Planet Formation:
Solving the riddle of our origins

Wladimir Lyra

Physics and Astronomy

California State University

Jet Propulsion Laboratory

Collaborators

Aaron Boley (Vancouver), Axel Brandenburg (Stockholm), Kees Dullemond (Heidelberg), Mario Flock (JPL), Anders Johansen (Lund), Tobias Heinemann (KITP), Hubert Klahr (Heidelberg), Min-Kai Lin (ASIAA), Mordecai-Mark Mac Low (AMNH), Colin McNally (Copenhagen), Krzysztof Mizerski (Warsaw), Satoshi Okuzumi (JPL), Sijme-Jan Paardekooper (London), Nikolai Piskunov (Uppsala), Natalie Raettig (Heidelberg), Alex Richert (PSU), Neal Turner (JPL), Miguel de Val-Borro (Princeton), Andras Zsom (MIT).

CSUN IRIS, Oct 19st, 2018

Quick Bio

Wladimir Lyra

B.Sc. in Astronomy, Federal University of Rio de Janeiro (UFRJ, **Brazil**), 1999-2003.

Research Assistant 2003-2004

Space Telescope Science Institute (*STScI*, Baltimore **MD**)
Cerro Tololo Interamerican Observatory (*CTIO*, La Serena – **Chile**)
European Southern Observatory (*ESO*, Munich – **Germany**)
Lisbon Observatory, **Portugal**.

Ph.D. in Astronomy, Uppsala University (Uppsala, **Sweden**), 2004-2009.

Nordic Institute for Theoretical Physics (*NORDITA*, Stockholm, **Sweden**)
Max-Planck Institute for Astronomy (*MPIA*, Heidelberg, **Germany**)

Postdoctoral Researcher

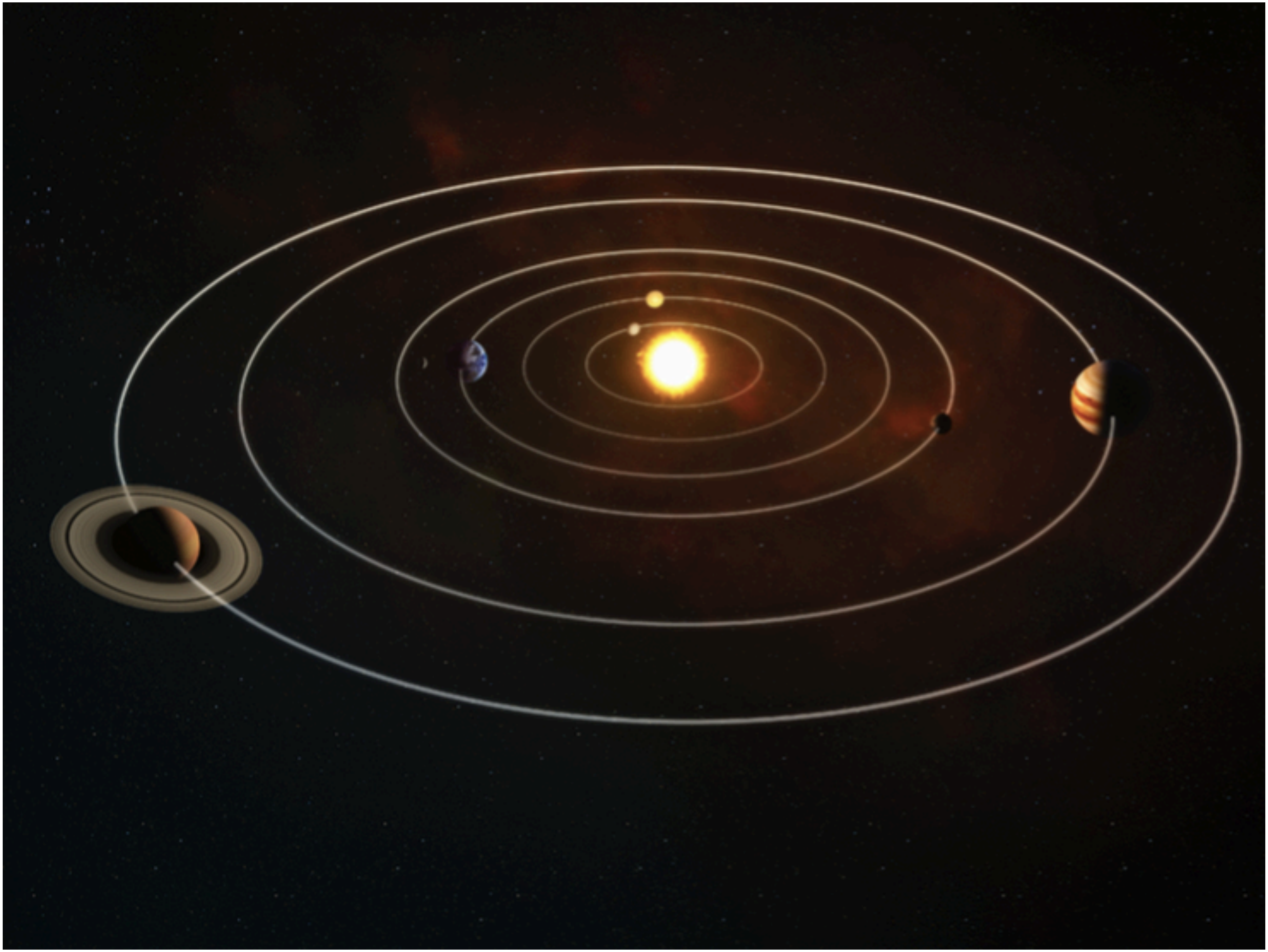
American Museum of Natural History (*AMNH*, New York **NY**), 2009-2011.
Jet Propulsion Laboratory (NASA-JPL/Caltech, Pasadena **CA**), 2011-2015.

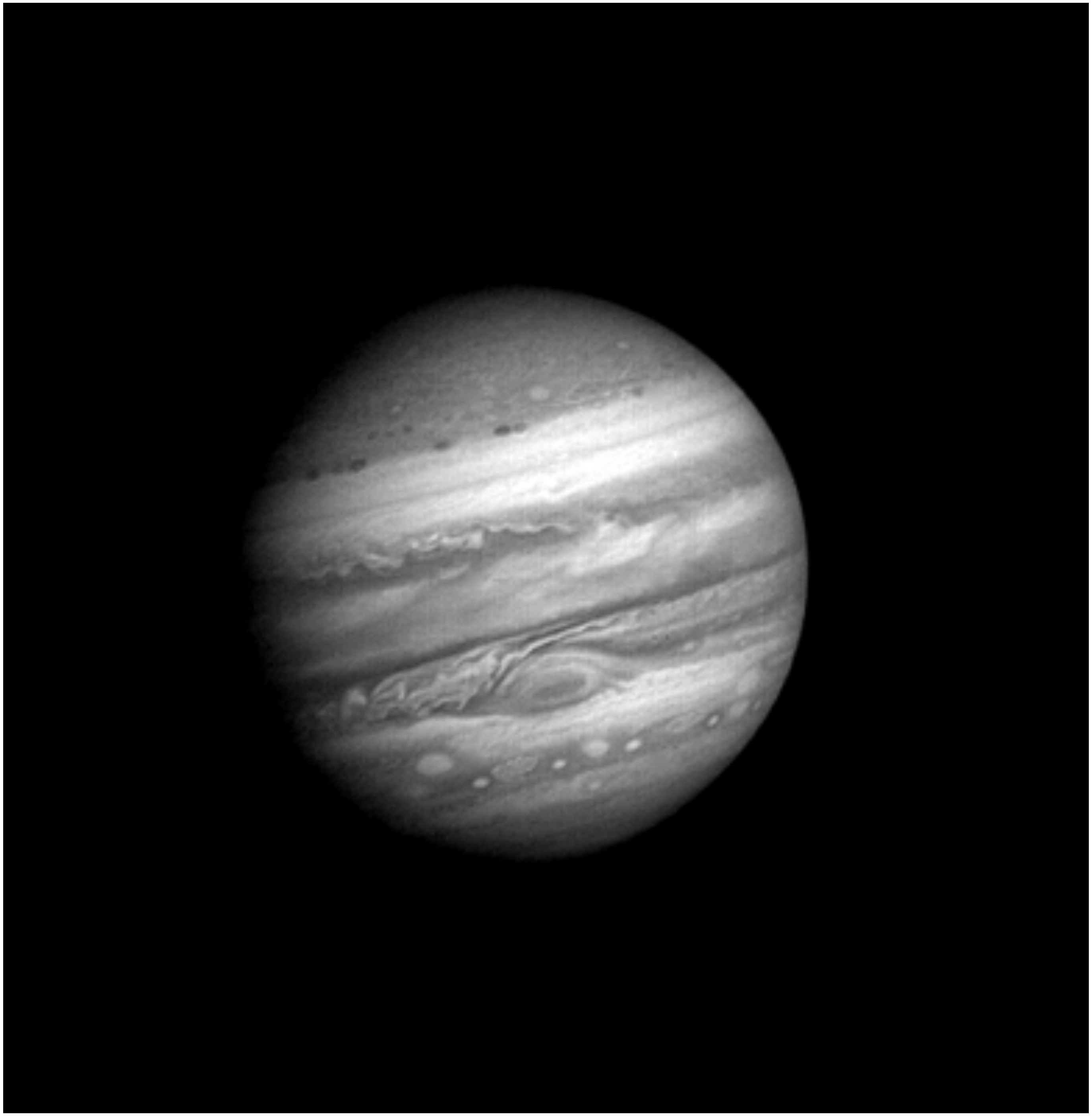
Stellar Astrophysics, Planetary Sciences

Solar-type stars, extrasolar planets, star formation, *circumstellar disks and planet formation*.
Hydrodynamics, plasma physics, turbulence, life in the universe, *icy moons and Europa*.

Outline

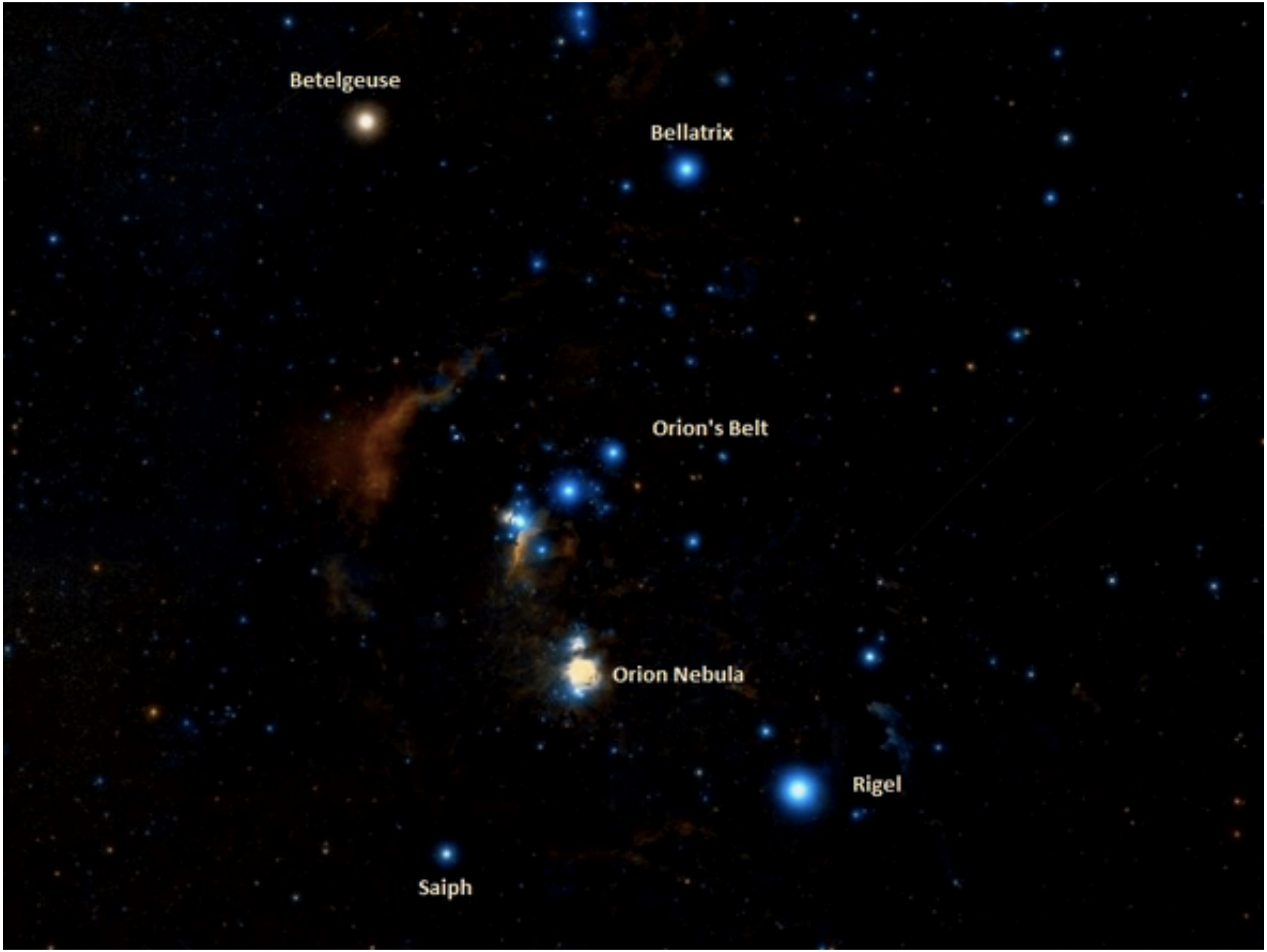
- Observational constraints
- The need for turbulence
    - "Streaming" Instability
    - Vortex trapping
- The importance of ionization: "active" and "dead" zones
    - Vortices in the "dead" zone
- The view of ALMA
- Observability

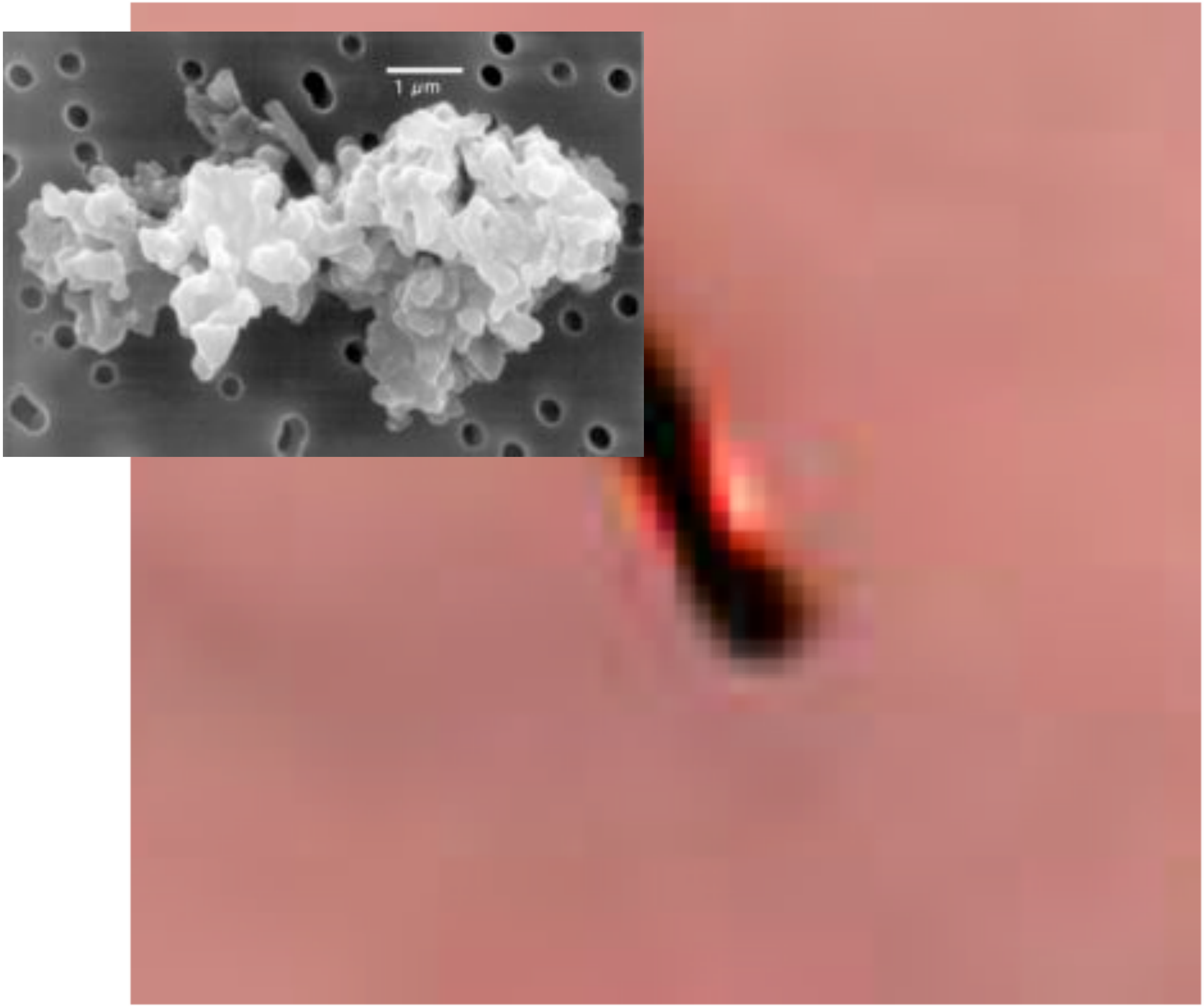




The Solar Nebula

Artistic concept


Betelgeuse
Bellatrix
Orion's Belt
Orion Nebula
Rigel
Saiph


1 μm

Protoplanetary Disks

PP disk fact sheet

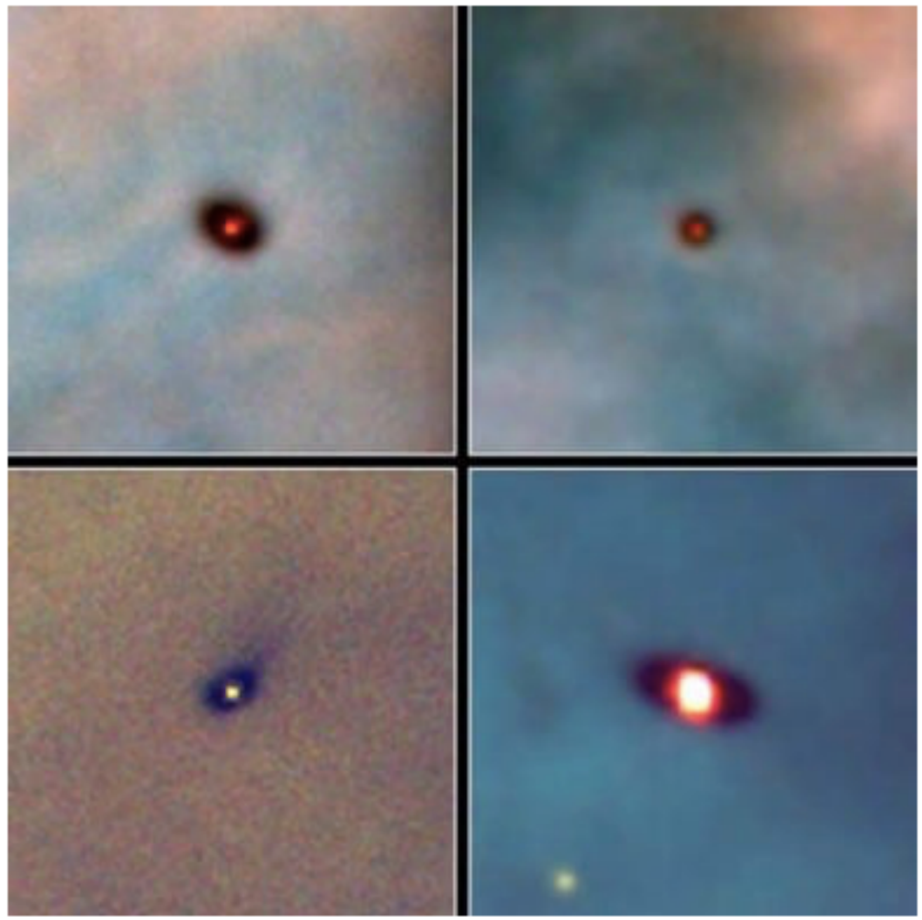
Density: $10^{13} - 10^{15}$ cm^{-3}
(Air: 10^{21} cm^{-3})

Temperature: 10-1000 K

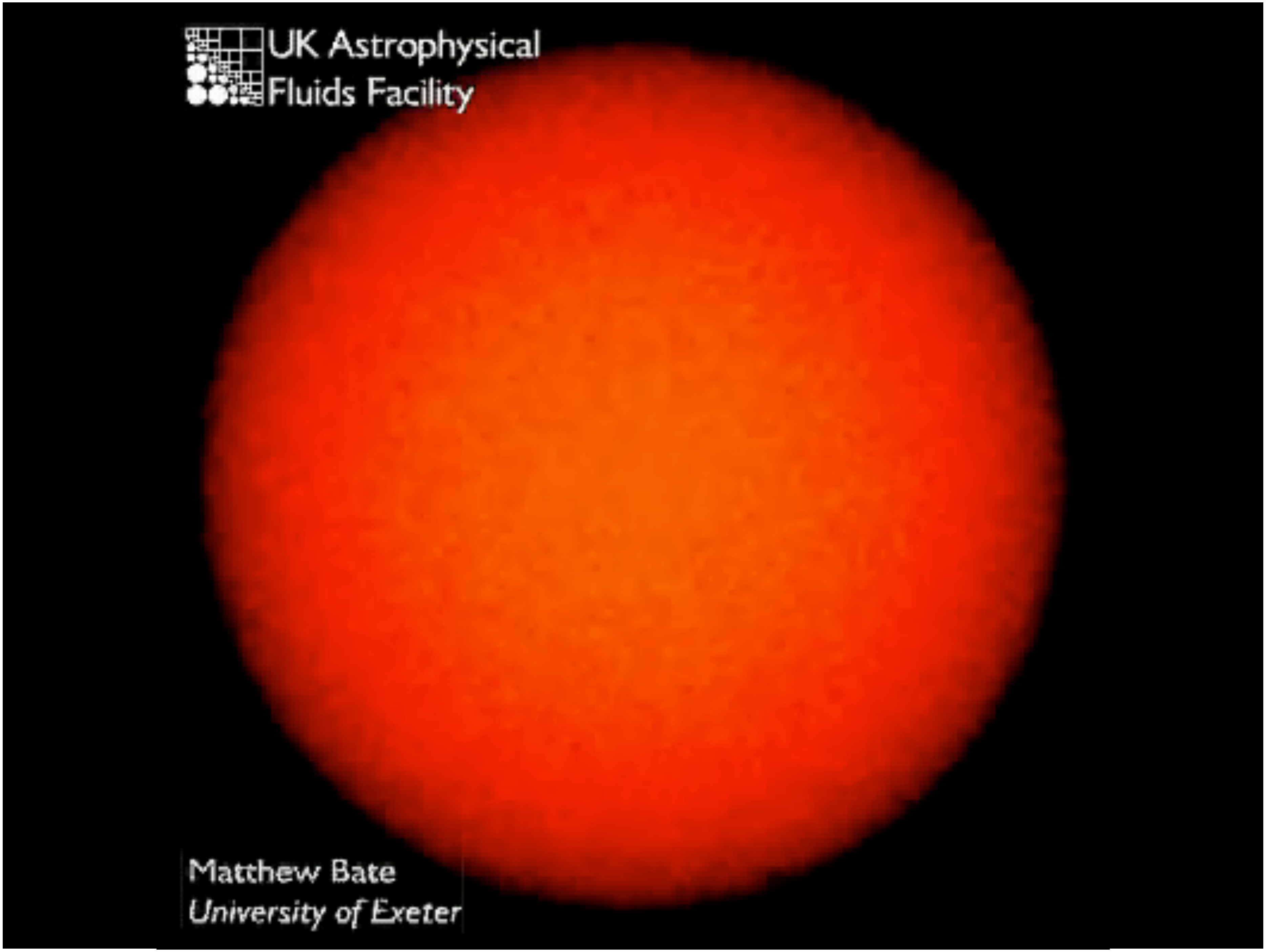
Scale: 0.1-100AU
(1 AU = 1.49×10^{13} cm)

