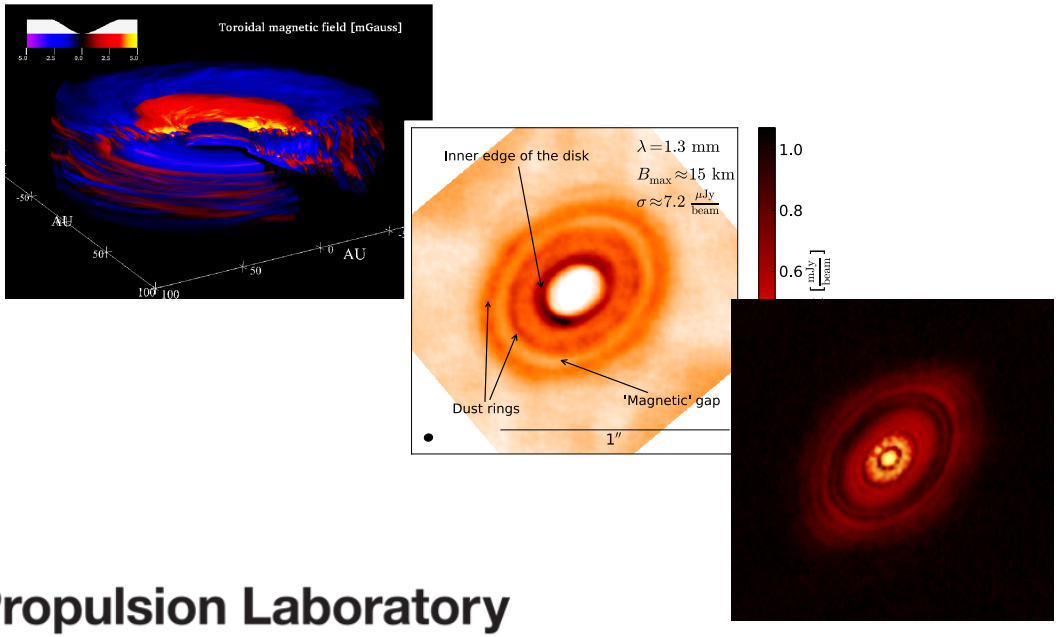
Closing the gap between simulations and observations

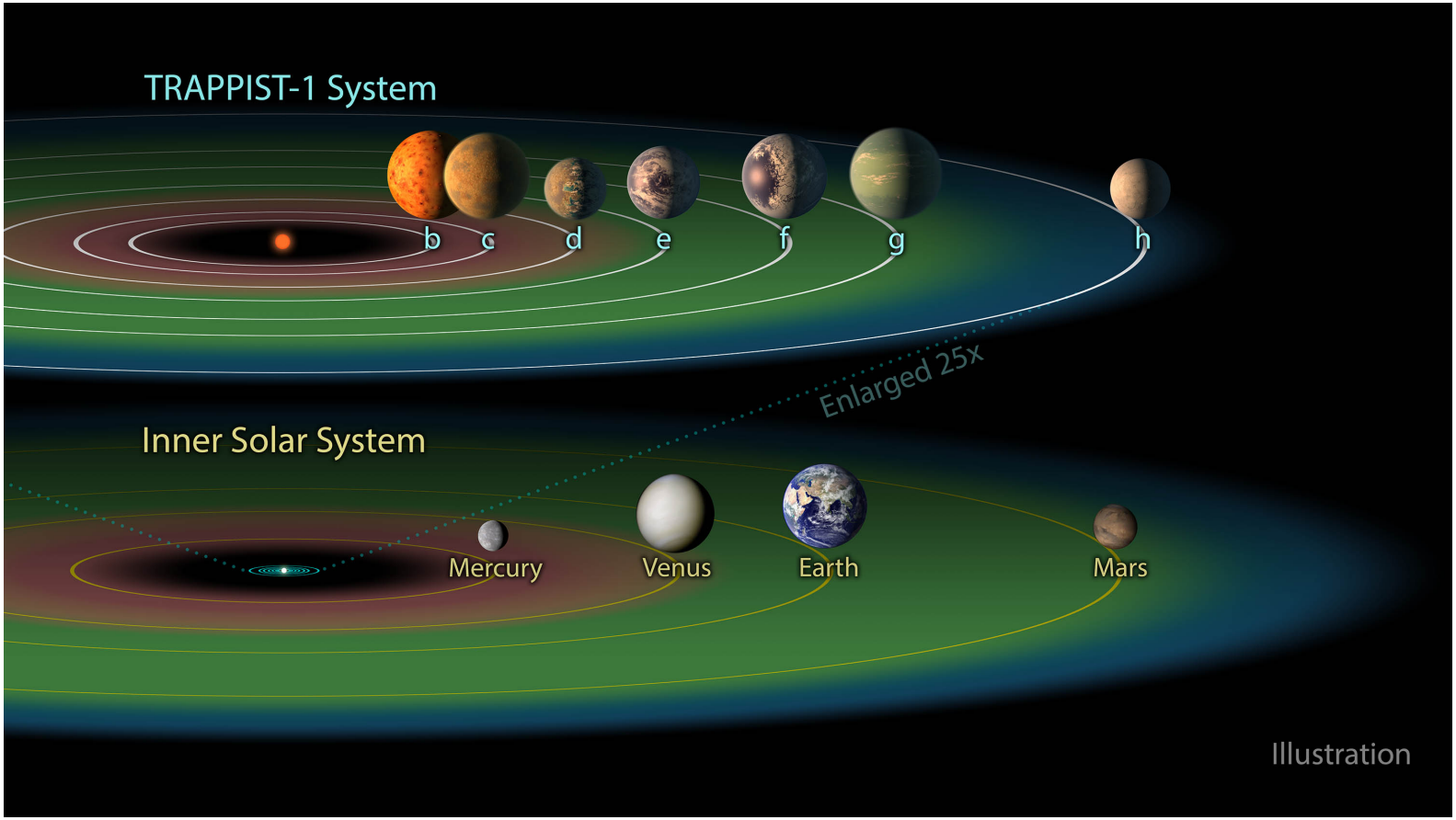


Jet Propulsion Laboratory
California Institute of Technology

Mario Flock, Jan Philipp Ruge, Neal J. Turner, Sebastien Fromang, Gesa Bertrang, Paola Pinilla Myriam Benisty, Carlos Carrasco González

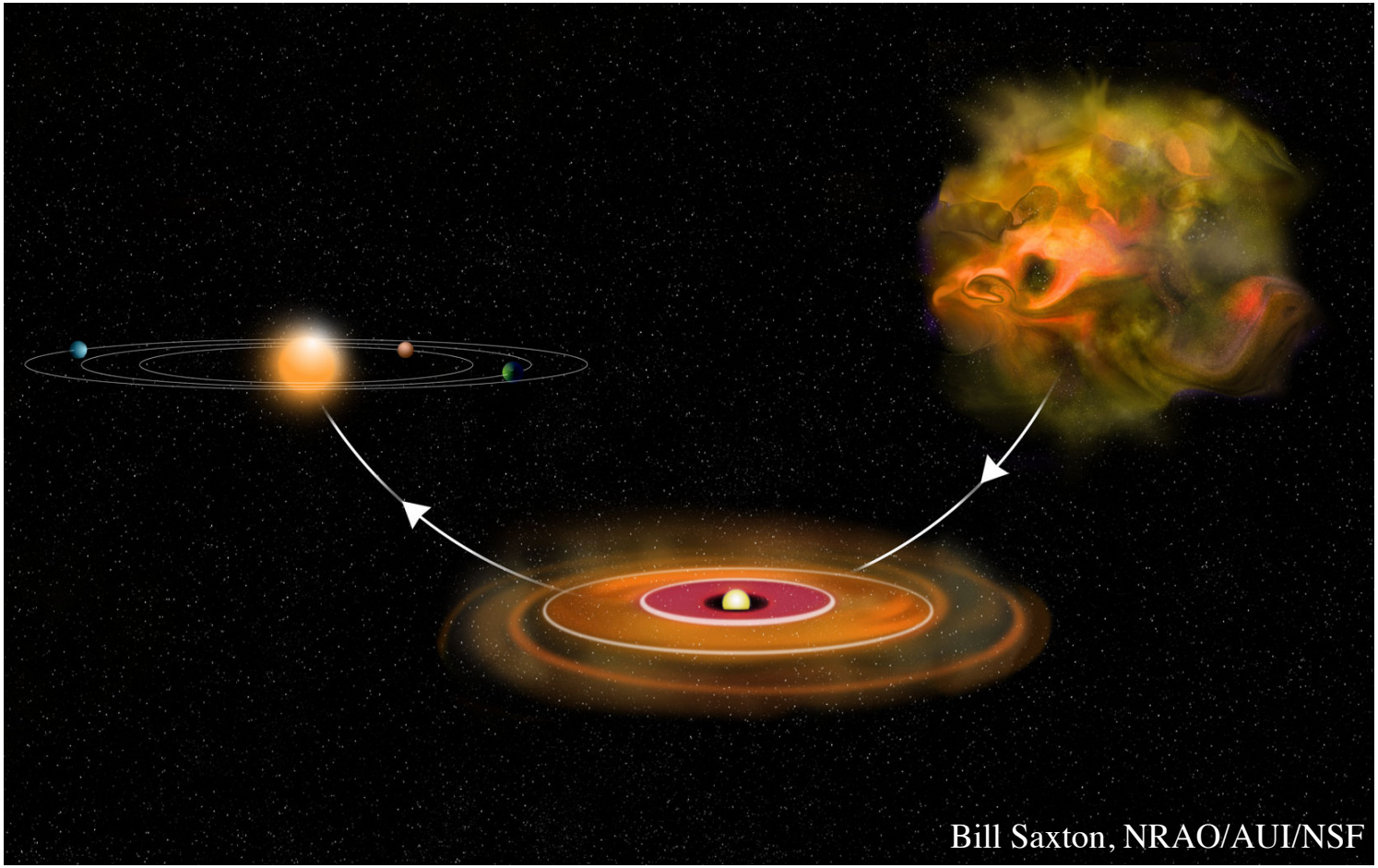
Rice university, Houston
3.7.2018

How are planets formed ?



NASA

Planet formation in disks



Protoplanetary disks

What do we see* ?

* thermal dust emission

What do we model** ?

** gas disk

Protoplanetary disks

What do we see* ?

* thermal dust emission

What do we model** ?

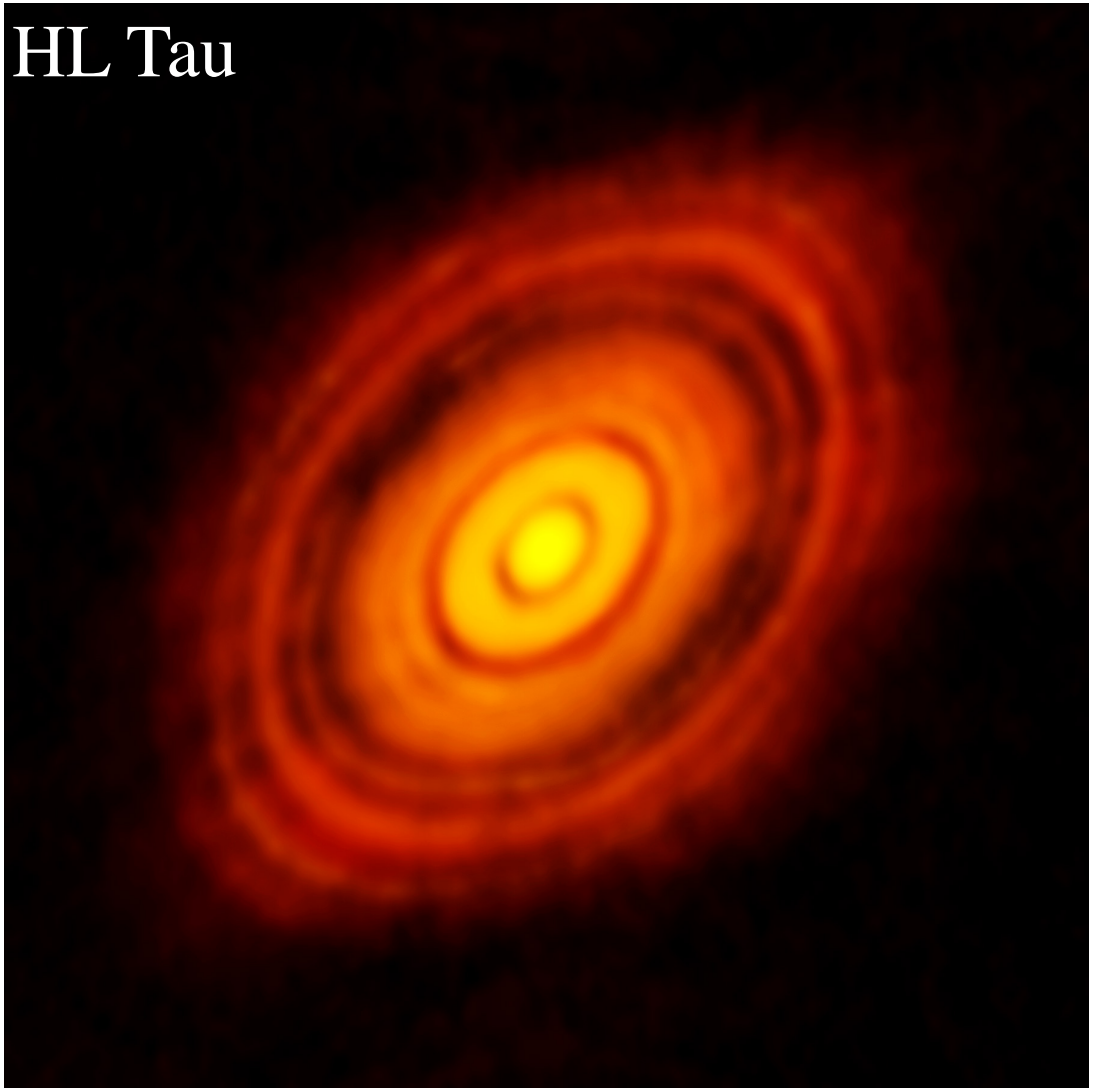
** gas disk

What do we understand ?

