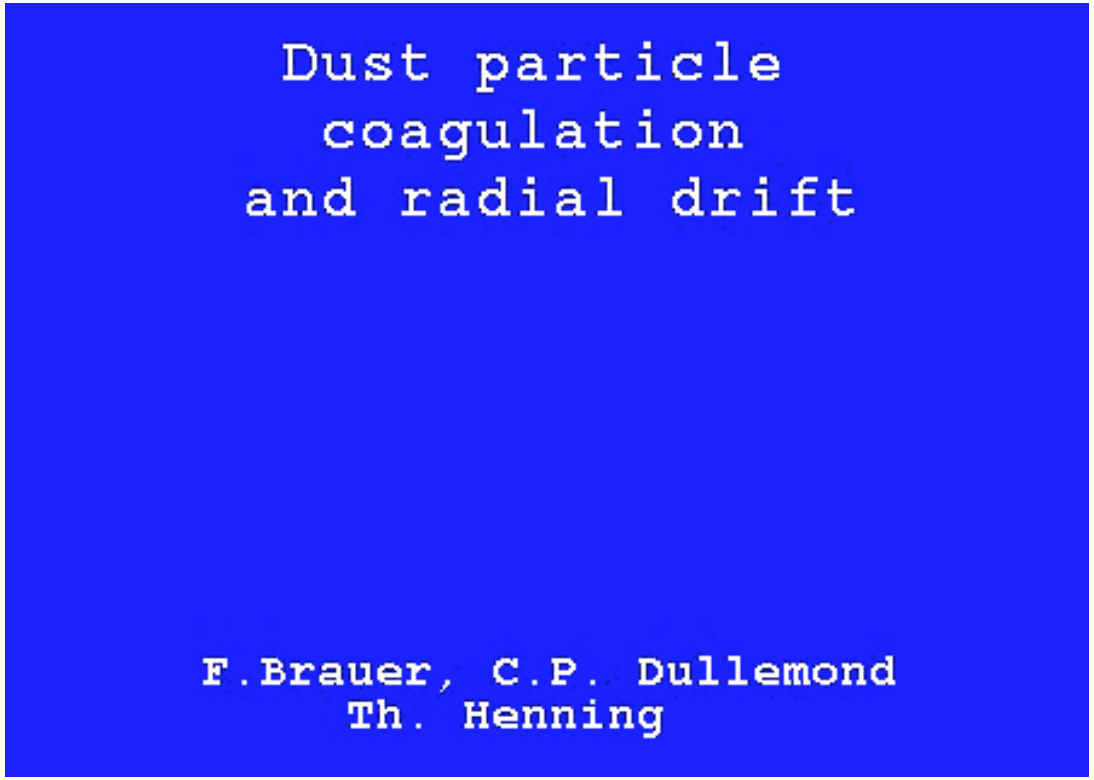
Dust Drift



Adapted from Whipple (1972)



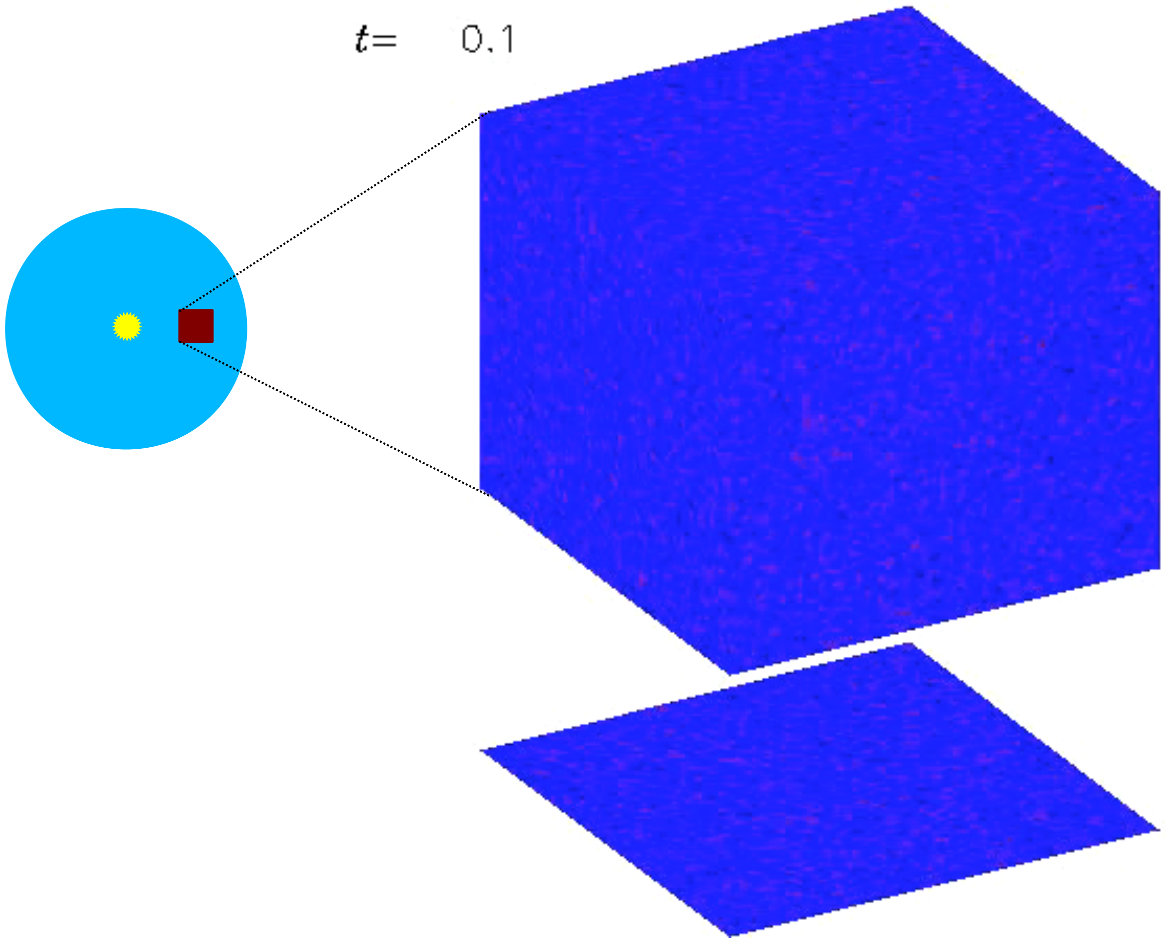
Dust coagulation and drift



Brauer+ '08

Streaming Instability

The dust drift is hydrodynamically unstable

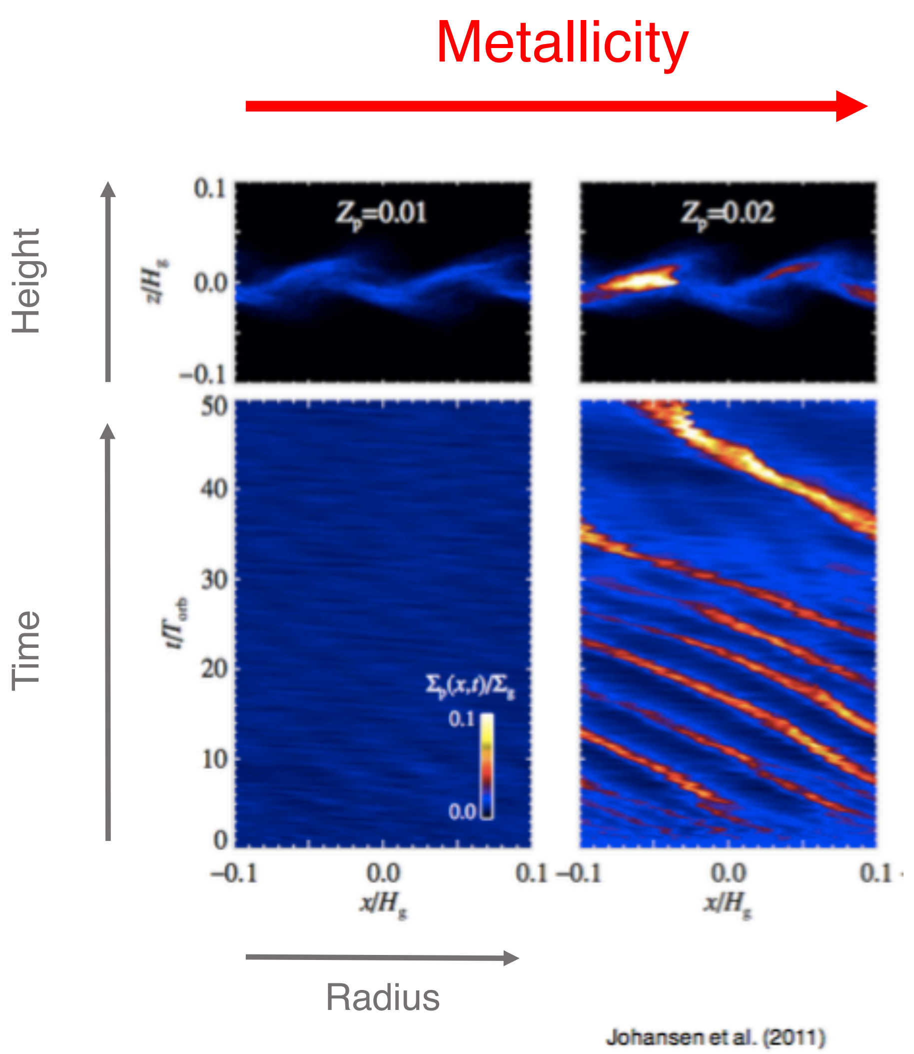


Youdin & Goodman ‘05,
Johansen & Youdin ‘07,
Youdin & Johansen ‘07

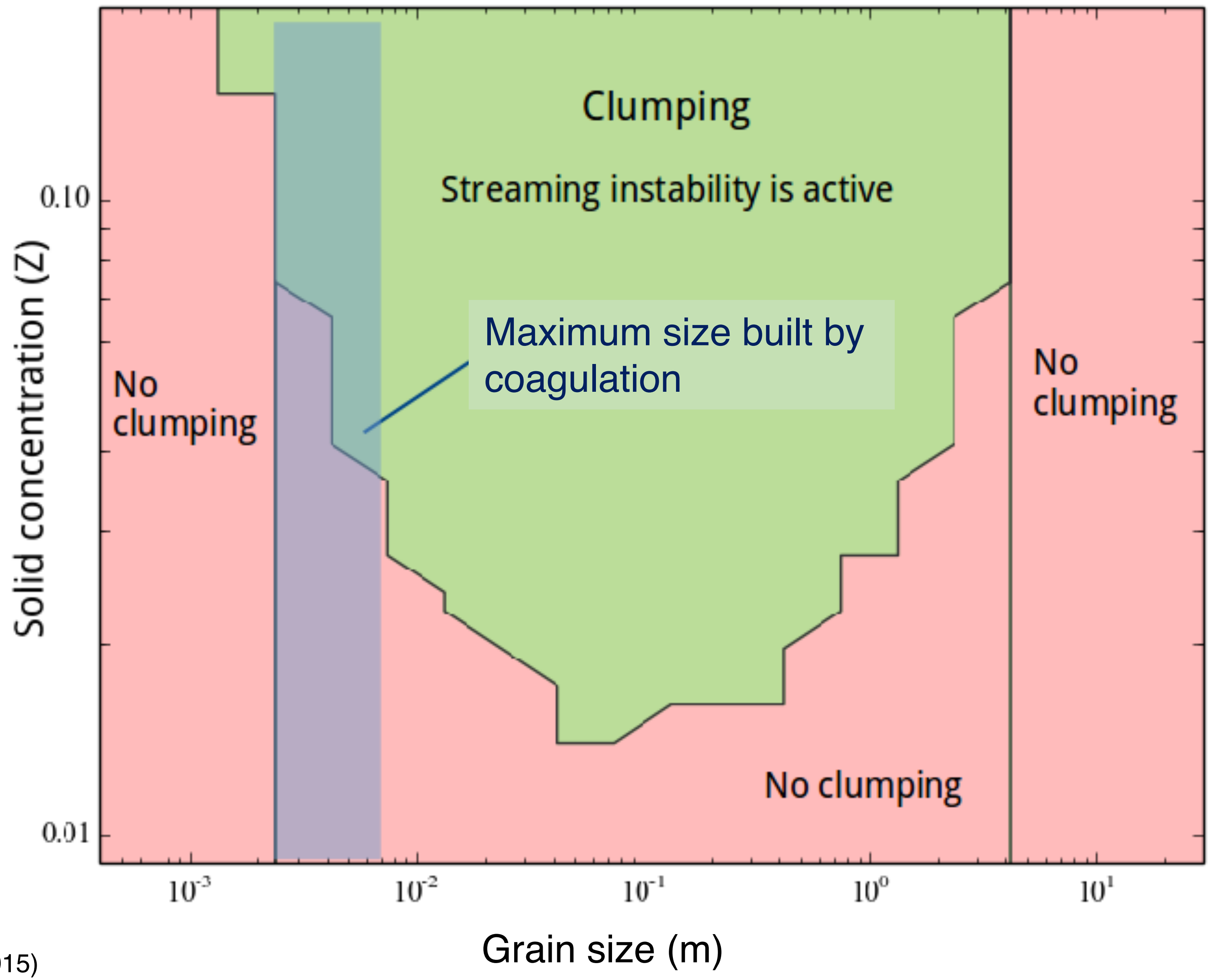
Streaming Instability does not "work" for solar composition

Solar composition:

H (X) ~ 0.74
He (Y) ~ 0.25
Metals (Z) ~ 0.01

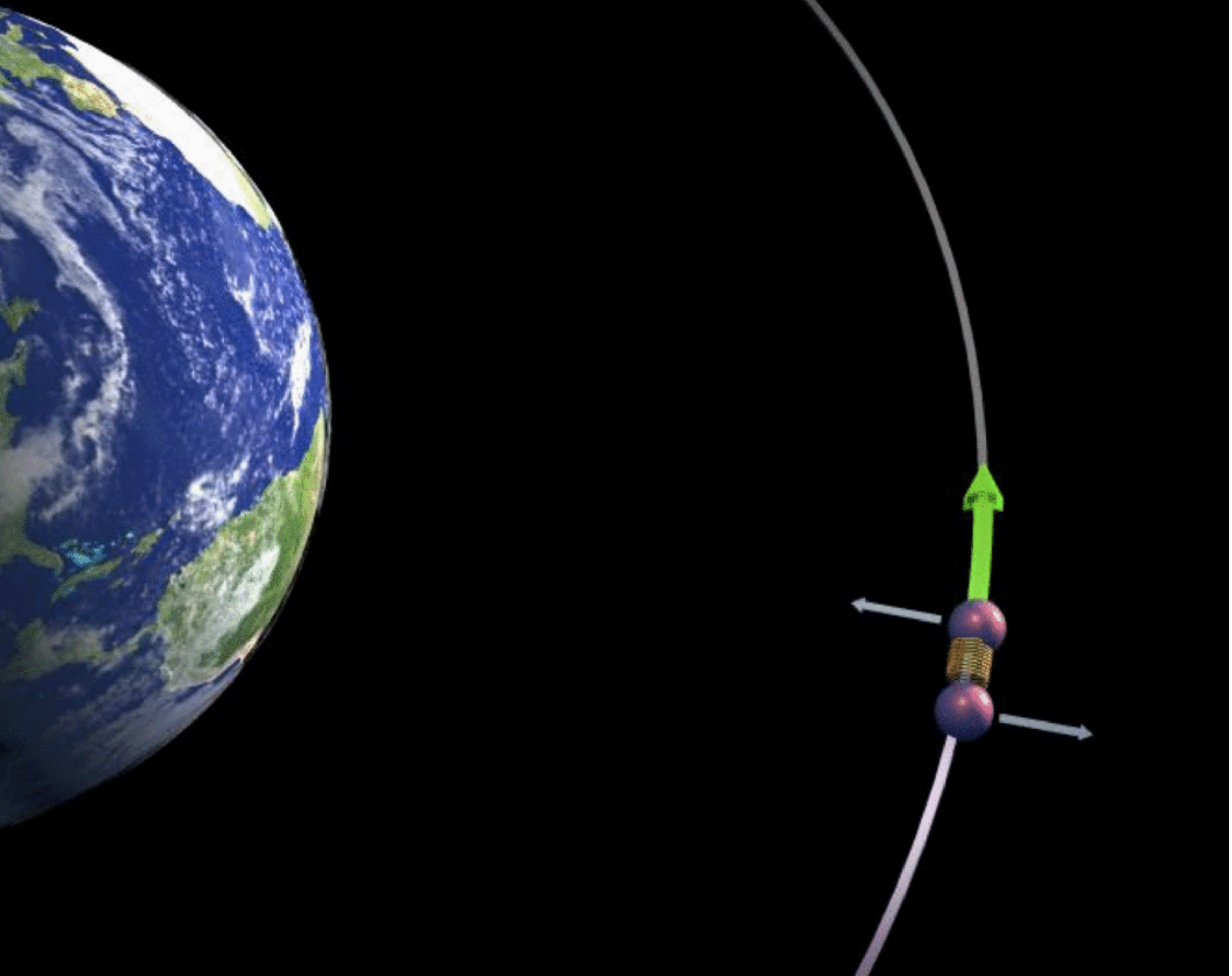


Streaming instability does not "work" for solar metallicity



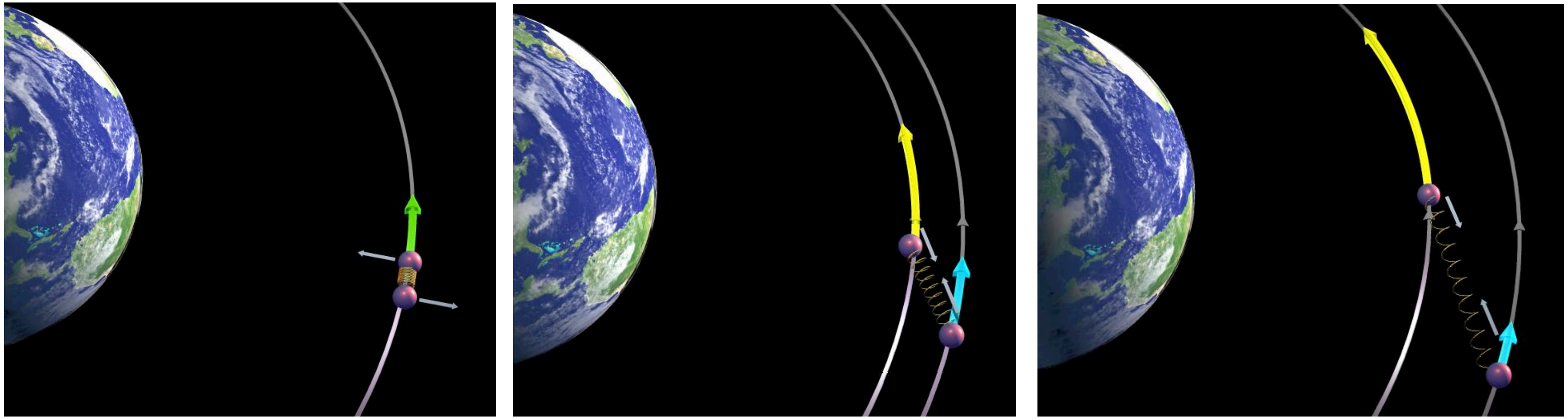
Carrera et al. (2015)

Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk



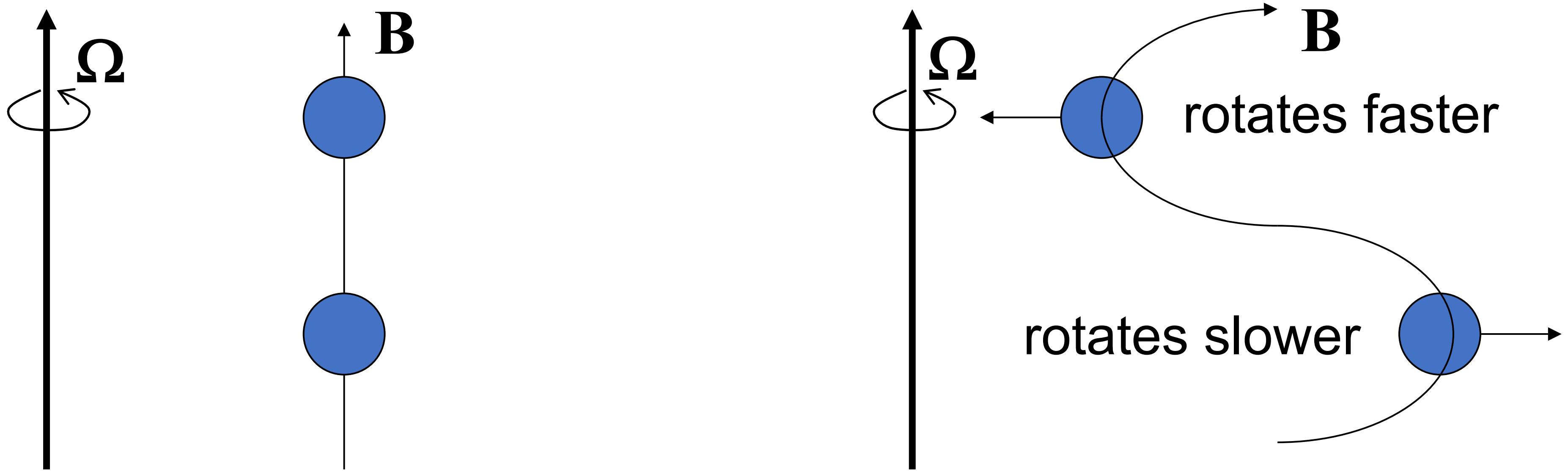
Stretching builds up tension

Tension resists shear



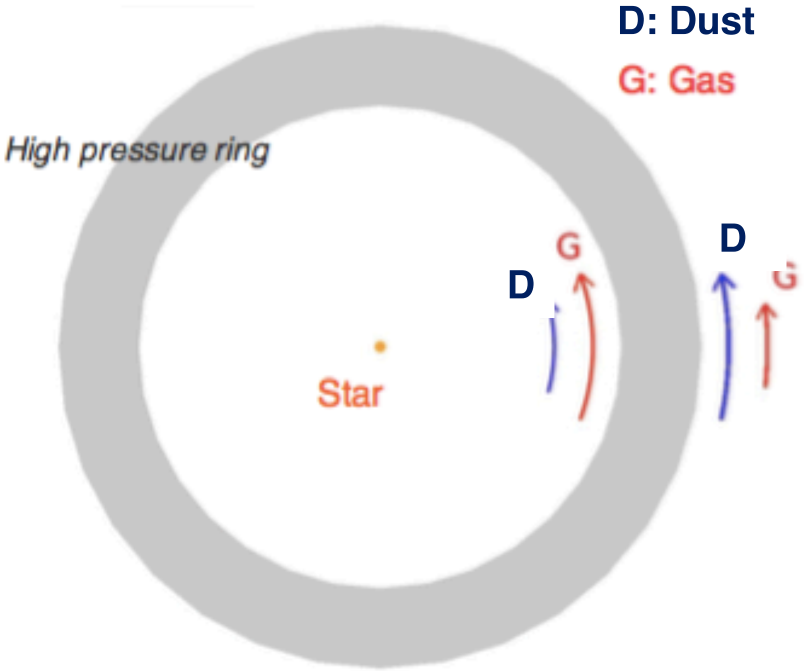
Beads exchange angular momentum

Magnetorotational Instability (MRI)



Magnetic fields
in a conducting rotating plasma behave
EXACTLY like ***springs***!

Pressure Trap



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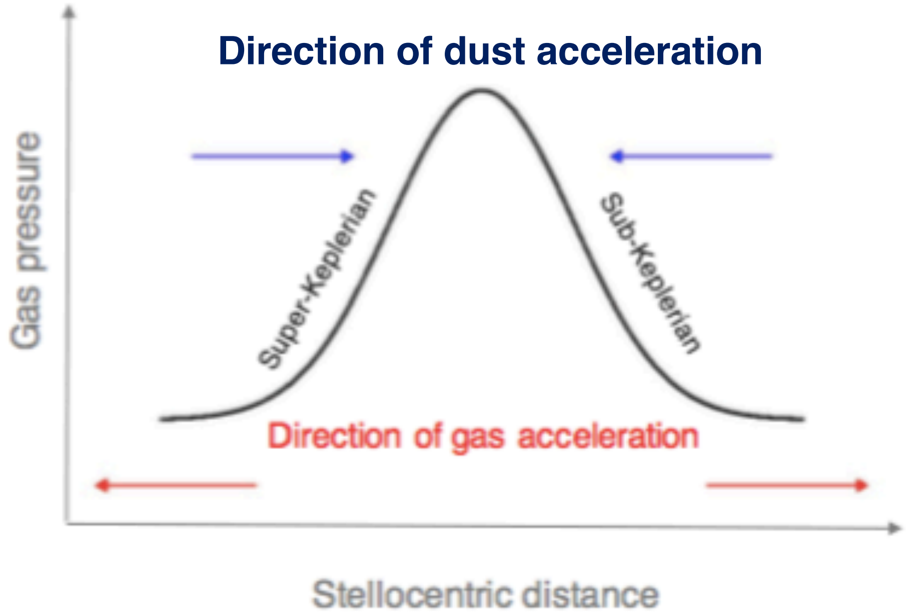
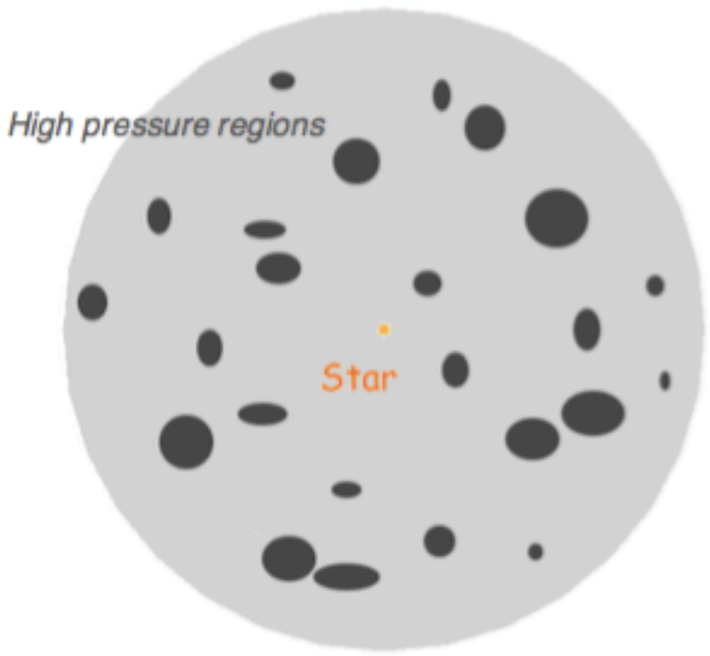
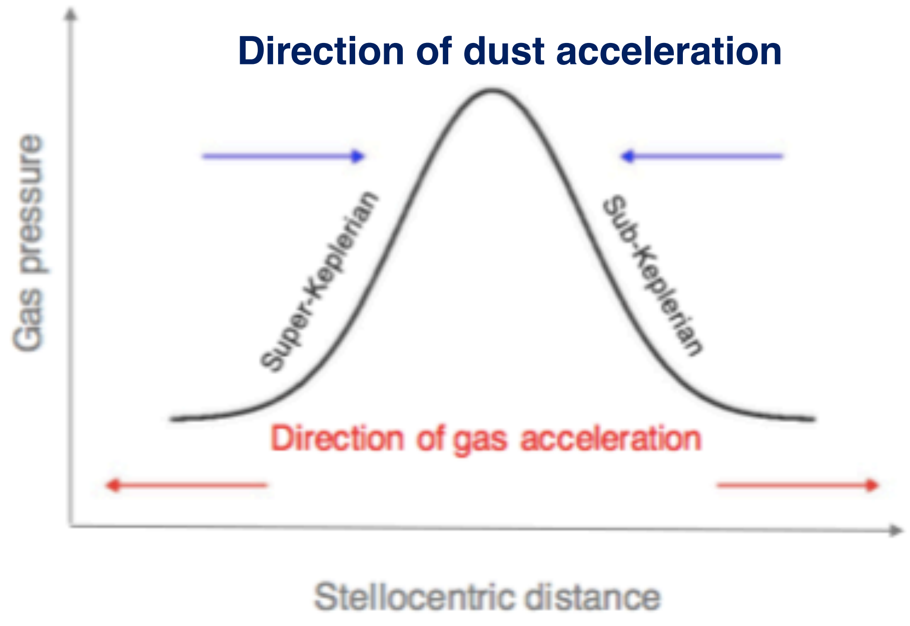
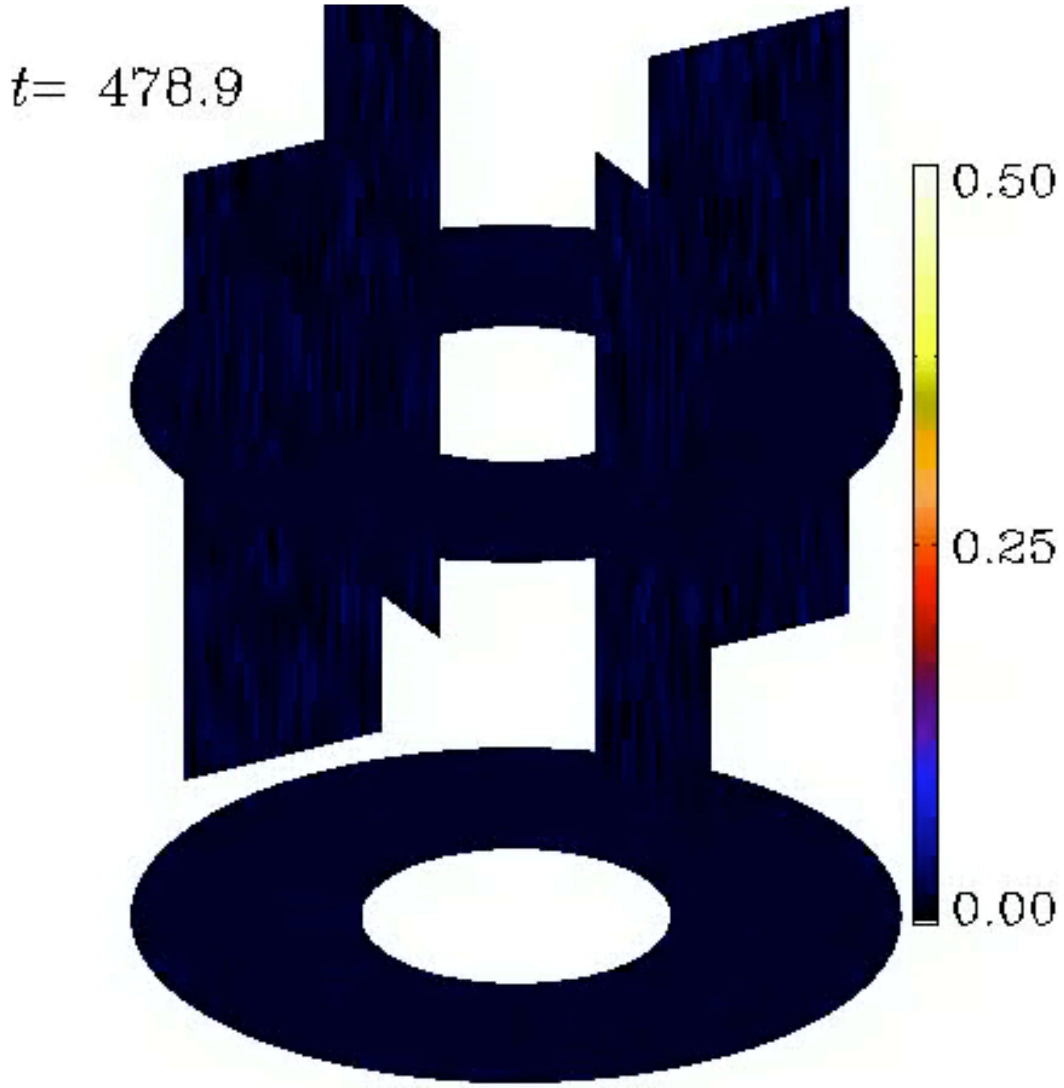


Turbulence


High pressure regions
Star

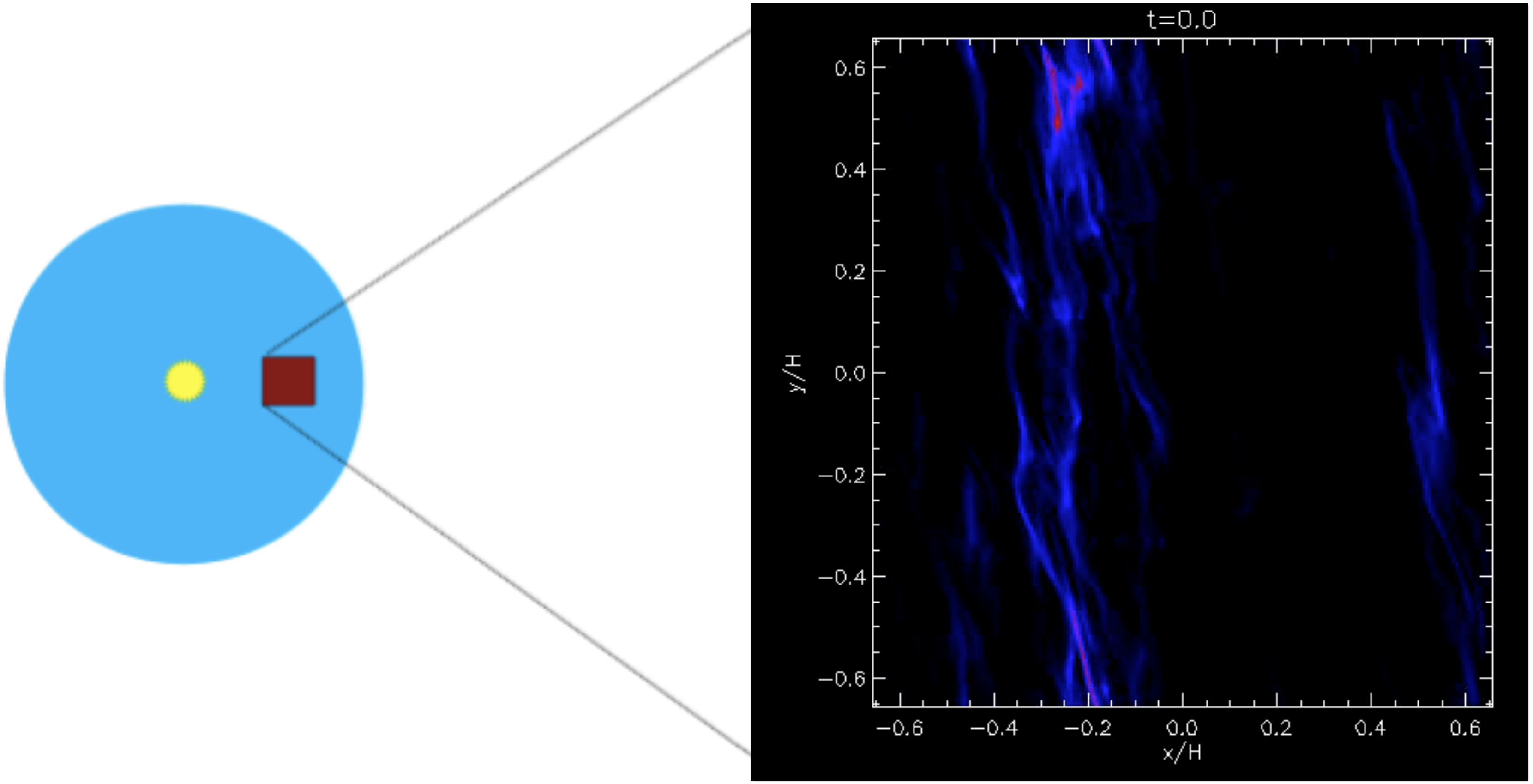

Direction of dust acceleration
Gas pressure
Super-Keplerian
Sub-Keplerian
Direction of gas acceleration
Stellocentric distance

Turbulence concentrates solids mechanically in pressure maxima



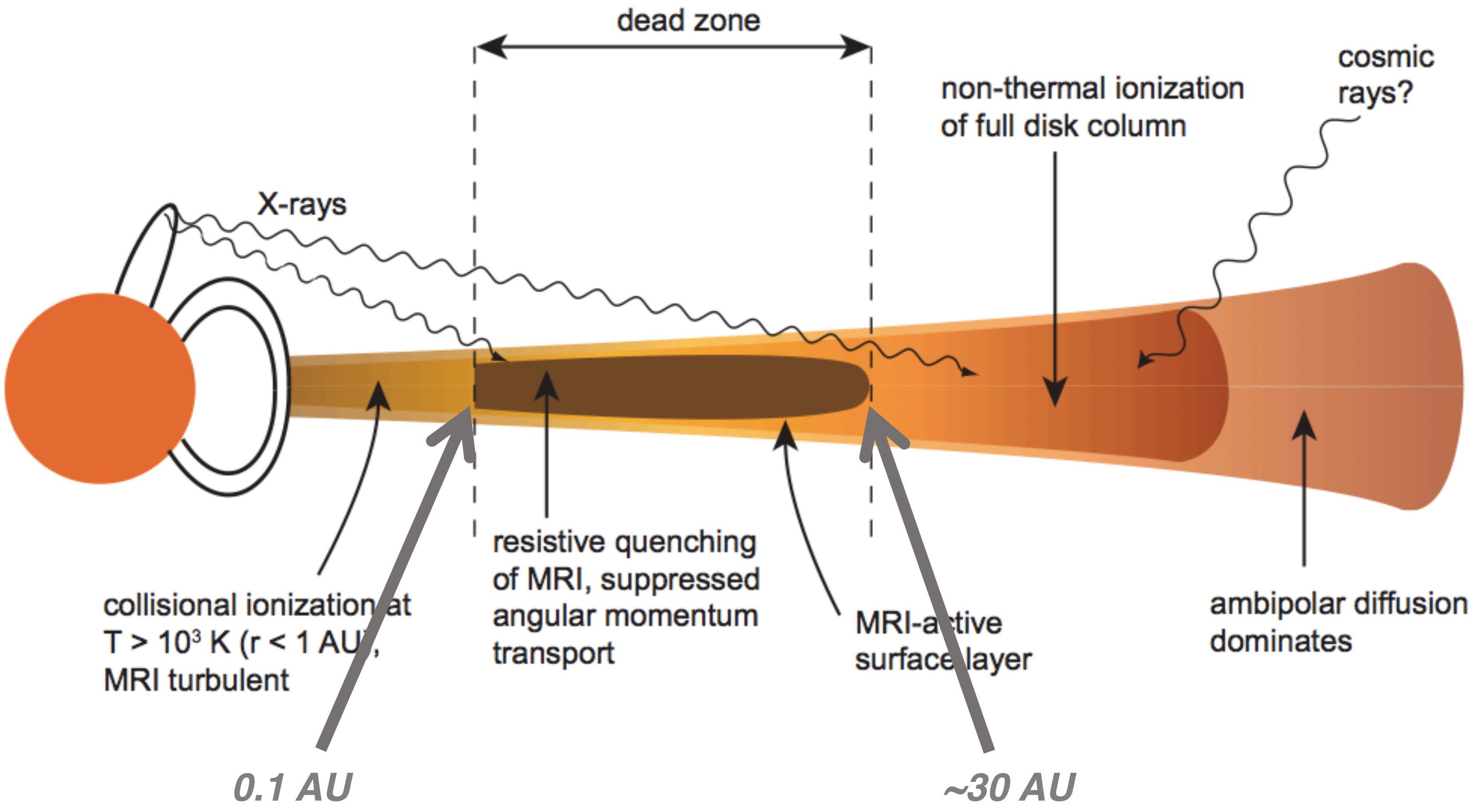
Lyra et al. (2008a)

Gravitational collapse into planetesimals



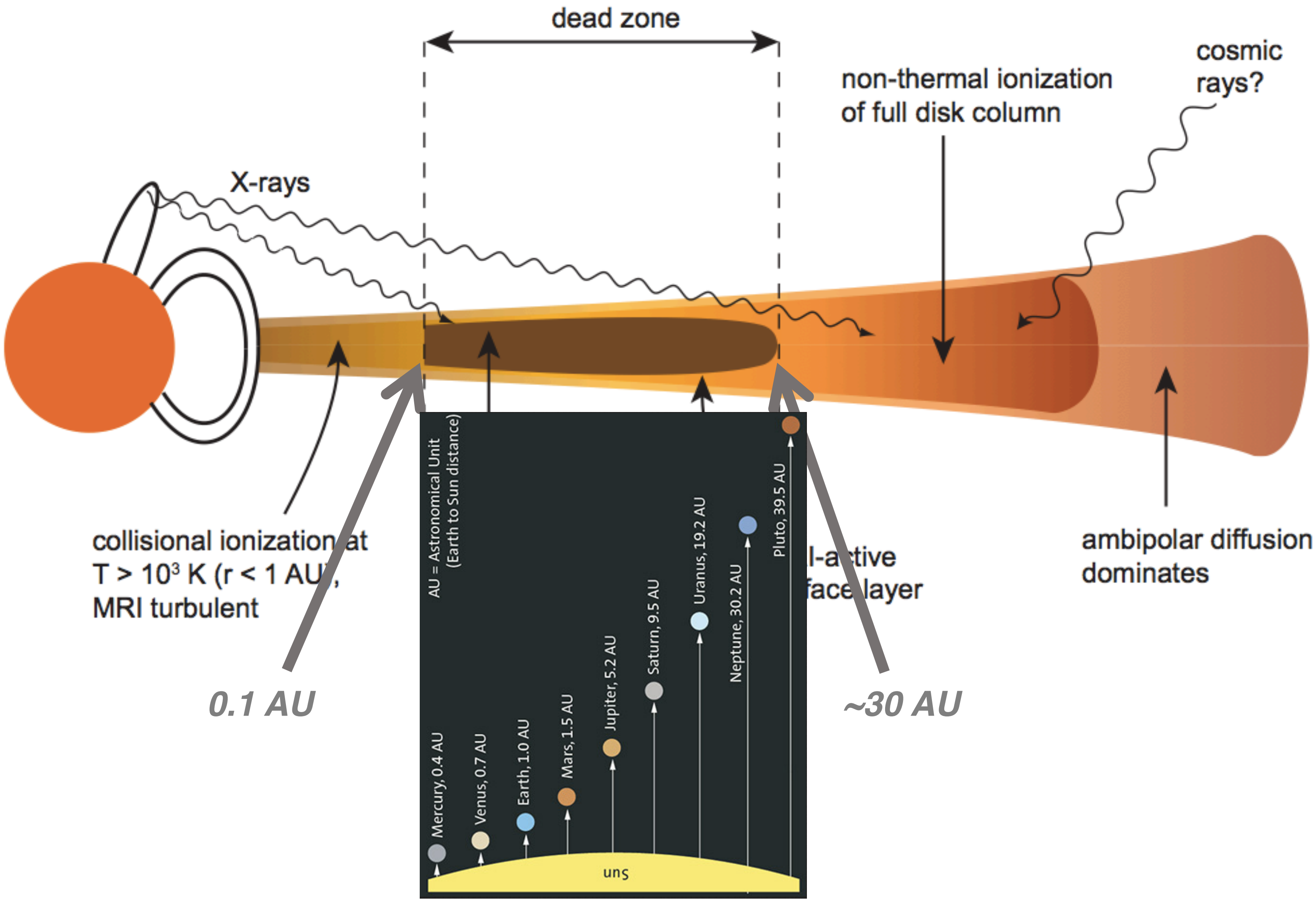
Johansen et al. (2007)

Dead zones

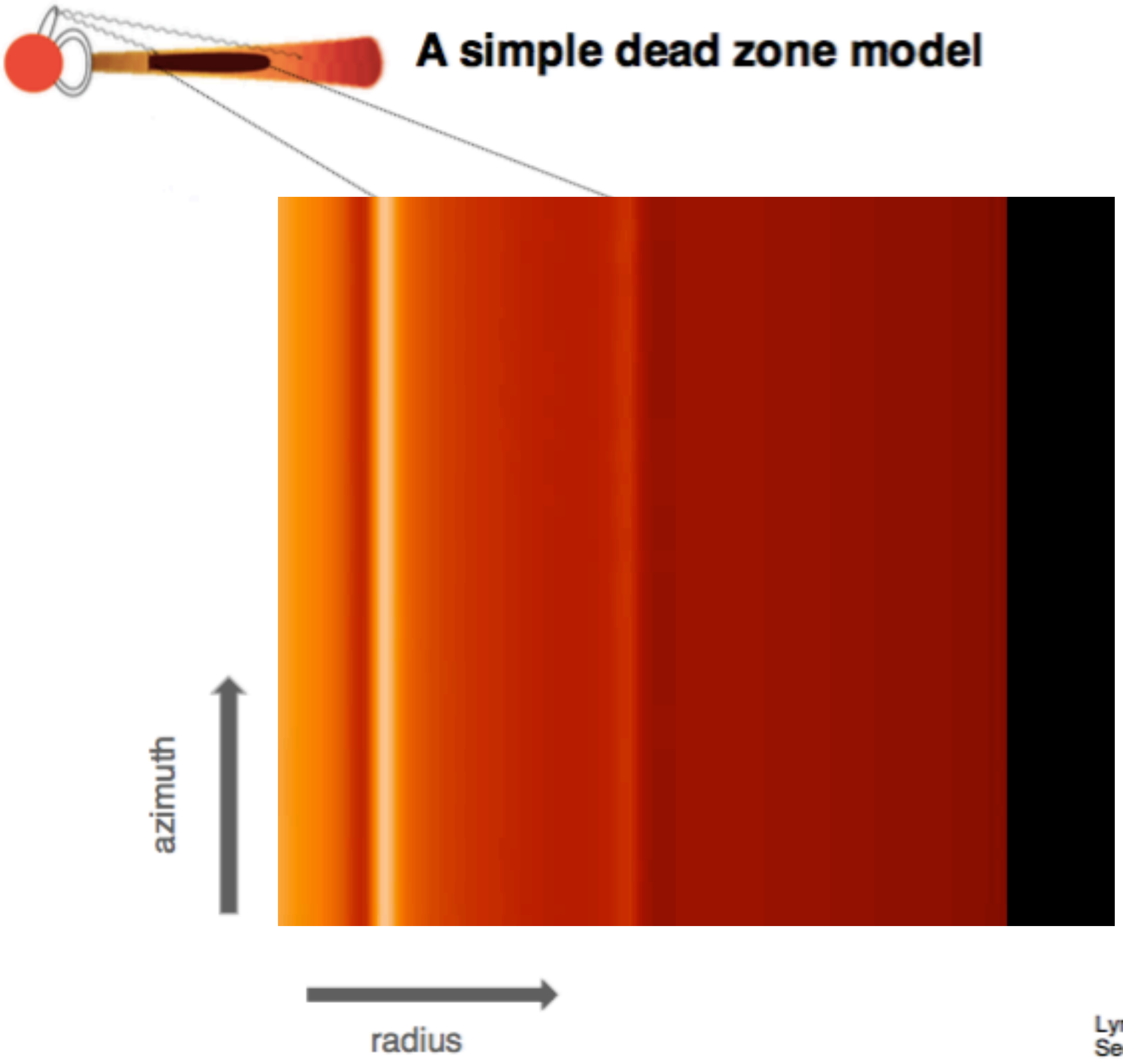


There should be a **magnetized, active zone**
and a **non-magnetic, dead zone**

Dead zones


dead zone
non-thermal ionization of full disk column
cosmic rays?
X-rays
collisional ionization at T > 10³ K (r < 1 AU), MRI turbulent
l-active
face layer
ambipolar diffusion dominates
0.1 AU
~30 AU
AU = Astronomical Unit (Earth to Sun distance)
Mercury, 0.4 AU
Venus, 0.7 AU
Earth, 1.0 AU
Mars, 1.5 AU
Jupiter, 5.2 AU
Saturn, 9.5 AU
Uranus, 19.2 AU
Neptune, 30.2 AU
Pluto, 39.5 AU
Sun

