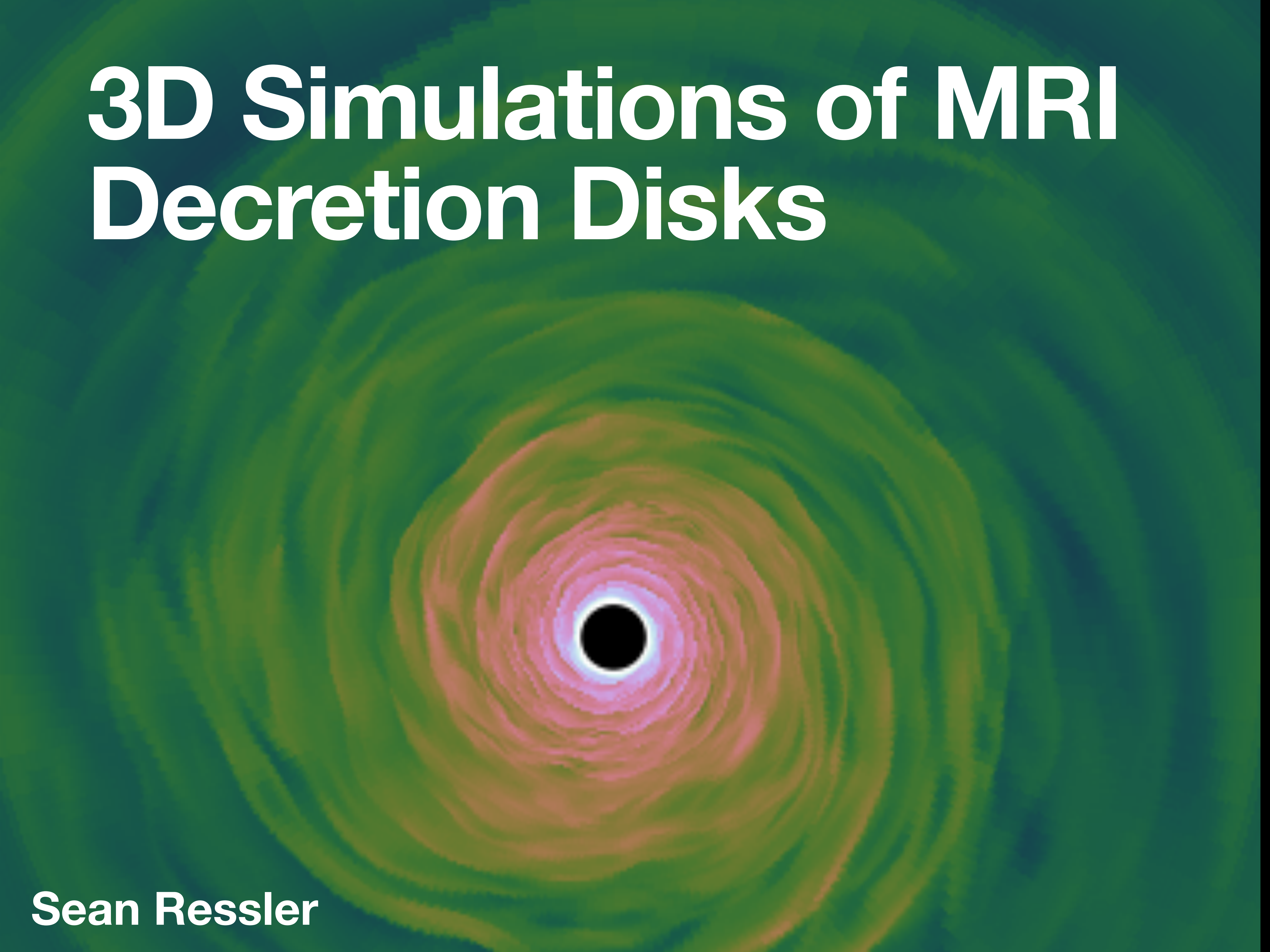
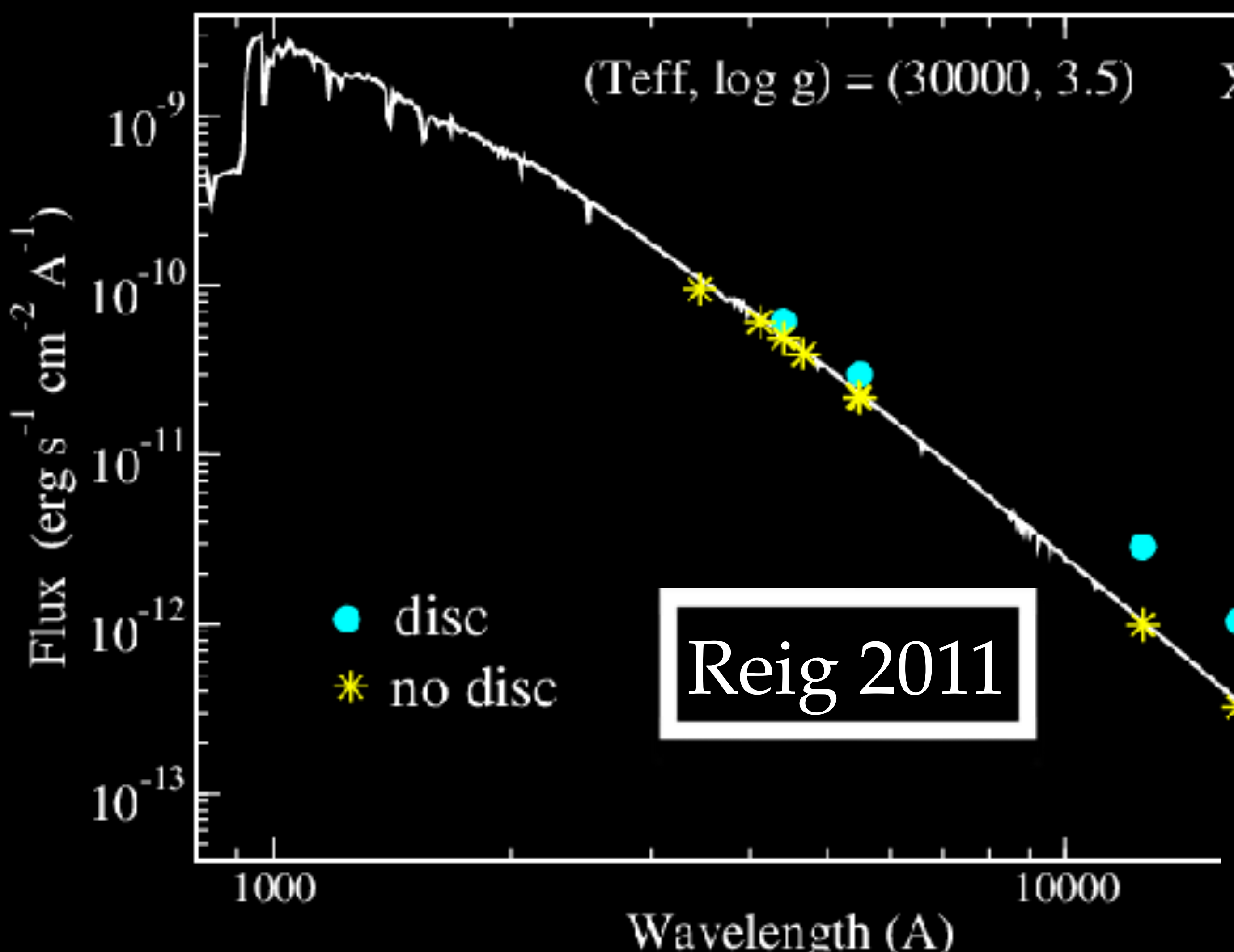
3D Simulations of MRI Decretion Disks

