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. €)

StrongGravity (2013-2017)

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 Scientific (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

Available (almost) at *http://stronggravity.eu/results/models-and-data*:

- **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*)

- <u>relativistic fluorescent line models:</u>
  - **KYNrline** – broken power-law emissivity,
  - **KYNrlpli** – lamp-post geometry,
- <u>relativistic convolution models:</u>
  - **KYNconv** – broken power-law emissivity,
  - **KYNconvlp** – lamp-post geometry,
- <u>relativistic reflection models:</u>
  - **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),
- <u>relativistic thermal radiation models:</u>
  - **KYNbbphen** - radial power-law temperature profile,
  - **KYNbb** - Novikov-Thorne temperature profile with colour correction factor.

KYNrefionx

```
kynrefionx: initializing reflionx.mod tables...
Ross & Fabian (2005), MNRAS, 358, 211
-------------------------------------------------
ide: initializing data tables, please wait...
     Ref.: Dovciak M., Karas V. & Yaqoob T.
           ApJS July 2004, Volume 153, Issue 1, pp. 205-221
     -------------------------------------------------------
     ...initializing finished

==========================================================================
Model kynrefionx<1> Source No.: 1   Active/Off
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   kynrefionx a/M        GM/c     1.00000      +/-  0.0
   2    1   kynrefionx theta_o    deg      30.0000      +/-  0.0
   3    1   kynrefionx rin        GM/c^2   1.00000      frozen
   4    1   kynrefionx ms                  1            frozen
   5    1   kynrefionx rout       GM/c^2   400.000      frozen
   6    1   kynrefionx phi        deg      0.0          frozen
   7    1   kynrefionx dphi       deg      360.000      frozen
   8    1   kynrefionx M/M8                1.00000      +/-  0.0
   9    1   kynrefionx height     GM/c^2   3.00000      frozen
  10    1   kynrefionx PhoIndex            2.00000      frozen
  11    1   kynrefionx L/Ledd              1.00000E-03  +/-  0.0
  12    1   kynrefionx Np:Nr               0.0          frozen
  13    1   kynrefionx density             1.00000      +/-  0.0
  14    1   kynrefionx den_prof            0.0          +/-  0.0
  15    1   kynrefionx abun                1.00000      +/-  0.0
  16    1   kynrefionx alpha      GM/c^2   -6.00000     +/-  0.0
  17    1   kynrefionx beta       GM/c^2   0.0          +/-  0.0
  18    1   kynrefionx rcloud     GM/c^2   0.0          +/-  0.0
  19    1   kynrefionx zshift              0.0          frozen
  20    1   kynrefionx limb                0.0          frozen
  21    1   kynrefionx tab                 2            frozen
  22    1   kynrefionx sw                  2            frozen
  23    1   kynrefionx ntable              80.0000      frozen
  24    1   kynrefionx nrad                500.000      frozen
  25    1   kynrefionx division            1.00000      frozen
  26    1   kynrefionx nphi                360.000      frozen
  27    1   kynrefionx smooth              1.00000      frozen
  28    1   kynrefionx nthreads            2.00000      frozen
  29    1   kynrefionx norm                1.00000      +/-  0.0

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XSPEC12>
```

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

KYNrefrev

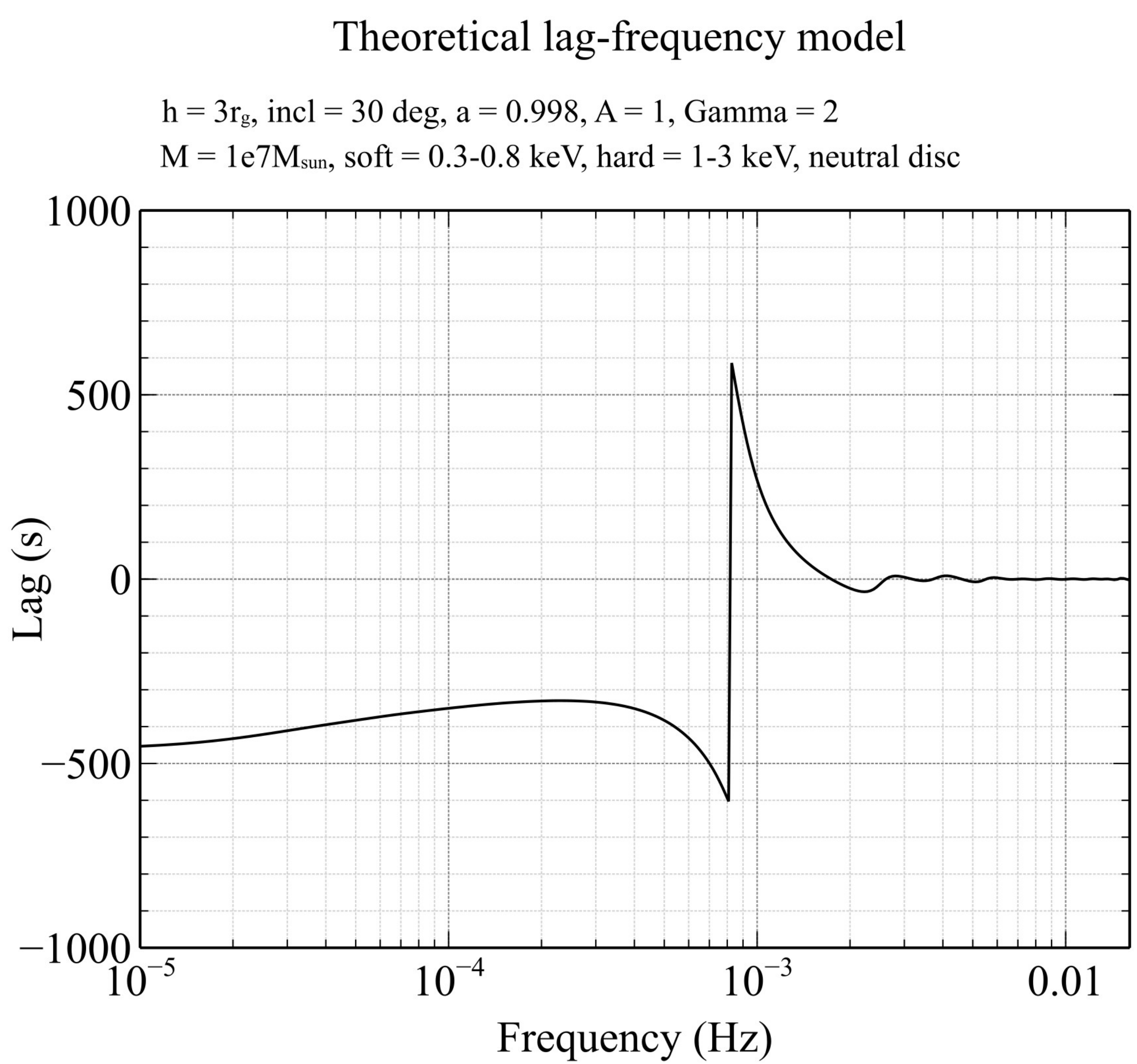
Some additional notes:

