Beyond RXTE: The Future of X-ray Timing

. . . or: what do do with bright sources. . .

Jörn Wilms
Dr. Remeis-Sternwarte
& ECAP

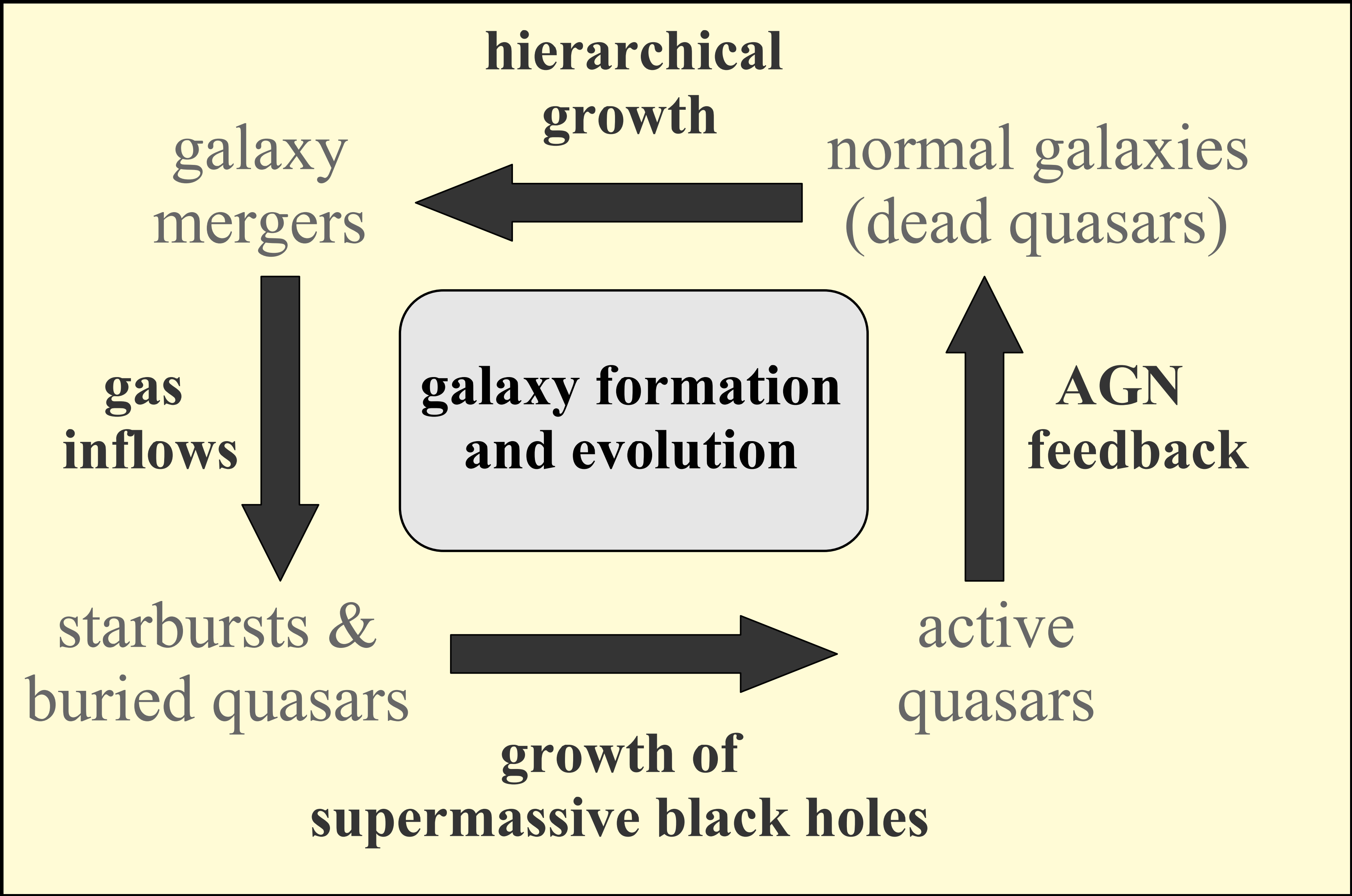
with input from

D. Barret, M. Méndez, Ph. Uttley, C. Schmid,
and the IXO-HTRS systems and science teams

HTRS iXO

Black Hole Universe

ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



(Hopkins et al., 2006)

AGN Feedback: Accretion onto Black Holes regulates star formation

$\Longrightarrow$ anti-hierarchical structure formation $\Longrightarrow$ “co-evolution”

Need to understand accretion processes!

Wide field

18' diameter (<15 keV)

Effective area

3 m2 @ 1 keV
0.65 m2 @ 6 keV
150 cm2 @ 30 keV

Angular resolution

<5" HPD (<10 keV)
30" HPD (>10 keV)

Spectral resolution

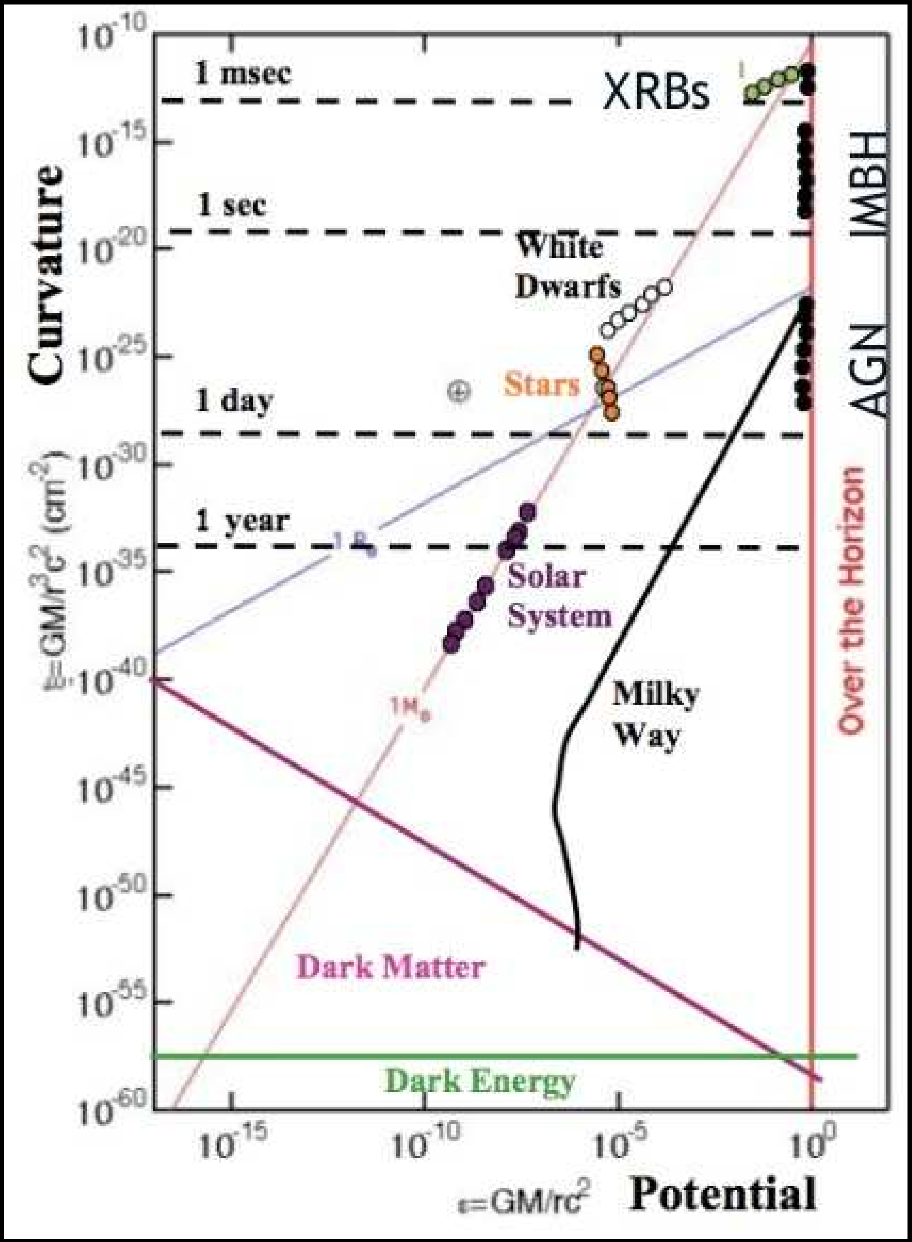
2.5 eV (2'x2', <7 keV)
10 eV (5'x5', < 7 keV)
R=3000 (0.3-1.5 keV)

Timing

>90% livetime (detection efficiency.) at 1 Crab

Polarimetry

1% MDP @ 1 mCrab



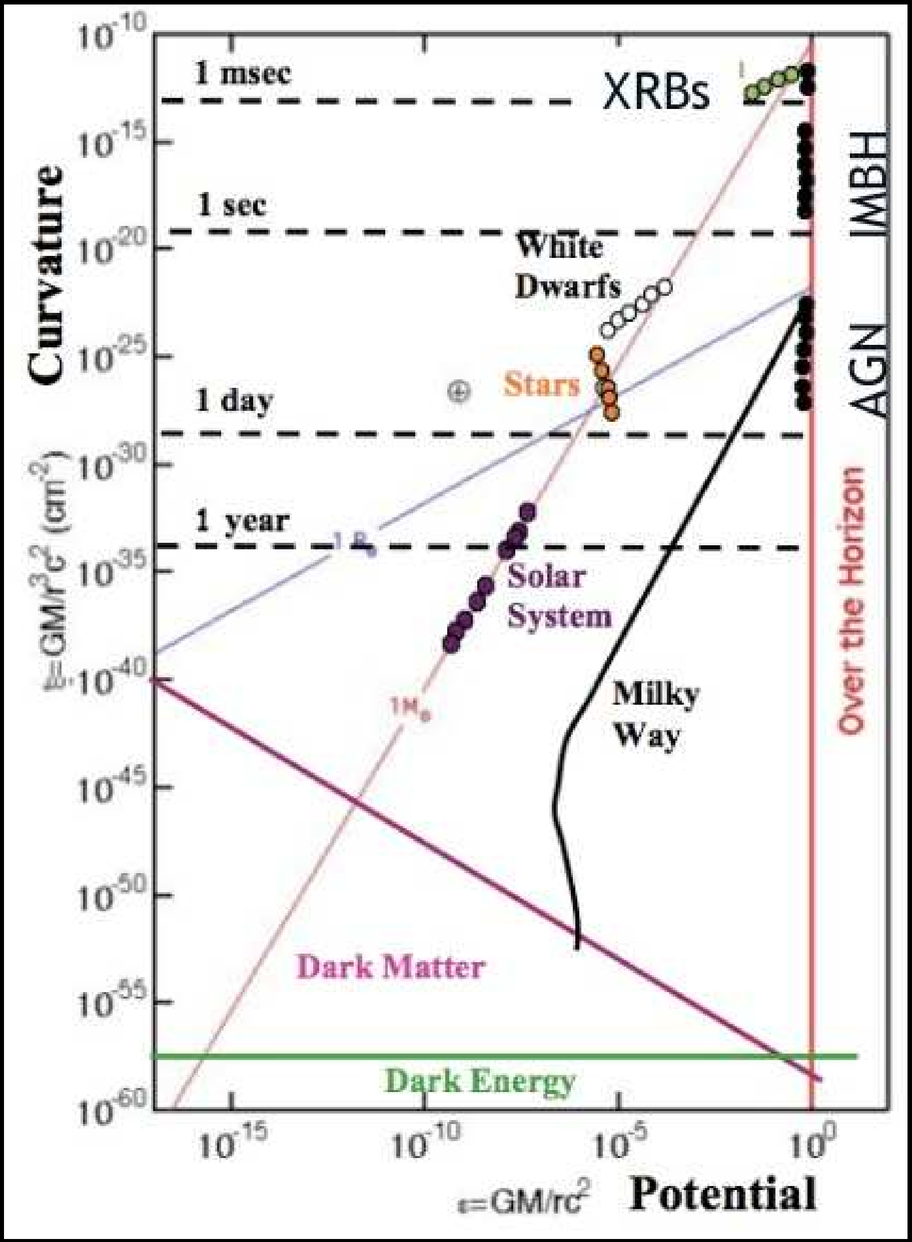
Open questions:

- How do supermassive black holes grow and evolve?
- How does accretion work?
- How does gravity behave in the strong field limit?
- What is the spin distribution of Black Holes?
- Does matter orbiting black holes follow general relativity?

. . . and, in general,

- What is the behavior of matter under the most extreme conditions?

V.L. Ginzburg: If the cosmological problem is the number one problem of astronomy, then problem number two should be the problem of black holes.



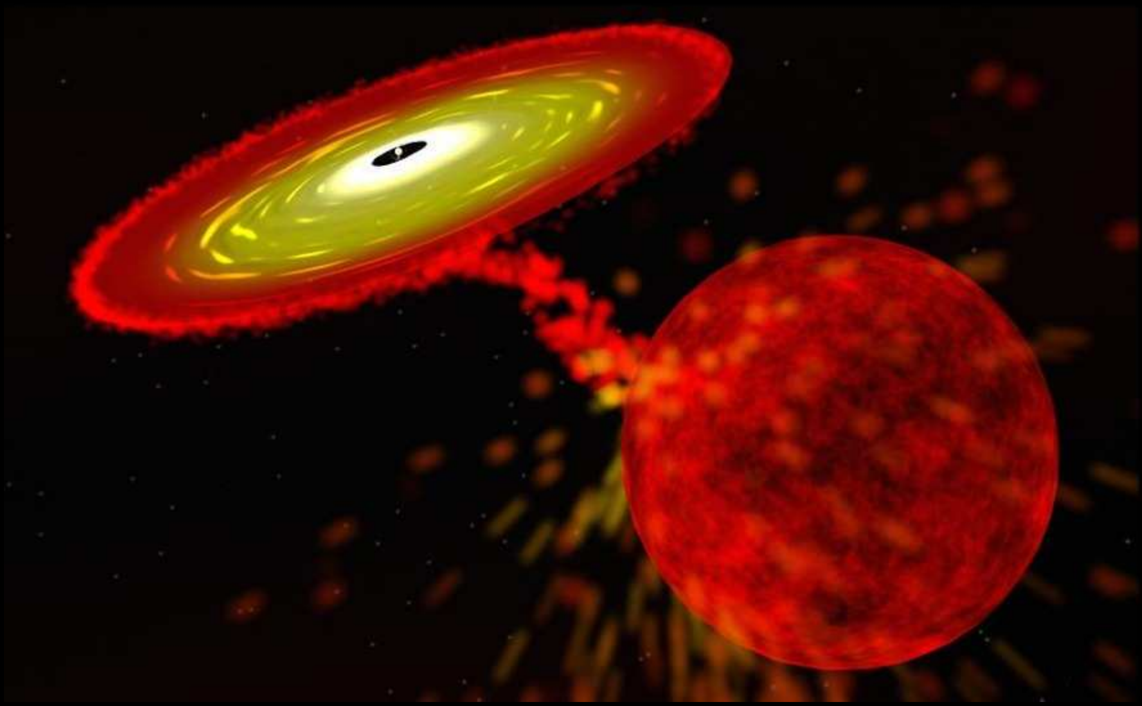
Three items dealt with here:

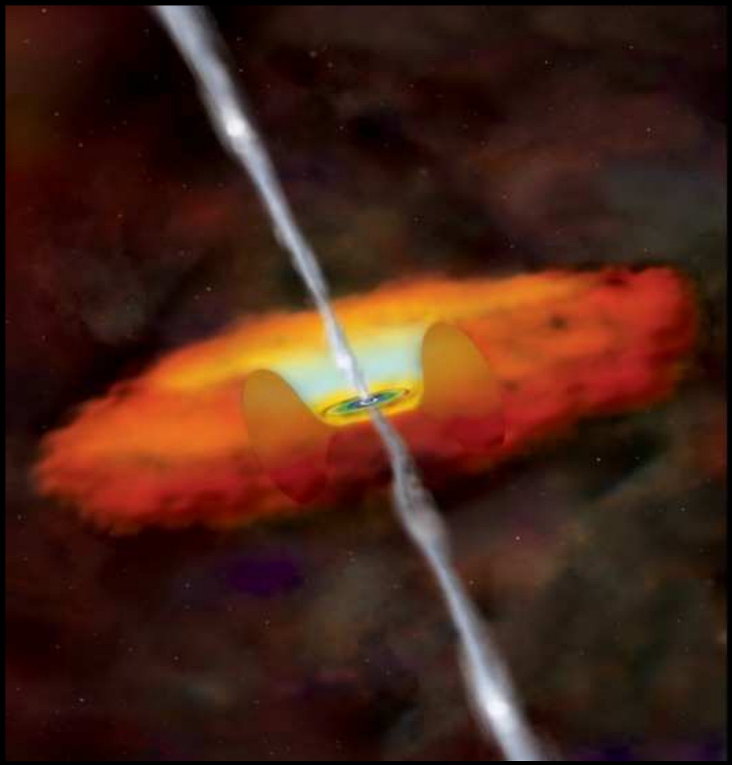
1. Testing General Relativity
2. Probing the Fastest Variablity
3. Studying the densest "normal matter"

. . . using examples drawn from IXO

V.L. Ginzburg: If the cosmological problem is the number one problem of astronomy, then problem number two should be the problem of black holes.