Protoplanetary disks

What do we see* ?

* thermal dust emission



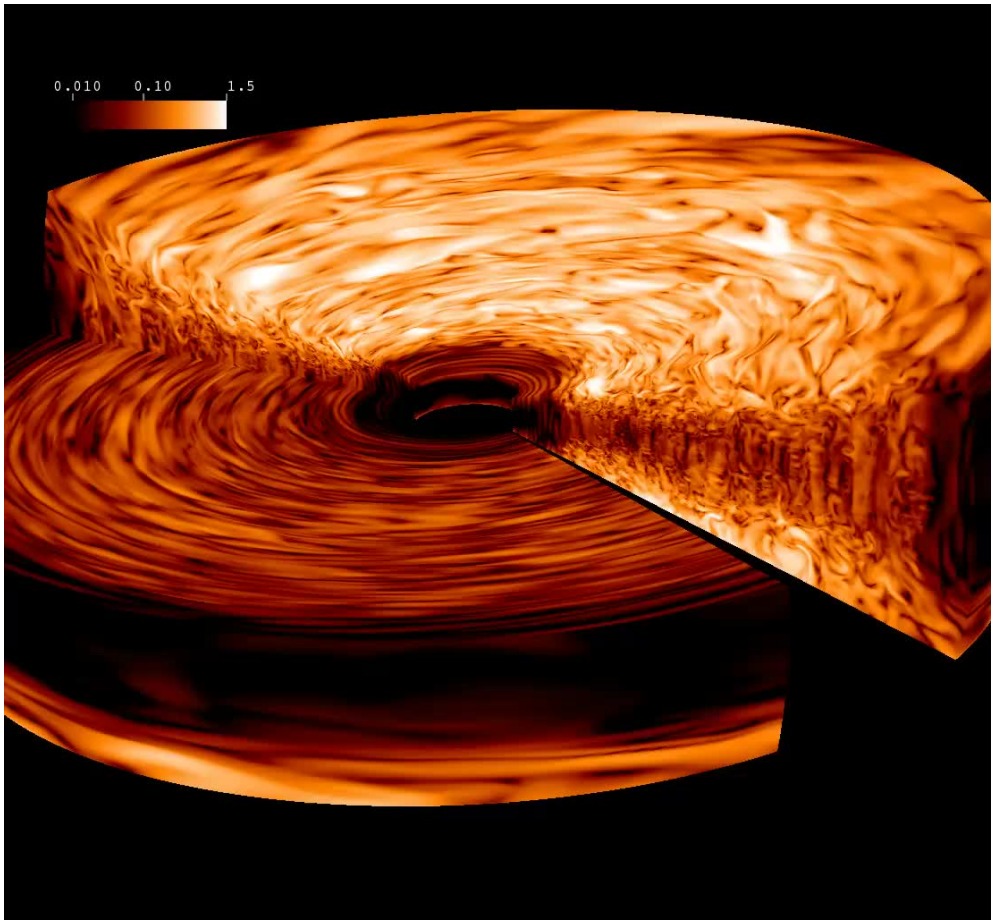
ALMA Partnership+2015

Rings also seen
in TW Hya, HD 163296 …

Protoplanetary disks

What do we model** ?

** gas disk

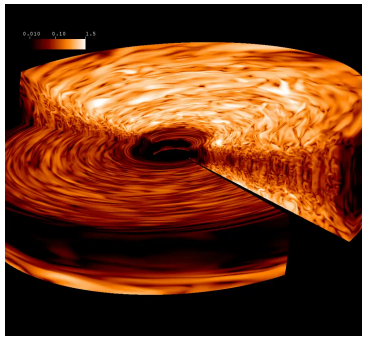


Inner disk

Flock et al. 2011

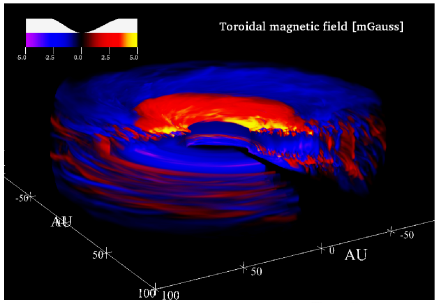
Protoplanetary disk

Flock et al. 2011



MRI turbulence

Flock et al. 2015

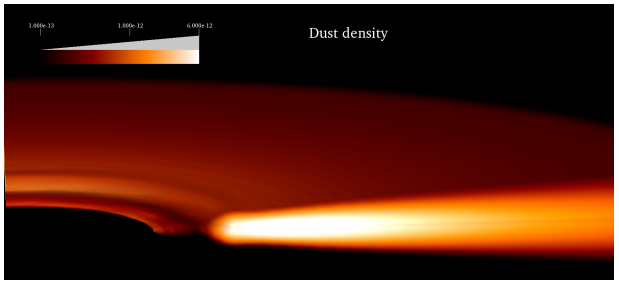


MRI turbulence

Disk wind

Dead-zone

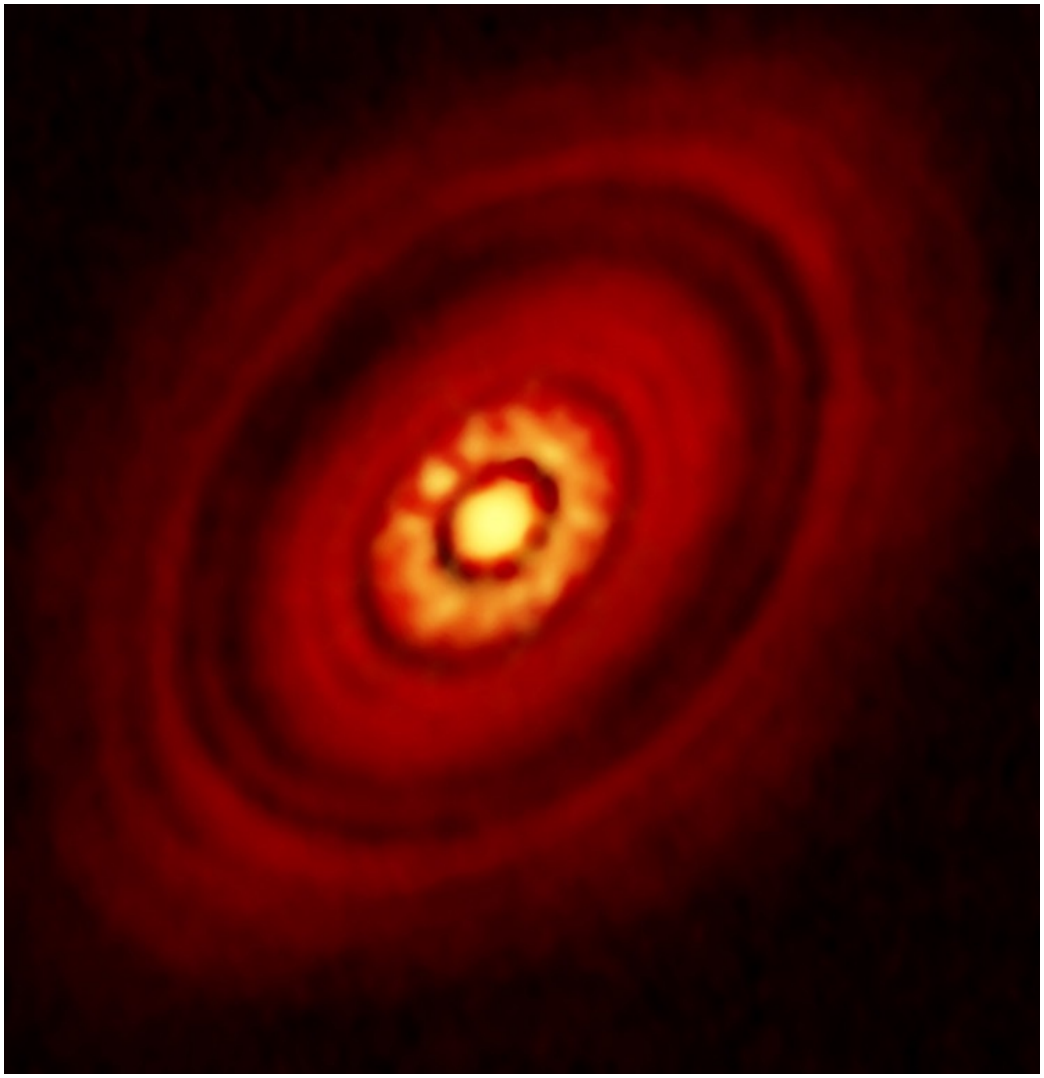
Inner rim
- T =1500 K
- NIR emission (VLTI)



Flock et al. 2017

Outer disk
- T <100 K
- (sub)mm (ALMA)

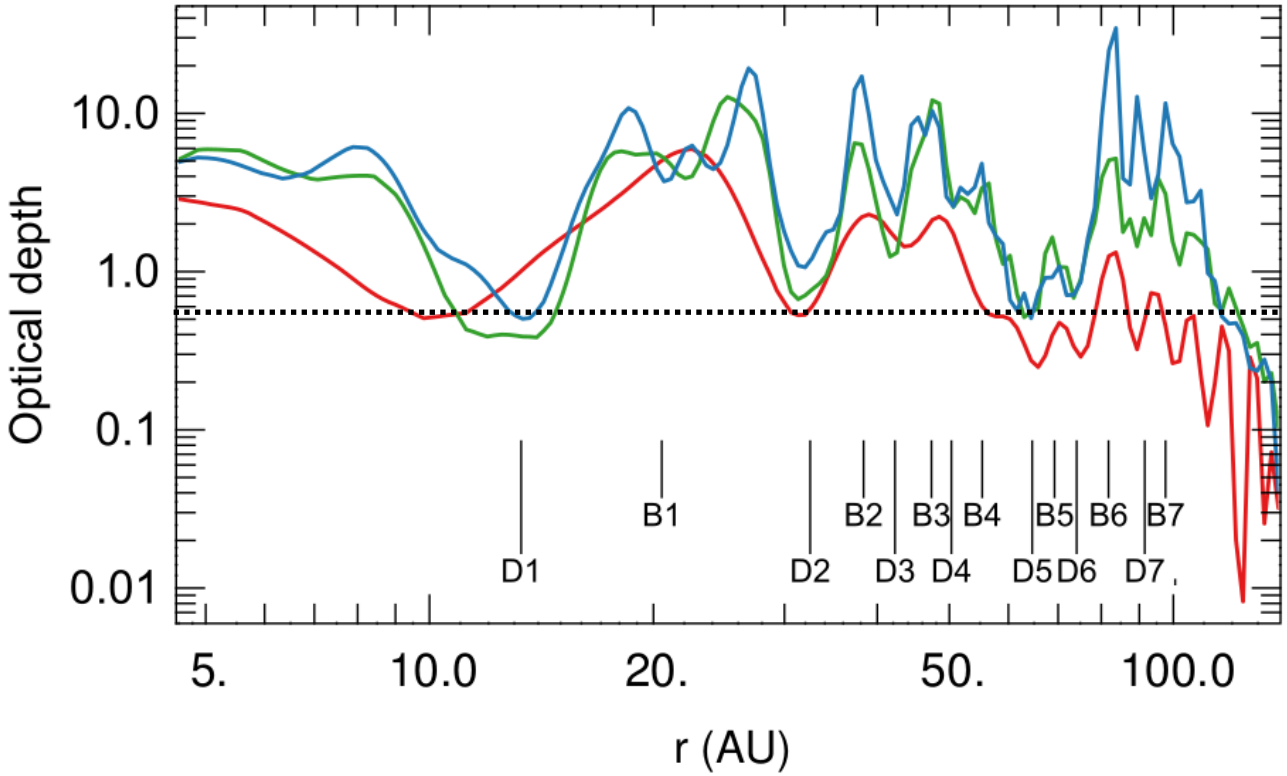
Dust continuum emission



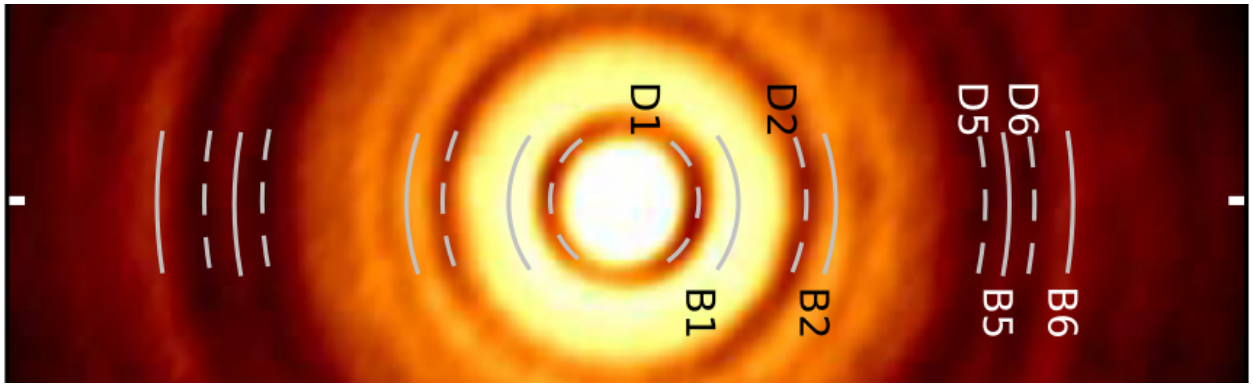
ALMA Partnership+2015
Carrasco-González et al. 2016

