Modeling Relativistic Reflection: Review and Recent Developments

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in collaboration with

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and many others

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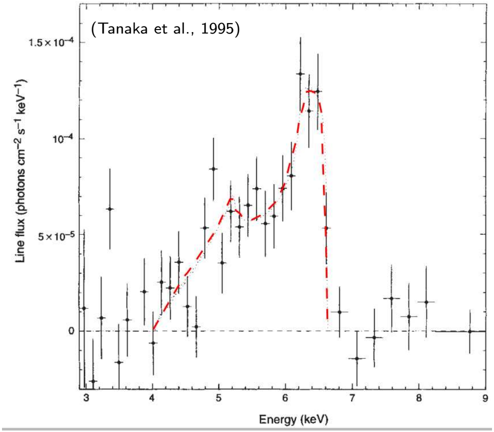
NATURWISSENSCHAFTLICHE FAKULTÄT

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

The History of Modeling Relativistic Reflection



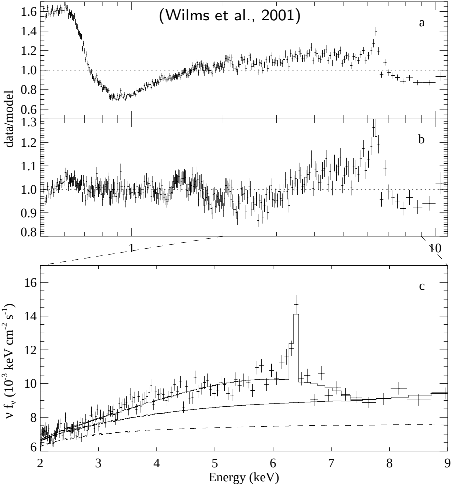
Broad lines found in observations
(White et al., 1986; Nandra et al., 1989; Fabian et al., 1989; Pounds et al., 1990, ...)

Explanation by relativistic broadening of the Fe Kα line
(Fabian et al., 1989; Laor, 1991; Matt et al., 1992, ...)

Evidence for an **accretion disk** very close to the black hole

The History of Modeling Relativistic Reflection

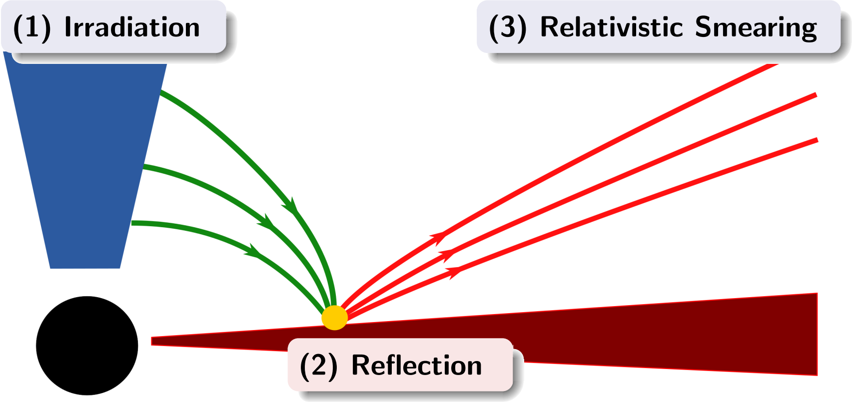
the *XMM-Newton*, *Chandra*, *Suzaku*, and *NuSTAR* era



Complete reflection spectrum relativistically smeared
(Wilms et al., 2001; Fabian et al., 2002; Iwasawa et al., 2004; Miniutti et al., 2007; Nandra et al., 2007; Fabian et al., 2009; Cackett et al., 2009; Duro et al., 2011; Marinucci et al., 2014, **talk by D. Walton**, ...)

Several **robust black hole** spin **measurements** of a sample of selected sources (see, e.g., Reynolds, 2013; Walton et al., 2013; Risaliti et al., 2013)

Relativistic Reflection: The Big Picture



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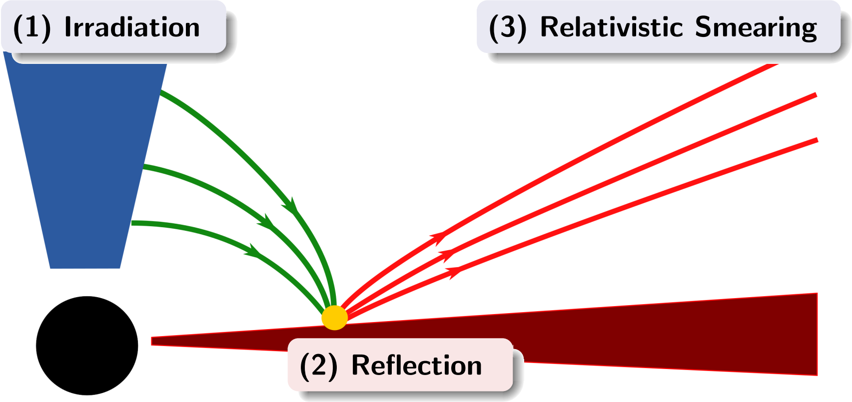
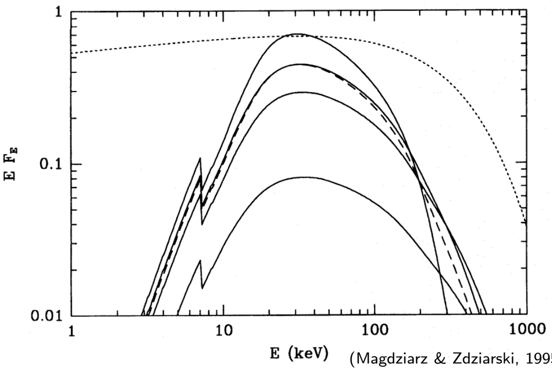


