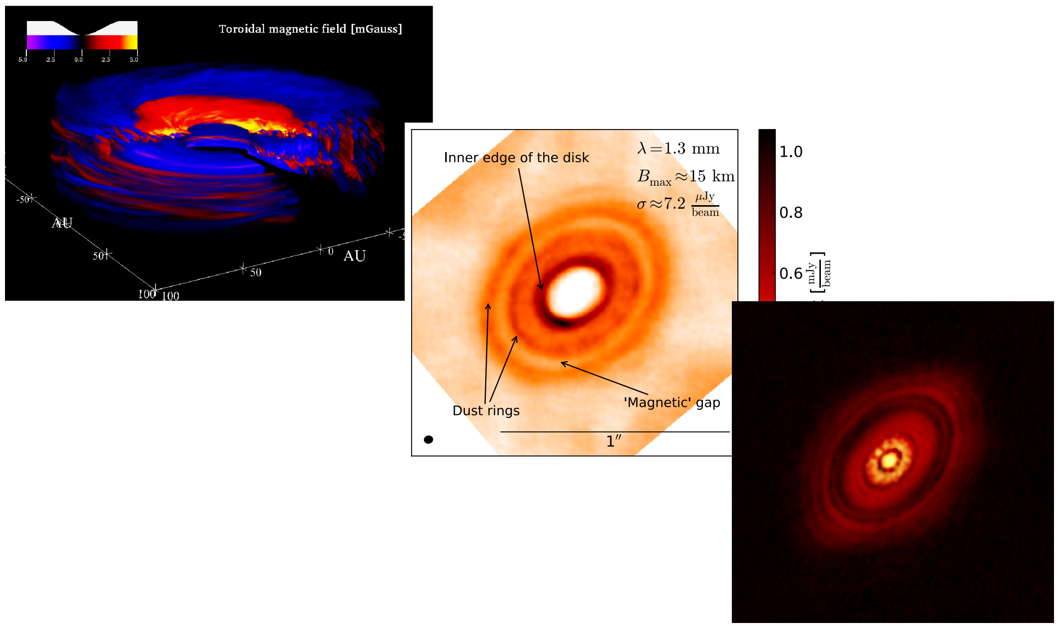
Feasibility of observing MHD turbulence in protostellar disks with ALMA



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

Jet Propulsion Laboratory
California Institute of Technology

Confronting MHD Theories of Accretion Disks with Observations, KITP, 1.31.2017

Overview

I. What do we see* ?

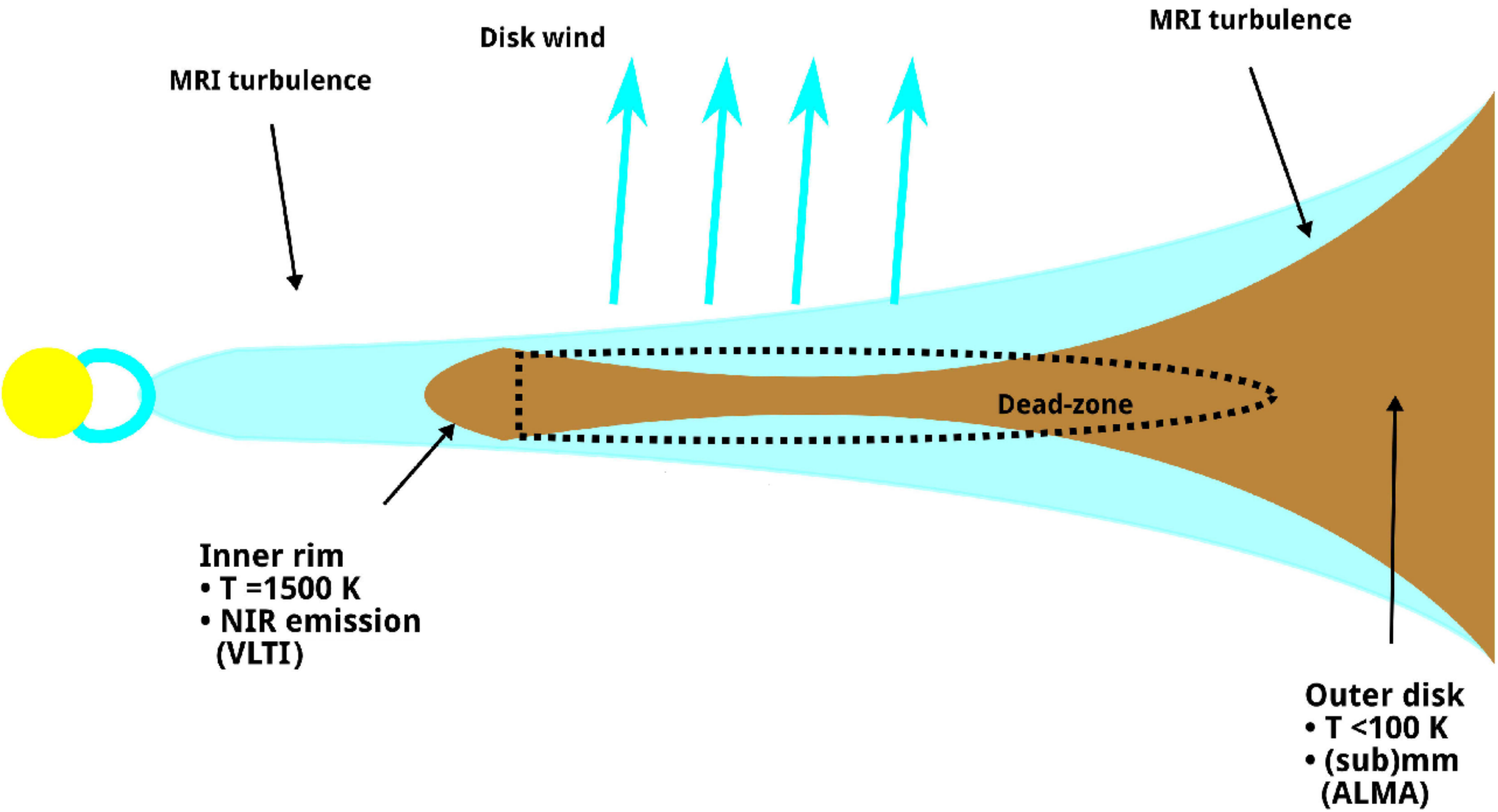
II. What do we model** ?

III. What do we understand ?

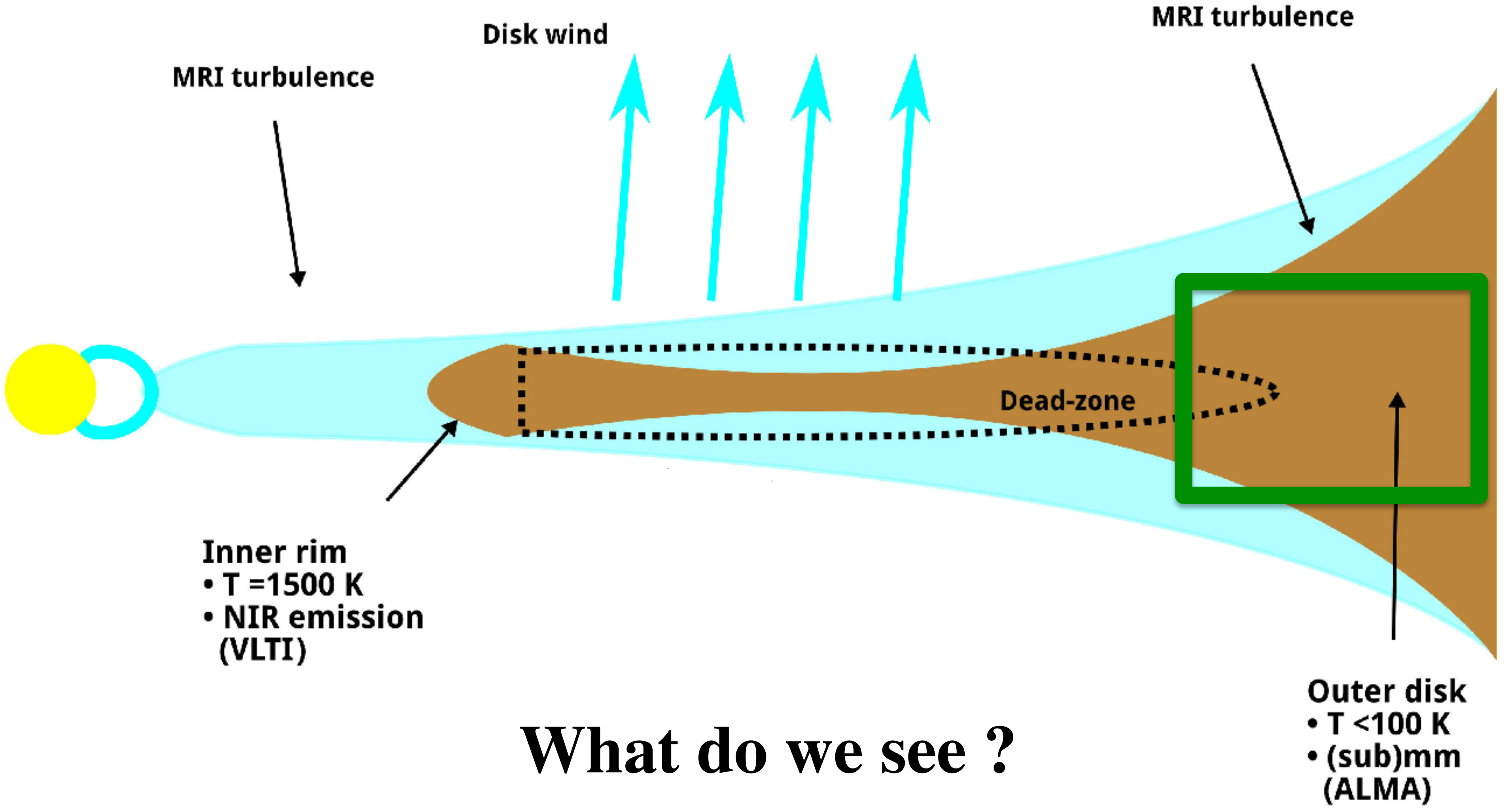
* thermal dust emission

** gas disk

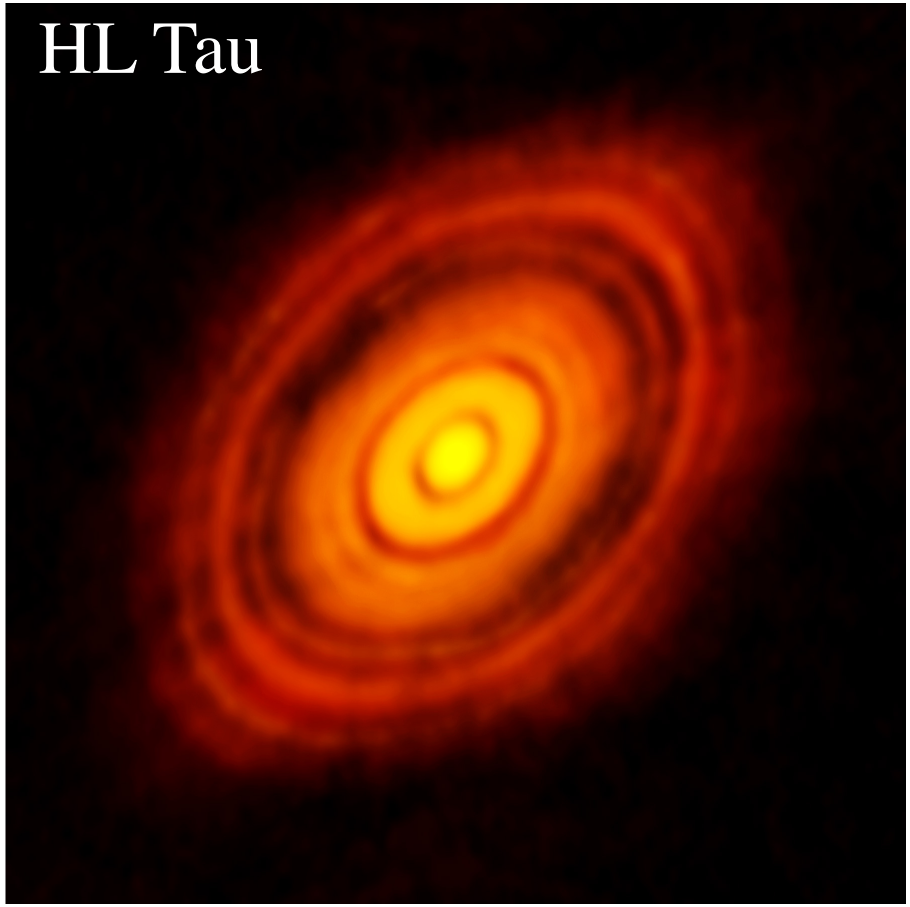
Overview


Disk wind
MRI turbulence
MRI turbulence
Dead-zone
Inner rim
• T =1500 K
• NIR emission
(VLTI)
Outer disk
• T <100 K
• (sub)mm
(ALMA)

Overview



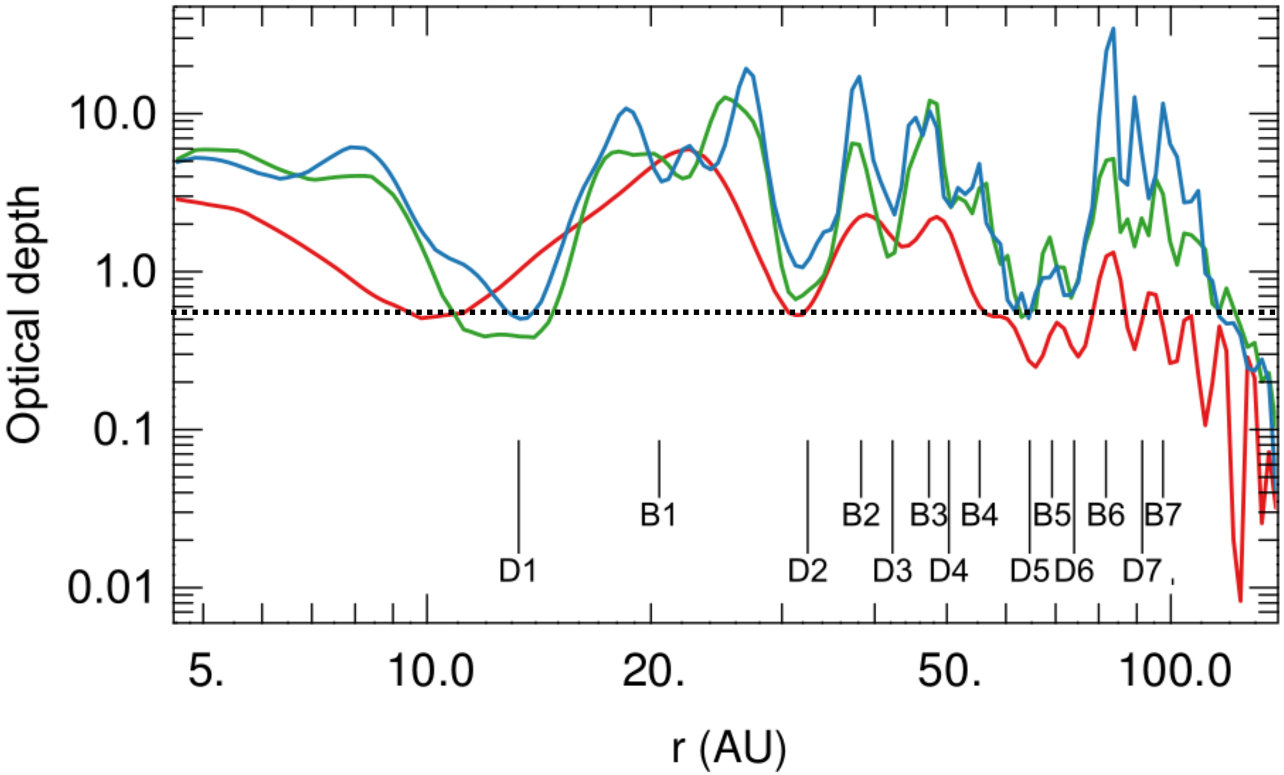
What do we see ?



