Relativistic Astrophysics in Active Galactic Nuclei

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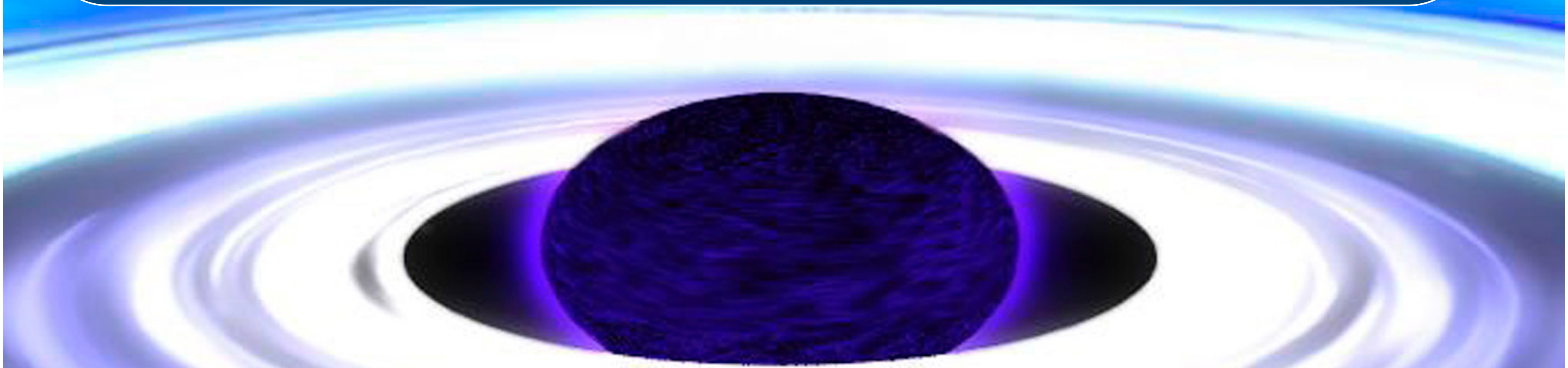
The disk/jet/wind system :

- How much energy, and in what forms, do AGN pump out into their surroundings?
- What is physics of disk/jet/wind, and their coupling?
- What is physical nature of X-ray source in AGN?



The Black Hole :

- Origin and growth history?
- Really described by General Relativity?

Outline

- Are AGN disks naked?
- SMBH spin measurements; update and cautions
- Relativistic modeling of X-ray reverberation signals
- The (bright) future

Collaborators:

- Laura Brenneman
- Ed Cackett
- Andrew Fabian
- Erin Kara
- Anne Lohfink
- Jon Miller
- Richard Mushotzky
- Mike Nowak
- Rubens Reis
- Abdu Zoghbi

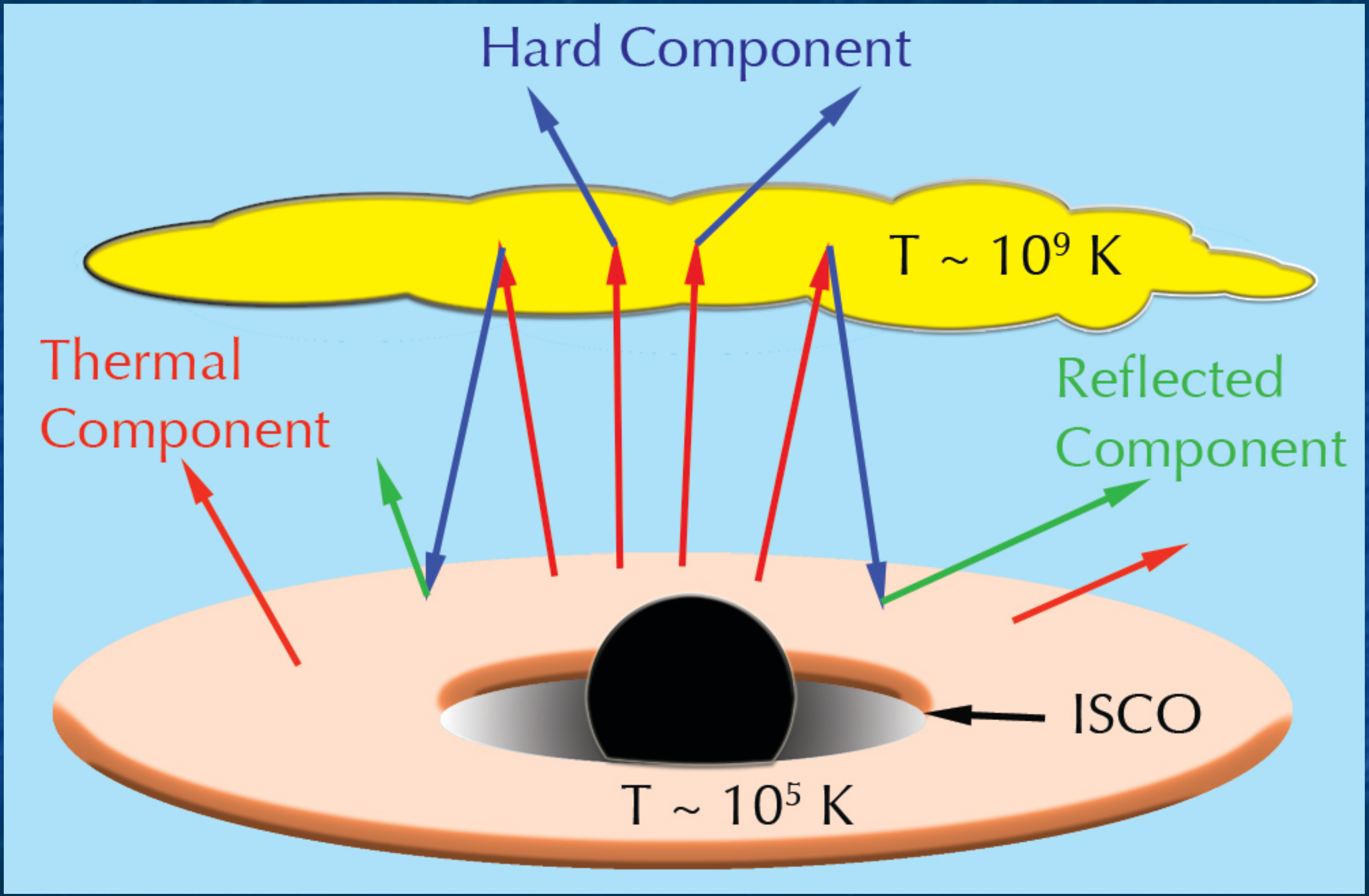
I : Can we even see the relativistic region?

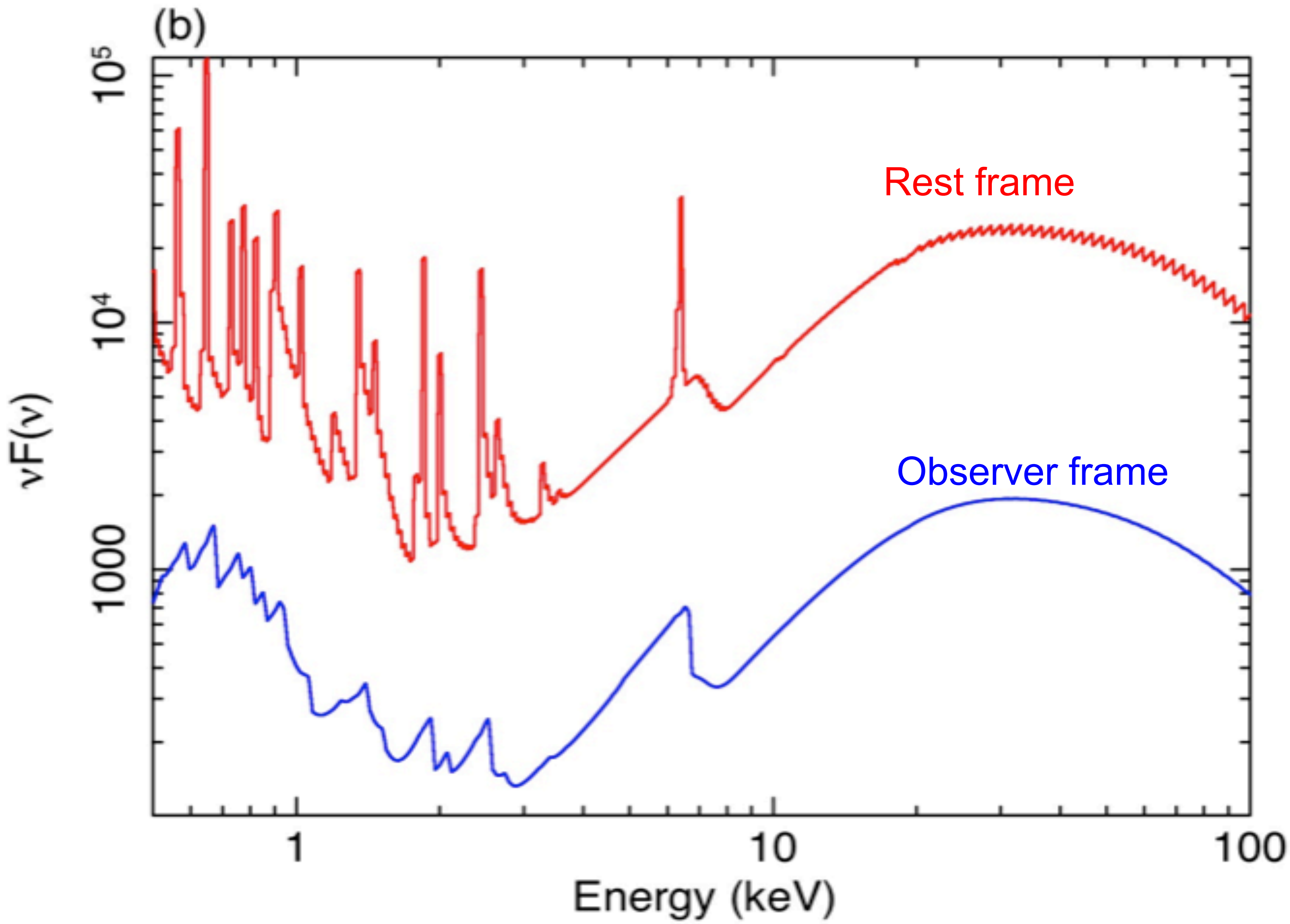
Can the central accretion disk generate a Compton-thick cloak?

