Fe line diagnostic in accreting black holes

Accretion under strong field gravity regime

Alessandra De Rosa  IAPS/INAF

eXTP Workshop - Rome 2017
The two flavours  Accreting BH

stellar mass BHs scattered in galaxies
  (X-ray binaries)

supermassive BHs in the center of
  galaxies (AGN and quasars)

Close to the BH, most of the physical
  processes are the same. we can learn
  a great deal by comparing the two
  families

What really matters in these studies is
  the n. of photons (i.e. flux, $F_{\text{obs}}$) per
  unit of light crossing time scale
  $$\sim \frac{R_g}{c} \sim \frac{GM}{c^3} \sim 500 \text{ M}_\odot \text{ s}$$

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$10^6-10^9 \text{ M}_\odot$
$R_g/c=50 \text{ s}$

$8-10 \text{ M}_\odot$
$R_g/c=50 \mu \text{s}$
(some) Open questions

- how does matter behave in the strong GR field regime?
- what are the processes near the event horizon? (accretion/ejection)
- How does the spin affect the emission/jet processes?
- how are BH spins distributed? (BH birth/growth)
- . . . . . .

X-ray tools (some)
Relativistic reflection - spectral
Thermal disc emission - spectral
High Frequency QPOs - timing
Polarization degree - polarimetry
The Broadband X-ray spectra

Type 1 AGN  XRB-high soft state

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The X-ray reflection spectrum

Compton Scattering & Photoelectric absorption

$\propto$ Inclination
$\propto \Omega/2\pi$ (coverage, isotropy)

Reynolds 96
Ross & Fabian 99, 05
Fe Kα emission line from different disk radii

The big advantage of this method: it is independent on the BH’s mass. Everything is expressed in terms of $R_g$.

Brenneman & Reynolds 2006; Dauser+ 2010
Doppler shifts
relativistic beaming
gravitational redshift
gravitational light bending

The Effects of SFG are all involved in modelling the spectral-timing results in a wide energy band

rest frame observed

$\xi = 2 \times 10^2$
SFG BH diagnostic: Fe line (variability)

- SMBHs - AGN
  - Disk Fe line profile
  - Phase resolved Fe line. Orbiting Hot Spot
  - X-ray reverberation. Time lags

- Stellar mass BH - XRB
  - Disk Fe line profile
  - Continuum fitting
  - X-ray reverberation. Time lags
  - QPOs
  - QPOs phase resolved polarimetry
SFG BH diagnostic: Fe line (variability)

- SMBHs - AGN
  - Disk Fe line profile
  - Phase resolved Fe line. Orbiting Hot Spot
  - X-ray reverberation. Time lags - Uttley’s talk

- Stellar mass BH - XRB
  - Disk Fe line profile
  - Continuum fitting - Lijun’s talk
  - X-ray reverberation. Time lags
  - QPOs - Stevens’s talk
  - QPOs phase resolved polarimetry - Ingram’s talk
AGN SMBHs
Measuring the SMBHs spin

Ingredients

- High S/N in X-ray band: ≥ 2x10^5 counts in 2-10 keV
- Broad line with $r_{in} \leq 10 \, r_g$ in unobscured ($N_H < 10^{22} \, \text{cm}^{-2}$) AGN
- Broad energy band is needed to model simultaneously all spectral complexities: Complex absorption, disk ionization, disk emissivity, soft excess, Fe abundance

~30 bright AGN in the nearby Universe (Miller+ 2007, Nandra+ 2007, de La Calle Perez+ 2010, Reynolds 2013, Marinucci+14, Patrick+14, Risaliti+13) but ~$10^{12}$ accessible universe
Very Broad Fe-K line profiles with XMM in:

**AGN**
- MCG-6-30-15
- NGC2992
- IRAS18325
- MCG-5-23-16
- Fairall 9
- 3C382
- type-1 AGN (EW=700)
- PG1211
- NGC3516
- NGC4151
- Mrk766