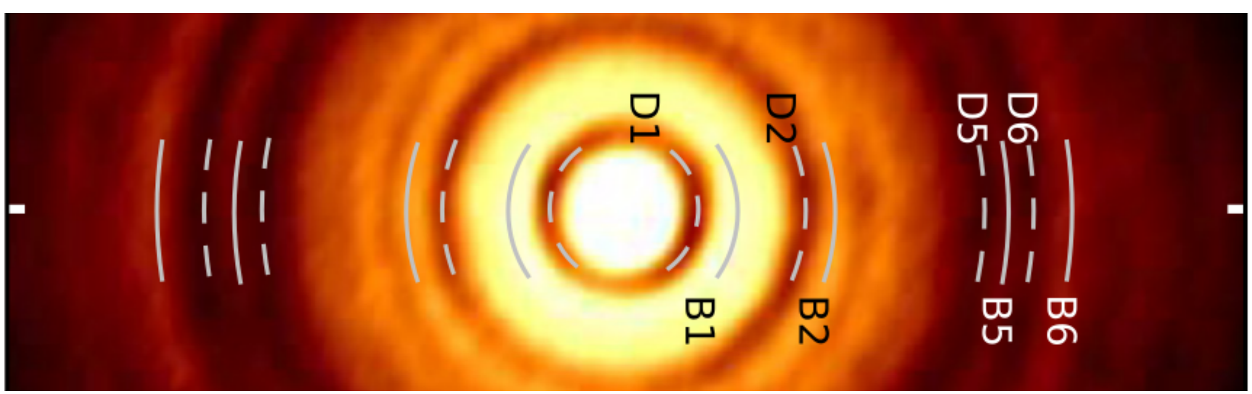
ALMA Partnership+2015

Other systems with rings: TW Hya, HD 163296, …

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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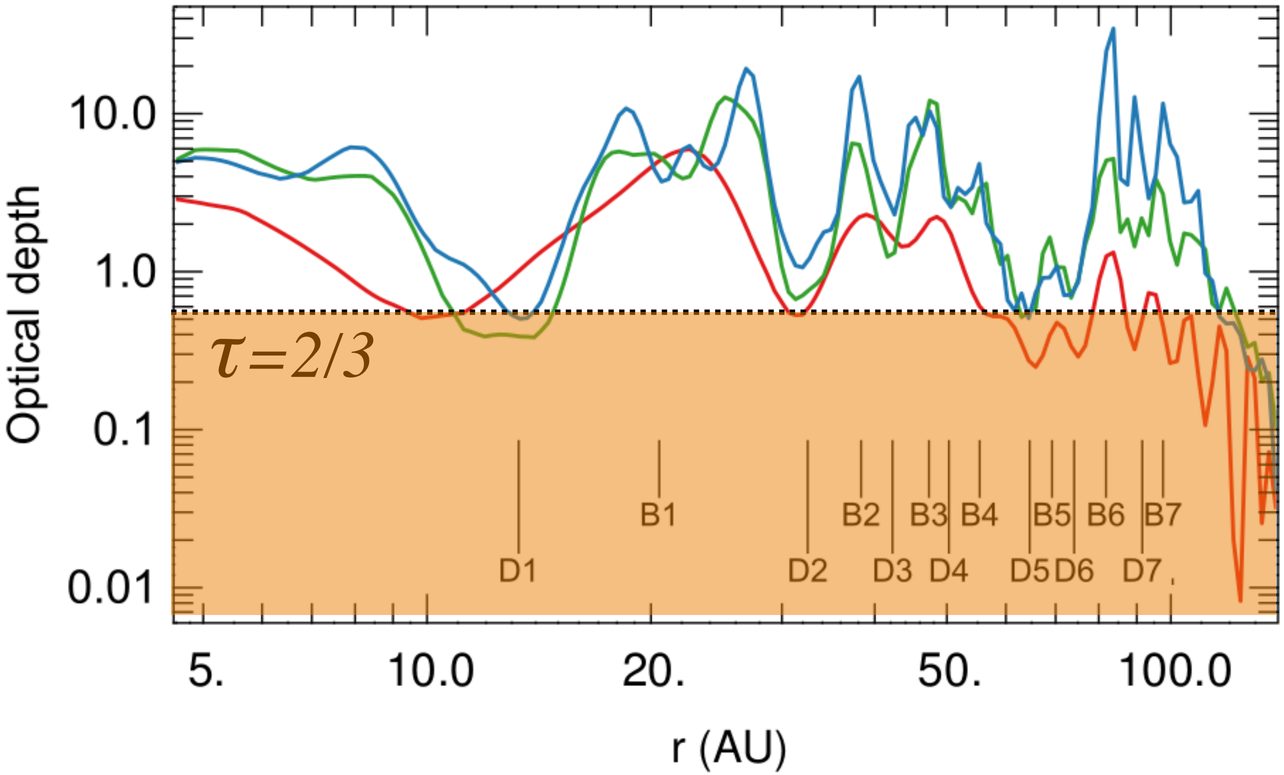
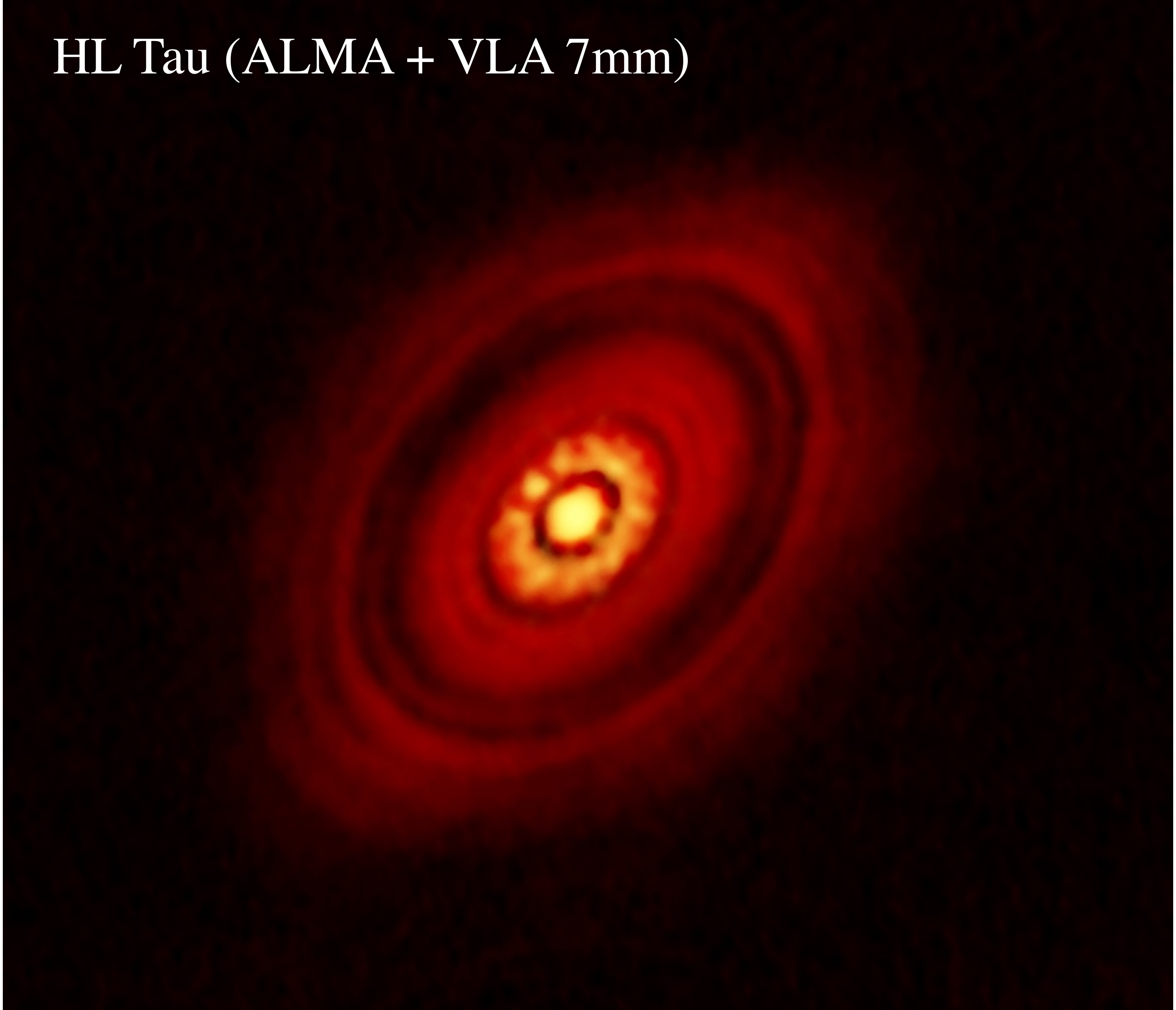


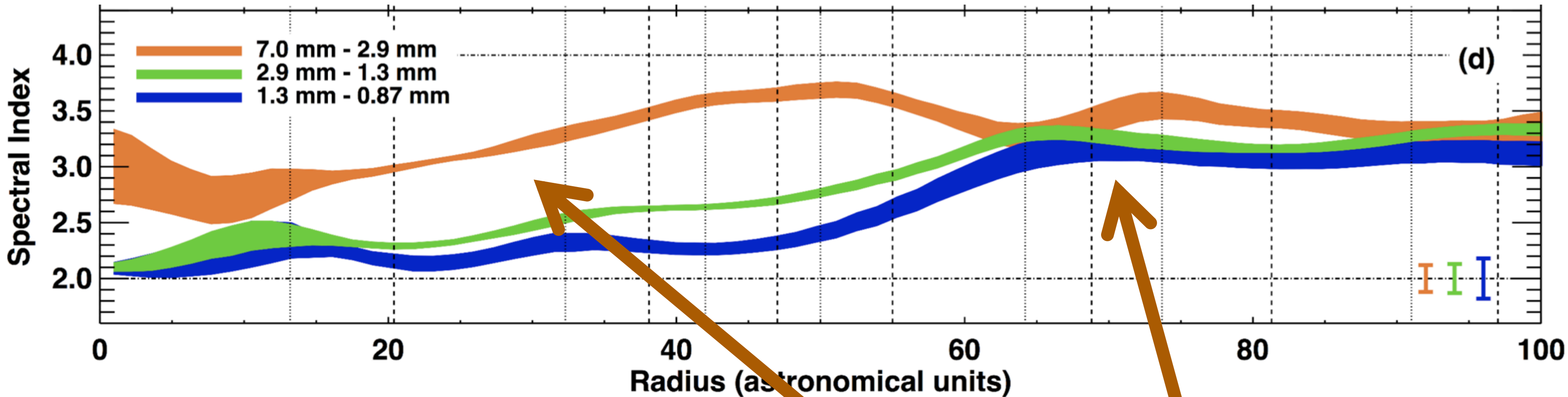
Band	
3 mm	3
1.3 mm	6
0.87 mm	7

optical thin emission needed !


HL Tau (ALMA + VLA 7mm)

Carrasco-González et al. 2016

$$\alpha_{Sp} = -\frac{\partial \log_{10}(F_\lambda)}{\partial \log_{10}(\lambda)} \qquad \alpha_{Sp} = 2 \text{ (optical thick)}$$



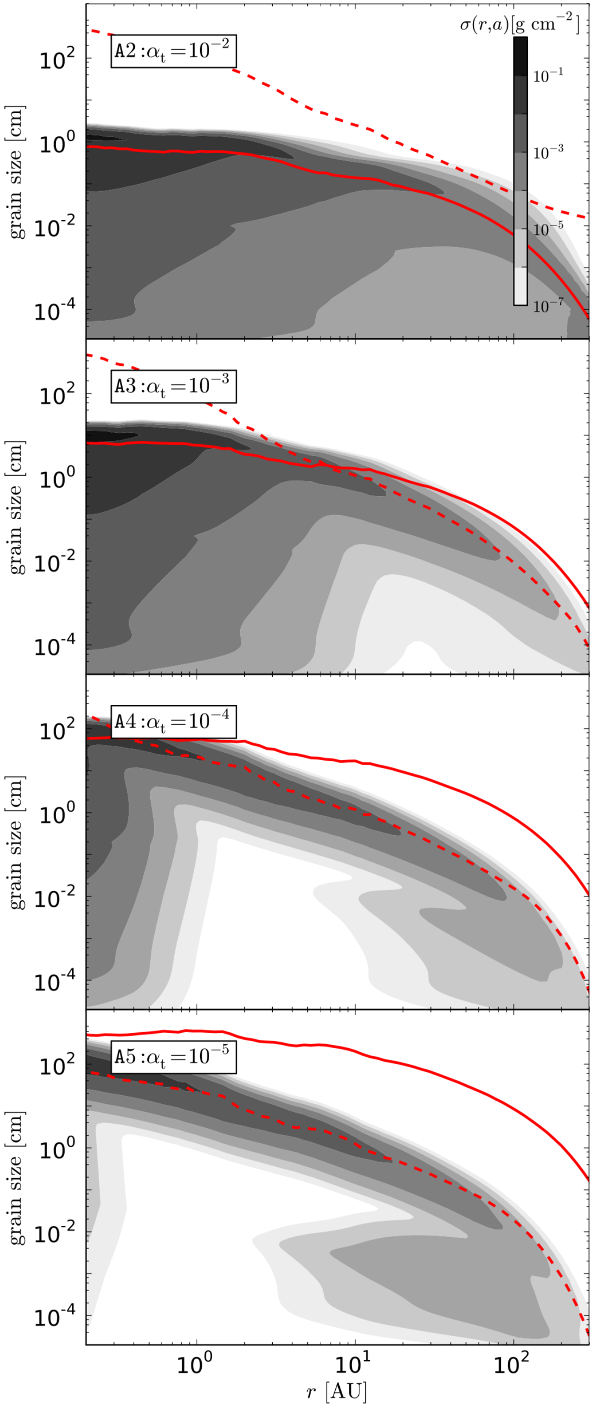
enrichment depletion

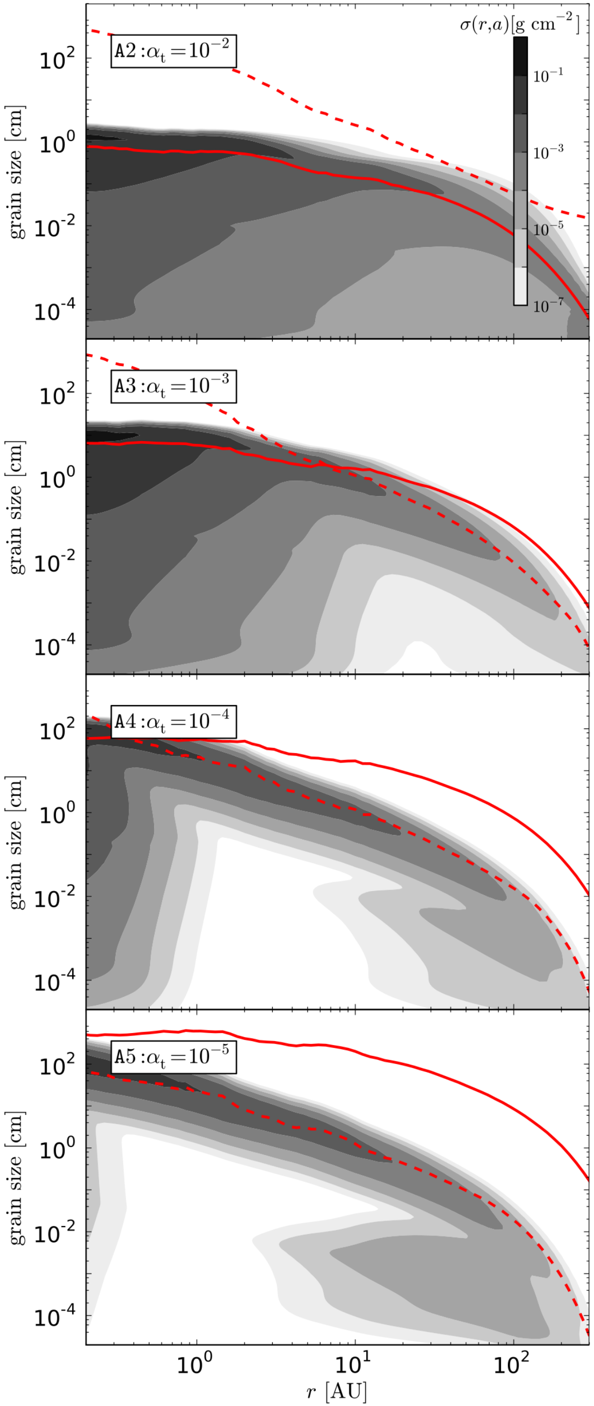
of larger grains

Drop in α_{Sp} due to grain size segregation

Can we connect grain sizes to the turbulence in disks ?

