STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017

SEVENTH FRAMEWORK PROGRAMME

X-ray reverberation in Active Galactic Nuclei

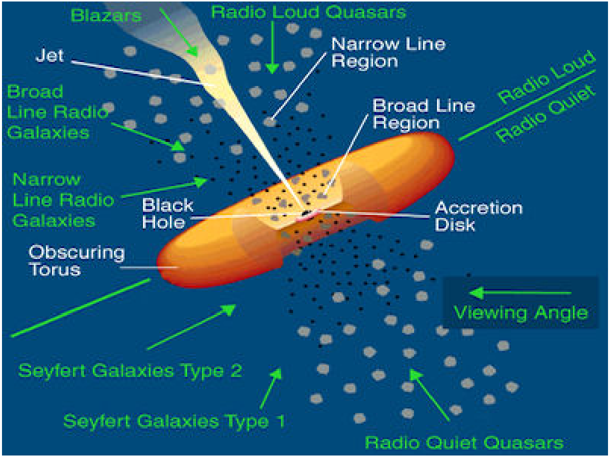
Michal Dovčiak

Astronomical Institute
Academy of Sciences of the Czech Republic, Prague

Seminar of the Astronomical Institute ASCR, Ondřejov, Czech Republic

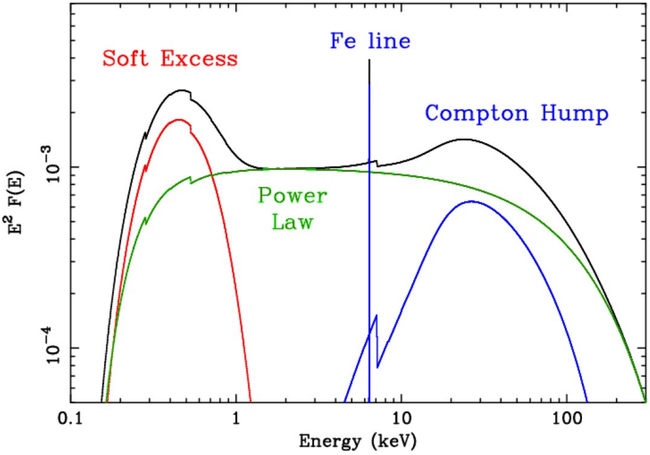
17th December 2014

Active Galactic Nuclei – scheme



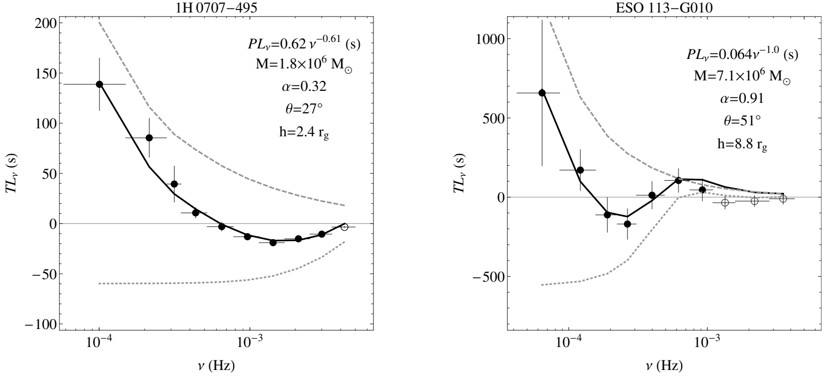
Urry C. M. & Padovani P. (1995)
Unified Schemes for Radio-Loud Active Galactic Nuclei
PASP, 107, 803

Active Galactic Nuclei – X-ray spectrum



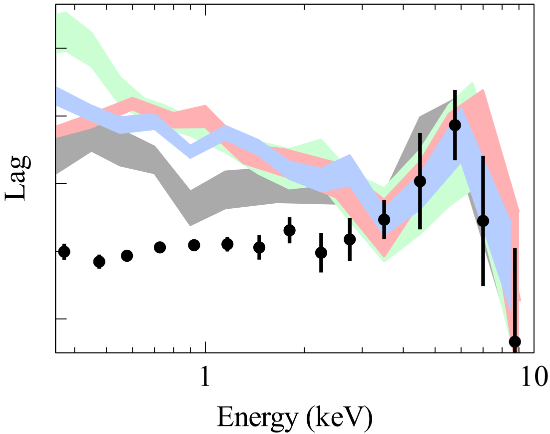
Fabian A.C. (2005)
X-ray Reflections on AGN,
in proceedings of “The X-ray Universe 2005”, El Escorial, Madrid, Spain, 26-30/9/2005