- 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

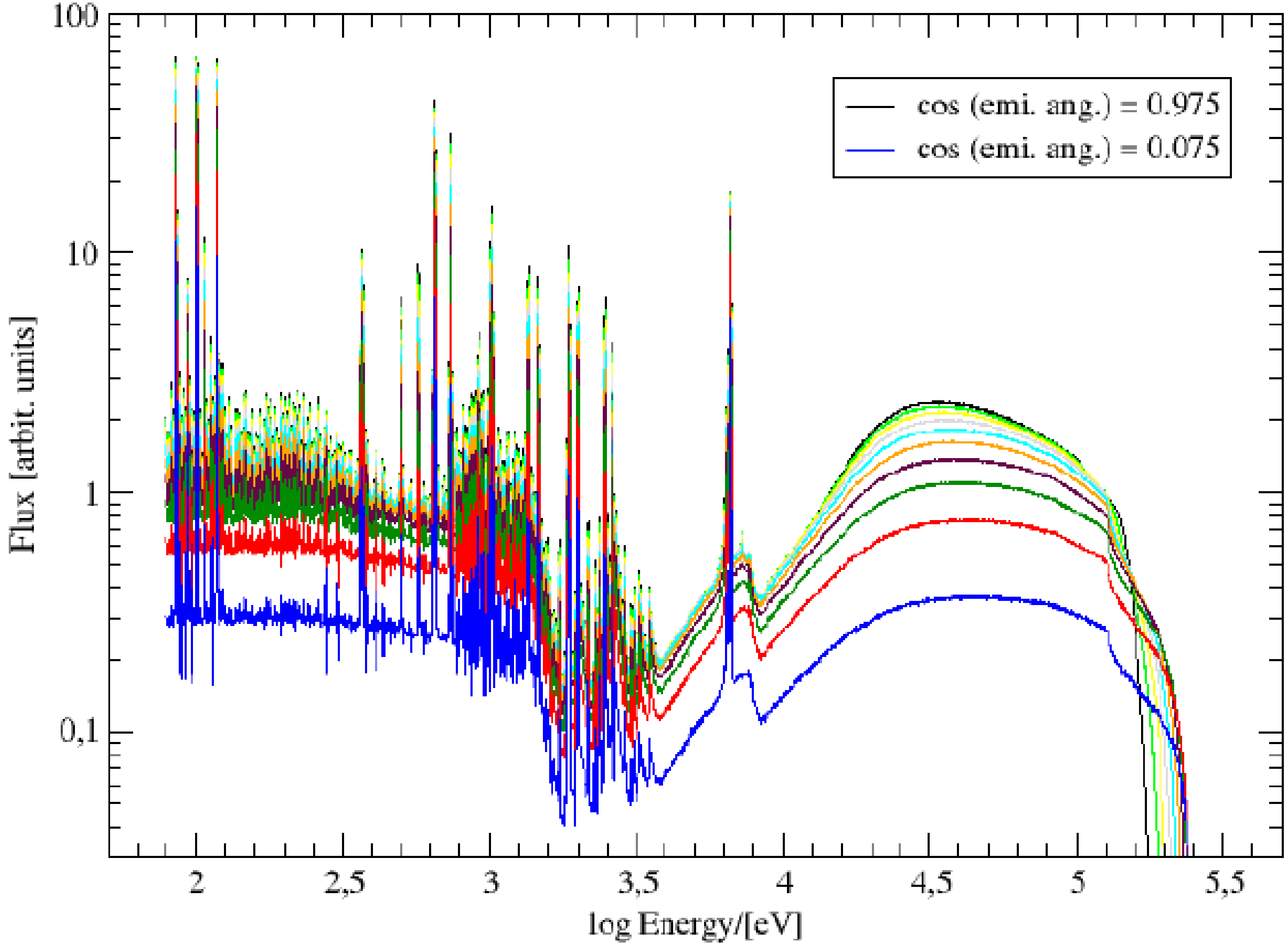
KYNrefrev



Theoretical lag-frequency model
h = 3rg, incl = 30 deg, a = 0.998, A = 1, Gamma = 2
M = 1e7Msun, soft = 0.3-0.8 keV, hard = 1-3 keV, neutral disc
1000
500
0
−500
−1000
Lag (s)
10−5
10−4
10−3
0.01
Frequency (Hz)

