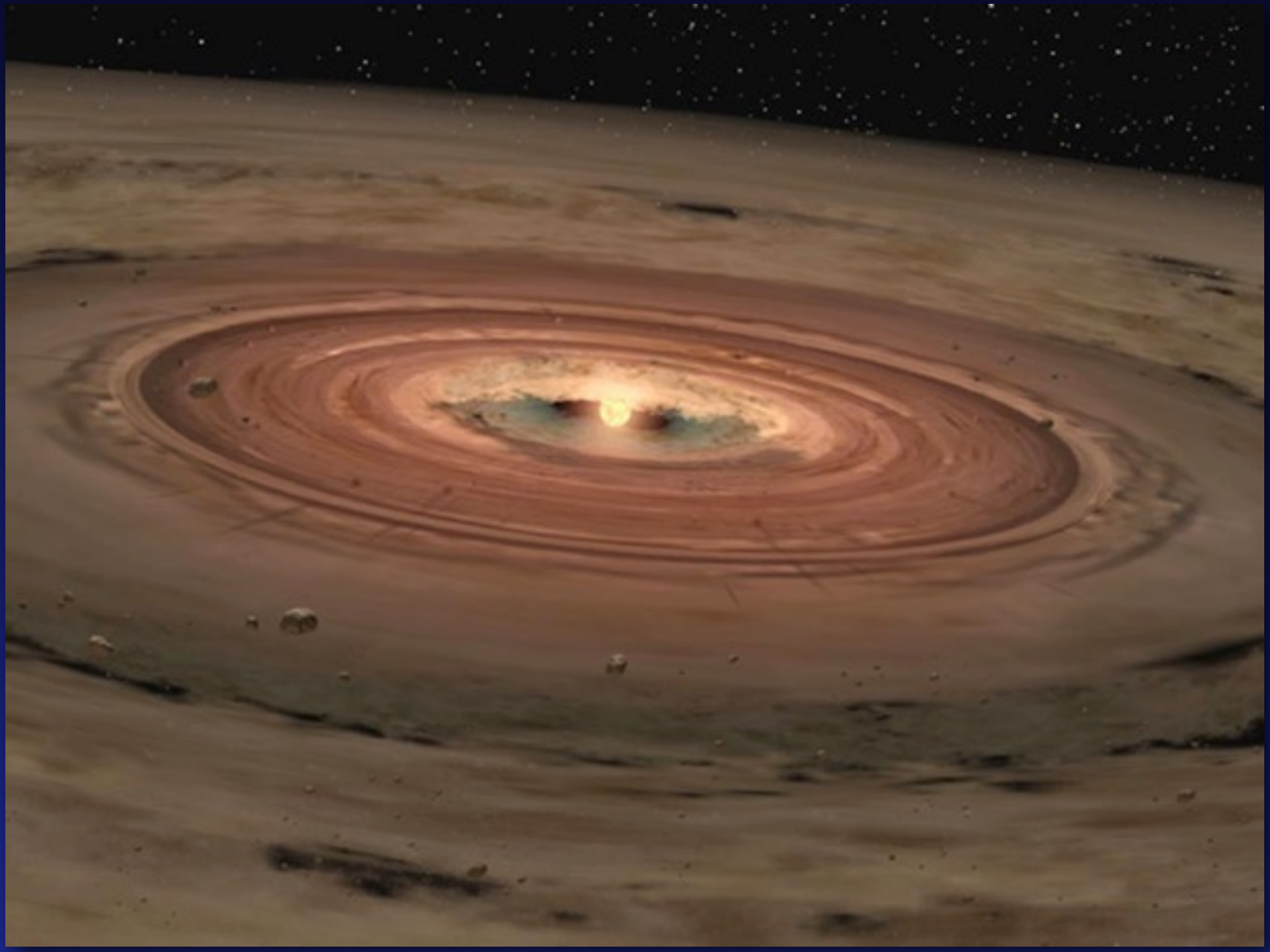
Turbulence vs. Wind
How is angular momentum transported in protoplanetary disks?



Courtesy: NASA

Jacob B. Simon

CU Boulder

SwRI

Collaborators

Meredith Hughes

Kevin Flaherty

Xuening Bai

Geoffroy Lesur

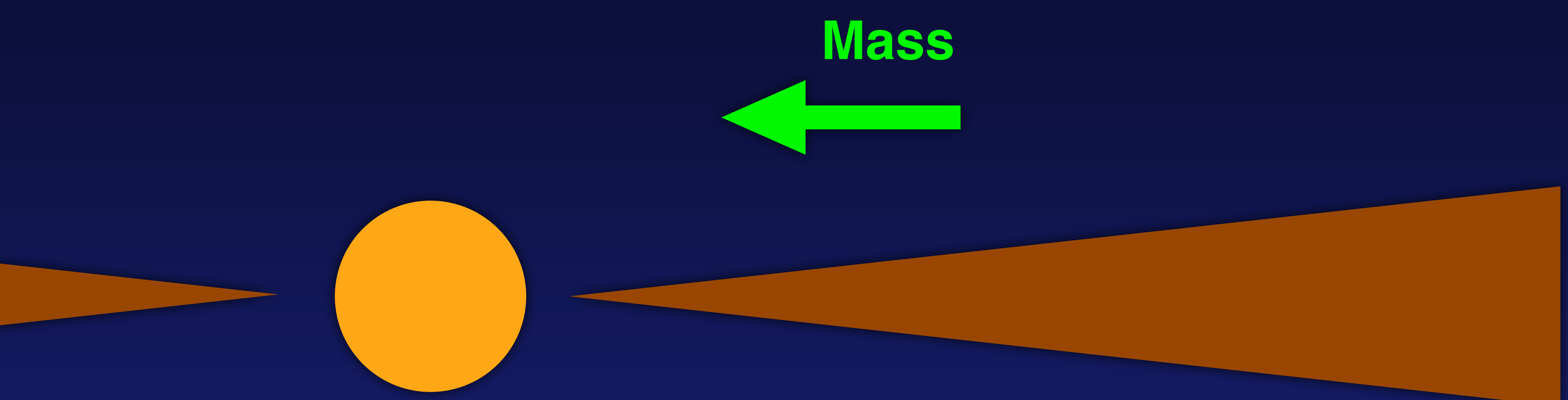
Matt Kunz

Phil Armitage

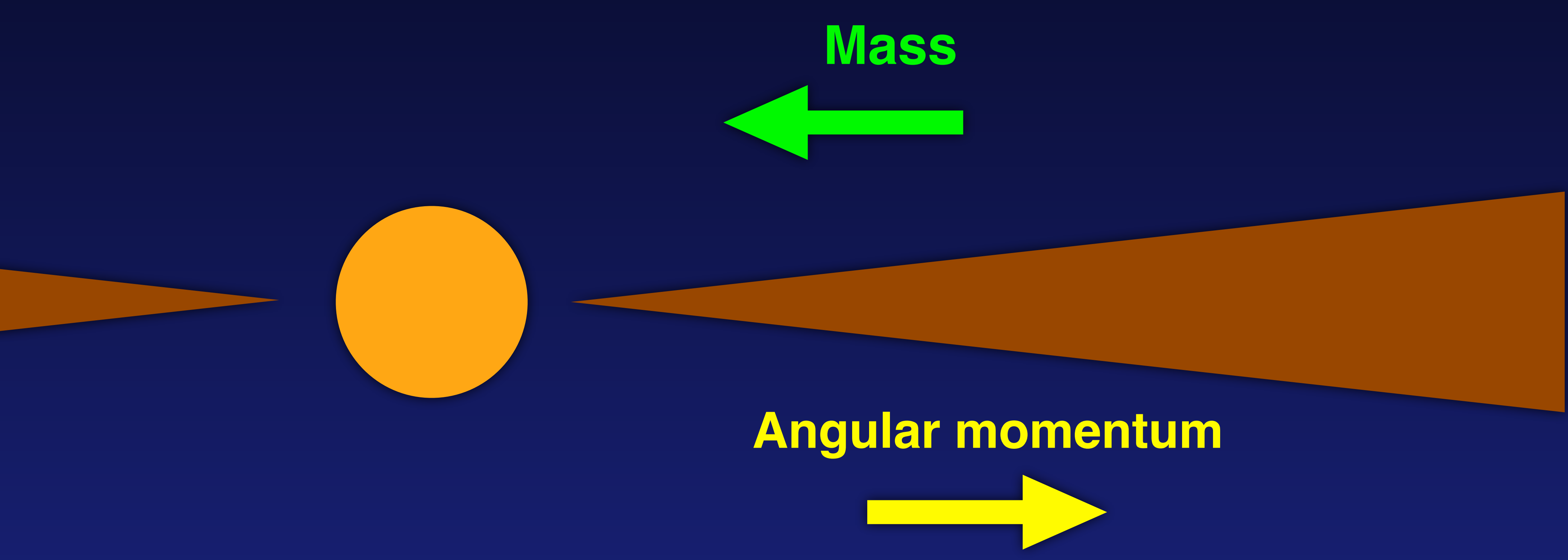
February 23, 2017

KITP

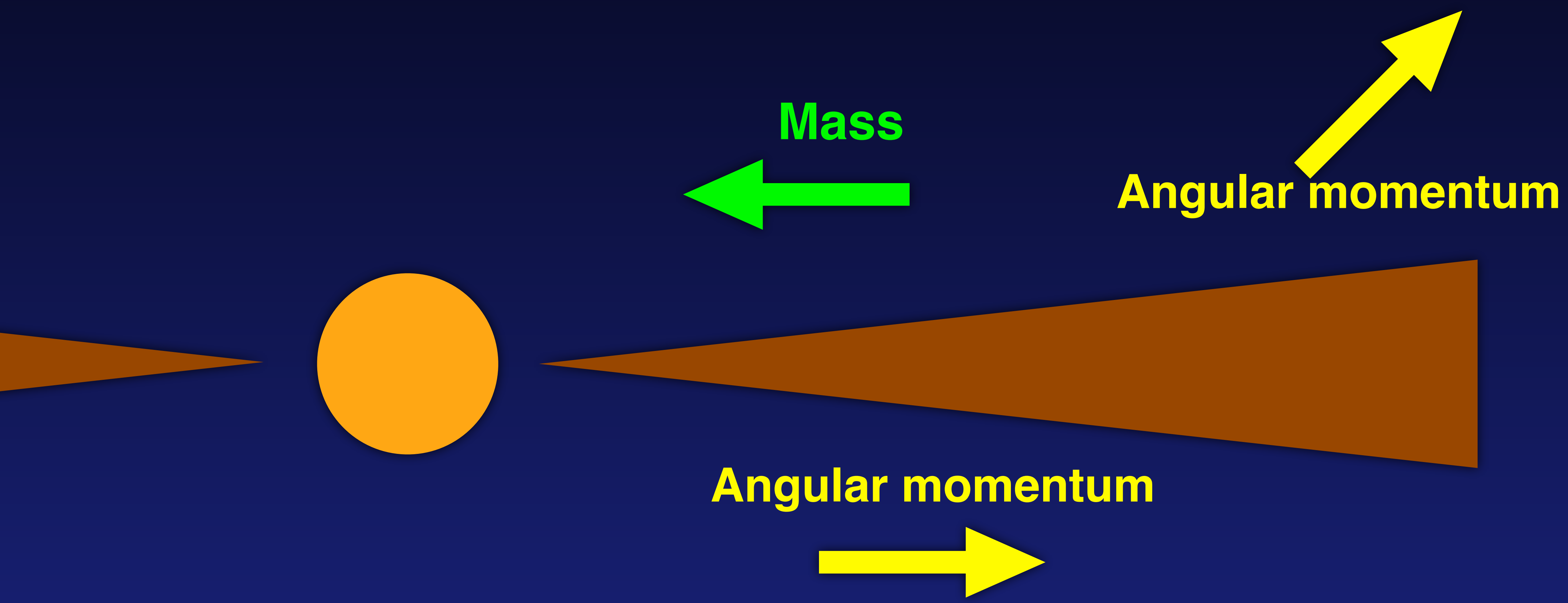
How does disk gas lose angular momentum and accrete onto the star?



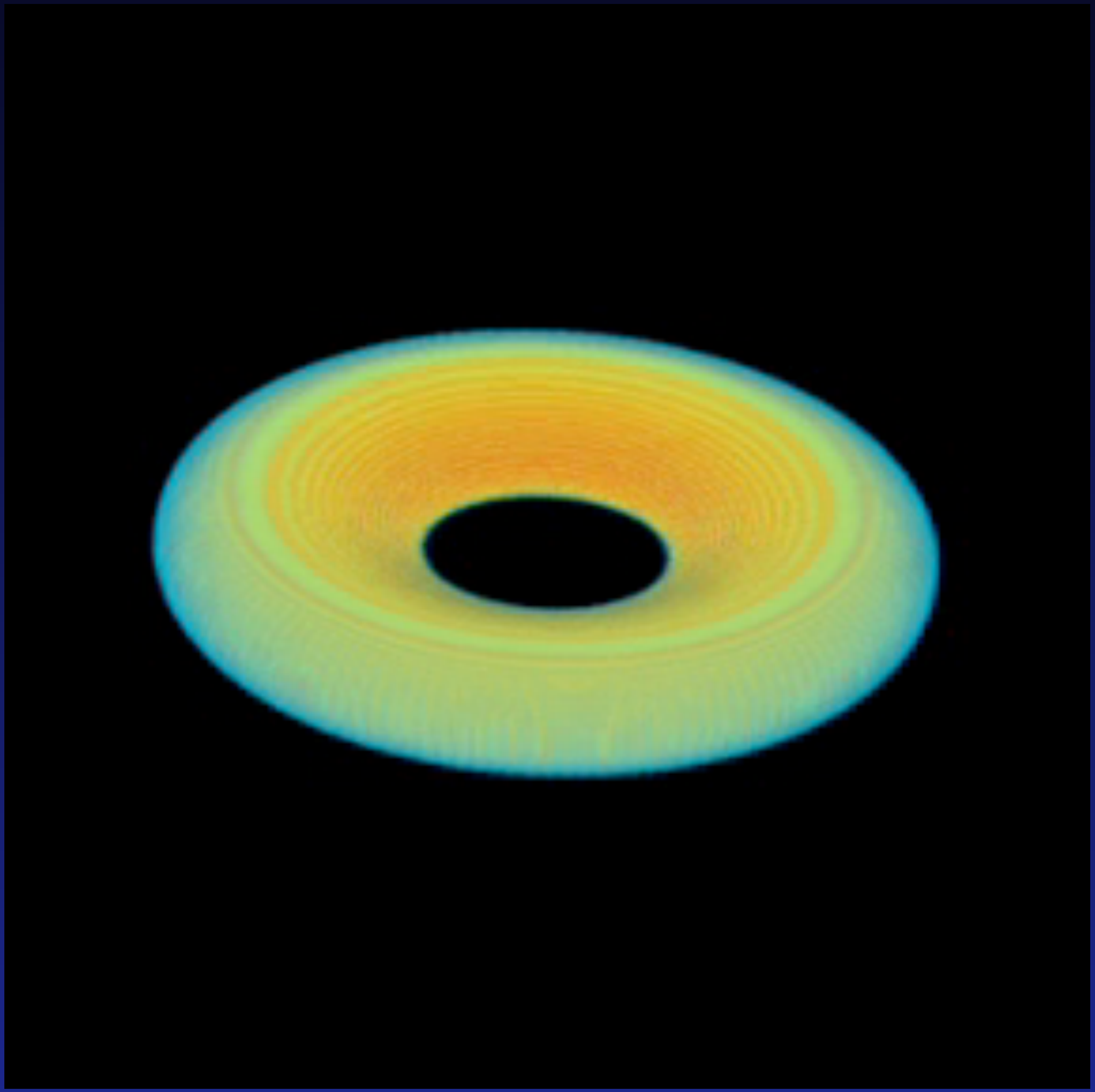
How does disk gas lose angular momentum and accrete onto the star?



How does disk gas lose angular momentum and accrete onto the star?

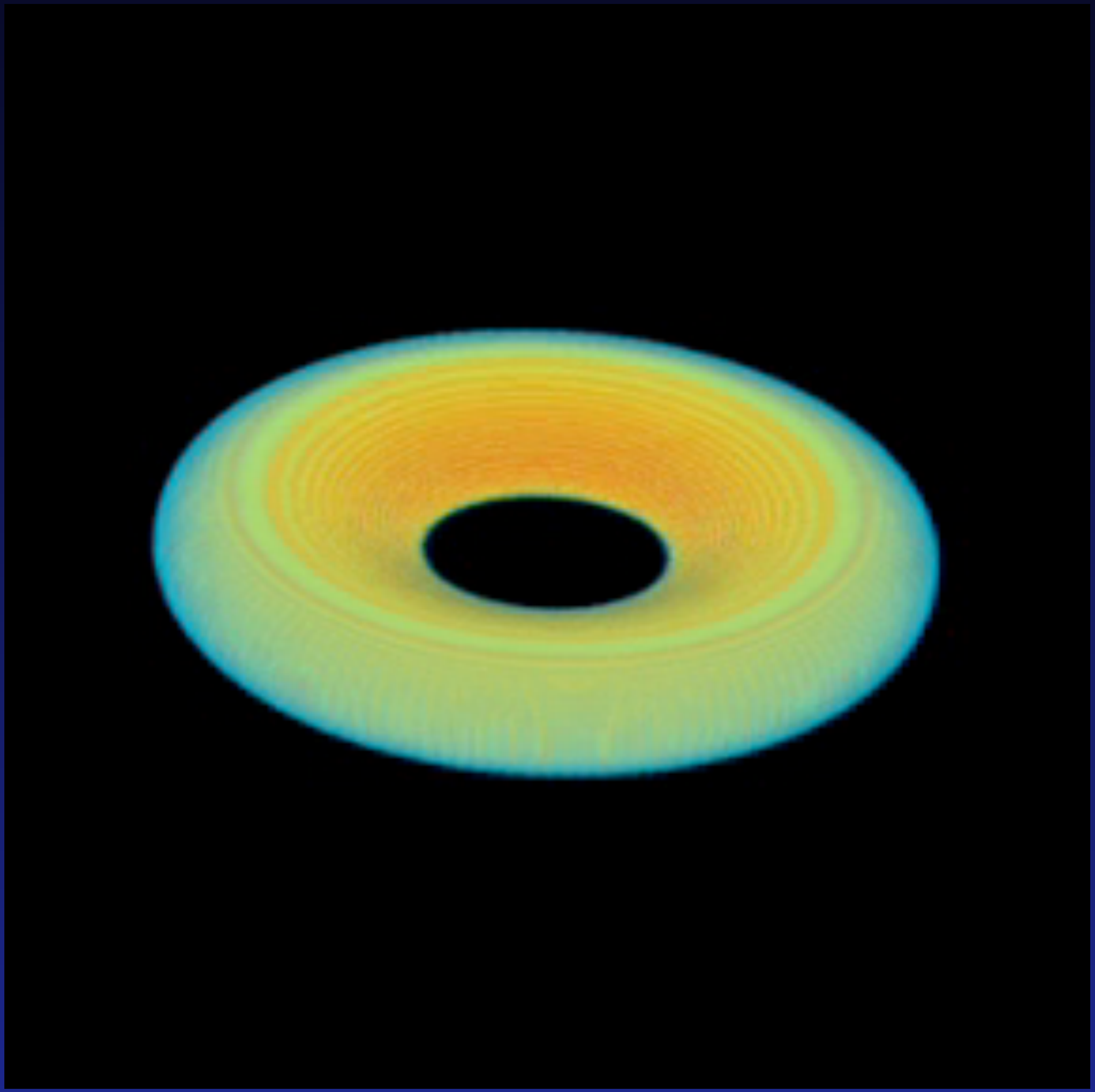


A very likely candidate for radial transport is turbulence via the *magnetorotational instability (MRI)* (though there are others…)



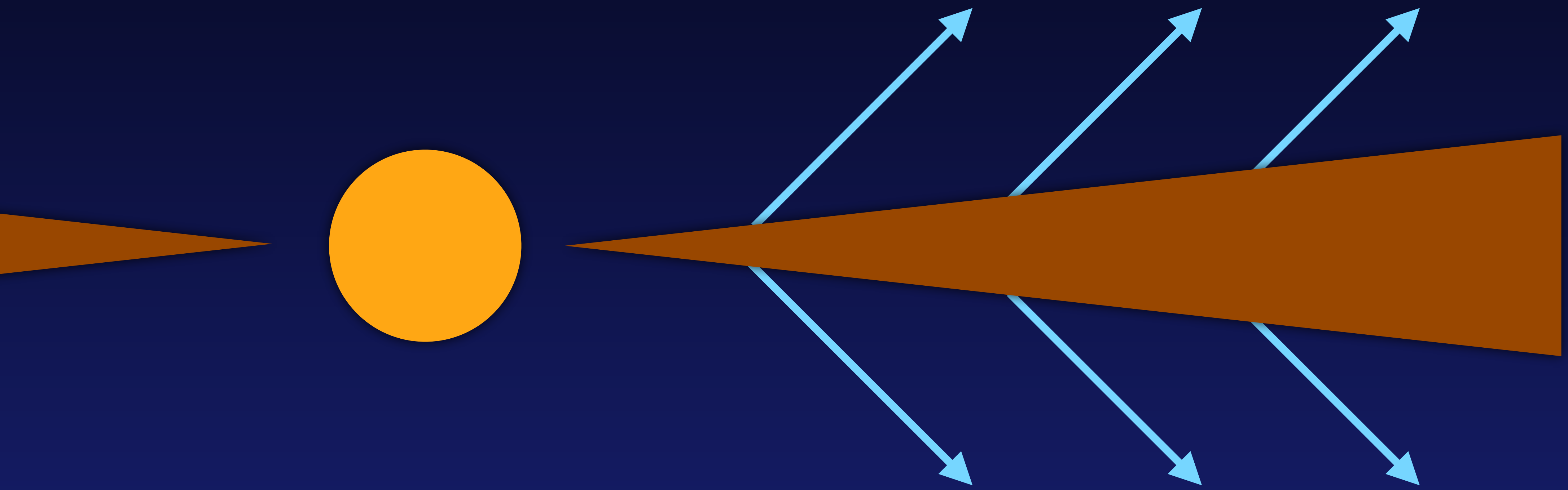
Hawley (2000)

A very likely candidate for radial transport is turbulence via the *magnetorotational instability (MRI)* (though there are others…)

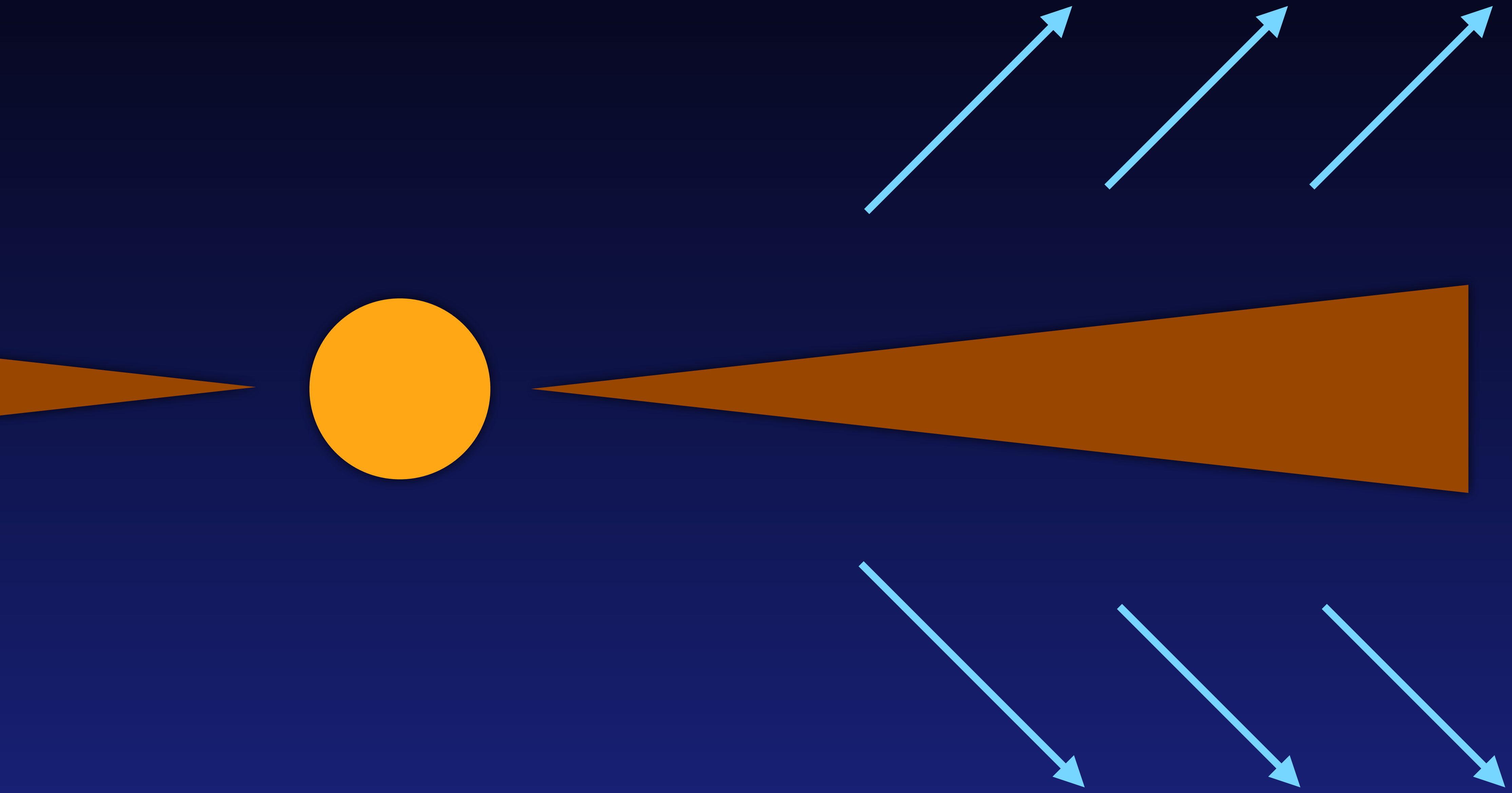


Hawley (2000)

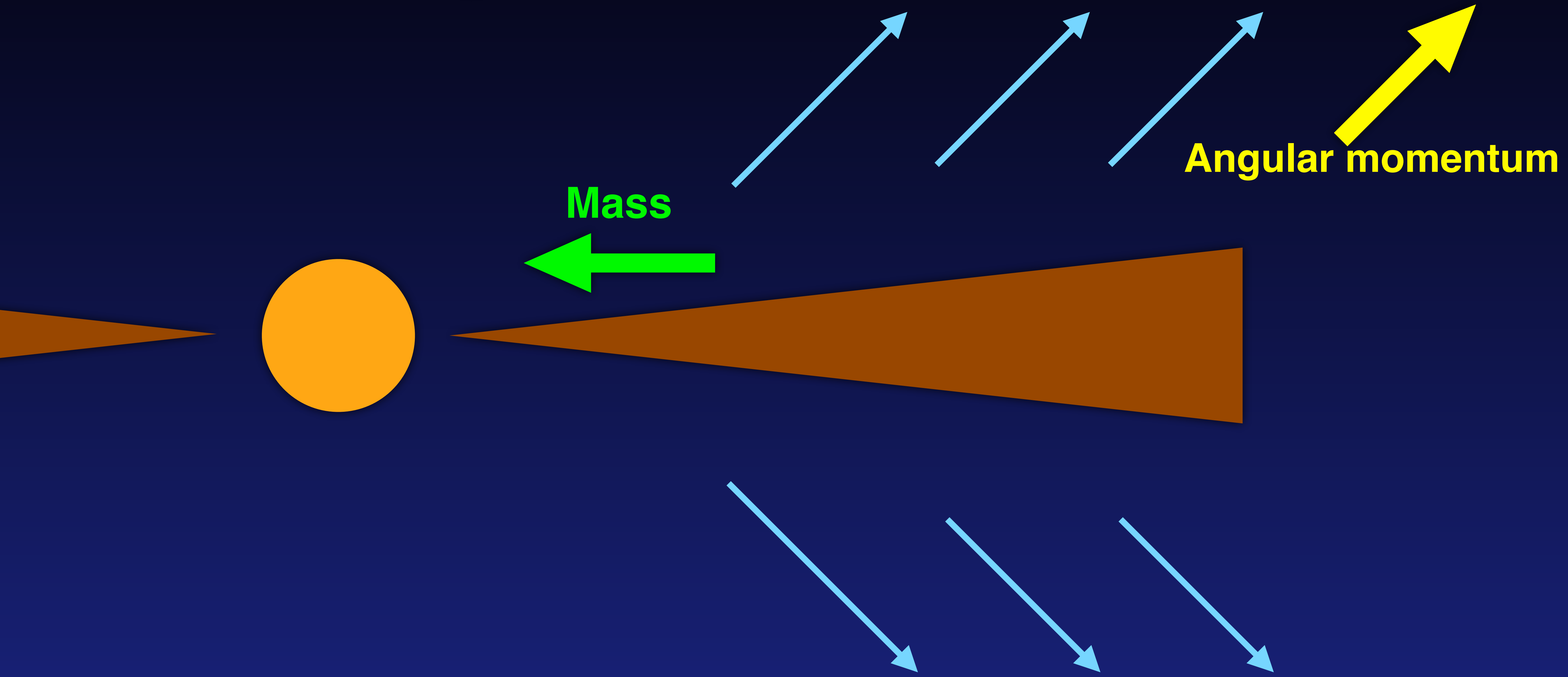
To remove angular momentum vertically, there needs to be a *wind*



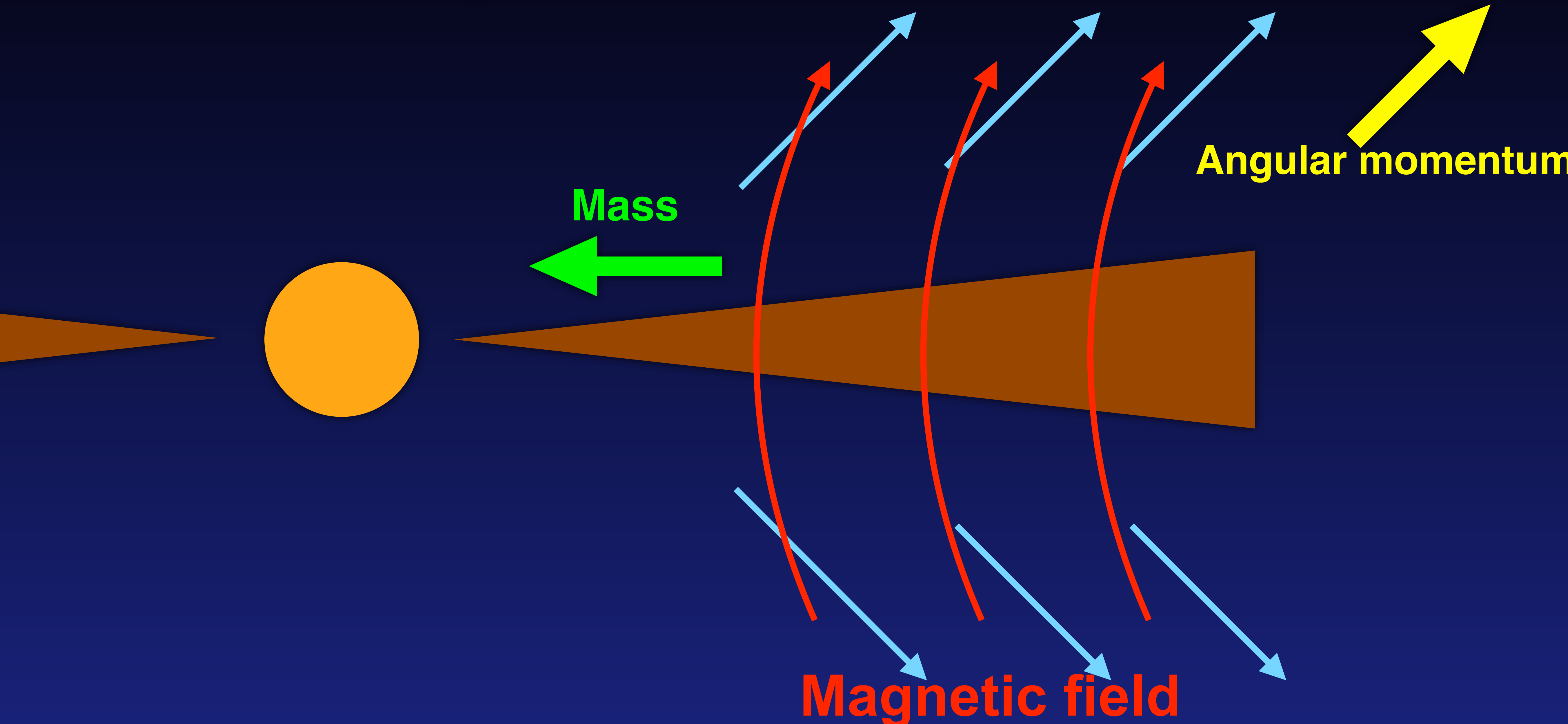
To remove angular momentum vertically, there needs to be a *wind*



To remove angular momentum vertically, there needs to be a *wind*



To remove angular momentum vertically, there needs to be a *wind*



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

Three effects

1. Ohmic resistivity → e^- / ion$^+$ collide with neutrals

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

Three effects

1. Ohmic resistivity → e^-, ion^+ collide with neutrals

2. Hall effect → e^- tied to mag. field; ion^+ collide with neutrals

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

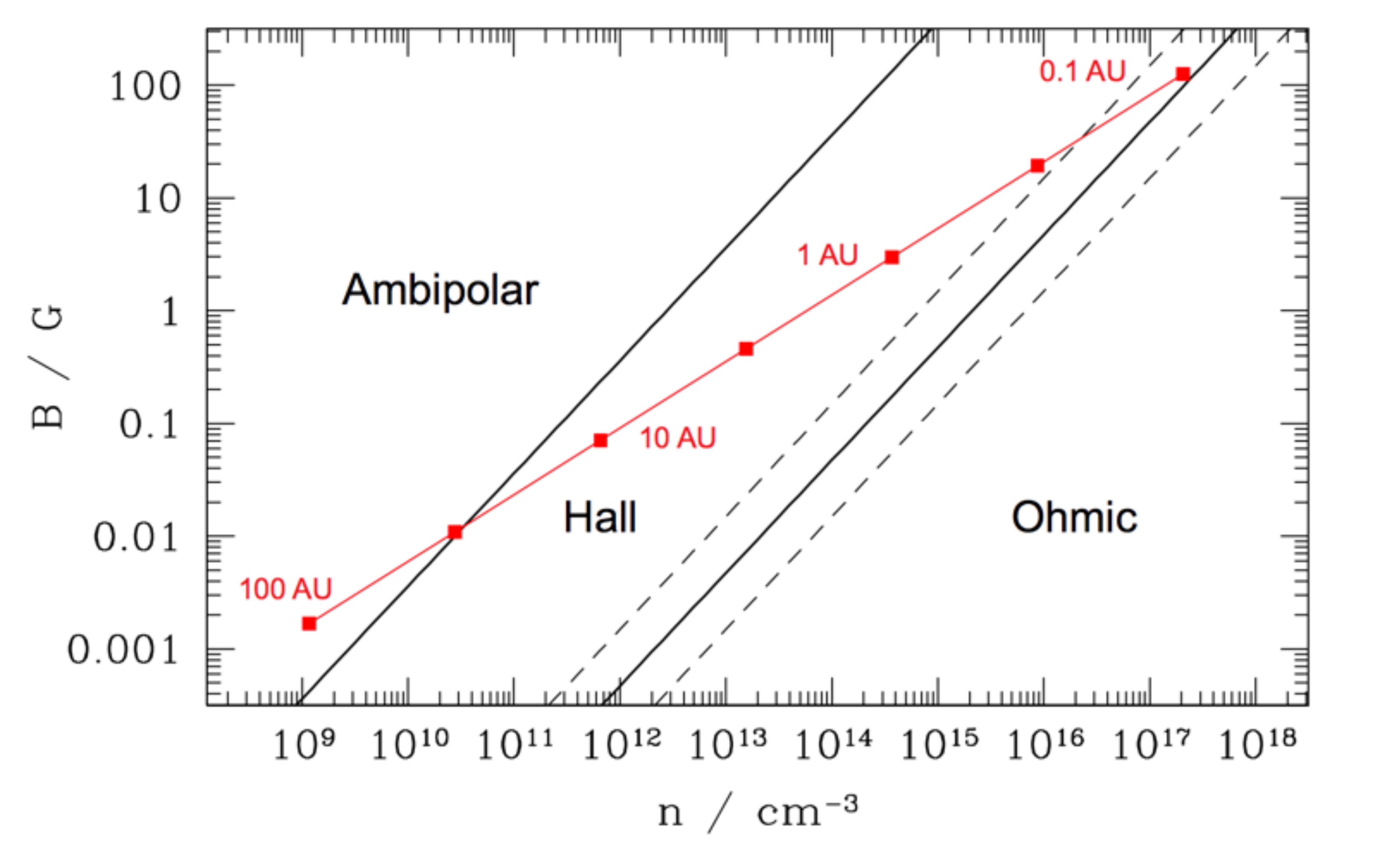
Three effects

1. Ohmic resistivity → e^-, ion^+ collide with neutrals

2. Hall effect → e^- tied to mag. field; ion^+ collide with neutrals

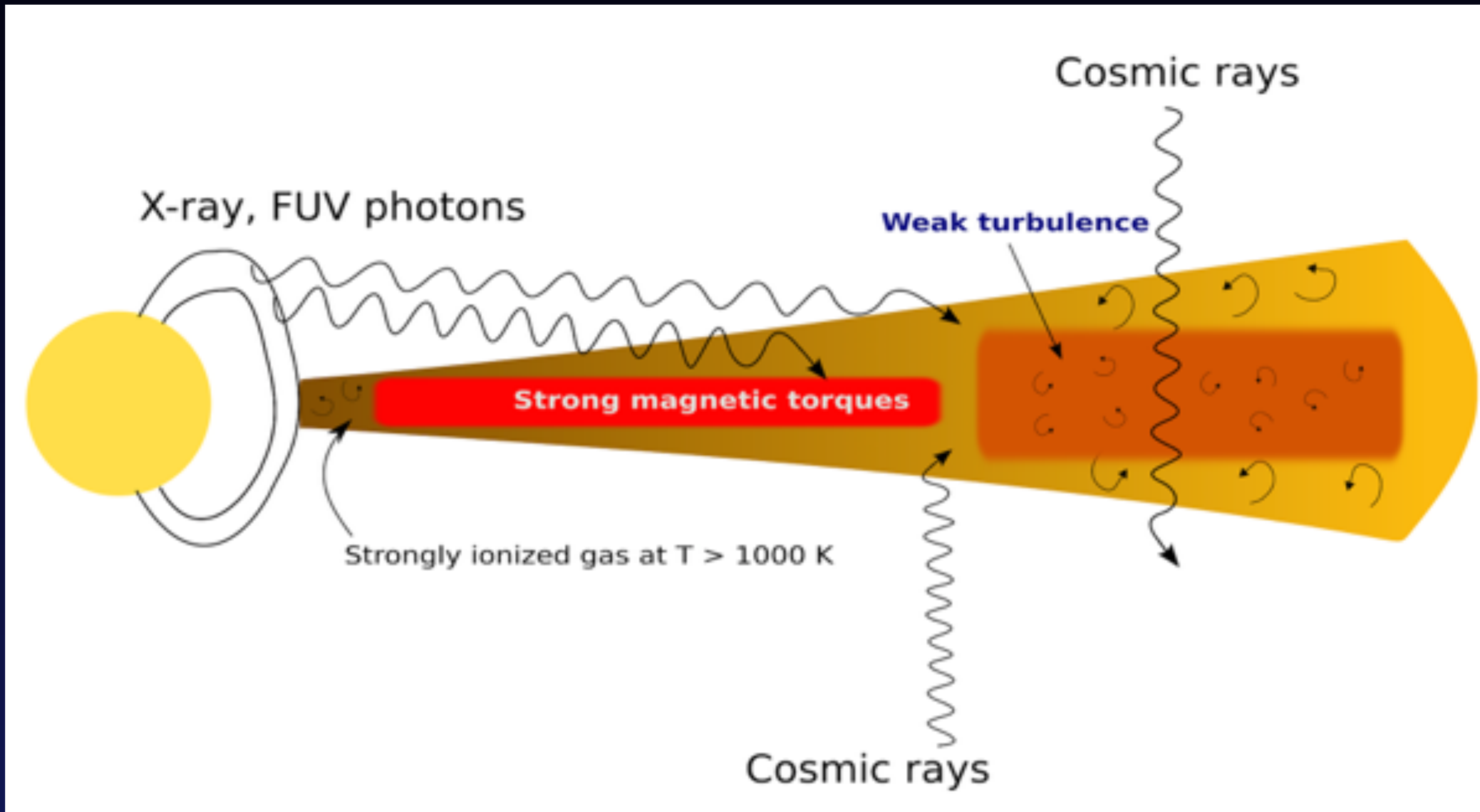
3. Ambipolar diffusion → e^-, ion^+ tied to mag. field

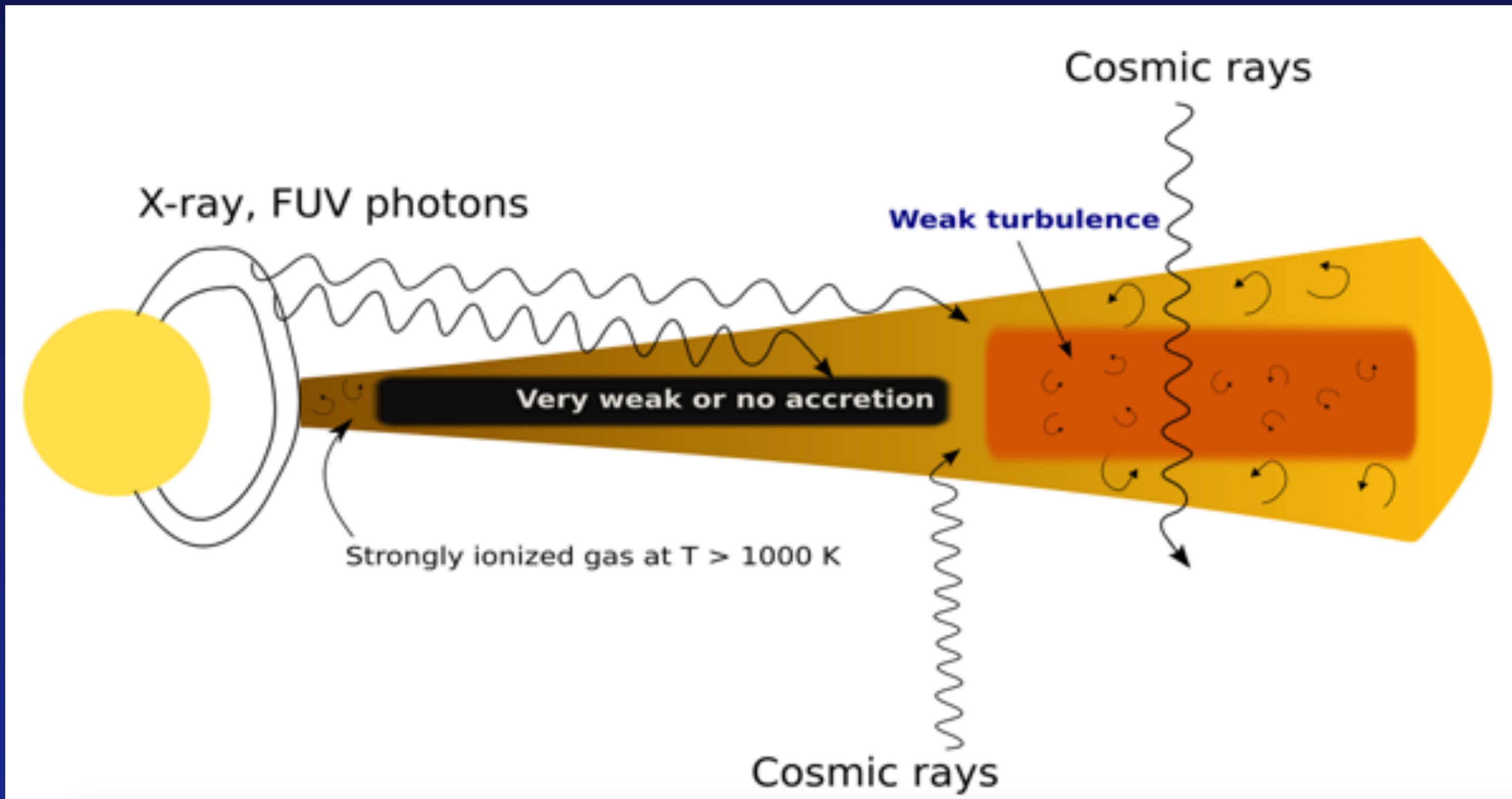
The importance of each non-ideal effect depends on density and magnetic field strength

