Toward a new generation of reflection models for precision measurements of accreting black holes

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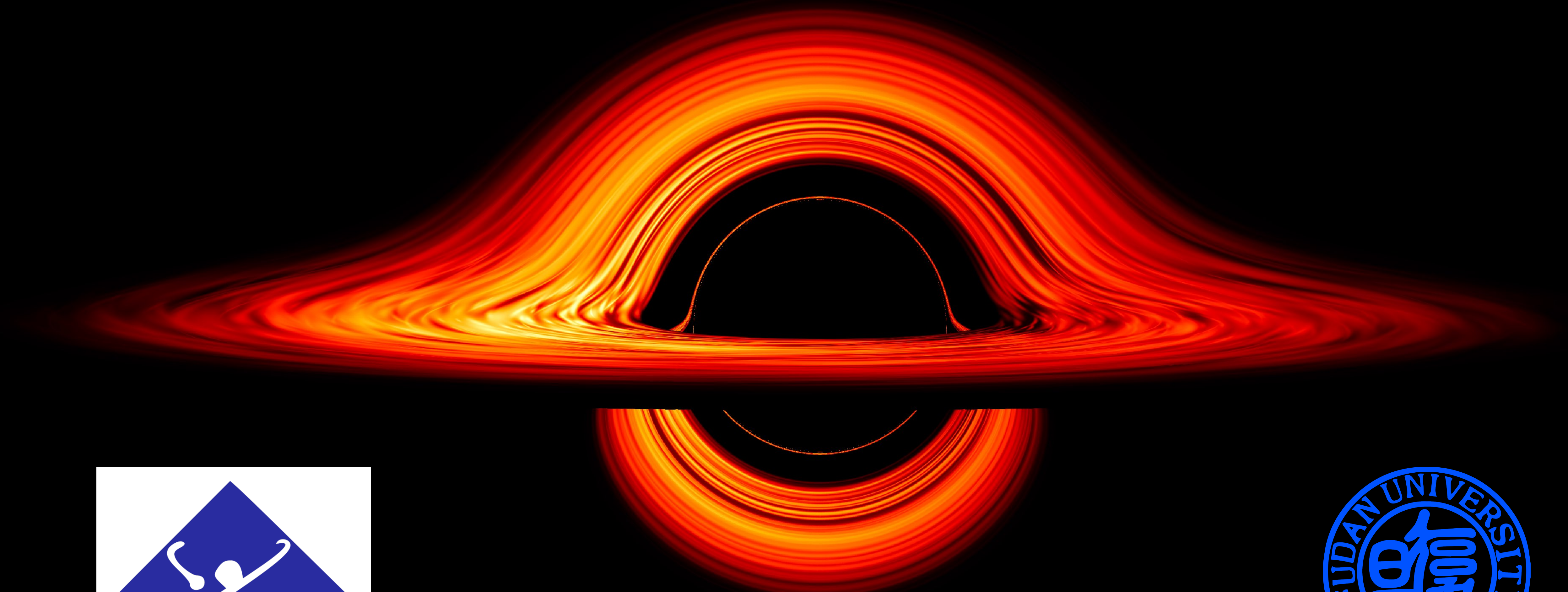


NAOC, Beijing (18 October 2023)

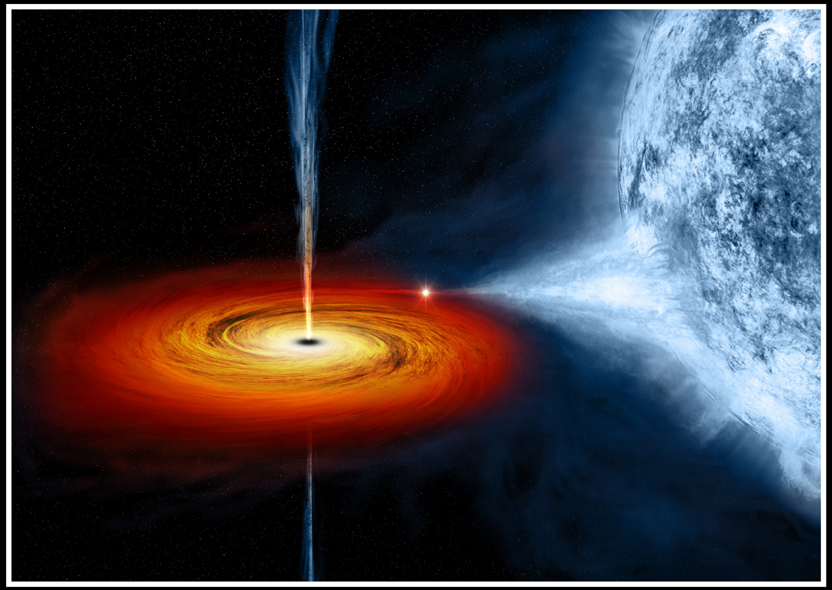
Part I:

X-Ray Reflection Spectroscopy

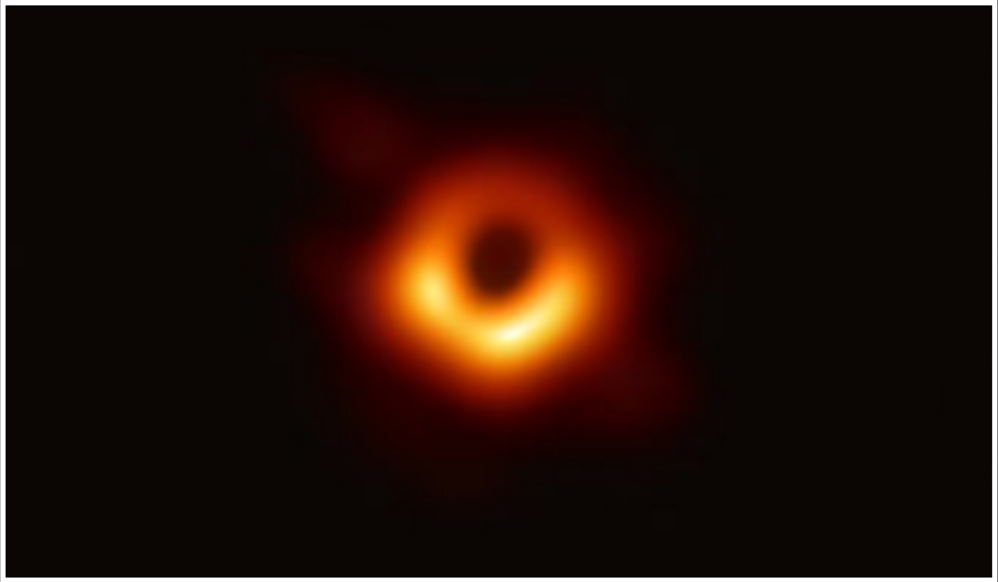
Introduction

Astrophysical Black Holes

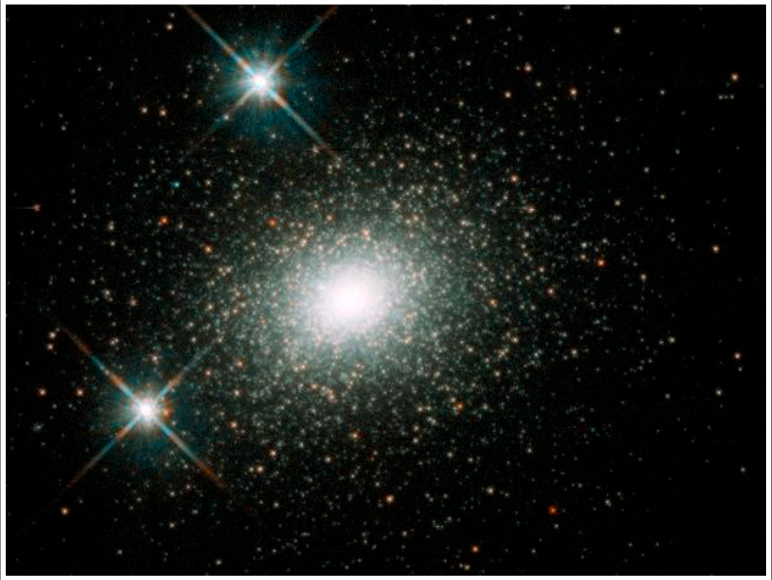
Stellar-mass black holes
(~3-100 $M_\odot$)



Supermassive black holes
(~10^5-10^{10} $M_\odot$)

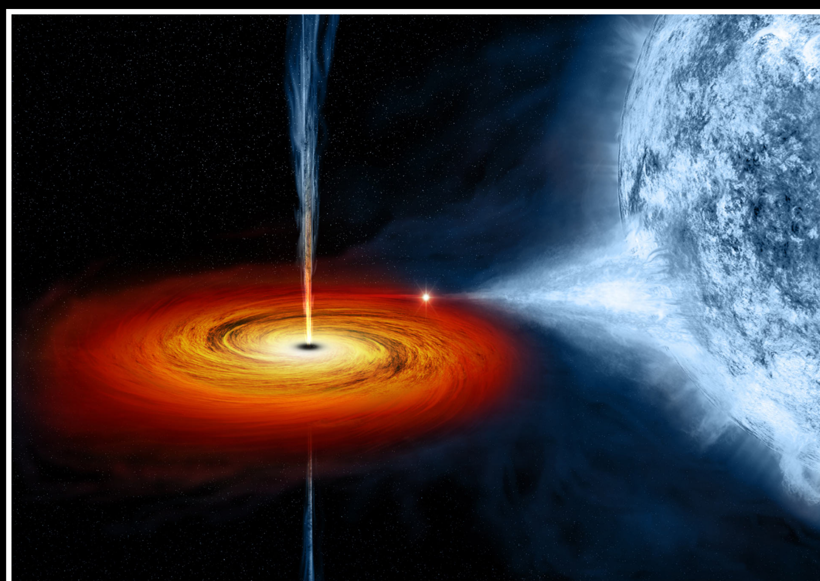


Intermediate-mass
black holes



Astrophysical Black Holes

Stellar-mass black holes
(~3-100 $M_\odot$)



~10^8-10^9 objects
in the Milky Way

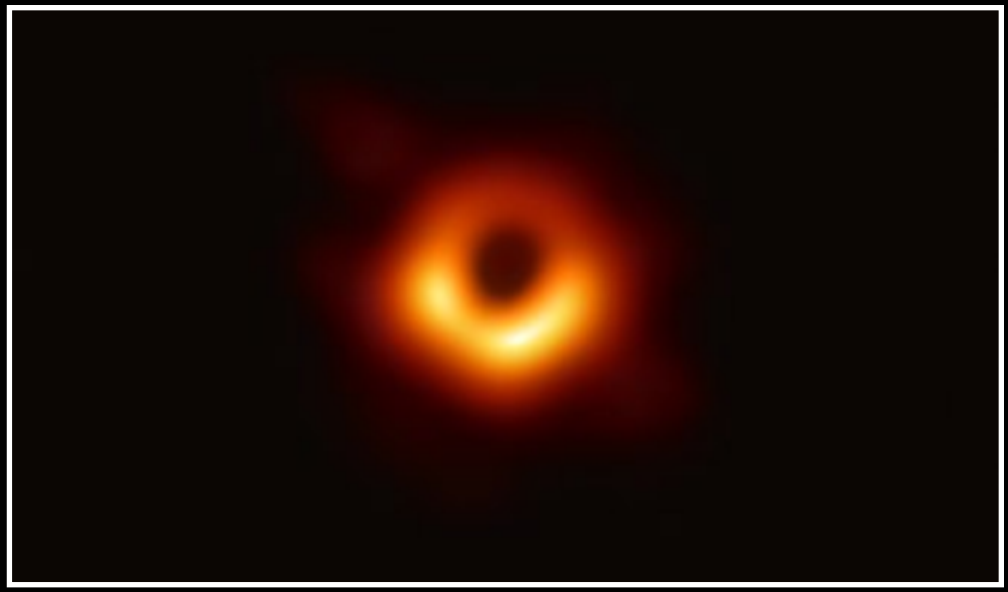
~70 objects
in X-ray binary systems

~40 objects
with a measurement
of the spin with XRS

~a few objects
suitable for
precise GR tests with XRS

Astrophysical Black Holes

Supermassive black holes
($\sim 10^5$-10^{10} $M_\odot$)



