The (Milky) Way The Wind Blows:

MHD Simulations Of Wind Accretion In The Galactic Center

Sean Ressler (Berkeley —> KITP);
Eliot Quataert (Berkeley);
Jim Stone (Princeton—>IAS)

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MHD Simu
Wind Ac
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“Resting mountain climbers”

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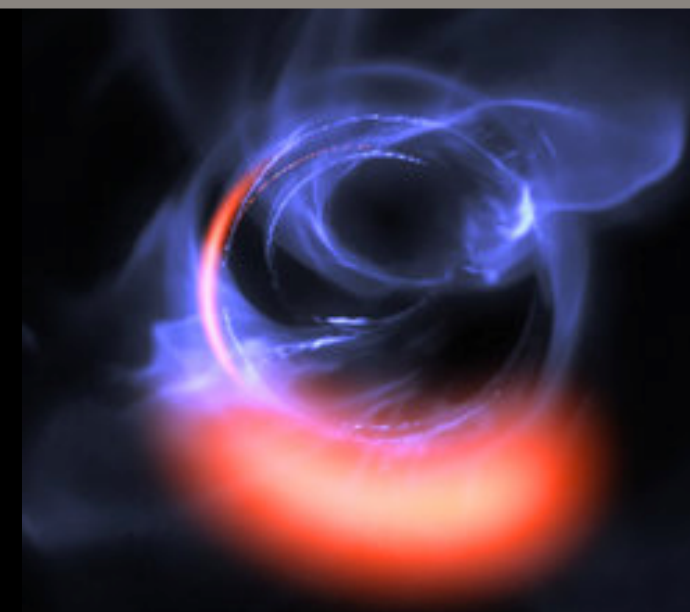
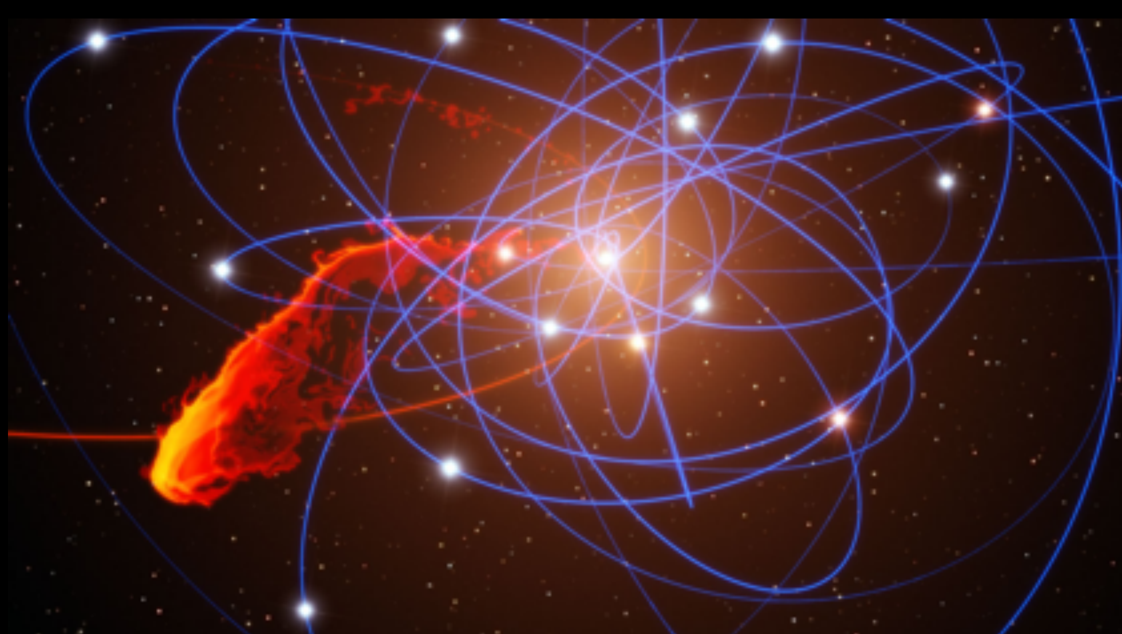
Sgr A* : Best "Lab" For SMBH Accretion

Credit: ESO/Gravity Consortium/L. Calçada



ALMA

- Surrounding stellar population/gas resolved
- Huge amount of data + time variability



Credit: Keck/UCLA Galactic Center Group

- Angular size ~ micro arc secs (GRAVITY, EHT)
- Extremely low luminosity (10^{-9} Edd) —-> optically thin, geometrically thick, collisionless at small scales

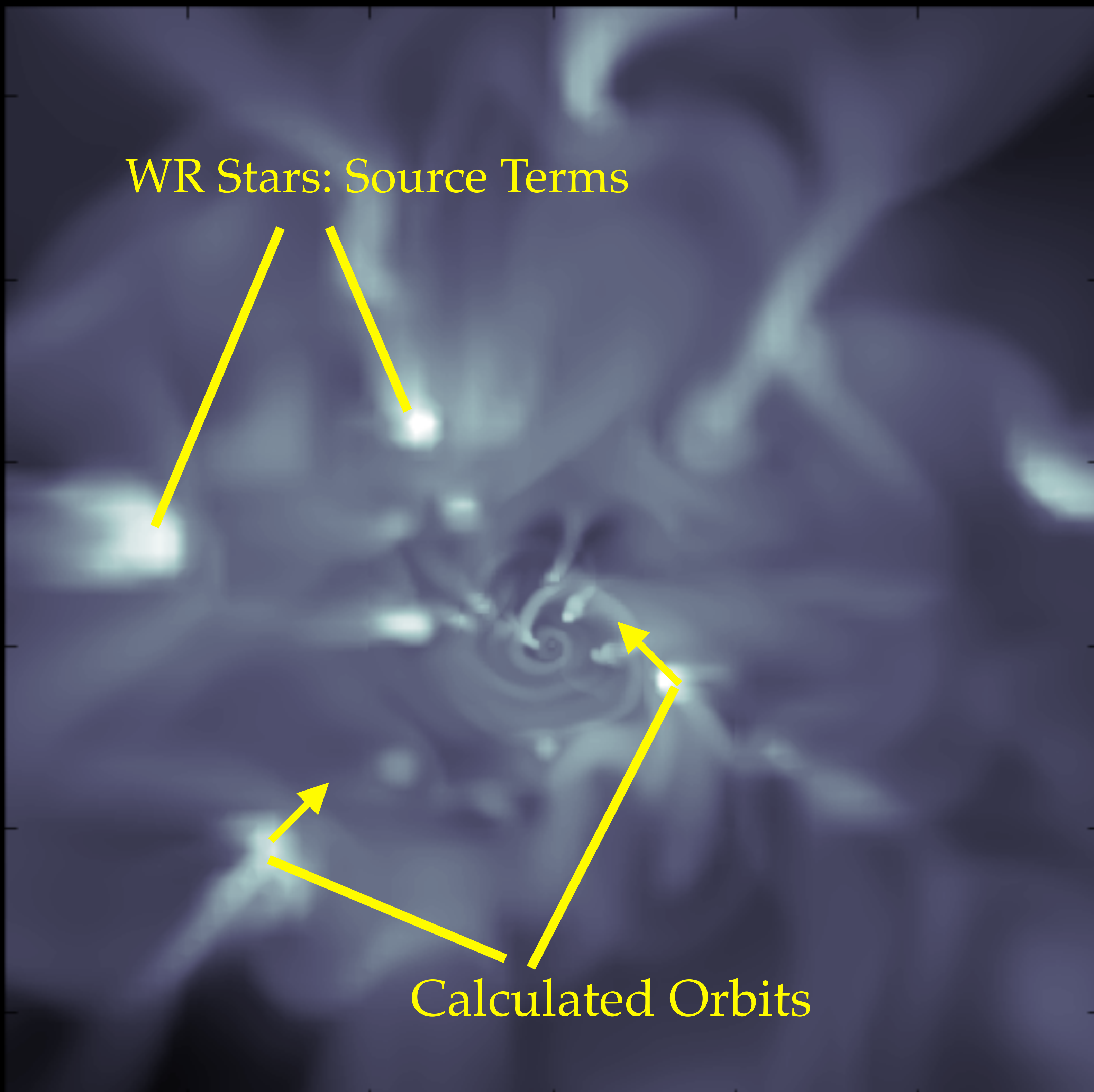
Sagittarius A*: A Simple Sketch

Sagittarius A*: A Simple Sketch

Questions I Seek To Address

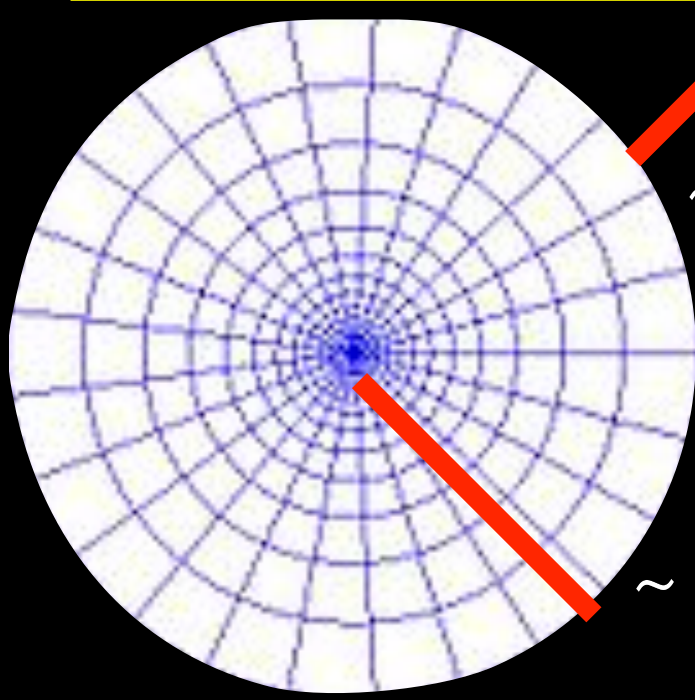
- What limits accretion? $\dot{M} \ll \dot{M}_{\rm bondi}$ Outflow, convection, angular momentum?
- How important are magnetic fields in terms of angular momentum transport? Are they necessary for accretion?
- What conditions lead to a strong jet/outflow?
- Can we explain observables such as the X-ray luminosity (yes), the rotation measures of the black hole (yes) and magnetar (yes, but fine-tuned)?
- What do we predict for the flux threading the black hole? The geometry of the field?
- Which initial/boundary conditions for GRMHD simulations are appropriate?