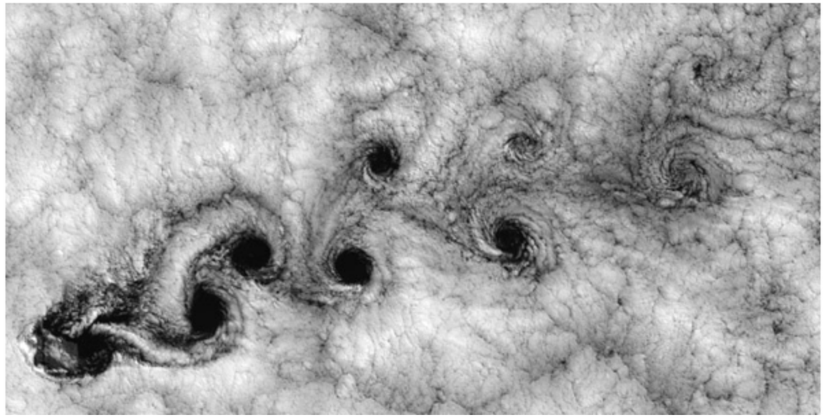
A simple dead zone model



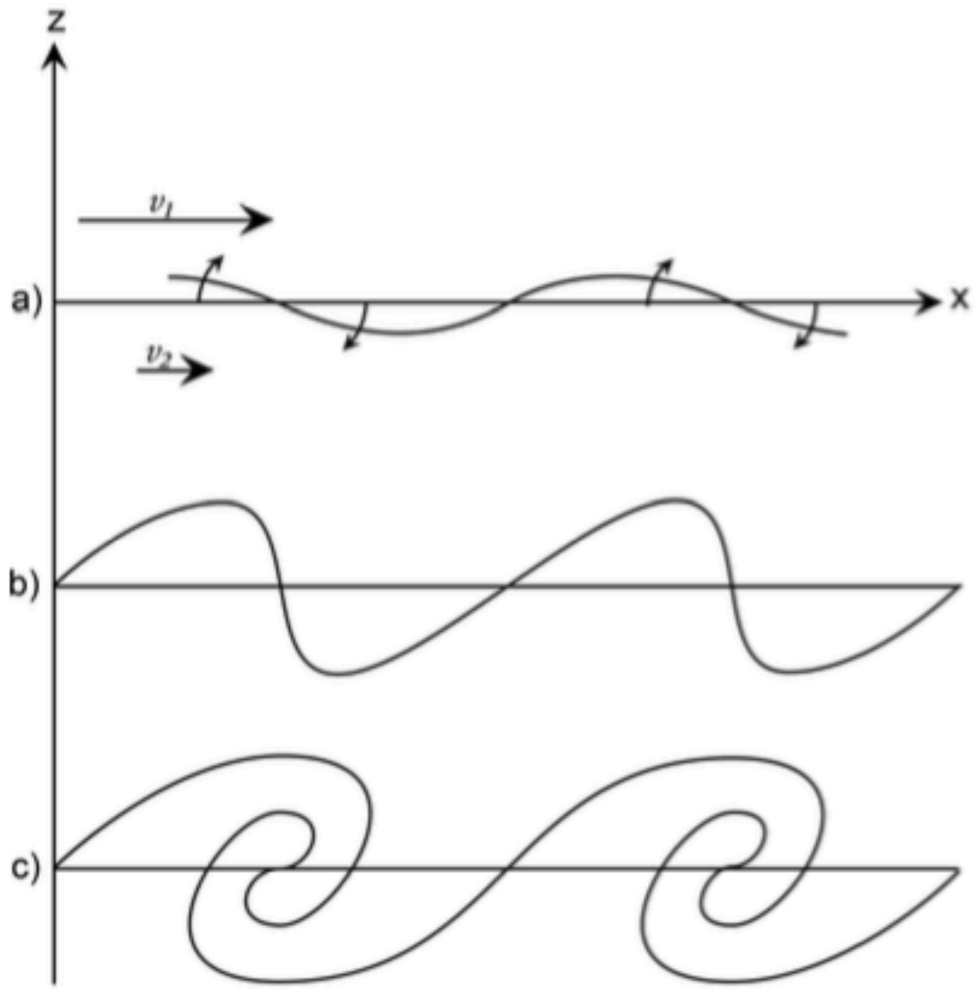
Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

Vortices – an ubiquitous fluid mechanics phenomenon

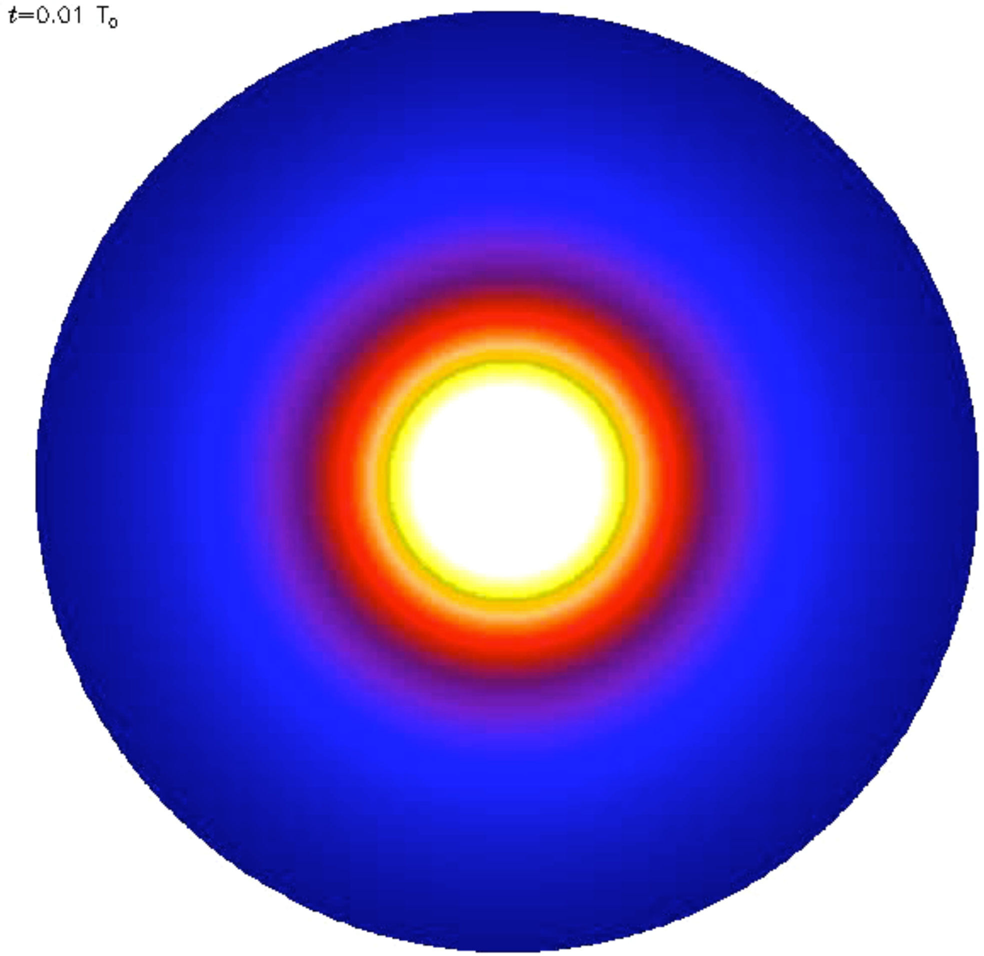
Von Kármán *vortex street*



Rossby wave instability
(Kelvin-Helmholtz Instability in rotating disks)



Inner (0.1 AU) active/dead zone boundary

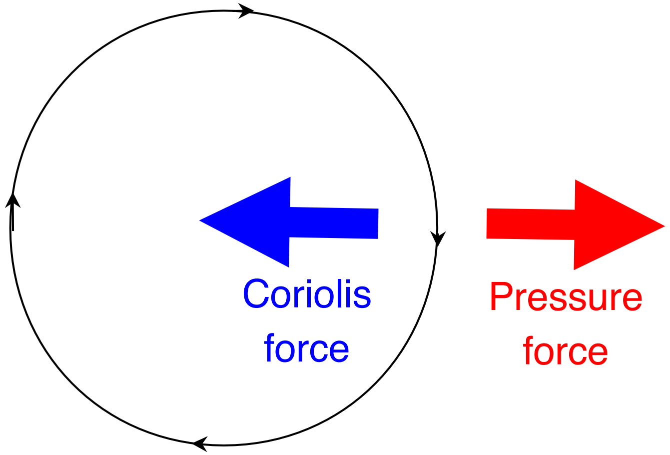


Magnetized inner disk + resistive outer disk

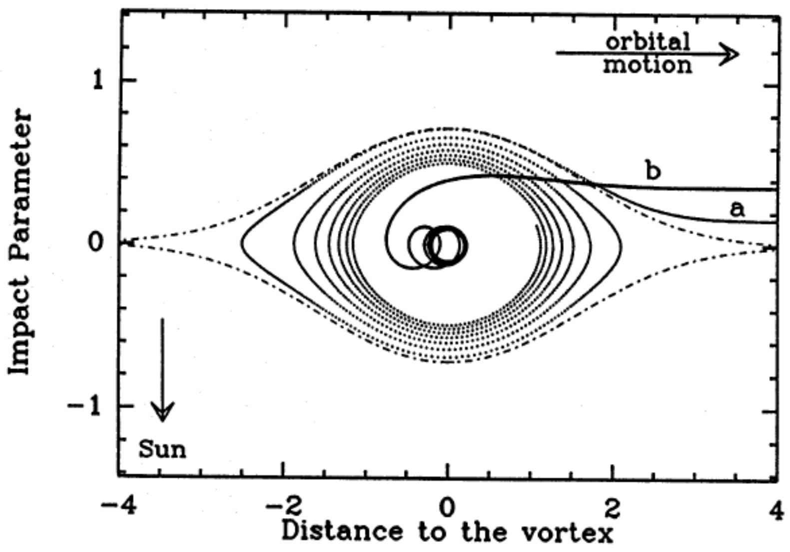
Lyra & Mac Low (2012)

Vortex Trapping

Geostrophic balance:



Vortex
streamline



Barge & Sommeria (1995)

Grains do not feel the pressure gradient.
They sink towards the center, where they accumulate.

Aid to planet formation

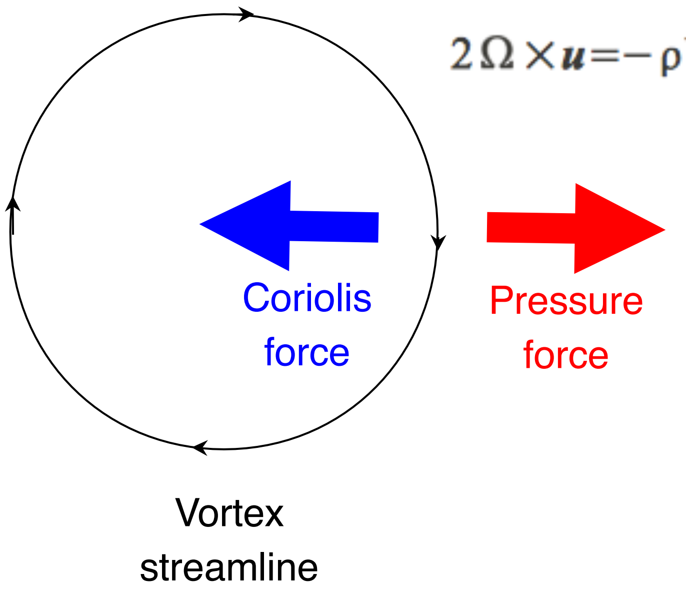
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speeds up planet formation enormously

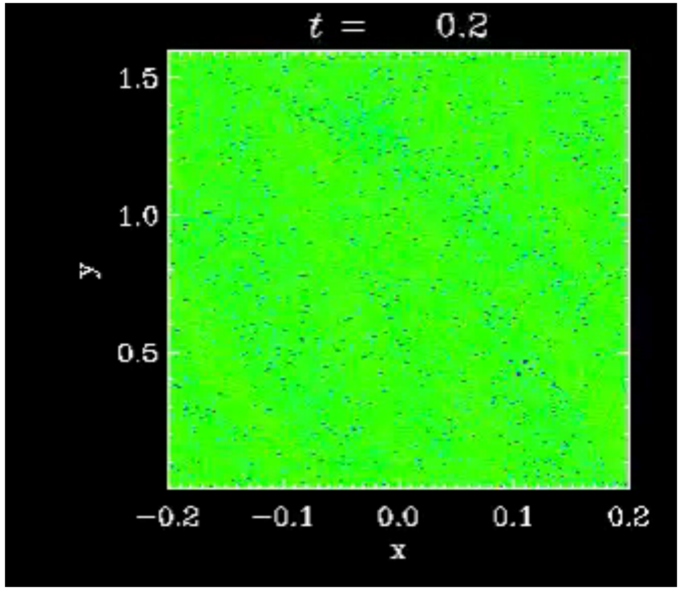
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

Vortex Trapping

Geostrophic balance:



$$2\Omega\times\boldsymbol{u}=-\rho^{-1}\nabla p$$



Raettig, Lyra, & Klahr (2013)

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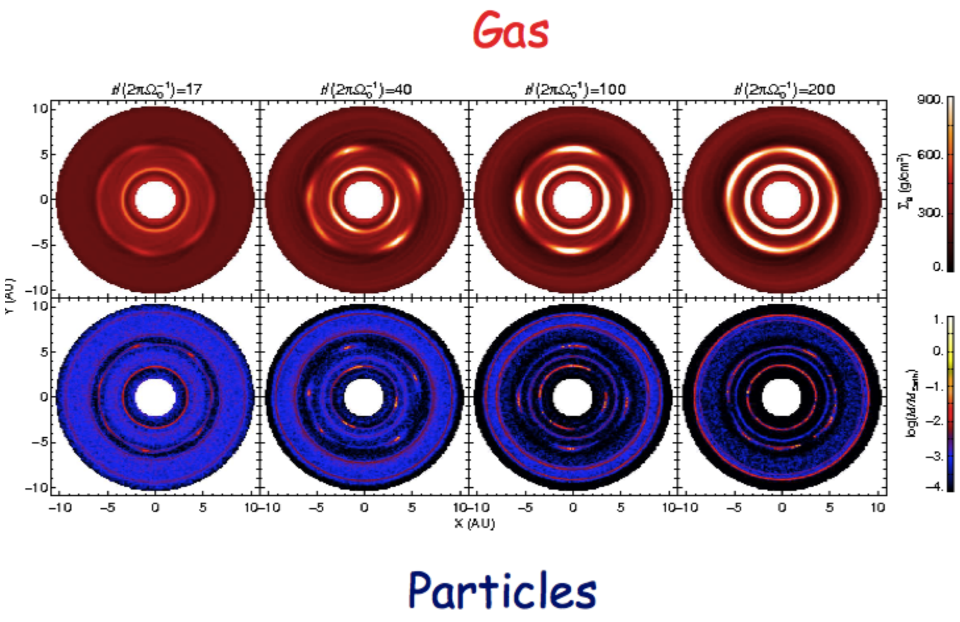
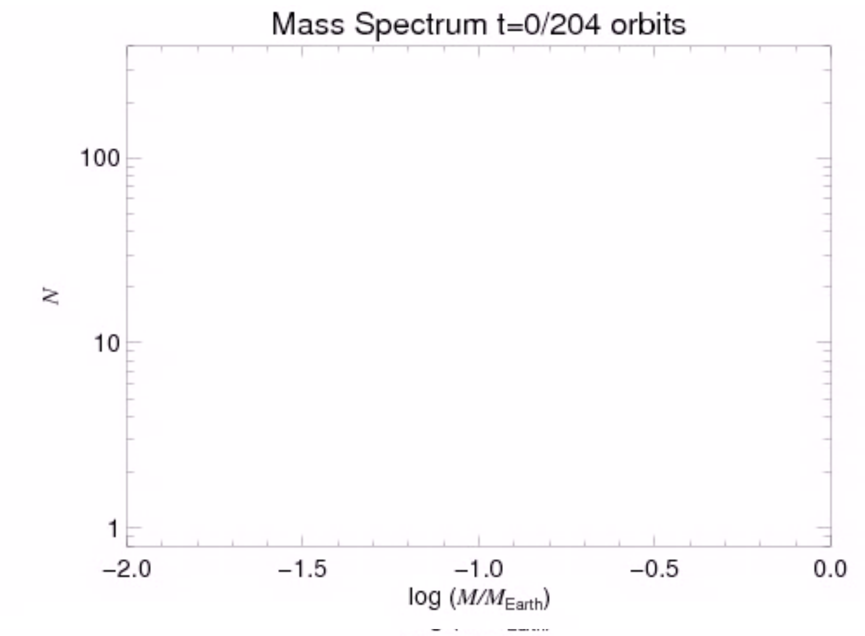
Vortices and Planet Formation

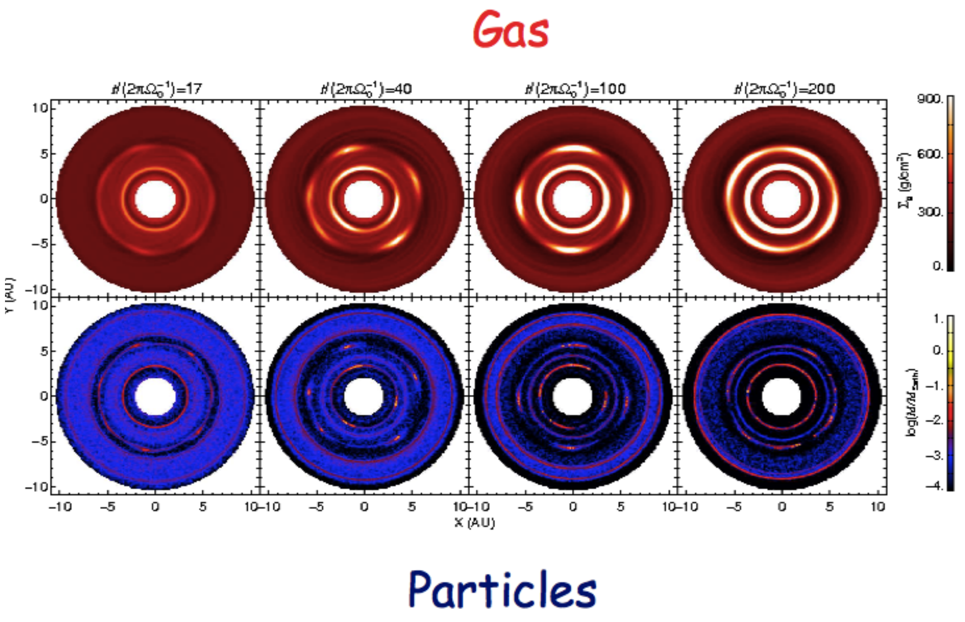


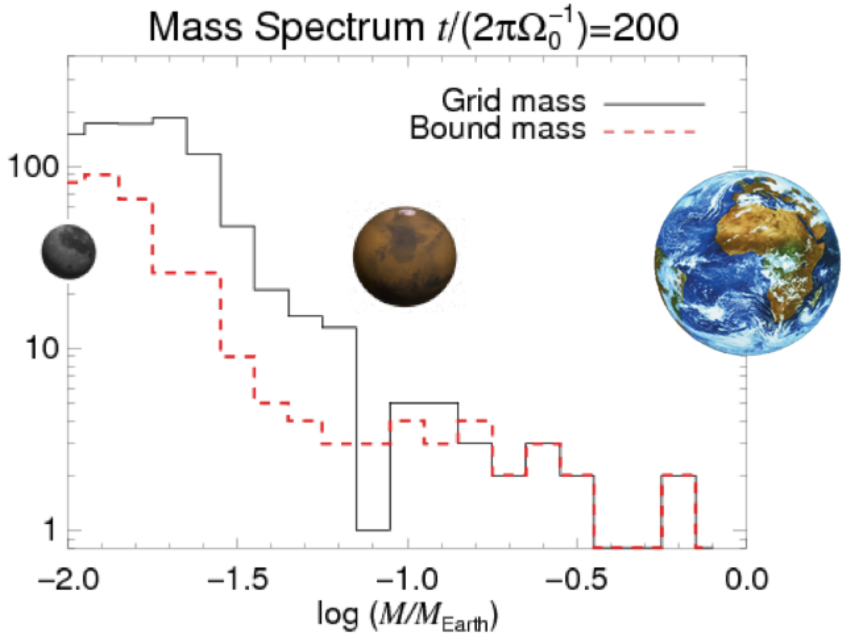


Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a, Lambrechts & Johansen 2012)

Vortices and Planet Formation





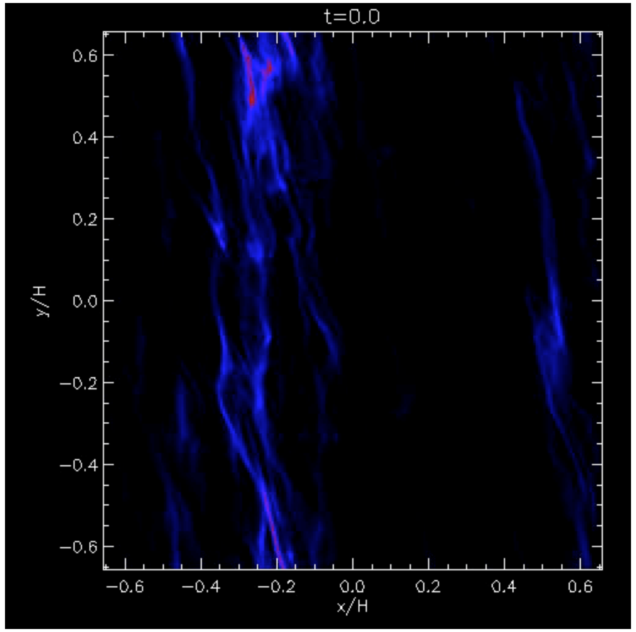
Collapse into Mars mass objects

(Lyra et al. 2008b, 2009a,
Lambrechts & Johansen 2012)

Take home message

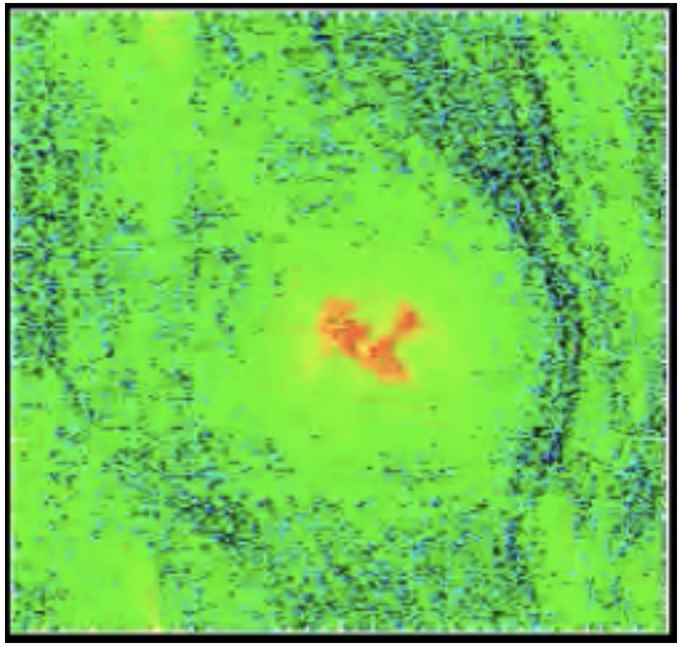
- Two routes for planet formation

Streaming Instability



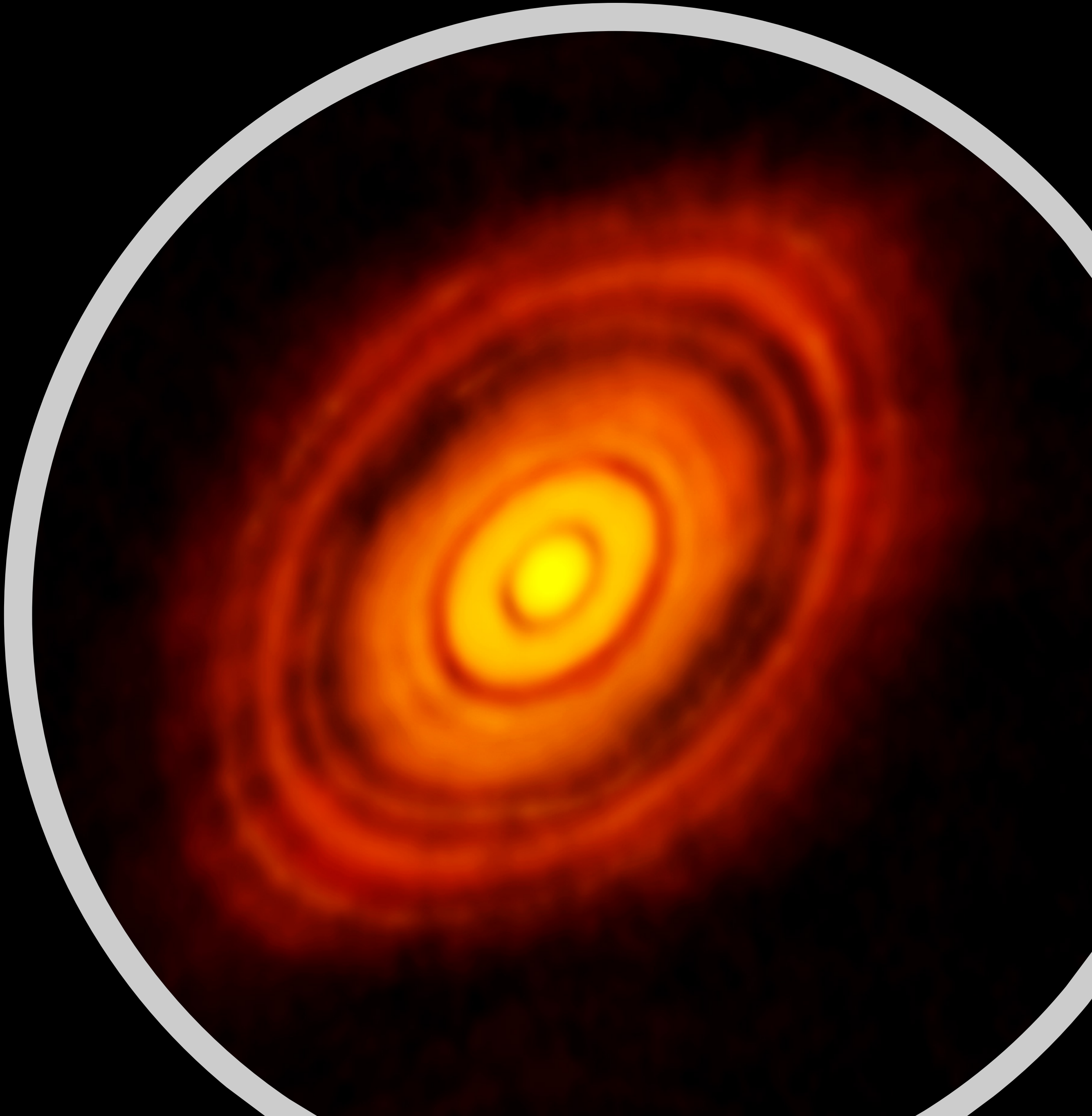
Johansen+ 07

Vortex Trapping

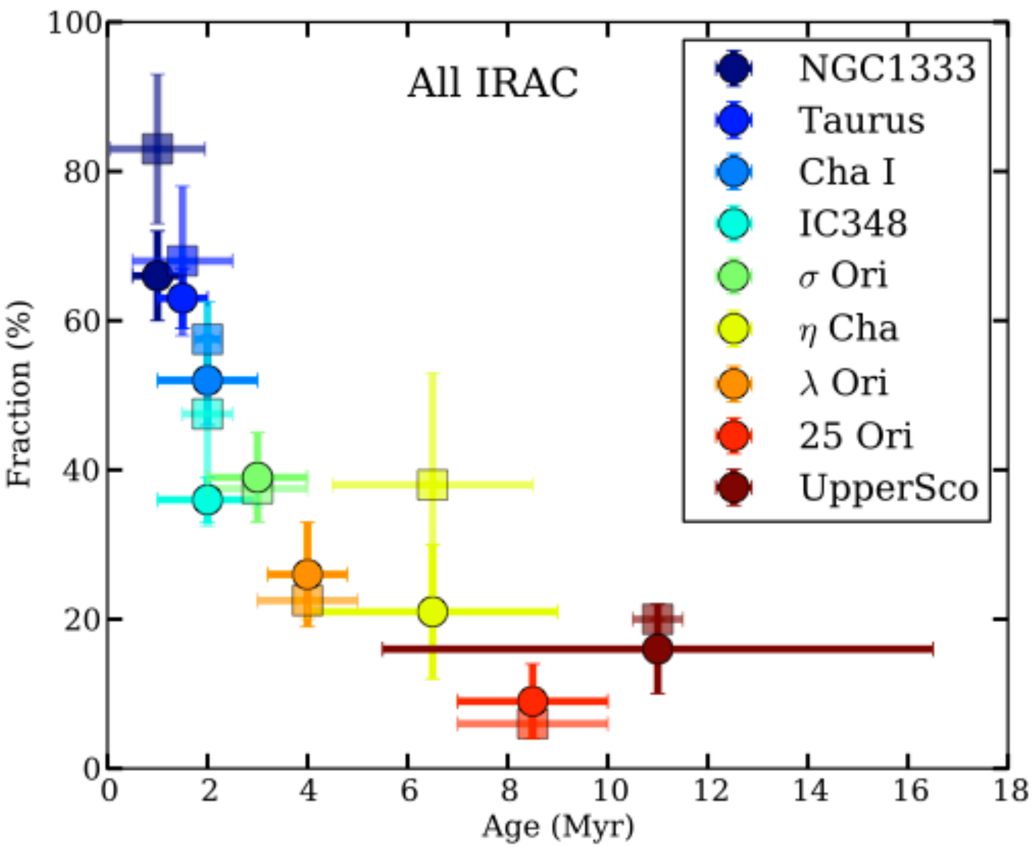


Lyra+08, Raettig+Lyra 12

Part 2: Disk Observations



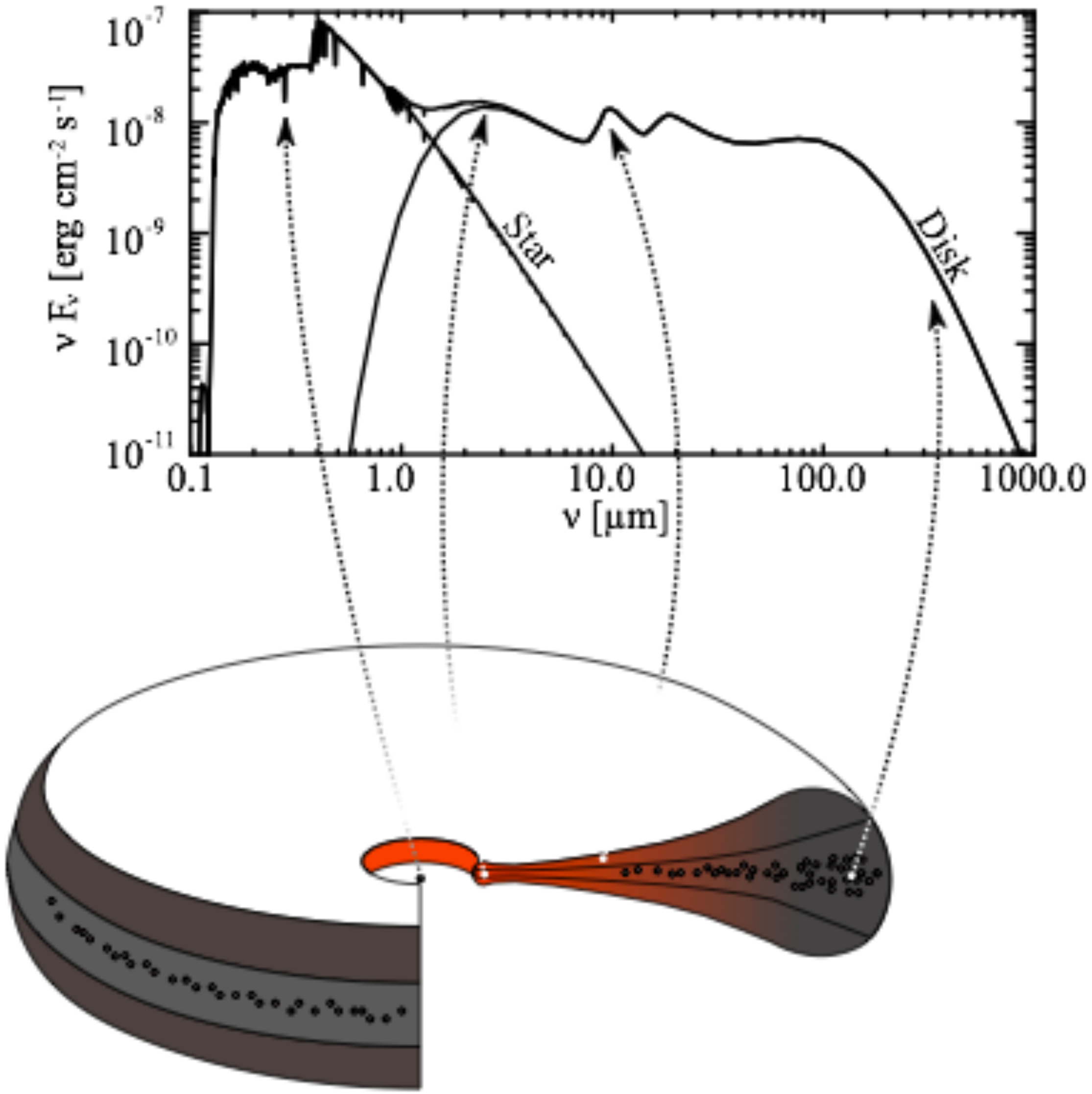
Disk lifetime



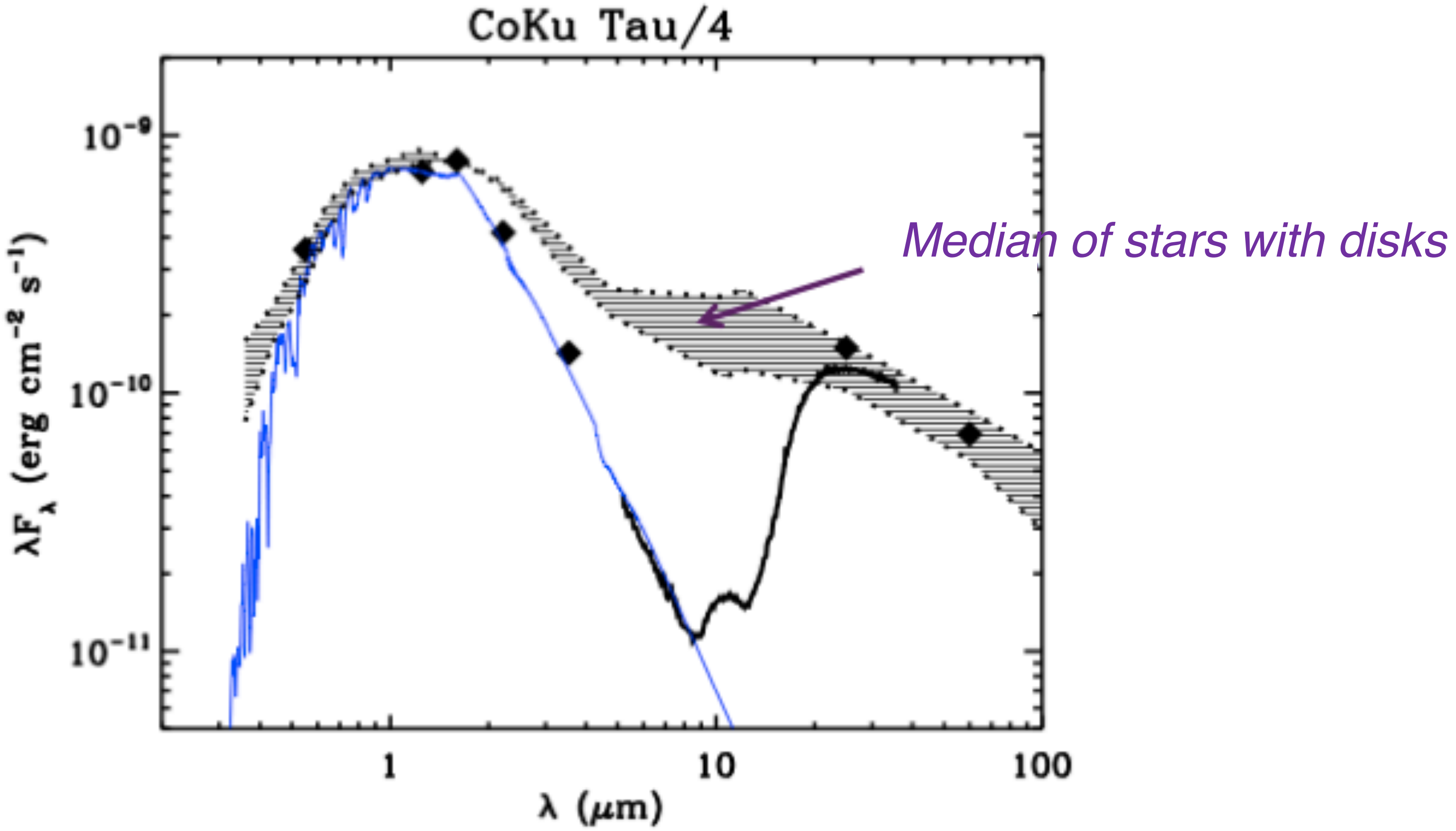
(Ribas et al. 2014)

Disks dissipate within ~10Myr

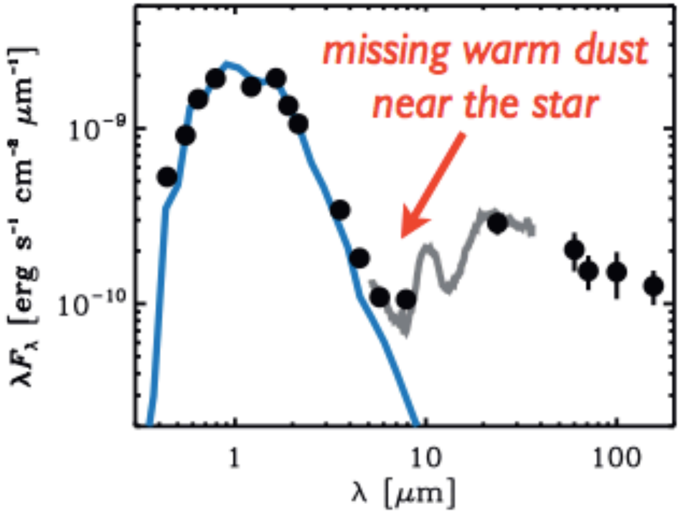
Disk spectra



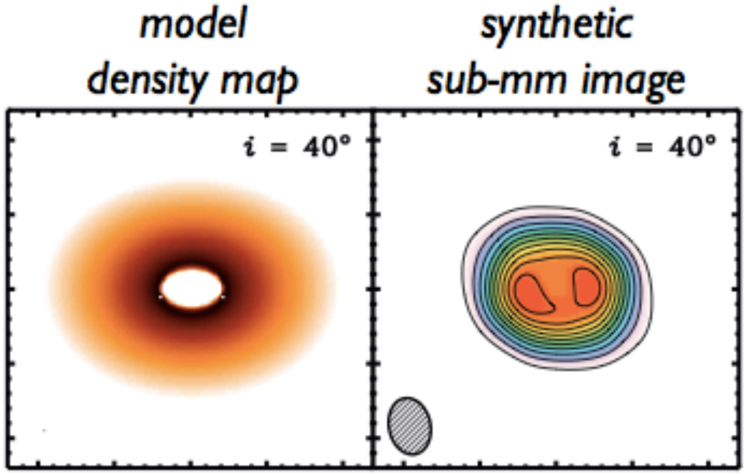
A class of disks with missing hot dust.



Disks with missing hot dust.