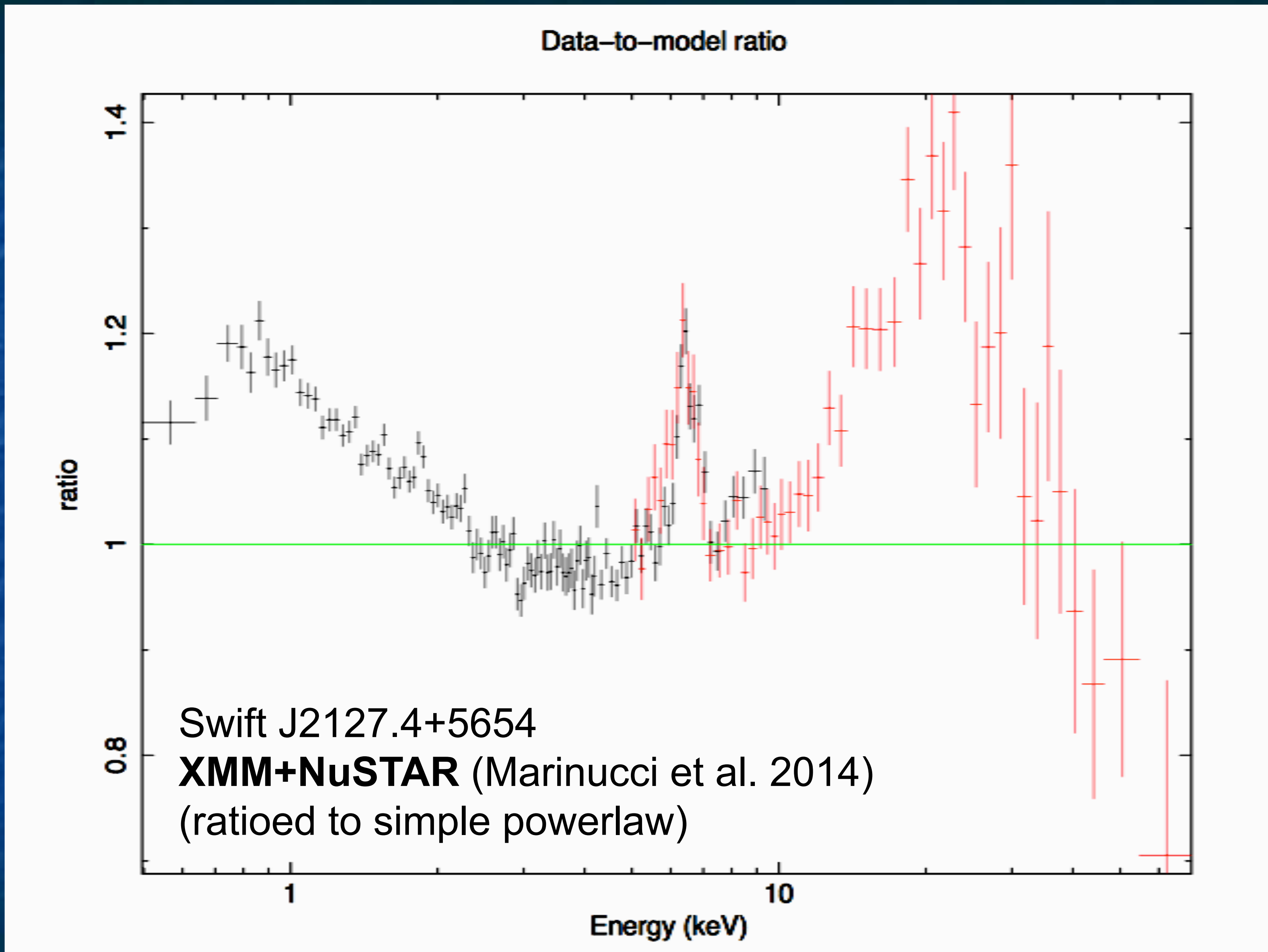
- Optical depth related to mass-flux or momentum of wind
- Constraints from acceleration physics
  - Radiative driving – wind momentum capped by photon field momentum
  - Magnetocentrifugal acceleration – wind mass-flux limited by angular momentum available in disk
  - Thermal driving – only works at large distances (torus?)
- Conclusion : The inner-disks of sub-Eddington AGN cannot support CT-winds

Reynolds (2012)

II : Supermassive Black Hole Spin

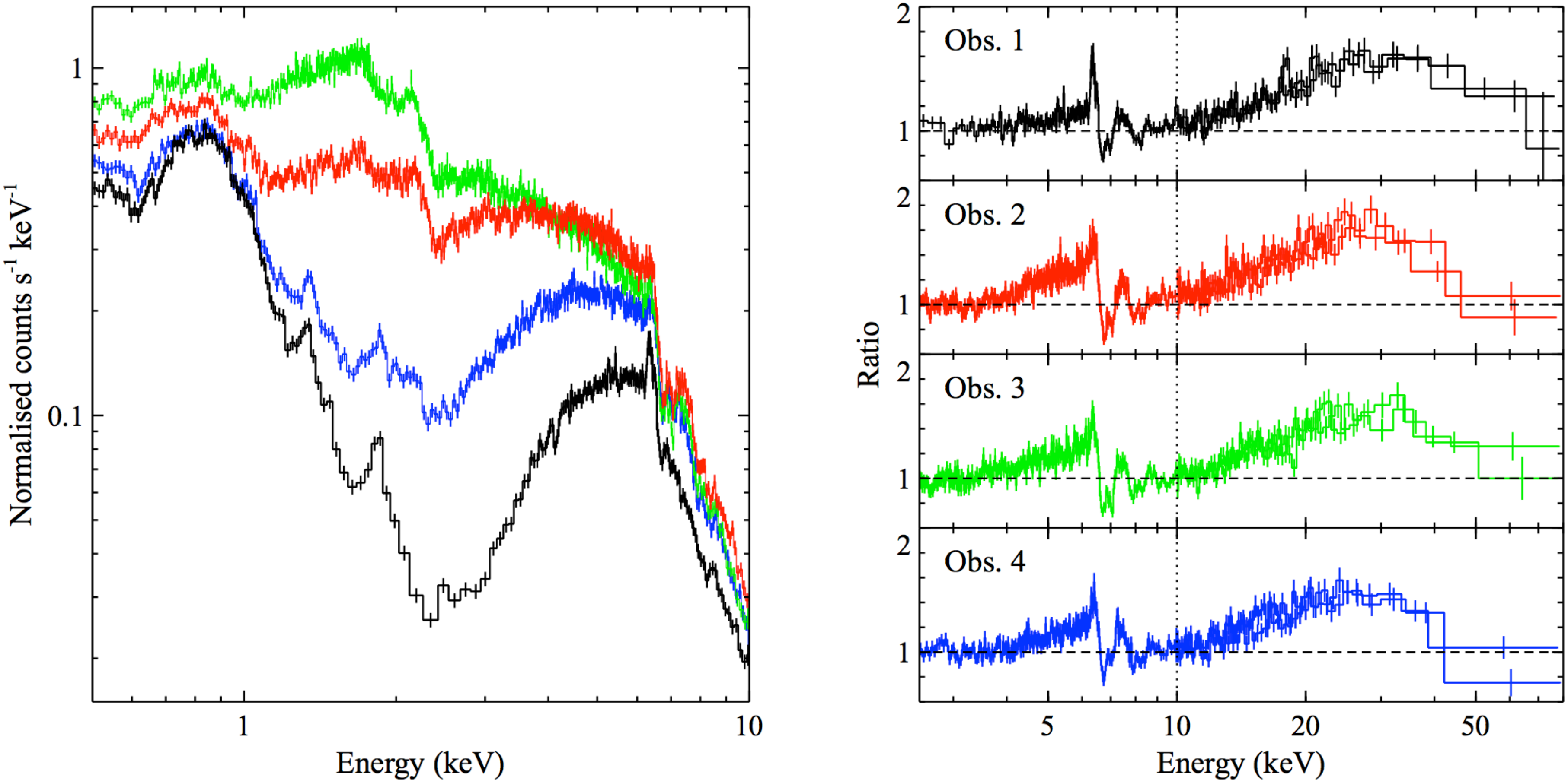



(b)
Rest frame
Observer frame
νF(ν)
10^5
10^4
1000
1
10
100
Energy (keV)



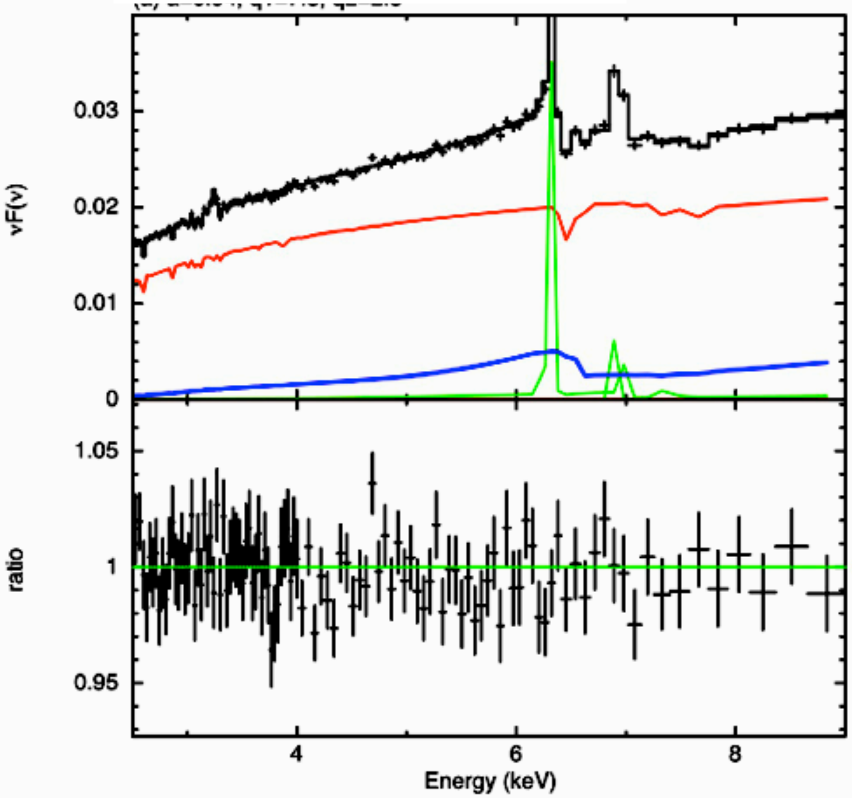
Data–to–model ratio
ratio
1.4
1.2
1
0.8
1
10
Energy (keV)
Swift J2127.4+5654
XMM+NuSTAR (Marinucci et al. 2014)
(ratioed to simple powerlaw)

NGC1365 with XMM+NuSTAR (Walton et al. 2014)

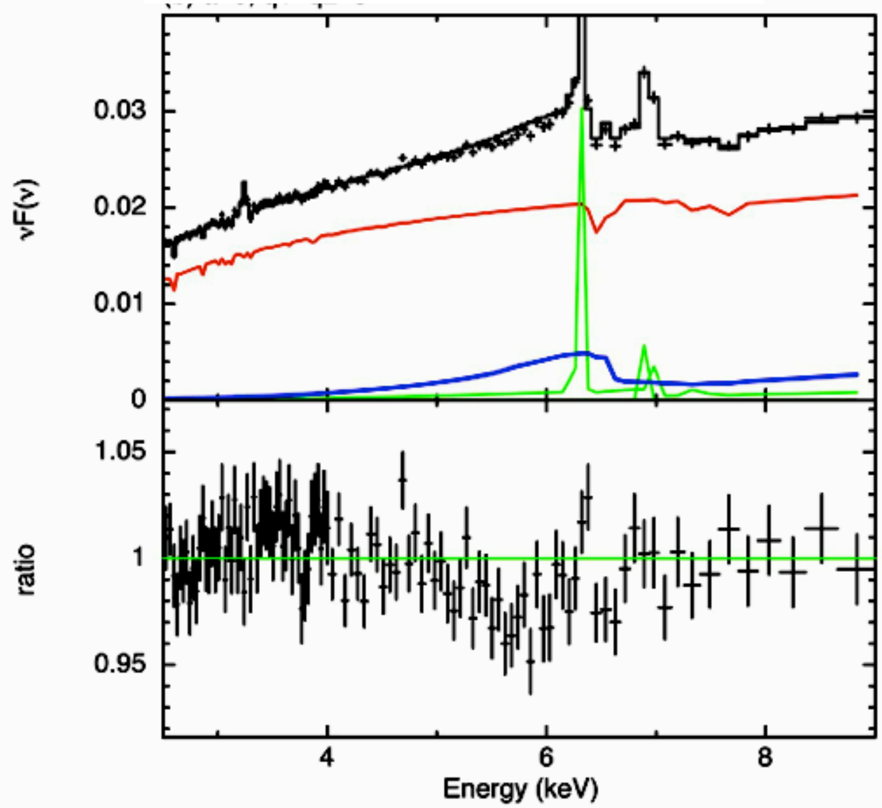


NGC3783 w/Suzaku (210ks)