Mass: $10^{-3} - 10^{-1}$ M_{sun}
(1 M_{sun} = 2×10^{33} g)

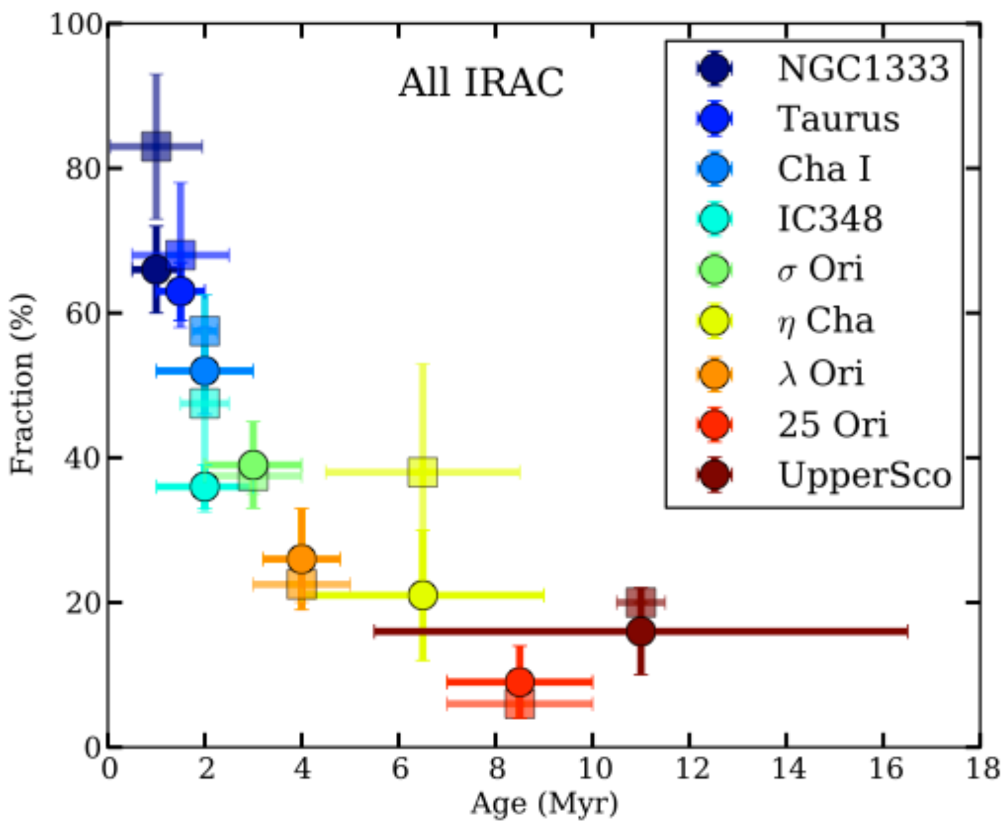
The Hubble view of Protoplanetary disks



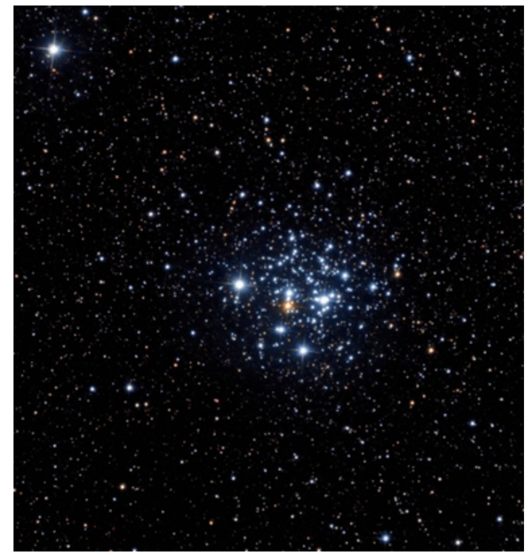
Proto-planetary disk of dust and gas surrounding newborn stars in the Orion Nebula photographed by Hubble. Credit: NASA/ESA


UK Astrophysical
Fluids Facility
Matthew Bate
University of Exeter

Disk lifetime

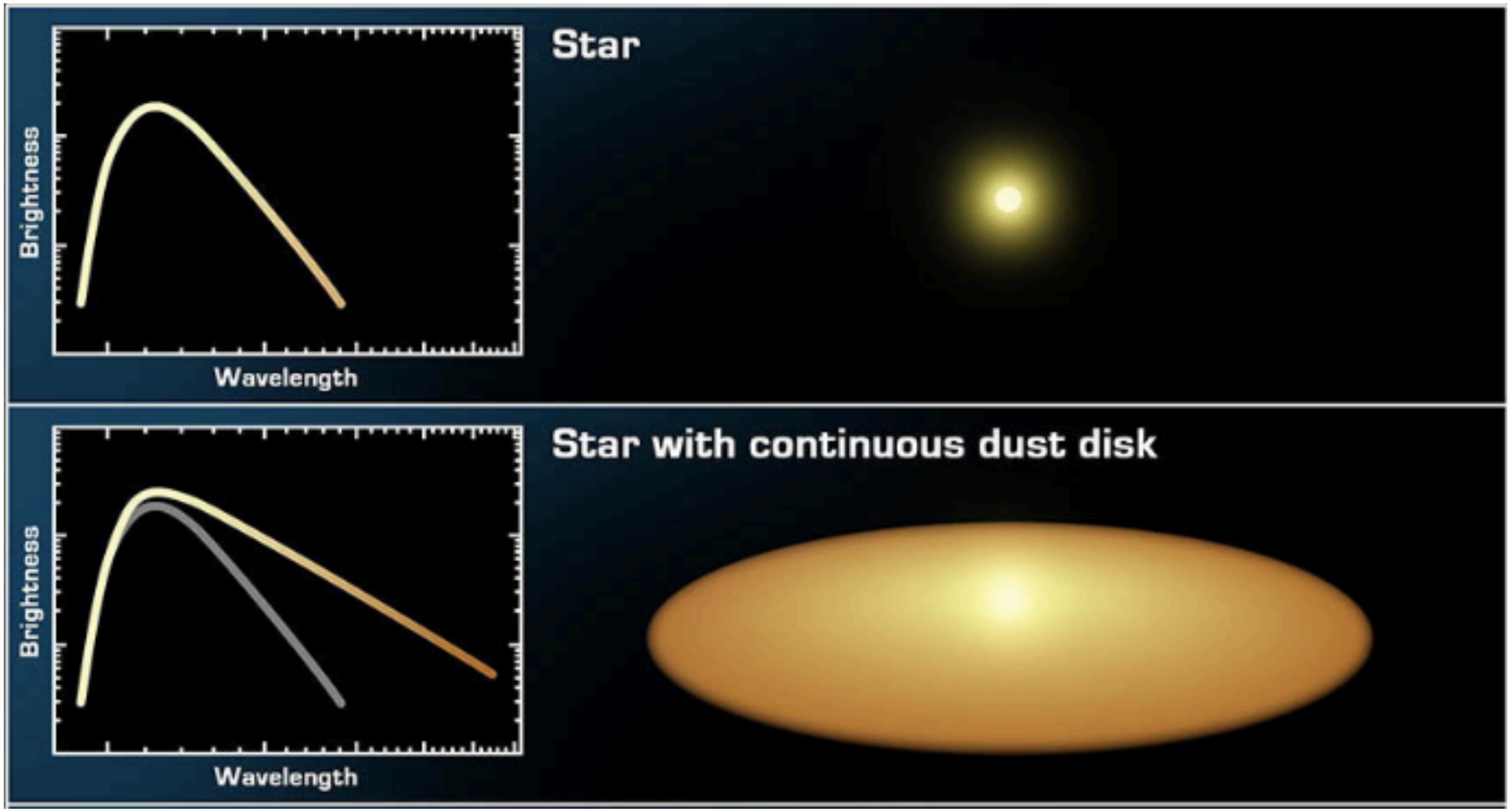


(Ribas et al. 2014)



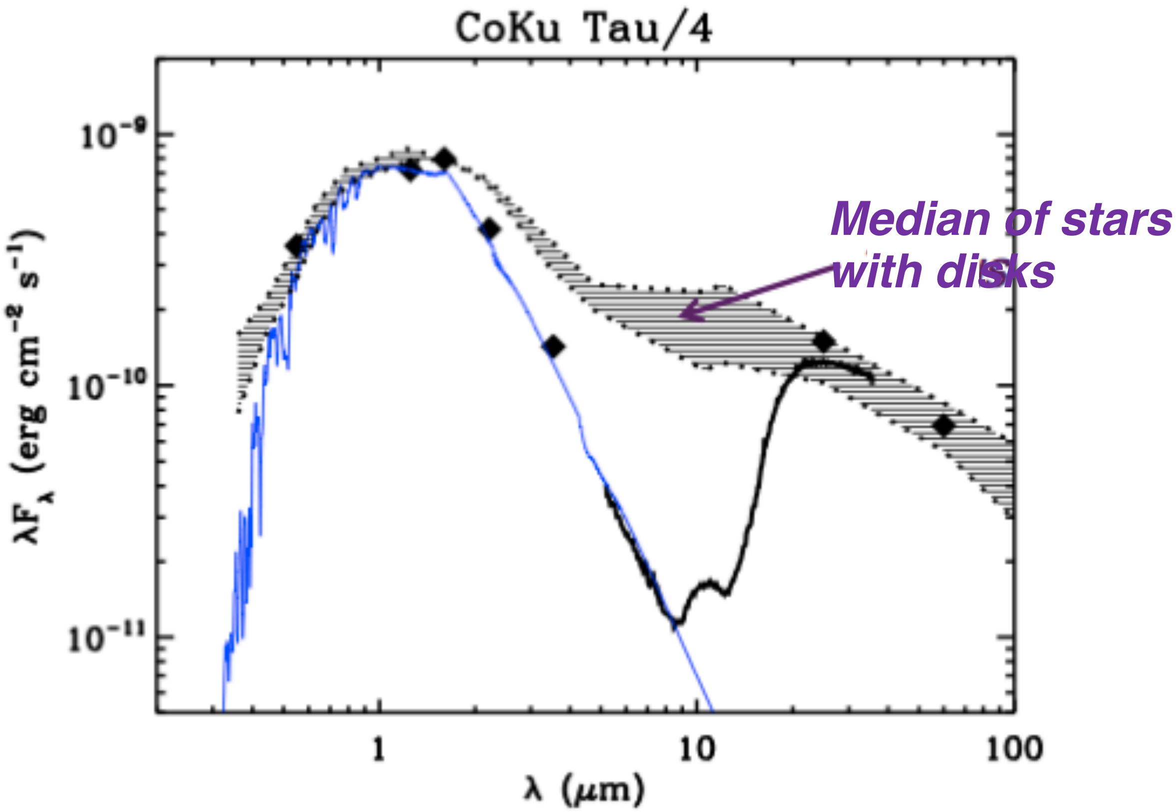
Disks dissipate within ~10Myr

Spectral Energy Distribution

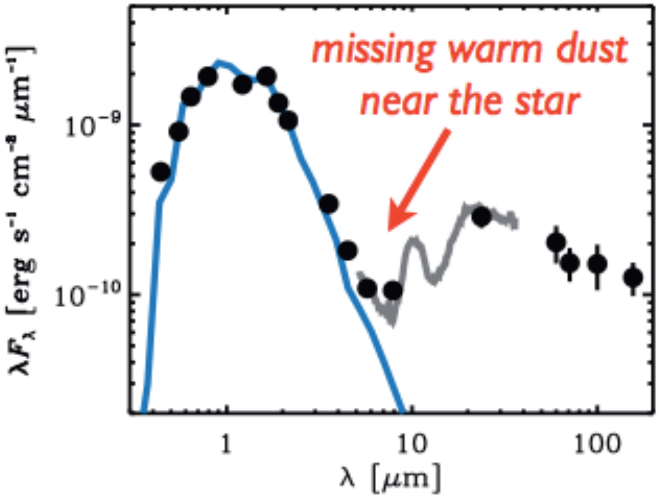


Spitzer (Infrared) Space Telescope

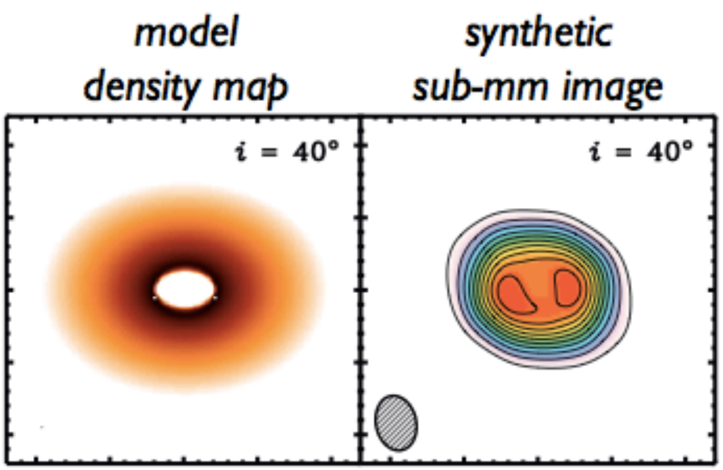
A disk with missing hot dust



Transition Disks: Disks with missing hot dust.

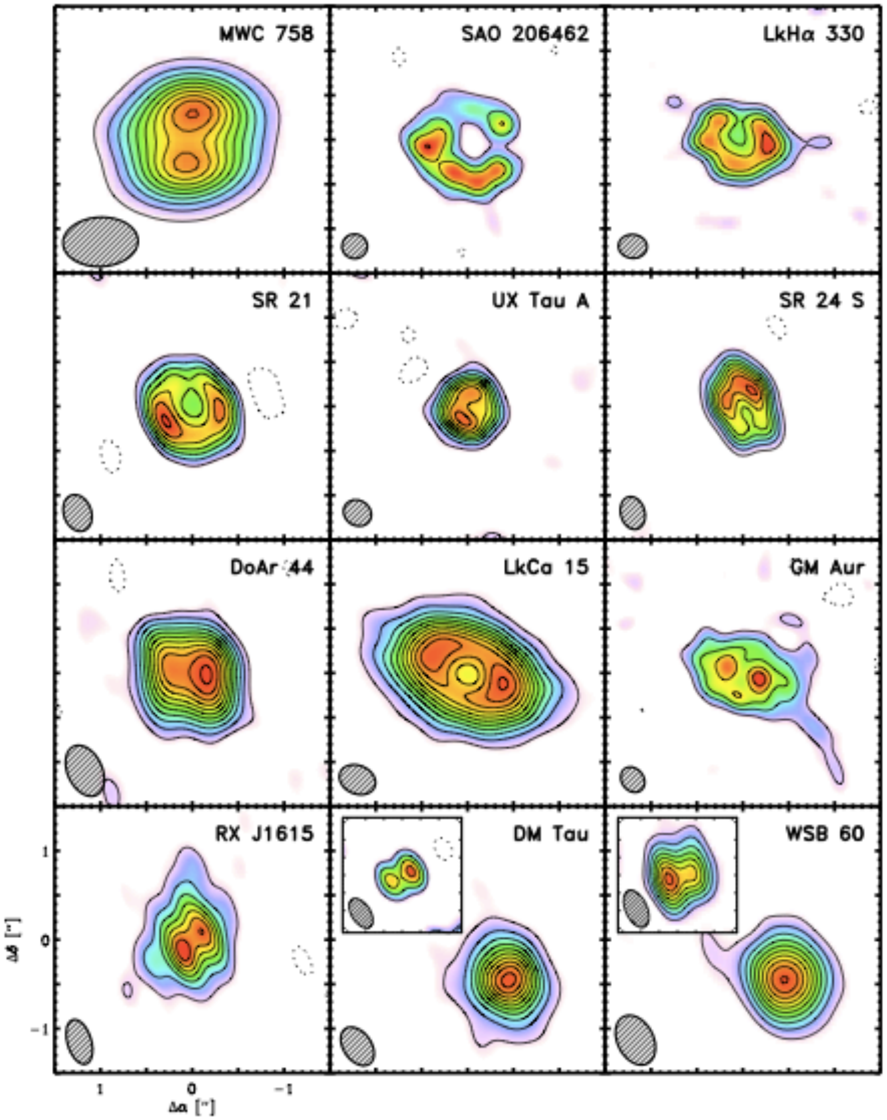


[e.g., Furlan et al. 2009]

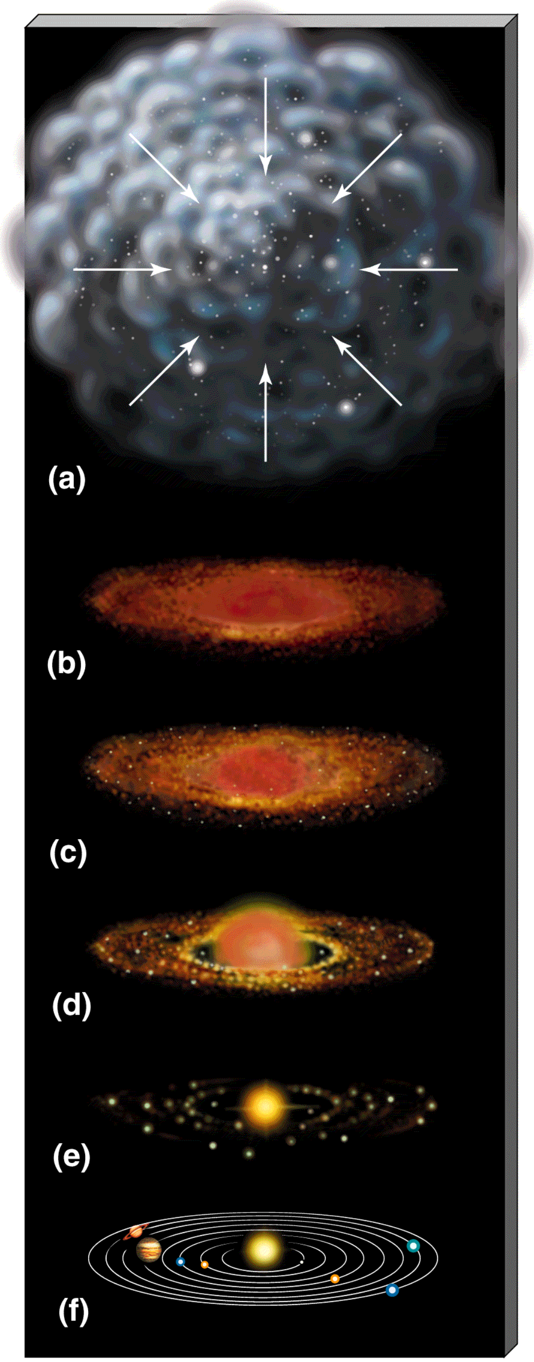


a disk with a large reduction
in optical depth near the star
(i.e., a "cavity" or "hole")

Resolved transition disks with the Sub-millimeter Array (SMA)



0.85mm
0.3'' ~ 20 AU resolution



Disk Evolution

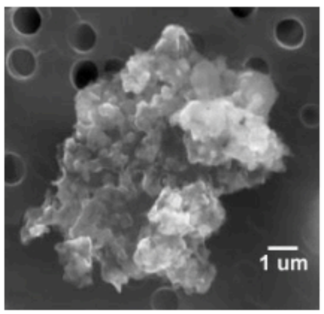
Gas-rich phase (< 10 Myr)
Primordial Disks

”Gapped” disks (<~10 Myr)
Conjecture : Transition Disks

Gas-poor phase (>10 Myr)
Debris Disks

Planet Formation

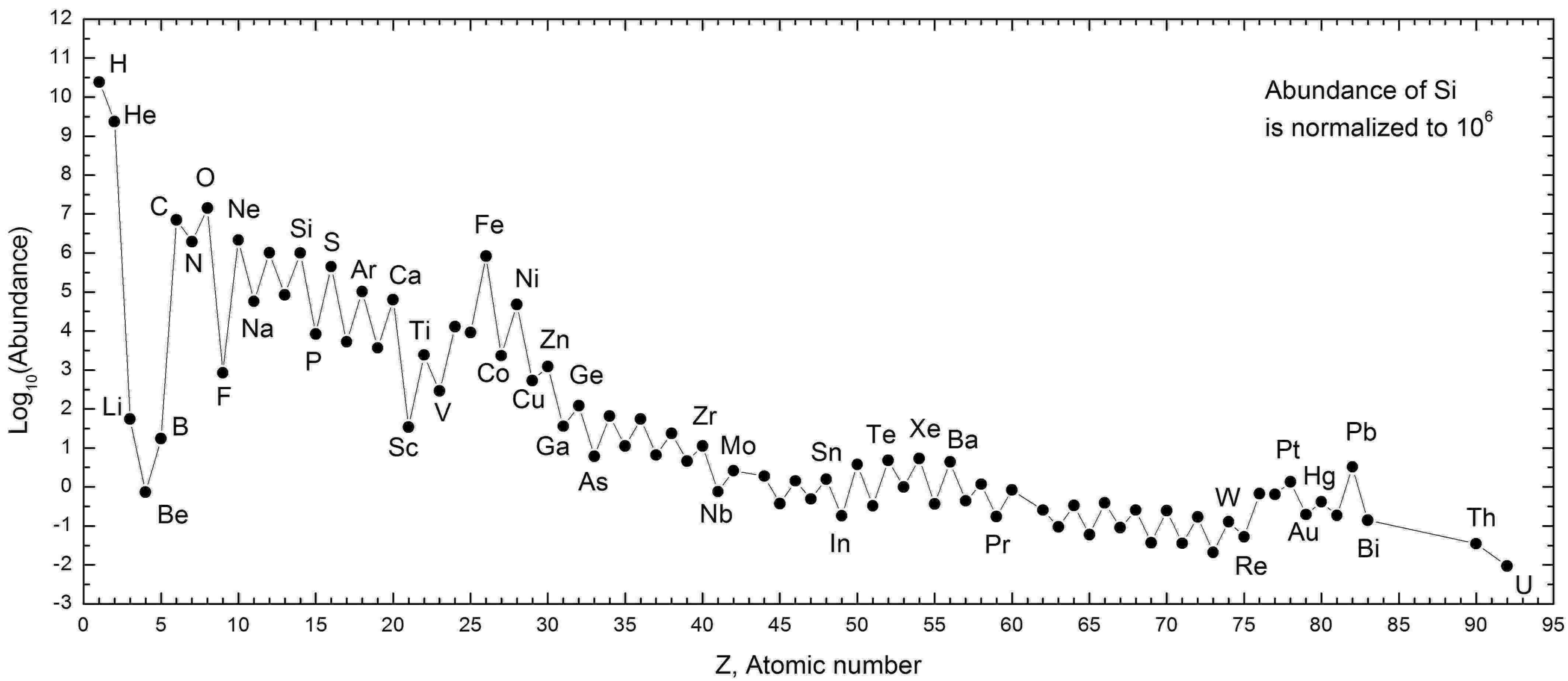
"Planets form in disks of gas and dust"



A miracle happens →

Chemical Composition

The chemical composition of the Sun



<u>Most abundant elements, in order:</u>

H (71%) He (27%)

0 (1.04%) C (0.46%)

Ne (0.13%) Fe (0.11%) N (0.1%)

Si (0.06%), Mg (0.05%), S (0.04%)

What will the chemistry of the mixture be?

