Photon Index - Mass Accretion Rate Correlation and Evaluation of Black Hole Mass in NGC 4051

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25 years ago when Narrow Line Seyfert-1 galaxies were discovered…

I already measured mass of a narrow-line object, but much smaller one:

- "Precision measurement of omega-meson mass" – subject of my thesis, published in 1986.
- M_{omega}=782 MeV ~ 0.8 M_{proton} ~ 10^{-57} M_{sun}

Today's presentation is about measurement of black hole mass ~10^{6} M_{sun}

The idea of the study

- Search for similarity in evolution of X-ray spectra between
  - supermassive black hole in Seyfert-1 galaxy (NGC4051) and
  - galactic black hole binary (Cygnus X-1)
- Look at correlation between
  - spectral state (photon index) and
  - mass accretion rate
    - Represented by normalization of “seed” black body component in generic Comptonization model
- Hypothesis:
  - for the same photon index the luminosity (of seed component) is equal to the same fraction of Eddington limit
    - For two black holes in the same spectral state the apparent luminosity is
      - Proportional to black hole mass
      - Inverse proportional to square of the distance
  - Verified for many galactic black hole binaries:
    - see *Shaposhnikov, N., & Titarchuk, L. “Determination of black hole masses in galactic black hole binaries using scaling of spectral and variability characteristics”, 2009, ApJ, 699, 453*
  - *Applied to intermediate mass black holes (~100 solar masses)*
  - Never tested for supermassive black holes
    - the subject of the present work

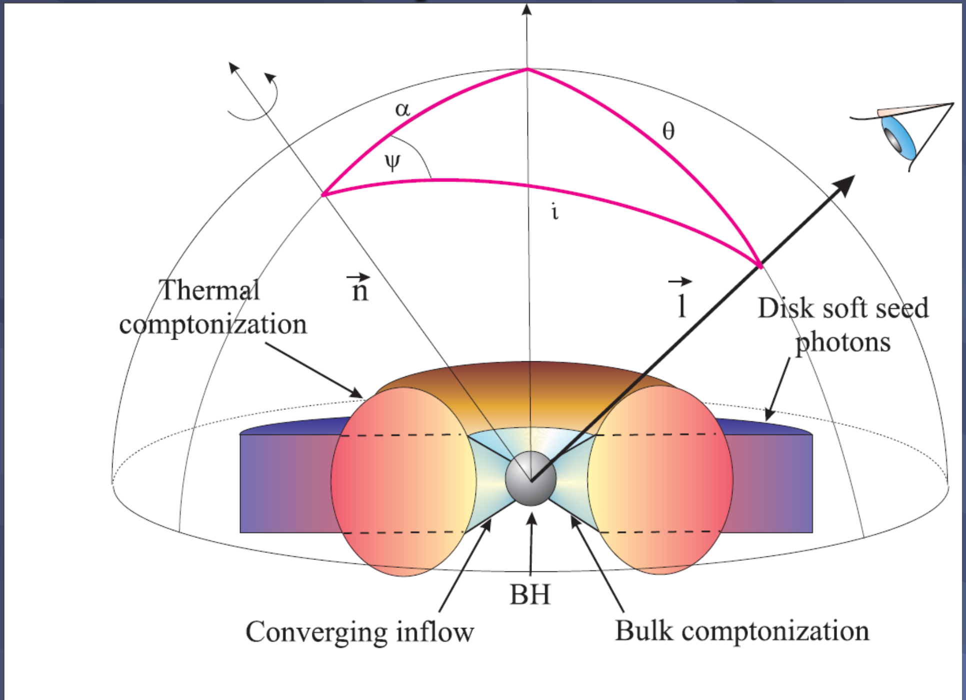
What is already known

- similarity between NGC4051 and galactic BH binaries in power spectrum shape
  - break in power spectrum shape similar to Cygnus X-1 gives BH mass estimate ~3x10^5 solar masses
    - McHardy et al., MNRAS 348, 783-801 (2004)
    - this is consistent (within error bars) with reverberation mapping estimate ~(5+-3)x10^5 (Shemmer et al., 2003), and later measurement ~(1.7+-0.5)x10^6 (Denney et al. 2009)
  - But the quasi-periodic oscillation were not found in NGC4051 power spectrum
    - Vaughan et al. MNRAS, 000, 1-12(2011)
    - We use the same set of XMM observations
    - There are BH binaries which do not have QPO detected, while showing different spectral states