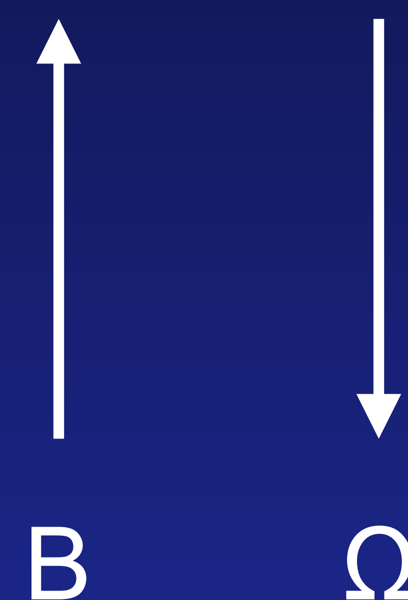


Armitage

A new paradigm

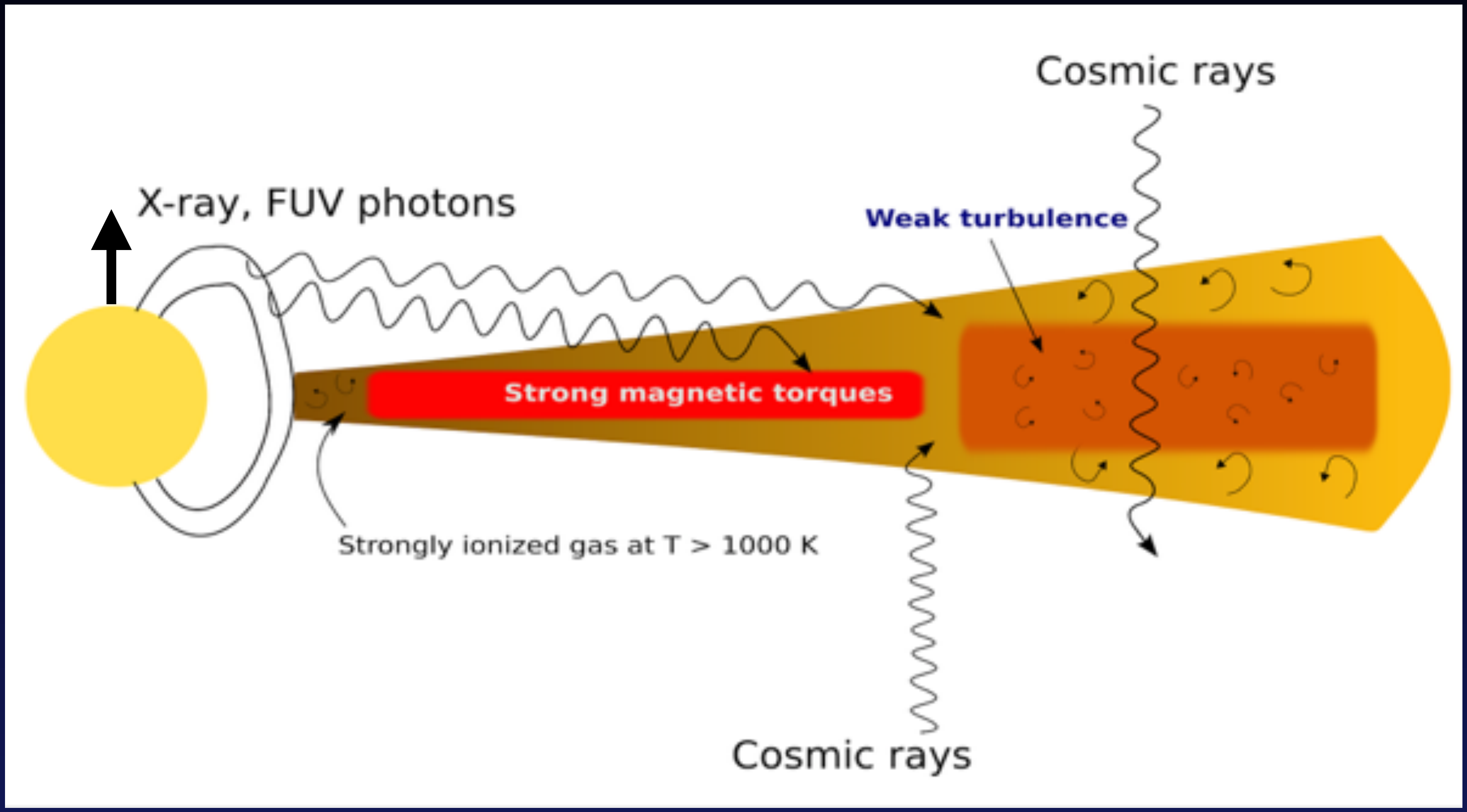


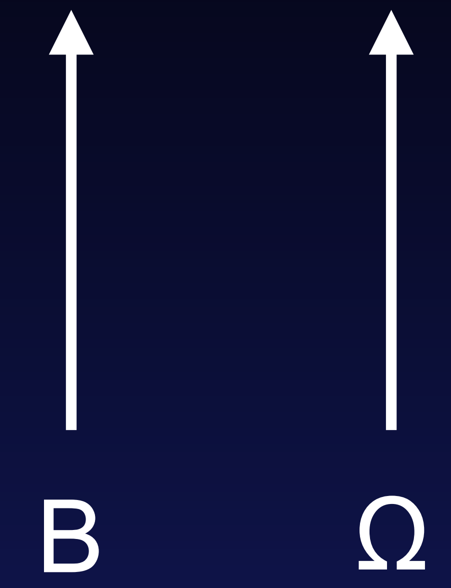


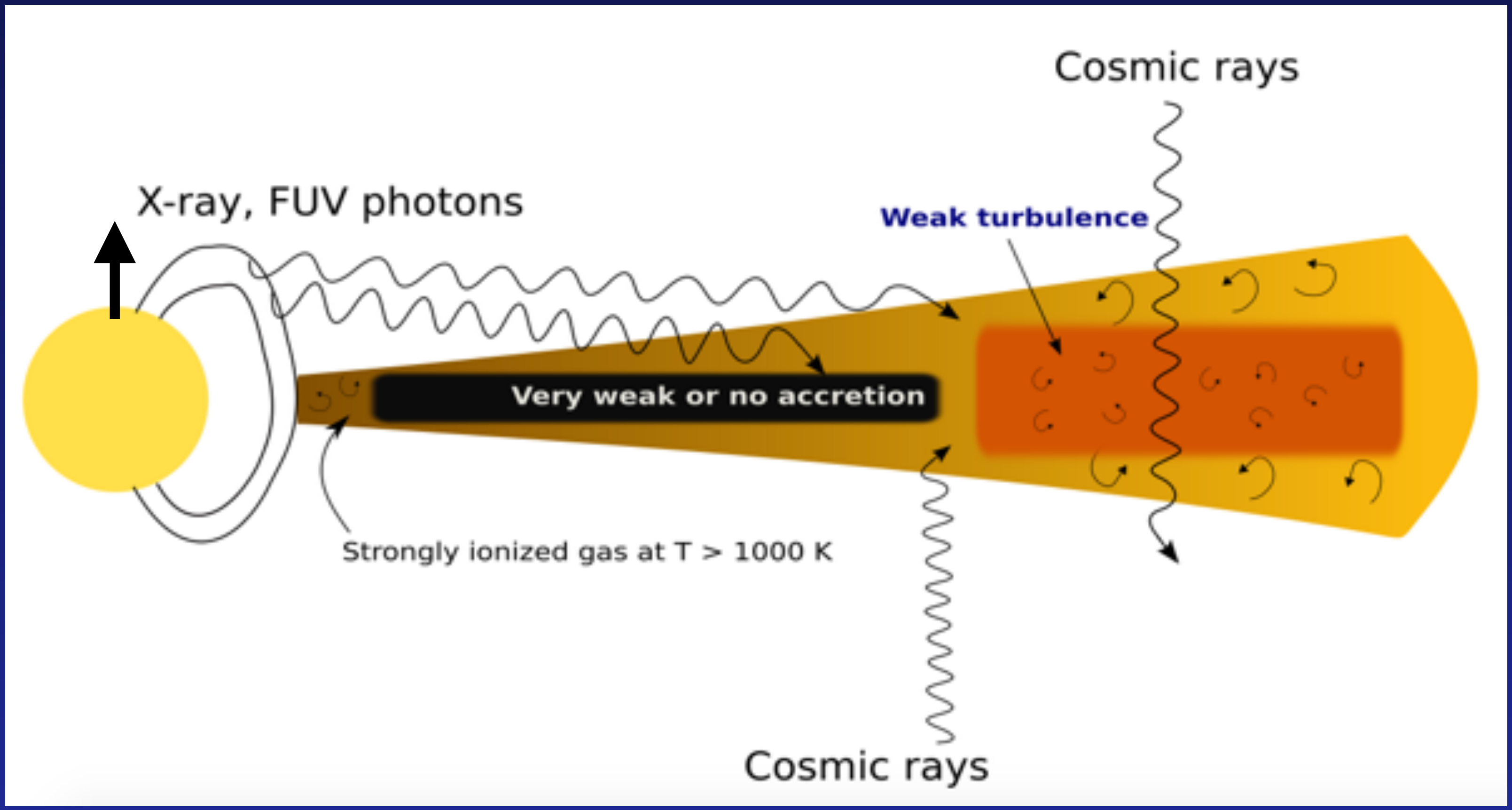


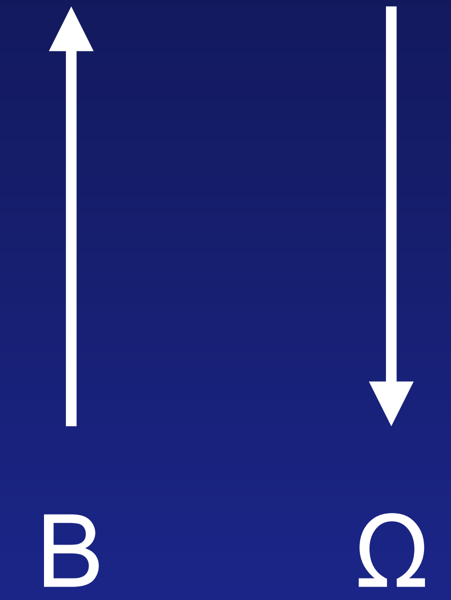
Based on work by Jake Simon, Xue-Ning Bai, Geoffroy Lesur, and others…

A new paradigm



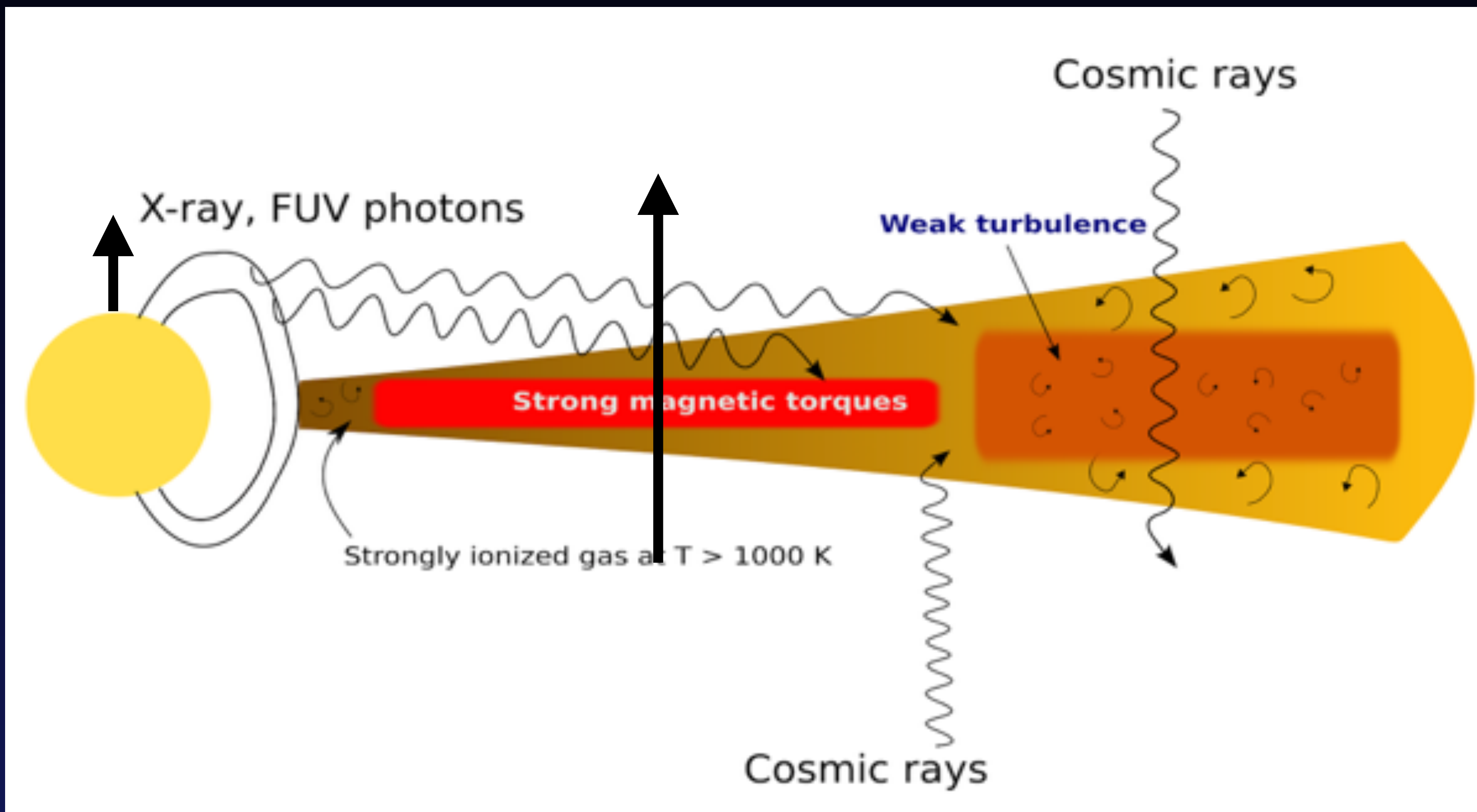


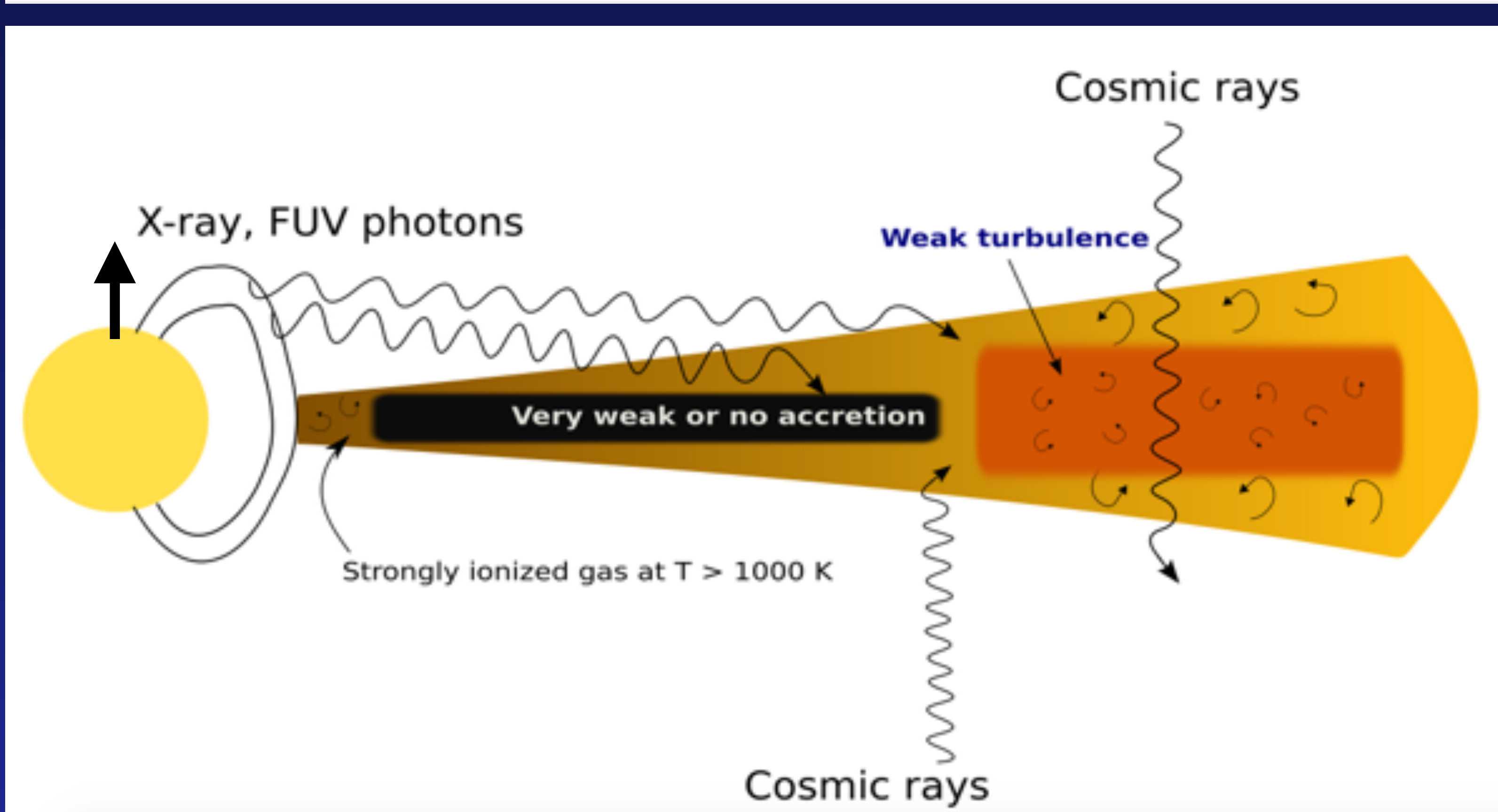


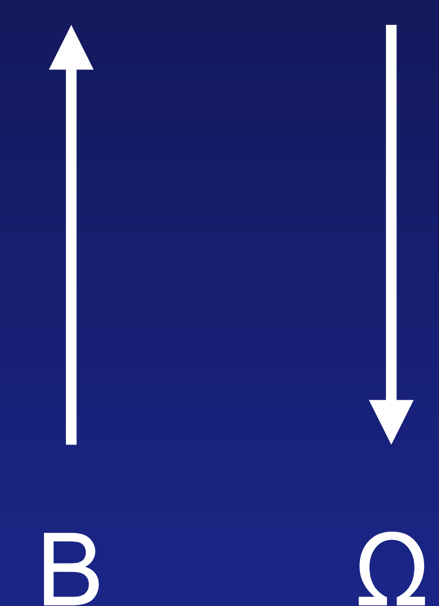


Based on work by Jake Simon, Xue-Ning Bai, Geoffroy Lesur, and others…

A new paradigm

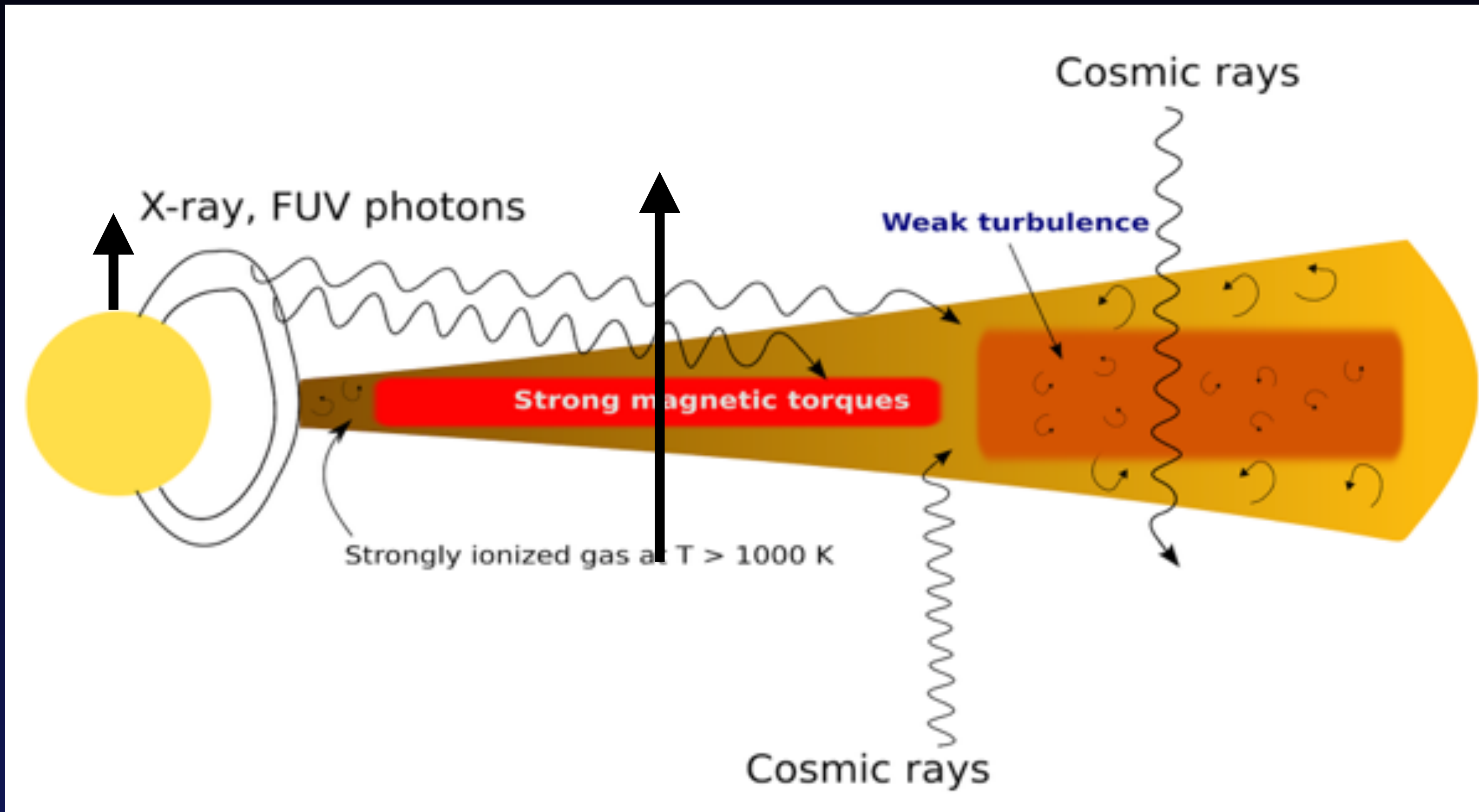


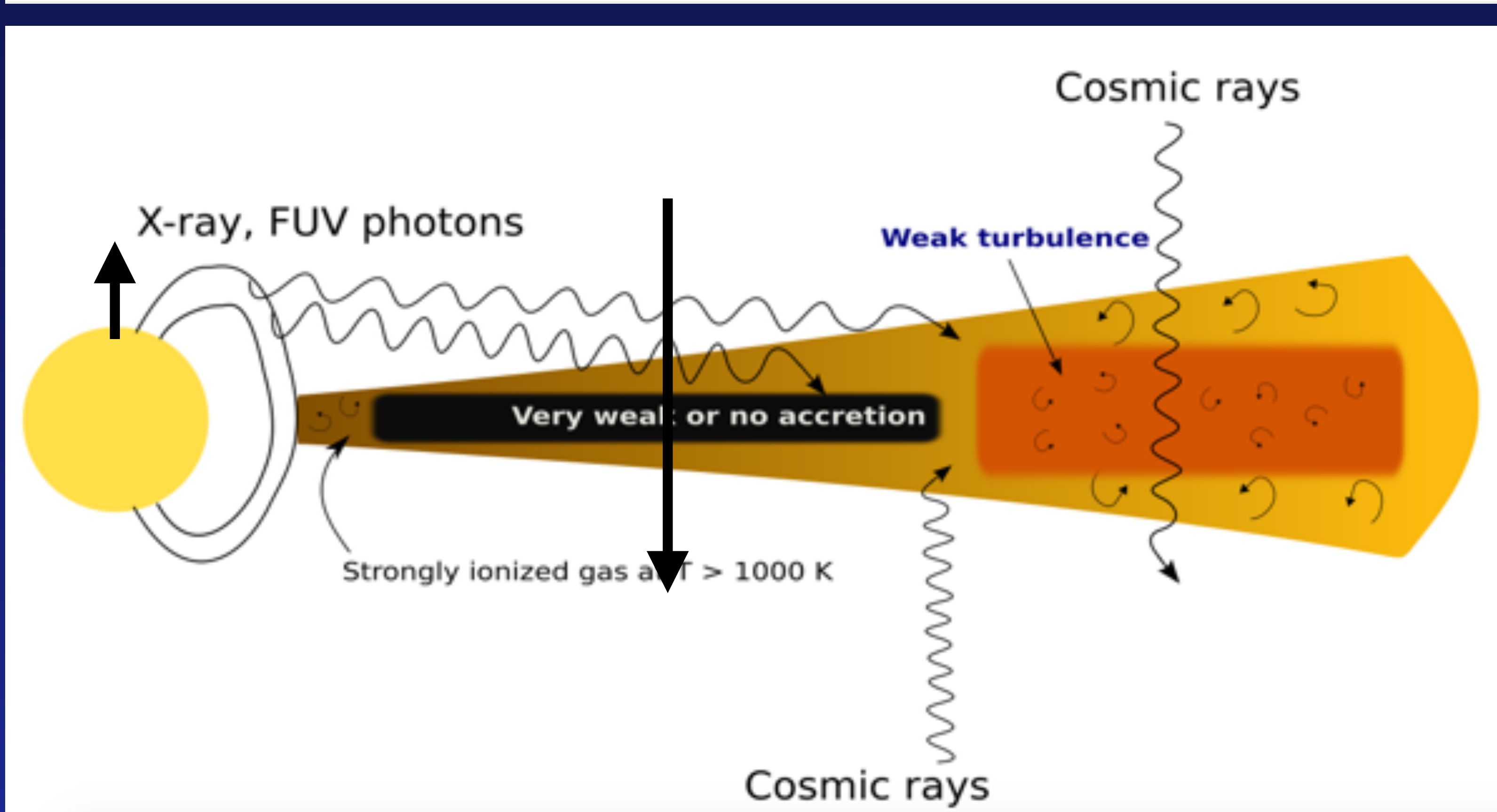


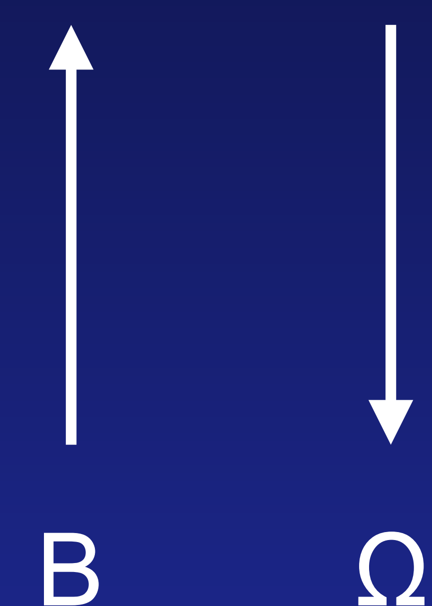


Based on work by Jake Simon, Xue-Ning Bai, Geoffroy Lesur, and others…

A new paradigm

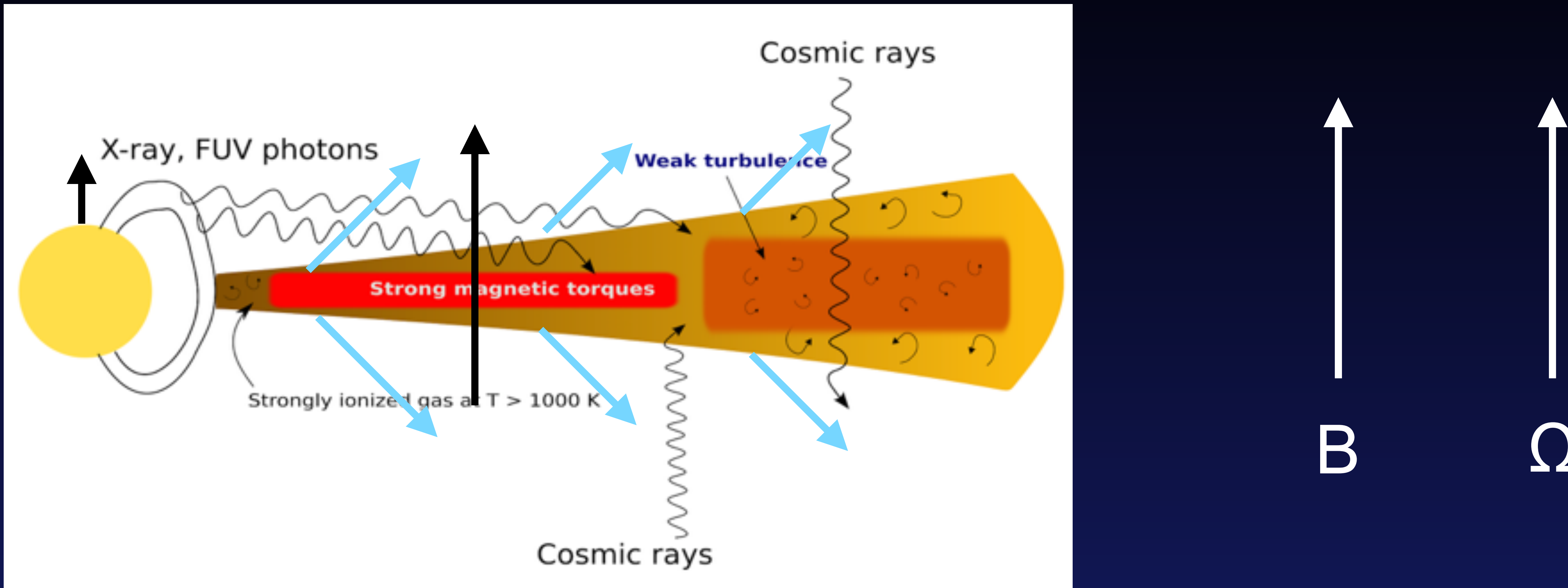


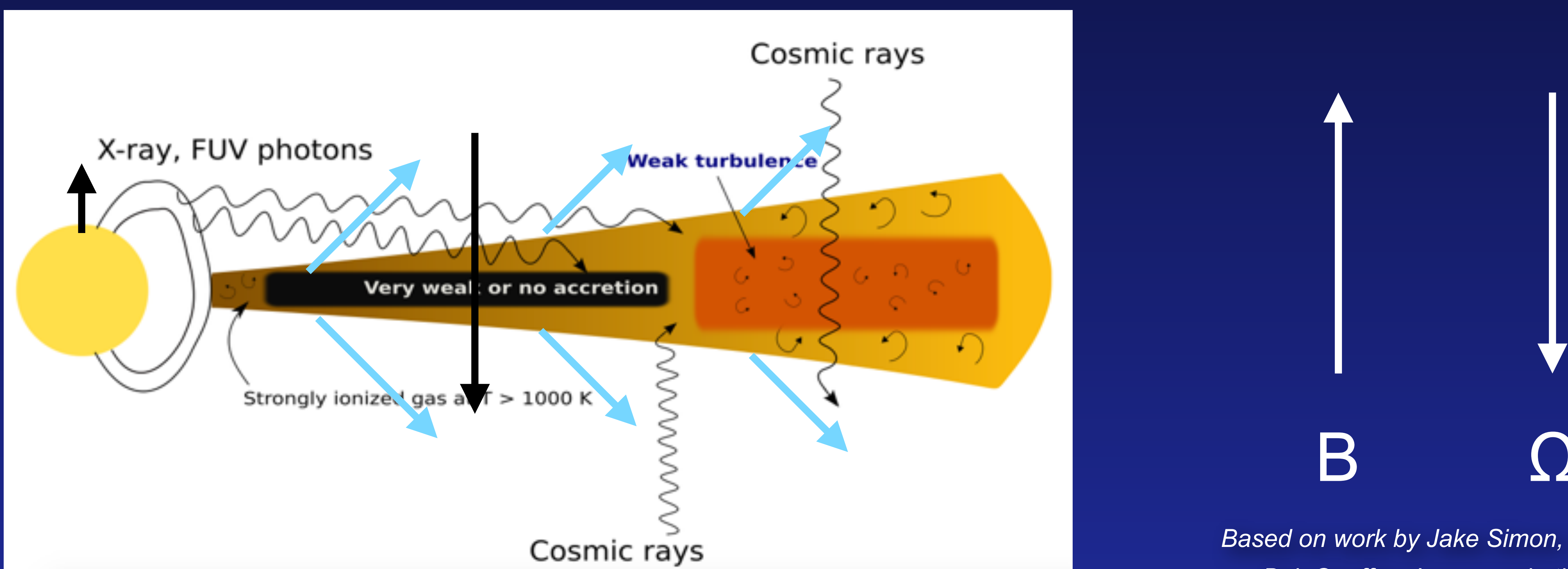




Based on work by Jake Simon, Xue-Ning Bai, Geoffroy Lesur, and others…

A new paradigm

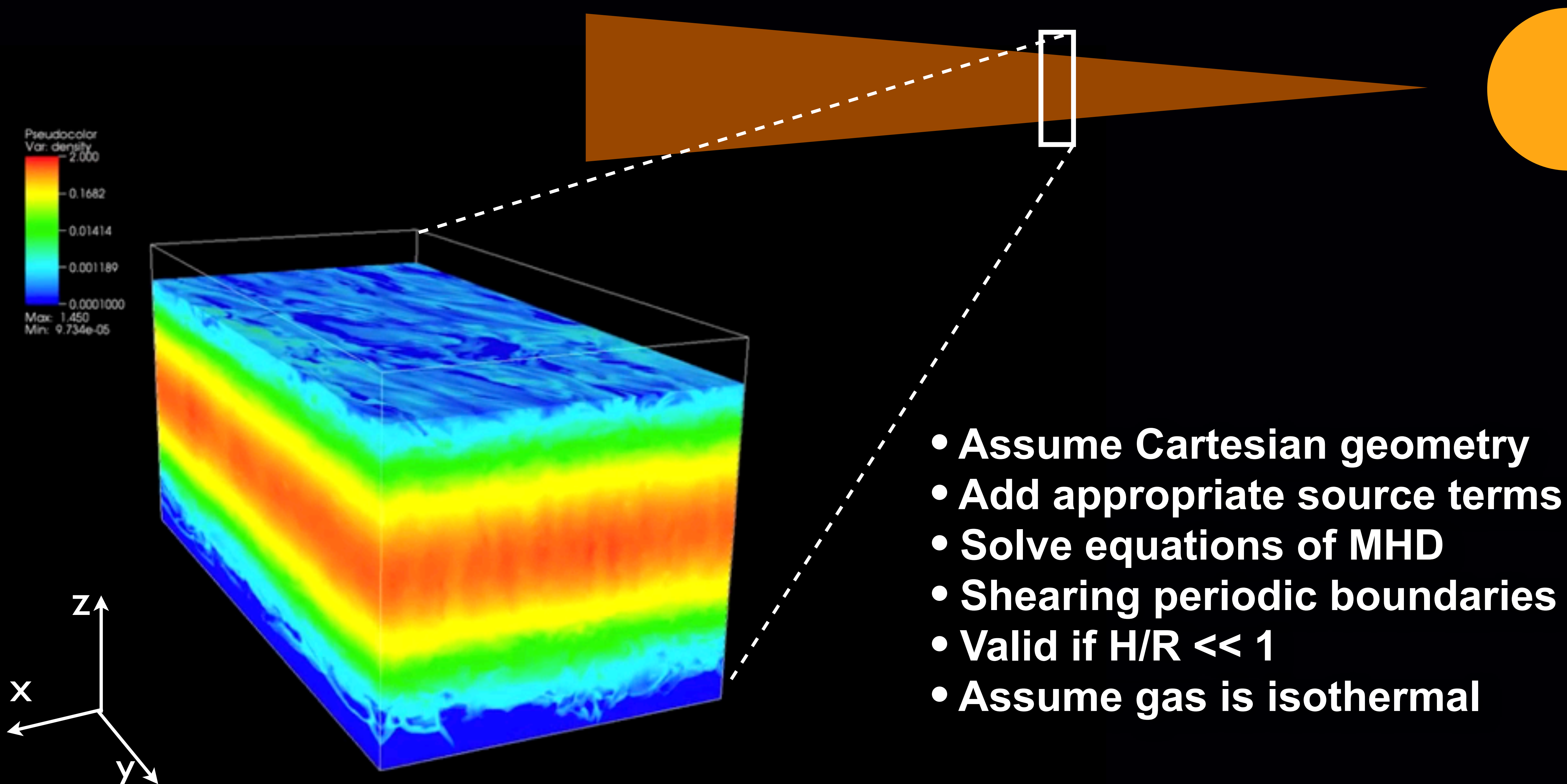




Based on work by Jake Simon, Xue-Ning Bai, Geoffroy Lesur, and others…

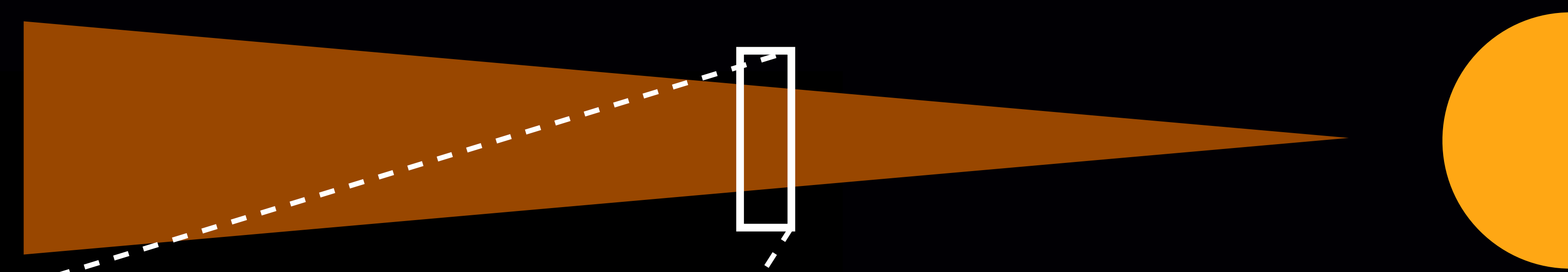
Let’s look at this new paradigm a little more closely

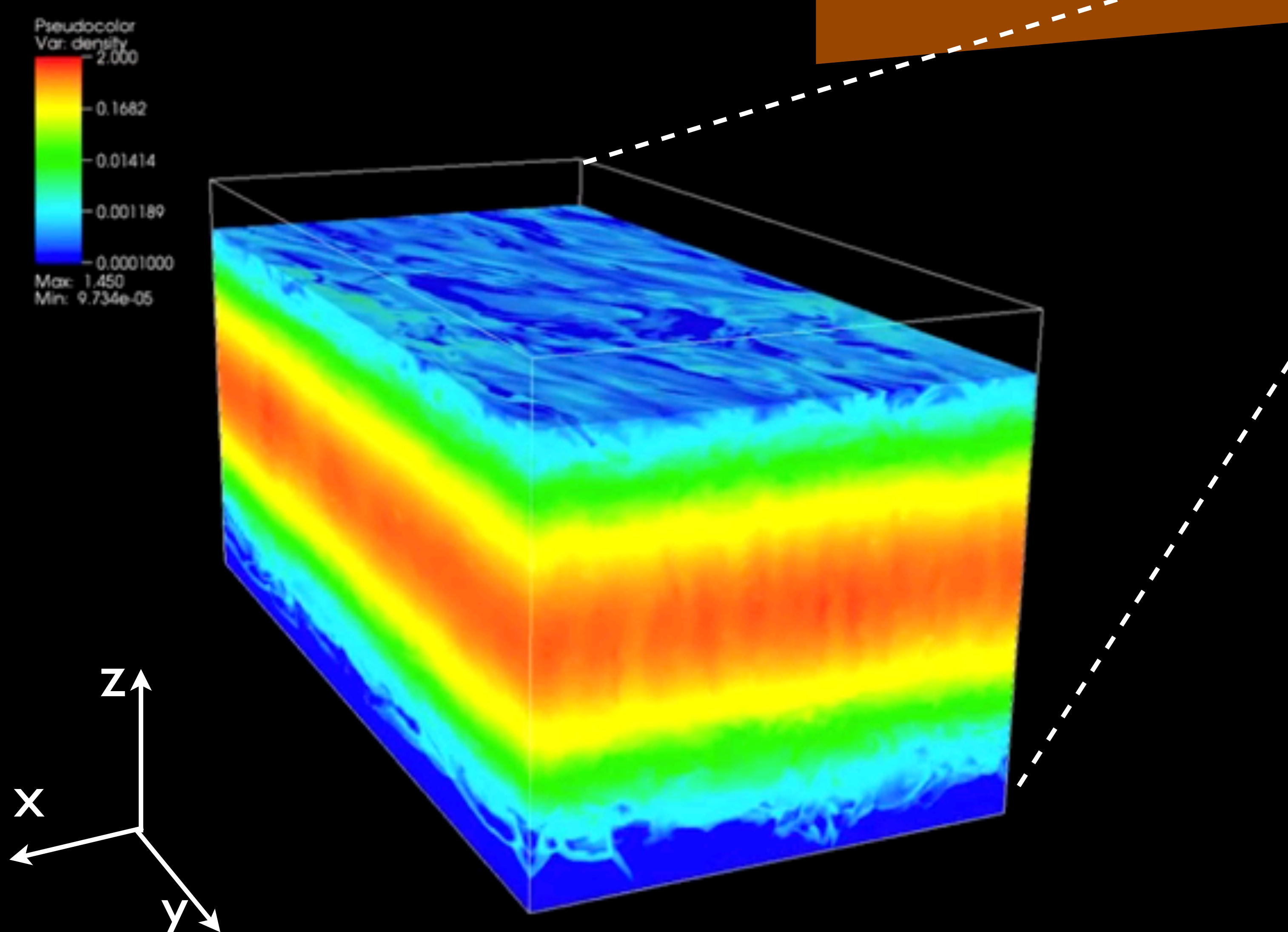
Local simulations: examine small co-rotating disk patch



