Investigating the early formation and evolution of planetary systems: the ALMA revolution

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Collaborators:

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JPL Astro Lunch, February 5 2018

Talk Outline

- Growth of solids to mm-sized grains
  in disks around young stars & brown dwarfs

- Disk substructures from the first 6 years of ALMA

- Future prospects from ALMA Large Program and ngVLA

Credit: NASA/ESA, Ricci, Robberto, HST Treasury program in ONC

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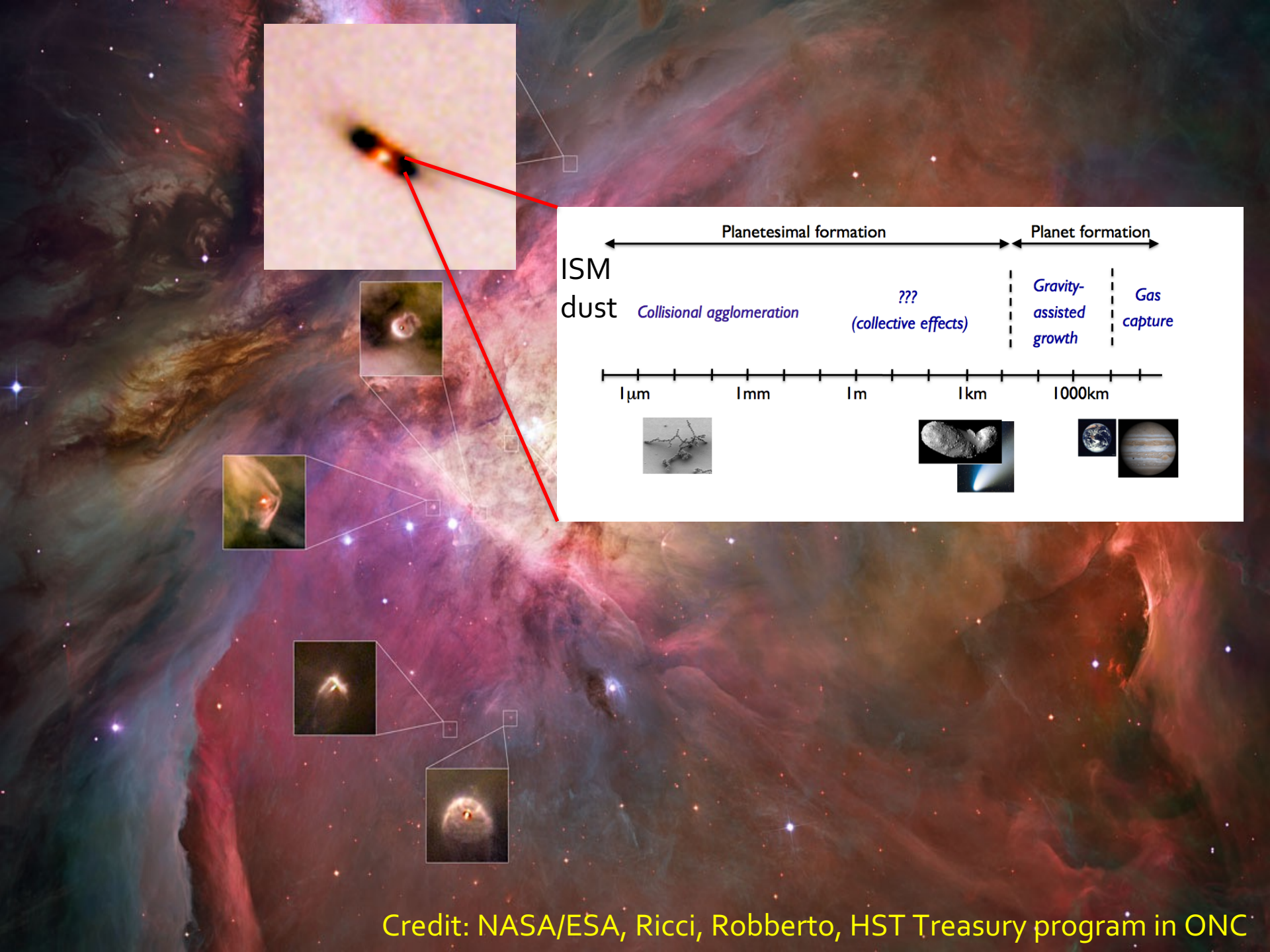
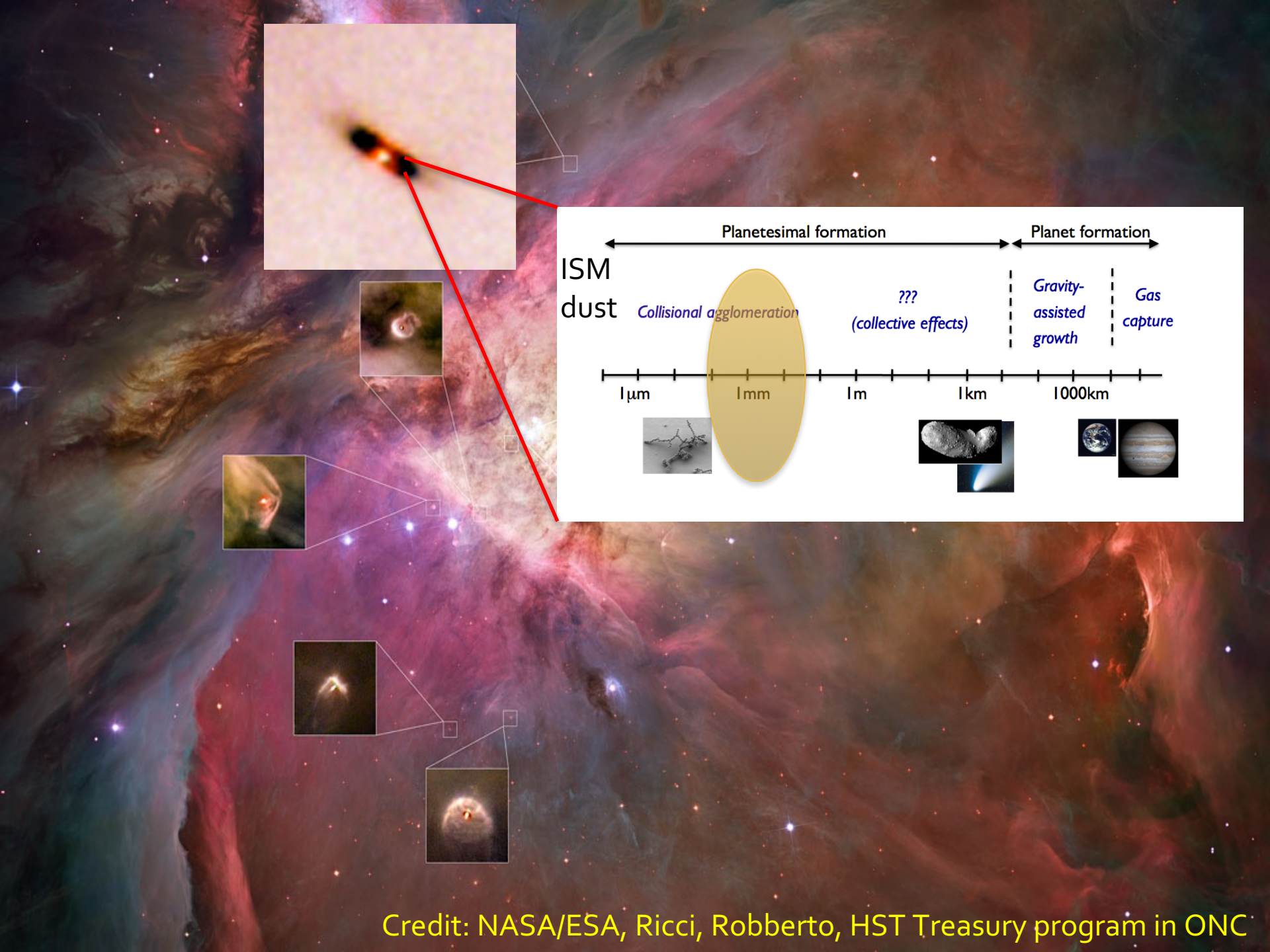
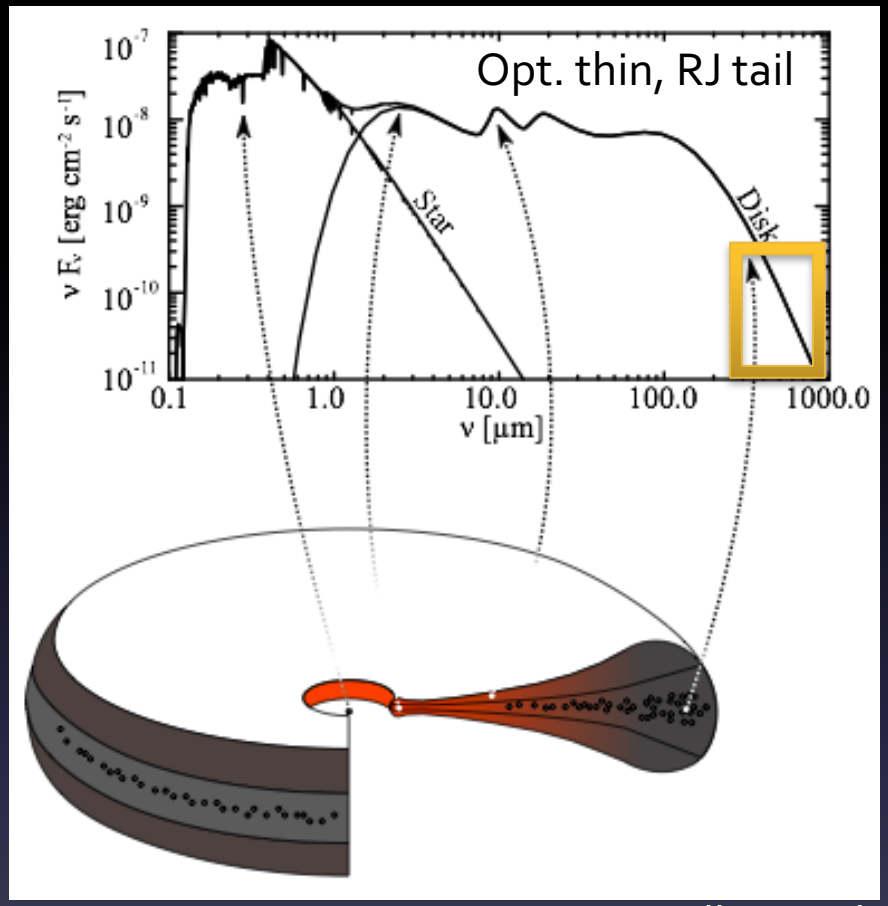


Credit: NASA/ESA, Ricci, Robberto, HST Treasury program in ONC



Credit: NASA/ESA, Ricci, Robberto, HST Treasury program in ONC

Grain sizing from mm-SED slope

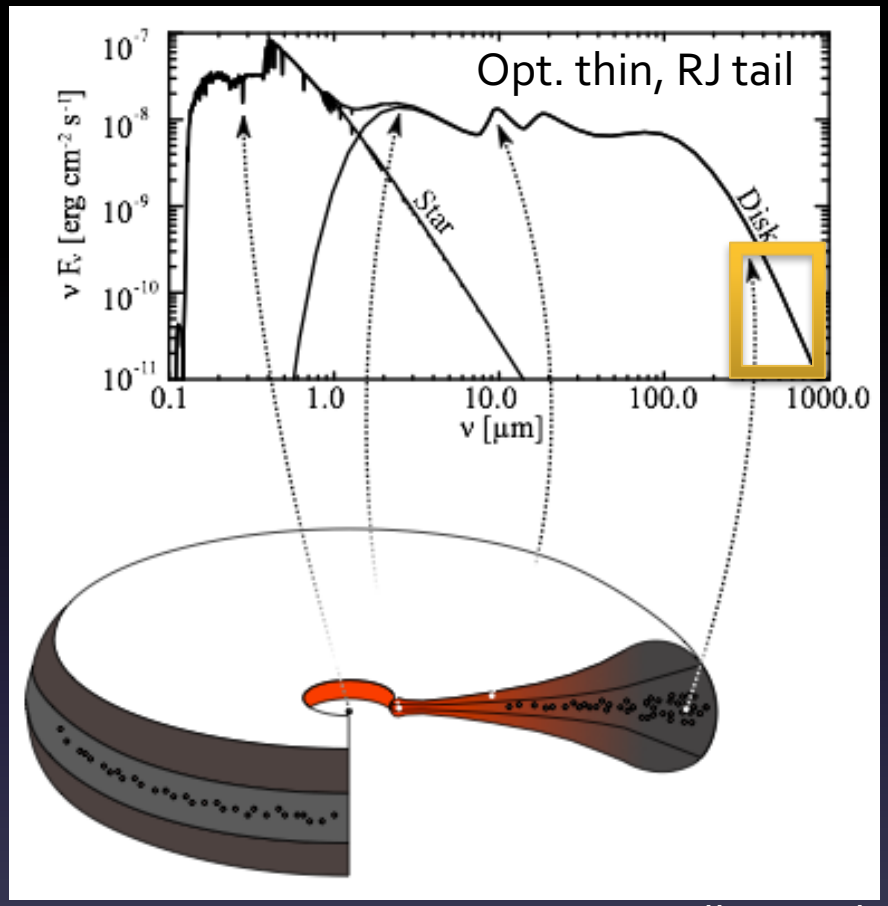


Dullemond

$F_\nu \sim \nu^2 \kappa_\nu$; $F_\nu \sim \nu^\alpha, \kappa_\nu \sim \nu^\beta$

