Black hole astrophysics in the new century

X-ray probes of strong gravity and cosmic feedback

Chris Reynolds
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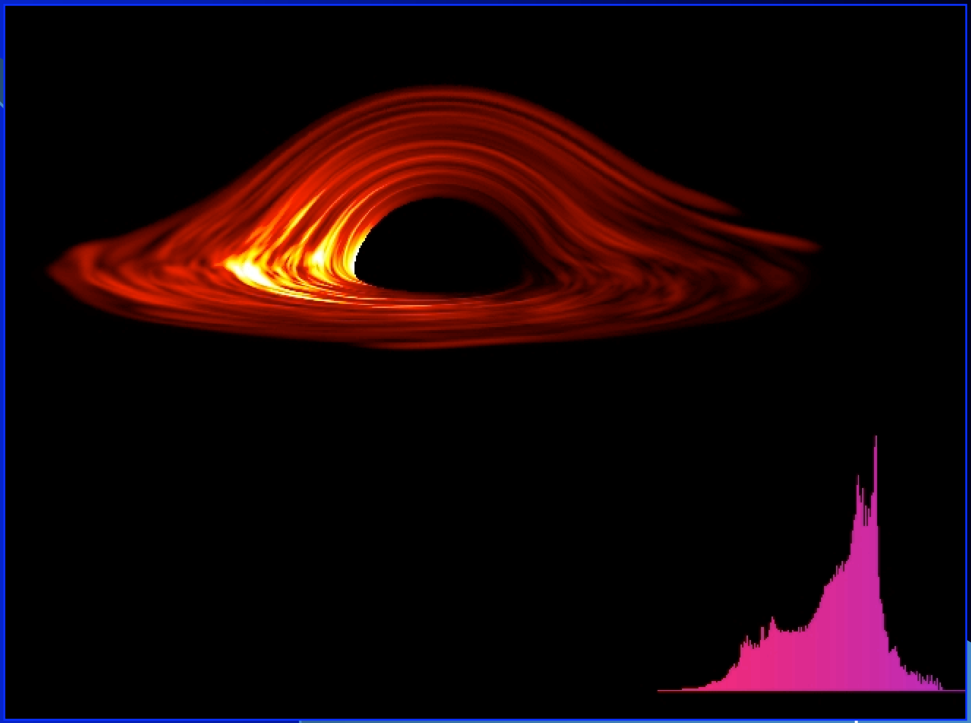
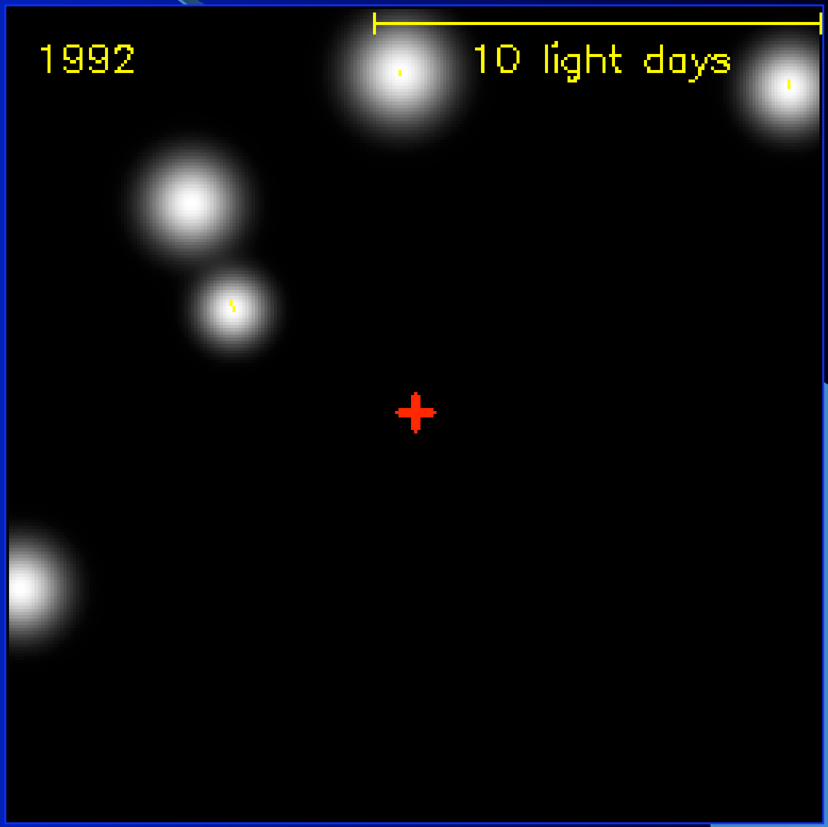


Armitage & Reynolds (2004)

A new era of black hole research

- Existence of both stellar and supermassive black holes seems secure
  - Exotic physics required to escape black hole conclusion in Galactic Center

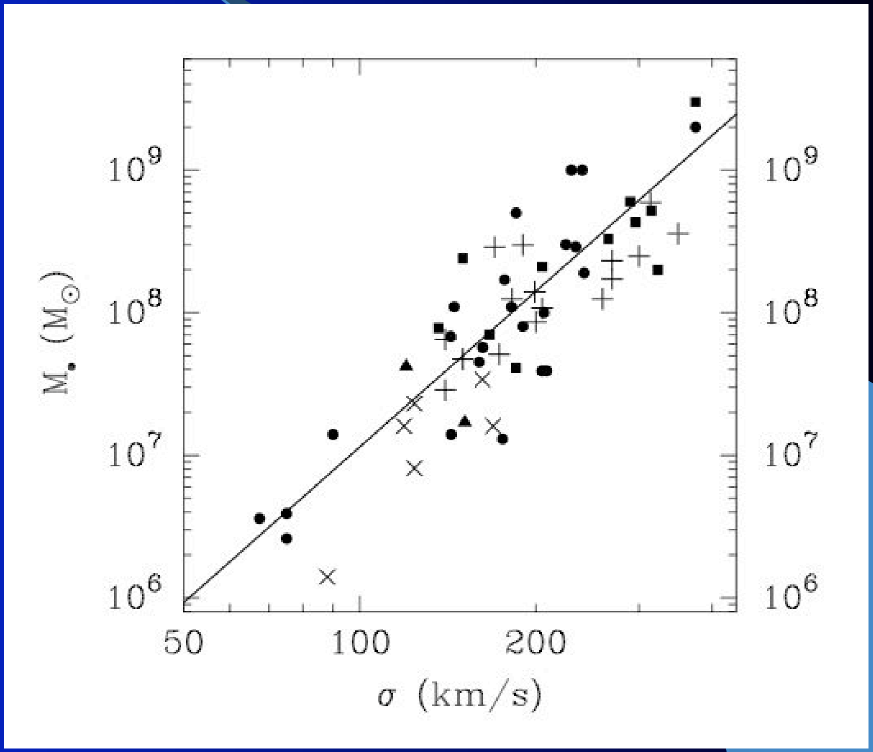
- Every galactic bulge seem to host a supermassive black hole



Movie from Genzel group
Similar work by Ghez group

The wider importance of black holes

- Supermassive black holes have cosmological importance…
- Energy output from black holes growth may be crucial factor in formation/evolution of massive galaxies
- Galaxy and SMBH growth coupled by powerful feedback processes



Kormendy & Gebhardt (2001)
Gebhardt et al. (2000)
Ferrarese & Merritt (2000)

Open issues…

- Are black holes really described by General Relativity?
  - Is the Kerr metric a good description of black hole spacetime?
- How does black hole accretion and jet production work?
  - How is accretion energy channeled into radiation & kinetic energy?
  - What is the role of black hole spin?
- How is massive black hole growth and galaxy formation coupled?
  - How do feedback processes couple enormous spatial scales?

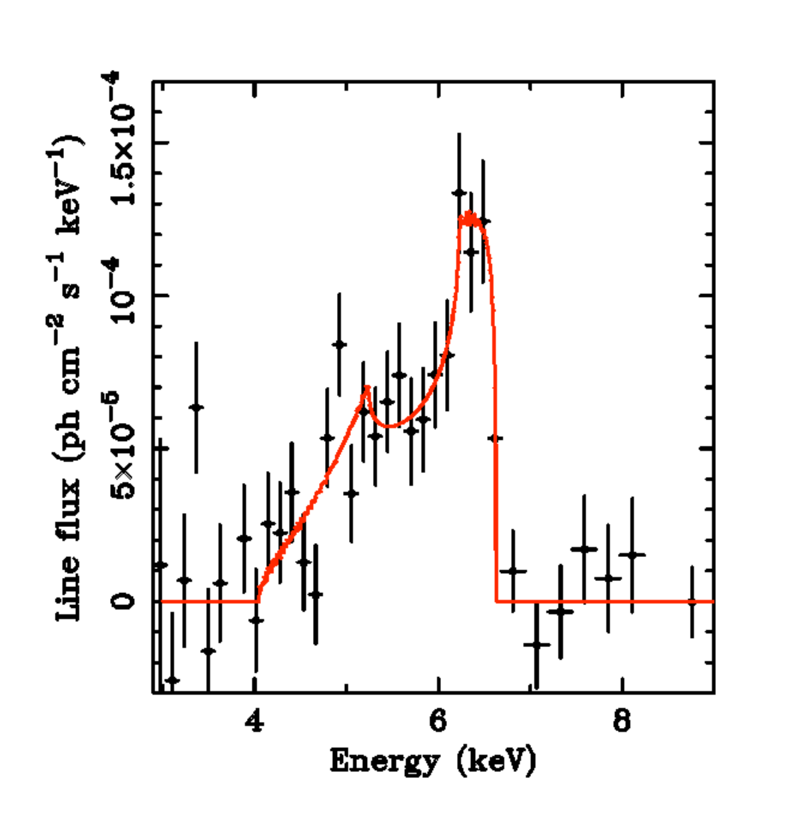
Outline

- Talk about progress due to developments in X-ray instrumentation
- Probing the strong gravity regime with X-ray spectroscopy
  - The robustness of the relativistic signatures
  - Confronting accretion disk theory with data
  - Measurements of black hole spin
- Large scale environmental impact of black holes
  - The cooling flow problem and the radio-galaxy solution
  - Difficulties faced by radio-galaxy feedback models and possible solutions

I : PROBES OF THE STRONG GRAVITY REGIME

- ASCA observation of MCG-6-30-15…
  - Revealed extremely broadened/skewed iron emission line (Tanaka et al. 1995)
  - Confirmed by XMM

- What are we seeing?
  - Believe line to originate from surface layers of innermost accretion disk
  - Line broadened and skewed by Doppler effect and gravitational redshifting



Power-law continuum subtracted
ASCA: Tanaka et al. (1995)

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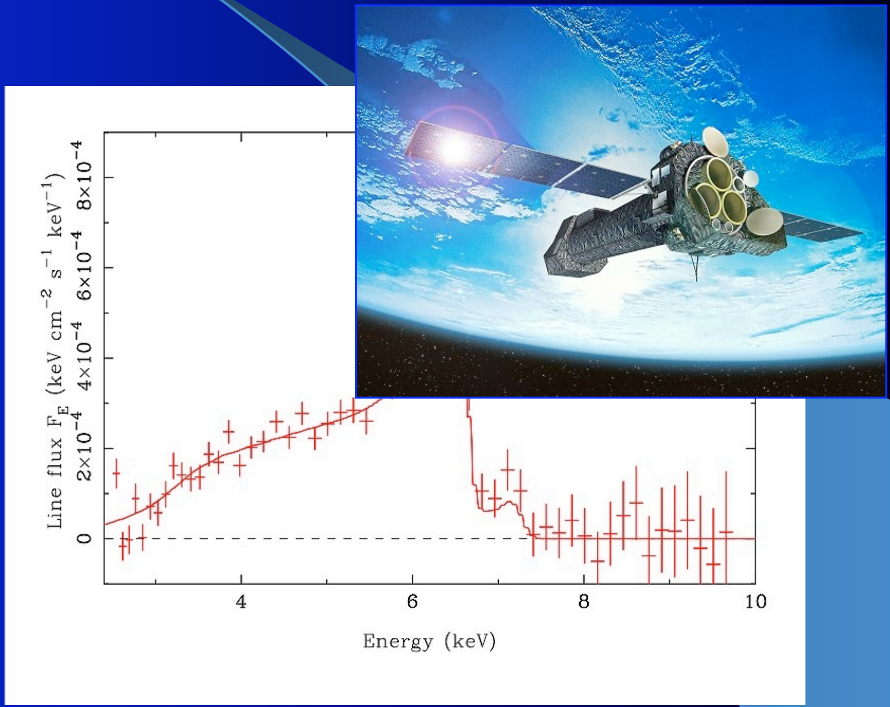

Power-law continuum subtracted XMM: Fabian et al. (2002)