1. Testing General Relativity

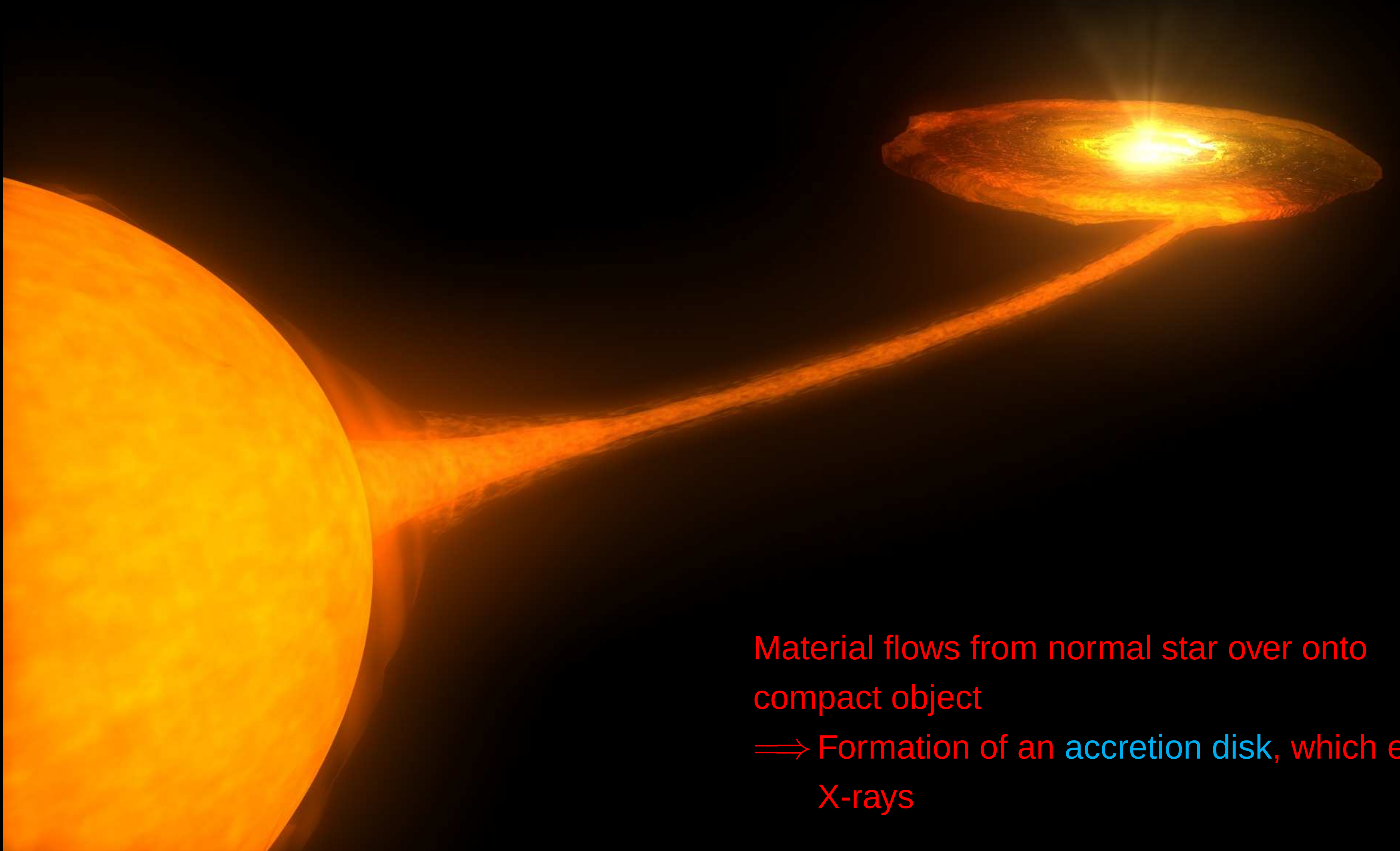




There are two flavors of accreting black holes:

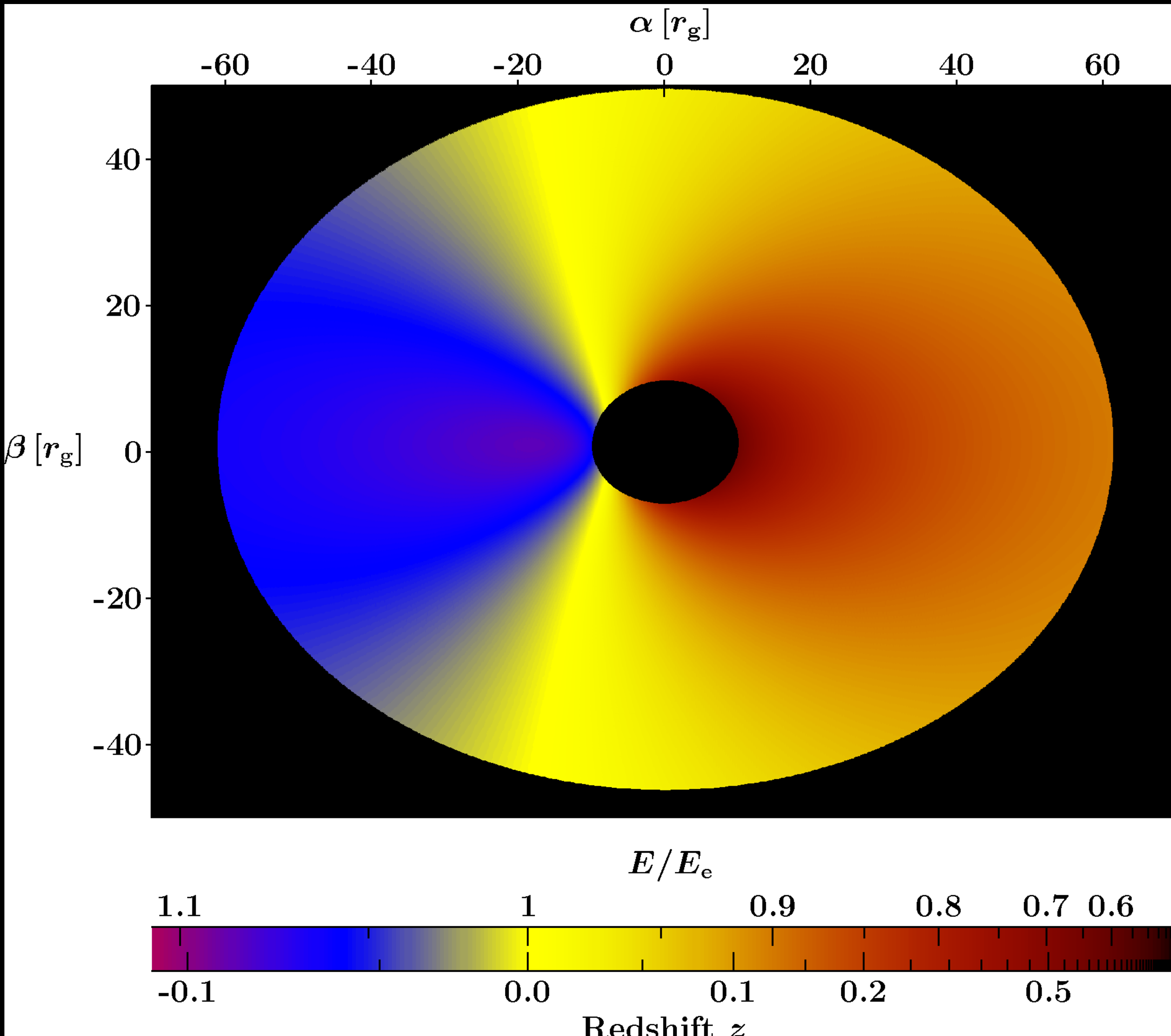
- Galactic BHs – few $M_\odot$
  long-term variability, accretion modes,. . .
- Supermassive BHs – $10^6 \ldots 10^8\, M_\odot$
  detailed studies on Kepler timescale possible

. . . since characteristic timescales and radii are $\propto M$

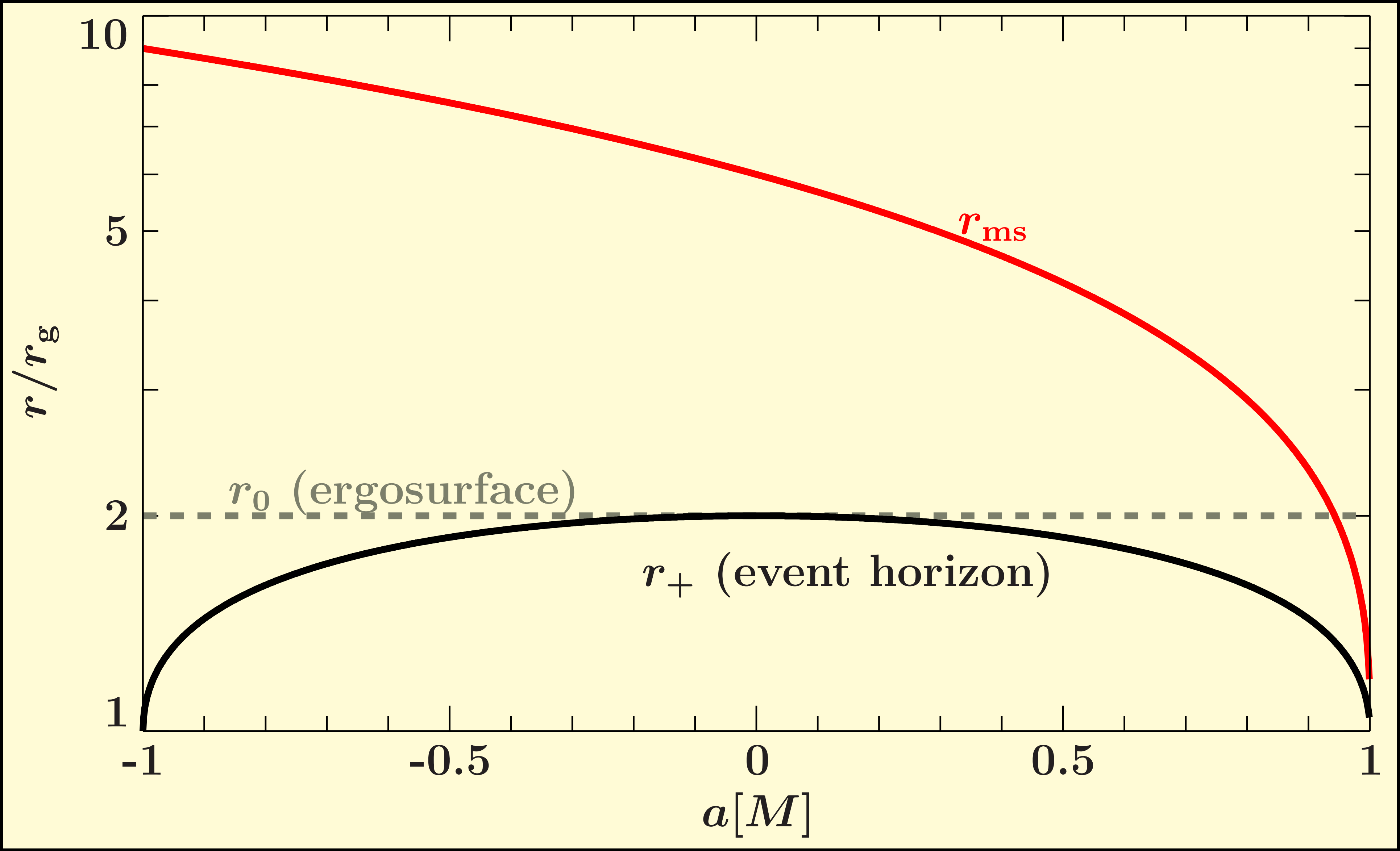


Material flows from normal star over onto compact object

$\Longrightarrow$ Formation of an accretion disk, which emits X-rays

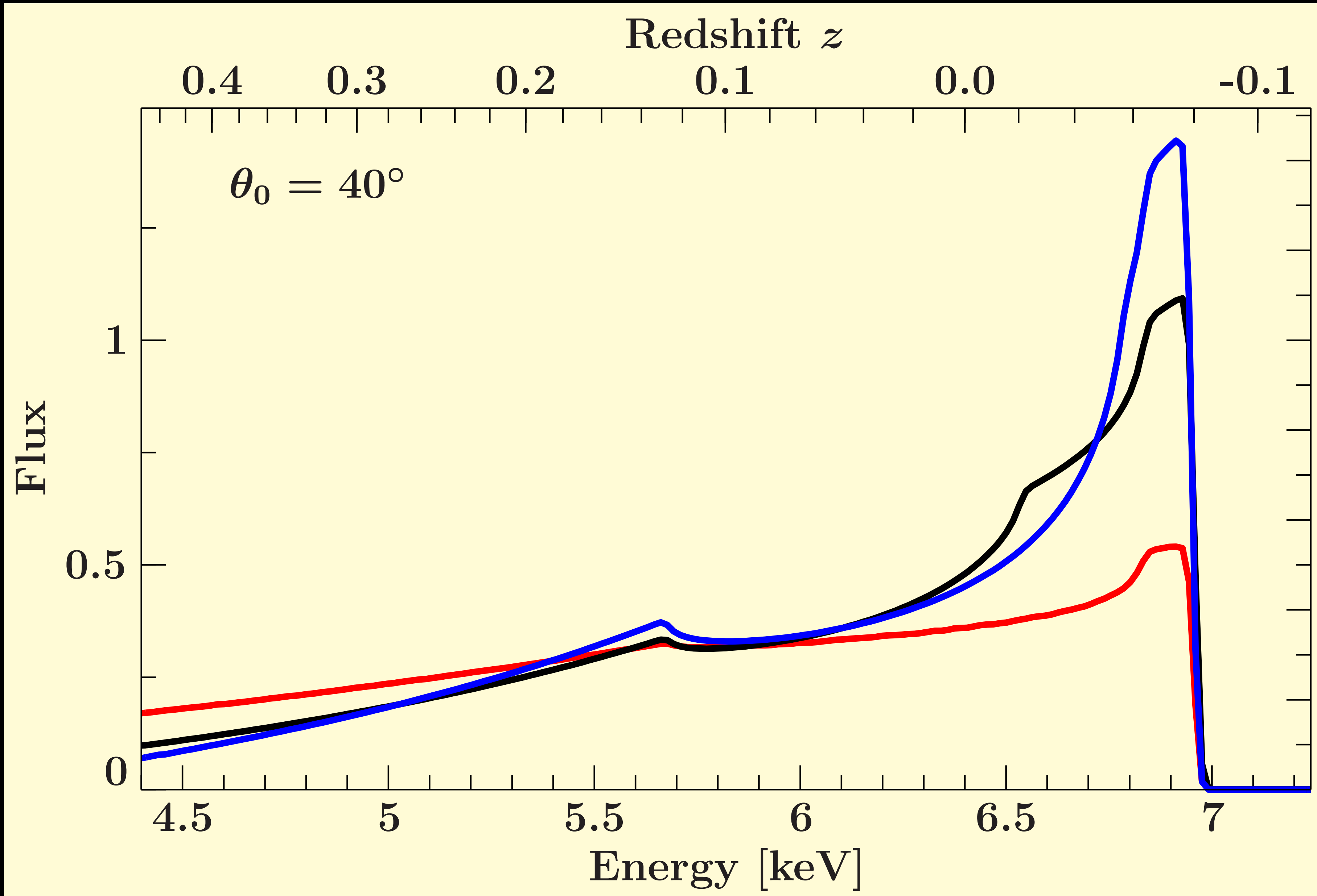


(Disk for $a = -1$, Dauser et al., submitted)



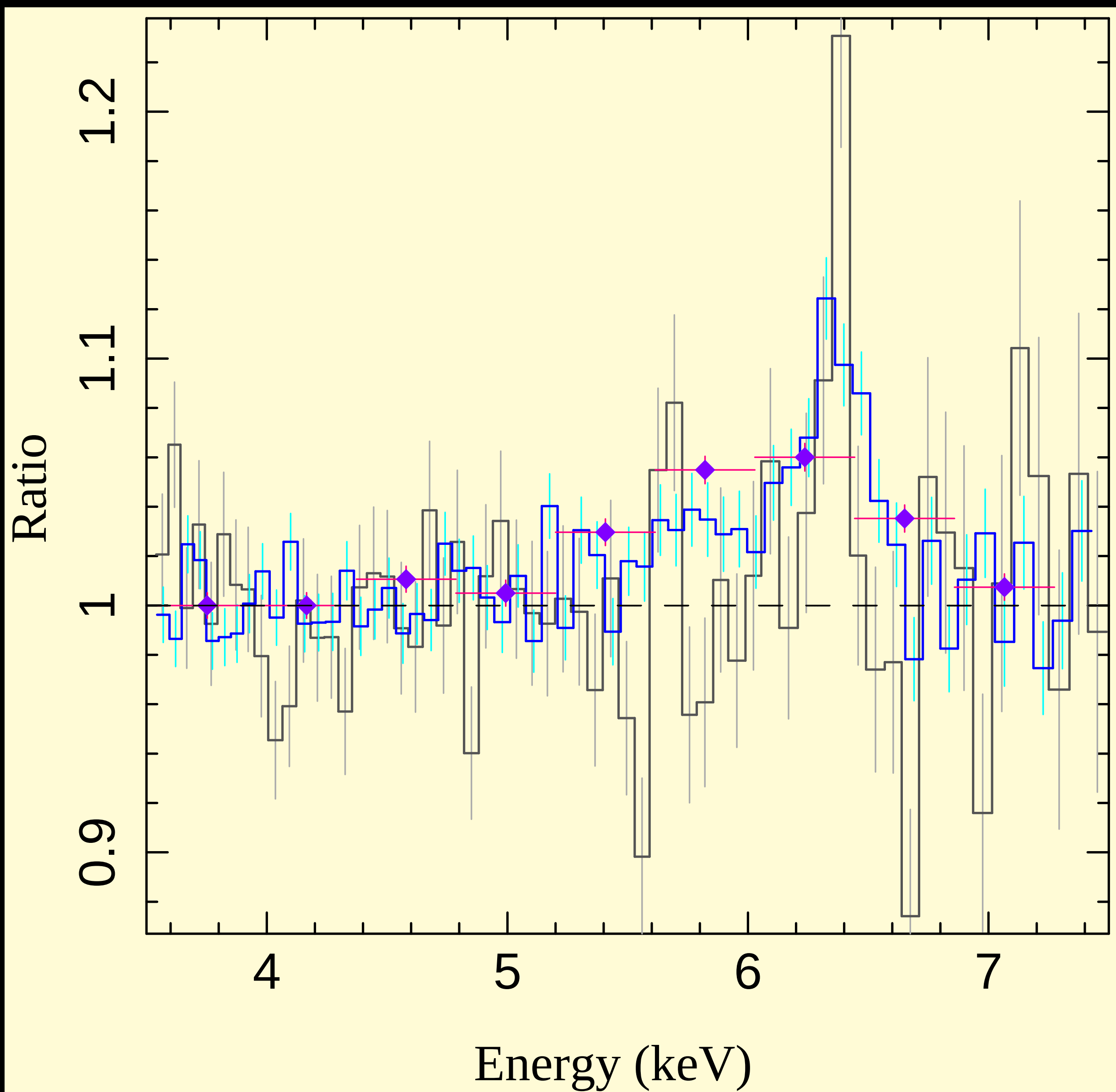
Dauser et al., submitted

Shape of relativistic Fe Kα lins is *the* tracer of geometry of accretion flow close to the black hole.