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

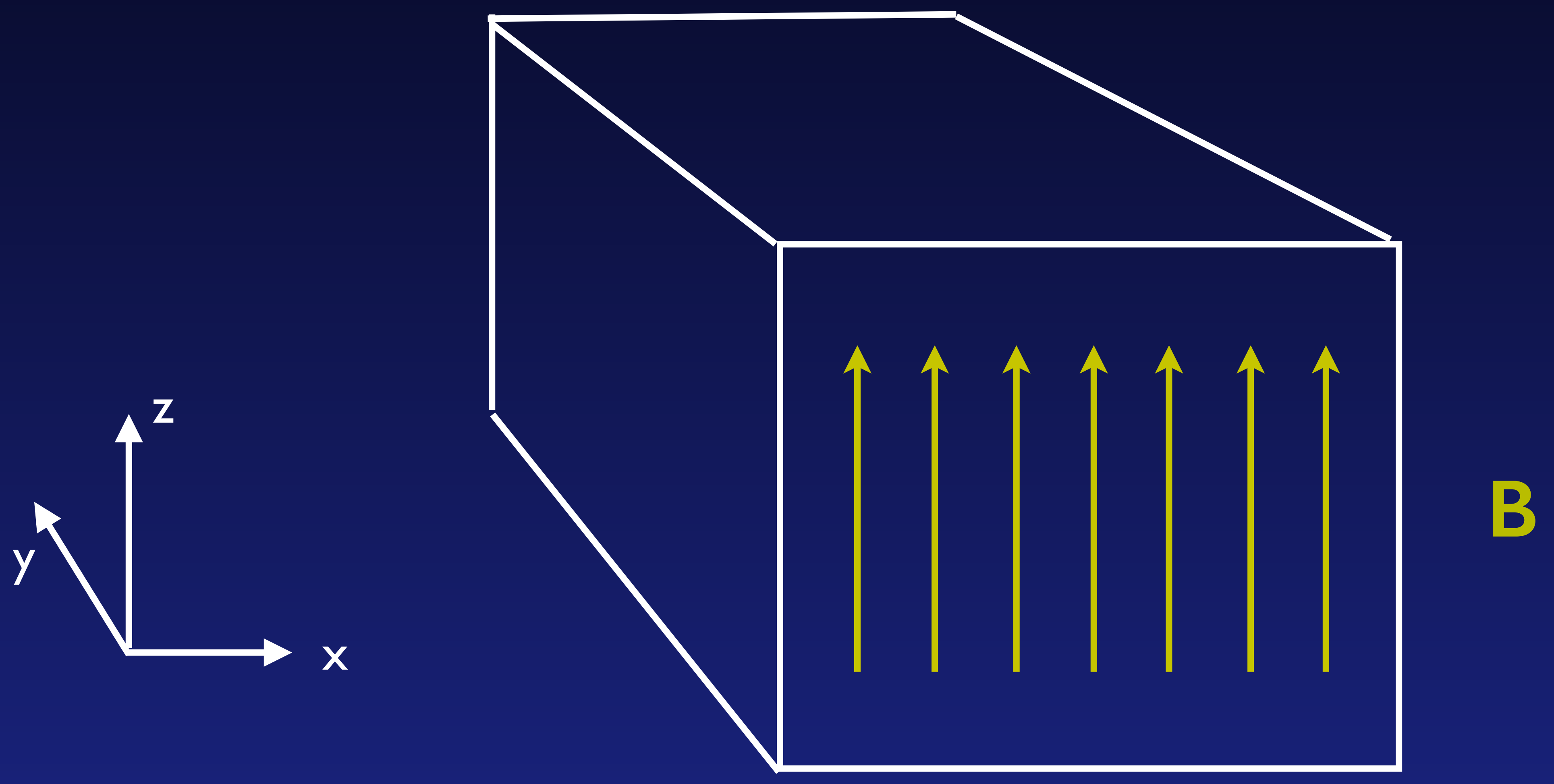
Local simulations: examine small co-rotating disk patch



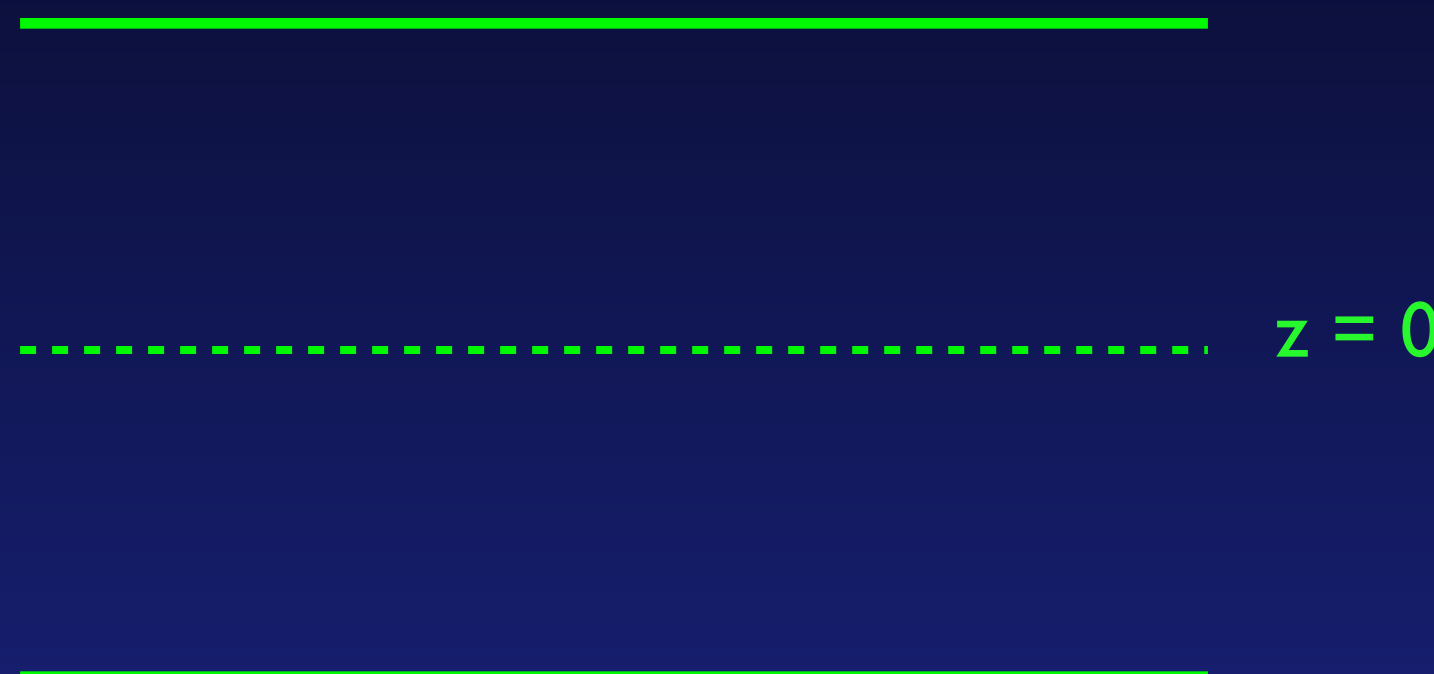


- Assume Cartesian geometry
- Add appropriate source terms
- Solve equations of MHD
- Shearing periodic boundaries
- Valid if H/R << 1
- Assume gas is isothermal

Net vertical field

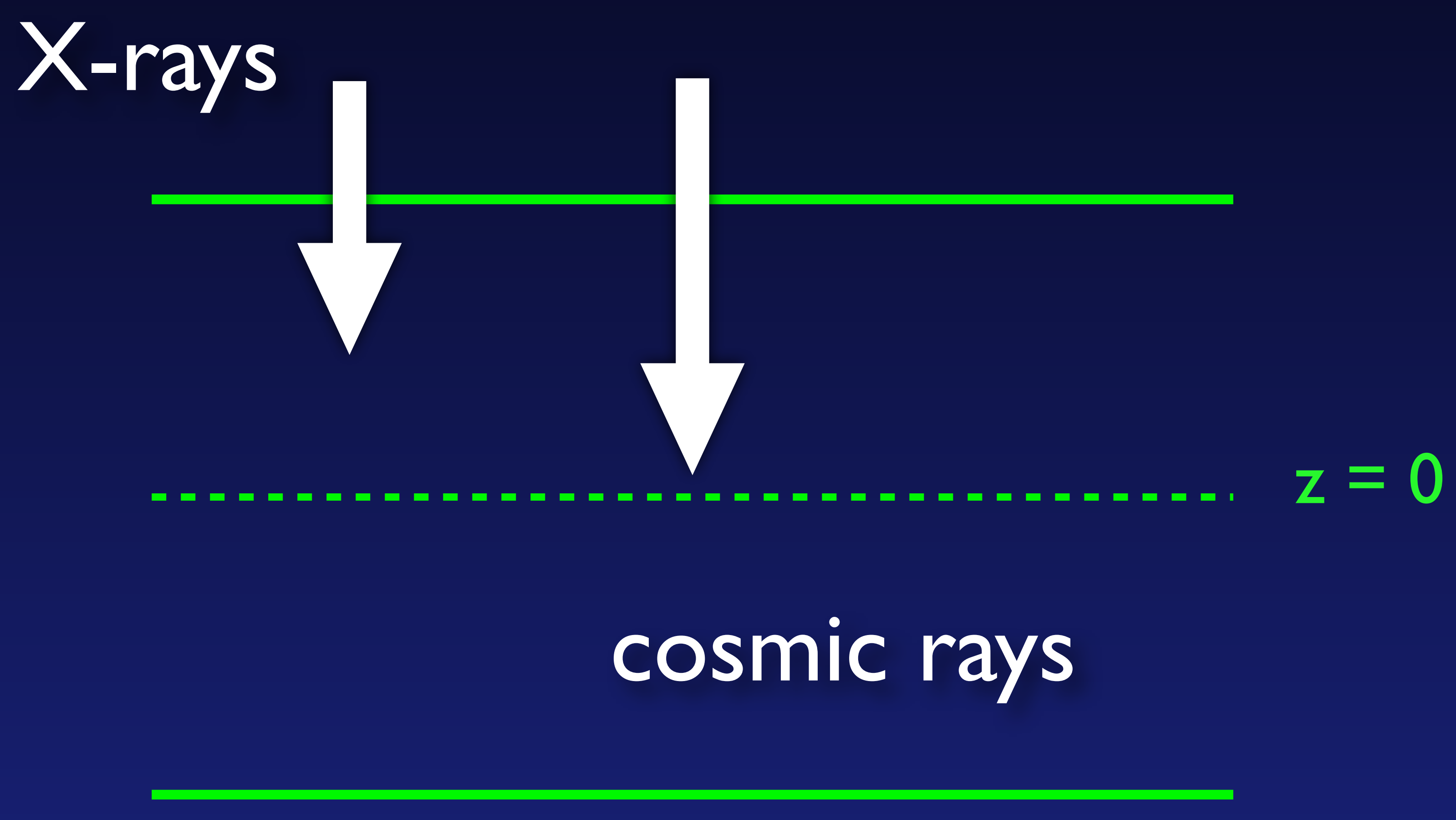


We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)

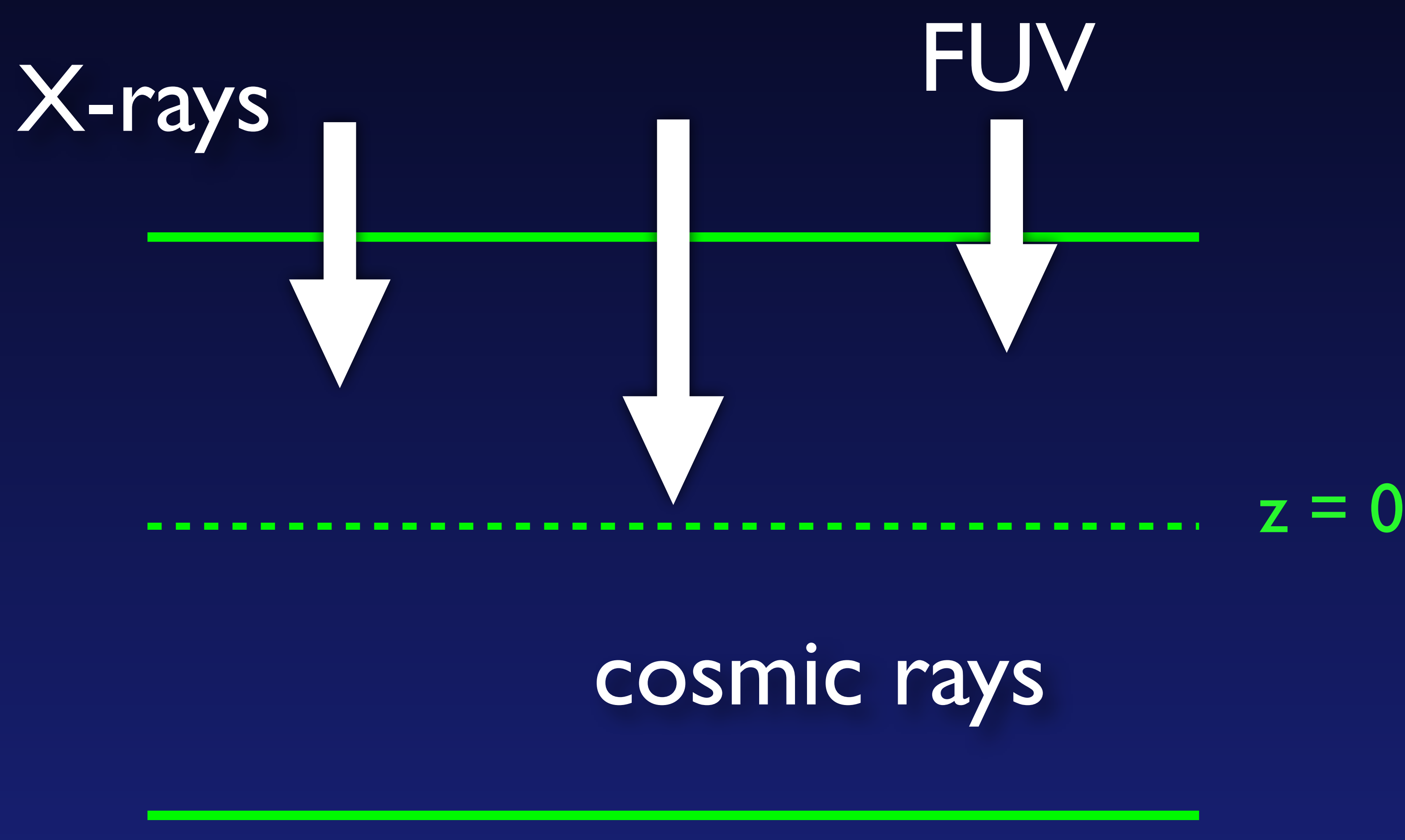


We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)

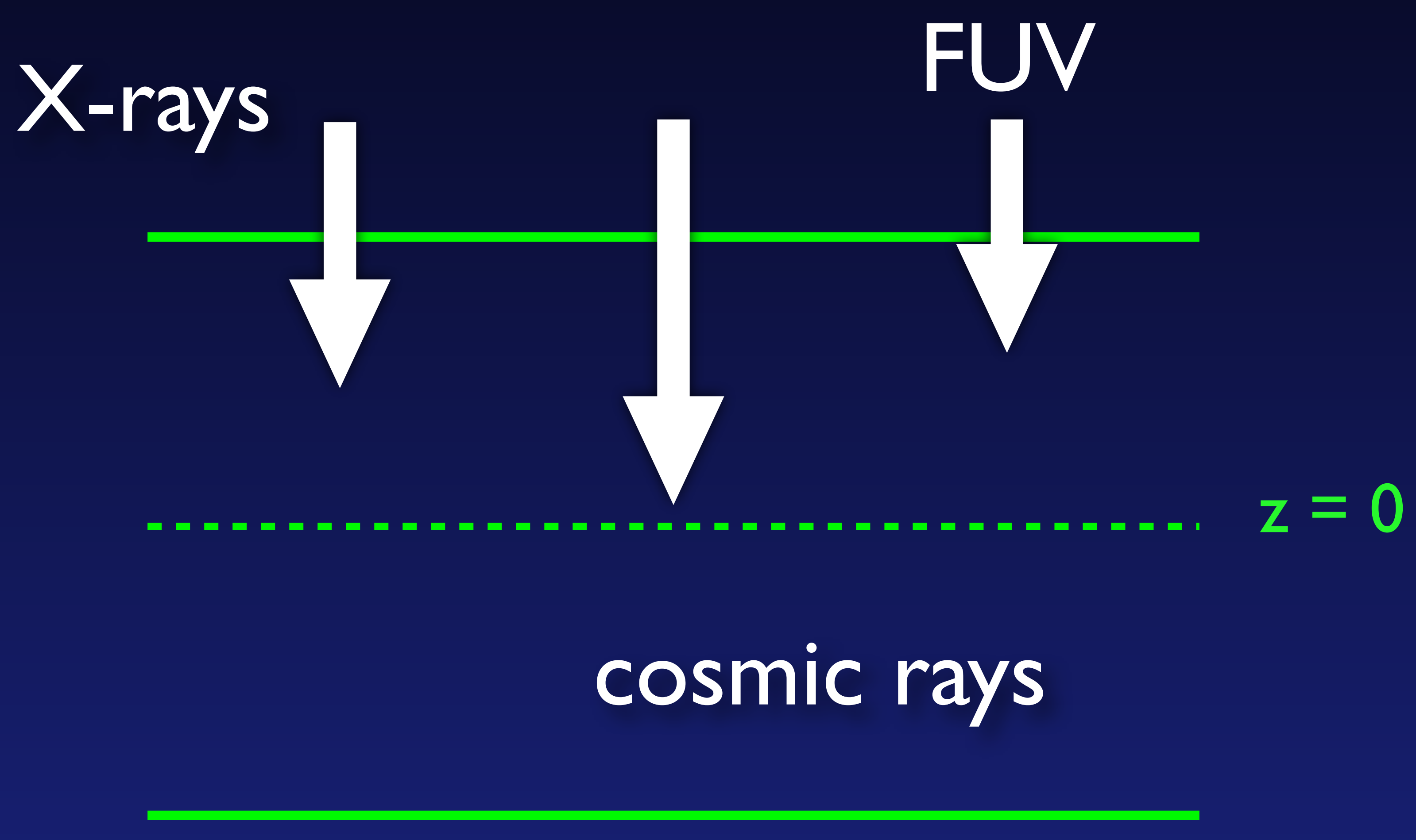
We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)



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

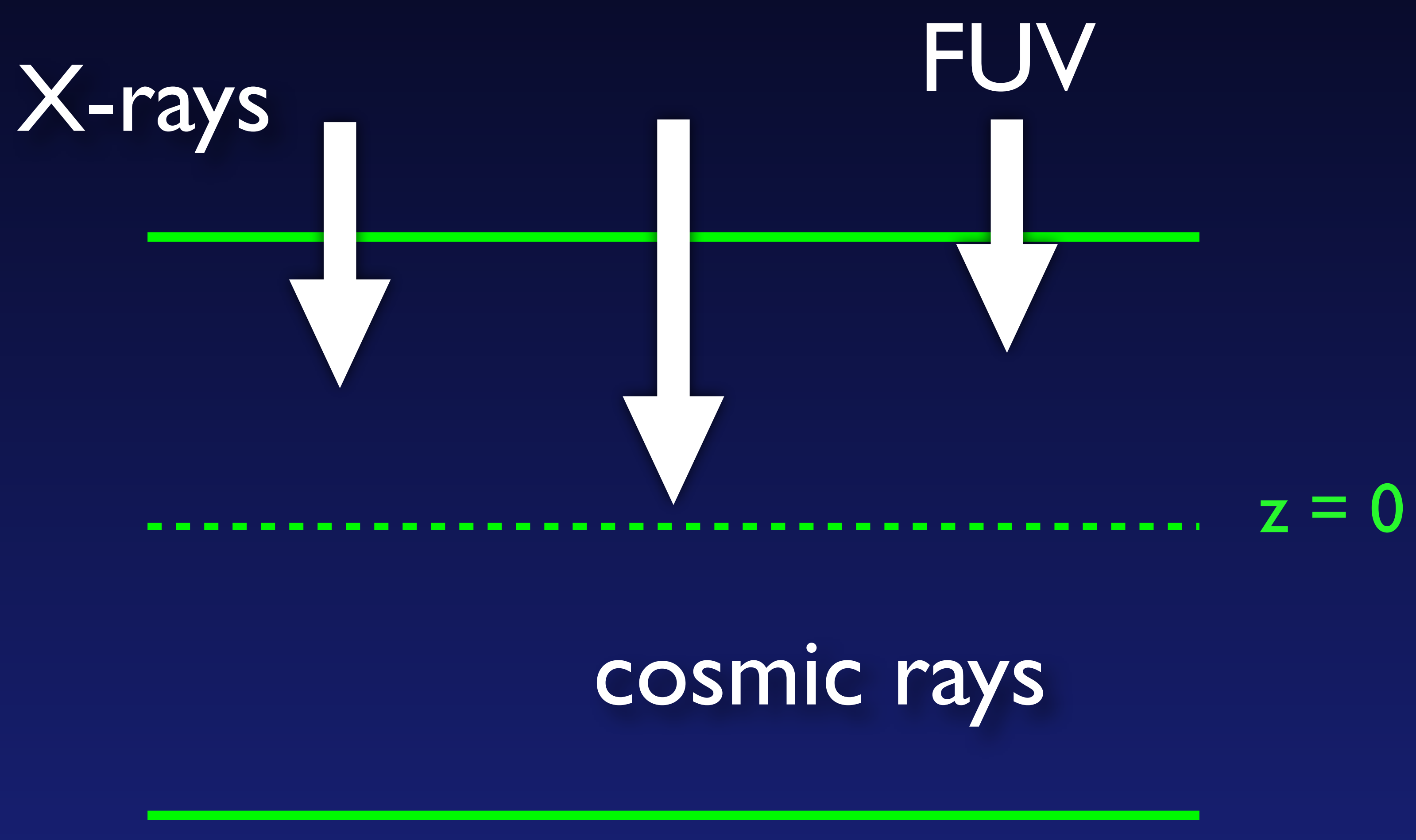


We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)



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

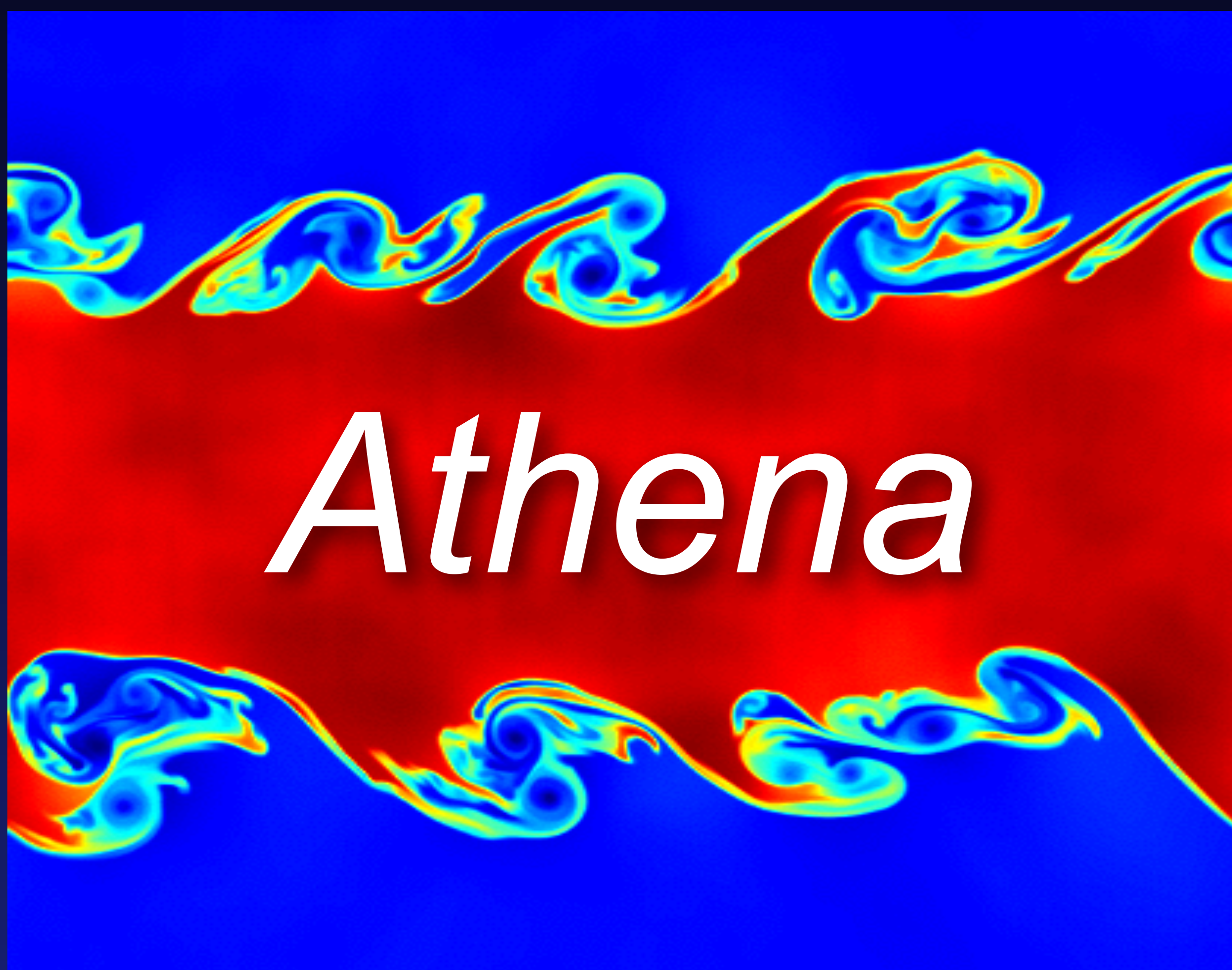
We use an ionization model based on a chemical network and ionizing particles/photons (including FUV)



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

As a result, we have all three non-ideal effects included in our simulations.

State-of-the-art MHD codes

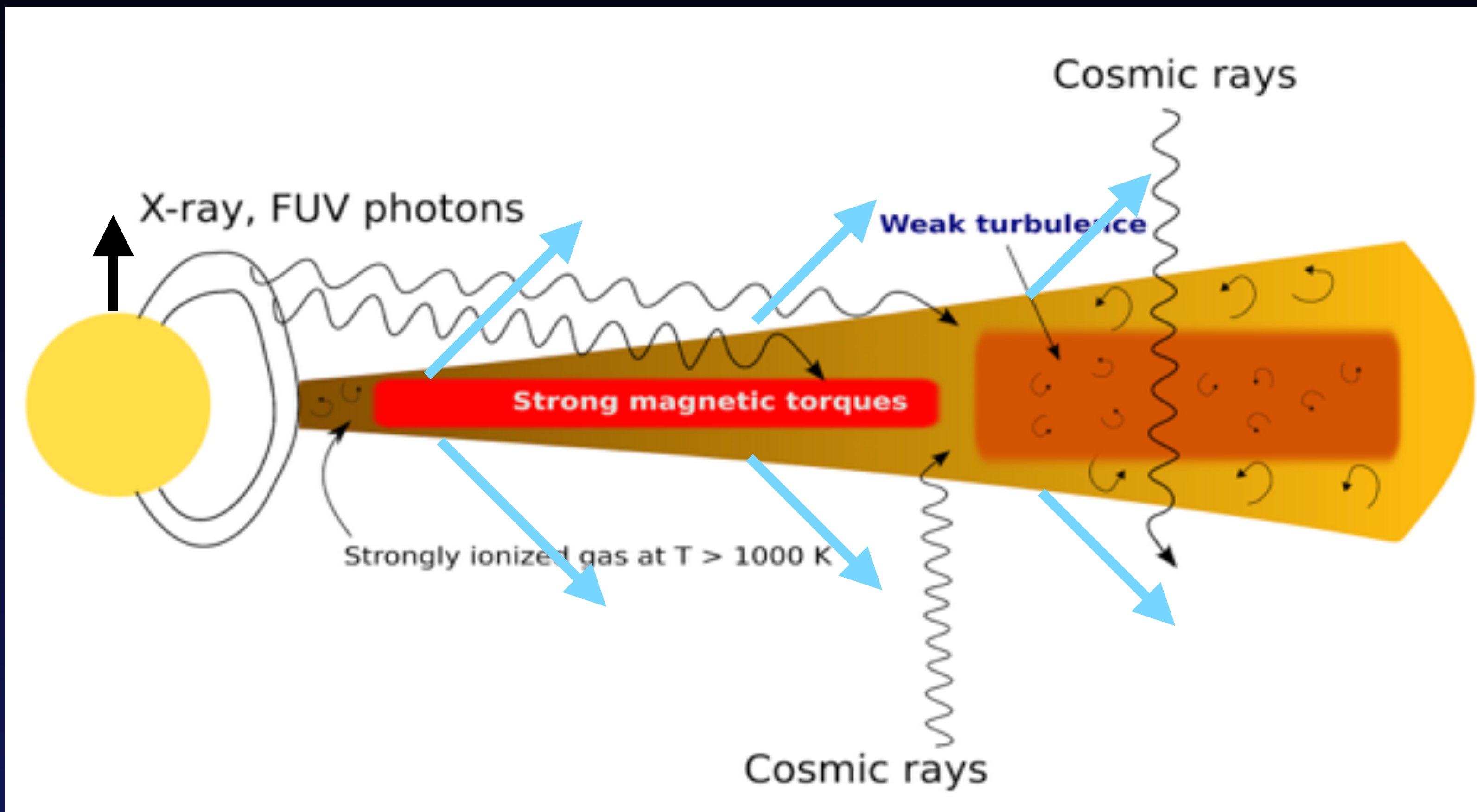


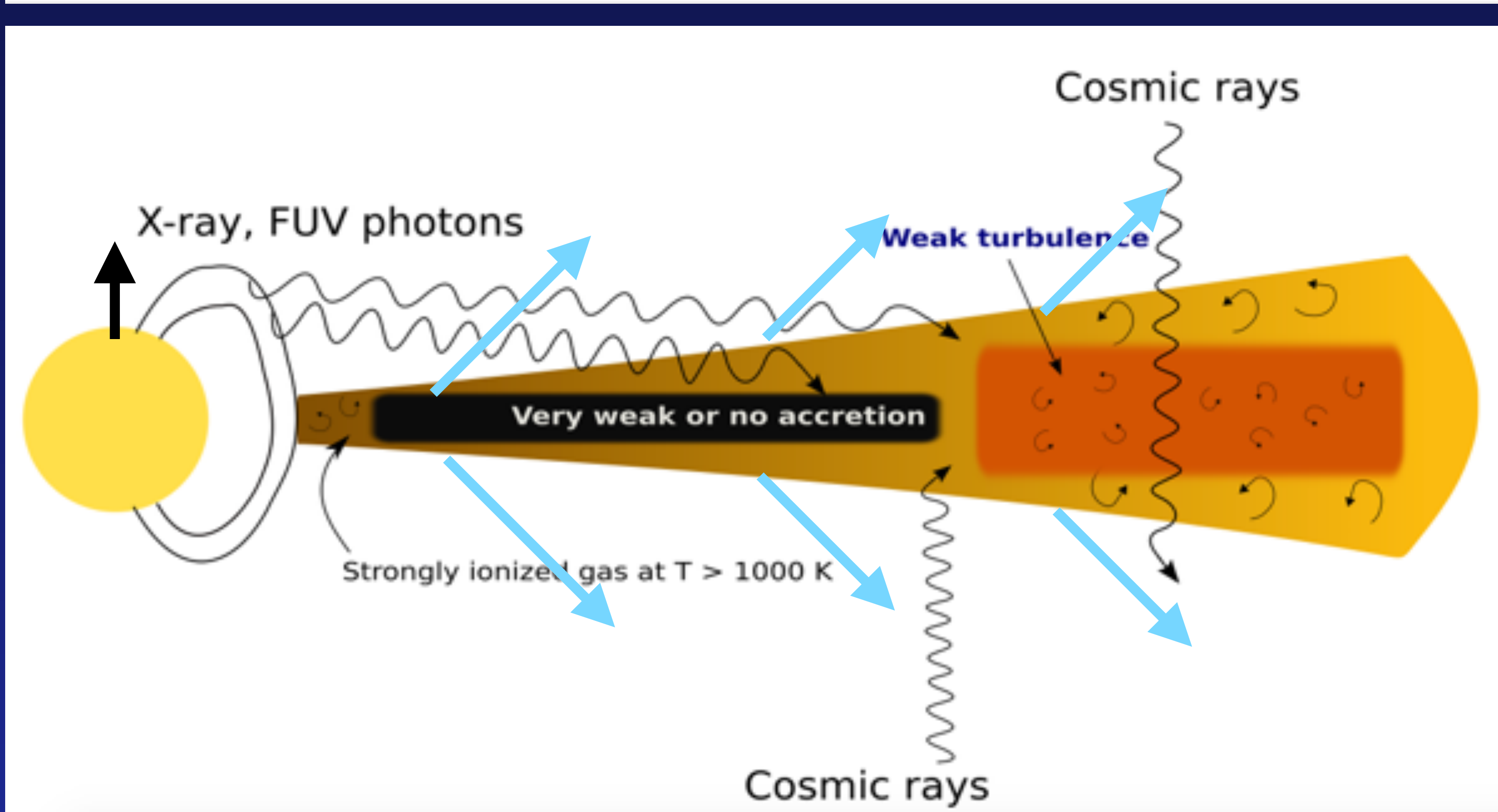
See Stone et al. (2008) for code details

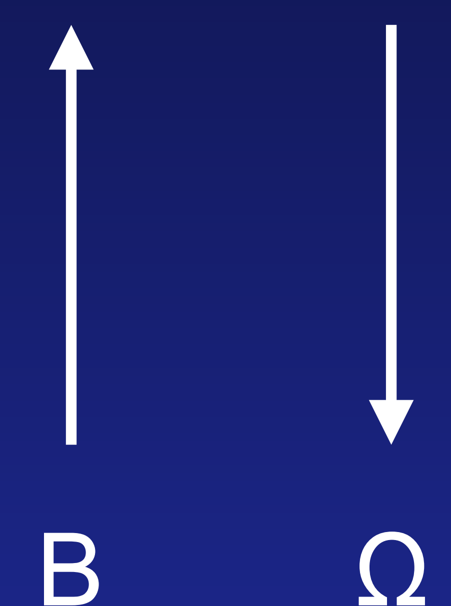
PLUTO

Mignone et al. (2007)

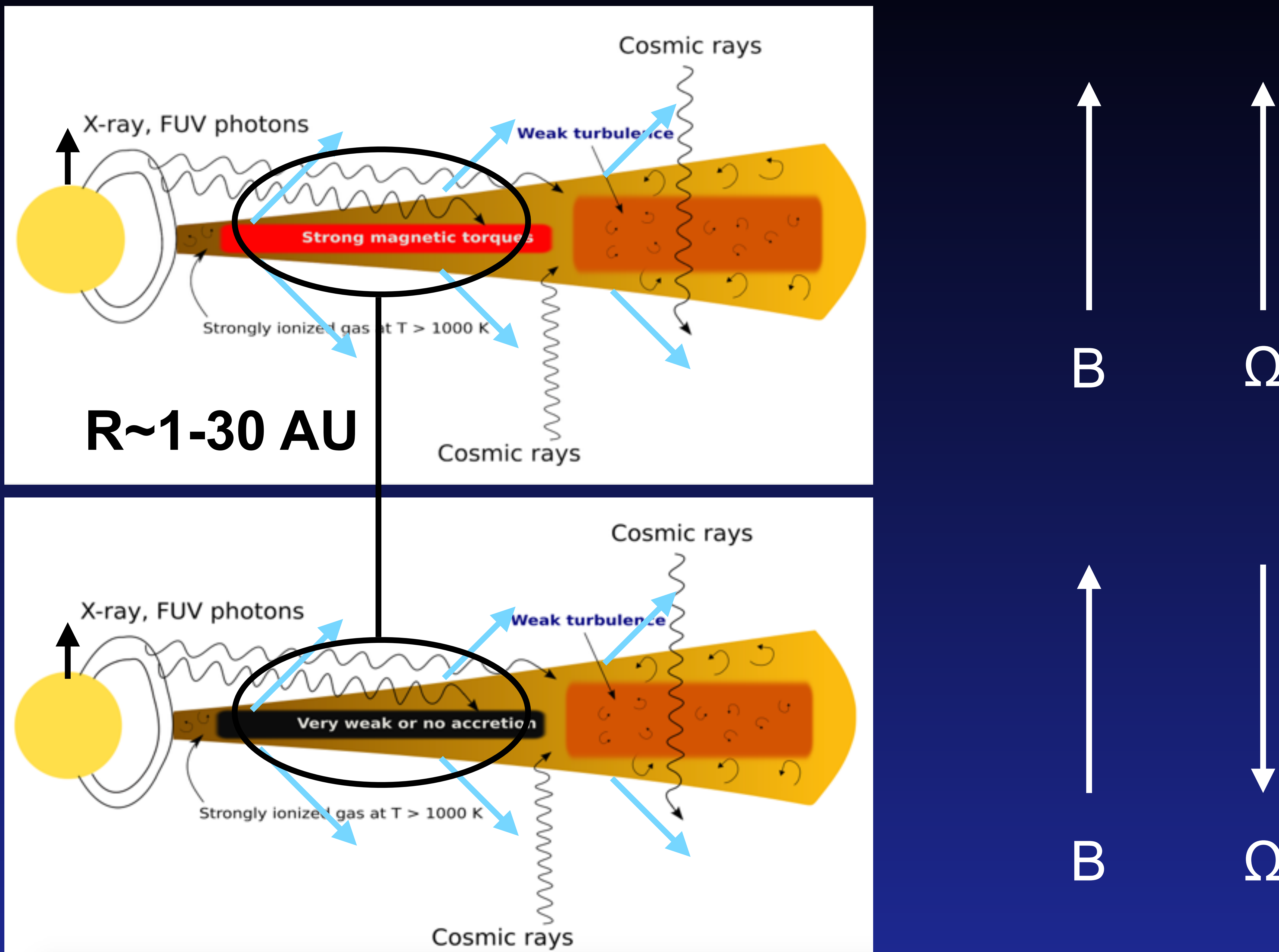
Focus first on Hall-dominated regime



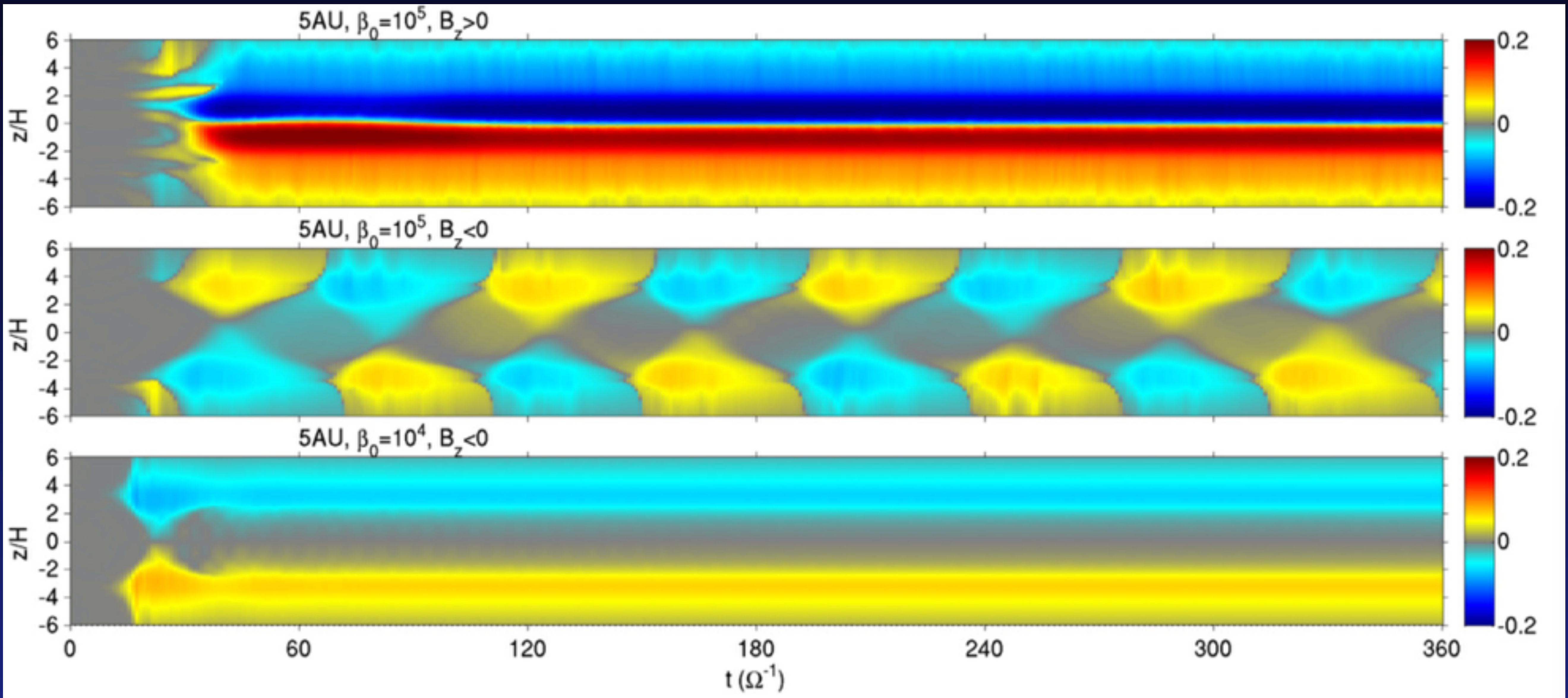




Focus first on Hall-dominated regime



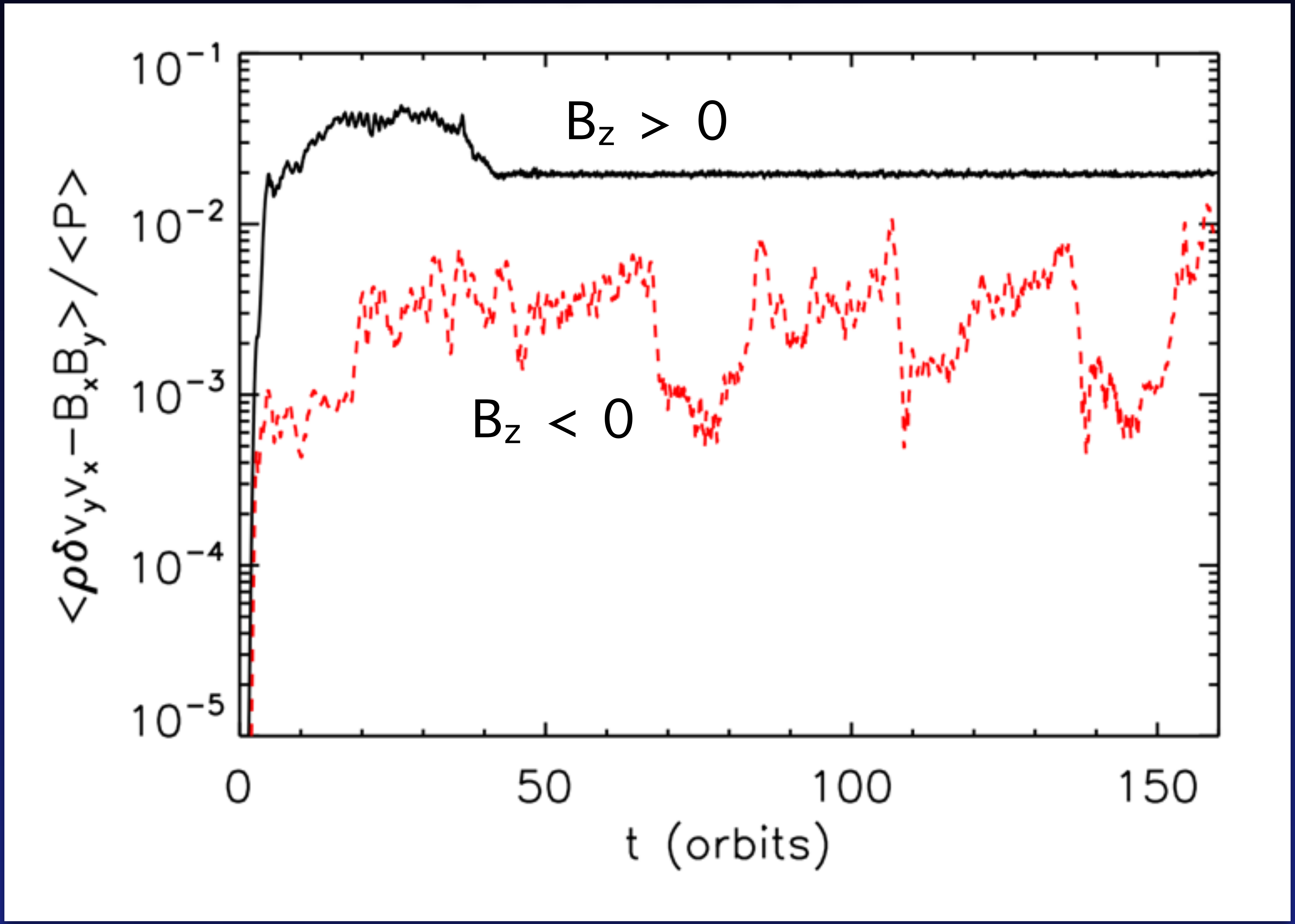
Inner disk (1-10 AU) Dramatic differences depending on field orientation



Bai (2015)