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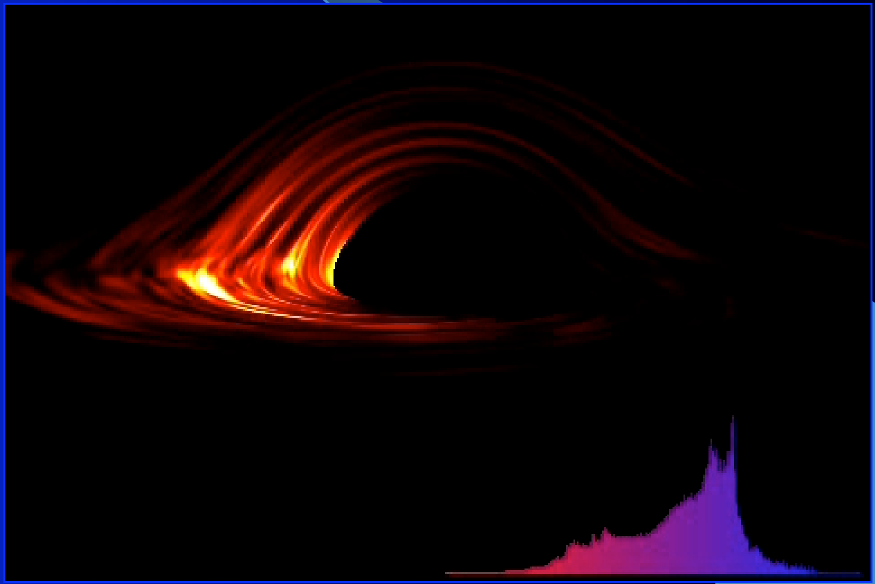
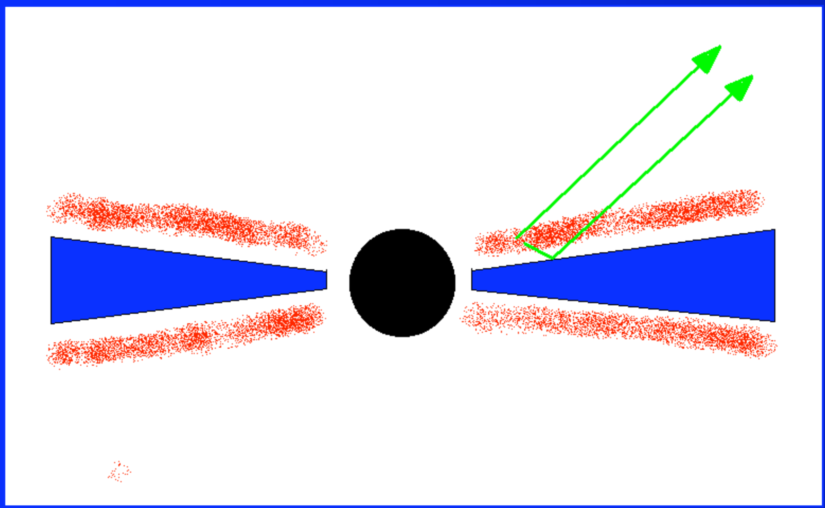


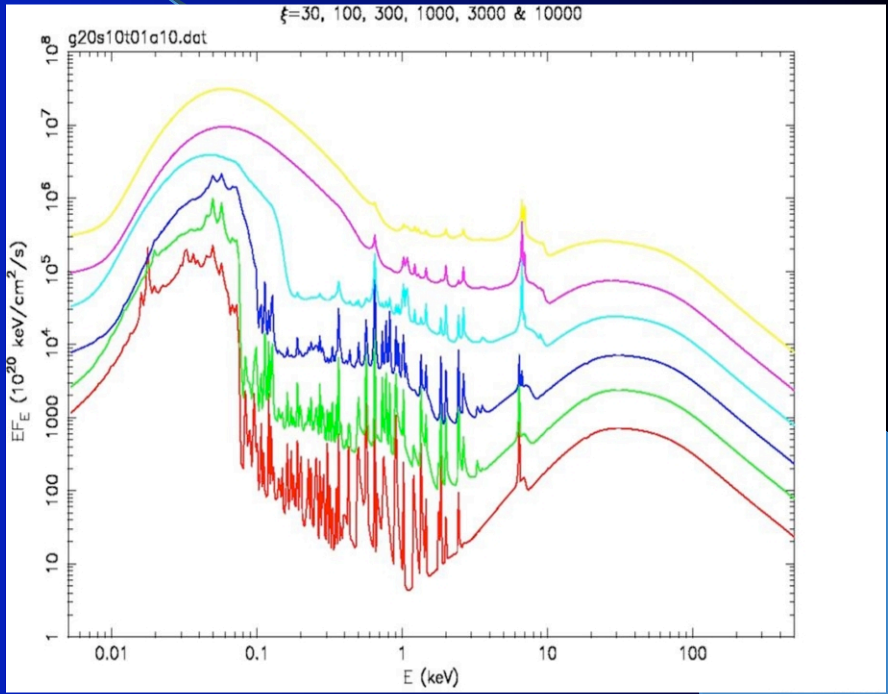
Pseudo-Newtonian MHD simulation
Ray-traced through Schwarzschild metric
Armitage & Reynolds (2004)

Iron line from X-ray reflection

Backscattered spectrum from X-ray irradiation of the "cold" optically-thick disk…

- Fluorescence/radiative recomb.lines
- Radiative recombination continuum
- Compton backscattered continuum

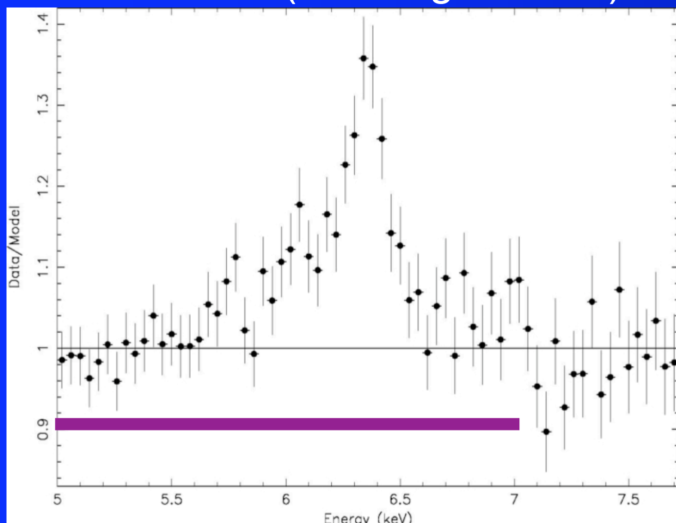




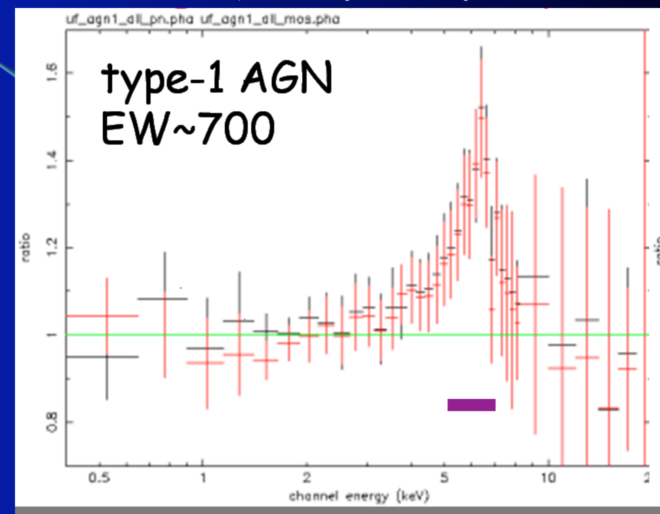
Self-consistent model of X-ray reflection from ionized disk (Ross & Fabian 2005)

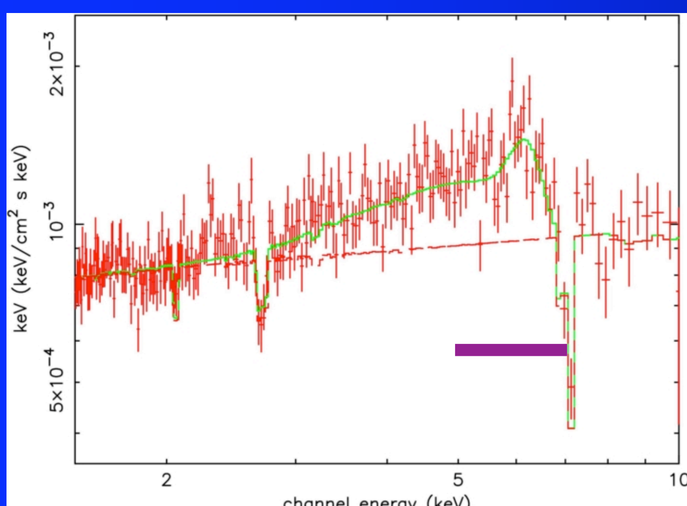
Iron lines in AGN

MCG-5-23-16 (Dewangan 2003)

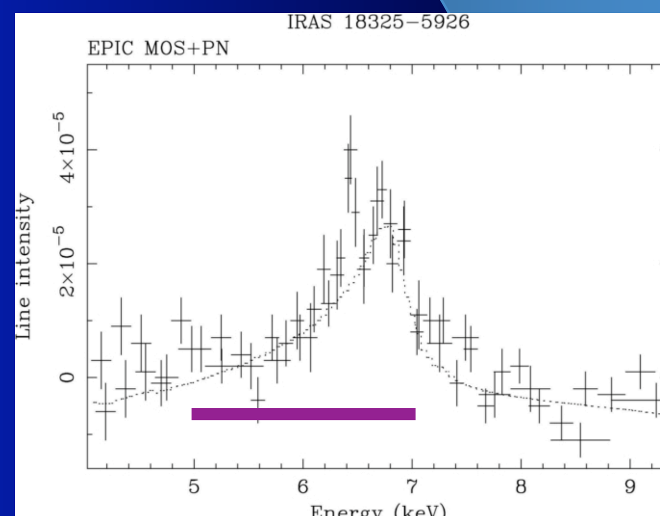


Lockman hole (Streblyanskaya et al 2004)





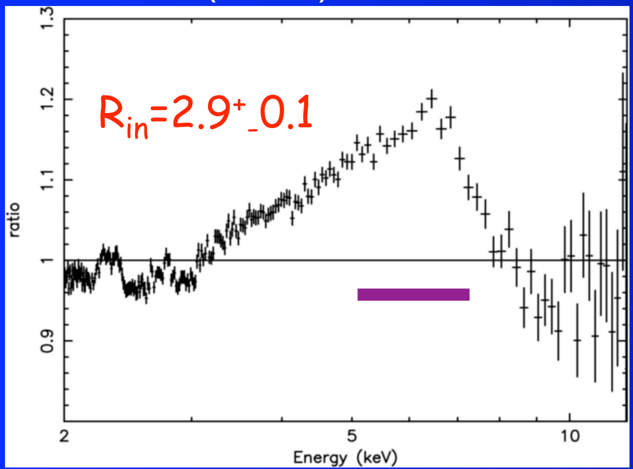
PG 1211+143 (Pounds 2003)



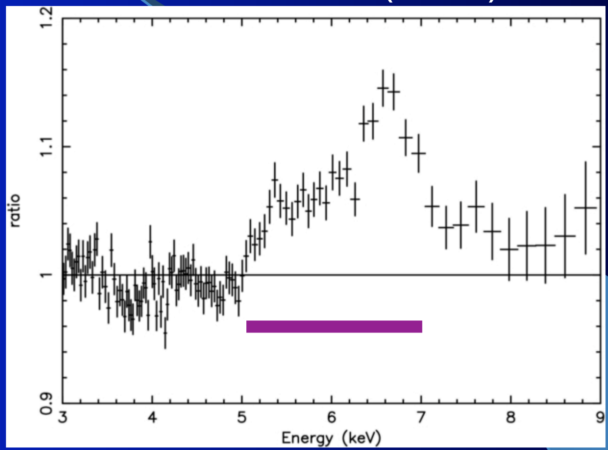
IRAS 18325 (Iwasawa 2004)

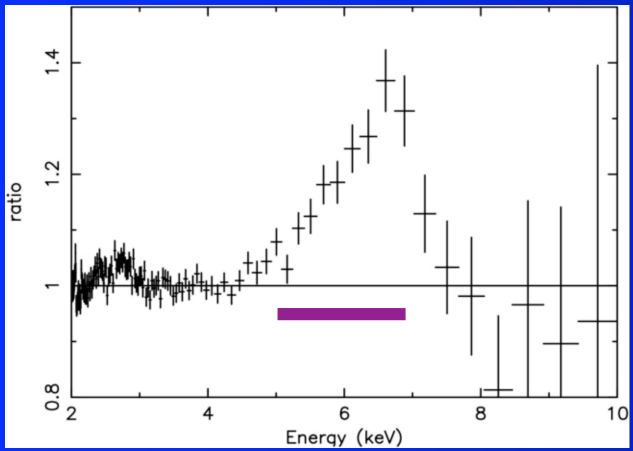
Iron lines in Galactic Black Hole Binaries

GX 339-4 (XMM)



GRS 1915+105 (CXO)