$$\boxed{\alpha \sim 2 + \beta}$$

Grain sizing from mm-SED slope



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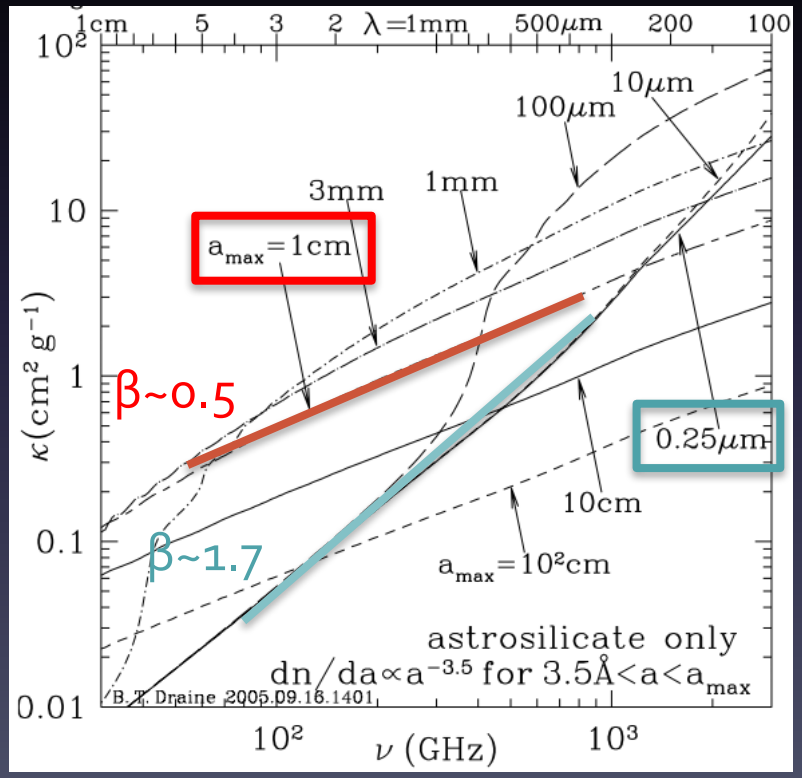
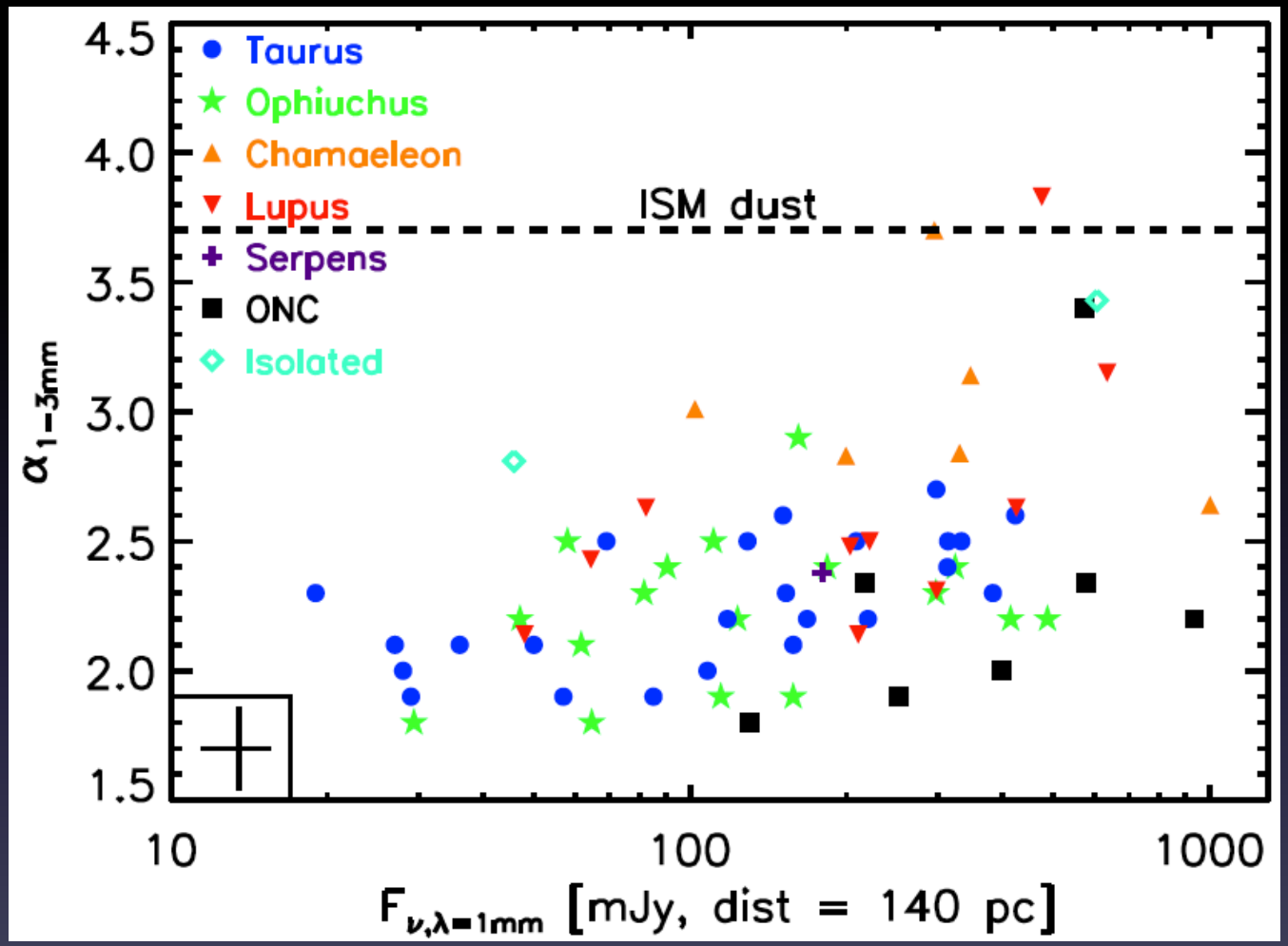


Draine 06

$\alpha < 3$ ($\beta < 1$) only if ~ mm pebbles in the "outer disk" (R > few x 10 AU)

Grain growth: sub-mm/mm observations

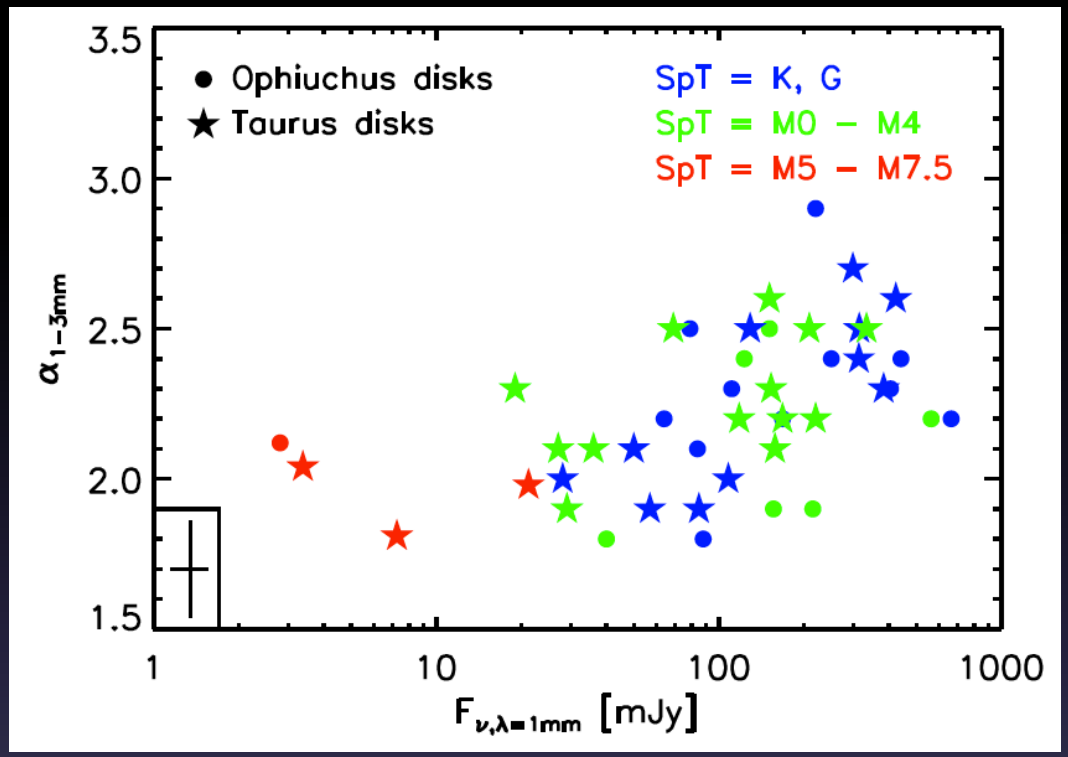
Grain growth: observational results



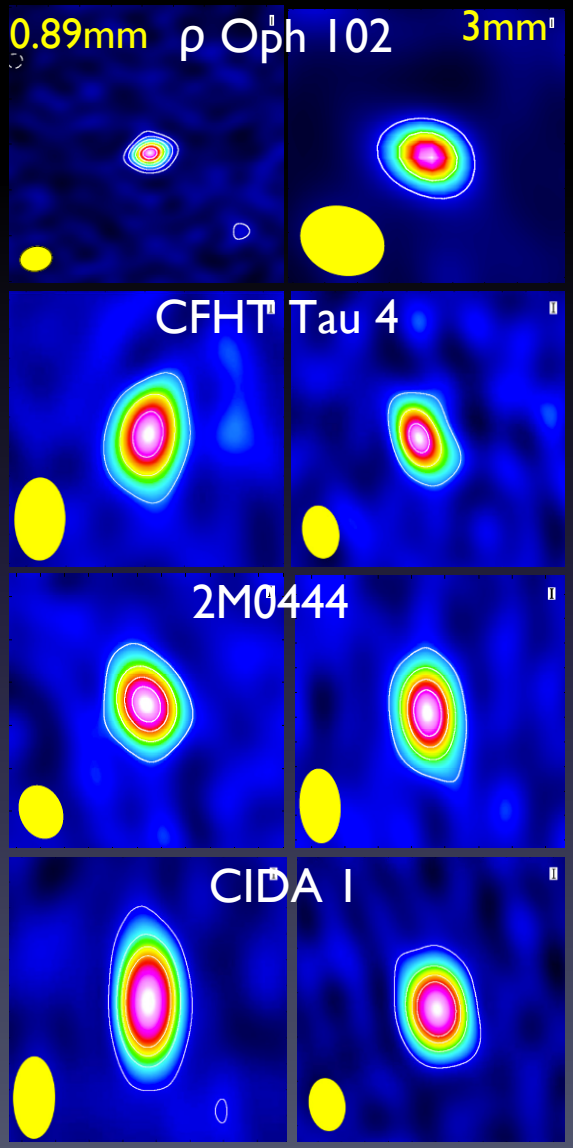
Andrews & Williams 05, 07, Rodmann+07 Lommen+ 07, 10, Ricci+ 10a,b,11, Mann+ 10, Ubach+ 12, Testi+ 14