Large complexity of the problem:
Fundamental technical differences between (1,3) and (2)

Reflection at the Accretion Disk



(Magdziarz & Zdziarski, 1995)

First calculations of **Compton scattering**
(Lightman & Rybicki, 1980; Lightman et al., 1981; Lightman & White, 1988)

A reflection model for fitting data: `pexrav`
(Magdziarz & Zdziarski, 1995)

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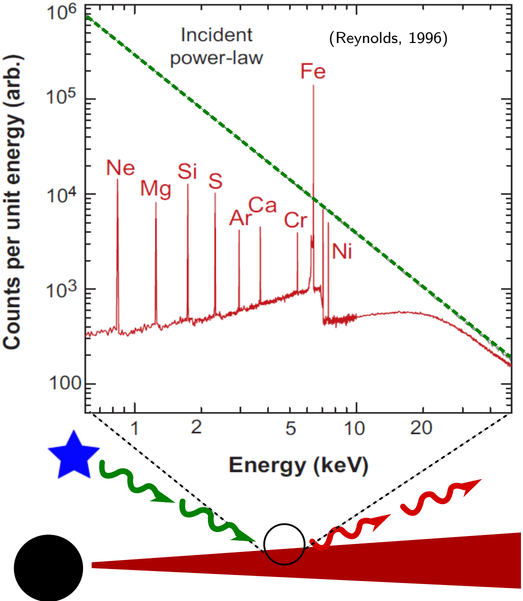

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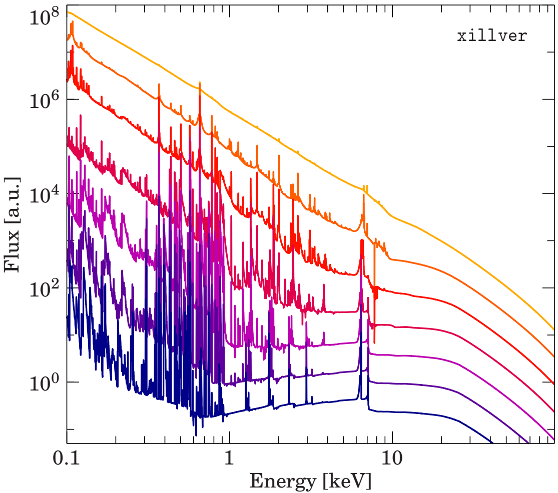

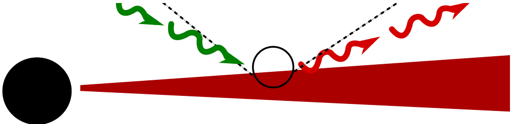

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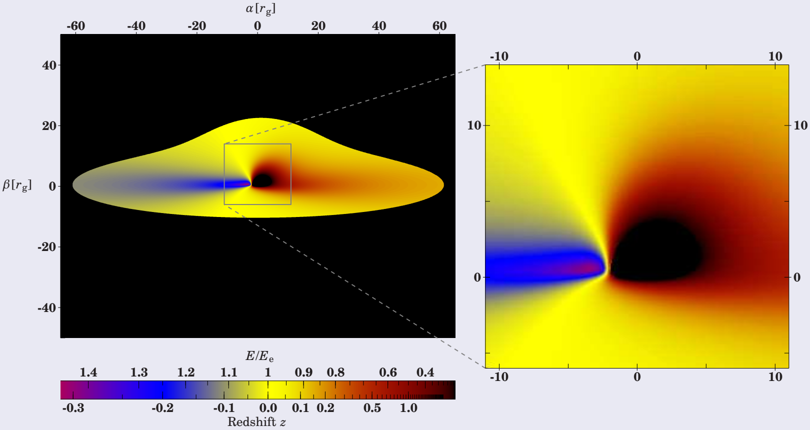
A reflection model for fitting data: `pexrav`
(Magdziarz & Zdziarski, 1995)

including line emission
(Matt et al., 1991; Reynolds, 1996, ...)

Including **ionization** of the disk (Ross & Fabian, 1993; Rozanska & Czerny, 1996; Nayakshin & Kallman, 2001; Dumont et al., 2002, ...)

- `reflionx` (Ross & Fabian, 2005; Ross & Fabian, 2007)
- `xillver`, using `xstar` atomic data (García & Kallman, 2010; García et al., 2011)

Relativistic Effects Close to the Black Hole



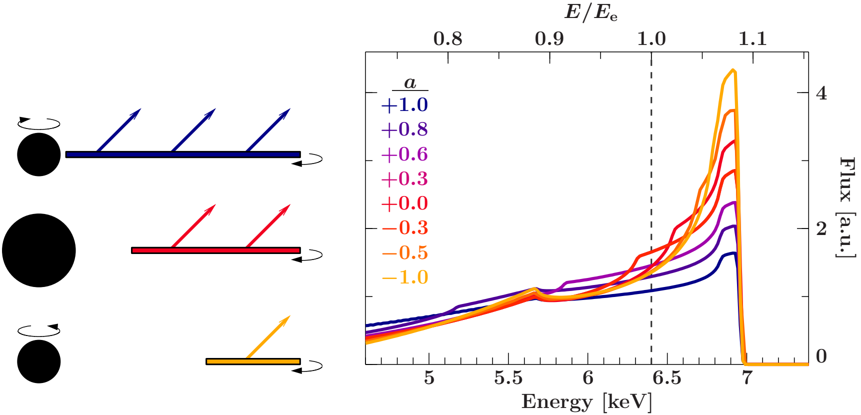
(Dauser et al., 2010)

Rotating black hole: Metric depends on **M** (mass) and **a** (spin)

→ special relativistic beaming, light bending, and gravitational redshift

(Kerr, 1963; Cunningham, 1975; Fabian et al., 1989; Laor, 1991; Dovčiak et al., 2004; Dauser et al., 2010)

