

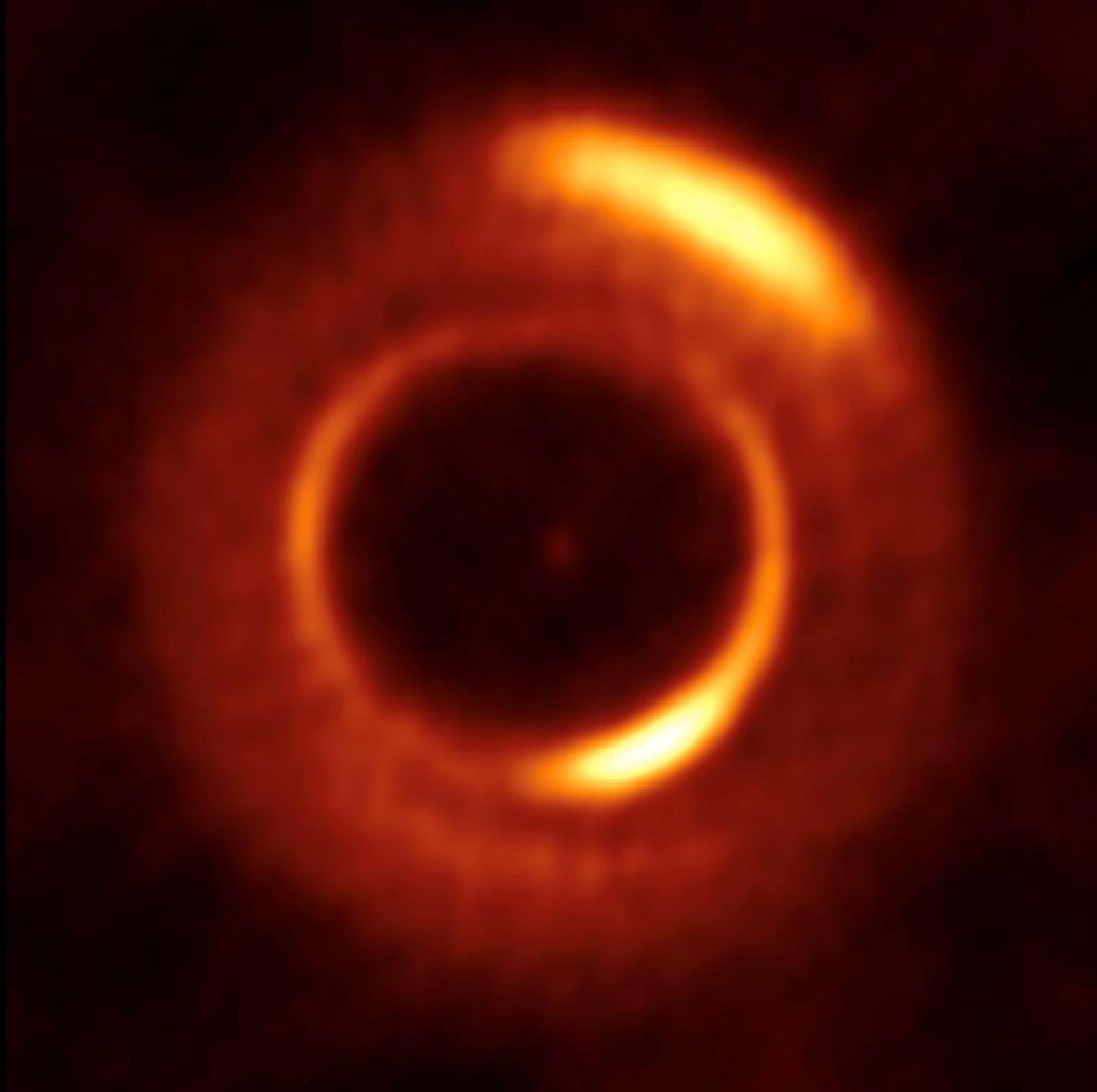
3D simulations of planet formation by vortex trapping



Wladimir Lyra
New Mexico State University



MWC 758



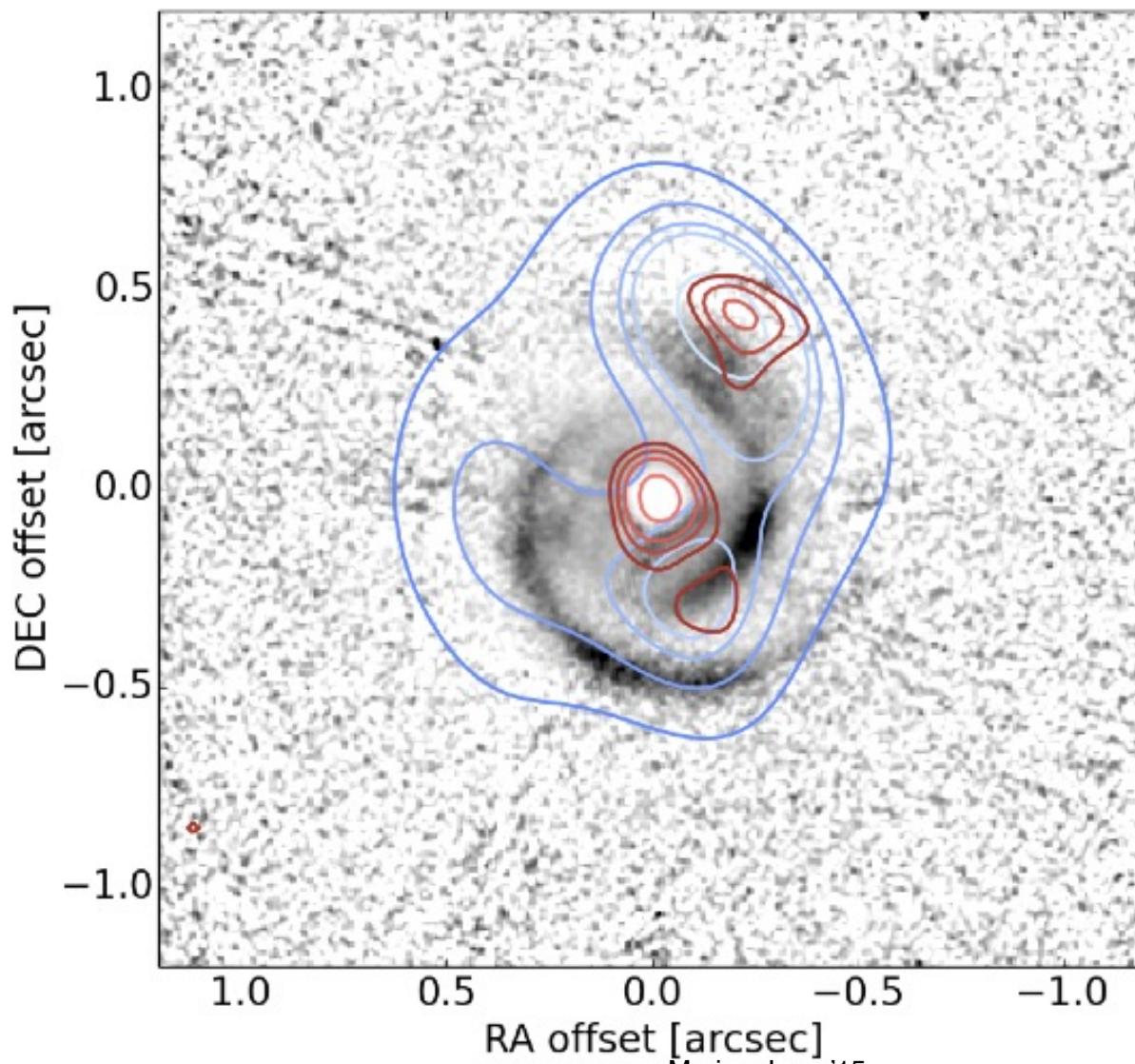
Disk Tomography

SPHERE-ALMA-VLA overlay of MWC 758

SPHERE (μm)

ALMA ($\sim \text{mm}$)

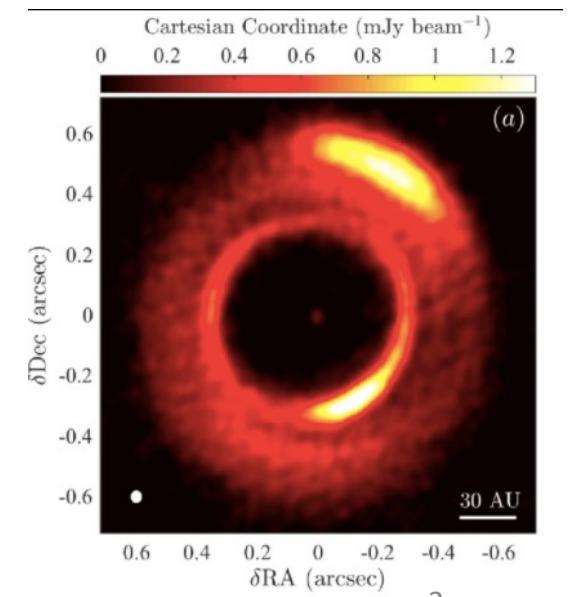
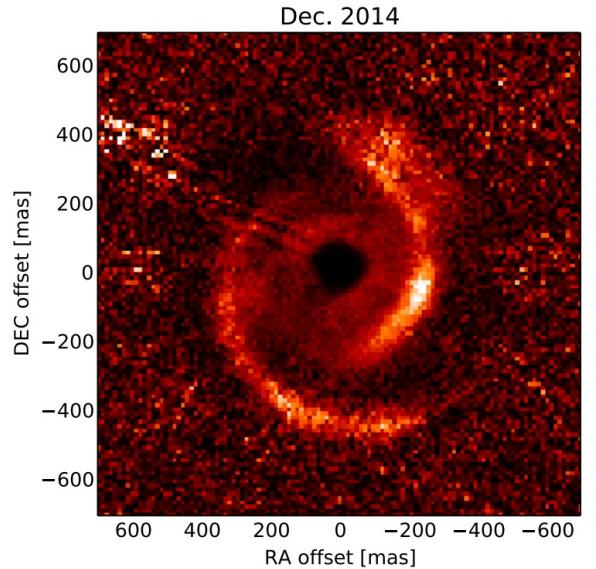
VLA (cm-m)



