Radiation-Dominated Accretion Disks

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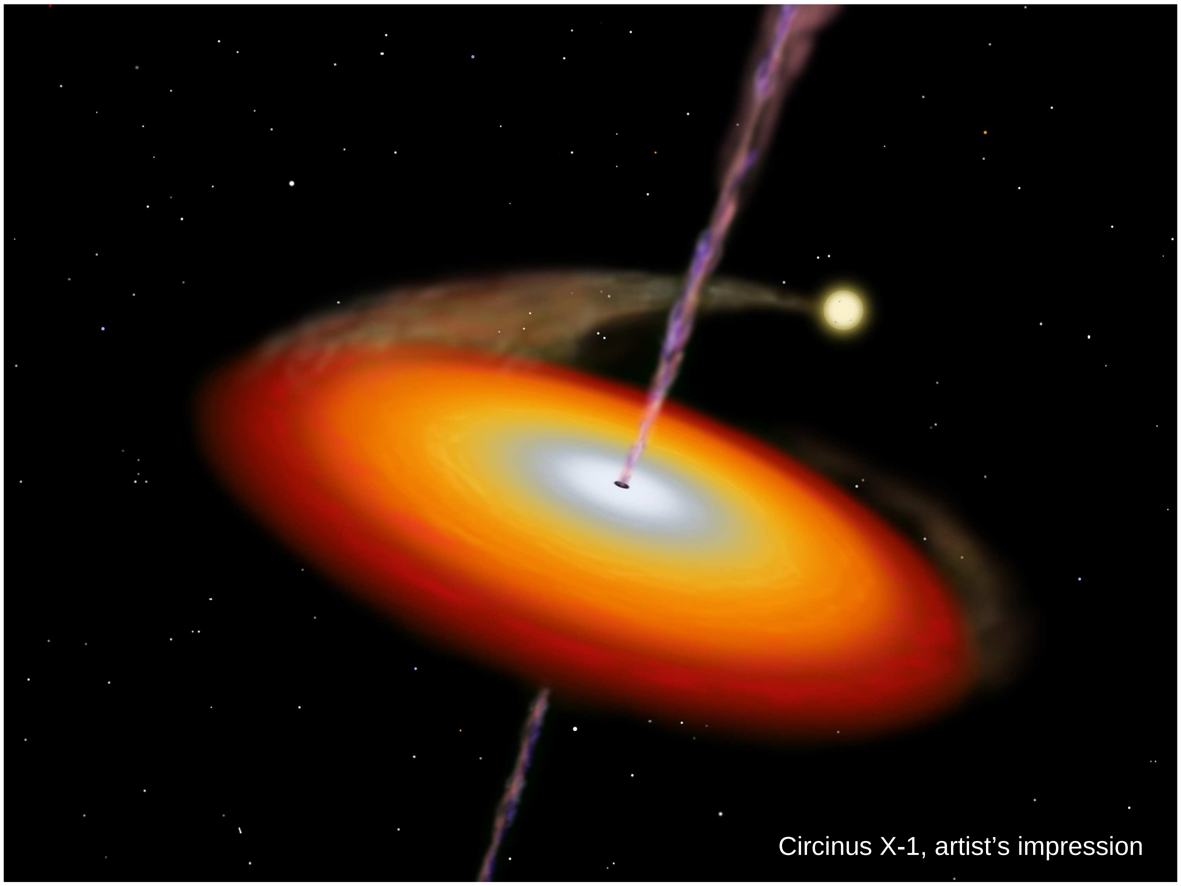
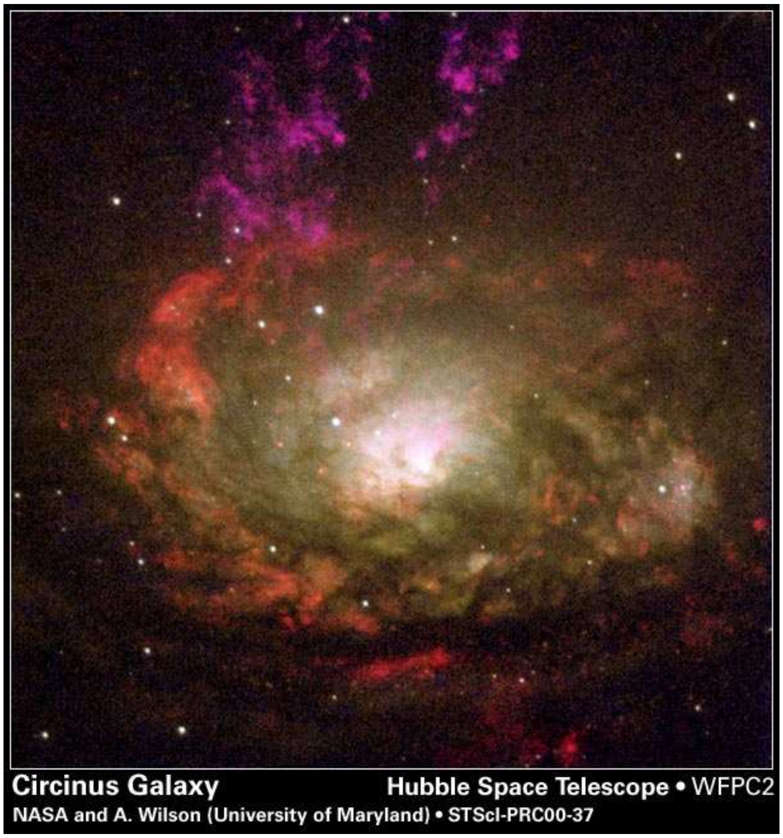


Circinus X-1, artist’s impression



Circinus Galaxy Hubble Space Telescope • WFPC2
NASA and A. Wilson (University of Maryland) • STScI-PRC00-37

To Make Accreting Gas Shine:

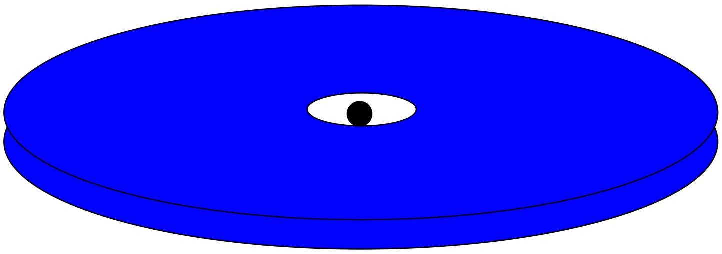
- Remove angular momentum
- Dissipate orbital kinetic energy
- Radiate photons

Shakura-Sunyaev Picture – Assumptions:

1. Hydrostatic equilibrium
2. Stress = αP
3. Vertical thermal balance:
    * viscous heating = diffusion cooling
    * dissipation ~ density
4. Inflow equilibrium

Innermost 300 R_{Schw}:

- Radiation Pressure > Gas Pressure
- Flat, thickness ≈ $2R_{Schw}$
- Uniform Density and Dissipation



Instabilities of Shakura-Sunyaev model:

- Convective
- Thermal
- Viscous

Overview

1. Shakura-Sunyaev Picture
2. Radiation-MHD Equations
3. **Heating**
4. **Cooling**
5. X-Ray Reflection
6. Summary

Equations of Radiation MHD

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{v} = 0$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} + \frac{\chi\rho}{c}\mathbf{F} - 2\rho\mathbf{\Omega_0}\times\mathbf{v} + 3\rho\Omega_0^2\mathbf{x} - \rho\Omega_0^2\mathbf{z}$$

$$\rho\frac{D}{Dt}\left(\frac{E}{\rho}\right) = -\nabla\cdot\mathbf{F} - \nabla\mathbf{v}:\mathsf{P} + \kappa\rho(4\pi B - cE)$$

$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -p\nabla\cdot\mathbf{v} - \kappa\rho(4\pi B - cE)$$

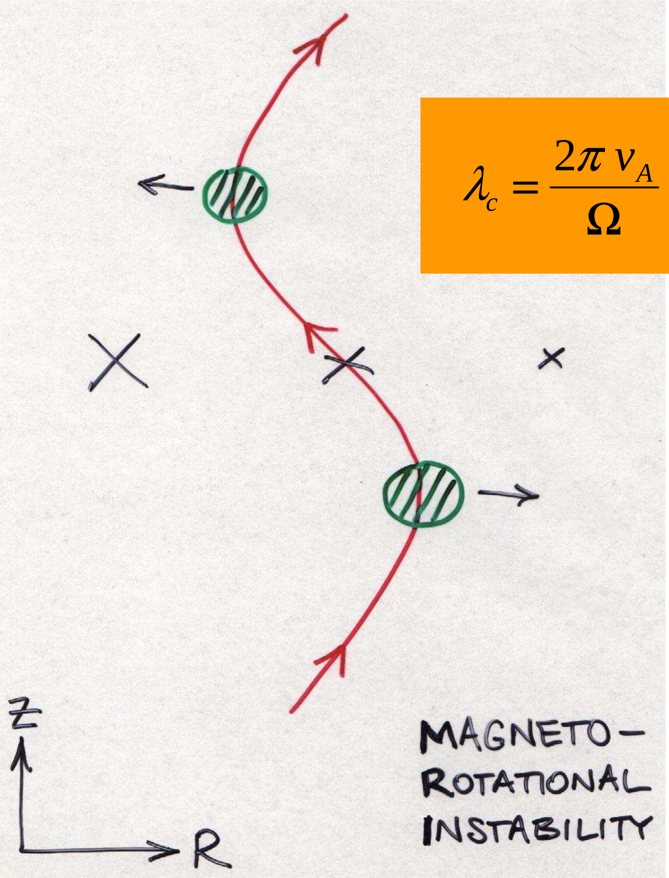
$$\mathbf{F} = -\frac{c\Lambda}{\chi\rho}\nabla E$$