Dauser et al., submitted

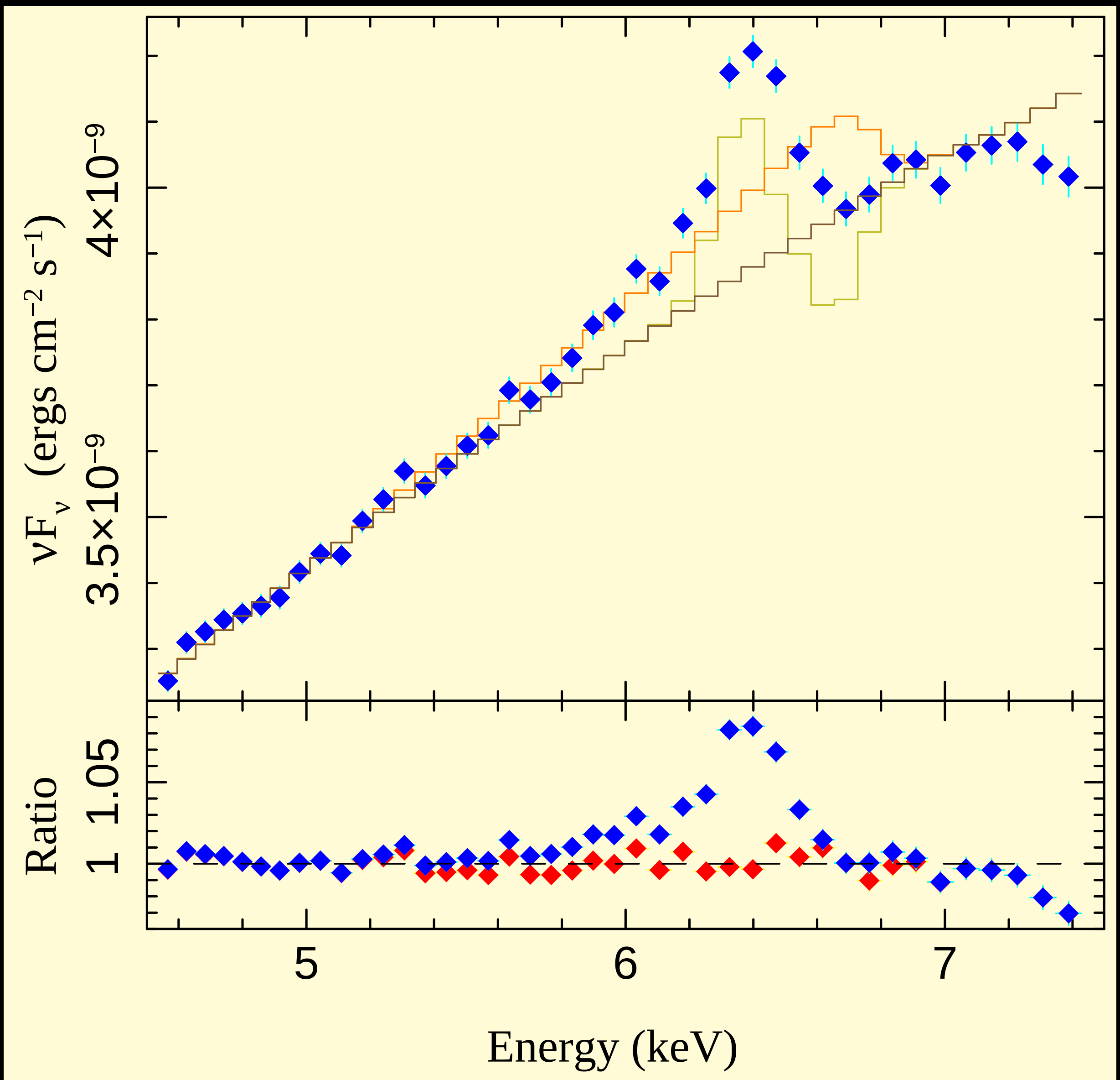
Shape of relativistic Fe Kα lins is *the* tracer of geometry of accretion flow close to the black hole.



In the hard and intermediate states, galactic black holes show strong and broad Fe Kα lines.

Cyg X-1: $a \sim 0$ (?), $i > 45^{\circ}$, $\epsilon \propto r^{-3}$ (see Fritz, PhD Tübingen)

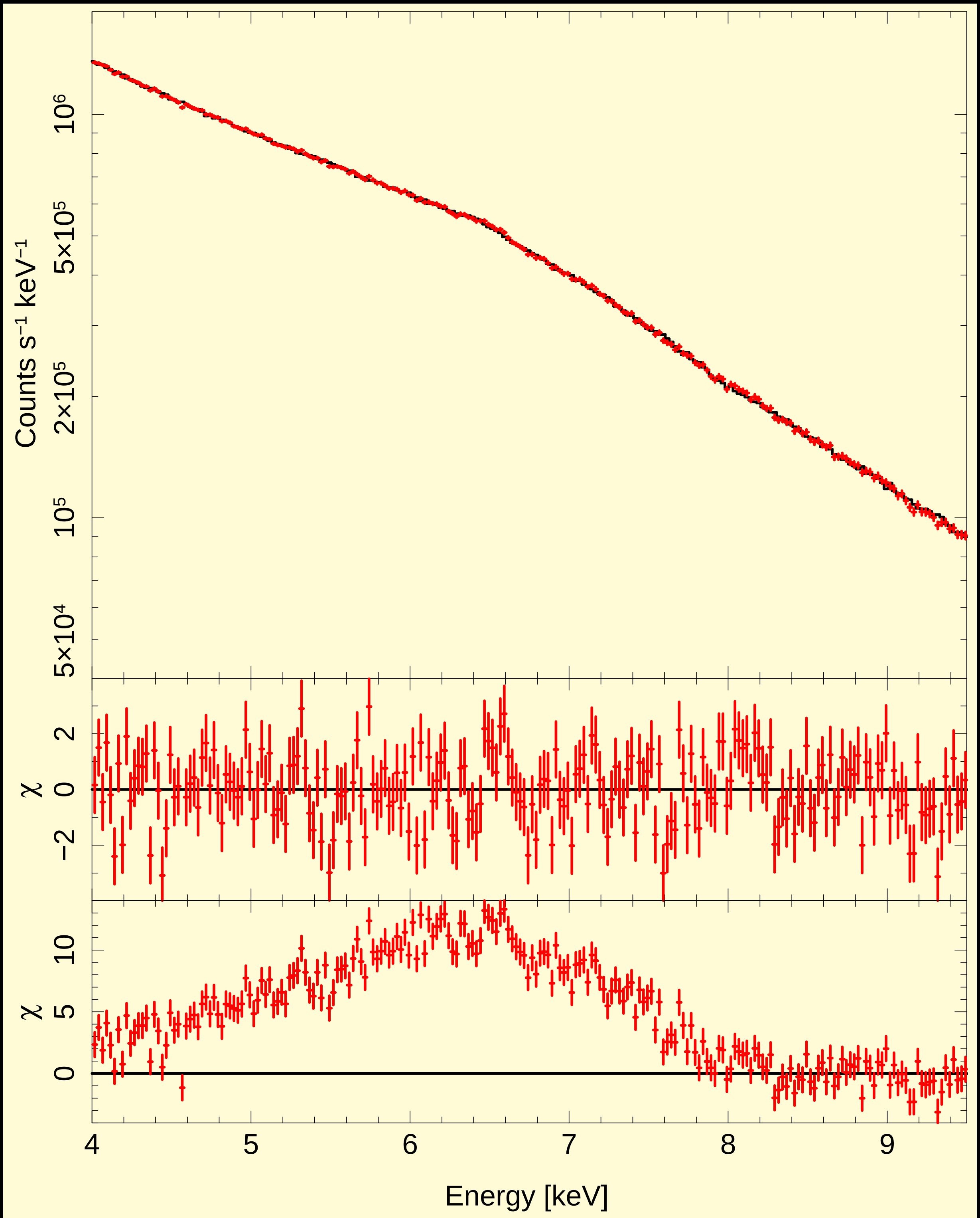
Nowak et al. (2010, submitted)



In the hard and intermediate states, galactic black holes show strong and broad Fe Kα lines.

Cyg X-1: $a \sim 0$ (?), $i > 45^\circ$,
$\epsilon \propto r^{-3}$ (see Fritz, PhD Tübingen)

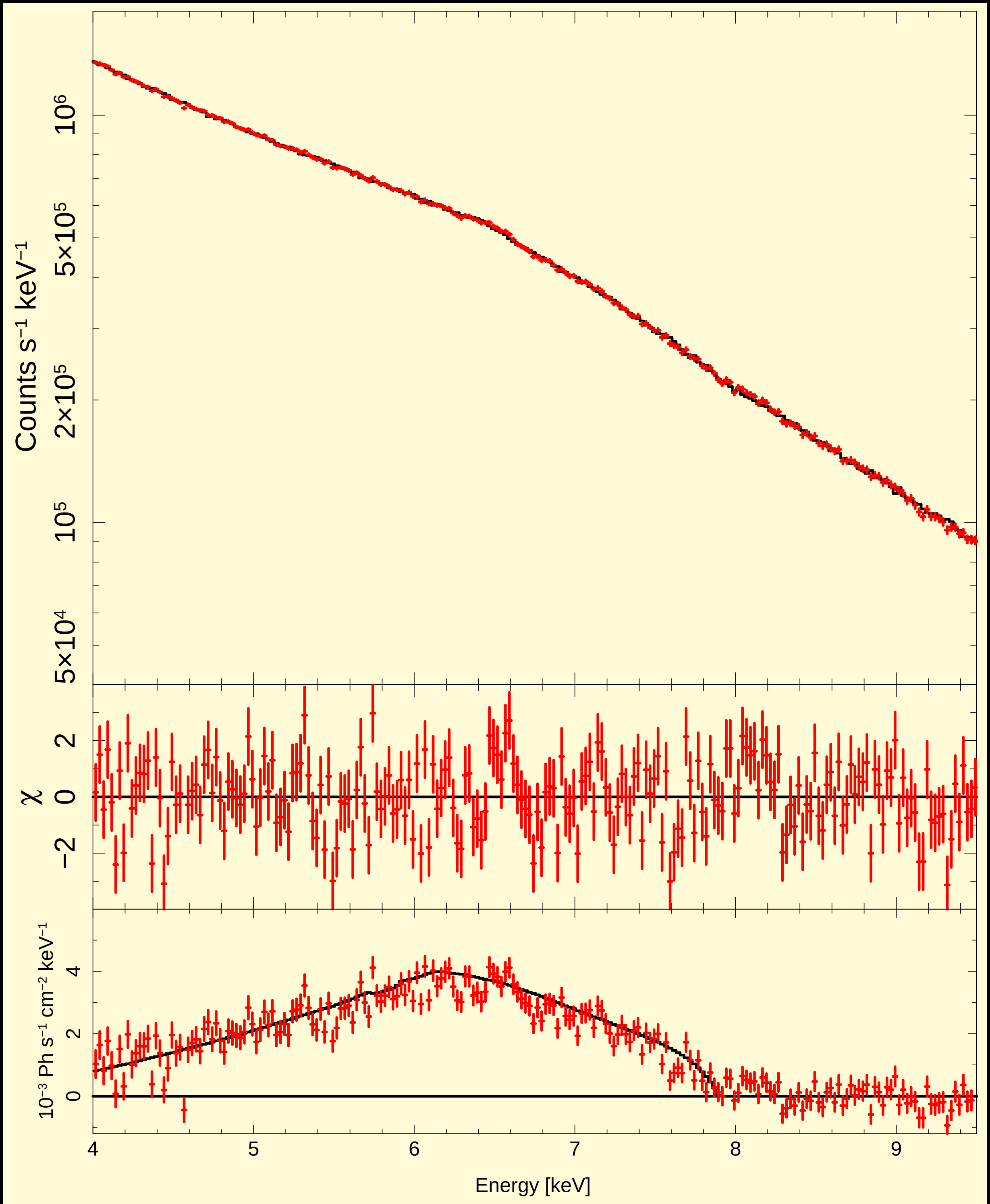
Nowak et al. (2010, submitted)



In the hard and intermediate states, galactic black holes show strong and broad Fe Kα lines.

Cyg X-1: $a \sim 0$ (?), $i > 45^\circ$, $\epsilon \propto r^{-3}$ (see Fritz, PhD Tübingen)

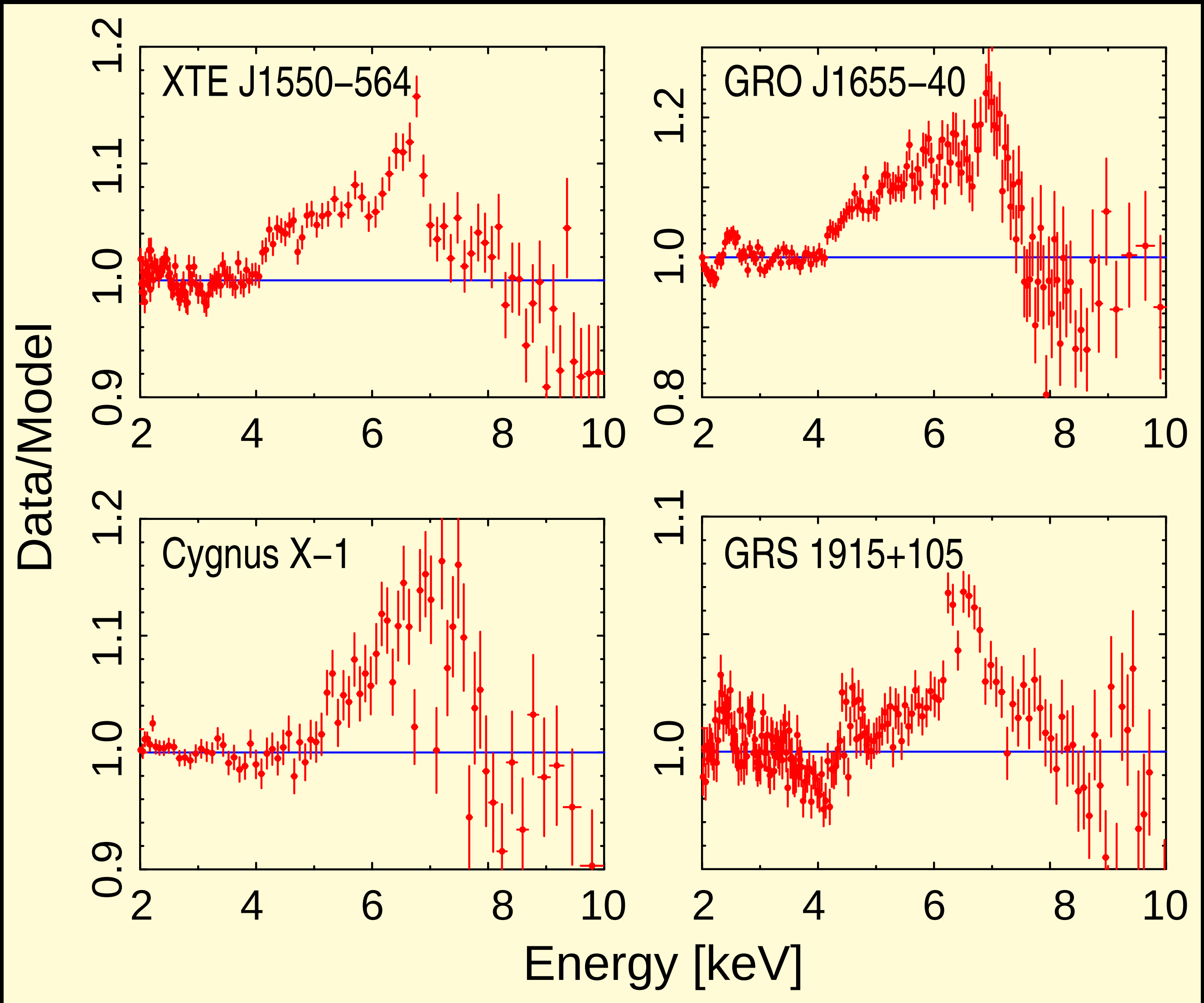
Duro et al. (2010, to be submitted)



In the hard and intermediate states, galactic black holes show strong and broad Fe Kα lines.

