Why do black holes shine?

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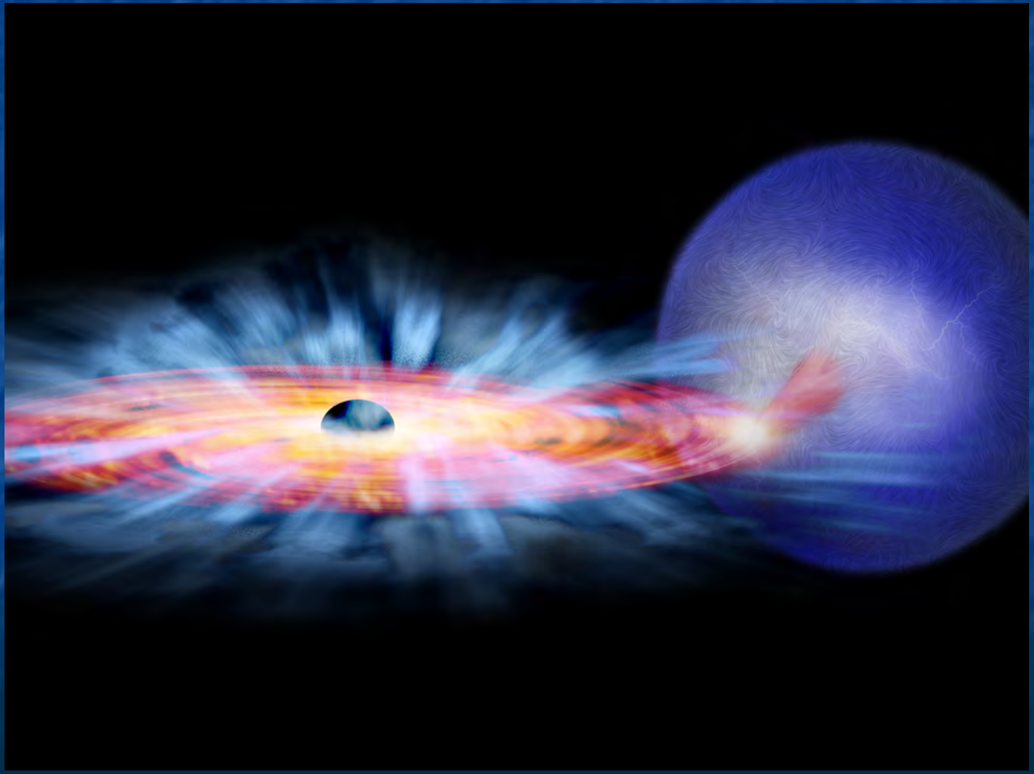
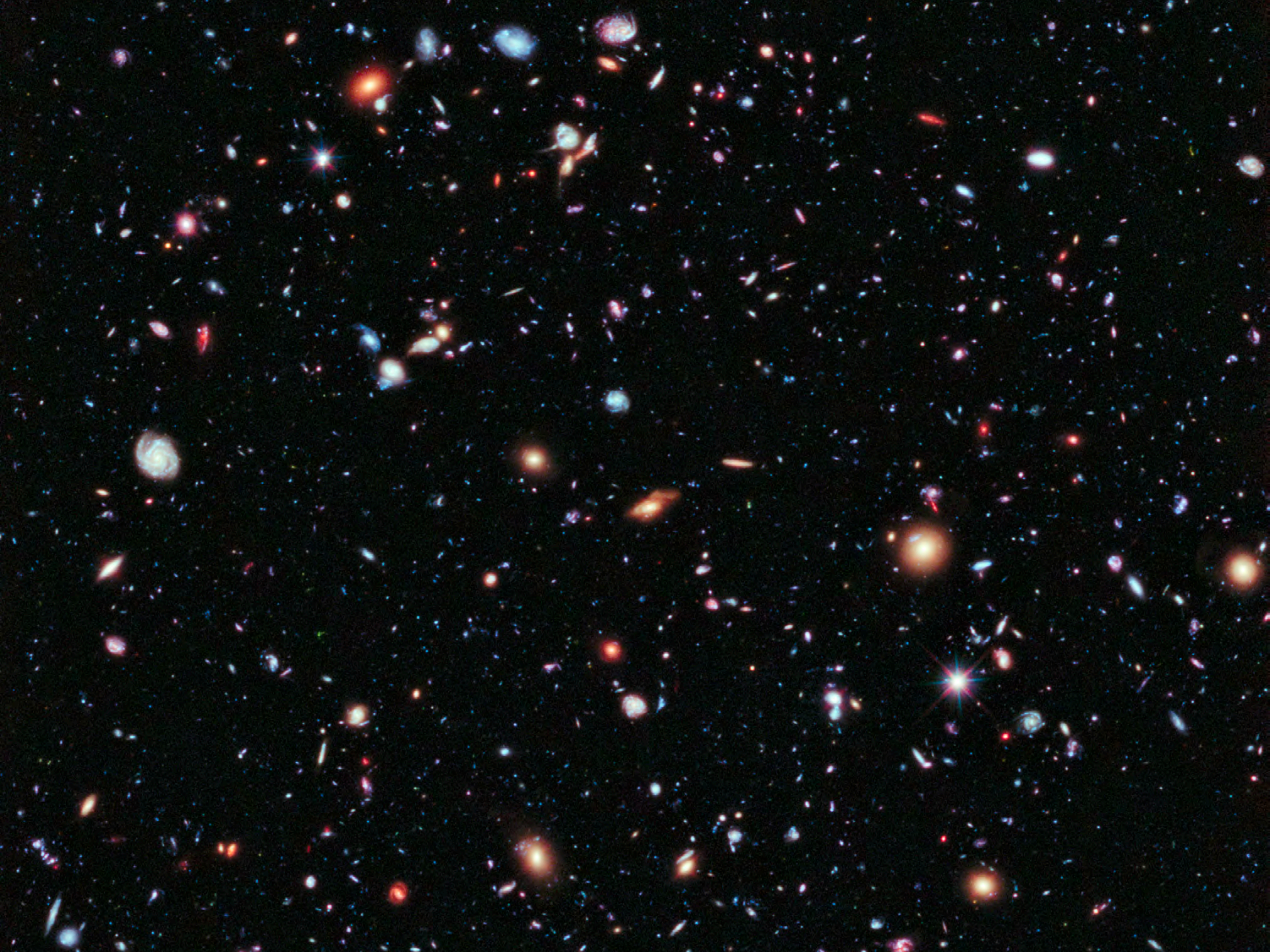
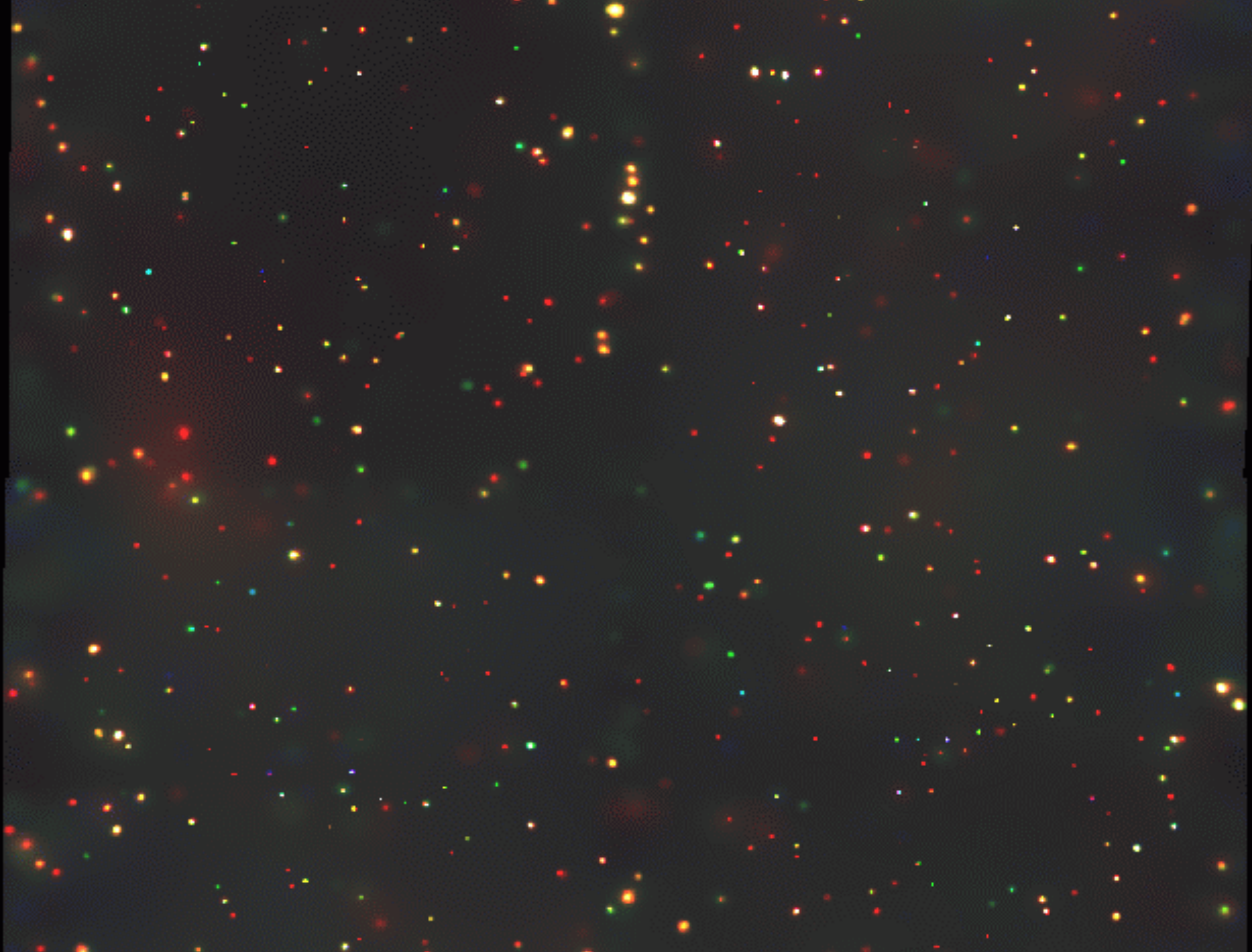
USA

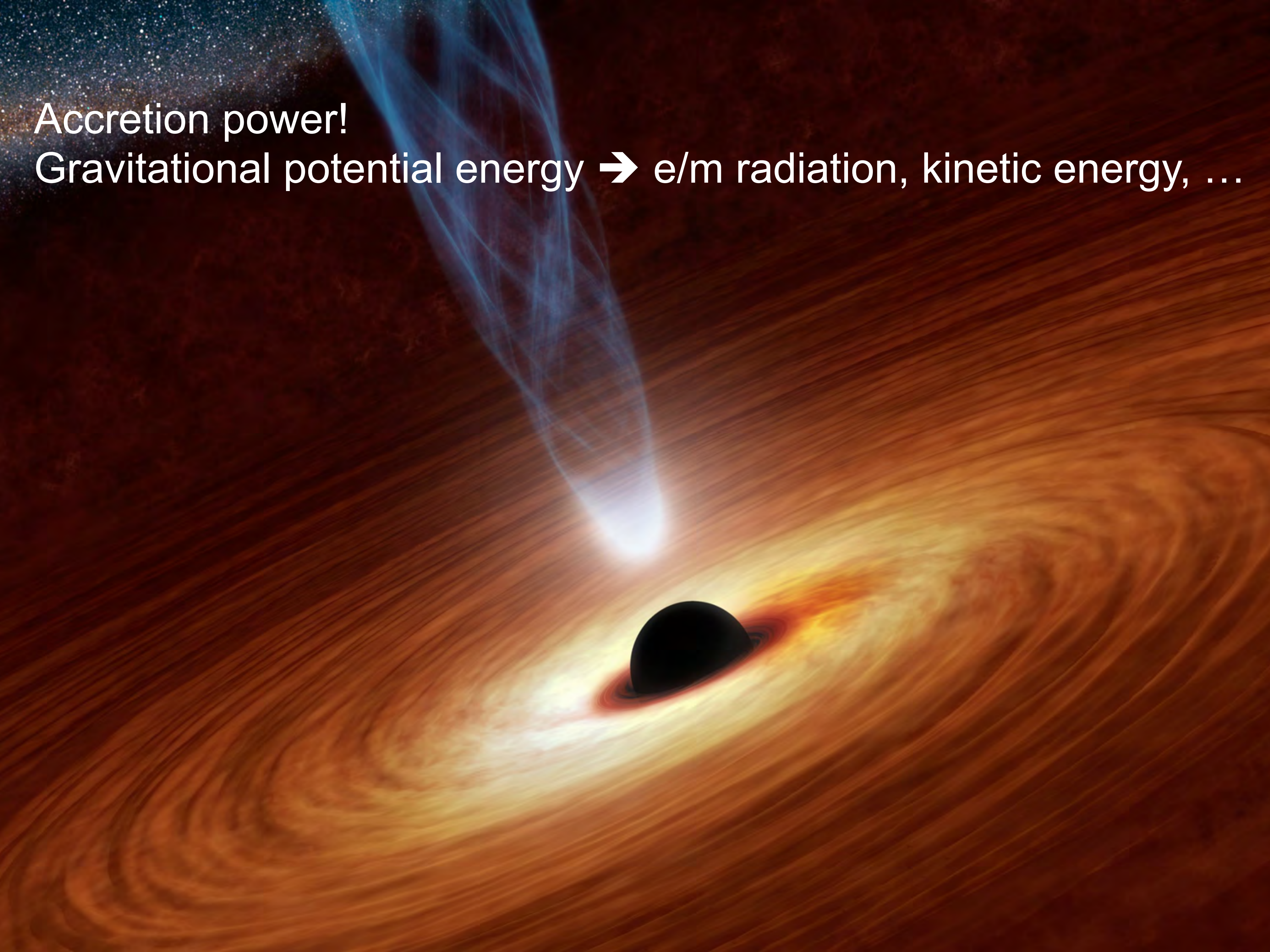






Accretion power!

Gravitational potential energy ➔ e/m radiation, kinetic energy, …



Need to overcome conservation of angular momentum!

Example of a non-accreting disk!