$\sim 10^{12}$ galaxies in the observable Universe

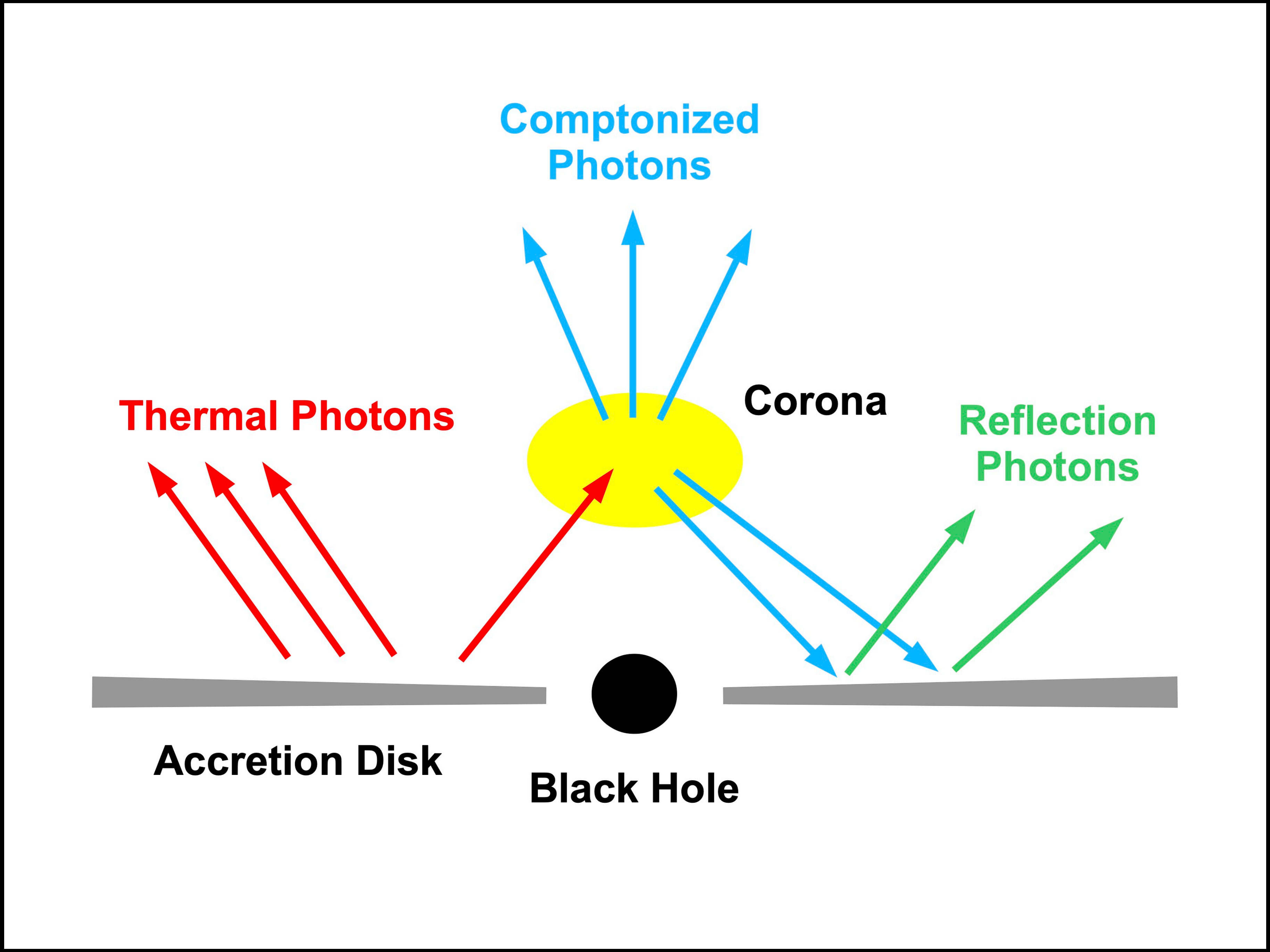
0.035% AGN

~40 objects
with a measurement
of the spin with XRS

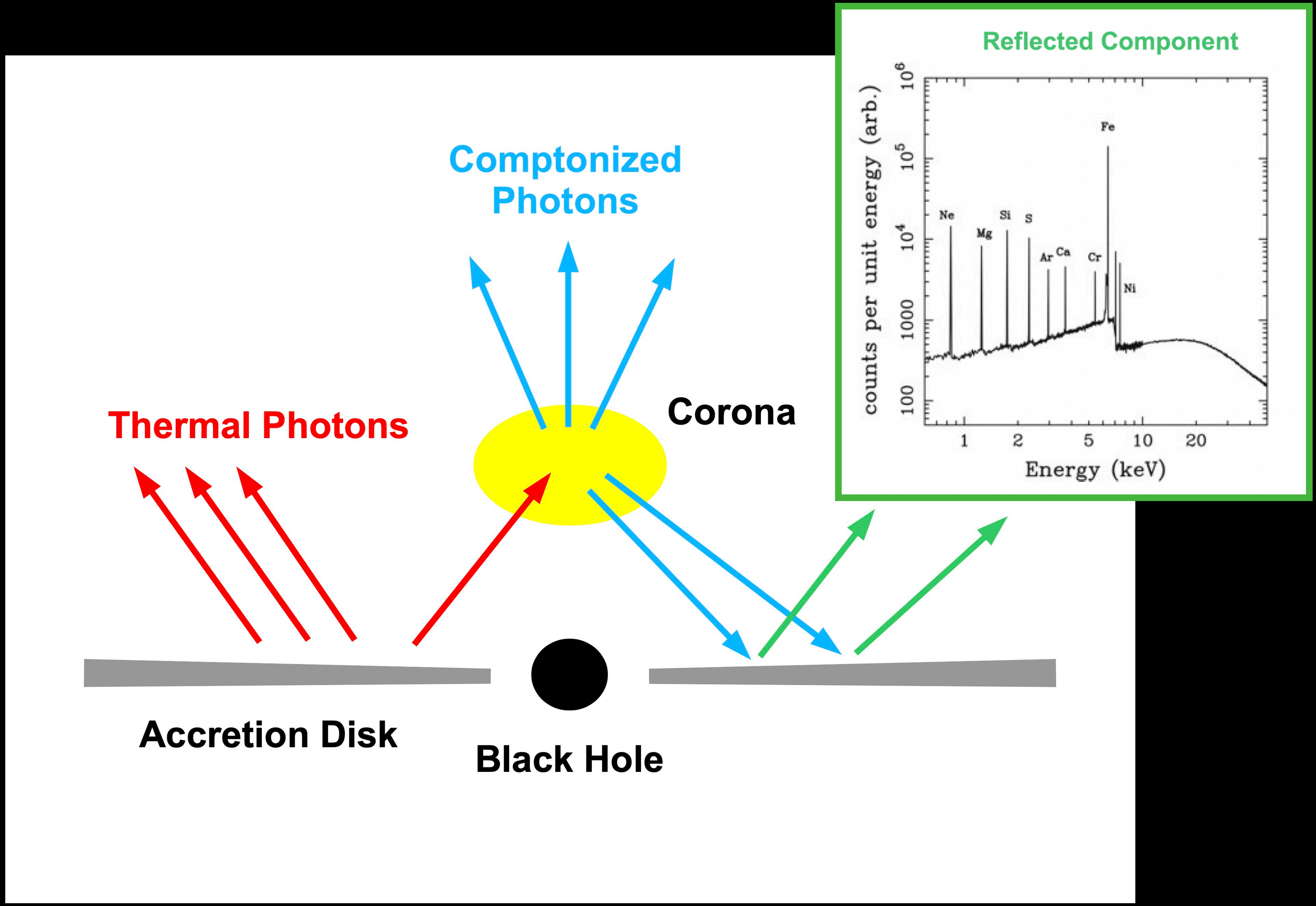
~a few objects
suitable for
precise GR tests with XRS

Disk-Corona Model

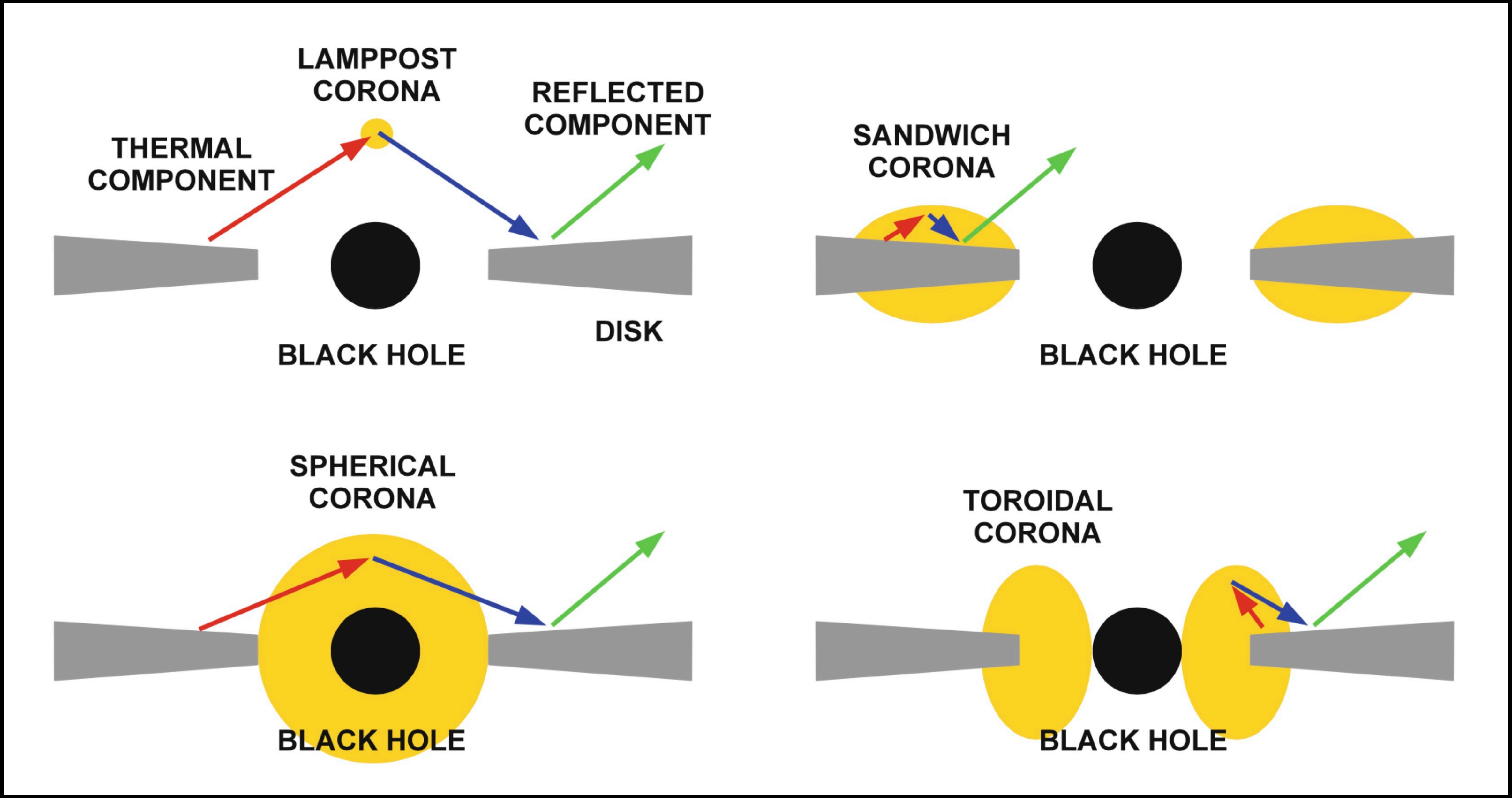
Disk-Corona Model



Disk-Corona Model



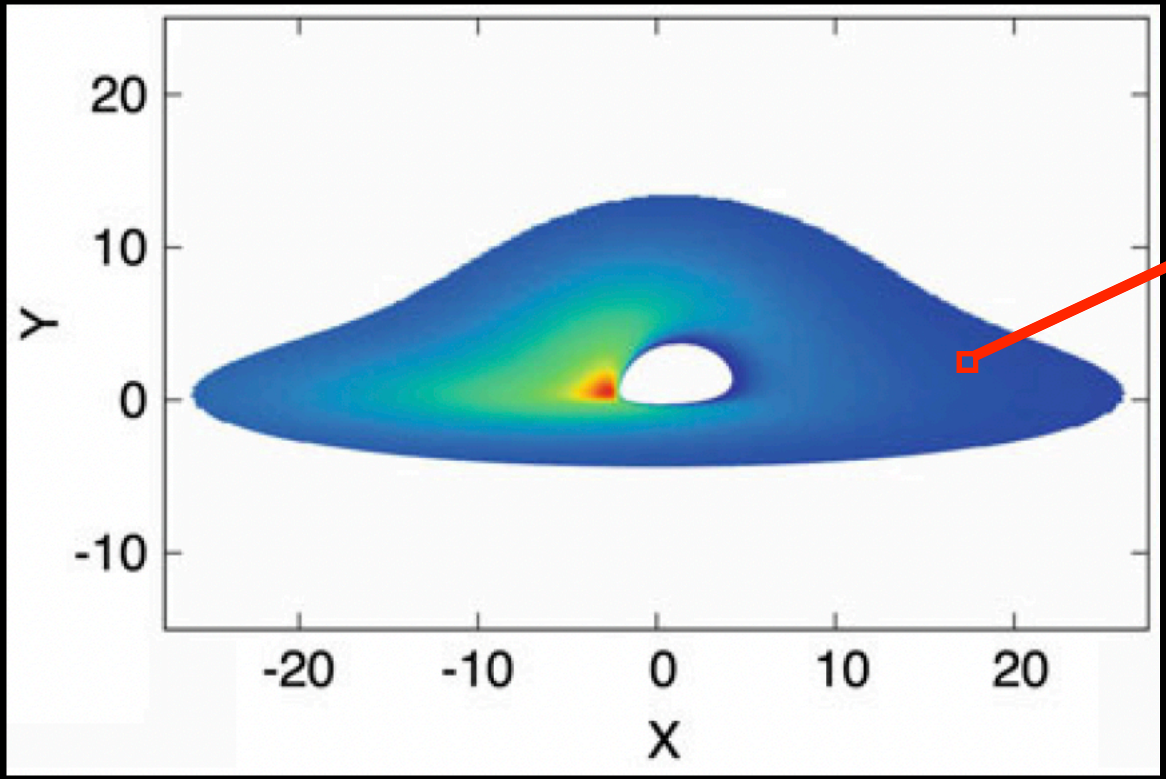
Coronal Geometries

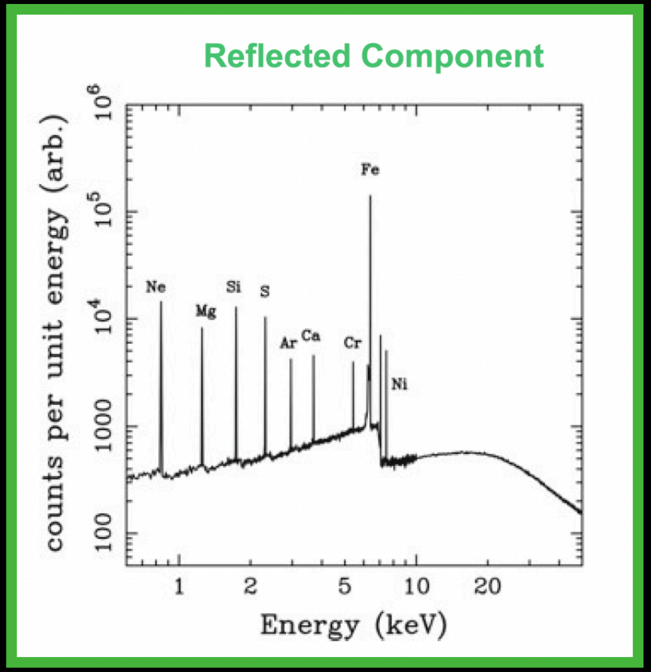


Synthetic Spectra

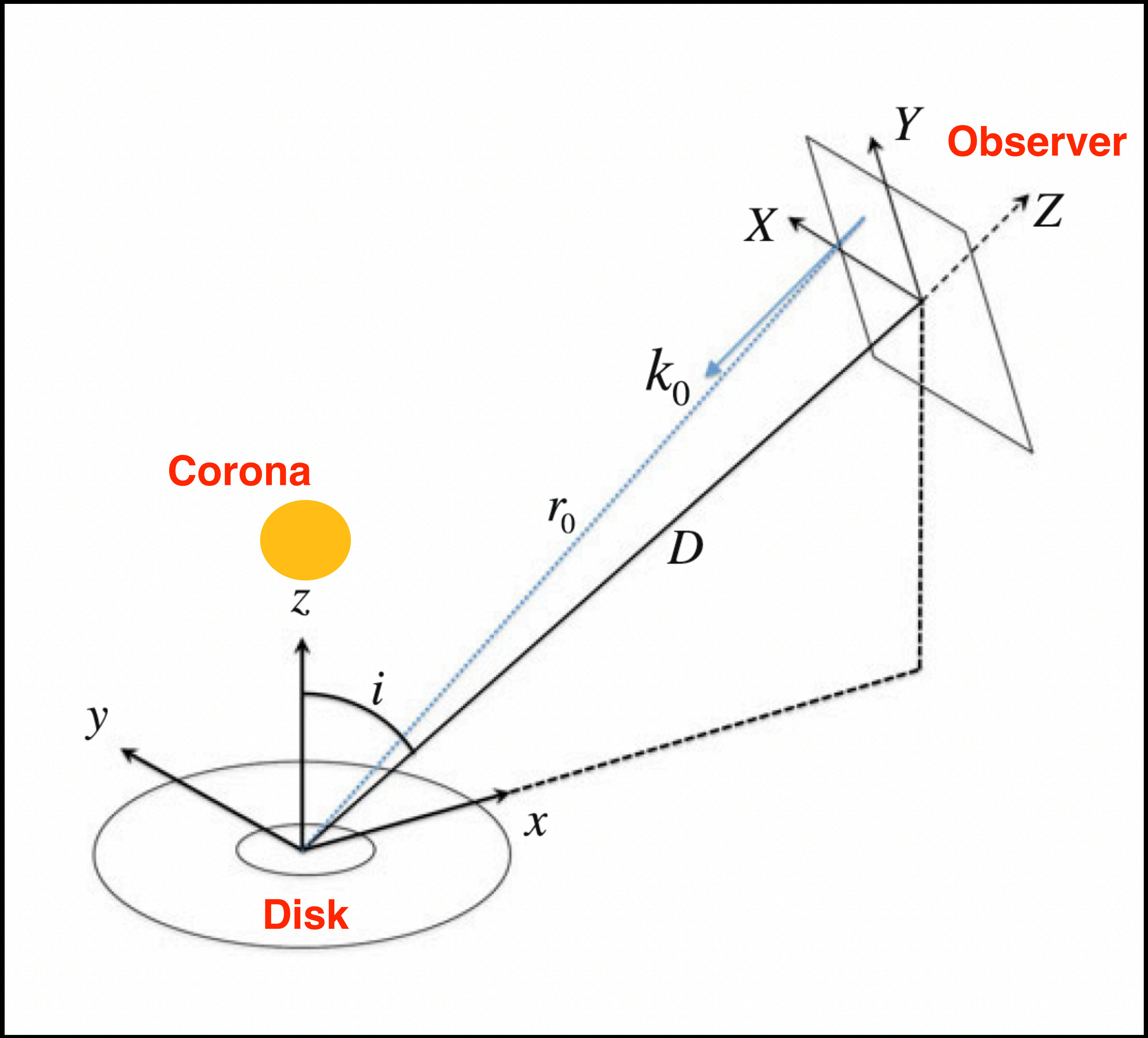
Observed Flux

$$F_{\rm obs}(\nu_{\rm obs}) = \int I_{\rm obs}(\nu_{\rm obs}, X, Y) d\tilde{\Omega} = \int g^3 I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e}) d\tilde{\Omega} \, ,$$





