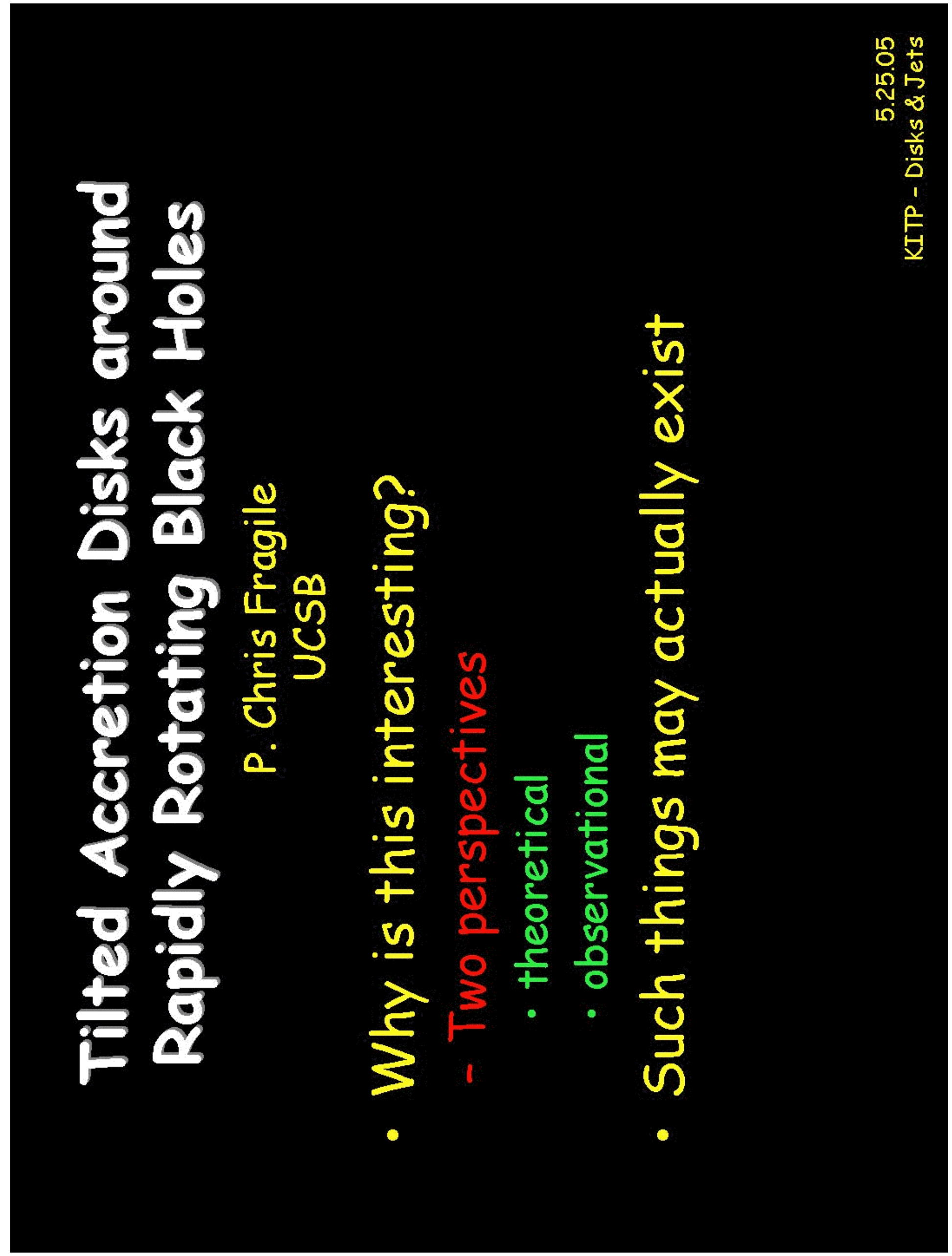
Tilted Accretion Disks around
Rapidly Rotating Black Holes
P. Chris Fragile
UCSB
• Why is this interesting?
– Two perspectives
• theoretical
• observational
• Such things may actually exist
5.25.05
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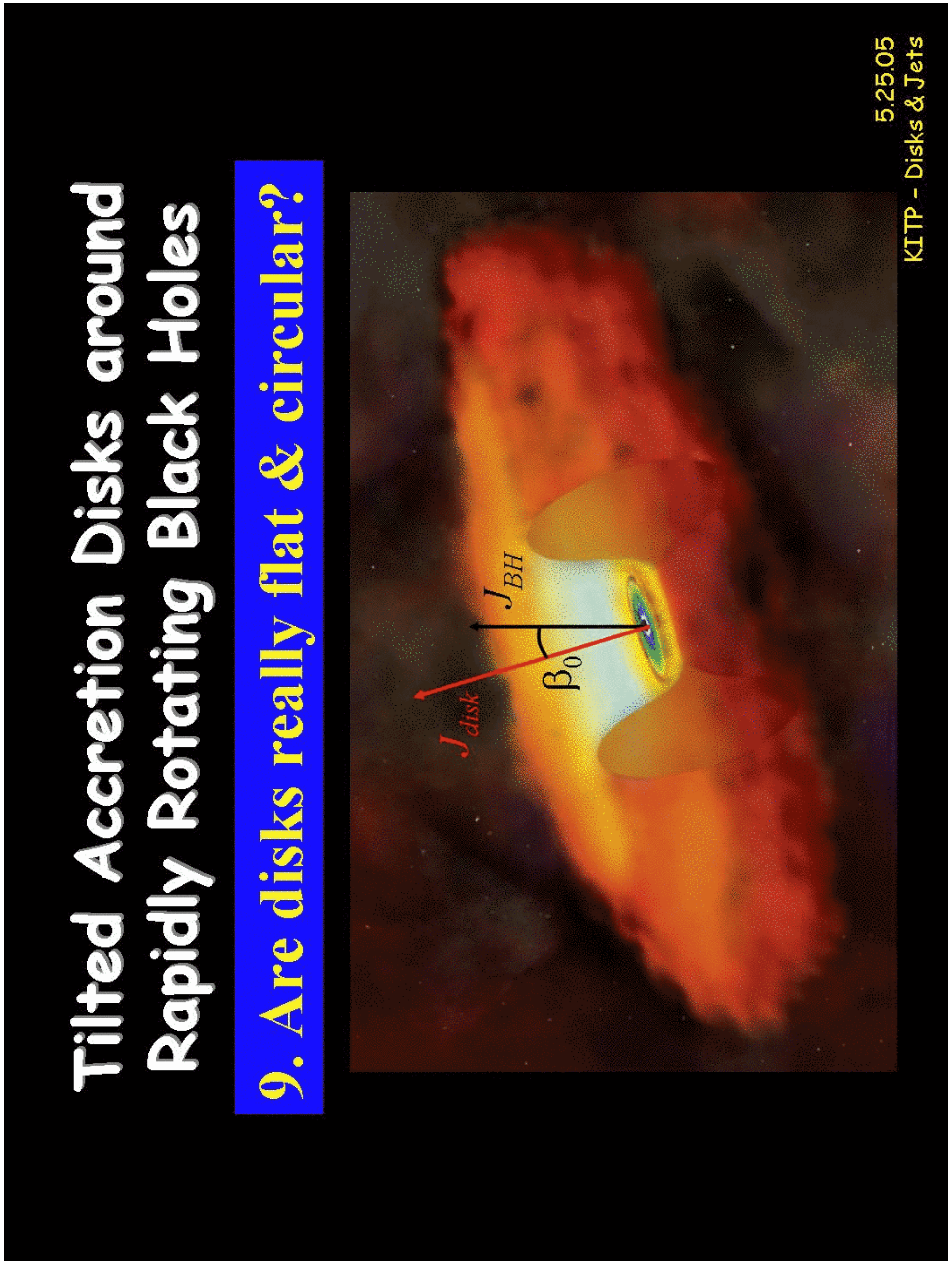
Tilted Accretion Disks around
Rapidly Rotating Black Holes
9. Are disks really flat & circular?
$J_{disk}$
$J_{BH}$
$\beta_0$
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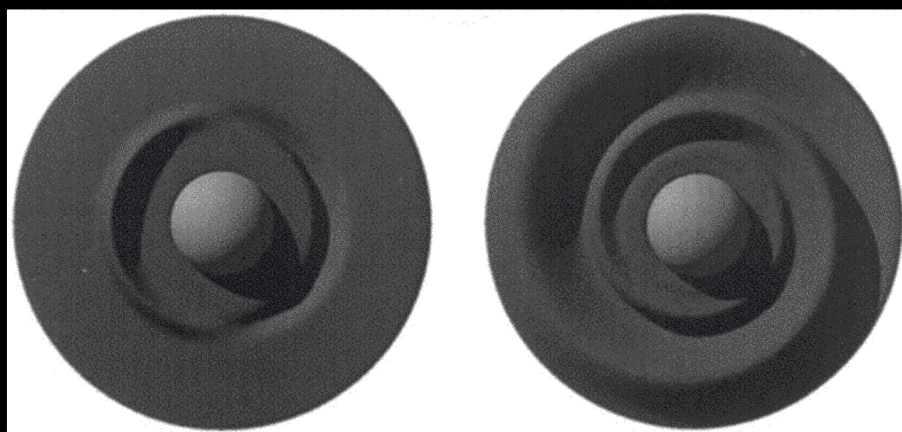
# GR Effects of Rotating Black Hole