mm-grains in the outer regions of ~ all disks around young stars

Grain growth: BD disks



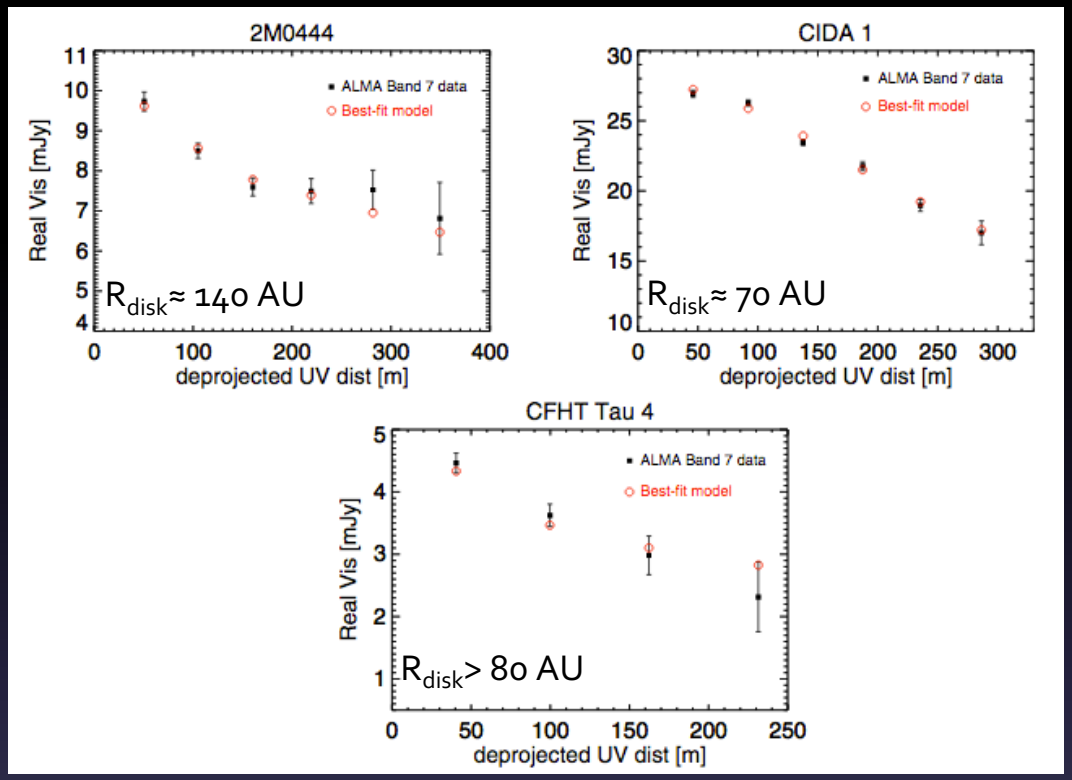
Ricci+ 12, 13, 14



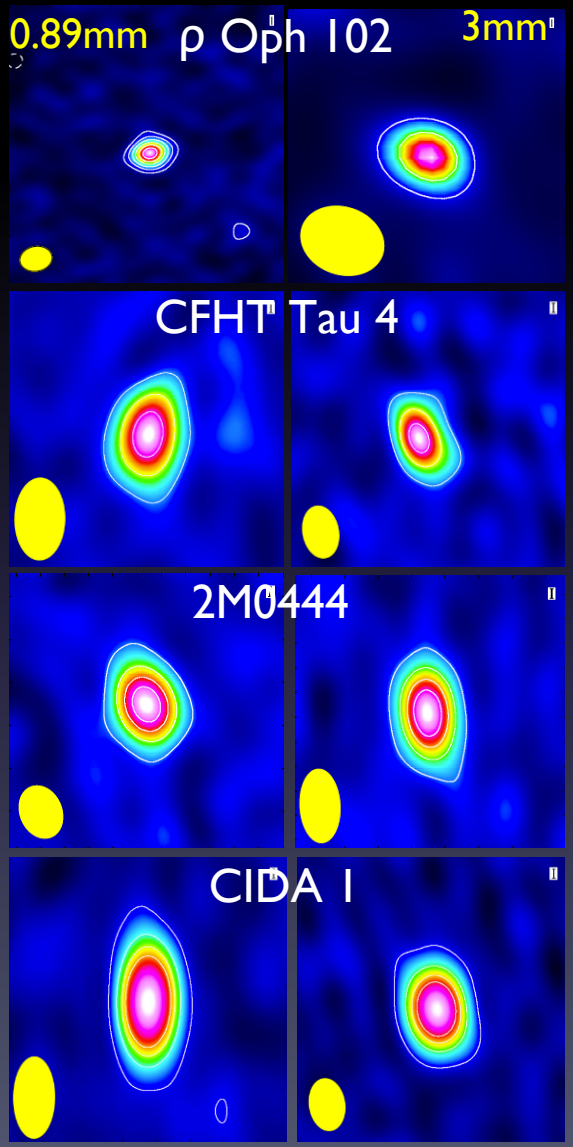
- mm-grains also in low mass disks around BDs ;

for 2M0444: α ~ 2.3 up to 1 cm (VLA, Ricci+17a)

BD disks: physical structure



Ricci+ 12, 13, 14

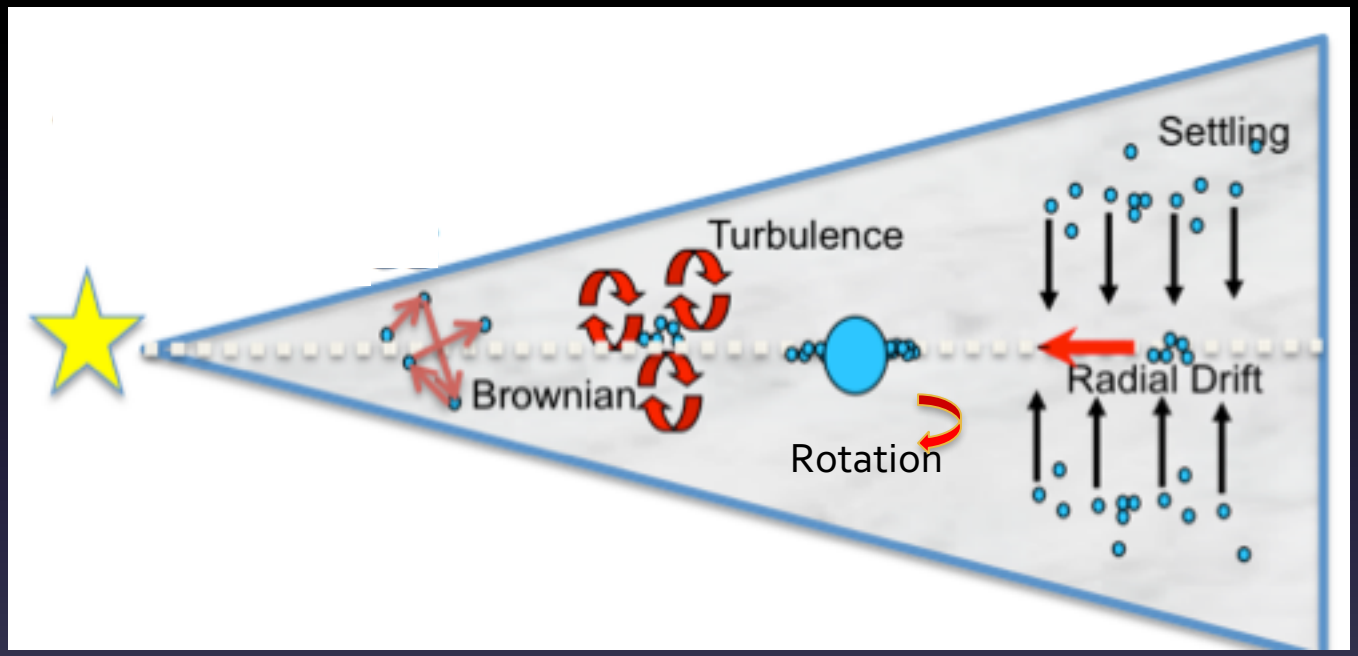


- mm-grains also in low mass disks around BDs
- First measurements of BD disks radii (stellar-like vs ejection formation of BDs?)

Theory of dust evolution

Models of evolution of solids in disks

- Time evolution of gas density & temperature
- Solids are coupled to the gas and gain velocity



Brauer+ 08, Birnstiel+ 10

- Solids with different sizes acquire relative velocities, i.e. they collide

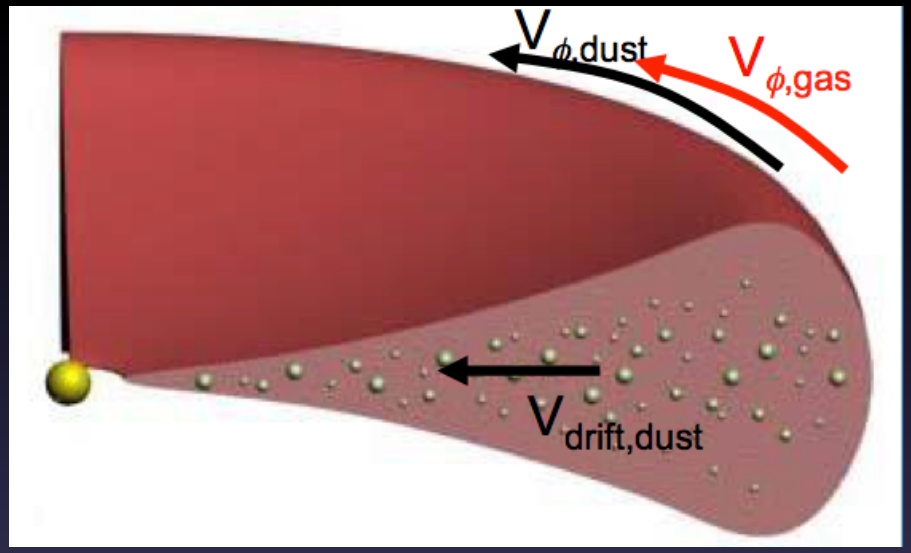
Collision outcome: Δv $< v_{frag}$ → coagulation

$> v_{frag}$ → fragmentation

Radial motion of small solids: radial drift

Solids: $v_{rot} = v_{Kepler}(r)$

Gas: $v_{rot} < v_{Kepler}(r)$ ($dP/dr < 0$)

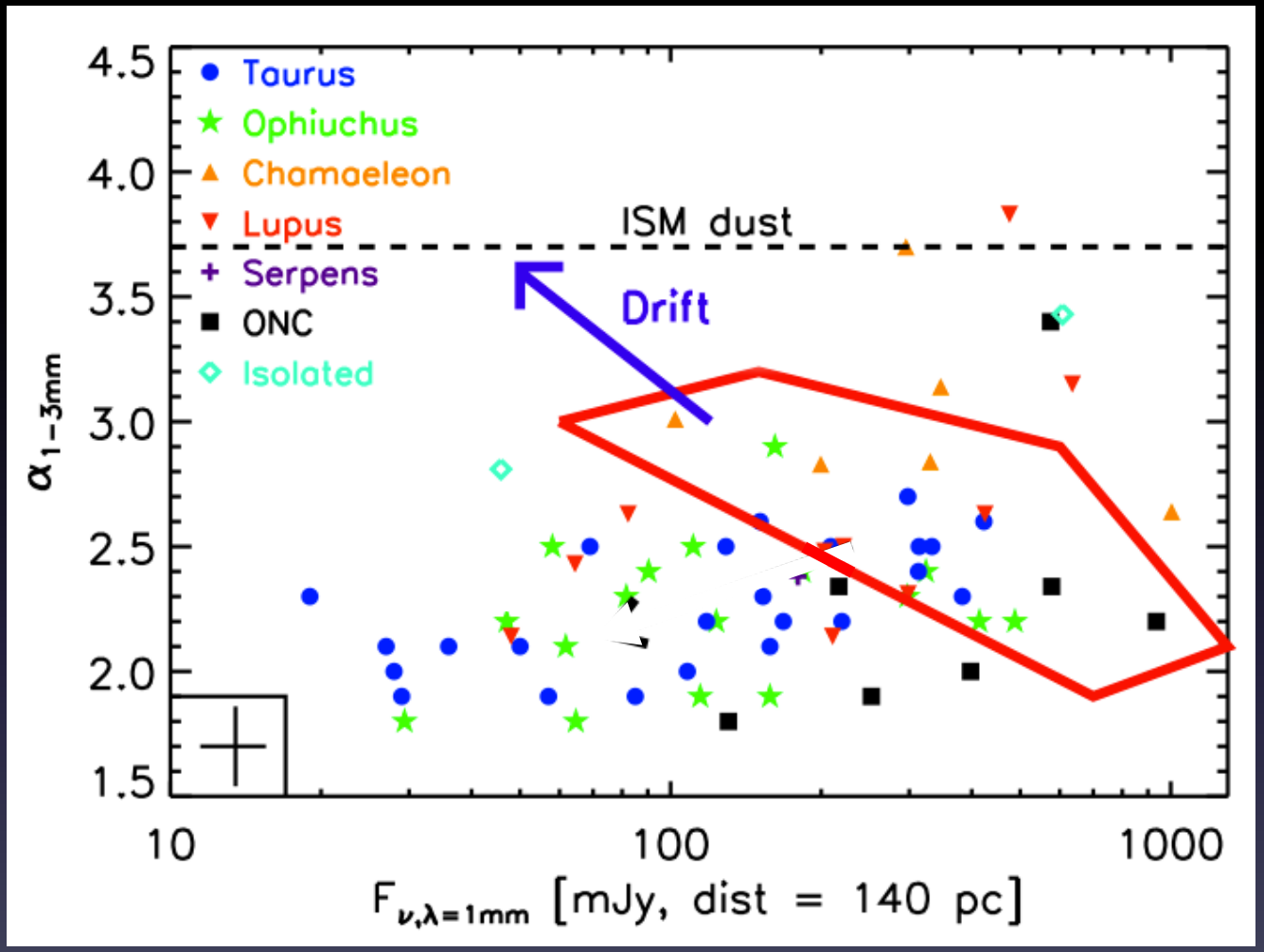


Fastest for $St = \frac{a}{\Sigma_{gas}} \rho_{solid} = 1$

For young disks: ~ 1 – 10 mm pebbles @ 100 AU drift in < 1 Myr

Relative velocities > 10 m/s → fragmentation

Grain growth: the effect of drift



Birnstiel, Ricci+ 10, Pinilla, Ricci+ 12

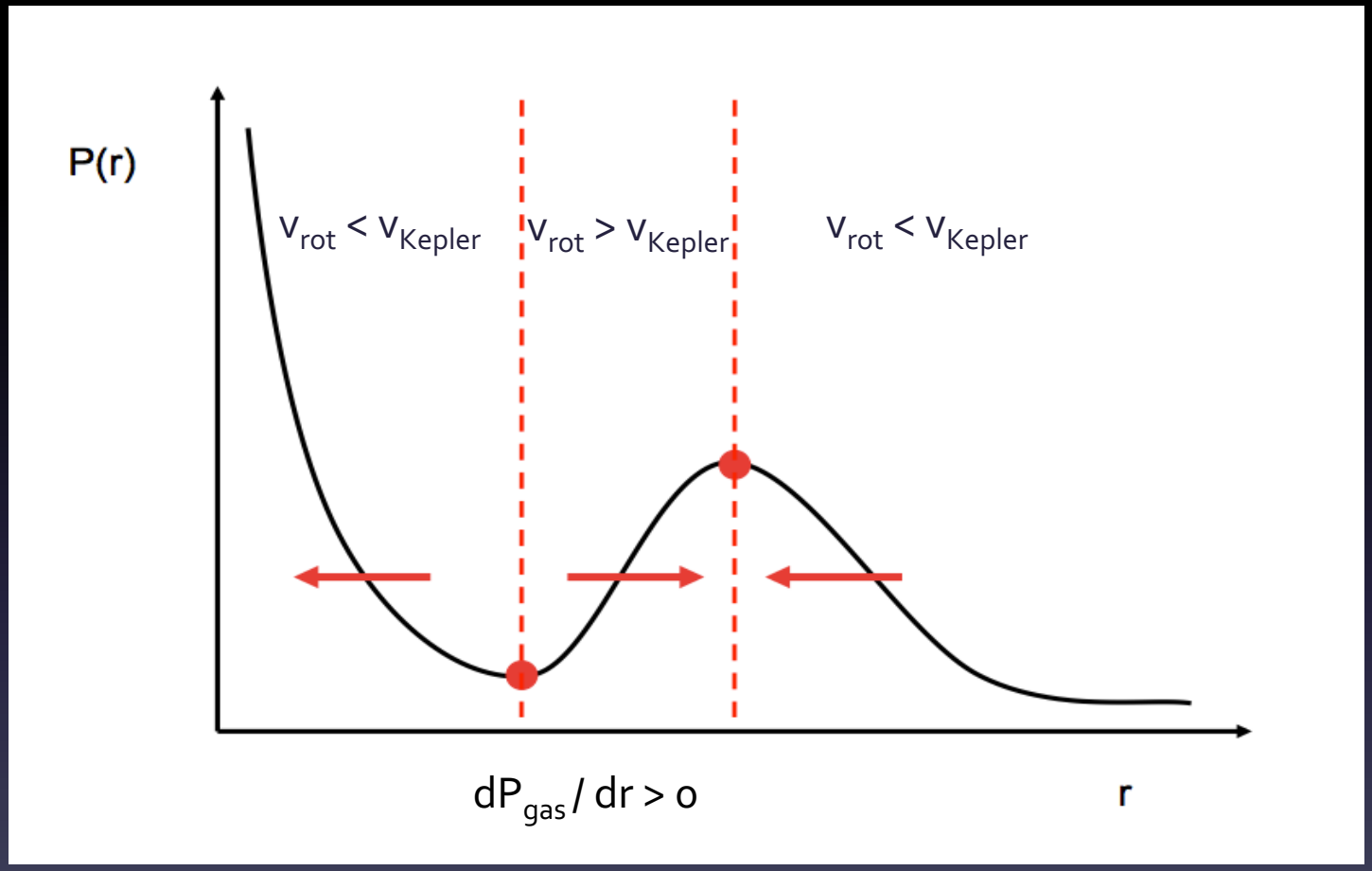
"mm-size problem"
@ 100 AU

"m-size problem"
@ 1 AU

(Weidenschilling 1977)