**X-ray Binaries**
- GX339-4
- GRS1915+105
- XTEJ1550
- Cygnus X-1

Similar line profiles from stellar-mass and supermassive black hole systems... demonstrates insensitivity of line profile to mass.
Broadband relativistic reflection with NuStar

Simultaneous observation of Fe line and Reflection Continuum above 10 keV

Better results using spectral diagnostics have been obtained with combined XMM/NuStar data

Fabian+2015
NGC1365, Risaliti+13
<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>Data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1H0707-495</td>
<td>&gt; 0.988</td>
<td>XMM-Newton/NuSTAR</td>
<td>Kara et al. (2015)</td>
</tr>
<tr>
<td>Ark 120</td>
<td>~0.5</td>
<td>XMM-Newton/NuSTAR</td>
<td>Matt et al., 2014</td>
</tr>
<tr>
<td>Fairall 9</td>
<td>0.973 ± 0.003</td>
<td>XMM-Newton/NuSTAR</td>
<td>Lohfink et al. (2016)</td>
</tr>
<tr>
<td>MCG-6-30-15</td>
<td>0.91^{+0.06}_{-0.07}</td>
<td>XMM-Newton/NuSTAR</td>
<td>Marinucci et al., 2014a</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>&gt; 0.9</td>
<td>Swift/NuSTAR</td>
<td>Parker et al., 2014</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>&gt; 0.97</td>
<td>XMM-Newton/NuSTAR</td>
<td>Risaliti et al., 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Walton et al., 2014</td>
</tr>
<tr>
<td>NGC4151</td>
<td>&gt; 0.9</td>
<td>Suzaku/NuSTAR</td>
<td>Keck et al. (2015)</td>
</tr>
<tr>
<td>SWIFT J2127.4</td>
<td>0.58^{+0.11}_{-0.17}</td>
<td>XMM-Newton/NuSTAR</td>
<td>Marinucci et al., 2014b</td>
</tr>
</tbody>
</table>
The current uncertainties on the continuum decrease the statistical quality of present measurements (if the continuum is properly modelled) and, more importantly, may introduce systematic errors on spin (if the continuum is improperly modelled).
Relativistic vs absorption scenario

Physically consistent broadband reflection model

Miller+08

Miniutti+07

Jan 06, 300ks exposure

Strong Reflection (R>2)

Ratio

Energy (keV)

0.5

1

1.5

Mean spectrum

Partial covering absorption

absorbed reflection

CXB

a

b

c

d

Eff(E) / keV s^(-1) cm^(-2)

5x10^(-4) 10^(-3) 2x10^(-3) 3x10^(-3) 0.01 0.02

E_{observed} / keV

1 10
Soft-excess NGC 3783

Soft excess $<2$ keV reproduced with Scattered component + relativistic reflection

$a>0.9$ Brenneman+11

e.g. Mkn509. Petrucci+13

Soft excess $<2$ keV reproduced with comptonized component $a<0.3$ Patrick+11

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AGN variability is likely associated to “activation” of the X-ray regions above the disk. The flares produce an echo in the observed reflection components on time-scales comparable light-crossing of $1 \, R_g$.

While *time averaged* Fe profiles can be expressed in terms of $r_g$, losing any information about BH mass, assuming the ‘hotspot’ (keplerian) corotating with the disc, the orbital period (and then the BH mass) can be measured

$$T_{\text{orb}} = 310 \, (r^{3/2} + a) M_7 \, \text{s},$$

Iwasawa+04
De Marco+08
Orbiting spots: Disc Doppler tomography

reflection components vary on orbital period time-scales

$$T_{orb} = 310 \left( \frac{r^{3/2} + a}{M_*} \right) \text{s}$$

From **time resolved spectroscopy** it is possible to derive the radius both in units of the BH mass and in standard units

→ BH mass (and l.l to the spin)
Orbiting spot observations: NGC3516

The excess emission map on the time-energy plane. The pixel size is 2 ks in time and 100 eV in energy. 4 cycles 25 ks orbital period at 9Rg (Iwasawa+04, Turner+06)

The Fe K line profiles during the on (solid circles) and off (open squares) phases of the red feature.

\[ M_{\text{X-ray}} = 1.5 \times 10^7 \, M_{\text{sun}} - M_{\text{opt}} = 1.68(0.33) \times 10^7 \, M_{\text{sun}} \]
Fe line variability in the red and blue energy bands (5.4-6.1/6.8-7.2 keV) has been found in 12 out of 36 observations but still to be confirmed at high confidence.