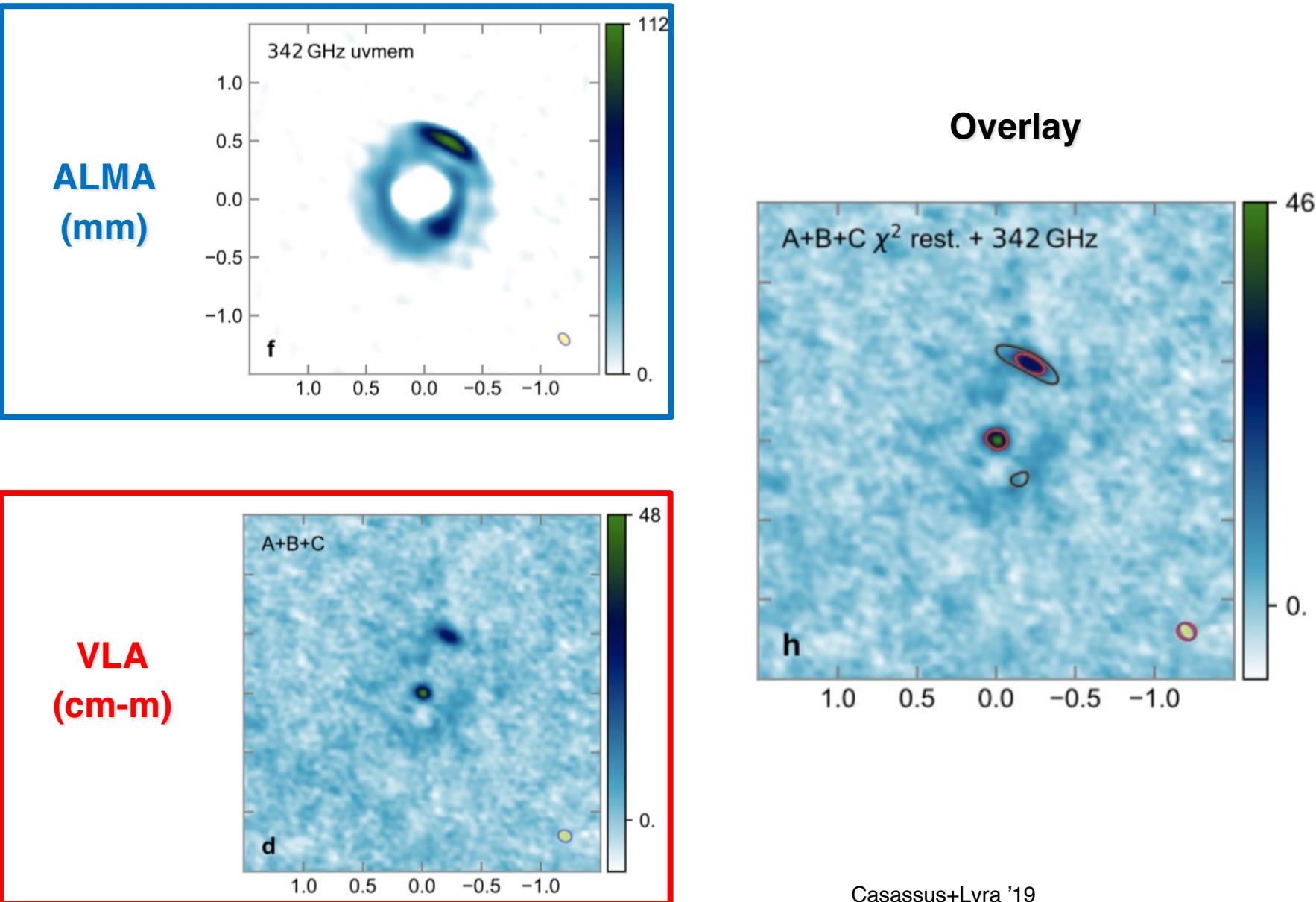
SPHERE

ALMA

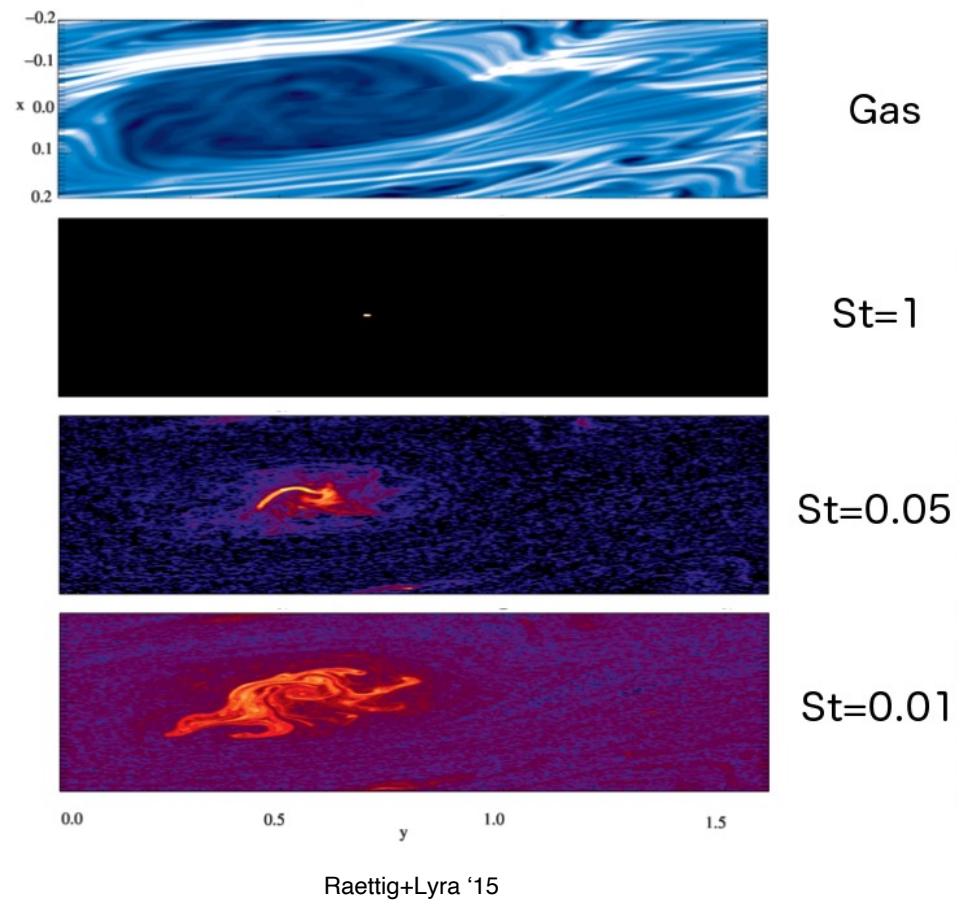
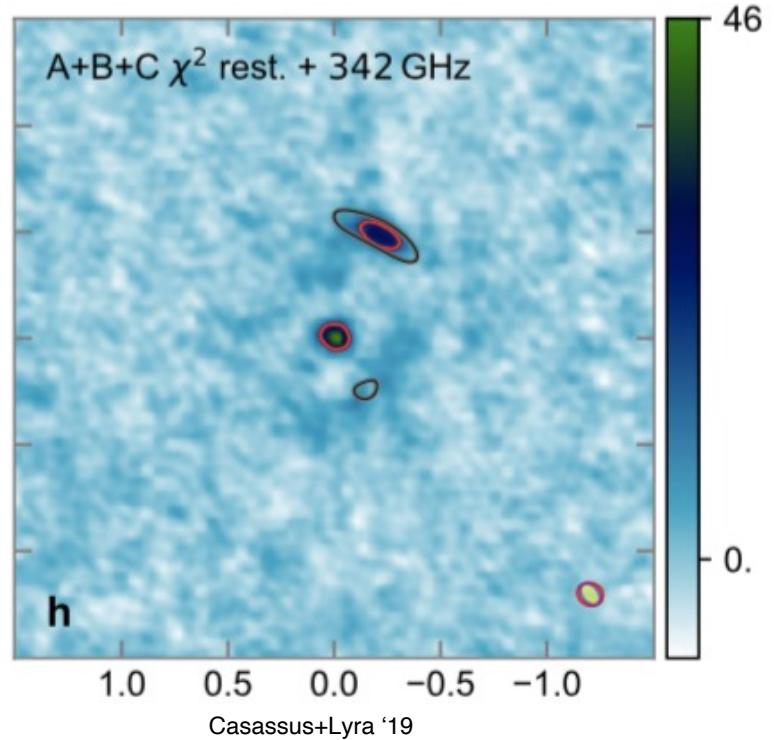
Dec. 2014