Magnetized Wind Simulations



Observational Input:
Wind Speeds
Mdots
Orbits

MHD Parameters:
$B = B_\phi \quad \beta_w \equiv \frac{\rho v_w^2}{P_B}$
Spin Axes: Random

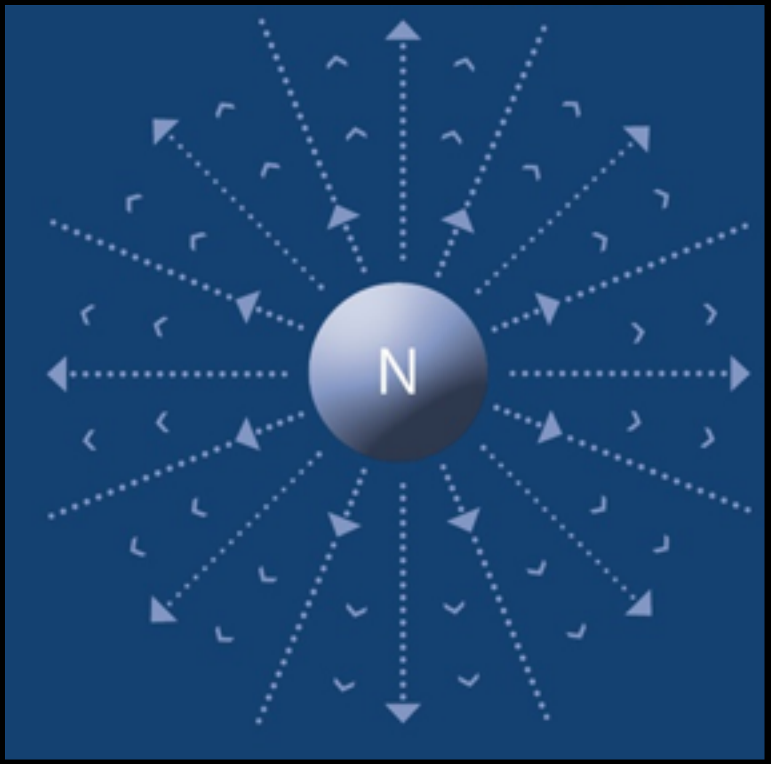


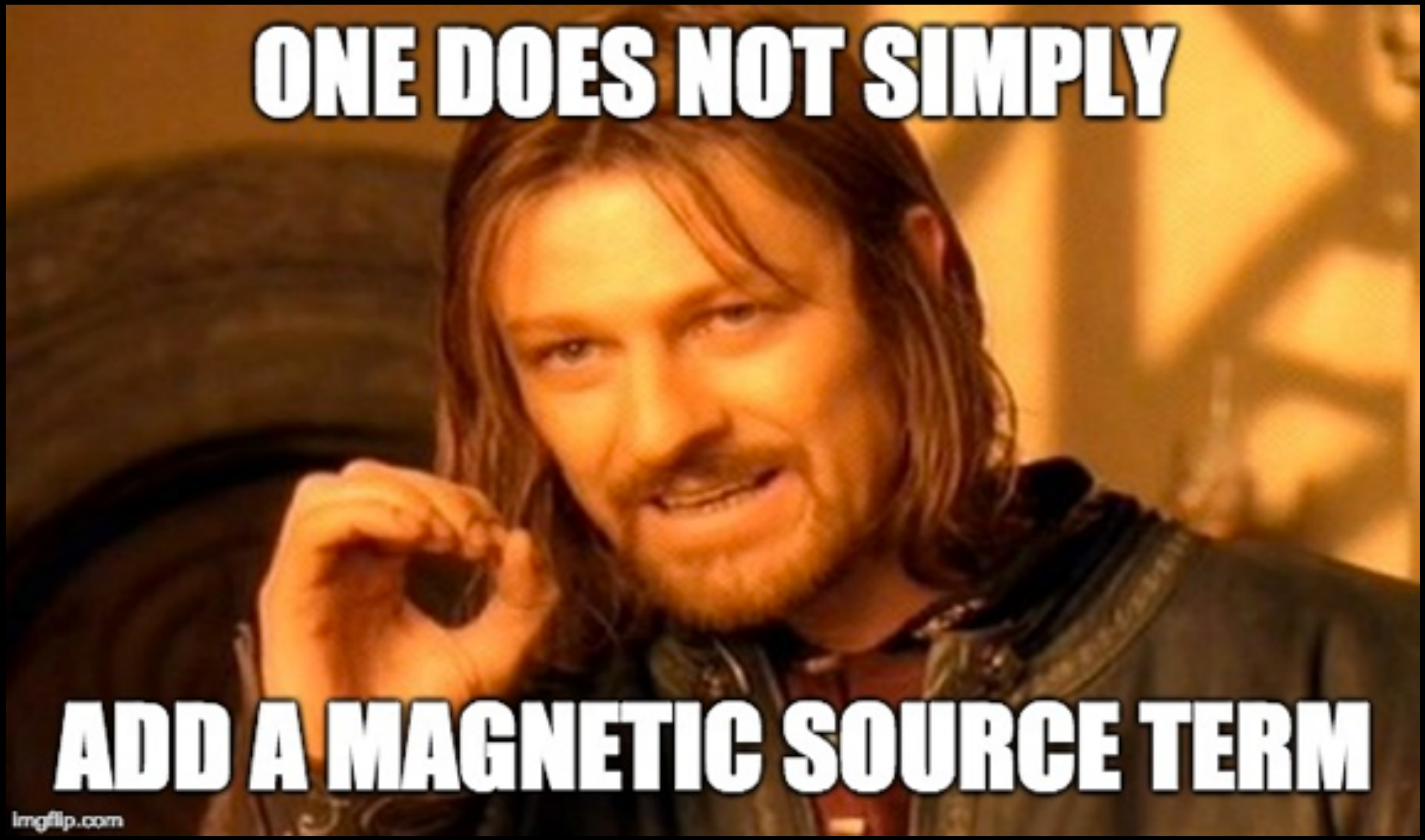
~ 1 pc
$\sim 2.5 \times 10^5 \, r_H$

$\sim 0.6 \times 10^{-5}$ pc
$\sim 150 \, r_H$

Stellar Wind Magnetic Field

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = \dot{B}_w \hat{\varphi}$$





Stellar Wind Magnetic Field: Work With E

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right)$$

Stellar Wind Magnetic Field: Work With E

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} + \vec{E}_w \right)$$

$$\vec{E}_w = -\frac{\pi v_w}{r_w^2} \sqrt{\frac{2\dot{M}_w v_w}{\beta_w}} \cos(\theta') \sin\left(\frac{r'}{r_w} \pi \right) \vec{r'}$$

$$\vec{\nabla} \times \vec{E}_w = \frac{\pi v_w}{r_w^2} \sqrt{\frac{2\dot{M}_w v_w}{\beta_w}} \sin(\theta') \sin(\frac{r'}{r_w} \pi) \hat{\varphi}'$$