Cyg X-1: $a \sim 0$ (?), $i > 45^\circ$,
$\epsilon \propto r^{-3}$ (see Fritz, PhD Tübingen)

Duro et al. (2010, to be submitted)

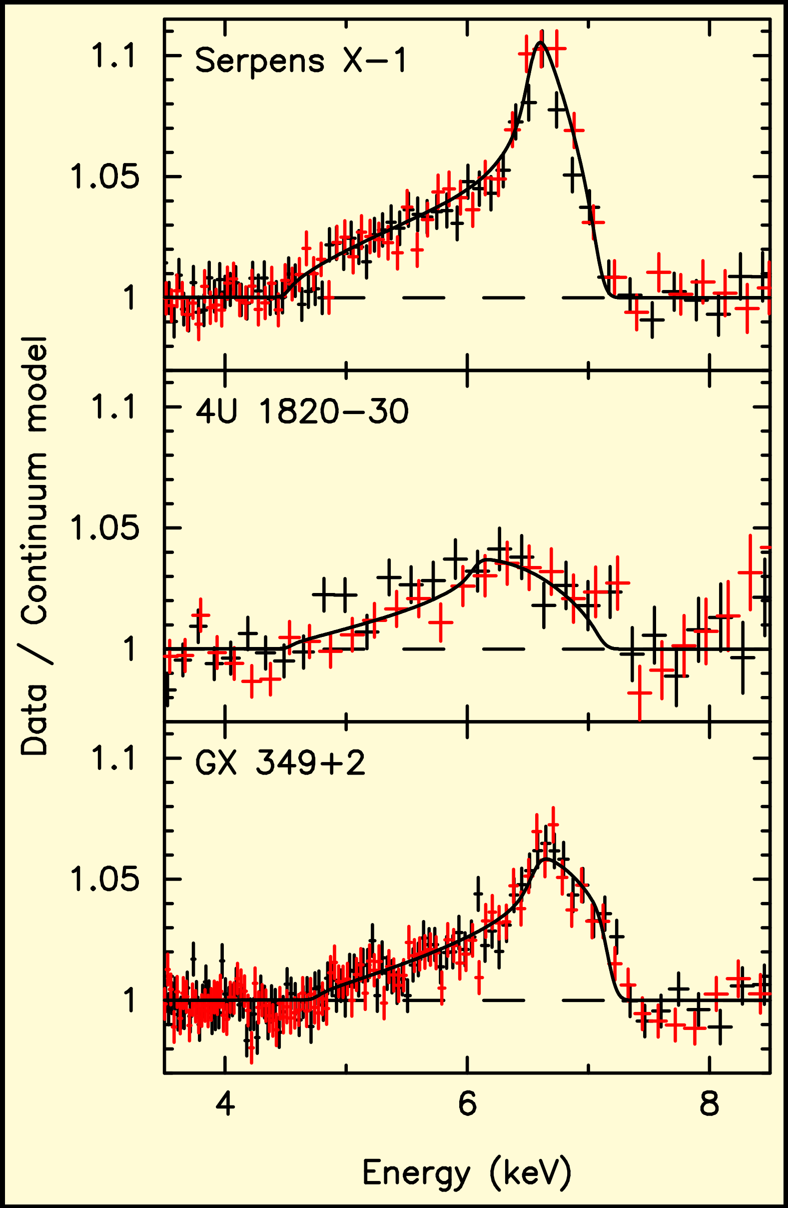


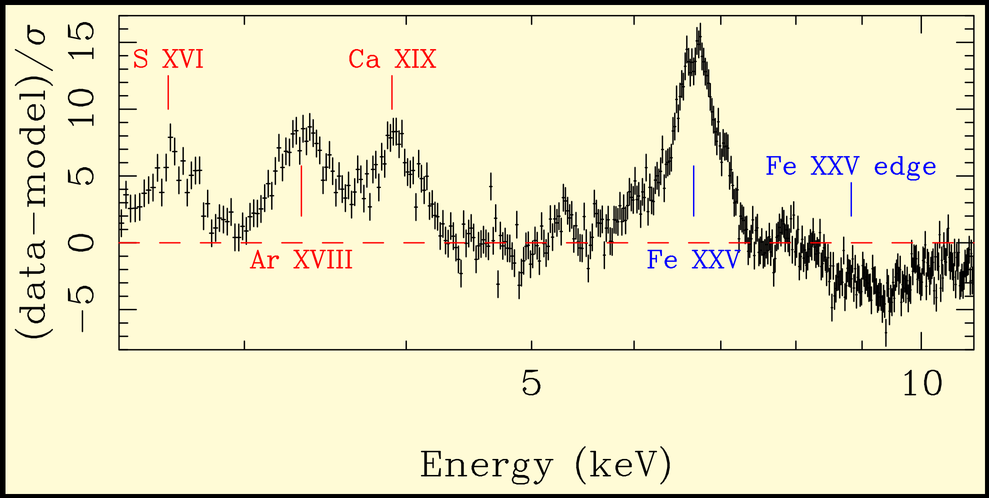
Relativistic lines are also seen in many Galactic Black Holes

- GX 339−4: Nowak et al. (2002); Miller et al. (2004); Caballero-García et al. (2009)
- GRO J1655−40: Bałucińska-Church & Church (2000)
- Cyg X-1: Miller et al. (2002); Fritz et al. (2006)
- XTE J1650−500: Miller et al. (2002)

. . . and many more more (see Miller et al. 2009)

(*ASCA*; after Miller 2007)



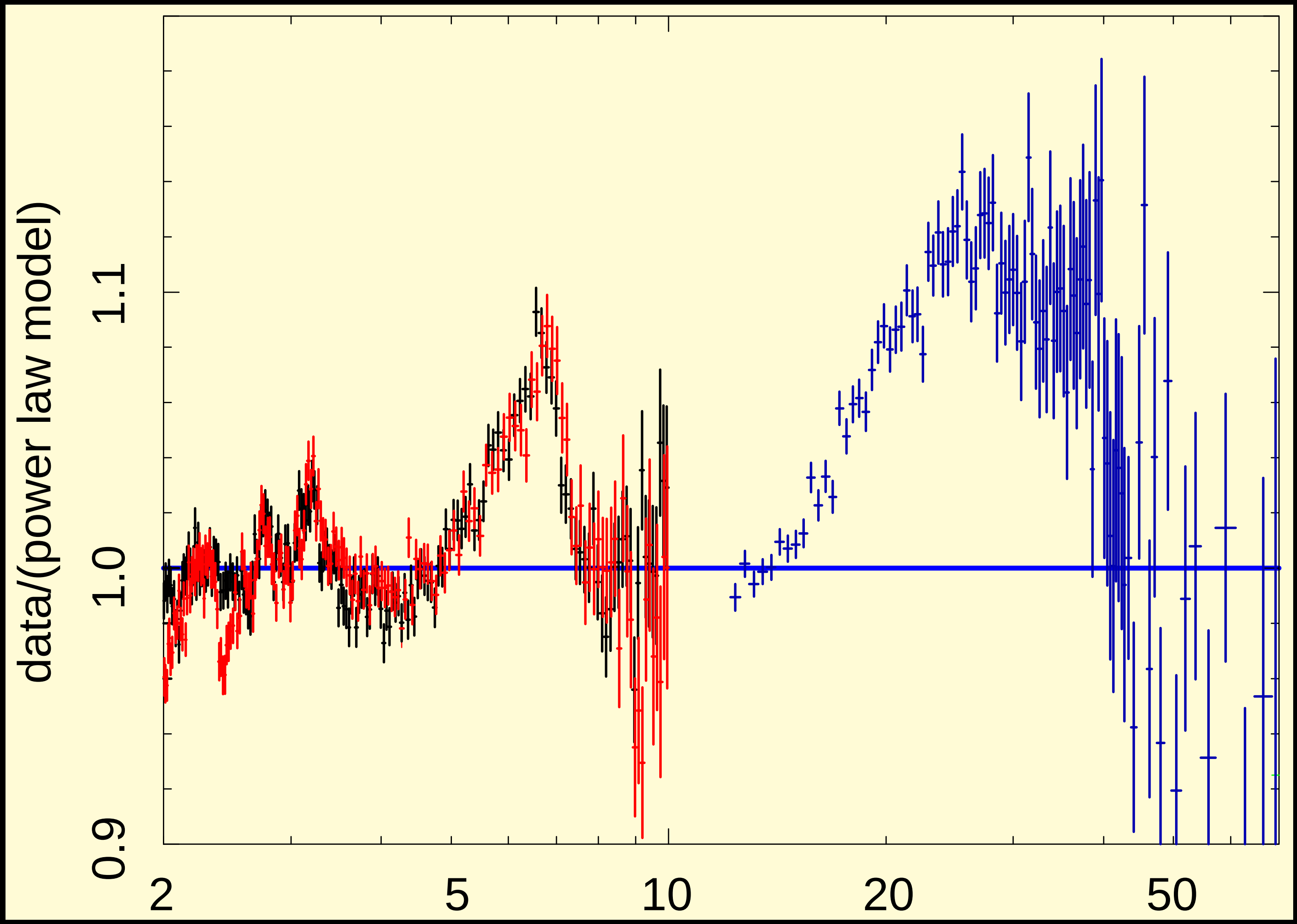


(4U 1705−44, *XMM-Newton*; di Salvo et al., 2009)

Neutron Star X-ray Binaries also seem to have broad lines

But not all NSs show broad lines (2 out of 6 in sample of Cackett et al. 2009) – ionization effect?

(Suzaku; Cackett et al., 2008)



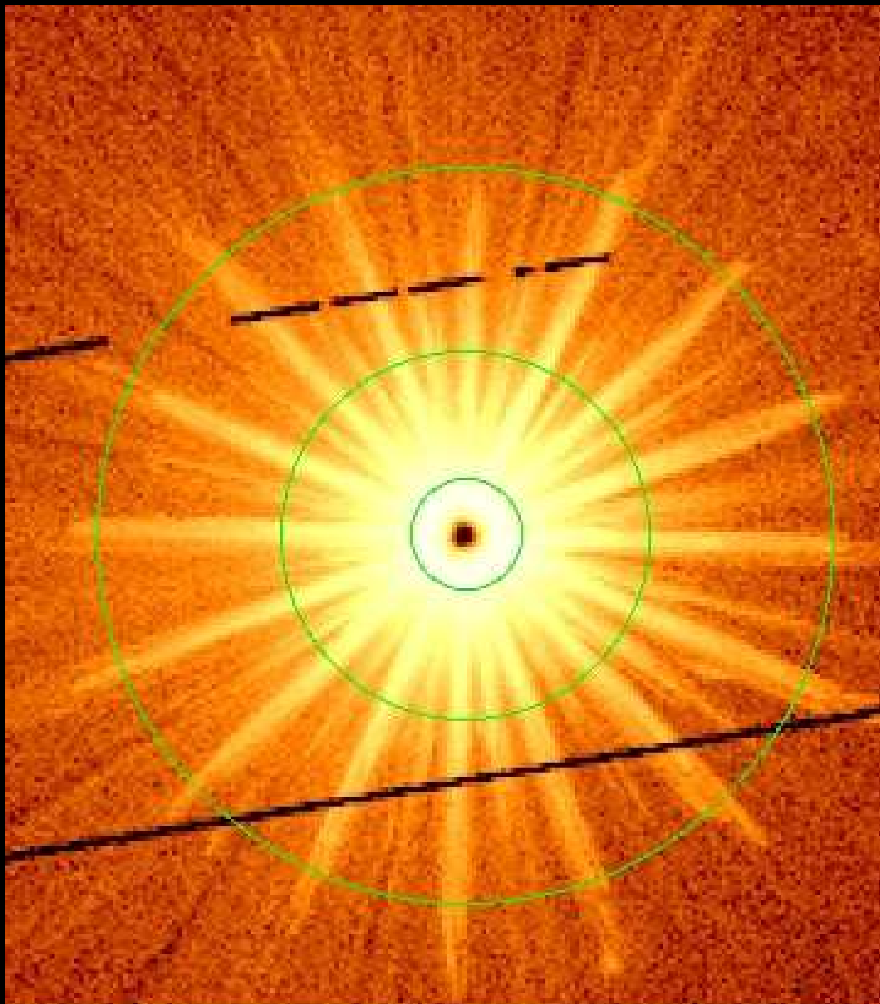
(GX 339−4; Suzaku Miller et al., 2008)

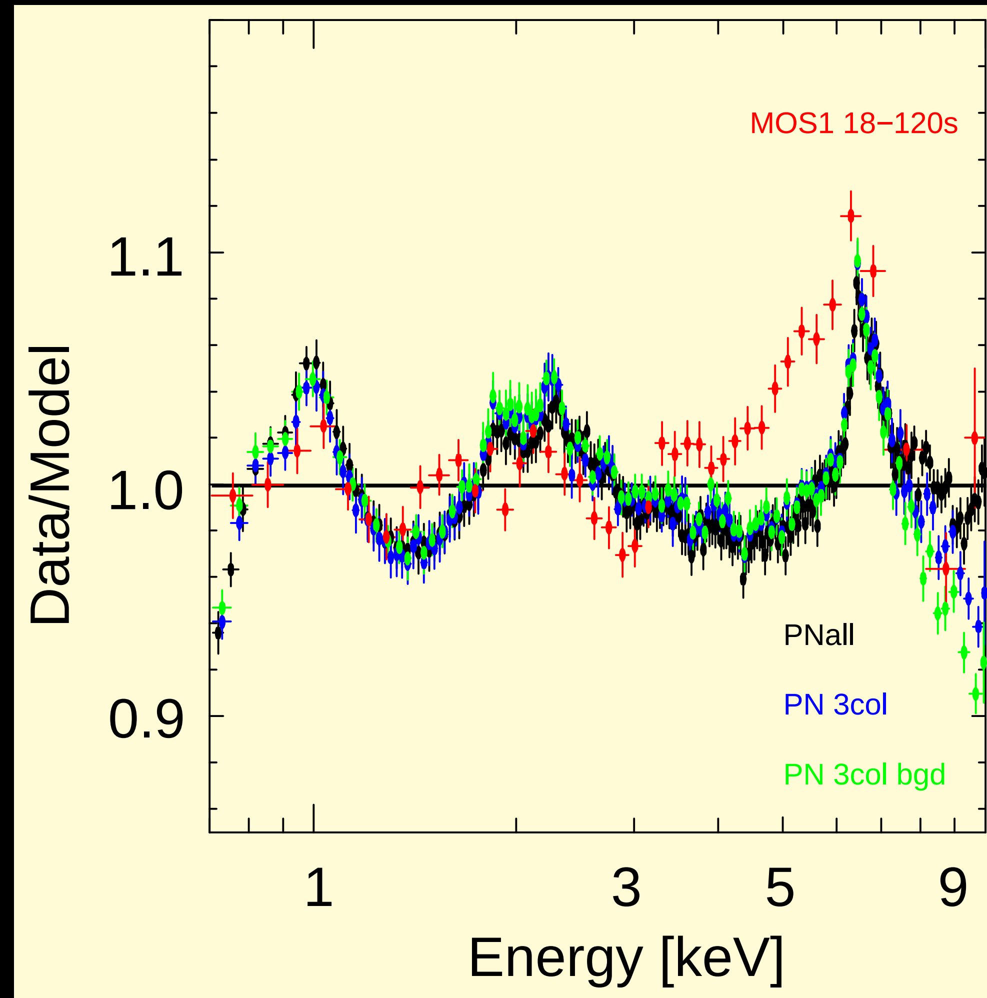
Broad-band data $\Longrightarrow$ can try to measure black hole angular momentum.

E.g., GX 339−4: Suzaku: $a = 0.89 \pm 0.04$ (Miller et al., 2008),

XMM-Newton: $a = 0.93 \pm 0.01$ (Miller et al., 2004)

Warning: Uncertainties do not take into account systematic uncertainty in continuum modeling or detector effects!