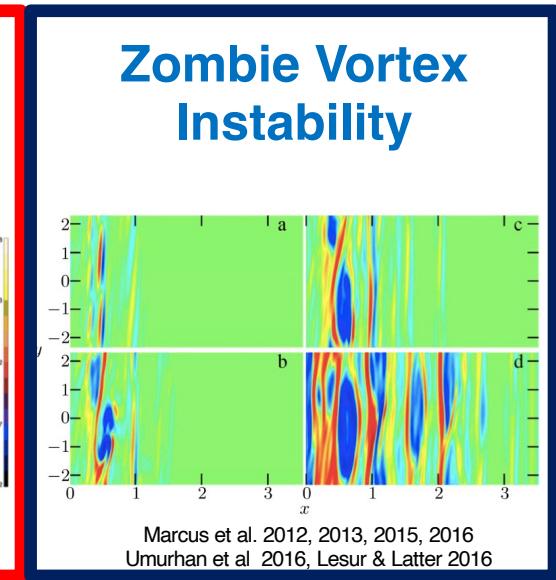
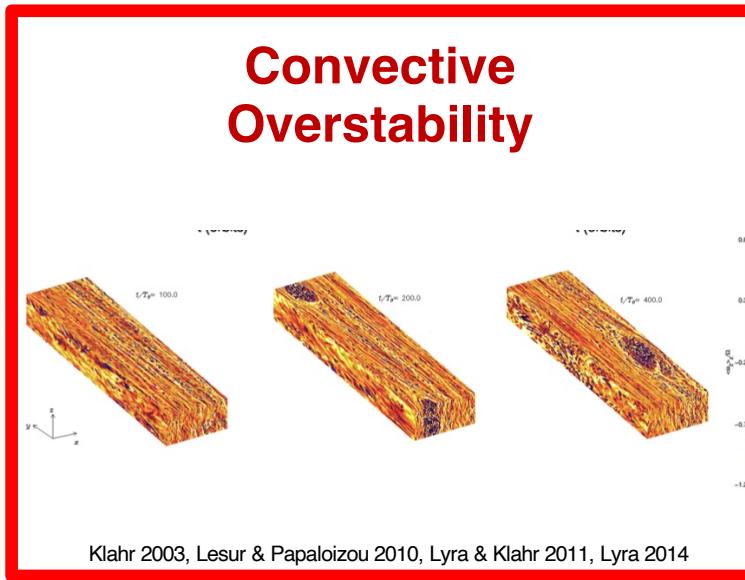
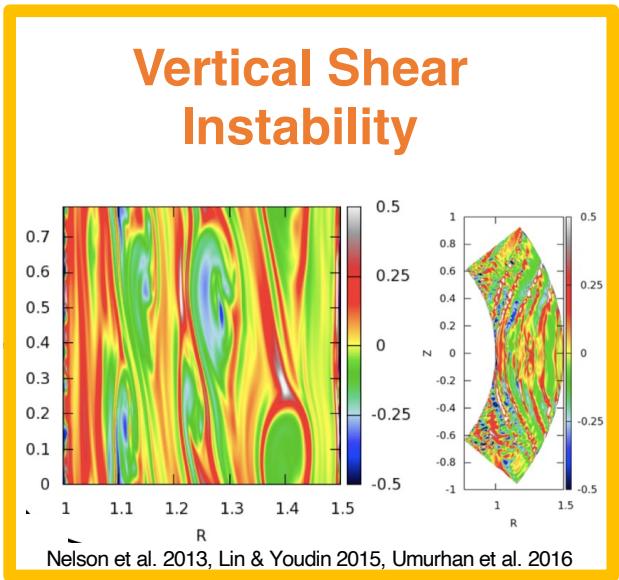
Pebble Trapping ALMA-VLA overlay of MWC 758



Pebble Trapping



Hydrodynamical Instabilities



$\Omega\tau \ll 1$
($\kappa < 1 \text{ cm}^2/\text{g}$)

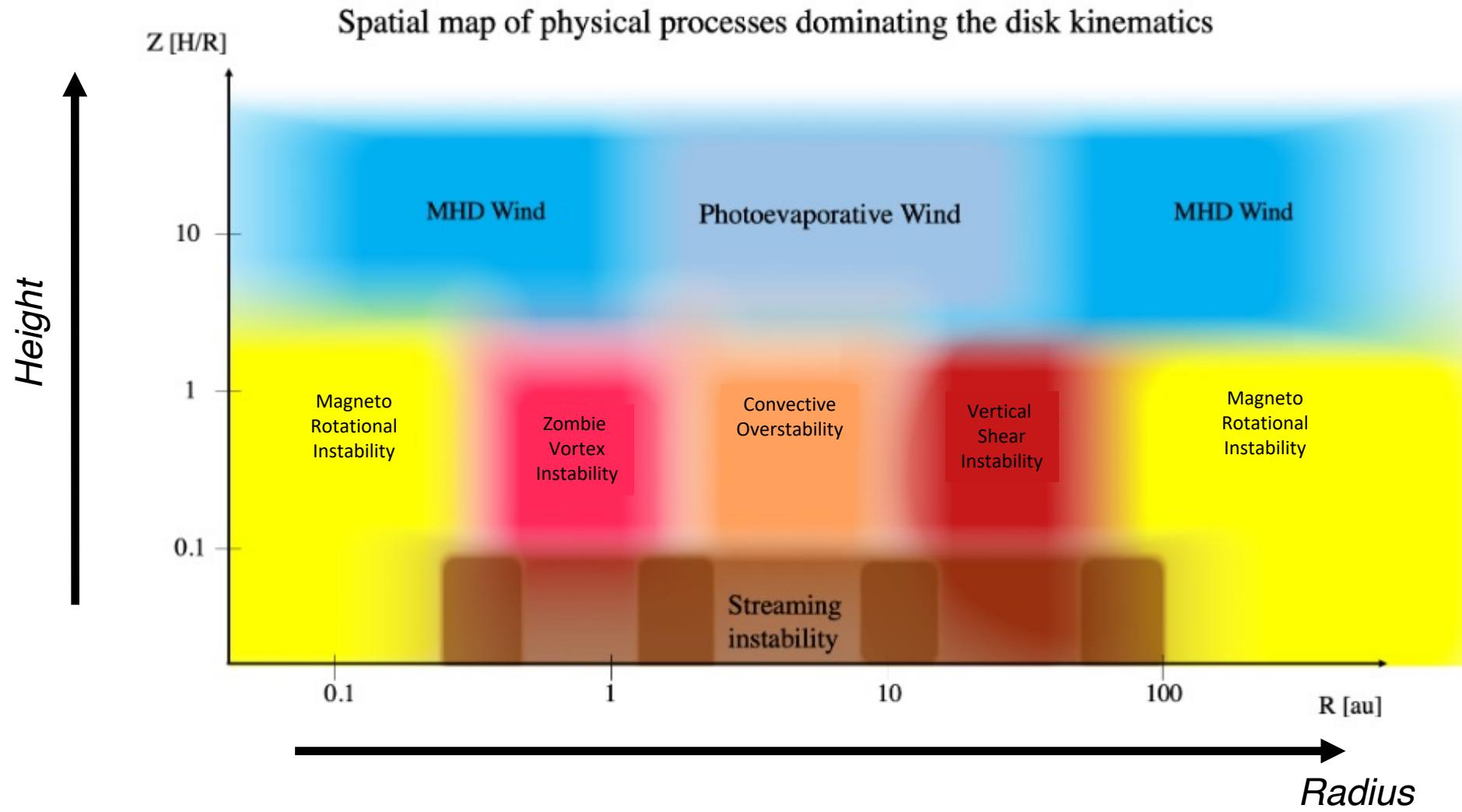
$\Omega\tau \sim 1$
($\kappa \sim 1\text{--}50 \text{ cm}^2/\text{g}$)

$\Omega\tau \gg 1$
($\kappa > 50 \text{ cm}^2/\text{g}$)



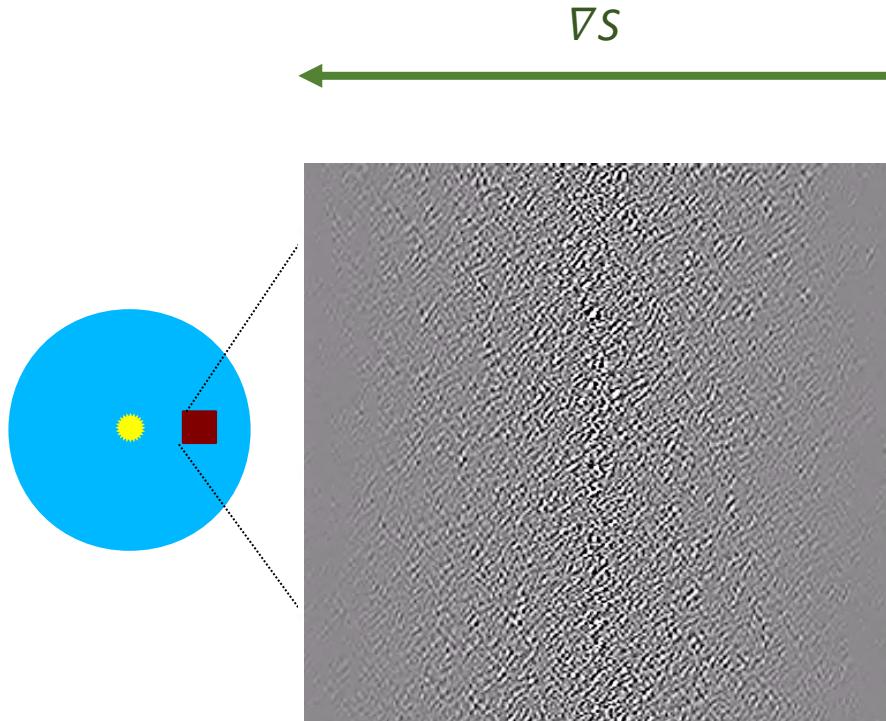
Opacity

Instability Map

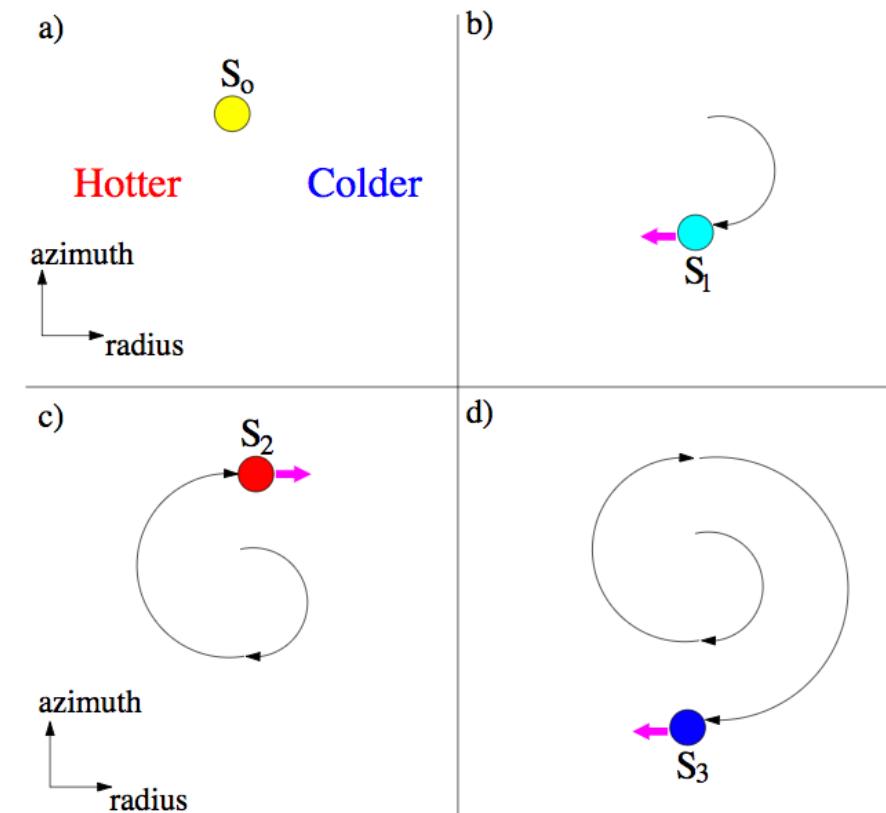


Lesur et al. (2022)