Relativistic Effects: **Black Hole Spin**

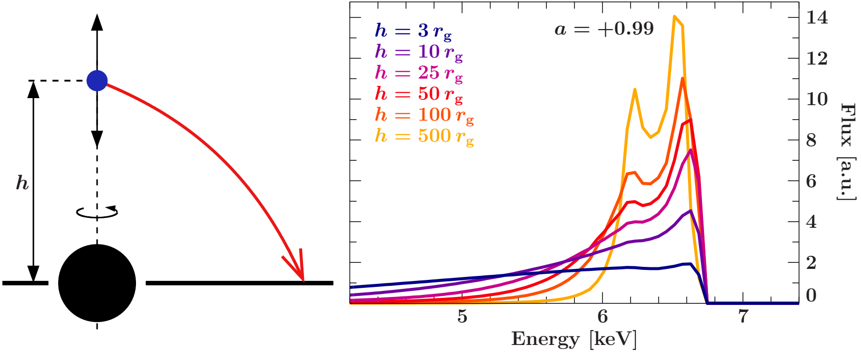


high spin ⟶ smaller inner radius? **yes!**(∗)

smaller inner radius ⟶ **broad line**? **not really!**

(∗)assuming the disk extends to the ISCO

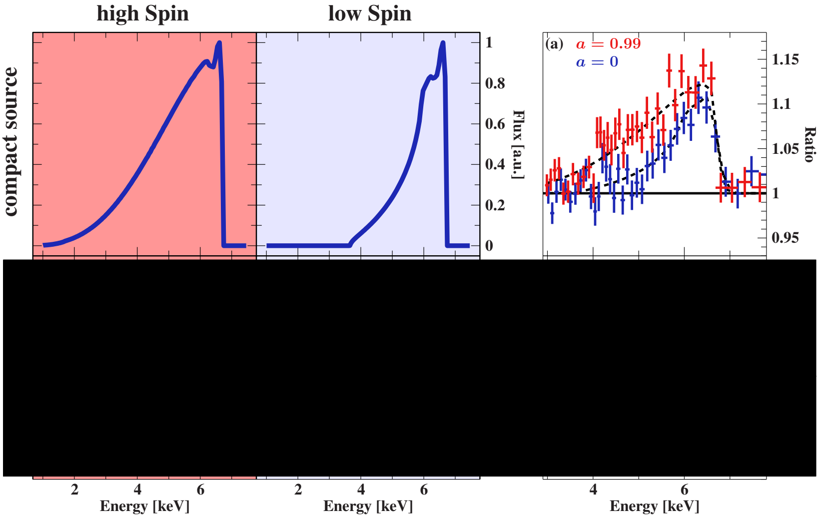
Relativistic Effects: **Irradiating Source Height**



low height implies **enhanced irradiation** of the **inner parts**

Relativistic Effects: **Measuring Spin**

How well can we distinguish high spin from low spin in observations?



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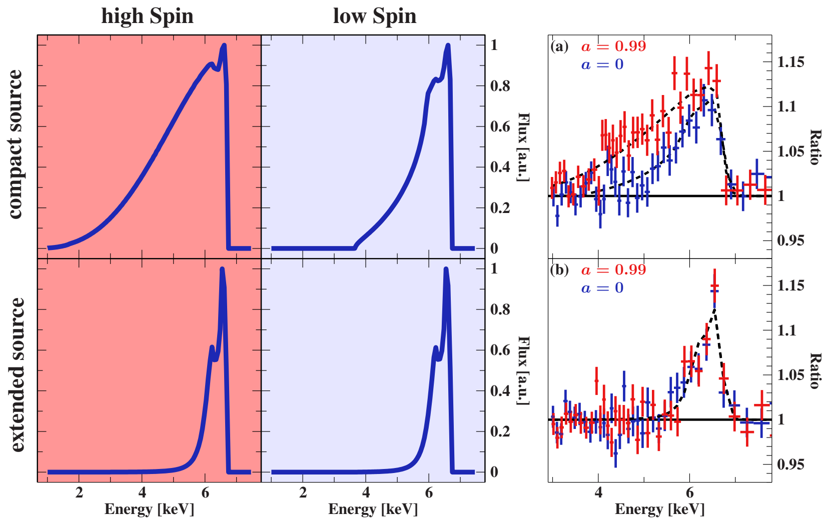
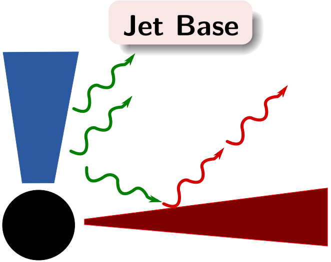
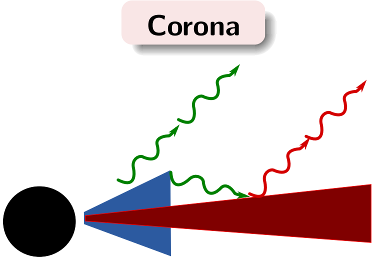


A **broad line** indicates a **compact emission region** ($< 10\, r_g$).
(Dauser et al., 2013; Fabian et al., 2014)

Accretion Geometry: Irradiating Intensity



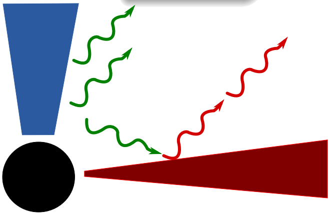
(Matt et al., 1992; Martocchia et al., 2000; Markoff et al., 2005, . . .)

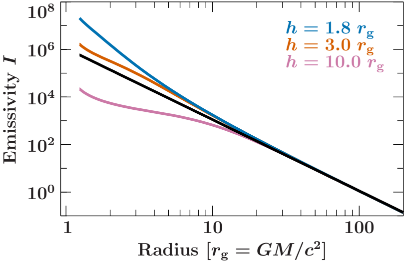


(Haardt, 1993; Dove et al., 1997; Rozanska & Czerny, 1996, . . .)

