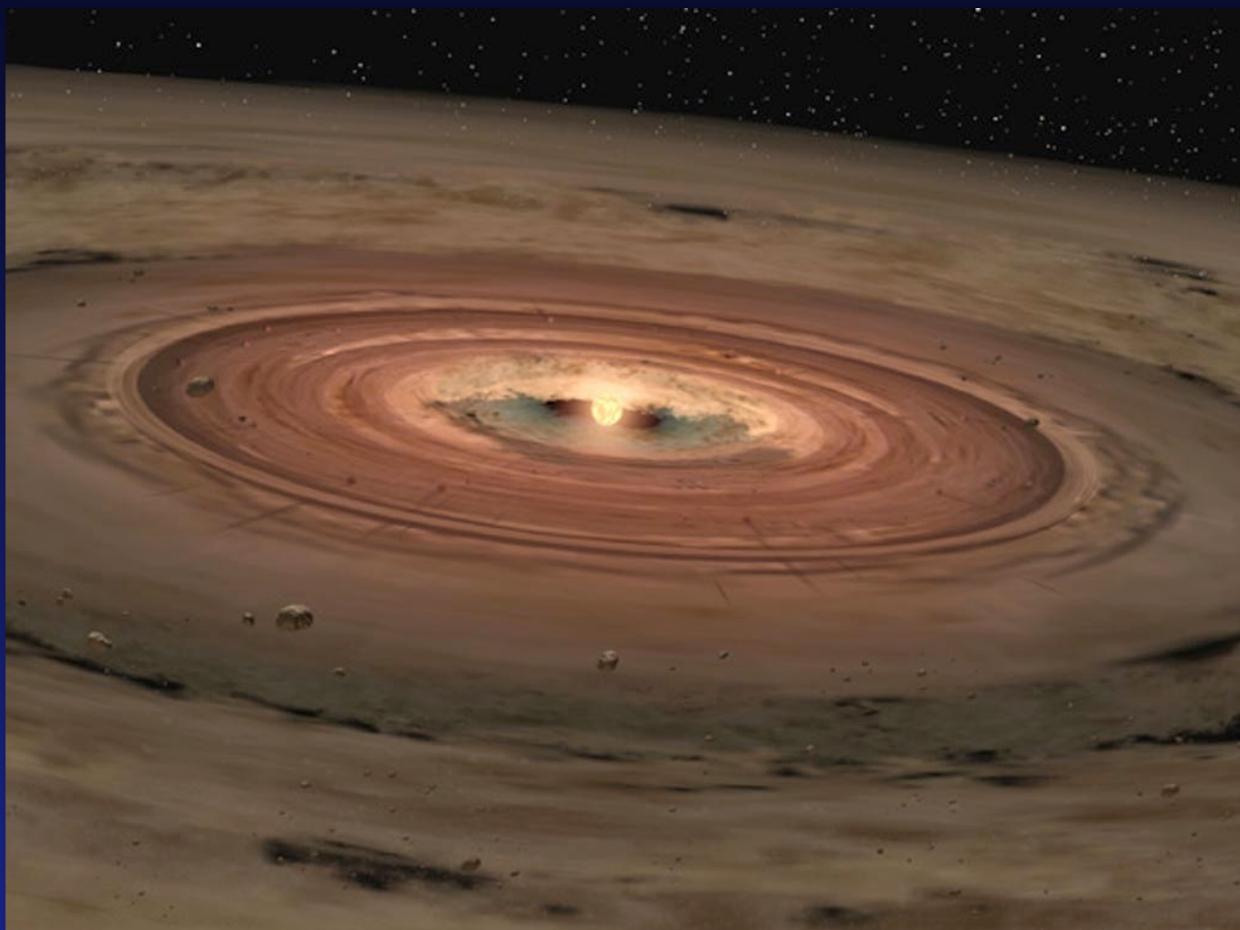
Observational Signatures of MRI-driven Turbulence in Protoplanetary Disks

Connecting Numerical Simulations with ALMA



Courtesy: NASA

Jacob B. Simon

Sagan Fellow

SwRI, Univ. of Colorado

Collaborators

Meredith Hughes

Kevin Flaherty

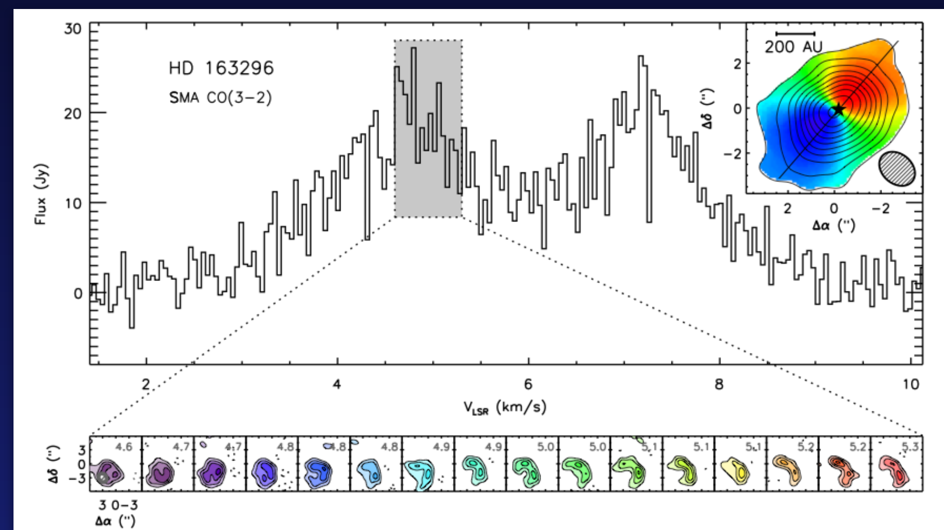
Phil Armitage

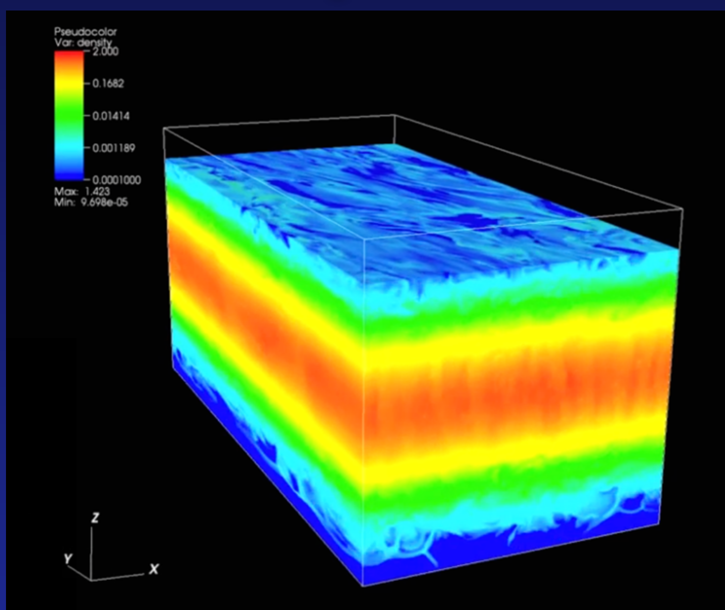
Xuening Bai

August 7, 2014

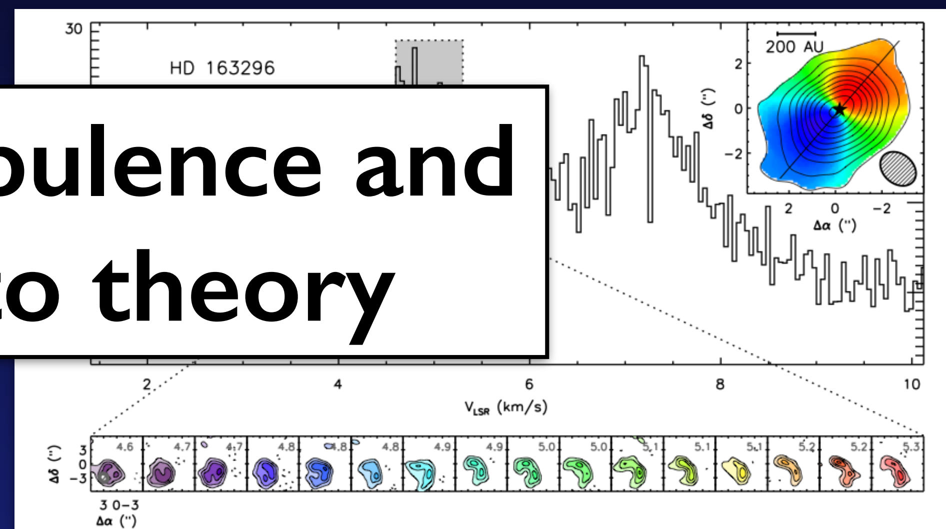
Non-ideal MHD, Stability, and Dissipation in Protoplanetary Disks

The big picture

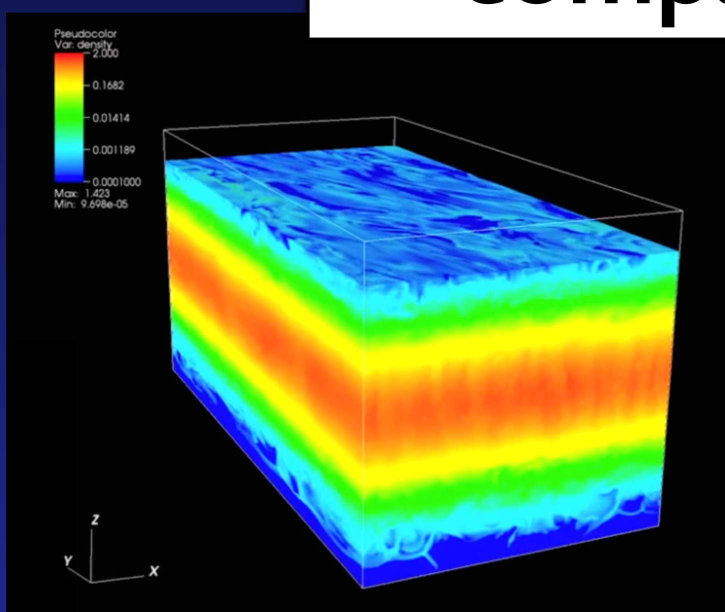




The big picture



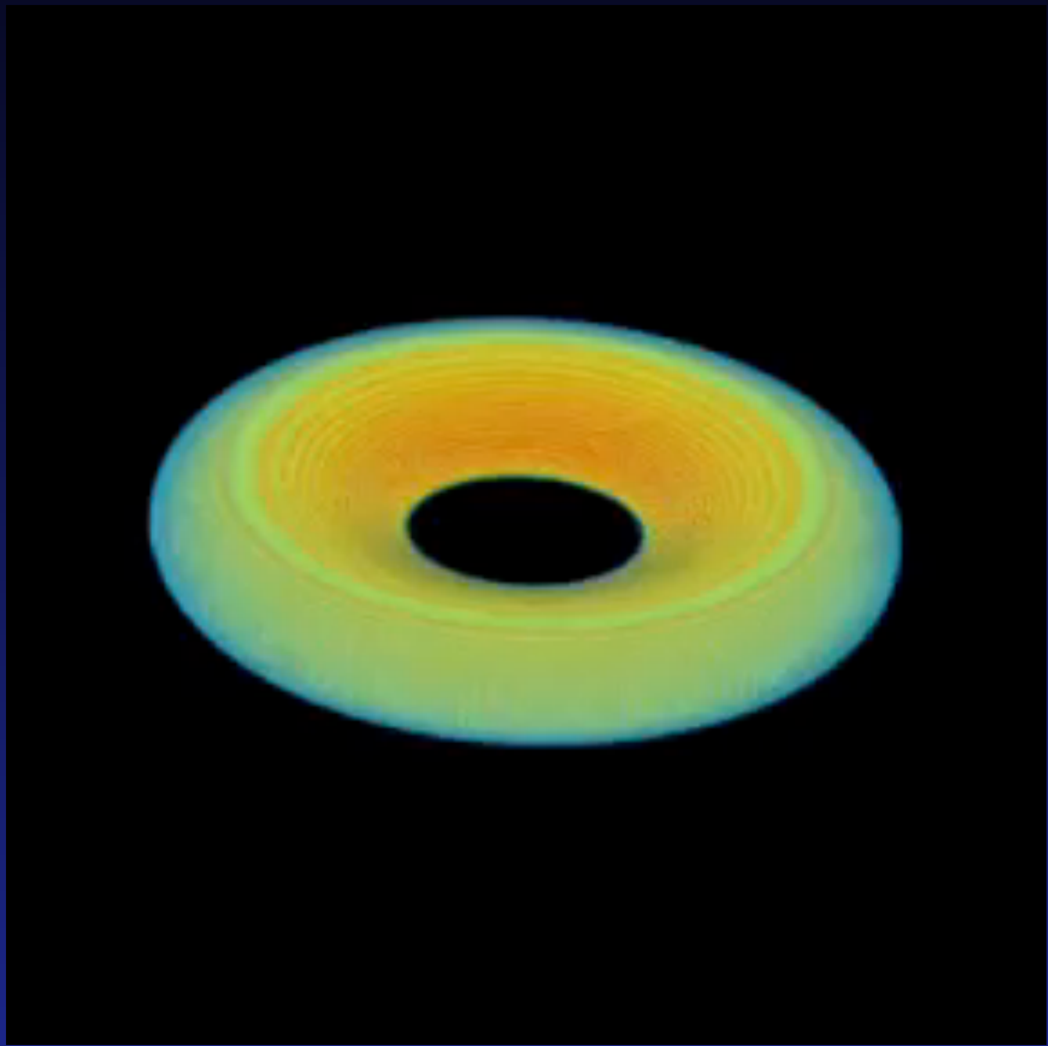
Observe turbulence and compare to theory



The big picture

Look for a “smoking gun” for MRI turbulence

The MRI generates vigorous disk turbulence



Hawley (2000)

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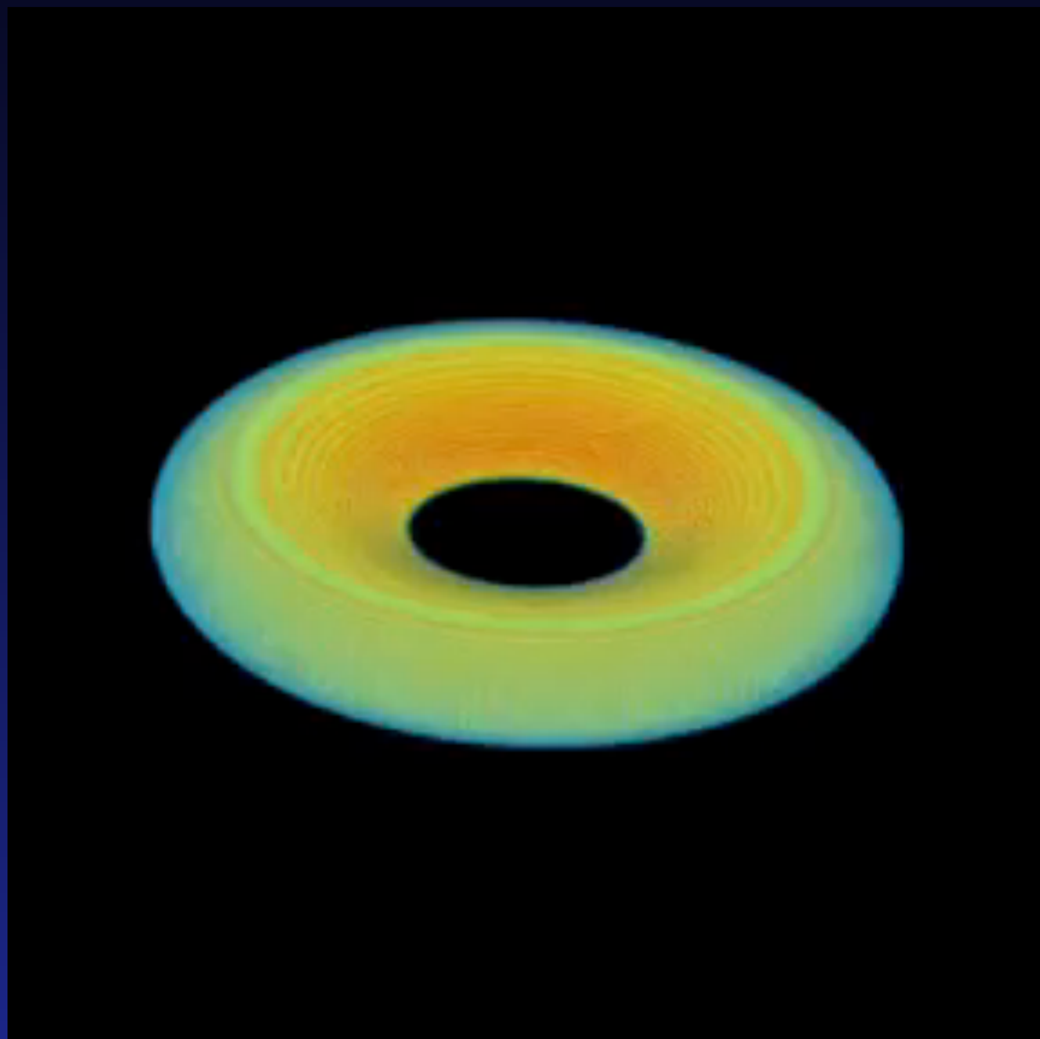
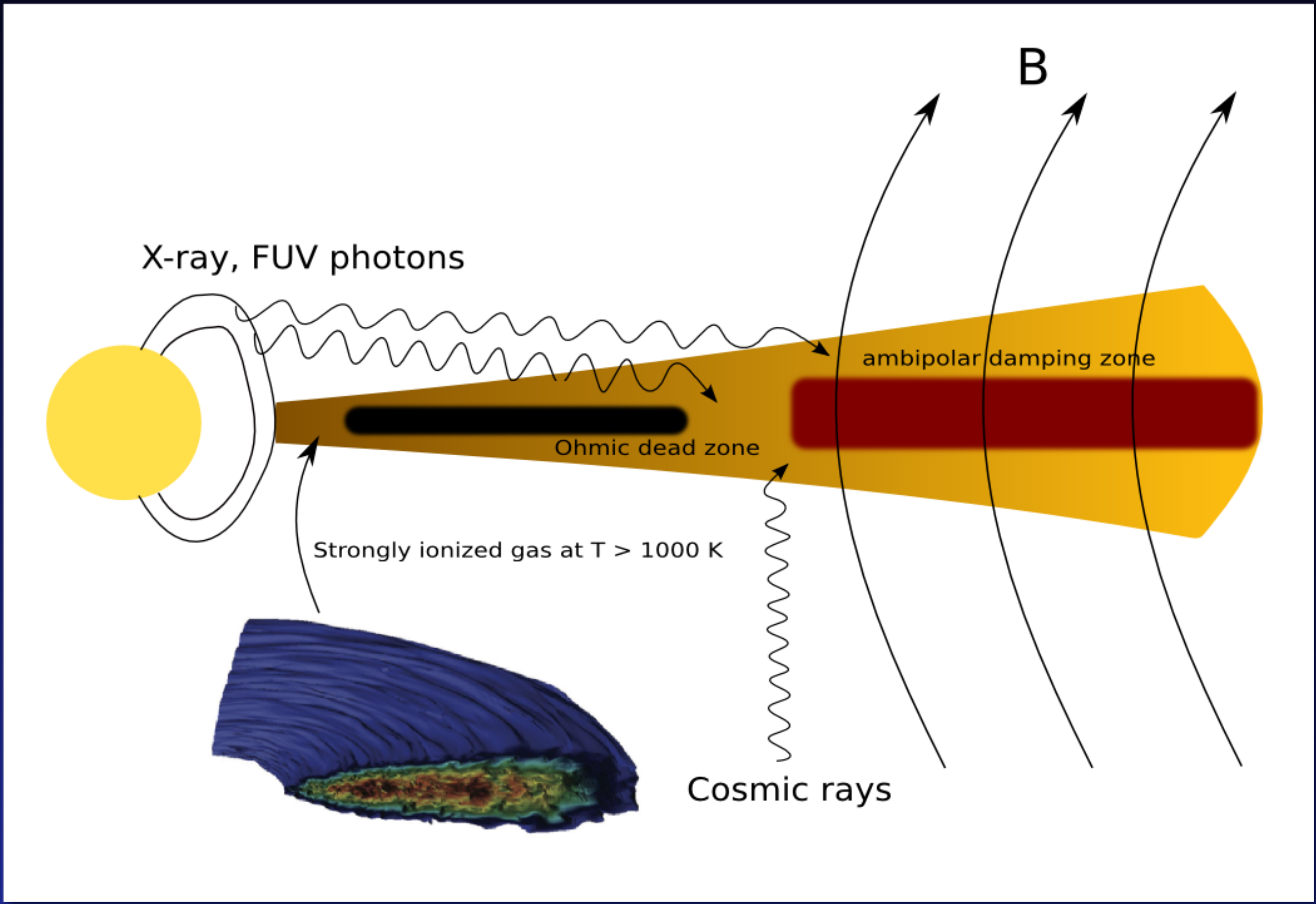