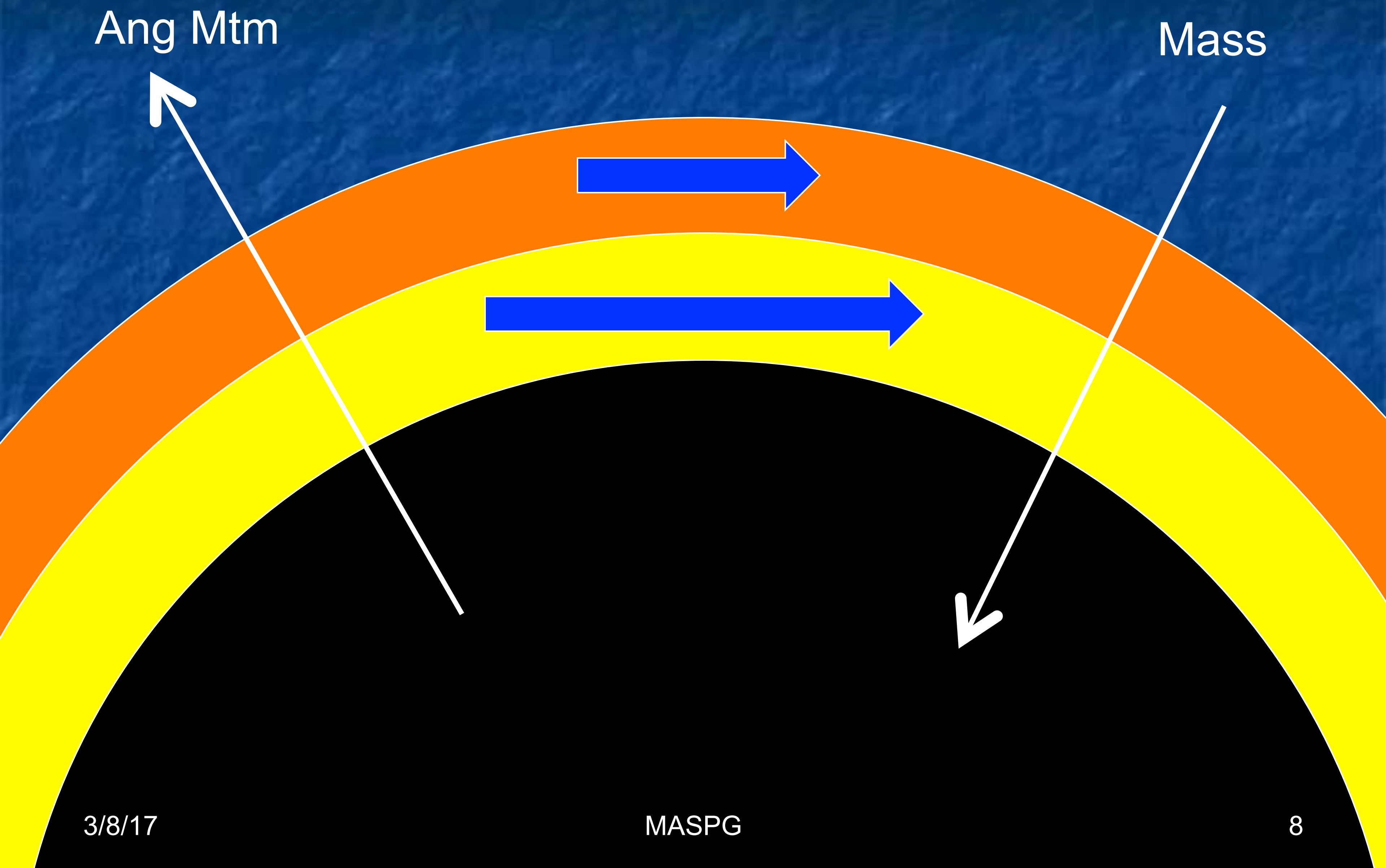
$$\frac{GM}{R^2} = \frac{V^2}{R} \quad \Rightarrow \quad V = \sqrt{\frac{GM}{R}}$$

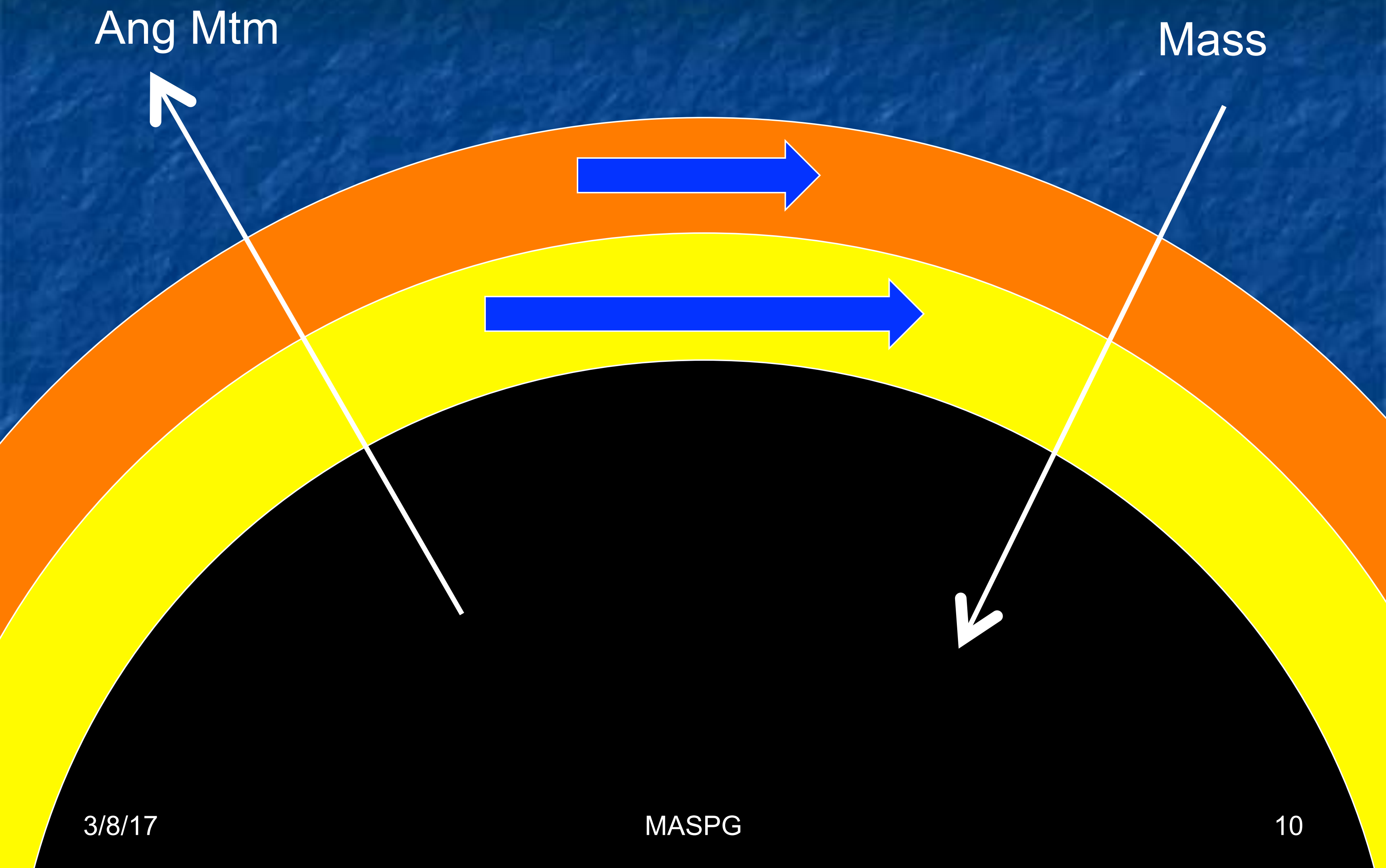
Angular momentum given by $J = mVR$

$$\therefore \; J = m\sqrt{\frac{GM}{R}}R = m\sqrt{GMR}$$

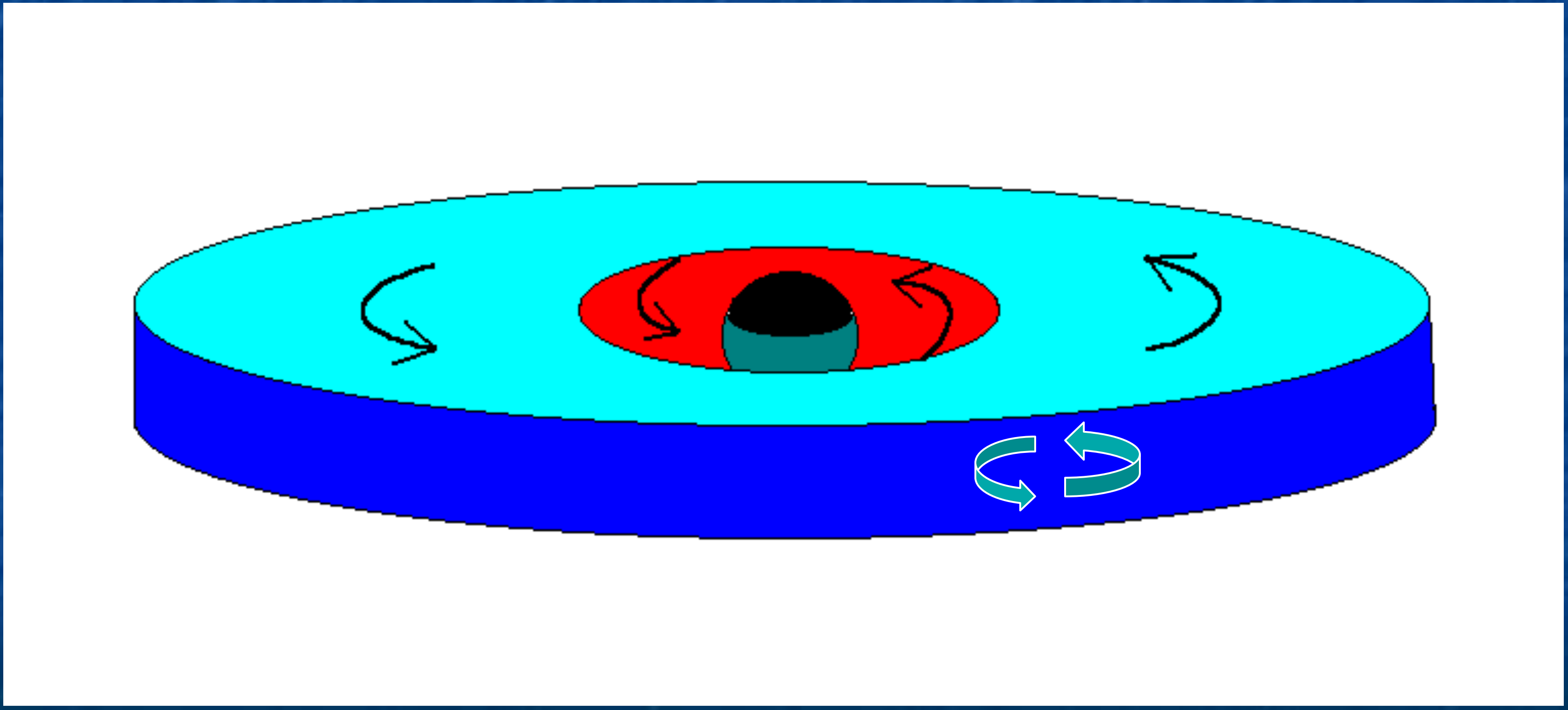
Matter must lose angular momentum to accrete!

