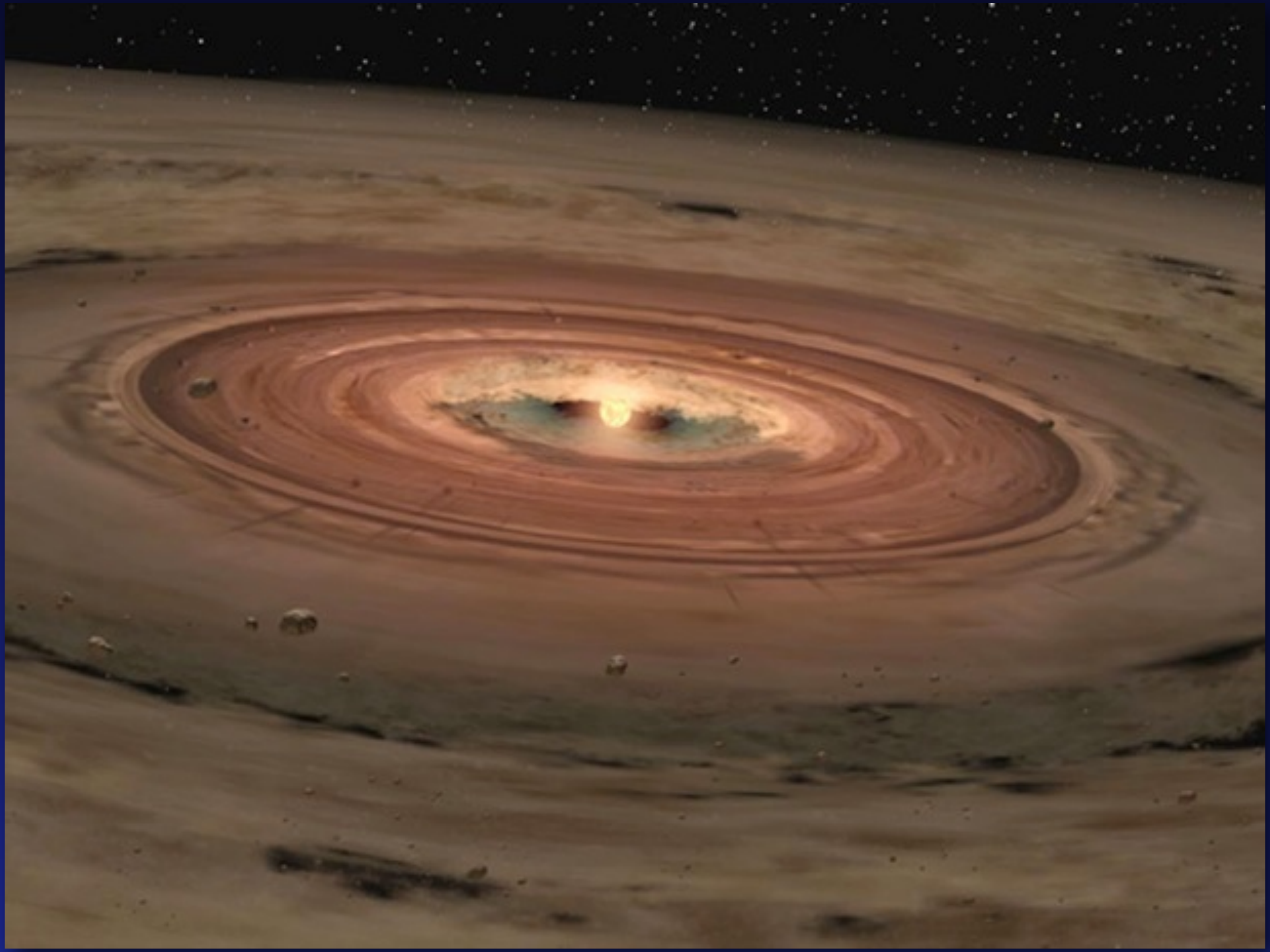
Probing the Nature of Accretion and Planet Formation in Protoplanetary Disks

Connecting Theory with ALMA Observations



Courtesy: NASA

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Collaborators

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Kevin Flaherty

Phil Armitage

Xuening Bai

Eugene Chiang

Sagan Fellows Symposium

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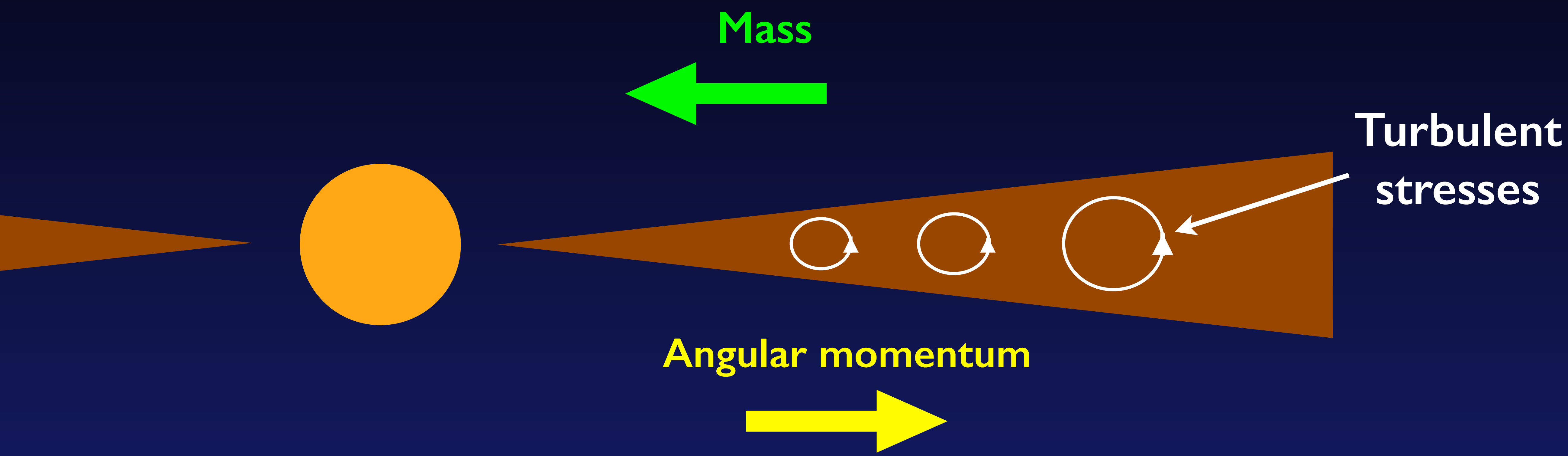
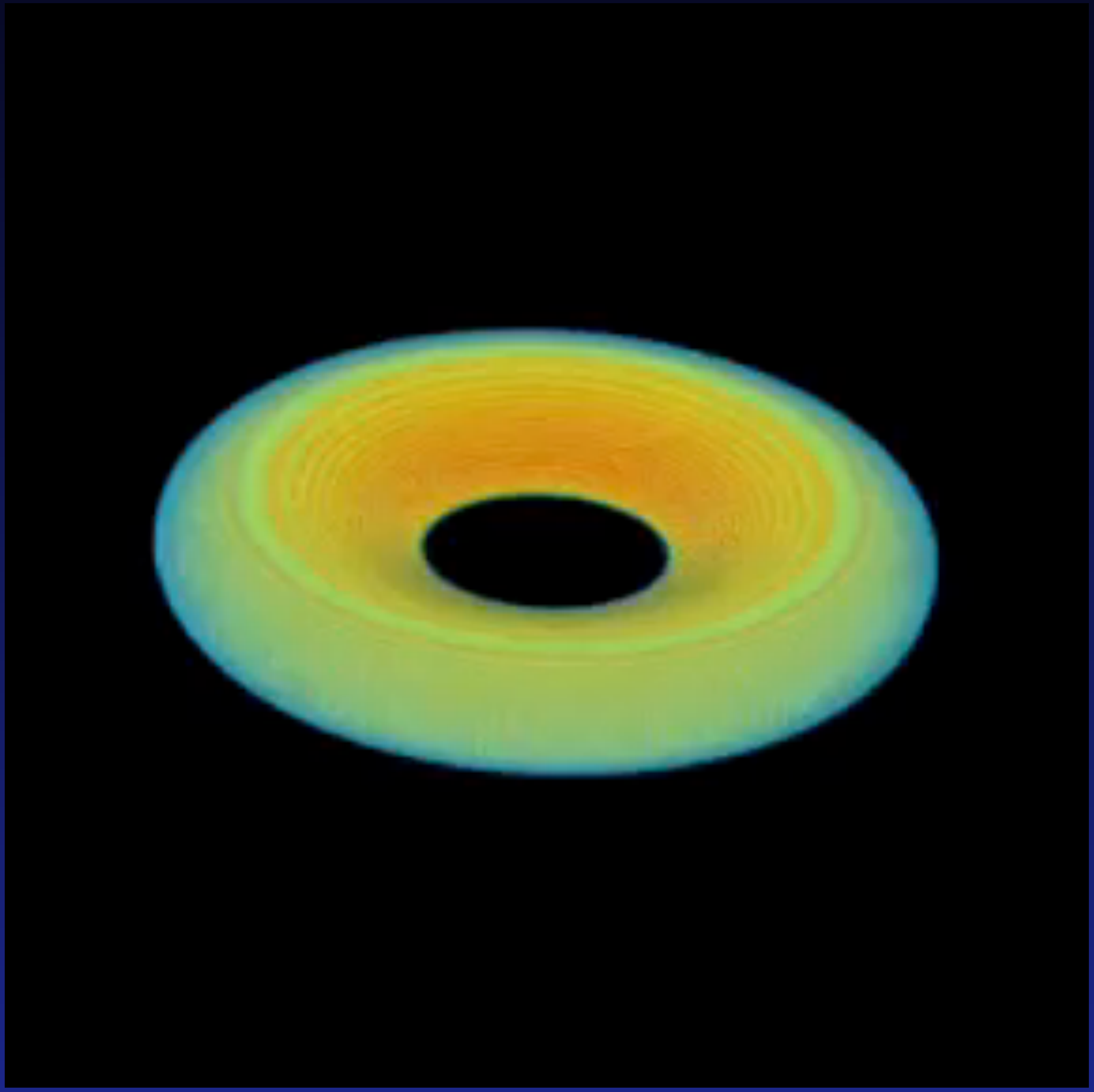
Disk turbulence is likely tied to angular momentum transport



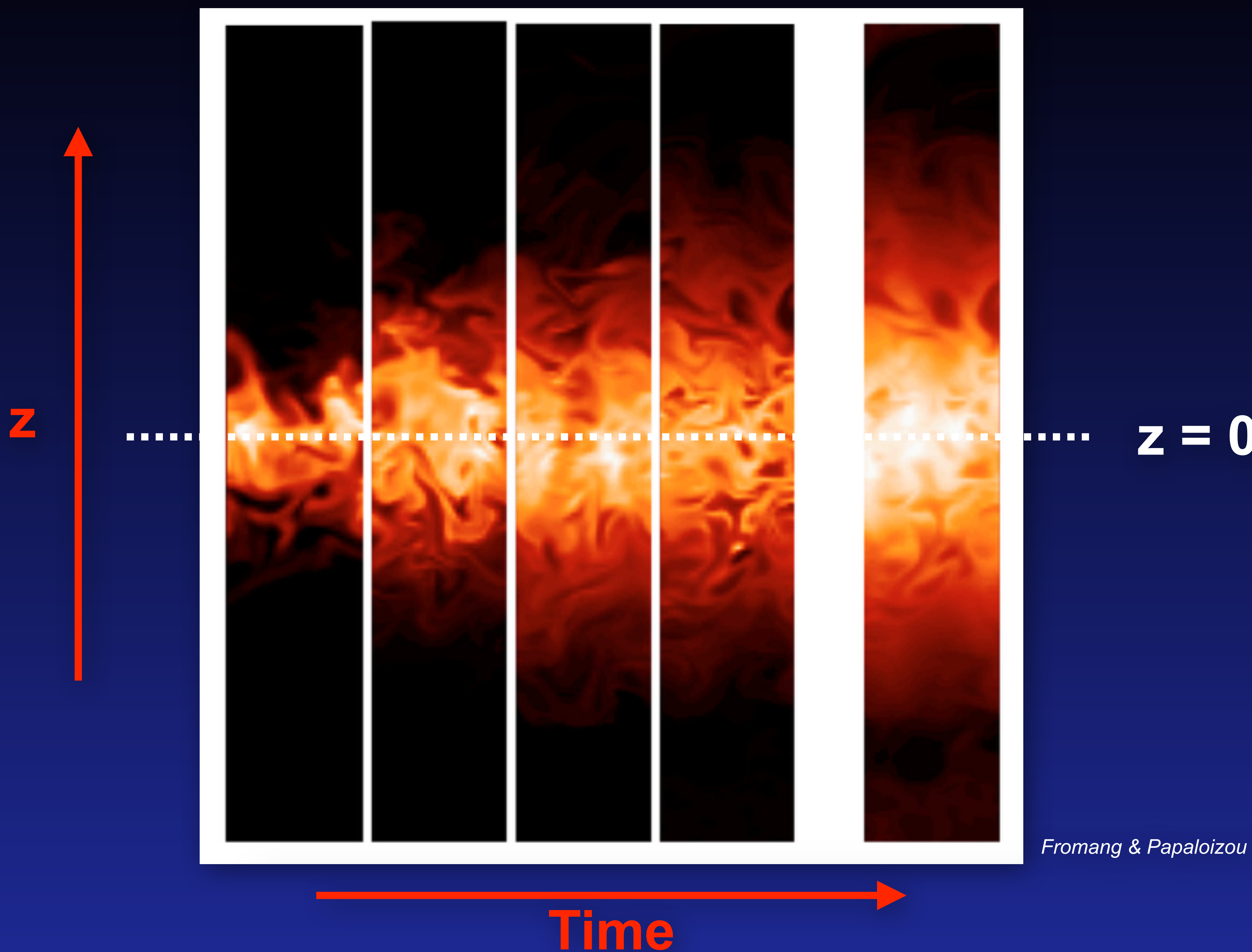
- Microphysical viscosity is way too small to transport angular momentum.
- Shakura and Sunyaev (1973) suggested turbulent angular momentum transport

MRI turbulence drives accretion…



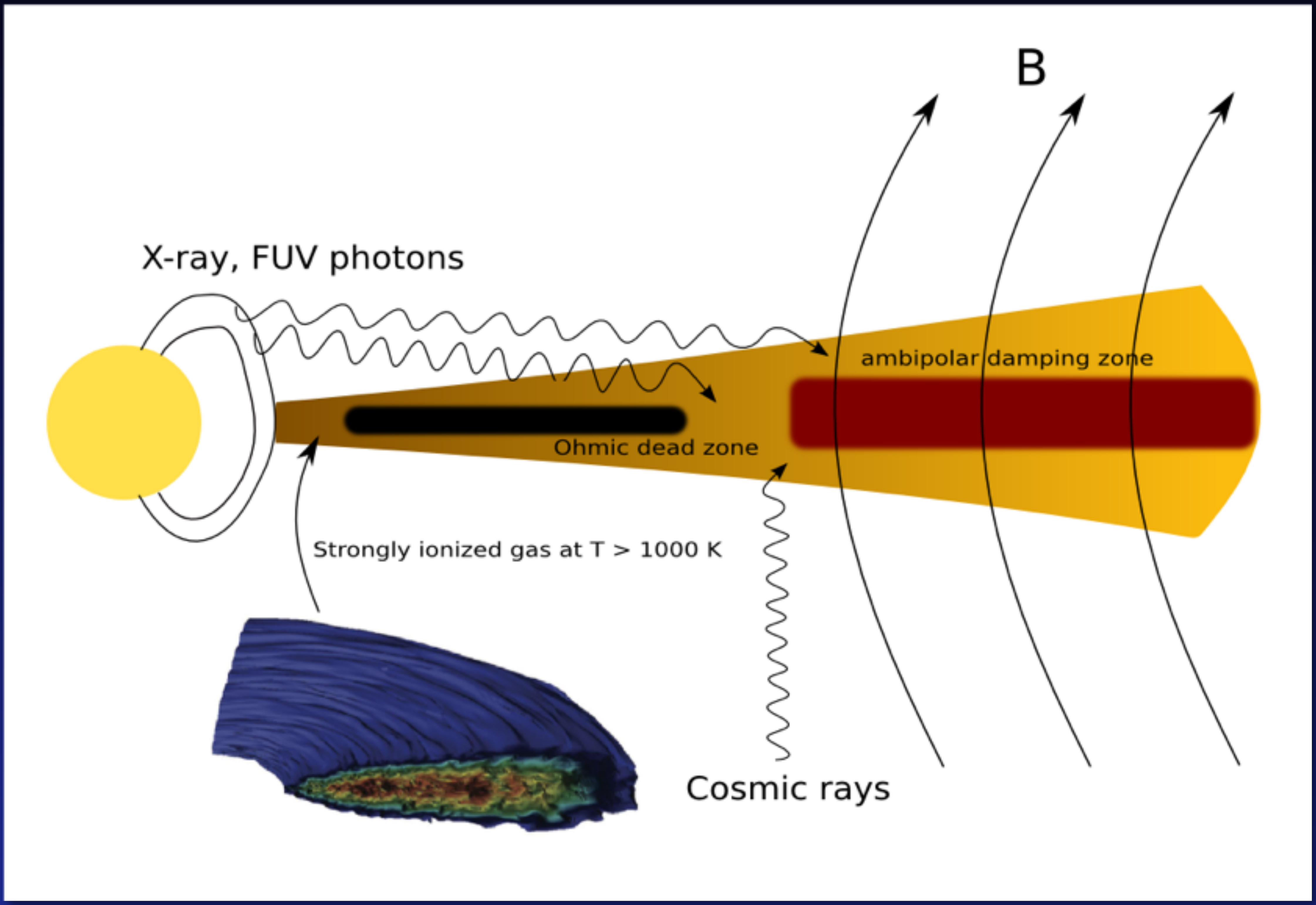
Hawley (2000)