What is new in this analysis

- We use generic Comptonization model COMPTB for continuum emission spectrum
  - Model described in Farinelli et al., ApJ, 680:602-614, 2008
  - available in "contributed models" page of XSPEC web site
    - http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xanadu/xspec/models/comptb.html
  - similar to COMPTT (included in XSPEC)
    - has more convenient parametrization (includes photon index as parameter)
    - works properly for any optical thickness of compton cloud (even significantly bigger than 1)
      - Important to reproduce hard spectra of NGC4051 with photon index <1.5
- We use normalization of "seed" black body spectrum as a measure of disk accretion rate
- We search for it's correlation with photon index defined from model fit

Comptonization model geometry



Configuration includes:

- Optically thick disc with temperature T_s
  - for GBH: kT_s ~1 keV
  - for NLS1: kT_s ~0.1 keV
- Hot compton cloud (corona) with electron temperature $T_e >> T_s$
  - Optically thin for true absorbtion (free-free)
  - Could have few compton scattering lengths

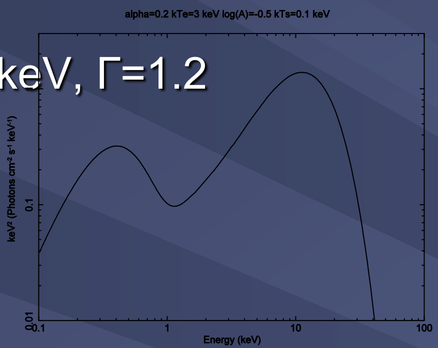
Generic Comptonization model COMPTB includes:

- Fraction of disk black body spectrum with temperature T_s visible directly = 1/(1+A)
- Fraction of disk black body emission convolved with thermal Comptonization Green's function (compton cloud response to monochromatic photons) =A/(1+A)
- Fraction of disk black body convolved with Green's function of bulk motion Comptonization on converging flow (not used for NGC4051 modeling)

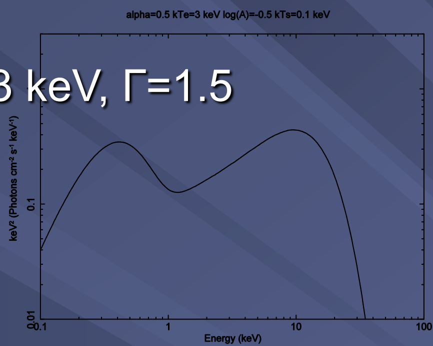
Free parameters: kT_s, kT_e, alpha=Γ-1, log(A), Normalization

