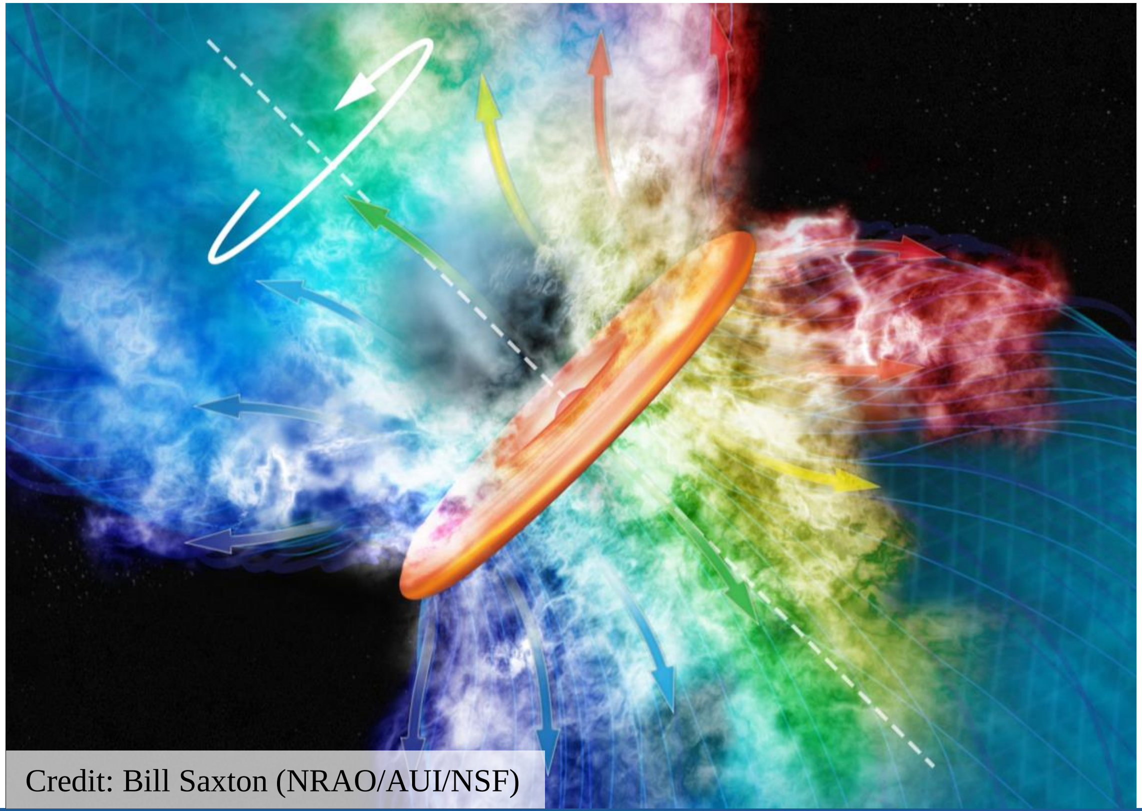
Disk Formation in Magnetized Dense Cores with Turbulence and Ambipolar Diffusion

March 21, 2019

Ka Ho (Andy) Lam
(University of Virginia)

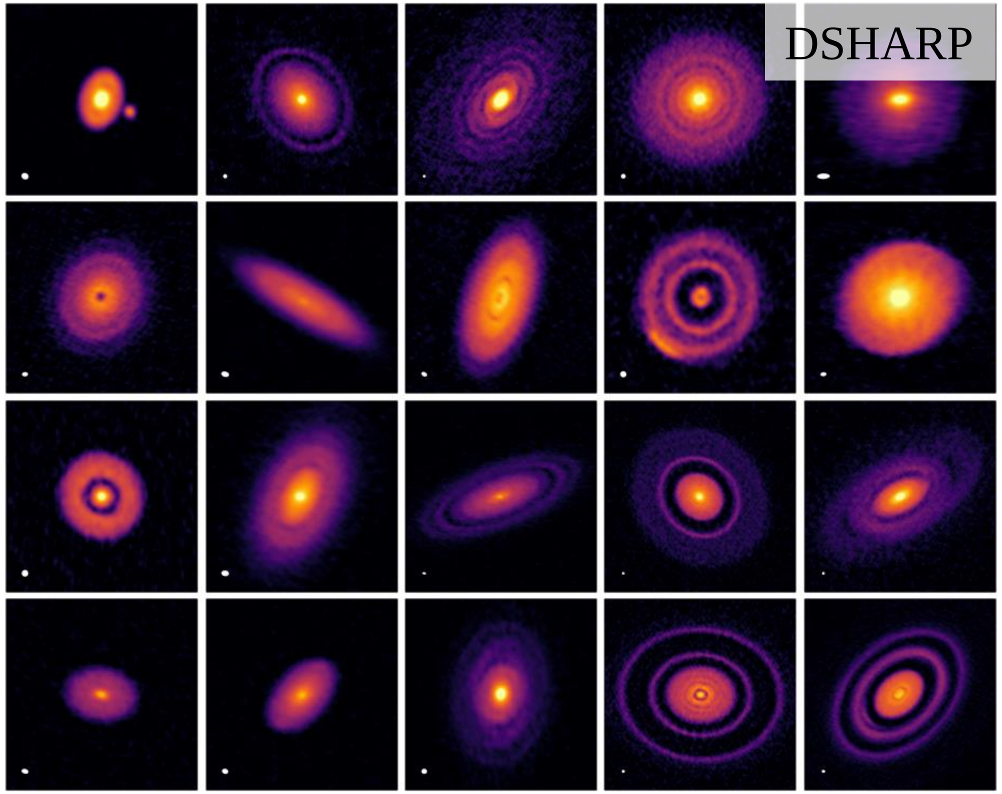
Zhi-Yun Li (UVa)
Che-Yu Chen (UVa)
Kengo Tomida (OsakaU/Princeton)
Bo Zhao (MPE)

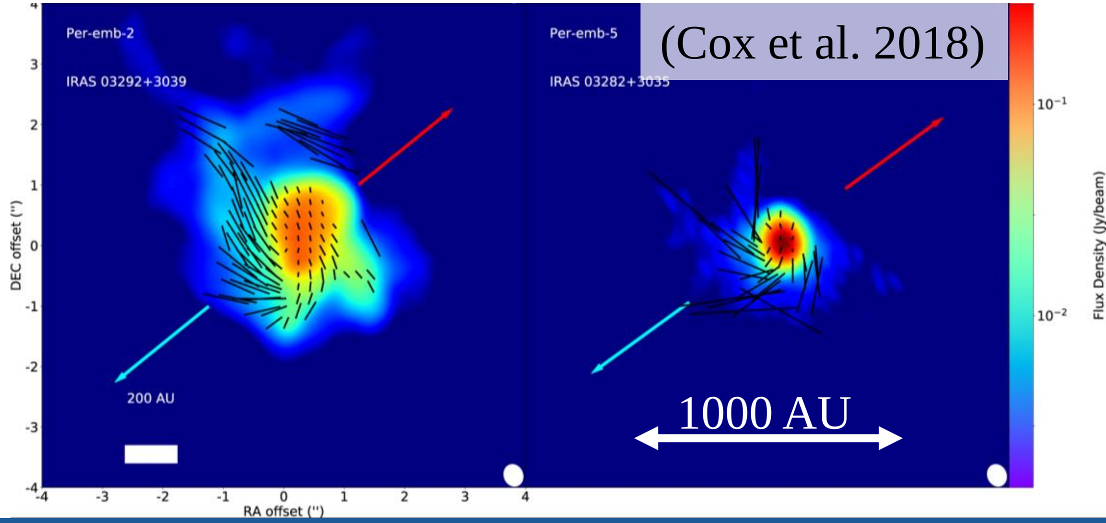


Credit: Bill Saxton (NRAO/AUI/NSF)

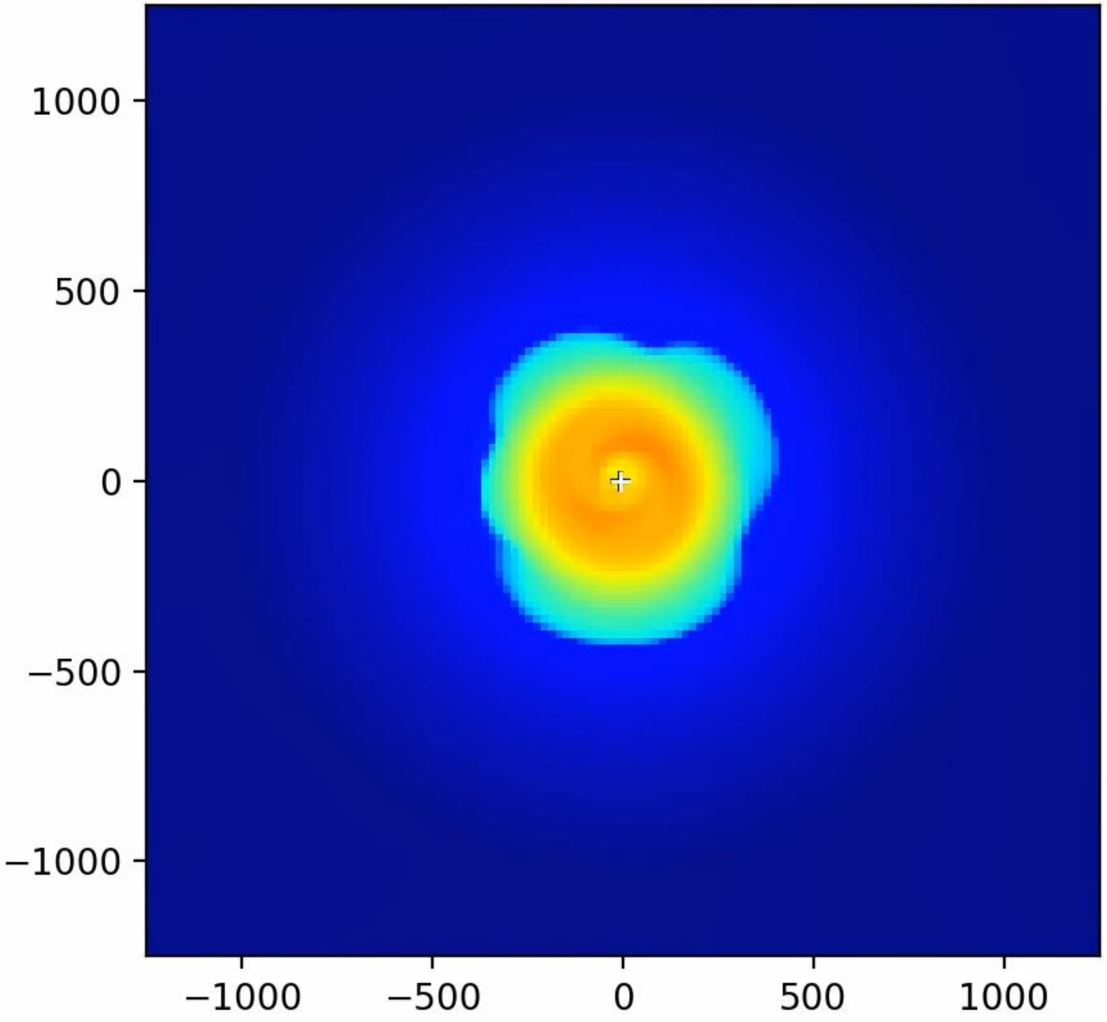
Motivation

- Provide initial conditions for protoplanetary disk simulations
- Large amount of telescope data
  - Young disks with polarization, e.g., Cox et al. (2018), Kwon et al. (2018)
- Numerical simulations show that disks cannot form easily


DSHARP

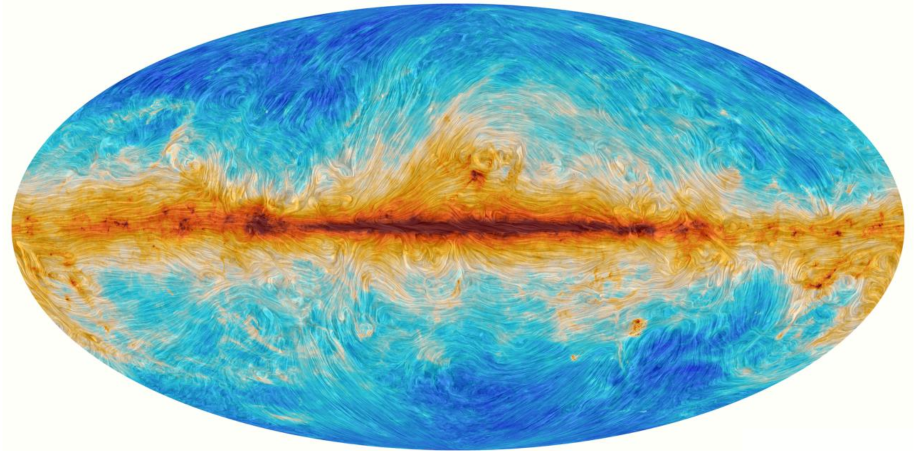

(Cox et al. 2018)

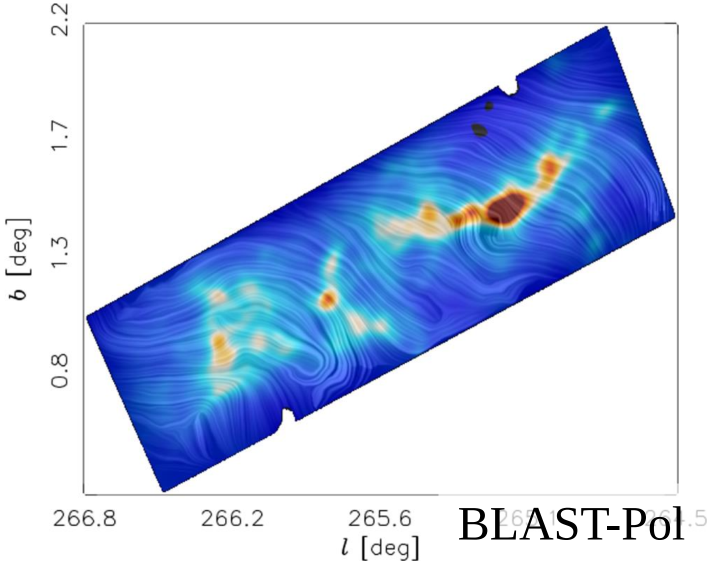
Hydrodynamic Simulation



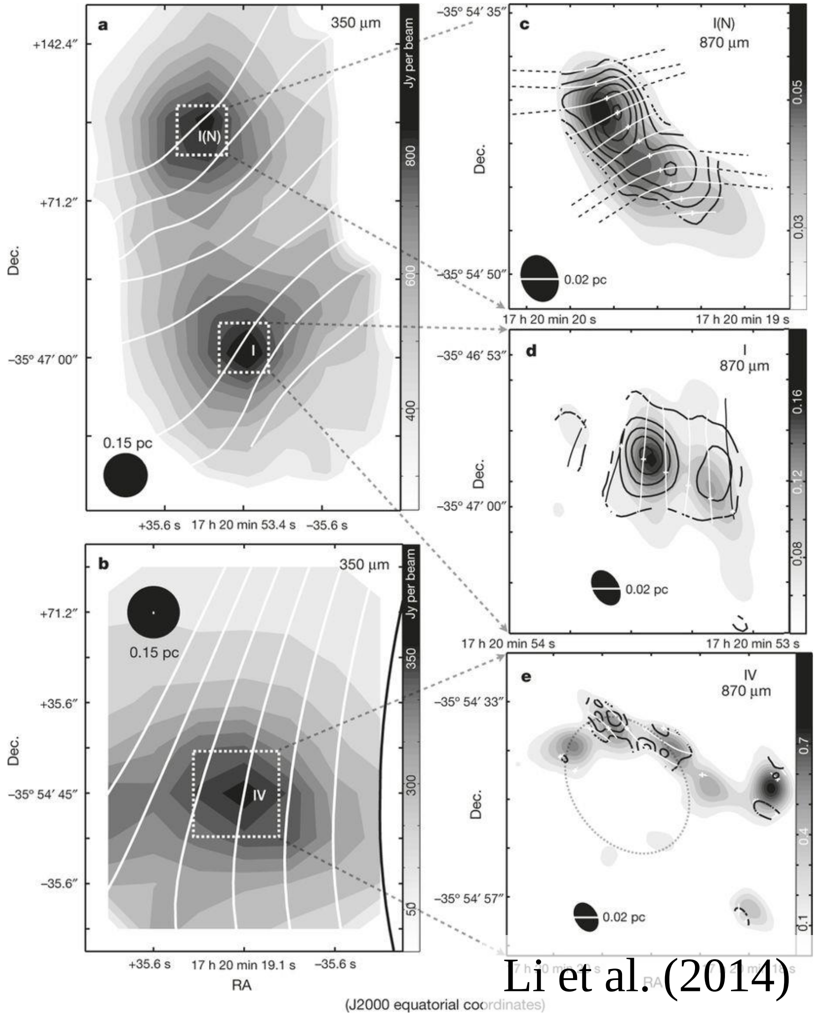
Magnetic Braking Catastrophe

- Dust emissions are polarized (on all scales)
  - Grains align to magnetic field lines
- Hourglass-shaped magnetic field lines
  - Magnetic field interacts strongly with mass