Birnstiel et al. 2012





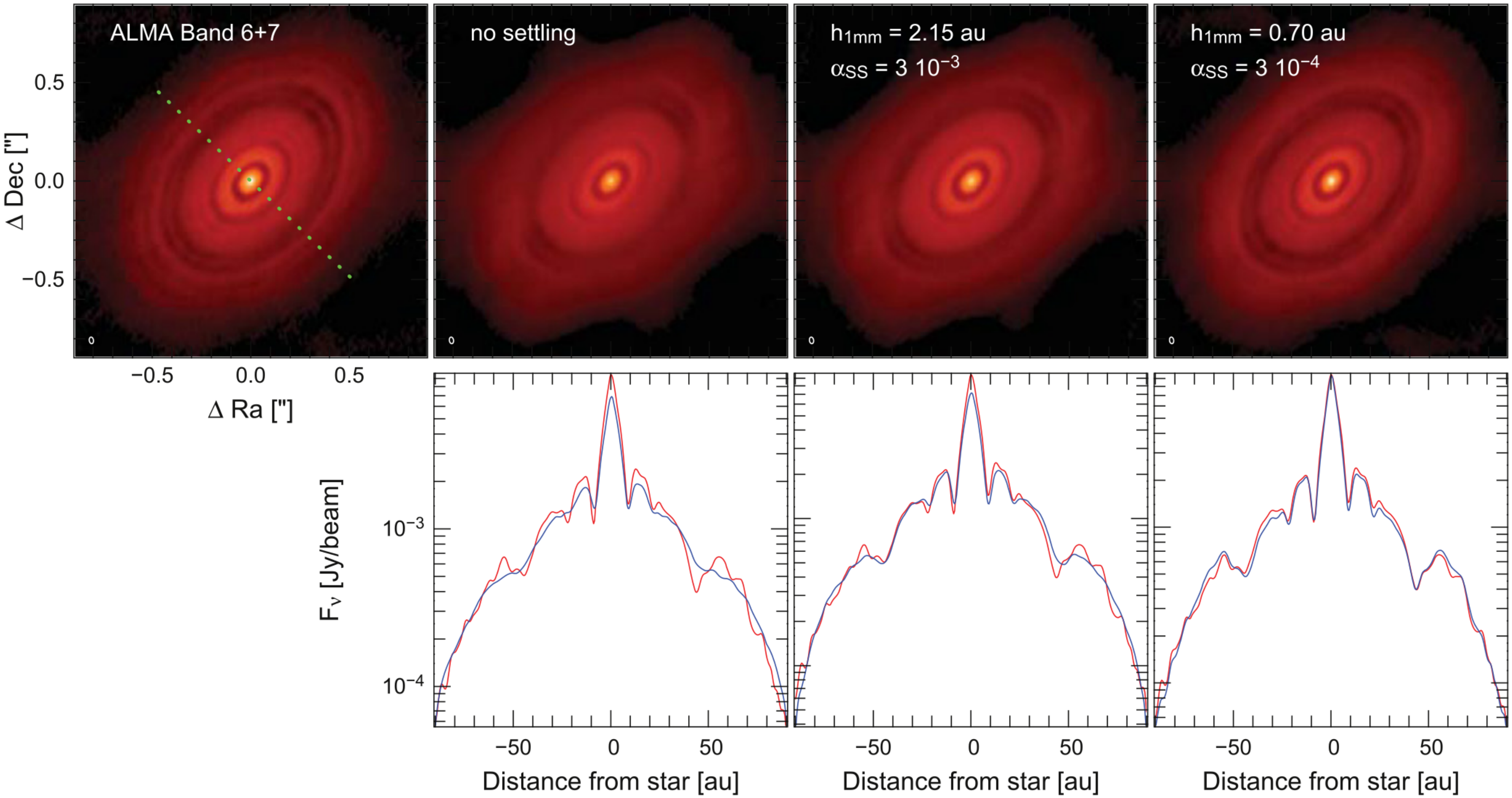
Birnstiel et al. 2012

Large grains limited by drift
Small grains produced by turbulence

ALMA and VLA sensitive to larger grains
smaller wavelengths optical thick

Can we connect the grain sizes vertical height to the turbulence ?

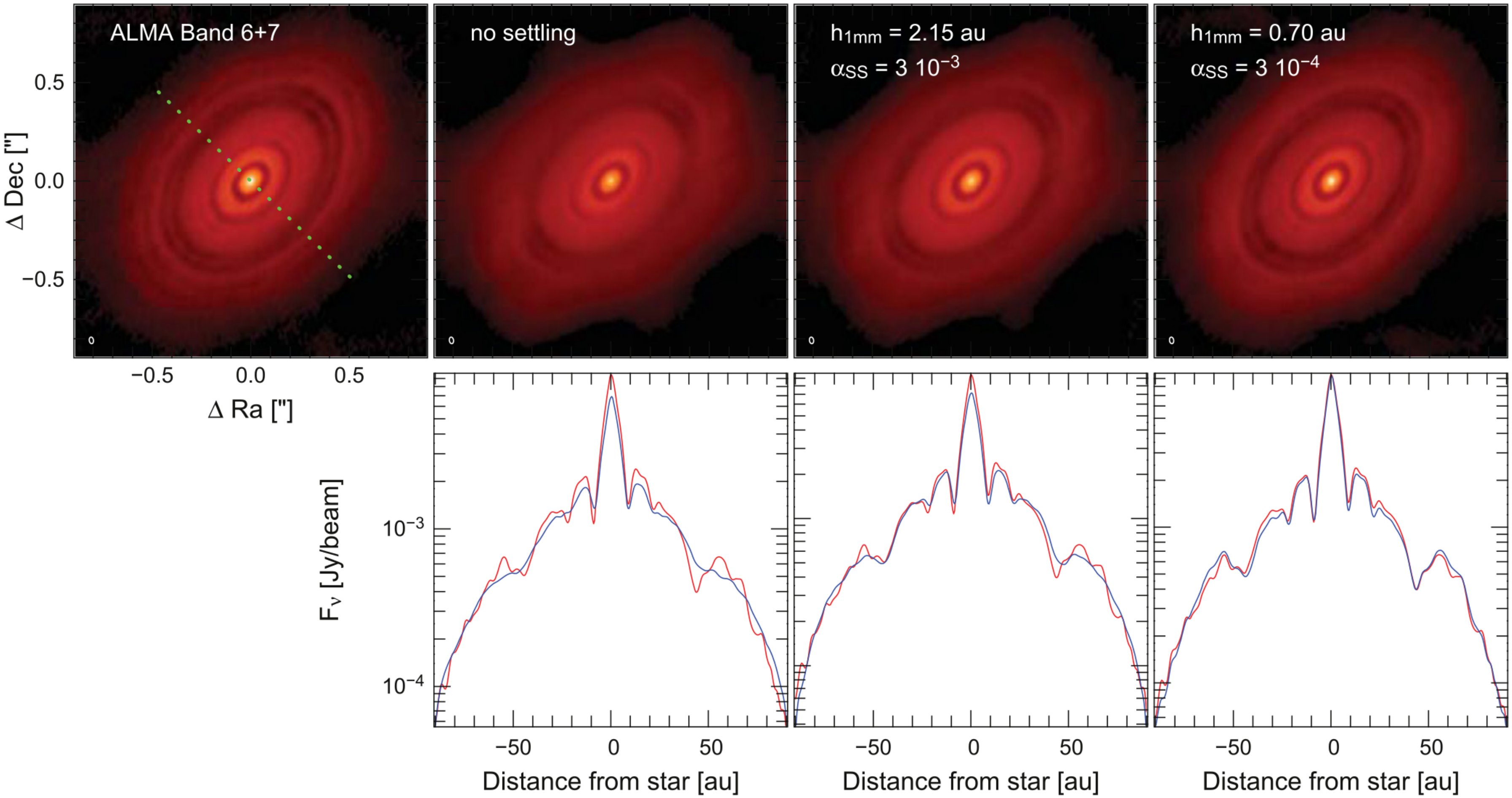
Pinte et al. 2016



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

***based on 1mm grains**

Pinte et al. 2016



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

α_{ss} at the midplane

<u>total α_{ss} probably higher</u>

***based on 1mm grains**

What do we see ?

- We can’t see turbulence directly in the bulk of the disk.
- Currently best fit RT models of HL Tau doesn’t rule out MRI turbulence
- Understanding the grain size distribution could be a link to the turbulence strength

What do we model ?

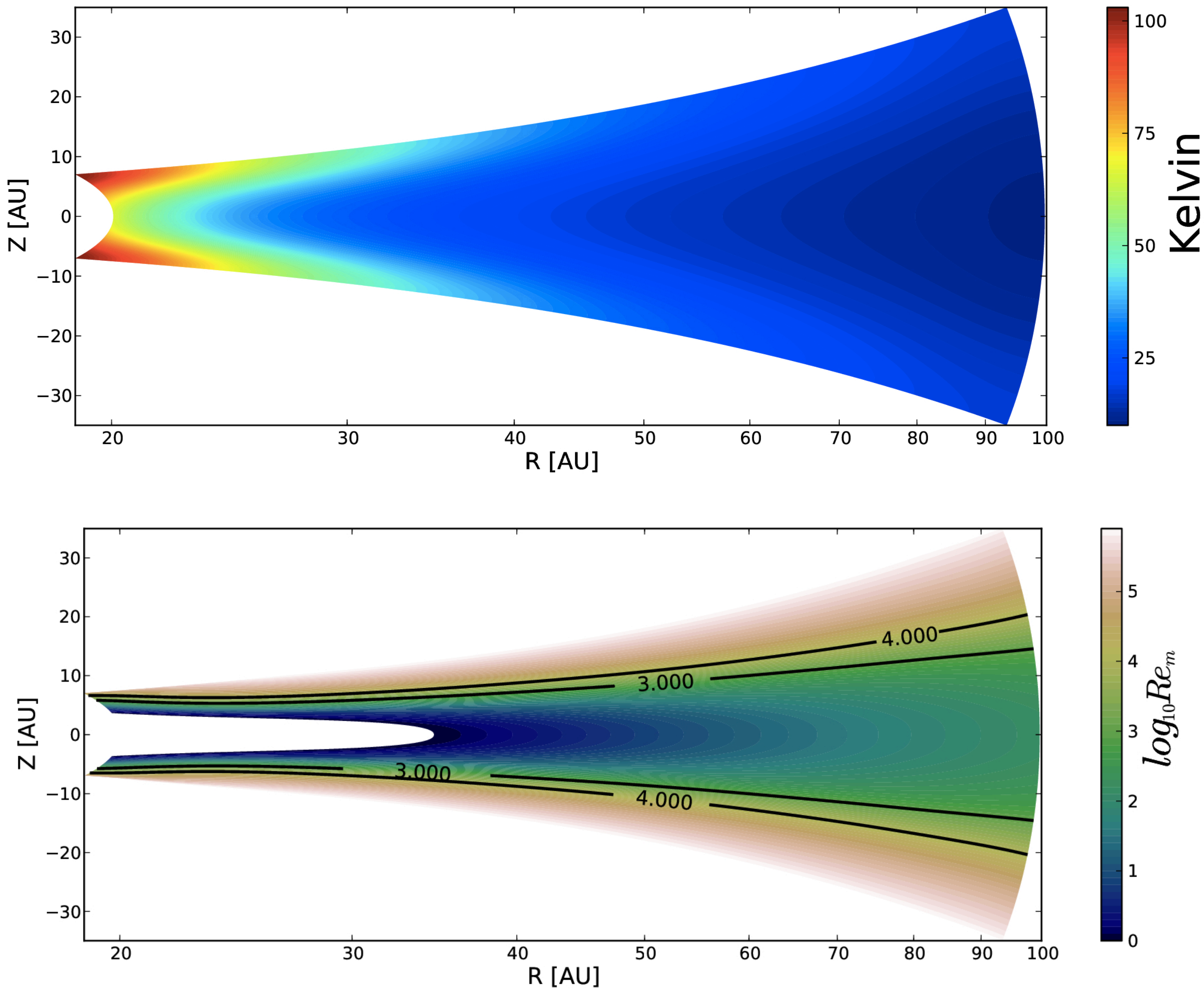
3D global stratified non-ideal MHD simulations

Flock et al. 2015

PLUTO code: (2^{nd} PLM, HLLD, CT)
Initial magnetic field: vertical net flux
Ohmic resistivity: ionization + dust-chemistry
Radiation transfer: Best fit RT initial conditions from observation