Hoop stress finite at poles

Continuous at boundary of wind

Prime = Frame aligned with spin of star

Small β_w: Acceleration and Collimation

β_w <~ 100

wind collimates

Physical, but complicates analysis

β_w <~ 5

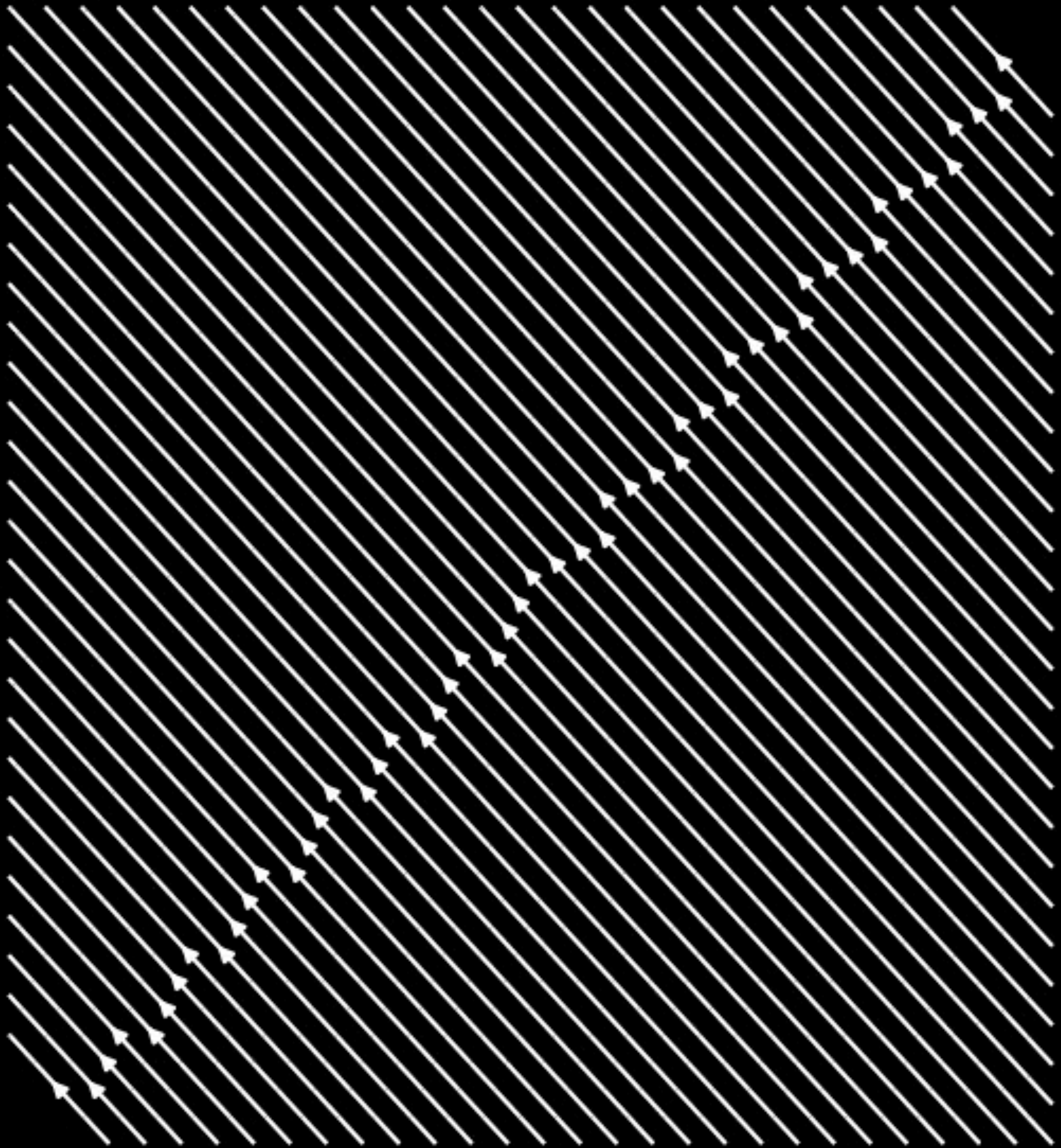
wind accelerates

Inconsistent

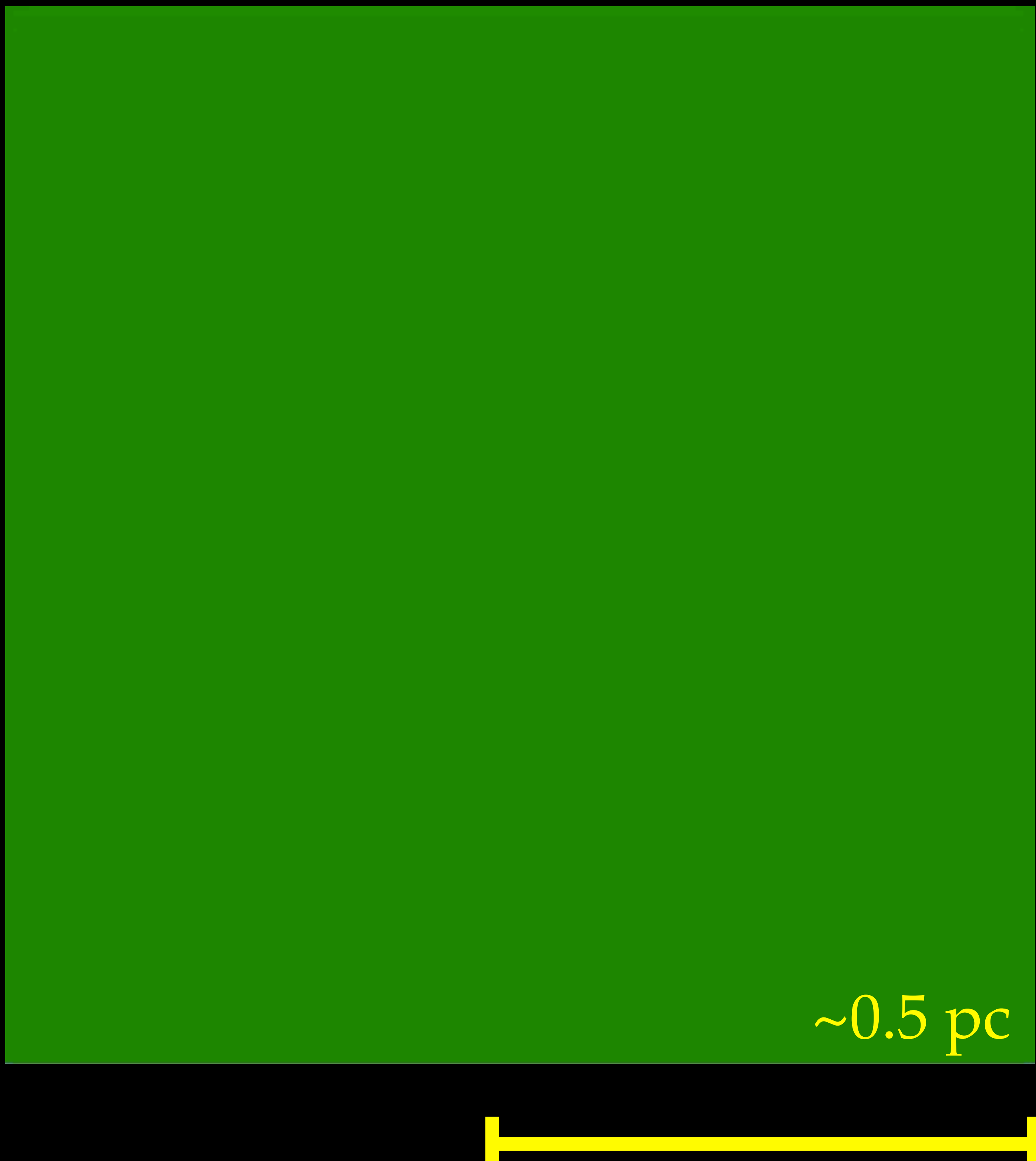
Hereafter:
$\beta_w = 100$

$$B_A = \frac{5.1\mathrm{kG}}{\sqrt{\beta_w}} \sqrt{\frac{\dot{M}}{10^{-5} M_\odot/\mathrm{yr}}} \sqrt{\frac{v_w}{1000\mathrm{km/s}}} \left(\frac{R_\odot}{r_A}\right)$$

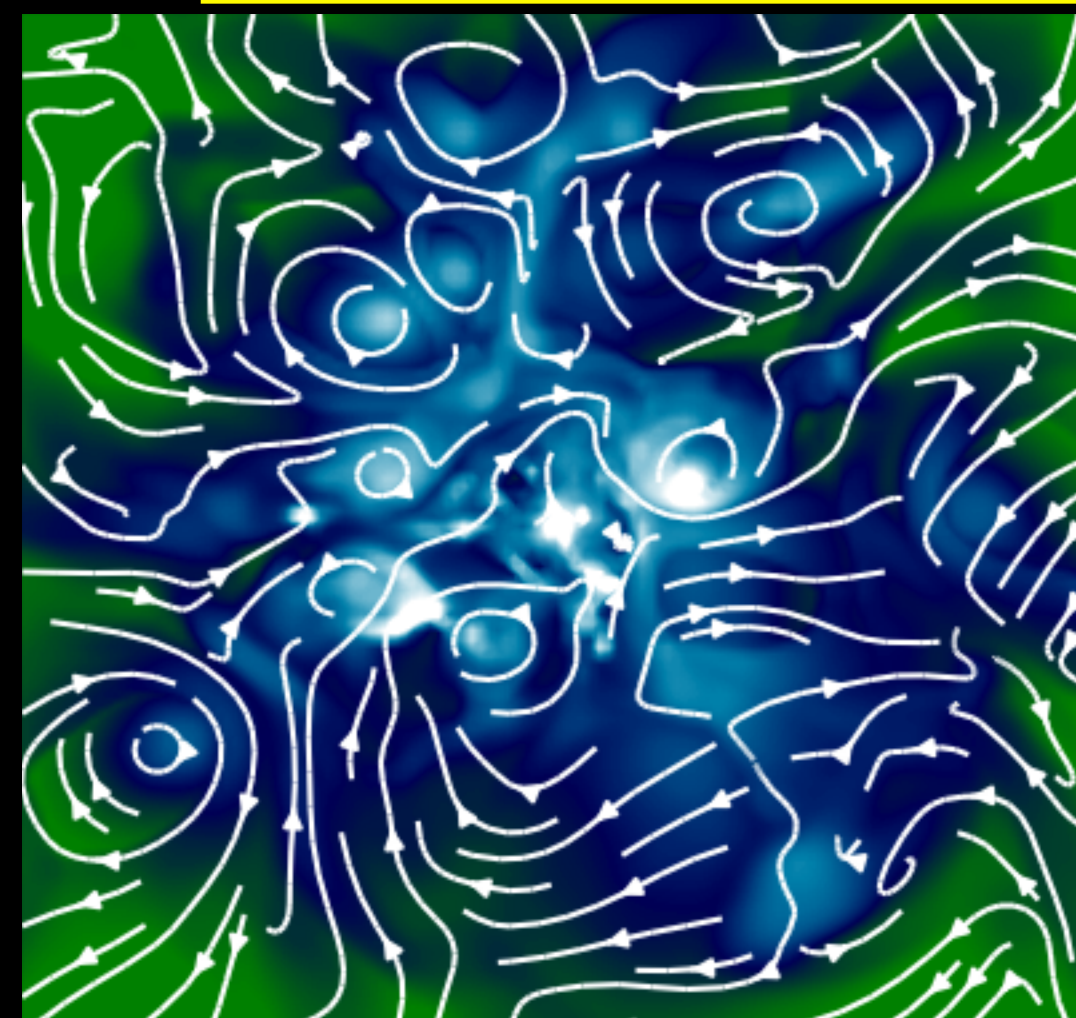
Massive O-stars: 10% as high as 0.1 - 20 kG at *surface*