- Rotating massive body exerts gravitomagnetic torque
  - particles orbits -> Lense-Thirring precession
  - disks -> differential Lense-Thirring precession -> warping



Armitage & Natarajan (1999)

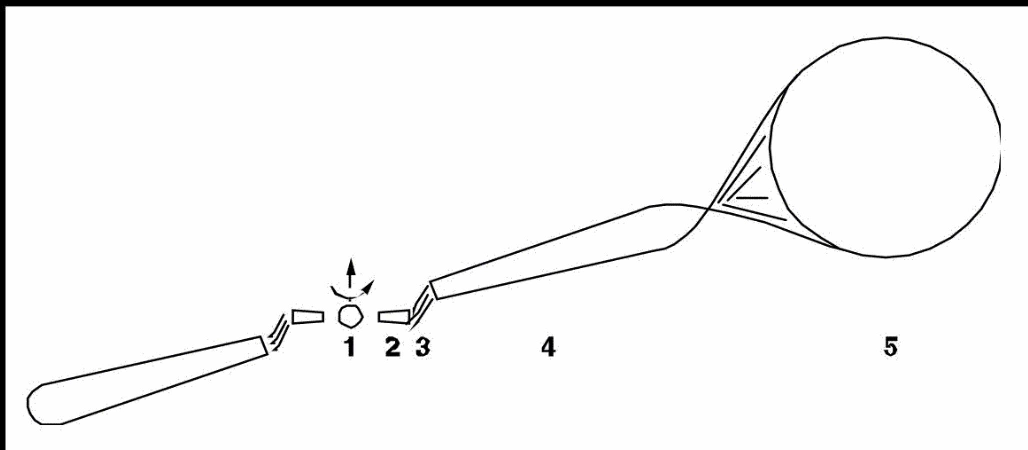


# GR Effects of Rotating Black Hole

- Rotating massive body exerts gravitomagnetic torque
  - particles orbits -> Lense-Thirring precession
  - disks -> differential Lense-Thirring precession -> warping
- Consider two general cases:
  - Viscous (thin) disk ($\alpha > H/R$)
    - warps are transported via viscous stresses
  - Inviscid (thick) disk ($\alpha < H/R$)
    - warps are transported by waves

# Bardeen-Petterson Effect

- Combined result of differential Lense-Thirring precession and internal "viscosity"




Open questions:
- Where is the transition radius ($10r_G < r_{BP} < 100r_G$)?
- How wide (or narrow) is the transition region?
- What role do magnetic fields and the MRI play?



