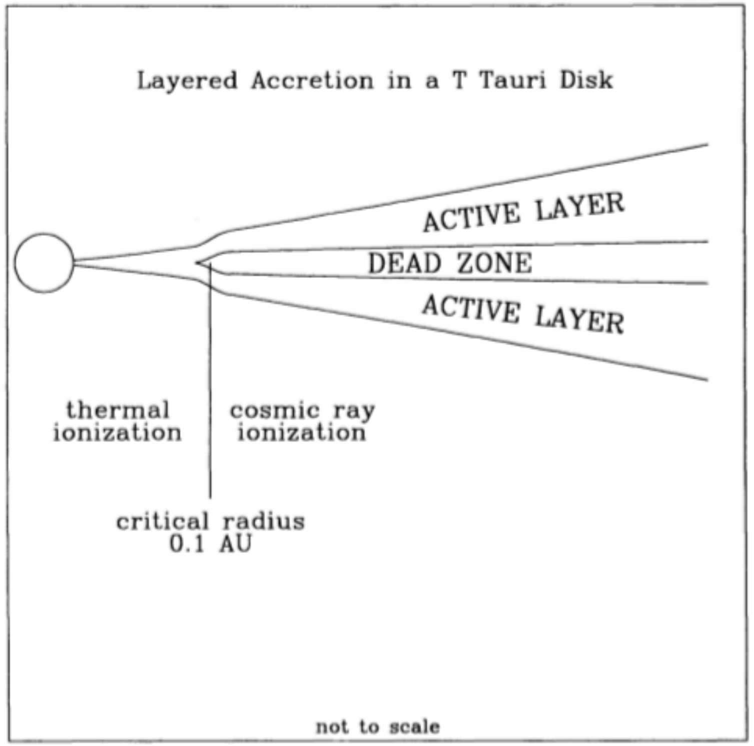
Class 15 – Mar 12th, 2020

Highly ionized disks -> MRI
Weakly ionized disks -> ?



Some MHD "rules-of-thumb"

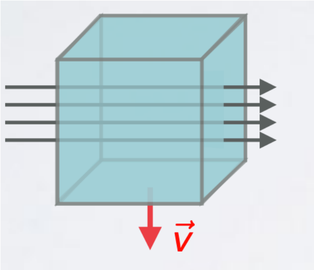
Field lines do not want to be bent
(magnetic tension; resists stretching)

Field lines do not want to be close to each other
(magnetic pressure; resists compression)

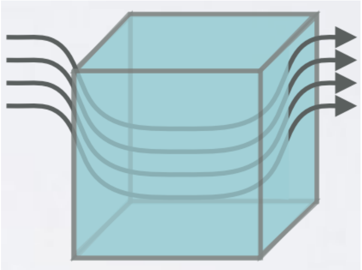
Some MHD “rules-of-thumb”

Behavior depends on the field strength

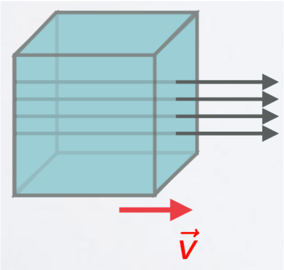
Weak field: $P_{mag} << P_{th}$



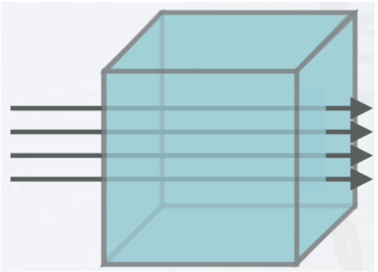
Magnetic field forced along gas flow
(passively advected)