3D Accretion Simulations

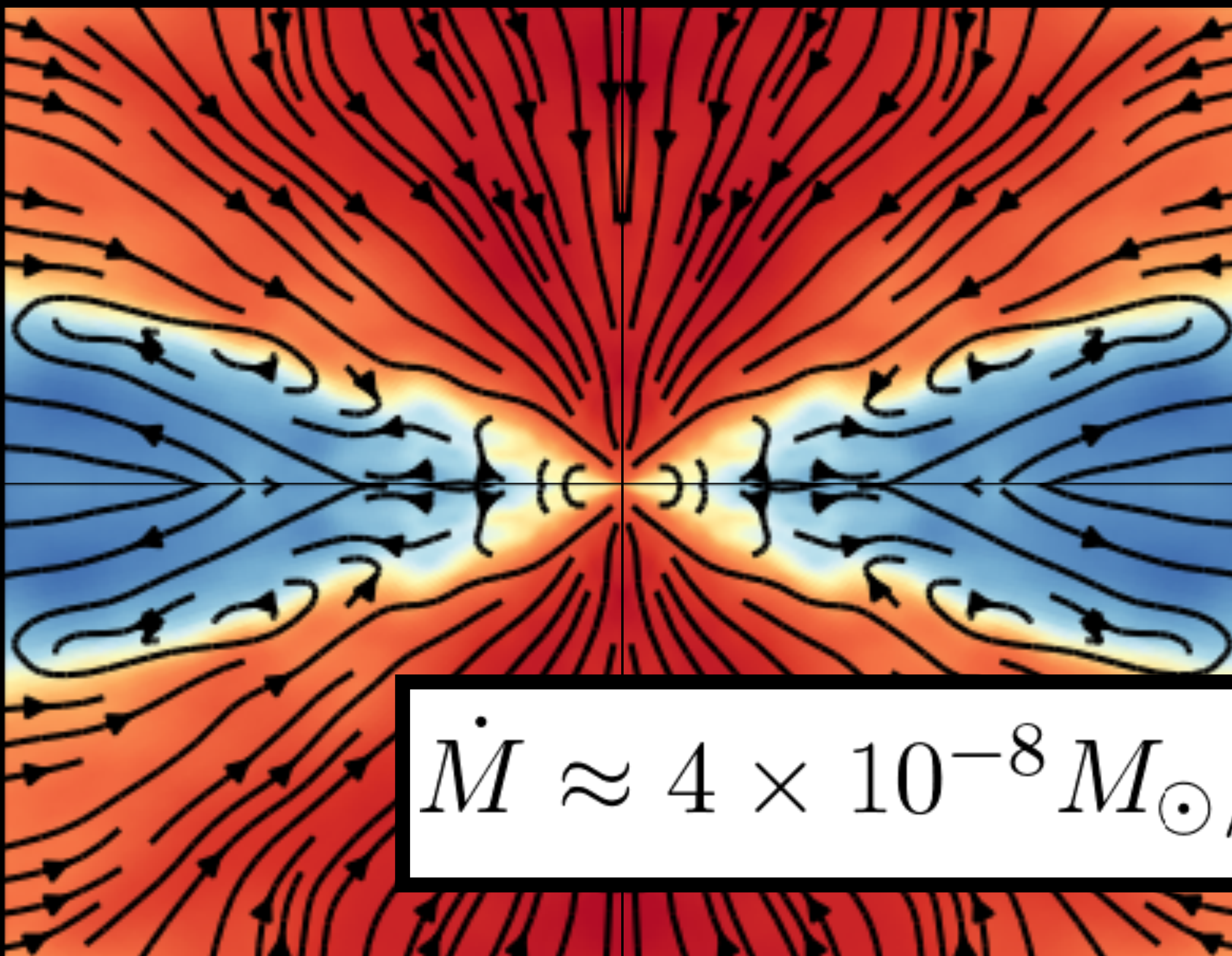


White - High Density
Green - Low Density



c.f Proga & Begelman 2008

Hydro: Accretion of Low Angular Momentum Gas



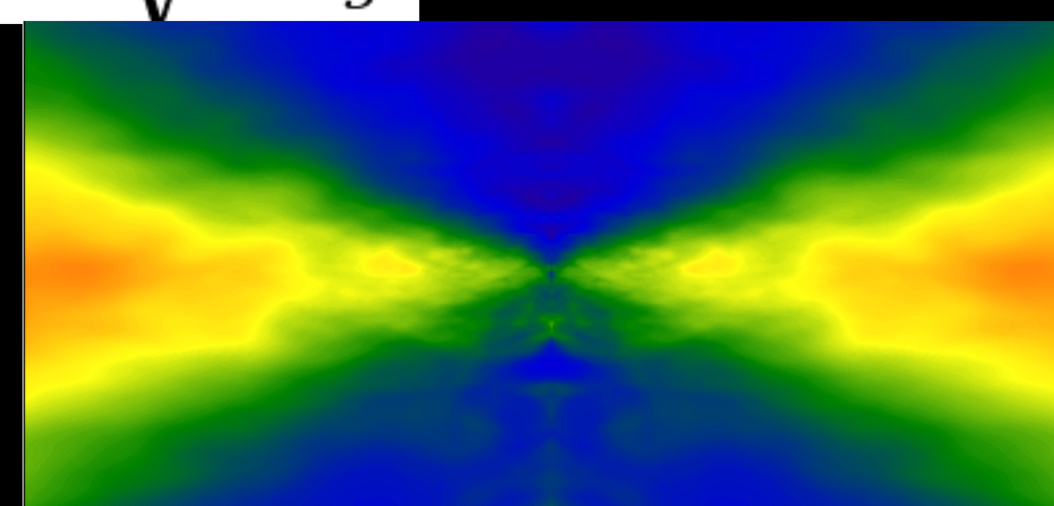
Low Angular Momentum, Accreting Gas

High Angular Momentum, Outflowing Gas

$$\dot{M} \approx 4 \times 10^{-8} M_{\odot}/\mathrm{yr}\sqrt{\frac{r_{in}}{2r_g}}$$