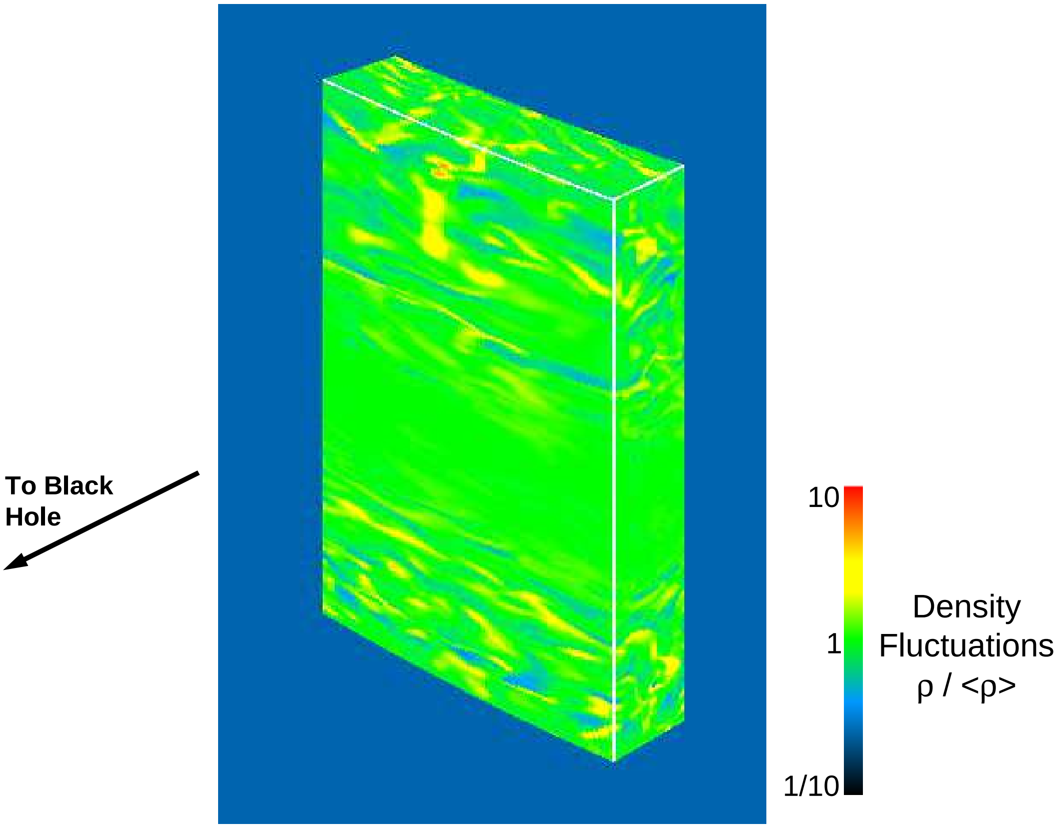
$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B})$$

Heating

Balbus &
Hawley
1991

$$\lambda_c = \frac{2\pi v_A}{\Omega}$$





Flow is heated by

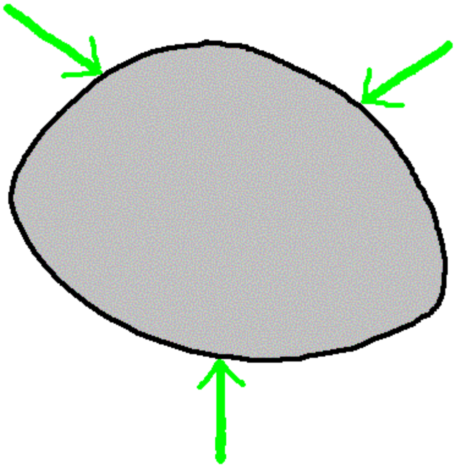
1. Microscopic viscosity
2. Magnetic dissipation
3. Radiation damping

