StrongGravity - probing strong gravity by black holes across the range of masses

Michal Dovčiak on behalf of StrongGravity consortium

*From the Dolomites to the event horizon: Sledging down the Black Hole potential well (4th edition)*

Sesto Val Pusteria, Italy, 13/7/2017
EU 7th Framework Programme (2007-2013)

Space Call 5 – FP7-SPACE-2012-1 (€ 84 mil.)

Activity 9.2.: Strengthening the foundations of Space science and technology
Area 9.2.1: Research to support space science and exploration
Topic SPA.2012.2.1-01: Exploitation of space science and exploration data (8 mil. €)

→ collaborative project – small or medium-scale focused research project (at least 3 partners, 2 mil. €)

Call date: 20/7/2011 Submission deadline: 23/11/2011

Altogether 6 Space calls in FP7 (one per year: 2008-2013)

Horizon 2020 – only 2 relevant calls in 2014-2017:
→ COMPET-5-2015 and COMPET-4-2017 (one every other year)
→ research and innovation action – budget 1.5 mil. € (out of 6 mil. €)

Title: Probing Strong Gravity by Black Holes Across the Range of Masses
- http://stronggravity.eu
- 5-year project (proposal planning in 2011, evaluation and negotiations in 2012)
- EU contribution: € 1 989 320
- Overall budget: € 2 644 556
- Number of partners: 7
- Number of researchers (including postdocs): 30 (on average)

Participating Institutions:
- Astronomical Institute of the CAS (AsU), Czech Republic → coordinator
- Centre National de la Recherche Scientifc (CNRS), France (Observatoire astronomique de Strasbourg, Université de Strasbourg)
- Università degli Studi Roma Tre (UNIROMA3), Italy
- Institute of Astronomy, University of Cambridge (UCAM), UK
- Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), Spain (Centro de Astrobiología)
- I. Physikalisches Institut, Universität zu Köln (UCO), Germany
- Centrum Astronomiczne im. M. Kopernika, PAN (CAMK), Poland
StrongGravity aims

What do we study?

• Astrophysical black holes and their close environment
  → supermassive Black Holes residing in AGN (radio quite)
  → the supermassive Black Hole in the centre of the Milky Way
  → stellar-mass Black Holes in the binary systems of our Galaxy

Our goal:

→ develop new analytical tools (General Relativity, radiative transfer effects)

→ apply these new tools to observational data from archives of European space-based and ground-based observatories or obtained in new observational campaigns

→ actively help in planning future missions and use our tools for simulations of observations to estimate their capabilities
StrongGravity aims

• On the theoretical side:
  SMBHs → improvement in modeling of all spectral components
    → the primary component: special rel. Comptonization code
    → the refl. component: different ionization states, modeling of lags between primary and reflected emission
    → the iron line emission: realistic emissivity laws
    → the warm absorber: treating absorption and emission lines self-consistently
    → develop and use 3D polarization code for modeling the light curves and polarized emission of Sgr A*
  GBHs → improvement on present disc emission models
    → disc self-irradiation
    → advection processes
    → properties of the disc corona
    → refine QPO models
    → GR effects correctly accounted for in all of these models
StrongGravity aims

- On the observational side:

→ explore the public archives and propose new observations with the current and near-future X-ray facilities

→ to solve the ambiguity between reflection and absorption model

→ determine more robustly the iron line profile and the spin

→ search for time lags between primary and refl. components

→ study timing and polarisation properties of Sgr A* in different wavebands

→ measure the spin with different methods in GBHs
Analytical tools developed


- **KYN** - non-axisymmetric version of several KY general relativistic XSPEC spectral models,
- **KYNrefrev** - XSPEC model for X-ray reverberation modelling in AGN (see also Maria‘s talk),
- **SLIMBH** - XSPEC model for thermal spectra of slim disks around stellar mass black holes,
- **SLIMBHirr** - spectral model of spectra of self-irradiated accretion disks,
- **SLIMULX** - XSPEC model for thermal spectra of slim disks around stellar mass black holes in super-Eddington regime (see also Michal‘s talk),
- **LFQPO comptonization** - Monte Carlo code for modelling LFQPO by comptonization of disk seed photons in a precessing corona (see also Piotr‘s talk),
- **STOKES** - Monte Carlo radiative transfer code for modeling multi-wavelength polarization designed to model astrophysical objects of various geometries that considers polarization induced by electron and dust scattering (see also Frederic‘s talk),
- **MOCA** - fully relativistic Monte Carlo code to compute the spectrum and polarization of the continuum emitted in a corona of hot electrons via inverse Compton of UV/Soft X-ray photons emitted from the accretion disc (see also Francesco‘s talk),
- **MAGSPOT** - polarized lightcurves for a toy model of magnetized spot orbiting a black hole,
- **Cpwabs** - XSPEC model for transmitting spectra through a constant pressure warm absorbing material layer (see also Agata‘s talk),
- **SIM5** - general propose library for relativistic raytracing.
Reflection from black-hole accretion discs – tools