Convective Overstability



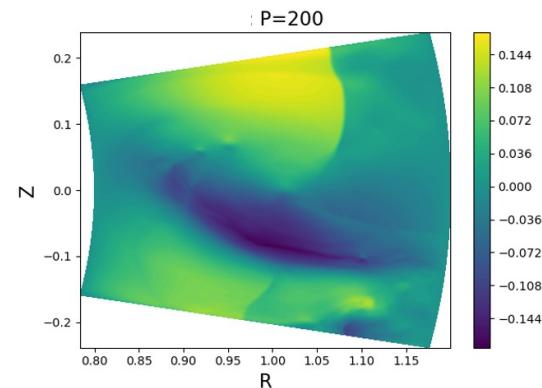
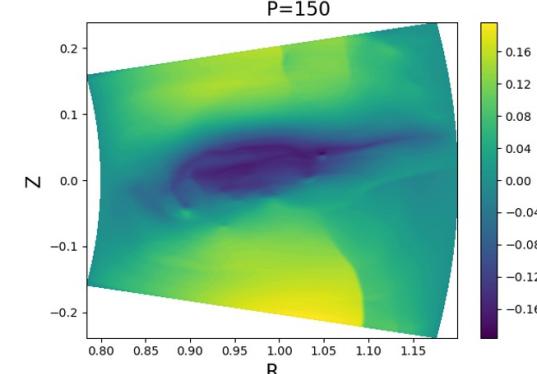
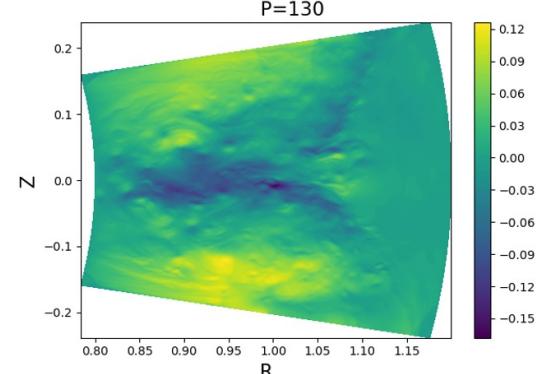
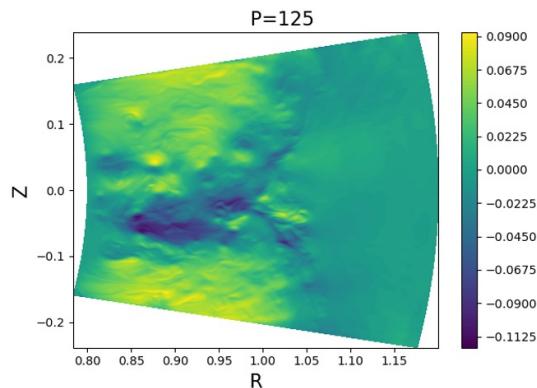
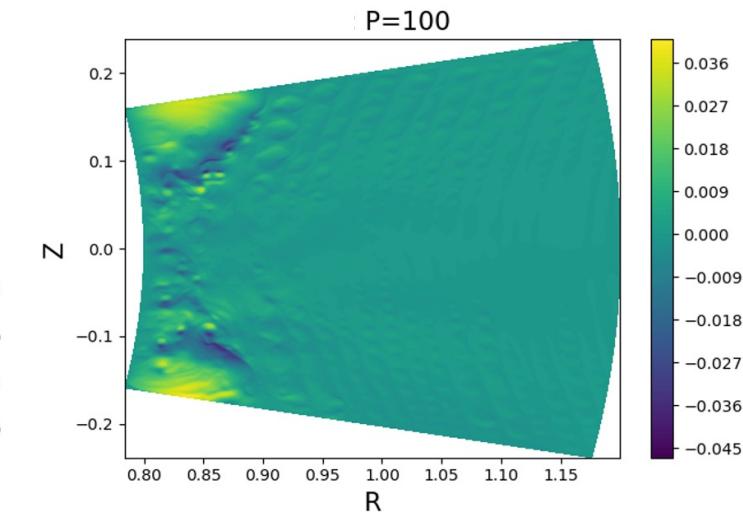
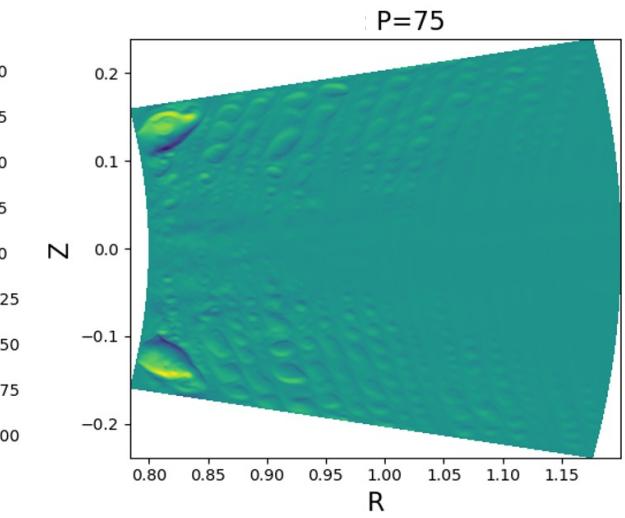
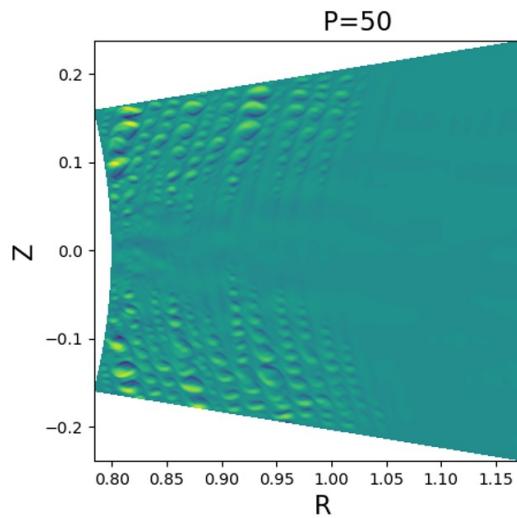
Lesur & Papaloizou (2010)
Lyra & Klahr (2011)
Klahr & Hubbard (2014)
Lyra (2014)
Latter (2016)
Volponi (2016)
Reed & Latter (2021)
Raettig et al. (2021)



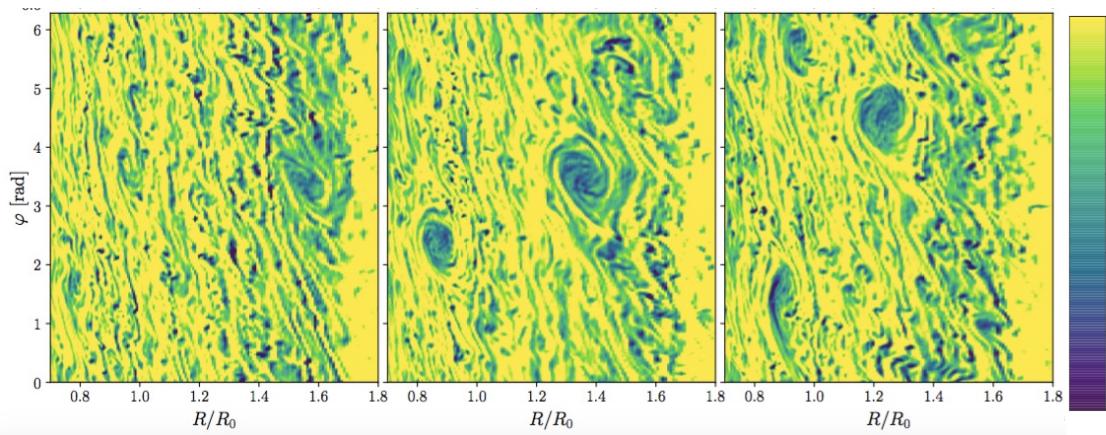
Latter (2016)

Global models of Convective Overstability

Radial Velocity contours

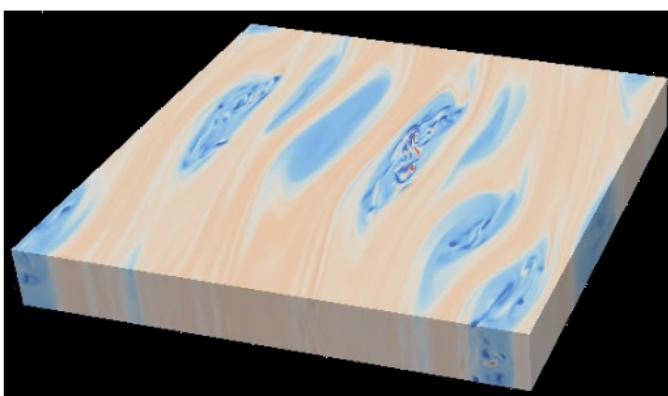


Saturation



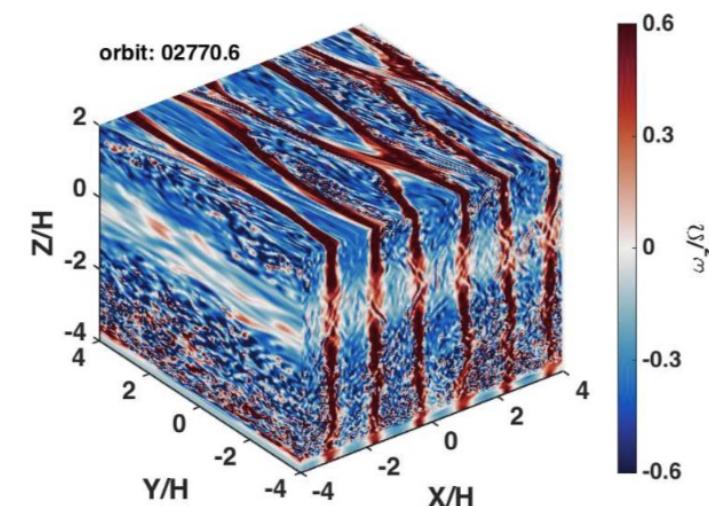
Manger & Klahr (2018)