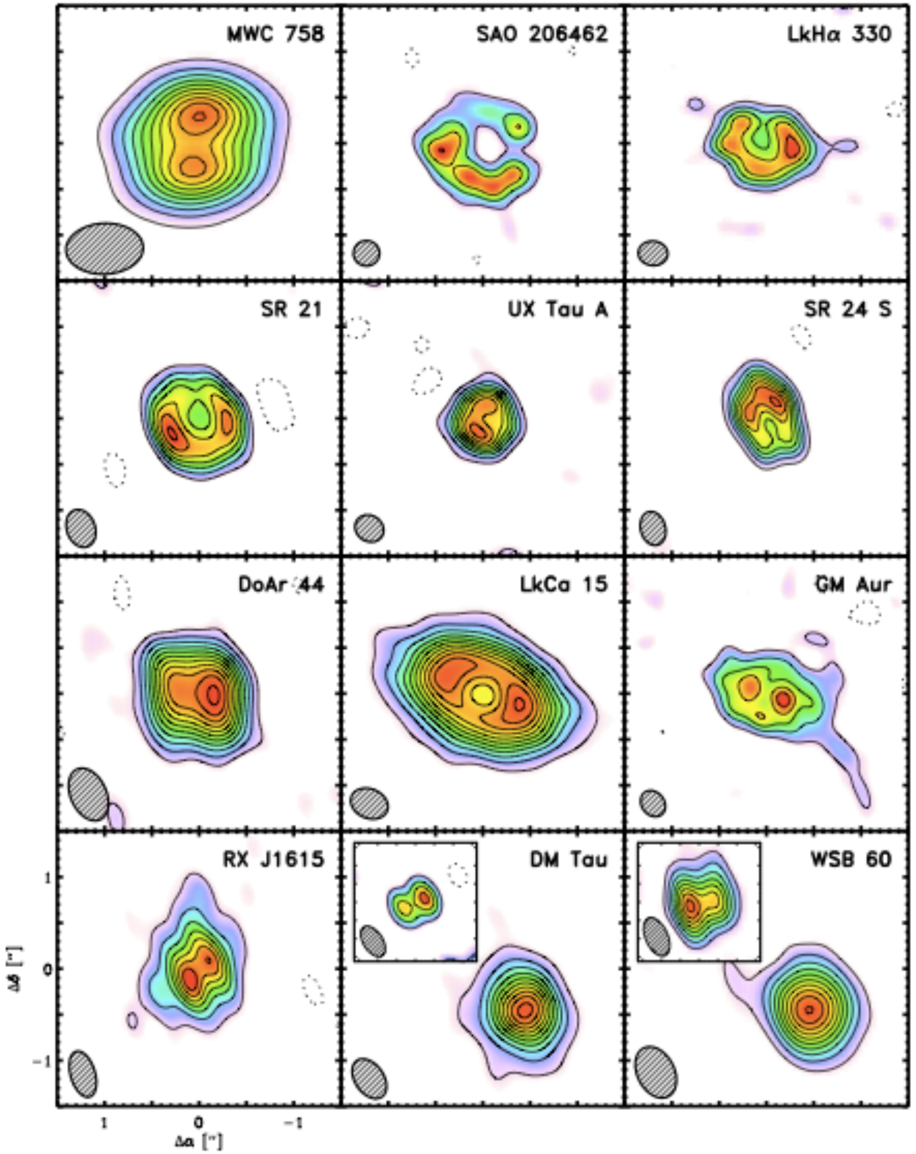


[e.g., Furlan et al. 2009]



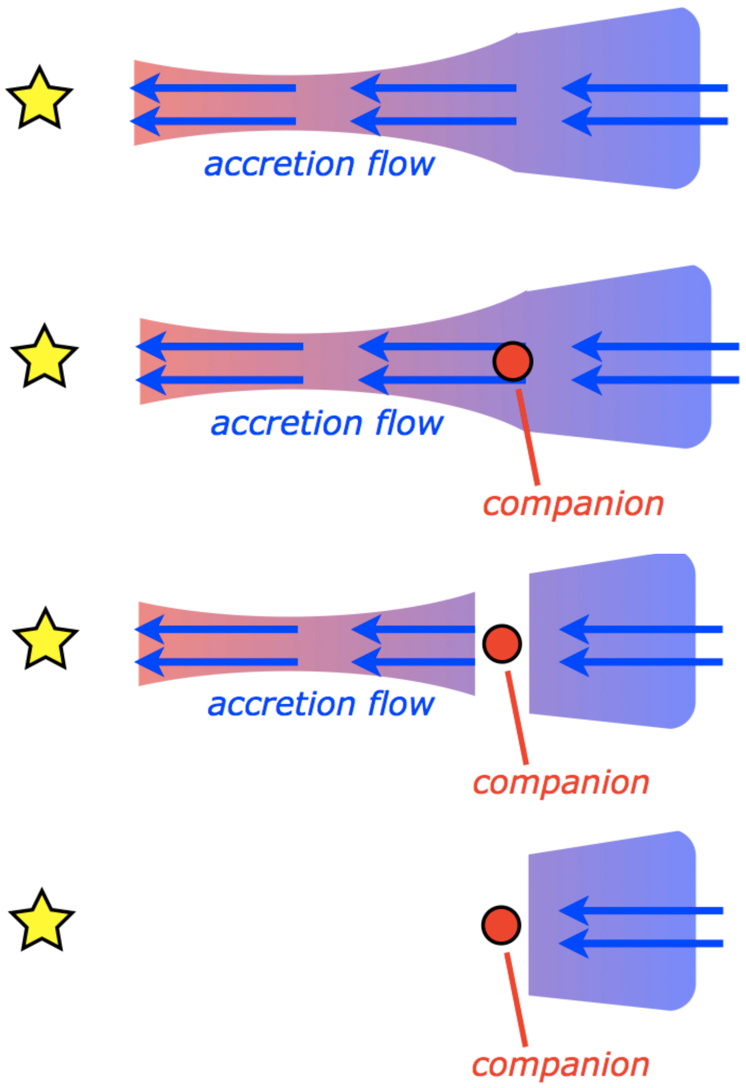
a disk with a large reduction
in optical depth near the star
(i.e., a “cavity” or “hole”)

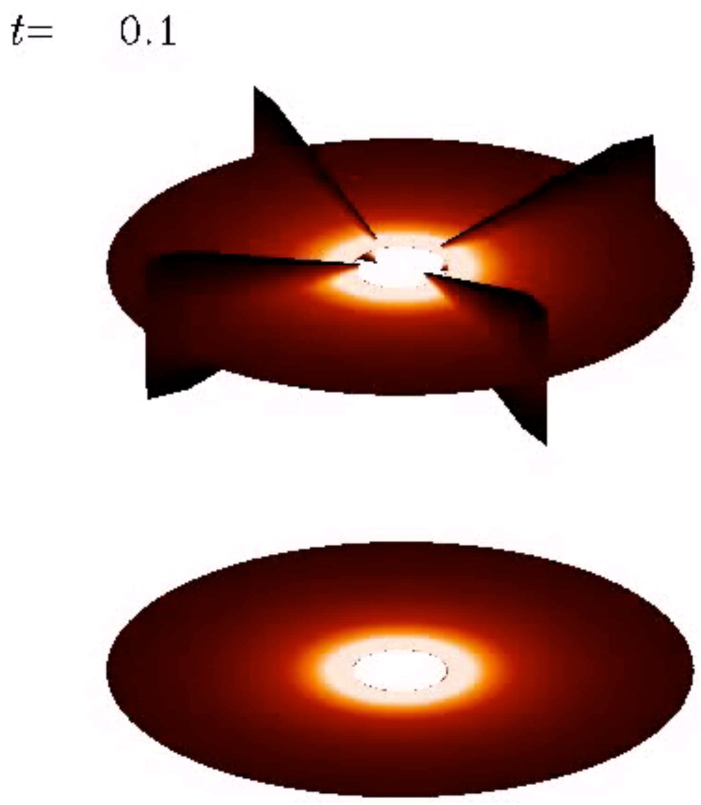
Resolved disks with the Sub-millimeter Array (SMA)



0.85mm
0.3'' ~ 20 AU resolution

Planetary companion

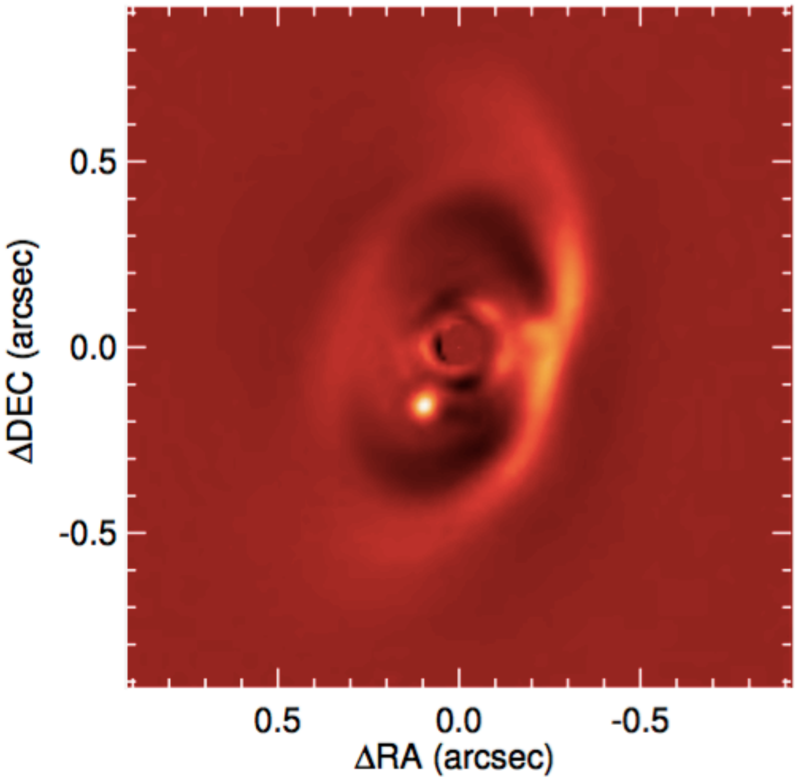




(Lyra 2009)

These cavities may be the telltale signature of forming planets

PDS 70 and PDS 70b



(Muller et al. 2018)

(Lyra et al. 2009b)

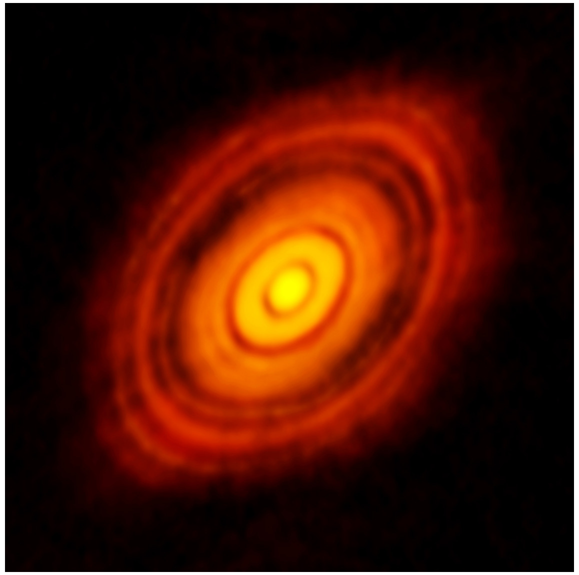
A way to directly study planet-disk interaction

Planet-disk interaction: gaps, spirals, and vortices.

(Lyra et al. 2009b)

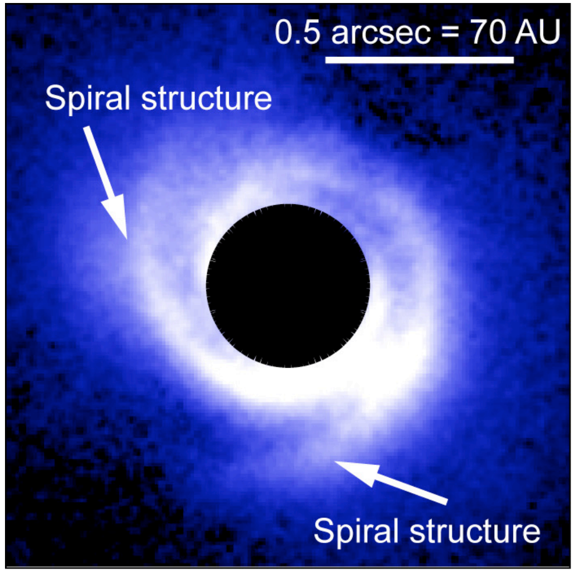
Observational evidence: gaps, spirals, and vortices

HL Tau



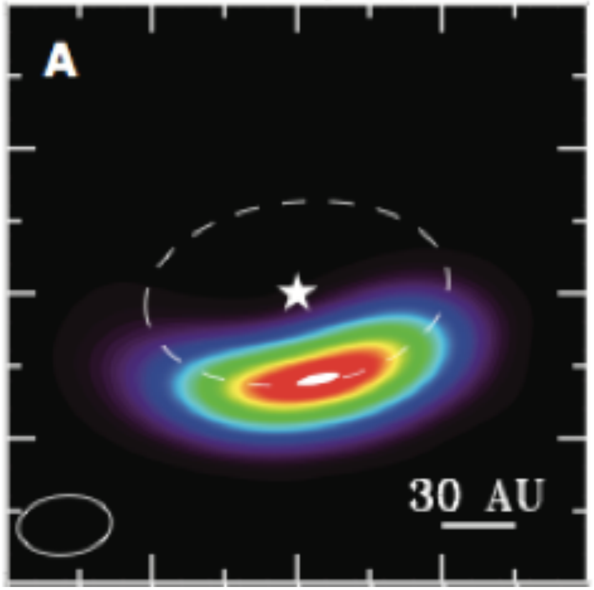
The ALMA Partnership et al. (2015)

SAO 206462



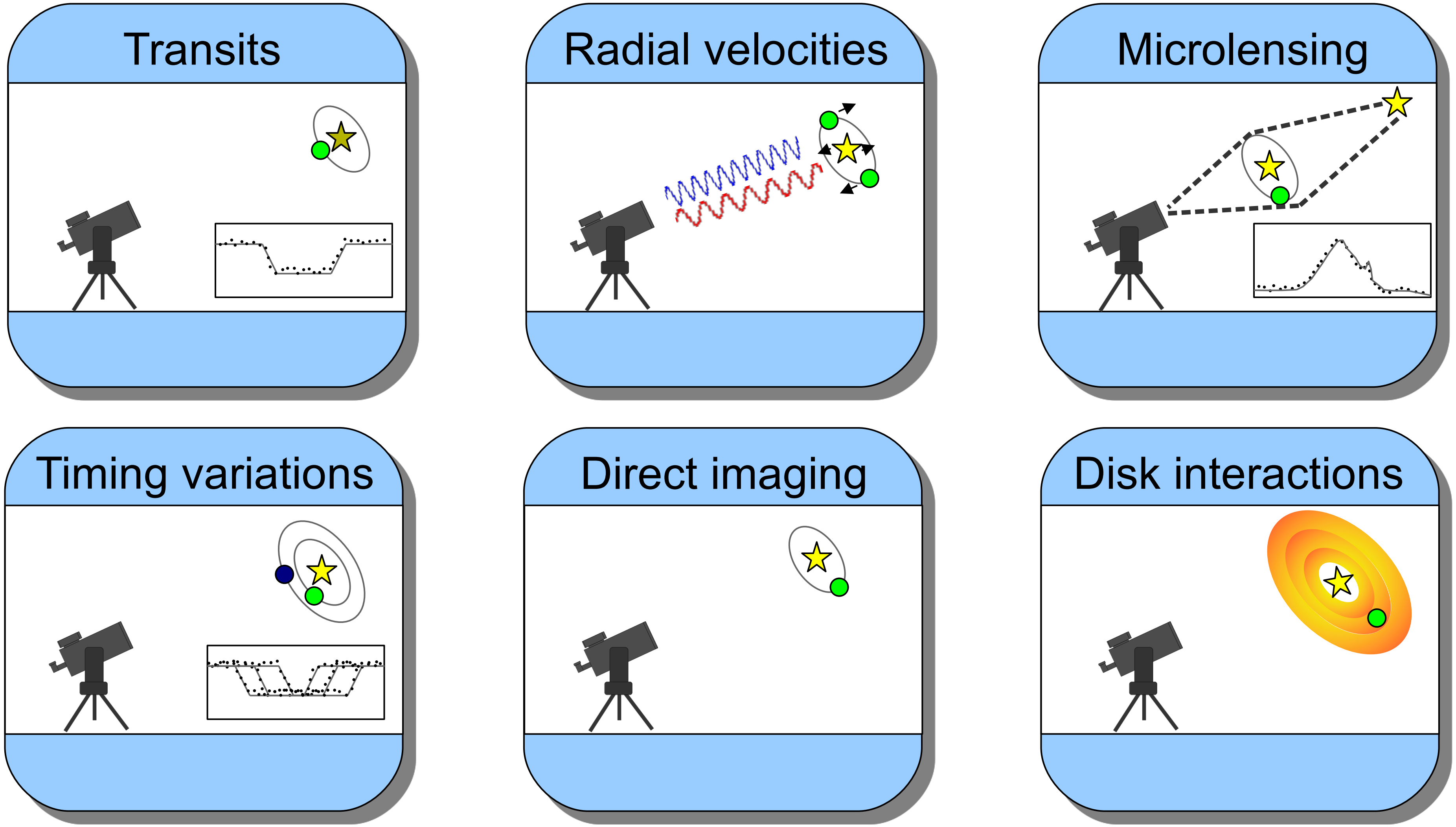
Muto et al. (2012)

Oph IRS 48



van der Marel et al. (2013)

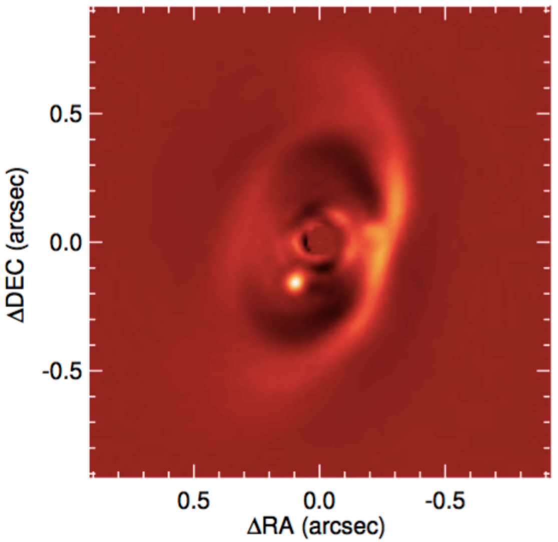
Planet detection methods

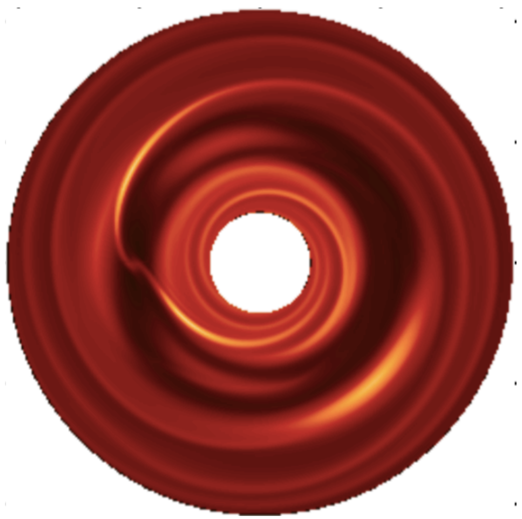


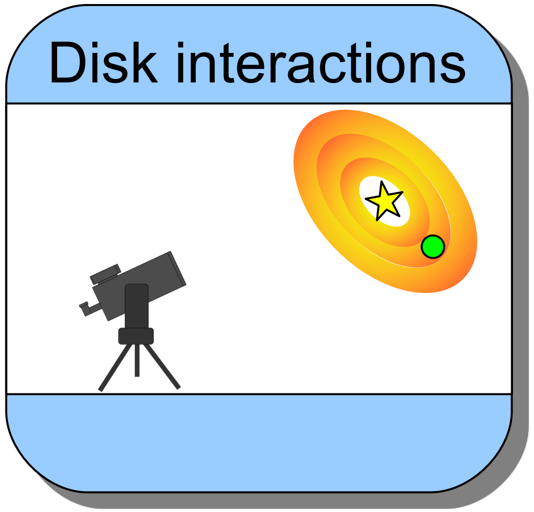
Slide by A. Richert

Take home message

- Disk-planet interaction is a new way to find planets



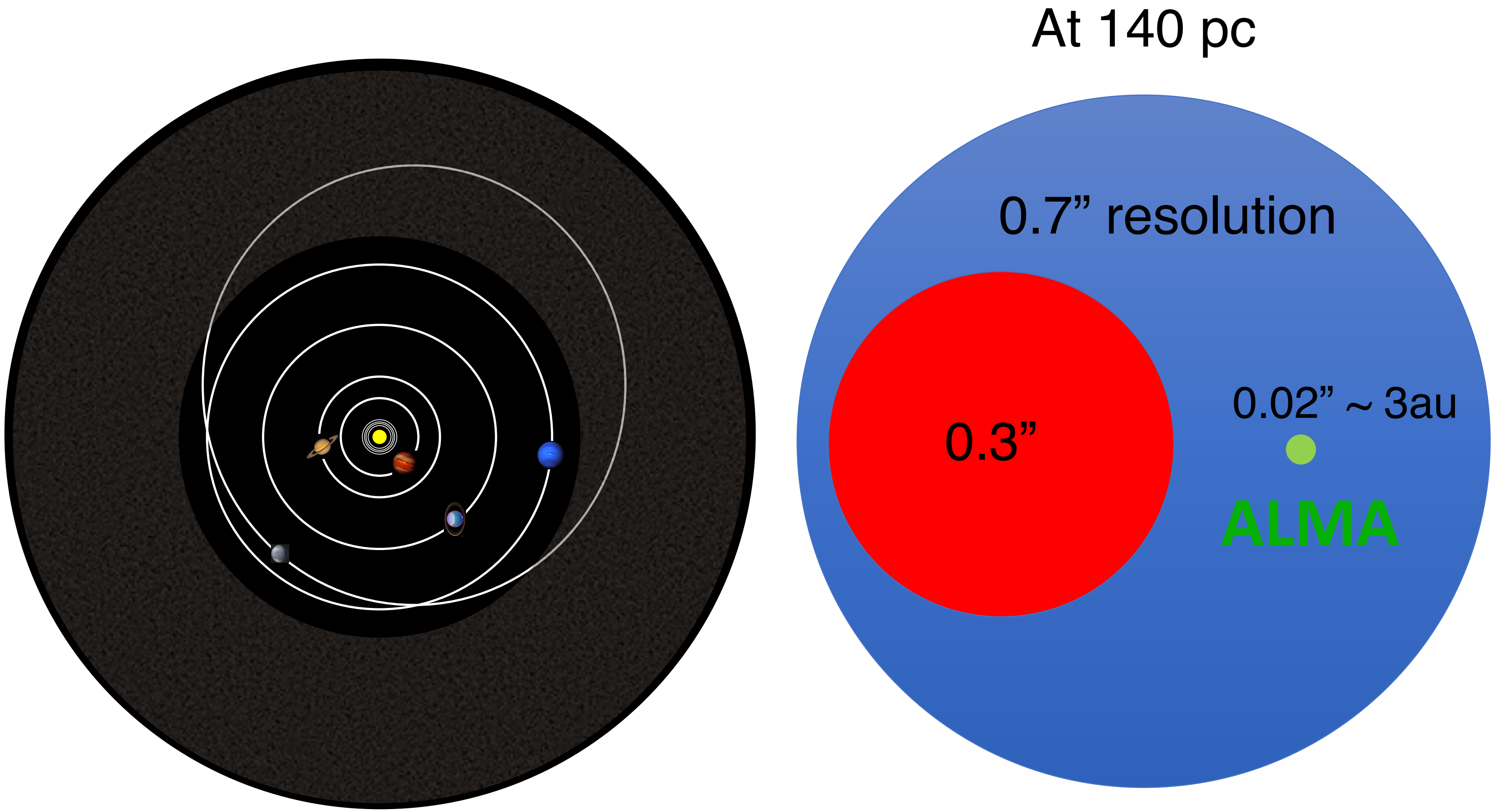




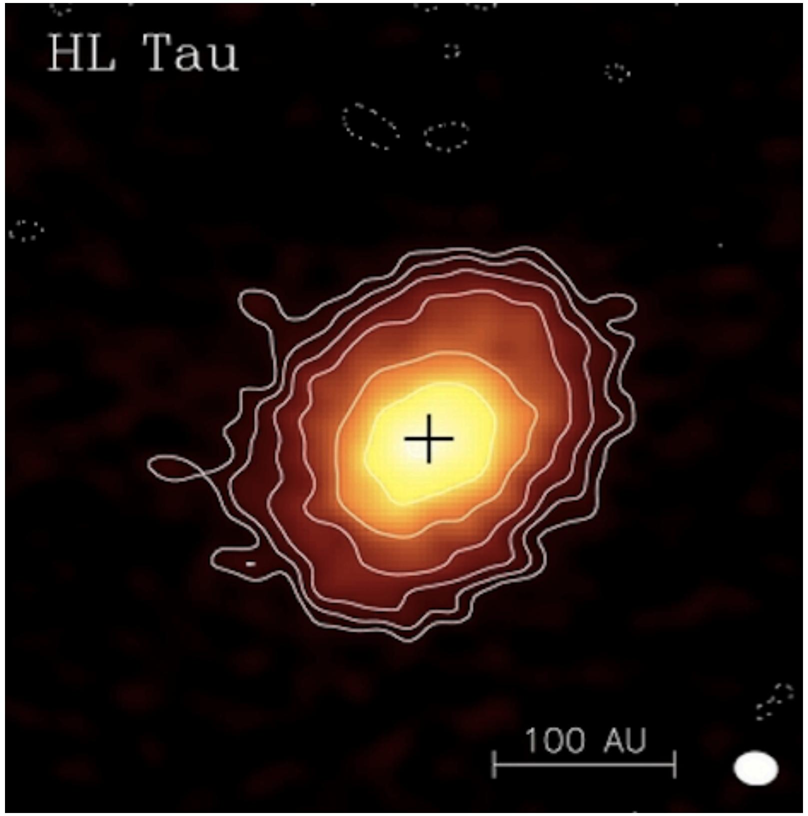
Part 3.
The ALMA Revolution

The Atacama Large (sub-)Millimeter Array (ALMA)

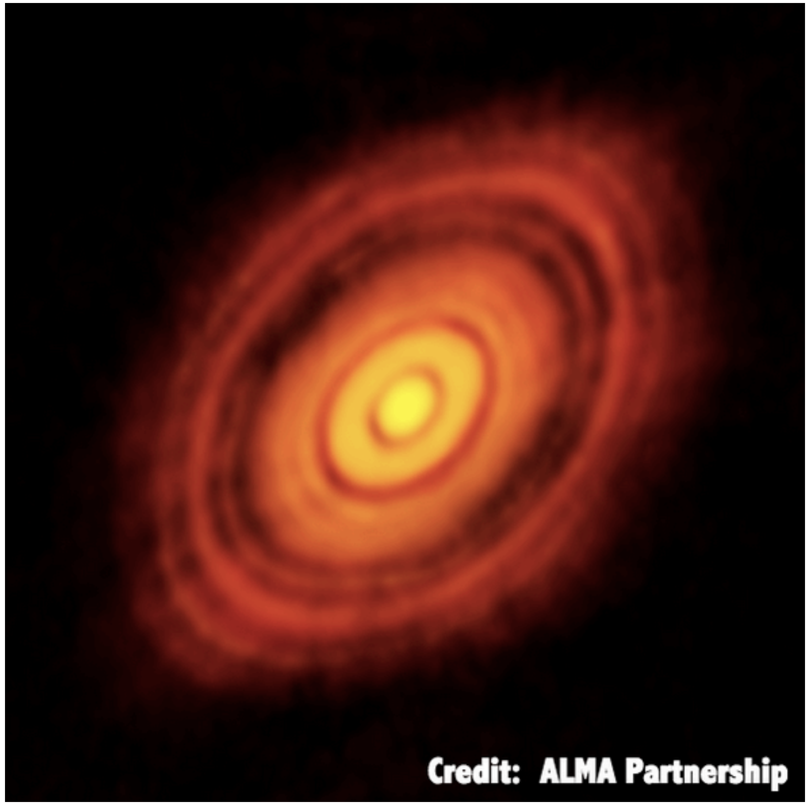
The ALMA ReSolution



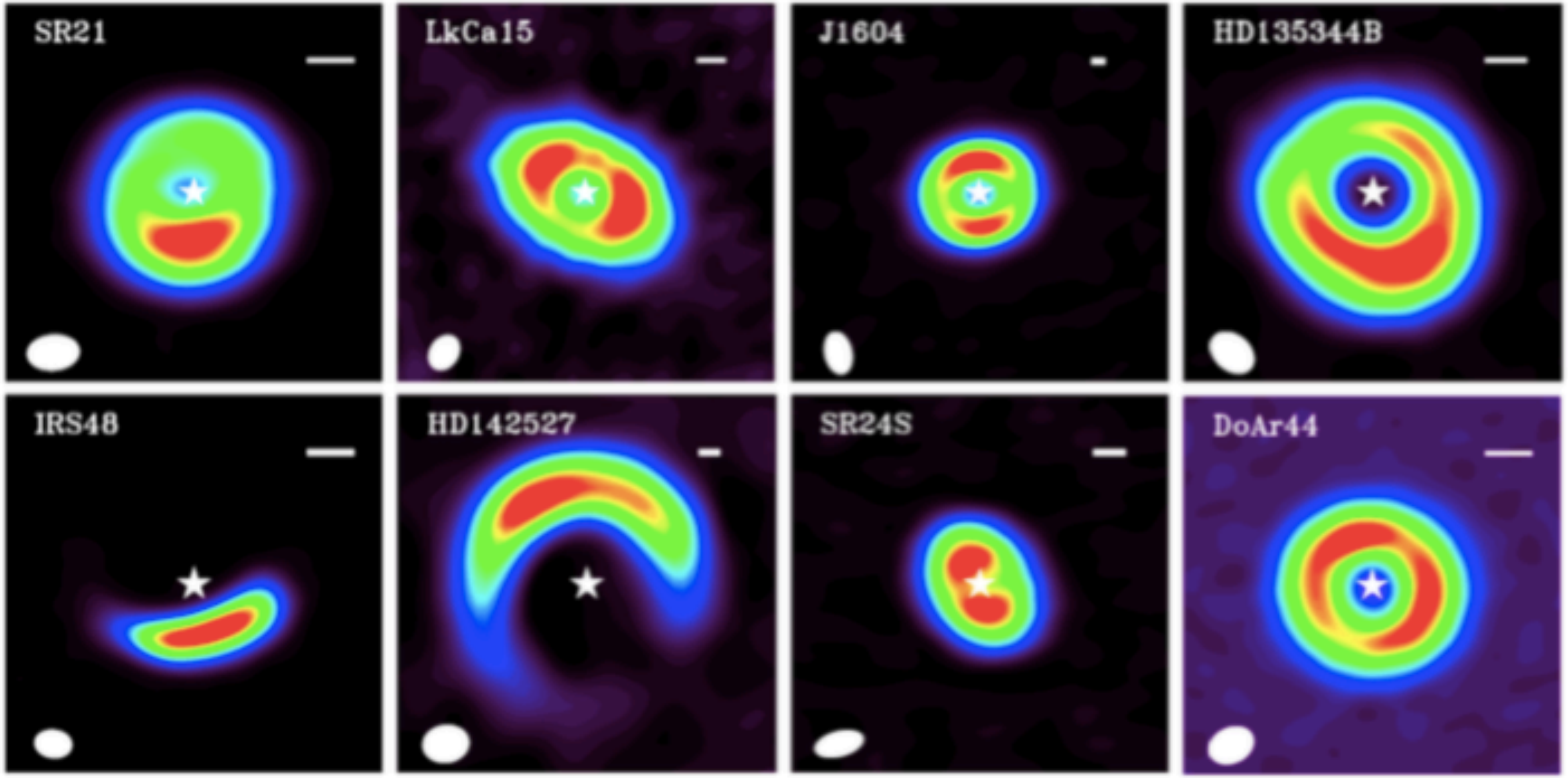
Before ALMA

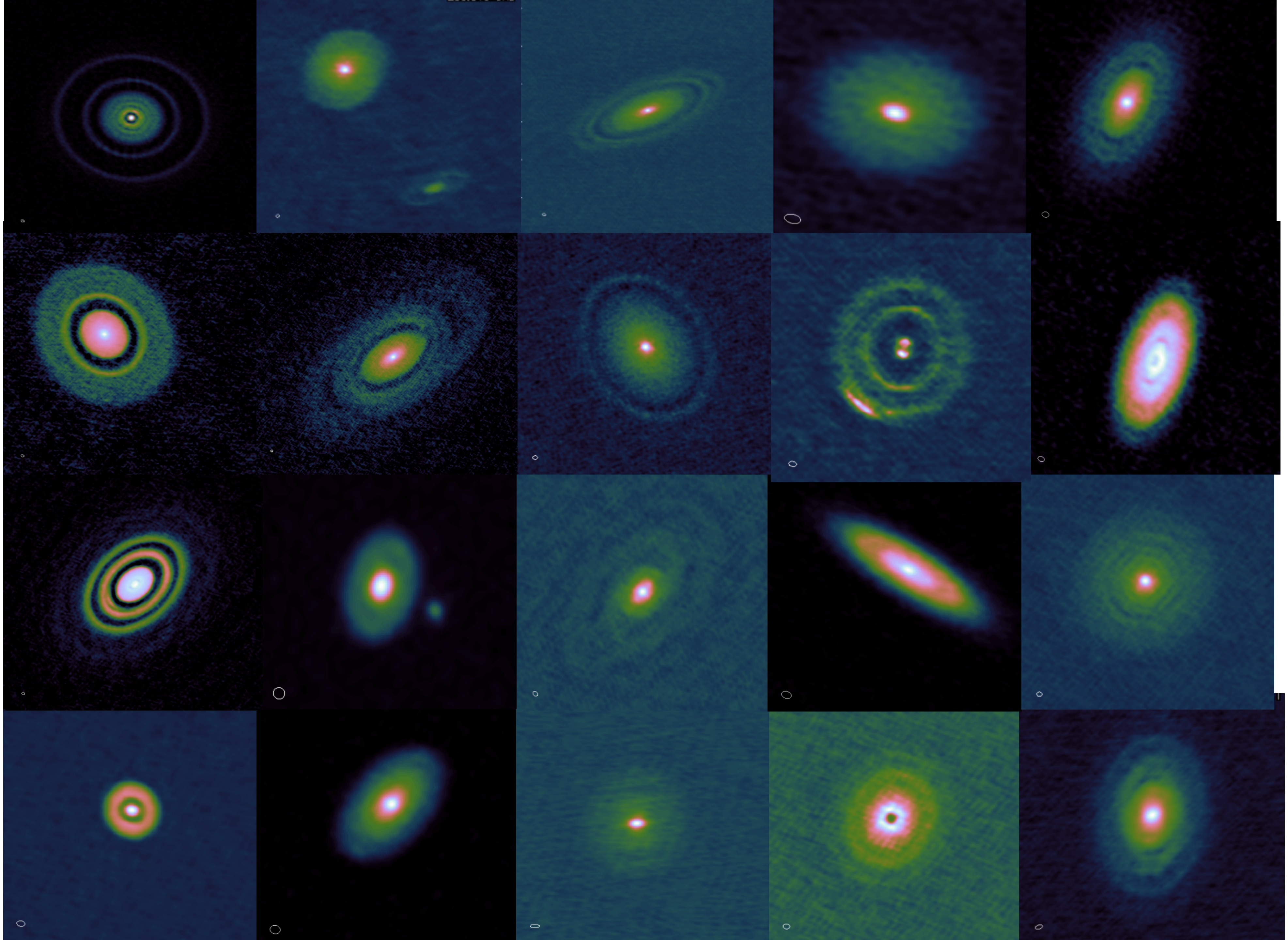


ALMA



Dust traps in disks: ALMA Cycle 0 (2012)





Oph IRS 48

A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

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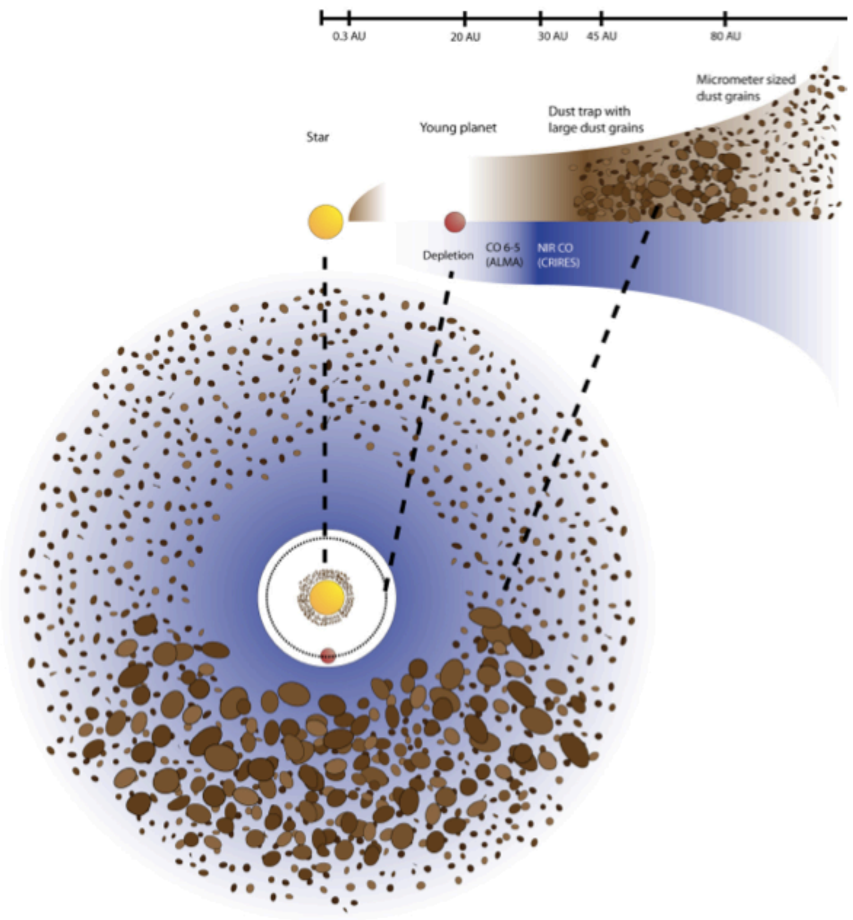
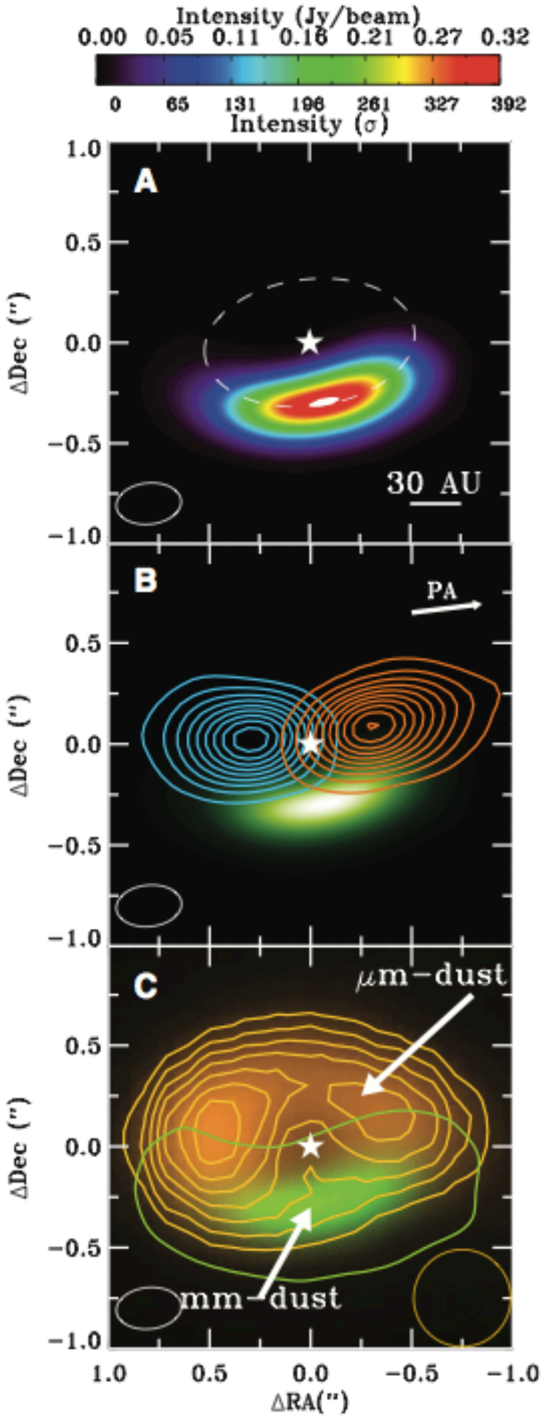
van der Marel+ ‘13

A huge vortex observed with ALMA

The Oph IRS 48 "comet formation factory"



van der Marel+. '13

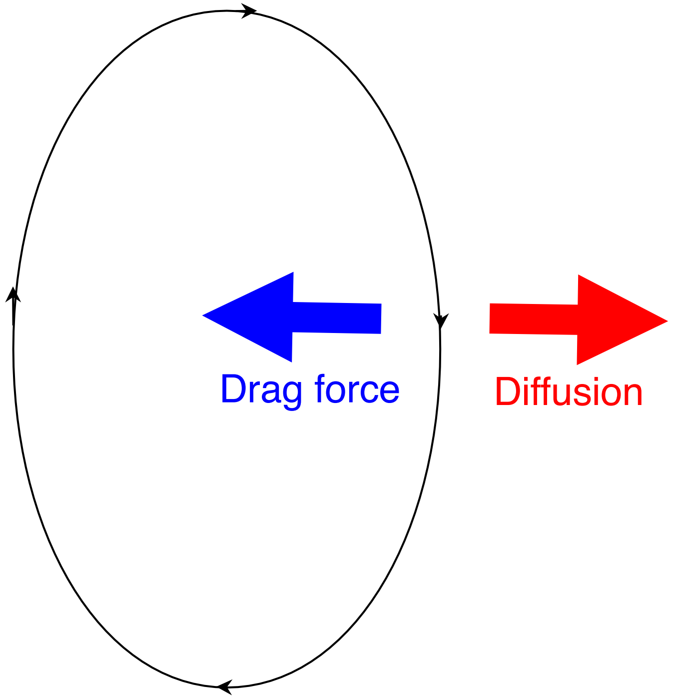


asymmetric mm dust at 63 AU

Gas detection: Keplerian rotation

Micron-sized dust follows gas

Drag-Diffusion Equilibrium



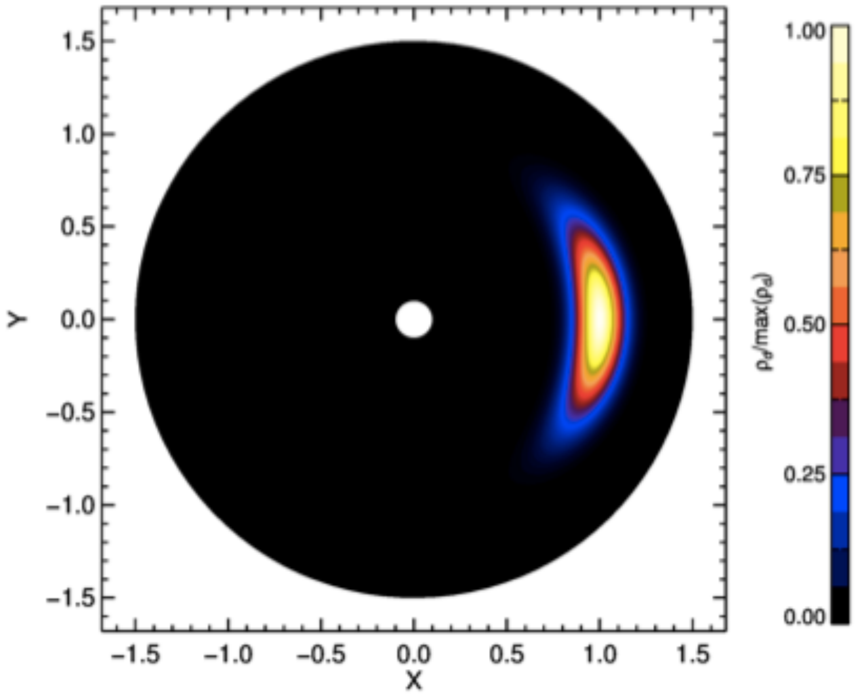
Trapped particle

Dust continuity equation

$$\frac{\partial \rho_d}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\rho_d - \rho_d \boldsymbol{\nabla} \cdot \boldsymbol{v} + D\nabla^2 \rho_d,$$

advection **compression** **diffusion**

Analytical Solution for dust in Drag-Diffusion Equilibrium



Solution for

H/r=0.1 χ=4 *S*=1

Steady-state solution

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{-\frac{[a^2 f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin '13

$$S = \frac{St}{\delta}$$

$$\delta = v_{\rm rms}^2 / c_s^2,$$

a = vortex semi-minor axis
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
f(χ) = model-dependent scale function

The Lyra-Lin Solution

$$\rho_d(a,z) = \varepsilon\rho_0\,(S+1)^{3/2}\exp\left\{-\frac{[a^2f^2(\chi)+z^2]}{2H^2}(S+1)\right\}$$

Lyra & Lin '13

Gas distribution

$$\rho_g(a) = \rho_{g\,\max}\exp\left(-\frac{a^2}{2H_g^2}\right),$$

Maximum dust density

$$\rho_{d\,\max} = \varepsilon\,\rho_0\,(S+1)^{3/2}$$

Gas contrast

$$\frac{\rho_{g\,\max}}{\rho_{g\,\min}} = \exp\left[\frac{f^2(\chi)}{2\chi^2\omega_V^2}\right],$$

Dust contrast

$$\frac{\rho_{d\,\max}}{\rho_{d\,\min}} = \frac{\rho_{g\,\max}}{\rho_{g\,\min}}\exp(S),$$

Total trapped mass

$$\int\rho_d(a,z)dV = (2\pi)^{3/2}\,\varepsilon\rho_0\,\chi H H_g^2$$

Vortex size

$$a_s = H(\chi\omega_V)^{-1}$$

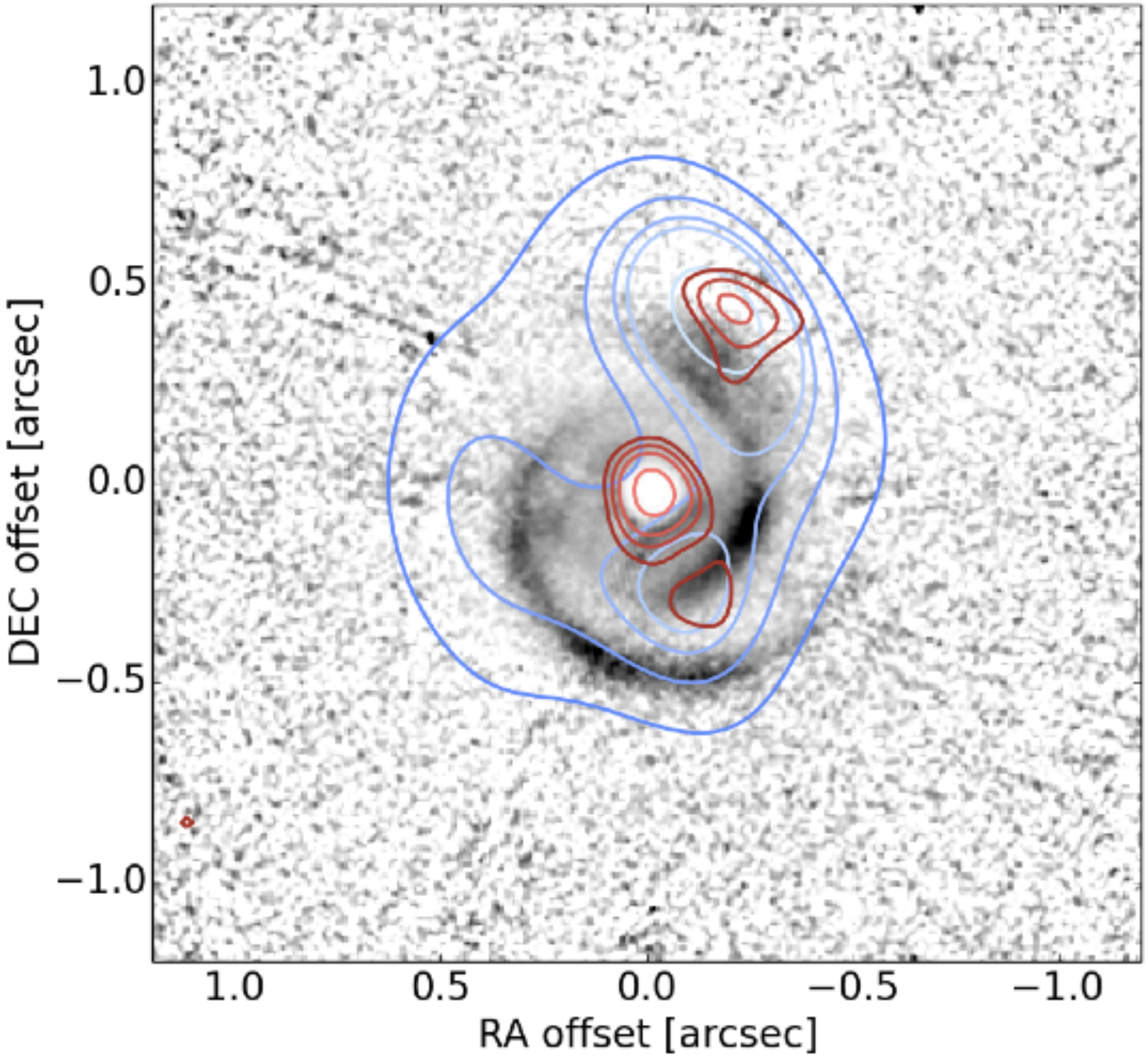
H = disk scale height (temperature)
χ = vortex aspect ratio
δ = diffusion parameter
St = Stokes number (particle size)
$f(\chi)$ = model-dependent scale function
ε = dust-to-gas ratio