**KYN** – package of *non-axisymmetric* models for XSPEC:
(available at [https://projects.asu.cas.cz/stronggravity/kyn](https://projects.asu.cas.cz/stronggravity/kyn))

- relativistic fluorescent line models:
  - **KYNrline** – broken power-law emissivity,
  - **KYNrlpli** – lamp-post geometry,

- relativistic convolution models:
  - **KYNconv** – broken power-law emissivity,
  - **KYNconvlp** – lamp-post geometry,

- relativistic reflection models:
  - **KYNlpcr** – lamp-post geometry, neutral disc (local emissivity computed by NOAR),
  - **KYNrefionx** – lamp-post geometry, ionised disc (based on REFLIONX),
  - **KYNxillver** – lamp-post geometry, ionised disc (based on XILLVER),

- relativistic thermal radiation models:
  - **KYNbbphen** - radial power-law temperature profile,
  - **KYNbb** - Novikov-Thorne temperature profile with colour correction factor.
KYN – properties:
- emission from a hot spot (section of the accretion disc)
- obscuration by a spherical cloud
- BH spin range: $-1 < a < 1$
- multiple computing threads possible
Some additional notes:

- the ionisation of the disc is set for each radius according to the amount of the incident primary flux and the density of the accretion disc,
- thermal reverberation is included, i.e. increase in the disc temperature due to partial thermalisation of the illuminating flux

Output of the code:

- lag as a function of frequency between given energy bands,
- lag as a function of energy for different frequencies,
- response to the flash:
  - integrated spectrum of the response,
  - light curve for a given energy band,
  - Fourier transform products (Re, Im, amplitude, phase, lag),
- all the above may include only the response or primary as well
Theoretical lag-frequency model

$h = 3r_g$, incl = 30 deg, $a = 0.998$, $A = 1$, $\Gamma = 2$

$M = 1e7M_{\odot}$, soft = 0.3-0.8 keV, hard = 1-3 keV, neutral disc
Reprocessing in the disc

Monte Carlo computations of re-processing in the disc illuminated by power-law radiation with Stokes/Titan (examples for $\Gamma=2$, $\xi=200$):
Reprocessing in the disc

- azimuthal dependence is also included
Reprocessing in the disc

- polarisation for unpolarised illumination is computed as well
3D polarisation modelling of blob

Image of the hotspot while it is behind the black hole. Due to gravitational lensing it can be seen as an Einstein ring.

The green lines represent the polarization - the length represents the polarization degree and the orientation the polarization angle.
Observations

- **AGN spectra** (Marinucci, Matt)
  - black hole spin measurements
  - properties of corona (electron temperature from power-law cut-off, optical thickness from photon index using MOCA – still ongoing effort)
  - importance of NuSTAR data

- **AGN lags** (Kara, Fabian, Alston)
  - lags measured in several sources (lags vs. frequency and energy)
  - Lags observed also in broad iron line energy band
  - lags vs. energy found to be similar to reflection spectrum
  - drop in hard lags at very low frequencies (additional soft component due to absorption?)
  - lags confirmed by NuSTAR in Compton hump
  - lags in QPO
  - long observational campaign proposals (IRAS 13224-3809)
Radio quite AGN observed by NuSTAR

<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>Data</th>
<th>Reference</th>
</tr>
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<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>
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<td></td>
<td></td>
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<td>Walton et al., 2014</td>
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<tr>
<td>NGC4151</td>
<td>&gt; 0.9</td>
<td>Suzaku/NuSTAR</td>
<td>Keck et al. (2015)</td>
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<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>
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</table>
Lags in AGN QPO

RE J1034+396

MS 22549-3712
Observations

• **Sgr A***
  - Polarised light from Sgr A* in the NIR K-band  
    (Shahzamanian et al. A&A 2015)
  - Simulating the emission of SgrA* with an orbiting hotspot model  
    (Karssen et al., submitted)
  - NIR observations (also polarisation detected) and modelling of G2/DSO  

• **GBHBs**
  - spin determination with continuum method vs. reflection (Kohlemainen et al., in prep.) in GBHs from BLACKCAT
  - testing wind explanation for the spin problem in the continuum-fitting method when \( L > 0.3L_{\text{Edd}} \) (You et al. 2016)
  - study of accretion/ejection processes in Swift J1753.5-0127 (Rushton et al.)
  - spin determination with relativistic reflection method (Parker et al. papers)
Observation of G2/DSO

Observation of G2/DSO

- Modelling in Zajacek, Karas, Eckart A&A 2014

DSO polarisation

Zajacek et al. A&A 2017
Final remarks

• StrongGravity (collaborative) project funded by EU:
  - enabled extended collaboration between our teams,
  - enabled more intensive interaction between scientist working in theory, modelling and observations,
  - supported research through funding of postdoc positions,
  - supported international collaboration

• EU support for such projects in space research decreased in last years (RIA)

• Other opportunities in e.g. European Training Networks (ETN) as part of the Innovative Training Networks (ITN) in Marie Skłodowska-Curie Actions of EU
  - however, these are not only in SPACE programme
  - heavily oriented to industry and applied research
  - main objective is training and acquiring skills