Best Fit (a=0.94)

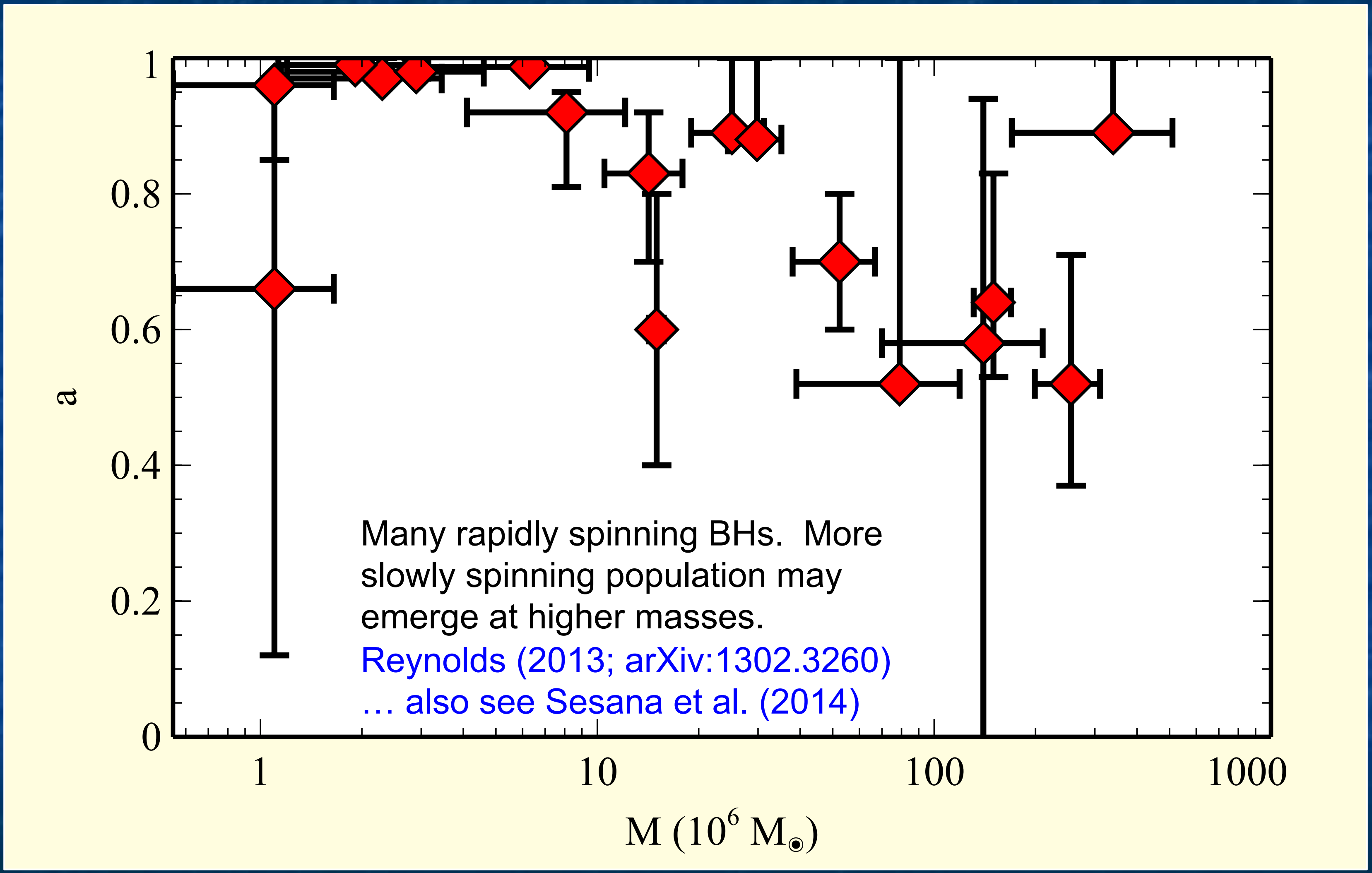


Force a=0 (and q=3)



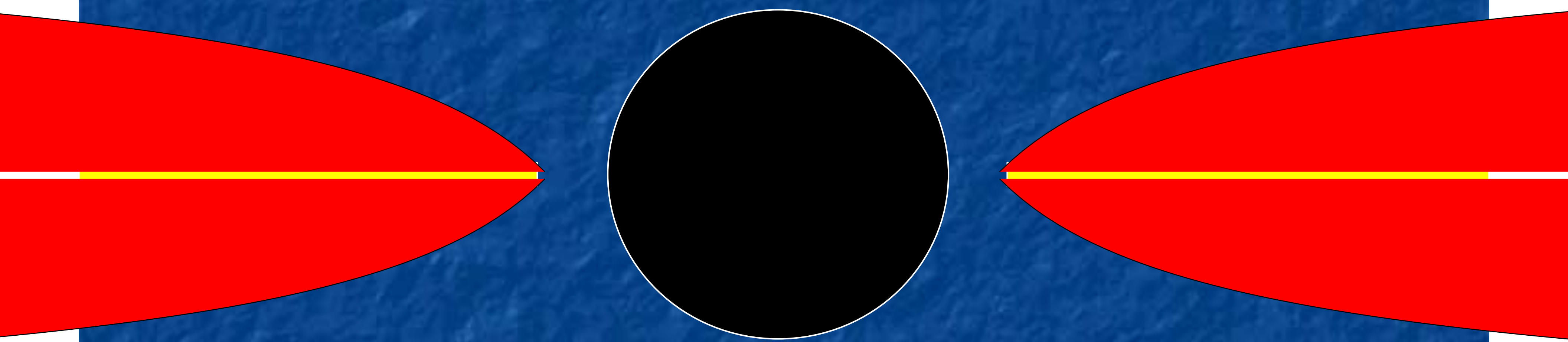
Reynolds et al. (2012)

Current compilation of spin constraints



Beware of conclusions regarding very very rapid spins!

For high spins (a>0.95), current quantitative measures are probably compromised by finite-thickness effects…
(Reynolds & Fabian 2008)



$$h \approx \frac{2(L/L_{\mathrm{Edd}})}{\eta} r_g$$

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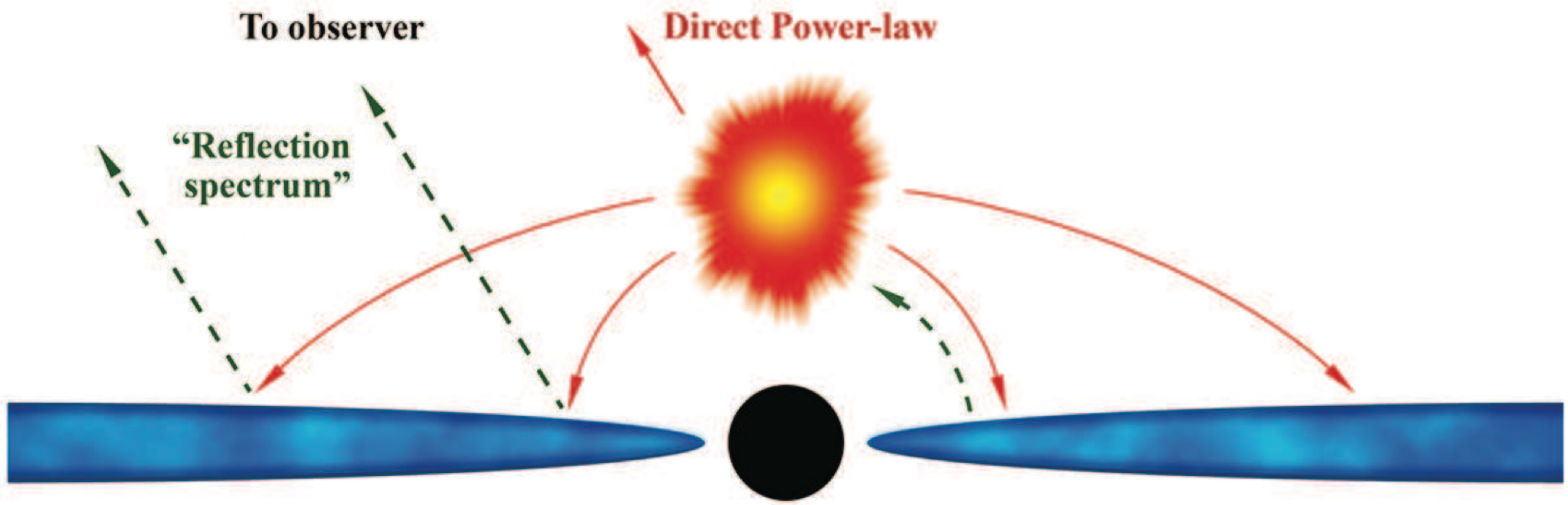
$$h \approx \frac{2(L/L_{\rm Edd})}{\eta} r_g$$

III : Variability and relativistic reverberation



The basic timescales of BH disks…

- Light cross time of r ; $t_{lc} = r/c = 1.4\ M_8 r_1$ hours
- Dynamical timescale ; $t_{dyn} = \Omega^{-1} = 4.4\ M_8 r_1^{3/2}$ hours
- Thermal timescale ; $t_{th} = t_{dyn}/\alpha = 1.8\ M_8 \alpha_{-1} r_1^{3/2}$ days
- Viscous timescale ; $t_{vis} = t_{th}/(h/r)^2 = 6\ M_8 \alpha_{-1} h_0^2 r_1^{7/2}$ months

$M=10^8 M_8 M_{sun}$; $r=10 r_1 r_g$; $\alpha=0.1\alpha_{-1}$; $h=h_0 r_g$

The basic timescales of BH disks…

- Light cross time of r ; $t_{lc} = r/c = 1.4\ M_8 r_1$ hours

  REVERBERATION TIME DELAYS EFFECTS
- Dynamical timescale ; $t_{dyn} = \Omega^{-1} = 4.4\ M_8 r_1^{3/2}$ hours