De Marco et al. (2009) performed a systematic analysis of 72 XMM observations of the brightest/variable RQ AGN of the FERO sample (de la Calle+10) with the aim of characterizing the temporal behaviour of Fe K complex features.
Spin in BHB

I. Relativistic reflection (like SMBHs)

II. Continuum fitting: Fitting the thermal 1-10 keV spectrum of the accretion disk
Relativistic reflection with NuStar

No Pile-up!
Measuring BH spins in XRB: where do we stand?

- Huge S/N no pile-up (NuStar)
- Cold/Warm photoionized absorbers
- Relativistic reflection
- Disk inclination disagrees with optical measurements
- Different models for disc emissivity profile produce different value of the BH spin

Cyg X-1 high-soft state 30ks

A big advantage will be to have different simultaneous diagnostics

Tomsick+14
Continuum fitting technique

• Requires accurate values of $M$, $i$, $D$; also knowledge of spectral hardening from disk atmosphere (e.g., Davis+ 2006).

Radius $R_{ISCO}$ of Disk Hole

$F$ and $T \rightarrow$ solid angle

$D$ and $i \rightarrow R_{ISCO}$

$F, T \rightarrow$ X-ray observations, assume $T = T_{ISCO}$

$\cos (i)$ and $D$ are known

calculate $a$ from $R_{ISCO}$ and $M_{BH}$

McClintock+11
A. De Rosa

Requirements:

- Spectrum dominated by Disk components
- Theoretical profile for F(R)
- Thin disk
- Knowledge of i, D, M

Steiner+ 09,+11
## BH Spin in XRBs

<table>
<thead>
<tr>
<th>Black Hole</th>
<th>Spin (CF)</th>
<th>Spin (Fe K)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRS 1915+105</td>
<td>&gt; 0.98</td>
<td>0.98 ± 0.01</td>
<td>McClintock+ (2006); Blum+ (2009)</td>
</tr>
<tr>
<td>Cygnus X-1</td>
<td>&gt; 0.97</td>
<td>0.05 ± 0.01</td>
<td>Gou+ (2011); Miller+ (2009)</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>0.92 ± 0.06</td>
<td>---</td>
<td>Gou+ (2009)</td>
</tr>
<tr>
<td>M33 X-7</td>
<td>0.84 ± 0.05</td>
<td>---</td>
<td>Liu+ (2008, 2010)</td>
</tr>
<tr>
<td>4U 1543-47</td>
<td>0.80 ± 0.05</td>
<td>0.3 ± 0.1</td>
<td>Shafee+ (2006); Miller+ (2009)</td>
</tr>
<tr>
<td>GRO J1655-40</td>
<td>0.70 ± 0.05</td>
<td>0.98 ± 0.01</td>
<td>Shafee+ (2006); Miller+ (2009)</td>
</tr>
<tr>
<td>XTE J1550-564</td>
<td>0.34 ± 0.24</td>
<td>0.76 ± 0.01</td>
<td>Steiner+ (2011); Miller+ (2009)</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>&lt; 0.3</td>
<td>---</td>
<td>Davis+ (2006)</td>
</tr>
<tr>
<td>A 0620-00</td>
<td>0.12 ± 0.18</td>
<td>---</td>
<td>Gou+ (2009)</td>
</tr>
<tr>
<td>GX 339-4</td>
<td>---</td>
<td>0.94 ± 0.02</td>
<td>Reis+ (2009)</td>
</tr>
<tr>
<td>XTE J1650-500</td>
<td>0.87 ± 0.01*</td>
<td>0.79 ± 0.01</td>
<td>Miller+ (2009); Miller+ (2009)</td>
</tr>
<tr>
<td>SAX J1711.6-380</td>
<td>0.6 ± 0.4*</td>
<td>0.6 ± 0.3</td>
<td>Miller+ (2009); Miller+ (2009)</td>
</tr>
<tr>
<td>XTE J1752-223</td>
<td>---</td>
<td>0.55 ± 0.11</td>
<td>Reis+ (2010)</td>
</tr>
<tr>
<td>XTE J1908+094</td>
<td>0.75 ± 0.09*</td>
<td>0.75 ± 0.09</td>
<td>Miller+ (2009); Miller+ (2009)</td>
</tr>
<tr>
<td>SWIFT J1753.5-0127</td>
<td>---</td>
<td>0.76 ± 0.15</td>
<td>Reis+ (2009)</td>
</tr>
<tr>
<td>XTE J1652-453</td>
<td>---</td>
<td>0.5 ± 0.1</td>
<td>Hiemstra+ (2009)</td>
</tr>
</tbody>
</table>
Where are we?

