Dust Particle Dynamics in Turbulent Protoplanetary Disks

Zhaohuan Zhu

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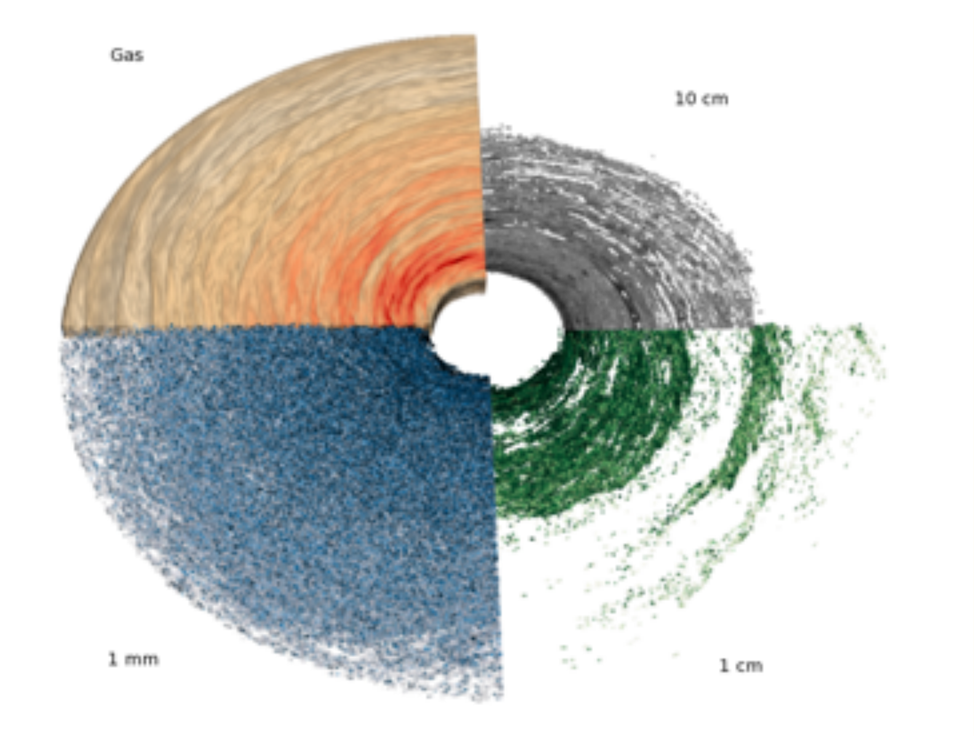
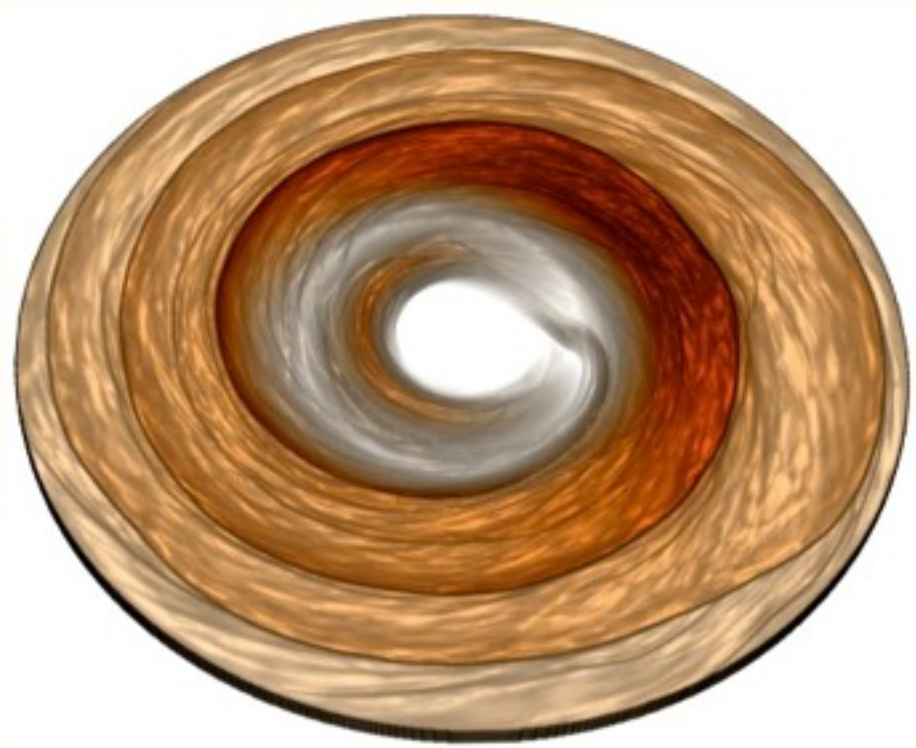
Collaborators:

Jim Stone, Roman Rafikov, Xuening Bai, Ruobing Dong

Lee Hartmann, Nuria Calvet, Catherine Espaillat, Richard Nelson



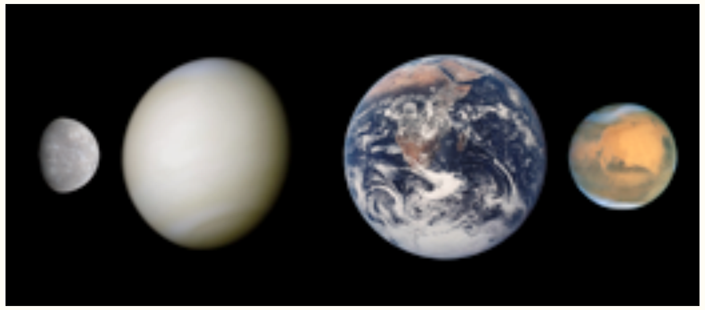


Outlines

- Why dust particle dynamics is important?
- Dust particle dynamics in MRI turbulent flows
- Dust particle dynamics in MRI turbulent disks with the presence of a planet

Why dust particle dynamics is important?

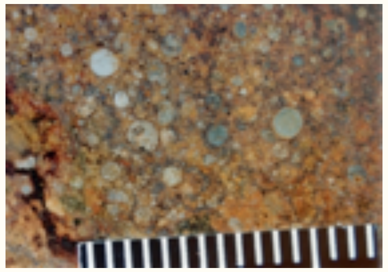
- Planet Formation:



Terrestrial planets are made of solids

Giant planets need 10 M_{earth} rocky cores in the core accretion scenario

- Meteoritics



Almost all about solids (Chondrule, CAIs)

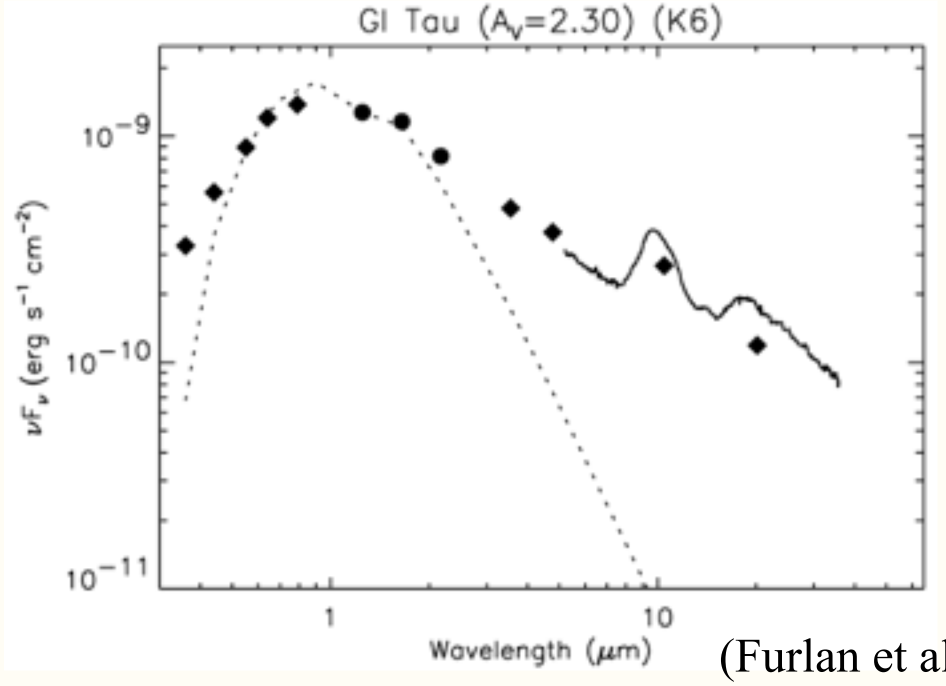
Age and composition of the Solar systems

- Astrochemistry

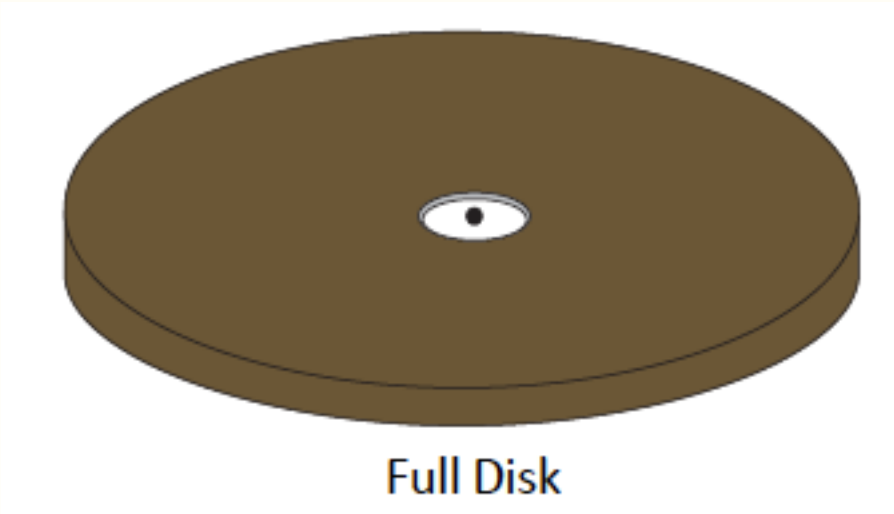
Ionization Calculations, Molecules, Grain surface reactions

• Observations

Observational evidence that dust and gas decouple in protoplanetary disks



(Furlan et al 2006)



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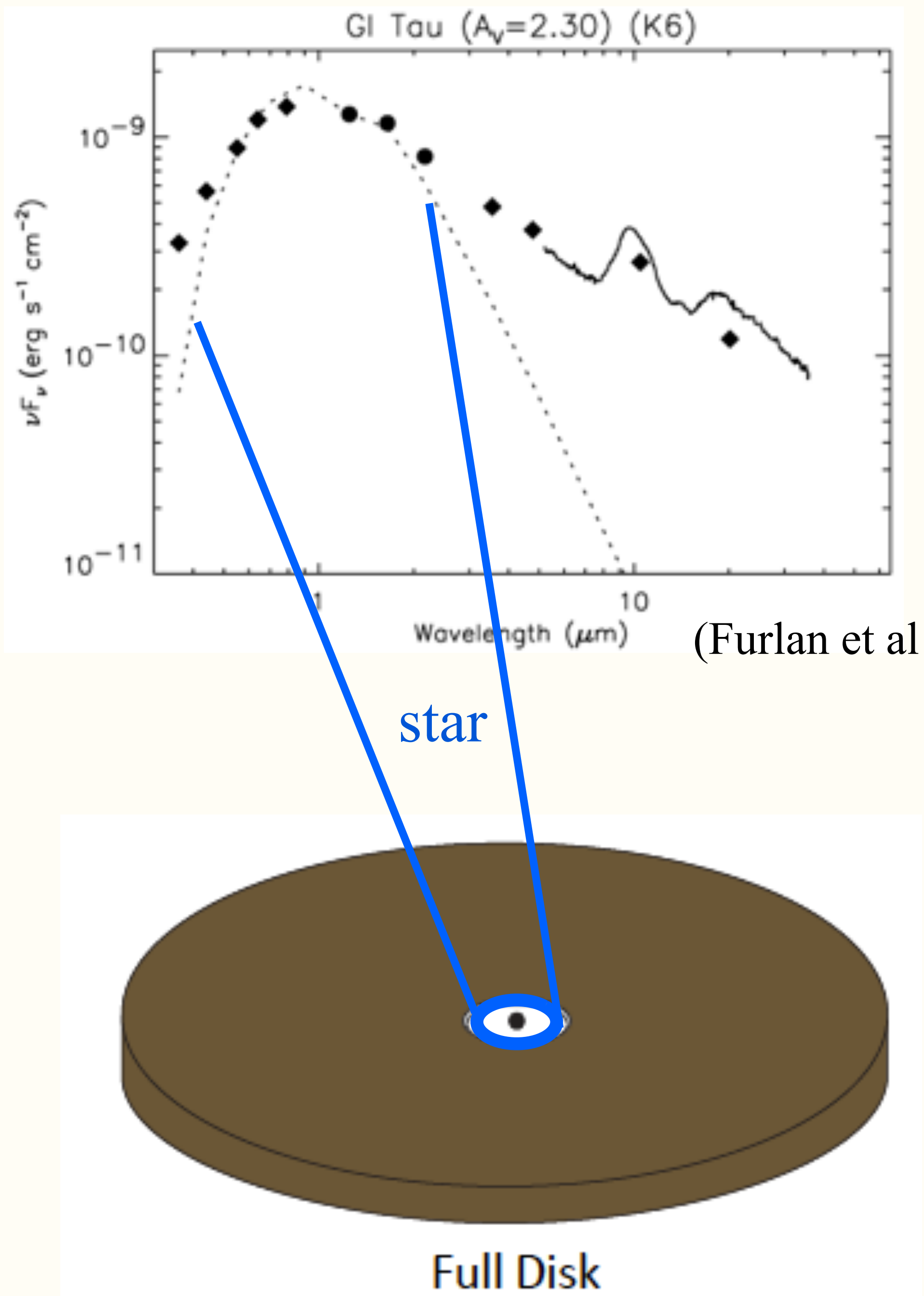

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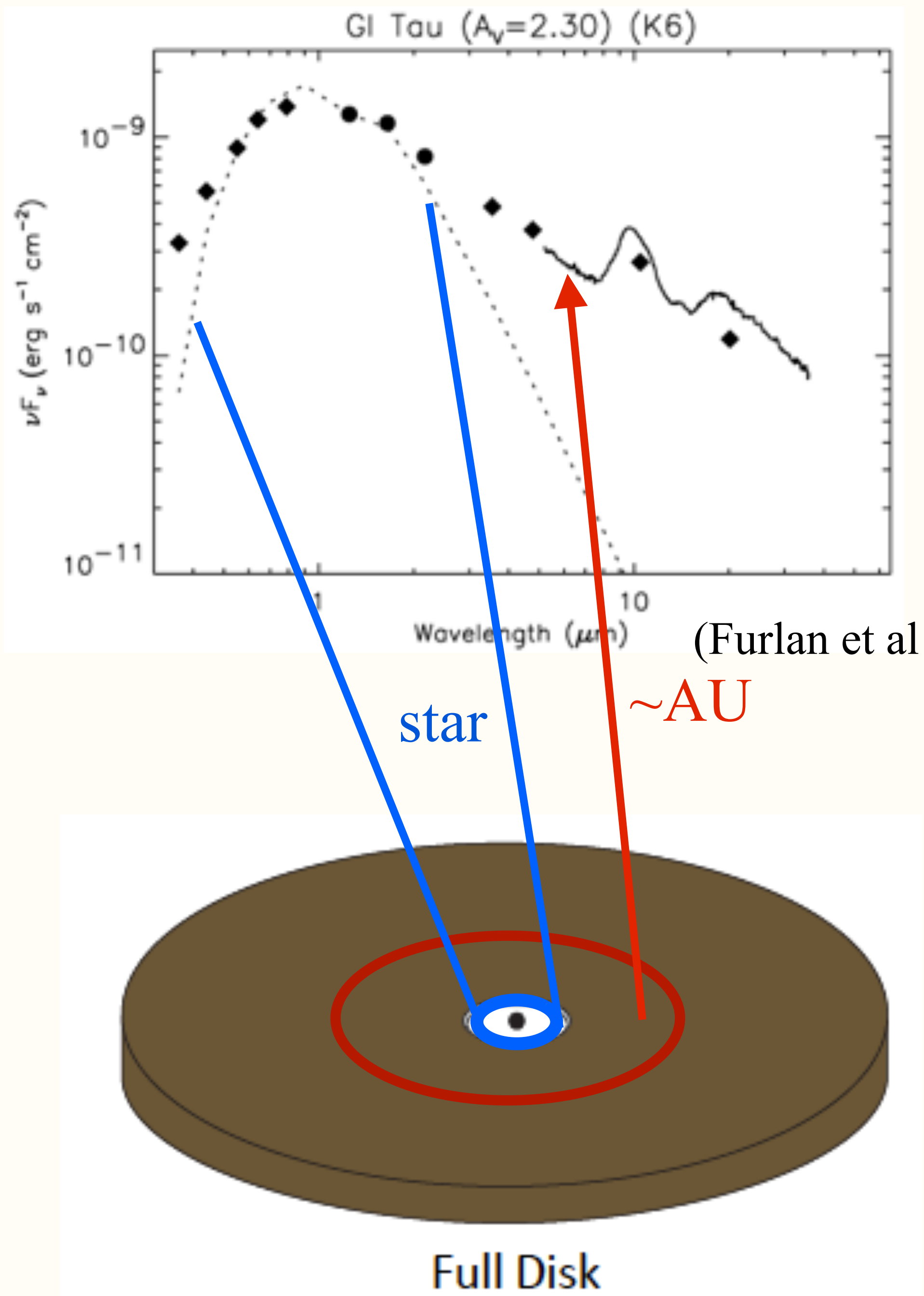

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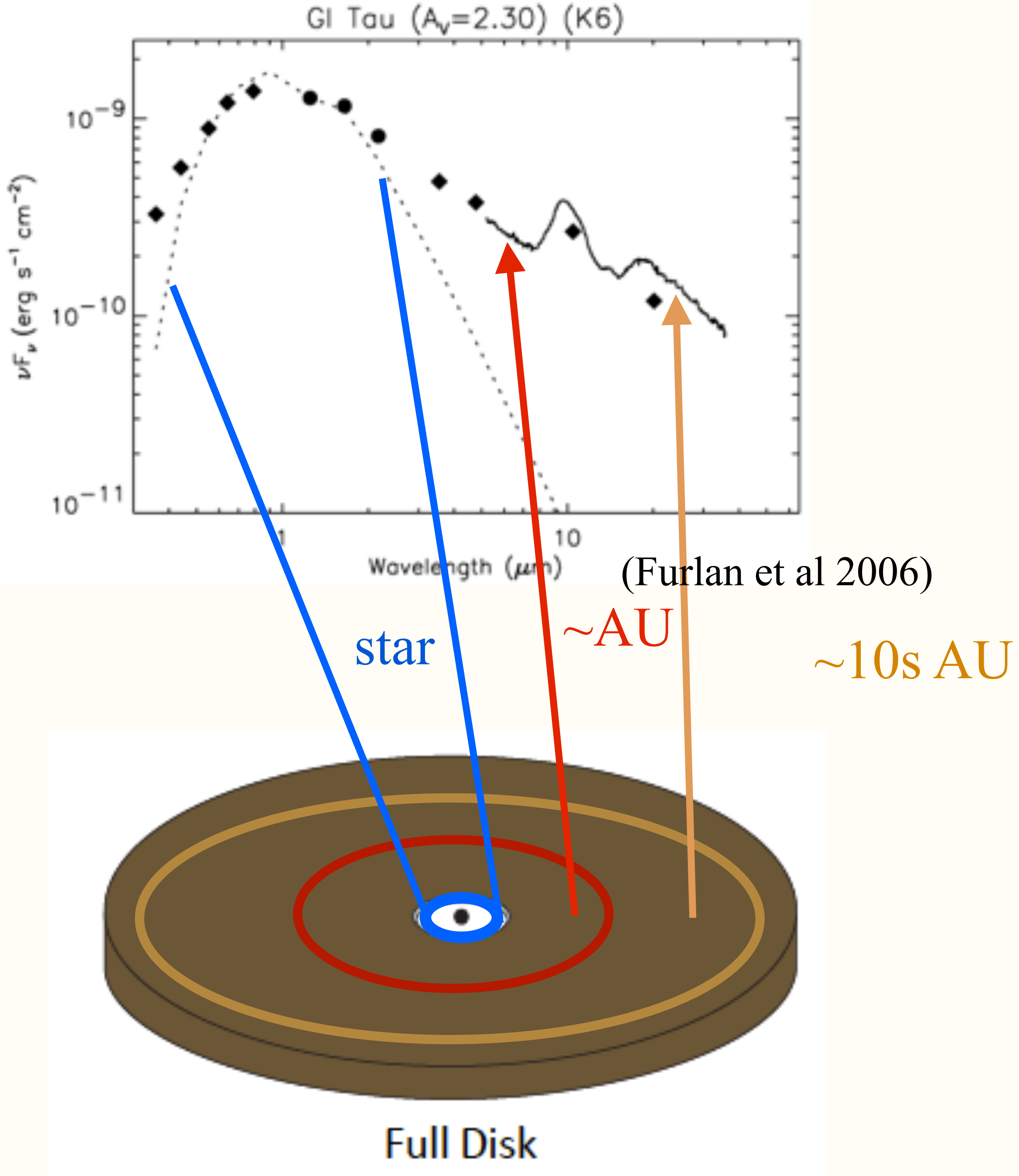

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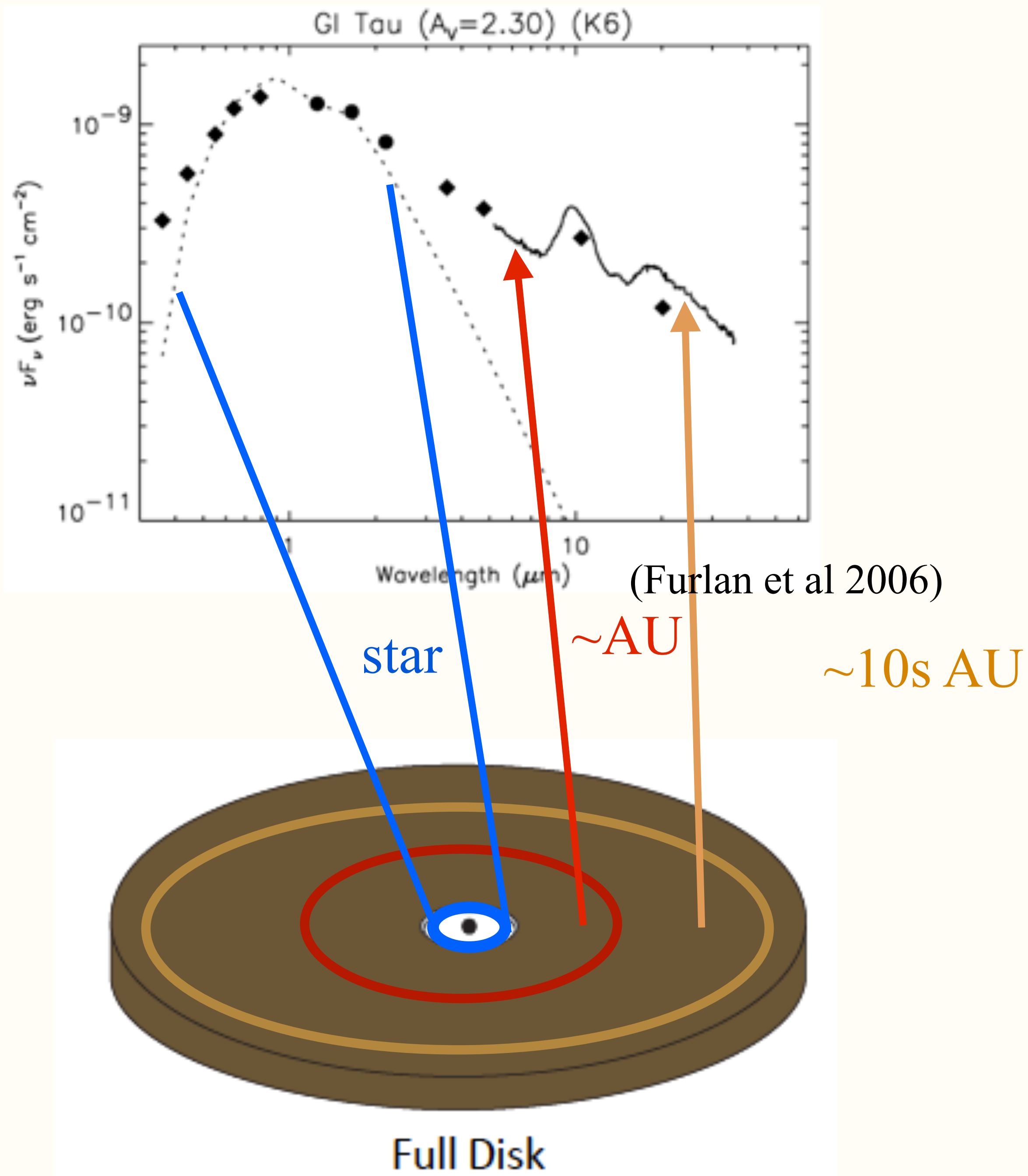