Disk Tomography
SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

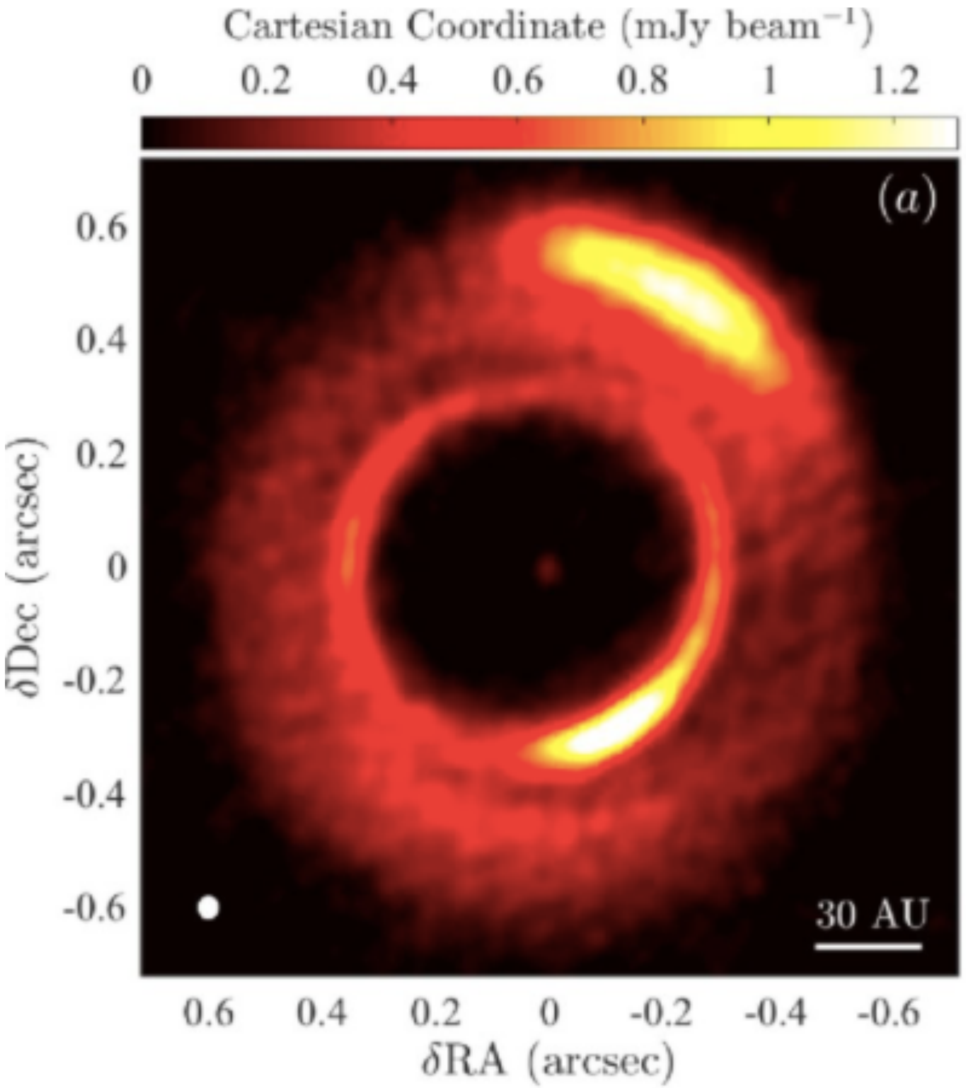
ALMA (~ mm)

VLA (cm-m)



Marino+Lyra '15

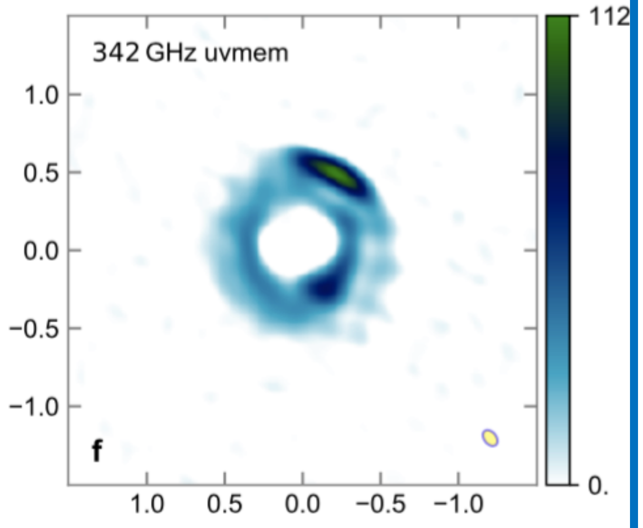
MWC 758



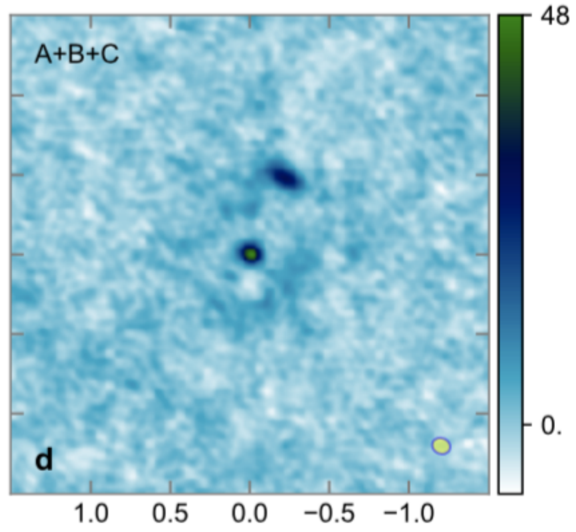
Dong+ '18

Pebble trapping

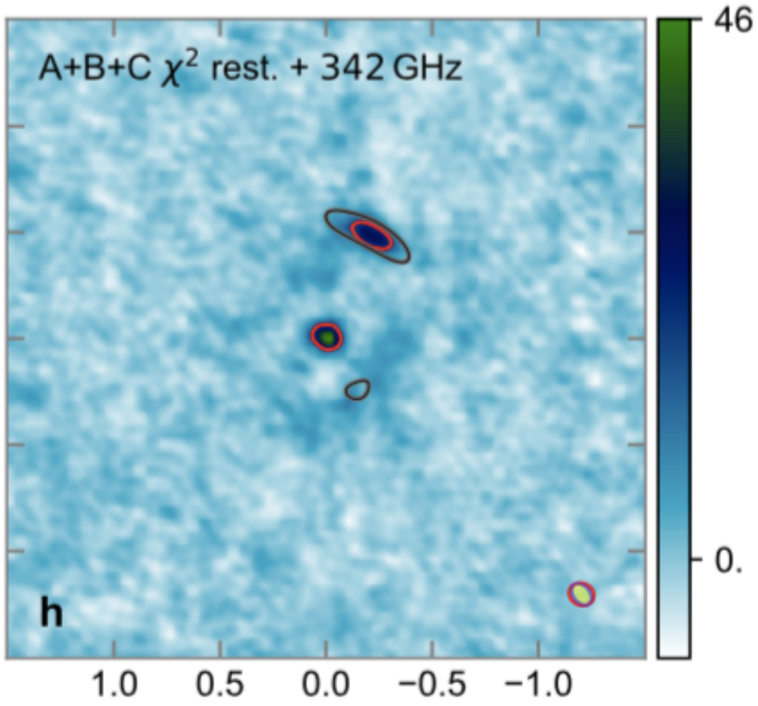
ALMA (mm)



VLA (cm-m)

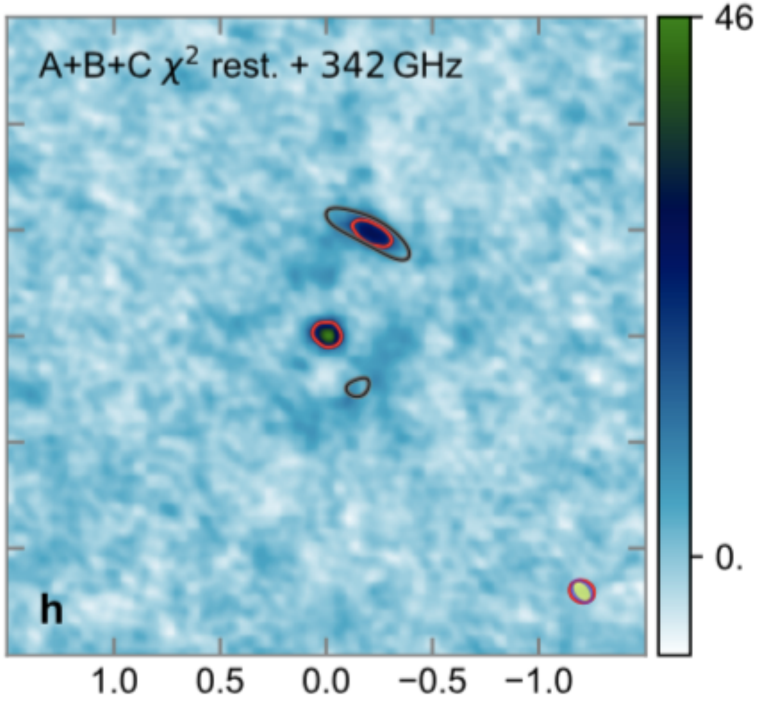


Overlay

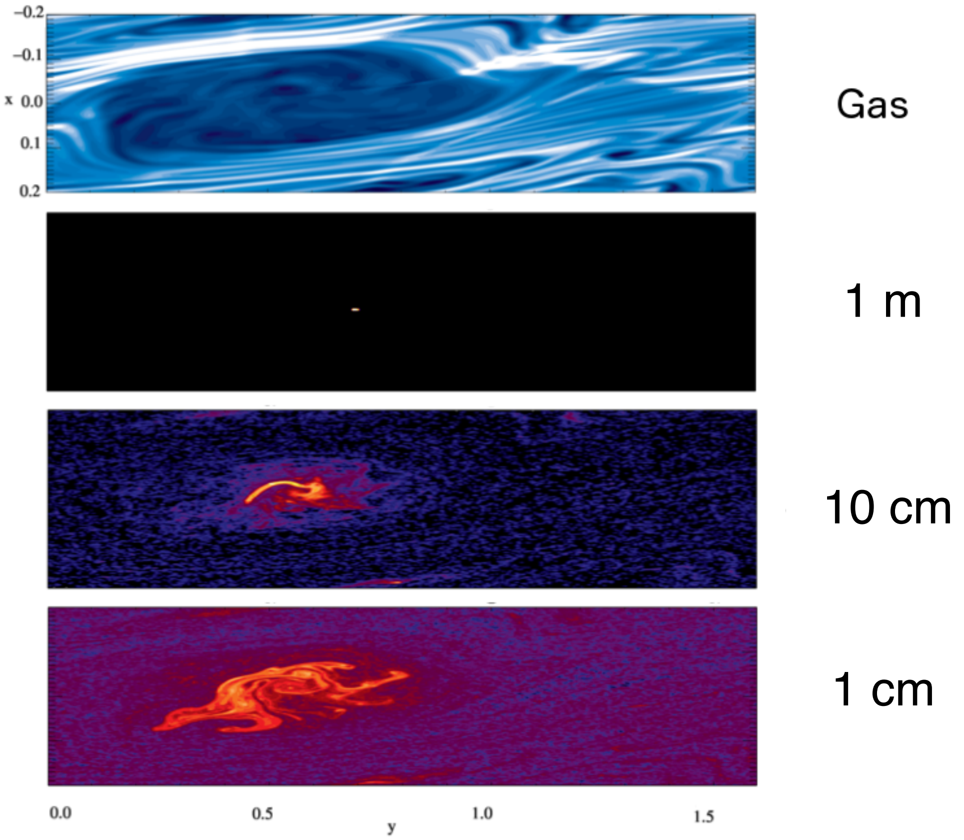


Casassus+Lyra ’19

Model vs Observation



Casassus+Lyra ‘19



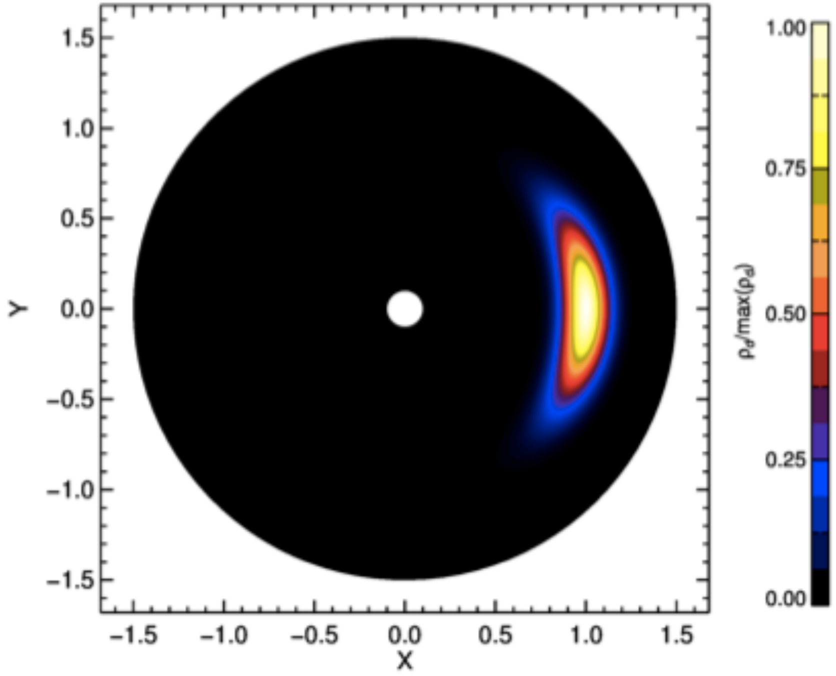
Raettig+Lyra ‘15

Take home message

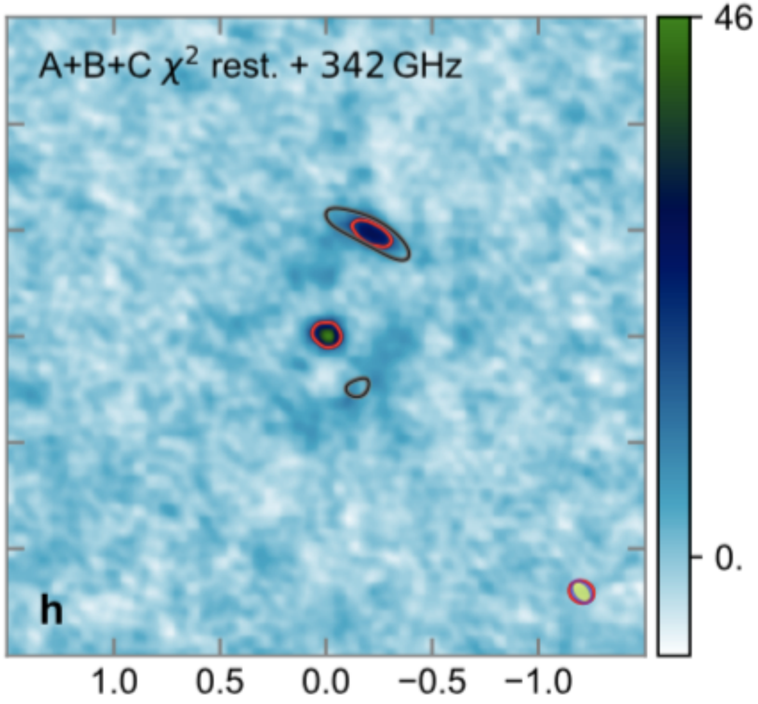
- Vortex-trapped dust in drag-diffusion equilibrium explains the observations

$$\rho_d(a,z) = \varepsilon \rho_0 (S+1)^{3/2} \exp\left\{ -\frac{[a^2 f^2(\chi) + z^2]}{2H^2}(S+1) \right\}$$

Lyra-Lin solution



Observed Disk



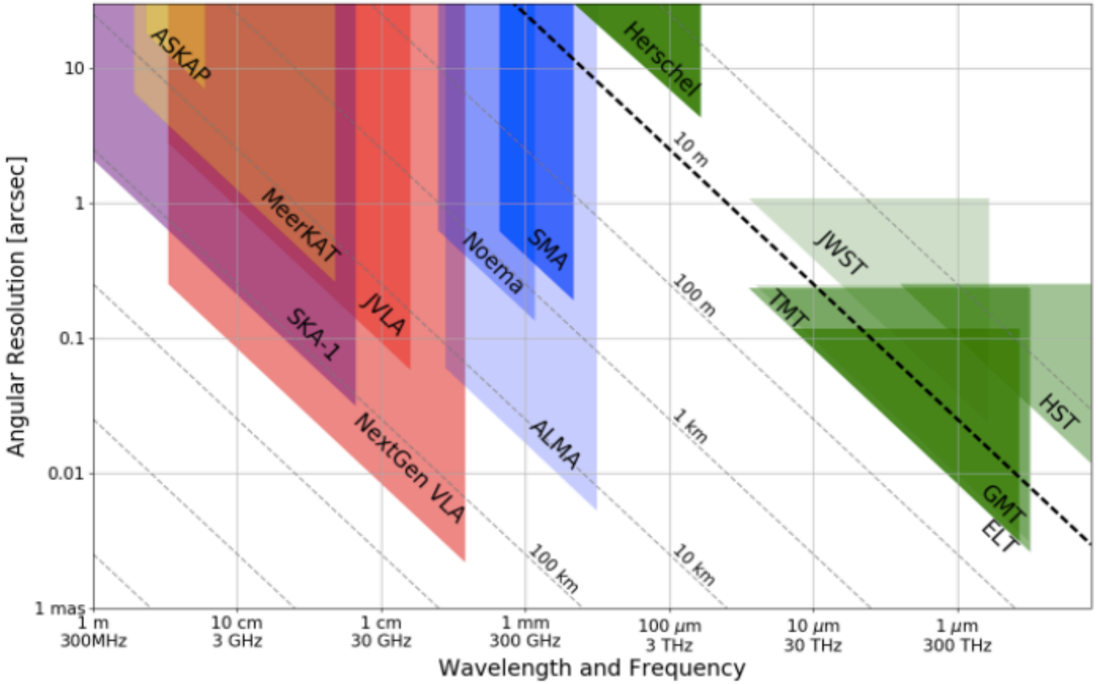
The future

After 7 years of ALMA…

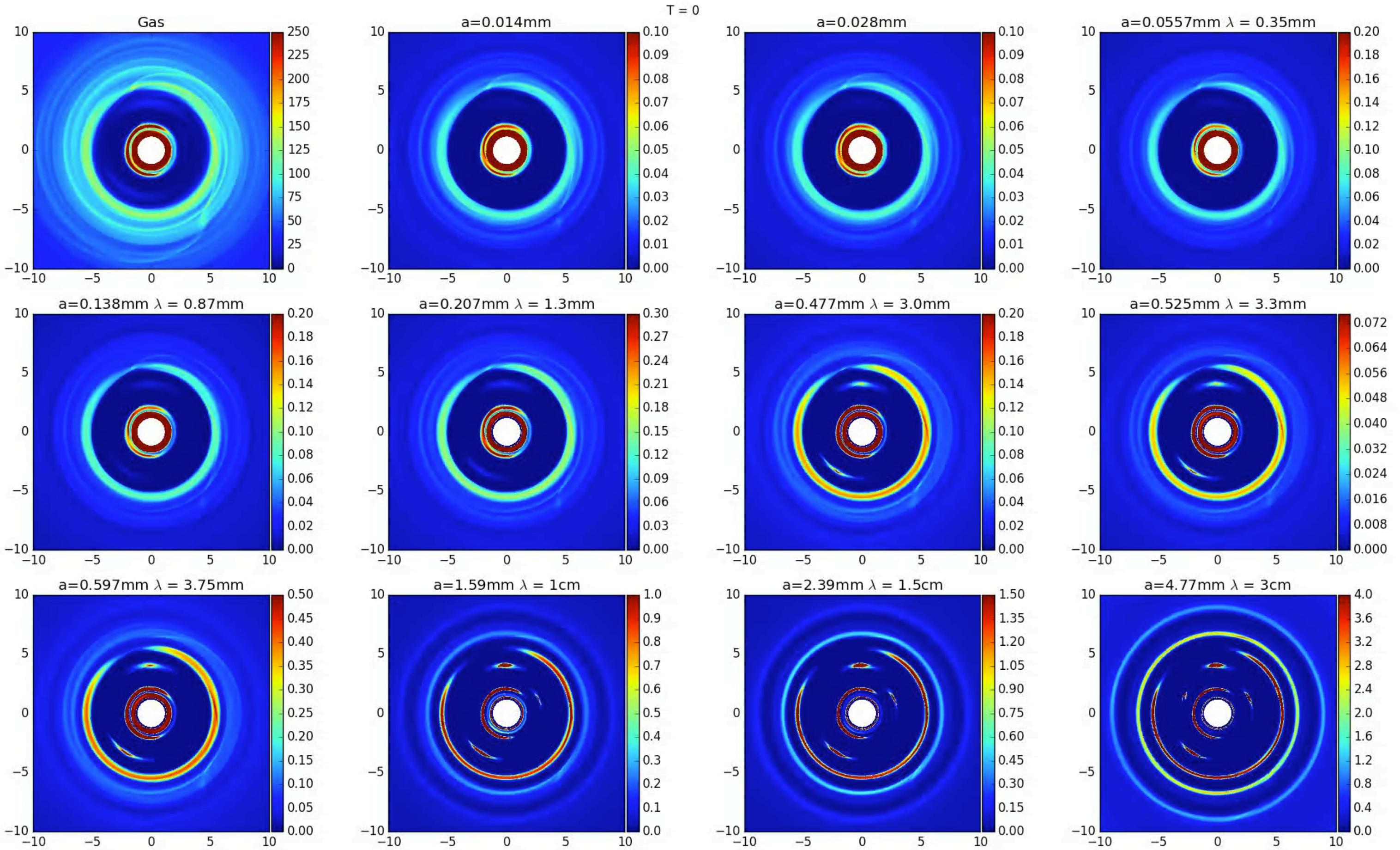
Nearly all nearby disks observed at <0.1” (< 20-30AU) show substructures.

3 main types of substructures
- Crescent-shaped
- Spiral arms
- Rings/Gaps

Next Generation Very Large Array (ngVLA)



Disk + planet hydrodynamical simulations



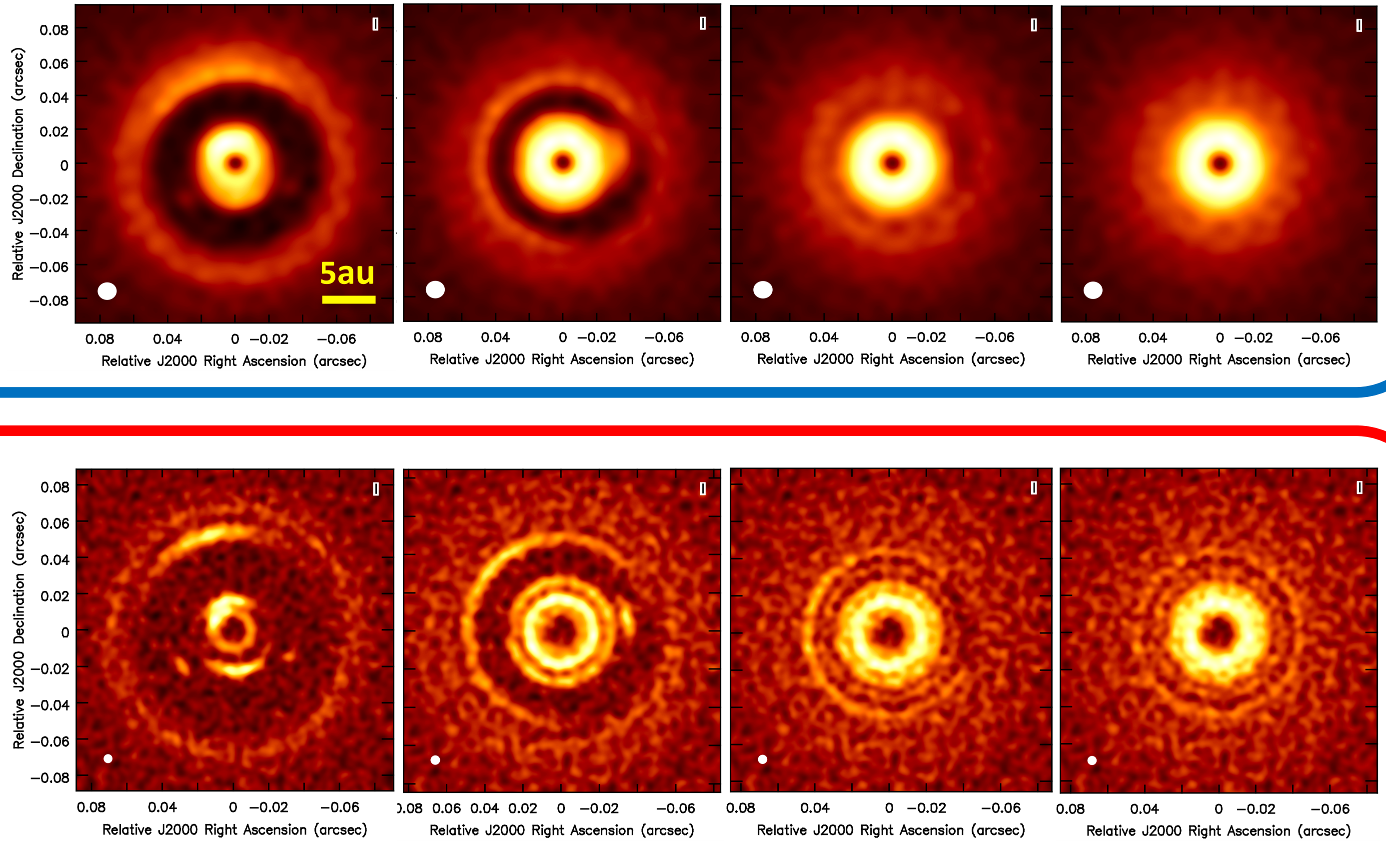
Planets at 5AU

Jupiter | Saturn | Neptune | 10 M_{Earth}

ALMA @ 0.87mm

ngVLA @ 3mm

5 mas = 0.7 AU
rms = 5x10^{-7} Jy/b

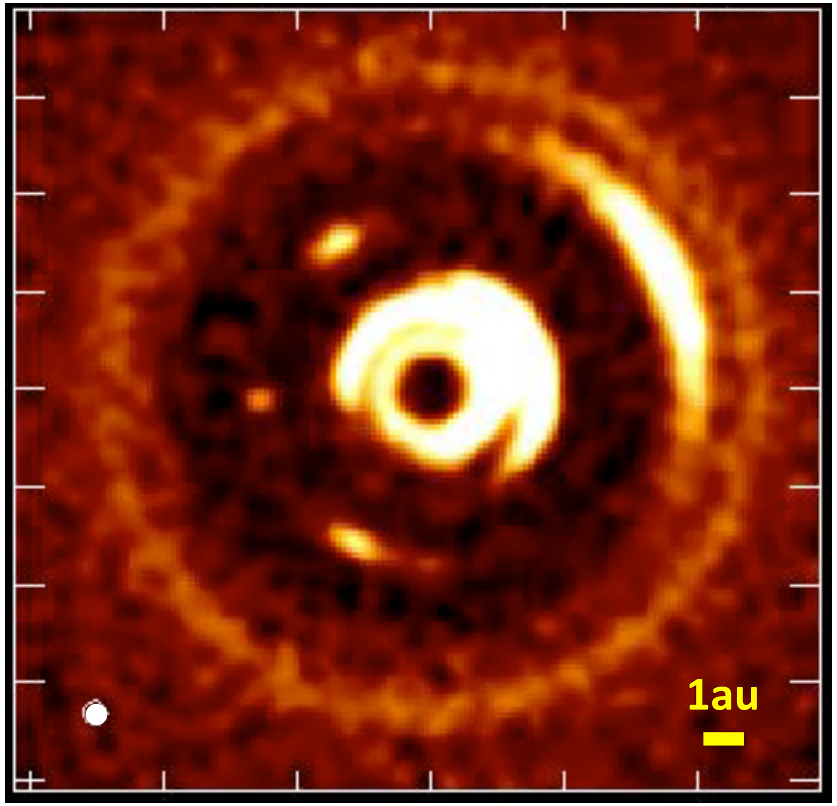


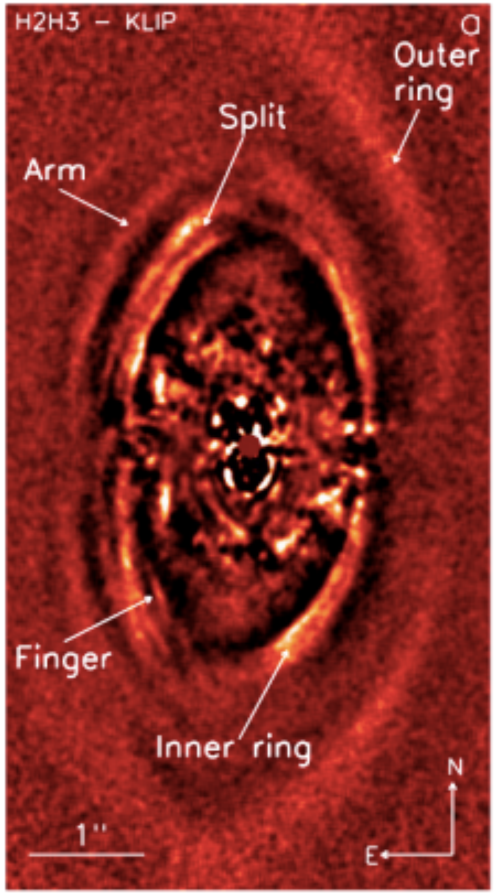
ngVLA will identify gaps/substructures down to ~5-10 M_{Earth}

Ricci+ ‘18

ngVLA: Proper motions

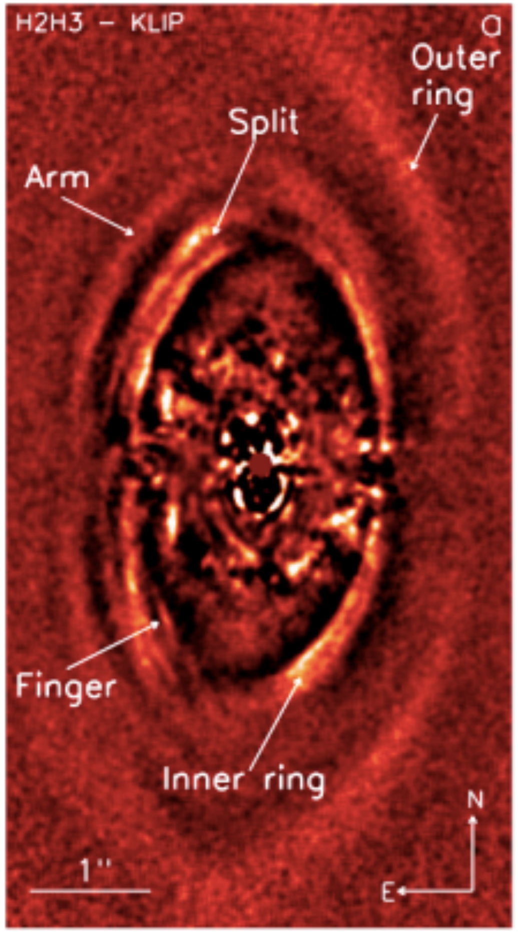
Jupiter at 5 AU

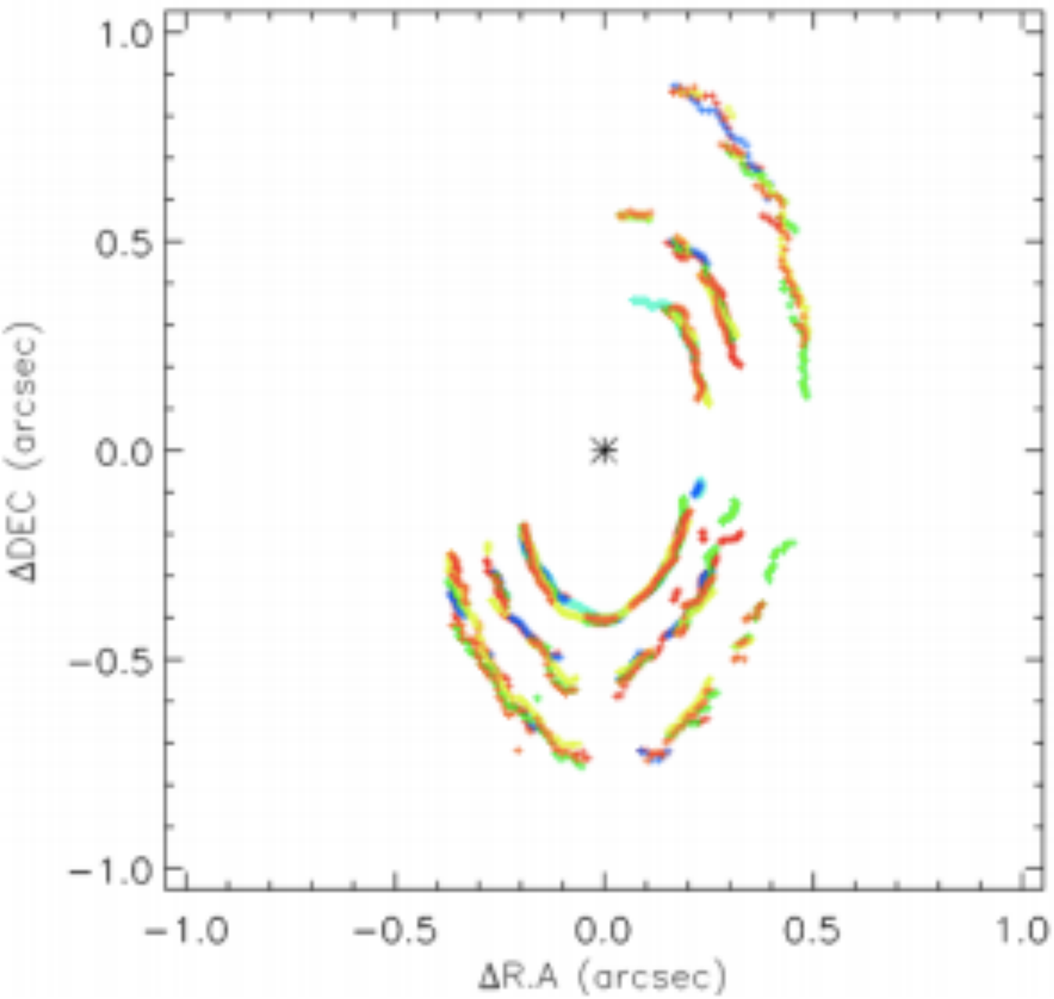




Other projects

HD 141569 A

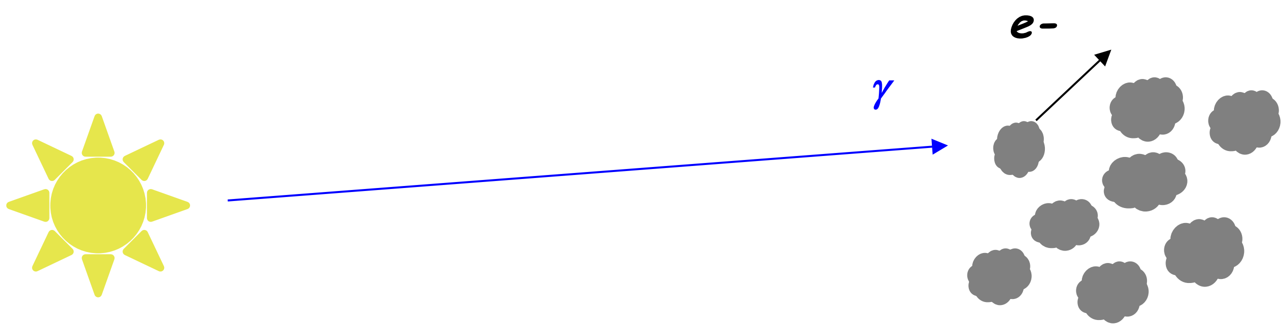




Perrot+ '16

Photoelectric heating

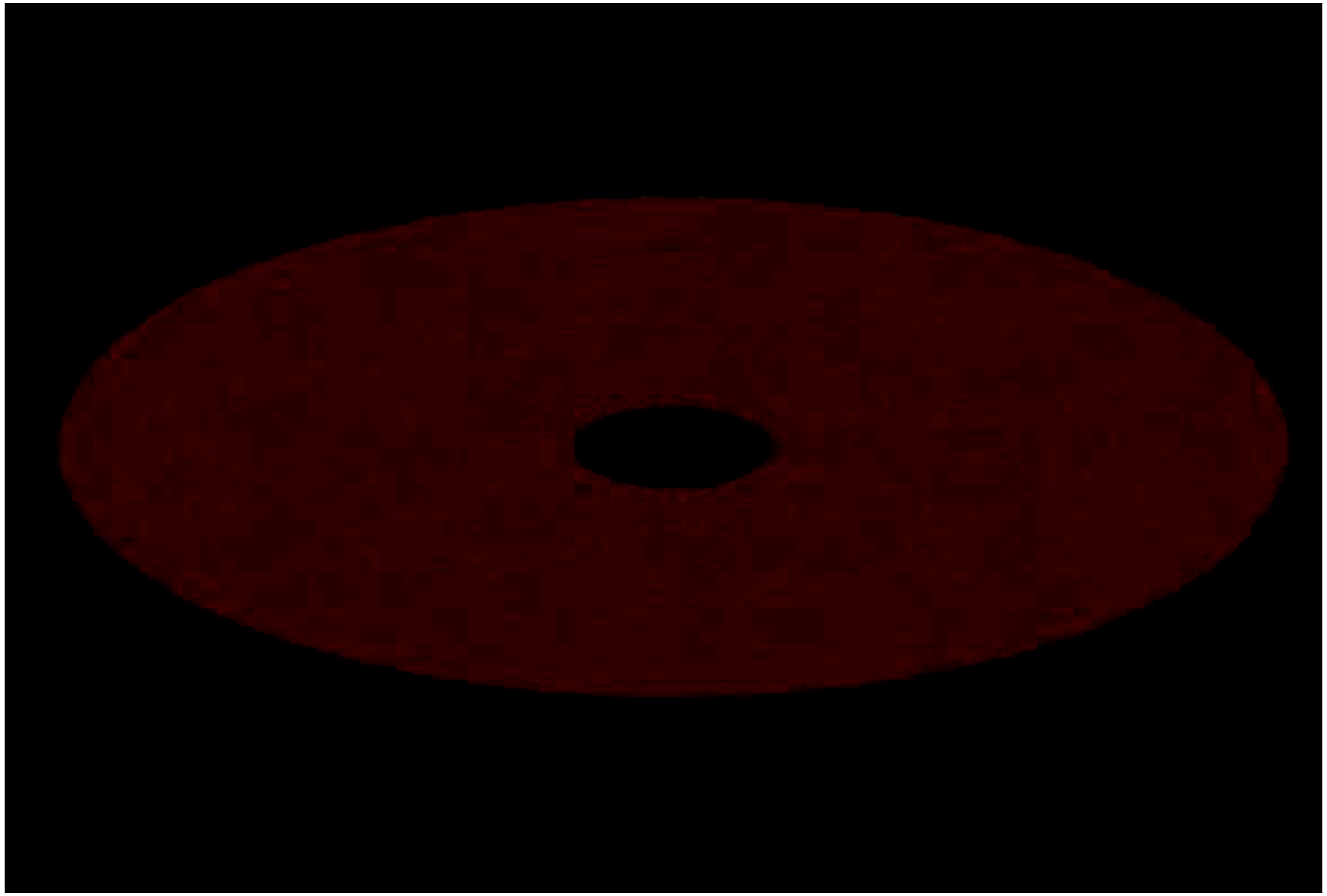
In optically thin disks,
the **dust** is the **main heating agent** for the gas.



Dust intercepts starlight directly,
emits electron, that heats the gas.

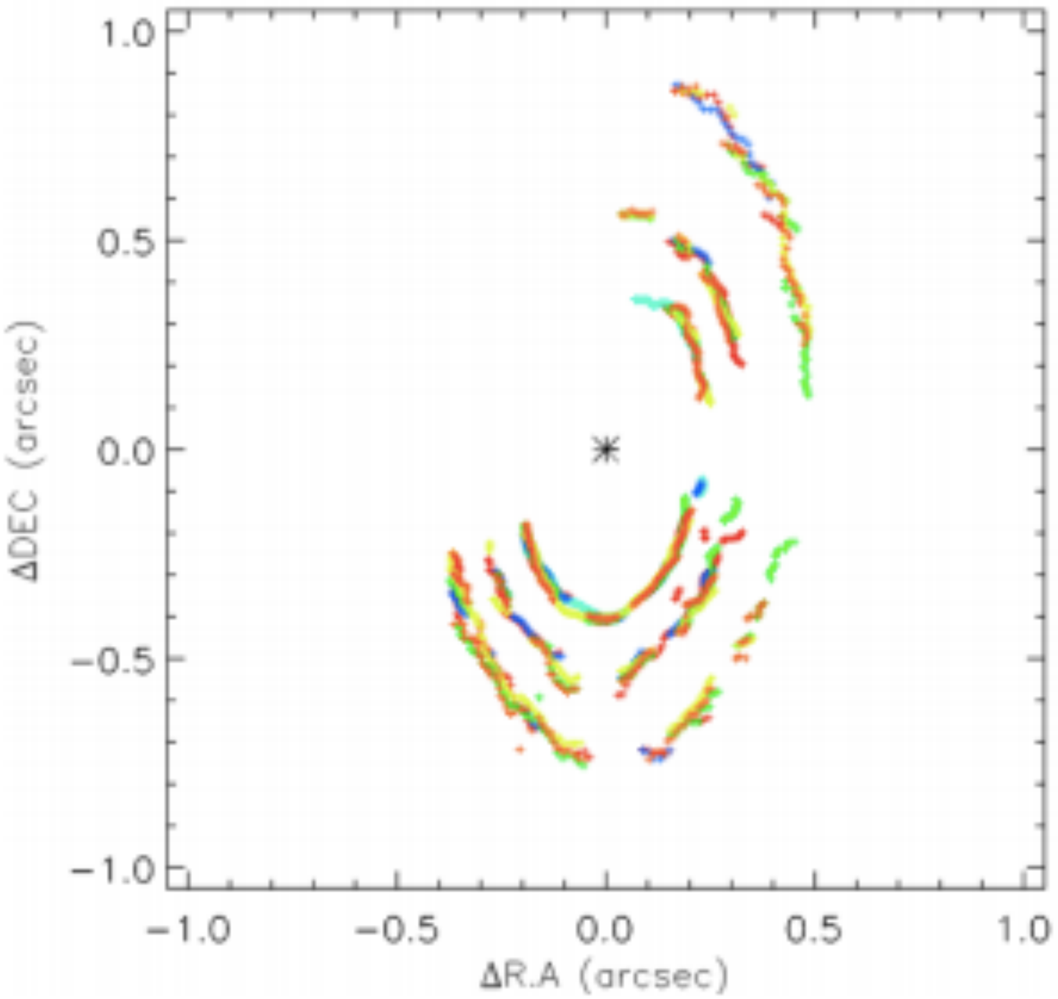
Gas is photoelectrically heated by the dust

Photoelectric Instability in optically thin disks

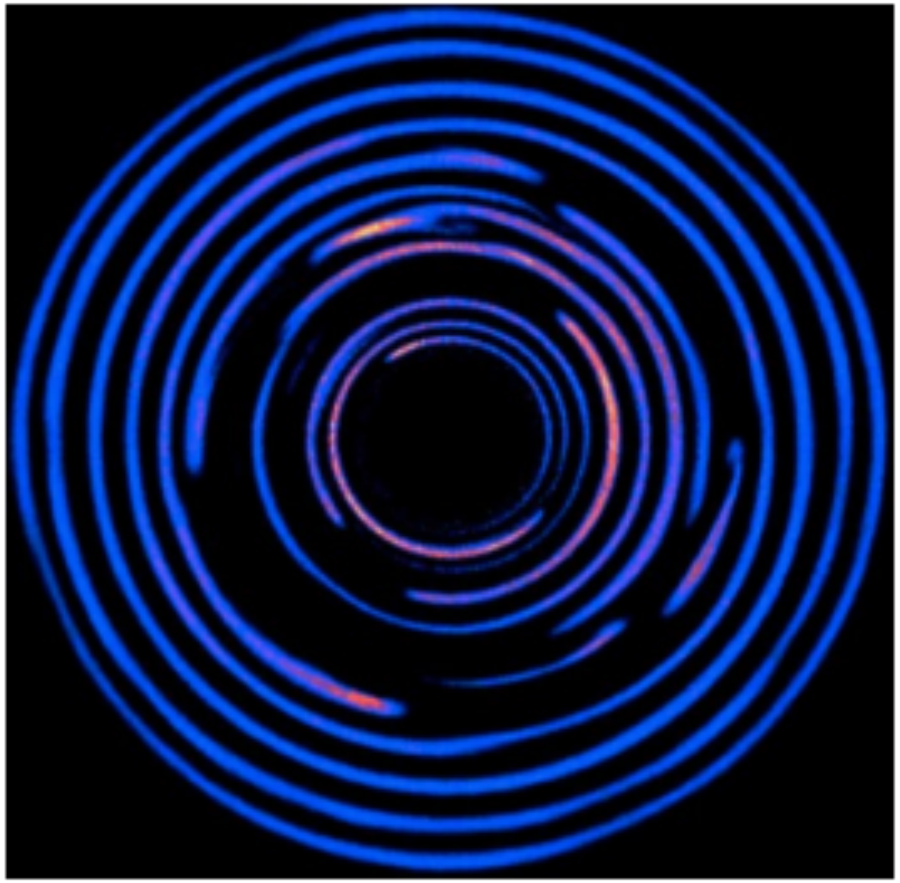


Lyra & Kuchner (2013, Nature, 499, 184)

Photoelectric Instability: Observations vs Model



Perrot+ ‘16



Lyra & Kuchner ‘13

LETTER

doi:10.1038/nature12281

Formation of sharp eccentric rings in debris disks with gas but without planets

W. Lyra[1,2,3] & M. Kuchner[4]

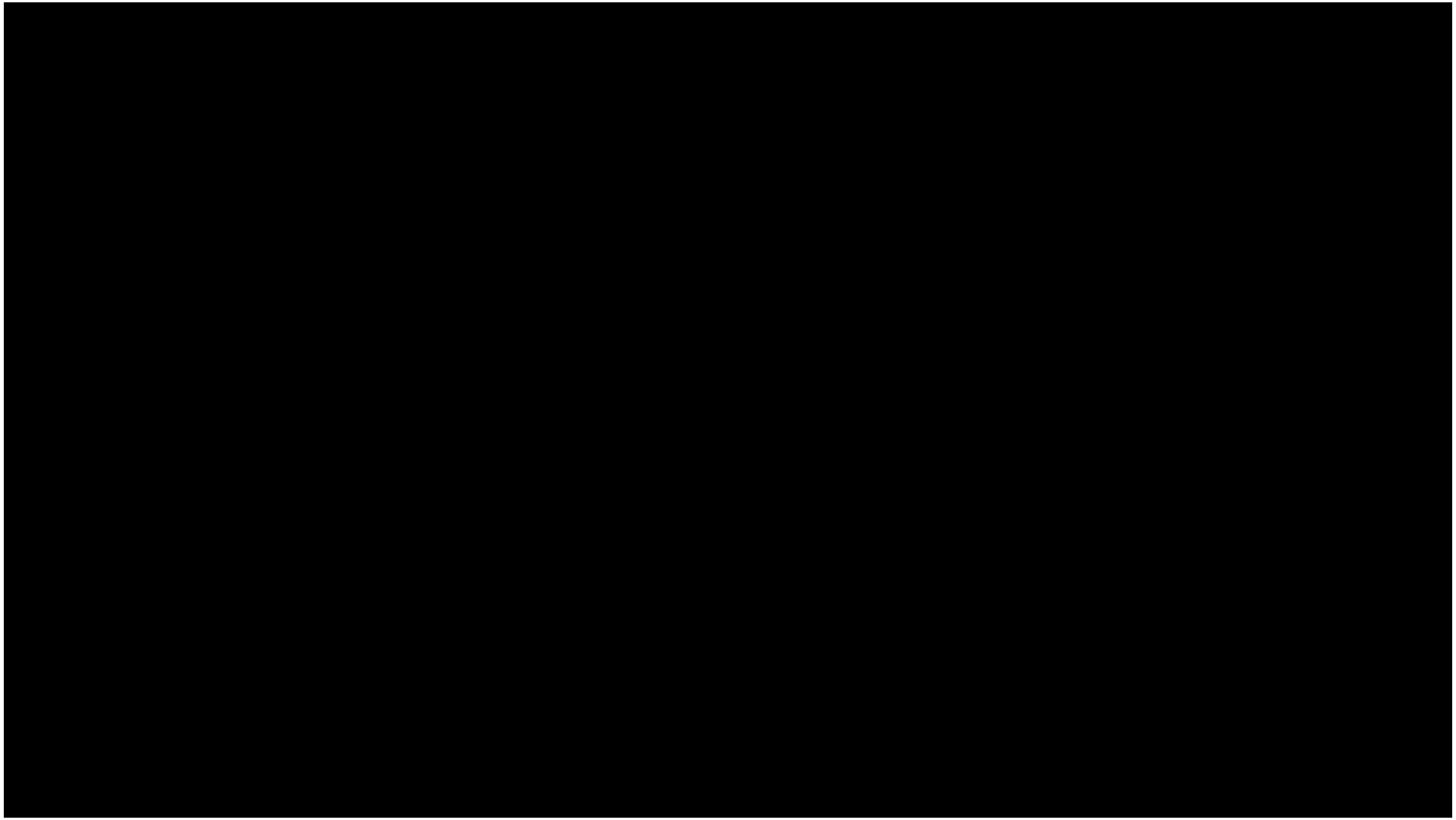
'Debris disks' around young stars (analogues of the Kuiper Belt in our Solar System) show a variety of non-trivial structures attributed to planetary perturbations and used to constrain the properties of those planets[1–3]. However, these analyses have largely ignored the fact that some debris disks are found to contain small quantities of gas[4–9], a component that all such disks should contain at some level[10,11]. Several debris disks have been measured with a dust-to-gas ratio of about unity[4–9], at which the effect of hydrodynamics on the structure of the disk cannot be ignored[12,13]. Here we report linear and nonlinear modelling that shows that dust–gas interactions can produce some of the key patterns attributed to planets. We find a robust clumping instability that organizes the dust into narrow, eccentric rings, similar to the Fomalhaut debris disk[14]. The conclusion that such disks might contain planets is not necessarily required to explain these systems.