Disk-Observer System



Redshift Image of the Disk

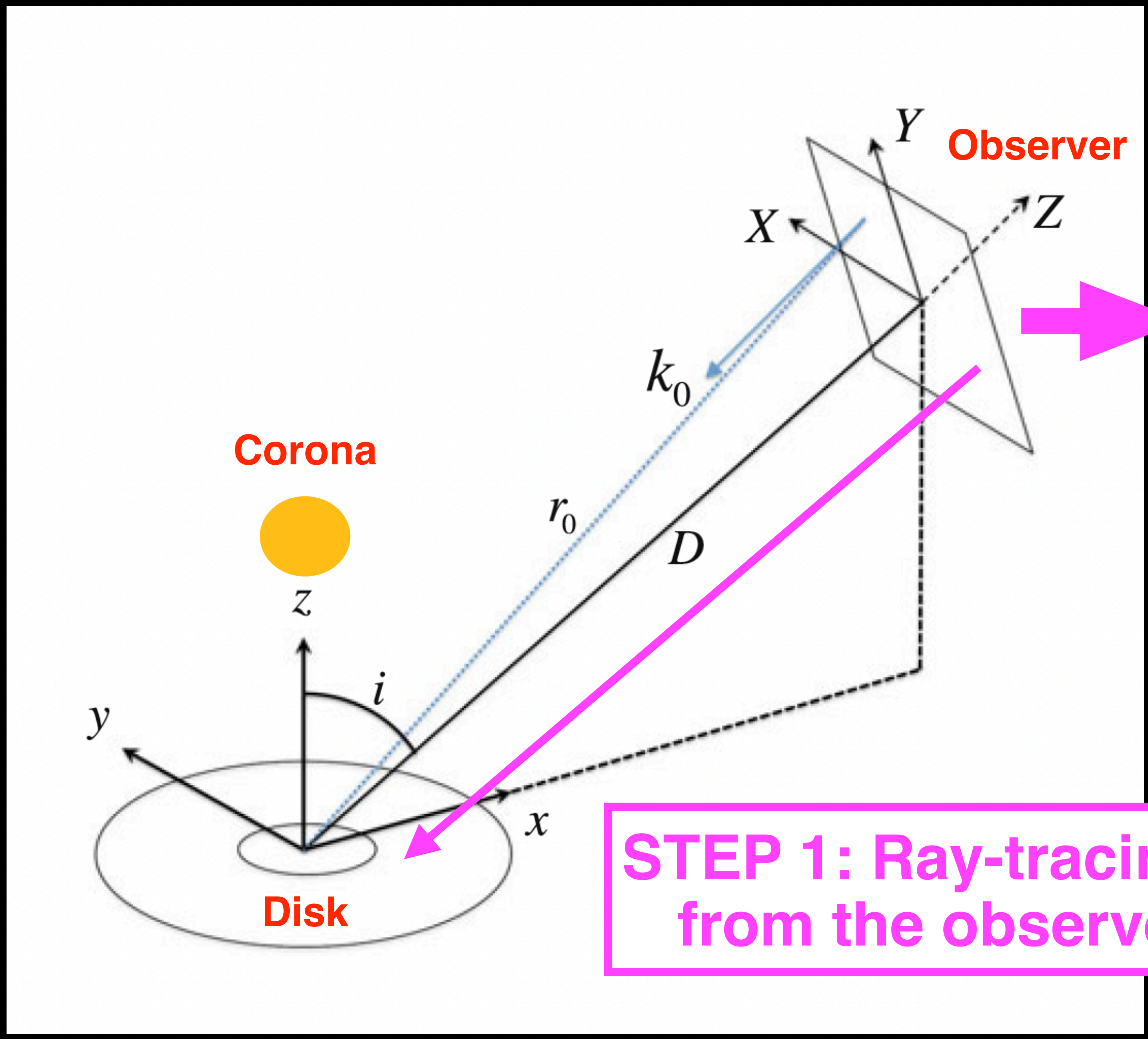
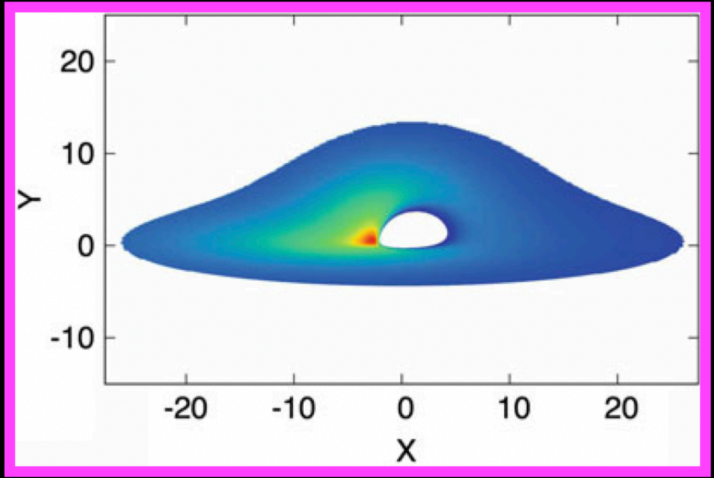


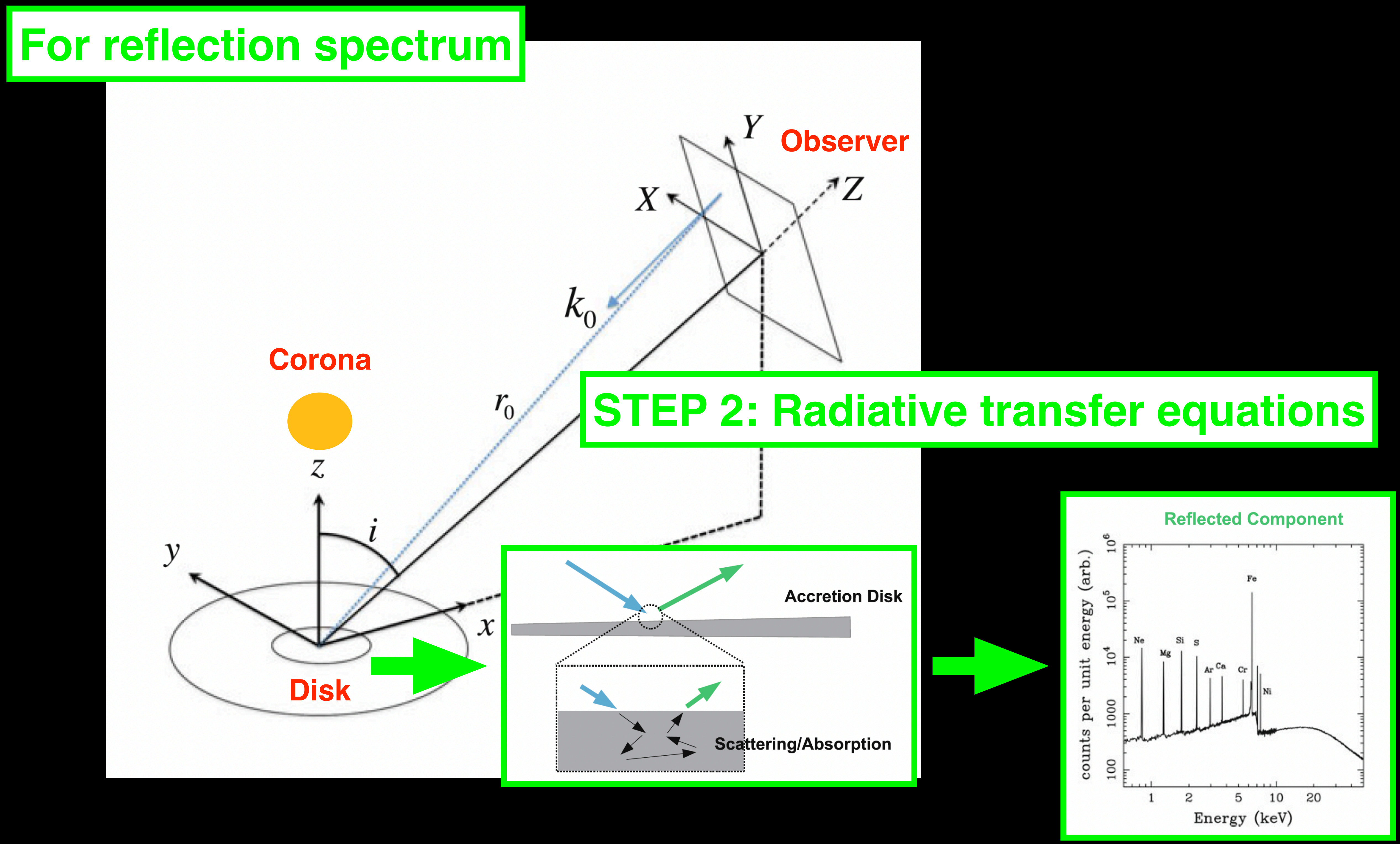
Image of the accretion disk



Every point on the image is characterized by its redshift factor *g*

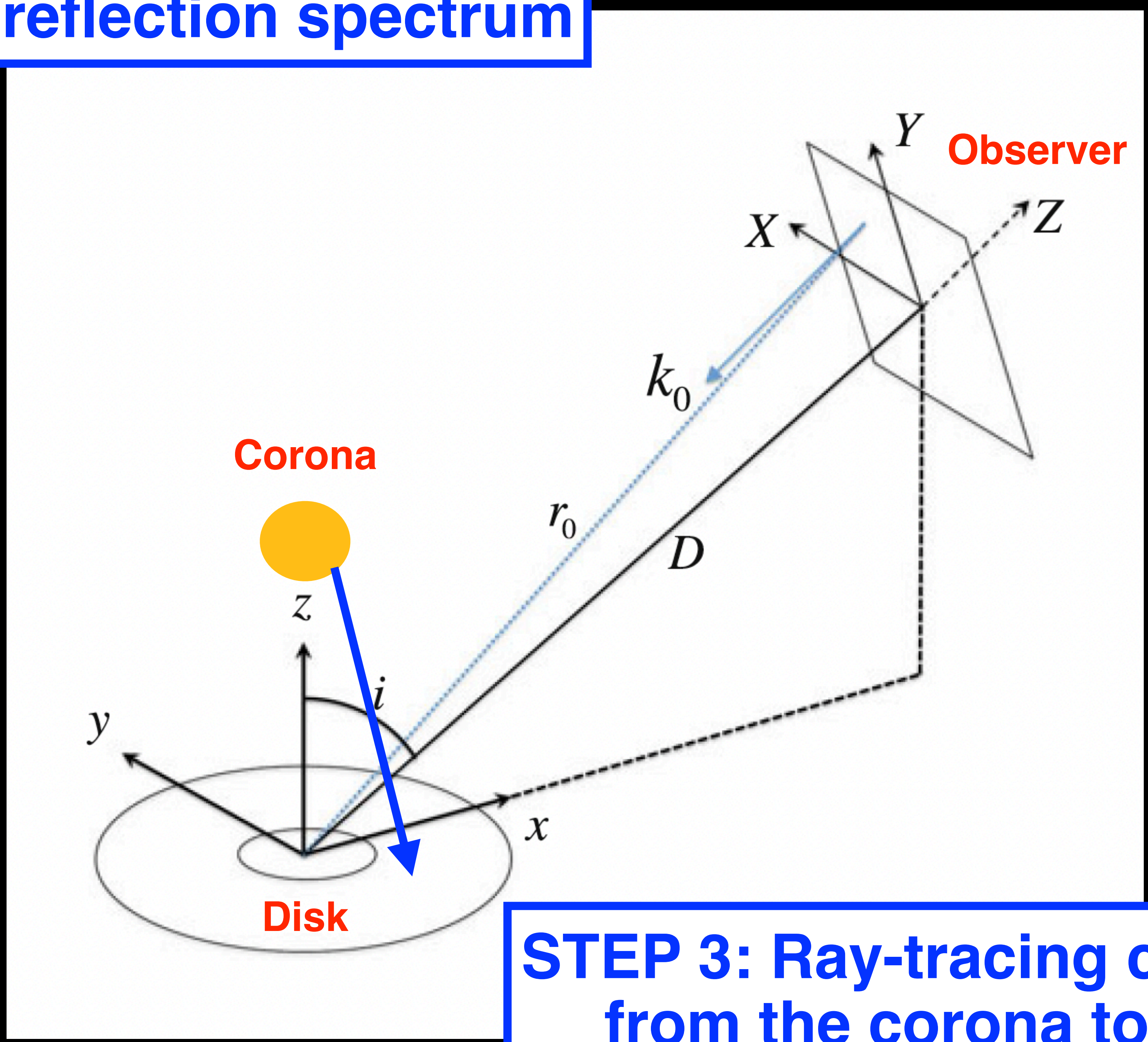
STEP 1: Ray-tracing calculations from the observer to the disk

Local Spectrum



Emissivity Profile of the Disk

For reflection spectrum



STEP 3: Ray-tracing calculations from the corona to the disk

Transfer Function

$$F_{\rm obs}(\nu_{\rm obs}) = \int I_{\rm obs}(\nu_{\rm obs}, X, Y) d\tilde{\Omega} = \int g^3 I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e}) d\tilde{\Omega} \, ,$$

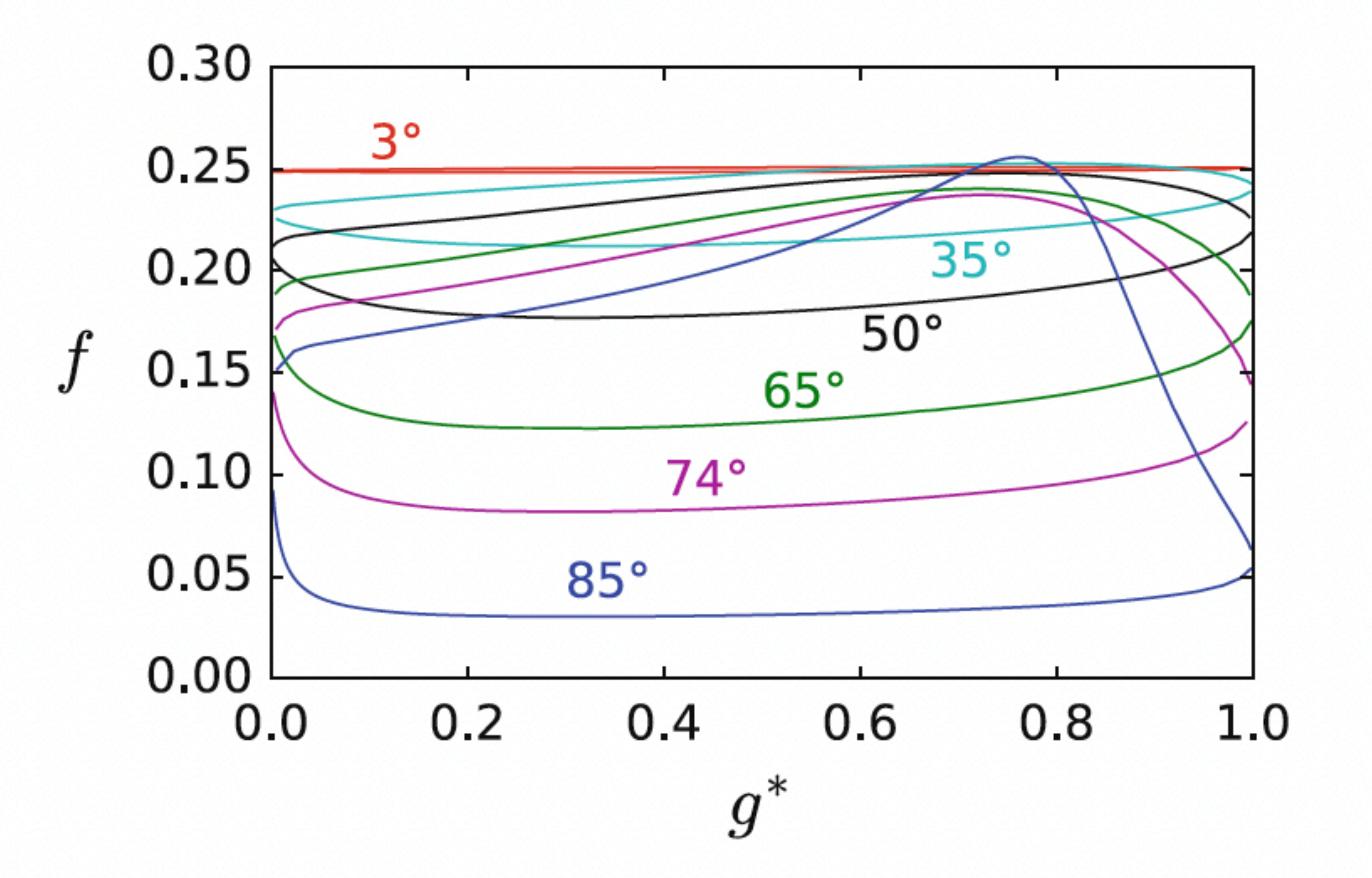
$$F_{\rm obs}(\nu_{\rm obs}) = \frac{1}{D^2} \int_{r_{\rm ISCO}}^{\infty} \int_0^1 \pi r_{\rm e} \frac{g^2}{\sqrt{g^*(1-g^*)}} f(g^*, r_{\rm e}, i) I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e}) \, dg^* \, dr_{\rm e} \, .$$

$$g^* = \frac{g - g_{\rm min}}{g_{\rm max} - g_{\rm min}} \, ,$$

$$f(g^*, r_{\rm e}, i) = \frac{1}{\pi r_{\rm e}} g \sqrt{g^*(1-g^*)} \left| \frac{\partial \, (X, Y)}{\partial \, (g^*, r_{\rm e})} \right| \, ,$$