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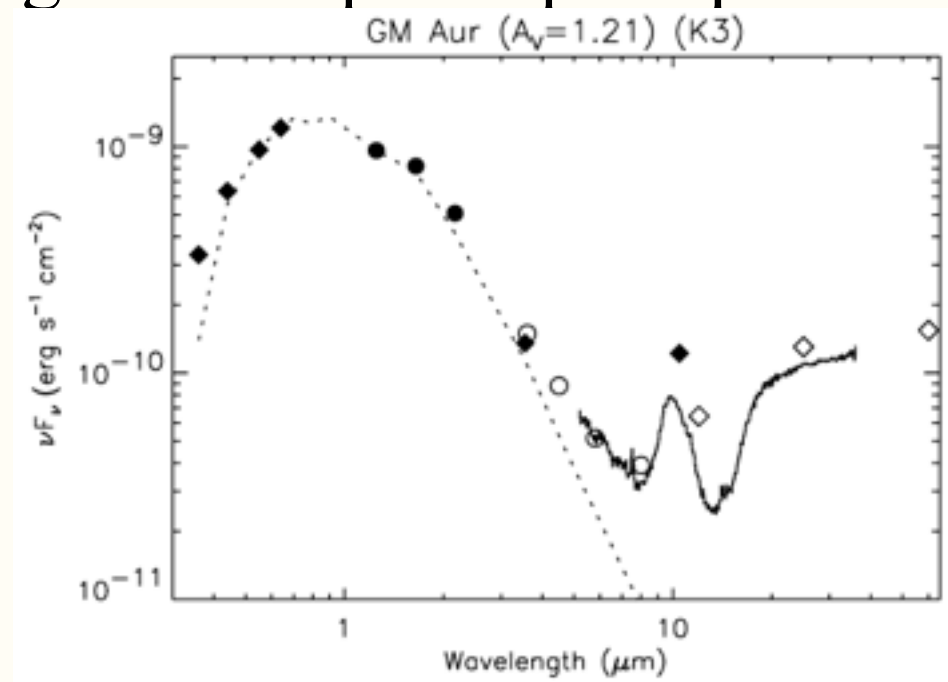

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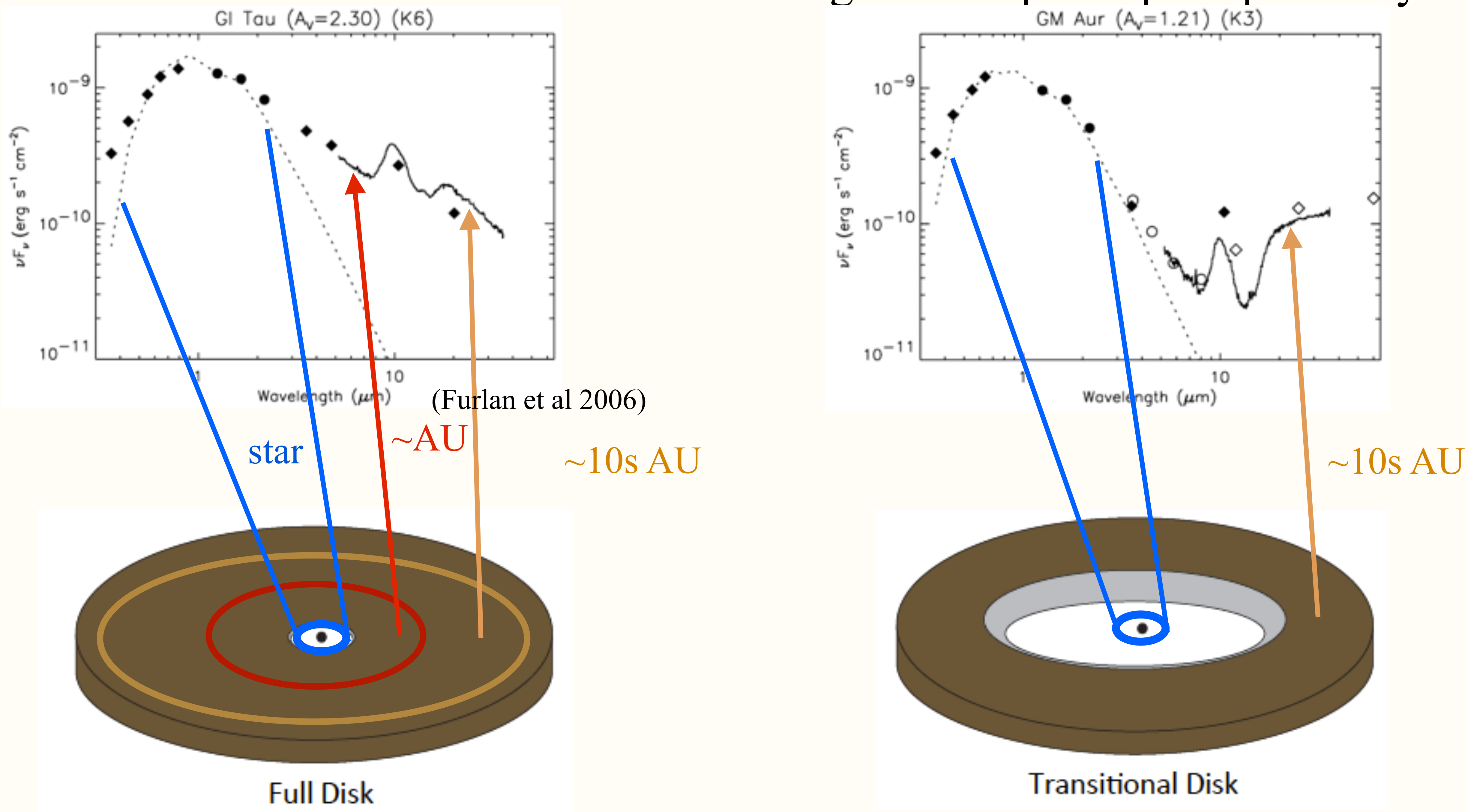

(Furlan et al 2006)

(Strom et al. 1989, Espaillat et al. 2014 PPVI)

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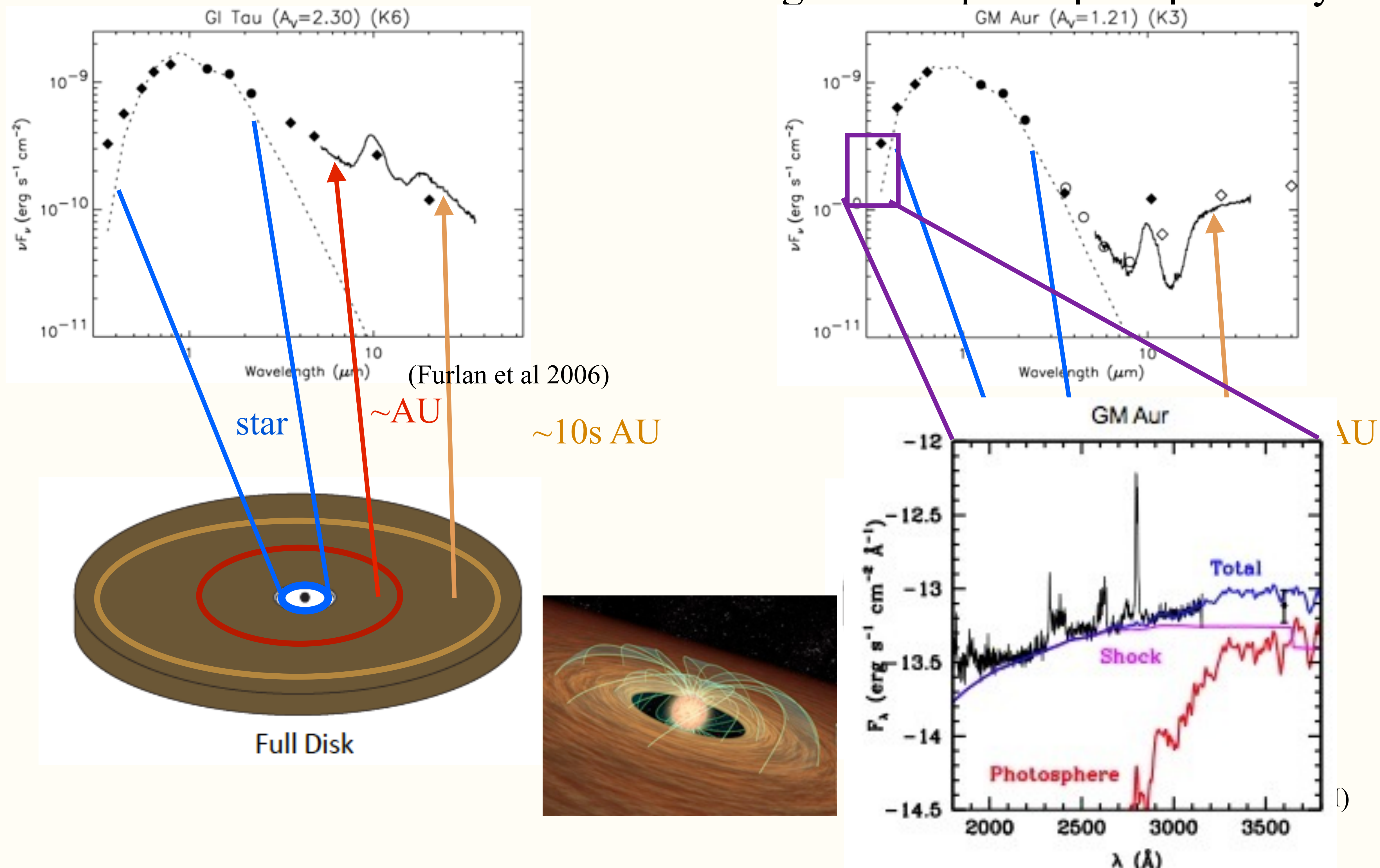

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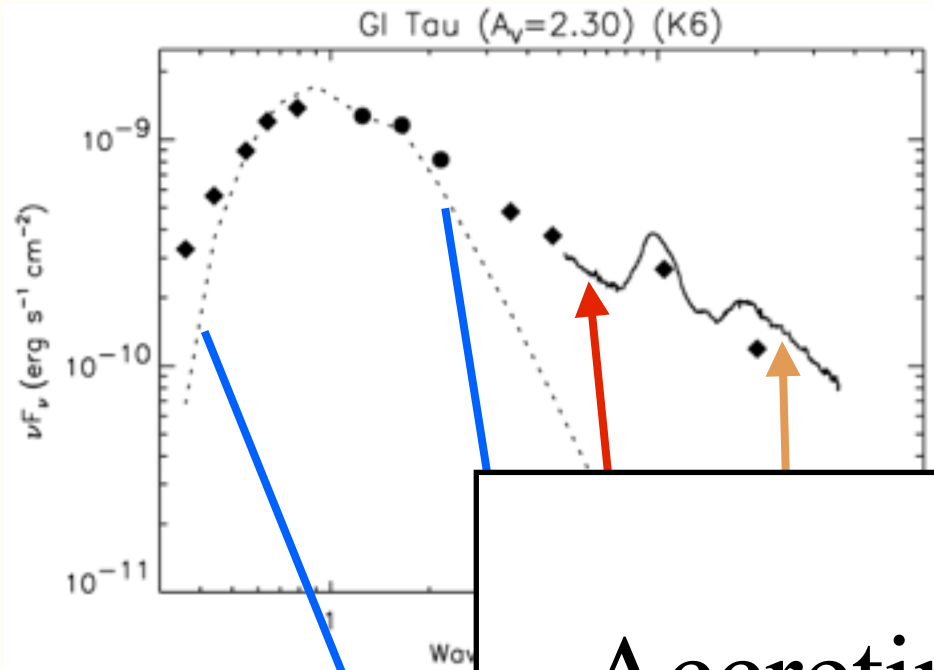
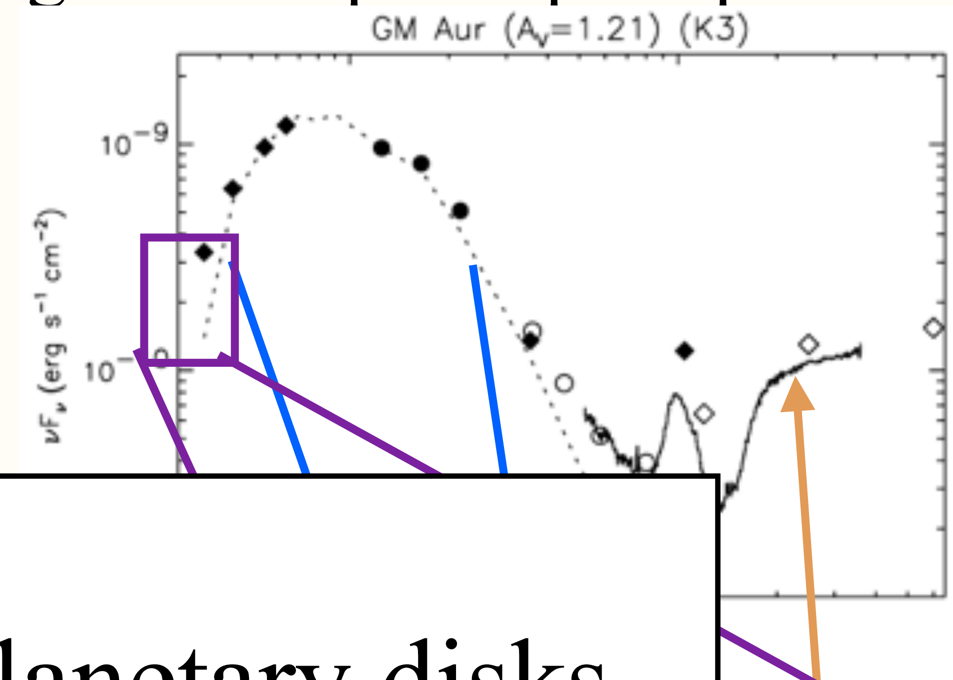
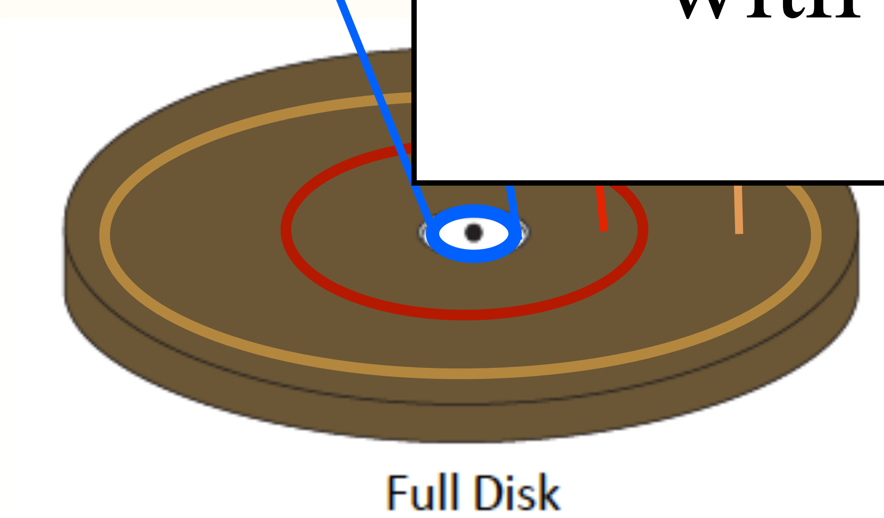
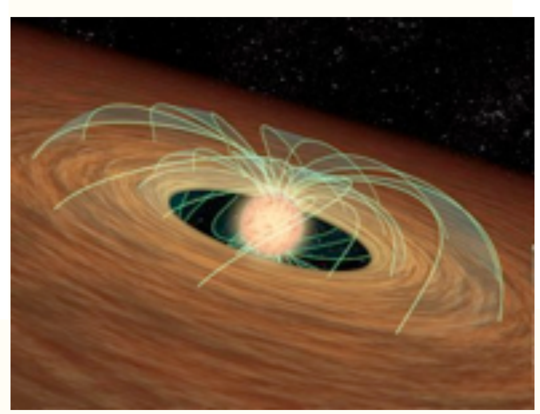




Accreting protoplanetary disks with dust gaps and holes





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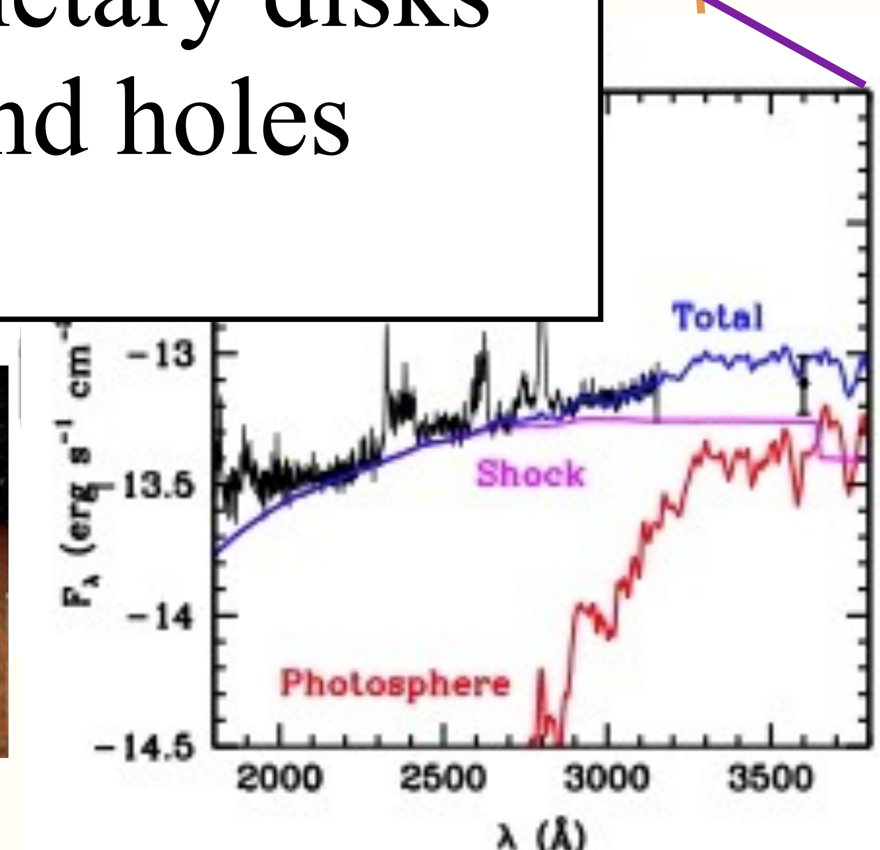
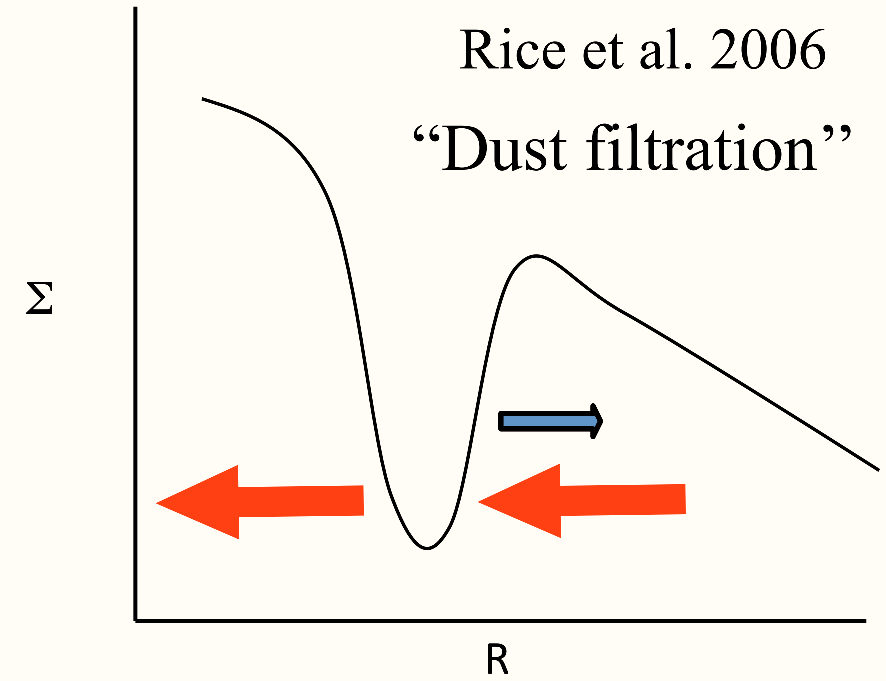


(Ingelby et al 2013)

Two-fluid (Dust/Gas) viscous simulations

$3M_J$



Zhu et al. 2012

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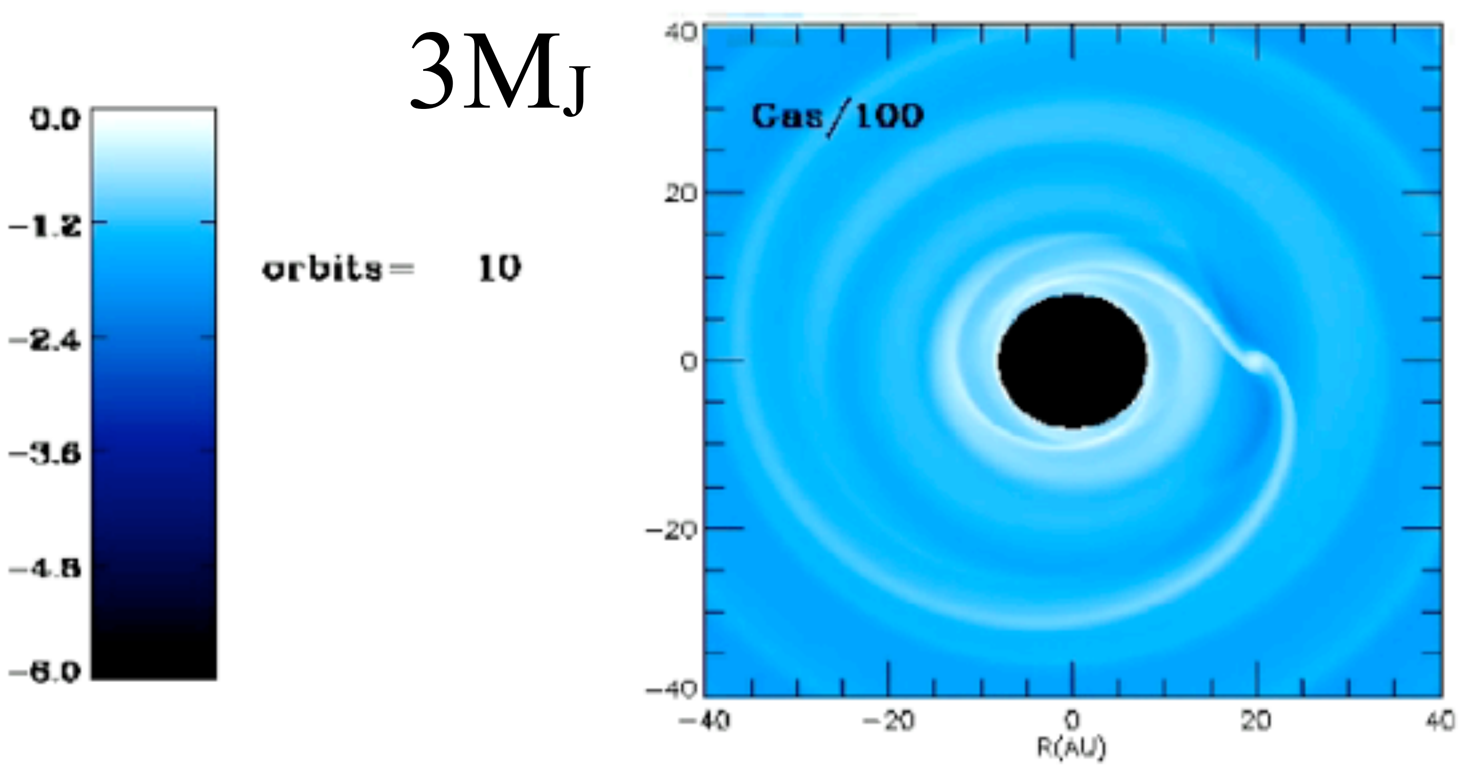
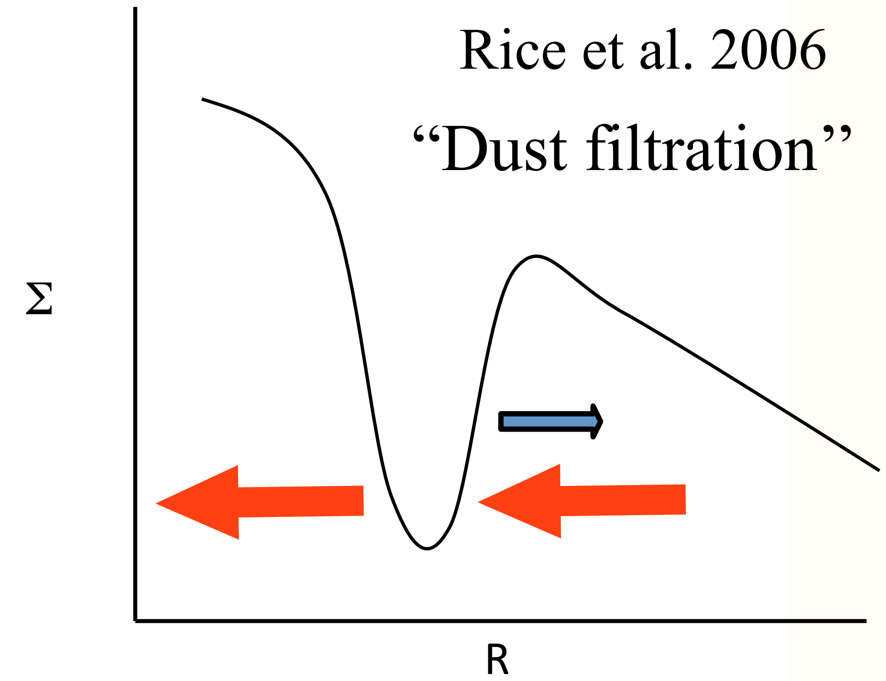
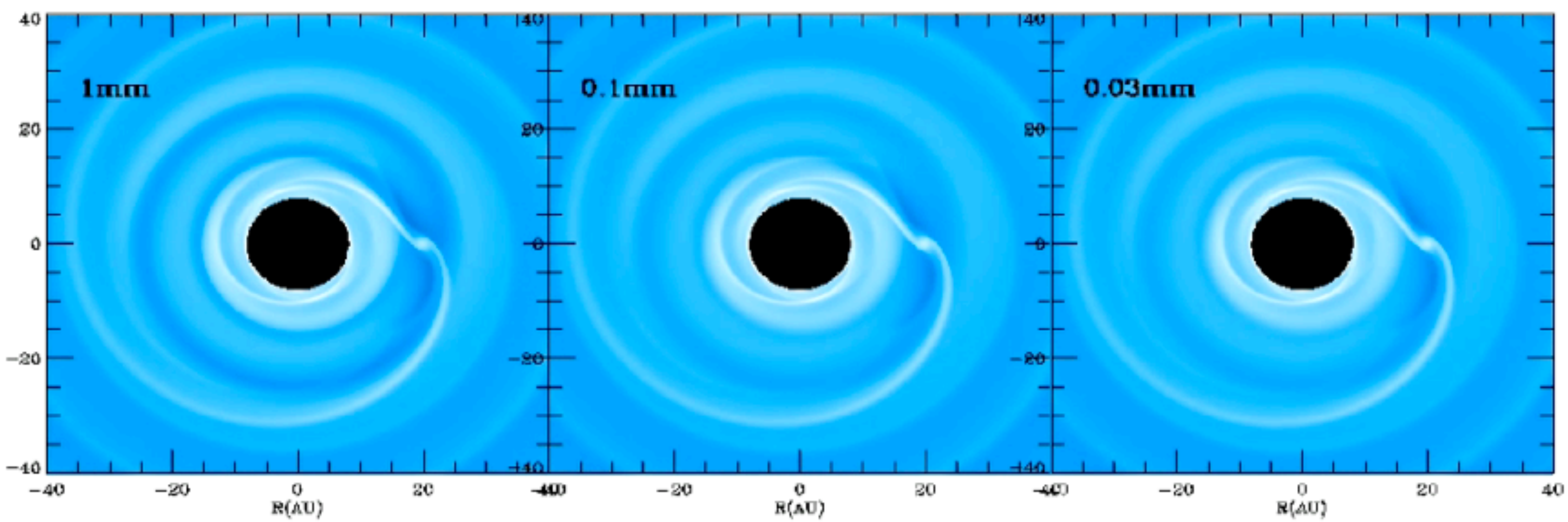


