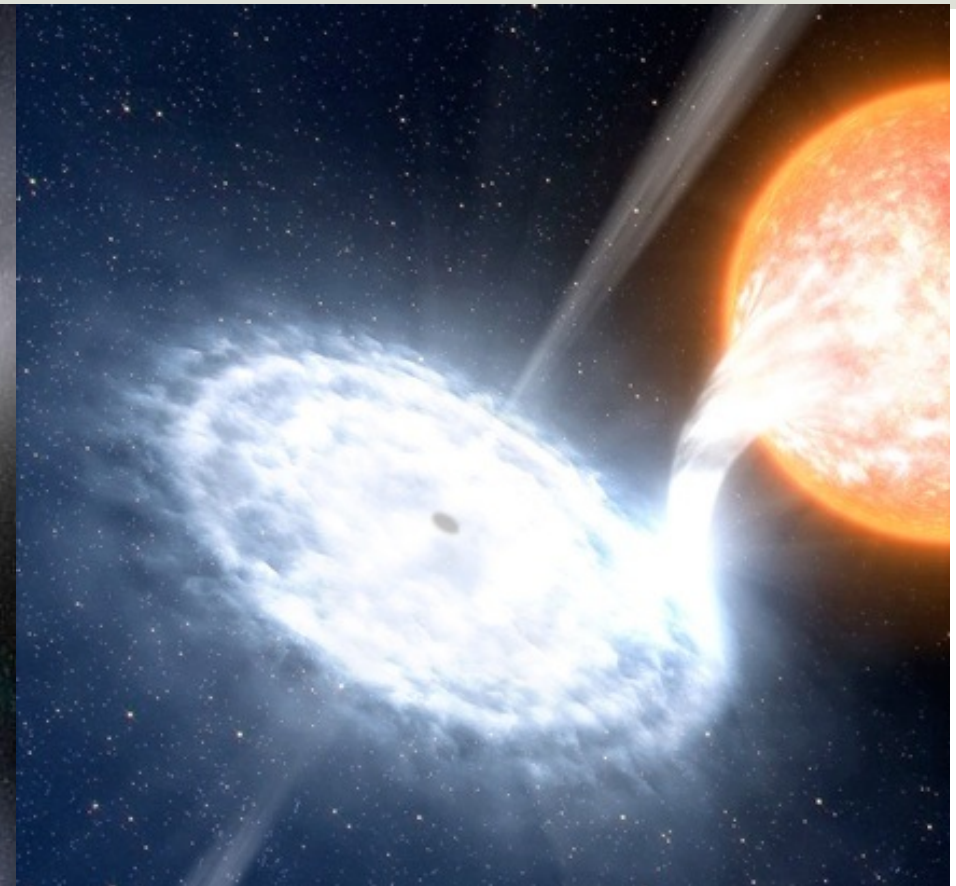

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Beyond the Lamppost: Lag spectra arising from extended coronae

Dan Wilkins

Saint Mary's University

with Ed Cackett, Andy Fabian, Chris Reynolds

Lorentz Center Workshop - 'The X-ray Spectral-Timing Revolution' – February 2016

Outline

1. X-ray reverberation observations – what are we trying to model?
2. Inadequacies of the lamppost model
3. Developing an extended corona model
4. How does it compare to data?

Everything in this presentation is open to discussion!

Kara et al. 2012, MNRAS 428, 2795-2804

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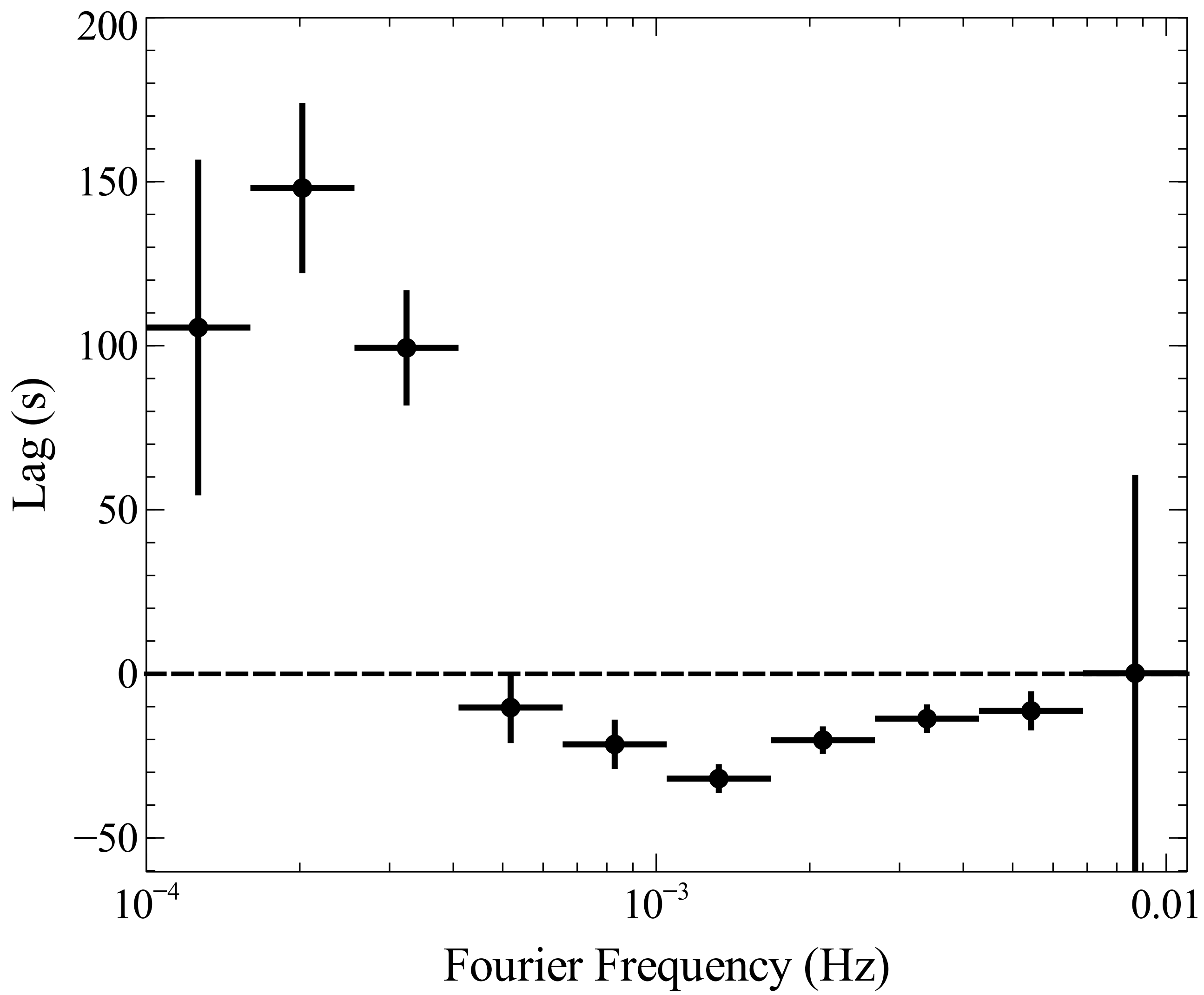

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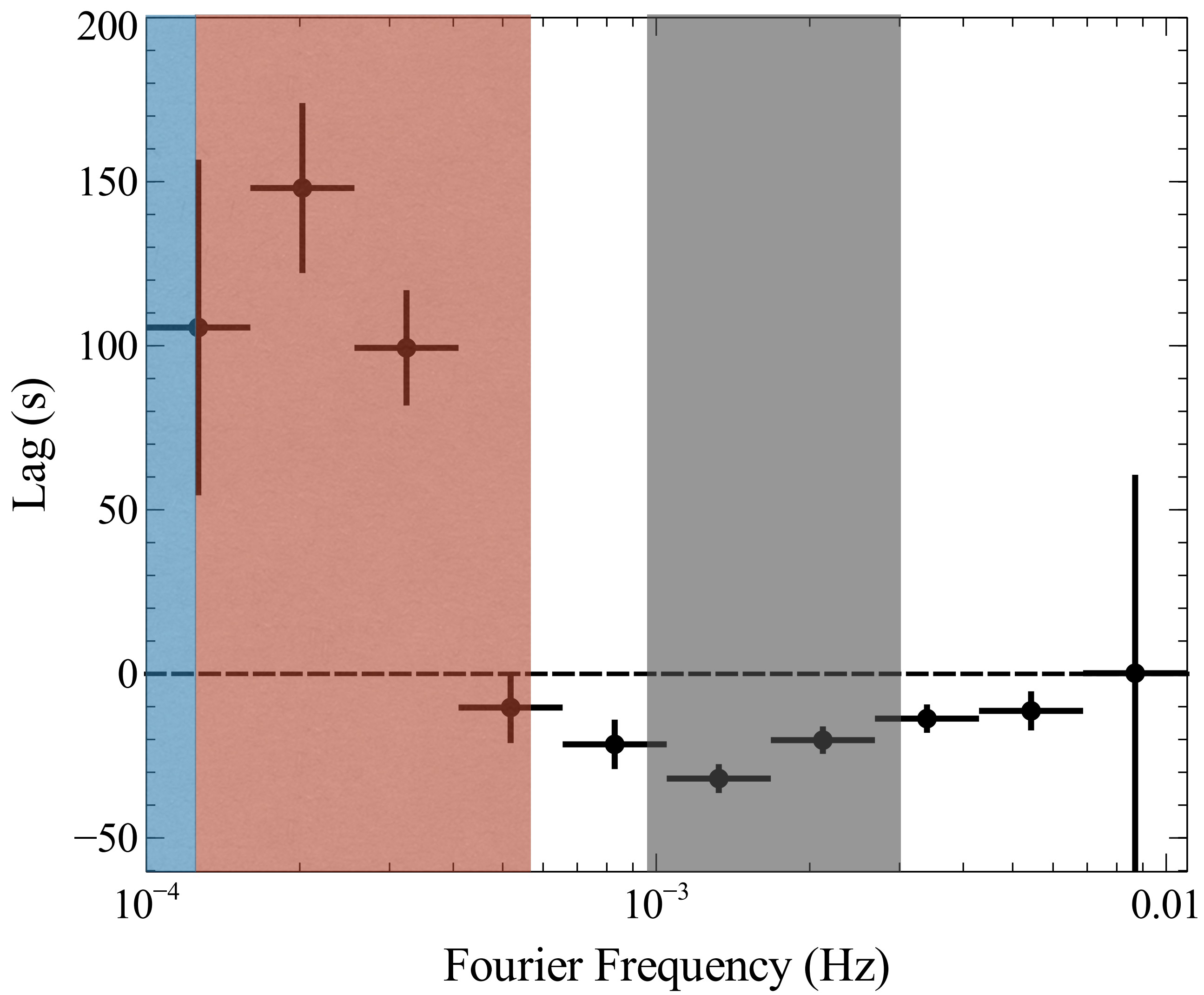
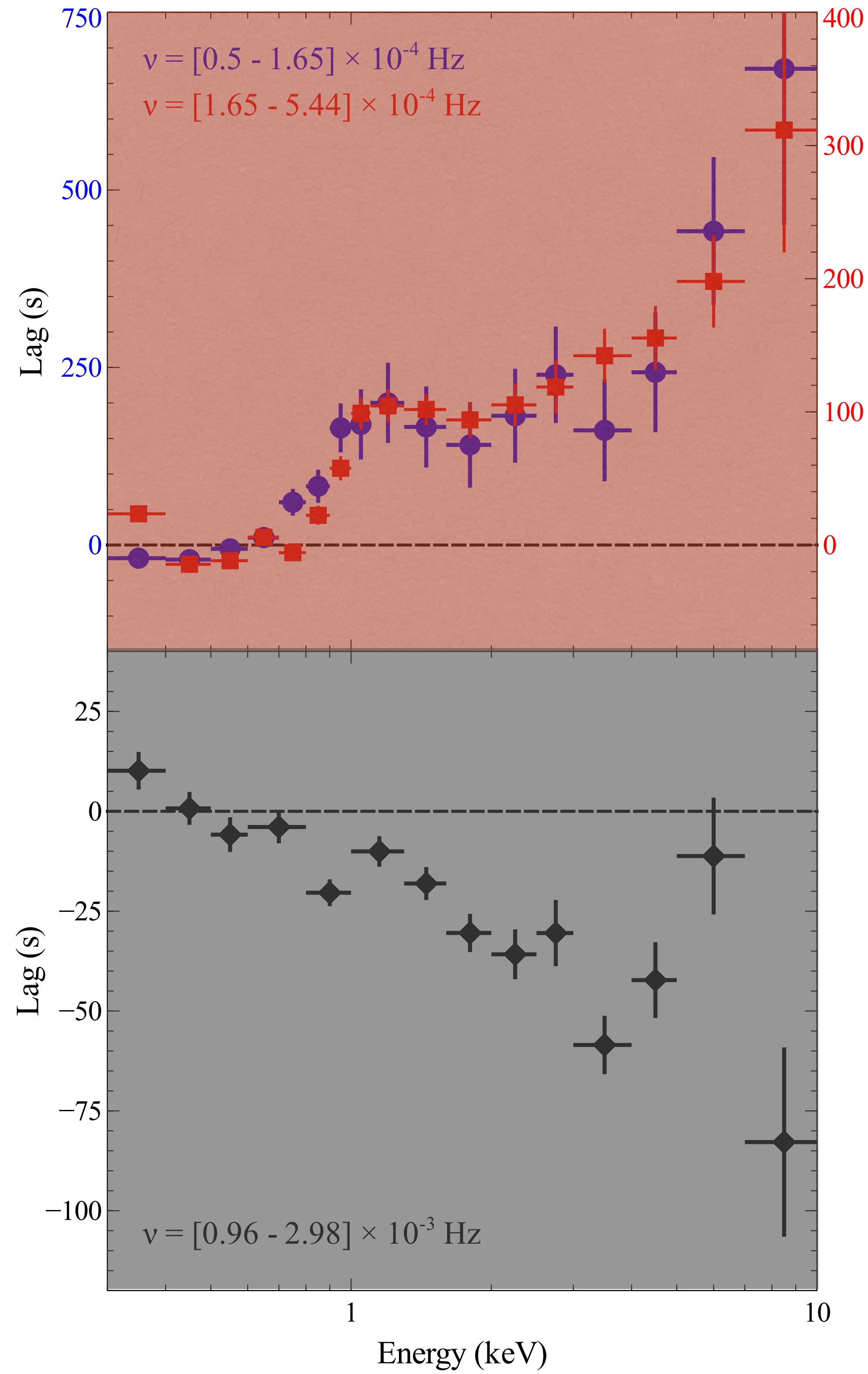
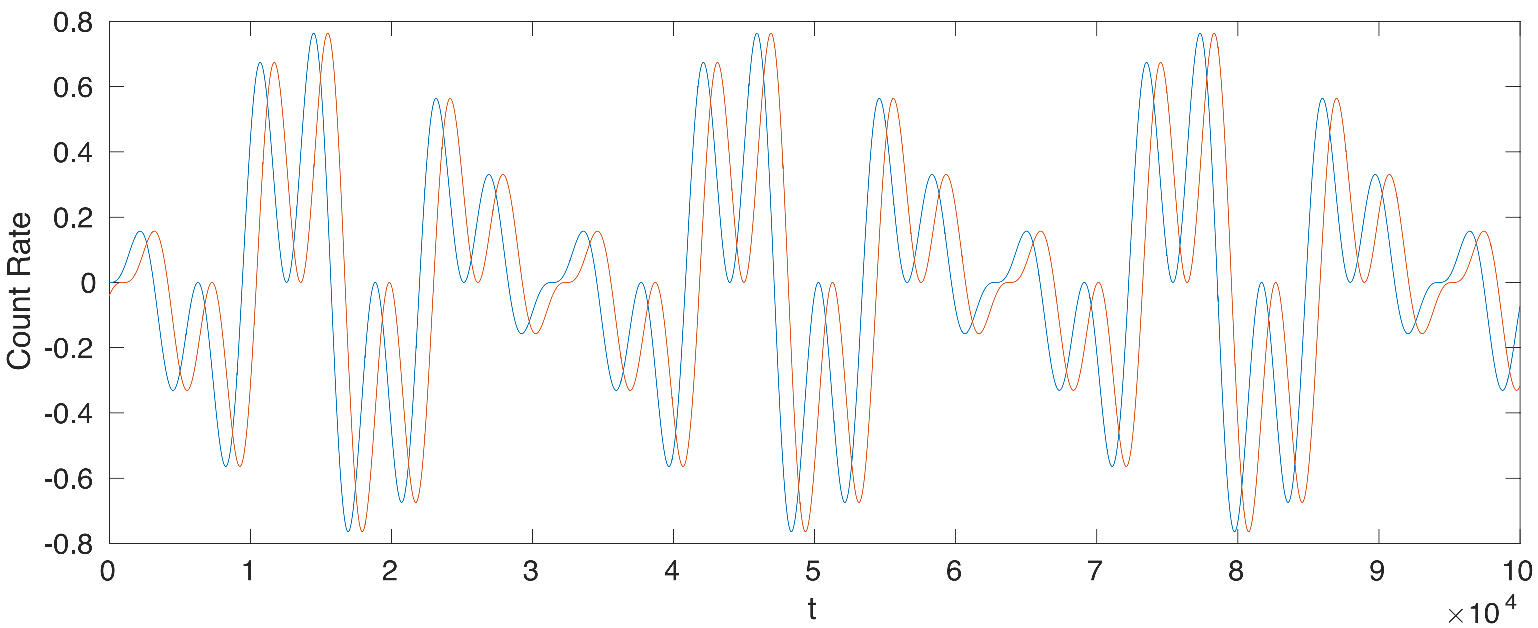
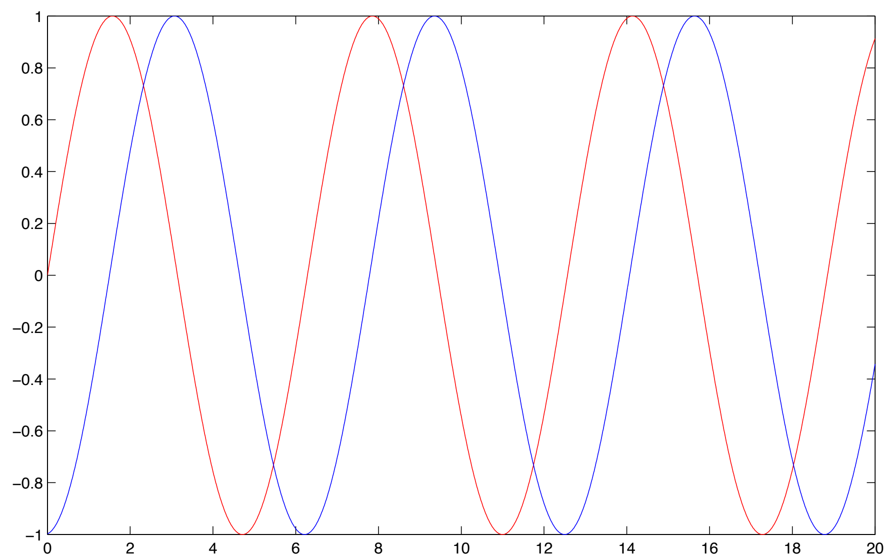




Reverberation from a lamppost

Reminder – the lag formalism





$$\tilde{H}(\omega) = \left|\tilde{H}(\omega)\right| e^{i\varphi}$$

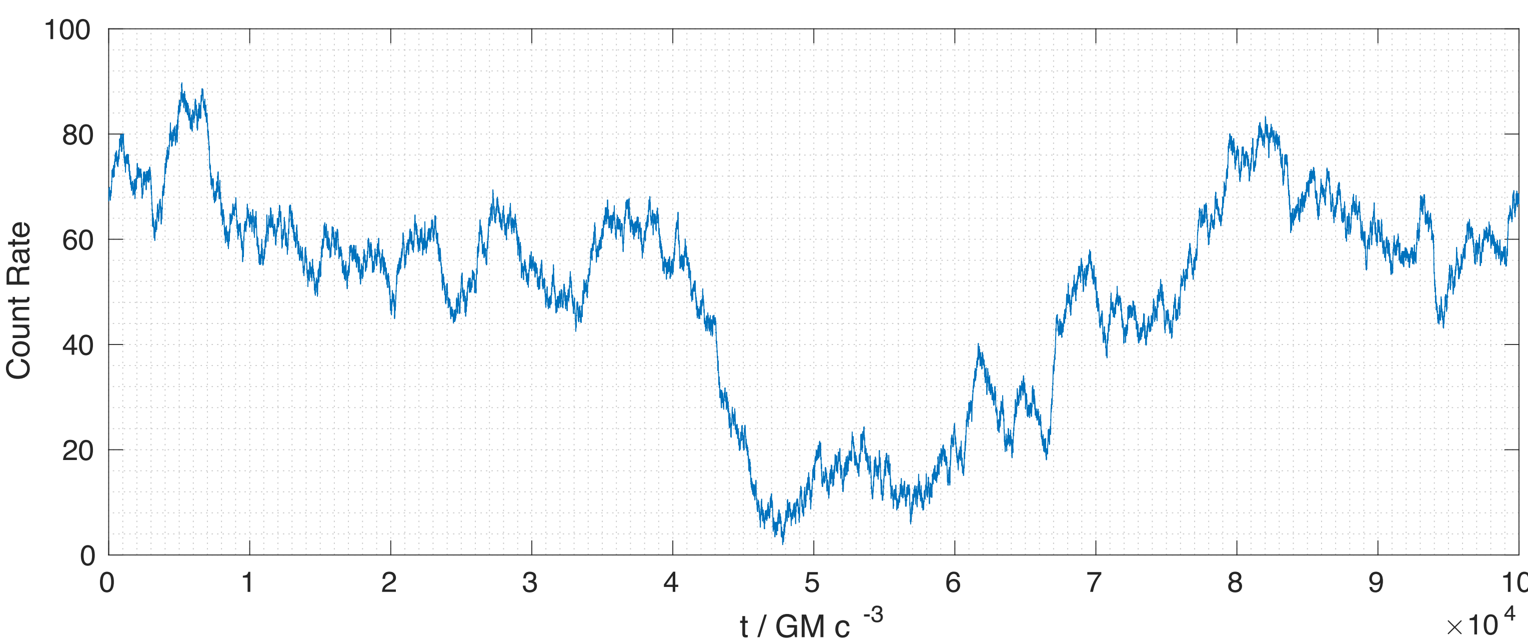
$$\tilde{S}(\omega) = \left|\tilde{S}(\omega)\right| e^{i\theta}$$

$$\tilde{C} = \tilde{S}^{*}\tilde{H} = \left|\tilde{S}\right|\left|\tilde{H}\right| e^{i(\varphi-\theta)}$$