Hawley (2000)

Protoplanetary disks are not so simple…



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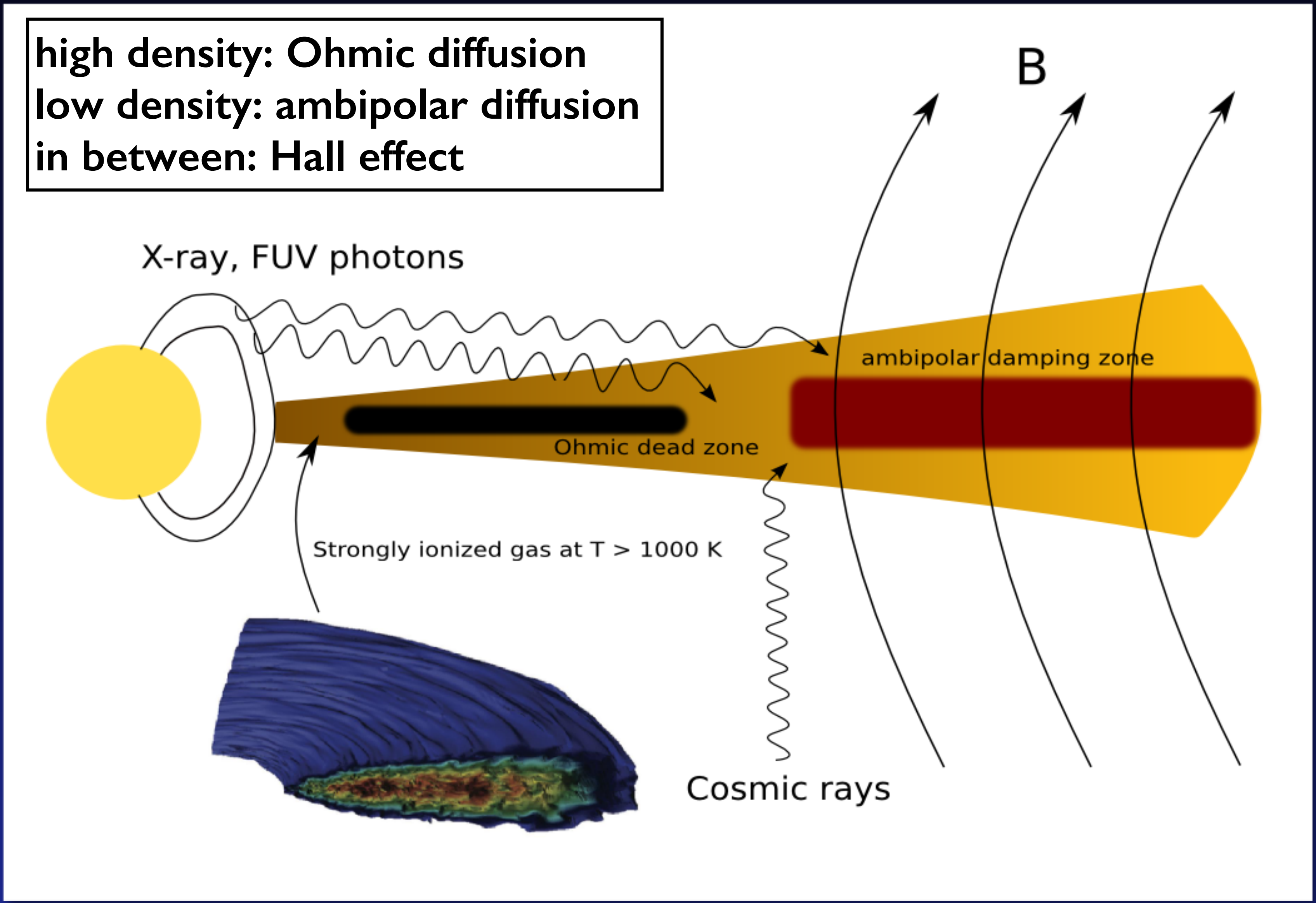
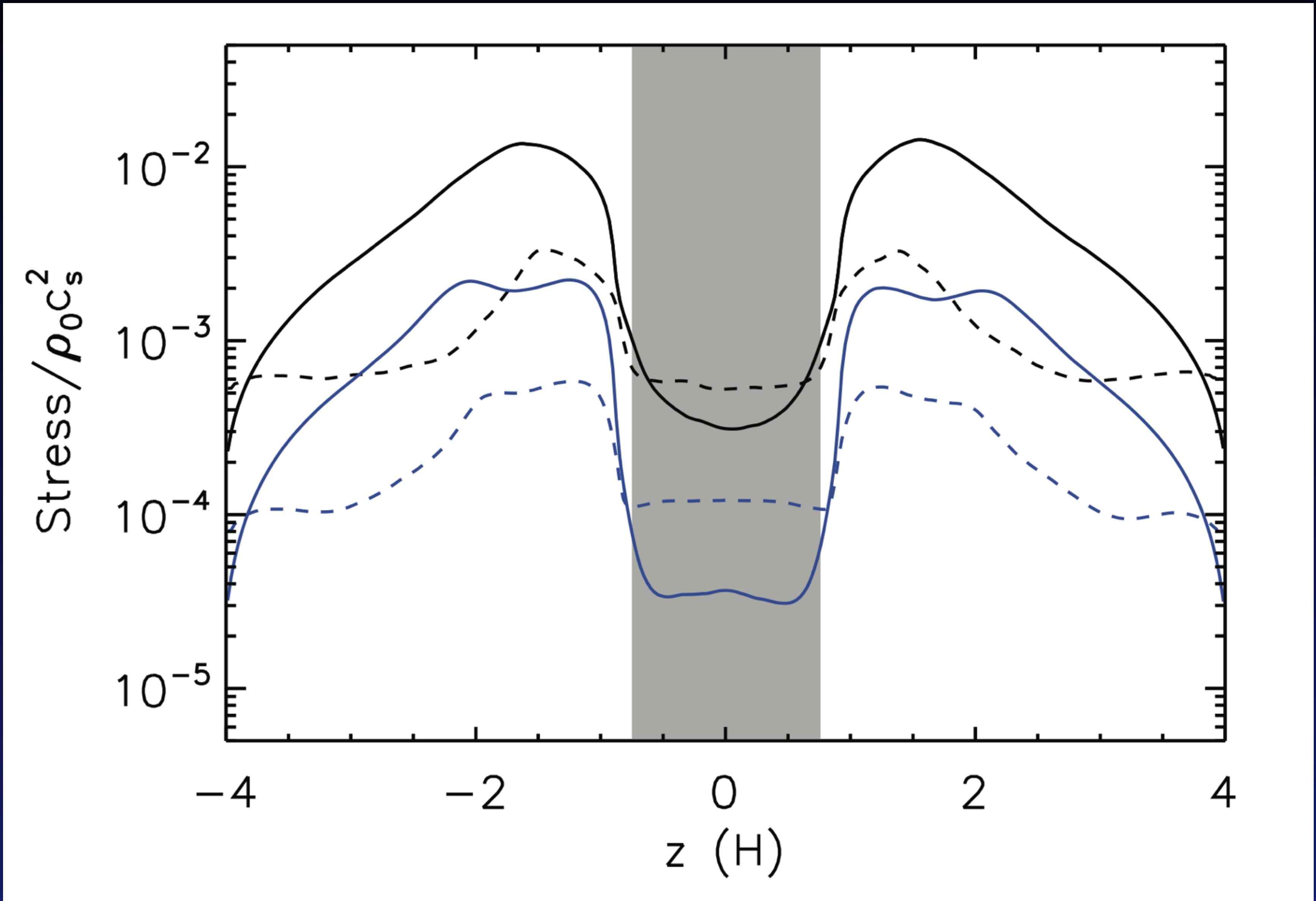


The ambipolar damping zone

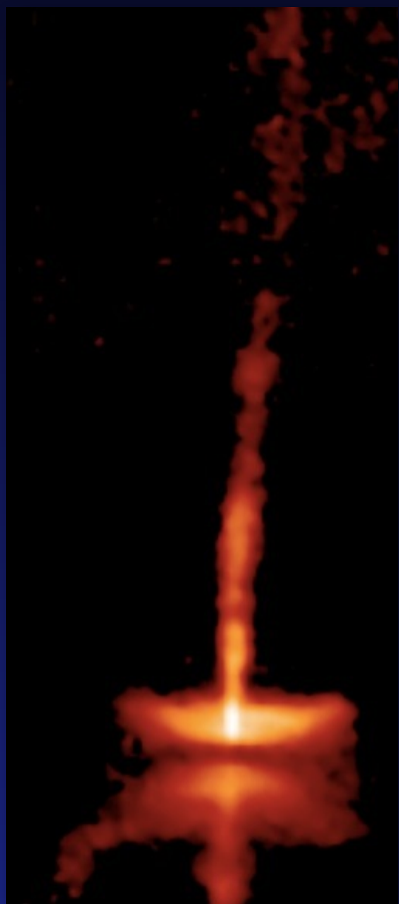


Simon et al. 2013 (see also Bai & Stone 2011)

This added complexity is both a blessing and a curse!

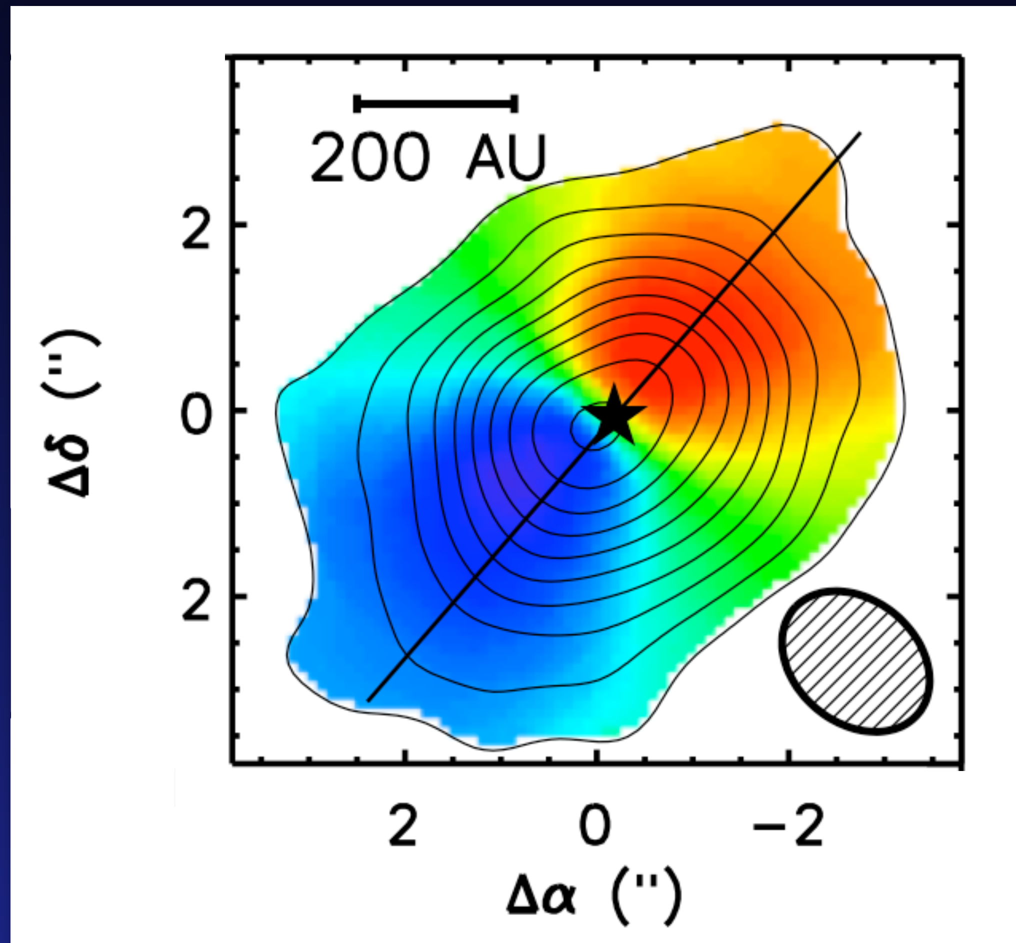
Another blessing: we can spatially resolve these disks!