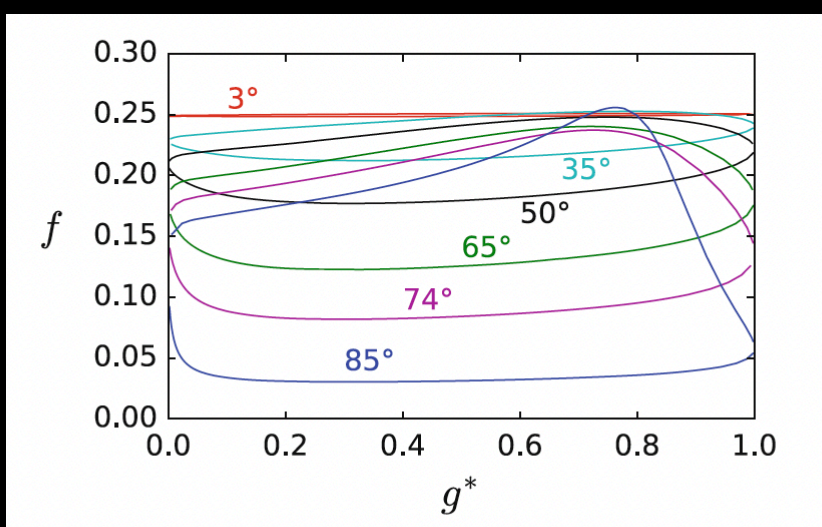
Transfer Function

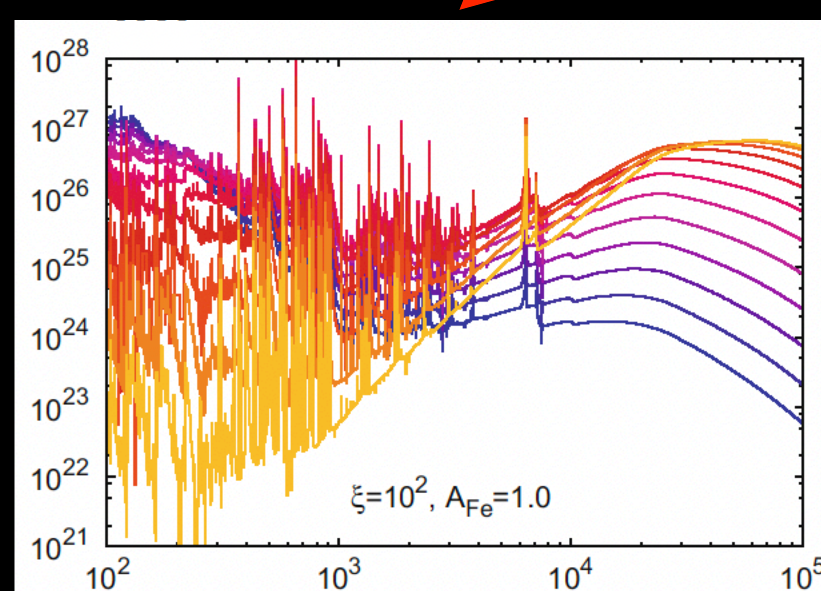
$$F_{\mathrm{obs}}(\nu_{\mathrm{obs}}) = \frac{1}{D^2}\int_{r_{\mathrm{ISCO}}}^{\infty}\int_0^1 \frac{\pi r_{\mathrm{e}}\, g^2}{\sqrt{g^*(1-g^*)}} f_1(g^*, r_{\mathrm{e}}, i) I_{\mathrm{e}}(\nu_{\mathrm{e}}, r_{\mathrm{e}}, \vartheta_{\mathrm{e},1})\, dg^*\, dr_{\mathrm{e}}$$
$$+\frac{1}{D^2}\int_{r_{\mathrm{ISCO}}}^{\infty}\int_0^1 \frac{\pi r_{\mathrm{e}}\, g^2}{\sqrt{g^*(1-g^*)}} f_2(g^*, r_{\mathrm{e}}, i) I_{\mathrm{e}}(\nu_{\mathrm{e}}, r_{\mathrm{e}}, \vartheta_{\mathrm{e},2})\, dg^*\, dr_{\mathrm{e}} \,,$$

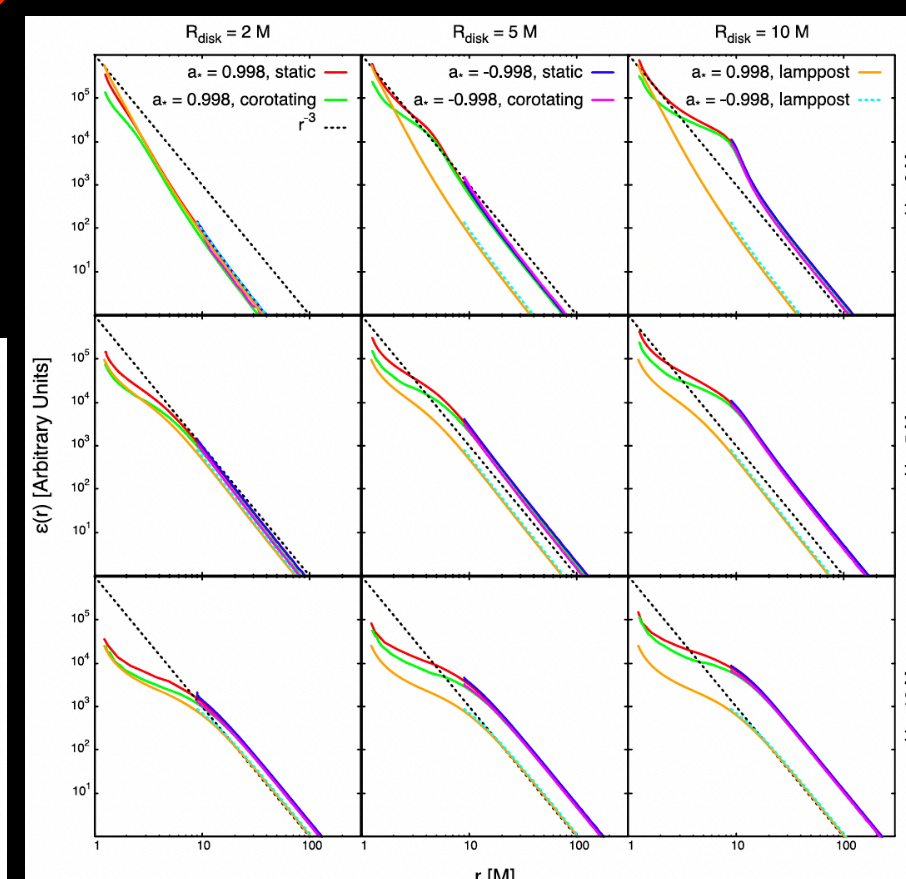


FITS Files

$$F_{\rm obs}(\nu_{\rm obs}) = \frac{1}{D^2}\int_{r_{\rm ISCO}}^{\infty}\int_0^1 \frac{\pi r_{\rm e}\, g^2}{\sqrt{g^*(1-g^*)}} f_1(g^*, r_{\rm e}, i) I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e,1})\, dg^*\, dr_{\rm e}$$
$$+ \frac{1}{D^2}\int_{r_{\rm ISCO}}^{\infty}\int_0^1 \frac{\pi r_{\rm e}\, g^2}{\sqrt{g^*(1-g^*)}} f_2(g^*, r_{\rm e}, i) I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e,2})\, dg^*\, dr_{\rm e}\,,$$



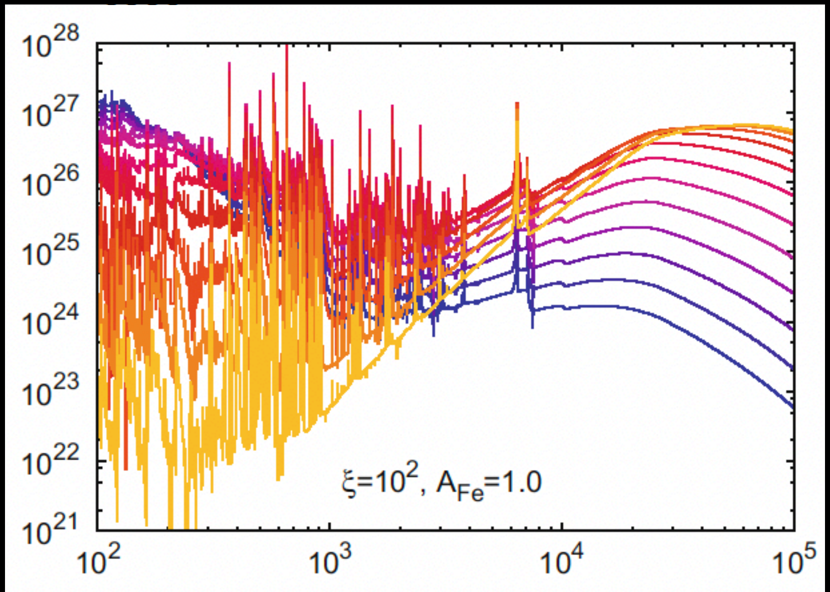




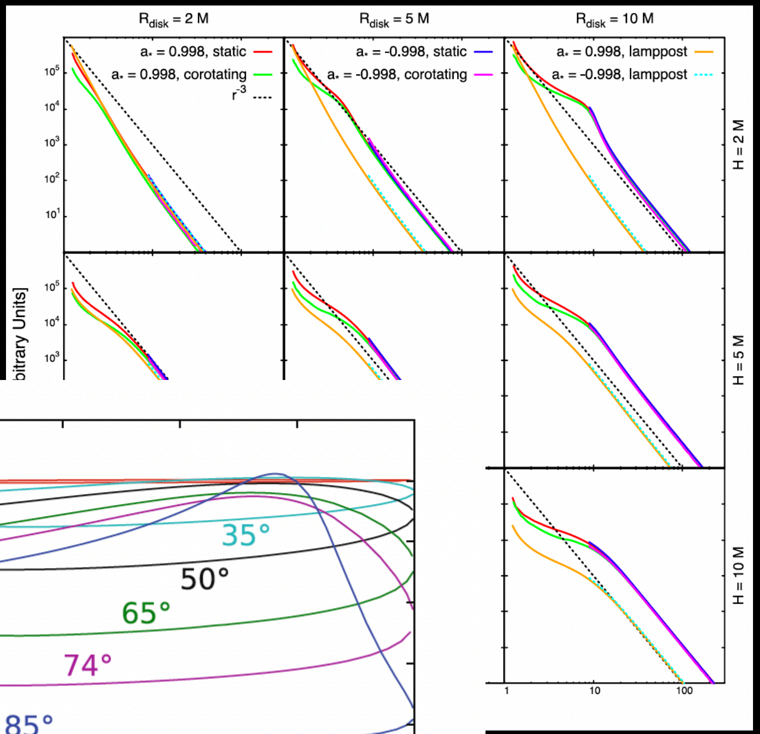
Reflection Models

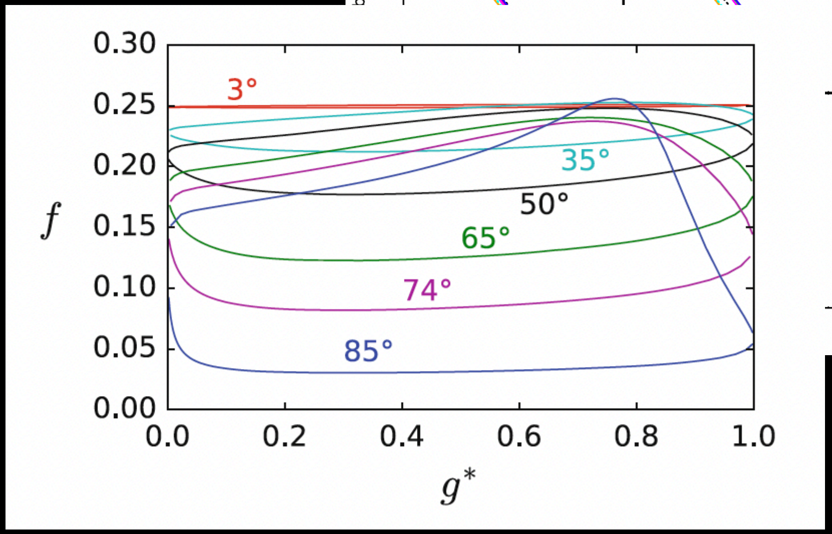
Reflection Models

- Non-relativistic reflection models:
  - `reflionx` (Ross & Fabian)
  - `xillver` (Garcia & Kallman)
  - `ireflect` (Magdziarz & Zdziarski)



- Relativistic reflection models:
  - `relxill` (Dauser & Garcia)
    - `relxill_nk` (Fudan)
  - `kyn` (Dovciak)
  - `reflkerr` (Niedzwiecki)
  - `reltrans` (Ingram)





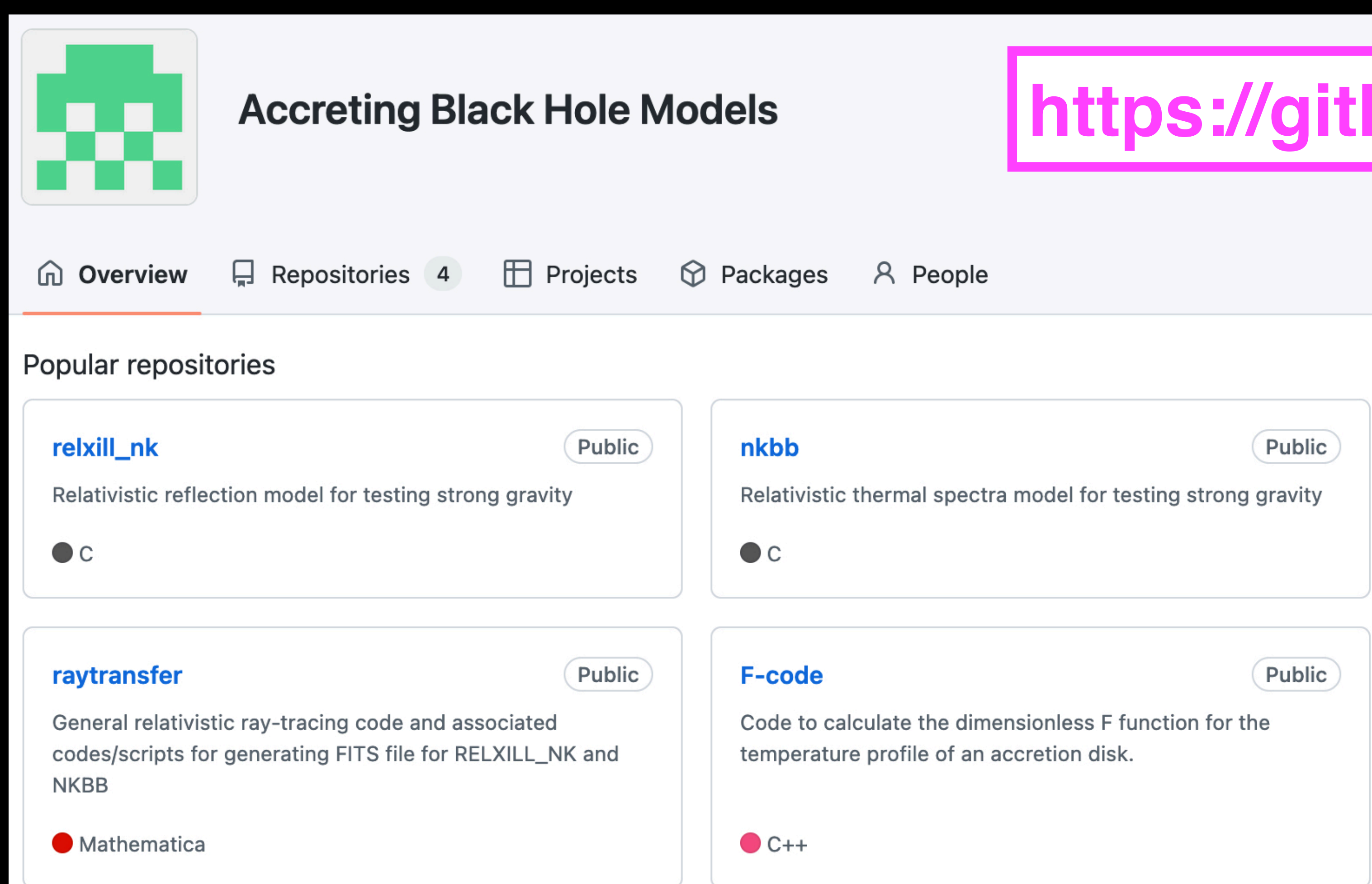
ABHModels

- `relxill_nk` (Bambi et al. 2017; Abdikamalov et al. 2019)