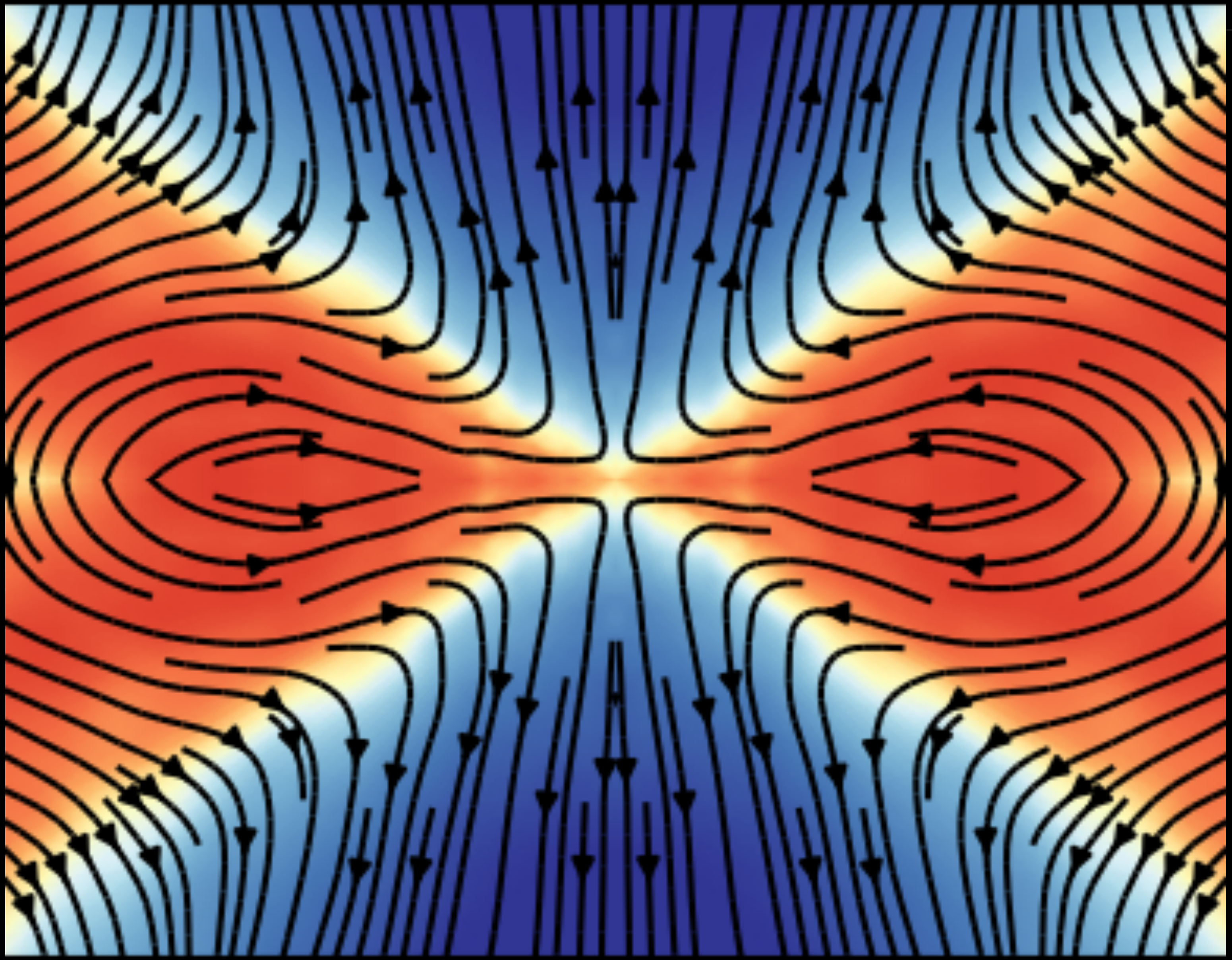
~1000 r_S ~ 5 mpc

$$\dot{M}_{in} \propto l \Rightarrow \dot{M}_{in} \propto \sqrt{r}$$



c.f Proga & Begelman 2008

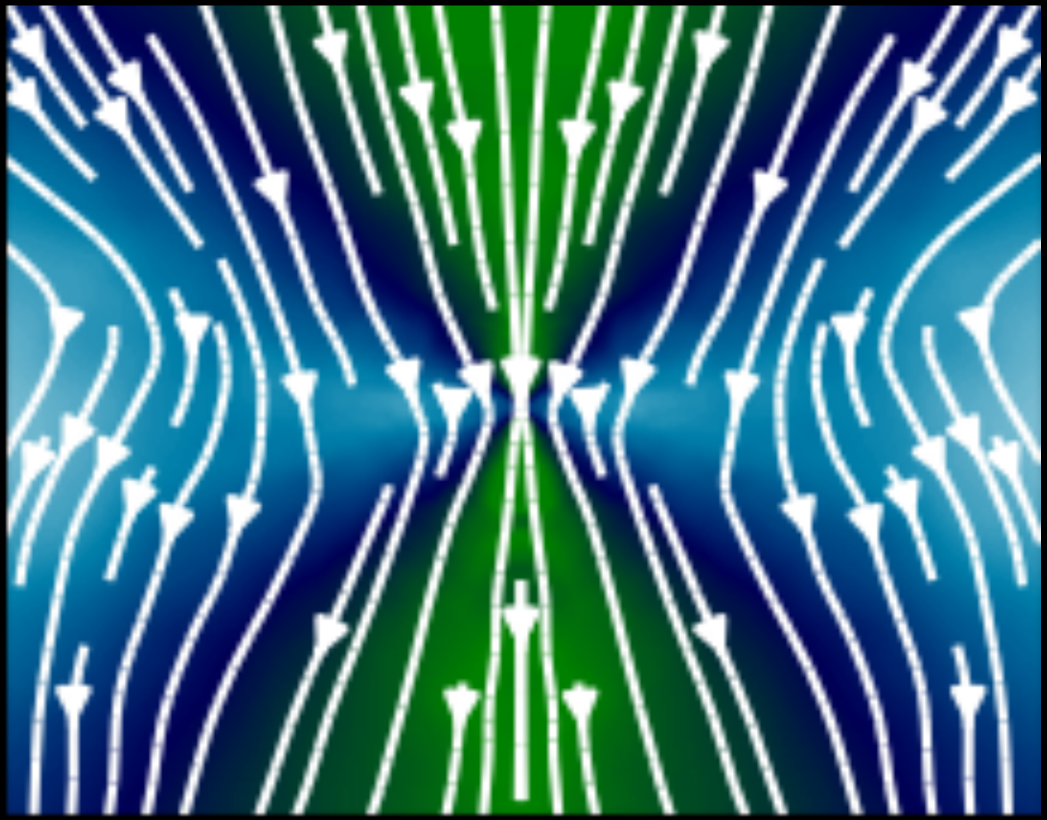
MHD: L-Transport and Polar Outflow



~1000 r_S ~ 5 mpc

Magnetically Driven
$\beta \sim 1$
Outflow

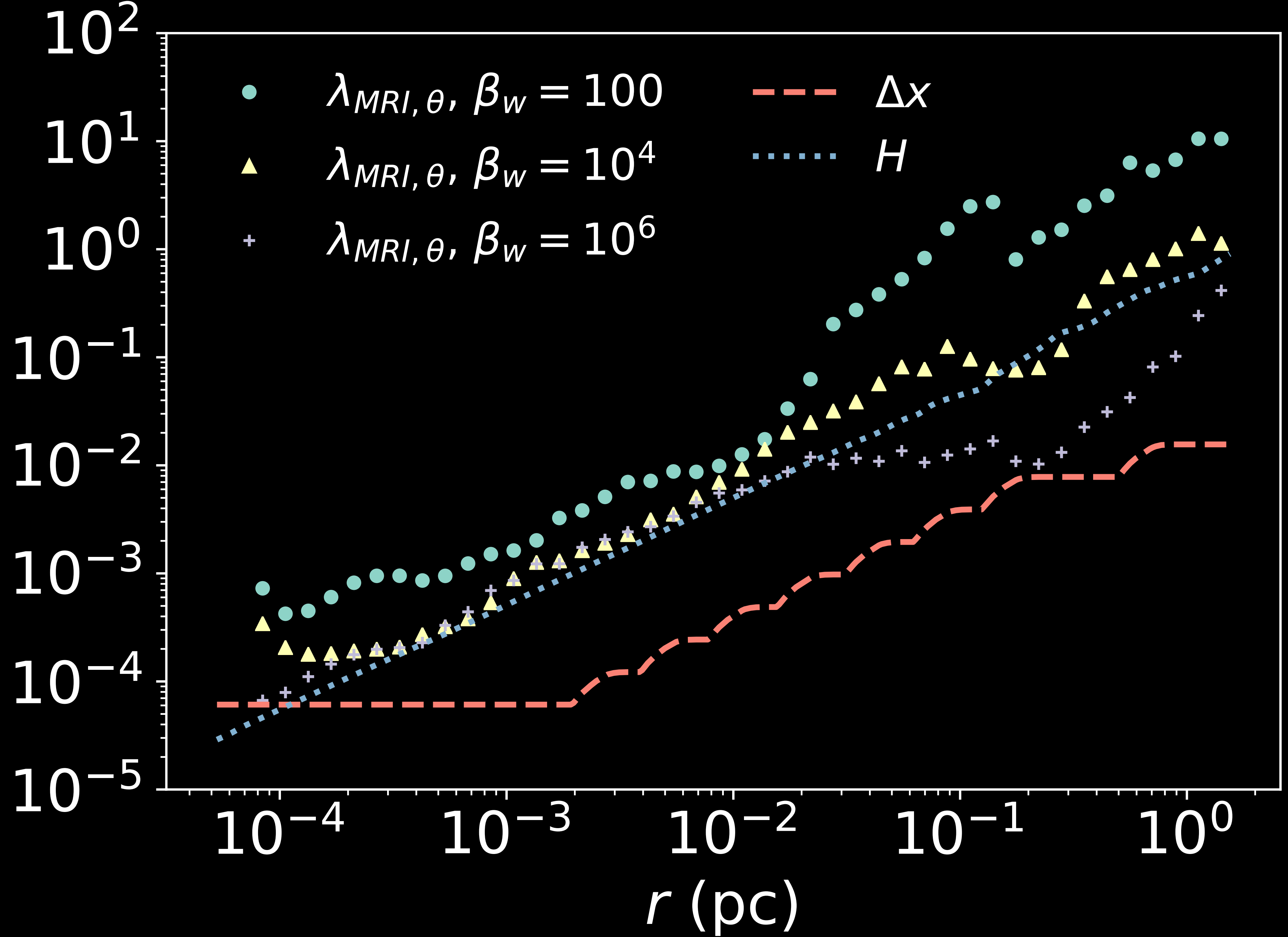
High Angular Momentum,
$\beta \sim 3$
Accreting Gas



$$\alpha_m \equiv \frac{\langle -B_r B_\varphi \sin(\theta) \rangle}{\langle P \rangle} \approx \text{const.} \approx 0.2$$