…and is important for planet formation

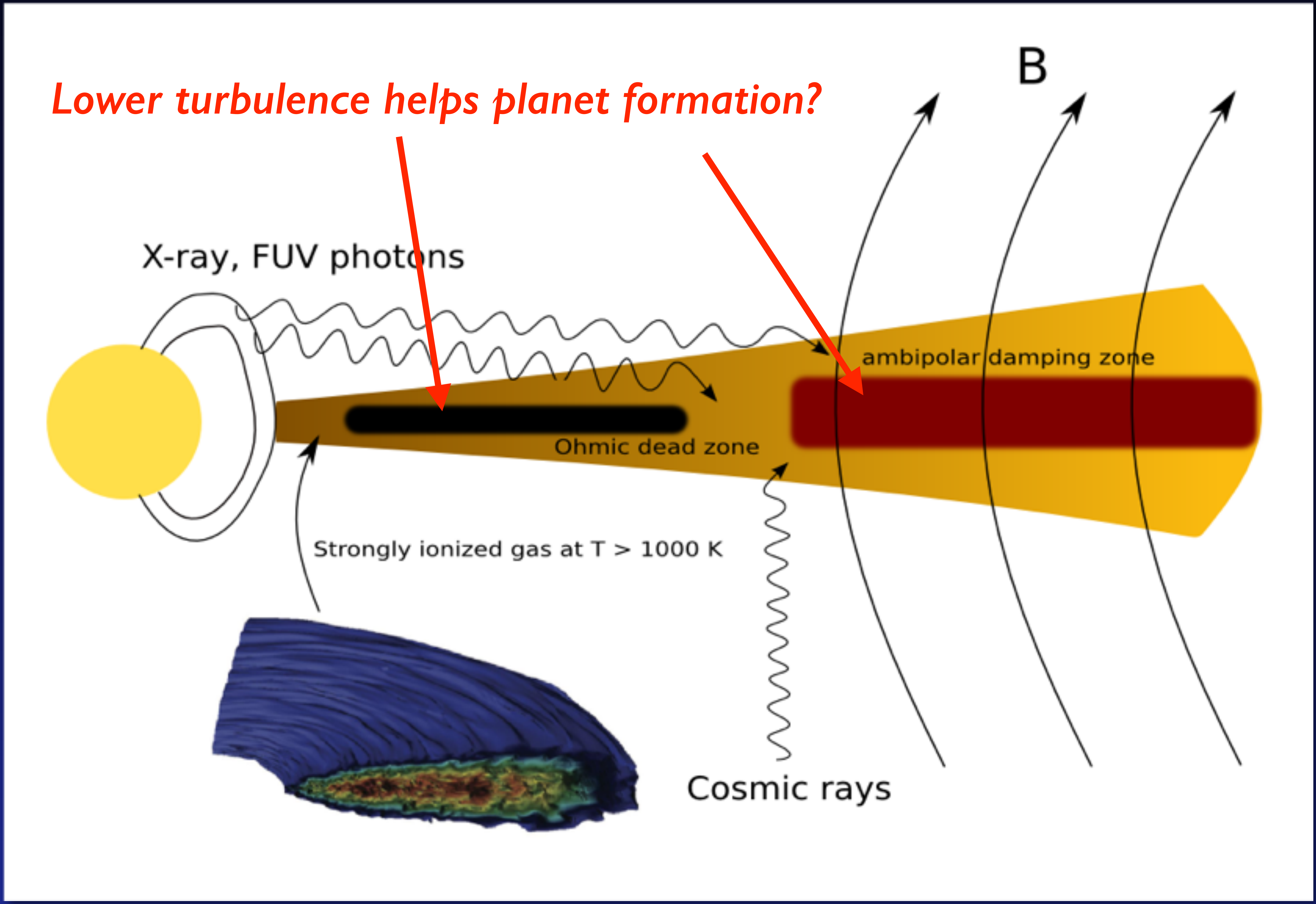


Fromang & Papaloizou (2006)

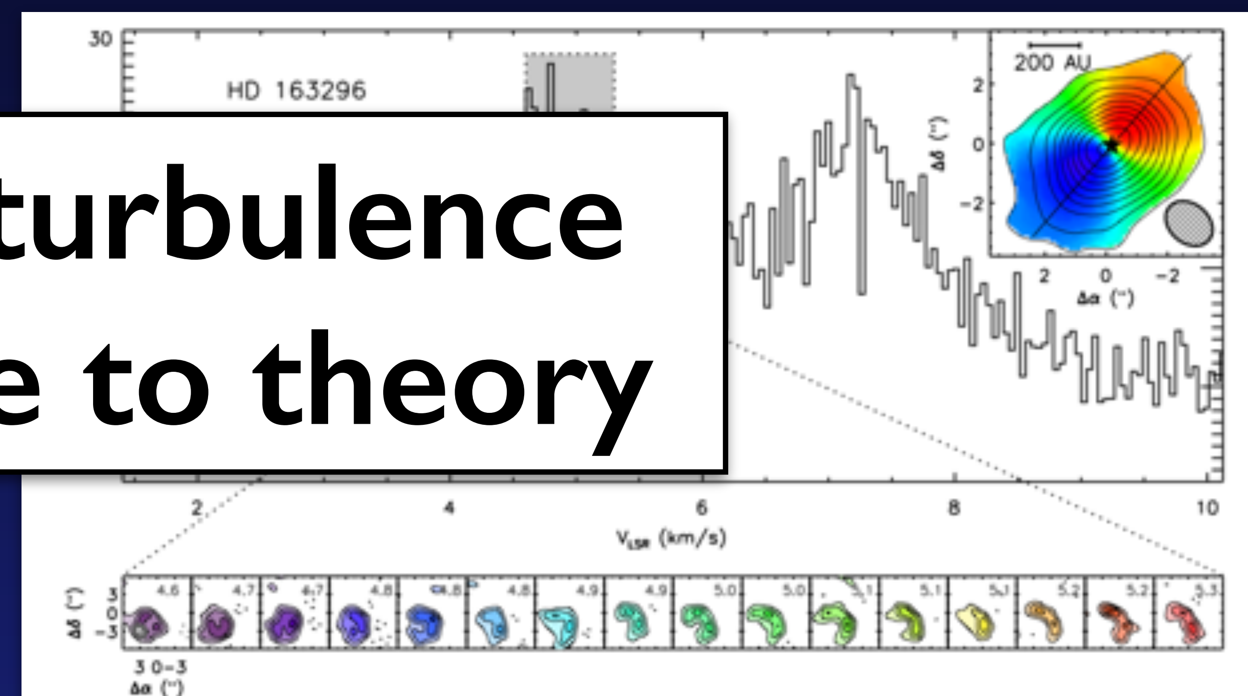
Low ionization levels enhance non-ideal magnetohydrodynamic (MHD) effects



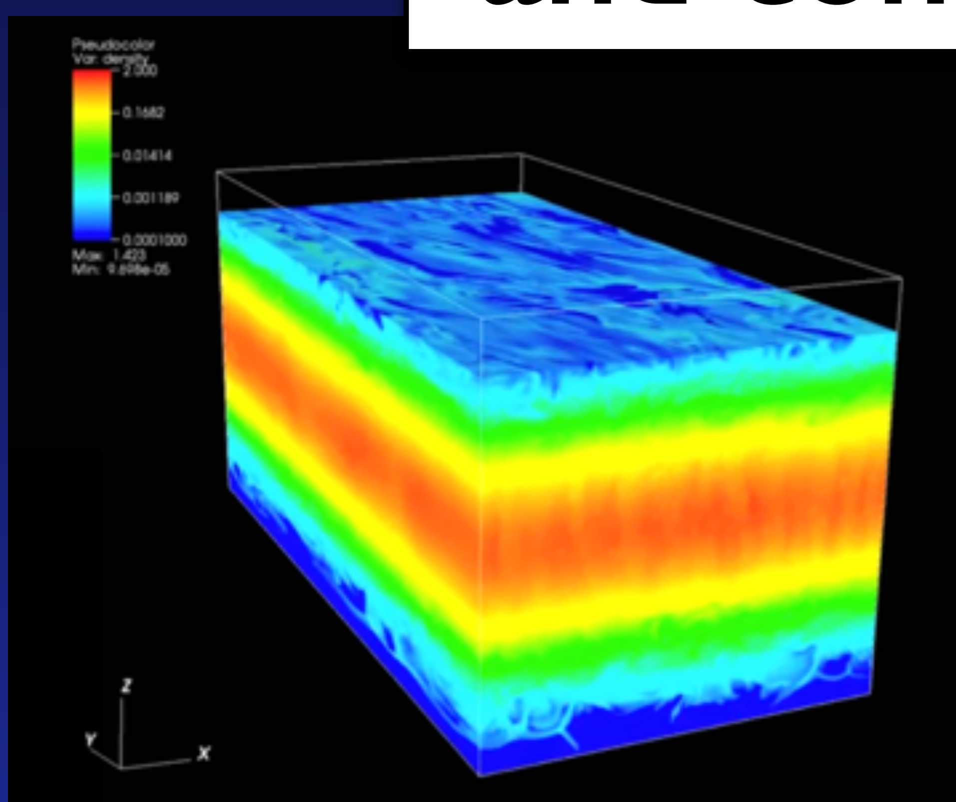
Planet formation may prefer locations of low turbulence, such as these *dead/damping zones*

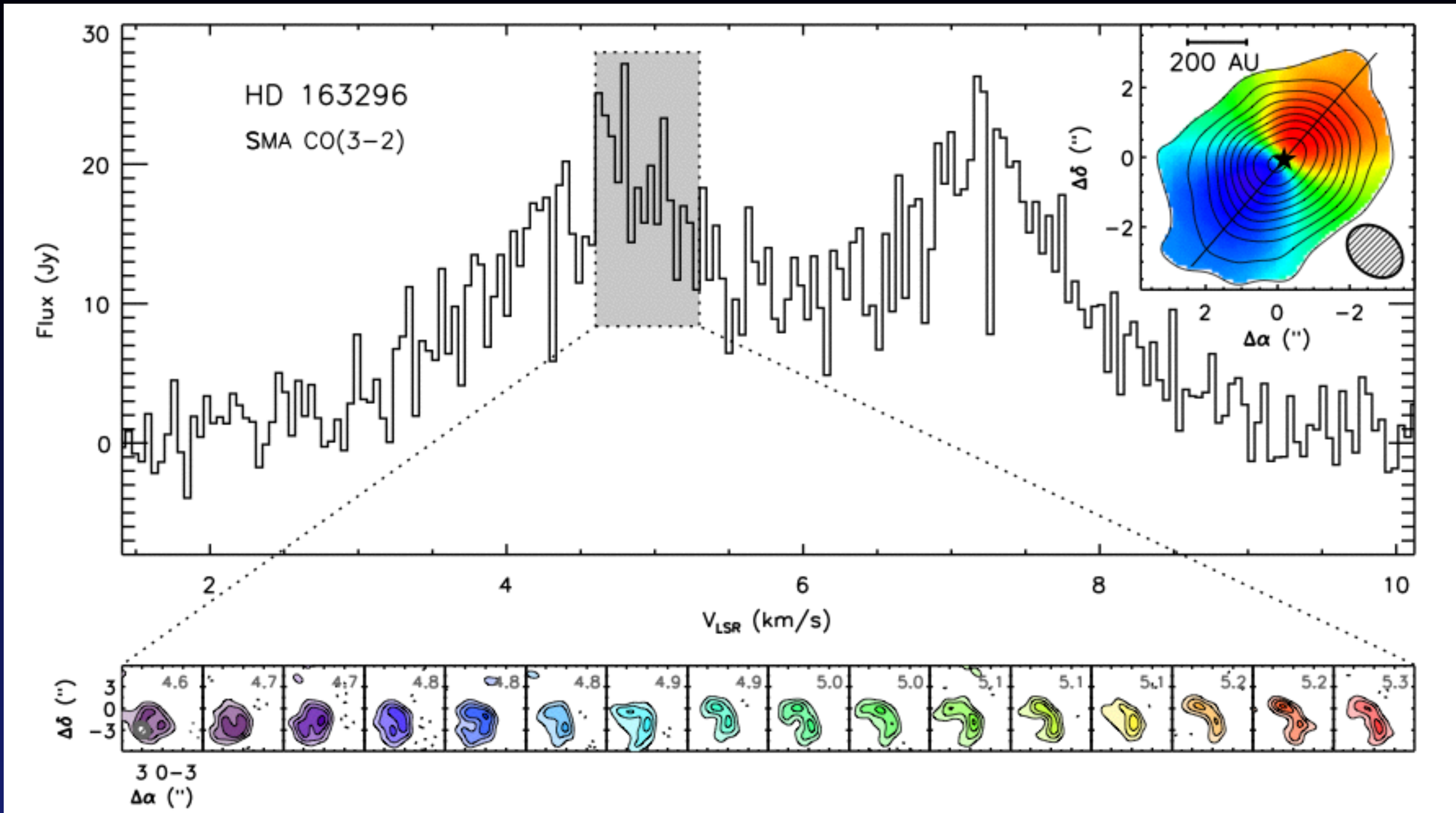


Constraining theory with observations



“Observe” turbulence and compare to theory

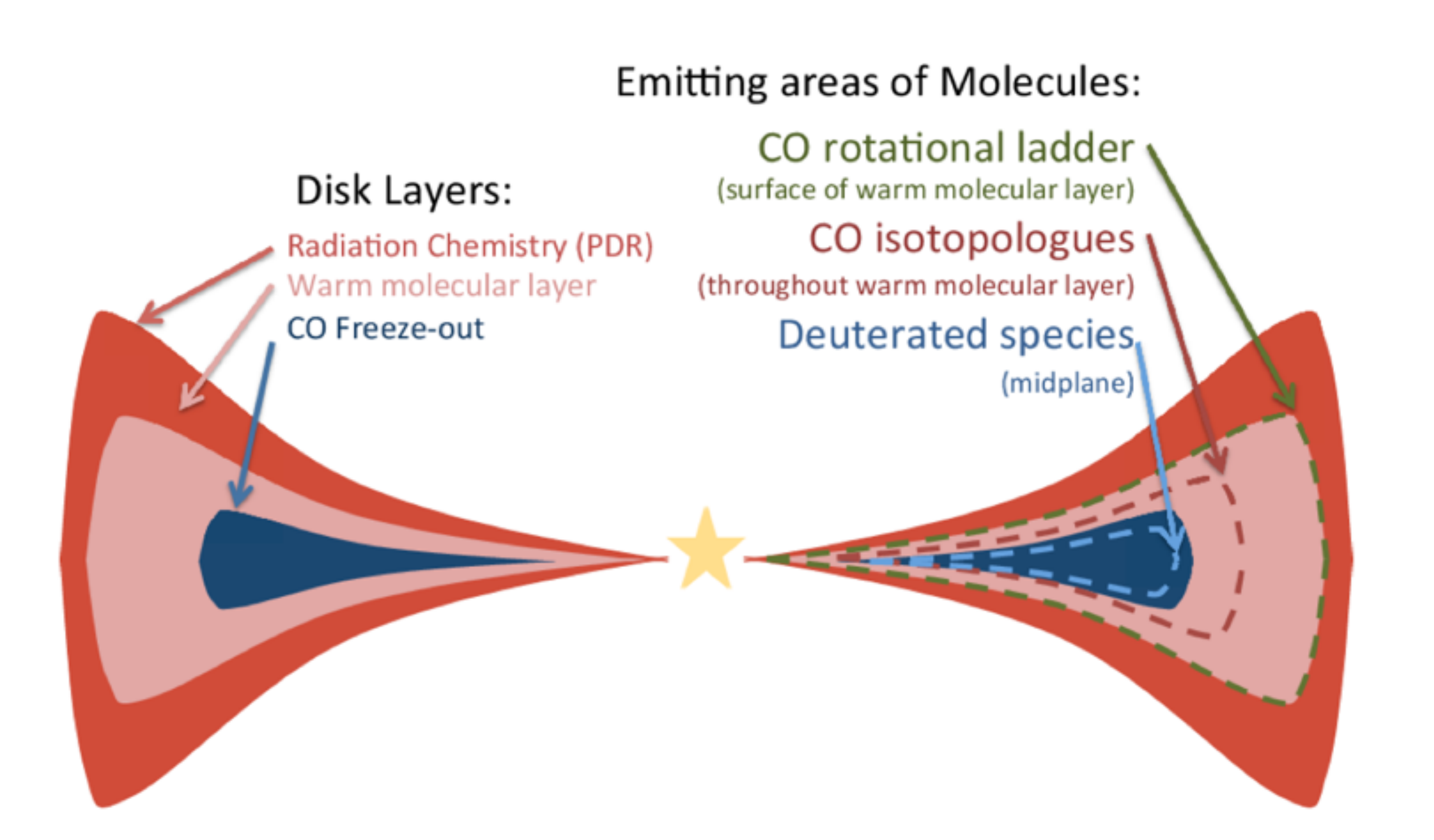




Hughes et al. (2011)