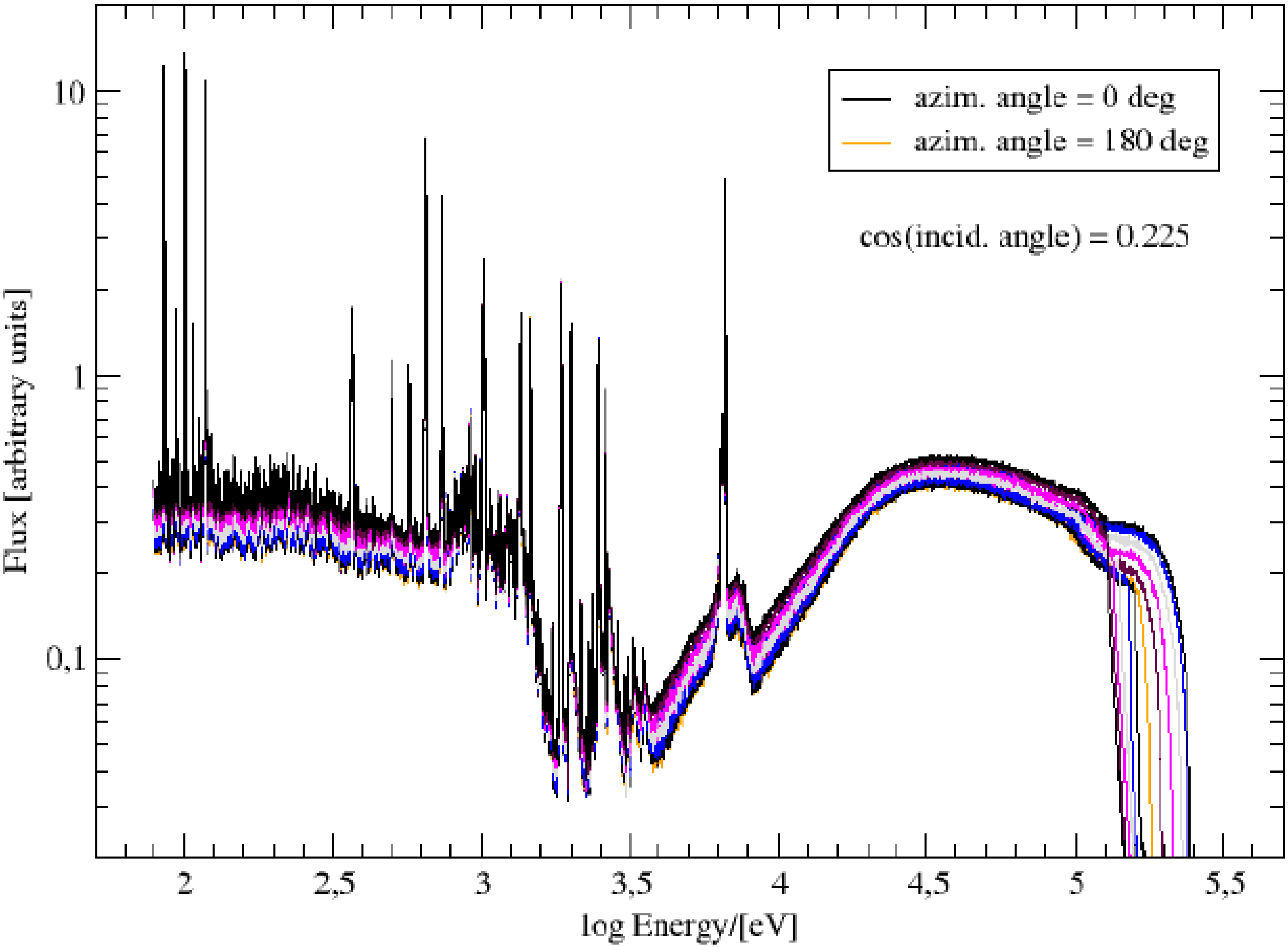
Reprocessing in the disc

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



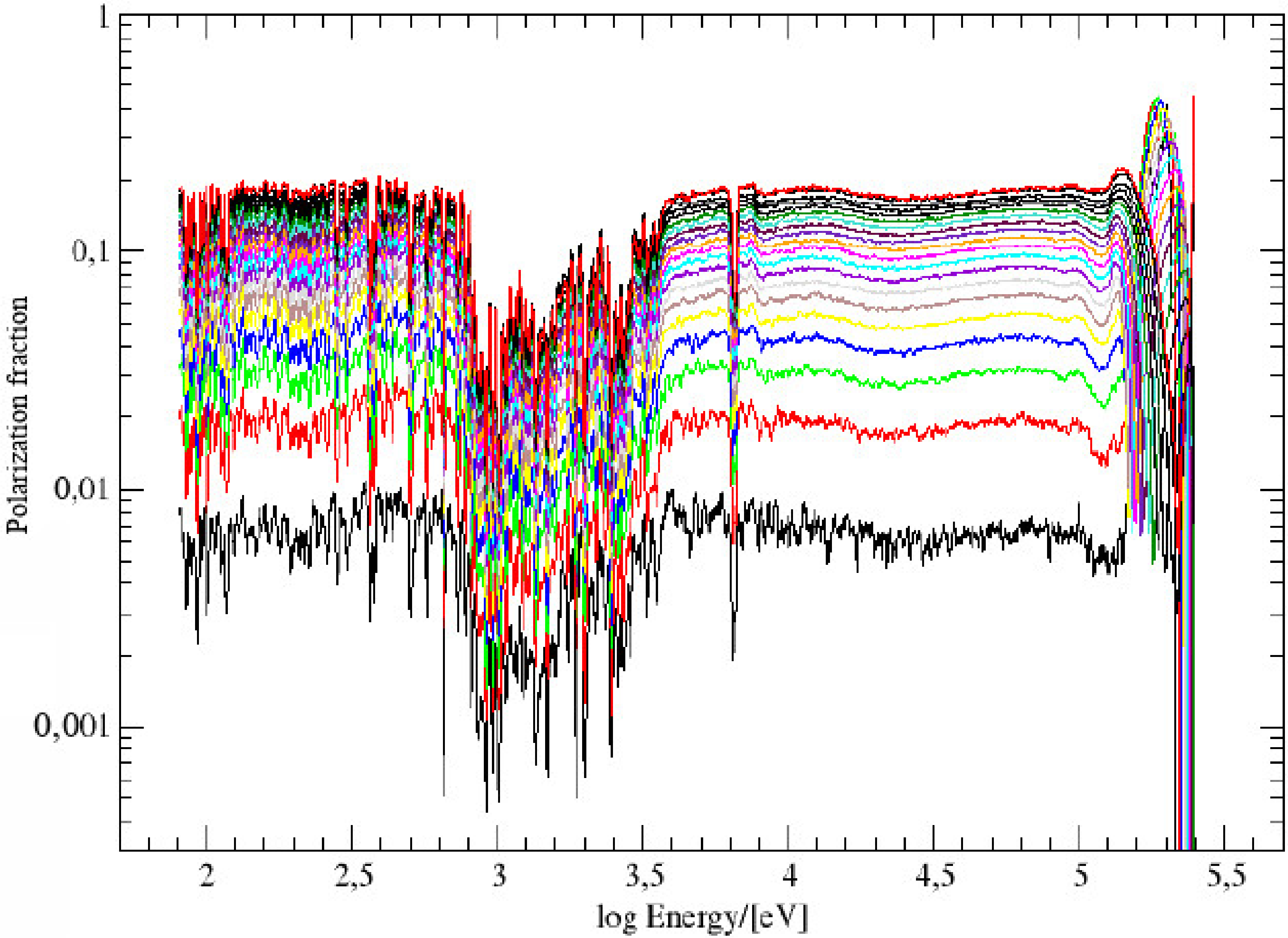
Reprocessing in the disc

- azimuthal dependence is also included



Reprocessing in the disc

- polarisation for unpolarised illumination is computed as well



3D polarisation modelling of blob

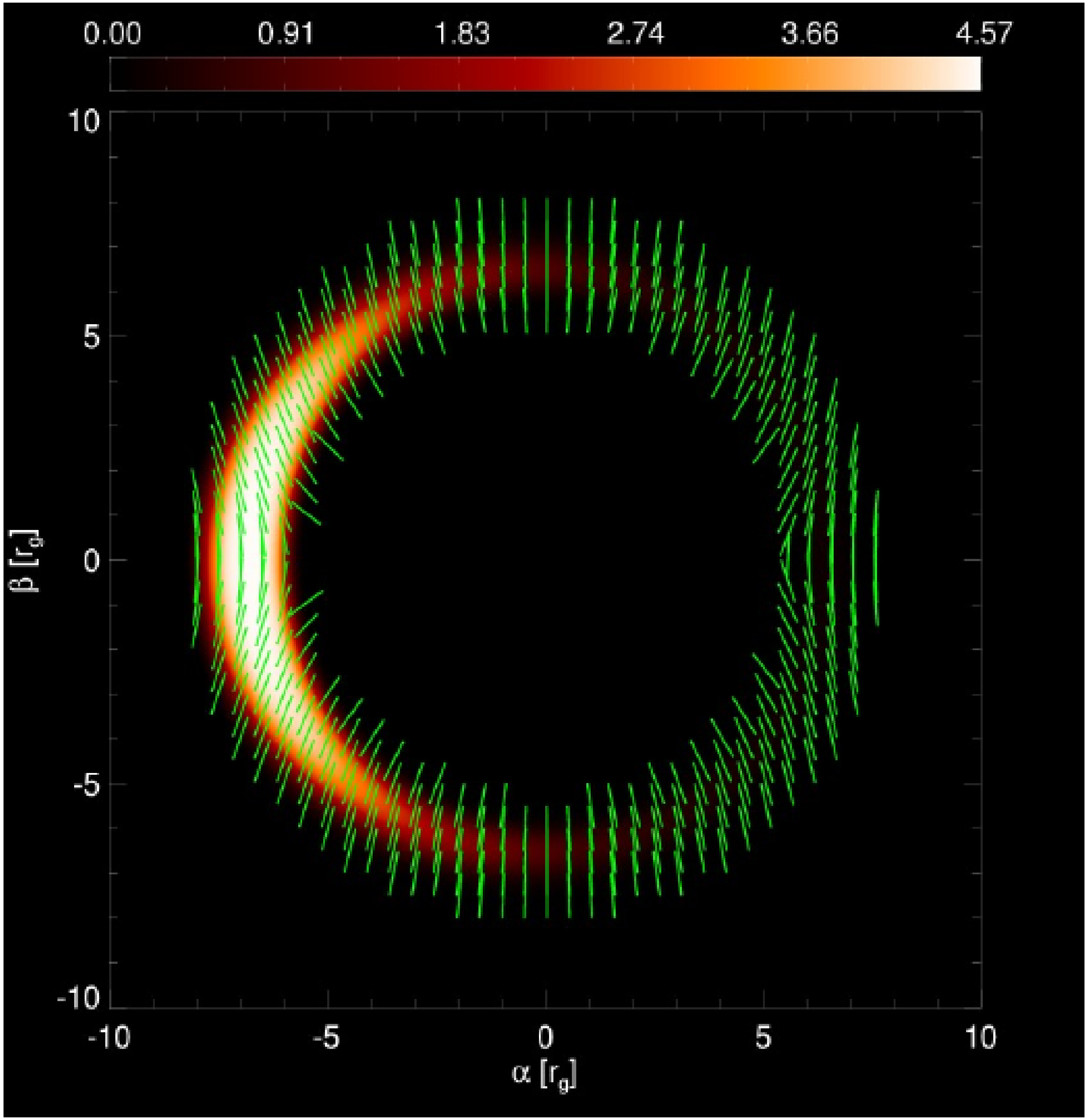


Image of the hotspot while it is behind the black hole. Due to gravitational lensing it can be seen as an
Einstein ring.