Radial drift vs data, especially fainter disks around BDs (Pinilla,Ricci+13)

Way out: particle trapping in pressure bumps



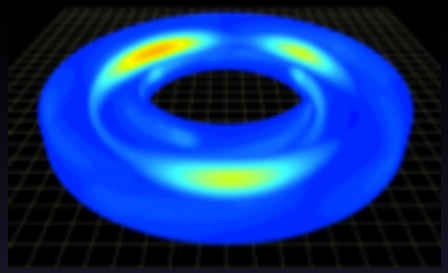
Whipple 1972

mm-grains (St ~ 1) accumulate on local pressure maxima

Dust trapping in disks: possible mechanisms

Vortices

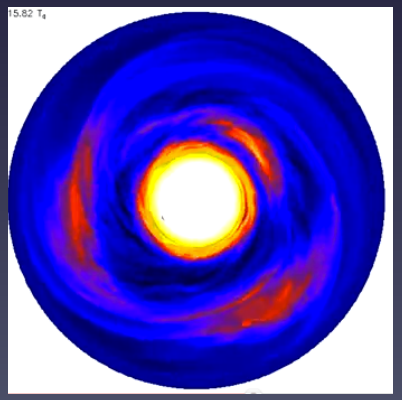
Rossby-wave HD instability



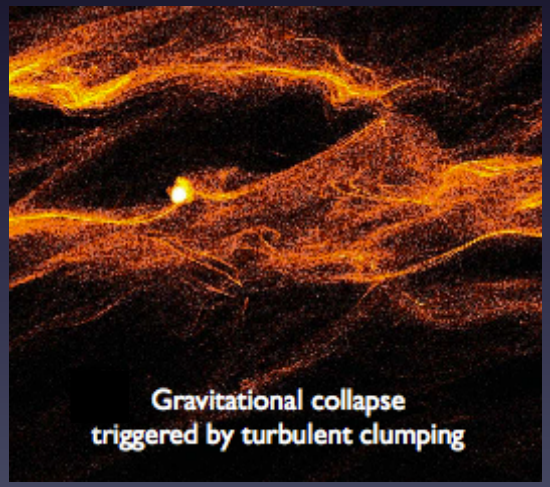
Richard, Barge+ 13

Johansen

Dead zone edge in MHD



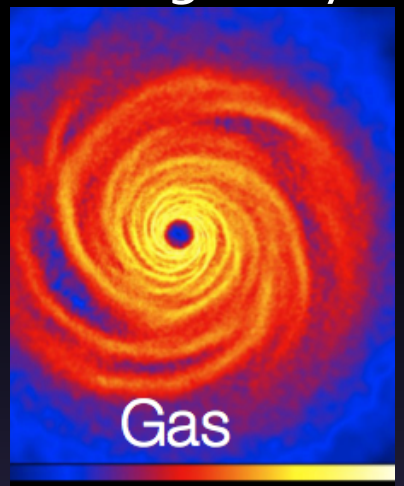
W. Lyra

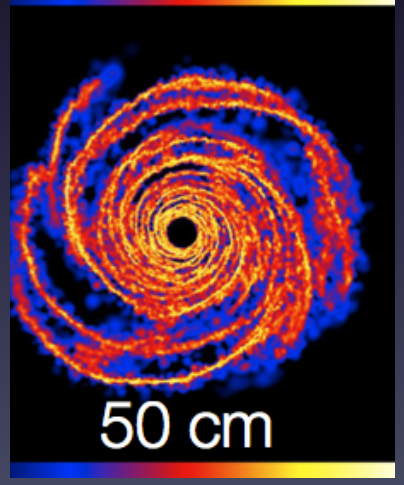


Chiang & Youdin 10

Spiral arms and rings

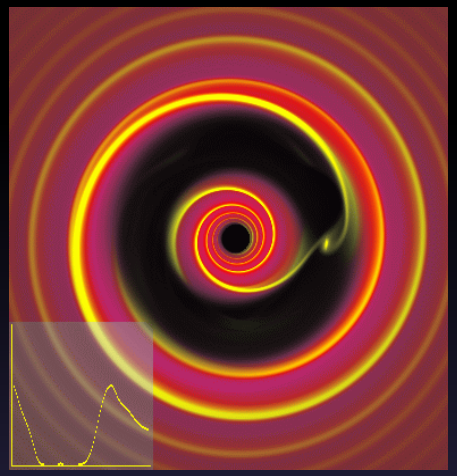
Self-gravity





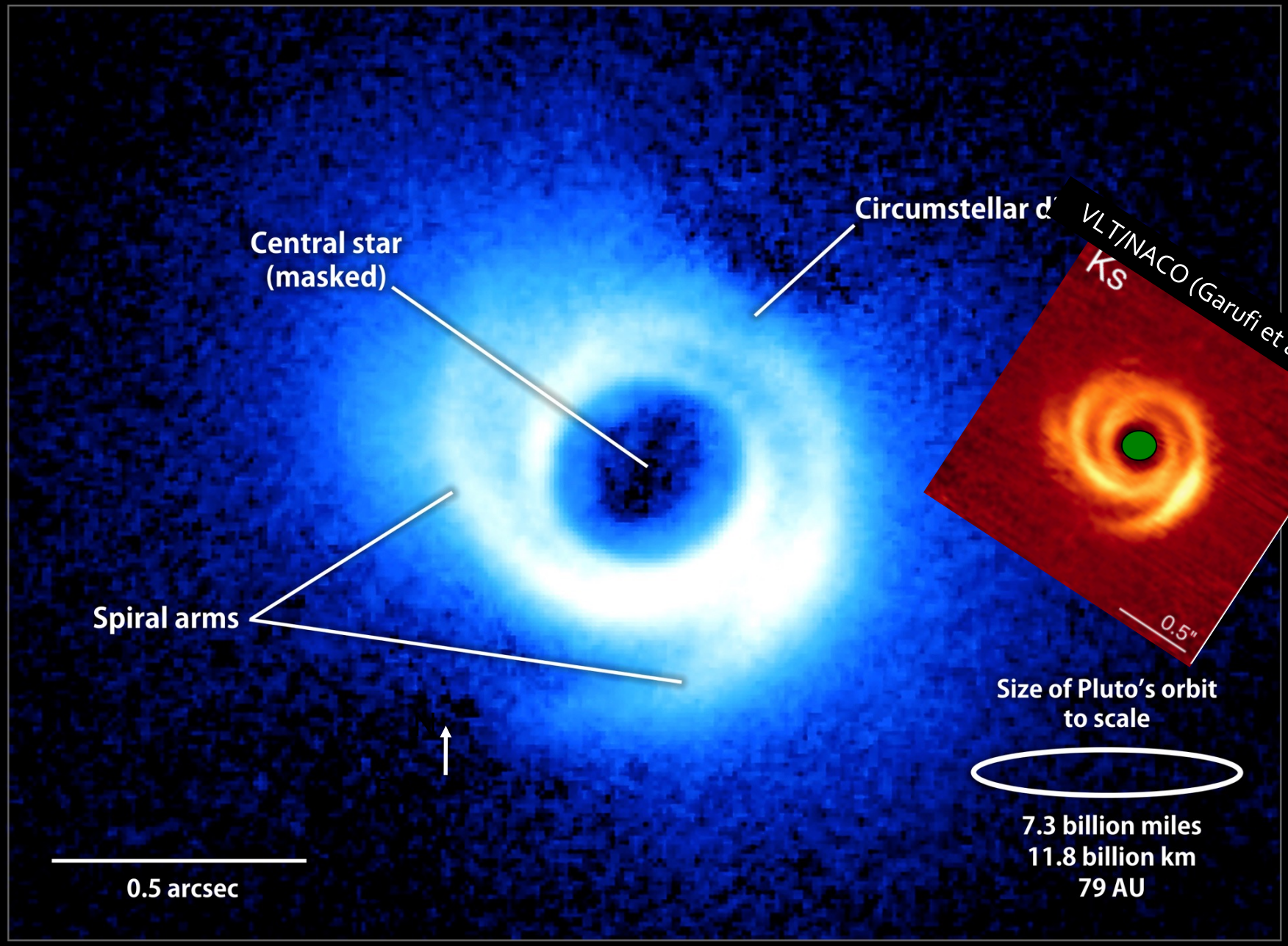
Rice+ 06

Planet



G. Bryden

Spiral features revealed in SAO 206462's dust disk



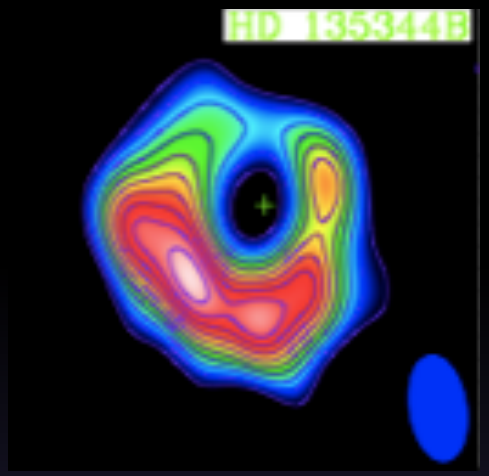
Credit: NAOJ/Subaru

Spiral features revealed in SAO 206462's dust disk

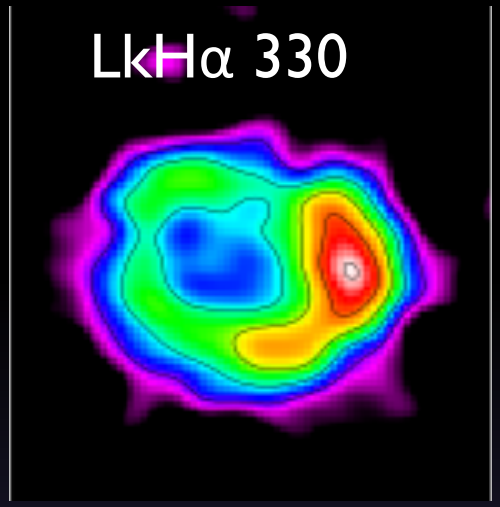
Credit: NAOJ/Subaru

Sub-mm observations of disks "substructures"

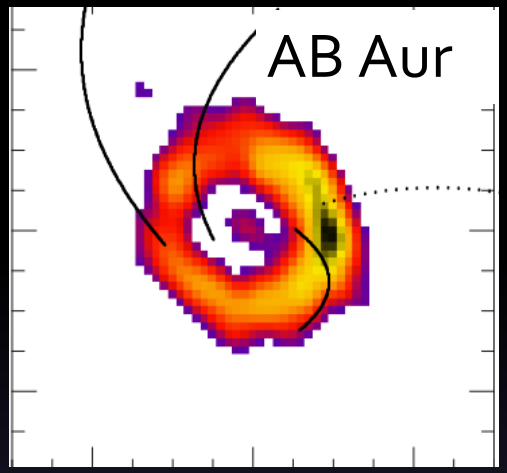
Dust traps in disks: sub-mm observations