H_2

He

H_2O

CH_4

Ne

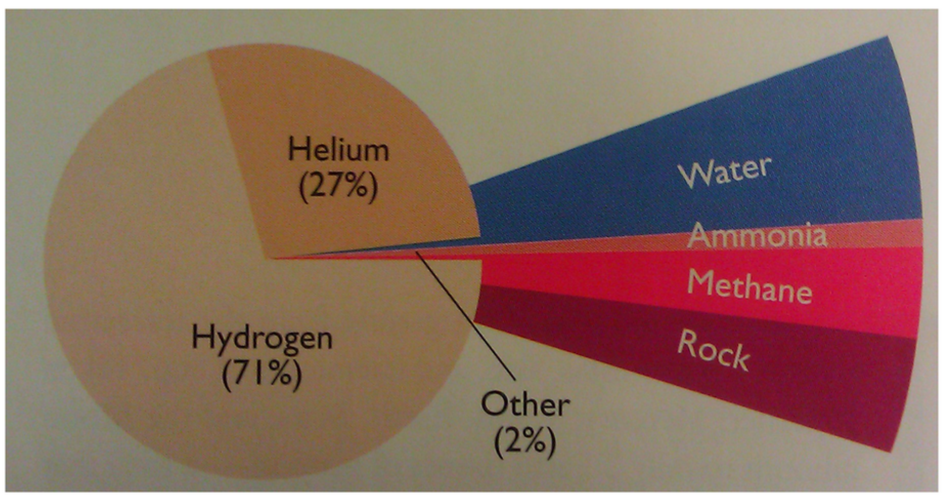
NH_3

Fe, Si

What will the chemistry of the mixture be?

H (71%)
He (27%)
0 (1.04%)
C (0.46%)
Ne (0.13%)
Fe (0.11%)
N (0.1%)
Si (0.06%)

H_2 He
H_20 - Water
CH_4 - Methane
Ne
NH_3 - Ammonia
Fe, Si – Rocks (metals and silicates)



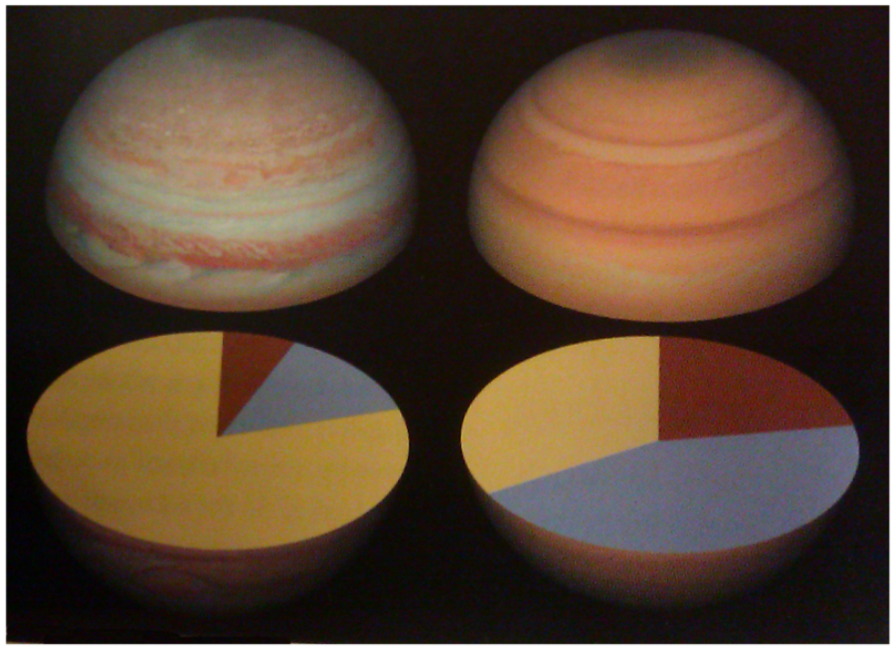
Classes of planets

Rocky Planets

Earth

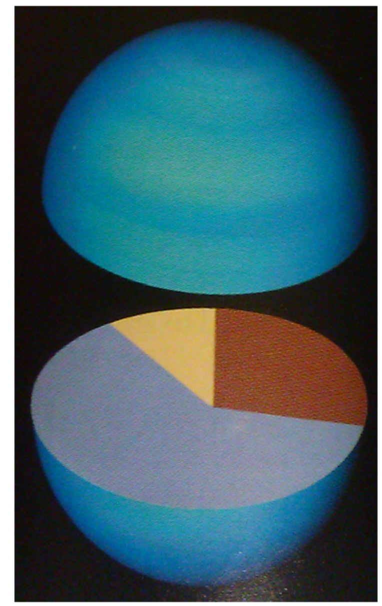
Gas Giants

Jupiter Saturn



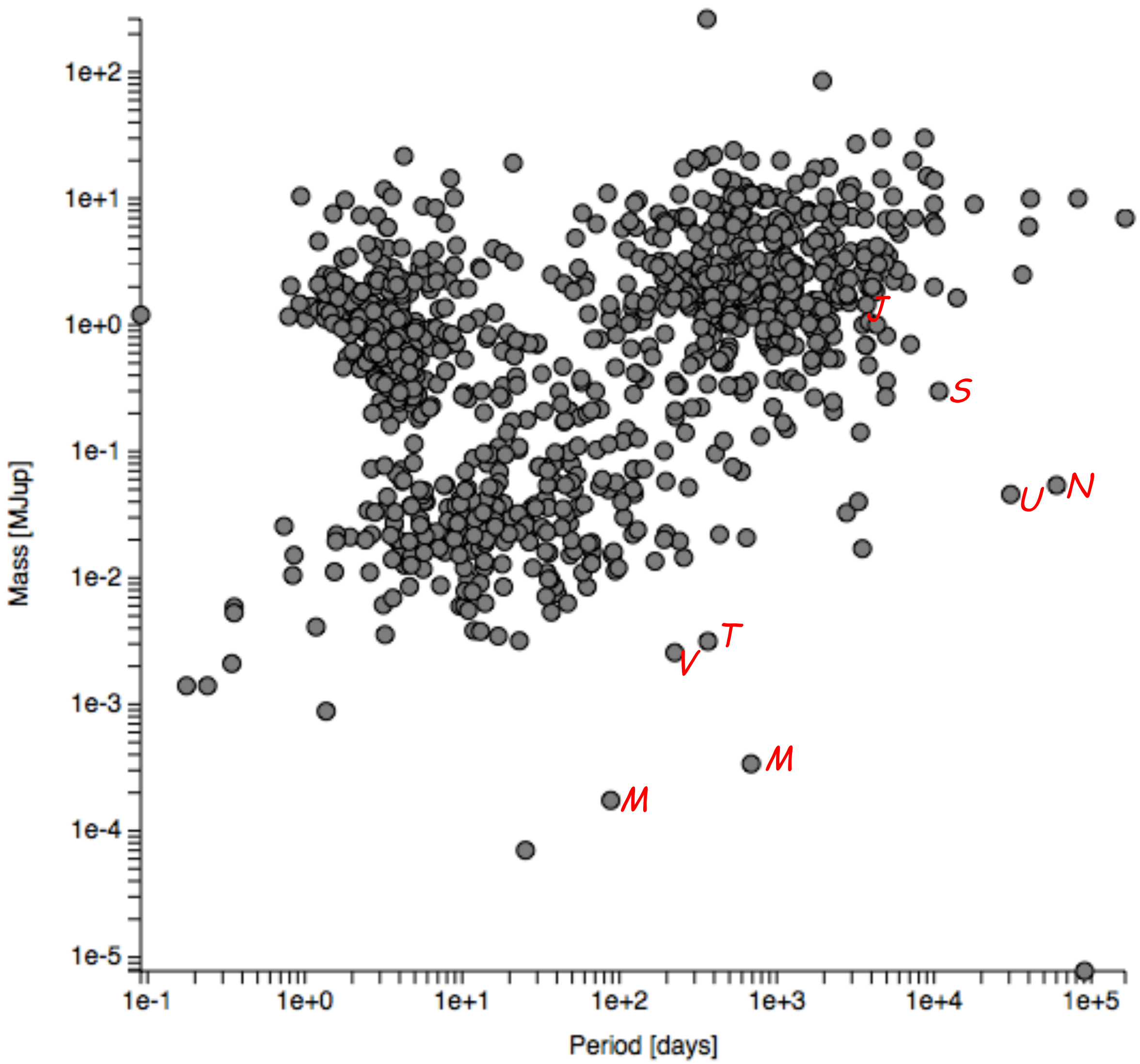
Ice Giants

Uranus/Neptune

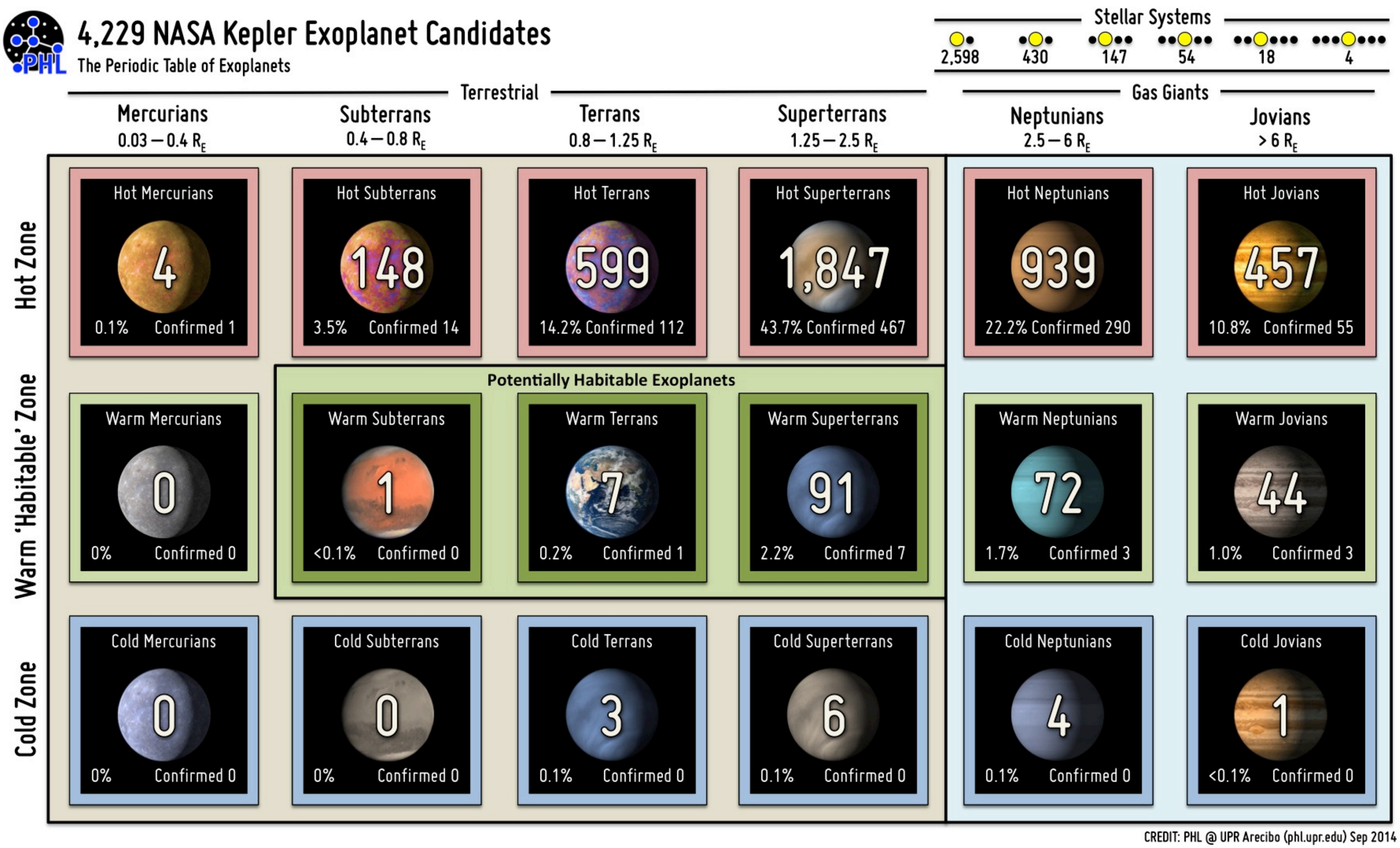


Rock Gas Ice

Mass-period distribution of planets



Kepler: "Period table" of exoplanets



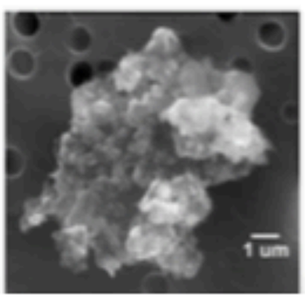
Planet Formation

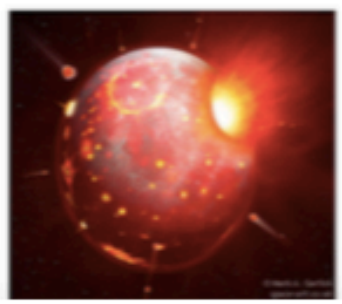
Planetesimal Hypothesis (Safronov 1969)

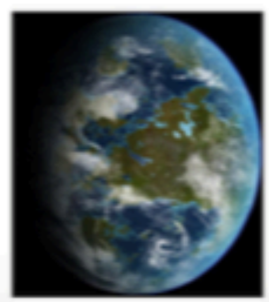
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

From planetesimals to planetary embryos
km -> 1000 km : Gravity

From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope







Planet Formation

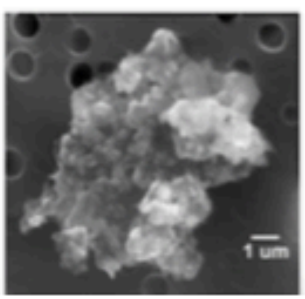
Planetesimal Hypothesis (Safronov 1969)

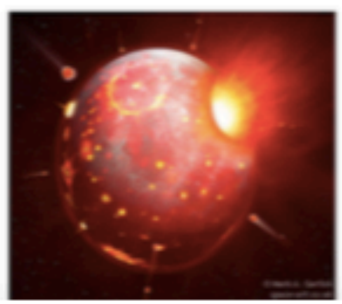
From dust to peebles
μm -> cm : hit-and-stick by van der Walls

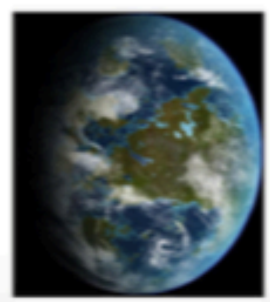
From pebbles to planetesimals
Here be dragons….

From planetesimals to planetary embryos
km -> 1000 km : Gravity

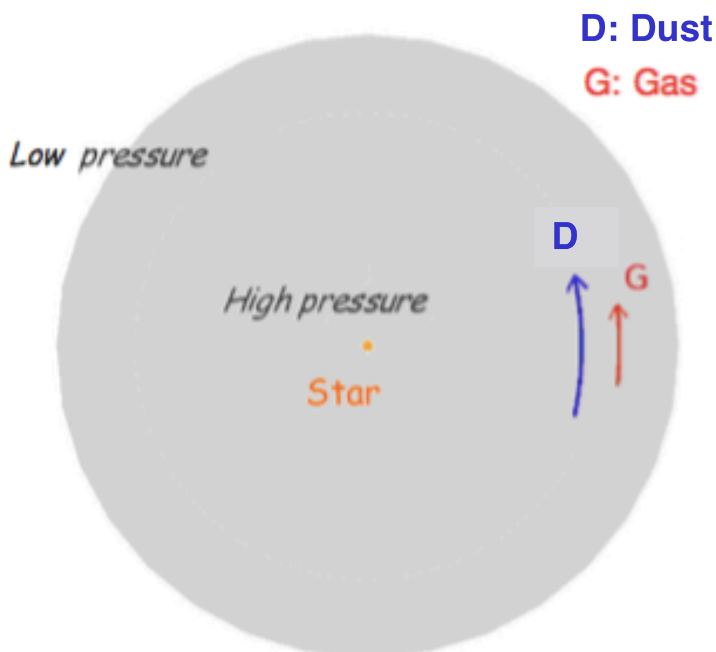
From planetary embryos to planets
Rocky planets: binary collisions
Gas giants: Attract gaseous envelope



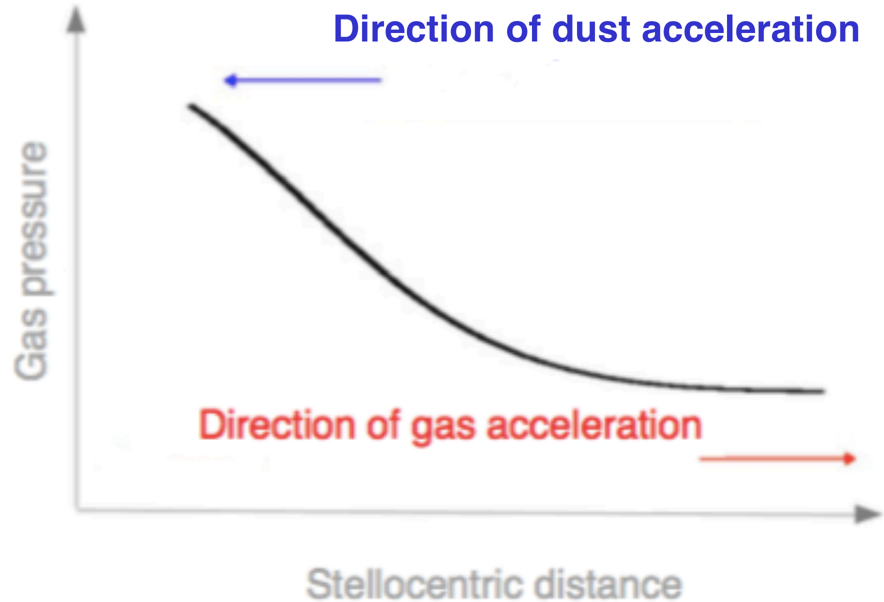




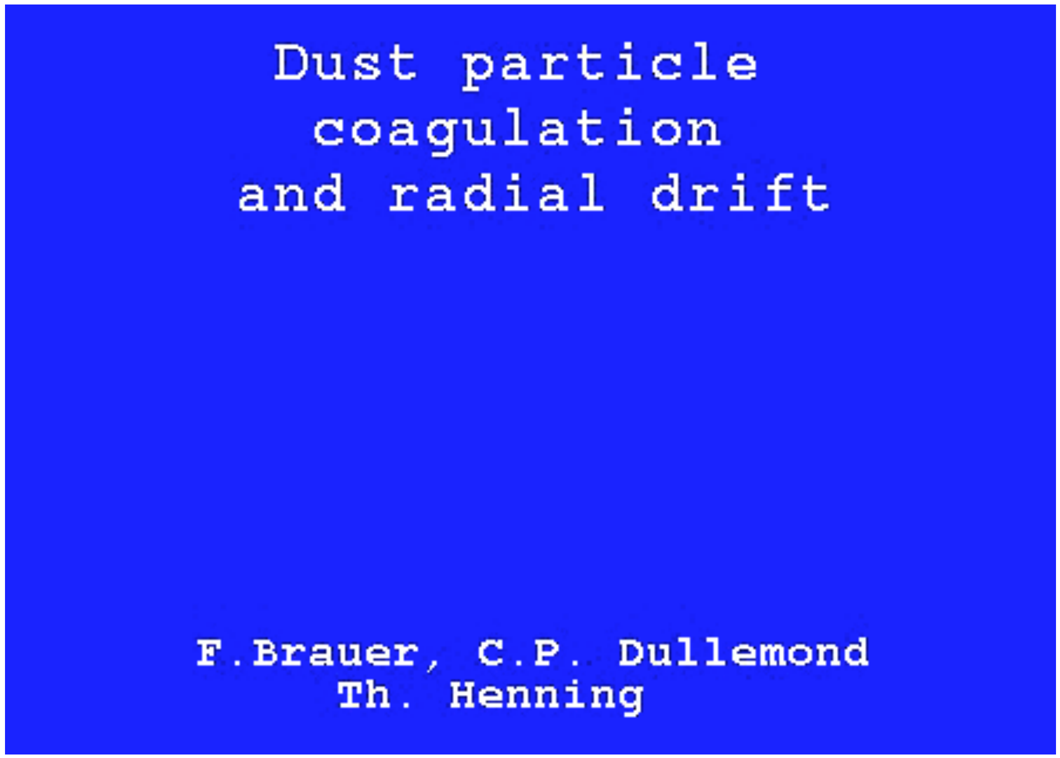
Dust Drift



Adapted from Whipple (1972)