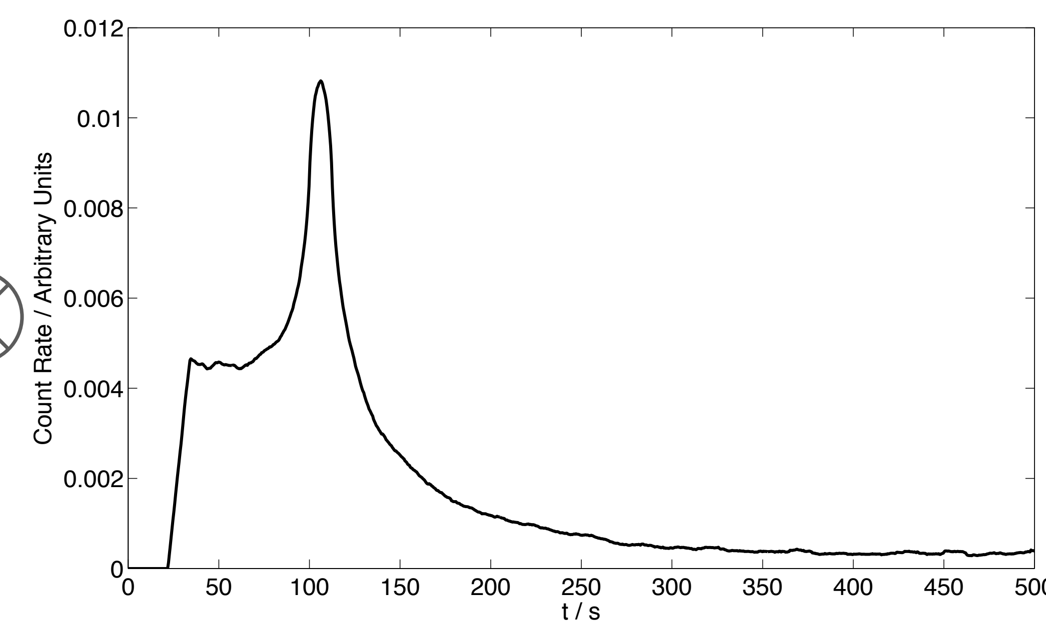
$$\varphi = \omega t$$

$$\therefore \tau(f) = \frac{\arg(\tilde{C}(f))}{2\pi f}$$

The Response Function

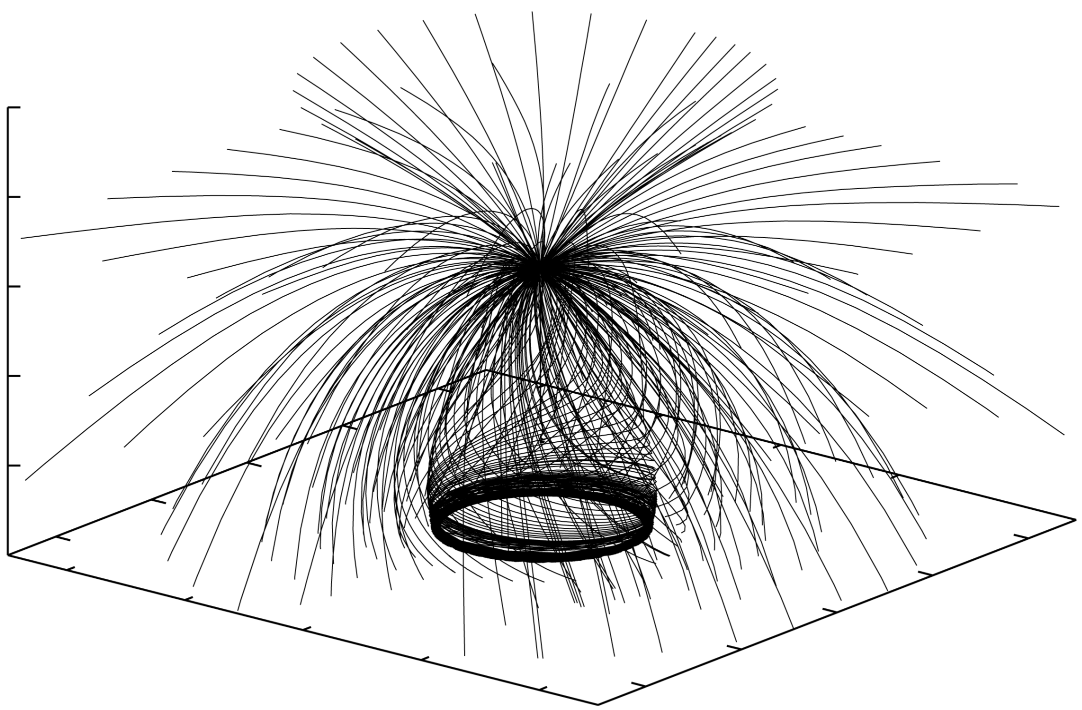


$\otimes$

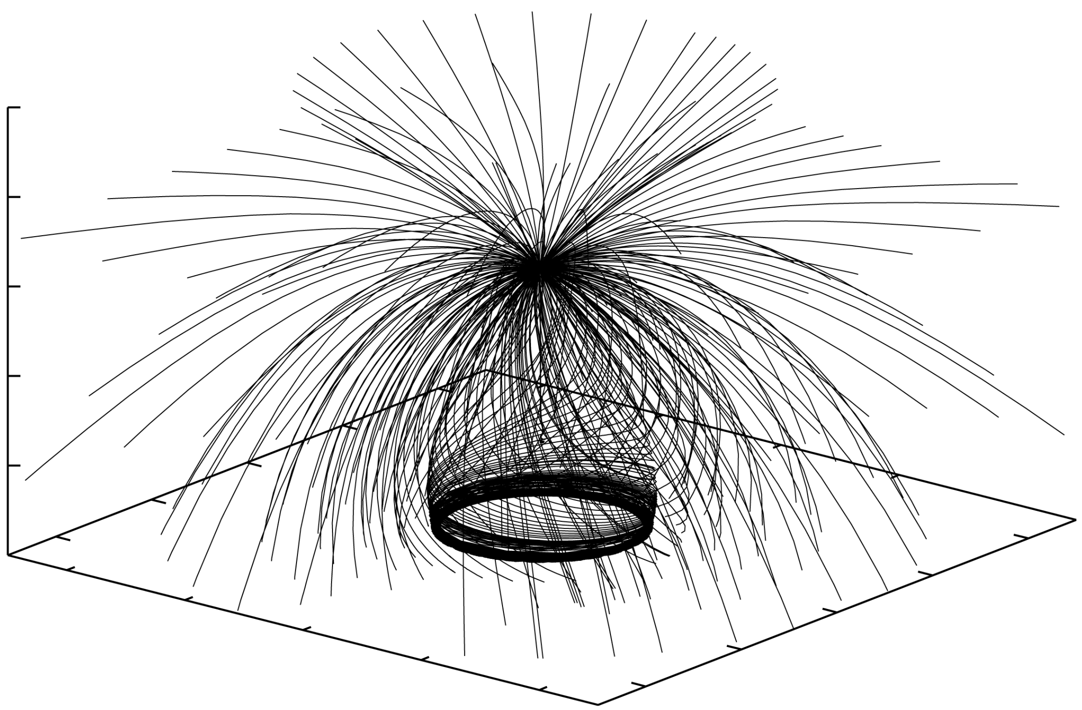


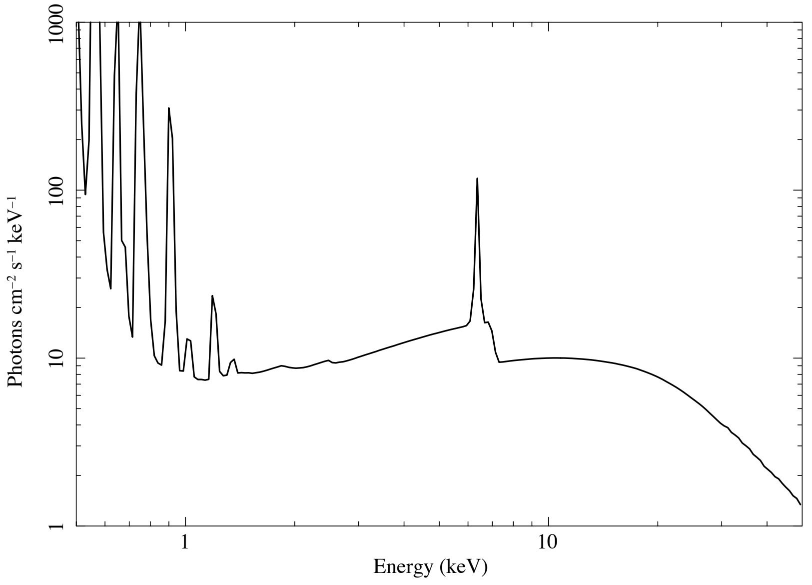
$$L_E(t) = L(t) \otimes T(E,t)$$

Calculating the Response

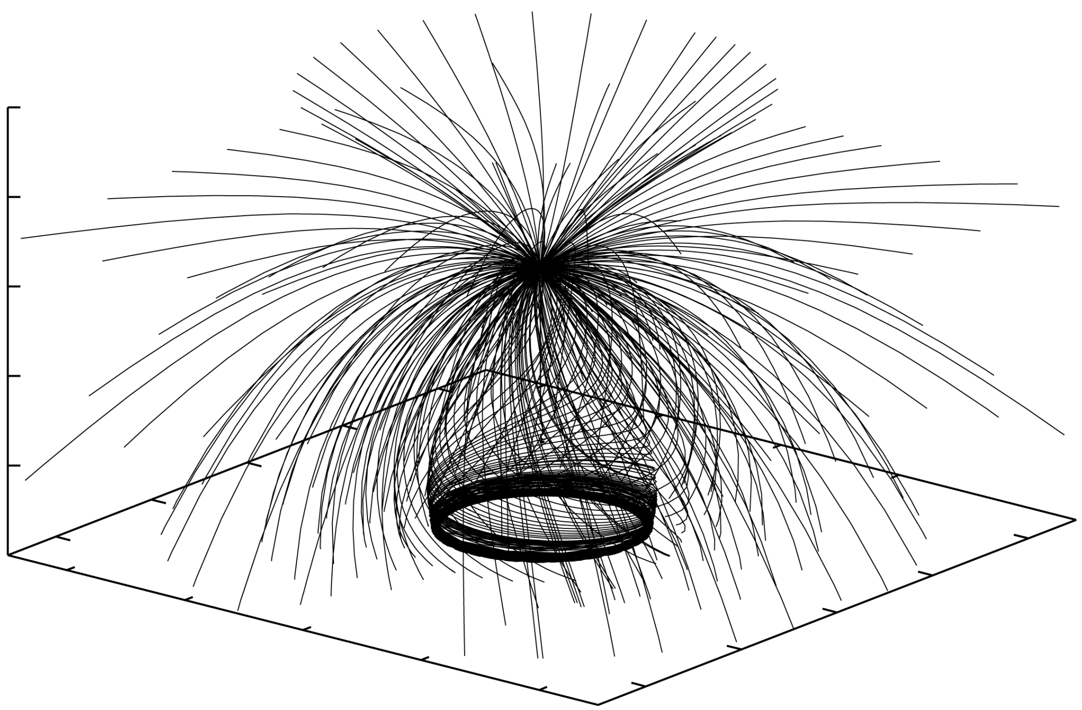


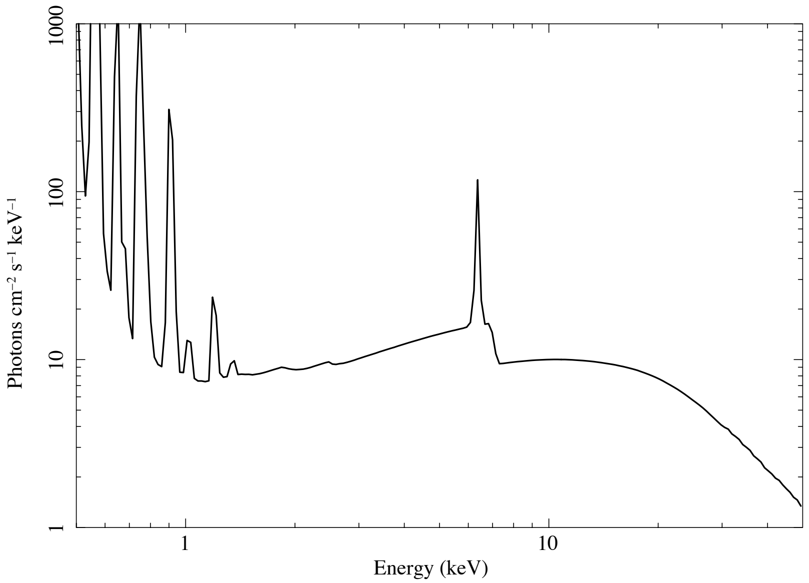
Calculating the Response

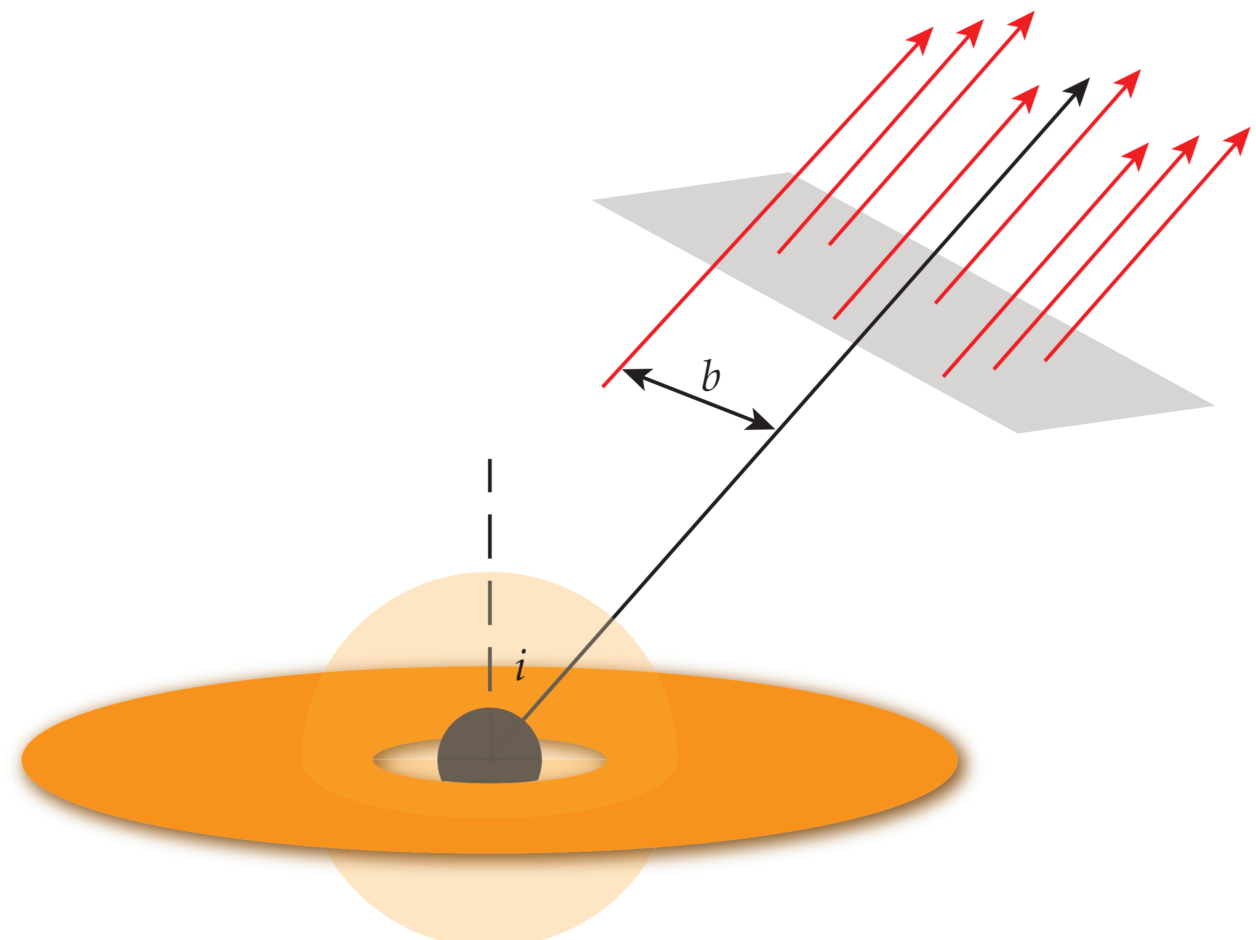


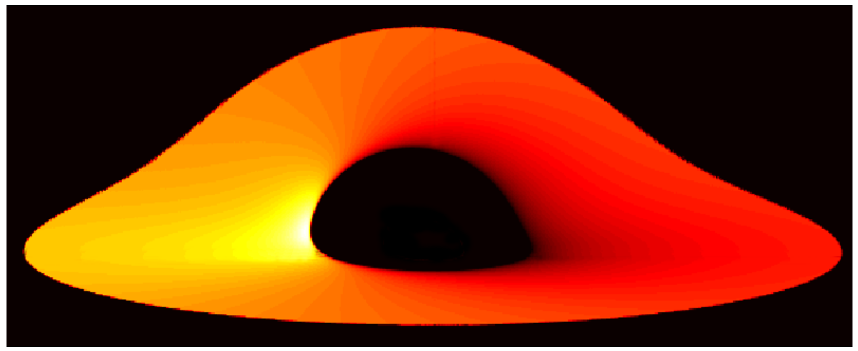


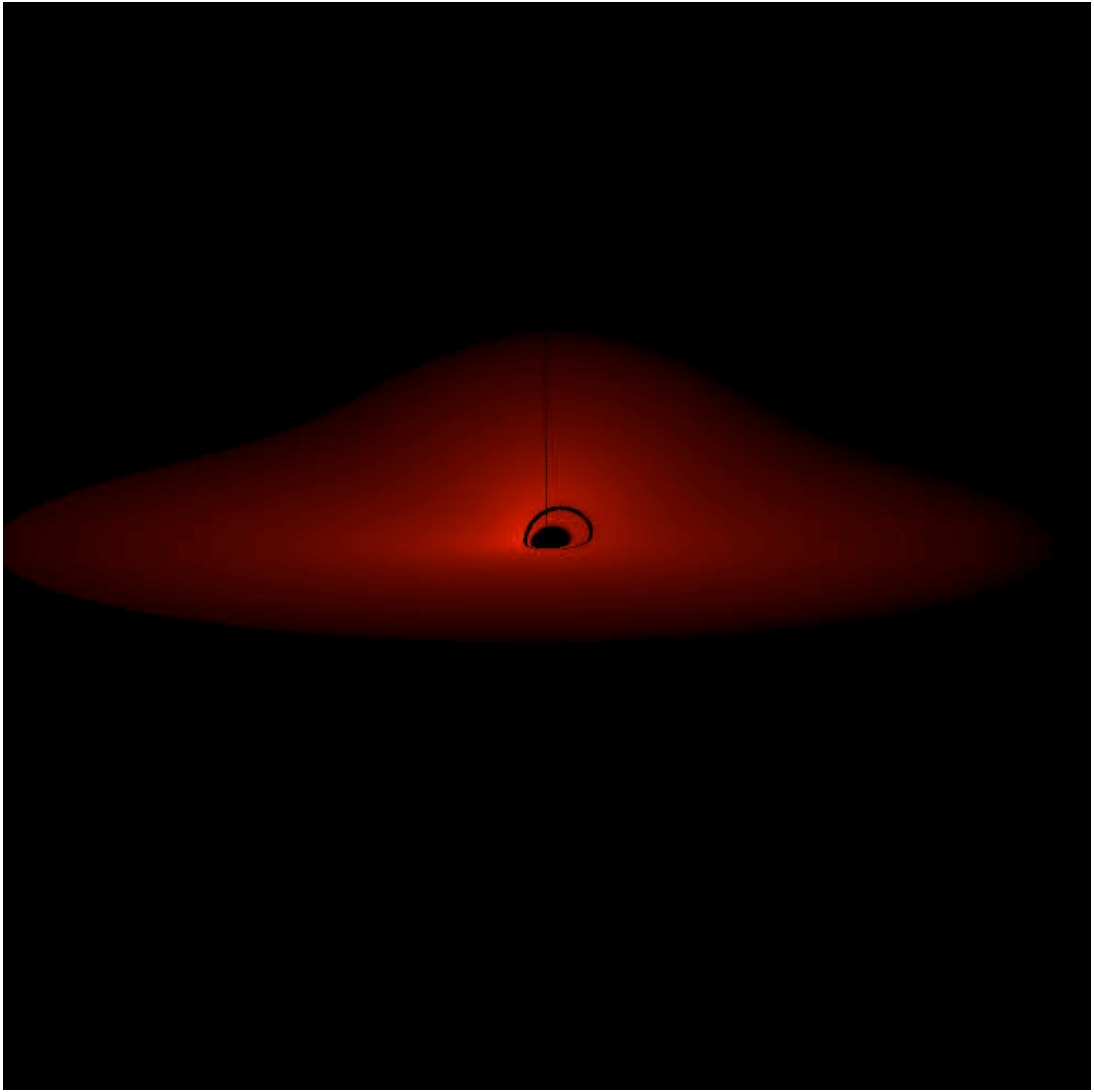