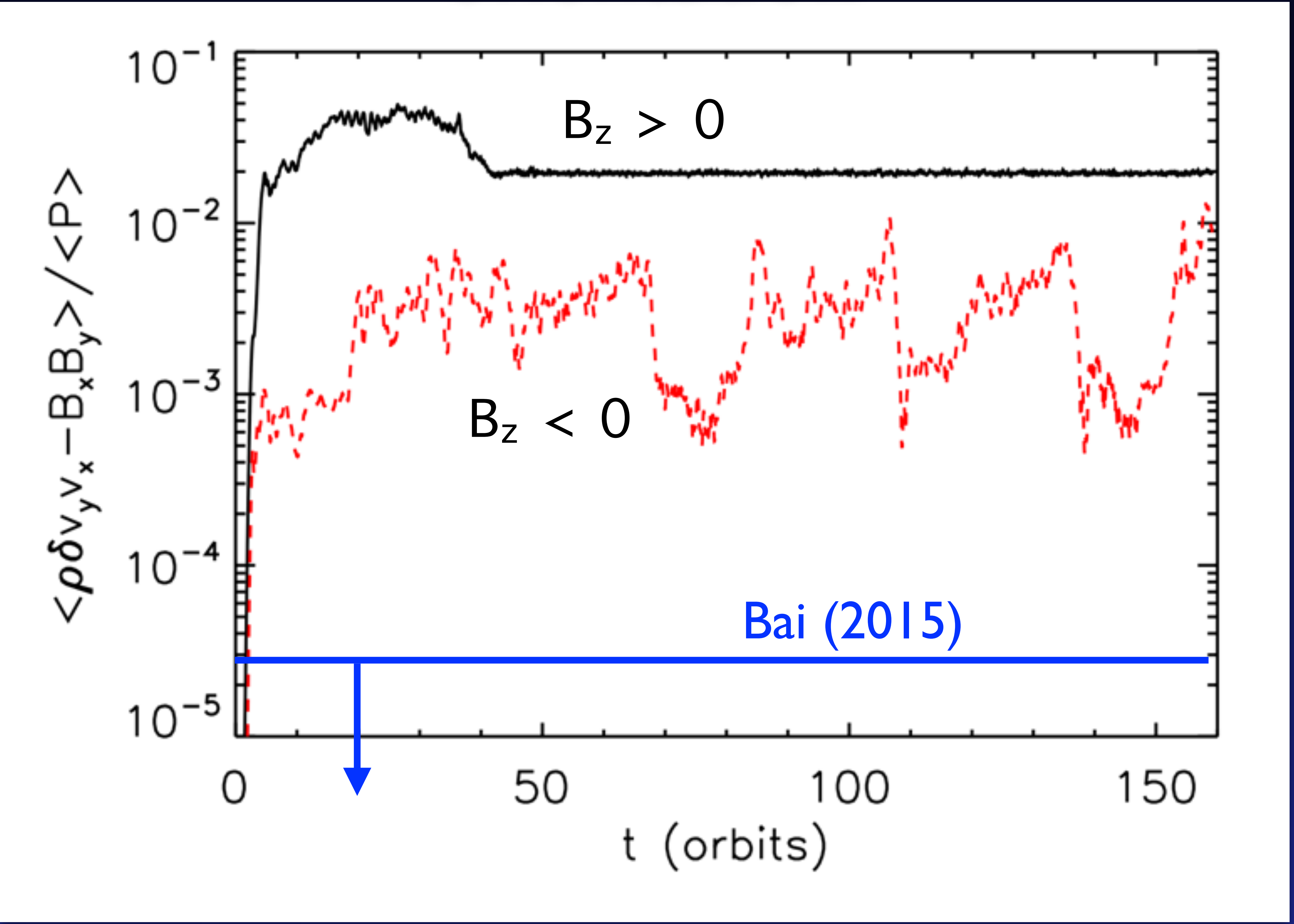
$$\beta_0 = \frac{2P_{\mathrm{mid}}}{B_{\mathrm{mid}}^2}$$

Inner disk (1-10 AU)
Dramatic differences depending on field orientation



Simon et al. (2015b), MNRAS

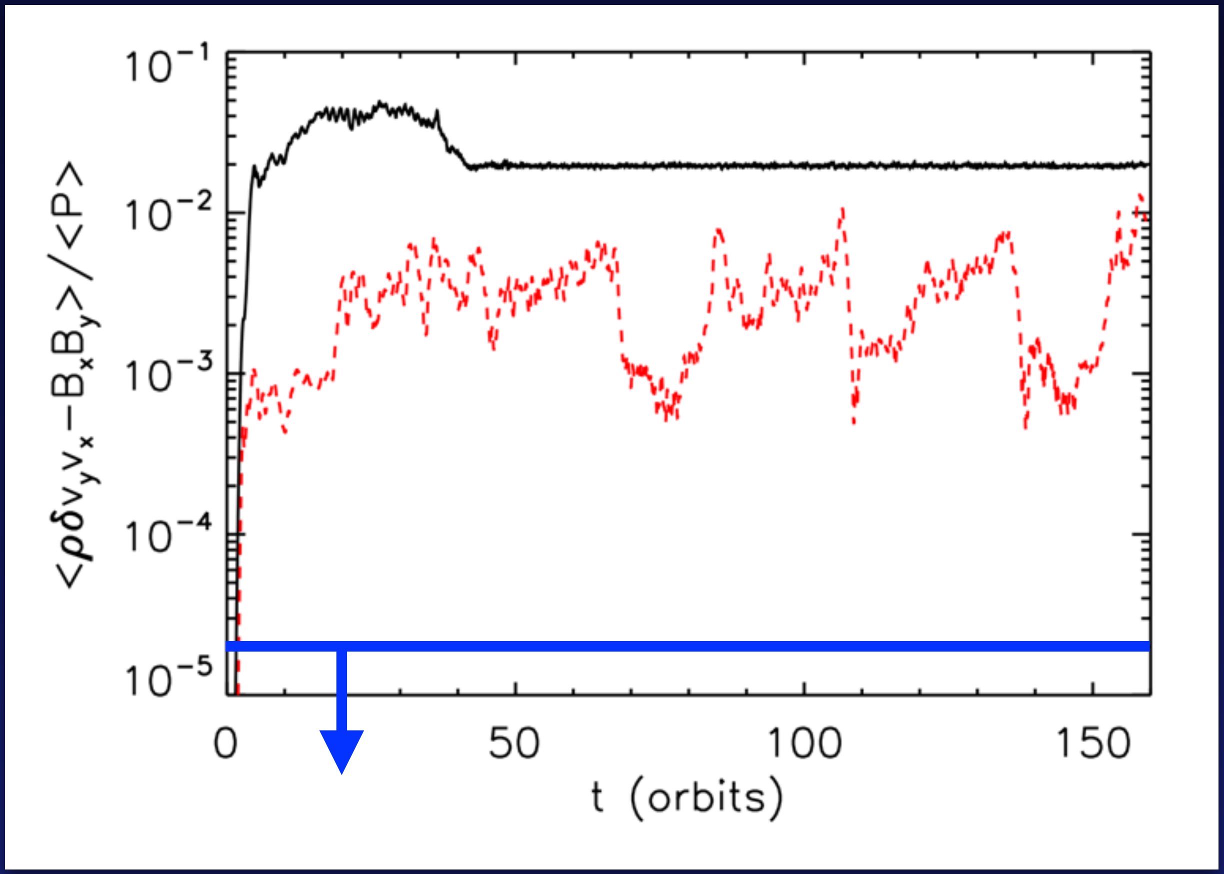
Inner disk (1-10 AU)
Dramatic differences depending on field orientation



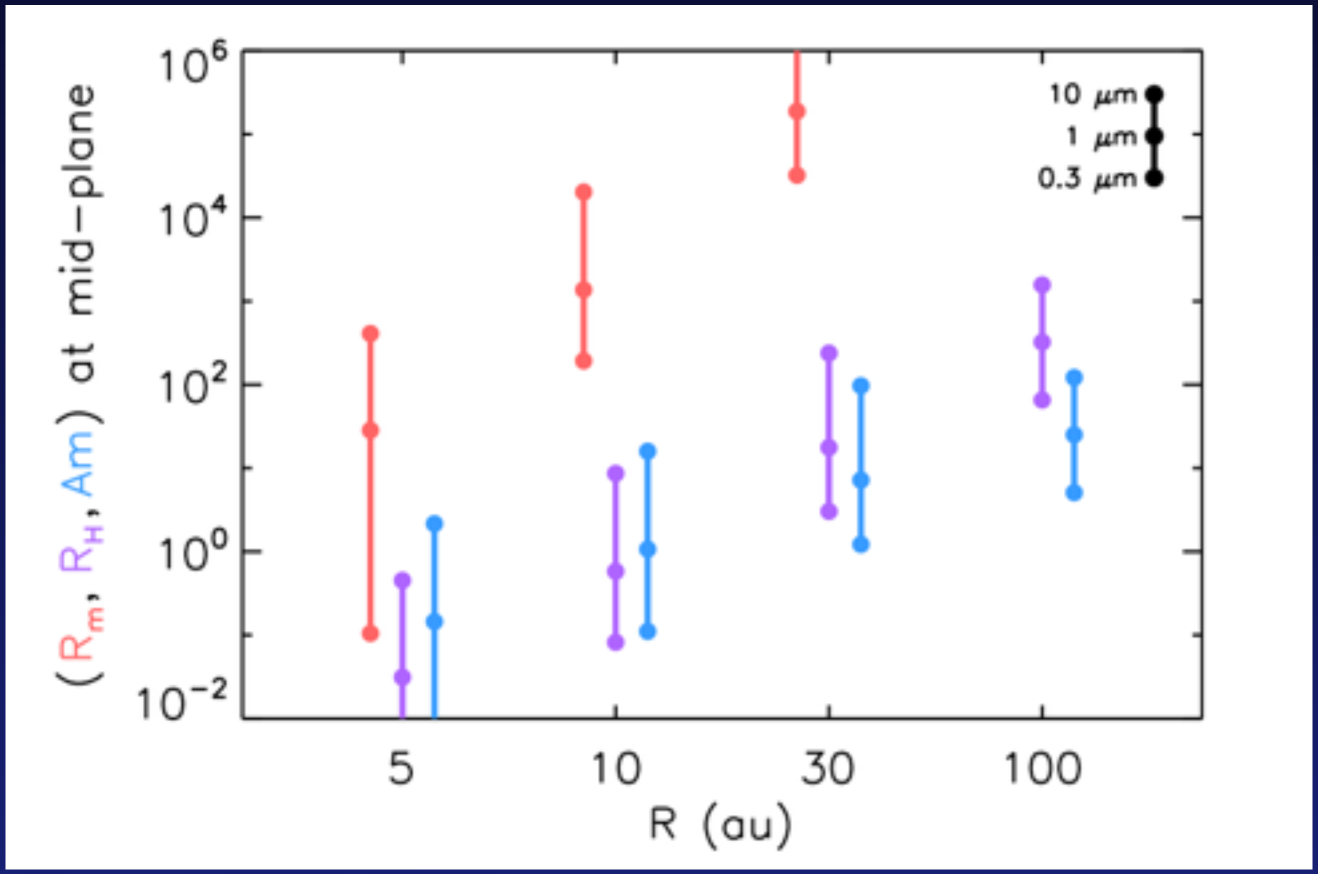
Simon et al. (2015b), MNRAS

Inner disk (1-10 AU)
Dramatic differences depending on field orientation

$B_z > 0$



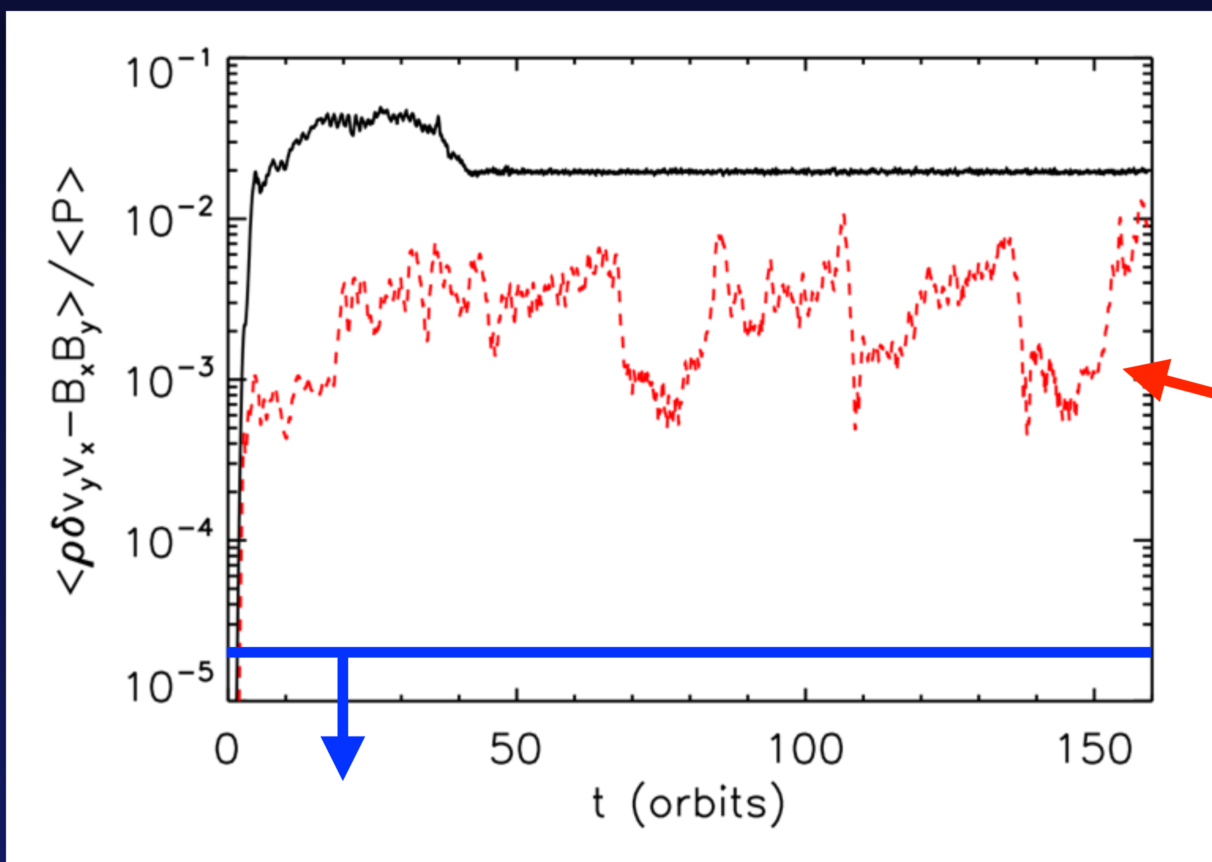
0



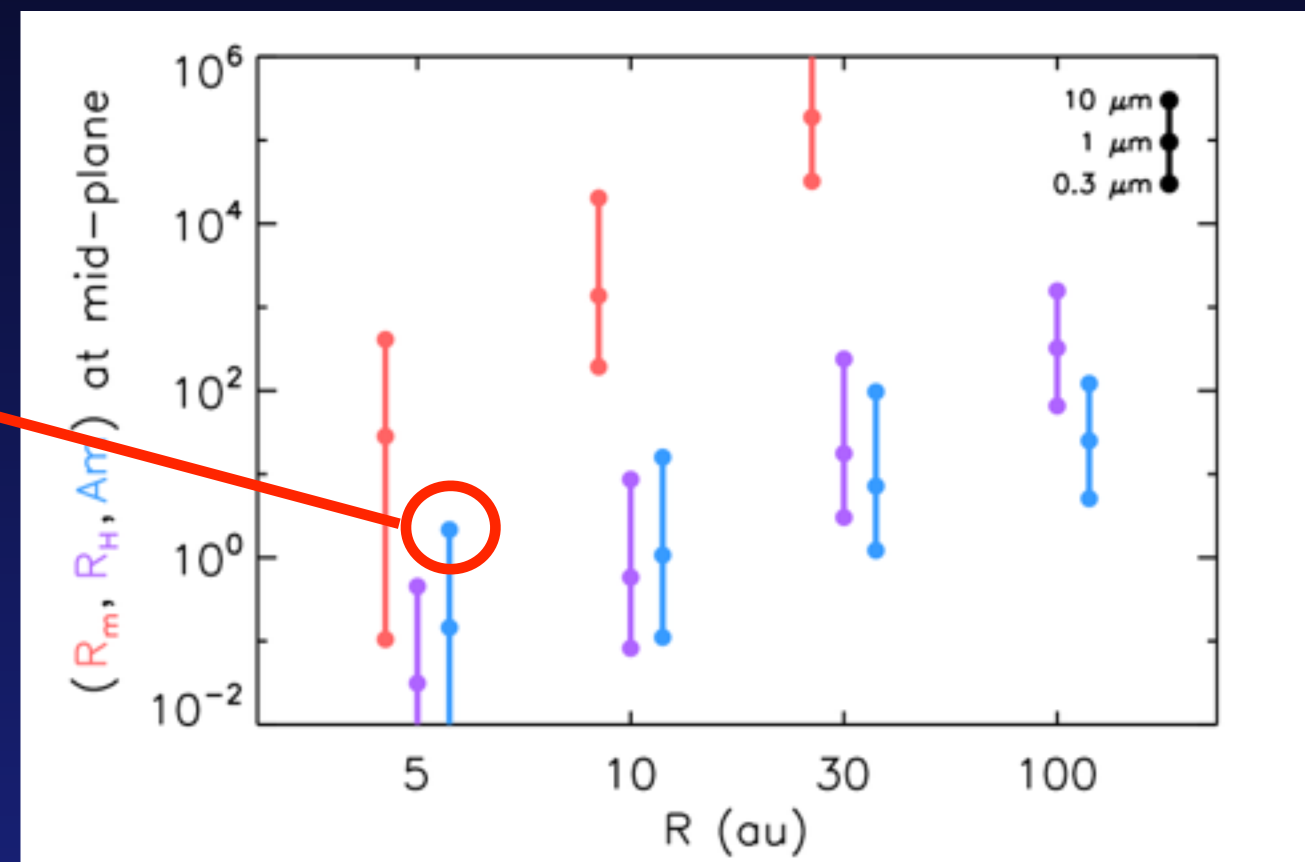
Simon et al. (2015b), MNRAS

Inner disk (1-10 AU)
Dramatic differences depending on field orientation

$B_z > 0$



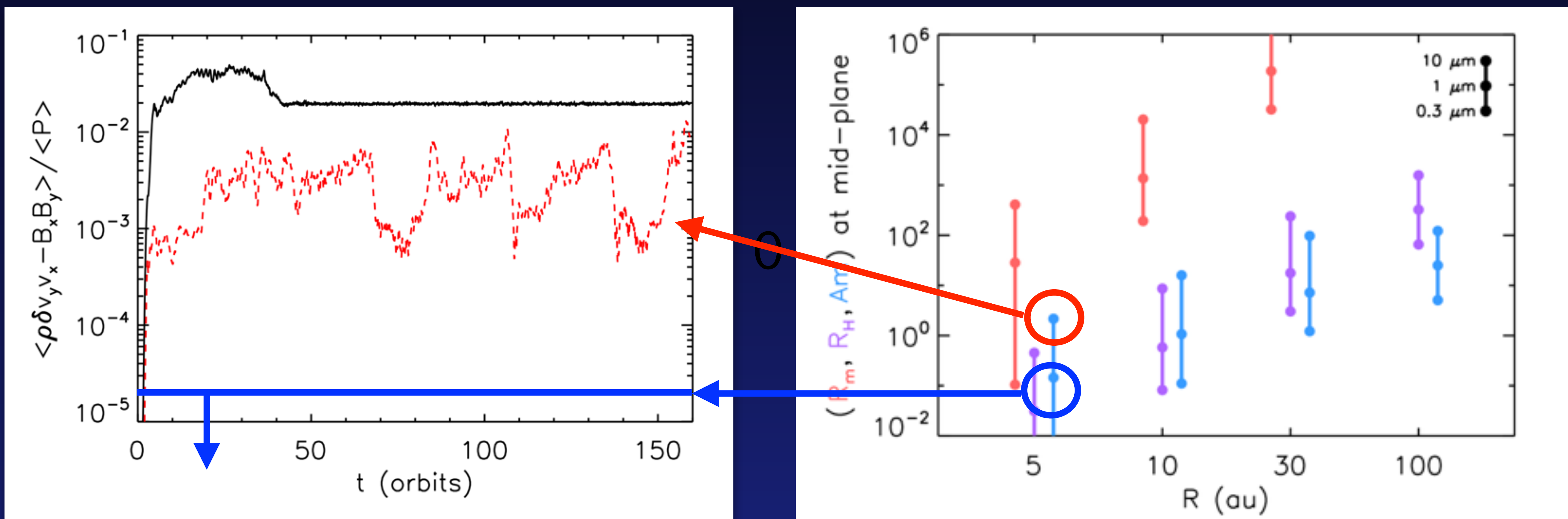
0



Simon et al. (2015b), MNRAS

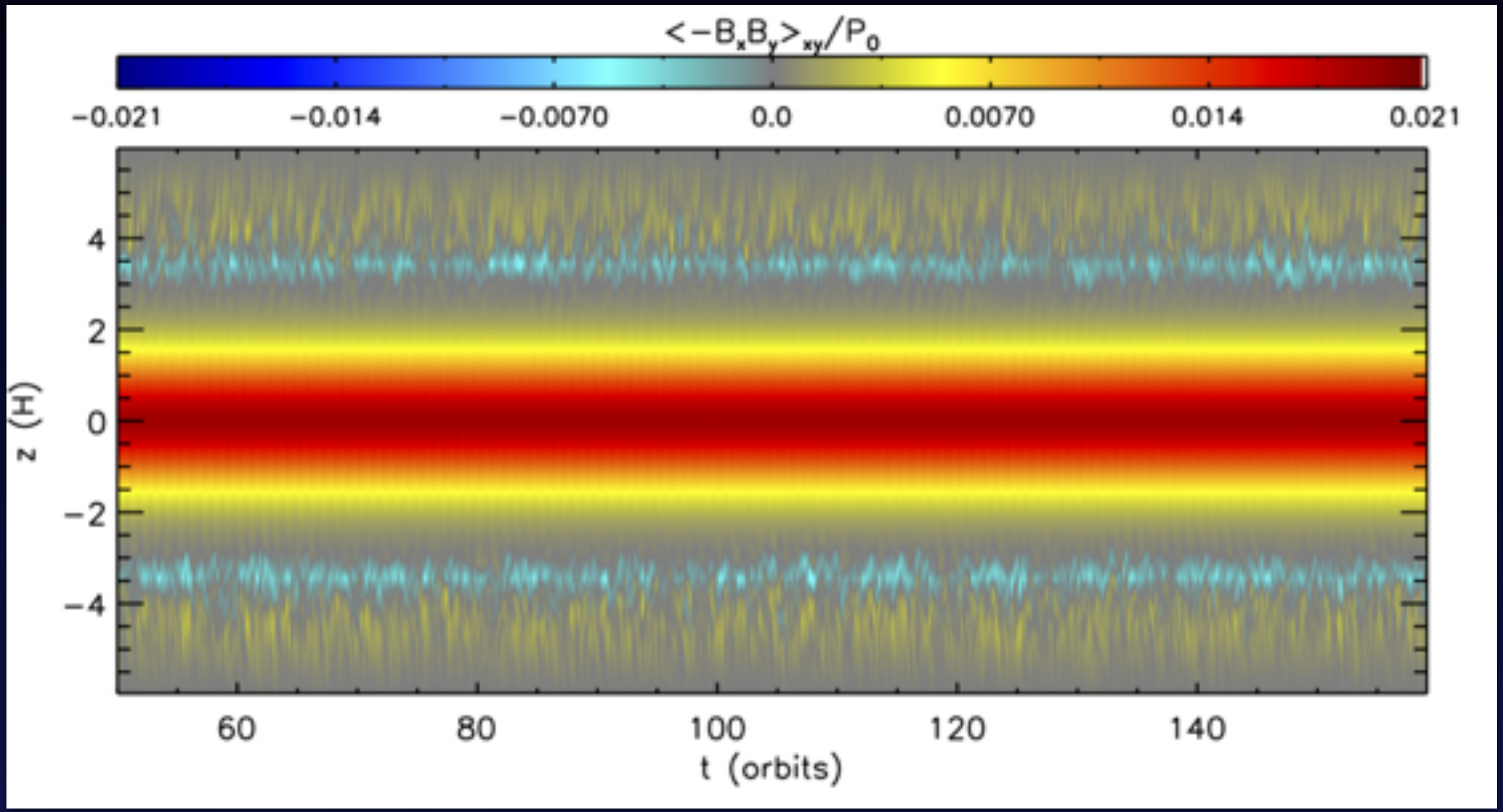
Inner disk (1-10 AU)
Dramatic differences depending on field orientation

$B_z > 0$



Simon et al. (2015b), MNRAS

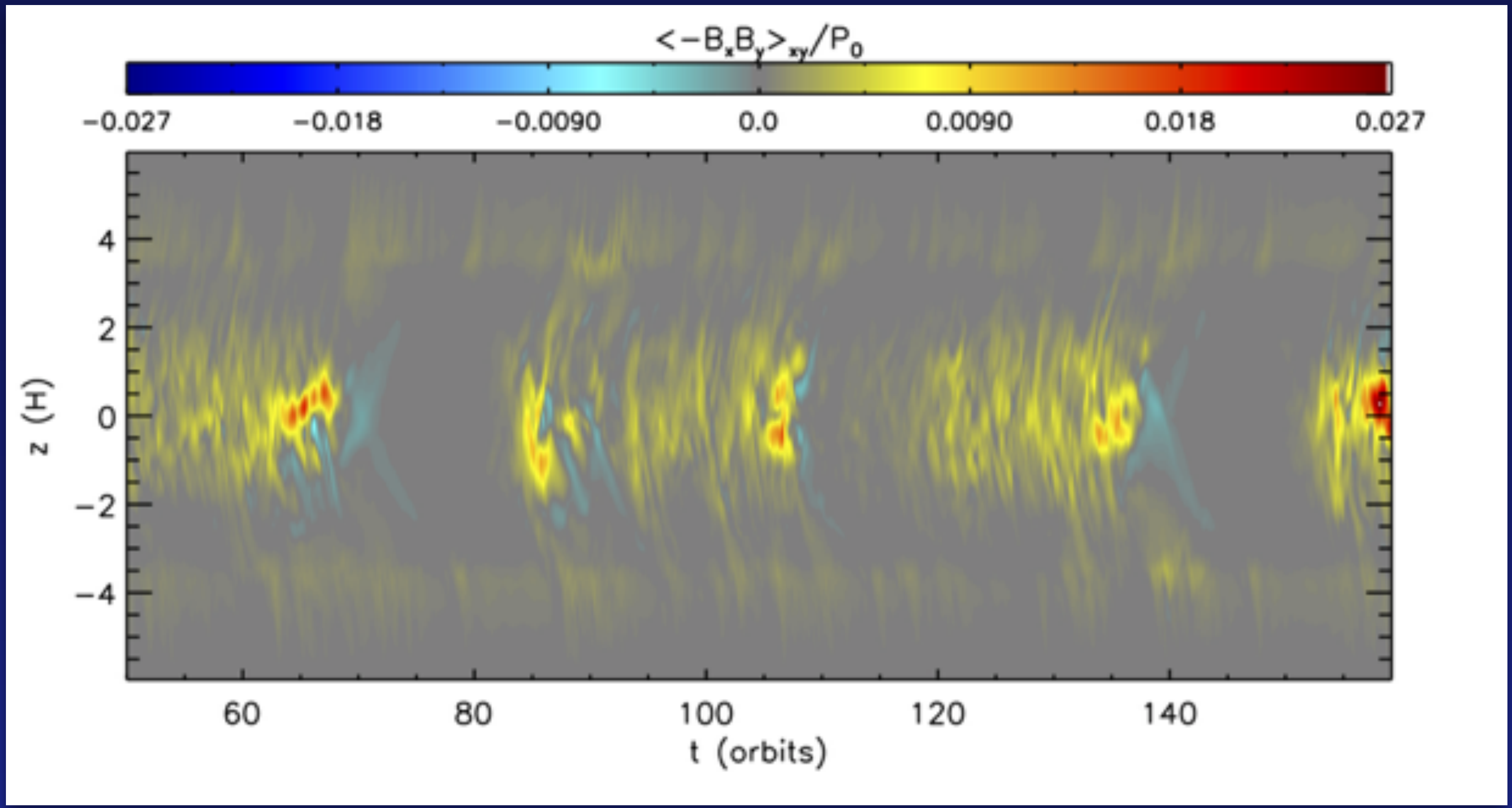
Inner disk (1-10 AU)



Simon et al. (2015b), MNRAS

$B_z > 0$

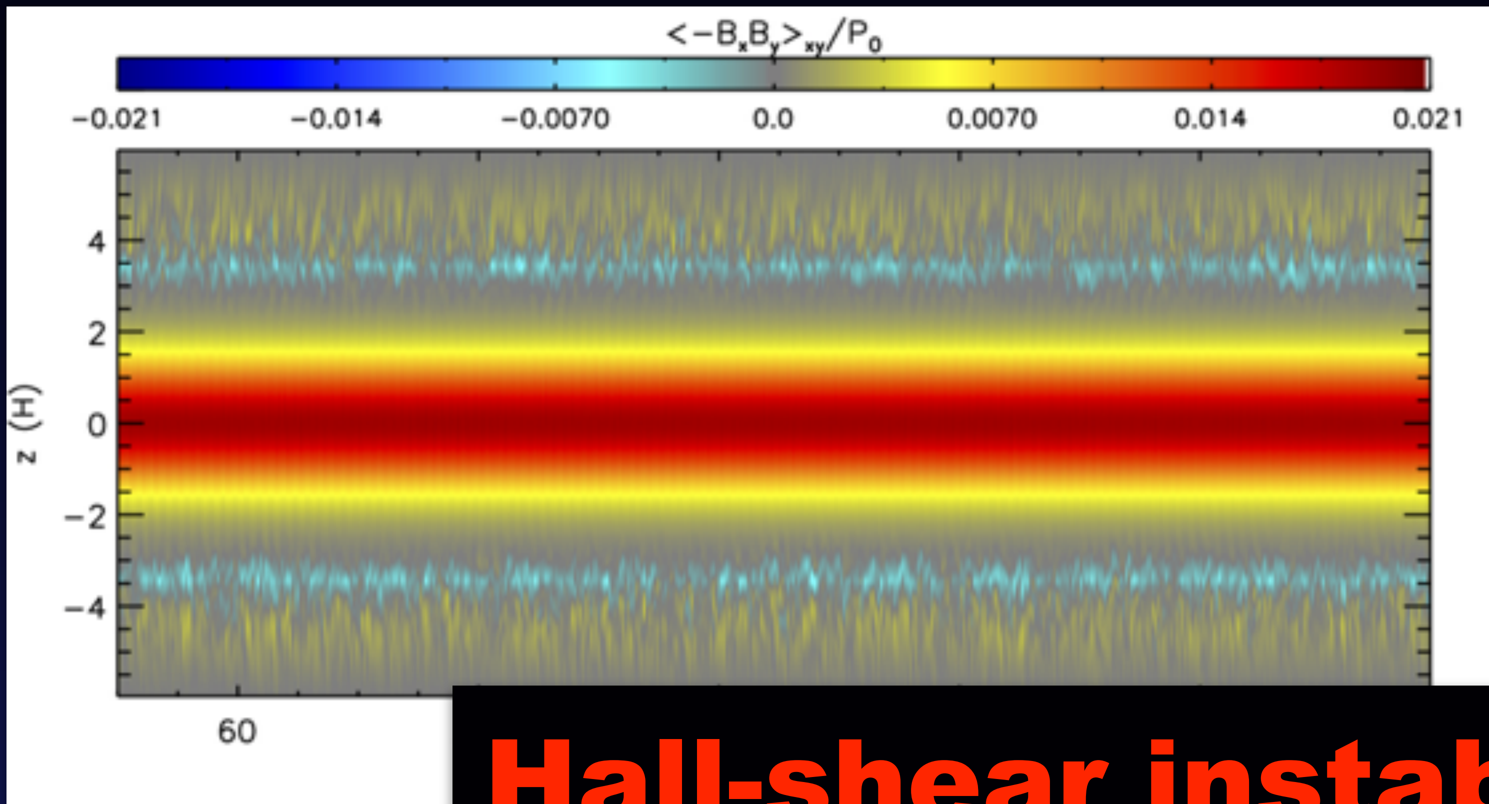
Strong, large-scale toroidal field



Non-axisymmetric bursts

$B_z < 0$

Inner disk (1-10 AU)



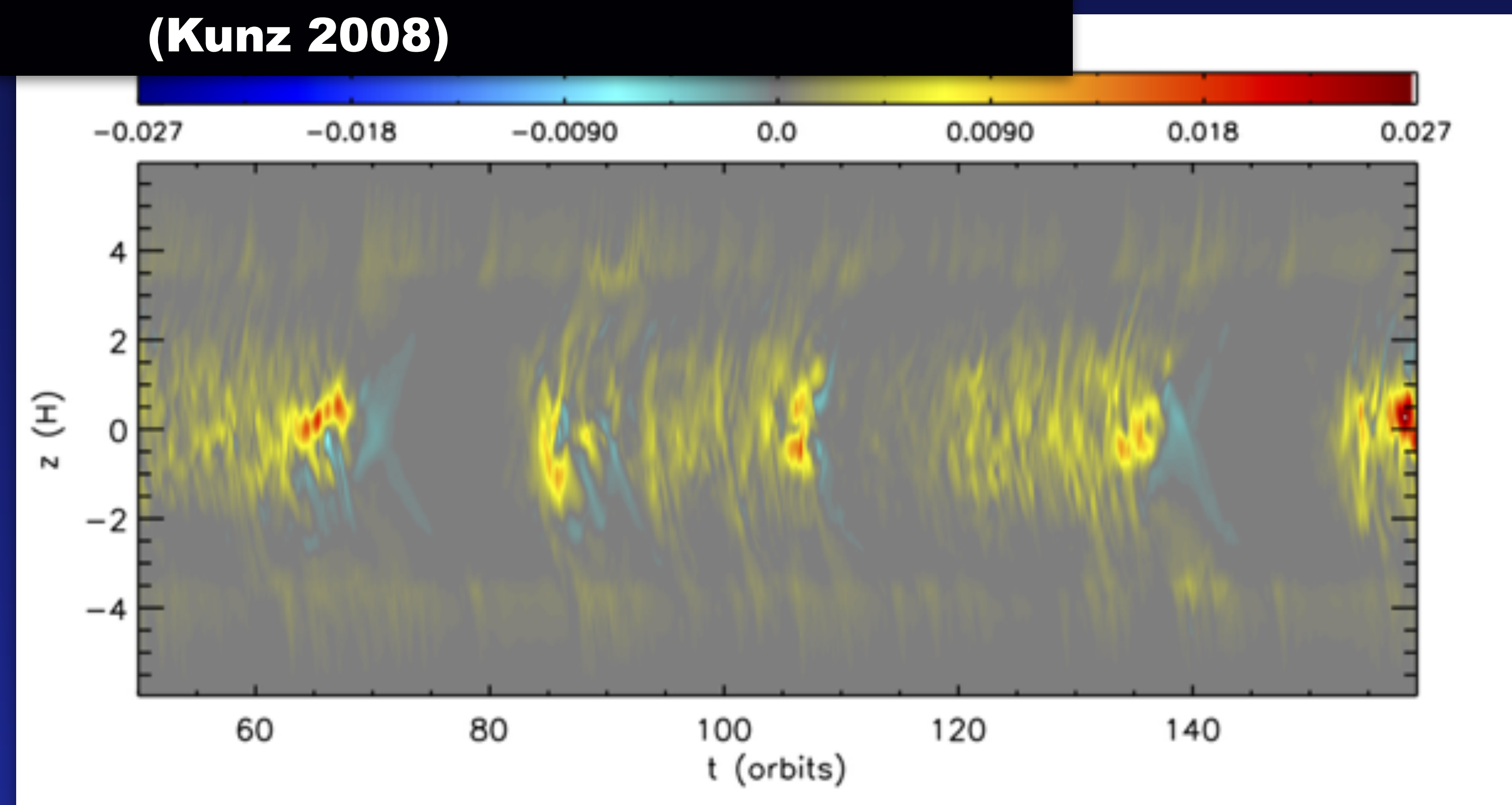
Simon et al. (2015b), MNRA

$B_z > 0$

Strong, large-scale toroidal field

Hall-shear instability (HSI)

(Kunz 2008)

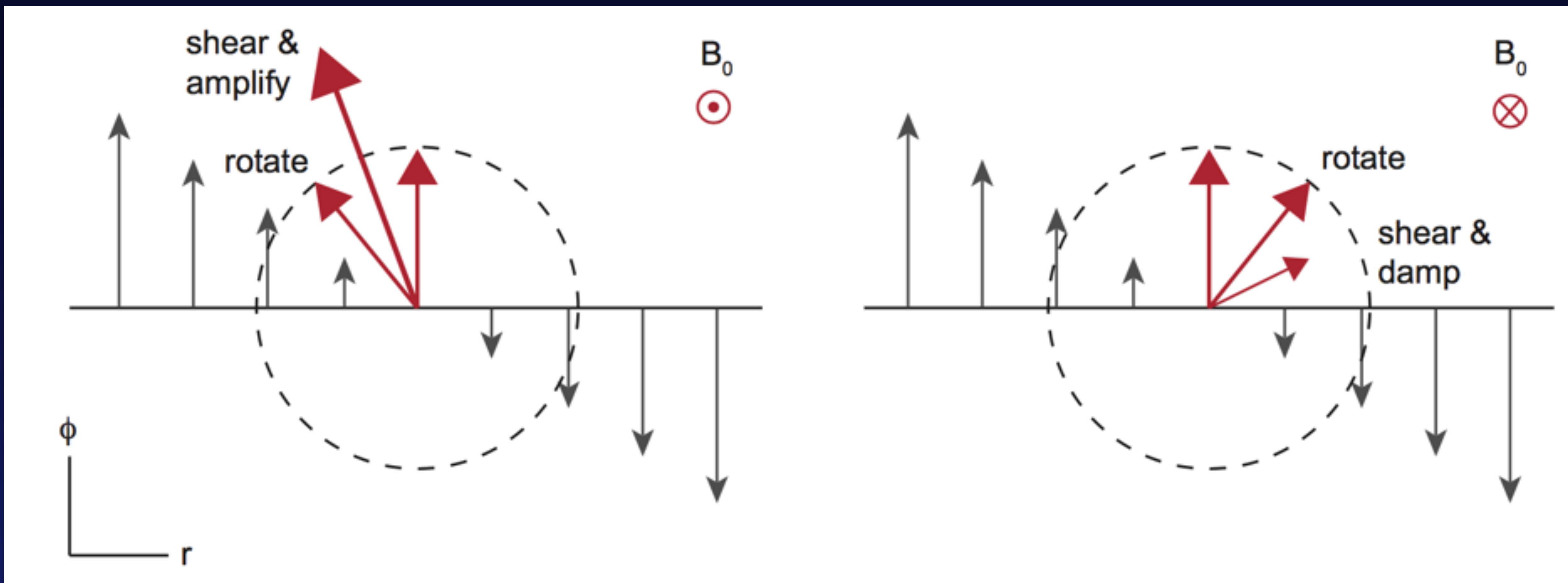


Non-axisymmetric bursts

$B_z < 0$

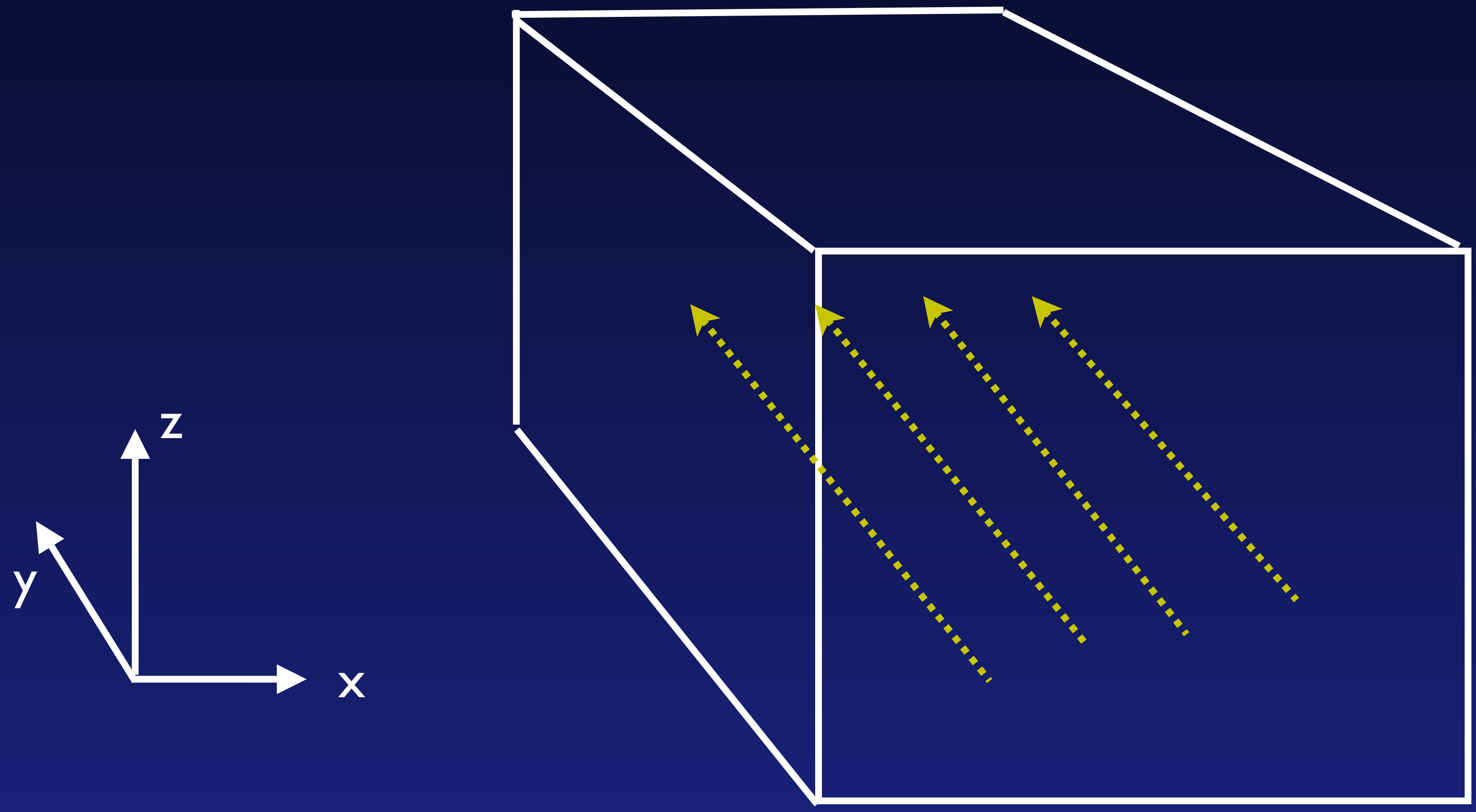
The Hall-shear instability (in detail)