HL Tau
(ALMA + VLA 7mm)

HL Tau RT model by
Pinte et al. (2016)



Band	
3 mm	3
1.3 mm	6
0.87 mm	7



HL Tau RT model by
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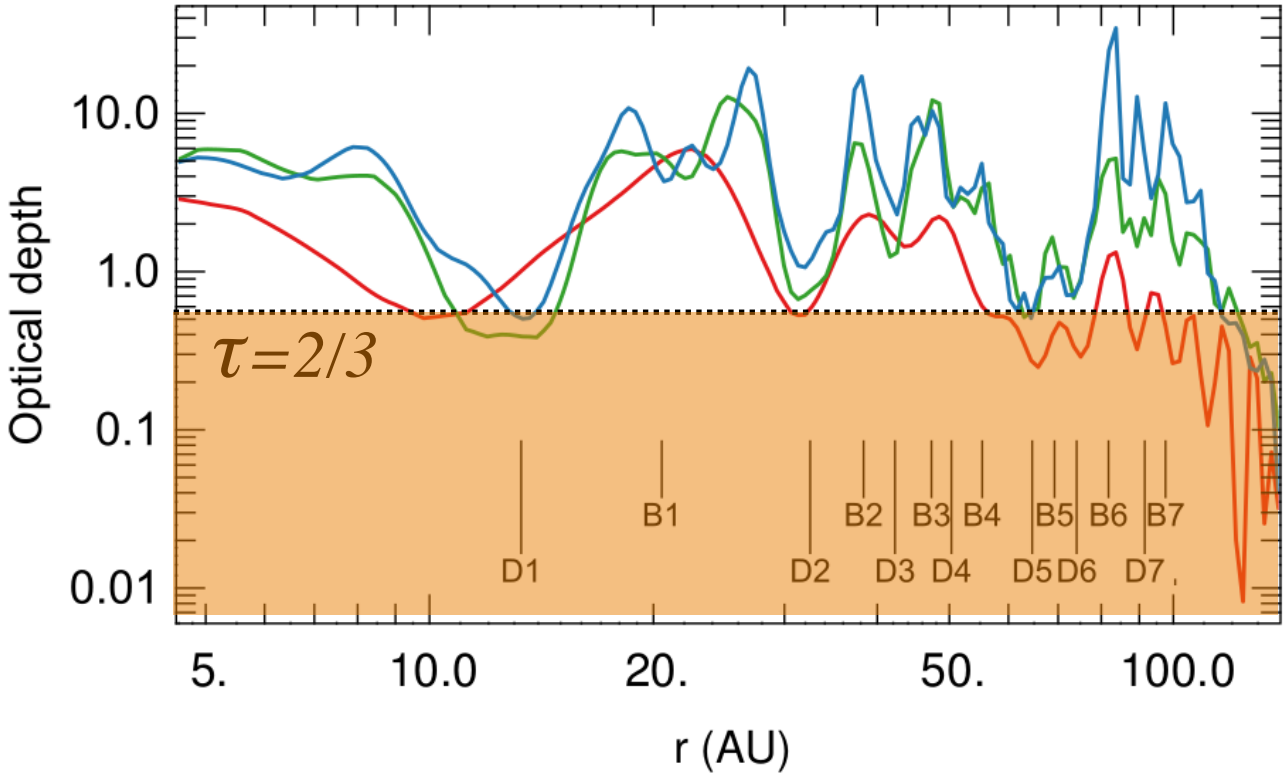
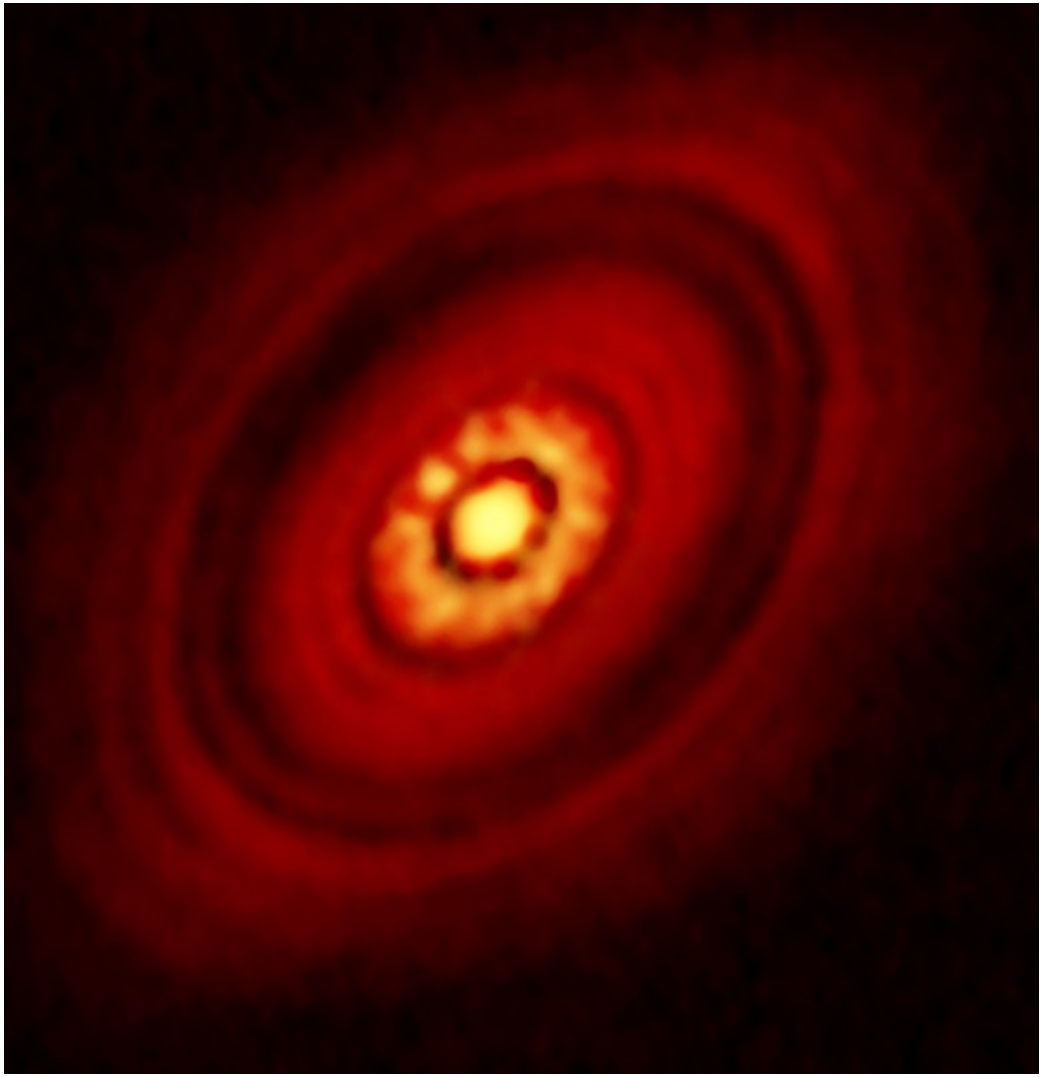


	Band
3 mm	3
1.3 mm	6
0.87 mm	7

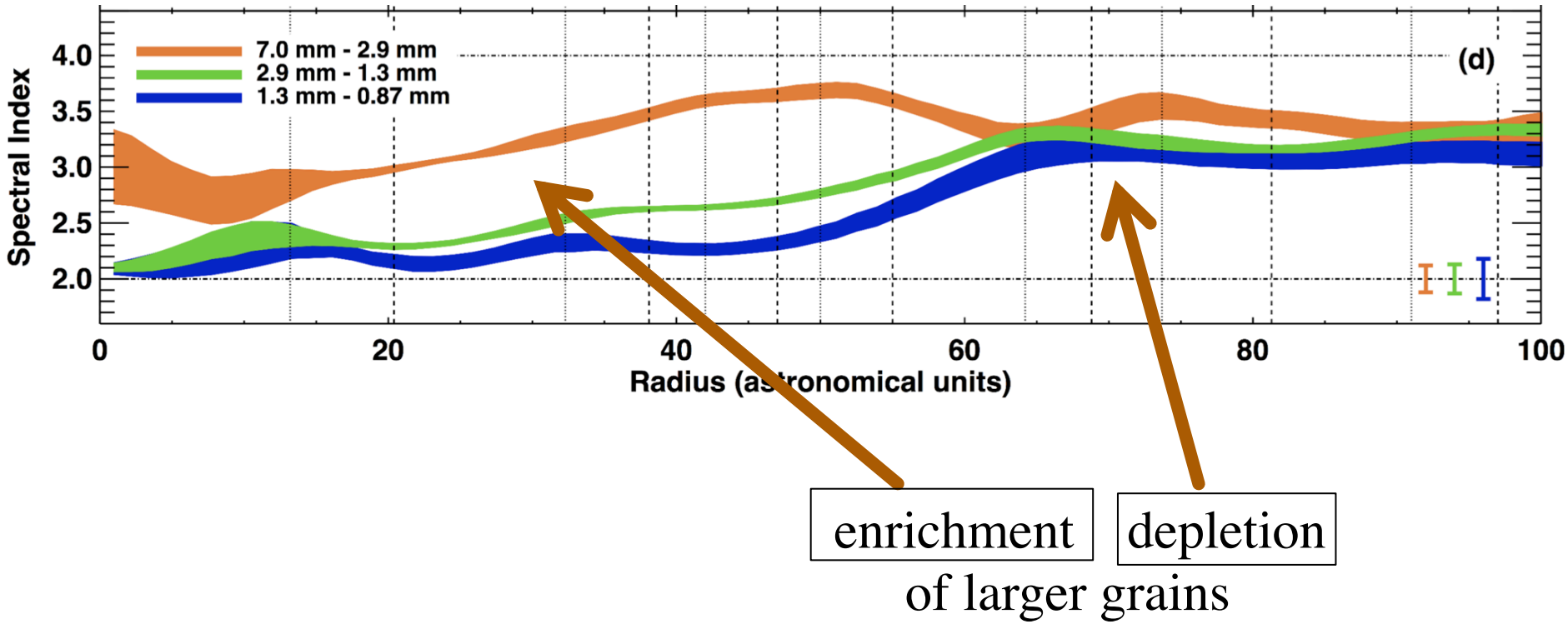
optical thin emission needed !

HL Tau (ALMA + VLA 7mm)