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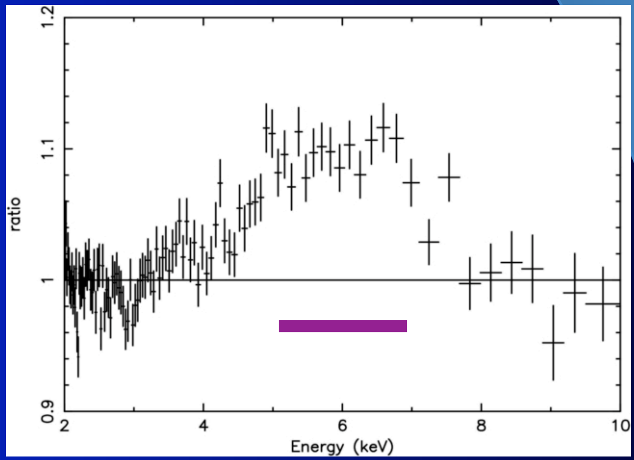
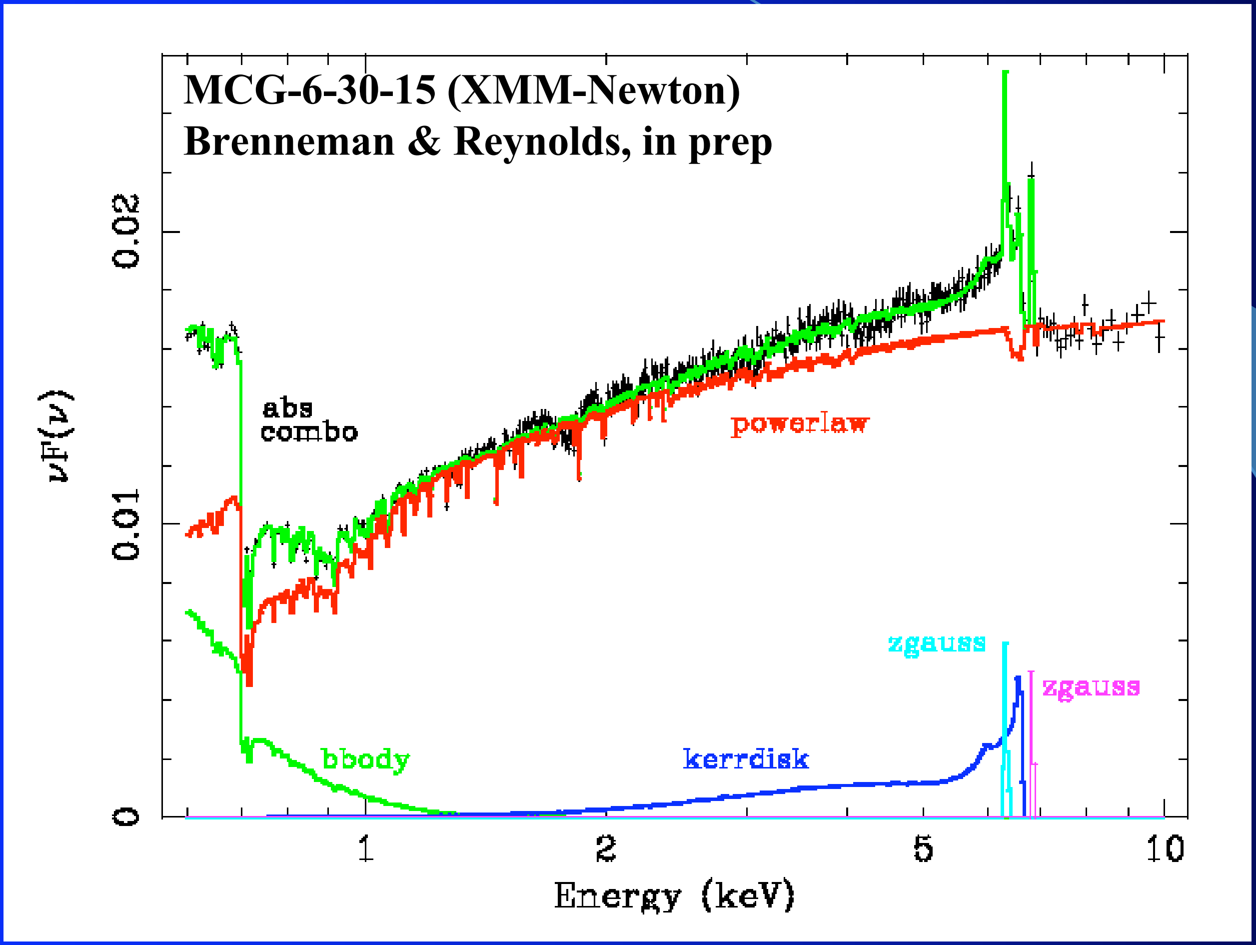


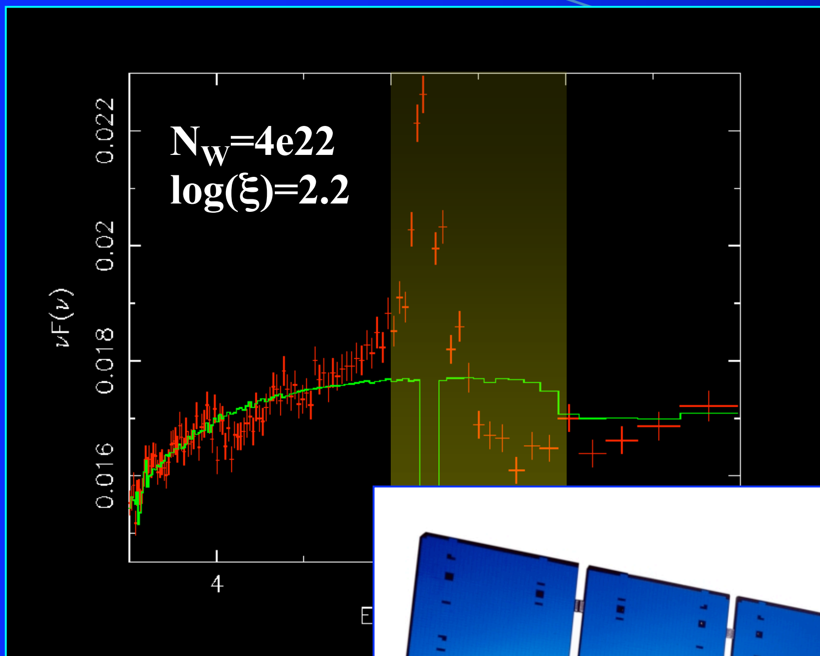
XTE J1650-500 (XMM)

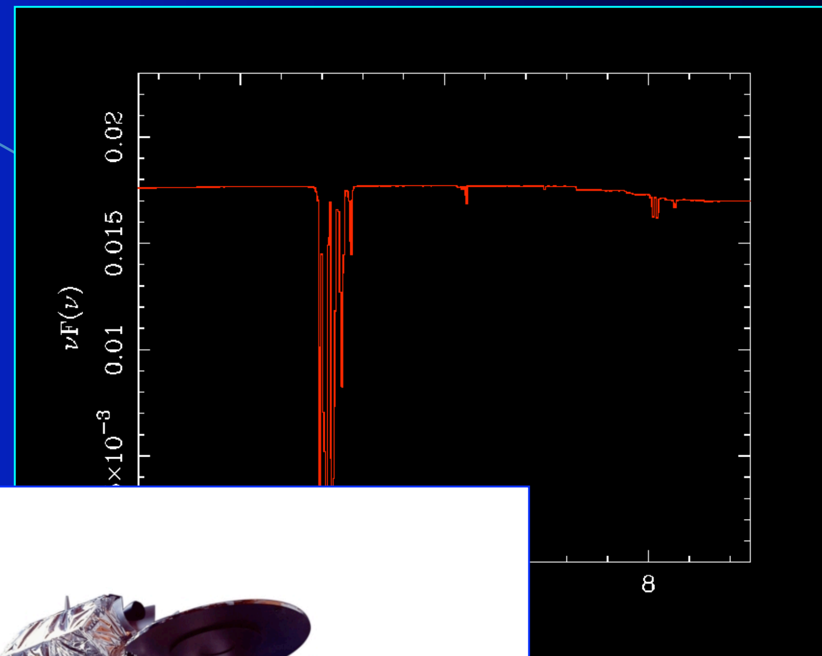
JM Miller

COMPLEXITY FROM ABSORPTION



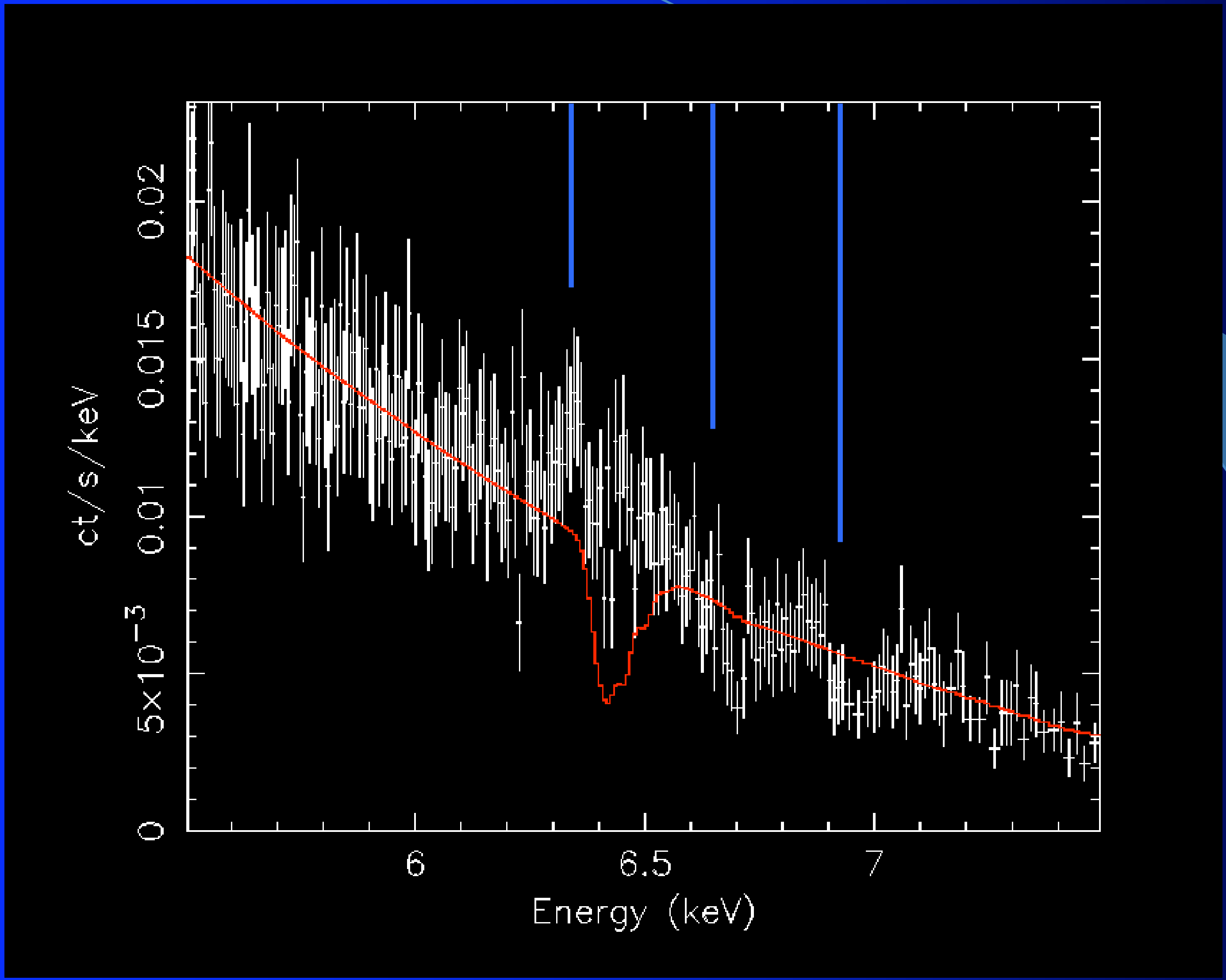
Must be careful to account for effects of absorption…





- Fitting 3-6 … ”curvature from iron-…
- Generic prediction - significant iron K line absorption from FeXVII-FeXXIII (~6.4-6.6 keV)

MCG-6-30-15; 522ks Chandra-HETG observation

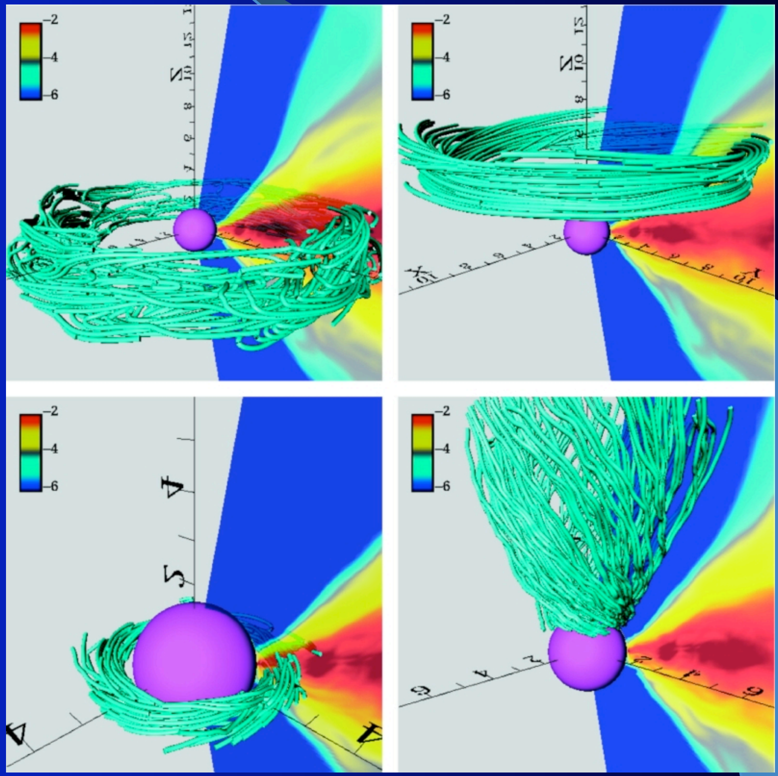


Clearly do not see the FeXVII-FeXXIII abs lines that accompany a "broad-line mimicking" WA

[Young, Lee, Fabian, Reynolds et al., ApJ, 2005]

TESTING BLACK HOLE ACCRETION DISK MODELS

- Current paradigm
  - Accretion proceeds through disk due to MHD turbulence (Shakura & Sunyaev 1973; Balbus & Hawley 1991)
  - Full GR-MHD simulations of **<u>non-radiative</u>** disks possible
- Radiatively-efficient disks
  - Gross properties amenable to semi-analytic modeling
  - Novikov & Thorne (1974)
    - Geom. thin, efficient disk
    - Material plunges into BH ballistically once within the innermost stable circular orbit



Hirose et al. (2004); also see Koide et al. (2000), McKinney (2005), Komissarov (2005).