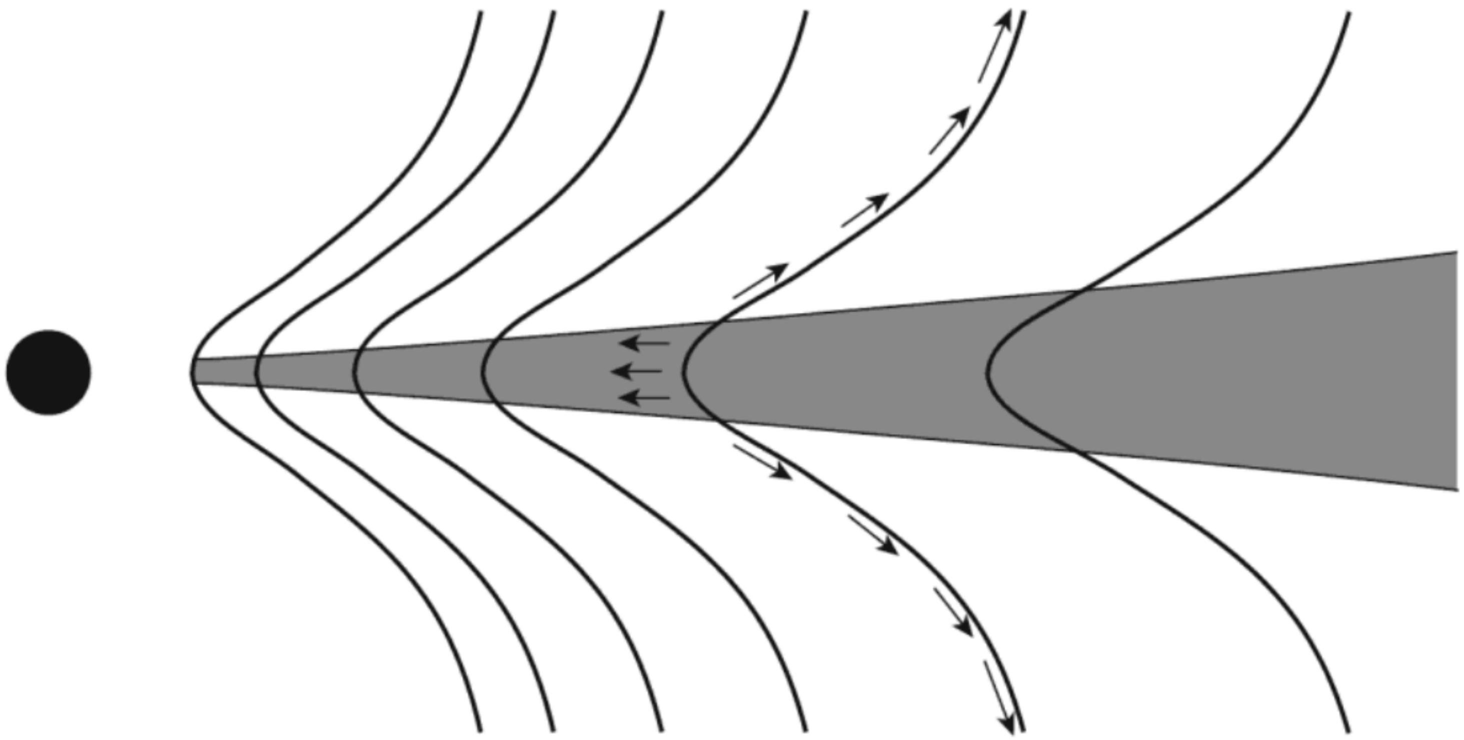
Strong field: $P_{mag} >> P_{th}$



Gas can only move along magnetic field lines



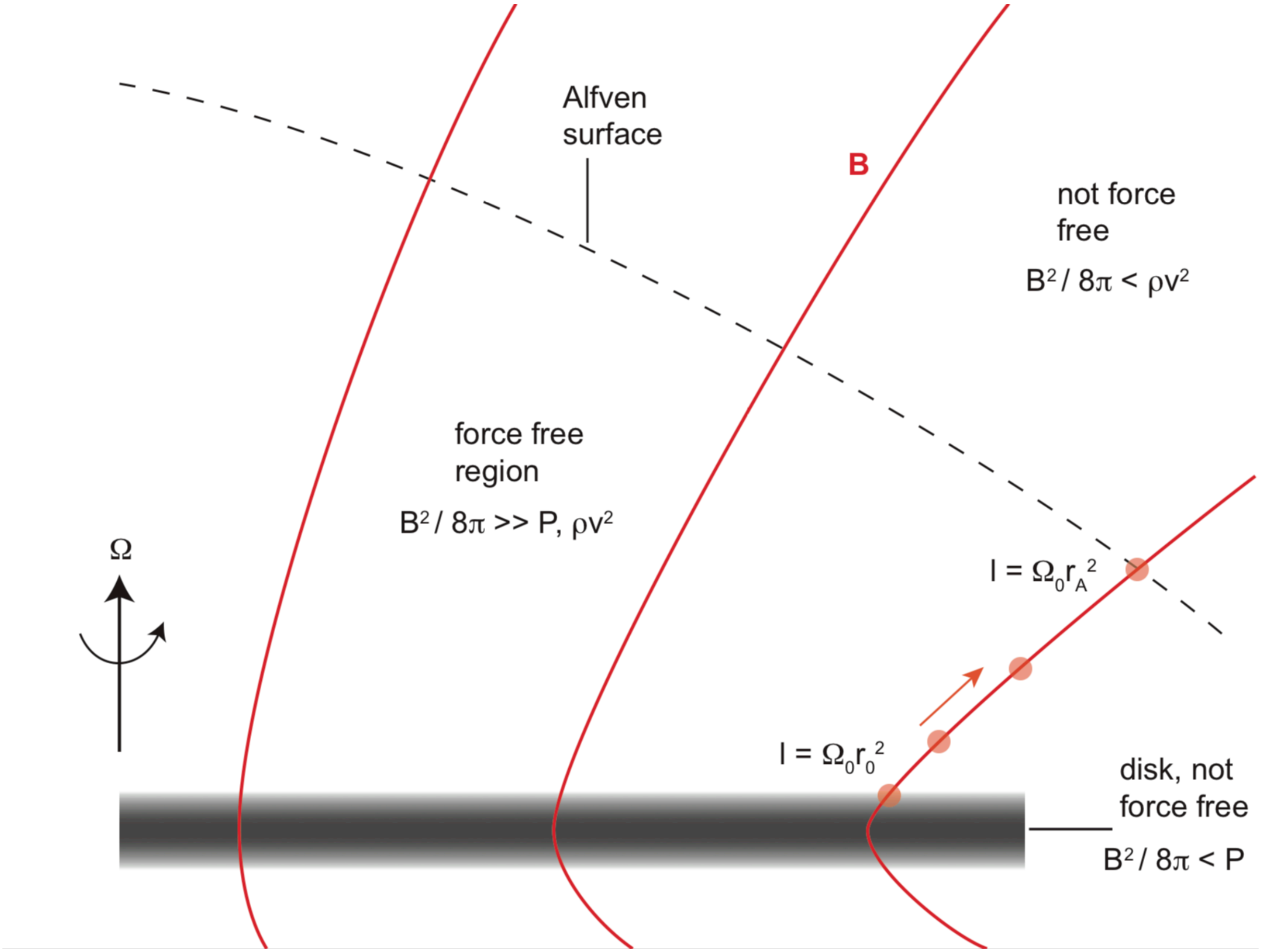
Disk winds

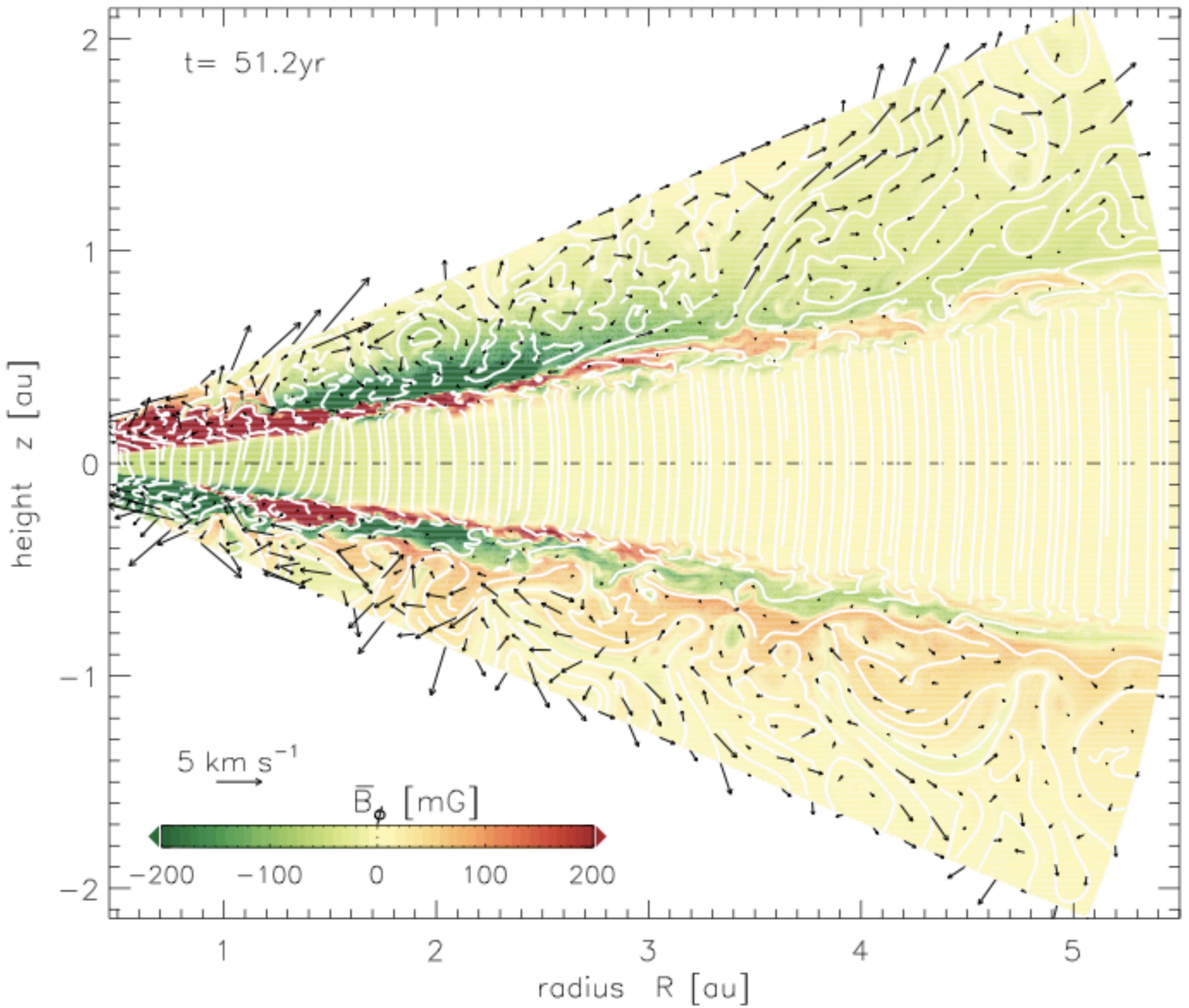


Magnetic torques remove angular momentum from gas

Gas falls toward star

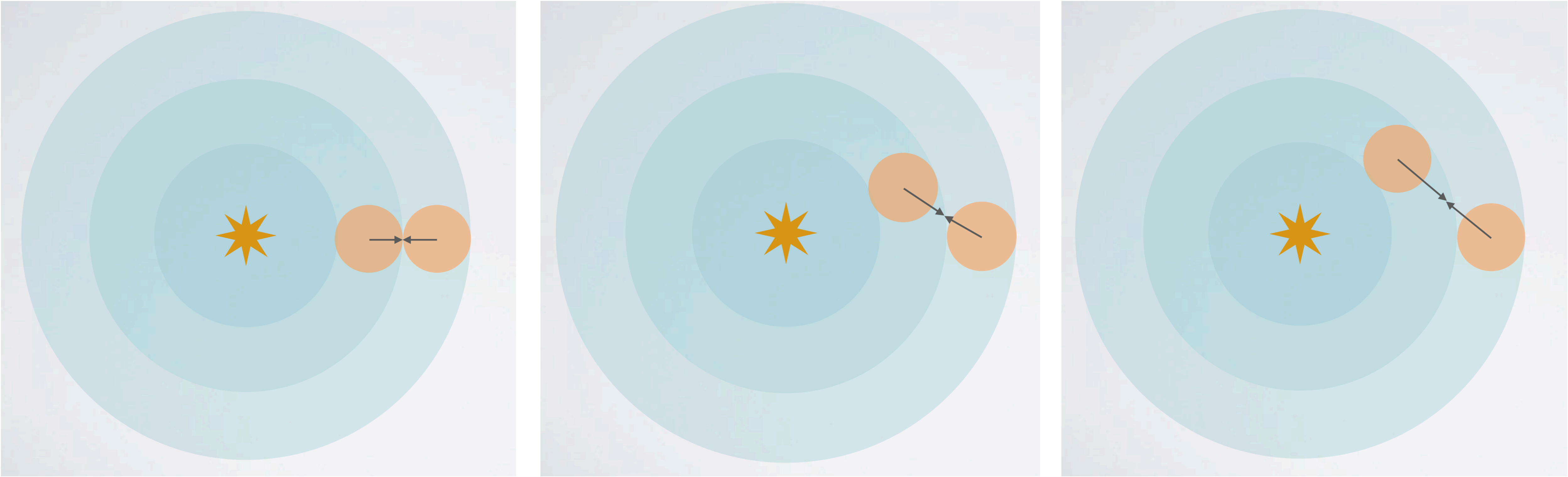
Wind launching



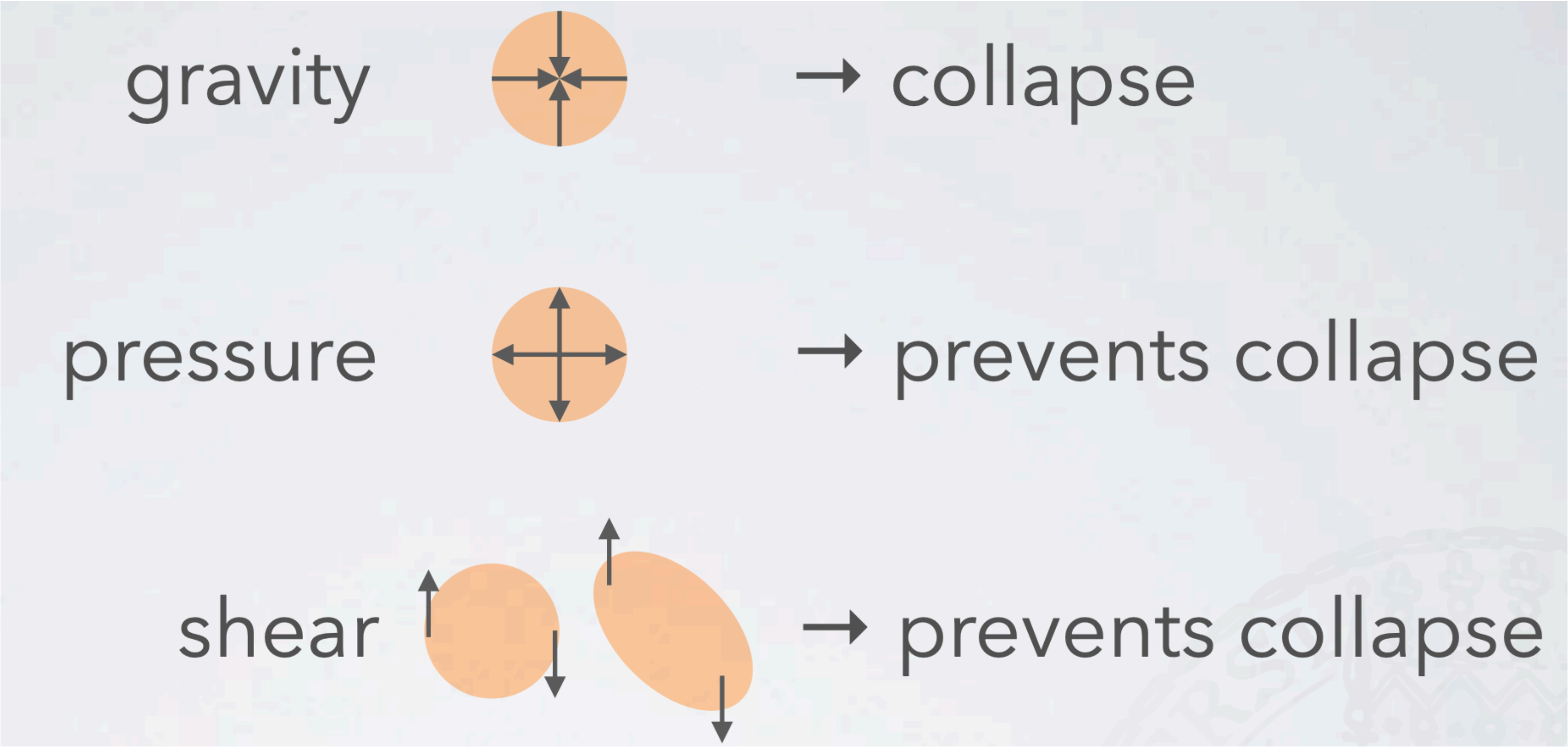


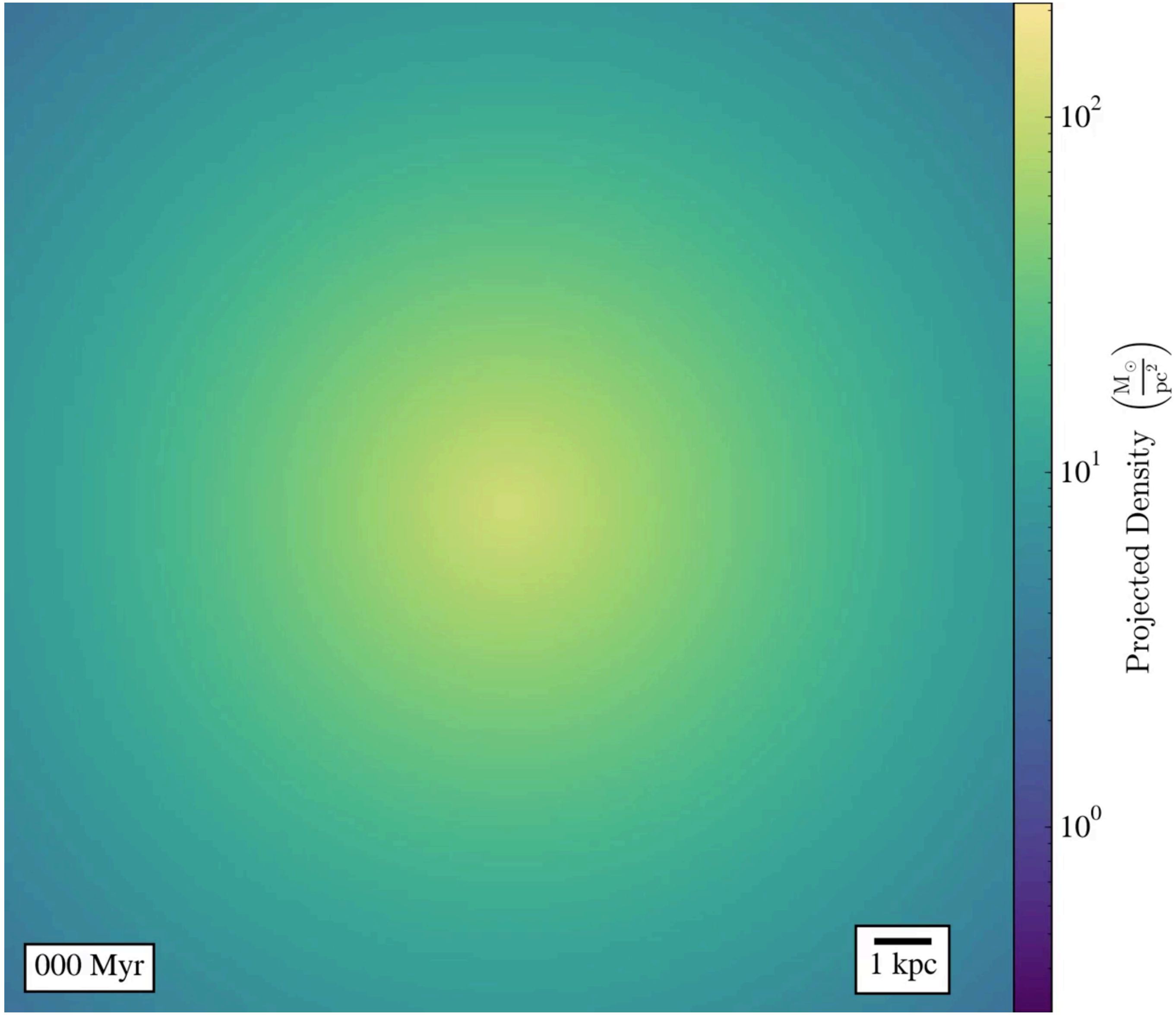
t= 51.2yr
height z [au]
radius R [au]
5 km s^{-1}
$\bar{B}_\phi$ [mG]
−200
−100
0
100
200
2
1
0
−1
−2
1
2
3
4
5