# BP Transition Radius

Expect Lense-Thirring to dominate provided

$$\tau_{LT} \leq \tau_*$$

Lense-Thirring precession timescale

$$\tau_{LT} \equiv \Omega_{LT}^{-1} = \frac{r^3}{2aM}$$

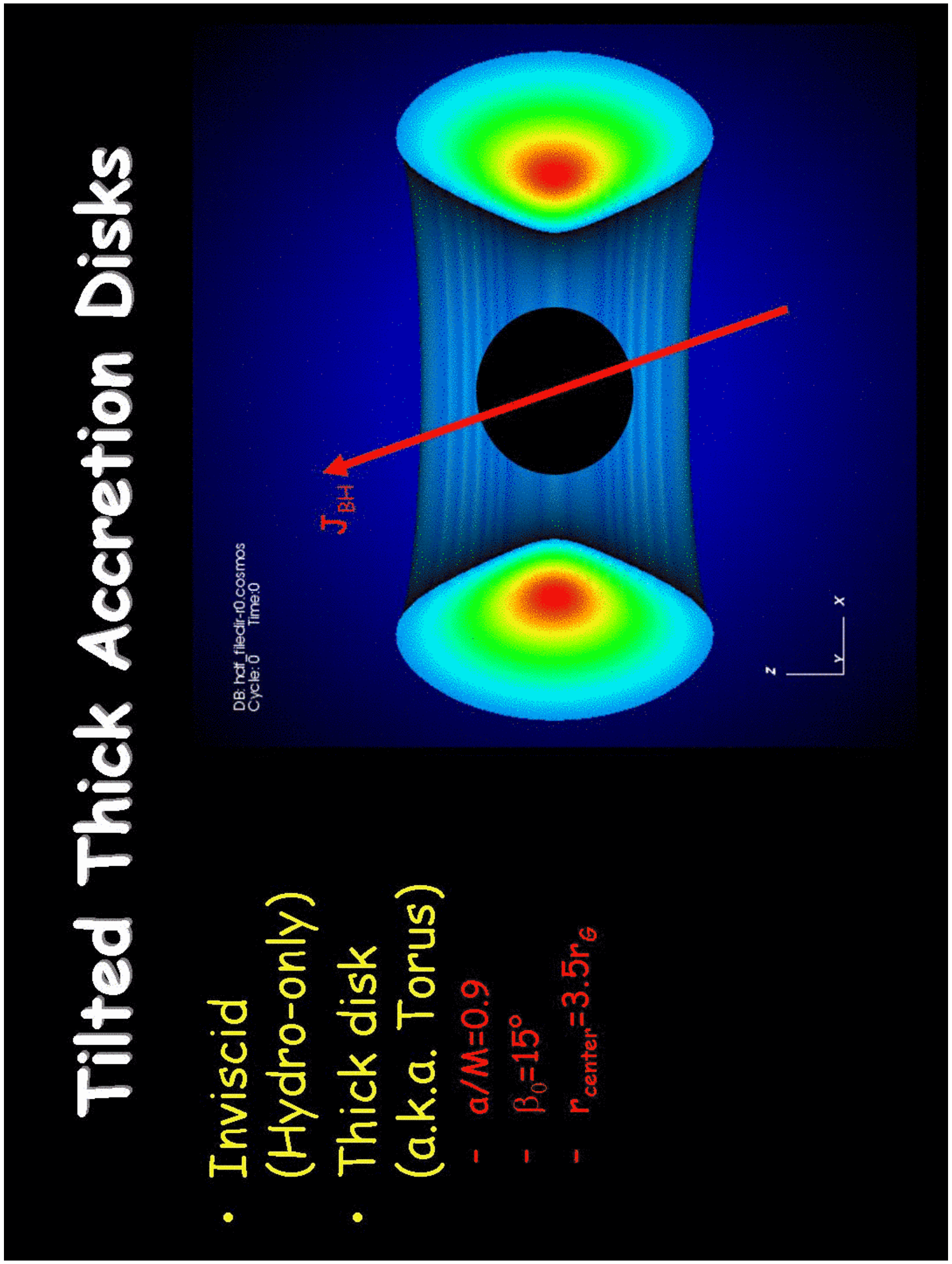
Accretion timescale

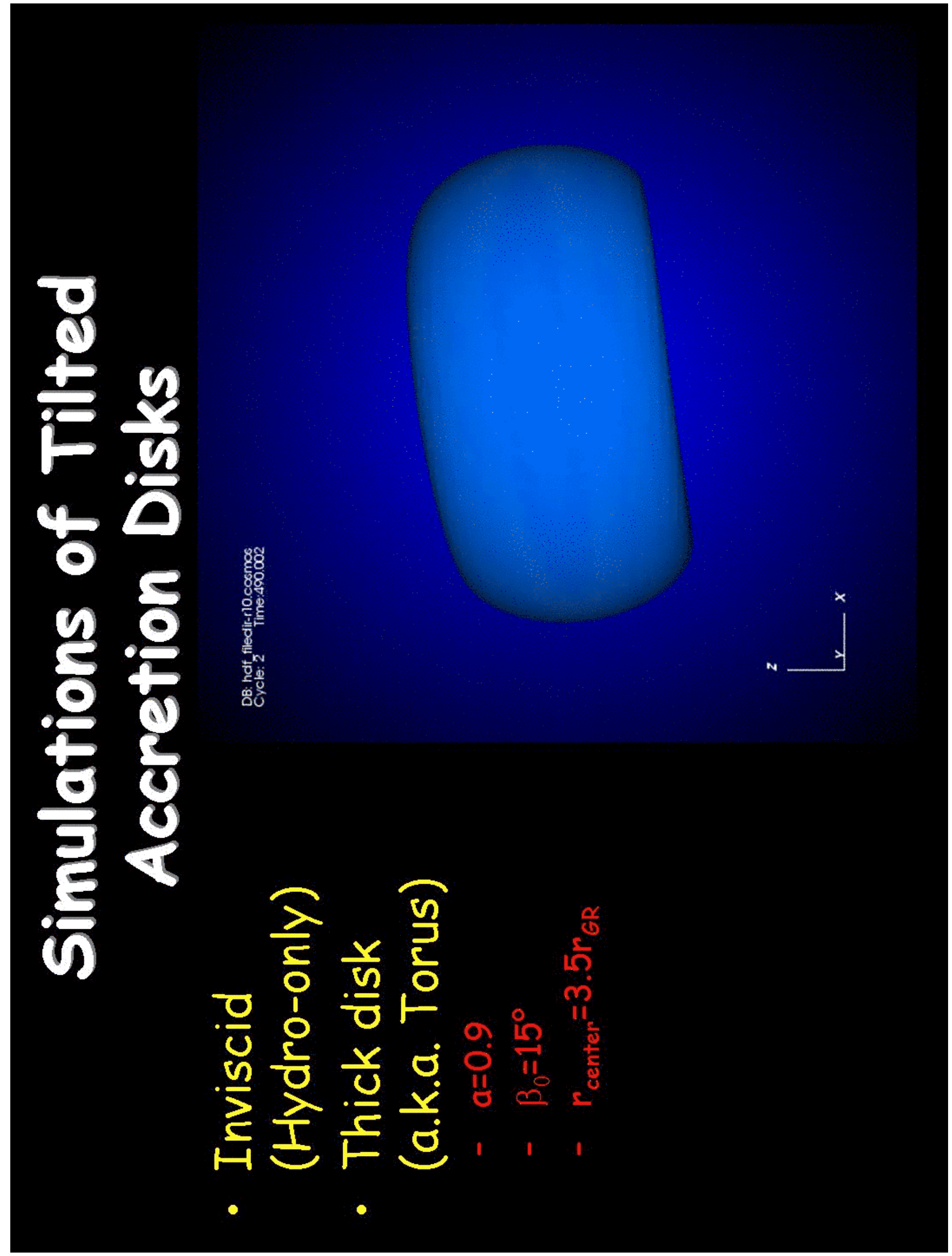