COMPTB spectra with different parameters

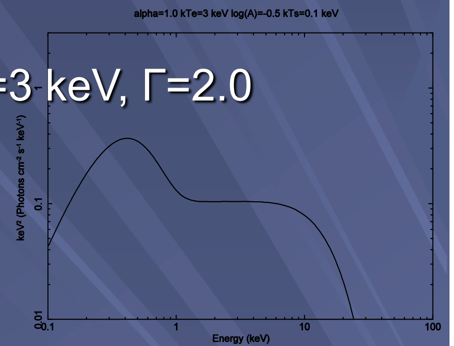
kT_e=3 keV, Γ=1.2



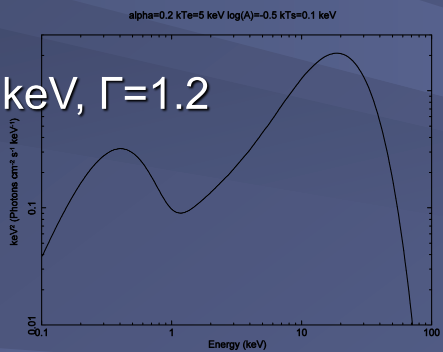
kT_e=3 keV, Γ=1.5



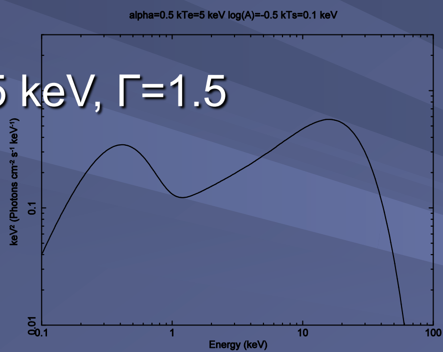
kT_e=3 keV, Γ=2.0



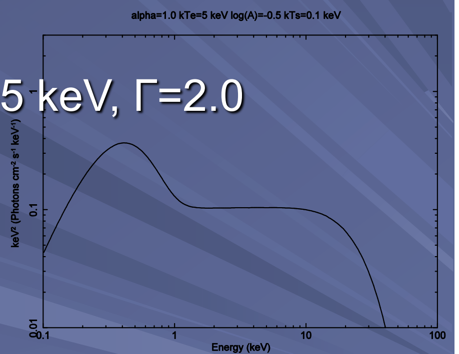
kT_e=5 keV, Γ=1.2



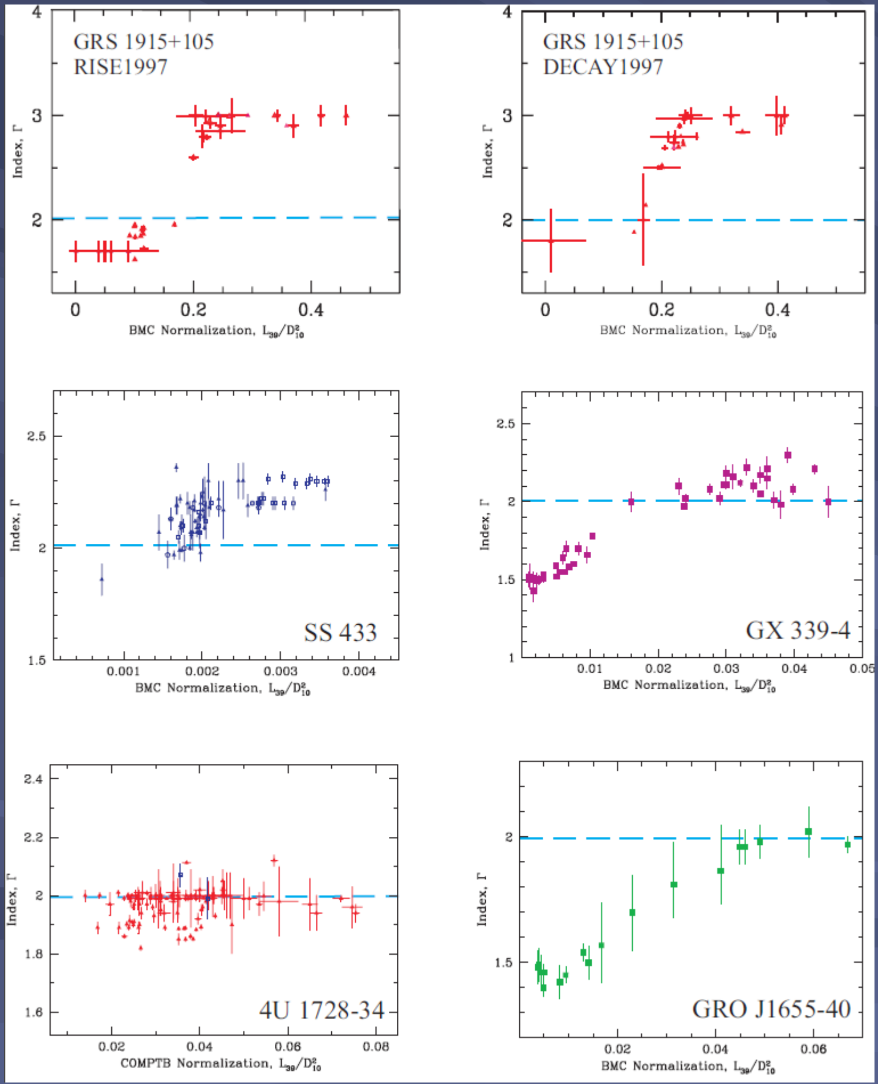
kT_e=5 keV, Γ=1.5



kT_e=5 keV, Γ=2.0



X-ray photon index – normalization correlation for galactic BH and NS



- Neutron star
  - Bottom left plot
  - Photon index doesn't change with normalization
- BH binaries
  - As normalization (accretion rate) increases, photon index shows spectral state transition from hard to soft state
    - Due to decrease of temperature and size of hot compton cloud
  - Starting from certain accretion rate photon index saturates:
    - Compton cloud disappears and we see comtonization on bulk motion of converging flow into the black hole
  - These two properties are characteristic features of black hole