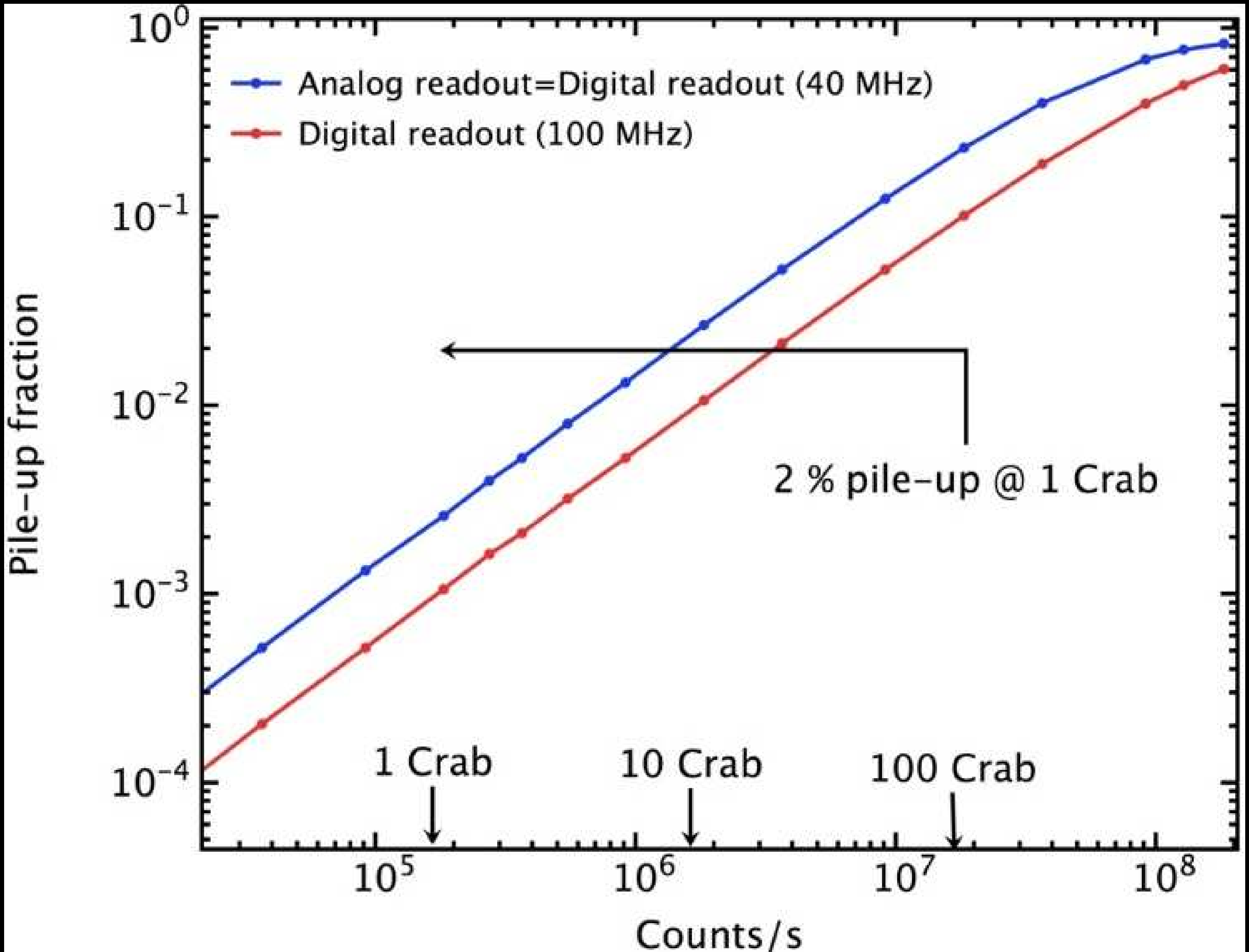


(Done & Díaz Trigo, 2009)

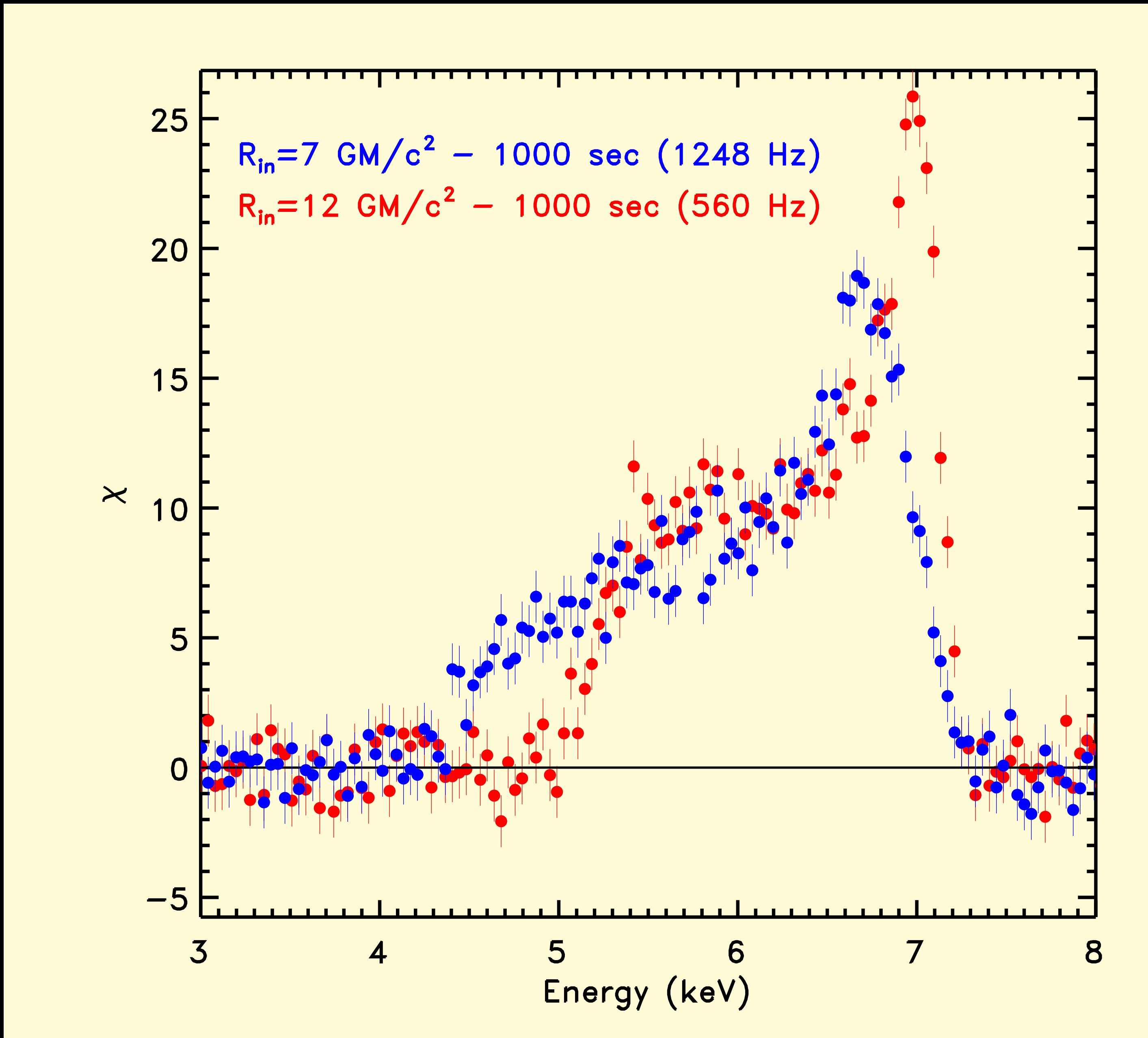
But beware: bright source effects in detectors can affect the line shape!

(Yamada et al., 2009; Done & Díaz Trigo, 2009)

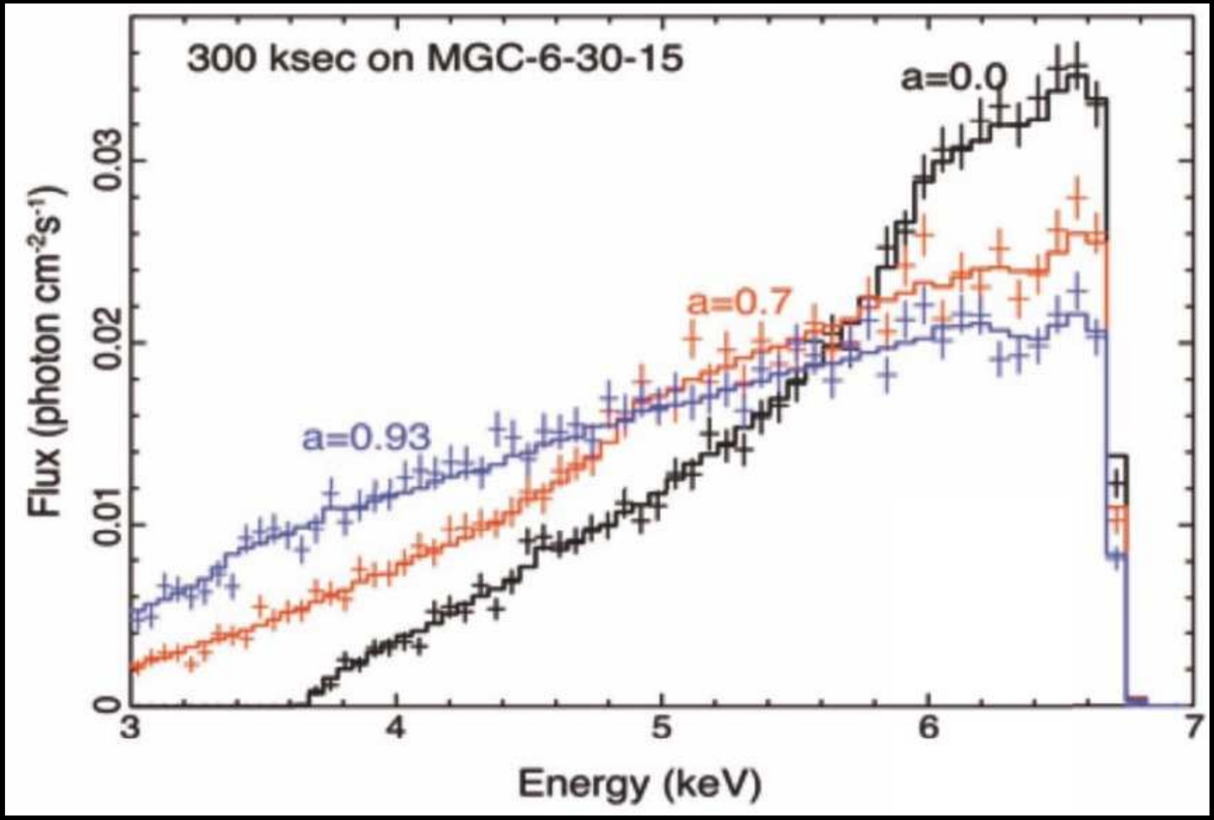
Pileup effects, background subtraction,. . .



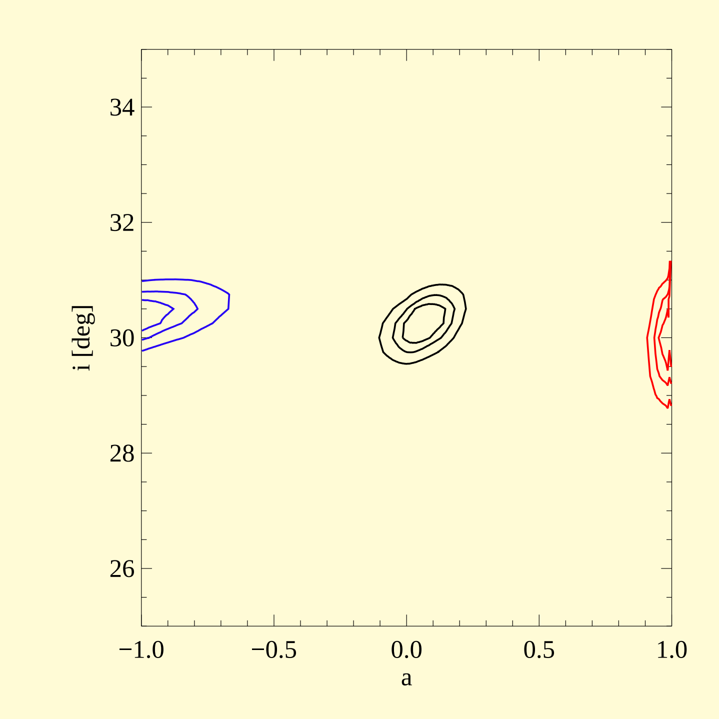
(M. Martin, E. Kendziorra [IAAT], C. Schmid, J. Wilms [ECAP])



HTRS will allow to measure relativistic lines without danger of pile up.

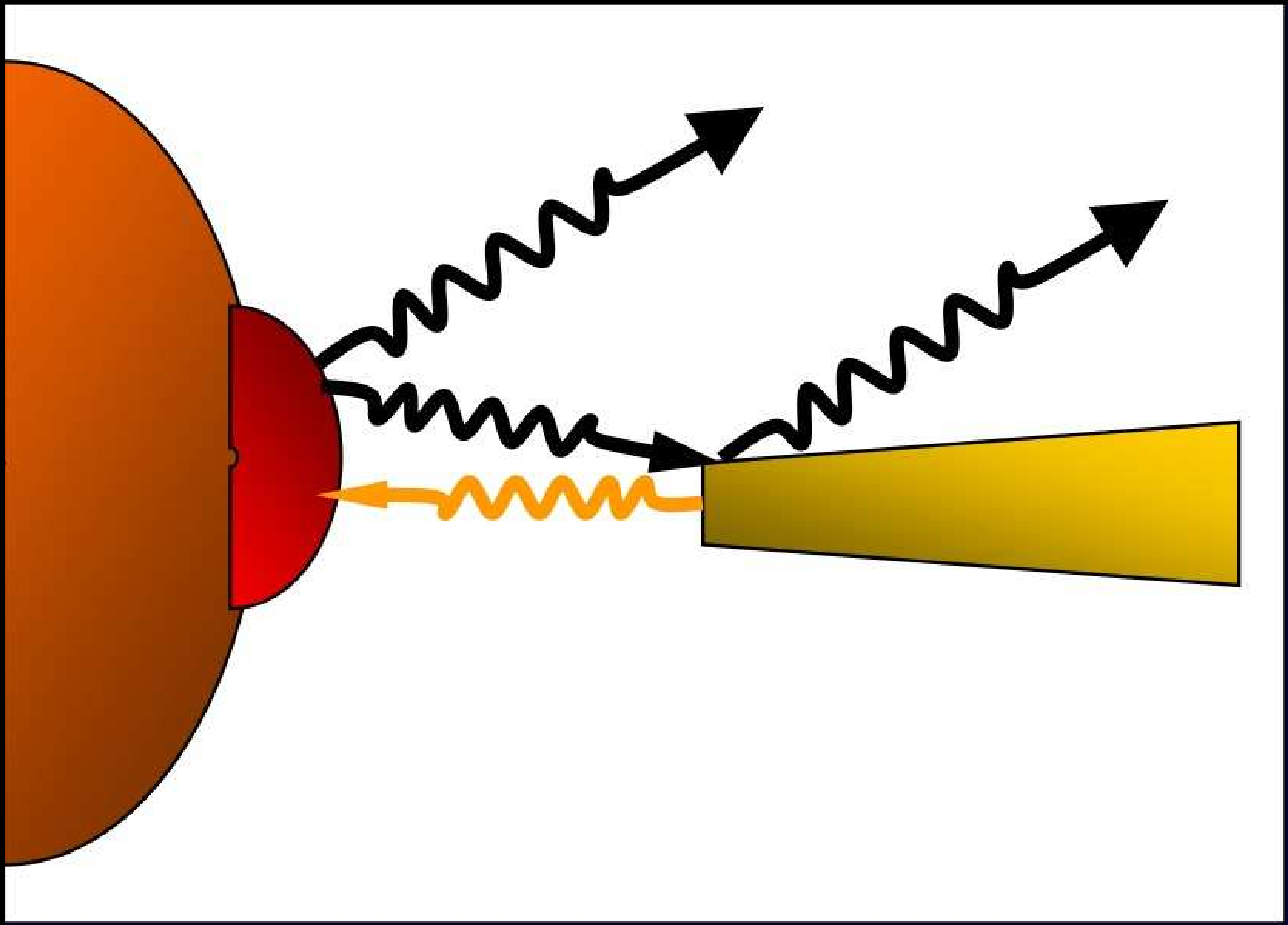


IXO-WFI will deliver complementary spins for AGN



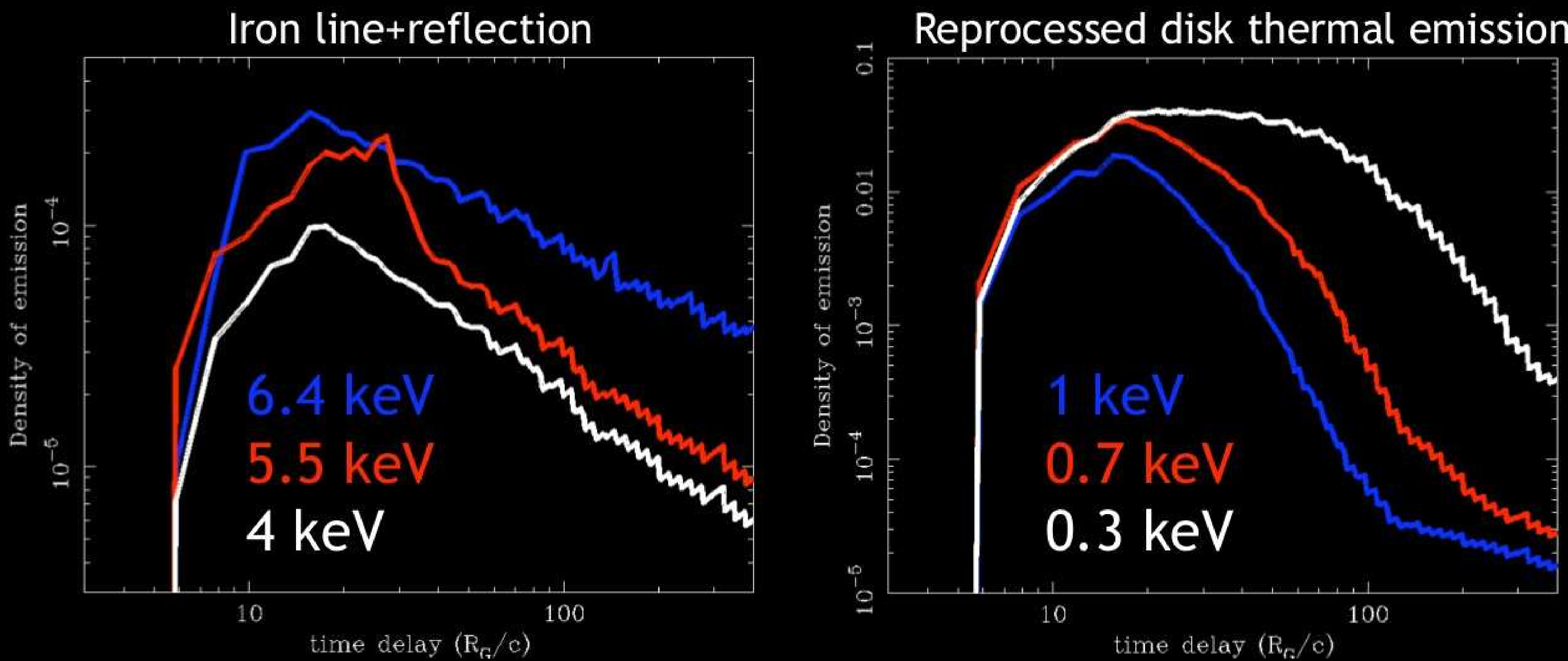
IXO-WFI simulations for MCG−6-30-15, 50 ksec