SMA



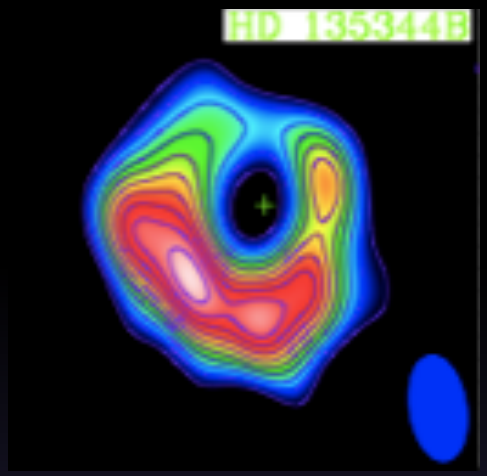
CARMA



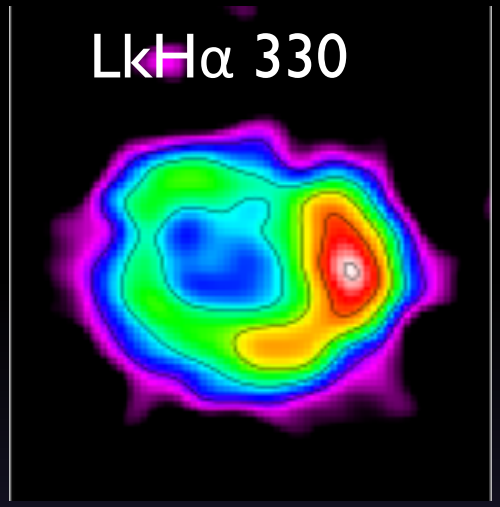
PdBI

Brown+ 09, Tang+ 12, Isella+ 13

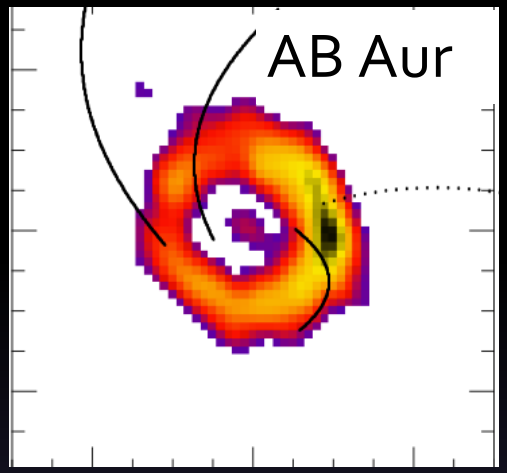
Dust traps in disks: sub-mm observations



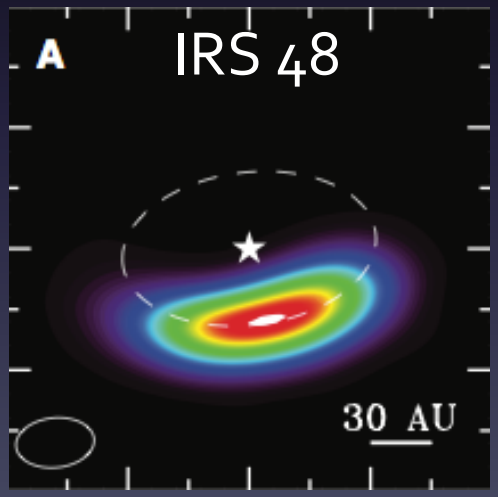
SMA

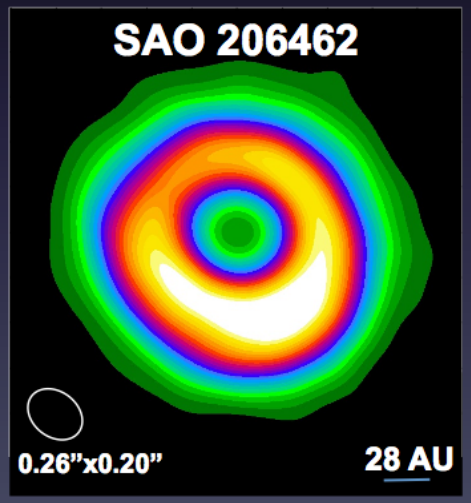


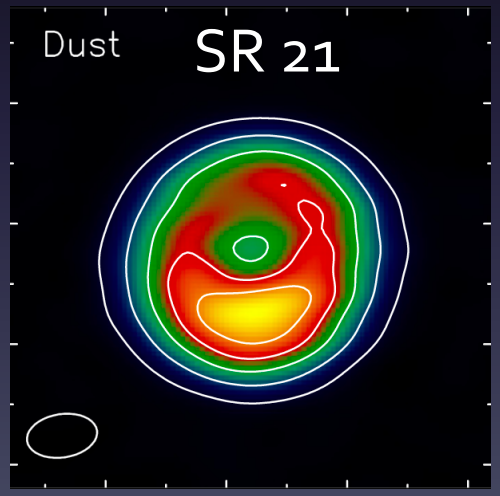
CARMA

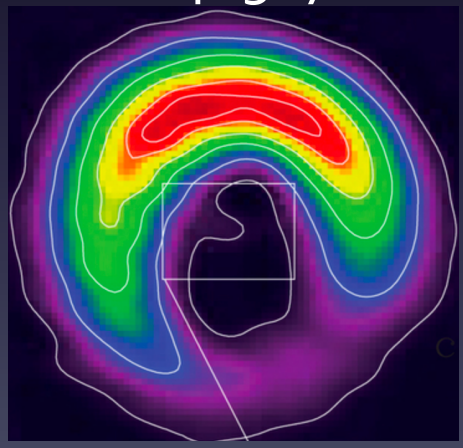


PdBI









ALMA - Cycle 0 (2012)

Brown+ 09, Tang+ 12, Isella+ 13, van der Marel+ 13, Casassus+13, Perez+ 14

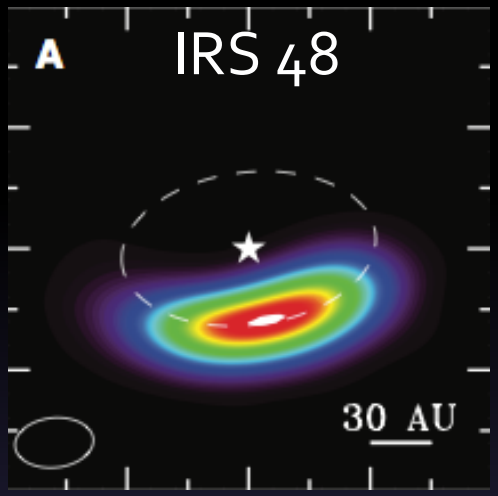
After 6 years of ALMA…

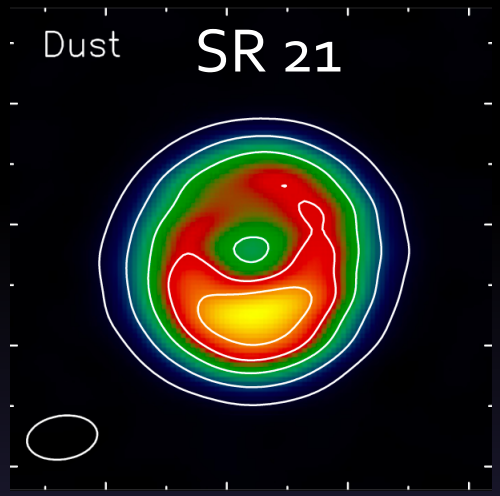
Nearly all nearby disks observed at $\theta < 0.1''$ (< 20 - 30 au) show substructures

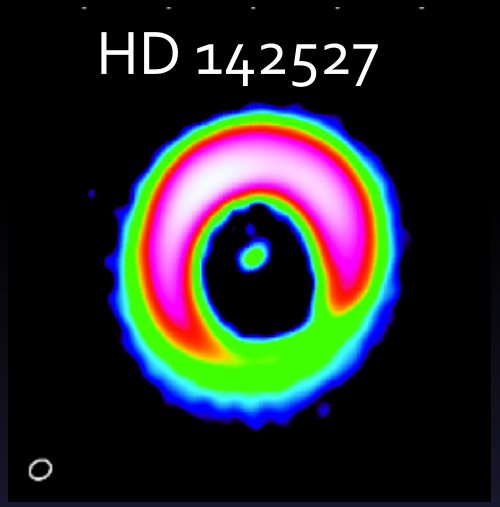
3 main types of substructures:

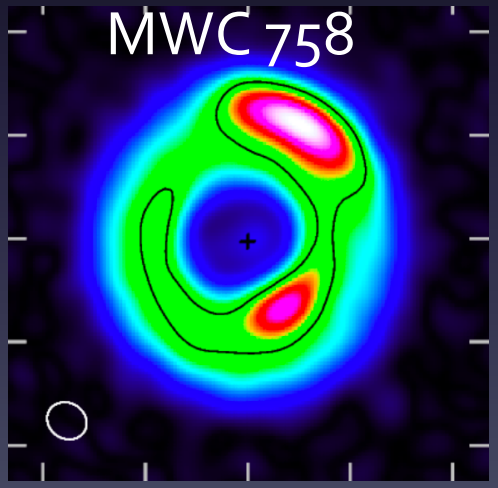
- **"Crescent-shaped"**
- **Spiral arms**
- **Rings/Gaps**

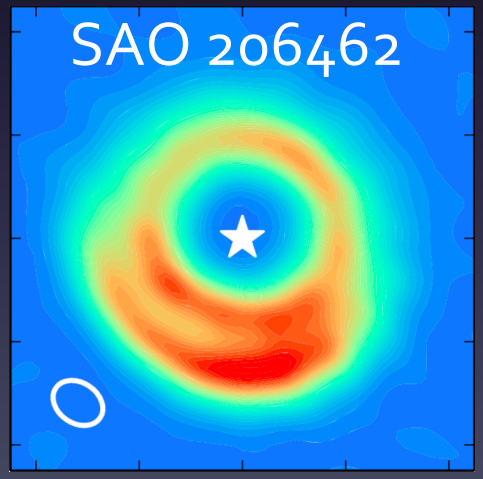
Crescent-shaped substructures





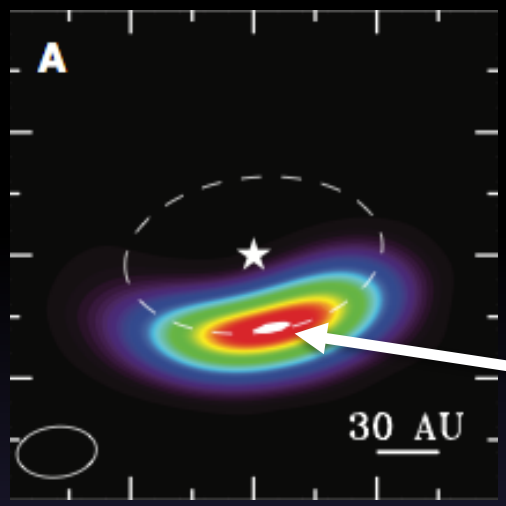




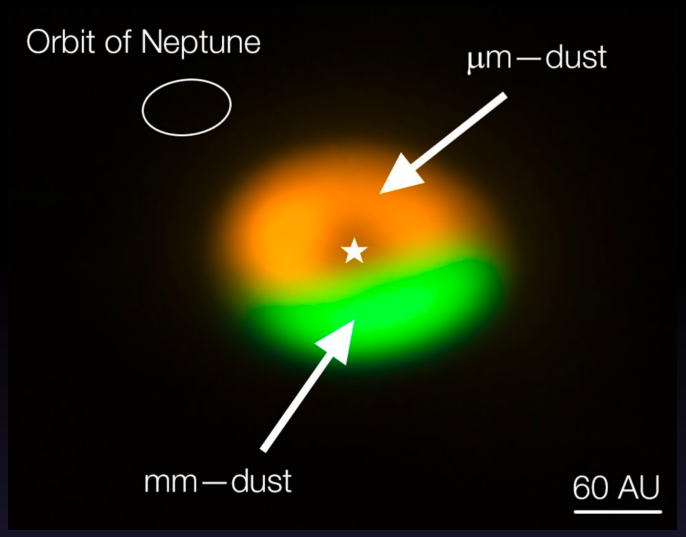


Brown+ 09, Tang+ 12, Isella+ 13, van der Marel+ 13, Casassus+13, Perez+ 14, Boehler+ 16

Crescent-shaped substructures: IRS 48



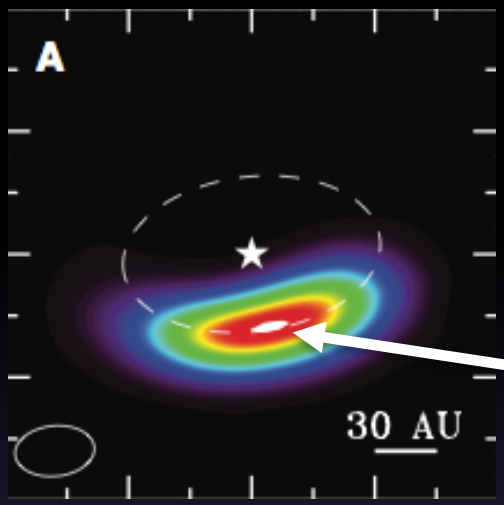
S/N ~ 180



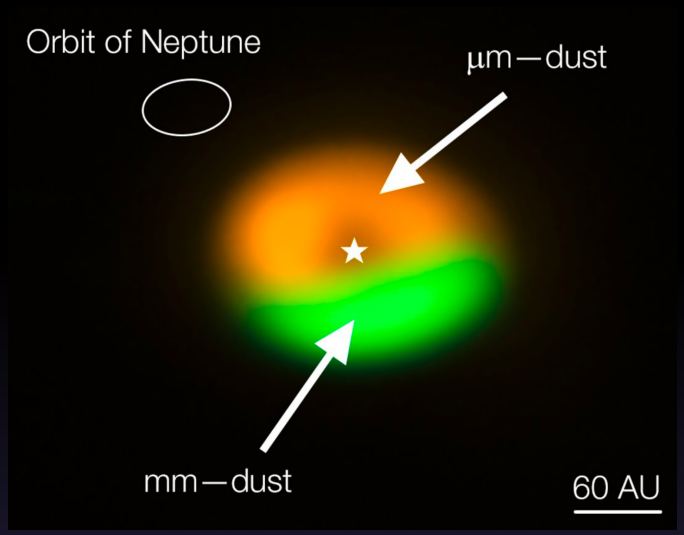
van der Marel+ 13, van der Marel, Ricci+15, Richard+ 13