Active Galactic Nuclei – lags



Emmanoulopoulos et al. (2014)
General relativistic modelling of the negative reverberation X-ray time delays in AGN, MNRAS **439** 3931

Active Galactic Nuclei – lags



Kara et al. (2014)

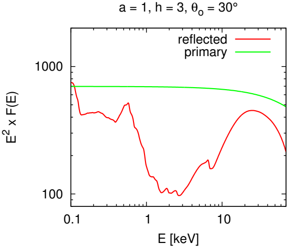
The curious time lags of PG 1244+026: Discovery of the iron K reverberation lag, MNRAS **439** L26

Why to study toy model of lamp-post geometry?

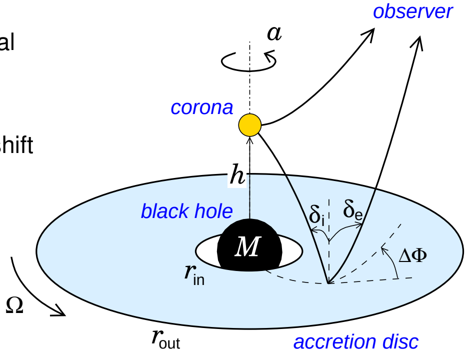
- Astrophysical motivation:
  - observational evidence of a rather compact X-ray source (variability, micro-lensing) – corona size of tens of $R_g = GM/c^2$
  - base of a (possibly aborted) jet?
- Useful simplification:
  - many effects should be qualitatively similar with this simple geometry
  - it can give us certain limits on the model
    (e.g. limits on possibility of spin measurements)
  - we can easily explore the dependence on many parameters
    (height of the corona, ionization of the disc, ...)
  - if we want to study the dependence on geometry, we should know how other parameters influence the results

    (e.g. *Is the idea of measuring geometry of the corona via reverberation feasible?*)

Scheme of the lamp-post geometry

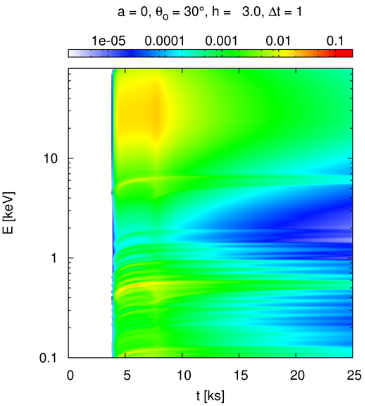


- central black hole – mass, spin
- compact corona with isotropic emission
  → height, photon index
- accretion disc
  → Keplerian, geometrically thin, optically thick
  → ionisation due to illumination
  (L_p, h, M, a, n_H, q_n)
- local re-processing in the disc
  → REFLIONX with different directional emissivity prescriptions
- relativistic effects:
  → Doppler and gravitational energy shift
  → light bending (lensing)
  → aberration (beaming)
  → light travel time
- KYREFLIONX

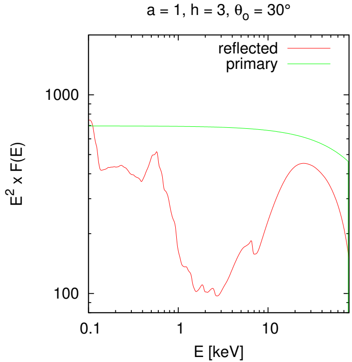


Dynamic spectrum – ionised disc

$$E^2 \times F(E)$$



Parameter values and integrated spectrum



$$
\begin{aligned}
M &= 10^8 M_\odot \\
a &= 1\ (0) \\
\theta_\mathrm{o} &= 30^\circ\ (60^\circ) \\
h &= 3\ (1.5,\ 6,\ 15,\ 30) \\
L_\mathrm{p} &= 0.001\, L_\mathrm{Edd} \\
\Gamma &= 2\ (1.5,\ 3) \\
n_\mathrm{H} &= 0.1\ (0.01,\ 50,\ 5,\ 0.2) \times 10^{15}\mathrm{cm}^{-3} \\
q_\mathrm{n} &= -2\ (0,\ -5,\ -3)
\end{aligned}
$$