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

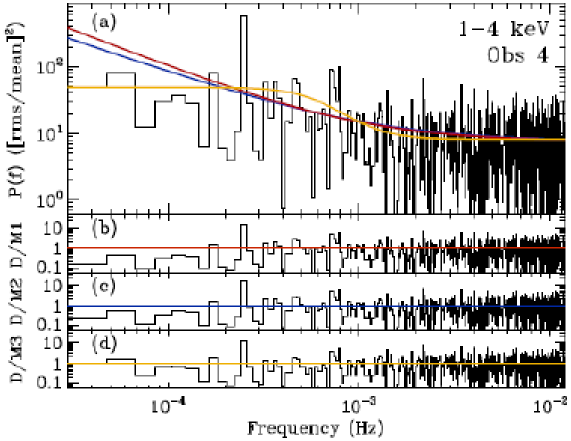
- AGN lags (Kara, Fabian, Alston)
  - lags measured in several sources (lags vs. frequency and energy)
  - Lags observed also in broad iron line energy band
  - lags vs. energy found to be similar to reflection spectrum
  - drop in hard lags at very low frequencies (additional soft componnet due to absorption?)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

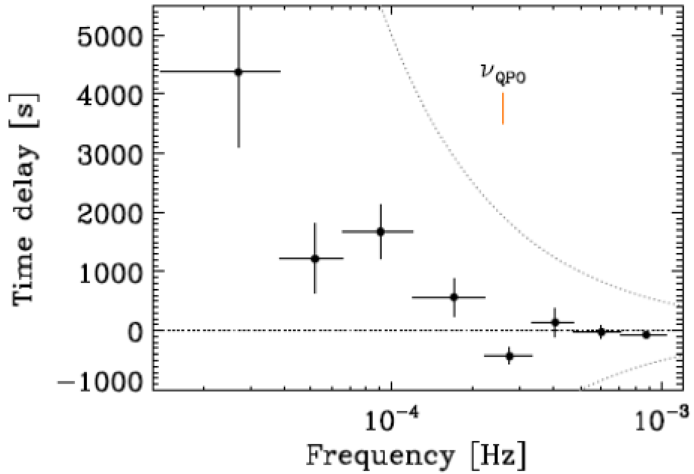
Radio quite AGN observed by NuSTAR

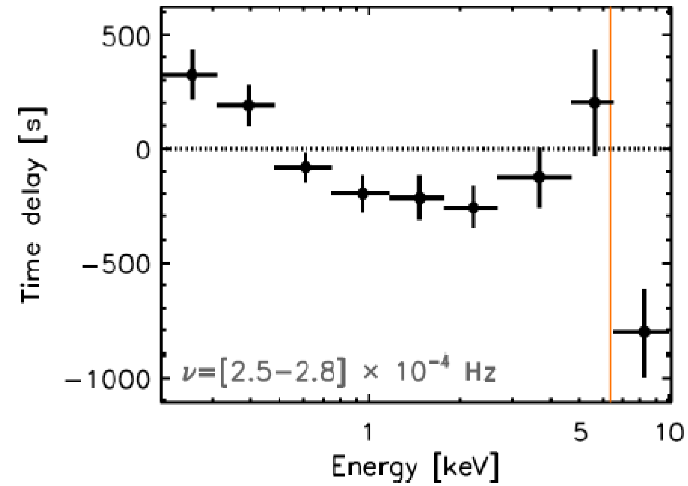
Target	Spin	Data	Reference
1H0707-495	> 0.988	XMM-Newton/NuSTAR	Kara et al. (2015)
Ark 120	~ 0.5	XMM-Newton/NuSTAR	Matt et al., 2014
Fairall 9	0.973 ± 0.003	XMM-Newton/NuSTAR	Lohfink et al. (2016)
MCG-6-30-15	$0.91^{+0.06}_{-0.07}$	XMM-Newton/NuSTAR	Marinucci et al., 2014a
Mrk 335	> 0.9	Swift/NuSTAR	Parker et al., 2014
NGC 1365	> 0.97	XMM-Newton/NuSTAR	Risaliti et al., 2013 Walton et al., 2014
NGC4151	> 0.9	Suzaku/NuSTAR	Keck et al. (2015)
SWIFT J2127.4	$0.58^{+0.11}_{-0.17}$	XMM-Newton/NuSTAR	Marinucci et al., 2014b