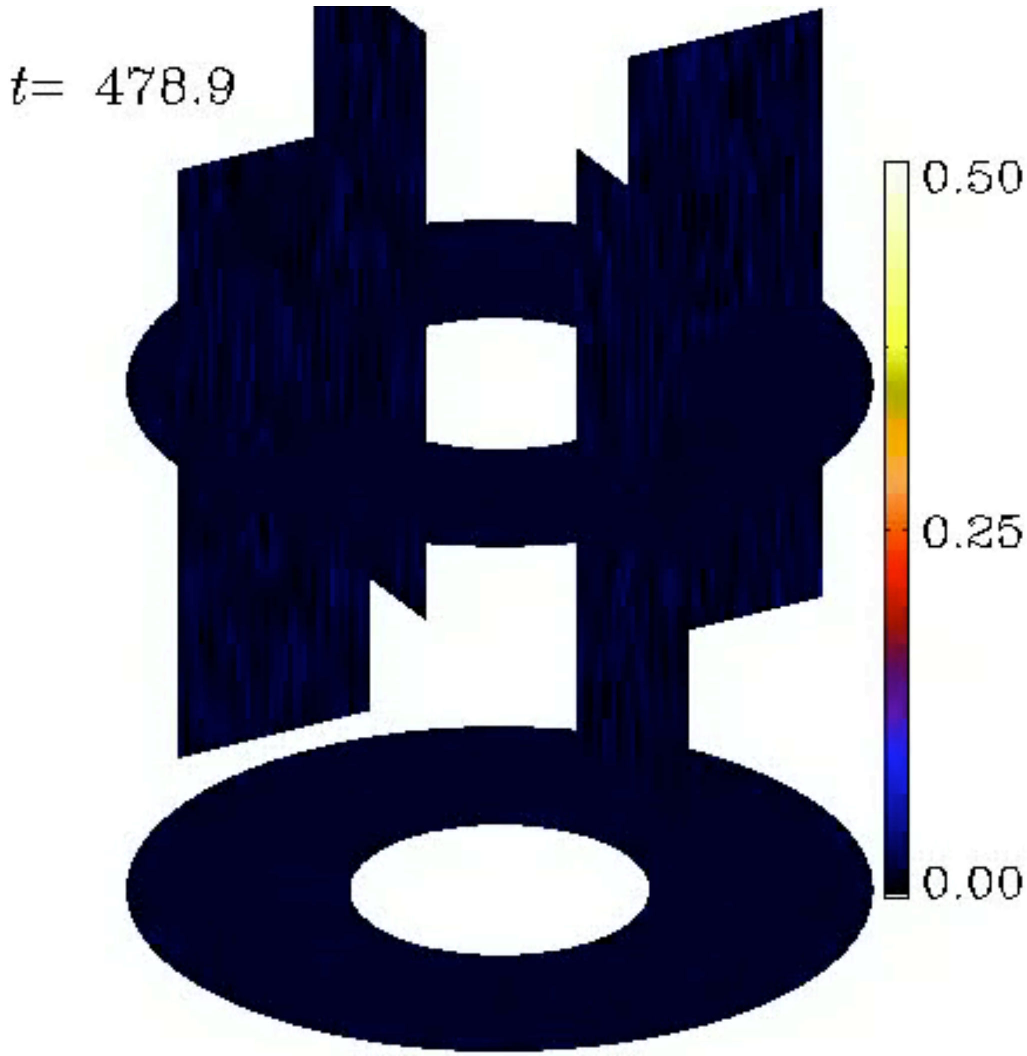
Dust Coagulation and drift



Brauer et al. (2008)

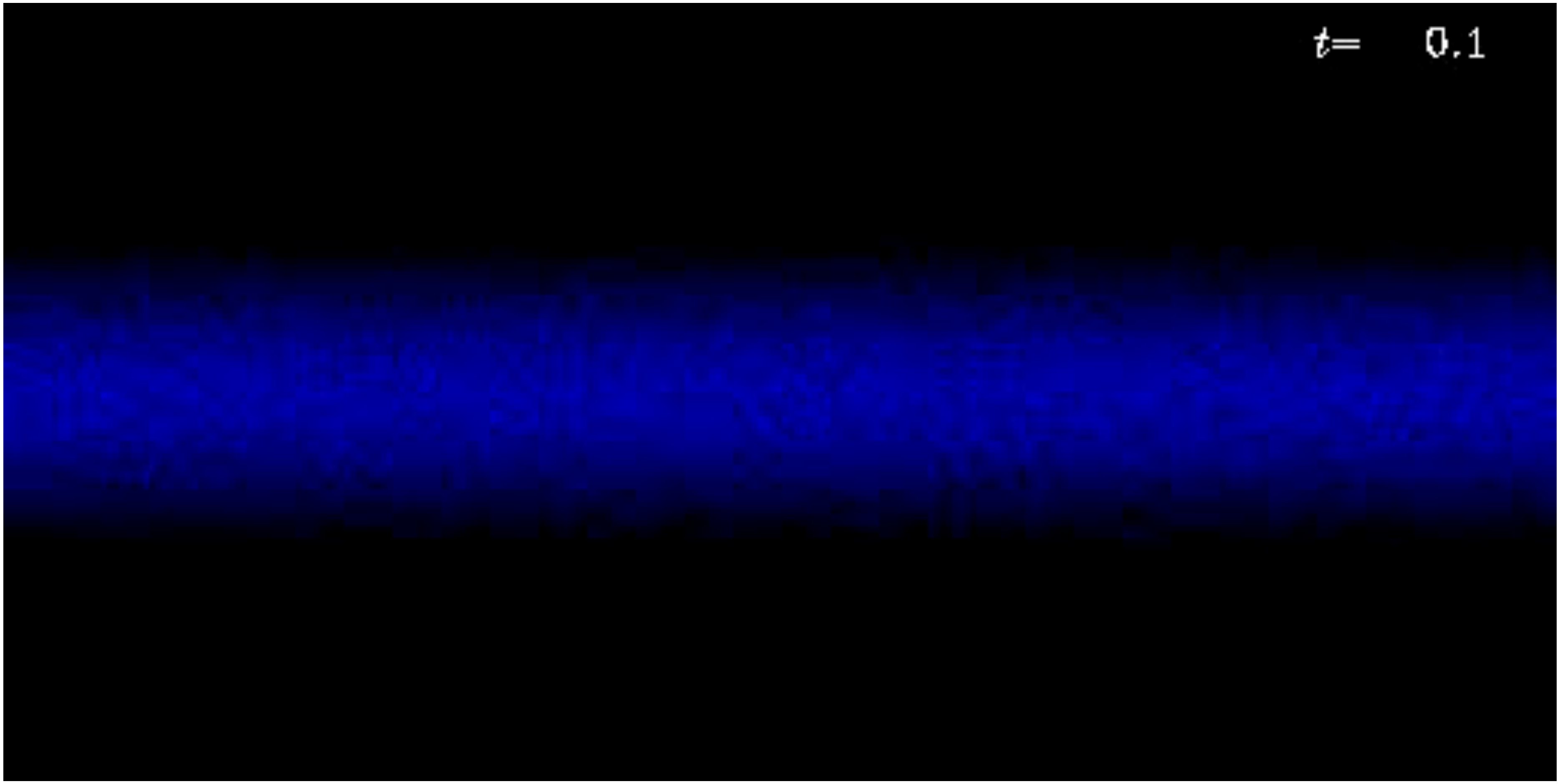
Turbulence and Accretion in 3D Global MHD Simulations of Stratified Protoplanetary Disk

Turbulence concentrates solids mechanically in pressure maxima



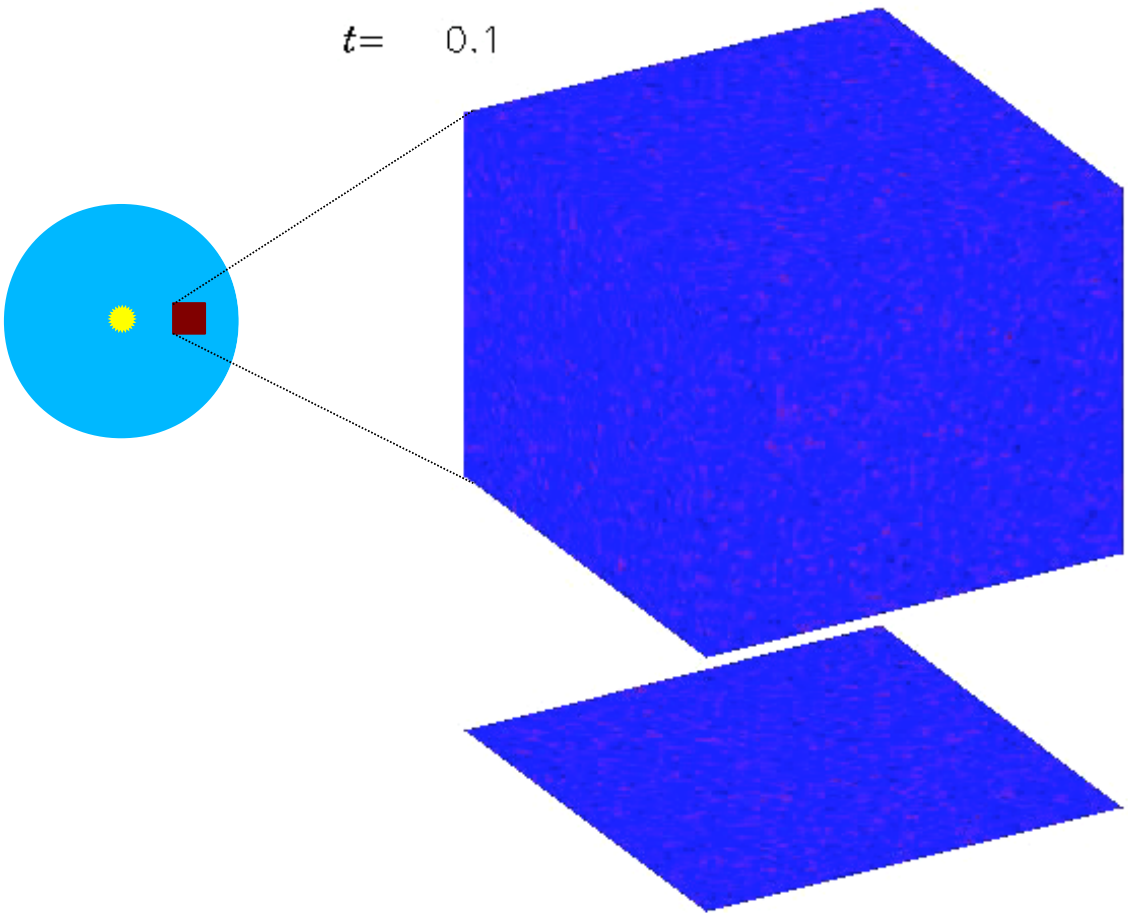
Lyra et al. (2008a)

Sedimentation



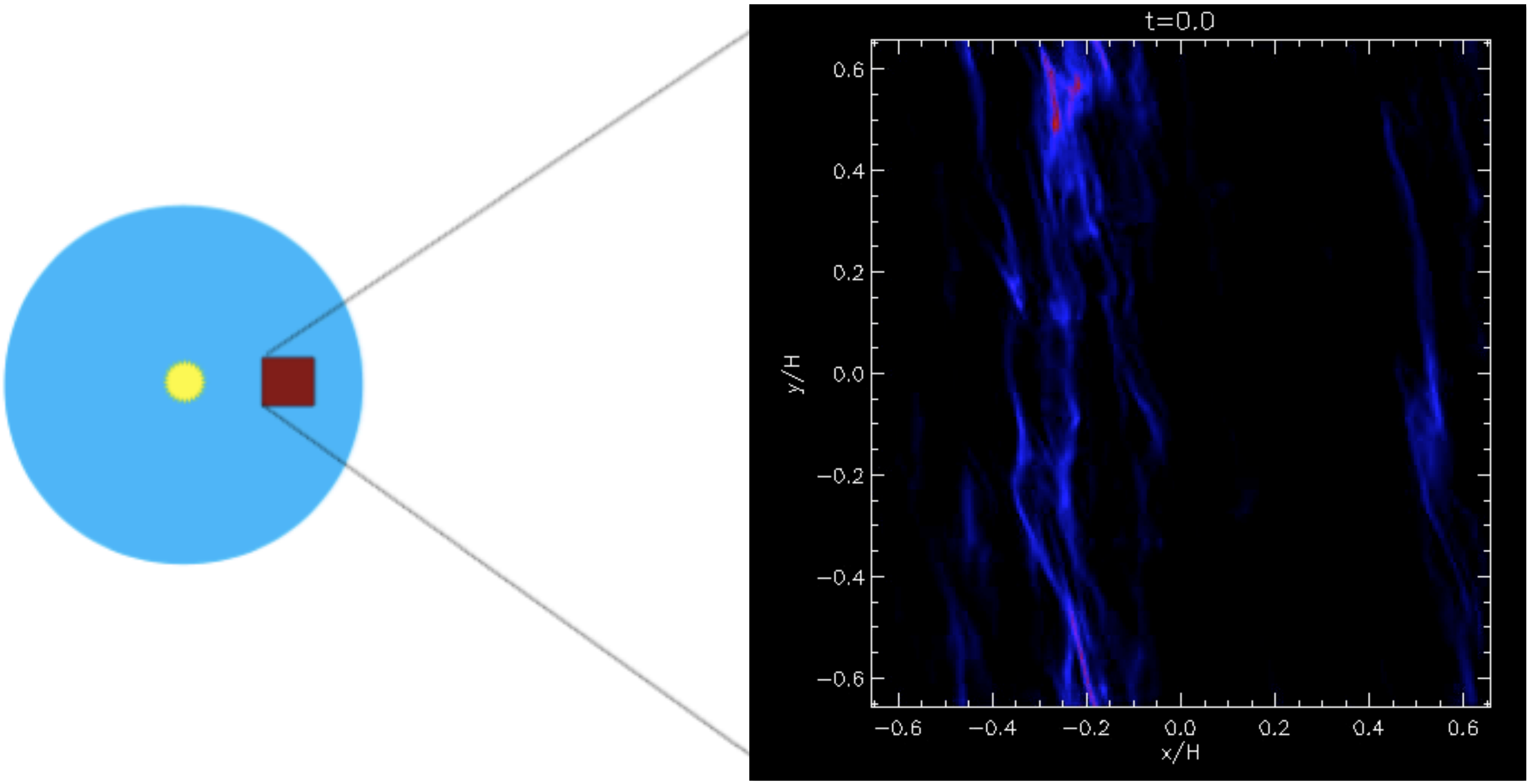
Streaming Instability

The dust drift is hydrodynamically unstable



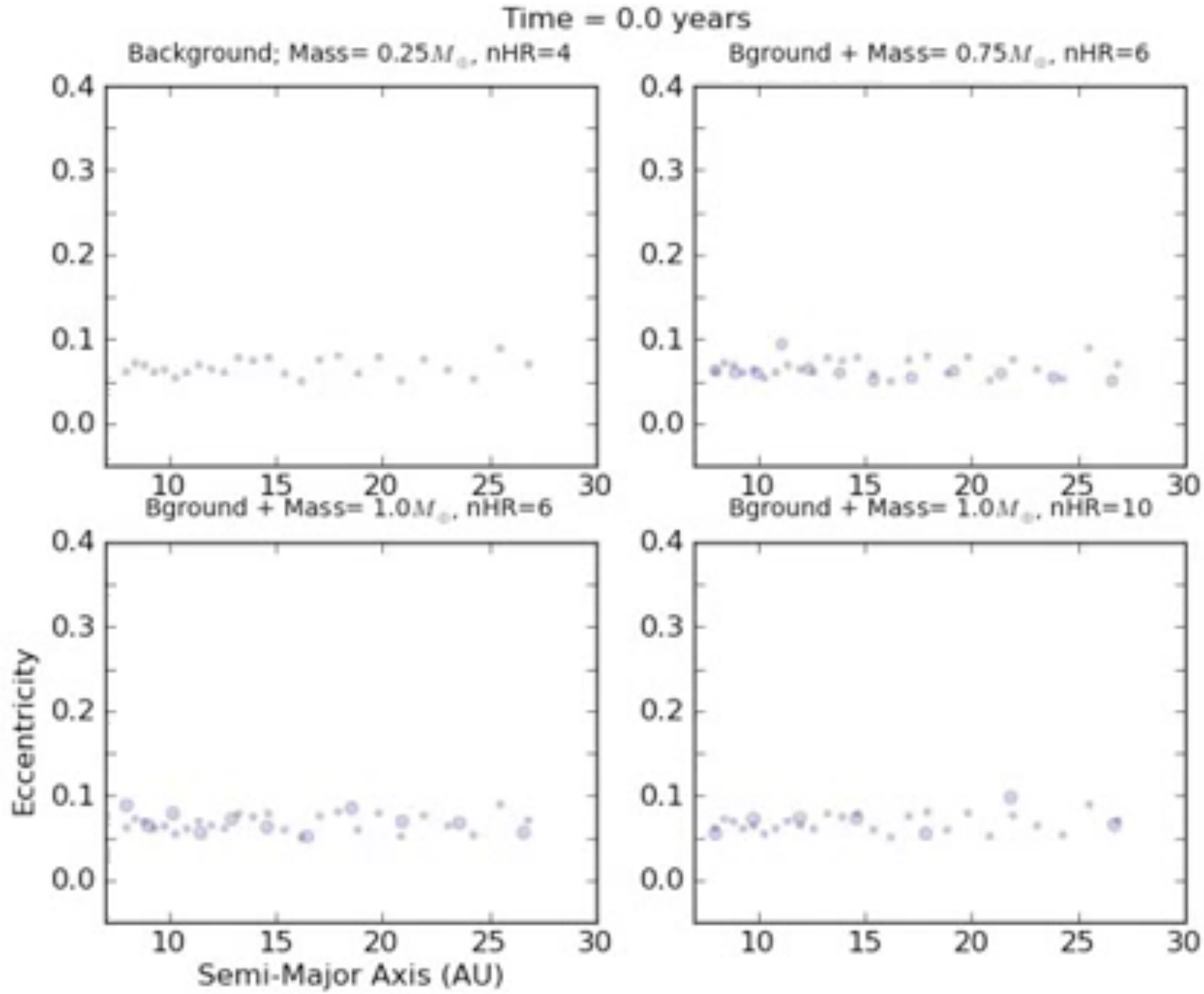
Youdin & Goodman (2005), Johansen & Youdin (2007), Youdin & Johansen (2007)

Gravitational collapse into planetesimals

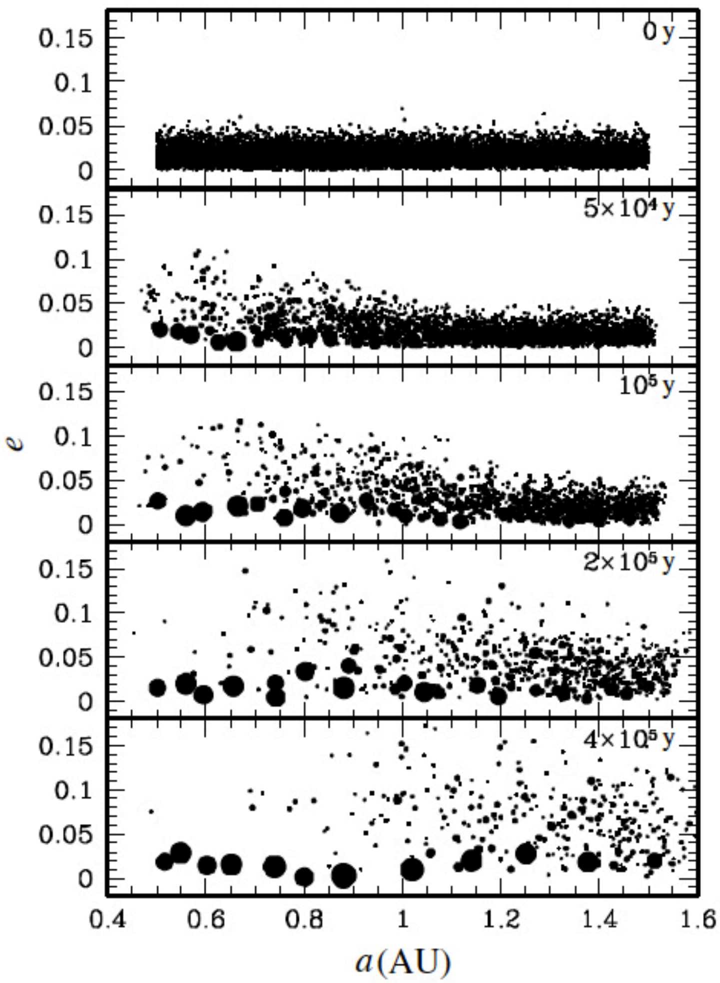


Johansen et al. (2007)

Core Accretion

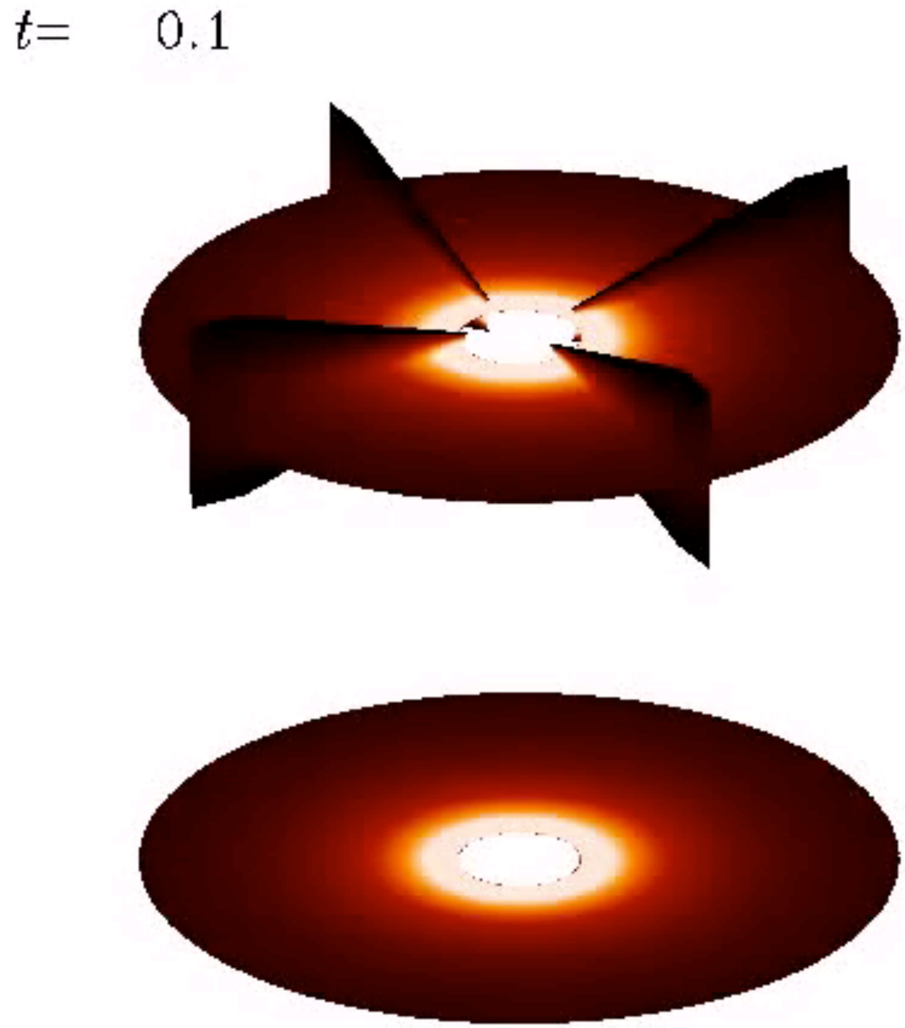


Oligarchs

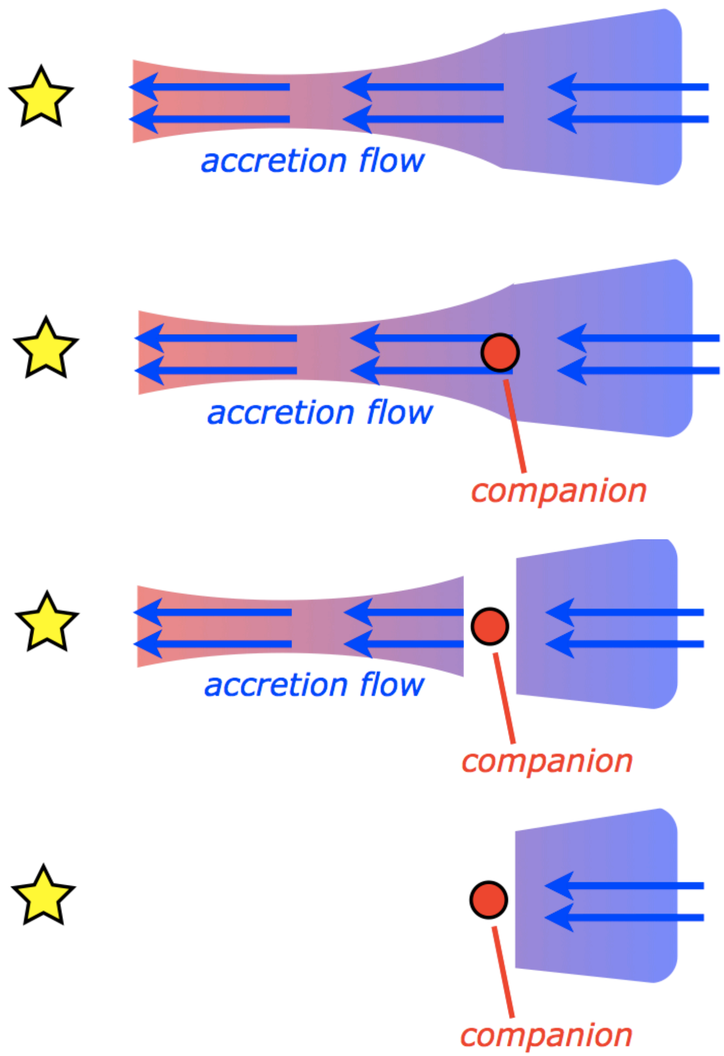


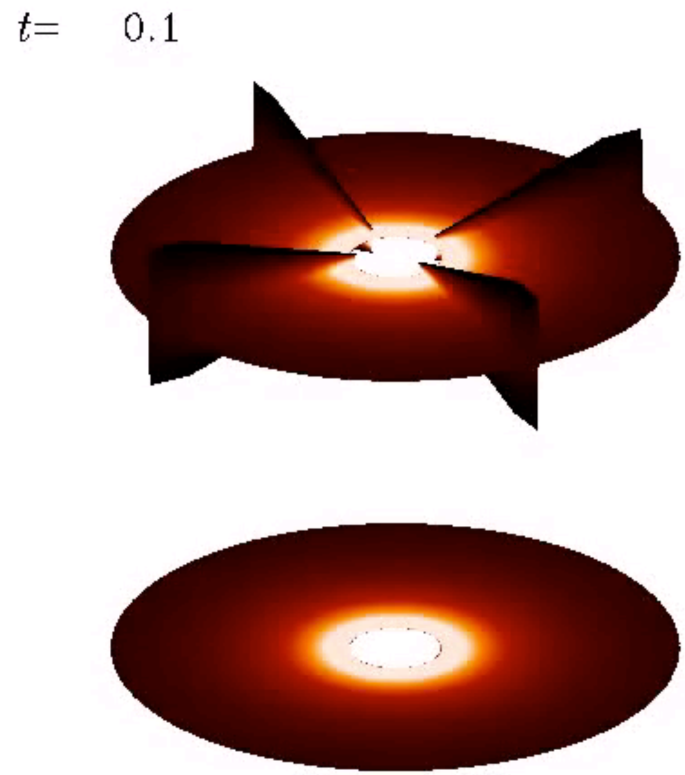
(Kokubo + Ida 2002)