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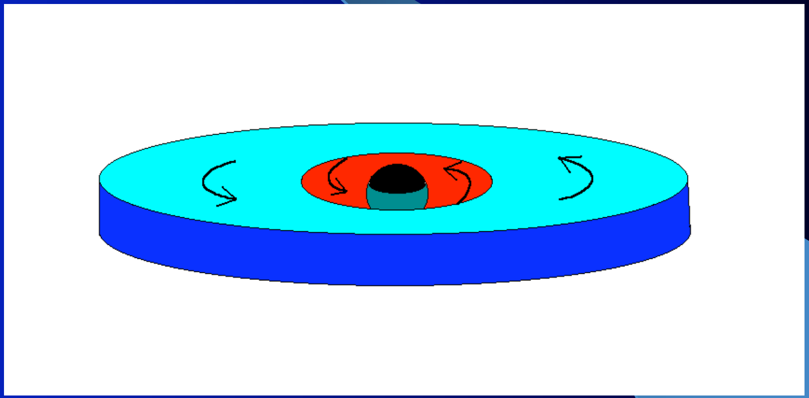

$$r_{\rm in} \rightarrow \frac{6GM}{c^2} \qquad a = 0$$

$$r_{\rm in} \rightarrow \frac{GM}{c^2} \qquad a \rightarrow 1$$

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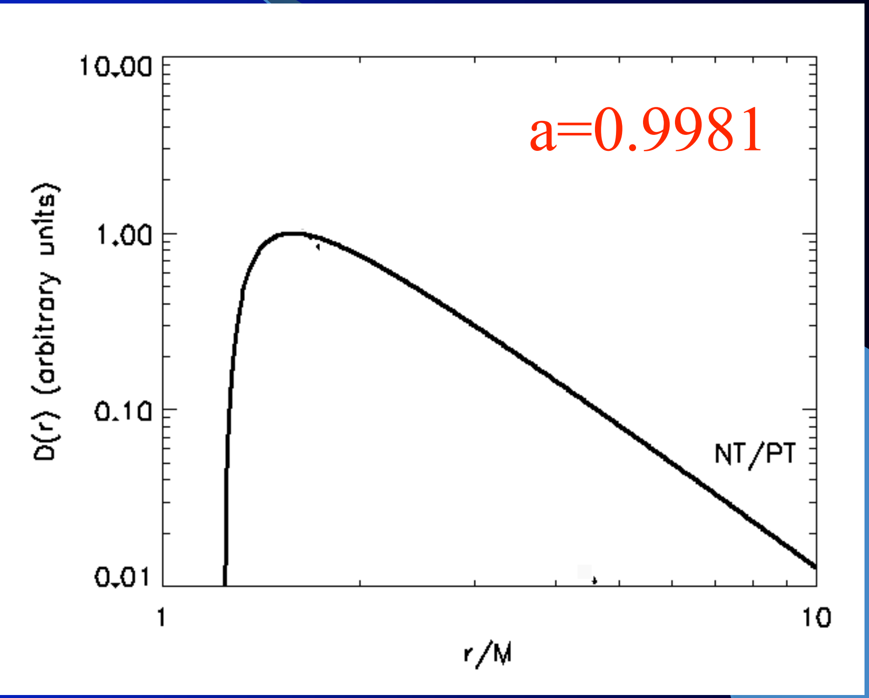

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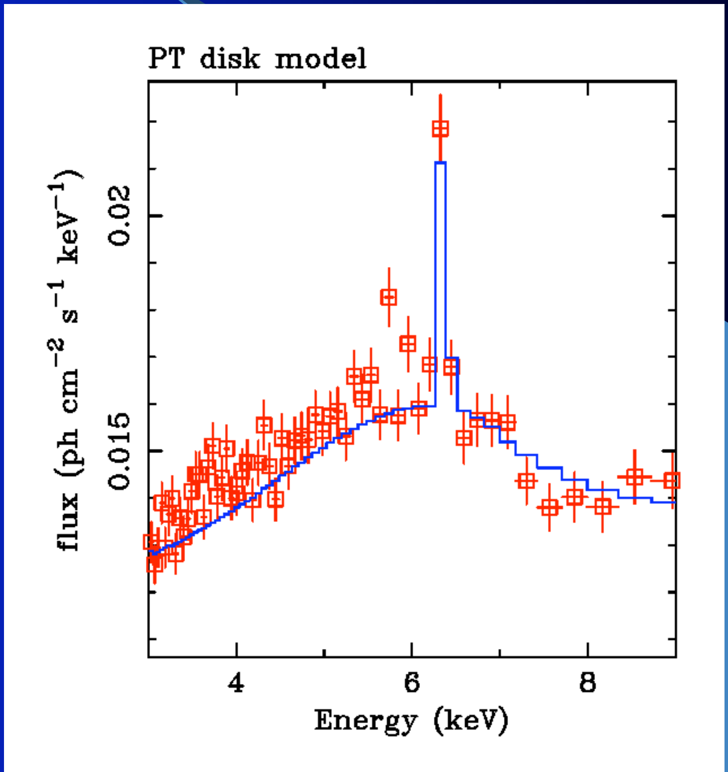


Deep Minimum of MCG-6-30-15 XMM (Reynolds et al. 2004)

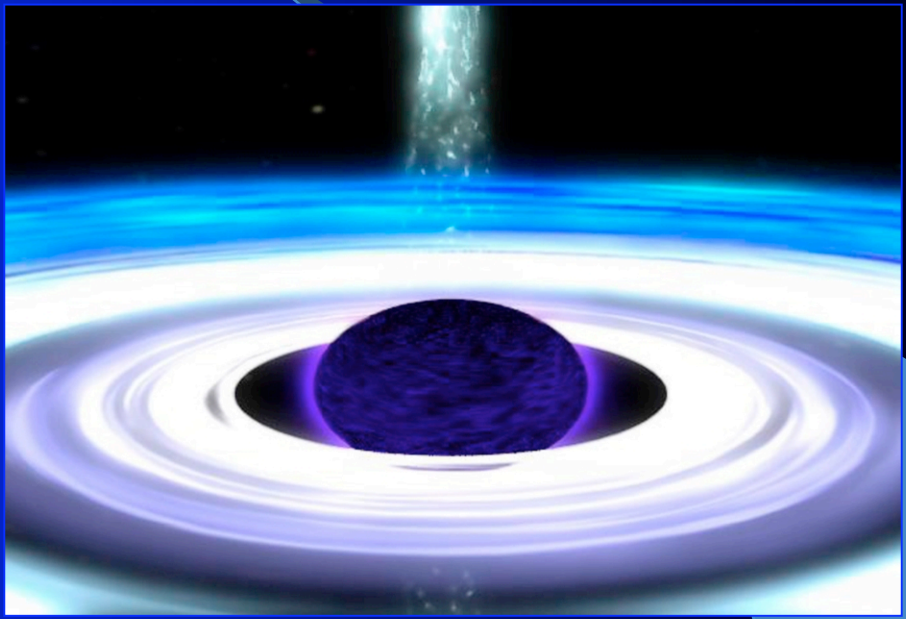
Iron lines broader than predicted from NT disk $\Rightarrow$ Irradiation more centrally concentrated than NT prediction

Underlying disk is NT-like, but X-ray irradiation does not track local dissipation (need light bending)

Irradiation tracks a dissipation that is much more centrally concentrated than NT law

Gravitational light bending?

- Suppose X-ray source is base of a jet?
  - X-rays will be gravitationally focused onto central parts of disk
  - Can produce very centrally concentrated irradiation pattern!
  - Data suggest h~few GM/c^2



• Geometry first discussed in Fe-K line context by Marttochia & Matt (1996)
• Applied to ASCA data for MCG-6-30-15 by Reynolds & Begelman (1997)
• Applied to XMM data for MCG-6-30-15 by Minuitti & Fabian (2004)

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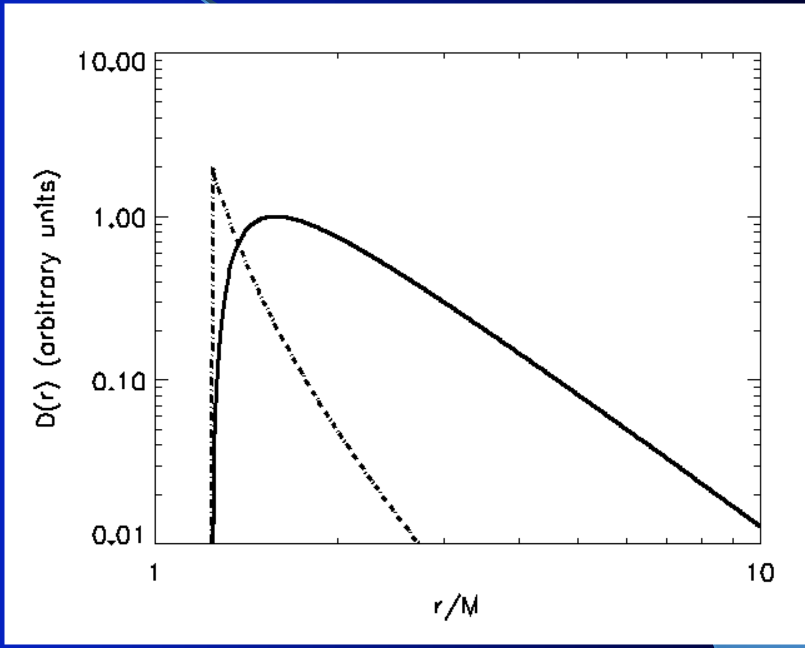
Enhanced dissipation in central regions of disk?

- Recent work suggests importance of "torqued accretion disks"
  - Magnetic fields may lead to continued extraction of energy/ang-momentum of matter plunging within ISCO
  - Plunging matter exerts torque on rest of disk
  - Work done by torque dissipated in innermost regions of the disk
- In extreme case, this might produce a Penrose process and allow the BH spin to be tapped.



Analytic: Gammie (1999), Krolik (1999), Li (2000), Agol & Krolik (2000), Garofalo & Reynolds (2005)
Numerical: Hawley (2000), Hawley & Krolik (2001), Armitage, Reynolds & Chiang (2001), Reynolds & Armitage (2003)

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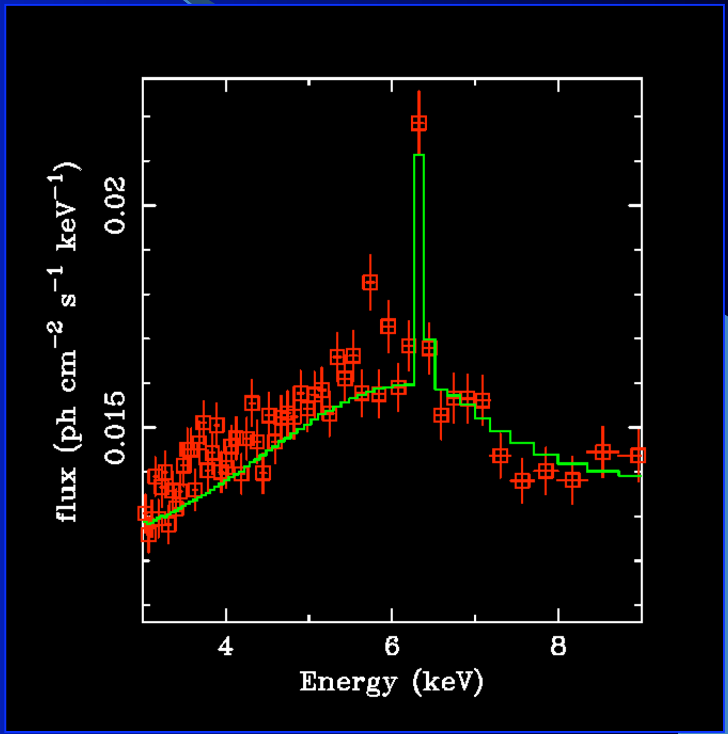