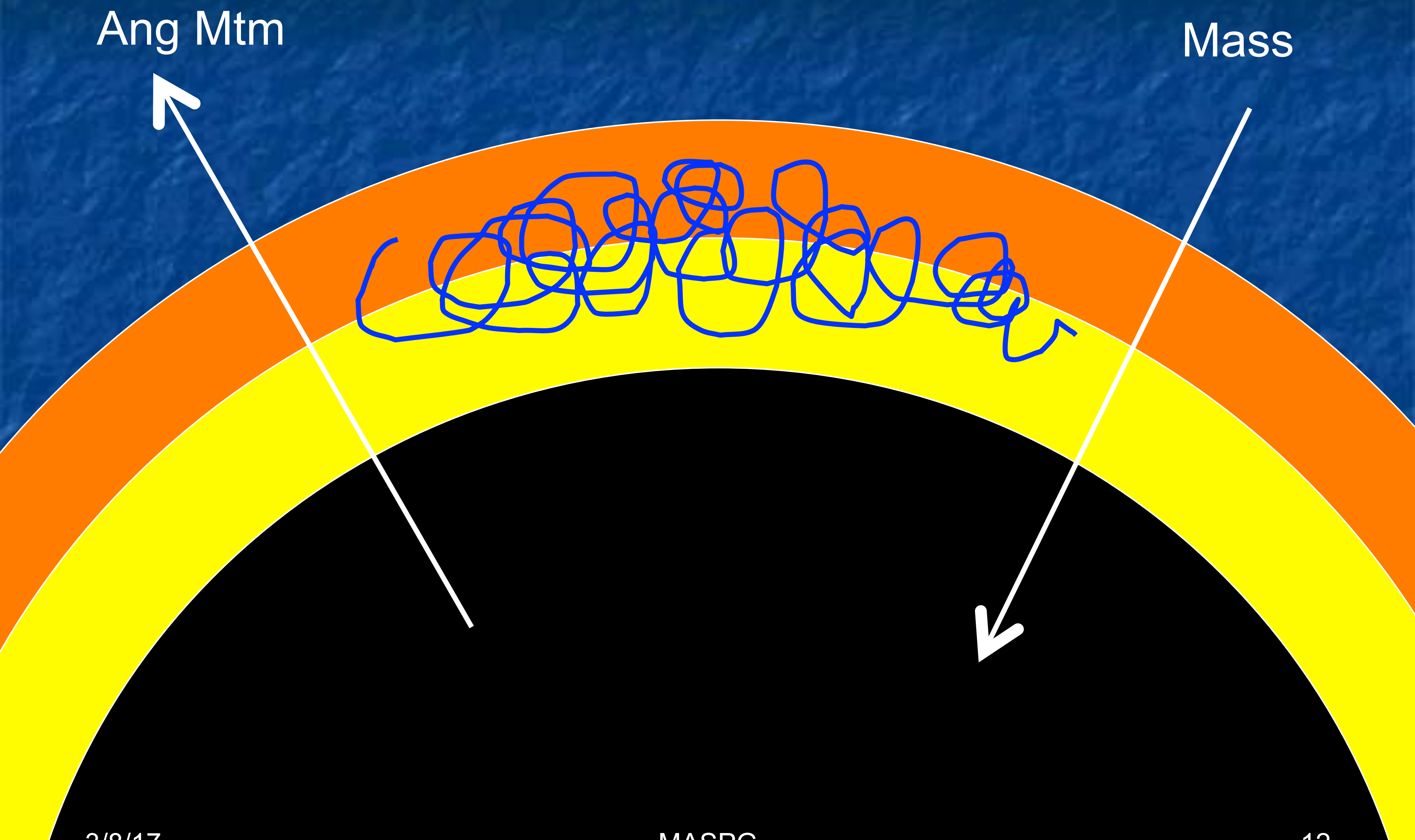
$$Re = \frac{LV}{\nu} \sim 10^{14}$$

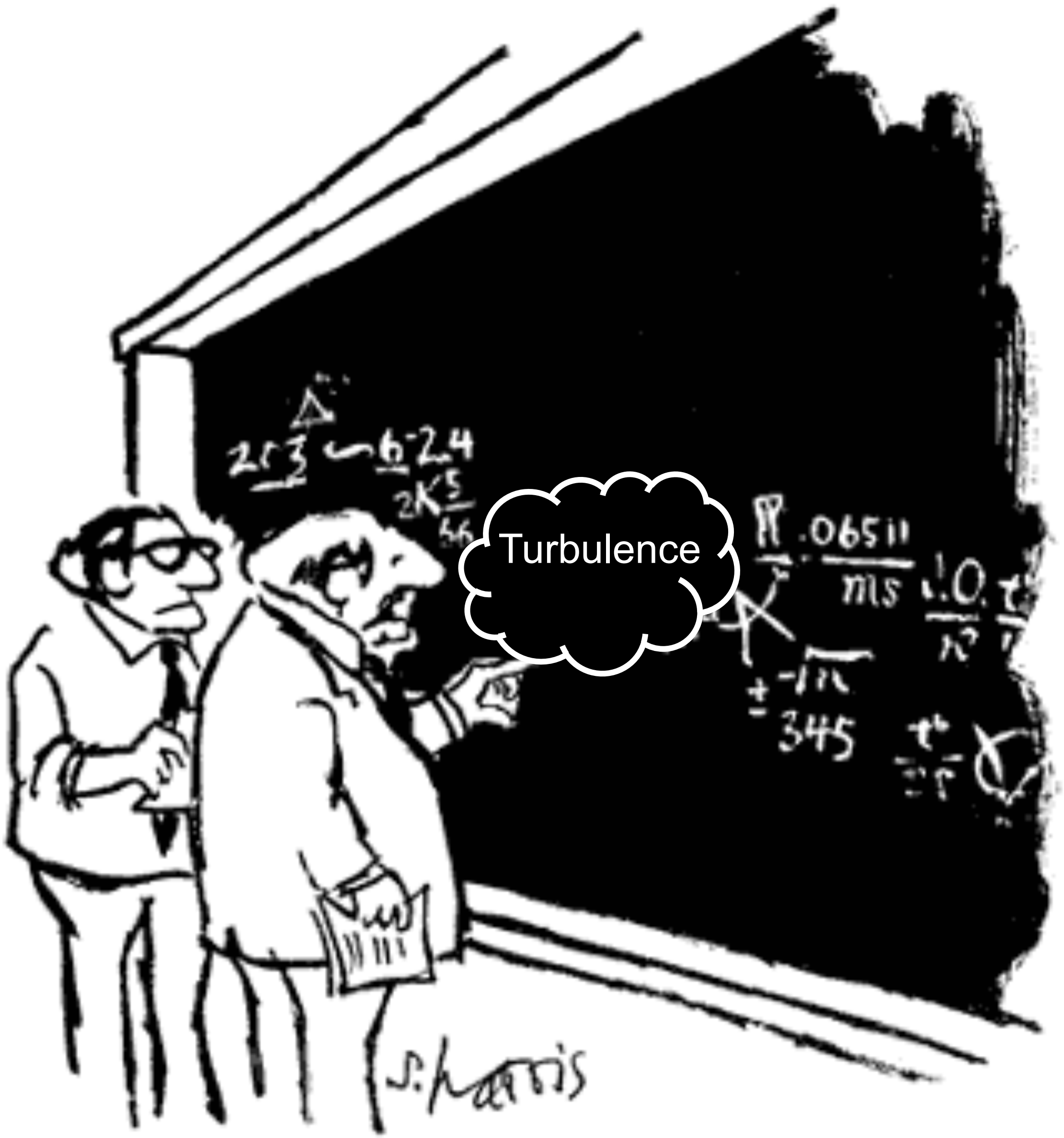



Ang Mtm
Mass

Shakura & Sunyaev (1973)... dimensional analysis
(kinematic) viscosity coefficient = $\alpha c_s h$




Ang Mtm
Mass

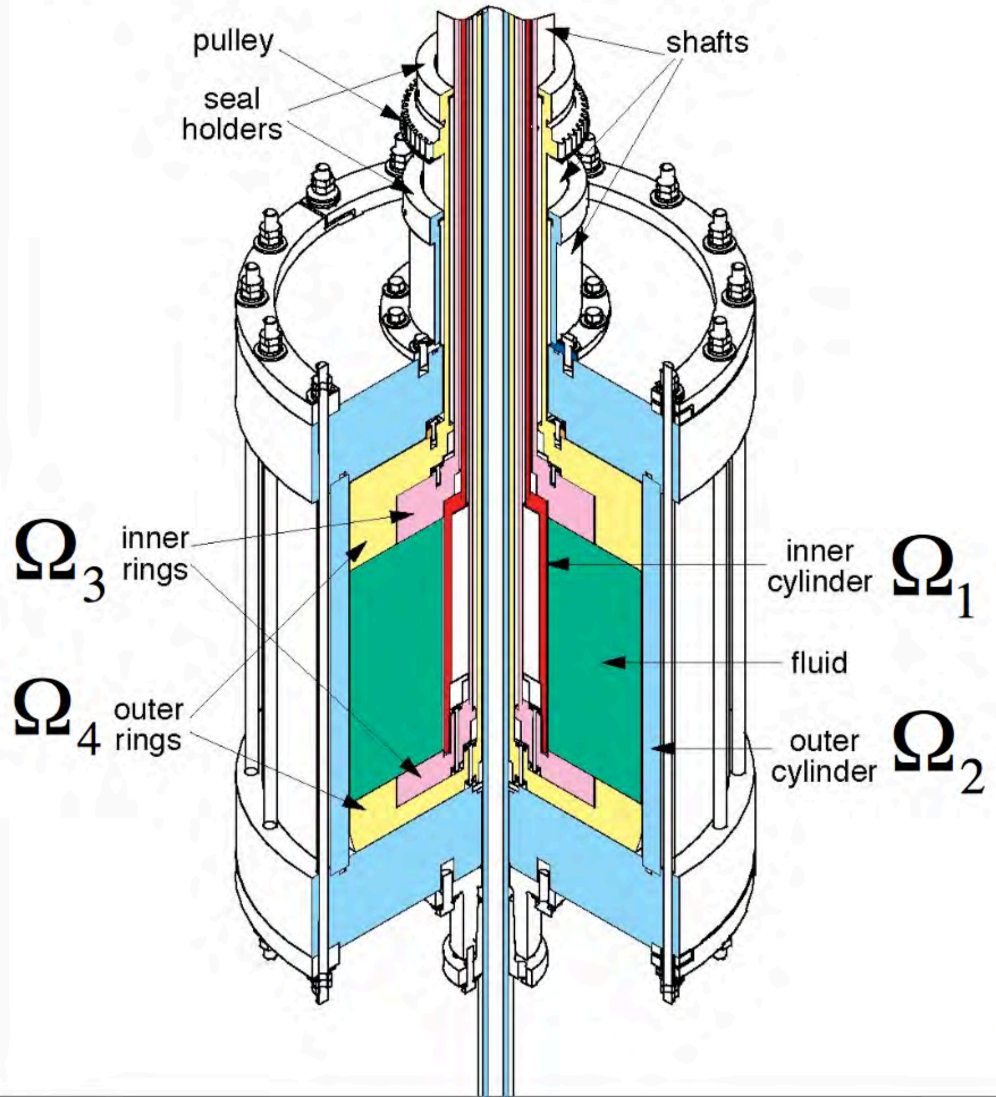


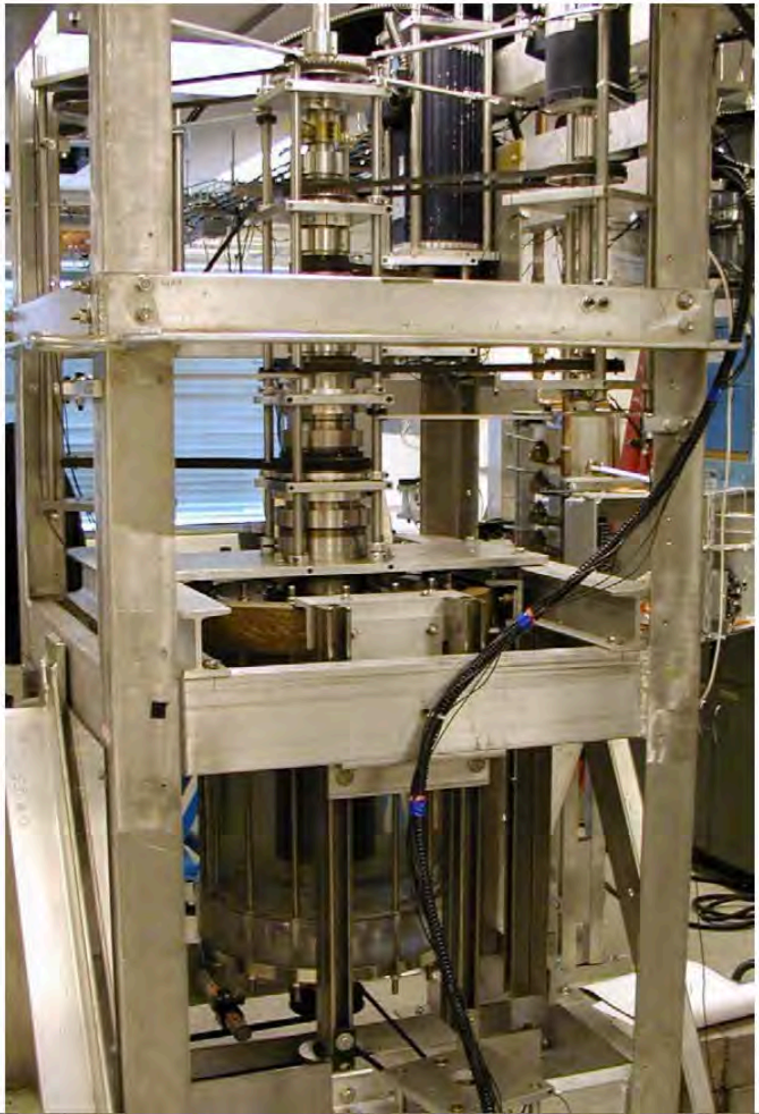
"I think you should be more explicit here in step two."

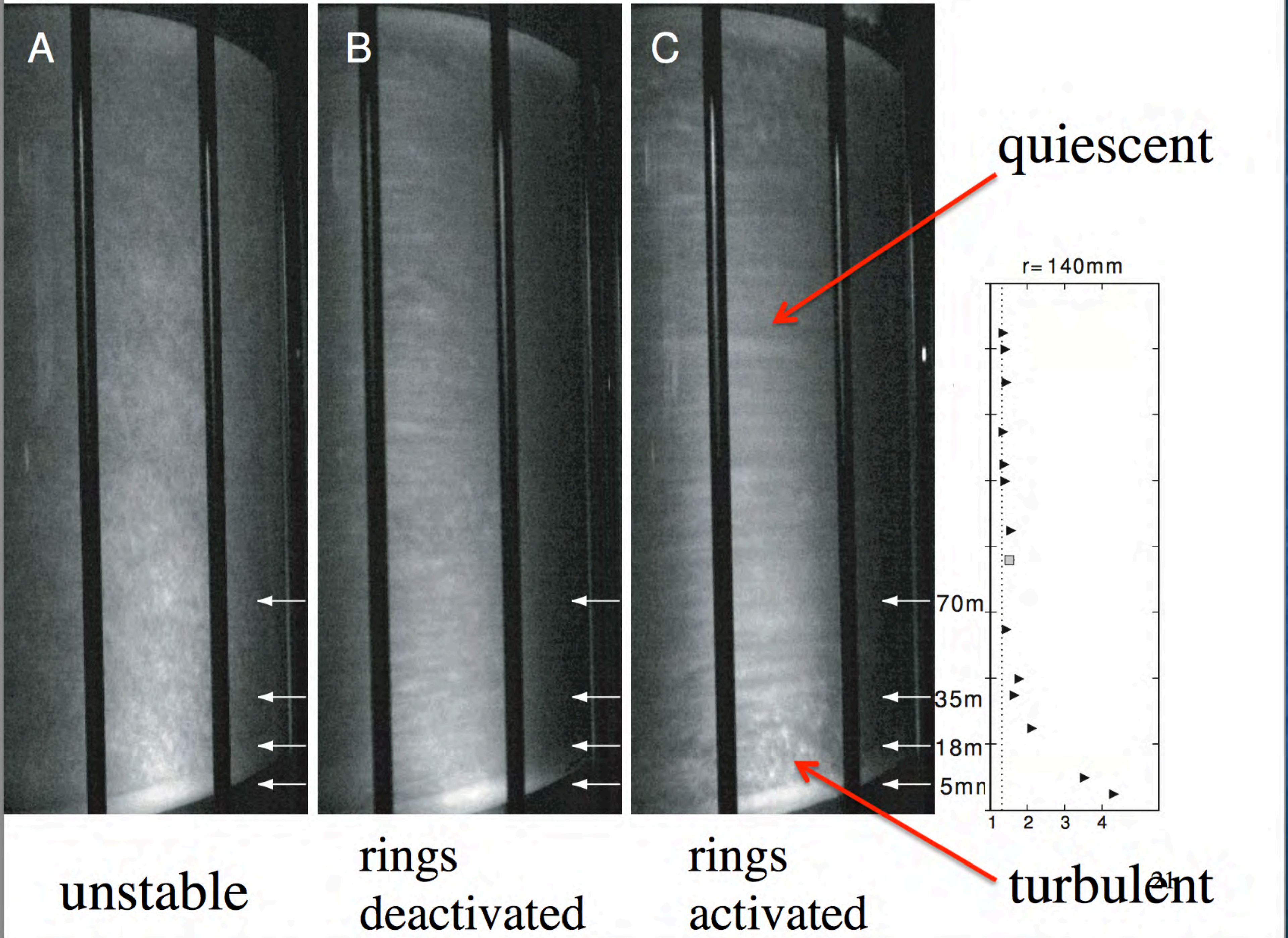
Ji, Burin, Schartman, Goodman (2006)

r_1=7.06cm, r_2=20.30cm, h=27.86cm

η=0.348, Γ=2.10, Re<2×10^6 (now 2×10^7 in liquid gallium)