Planets in Disks



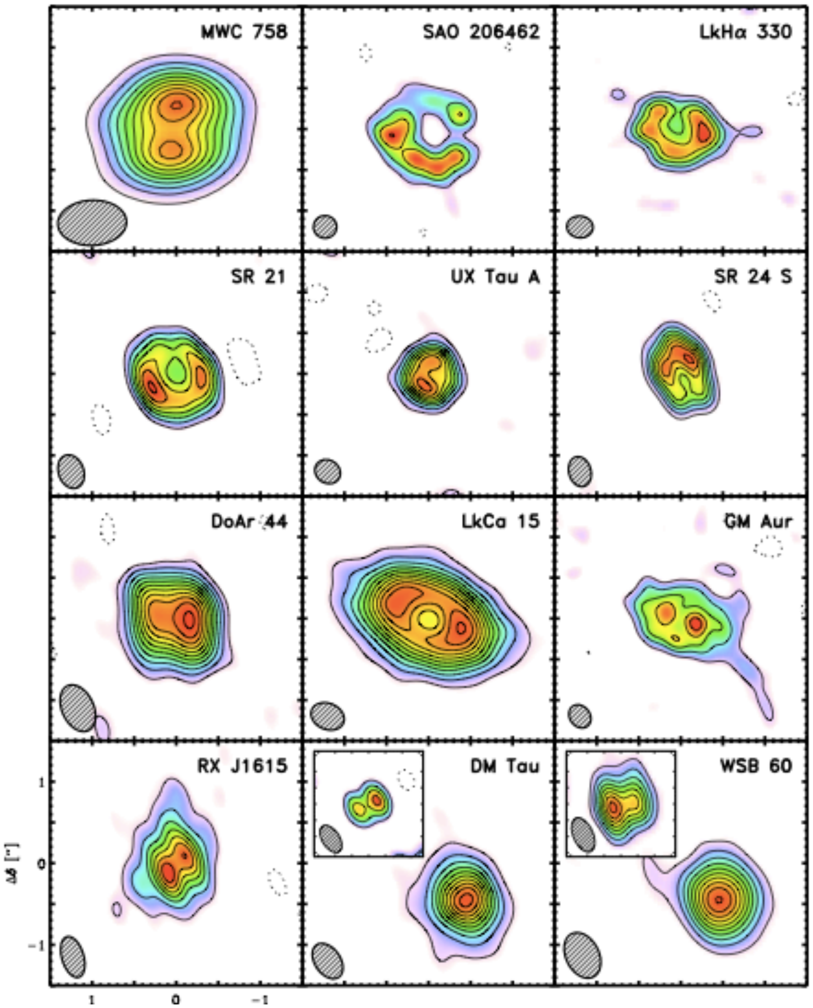
Planetary companion

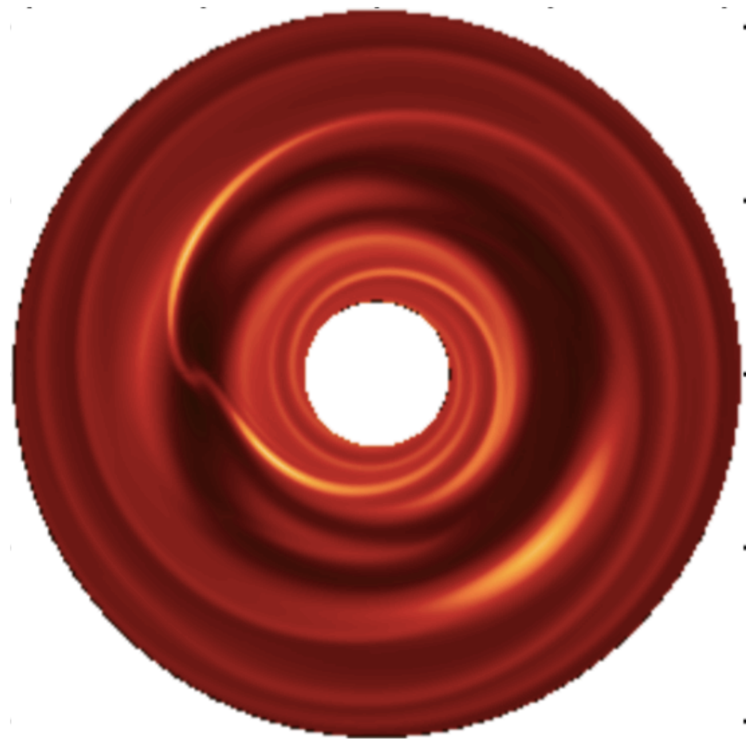




(Lyra 2009)

These cavities may be the telltale signature of forming planets

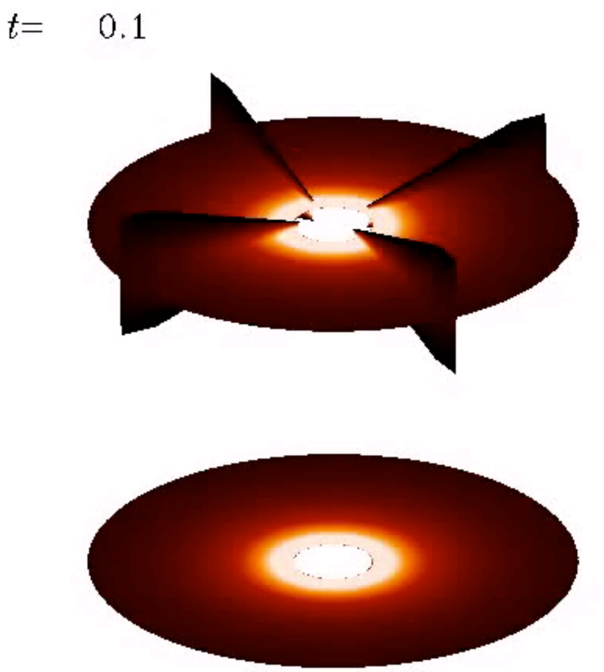




(Lyraet al. 2009)

A way to directly study planet-disk interaction

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

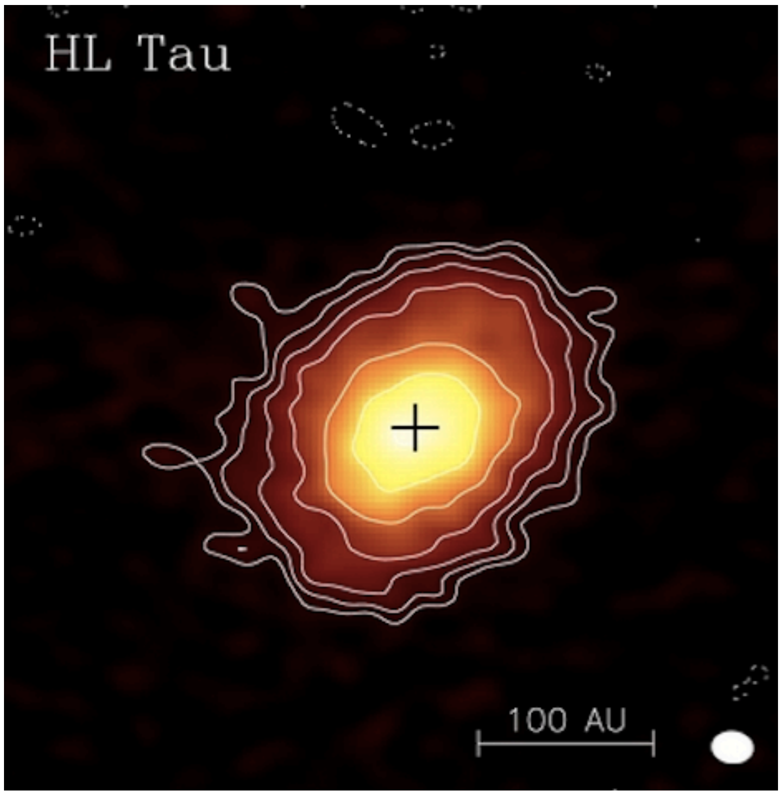


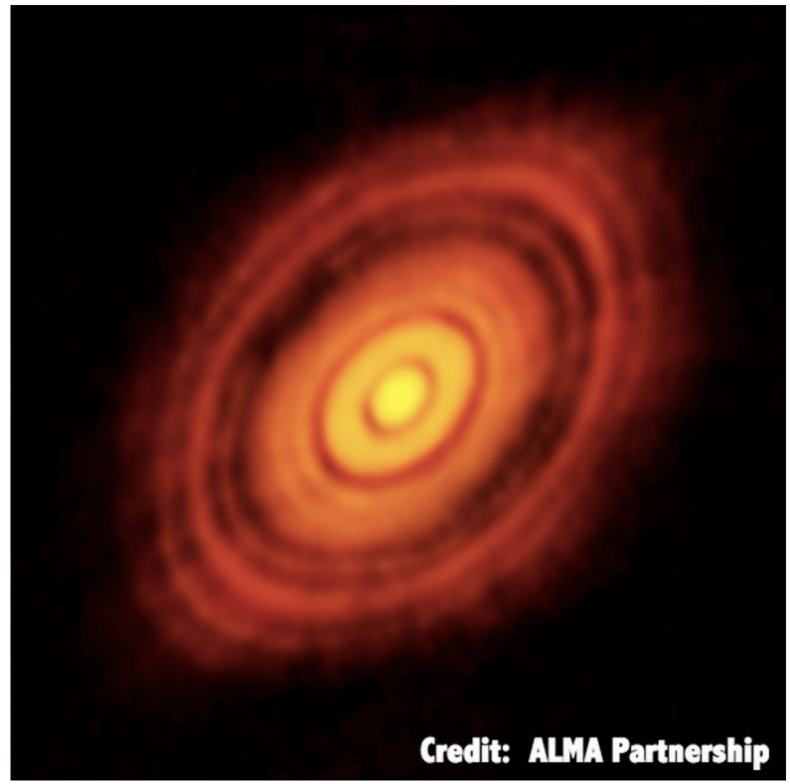
(Lyra et al. 2009b)

The Atacama Large Millimeter Array (ALMA)

Before ALMA

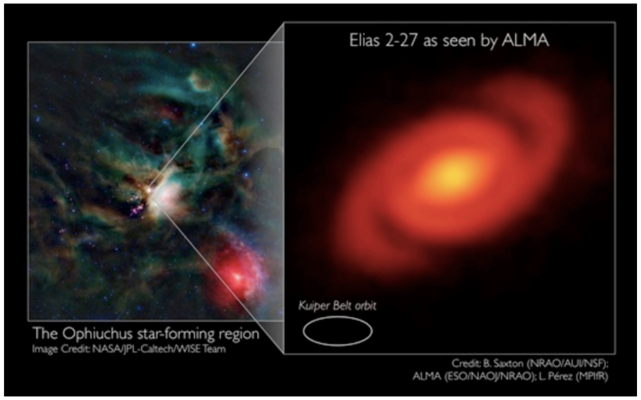
ALMA



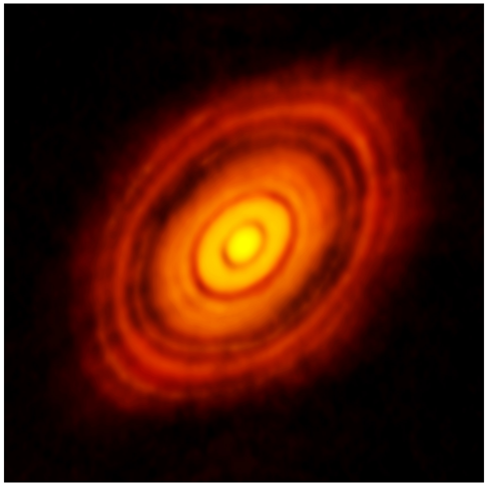


The ALMA view of Protoplanetary Disks

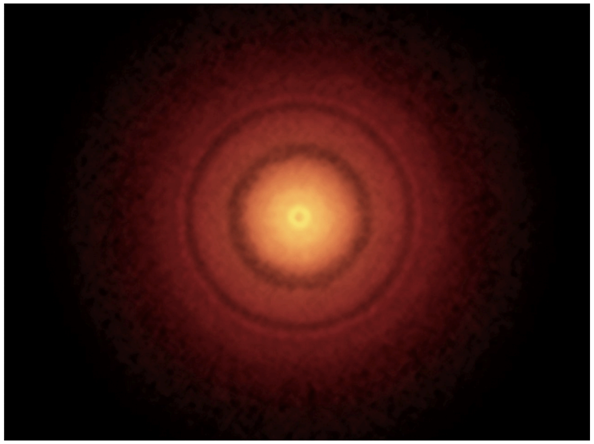
Elias 2-27



HL Tau

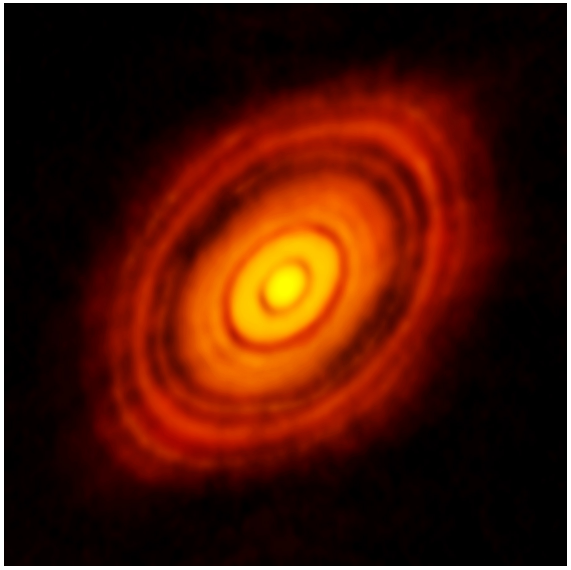


TW Hya

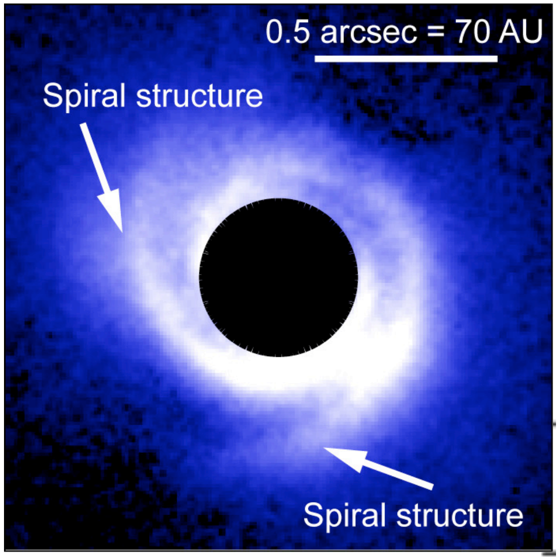


Observational evidence: gaps, spirals, and vortices

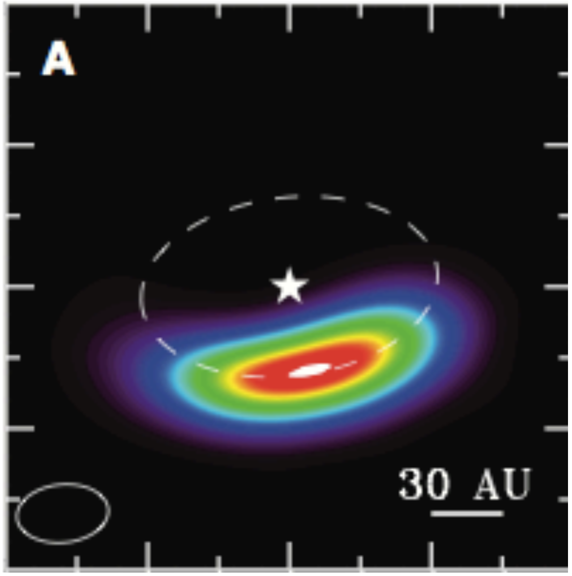
HL Tau



SAO 206462



Oph IRS 48



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]

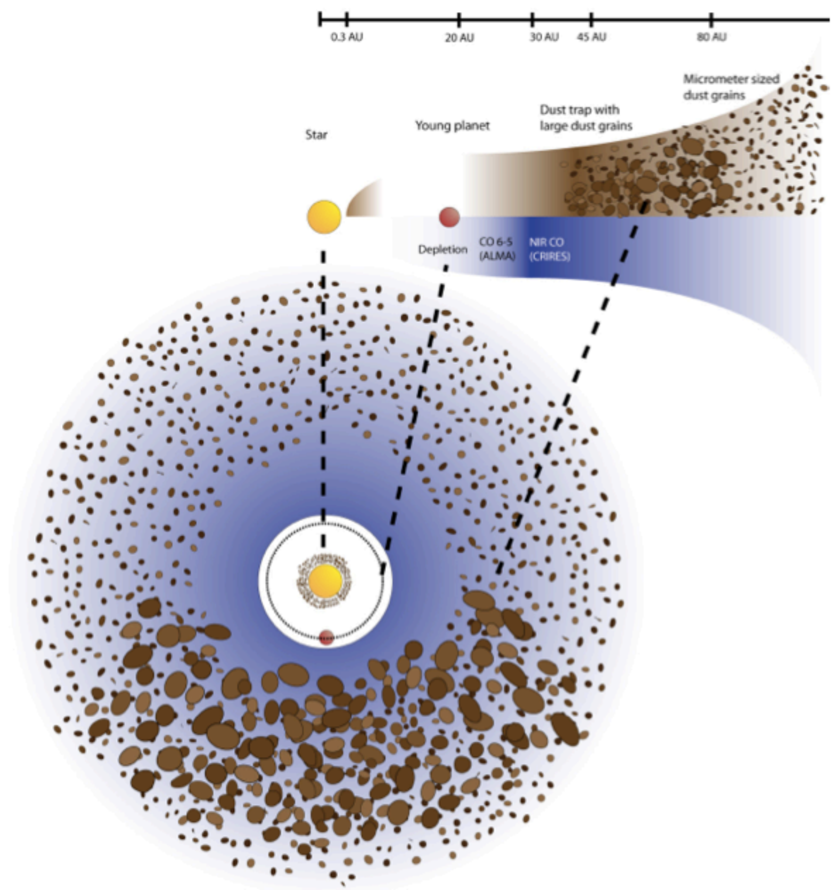
The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection 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