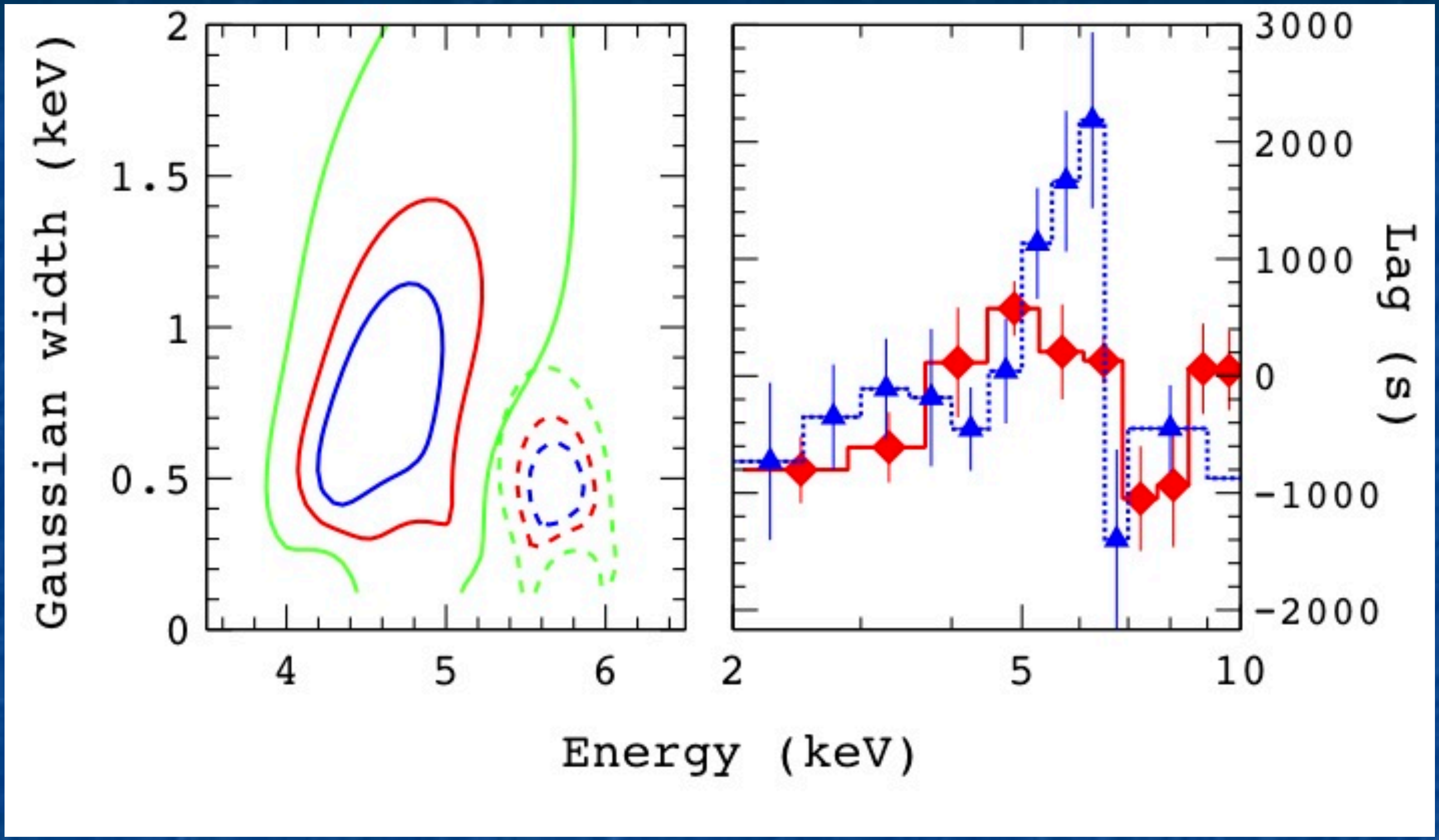
  RAPID CONTINUUM FLICKERING
- Thermal timescale ; $t_{th}=t_{dyn}/\alpha = 1.8\ M_8 \alpha_{-1} r_1^{3/2}$ days

  THERMAL INSTABILITY ?
- Viscous timescale ; $t_{vis} = t_{th}/(h/r)^2 = 6\ M_8 \alpha_{-1} h_0^2 r_1^{7/2}$ months

  SECULAR CHANGES IN ACCRETION RATE

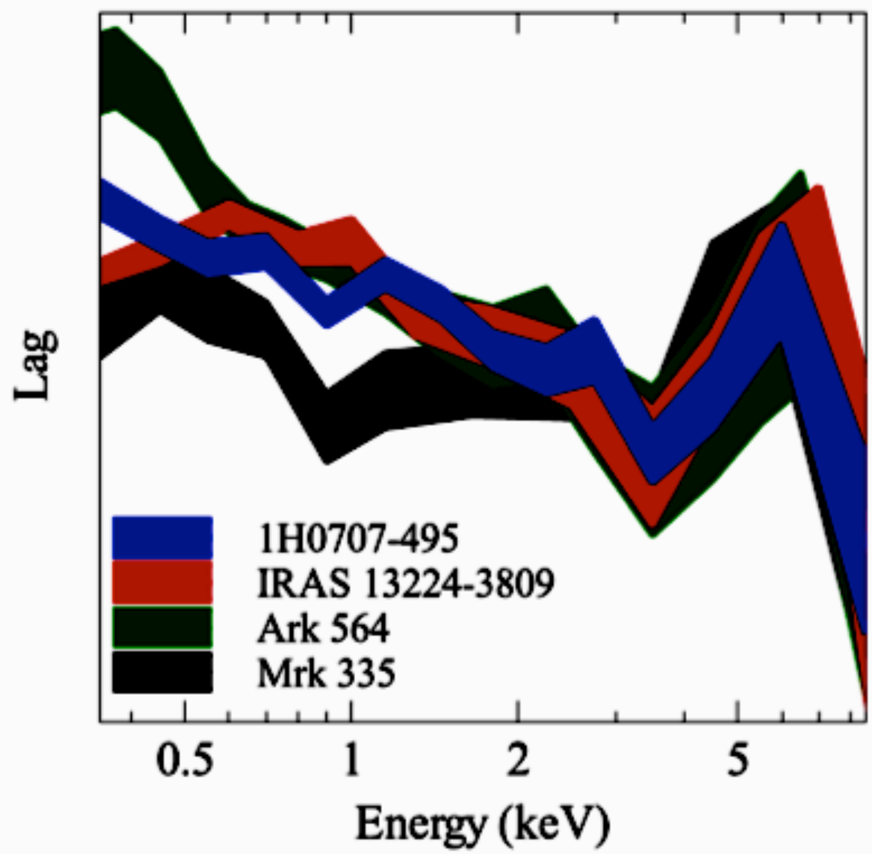
$M=10^8 M_8 M_{sun}$; $r=10 r_1 r_g$; $\alpha=0.1\alpha_{-1}$; $h=h_0 r_g$

Iron line reverberation in NGC4151 (Zoghbi et al. 2012)



Observed Iron K lags

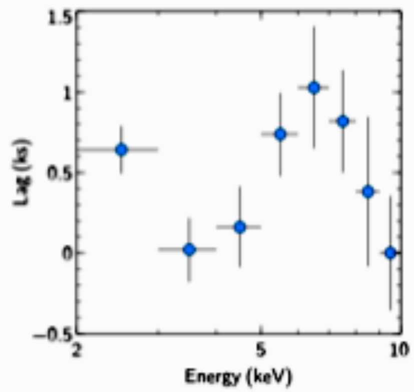
The whole lag spectrum.

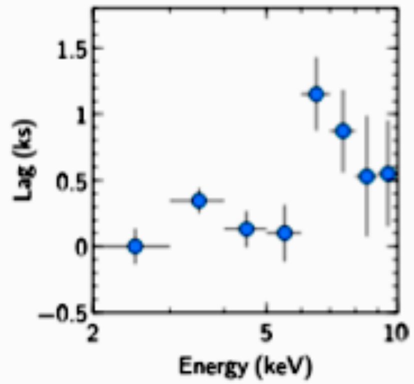


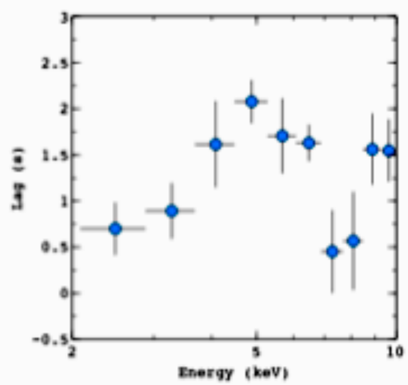
Kara+13

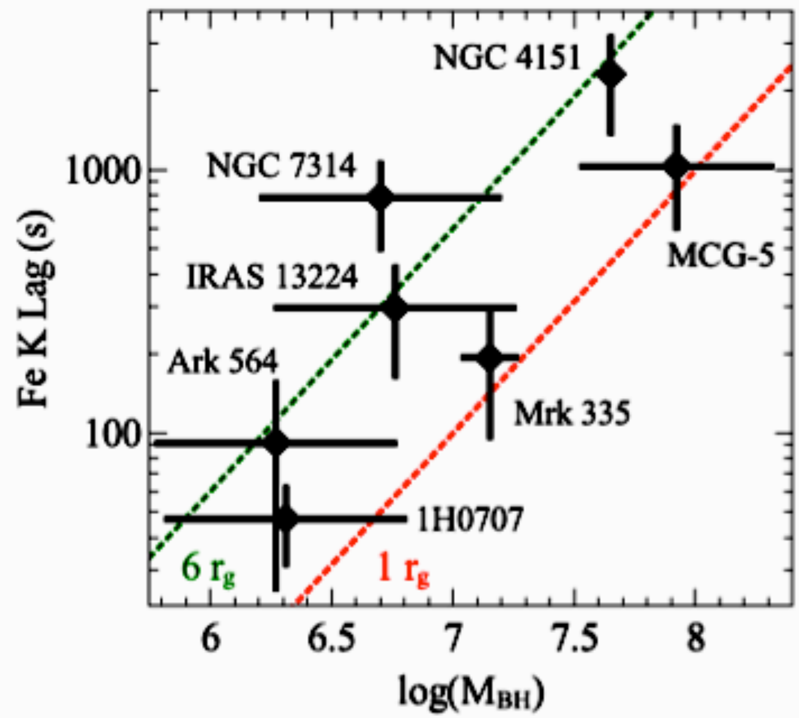
Observed Iron K lags

The reverberation lag scales with black hole mass.