ALMA Partnership+2015
Carrasco-González et al. 2016

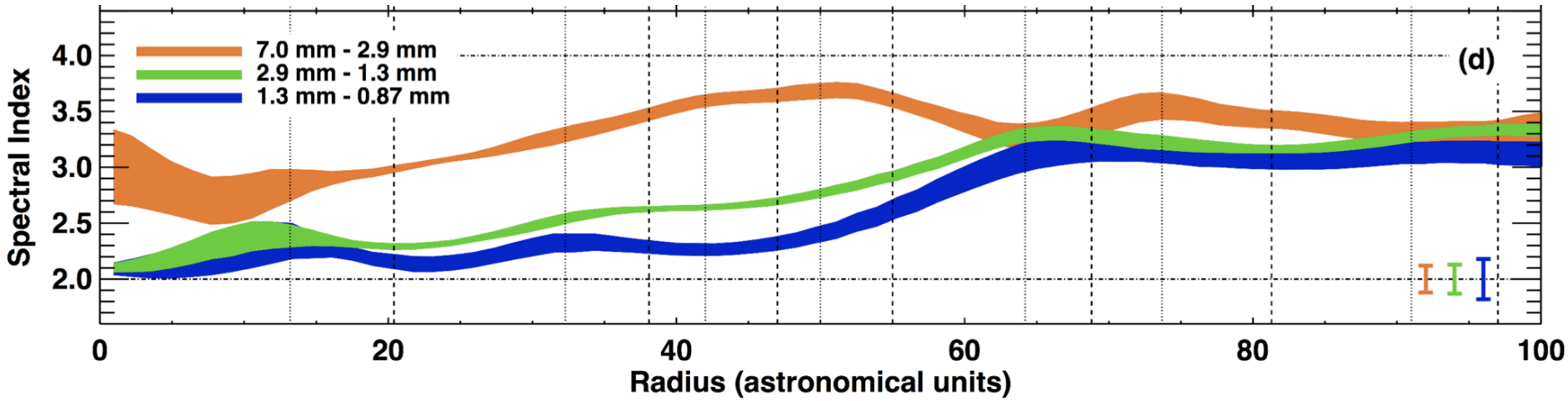


Carrasco-González et al. 2016



Drop in α_{Sp} due to grain size segregation

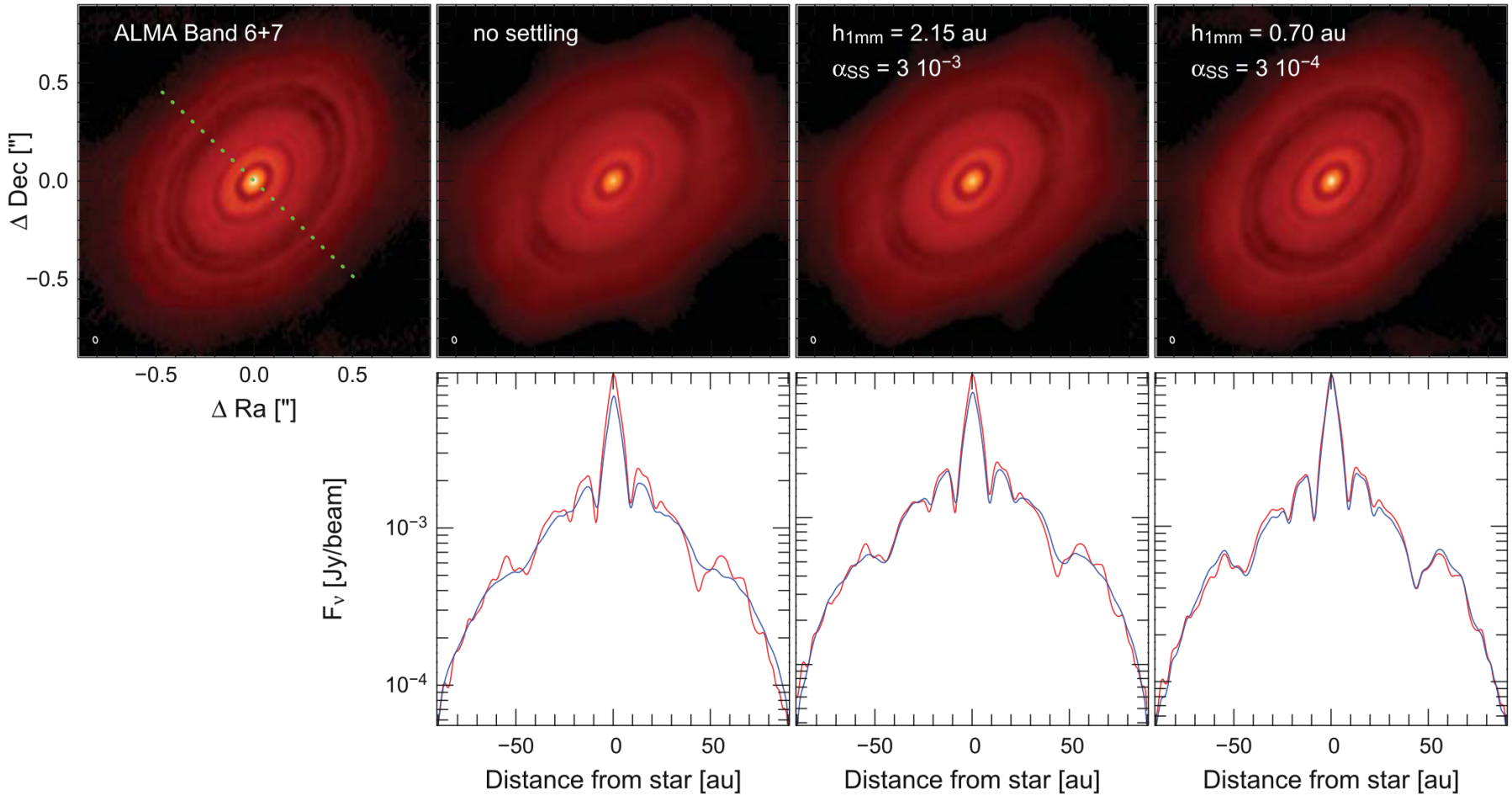
Carrasco-González et al. 2016



Grains drift and settle fast !

What can we learn about the turbulence ?

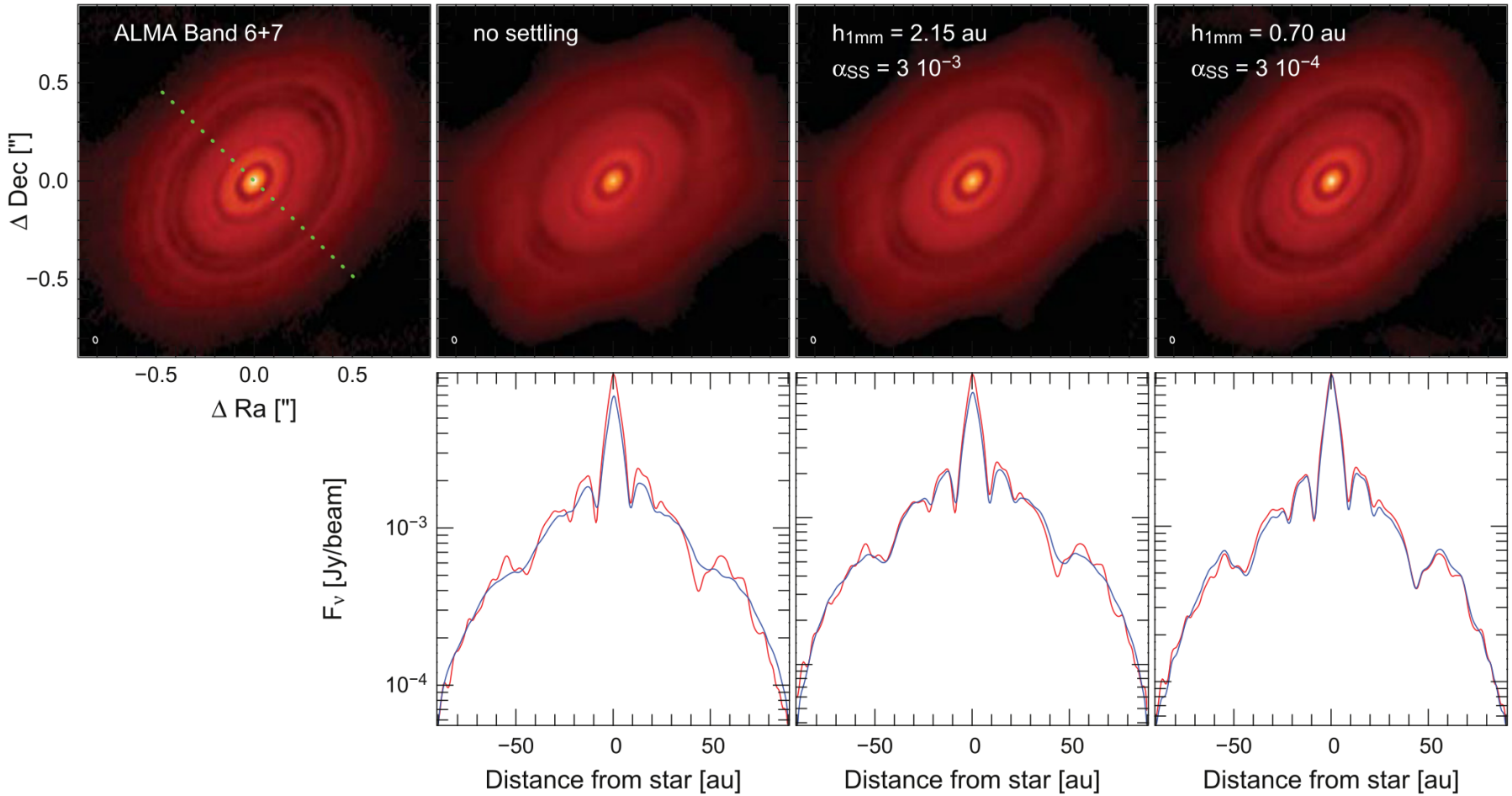
Pinte et al. 2016



(α_{ss}= 3·10^{-4}, H$^{*}_{dust}$/R = 0.007)

***based on 1mm grains**

Pinte et al. 2016



(α_{ss}= 3·10^{-4}, H$^{*}_{dust}$/R = 0.007)

α_{ss} at the midplane

<u>total α_{ss} higher !</u>

***based on 1mm grains**

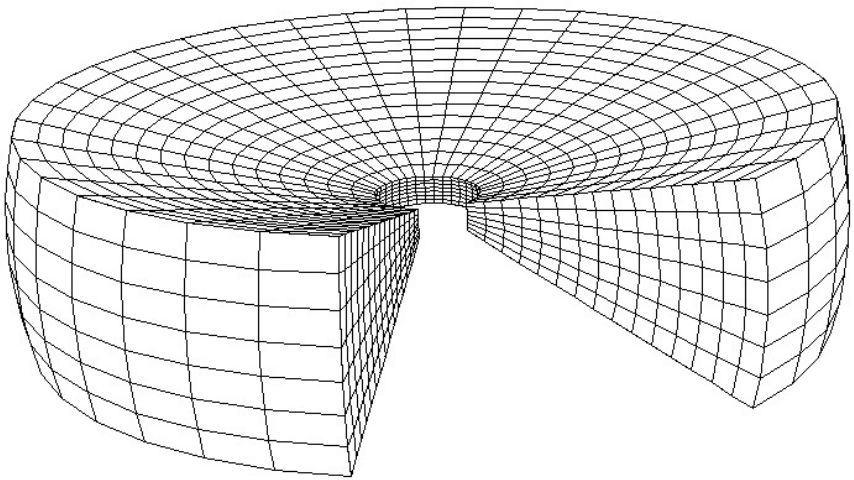
What do we see – summary

- Thermal dust emission of ‘larger’ grains show ring structures.
- Larger dust grains depleted in the outer disk.
- Turbulence difficult to trace from the dust emission. Best fit RT models of HL Tau predict small midplane turbulence

What do we model ?

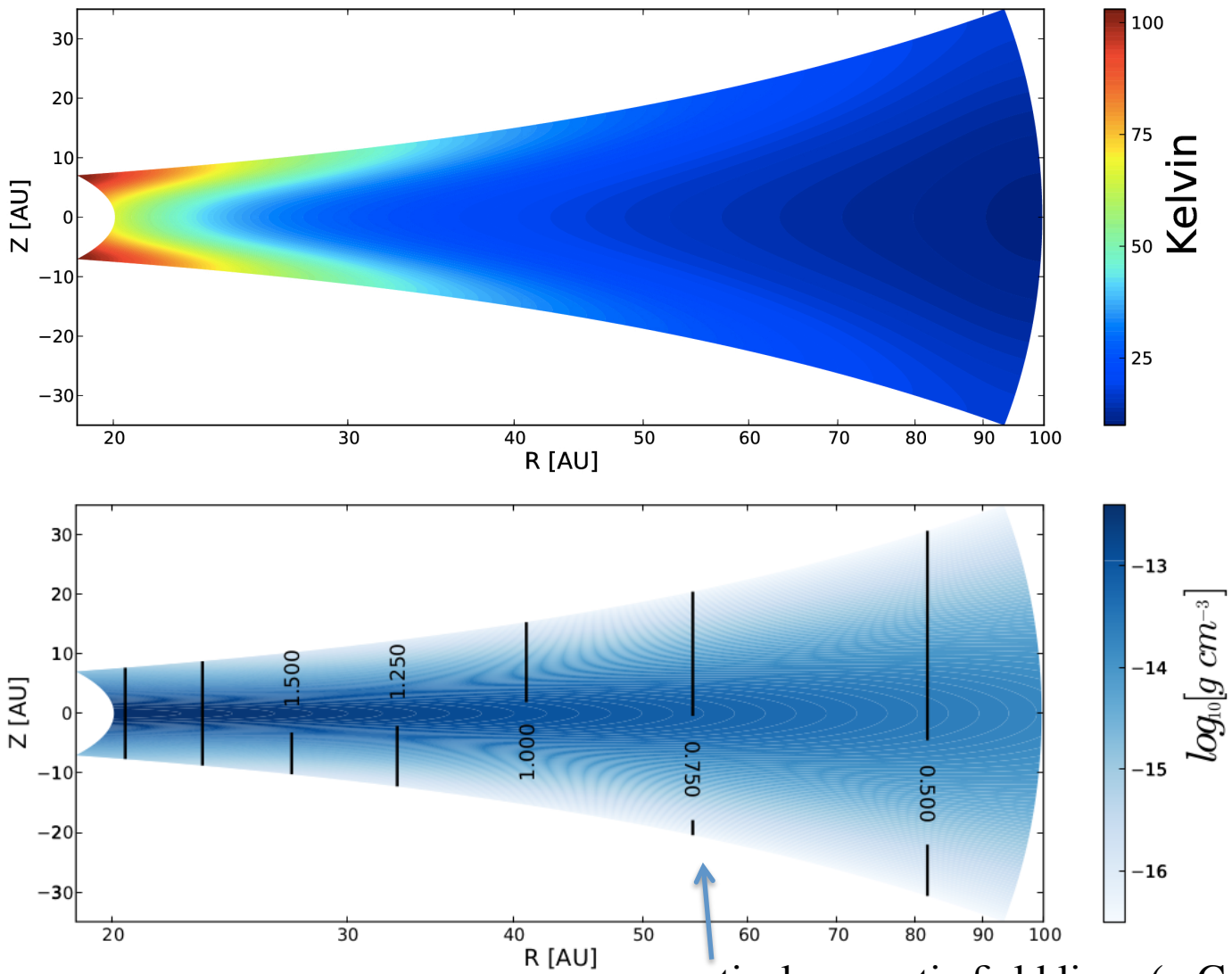
3D global stratified non-ideal MHD simulations