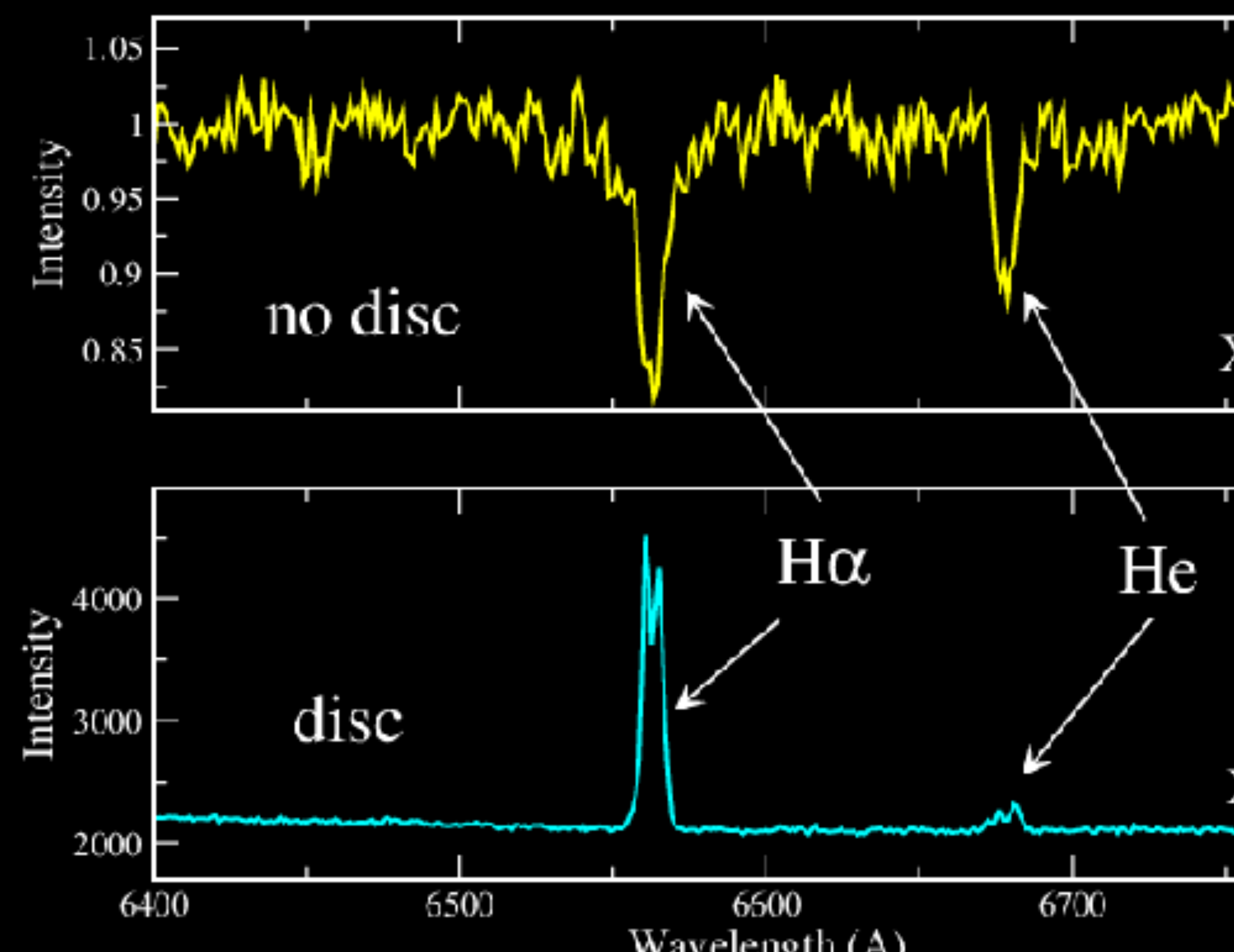


Sean Ressler

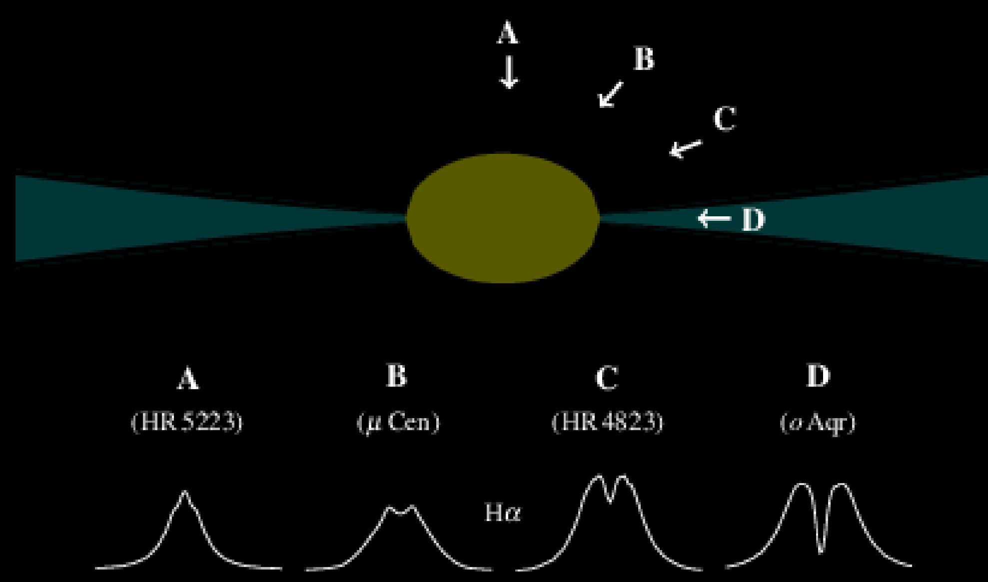
Distinctive Observational Features of Be Stars