Self gravity

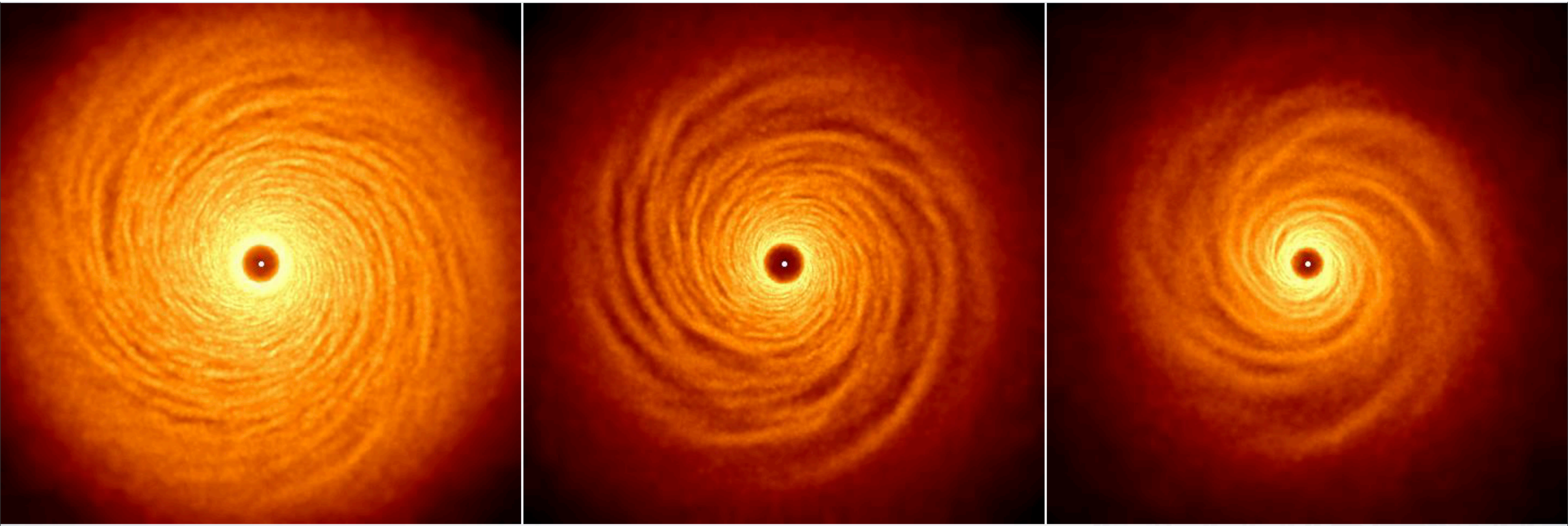


Self gravity

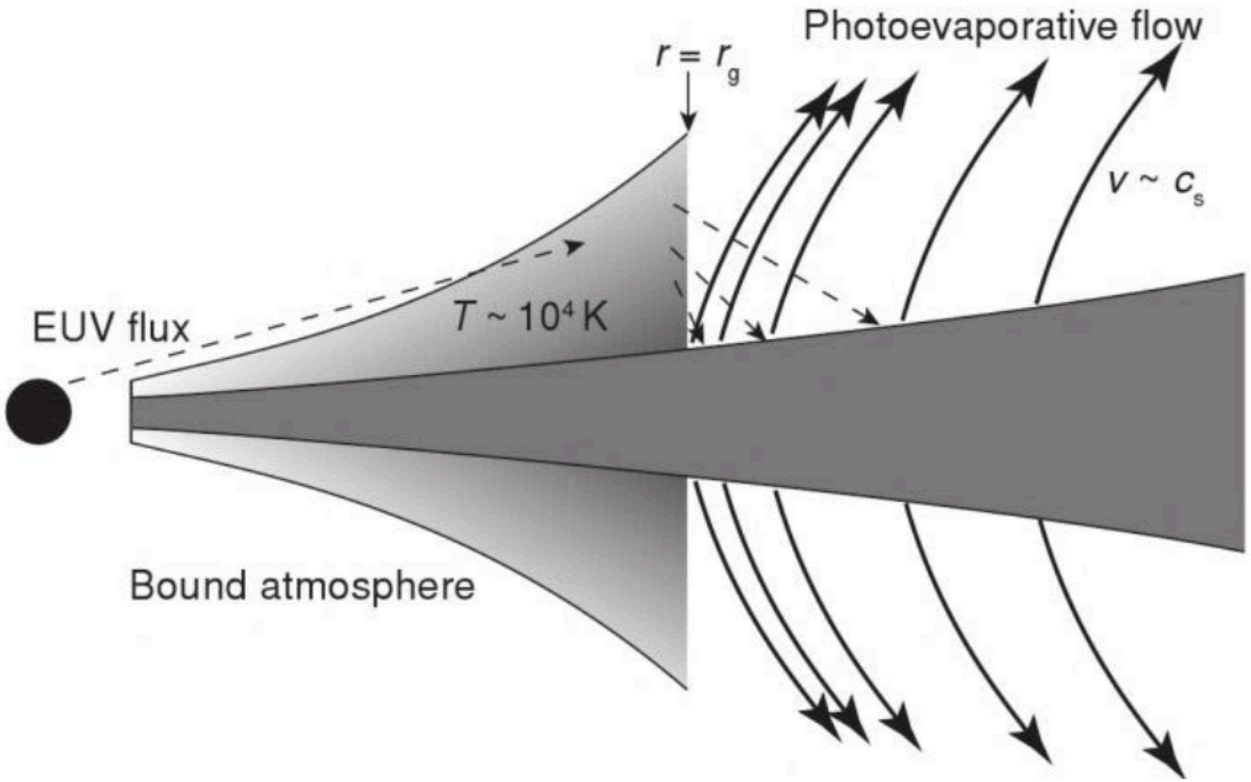




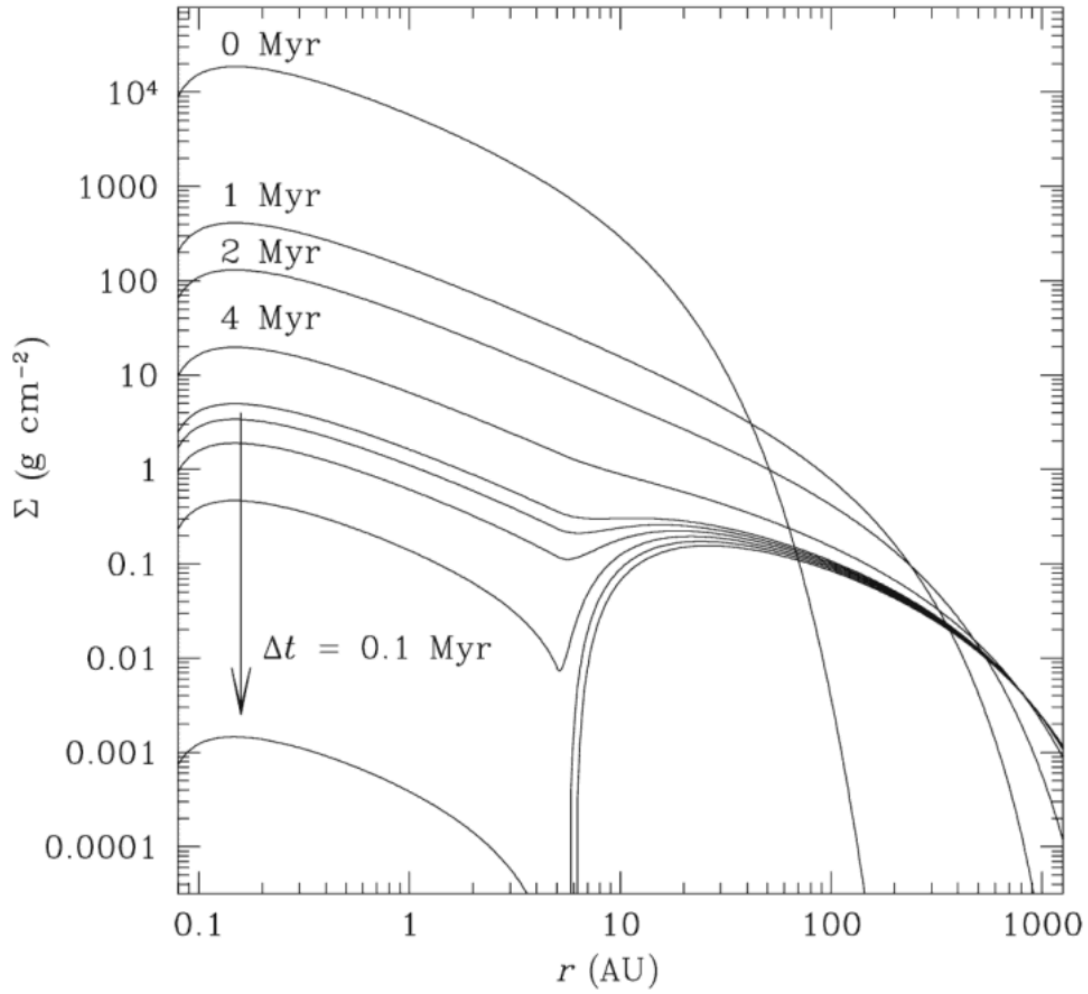
000 Myr
1 kpc
10^2
10^1
10^0
Projected Density $\left(\frac{M_\odot}{pc^2}\right)$

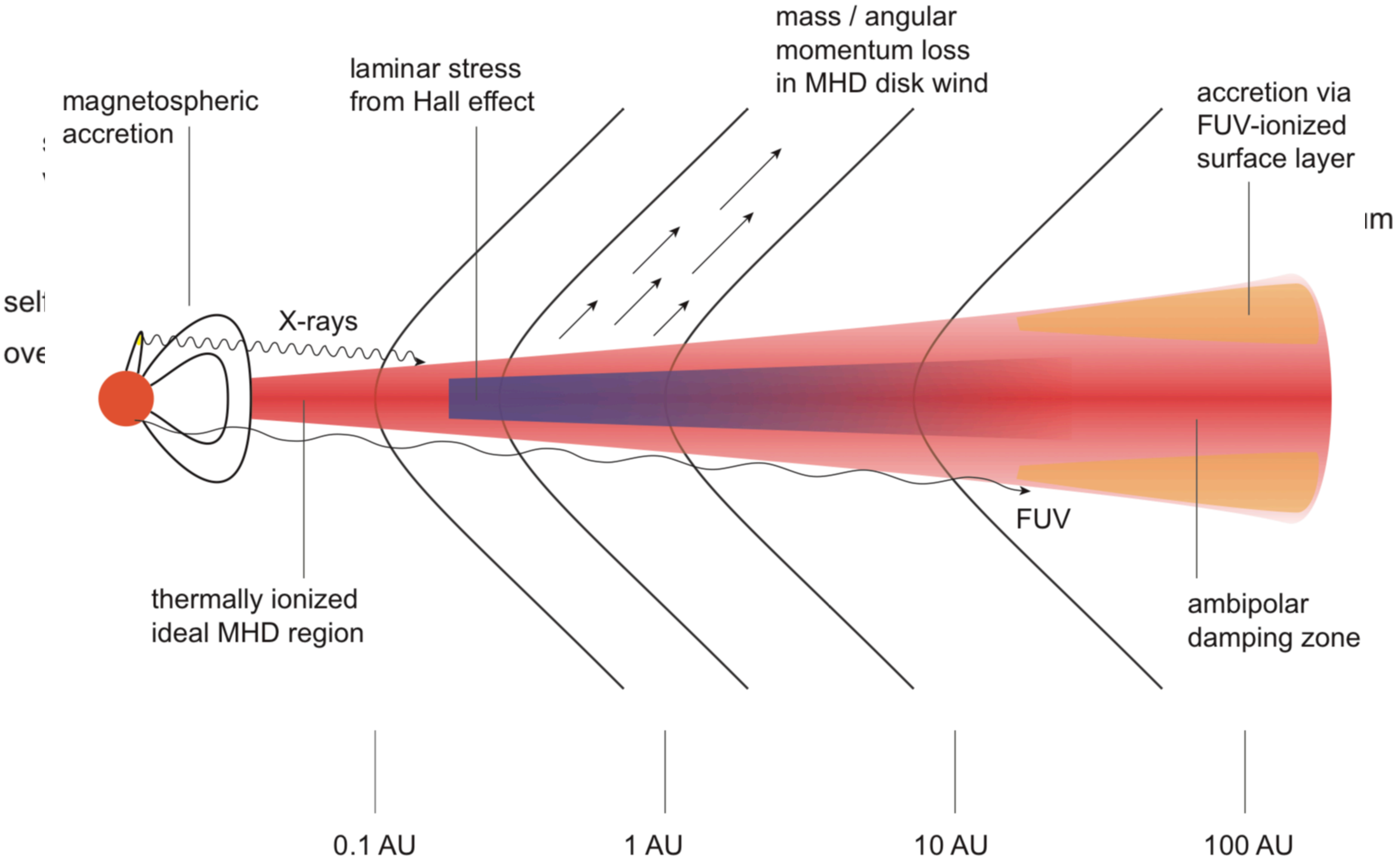


$M_{\rm disk}/M_\star = 0.05$ $M_{\rm disk}/M_\star = 0.1$ $M_{\rm disk}/M_\star = 0.25$

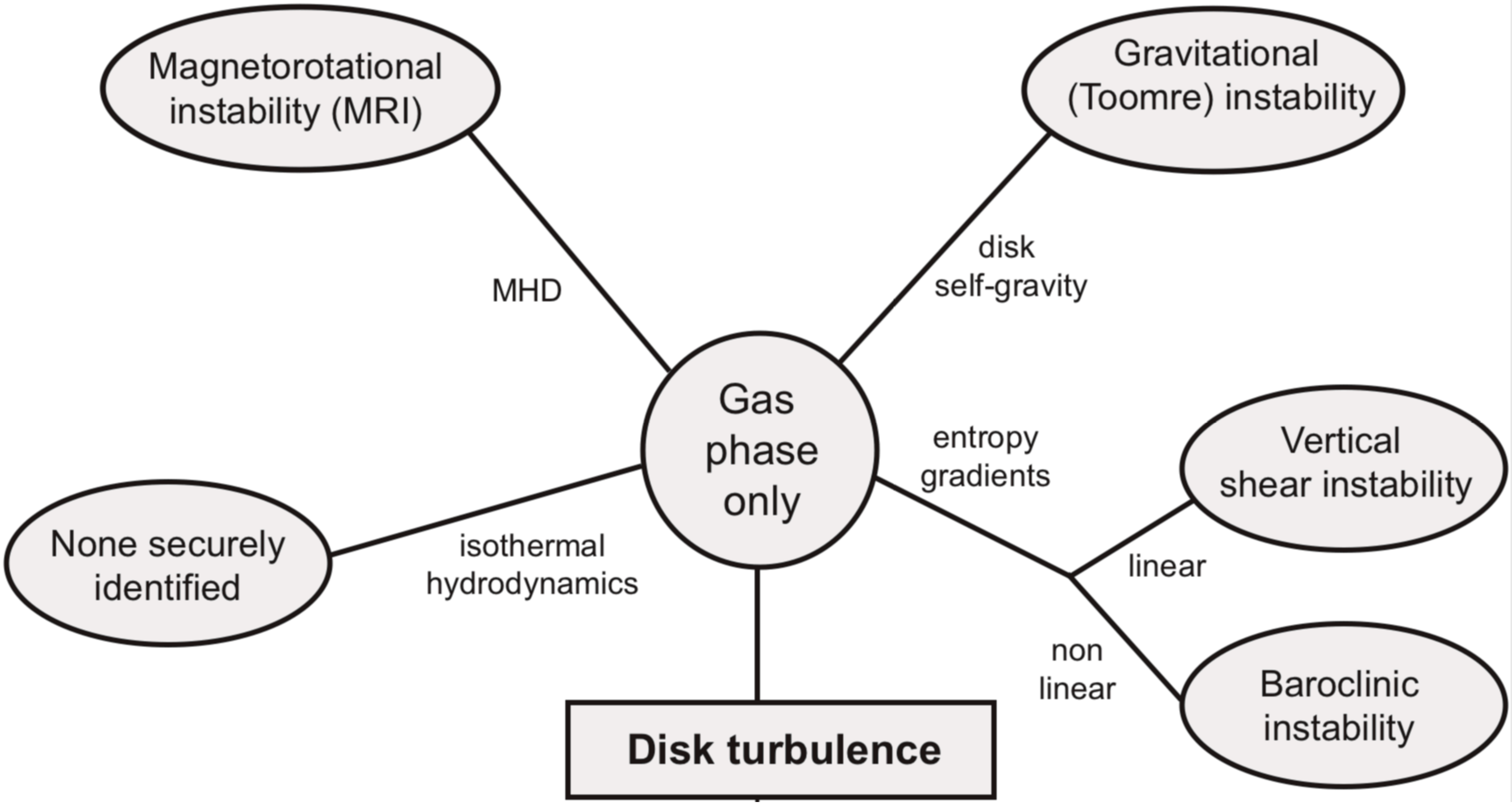

Photoevaporative flow
$r = r_g$
$v \sim c_s$
EUV flux
$T \sim 10^4$ K
Bound atmosphere