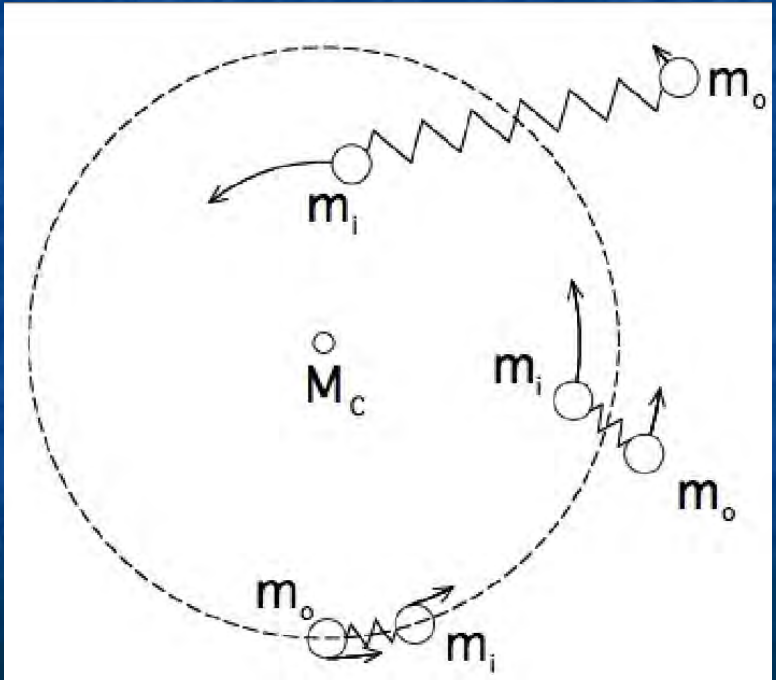


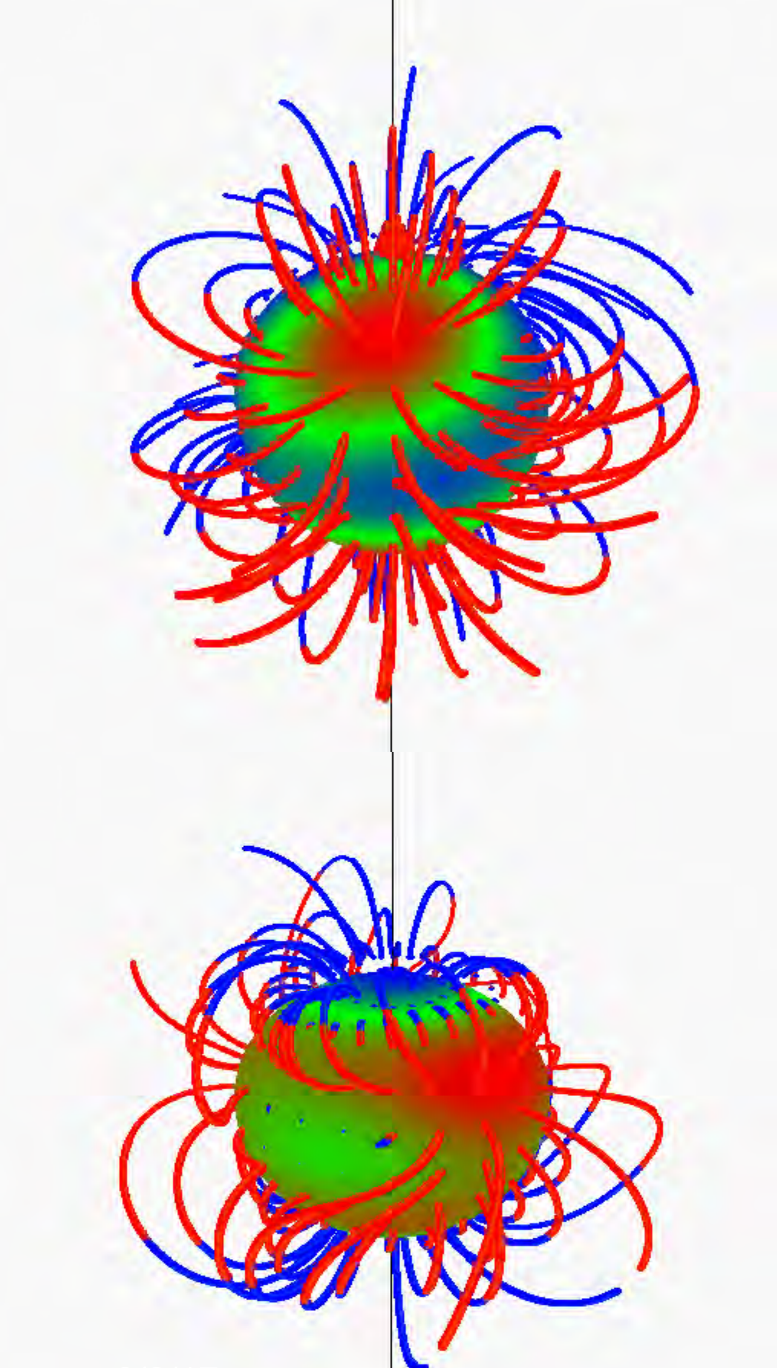

A
B
C
quiescent
r= 140mm
70m
35m
18m
5mn
1
2
3
4
turbulent
unstable
rings
deactivated
rings
activated

Driving of turbulence

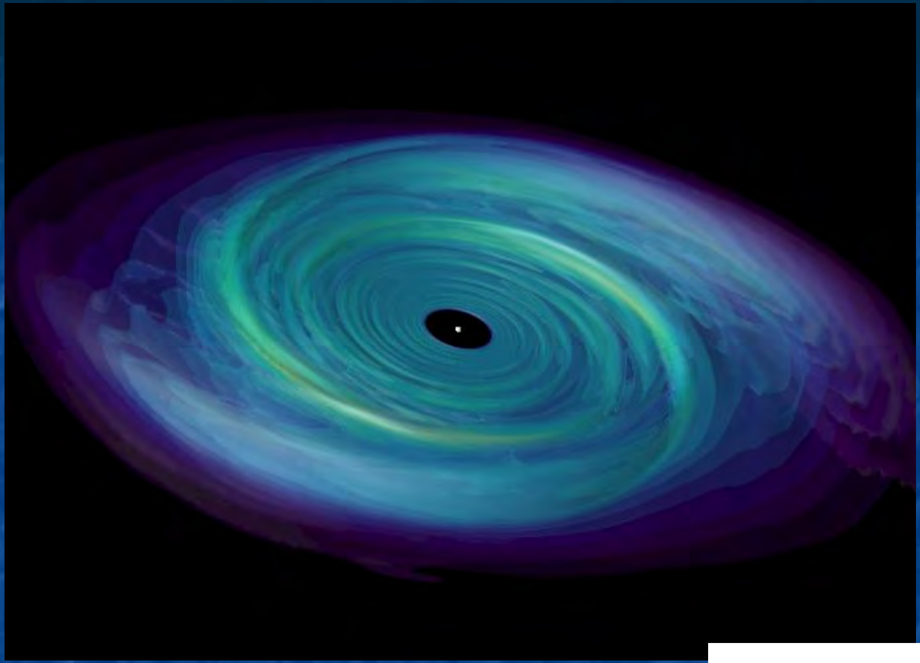
- What drives/sustains the turbulence?
- **Hydrodynamic** accretion disks seem to be stable and hence not turbulent
- Situation different for **magnetized** accretion disks

  - Weak magnetic field makes flow unstable (magneto-rotational instability; Balbus & Hawley 1991)
  - Instability grows quickly (orbital timescale), eventually transitioning to turbulence
  - Correlations within the turbulence transport angular momentum





Slide courtesy of D.Lathrop (UMd)



$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \mathbf{v}] = 0, \qquad (1)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \mathsf{P}^*\right] = 0, \qquad (2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P^*)\mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})\right] = 0, \qquad (3)$$

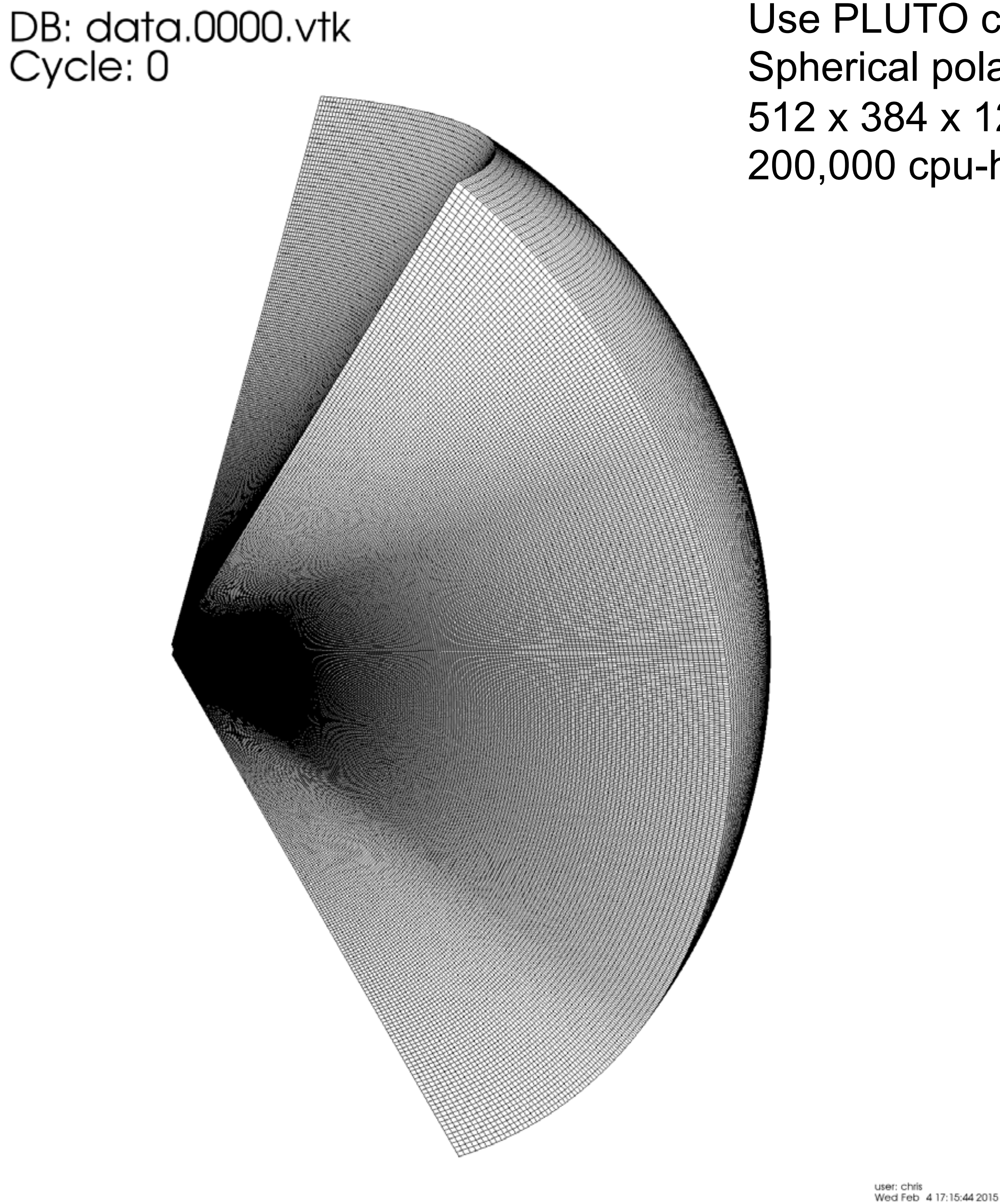
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \qquad (4)$$

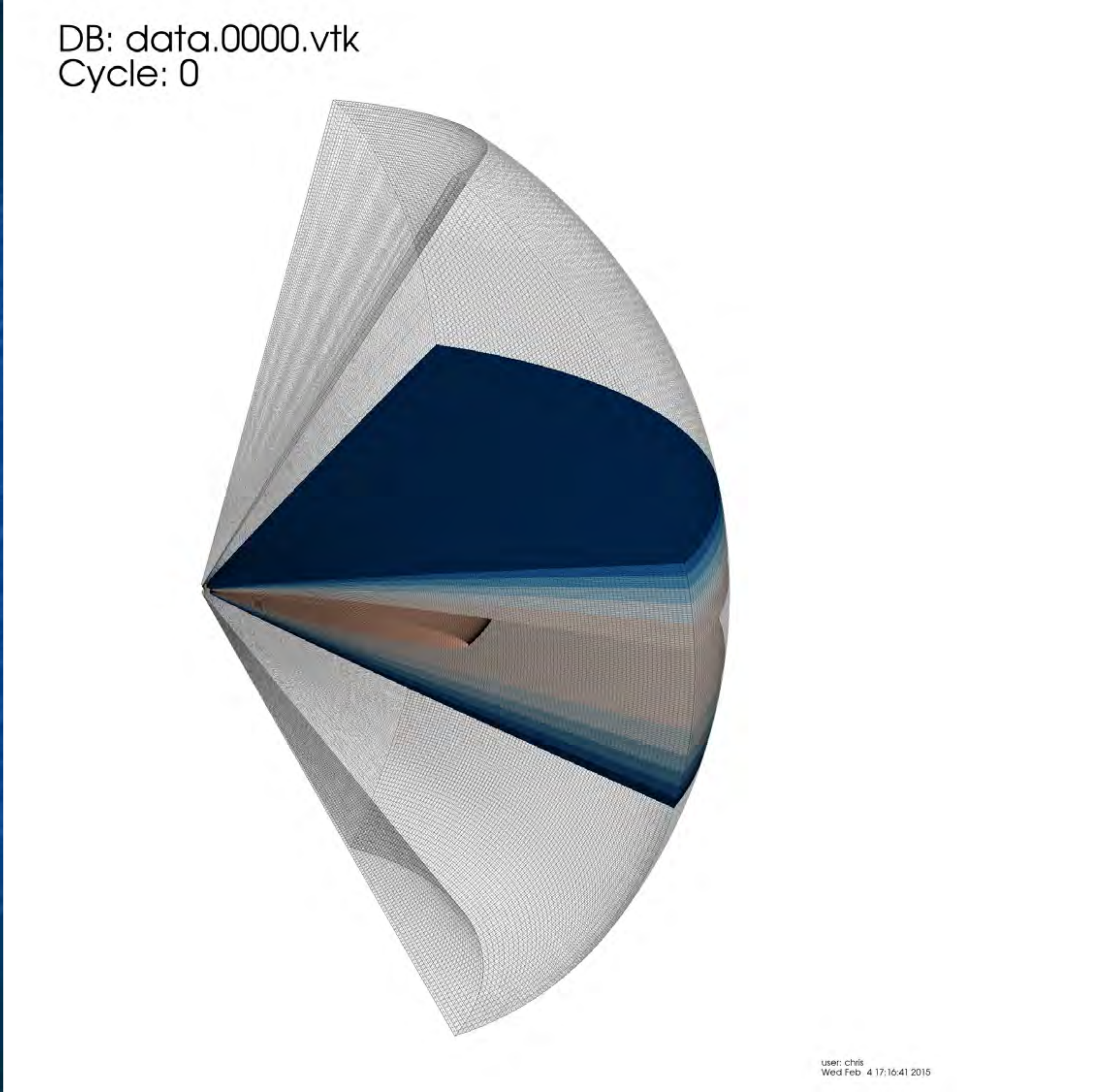
where P^* is a diagonal tensor with components $P^* = P + B^2/2$ (with P the gas pressure), E is the total energy density

$$E = \frac{P}{\gamma - 1} + \frac{1}{2}\rho v^2 + \frac{B^2}{2}, \qquad (5)$$

Stampede (Texas Advanced Computer Center)
6,400 Dell C8220 nodes (102,000 cores + 390,000 co-proc cores)
10 Pflops aggregate performance