Disks around young stars seem to pass through an evolutionary phase when the disk is optically thin and the dust-to-gas ratio ε ranges from 0.1 to 10. The nearby stars β Pictoris[5,6,15–17], HD32297 (ref. 7), 49 Ceti (ref. 4) and HD 21997 (ref. 9) all host dust disks resembling ordinary debris disks and also have stable circumstellar gas detected in molecular CO, Na I or other metal lines; the inferred mass of gas ranges from lunar masses to a few Earth masses (Supplementary Information). The gas in

We present simulations of the fully compressible problem, solving for the continuity, Navier–Stokes and energy equations for the gas, and the momentum equation for the dust. Gas and dust interact dynamically through a drag force, and thermally through photoelectric heating. These are parametrized by a dynamical coupling time τ_f and a thermal coupling time τ_T (Supplementary Information). The simulations are performed with the Pencil Code[21–24], which solves the hydrodynamics on a grid. Two numerical models are presented: a three-dimensional box embedded in the disk that co-rotates with the flow at a fixed distance from the star; and a two-dimensional global model of the disk in the inertial frame. In the former the dust is treated as a fluid, with a separate continuity equation. In the latter the dust is represented by discrete particles with position and velocities that are independent of the grid.

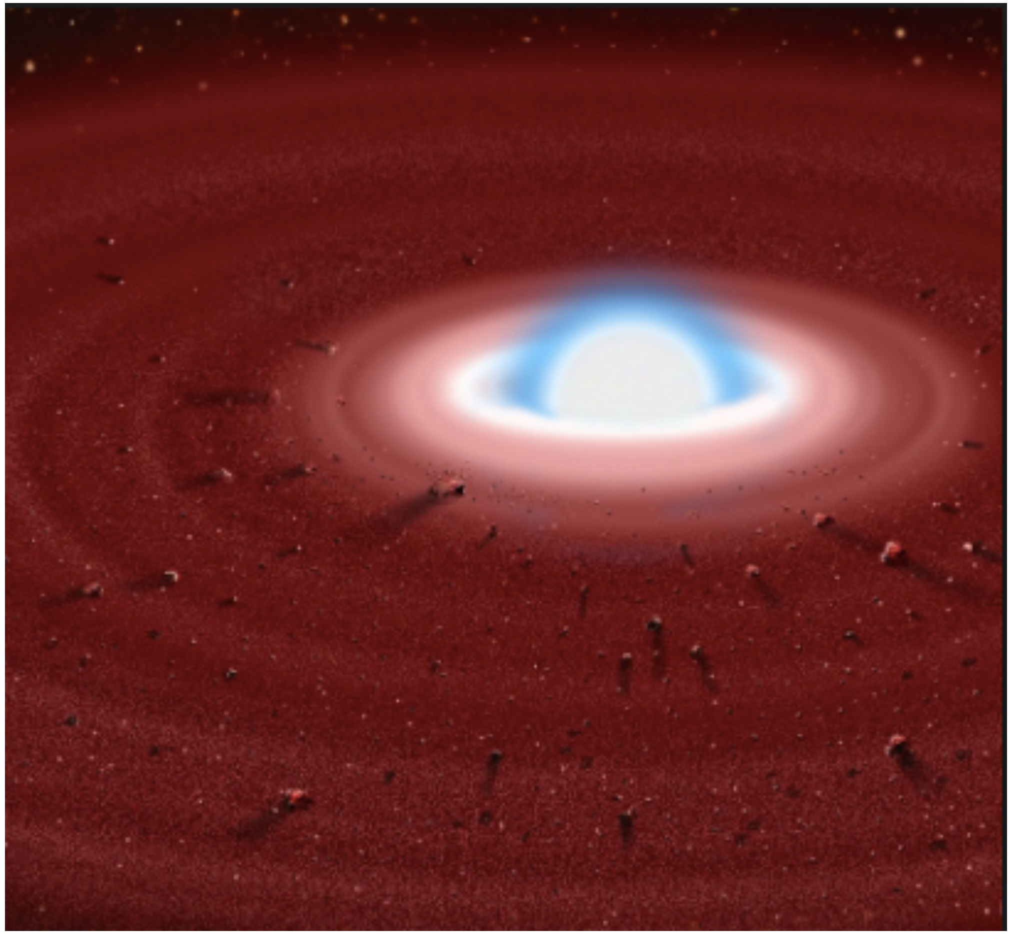
We perform a stability analysis of the linearized system of equations that should help interpret the results of the simulations (Supplementary Information). We plot in Fig. 1a–c the three solutions that show linear growth, as functions of ε and $n = kH$, where k is the radial wavenumber and H is the gas scale height ($H = c_s/\sqrt{\gamma}\Omega_K$, where c_s is the sound speed, Ω_K the Keplerian rotation frequency and γ the adiabatic index). The friction time τ_f is assumed to be equal to $1/\Omega_K$. The left and middle panels show the growth and damping rates. The

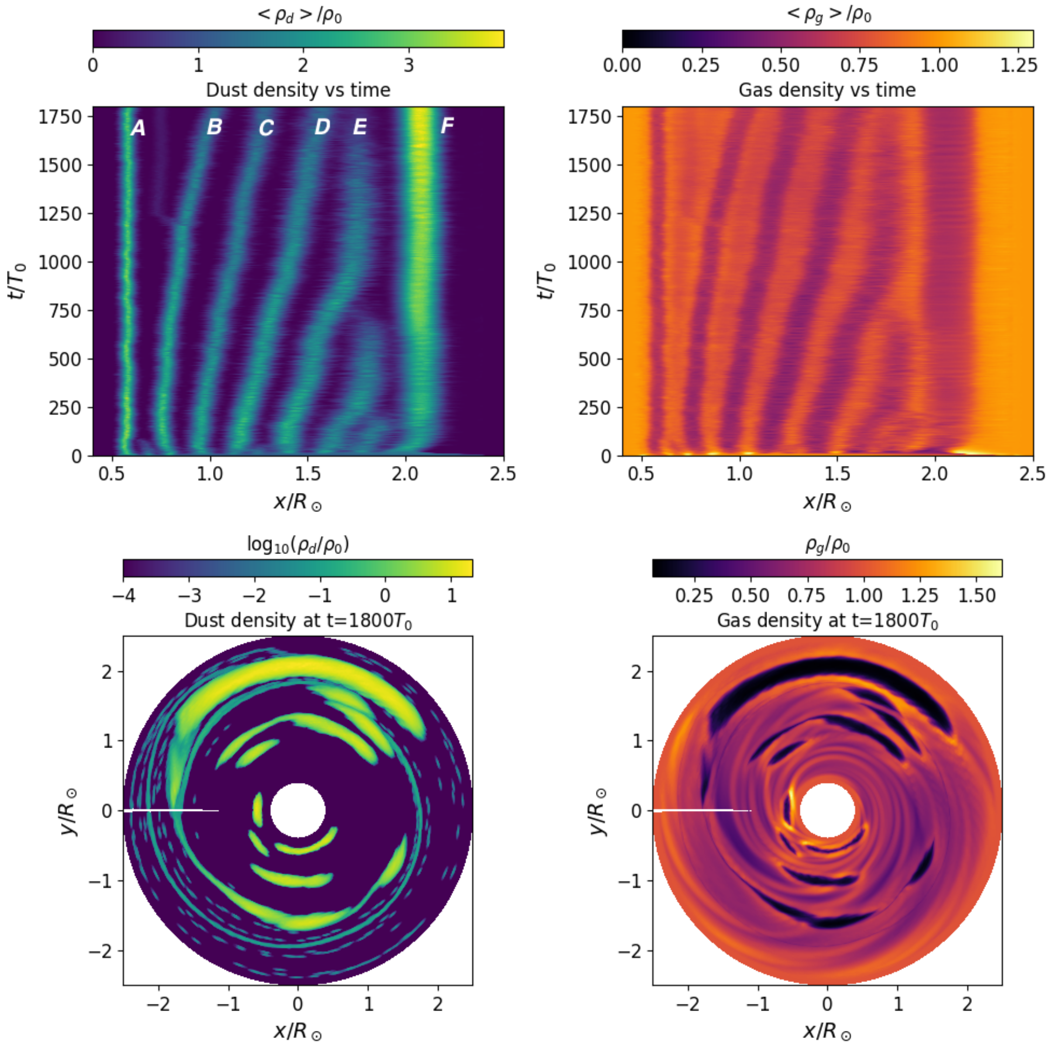
Photoelectric Instability with radiation pressure



Richert+ Lyra '18

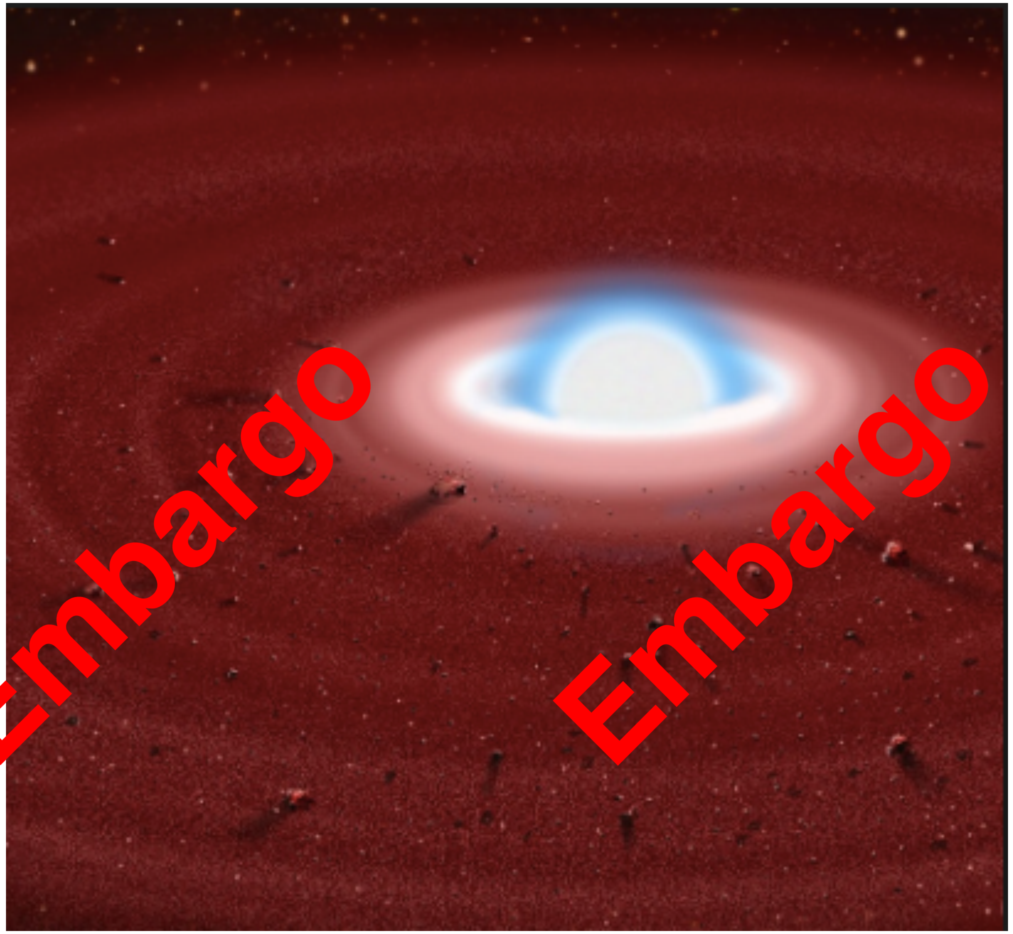
White dwarf disks

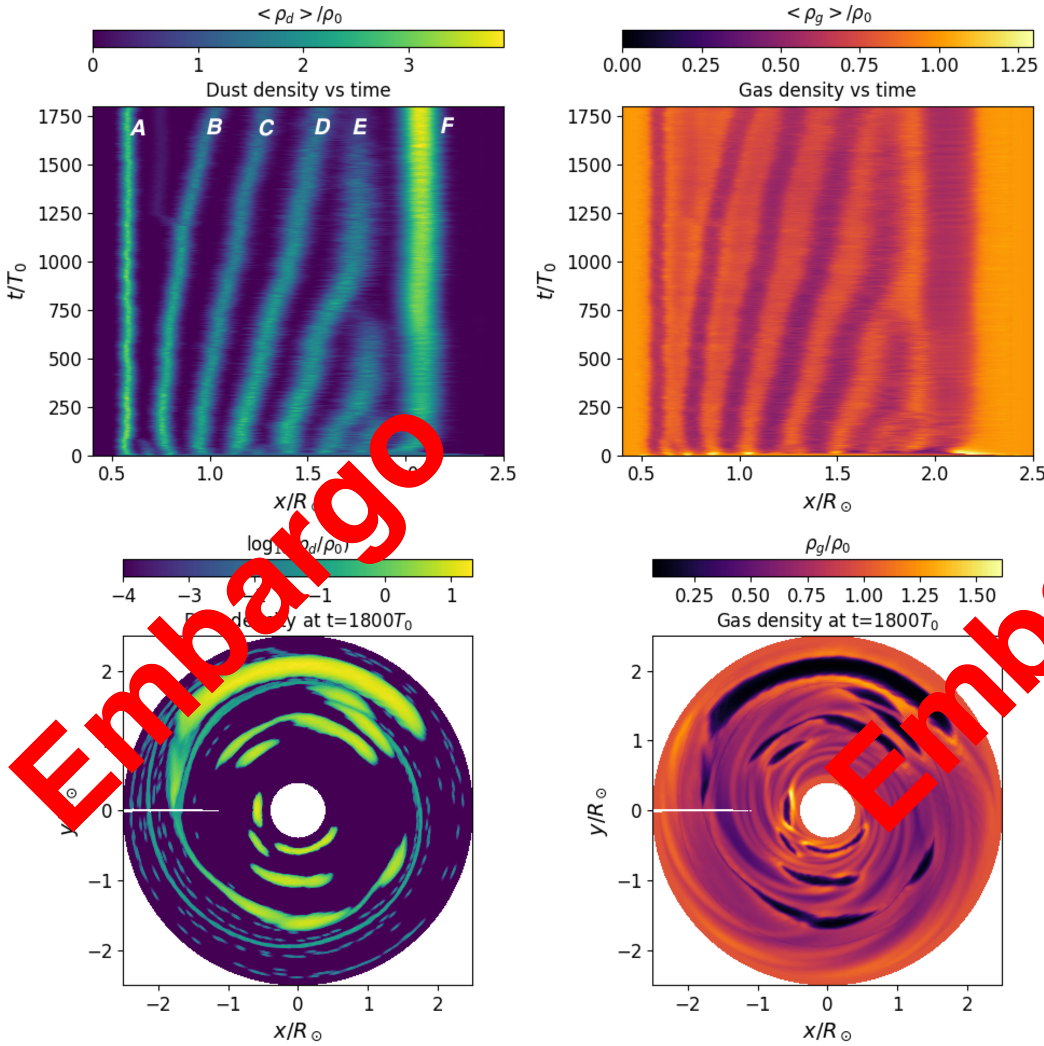




?+ Lyra, Science, '19

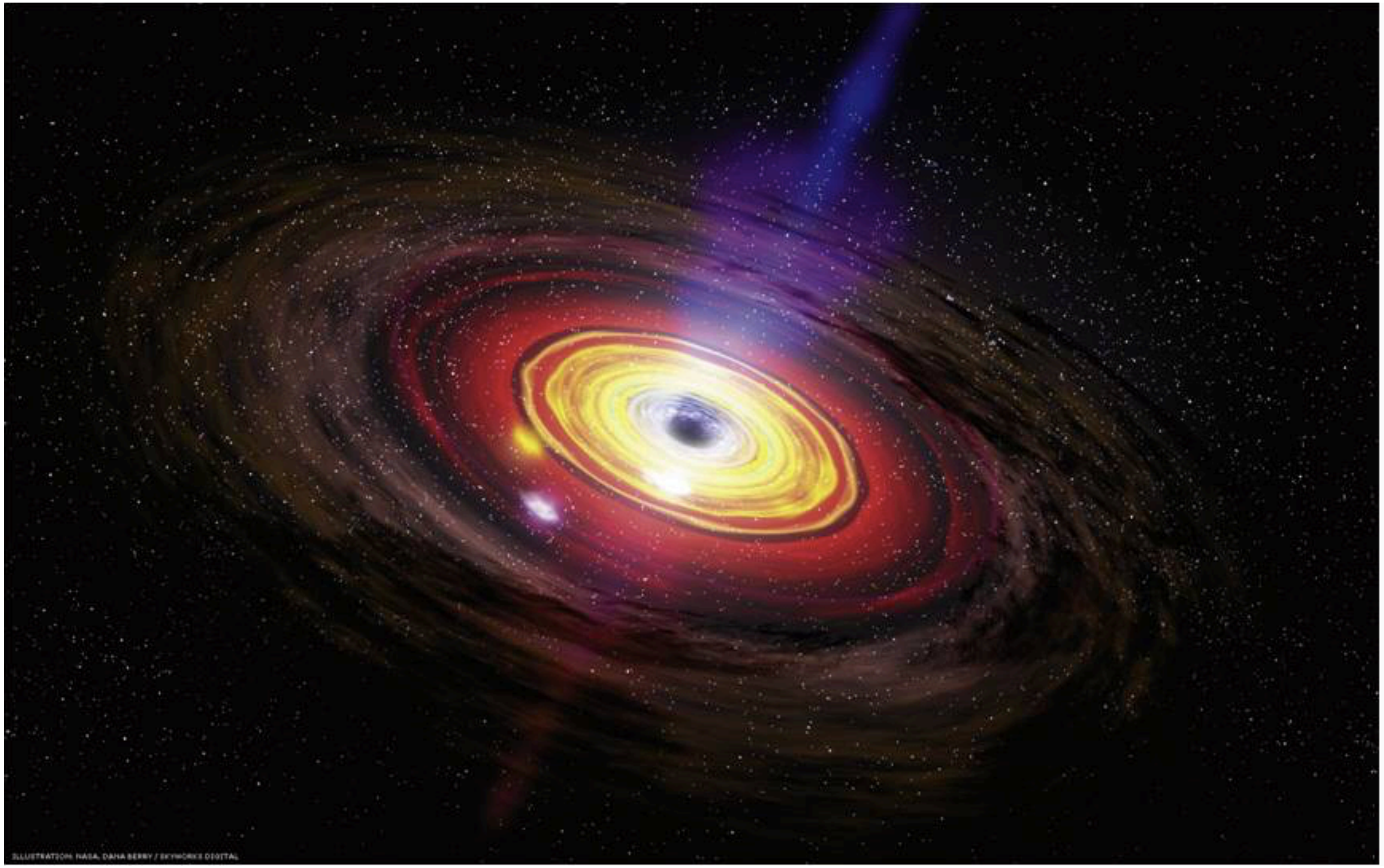
White dwarf disks





? + Lyra, Science, '19

Black hole mergers in AGN disks



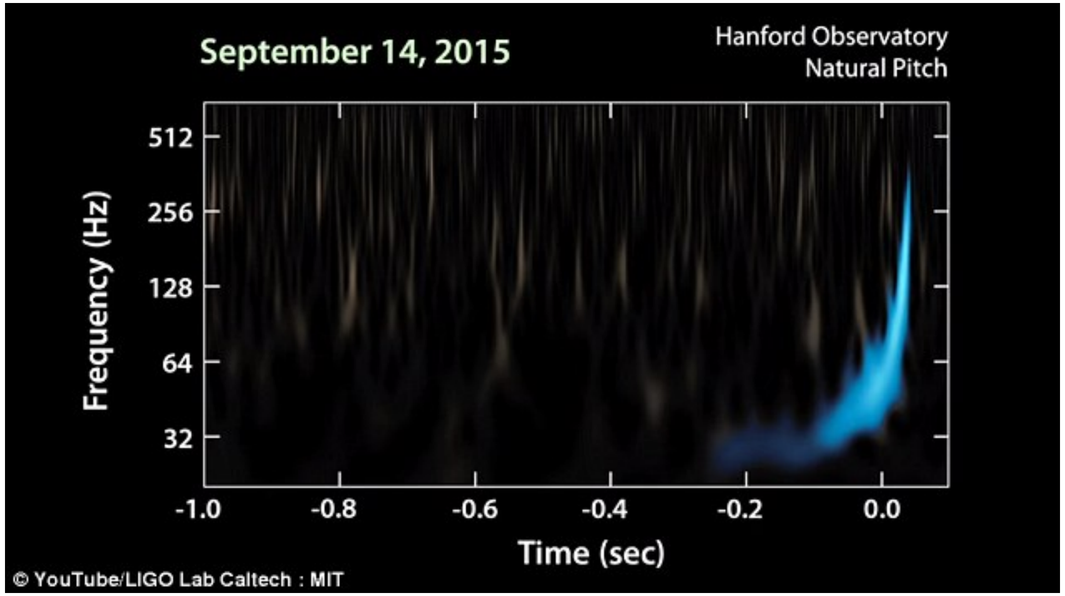
LIGO Black Hole Masses

GW150914: 36 and 29 $M_\odot$

LVT151012: 23 and 13 $M_\odot$

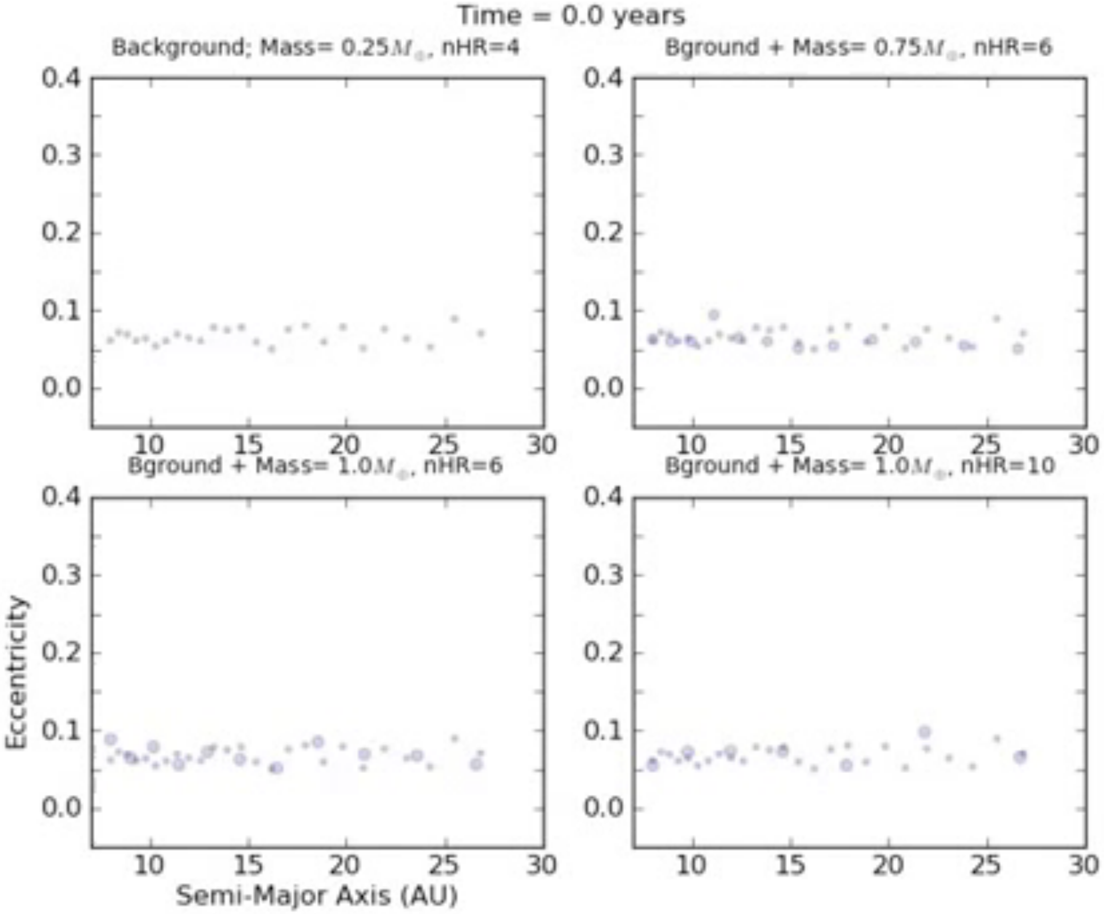
GW151226: 14 and 7 $M_\odot$

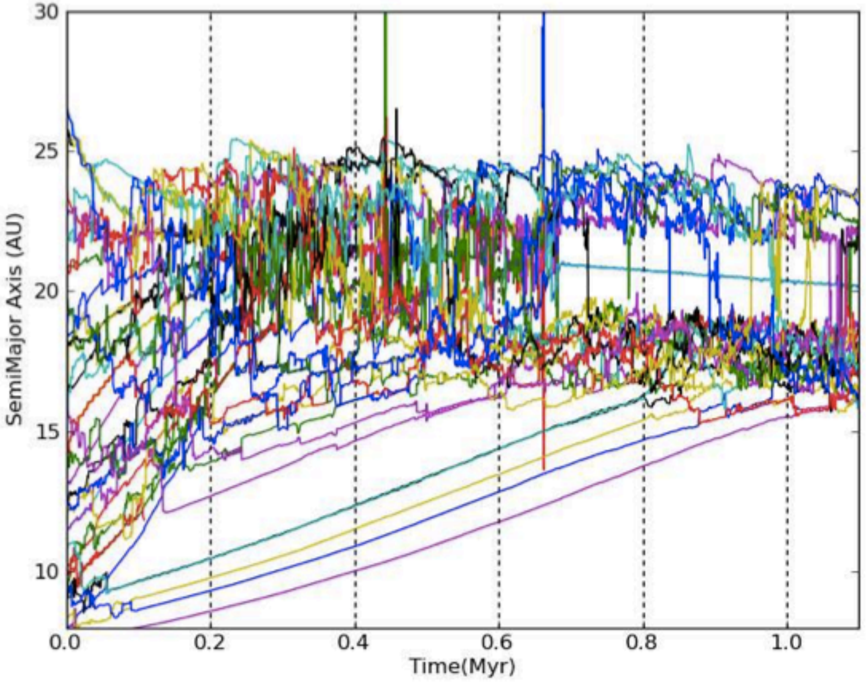
GW170104: 31 and 19 $M_\odot$



Large masses challenge stellar evolution-based BH-BH merger theories

Planet Formation by Core Accretion

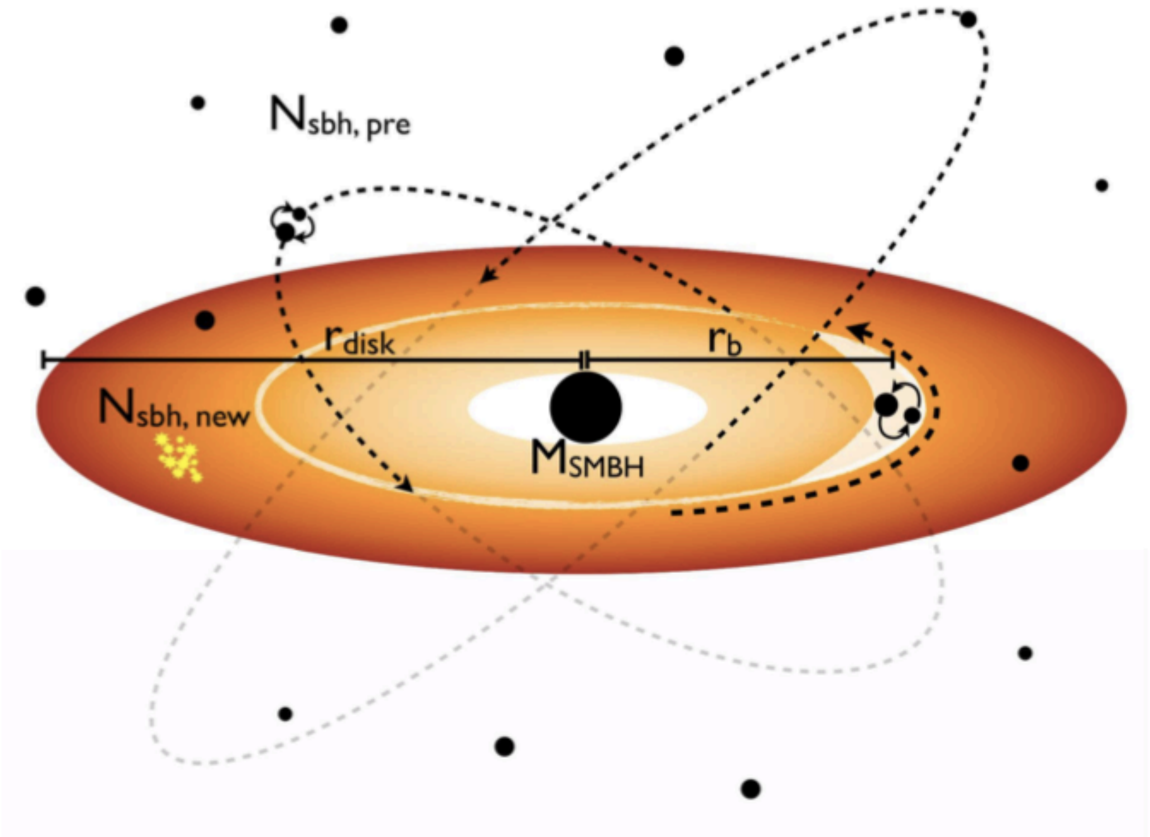




Horn+Lyra '12

“Blackholenitesimals”

The circumstellar disk-AGN analogy



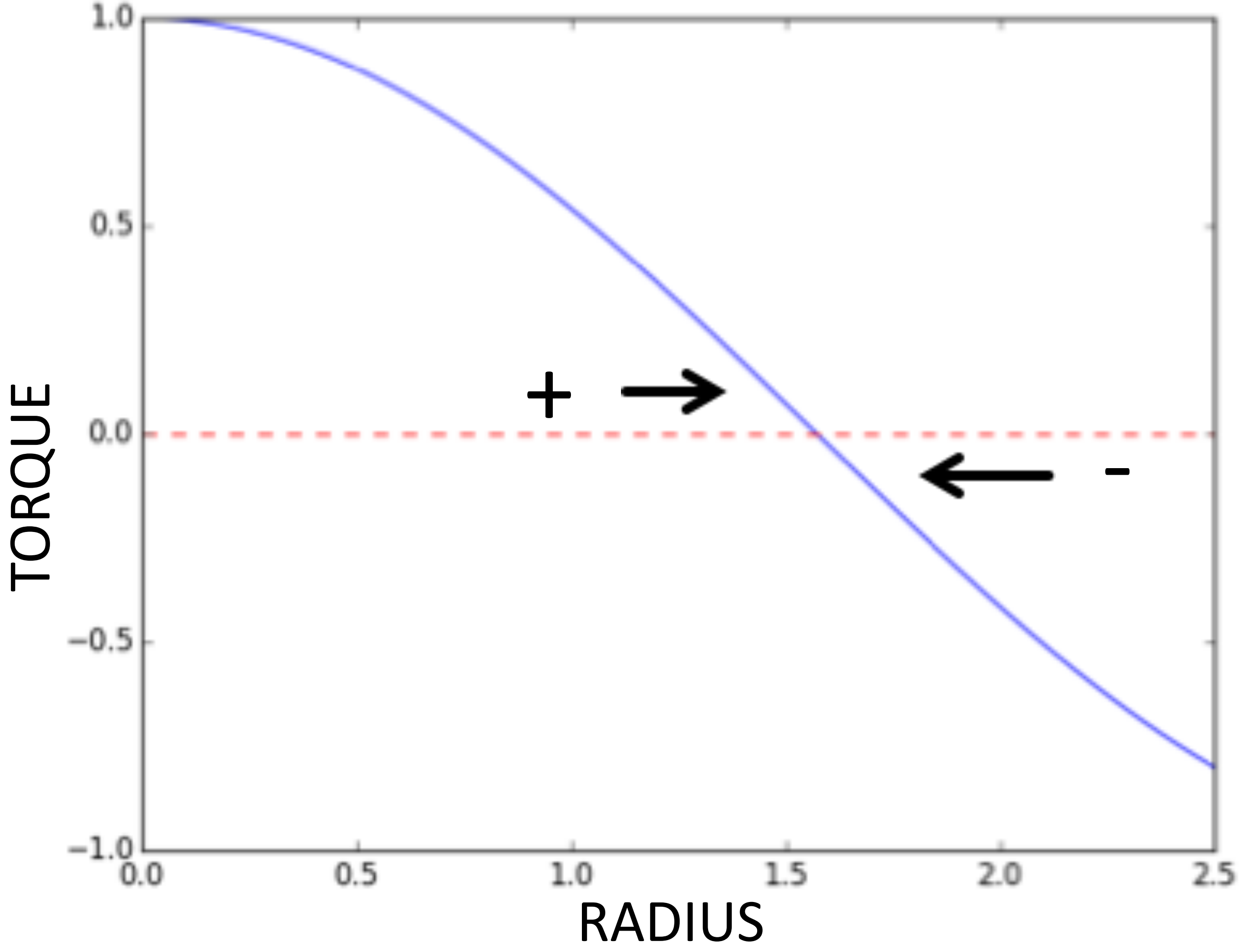
Protoplanets → stellar-mass black holes

Circumstellar disk → SMBH accretion disk

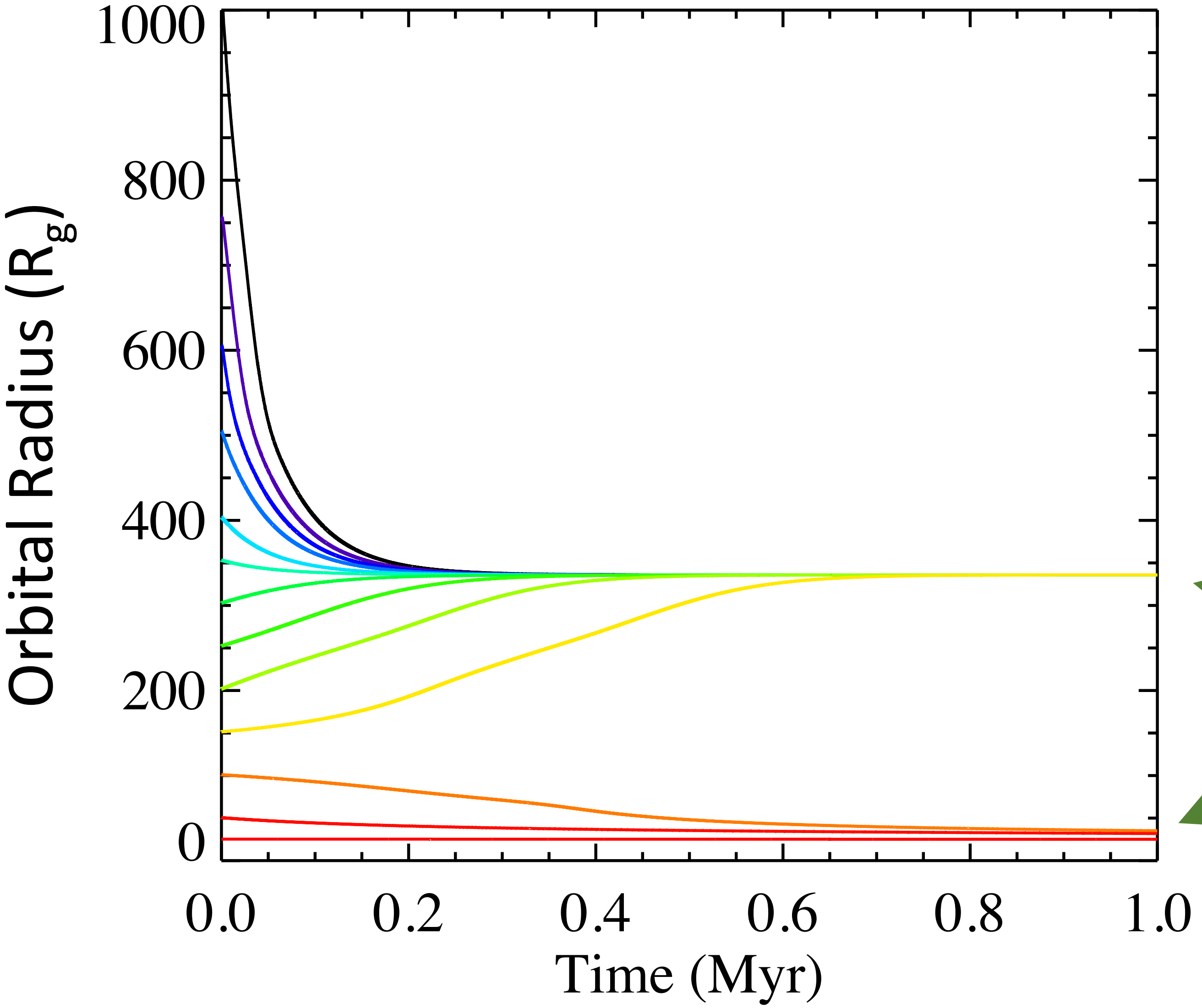
Stellar-mass black holes migrate and merge like planetesimals

McKernan+Lyra ‘12

Migration Traps



Migration of a single object



Predicted traps:

