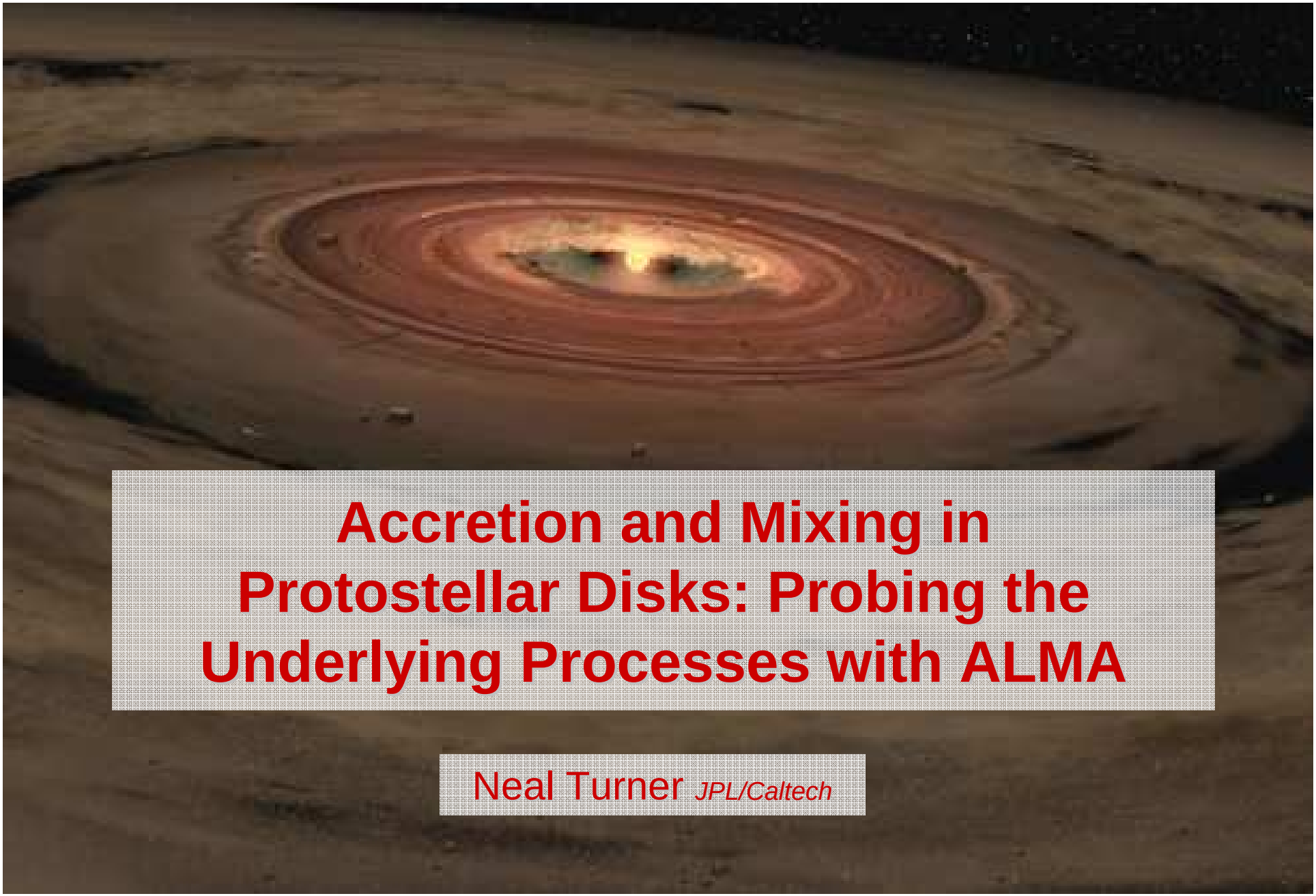


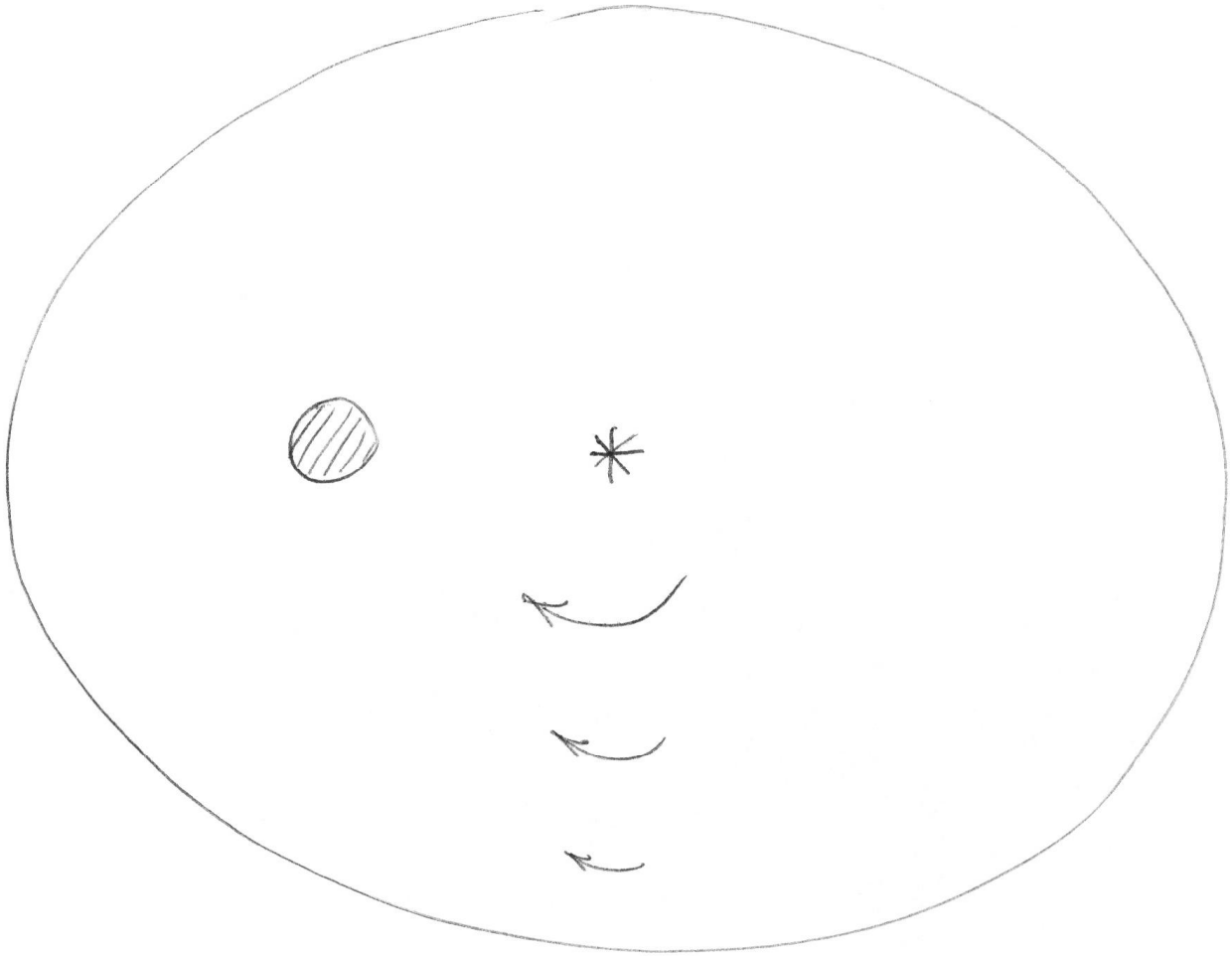
Accretion and Mixing in Protostellar Disks: Probing the Underlying Processes with ALMA

Neal Turner *JPL/Caltech*

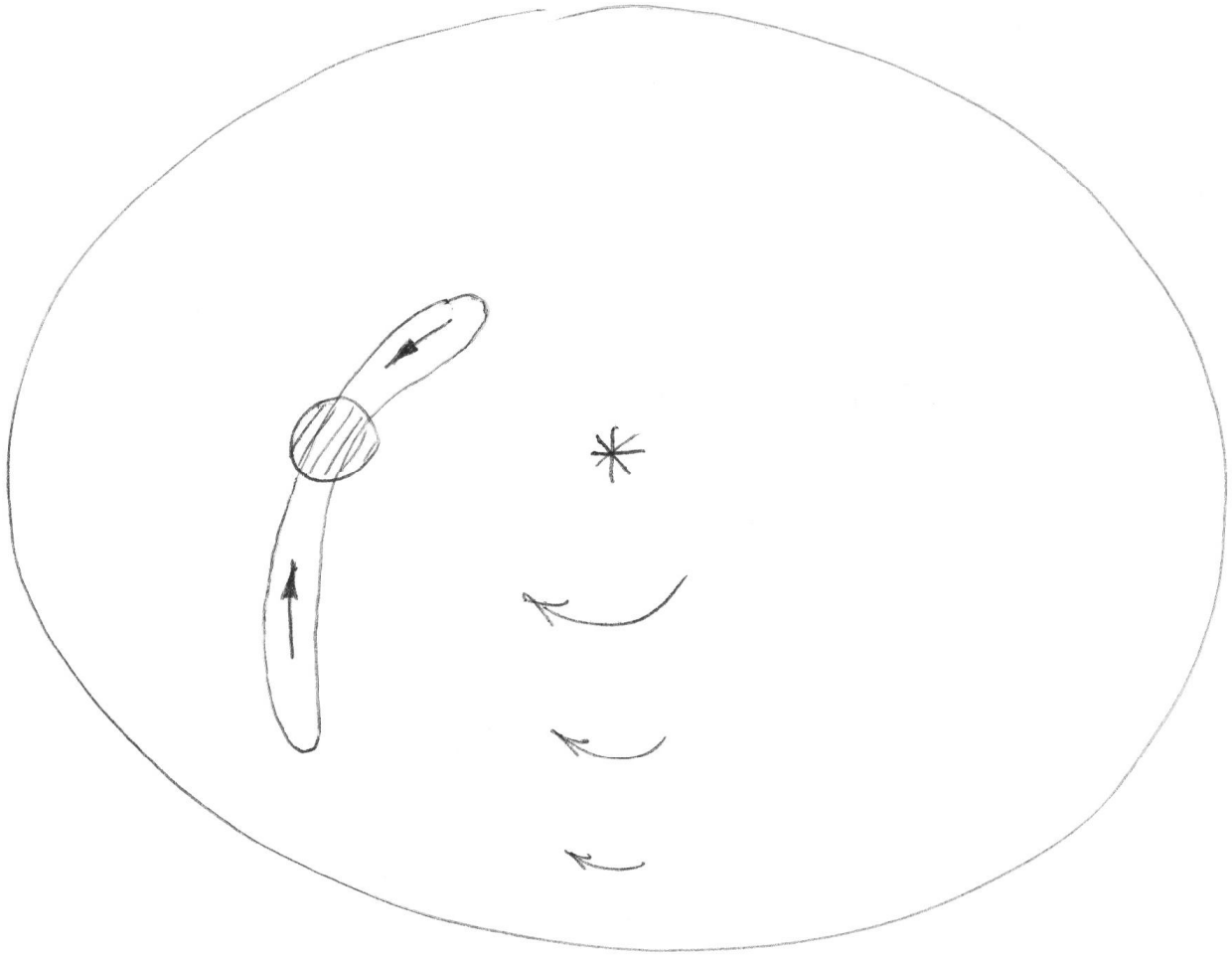
Outline

- **Current Picture:**
  1. **Gravitational Instability.**
  2. **Magneto-Centrifugal Winds.**
  3. **Magneto-Rotational Turbulence.**
- **Prospects with ALMA.**