Planck



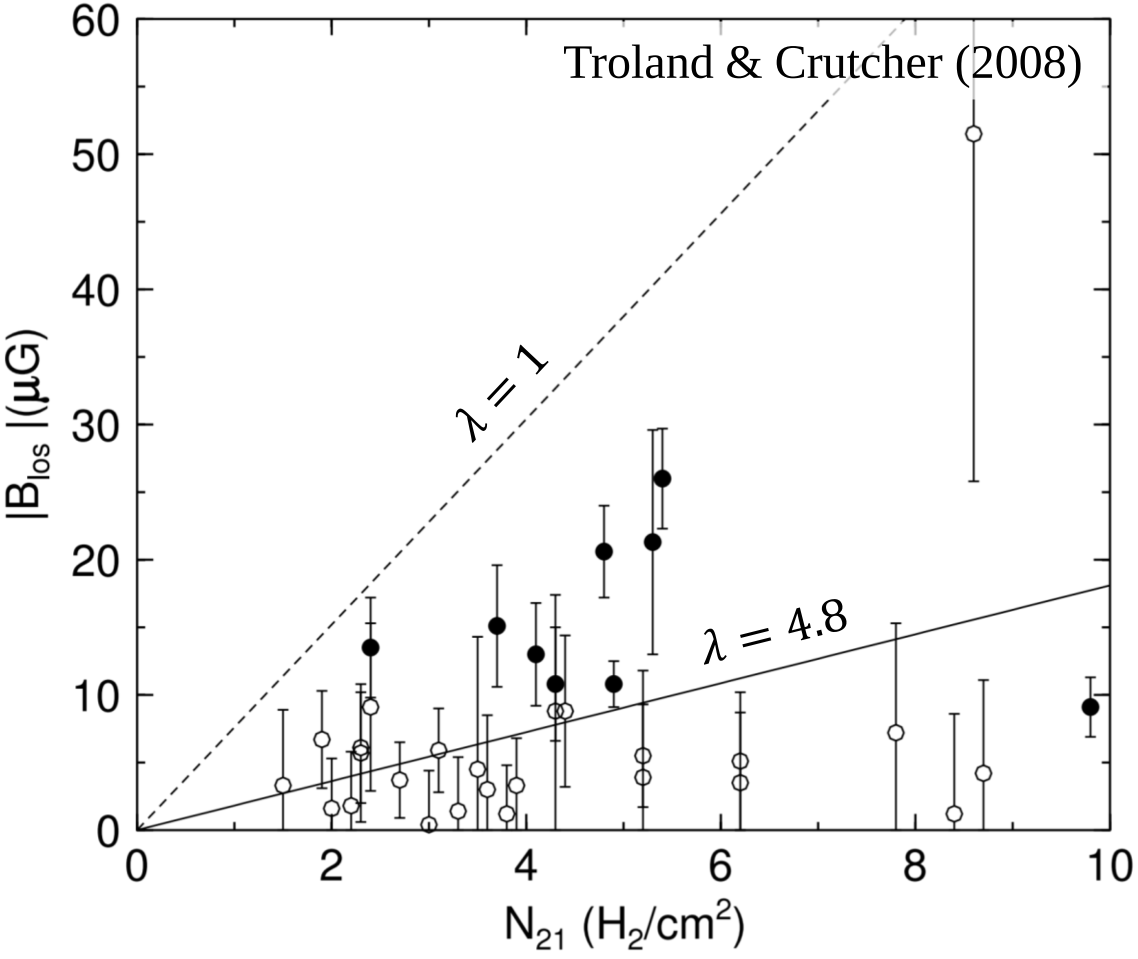
BLAST-Pol



Li et al. (2014)

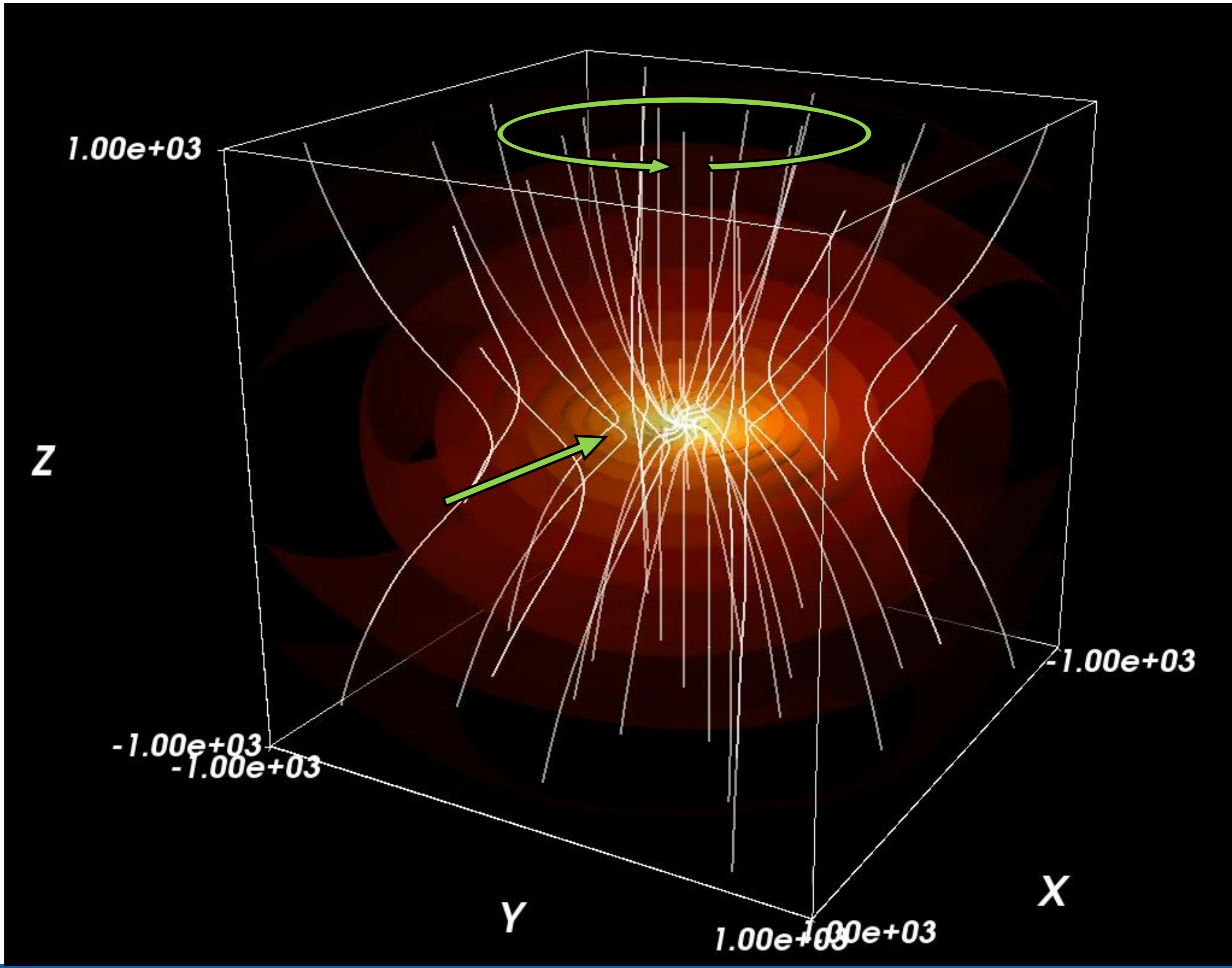
Magnetic Braking Catastrophe

- Mass-to-flux ratio
  - $\lambda = 2\pi\sqrt{G}\,\frac{M}{\Phi}$
  - $\lambda < 1$ → magnetically supported
  - Observationally, $\lambda \sim 2$ (corrected for geometry)
- $\lambda = 2.63$ in our simulations



Magnetic Braking Catastrophe

- Ideal MHD simulation
- B field-induced flattened structure
  - Not rotationally supported
  - Pseudodisk
- Pinched B field lines causes magnetic tension torque
- No rotationally supported disk

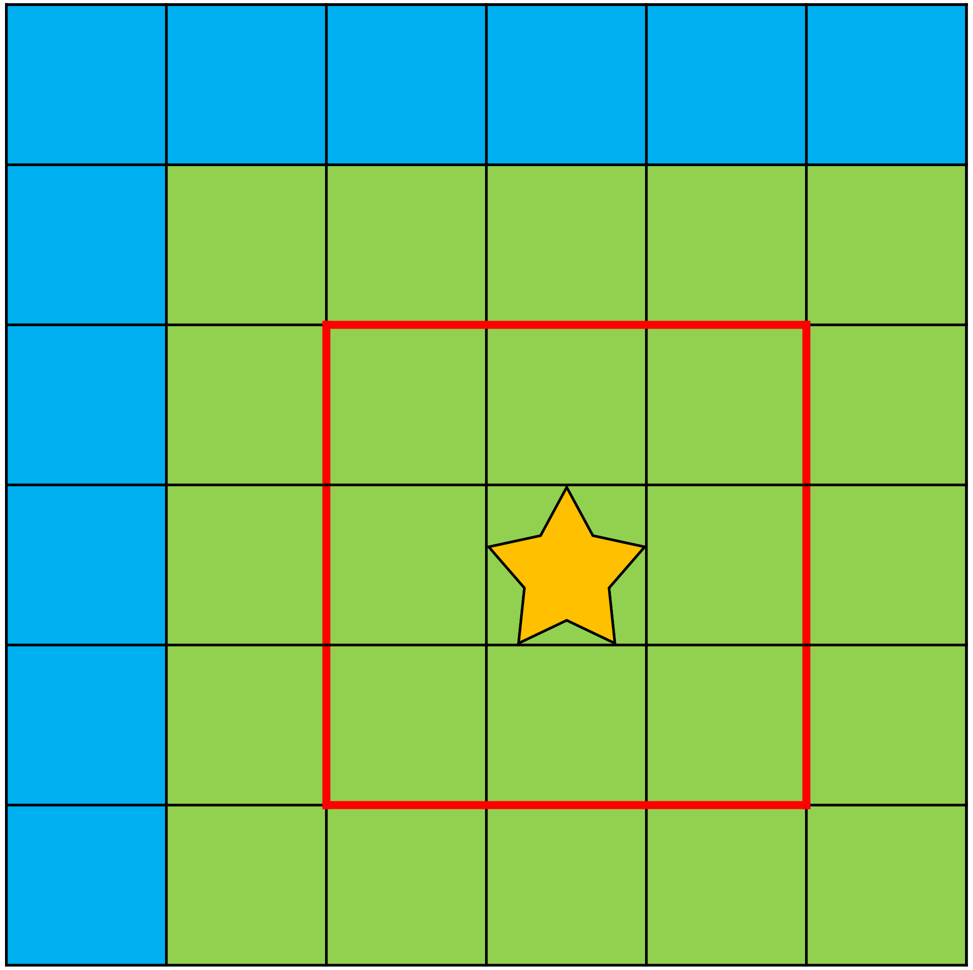


Resolutions

- Magnetic field-rotation misalignment
- Turbulence
- Non-ideal MHD effects
  - Ohmic dissipation
  - Hall effect
  - Ambipolar diffusion
- Non-ideal MHD effects have been studied alone in detail
  - Small disks at early phase, e.g., Vaytet et al. (2018), Tomida et al. (2015)
  - Long-term evolution requires sink particle treatment, e.g., Tomida et al. (2017)

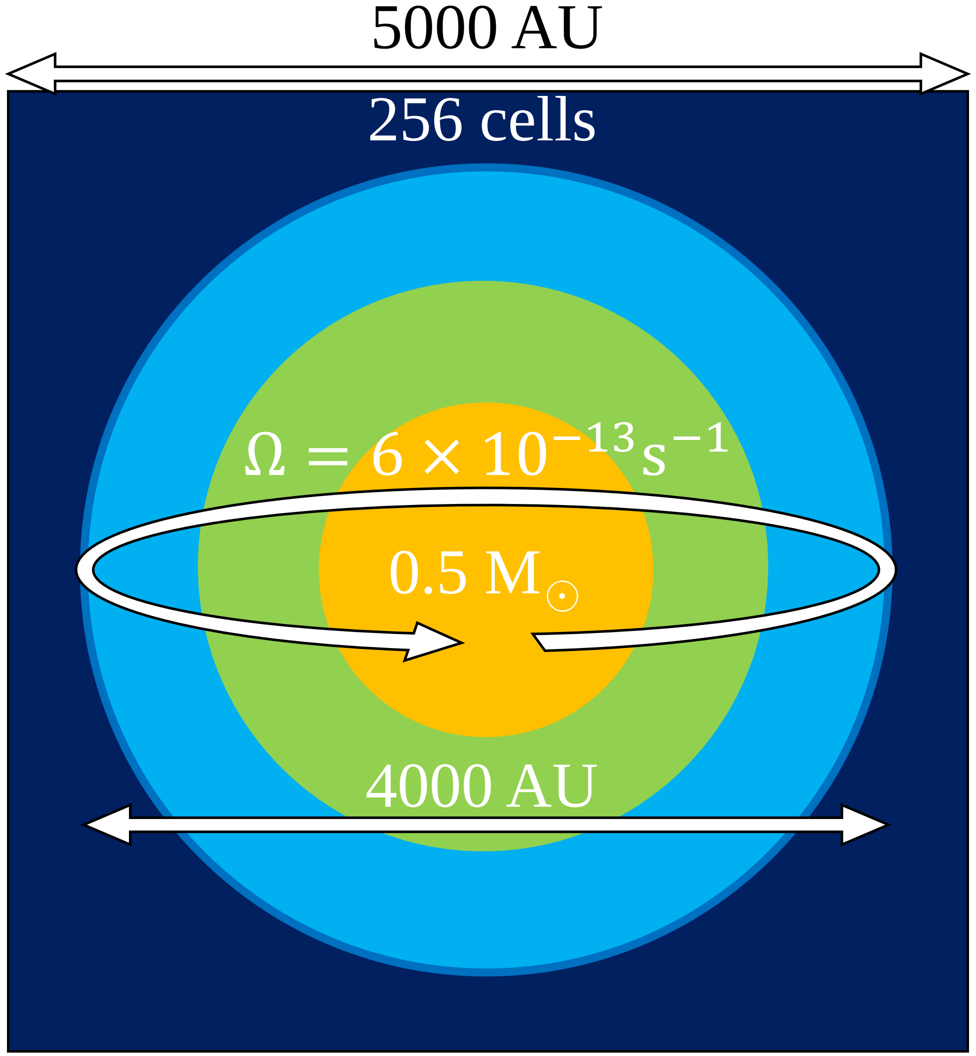
Sink Particle Treatment

- Gong & Ostriker (2013)
- Sink particles are created when conditions are fulfilled
  - Density threshold, minimum of potential, …
- $3 \times 3 \times 3$ sink regions
- Excess mass and momentum are put onto sink particles
- Magnetic field is untouched
  - Magnetic field decoupled from gas and accumulate in sink regions
  - Magnetic flux problem: $\lambda_* = 10^3 - 10^4$