1) Emission Lines

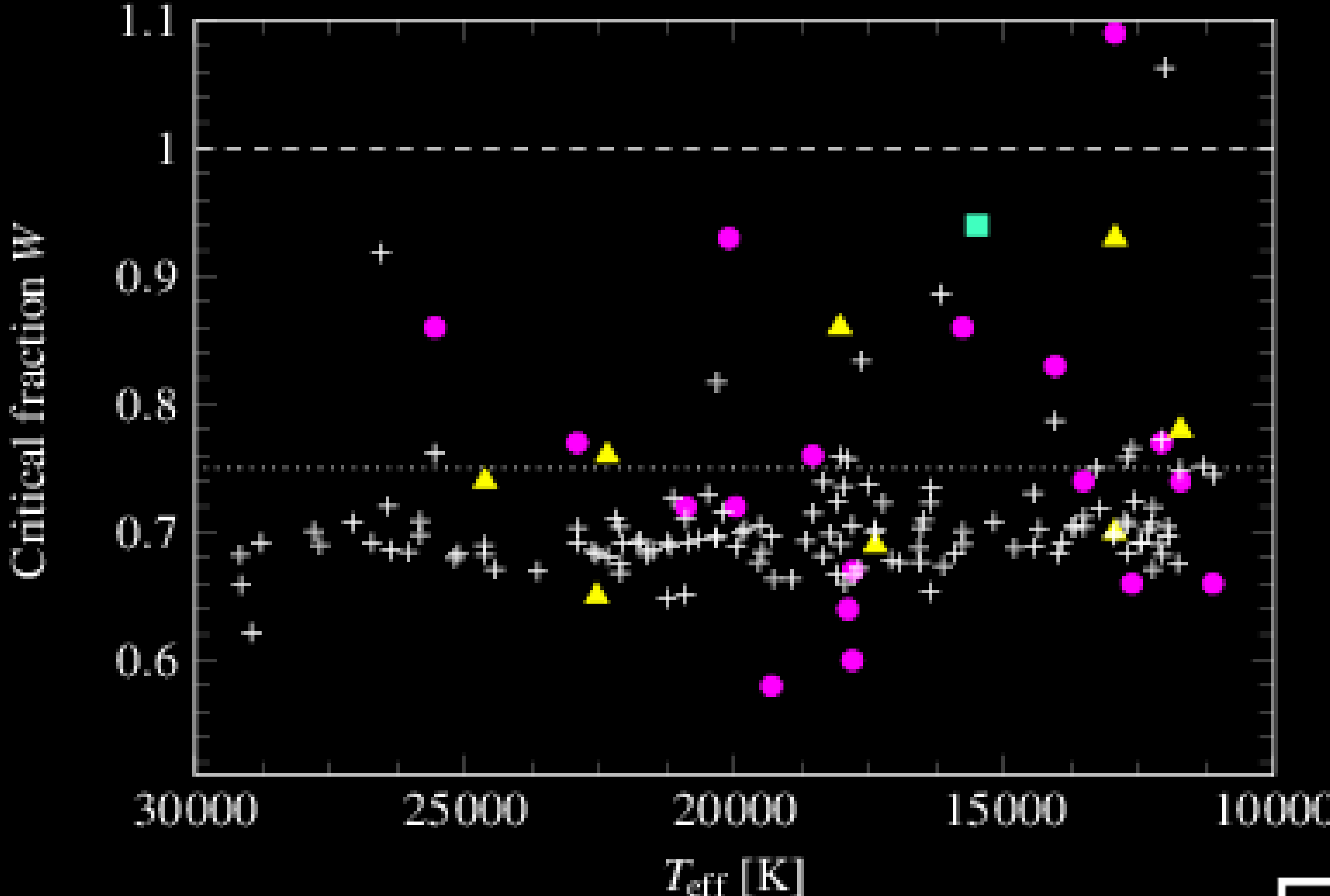


2) Infrared Excess



Rivinius+ 2013

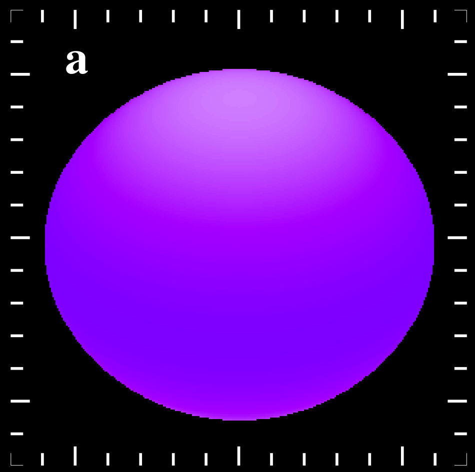
Be Stars: Rapid Rotators



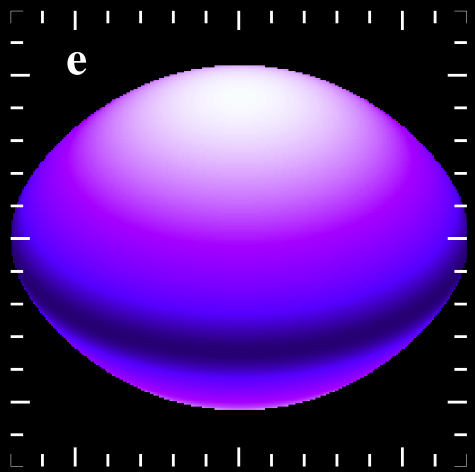
Rivinius+ 2013

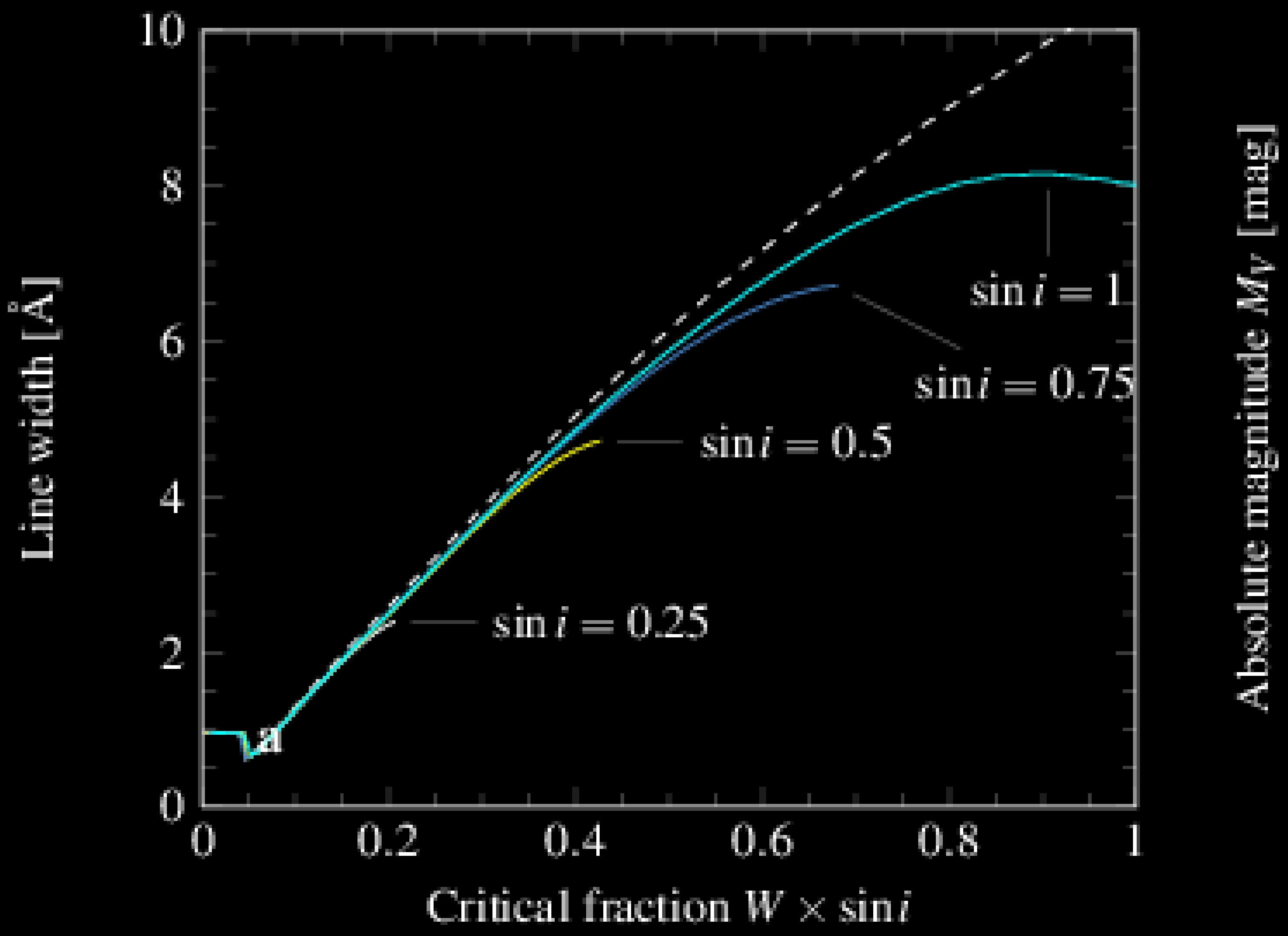
Be Stars: Gravity Darkening

0.62 Ω/Ω_{crit}



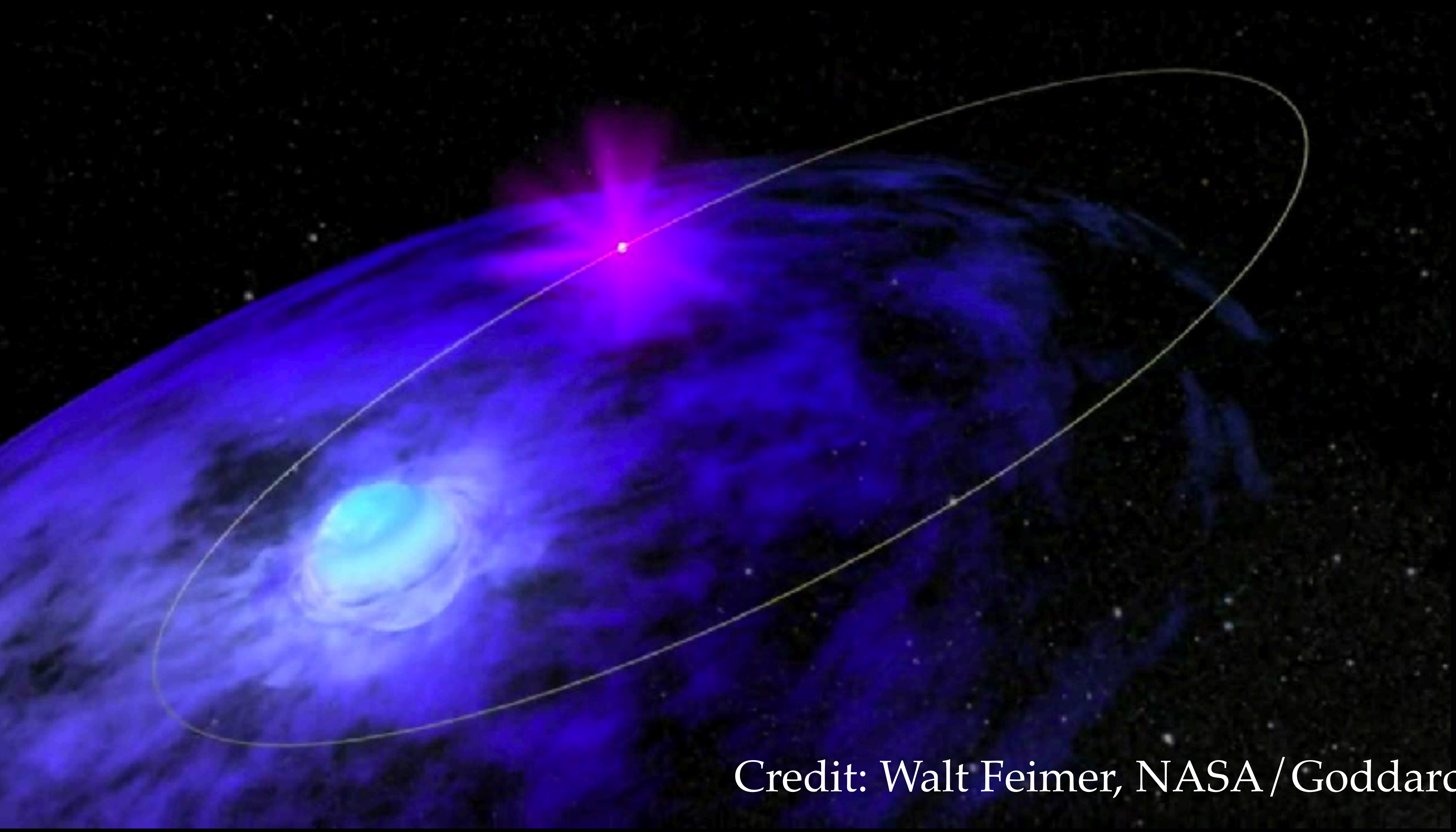
0.9 Ω/Ω_{crit}





Rivinius+ 2013

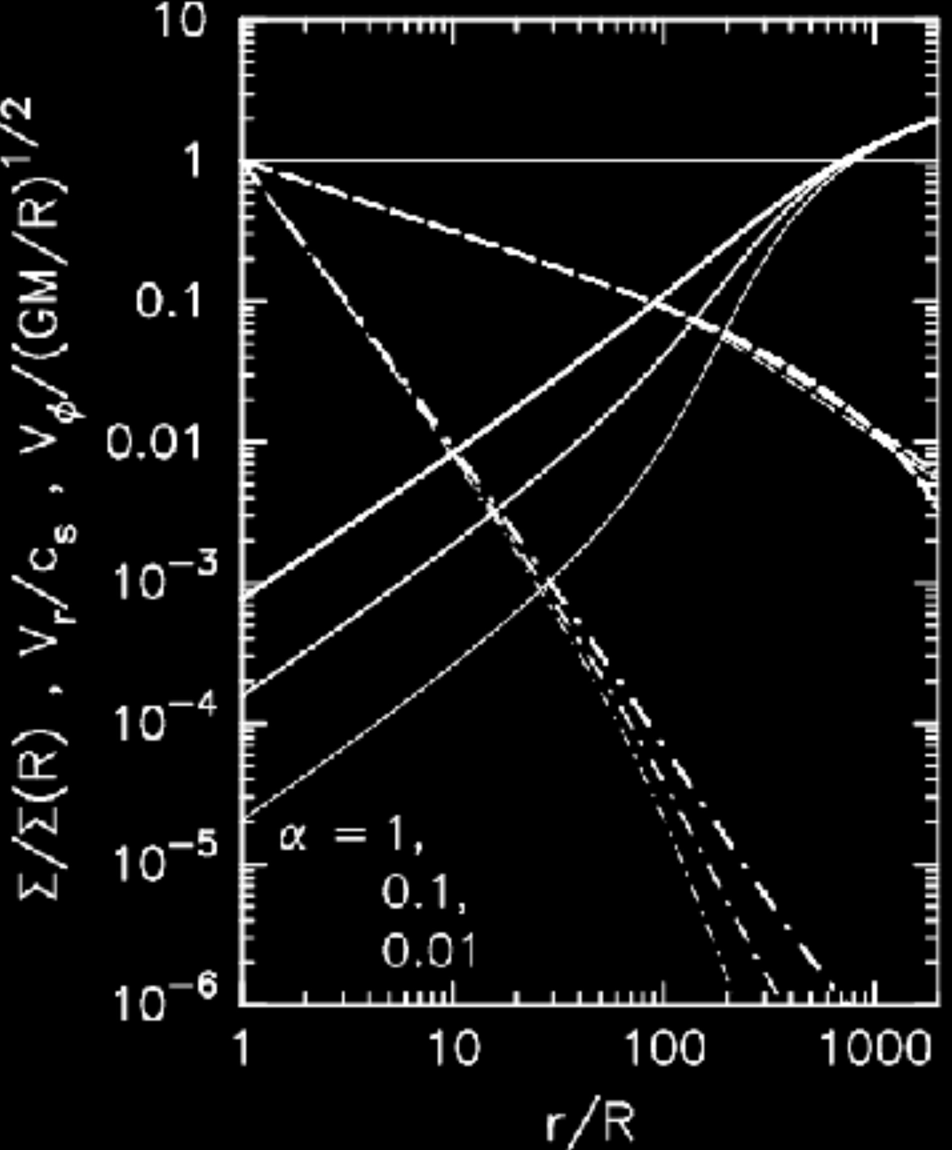
Also Found In: Be/Neutron Star X-ray Binaries



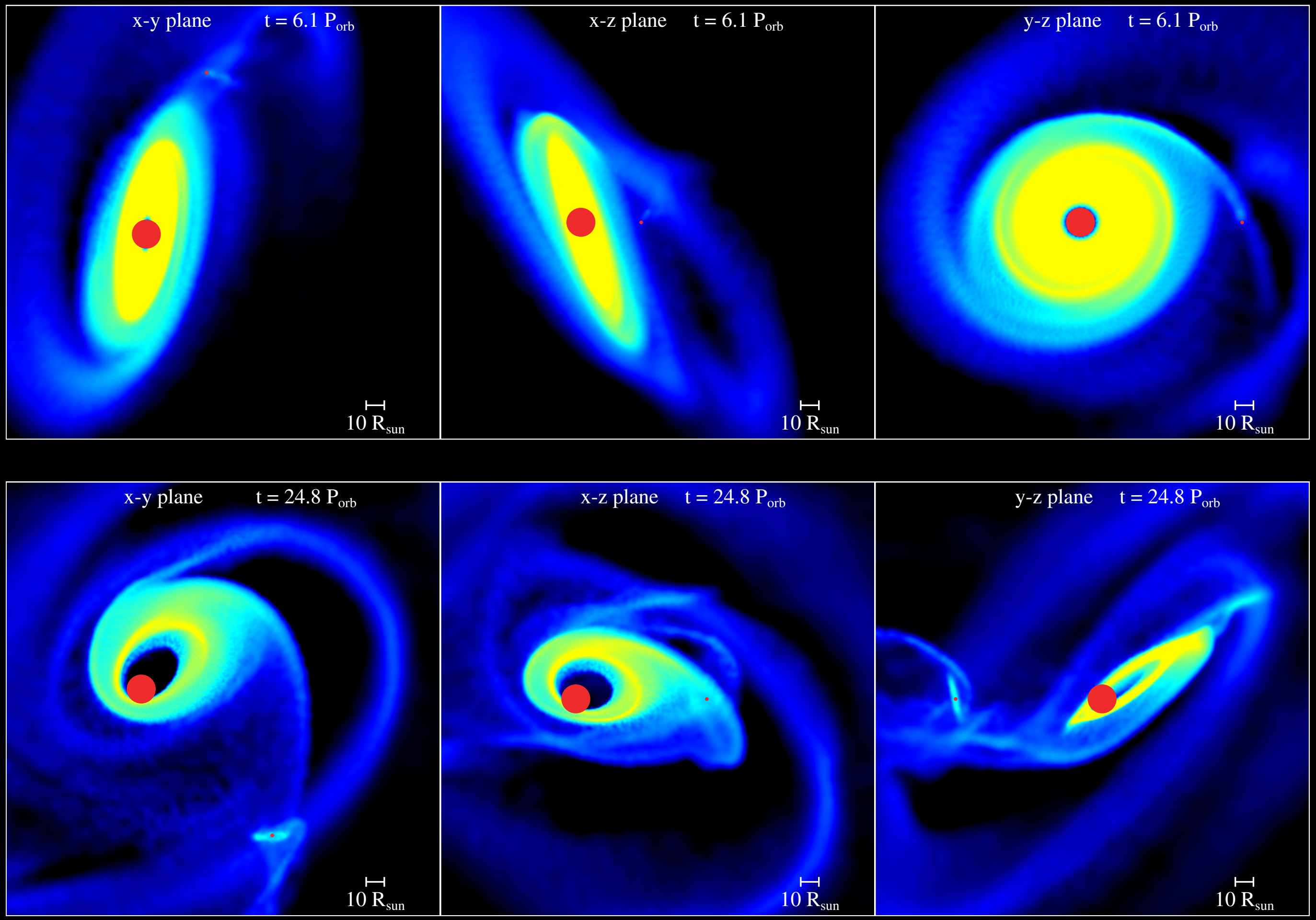
Credit: Walt Feimer, NASA / Goddard Space Flight Center

