OPEN-SOURCE REVERBERATION MODELLING WITH GRADUS.JL

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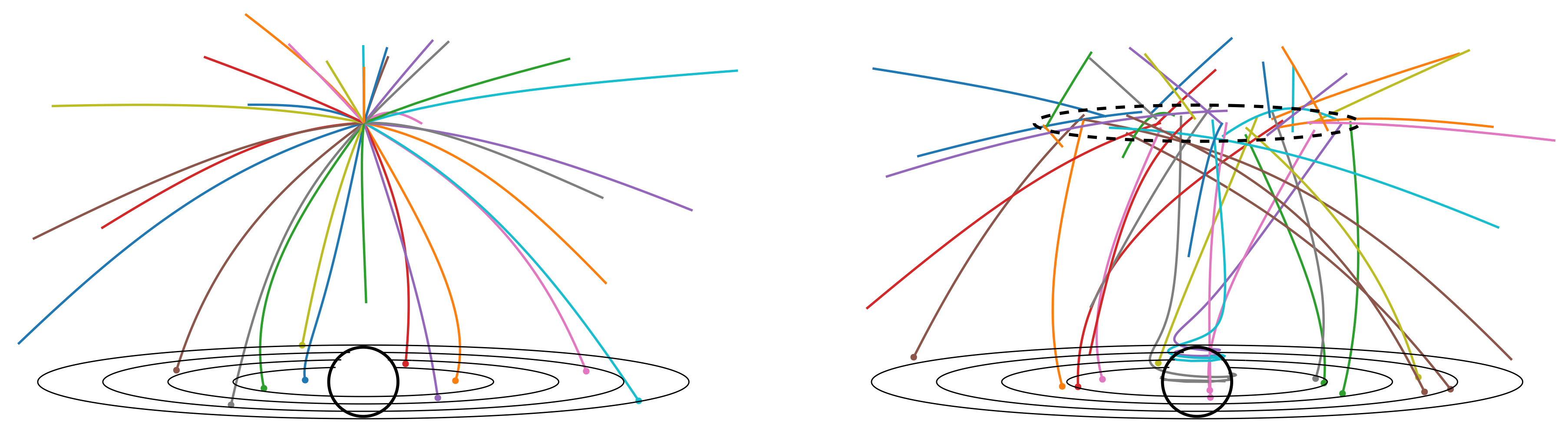
GitHub: `https://github.com/astro-group-bristol/Gradus.jl`



(a) Lamppost (b) Extended corona

Figure 1: Example photon trajectories for two coronal models in the Kerr spacetime ($a = 0.998$). The accretion disc is shown in the equatorial plane. The event horizon is illustrated by the thick line.