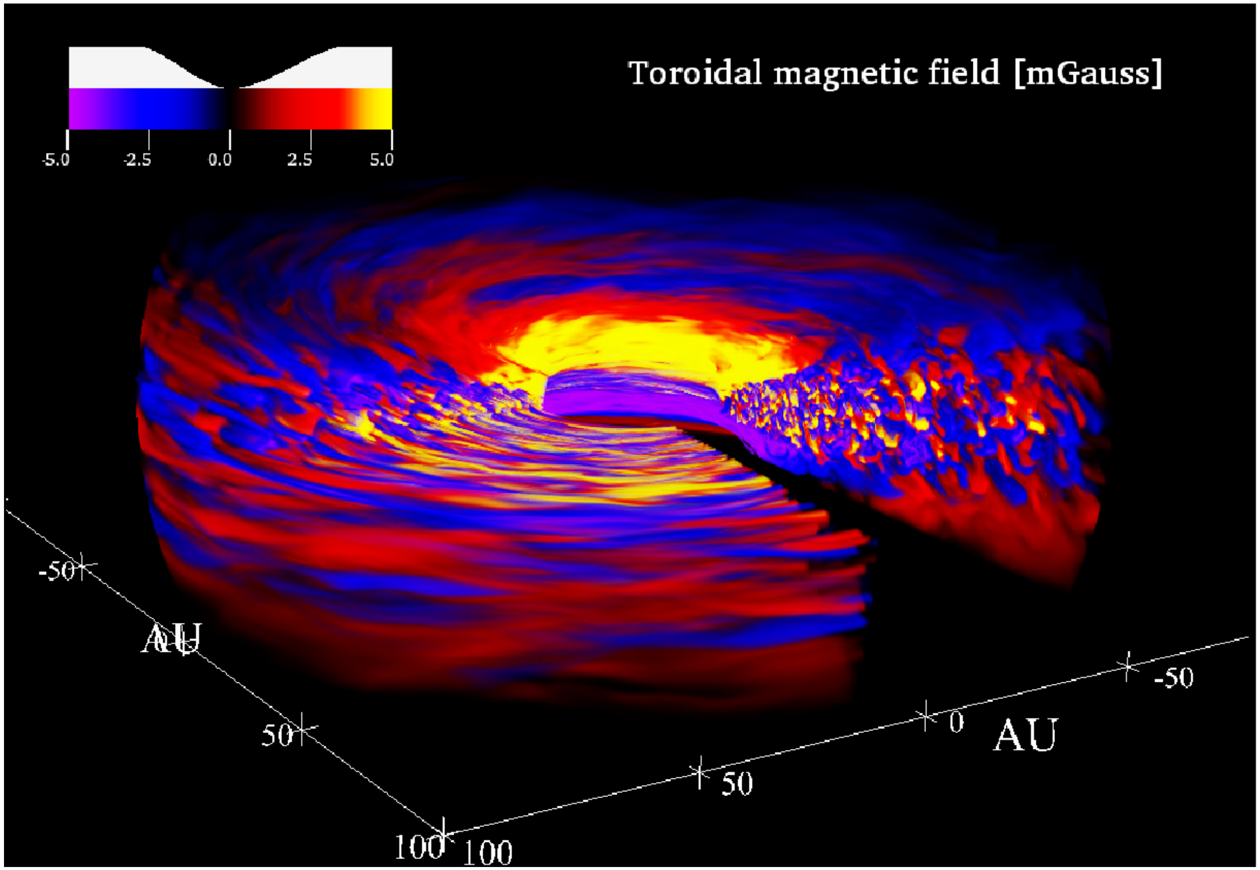
3D global stratified non-ideal MHD simulations

Flock et al. 2015



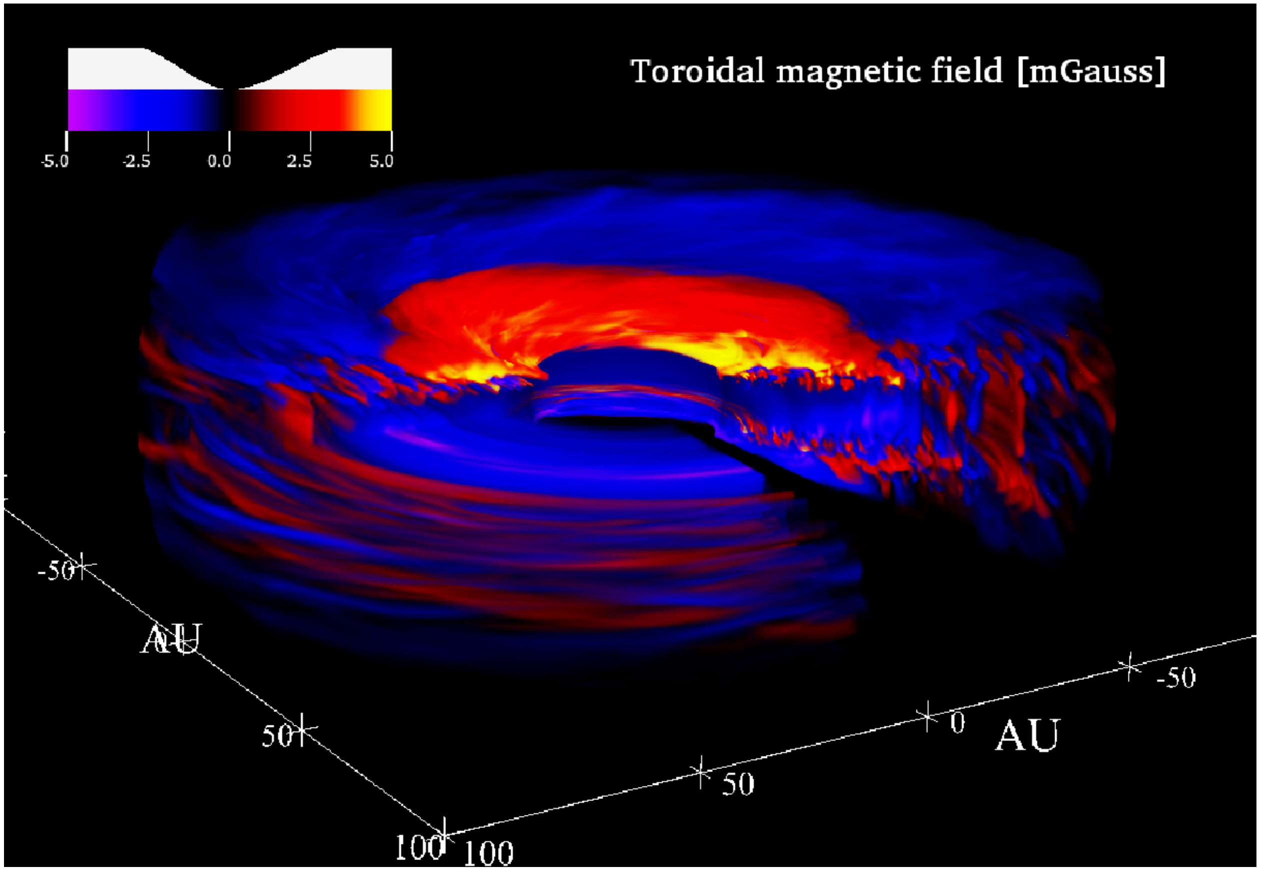
3D global stratified MHD simulations

Flock et al. 2015

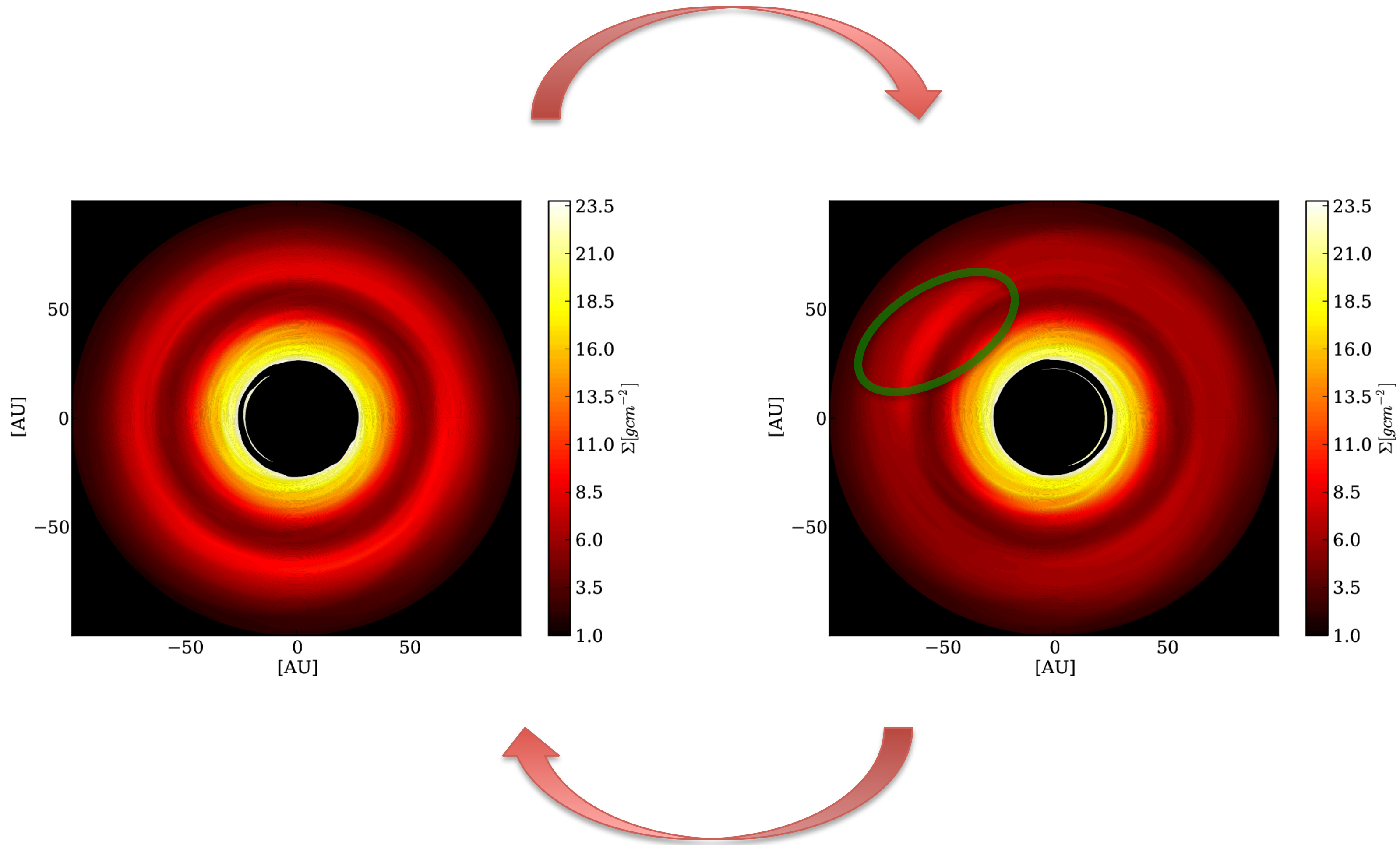


3D global stratified non-ideal MHD simulations

Flock et al. 2015



This two states are alternating
Ring state (1/3) vs. Vortex state (2/3)



Result summary I

- Variations in MRI activity lead to gap and ring formation
- Alternating states between vortex and ring state

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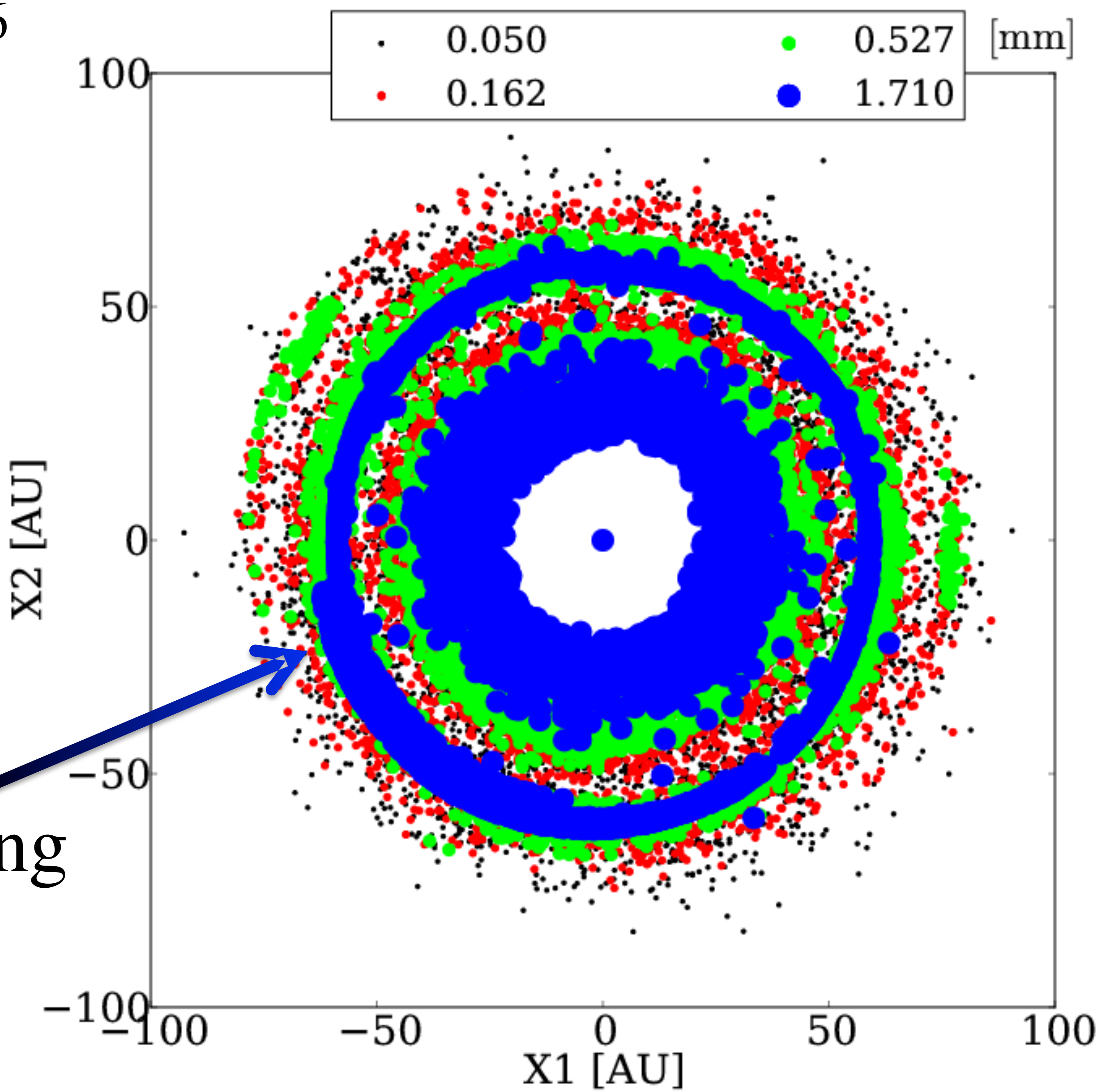
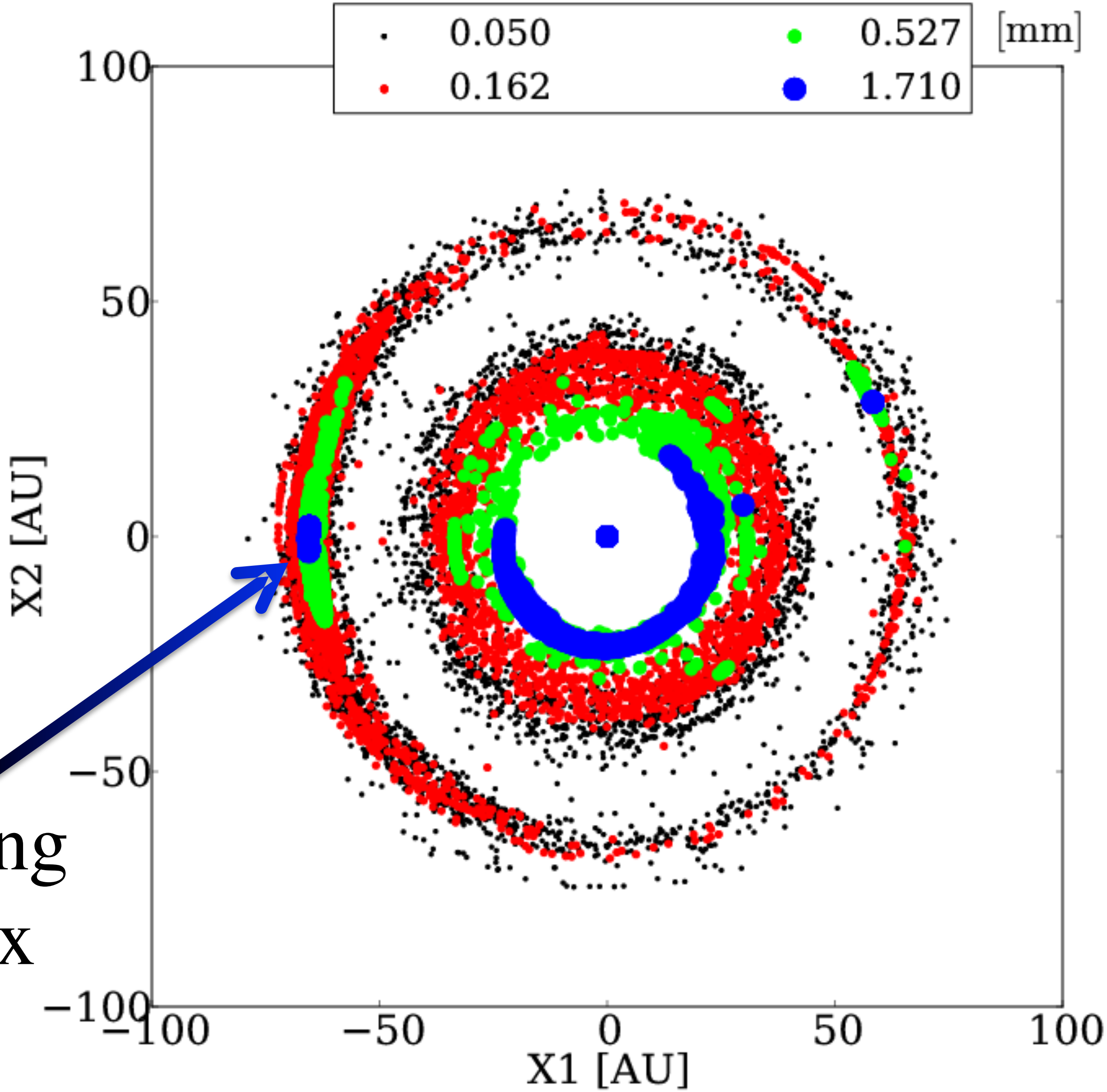
- Variations in MRI activity lead to gap and ring formation
- Alternating states between vortex and ring state