Vertical Shear Instability
saturates into **vortices**



Lesur & Papaloizou (2010)

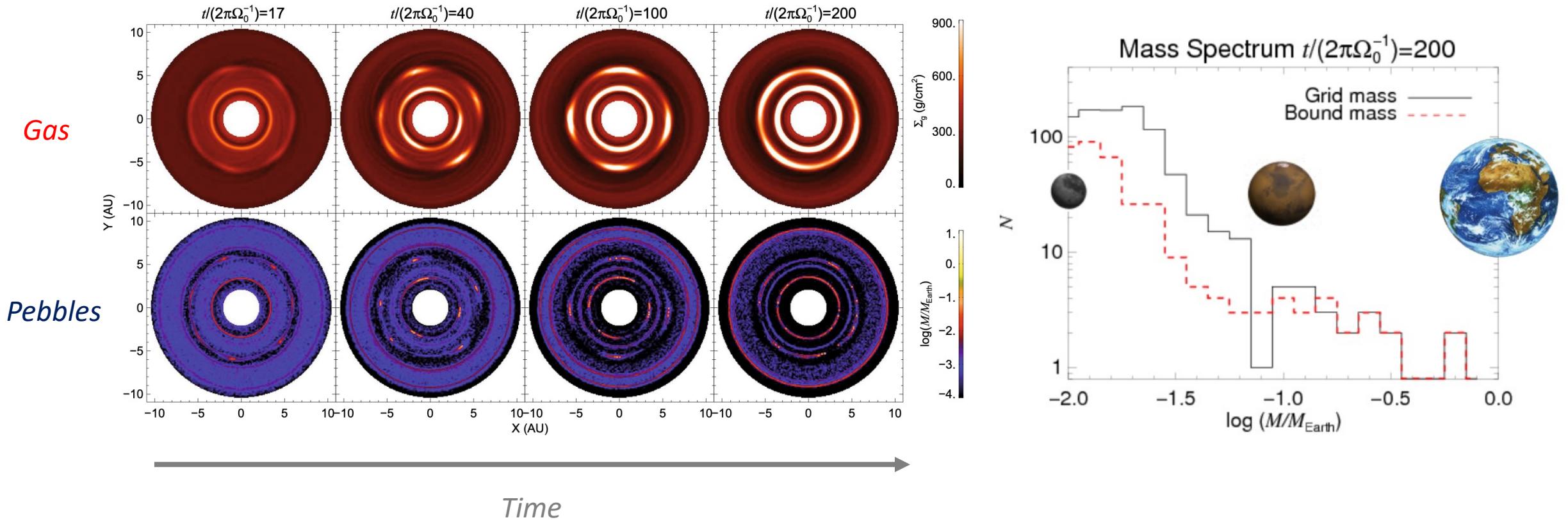
Zombie Vortex Instability
saturates into **vortices**



Barranco et al. (2019)

Convective Overinstability
saturates into **vortices**

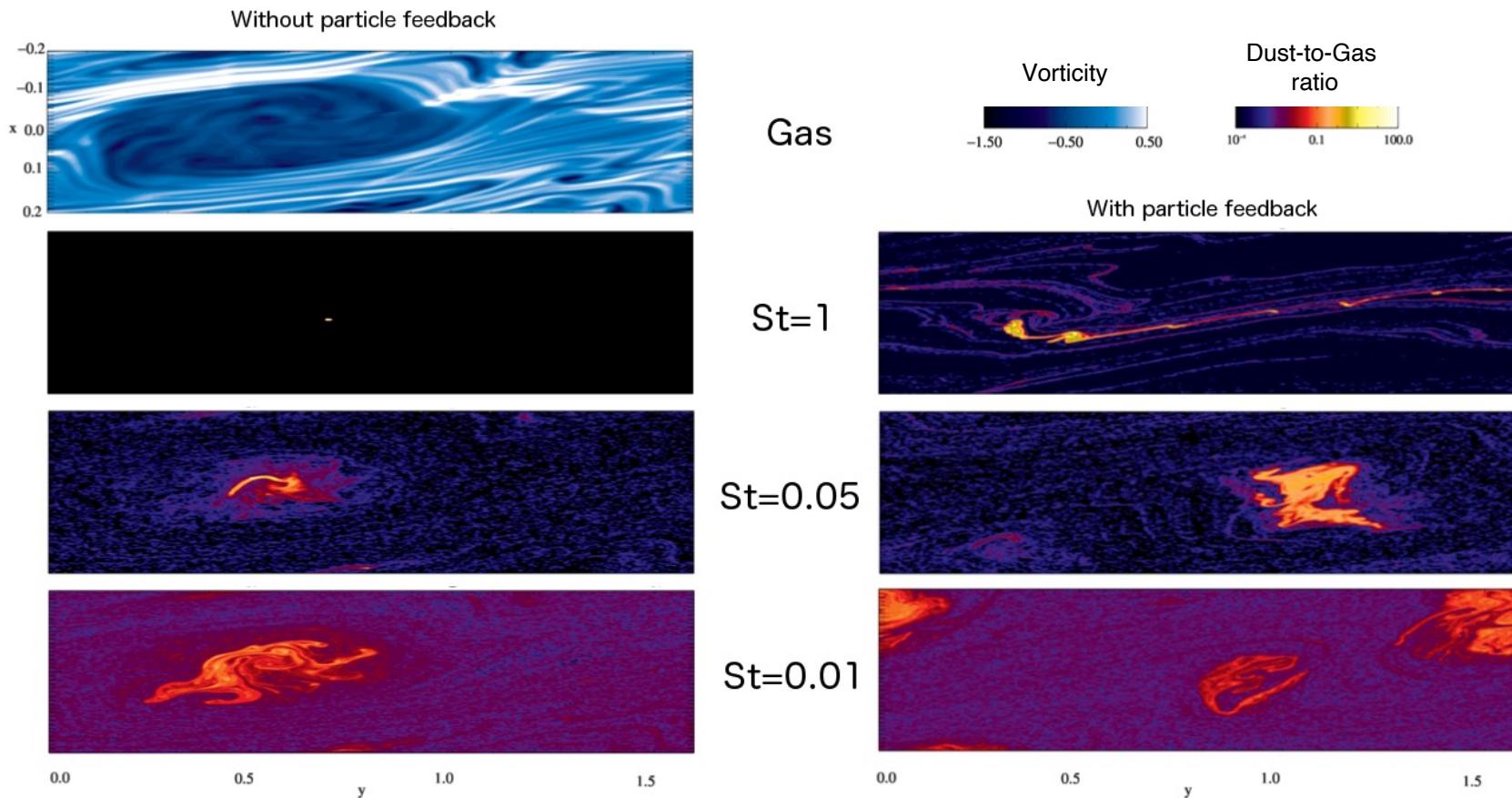
Vortices and Planet Formation Results from Classical Antiquity



Lyra et al. (2008)