- Plot from the paper:
  - Seifina, Titarchuk, 2011 (submitted to ApJ)

Observations used in the analysis

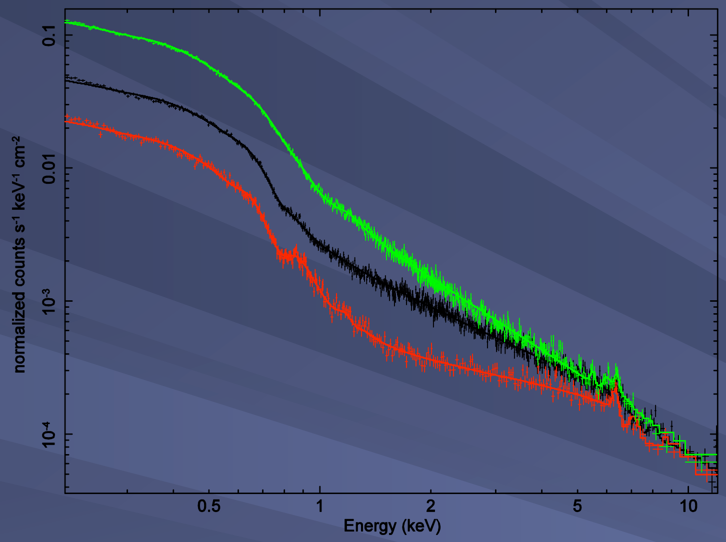
XMM-Newton:

Observation ID	Date	Duration, s
109141401	2001-05-16	121958
157560101	2002-11-22	51866
606320101	2009-05-03	45717
606320201	2009-05-05	45645
606320301	2009-05-09	45548
606320401	2009-05-11	45447
606321301	2009-05-15	32644
606321401	2009-05-17	42433
606321501	2009-05-19	41813
606321601	2009-05-21	41936
606321701	2009-05-27	44919
606321801	2009-05-29	43726
606321901	2009-06-02	44946
606322001	2009-06-04	39756
606322101	2009-06-08	43545
606322201	2009-06-10	44453
606322301	2009-06-16	42717

Chandra:

Observation ID	Date	Instrument	Grating	Duration, s
859	2000-03-24	ACIS-S	HETG	80790
3144	2001-12-31	HRC-S	LETG	92030
4160	2003-07-23	HRC-S	LETG	94980
10777	2008-11-06	ACIS-S	HETG	27840

X-ray spectra obtained by XMM-Newton EPIC instrument for NGC4051 in different states (normalized counts)