+ size dependent gas drag (settling/drift)
for multiple grain sizes

Ruge et al. 2016

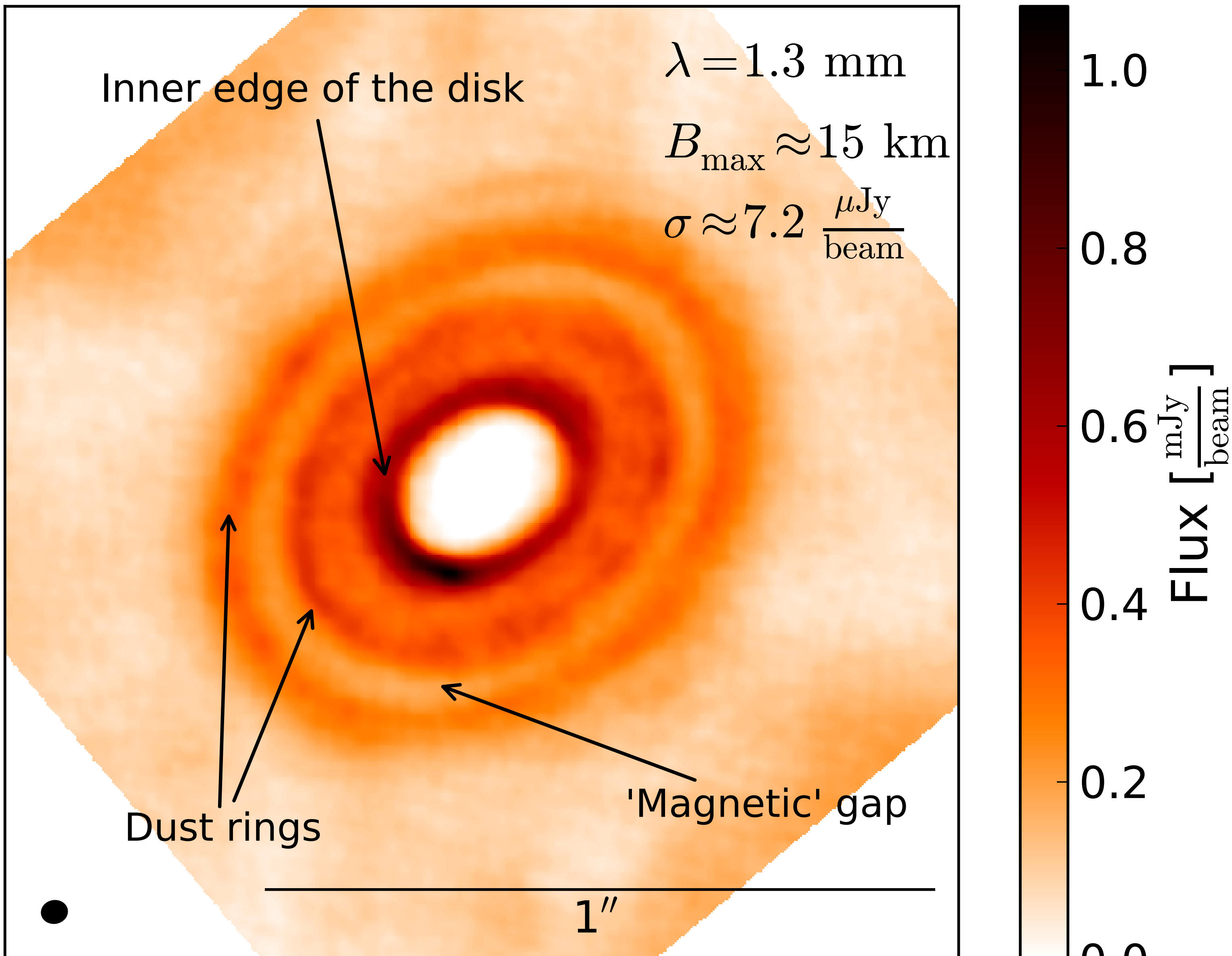


Dust trapping in the ring



Dust trapping
in the vortex

Simulated ALMA image of ring state



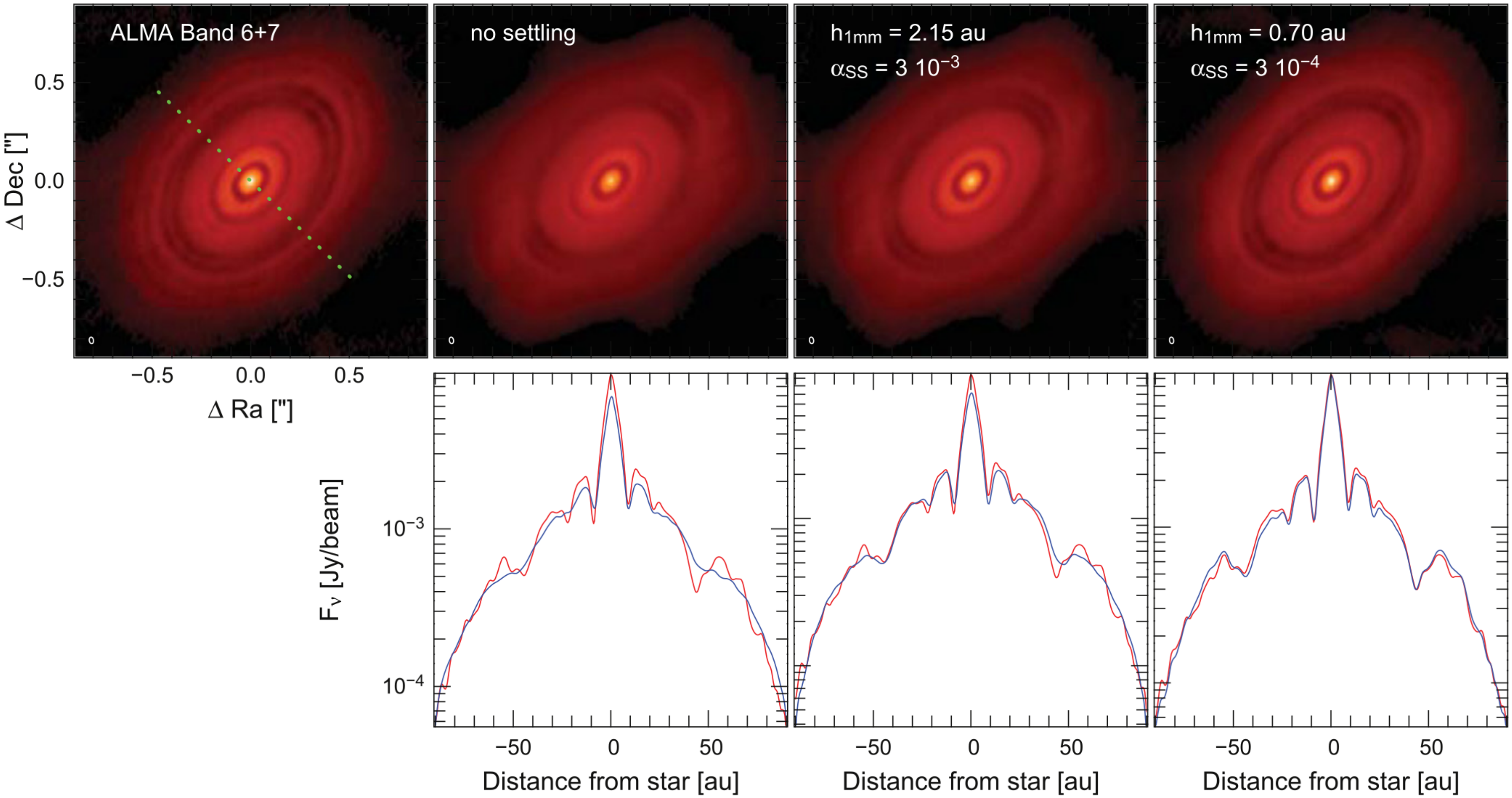
Result summary II

- Surface density gap and jump can lead to dust trapping

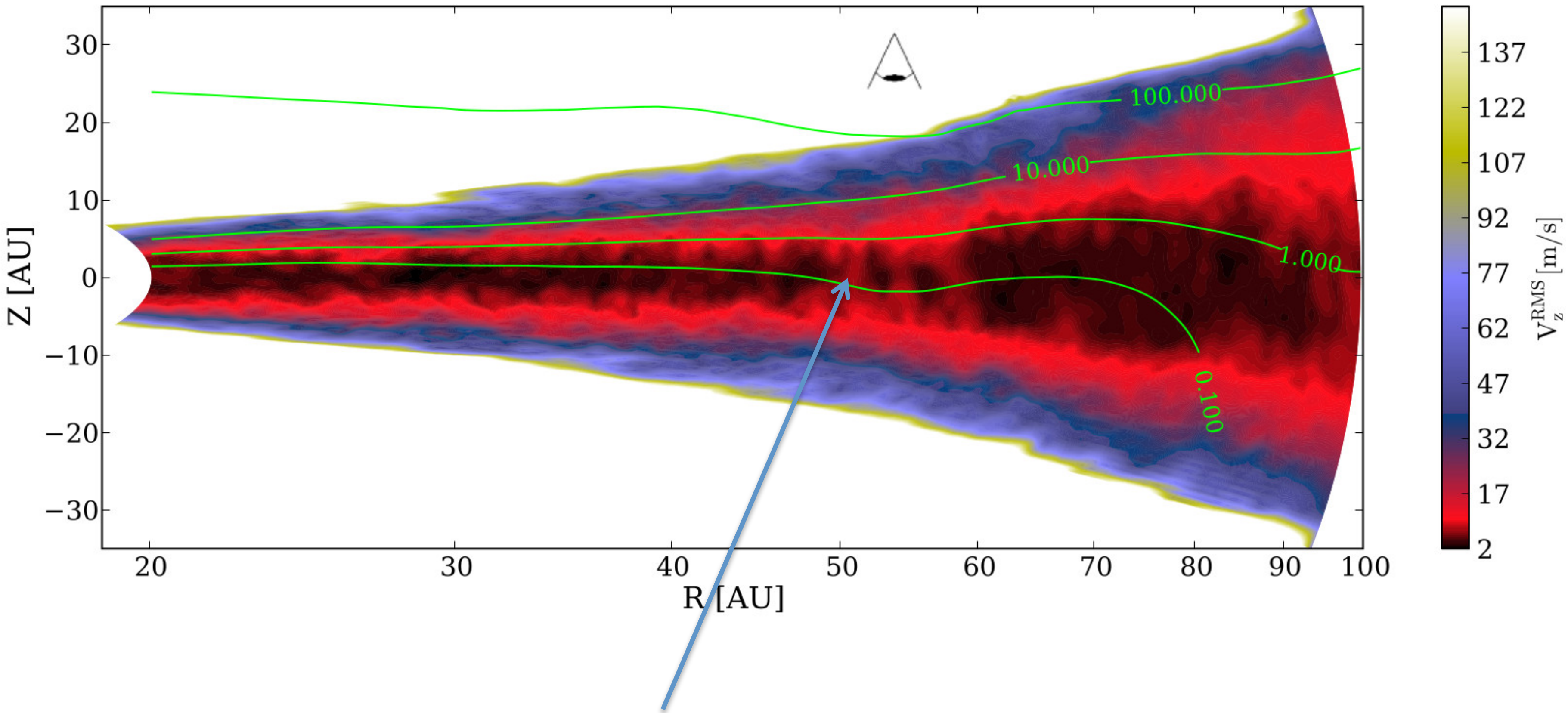
- Gap and jump structure can be detected by ALMA

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

Pinte et al. 2016



(α_{ss}~10^{-4}, H_{dust}/R = 0.007)

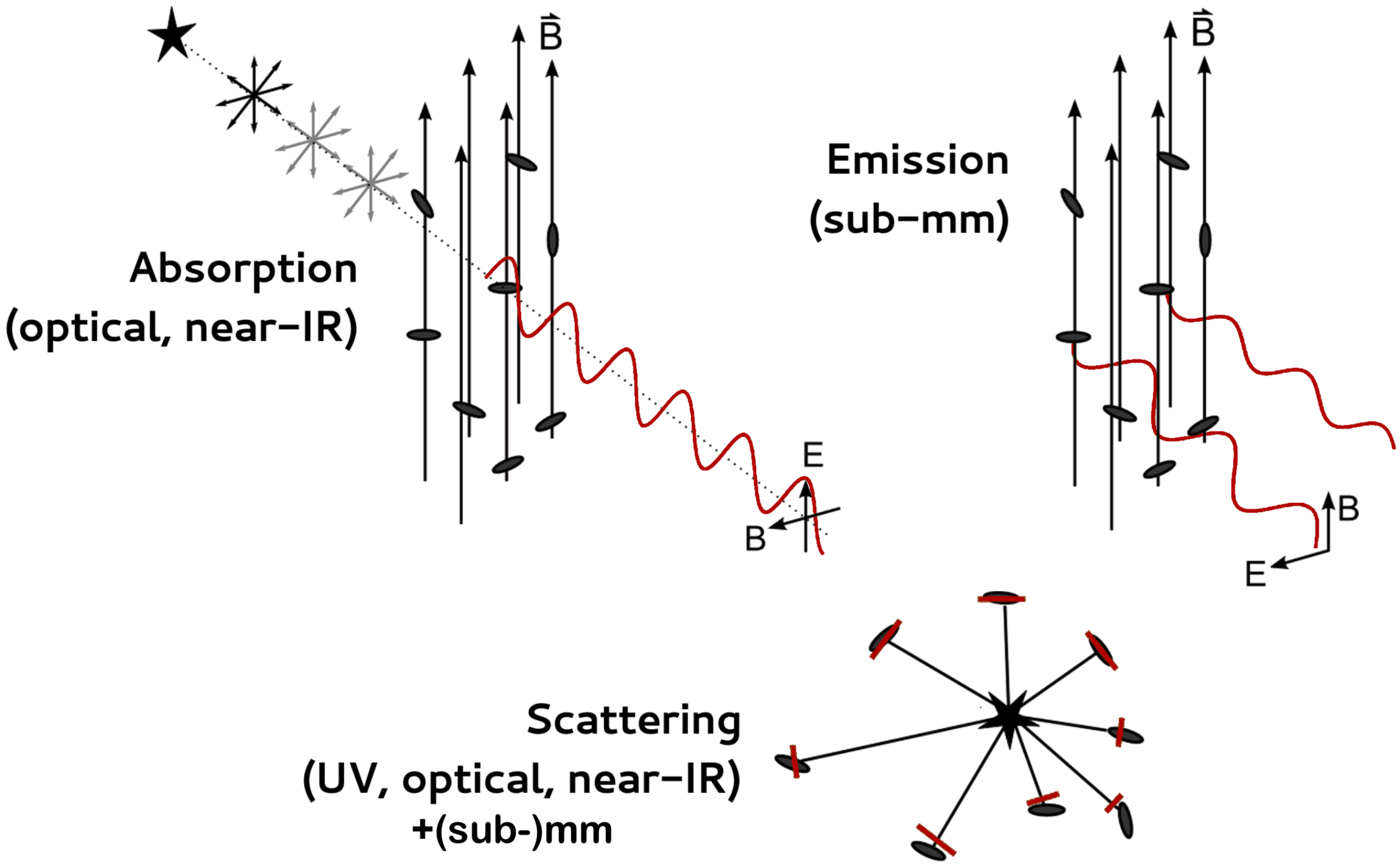


~1 % of c_s at the midplane (alpha~1e-4)