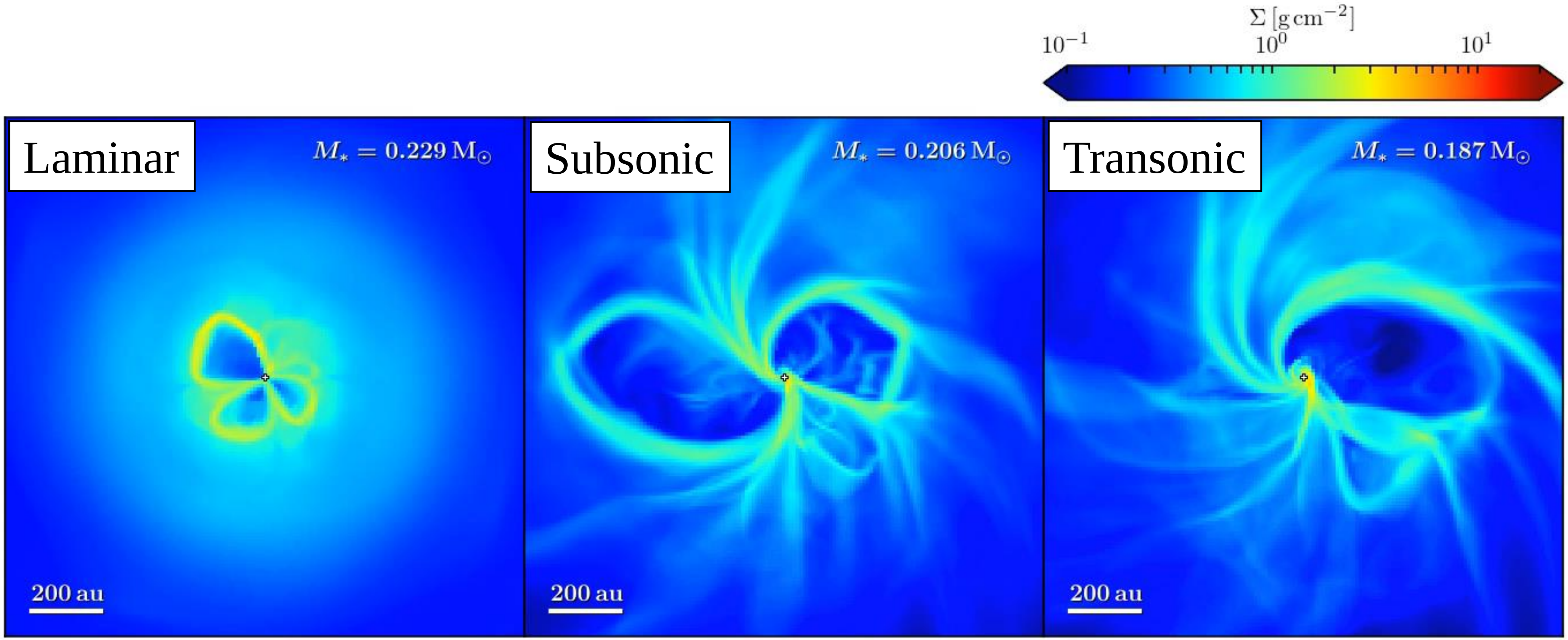


Simulation Setup

- Pseudo-Bonner-Ebert sphere ($\alpha = 0.4$)
- Solid-body rotation ($\beta_{\text{rot}} = 0.03$)
- Isothermal EOS ($c_s = 0.2\ \text{km/s}$)
- Turbulence
  - Angular momentum removed globally
  - Mach 0, 0.5, 1
- Ambipolar diffusivity
  - Assume cosmic-ray ionization-recombination equilibrium, $\eta_\text{A} = Q_\text{A} \frac{B^2}{4\pi\rho^{3/2}}$
  - $Q_\text{A} = 0.1\times, 0.3\times, 1\times, 3\times, 10\times$ standard value (Shu 1992)
- Evolve to at least 0.2 $\text{M}_\odot$, sometimes 0.3 $\text{M}_\odot$

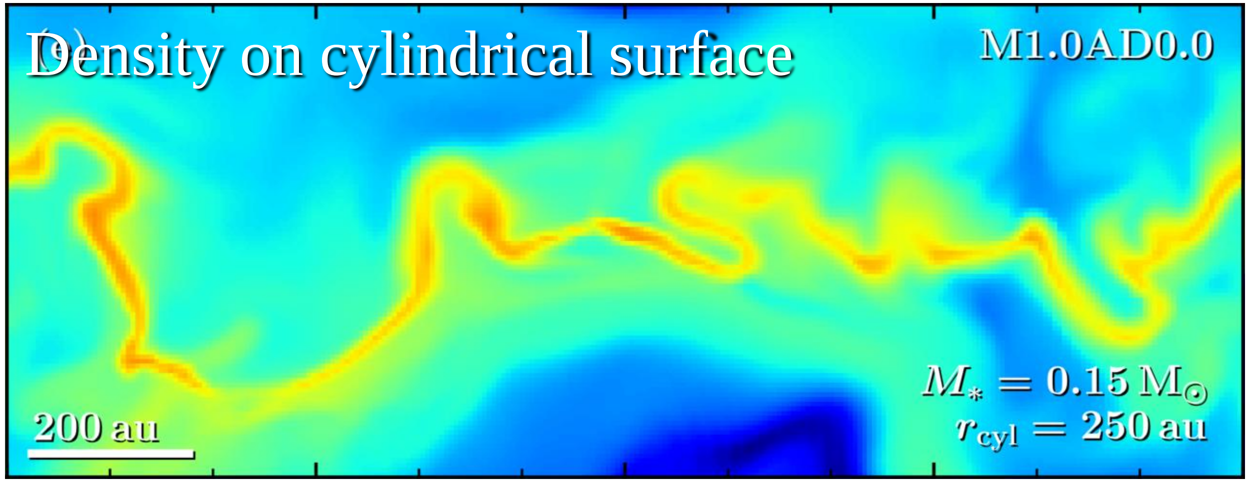


Ideal MHD – Turbulence

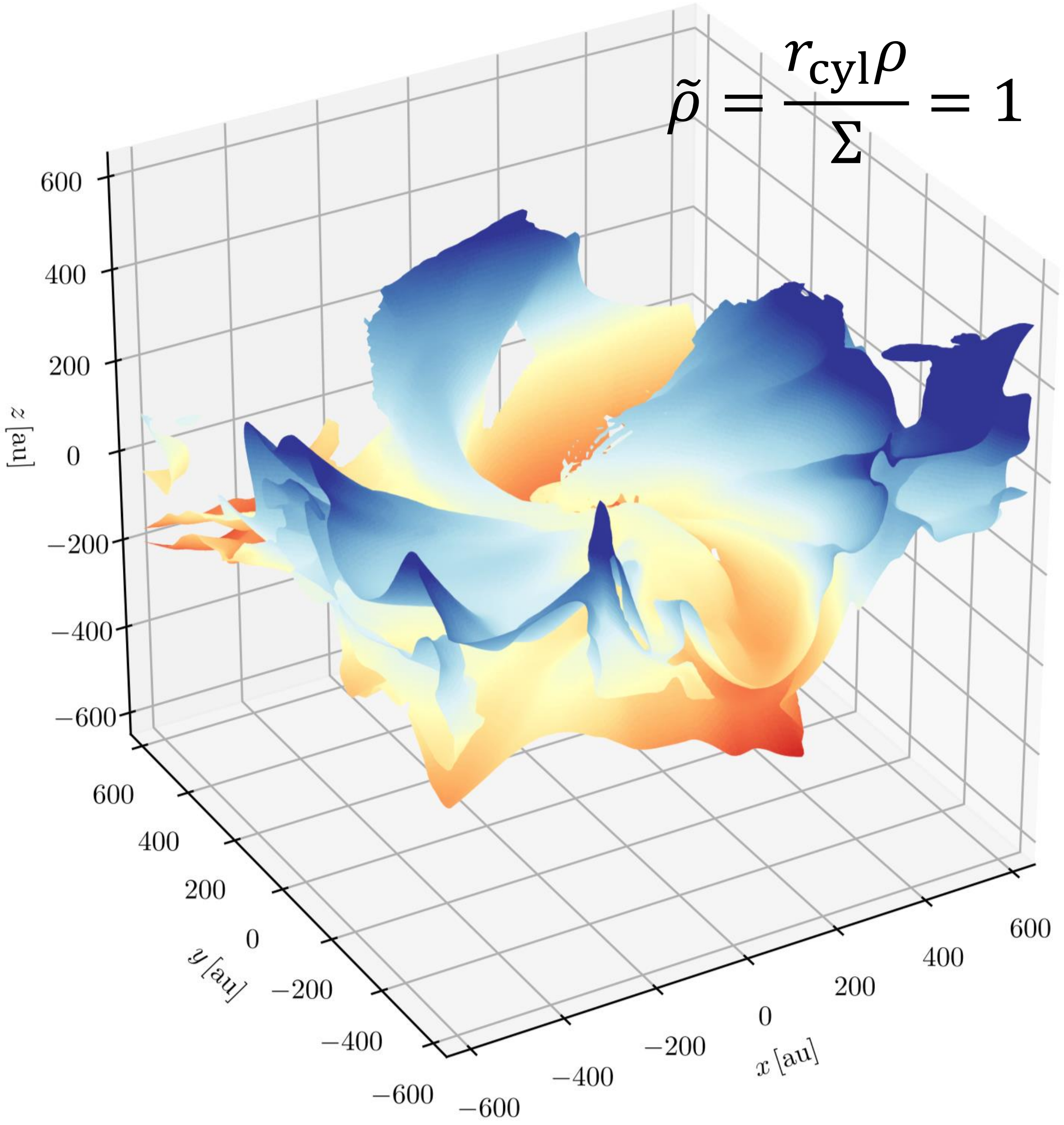


Ideal MHD – Turbulence

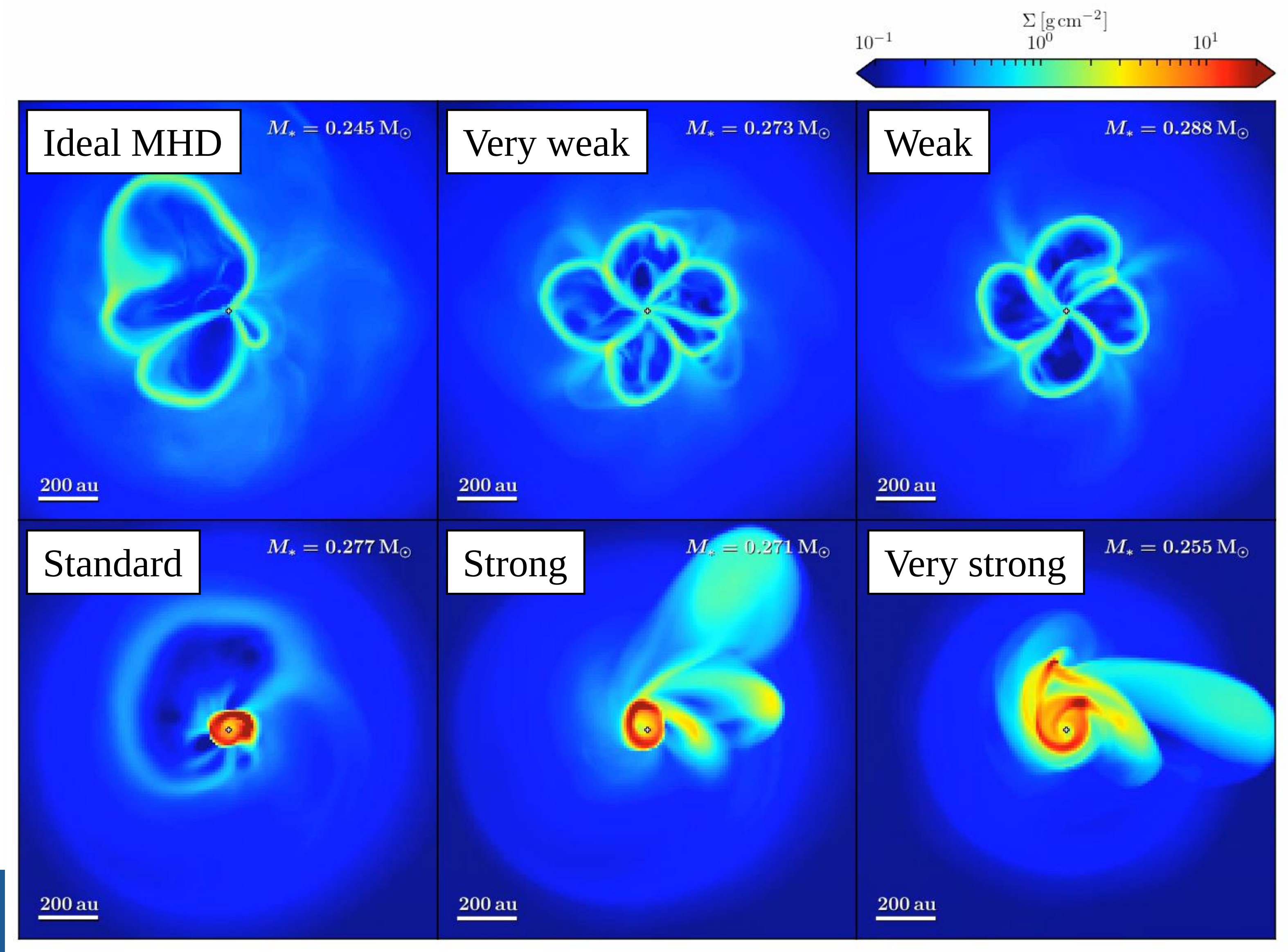
- Confirm findings in Li et al. (2014)
  - Warped pseudodisk
  - Promote disk formation
- Proposed mechanisms
  - Earlier leakage of magnetic flux
  - Self-sorting of angular momentum