Calculating the Response

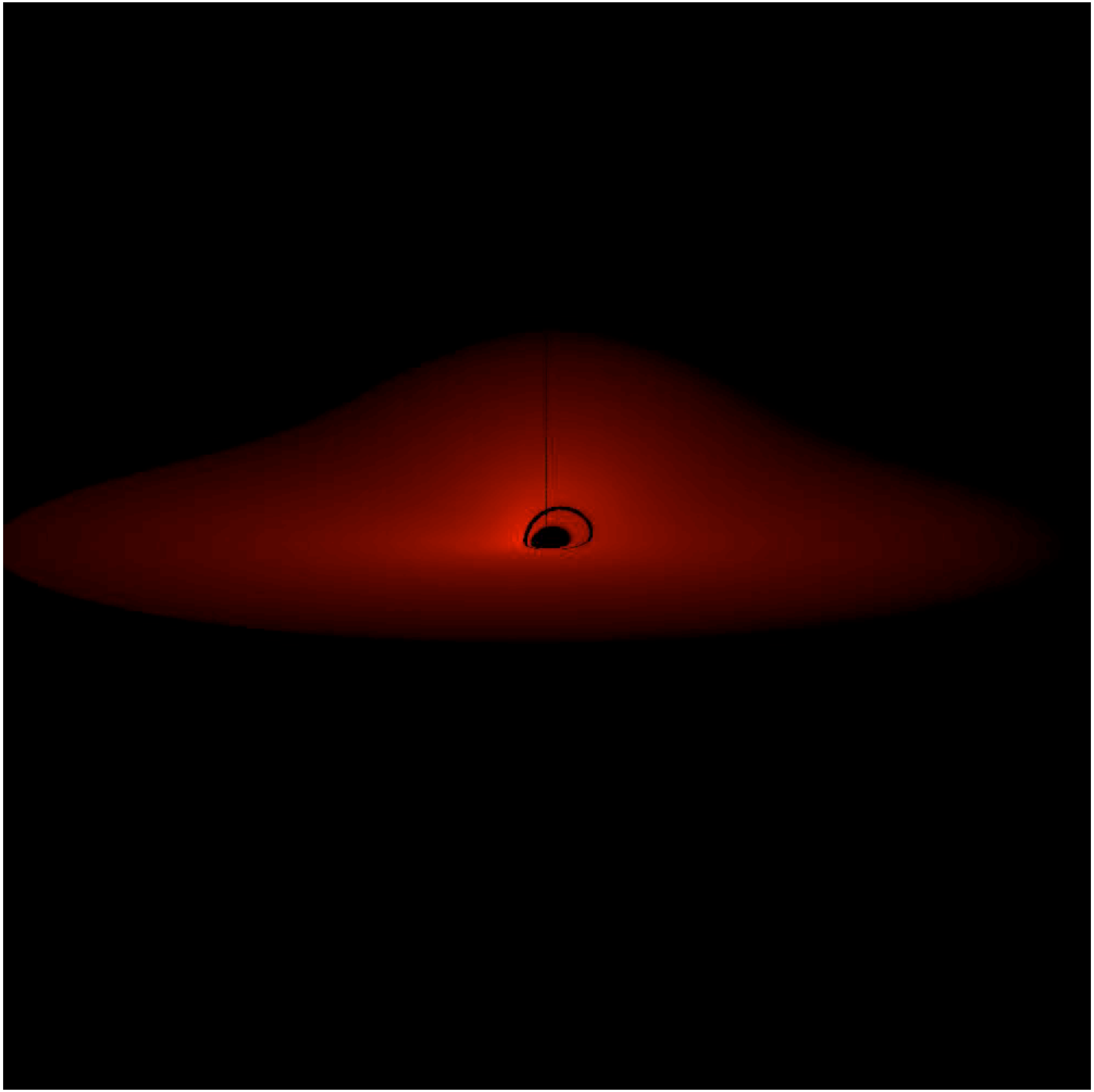


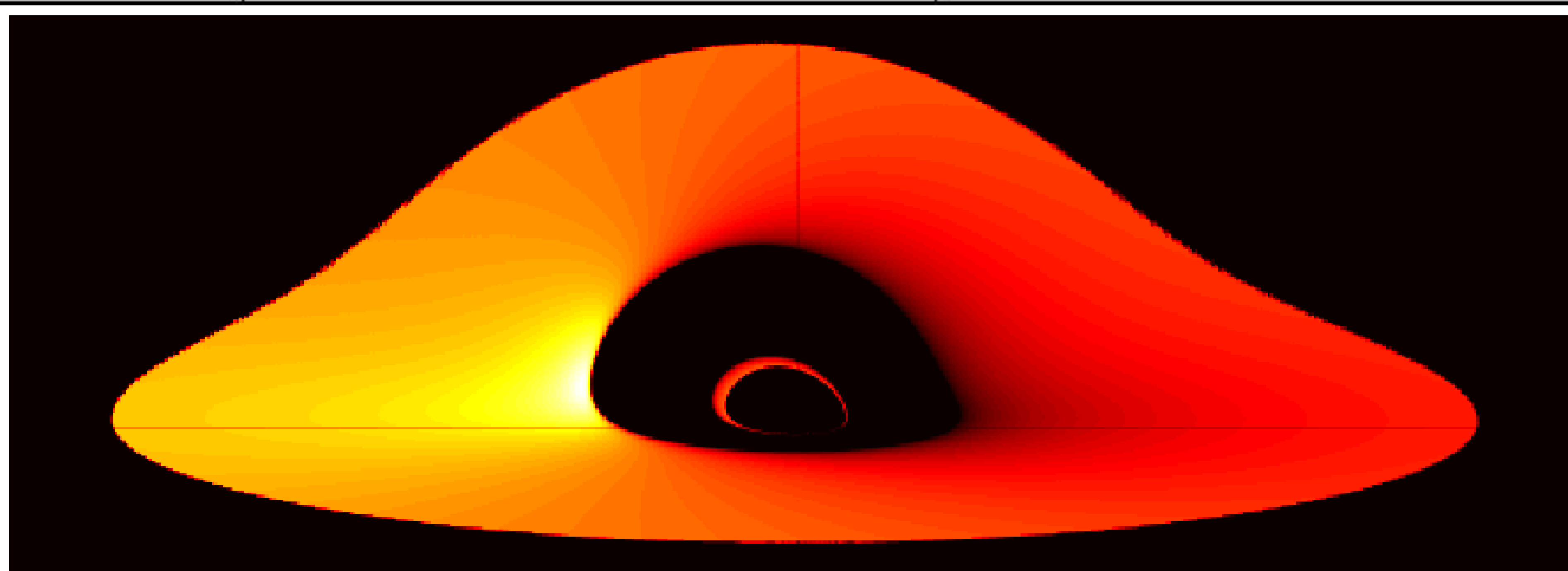


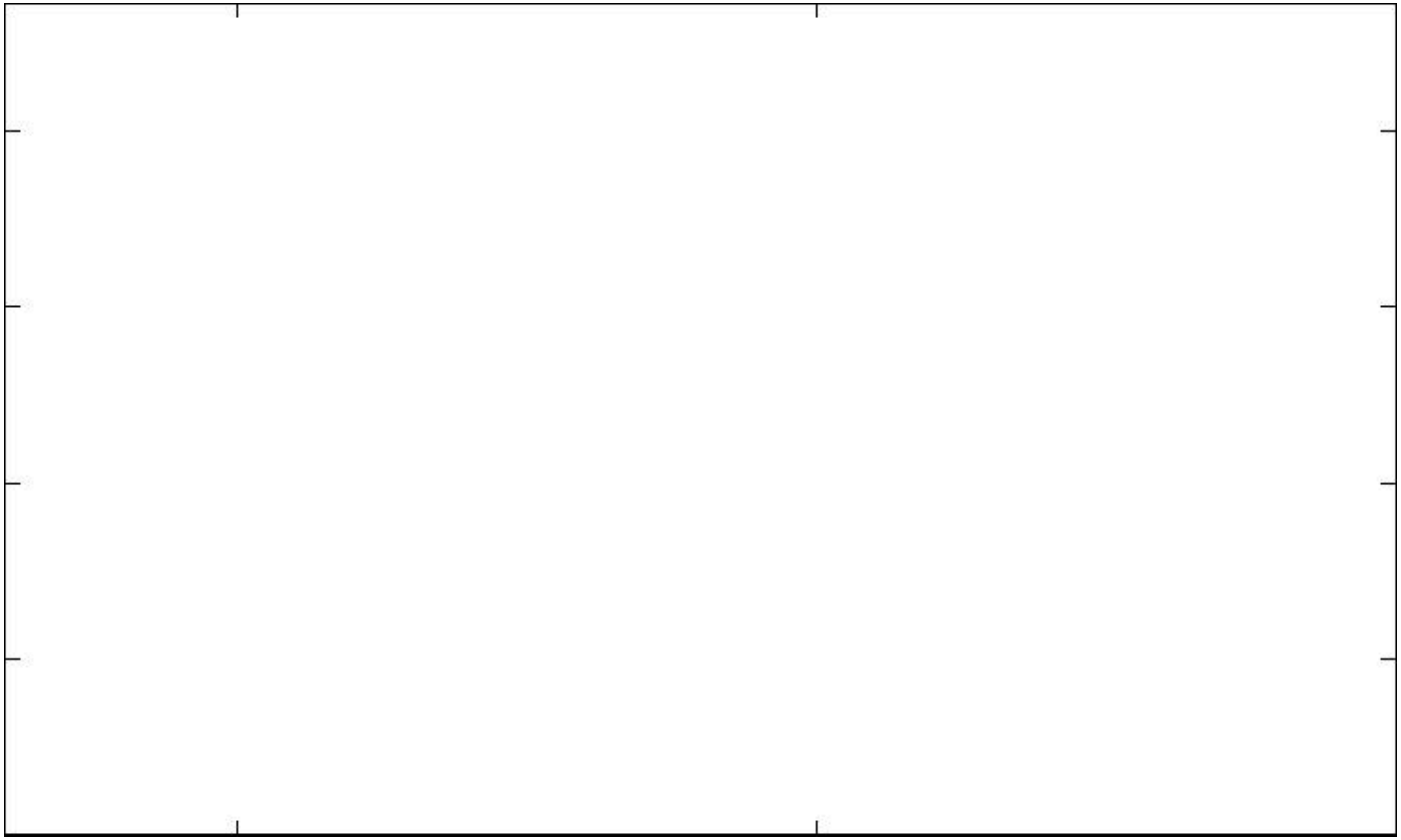


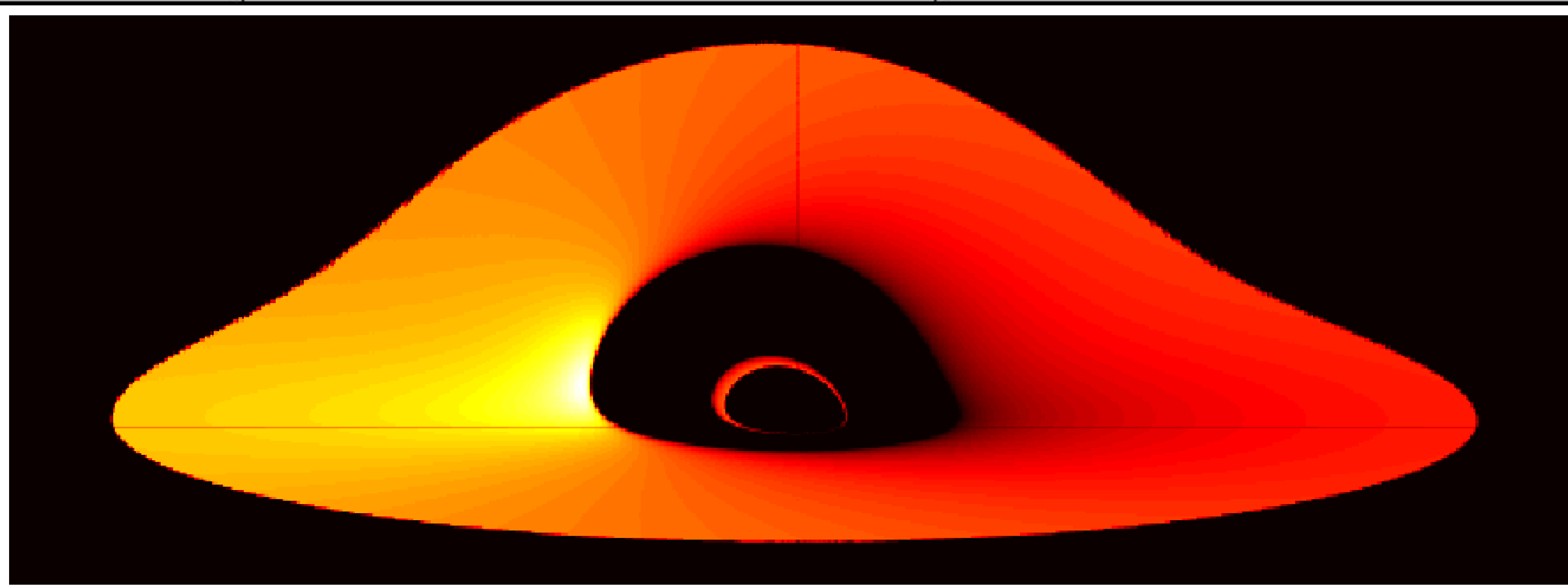












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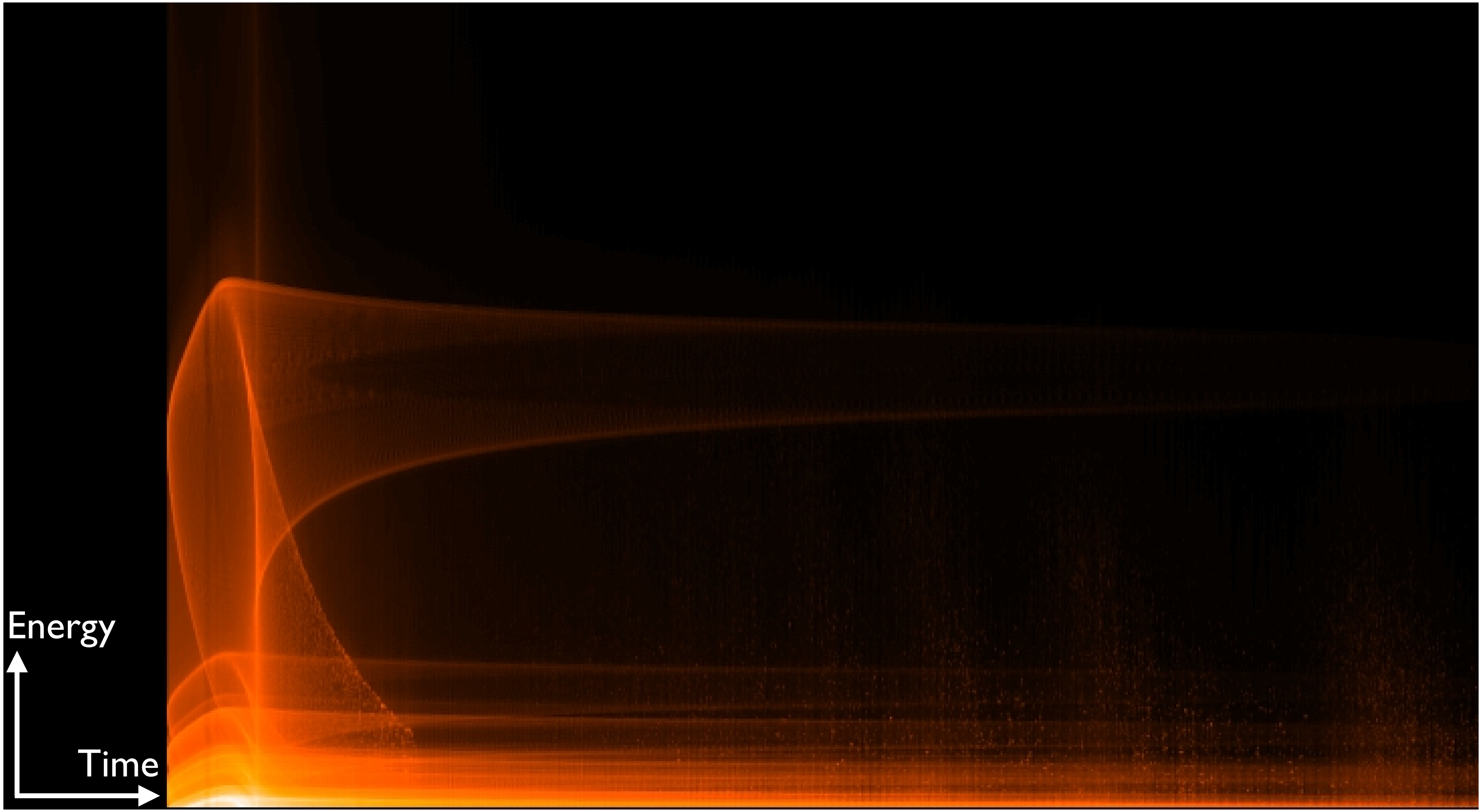
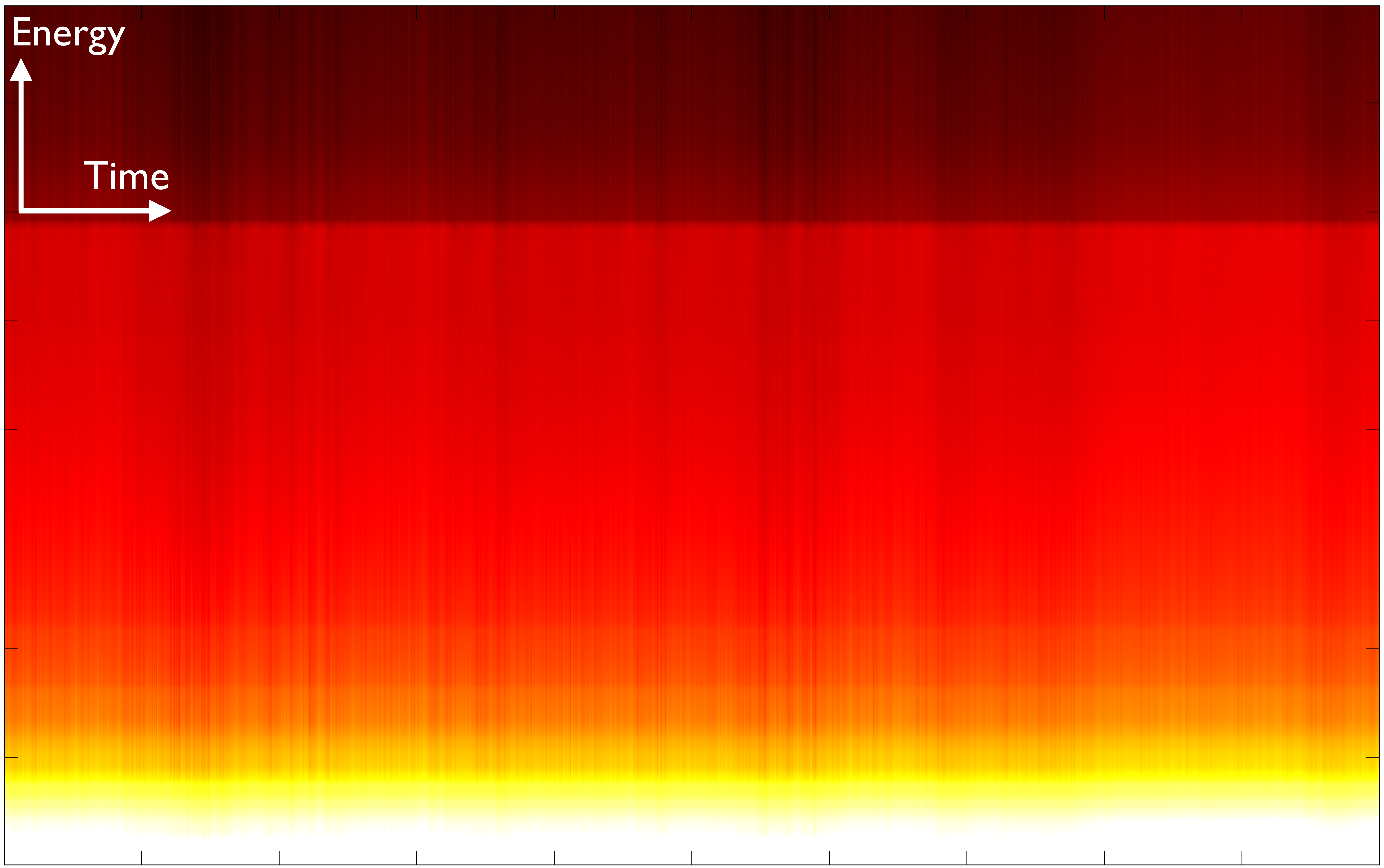
The Response Function



The Response Function



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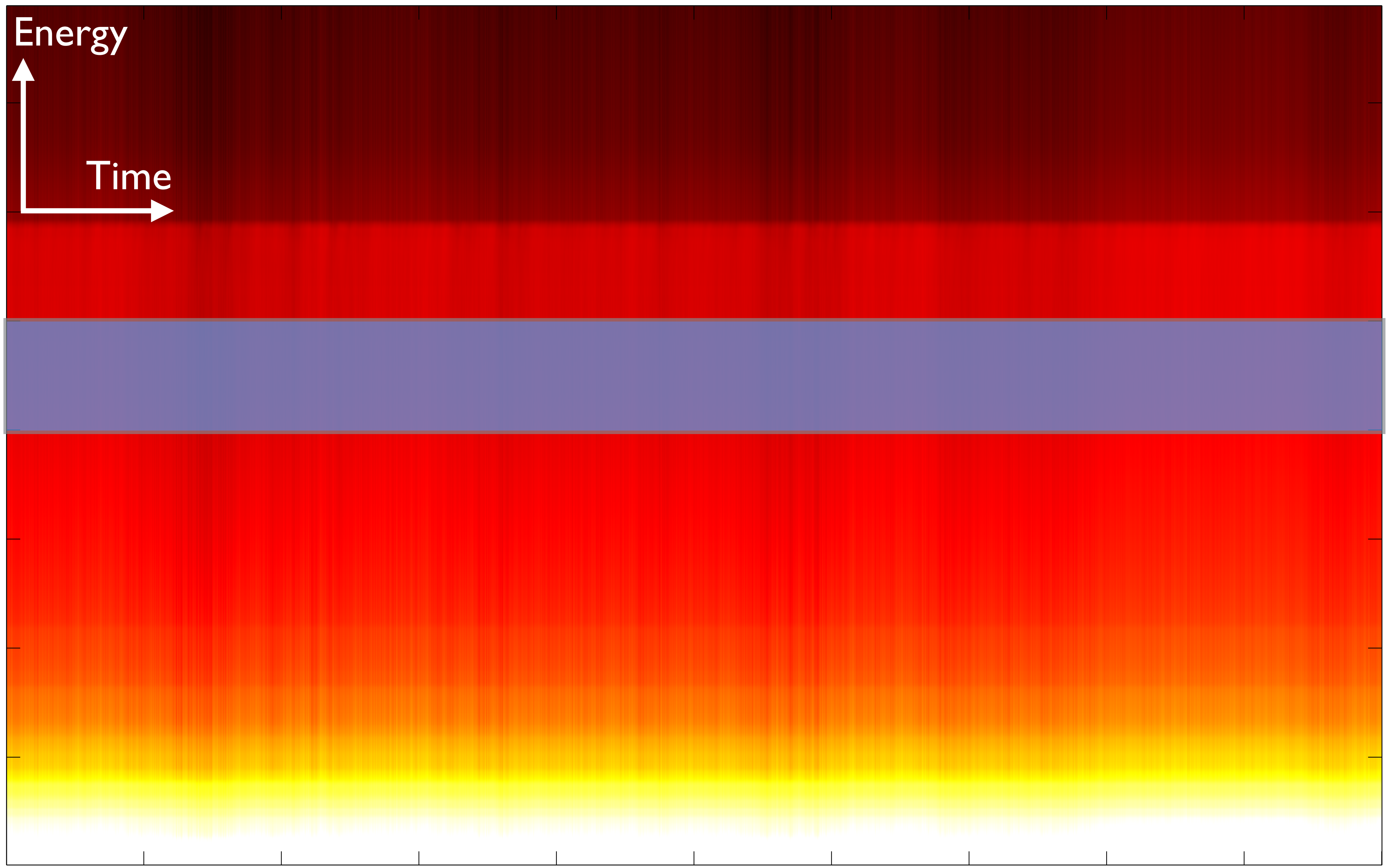
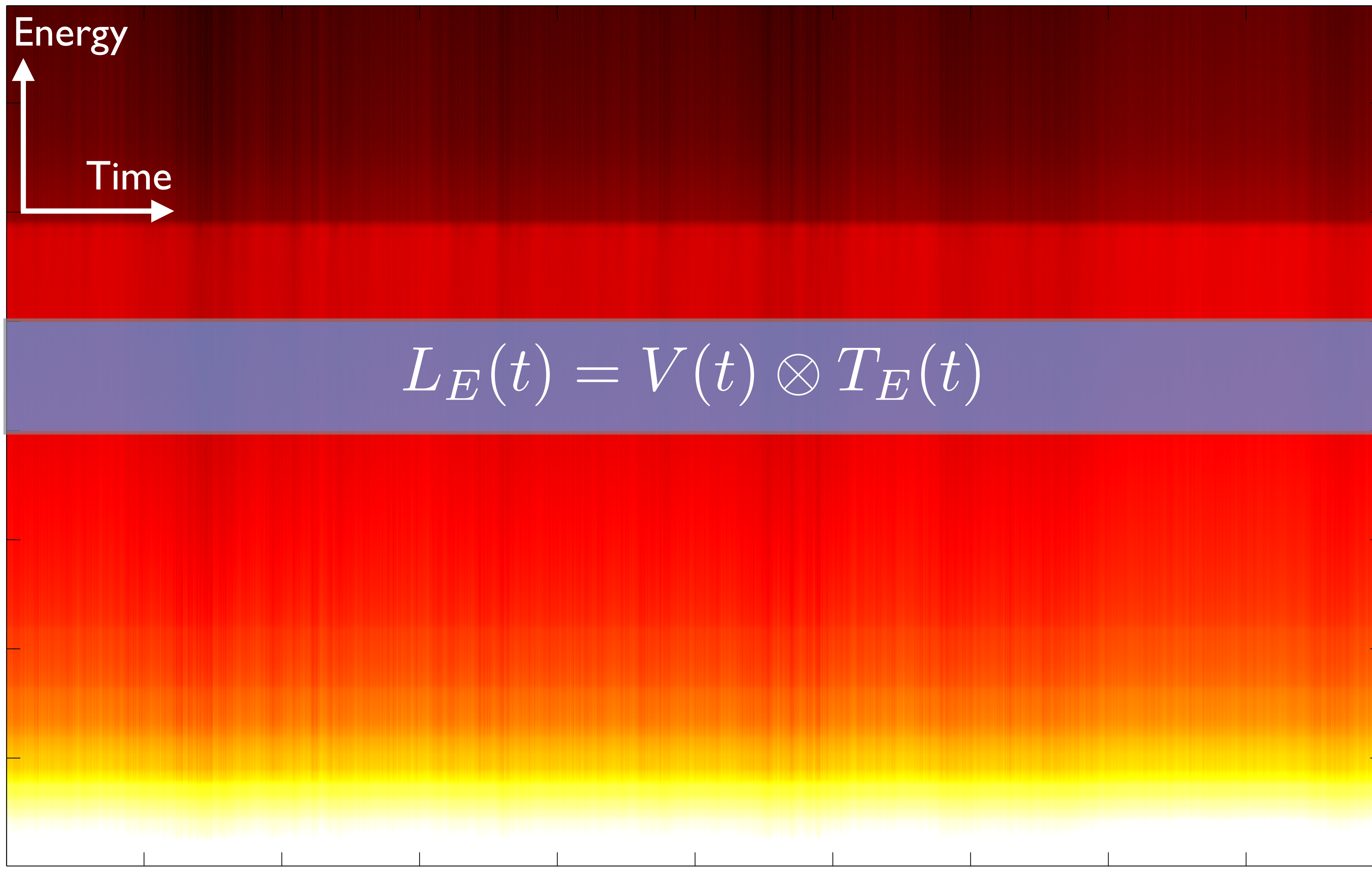
The Response Function