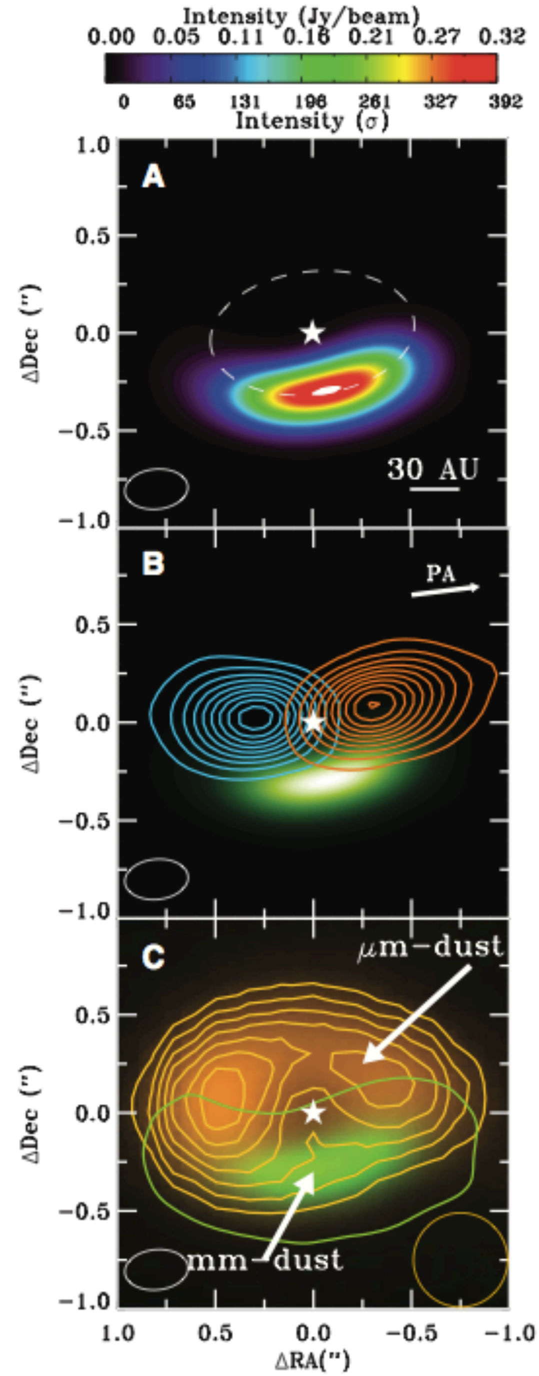
van der Marel et al. 2013

A possible huge vortex observed with ALMA

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

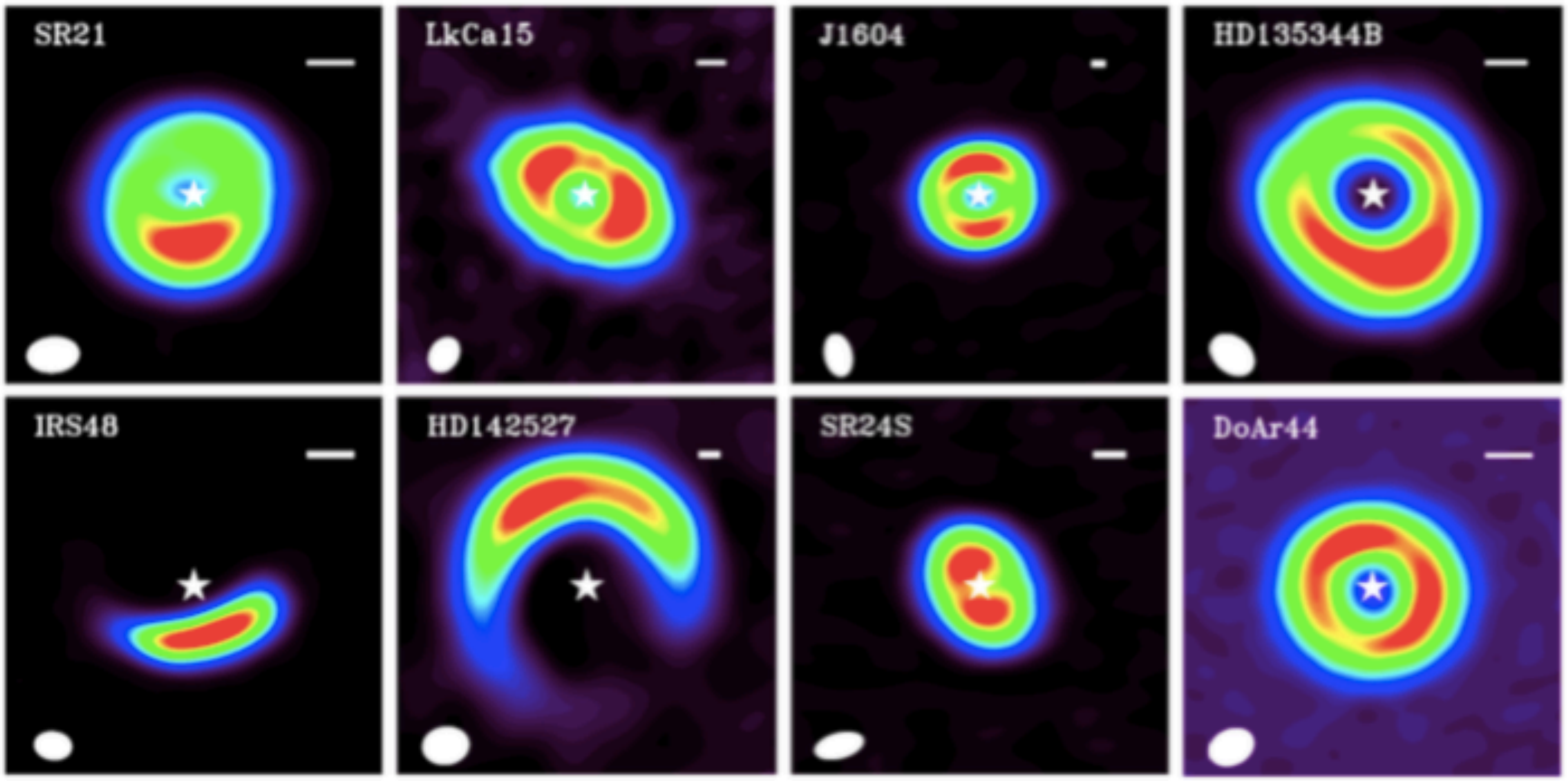


asymmetric
mm dust
at 63 AU

Gas detection:
Keplerian rotation

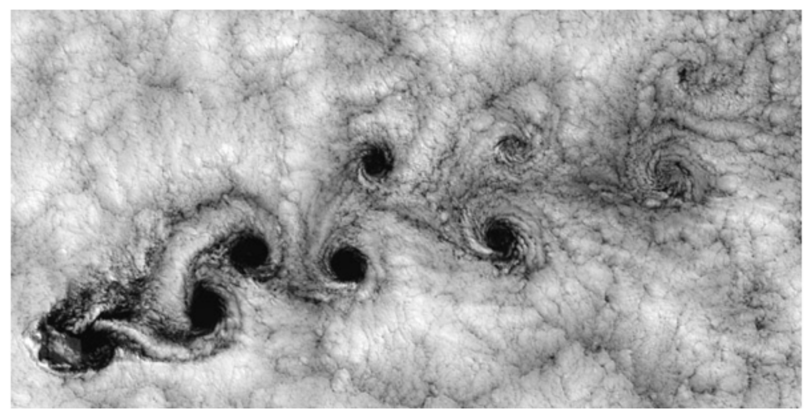
Micron-sized
dust follows gas

Vortices everywhere!

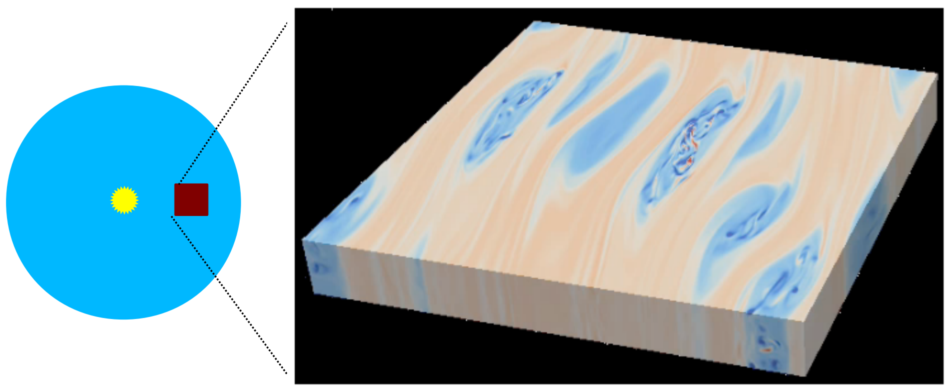


Vortices – an ubiquitous fluid mechanics phenomenon

Von Kármán *vortex street*

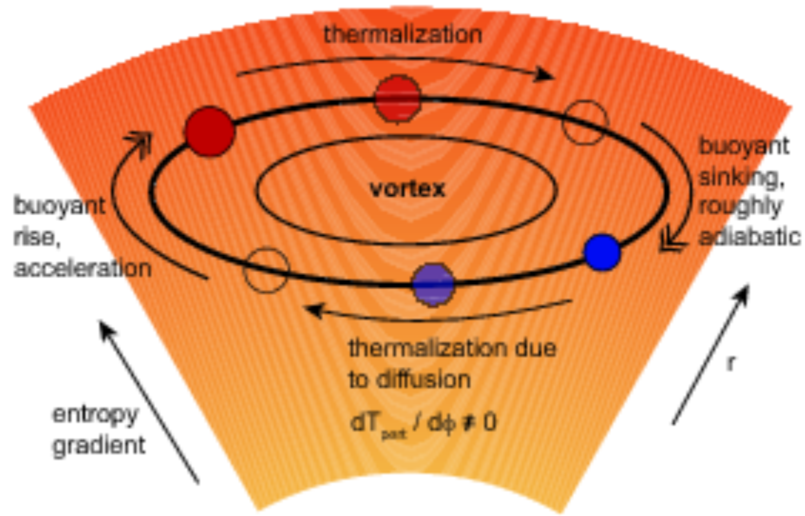


Convection



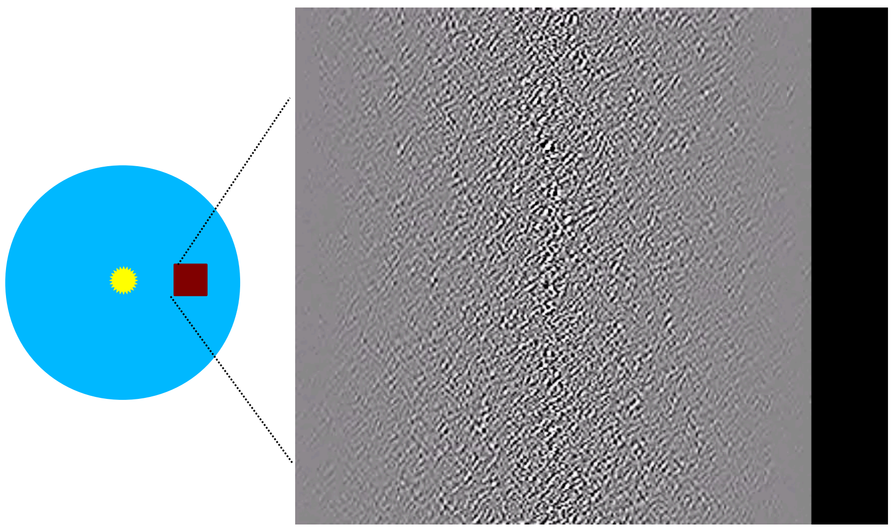
Lesur & Papaloizou (2010)

Sketch of Convection

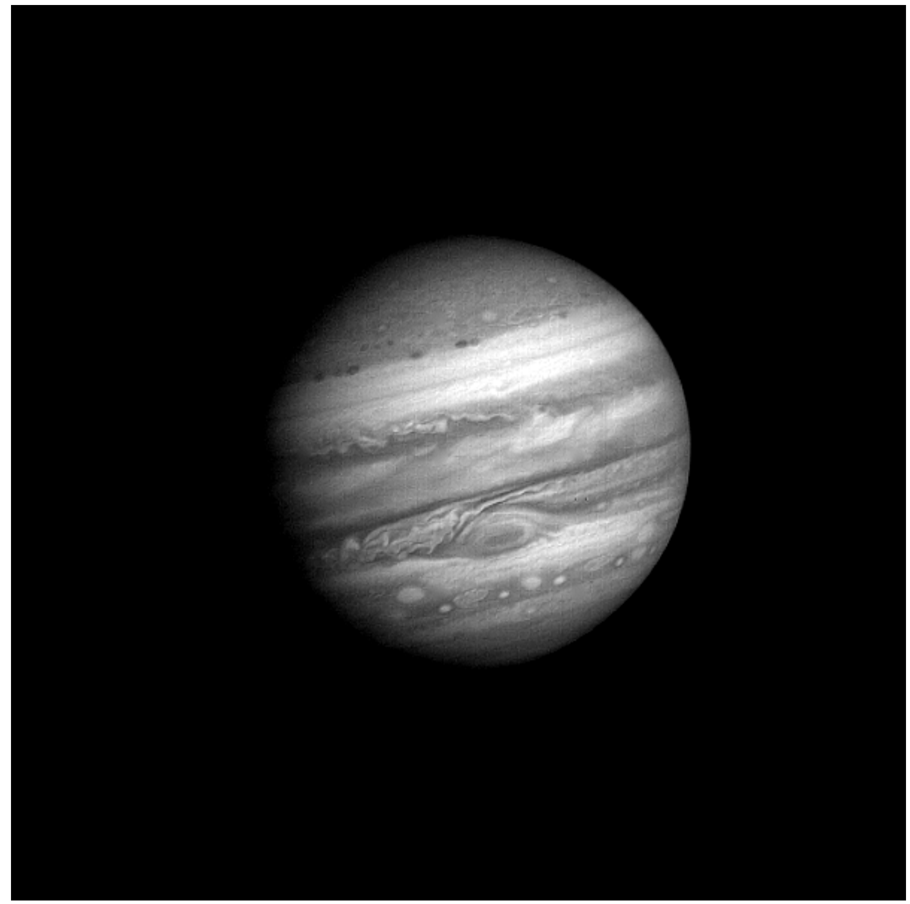


Armitage (2010)

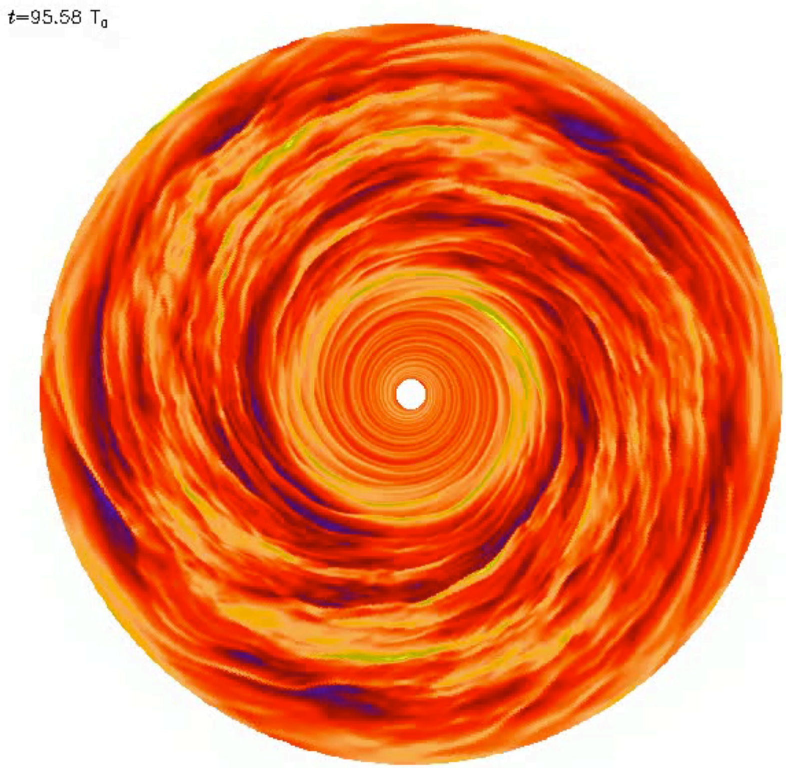
Convective vortices

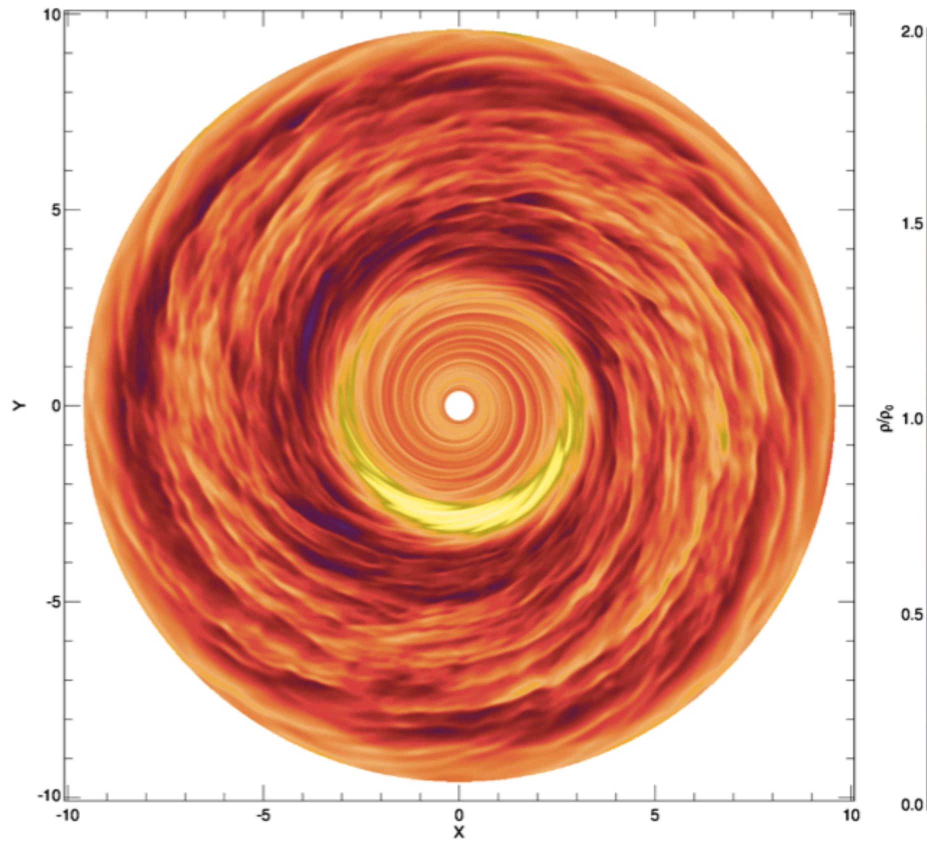


Lyra & Klahr (2011)



Dead/Active zone transition





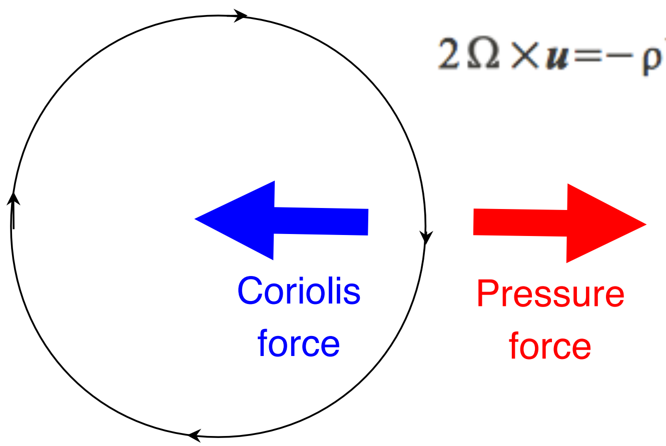
Quiescent inner disk + turbulent outer disk

Lyra, Turner, & McNally (2015)

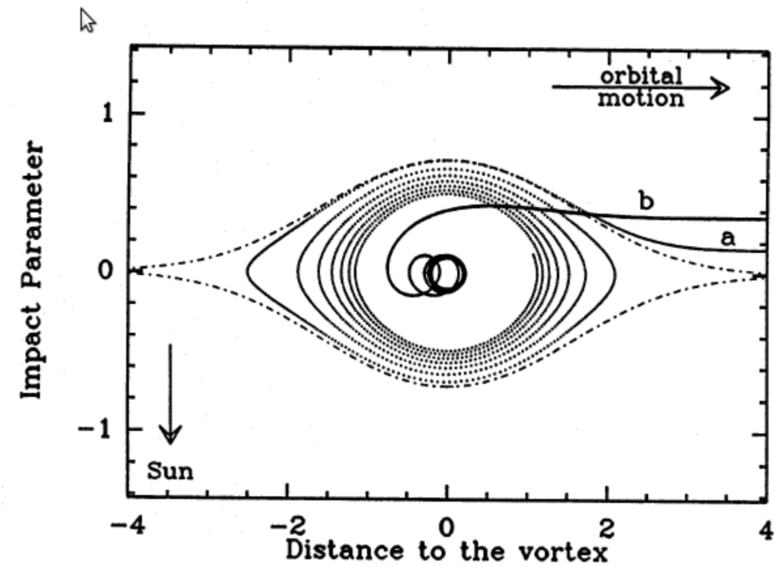
The Tea-Leaf effect

Geostrophic balance:

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



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)

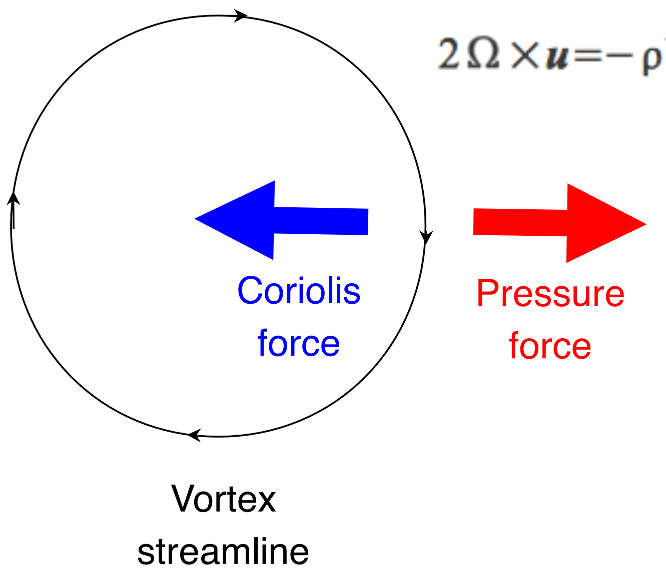
Speed up planet formation enormously

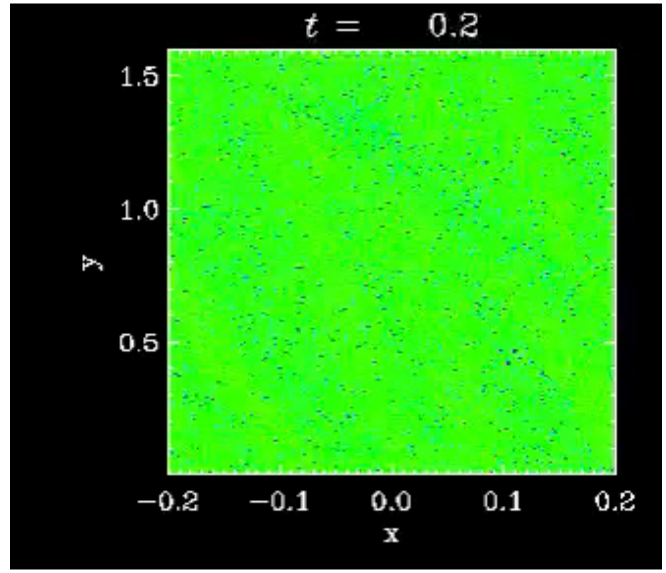
(Lyra et al. 2008b, 2009ab, Raettig et al. 2012)

The Tea-Leaf effect

Geostrophic balance:

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





Raettig, Lyra, & Klahr (2013)