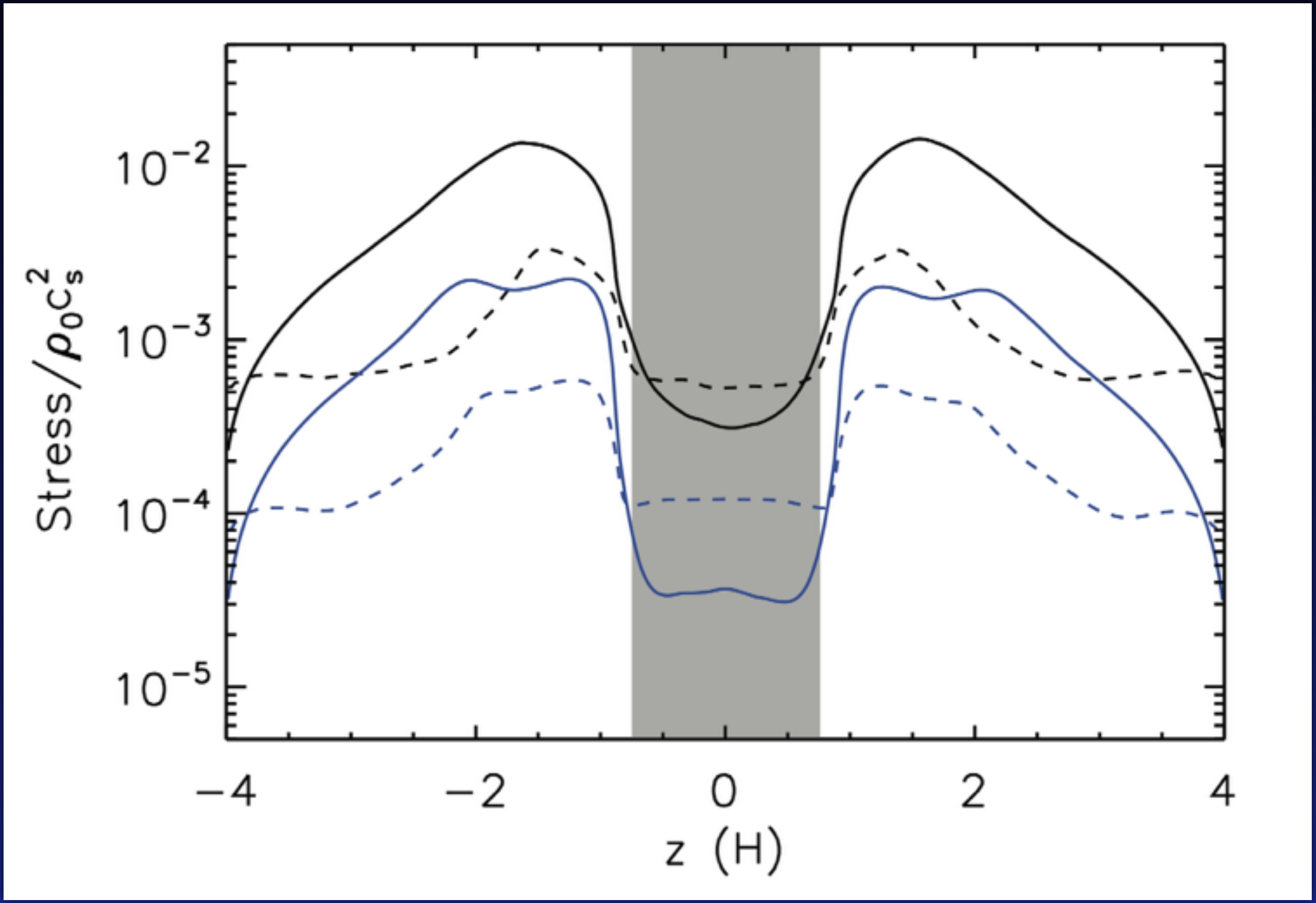
Fitting a turbulent broadening to the line gives a typical turbulent velocity of ~ 0.4 c_s

We can examine vertical structure of turbulence using different lines that are only observable at high sensitivity



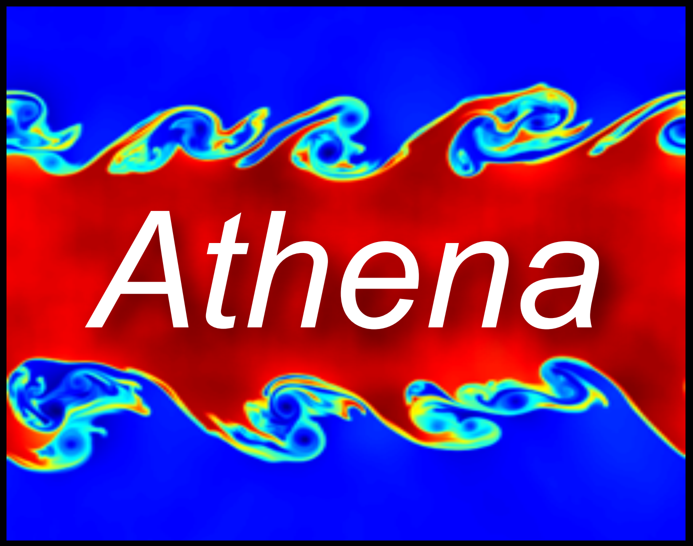
Meredith Hughes

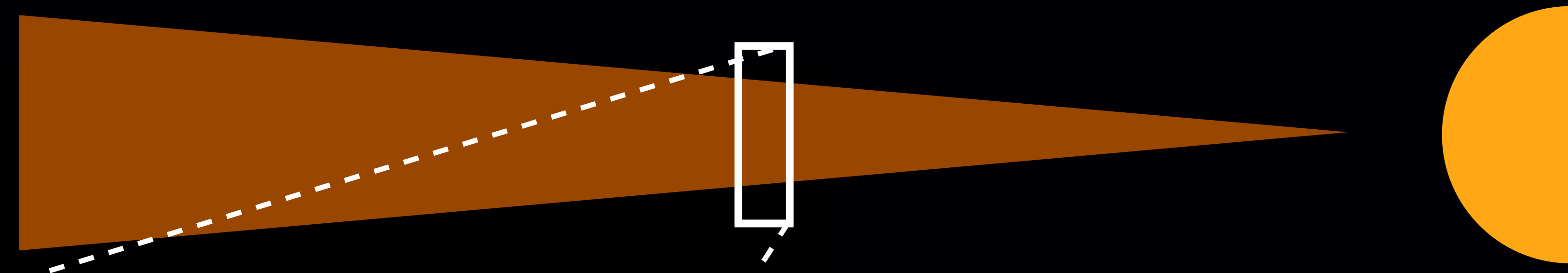
Will we *see* the existence of the dead zones or ambipolar damping zones?

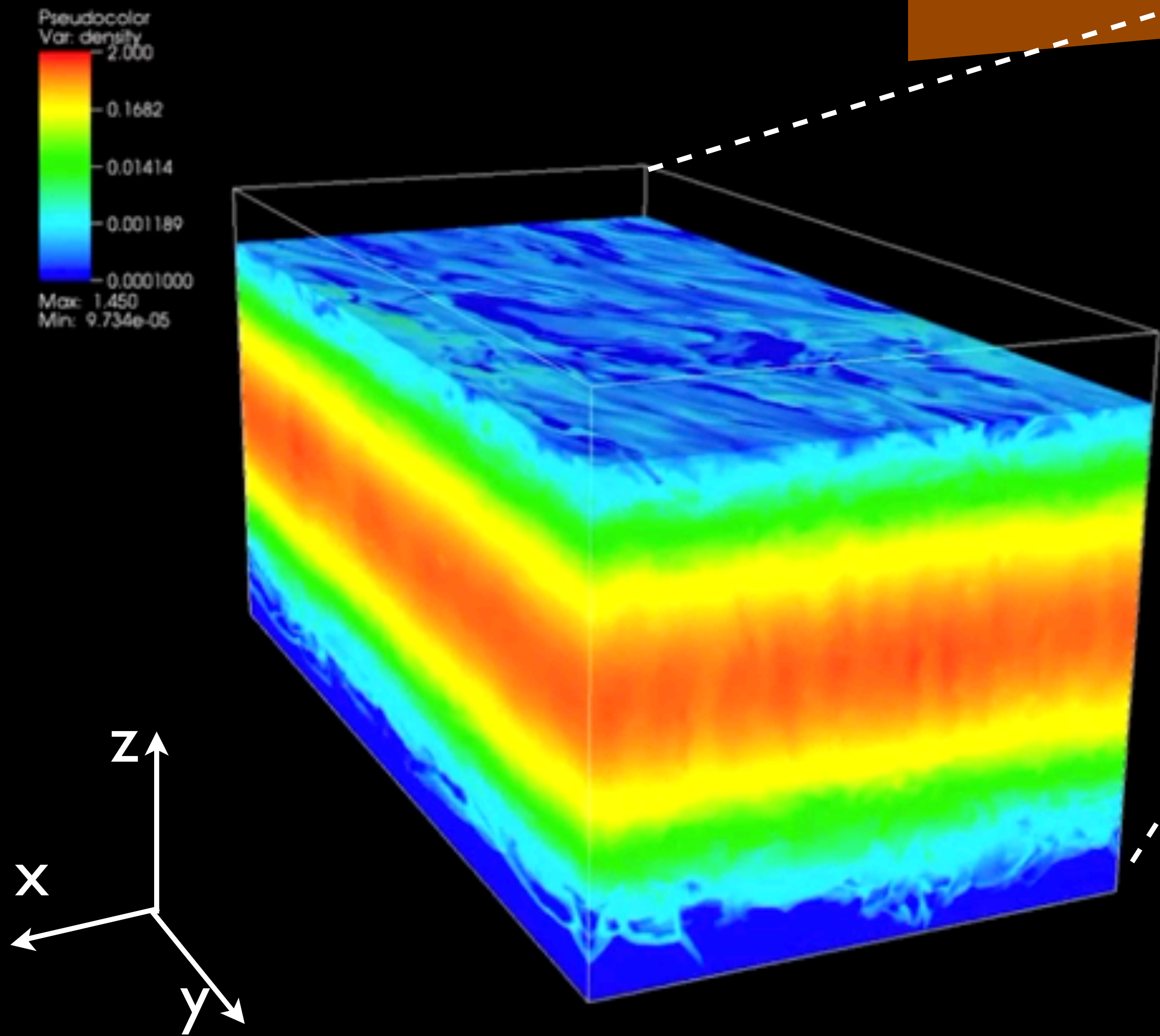


Simon et al. 2013b (see also Bai & Stone 2011)

Local simulations: examine small co-rotating disk patch

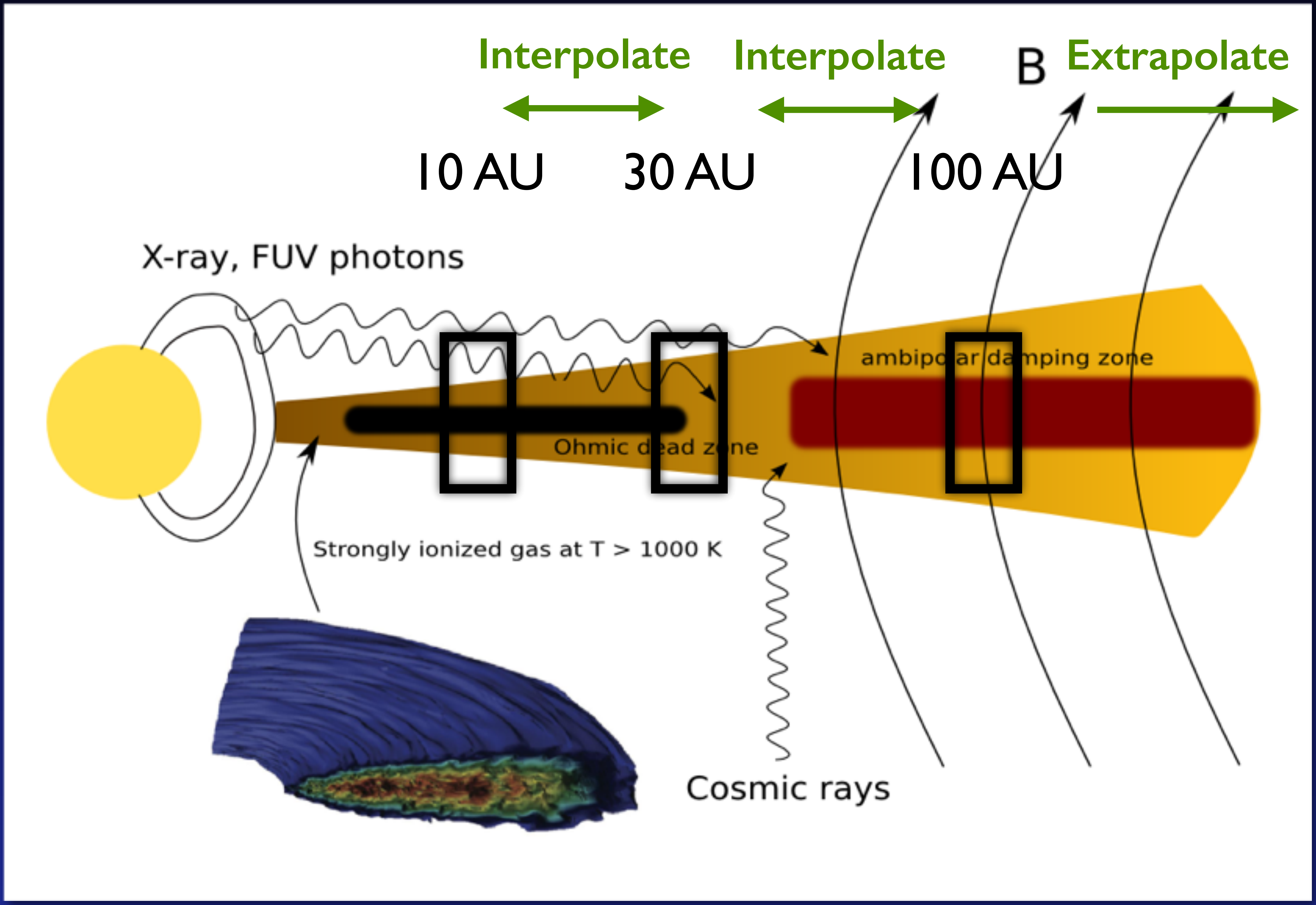




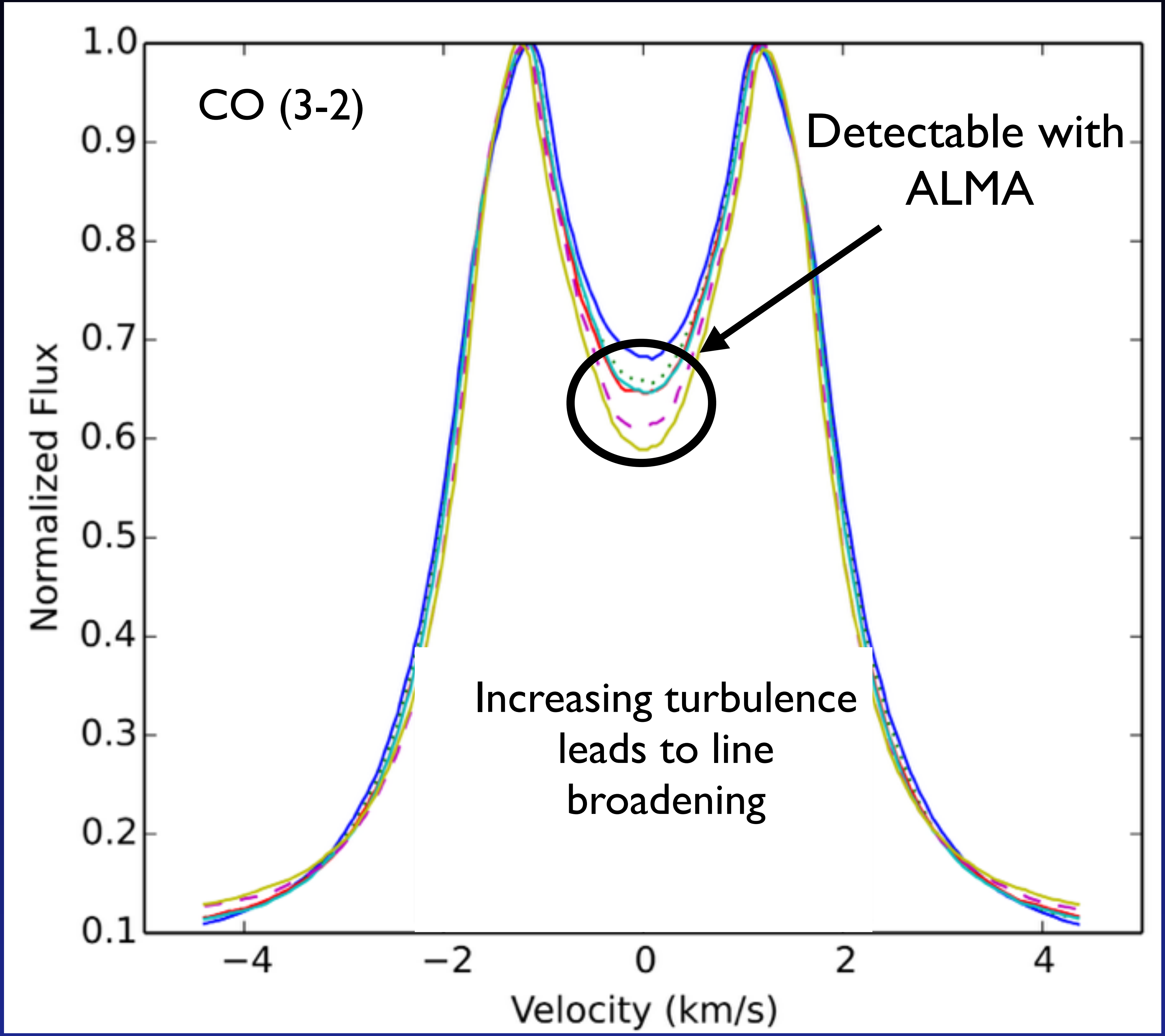


- Assume Cartesian geometry
- Add appropriate source terms
- Solve equations of MHD
- Shearing periodic boundaries
- Valid if H/R << 1
- Assume gas is isothermal