Rice et al. 2006

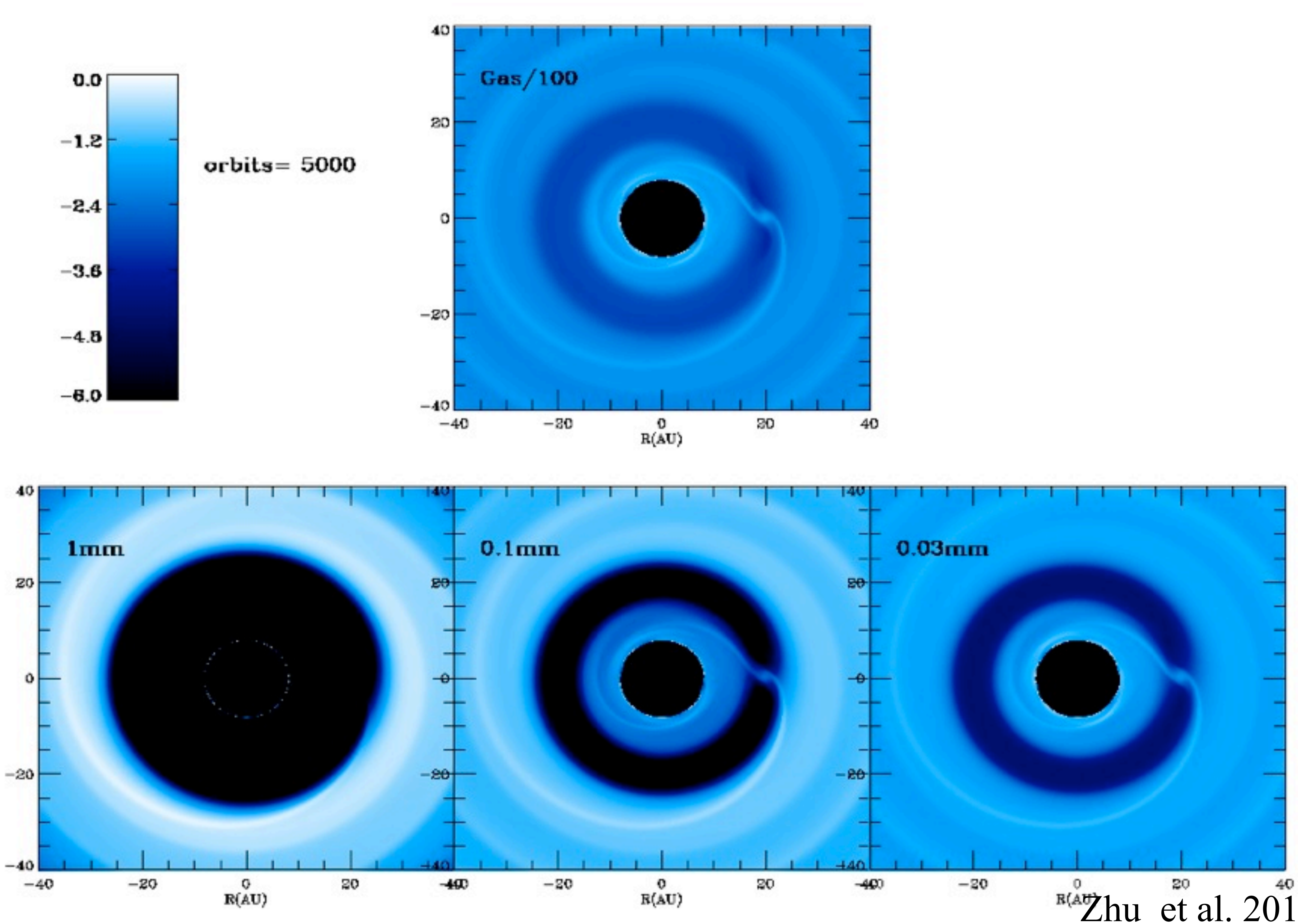
"Dust filtration"





Zhu et al. 2012

Dust Filtration: Submm vs Near-IR



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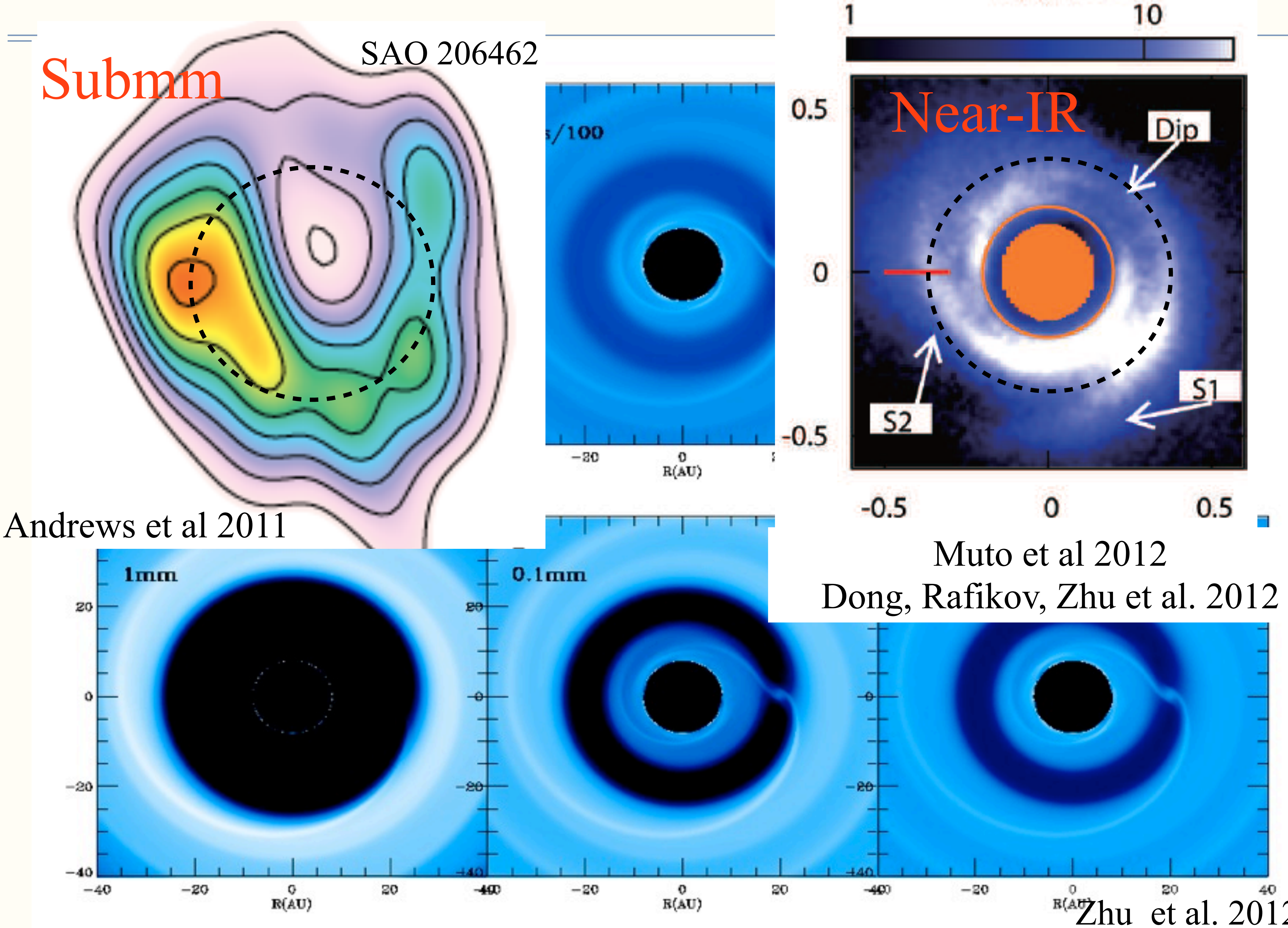

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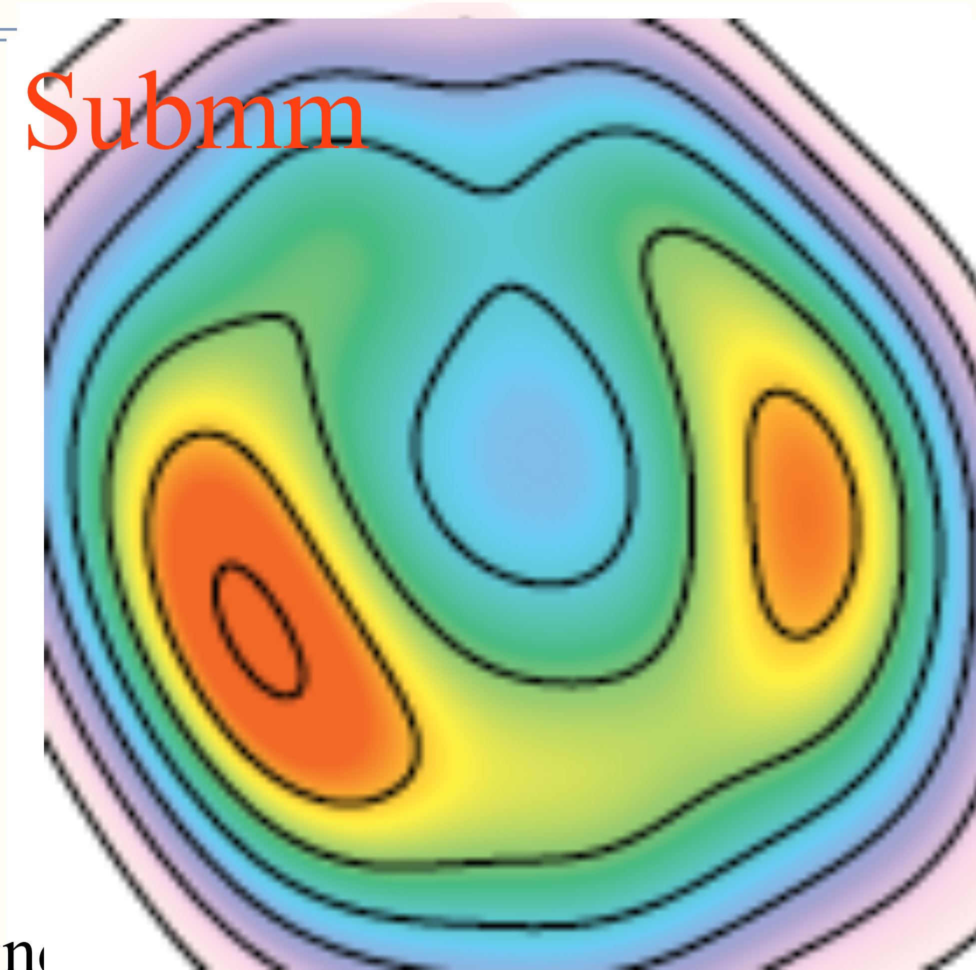
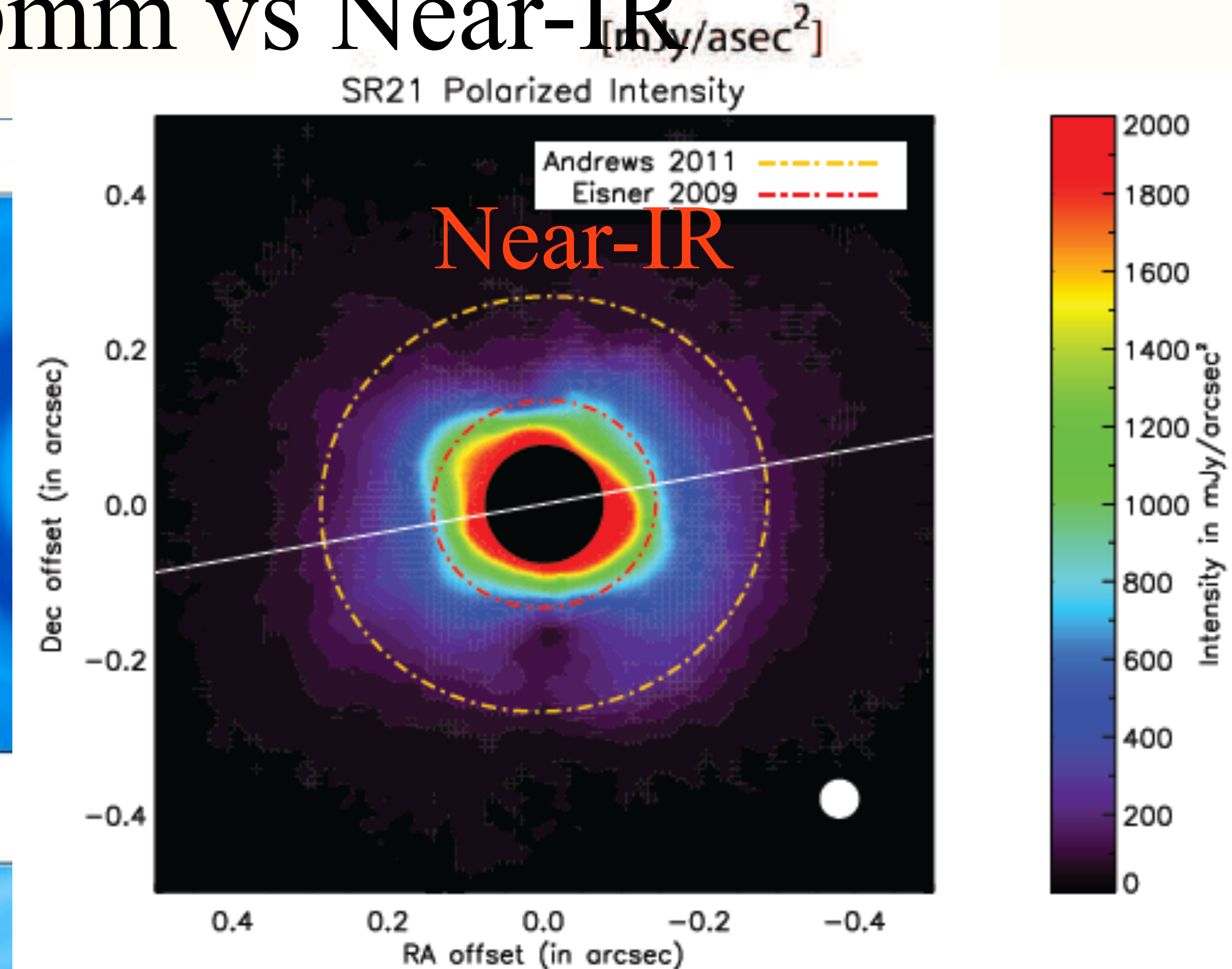
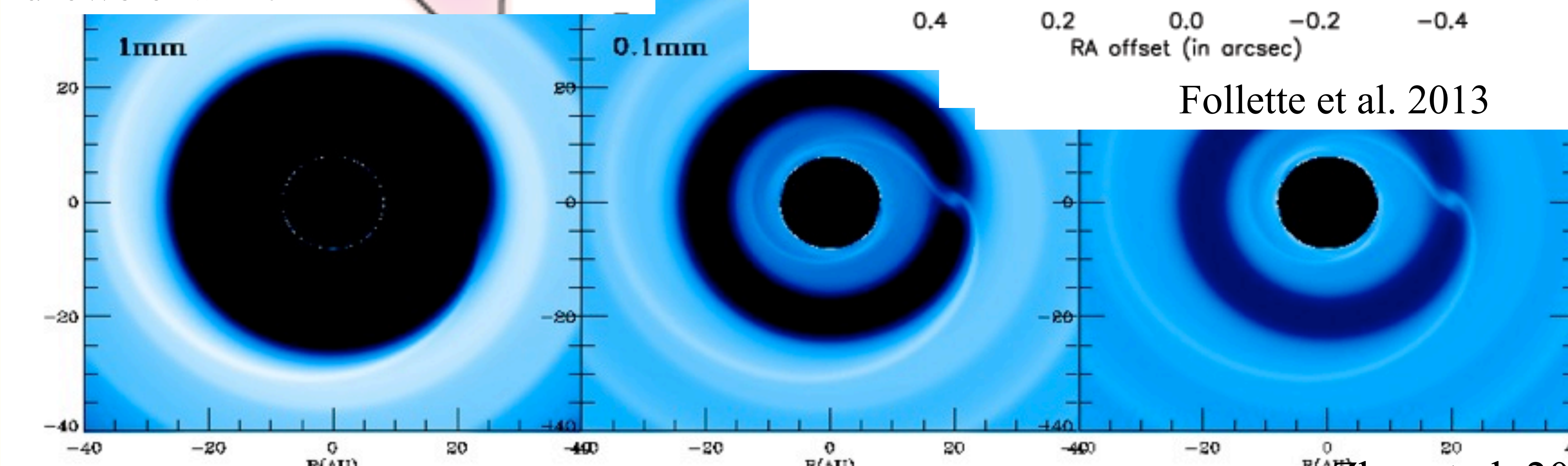


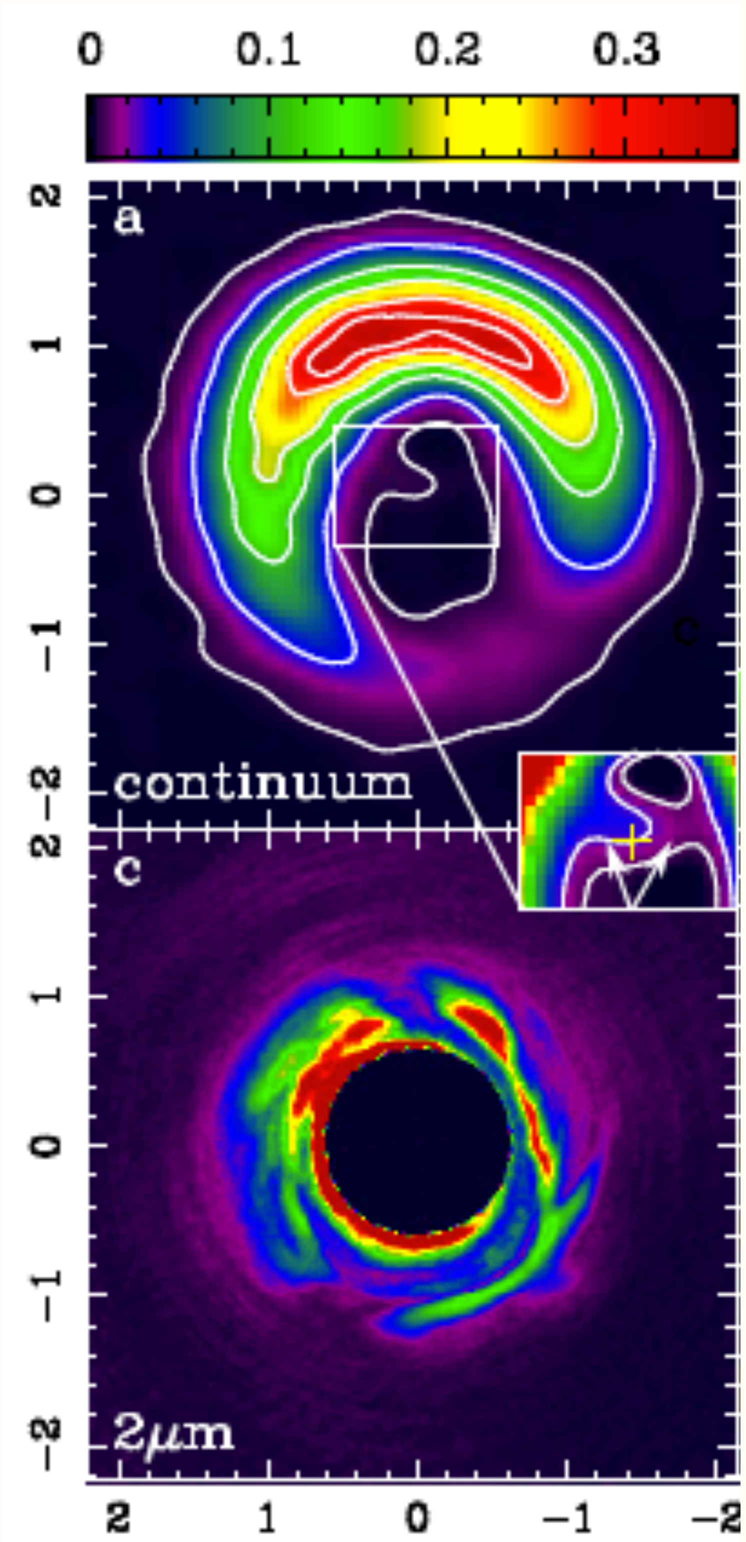


Follette et al. 2013



Zhu et al. 2012

Protoplanetary Disks in ALMA Era



Casassus et al (2013)

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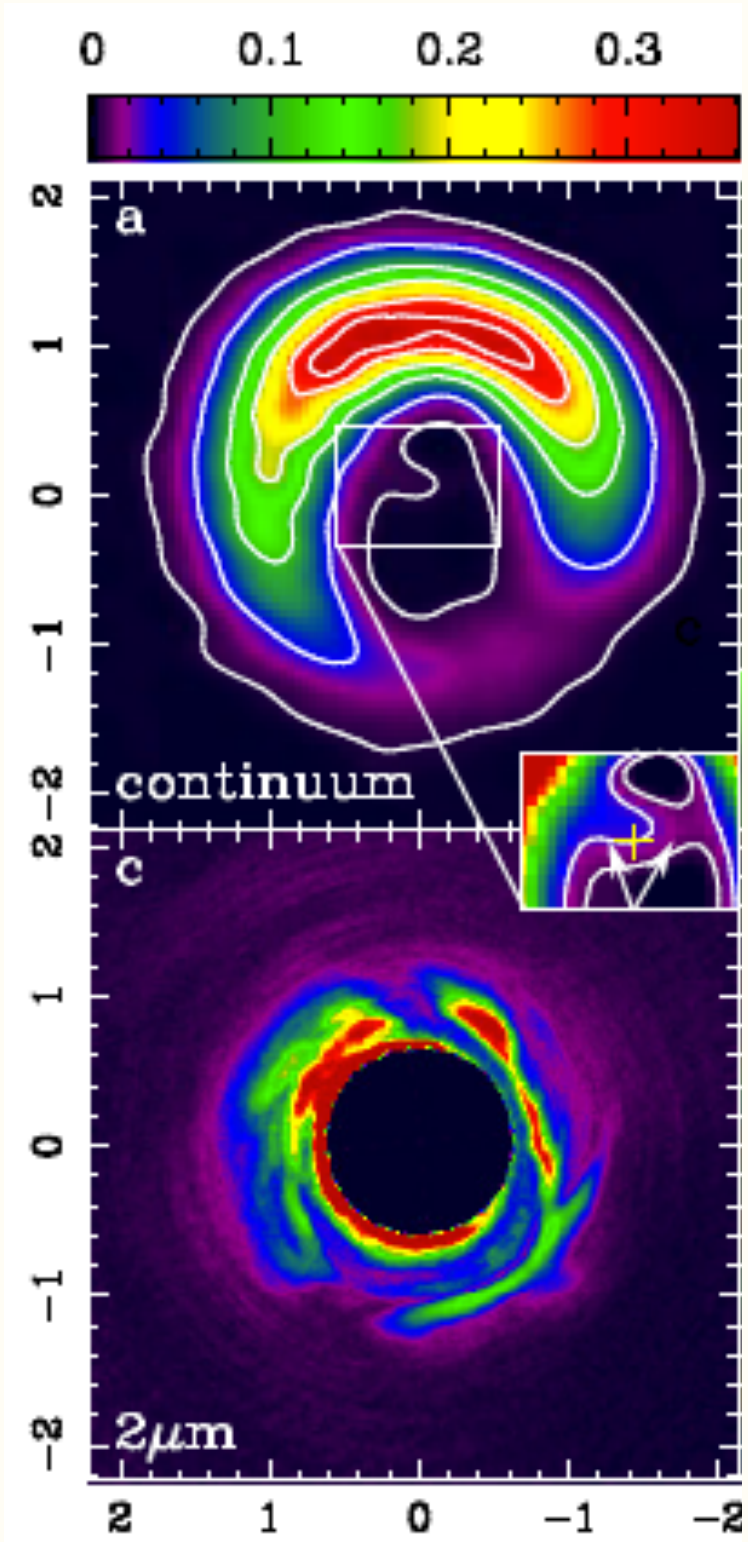