1. Gravitational Instability



1. Gravitational Instability

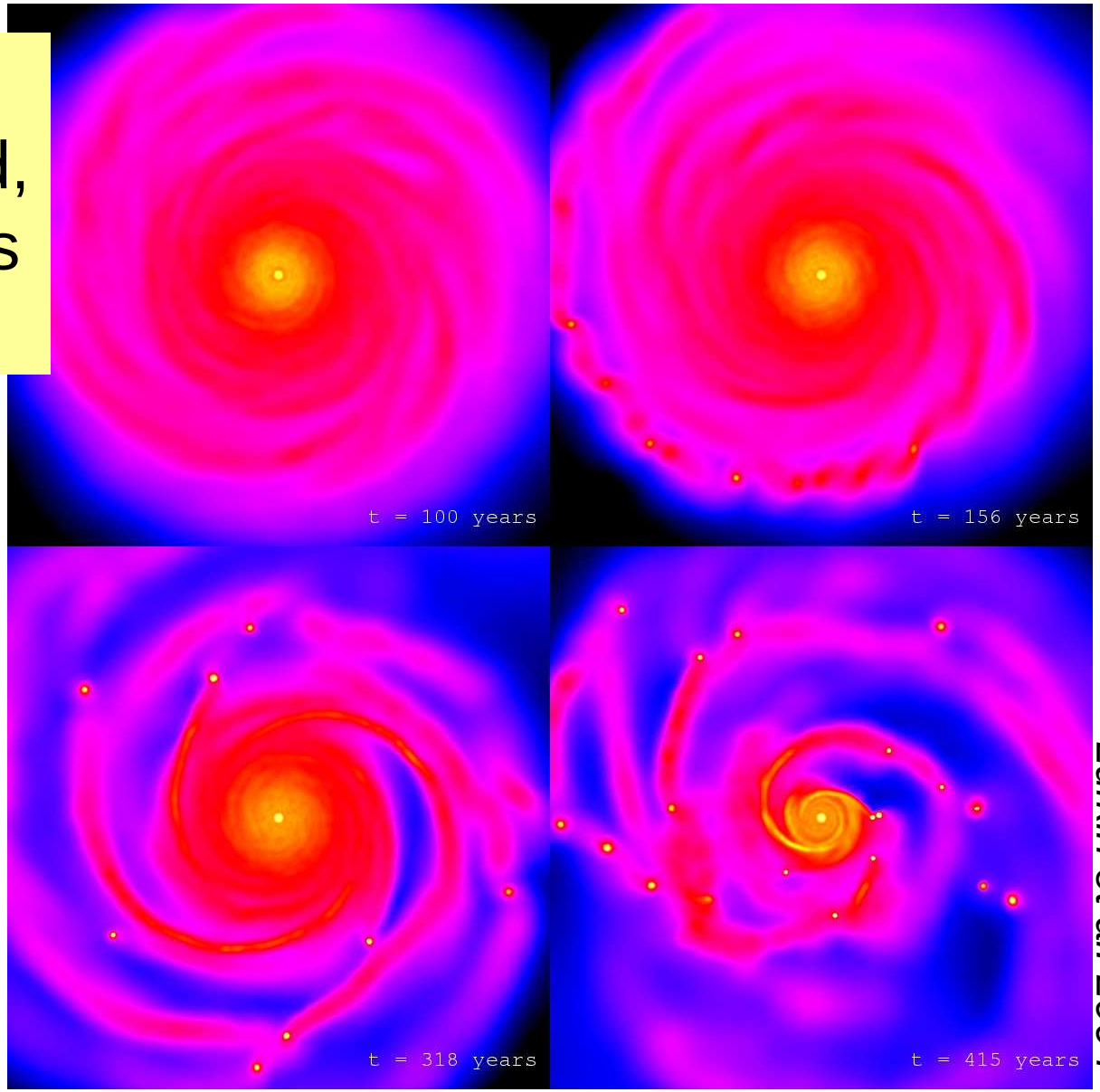


1. Gravitational Instability

Small disturbances grow if

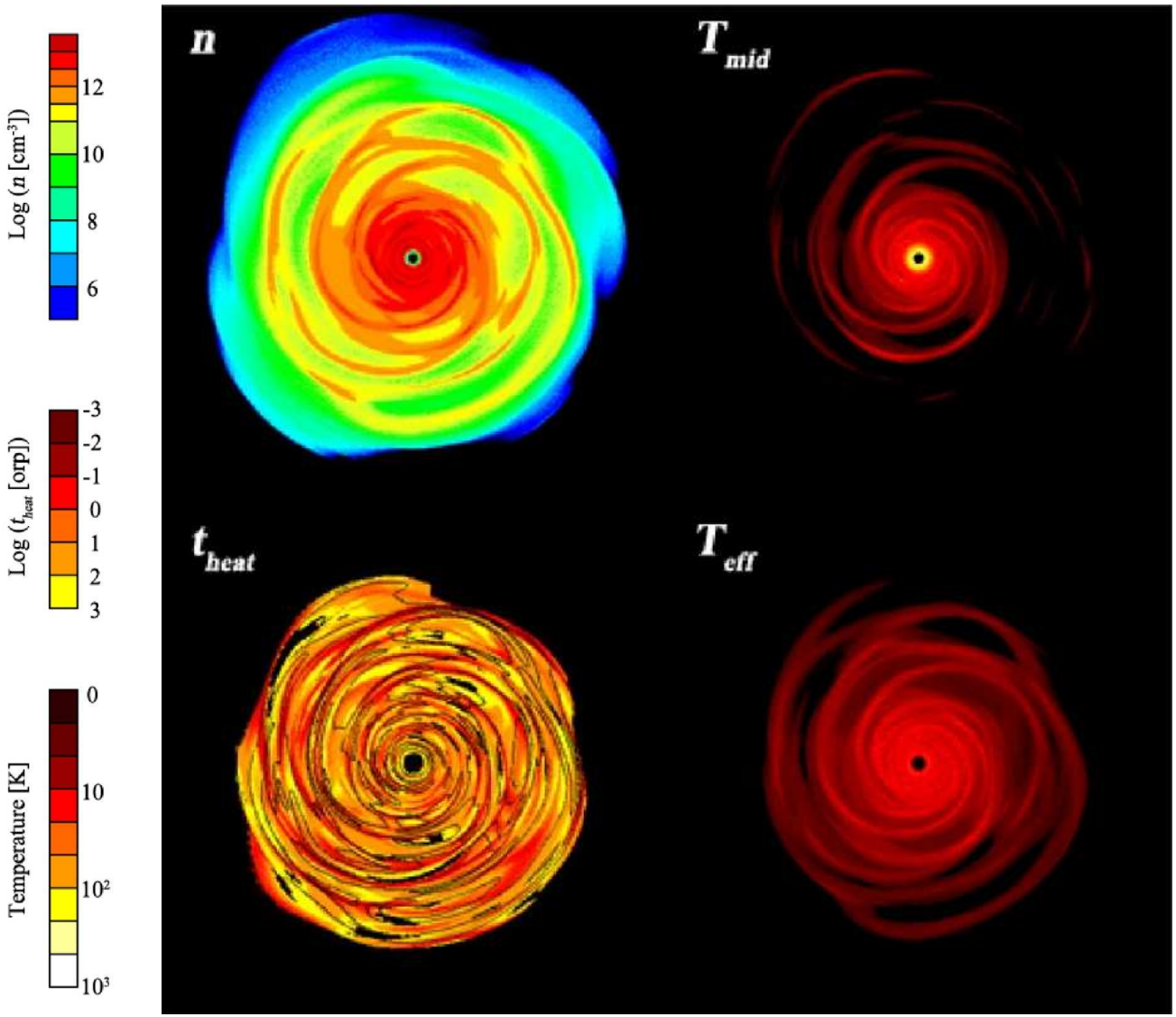
$$\frac{r^2\Sigma}{M_*} > \frac{H}{r}$$

If cooling time < orbital period, instability leads to collapse.



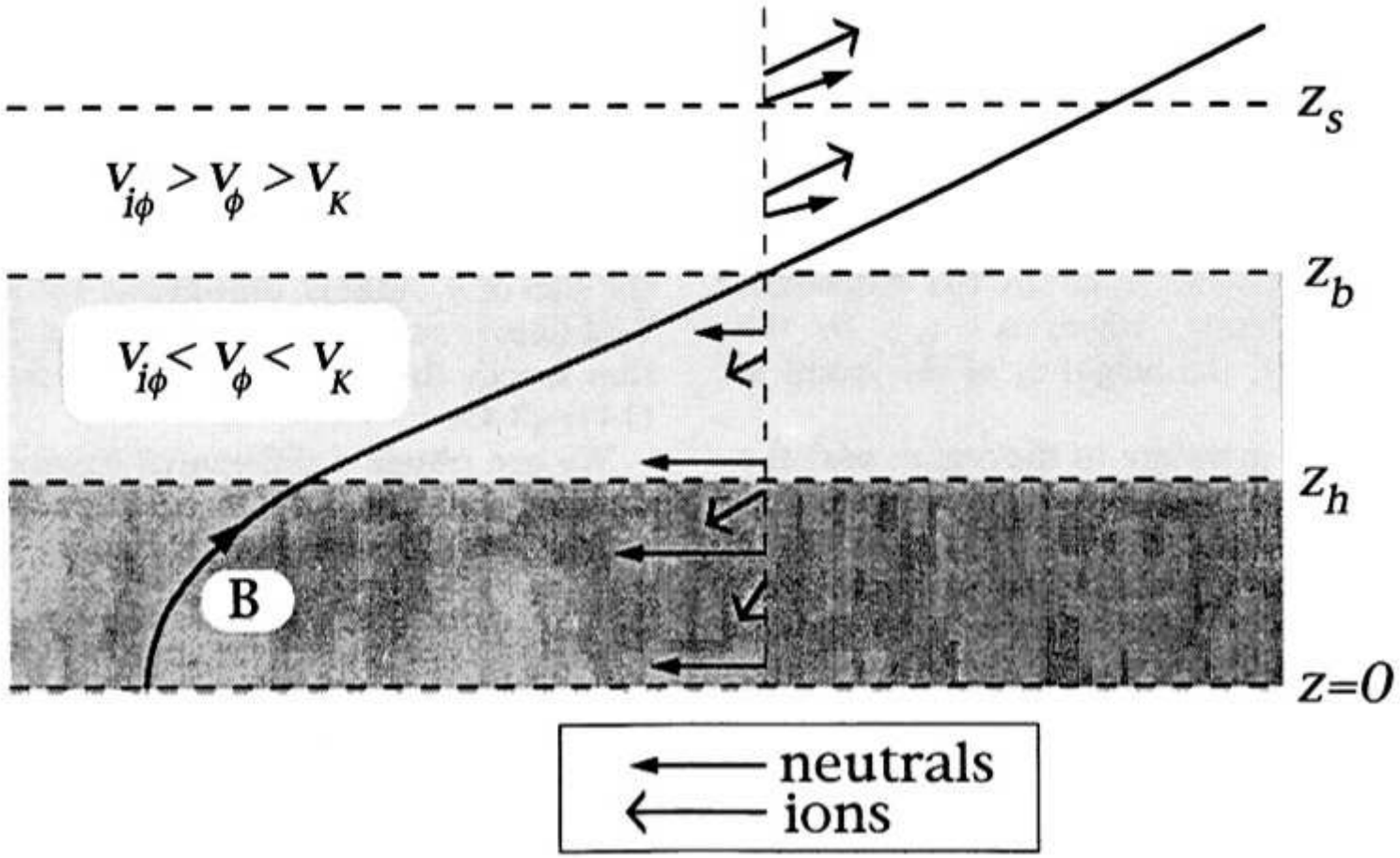
Lufkin et al. 2004

With slower cooling, instability leads to sustained accretion.