HH30

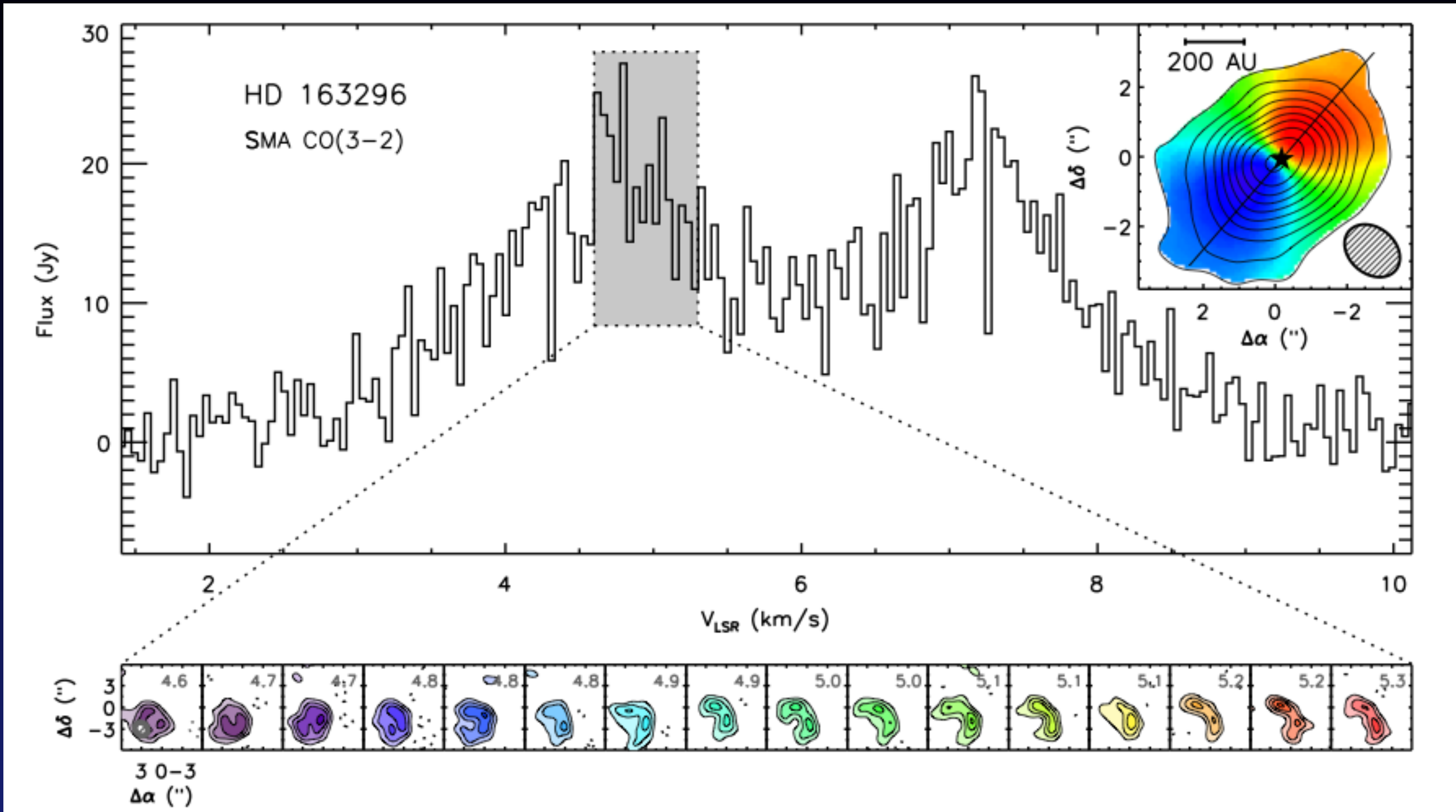


Courtesy: NASA

HD 163296



Hughes et al. (2011)



Hughes et al. (2011)

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

These numbers are roughly consistent with theoretical estimates

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$$v_{turb} \sim \alpha^{1/2} c_s$$

$$\alpha \sim 0.01,\ v_{turb} \sim 0.1 c_s$$

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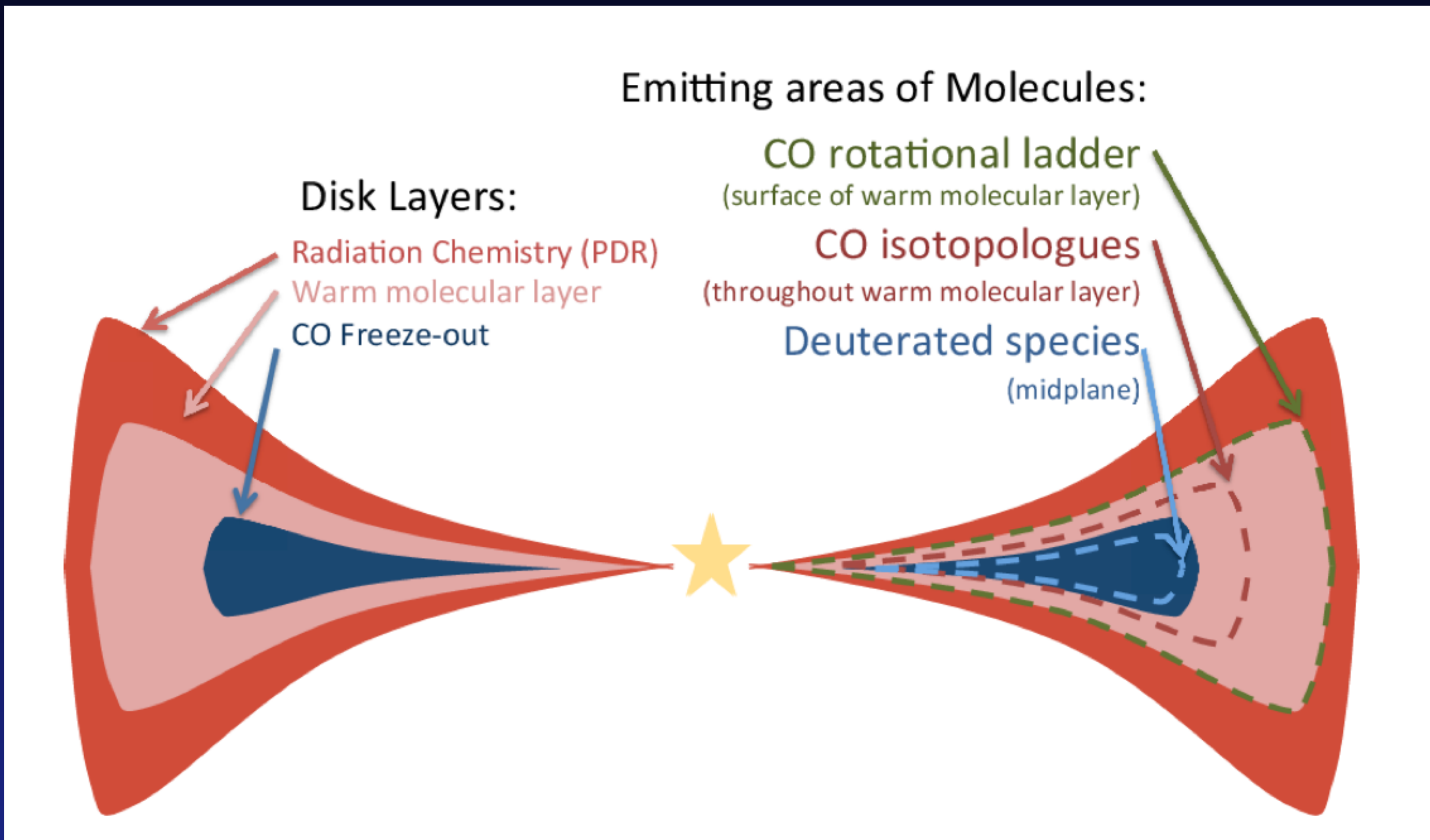
$$v_{turb} \sim \alpha^{1/2} c_s$$

$$\alpha \sim 0.01, \; v_{turb} \sim 0.1 c_s$$

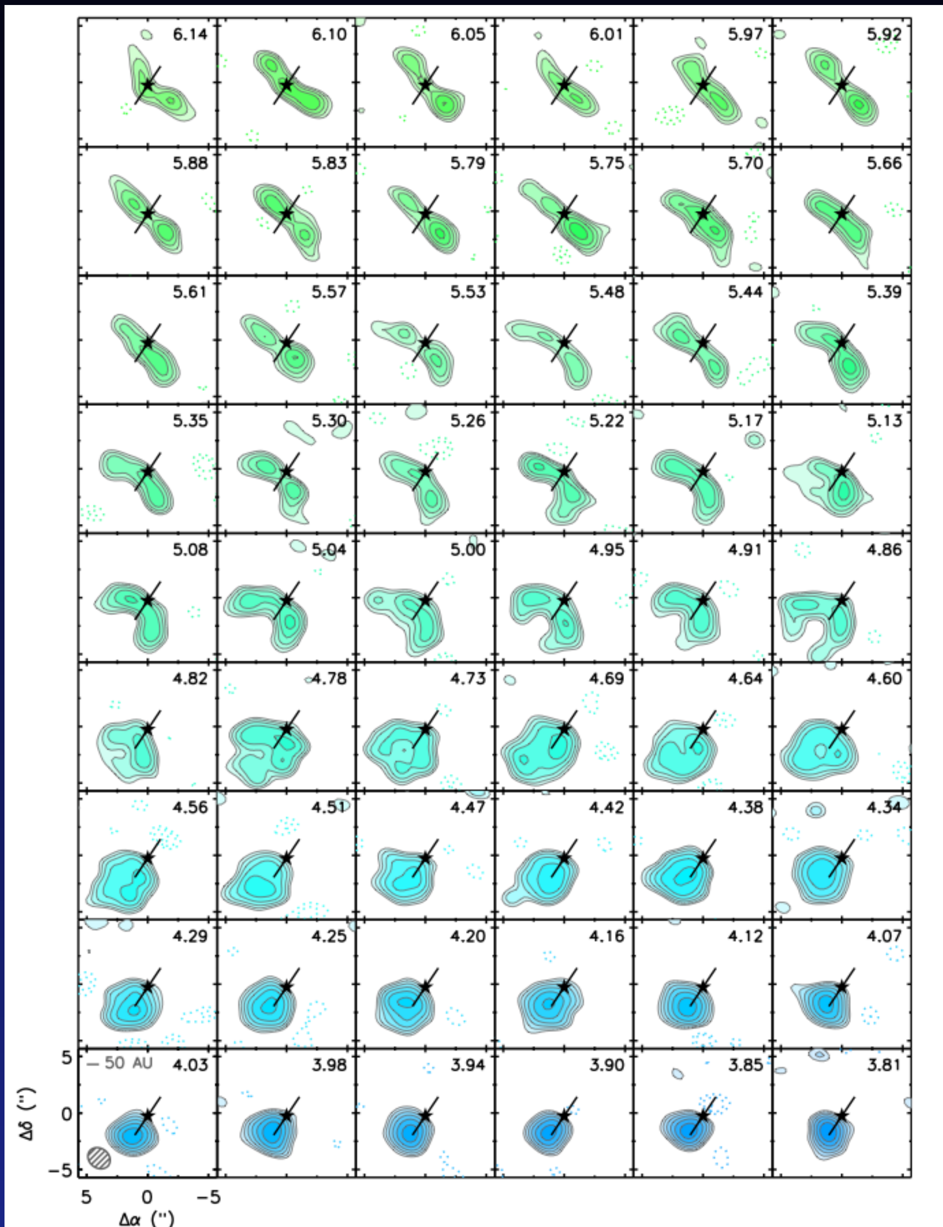
But we can do better!
(both with observations and theory)

Can examine vertical structure of turbulence using different lines



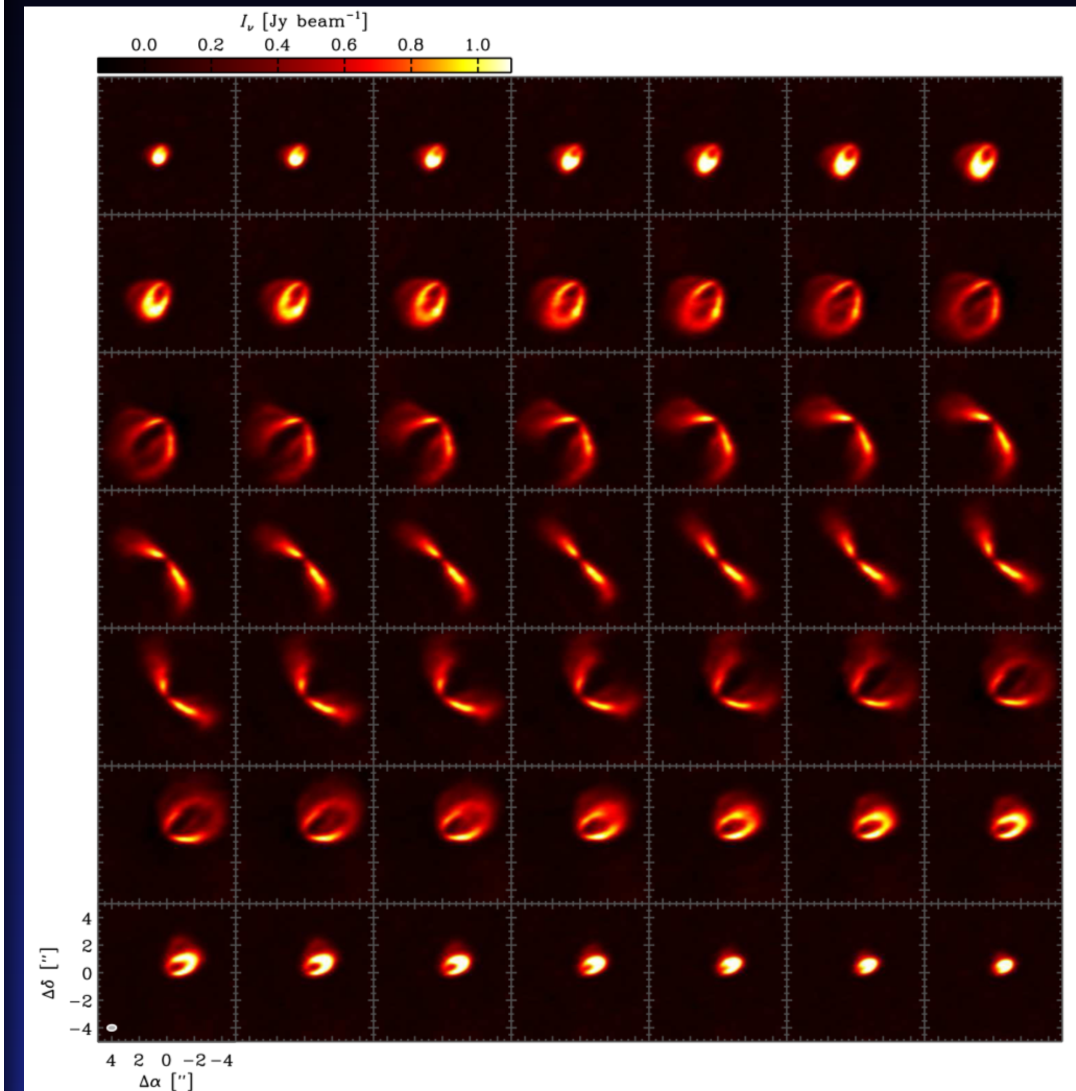
Meredith Hughes

At much higher resolution!



Hughes et al. (2011)

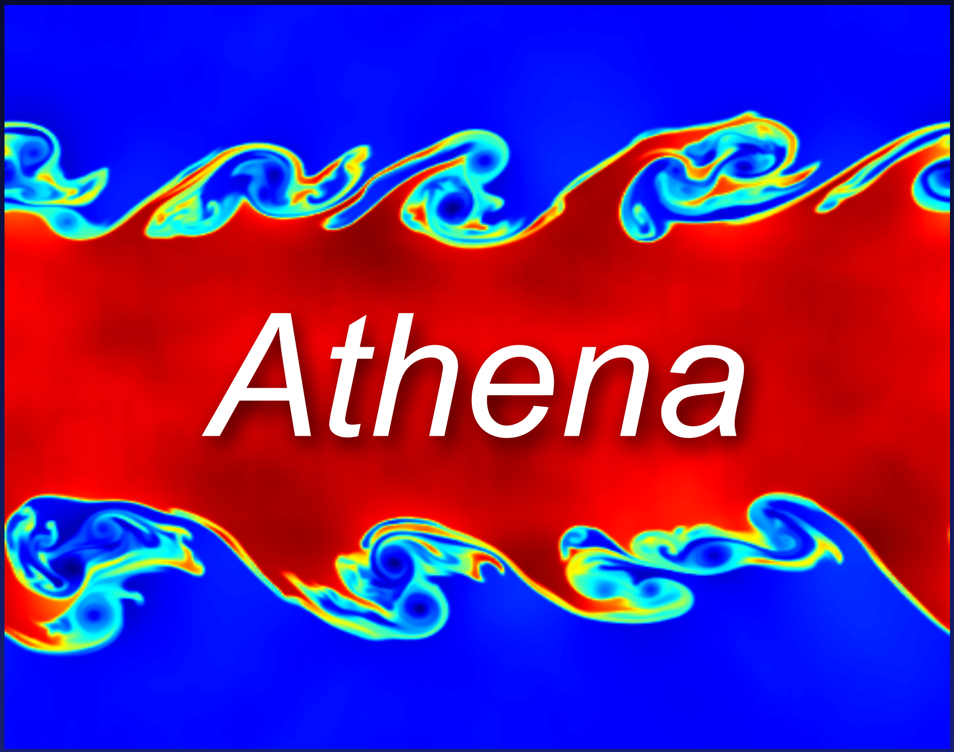
SMA



Rosenfeld et al. (2013)

ALMA

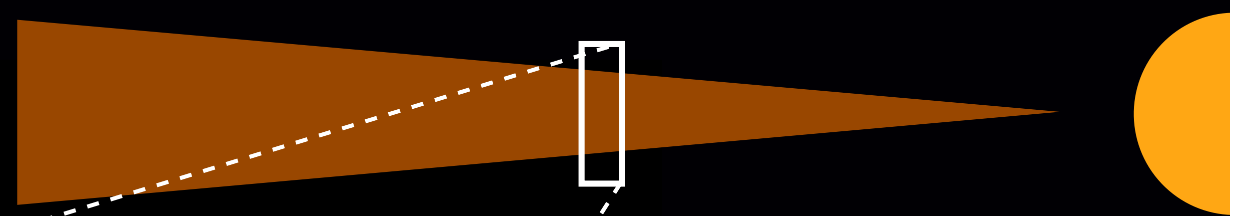
State-of-the-art MHD code

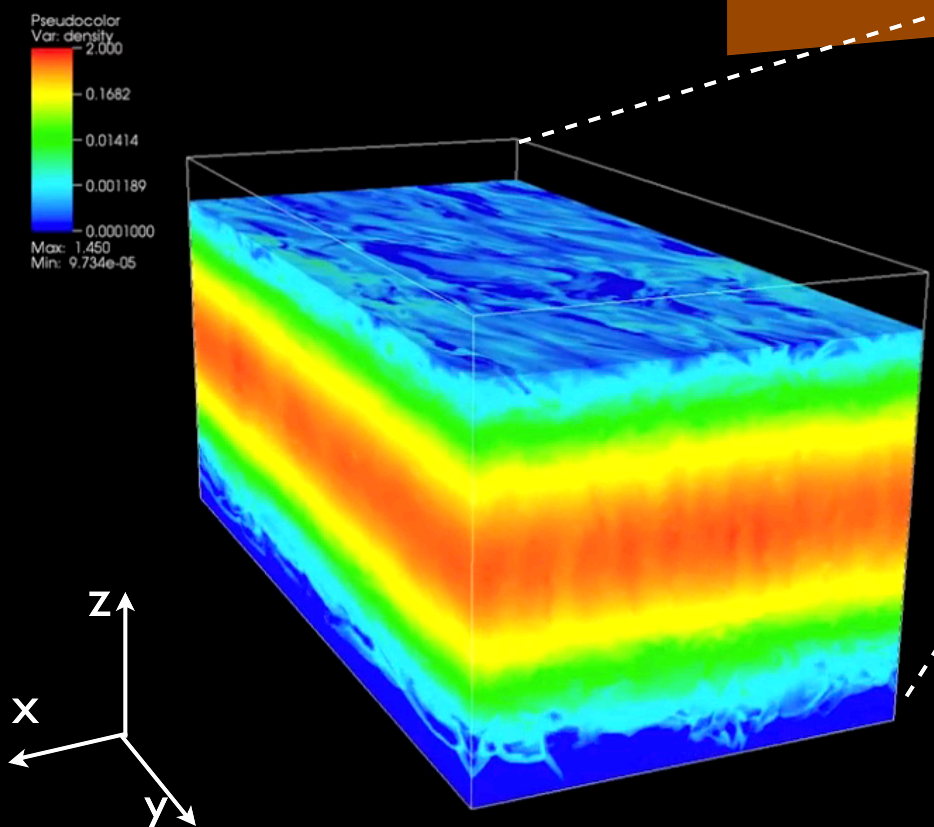


See Stone et al. (2008)

for code details

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
- Net vertical magnetic field