Density on cylindrical surface

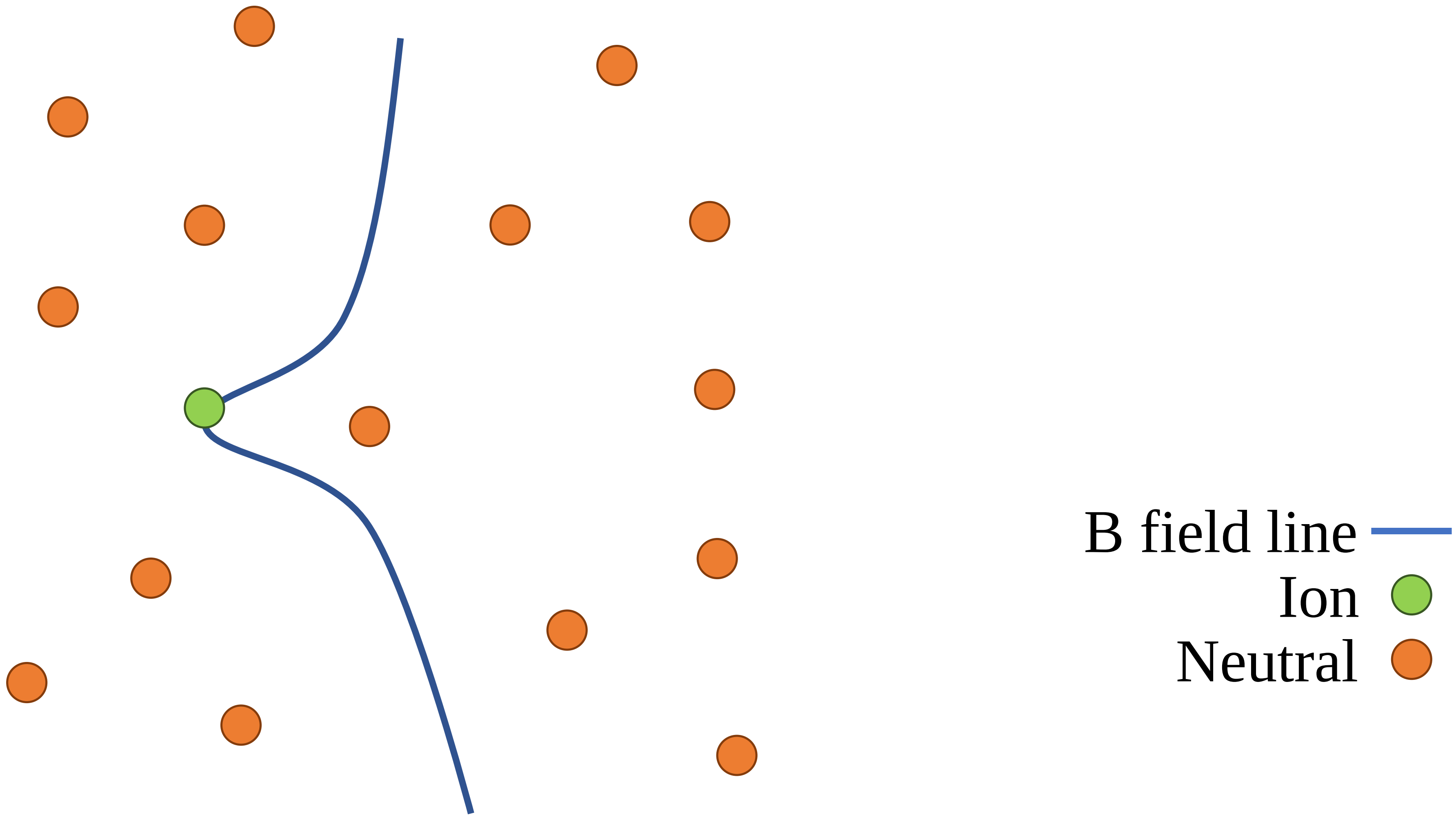
$$\tilde{\rho} = \frac{r_{\rm cyl}\rho}{\Sigma} = 1$$



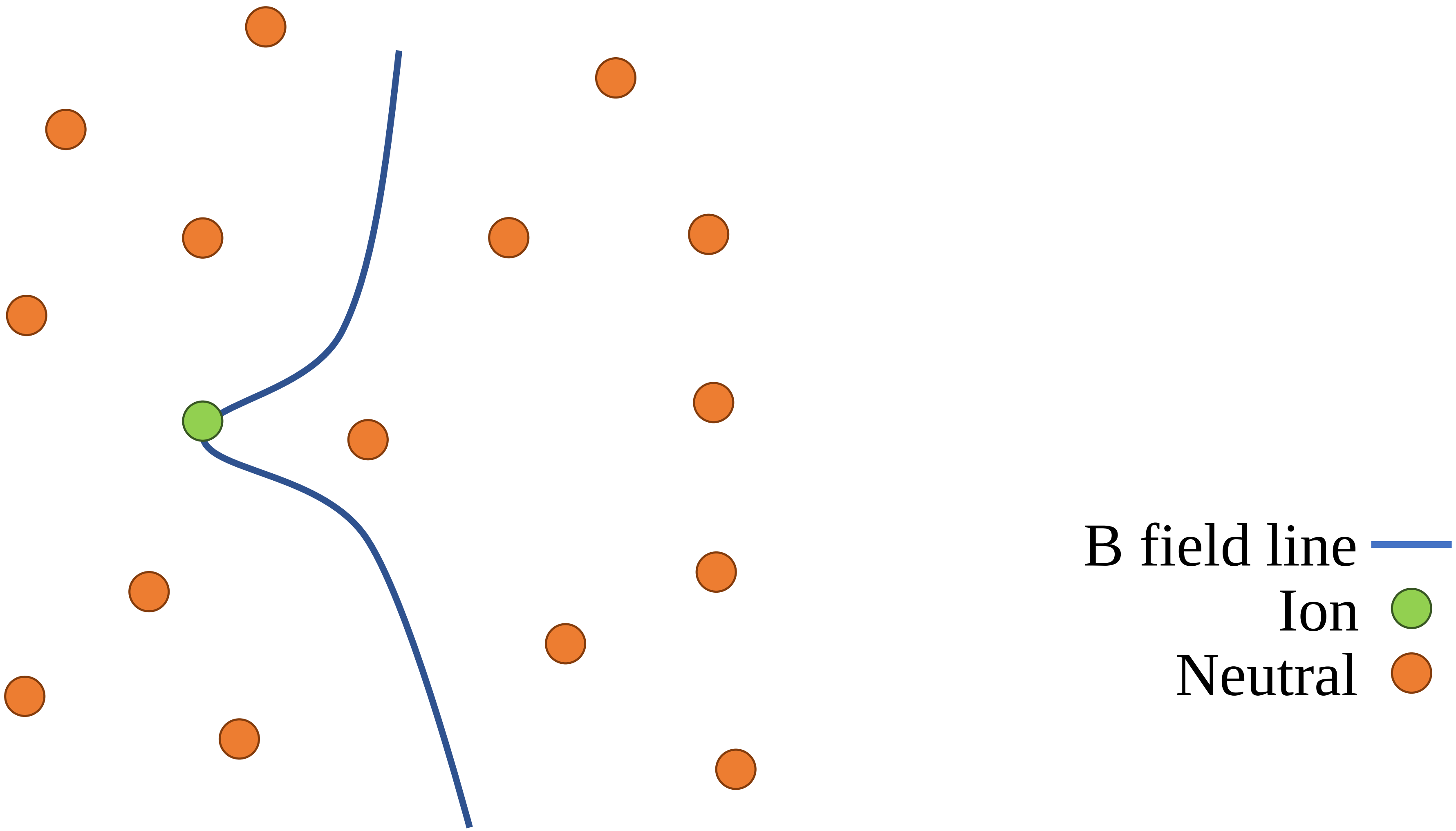
Non-ideal MHD – Ambipolar Diffusion (AD)



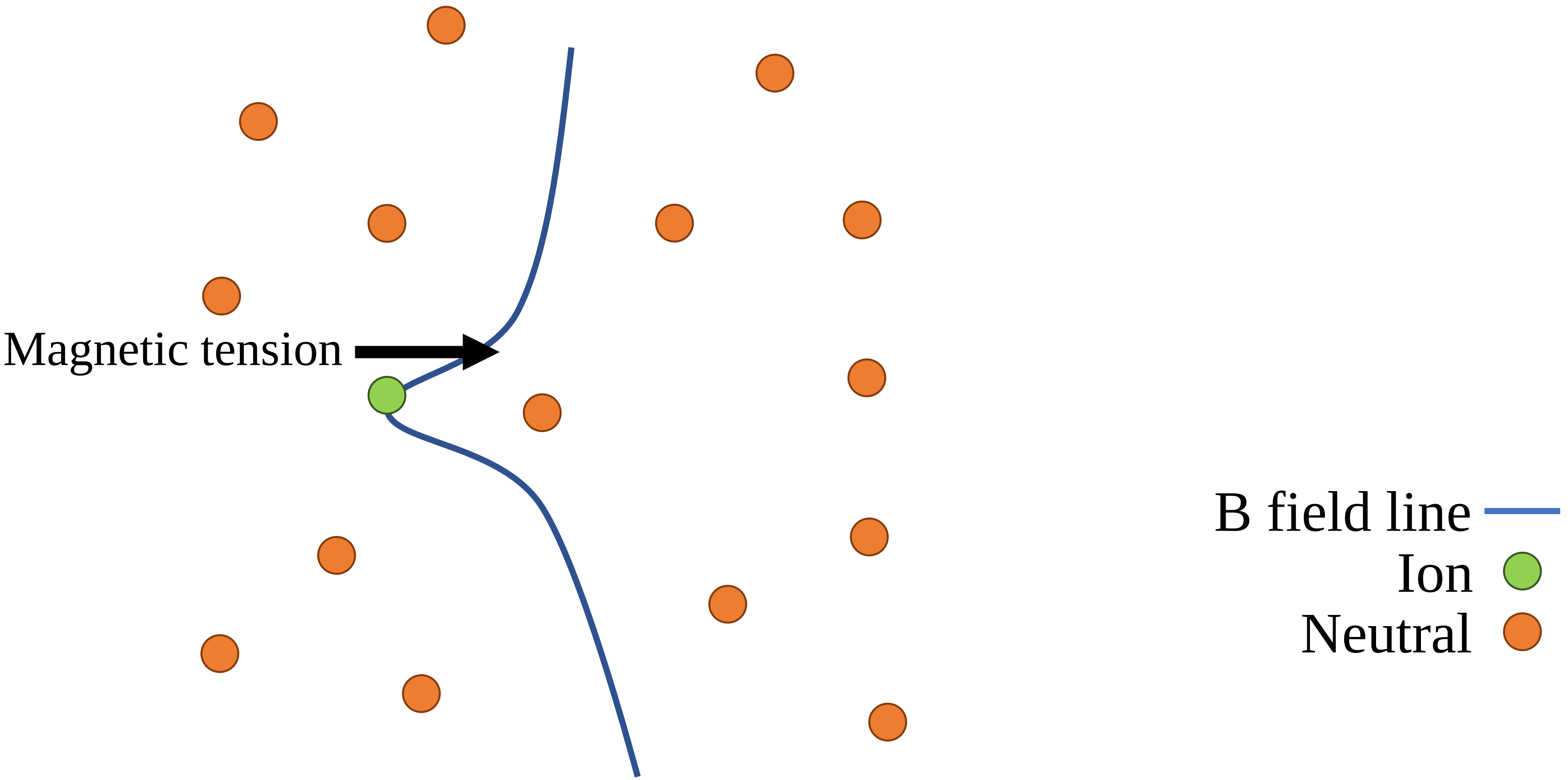
Non-ideal MHD – Ambipolar Diffusion (AD)



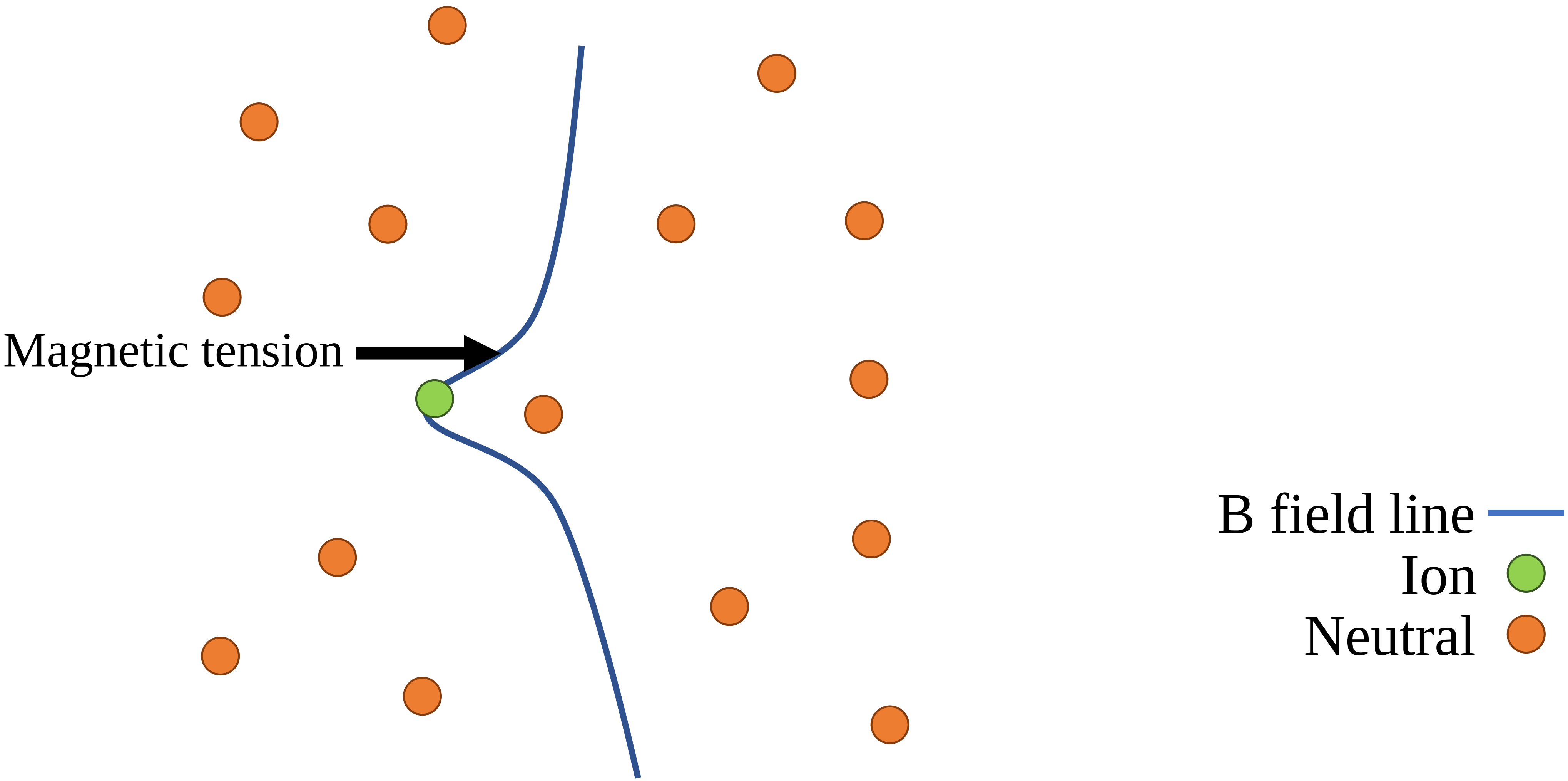
Non-ideal MHD – Ambipolar Diffusion (AD)