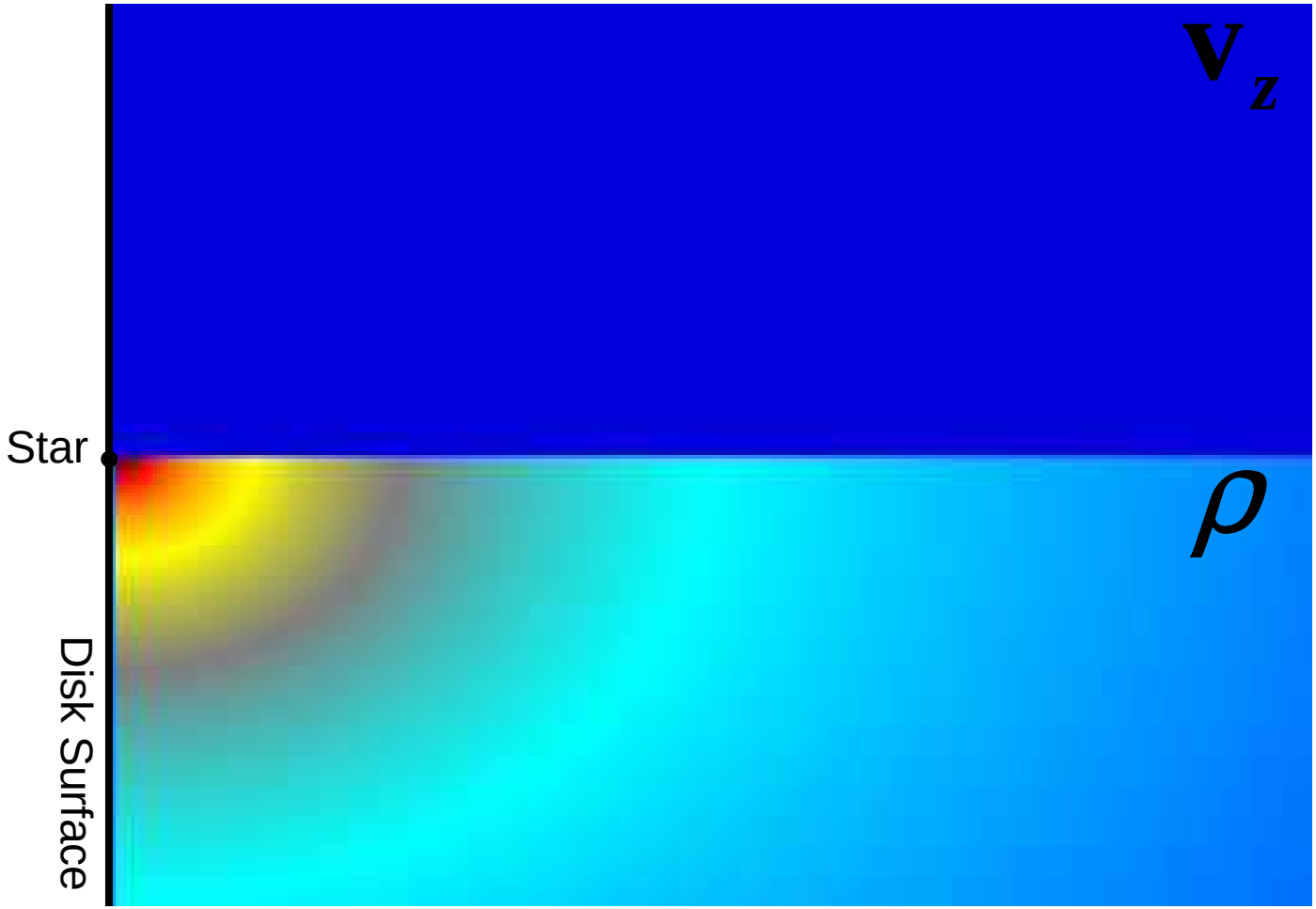
Mejia et al. 2005

2. Magneto-Centrifugal Winds



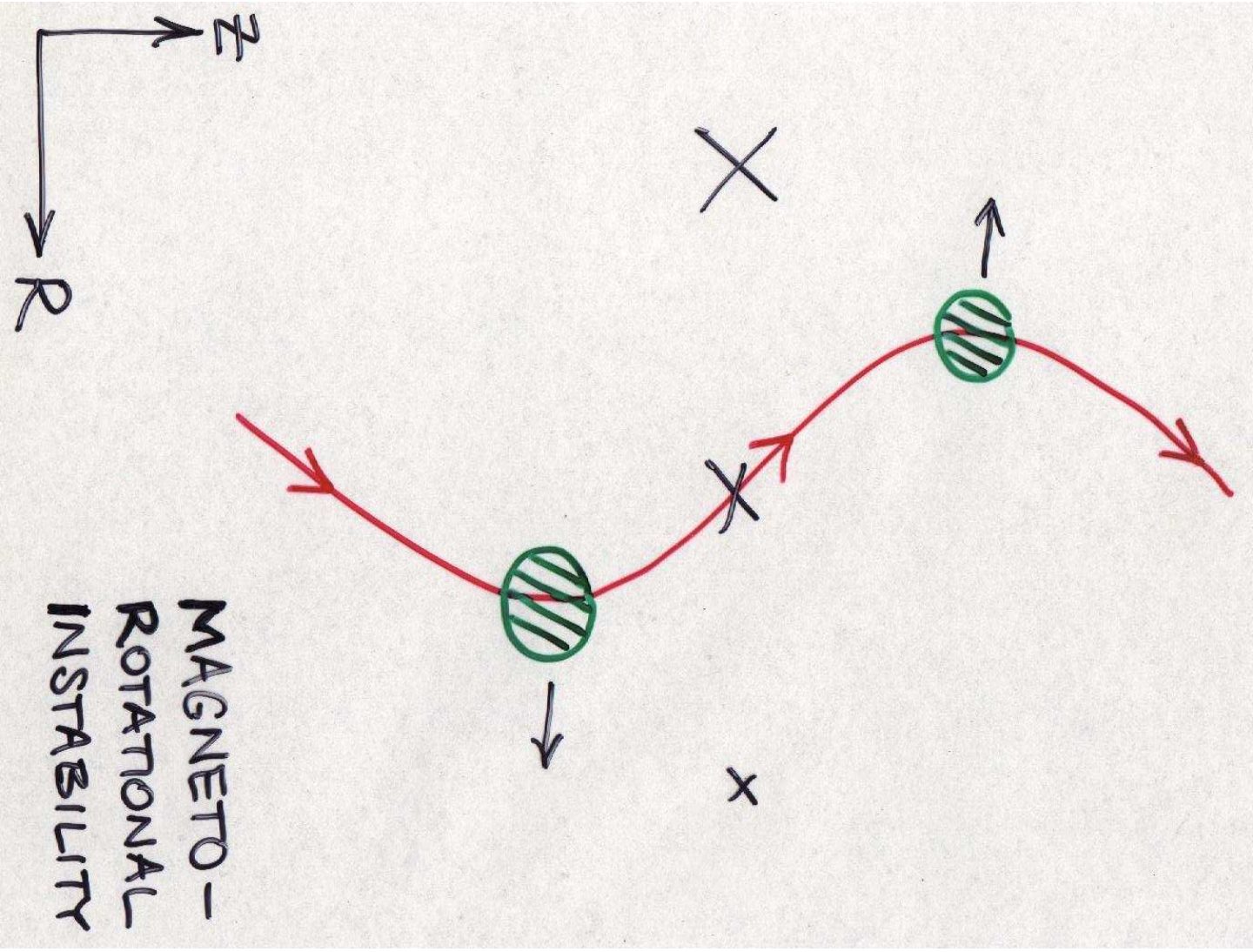
Conditions for operation?

Wardle & Koenigl 1993



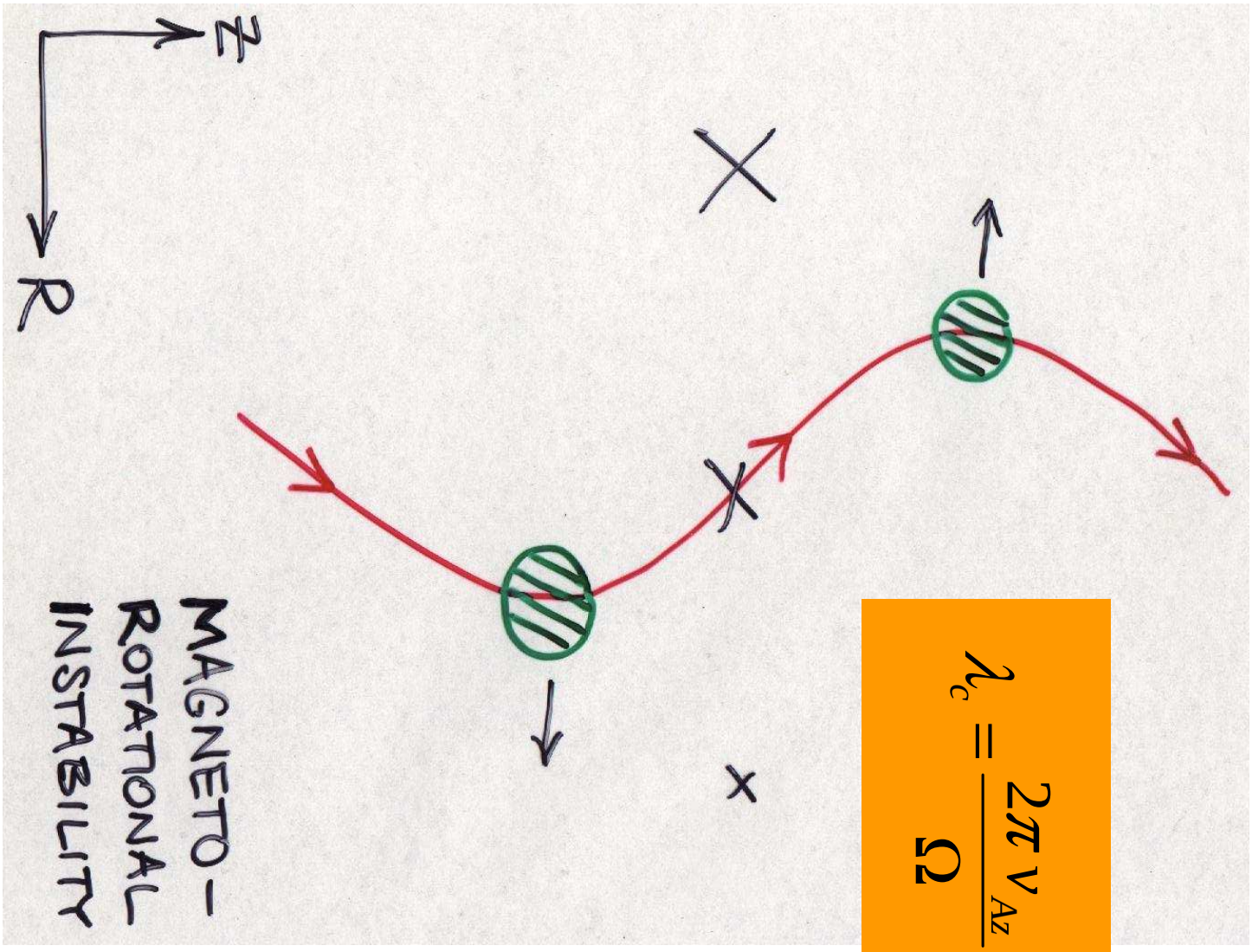
Ouyed & Pudritz 1997
Anderson et al. 2003