systematic uncertainties related to both the spectral models as well as the calibration of the spectral data (for XRB) dominate statistical errors; there is the danger that one will end up with very precise but inaccurate spin measures

key observations are

1. Time resolved spectroscopy
2. Reverberation: time lags (Uttley’s talk)
3. Spectral–polarimetry of QPOs (Ingram’s talk)

ALL these diagnostics together
Future perspective with eXTP
**XTP: SFA**

- 9000 cm$^2$ @ 2 keV
- 6000 cm$^2$ @ 6 keV
- 3700 cm$^2$ @ 10 keV
- Low background
- High energy res @ 6 keV
- <2 keV energy band

**LOFT: LAD**

- 3 m$^2$ @ 6 keV / 0.1 m$^2$ @ 30 keV
- Energy res CCD like
- Broad band 2-30(80) keV
## SFG Science Objectives

<table>
<thead>
<tr>
<th>Science topic</th>
<th>Key performance</th>
<th>Key Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN: Doppler tomography</td>
<td>Effective area – BKG – Ene resolution</td>
<td>SFA-LAD</td>
</tr>
<tr>
<td>AGN: Fe line</td>
<td>Effective area – BKG – Ene resolution</td>
<td>SFA</td>
</tr>
<tr>
<td>XRB: Fe line</td>
<td>Effective area</td>
<td>LAD</td>
</tr>
<tr>
<td>X-ray reverberation</td>
<td>Effective area – soft X coverage</td>
<td>LAD-SFA</td>
</tr>
<tr>
<td>Disc thermal emission/reverberation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QPOs</td>
<td>Effective area</td>
<td>LAD</td>
</tr>
<tr>
<td>QPO Phase resolved polarimetry</td>
<td>Effective area</td>
<td>LAD-GPD</td>
</tr>
</tbody>
</table>
eXTP: XRB Fe line

Flux=0.5 Crab
Texp=100 s
q = disc emissivity index

eXTP will improve the BH’s spin measurement accuracy on short timescale (<100s).

Unprecedentedly short timescale will allow us to investigate Variability of the innermost regions on a timescale comparable with outflows components (e.g disk winds. GRS1915 Nielsen+2011; 4U1630-47Diaz-Trigo+14 )
R_{\text{spot}} \sim 1-2\% 
Bh spin & from broad Fe line

r=3m\mu\text{Crab}, \text{EW(average)}=30\text{ eV}, a=0.5,
r_{\text{in}}=1r_g, \ r_{\text{out}}=100r_g, \ \theta=30^\circ, \ \varepsilon \sim r^{-3}, \ r_{\text{sp}}=10r_g
T_{\text{orb}}=9\text{ ks}
M=3-4 \times 10^6 \ M_{\odot}, \ a=0.4-0.6, \ R=0.9(0.1)
Doppler Tomography. Figure of Merit