Center local simulations at several radii

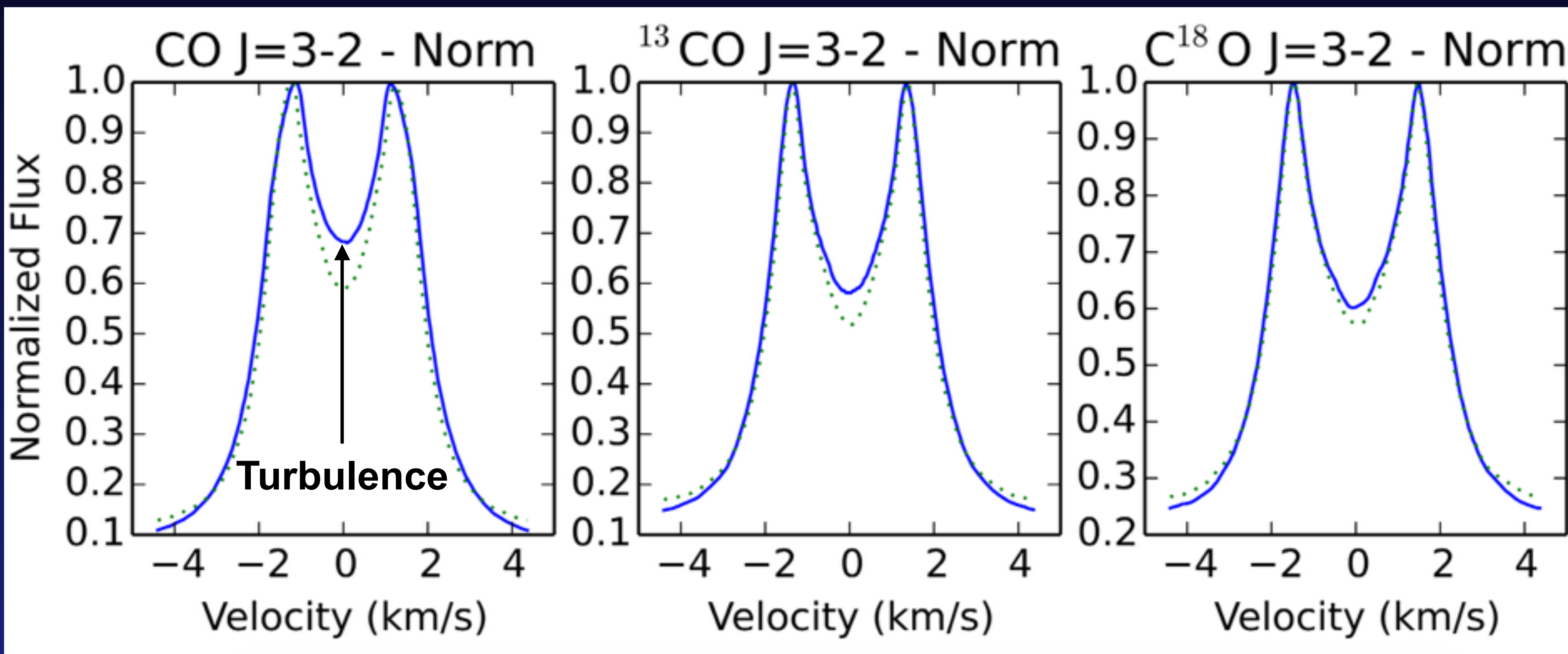


Put it all together!



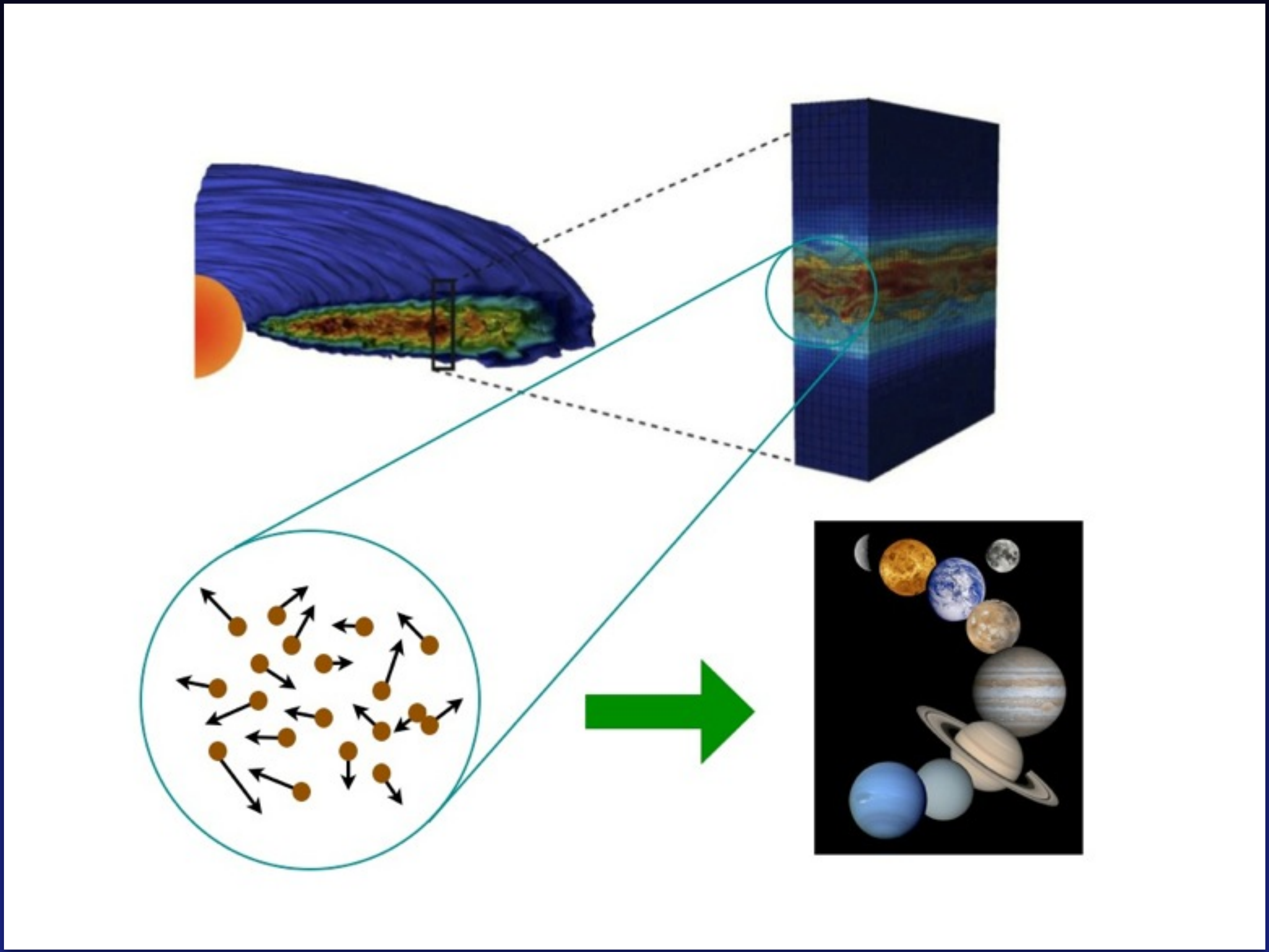
Simon et al. (2015)

Other observational diagnostics

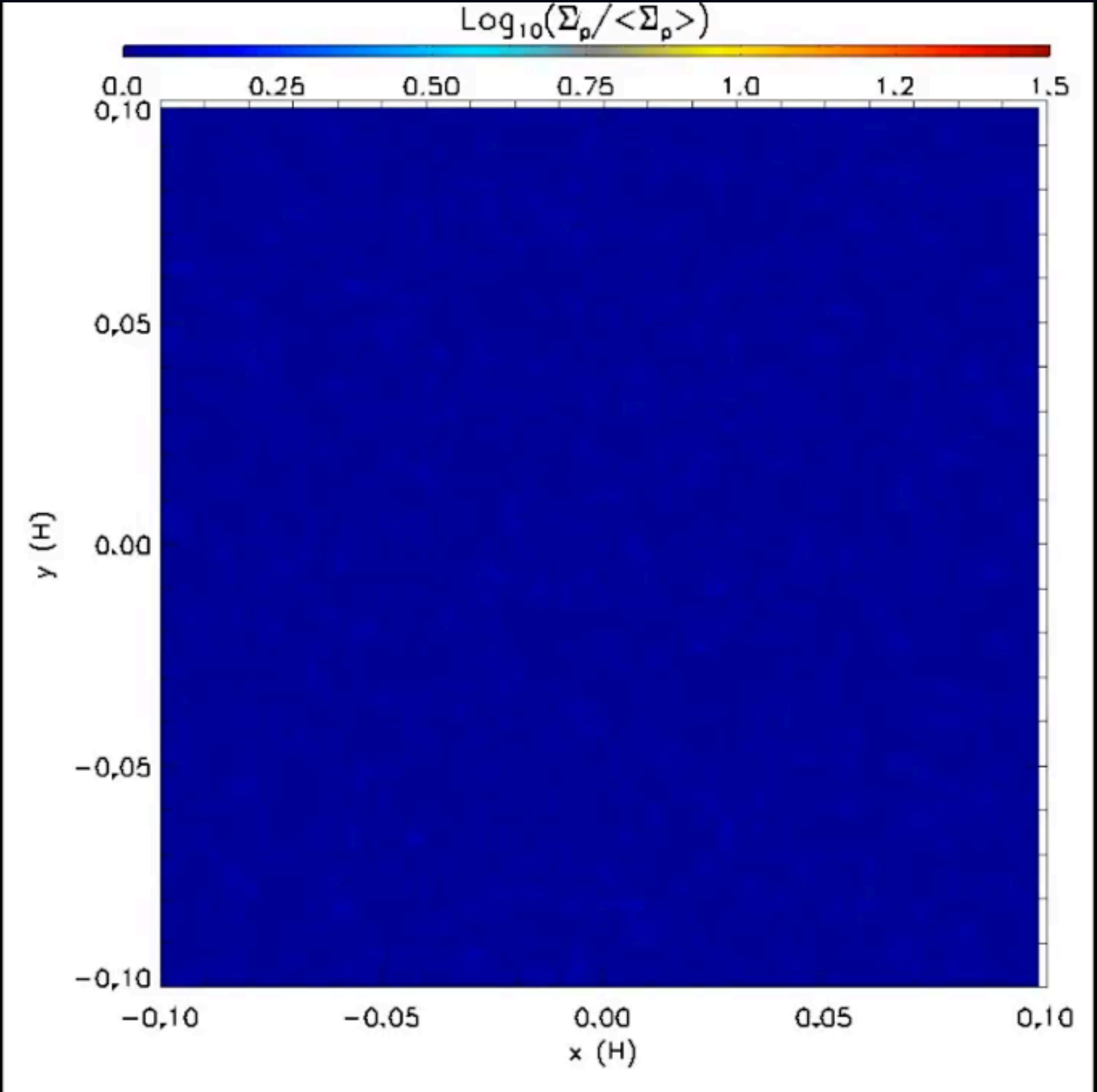


Simon et al. (2015)