Crescent-shaped substructures: IRS 48

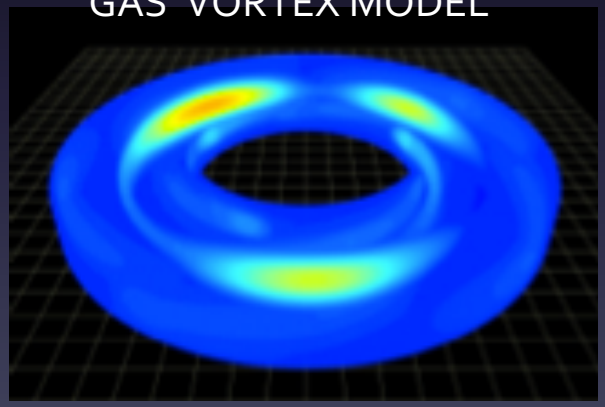
ALMA - 0.45 mm

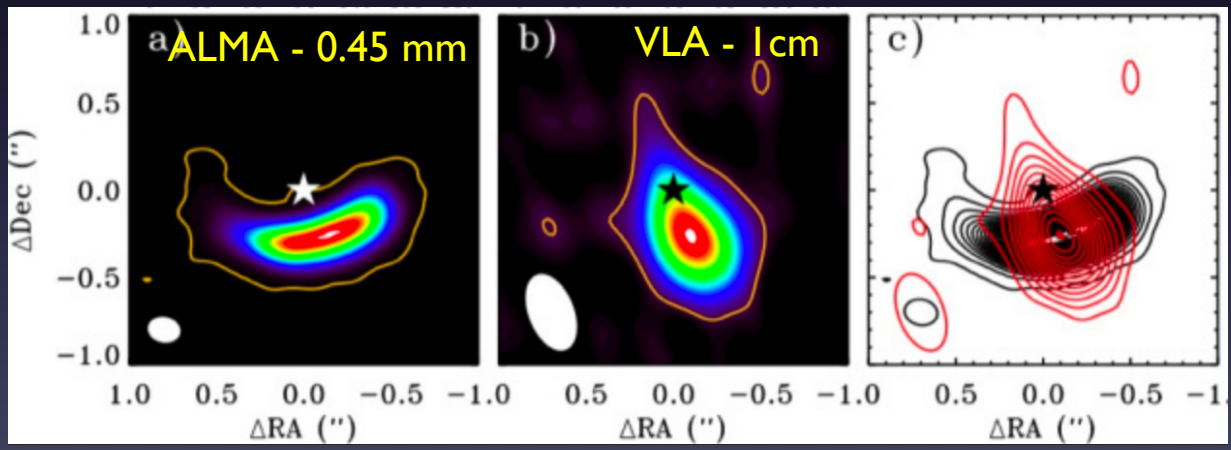


S/N ~ 180



GAS VORTEX MODEL



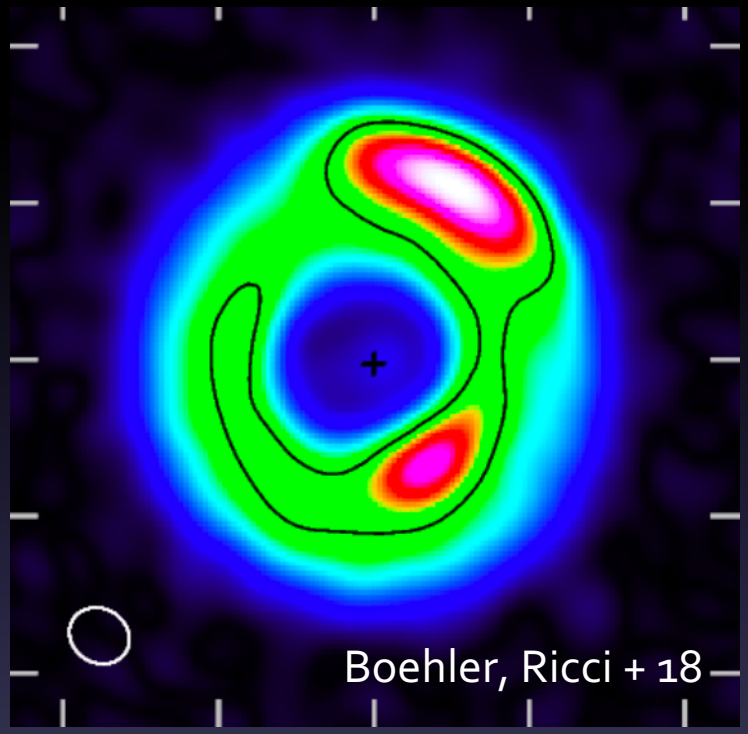


Kinematical signature of vortex rotation in gas?

van der Marel+ 13, van der Marel, Ricci+15, Lyra & Lin 13, Richard+ 13

Crescent-shaped substructures: MWC 758

ALMA - 0.87 mm, $\theta \sim 200$ mas = 30au



How small are dust concentrations?

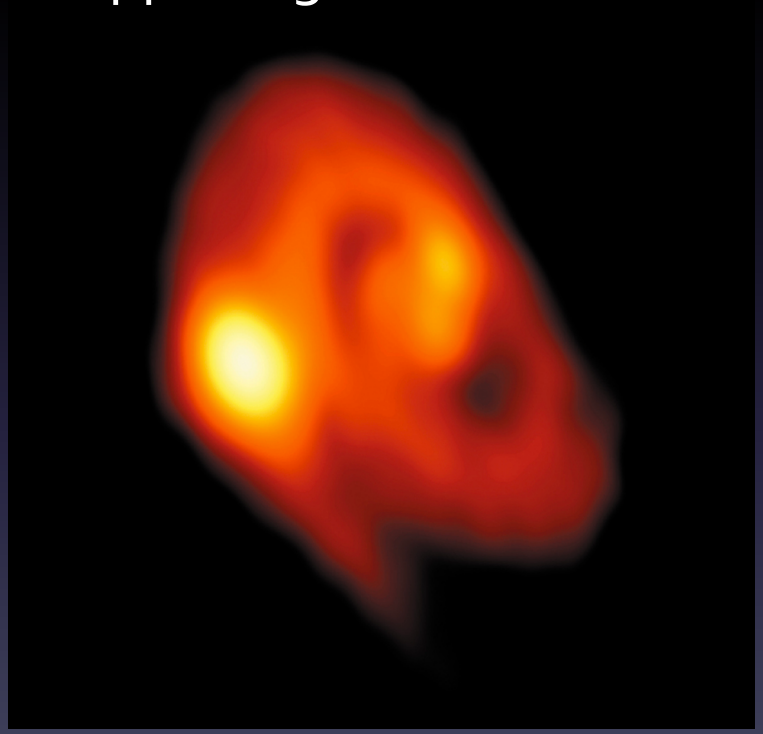
Are they dense and cold enough to be gravitationally unstable?

Sites of planetesimals formation?

Spiral arms

Elias 27

L1448 IRS3B

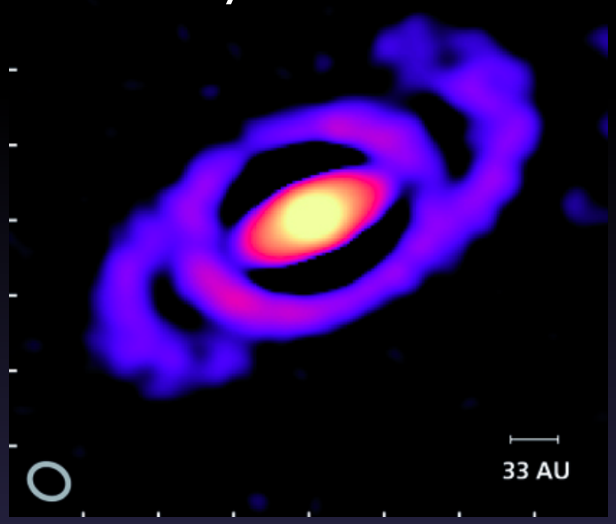


Perez, Ricci+16, Tobin+16

Spiral arms: what is making them?

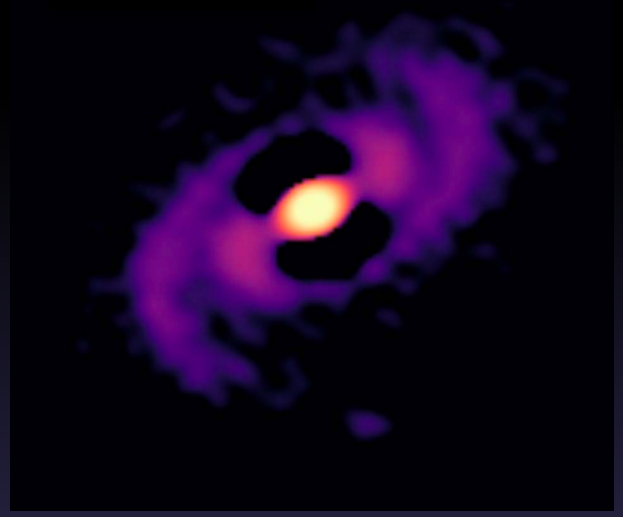
ALMA - 1.3 mm (Unsharp mask)

Elias 27



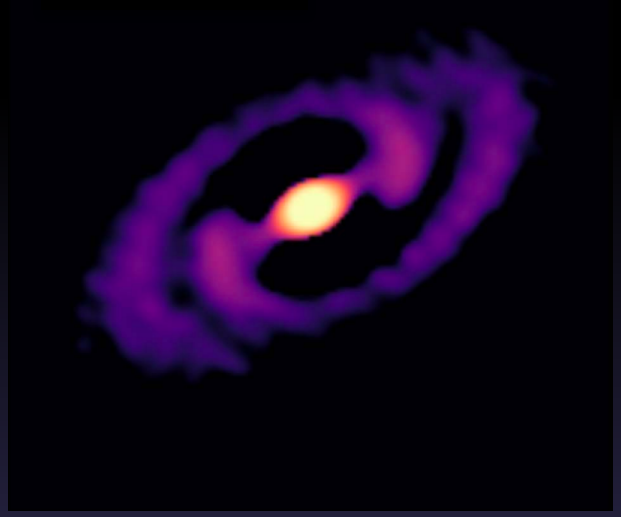
Model

External 10 M_{Jup} planet



Model

Disk self-gravity

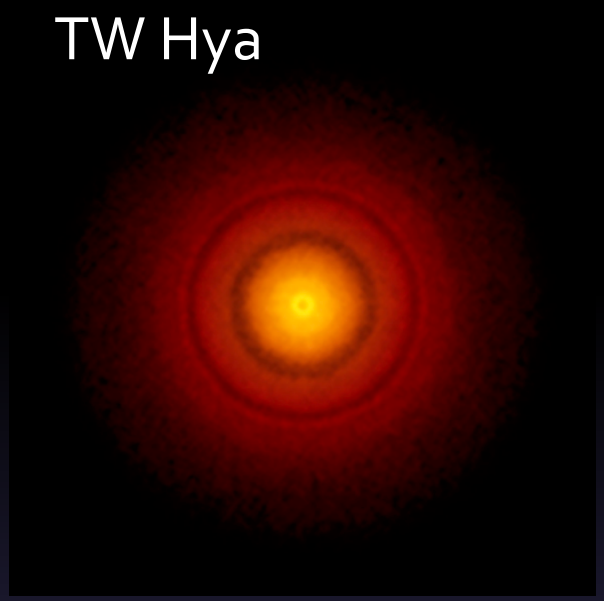


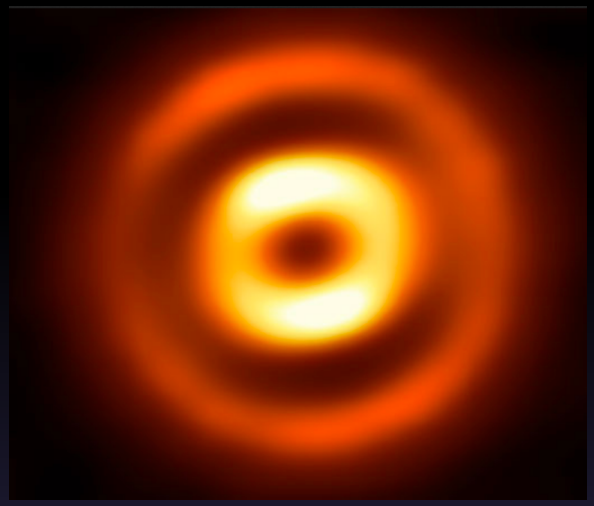
Spiral arms induced by an external planet sweep the disk at a *slower* speed than self-gravity induced arms

- More time to trap larger particles
  - Narrower spiral arms at longer wavelengths