Flock et al. 2015



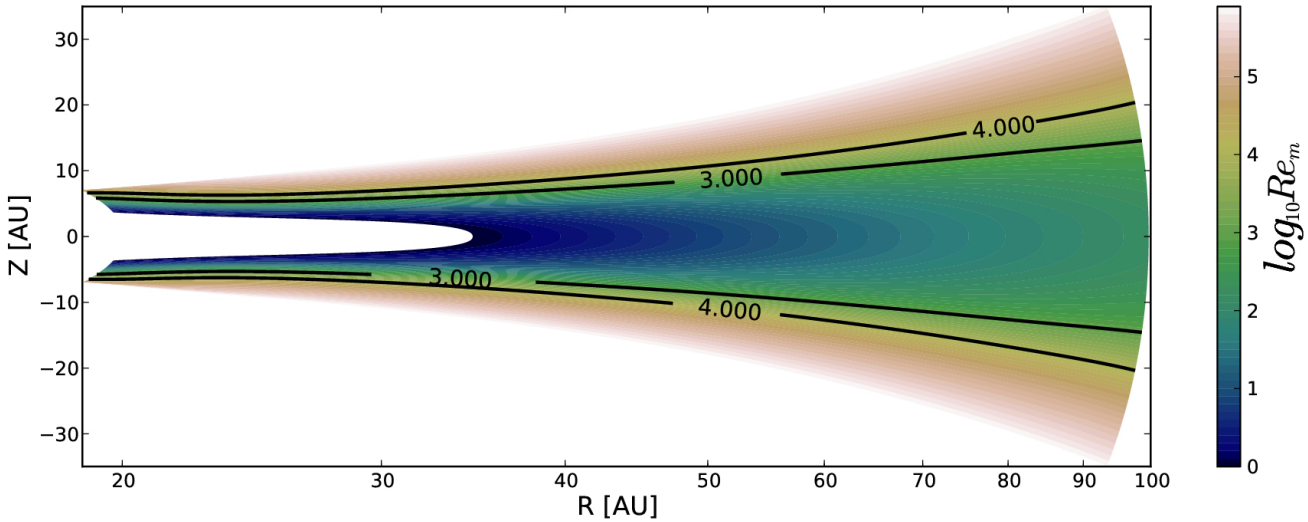
PLUTO code: (2nd PLM, HLLD, CT)

Initial conditions from best-fit models for observation



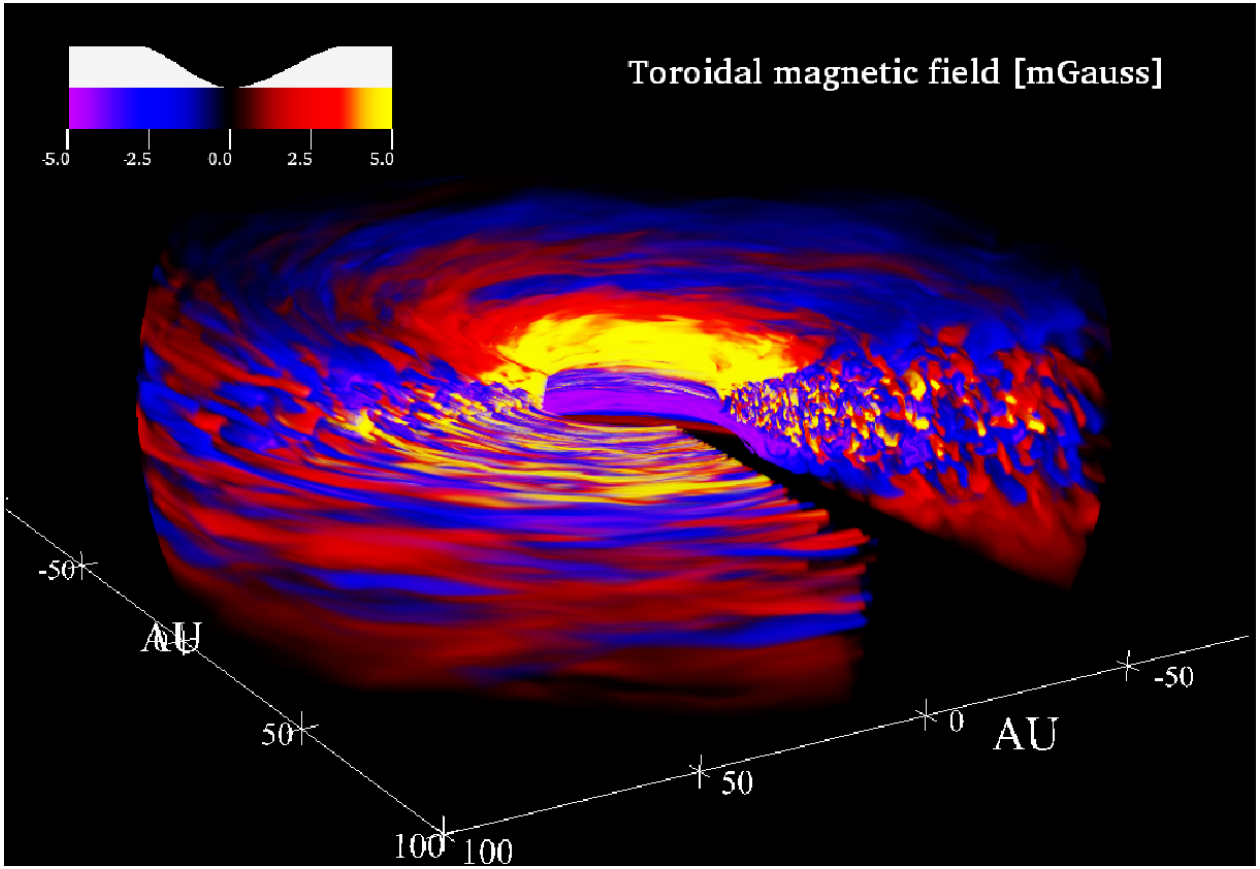
vertical magnetic field lines (mGaus)

Re_m – magnetic coupling

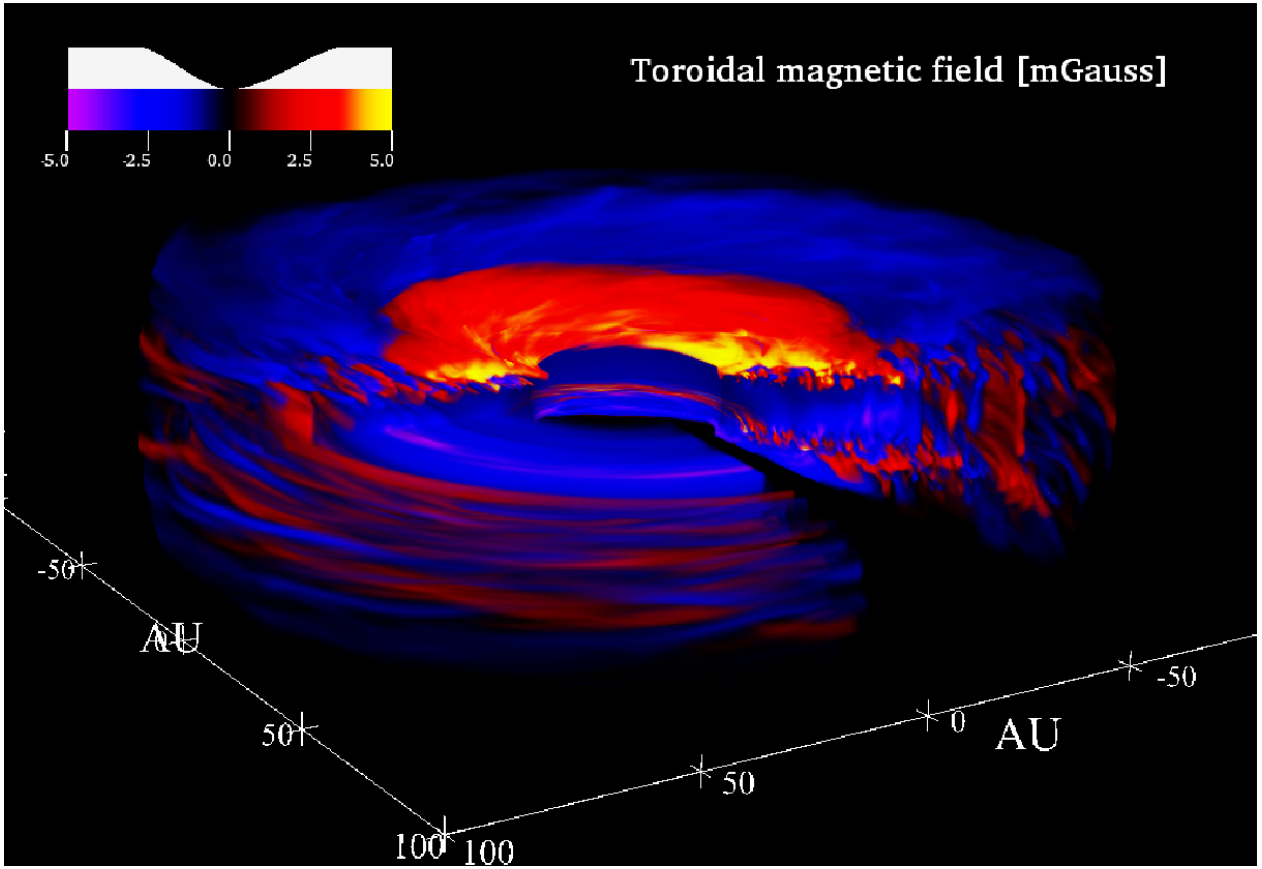


Calculated from Ohmic resistivity
(ionization + dust-chemistry by Dzyurkevich et al. 2013)