Disk Models

Okazaki 2001



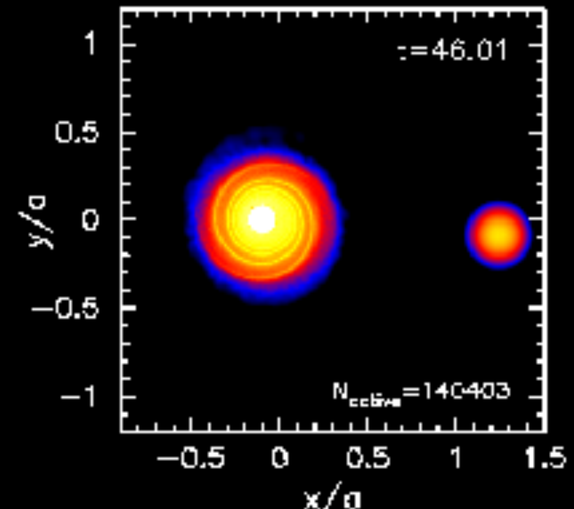
Martin+ 2014



Viscous Decretion Disk Model

$$\nu = \alpha c_s H$$

Typically isothermal

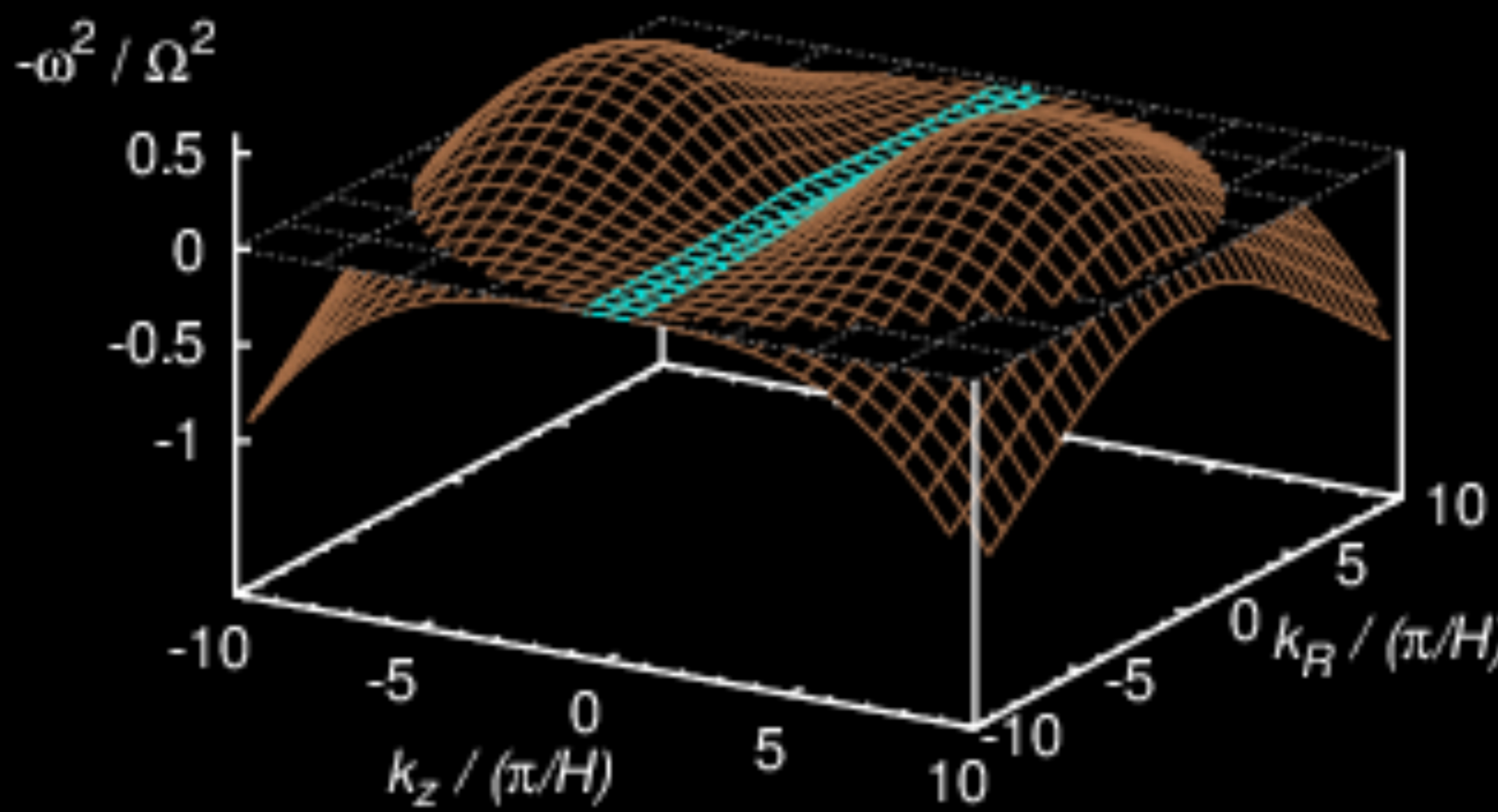


SPH alpha-disk Simulations

Okazaki+ 2002

What Provides α? MRI As Always (Probably)

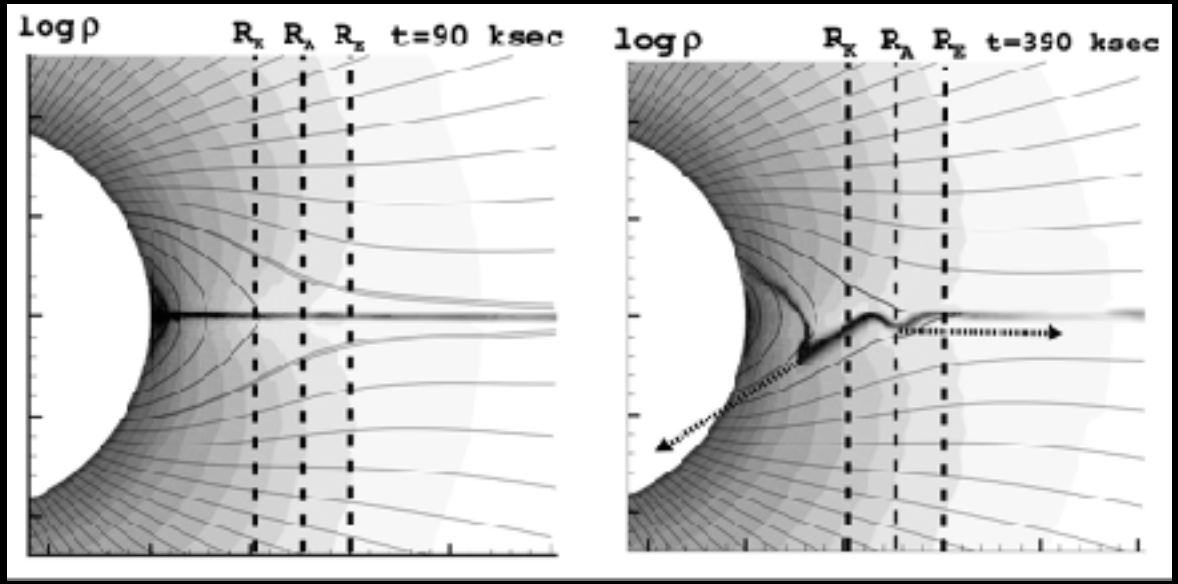
$$B_z < 250\,\mathrm{G}\left[\left(\frac{a/v_R}{10^3}\right)\left(\frac{v_\mathrm{K}}{100\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\dot{M}}{10^{-9}\,M_\odot\,\mathrm{year}^{-1}}\right)\right]^{1/2}\left(\frac{R}{1\,R_\odot}\right)^{-1}$$



Krticka+ 2015

Forming Disks: What Doesn't Seem To Work

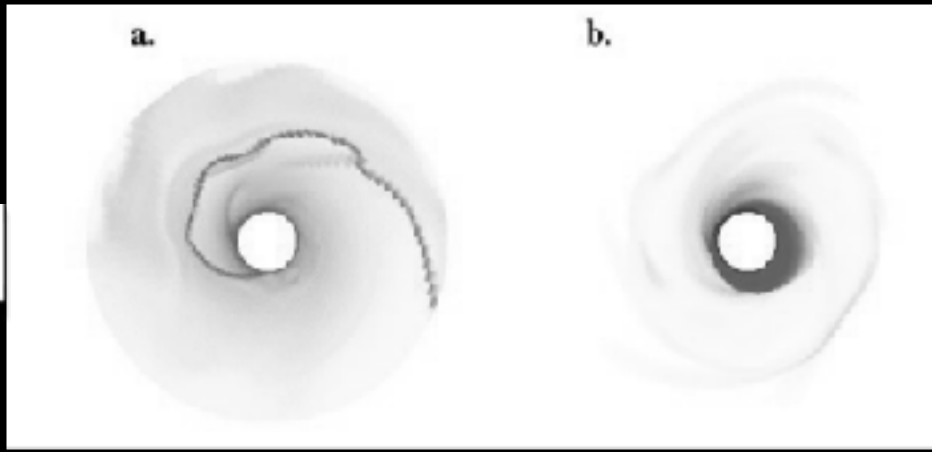
Magnetically Compressed Wind



Owocki 2006

Dense disk but unstable, not Keplerian

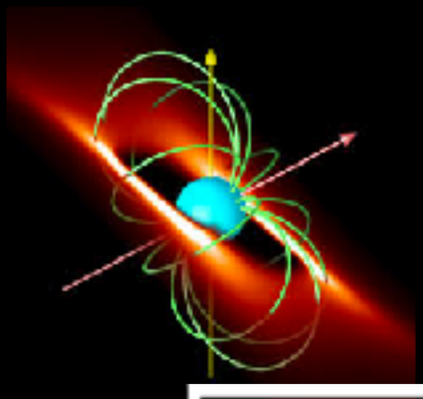
Radiatively Driven Orbital Mass Ejection (RDOME)



Owocki 2006

Tends to drive normal wind + spiral, not disk
Disk requires fine-tuning…turn off rad. force after small radius, beamed radiation, etc.