Accretion and Photoevaporation





mass / angular
momentum loss
in MHD disk wind
laminar stress
from Hall effect
magnetospheric
accretion
accretion via
FUV-ionized
surface layer
X-rays
FUV
thermally ionized
ideal MHD region
ambipolar
damping zone
0.1 AU
1 AU
10 AU
100 AU


Magnetorotational instability (MRI)
Gravitational (Toomre) instability
MHD
disk self-gravity
Gas phase only
entropy gradients
Vertical shear instability
linear
None securely identified
isothermal hydrodynamics
non linear
Baroclinic instability
Disk turbulence

The Astrophysical Journal, 789:77 (7pp), 2014 July 1 doi:10.1088/0004-637X/789/1/77

CONVECTIVE OVERSTABILITY IN ACCRETION DISKS: THREE-DIMENSIONAL LINEAR ANALYSIS AND NONLINEAR SATURATION

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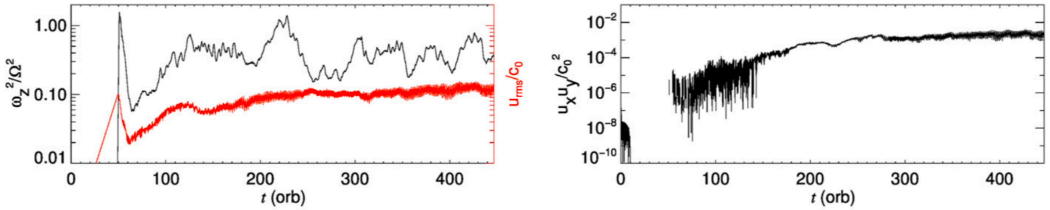
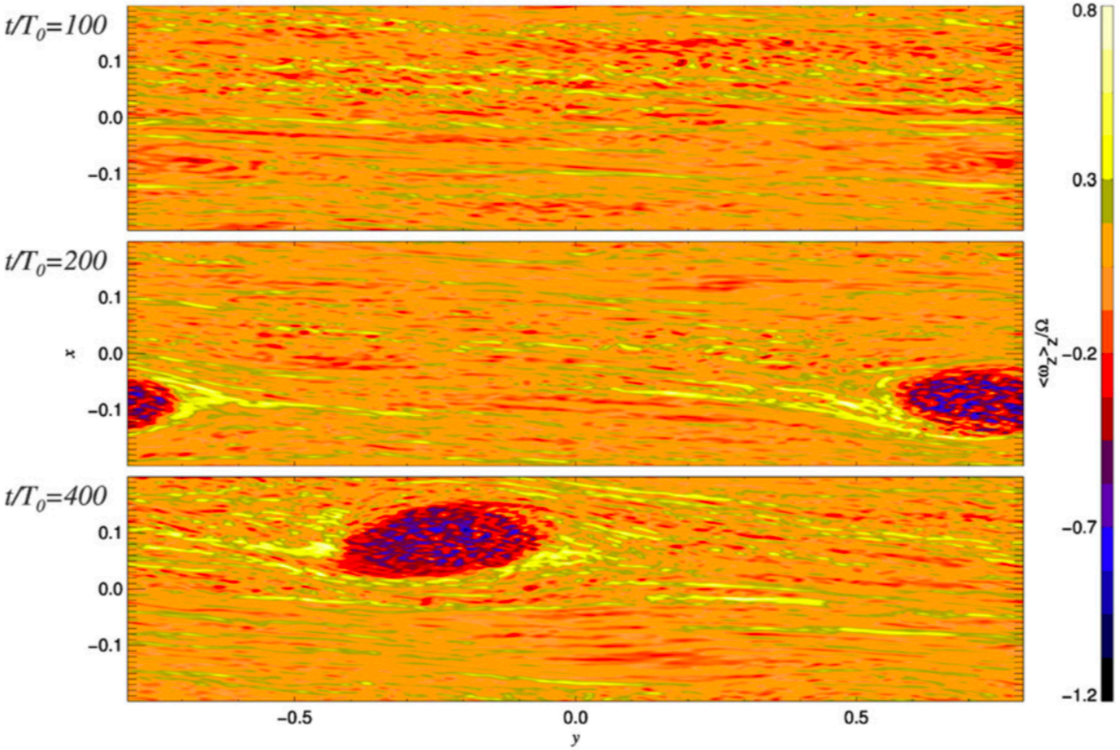
ABSTRACT

Recently, Klahr & Hubbard claimed that a hydrodynamical linear overstability exists in protoplanetary disks, powered by buoyancy in the presence of thermal relaxation. We analyze this claim, confirming it through rigorous compressible linear analysis. We model the system numerically, reproducing the linear growth rate for all cases studied. We also study the saturated properties of the overstability in the shearing box, finding that the saturated state produces finite amplitude fluctuations strong enough to trigger the subcritical baroclinic instability (SBI). Saturation leads to a fast burst of enstrophy in the box, and a large-scale vortex develops in the course of the next ≈100 orbits. The amount of angular momentum transport achieved is of the order of $\alpha \approx 10^{-3}$, as in compressible SBI models. For the first time, a self-sustained three-dimensional vortex is produced from linear amplitude perturbation of a quiescent base state.

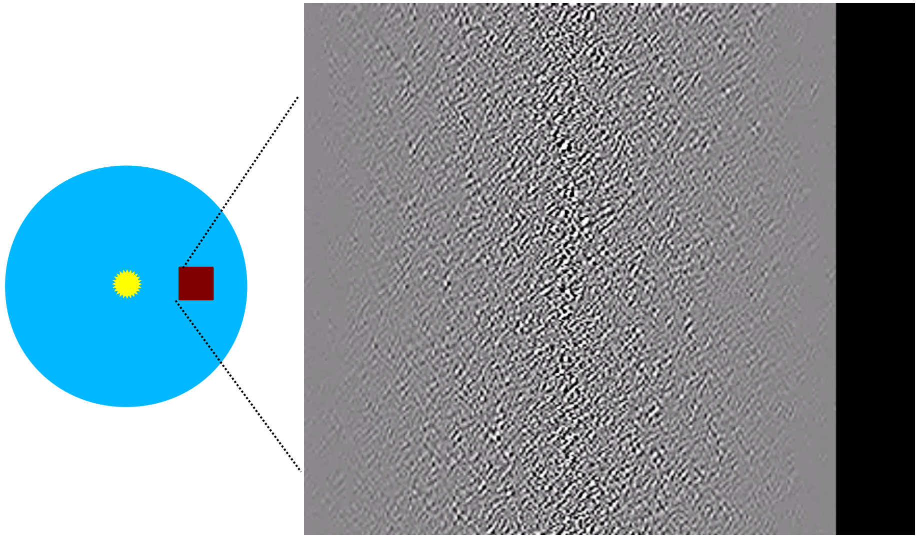
Key words: hydrodynamics – instabilities – methods: analytical – methods: numerical – planets and satellites: formation – protoplanetary disks

Online-only material: color figures

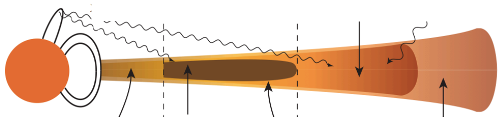




Convective Overstability

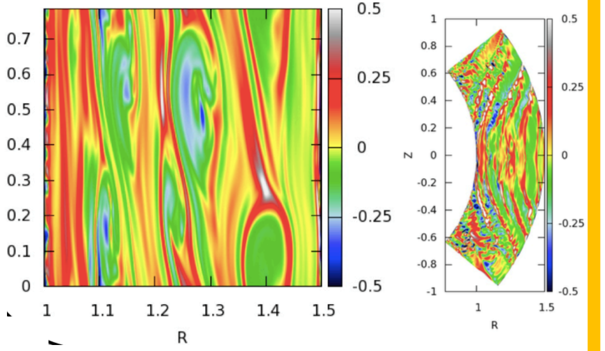


Lyra & Klahr (2011)



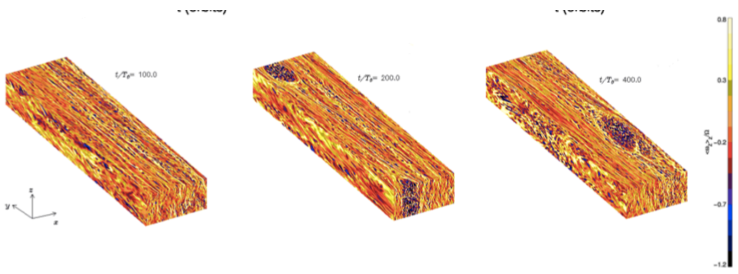
Hydrodynamical Instabilities

Vertical Shear Instability



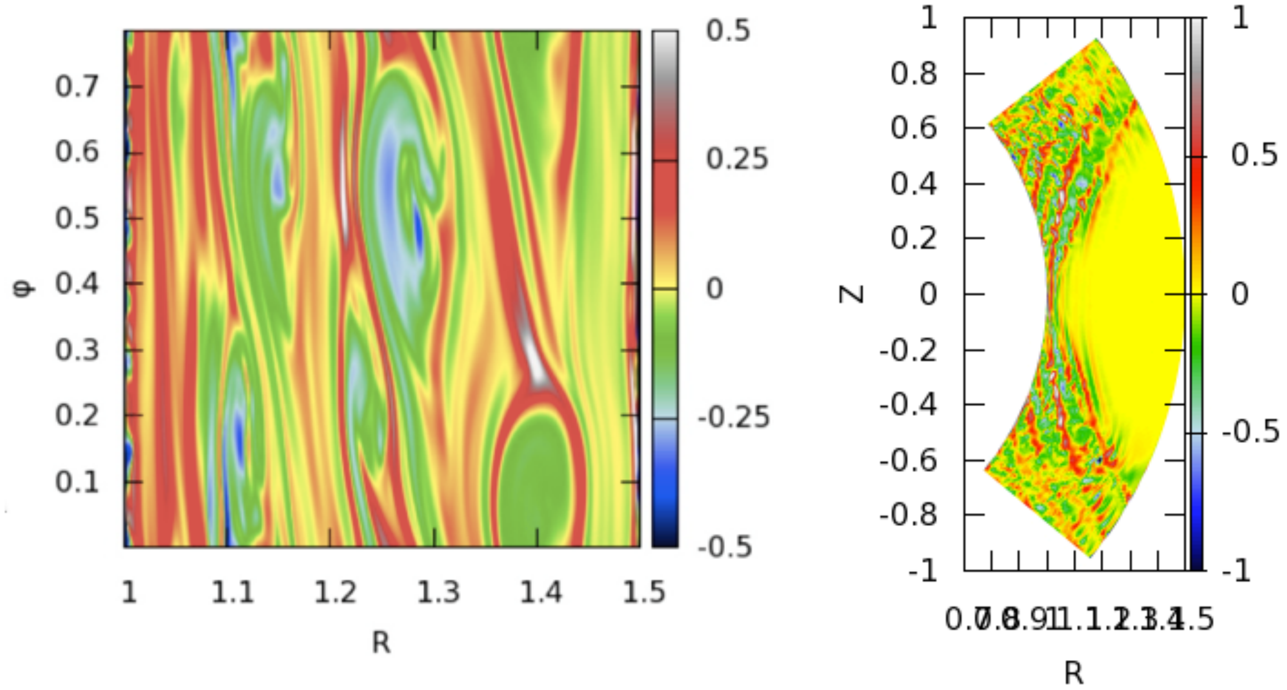
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



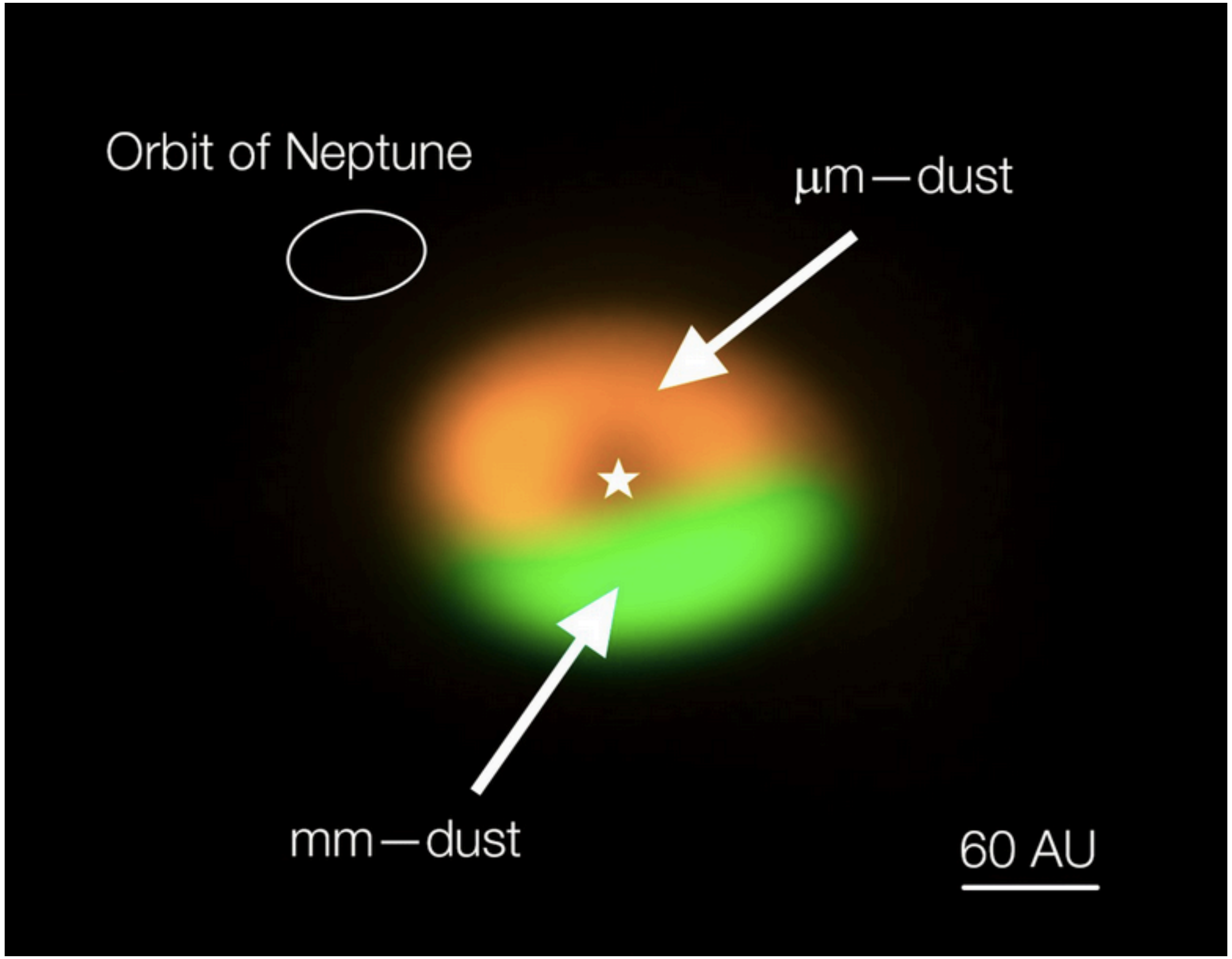
Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