$$\tau_{acc} \equiv \frac{r}{V_r}$$

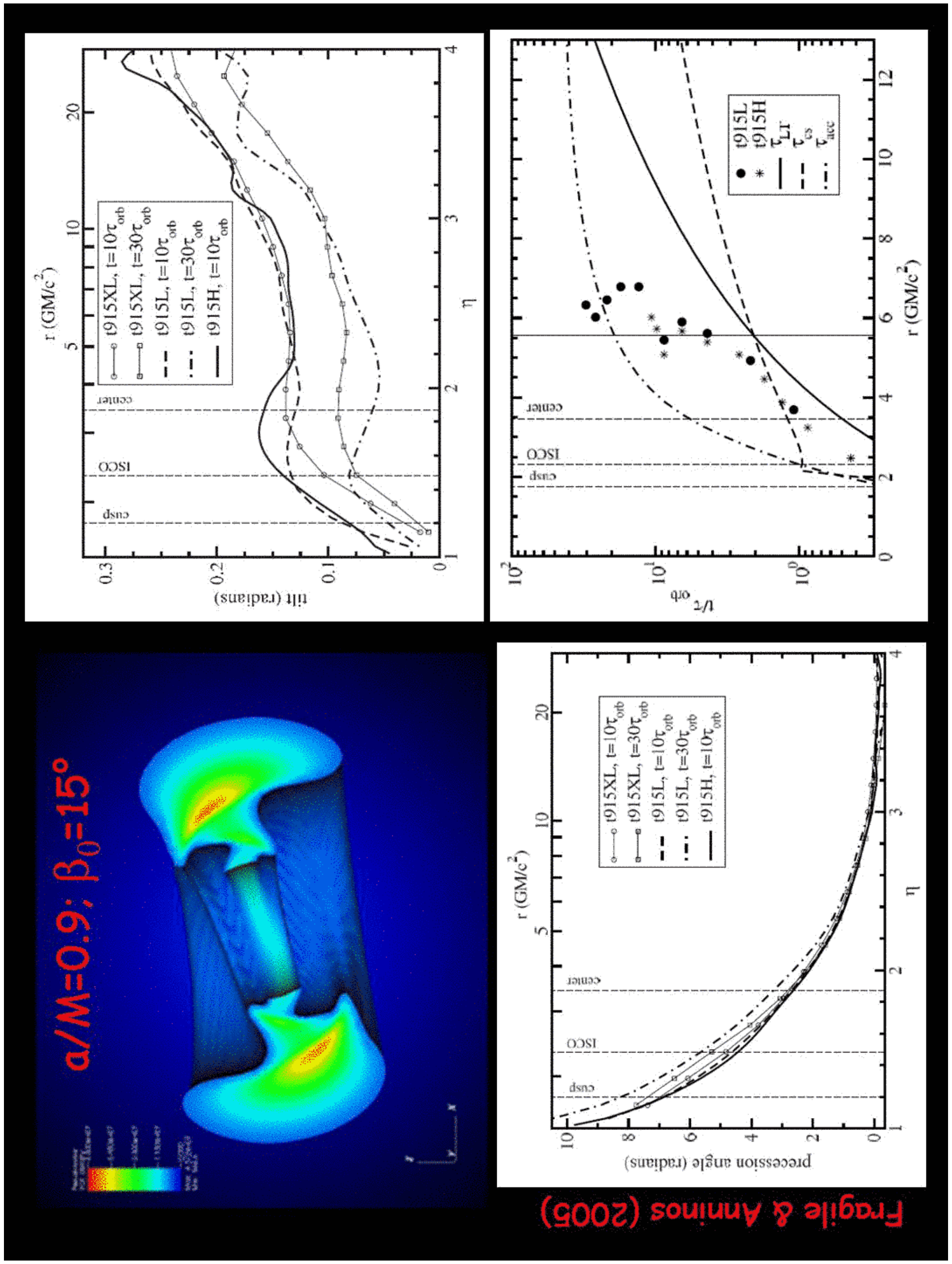
Sound-crossing time

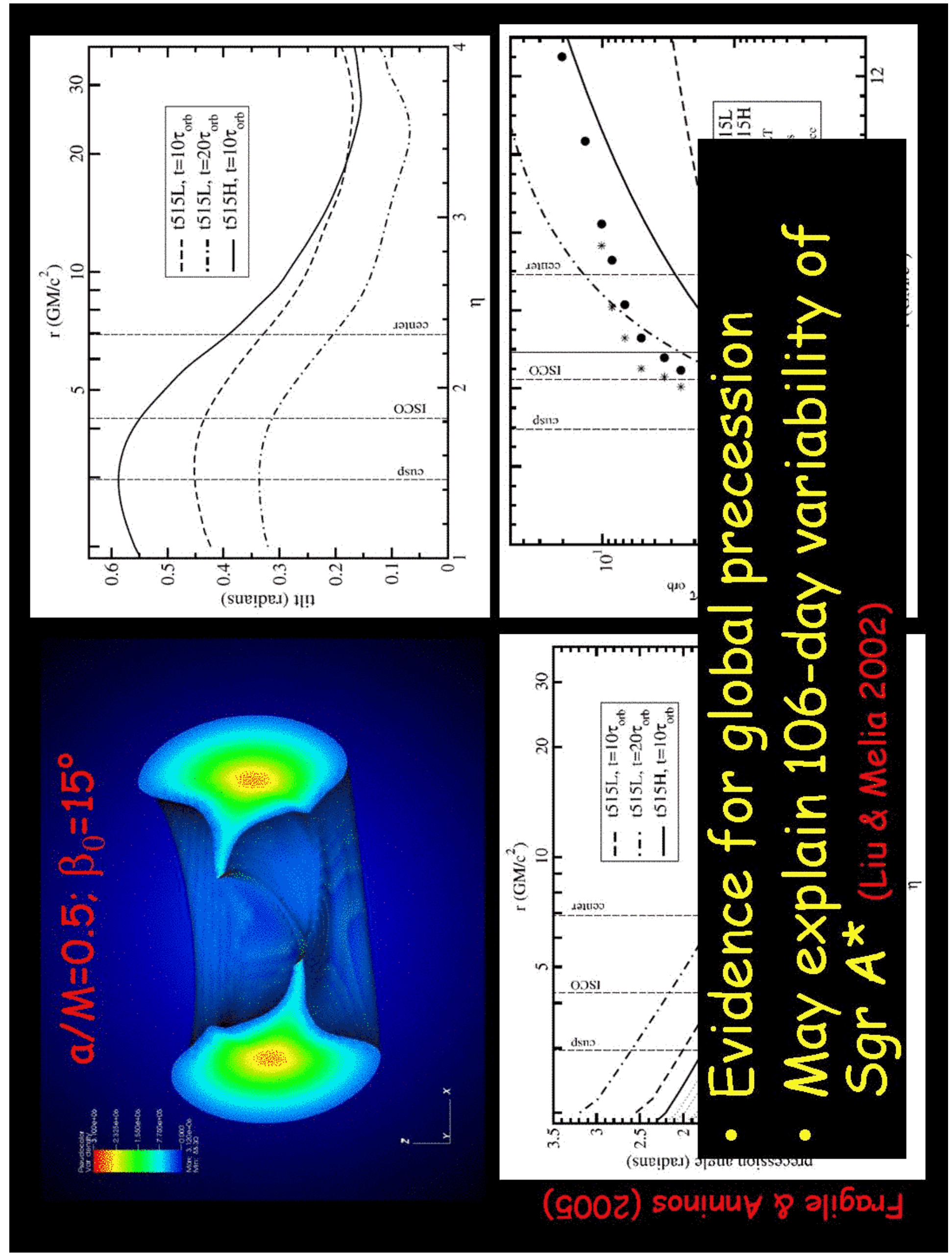
$$\tau_{cs} \equiv \frac{r}{c_s}$$

$$R_{BP} \sim 10 - 100\, R_{GR}$$


Tilted Thick Accretion Disks
• Inviscid (Hydro-only)
• Thick disk (a.k.a. Torus)
- a/M=0.9