  Reflection spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes

- `nkbb` (Zhou et al. 2019)

  Thermal spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes



https://github.com/ABHModels

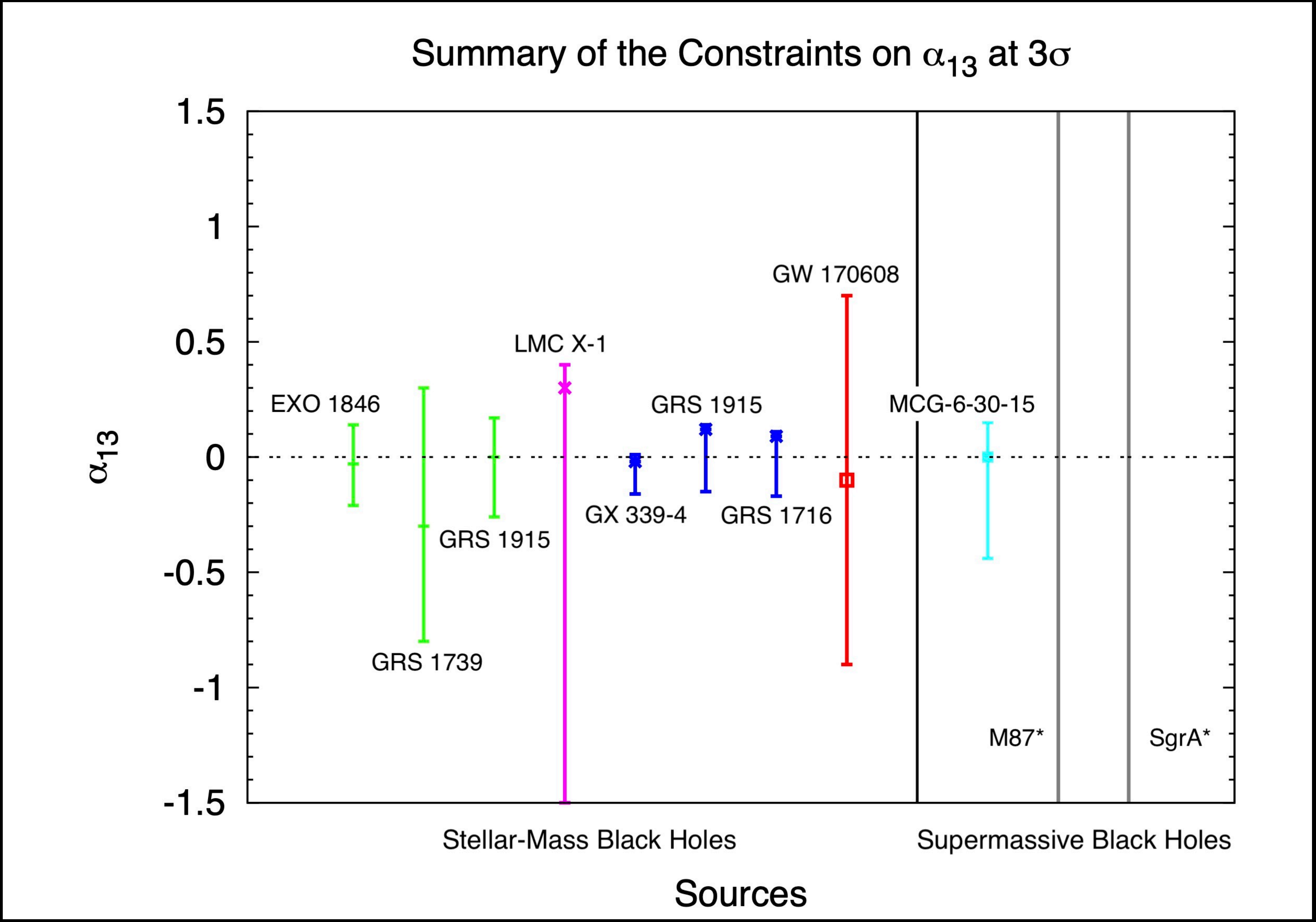
GR Tests with XRS

- **Tests of the Kerr black hole hypothesis**
  - Agnostic tests
  - Tests of specific gravity models (we need to know the rotating black hole solution of the theory that we want to test)

- Tests of geodesic motion/tests of the Weak Equivalence Principle
  - Non-minimal couplings between the matter and gravity sectors

- Tests of variation of fundamental constants
  - The atomic physics in strong gravitational fields is different from the atomic physics in our laboratories on Earth

Tests of the Kerr Hypothesis



Part II:

1) Are current XRS measurements of black holes accurate?

2) How can we improve current reflection models?

Are Current XRS Measurements of Black Holes Accurate?

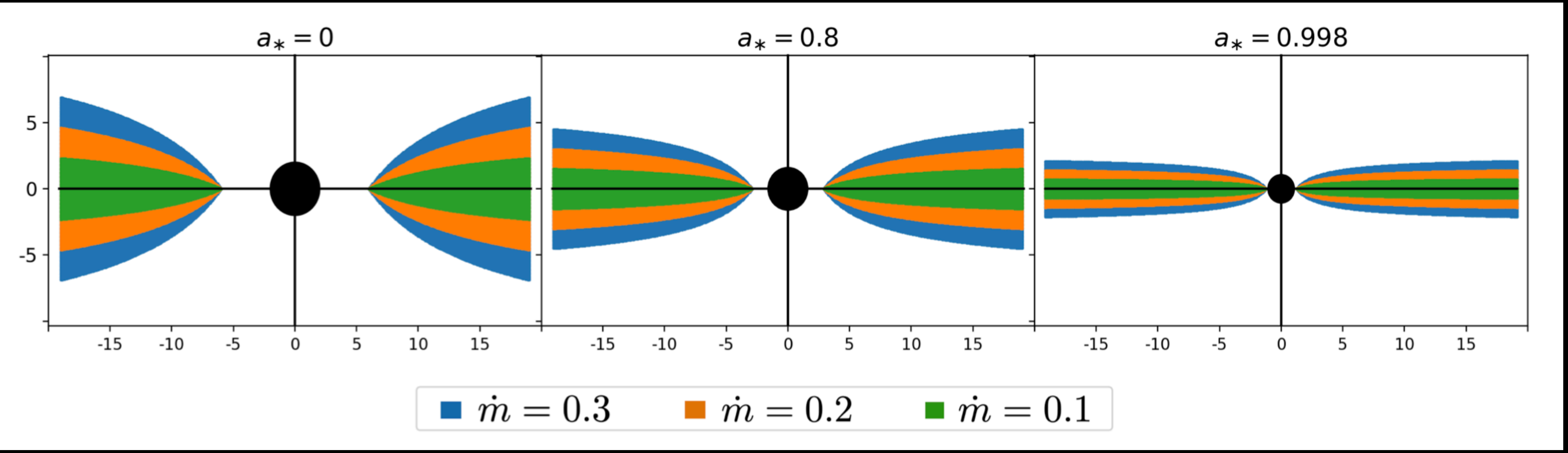
Quick (and personal) answer: yes, but only if we select the right sources and observations

- High spin ($a > 0.9$)
- Compact corona close to the black hole
- Prominent and broadened iron line
- $L \sim 0.05$-$0.30\ L_{Edd}$
- High resolution at the iron line + hard X-ray band

Disk Structure

Thickness of the Disk

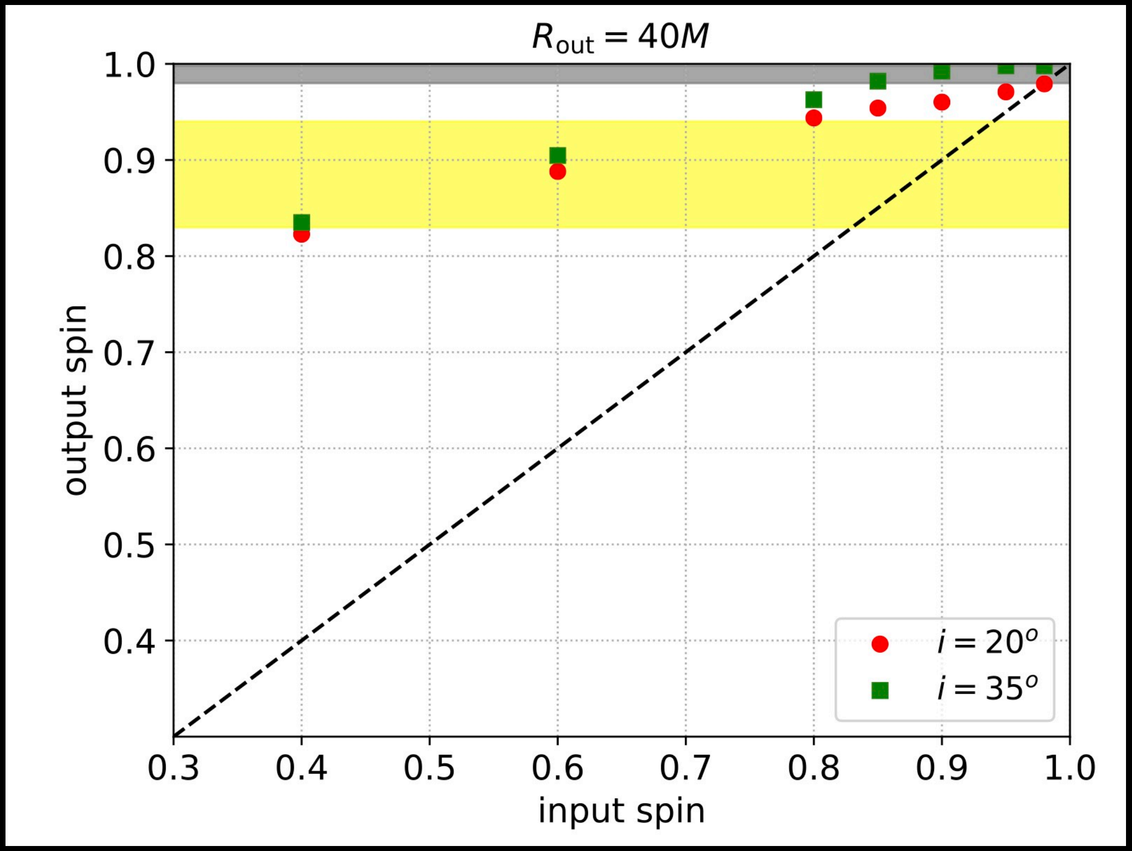
- Thin disks of finite thickness (from Taylor & Reynolds 2018)
- Abdikamalov et al. 2020 (model, GRS 1915+105)
- Tripathi et al. 2021 (MCG-6-30-15, EXO 1846-031)
- Jiang et al. 2022 (lamppost corona, MCG-6-30-15)

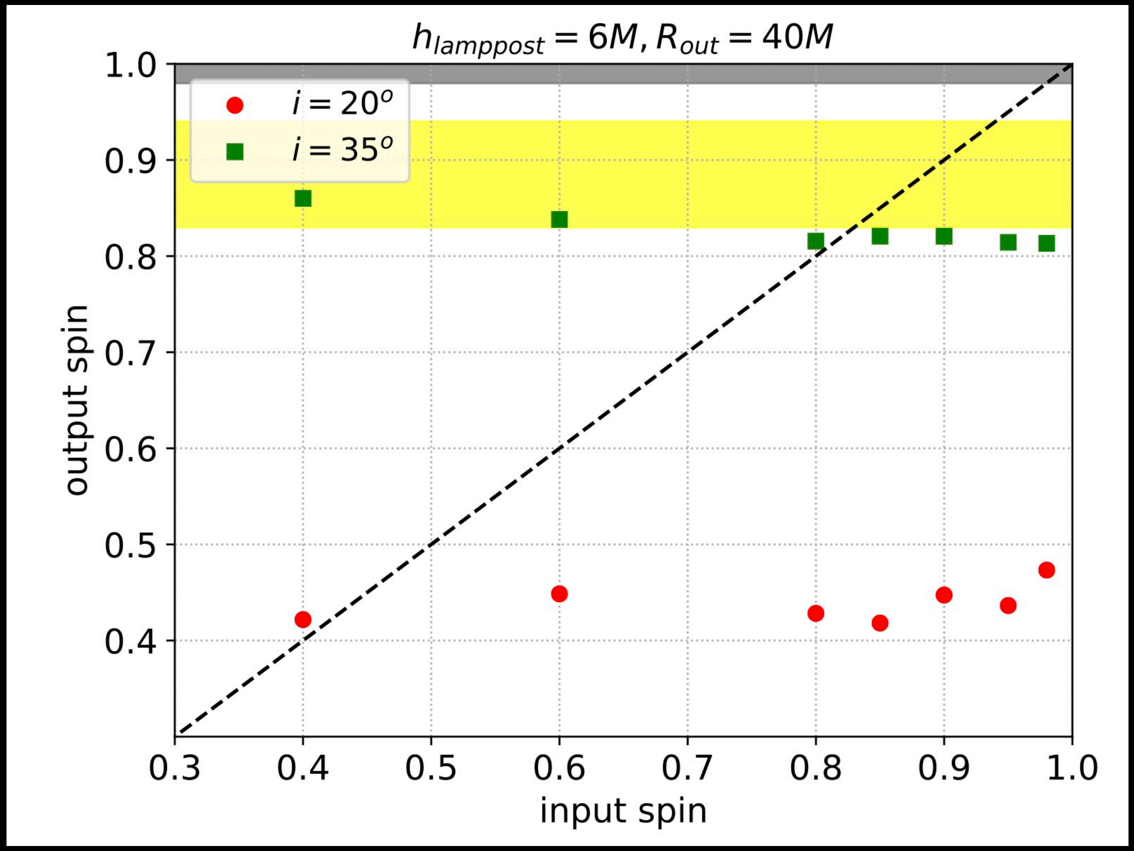


Conclusion: no significant impact on the parameter estimate for disks with high radiative efficiency