Accretion Geometry: Irradiating Intensity

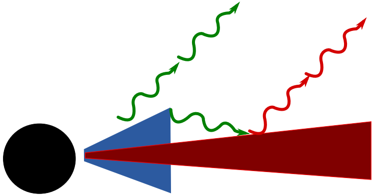
Jet Base

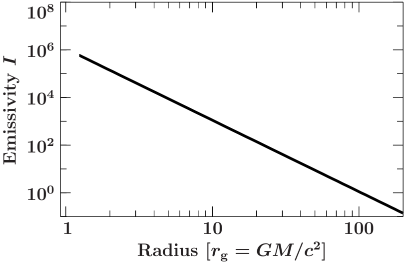




"lensing effect": steep emissivity

Corona

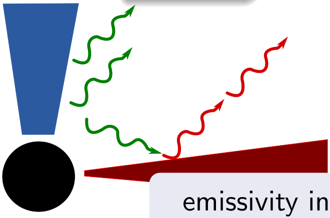




canonical α-disk: $I \propto r^{-3}$

Accretion Geometry: Irradiating Intensity

Jet Base



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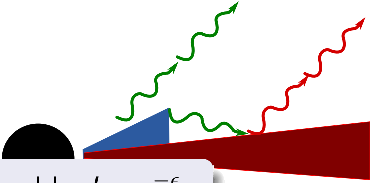
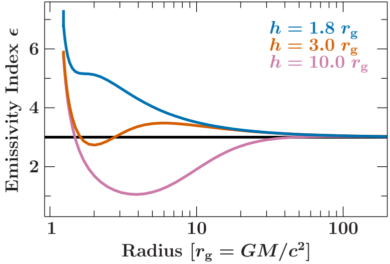
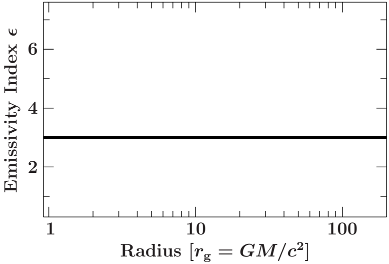


emissivity index ϵ defined by $I \propto r^{-\epsilon}$





"lensing effect": steep emissivity

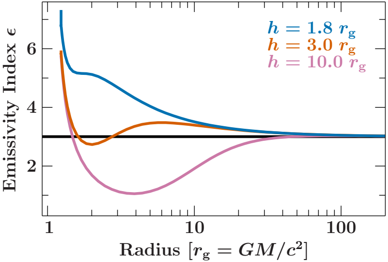
canonical α-disk: $I \propto r^{-3}$

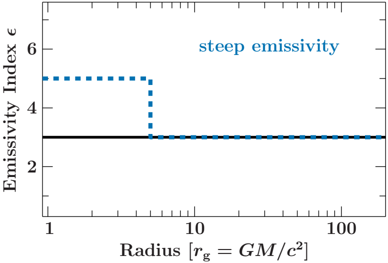
Accretion Geometry: Irradiating Intensity

Jet Base

Corona

Usually emissivities steeper than r^{-3} are observed (described by a **broken power law emissivity**) (see, e.g., Fabian et al., 2004; Miller et al., 2013)
⇒ naturally explained in the jet base geometry
⇒ agrees with measurements of the emissivity (see, e.g., Wilkins & Fabian, 2012)





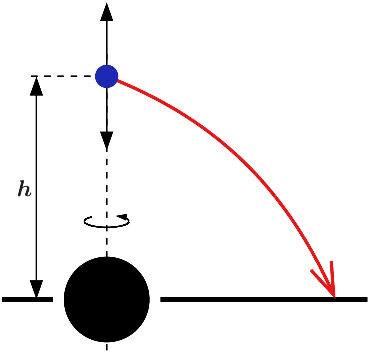
“lensing effect”: steep emissivity

canonical α-disk: $I \propto r^{-3}$

Accretion Geometry: The Jet Base Geometry

long history as **lamp post geometry** (Matt et al., 1991; Martocchia & Matt, 1996; Martocchia et al., 2000; Miniutti & Fabian, 2004)

spectral-timing and reverberation: source on rotational axis $< 10\, r_g$ (see, e.g., Kara et al., 2013; Uttley et al., 2014; Cackett et al., 2014, and also **talk by E. Cackett**)

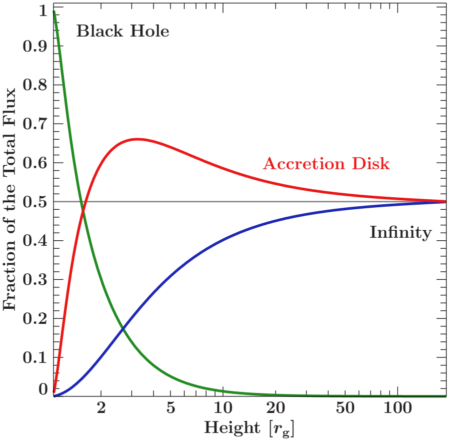


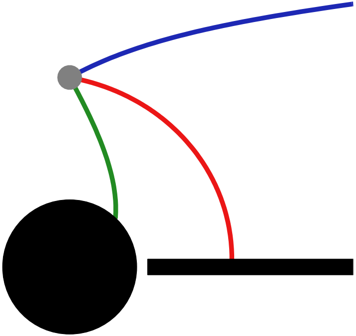
However, it is an idealized geometry:

radially changing primary source not compatible with a point-like geometry (see, e.g., Wilkins & Gallo, 2015, ⇒ **see talk later**)

⇒ extended and moving sources (Wilkins & Fabian, 2012; Dauser et al., 2013)