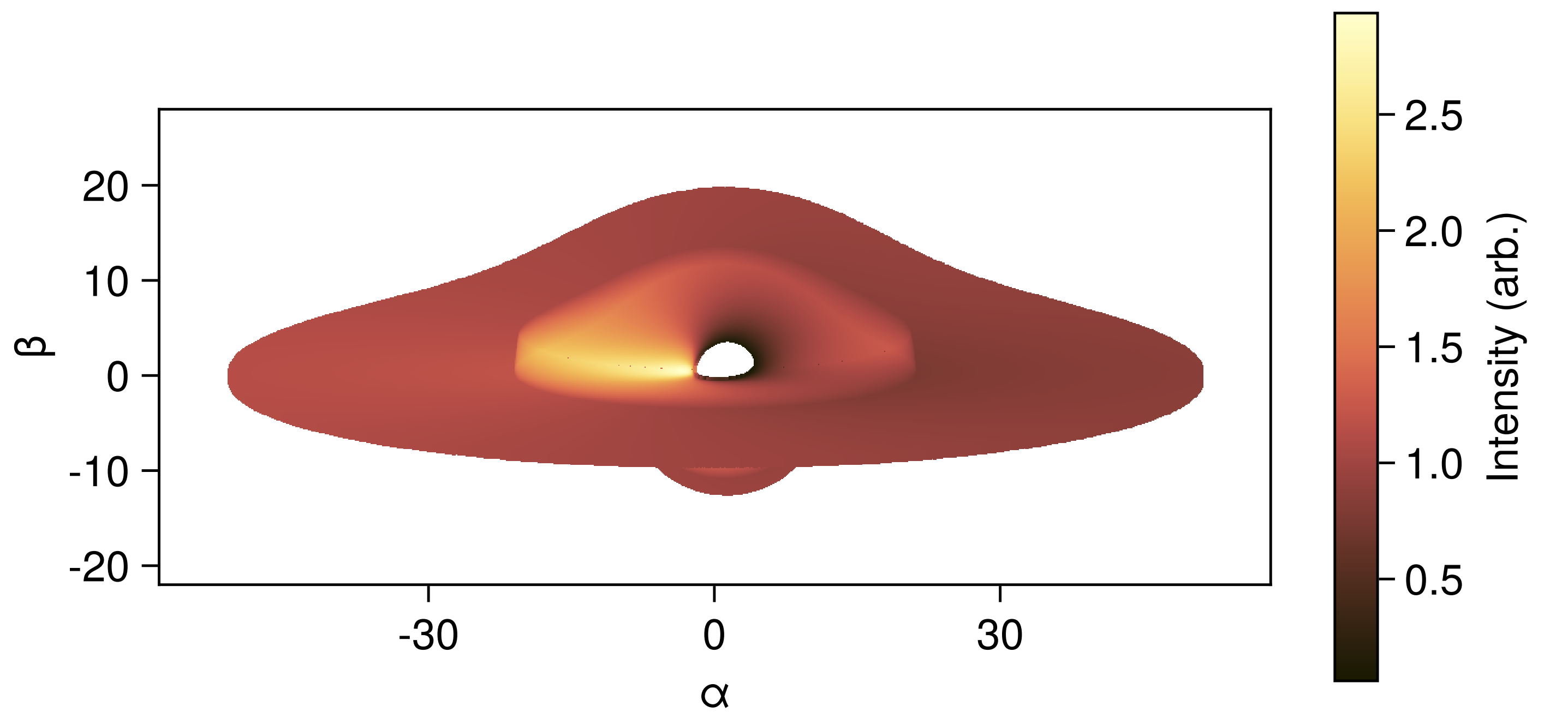
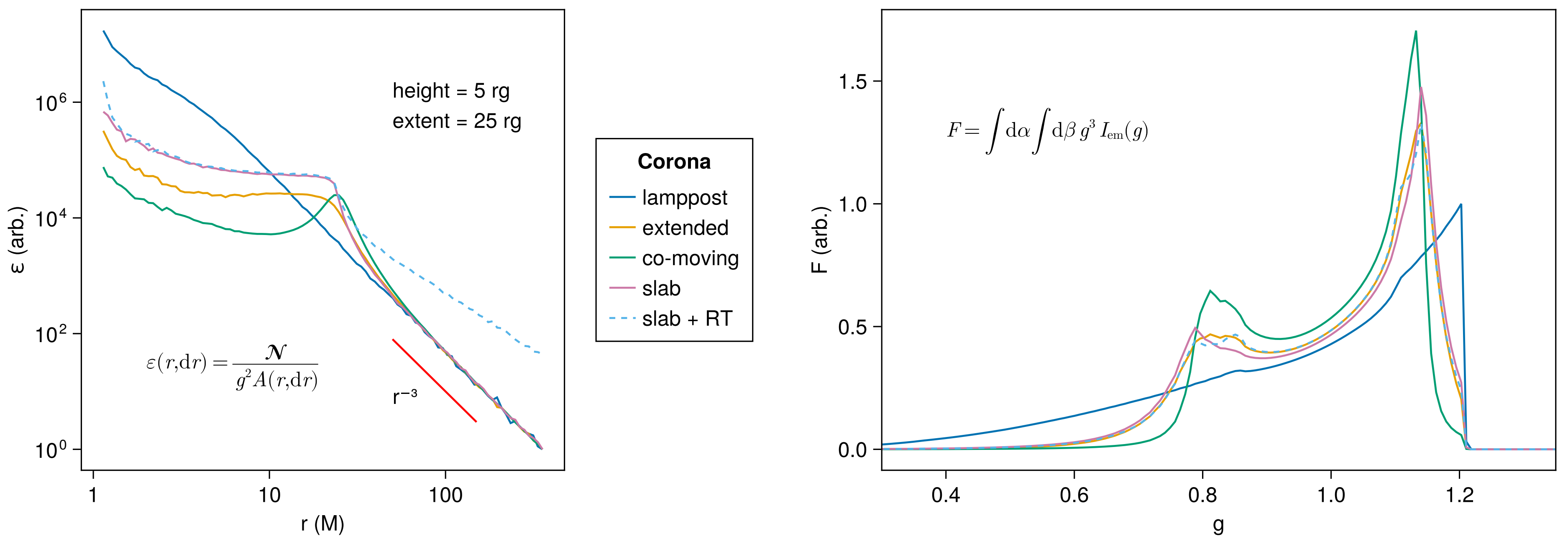


Figure 2: Apparent image of an equatorial disc in the Kerr spacetime ($a = 0.998$) with a translucent slab corona ($j_\nu = 0.1$). The colouring is proportional to observed intensity scaled by redshift.