[illegible] $\approx \sqrt{\alpha} H$

MRI wavelength $\approx \sqrt{\alpha} H$

Radiation Damping

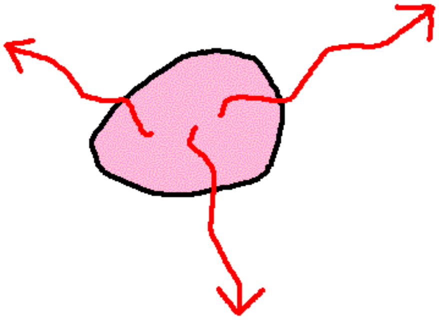
Agol &
Krolik
1998



1. Magnetic fields squeeze gas

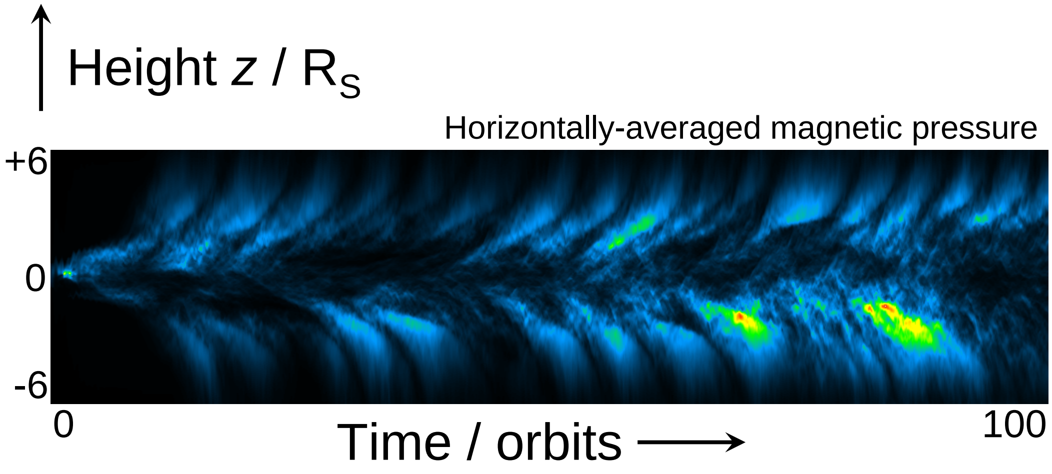
Radiation Damping

Agol &
Krolik
1998

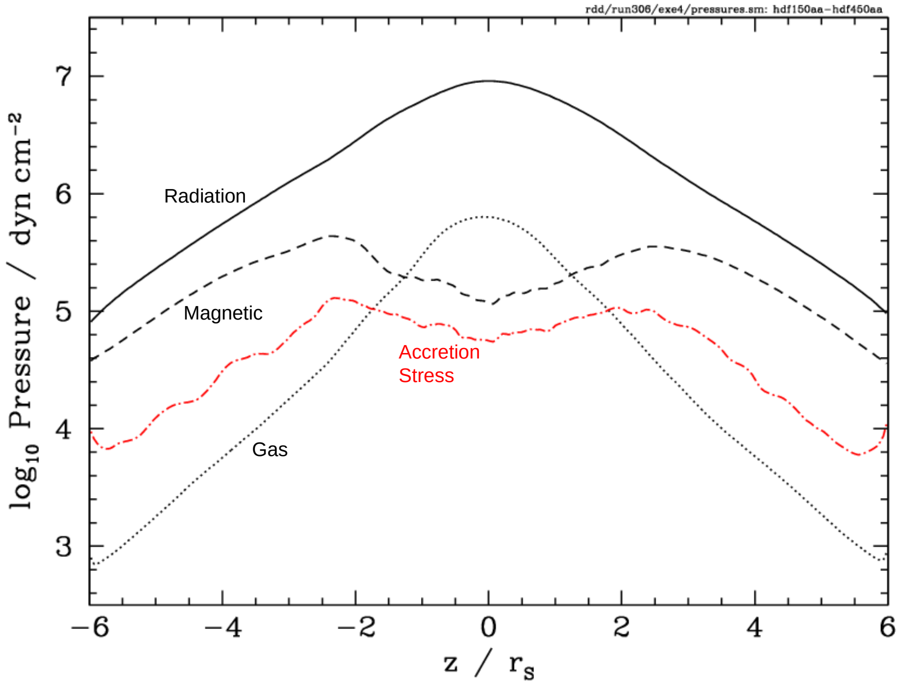


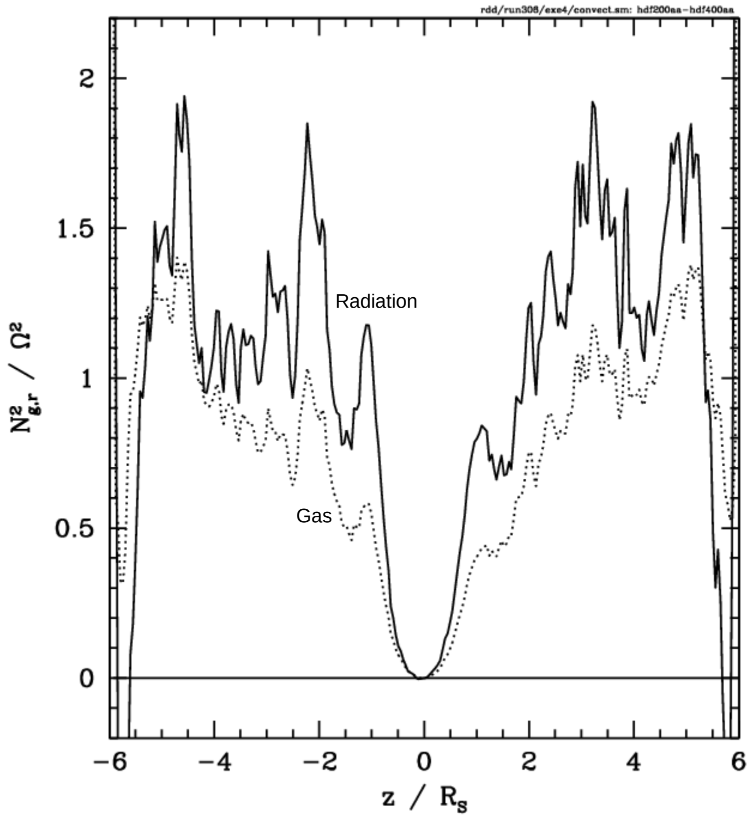
2. Gas radiates

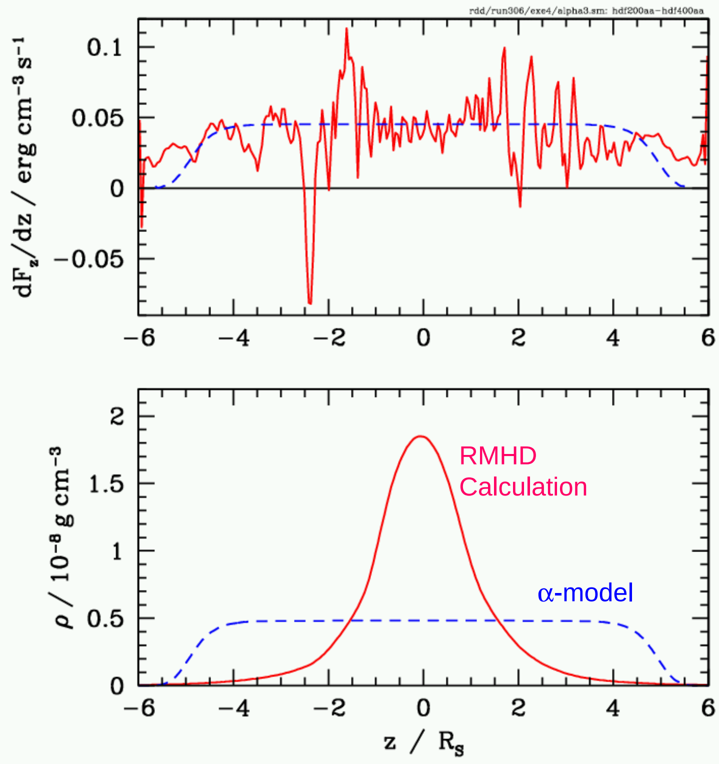