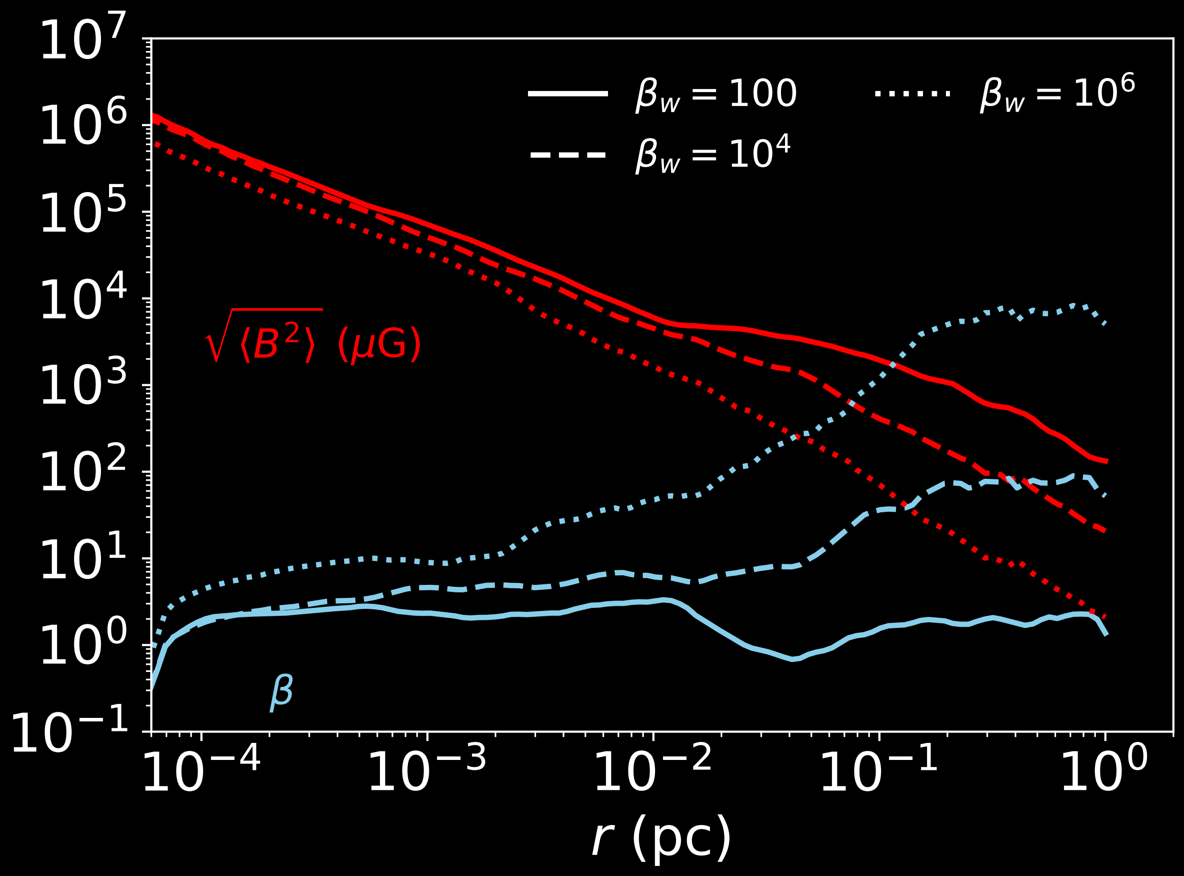
MRI Results Came Back Negative

$$\lambda_{MRI,\theta} \propto \frac{v_A}{\Omega}$$



MRI: Well resolved, but limited by size of disk

The More Things Change