Meru+17

Rings and gaps

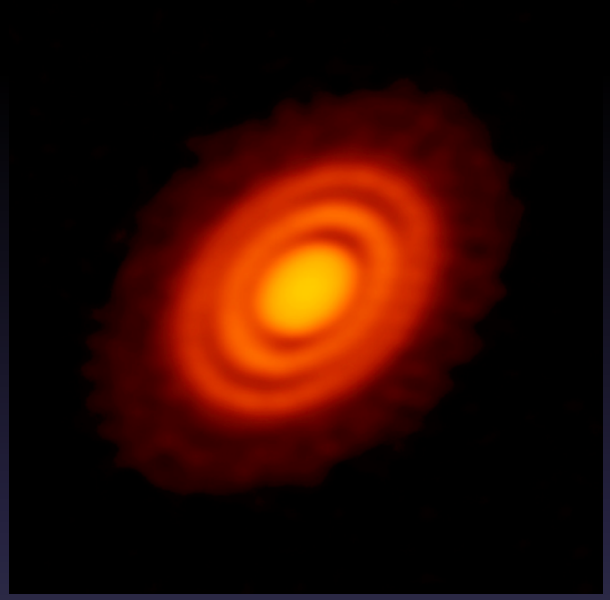




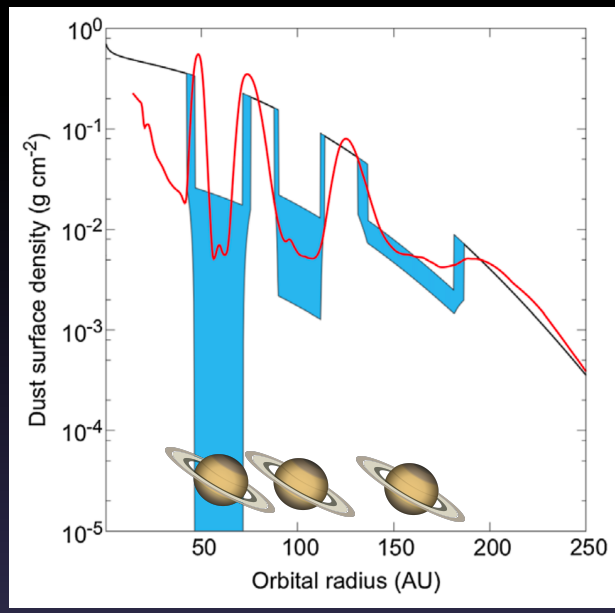
ALMA Partnership+15, Andrews, Ricci+16, Isella, Ricci+16, Cieza+16, Fedele+17

Rings and gaps: HD 163296

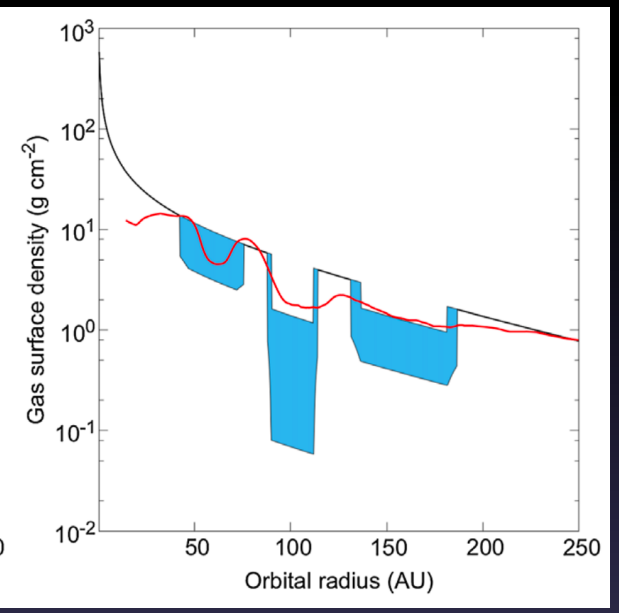
ALMA - 1.3 mm



Modeling of dust continuum



Modeling of ^{12}CO, ^{13}CO, $C^{18}O$

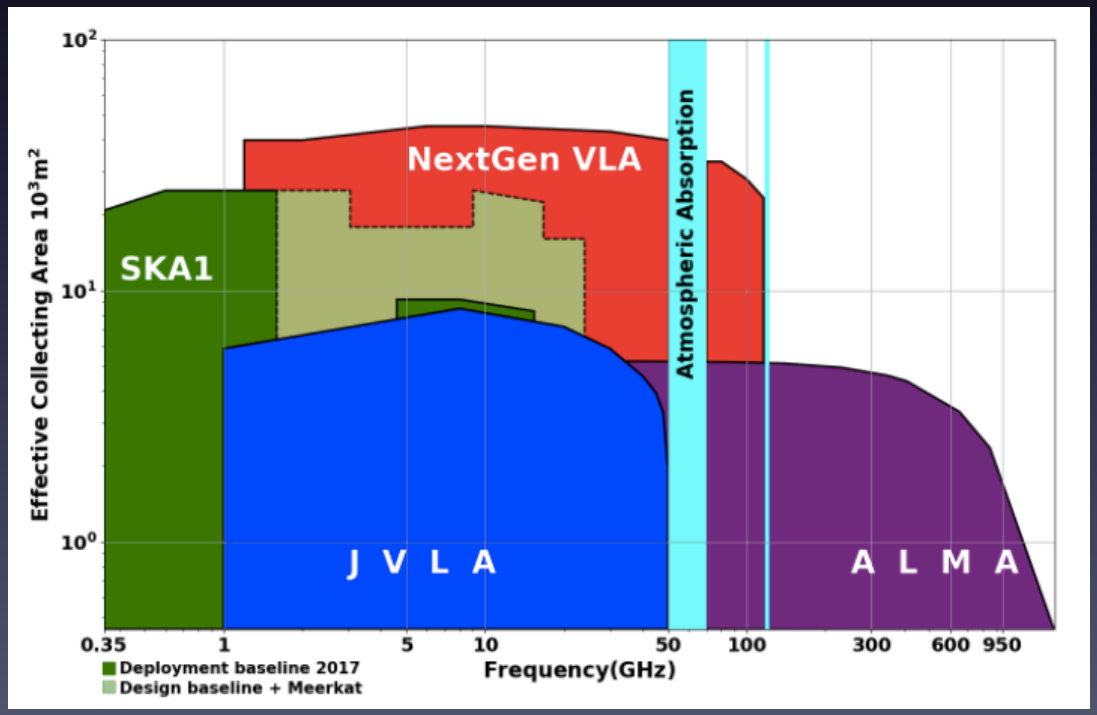


3 gaps in dust, 2 in gas

Hydro simulations with planets require ~ Saturn-mass planets at 60, 100, 160 au: JWST should detect them

Isella, Ricci+16, Liu+ submitted

Next Generation Very Large Array (ngVLA)



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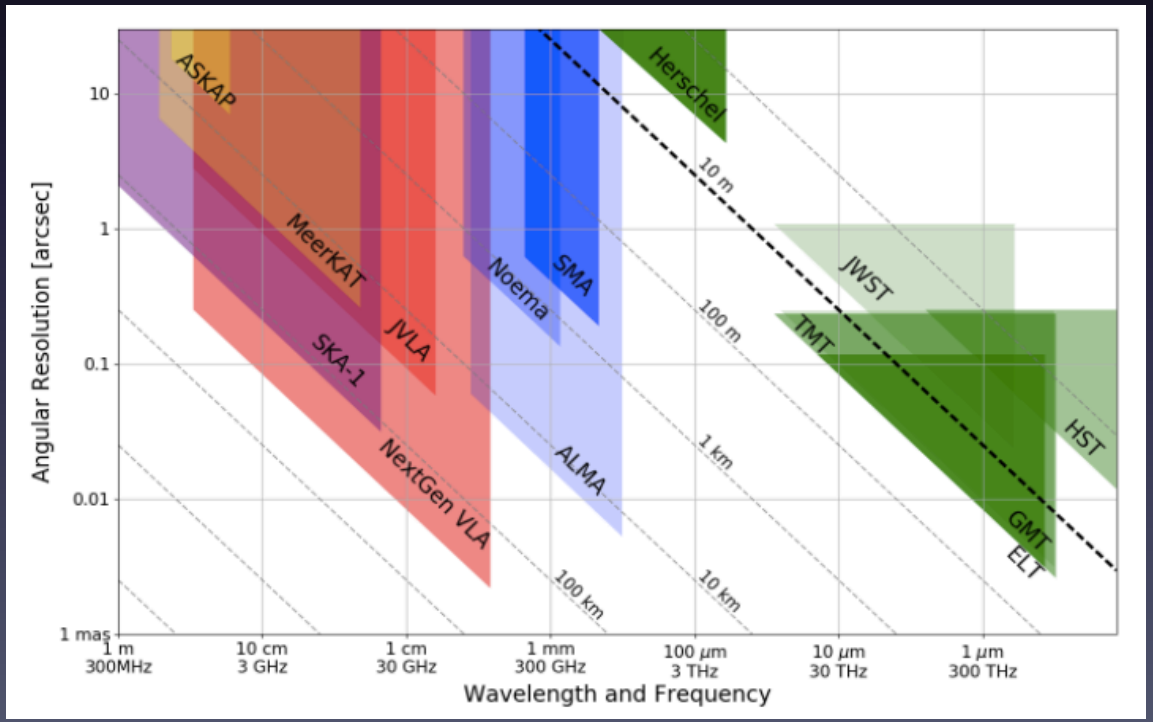

ngVLA Key Science Case: Detecting the signposts of planet formation with the ngVLA

- ngVLA potential to detect disks *substructures* in terrestrial planet forming region
- Complementarity with ALMA

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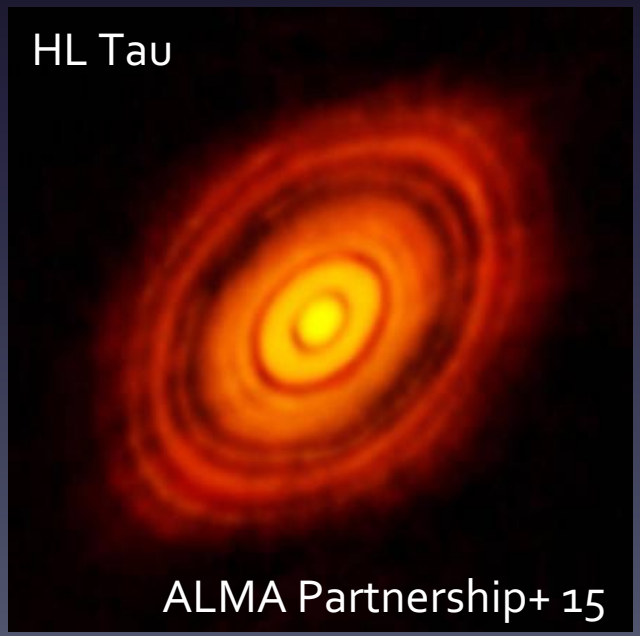

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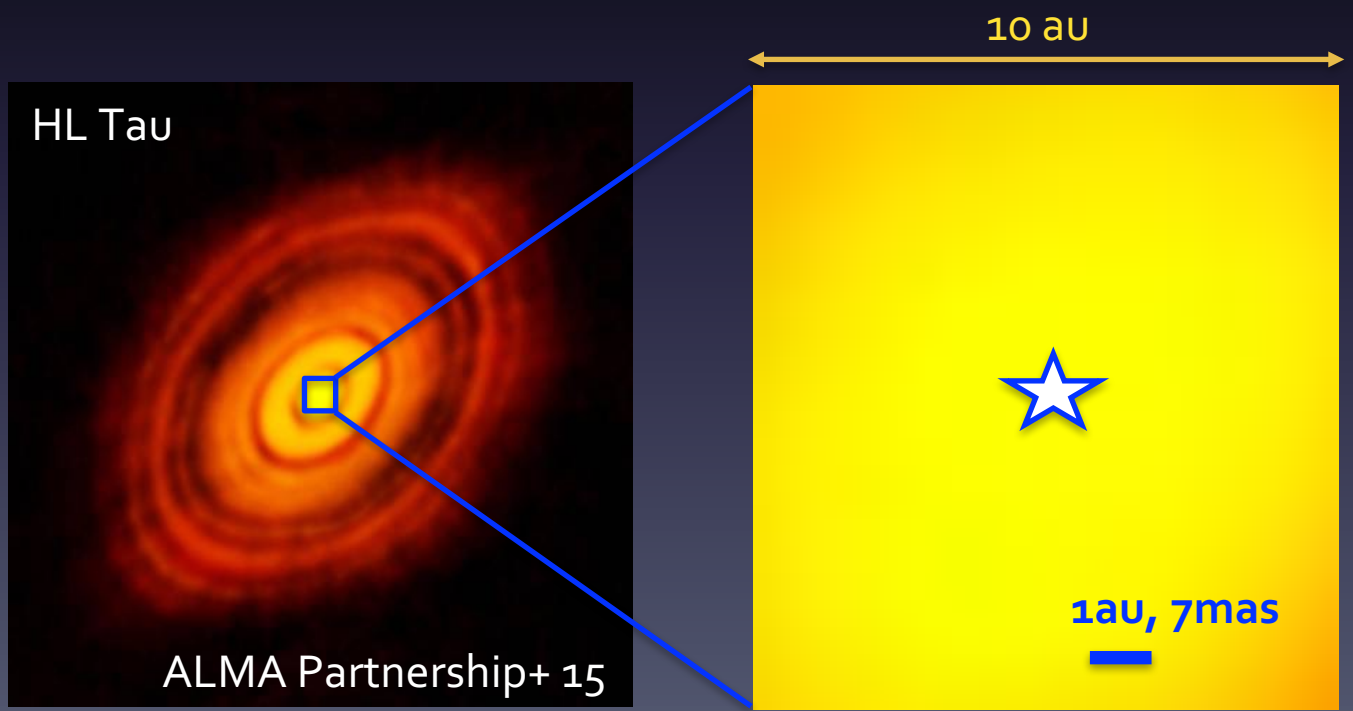
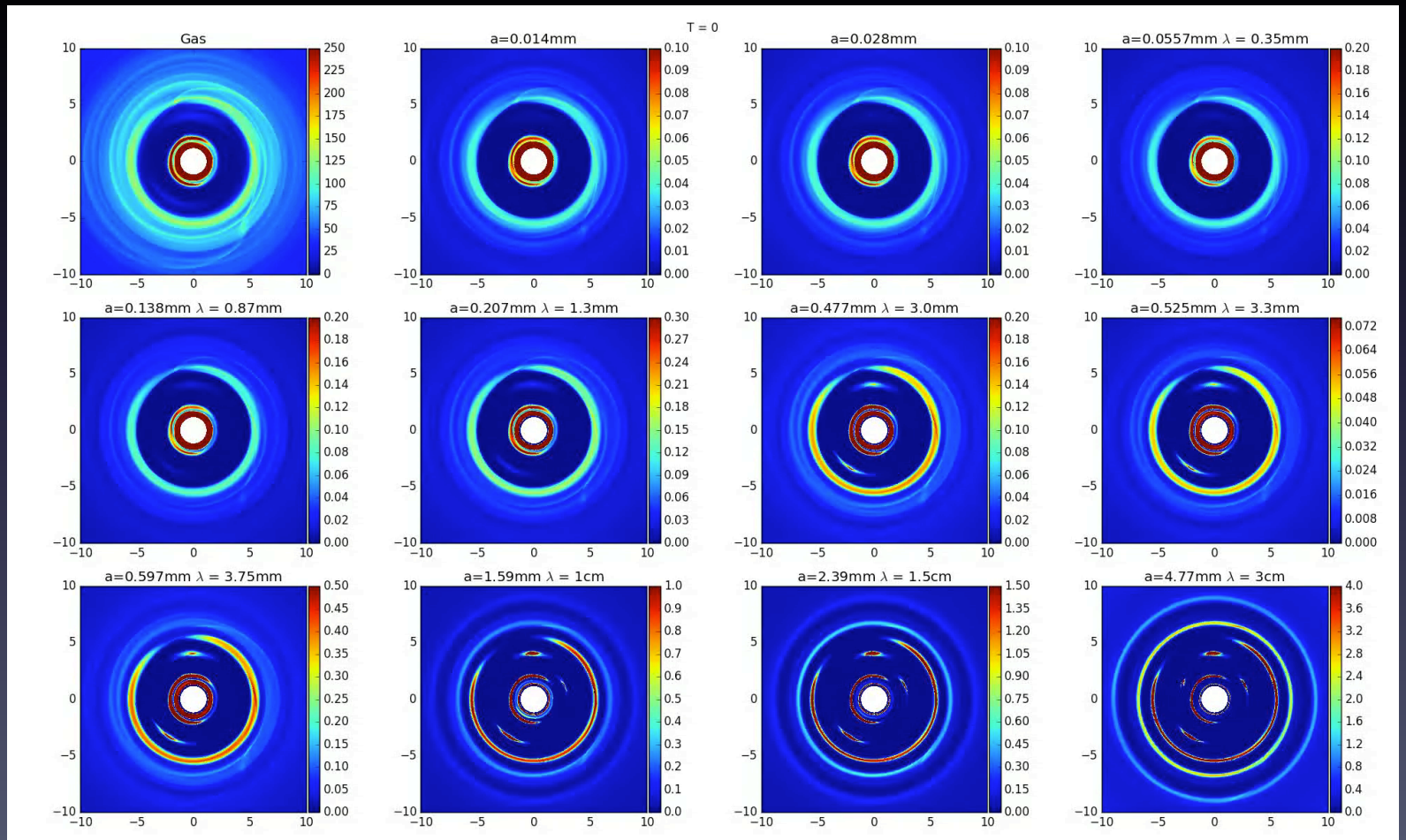