(a) (b)

Figure 3: Emissivity profiles (a) and corresponding line profiles (b) for a number of different coronal morphologies. For the line profiles, the observer observer is at an inclination $\theta = 60°$.

REVERBERATION MODELLING

Reverberation time lags are the apparent time delays between the **continuum emission** from an illuminating corona and the **reflected emission** from the accretion disc [1]. The time lag is modified by the increased light travel time due to relativistic effects close to the central singularity. Signatures of the spacetime are therefore imprinted in the spectra and time delay, providing a glimpse deep into the potential well of the singularity, close to the event horizon.

CORONAL MORPHOLOGY

The **continuum emission**, which may also drive variations in the reflected emission, is thought to originate from a luminous **corona**. The **morphology** of the corona alters the illuminating flux on the accretion disc, and therefore determines the **emissivity profile** of the disc.

Figure 1 conceptually illustrates two morphologies: the **lamppost** and **extended corona** model, whereas Figure 2 is a simulated apparent image of an optically thin **slab-like corona** over an accretion disc. The impact of the **morphology** on **emissivity** and consequently the **spectral profile** of the reflected emission is shown in Figure 3.

TESTS OF GRAVITY

Tests of general relativity to-date have been successful in measuring **deviation parameters** of Kerr-like spacetimes, with broad Fe-$K\alpha$ line fits yielding some of the tightest constraints [2]. These iron lines, however, are degenerate in the parameter space of some metrics. By considering the variability inherent in **reverberation lags**, it may be possible to lift some of these degeneracies, and to further study and constrain departures from general relativity.

GRADUS.JL

Gradus.jl is a Julia [3] package for **general relativistic ray-tracing**, that is designed to be **spacetime-agnostic** and extensible. Using **automatic differentiation**, the software requires only a symbolic implementation of the metric to compute a variety of results. Currently, Gradus.jl can be used to calculate:

- geodesic orbits and special radii (event horizon shapes, ISCO radii, etc.)
- null / time / space like trajectories, including for charged particles
- line profiles and spectra
- reverberation transfer functions
- time-lags from different coronal models

These may optionally use **covariant radiative transfer** and custom accretion geometry, and are scalable from personal computers to super computers.

FUTURE WORK

We have already created an XSPEC-compatible model for broad iron lines using emissivity profiles calculated with Gradus.jl, and are currently working on a paper that describes our software and methods in detail. We intend to use Gradus.jl, along with a novel spectral fitting library, to simultaneous fit multiple active galactic nuclei in an attempt to obtain tighter constraints on deviation parameters of Kerr-like metrics. Fitting lag-frequency spectra allows us to make the most out of available data, and potentially lift degeneracies in the parameter spaces.