331 R_g

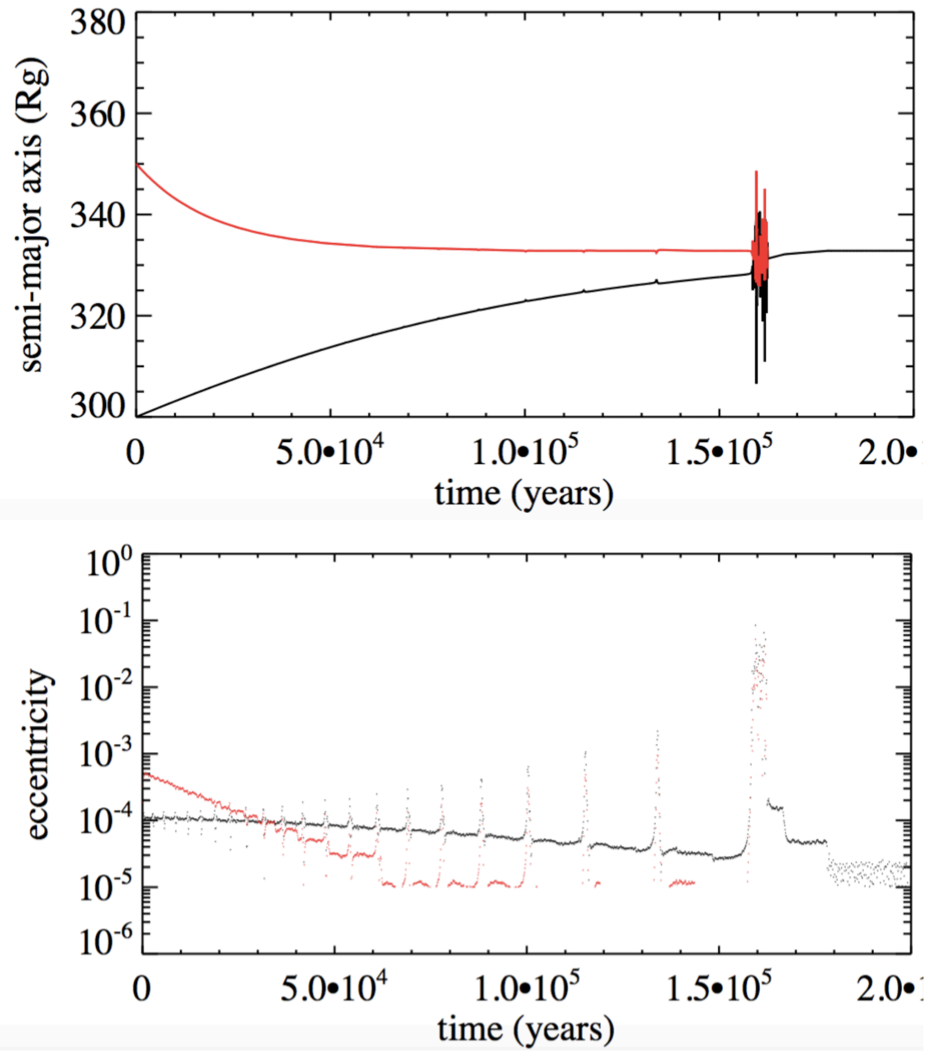
25 R_g

Bellovary+ '16

Migration and merger of two objects

- 50 $M_\odot$ BH and 30 $M_\odot$ BH

- Form a binary upon reaching trap

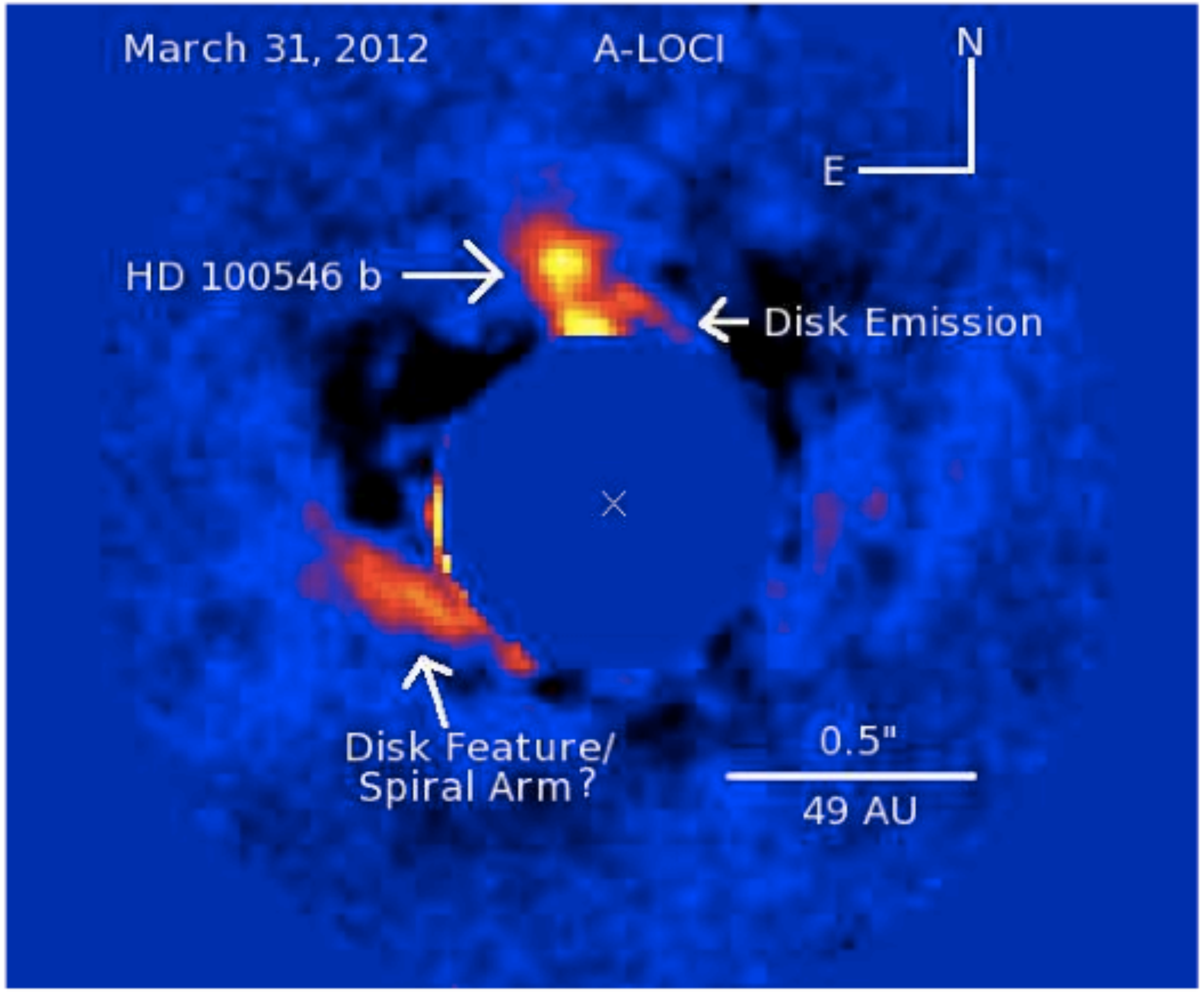


Secunda+Lyra '19

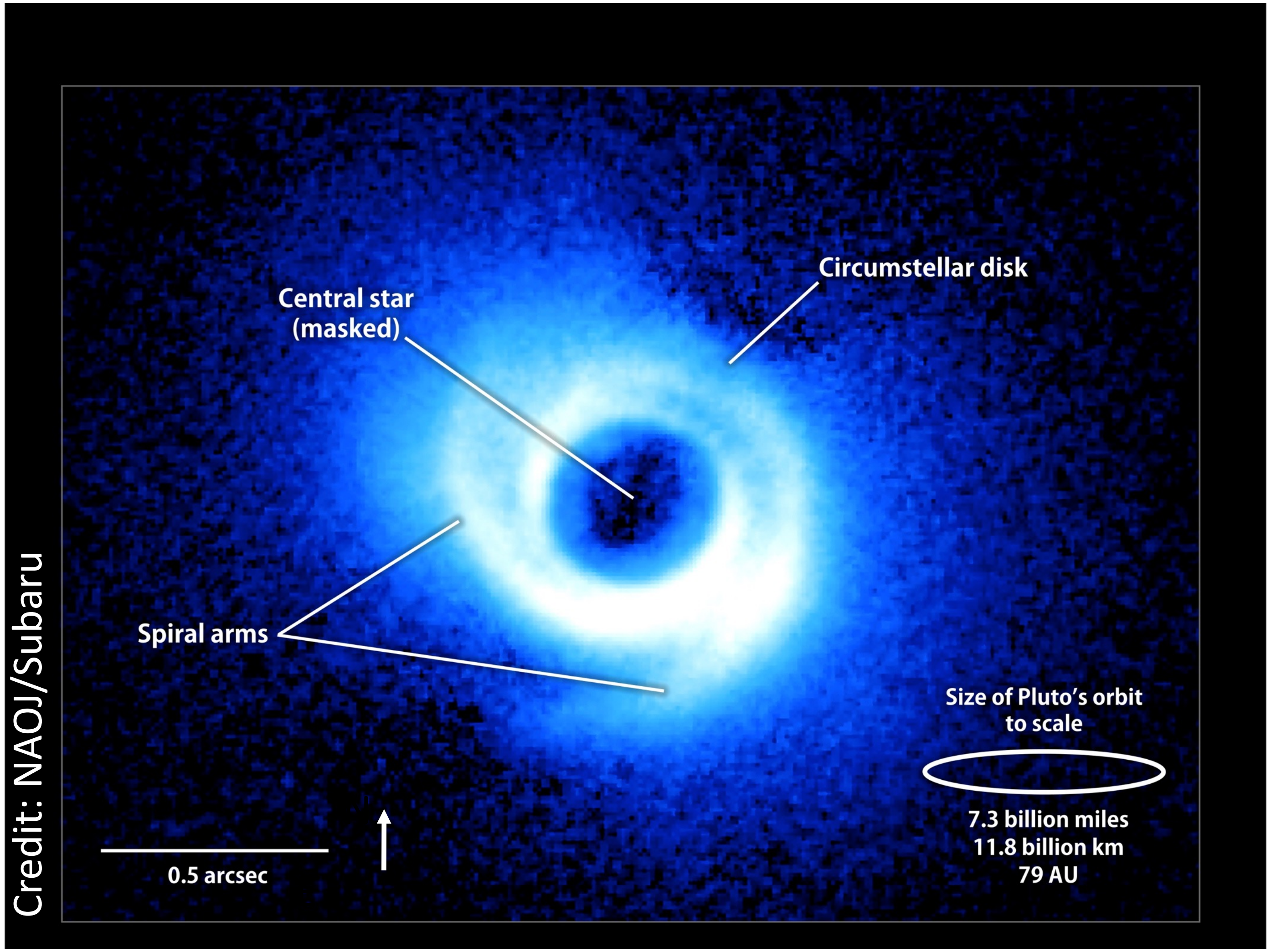
1st workshop on black hole mergers in AGN disks

Center for Computational Astrophysics, NYC
Mar 2019

Scattered Light Observations

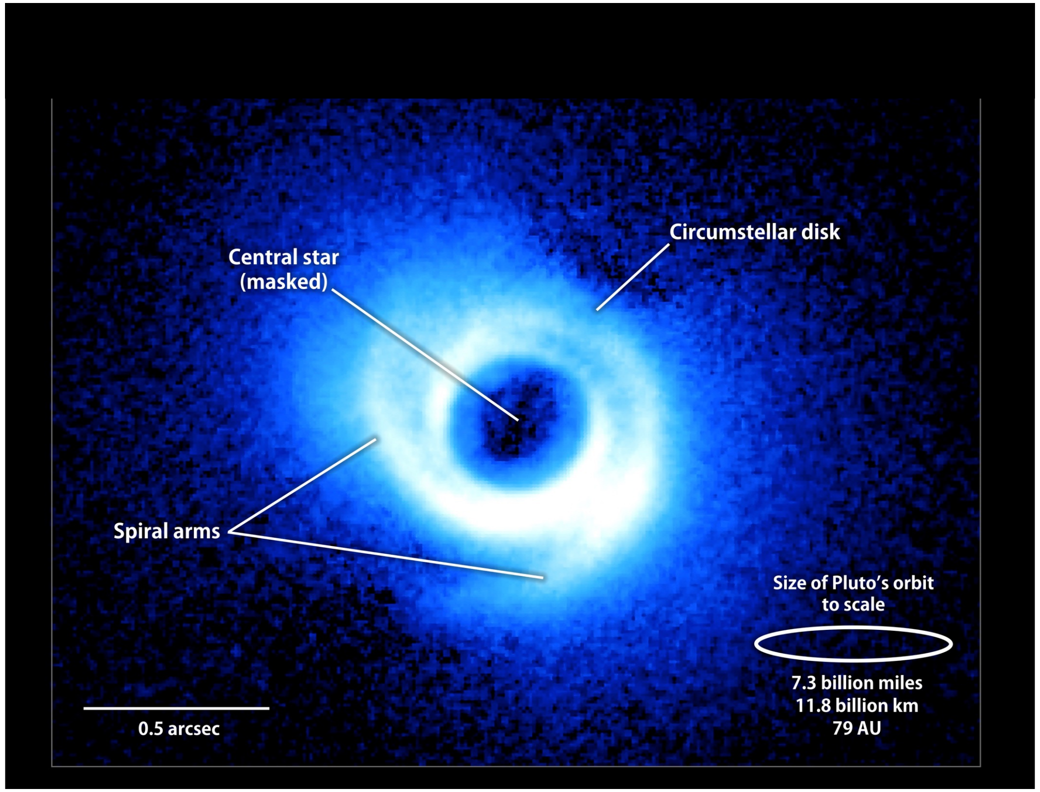


Spiral features in SAO 206462's dust disk



Muto et al. (2012)

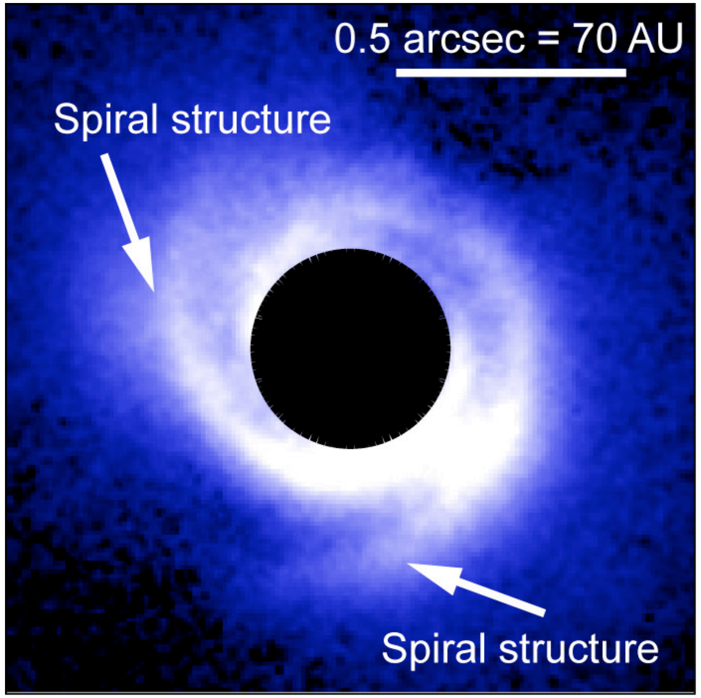
Scattered light



Muto et al. (2012)

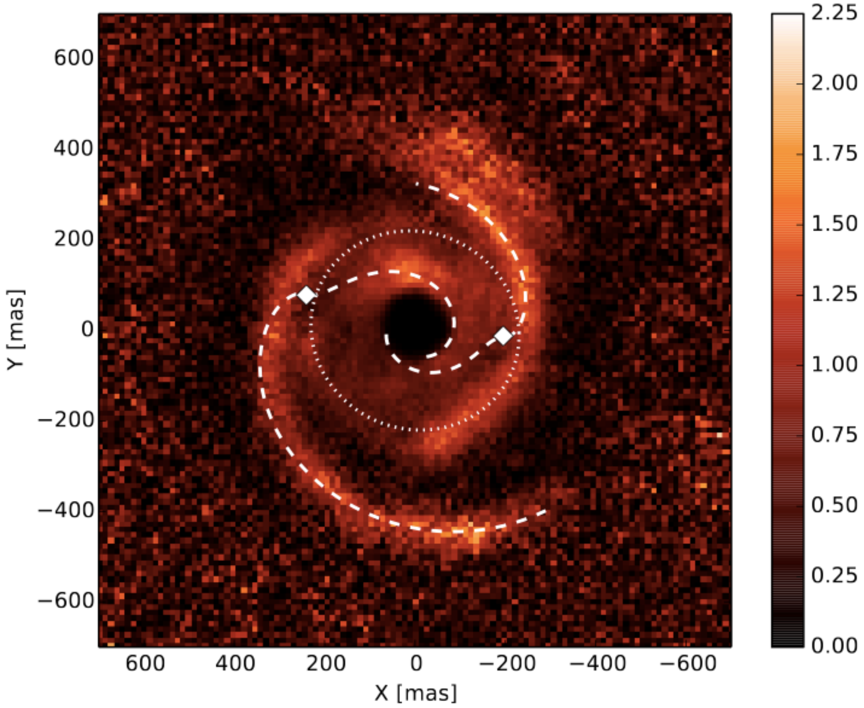
Observational Evidence: Spirals

SAO 206462



Muto+ '12

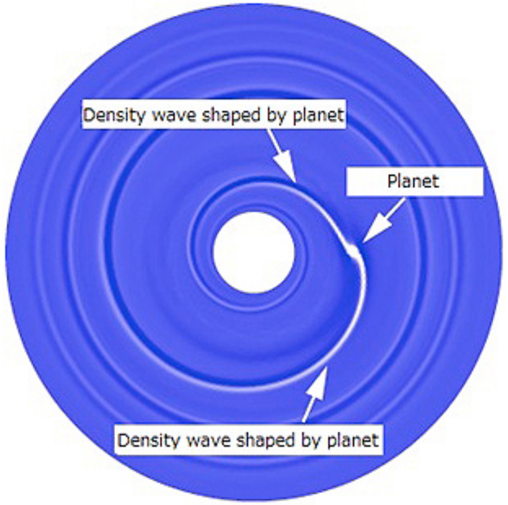
MWC 758



Benisty '15

Spiral arm fitting leads to problems

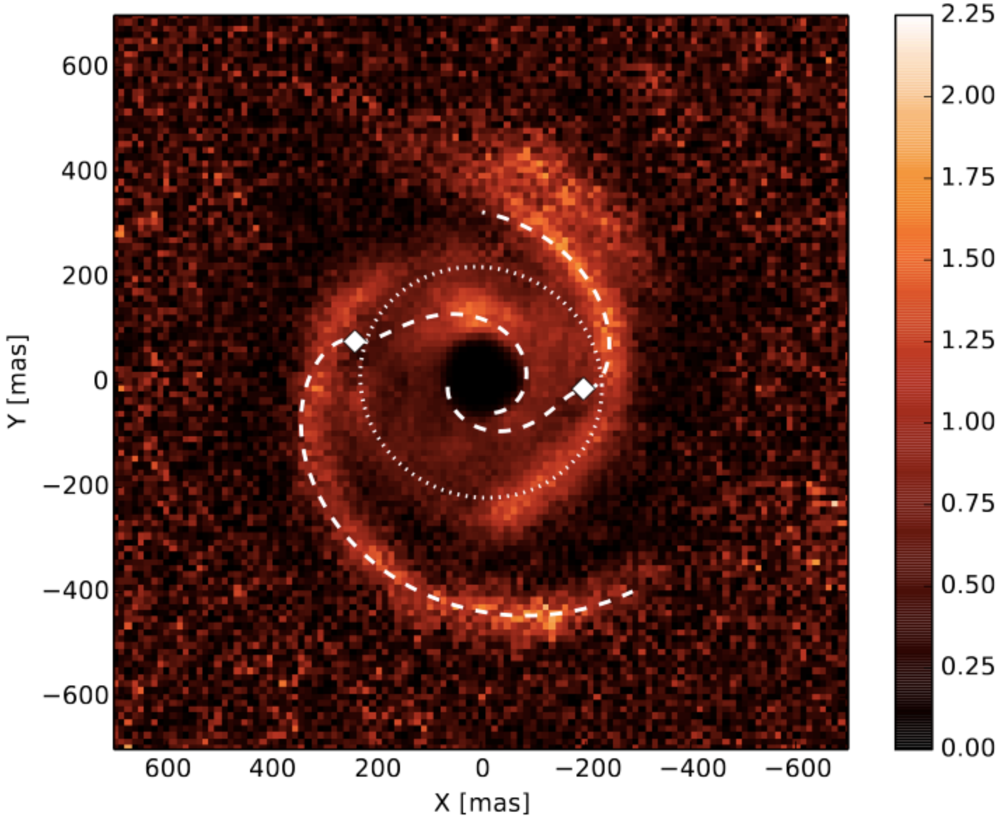
Analytical spiral fit



$$\theta(r) = \theta_c + \frac{\mathrm{sgn}(r - r_c)}{h_c} \times \left\{ \left(\frac{r}{r_c}\right)^{1+\beta} \left[\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\left(\frac{r}{r_c}\right)^{-\alpha}\right] - \left(\frac{1}{1+\beta} - \frac{1}{1-\alpha+\beta}\right)\right\},$$

Rafikov '02
Muto+ '12

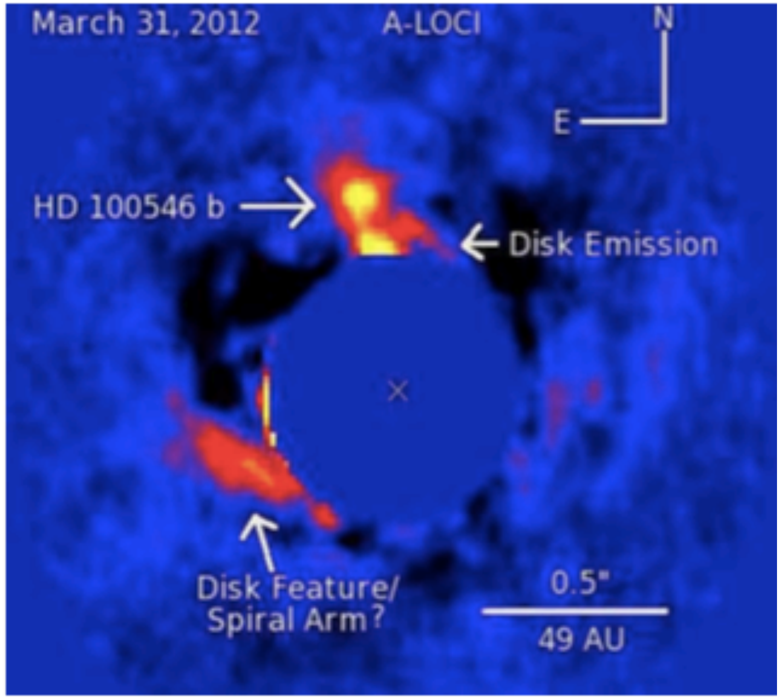
Spirals are **too wide**,
hotter (300K) than ambient gas (50K).



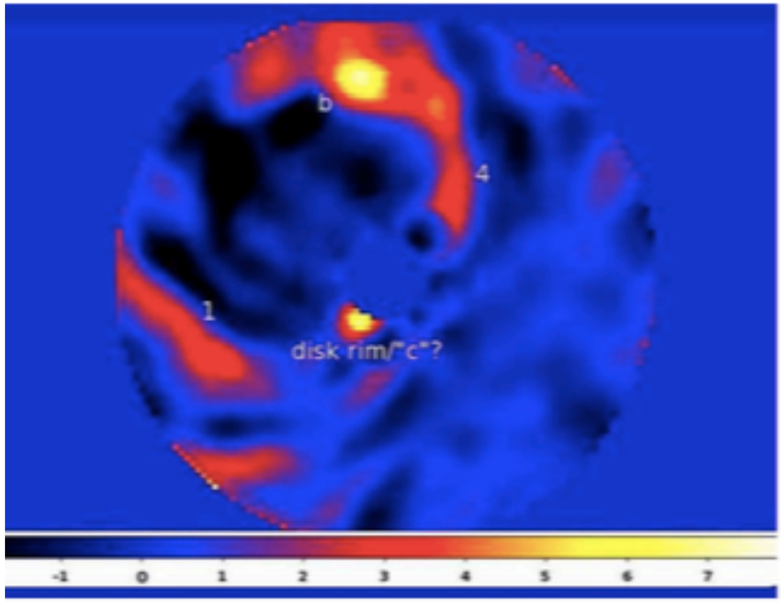
Benisty+ '15

The strange case of thermal emission in HD 100546

L band (~3.5 μm)

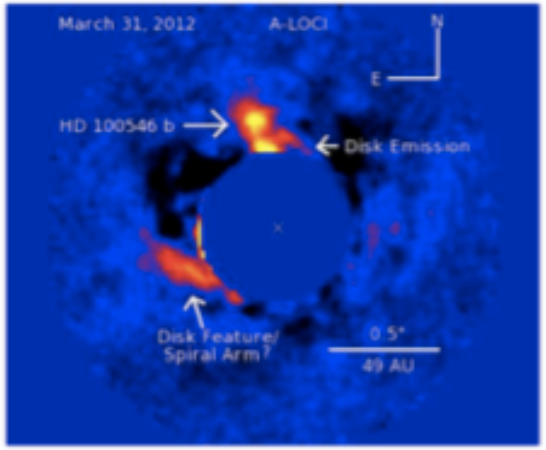


H band (~1.6 μm)

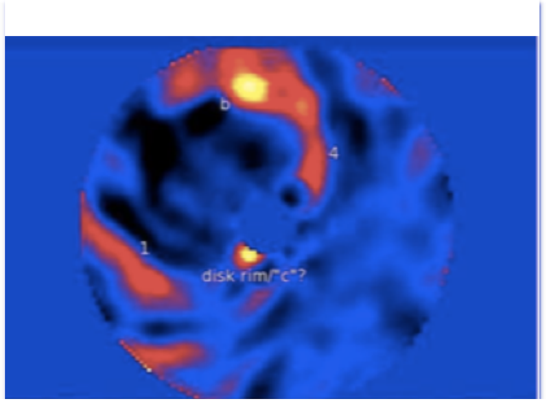


Currie et al. (2014), Currie et al. (2015)