Teague et al. 2016

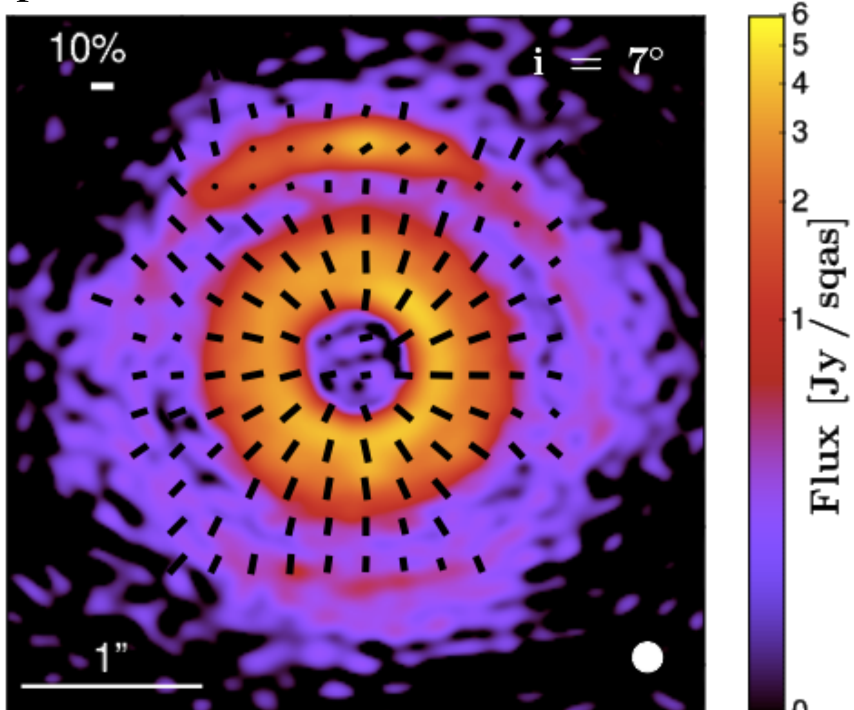
"Ultimately, ALMA is expected to reach a flux calibration of ≈3%, which will translate into a limit of $v_{turb} > 0.07\ c_s$ for a ≥3σ detection."

Polarization



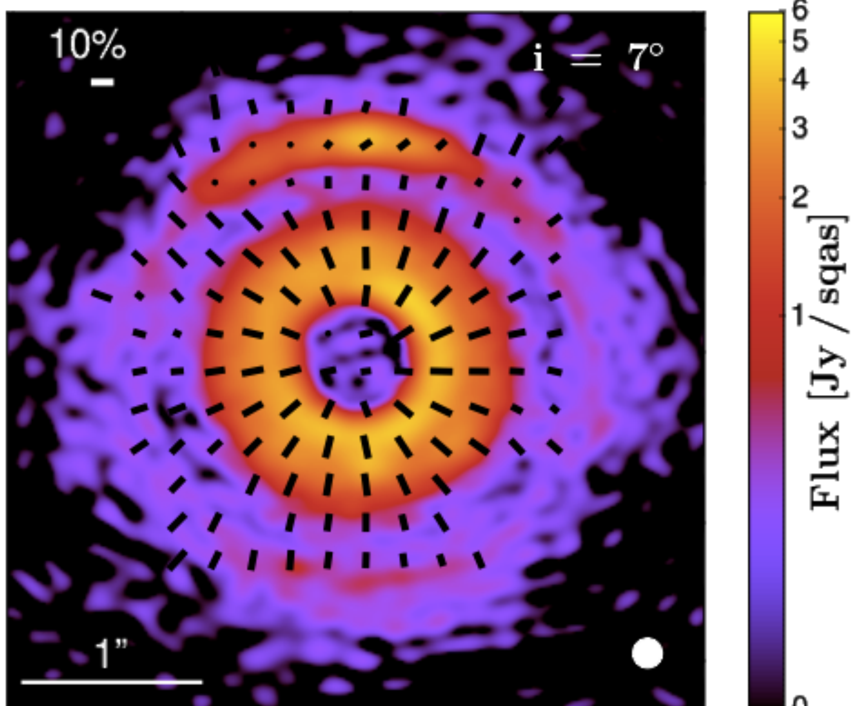
Bertrang et al. 2016

polarized continuum emission



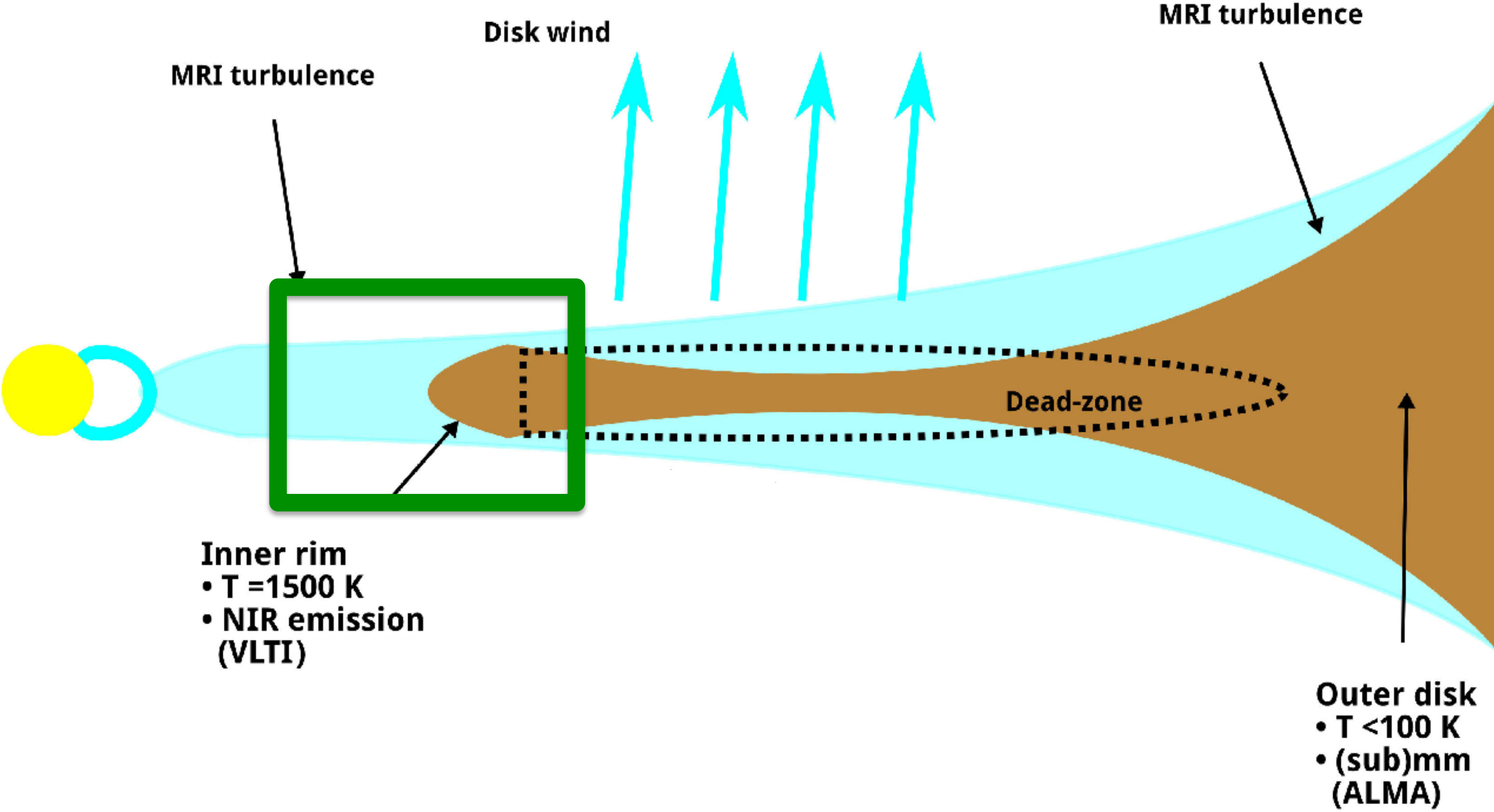
Bertrang et al. 2016

polarized continuum emission



self-scattering might produce a similar structure

no observational evidence for magnetic fields in protoplanetary disks


Disk wind
MRI turbulence
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• T =1500 K
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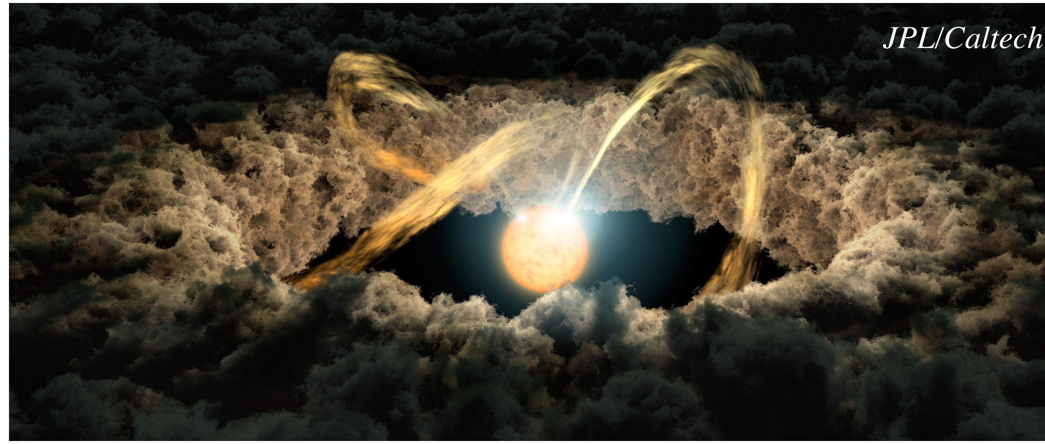
The Inner Rim

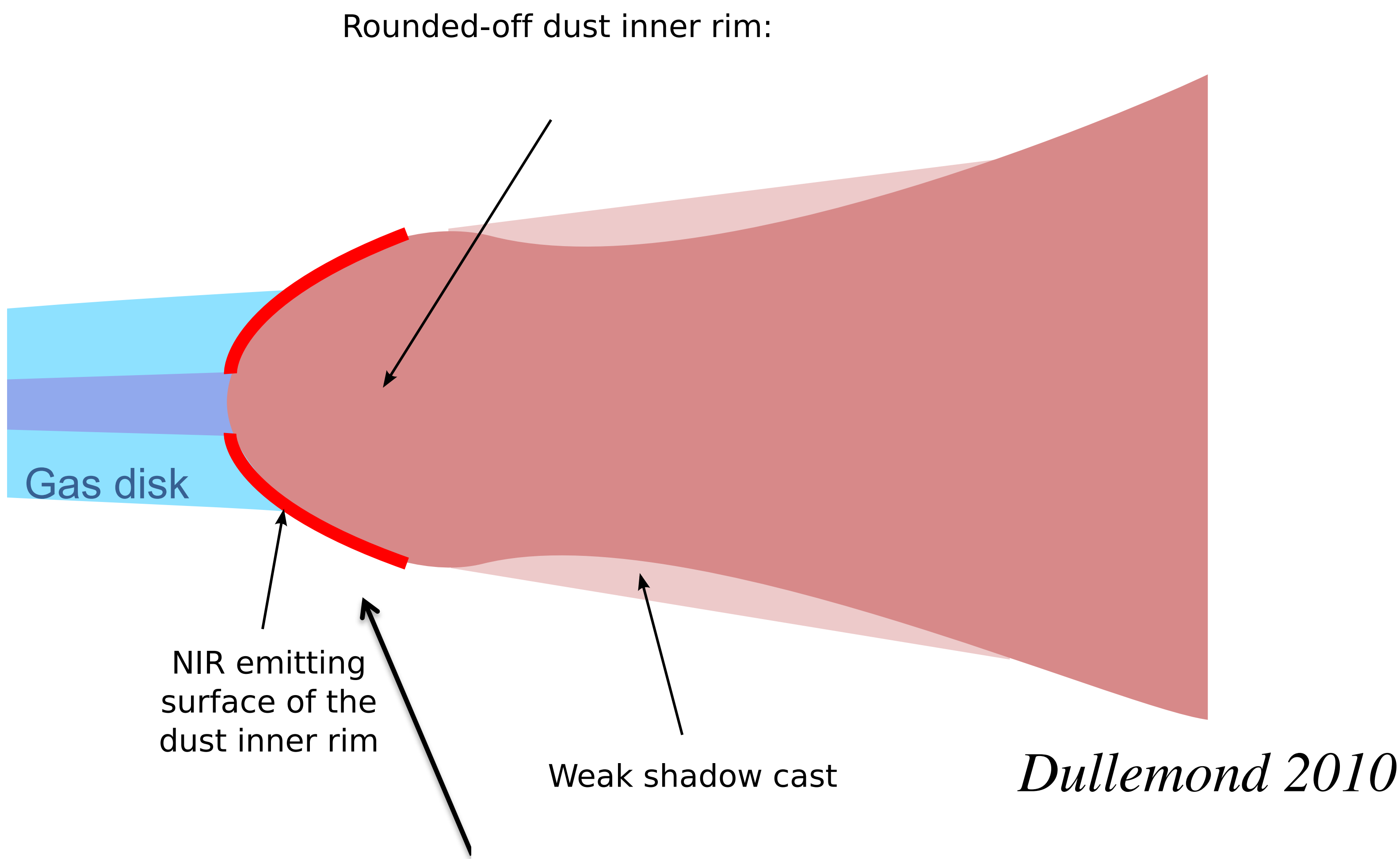


Sublimation of SiO_x

(50 % of solid material mass)