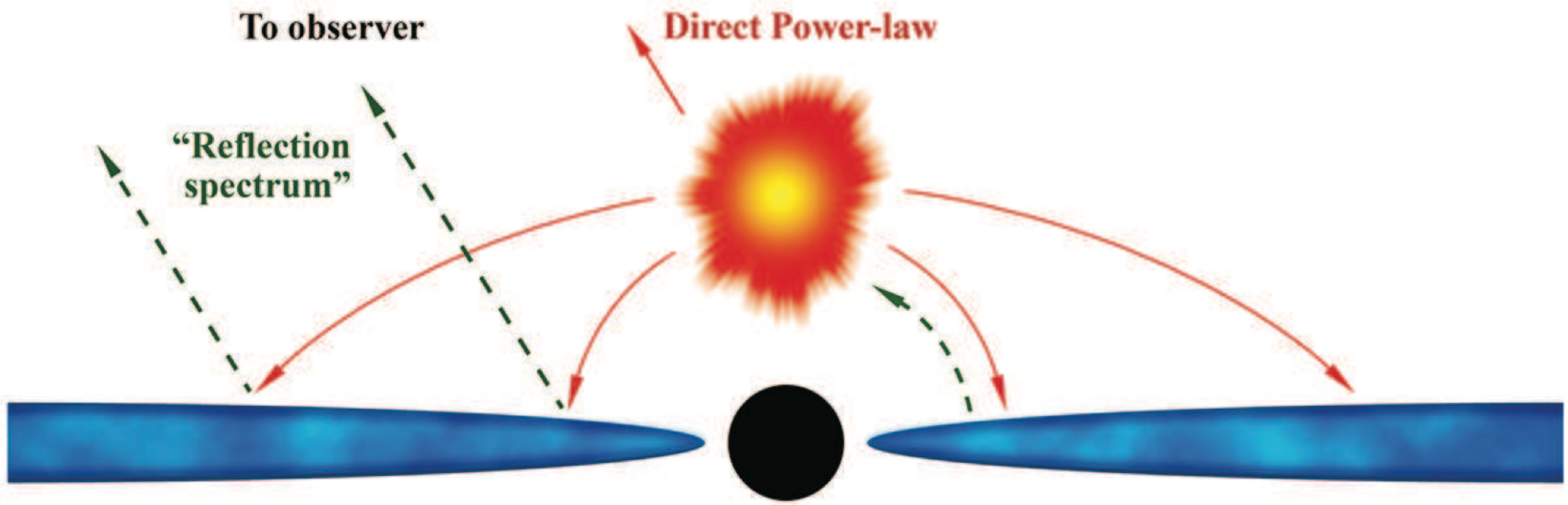


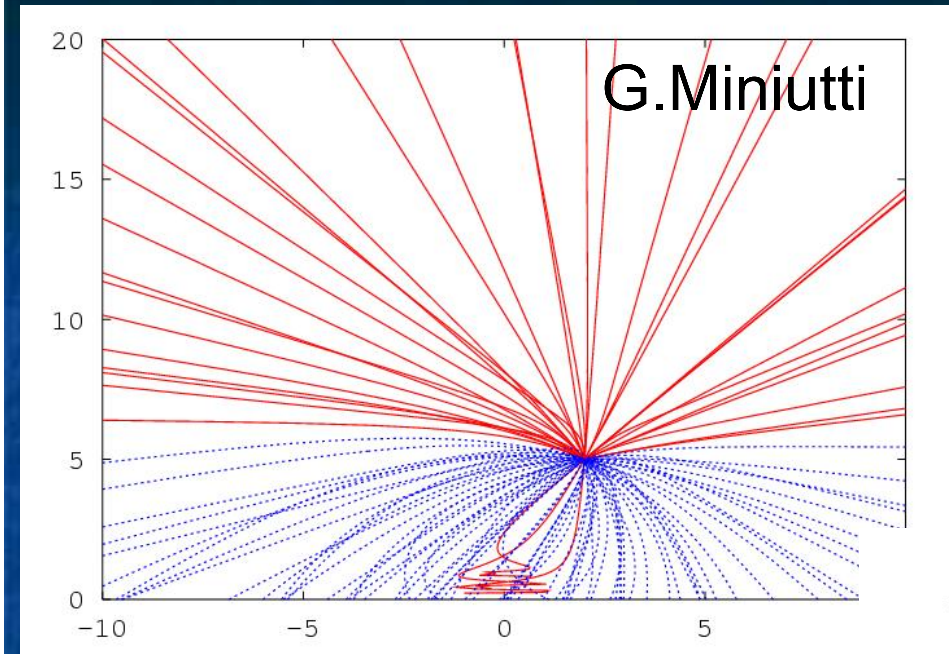


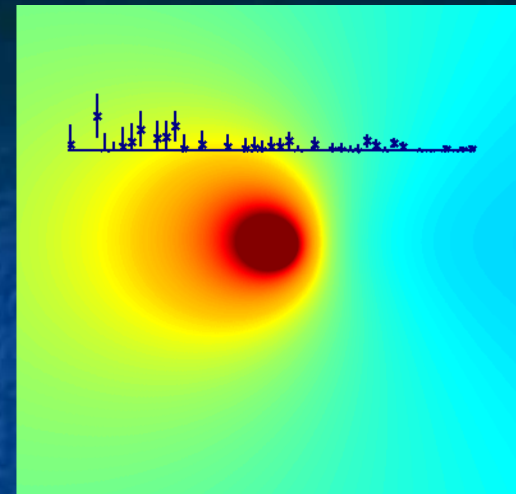


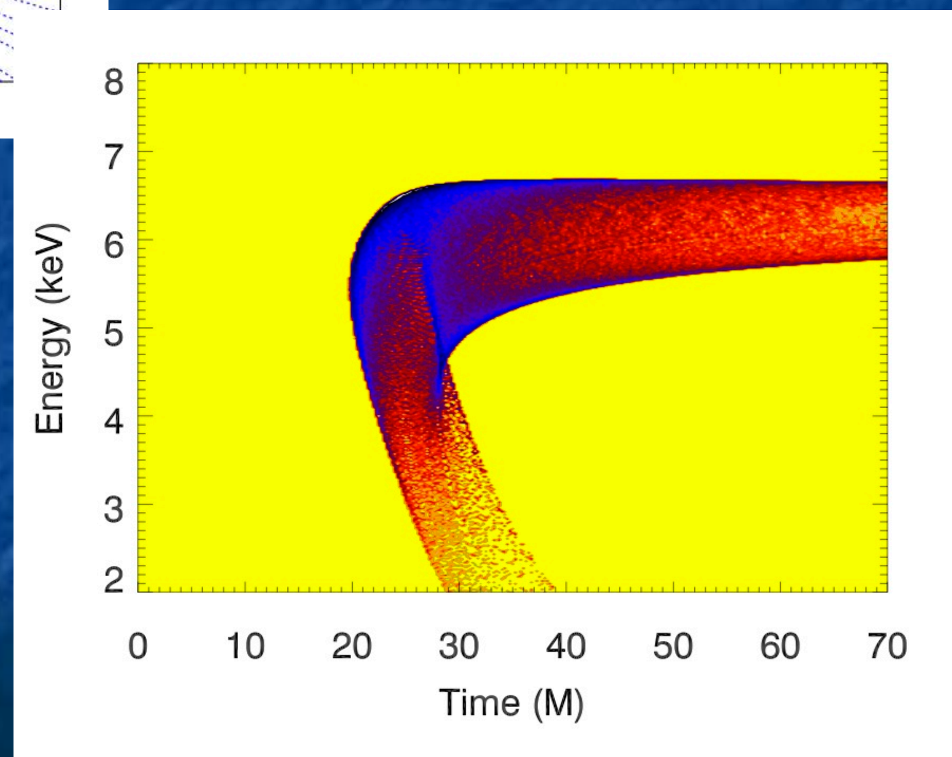
Zoghbi+12,13. Kara+13

$h=10r_g$

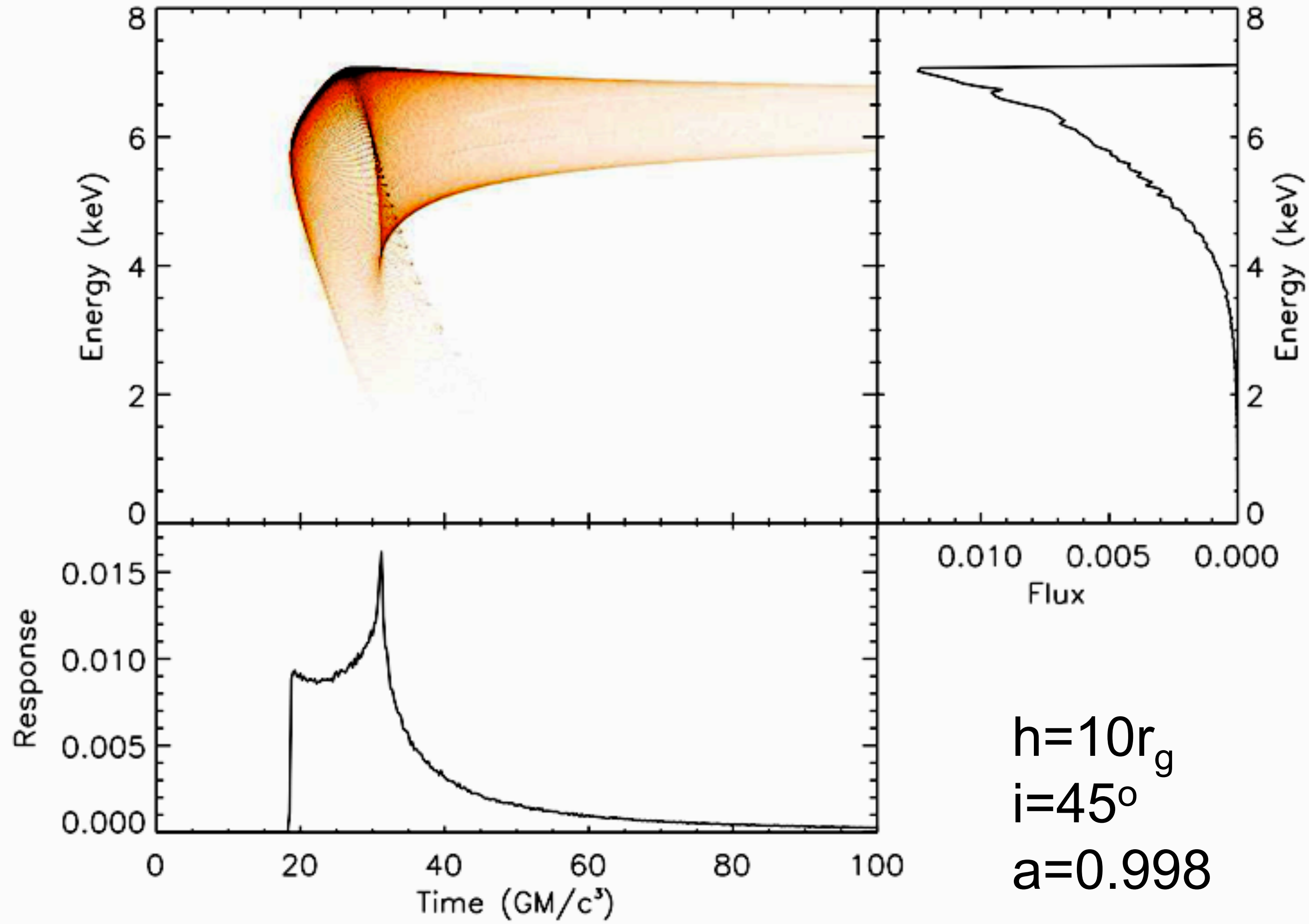








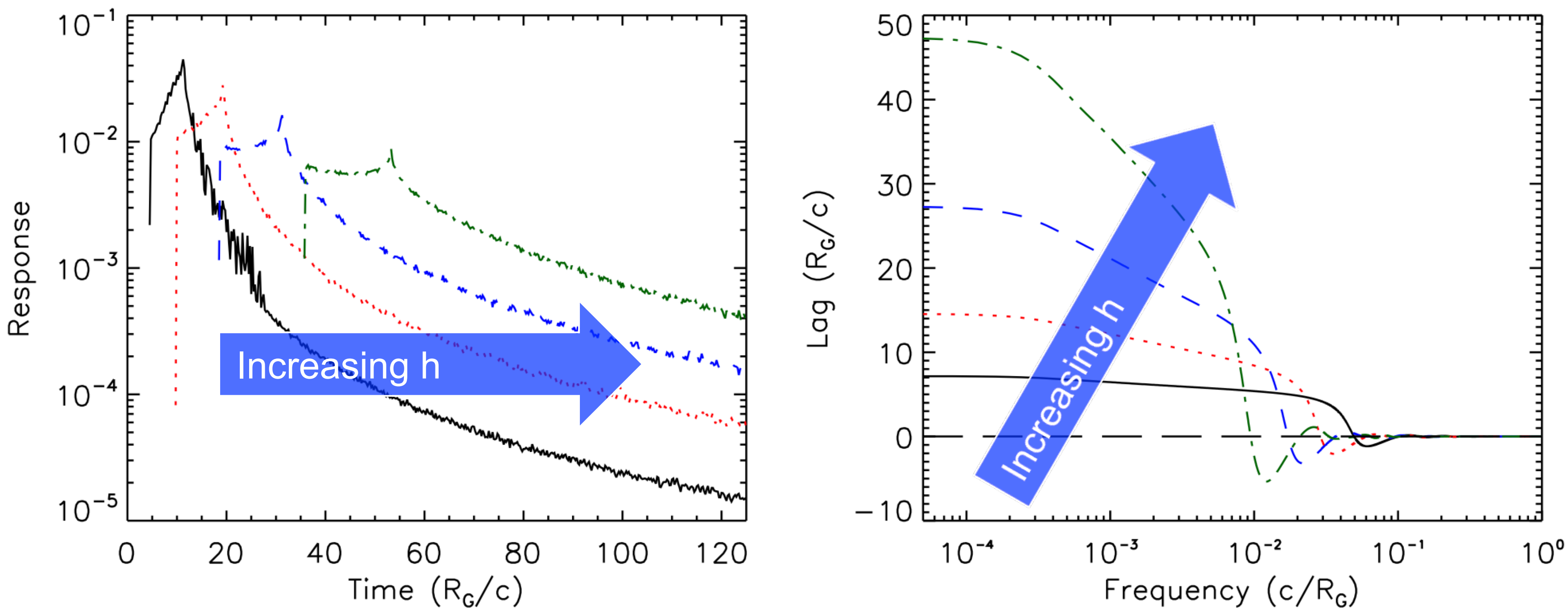
Reynolds et al. (1999)
Young & Reynolds (2000)