3. Magneto-Rotational Turbulence



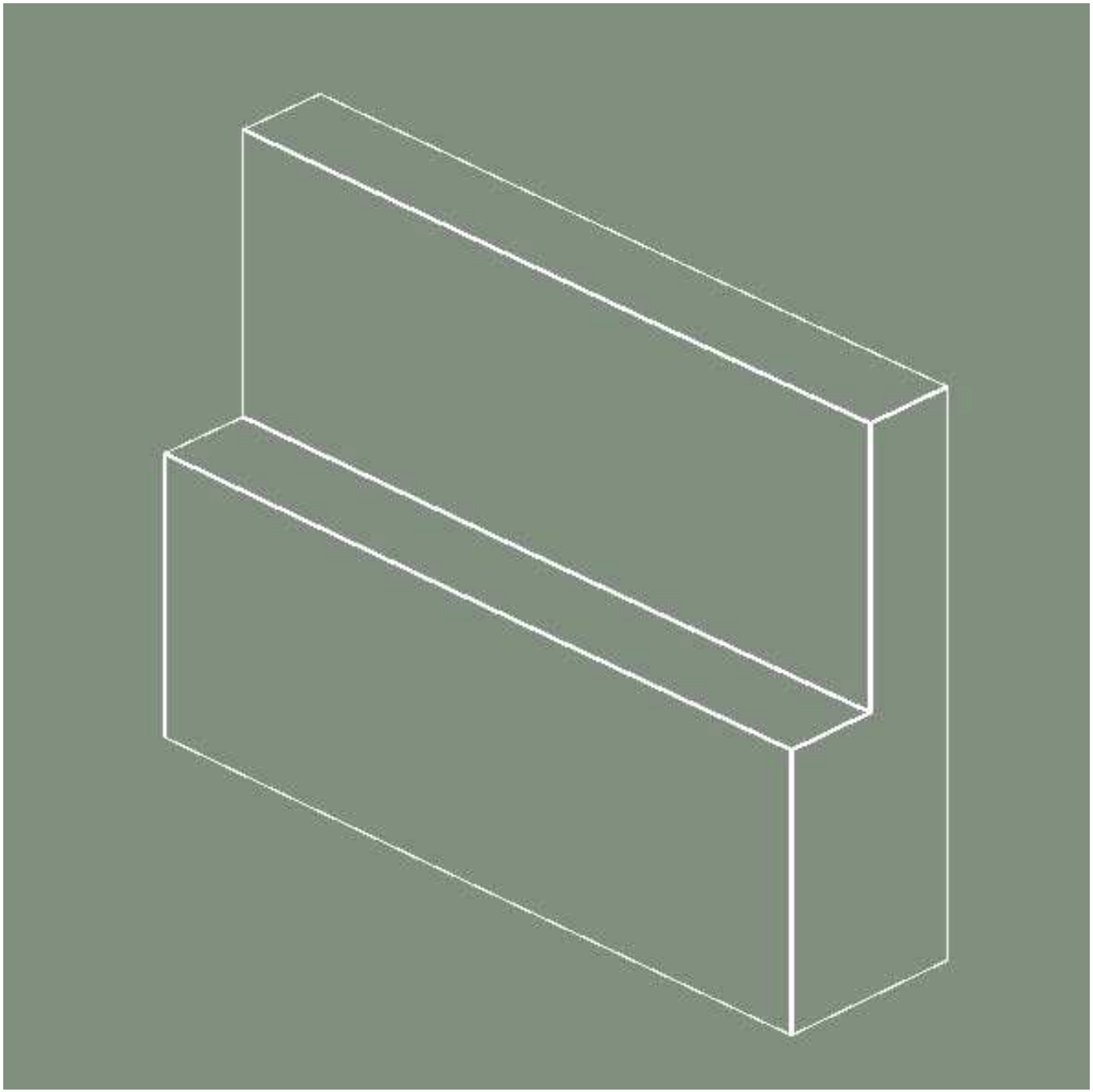
Balbus & Hawley 1991

3. Magneto-Rotational Turbulence



$$\lambda_c = \frac{2\pi v_{Az}}{\Omega}$$

Balbus & Hawley 1991



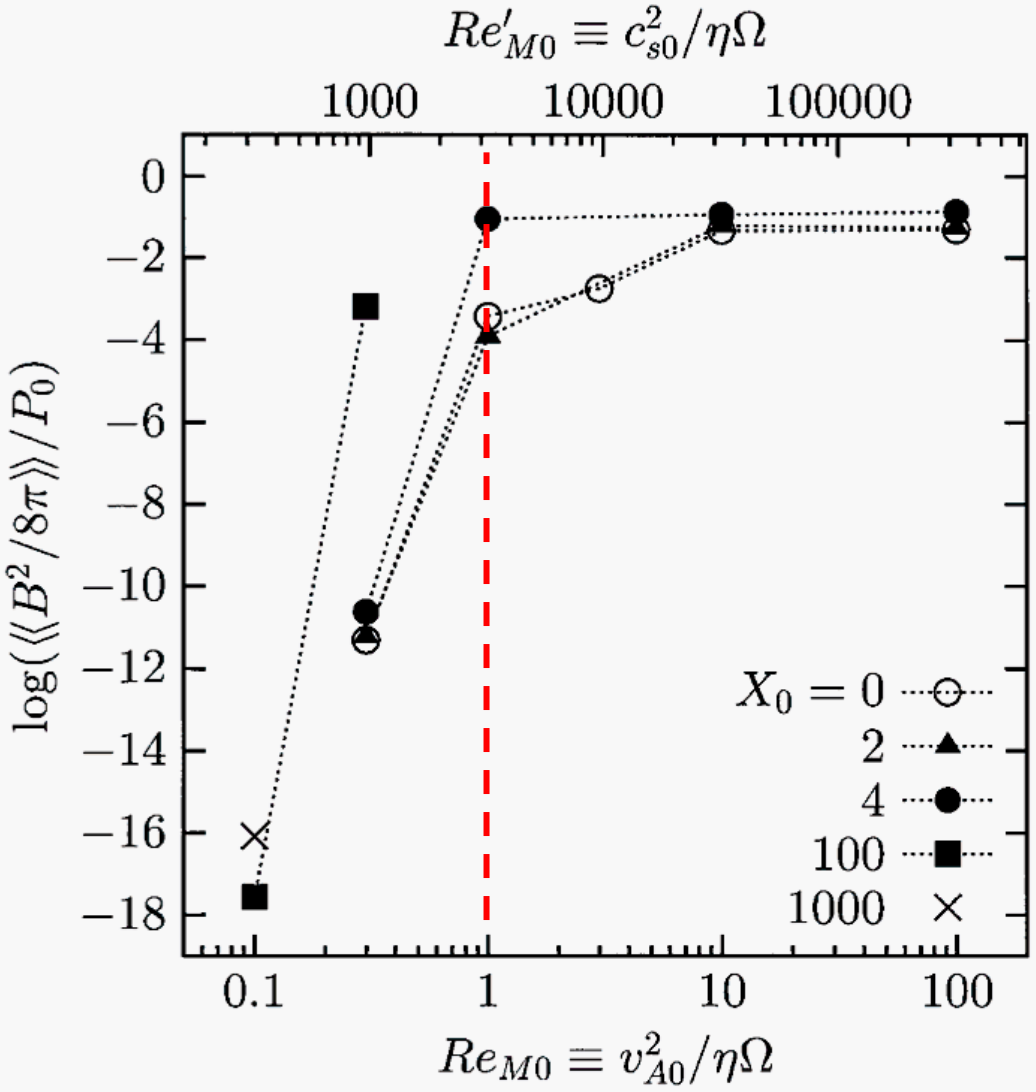


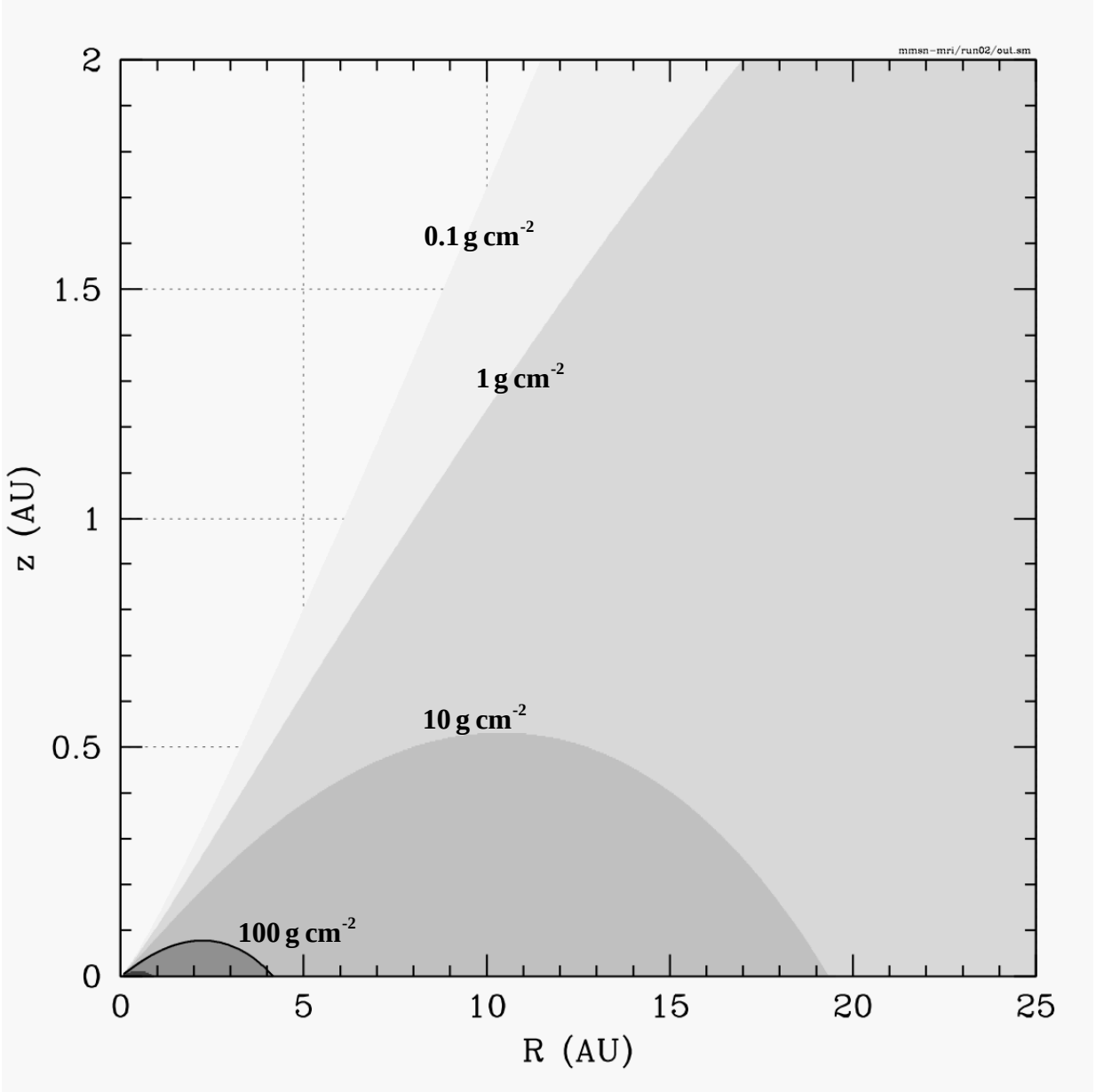
FIG. 14.—Saturation level of the magnetic energy as a function of the magnetic Reynolds number Re_{M0} for zero net flux B_z models ($\beta_0 = 3200$). Open circles denote the models with only the ohmic dissipation ($X_0 = 0$), and the other symbols are including also the Hall effect ($X_0 = 2$, 4, 100, and 1000).