Accretion Geometry: Reflection Fraction R_f





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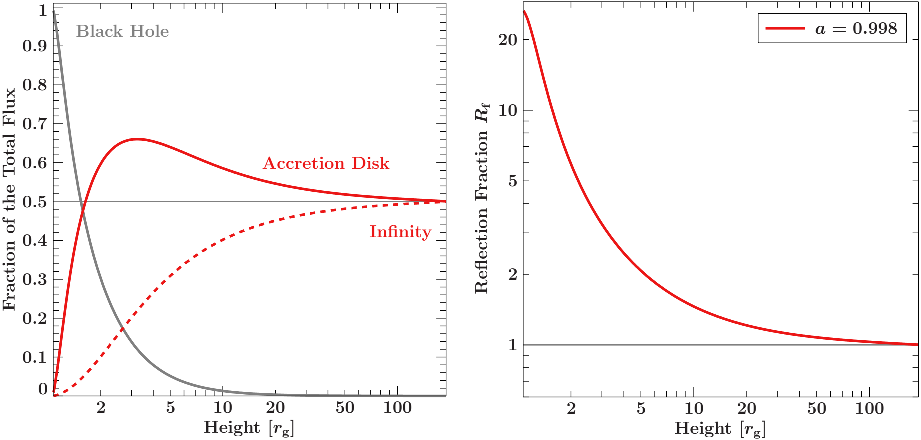
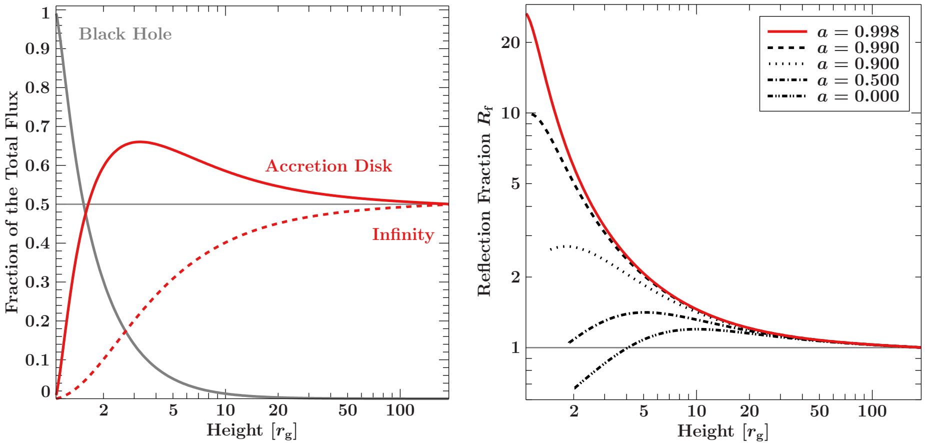


$$R_f = \frac{Flux(\text{Accretion Disk})}{Flux(\text{Infinity})}$$

definition similar to pexrav reflection fraction for $h << R_{out}$

Accretion Geometry: Reflection Fraction R_f



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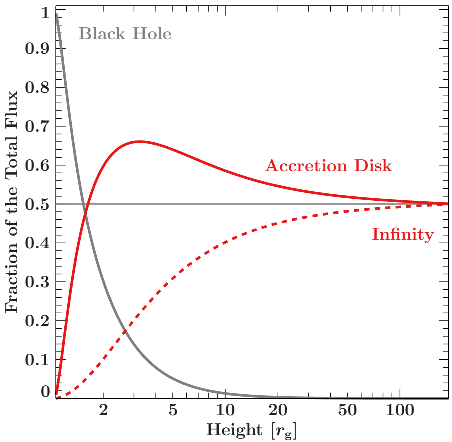
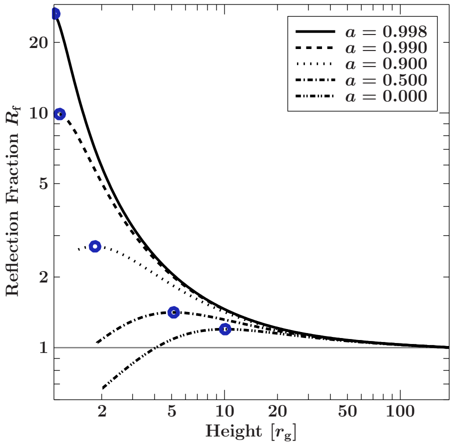
Accretion Geometry: Reflection Fraction R_f



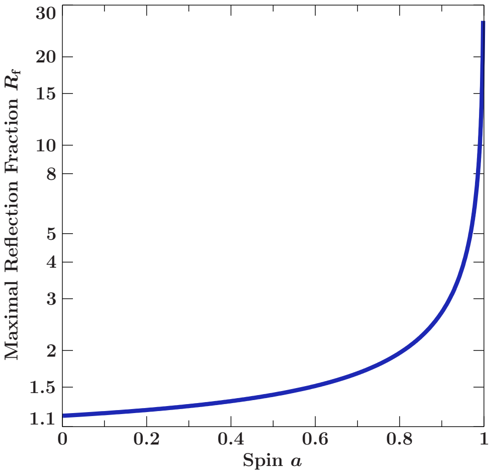


$$R_f = \frac{Flux(\text{Accretion Disk})}{Flux(\text{Infinity})}$$

Accretion Geometry: The Maximal Reflection Fraction

What is the **maximal possible** reflection fraction for a given spin?