Use PLUTO code
Spherical polar grid
512 x 384 x 128 zones
200,000 cpu-hours

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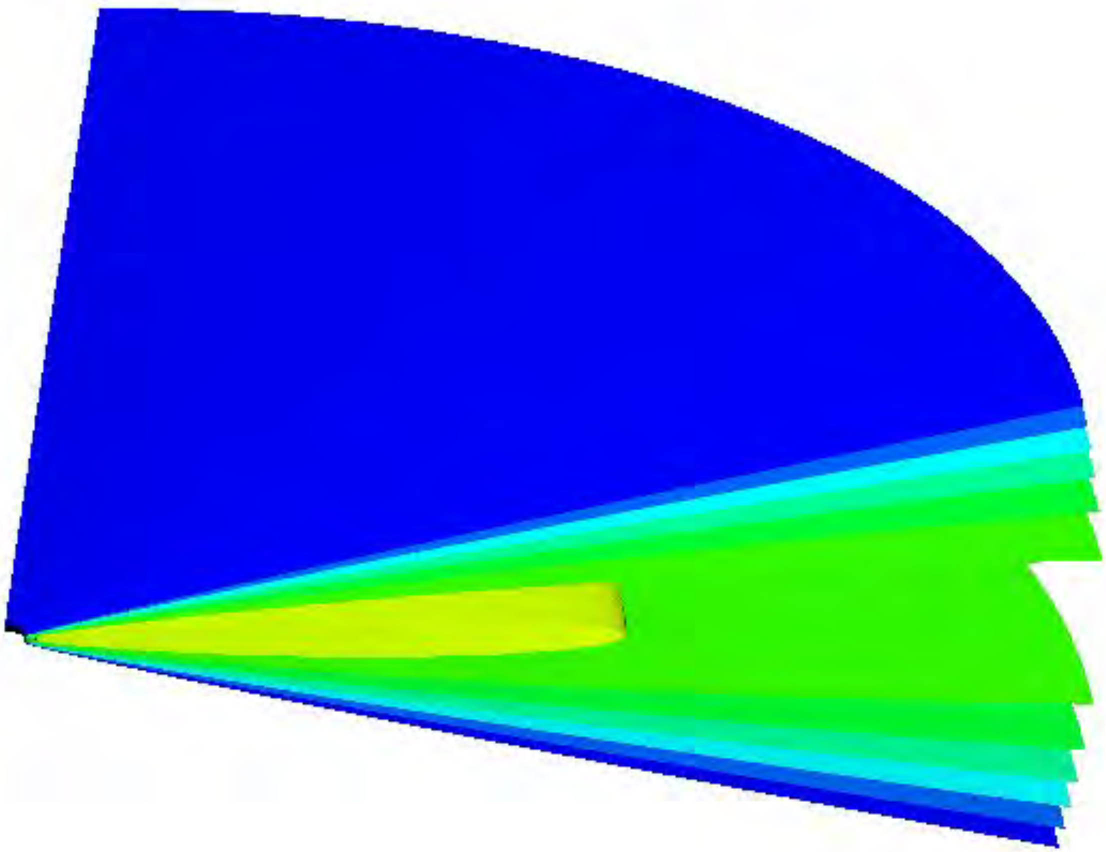
Cycle: 0
user: chris
Wed Feb 4 17:16:41 2015

DB: data.0000.vtk
Cycle: 0



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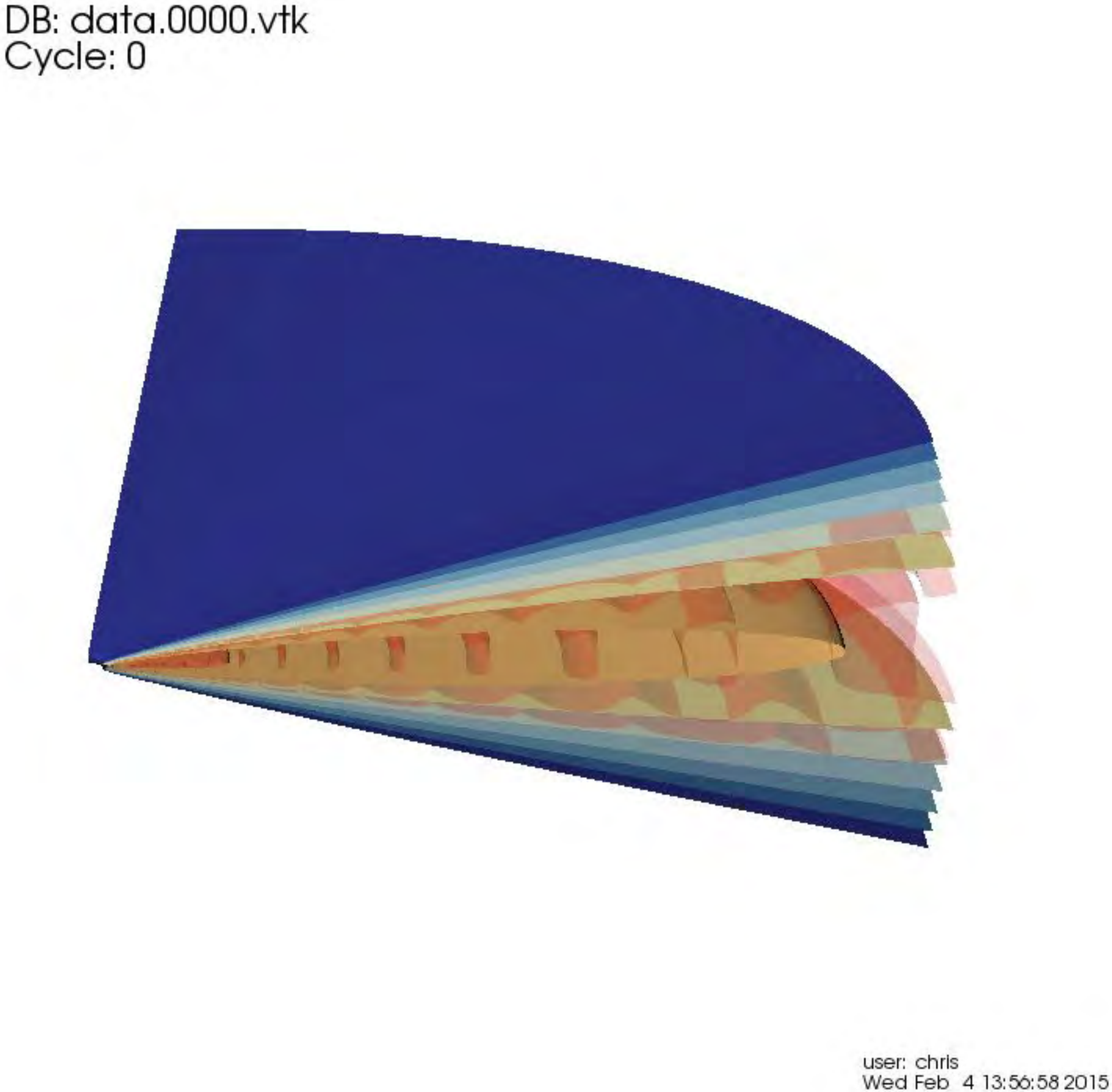
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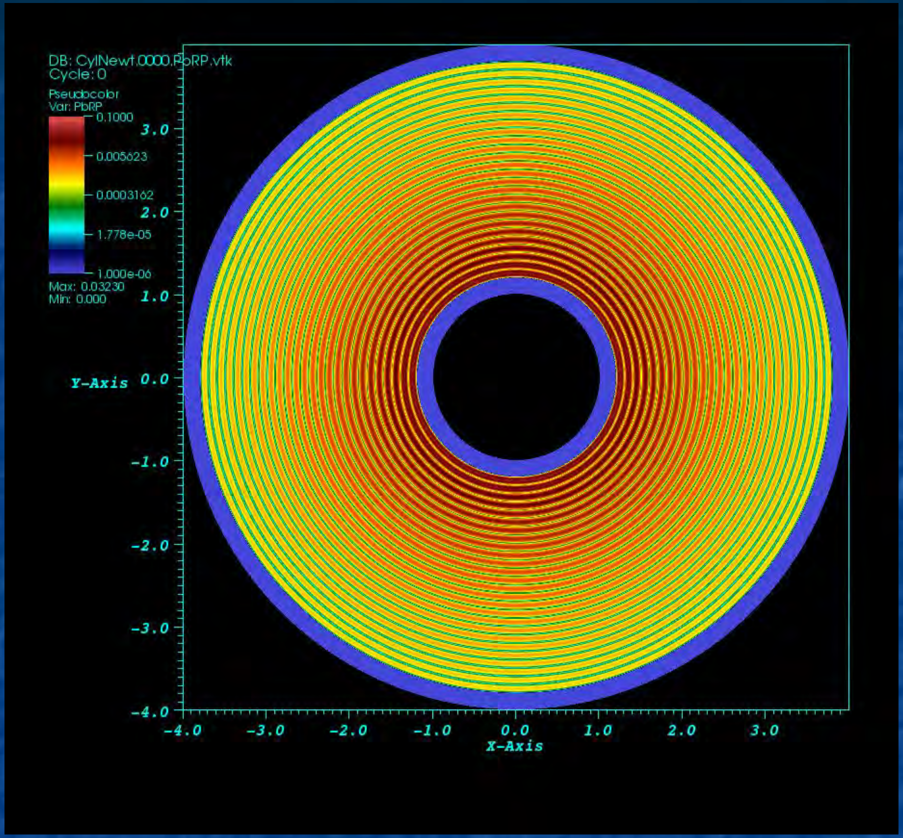
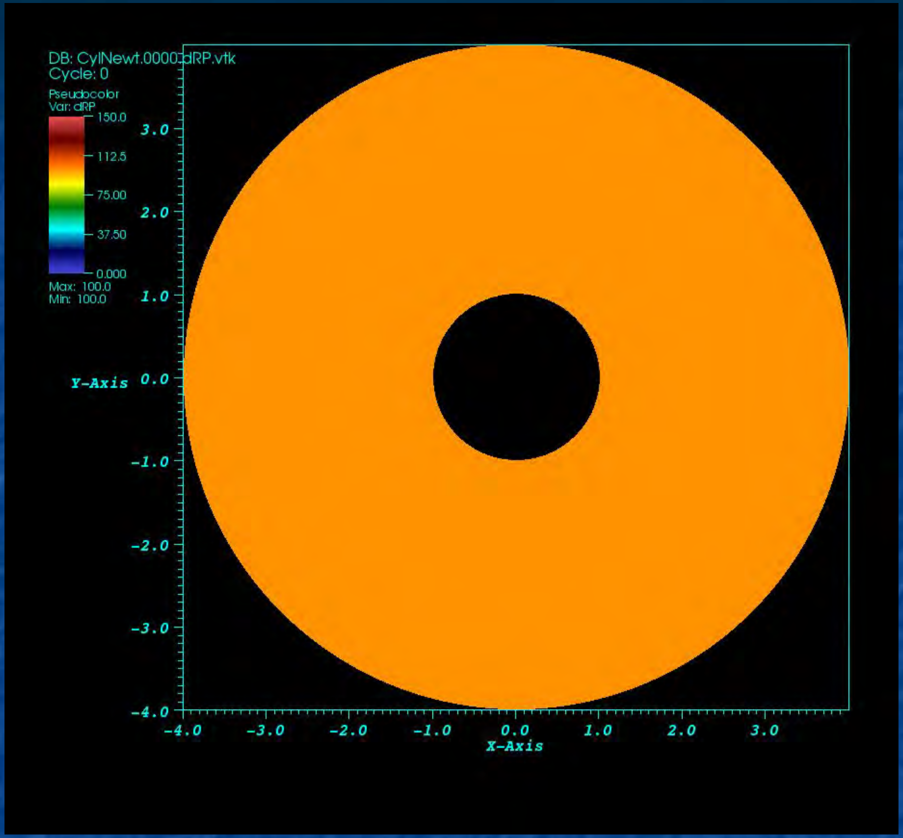
Magnetic Pressure (midplane)



Density (midplane)