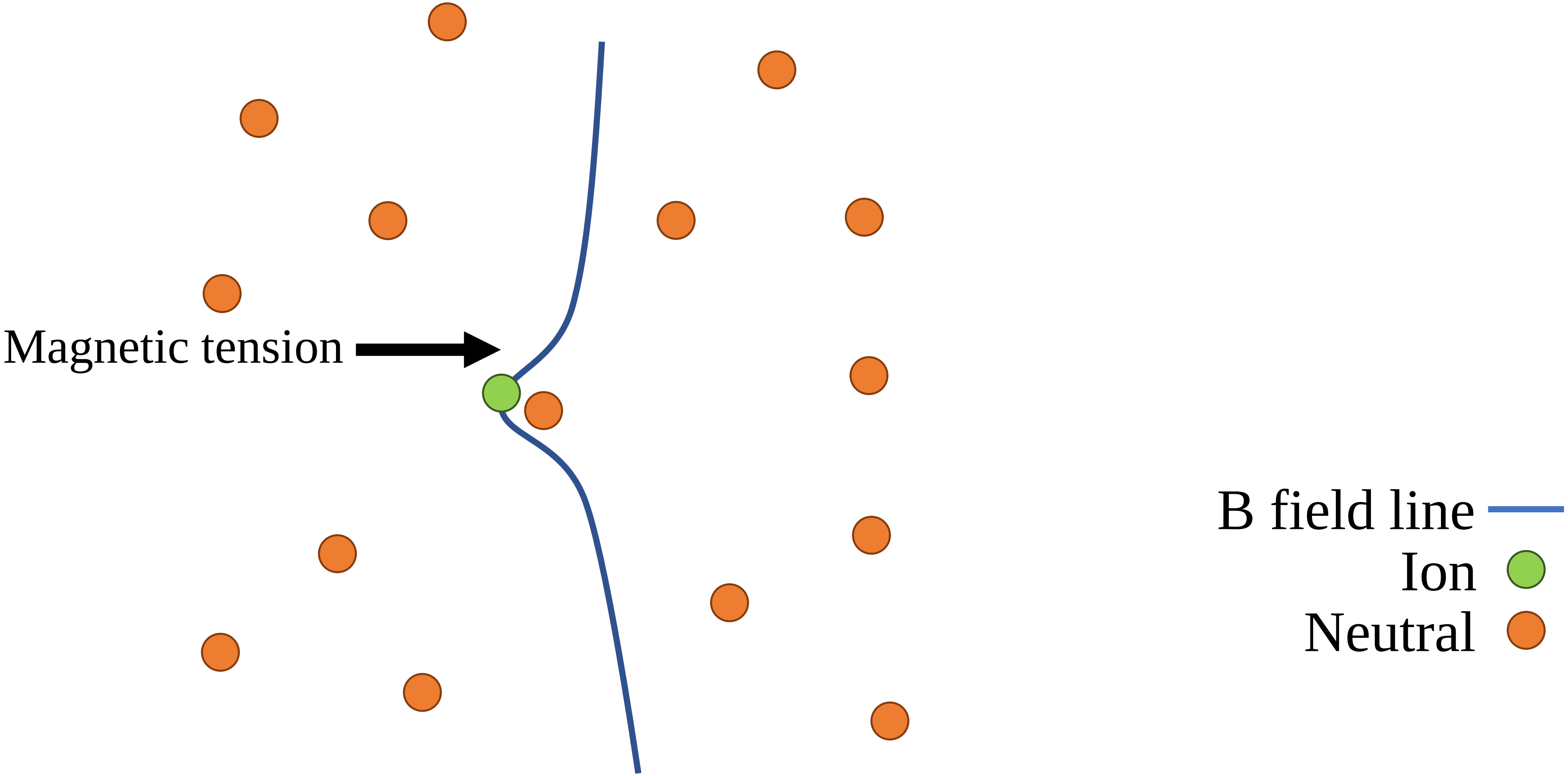
Non-ideal MHD – Ambipolar Diffusion (AD)



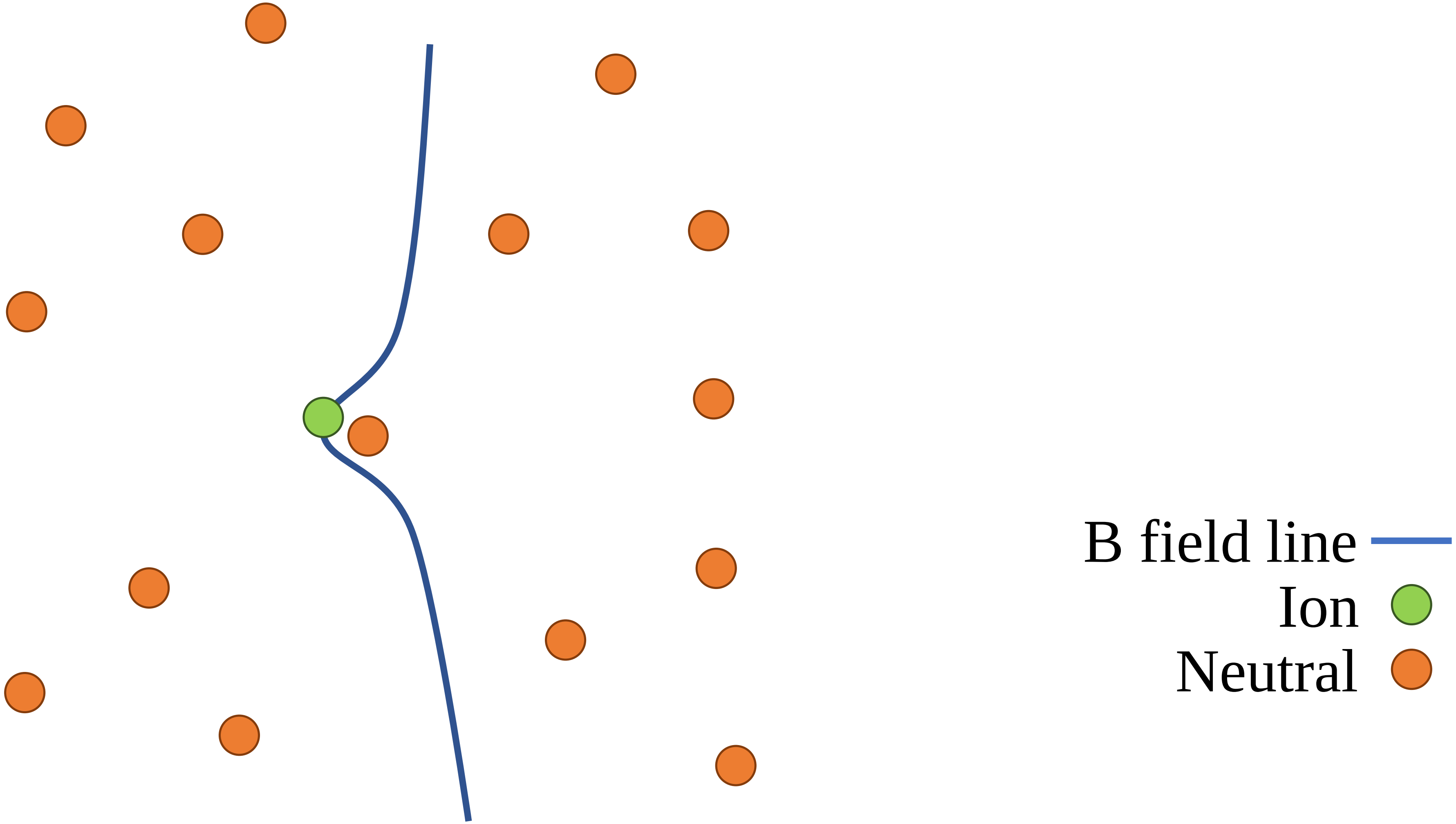
Non-ideal MHD – Ambipolar Diffusion (AD)



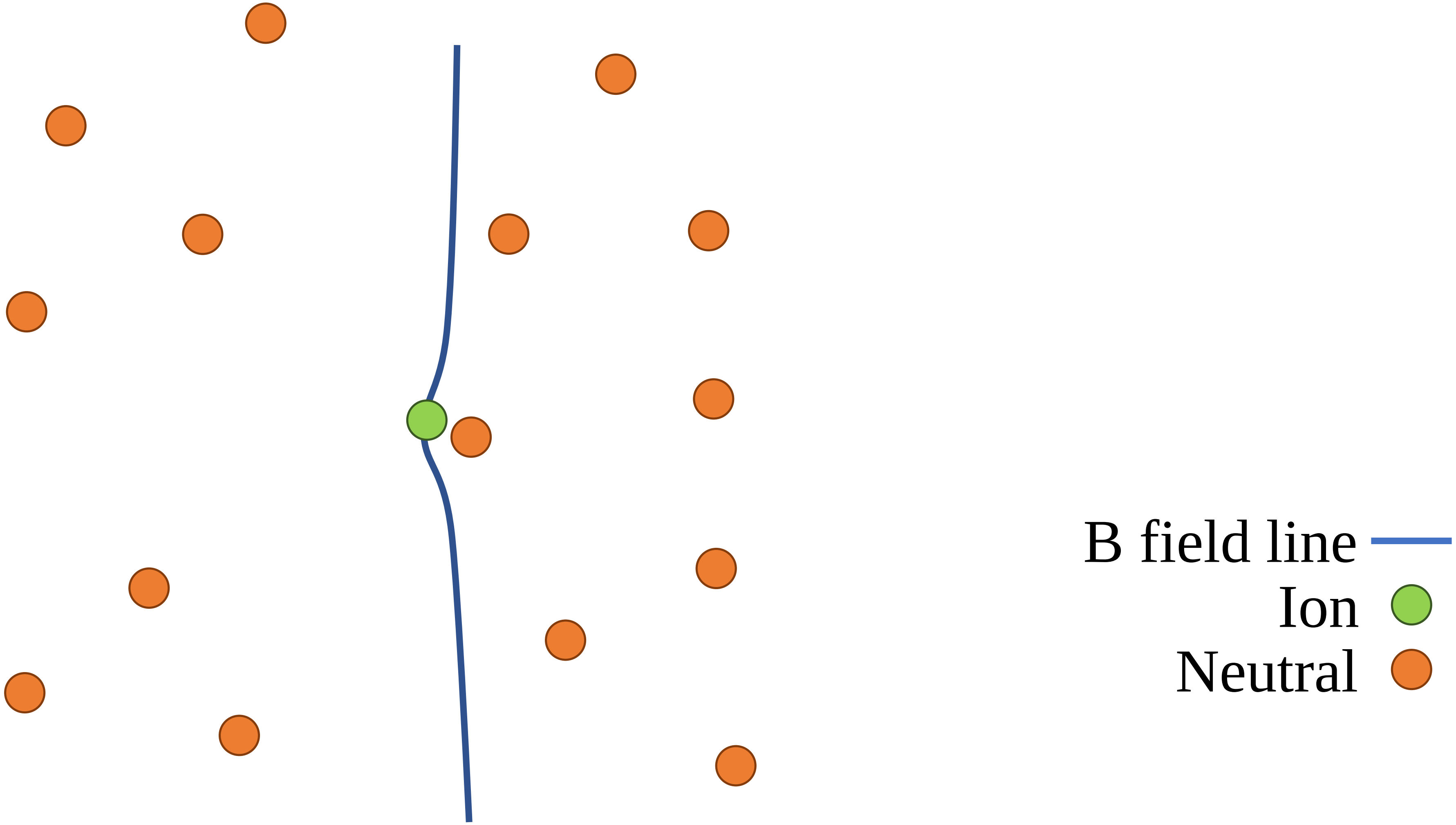
Non-ideal MHD – Ambipolar Diffusion (AD)



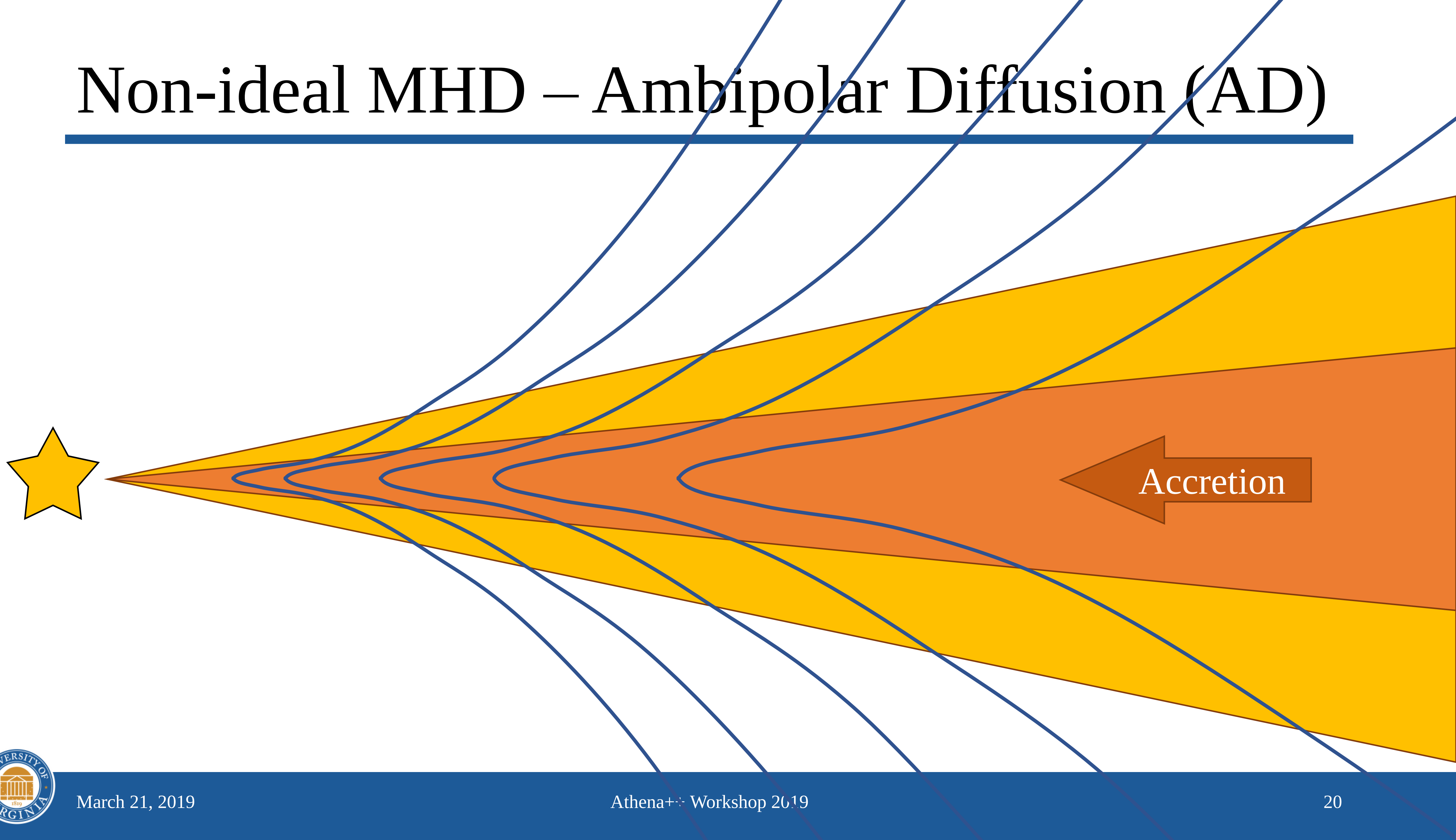
Non-ideal MHD – Ambipolar Diffusion (AD)