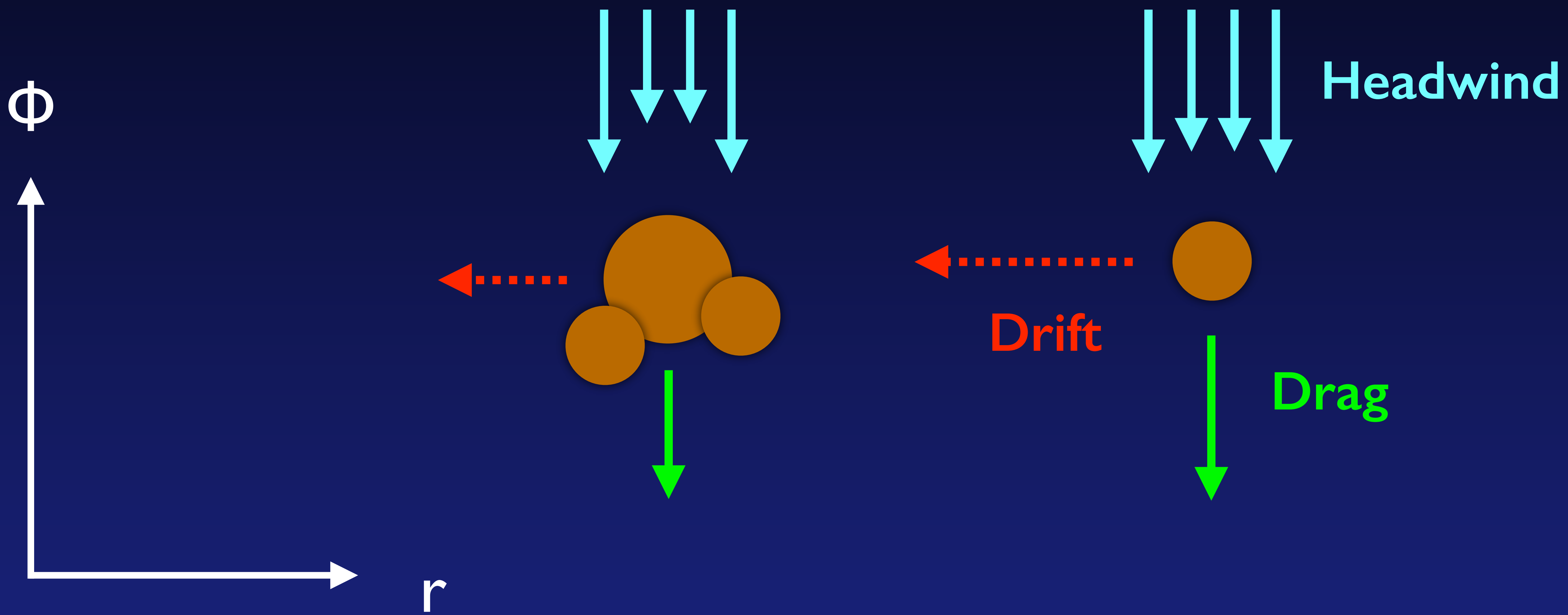
Planet formation processes



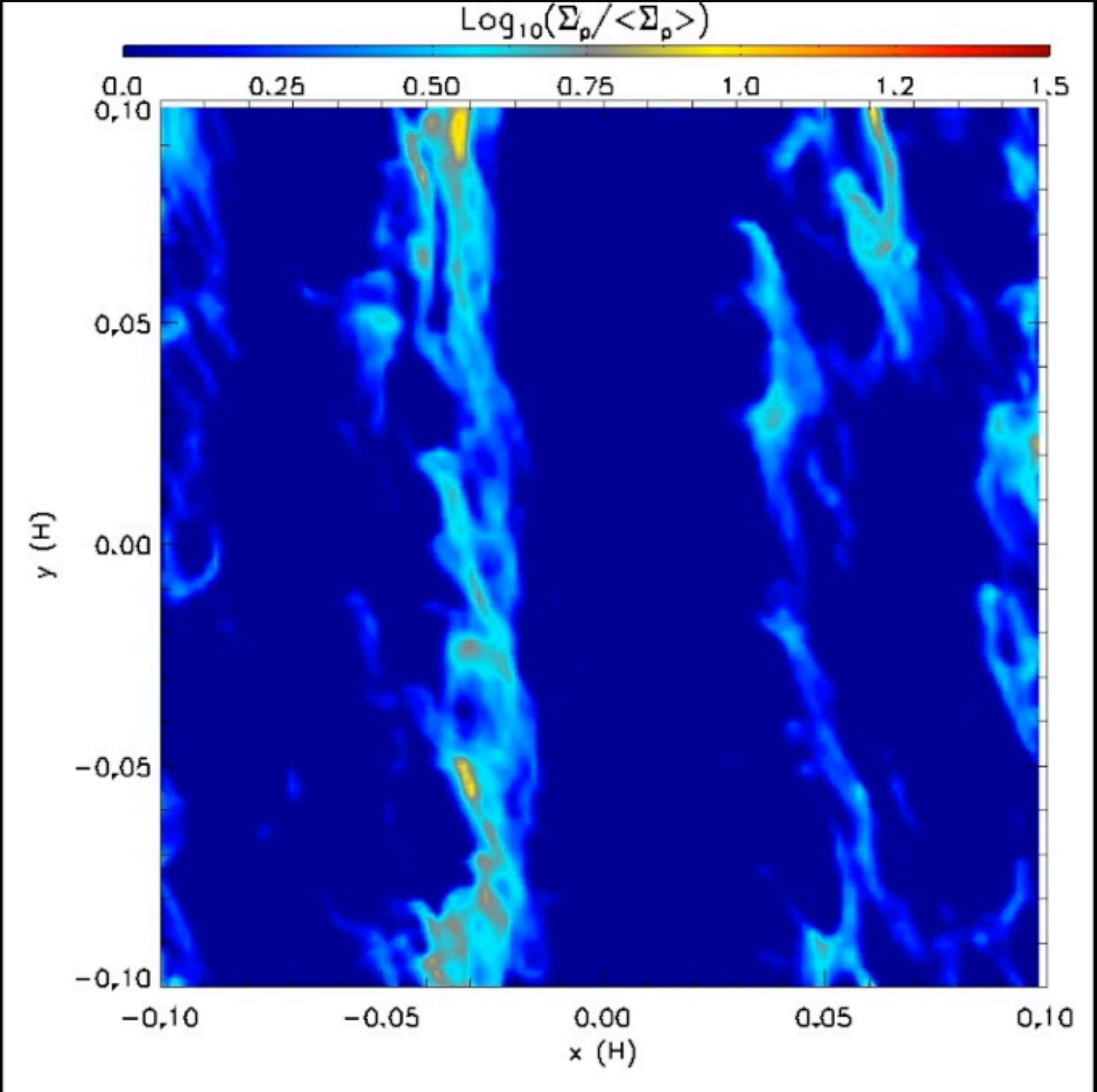
The streaming instability



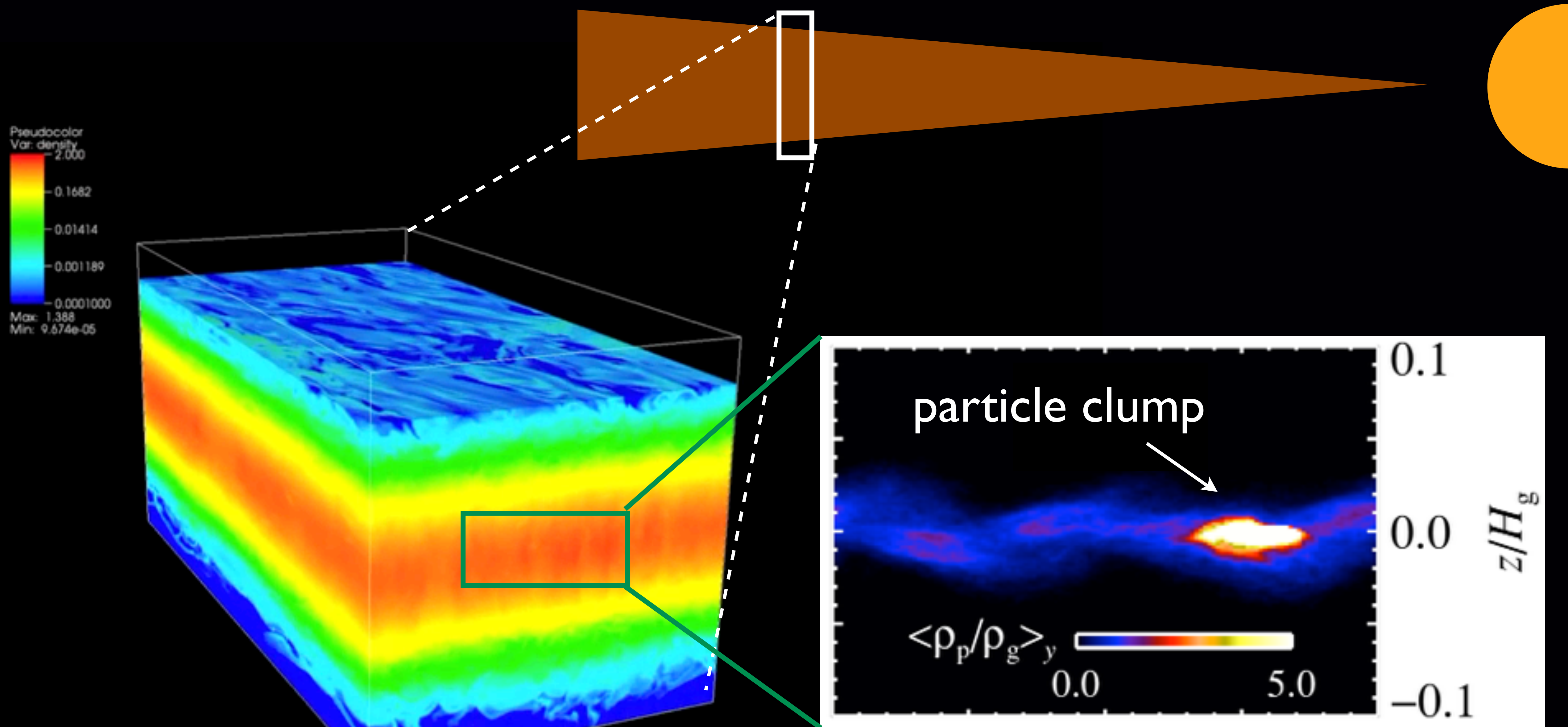
What's going on here?



The streaming instability



Next: run planetesimal formation simulations *including* the effects of turbulence, as constrained by a combination of theory and observations



Johansen, Youdin, Low (2009)

Conclusions

1. Differences in turbulent structure of disks should be observable with ALMA

2. If MRI turbulence is present in these disks, we should observe a strong increase in turbulent velocity away from the mid-plane.

3. The streaming instability is a robust mechanism by which to produce planetesimals

4. The inclusion of turbulence in streaming instability simulations will be essential for understanding how planetesimals form.

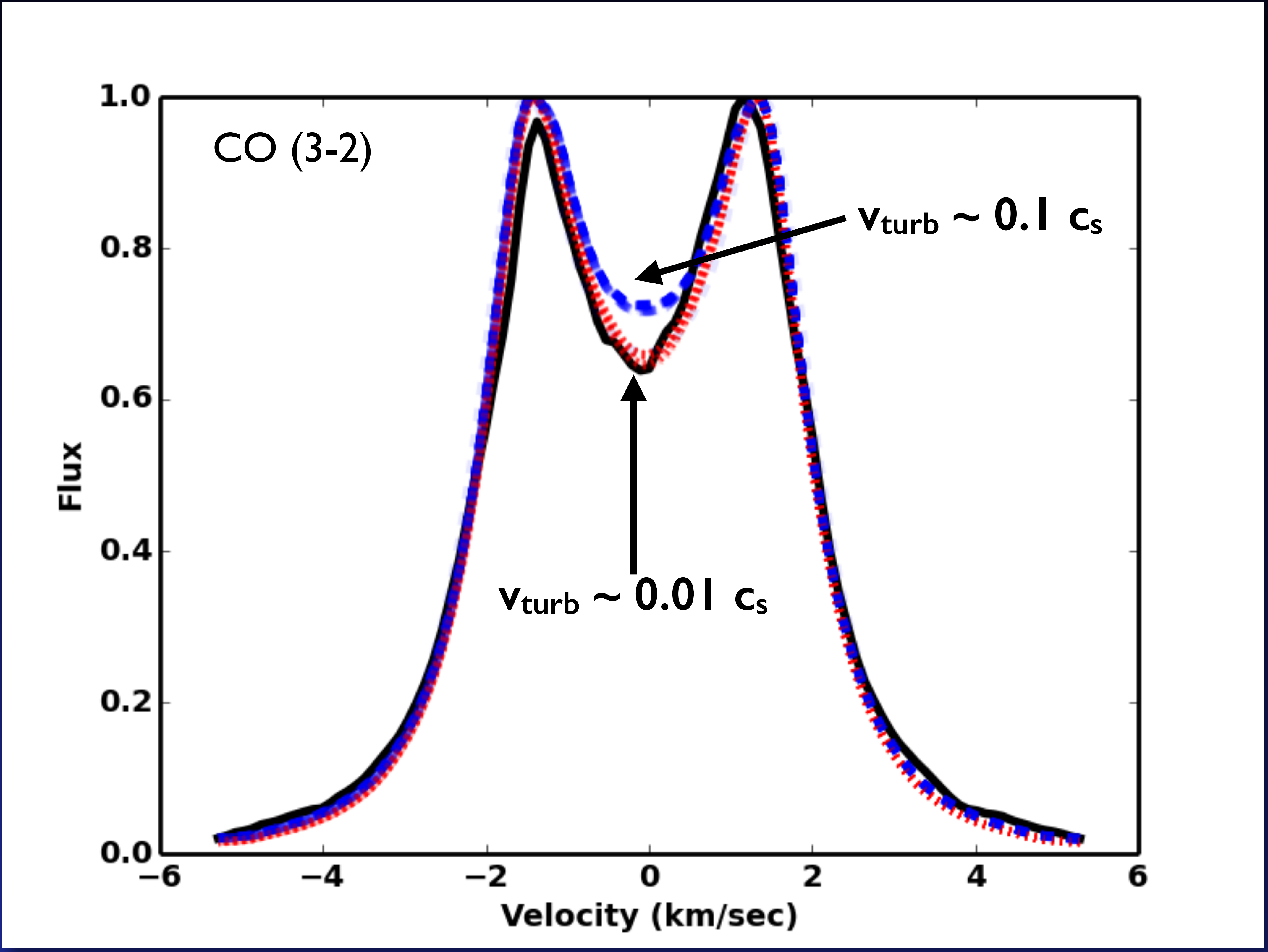
Extra Slides

So, what do ALMA observations tell us?

Our group (led by Kevin Flaherty) is finding turbulence consistent with *weak or no turbulence!*

For a system that is accreting at ~ 10^{-7} $M_{\odot}$/yr

Weak turbulence!

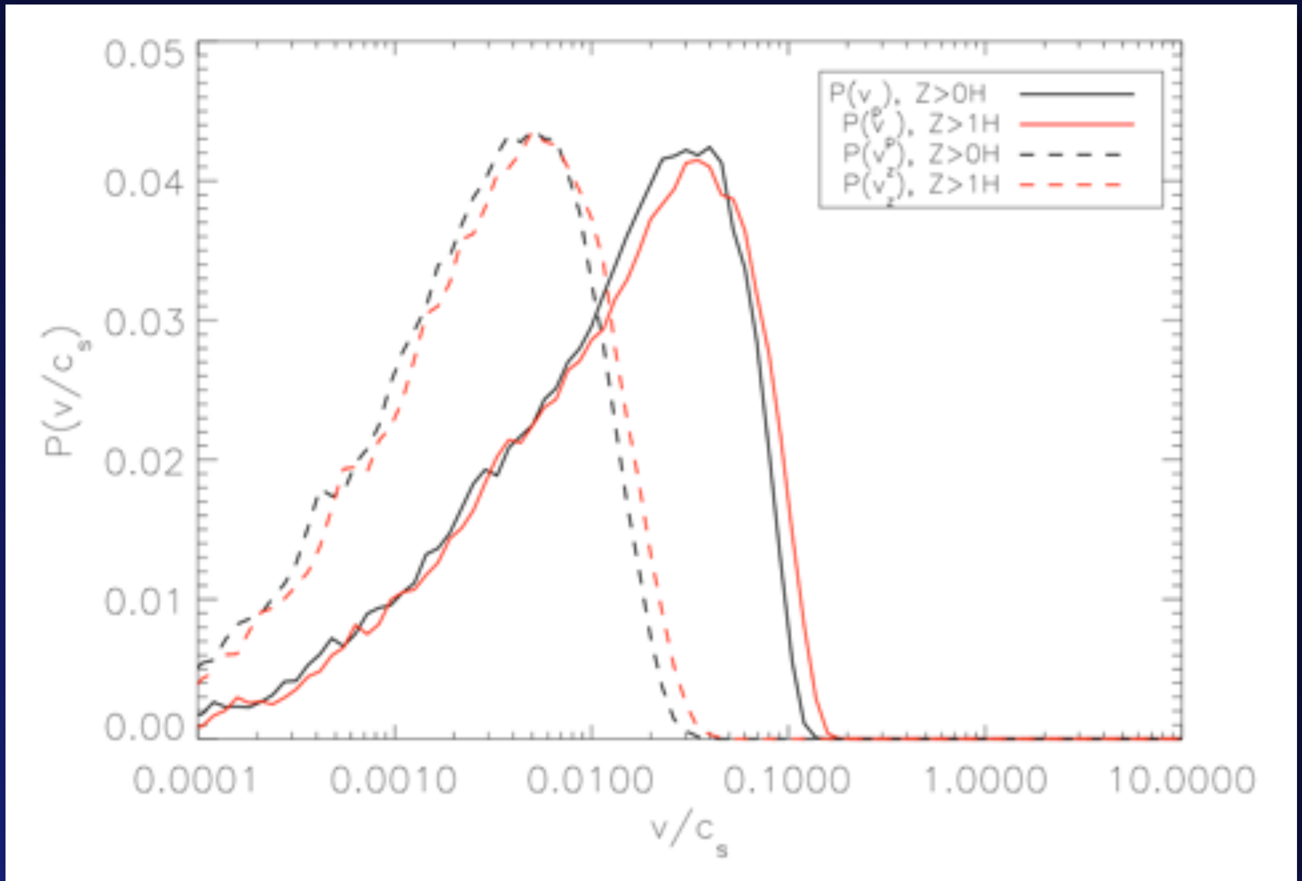


Flaherty … Simon et al. in prep

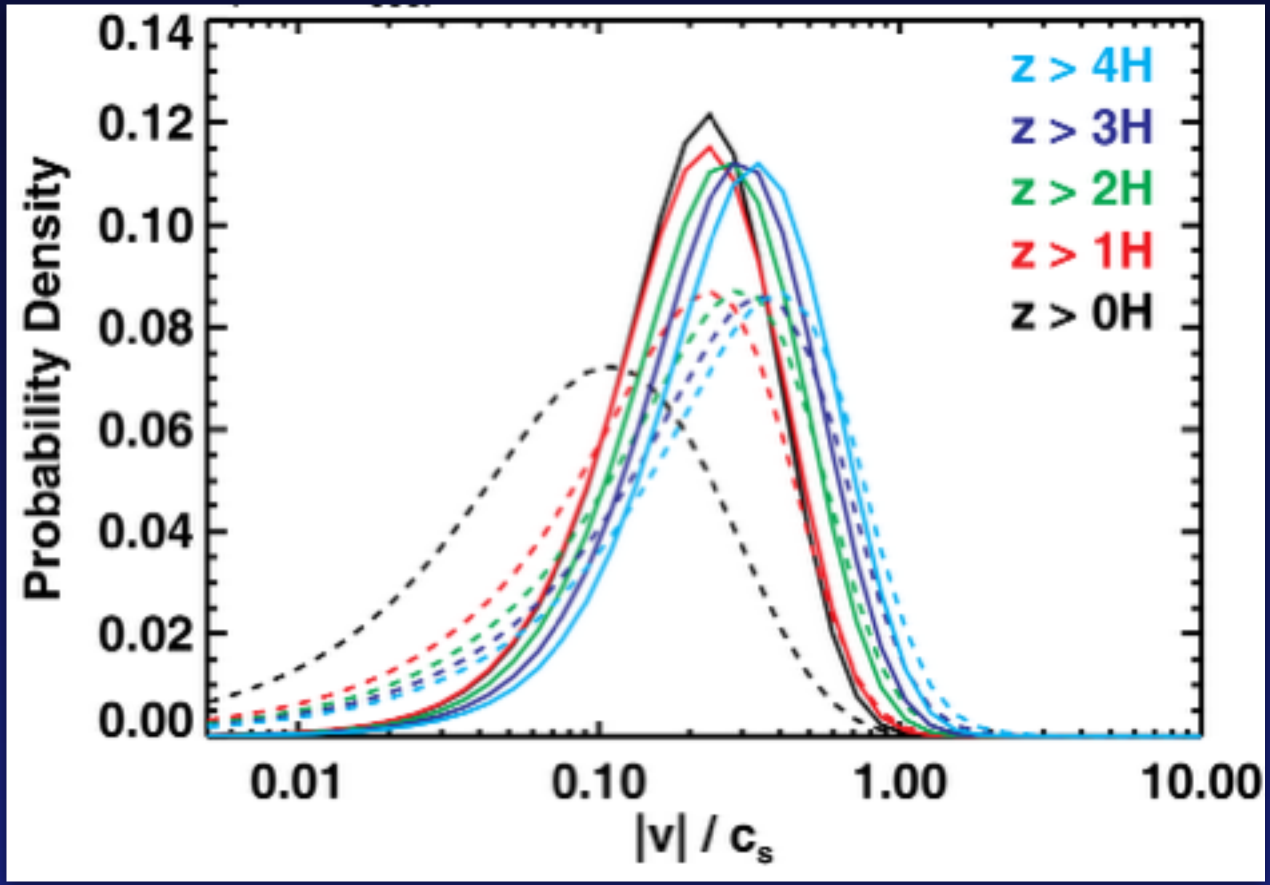
What does this mean??

Other accretion mechanisms

Self-gravity?