Magnetic Field Evolution



Gas and Radiation Pressures







Compare Shakura-Sunyaev Model

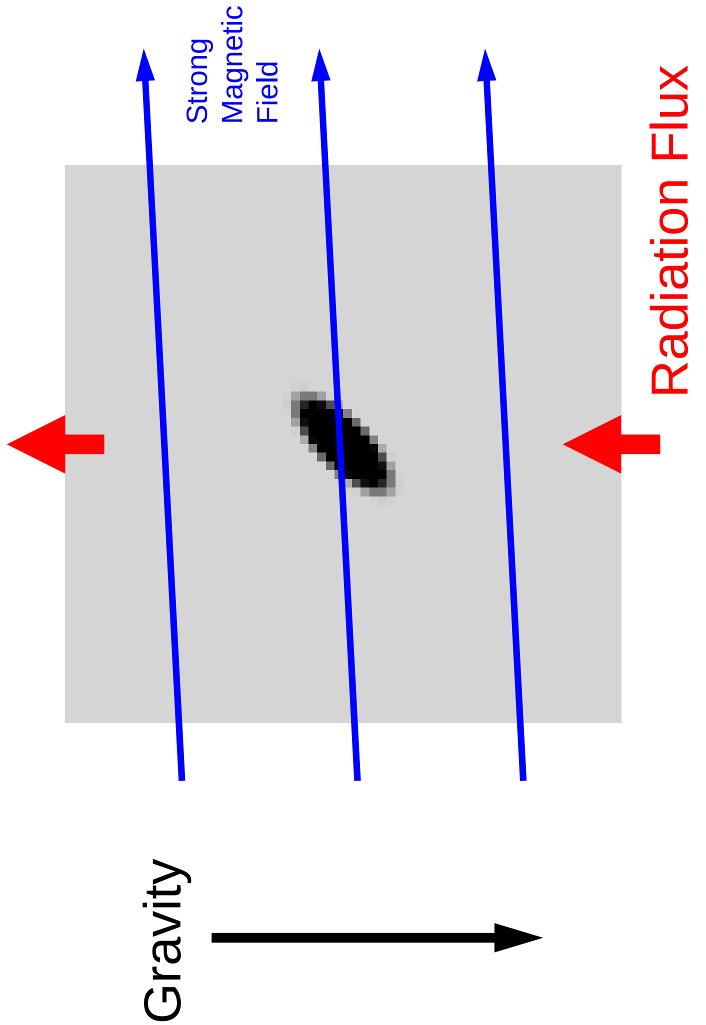
Same surface mass density and flux

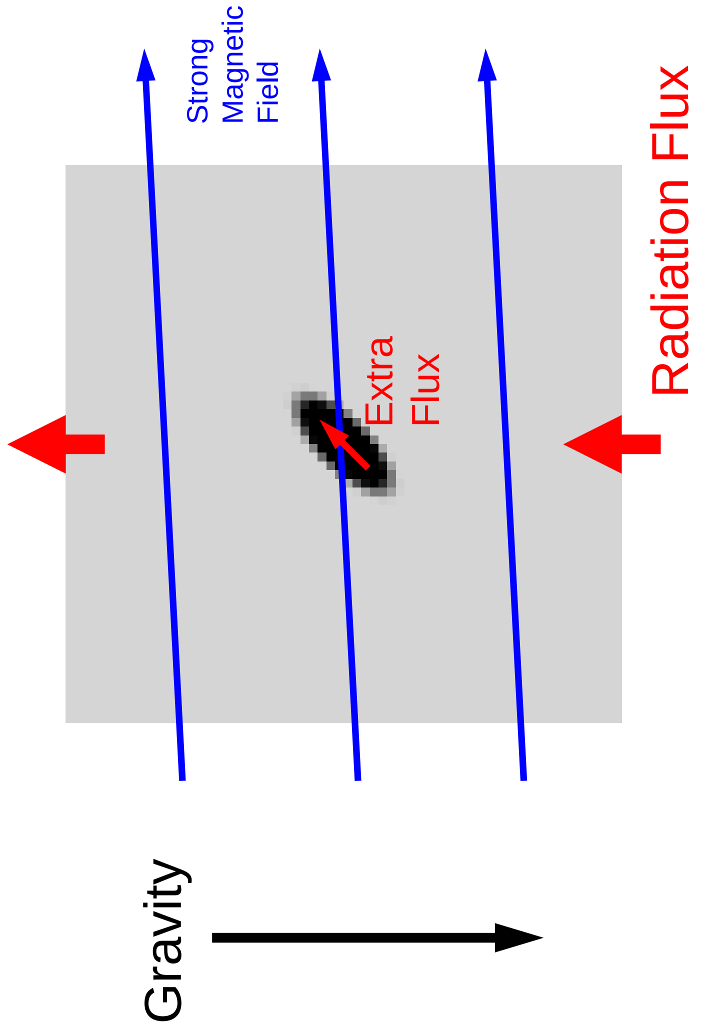
Cooling

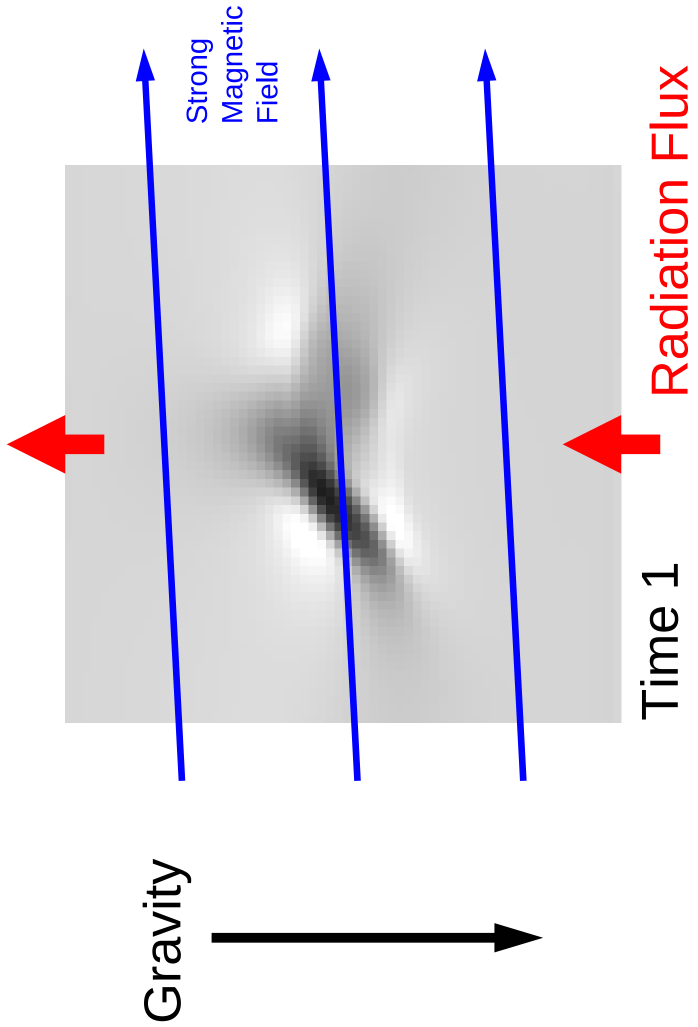
Radiation escapes by

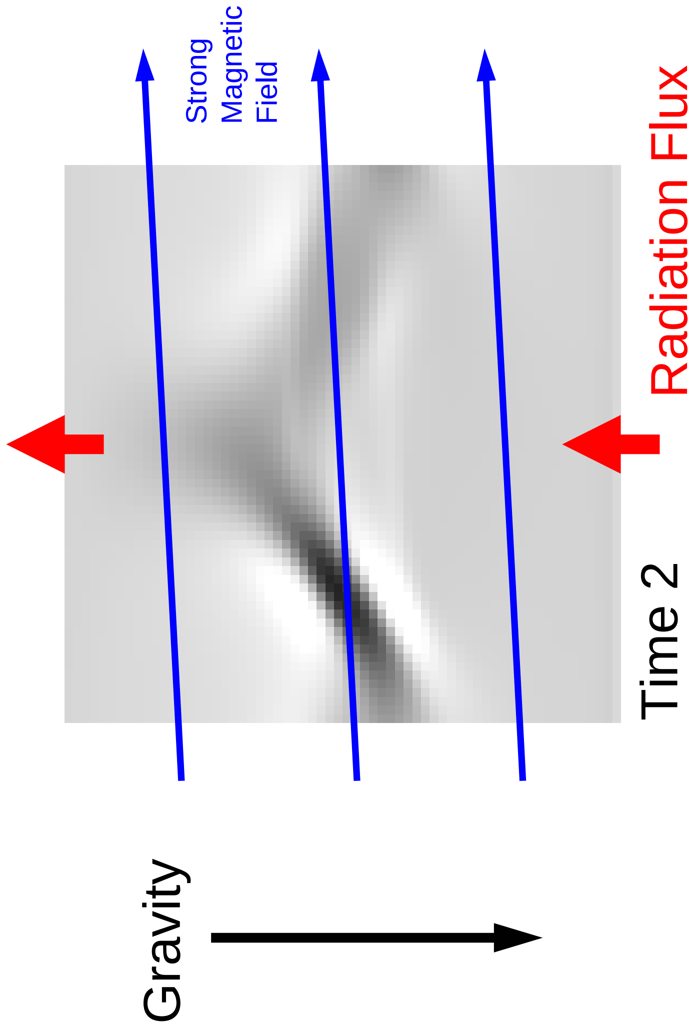
1. Vertical Diffusion
2. Convection
3. Photon Bubble Instability