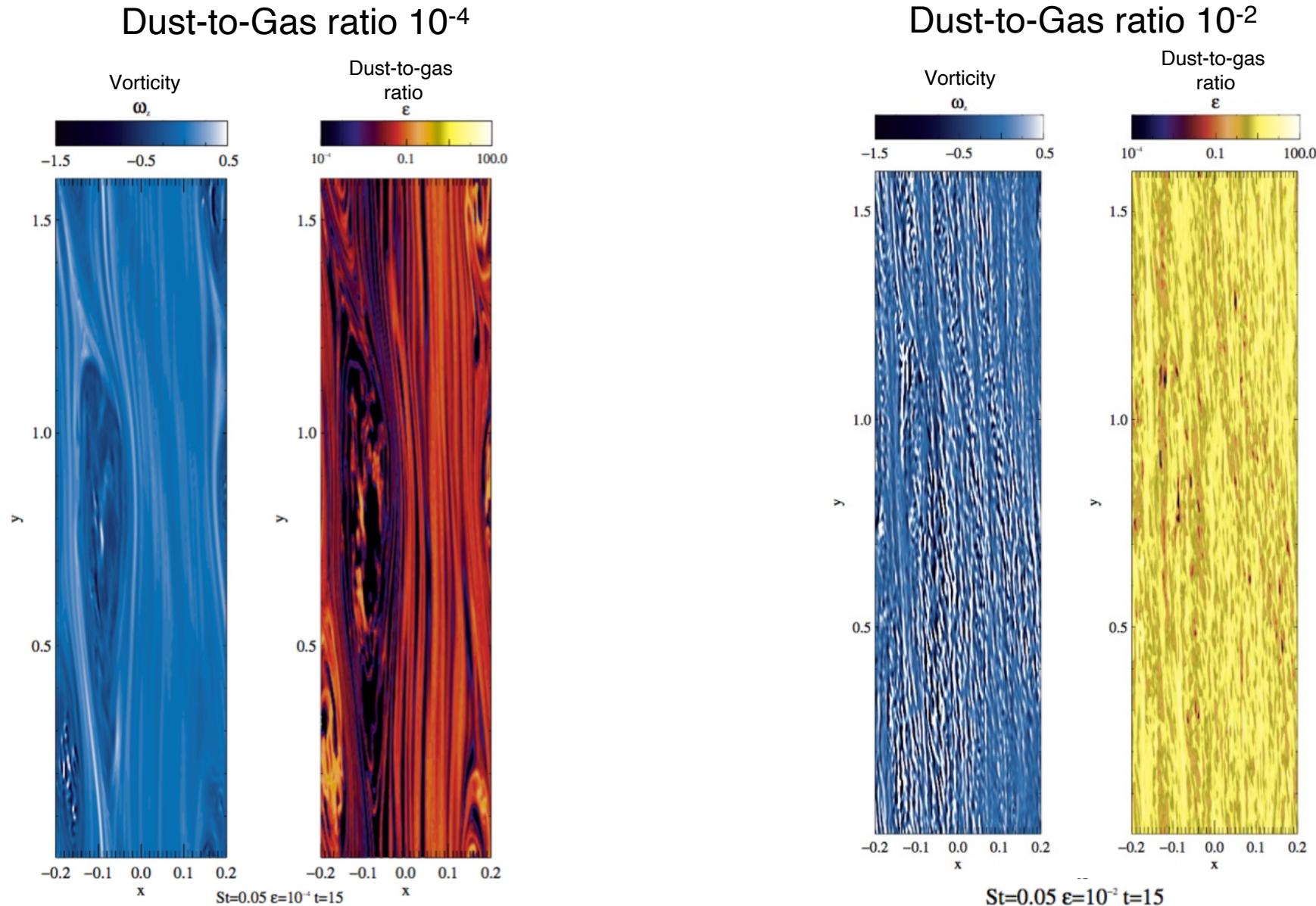
10

Pebble trapping in vortices in LOCAL models



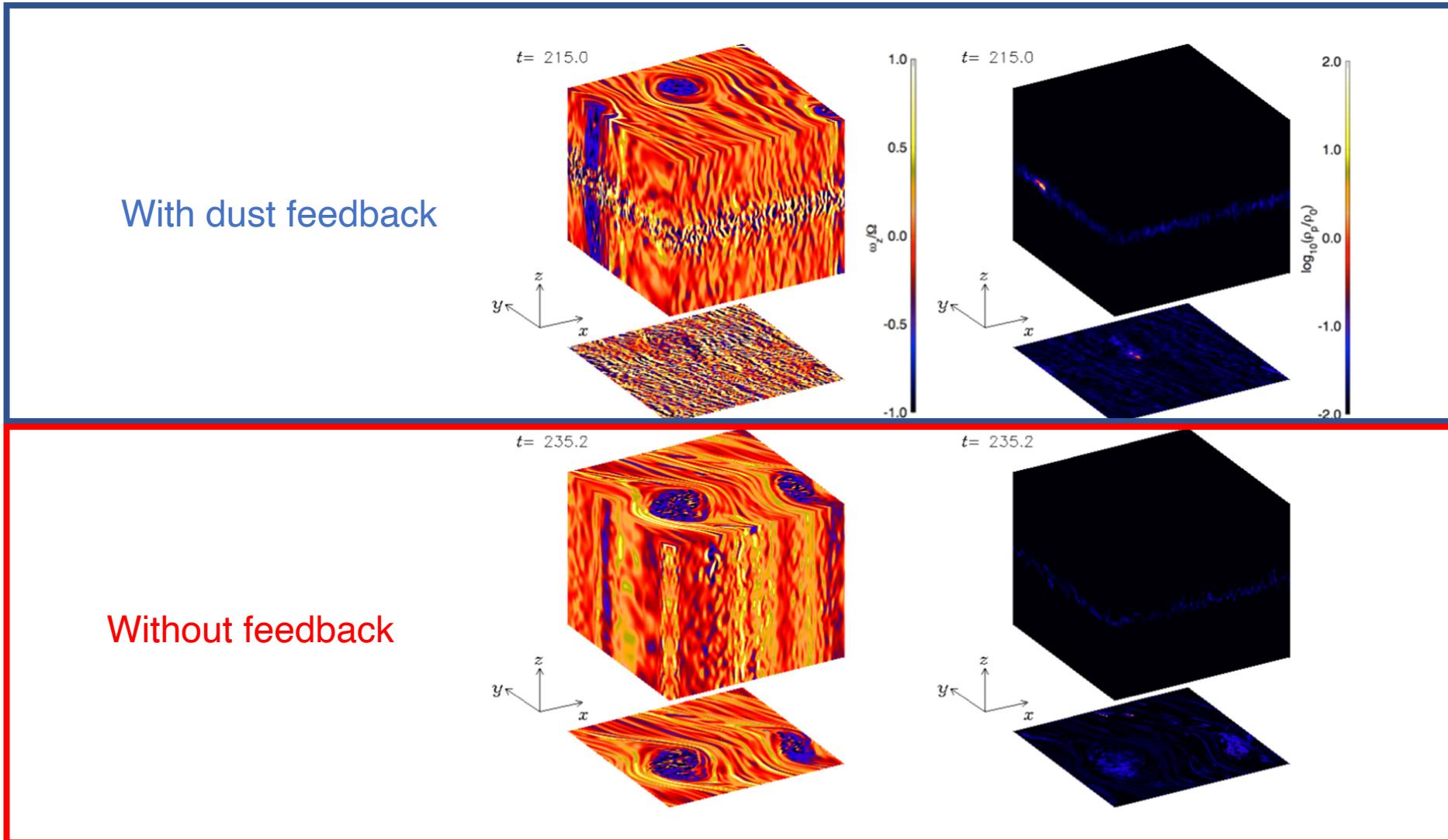
Raettig et al (2015)

Vortex destruction at high dust load?

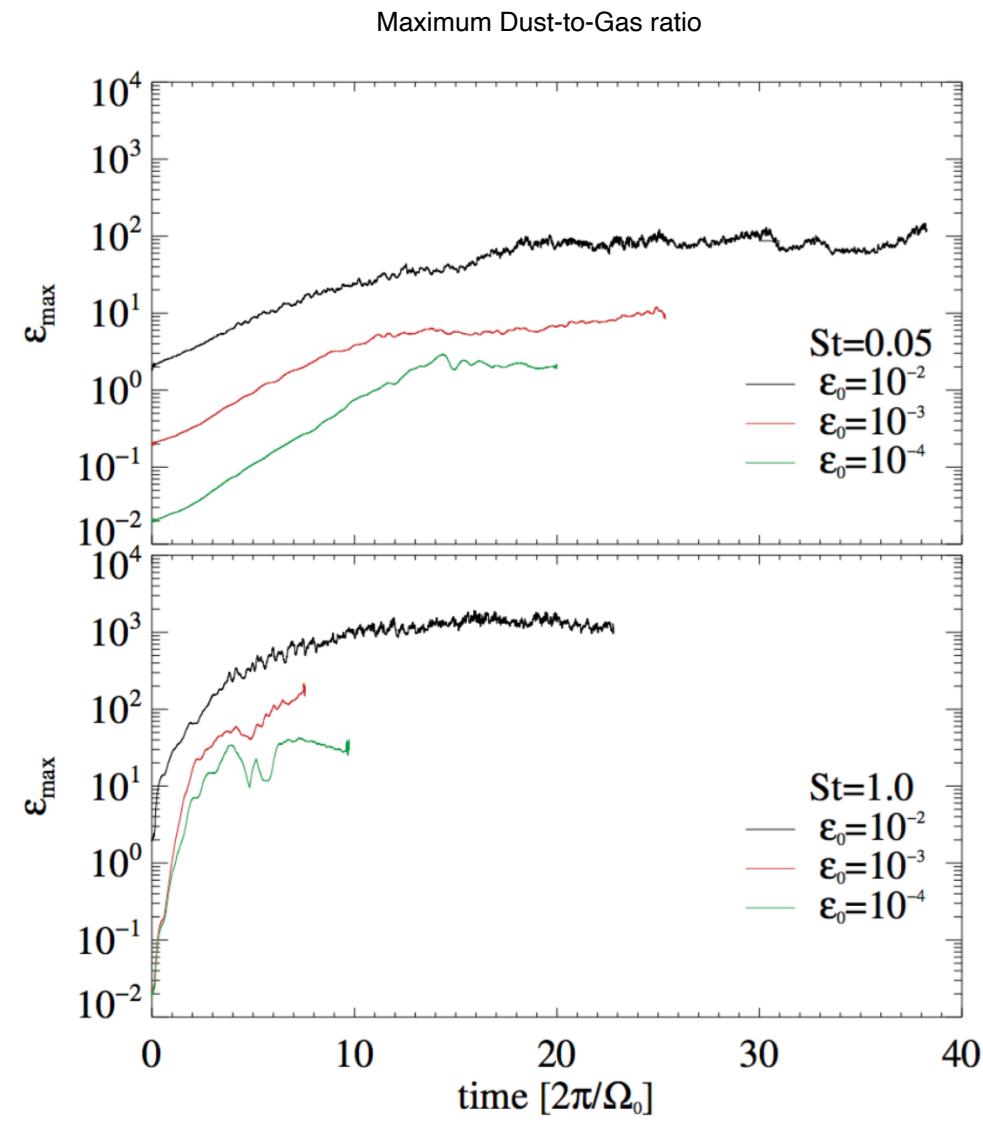
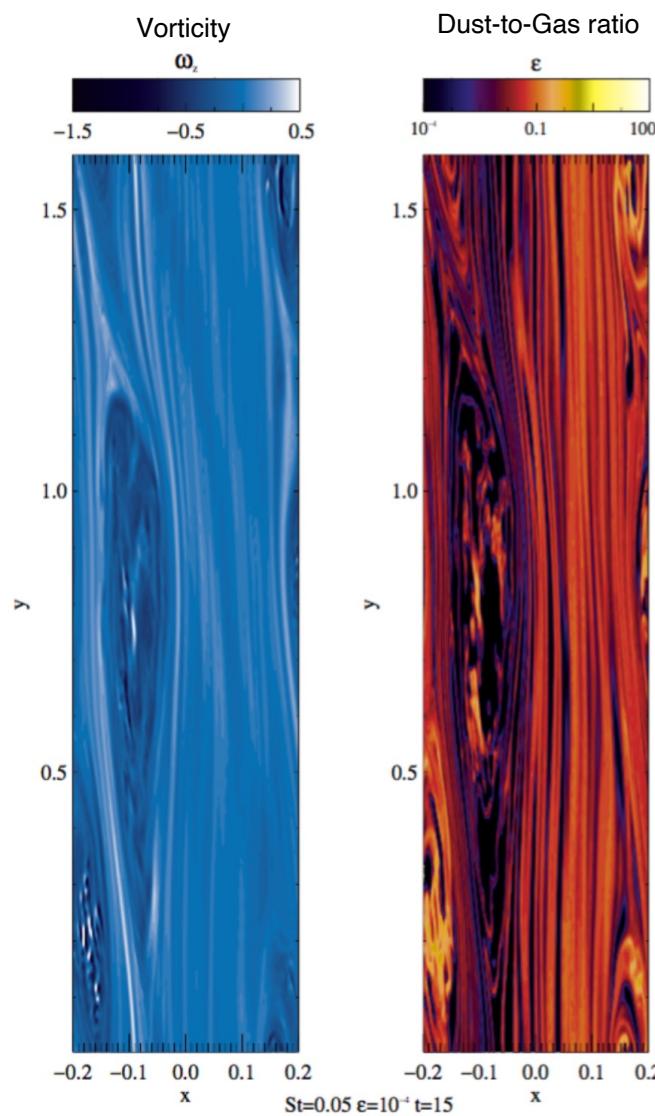