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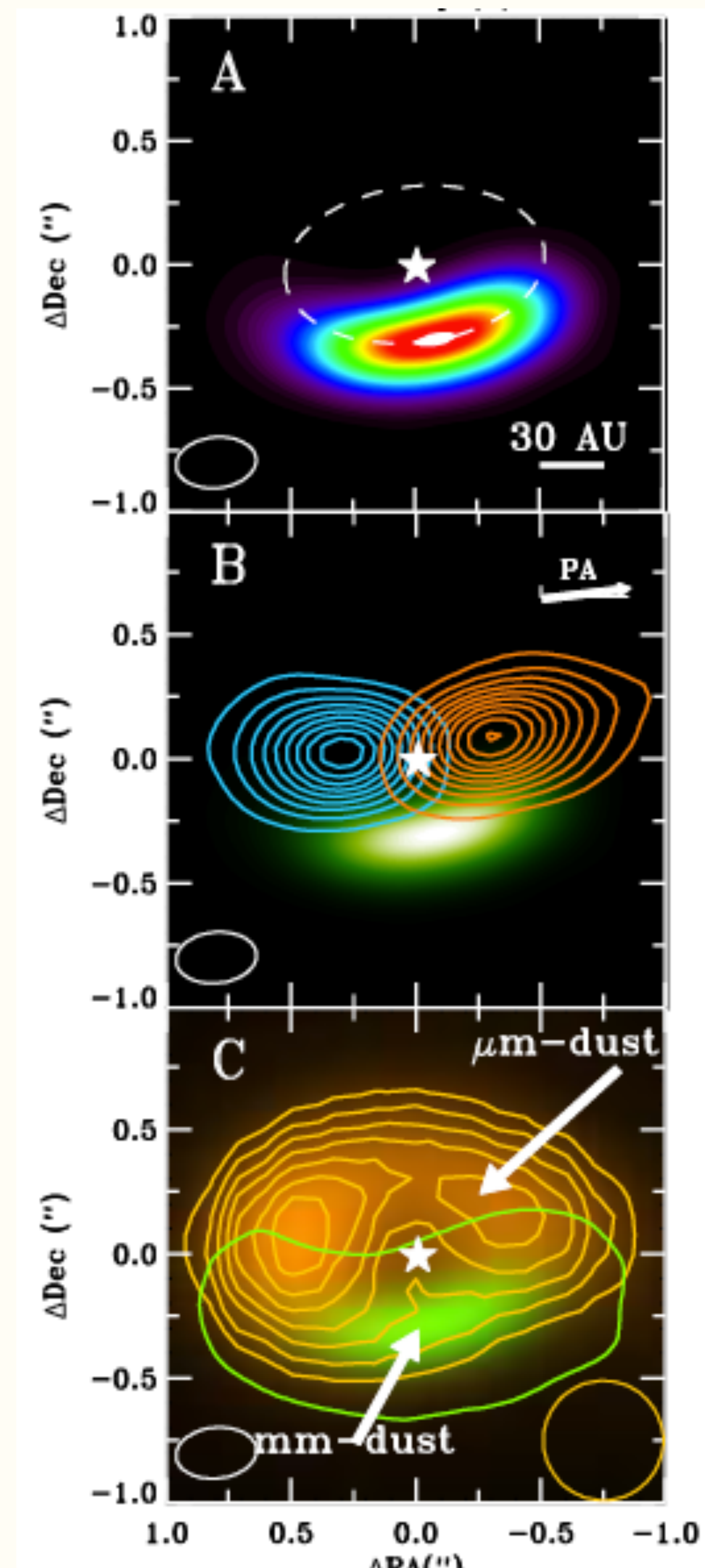
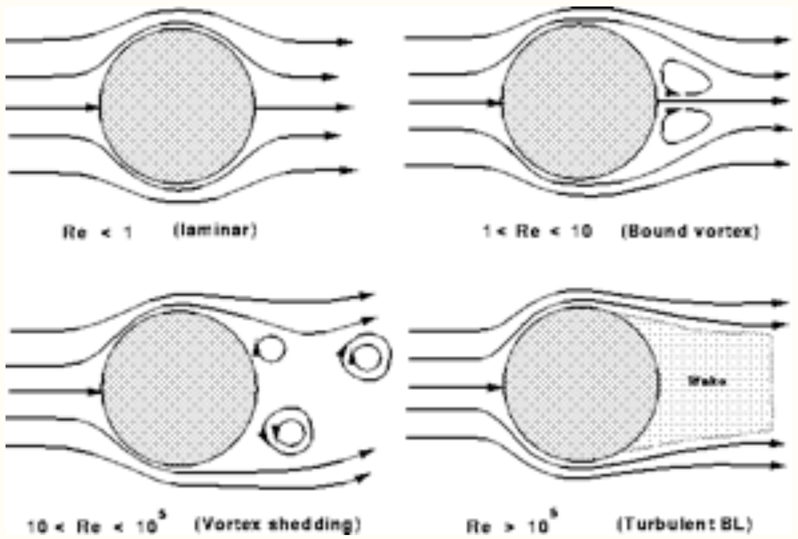


Nienke van der Marel et al. (2013)

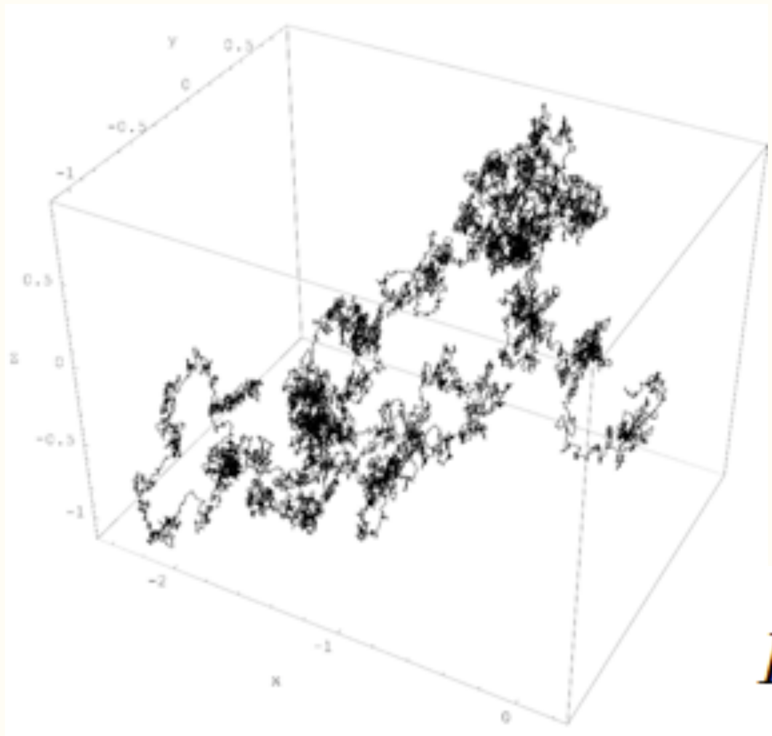
Dust gas interaction:

Gas Drag



Whipple (1972)

Turbulent diffusion



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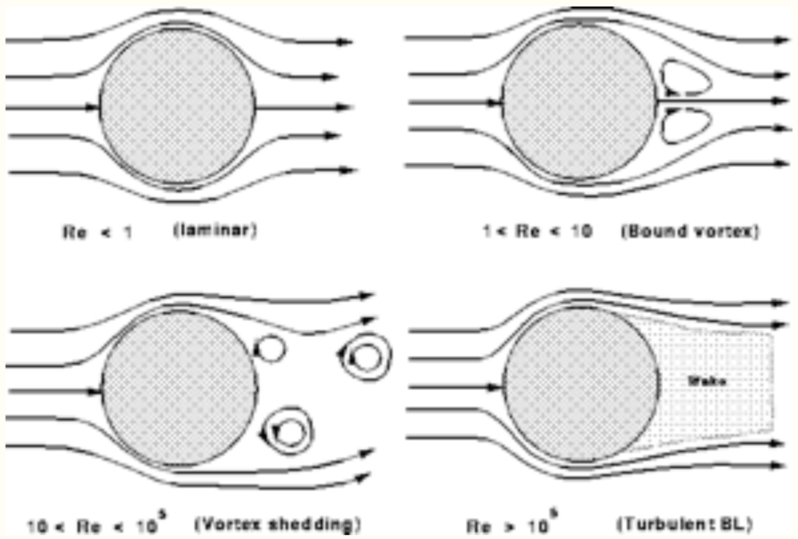

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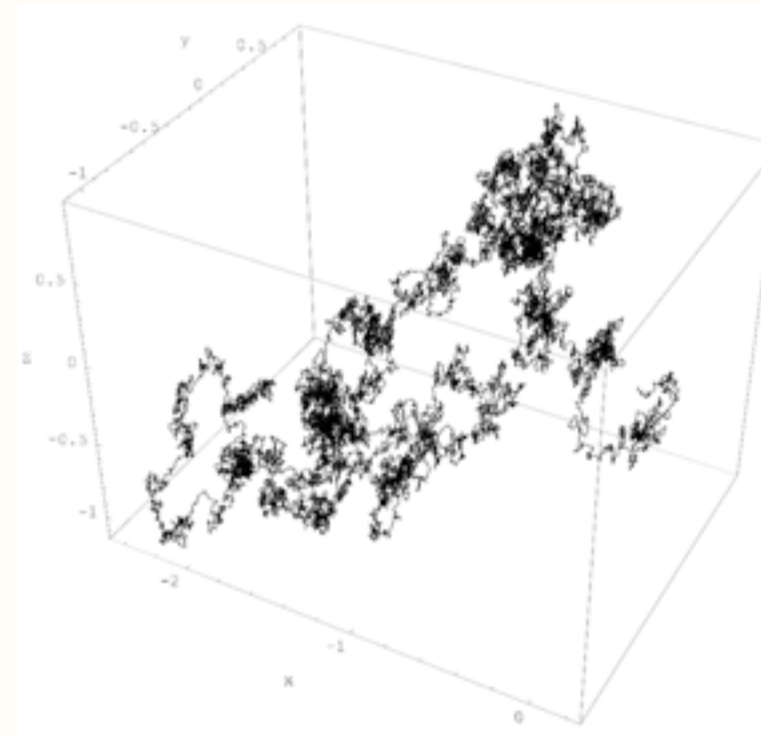

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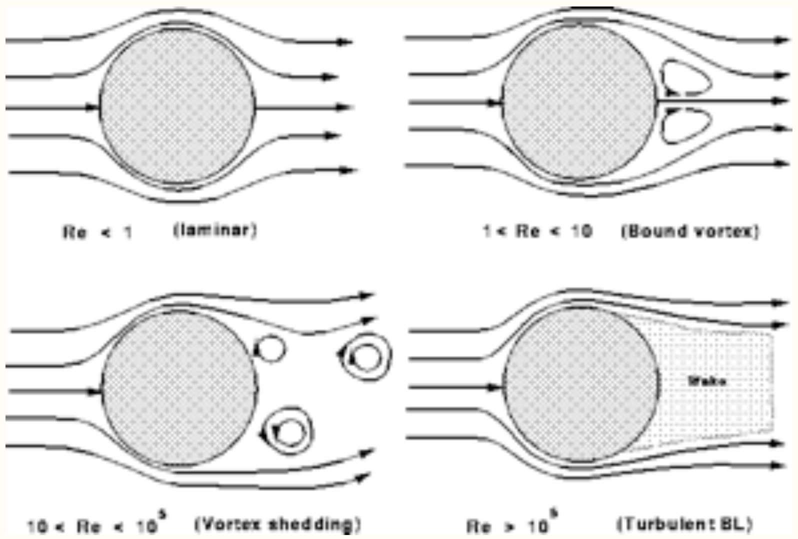

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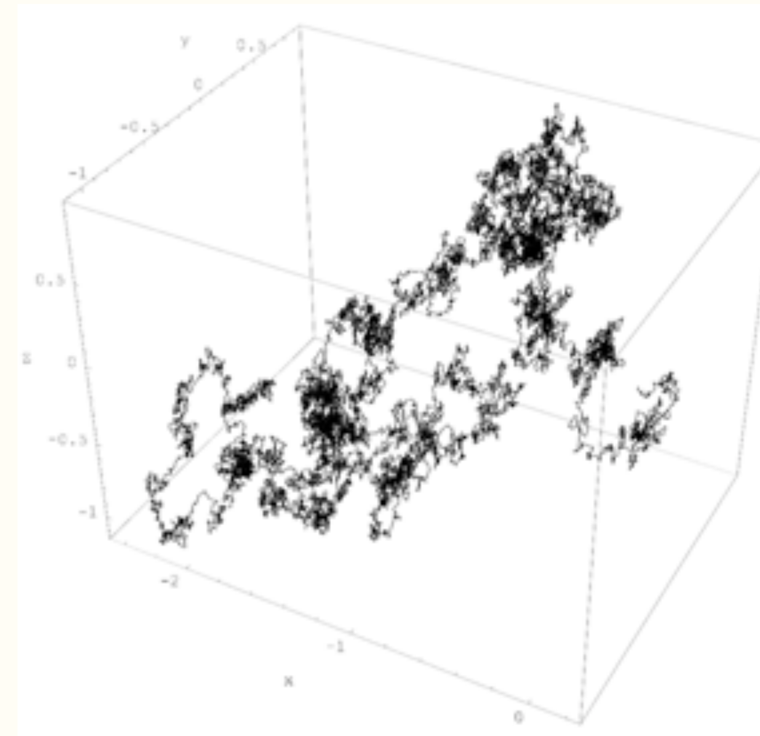

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$$\rho_d v_{d,t} = D_{d,z}\rho_g \frac{\partial}{\partial z}\frac{\rho_d}{\rho_g} \Rightarrow H_d = \sqrt{\frac{D_{d,z}}{\Omega T_s}}$$

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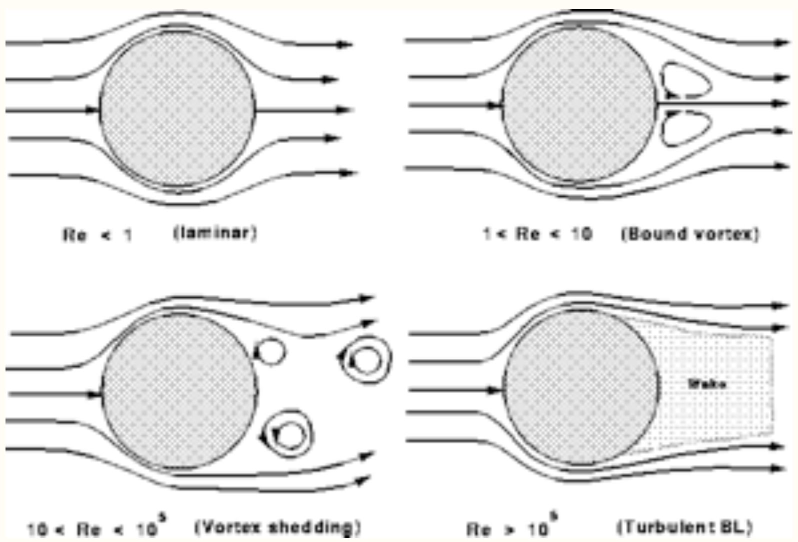

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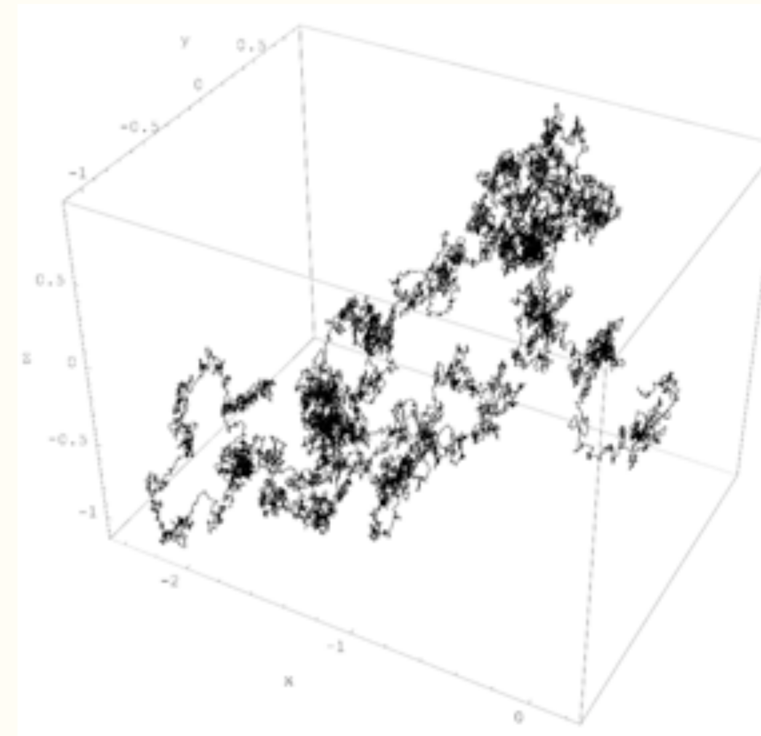

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Key parameters: D_d

D_g is related to the properties of turbulence:

Voelk et al. 1980
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MRI turbulence (ideal MHD):

$t_{eddy} \sim 1/\Omega$

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Carballido et al (2005) (2006) (2011)
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Fromang & Papaloizou (2006)
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Gas+Particle Simulations

Gas: Global unstratified MHD simulations using Athena. (Stone et al. 2008)

Both ideal MHD (Vert. and Tor.) and Ambipolar Diffusion (Am=1)

R: 0.5-4, Z: -0.1-0.1

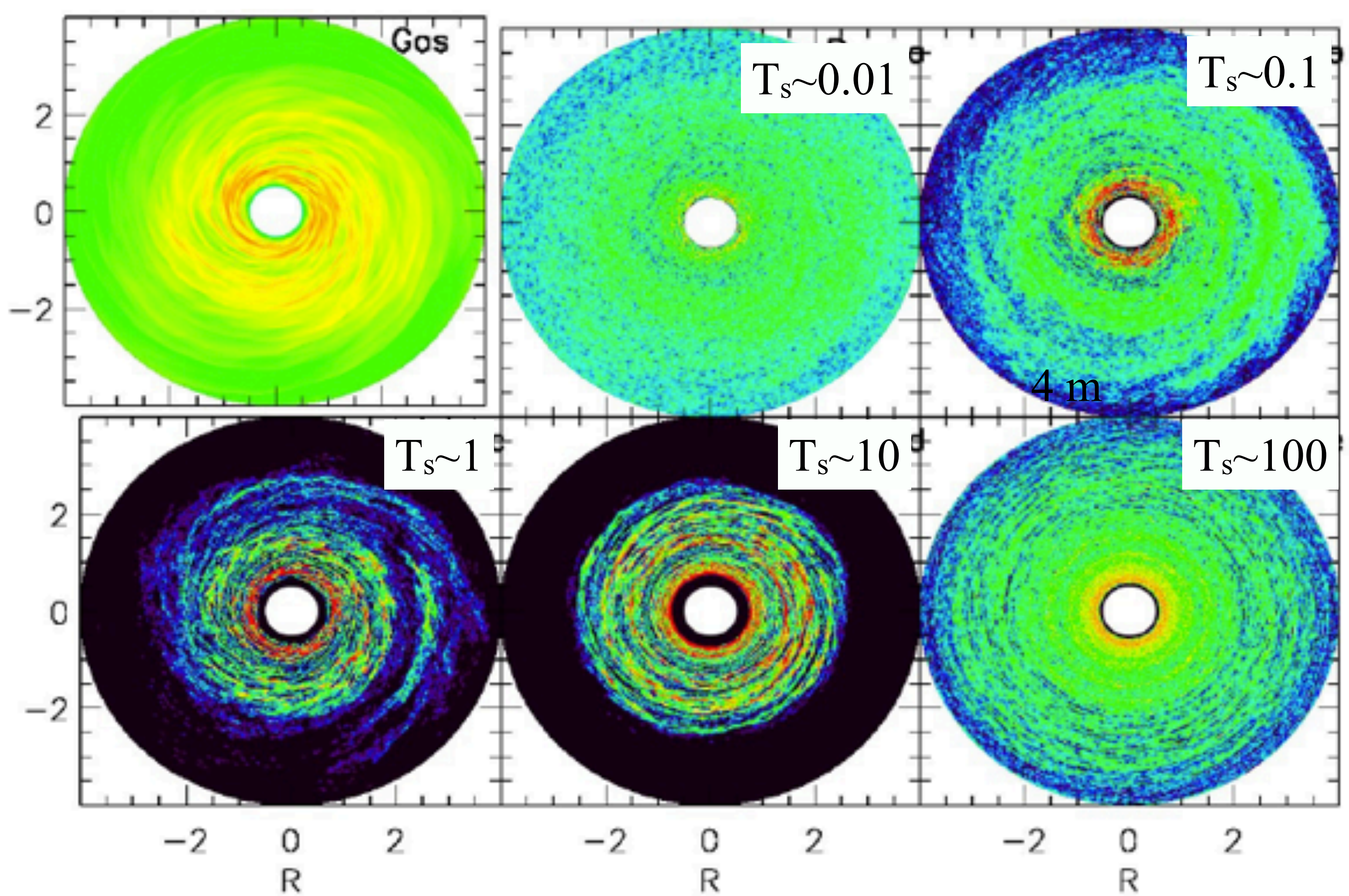
$\Sigma = \Sigma_0 (R/R_0)^{-1}$ $T = T_0 (R/R_0)^{-1/2}$

Particles: solve the orbit of each particle with the orbit integrator.