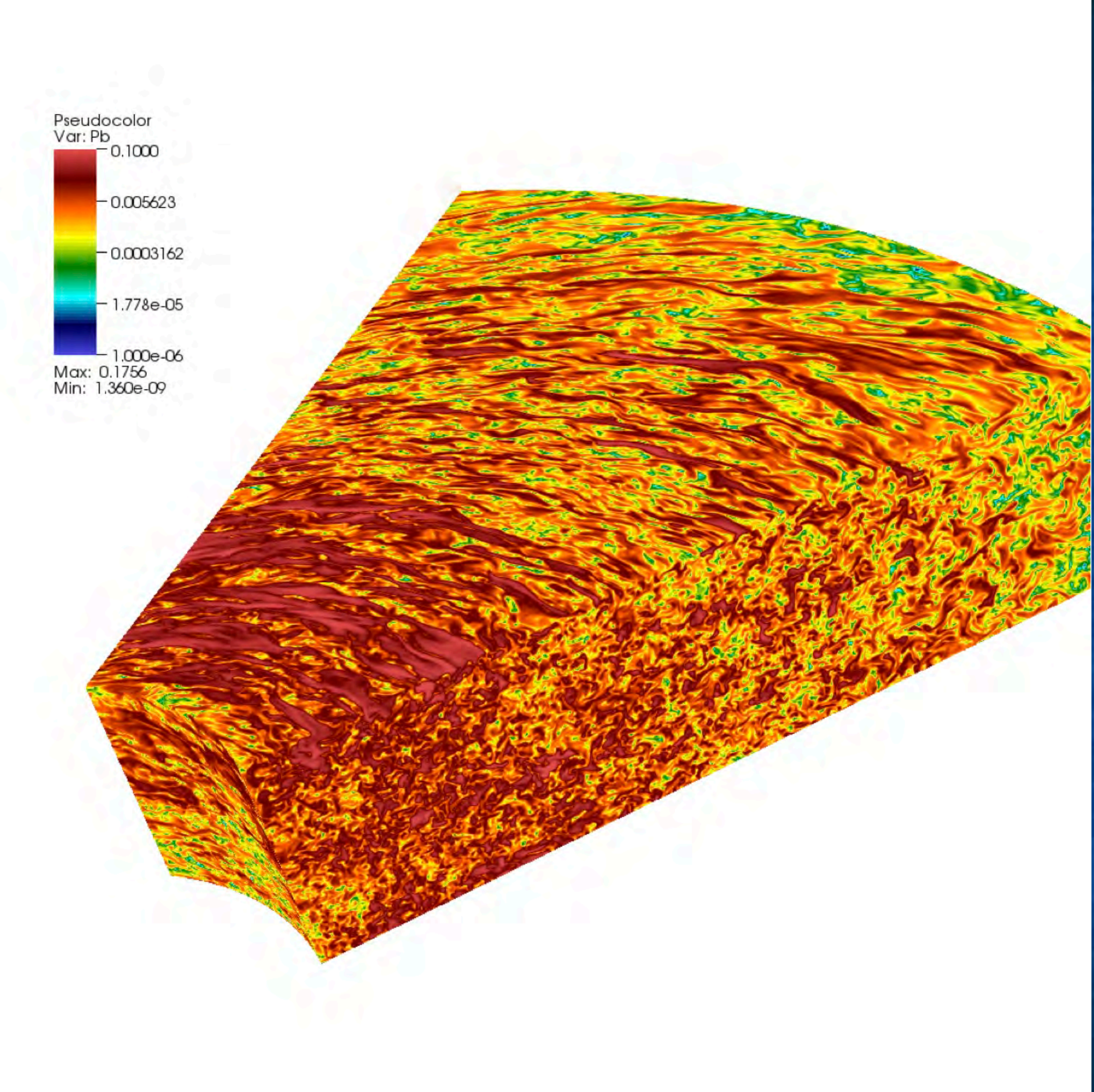
High resolution run using ATHENA : $n_r \times n_z \times n_\varphi = 480 \times 128 \times 2048$

32 zones/h at the fiducial radius

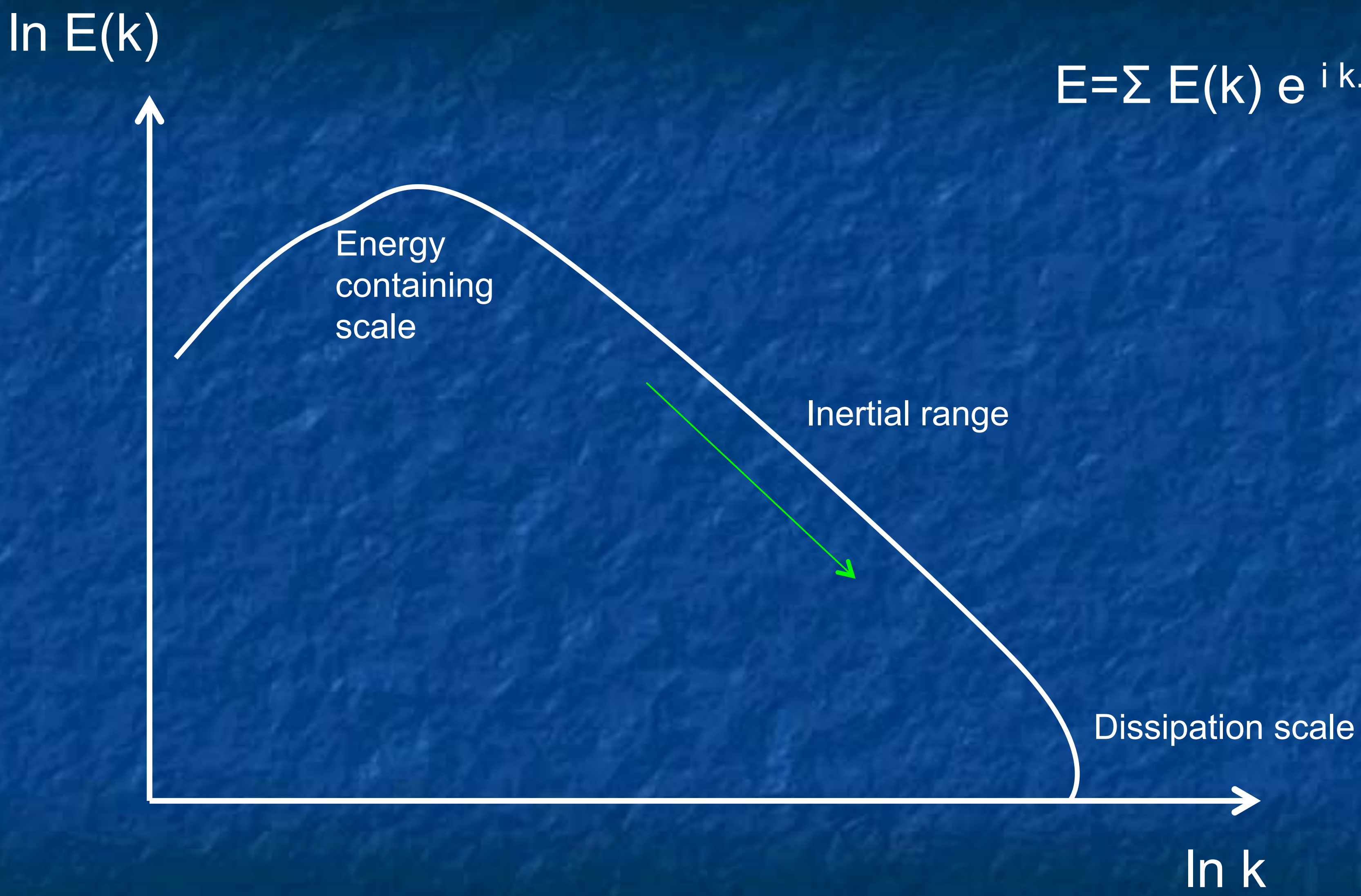
Use of orbital advection speeds up calculation by factor of 20

120,000 CPU hours on TeraGrid/Ranger

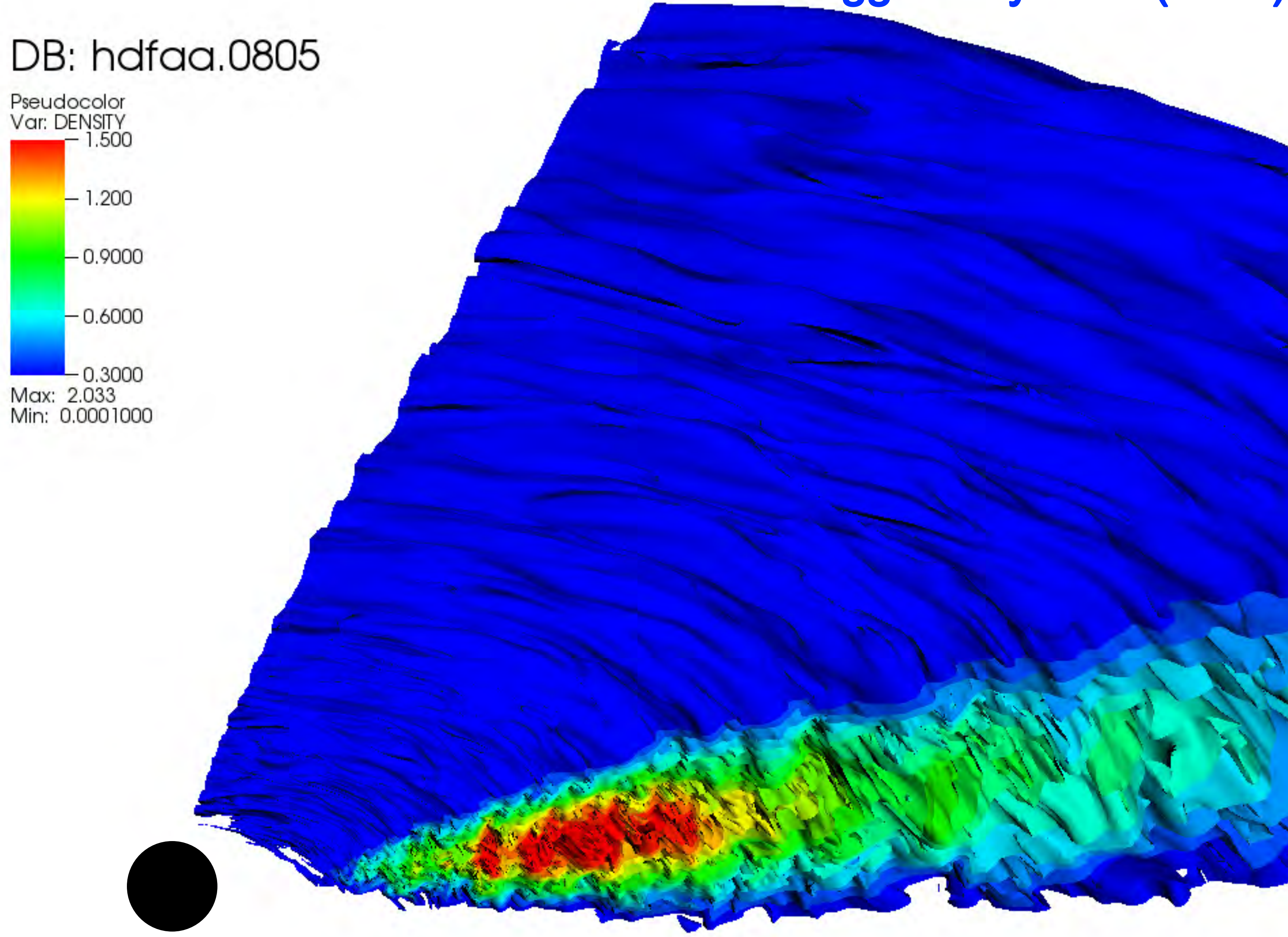
Sorathia, Reynolds, Stone, Beckwith (2012)


Pseudocolor
Var: Pb
0.1000
0.005623
0.0003162
1.778e-05
1.000e-06
Max: 0.1756
Min: 1.360e-09

$$E = \Sigma\, E(k)\, e^{i\, k.x}$$

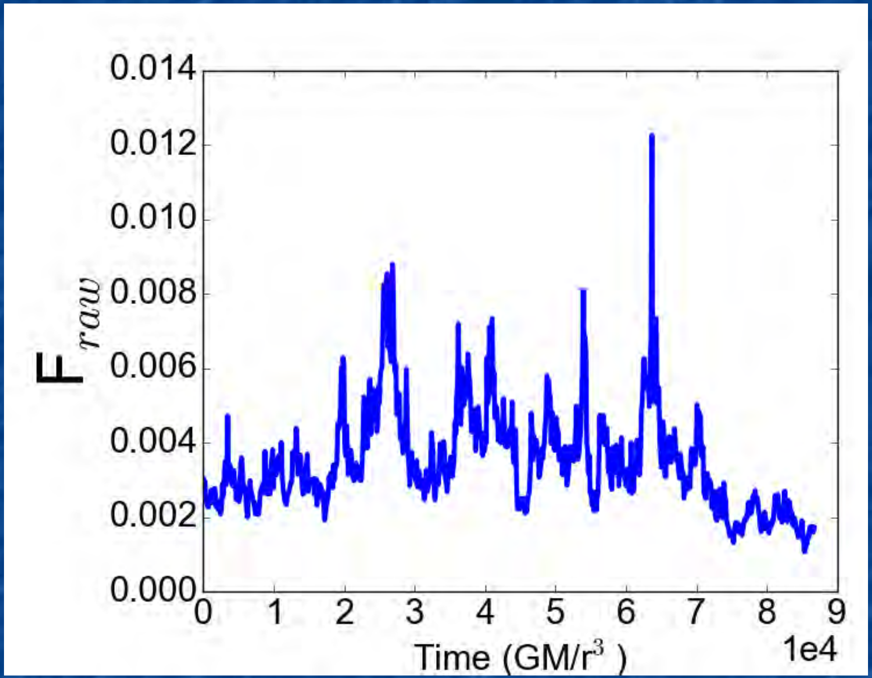


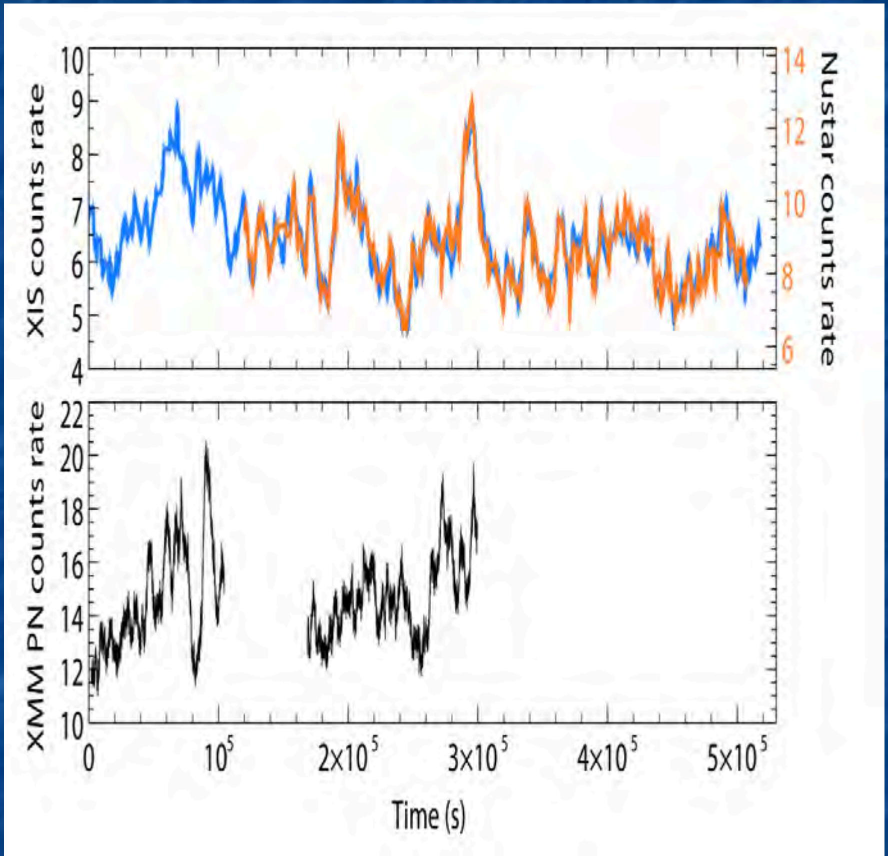
Hogg & Reynolds (2016)