Vertical shear instability



Nelson et al. (2013)

Oph IRS 48



Oph IRS 48

eso1325 — Science Release

ALMA Discovers Comet Factory

New observations of a “dust trap” around a young star solve long-standing planet formation mystery

6 June 2013

A Major Asymmetric Dust Trap in a Transition Disk

Nienke van der Marel,[1*] Ewine F. van Dishoeck,[1,2] Simon Bruderer,[2] Til Birnstiel,[3] Paola Pinilla,[4] Cornelis P. Dullemond,[4] Tim A. van Kempen,[1,5] Markus Schmalzl,[1] Joanna M. Brown,[3] Gregory J. Herczeg,[6] Geoffrey S. Mathews,[1] Vincent Geers[7]

The statistics of discovered exoplanets suggest that planets form efficiently. However, there are fundamental unsolved problems, such as excessive inward drift of particles in protoplanetary disks during planet formation. Recent theories invoke dust traps to overcome this problem. We report the detection of a dust trap in the disk around the star Oph IRS 48 using observations from the Atacama Large Millimeter/submillimeter Array (ALMA). The 0.44-millimeter–wavelength continuum map shows high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains, whereas both the mid-infrared image (micrometer-sized dust) and the gas traced by the carbon monoxide 6-5 rotational line suggest rings centered on the star. The difference in distribution of big grains versus small grains/gas can be modeled with a vortex-shaped dust trap triggered by a companion.

Although the ubiquity of planets is confirmed almost daily by detections of new exoplanets (*1*), the exact formation mechanism of planetary systems in disks of gas and dust around young stars remains a long-standing problem in astrophysics (*2*). In

iencemag.org SCIENCE VOL 340 7 JUNE 2013 1199

van der Marel et al. 2013

PERSPECTIVES

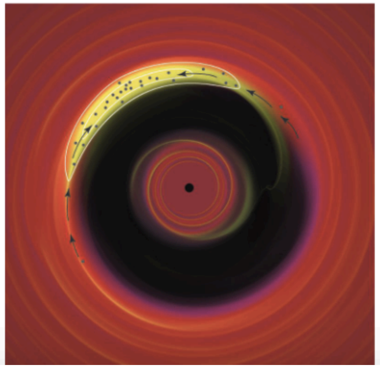
ASTRONOMY

A Trap for Planet Formation

The detection of a pocket of trapped particles may provide a hint to understanding the mechanism of planet formation.

Philip J. Armitage[1,2]

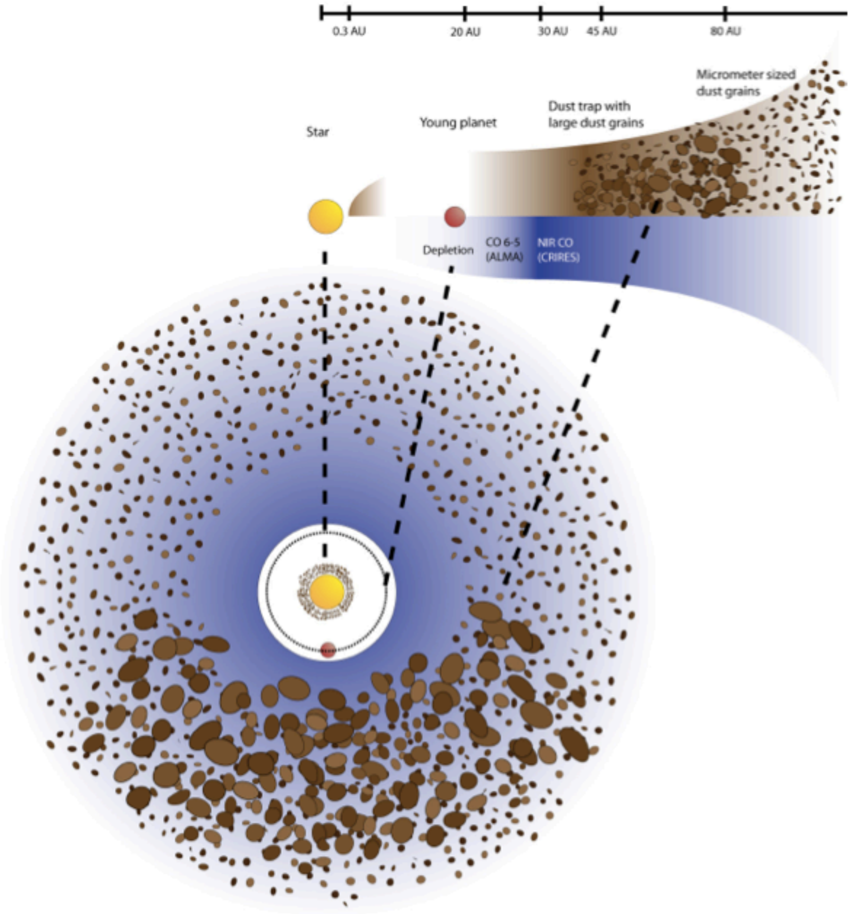
The raw material for forming planets is micrometer to millimeter-sized particles of dust that orbit along with gas in protoplanetary disks around young low-mass stars. These disks are known to be common and to persist for several million years (*1*). The Kepler mission (*2*) showed that mature planetary systems are also common. What is not known, however, is the full sequence of steps that allows the dust within protoplanetary disks to grow into planets. On page 1199 of this issue, van der Marel *et al.* (*3*) report observations from the Atacama Large Millimeter/submillimeter Array (ALMA) that hint at how the most problematic step may be surmounted—millimeter-sized par-



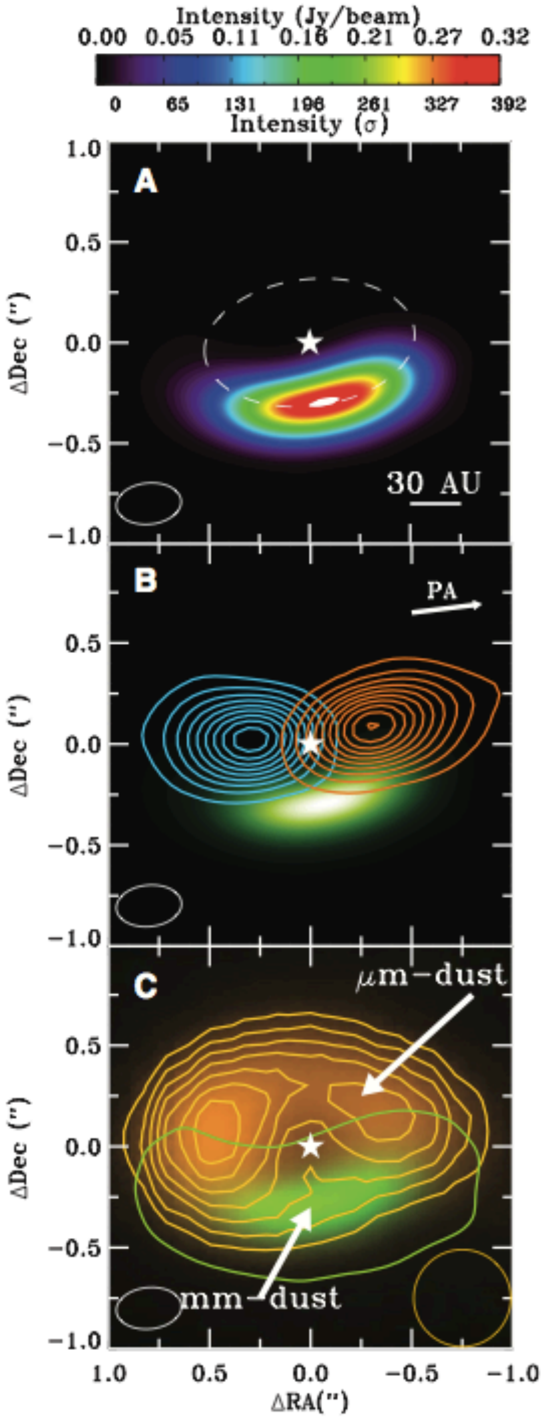
From dust to planet. Illustration of the proposed mechanism that creates a dust trap in the disk of IRS 48. A massive planet (plus symbol) creates an annular gap in the gas disk, whose surface density is shown as a color map. A high-pressure vortex (contours) forms at the gap edge, collecting and trapping millimeter-sized dust particles that would otherwise spiral rapidly inward through the disk.

metric distribution. The emission from smaller dust particles, measured separately at infrared wavelengths, is also distributed uniformly around the orbit (*11*). These observations are consistent with theoretical expectations for a dust trap, in which a modest peak in gas pressure is able to strongly concentrate the millimeter-sized solid particles that

The Oph IRS 48 "dust trap"



van der Marel et al. (2013)