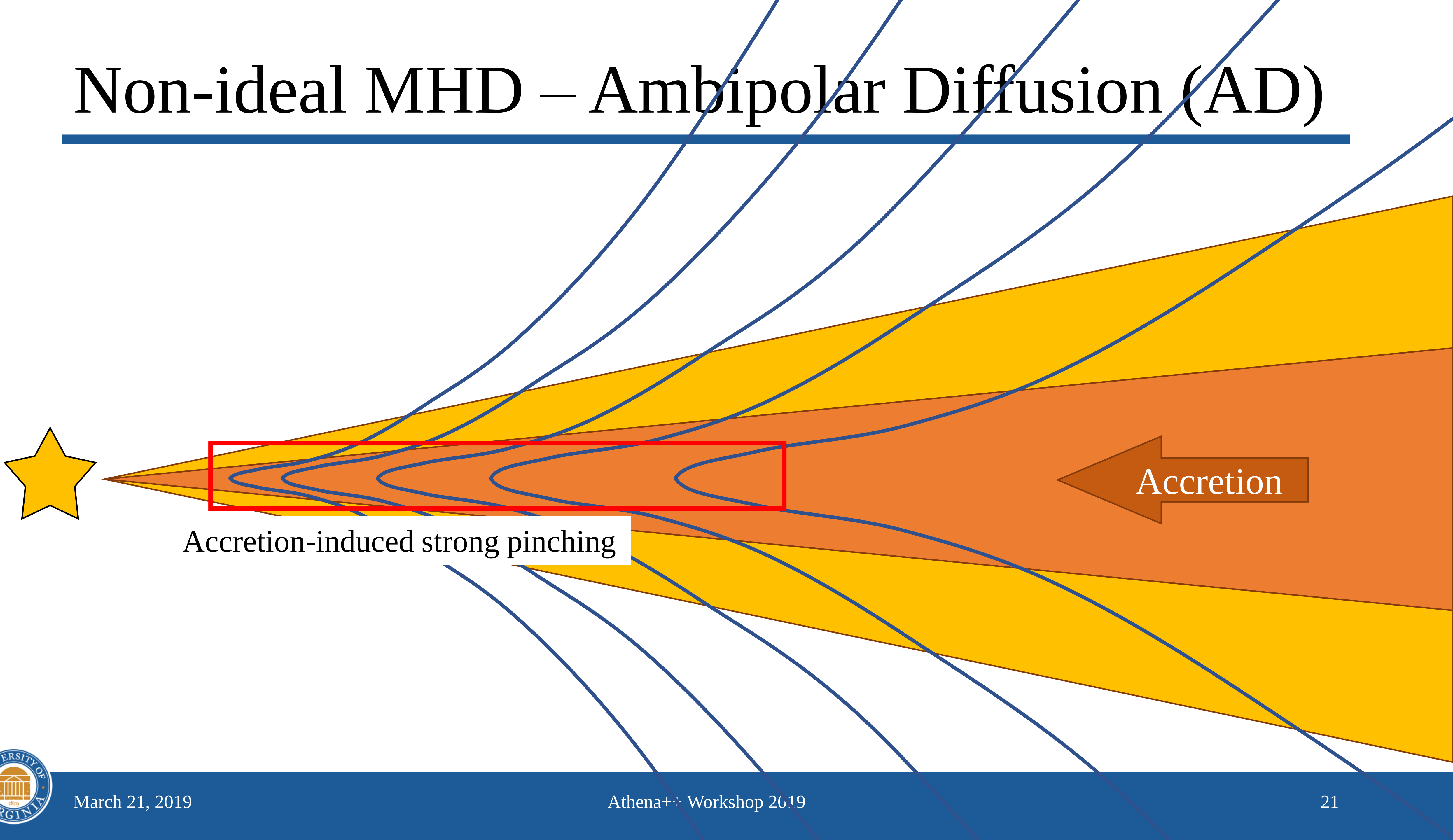
Non-ideal MHD – Ambipolar Diffusion (AD)



Non-ideal MHD – Ambipolar Diffusion (AD)

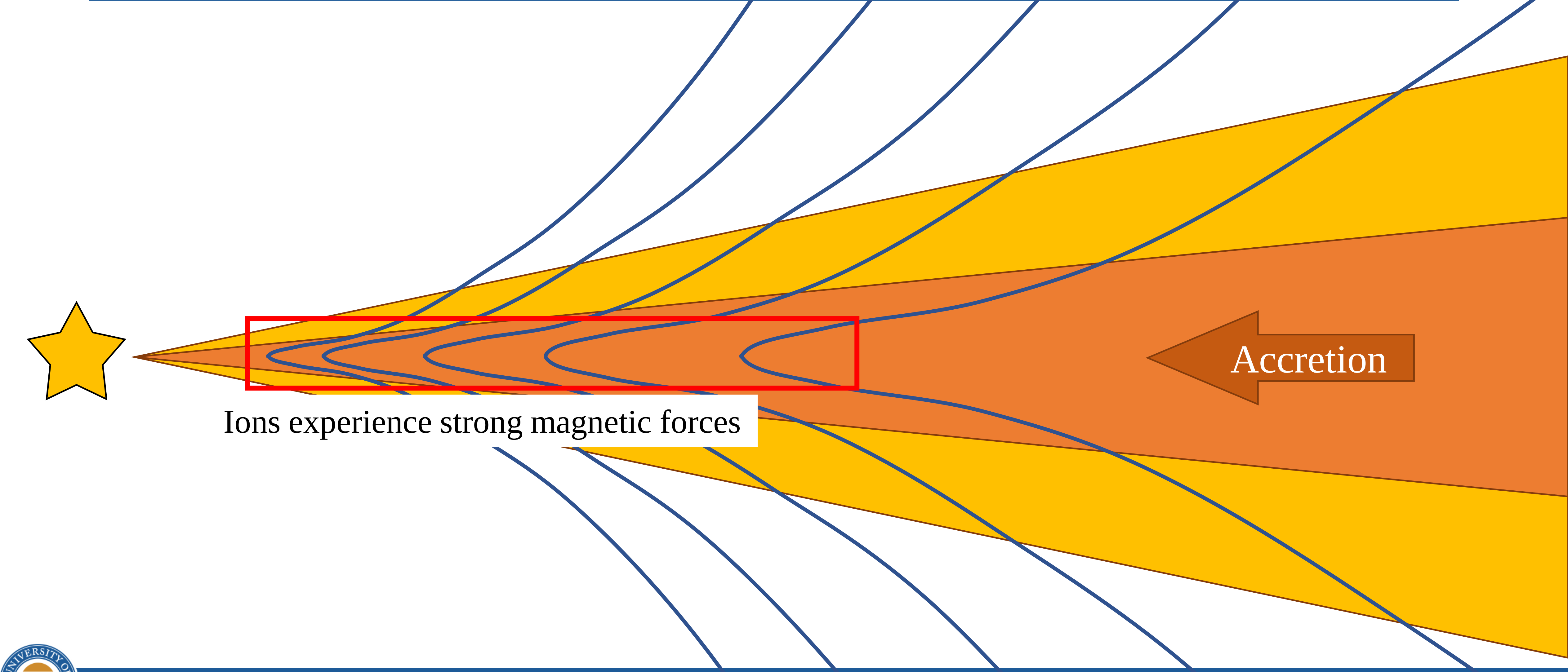


Non-ideal MHD – Ambipolar Diffusion (AD)



Accretion-induced strong pinching

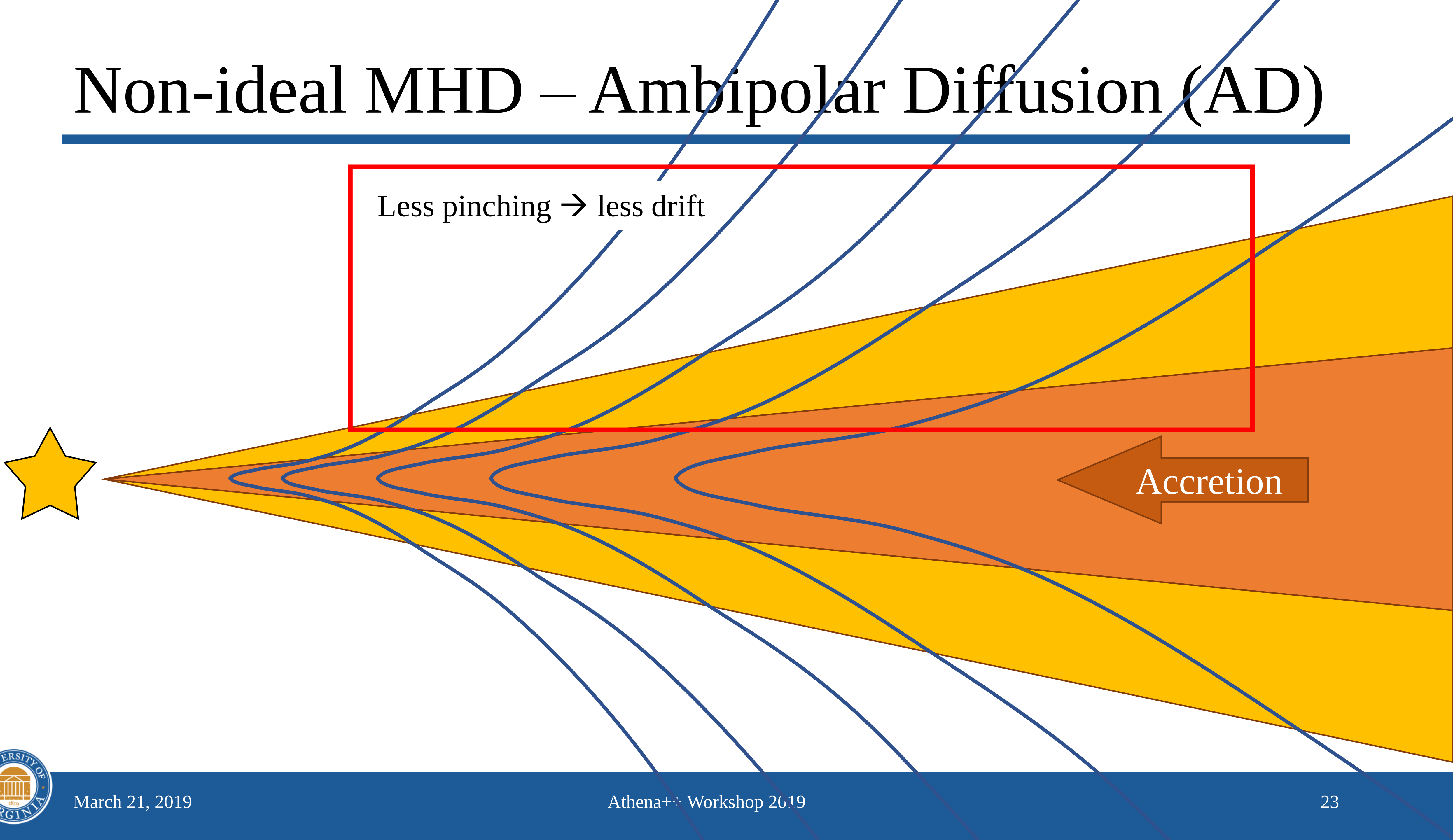
Non-ideal MHD – Ambipolar Diffusion (AD)



Ions experience strong magnetic forces

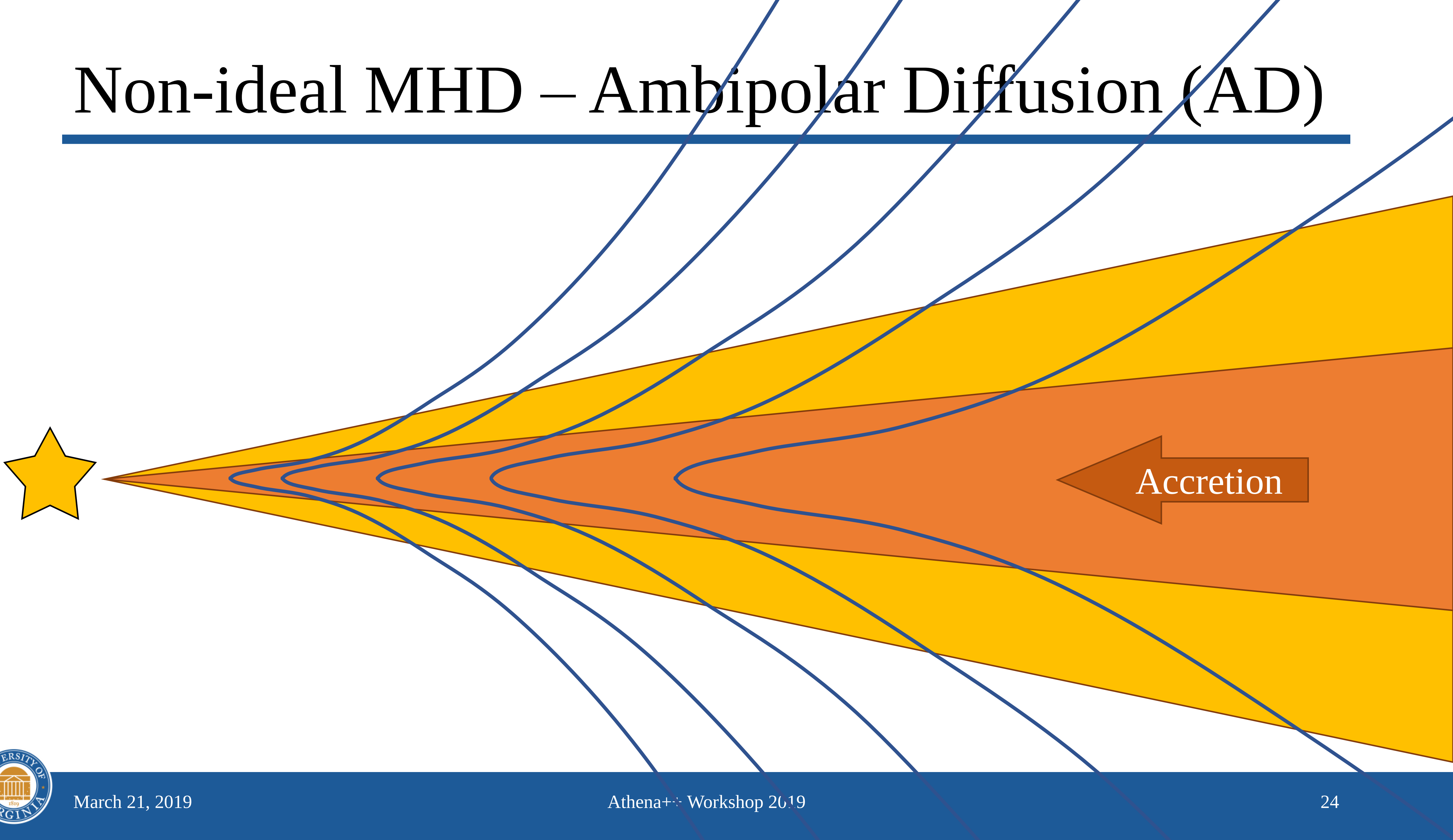
Accretion

Non-ideal MHD – Ambipolar Diffusion (AD)