MRI turbulence requires

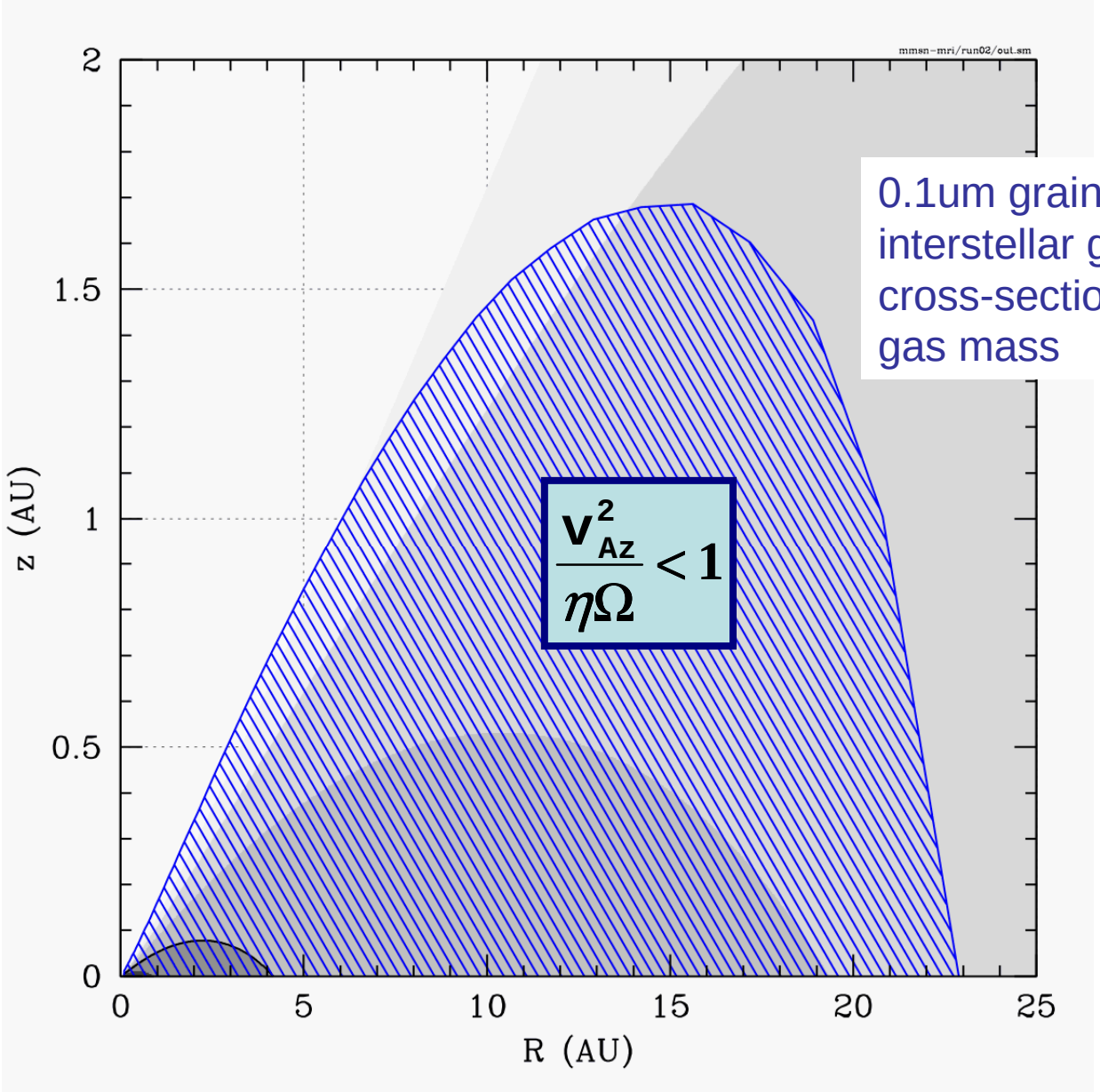
$$\frac{V_{Az}^2}{\eta\Omega} > 1$$

Sano & Stone 2002b

Dead Zone

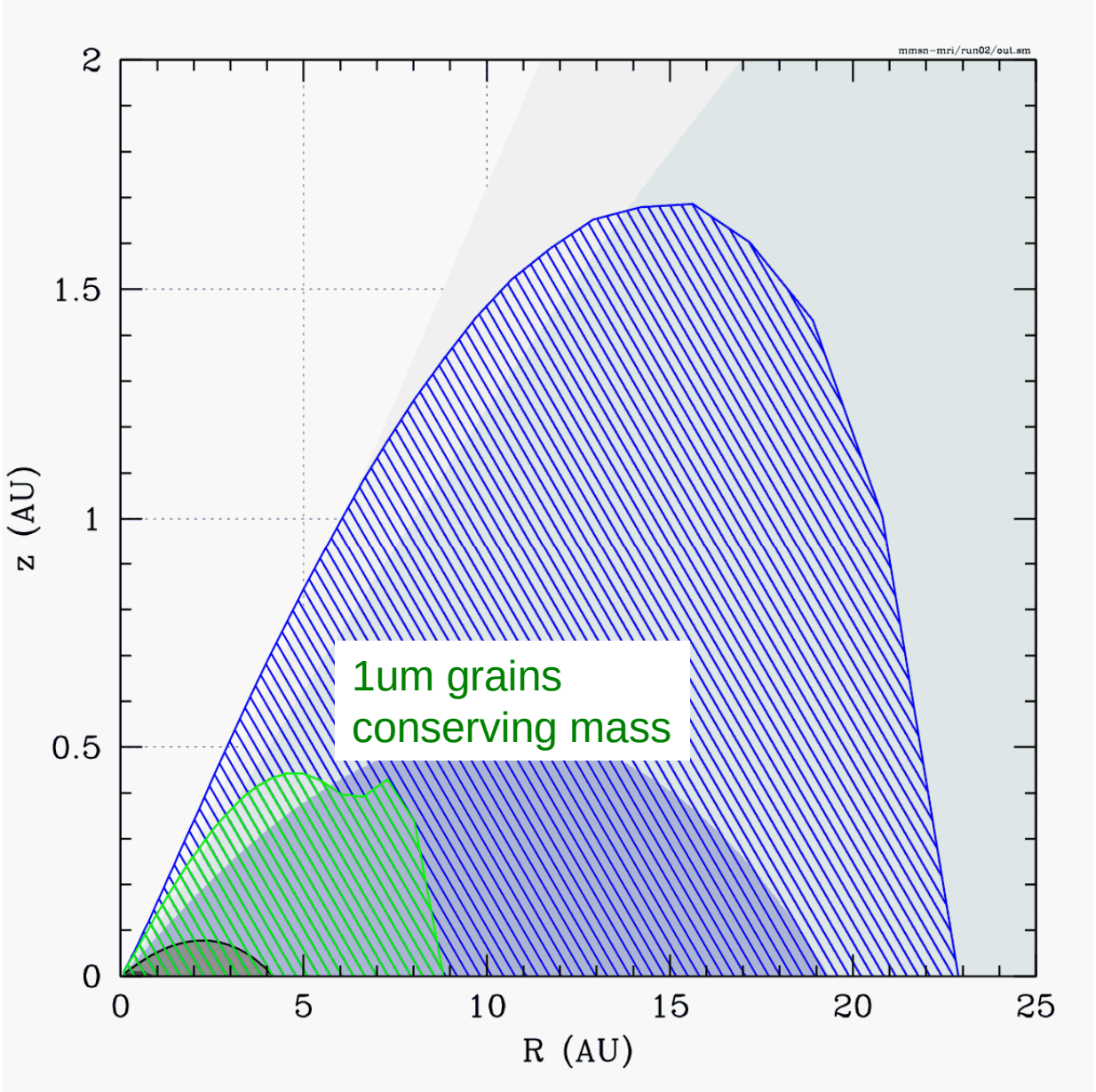

mmsn-mri/run02/out.sm
0.1 g cm-2
1 g cm-2
10 g cm-2
100 g cm-2
z (AU)
R (AU)
0
0.5
1
1.5
2
0
5
10
15
20
25

Dead Zone

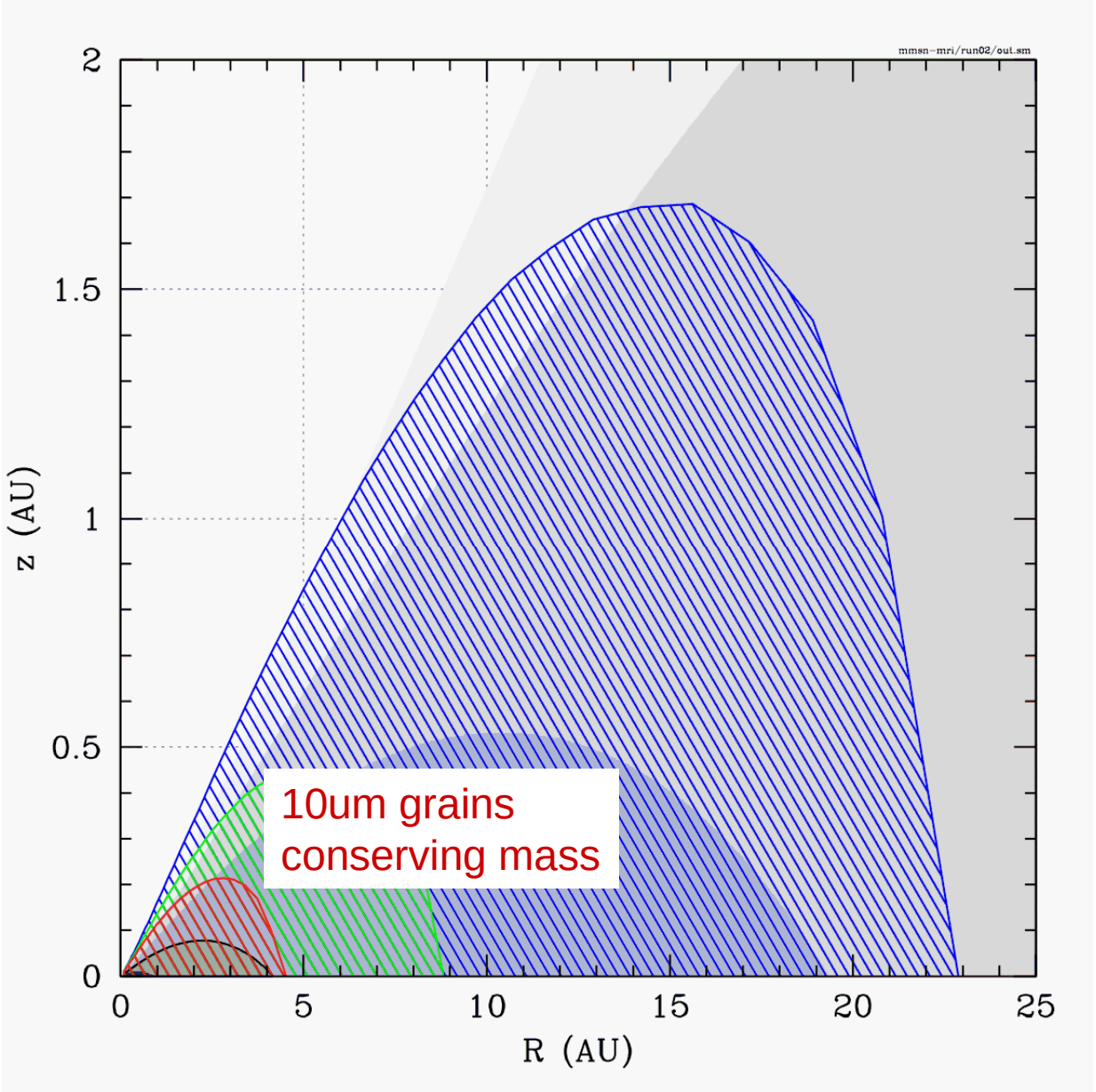


0.1um grains with the interstellar geometric cross-section per unit gas mass

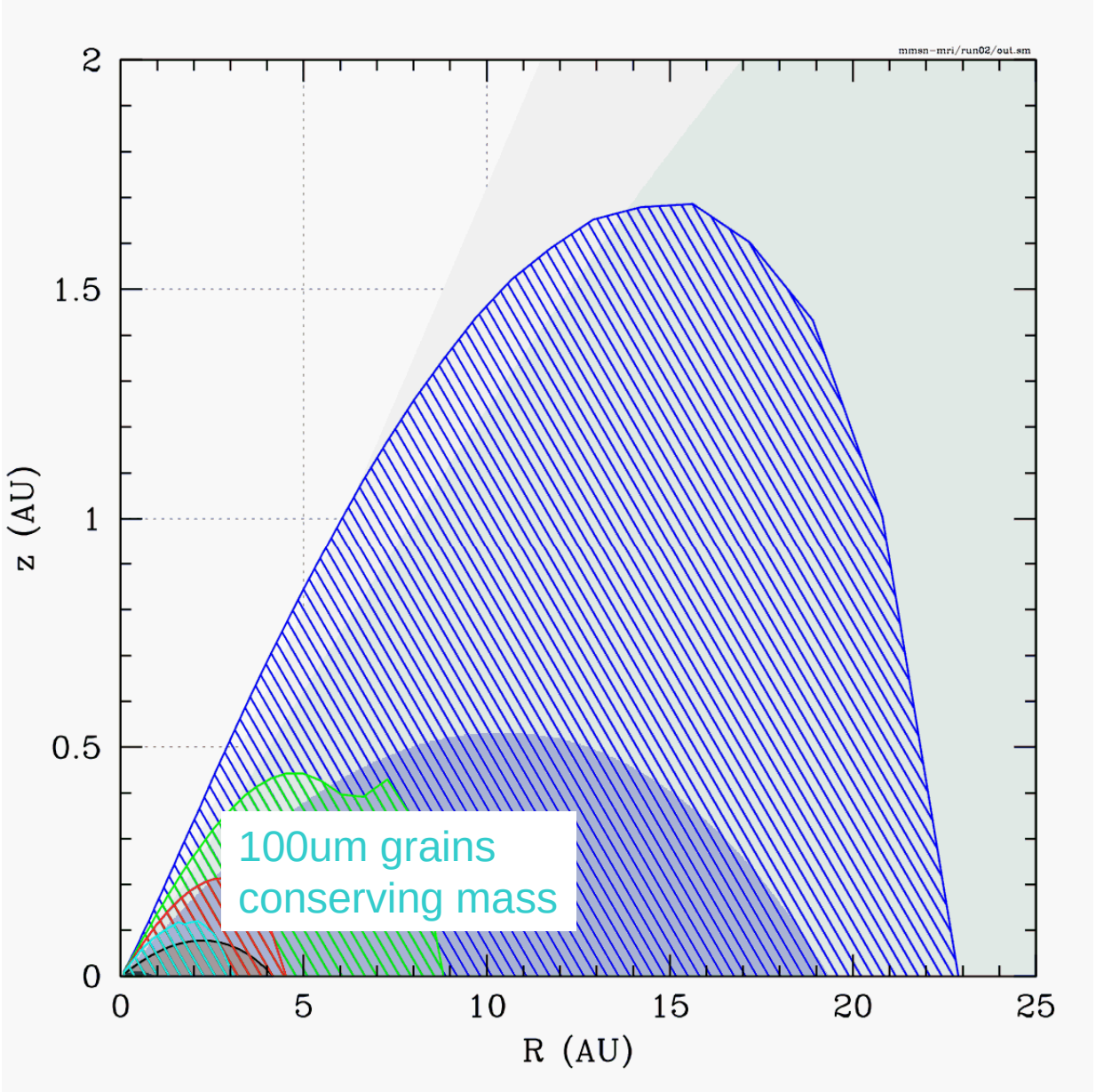
Dead Zone


mmsn-mri/run02/out.sm
2
1.5
1
0.5
0
z (AU)
0
5
10
15
20
25
R (AU)
1um grains
conserving mass