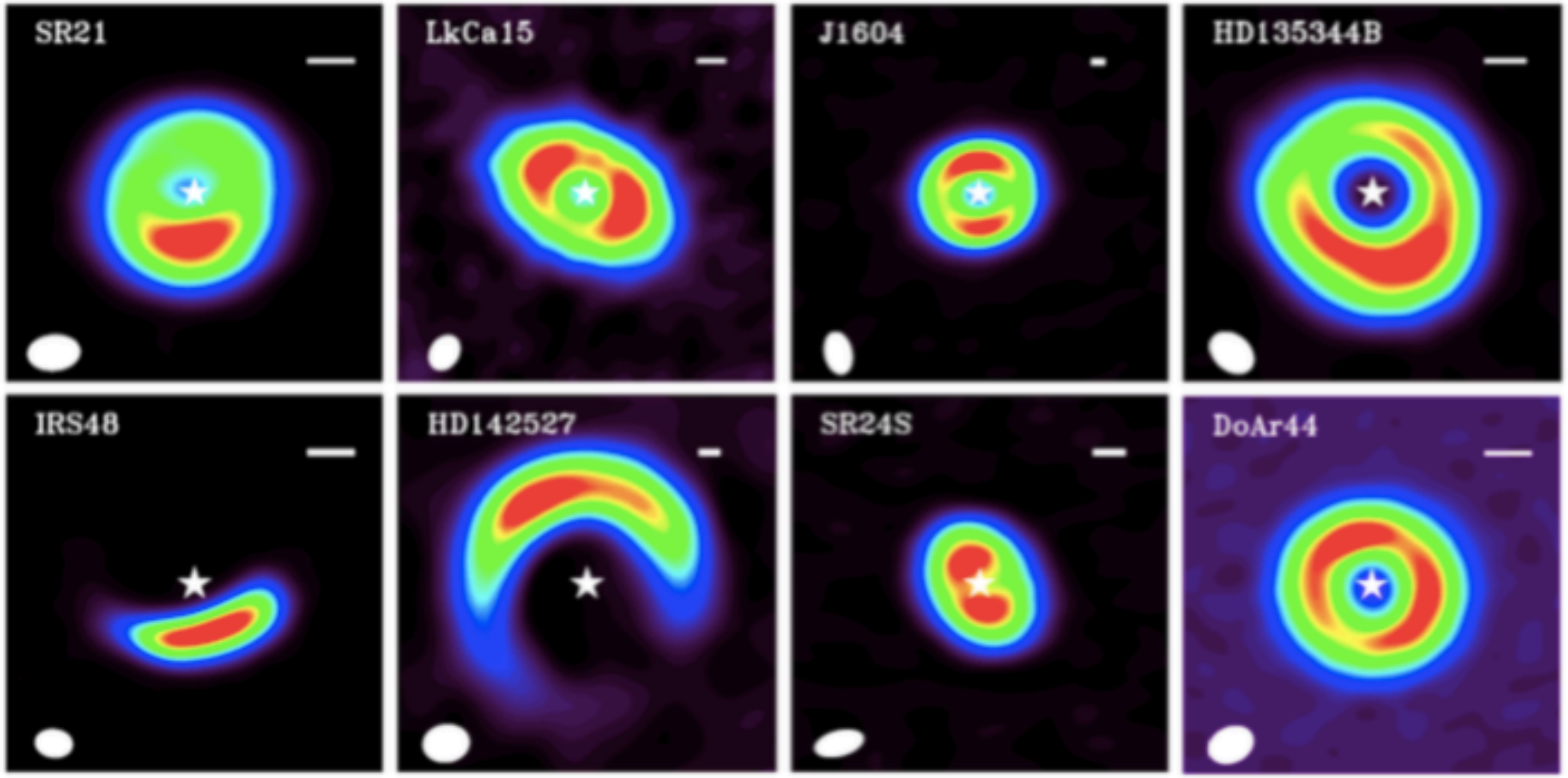


asymmetric mm dust at 63 AU

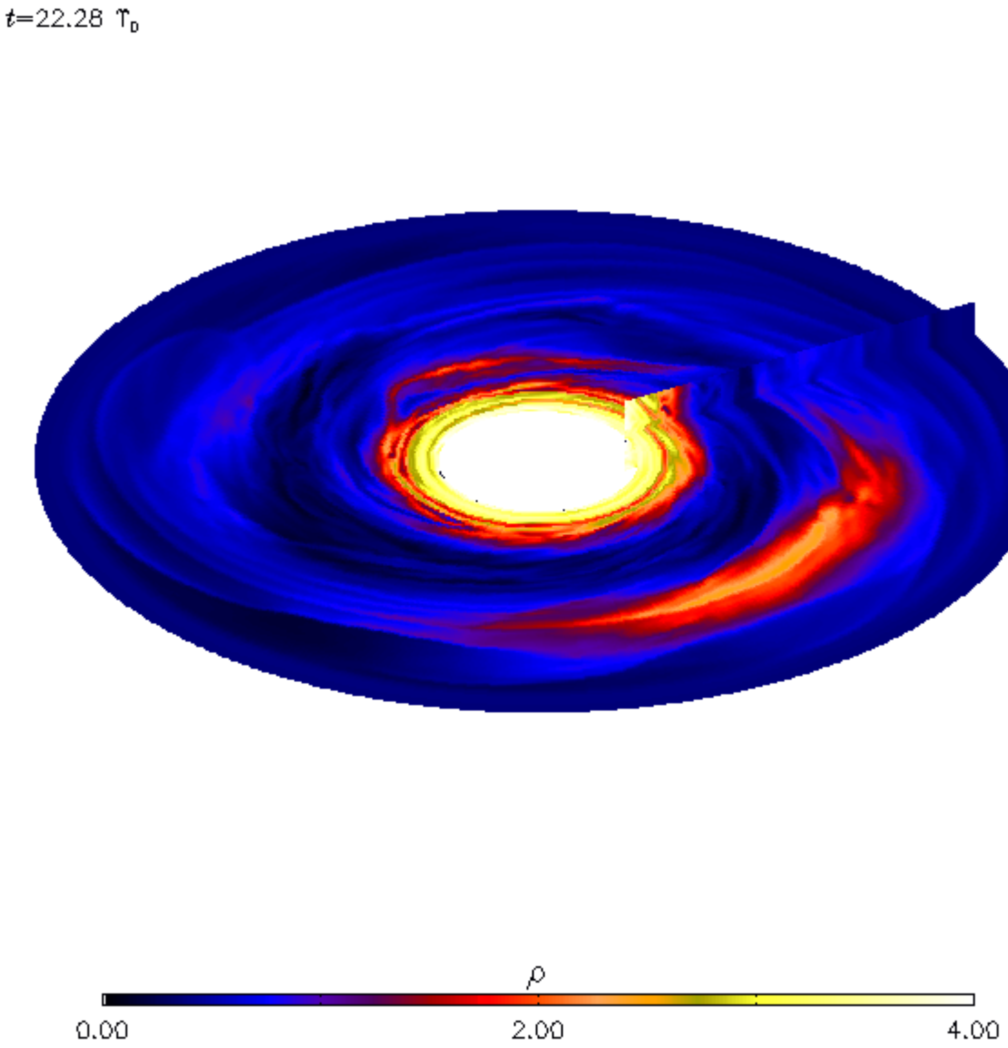
Gas detection: Keplerian rotation

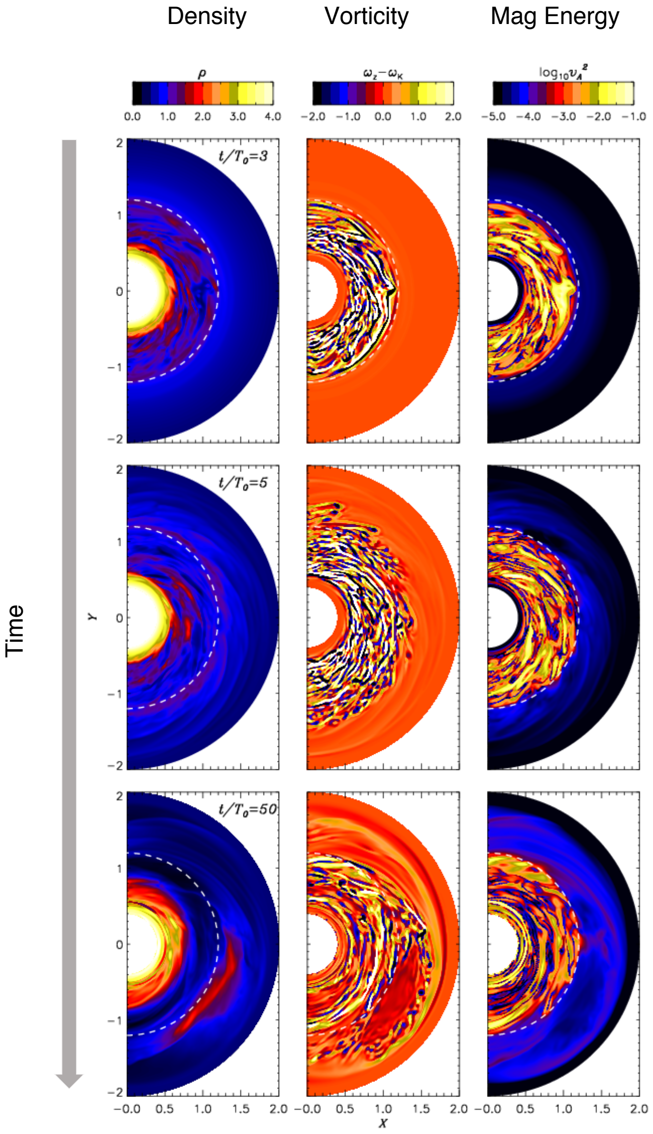
Micron-sized dust follows gas

"Asymmetries" everywhere



Active/dead zone boundary

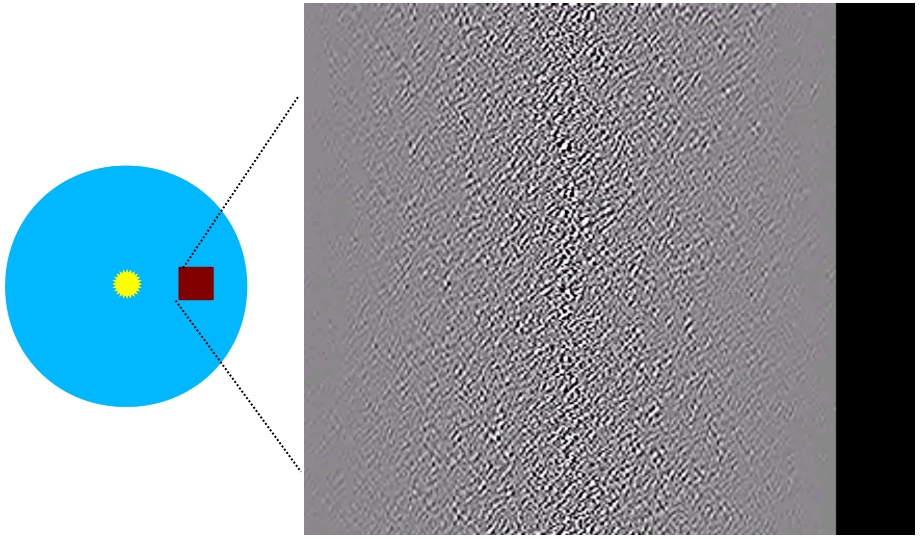




Magnetized inner disk + resistive outer disk

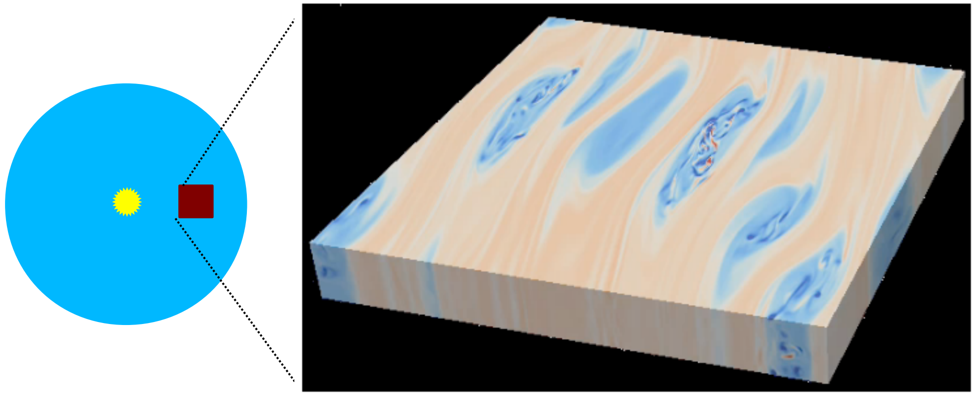
Lyra & Mac Low (2012)

Convective Overstability



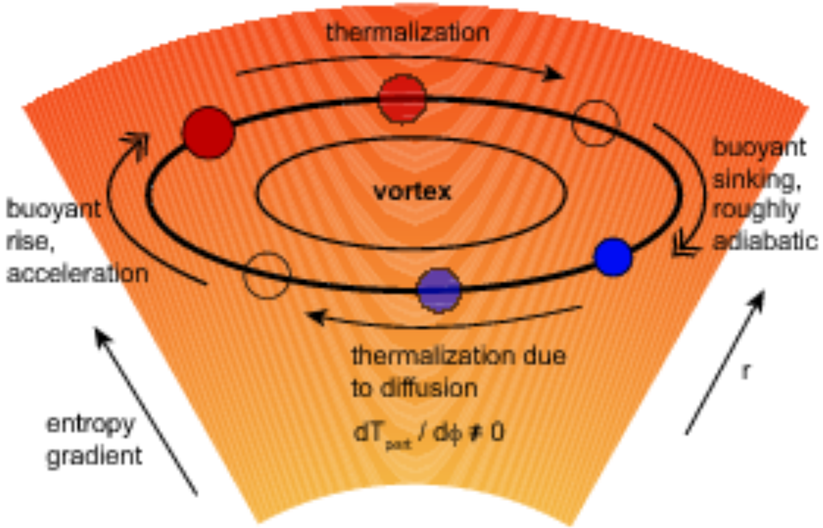
Lyra & Klahr (2011)

Convection



Lesur & Papaloizou (2010)

Sketch of Convection



Armitage (2010)

Convective Overstability

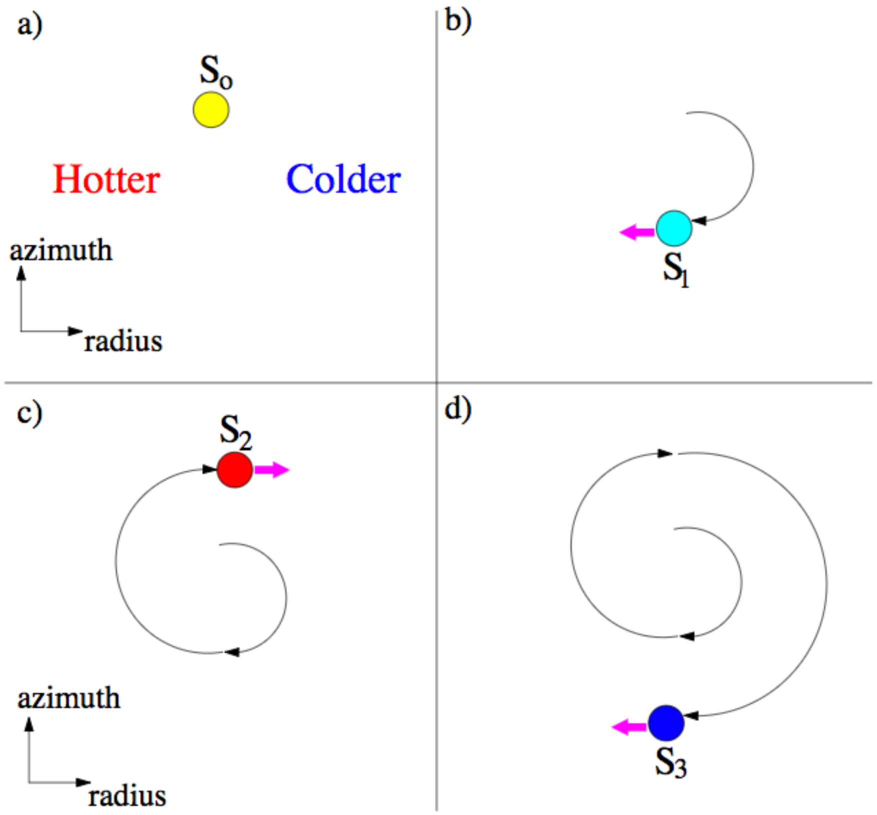
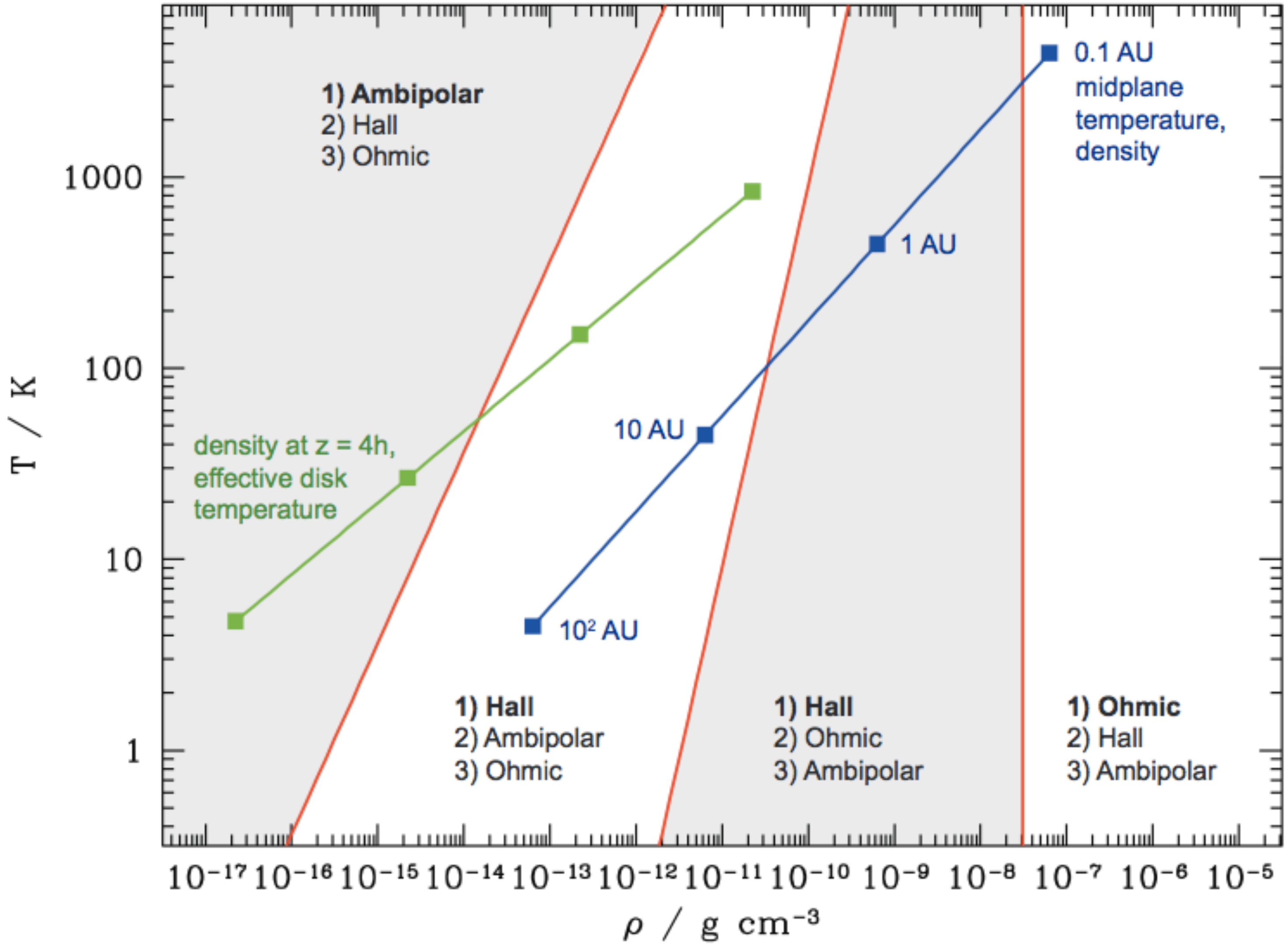