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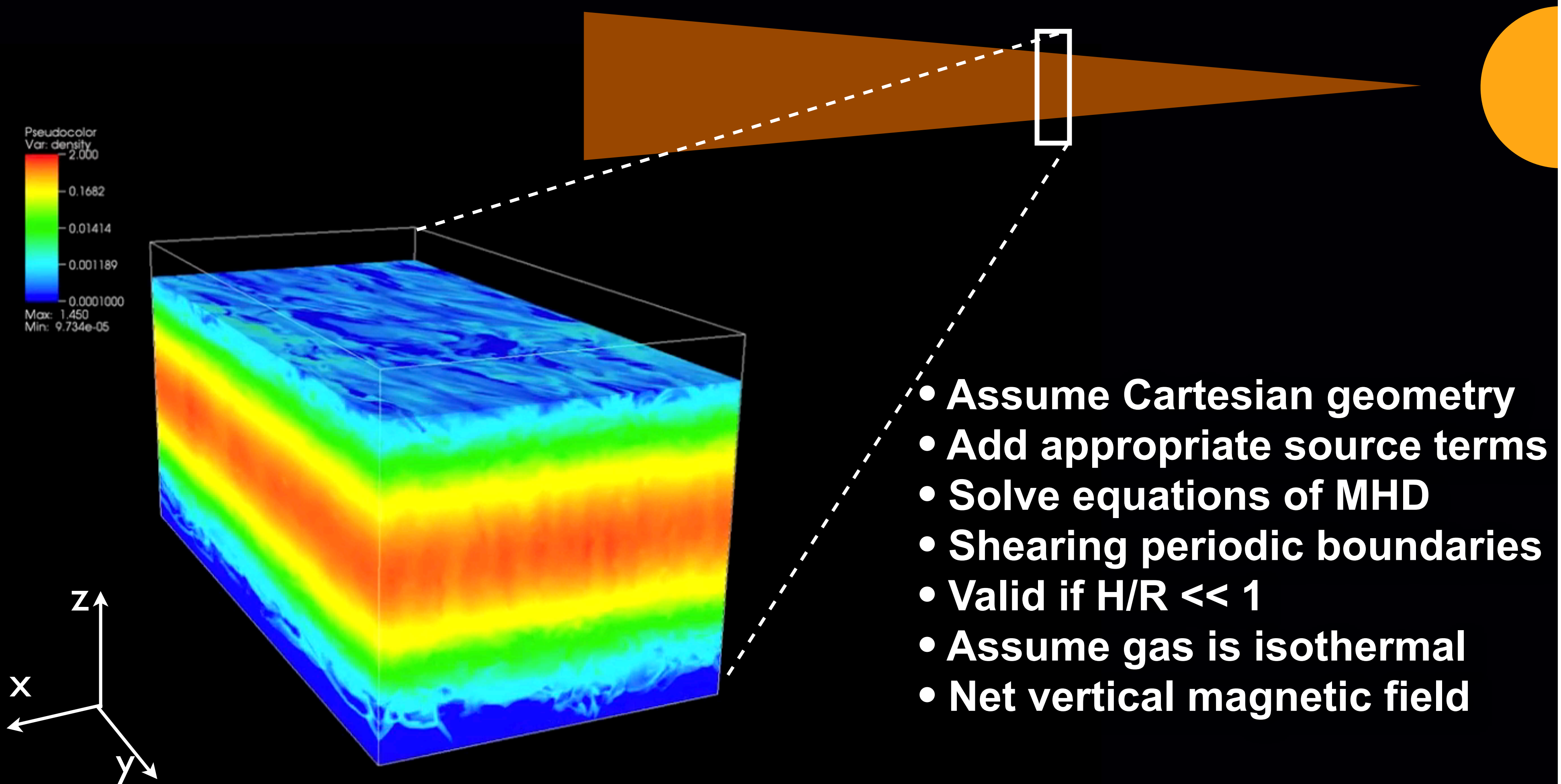

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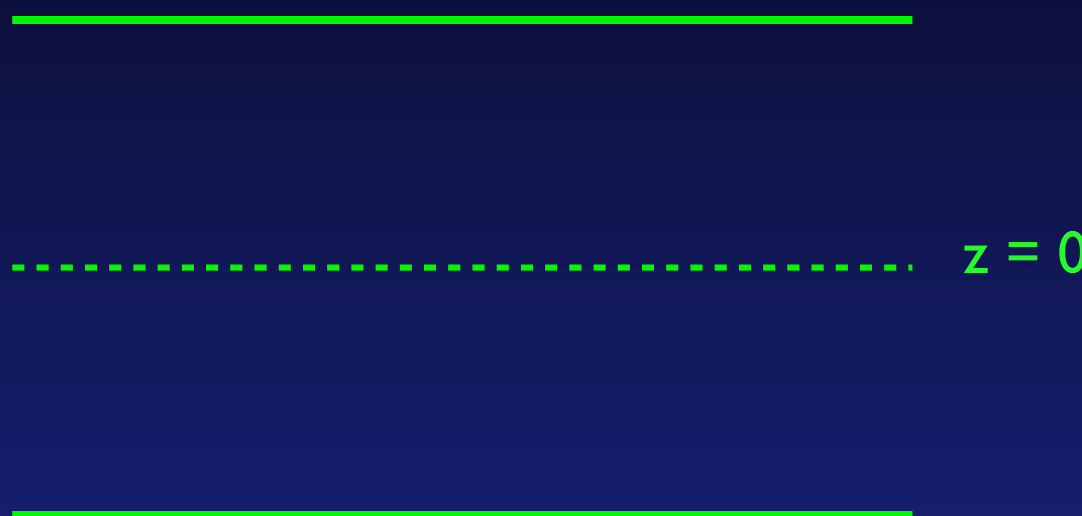
We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)



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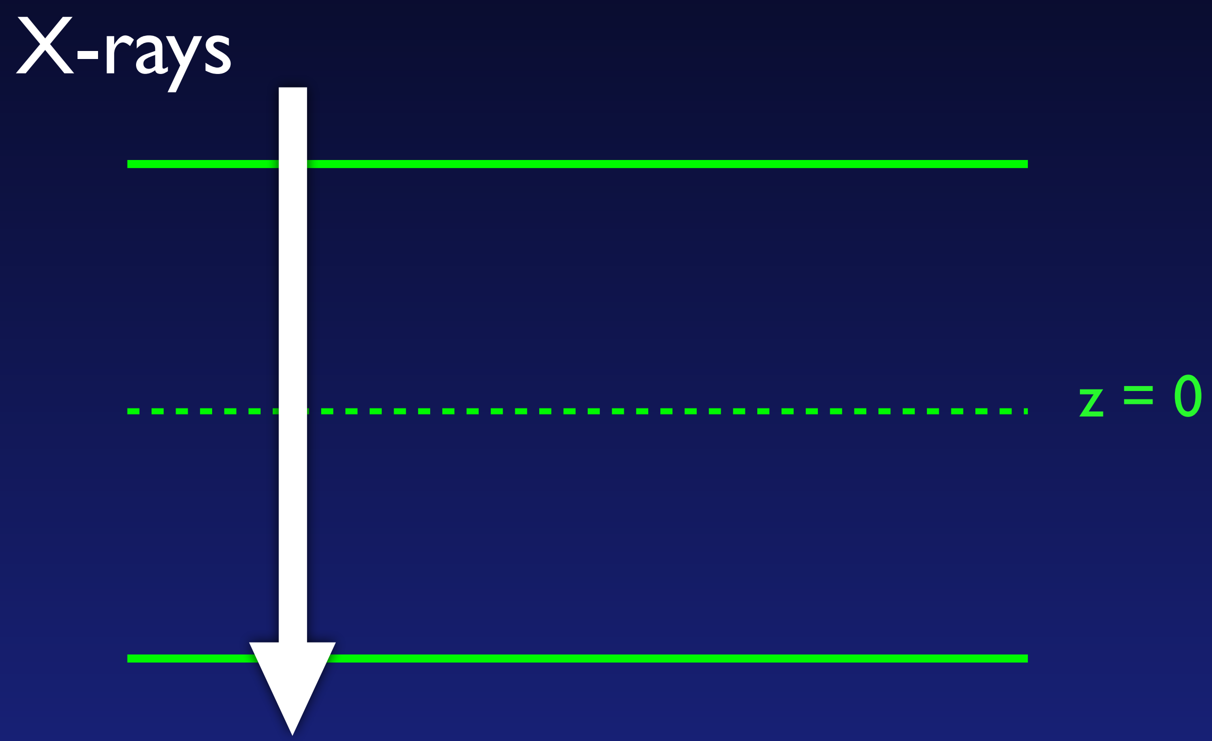

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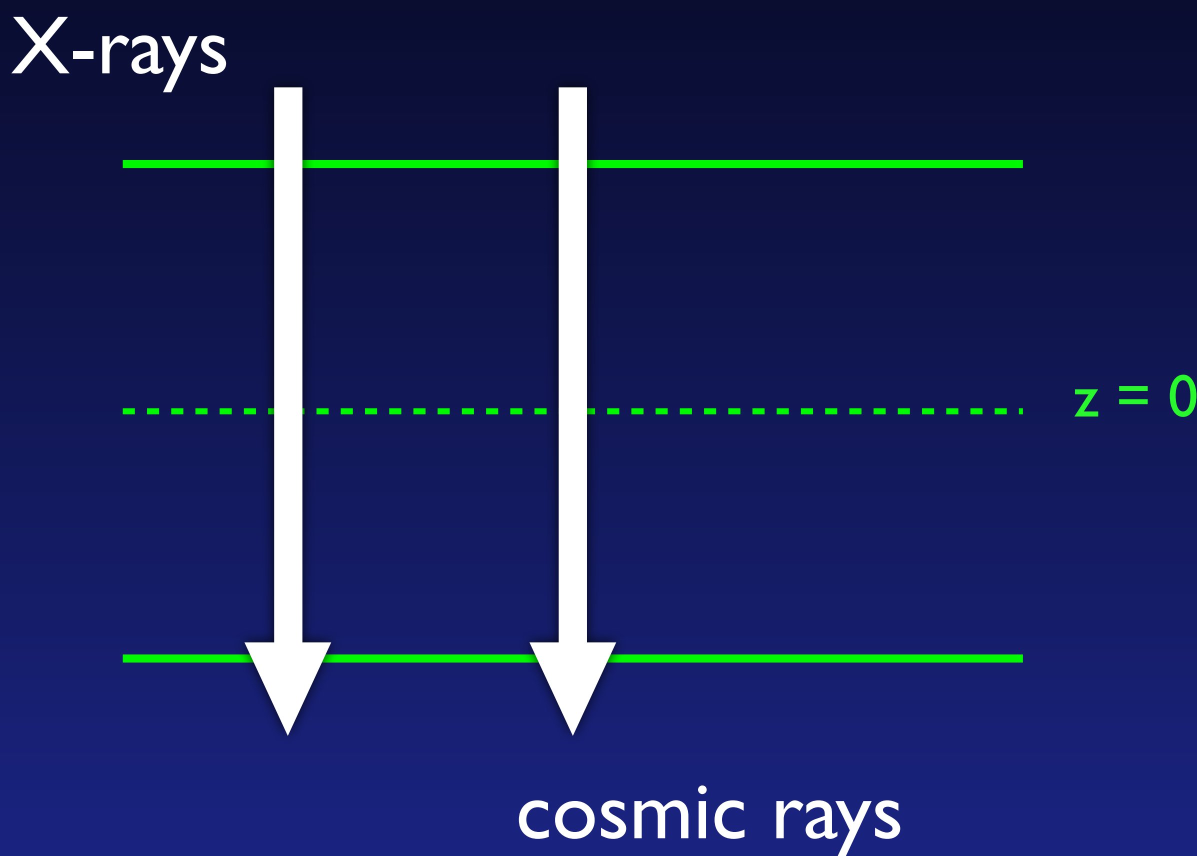

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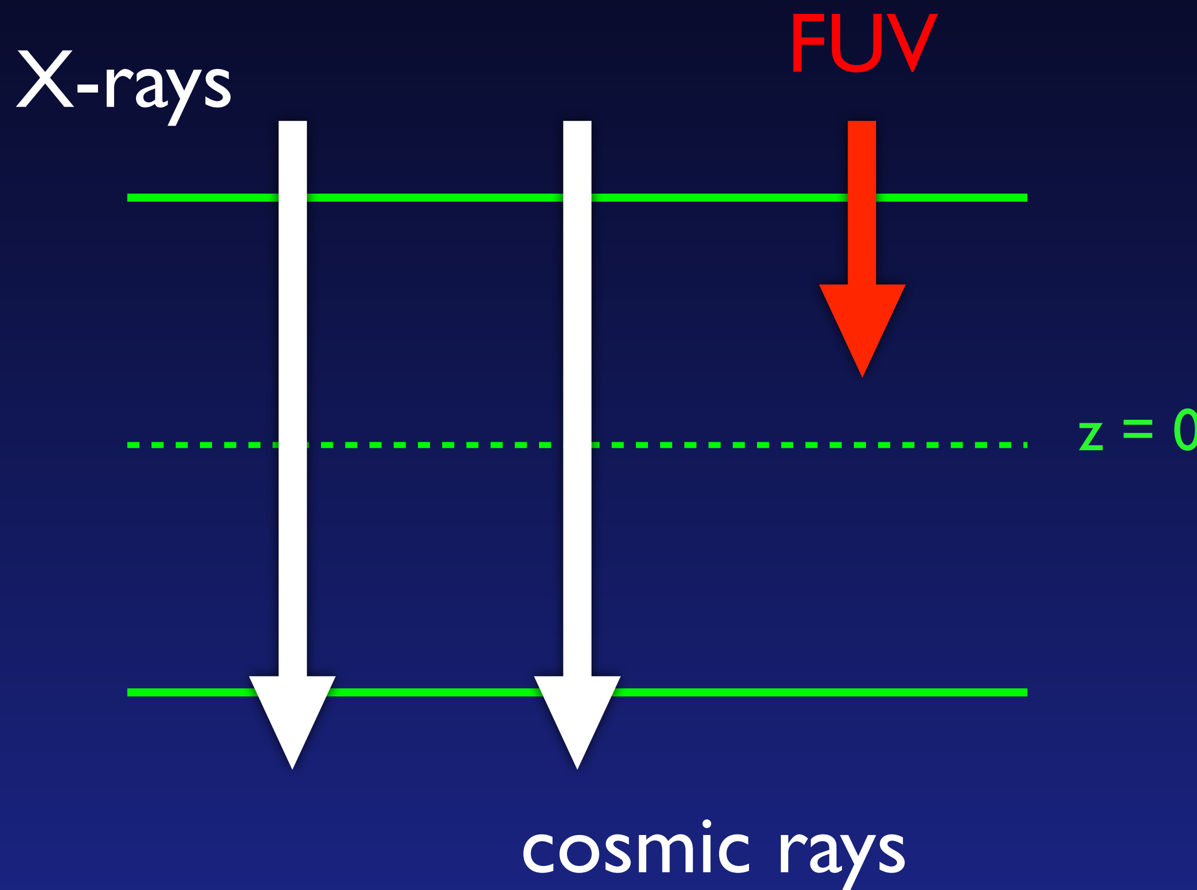