- β0=15°
- rcenter=3.5rG
JBH
DB: hdf_filedir-r0.cosmos
Cycle: 0 Time:0
z
y
x

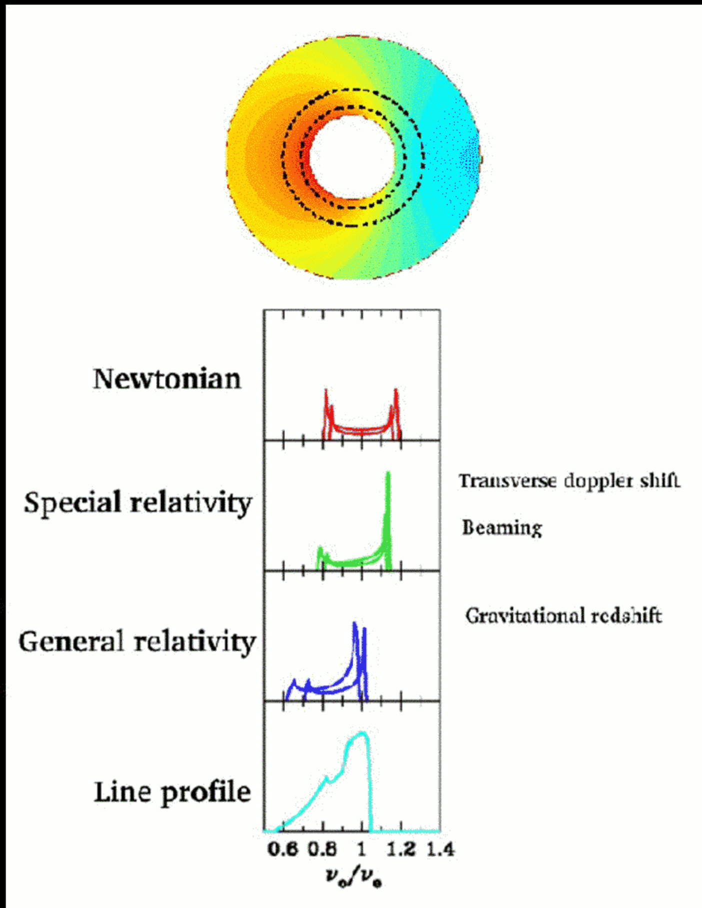

Simulations of Tilted Accretion Disks
• Inviscid (Hydro-only)
• Thick disk (a.k.a. Torus)
- a=0.9
- β0=15°
- rcenter=3.5rGR
DB: hdf_filedir-r10.cosmos
Cycle: 2 Time:490.002
z
y
x