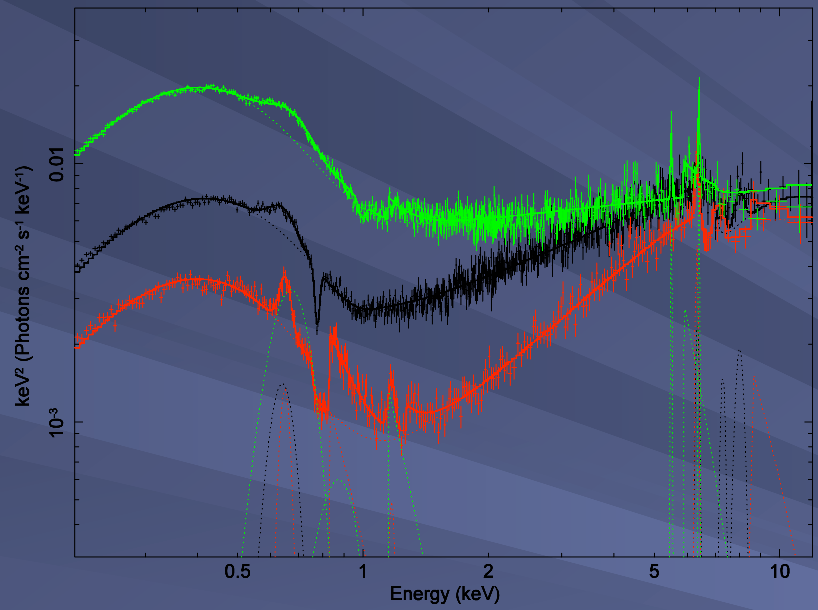
- low/hard state
  - May 11 (red points)
- intermediate state
  - May 3 (black points)
- high/soft state
  - May 15 (green points)

Curves – best model fits

Spectral features

- Our main goal was to extract parameters of continuum spectrum
- To make fit reasonable we have to add some lines to the model
  - Fe K_{α} (6.4 keV) and absorbtion edge (7 keV)
  - Lines and edges for H-like and He-like ions of Oxygen (0.55 keV, 0.74 keV, 0.87 keV)
- Lines are more prominent in low/hard state
- While evolution of these lines could give interesting information, we didn't analysed them now
  - Plan to do it in future

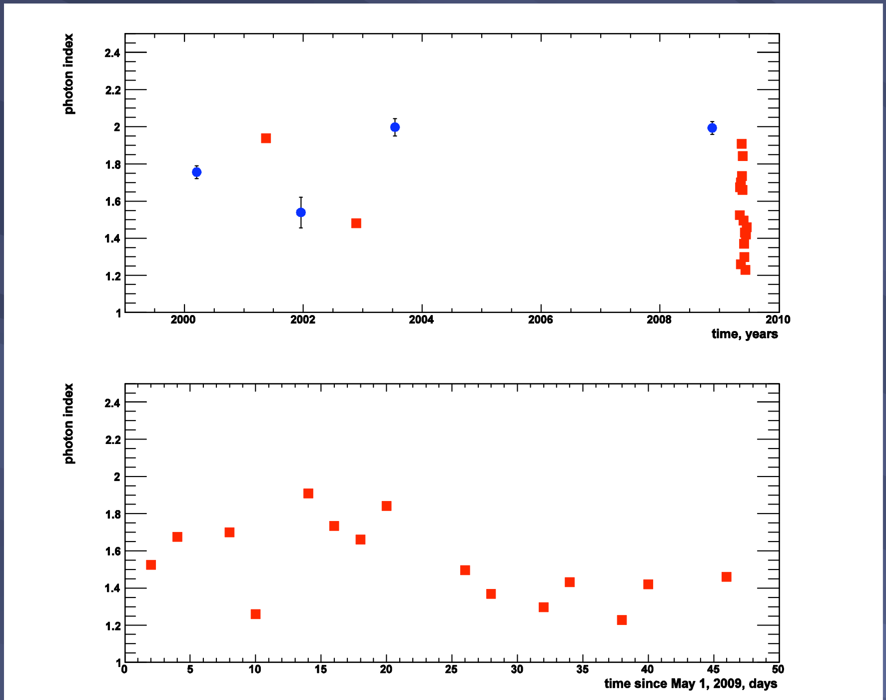
X-ray spectra obtained by XMM-Newton EPIC instrument for NGC4051 in different states (unfolded spectra)