The More They Stay The Same



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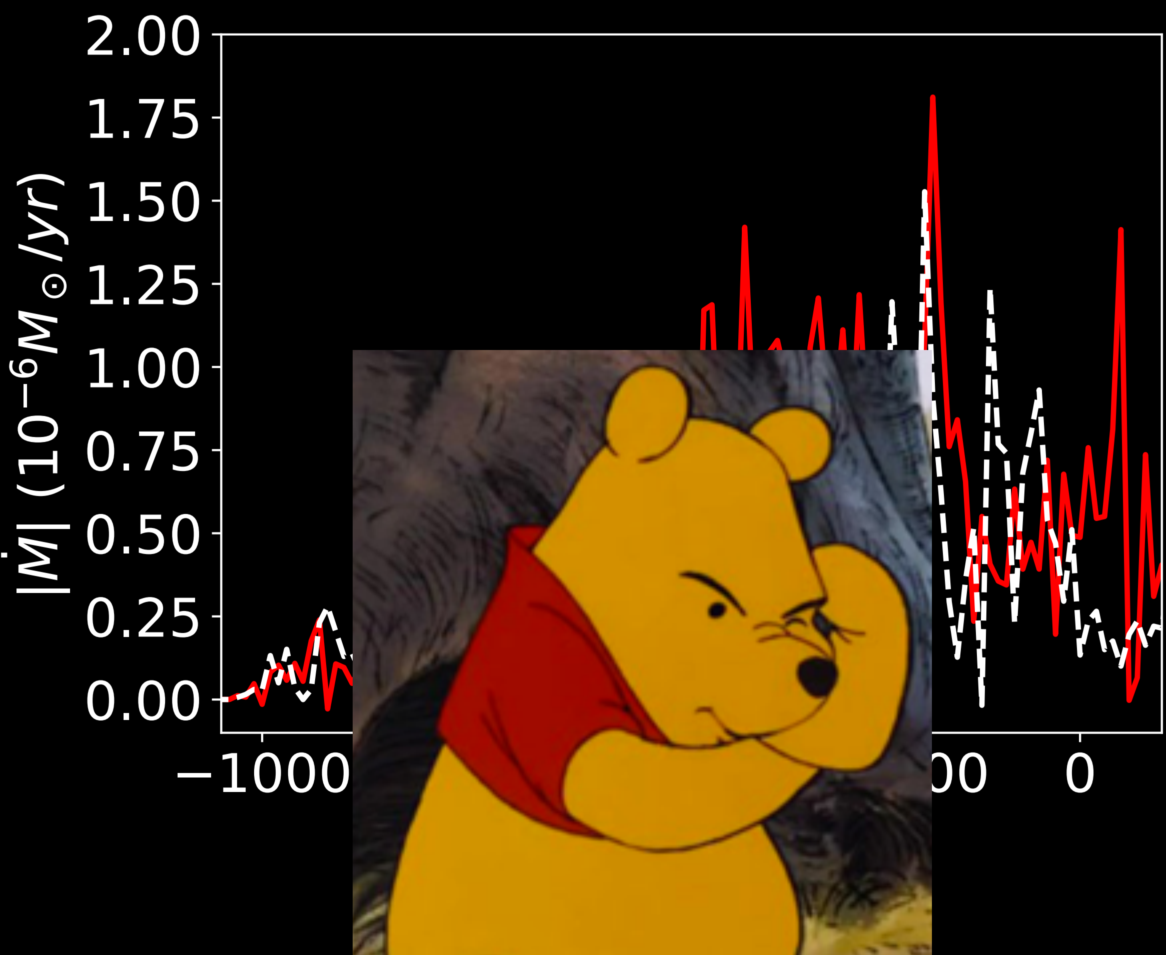
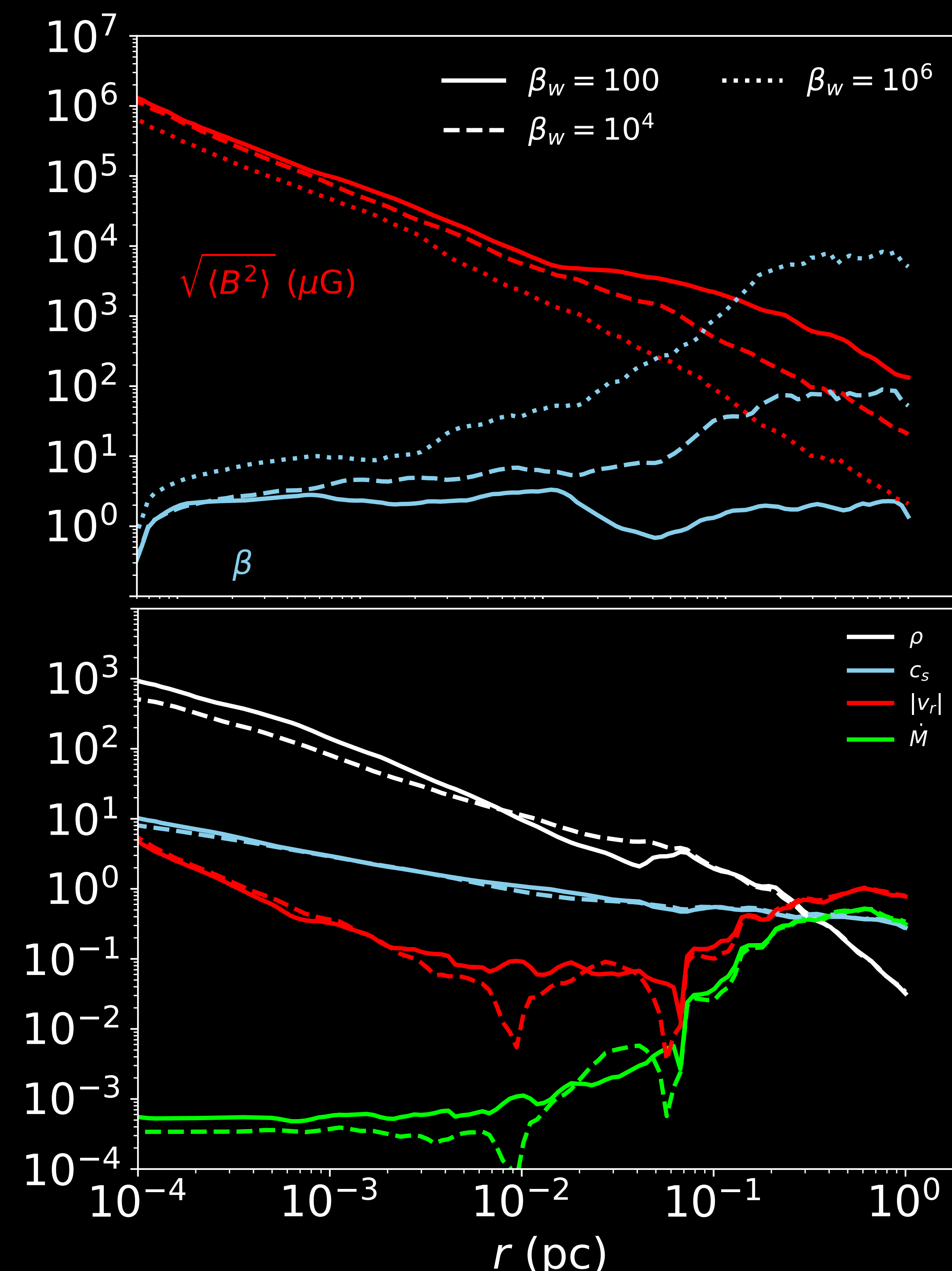
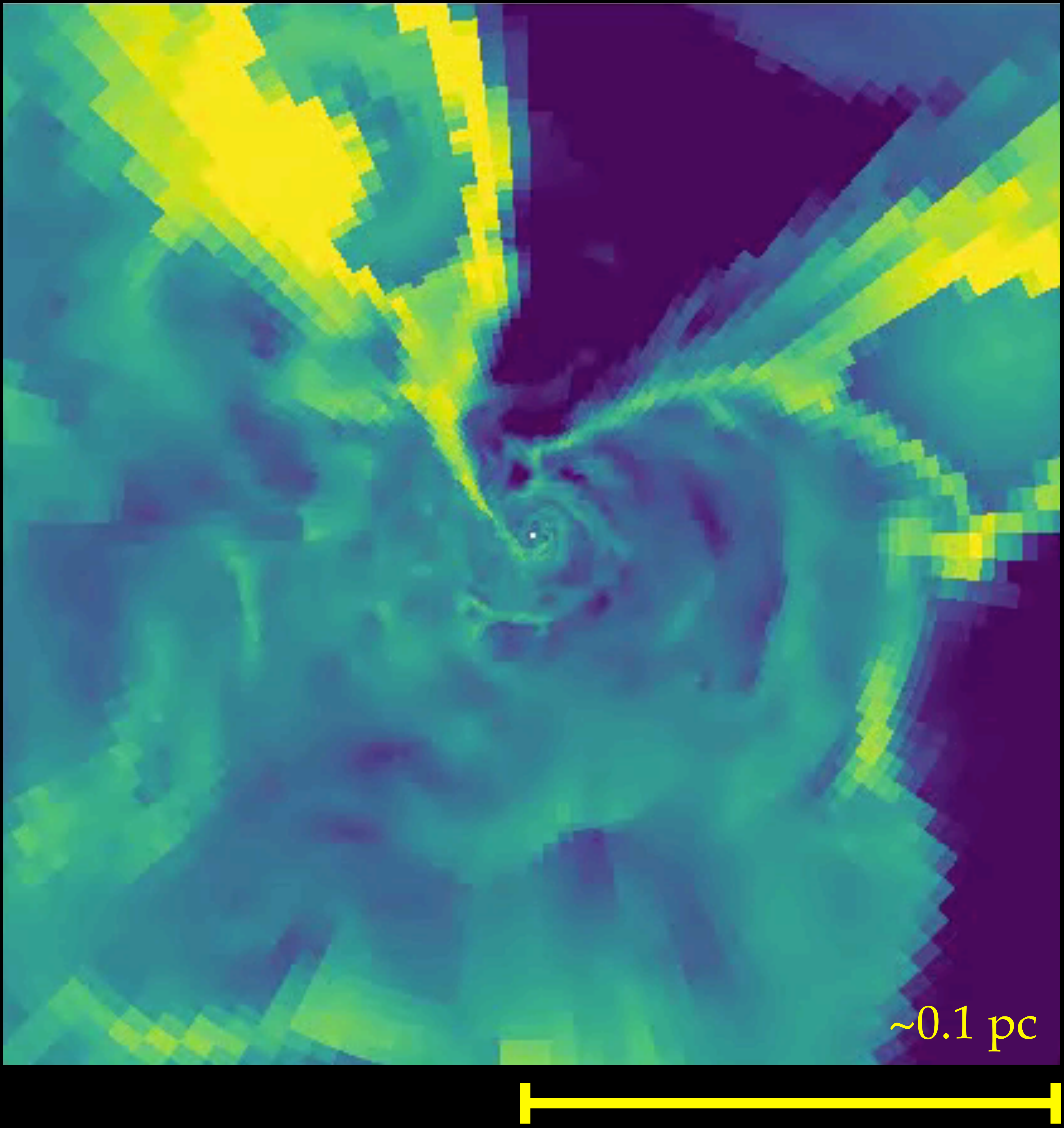