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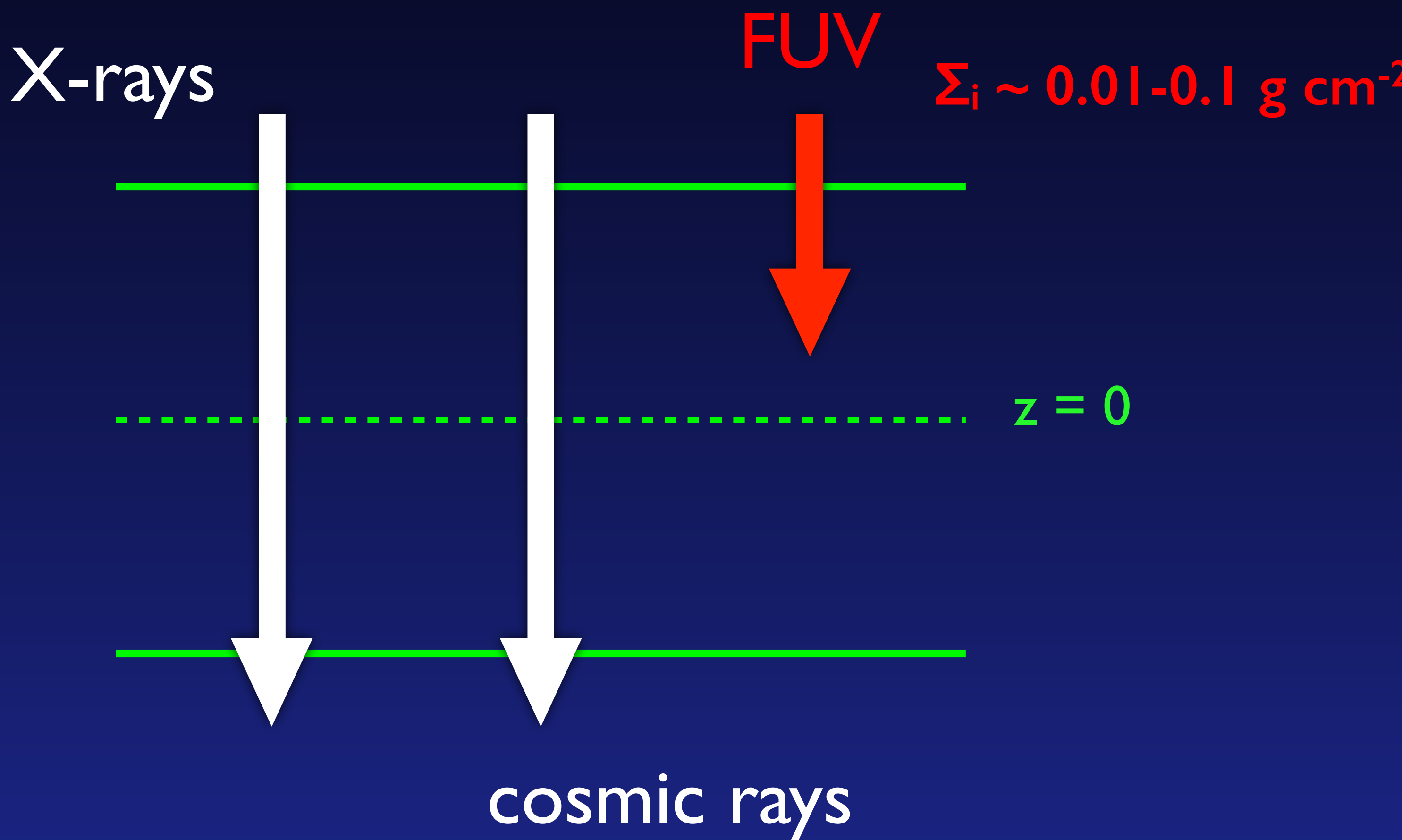

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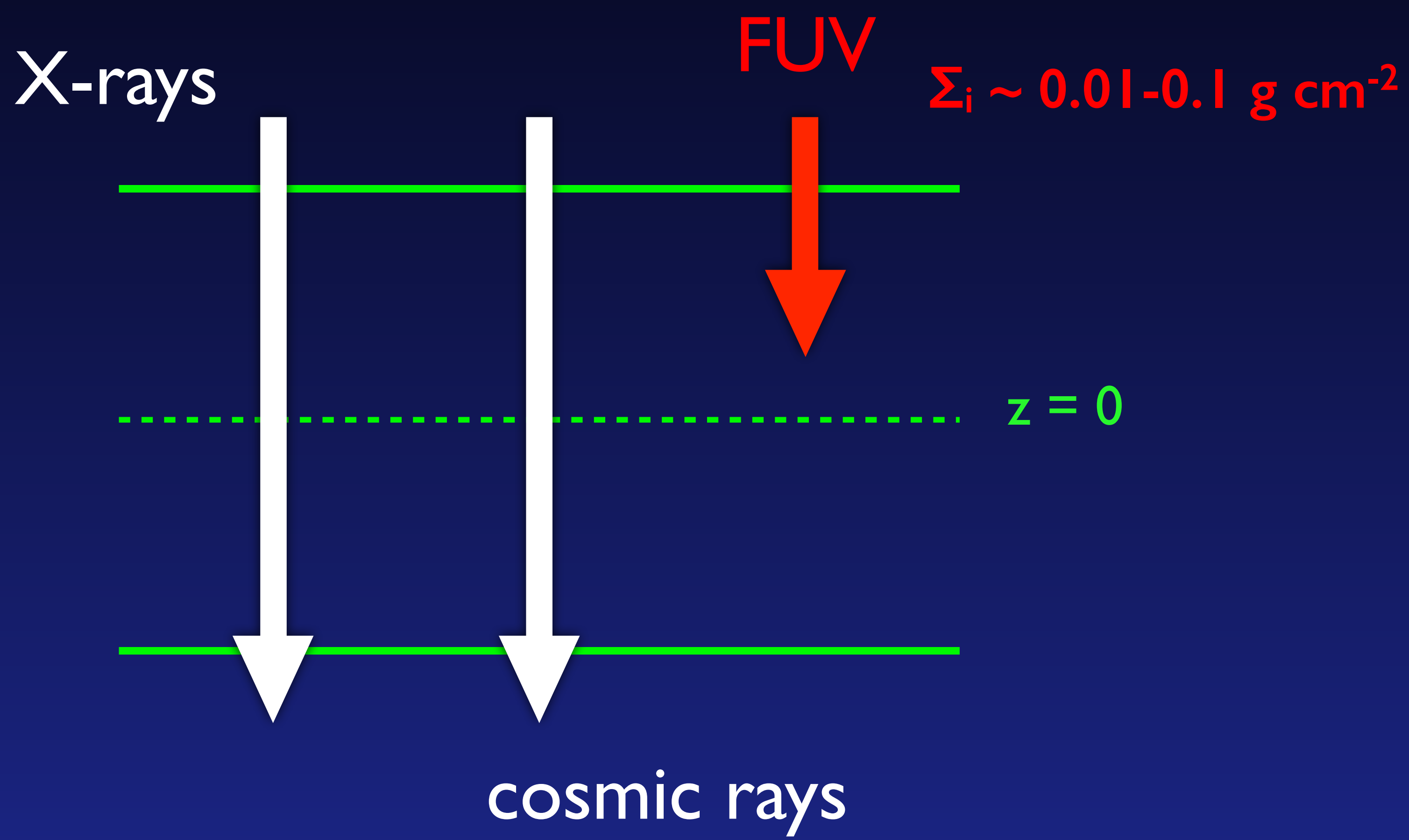
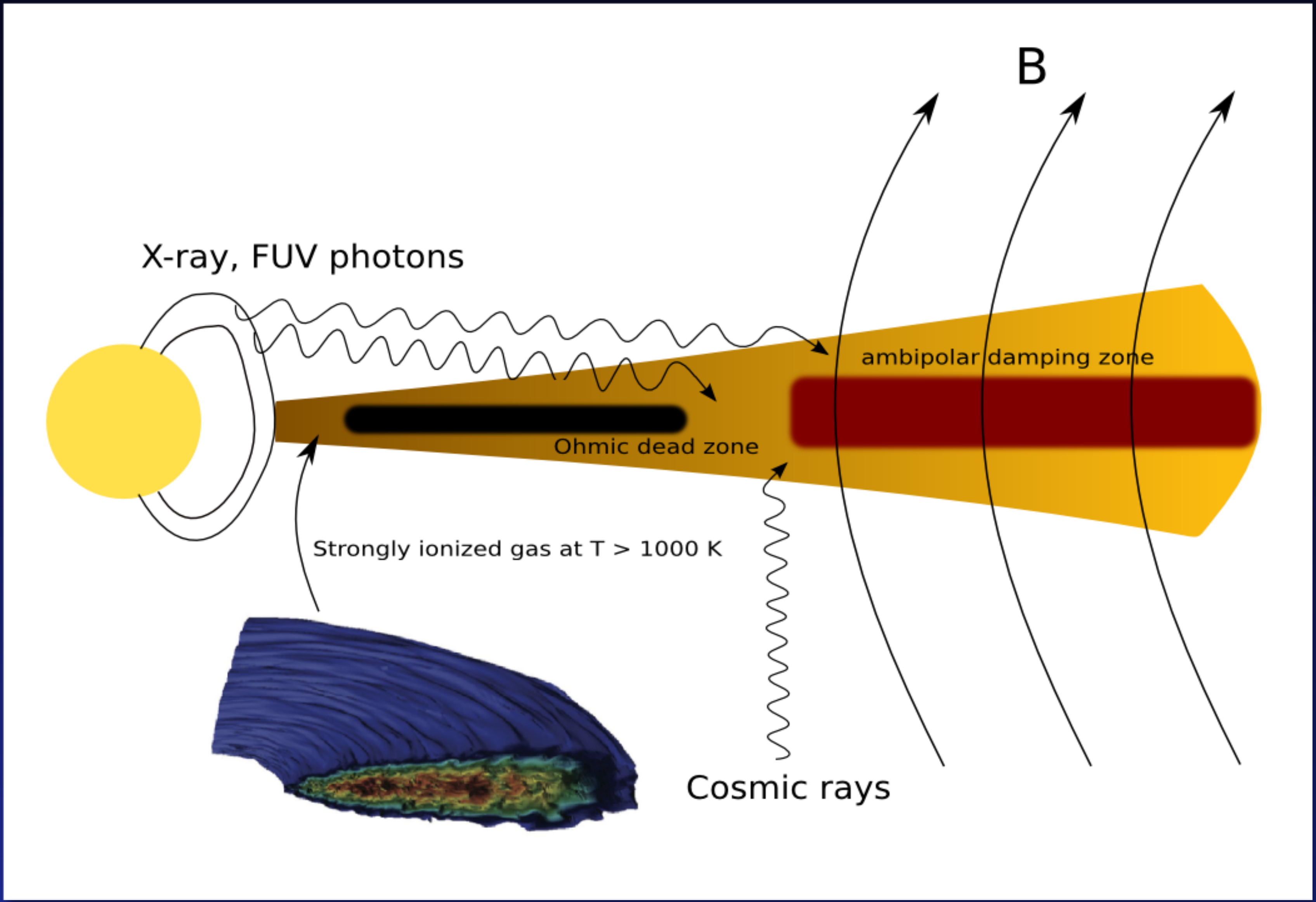


See Bai (2011) and Perez-Becker & Chiang (2011) for details

Center local simulations at several radii



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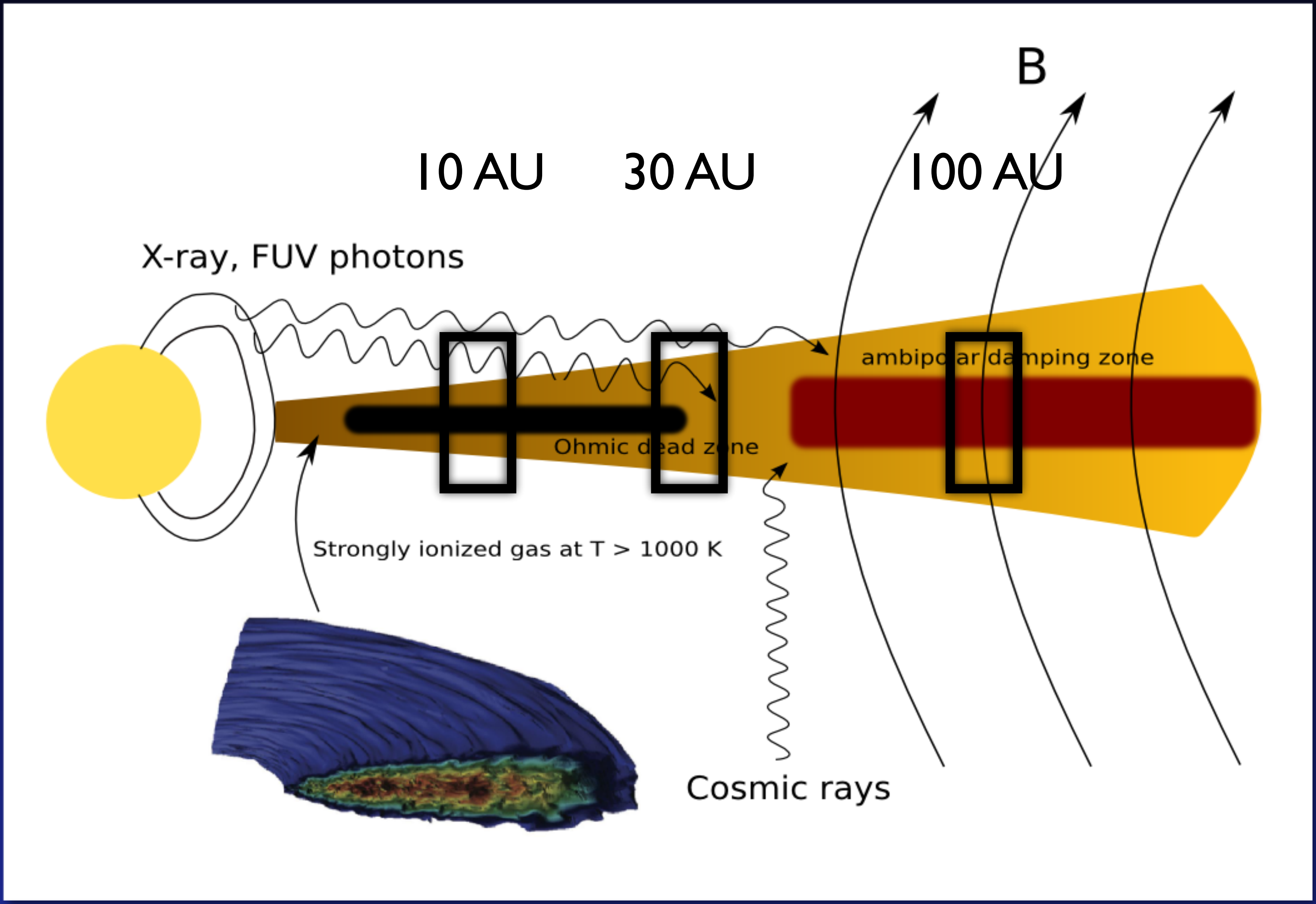
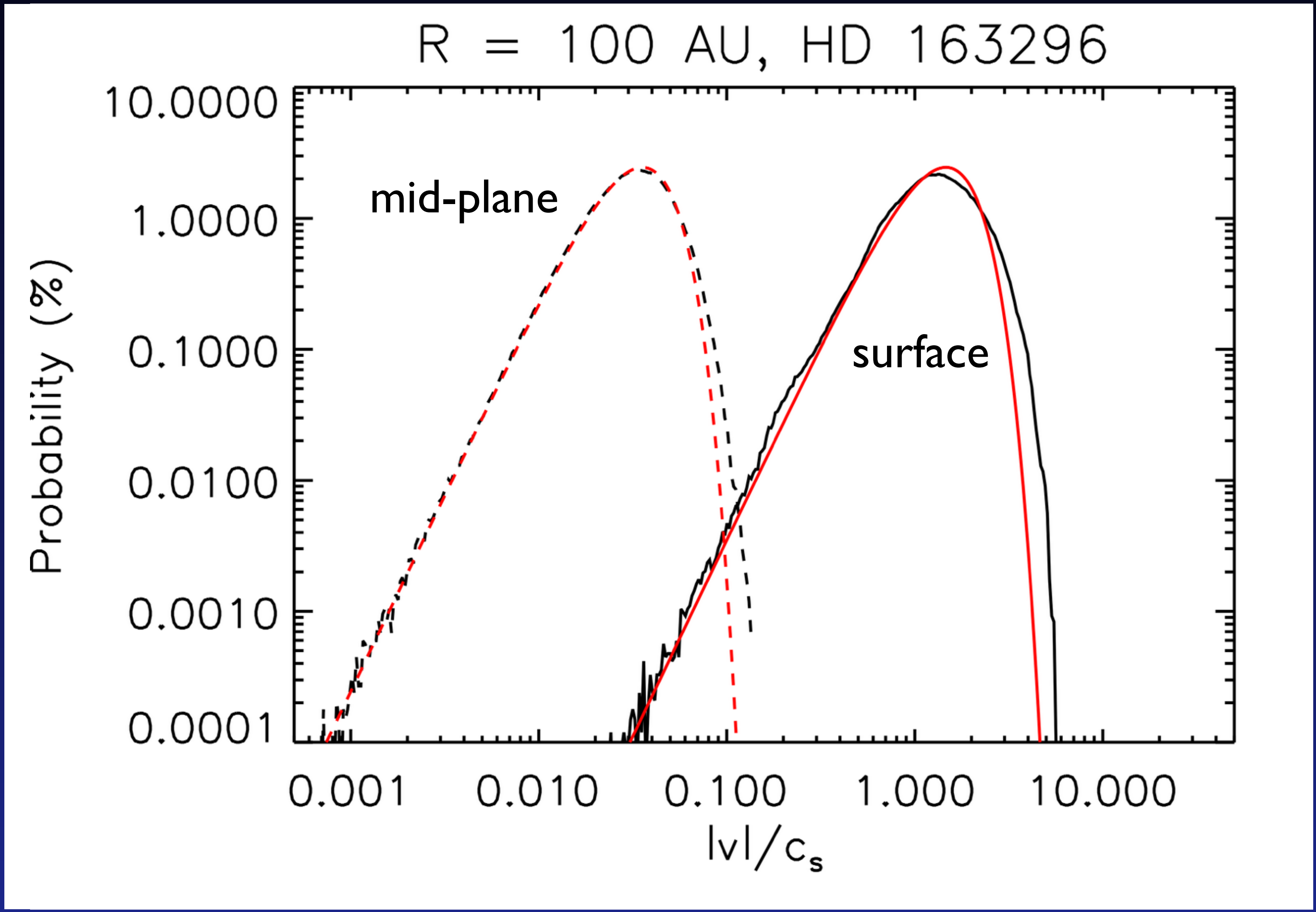


Probability distribution of turbulent velocity is fit by Maxwell-Boltzman.