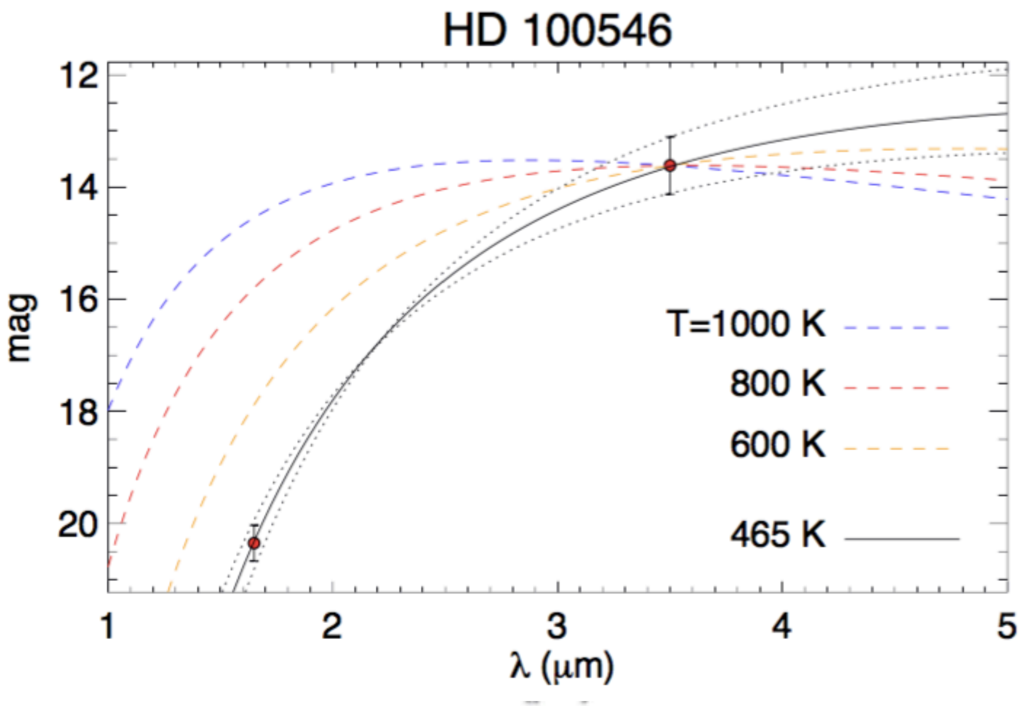
Pinning down the temperature



L band



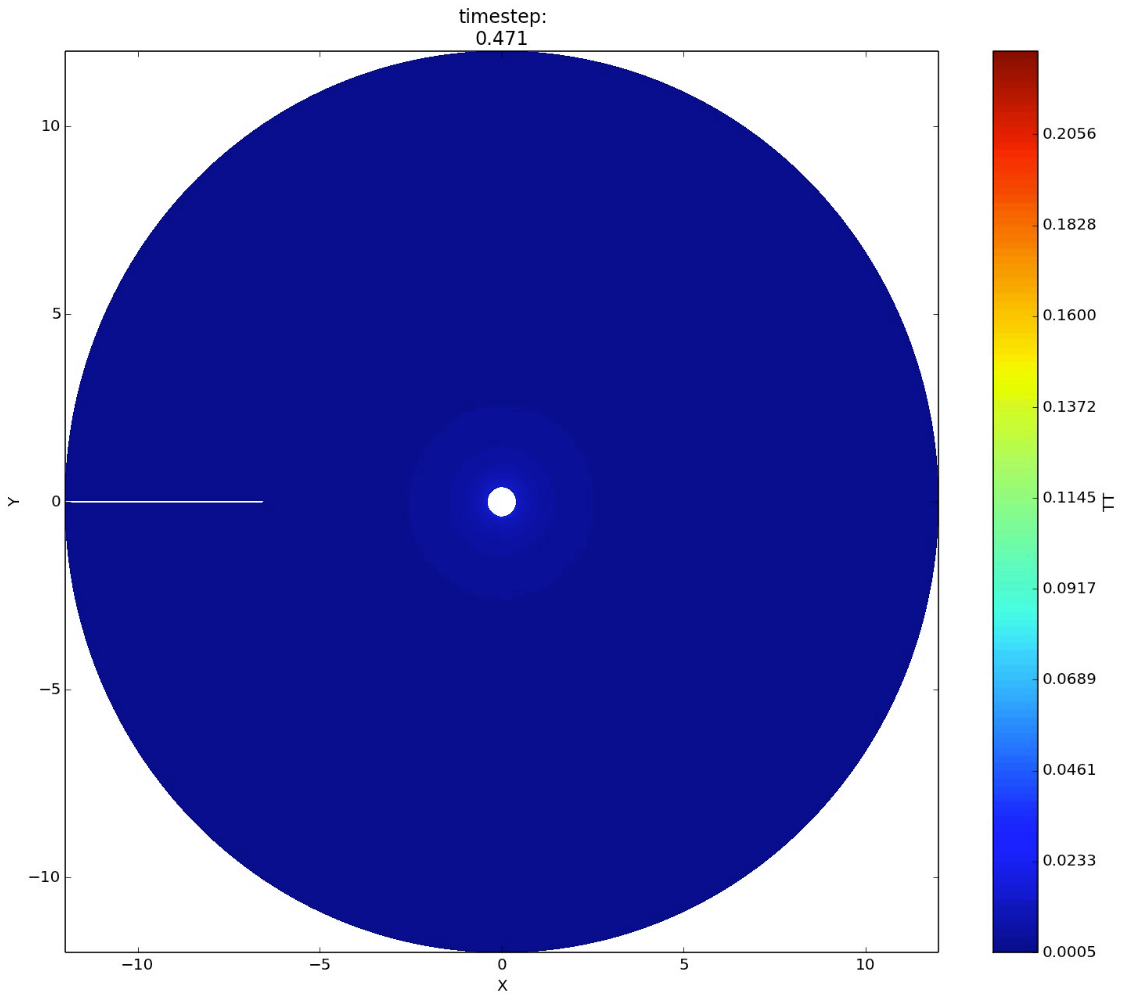
H band



Lyra+ '16

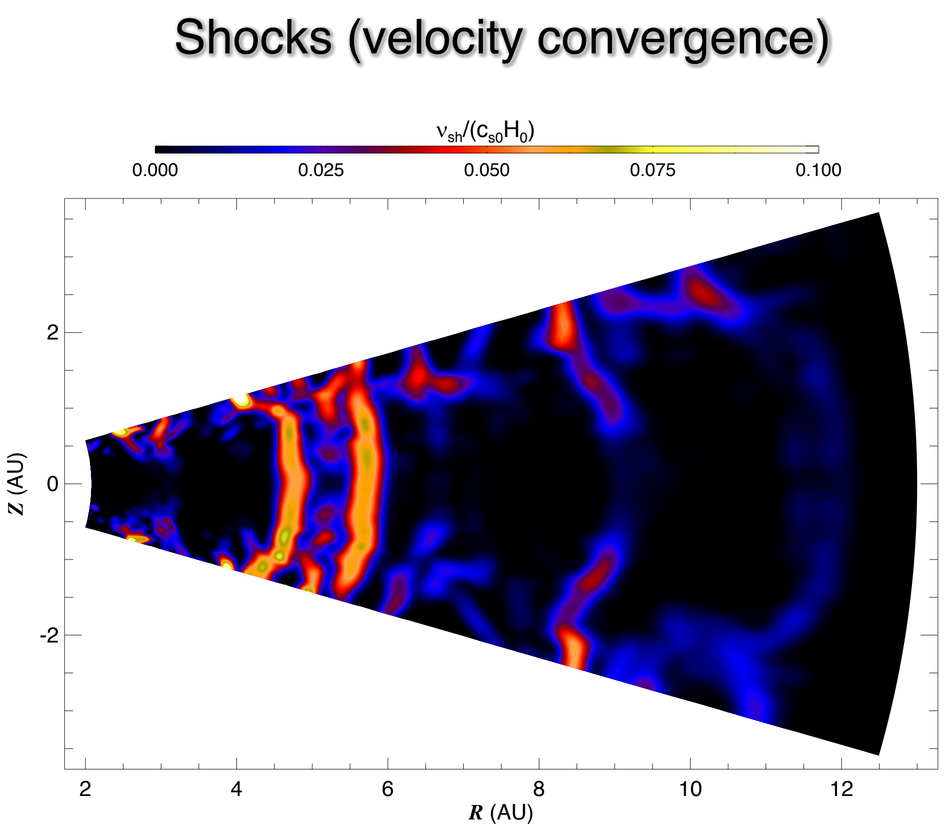
Currie+"14, '15

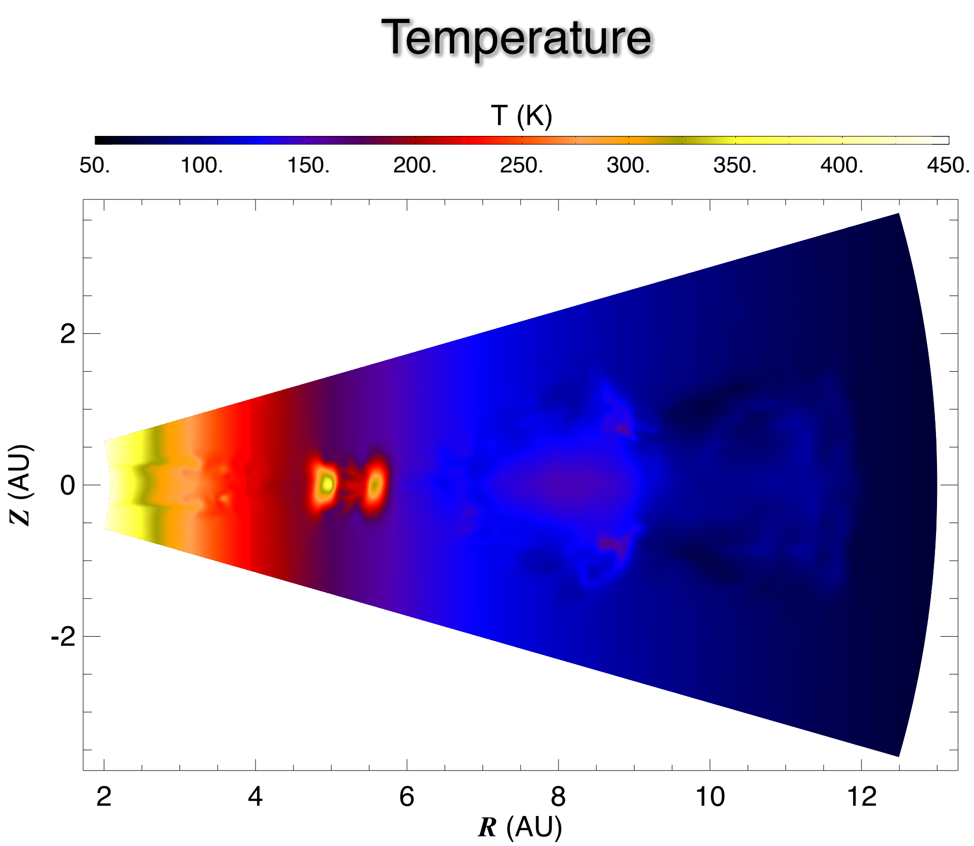
Planet-driven turbulence



Richert+Lyra '15

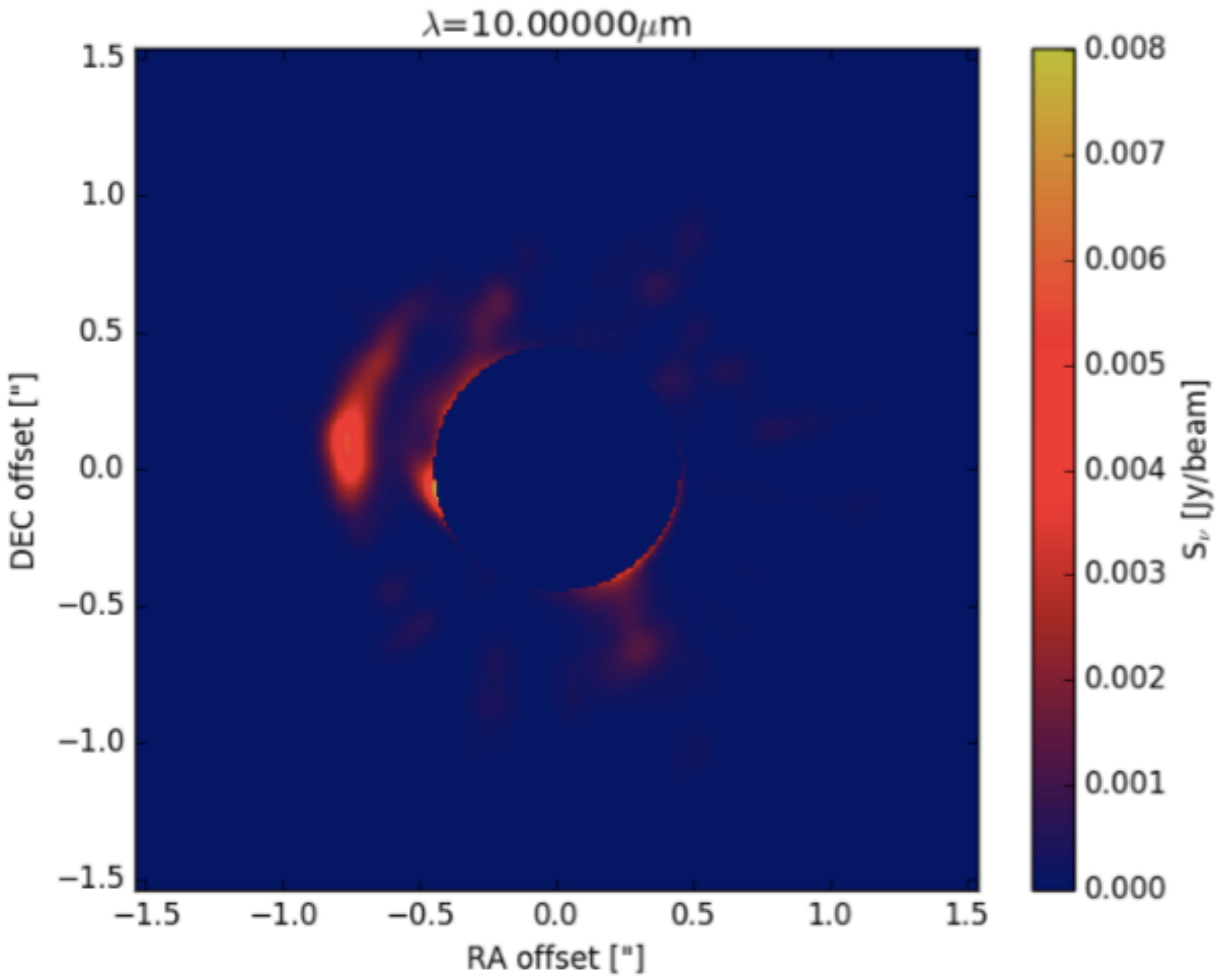
3D: Shock bores





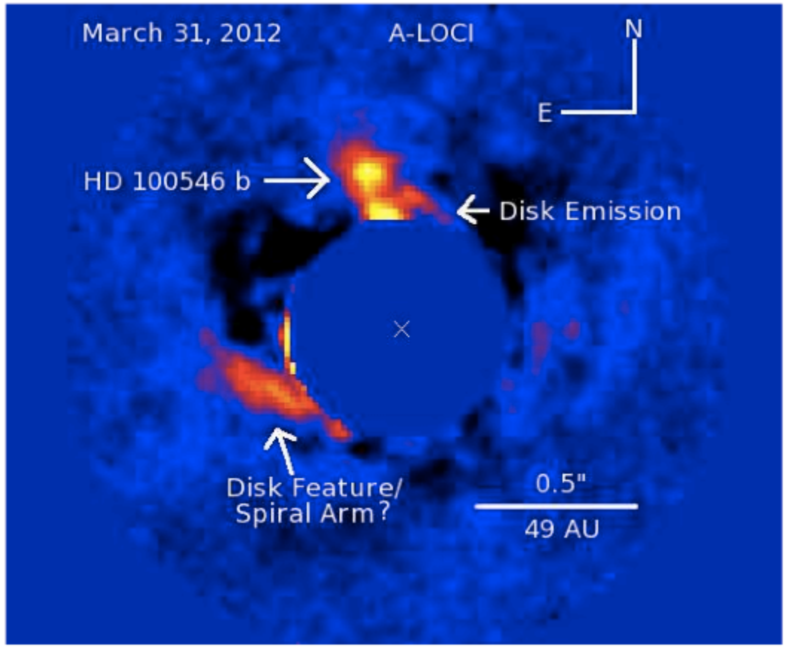
Lyra+ ‘16

Synthetic image by RADMC3D and shock heating

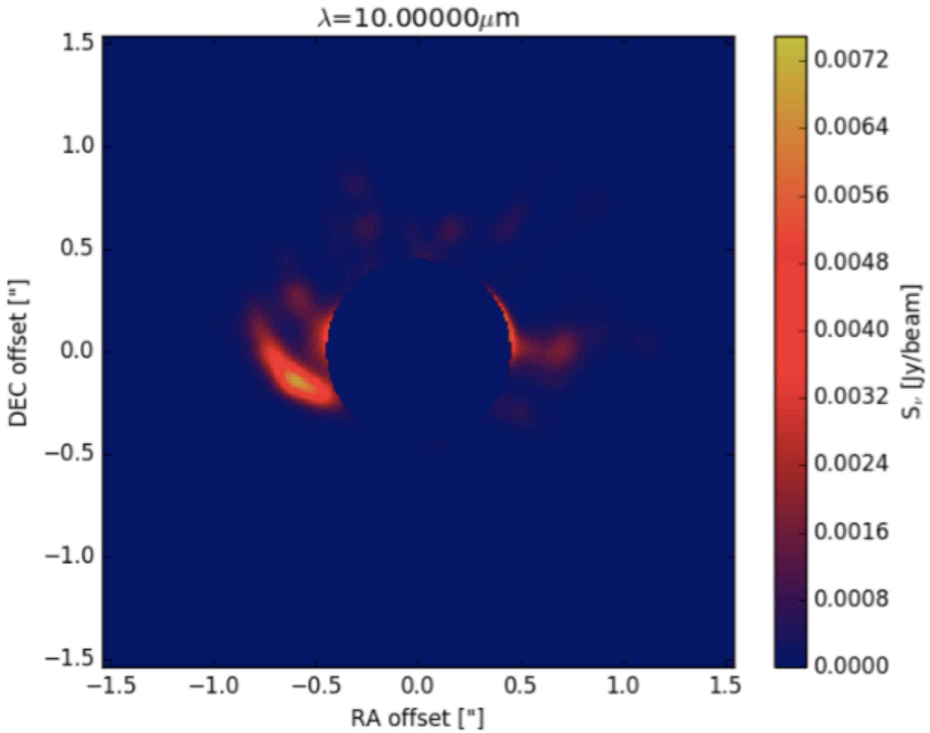


Hord+Lyra '17

Observation vs Synthetic Image

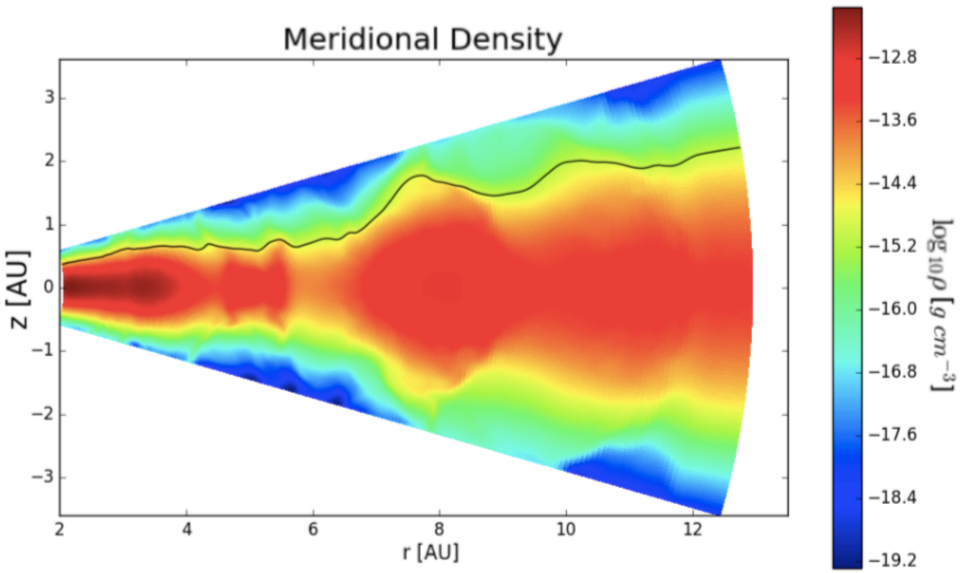


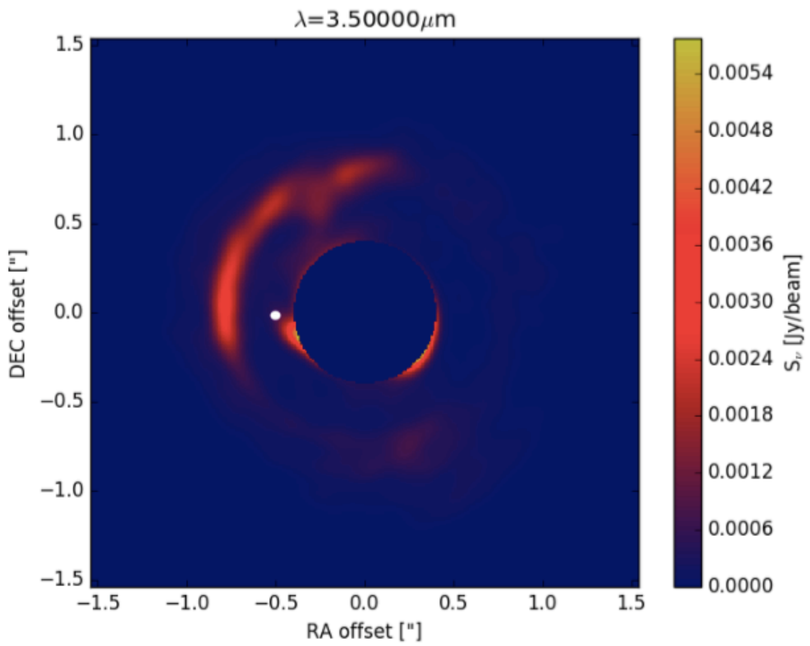
Currie+ '15



Hord+Lyra '17

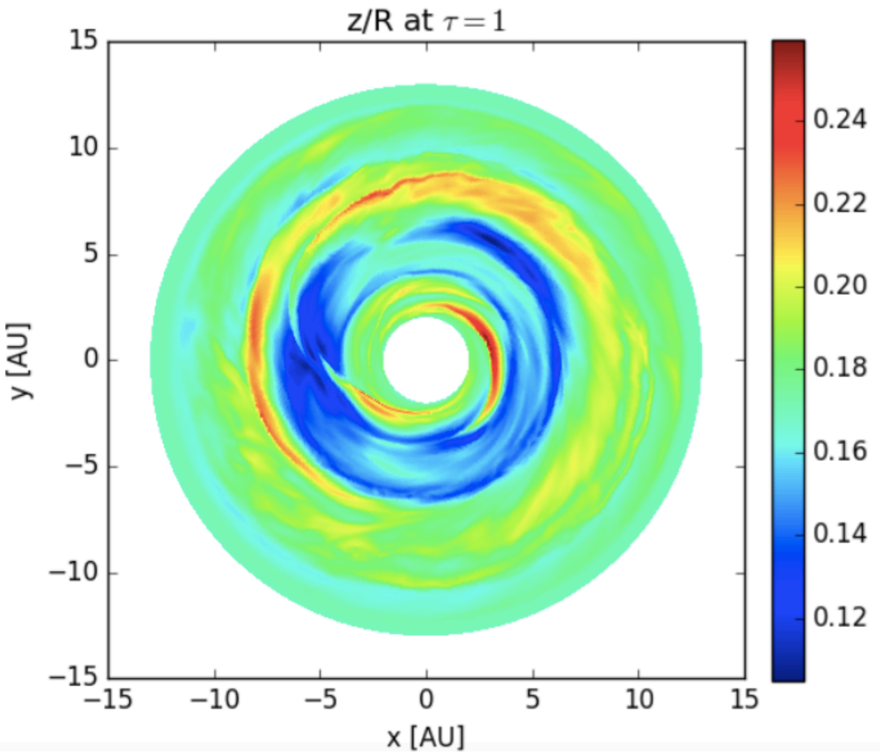
Scattering – A puffed up outer gap

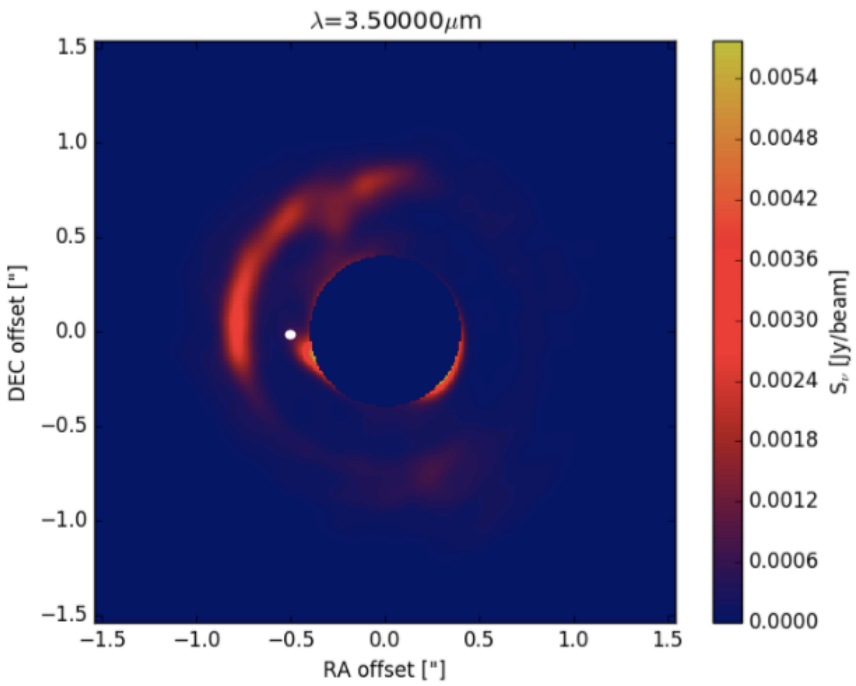




Hord+Lyra ‘17

Scattering

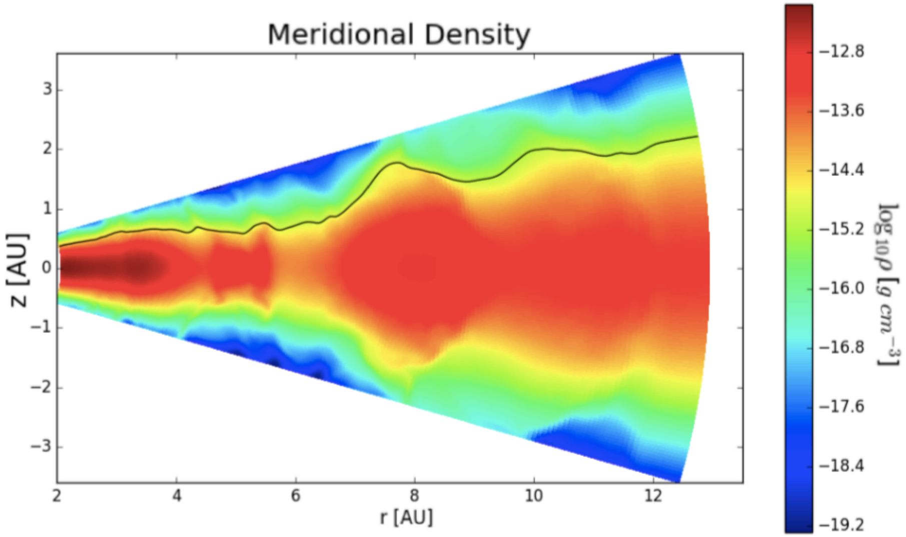


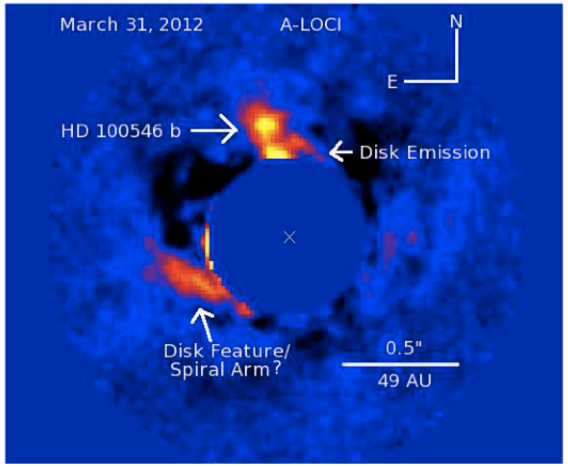


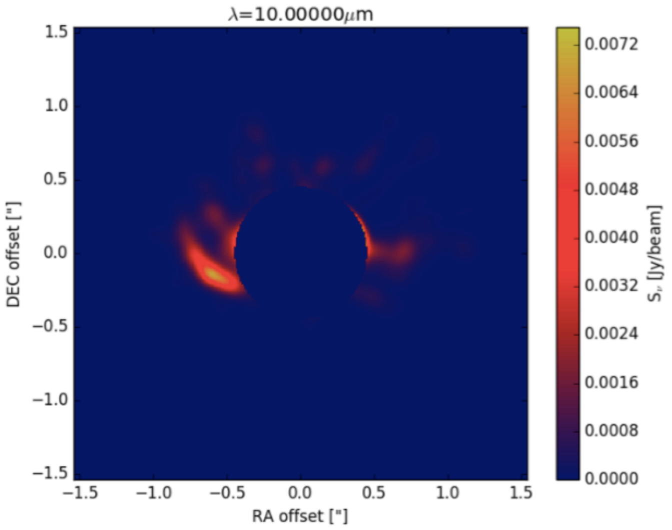
Hord+Lyra '17

Take home message

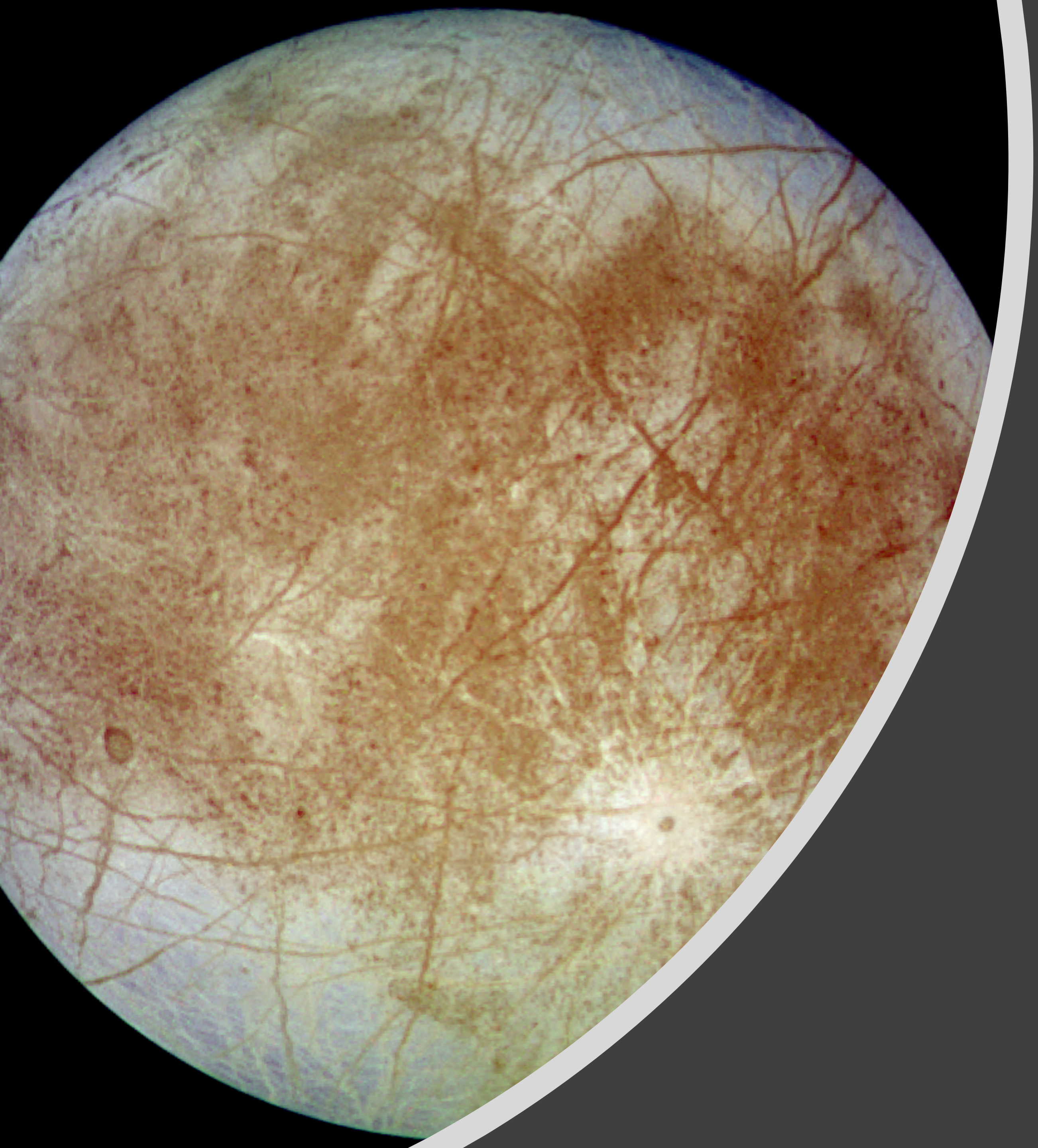
Planets puff their gap walls, visible in scattered light



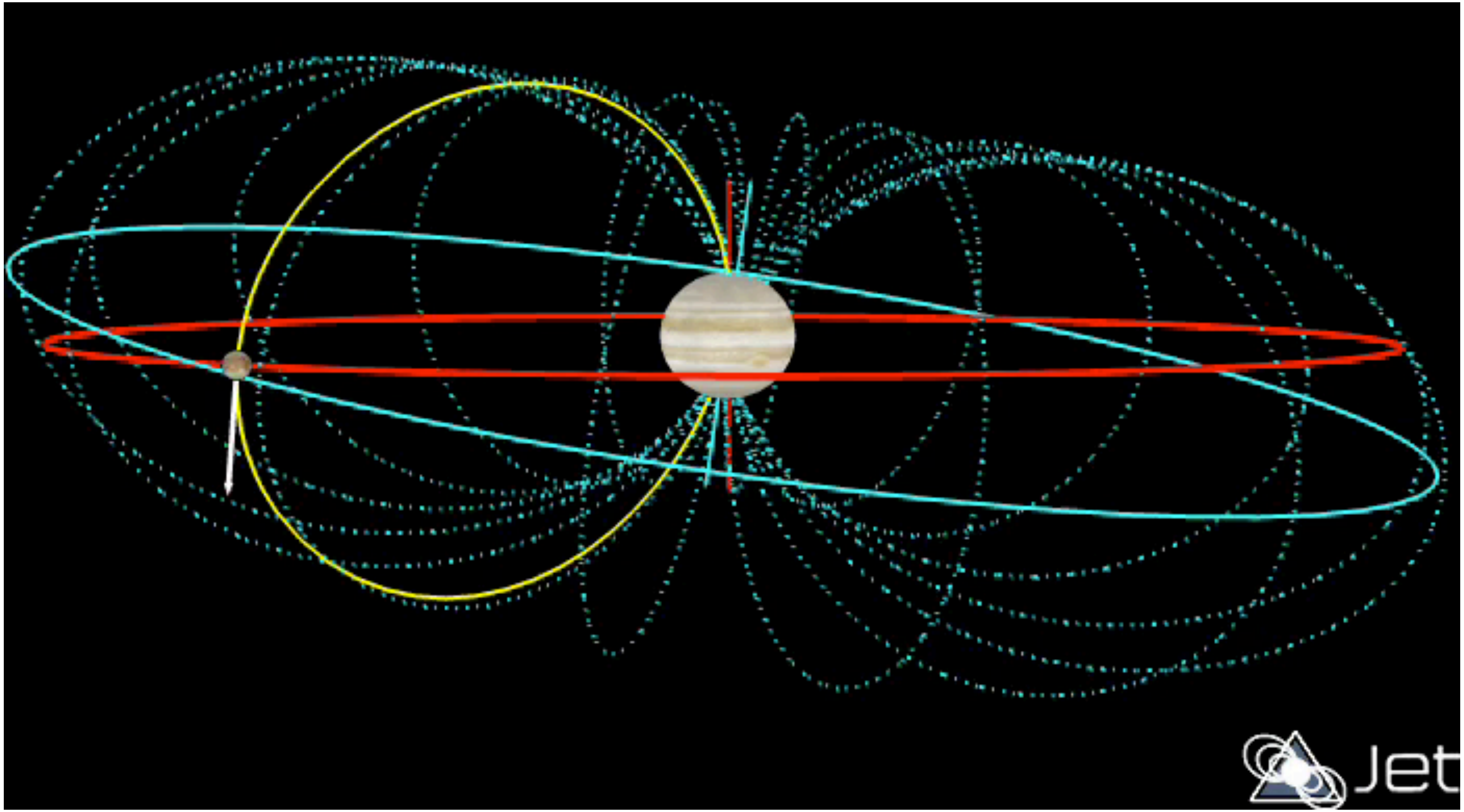


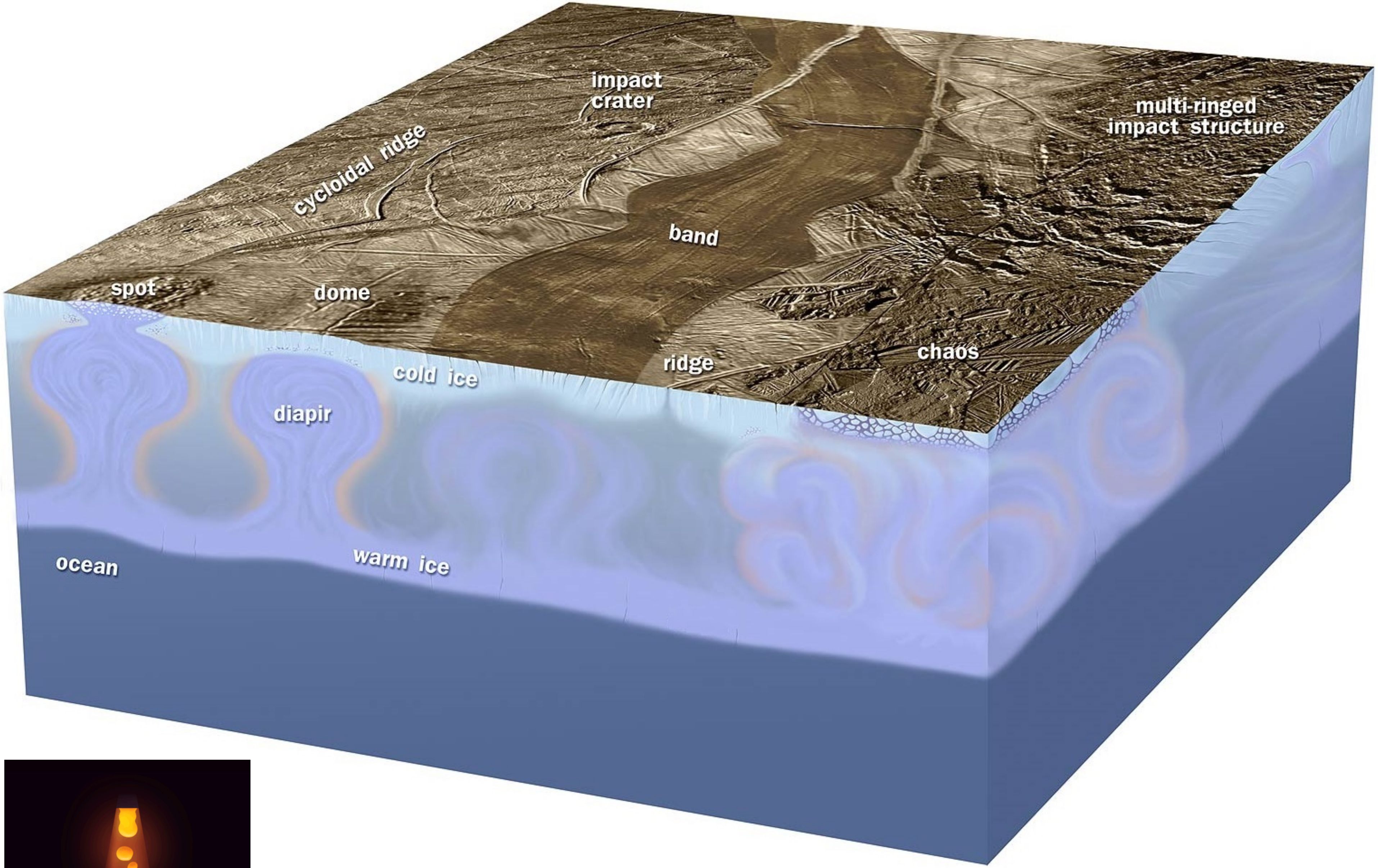


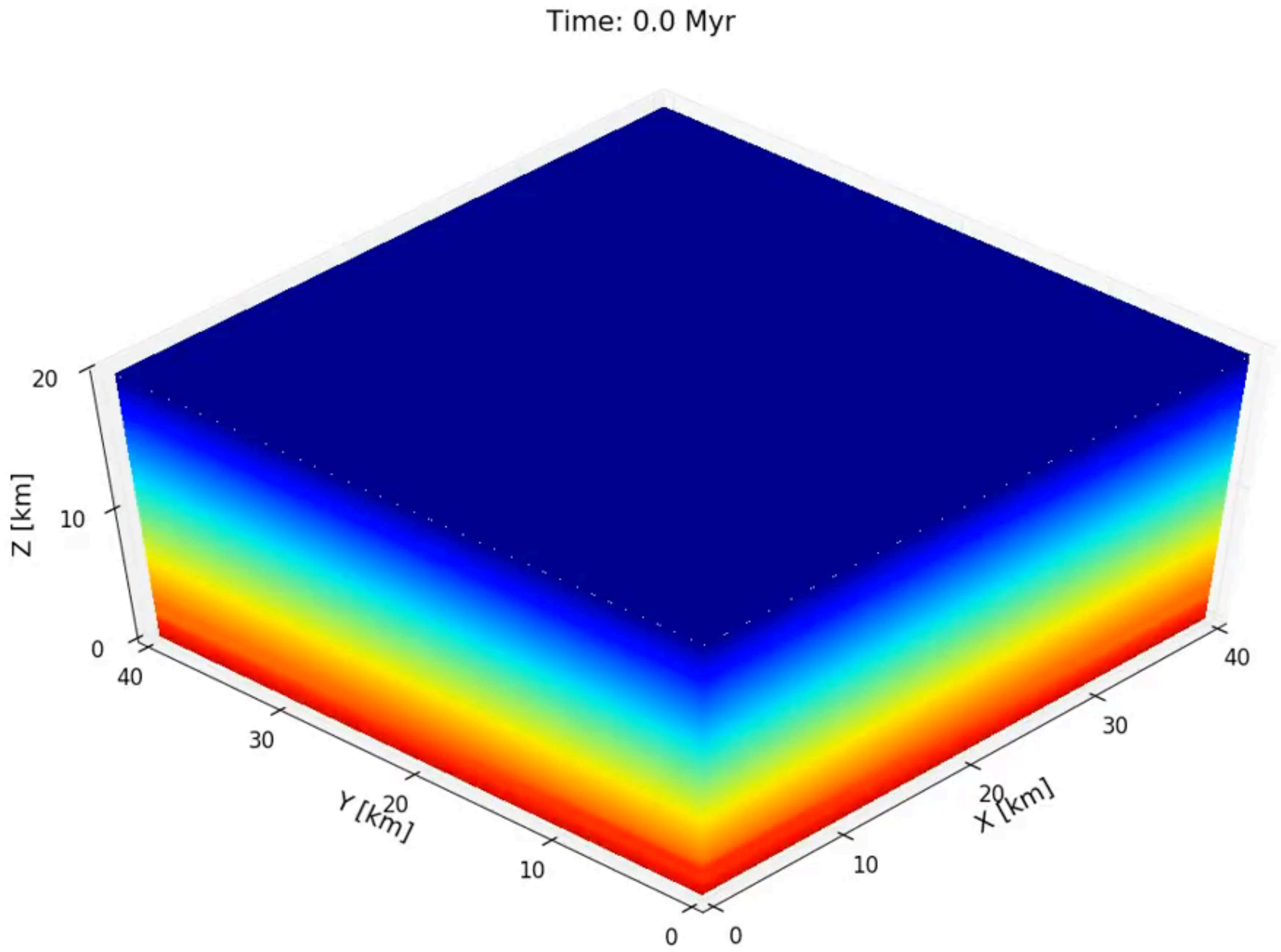
Hord+Lyra '17



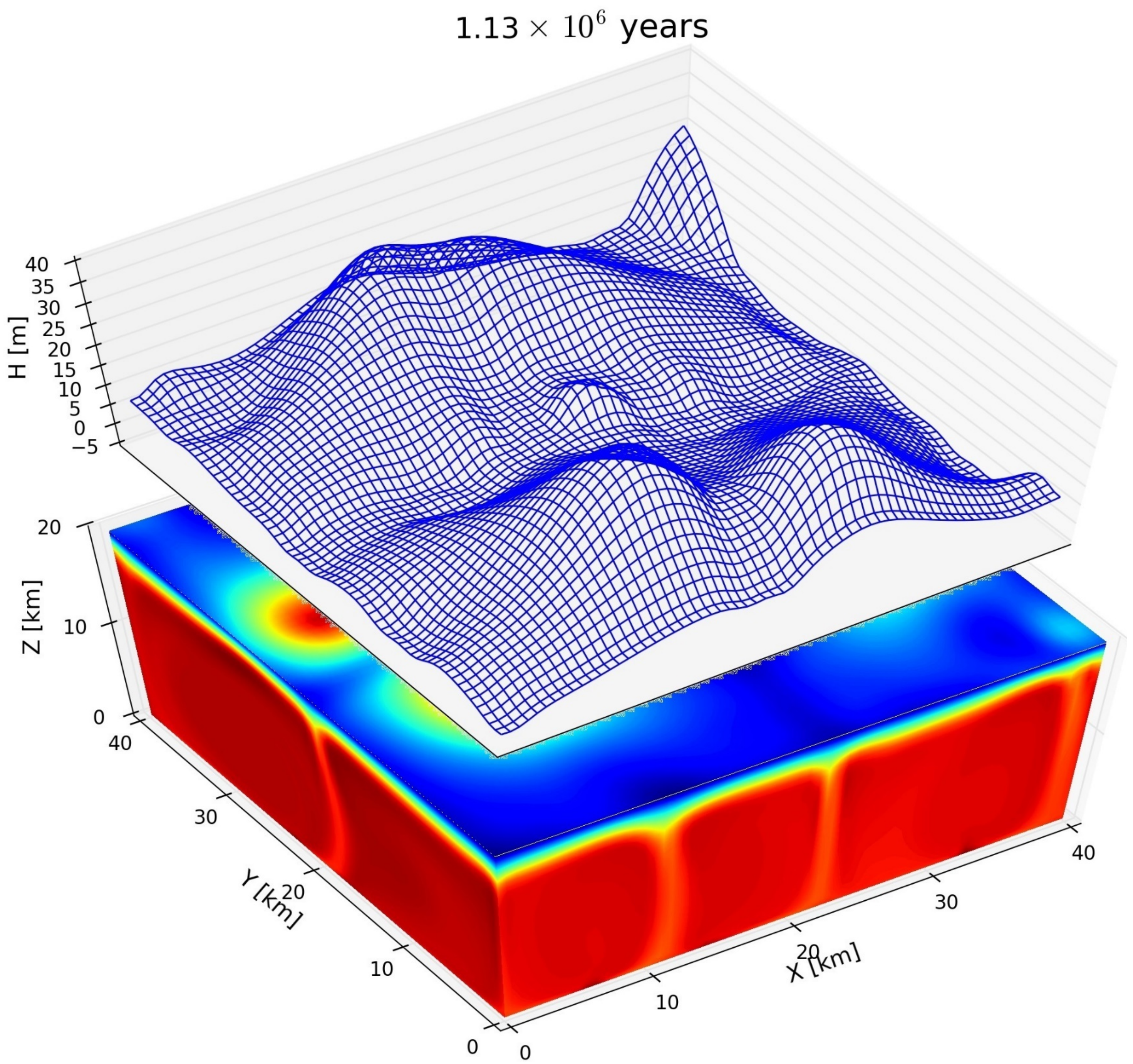
Europa


Jet


impact
crater
multi-ringed
impact structure
cycloidal ridge
band
spot
dome
chaos
ridge
cold ice
diapir
ocean
warm ice

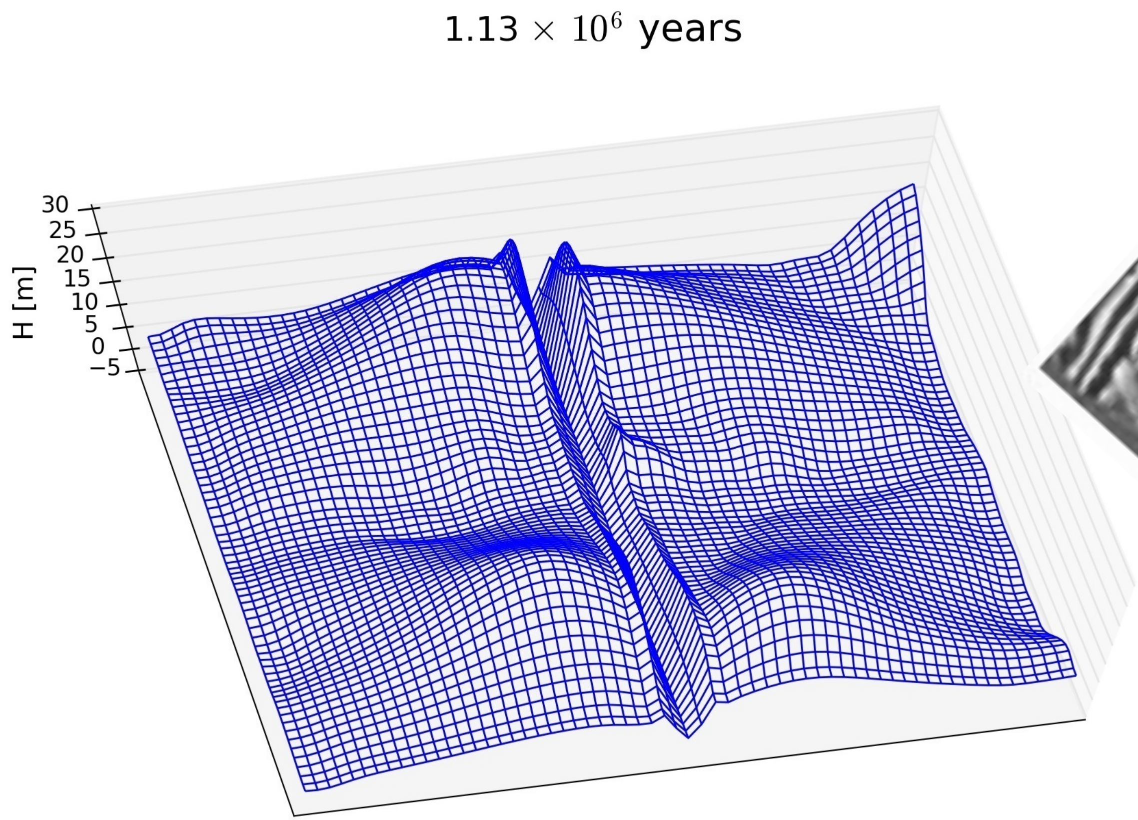


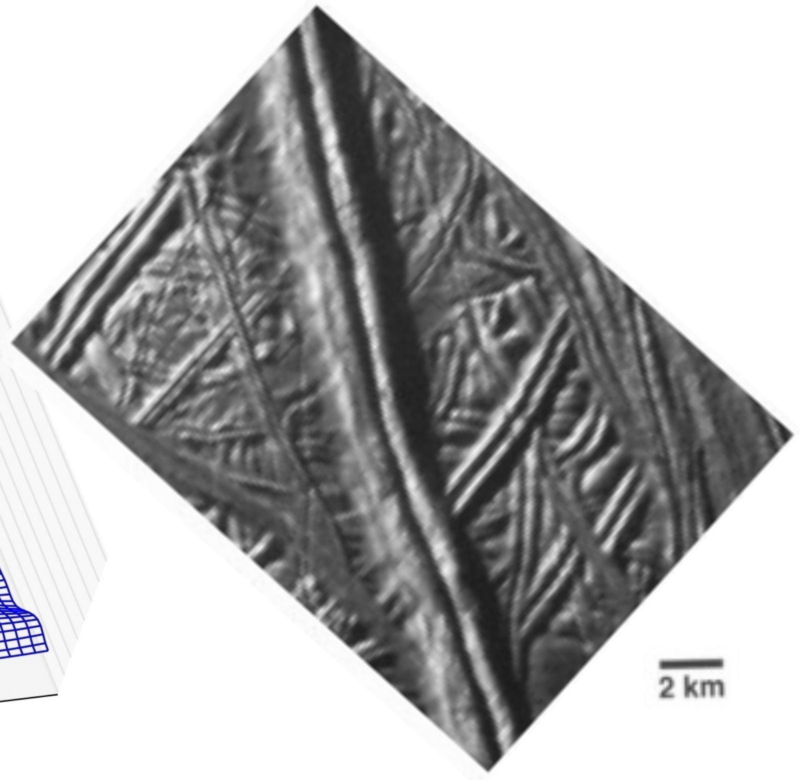
Cassara+Lyra '19



1.13×10^6 years
H [m]
40
35
30
25
20
15
10
5
0
−5
Z [km]
20
10
0
Y [km]
40
30
20
10
0
X [km]
0
10
20
30
40

Double ridges

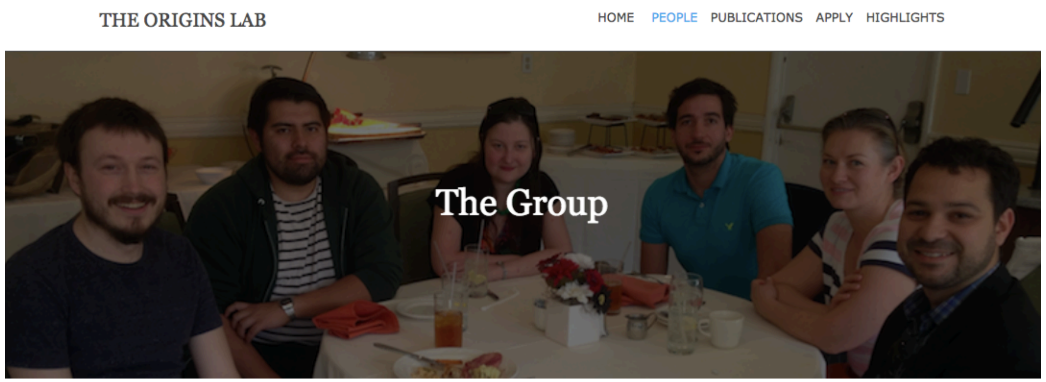




Cassara+Lyra '19

Mentoring

Research Group in 2016



The group in 2017

Mentoring - Postdocs

Postdocs

Natalia Dzyurkevich

Natalia has 9+ years of work experience in quantitative modelling, data analytics, and massive 3D numerical simulations, having worked on a broad range of problems in Astrophysics. Prior to joining the Origins Lab, she was a postdoc at ENS-Paris (France) and she has been employed at MPIA (Germany). Natalia holds a PhD in Astrophysics (Magna cum laude). She has extensive experience in Fortran, IDL, MPI, C/C++, and Python, and participating in several online courses in Machine Learning, Big Data, and Data Mining.

Luca Ricci

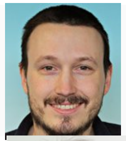
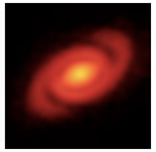
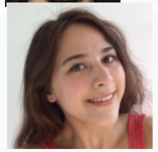
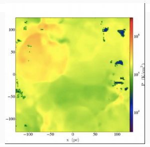
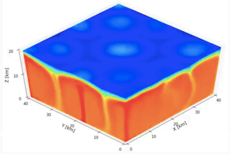
Luca is an expert in sub-mm observations of protoplanetary disks. With 63 papers published (14 as first author), he enriches the Origin Lab with observational capabilities with ALMA and VLA. Before joining the lab he was a postdoc at Rice University, Harvard CfA, and Caltech.

Ana Maria Piso

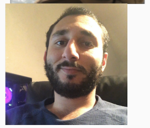
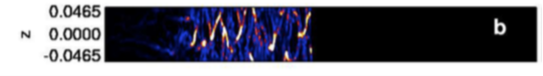
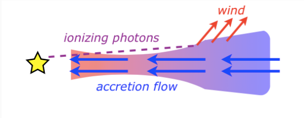
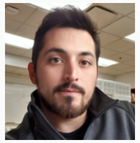
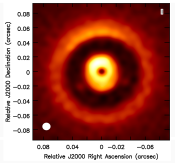
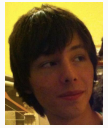
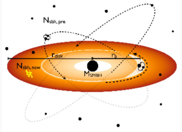
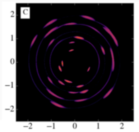
Ana Maria in an expert in disk volatile chemistry and dynamics in shaping the snowlines of volatile molecules. Prior to joining the Origins Lab she was a postdoc at UCLA, and a grad student at Harvard CfA.

Mentoring – M.Sc.

Graduated

Vincent Carpenter		Massive disks	
Alexandra Yep		Star Formation	
Leonardo Cassara		Ice convection in Europa	

Current

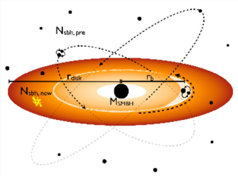
Chris Malek		Streaming Instability	
Konstantinos Koutsos		Magnetocentrifugal winds	
Juan Bernal		Radiative Transfer Postprocessing	
Joshua Shevchuk		AGN disks	
Areli Castrejon		Photoelectric Instability	

Mentoring– Undergraduates

Current

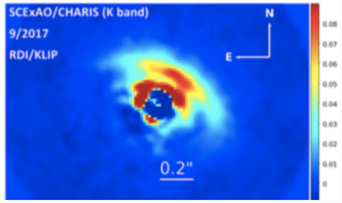
Emmanuel Durodola

AGN Disks



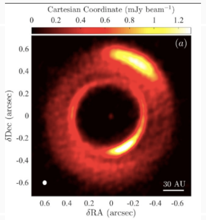
Scott Shannon

Transition Disks



Gerard Valdellon

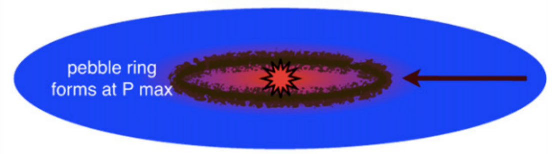
Vortices



Graduated

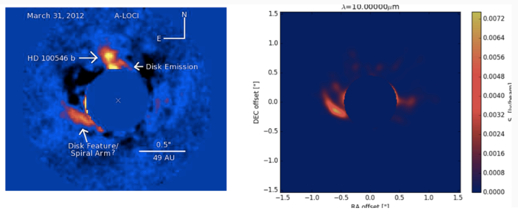
Sean Snyder

Streaming Instability



Blake Hord

Transition Disks



Grants!

NASA Exoplanets Research (2018) ~$150K

ngVLA (2017) ~$81K

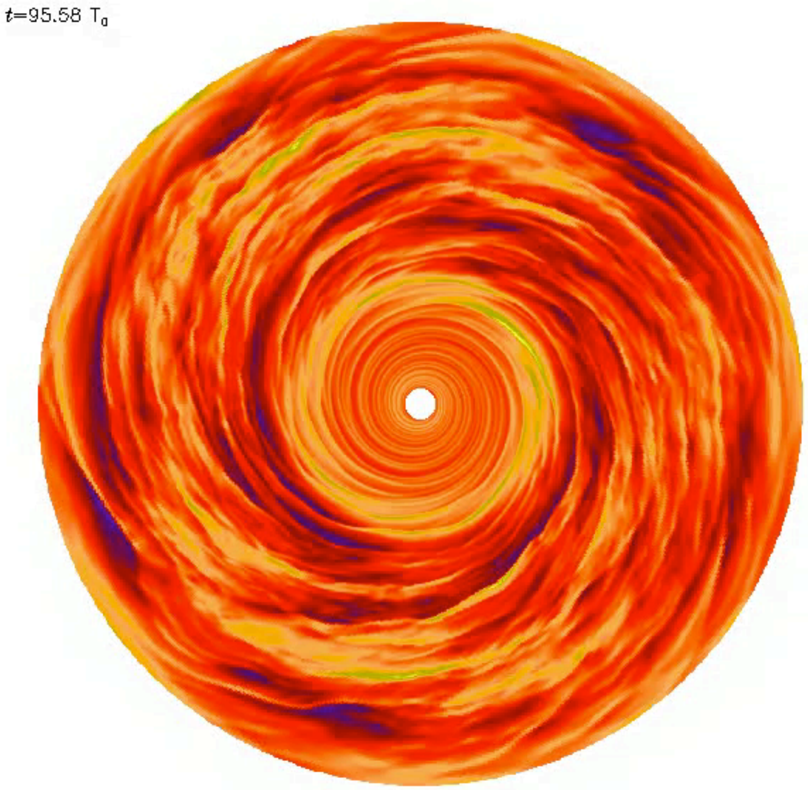
NASA Exoplanets Research (2016) ~$250K

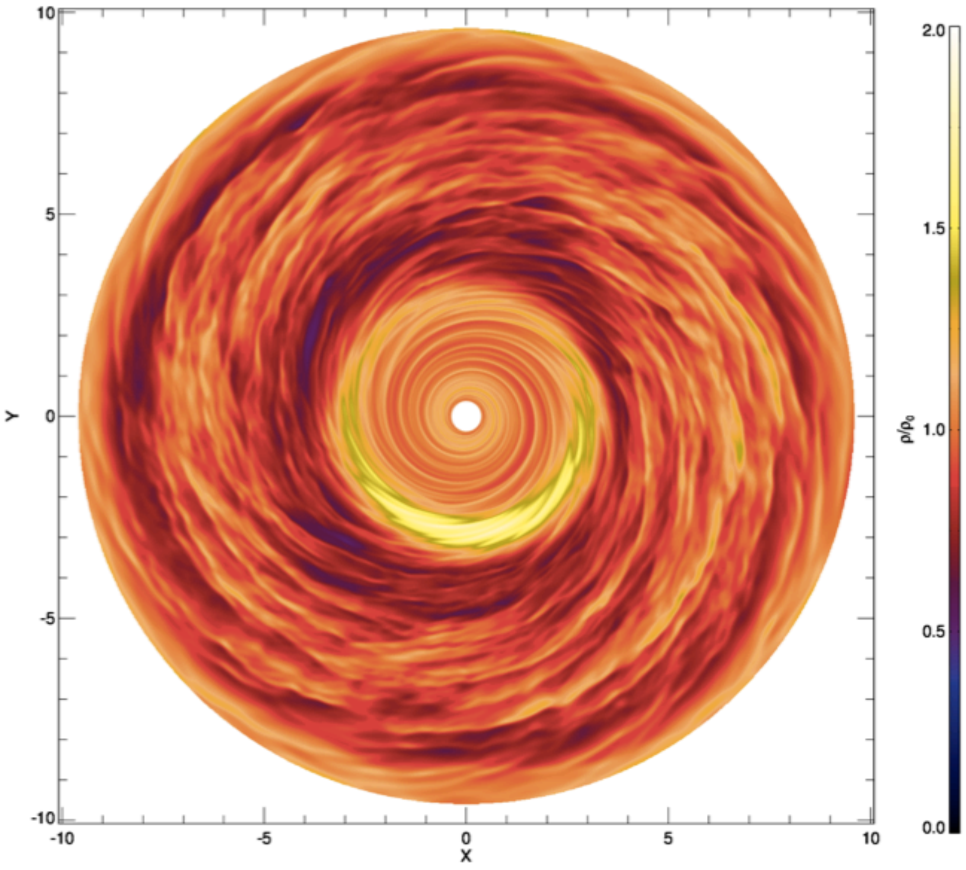
Hubble Cycle 24 (2016) ~$134K

NSF AAS (2010) ~$460k

Average of 10 grant proposals submitted per year

Boundary layers

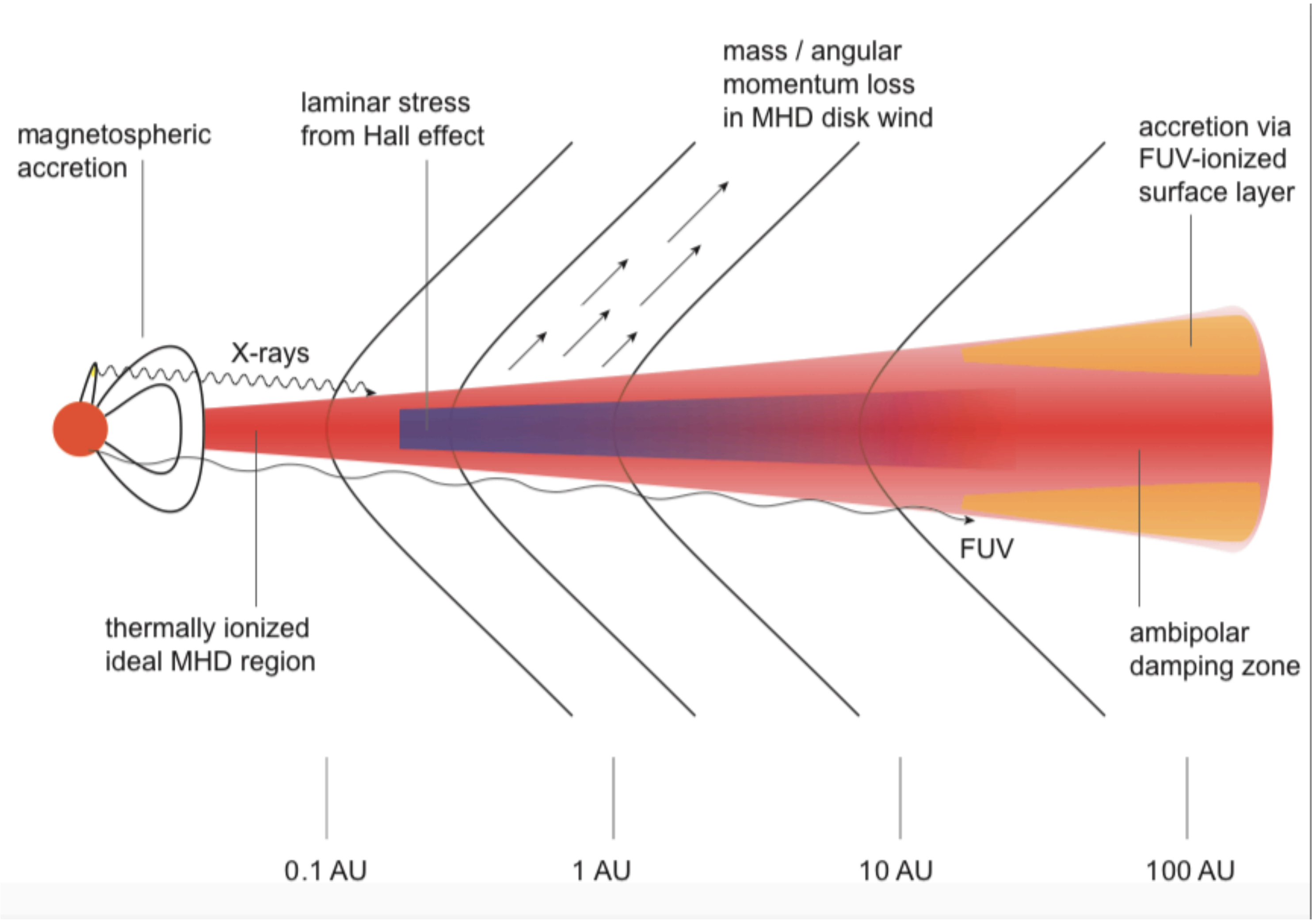




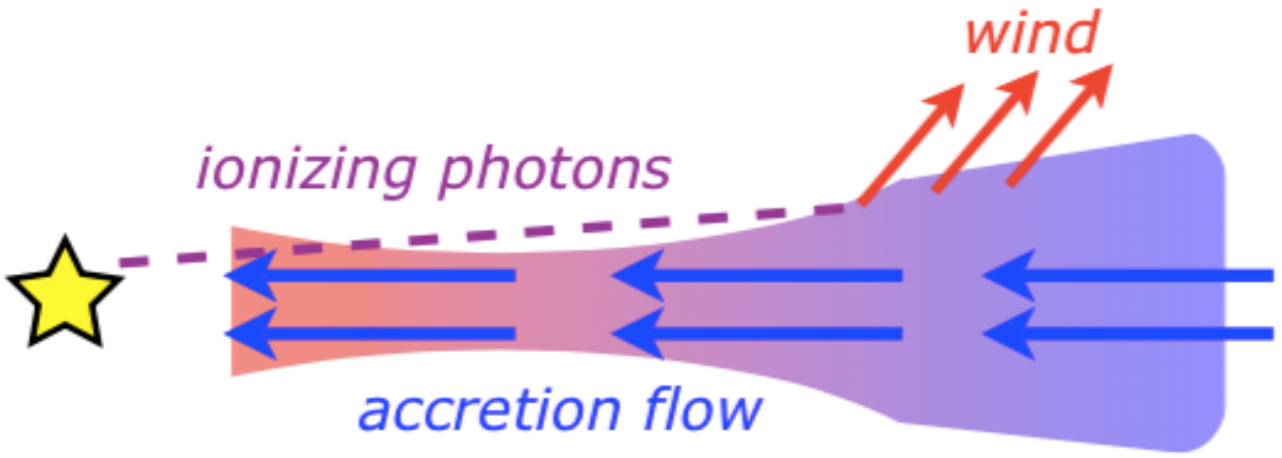
Quiescent inner disk + turbulent outer disk