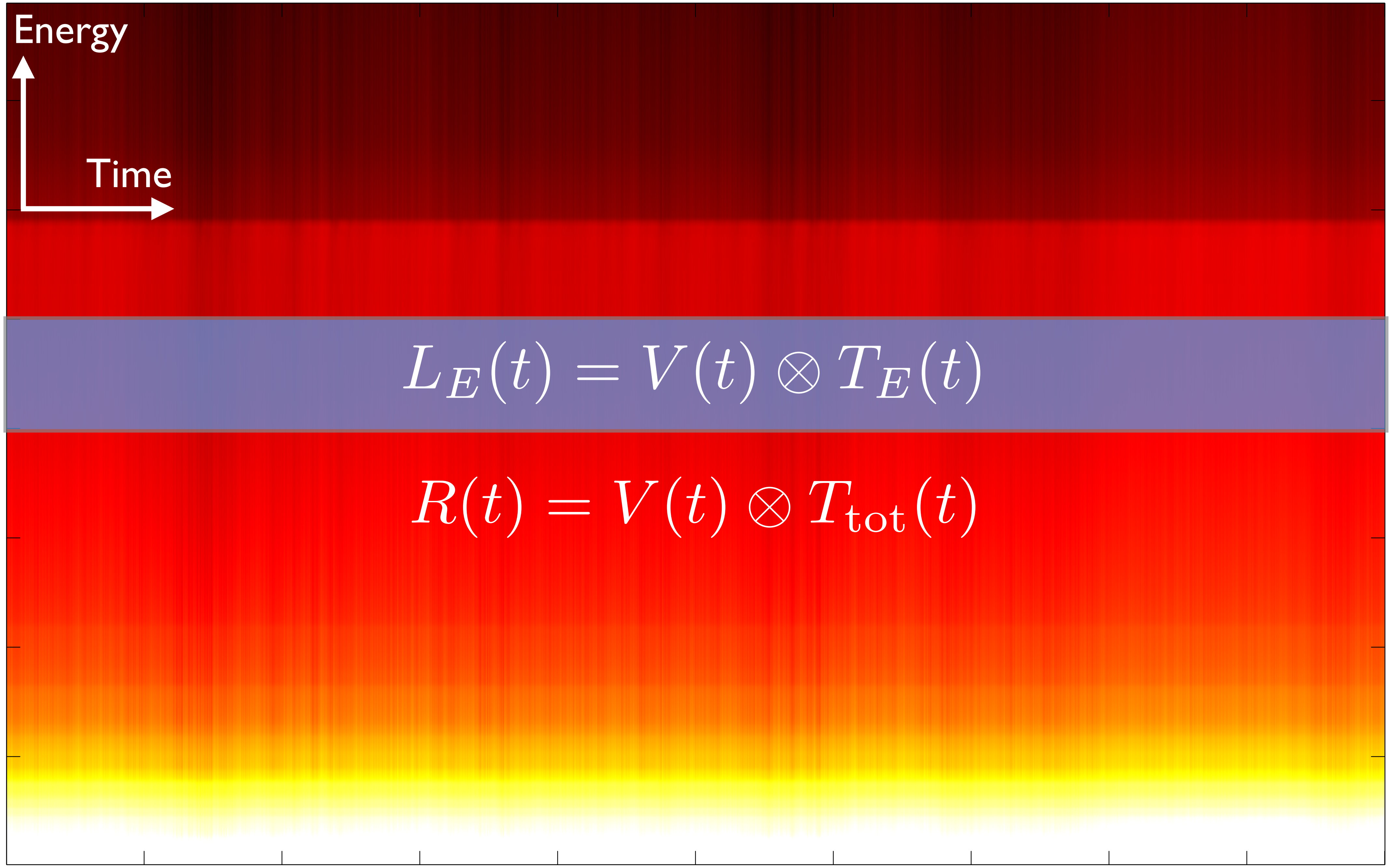


The Response Function

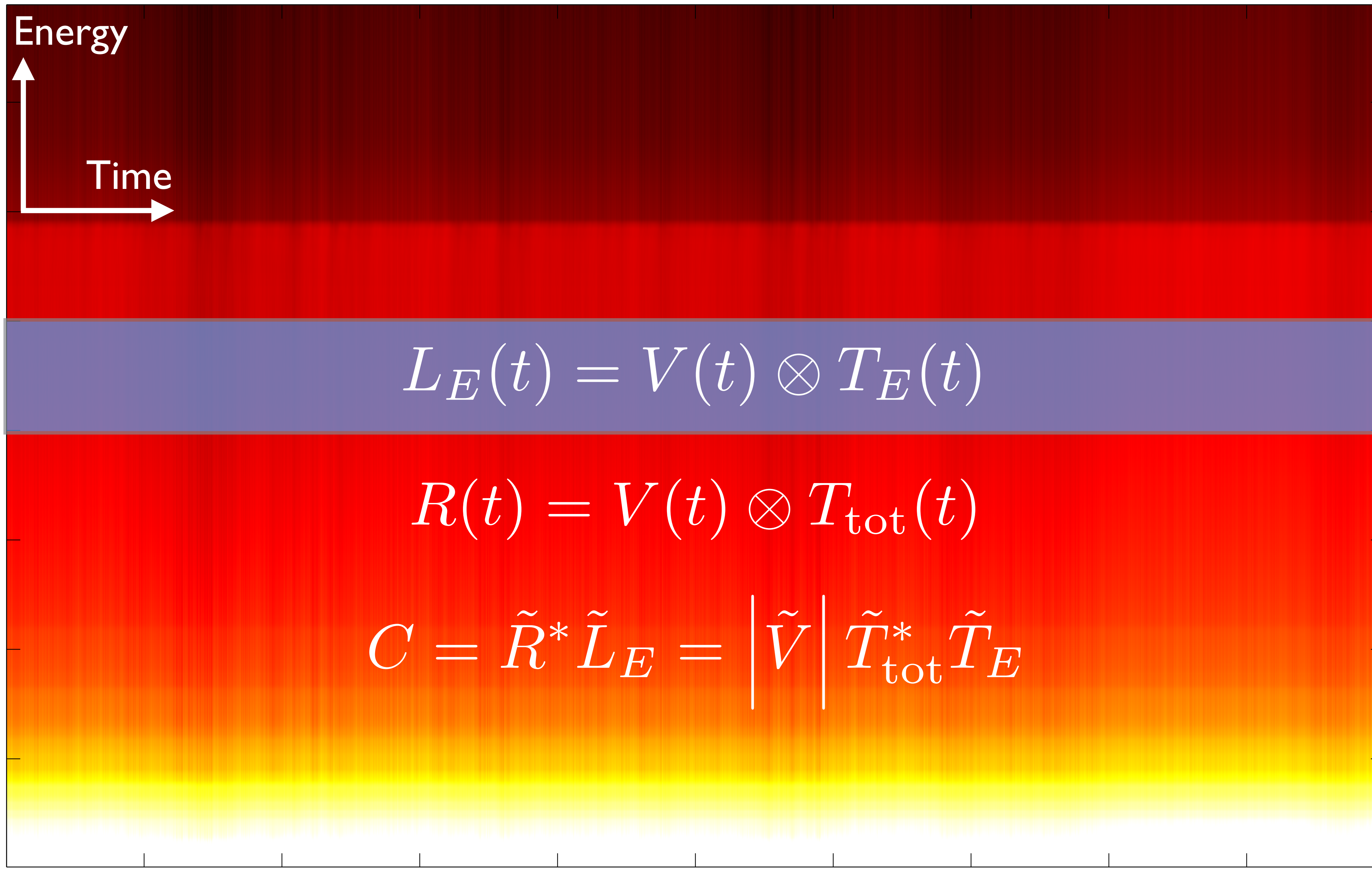


$$L_E(t) = V(t) \otimes T_E(t)$$

The Response Function



The Response Function



$$L_E(t) = V(t) \otimes T_E(t)$$

$$R(t) = V(t) \otimes T_{\mathrm{tot}}(t)$$

$$C = \tilde{R}^* \tilde{L}_E = \left|\tilde{V}\right| \tilde{T}^*_{\mathrm{tot}} \tilde{T}_E$$

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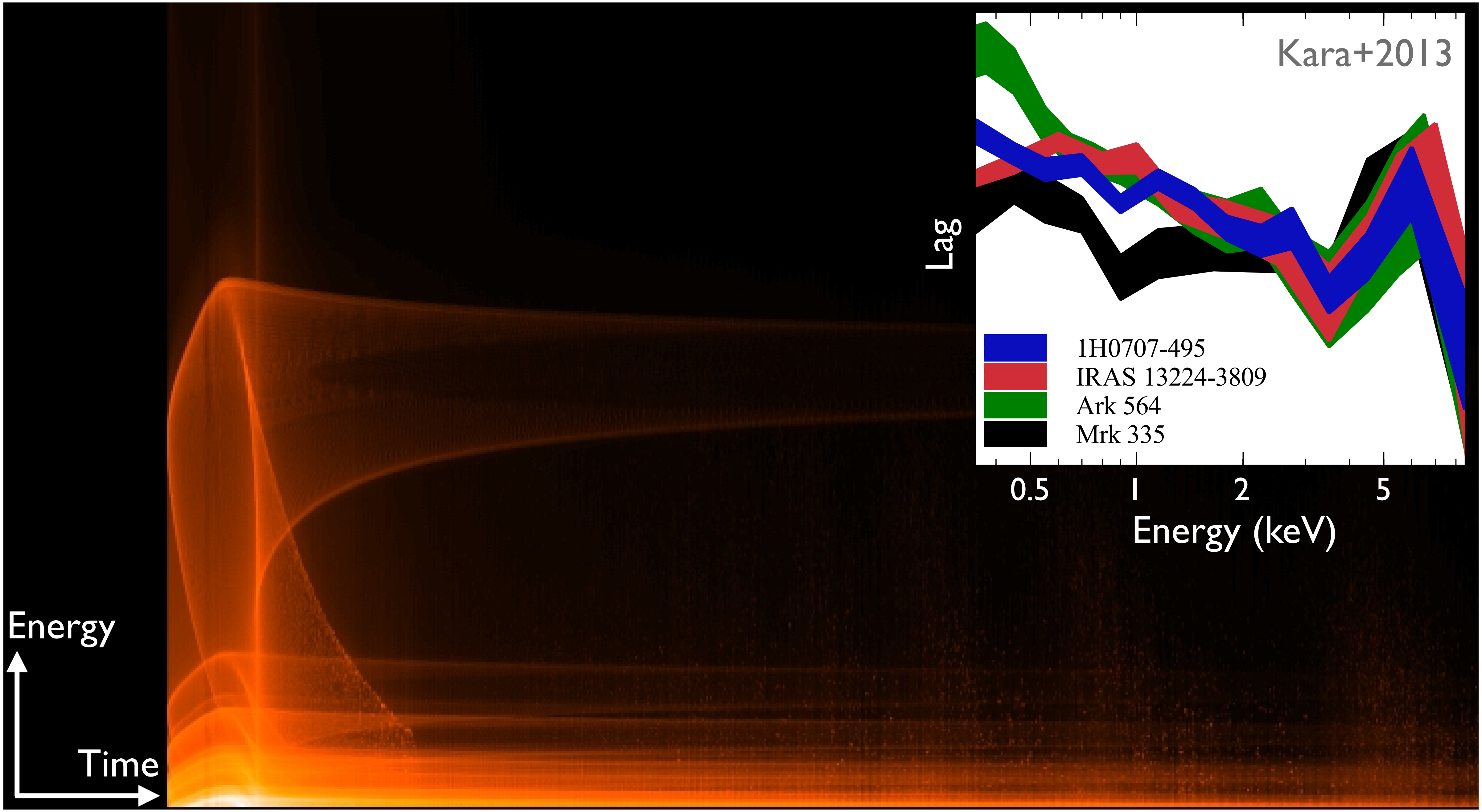
The Lamppost



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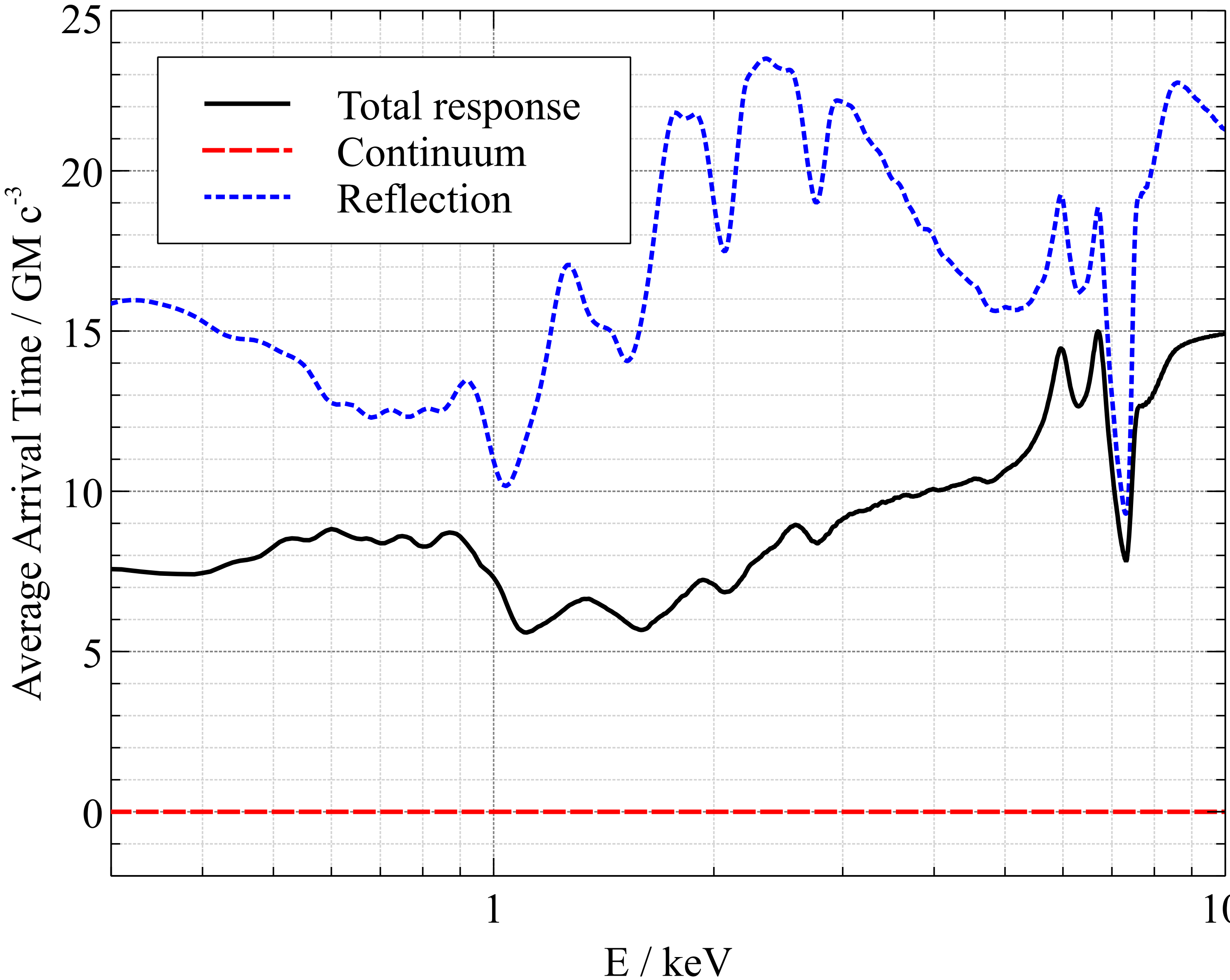
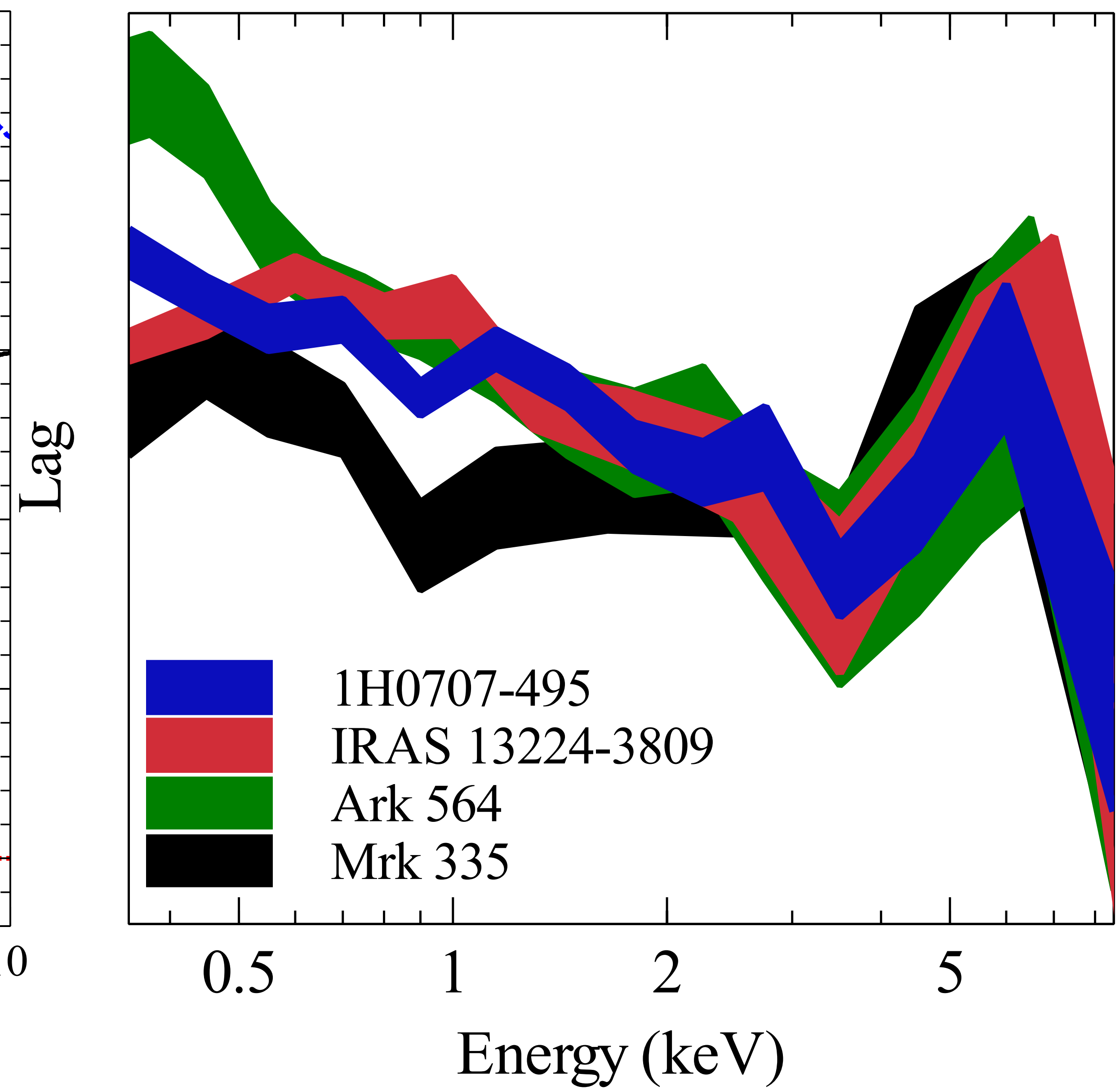
The Lamppost