Simon et al., in prep

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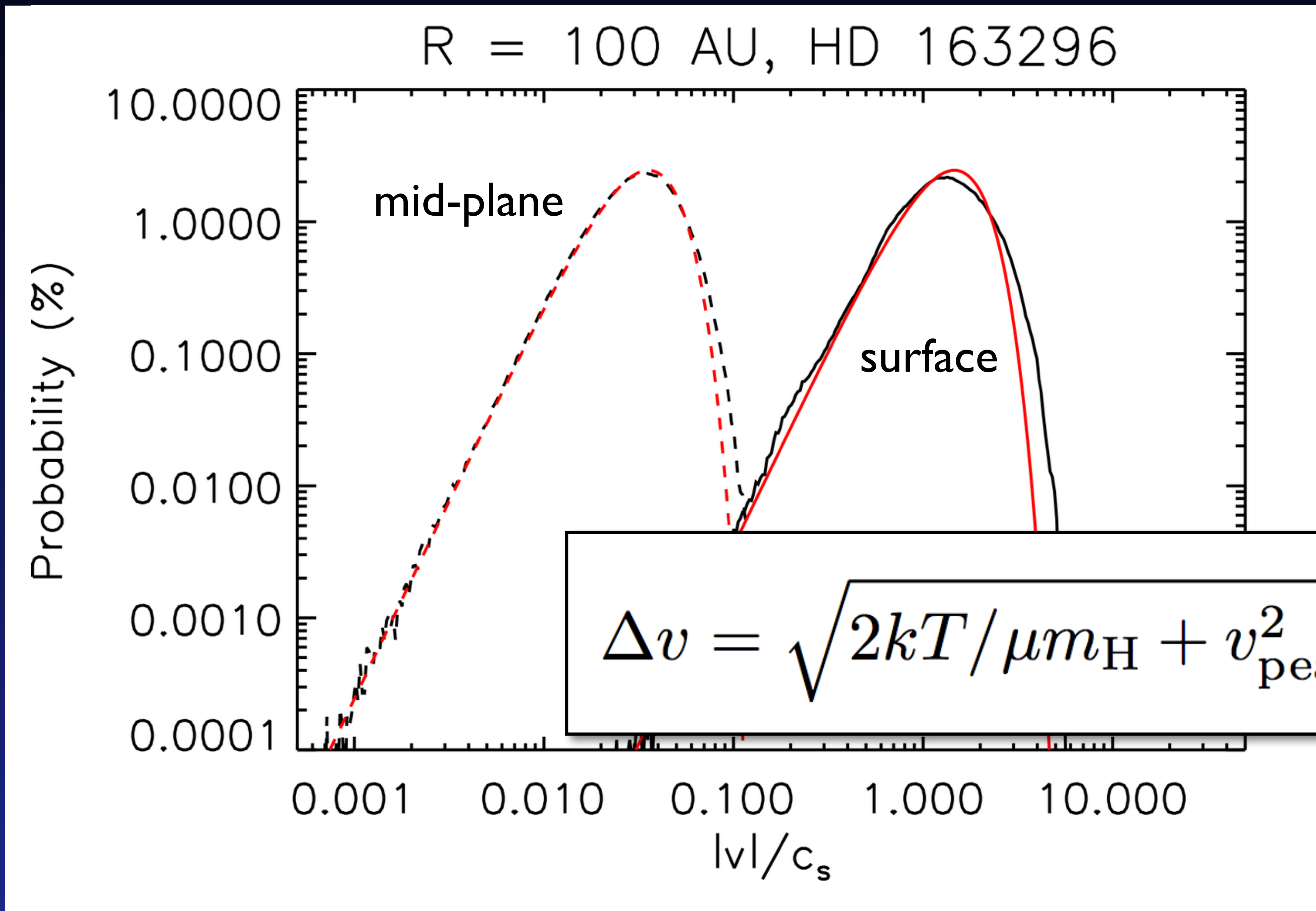

$$\Delta v = \sqrt{2kT/\mu m_{\mathrm{H}} + v_{\mathrm{peak}}^2}$$

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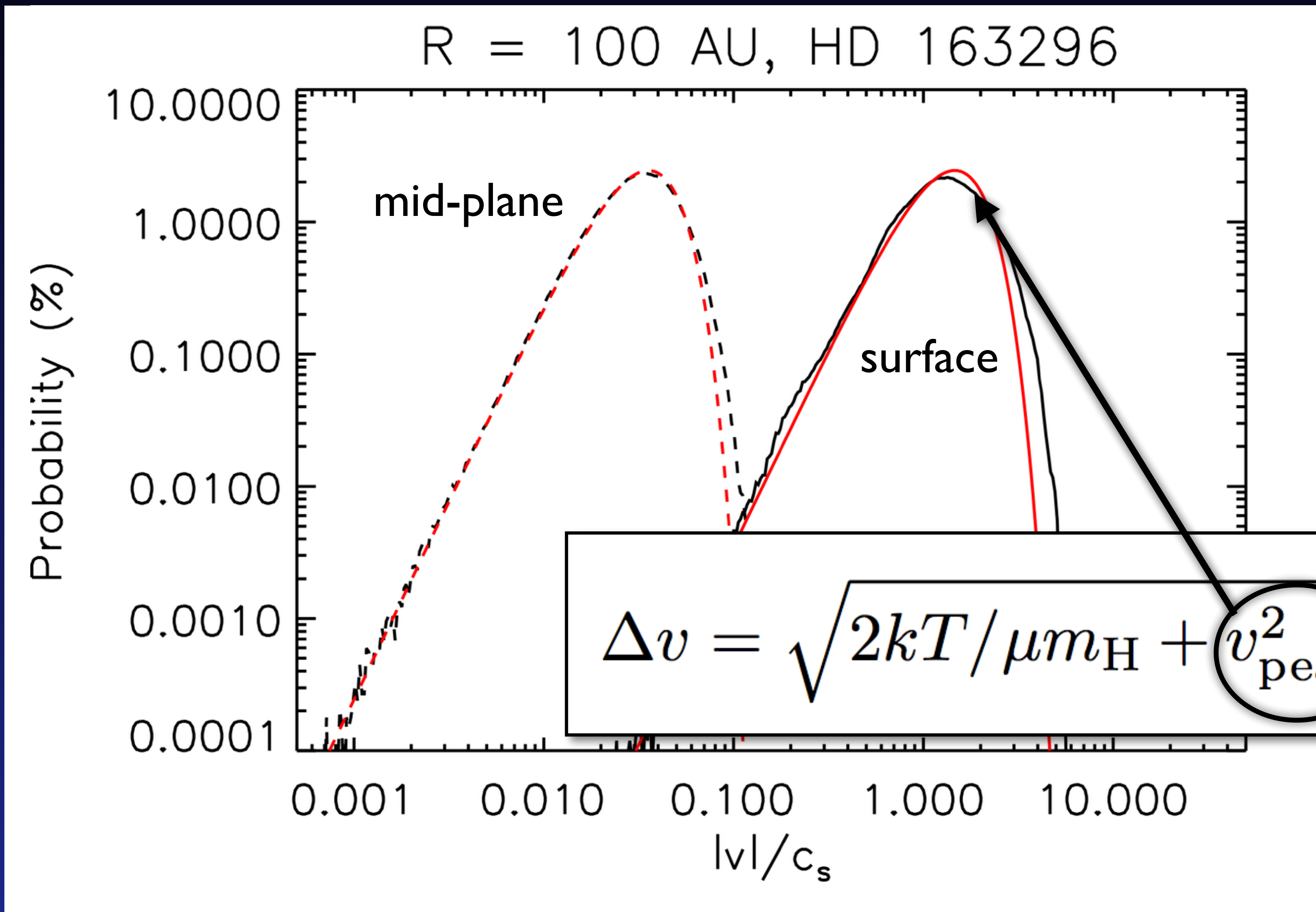

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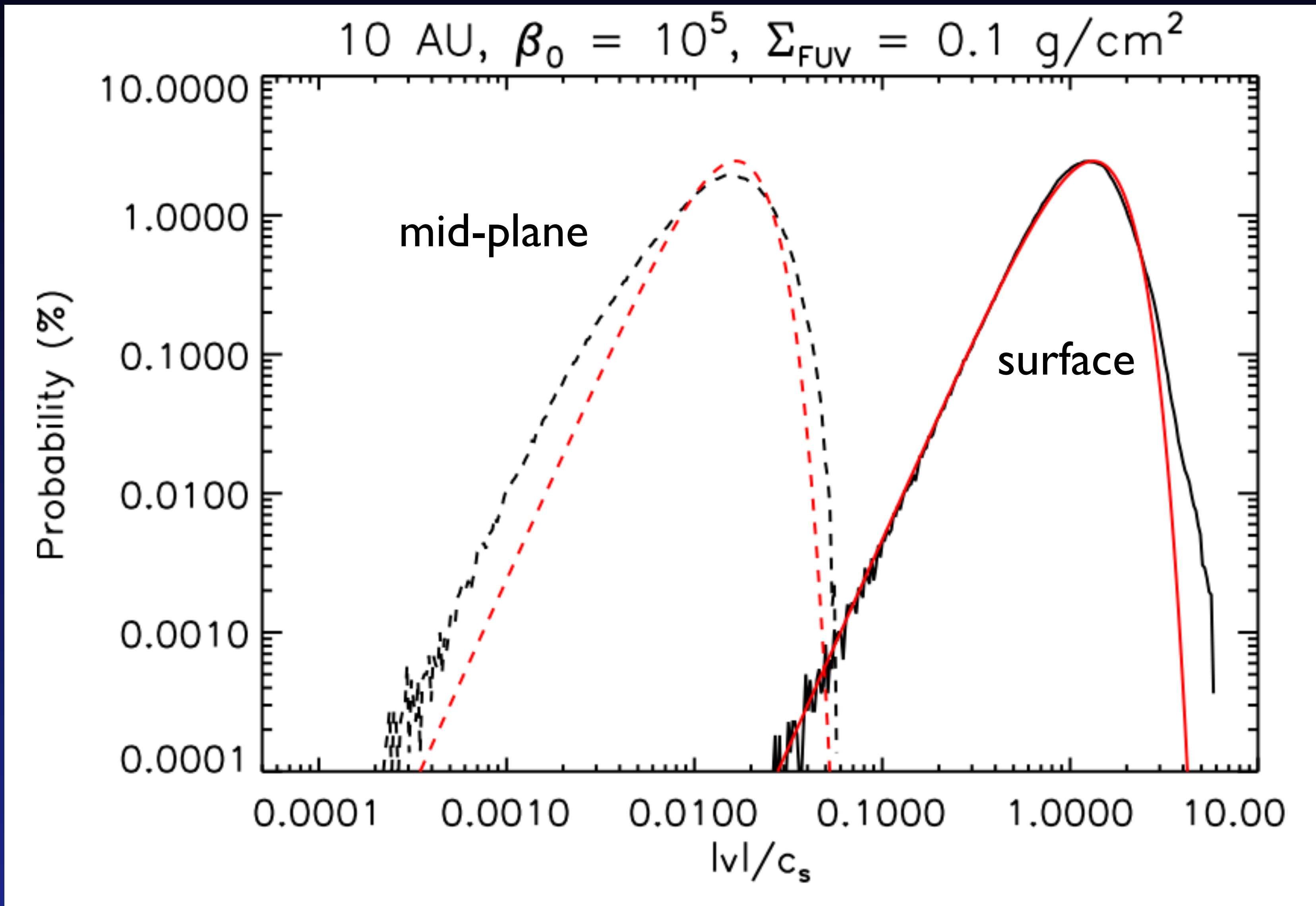
Not all distributions are fit as nicely with a Maxwellian, but we need to be consistent



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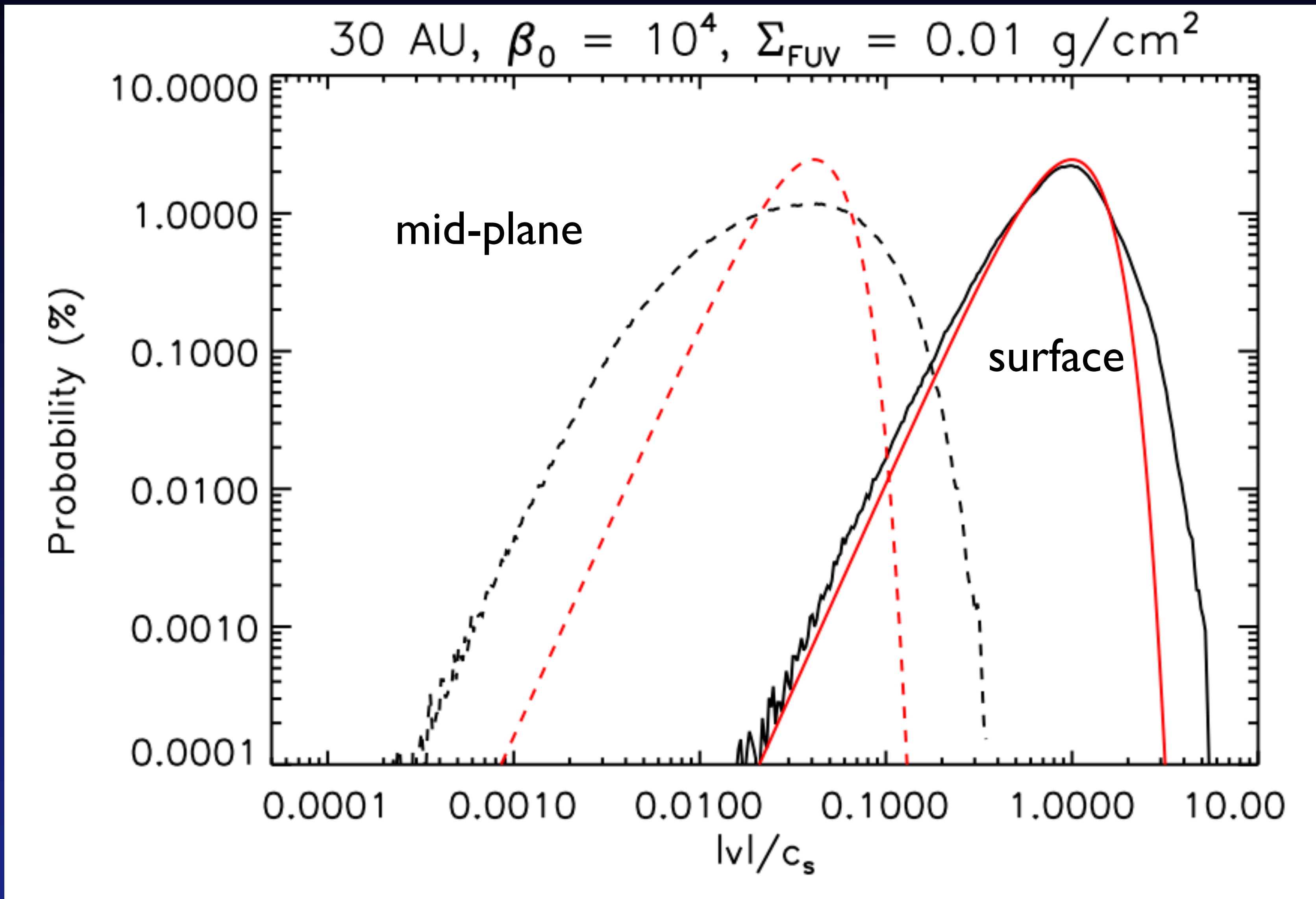
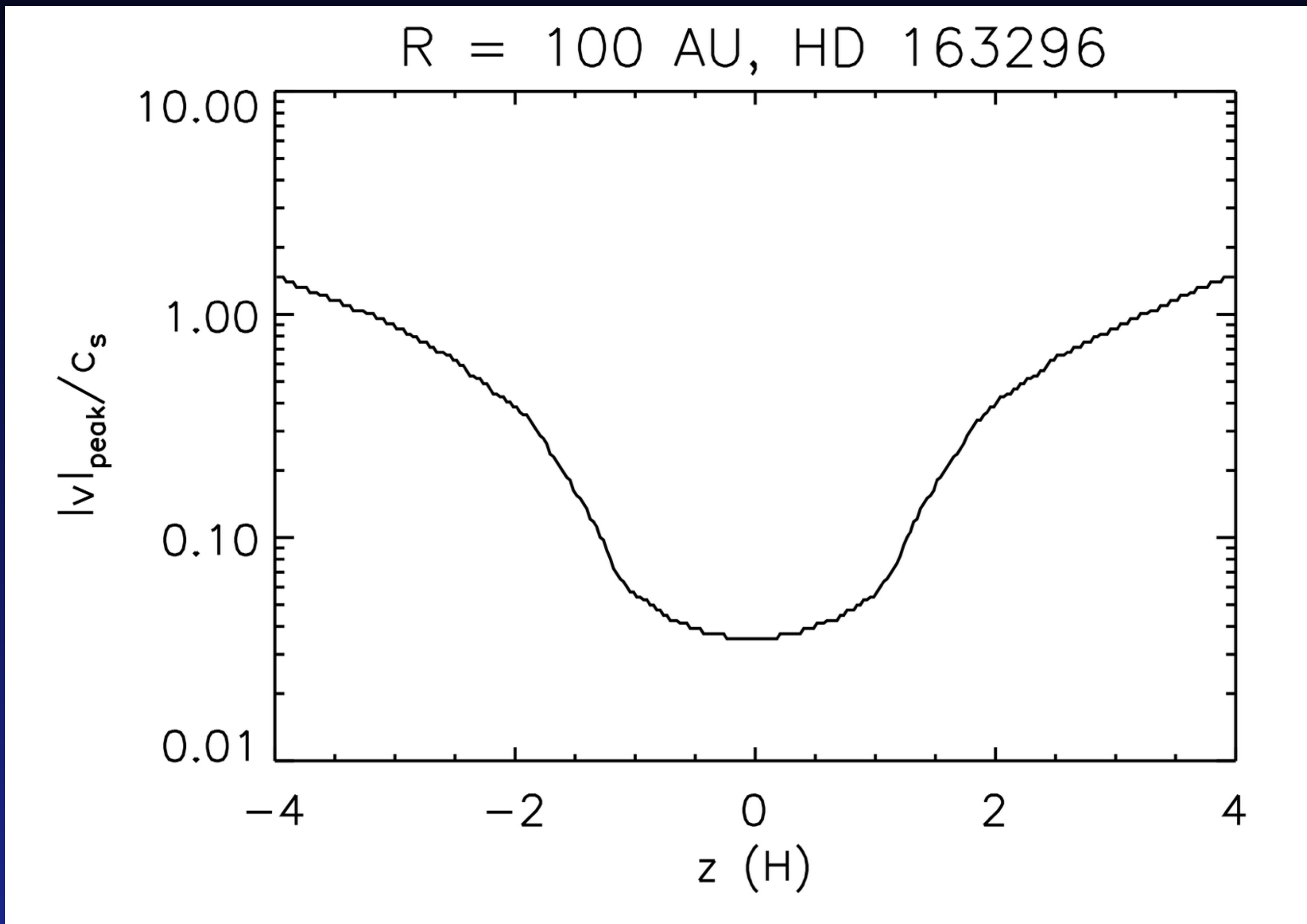