2. Probing the Fastest Signals

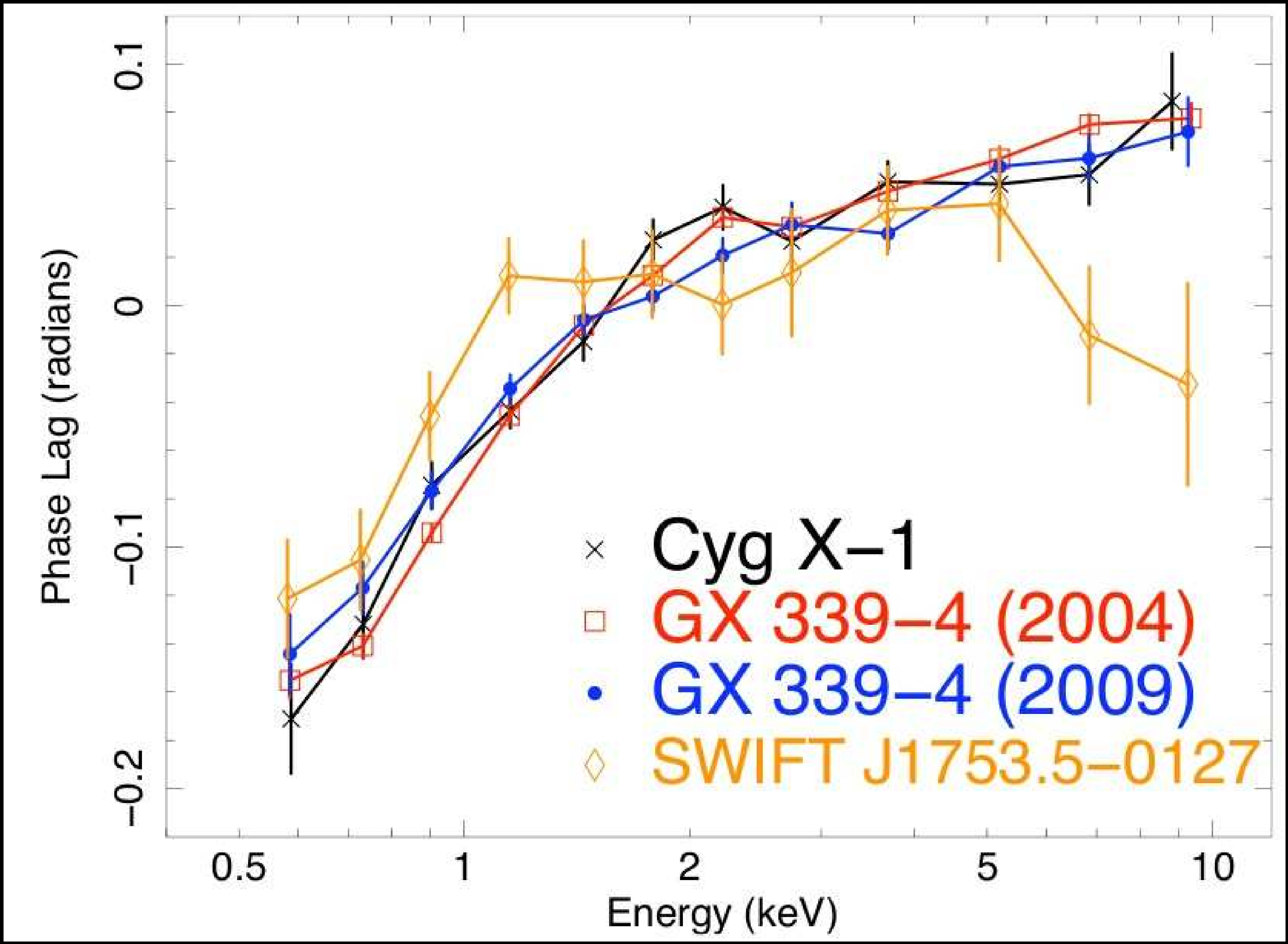


(Uttley et al., 2010)

Reprocessing of X-rays leads to X-ray time lags

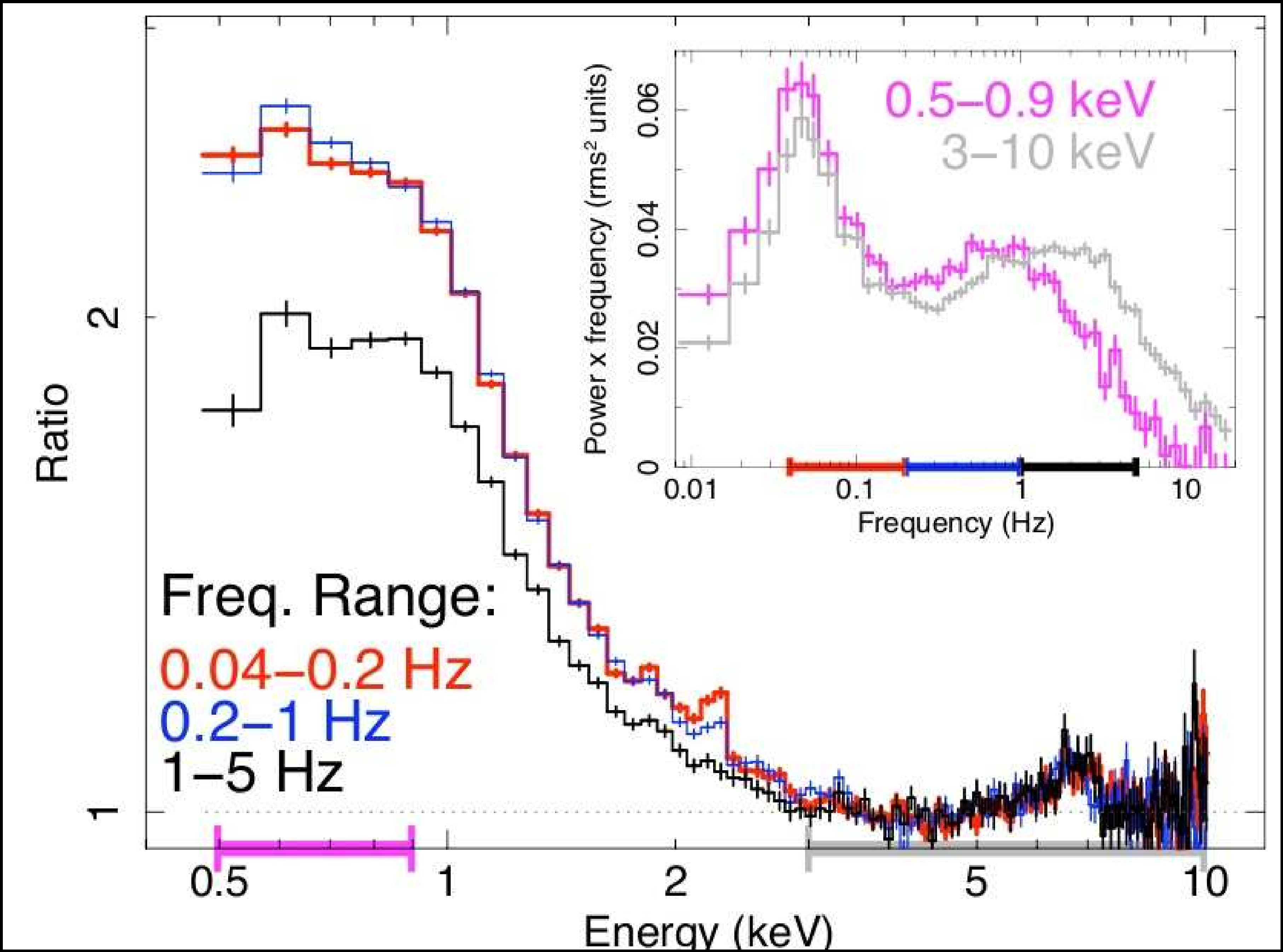


Different spectral components have different time response



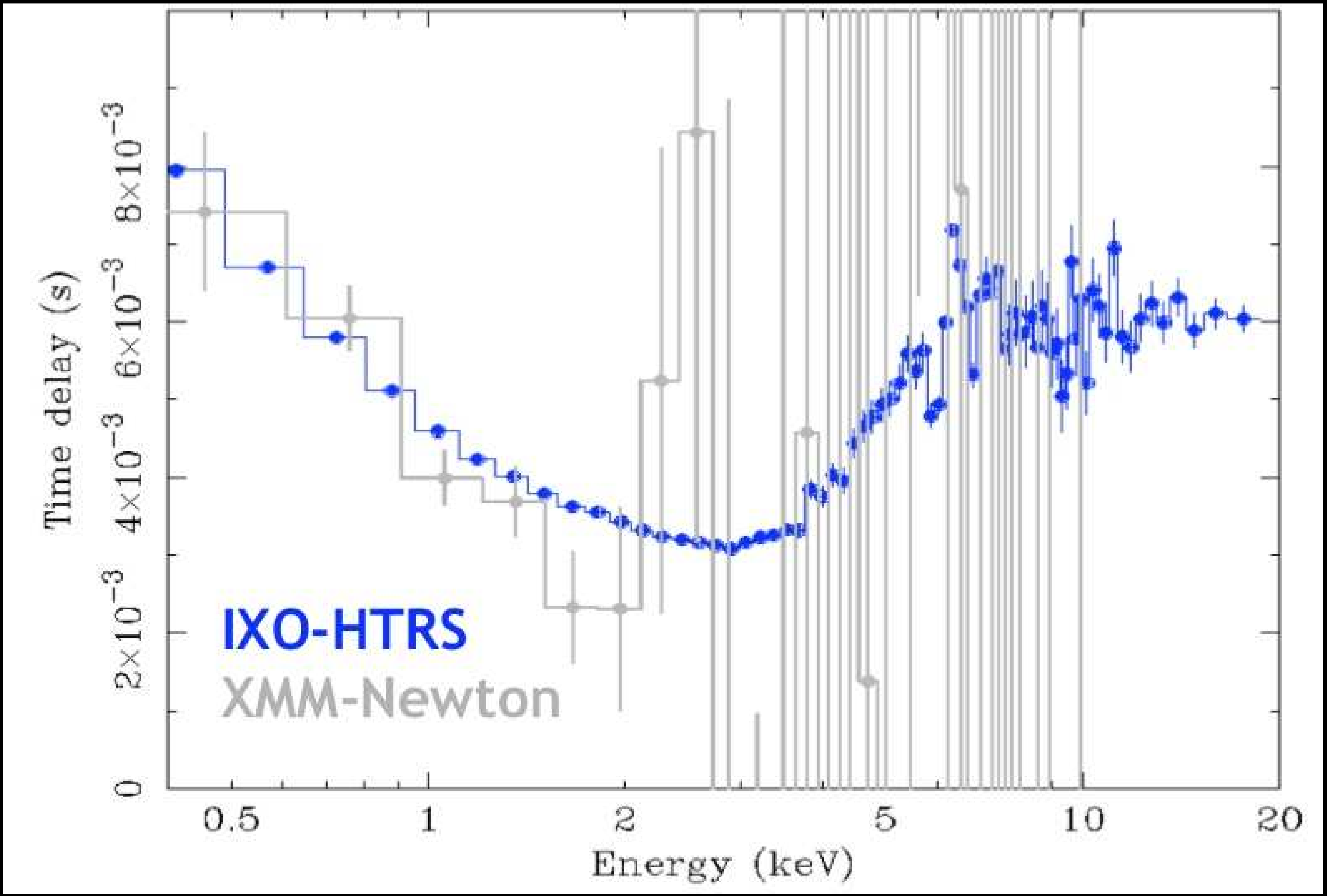
(Uttley et al., 2010, submitted)

XMM-Newton data show that disk leads reprocessed radiation



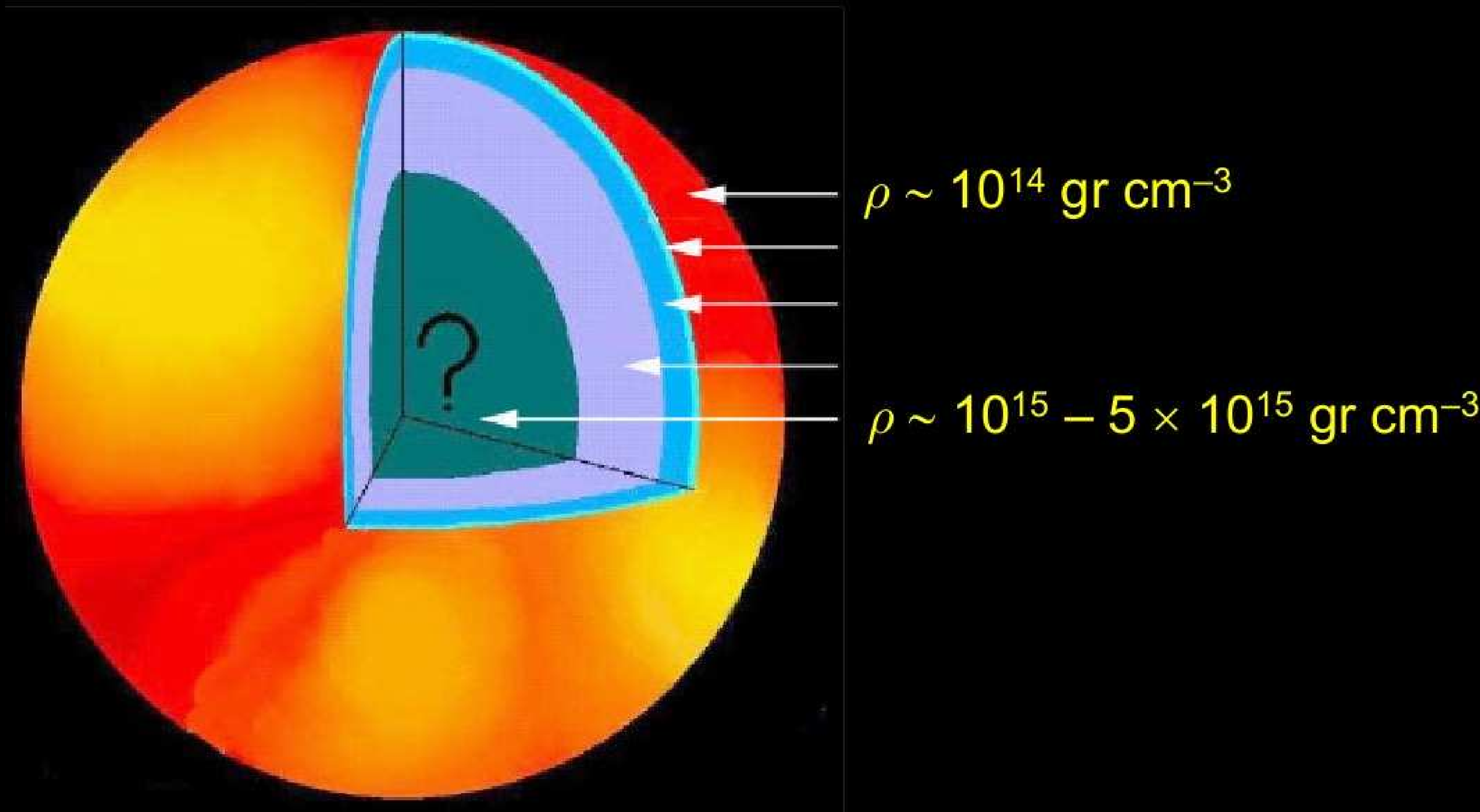
(Uttley et al., 2010, submitted)

XMM-Newton data show that disk leads reprocessed radiation



IXO-HTRS will allow high precision reverberation measurements

3. Studying the densest “normal matter”



$\rho \sim 10^{14}$ gr cm^{-3}
?
$\rho \sim 10^{15} - 5 \times 10^{15}$ gr cm^{-3}

How do we determine the structure of a neutron star?