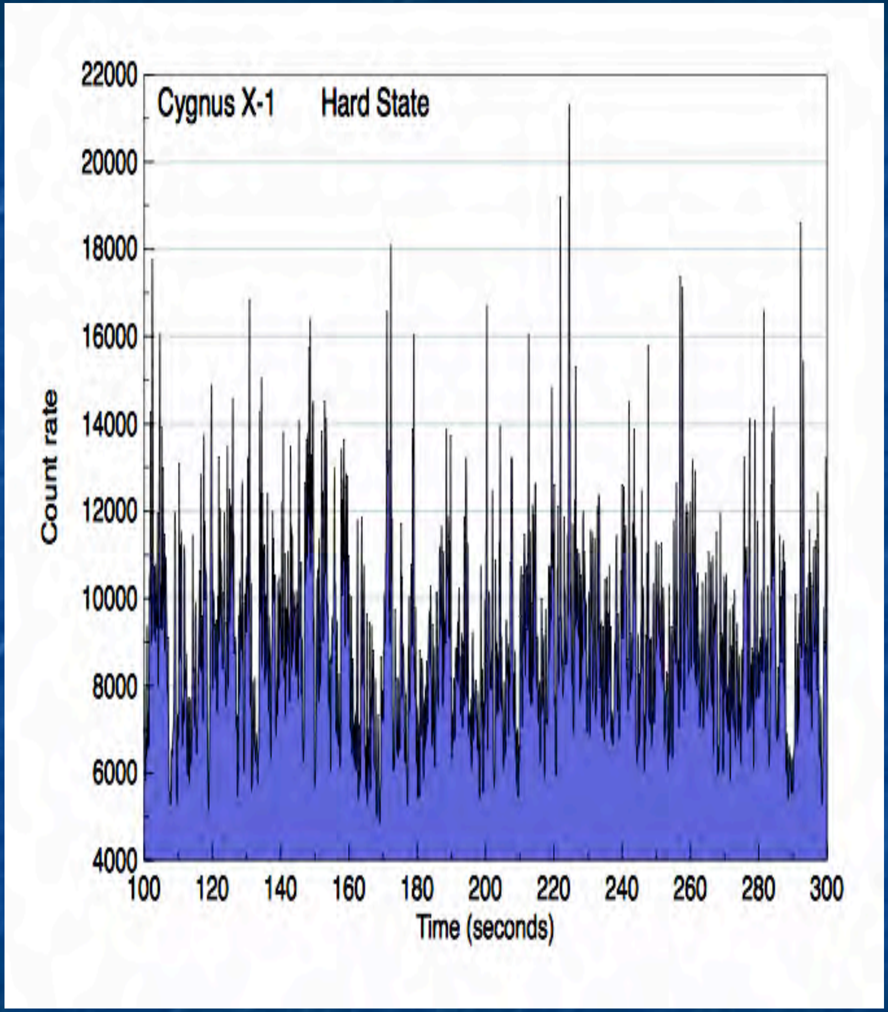
X-ray data of accreting super-massive black hole in MCG-5-23-16 (Zoghbi et al. 2014)

Simulated accretion disk (Hogg and Reynolds 2016)

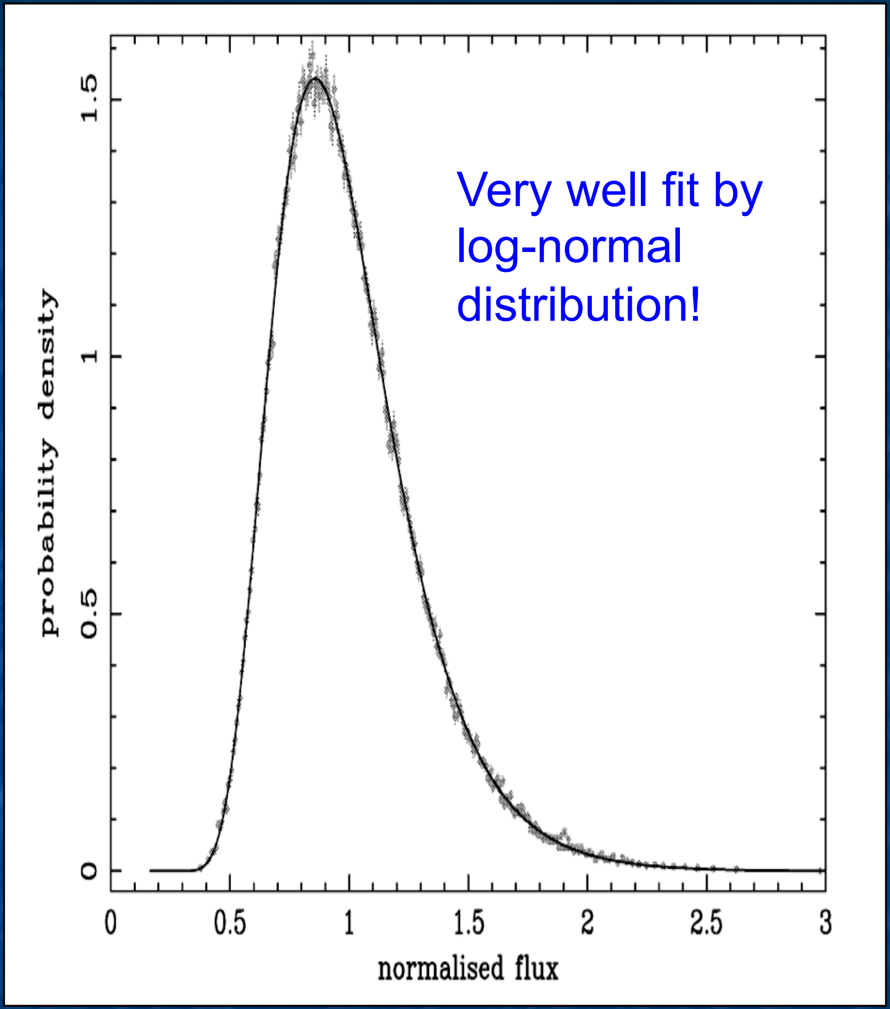




Cygnus X-1 (RXTE)



Belloni et al. (2010)



Uttley, McHardy & Vaughan (2005)

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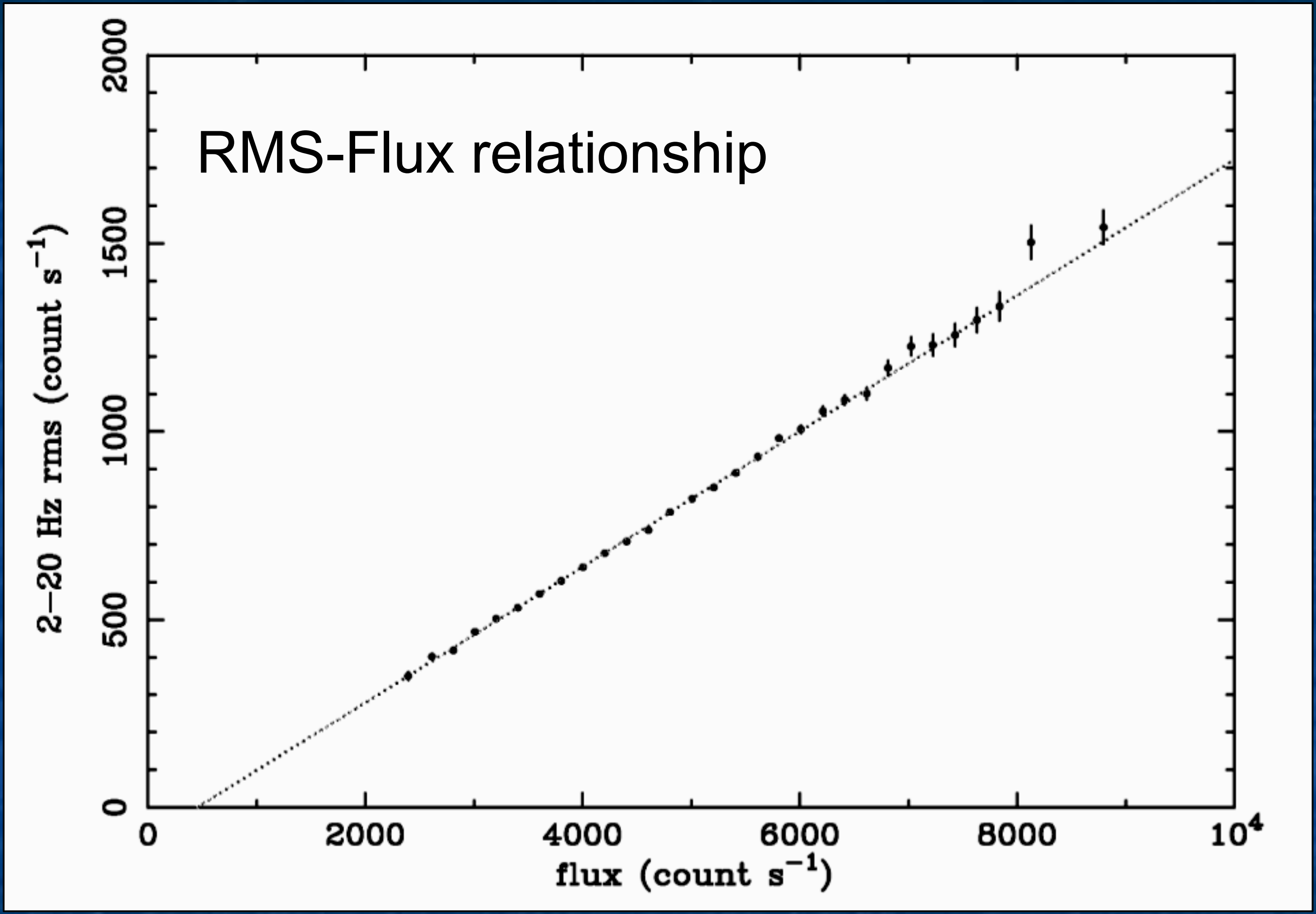
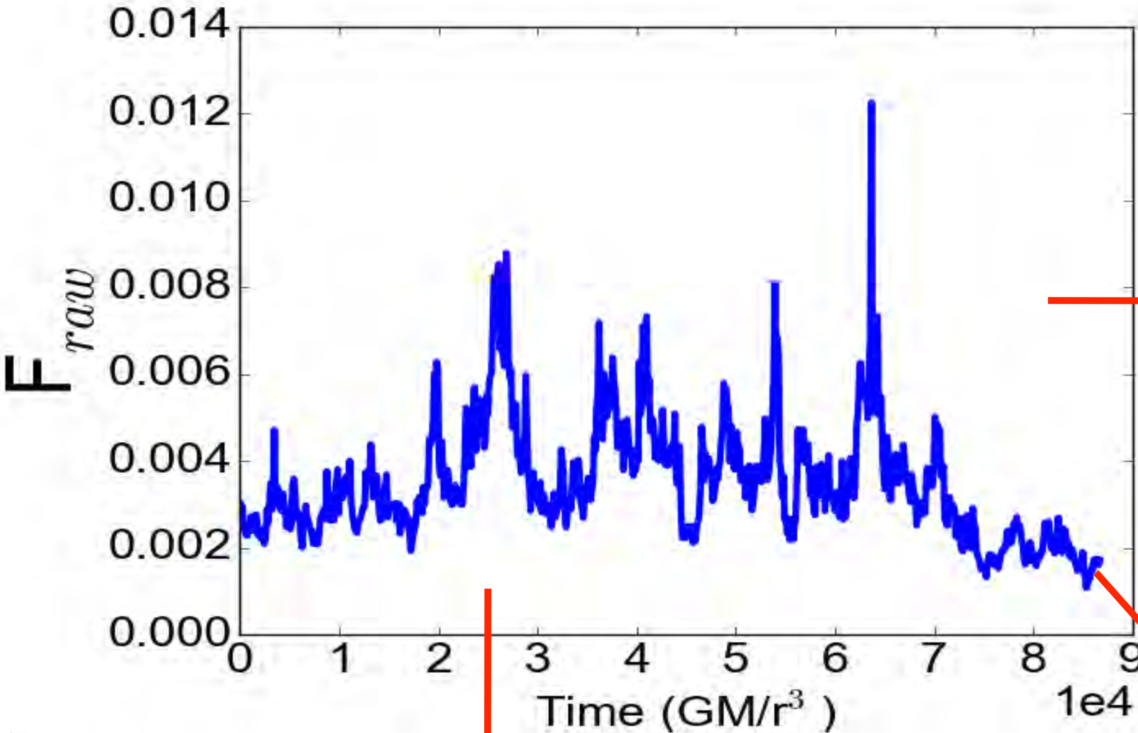
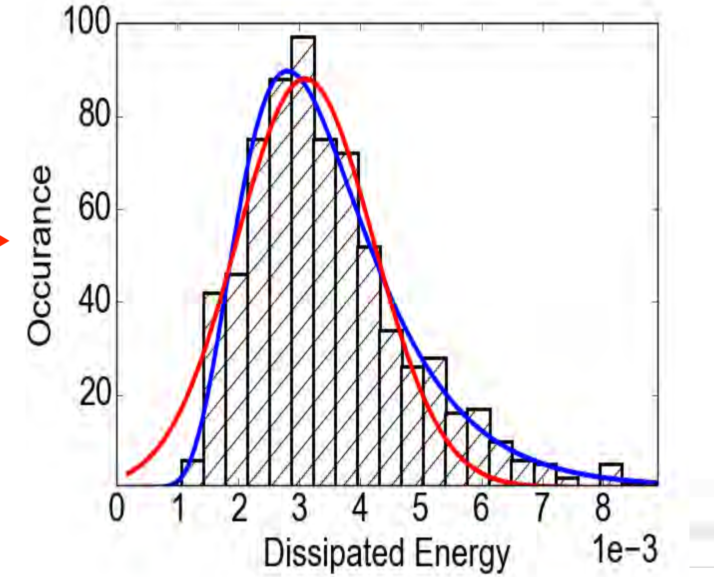
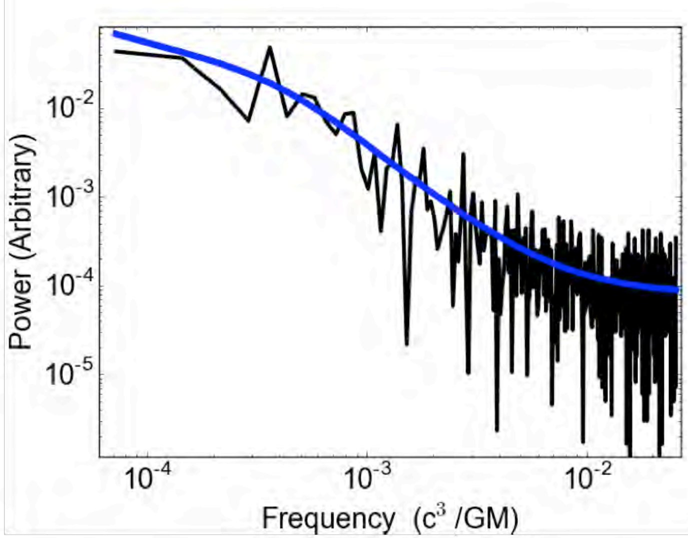