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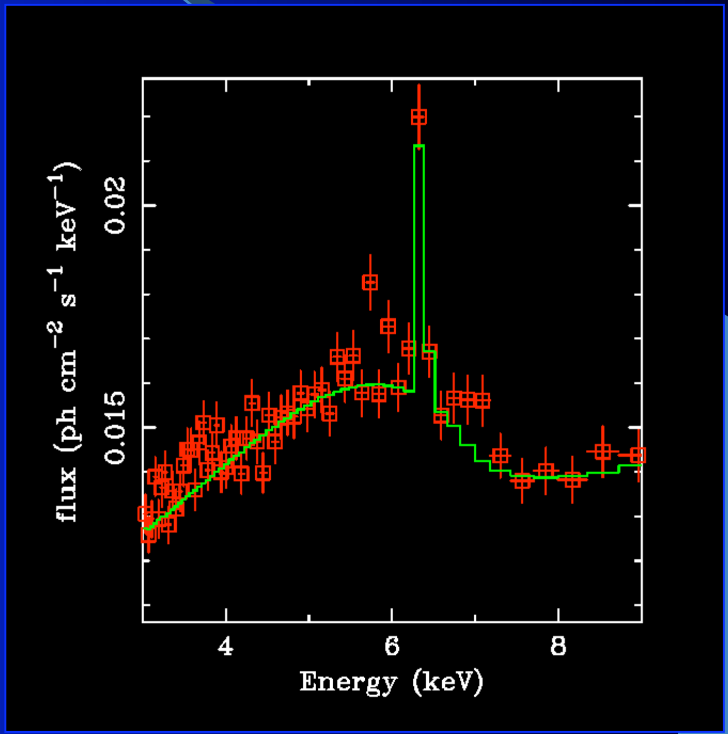
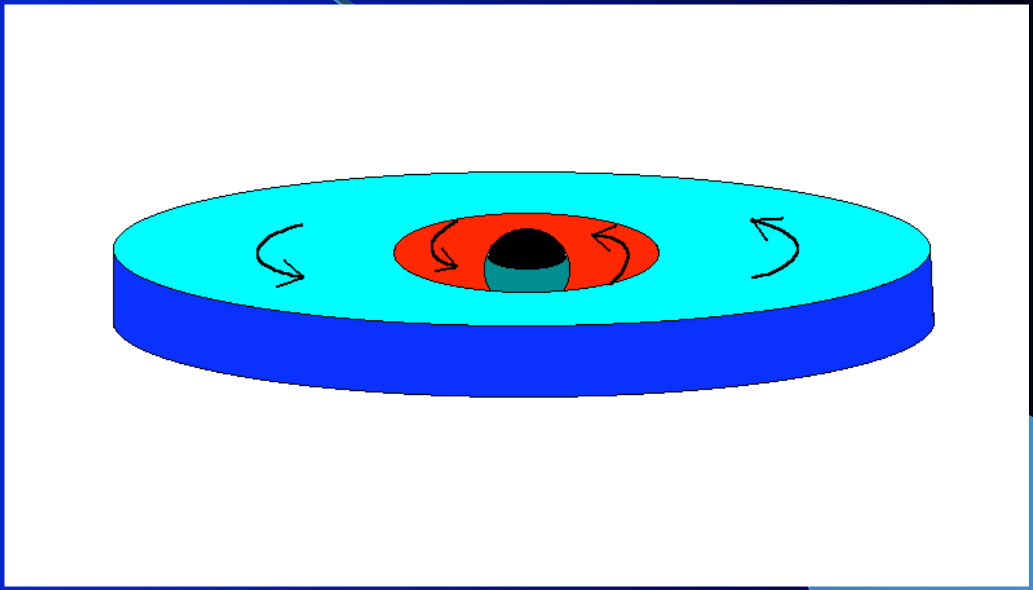


Deep Minimum of MCG-6-30-15 XMM (Reynolds et al. 2004)

BLACK HOLE SPIN

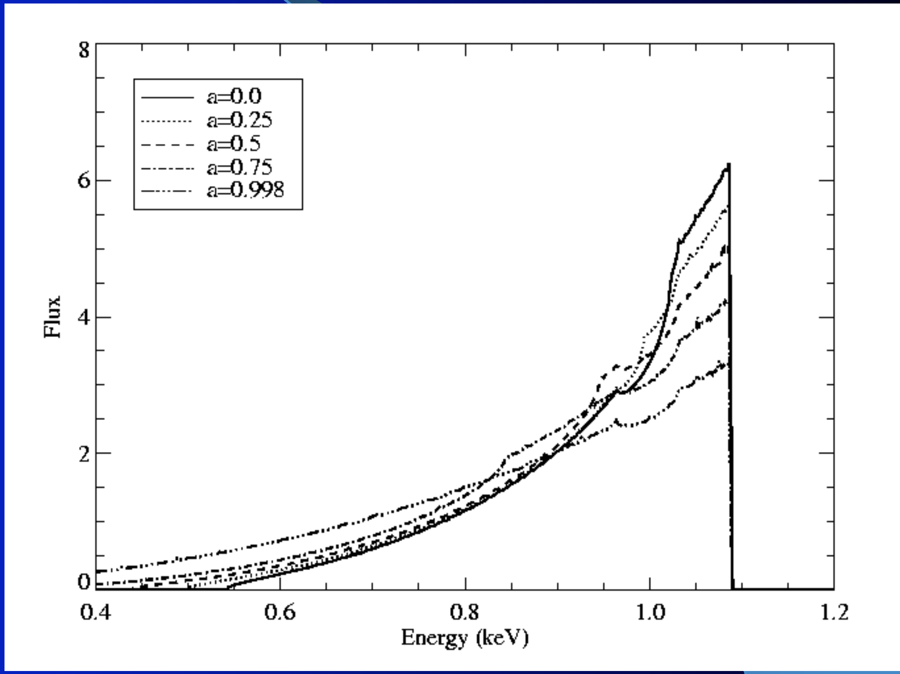
- Importance of spin
  - Large energy store (upto 29% of rest mass energy)
  - Spin may retain memory of black hole formation
  - First step in testing Kerr metric



- Diagnose spin through its effects on the accretion disk structure
  - Major effect change in the location of the innermost stable circular orbit (ISCO)

If we assume no X-ray reflection from within the ISCO…

- For progressively more rapidly rotating BHs…
  - ISCO moves inwards to a higher gravitational redshift region
  - For given inclination, maximum redshift of iron line increases
- Applied to long (350ks) XMM dataset for MCG-6
  - Data strongly prefers rapidly spinning BH solution
  - $a = 0.95 \pm 0.04$



Brenneman & Reynolds, in prep

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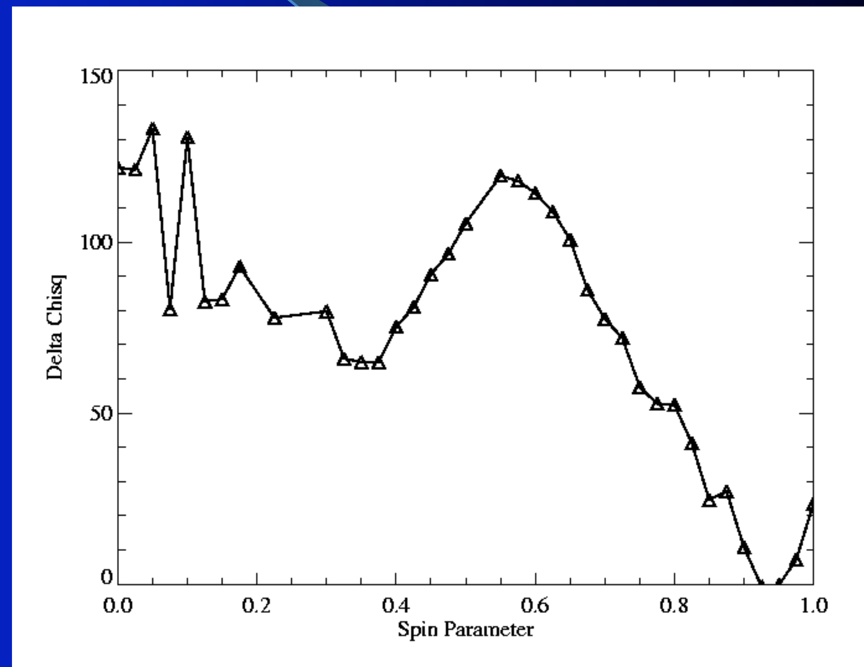

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THE PROMISE OF CONSTELLATION-X

- Constellation-X
  - Major component of NASA's Beyond Einstein program
  - Imaging spectroscopy with superior spectral resolution and collecting area

- Allows study of short-term broad iron line variability
  - Dynamical timescale variability ⇒ trace orbits of distinct structures in disk
  - Light crossing timescale variability ⇒ follow echos of X-ray flares across disk

Constellation-X

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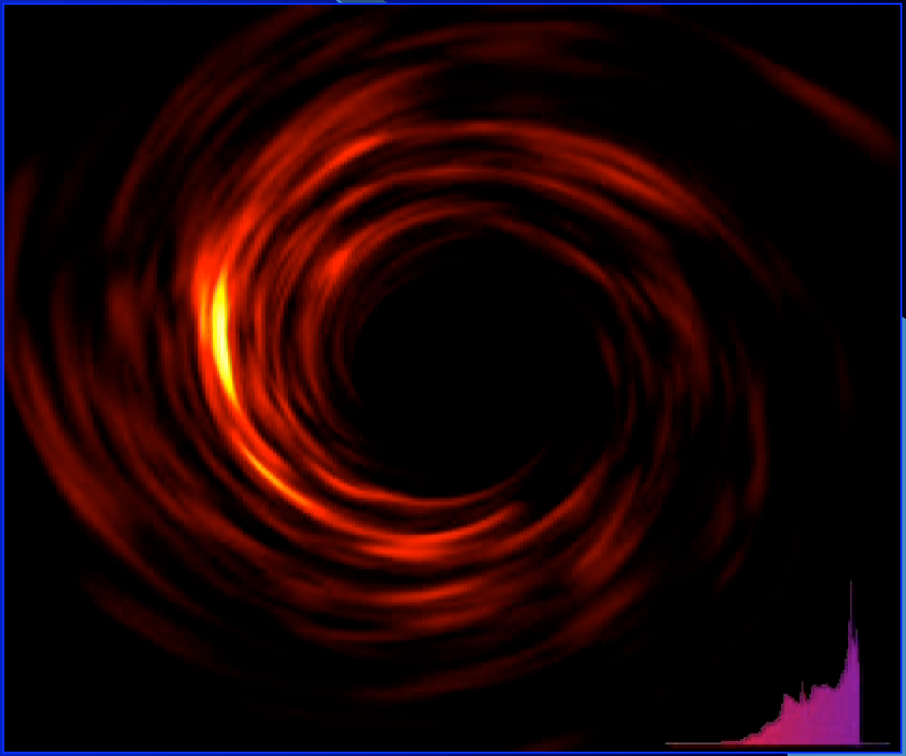

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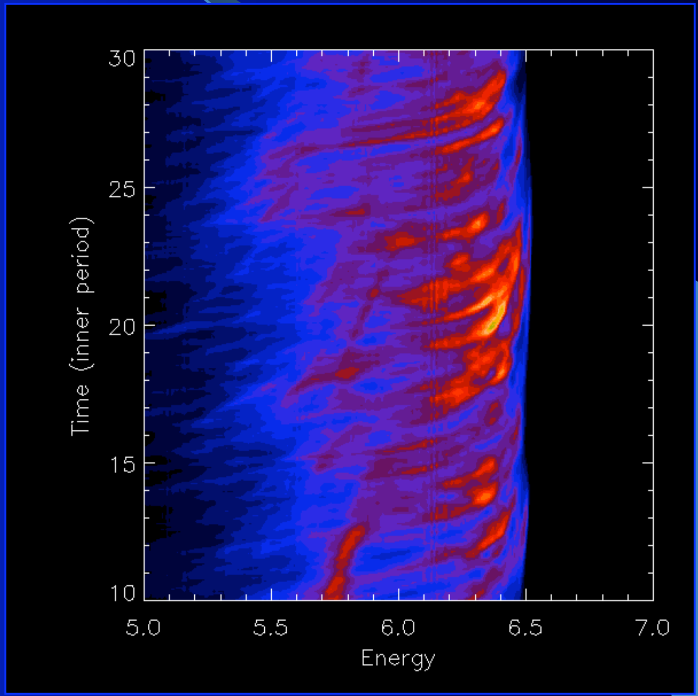

Armitage & Reynolds (2003)

Similar features from <u>outer</u> disk already hinted at by XMM-Newton NGC3516 (Iwasawa et al. 2004) & Mrk 766 (Turner et al. 2005)