Thickness of the Disk

- Thick disks
- Riaz et al. 2020a, 2020b

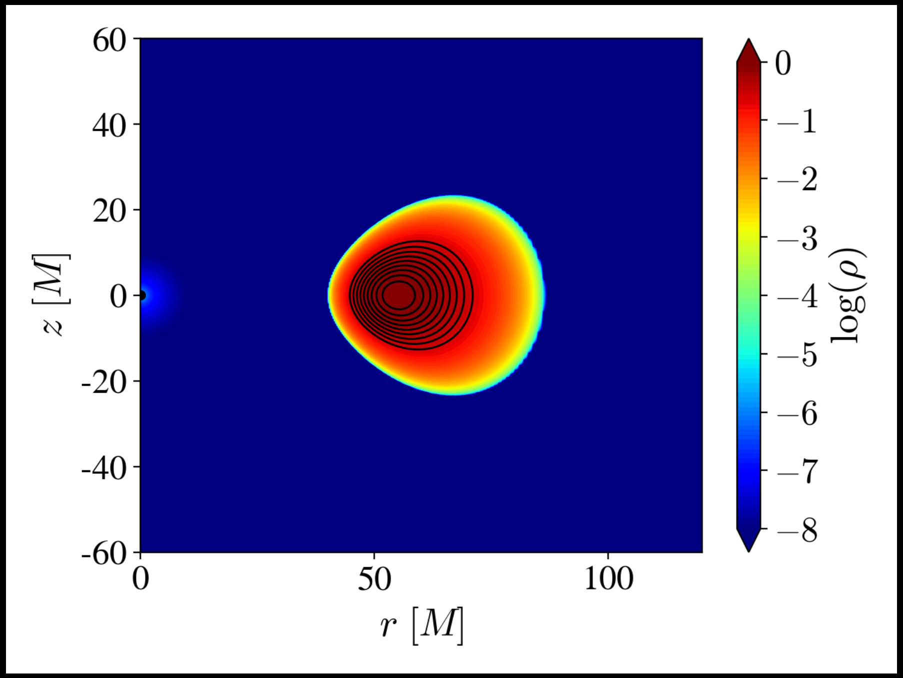


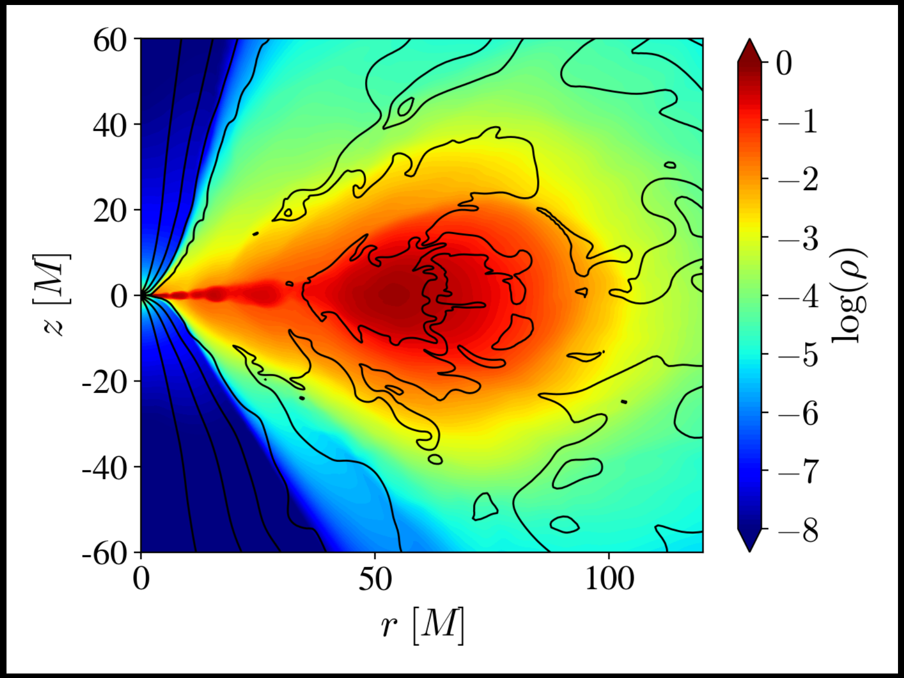


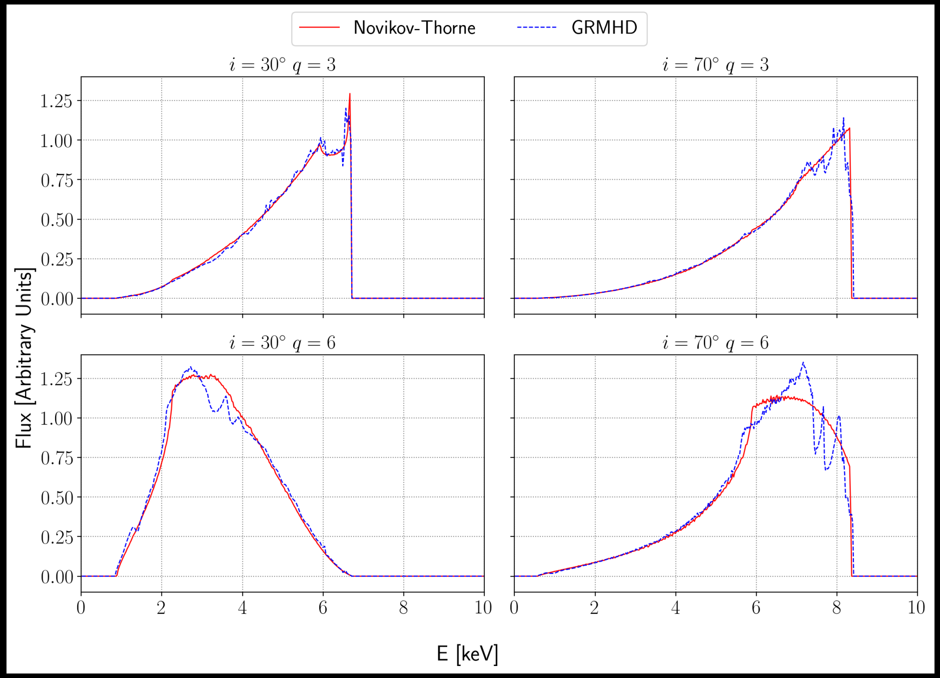
Conclusion: large systematic uncertainties, wrong measurements

GRMHD-Simulated Thin Disks

- Shashank et al. 2022



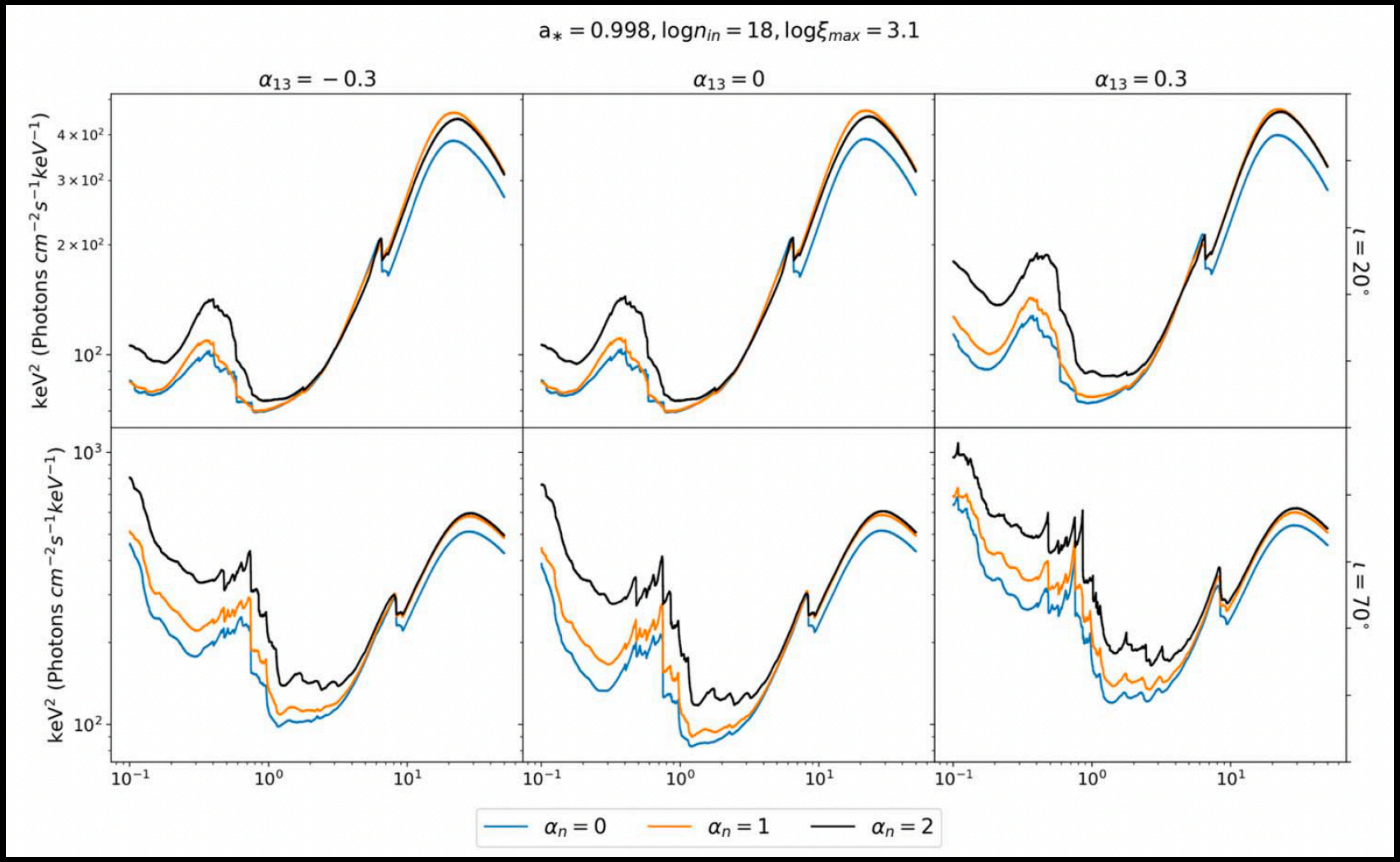




Conclusion: we recover well the input parameters

Ionization and Density Gradients

- Abdikamalov et al. 2021a (`relxillion_nk`, EXO 1846-031)
- Abdikamalov et al. 2021b (`relxilldgrad_nk`, EXO 1846-031)
- Mall et al. 2022 (GS 1354-645, GRS 1739-278, GRS 1915+105)

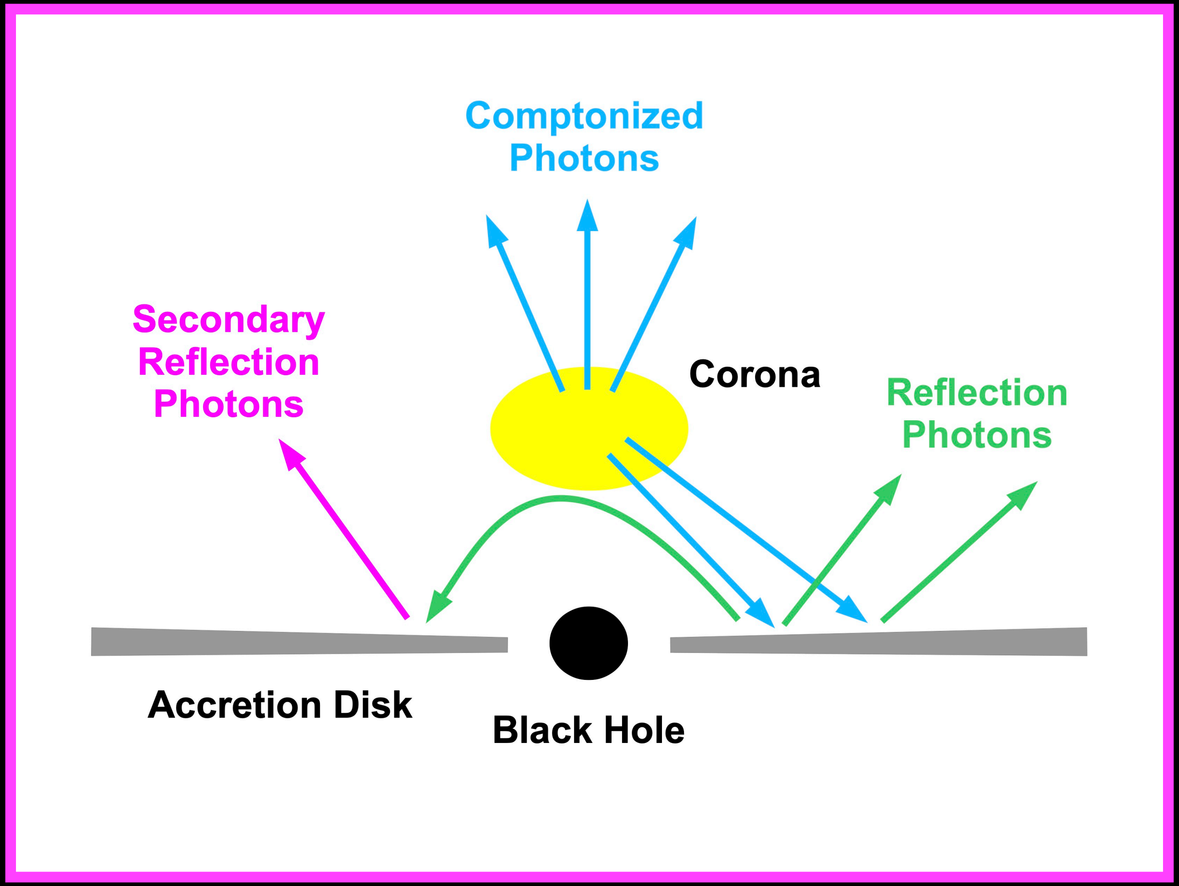


Conclusion: somewhat better fits,
but no significant impact on the parameter estimate

Returning Radiation

Returning Radiation

- Mirzaev et al. in preparation



Conclusion: we can have large systematic uncertainties when:
1) The black hole spin is high
2) The corona is compact and close to the black hole
3) The ionization parameter is not high

Plunging Region

Plunging Region

- Plunging region is optically thin:
    - Higher order disk images (Zhou et al. 2020)

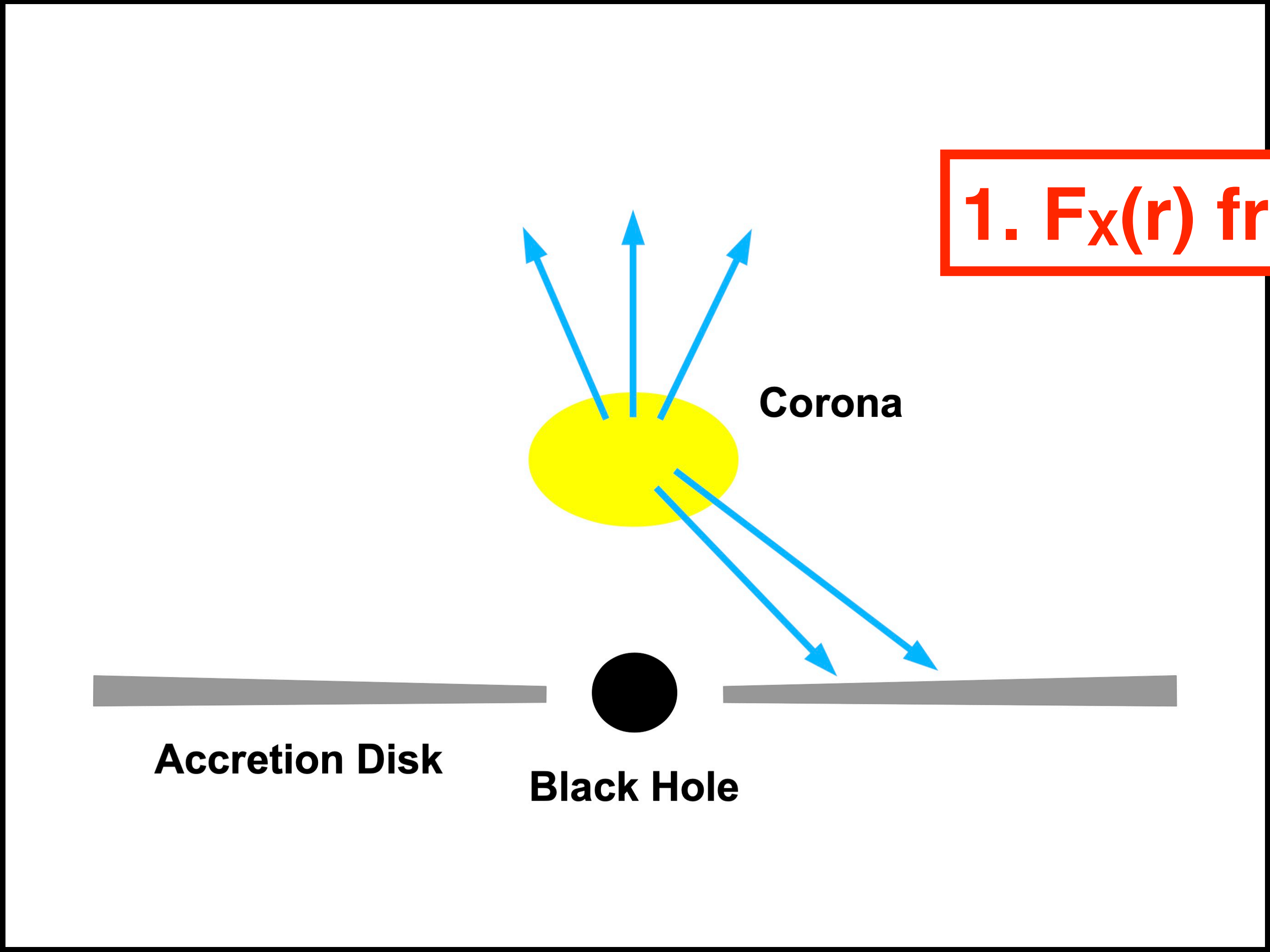
- Plunging region is optically thick:
    - Reflection spectrum from the plunging region (Cardenas-Avendano et al. 202)