No large reflection fractions possible for low values of spin
⇒ **additional constraint** when measuring the **spin**



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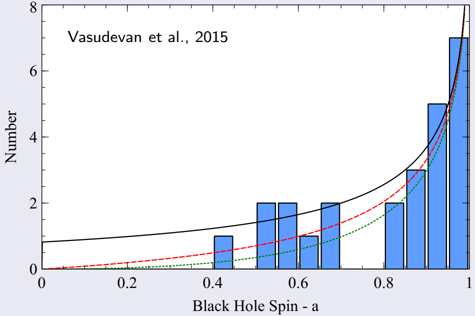
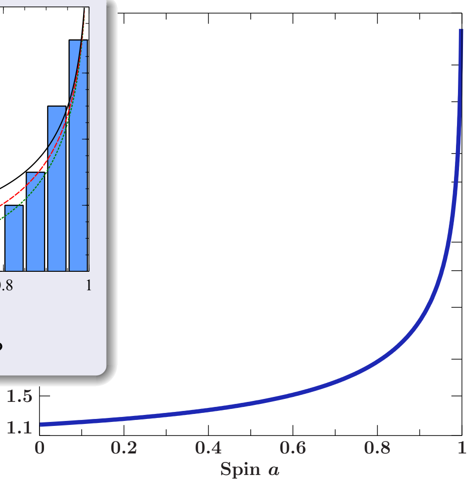
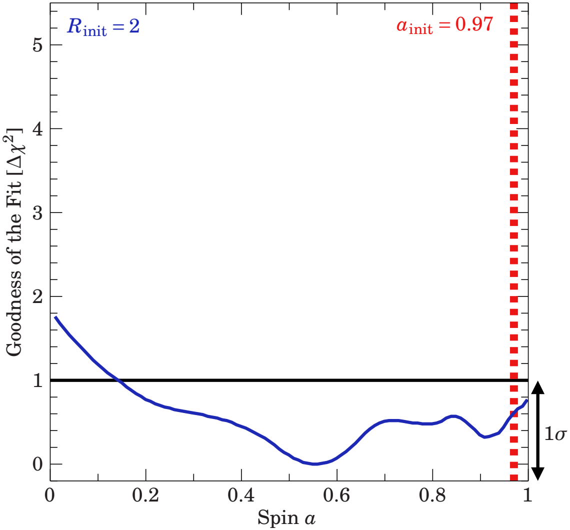


⇒ increases **high-spin preference**?



Accretion Geometry: The Maximal Reflection Fraction

Constraining the spin (simulation of a typical AGN)



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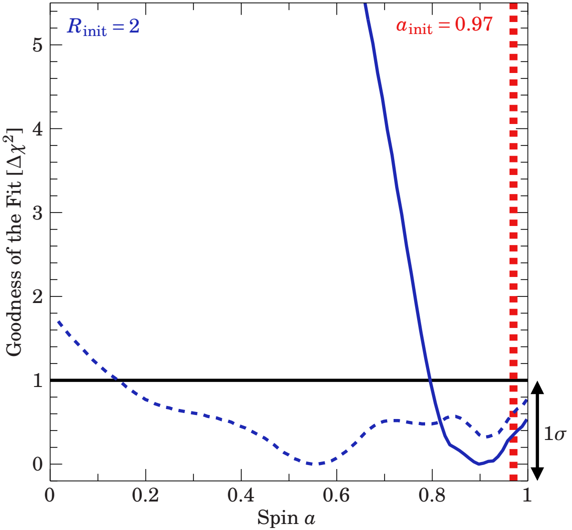
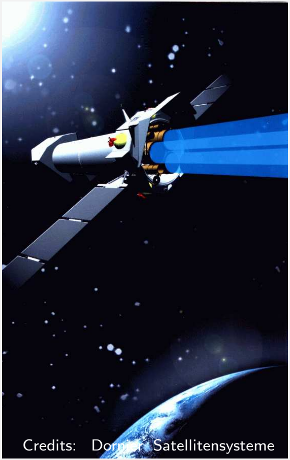
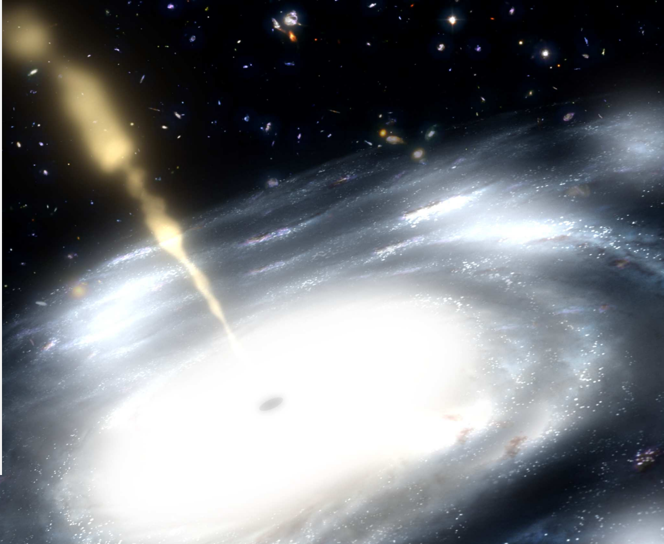


unphysical solutions excluded (Dauser et al., 2014)
$\rightarrow$ **spin better constrained**

Has been successfully applied to Mrk 335
(Parker et al., 2014)





Modeling Relativistic Reflection: Recent Developments

Commonly Used Reflection and Relativistic Models

Reflection Models

- `pexrav` first reflection model (Magdziarz & Zdziarski, 1995)
- `rfxconv` arbitrary input spectrum (Done & Gierliński, 2006; Kolehmainen et al., 2011)
- `reflionx` includes ionized disk (Ross & Fabian, 2005; Ross & Fabian, 2007)
- `xillver` updated atomic data base (García & Kallman, 2010; García et al., 2011)

Relativistic Models

- `diskline` first broad line model (Fabian et al., 1989)
- `laor` model for maximal spin (Laor, 1991, converted to `kdblur` later)
- `ky-models` arbitrary spin (Dovčiak et al., 2004)
- `kerrdisk` requires significantly less precalculated values (Brenneman & Reynolds, 2006)
- `relline` based on `kerrdisk`, including negative spin and lamp post (Dauser et al., 2010, 2013)