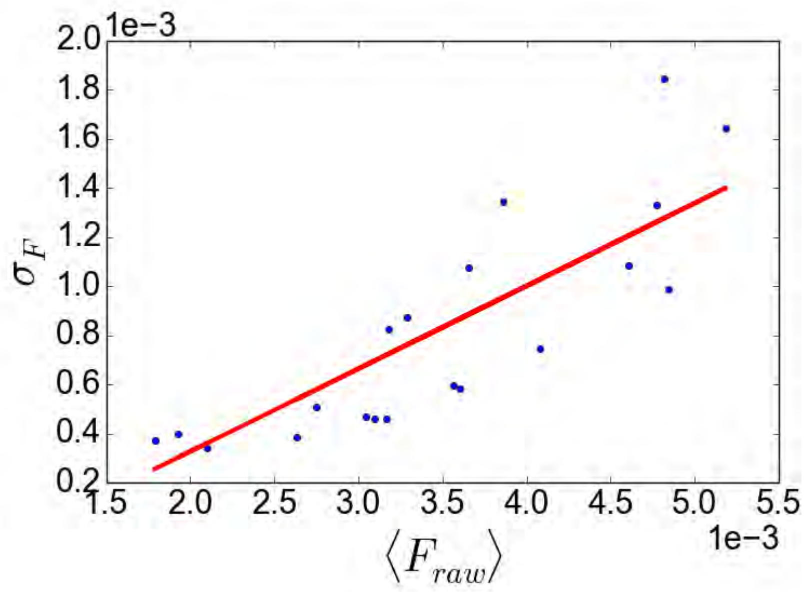
Uttley, McHardy & Vaughan (2005)

Hogg & Reynolds (2016)

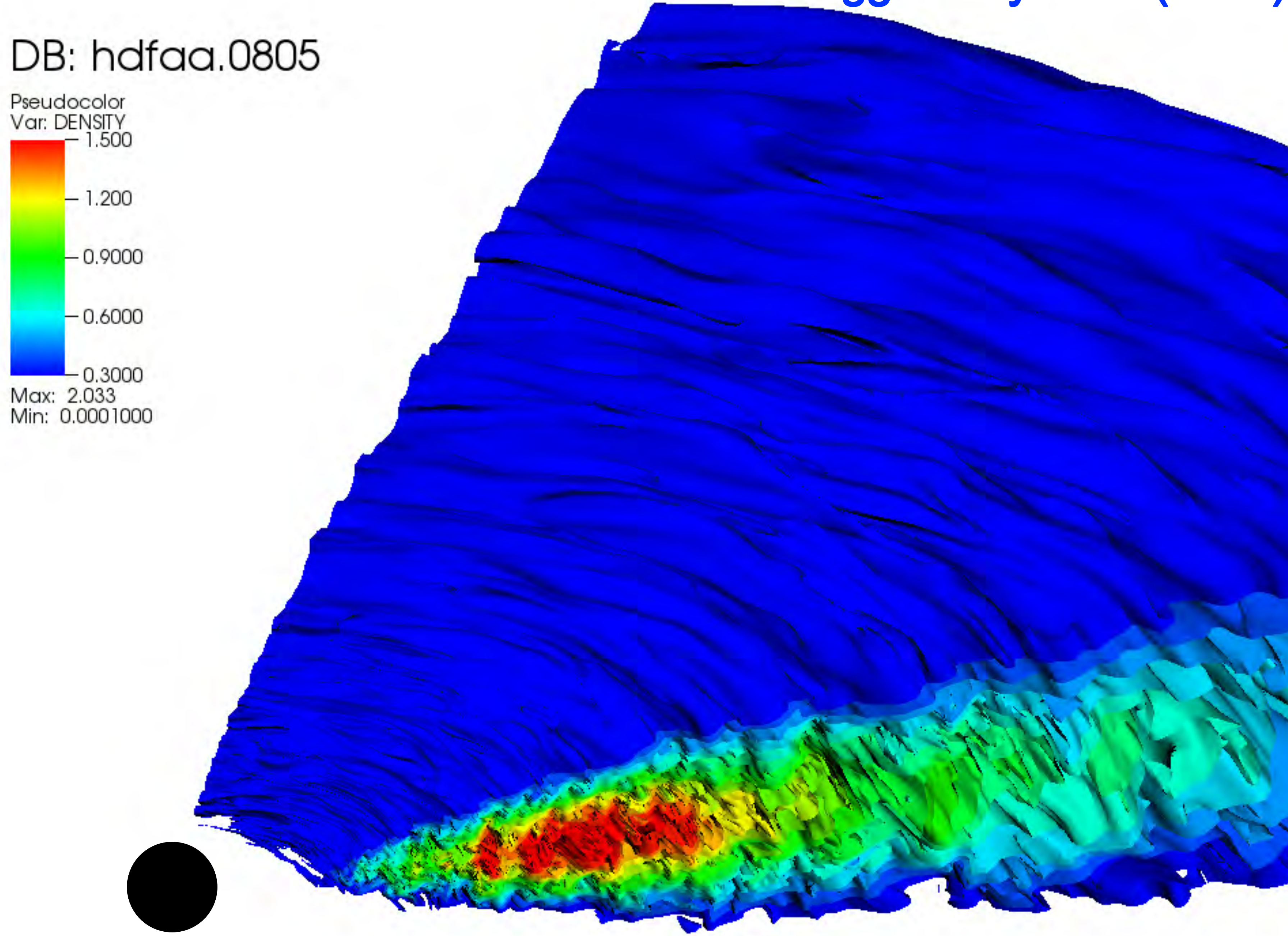




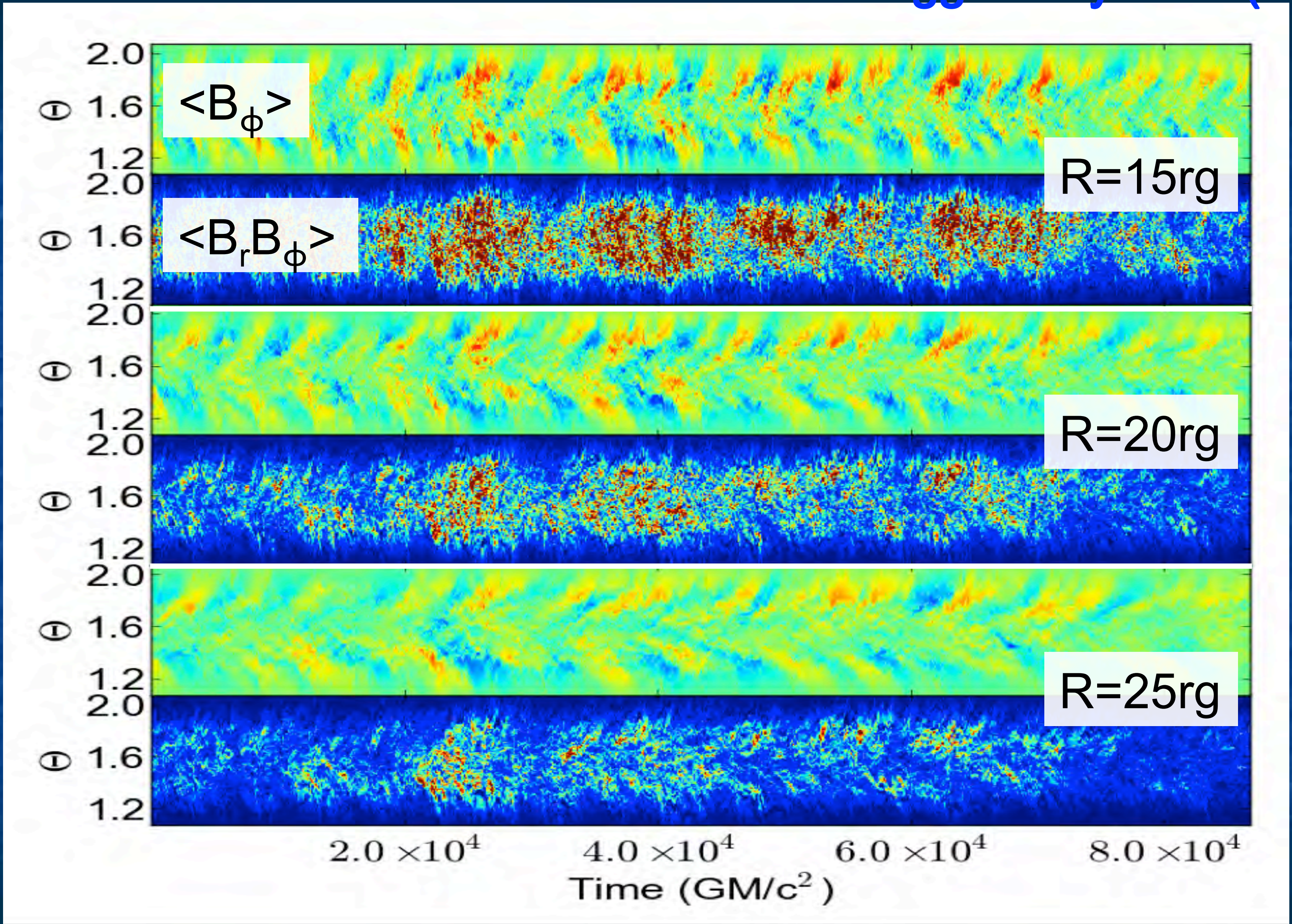




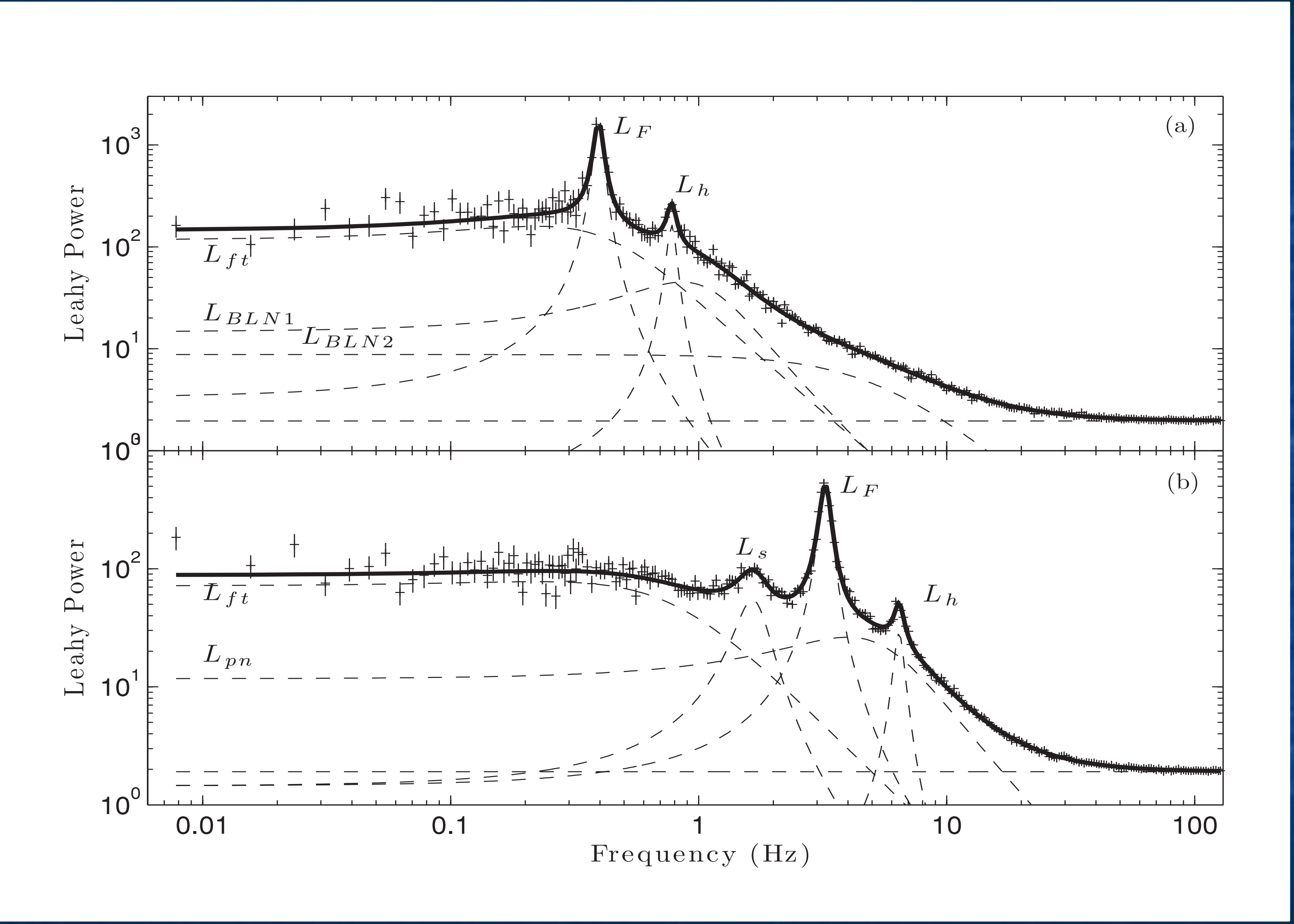
Hogg & Reynolds (2016)



Hogg & Reynolds (2016)



Stellar-mass black hole XTEJ1550-564; Rao et al. (2010)



Conclusions

- Need to overcome angular momentum in order for accretion to occur
  - Same problem exists in planet/star formation
- MHD turbulence paradigm seems firm
  - Large-scale computer simulations have been crucial tool for understanding implications of MRI
- Work underway to understand complex phenomenology of black holes
  - Basic properties of the turbulence
  - Role of other physics (radiation, plasma processes, relativity…)