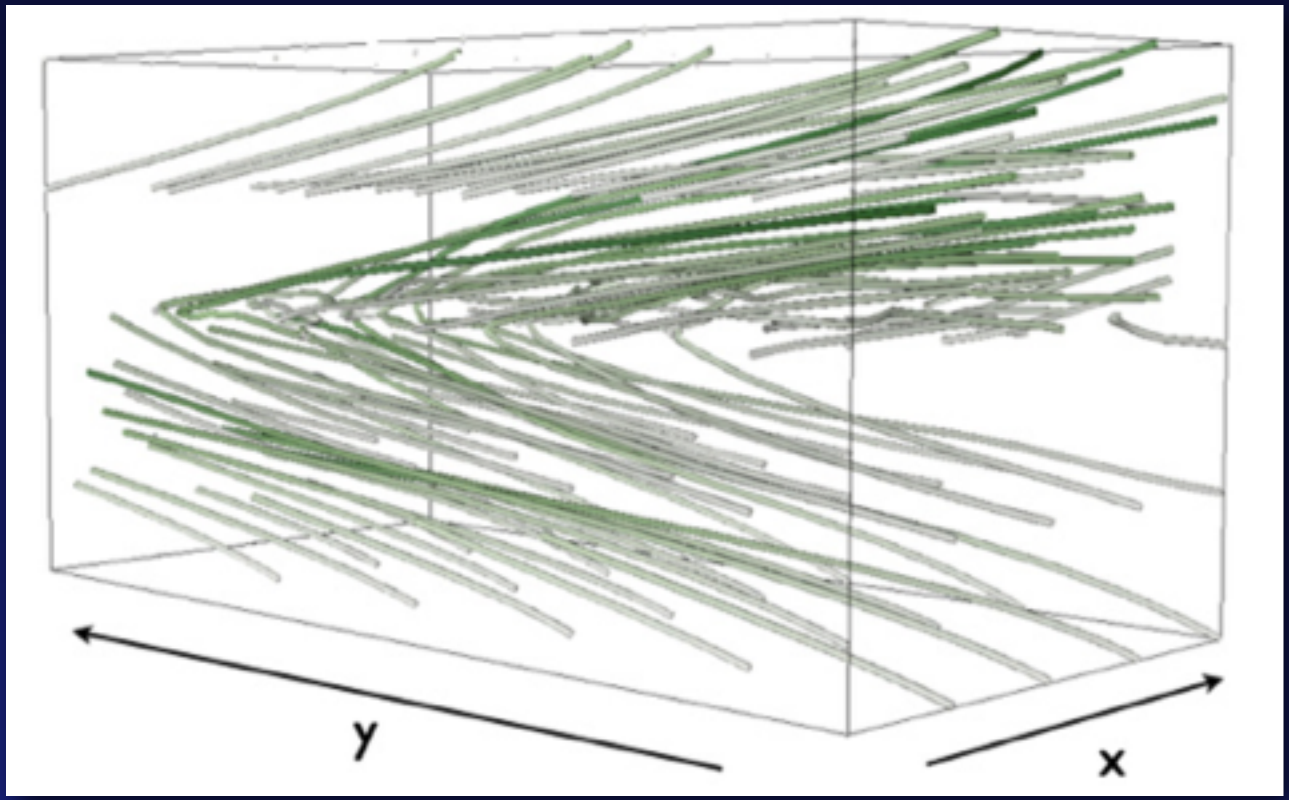
Forgan, Armitage, Simon (2012)



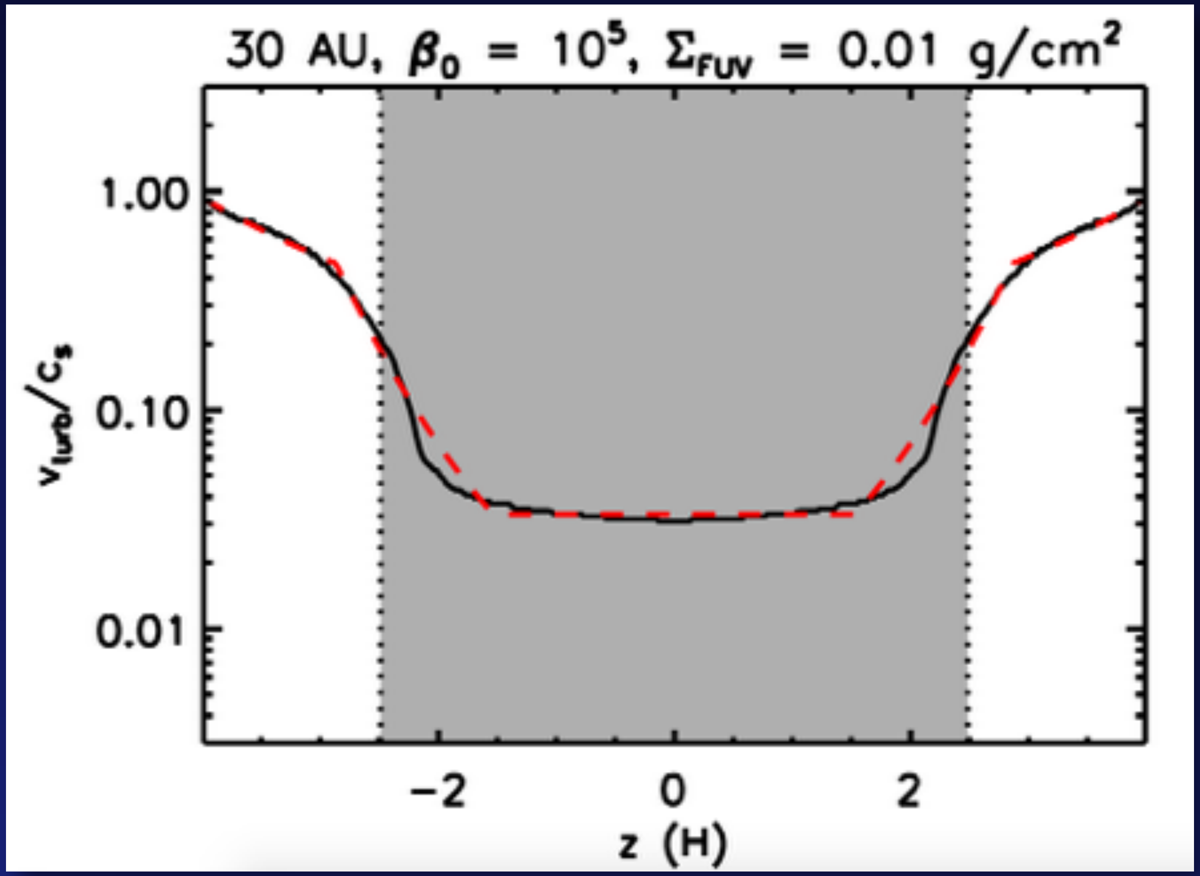
Shi & Chiang (2014)

Other accretion mechanisms

Wind?



Simon et al. (2013b)



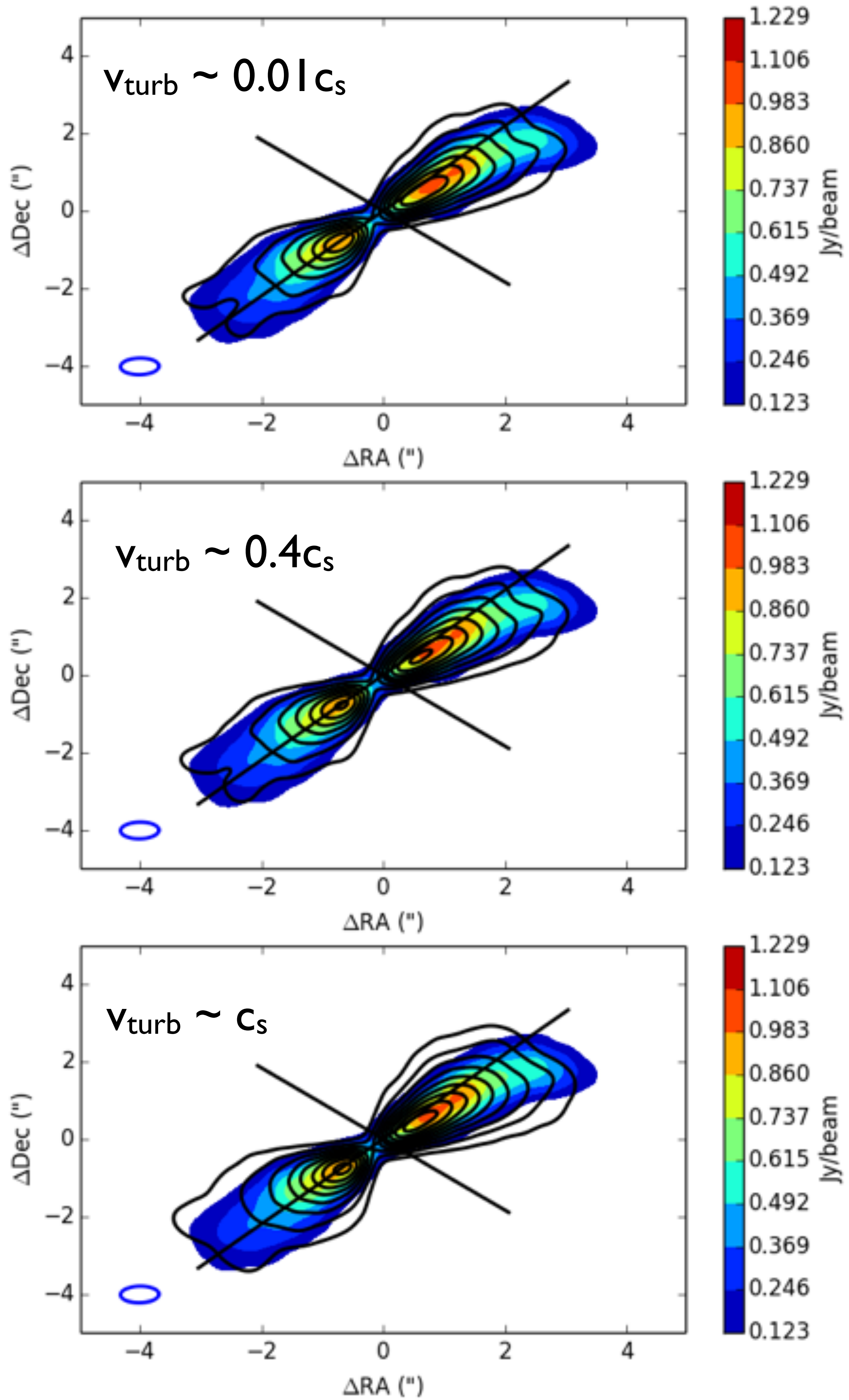
Simon et al. (2015)

Other accretion mechanisms

Some other form of turbulence?

Would expect non-negligible
turbulence at large disk heights

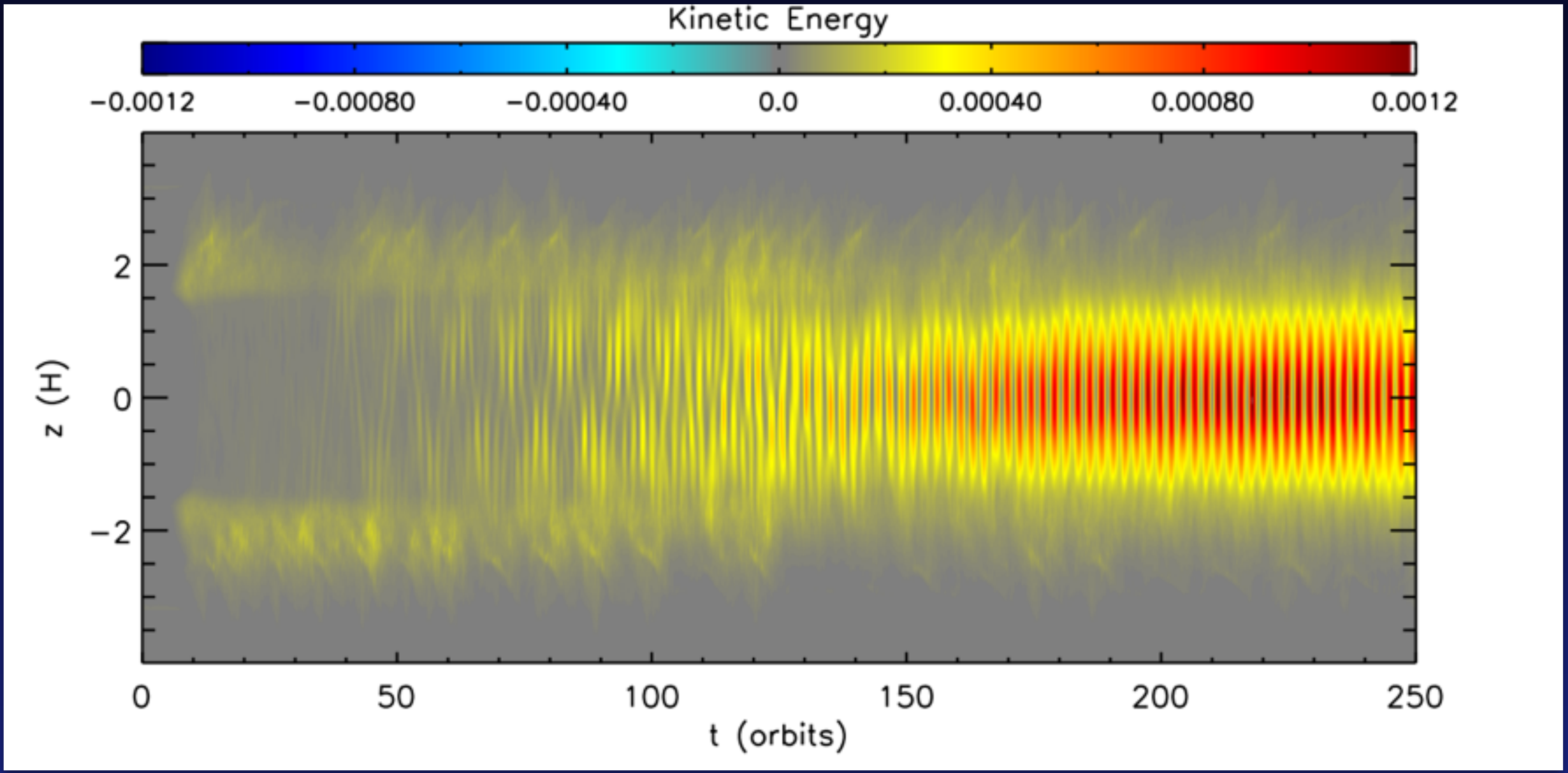
Maybe the outer disk just isn't accreting…



Study radial dependence for turbulence!

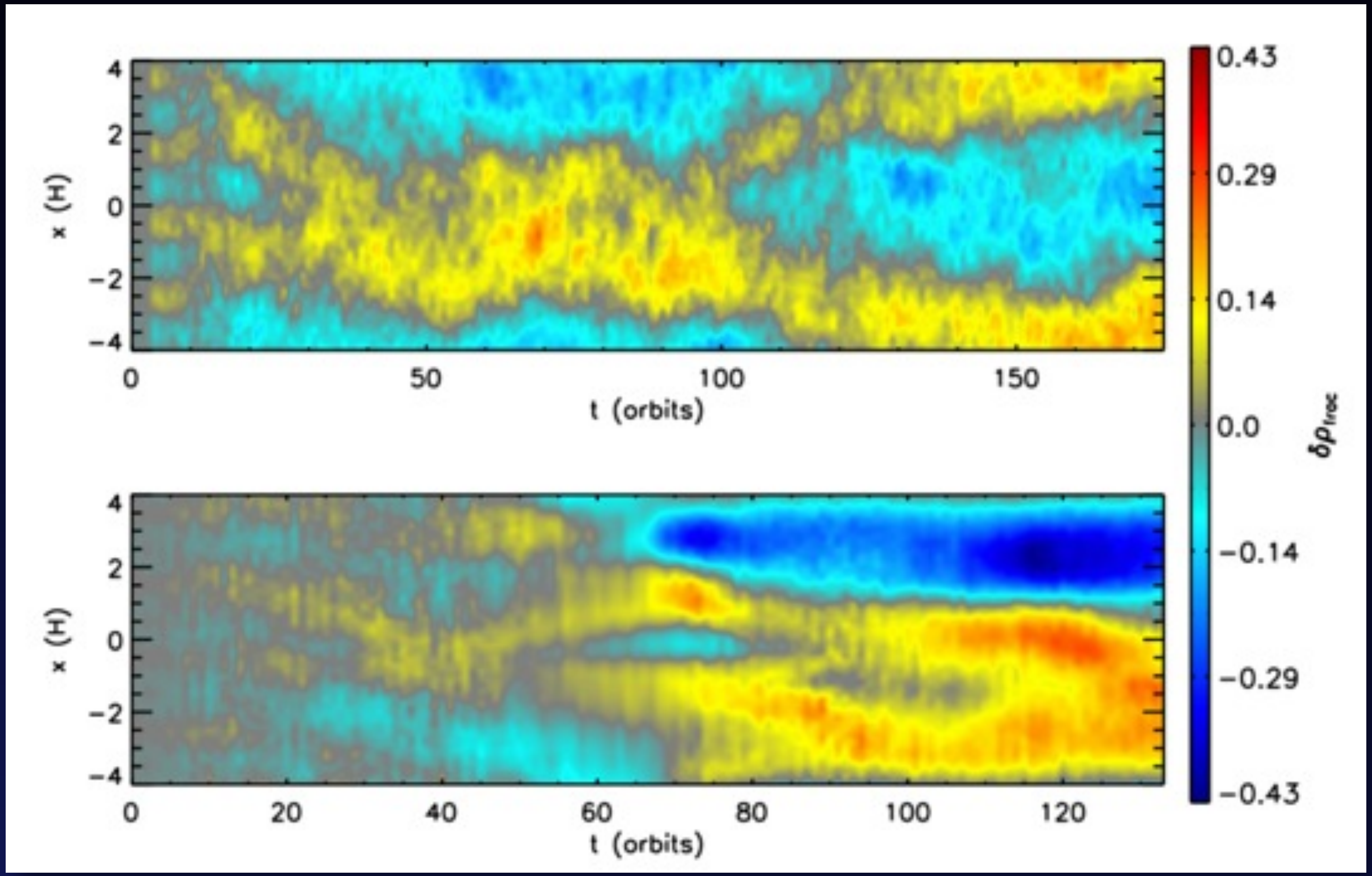
Kevin Flaherty

Must characterize the turbulence near the mid-plane



Gole, Simon, Armitage (in prep)