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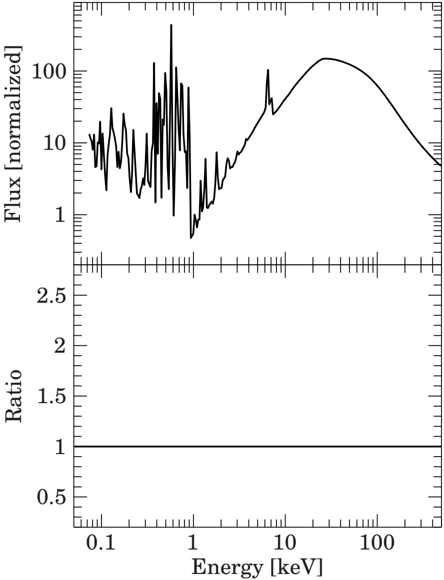
→ no **direct connection**

Angle Dependency of Reflection

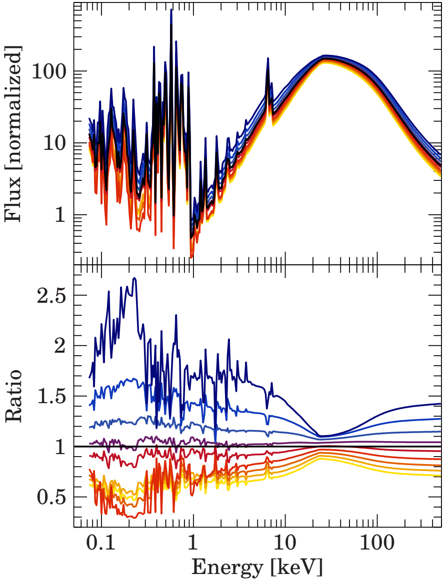
previous **relativistic** models:
→ **convolve** averaged reflection spectra



Angle Dependency of Reflection

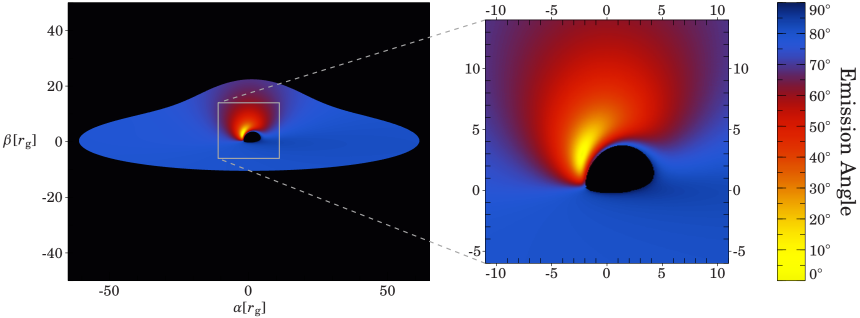
previous **relativistic** models:
→ **convolve** averaged reflection spectra

However, reflection spectra depend on the **emission angle** (Lightman & Rybicki, 1980; Magdziarz & Zdziarski, 1995; García et al., 2013, ...)



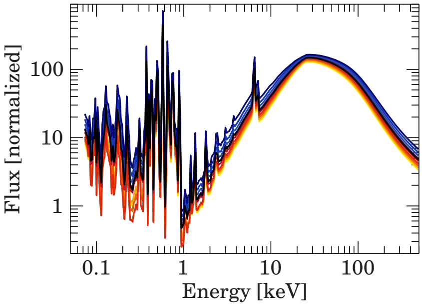
Angle Dependency of Reflection

Relativity: Inclination $\neq$ Emission Angle

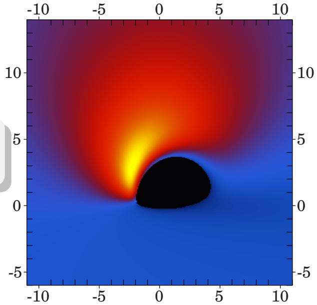


Many **emission angles** possible for a **fixed inclination**

relxill: Combining Relativity and Reflection



+



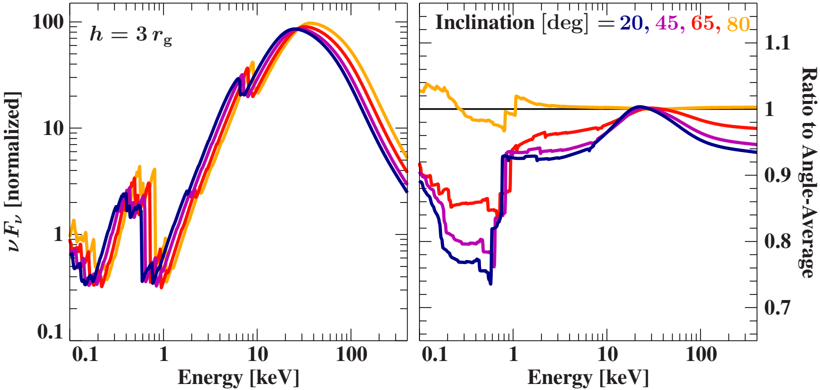
relxill accounts for these **angular effects** (García & Dauser et al. 2014)