$B_z > 0$ | $B_z < 0$

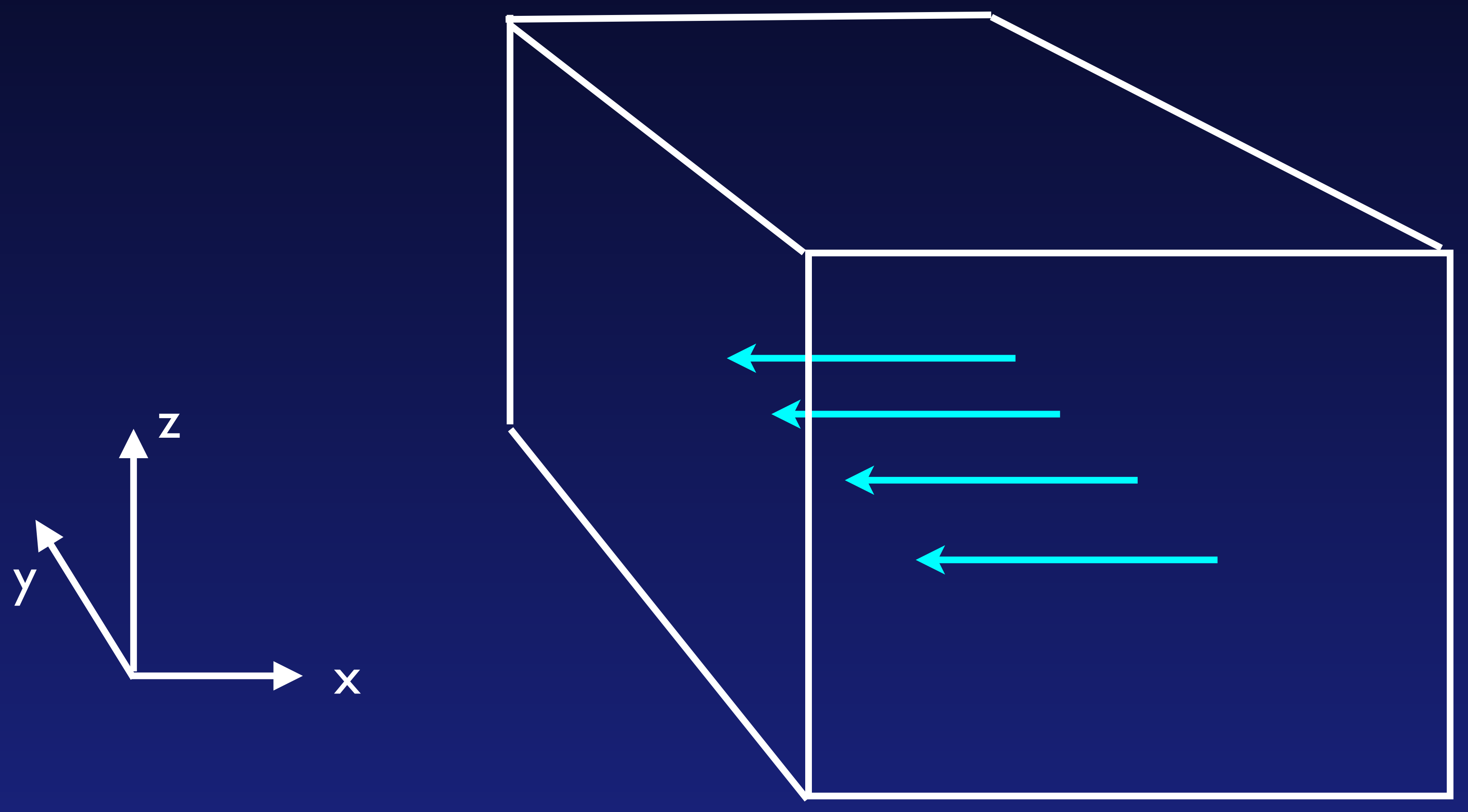


Lesur (unpublished), Armitage (Saas-Fee lectures)

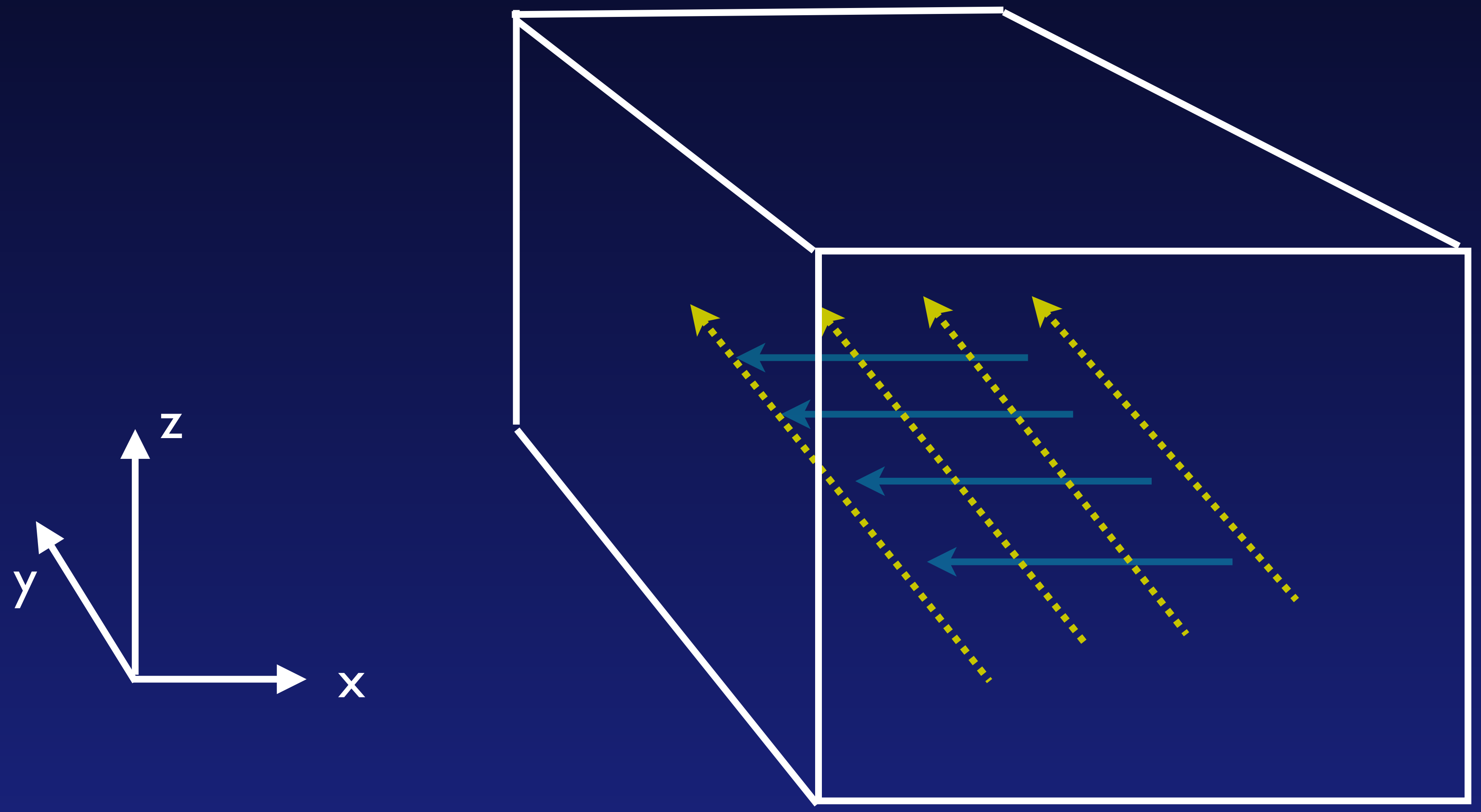
$B_z > 0$



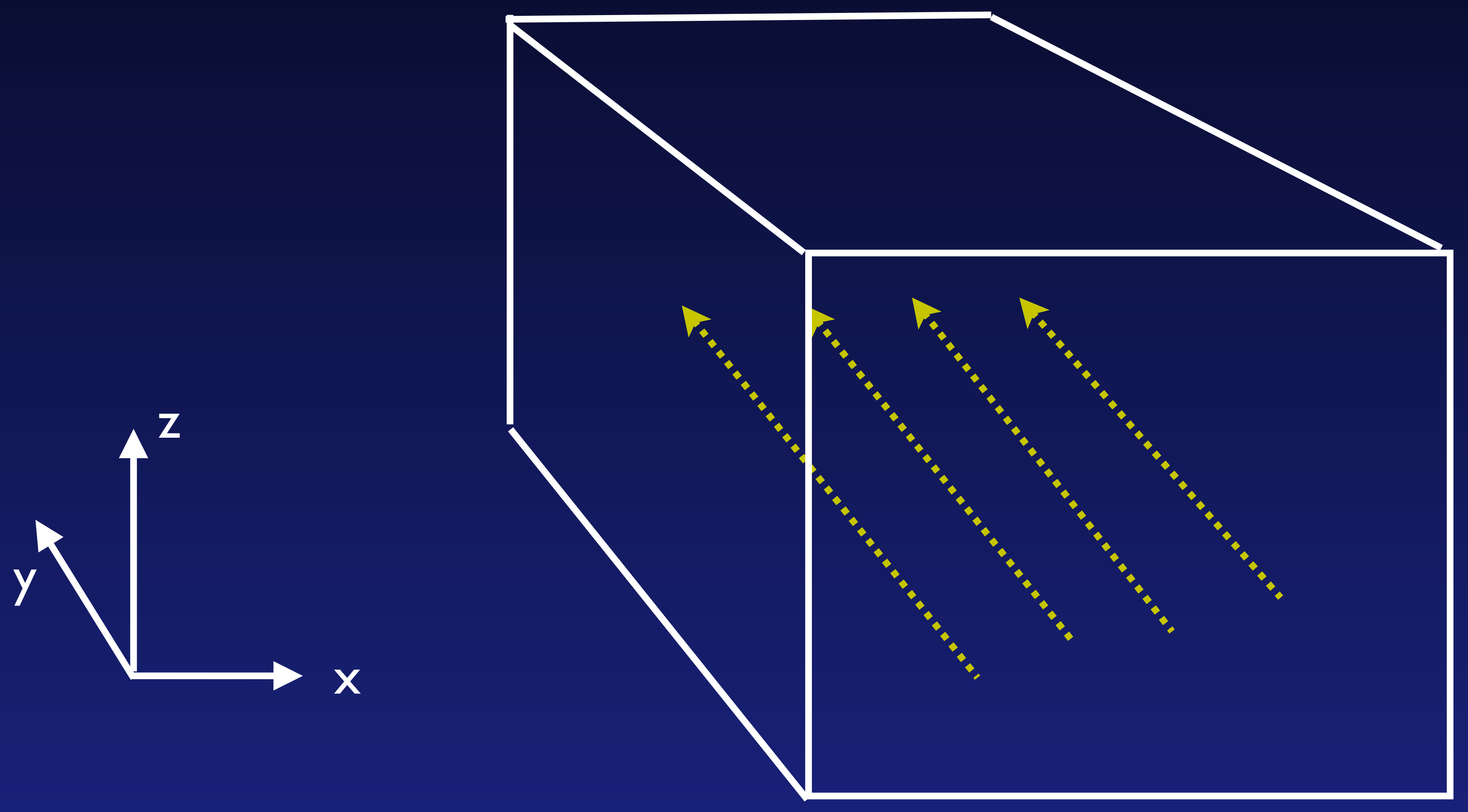
$B_z > 0$



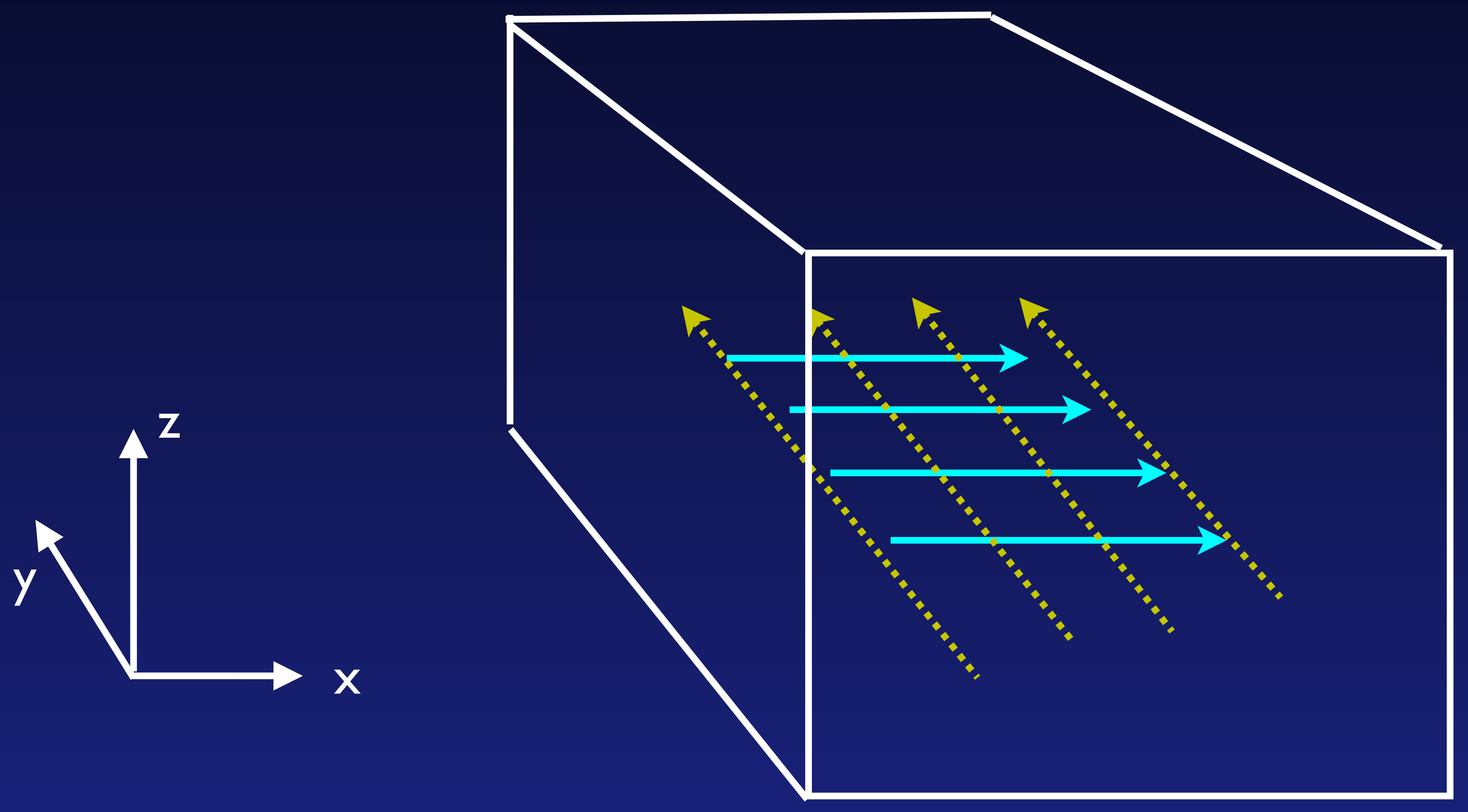
$B_z > 0$



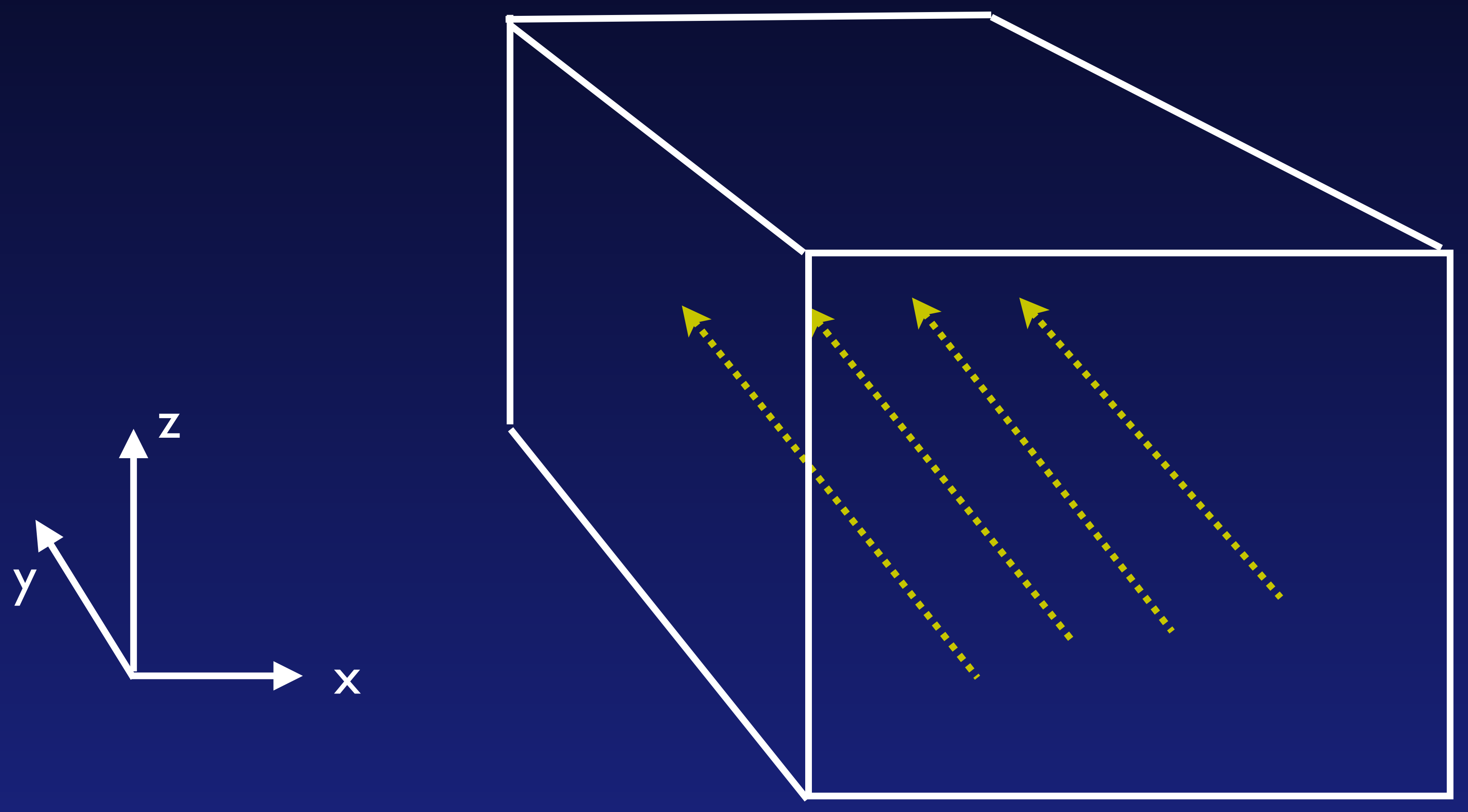
$B_z < 0$



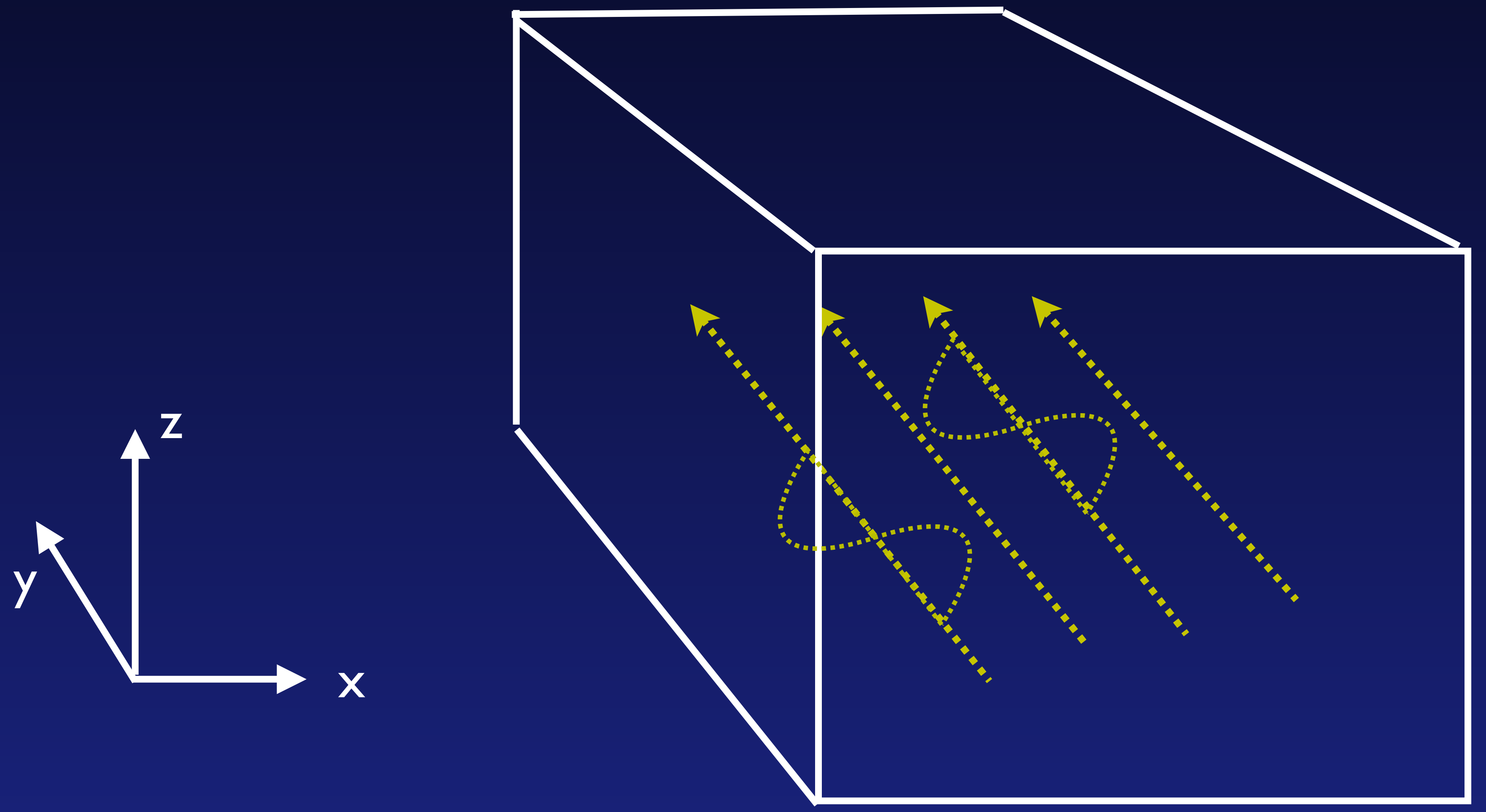
$B_z < 0$



$B_z < 0$

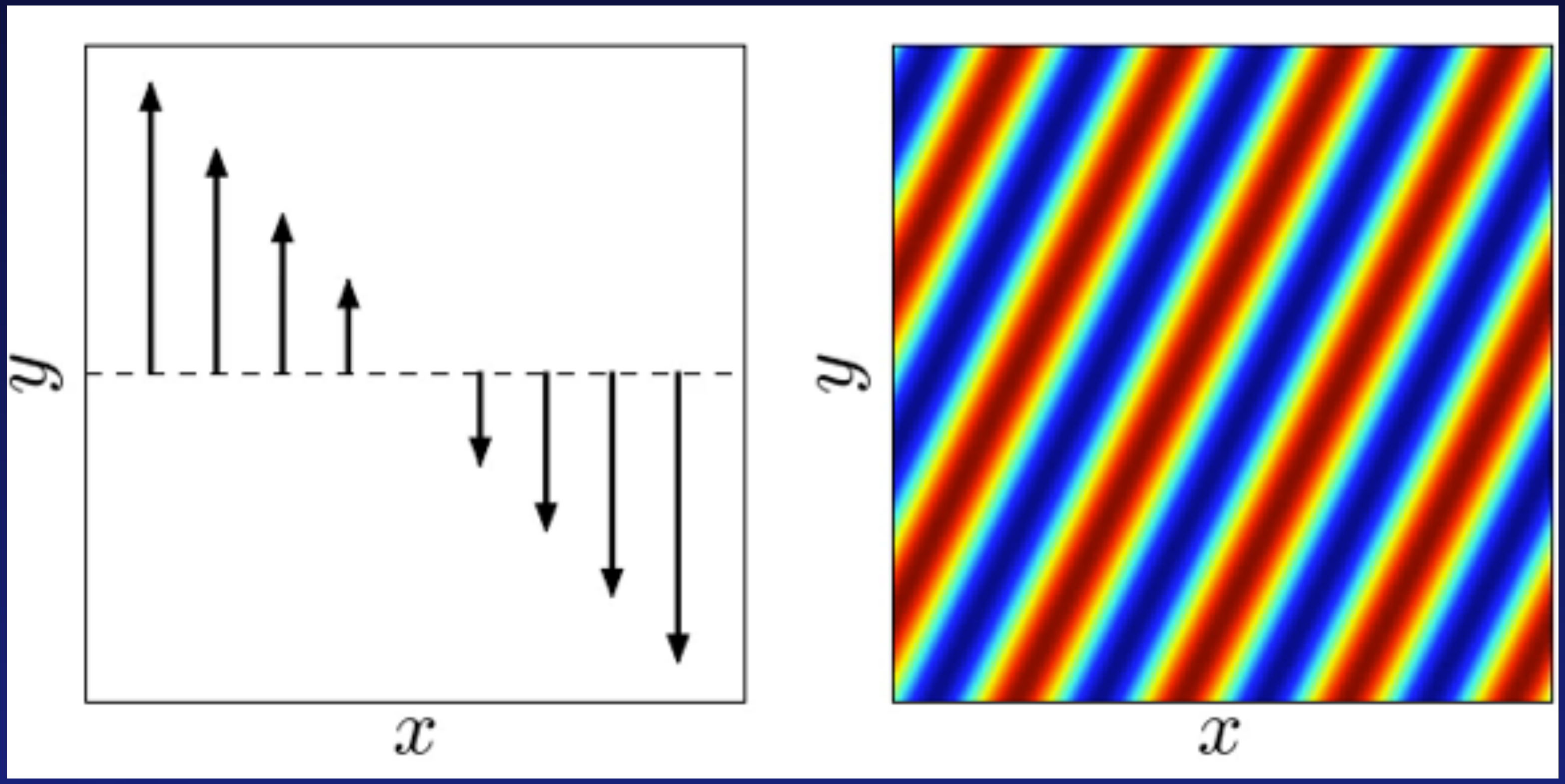


$B_z < 0$

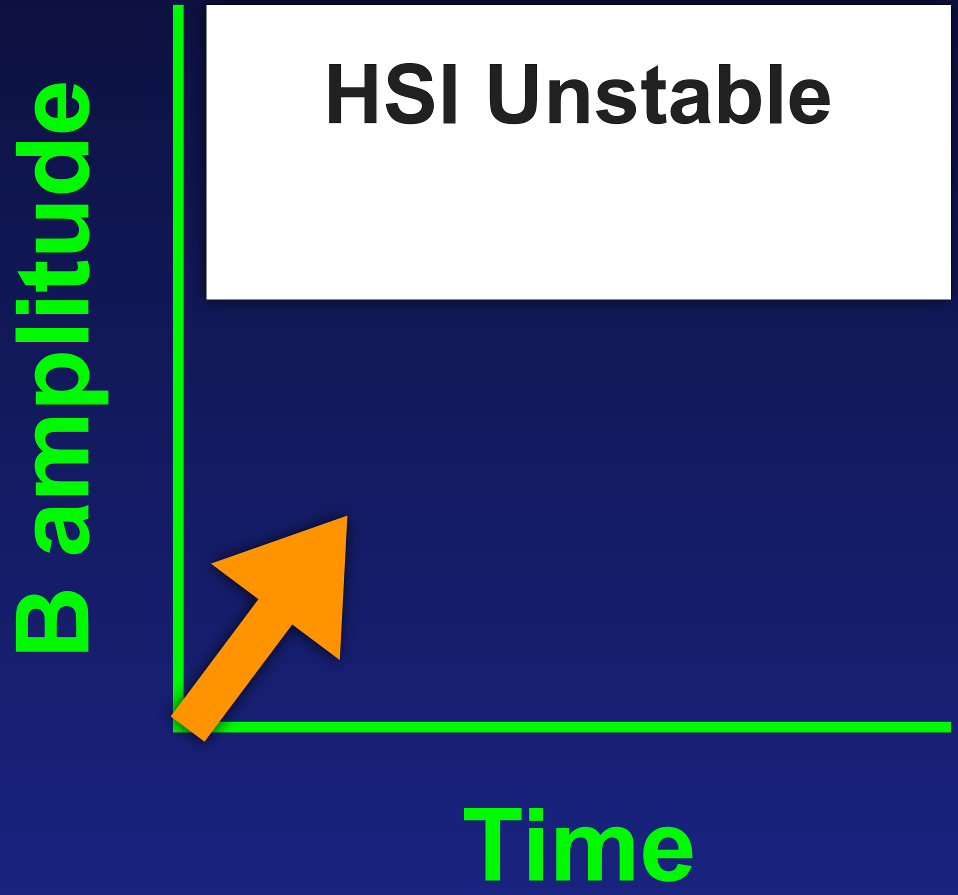


$B_z < 0$

Amplification of field due to shear leads to HSI unstable regime

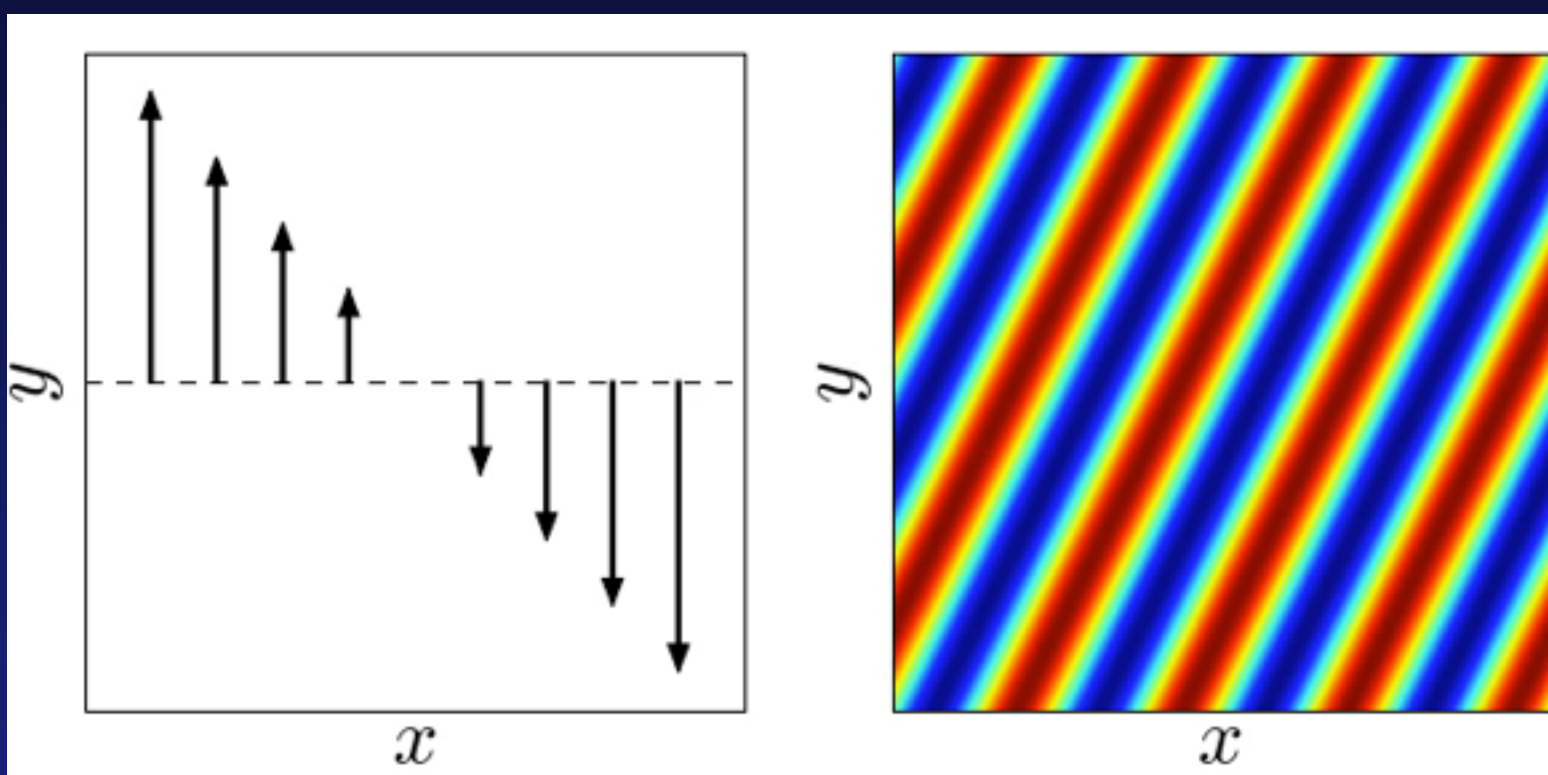


Toby Heinemann

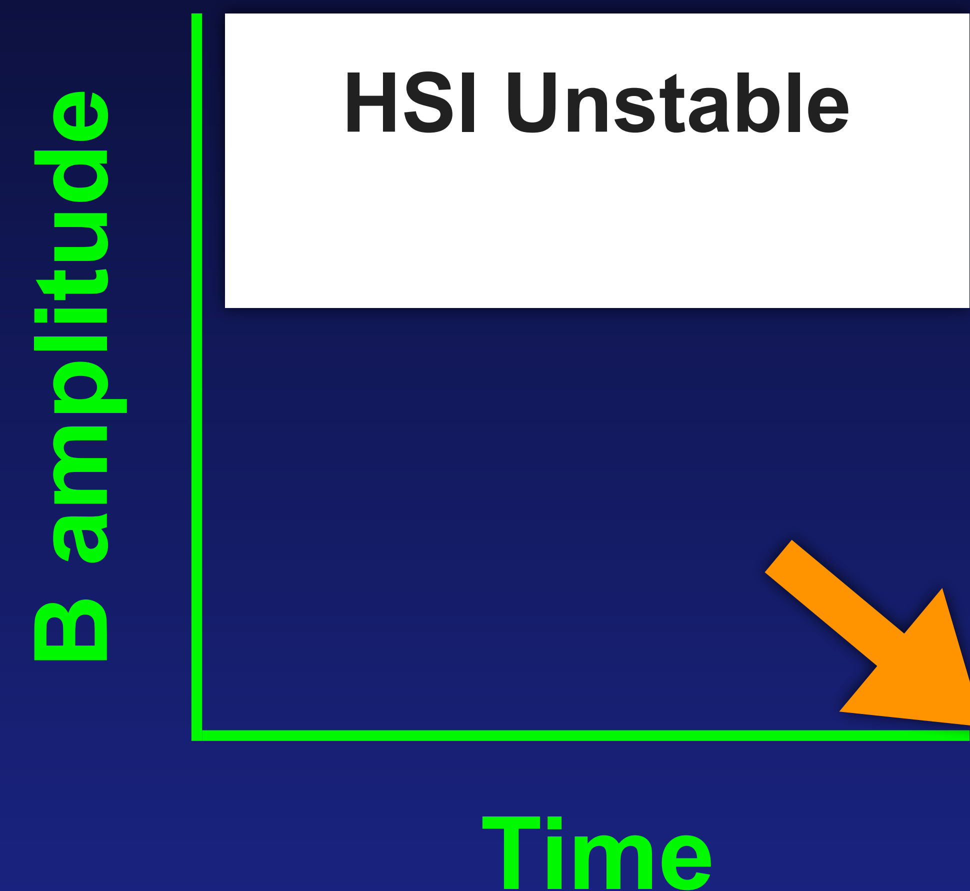


$B_z < 0$

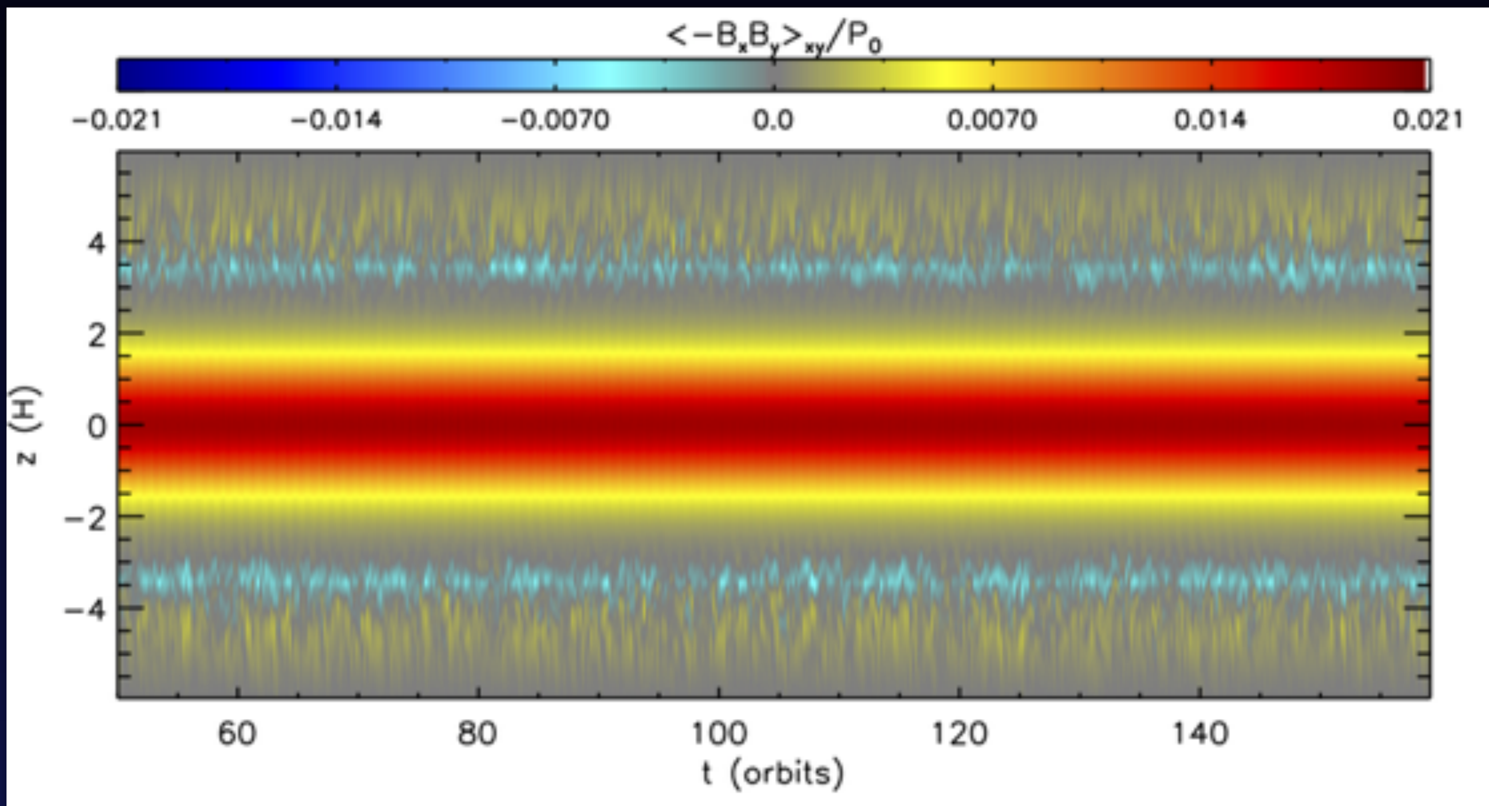
Amplification of field due to shear leads to HSI unstable regime



Toby Heinemann



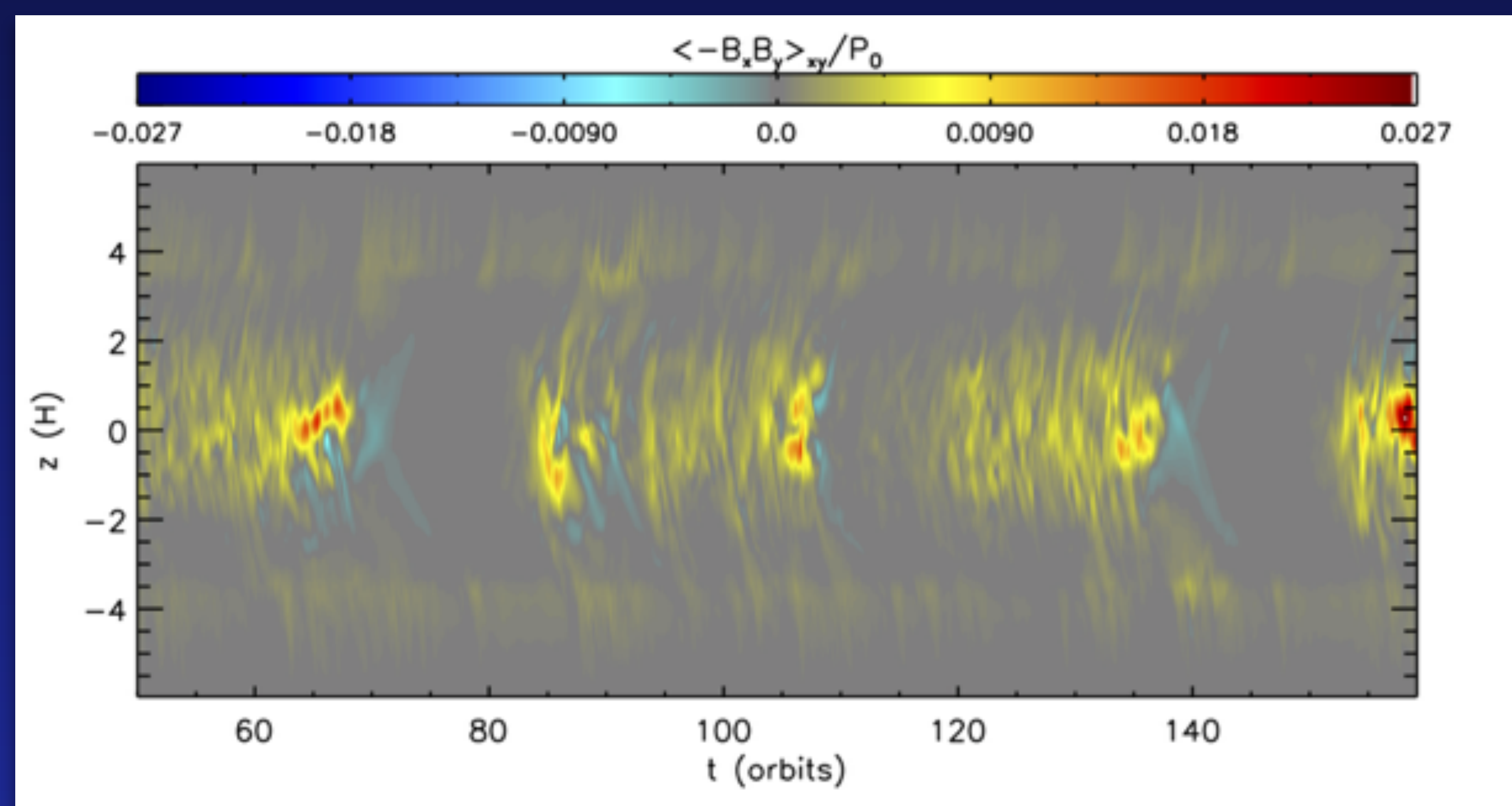
Inner disk (1-10 AU)



Simon et al. (2015b), MNRAS

$B_z > 0$

Strong, large-scale toroidal field



Non-axisymmetric bursts

$B_z < 0$

Take away points so far

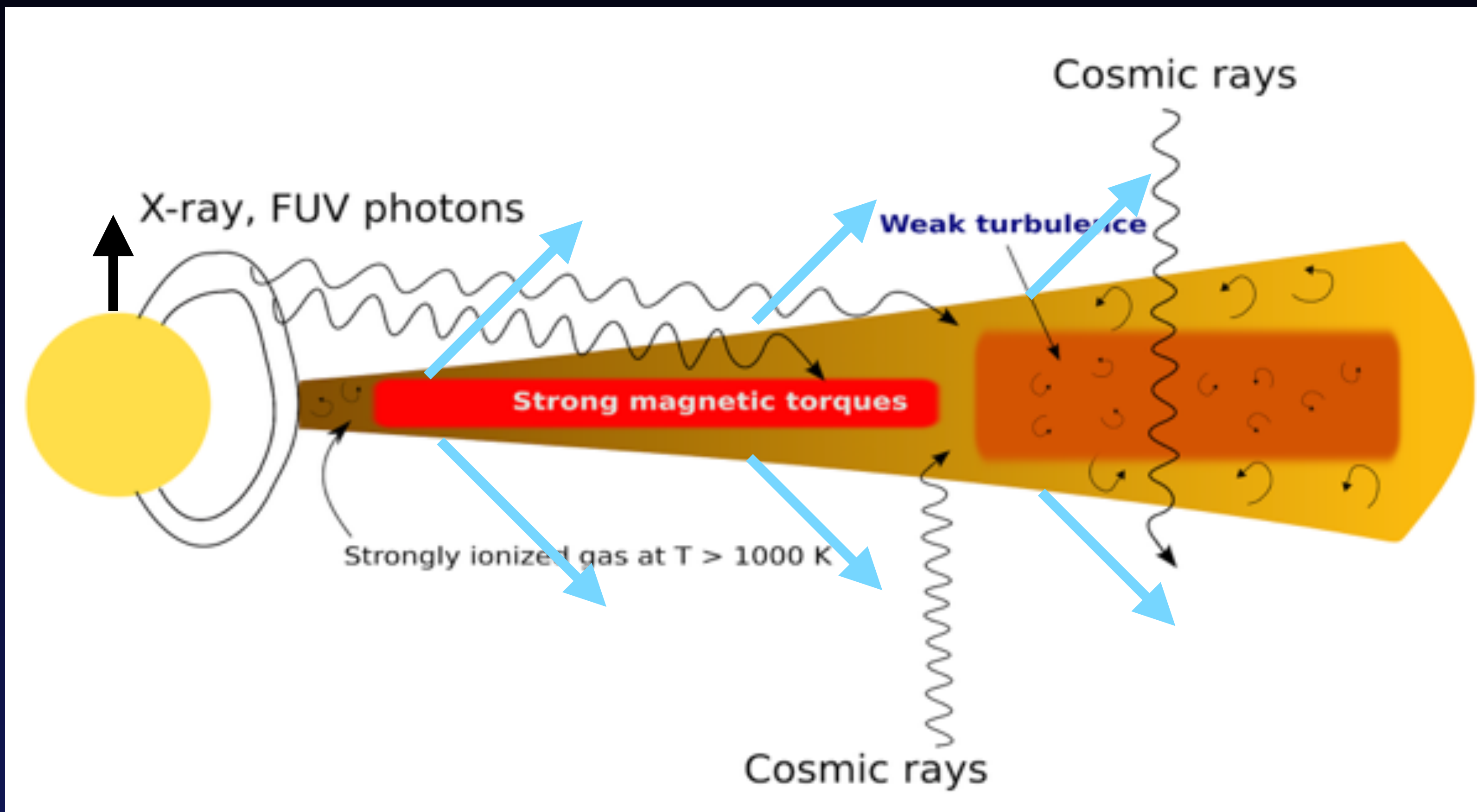
1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent “bursts” via the HSI

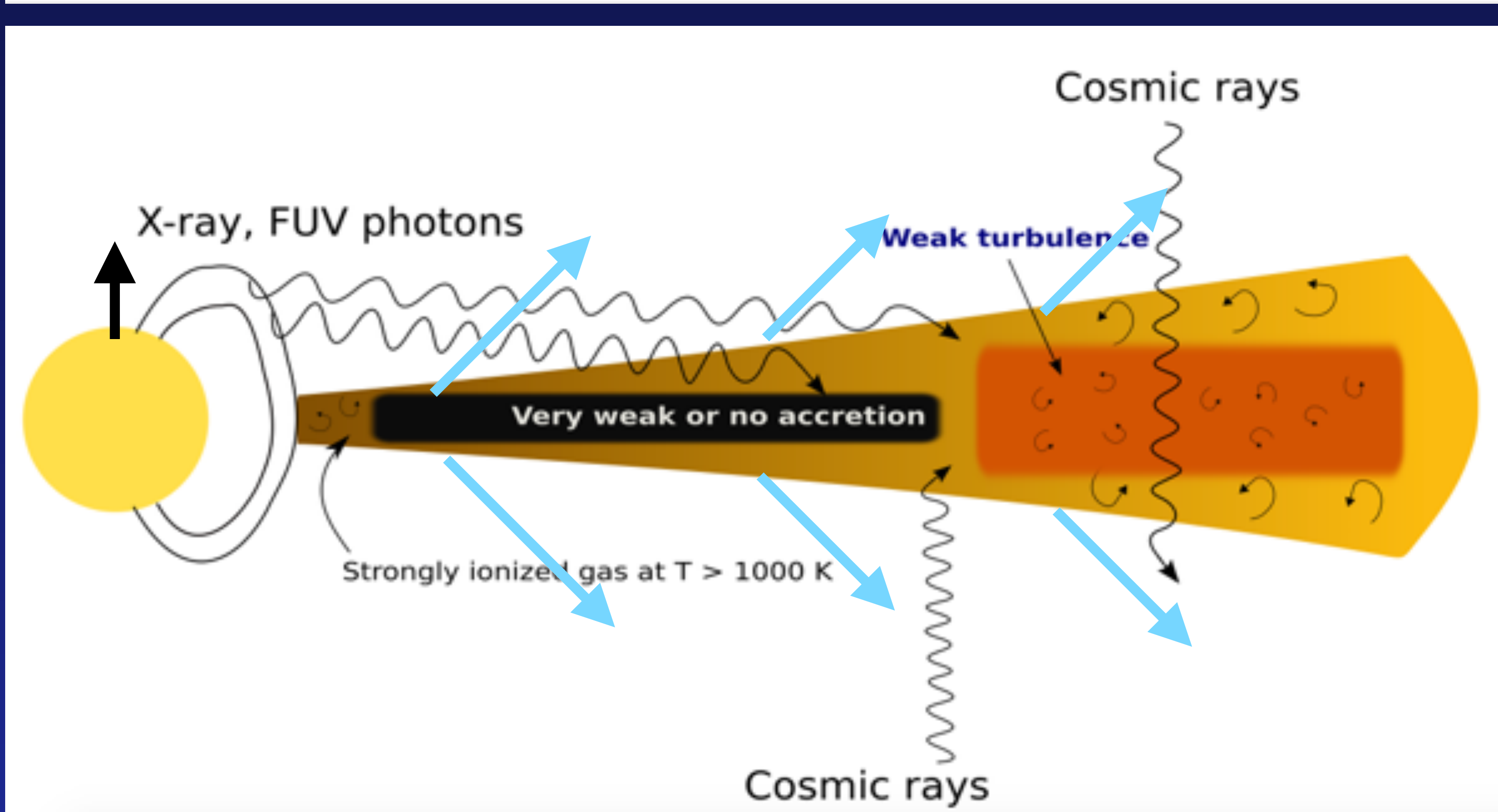
Take away points so far

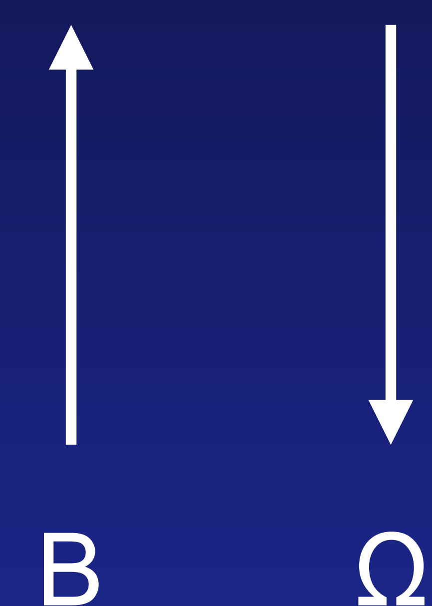
1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent "bursts" via the HSI

Turbulence can still be important!