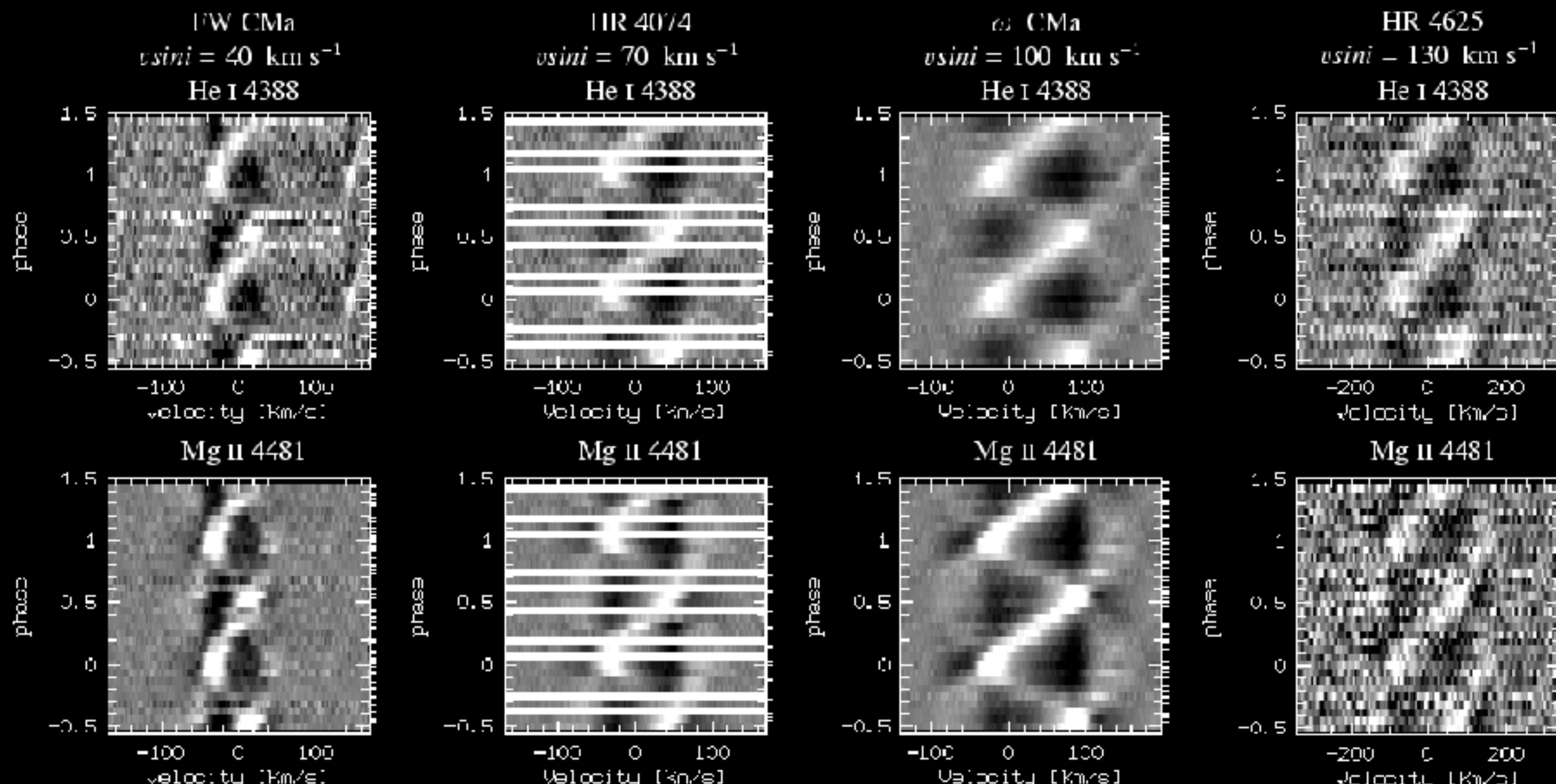
Magnetically Torqued Disk



Townsend, Owocki, & Groote 2005

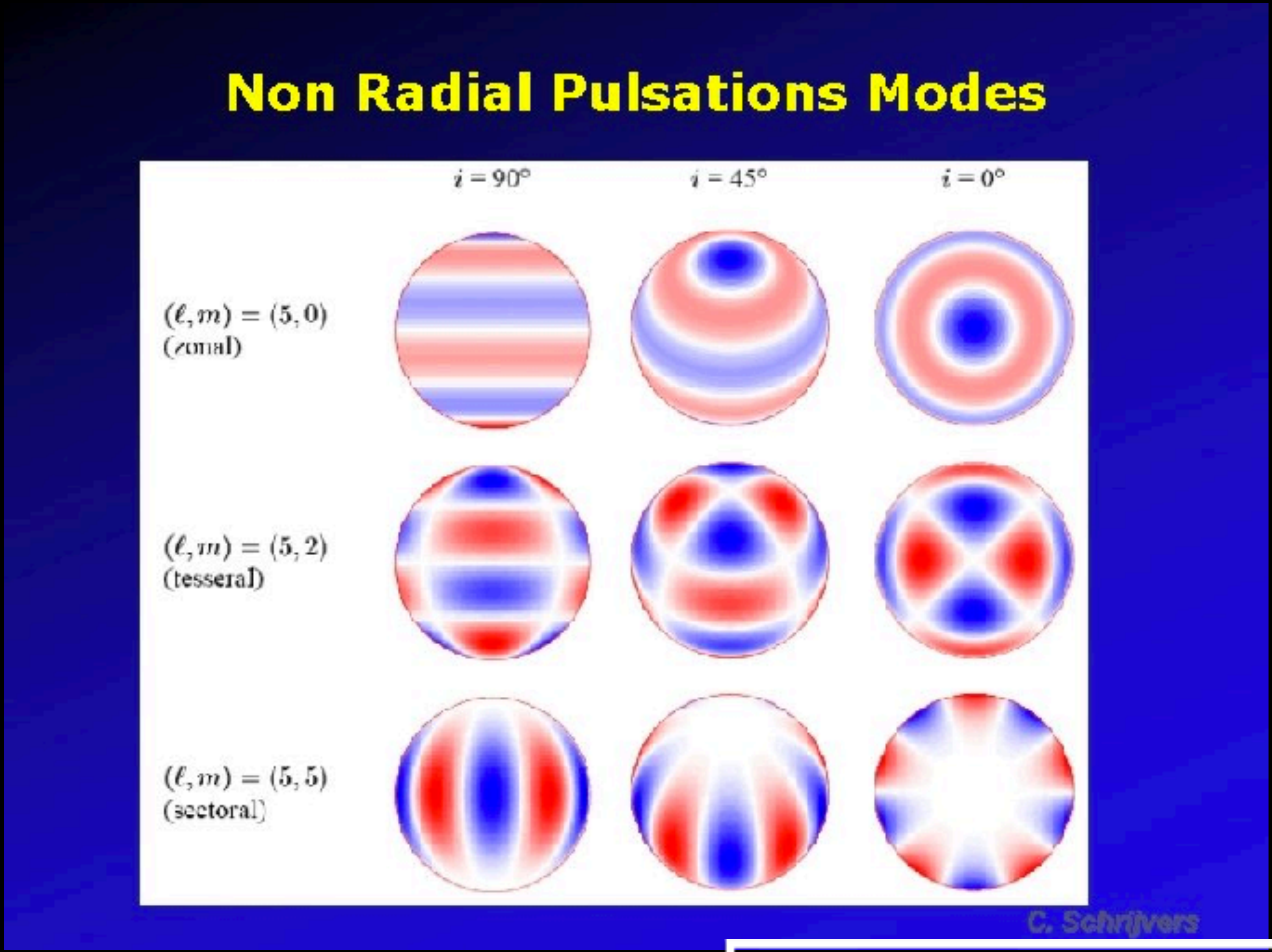
Rigid body rotation, not Keplerian
Fields probably too strong
Polar/rotation axes must be aligned

Non-radial Pulsations As Mass-Loss Mechanism



Rivinius+ 2003

Non-radial Pulsations As Mass-Loss Mechanism



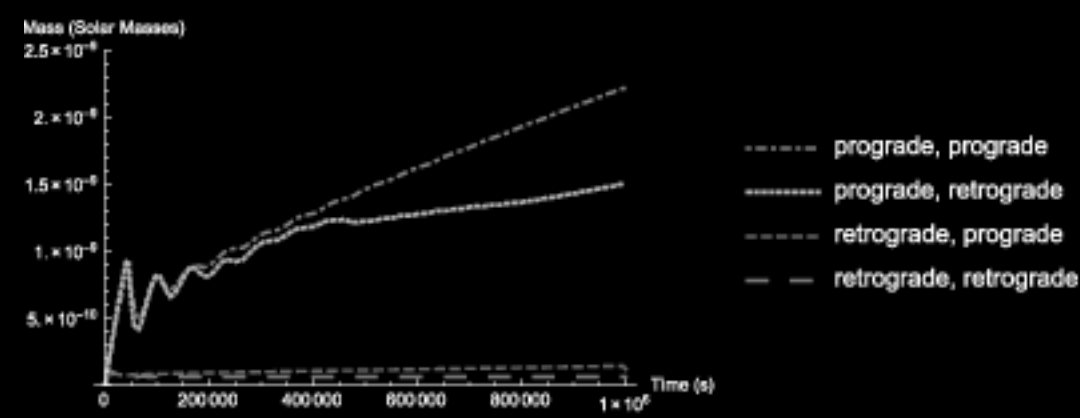
Credit: C. Schrijvers / Petr Skoda

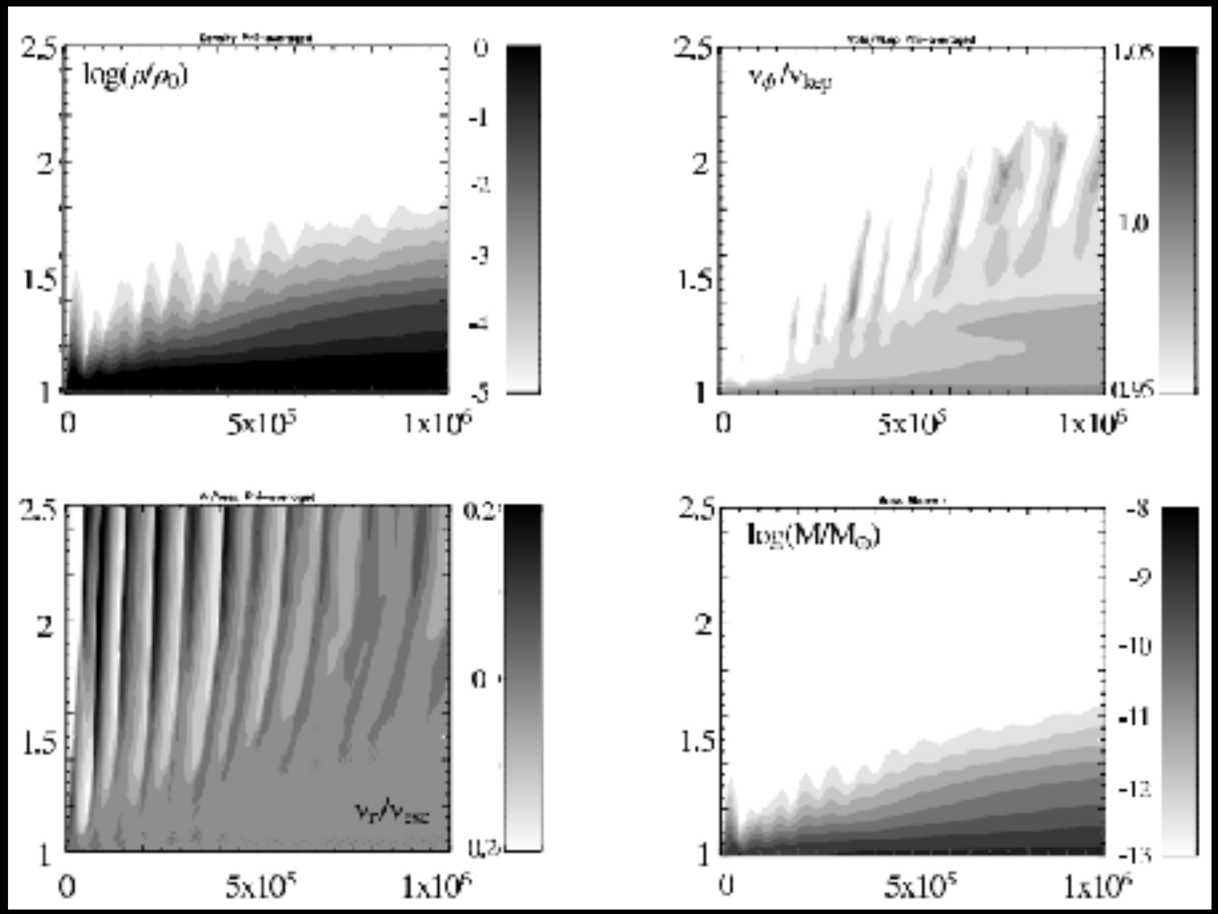
- Pulsational velocity amplitude <~ Sound speed ~ 20 km/s
- 20 km/s ~ 0.05 v_{crit} ——-> requires Ω/Ω_{crit} = 0.95
  - Ω/Ω_{crit} likely systematically higher than 0.75 value
  - Constructive interference? (Same l,m different n)
- Group Velocity must be prograde

Stealing A Good Idea

Kee, Owocki, Townsend, & Muller 2015

- “Star” = constant density/ temperature, rigid body rotator
- Omega = 0.95 Ω_{crit}
- Add m = -4 perturbations with $\Delta\ v_\varphi = 0.05\ v_{crit}$