can be used in all major X-ray software and is publicly available

reflection: Γ, E_{cut}, ionization parameter, iron abundance

relativistic: spin, inclination, R_f, emissivity profile, r_{in}

relxill: Difference to the Angle-Average



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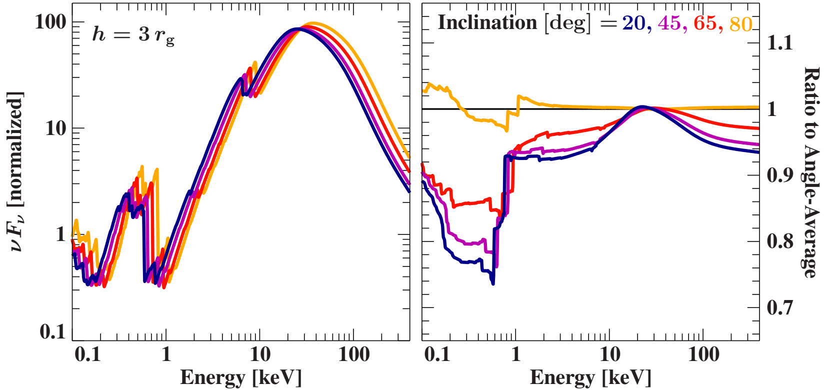
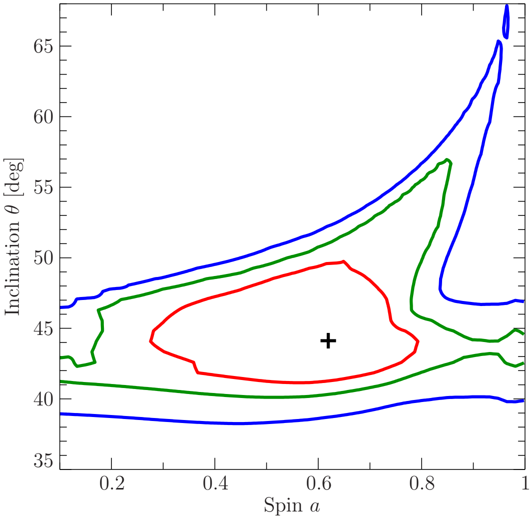


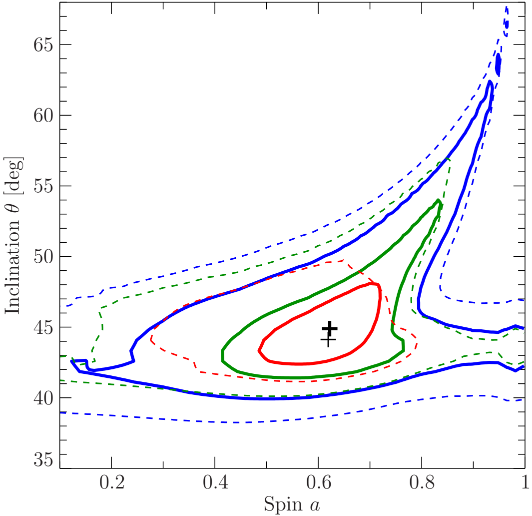
Systematic bias: iron abundance (up to a factor 2), but spin and inclination mainly constant (García et al., 2014)

relxill: Stronger Parameter Constraints



100 ksec *Suzaku* **observation of Ark 120**

`relxill`: Stronger Parameter Constraints

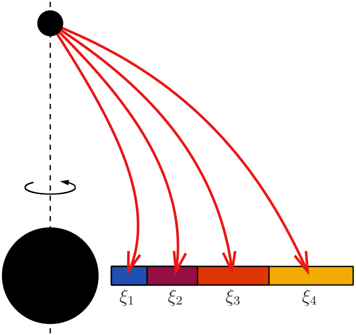


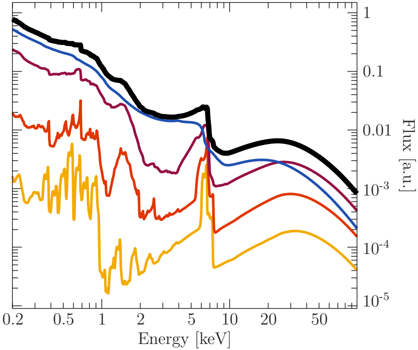
100 ksec *Suzaku* **observation of Ark 120**

Spin and **inclination**
better constrained
(García et al., 2014)

relxill: Ionization Gradient in the Disk

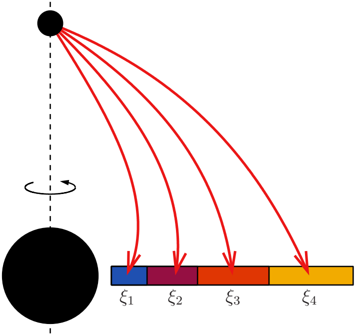
Irradiation in the jet base geometry: **self-consistently** calculate the **ionization gradient** and emerging **spectra** (Dauser et al., in prep.)

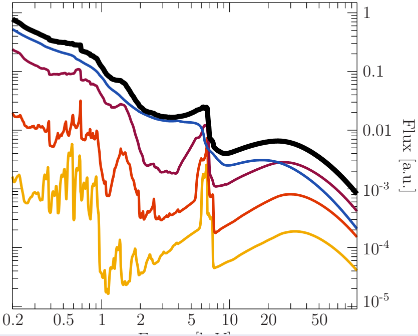




relxill: Ionization Gradient in the Disk

Irradiation in the jet base geometry: **self-consistently** calculate the **ionization gradient** and emerging **spectra** (Dauser et al., in prep.)





relxill_ion: ionization gradient as a model parameter

relxilllp_alpha: ionization gradient **predicted** by assuming an α-disk density profile (Shakura & Sunyaev, 1973)

relxilllp_ion: drop α-disk assumption → fit the density profile

Summary: Current Status and Future Prospects

Combining Relativity and Reflection: `relxill`

- Tighter parameter constraints and less systematic bias
- `relxilllp` takes **irradiation** into account
- Self-consistent ionization gradient in the disk

The next steps for modeling relativistic reflection:

- Apply **ionization gradient** to data (→ fit density?)
- Dependency on the **incident angle** (GX 339–4, García et al., subm.)
- Model for relativistic reflection in GBHs (including black-body)

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