Raettig et al (2015)

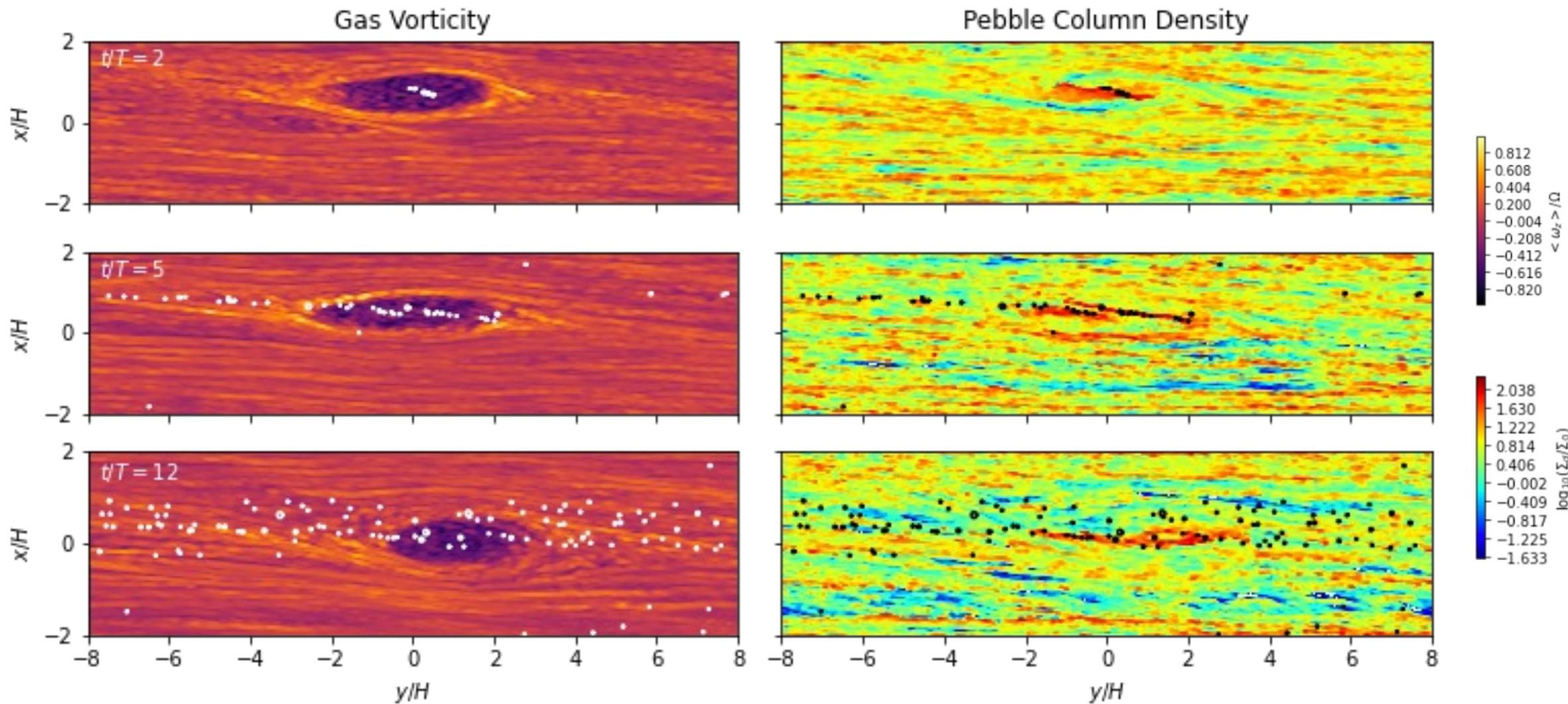
Pebble trapping does not destroy vortices