Simulation Model

μ Centauri-Like

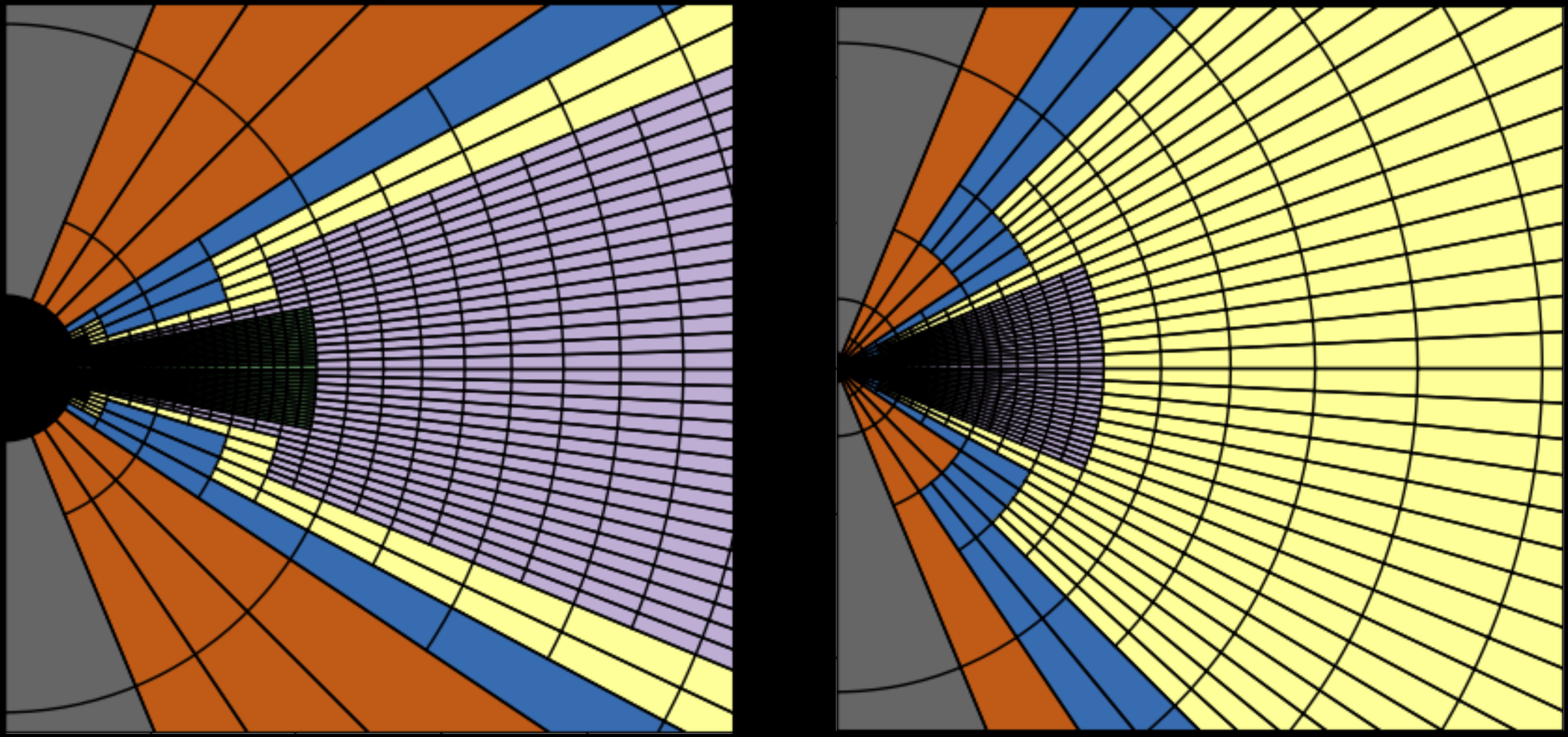
Stellar Parameters	
$M_\star$	$9.3M_\odot$
$R_\star$	$5.3R_\odot$
ρ_0	10^{-11} g/cm^3
T	41×10^4 K
c_s	58 km/s
W	0.95
β_0	5000
Pulsation Parameters	
$v_{\varphi,\mathrm{pert}}/v_{\mathrm{kep}}(r=R_\star)$	0.055
P	26 ks ≈ 0.3 d
m	2
l	2
φ_0	0
$\rho_{\max}/\rho_0$	1.1

$$\rho(\theta,\varphi)=\rho_0\exp\left\{-\frac{1}{2}\left[\frac{\Omega_\star R_\star}{c_\mathrm{s}}\cos(\theta)\right]^2\right\}\times 10^{\left[\log_{10}\left(\frac{\rho_\mathrm{max}}{\rho_0}\right)\sin\left(\frac{2\pi t}{P}+m\varphi\right)P_l^m(\cos\theta)\right]}$$

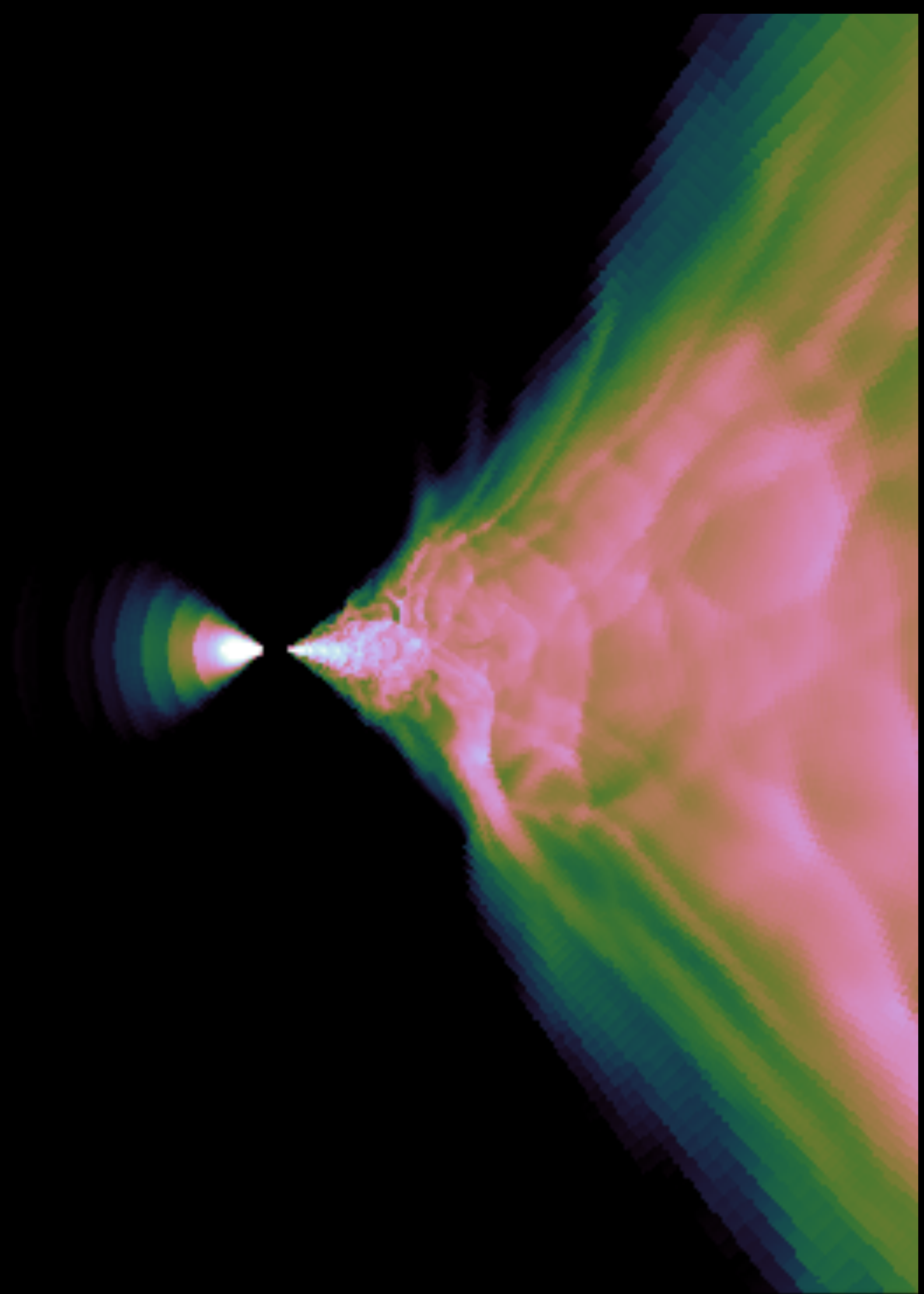
$$v_\varphi(\theta,\varphi)=\Omega_\star R_\star\sin(\theta)+v_{\varphi,\mathrm{pert}}\sin\left(\frac{2\pi t}{P}+m\varphi+\varphi_0\right)P_l^m(\cos\theta)$$