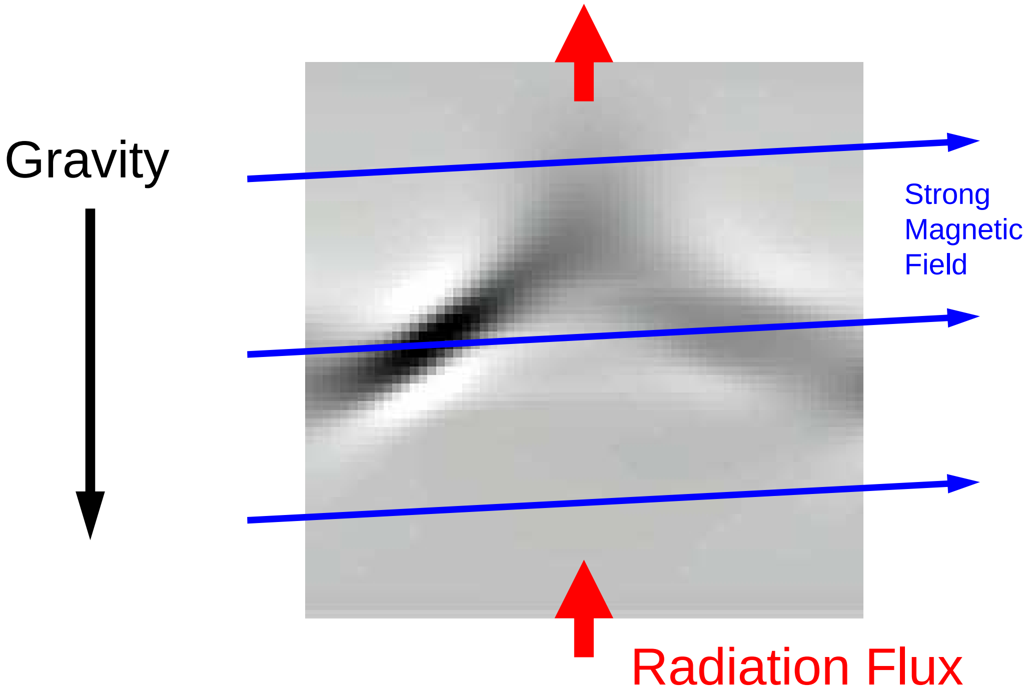
Arons 1992; Gammie 1998


Strong
Magnetic
Field
Radiation Flux
Gravity


Strong
Magnetic
Field
Radiation Flux
Extra
Flux
Gravity


Strong Magnetic Field
Radiation Flux
Time 1
Gravity


Strong Magnetic Field
Radiation Flux
Time 2
Gravity



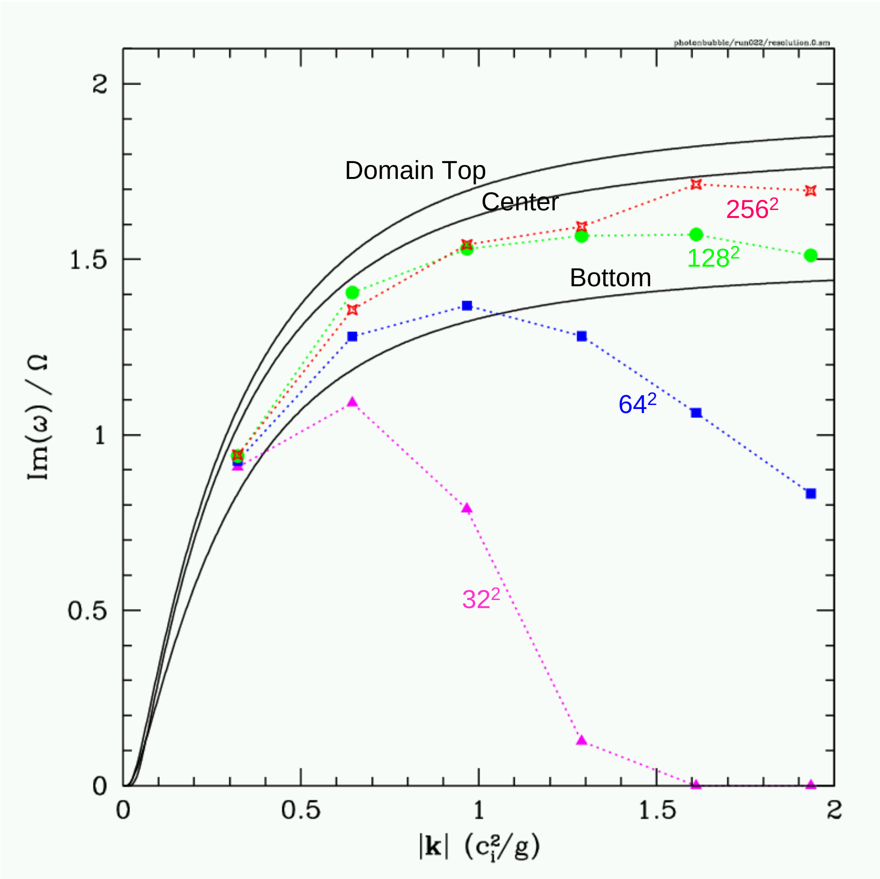
Lengths and Speeds

Radiation sound speed $c_r^2 = \frac{4P}{3\rho}$

Isothermal gas sound speed $c_i^2 = \frac{p}{\rho}$

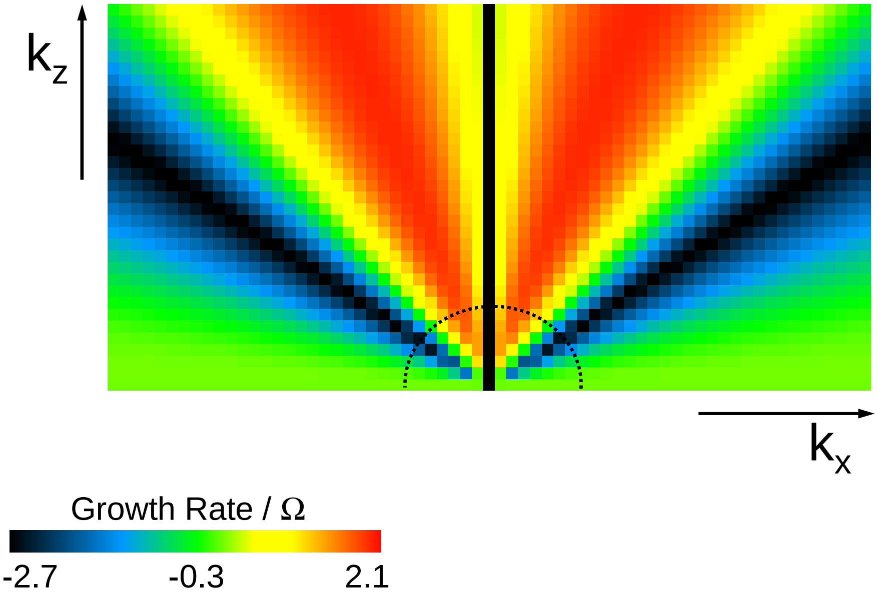