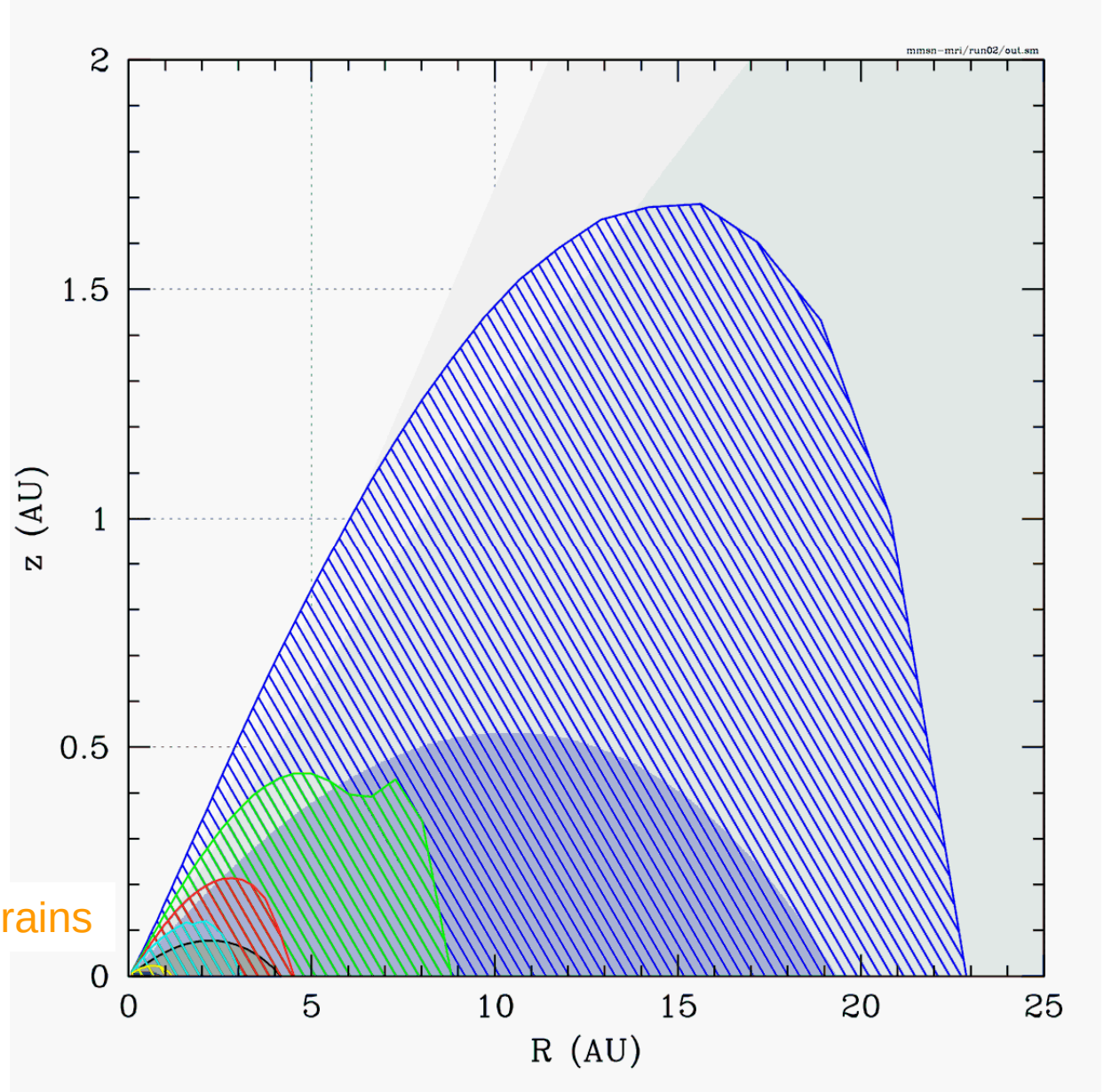
Dead Zone


mmsn-mri/run02/out.sm
2
1.5
1
0.5
0
z (AU)
0
5
10
15
20
25
R (AU)
10um grains
conserving mass

Dead Zone


mmsn-mri/run02/out.sm
2
1.5
1
0.5
0
z (AU)
0
5
10
15
20
25
R (AU)
100um grains
conserving mass