**Requirement:**
- 3sigma detection
- Line in 5.5-6.5 keV
- $\sigma = 100$ eV
- EW = 50 eV

**Time scale**
- $T_{\text{orb}}(\text{ISCO}) \sim 5000 \times (M/10^7 \text{ Msun}) \text{ s} - \text{Swartz.}$
- $T_{\text{orb}}(\text{ISCO}) \sim 500 \times (M/10^7 \text{ Msun}) \text{ s} - \text{Kerr}$

Graph showing flux (2-10 keV) vs. time (s) for different Crab flux levels: 2.7 mCrab, 0.6 mCrab, and 0.2 mCrab.
Doppler tomography with the brightest X-ray AGN

195

5x10^{-12} \text{erg/cm}^2/\text{s}

eXTP current baseline

120

-\log F(2-10 \text{keV})
AGN Astrophysics

✓ **Hot Corona** is compact, size \( \sim 10R_g \) (reverberation, microlensing Chartas+09, Fabian+15). Geometry and physics still unknown

✓ **Soft-excess** comptonised warm corona or blurred reflection

✓ **Cold absorption** regions (BLR, Torus), eclipses events, Unified Model for AGN

✓ **Warm absorption(s)**

✓ **Disk winds and UFOs**
AGN broad band properties

$F(2-10 \text{ keV}) = 2e^{-12} \text{ cgs} - 100 \text{ ks}$

- **Warm Absorber(s)**
  - High energy resolution (Athena)

- **Cold Reflection Broadband + WFM**

- **Soft Excess Broad band**

- **UFO**
  - High energy resolution (Athena)
AGN broad band properties
F(2-10 keV) = 2e-12 cgs – 10x10 ks

Time resolved spectral variability of the WA components!!

Map from the pc to Kpc scale: disc winds-BLR-torus

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AGN broad band properties

\[ F(2-10 \text{ keV}) = 2 \times 10^{-12} \text{ cgs} - 10 \times 10 \text{ ks} \]

Time resolved spectral variability of the primary component

**XMM – 4e-11 cgs x10 brighter**

credit S. Bianchi

Marinucci+14
White Paper

Accretion in Strong field gravity regime

Mapping the inner regions around BHs

A. De Rosa, P. Uttley, Lijun Gou, Yuan Liu
and the eXTP-SFG WG Team

Submit your application to the SFG-WG
http://www.isdc.unige.ch/extp/swg-registration.html
Summary

• X-ray spectroscopy and timing provide a strong tools for probing accretion under SFG regime. Latest XMM/NuStar results on BHs spin are still not conclusive.

• New key observations are needed to disentangle systematic effects mainly due to modellization (SMBH) or calibration (XRB)

• The eXTP mission is particularly suited to address these issues with 3 different key measurements which complement each other.

Thank you!
**Narrow Fe line Reverberation**

**Goal:** monitoring the Fe line and the continuum in order to investigate the geometry and location of the reprocessing material.

**Expected time-scales are from weeks to years (BLRs, Torus)**

**What can be done now?**

Swift BAT 'continuous' lightcurves for the continuum
Badly sampled Fe line fluxes from different instruments
Narrow Fe line reverberation with eXTP

- eXTP will perform a well-sampled monitoring for the narrow Fe line (and Compton reflection for the brightest AGN) with short observations
- in 1 ks for 1mCrab AGN the Fe line flux can be recovered with SFA+LAD with an uncertainty of ~5-10%
- The WFM will produce continuous light-curves with 3σ daily (on average) time-bins for bright sources (10^{-10} cgs in the 7-50 keV band, i.e., above the Fe K edge). Weaker objects (5 x10^{-11} cgs) will have 3σ weekly (on average) time-bins
- WFM+SFA+LAD combined capabilities!

These timescales are perfectly suited for the Fe narrow line reverberation analysis, since the expected timescales are from days to weeks to years (external disk, BLRs, Torus)
AGN variability with the WFM

The vertical colorbar shows the total number of AGN for which the WFM will return light curves with at least 10 points and where variability will be detected with S/N > 3.

Credit M. Paolillo