Radiation scale height c_r^2 / g

Gas scale height c_i^2 / g

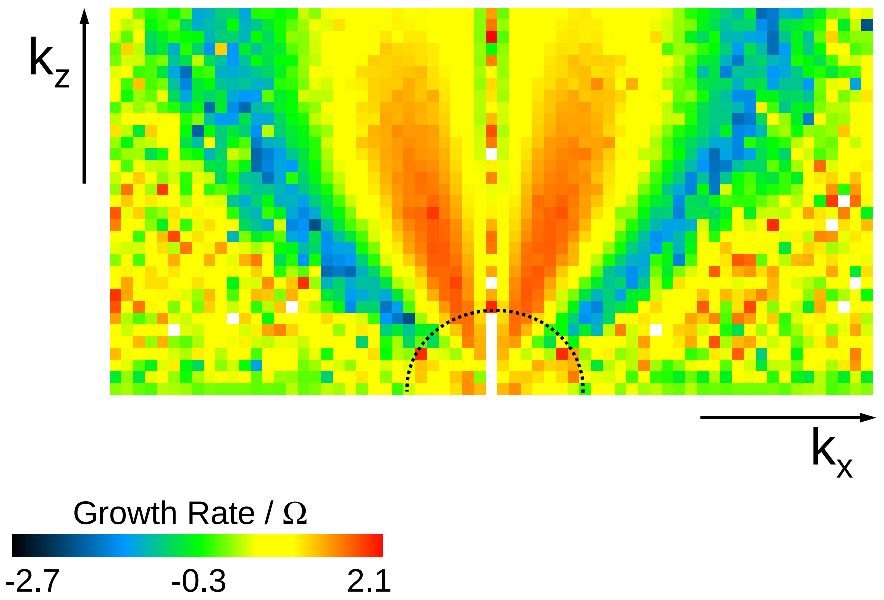


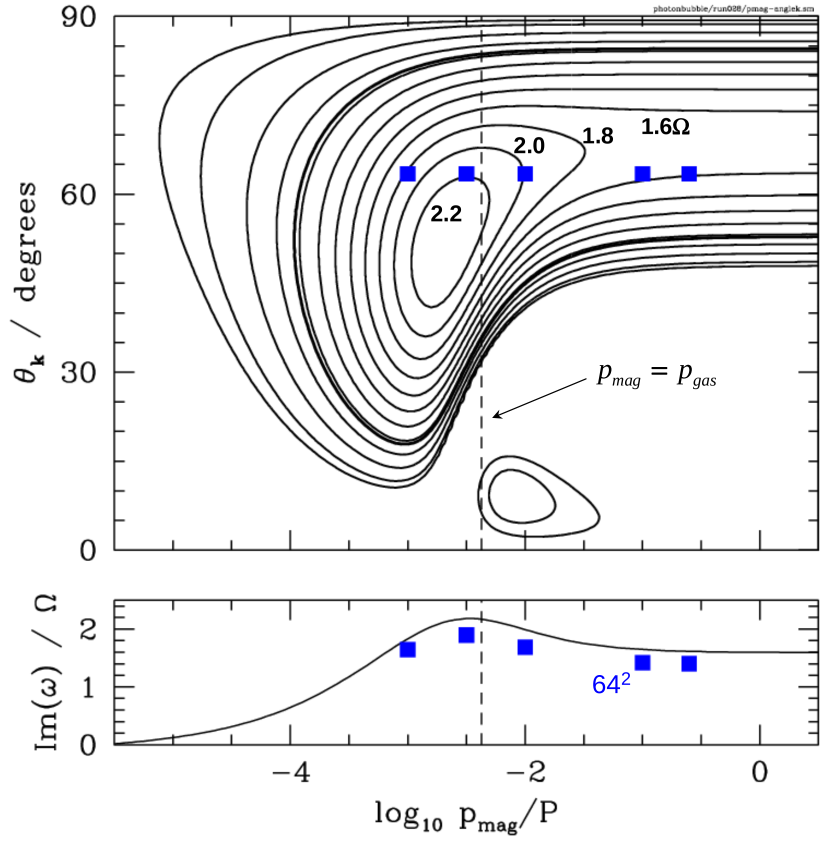
Blaes & Socrates 2003

Analytic Prediction

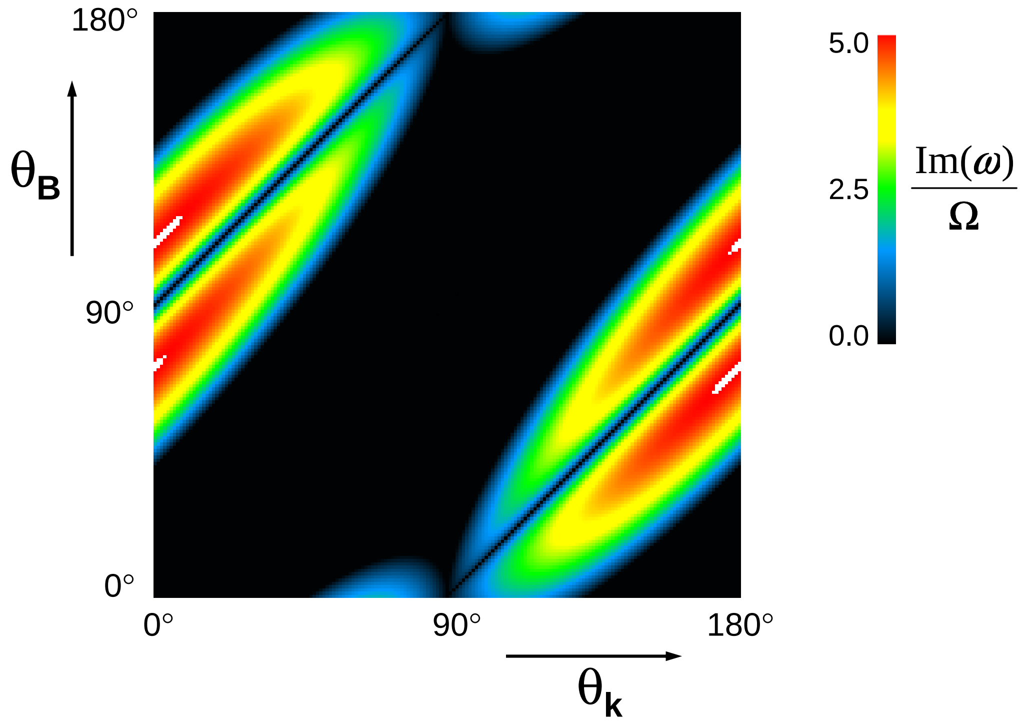


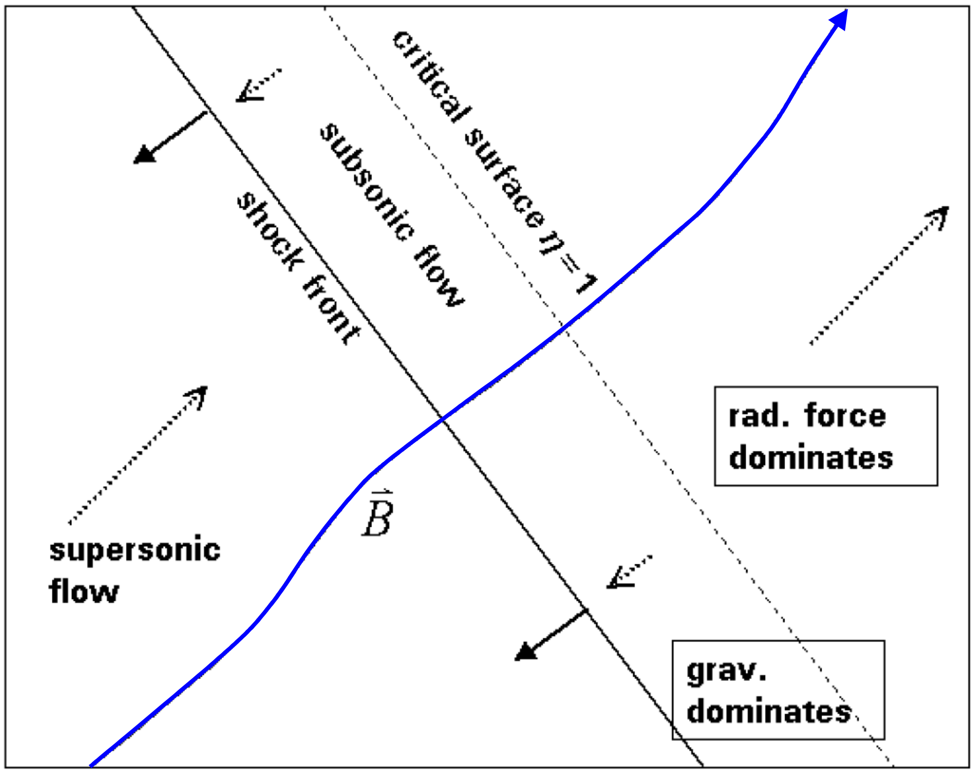
Numerical Results, 128^2 Zones



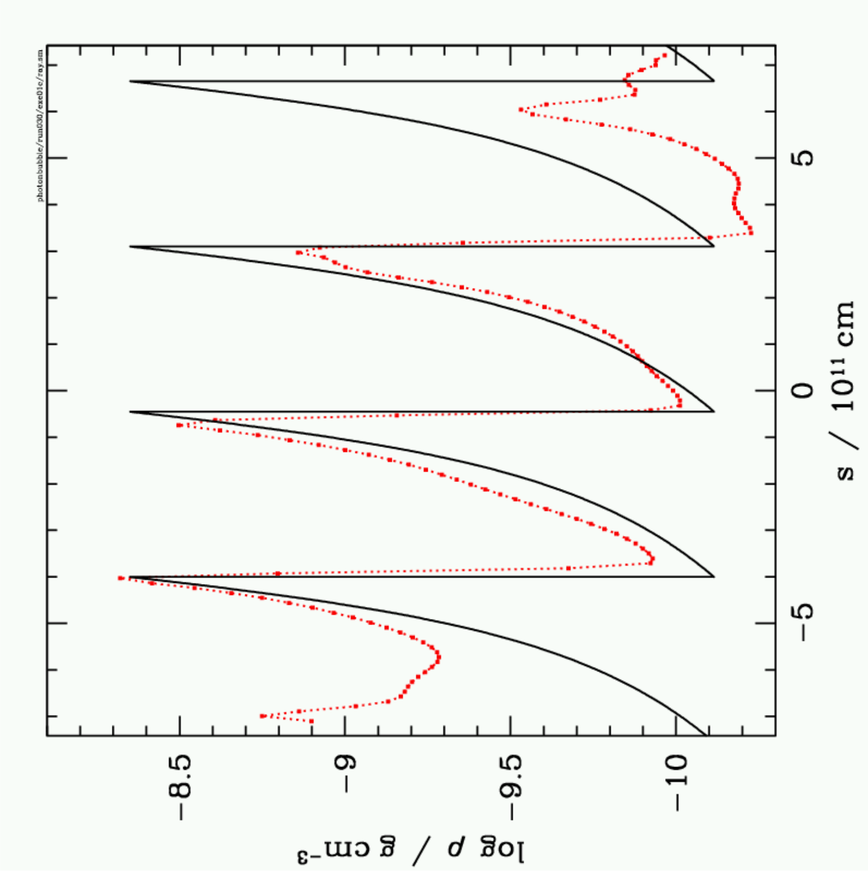


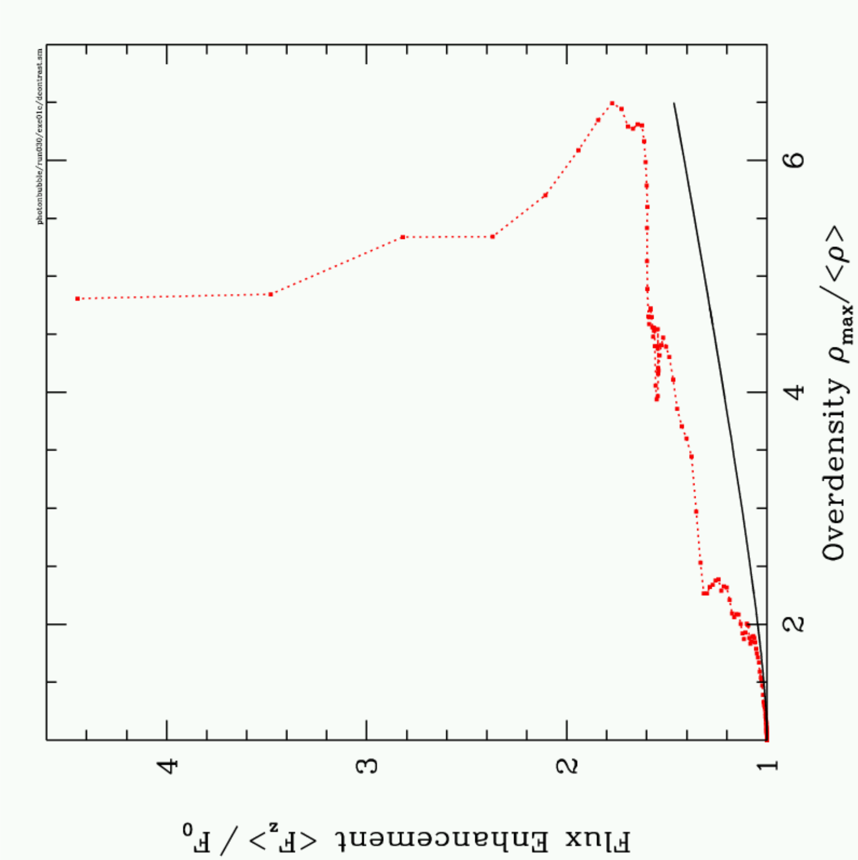
Growth on Inclined Fields

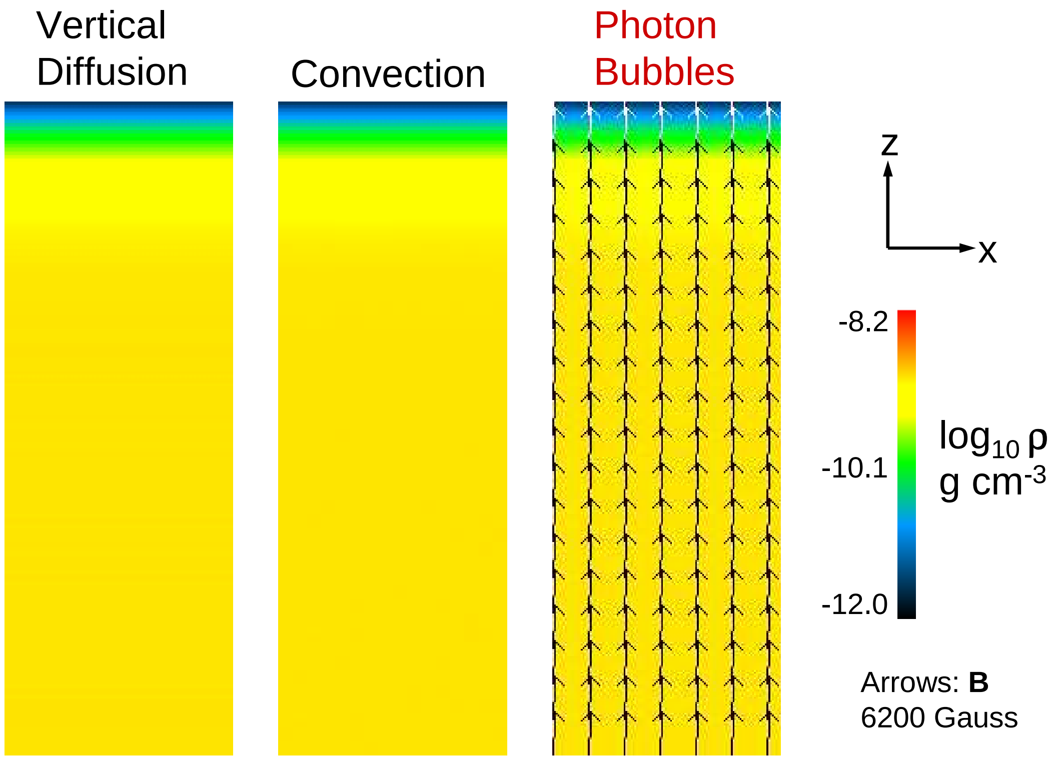