Kara+2013





Requirements

1. Simultaneous detection of the 'hard lag' at low frequencies and disc reverberation at high frequencies
2. Shape of the high frequency, 'reverberation' lag-energy spectrum – 3keV dip

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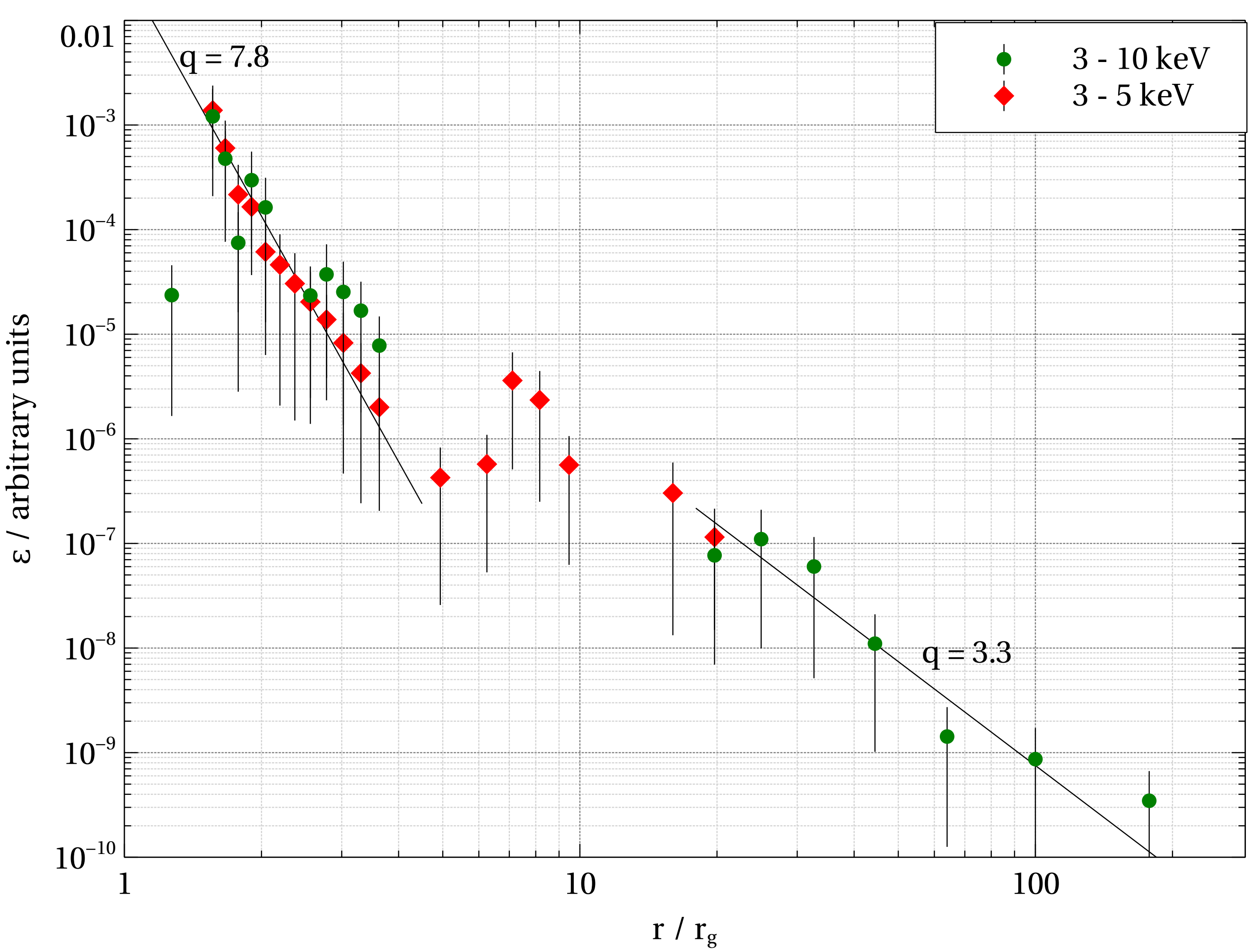
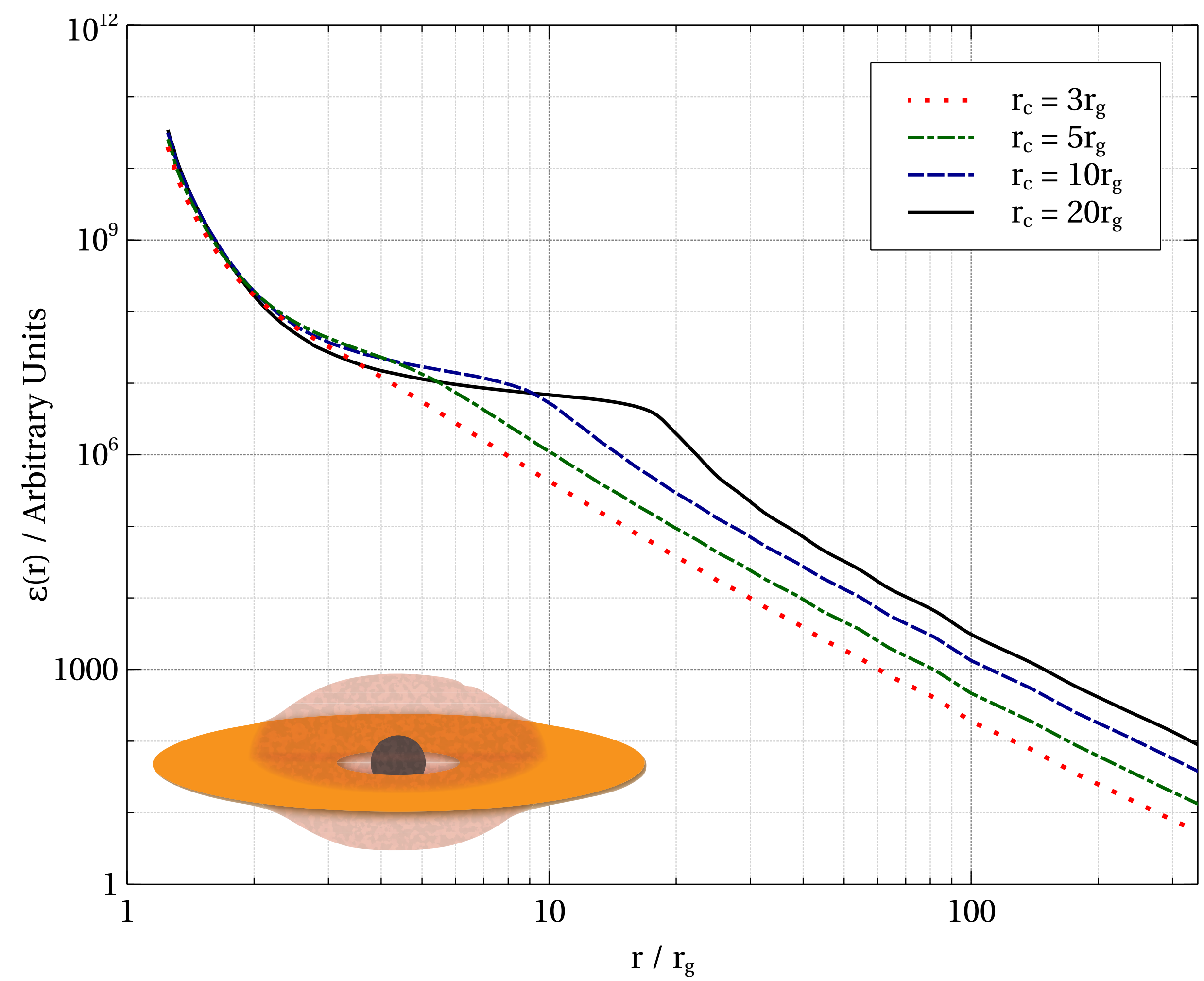
The X-ray Spectrum and Emissivity

1H 0707-495



Accretion Disc Emissivity



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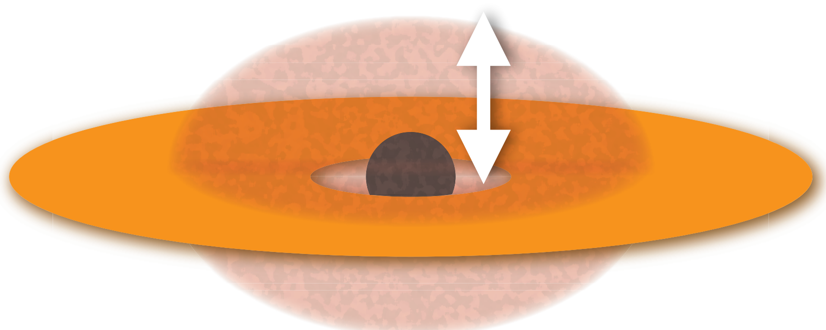
Developing an extended corona model

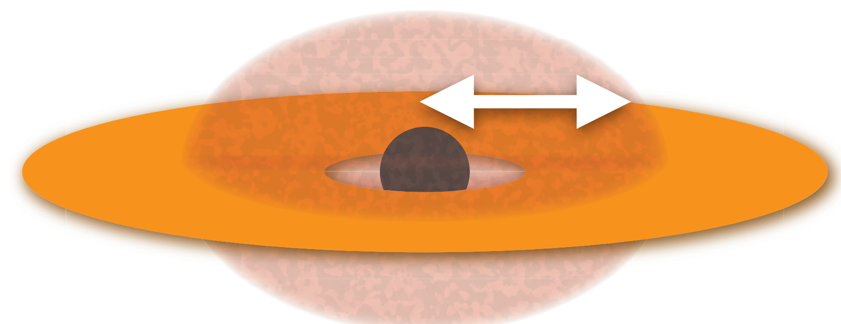
Developing an extended corona model

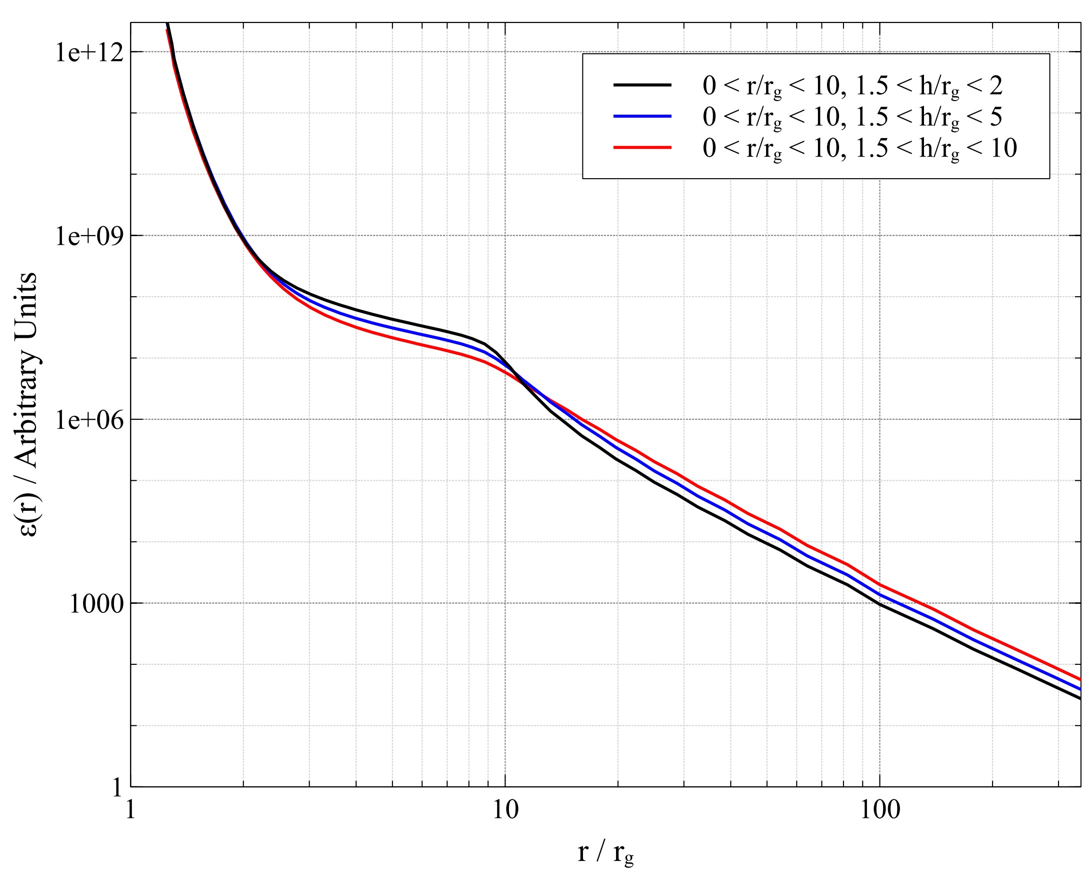
Self-consistent

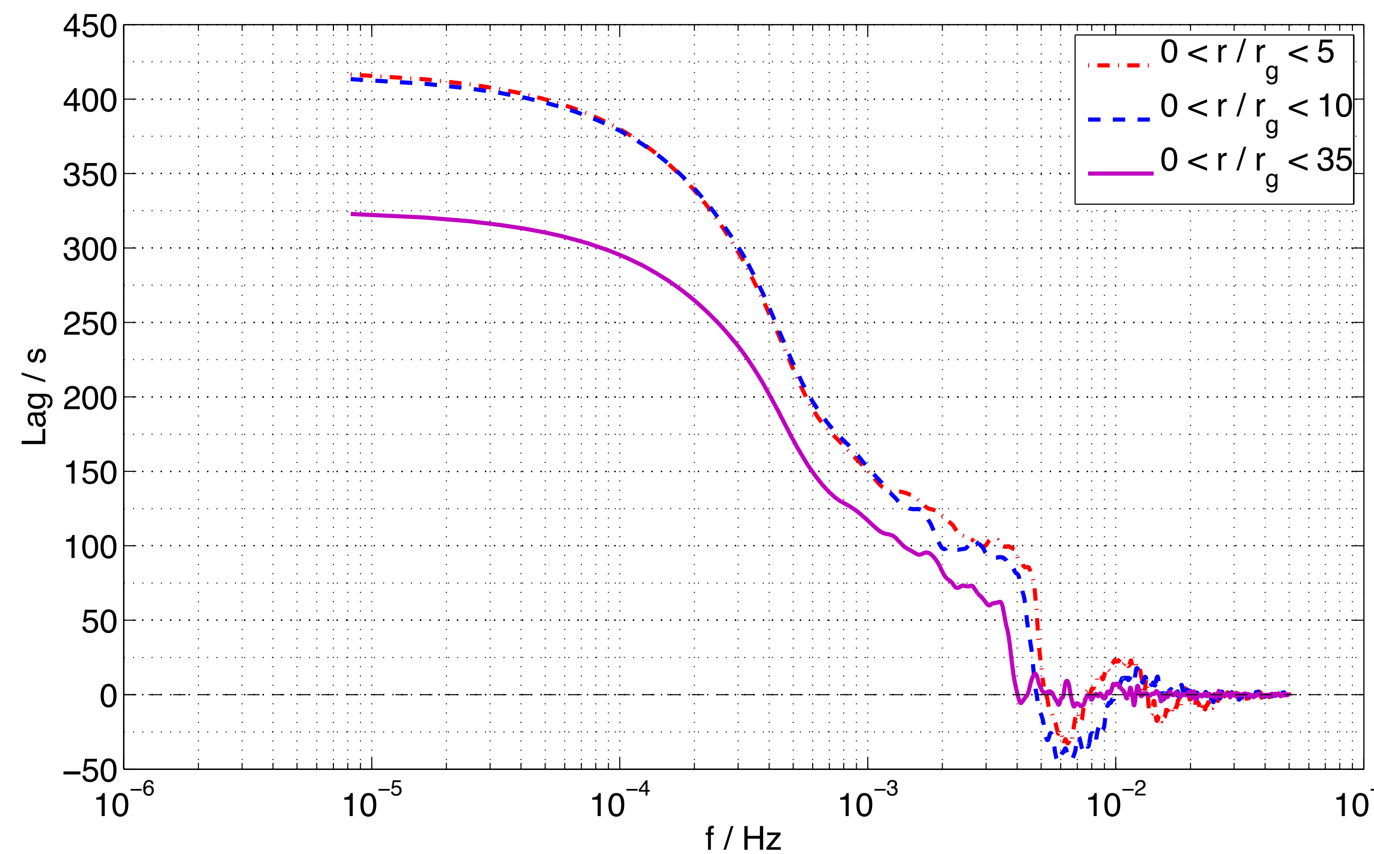
Physical

Extended Coronae

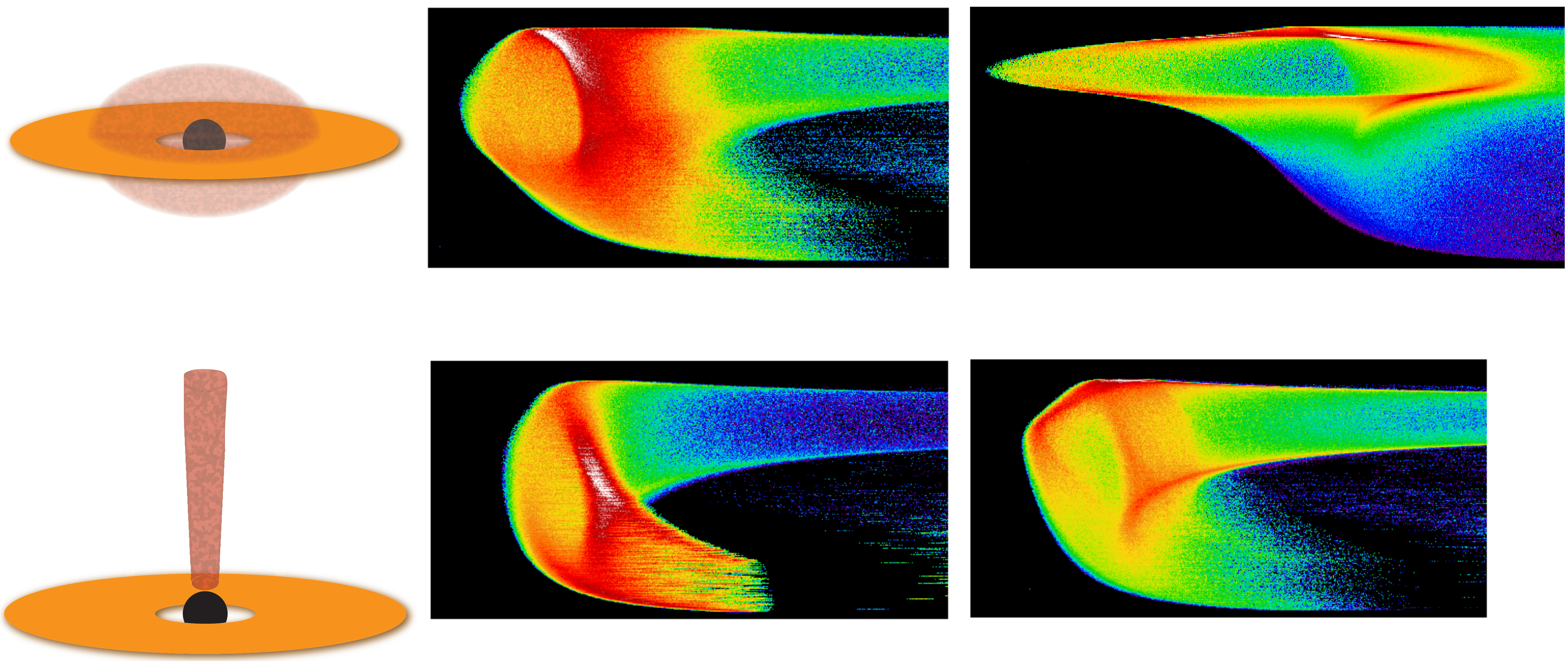








But with Lag/Energy…



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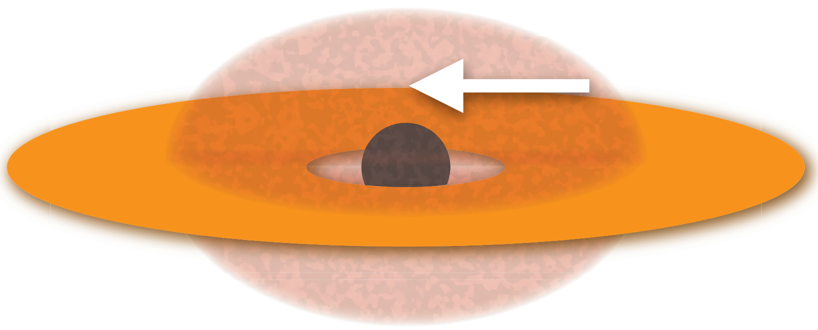
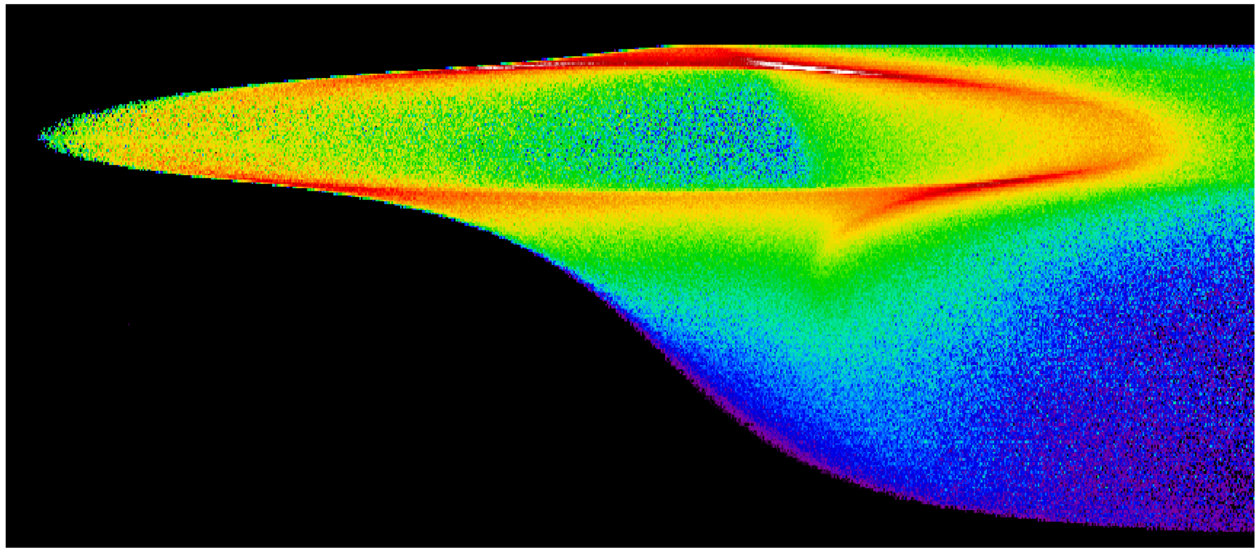
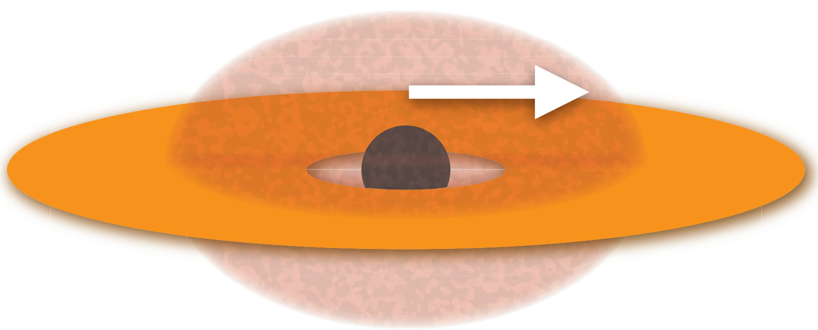
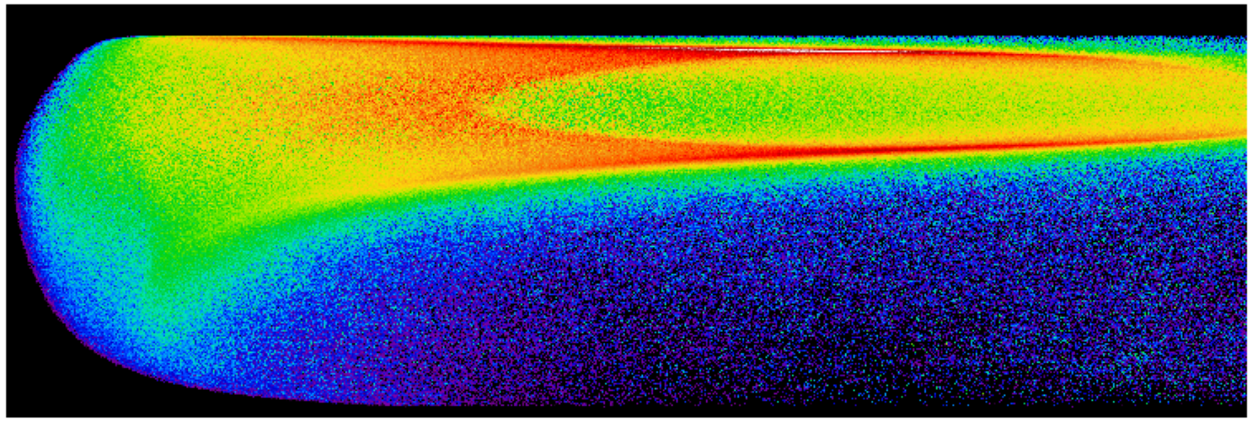
Propagation