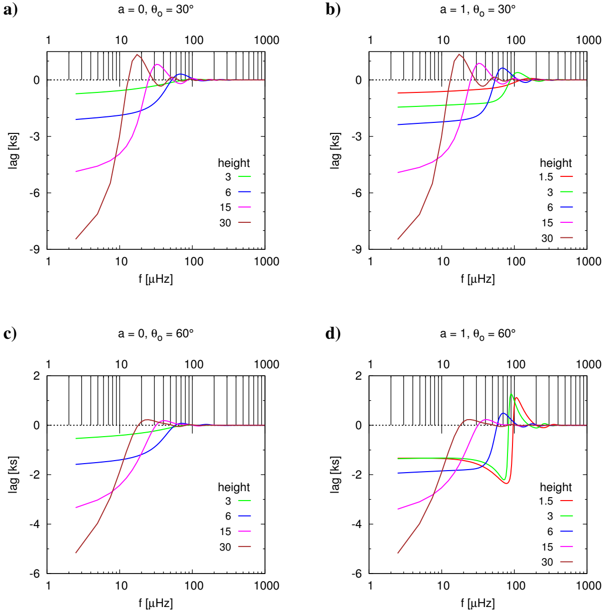
Energy bands: soft excess: 0.3 – 0.8 keV