(Zhu et al. 2013, built on Bai & Stone 2010)

7 types particles ($T_s \sim 10^{-2}$ - 10^4), each 1 Million particles

(Zhu, Stone & Bai 2014)



Ideal MHD simulations:

Dust Surface density evolution:

Particle distribution in MRI Simulations

VS

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$D_{d,x}$ from Youdin & Lithwick (2007) with $t_{eddy} \sim 1/\Omega$

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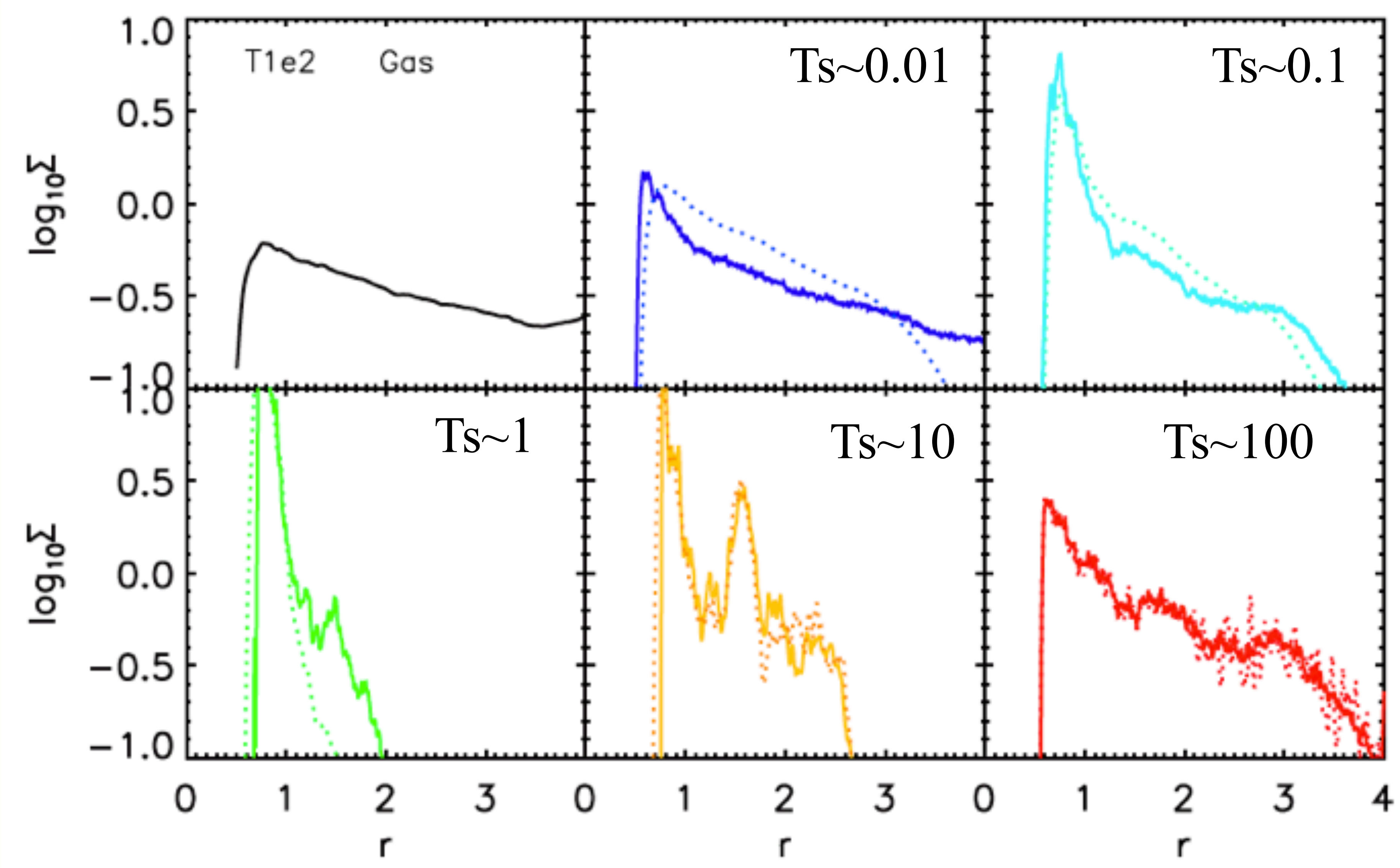

Ideal MHD simulations:

Disk vertical structure:

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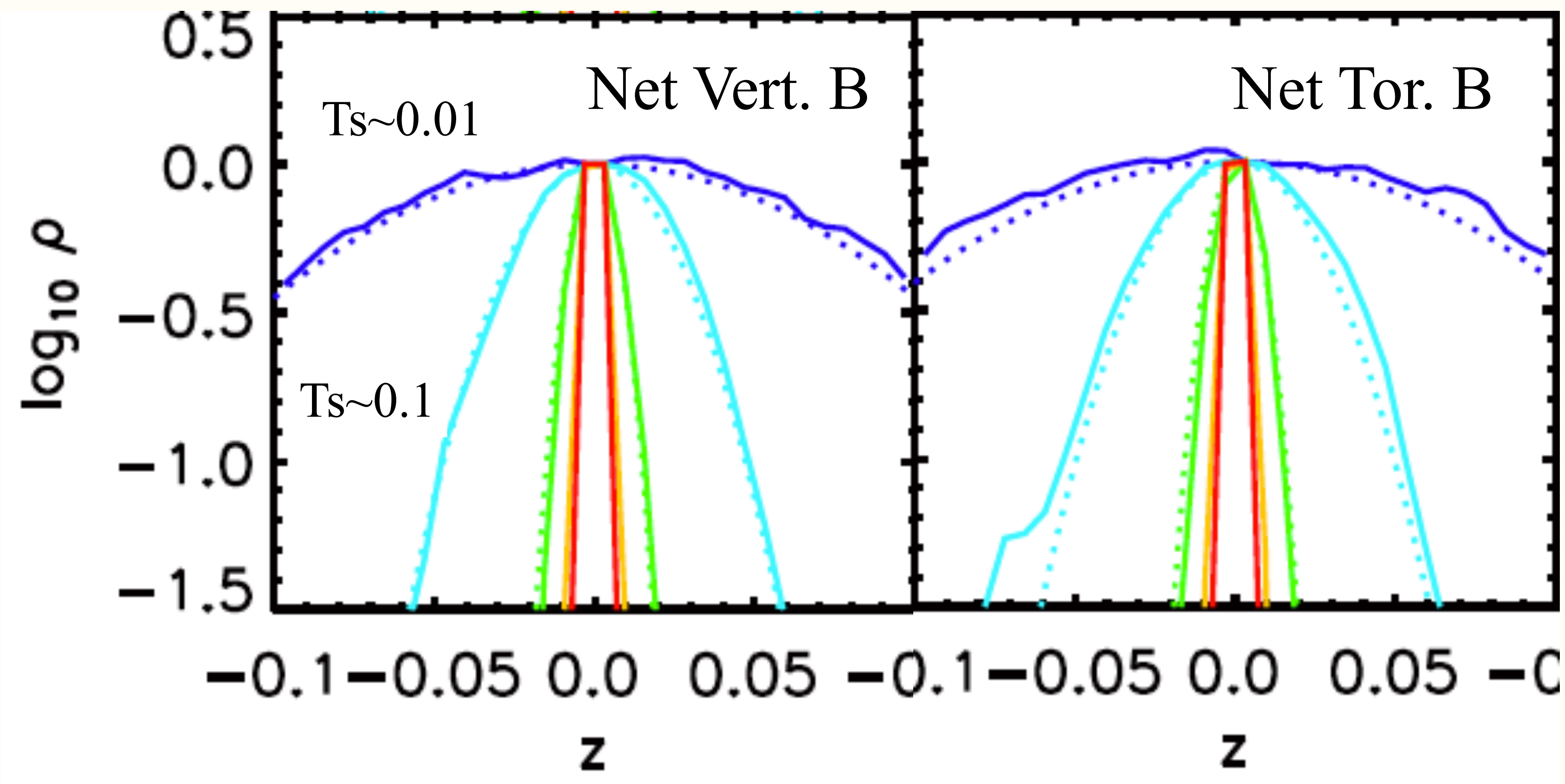
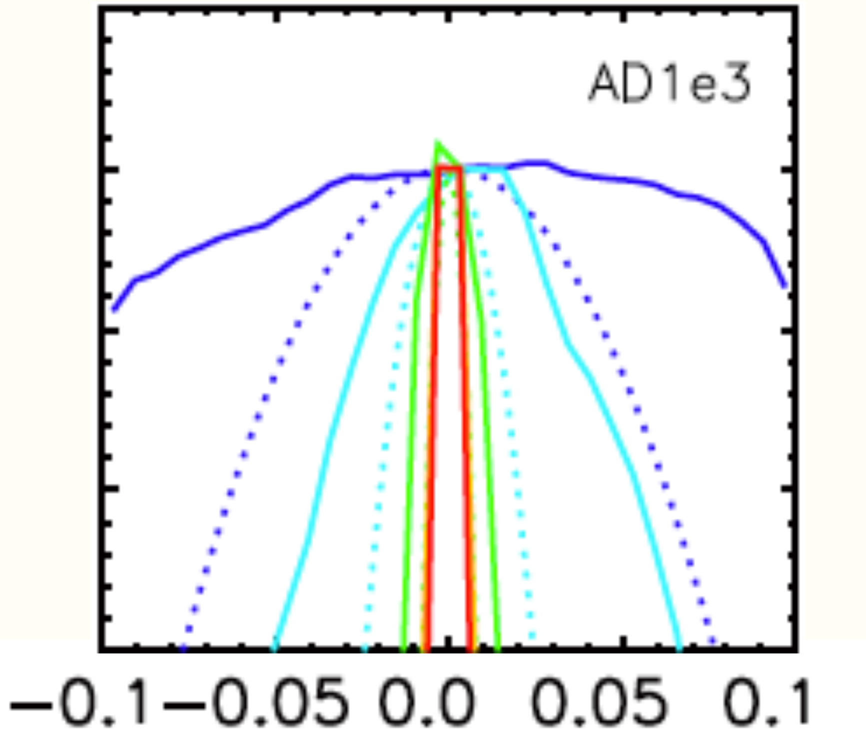


Ambipolar Diffusion

Disk vertical structure: $H_d = \sqrt{\dfrac{D_{d,z}}{\Omega T_s}}$



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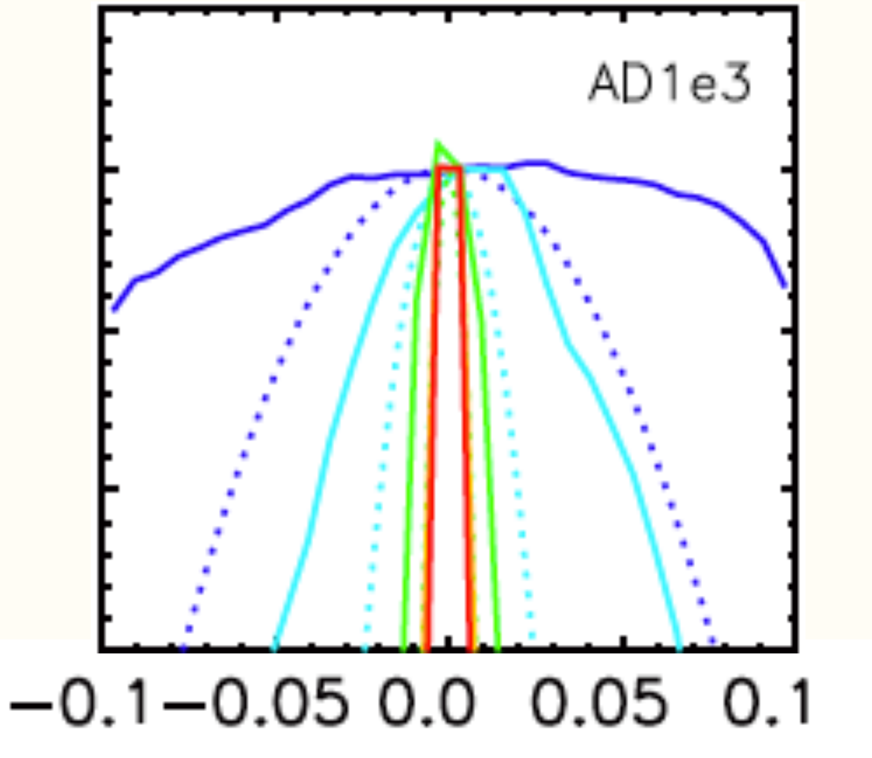

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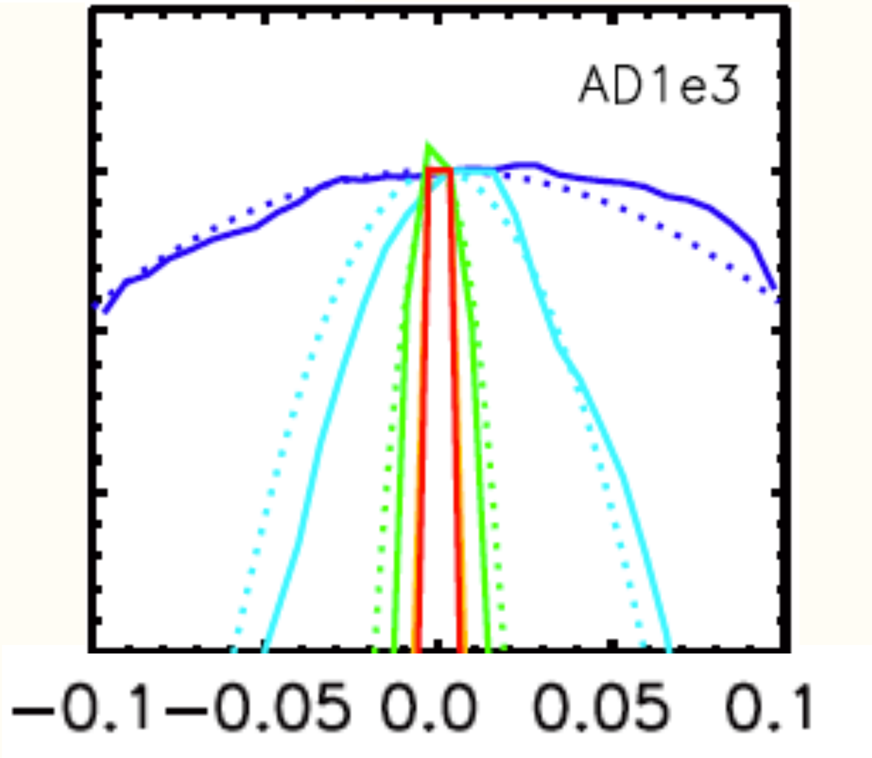

$t_{eddy,z} \sim 3/\Omega$

Why different? Measure $D_{g,z}$ directly

We have carried out Shearing Box simulations including dust particles. Then we follow ~100 particles for 20 orbits to calculate $D_{d,z} = \frac{1}{2}\frac{d\langle z_d^2\rangle}{dt}$ $t_{eddy,z} = D_{g,z}/\langle\langle v_z^2\rangle\rangle$

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Unstratified	
VR32	0.47
TR32	0.92
ZR32	0.78
ZR64	0.93
AD1R32	3.0
AD1R64	2.4
AD2R32	4.1
AD2R64	3.2
AD2R128	3.2
AD2R32W[c]	3.2
AD3R32	4.1
AD3R64	3.2

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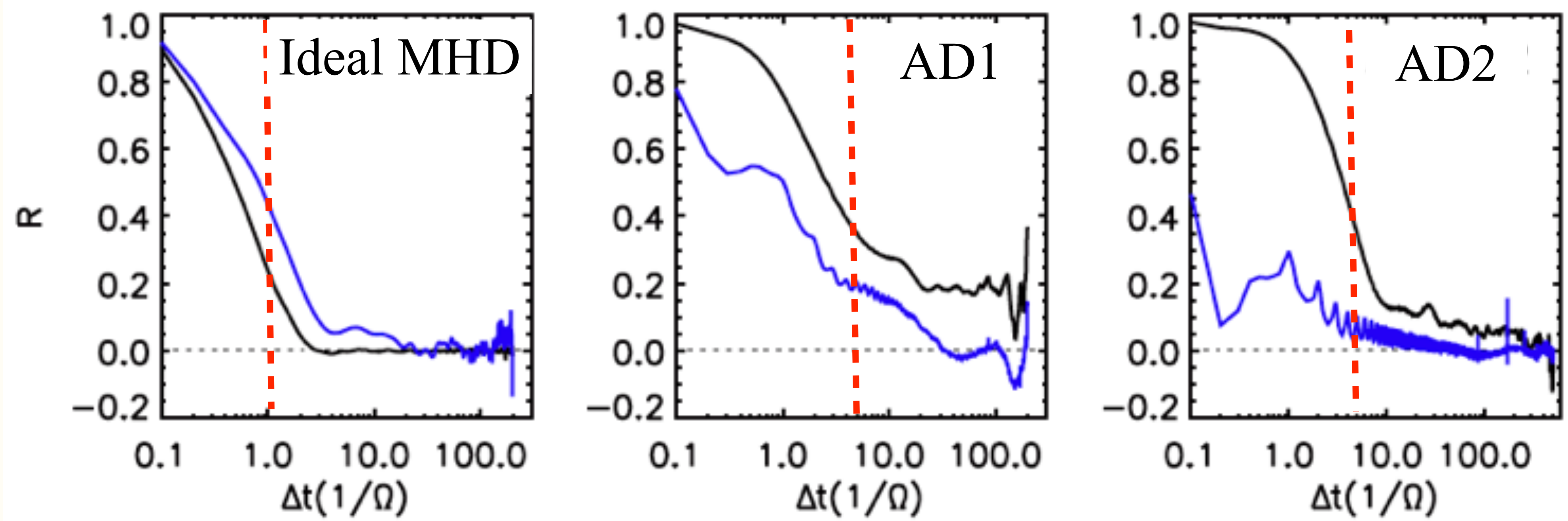
Am=1

In case stratification strikes back

Stratified	
AD2SR32	2.2
AD2SLR32	3.5

D_g strongly relates to the turbulent property

$$D_{g,z} = \frac{1}{2}\frac{d\langle z_g^2\rangle}{dt} = \int_0^\infty \langle v_{g,z}(\tau) v_{g,z}(0)\rangle d\tau \qquad \langle v_{g,z}(\tau) v_{g,z}(0)\rangle \equiv R_{zz}(\tau)$$



Black: v_z
blue: v_x

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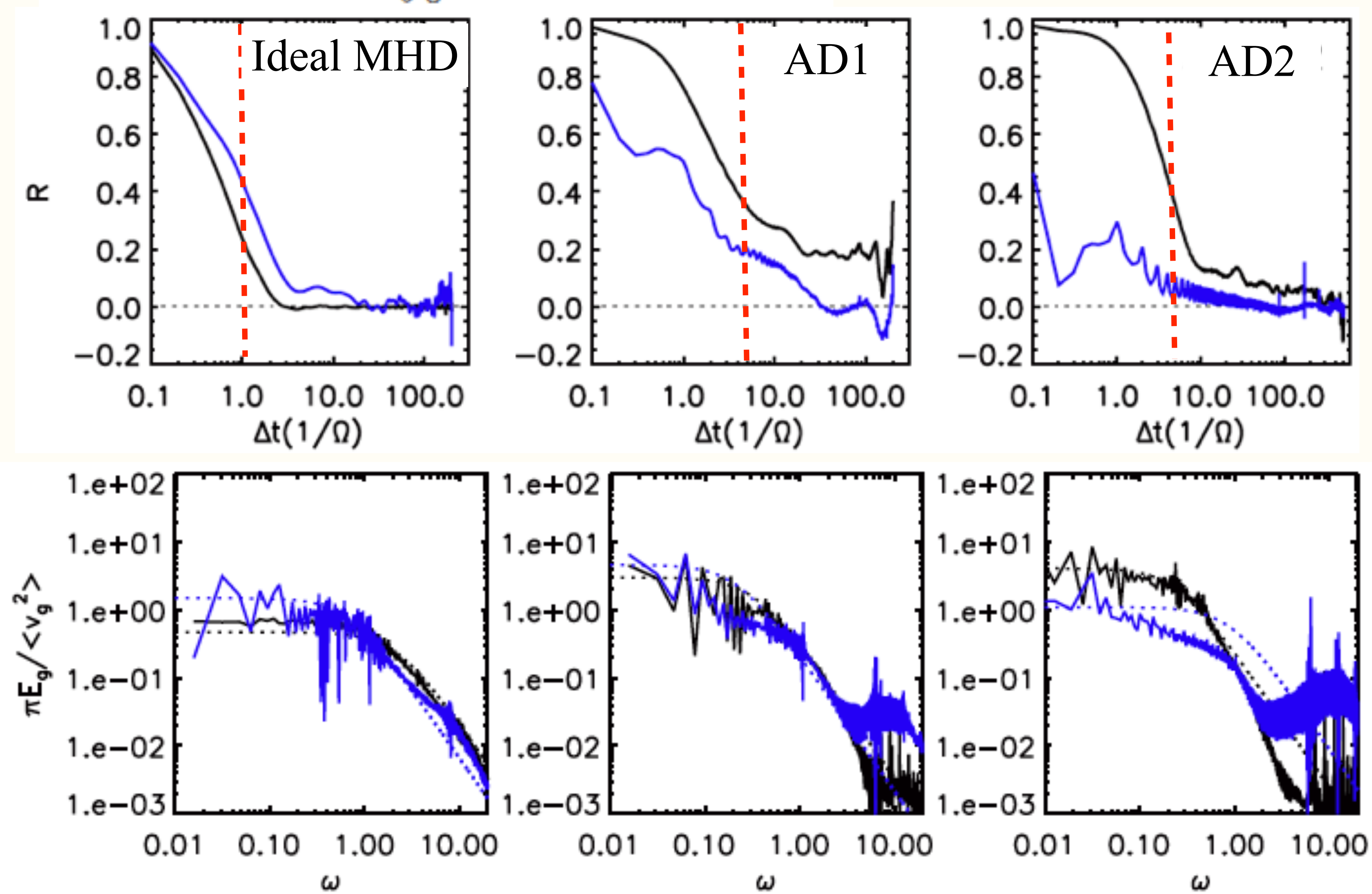

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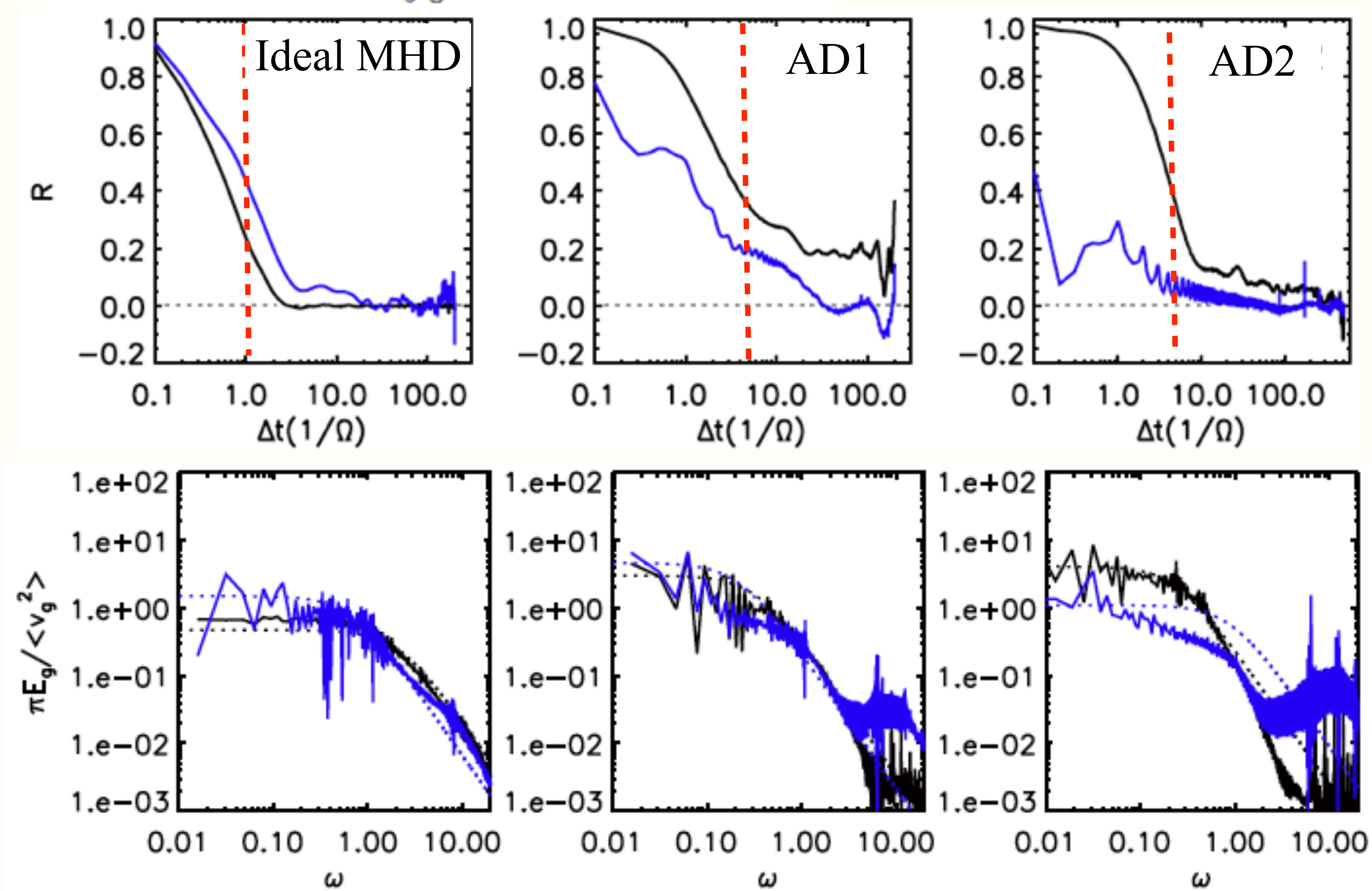

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The properties of turbulence has been changed by AD

Particle transport in Turbulent Disks

- $D_{g,r}$ and $D_{g,z}$ are the fundamental parameters to control particle transport in turbulent disks. t_{eddy} as important as α

- In turbulent disks with ideal MHD, $t_{eddy,r} \sim t_{eddy,z} \sim 1/\Omega$

  Excellent agreements between global simulations and analytical solutions for both dust evolution and dust disk vertical structure

- In turbulent disks with AD, $t_{eddy,r} \neq t_{eddy,z} \neq 1/\Omega$

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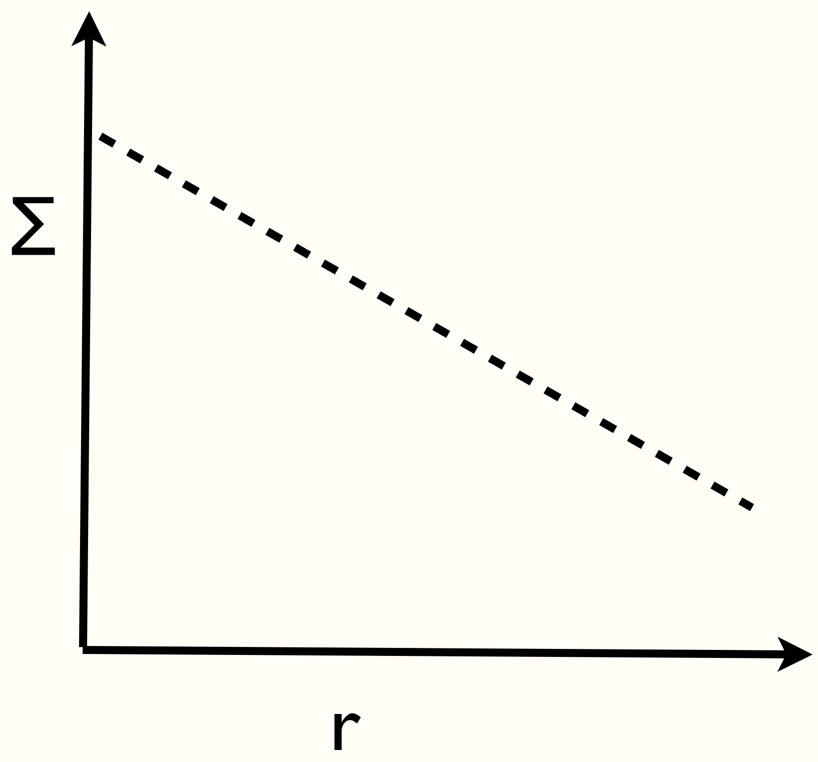
  Hall?