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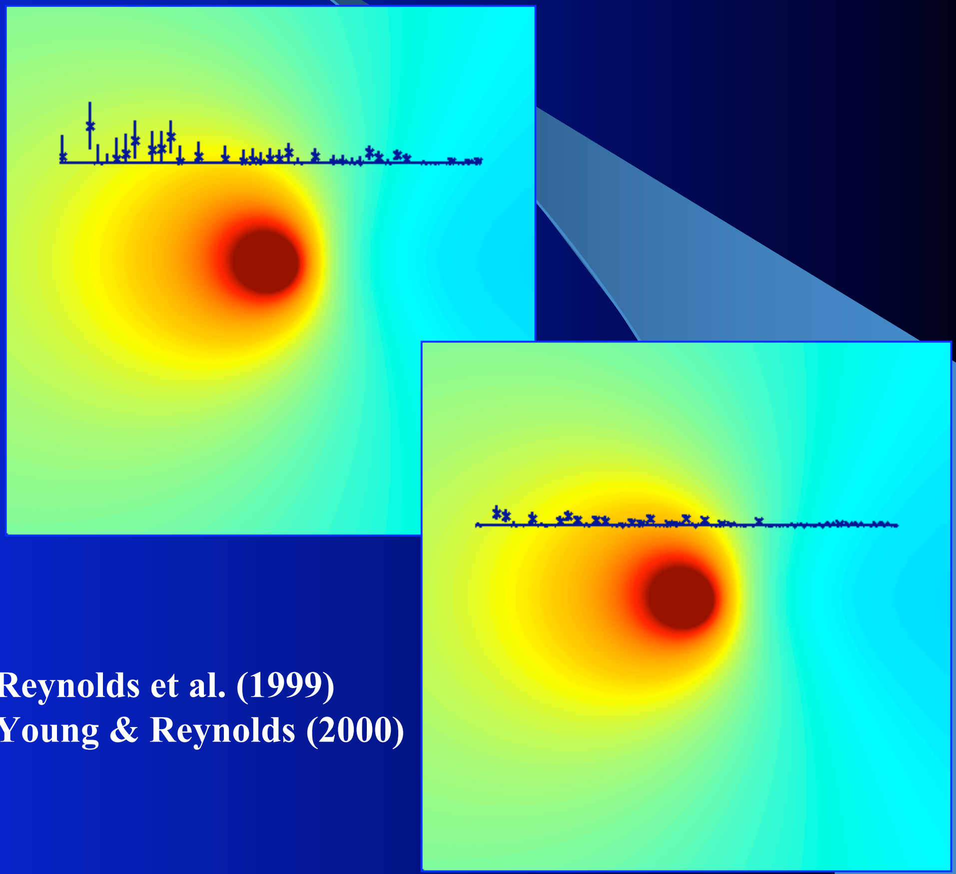
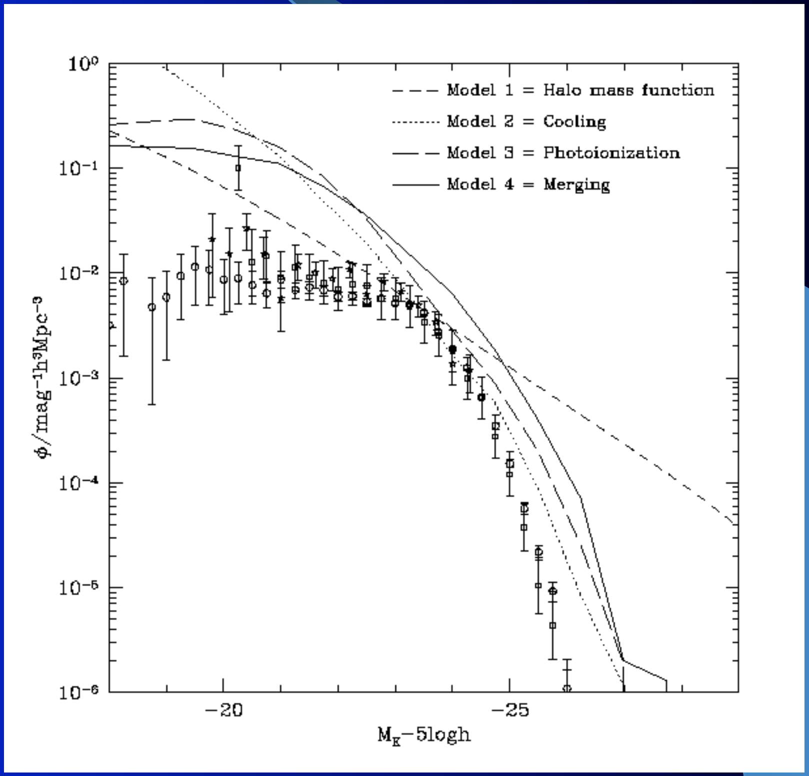


Reynolds et al. (1999)
Young & Reynolds (2000)

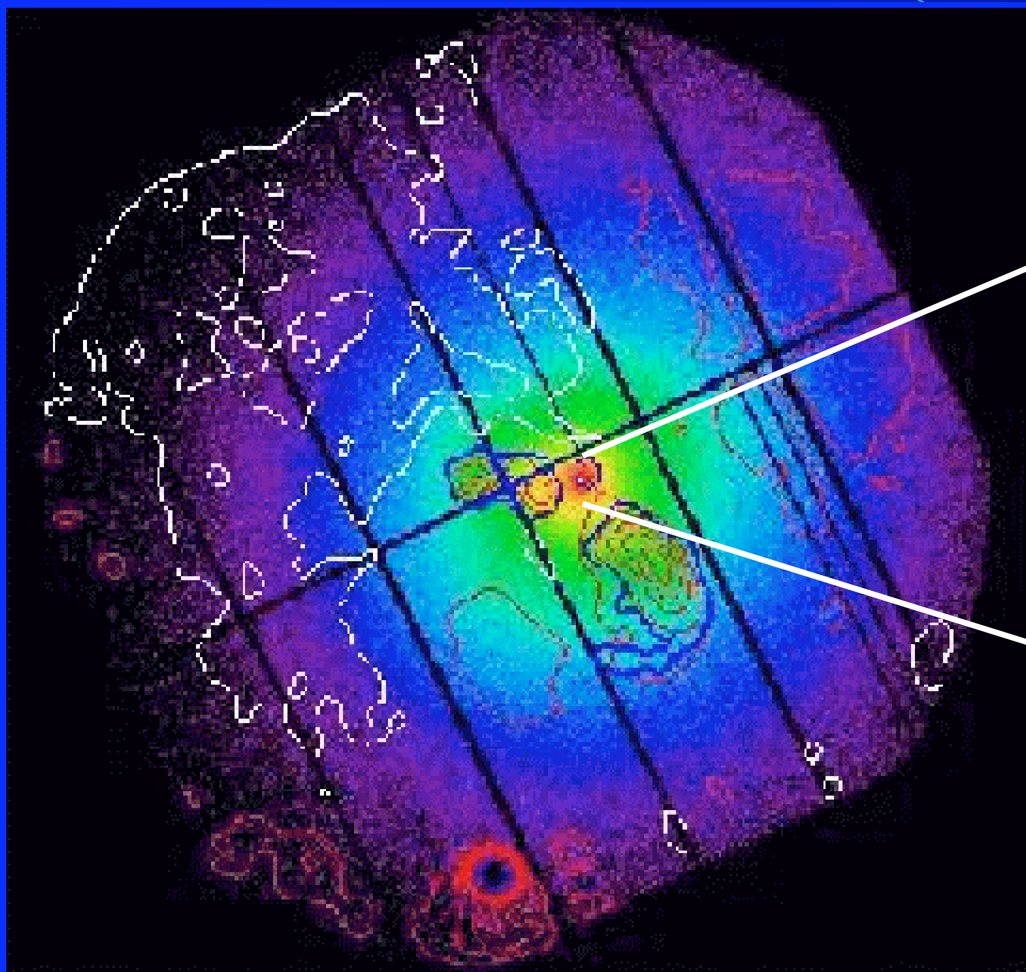
II : MASSIVE BLACK HOLES & MASSIVE GALAXY FORMATION

- Galaxy luminosity function
  - Suppressed at high and low luminosity end compared with simply ΛCDM predictions
  - High-L suppression must be more efficient that star formation
- Do AGN suppress high-end of galaxy LF?



Benson et al. (2003)

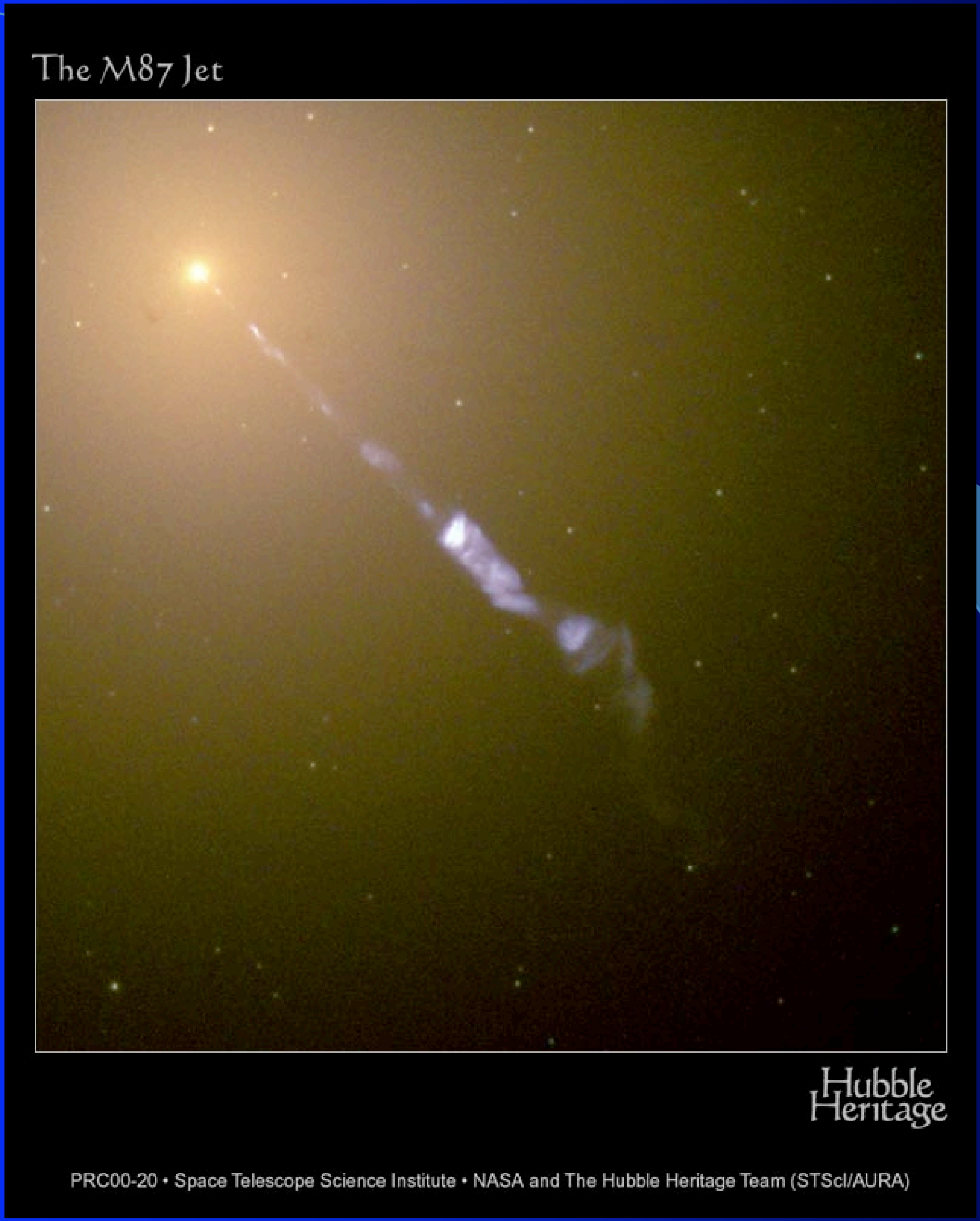
Cluster cooling flows
Massive galaxy suppression in action?



XMM-Newton observation of Virgo cluster
Matsushita et al. (2002)

Intracluster medium(ICM)
Hot (10^7-10^8K), tenuous (0.001-$0.1 cm^{-3}$) plasma.

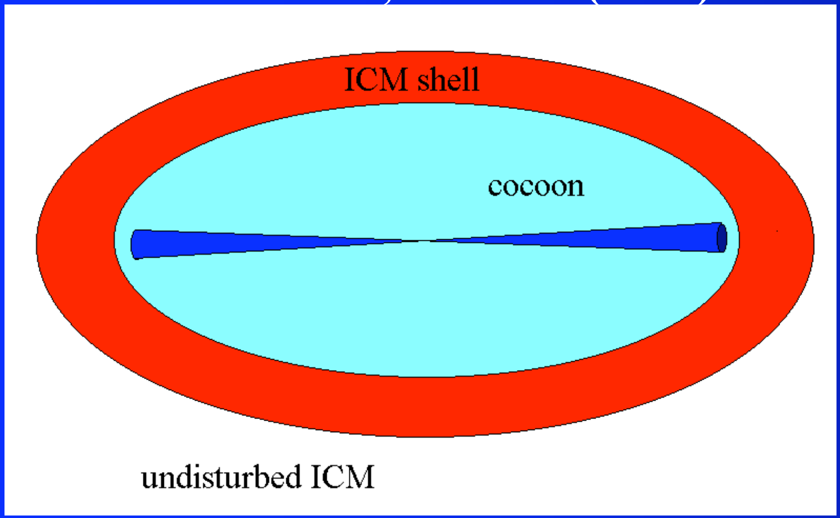
THE COOLING FLOW PROBLEM



The M87 Jet
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

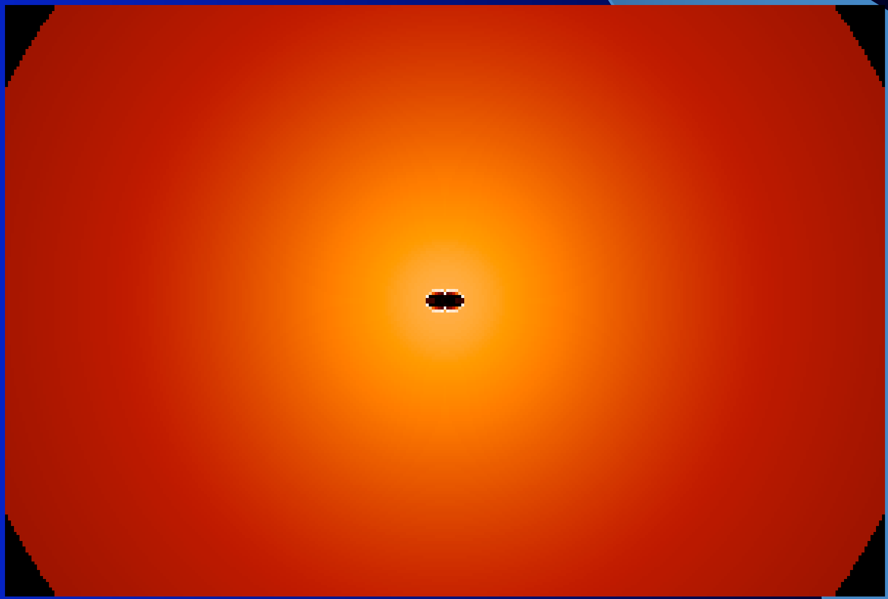
How can AGN jets heat ICM isotropically?