Conclusion: no significant impact on the parameter estimate, especially for fast-rotating black holes

How Can We Improve Current Reflection Models?

shuaa

1) Spacetime (Kerr: M, a)
2) Disk (n)
3) Corona (lamppost: h, Γ, T)

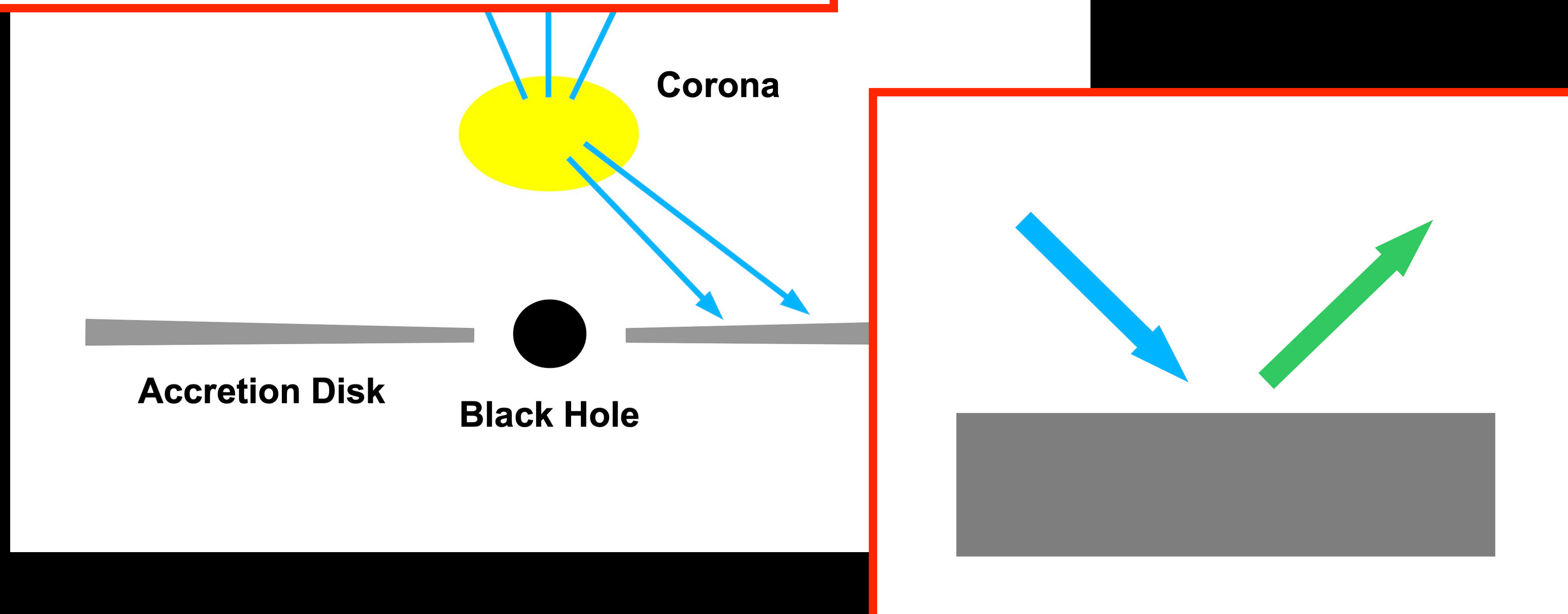


1. $F_X(r)$ from the corona

shuaa

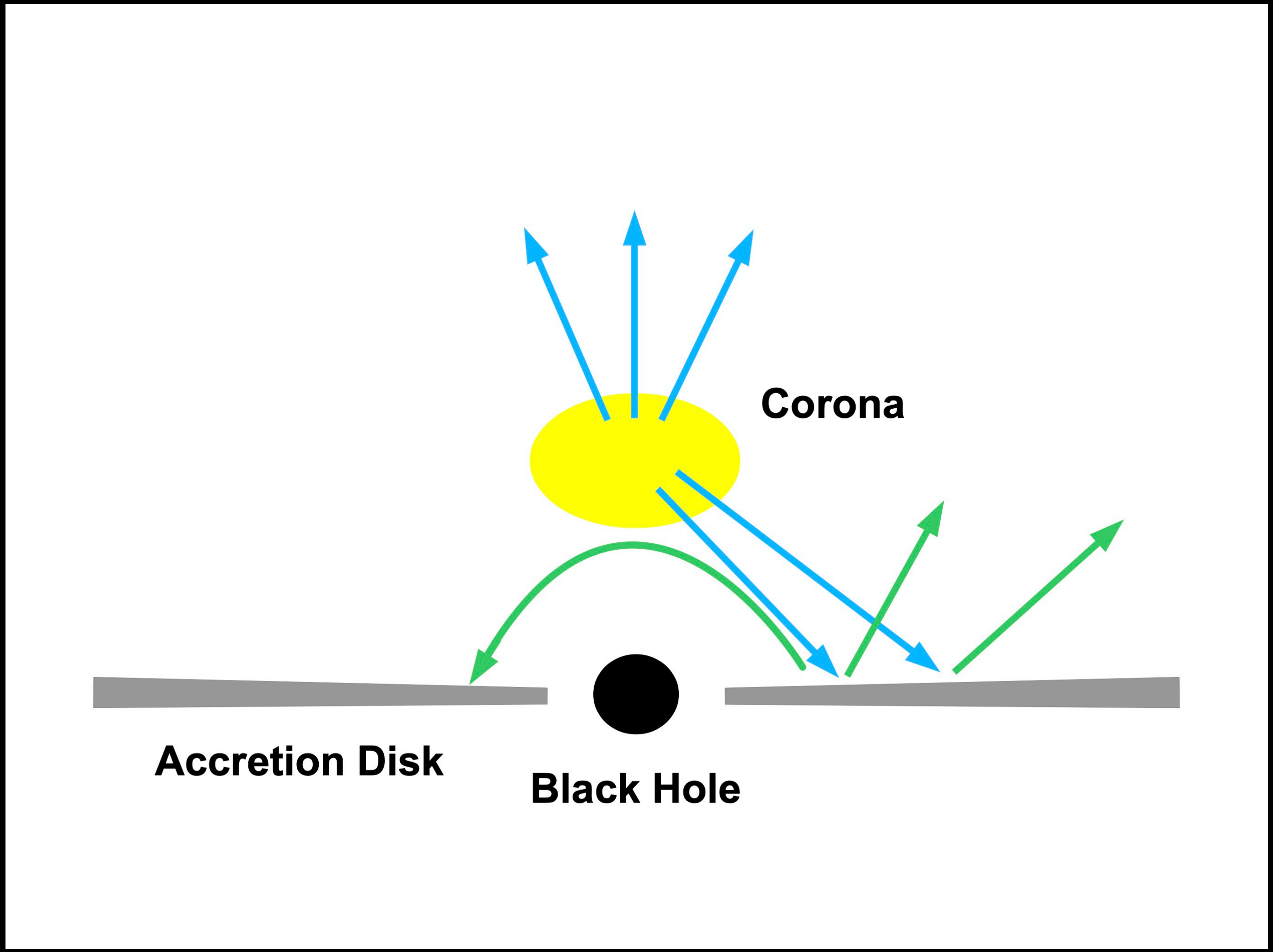
1) Spacetime (Kerr: M, a)
2) Disk (n)
3) Corona (lamppost: h, Γ, T)