Lags in AGN QPO

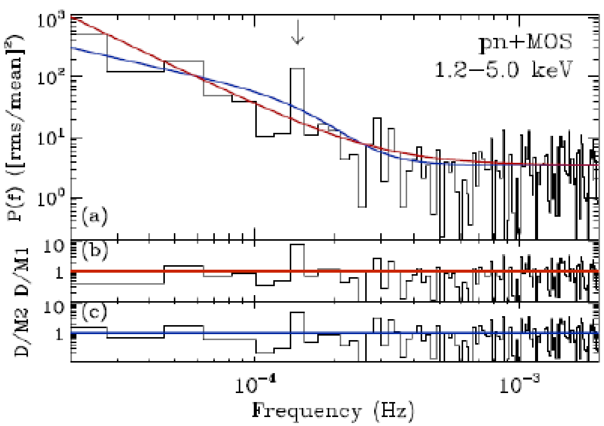
RE J1034+396

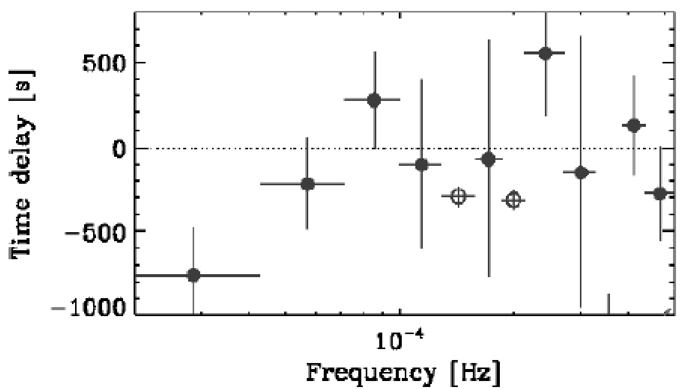


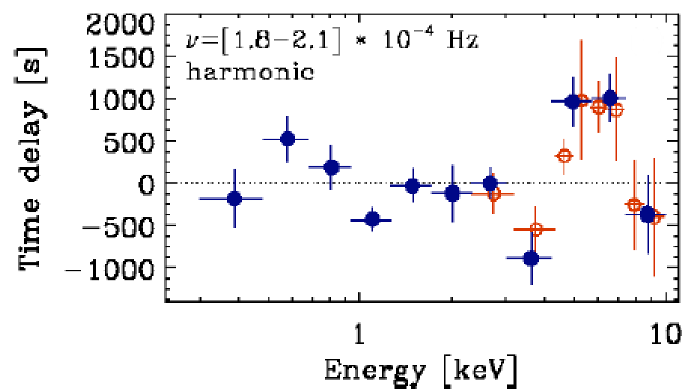




MS 22549-3712







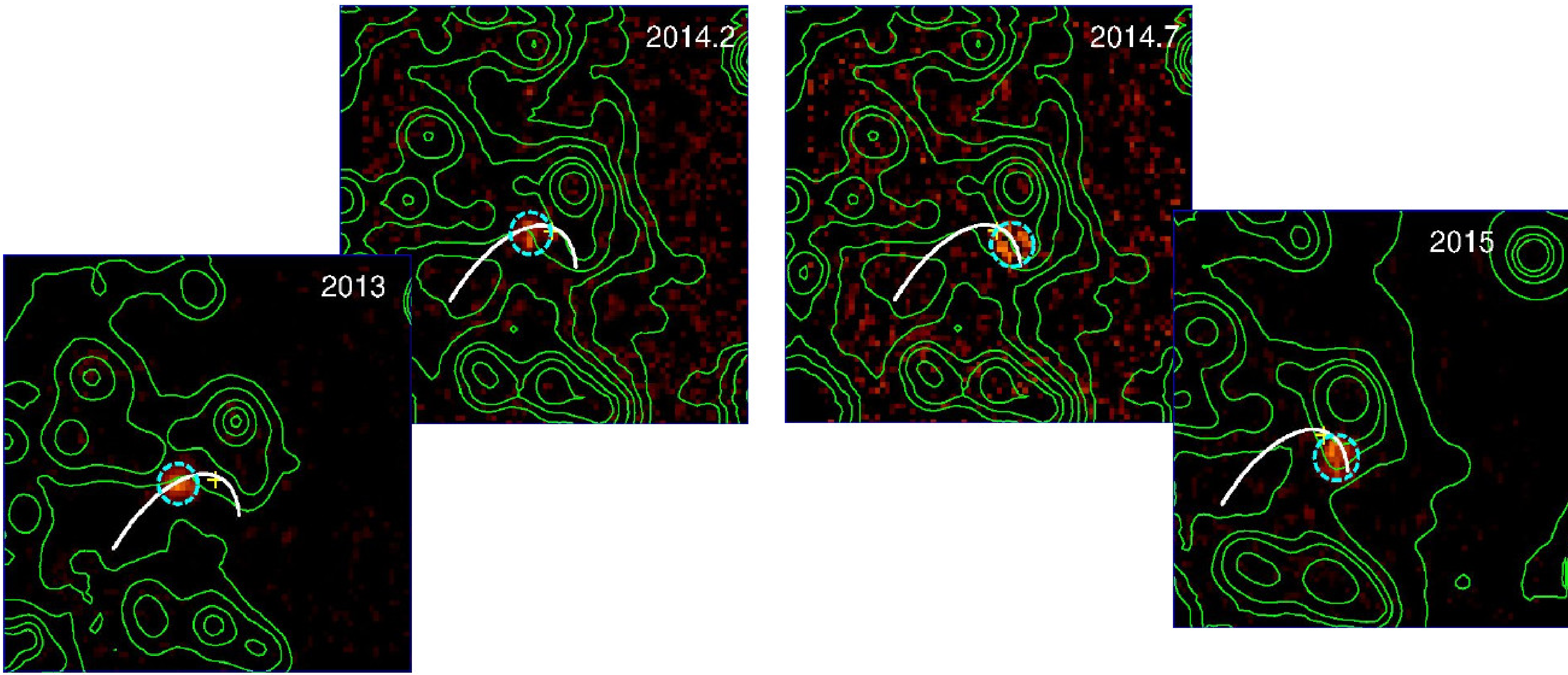
Observations

- 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 (Valencia-S et al. ApJ 2015, Shahzamanian et al. A&A 2016, Zajacek et al. A&A 2014)