Rim position: 0.01 - 1 AU

T_{subl}: 1200 - 1500 K



NIR excess needed

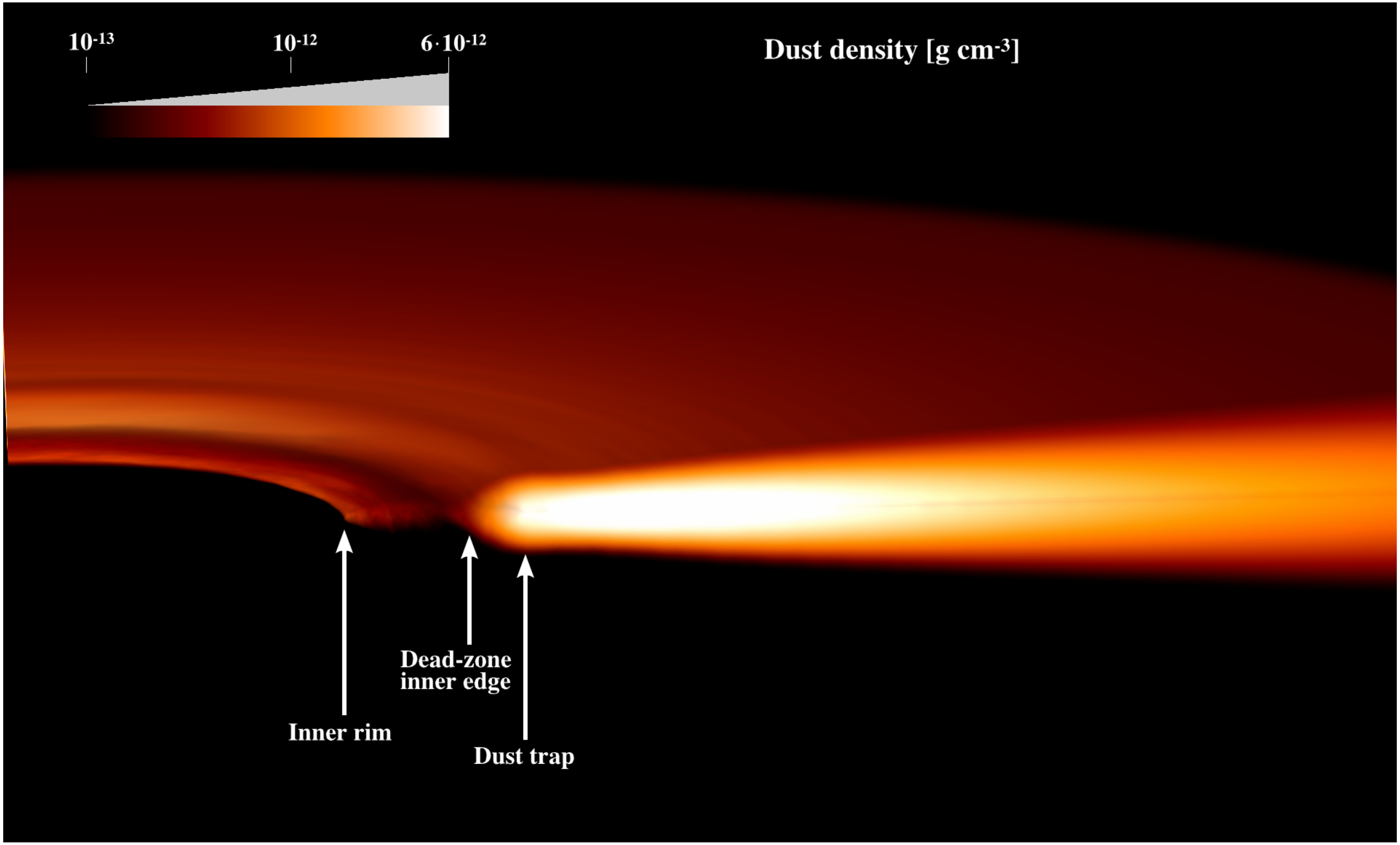
Possible solutions by a disk wind or magnetic fields

3D radiation non-ideal MHD models

Flock et al. 2017 ApJ 835 230

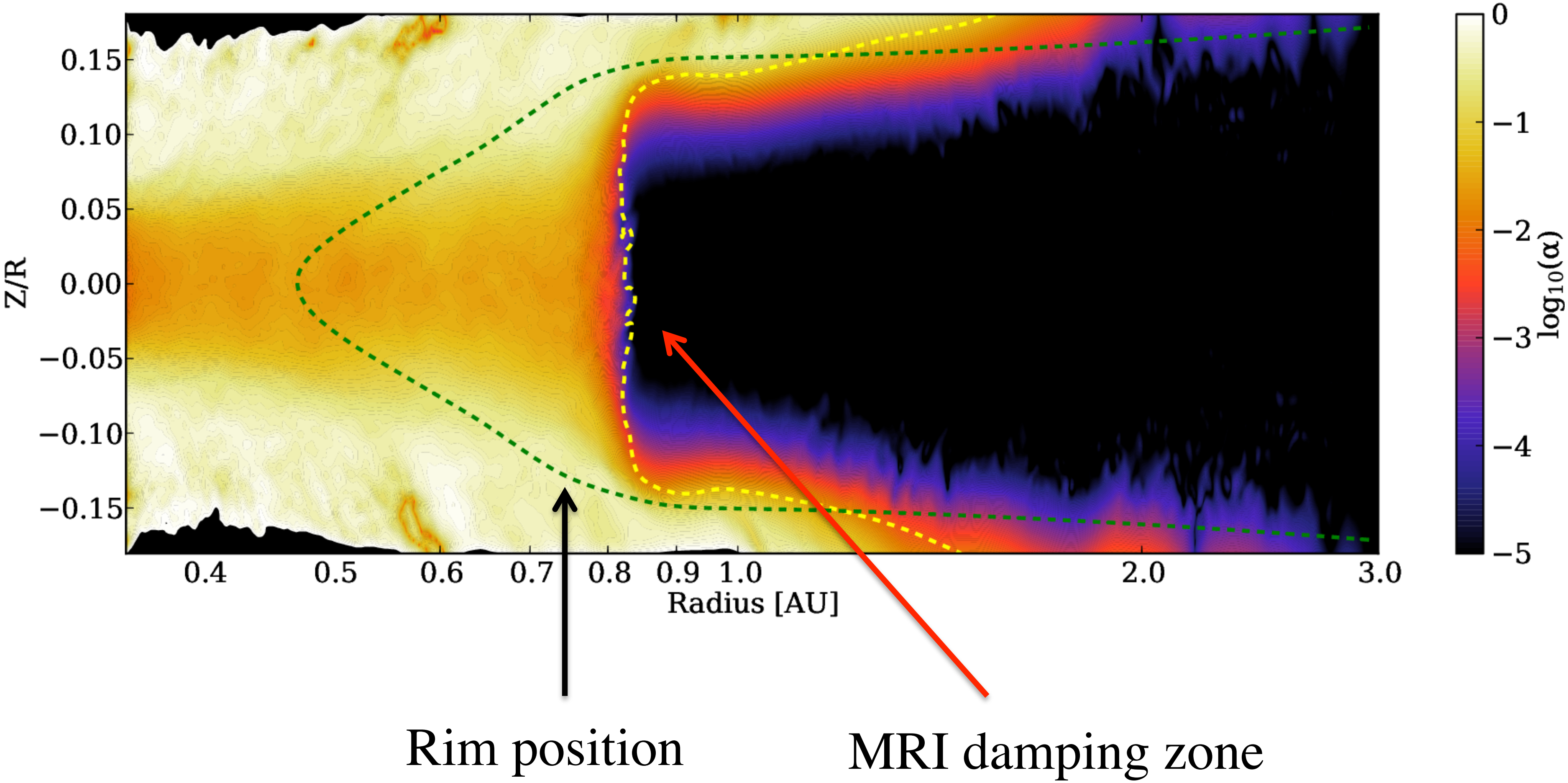
- Irradiation by the star, thermal cooling by the disk
- dust sublimation/deposition $T_{sub}(\varrho)$
- Zero-net flux + vertical magnetic field
- Ohmic dissipation $\varepsilon(T)$
- 896x128x512 spherical grid (0.3 - 3 AU, $\Delta\theta$=0.36, pi/2)

Input parameter: T_*, M_*, R_*, mass accretion rate
initial magnetic field

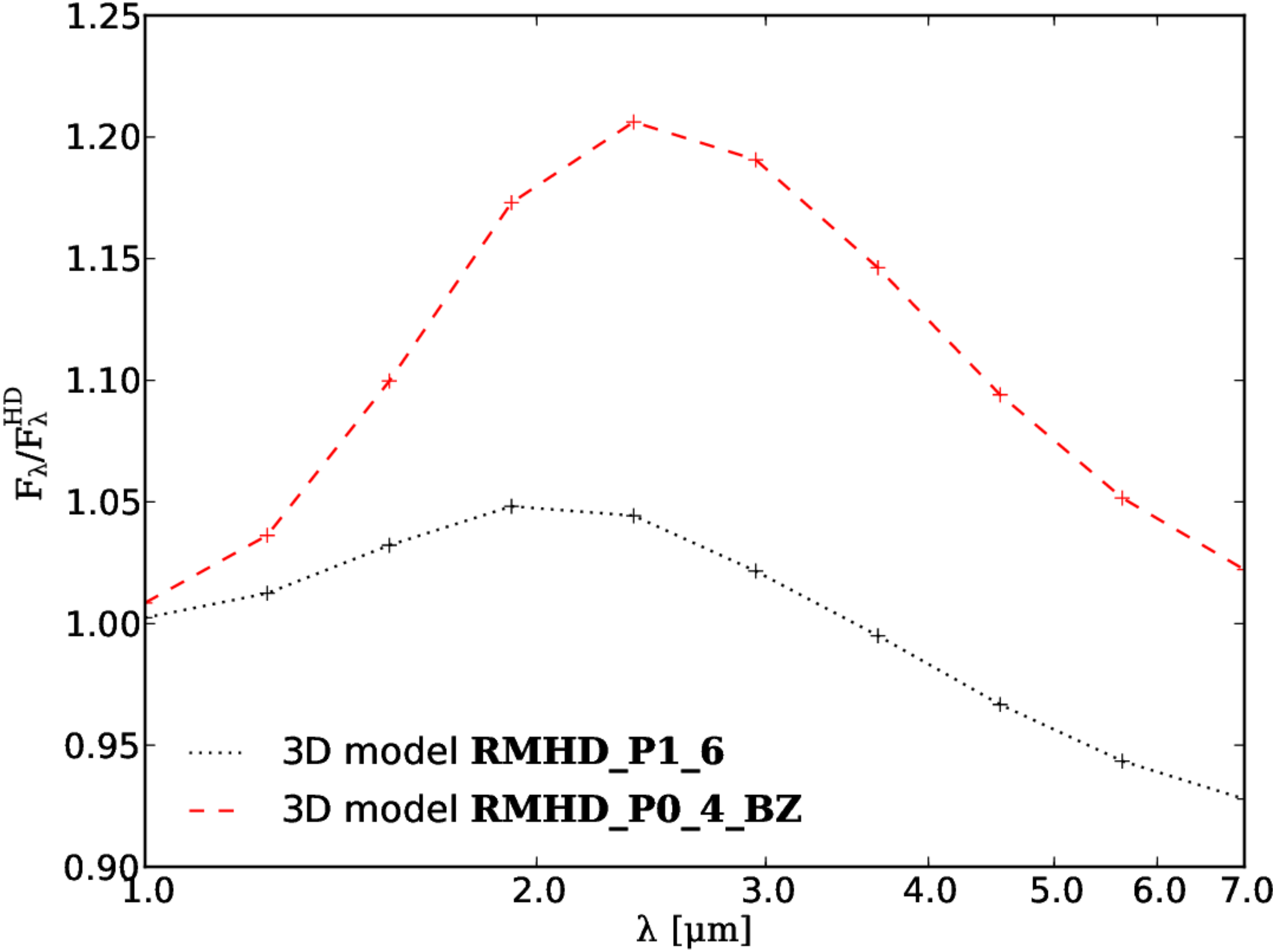


10-13
10-12
6·10-12
Dust density [g cm-3]
Dead-zone inner edge
Inner rim
Dust trap

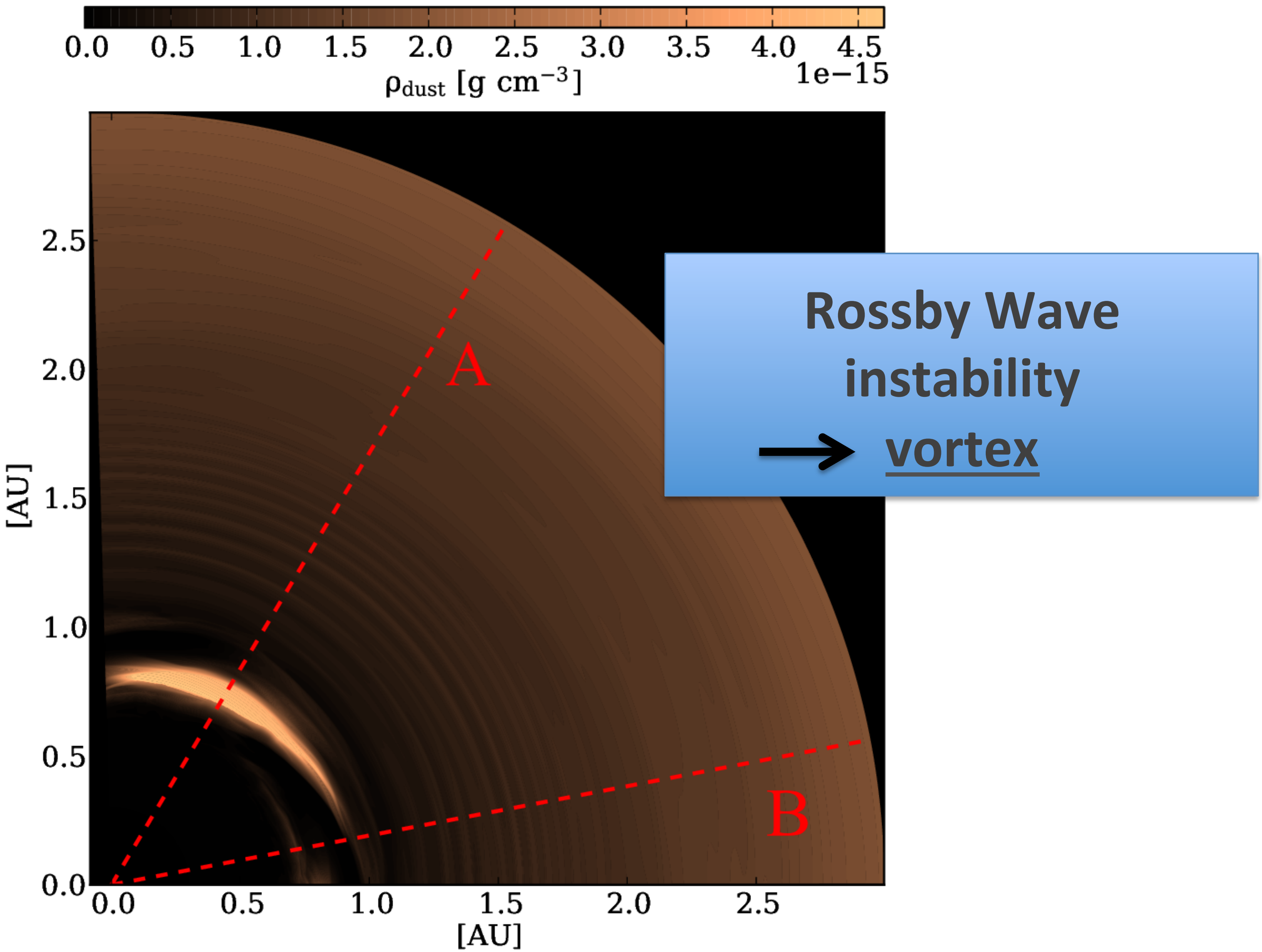
stress/pressure ratio $\frac{\rho v'_\phi v'_r}{P} - \frac{B_\phi B_r}{P}$