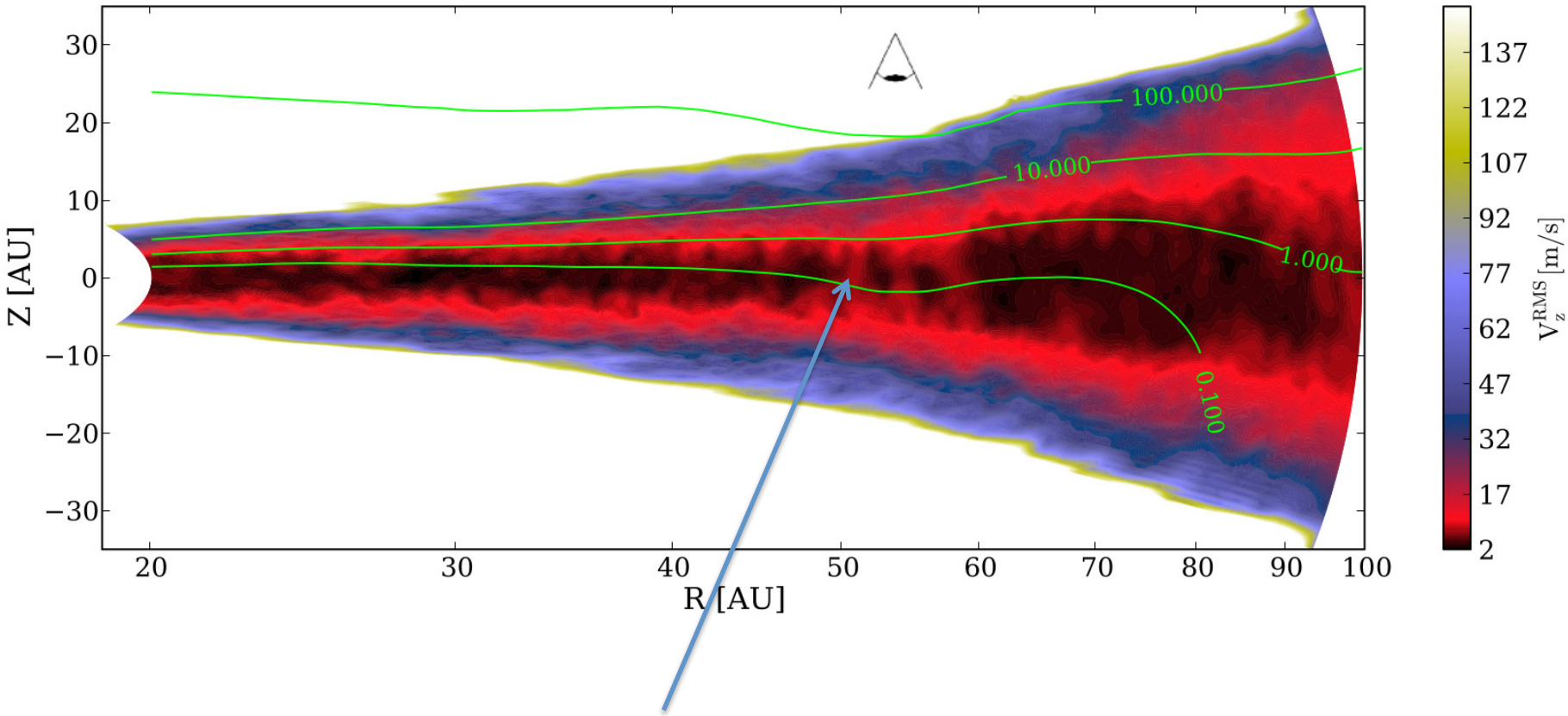
Fully ionized case



Including low ionization region

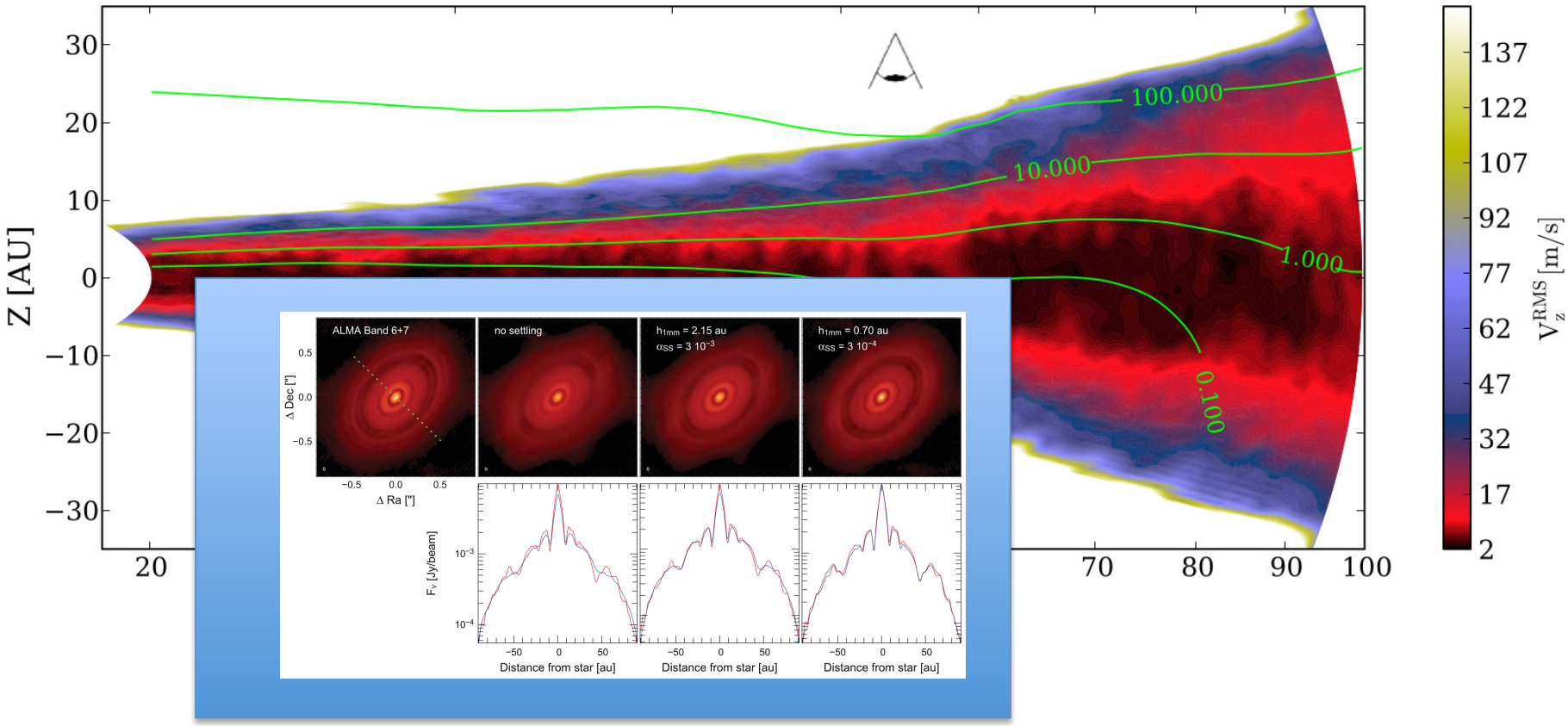


Turbulent velocity (face-on)



~ 1 % of c_s at the midplane ($\alpha \sim 10^{-4}$)

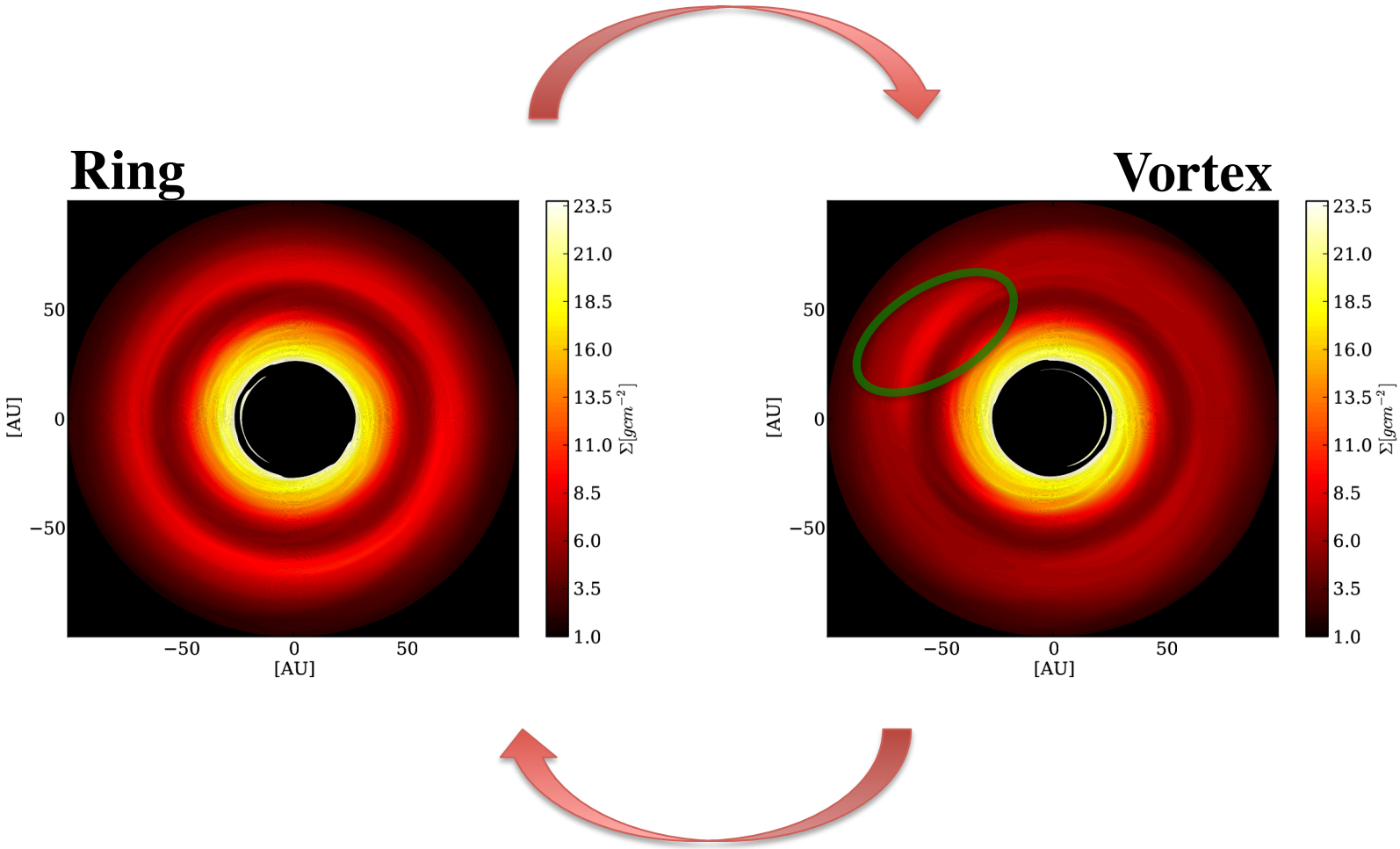
Turbulent velocity (face-on)



~ 1 % of c_s at the midplane ($\alpha \sim 10^{-4}$)

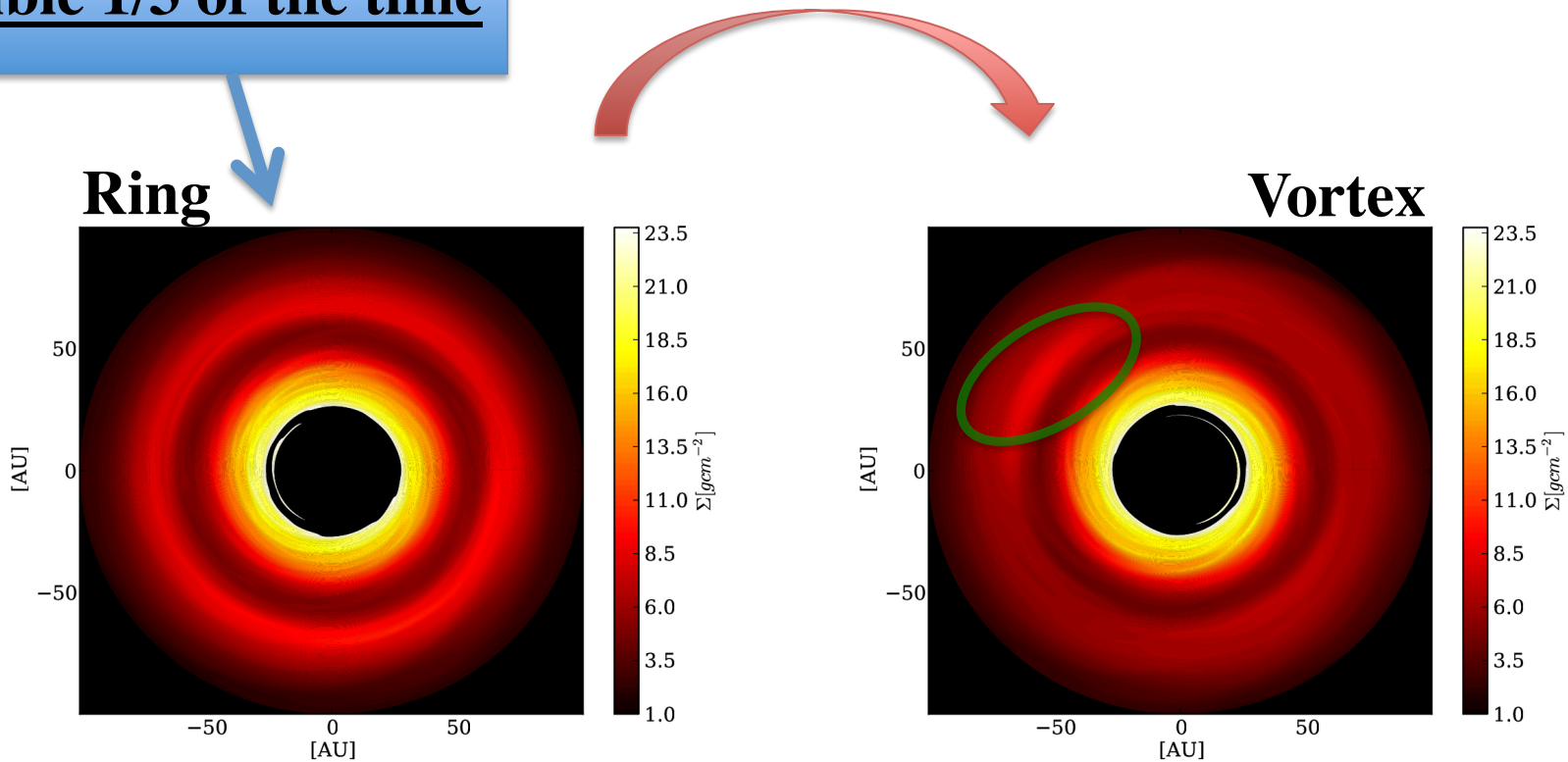
<u>Consistent with best-fit models of grain settling</u>

Formation of gap and ring structure



Formation of gap and ring structure

Visible 1/3 of the time



Flock et al. 2015

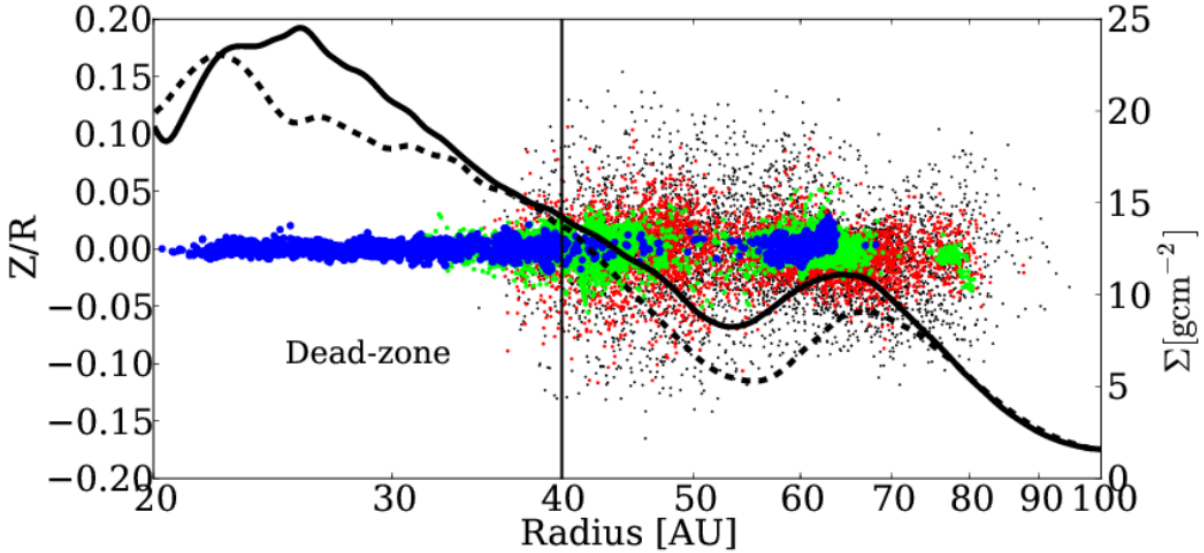
- Variations in MRI activity lead to gap and ring formation
- Alternating states between vortex and ring state
- Midplane turbulence consistent with best-fit models of grain settling