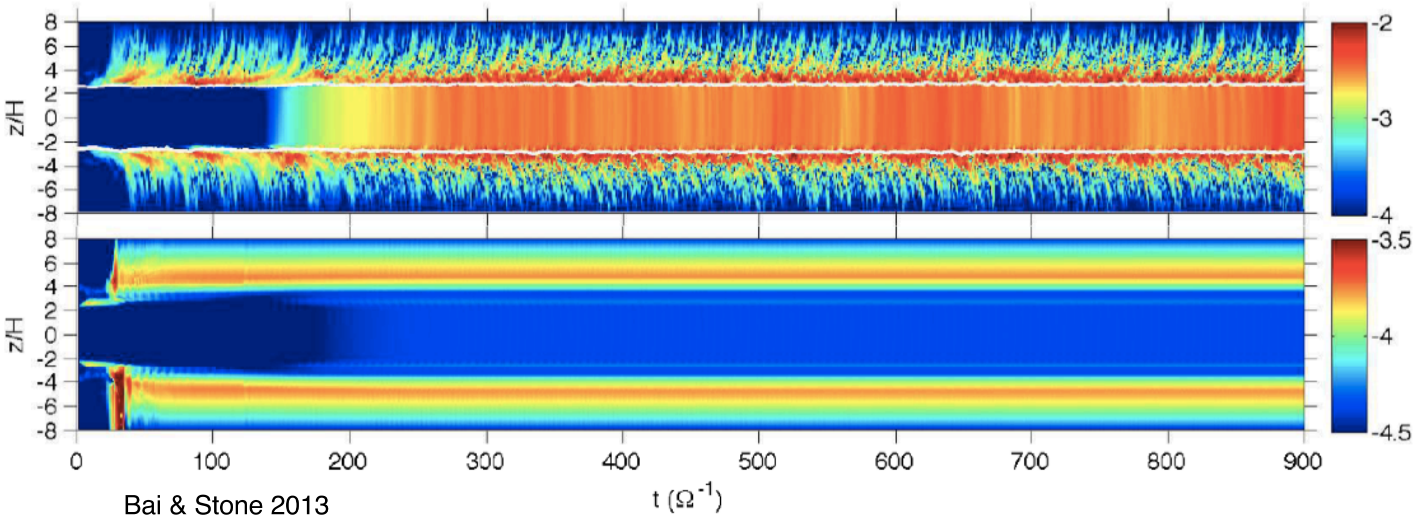
Figure 2. Four panels indicating the convective overstability mechanism. In panel (a) a fluid blob is embedded in a radial entropy gradient. In panel (b) it undergoes half an epicycle and returns to its original radius with a smaller entropy than when it begun $S_1 < S_0$. It hence feels a buoyancy acceleration inwards and the epicycle is amplified. The process occurs in reverse once the epicycle is complete, shown in panel (c), where now $S_2 > S_0$. The oscillations hence grow larger and larger.

Latter (2015)

Non-ideal MHD: Ohmic, Hall, Ambipolar terms



Ambipolar diffusion

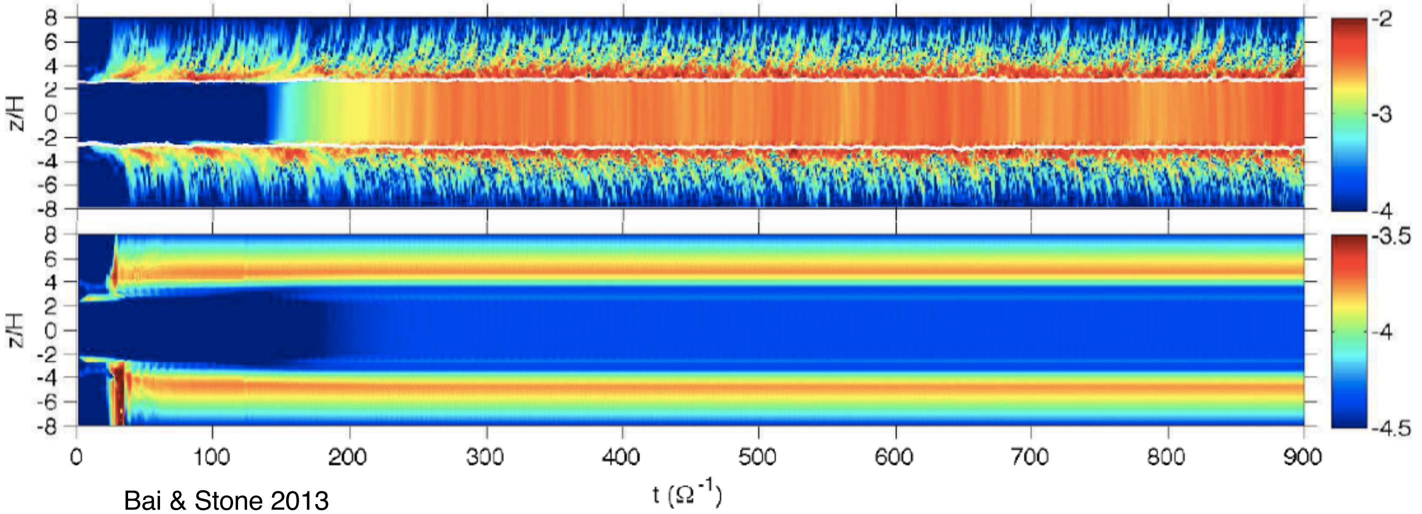


Ohmic

Ohmic + Ambipolar

Bai & Stone 2013

Ambipolar diffusion



Ohmic

Ohmic + Ambipolar

Bai & Stone 2013

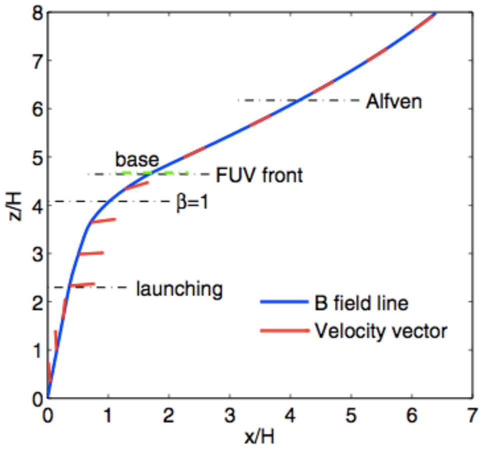
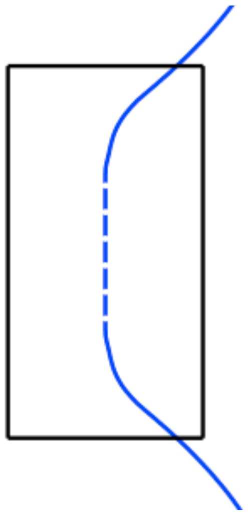
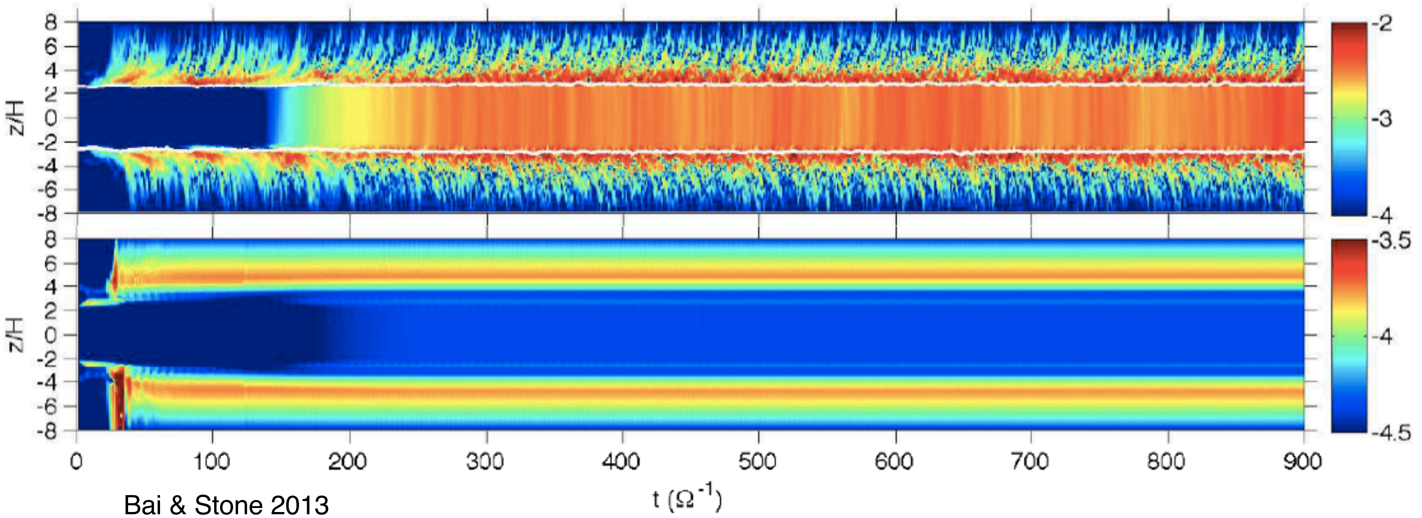


Figure 6. Poloidal field line geometry in our fiducial run OA-b5 (blue solid line). Overplotted are the unit vectors of the poloidal gas velocity (red arrows). The location of the wind launching point, the plasma $\beta = 1$ point, the FUV ionization front, and the Alfvén point are indicated (black dash-dotted). Also marked is the location at the base of the wind (green dashed).