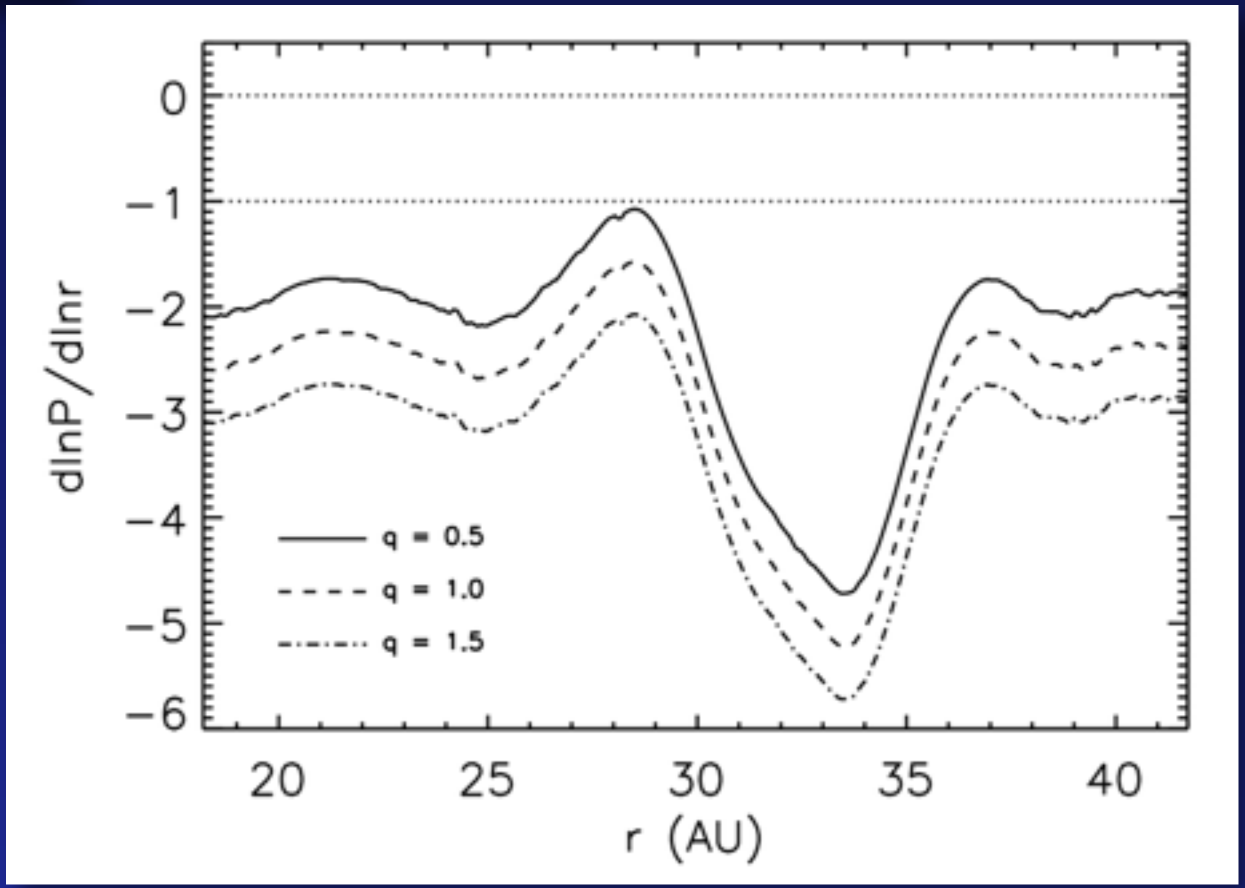
Particle trapping in zonal flows (no streaming inst.)



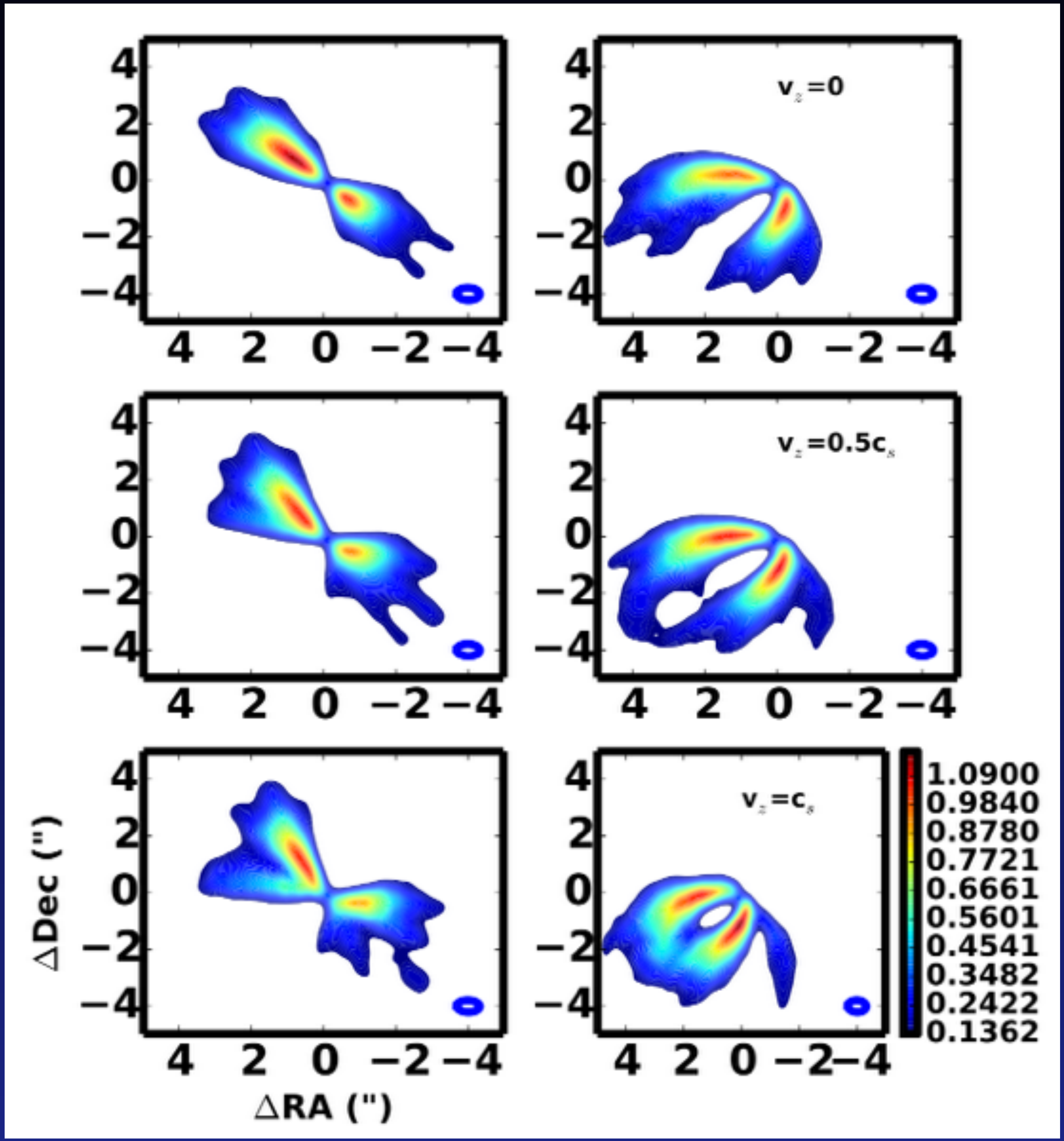
Simon & Armitage (2014)

Strong radial density/ pressure gradients in the outer disk regions

Despite their strength, these "pressure bumps" are not likely to trap small particles.

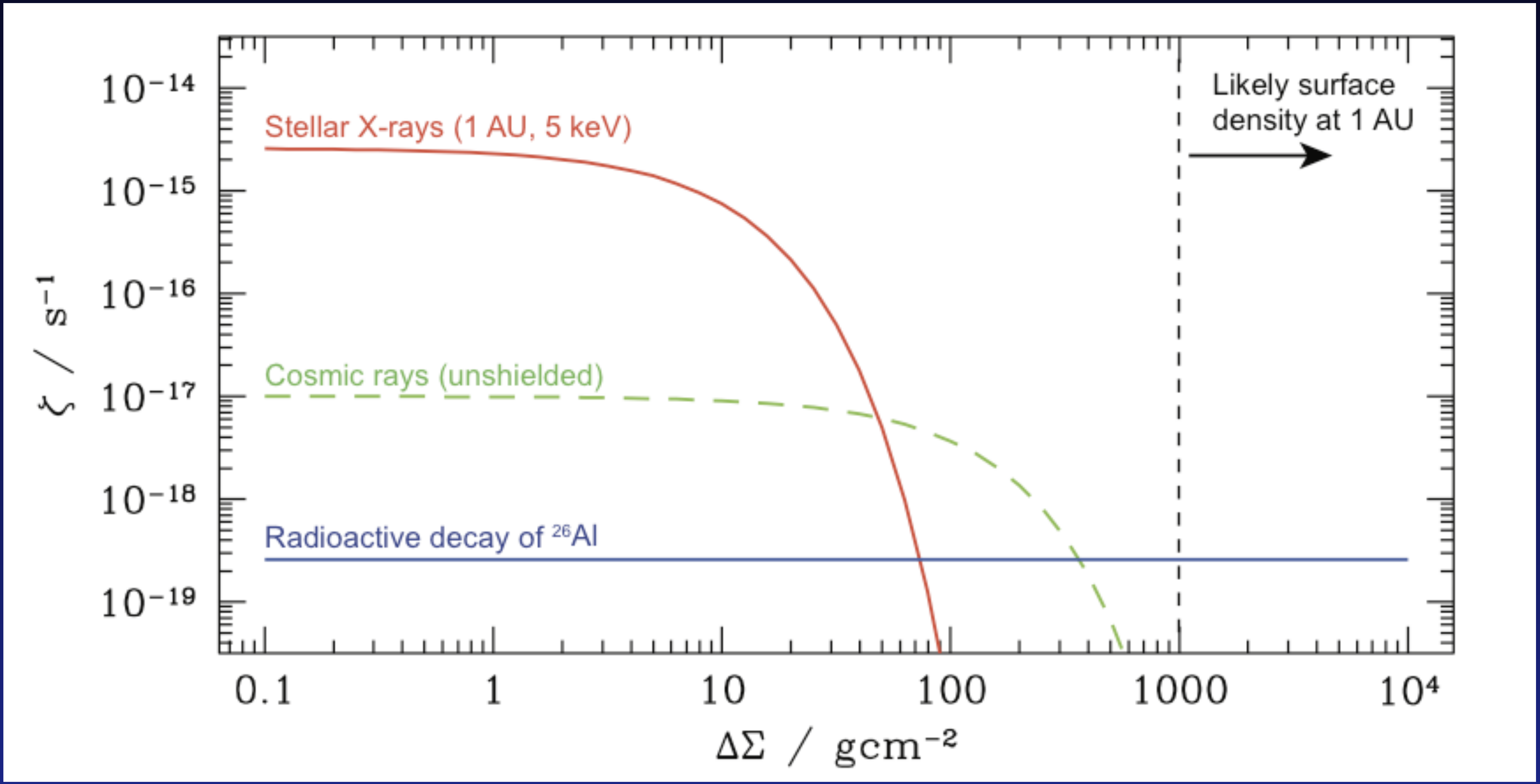


Simon & Armitage (2014)



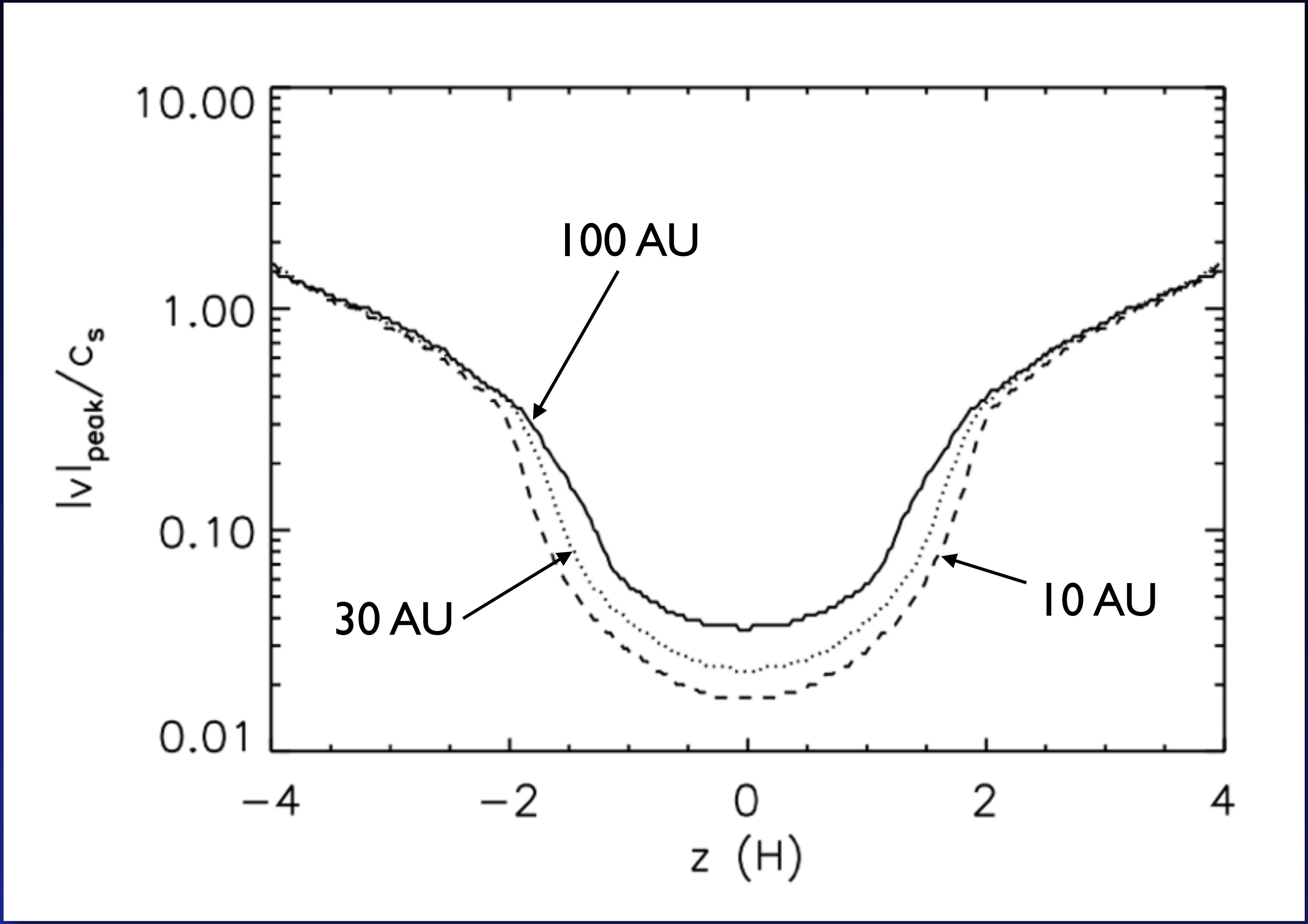
Flaherty et al. in prep

We use a minimum-mass solar nebula model and calculate the Ohmic resistivity at all radii and heights



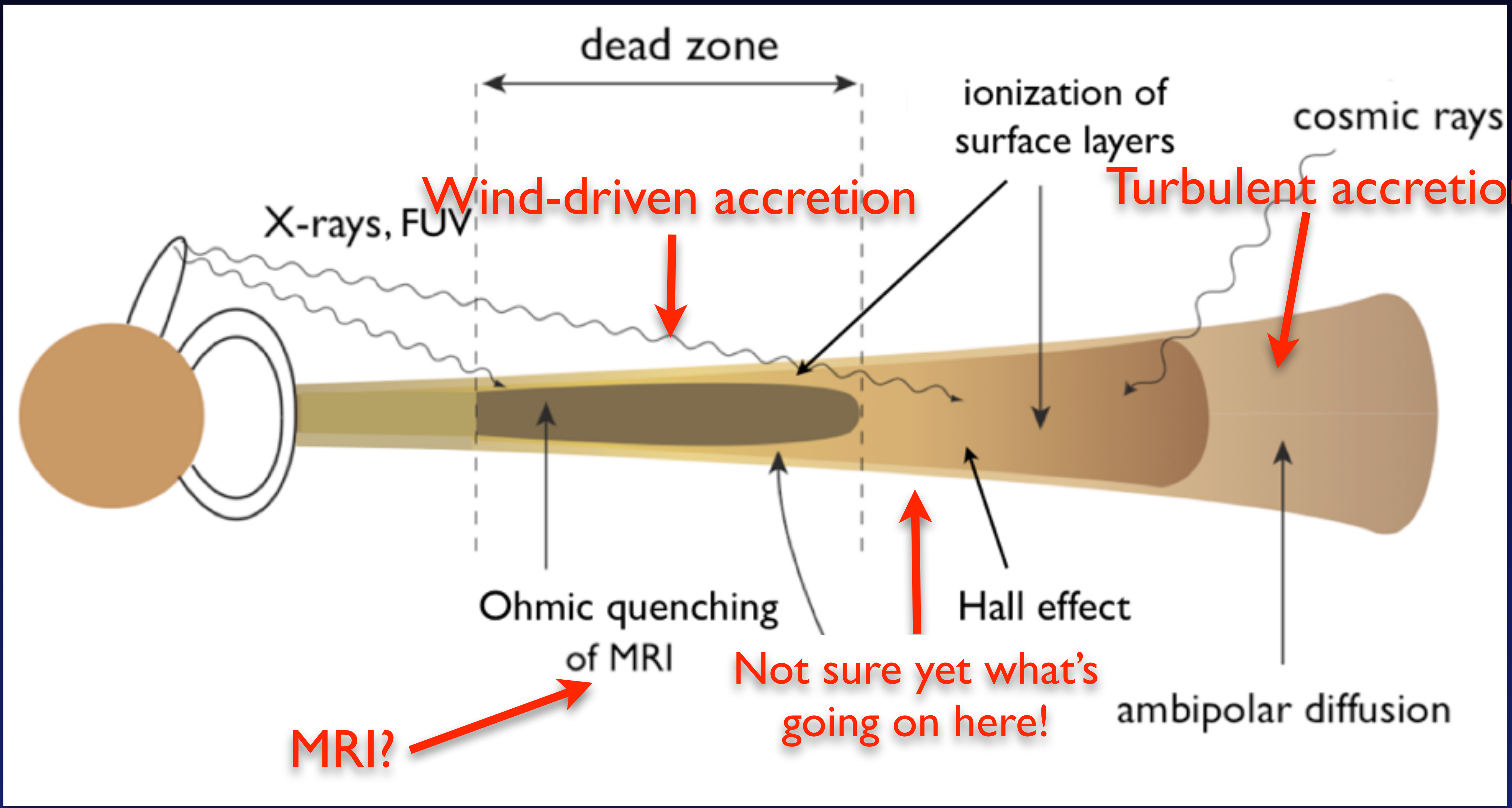
Armitage (2011)