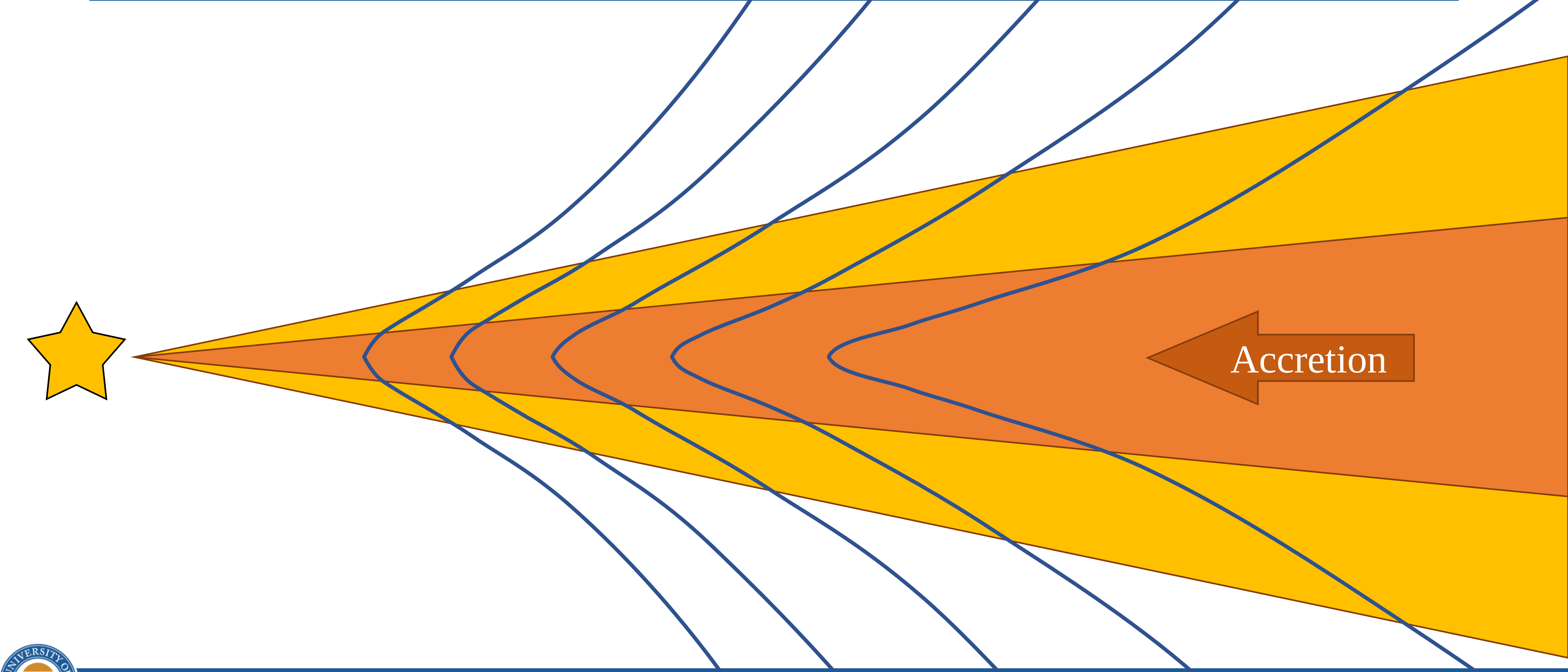


Less pinching → less drift

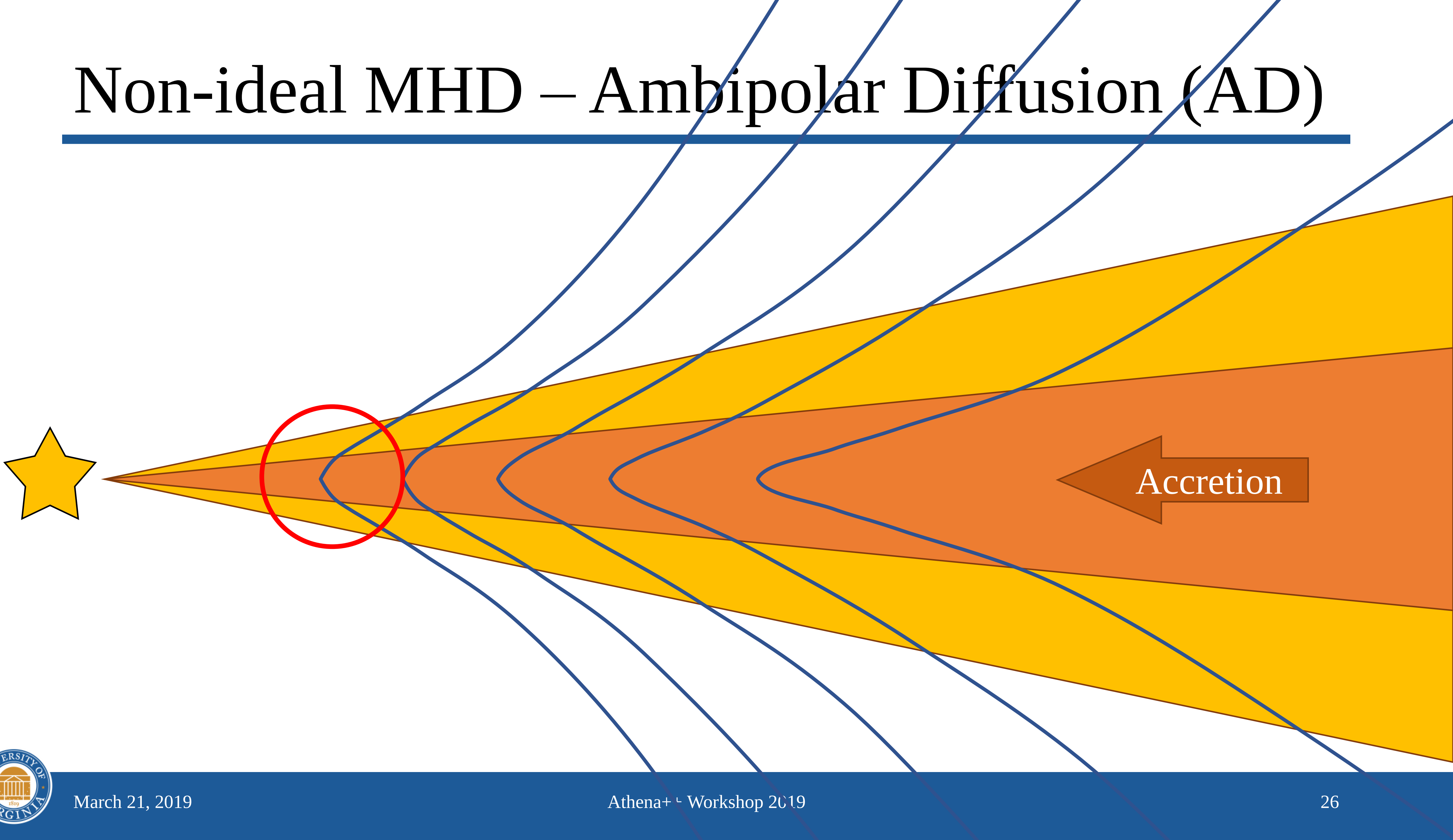
Non-ideal MHD – Ambipolar Diffusion (AD)



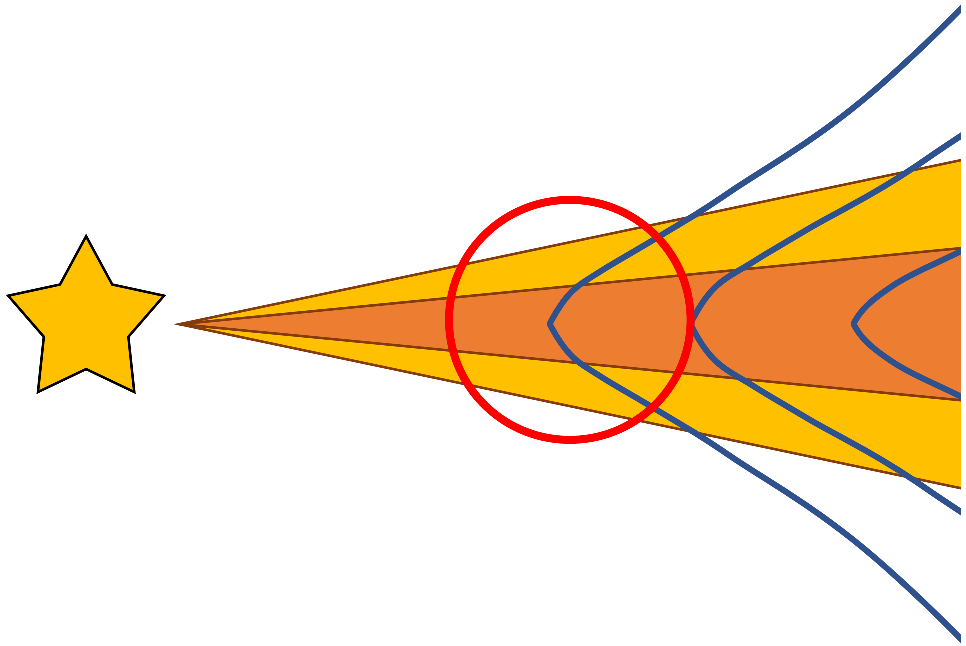
Non-ideal MHD – Ambipolar Diffusion (AD)

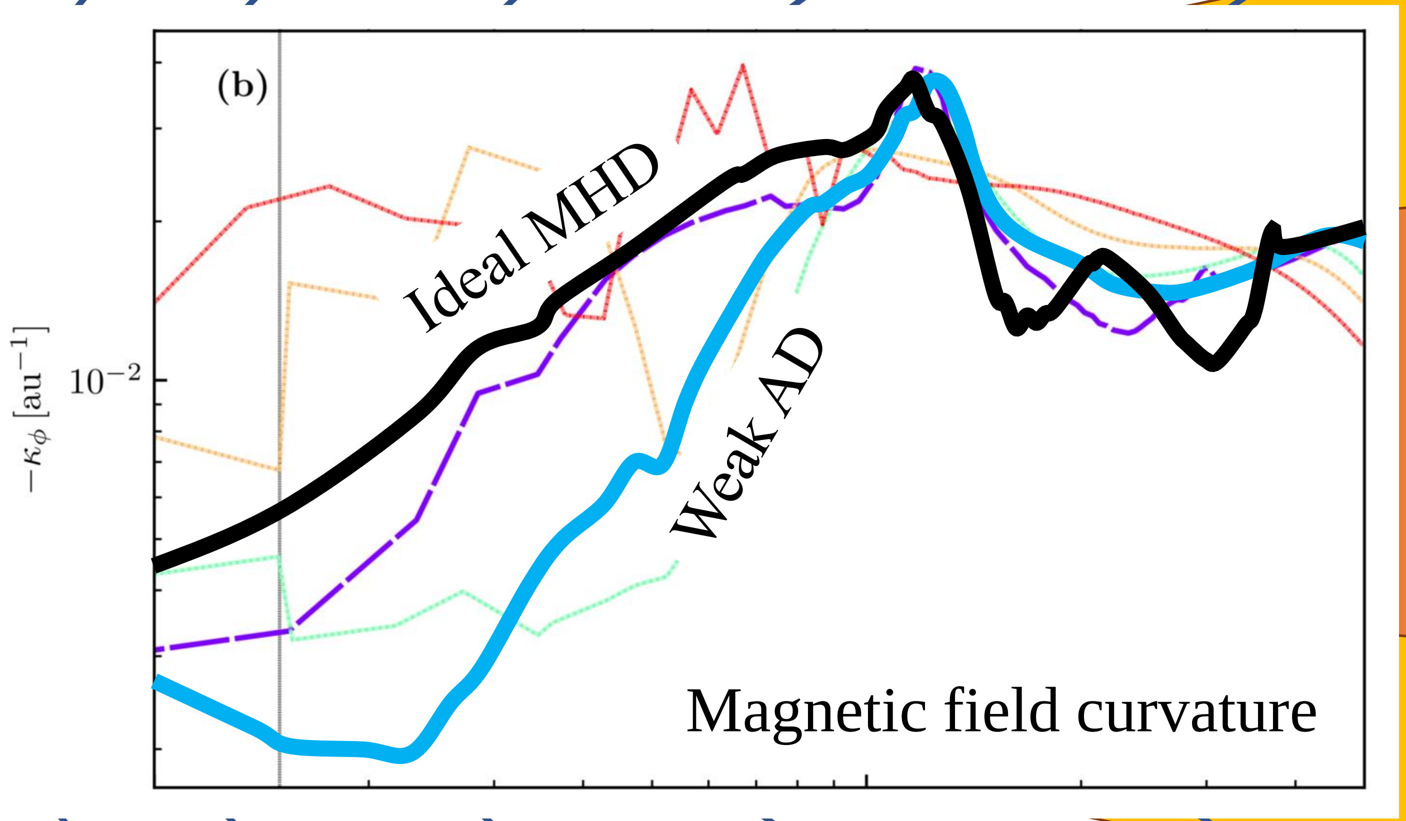


Non-ideal MHD – Ambipolar Diffusion (AD)



Non-ideal MHD – Ambipolar Diffusion (AD)