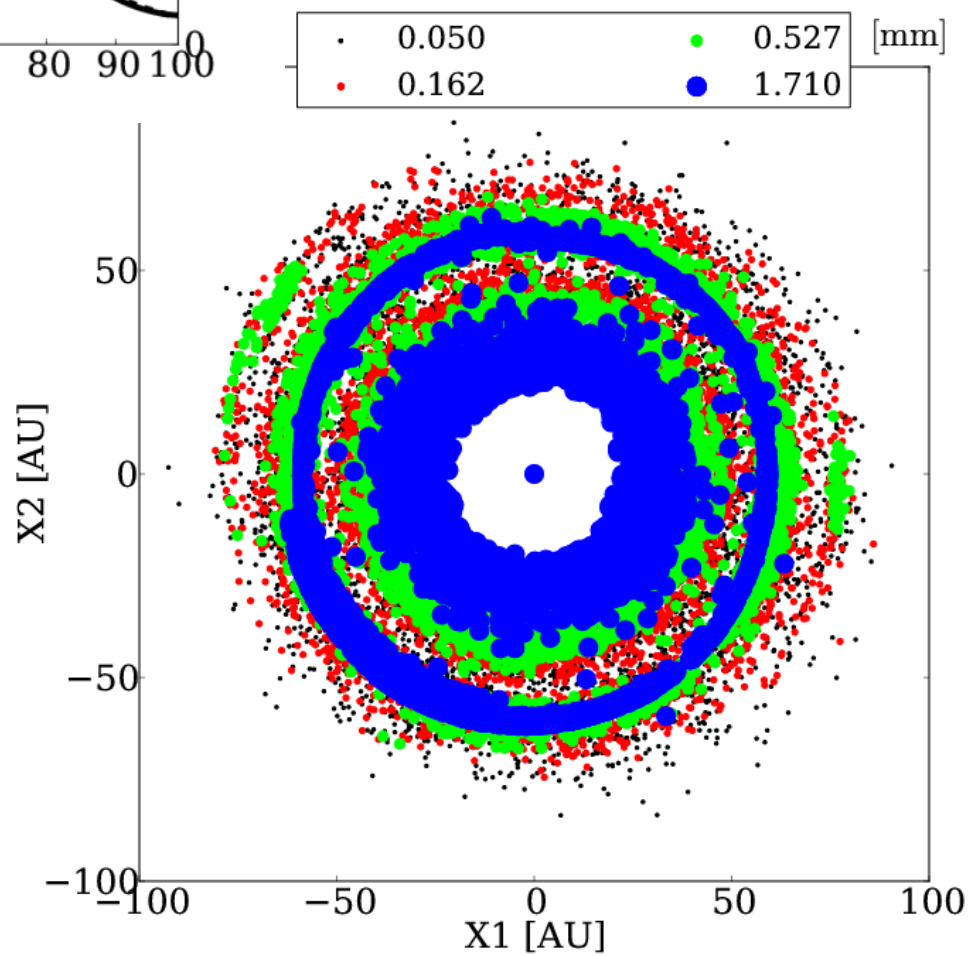
Ruge et al. 2016

Add size dependent gas drag (settling/drift) for multiple grain sizes (50 micron – 1 cm)

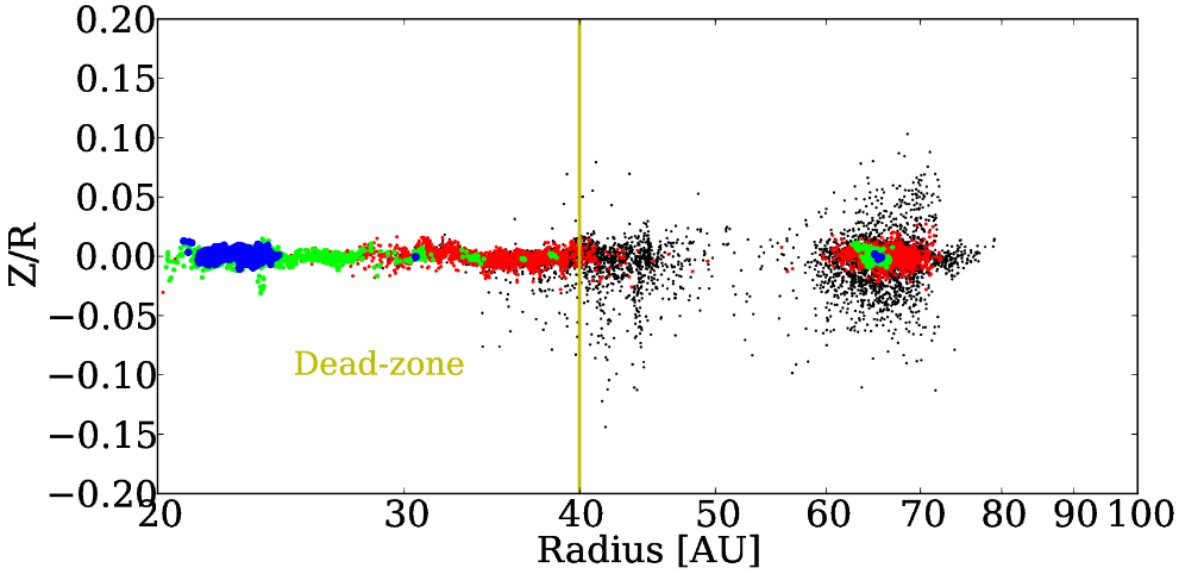
Drift and mixing of grains at the outer edge of the dead-zone