primary: 1 – 3 keV

iron line: 3 – 9 keV

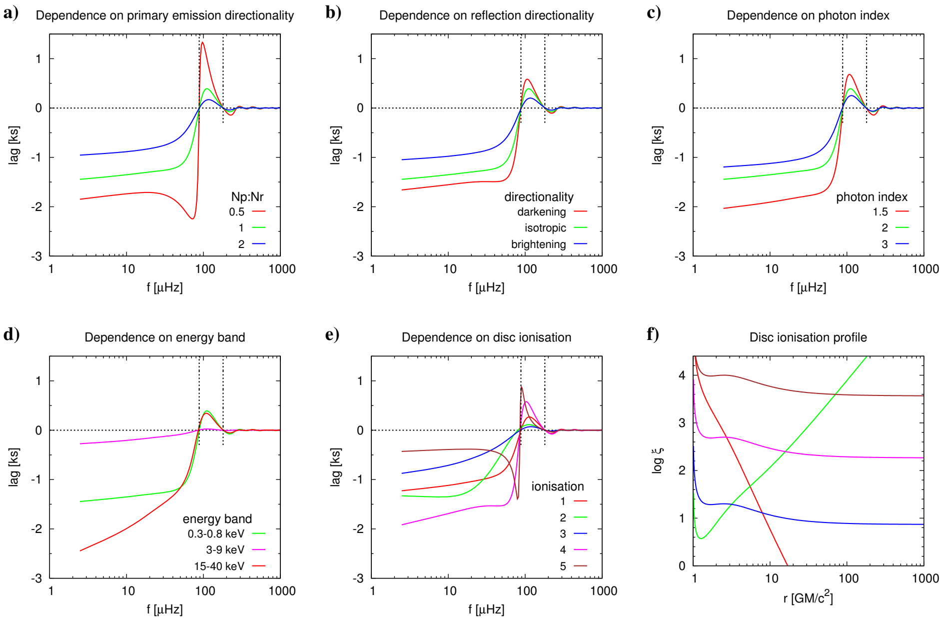
Compton hump: 15 – 40 keV

Lag dependence on geometry

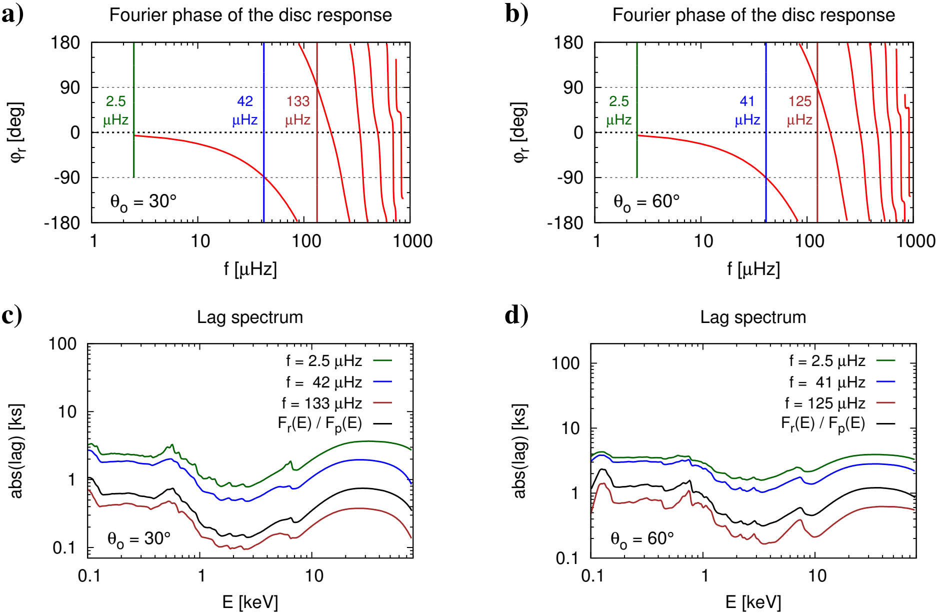


- the lag amplitude:
  - the lag increases with height
  - the lag decreases with inclination (exception: low heights and high spin)
  - the lag decreases with spin (exception: low heights and high inclination)
- the lag null points (due to phase wrapping)
  - shift to lower frequencies for higher heights due to longer timescales of response
  - change slightly with the inclination
  - change negligibly with the spin

Lag dependence on other parameters



Lag energy dependence



Summary

- the frequency dependence of the lag is mainly due to geometry (height of the corona)
- the magnitude of the lag depends on many details of the model (height, spin, ionisation, unisotropy, energy)
- lag versus energy follows the spectral shape at the right frequencies

Definition of the lag

$$F_{\rm refl}(E,t) = N_{\rm p}(t) * \psi(E,t) \qquad \Rightarrow \qquad \hat{F}_{\rm refl}(E,f) = \hat{N}_{\rm p}(f).\hat{\psi}(E,f)$$

where

$$\hat{\psi}(E,f) = A(E,f)e^{i\phi(E,f)}$$

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if

$$N_{\rm p}(t) = \cos(2\pi f_0 t) \qquad \text{and} \qquad \hat{\psi}(E,f) = A(E,f)\, e^{i\phi(E,f)}$$

then

$$F_{\rm refl}(E,t,f_0) = A(E,f_0)\cos\{2\pi f_0[t+\tau(E,f_0)]\} \qquad \text{with} \qquad \tau(E,f_0) \equiv \frac{\phi(E,f_0)}{2\pi f_0}$$

$$F(E,t) \sim N_{\rm p}(t) * (\psi_{\rm r}(E,t) + \delta(t)) \qquad \Rightarrow \qquad \hat{F}(E,f) \sim \hat{N}_{\rm p}(f).(\hat{\psi}_{\rm r}(E,f) + 1)$$

and

$$\tan\phi_{\rm tot}(E,f) = \frac{A_{\rm r}(E,f)\sin\phi_{\rm r}(E,f)}{1 + A_{\rm r}(E,f)\cos\phi_{\rm r}(E,f)} \qquad \psi_{\rm r}(E,t) = \frac{F_{\rm r}(E,t)}{F_{\rm p}(E)}$$

Lag energy dependence

for low f:

$$\begin{aligned} A_\mathrm{r}(E,f) &\simeq A_\mathrm{E}(E)A_\mathrm{f}(f) \quad \text{and} \quad A_\mathrm{E}(E) \simeq \psi_\mathrm{r}(E) \\ \phi_\mathrm{r}(E,f) &\simeq \phi_\mathrm{r}(f) \end{aligned}$$

and

$$\tau(E,f) \simeq \frac{1}{2\pi f}\,\mathrm{atan}\,\frac{A_\mathrm{r}(E,f)\sin\phi_\mathrm{r}(E,f)}{1+A_\mathrm{r}(E,f)\cos\phi_\mathrm{r}(E,f)}$$

for $f \to 0$:

$$\tau(E,f) \simeq \frac{\phi_\mathrm{r}(f)}{2\pi f}\,\frac{A_\mathrm{f}(f)\,\psi_\mathrm{r}(E)}{1+A_\mathrm{f}(f)\,\psi_\mathrm{r}(E)}$$

for f such that $\phi_\mathrm{r}(f) = \pm\dfrac{\pi}{2}$:

$$\tau(E,f_{\pm\pi/2}) \simeq \frac{1}{2\pi f_{\pm\pi/2}}\,\mathrm{atan}\left[A_\mathrm{f}(f_{\pm\pi/2})\,\psi_\mathrm{r}(E)\right]$$