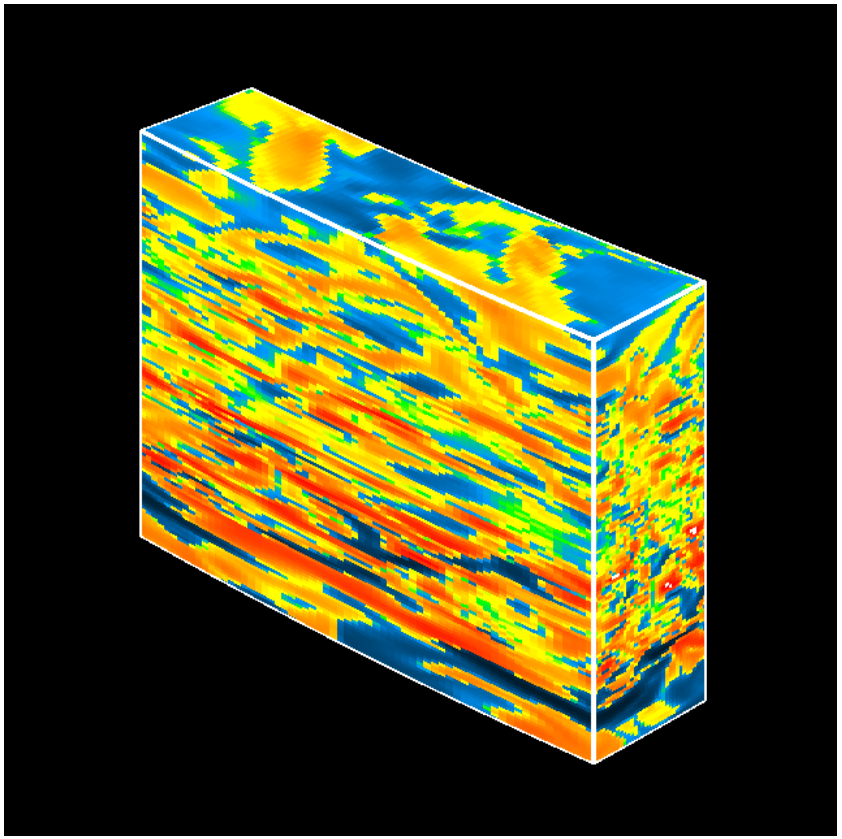
Dead Zone



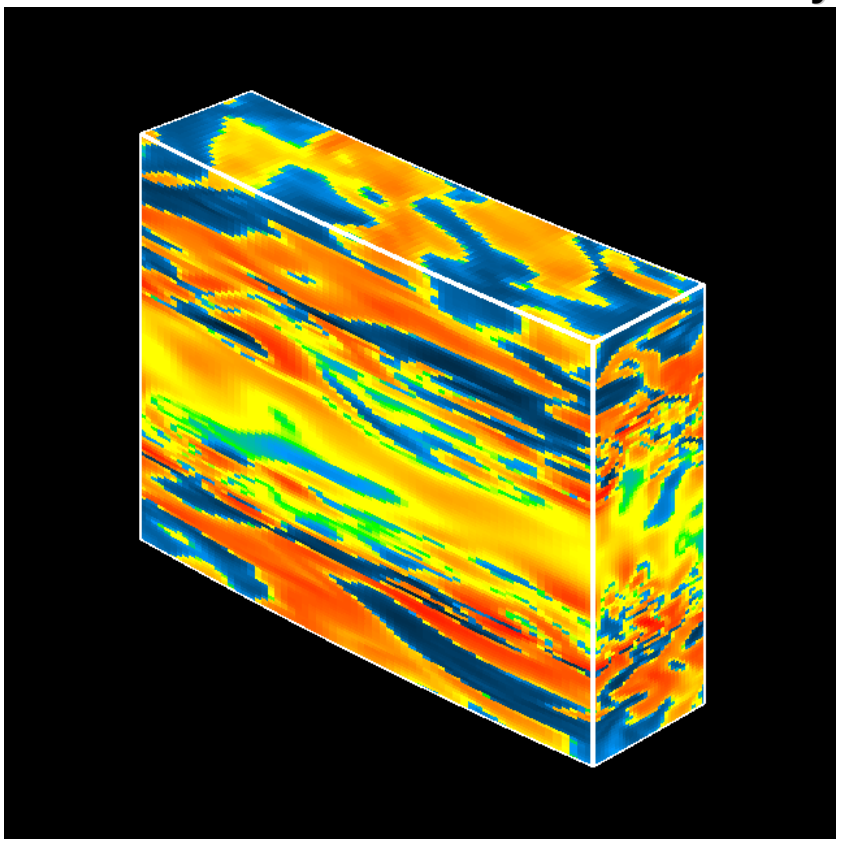
No grains

Magnetic Stresses Can Occur in the Dead Zone

Ideal MHD

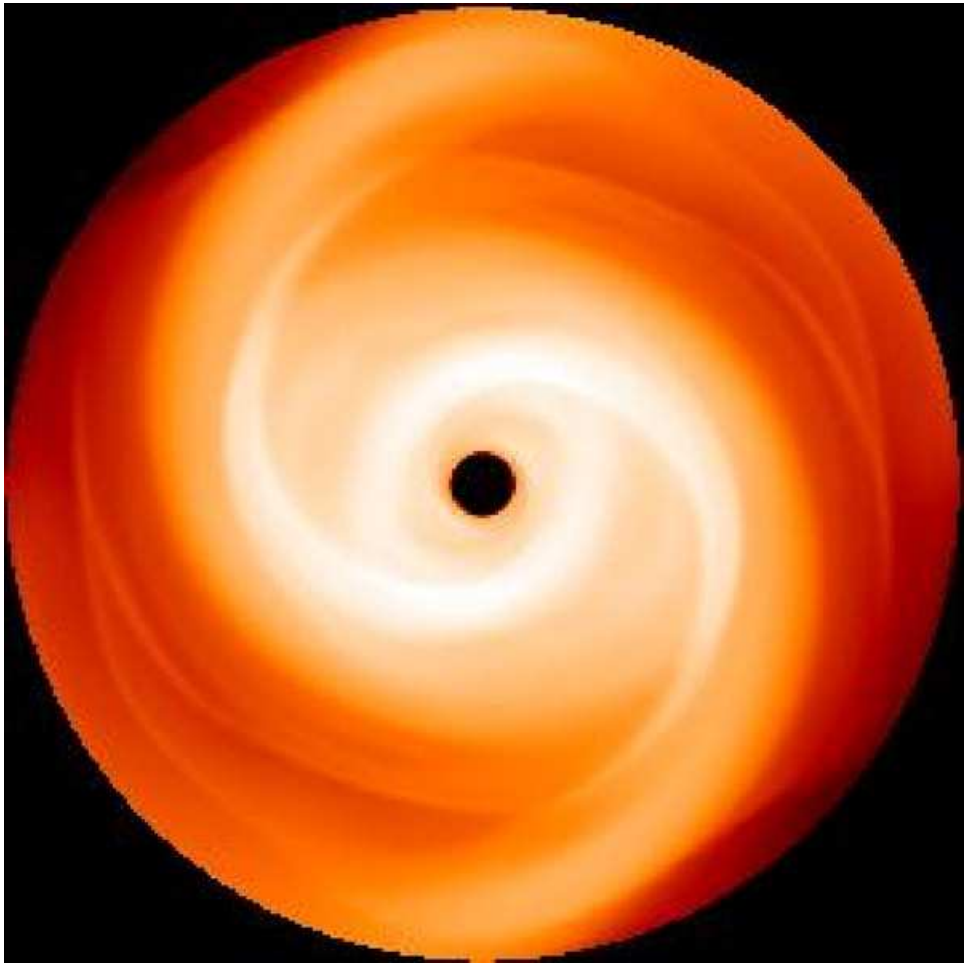


Resistive MHD with Ionization Chemistry



Turner et al. 2007

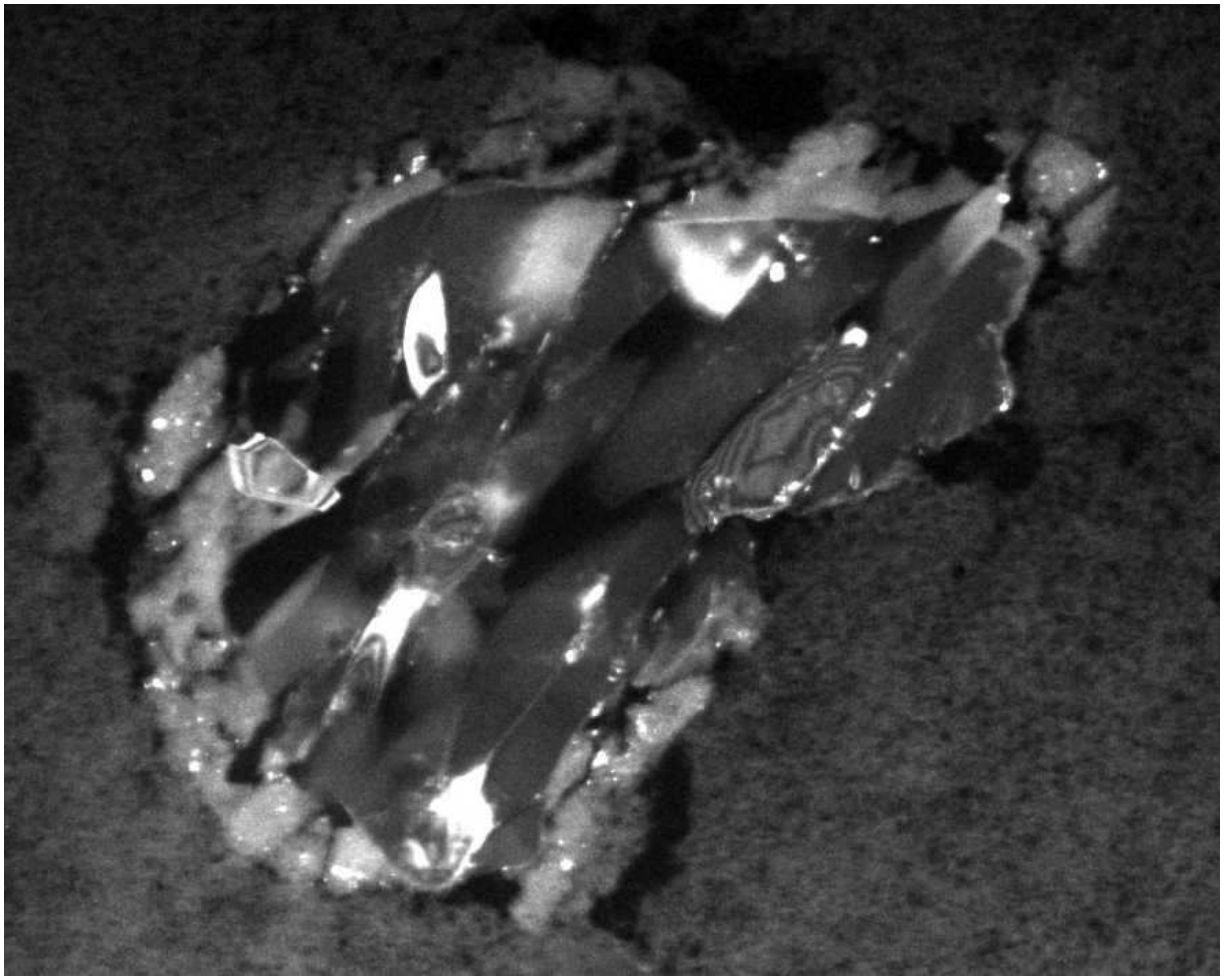
Do multiple A.M. transfer mechanisms coexist?



Fromang et al. 2004

Mass Transport

Crystalline forsterite grain from Comet Wild 2



Zolensky et al. 2006

- **G.I.** – little direct mixing, but shock heating => convection => mixing.

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- **Disk winds** – little mixing. Solids exchanged between disk & wind?

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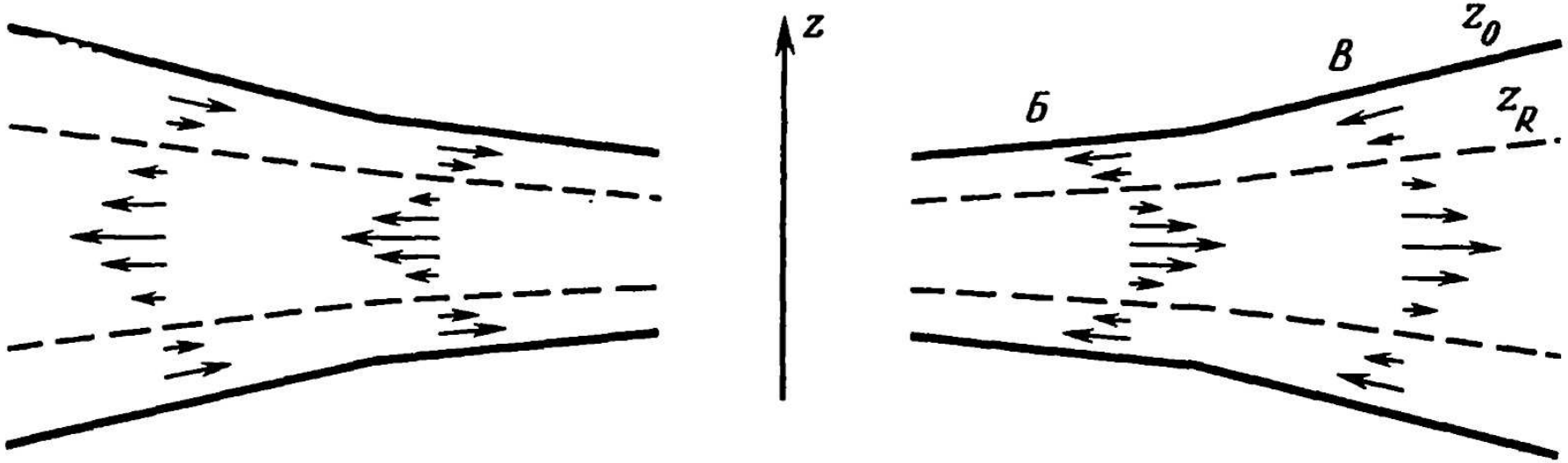
- **Disk winds** – little mixing. Solids exchanged between disk & wind?
- **MRI turbulence** – mixing and A.M. transfer coefficients roughly equal.

Global Circulation



Urpin 1984

Kley & Lin 1992

Takeuchi & Lin 2002

Prospects for ALMA

Two basic questions:

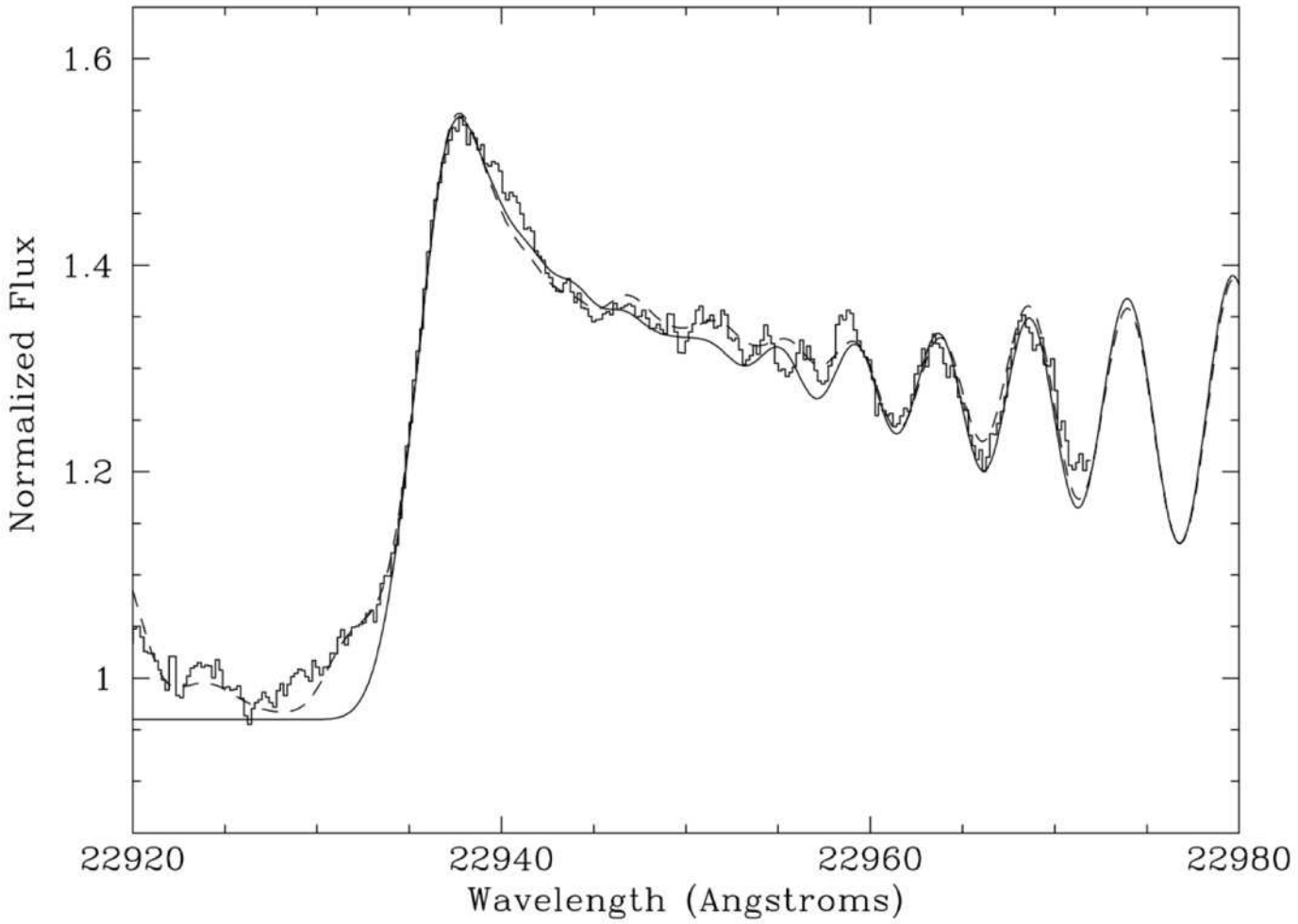
1. How is angular momentum removed?

2. What mixing processes are at work?

Prospects for ALMA

- **Directly detect gas flows.** Expect spiral shocks, helical outflow, or surface layer turbulence.

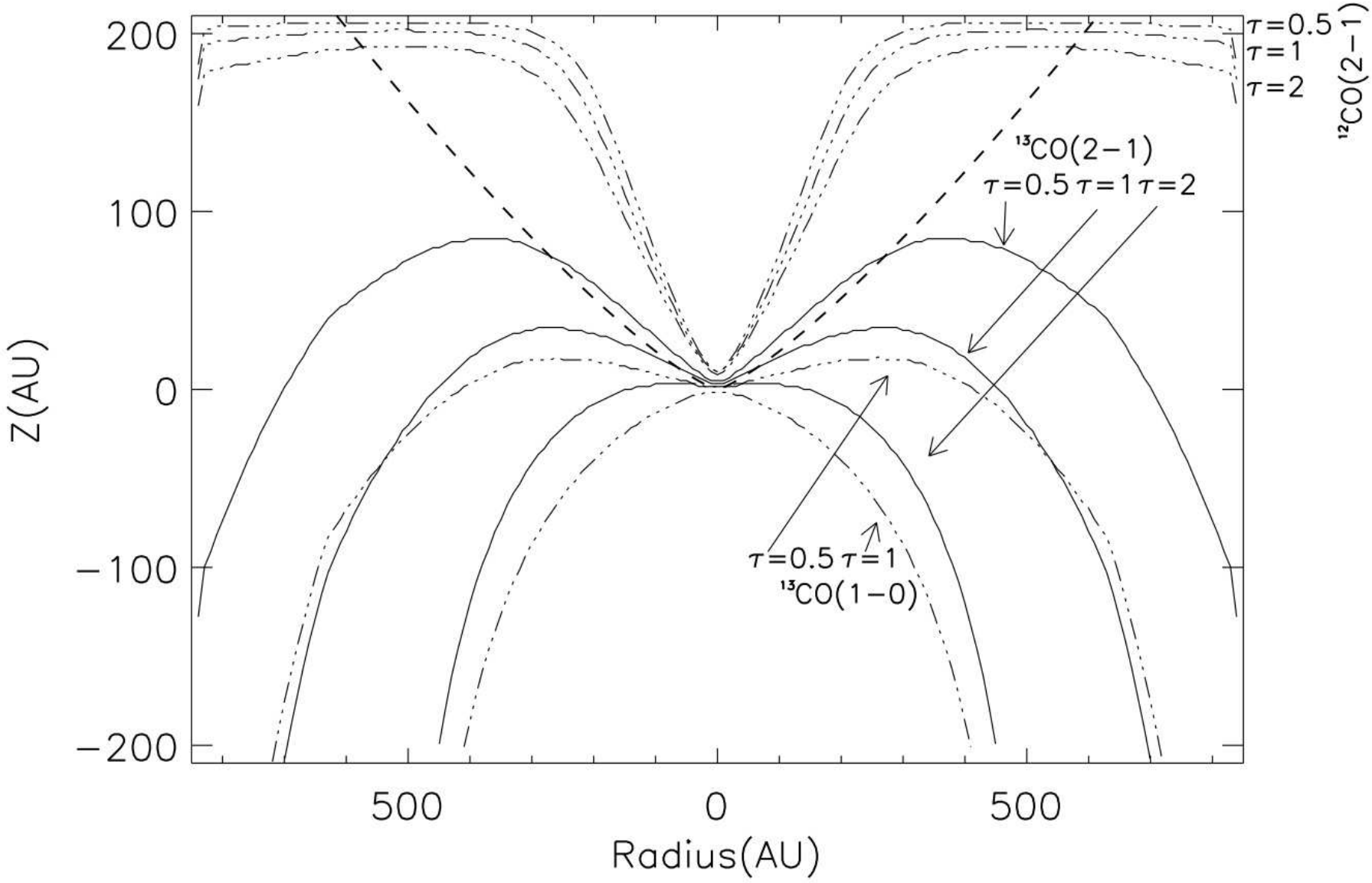
CO Overtone Bandhead in SVS13



Carr et al. 2004

Prospects for ALMA

- **Directly detect gas flows.**
- **Is gravitational instability active?**
  Map the surface density and midplane temperature.