$$A_\varphi\propto\rho$$

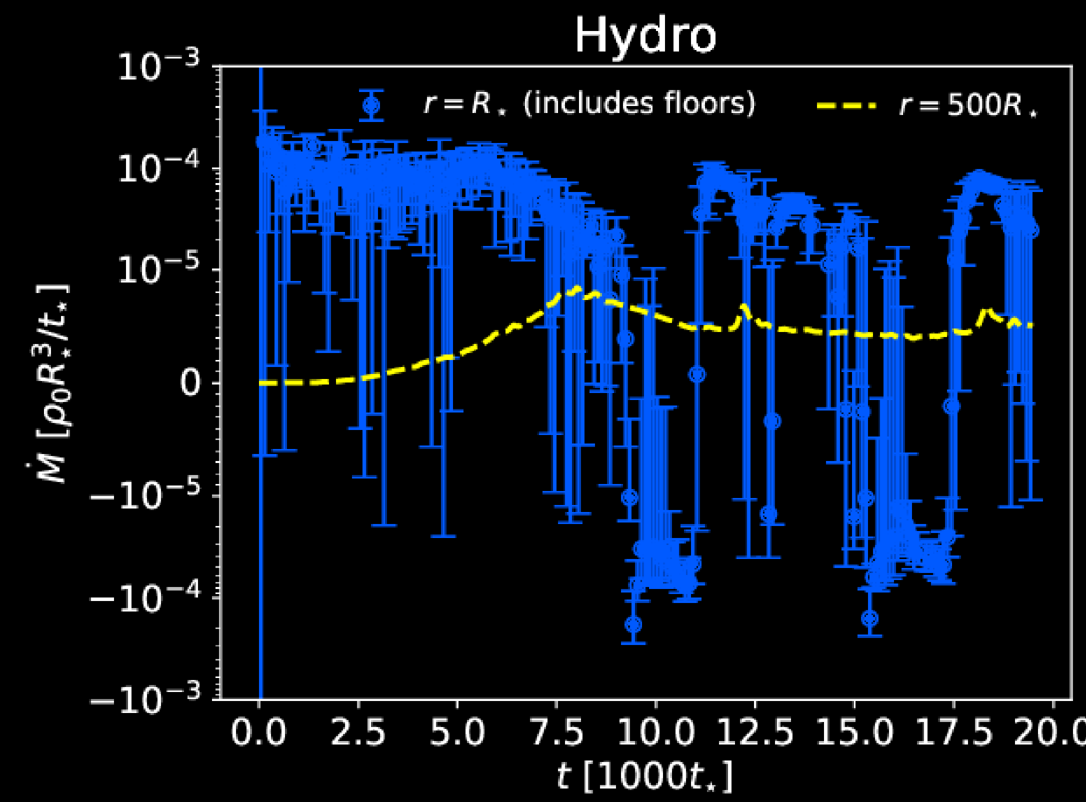
The Grid

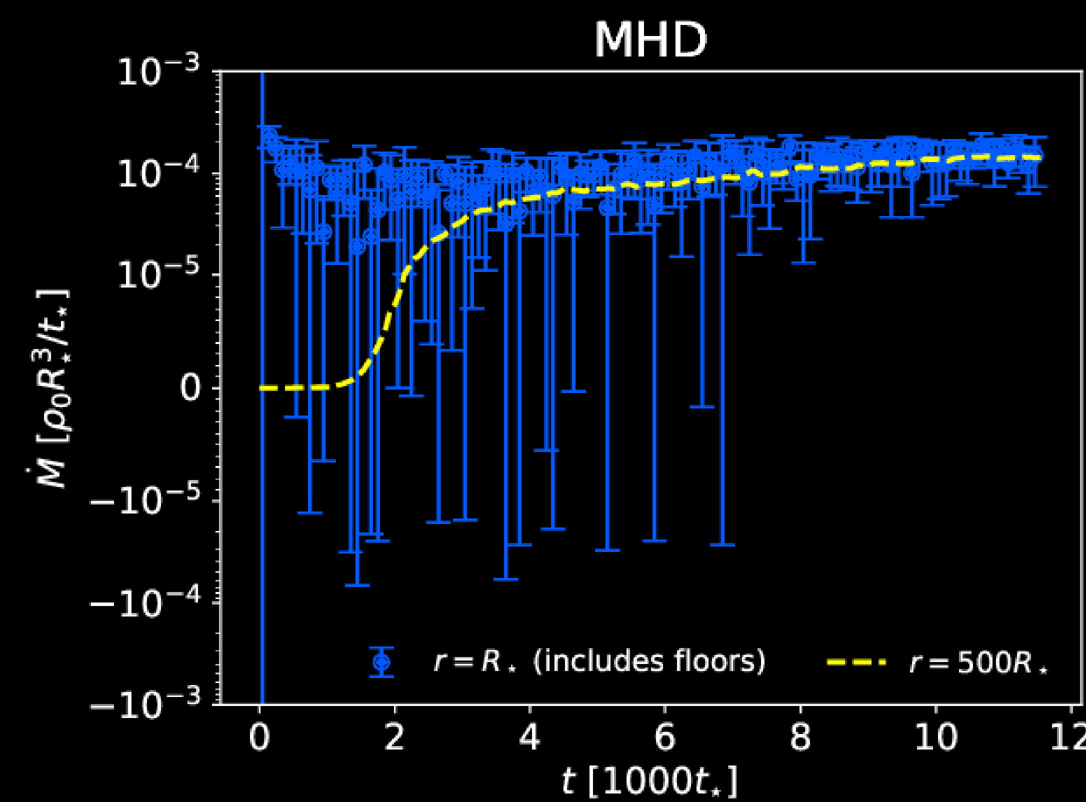


Hydro Vs. MHD



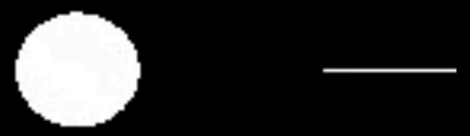
Hydro MHD



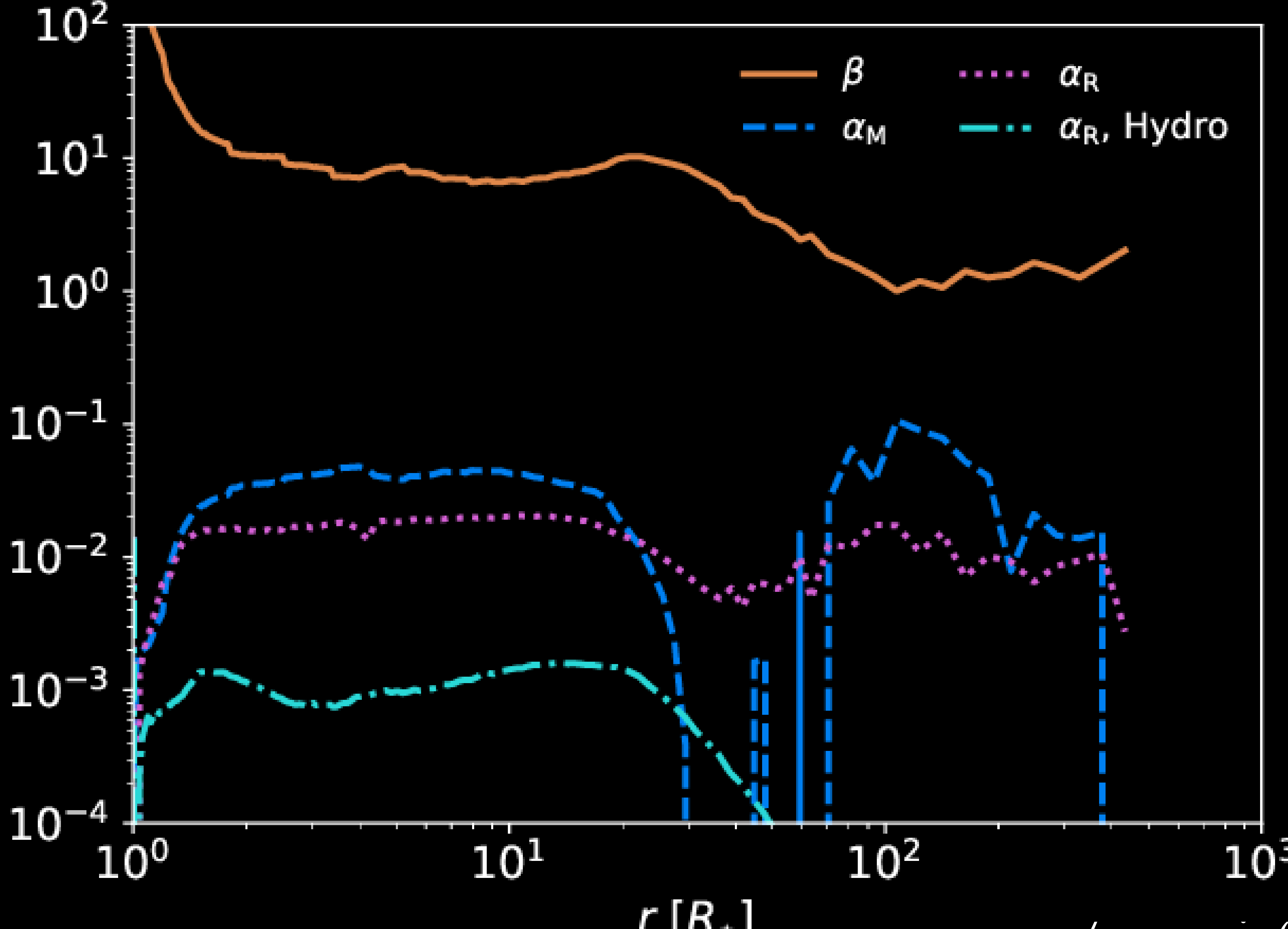


Hydro

MHD



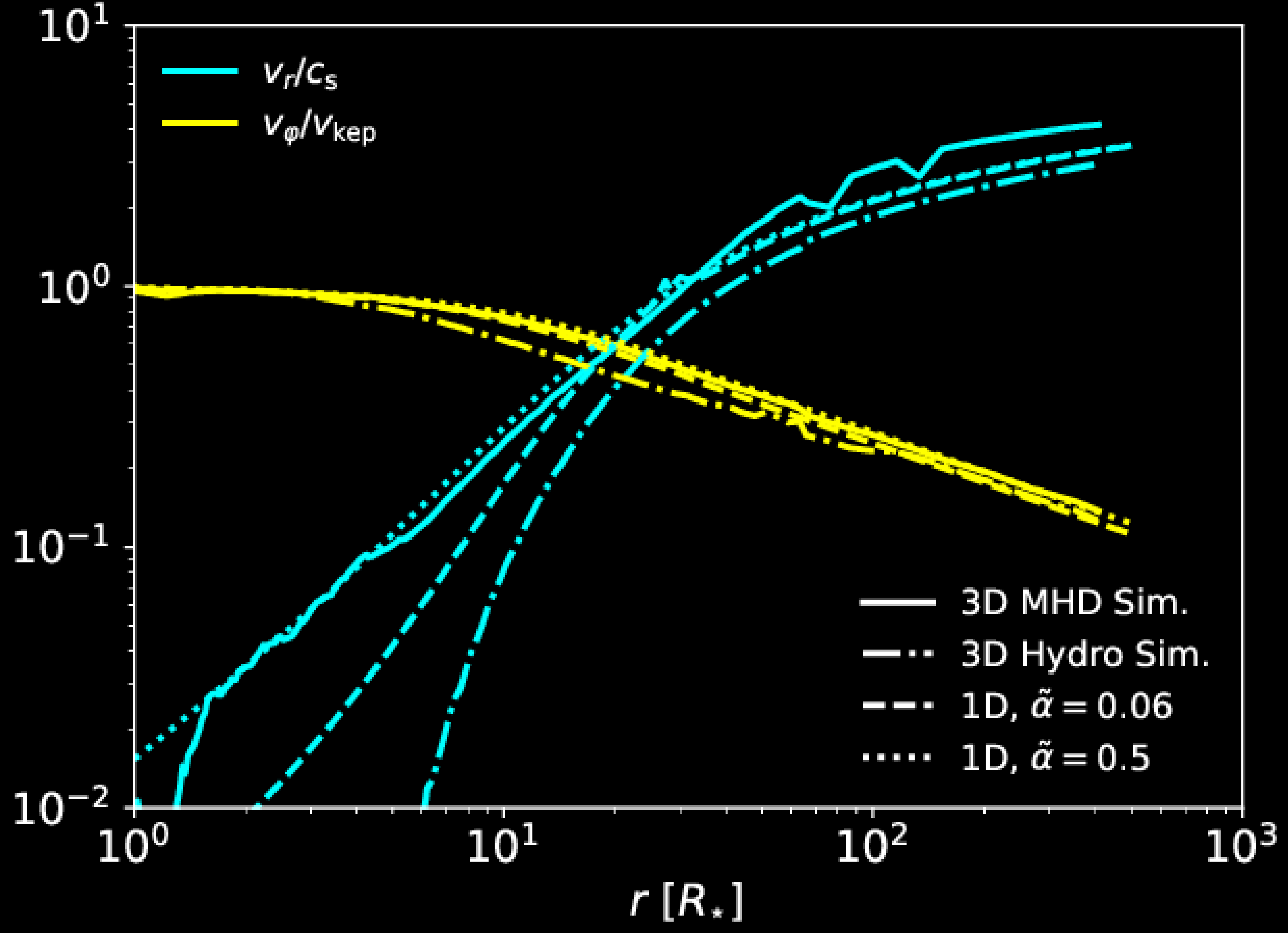
Stresses



$$\alpha_M = \frac{\langle -B_r B_\varphi \sin(\theta) \rangle}{\langle P + P_M \rangle}$$