- low/hard state
  - May 11 (red points)
- intermediate state
  - May 3 (black points)
- high/soft state
  - May 15 (green points)

Curves – best fit models

Evolution of photon index

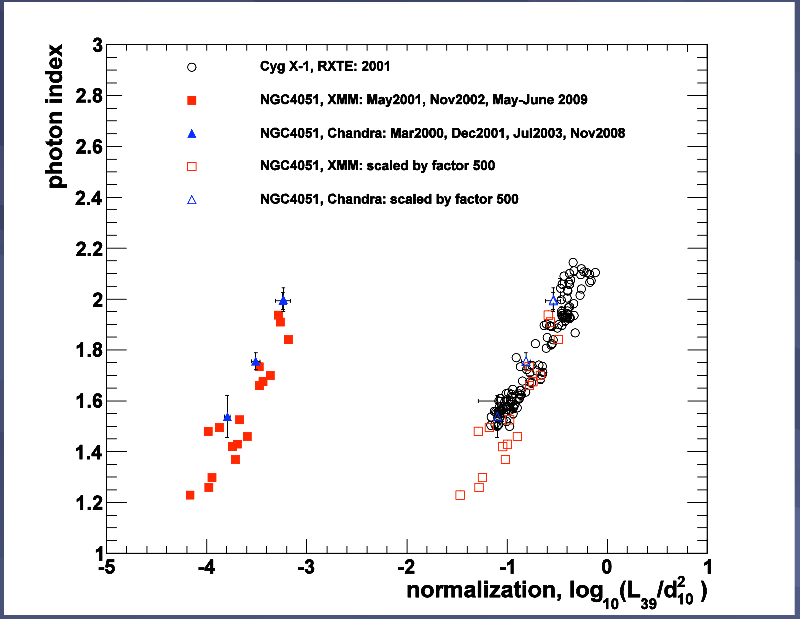


- Red squares
  - XMM data
- blue circles
  - CHANDRA data.

Bottom panel:

zoom on May-June 2009 XMM-Newton observations

Similarity of photon index – normalization correlation in NGC 4051 and Cygnus X-1



- This two sources demonstrate similar correlation
  - This is illustrated by superimposing NGC4051 points scaled by factor 500 on the Cygnus X-1 points

- Cygnus X-1 points – from Shaposhnikov, N., & Titarchuk, L., 2009, ApJ, 699, 453

Estimation of BH mass

- We consider following parameters
  - Cygnus X-1 (from Shaposhnikov, Titarchuk, 2009)
    - Mass=7.9+-0.1 solar masses
    - Distance=2.2+-0.3 kpc
  - For both sources line of site is ~orthogonal to accretetion disk
    - Geometric factor=1
  - NGC4051
    - Distance =15 Mpc
    - Relative luminosity = 0.002
    - Mass=0.002*7.9*$(15000/2.2)^2$ =7.3x10^5 solar masses
- Estimation is consistent with previous measurements (17+-5)x10^5 (reverberation) and (3+-2)x10^5 (power spectrum break)
  - Confirms that approach is reasonable

Conclusion

- Correlation photon index - mass accretion rate was found in BH with mass different by 4 orders of magnitude
  - This is a characteristic feature of a black hole
- Scaling method successfully used to estimate supermassive BH mass in NGC4051
  - Gives result consistent with other methods
- Method could be applied to any NSL1 showing change of spectral state