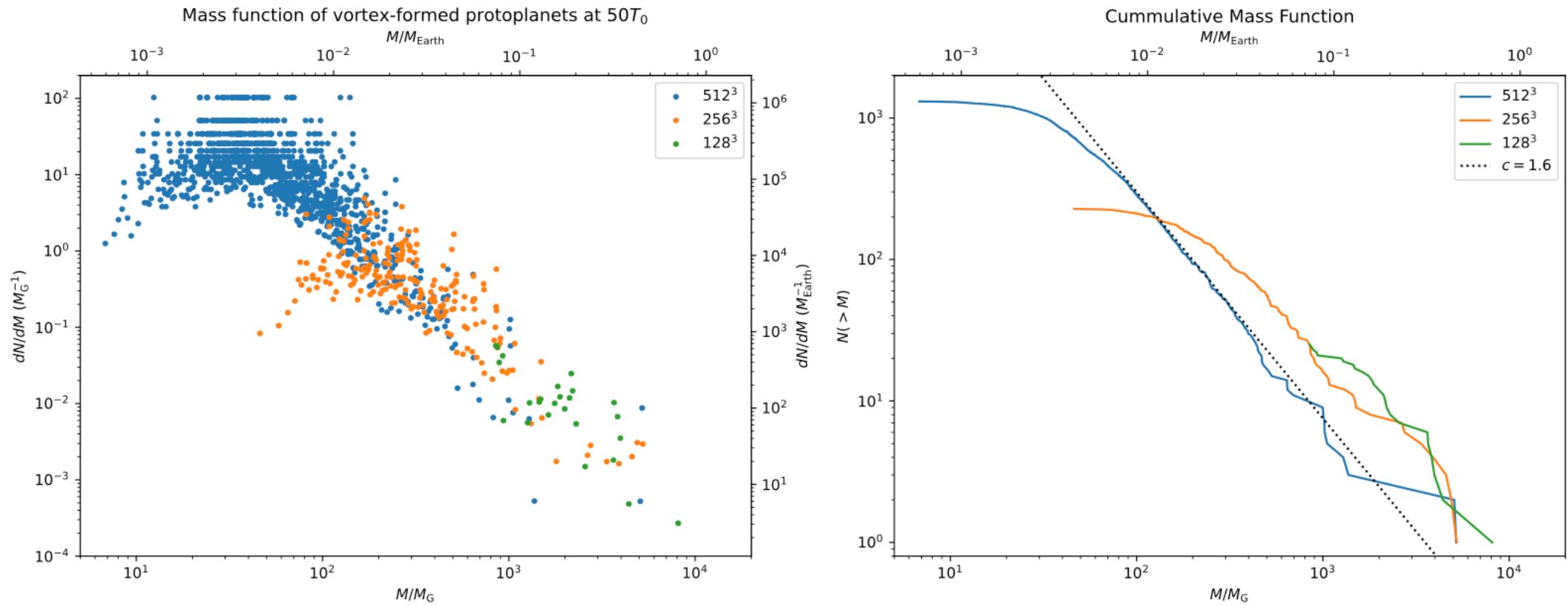
Pebble trapping in 3D vortices



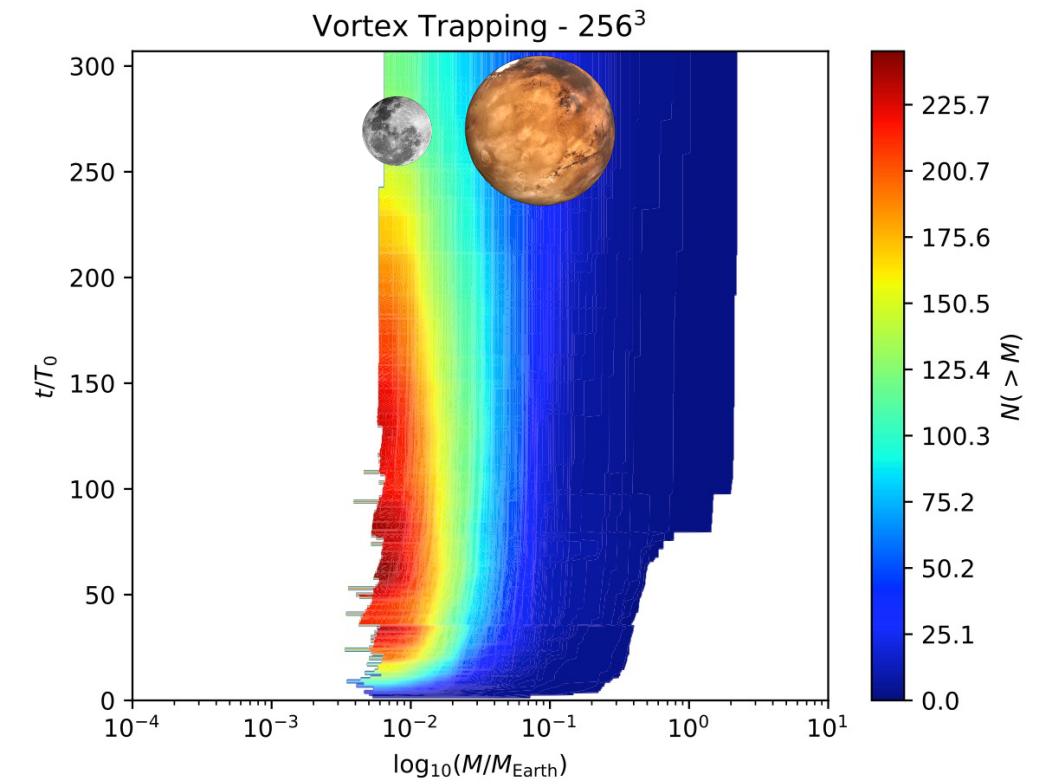
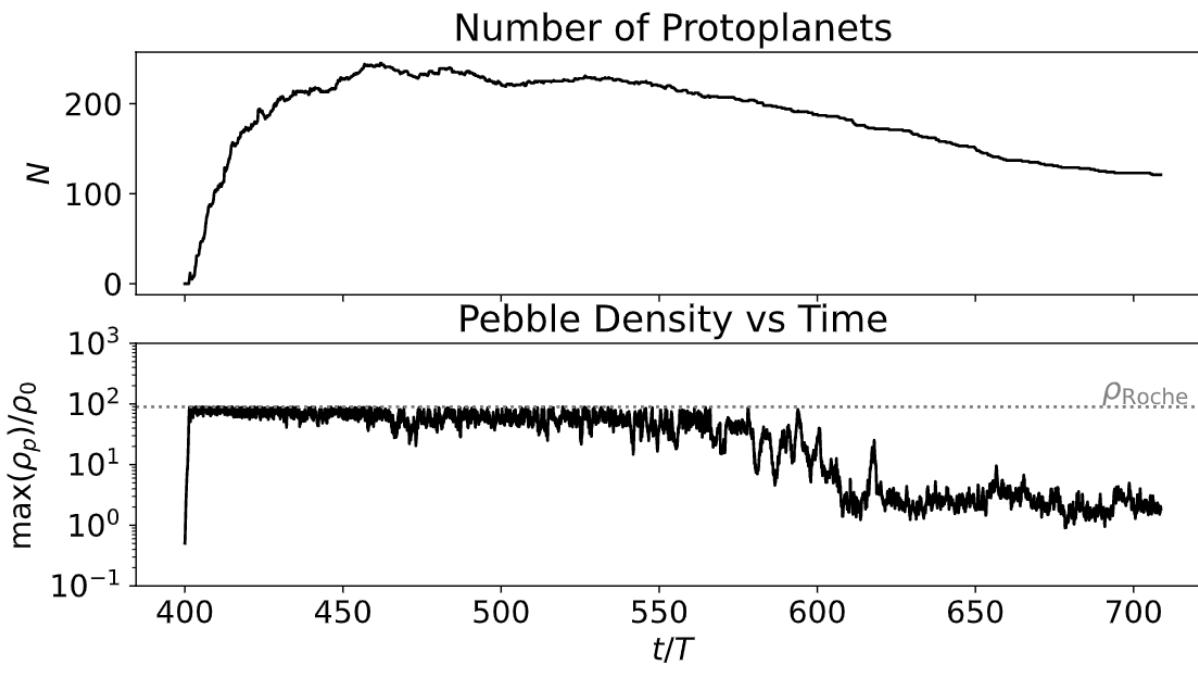
Including selfgravity: Direct Gravitational Collapse



Vortex Trapping – Initial Mass Function

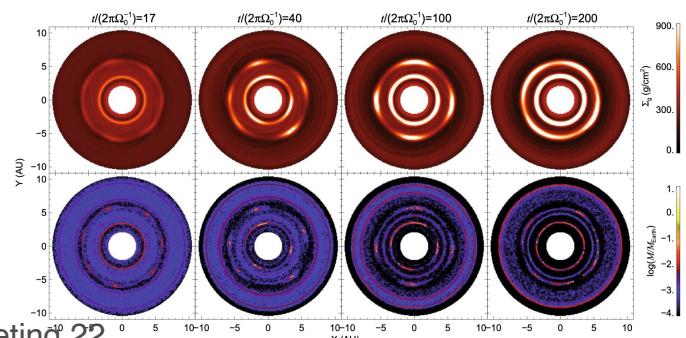
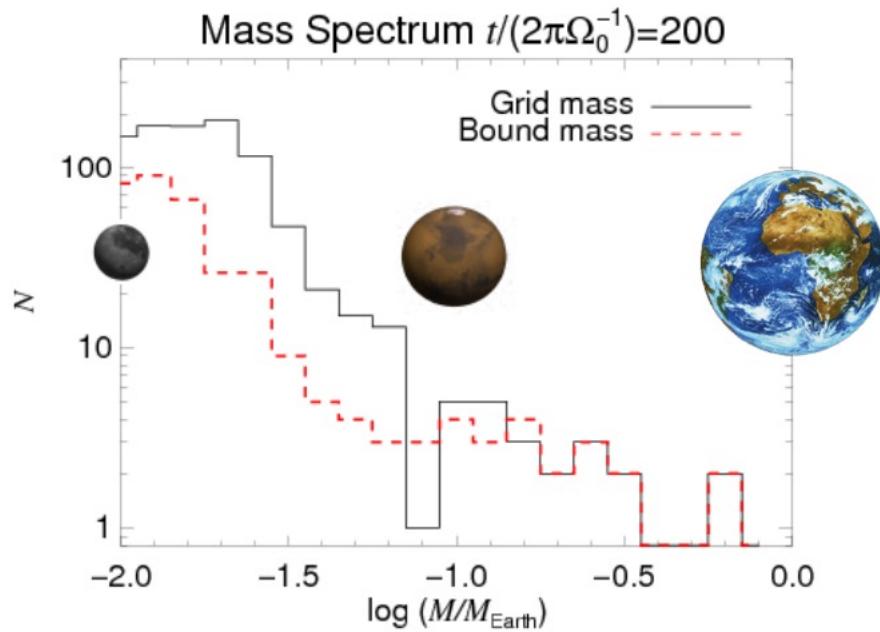


Initial Mass Function – Convergence

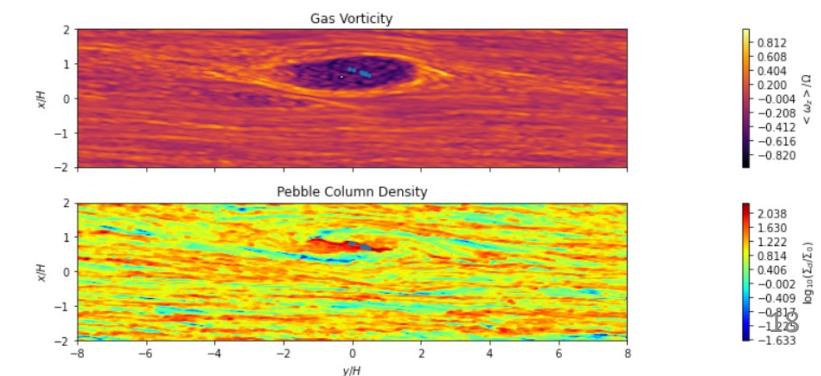
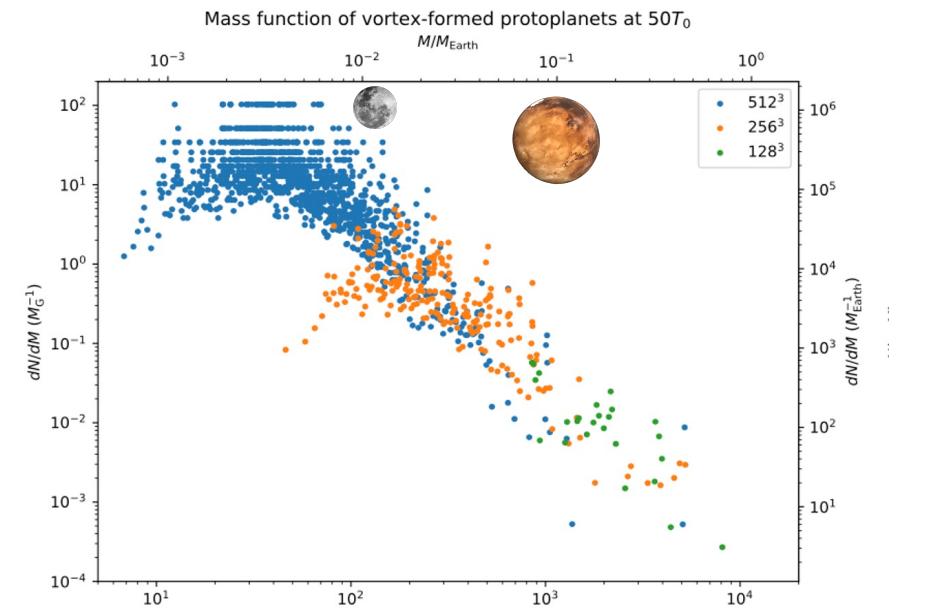


Initial Mass Function

Global 2D, Lyra et al. 2008



Local 3D, Lyra et al. in prep



Conclusions

- **Vertical Shear Instability and Convective Overstability may be relevant for planet formation**
 - Vertical Shear Instability: rapid cooling + radial temperature gradient
 - Convective Overstability finite cooling time + radial entropy gradient
 - Saturate into vortices
- **Vortices are very efficient pebble traps**
 - High particle load disrupts vertical motion around midplane, but not the full column
 - Trapping properties are retained
 - The pebble load is high enough to lead to direct gravitational collapse
- **Planet population is of planetary embryo mass**
 - Moon to Mars mass objects
 - Resolved simulation in both gas and pebbles
- **Limitations**
 - Streaming Instability not resolved
 - Coagulation/Fragmentation not modeled

The TCAN-2020 Planet Formation Collaboration



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