Lyra+ ‘15

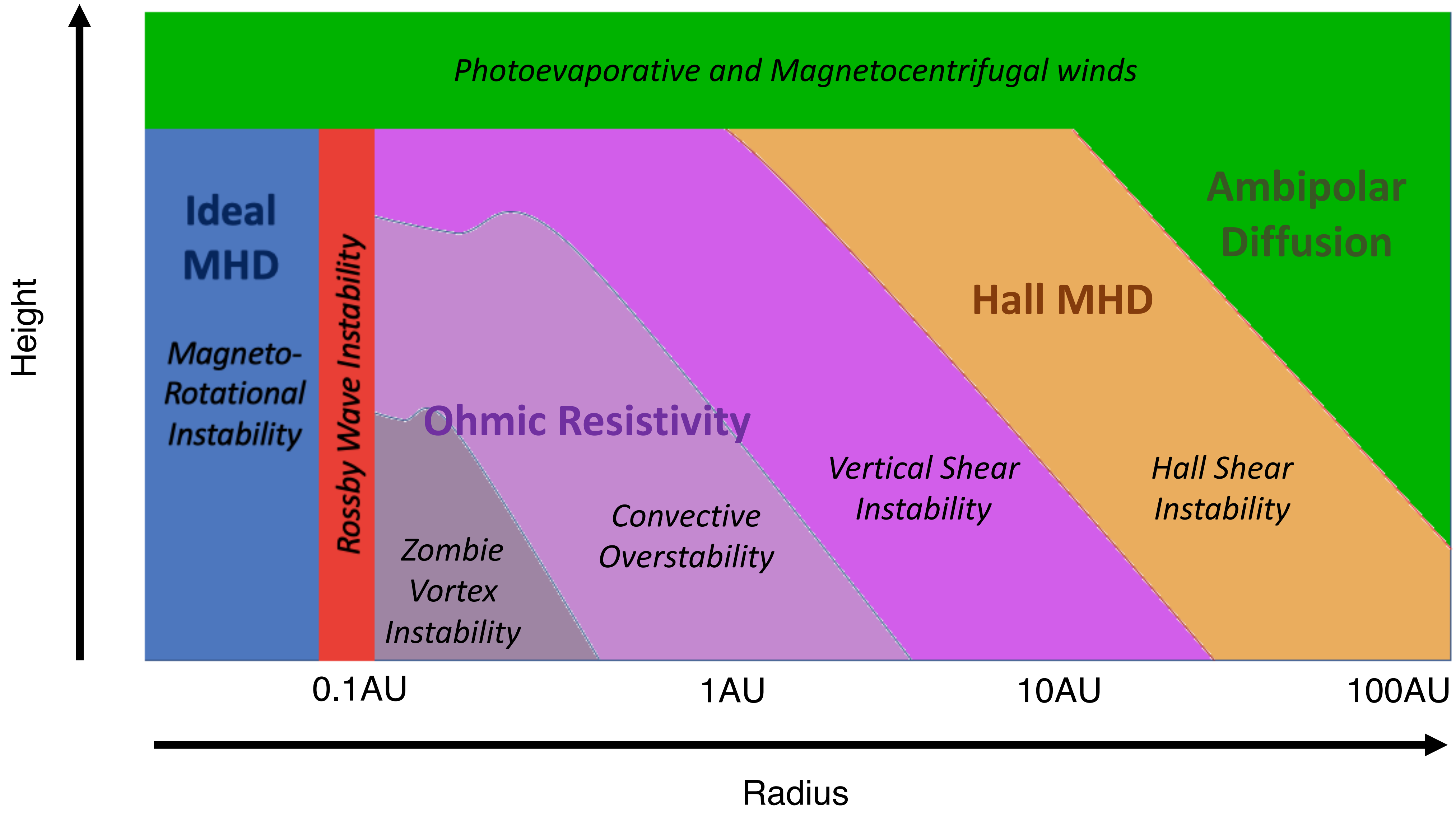
Disk Structure



Accretion and Photoevaporation

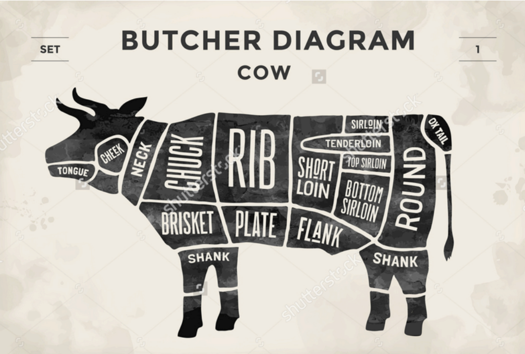


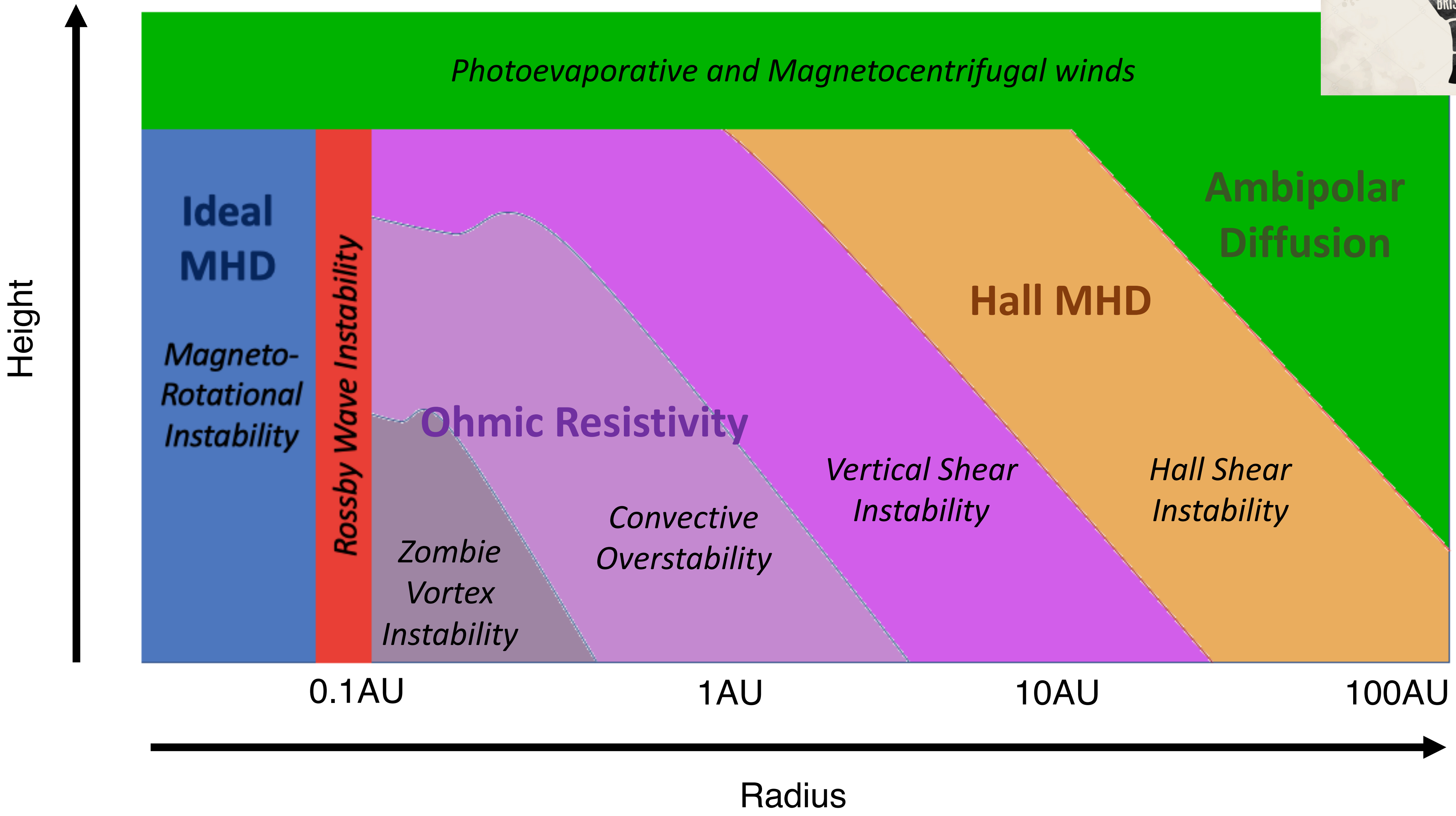
Disk structure



Lyra & Umurhan '18

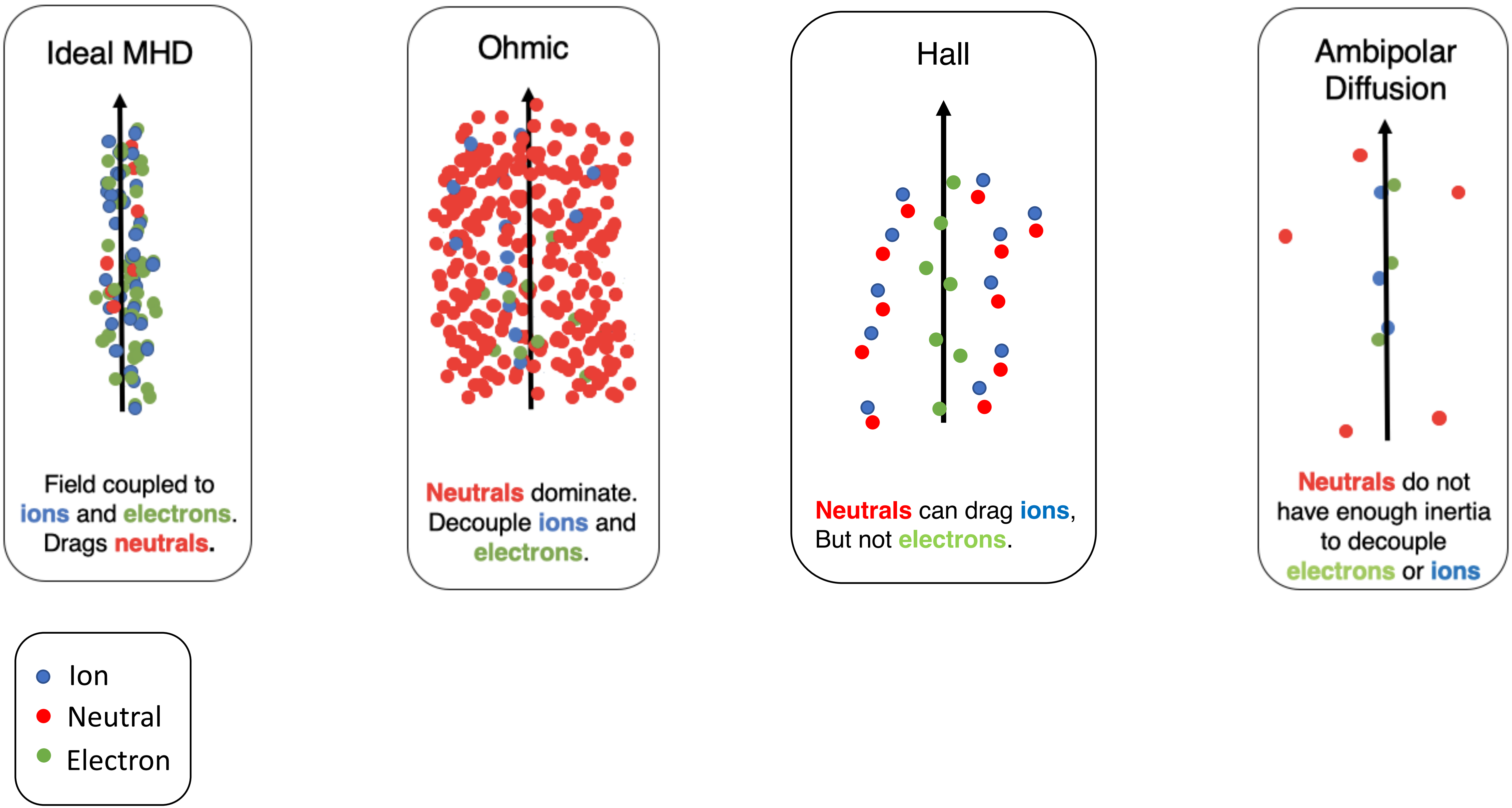
Disk structure
A “butcher diagram” for disks





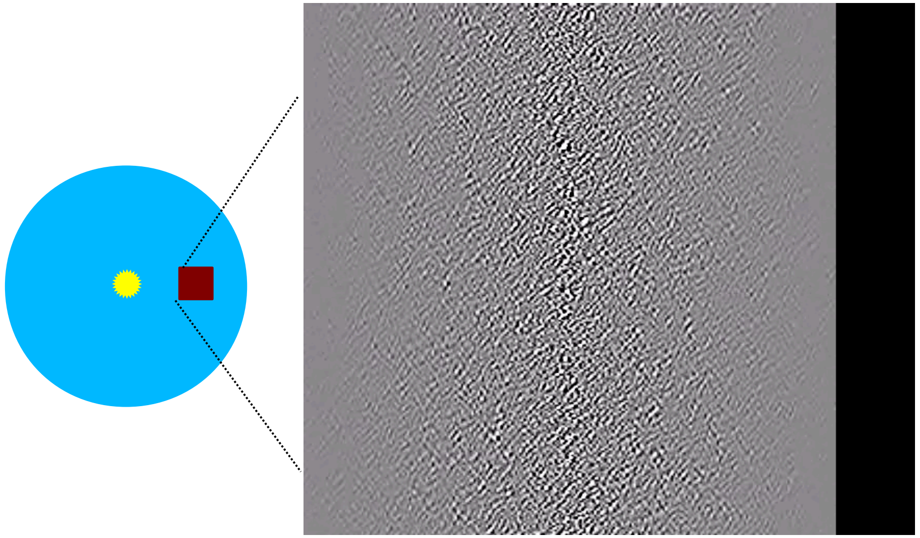
Lyra & Umurhan ‘18

MHD regimes


Ideal MHD
Field coupled to ions and electrons. Drags neutrals.
Ohmic
Neutrals dominate. Decouple ions and electrons.
Hall
Neutrals can drag ions, But not electrons.
Ambipolar Diffusion
Neutrals do not have enough inertia to decouple electrons or ions
Ion
Neutral
Electron

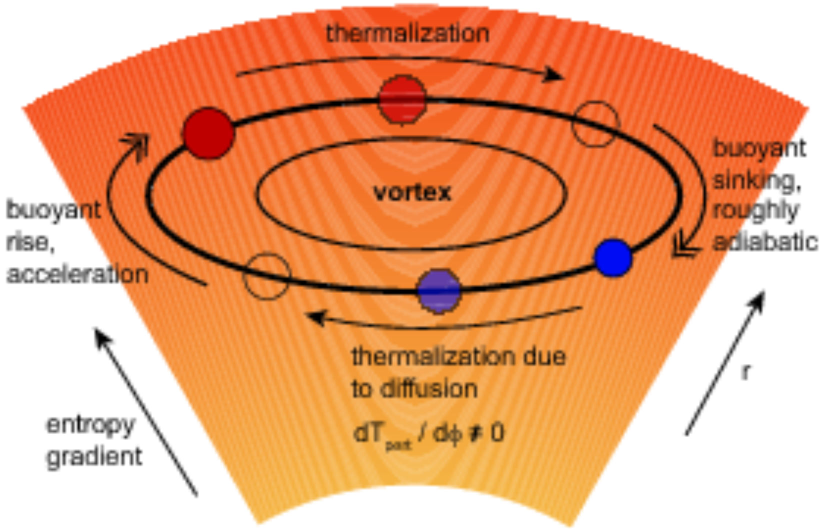
Convection

Convective Overstability



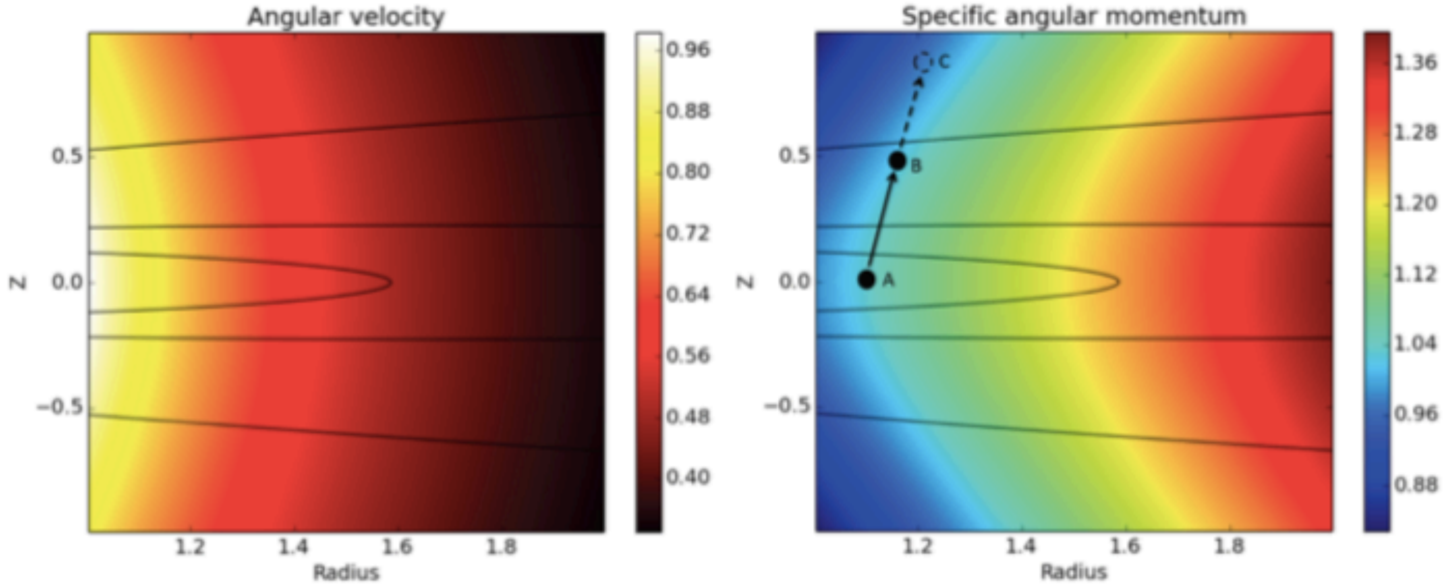
Lyra & Klahr (2011)

Sketch of the
Convective Overstability

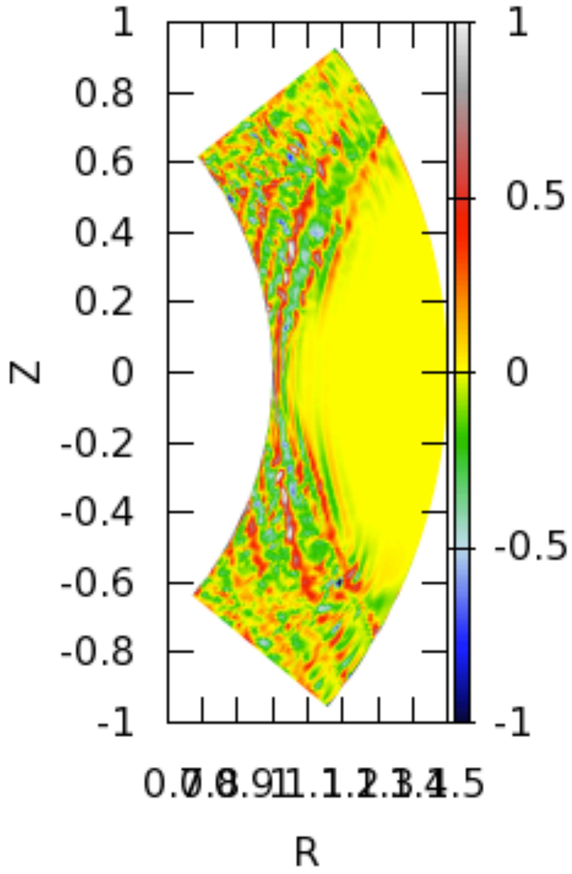


Vertical shear instability

Angular velocity not constant in cylinders: unstable

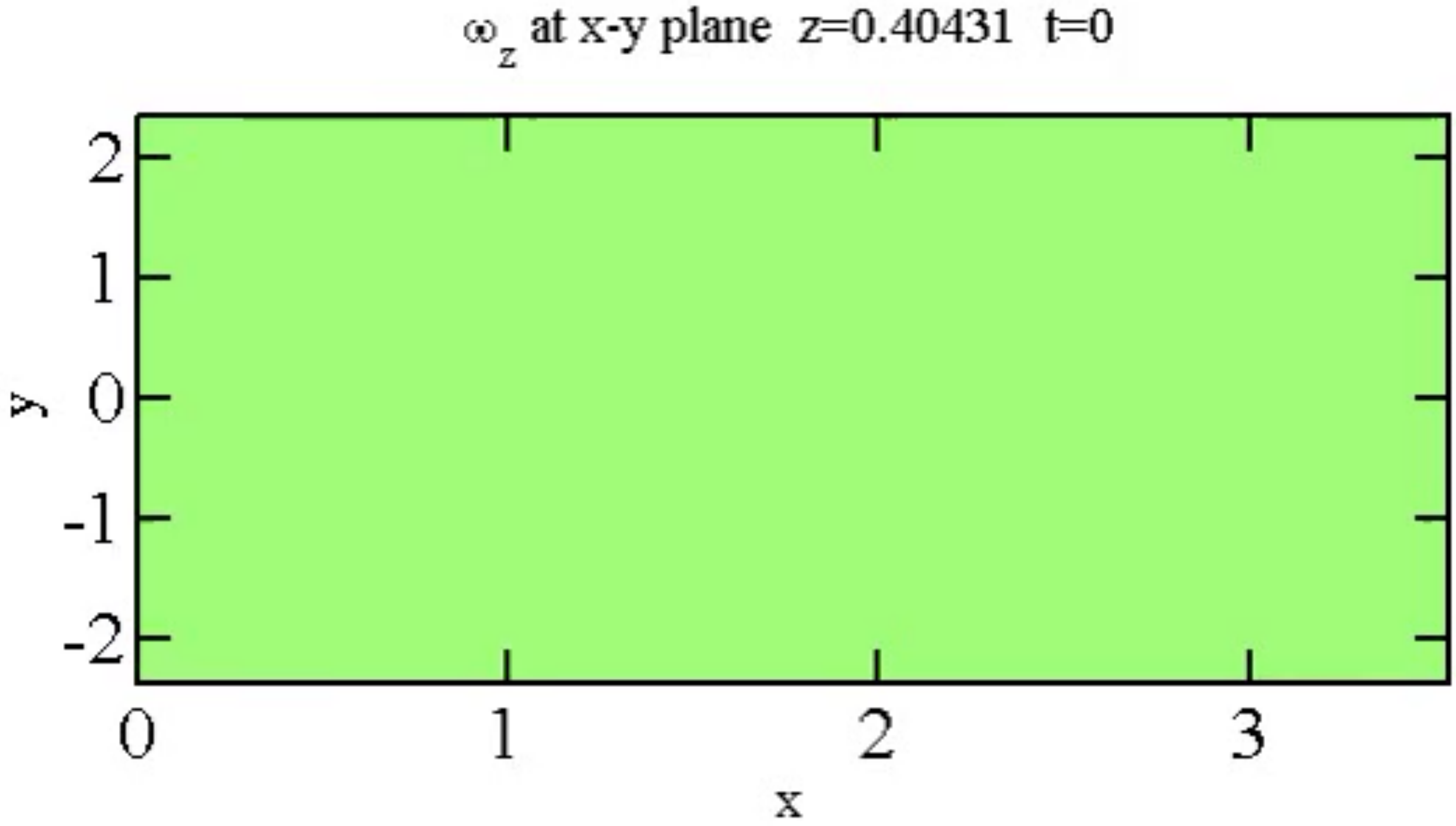


Fromang & Lesur (2017)



Nelson et al. (2013)

Zombie Vortex Instability

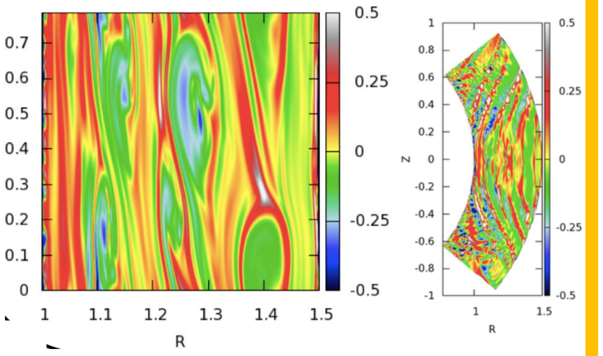


Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

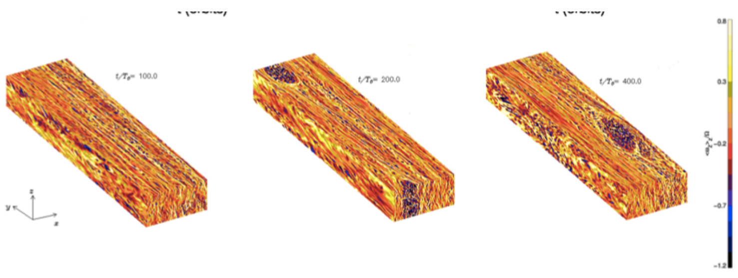
Thermal Instabilities

Vertical Shear Instability



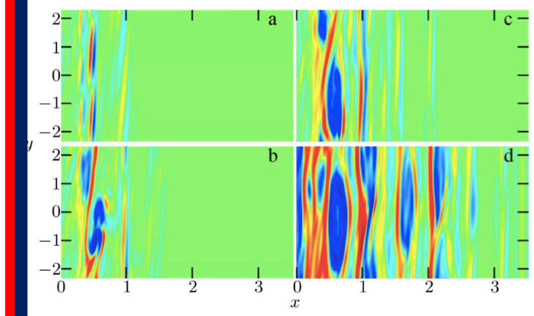
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Zombie Vortex Instability



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

$\Omega\tau << 1$
($\kappa < 1$ cm^2/g)

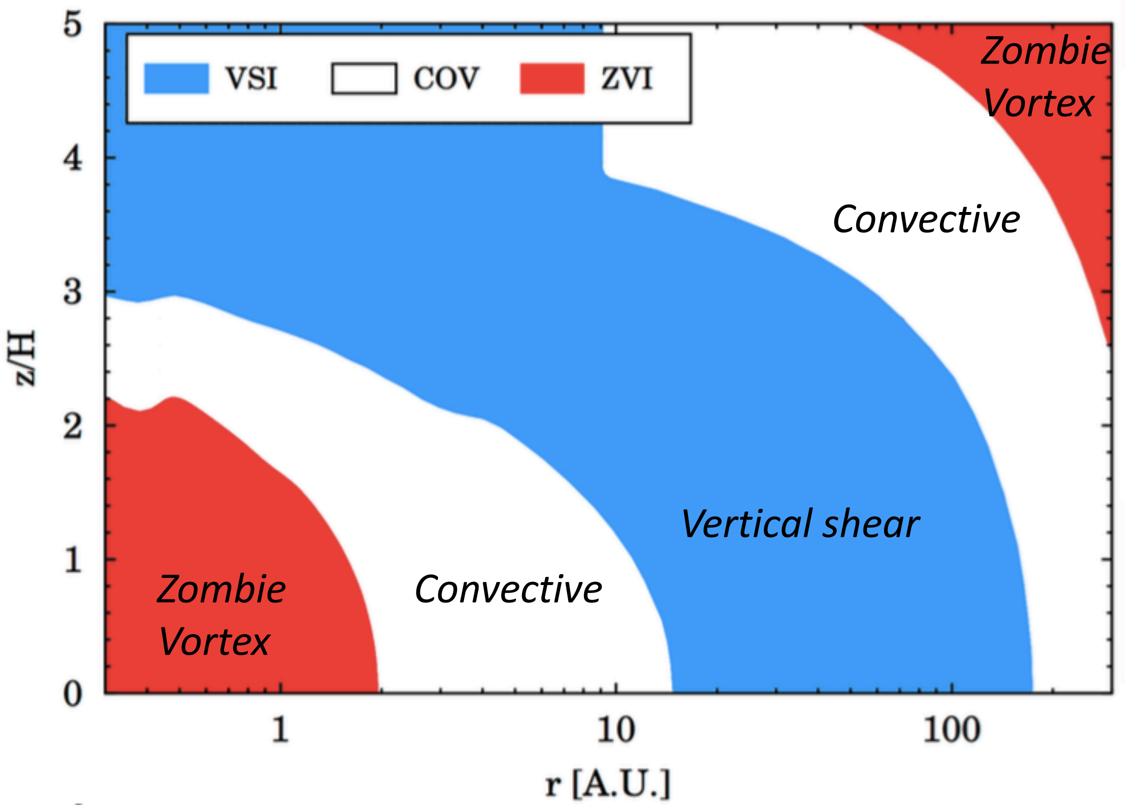
$\Omega\tau \sim 1$
($\kappa \sim 1$–50 cm^2/g)

$\Omega\tau >> 1$
($\kappa > 50$ cm^2/g)

Opacity

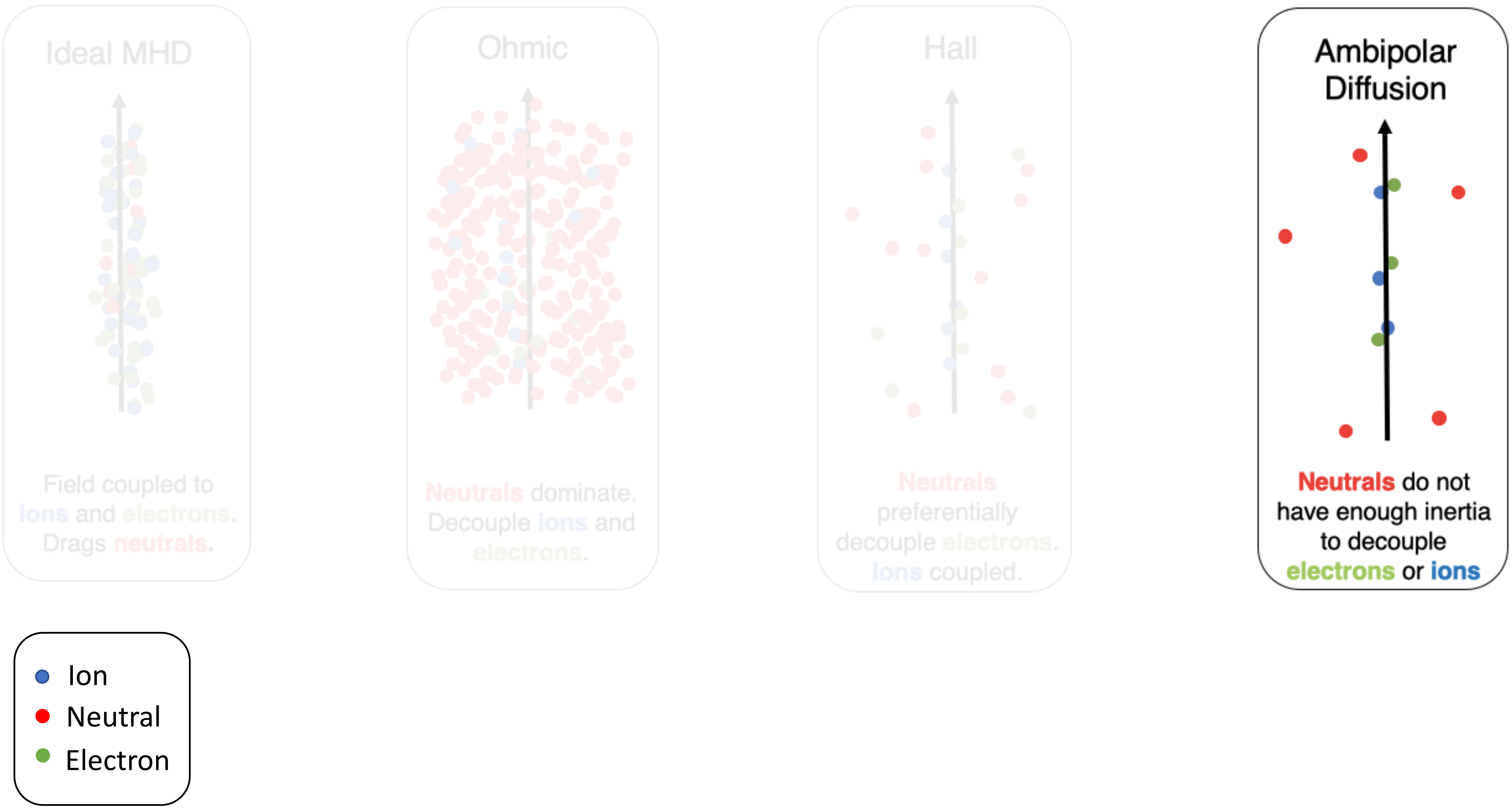
Malygin et al. (2017)
Lyra & Umurhan (2018)

Synthesis



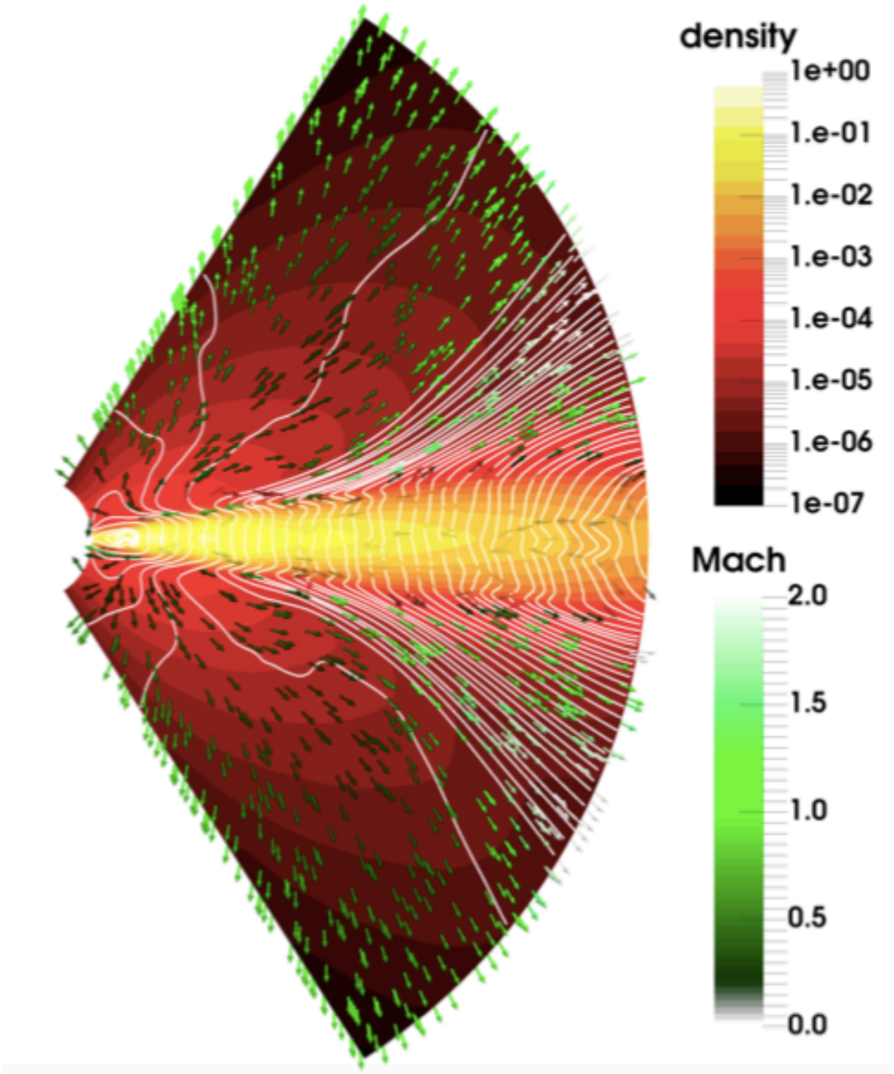
Estrada et al. 20917
Lyra & Umurhan 2018

MHD regimes

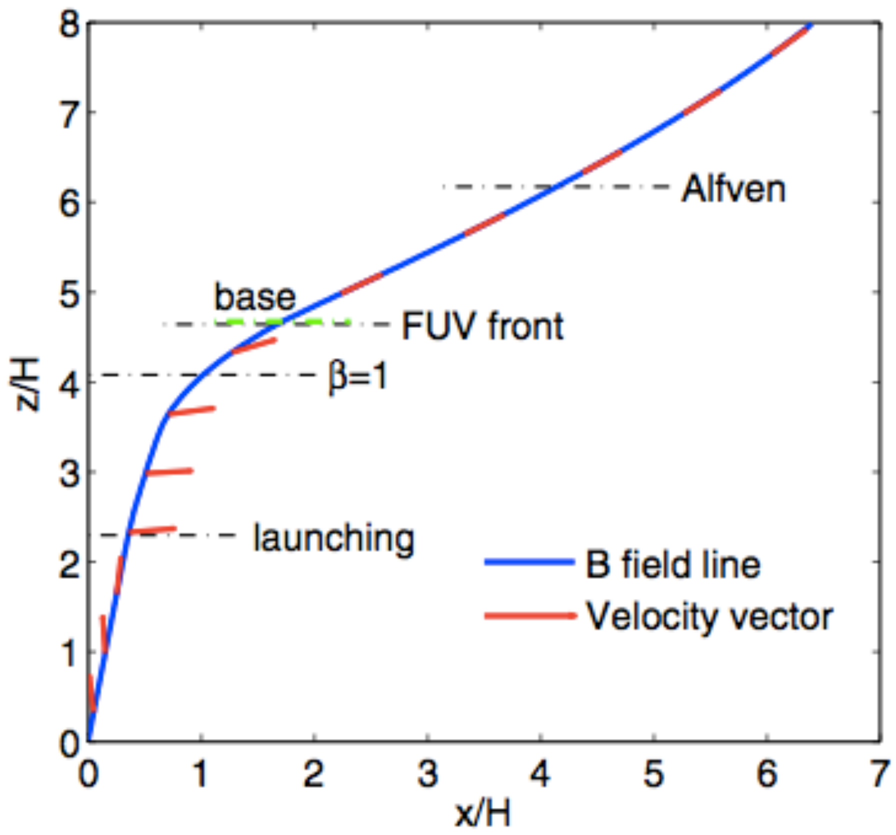


Ideal MHD
Field coupled to ions and electrons. Drags neutrals.
Ohmic
Neutrals dominate. Decouple ions and electrons.
Hall
Neutrals preferentially decouple electrons. Ions coupled.
Ambipolar Diffusion
Neutrals do not have enough inertia to decouple electrons or ions
Ion
Neutral
Electron

Magnetocentrifugal wind

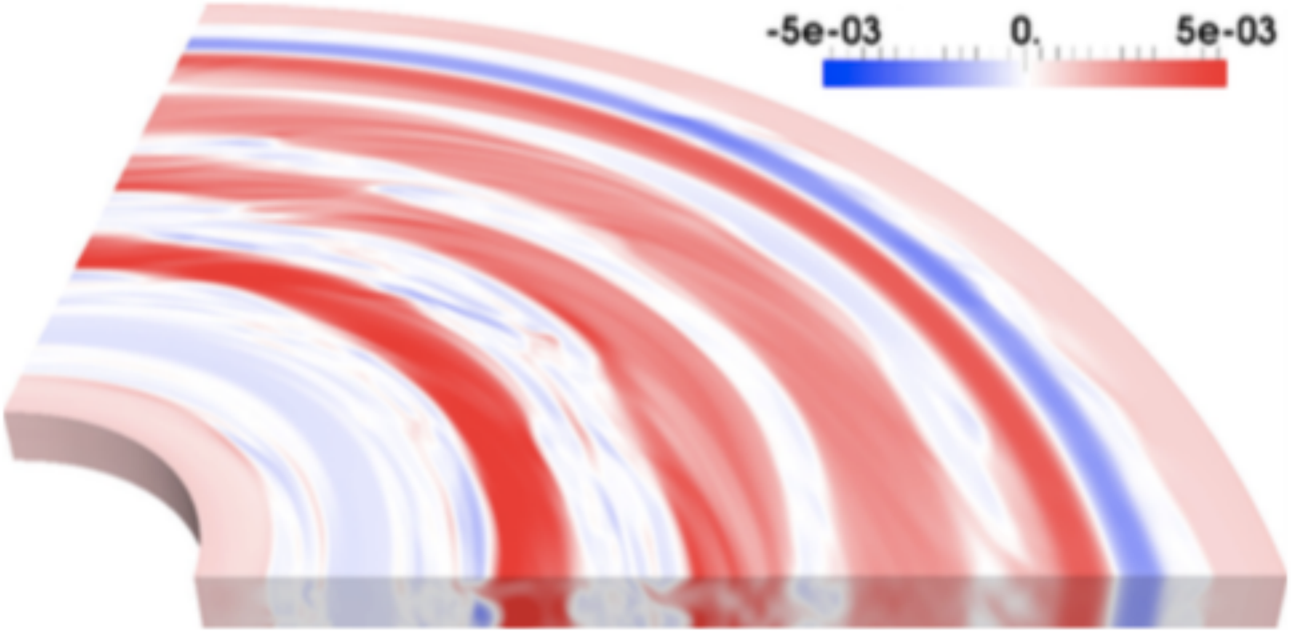


Bhétune et al. (2017)



Bai & Stone (2013)

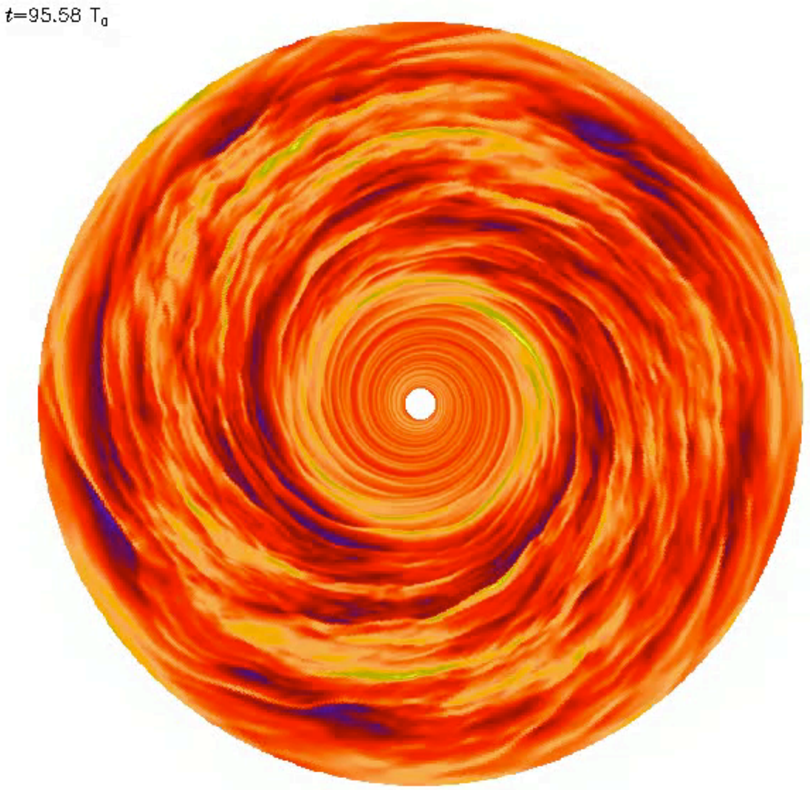
Hall MHD

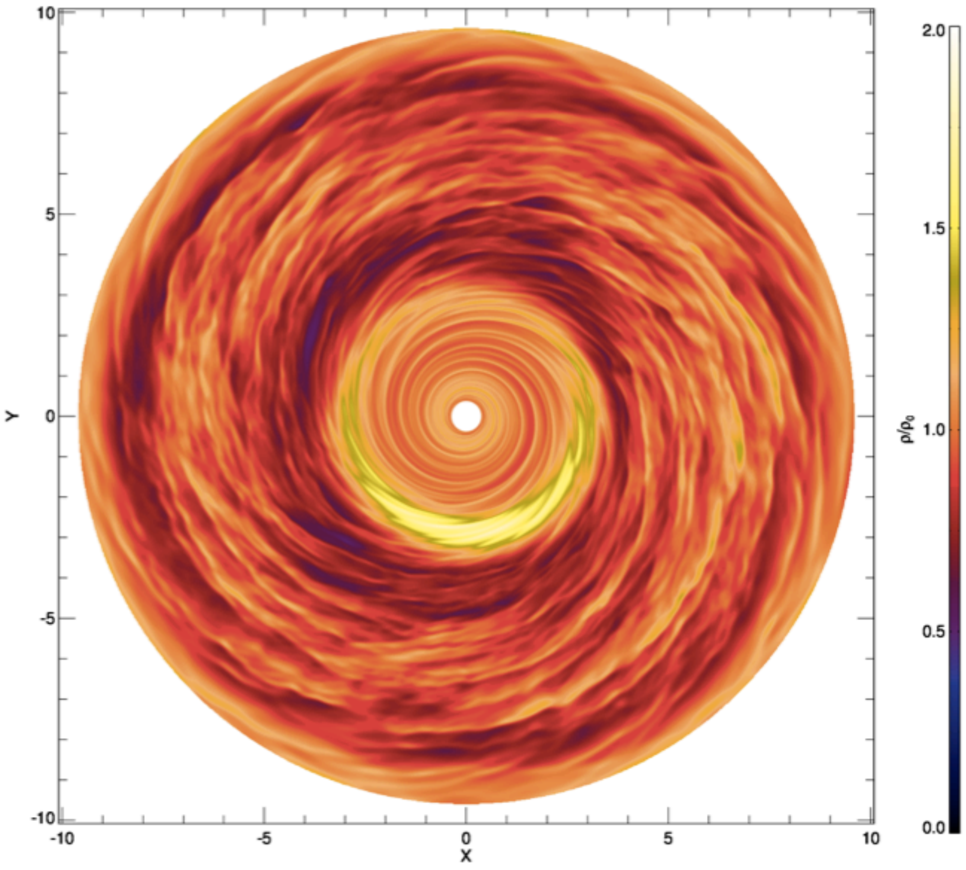


Self-organization

Lesur+ '14

Boundary layers





Quiescent inner disk + turbulent outer disk

Lyra+ '15

Thank you !