Inserting a giant planet in the simulations

Gap edges are
Rossby Wave Unstable
(Lovelace et al. 1999, Li et al. 2005, de Val-Borro et al 2007, Lyra et al 2009, Lin & Papaloizou 2010, Lin 2012ab, Meheut 2010, 2012)



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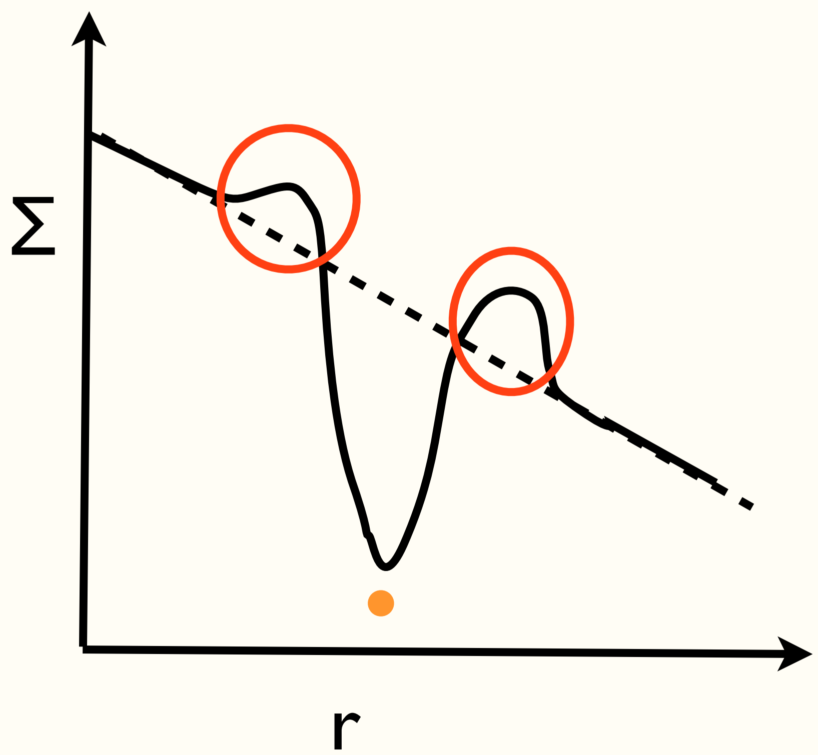

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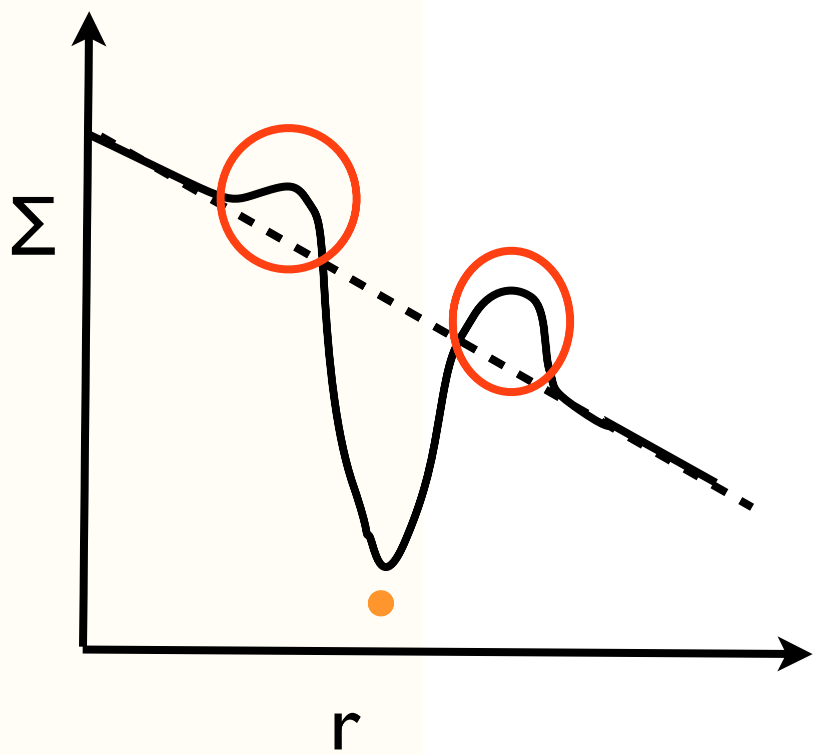
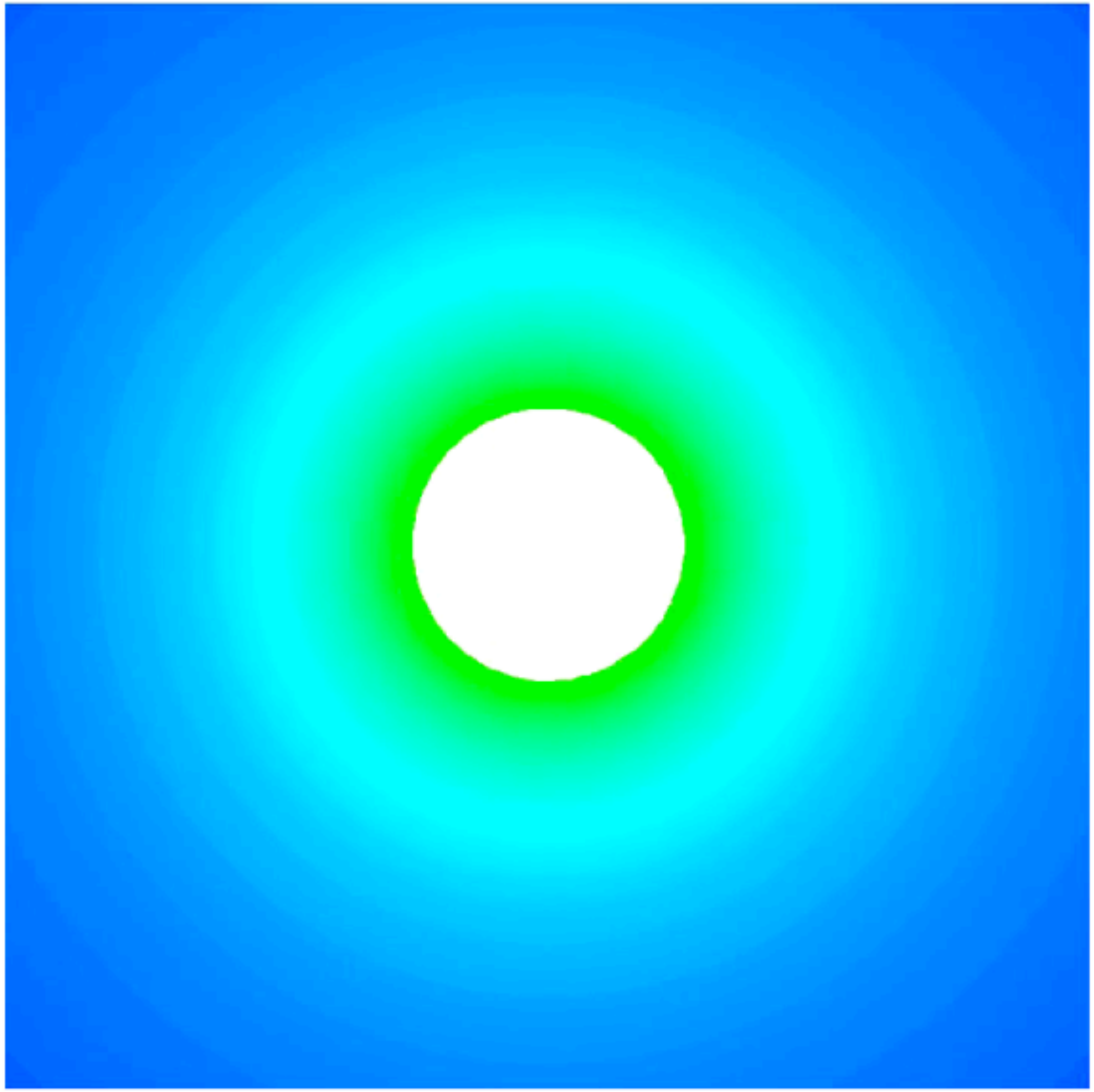
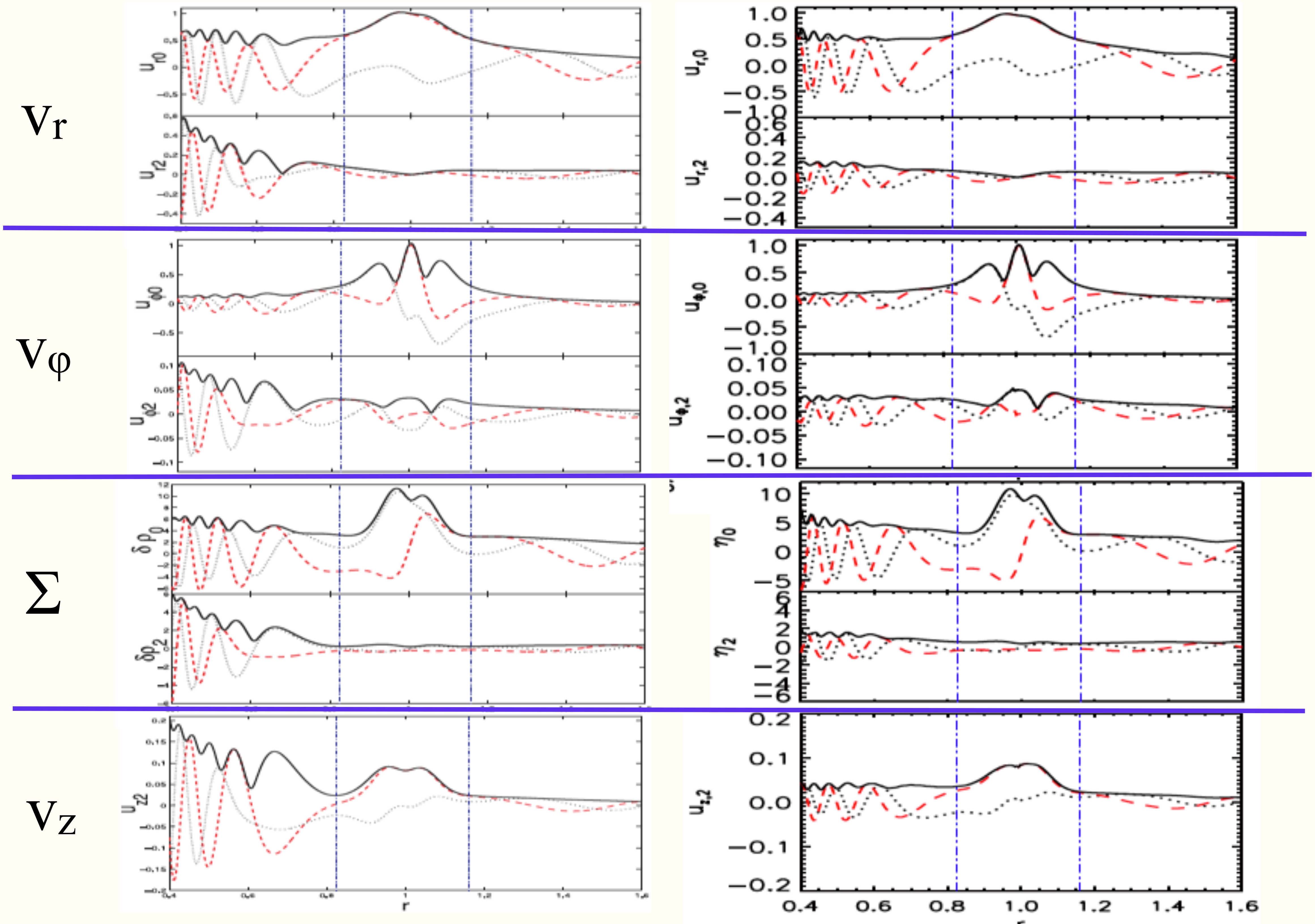


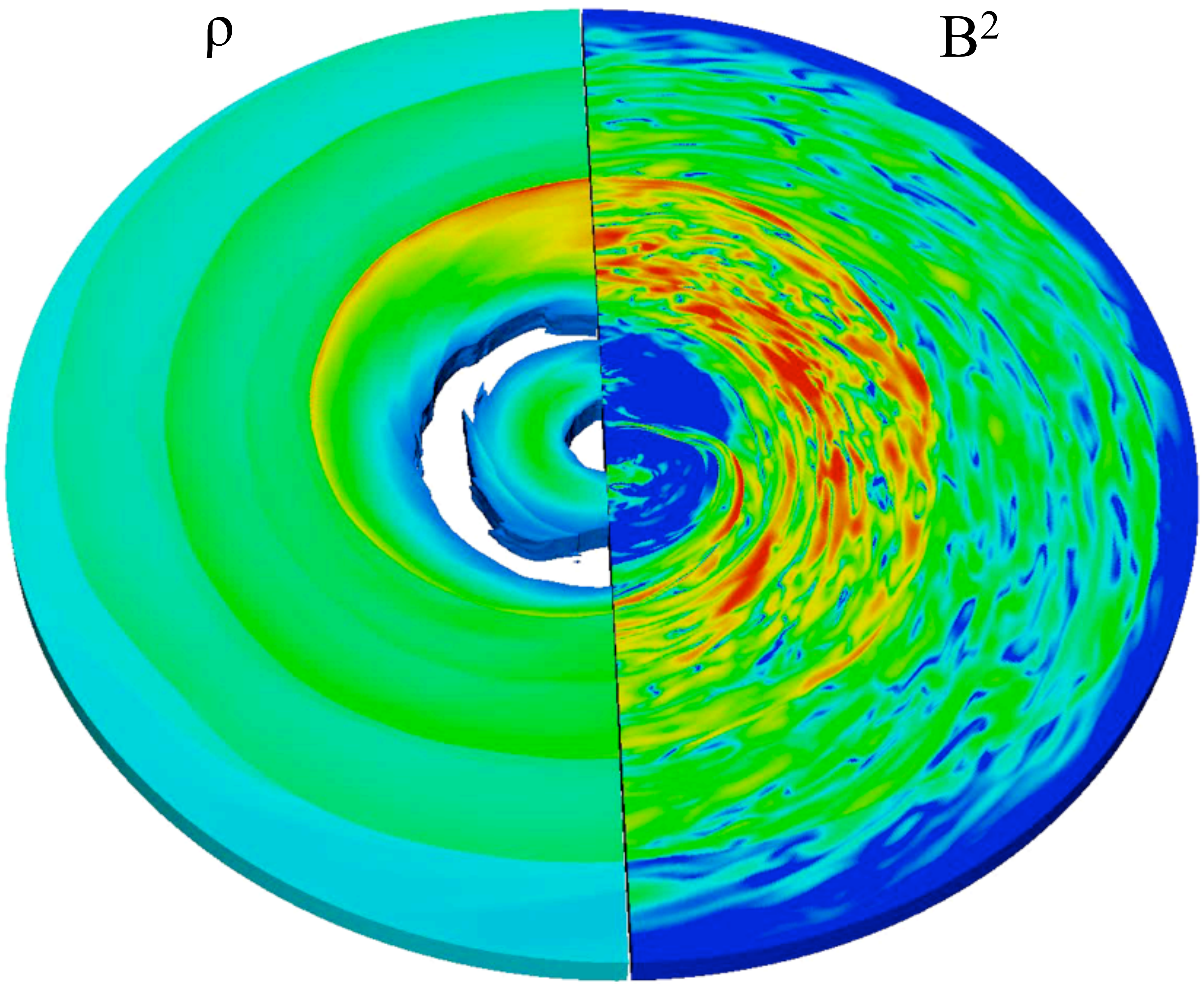


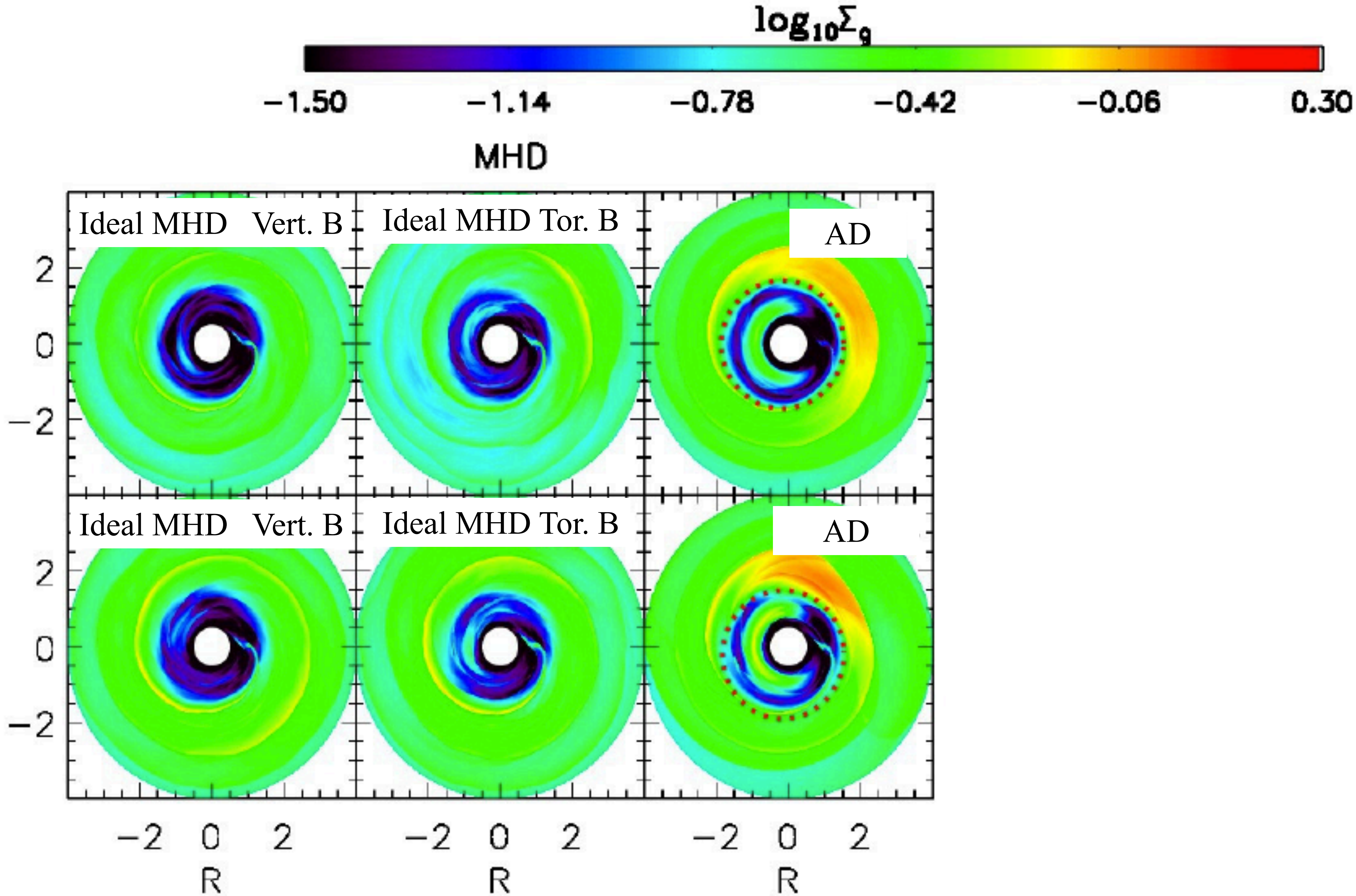
RWI in 3-D



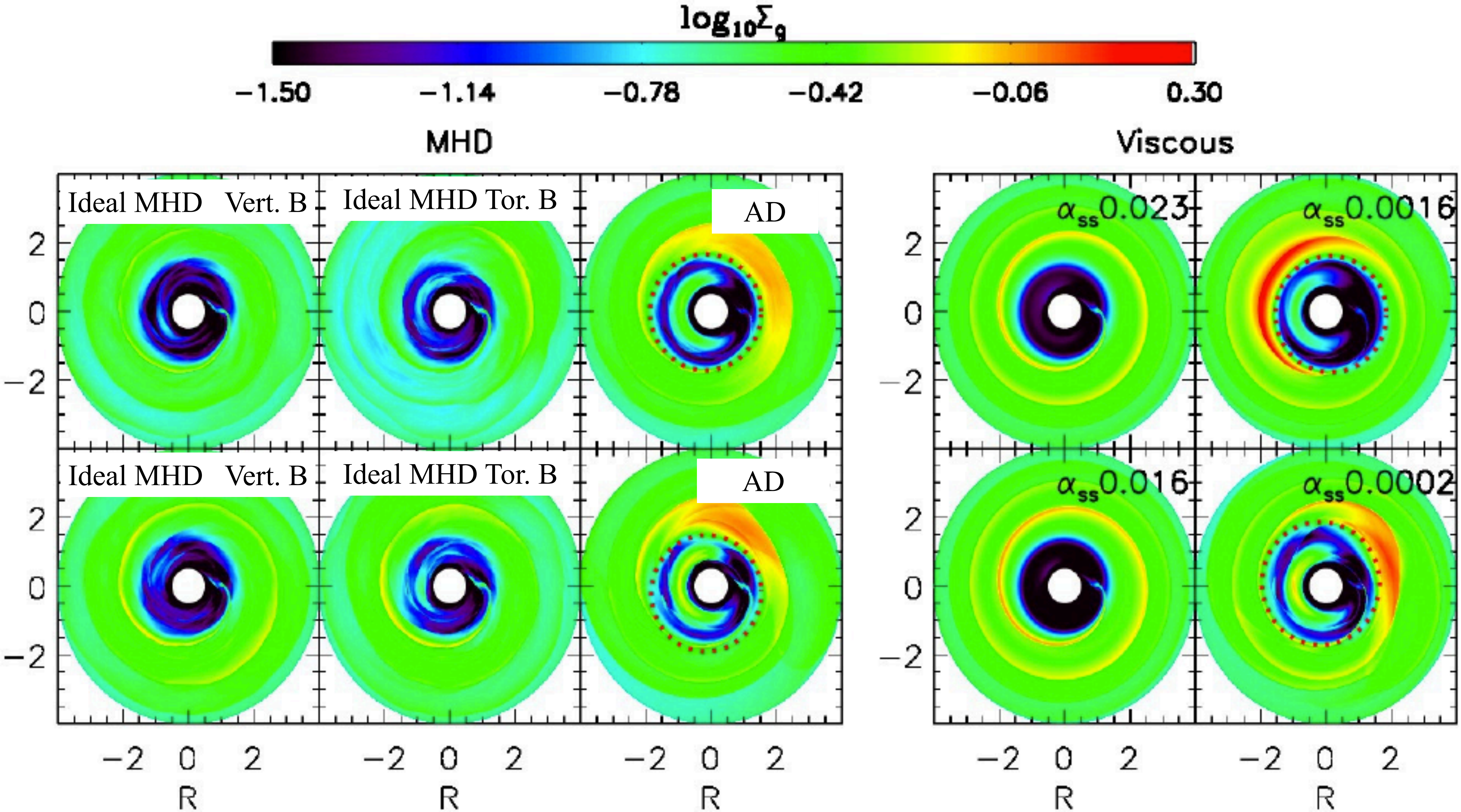
Meheut et al 2012

Zhu & Stone 2014b In prep.


ρ
B²



The vortex only appears in AD runs!