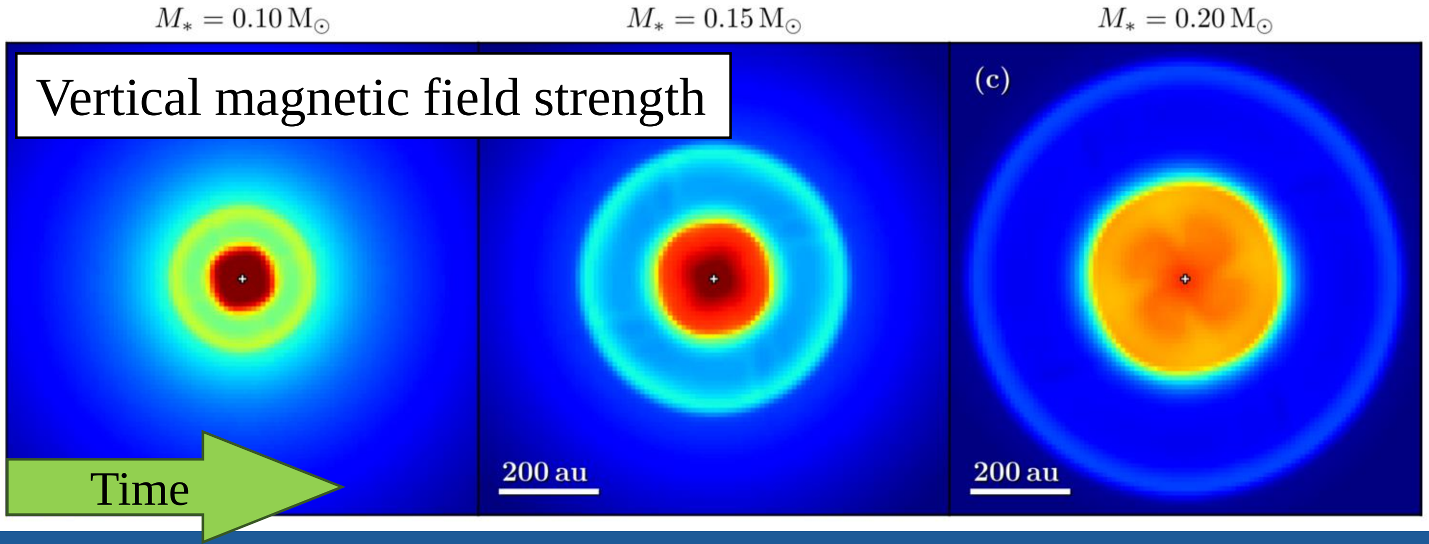




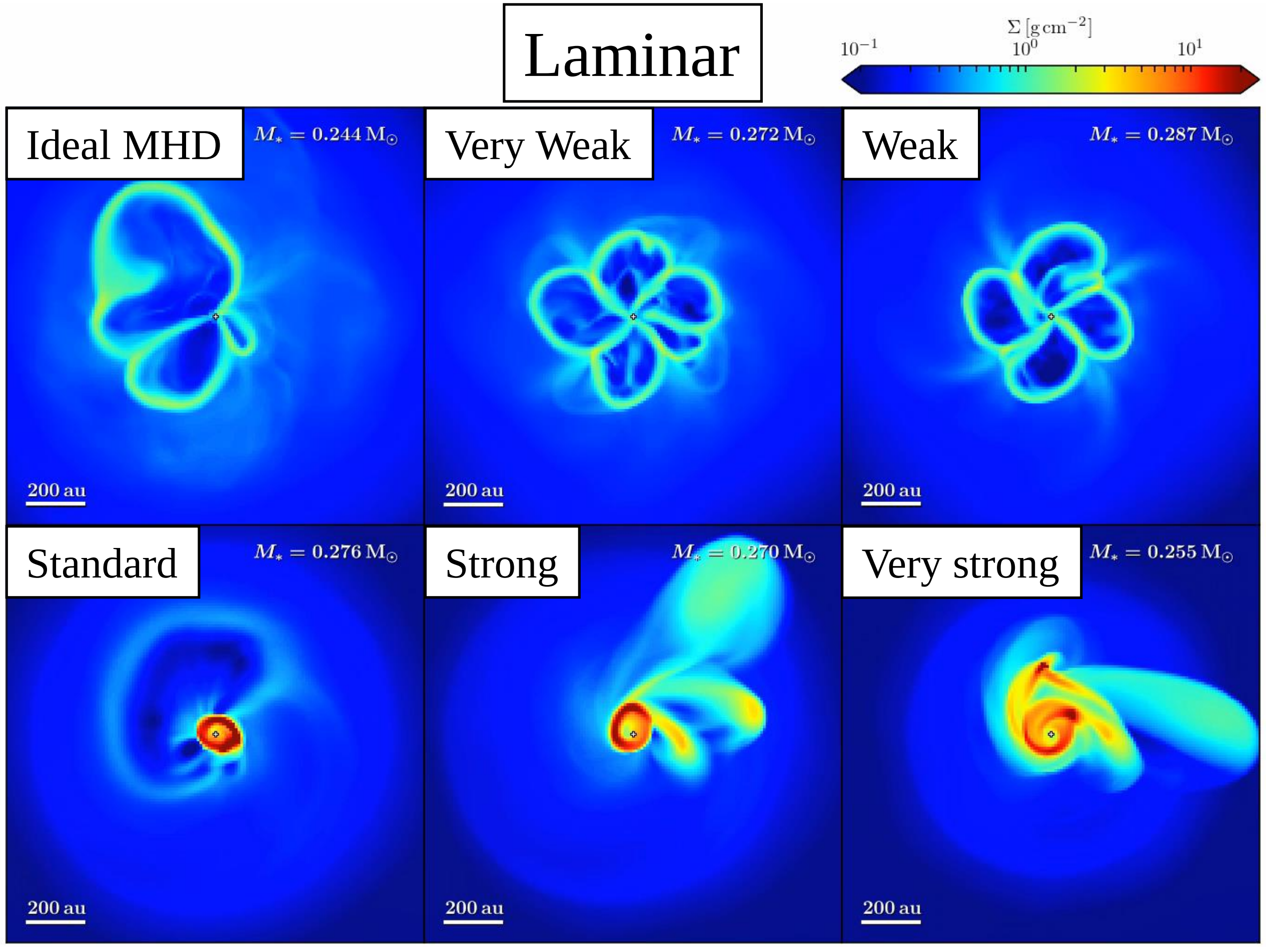
Magnetic field curvature

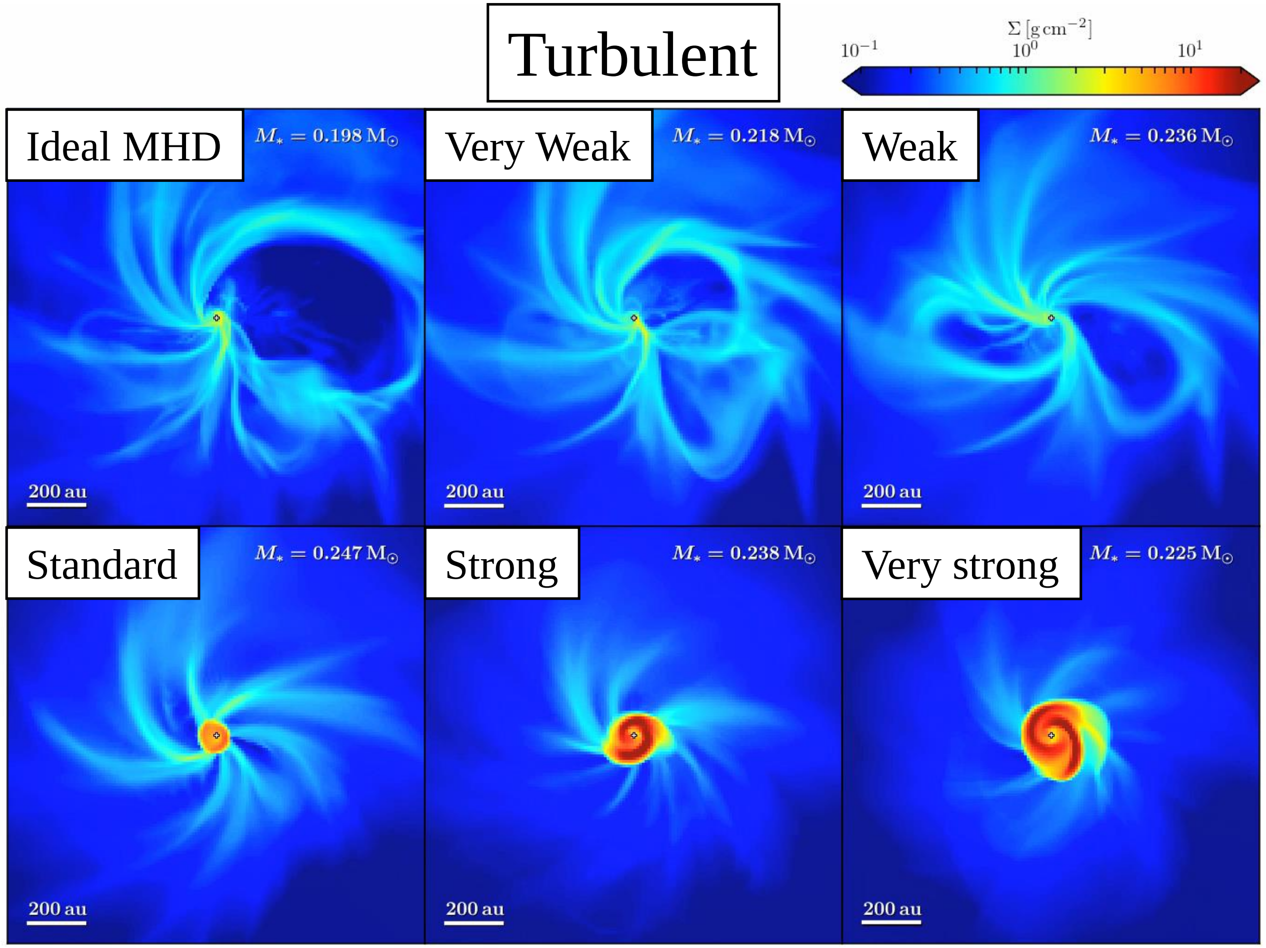
Non-ideal MHD – Ambipolar Diffusion (AD)

- As in other studies
  - AD shock (Li & Mckee 1996) or magnetic field plateau (Masson et al. 2016)
  - AD does not guarantee disk formation
    - Strong AD is needed (≥ standard level of AD)
  - Reduced magnetic field strength near the forming stars and in the disks
    - Reduced magnetic braking
- But reduced magnetic field strength does not explain reduced torque completely
  - Straighter B field lines



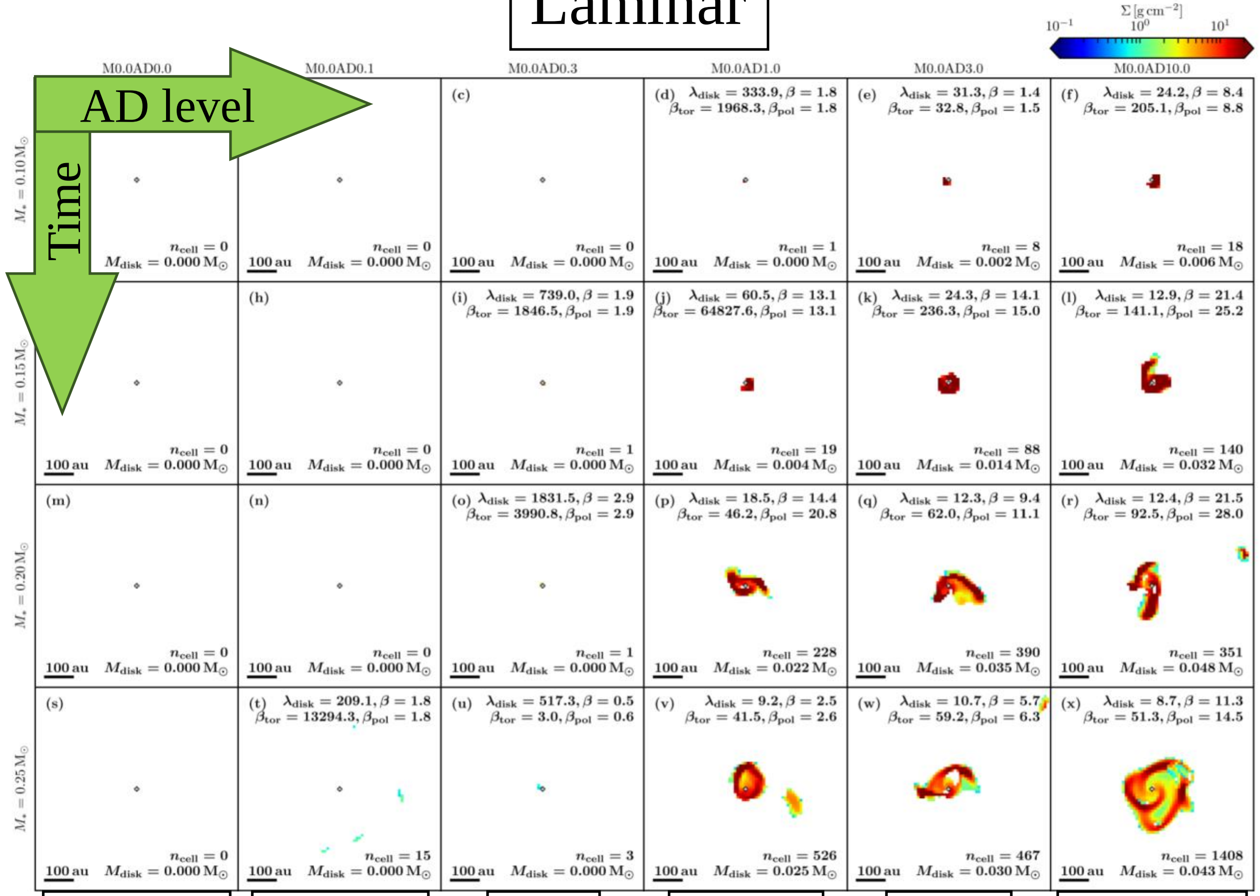
Disk Formation with Turbulence and AD





Disk Formation with Turbulence and AD

Laminar

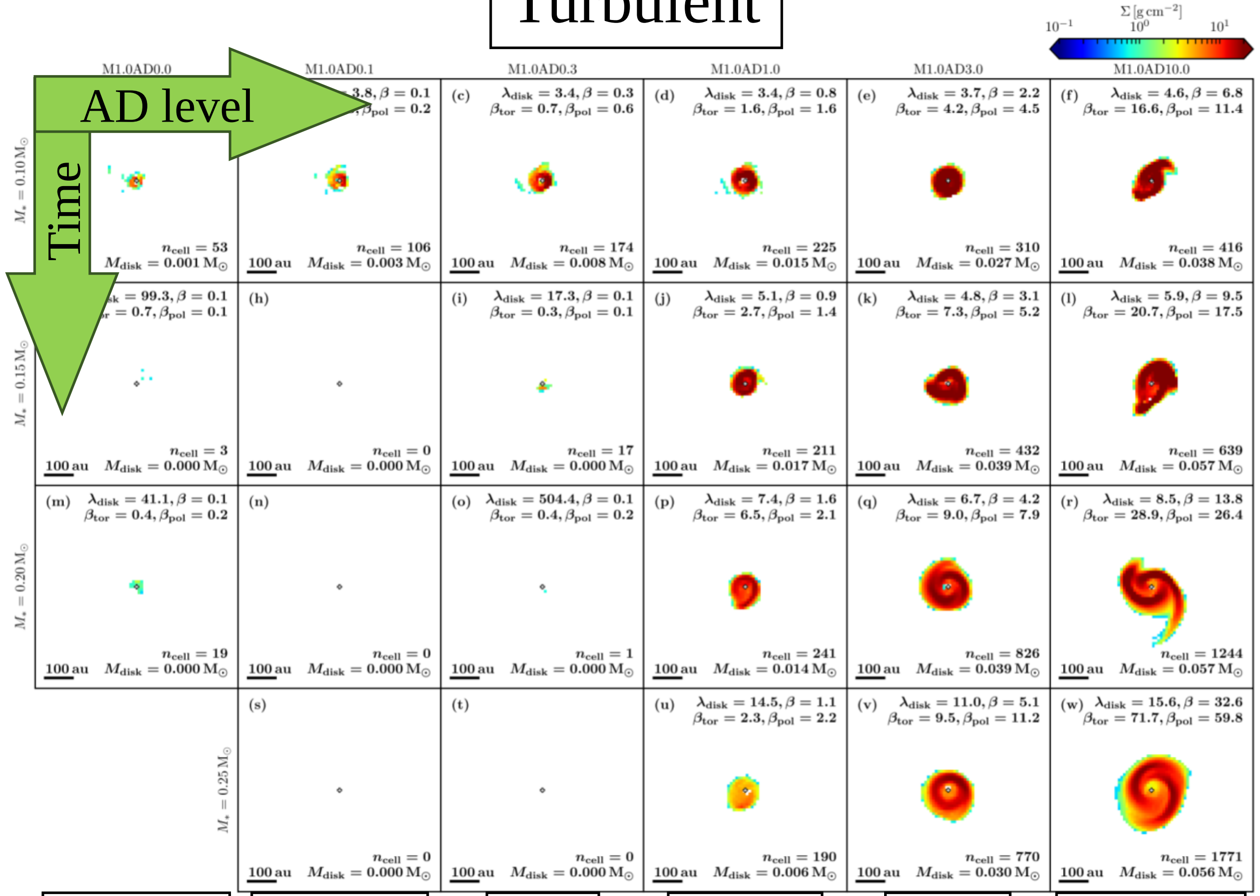


AD level

Time

Ideal MHD | Very weak | Weak | Standard | Strong | Very strong

Turbulent



AD level

Time

Ideal MHD | Very weak | Weak | Standard | Strong | Very strong

Disk Formation with Turbulence and AD

- Turbulence enables early (transient) disk formation
  - Earlier leakage of magnetic flux
  - Self-sorting of angular momentum
- Strong AD allows disks to survive
  - Decoupling of magnetic flux
  - Less magnetic field line pinching
- Turbulence suppresses fragmentation in the strong AD case
  - Asymmetry allow angular momentum transport
- Strong magnetization
  - $\beta < 10^2 \ll 10^5$ used in protoplanetary disk simulations

Disk Formation in Athena++

- Self-gravity with AMR
- General EOS / radiative transfer
- **Sink particle treatment**
- Turbulence
- Non-ideal MHD

Summary

- Implementation of sink particle treatment is needed
- Turbulence shapes the accretion flow into a warped pseudodisk
- Turbulence and ambipolar diffusion work in a complementary way
  - Turbulence allow early disk formation
  - Standard or stronger ambipolar diffusion allow disk to survive
- Disks formed in this study are strongly magnetized