Cocoon structure; Scheuer (1974)

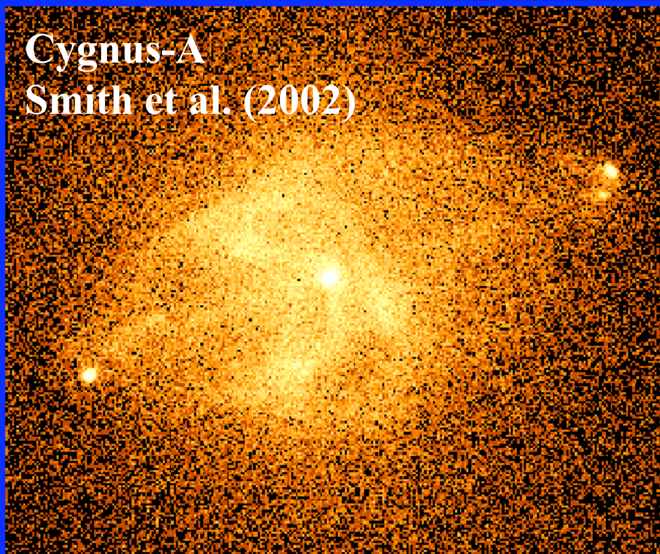


Can heat isotropically by either shock heating or dissipation of sound waves

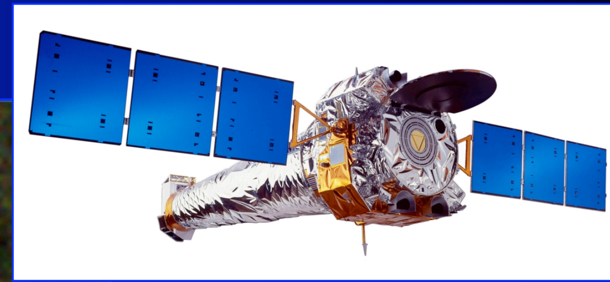
2-d hydro simulations
Reynolds et al. (2002)



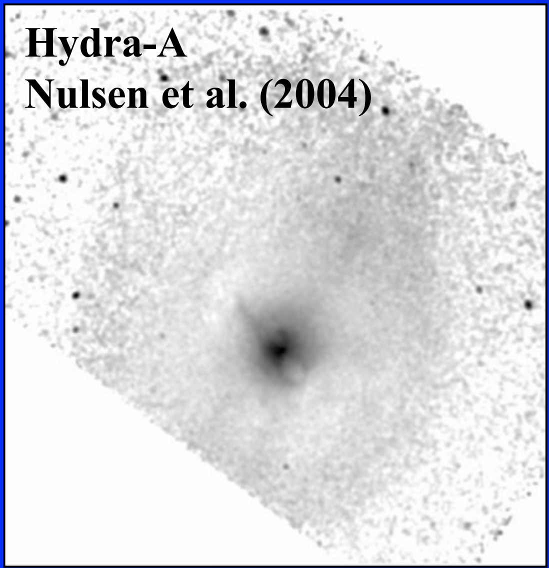
Chandra observations of cooling-core clusters

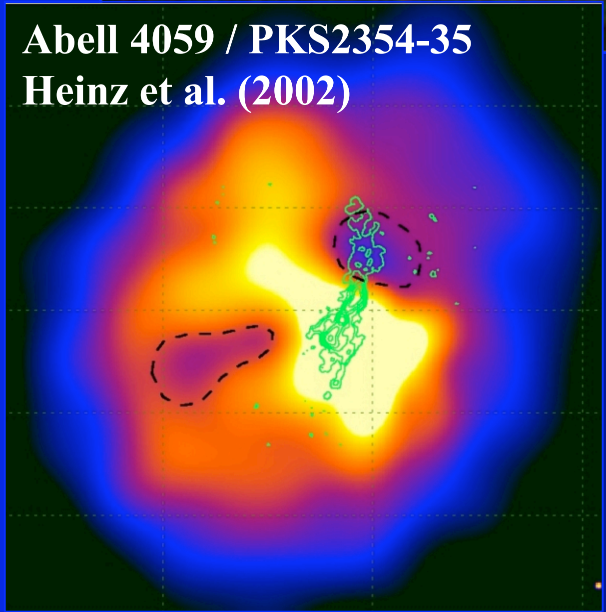

Cygnus-A
Smith et al. (2002)

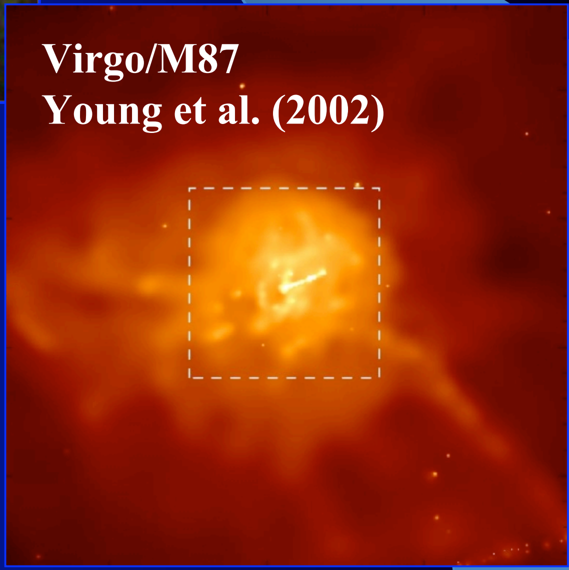

Perseus-A
Fabian et al. (2000)



<u>Synopsis:</u>
Jet-blown cavities common
"Ghost" cavities common
Strong shocks elusive!


Hydra-A
Nulsen et al. (2004)

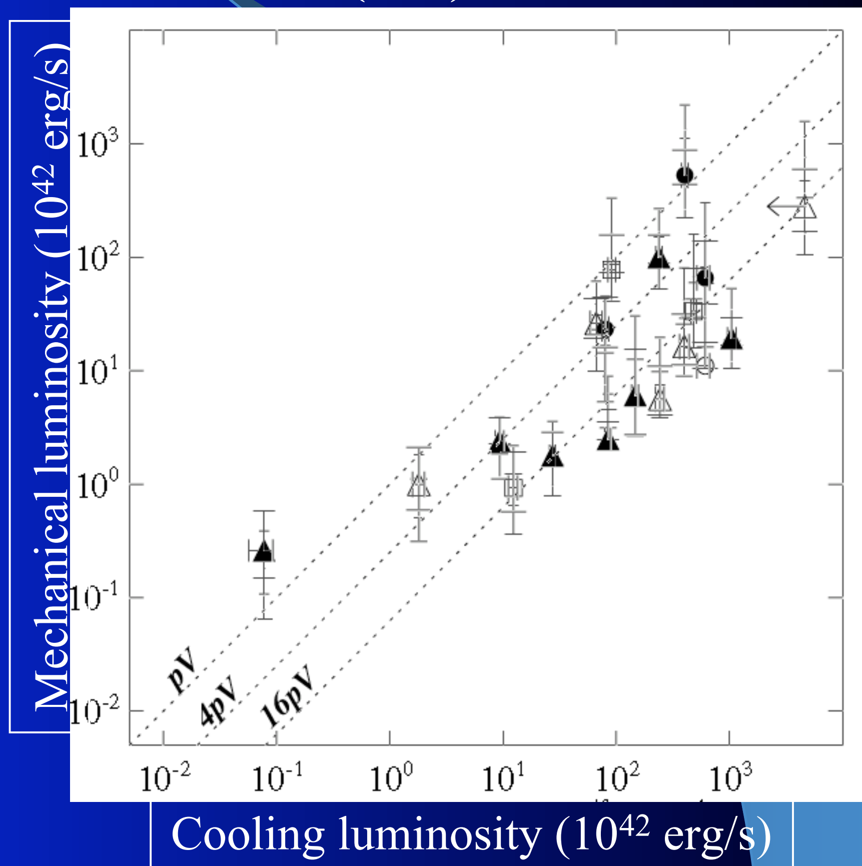

Abell 4059 / PKS2354-35
Heinz et al. (2002)


Virgo/M87
Young et al. (2002)

Modeling the feedback loop

- Feedback model ⇒ average AGN heating balances ICM cooling
- Analysis of ICM cavities shows that kinetic power and cooling luminosity are indeed related
- Nature must modulate AGN fueling according to ICM properties
- First attempts to model this…
  - Ideal hydro model of jet/ICM interaction
  - Jet power proportional to cooling flow rate
  - FAIL to produce successful balance

Birzan et al. (2004)



Also see McNamara (2000)

Does the "feedback" loop work?

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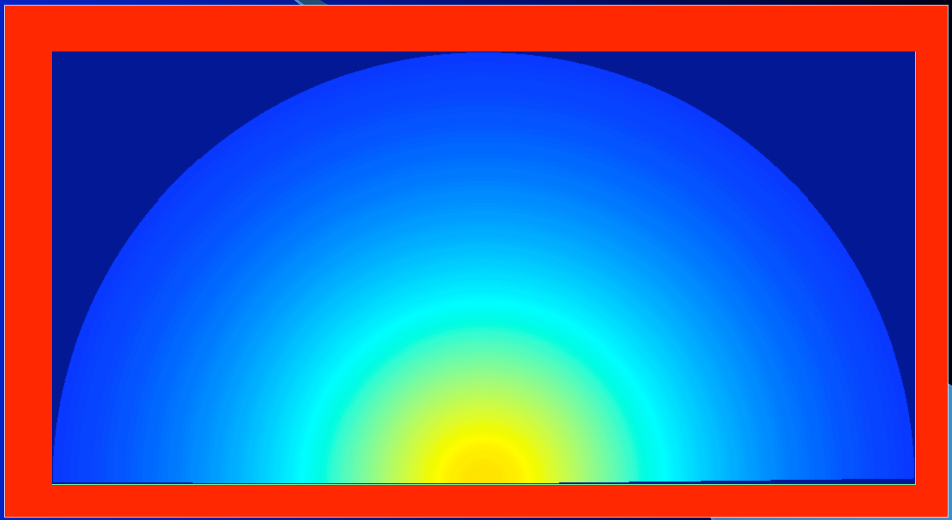

Delayed fueling scenario
Vernaleo & Reynolds, submitted

Runaway cooling in the equatorial regions

Does the "feedback" loop work?

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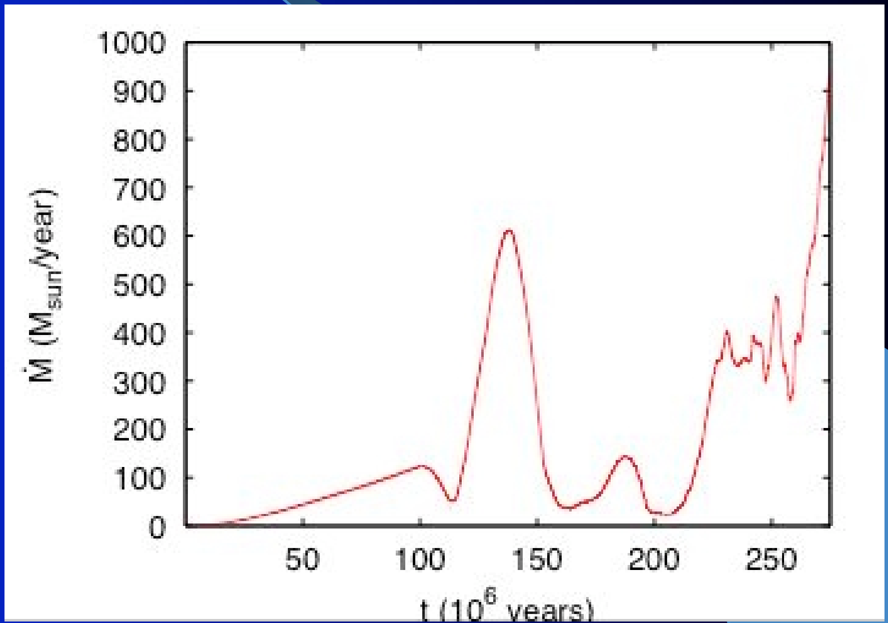
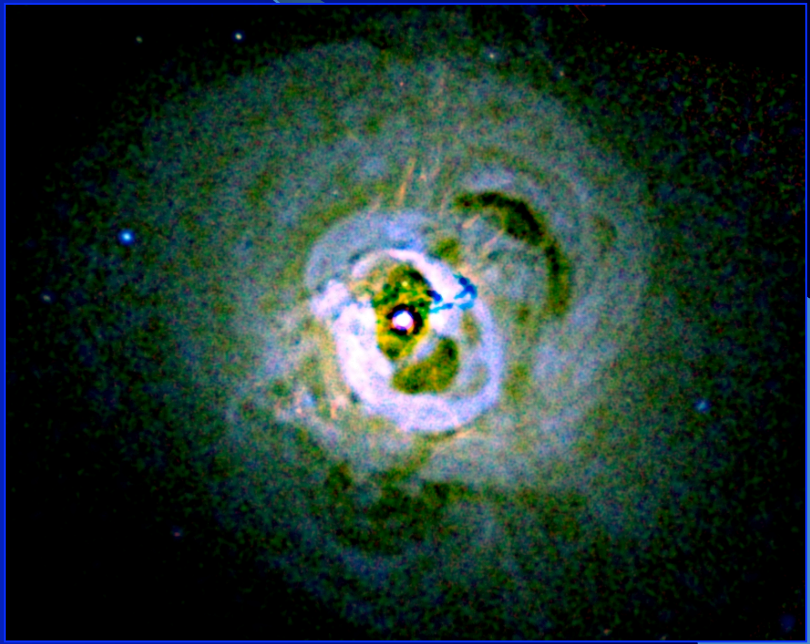


Delayed fueling scenario
Vernaleo & Reynolds, submitted

What ingredients are missing from the feedback model?