2. Reflection spectrum $I_e(r)$
Note: ξ(r), redshifted coronal spectrum



shuaa

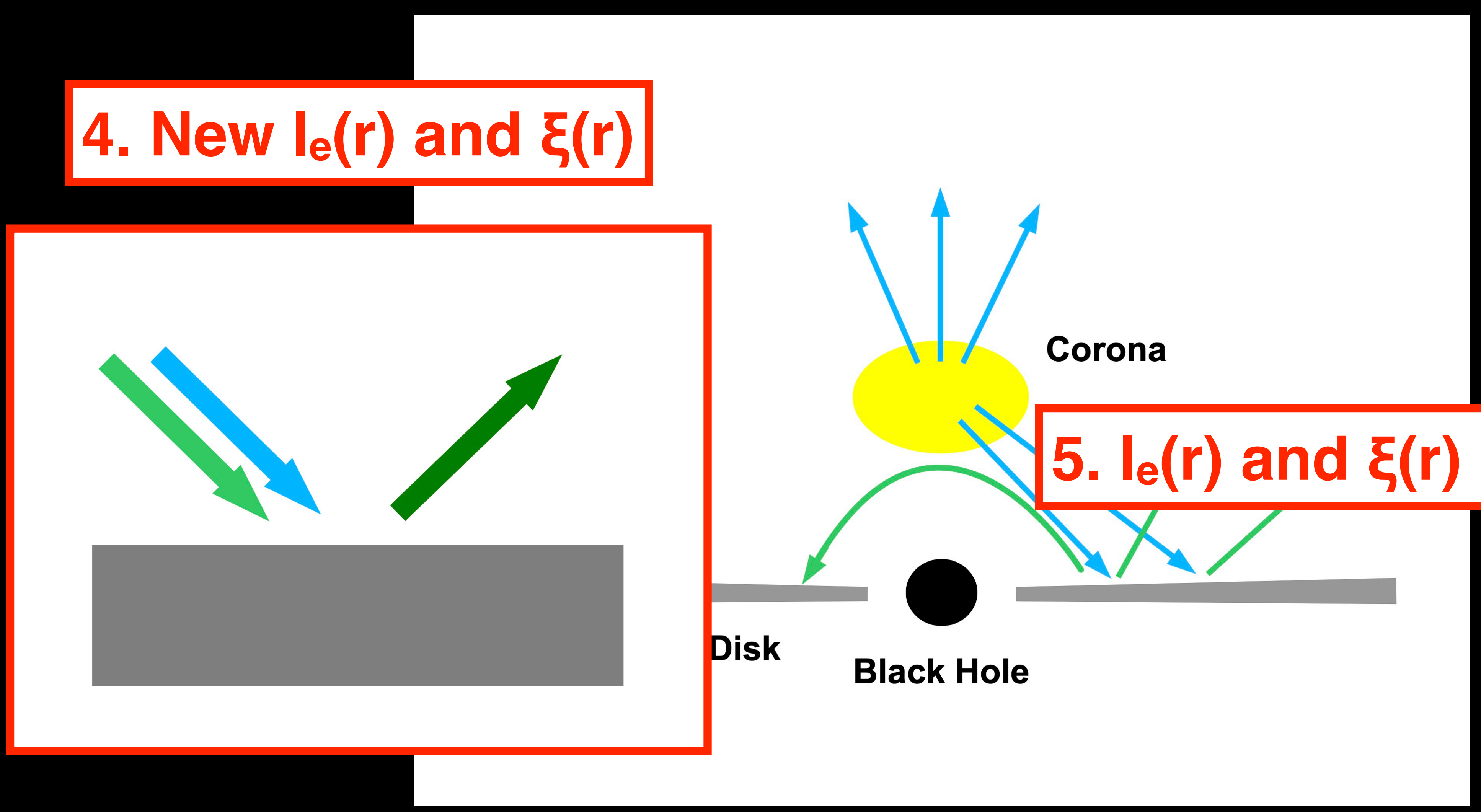
3. Returning radiation at every radius



shuaa

3. Returning radiation at every radius

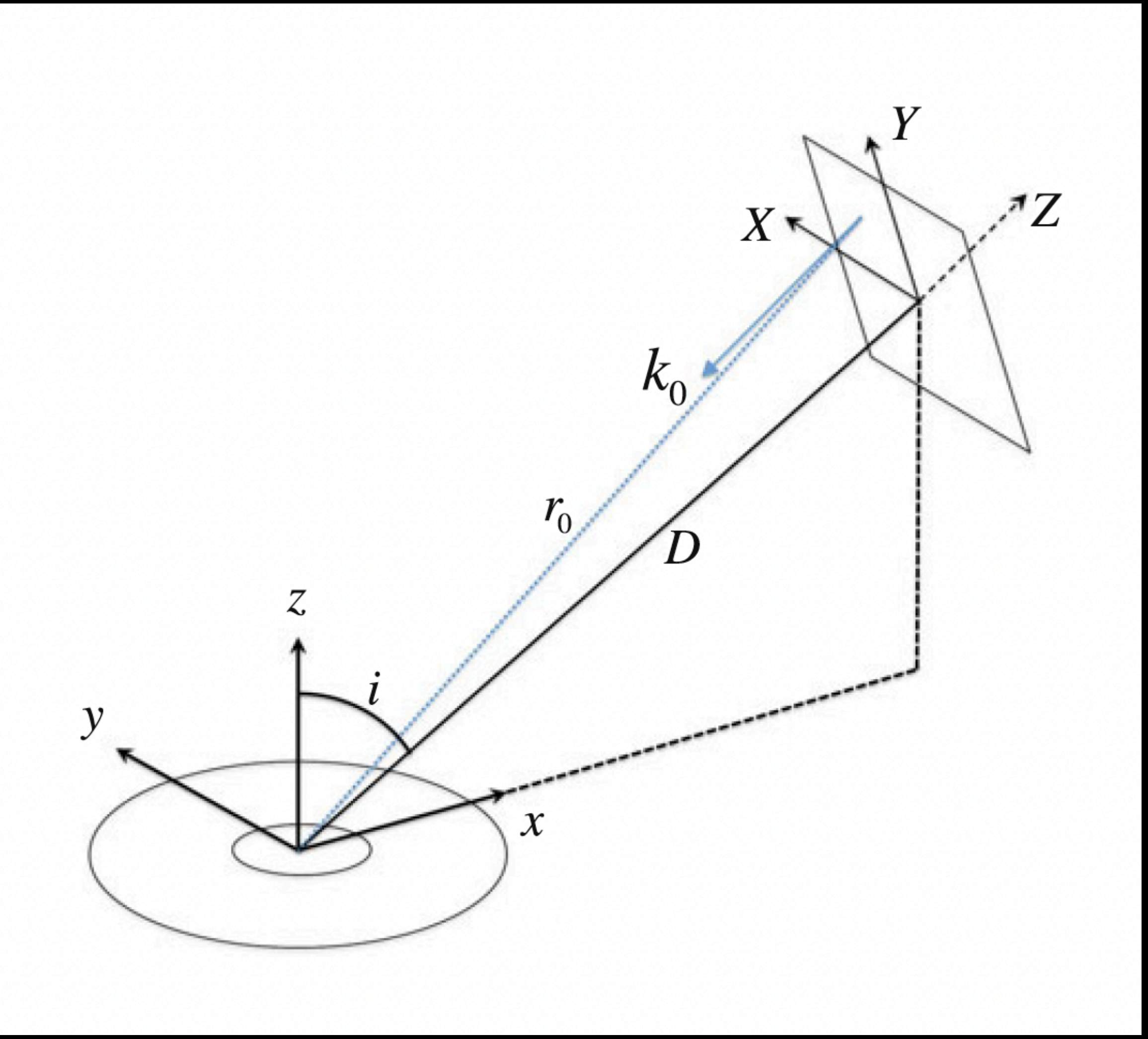
4. New $I_e(r)$ and $\xi(r)$



5. $I_e(r)$ and $\xi(r)$ at the 4th order

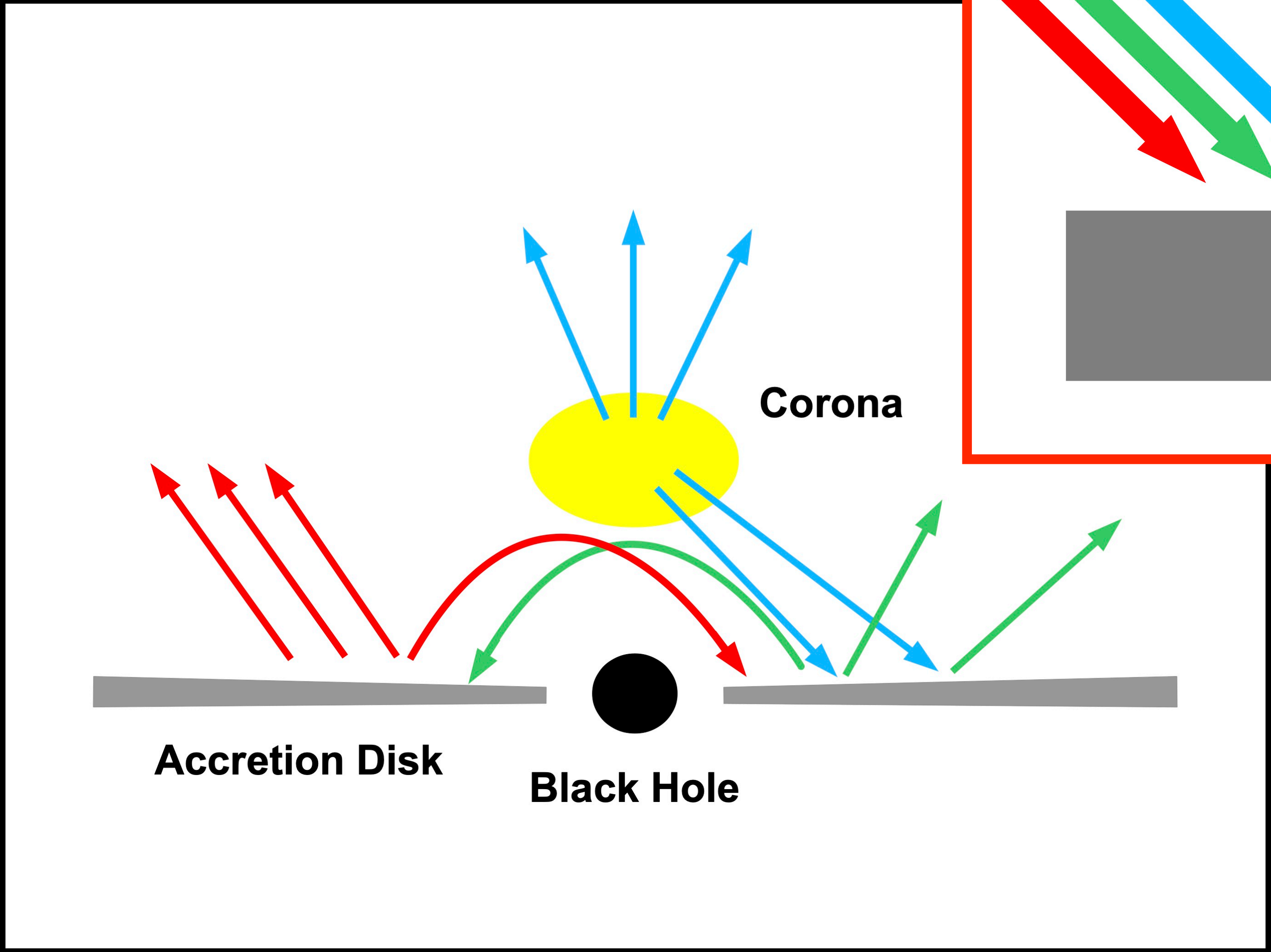
shuaa

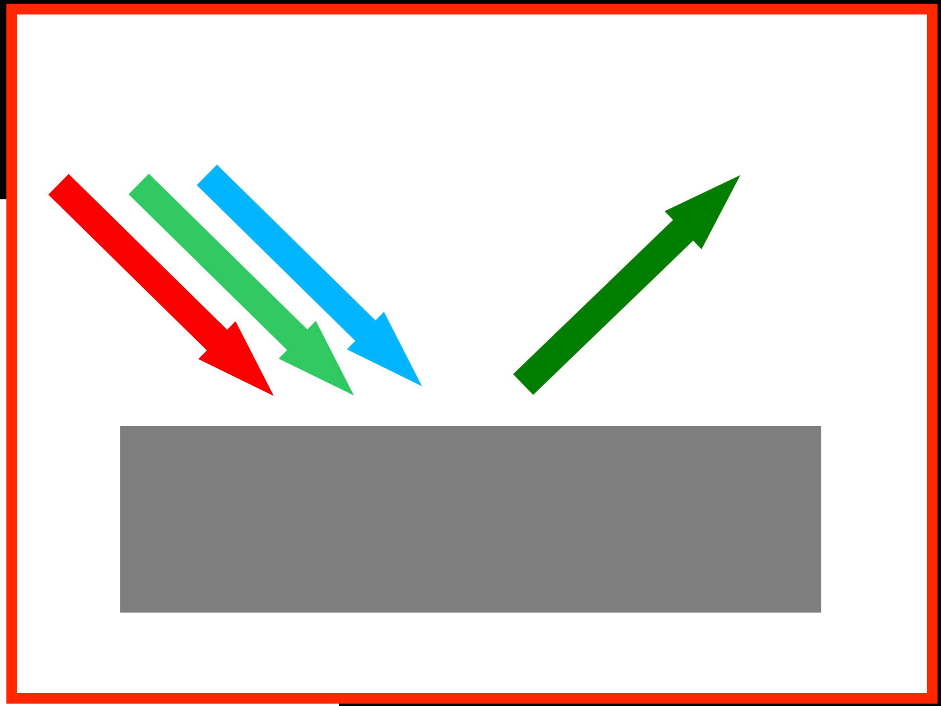
6. Observed reflection spectrum (viewing angle i)



shuaa

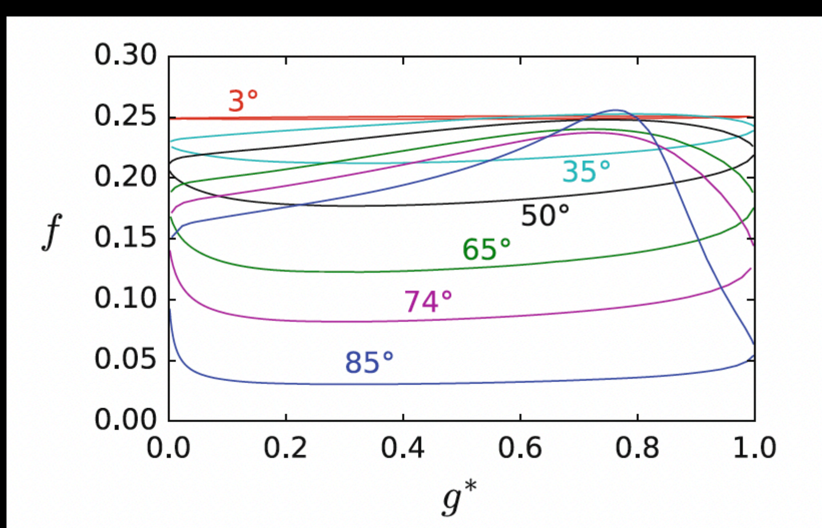
7. Thermal spectrum

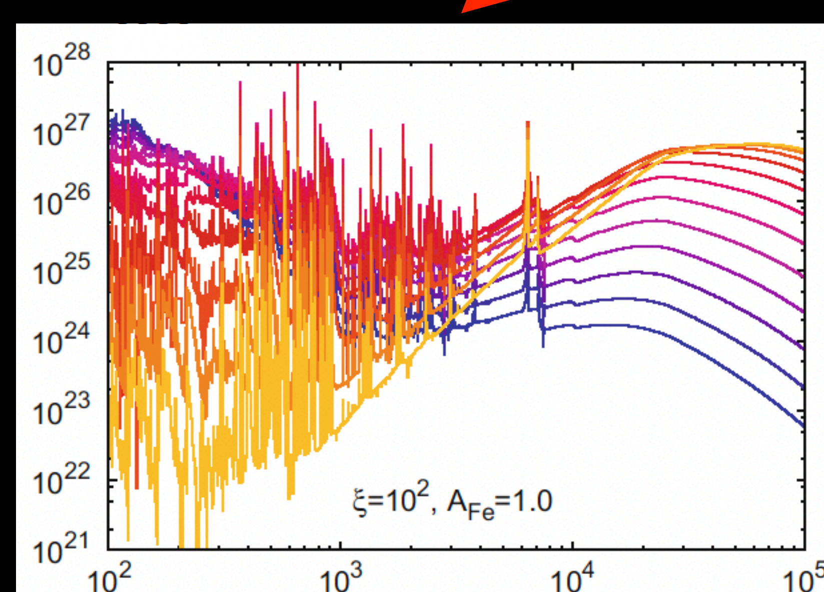


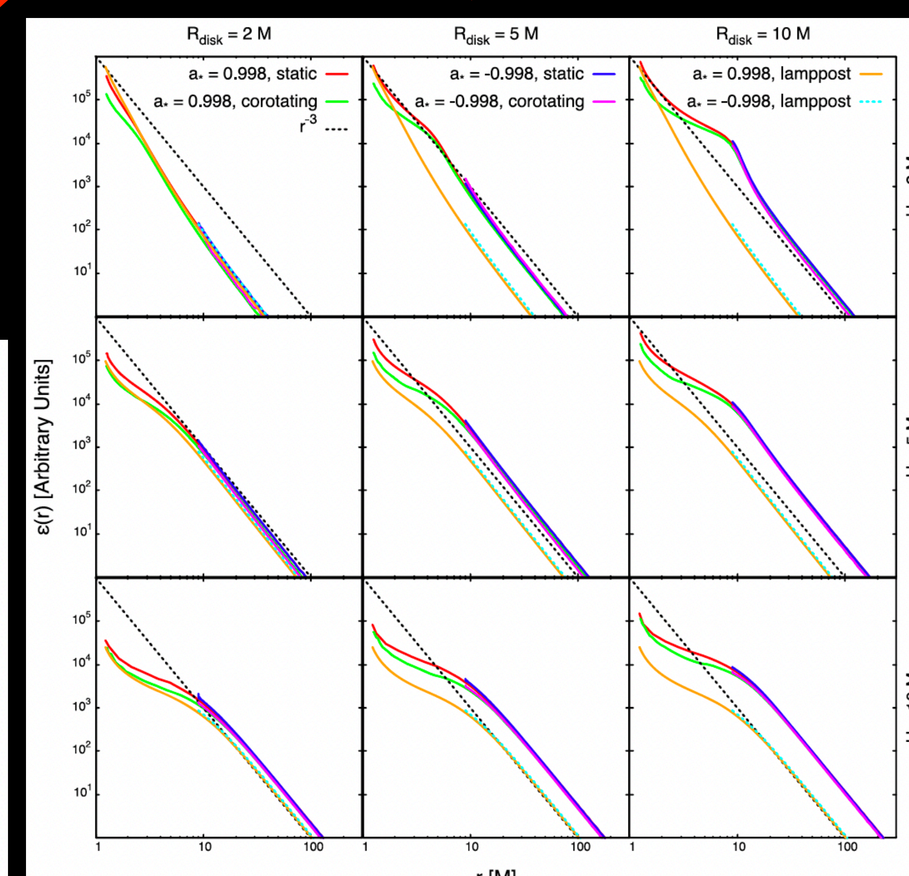


Current Reflection Models for Data Analysis

$$F_{\rm obs}(\nu_{\rm obs}) = \frac{1}{D^2}\int_{r_{\rm ISCO}}^{\infty}\int_0^1 \frac{\pi r_{\rm e}\, g^2}{\sqrt{g^*(1-g^*)}} f_1(g^*, r_{\rm e}, i) I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e,1})\, dg^*\, dr_{\rm e}$$
$$+\frac{1}{D^2}\int_{r_{\rm ISCO}}^{\infty}\int_0^1 \frac{\pi r_{\rm e}\, g^2}{\sqrt{g^*(1-g^*)}} f_2(g^*, r_{\rm e}, i) I_{\rm e}(\nu_{\rm e}, r_{\rm e}, \vartheta_{\rm e,2})\, dg^*\, dr_{\rm e}\,,$$

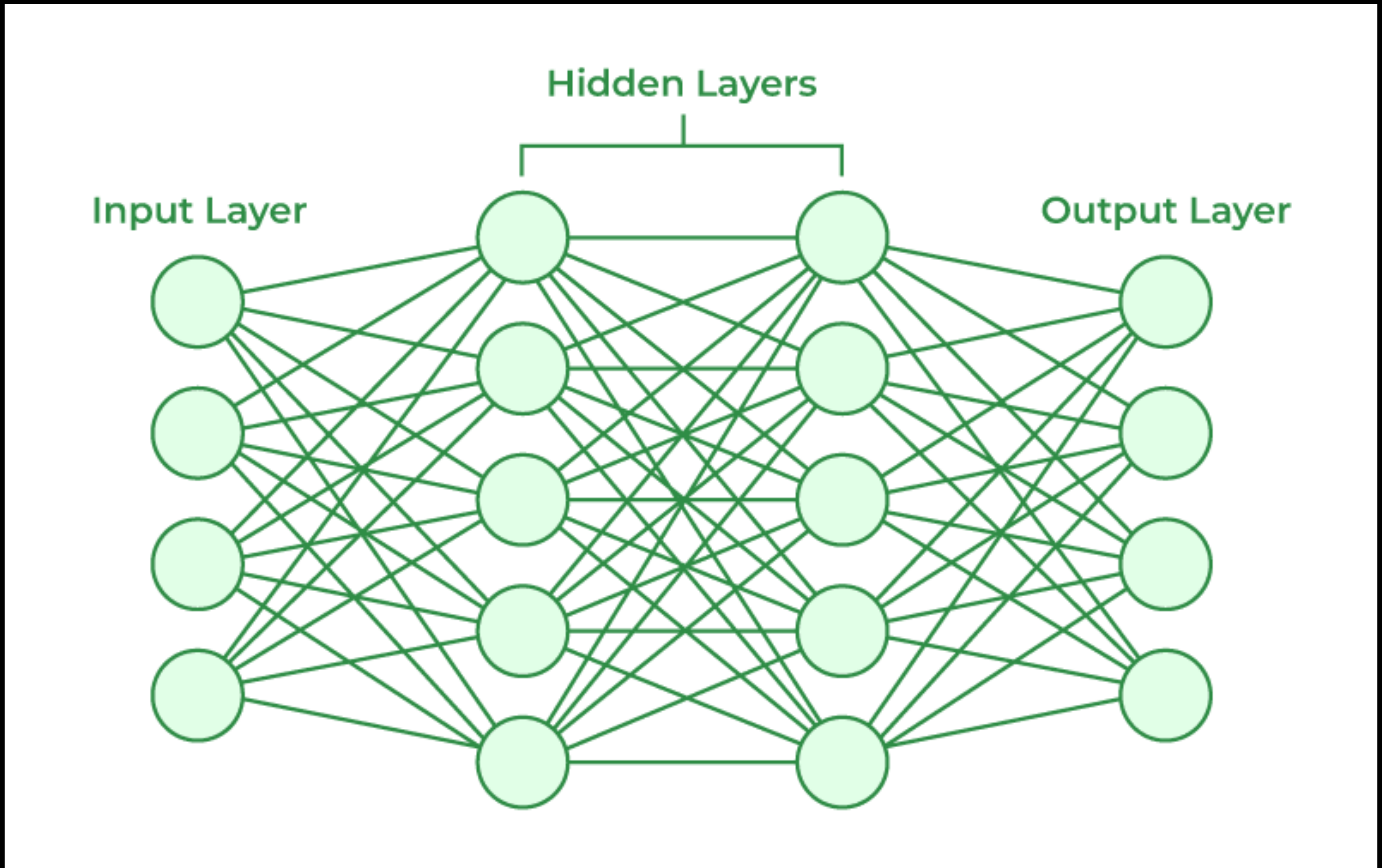






Neural Network

- Interconnected group of nodes that can be "trained" to make predictions



Neural Network

- Model parameters → Spectrum
- Spectrum → Model parameters
- Surrogate model (see gravitational waveforms)

Conclusions

Conclusions

- Current XRS measurements of black holes can be accurate and precise, but only if we carefully select the sources and observations

- The analysis of observations from the next generation of X-ray missions (eXTP, Athena, HEX-P, etc.) will necessarily require more sophisticated synthetic spectra than those available today

- New generation of reflection models (neural networks?)

Thank You!