Disk + planet hydrodynamical simulations

LA-COMPASS bi-fluid (gas+dust) hydro code (Li+05, 09):

- Gas evolves viscously, gravitational interaction with planet
- Dust and gas coupled aerodynamically, depends on grain size



Results: planets @ 5 au - $\alpha_{visc} = 10^{-5}$

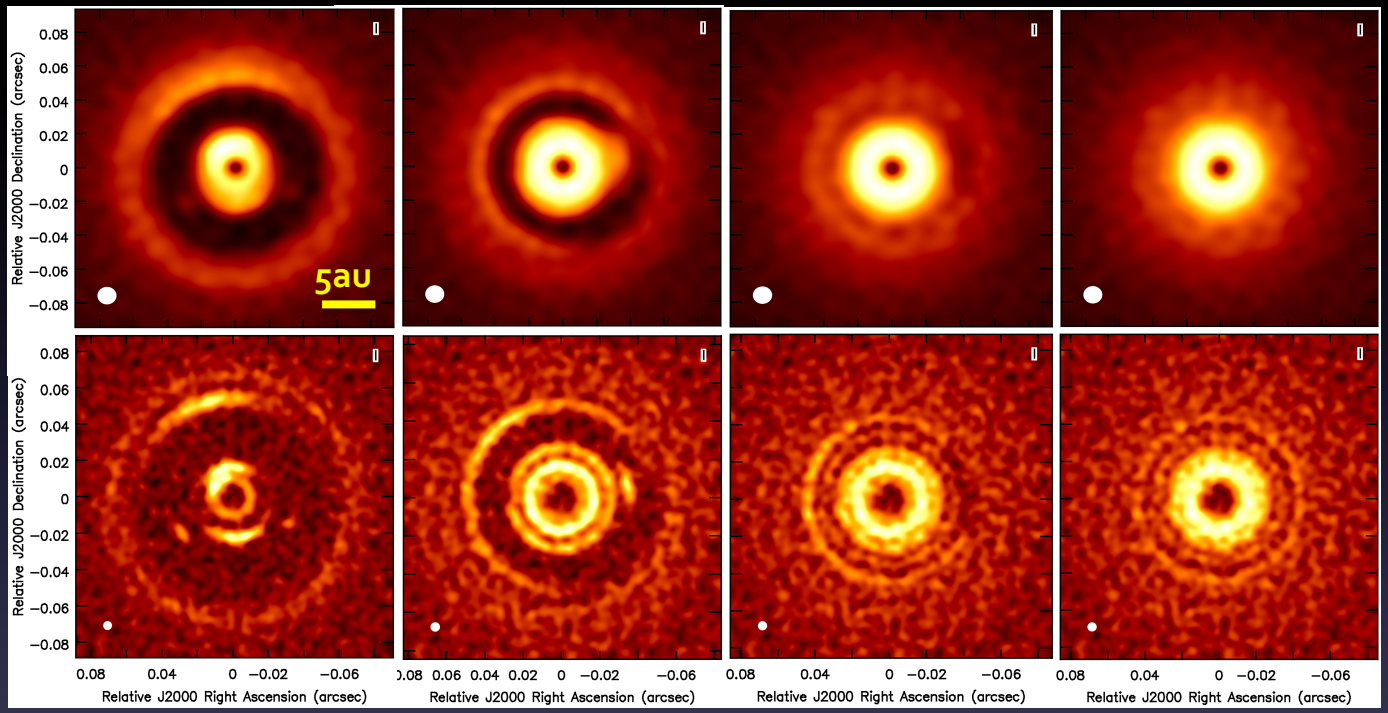
Jupiter | Saturn | Neptune | 10 M_{Earth}

ALMA @ 0.87mm

ngVLA @ 3mm

(θ = 5 mas = 0.7 au

rms = 5e-7 Jy/b)



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

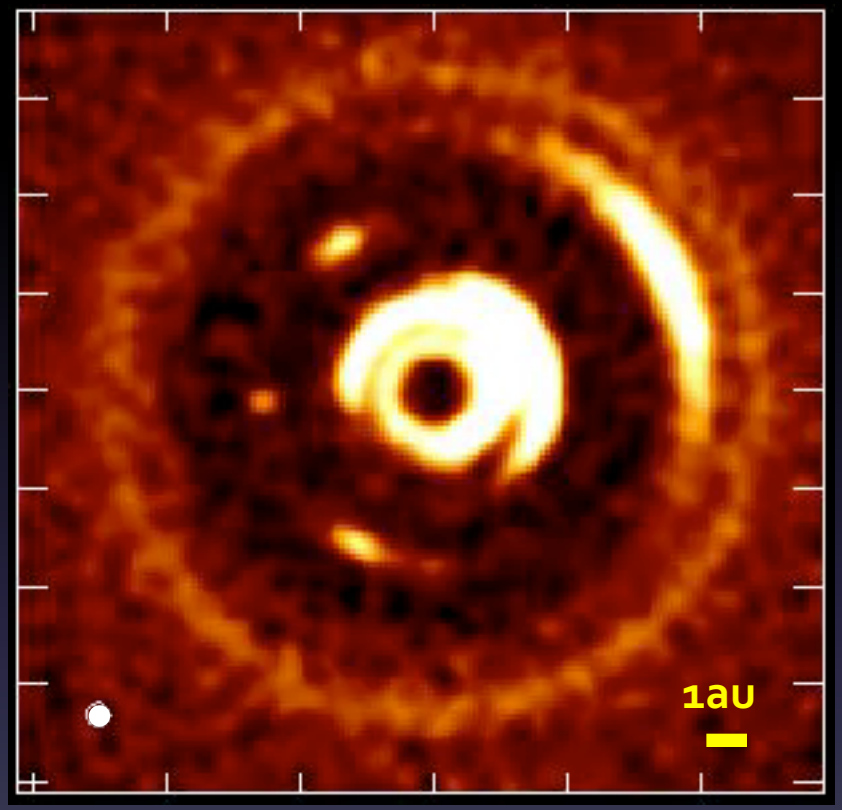
Ricci+ 18

Results: proper motions

ngVLA @ 3mm

(beam = 5mas
rms = 2e-7 Jy/b)

Jupiter @ 5au, $\alpha_{visc}=10^{-5}$



1 frame per month

1 orbit in 12 years

Circum-planetary disk:

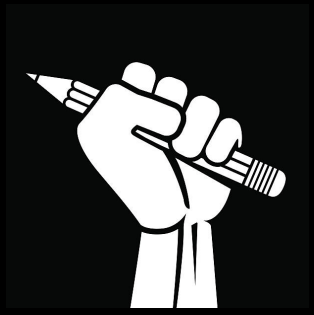
$M_{disk} = 10^{-4} M_{pl}$

$r_{disk} = 0.5\, r_{Hill}$

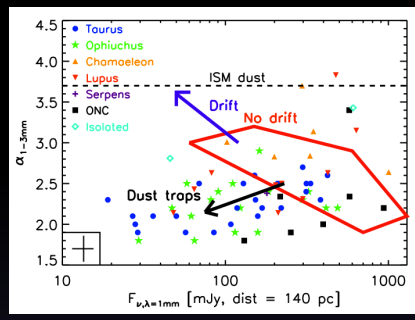
$M_{acc} = 10^{-7} M_{pl}\, yr^{-1}$

Tests to models of triggered planet/planetesimals formation

Take away messages

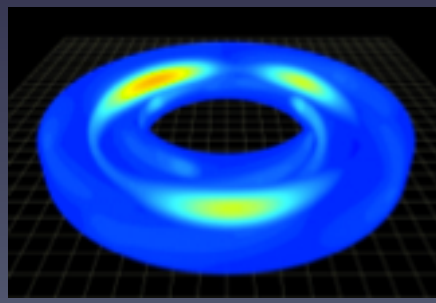


- mm-wave photometry of disks around young stars and BDs already required "dust traps" in the outer disk



- All disks show substructures at scales < 20 au, rings/gaps very common, some disks show azimuthal asymmetries; with ngVLA gaps due to ~ 5 M_{Earth} planets at < 10 au

- Theory & obs effort to pinpoint nature/origin and their role in planet formation



ALMA and VLA Community Event

Caltech 2018

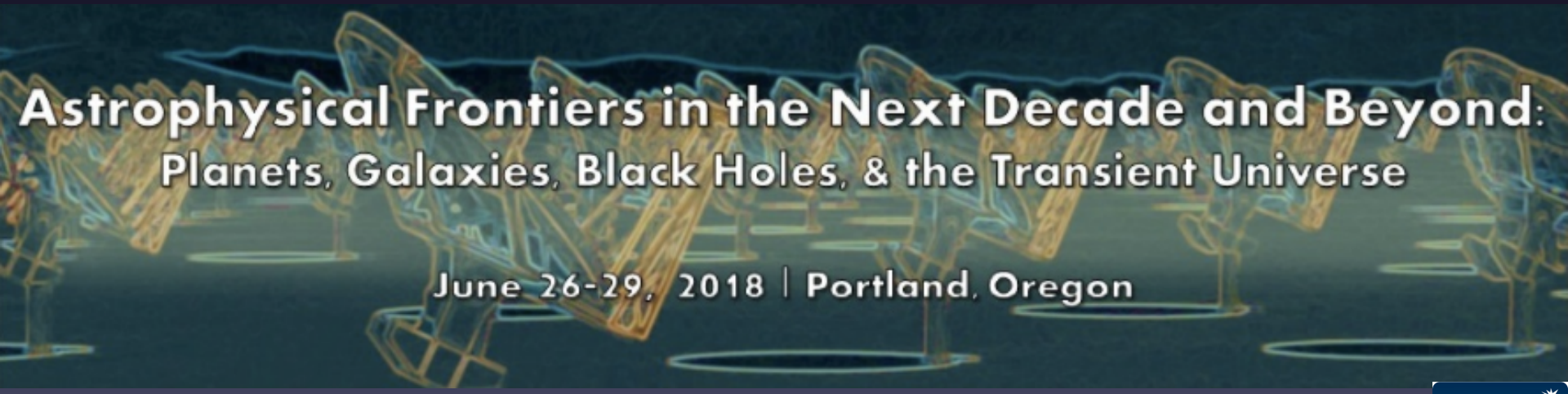
by Dong-Chan Kim — last modified Jan 25, 2018 by Emmanuel Momjian

NRAO and LBO will conduct a two day Community Event hosted by the California Institute of Technology (Caltech) and IPAC at Caltech on **March 27 and 28, 2018**.

Space is limited to 40 participants and registrations will be accepted on first come first serve bases; please contact the organizers for an invitation, if interested.

The registration deadline is March 12, 2018.

https://science.nrao.edu/science/meetings/2018/caltech18



NRAO