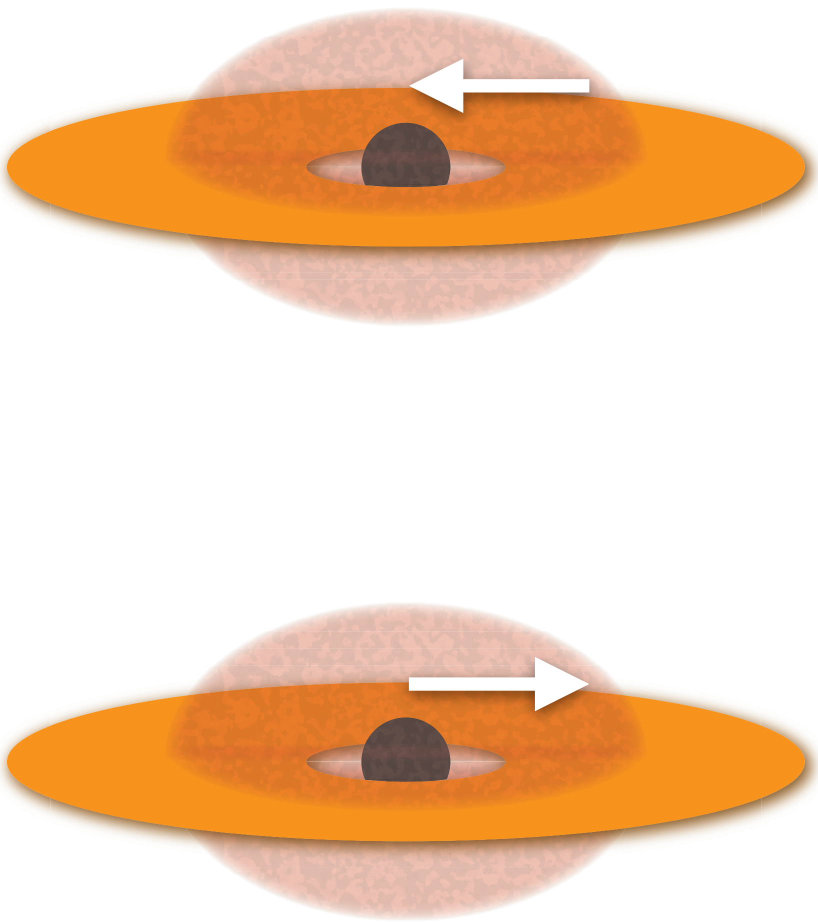


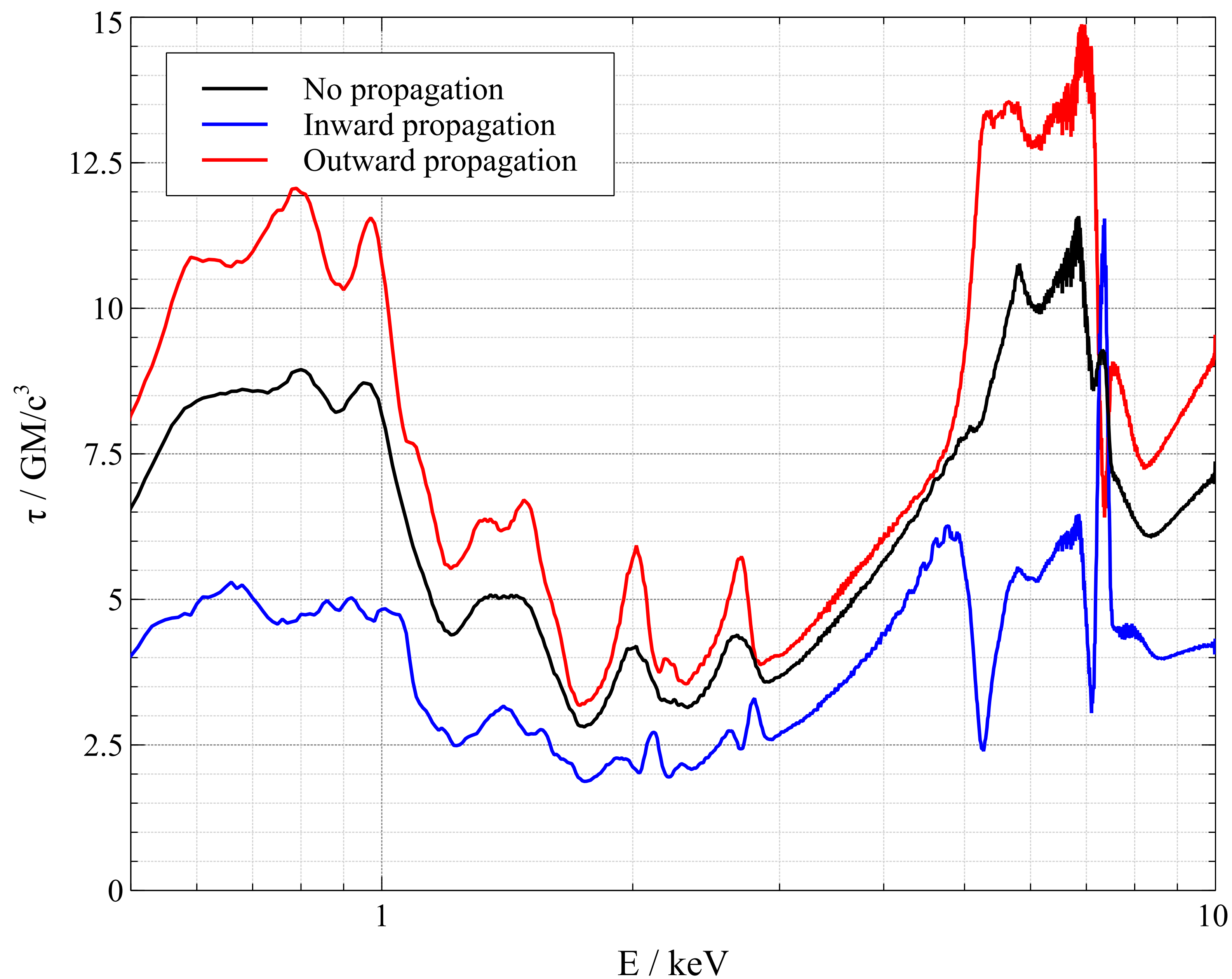






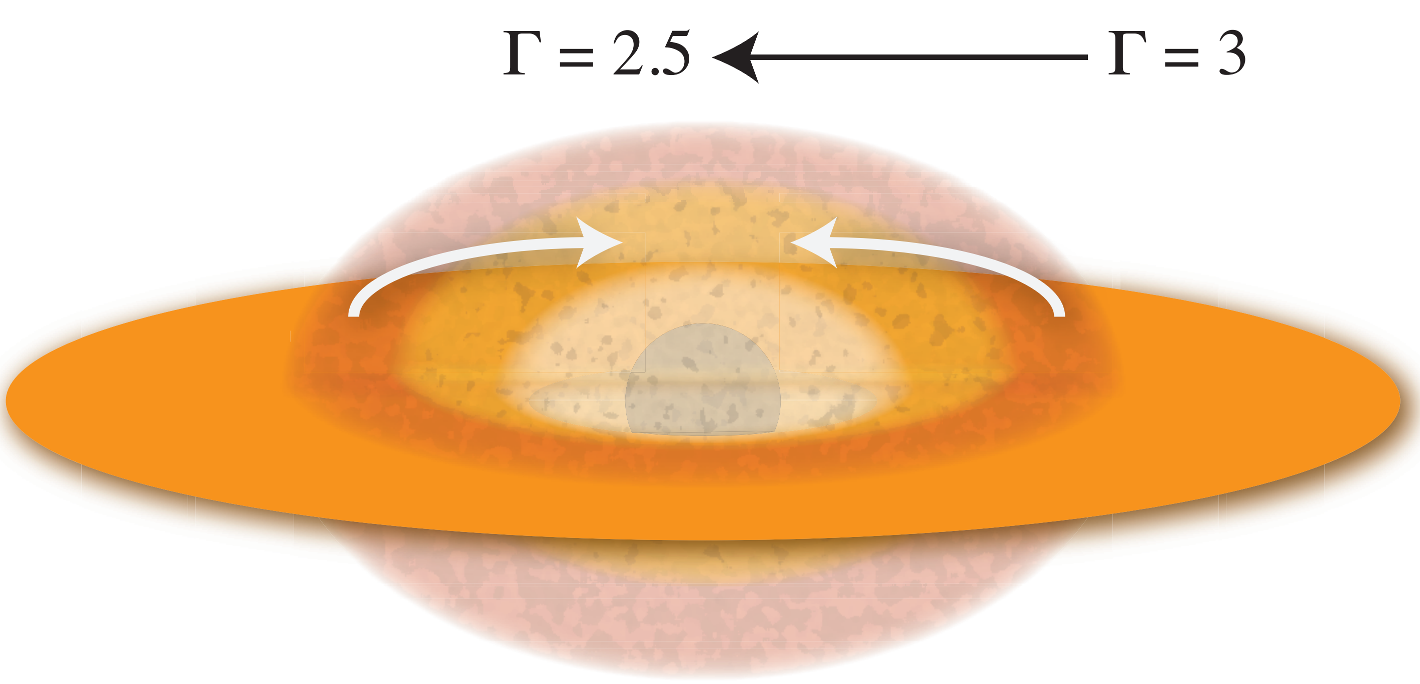
Propagation





What about the hard lags?

Modified version of Arévalo & Uttley 2006



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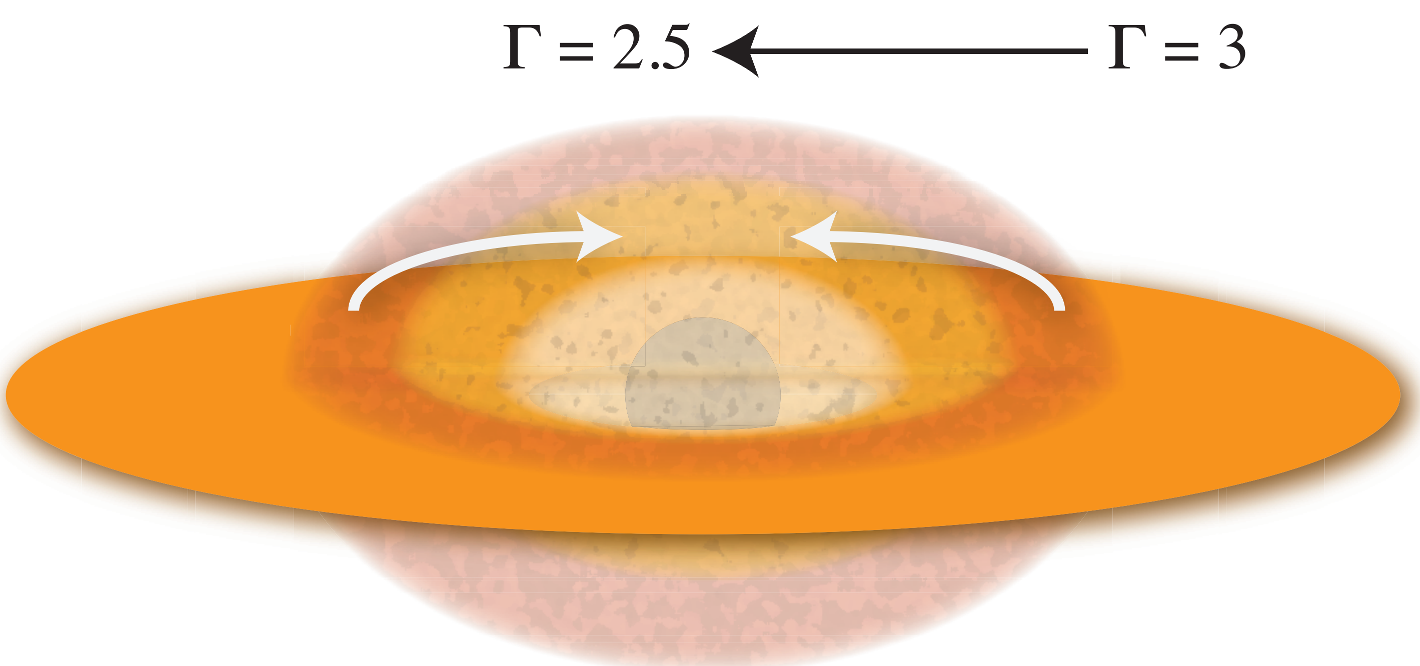
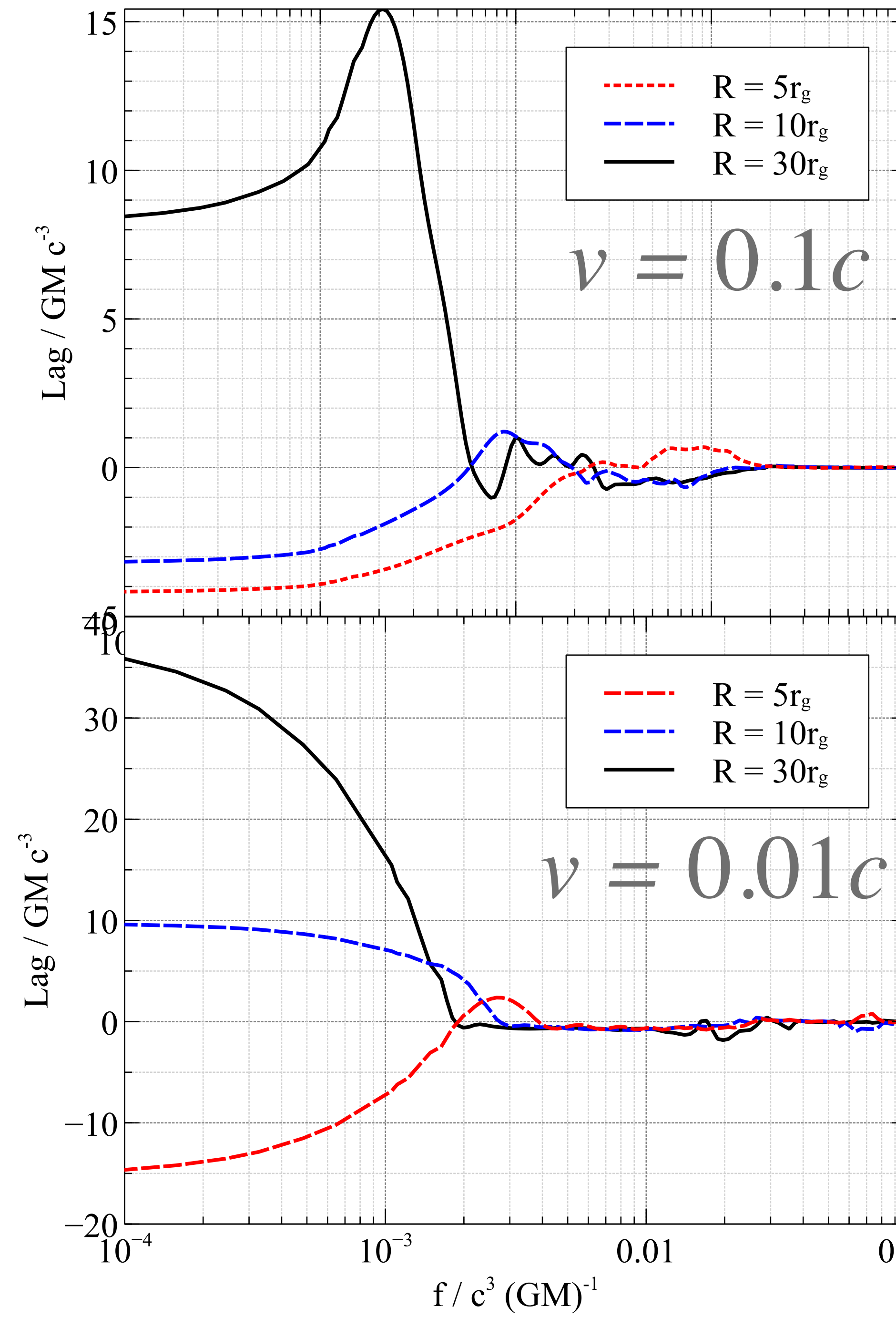
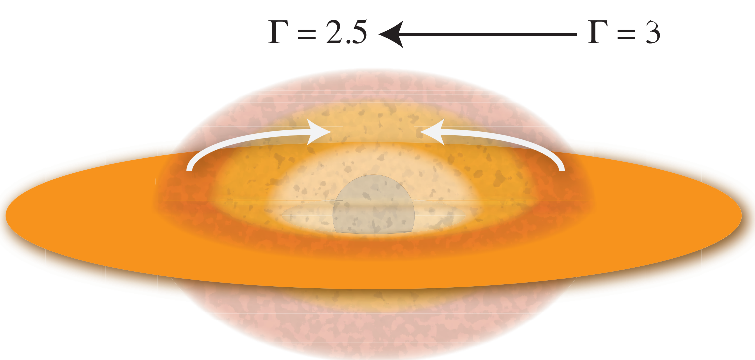
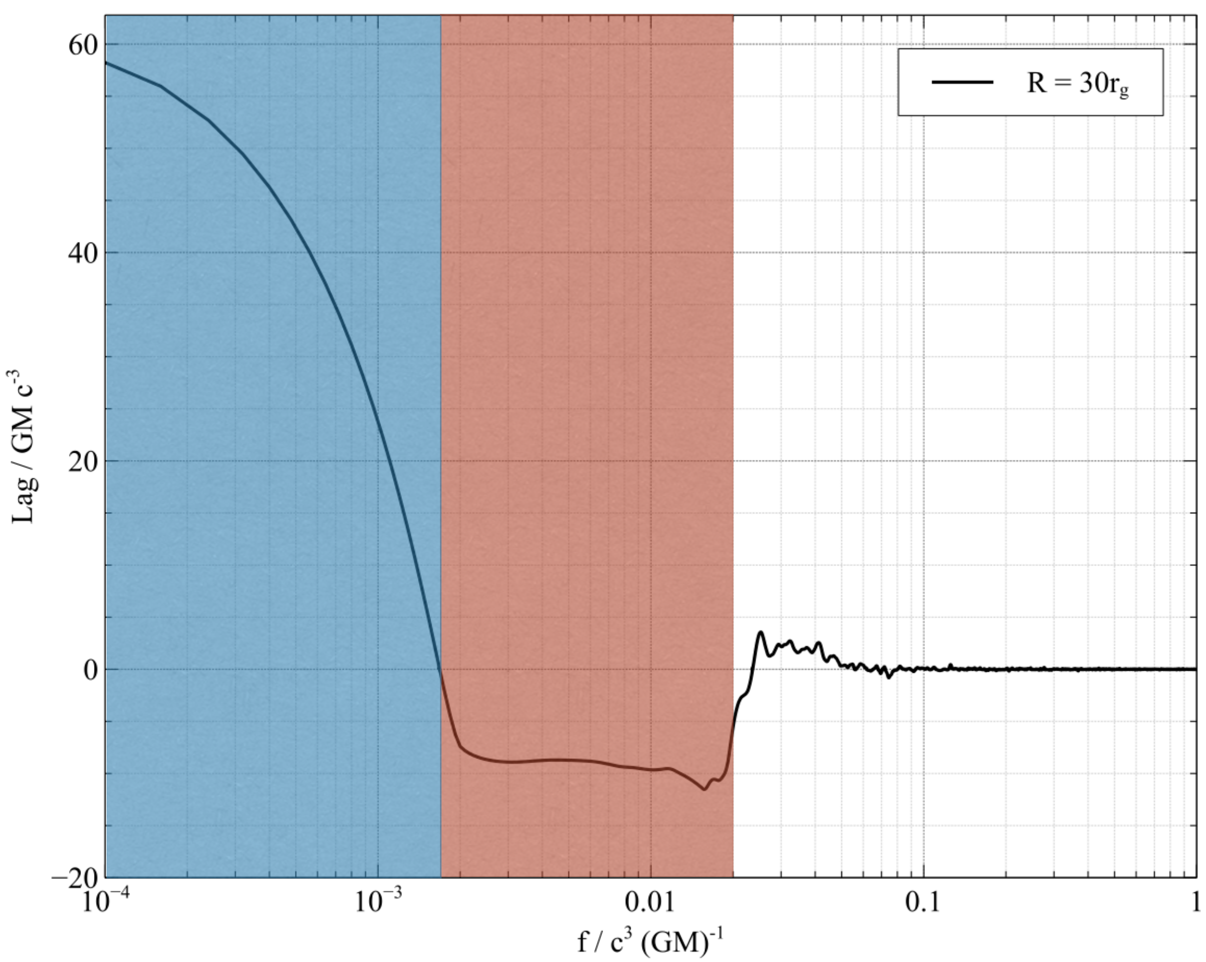