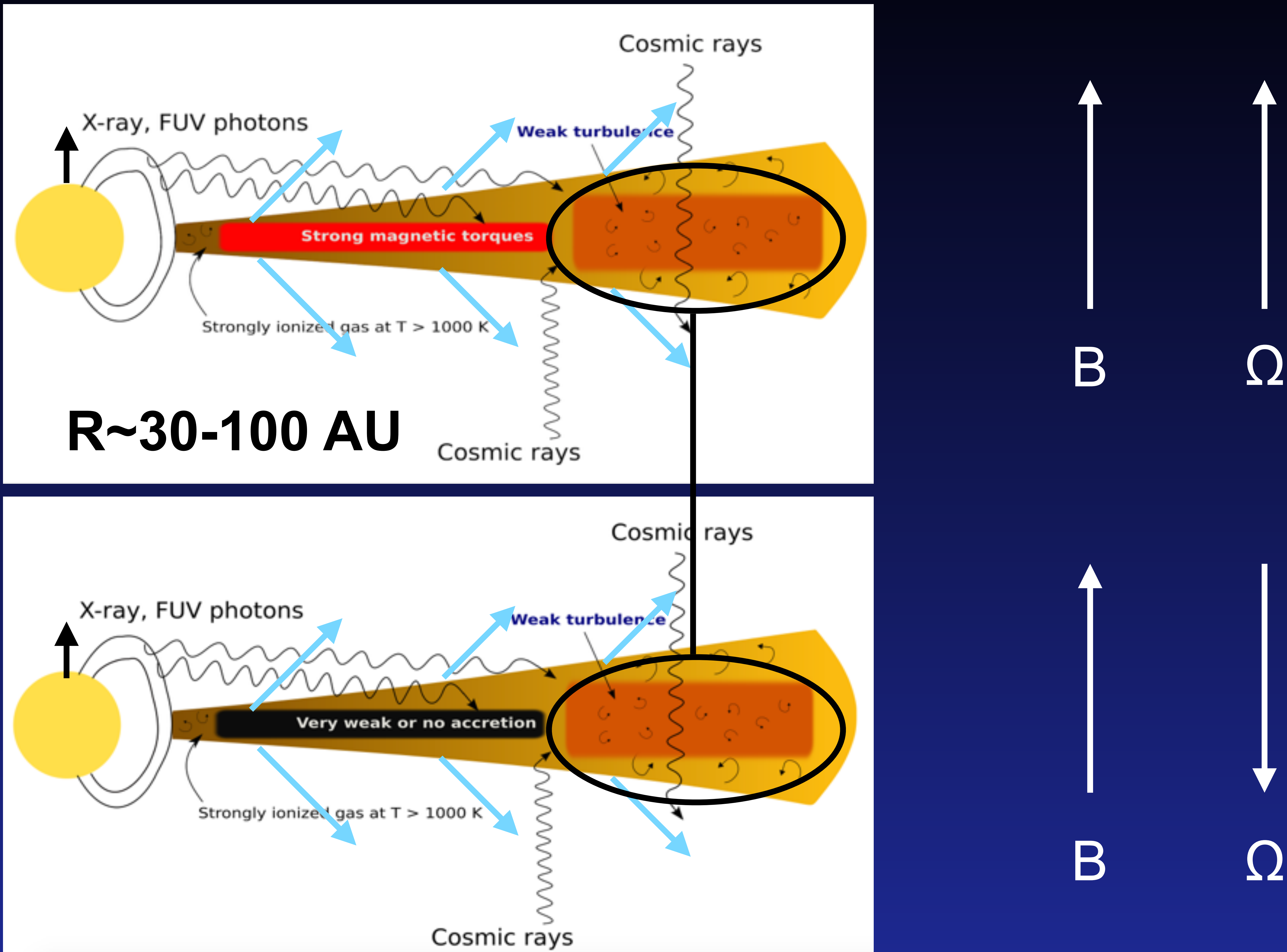
And now for the outer disk…



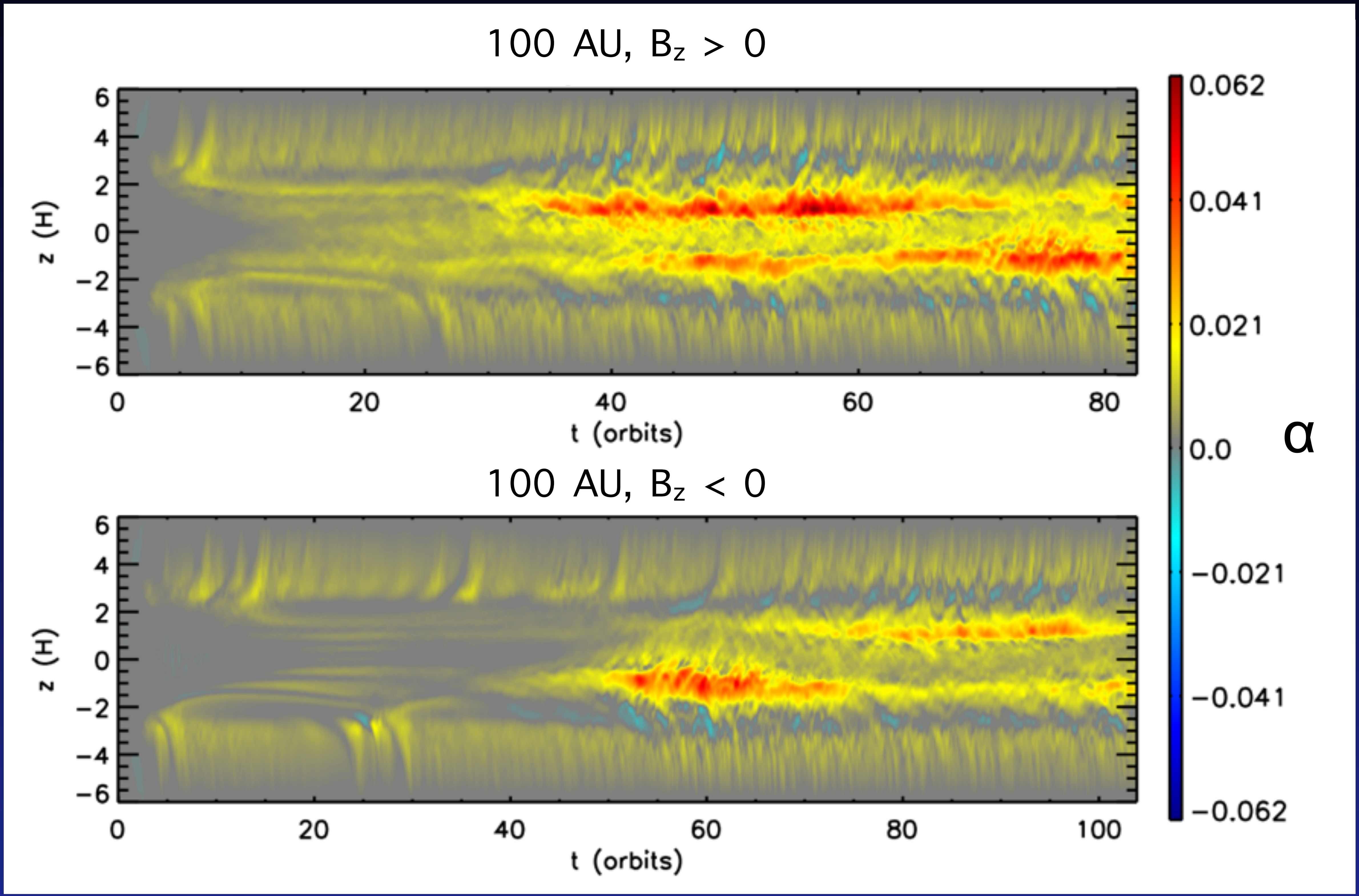




And now for the outer disk…

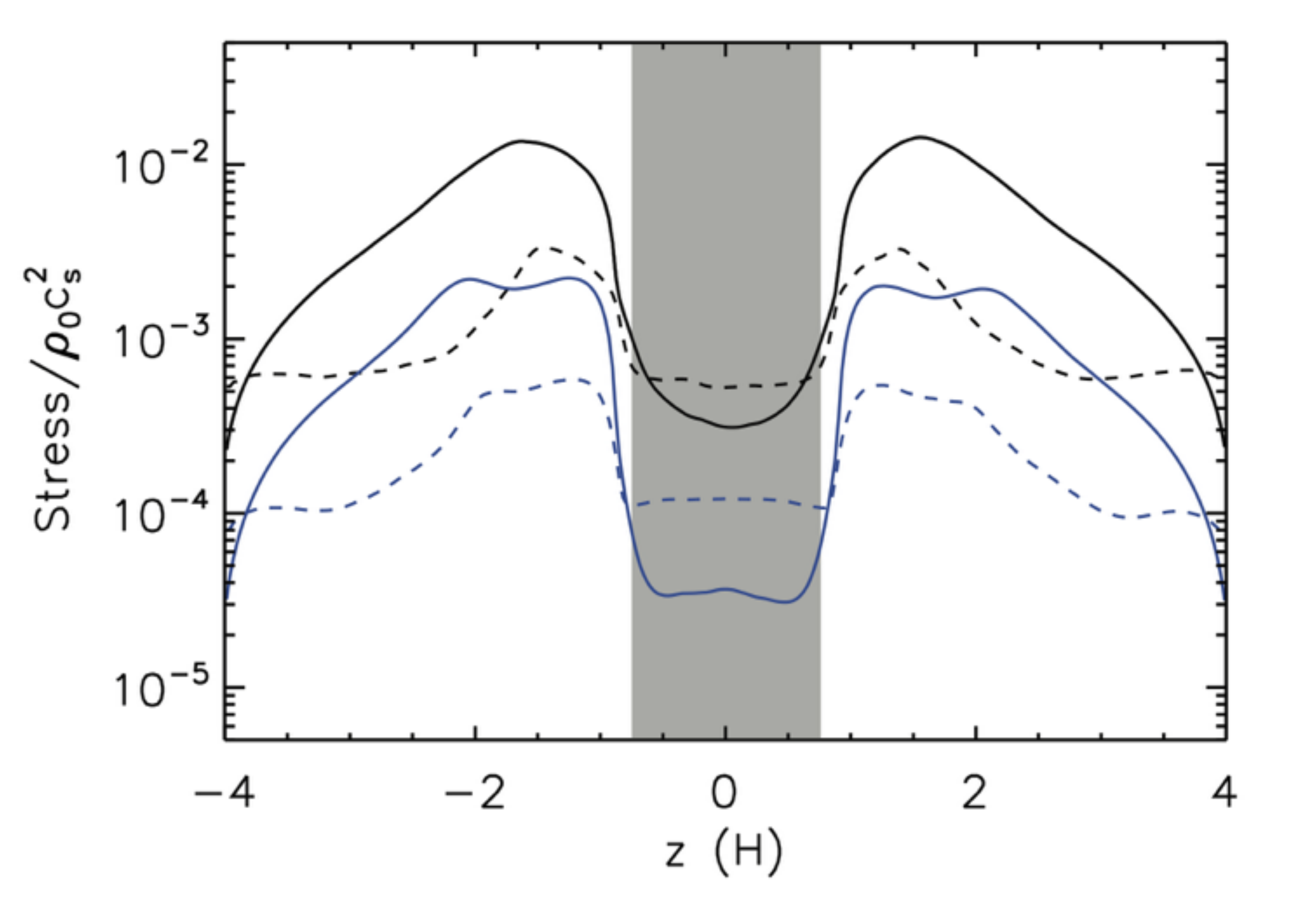


Outer disk (10-100 AU)
The field orientation does not matter



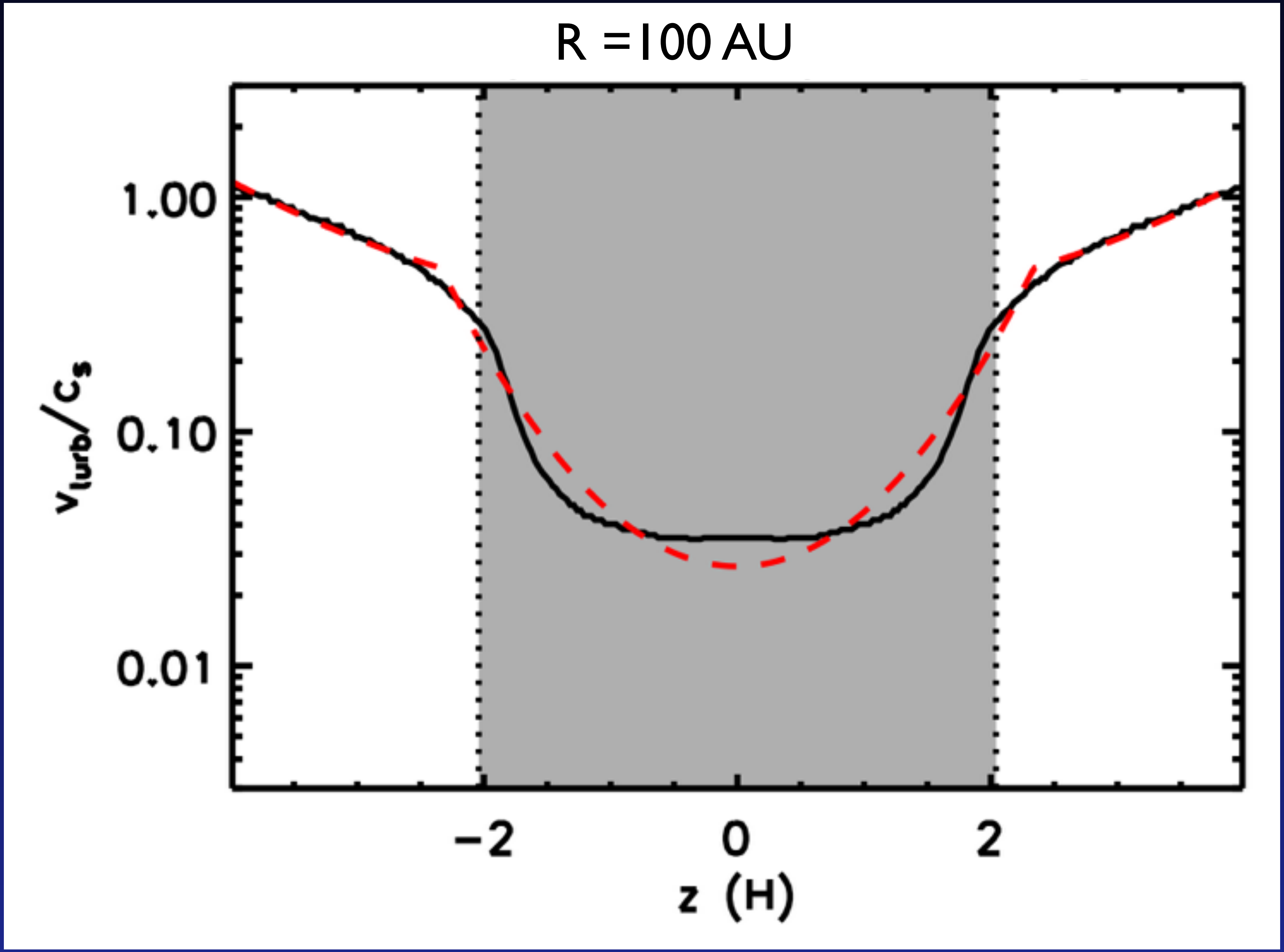
Simon et al. (2015b), MNRAS

Ambipolar diffusion causes damping of turbulence near the mid-plane



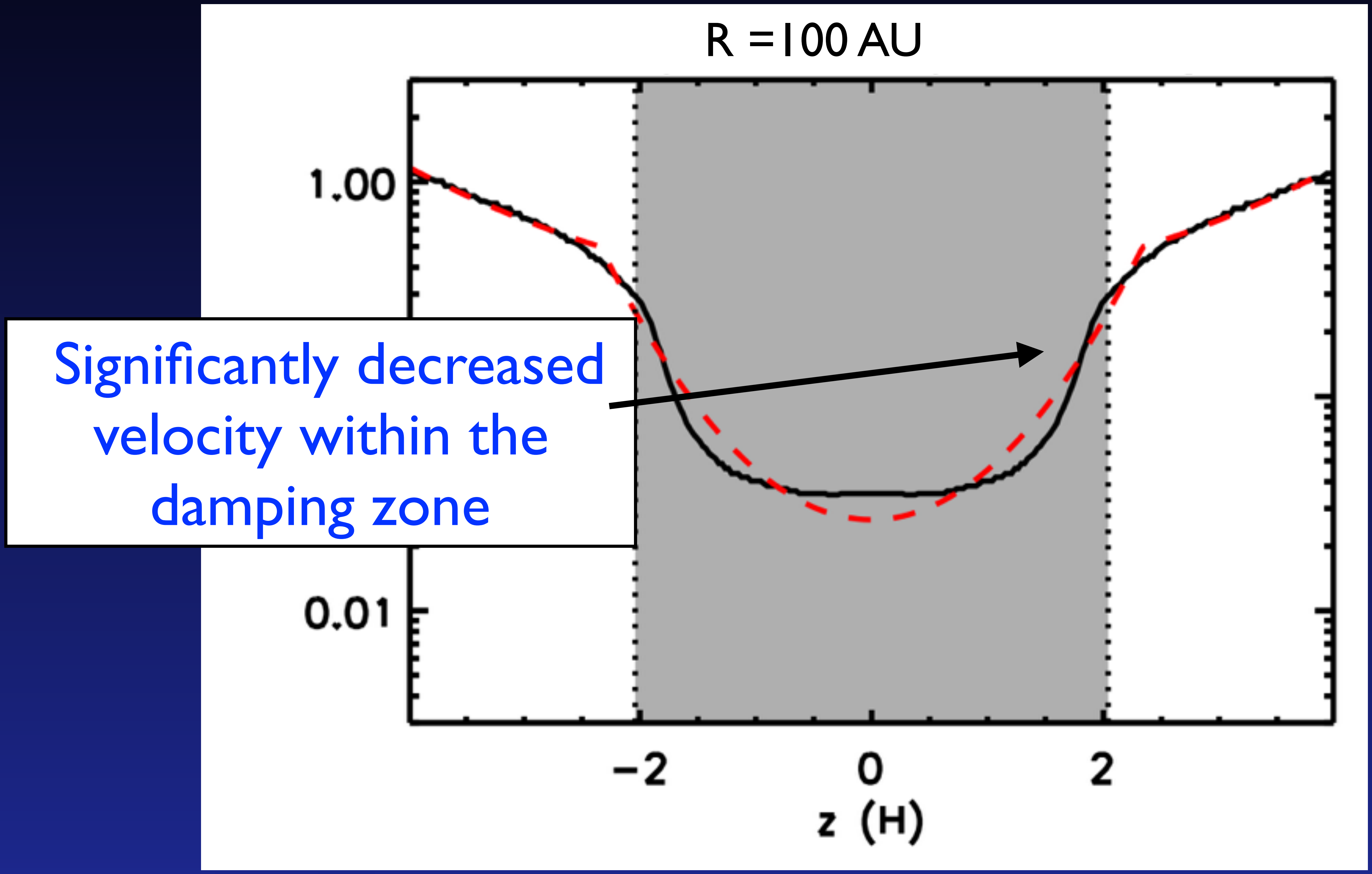
Simon et al. (2013b) (see also Bai & Stone 2011)

Strong gradient in turbulent velocity towards disk mid-plane

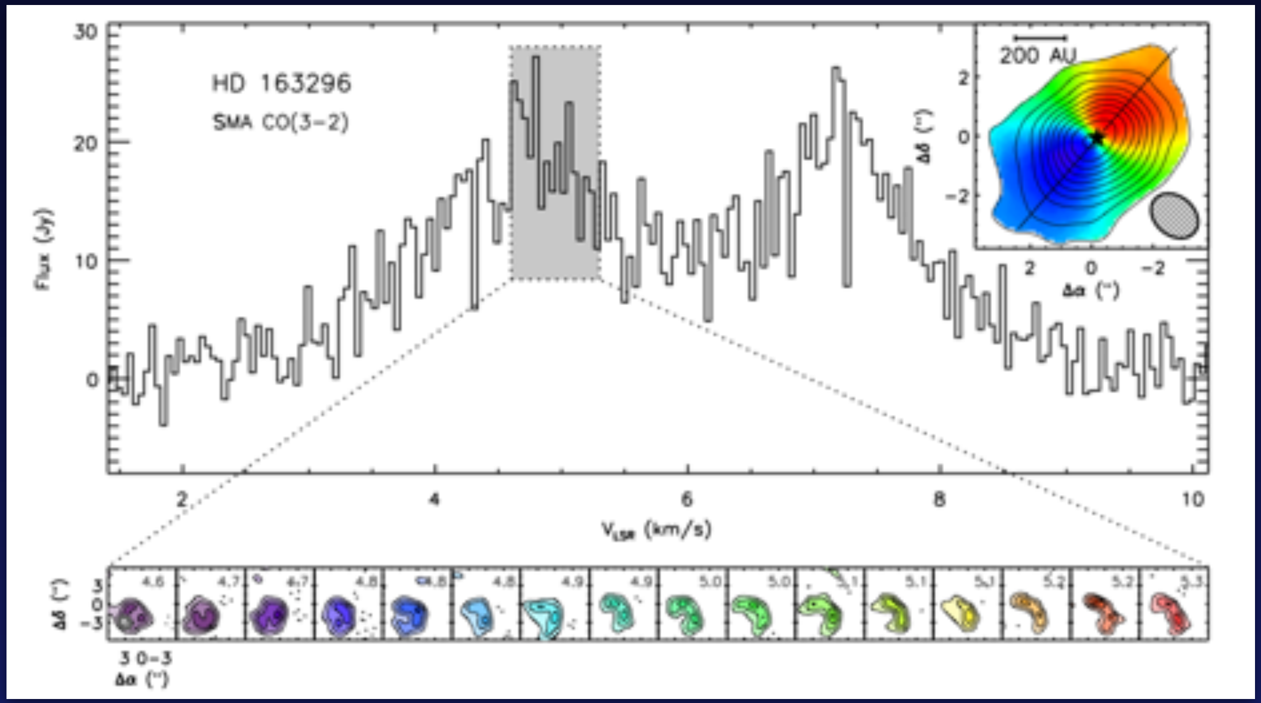


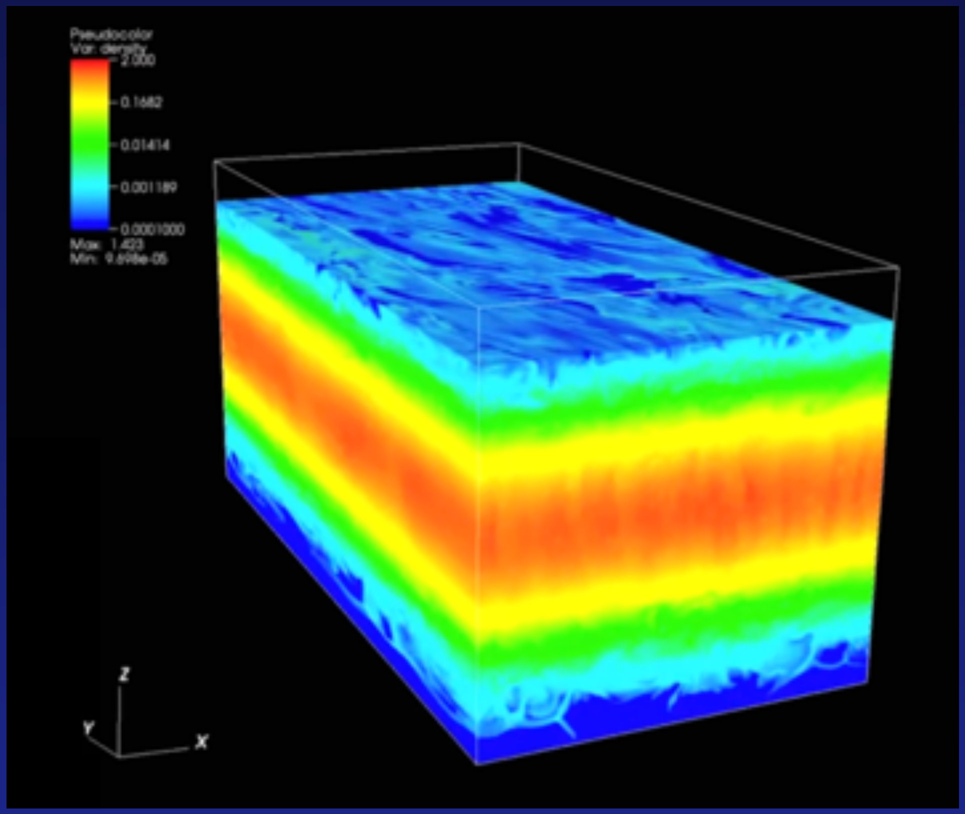
Simon et al. (2015a), ApJ

Strong gradient in turbulent velocity towards disk mid-plane

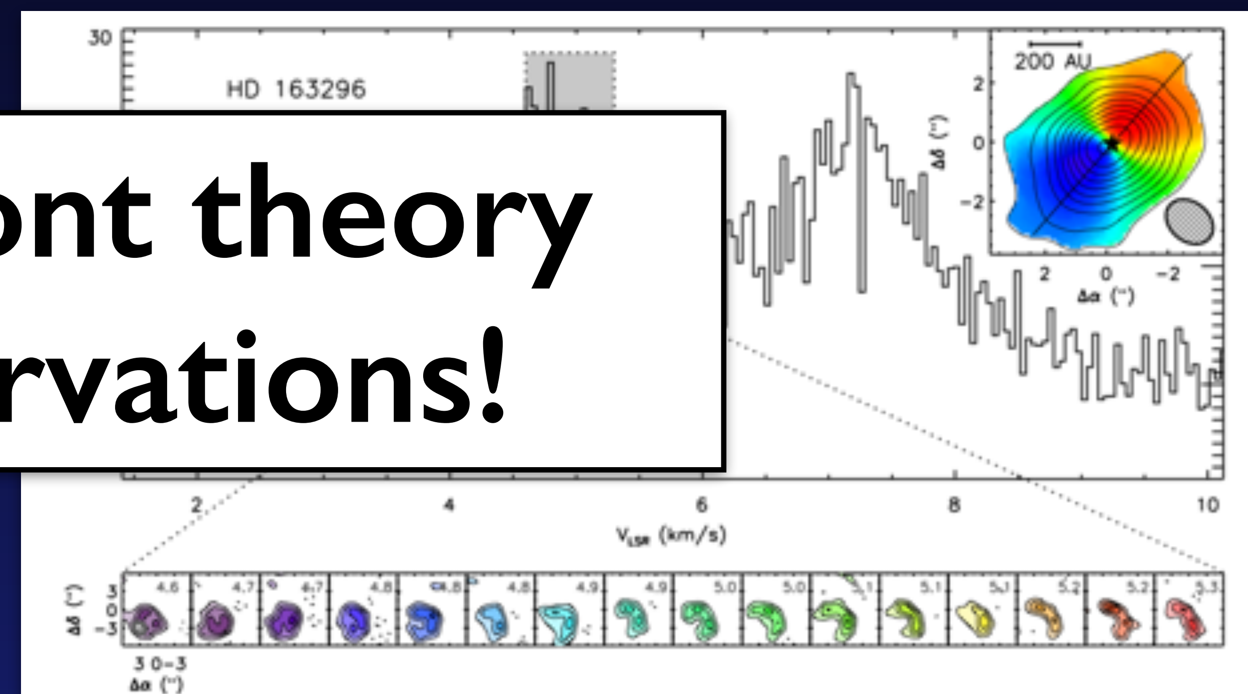


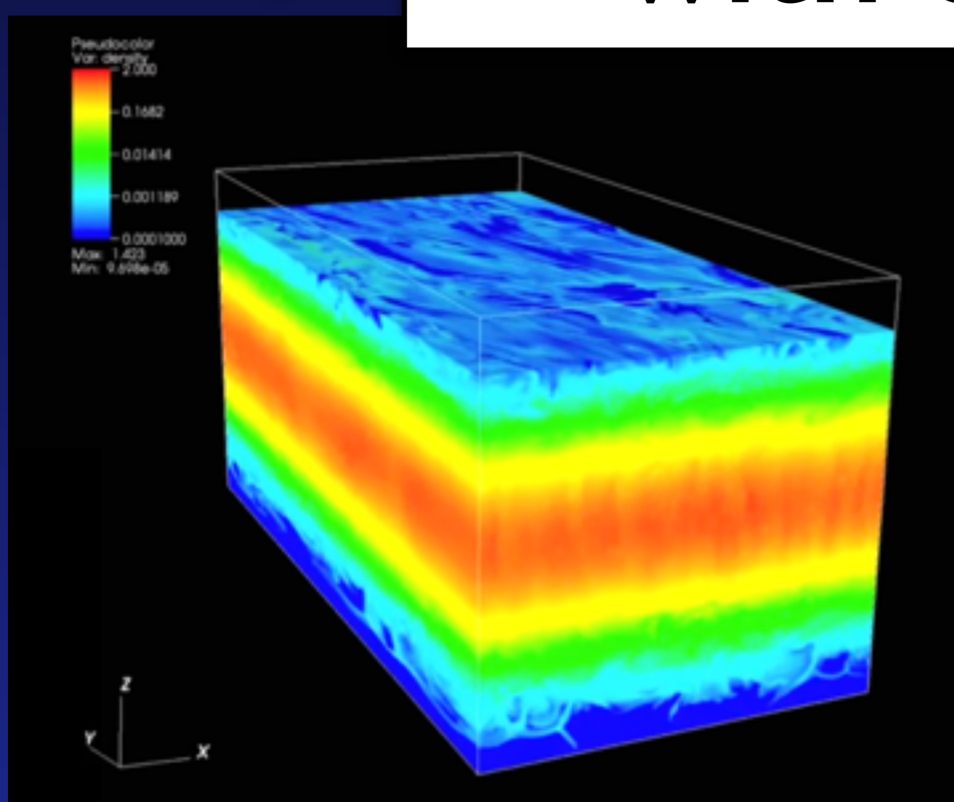
Simon et al. (2015a), ApJ


HD 163296
SMA CO(3−2)
Flux (Jy)
V_LSR (km/s)
200 AU
Δδ (")
Δα (")

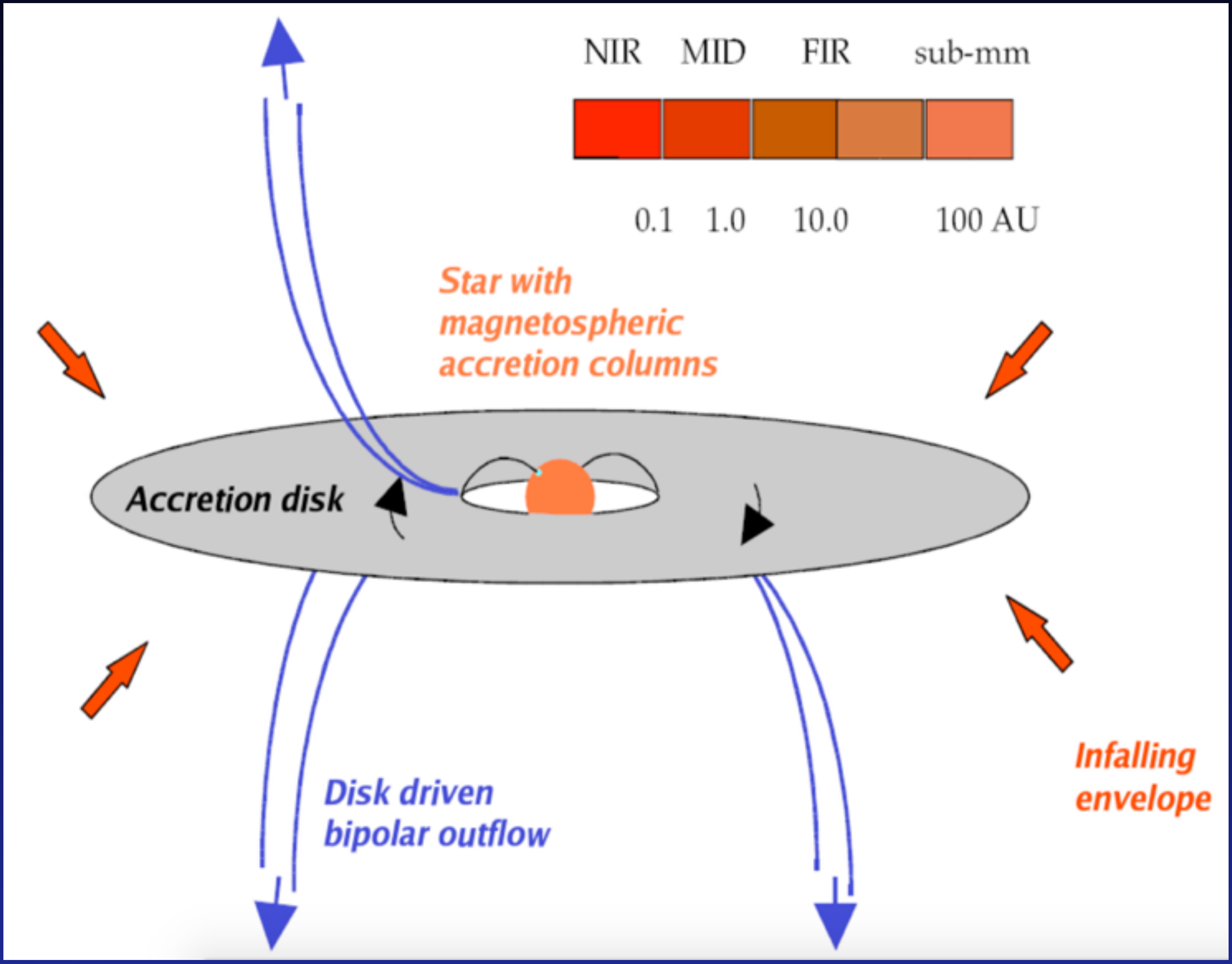

Pseudocolor
Var: density
2.000
0.1682
0.01414
0.001189
0.0001000
Max: 1.423
Min: 9.698e-05
Z
Y
X

Let’s confront theory with observations!