- 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 $L > 0.3L_{Edd}$ (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)

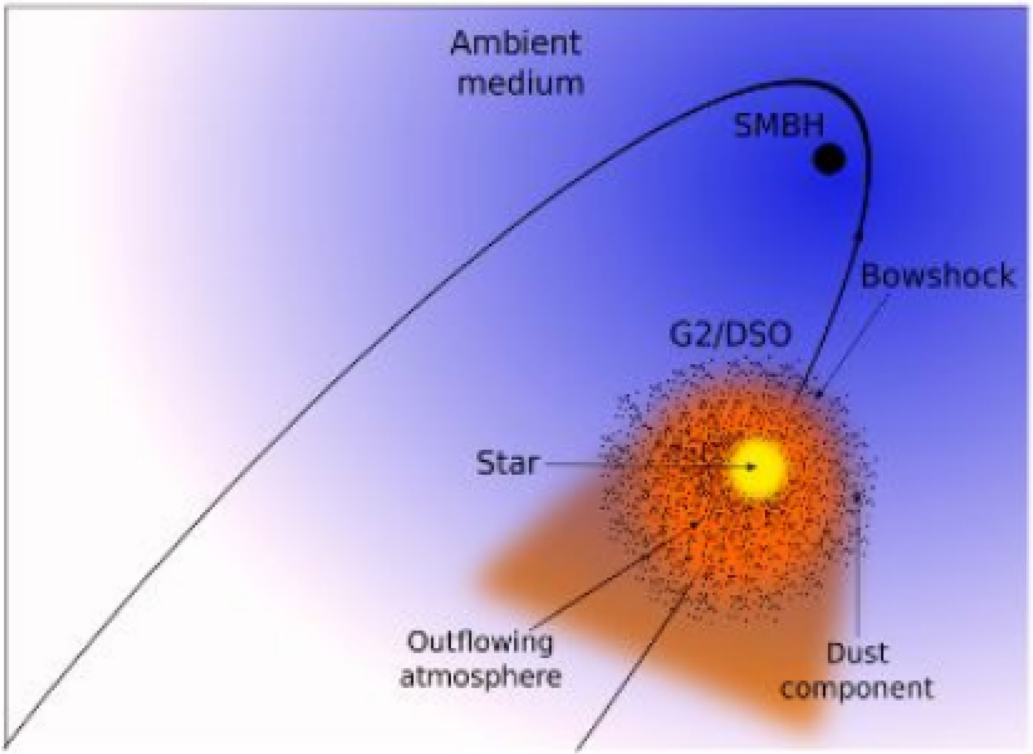
Observation of G2/DSO

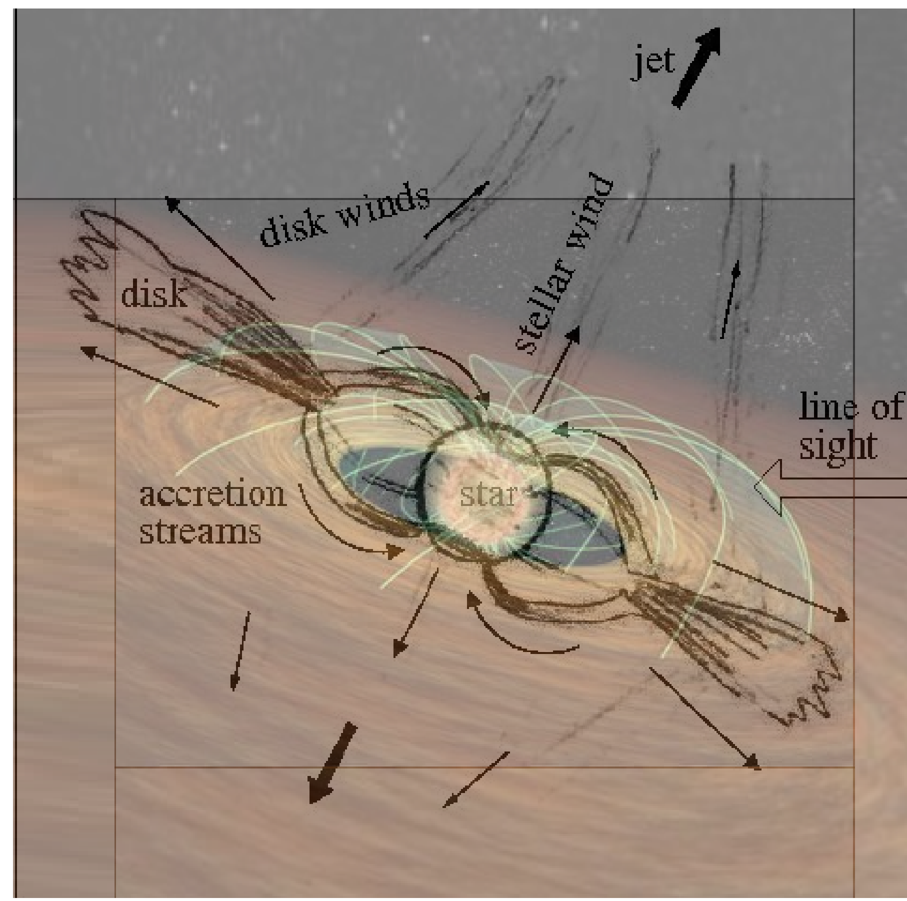
- NIR (Valencia-S, Eckart, Zajacek, Parsa, et al. ApJ 2015, Shahzamanian, Eckart, Zajacek, Valencia-S. et al. A&A 2016)