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

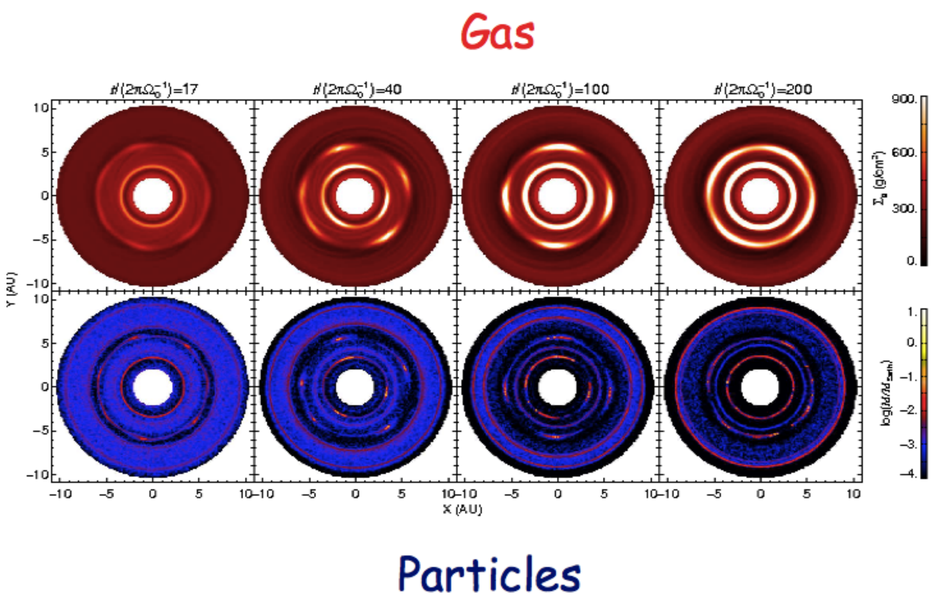
Aid to planet formation

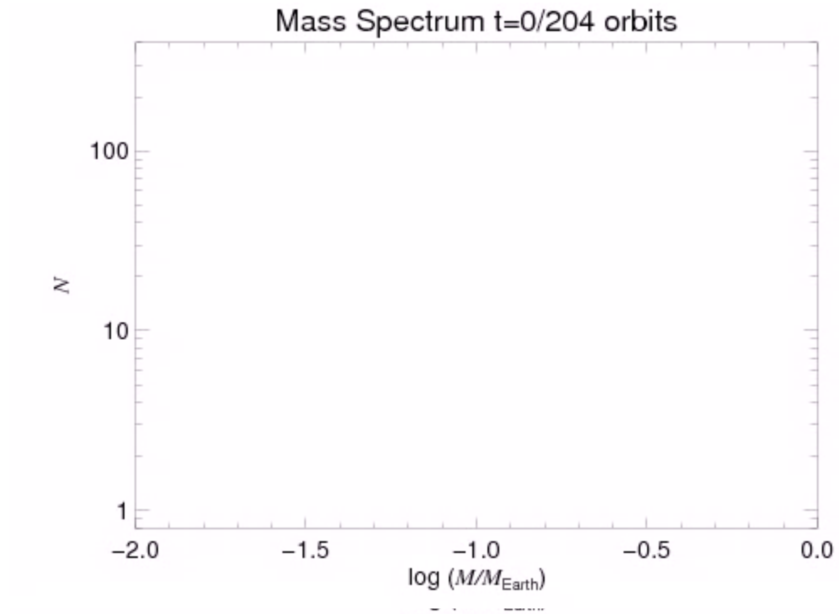
(Barge & Sommeria 1995, Tanga et al. 1996, Barranco & Marcus 2005)

Speed up planet formation enormously

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

Vortices and Planet Formation

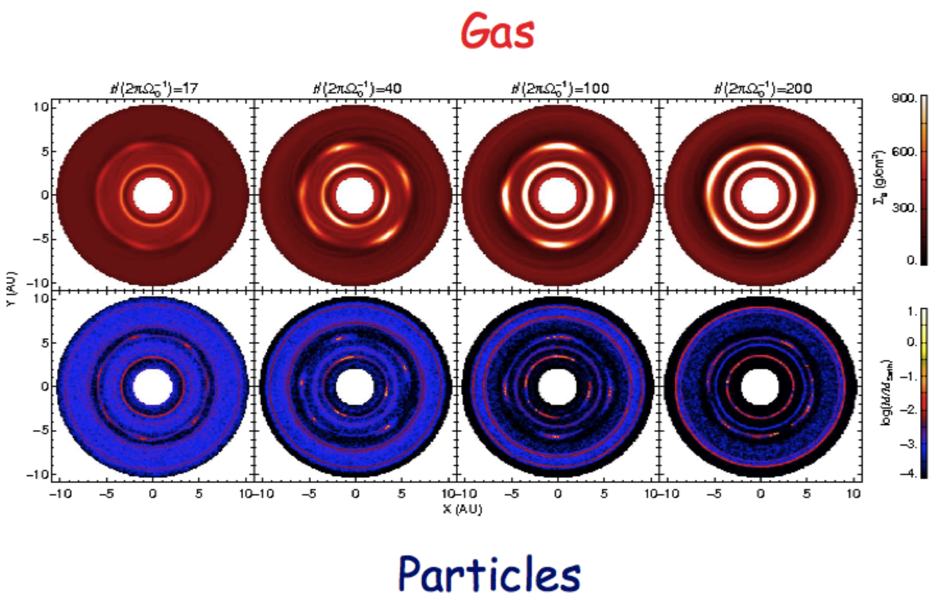


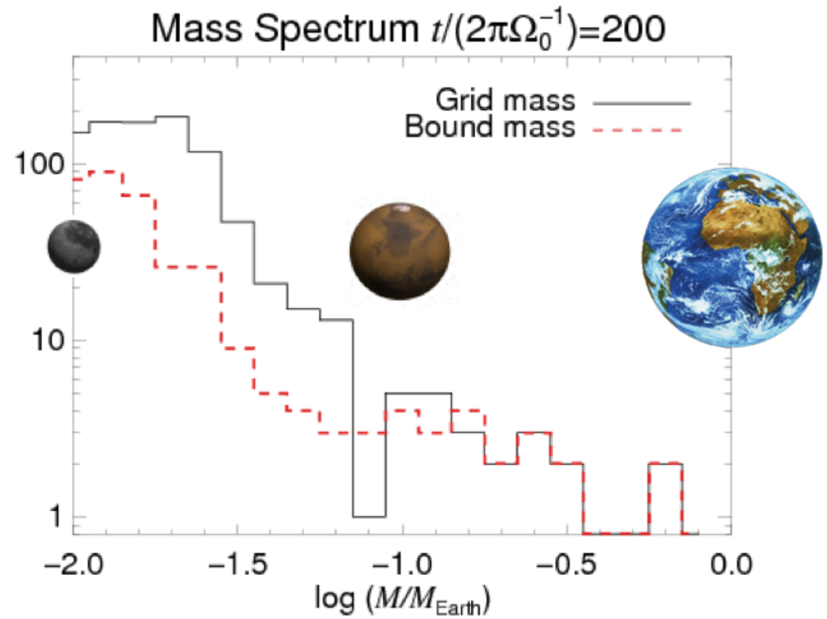


Collapse into Mars mass objects

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

Vortices and Planet Formation



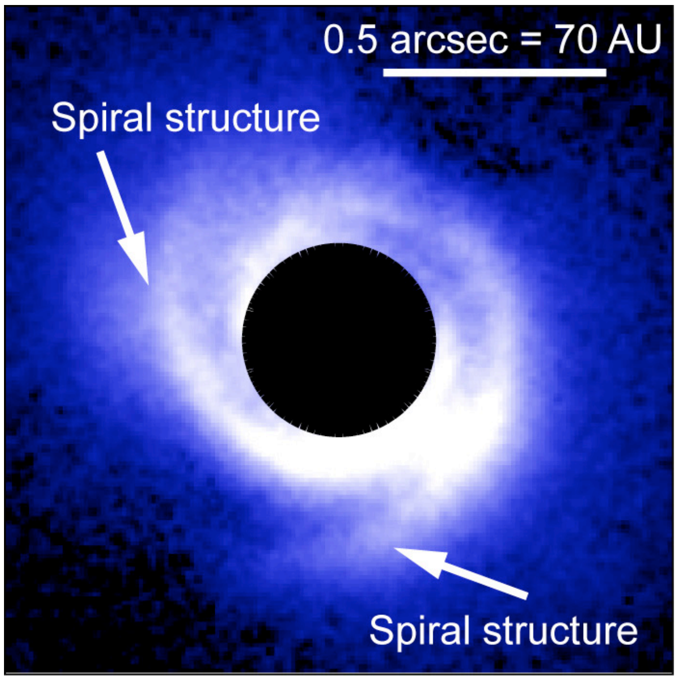


Collapse into Mars mass objects

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

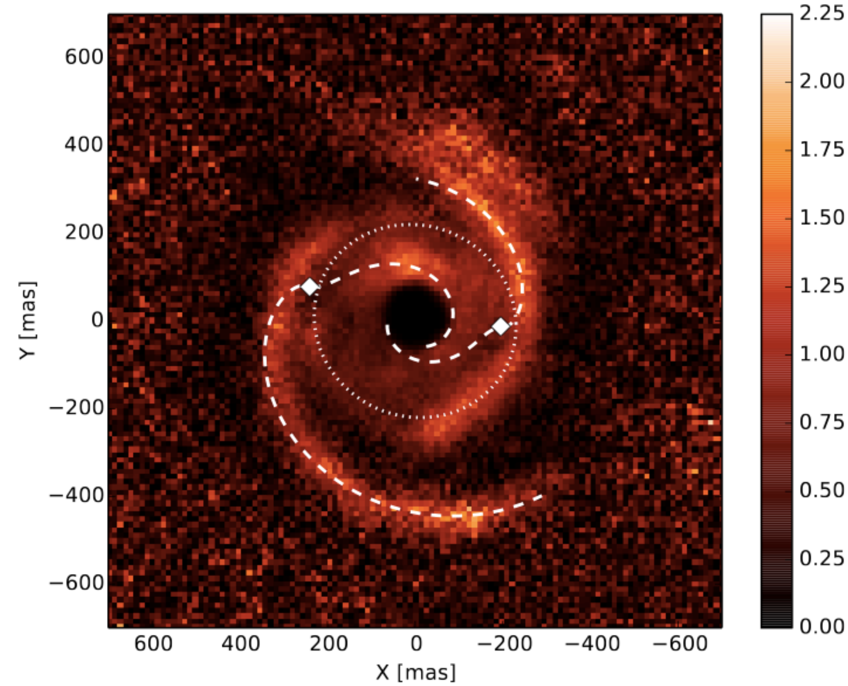
Observational Evidence: Spirals

SAO 206462



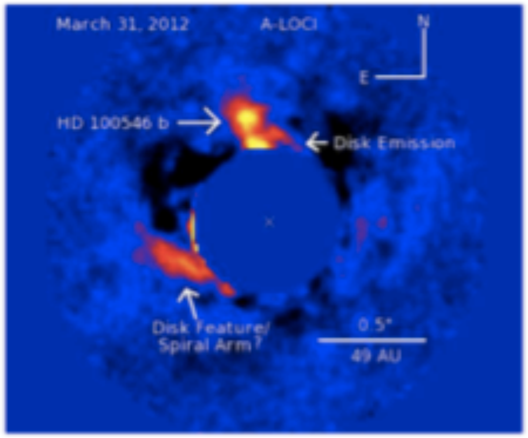
Muto et al. (2012)

MWC 748

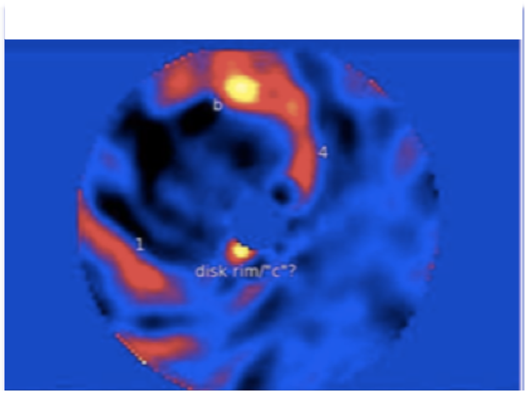


Benisty et al. (2015)

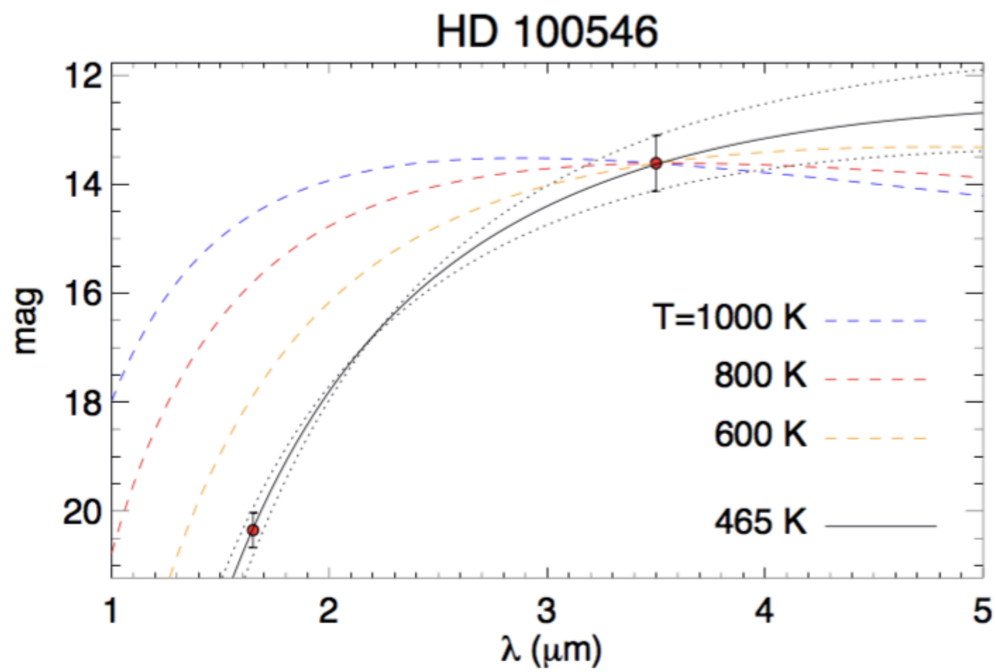
The strange case of HD 100546



L band

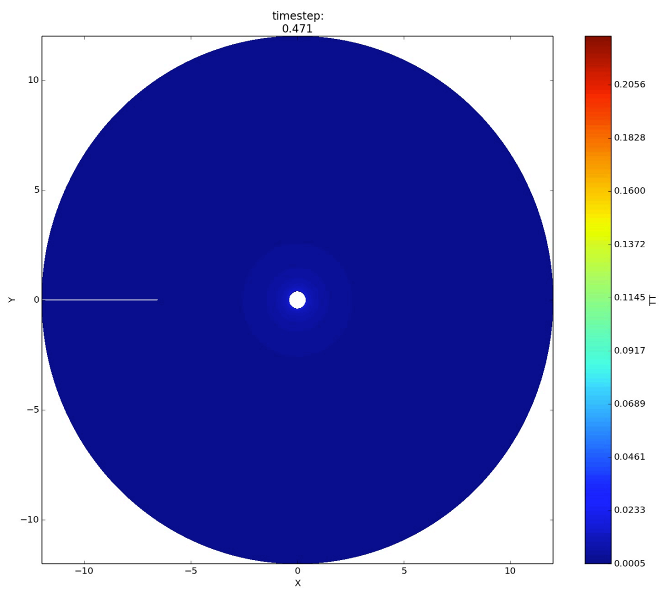


H band

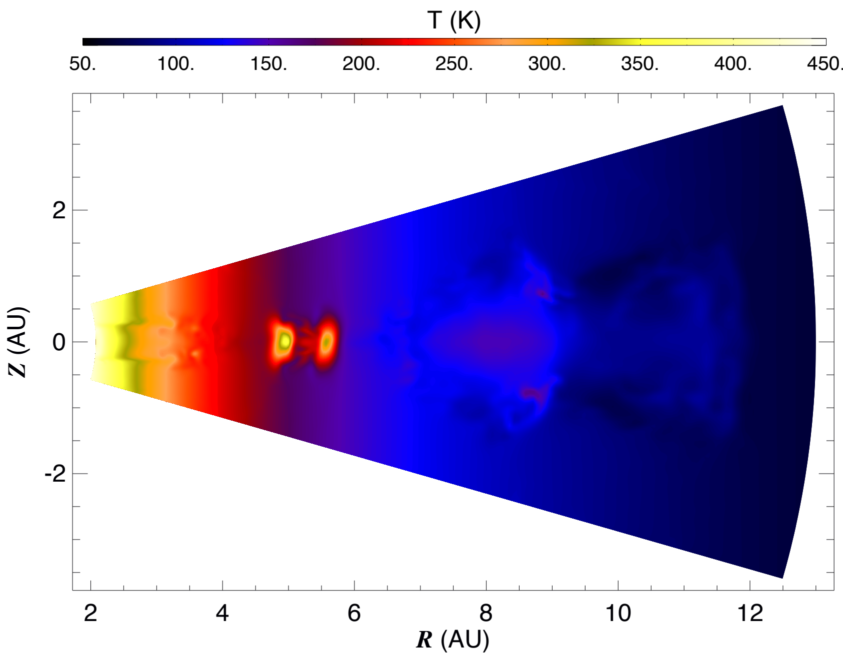


Lyra et al. (2016)

Shocks by high mass planets

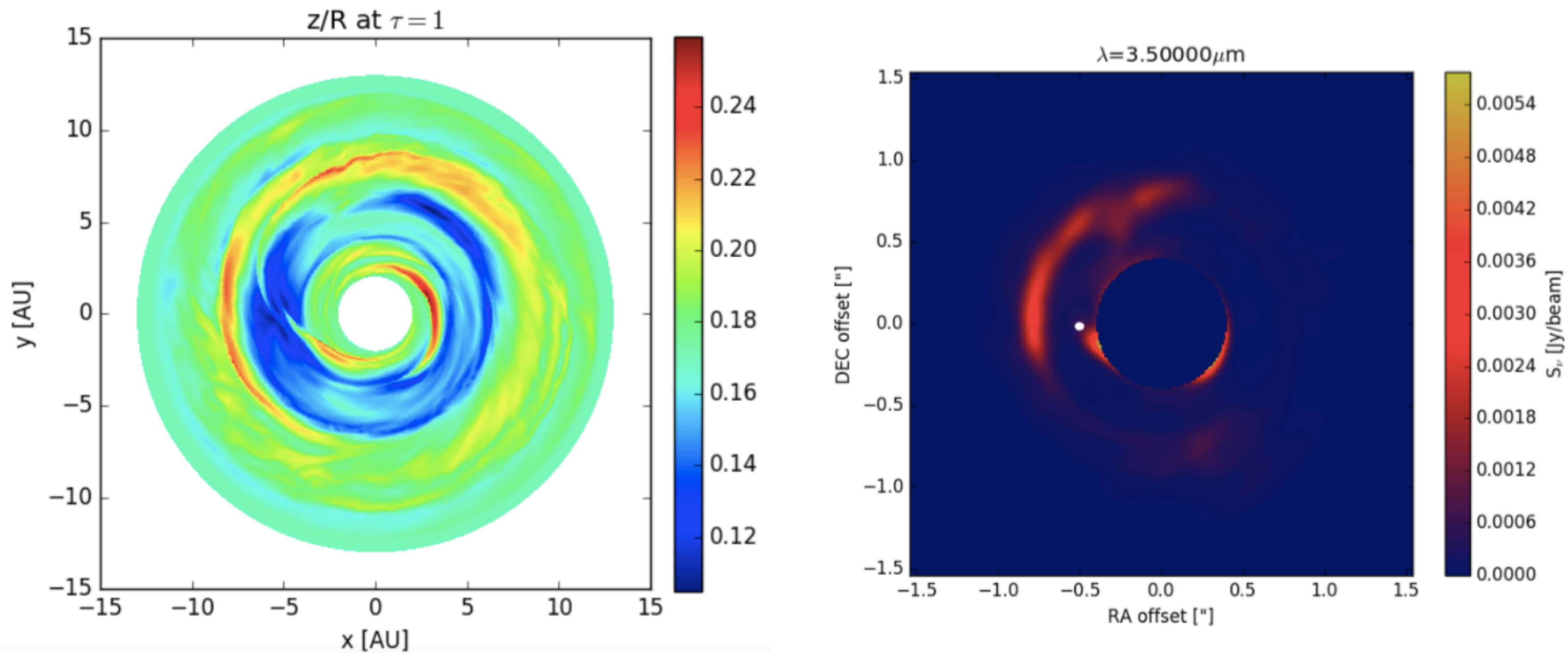


Richert et al. (2015)



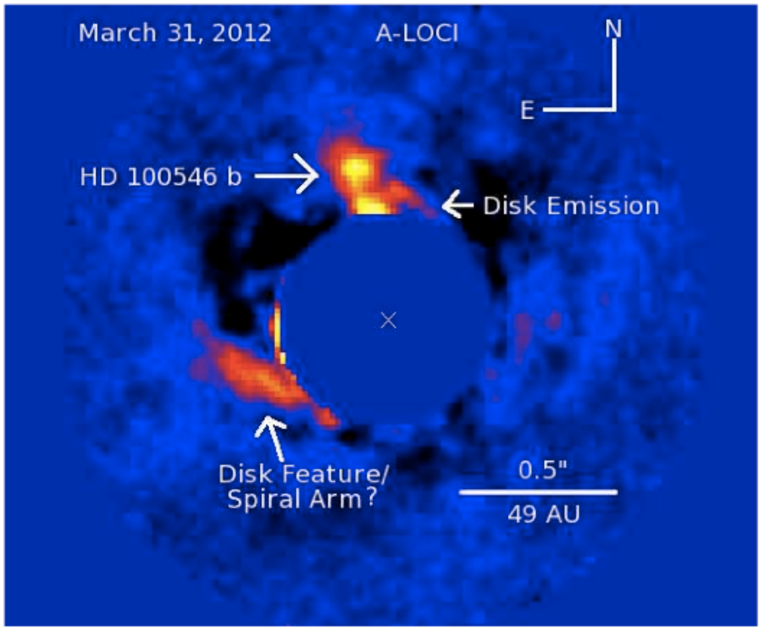
Lyra et al. (2016)

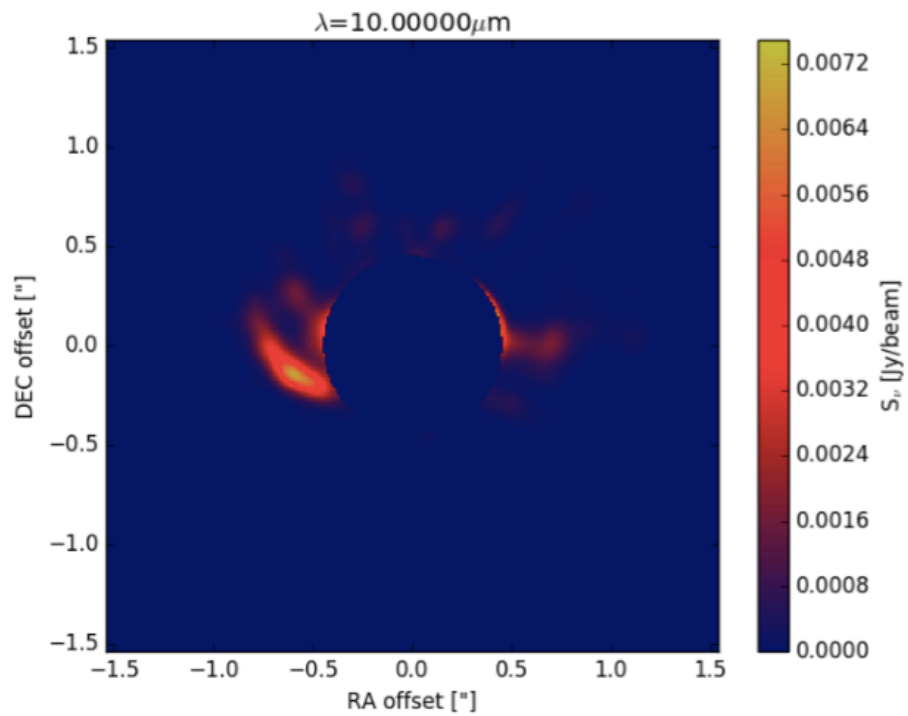
Synthetic Image



Hord et al. (2017)