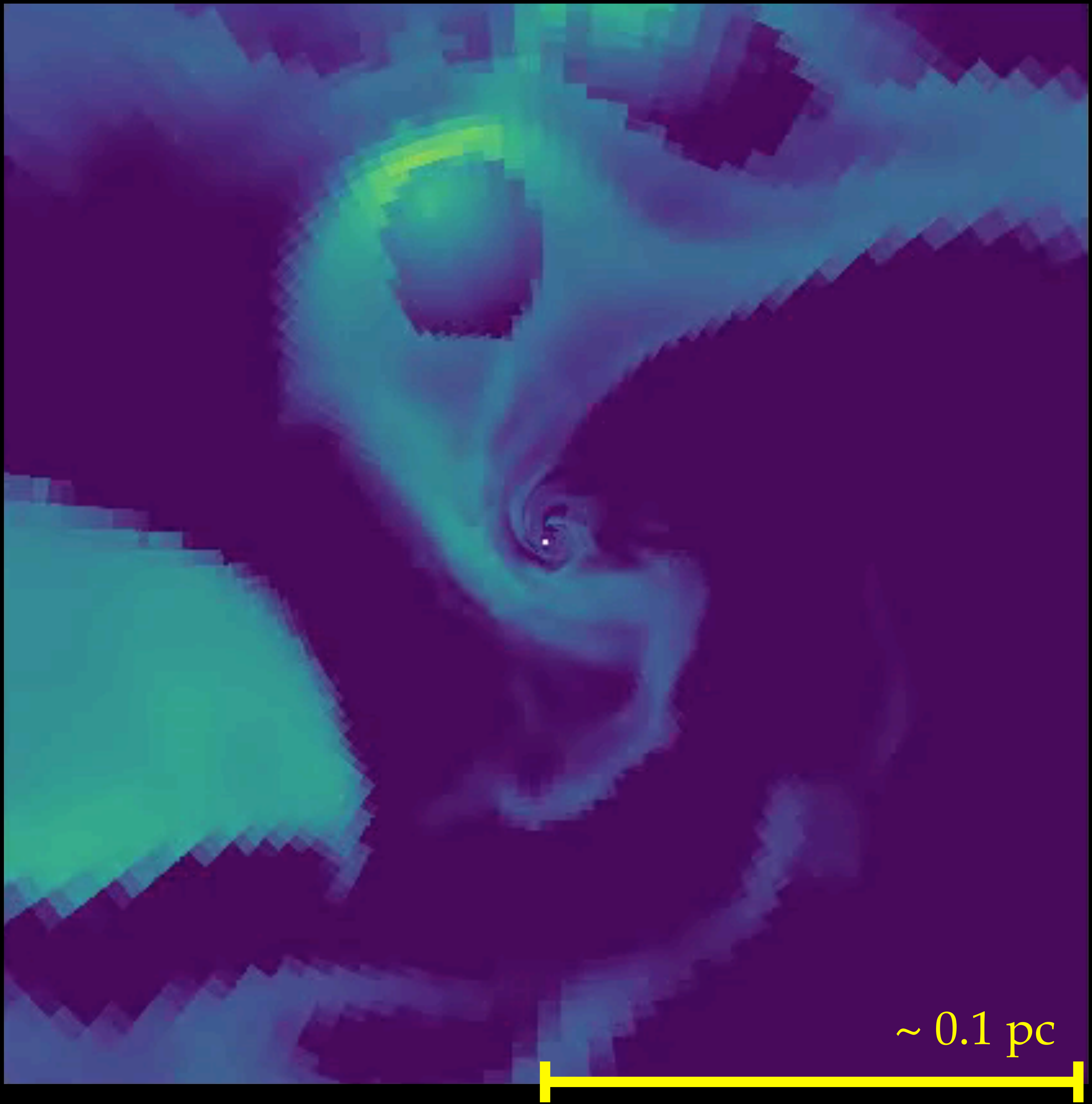


β ~ 3, α ~ 0.2, flow structure reversed

Mdot basically unchanged

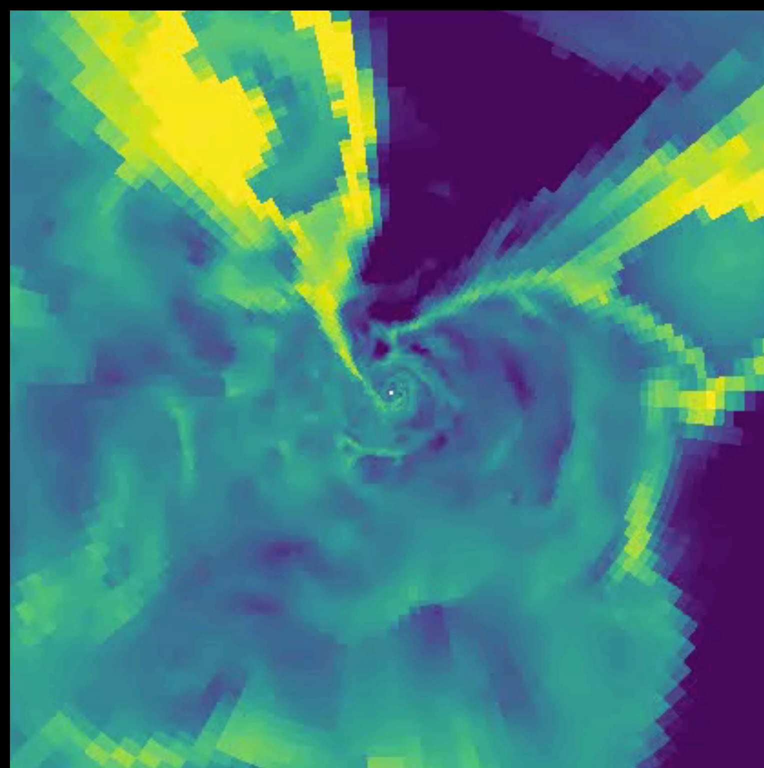


Hydro: In One Ear And Out The Other

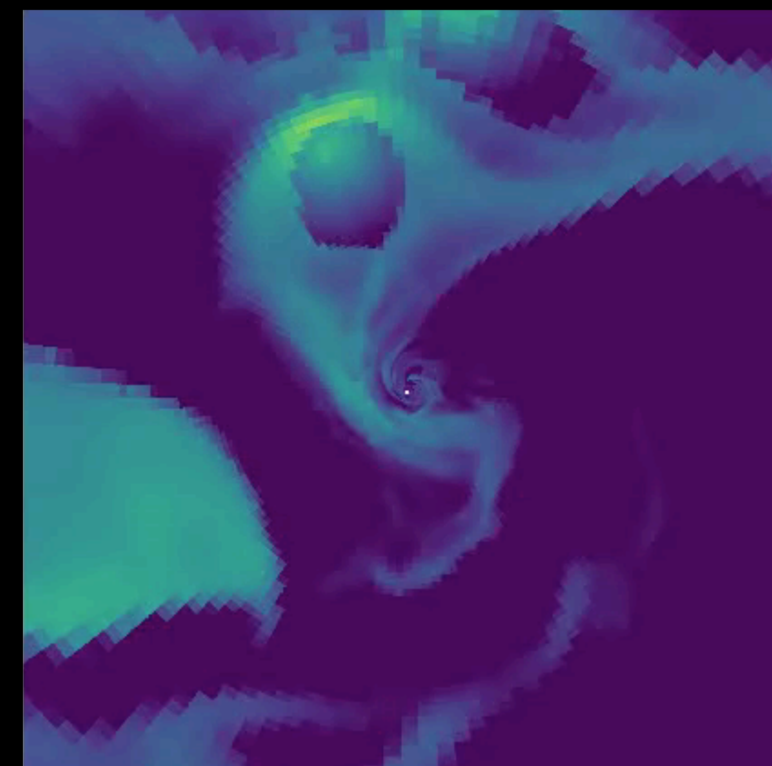


MHD: Down-ward Spiral

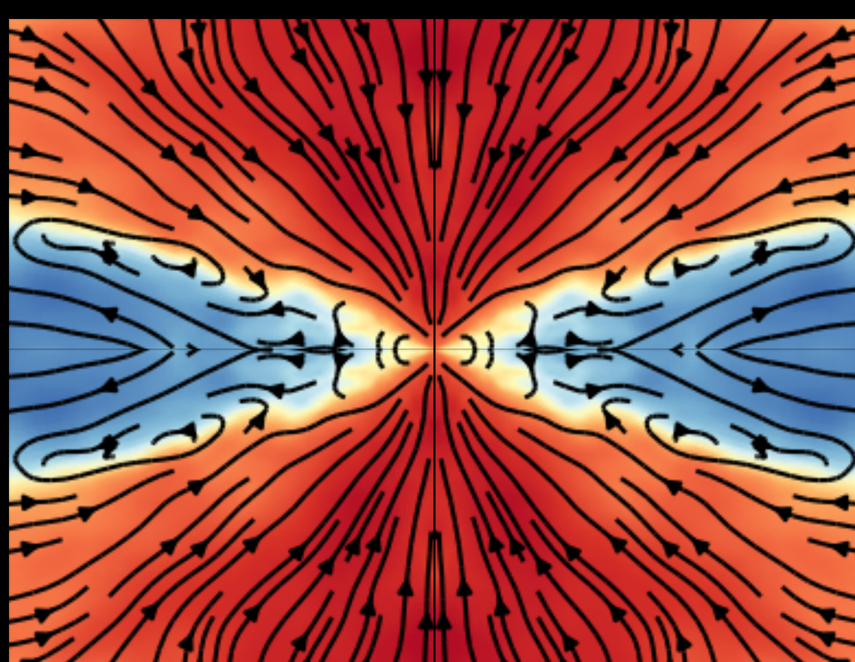
So What Exactly Is Going On?

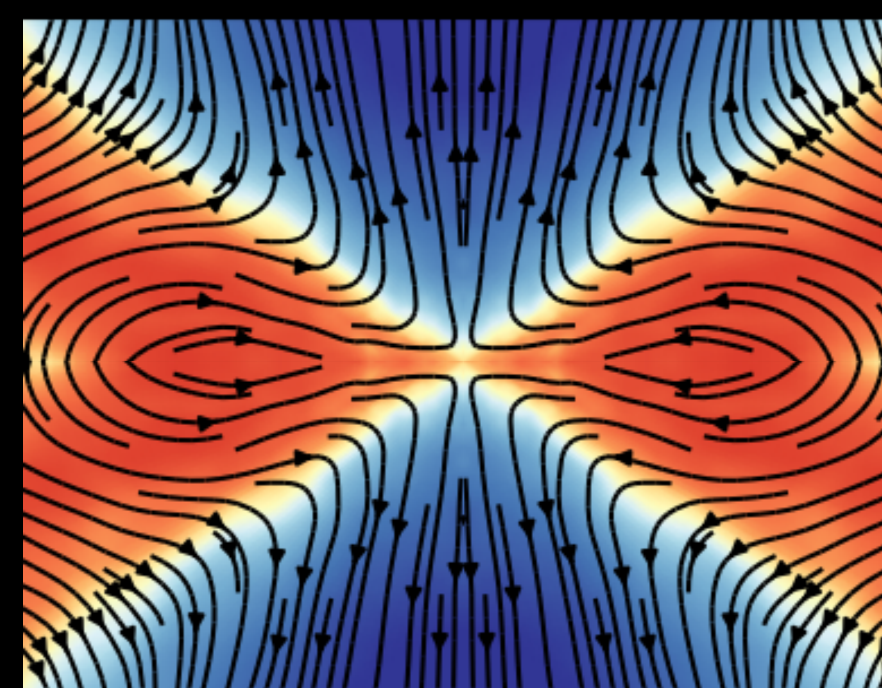


Hydro



MHD





Outflow

White - High Temp (> 10^8 K)
Black - "Low" Temp (< 5 x 10^6 K)

~ 10 kyr (hydro)

~ 1.5 kyr (MHD)

Conclusions

- Net accretion onto Sgr A* determined from mostly hydrodynamic considerations: few x 10^{-8} Msun/yr
- Field grows by flux freezing/compression, not MRI
- Hydro: high-L gas simply spirals in then out without circularizing, low-L gas accretes
- MHD: Strong coherent fields torque high-L gas, allowing it to accrete
- Magnetic fields, however, still can drive strong outflows