a/M=0.9; β0=15°
Fragile & Anninos (2005)


a/M=0.5; β0=15°
Fragile & Anninos (2005)
• Evidence for global precession
• May explain 106-day variability of Sgr A* (Liu & Melia 2002)

## Looking for BP Disks using Relativistic Iron Lines

- Reflection feature broadened by relativity
- Modeling is complicated, but line profile depends on:
  - $r_{in}$, $r_{out}$, i




Fabian et al. (2000)

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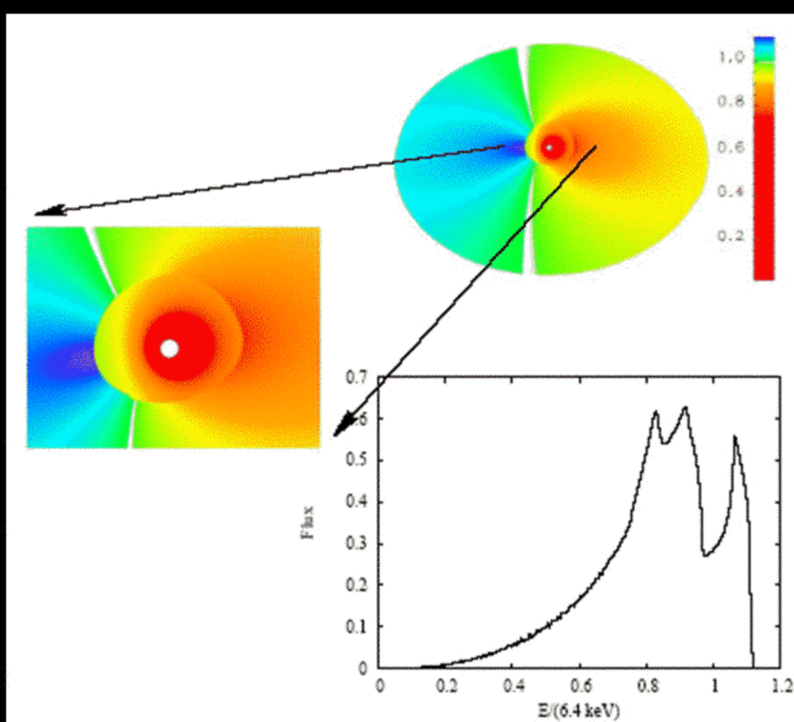
## Iron Lines in BP Disks

- Two-component disk model
- Three new parameters:
  - $r_{BP}$
  - $\{\beta, \theta_0, \varphi_0\}$
- "extra" peak
- "red"-horn dominant