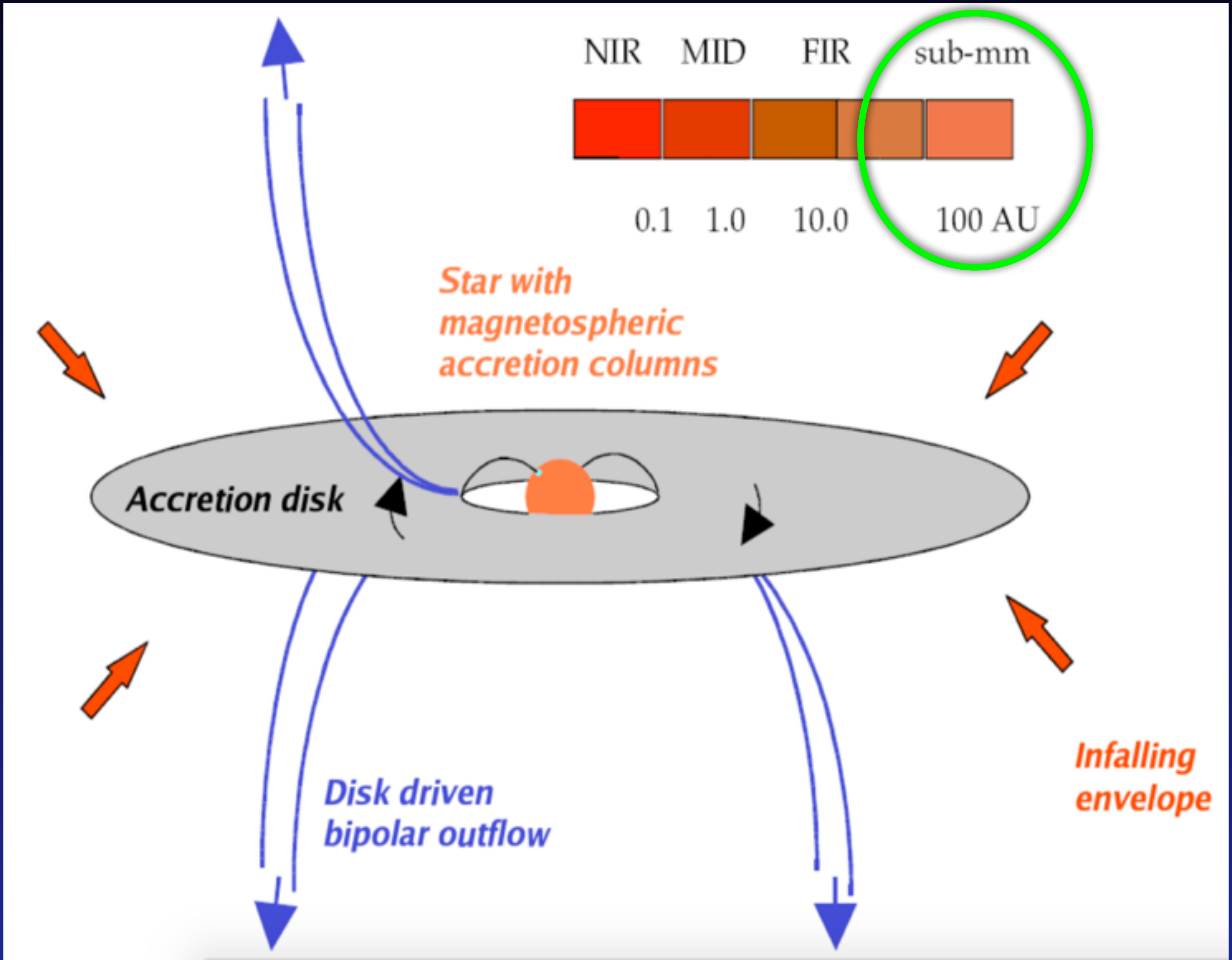


Develop observational diagnostics based on these predictions



Mark Wyatt

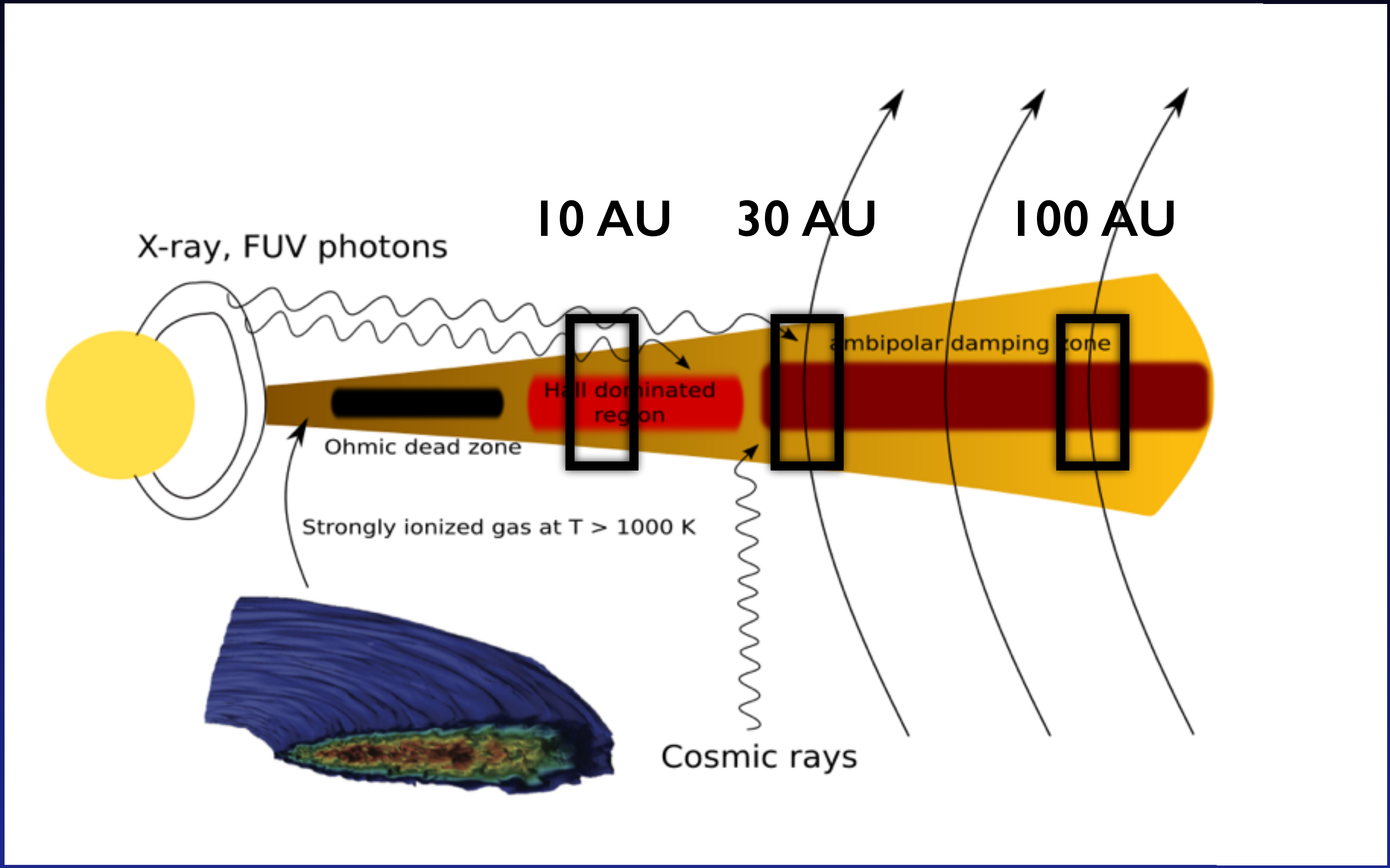
Develop observational diagnostics based on these predictions



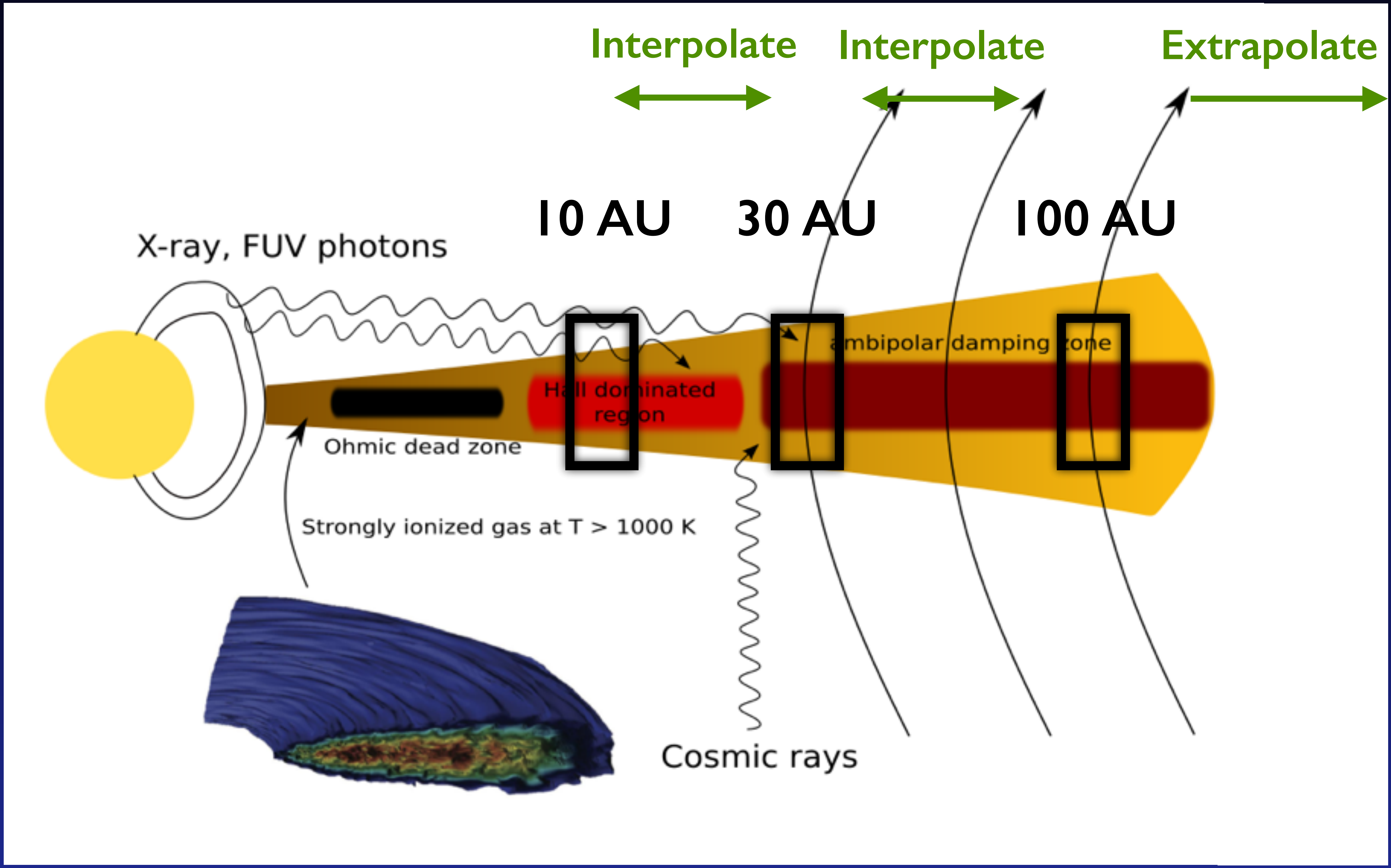
Mark Wyatt

ALMA

Construct global turbulence model by interpolating simulation results



Construct global turbulence model by interpolating simulation results



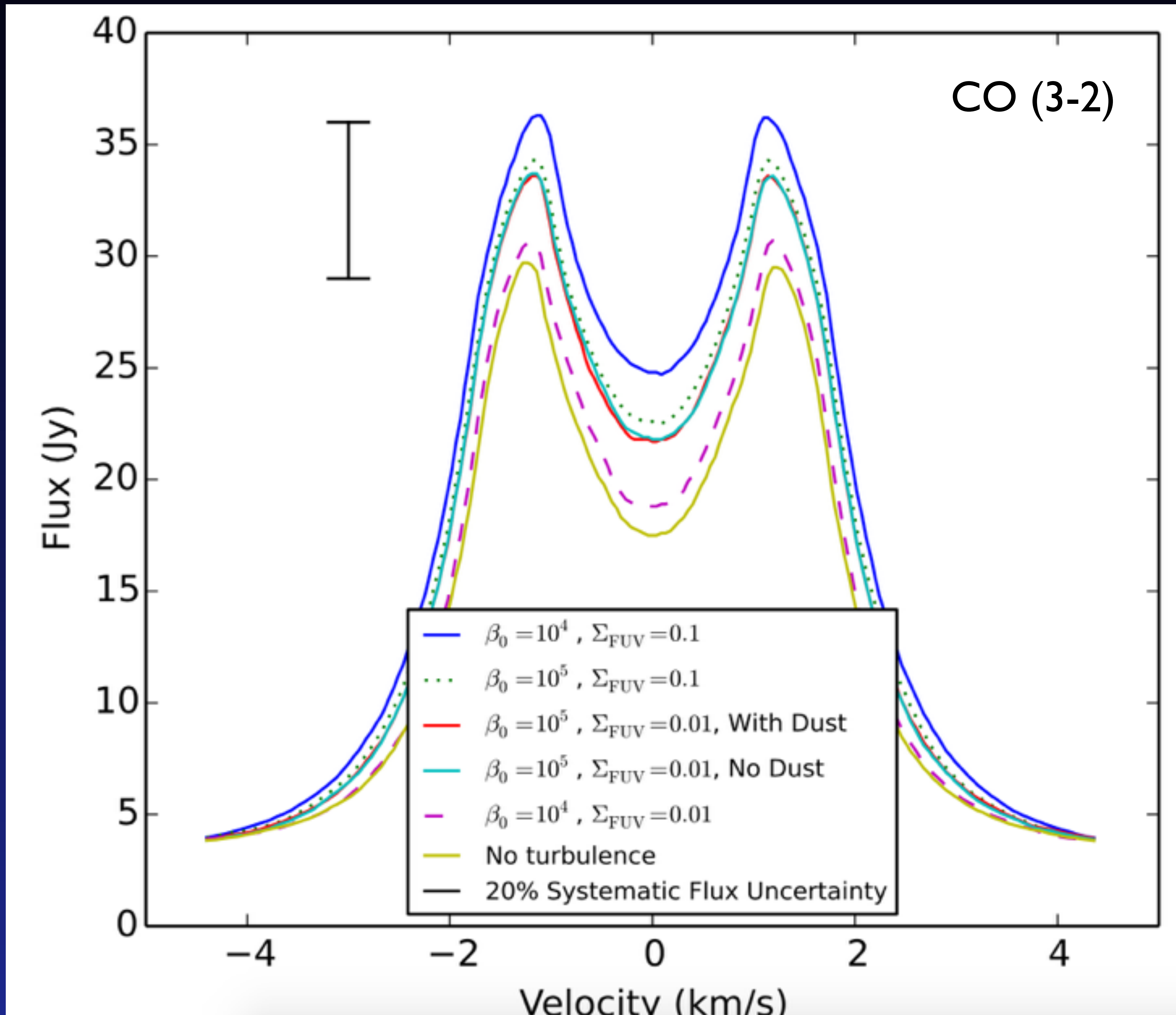
Another state-of-the-art code

LIME

Line Modeling Engine

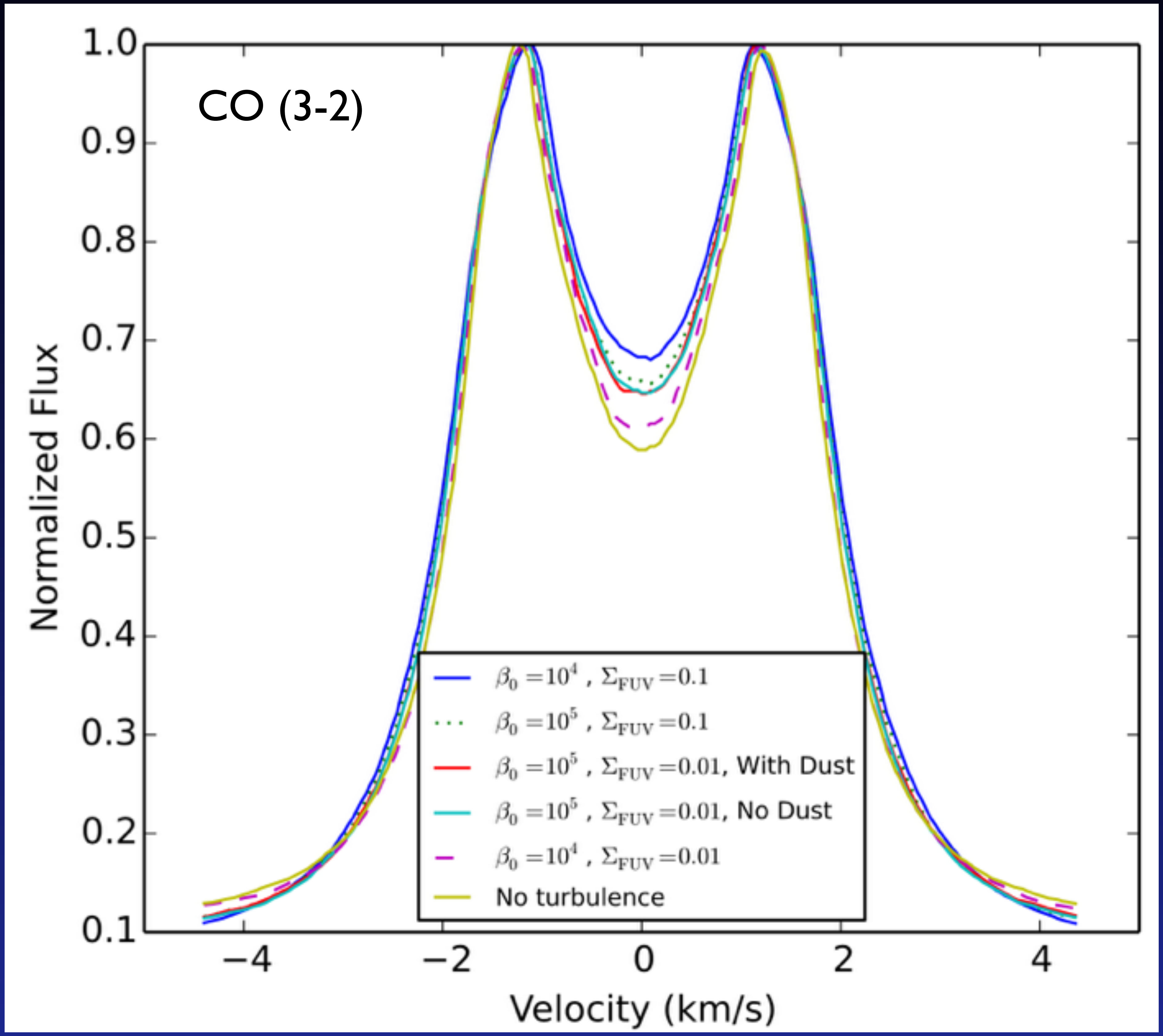
Brinch & Hogerheijde (2010)

Observational signatures: Line profile



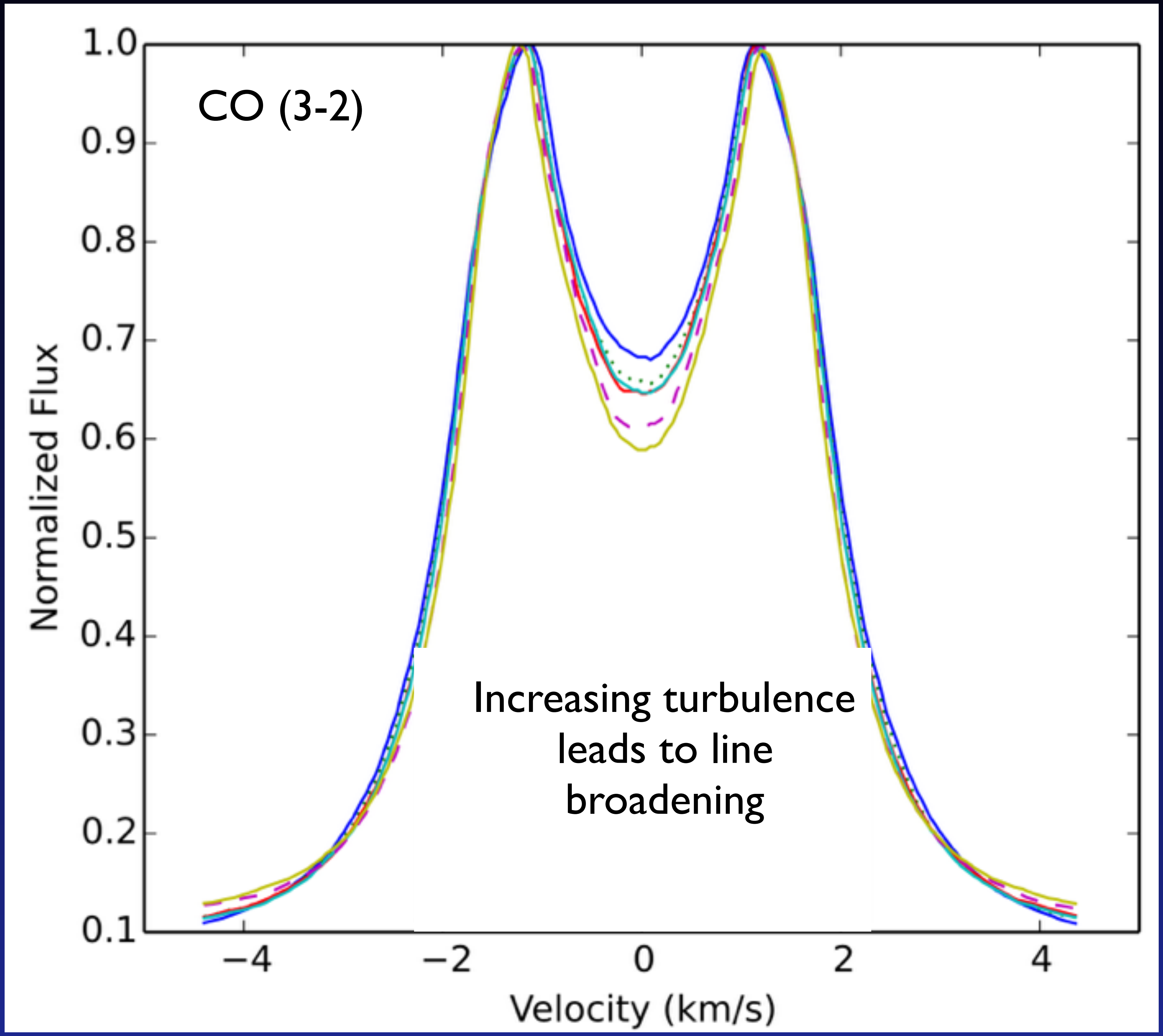
Simon et al. (2015a), ApJ

Observational signatures: Line profile



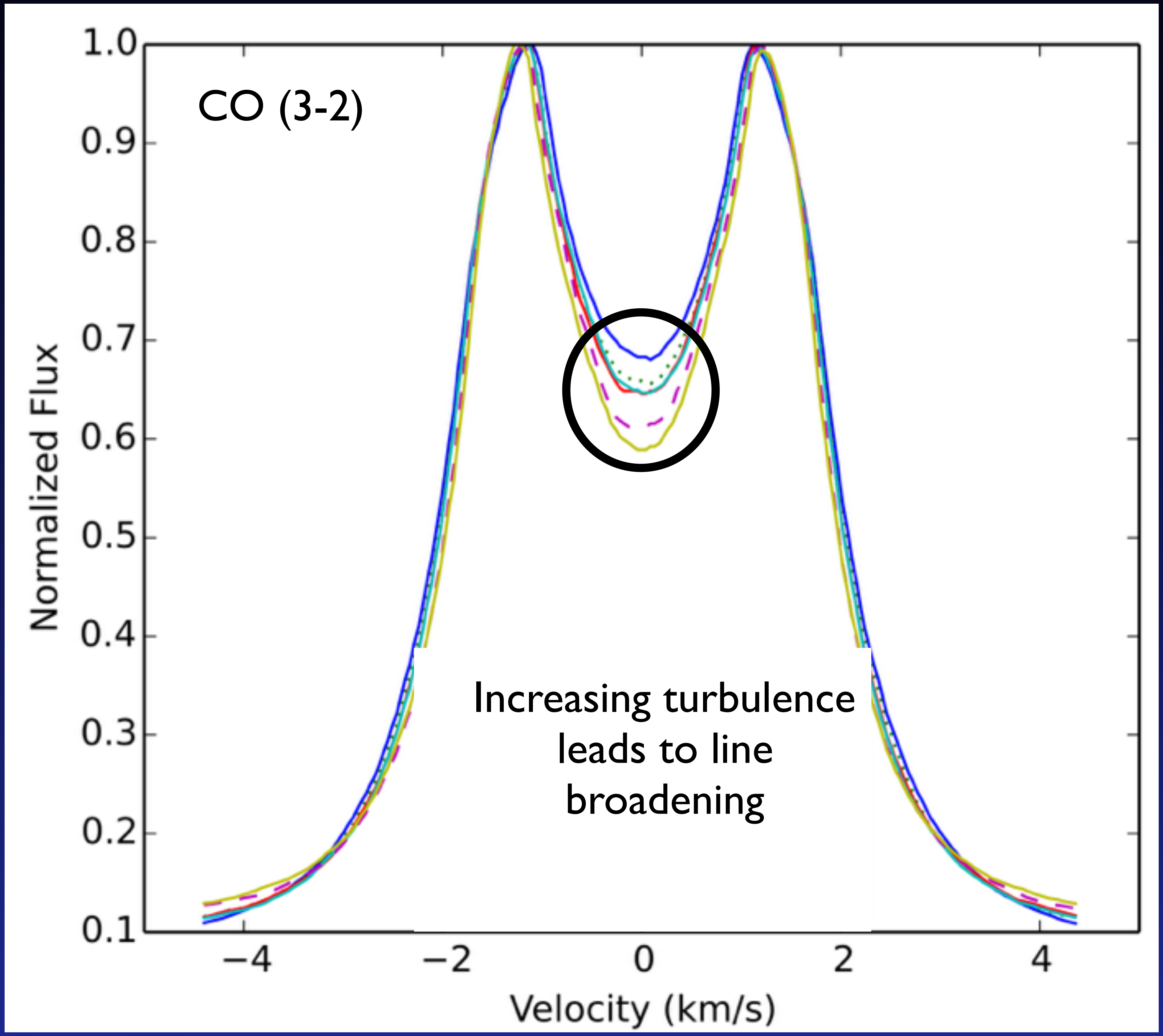
Simon et al. (2015a), ApJ

Observational signatures: Line profile



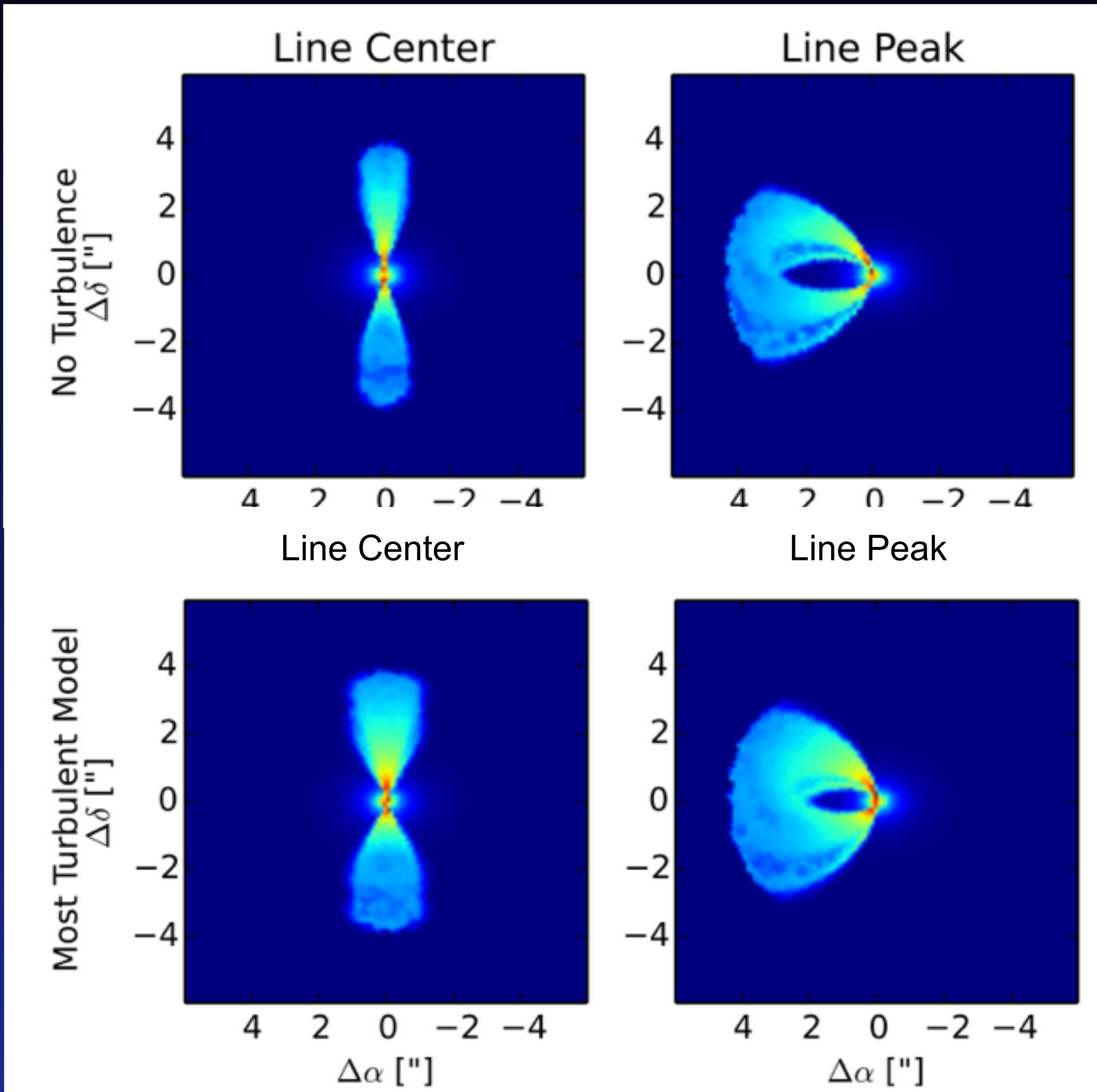
Simon et al. (2015a), ApJ

Observational signatures: Line profile



Simon et al. (2015a), ApJ

Observational signatures: Channel maps

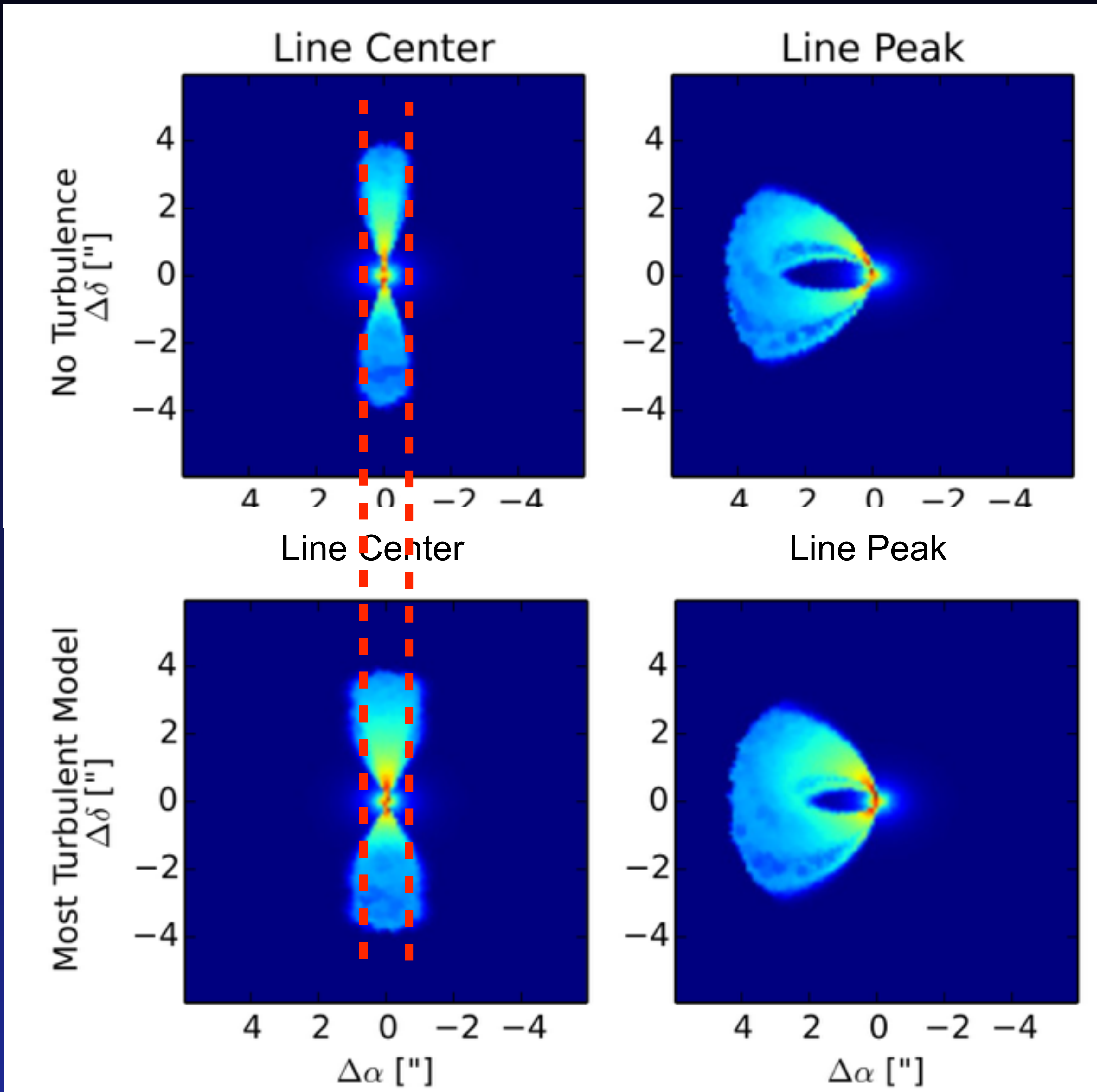


No turbulence

Turbulence: The flux is spread out

Simon et al. (2015a), ApJ

Observational signatures: Channel maps

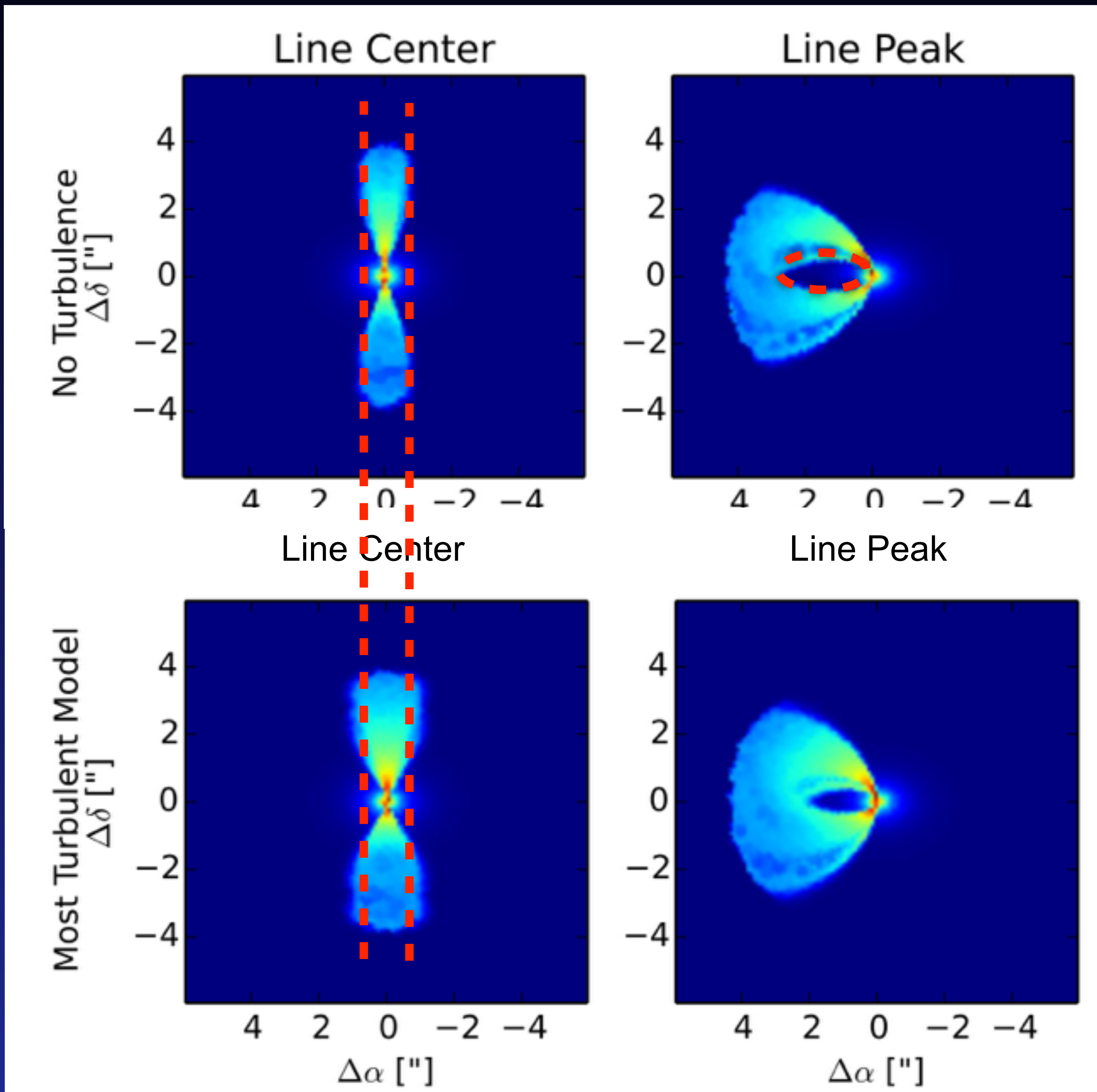


No turbulence

Turbulence: The flux is spread out

Simon et al. (2015a), ApJ

Observational signatures: Channel maps

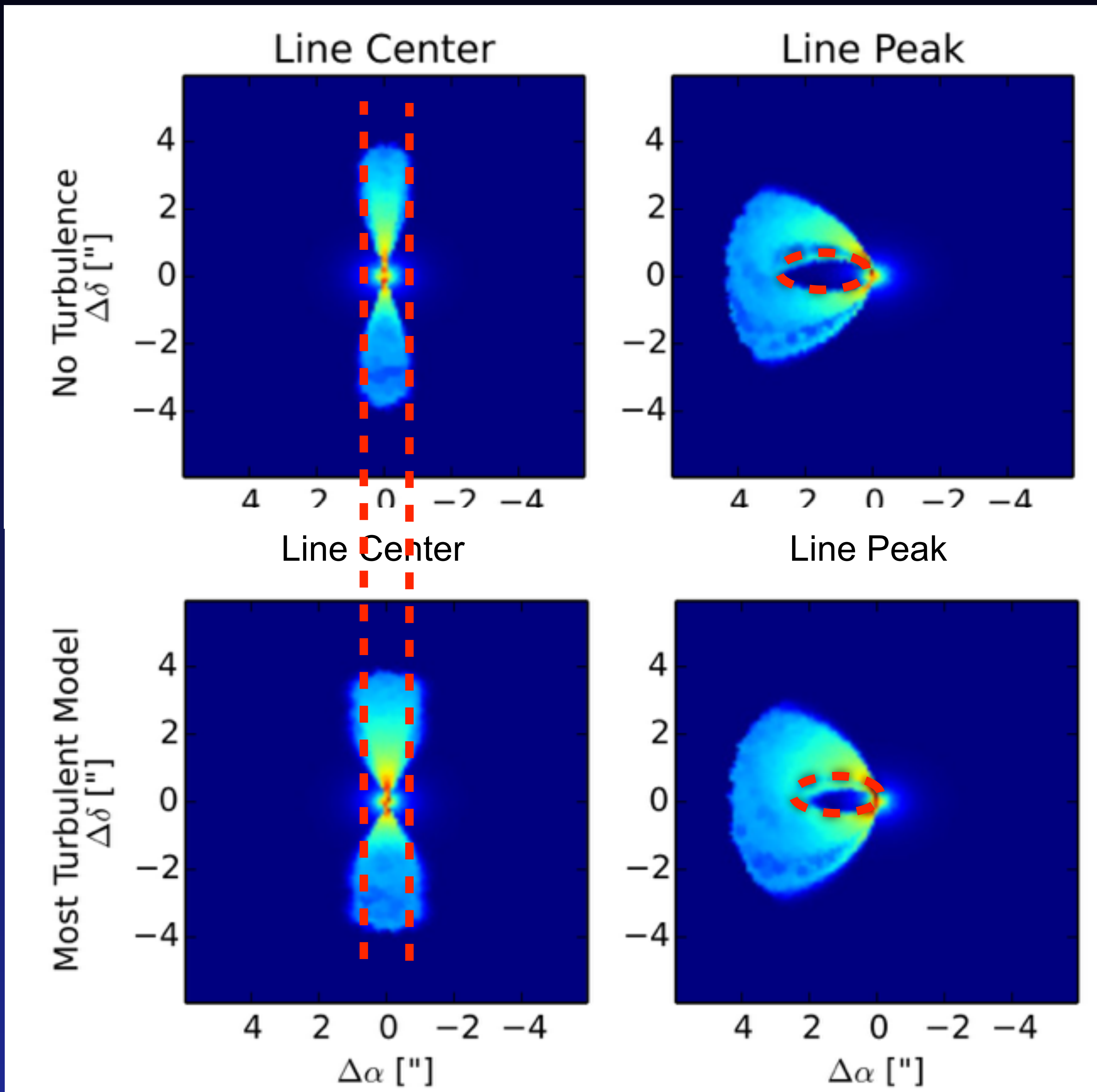


No turbulence

Turbulence: The flux is spread out

Simon et al. (2015a), ApJ

Observational signatures: Channel maps



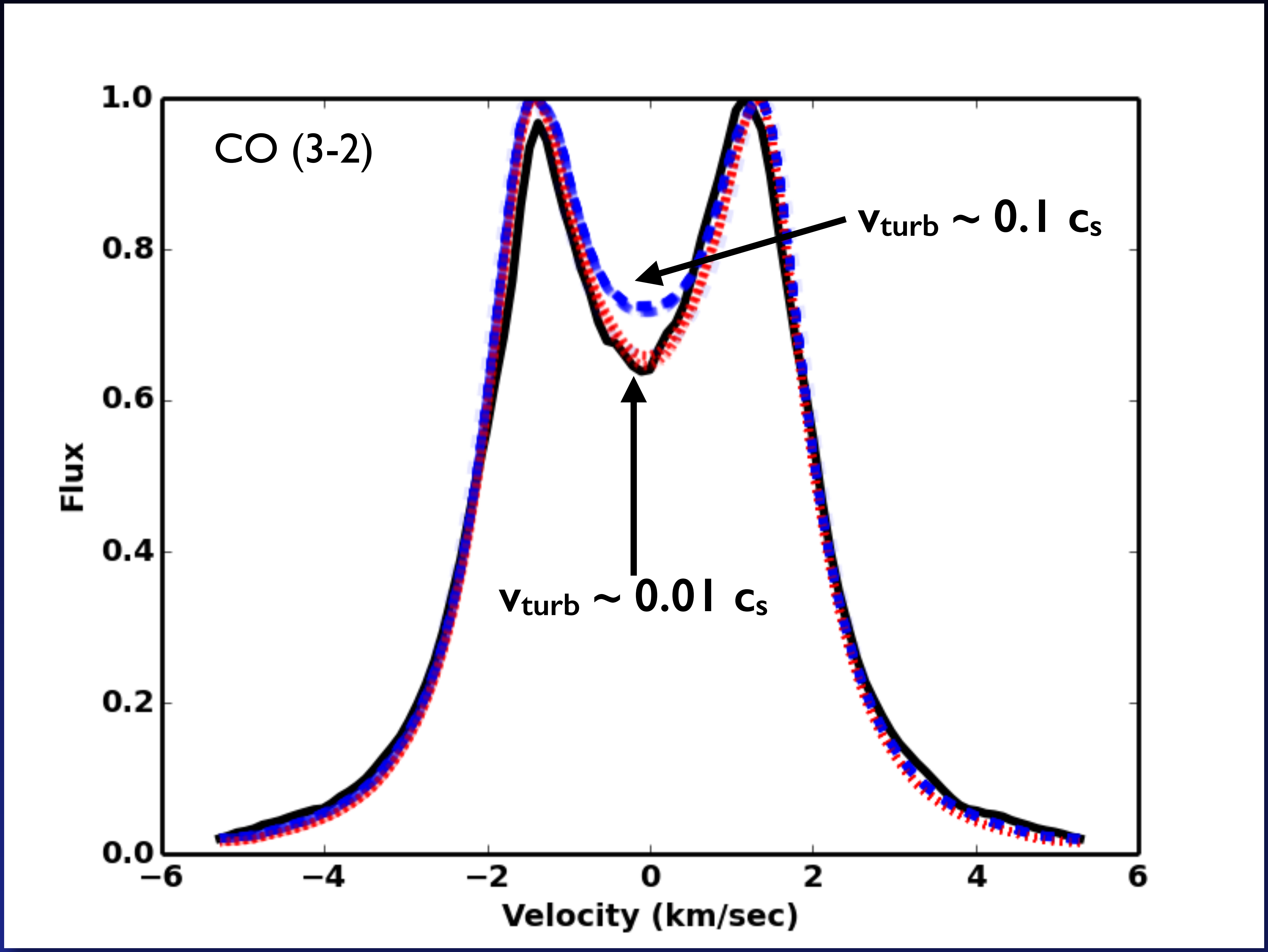
No turbulence

Turbulence: The flux is spread out

Simon et al. (2015a), ApJ

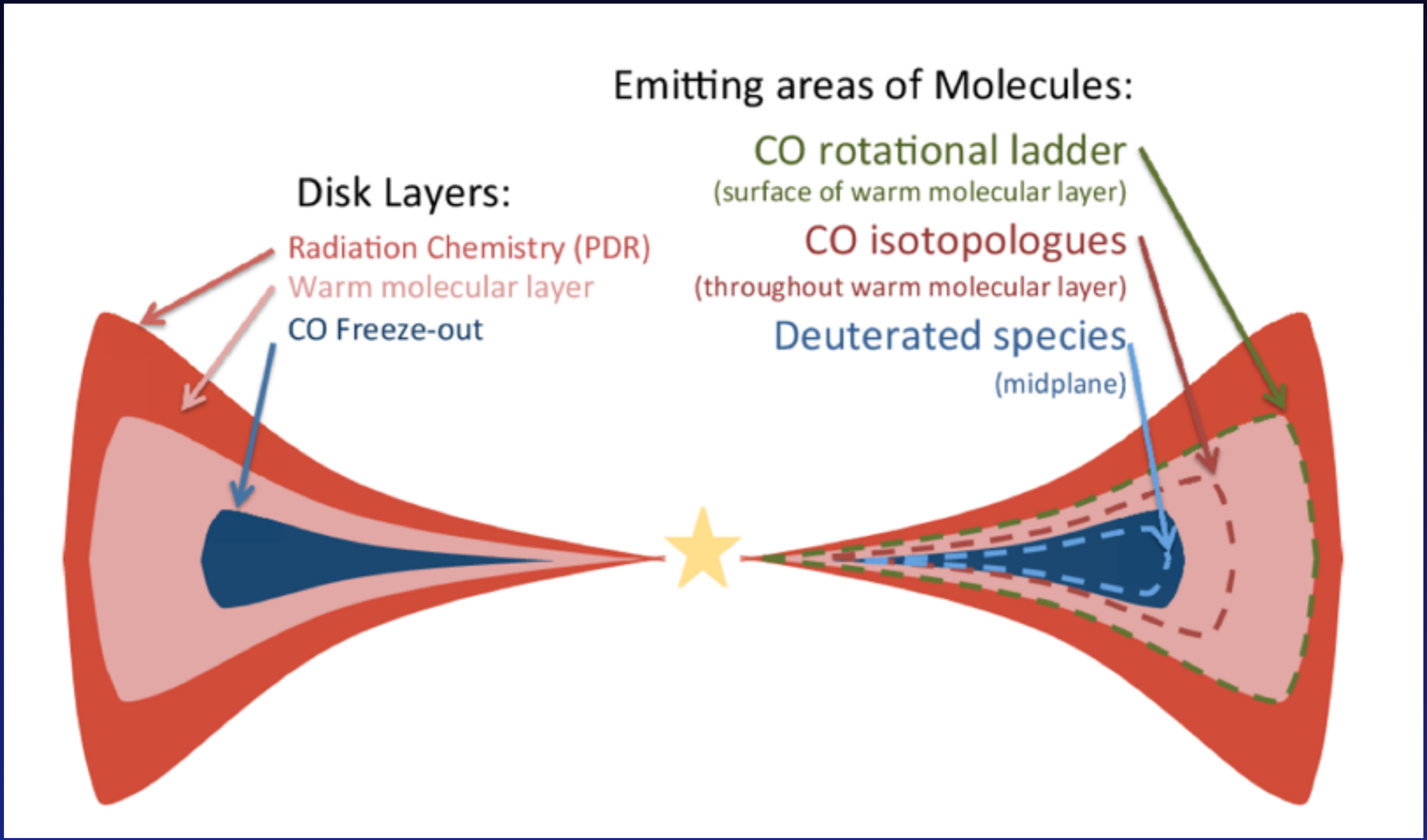
So, what do ALMA observations tell us?