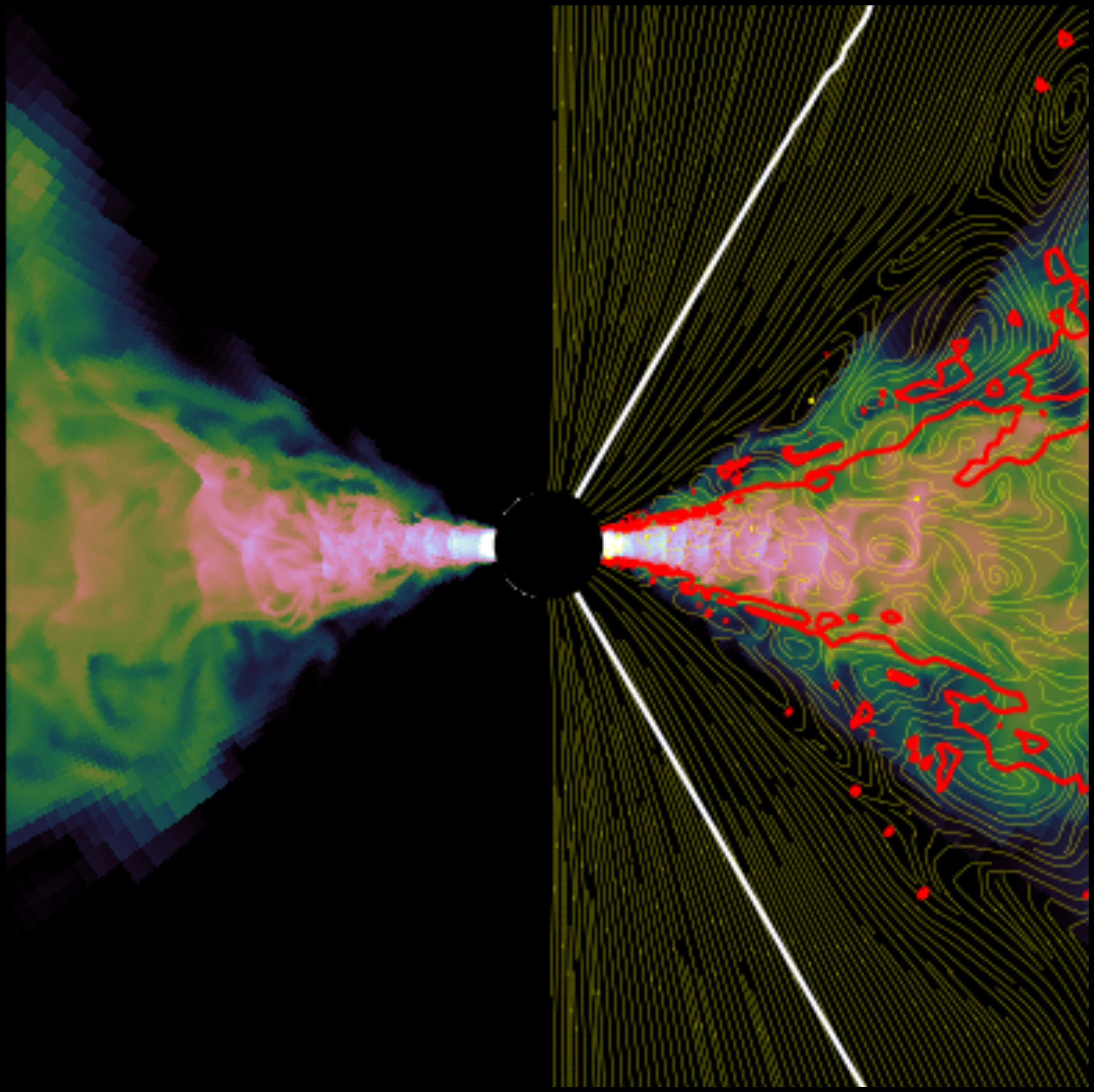
$$\alpha_R = \frac{\langle \rho v_r v_\varphi \sin(\theta) \rangle - \langle \rho v_r \rangle \langle v_\varphi \sin(\theta) \rangle}{\langle P + P_M \rangle}$$

Comparison to 1D



1D viscous α-decretion disk model works well but requires much higher α than measured

MHD Turbulence

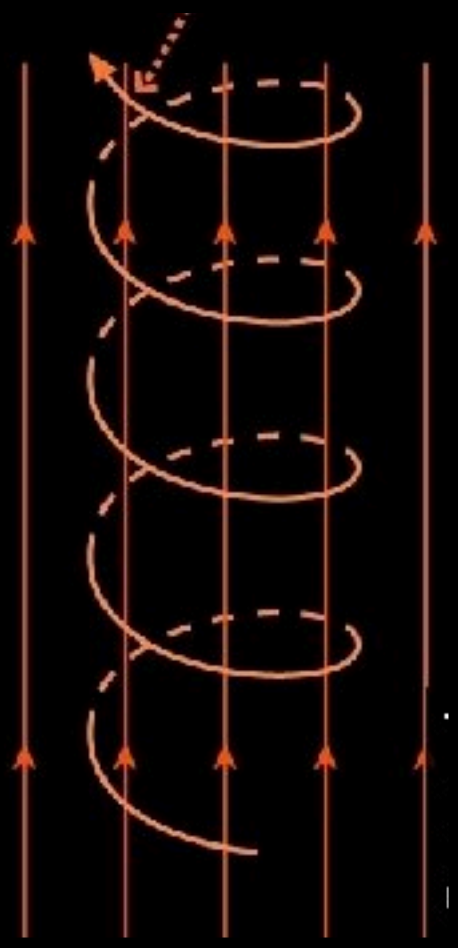


$$\frac{\langle B_r \rangle \langle B_\varphi \rangle}{\langle B_r B_\varphi \rangle} = 0.5$$

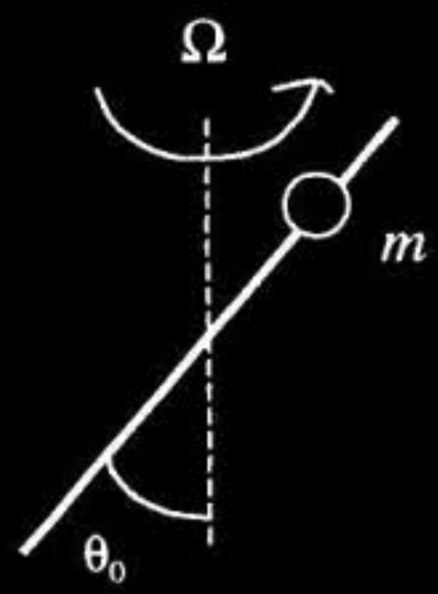
$$\arccos\left(\frac{|\mathbf{B} \cdot \hat{\mathbf{s}}|}{|\mathbf{B}_\mathrm{p}|}\right) = 60^\circ$$

Blandford & Payne Mechanism

β <~ 1 plasma
moves along field lines



Bead on a Wire

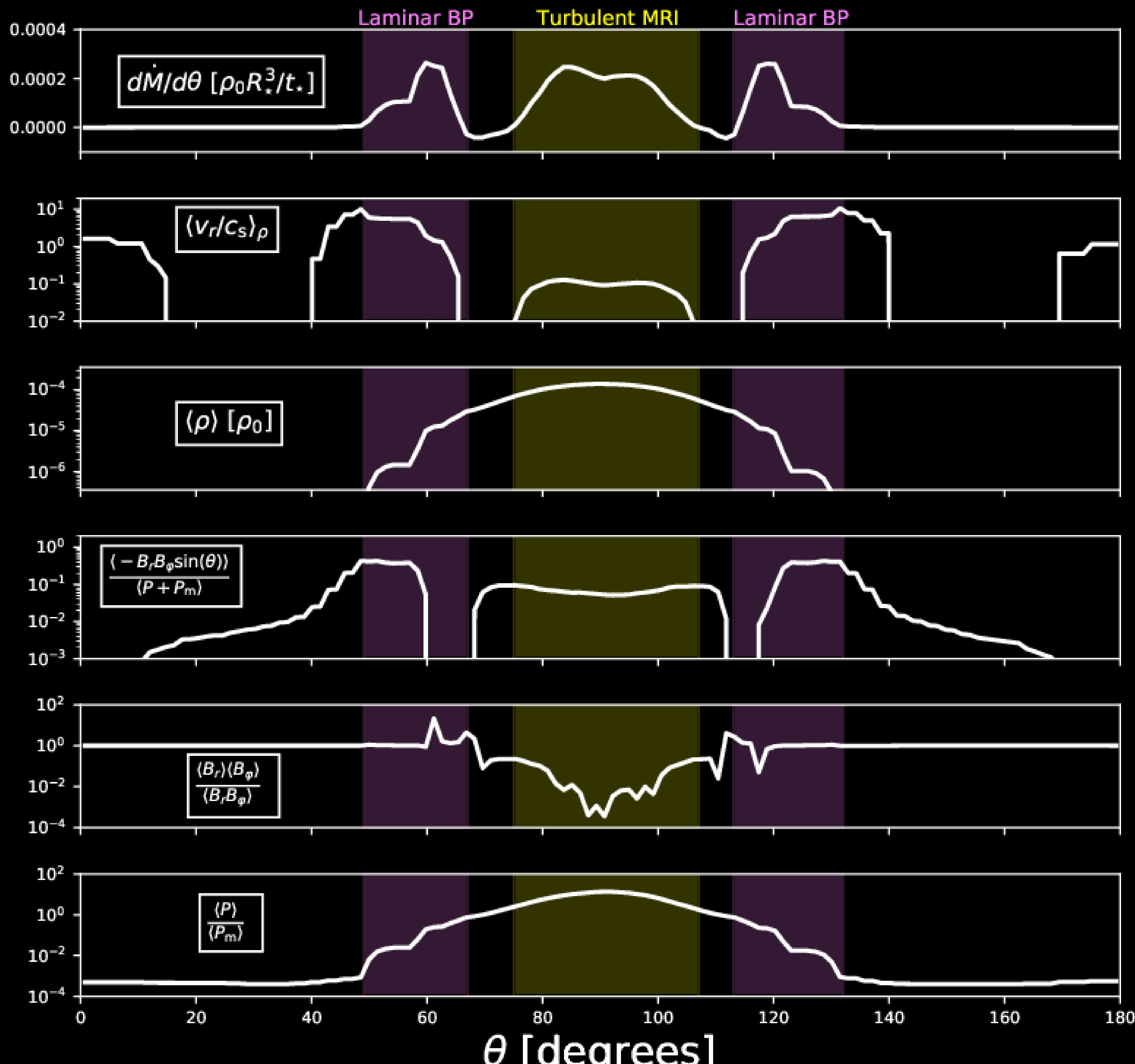


Flies off if

$$\arccos\left(\frac{|\mathbf{B}\cdot\hat{\mathbf{s}}|}{|\mathbf{B}_{\mathrm{p}}|}\right) < 60^\circ$$

TRANSTAR2021

Disk /Wind Angular Structure



Conclusions

- Non-radial pulsations + weak magnetic fields: promising mechanism for Be decretion disk formation
- 3D MRI decretion disk has significant angular structure
    - Slowly decreting midplane
    - Supersonic wind on disk surface
- 1D viscous decretion disk model reasonably captures angle-averaged structure but parameter estimation may be off
- Caveat: simulations assumed higher T than observed for computational reasons

Simulation Costs

MHD: 0.5 Million CPU-hours

$$H = r\frac{c_\mathrm{s}}{v_\mathrm{kep}} \propto \sqrt{T} \qquad t_\mathrm{visc} \propto \frac{r^2}{\alpha c_\mathrm{s} H} \propto T^{-1} r^{1/2}$$

$$r_\mathrm{disk} \propto \frac{GM}{c_\mathrm{s}^2} \propto T^{-1} \qquad t_\mathrm{visc}(r = r_\mathrm{disk}) \propto T^{-3/2}$$

$$dt \propto N_\varphi^{-1}$$

$$\mathrm{Cost} \propto \frac{\mathrm{t_{sim}}}{\mathrm{dt}} \mathrm{N_r N_\theta N_\varphi} \propto \mathrm{t_{sim} N_r N_\theta^2 N_\varphi} \propto \mathrm{H^2 t_{visc}(r = r_{disk})} \propto \mathrm{T}^{-5/2}$$

= 4 Billion CPU-hours

Spiral Density Waves