$h=10r_g$
$i=45^o$
$a=0.998$

Cackett, Zoghbi, Reynolds et al. (2014)

Illustration : response of 5-6keV lags to input parameters



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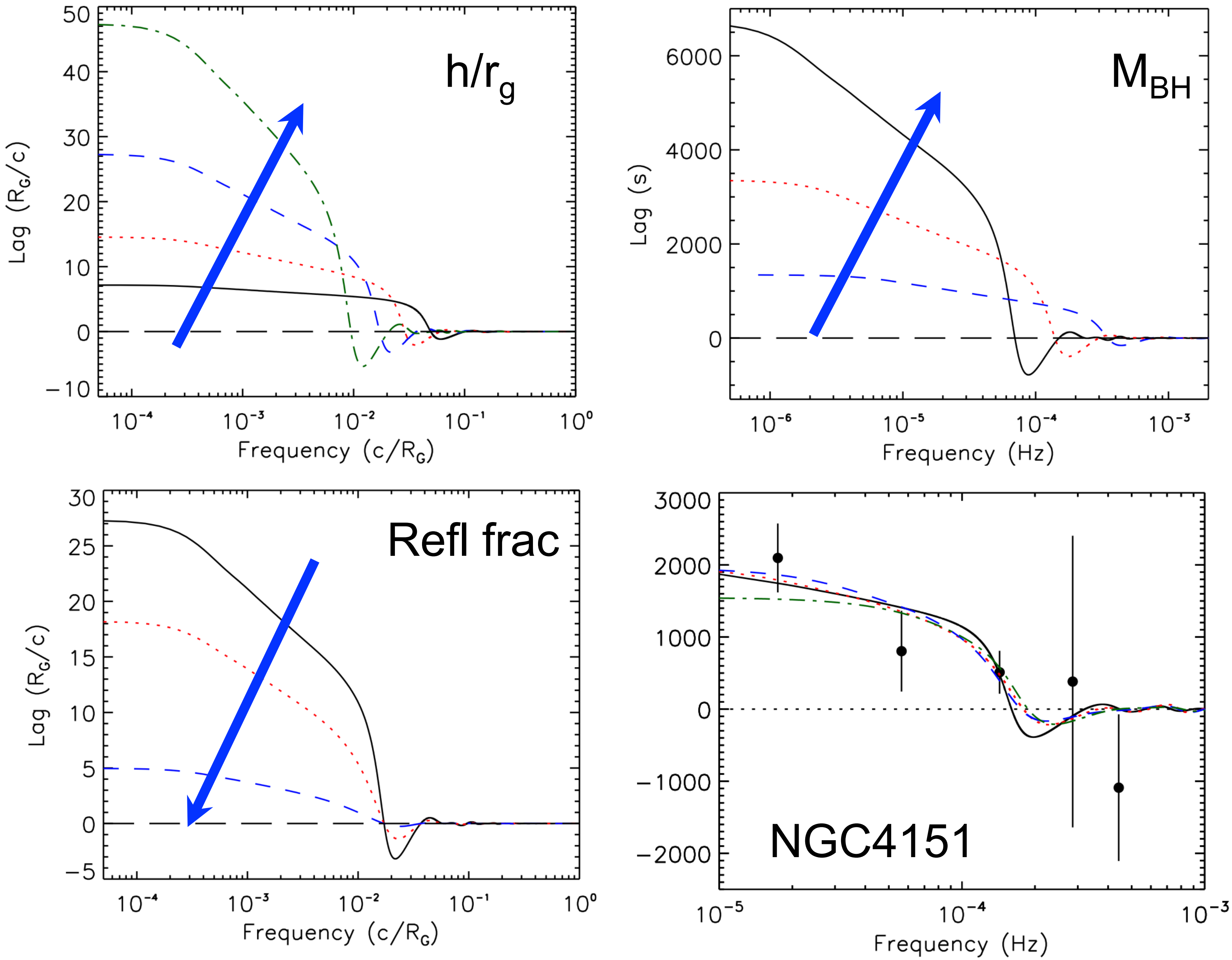
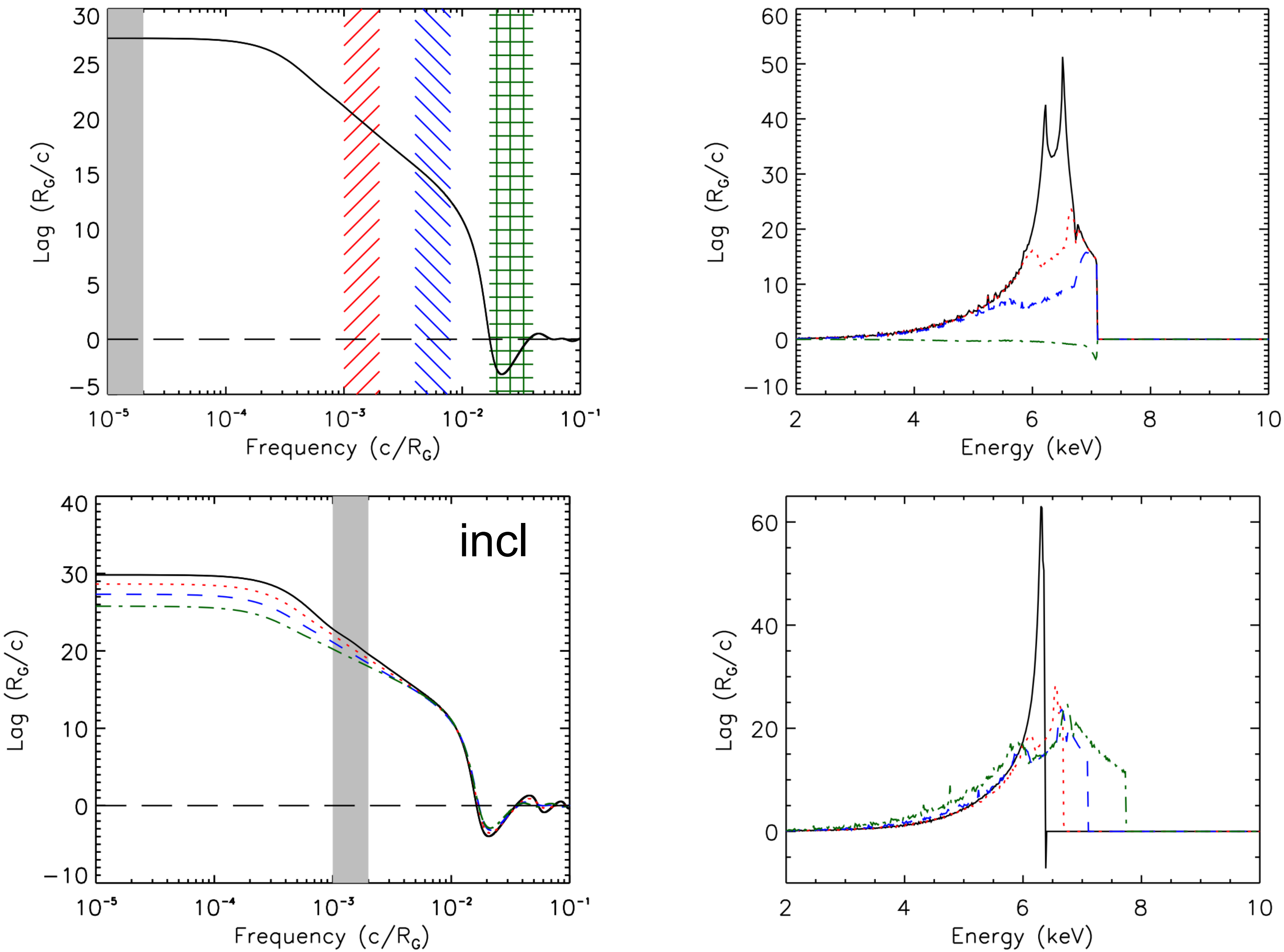
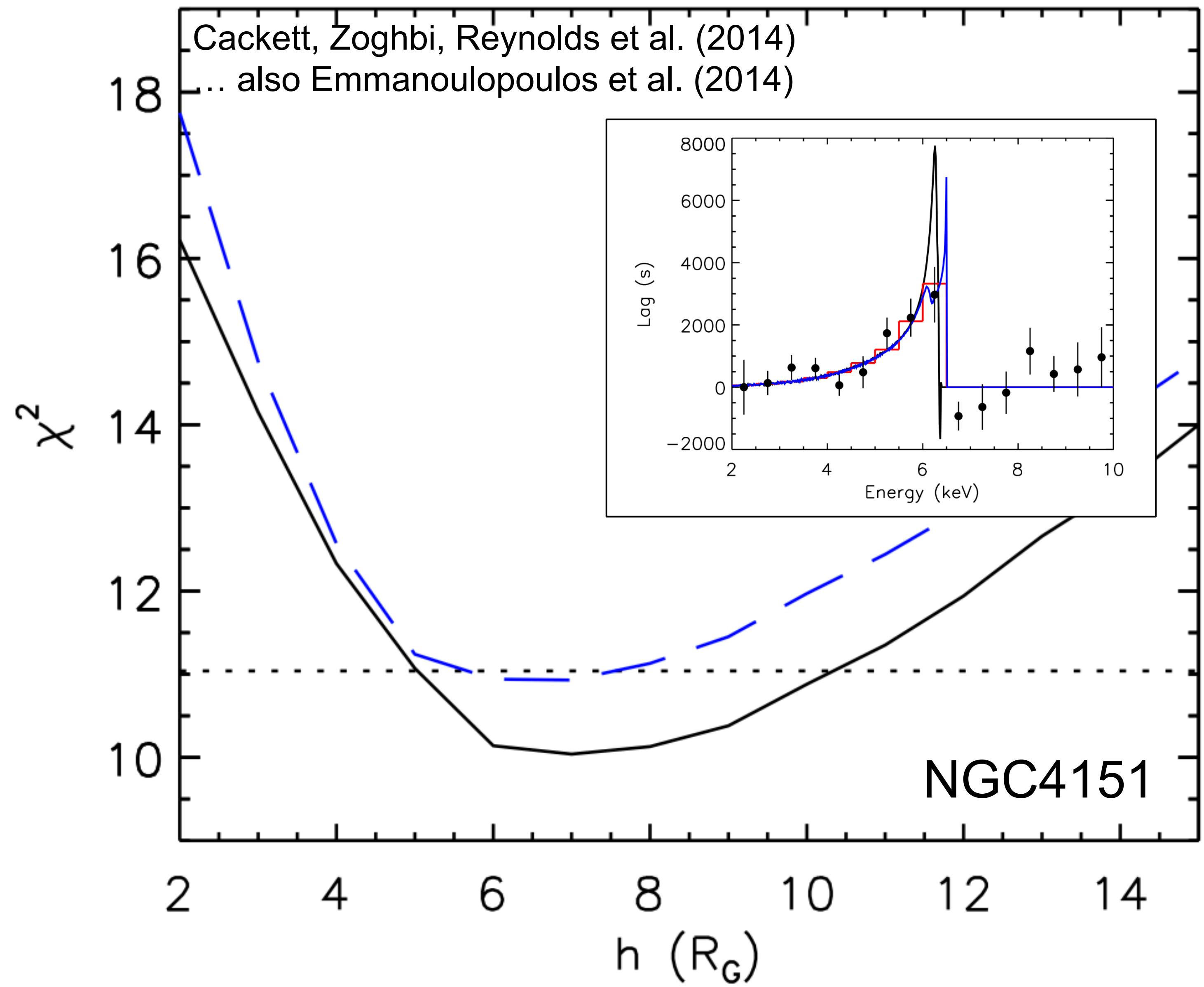
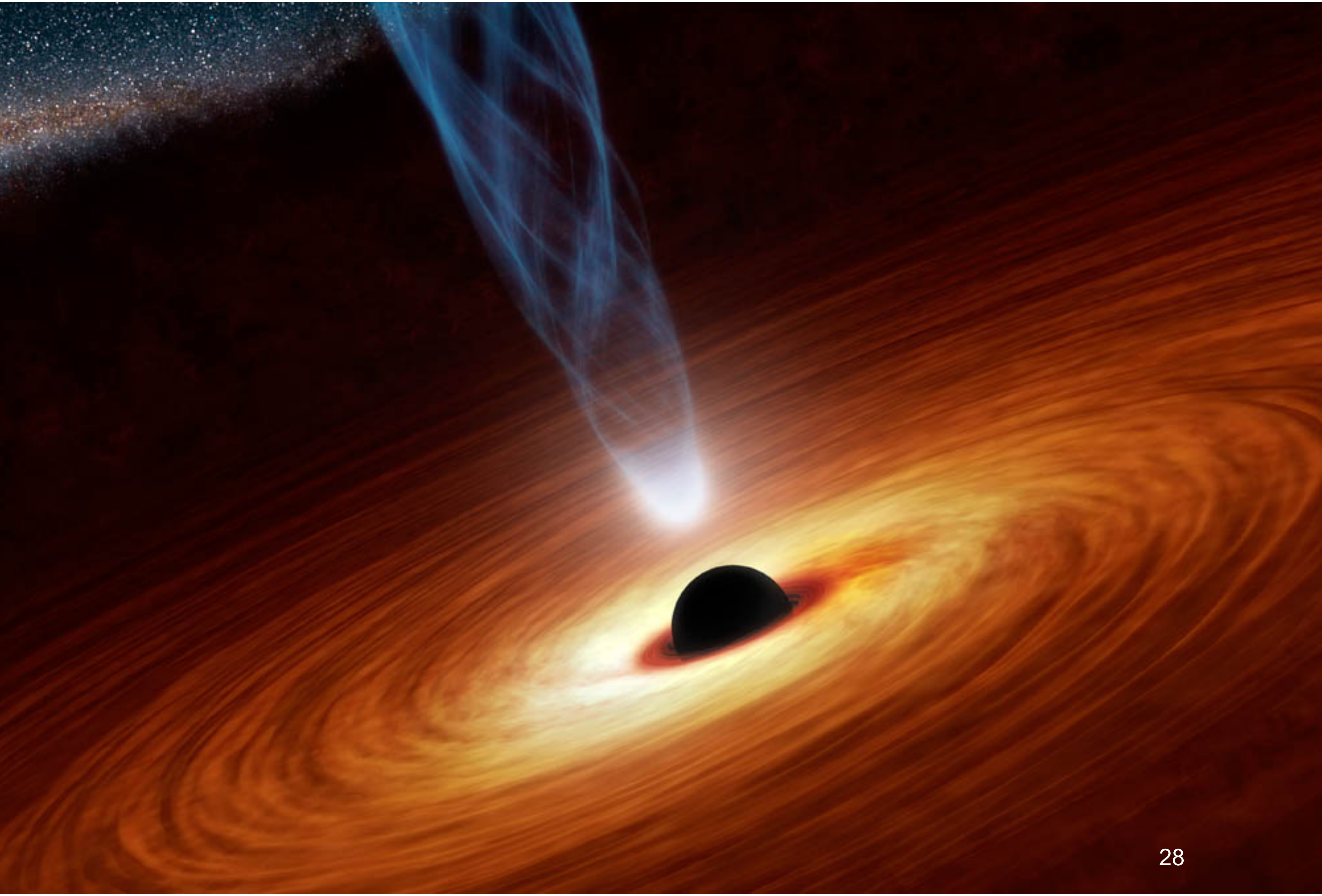