1. Use hydrostatic equilibrium and mass conservation in General Relativity:

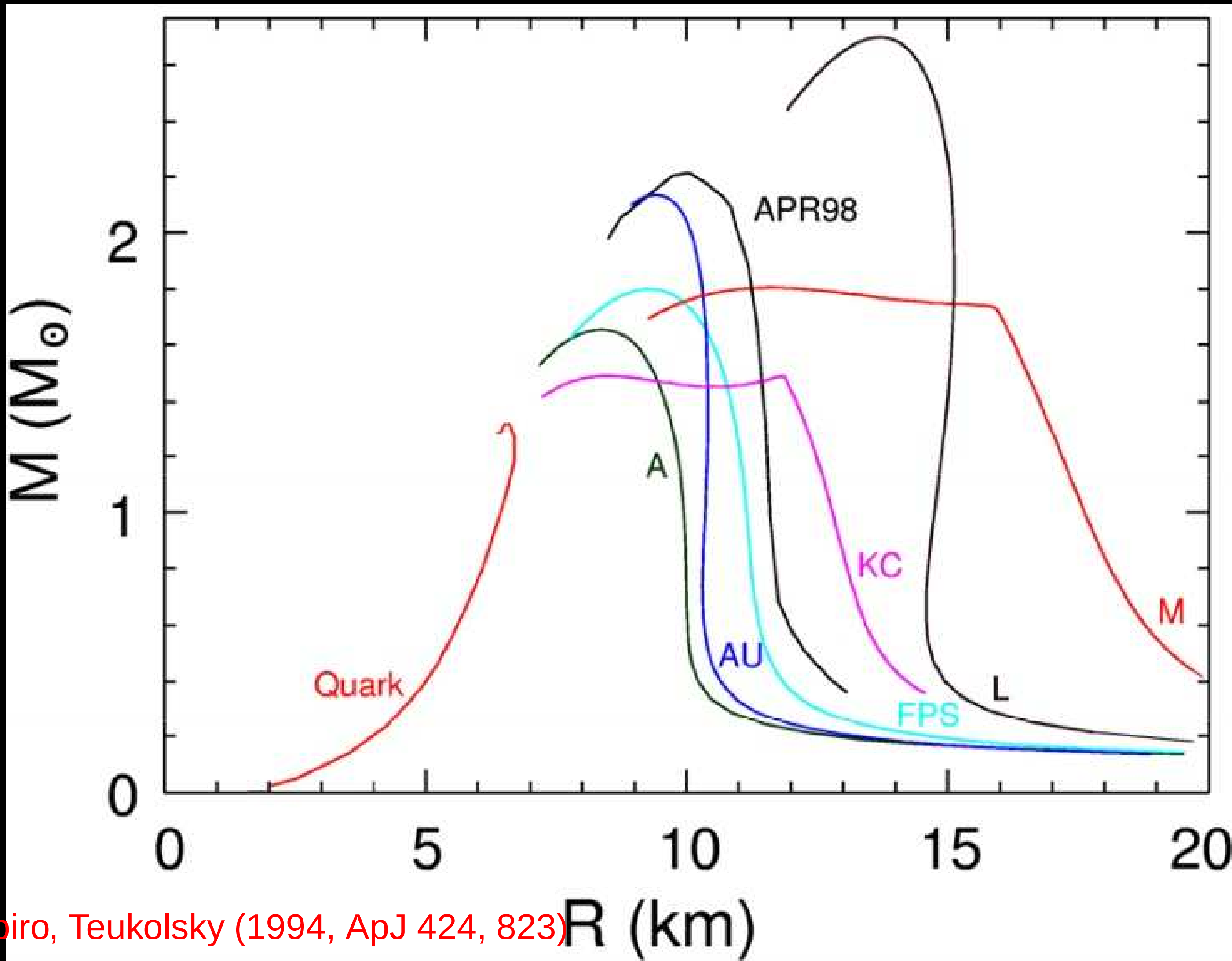
$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2GM}{c^2 r}\right)^{-1}$$
$$\frac{dm}{dr} = 4\pi r^2 \rho$$

2. Assume equation of state, i.e., prescription of relation between pressure and density,

$$P = P(\rho, \text{[other parameters]})$$

3. Integrate from $P(r=0) = P_c$ to $P = 0$, to obtain M and R

For each EoS, gives family of solutions as function of initial condition $P = P_c$.

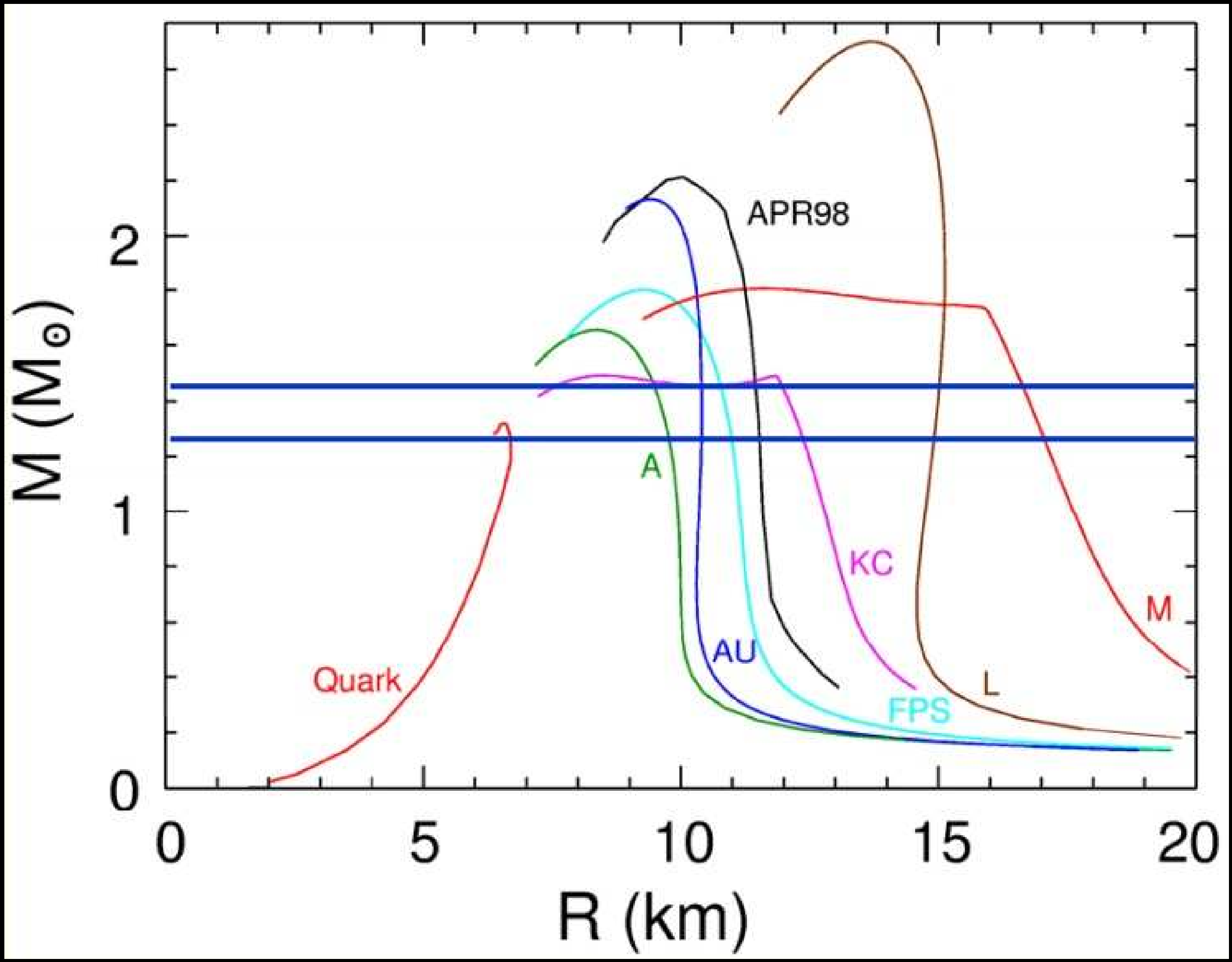


after Cook, Shapiro, Teukolsky (1994, ApJ 424, 823)

Equation of State: Dominated by (unknown) nuclear equation of state

Problems: trans. 50% protons to 0% protons, QCD condensates, quarks,. . .

Knowledge of EoS important for particle physics and astrophysics (SN explosions, NS-NS-mergers [progenitors of short GRBs, sources of gravitational waves])



Pulsars in binaries:

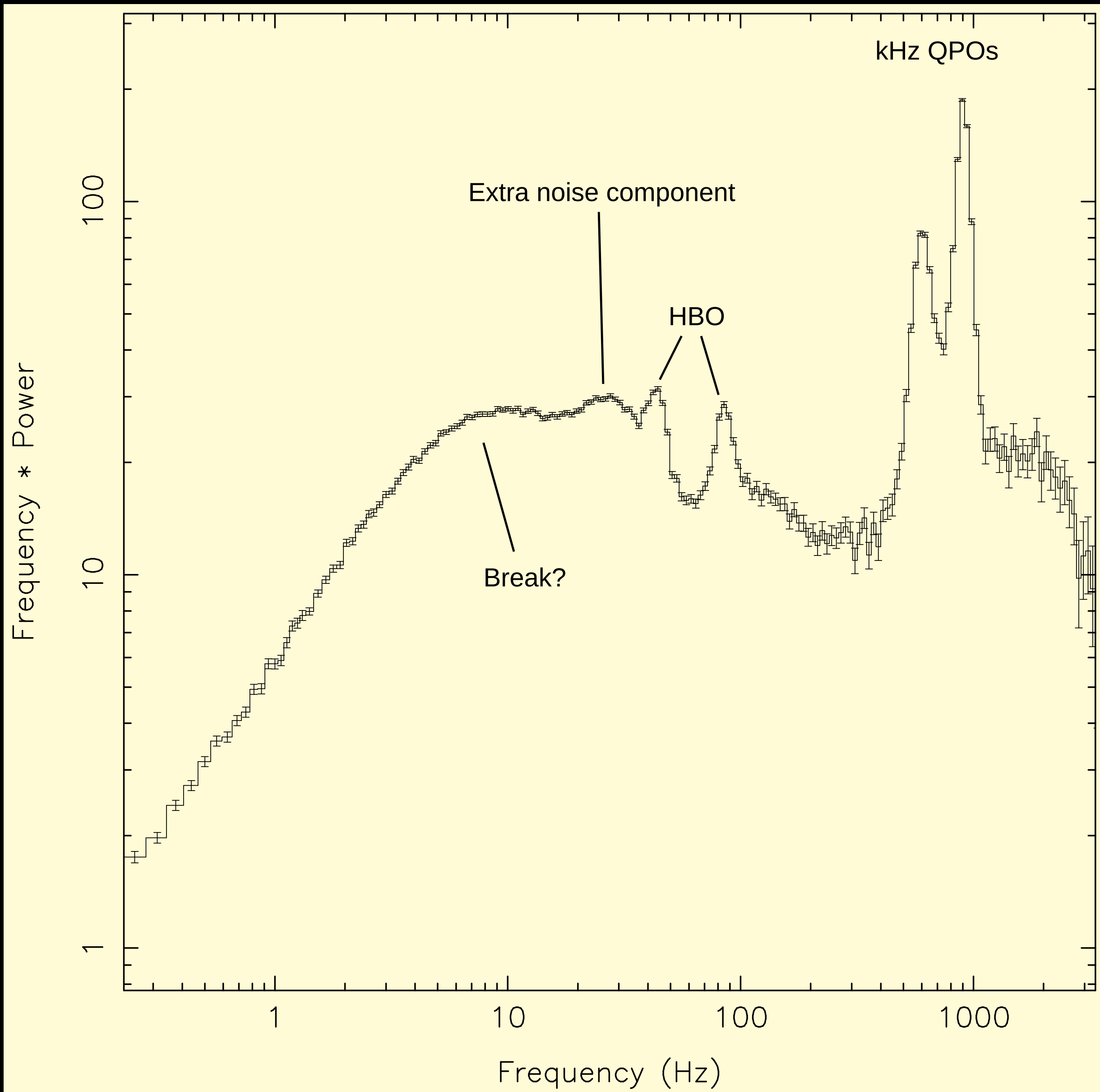
$$\langle M \rangle = 1.35(4)\, M_\odot$$

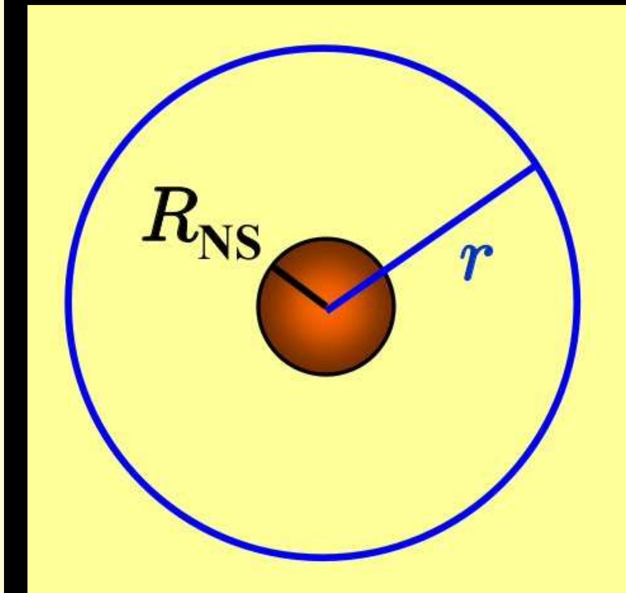
Not enough $\Longrightarrow$ need radius or any combination of M and R

Ways to measure combinations of M and R:

- Relativistically broadened lines $\Longrightarrow R(M)$
- Quasiperiodic oscillations $\Longrightarrow R(M)$
- Time-delay spectrum $\Longrightarrow R \lesssim R_{\rm in}$
- Redshifted photospheric lines $\Longrightarrow M/R$
- Absorption line profiles $\Longrightarrow M/R$
- Waveform of pulsations $\Longrightarrow M/R$

and more, see Özel & Psaltis (2009, Phys. Rev. D80, 103003)





Quasi periodic oscillations:

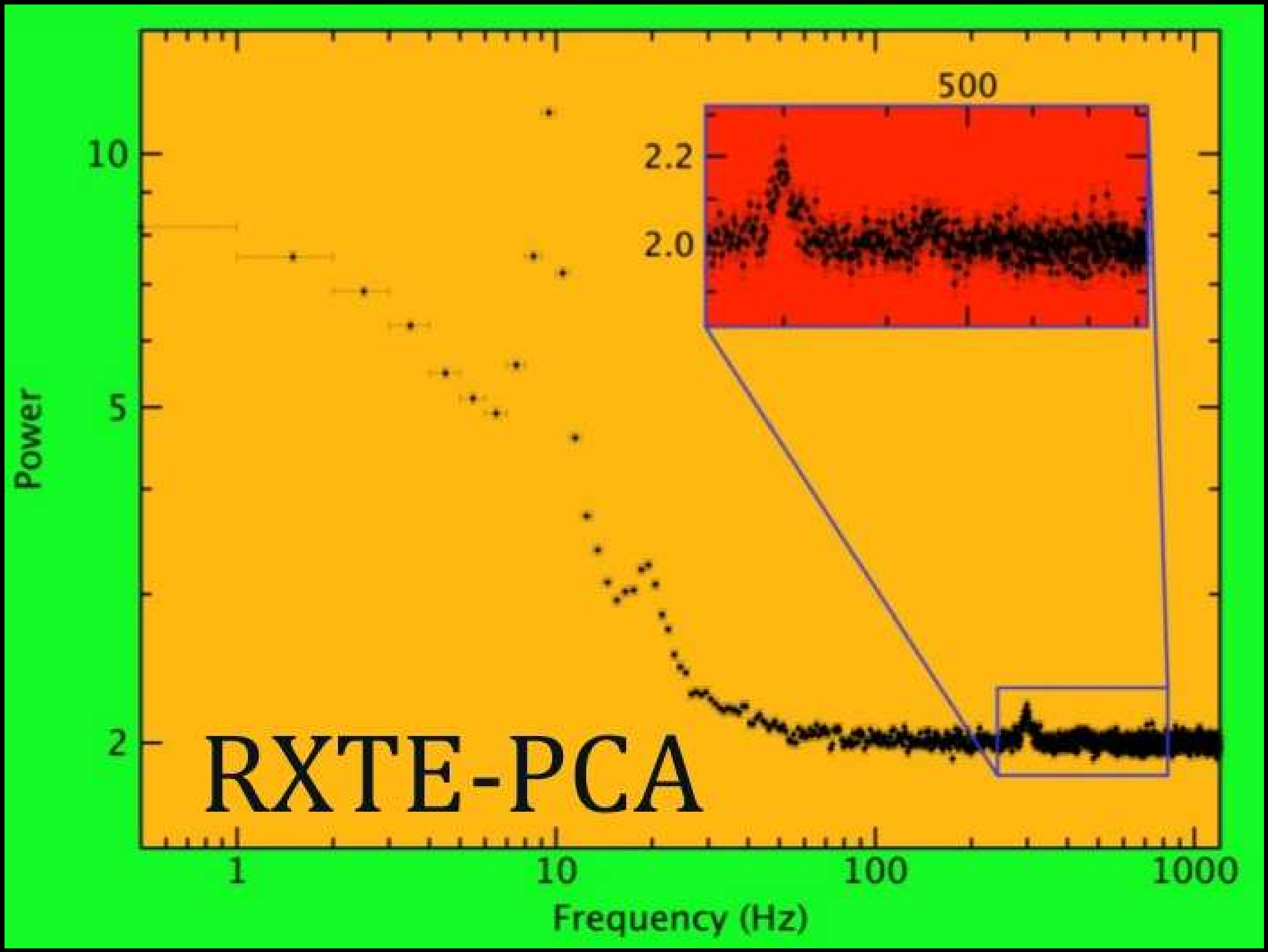
$$\nu < \frac{1}{2\pi}\sqrt{\frac{GM}{r^3}}$$

$$\Longrightarrow$$

$$R_{NS} < r$$

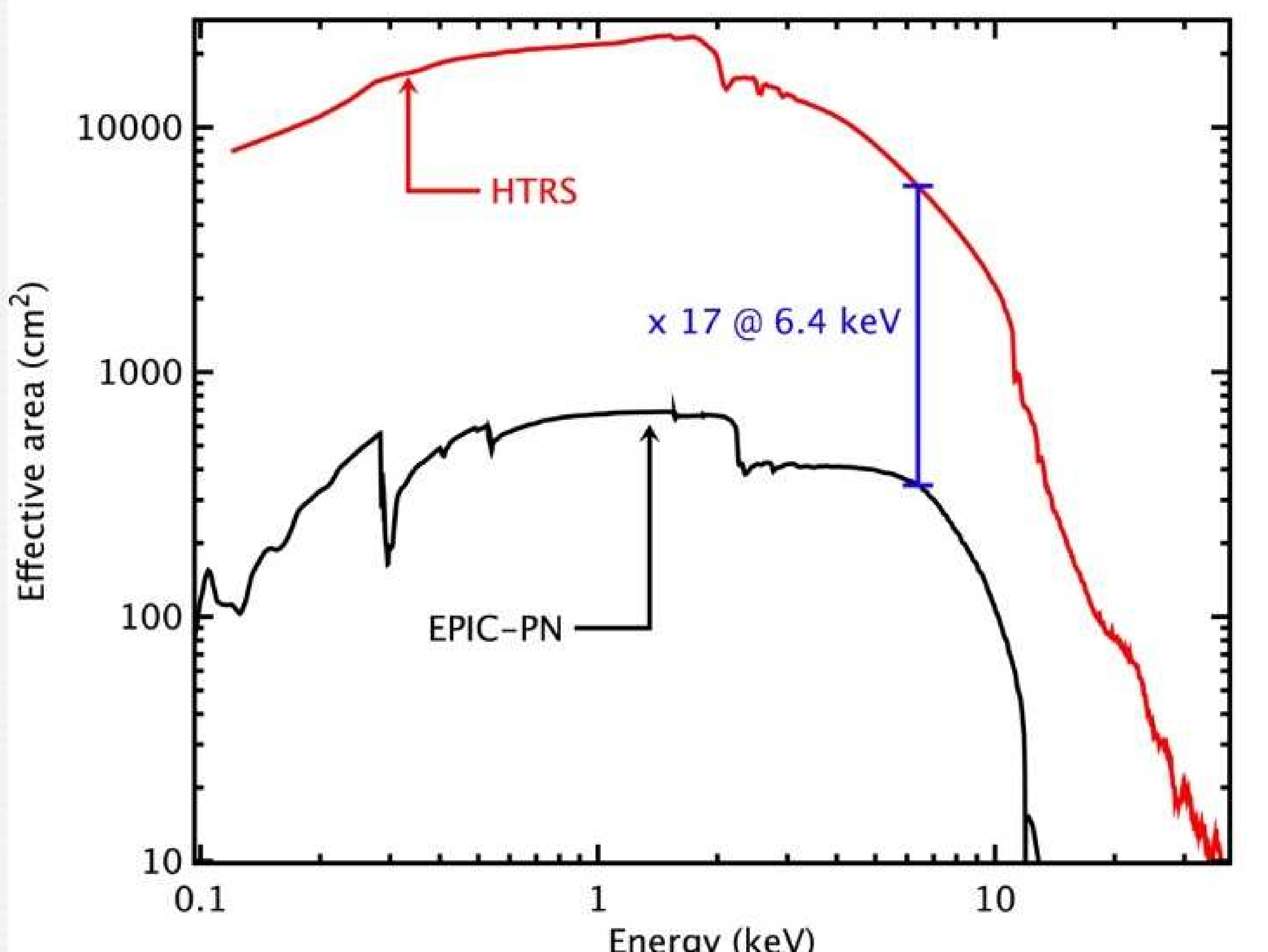
Sco X-1 (Wijnands et al., 1999)

$$M_{NS} \leq 2.2\, M_\odot \cdot \left(\frac{\nu}{1000\,\mathrm{Hz}}\right)^{-1} \quad \text{and} \quad R_{NS} \leq 14.6\,\mathrm{km} \cdot \left(\frac{M_{NS}}{M_\odot}\right)^{1/3} \left(\frac{\nu}{1000\,\mathrm{Hz}}\right)^{-2/3}$$

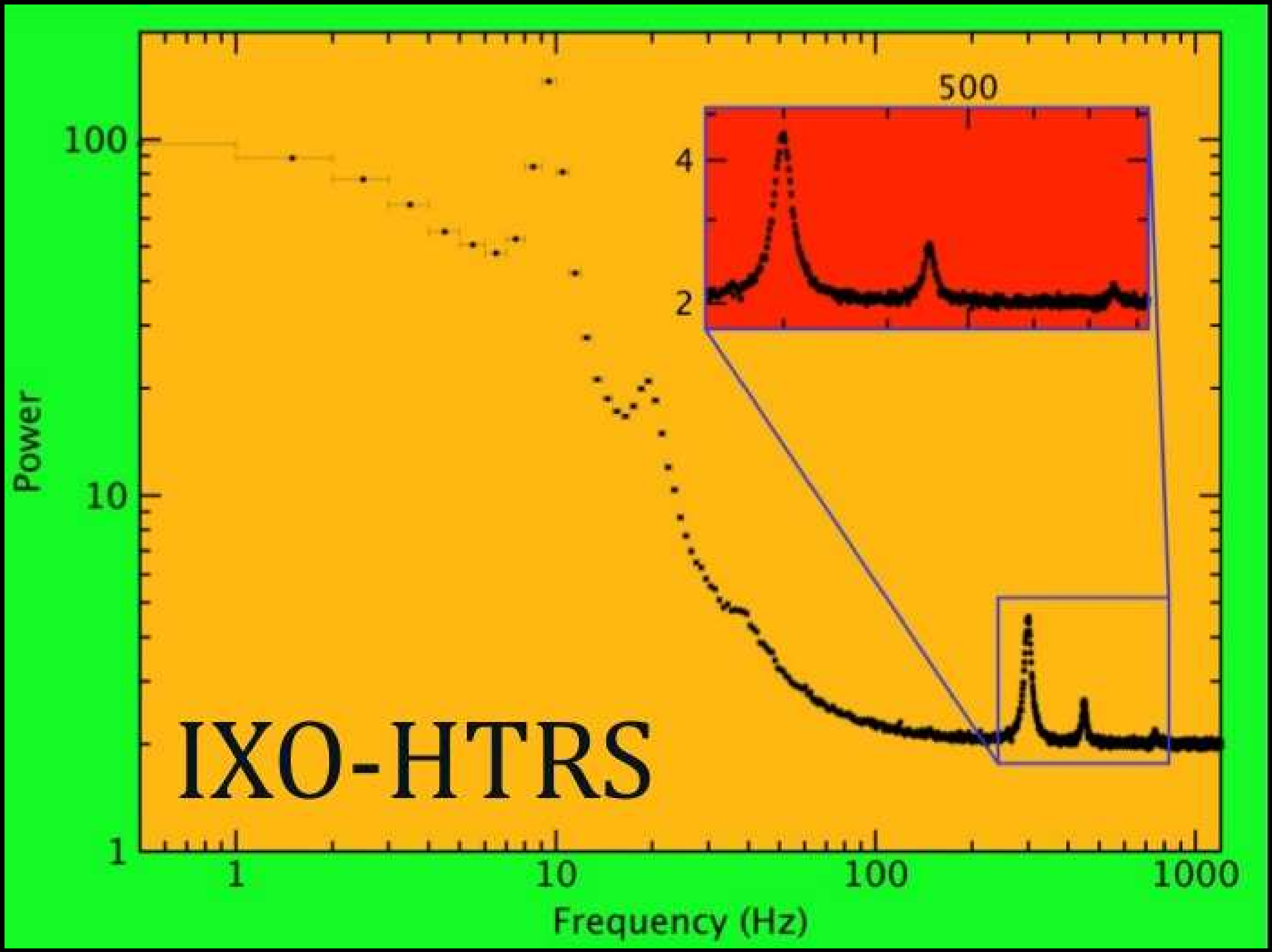


Detection significance of a QPO:

$$n_\sigma = \frac{1}{2}\frac{S^2}{S+B}r^2\sqrt{\frac{T}{\Delta\nu}} \propto S \cdot r^2$$

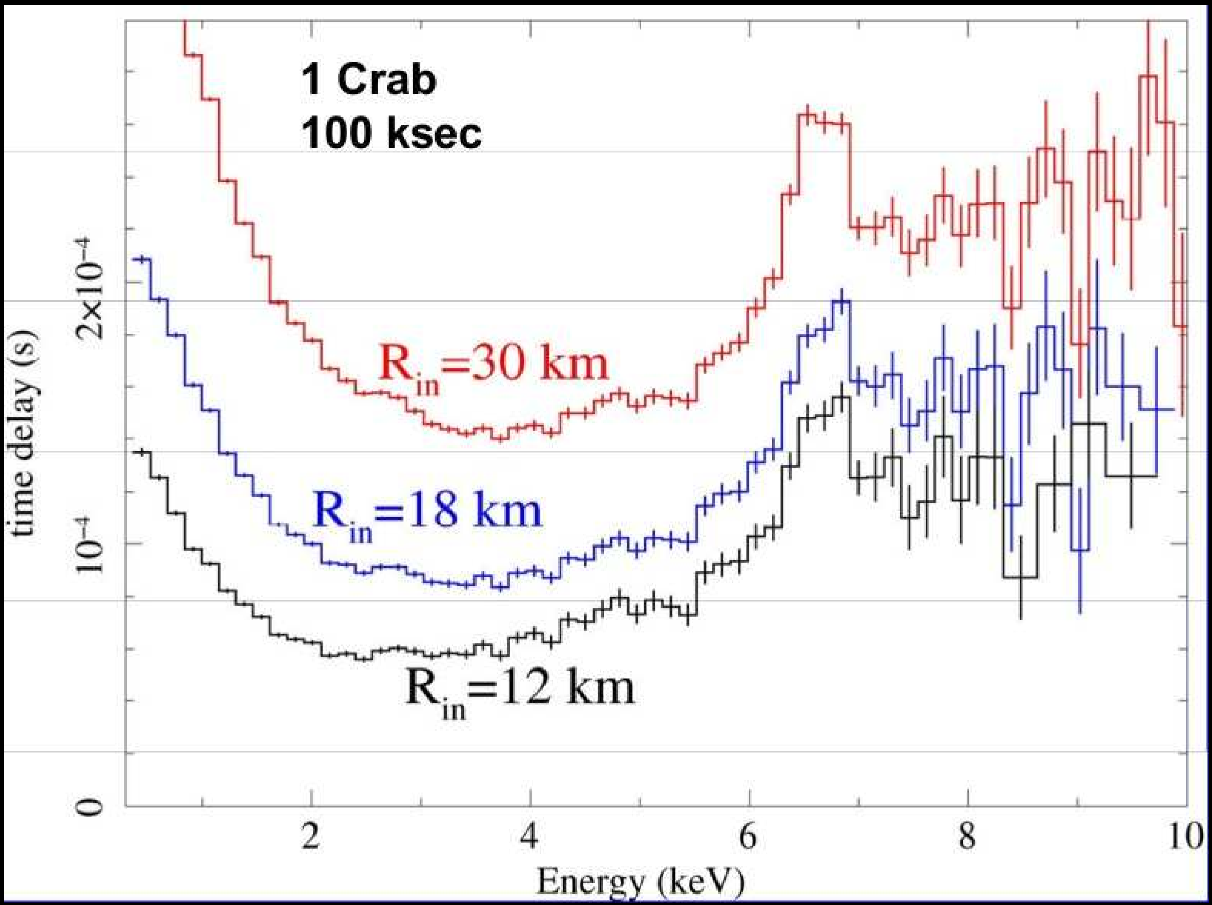


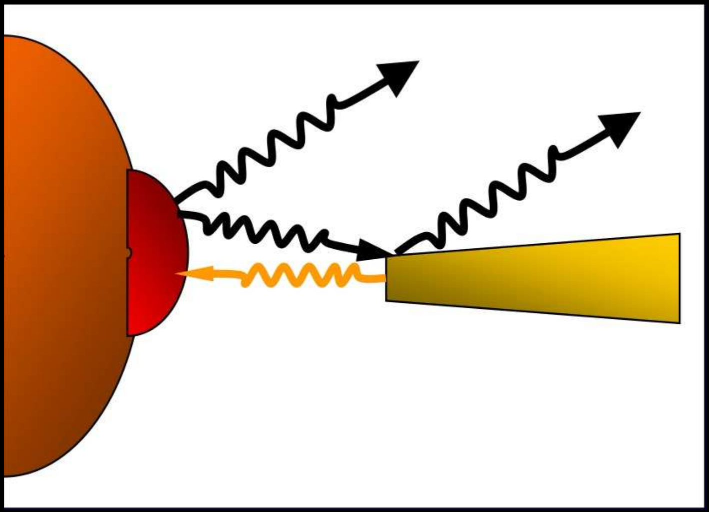
Effective area (cm^2)
Energy (keV)
HTRS
EPIC-PN
x 17 @ 6.4 keV
10000
1000
100
10
0.1
1
10



Detection significance of a QPO:

$$n_\sigma = \frac{1}{2}\frac{S^2}{S+B}r^2\sqrt{\frac{T}{\Delta\nu}} \propto S \cdot r^2$$





Reverberation measurements in neutron star systems will allow measuring response of disk to neutron star intensity variations and constrain the disk and neutron star radii.

Congratulations, Eckhard, I hope we have many more years to enjoy X-ray timing together!

Bibliography

Bałucińska-Church M., Church M.J., 2000, Mon. Not. R. Astron. Soc. 312, L55

Caballero-García M.D., Miller J.M., Trigo M.D., et al., 2009, Astrophys. J. 692, 1339

Cackett E.M., Miller J.M., Bhattacharyya S., et al., 2008, Astrophys. J. 674, 415

Cackett E.M., Miller J.M., Homan J., et al., 2009, Astrophys. J. 690, 1847

di Salvo T., D'Aí A., Iaria R., et al., 2009, Mon. Not. R. Astron. Soc. 398, 2022

Done C., Díaz Trigo M., 2009, Mon. Not. R. Astron. Soc. submitted (arXiv:0911.3243)

Fritz S., Wilms J., Pottschmidt K., et al., 2006, In: Sunyaev R., Grebenev S., Winkler C. (eds.) The 6th Integral Workshop: The Obscured Universe. ESA SP-622, ESA Publications Division, Noordwijk, p.341

Hopkins P.F., Hernquist L., Cox T.J., et al., 2006, Astrophys. J., Suppl. Ser. 163, 1

Miller J., 2007, Ann. Rev. Astron. Astrophys. 45, 441

Miller J.M., Fabian A.C., Reynolds C.S., et al., 2004, Astrophys. J. 606, L131

Miller J.M., Fabian A.C., Wijnands R., et al., 2002, Astrophys. J. 578, 348

Miller J.M., Fabian A.C., Wijnands R., et al., 2002, Astrophys. J. 570, L69

Miller J.M., Reynolds C.S., Fabian A.C., et al., 2008, Astrophys. J. 679, L113

Miller J.M., Reynolds C.S., Fabian A.C., et al., 2009, Astrophys. J. 697, 900

Nowak M.A., Wilms J., Dove J.B., 2002, Mon. Not. R. Astron. Soc. 332, 856

Yamada S., Makishima K., Uehara Y., et al., 2009, Astrophys. J. 707, L109