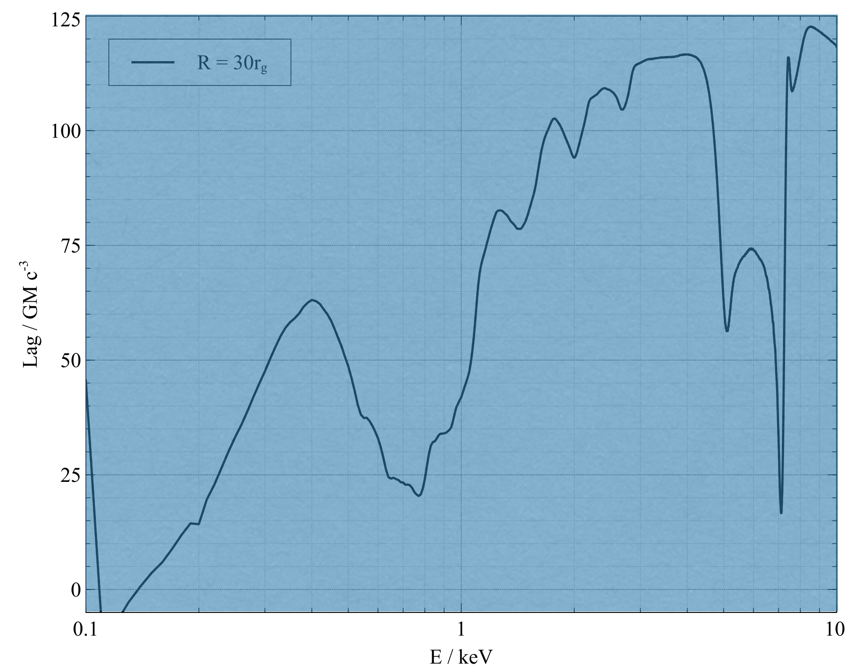


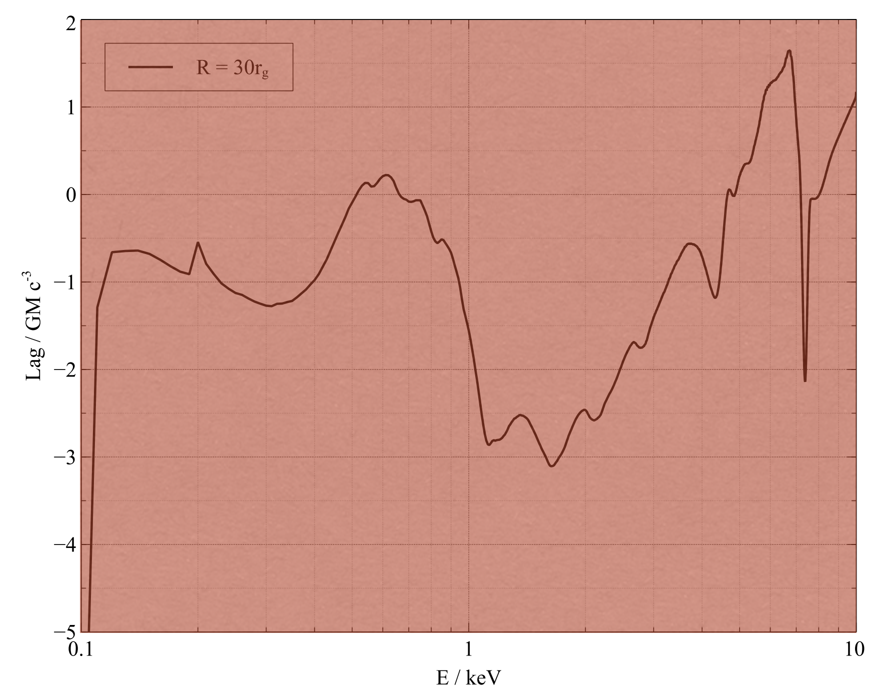
Viscous Propagation



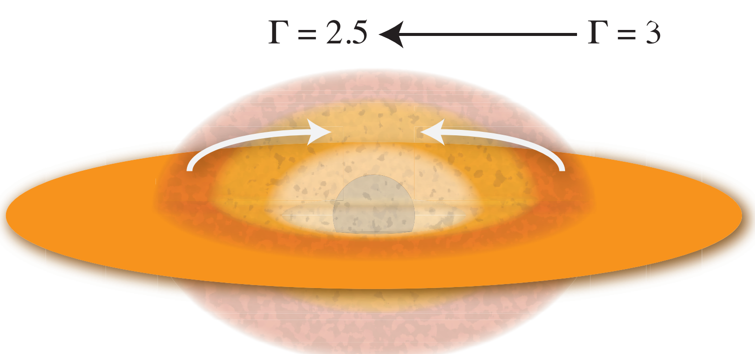
$$\dot{r} = r^{-\frac{1}{2}} \frac{\alpha}{\sqrt{GM}} \left(\frac{h}{r}\right)^2$$







Viscous Propagation



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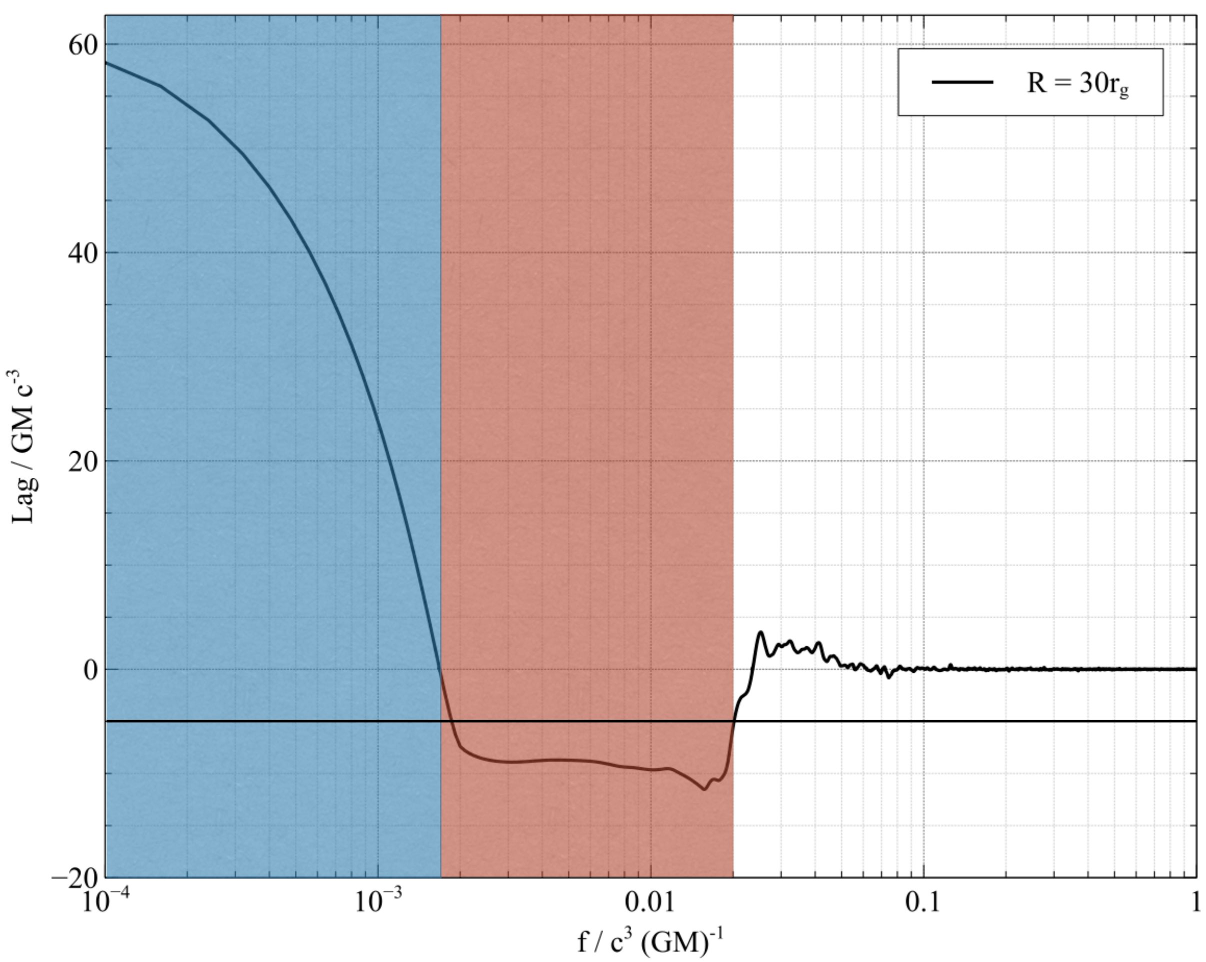

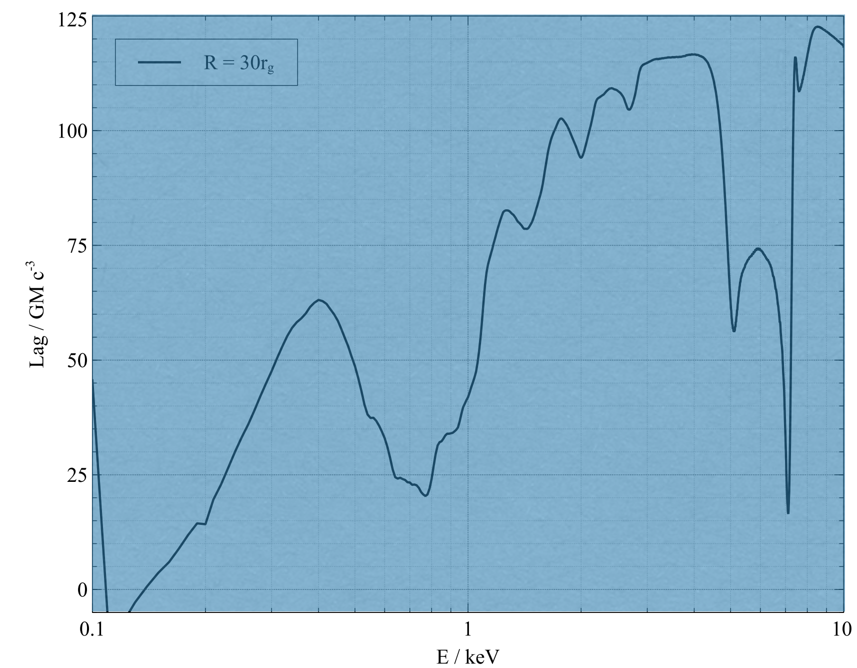

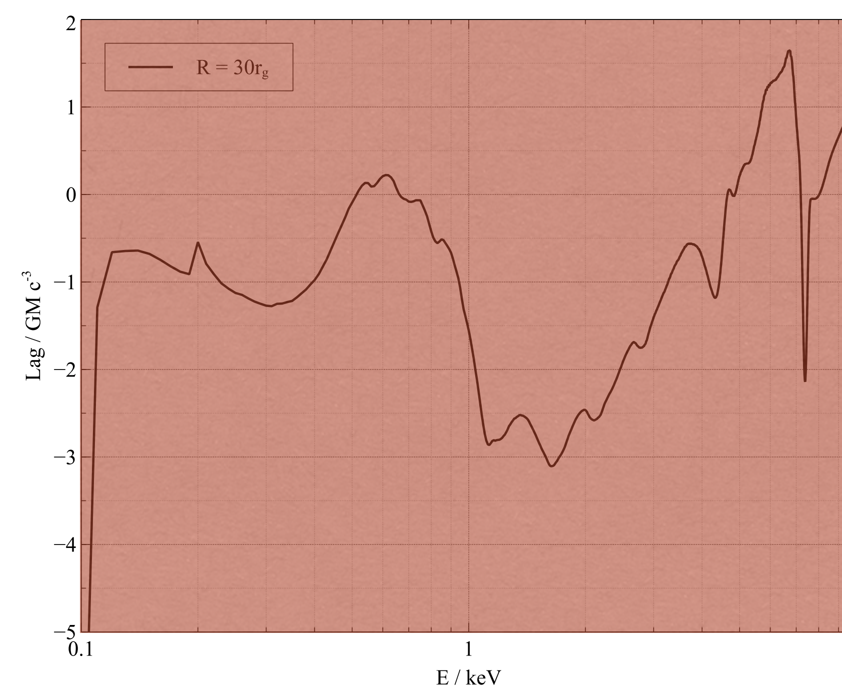

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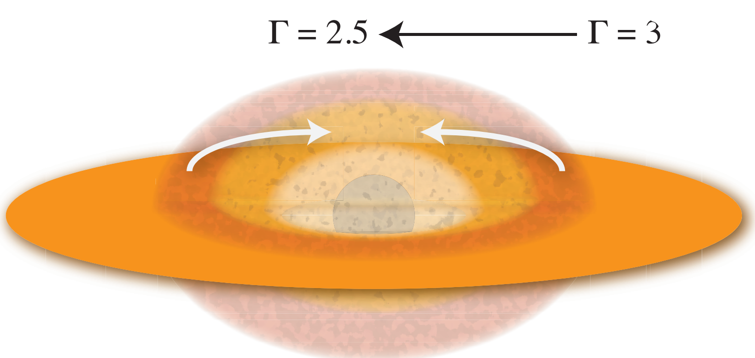
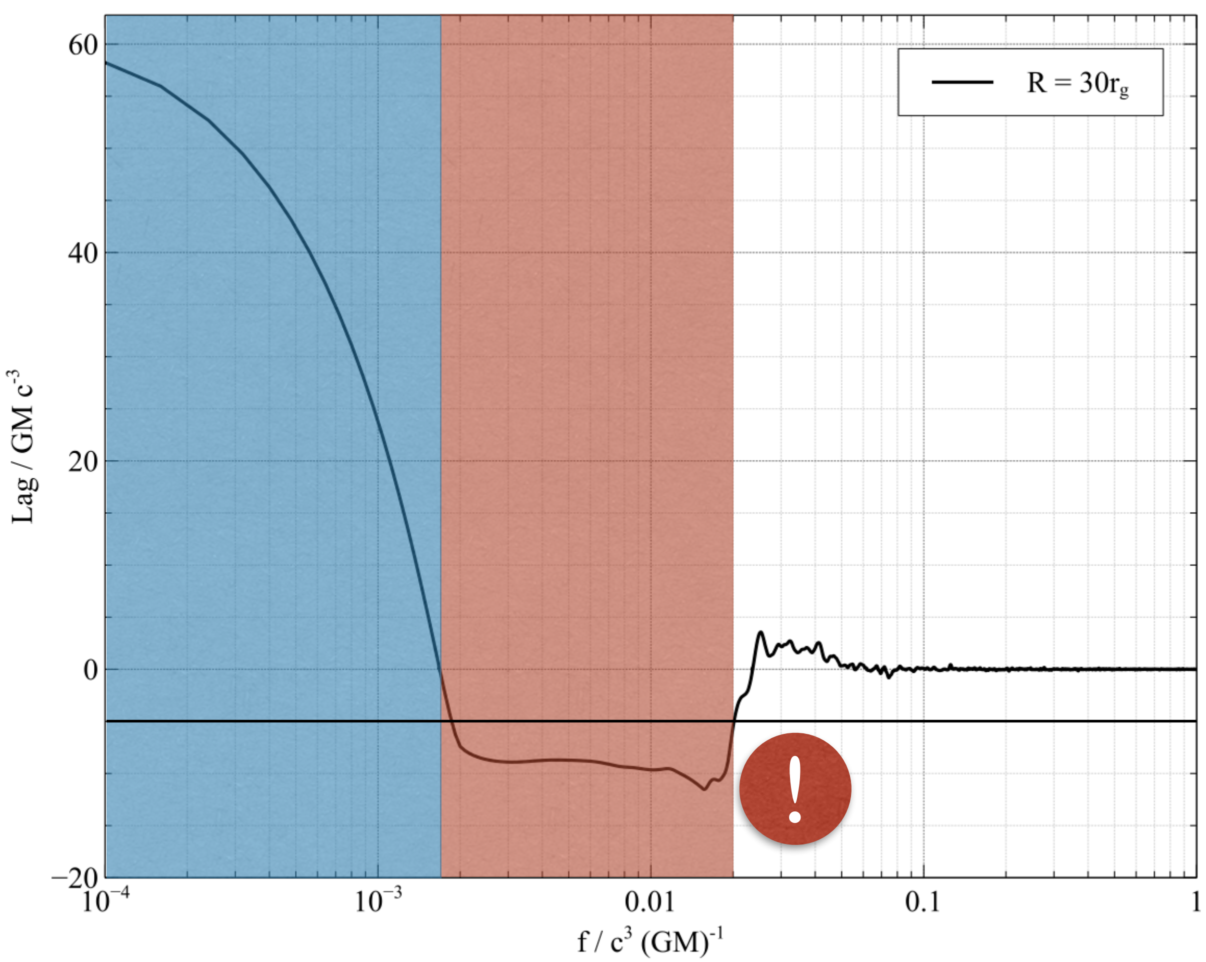
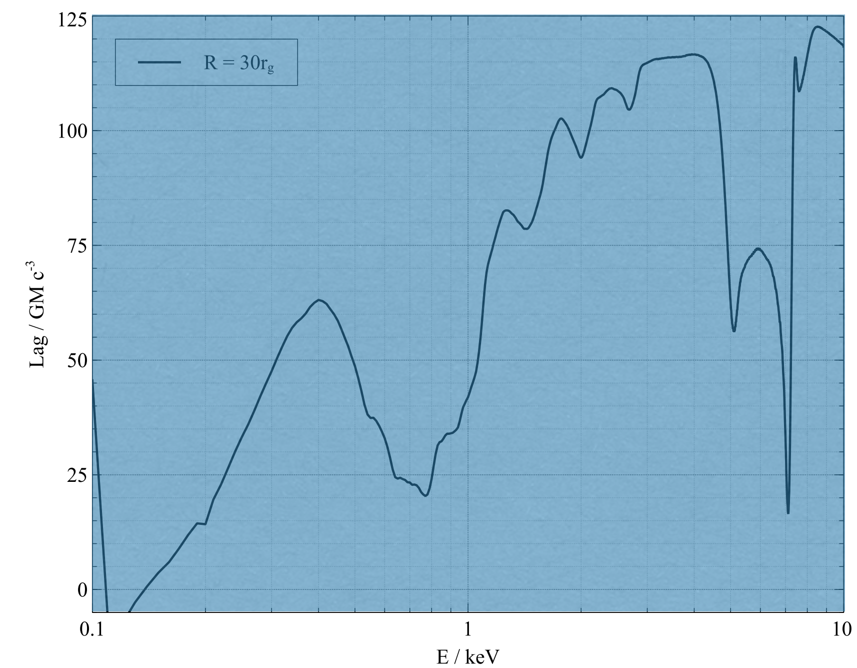
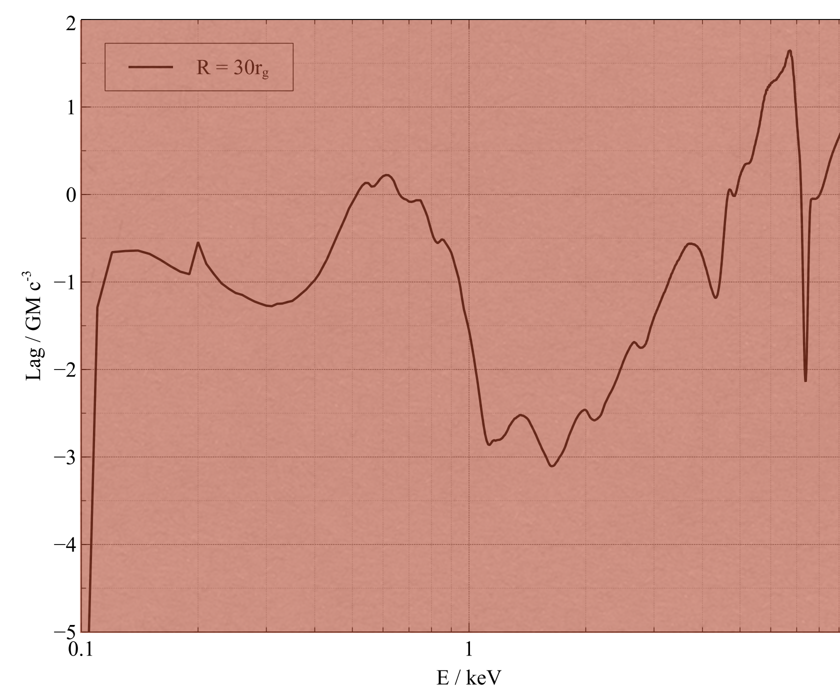
Viscous Propagation



$$\dot{r} = r^{-\frac{1}{2}} \frac{\alpha}{\sqrt{GM}} \left(\frac{h}{r}\right)^2$$