Cackett, Zoghbi, Reynolds et al. (2014)

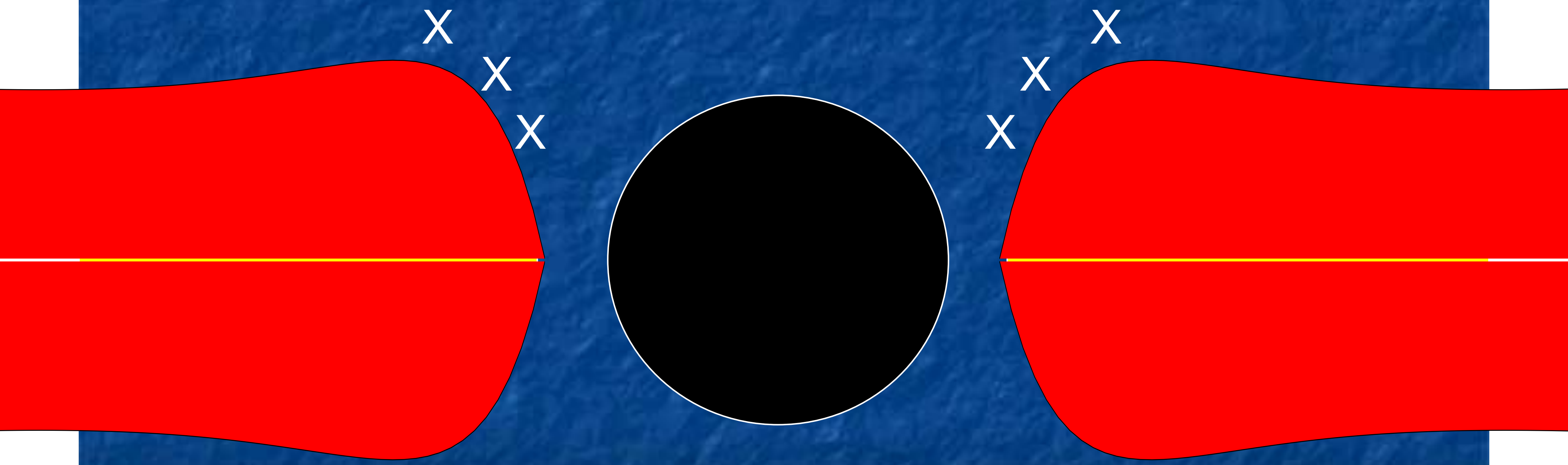


Cackett, Zoghbi, Reynolds et al. (2014)

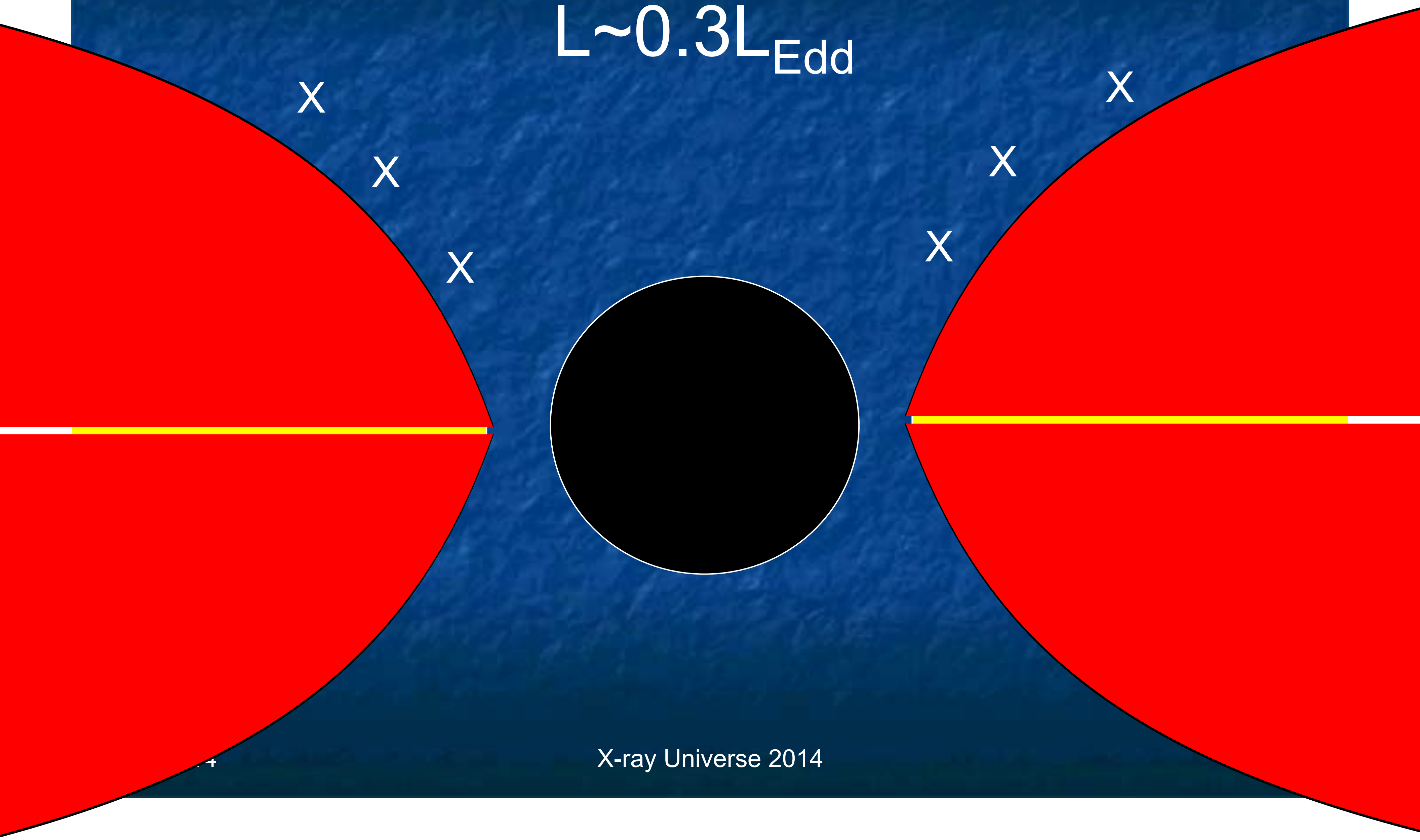

Cackett, Zoghbi, Reynolds et al. (2014)
… also Emmanoulopoulos et al. (2014)
18
16
14
12
10
χ^2
2
4
6
8
10
12
14
h (R$_G$)
NGC4151
8000
6000
4000
2000
0
−2000
Lag (s)
Energy (keV)