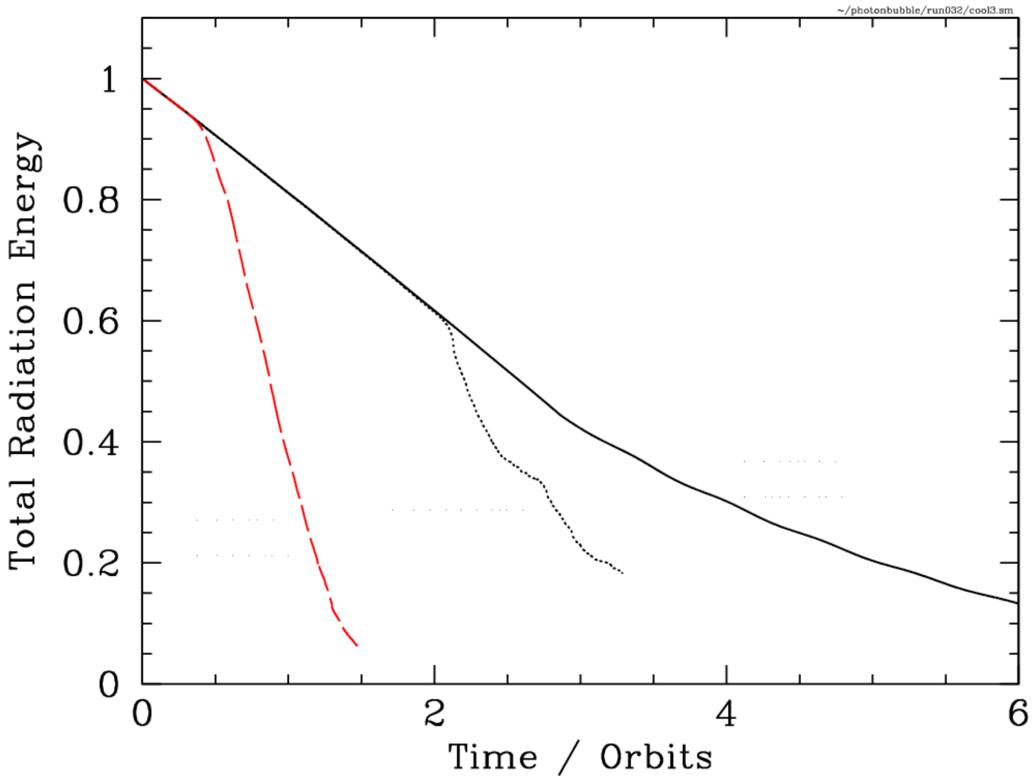


Begelman 2001

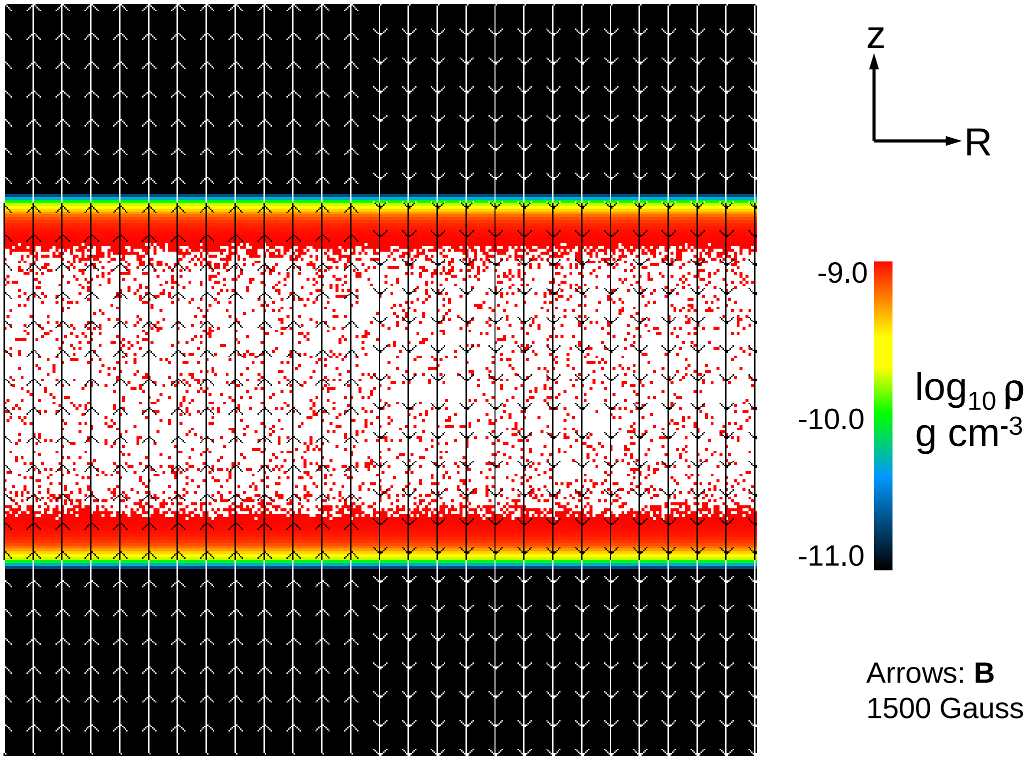

log ρ / g cm⁻³
−8.5
−9
−9.5
−10
s / 10¹¹ cm
−5
0
5
photonbubble/run030/exe01c/ray.sm


Flux Enhancement $\langle F_z \rangle / F_0$
1
2
3
4
Overdensity $\rho_{\max}/\langle\rho\rangle$
2
4
6
photonbubble/run030/exe01c/dcontrast.sm

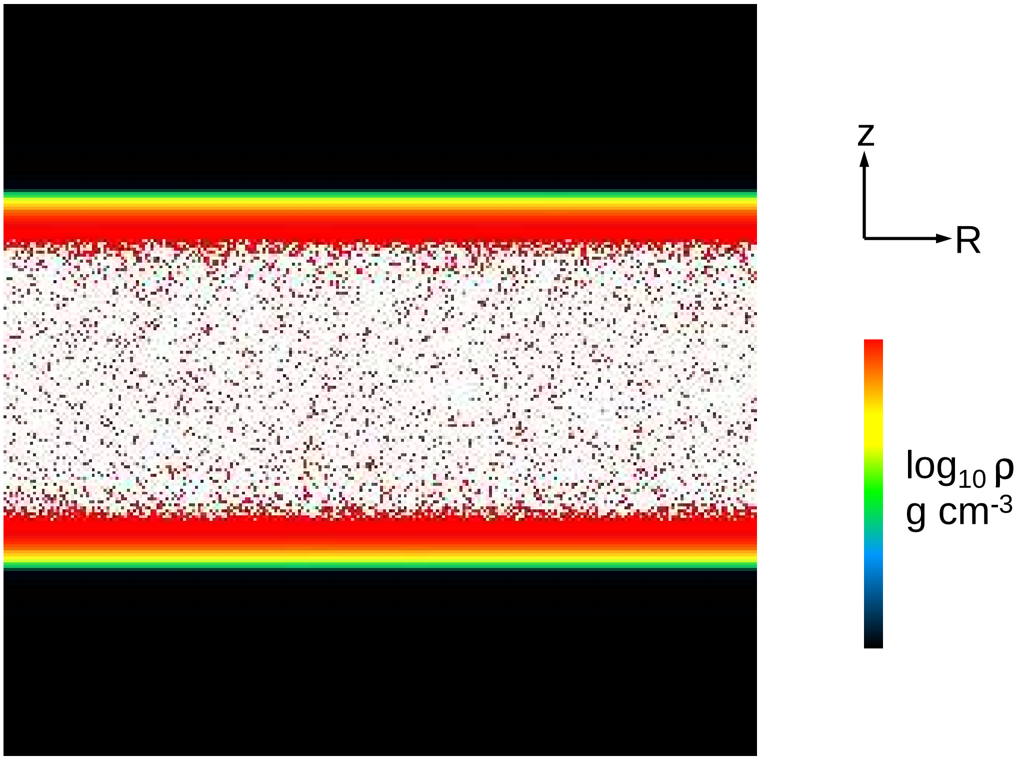

Vertical Diffusion
Convection
Photon Bubbles
z
x
-8.2
-10.1
-12.0
$\log_{10} \rho$
g cm^{-3}
Arrows: **B**
6200 Gauss