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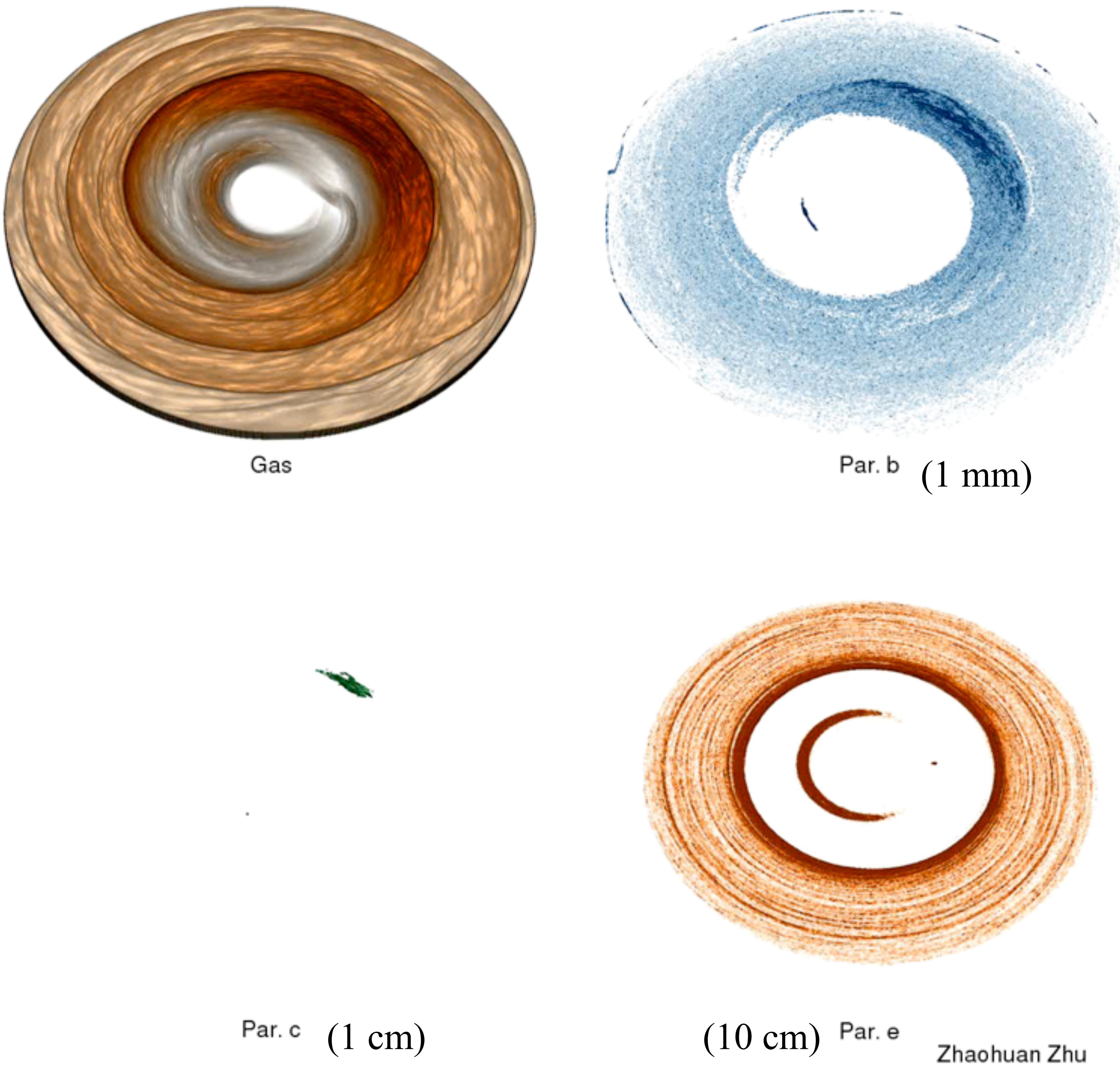
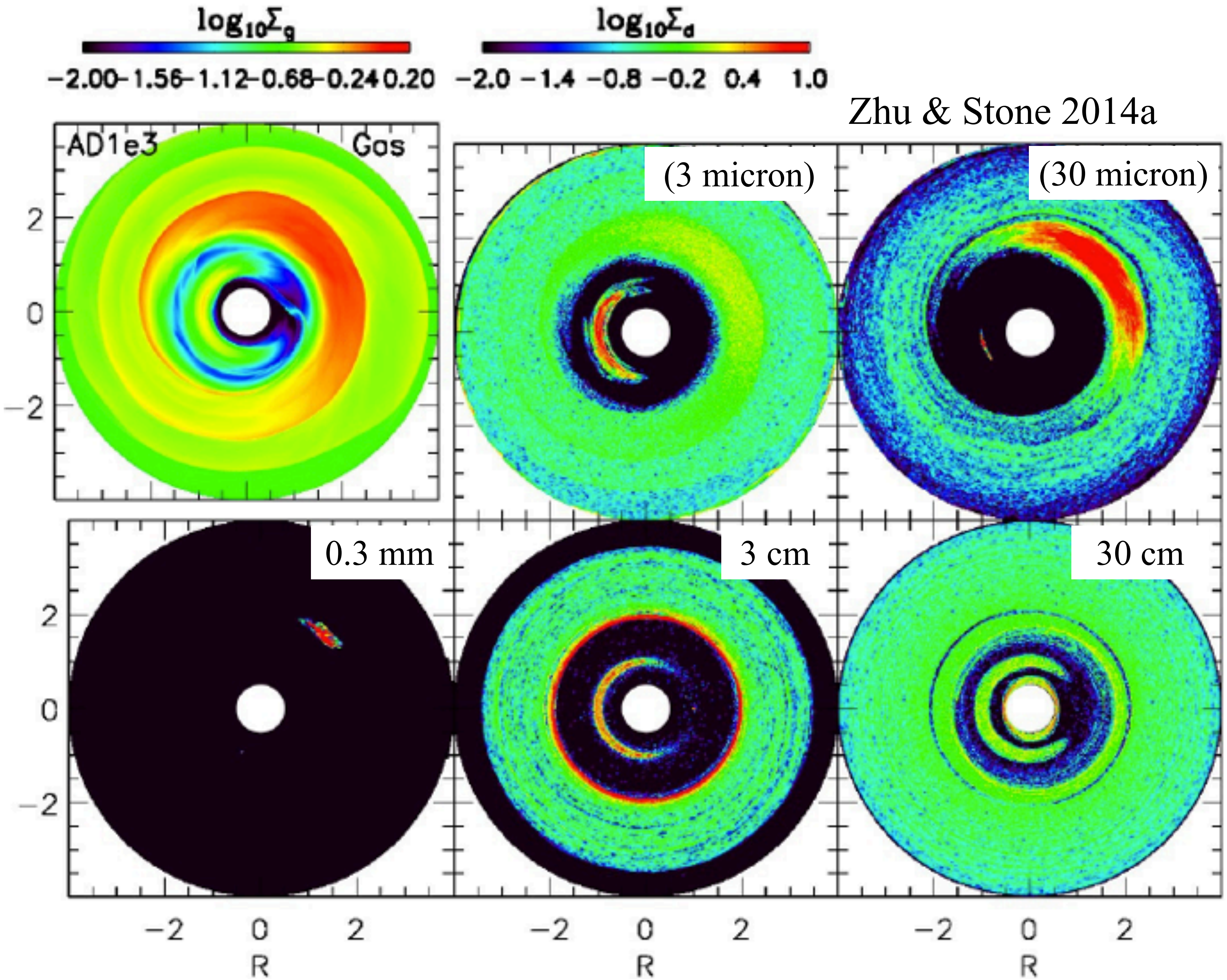
Similarity between MHD cases and equivalent viscous cases.


Gas
Par. b (1 mm)
Par. c (1 cm)
(10 cm) Par. e
Zhaohuan Zhu

Vortex develops only when AD is considered



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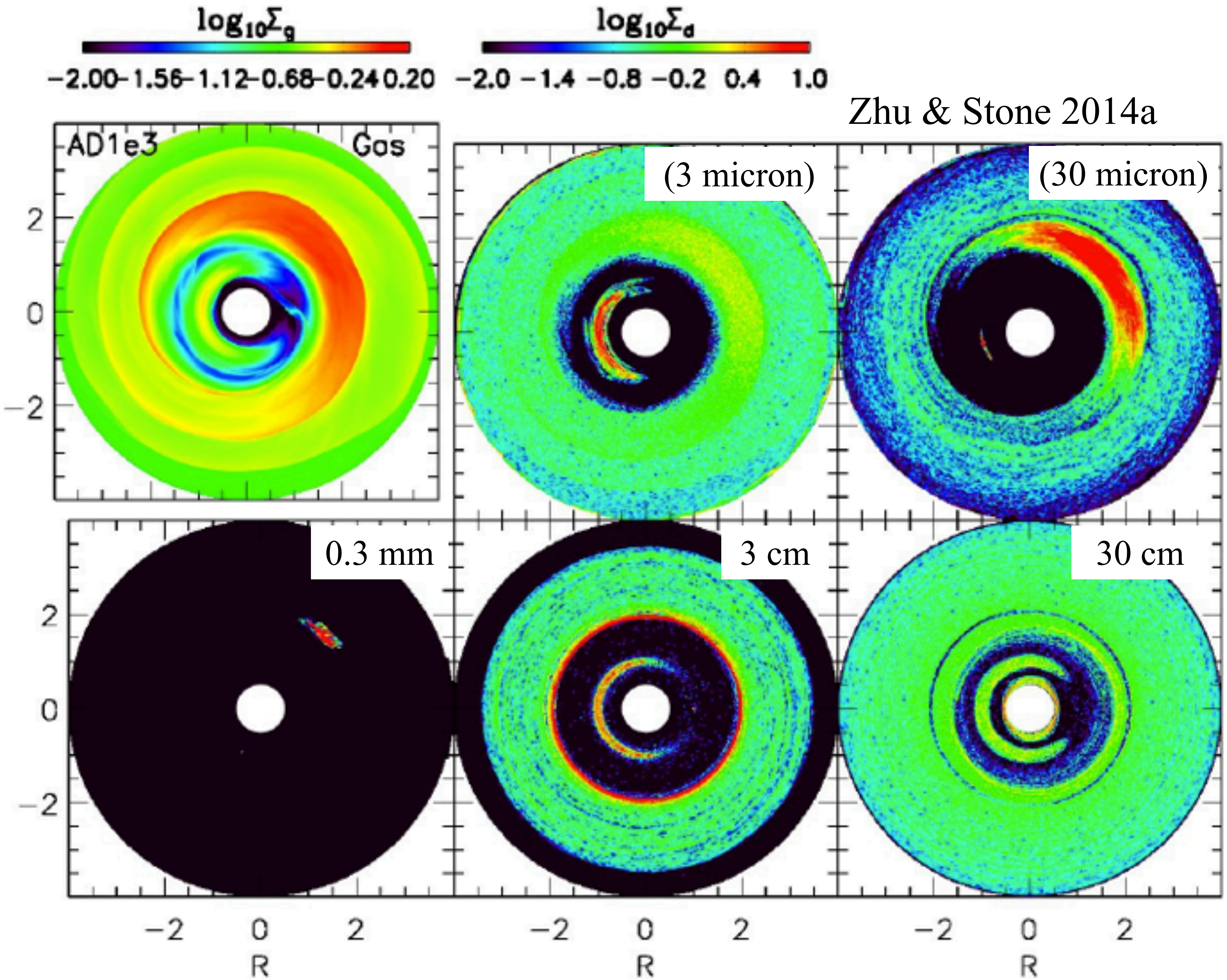
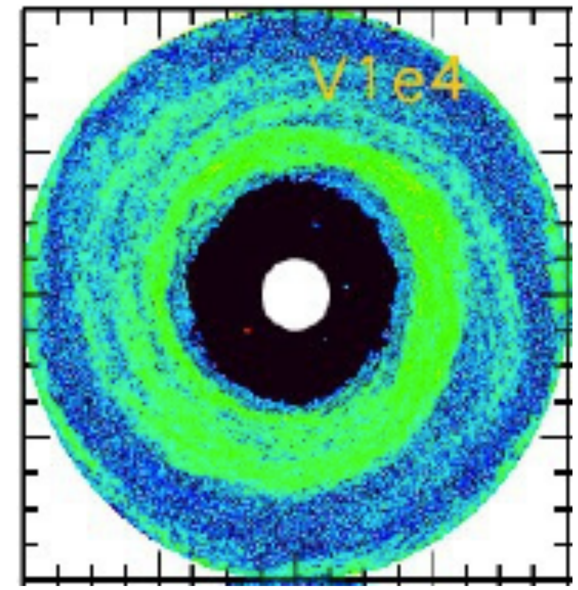


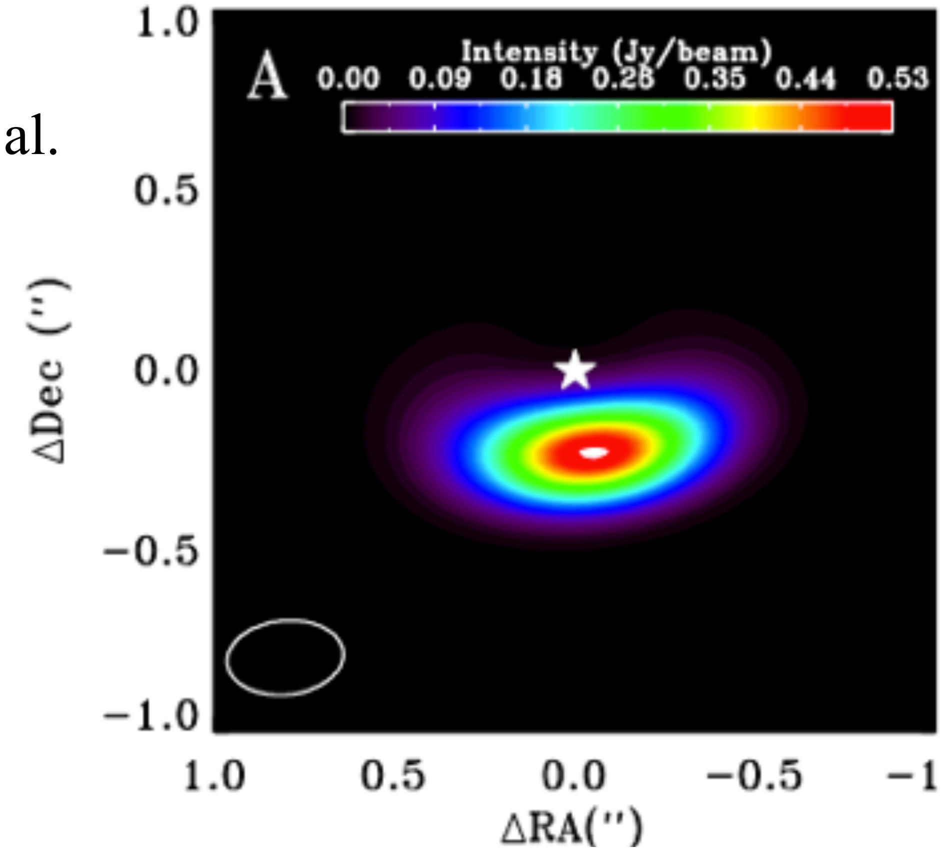
Zhu & Stone 2014a

Ideal MHD

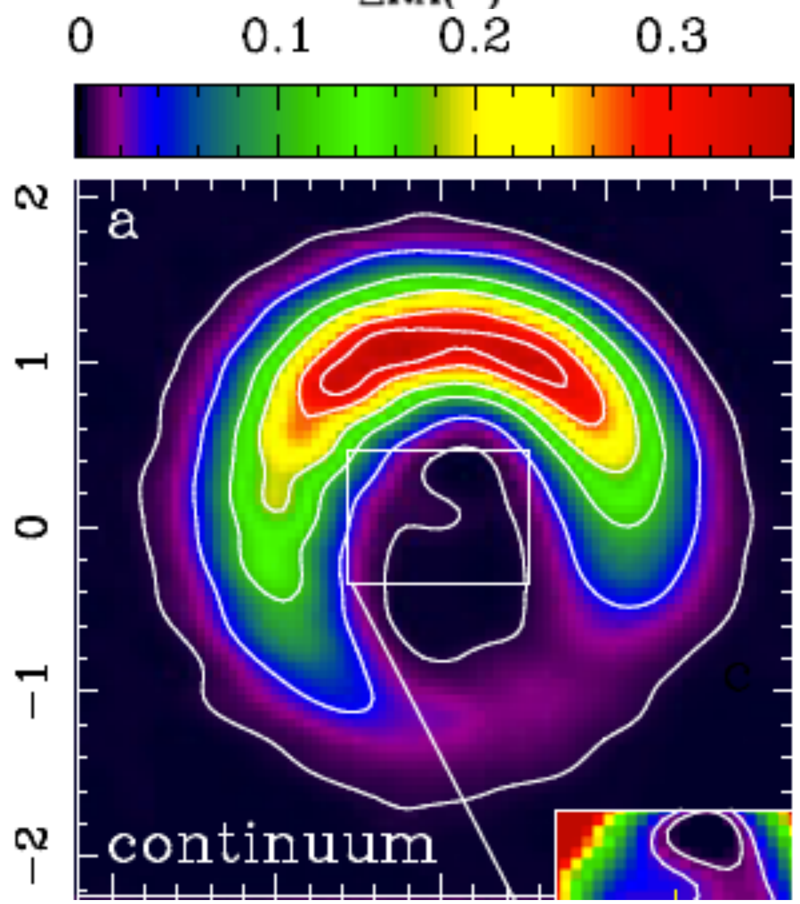


dust size $n(s) \sim s^{-3.5}$ from 0.005 μm to 500 or 100 μm

Oph IRS 48
van der Marel et al. (2013)



HD 142527
Casassus et al (2013)



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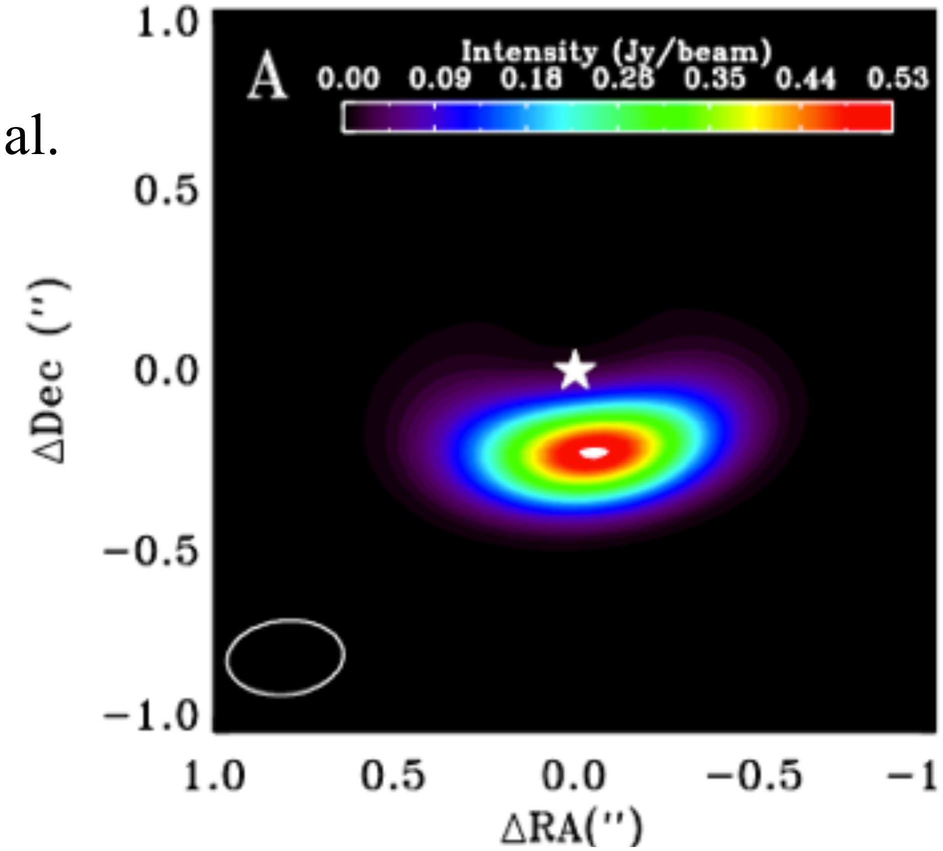

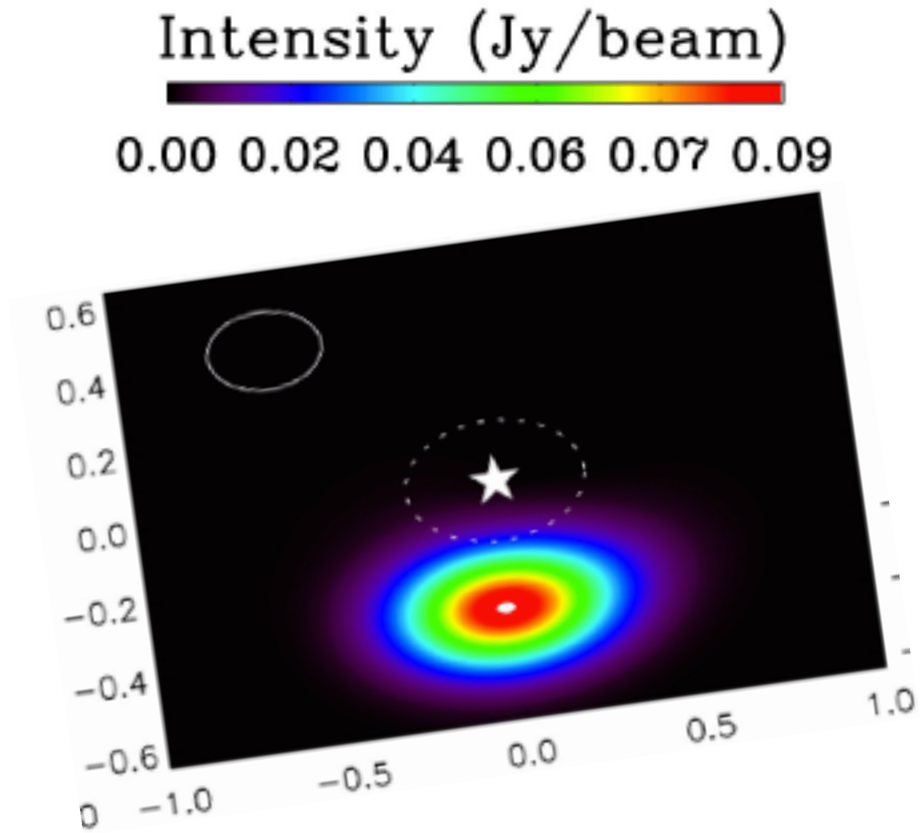

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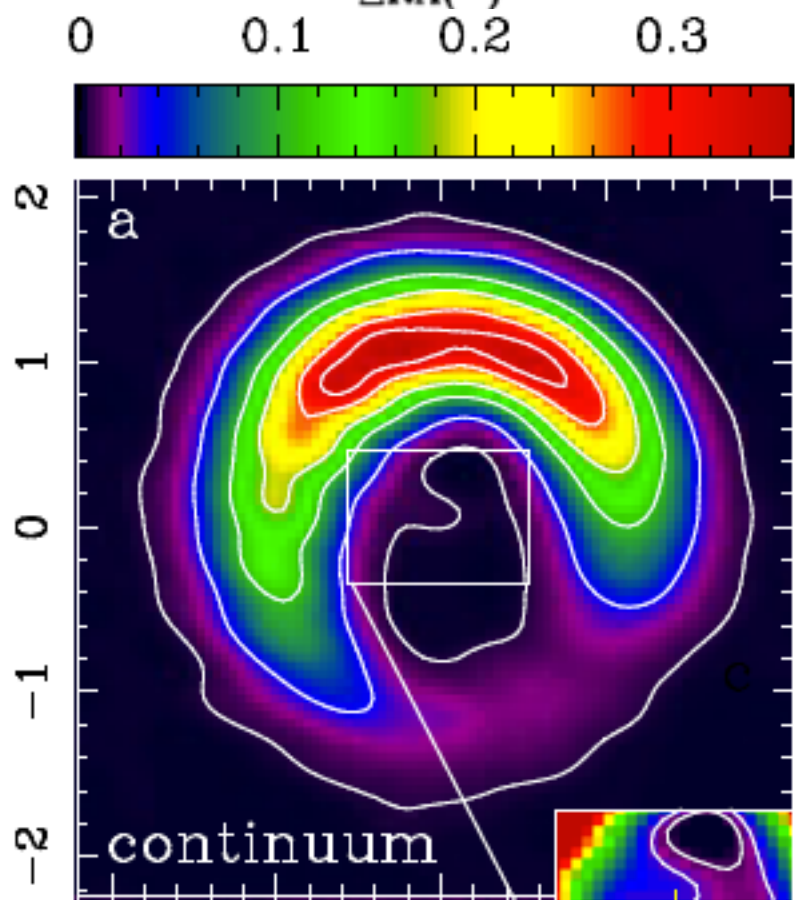