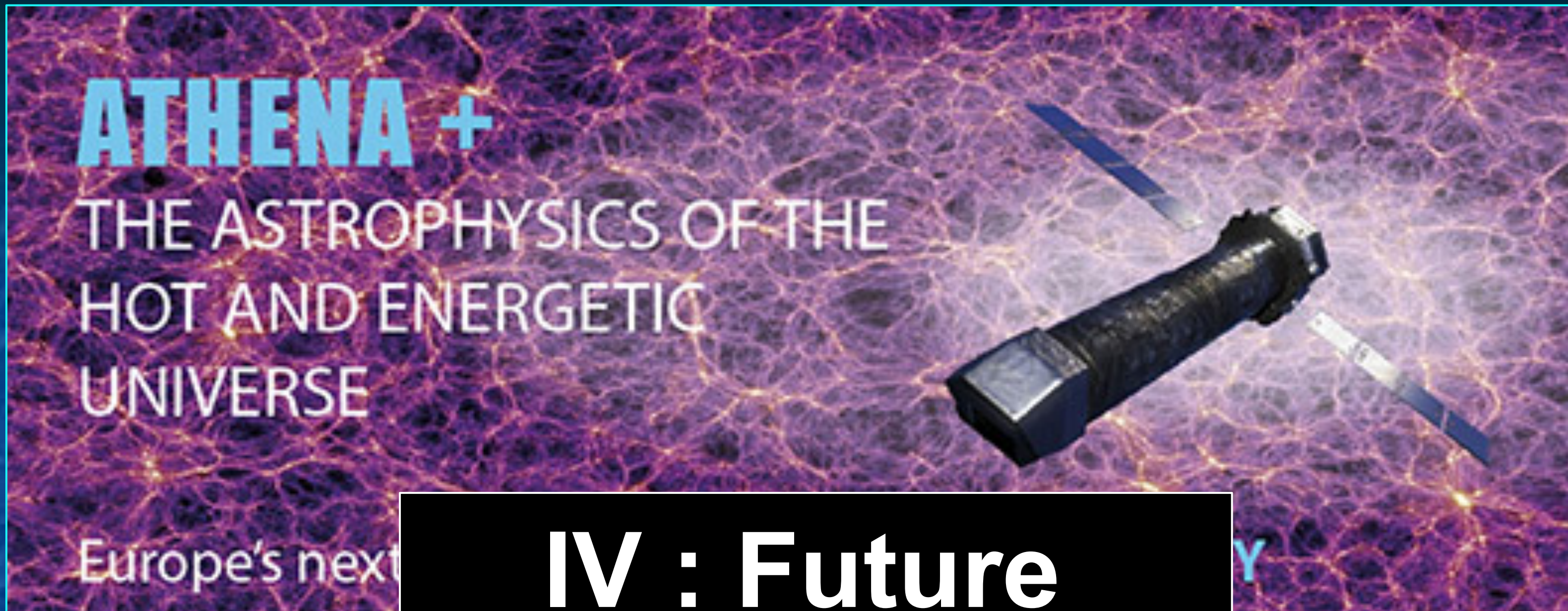


$L \sim 0.1 L_{Edd}$

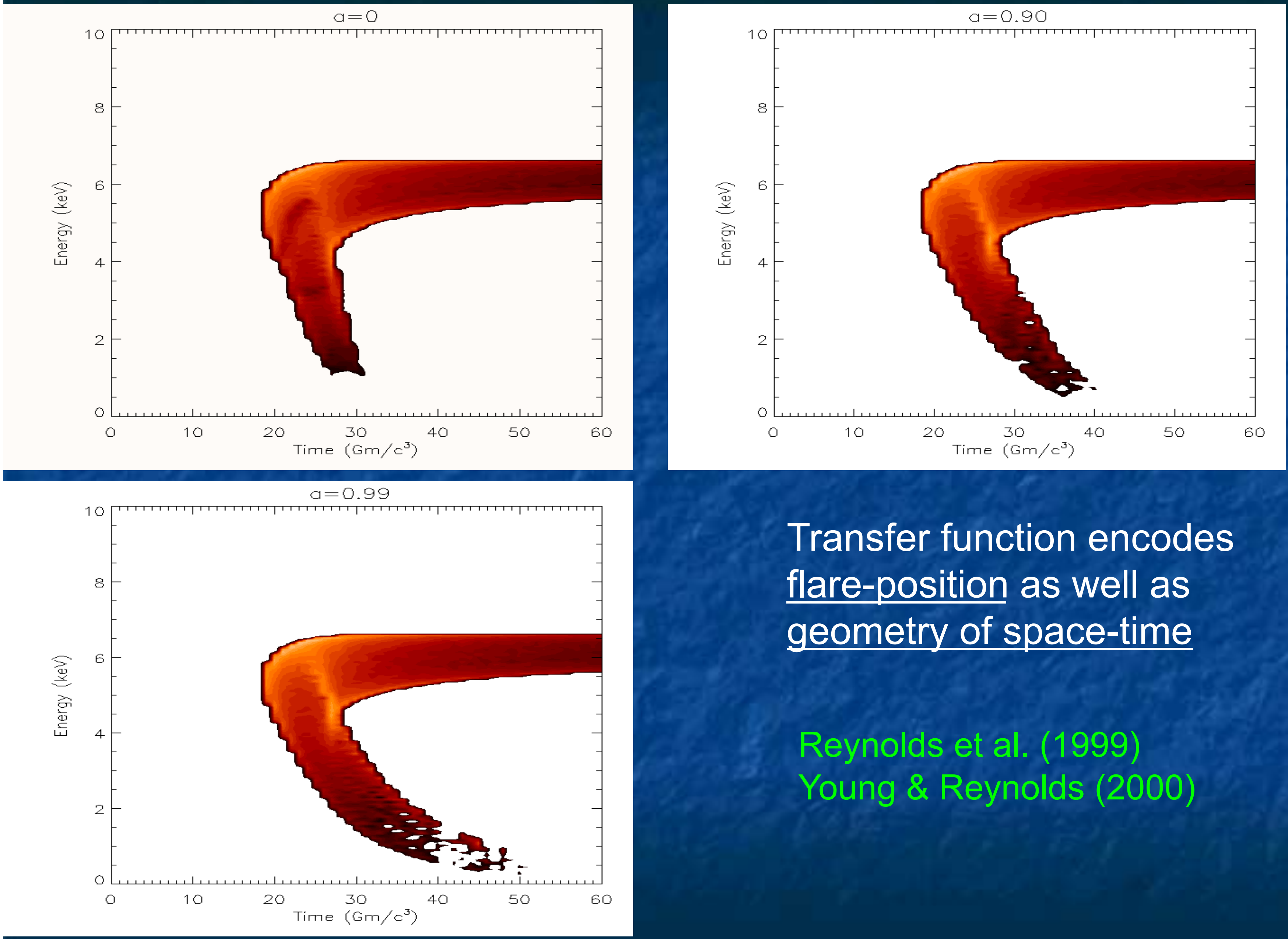


$L \sim 0.3 L_{Edd}$





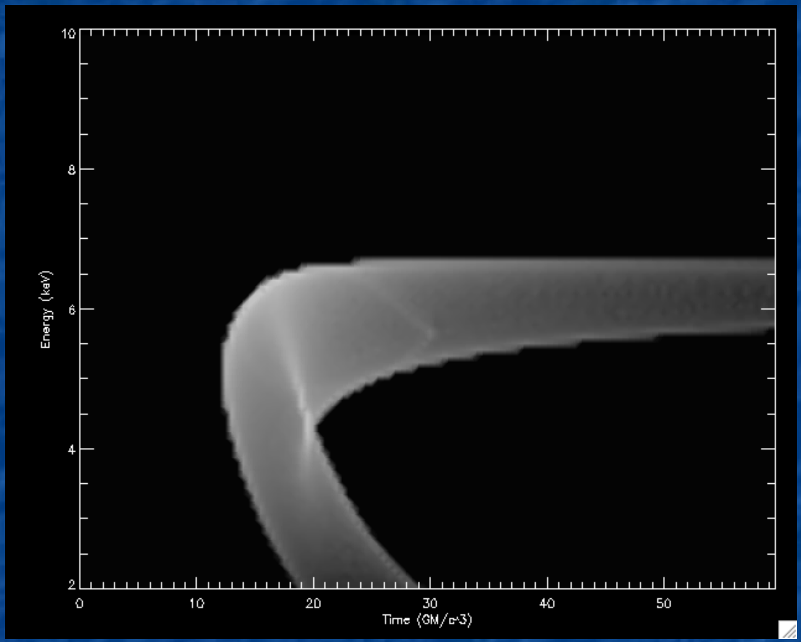
IV : Future Prospects

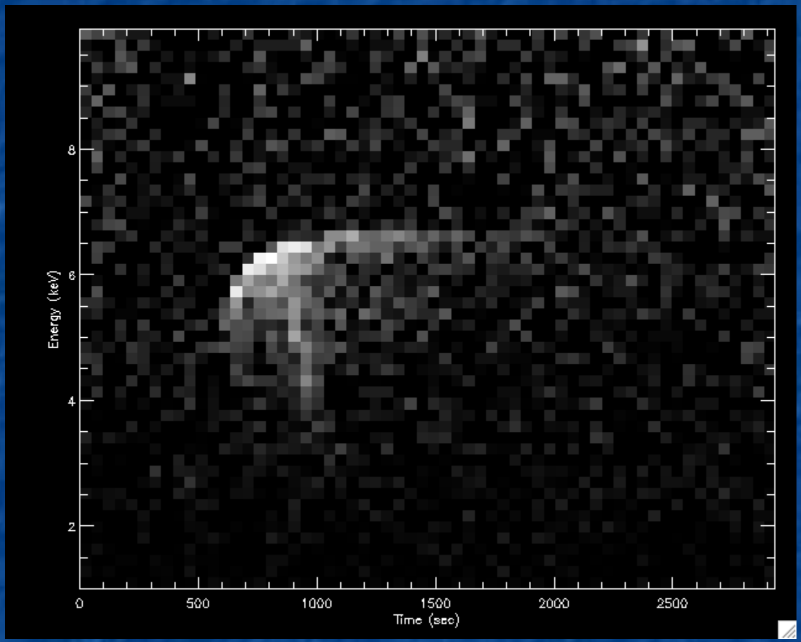


Transfer function encodes <u>flare-position</u> as well as <u>geometry of space-time</u>

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

Individual reverberation events unlock full power of reverberation mapping





Requires next generation high-throughput mission (ATHENA or even LOFT*)

Conclusions

- X-ray spectroscopy and timing providing powerful and complementary tools for probing relativistic physics
- SMBH spin measurements maturing… providing interesting input for SMBH growth models
- Relativistic reverberation seen in ~10 objects, providing puzzling picture of X-ray source