~/photonbubble/run032/cool3.sm
Total Radiation Energy
0
0.2
0.4
0.6
0.8
1
0
2
4
6
Time / Orbits

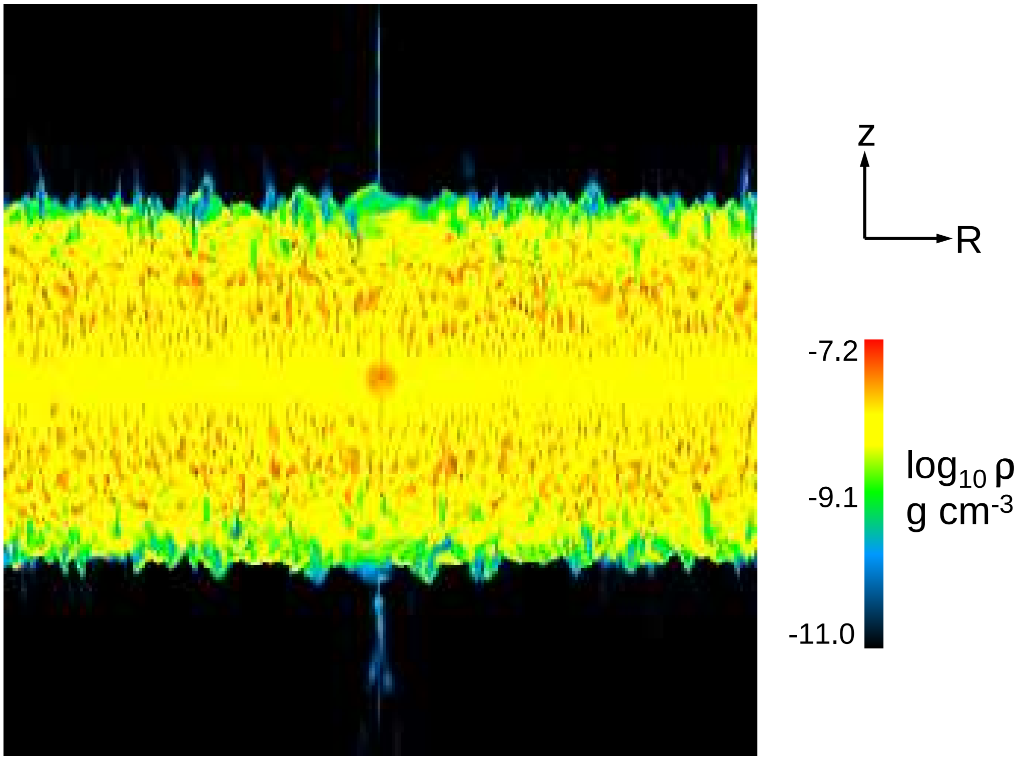
Photon Bubbles with MRI



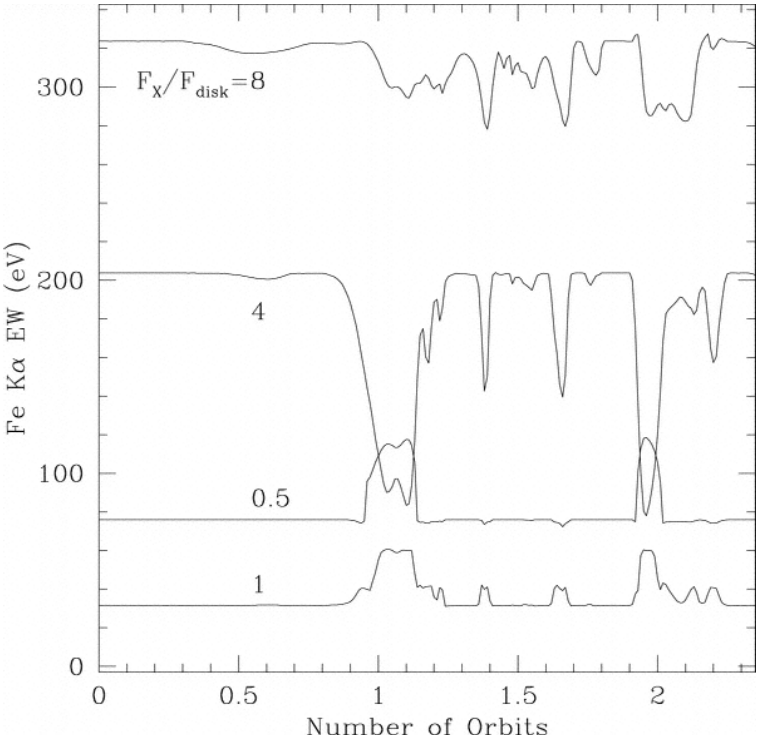
Photon Bubbles with MRI



Photon Bubbles with MRI



Effects on X-Ray Reflection Variability



Ballantyne et al. 2005

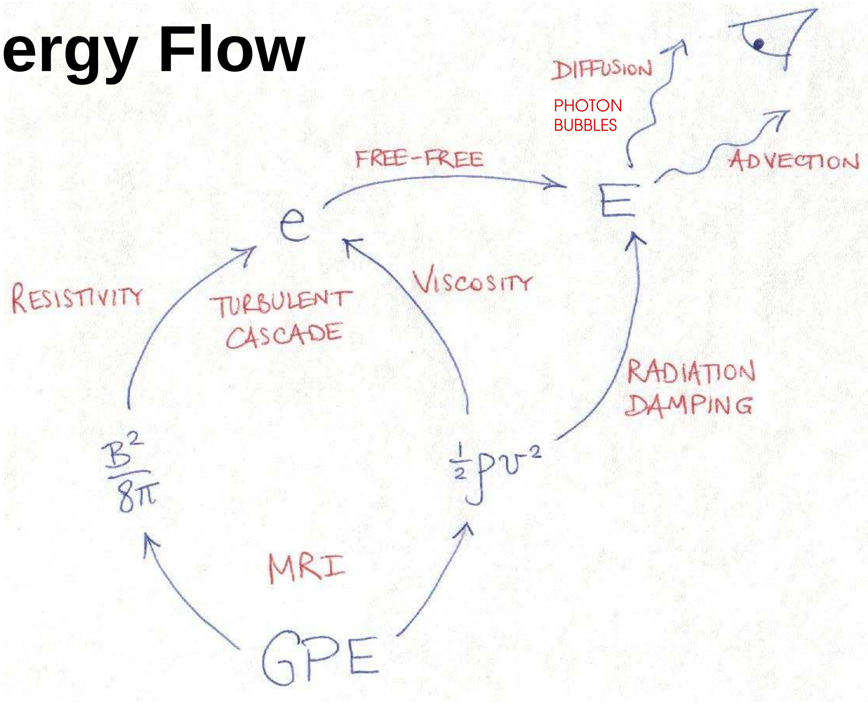
Assumptions tested:

1. Hydrostatic equilibrium ✗
2. Stress = αP ✗
3. Vertical thermal balance: ?
   * viscous heating = diffusion cooling ✗
   * dissipation ~ density ✗
4. Inflow equilibrium ?

Summary

1. **Radiation-dominated disks are heated by magnetic dissipation and photon damping.**
2. **Heating in low-density surface layers leads to convective stability and quick thermal evolution.**
3. **Short-wavelength photon bubbles grow faster than Ω if magnetic pressure > gas pressure.**
4. **The bubbles become propagating shocks, and radiation escapes through the gaps between.**

Energy Flow


DIFFUSION
PHOTON
BUBBLES
ADVECTION
FREE-FREE
E
e
RESISTIVITY
TURBULENT
CASCADE
VISCOSITY
RADIATION
DAMPING
B²/8π
½ρv²
MRI
GPE