Weak turbulence in HD 163296!



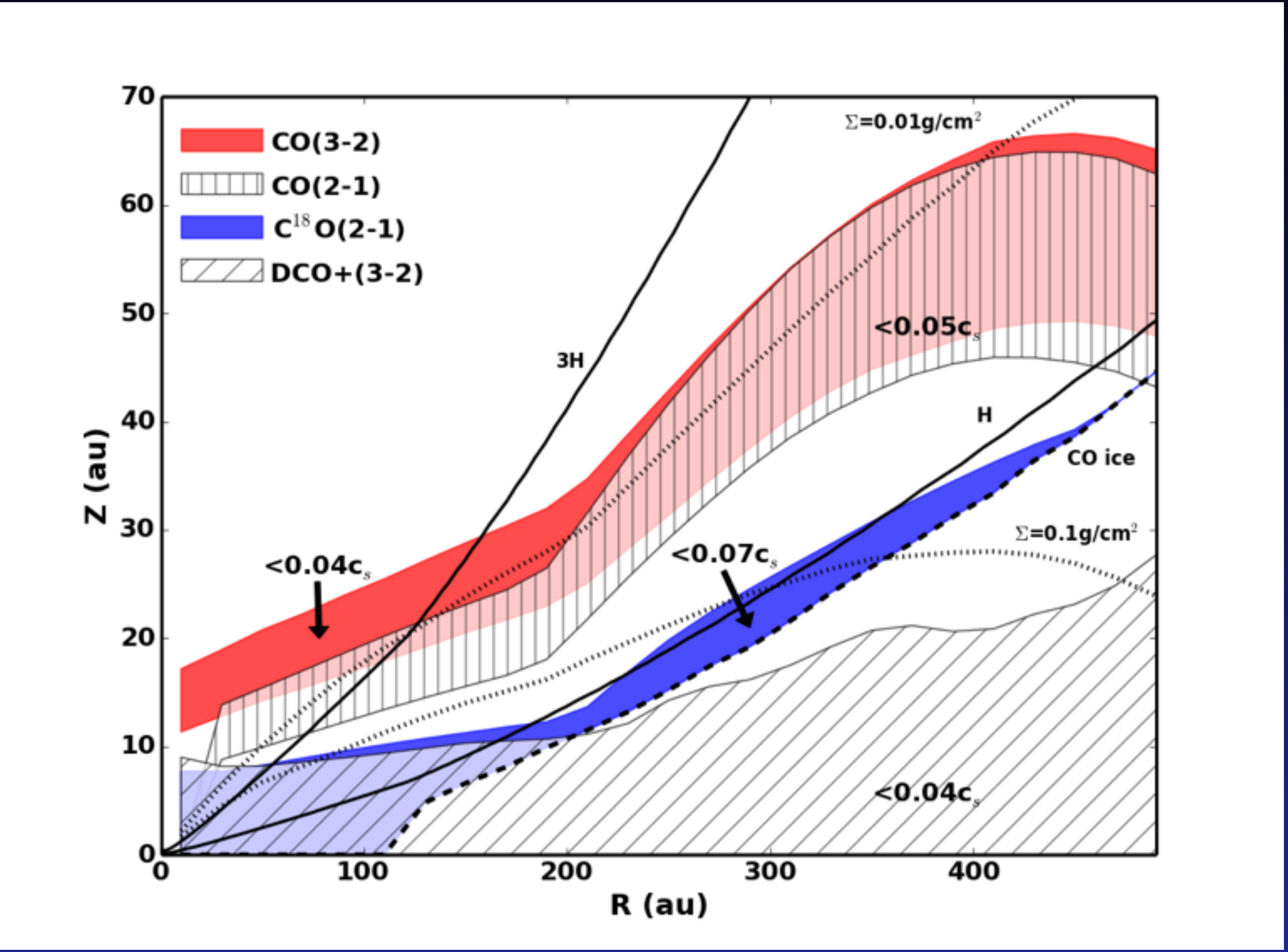
Flaherty … Simon et al. (2015), ApJ

Other observational diagnostics



Meredith Hughes

Weak turbulence in HD 163296!



Flaherty … Simon et al., in prep

Take away points so far

1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent “bursts” via the HSI

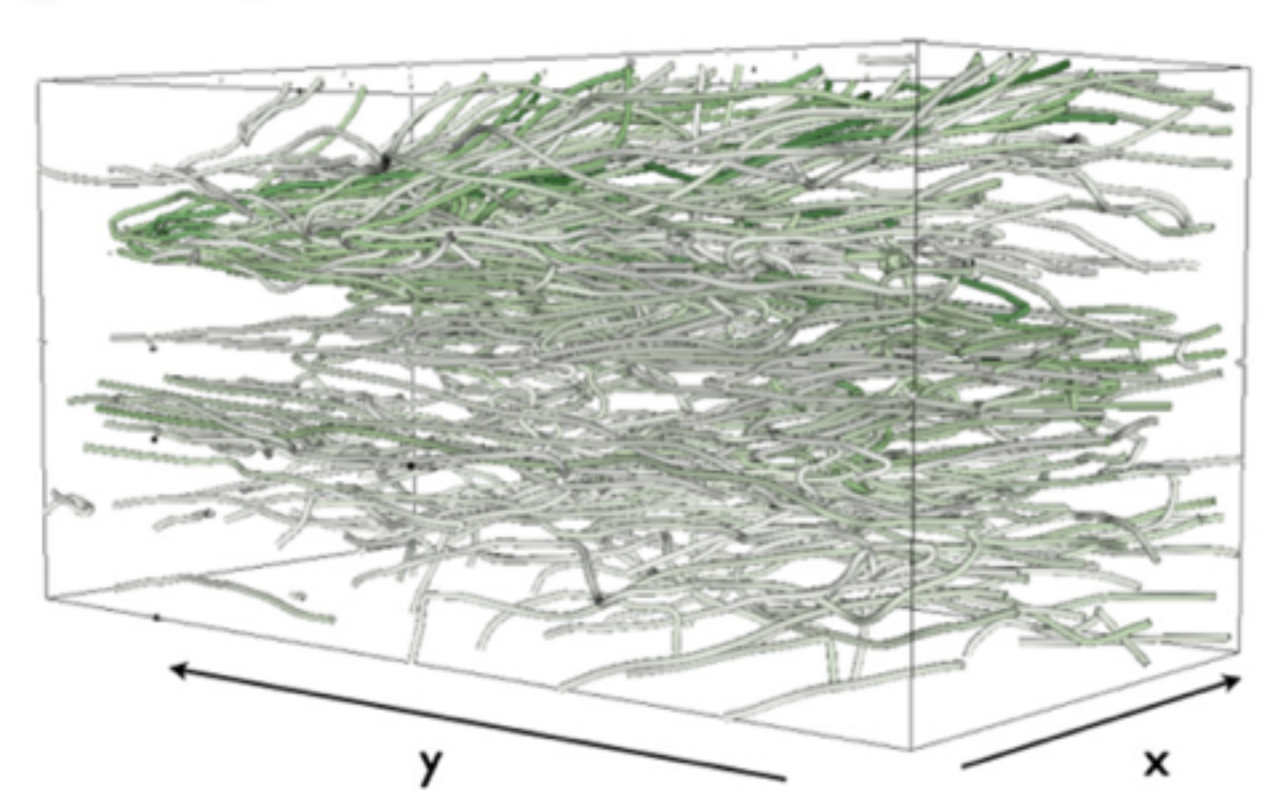
2. The outer regions of protoplanetary disk should have turbulent velocities on the order of >10-100% of the local sound speed for optically thick lines.

3. Observations of HD163296 suggest an upper limit of 5% of the sound speed.

So, if these results are right, it suggests that a wind is driving the accretion in the outer disk, right?

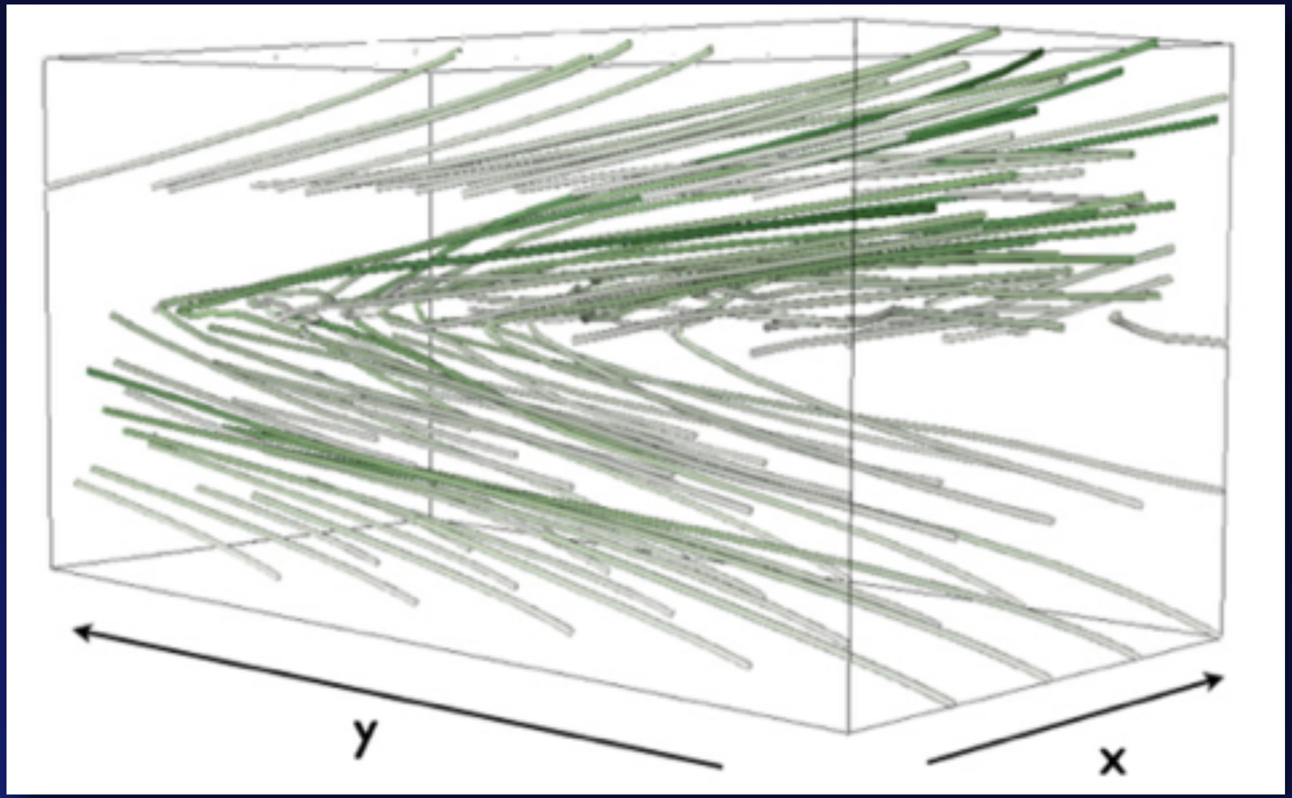
What is the effect of magnetic field strength?

β= 10^4, R = 30AU: Turbulent field



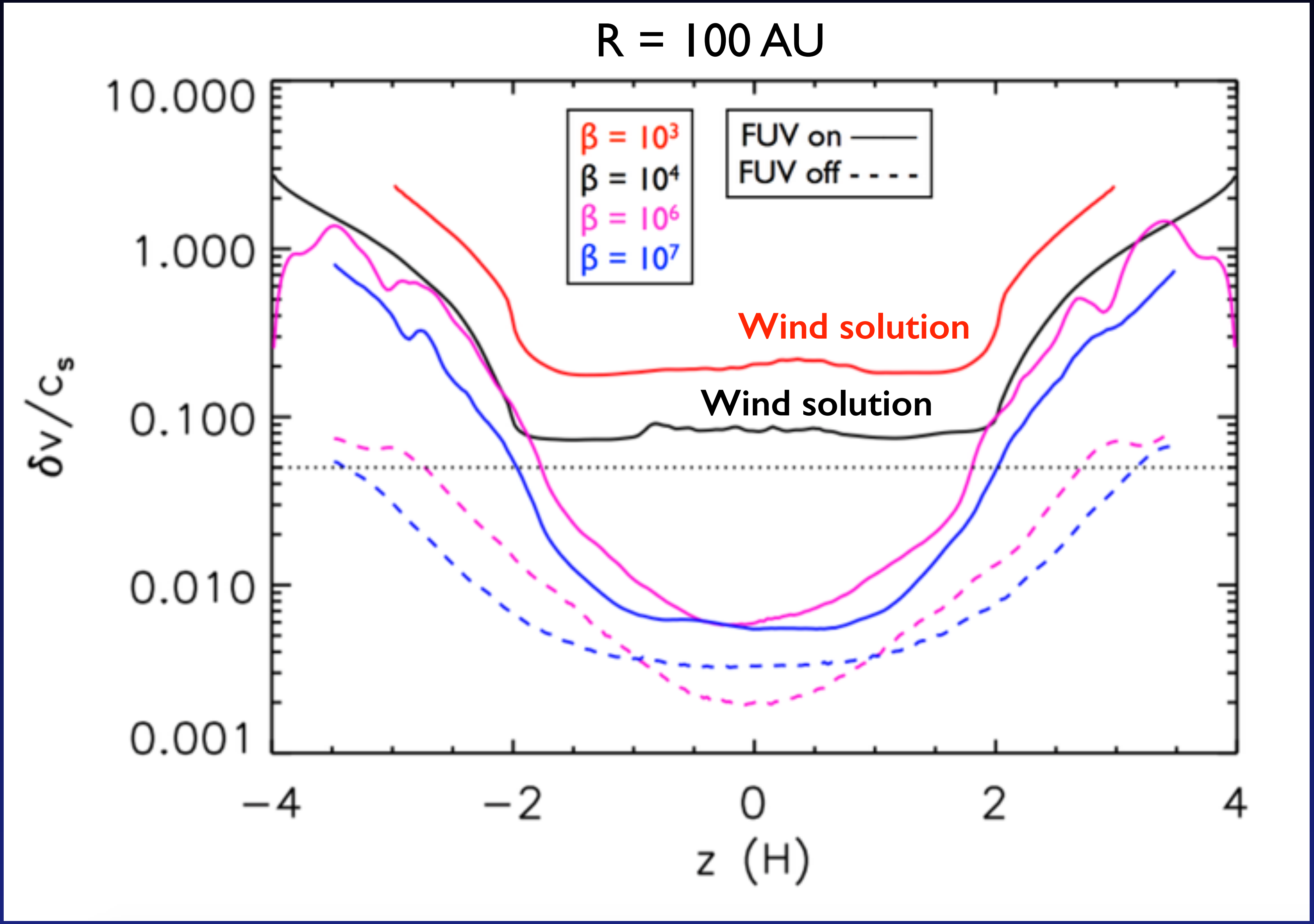
Simon et al. (2013b)

β= 10^3, R = 30AU: Laminar field



$$\beta = \frac{2P_{\rm mid}}{B^2_{\rm mid}}$$

What is the effect of magnetic field strength?

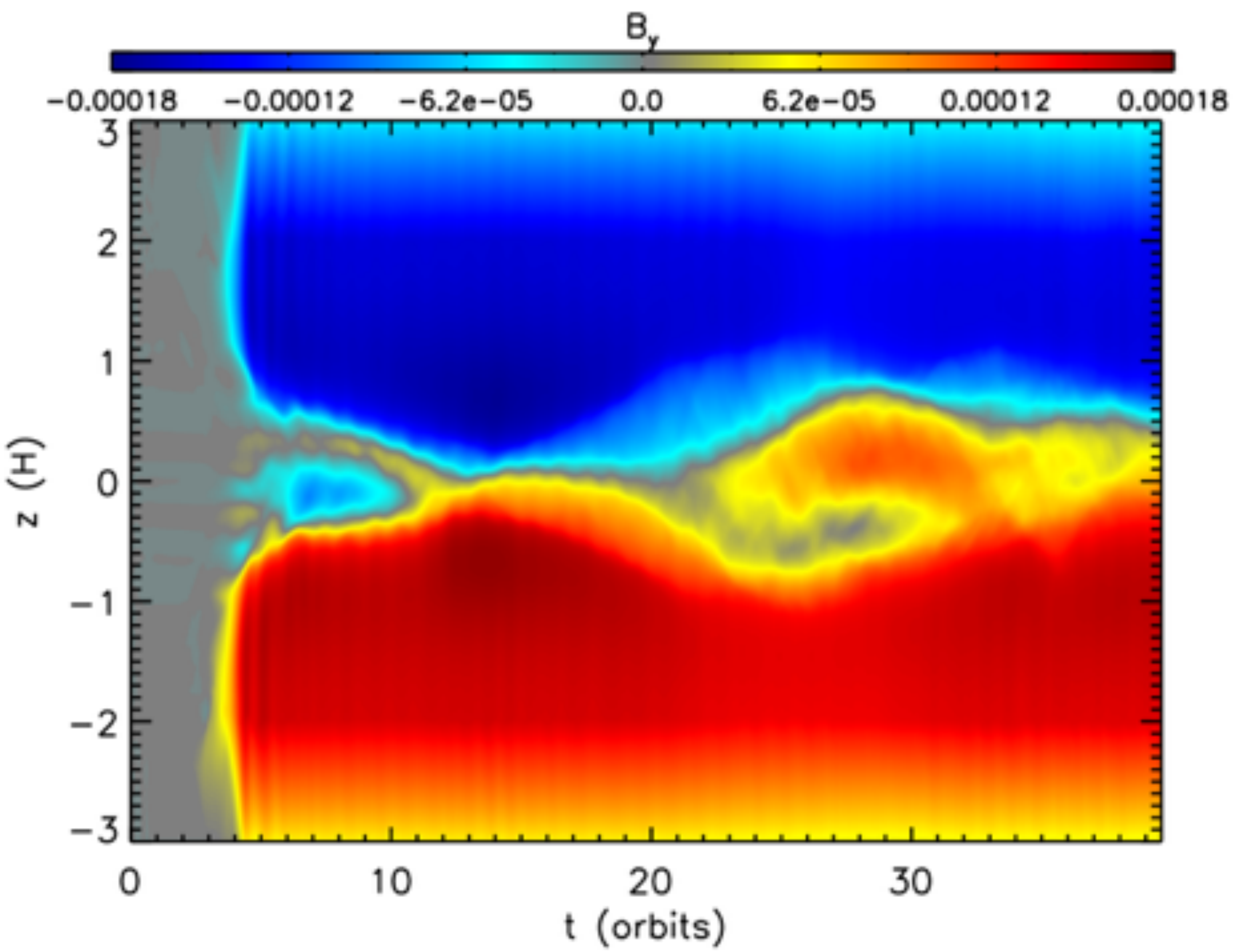


Simon et al., in prep

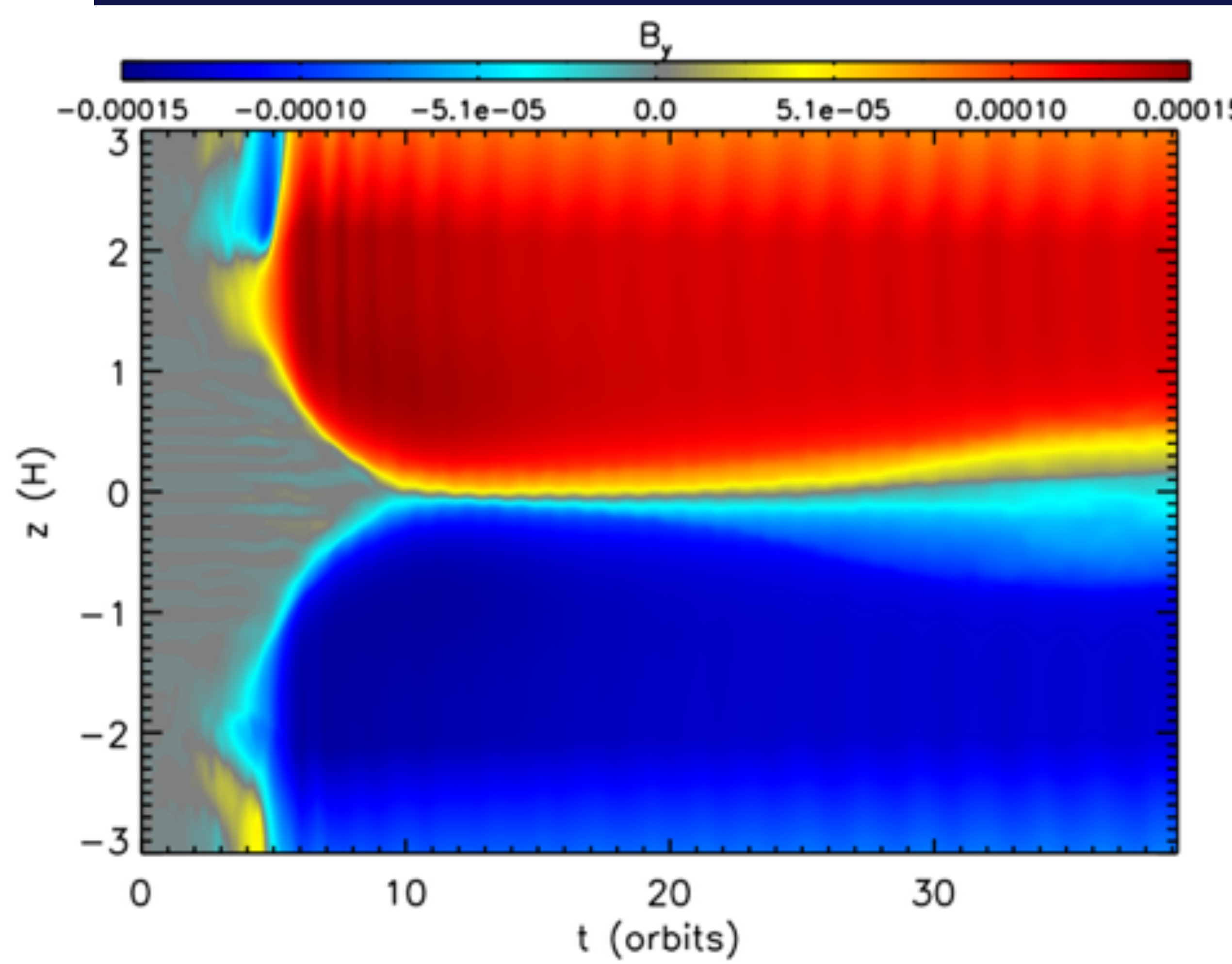
$$\beta = \frac{2P_{\mathrm{mid}}}{B^2_{\mathrm{mid}}}$$

What is causing such strong "turbulence" in an otherwise laminar flow?

Fluid motions induced by current sheet



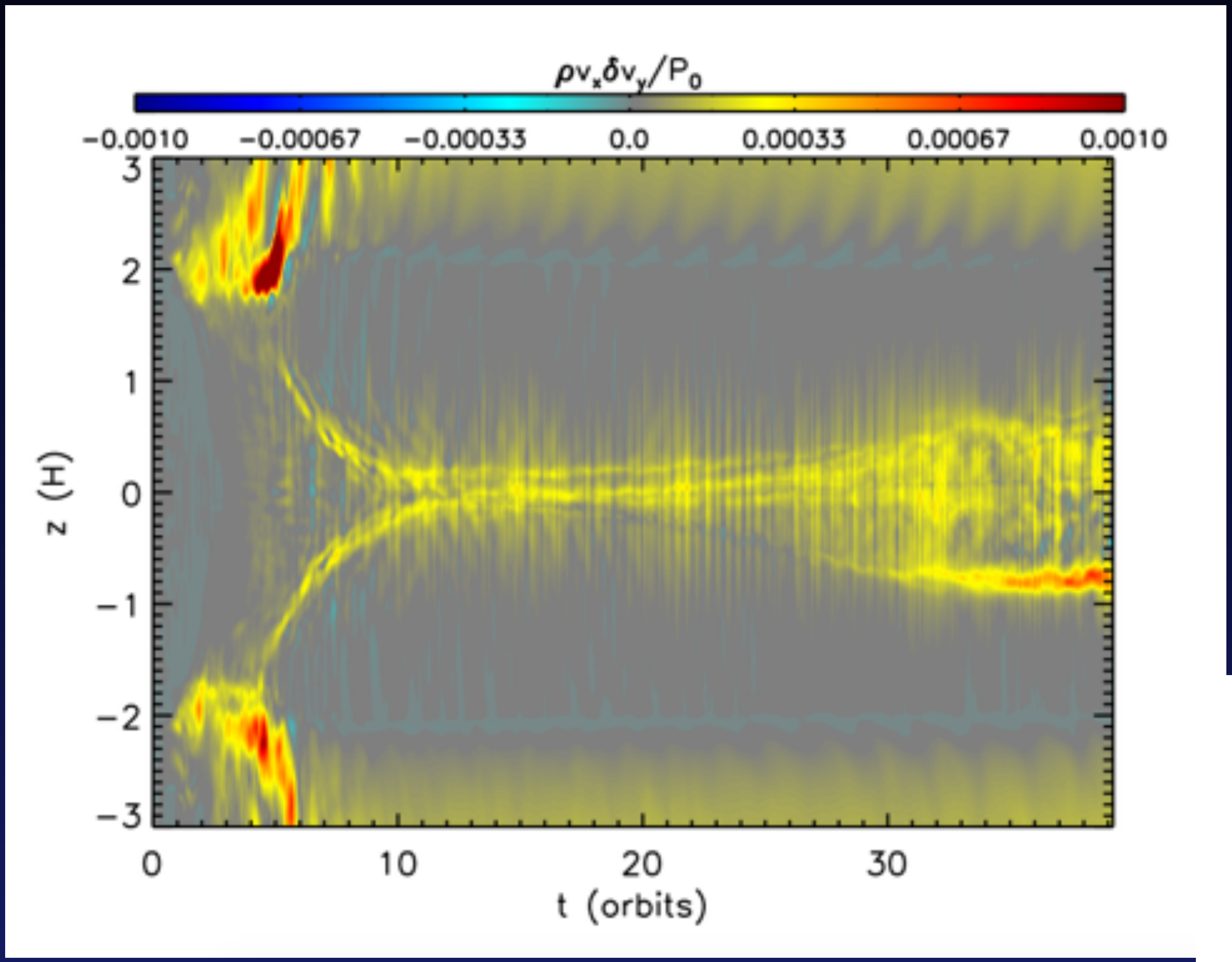
$\beta = 10^3$

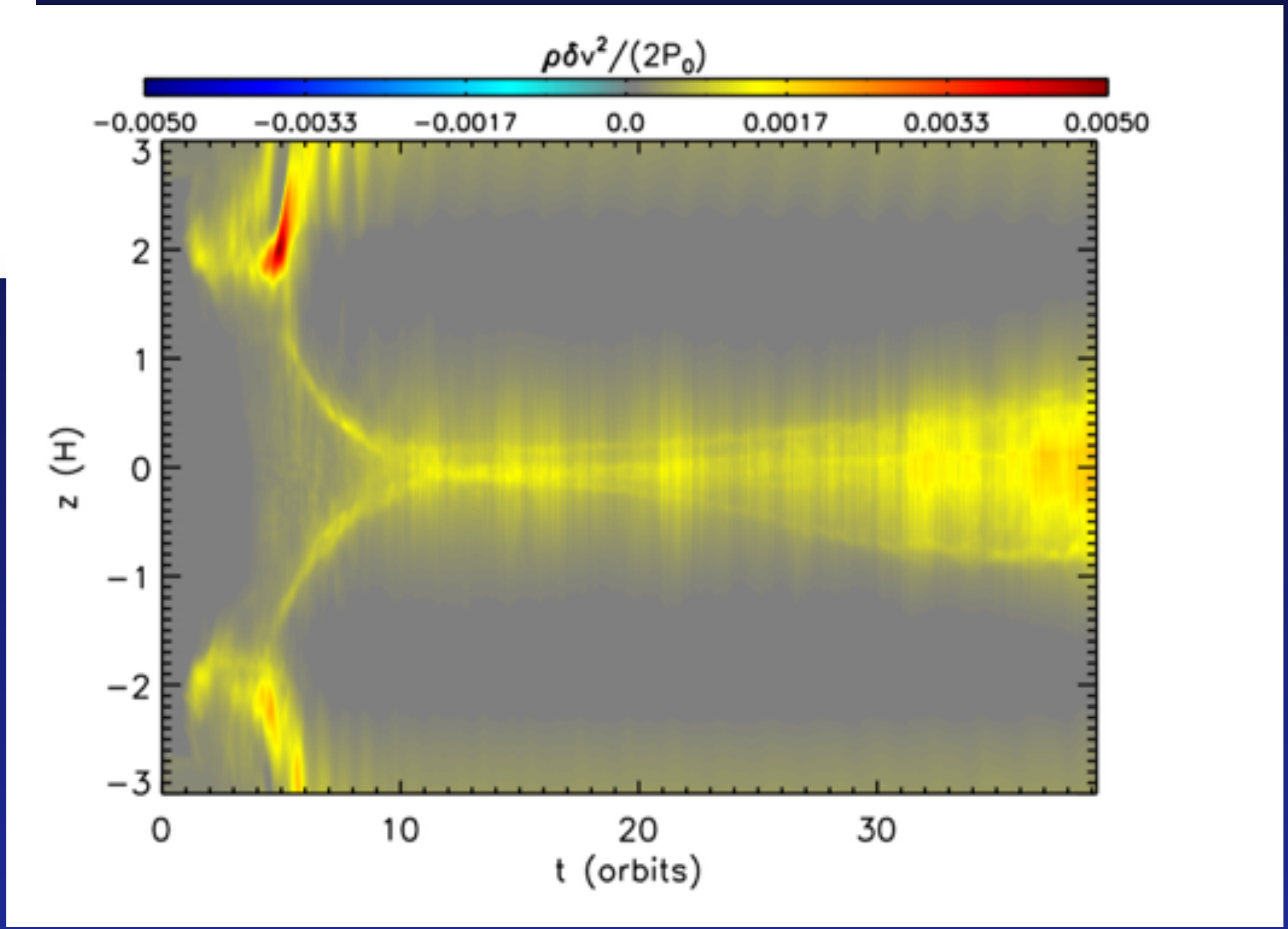


$\beta = 10^4$

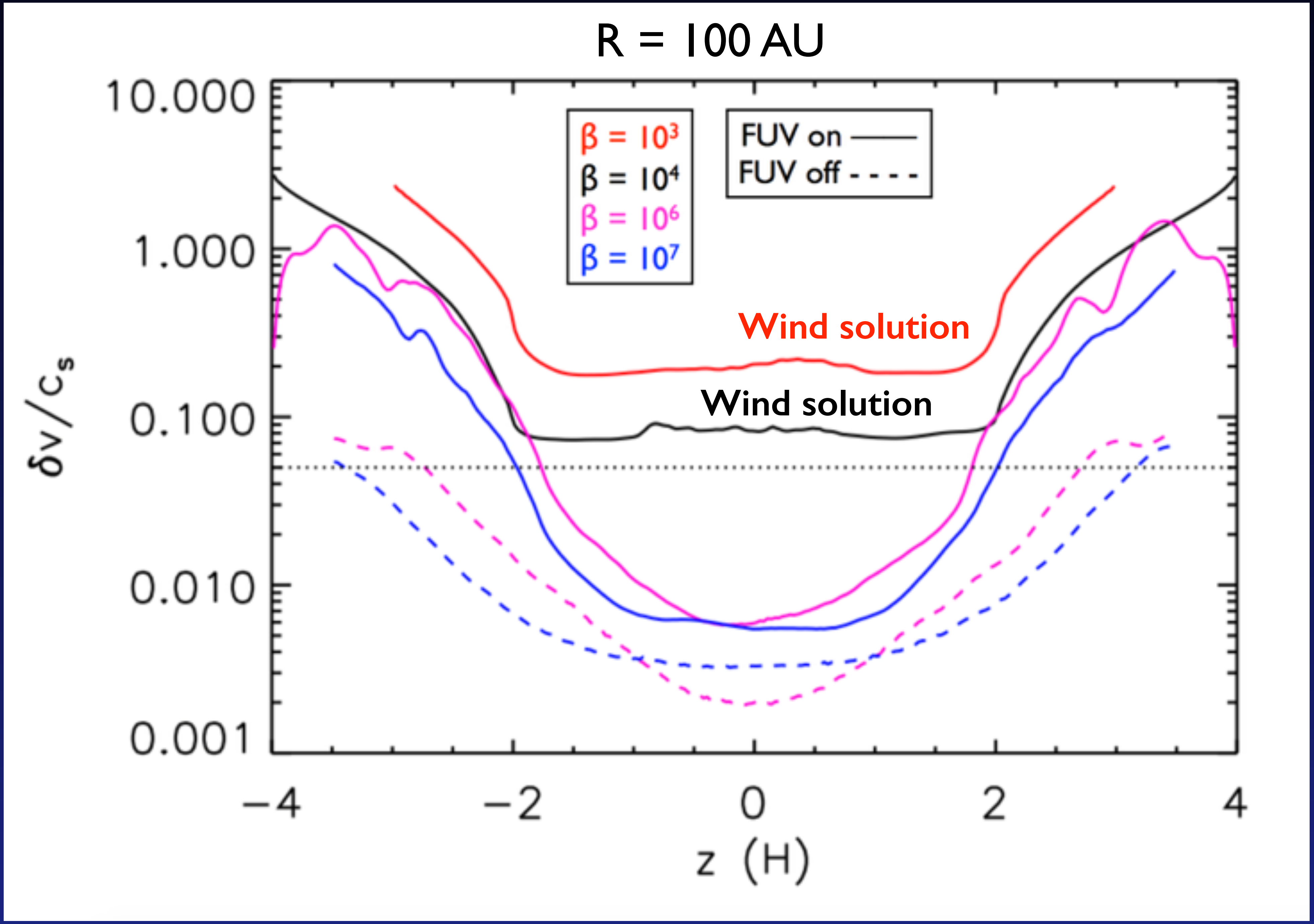
$$\beta = \frac{2P_{\rm mid}}{B^2_{\rm mid}}$$

Fluid motions induced by current sheet





Even wind flows have large $\delta v/c_s$

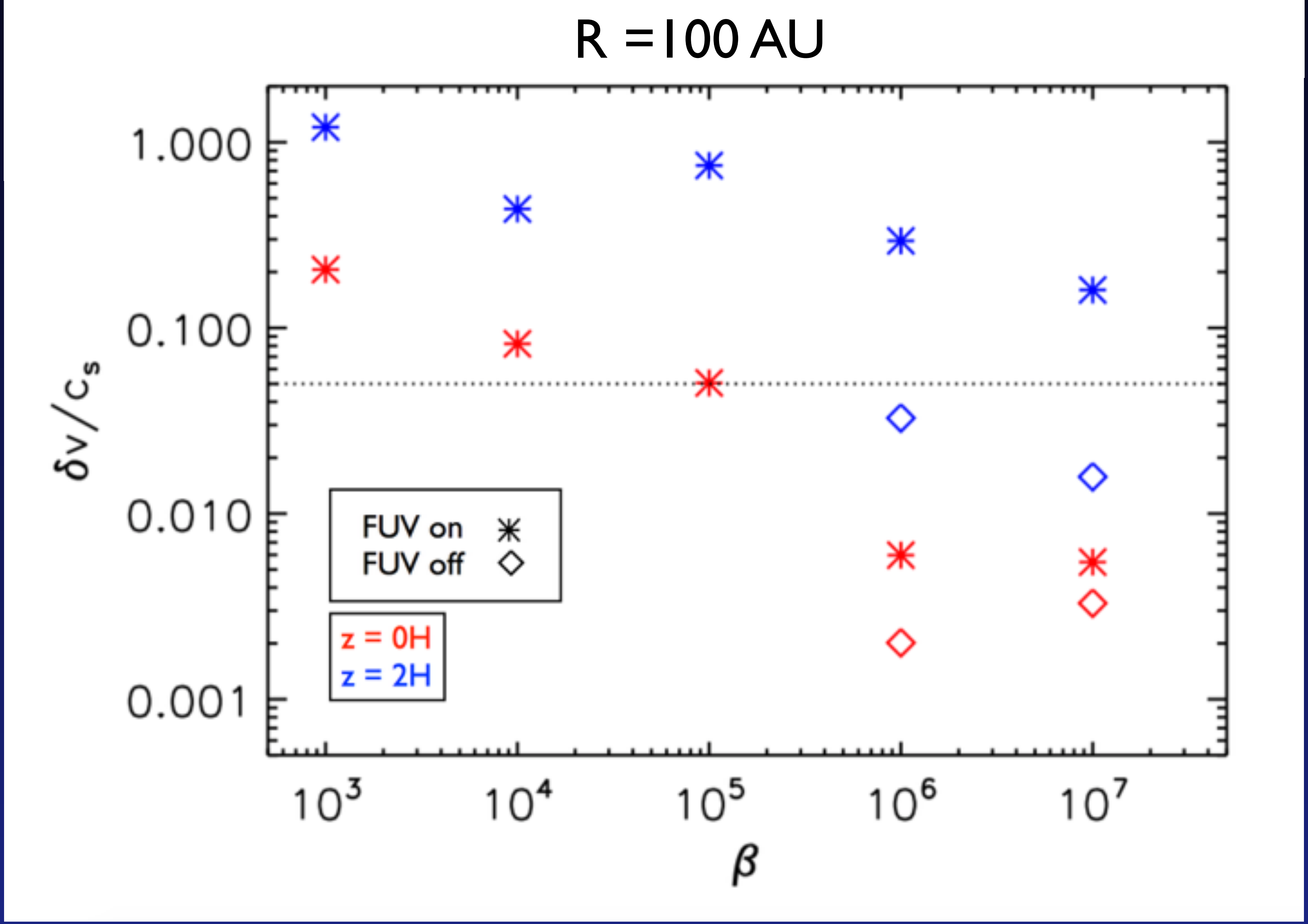


Simon et al., in prep

$$\beta = \frac{2P_{\mathrm{mid}}}{B^2_{\mathrm{mid}}}$$

Maybe the outer disk just isn't accreting…

Observations are consistent with a very weak magnetic field and NO FUV



Simon et al., in prep

$\beta=10^6 - 10^7$

Equates to B < 2-6 μG at 100 AU with no FUV

$$\beta = \frac{2P_{\text{mid}}}{B^2_{\text{mid}}}$$

Take away points so far

1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent “bursts” via the HSI

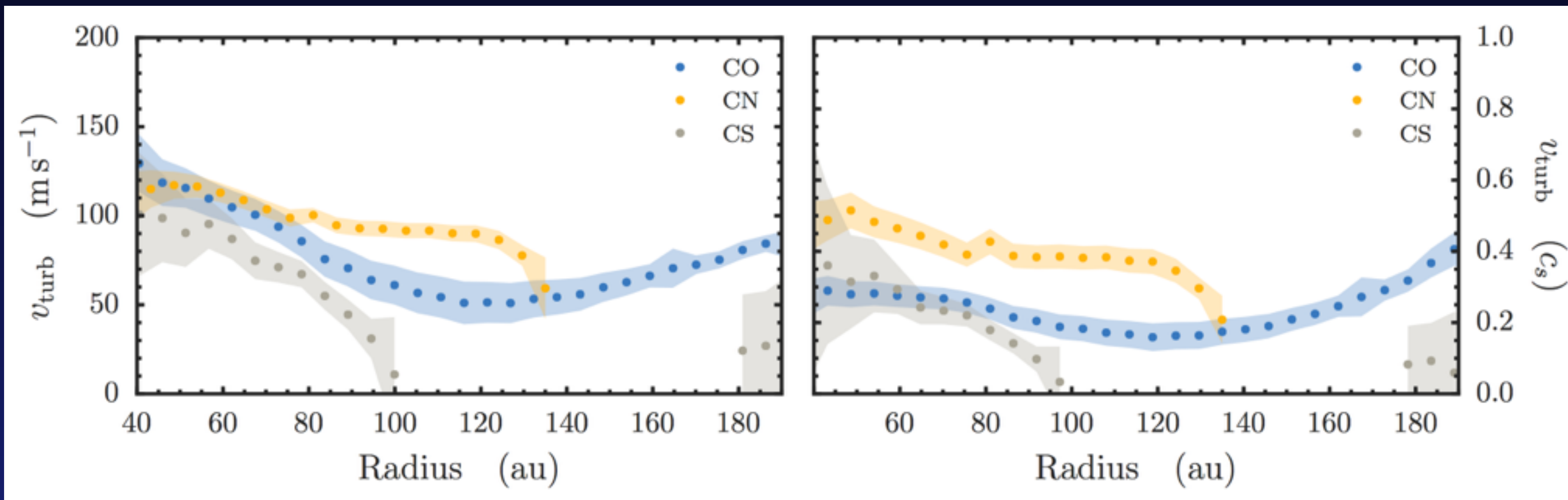
2. The outer regions of protoplanetary disk should have turbulent velocities on the order of >10-100% of the local sound speed for optically thick lines.

3. Observations of HD163296 suggest an upper limit of 5% of the sound speed.

4. Magnetic wind-driven accretion still produces significant “turbulent” motions within the cold molecular disk — we should have seen this!

Other sources?

Strong turbulence in TW Hya?



Teague et al. (2016)

Is this a result of differences in the two types of systems?

Or is it a result of two different methods?

Take away points so far

1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent “bursts” via the HSI

2. The outer regions of protoplanetary disk should have turbulent velocities on the order of >10-100% of the local sound speed for optically thick lines.

3. Observations of HD163296 suggest an upper limit of 5% of the sound speed.

4. Magnetic wind-driven accretion still produces significant “turbulent” motions within the cold molecular disk — we should have seen this!

5. We must reconcile the differences between the Teague TW Hya results and our HD163296 results — stay tuned!

Take away points so far

1. Winds are important in the inner disks, as shown by many studies, but radial angular momentum transport can arise from both laminar magnetic stresses and turbulent "bursts" via the HSI

2. The outer regions of protoplanetary disk should have turbulent velocities on the order of >10-100% of the local sound speed for optically thick lines.

3. Observations of HD163296 suggest an upper limit of 5% of the sound speed.

4. Magnetic wind-driven accretion still produces significant "turbulent" motions within the cold molecular disk — we should have seen this!

5. We must reconcile the differences between the Teague TW Hya results and our HD163296 results — stay tuned!

Next: Global simulations!

Turbulence vs. Wind
How is angular momentum transported in protoplanetary disks?

Both wind and turbulence!