Simon et al., in prep

Strong gradient in turbulent velocity towards disk mid-plane



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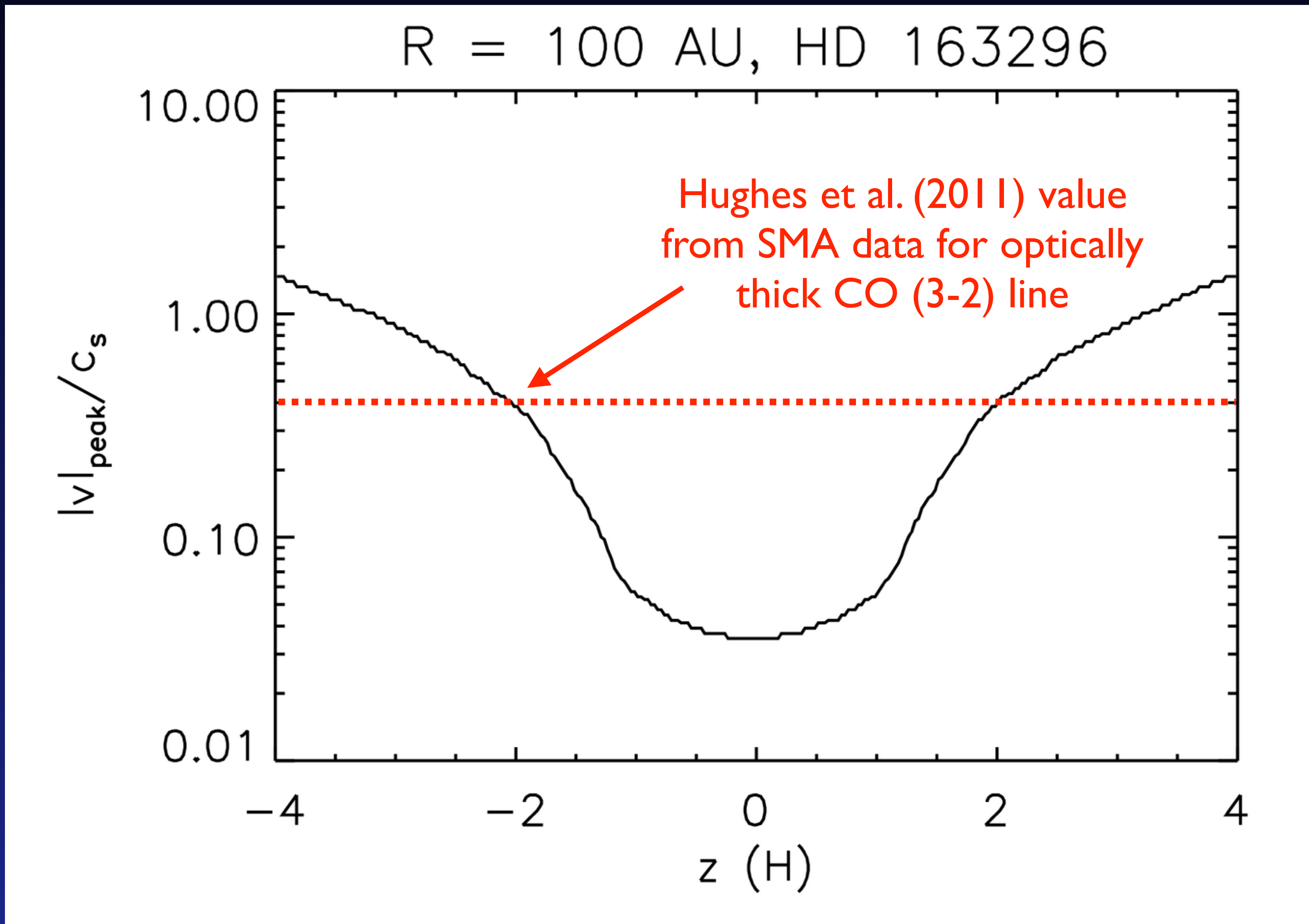

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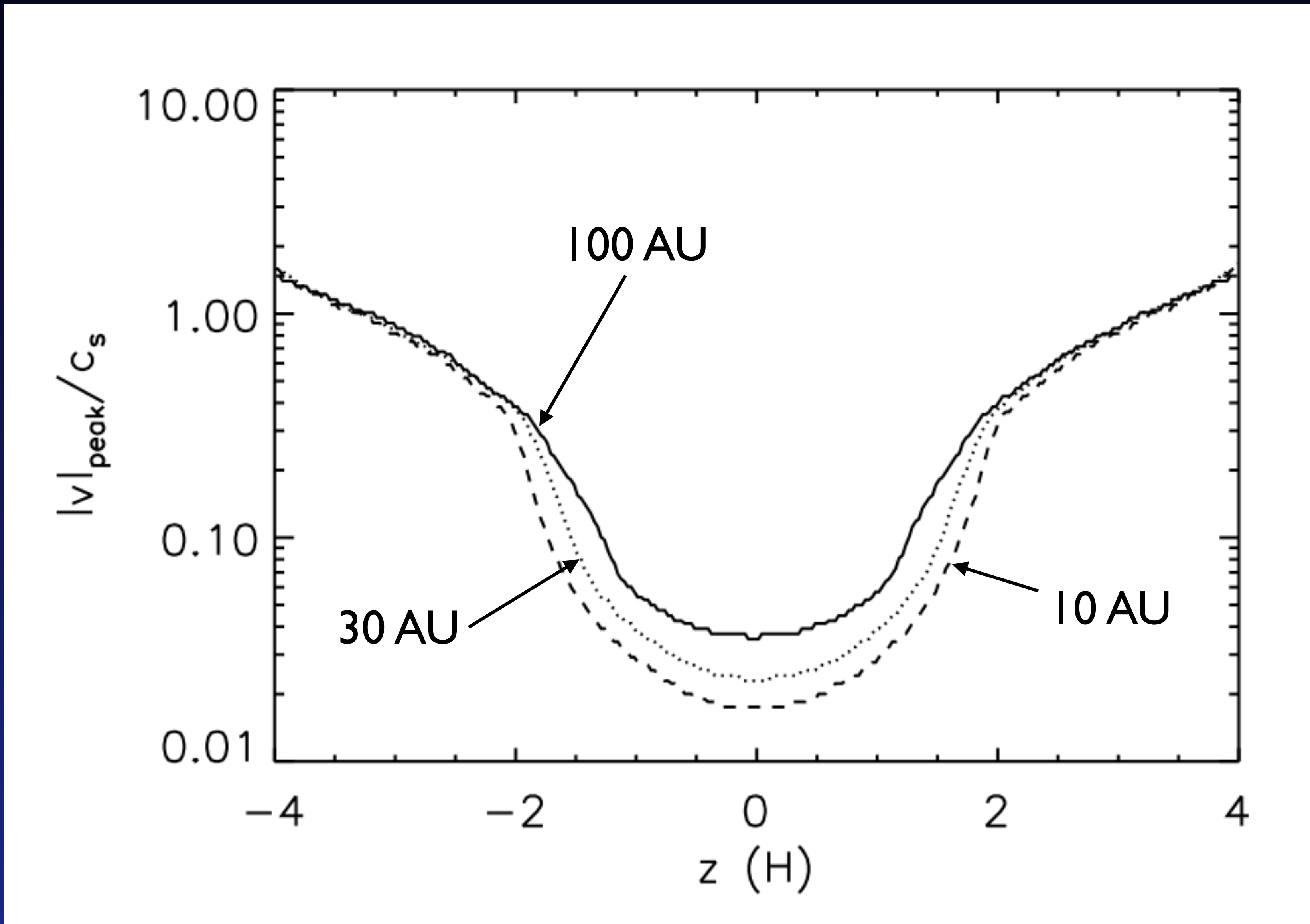
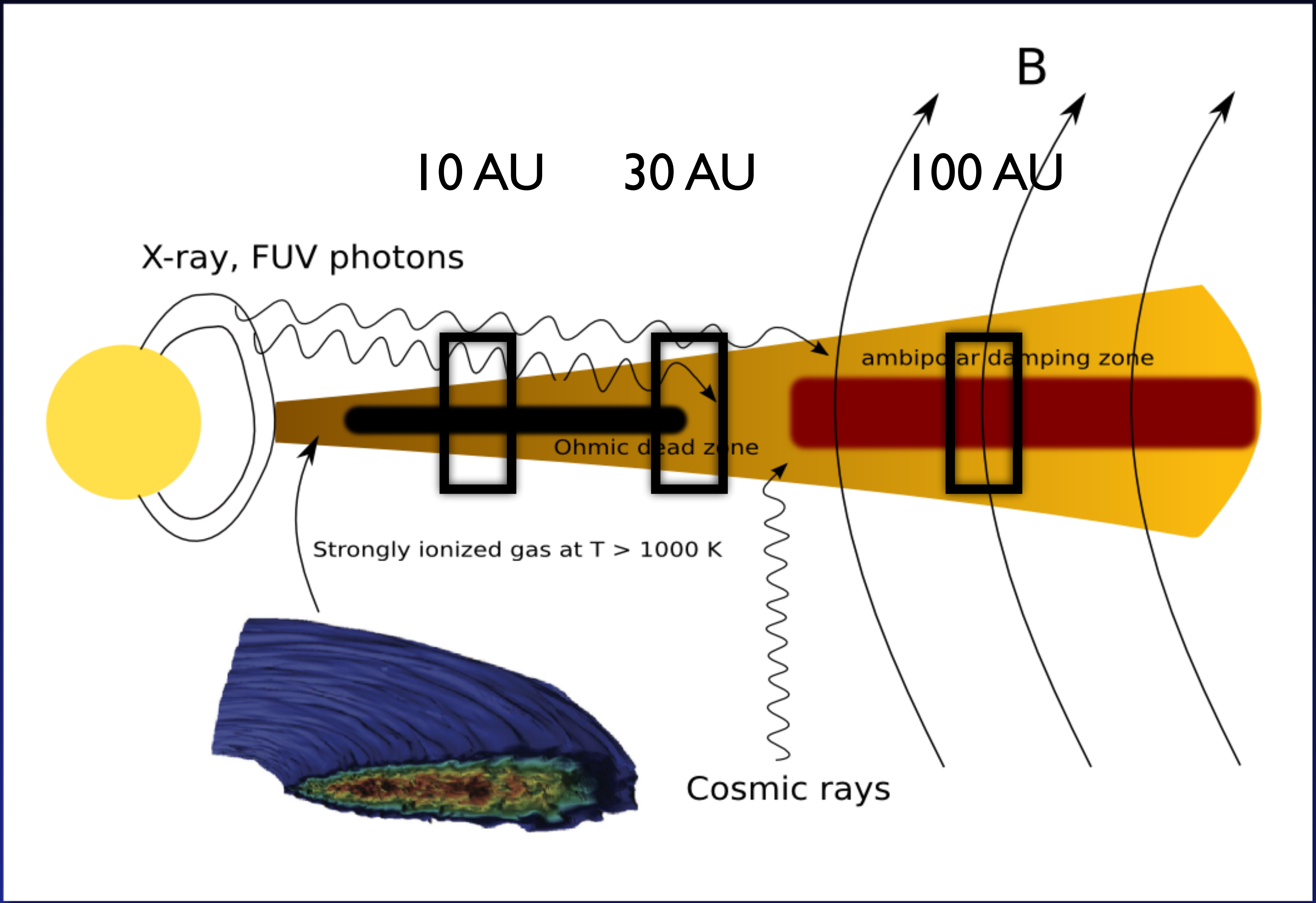


Simon et al., in prep

Construct turbulence model by interpolating simulation results



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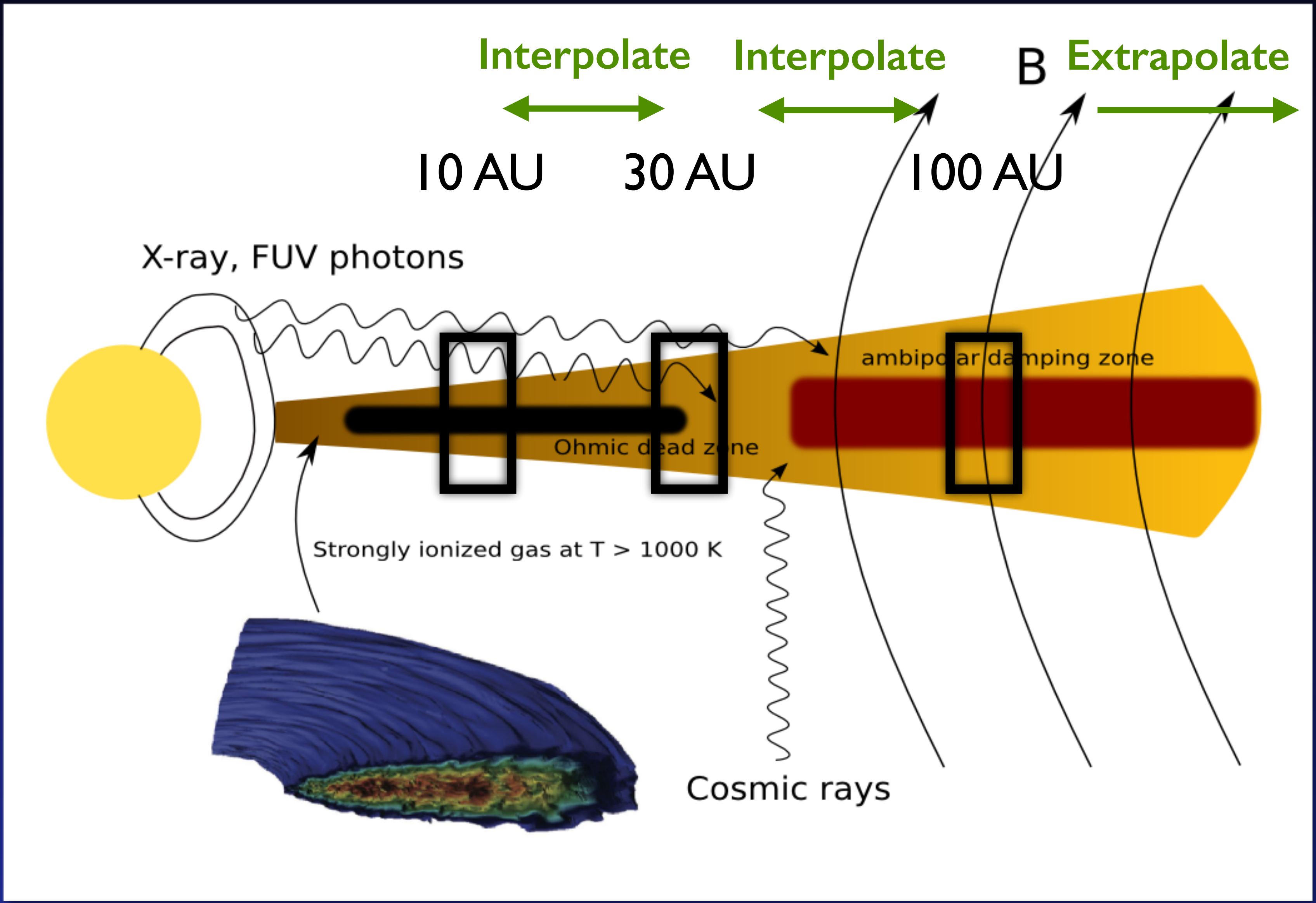
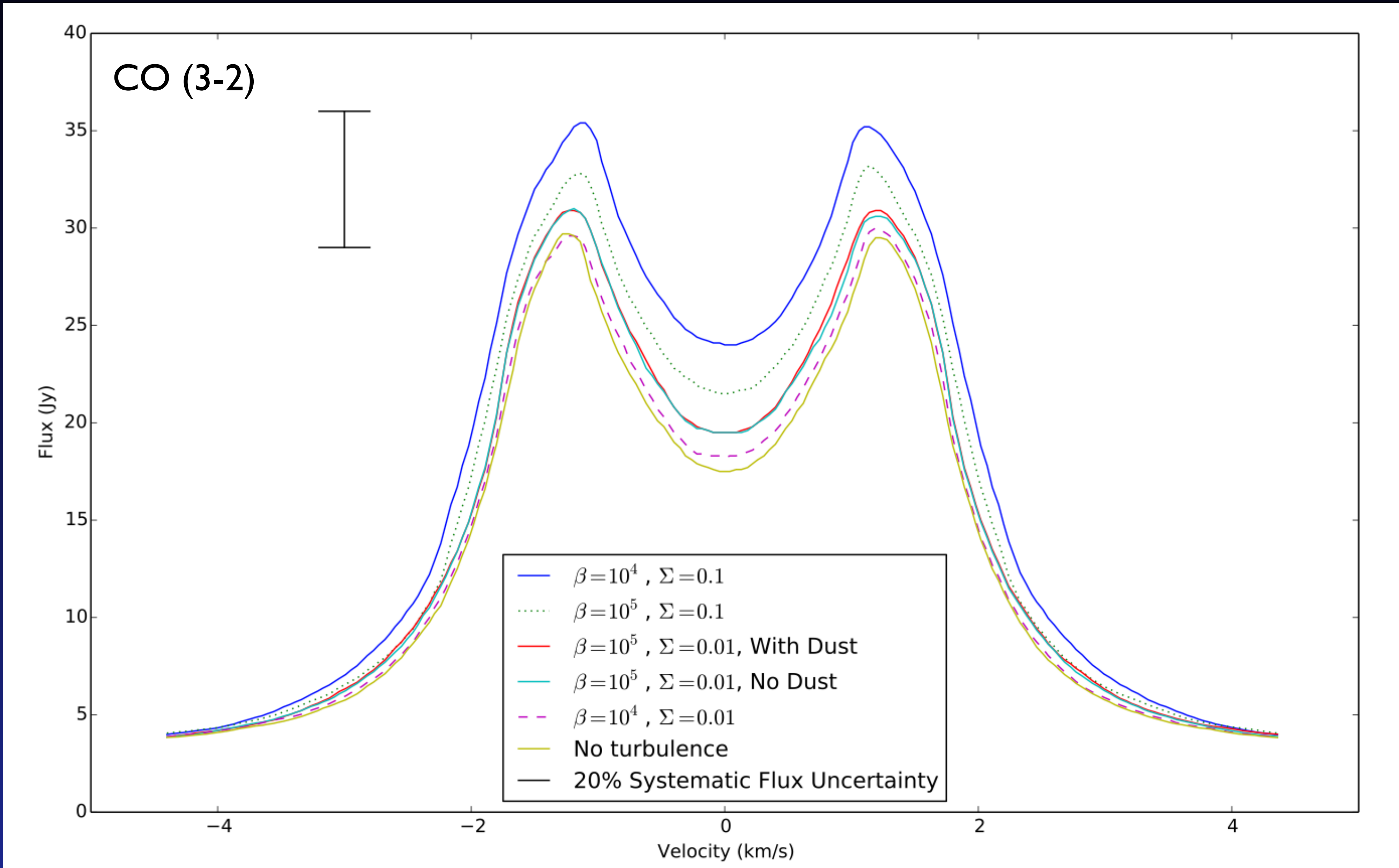


Put it all together!