Fragile et al. (2005) submitted to ApJ

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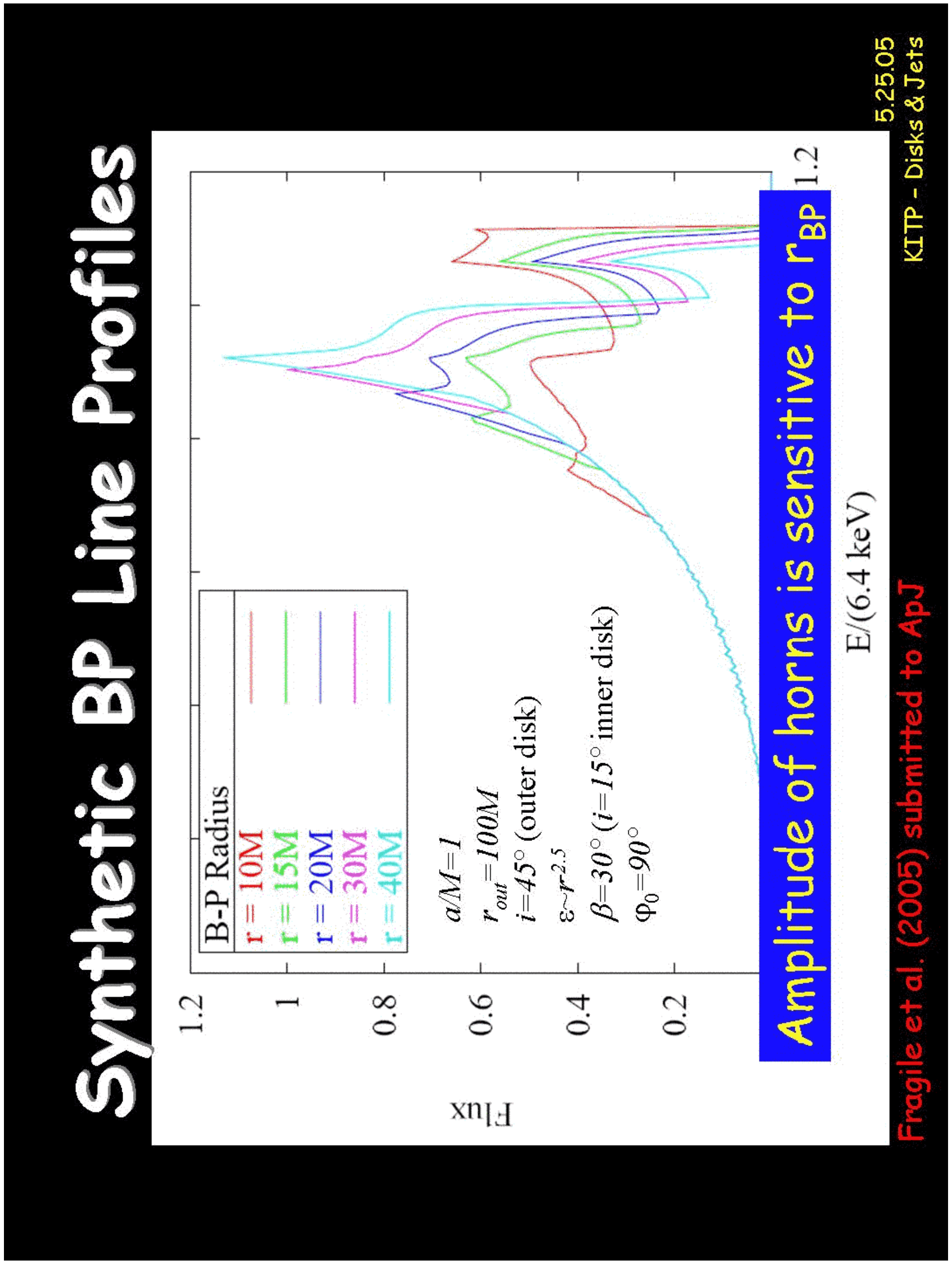
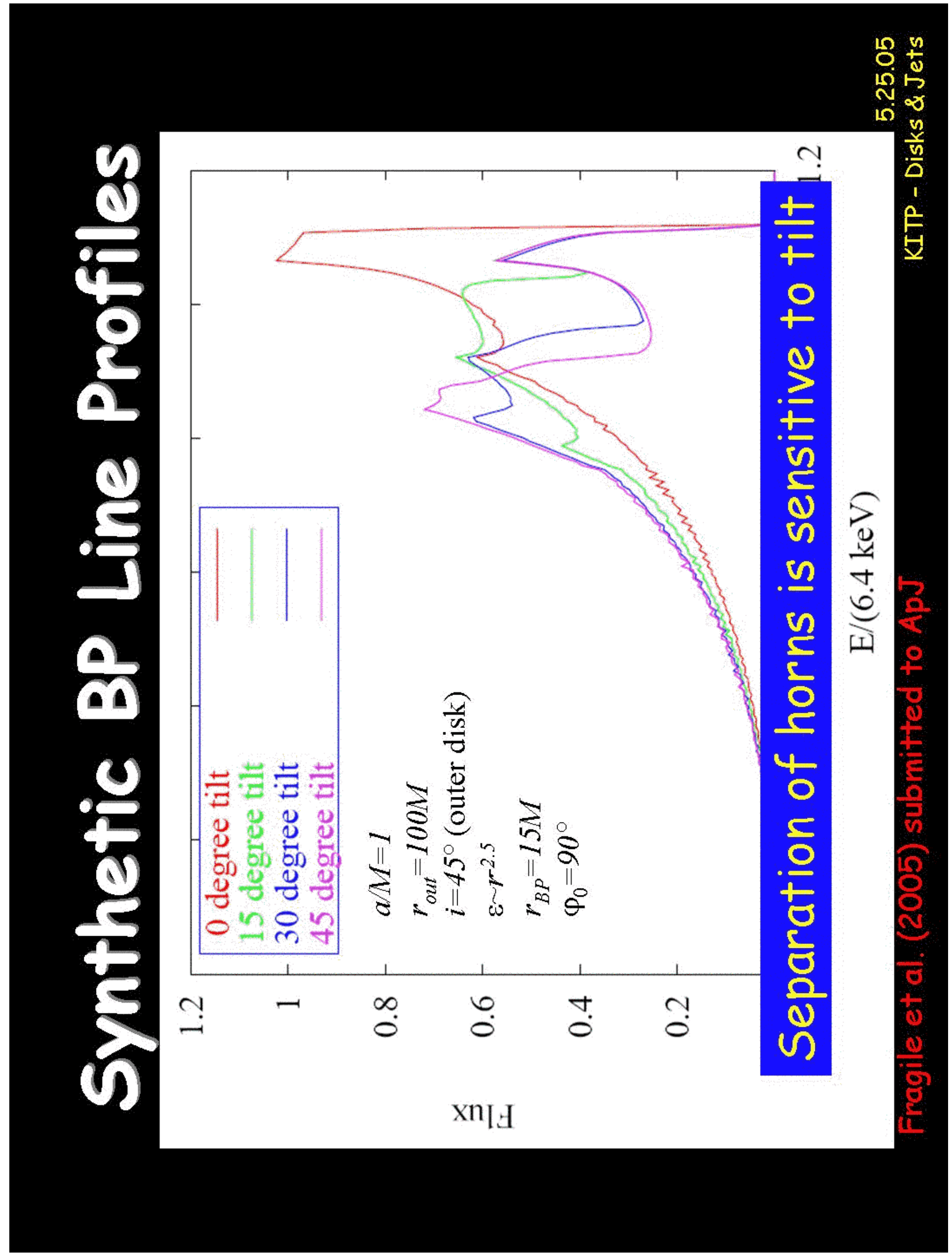

Synthetic BP Line Profiles
Flux
E/(6.4 keV)
B-P Radius
r = 10M
r = 15M
r = 20M
r = 30M
r = 40M
a/M=1
r_out=100M
i=45° (outer disk)
ε~r^-2.5
β=30° (i=15° inner disk)
φ0=90°
Amplitude of horns is sensitive to rBP
Fragile et al. (2005) submitted to ApJ
5.25.05
KITP - Disks & Jets