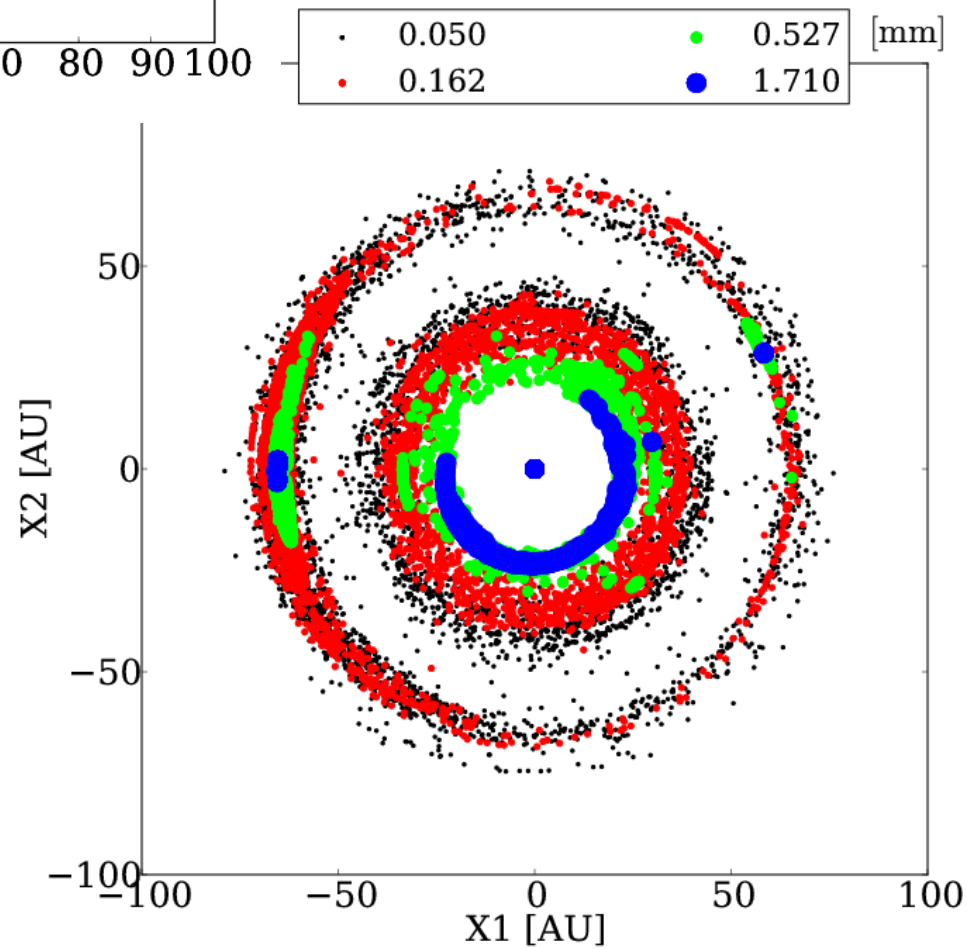
Sizes: 0.05 mm, 0.5 mm, 5 mm





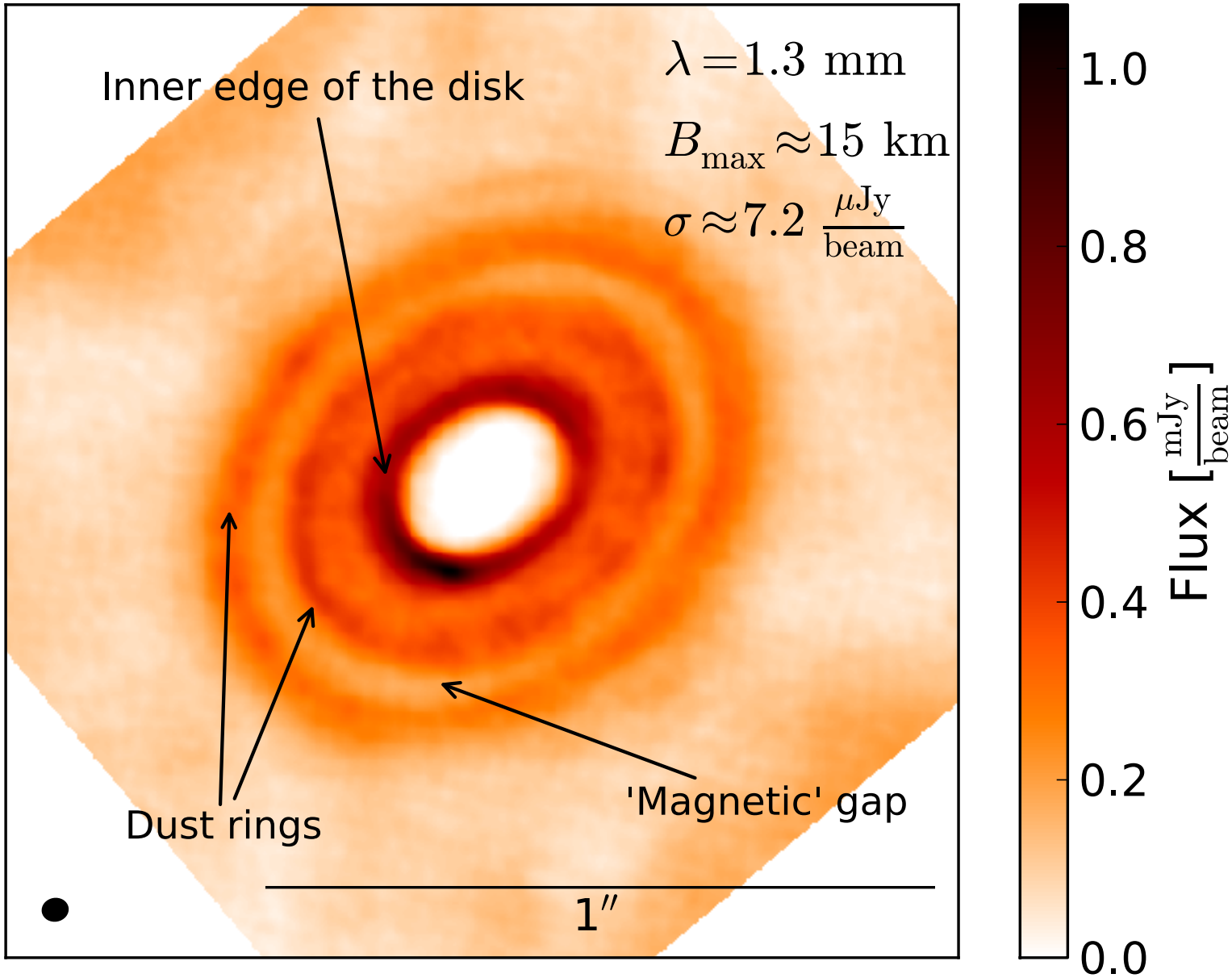
Radial dust trapping in the ring



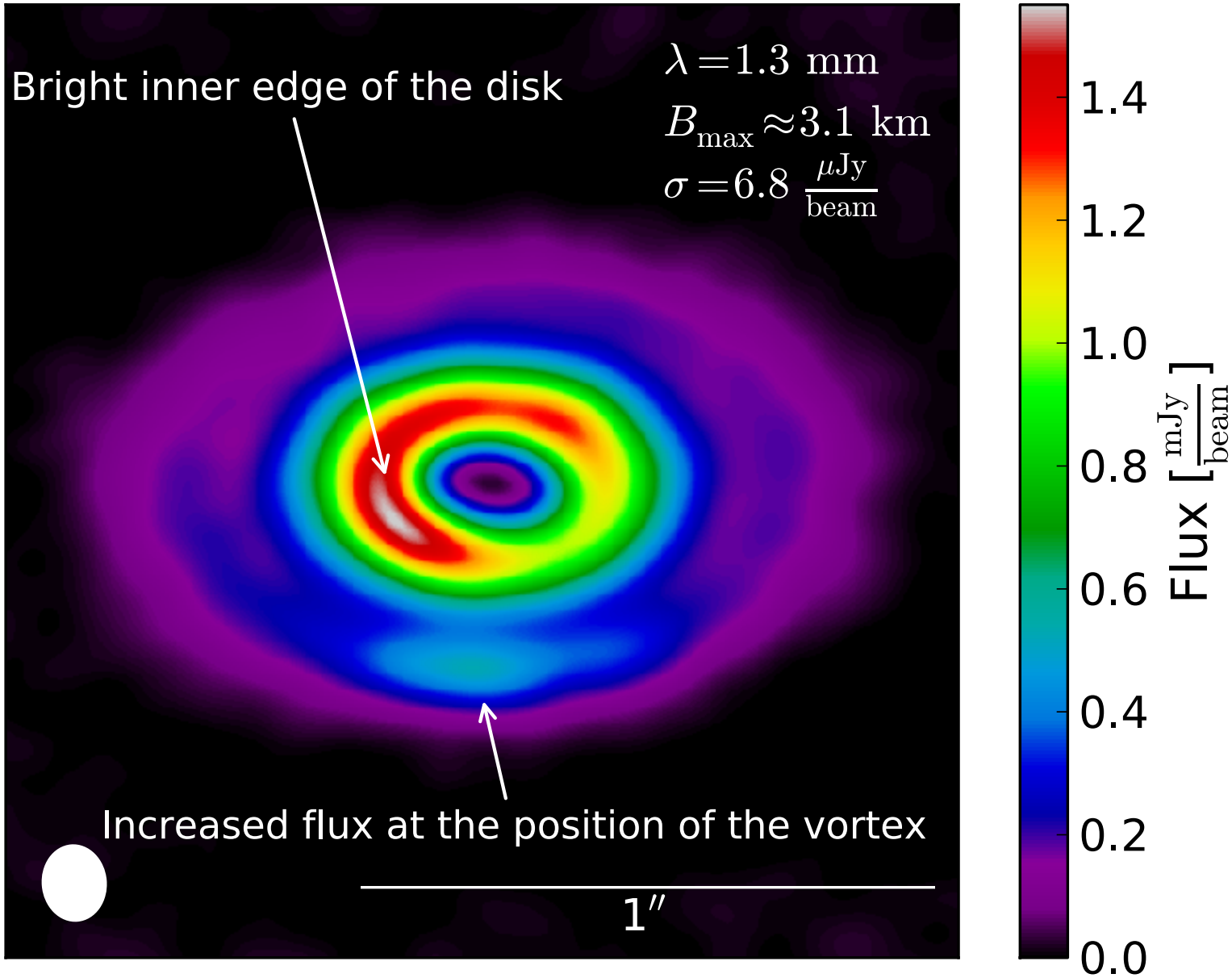


Azimuthal dust trapping in the vortex

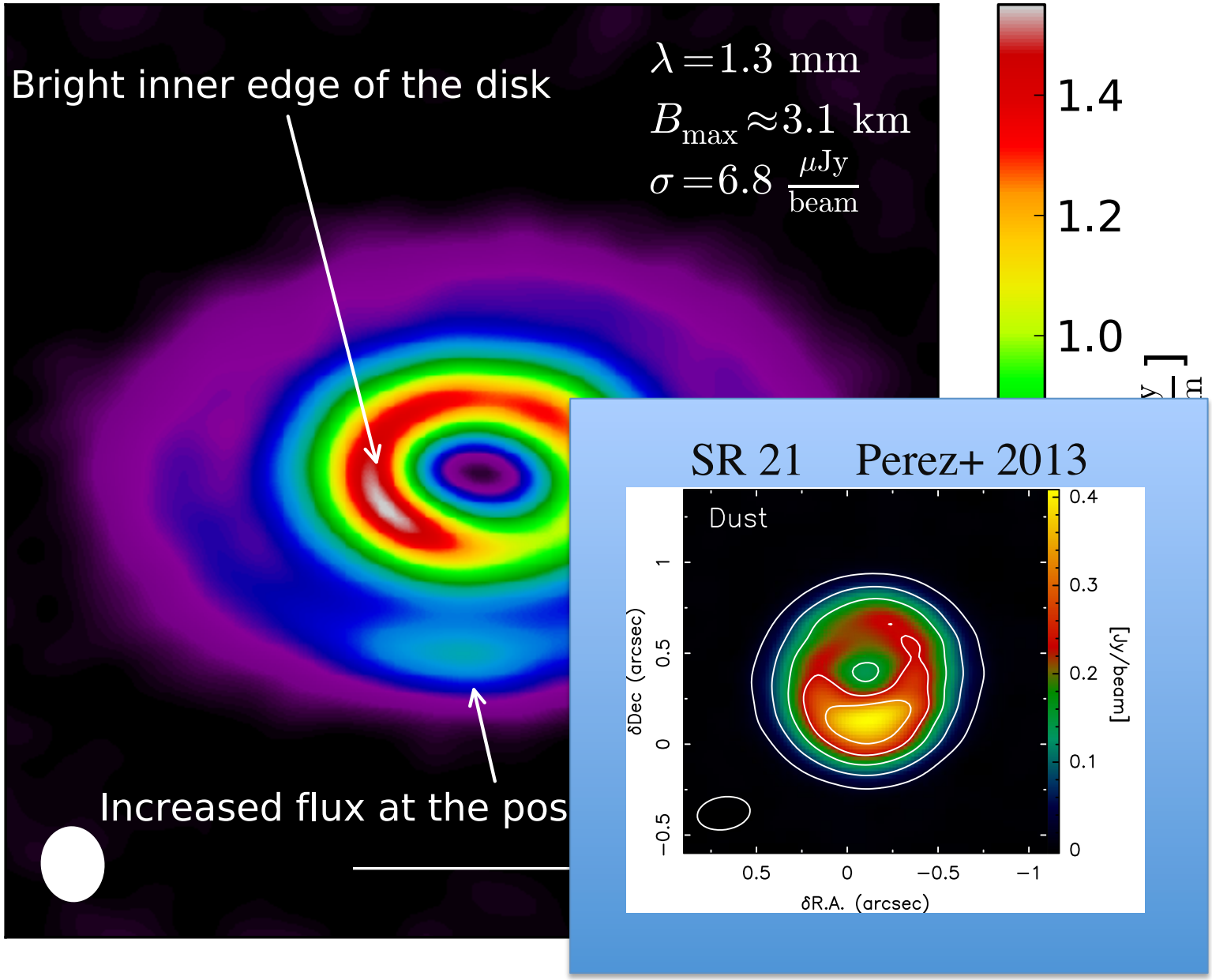
Simulated ALMA image of ring state



Simulated ALMA image of vortex state



Simulated ALMA image of vortex state



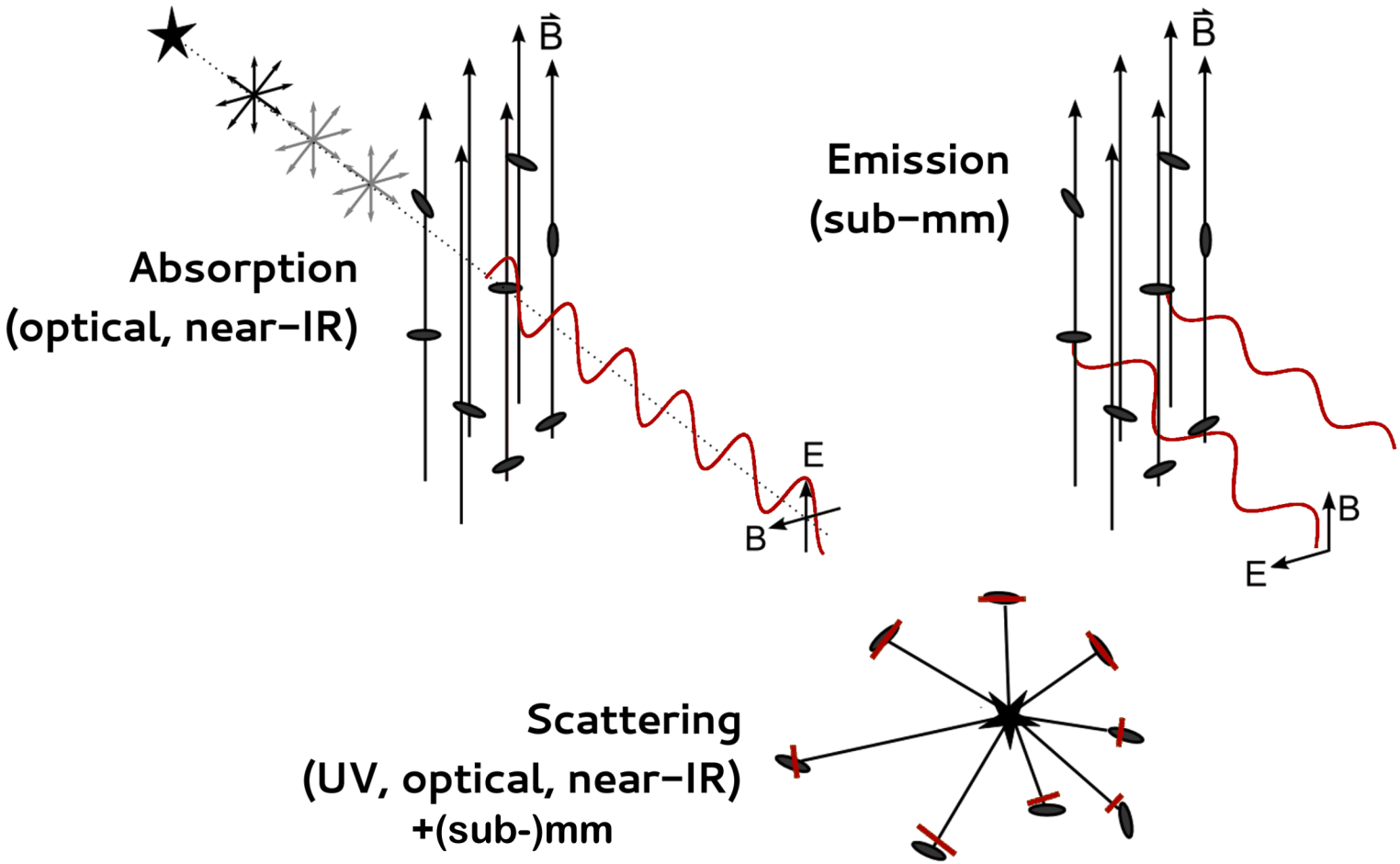
Ruge et al. 2016

- Surface density gap and jump can lead to radial dust trapping in a ring

- <u>Dust concentration leads to an contrast enhancement !</u> Can be detected by ALMA

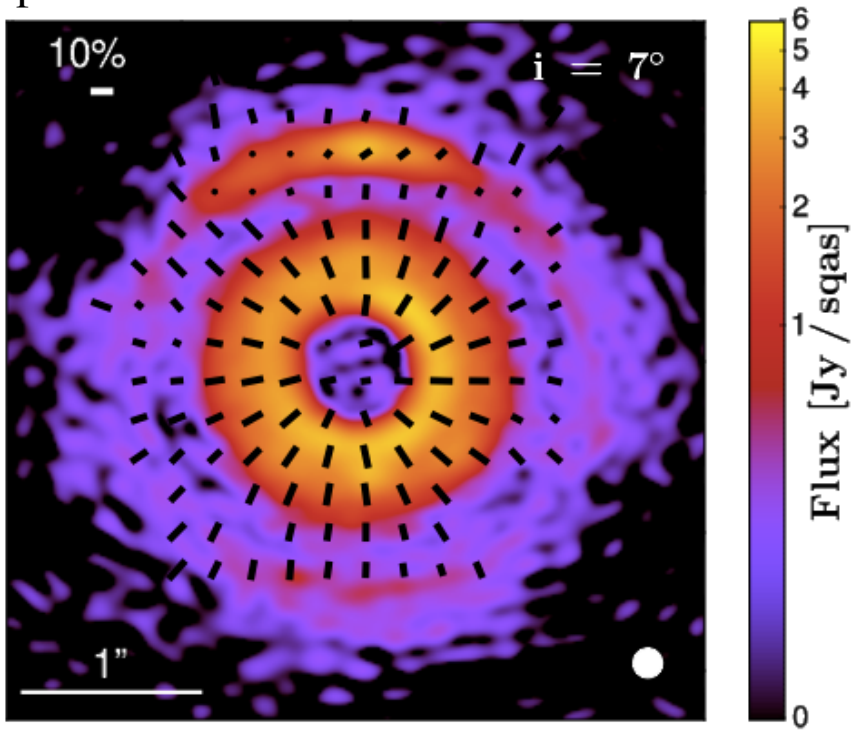
- Vortex can concentrate dust grains and cause azimuthal variations in the emission

Polarization



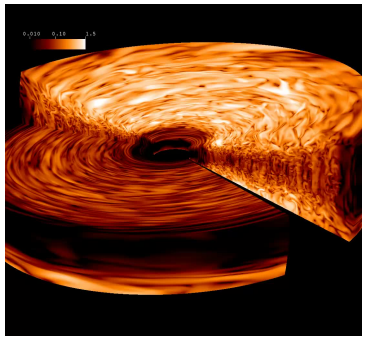
Bertrang et al. 2016

polarized continuum emission



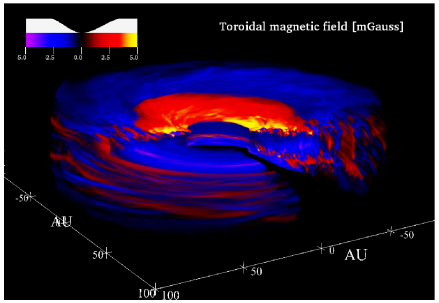
What do we understand ?

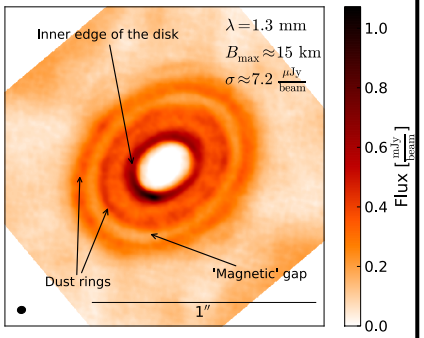
Flock et al. 2011



MRI turbulence

Flock et al. 2015



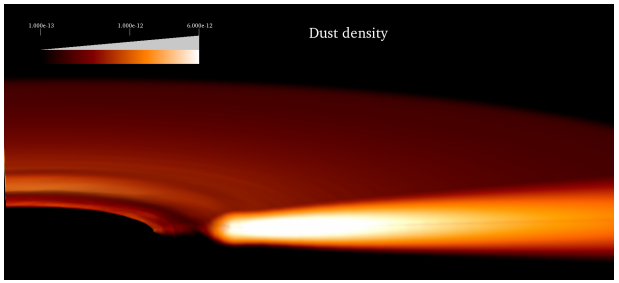


MRI turbulence

Disk wind

Dead-zone

Inner rim
- T =1500 K
- NIR emission (VLTI)



Flock et al. 2017

Outer disk
- T <100 K
- (sub)mm (ALMA)