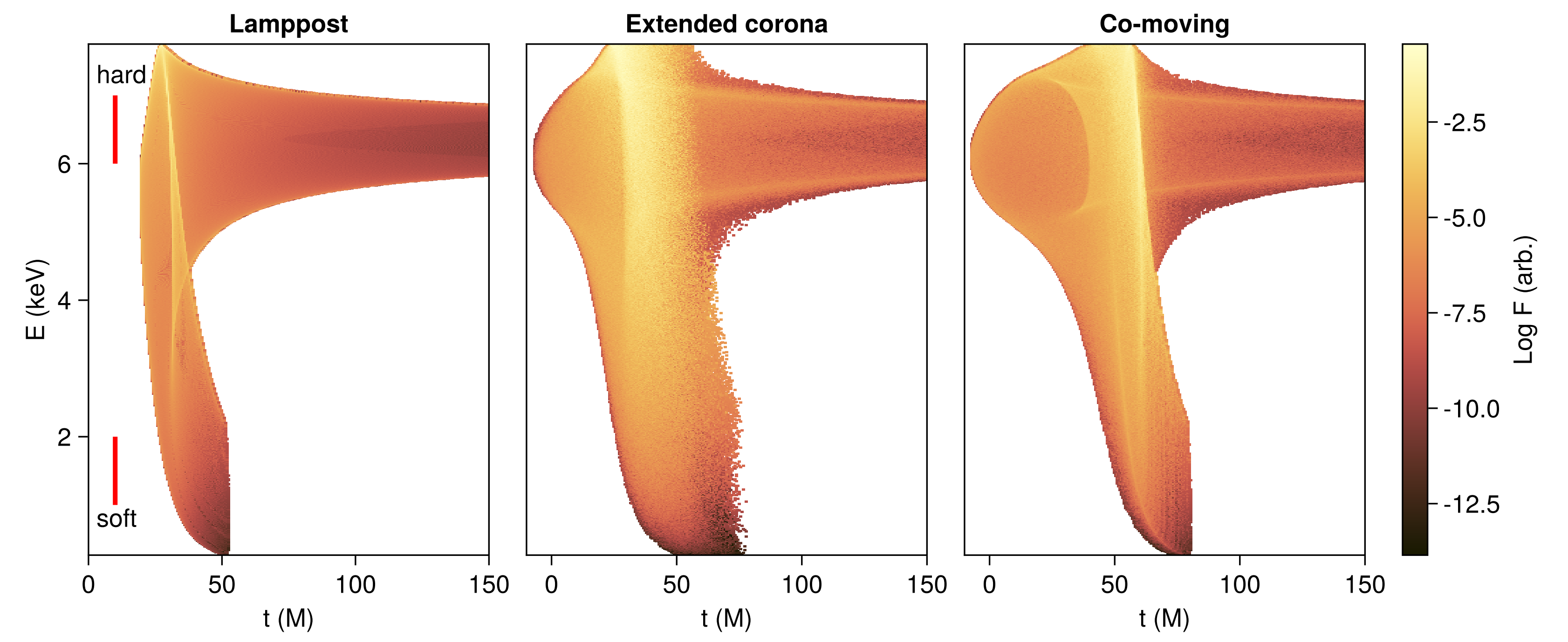


Figure 4: Lag-transfer functions for the coronal sources in Fig. 3, for an observer at inclination $\theta = 60°$.

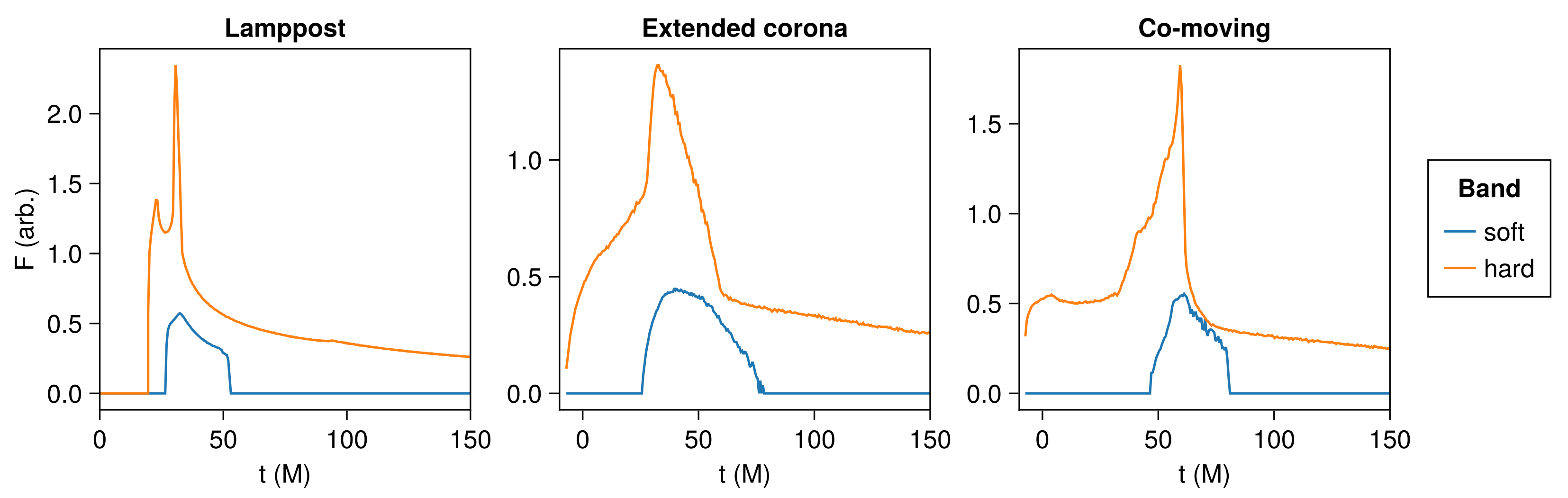


Figure 5: Impulse responses for the hard and soft bands highlighted in Fig. 4.

REFERENCES

[1] P. Uttley, E. M. Cackett, A. C. Fabian, E. Kara, and D. R. Wilkins, "X-ray reverberation around accreting black holes", Astronomy and Astrophysics Review **22**, 72 (2014).

[2] C. Bambi, "Testing Gravity with Black Hole X-Ray Data", en, arXiv:2210.05322 [astro-ph, physics:gr-qc] (2022).

[3] J. Bezanson, A. Edelman, S. Karpinski, and V. B. Shah, "Julia: A fresh approach to numerical computing", SIAM Review **59**, 65–98 (2017).