Ambipolar diffusion



Ohmic

Ohmic + Ambipolar

Bai & Stone 2013

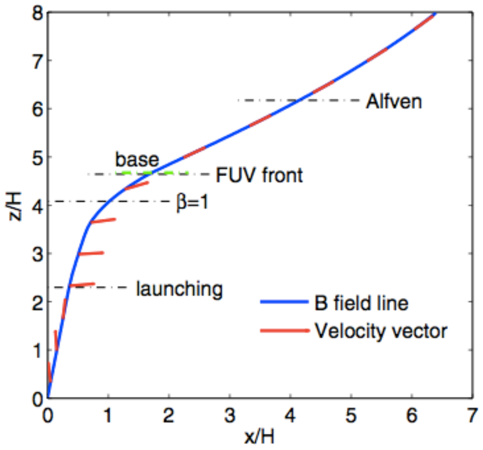
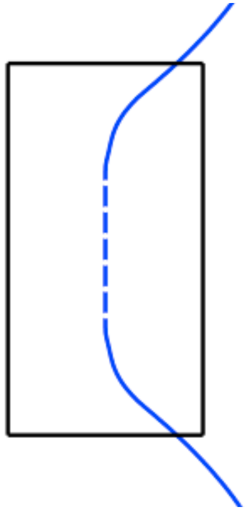
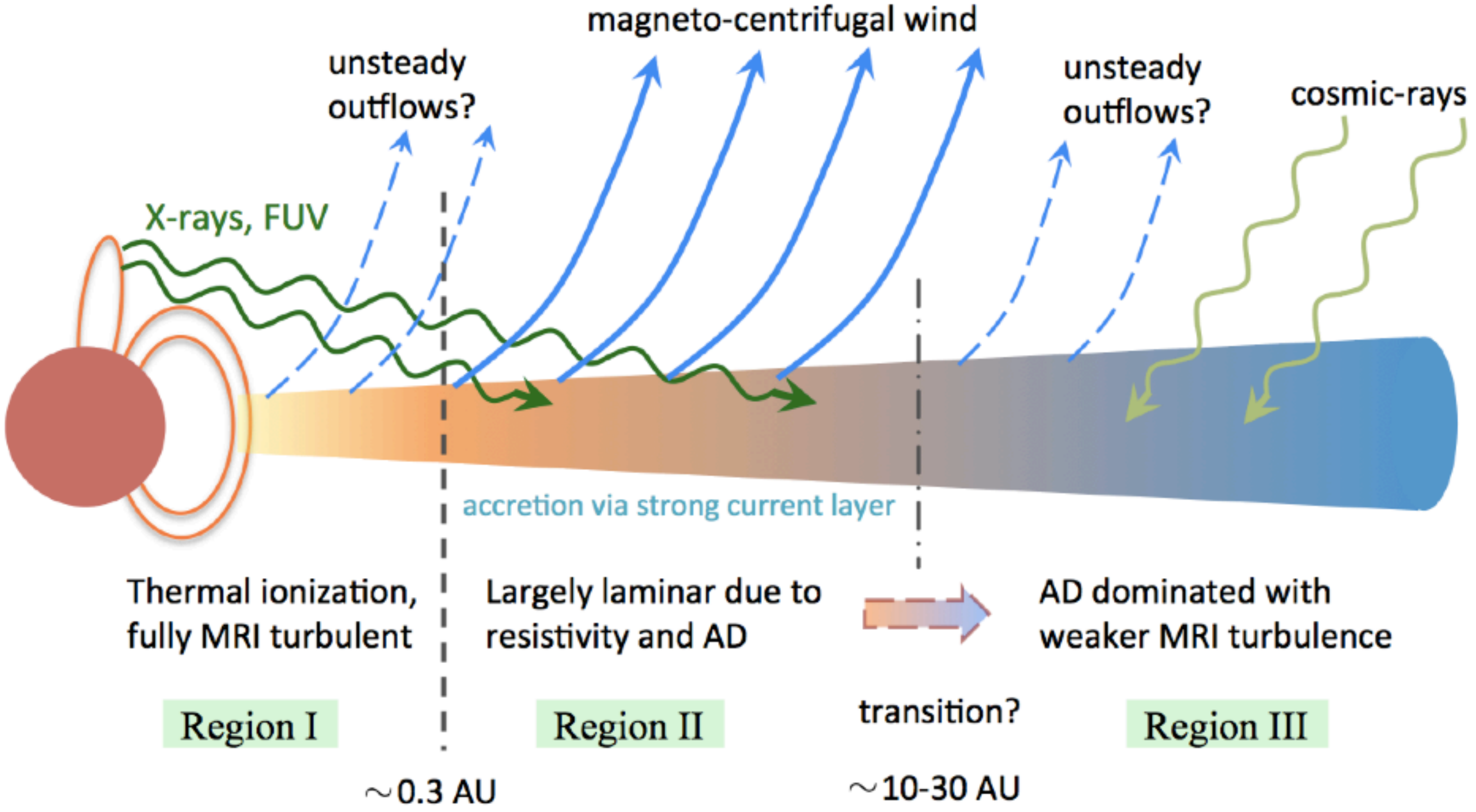
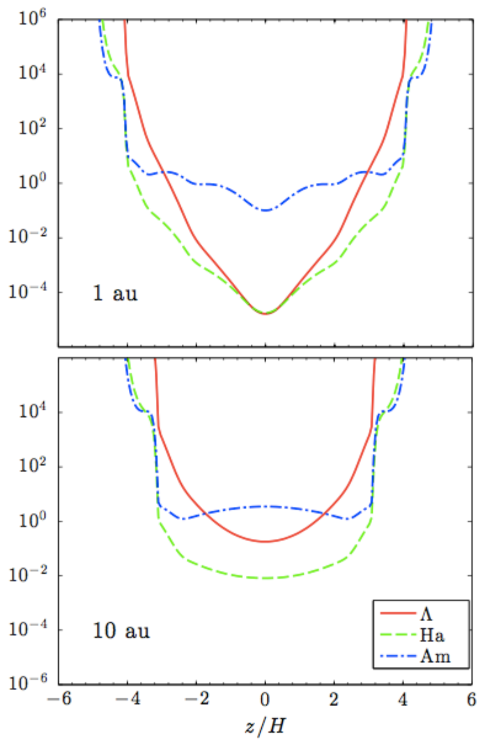


Figure 6. Poloidal field line geometry in our fiducial run OA-b5 (blue solid line). Overplotted are the unit vectors of the poloidal gas velocity (red arrows). The location of the wind launching point, the plasma $\beta = 1$ point, the FUV ionization front, and the Alfvén point are indicated (black dash-dotted). Also marked is the location at the base of the wind (green dashed).

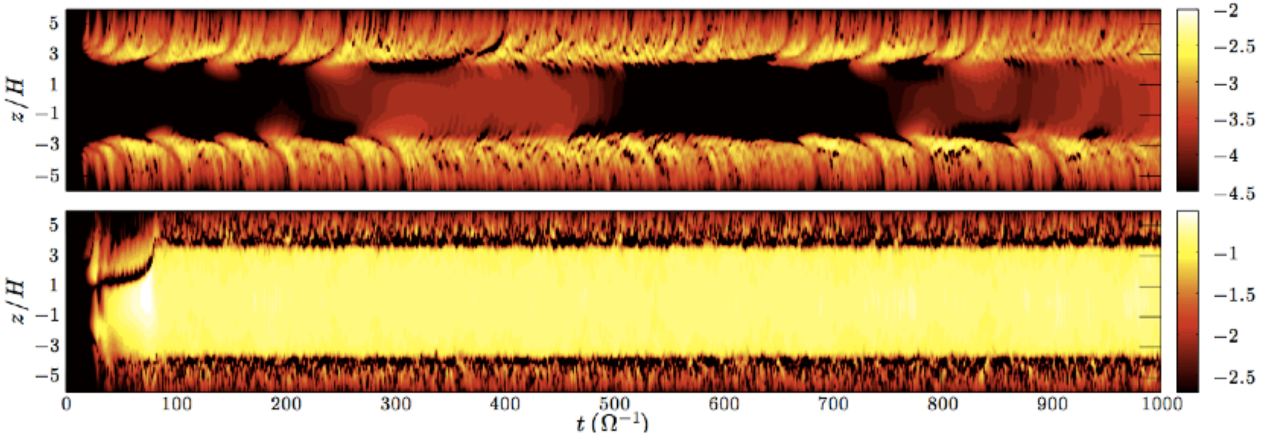



magneto-centrifugal wind
unsteady
outflows?
unsteady
outflows?
cosmic-rays
X-rays, FUV
accretion via strong current layer
Thermal ionization,
fully MRI turbulent
Largely laminar due to
resistivity and AD
AD dominated with
weaker MRI turbulence
Region I
Region II
transition?
Region III
∼0.3 AU
∼10-30 AU

Hall term



Large-scale azimuthal field generated. Couples to radial field fluctuations to generate large stress. The flow stays laminar

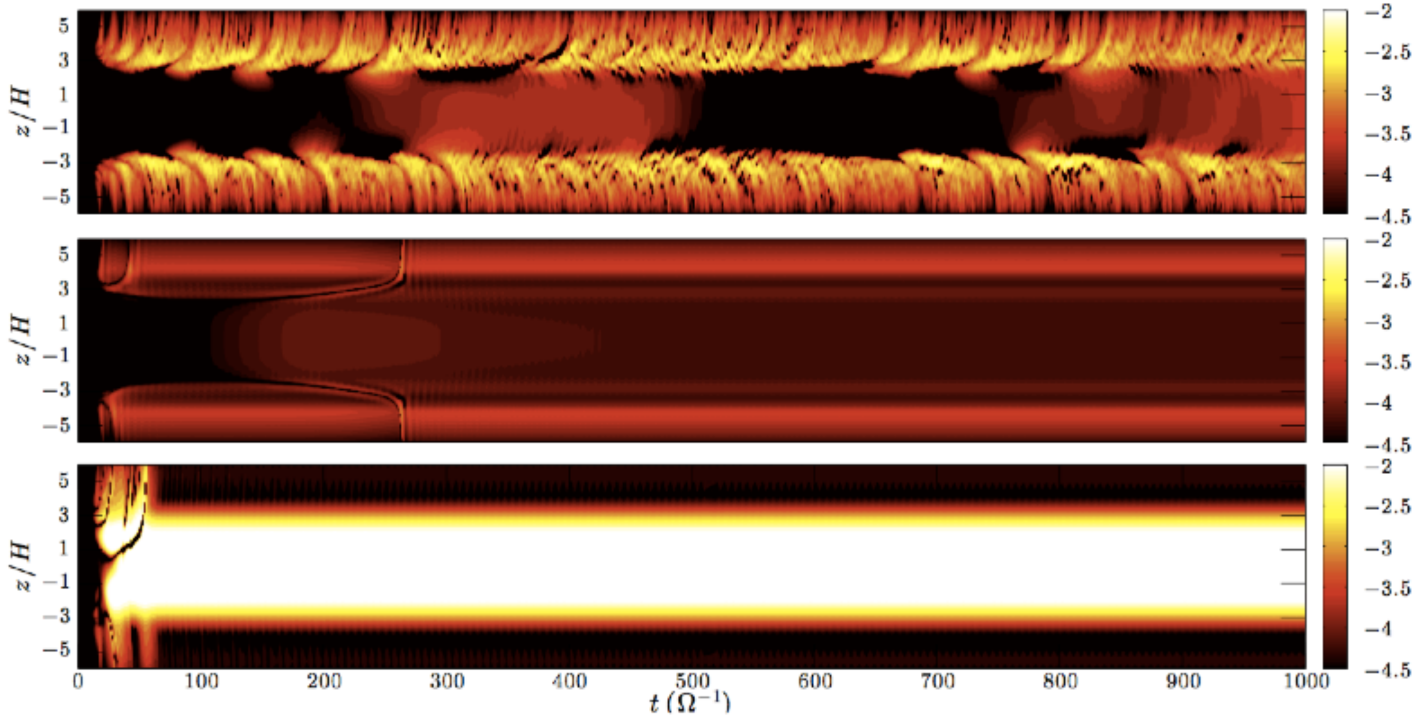


Ohmic

Ohmic + Hall

Fig. 6. Space-time diagram of the logarithm of the horizontally averaged Maxwell stress, $\log\langle -B_x B_y \rangle$, in the Ohmic (1-O-5; top) and Ohmic-Hall (I-OH-5; bottom) runs.

The full monty



Ohmic

Ohmic
+
Ambipolar

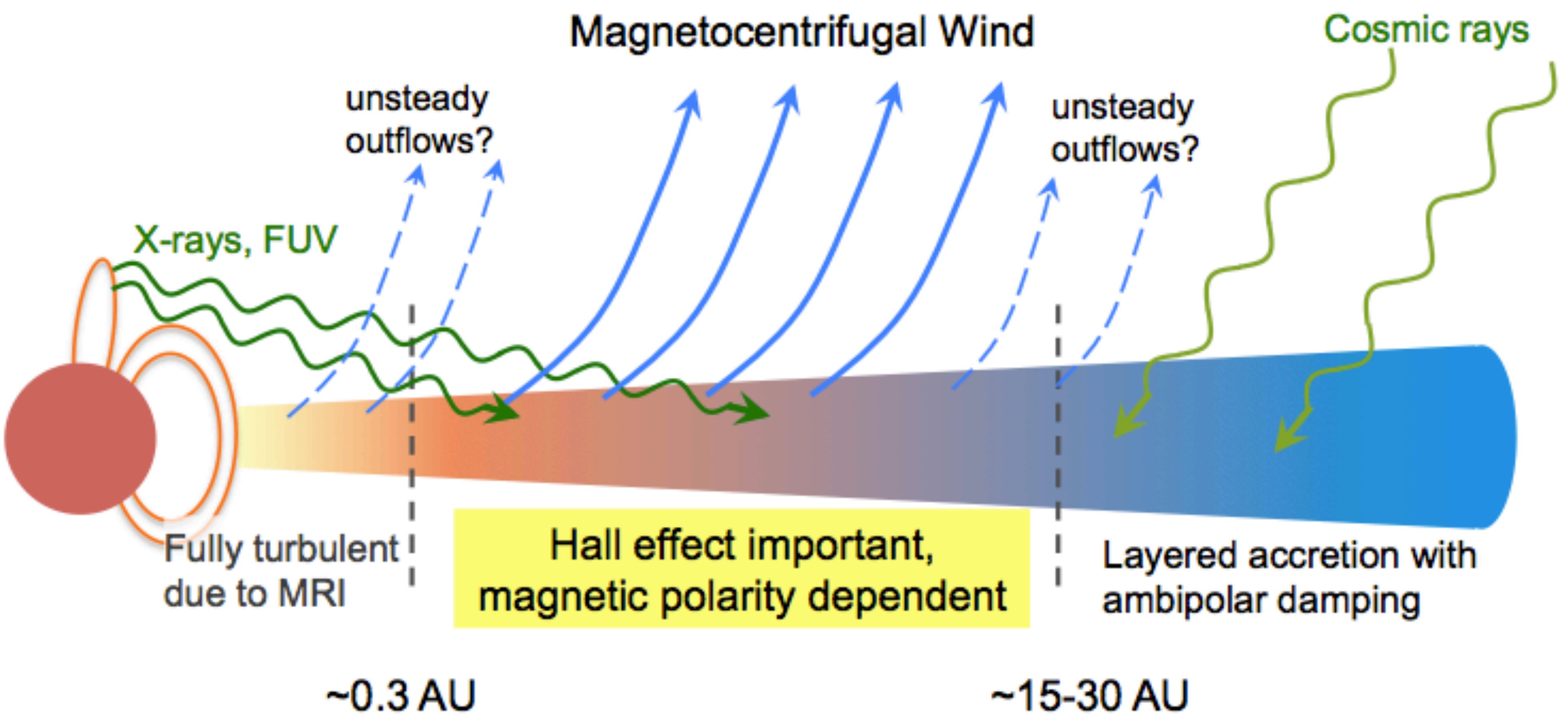
Ohmic
+ Ambipolar
+ Hall

Fig. 9. Space-time evolution of the logarithm of the horizontally-averaged magnetic stress, $\log\langle M_{xy}\rangle$, in the Ohmic (1-O-5; top), Ohmic-ambipolar (1-OA-5; middle), and Ohmic-ambipolar-Hall (1-OHA-5; bottom) runs.

Ambipolar "kills" accretion.
Hall "ressurects" it.

Large scale B_ϕ couples to δB_r, leading to laminar stress.
Wind is also amplified.

Lesur et al. (2014)



Magnetocentrifugal Wind
Cosmic rays
unsteady outflows?
unsteady outflows?
X-rays, FUV
Fully turbulent due to MRI
Hall effect important, magnetic polarity dependent
Layered accretion with ambipolar damping
~0.3 AU
~15-30 AU