Observation of G2/DSO

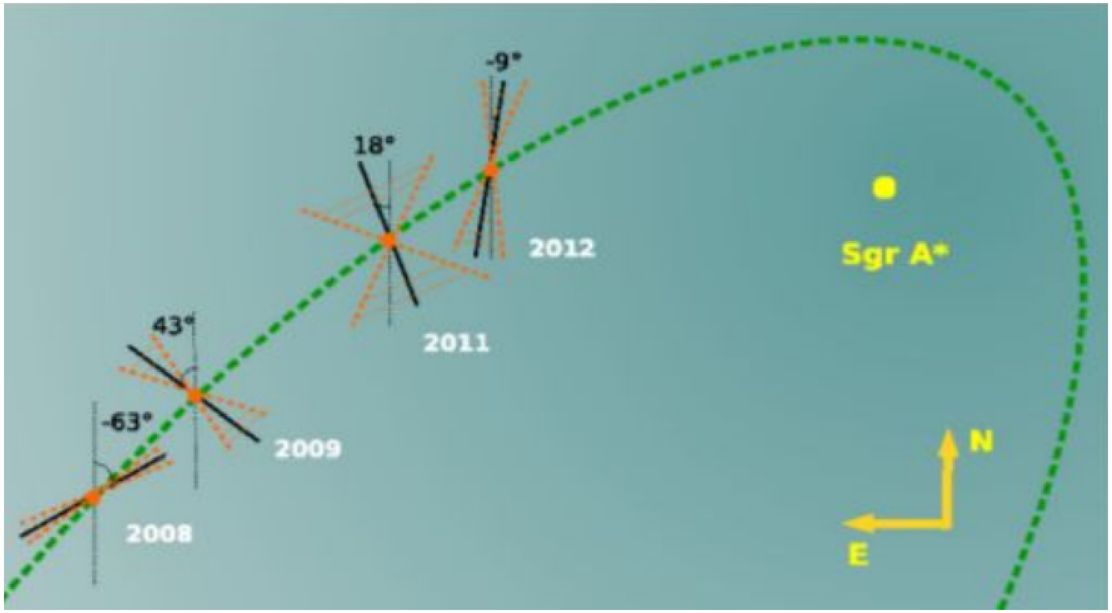
- Modelling in Zajacek, Karas, Eckart A&A 2014



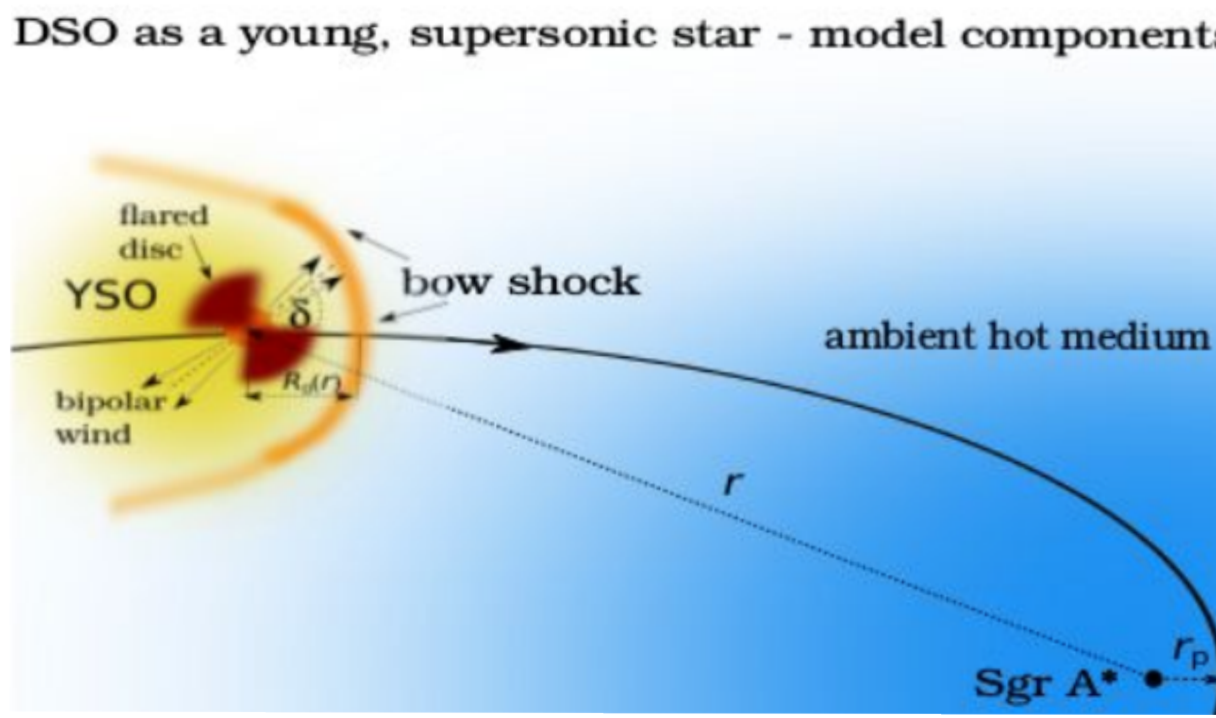


Davies et al. 2011; Rosen, Krumholz, Ramirez-Ruiz, 2012, Eckart et al. 2014

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