Synthetic BP Line Profiles
Flux
E/(6.4 keV)
0 degree tilt
15 degree tilt
30 degree tilt
45 degree tilt
a/M=1
r_out=100M
i=45° (outer disk)
ε~r^-2.5
r_BP=15M
φ0=90°
Separation of horns is sensitive to tilt
Fragile et al. (2005) submitted to ApJ
5.25.05
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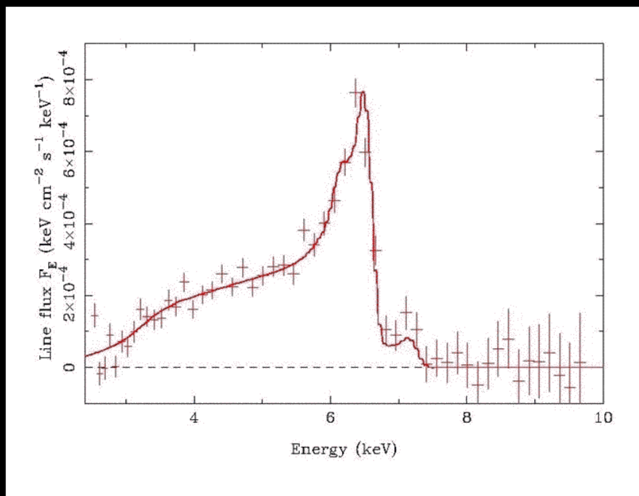
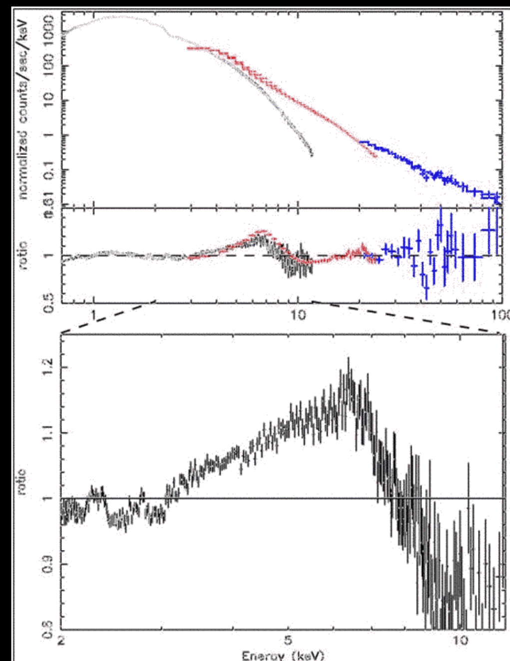
# Examples of Relativistic Iron Lines



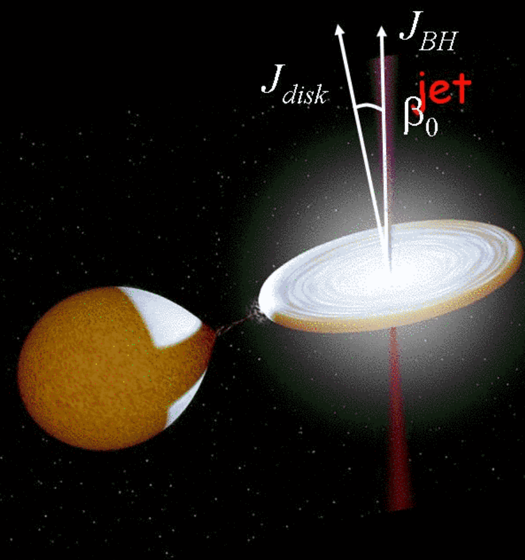

MGC 6-30-15 (Fabian et al. 2002)




GX339-4 (J. Miller et al. 2004)

# Evidence for tilted BHBs

- GRO J1655-40
  - Partially eclipsing binary (Orosz & Bailyn, 1997)
    - i=69.5°±0.1°
  - Relativistic jets (Hjellming & Rupen, 1995)
    - θ=85°±2°
  - "Tilt"
    - β>15°

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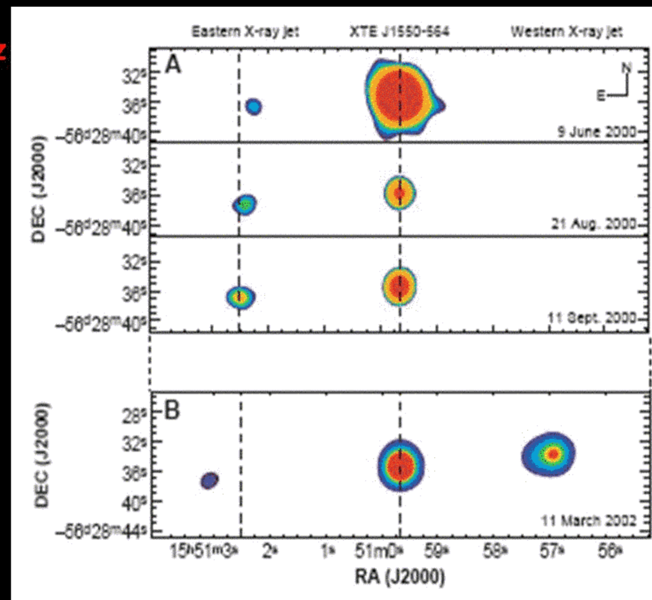
# Evidence for tilted BHBs

- XTE 1550-564
  - Binary inclination (Orosz et al. 2002)
    - i=72°±5°
  - Superluminal jets ($V_{app}$>2c; Hannikainen et al. 2001)

$$V_{app} = \frac{V\sin\theta}{1-(V/c)\cos\theta}$$

    - θ<53°
  - "Tilt"
    - β>14°




Corbel et al. (2002)



# Other evidence for warped disks

- Warped disks
  - NGC 4258 (Miyoshi et al. 1995; Greenhill et al. 1995)
- Precessing disks
  - Hercules X-1
  - SS433
- Precessing Jets
  - 3C 120 (Caproni & Abraham 2003)
- Jet-disk misalignment
  - Low-luminosity AGN (Kinney et al. 2000; Schmitt et al. 2002)
  - Galactic X-ray binaries (Fragile et al. 2001; Maccarone 2002)
- Multiple emitting regions (iron Kα lines)
  - Cygnus X-1 (Miller et al. 2002)
  - MCG-6-30-15 (Ballantyne et al. 2003)
- Quasi-Periodic Oscillations (QPOs)