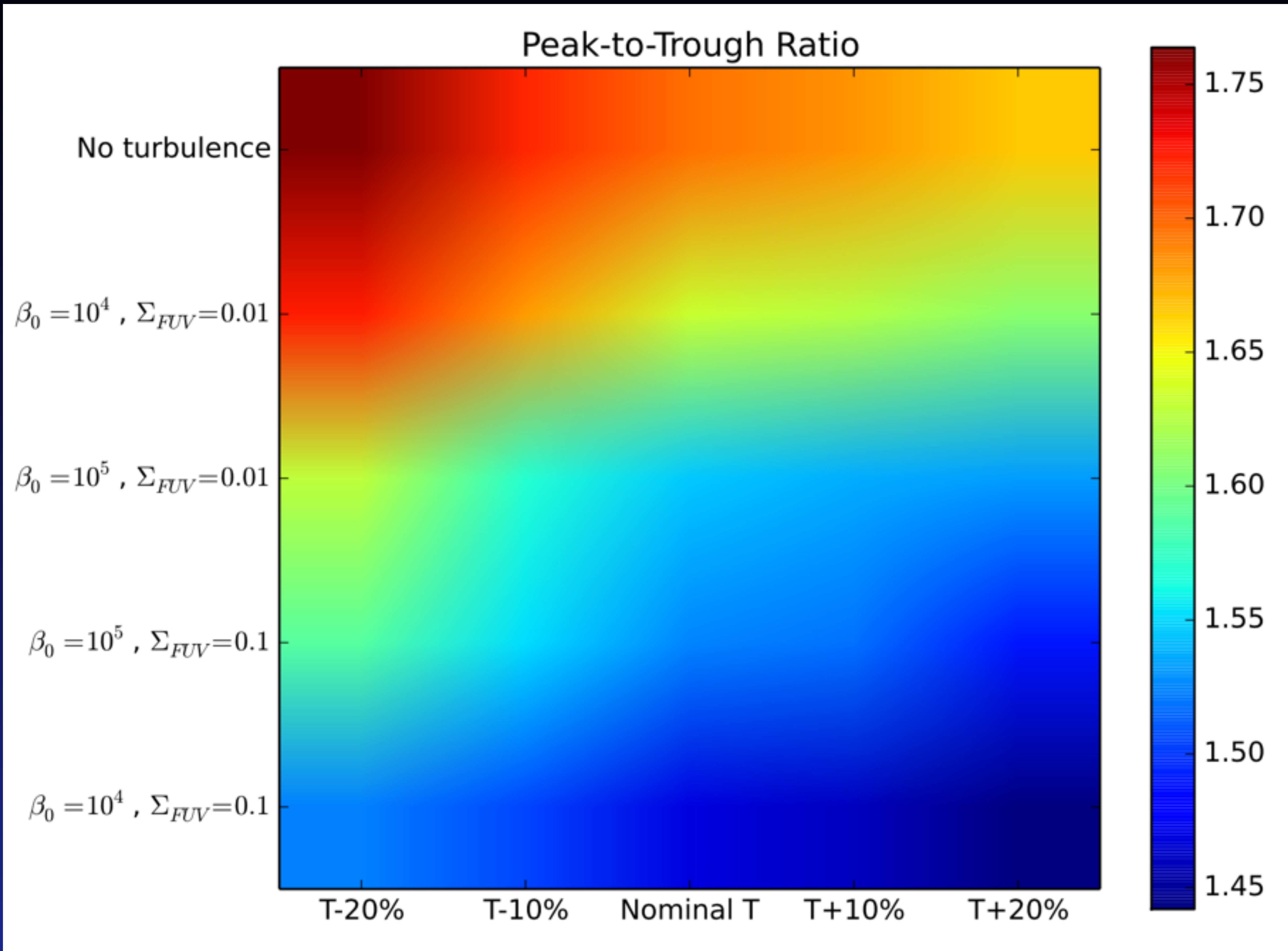
Strong gradient in turbulent velocity towards disk mid-plane



Simon et al., in prep

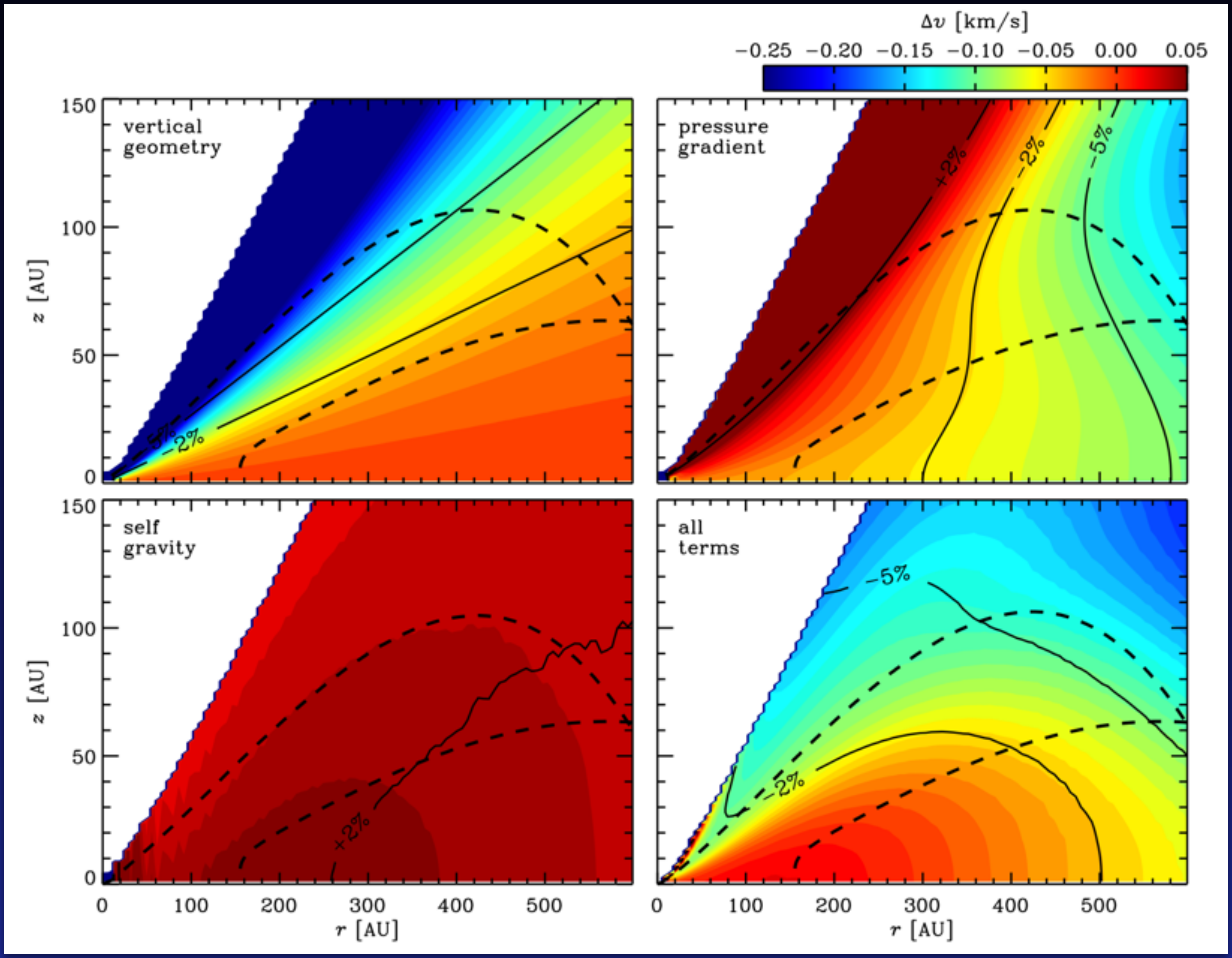
If we have a vertical magnetic field...





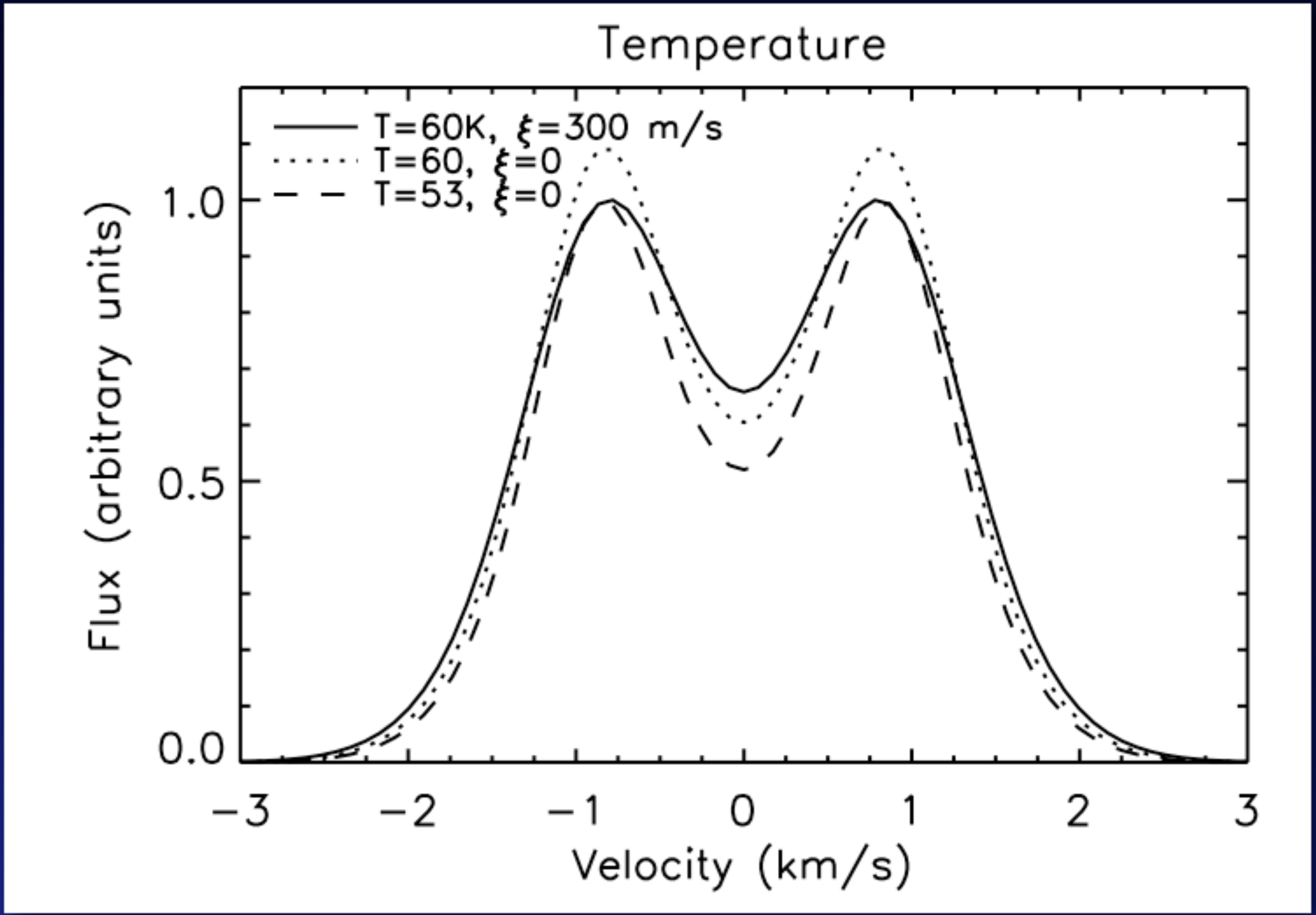
Peak-to-Trough Ratio
No turbulence
$\beta_0 = 10^4$, $\Sigma_{FUV} = 0.01$
$\beta_0 = 10^5$, $\Sigma_{FUV} = 0.01$
$\beta_0 = 10^5$, $\Sigma_{FUV} = 0.1$
$\beta_0 = 10^4$, $\Sigma_{FUV} = 0.1$
T-20%
T-10%
Nominal T
T+10%
T+20%
1.75
1.70
1.65
1.60
1.55
1.50
1.45

Effect of different disk structures

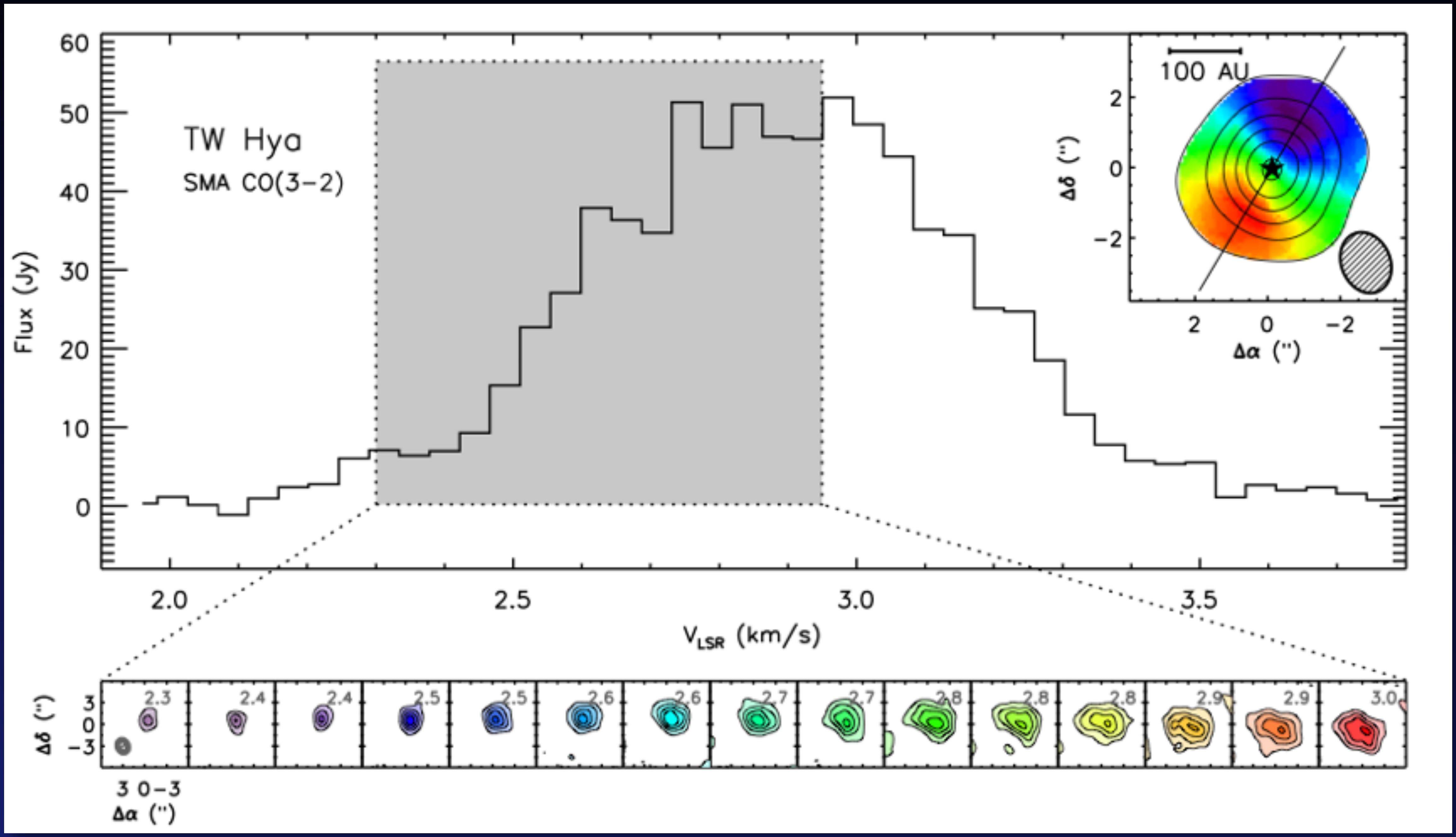


Rosenfield et al. (2013)

There are new sub-mm observations from which turbulent velocities can be inferred.



Hughes et al. (2011)



Hughes et al. (2011)

Derived an upper limit of ~ 0.1 c_s