LIME
Line Modeling Engine



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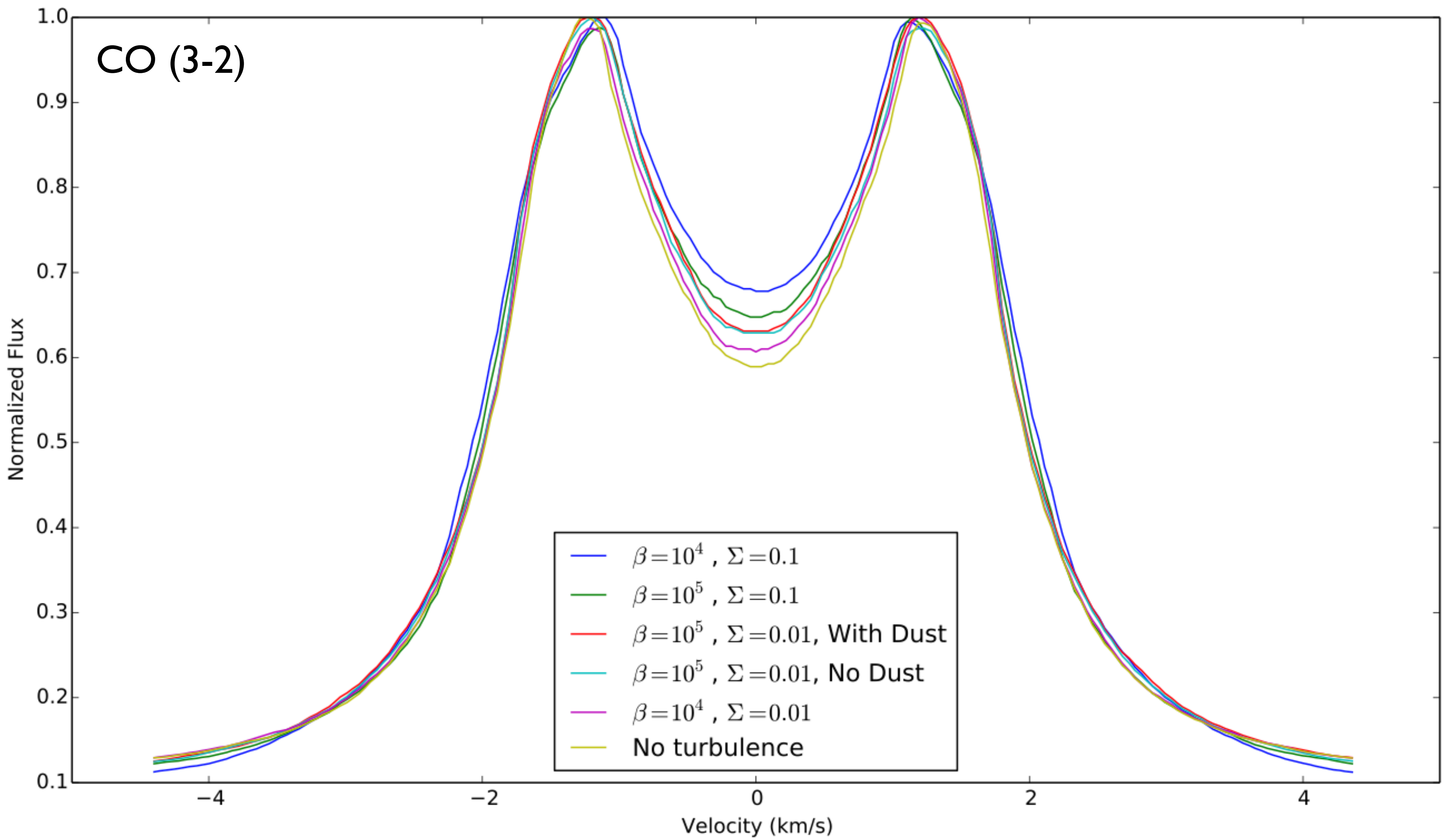

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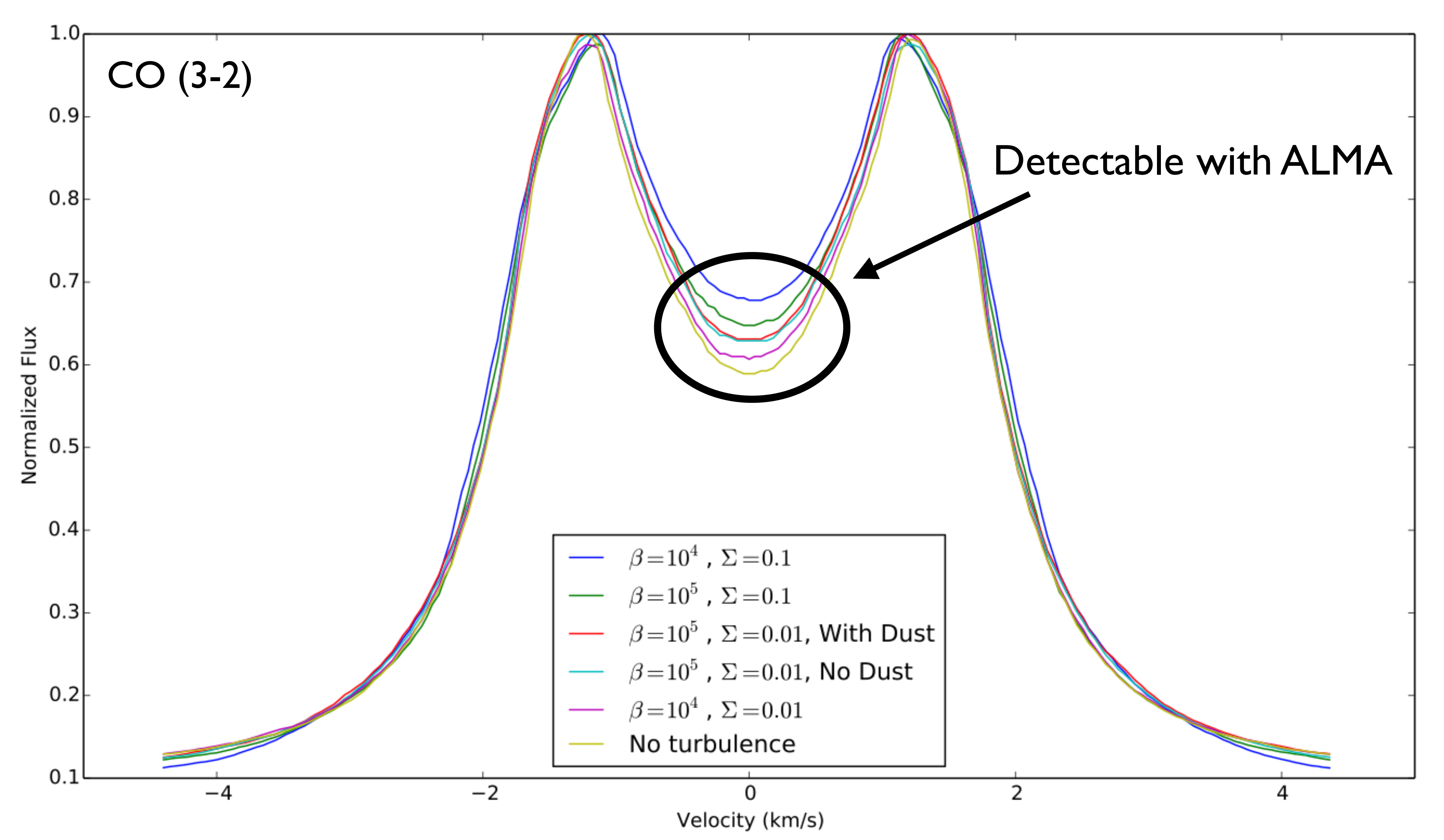
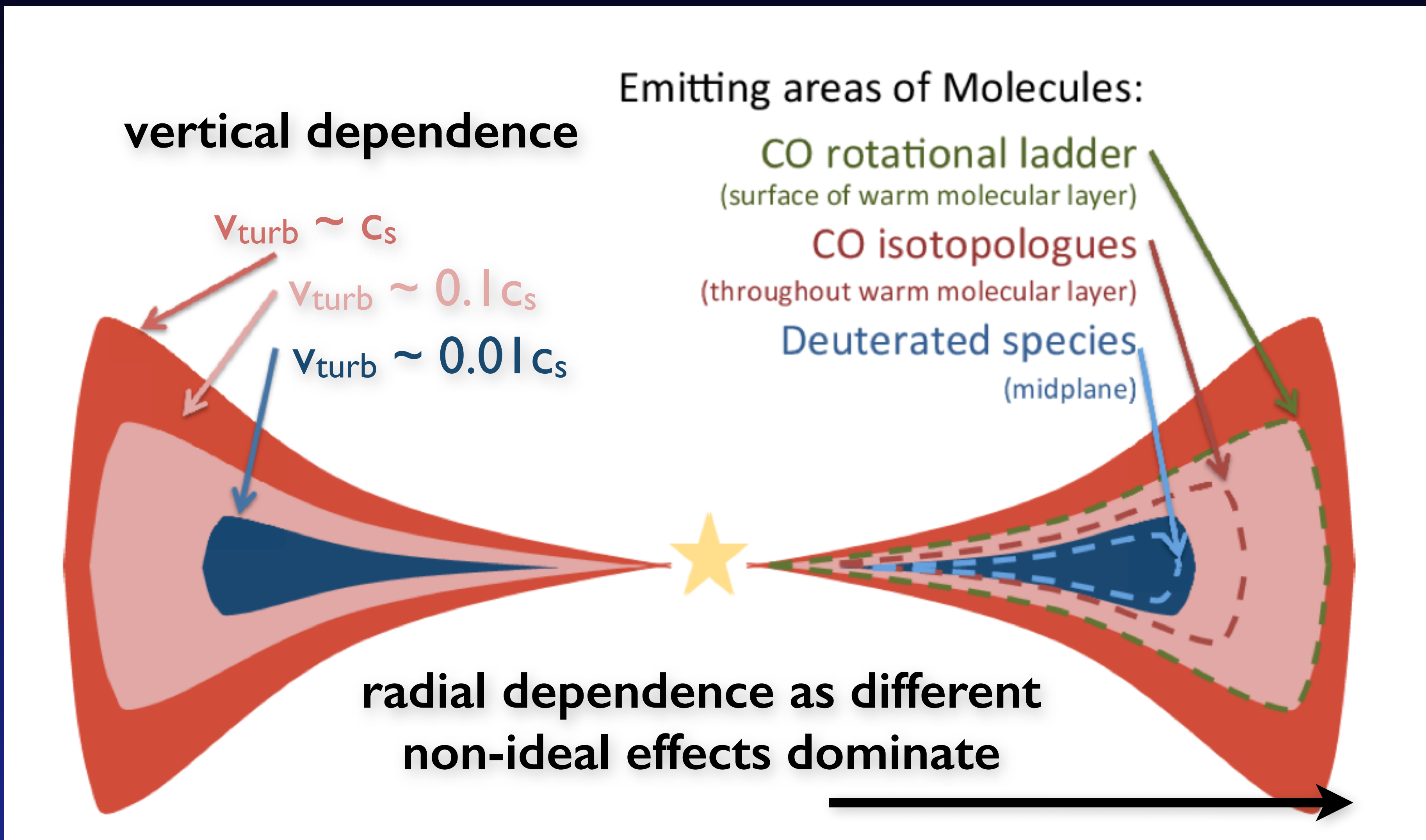
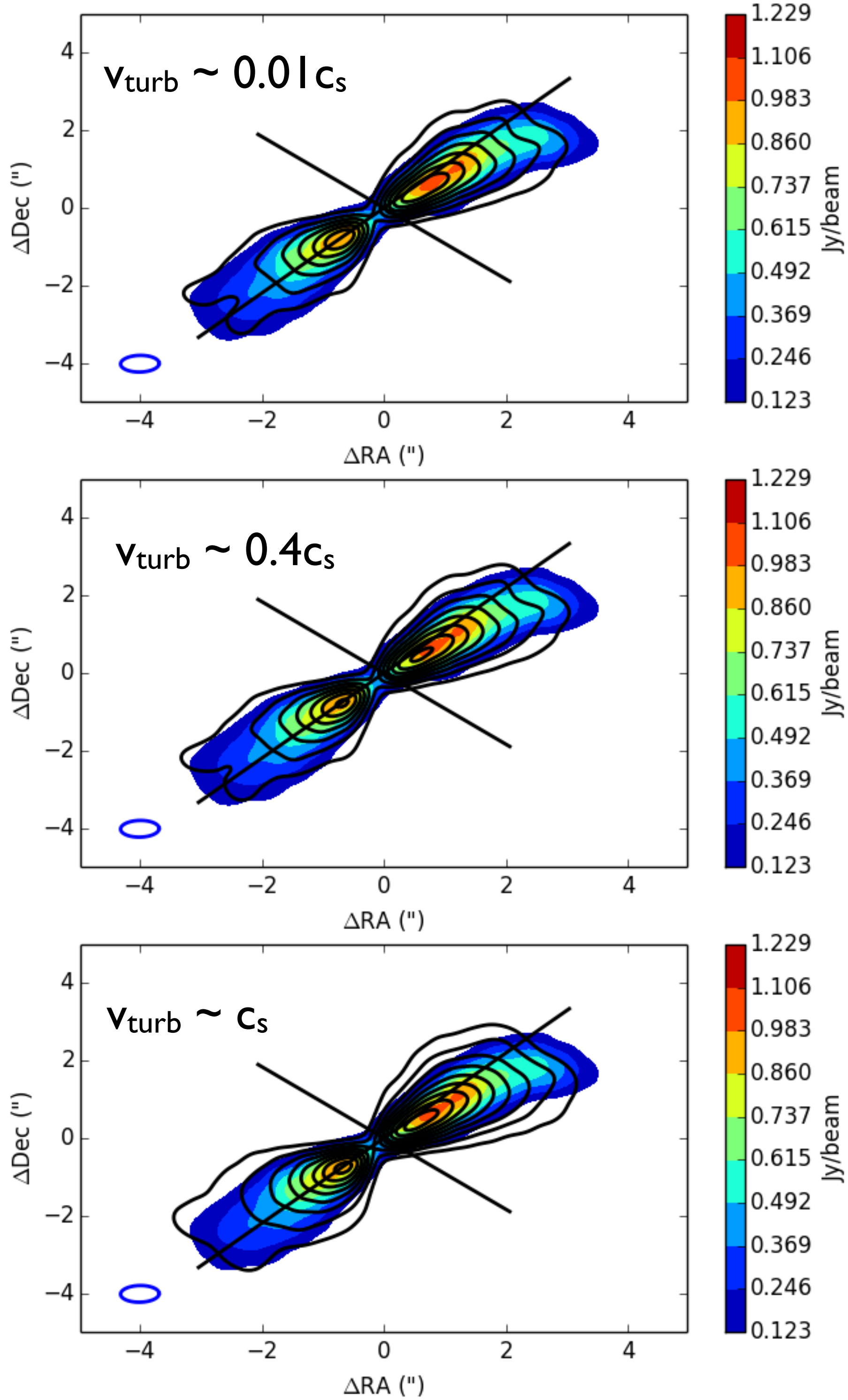


Simon et al., in prep

Next: Add more diagnostics and compare to observations



Meredith Hughes



Study radial dependence for turbulence!

Kevin Flaherty

Conclusions

- Differences in turbulent structure of disks should be observable with ALMA
- By directly combining state-of-the-art theory and observations, we will constrain protoplanetary disk models.
- If MRI turbulence is present in these disks, we should observe a strong increase in turbulent velocity away from the mid-plane.