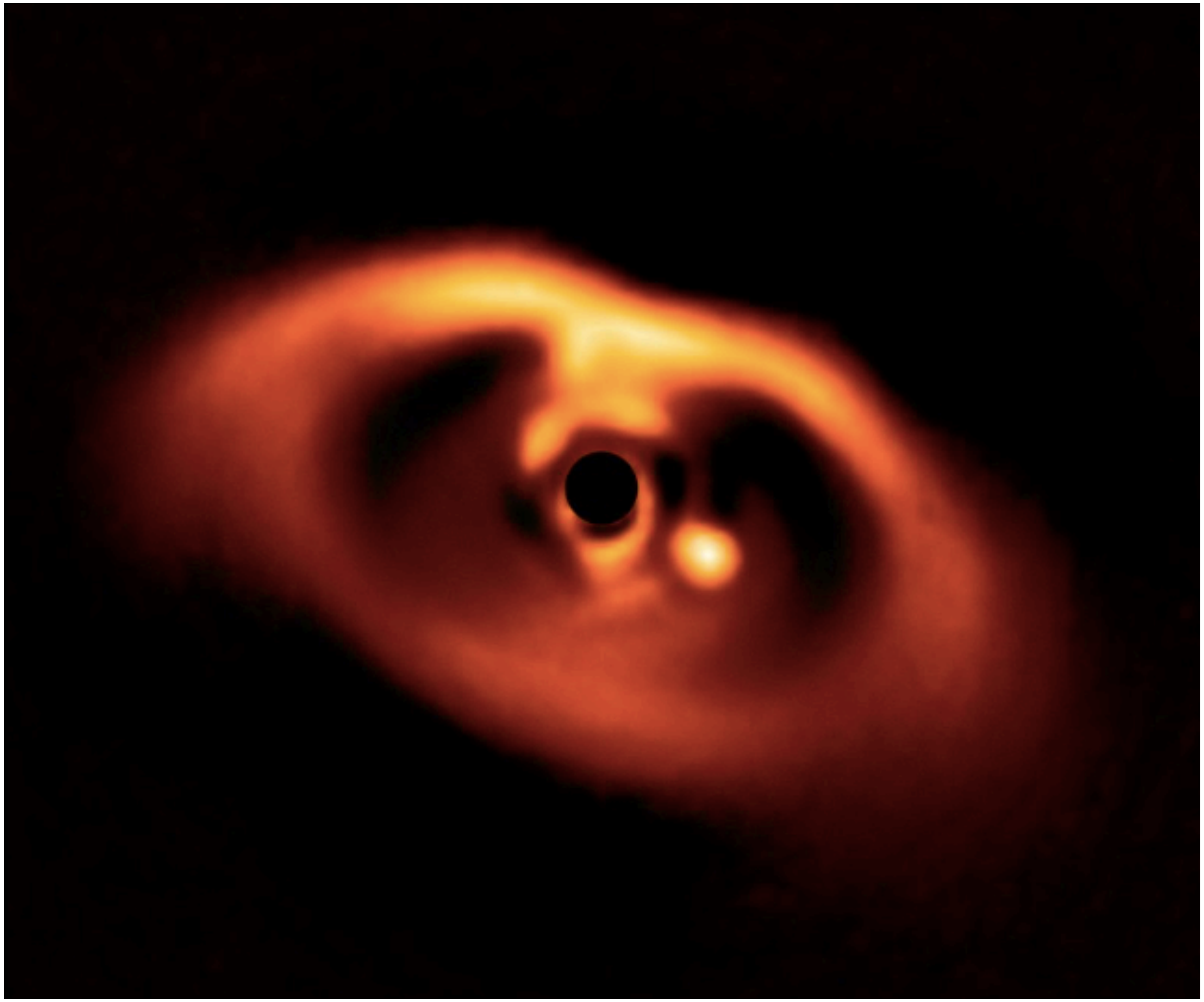
Observation vs Synthetic Image



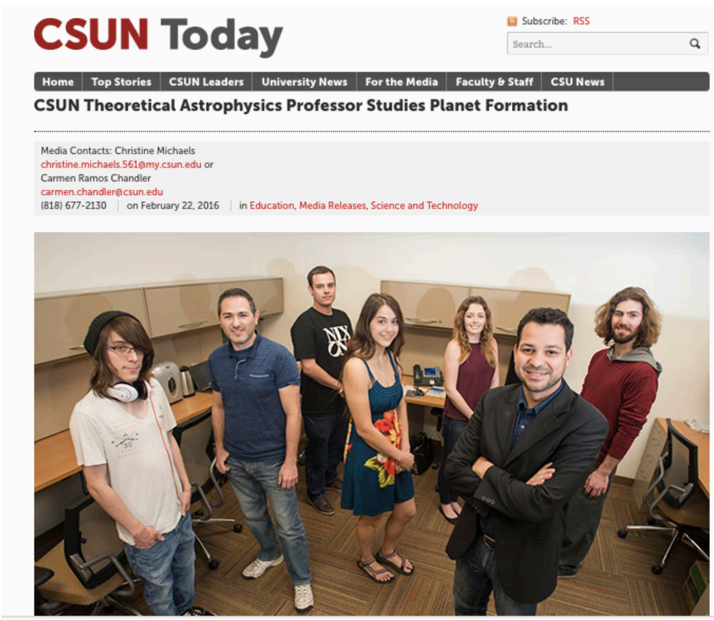


Hord et al. (2017)

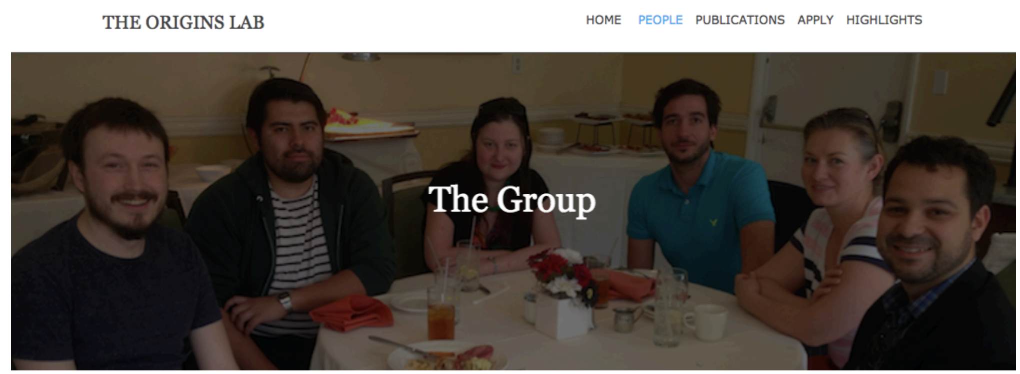
PDS70



Mentoring



Research Group in 2016



The group in 2017

Grants!

NASA Exoplanets Research (2018) ~$200K

ngVLA (2017) ~$81K

NASA Exoplanets Research (2016) ~$250K

Hubble Cycle 24 (2016) ~$134K

Average of 10 grant proposals submitted per year

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.

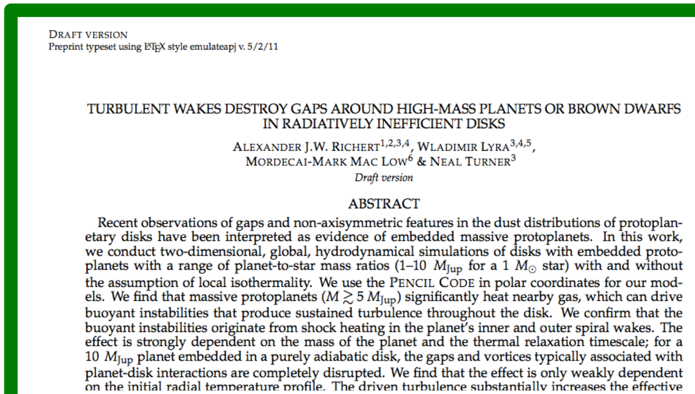
Luca Ricci

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.

Co-Mentoring - PhD



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Preprint typeset using LaTeX style emulateapj v. 5/2/11

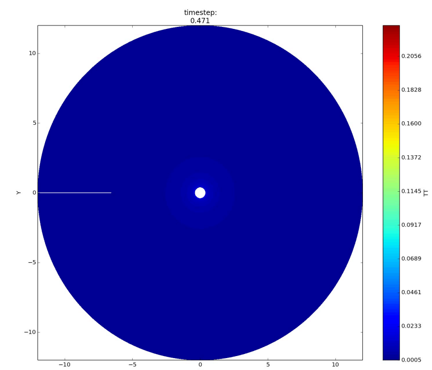
TURBULENT WAKES DESTROY GAPS AROUND HIGH-MASS PLANETS OR BROWN DWARFS IN RADIATIVELY INEFFICIENT DISKS

Alexander J.W. Richert[1,2,3,4], Wladimir Lyra[3,4,5], Mordecai-Mark Mac Low[6] & Neal Turner[3]

Draft version

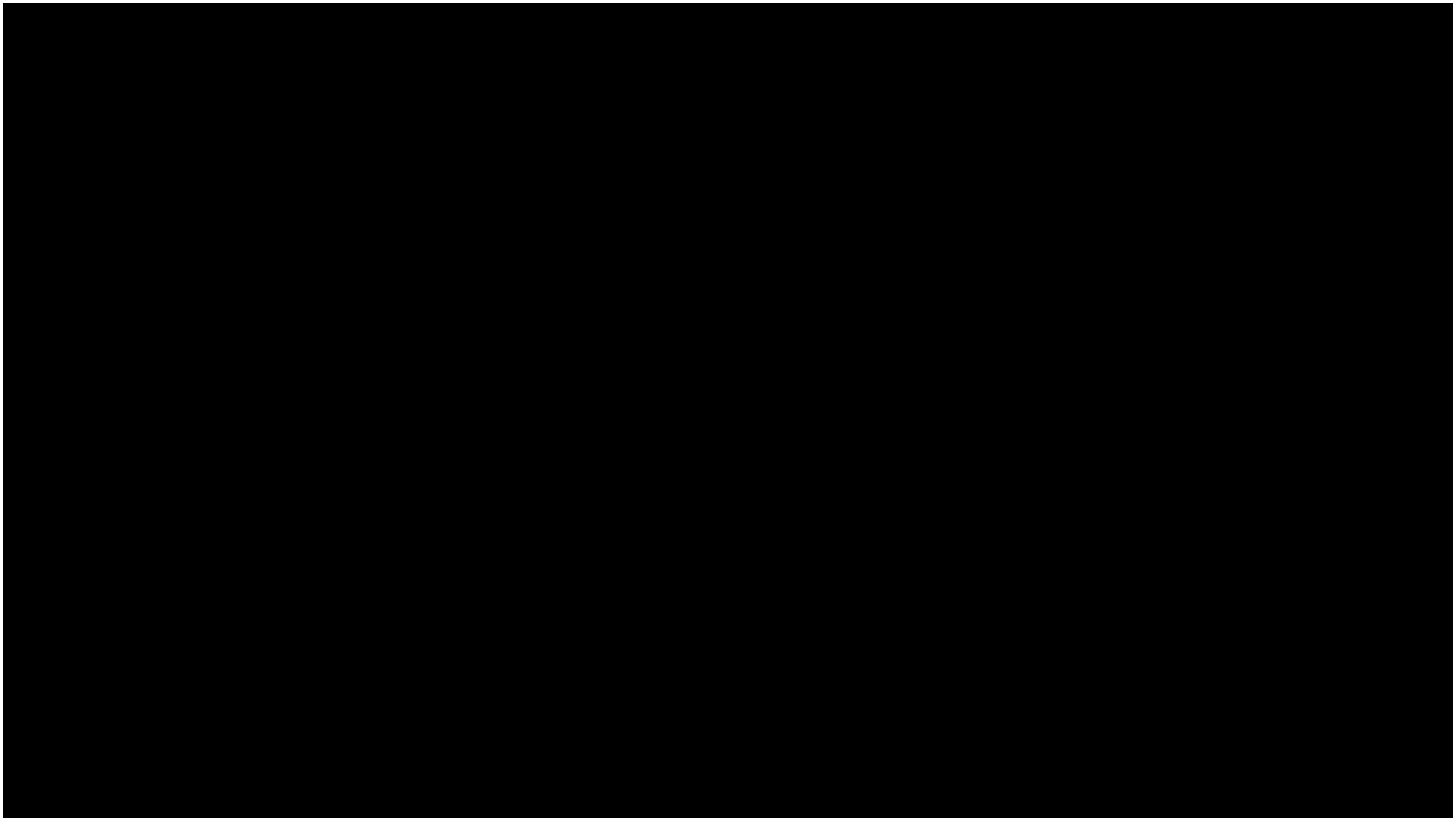
ABSTRACT

Recent observations of gaps and non-axisymmetric features in the dust distributions of protoplanetary disks have been interpreted as evidence of embedded massive protoplanets. In this work, we conduct two-dimensional, global, hydrodynamical simulations of disks with embedded protoplanets with a range of planet-to-star mass ratios (1–10 $M_{\rm Jup}$ for a 1 $M_\odot$ star) with and without the assumption of local isothermality. We use the Pencil Code in polar coordinates for our models. We find that massive protoplanets ($M \gtrsim 5\,M_{\rm Jup}$) significantly heat nearby gas, which can drive buoyant instabilities that produce sustained turbulence throughout the disk. We confirm that the buoyant instabilities originate from shock heating in the planet's inner and outer spiral wakes. The effect is strongly dependent on the mass of the planet and the thermal relaxation timescale; for a 10 $M_{\rm Jup}$ planet embedded in a purely adiabatic disk, the gaps and vortices typically associated with planet-disk interactions are completely disrupted. We find that the effect is only weakly dependent on the initial radial temperature profile. The driven turbulence substantially increases the effective



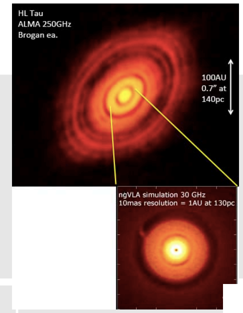
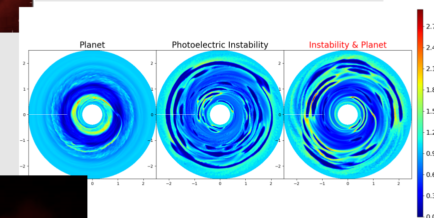
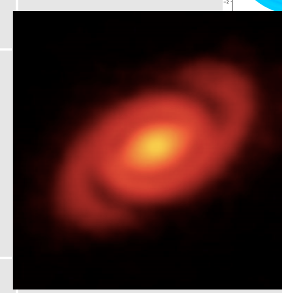
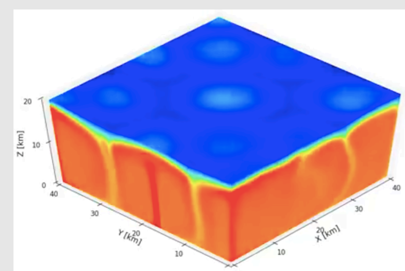
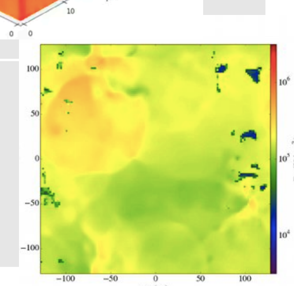
Alex Richert
Penn State 2015, 2018

Photoelectric Instability with radiation pressure

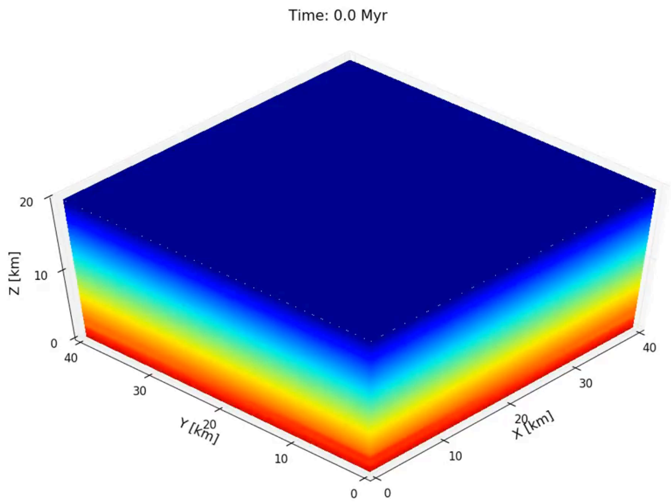


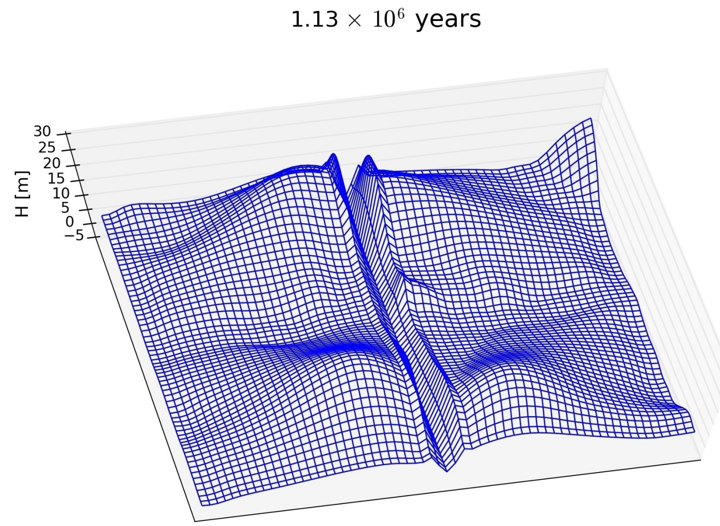
Richert, Lyra, & Kuchner (2018)

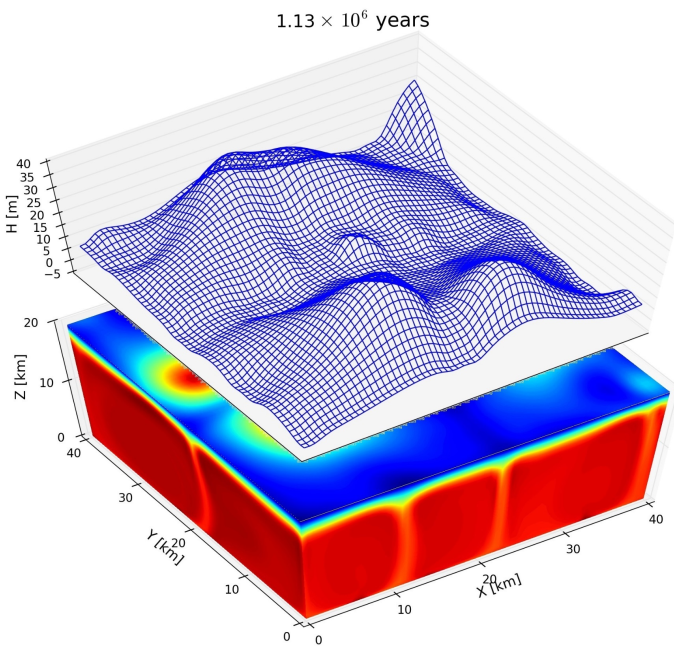
Mentoring – M.Sc.

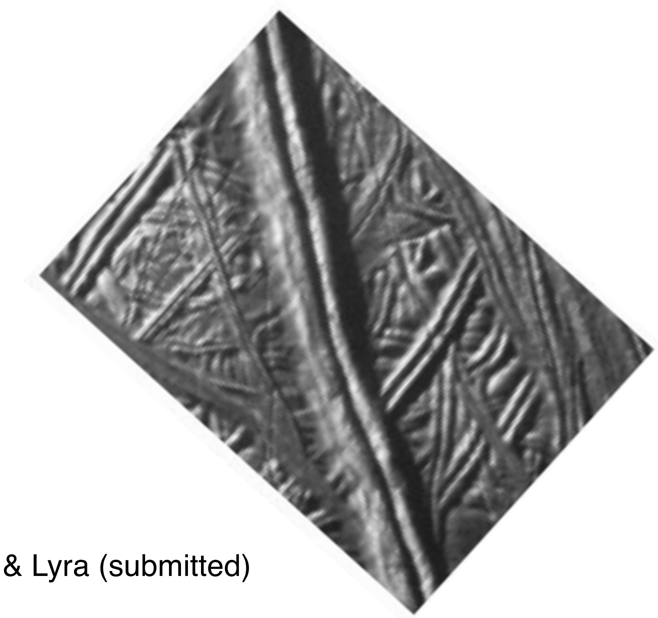
Joshua Garret	Observations with ngVLA	
Areli Castrejon	Debris disk models	
Vincent Carpenter	Massive disks	
Leonardo Sattler Cassara	Ice convection in Jupiter’s moon Europa	
Alexandra Yep	Star Formation	

Ice Convection



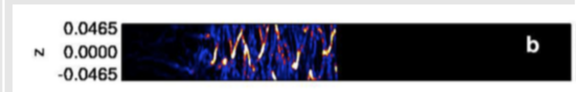
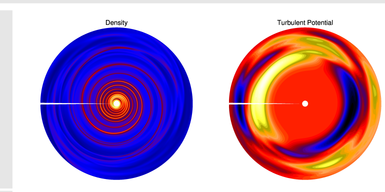
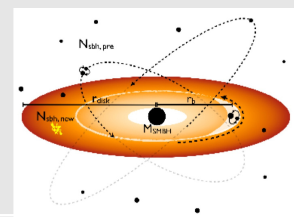
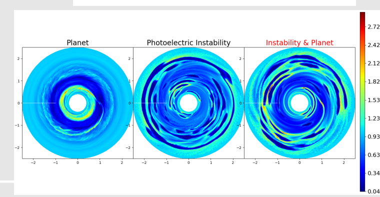
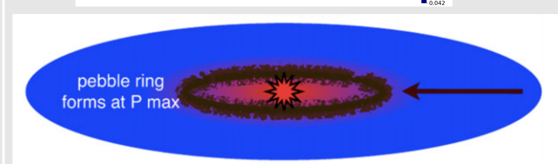






Sattler-Cassara & Lyra (submitted)

Mentoring– Undergraduates

Chris Malek	Streaming Instability	
Gabriel Bretado	Dead zone turbulence	
Joshua Shevchuk	AGN disks	
Areli Castrejon	Debris Disks	
Sean Snyder	Streaming Instability	
Blake Hord	Transition Disks