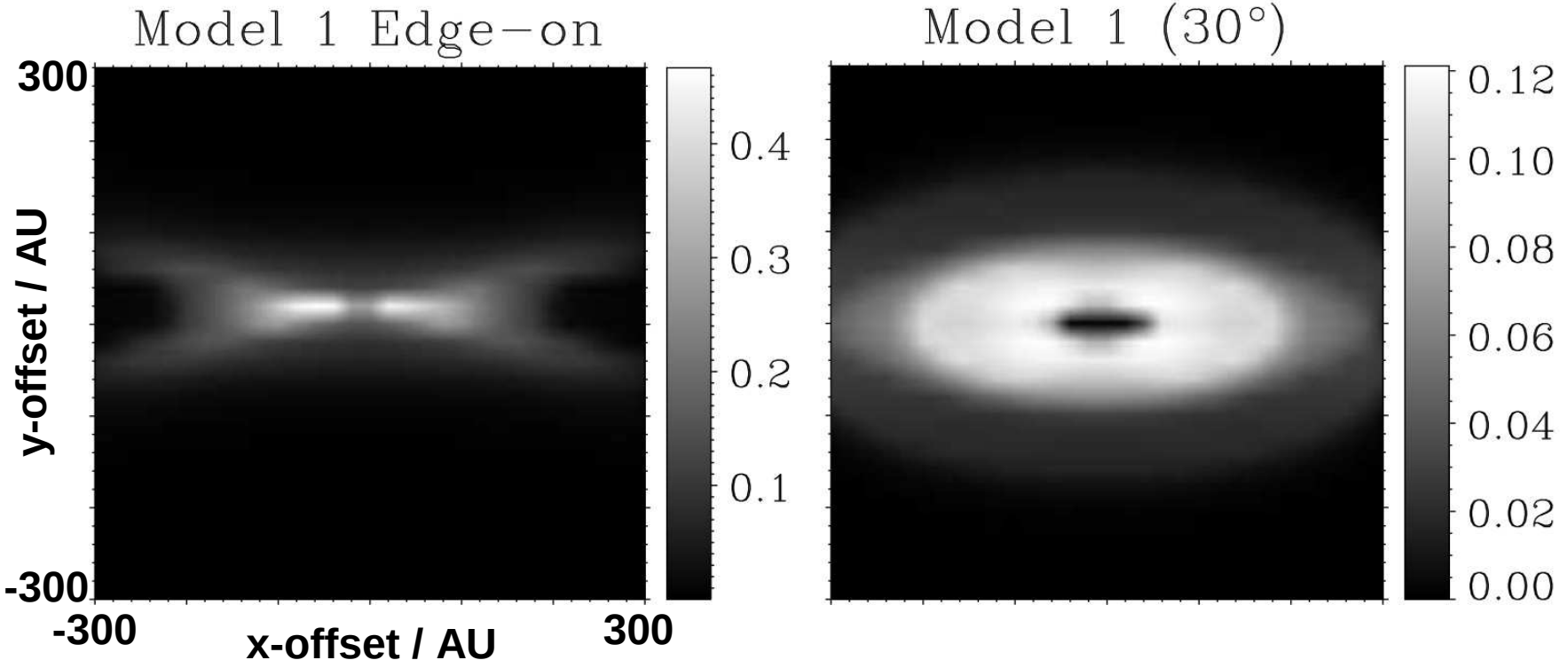


Dartois et al. 2003

Prospects for ALMA

- **Directly detect gas flows.**
- **Is gravitational instability active?**
- **Is the gas tied to magnetic field lines?**
  Measure charged particle fraction.

Model H_2D^+ 372.4 GHz Maps

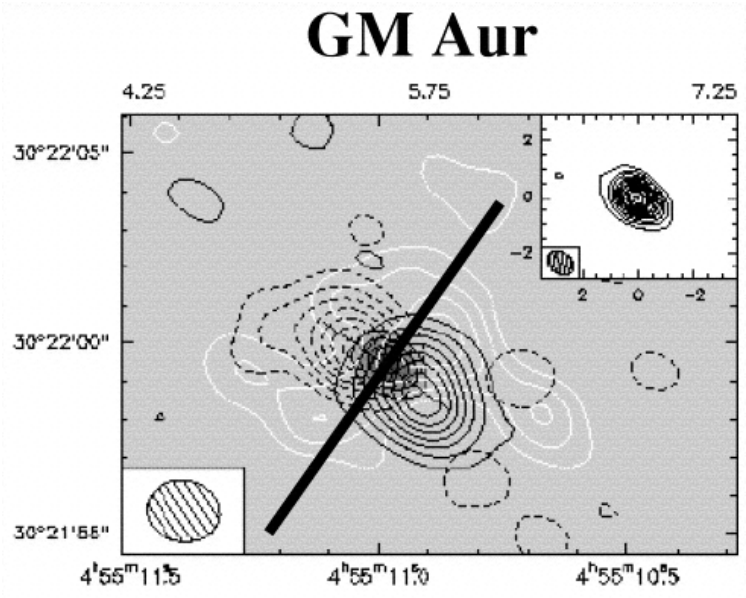


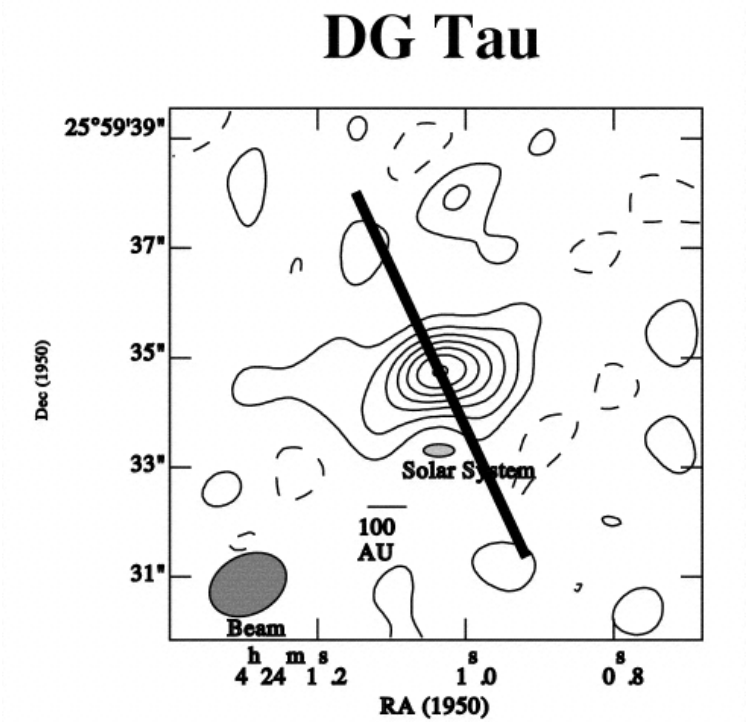
Intensity units 10^{-6} erg cm^{-2} s^{-1} sr^{-1}

Asensio Ramos et al. 2007

Prospects for ALMA

- **Directly detect gas flows.**
- **Is gravitational instability active?**
- **Is the gas tied to magnetic field lines?**
- **Are the fields straight or tangled?**
  Are the strength and orientation consistent with a wind? With MRI?





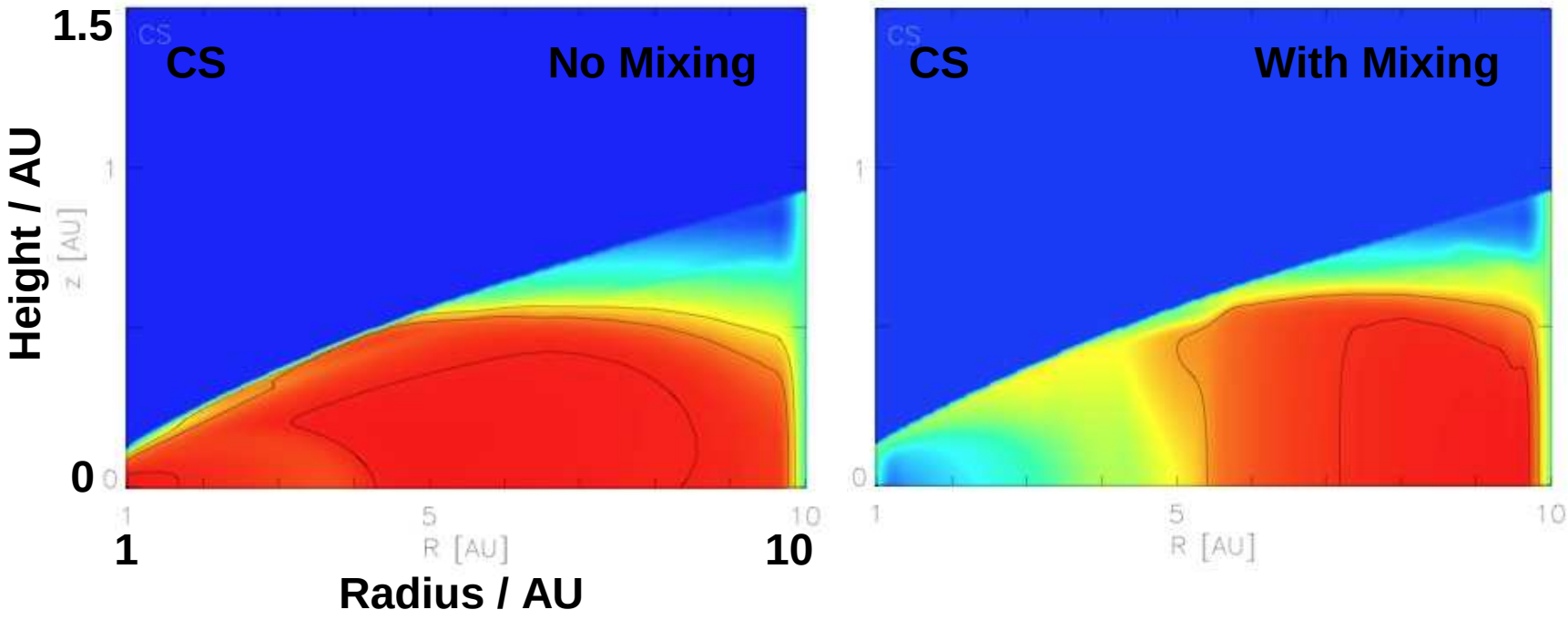
850μm continuum polarization vectors from JCMT

Tamura et al. 1999

Prospects for ALMA

- **Directly detect gas flows.**
- **Is gravitational instability active?**
- **Is the gas tied to magnetic field lines?**
- **Are the fields straight or tangled?**
- **What are the mixing rates?** Match abundances against chemical models including mixing.

Abundances can be increased or reduced by vertical mixing.



Ilgner et al. 2004

Prospects for ALMA

- Directly detect gas flows.
- Is gravitational instability active?
- Is the gas tied to magnetic field lines?
- Are the fields straight or tangled?
- What are the mixing rates?