NIR excess

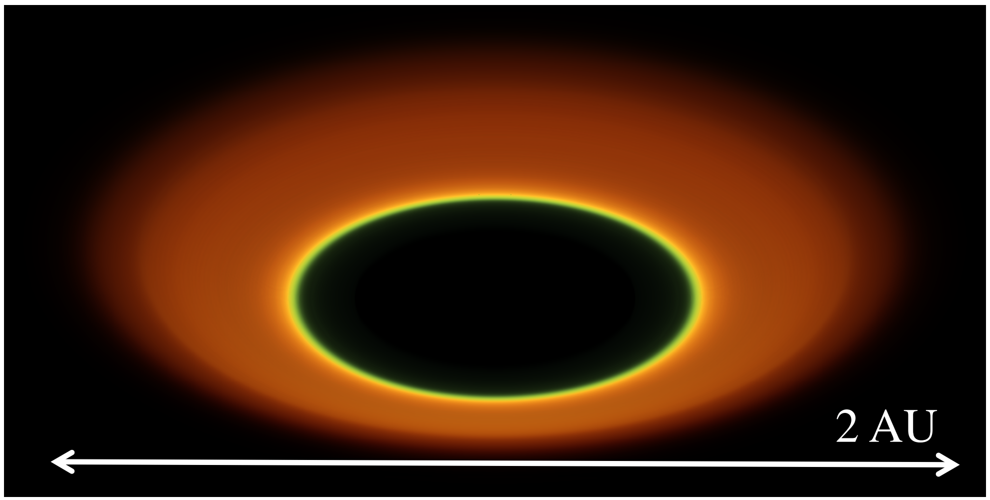


1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
F_λ/F_λ^{HD}
1.0
2.0
3.0
4.0
5.0
6.0
7.0
λ [μm]
3D model **RMHD_P1_6**
3D model **RMHD_P0_4_BZ**

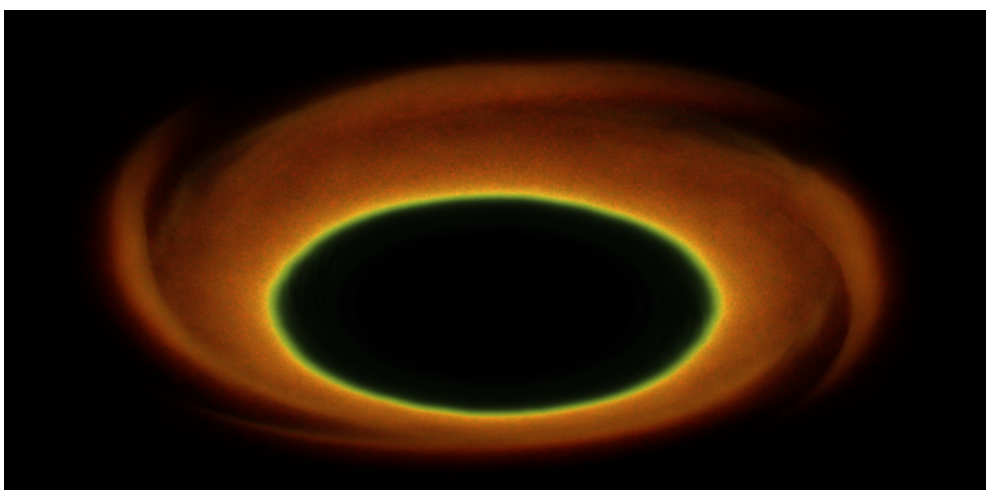

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
1e−15
ρ_{dust} [g cm^{-3}]
[AU]
[AU]
A
B
Rossby Wave instability
→ vortex

Synthetic images

$i = 60^0$ 1.25 - 2.2 - 4.8 micron (B-G-R)



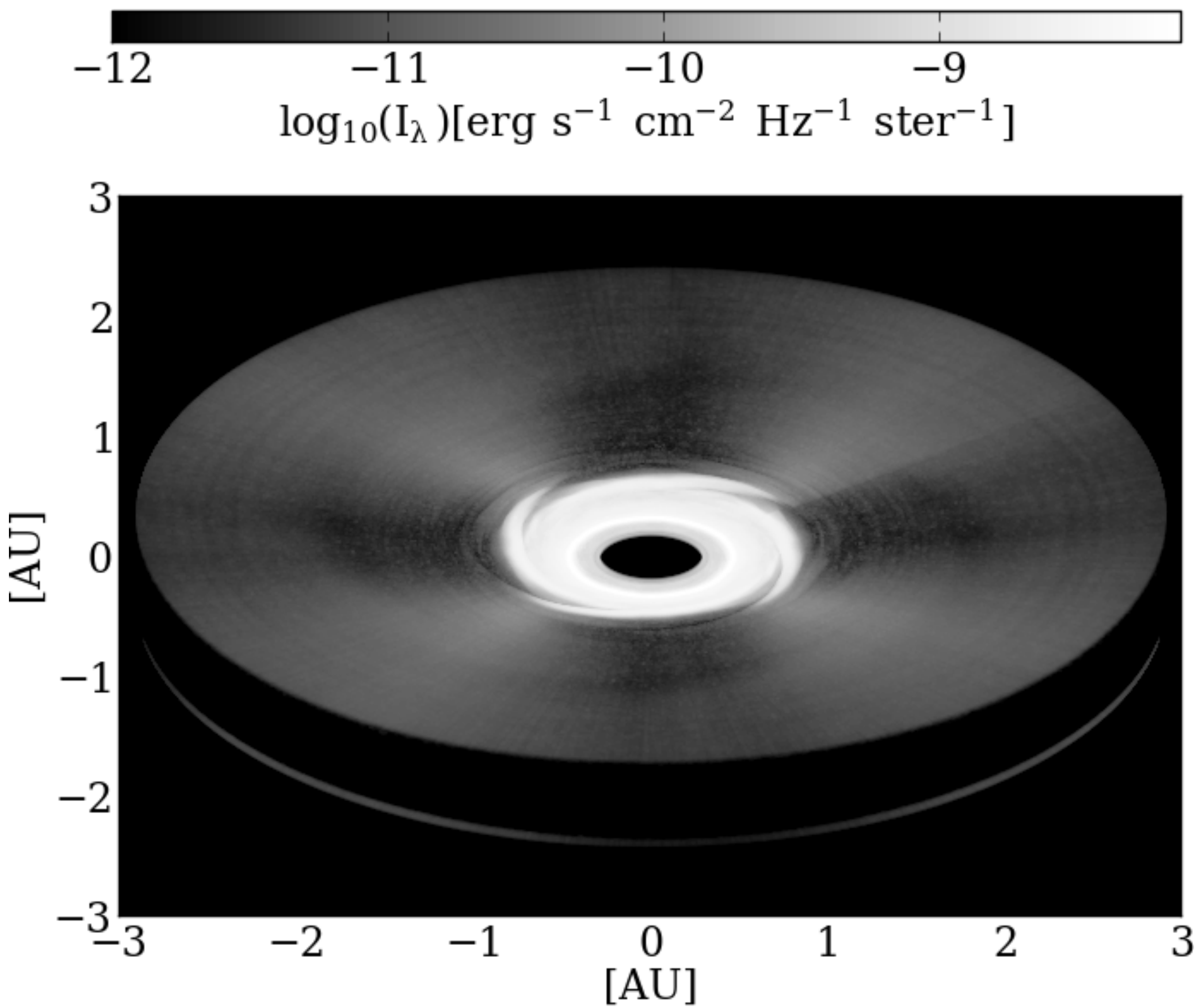
2D R-HD



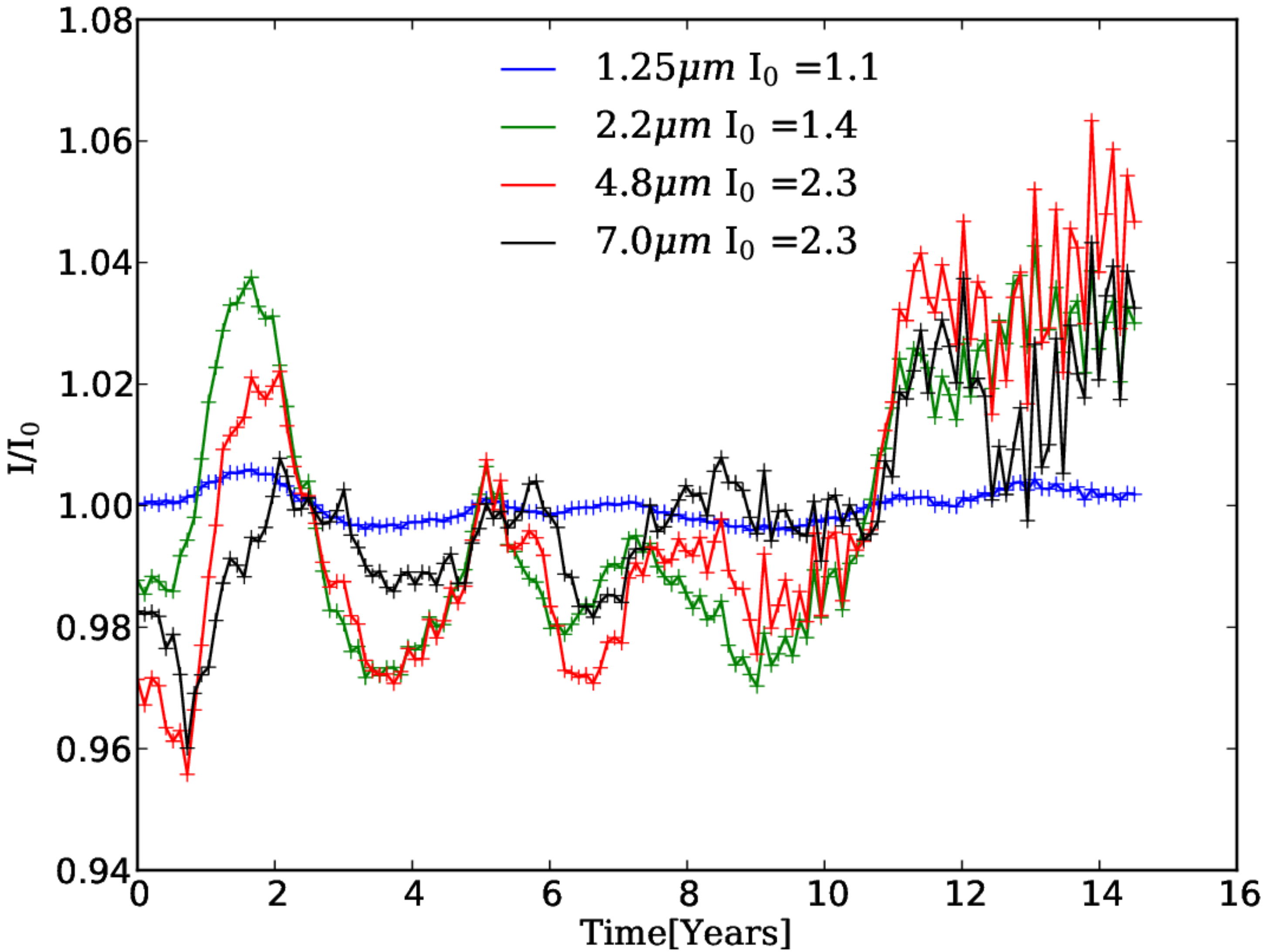
3D R-MHD

Synthetic images

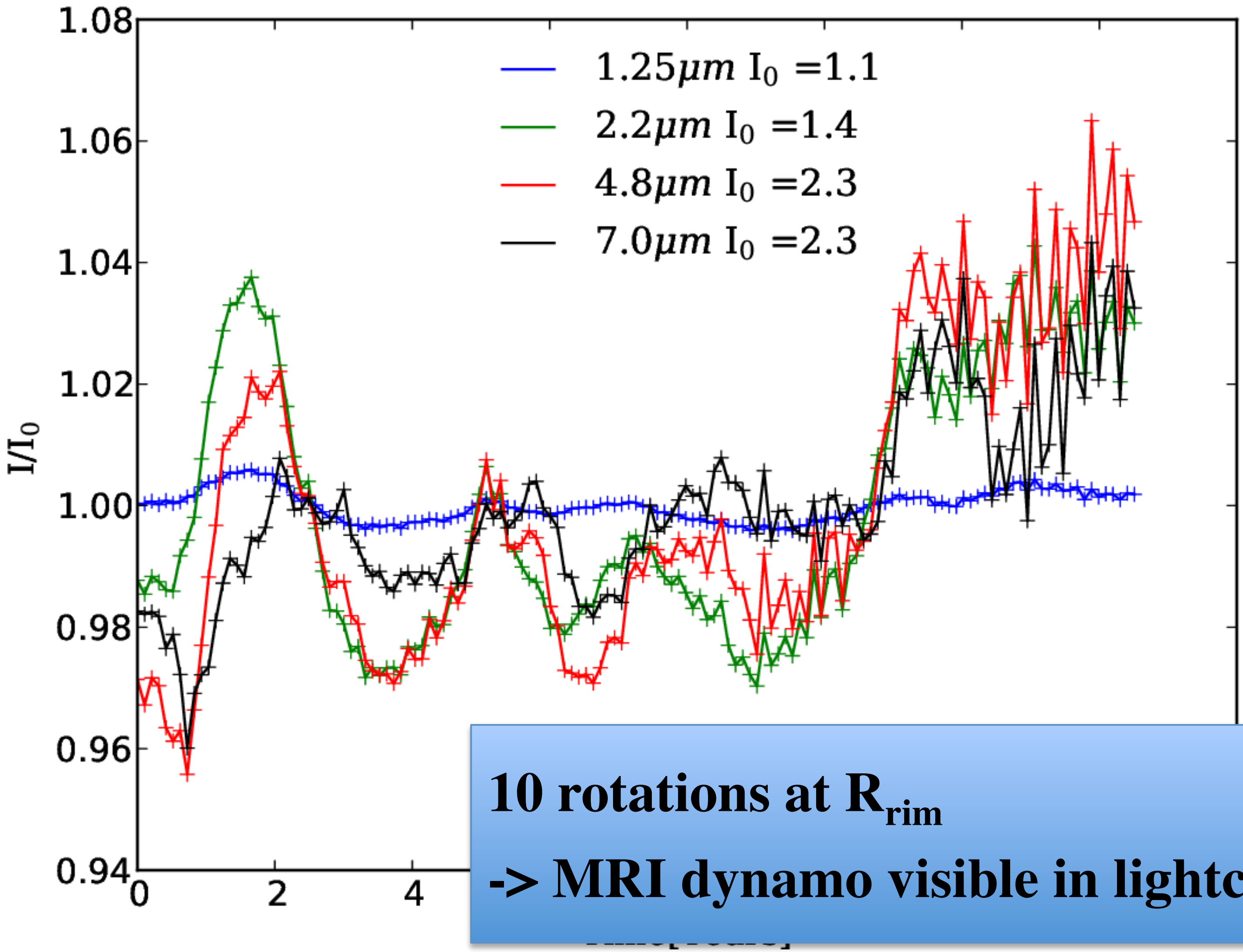
$i = 45^0$ 0.3 micron



Variability



Variability



10 rotations at R_{rim}

-> MRI dynamo visible in lightcurve

What do we understand ?

- Current observational constraints don't confirm nor rule out MHD turbulence
- Estimating detailed turbulent velocities on 1% c_s remains difficult for current telescope facilities
- Lightcurve variations could give us some hints