- MHD and Plasma transport processes
  - Thermal conduction and Viscosity
  - Dissipation of wave energy
  - New instabilities of the ICM atmosphere
- Precession of the jet axis
  - Need to be quasi-isotropic on cooling timescale (few$\times 10^8$ yr)
- Dissipation of energy stored in global ICM modes?



Evidence for dissipation of sounds waves by thermal conduction (see Fabian, Reynolds et al. 2005)

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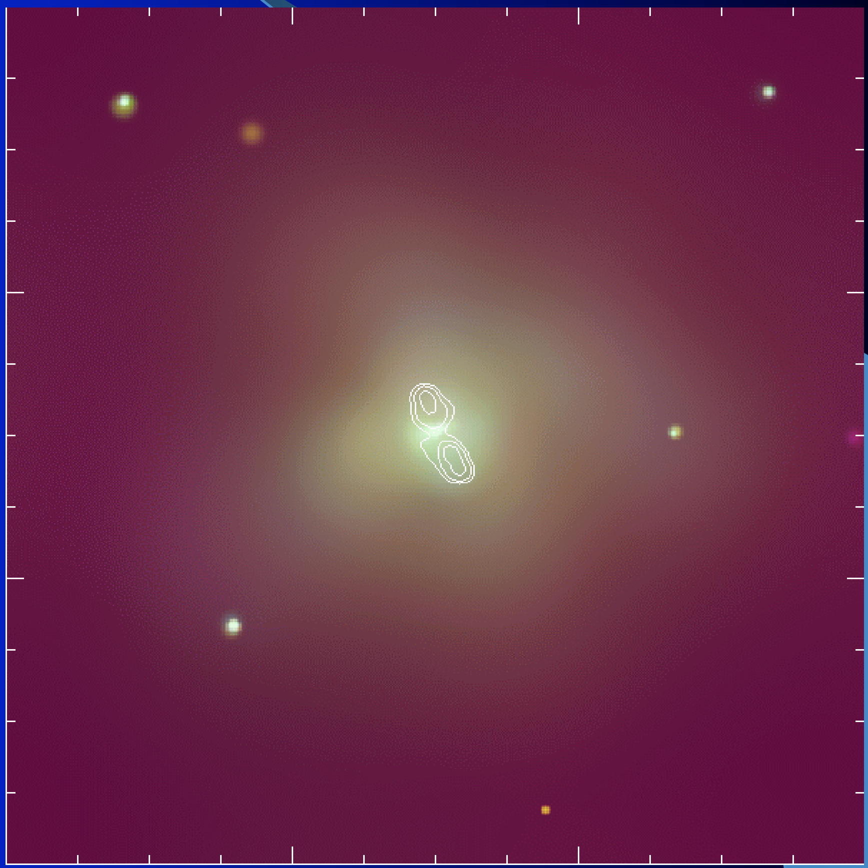


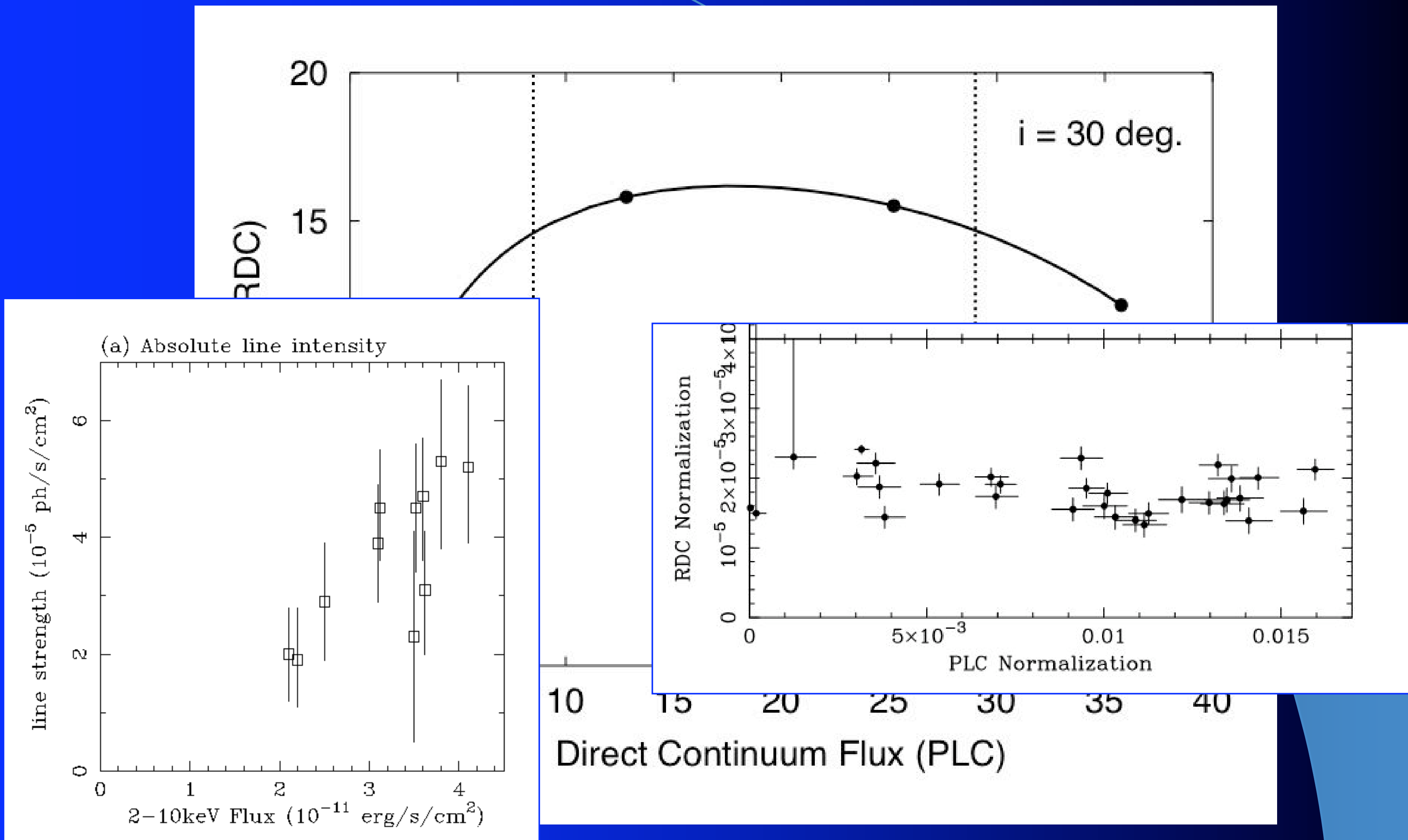
3C401 (Chandra and MERLIN cont.)
Reynolds, Brenneman & Stocke (2005)

Conclusions

- New era of black hole research
  - Detailed studies of black hole physics and relativistic accretion
  - Impact of black holes on galactic scale structure
- Strong gravity studies with XMM and Chandra
  - Robust signatures of strong gravity exist
  - Measurements of black hole spin and signs of interesting spin-related astrophysics
  - Constellation-X and LISA will bring tremendously exciting future
- Jetted AGN and cluster cooling flows
  - Puzzles; how are ICM cores being heated?
  - Need for more physics

The End

Iron line variability

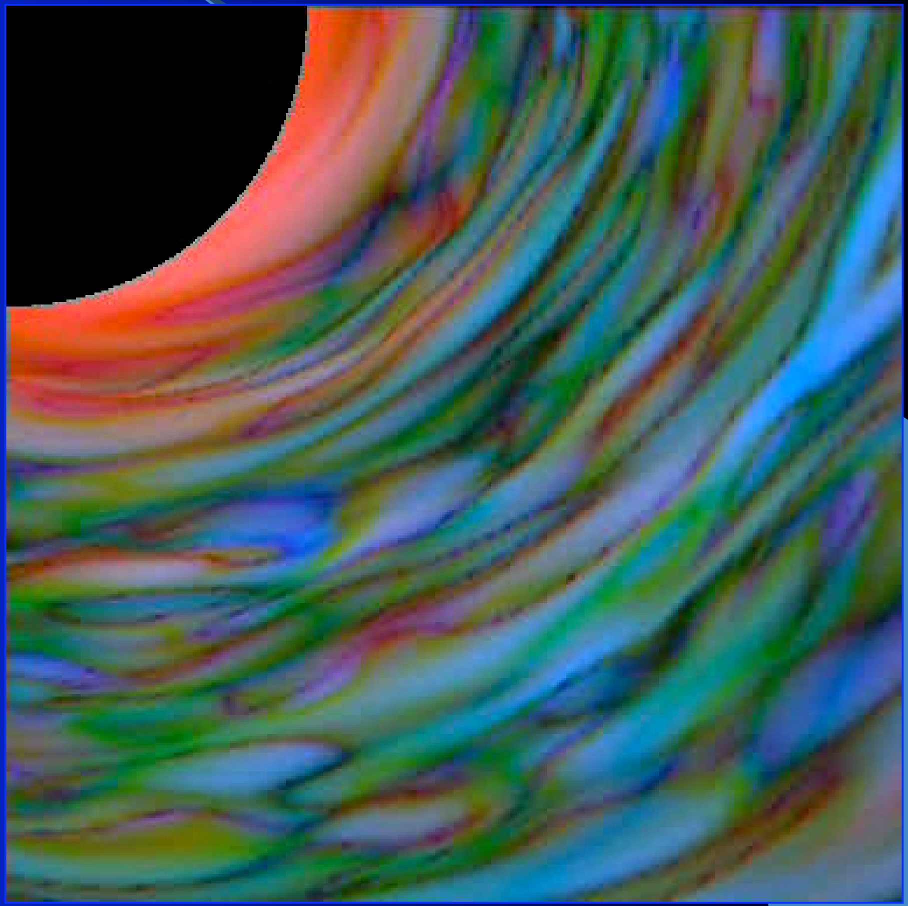


Model : Miniutti & Fabian (2004)
Low flux data : Reynolds et al. (2004)
High flux data : Fabian et al. (2002)

Enhanced dissipation in central regions of disk?

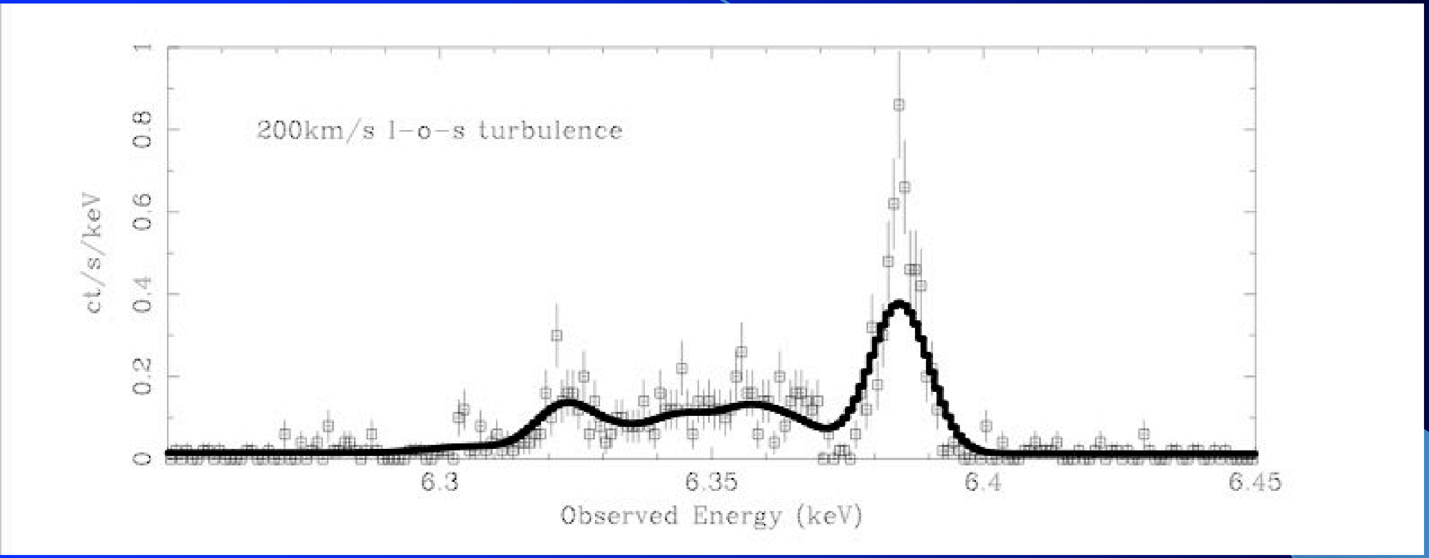
- Recent work suggests importance of "torqued accretion disks"
  - Magnetic fields may lead to continued extraction of energy/ang-mtm of matter plunging within ISCO
  - Plunging matter exerts torque on rest of disk
  - Work done by torque dissipated in innermost regions of the disk

- In extreme case, this might produce a Penrose process and allow the BH spin to be tapped.



Armitage, Reynolds & Chiang (2001)
Reynolds & Armitage (2001)

The way forward



Simulated Astro-E2 XRS data
Abell 4059 (z=0.049)

- Better modeling
  - More physics (MHD, plasma processes)
  - Put in cosmological setting
- Better data
  - More deep Chandra observations
  - Direct kinematics from high-resolution X-ray spectroscopy (rebuild of Astro-E2?, Constellation-X)