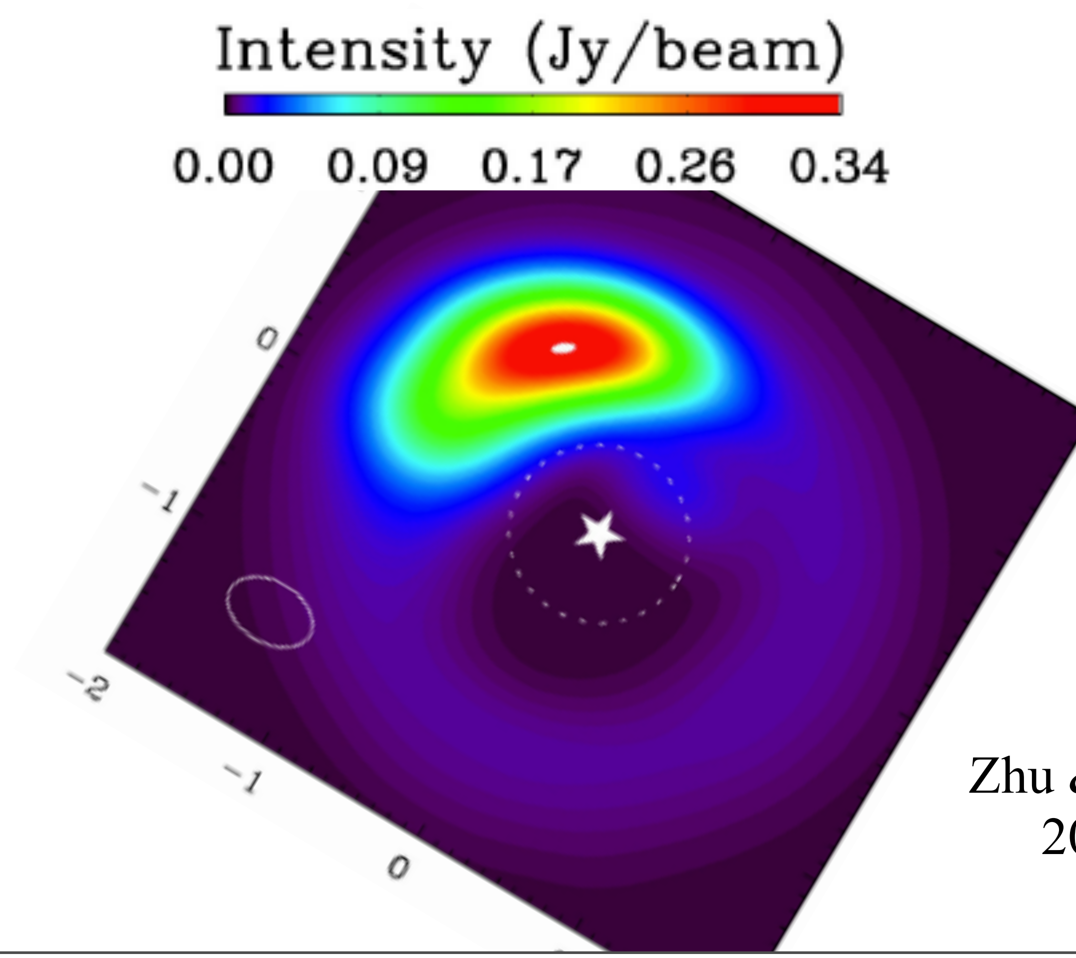

Zhu & Stone
2012a

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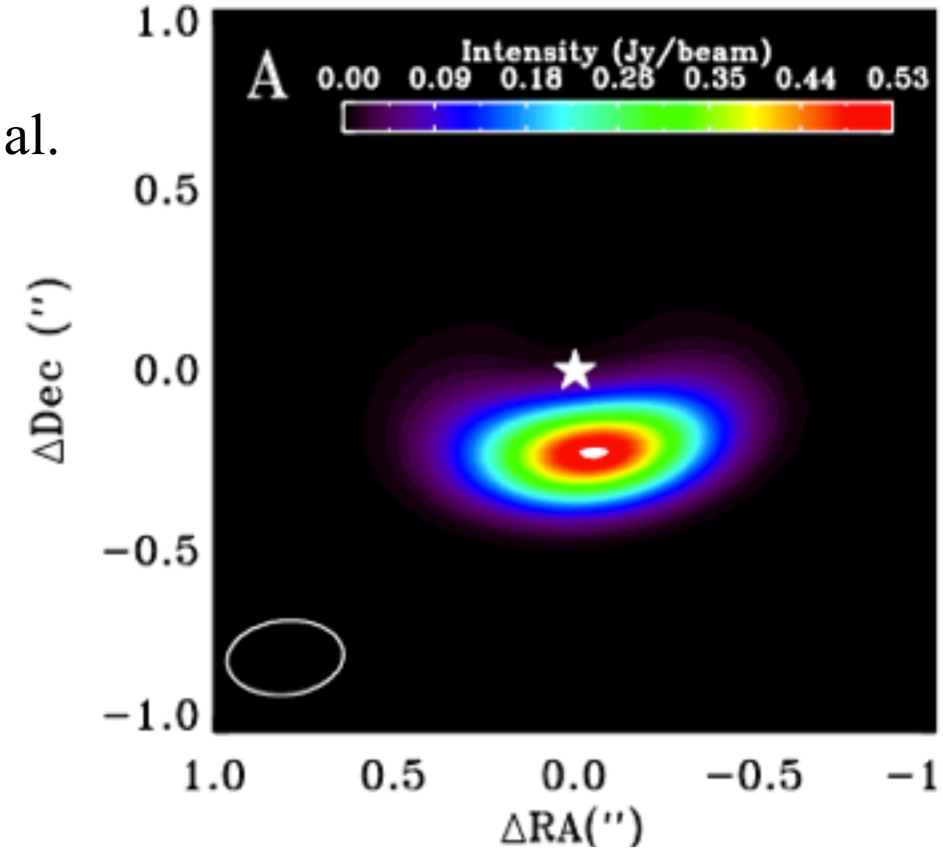
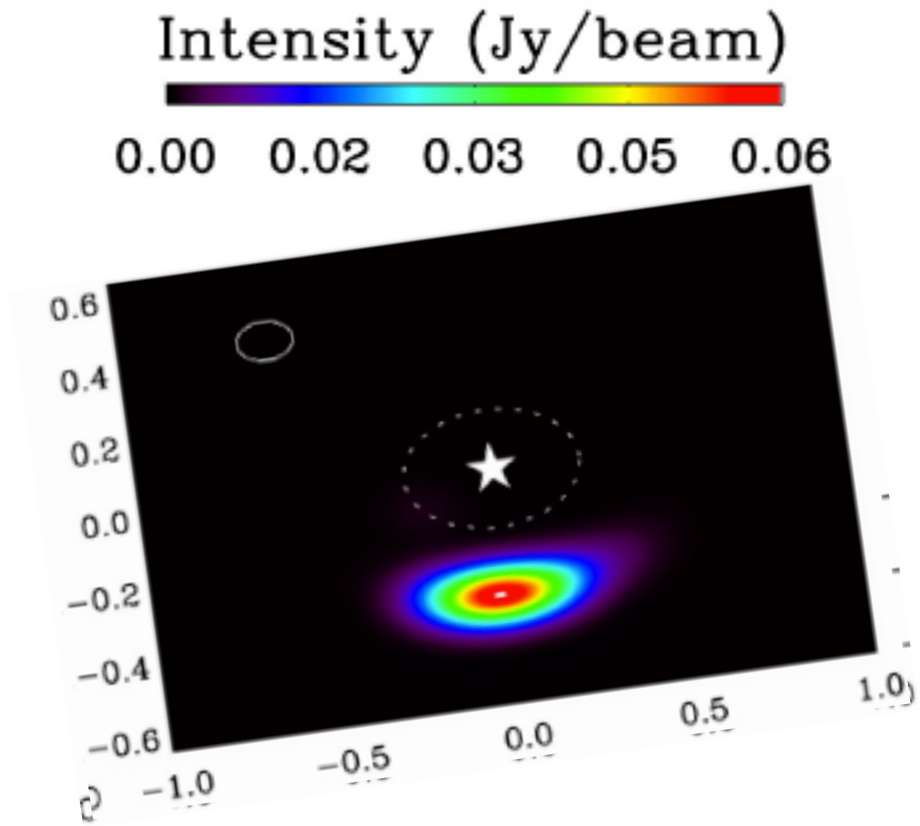
Cycle 2

Oph IRS 48
van der Marel et al. (2013)





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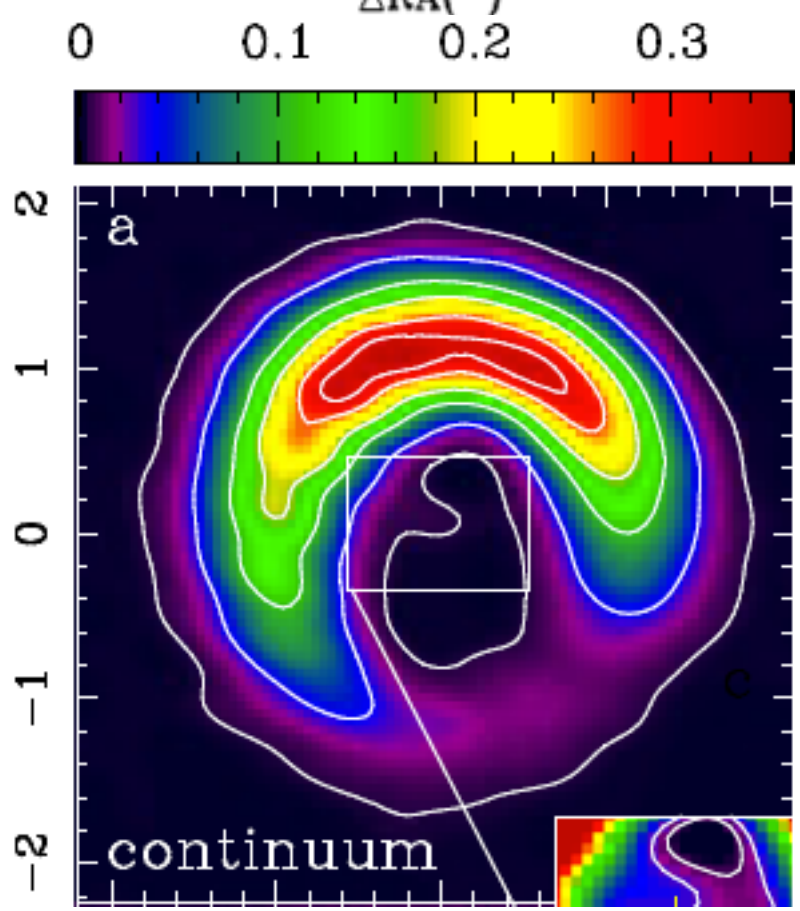

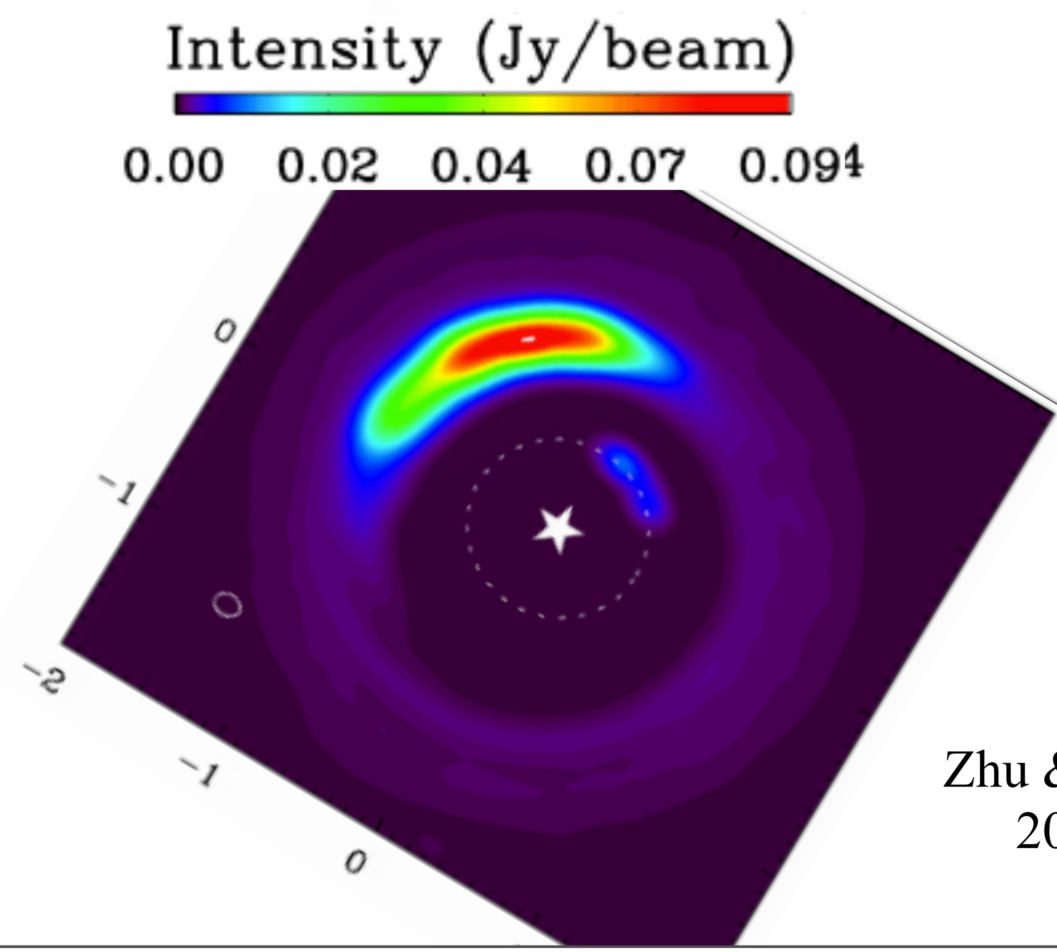

Zhu & Stone
2012a

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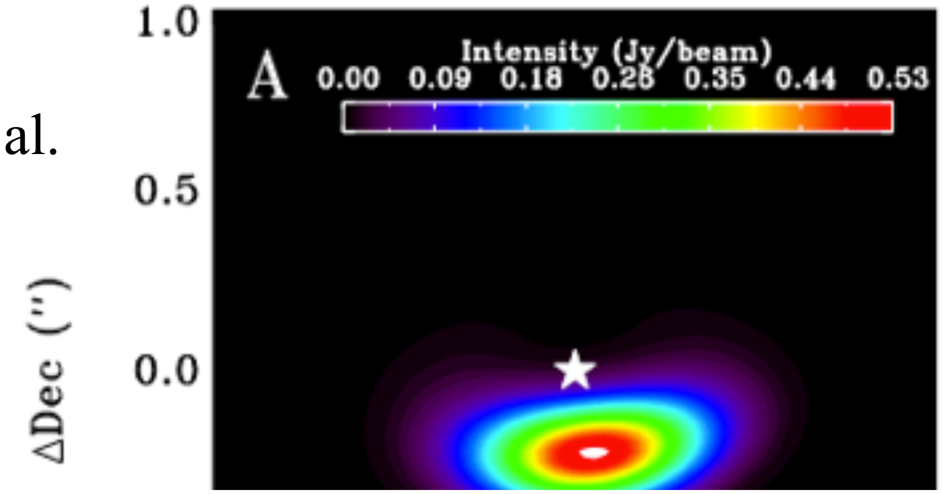
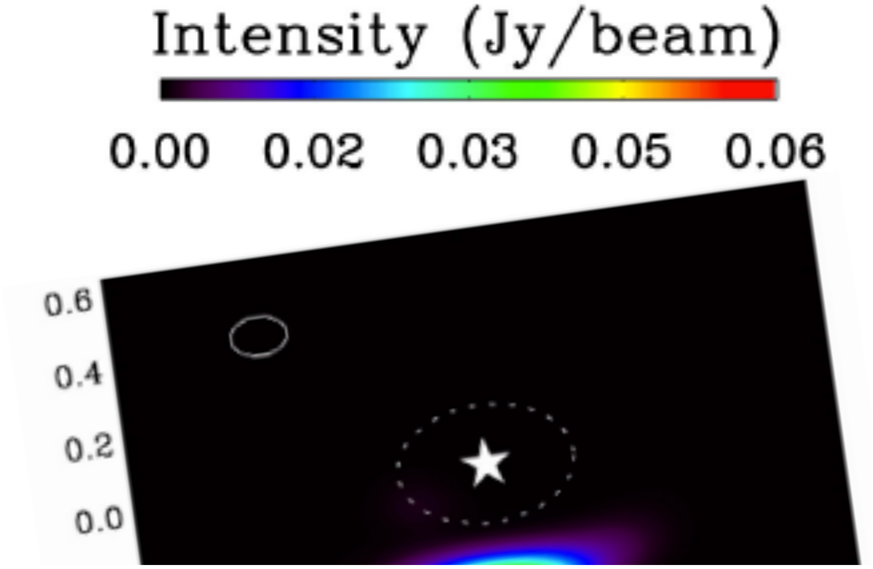
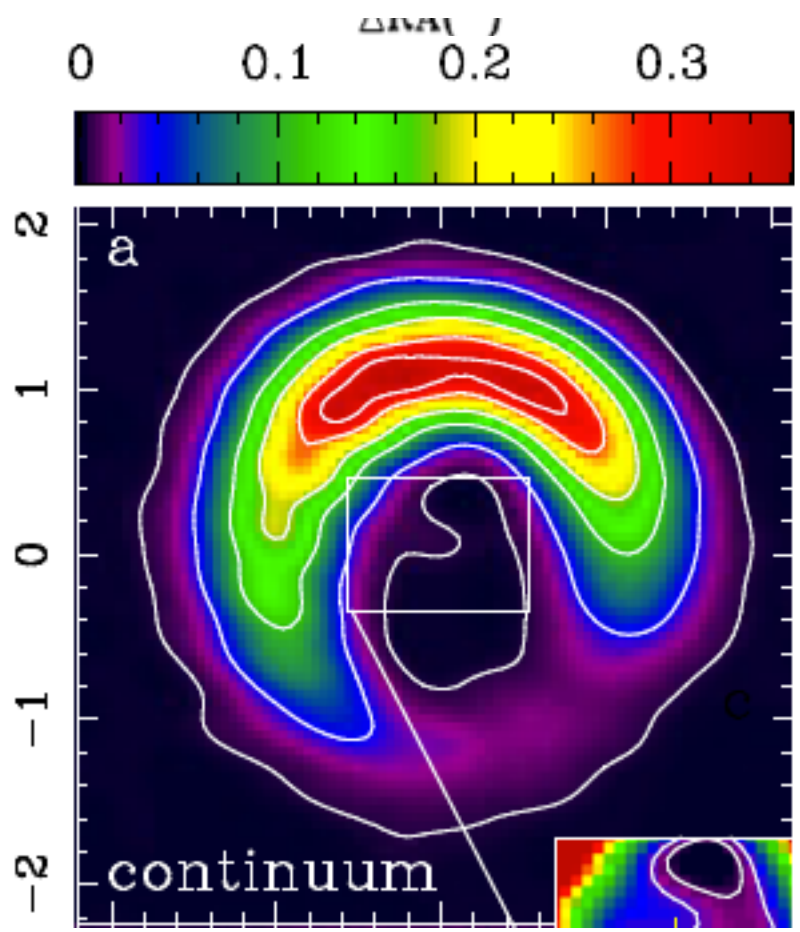


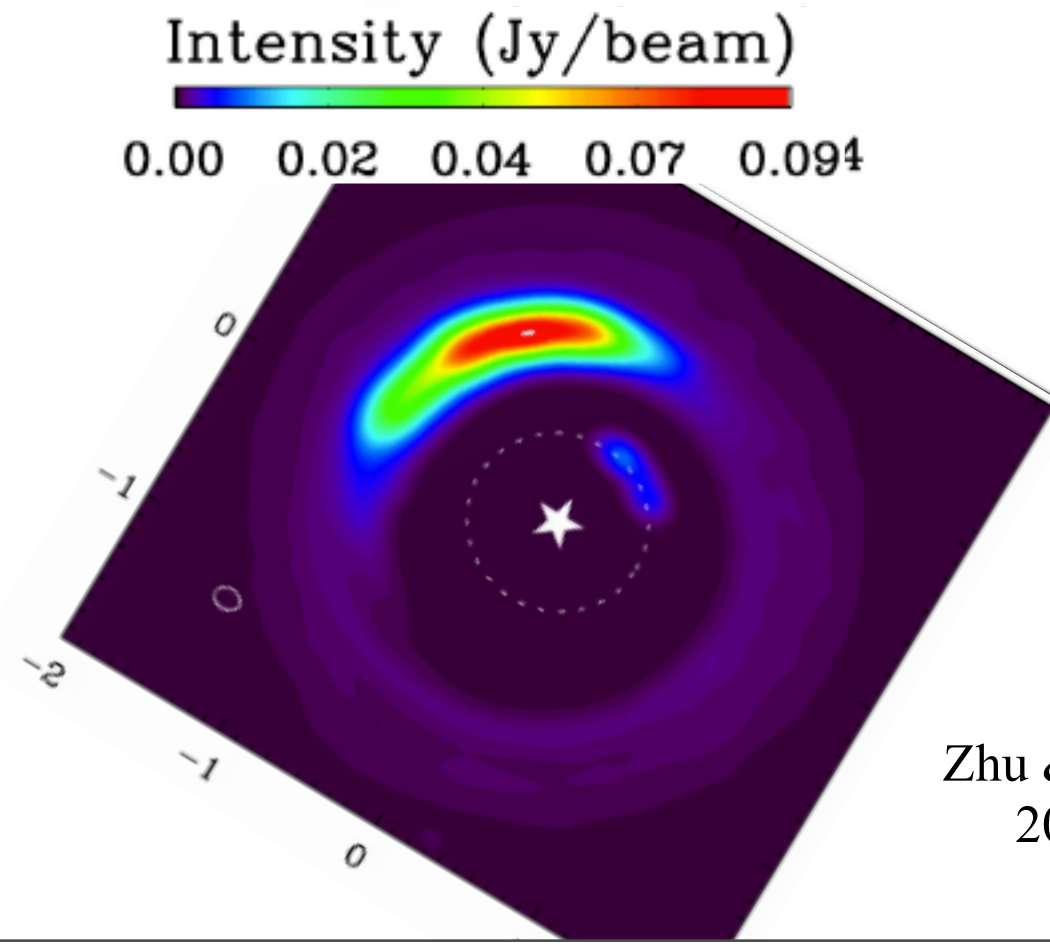


The Dust trapping vortex may indicate non-ideal MHD effects are operating in outer disks!

$\alpha < 10^{-3}$ at the outer disk

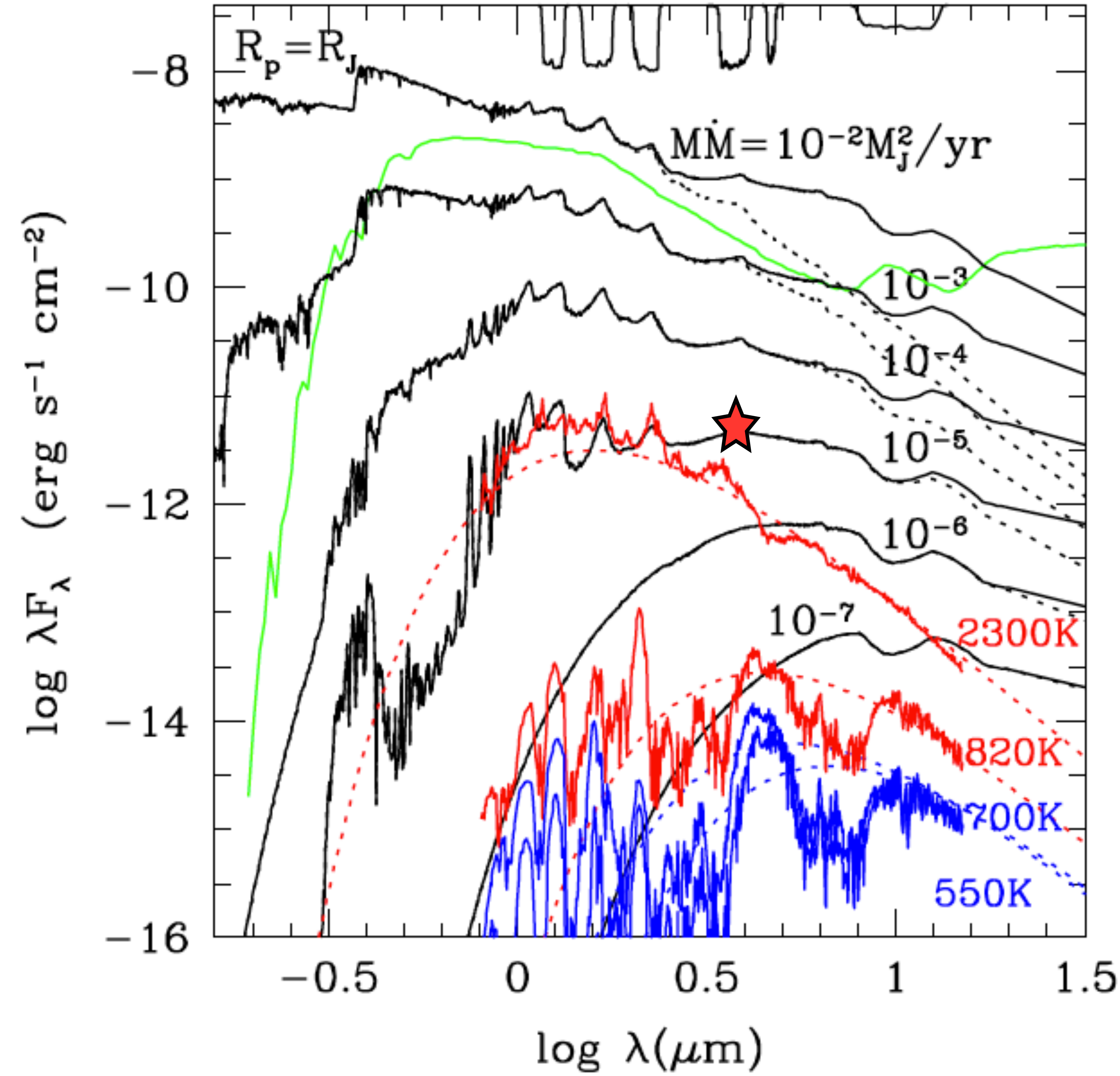
HD 142527
Casassus et al (2013)





Zhu & Stone
2012a

Accreting circumplanetary disks: mini FU Ori



Accreting circumplanetary disks could be as bright as L type brown dwarf.

Reggiani et al.
Biller et al.
HD 169142

Predictions:
M band 11.6
N band 10.1

Zhu 2014 In prep.