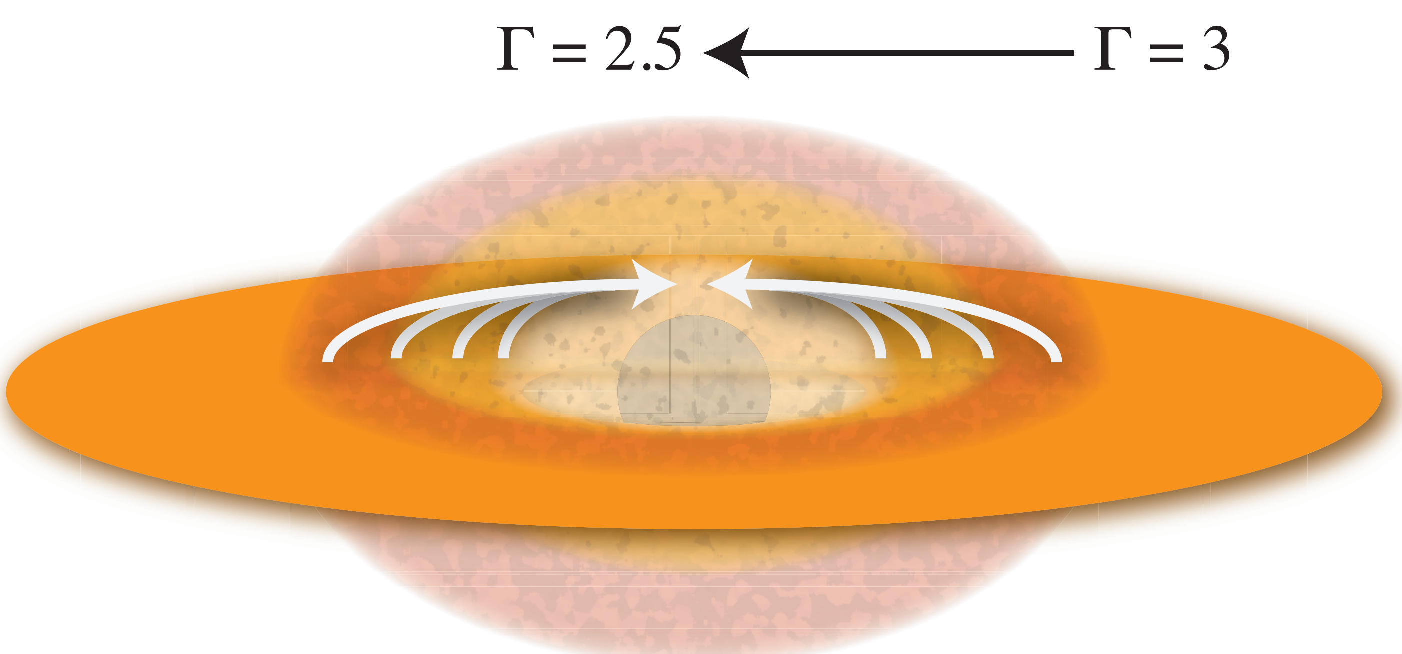






Propagating Fluctuations

e.g. Ingram & Done 2011, Ingram & van der Klis 2013



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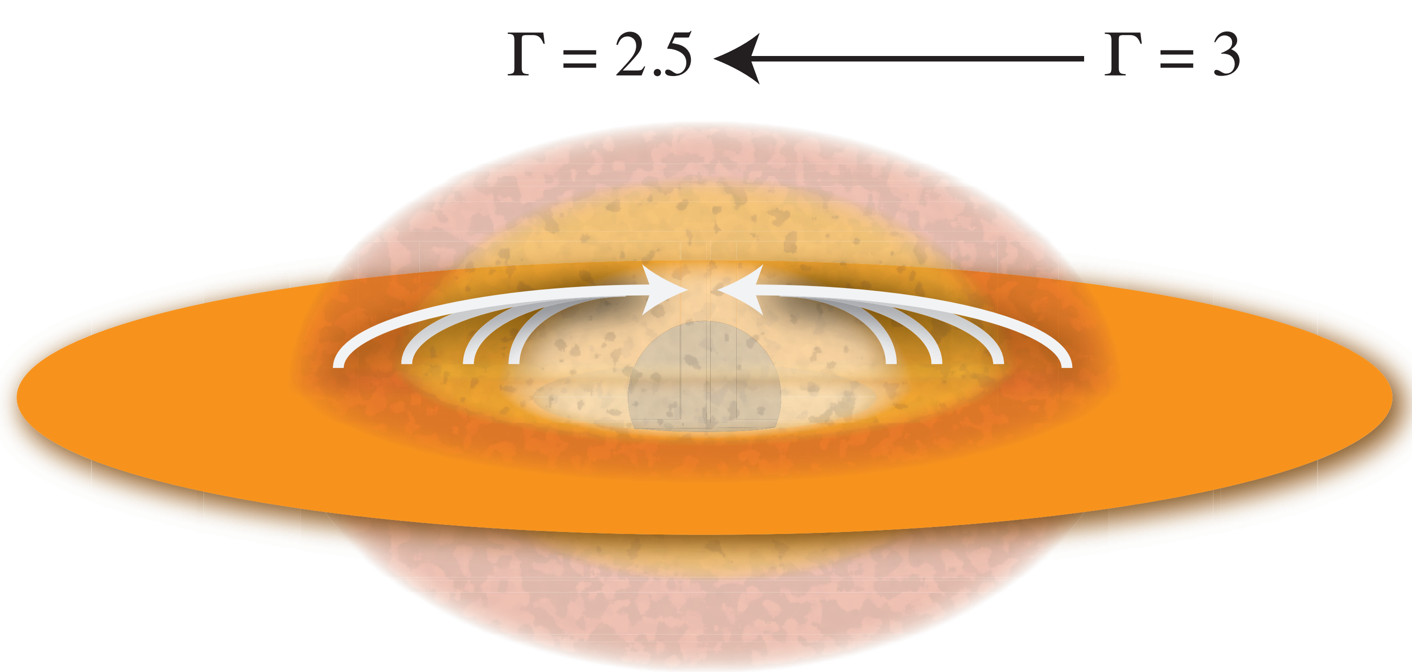

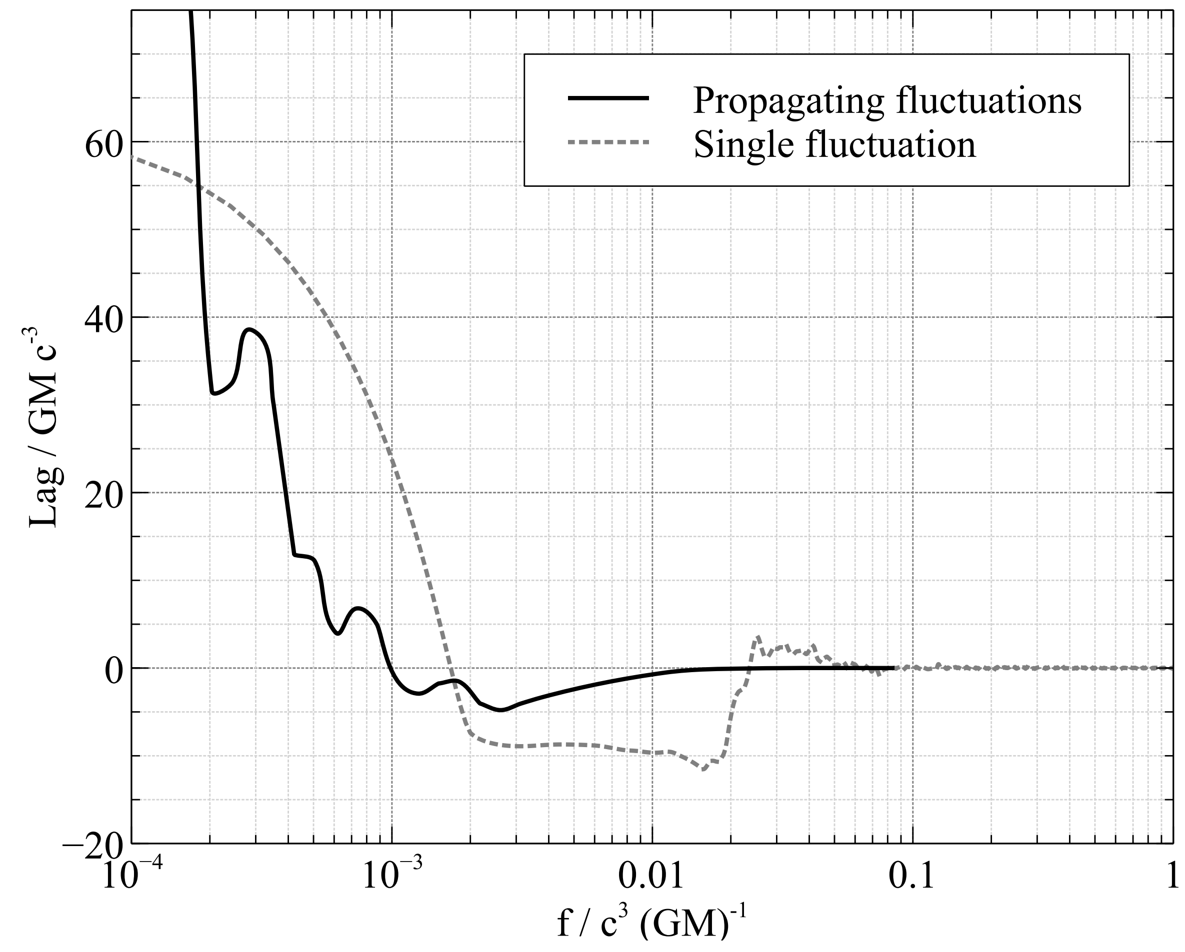

What about vertical propagation?

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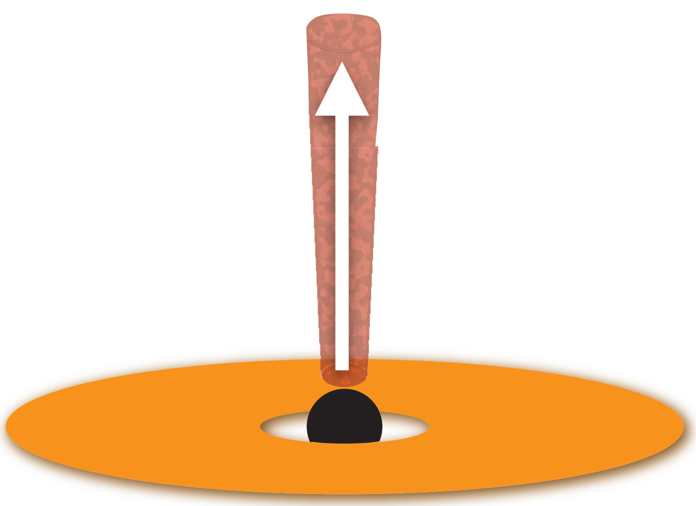
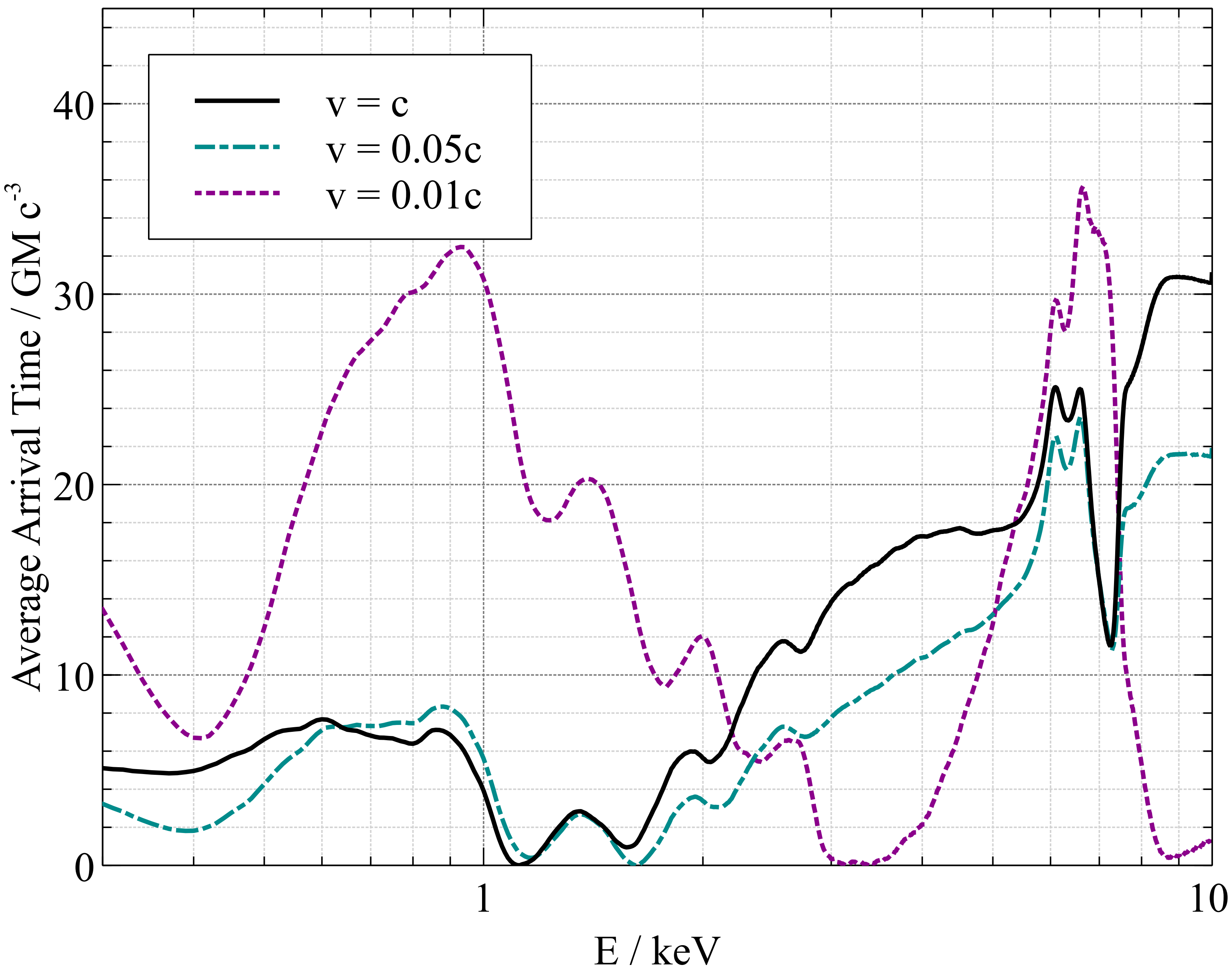
Vertical Propagation





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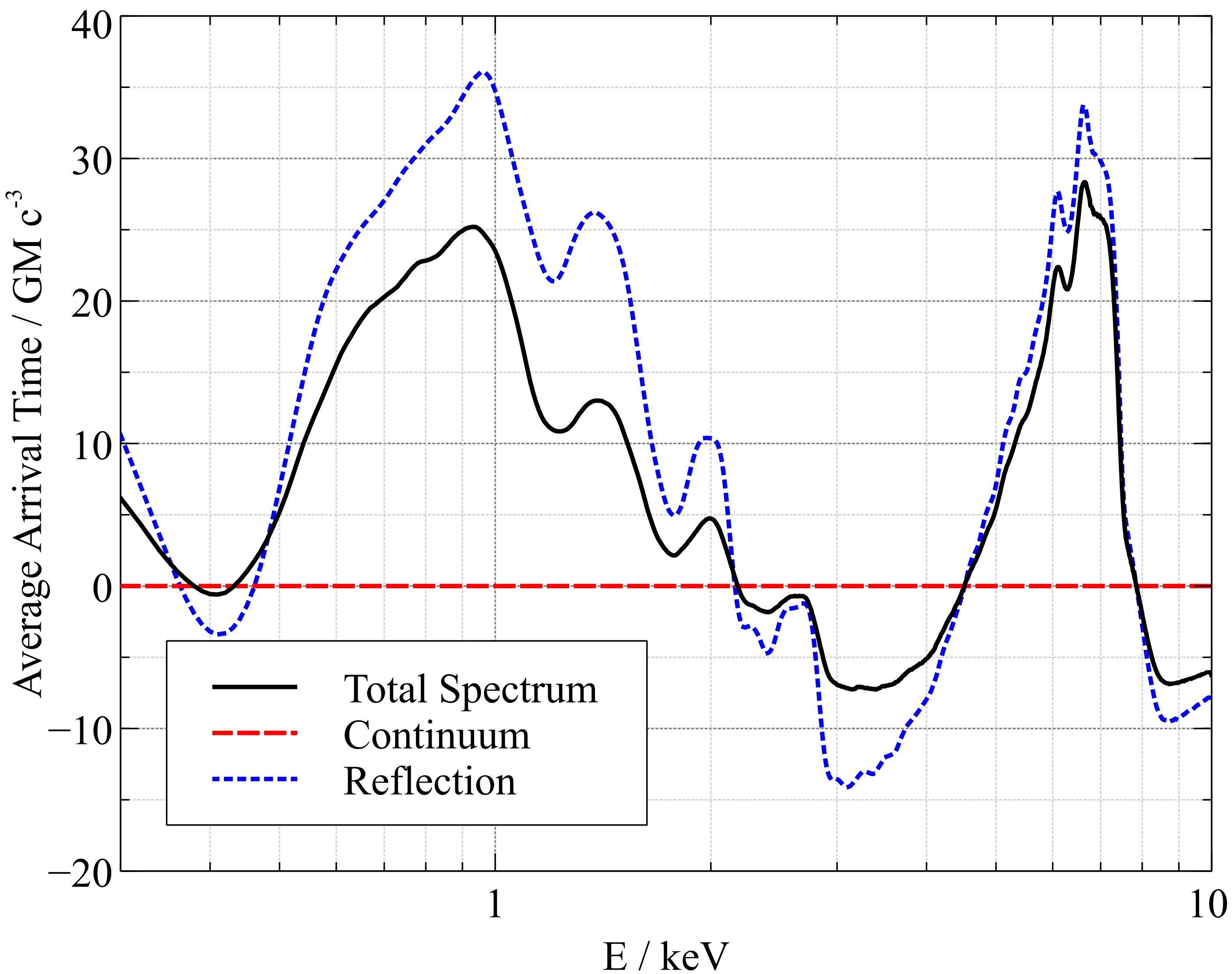
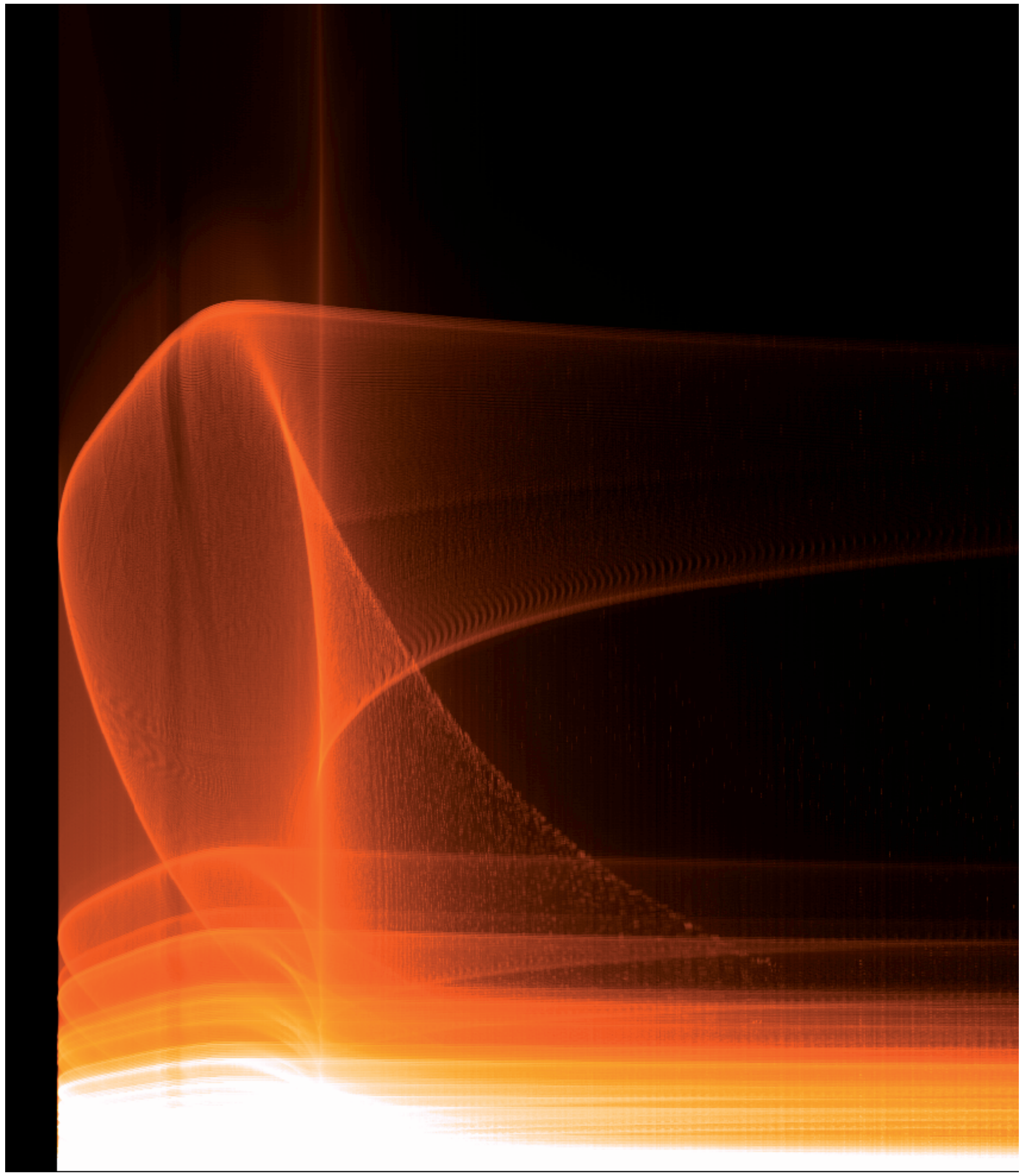
What is the dip at 3keV?





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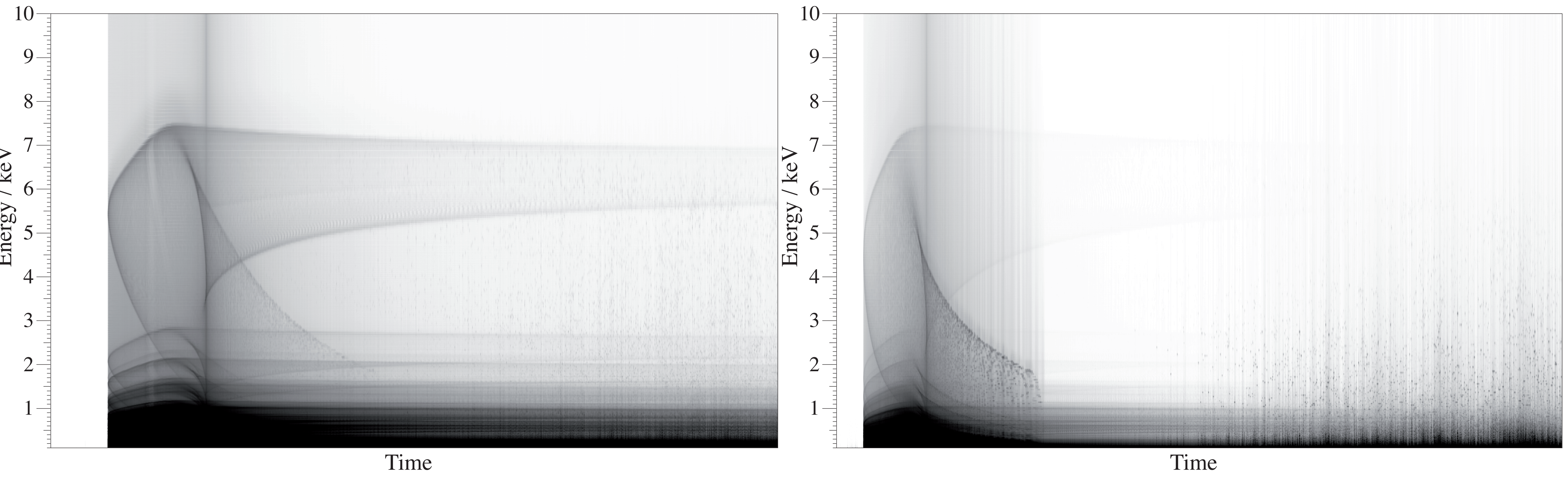
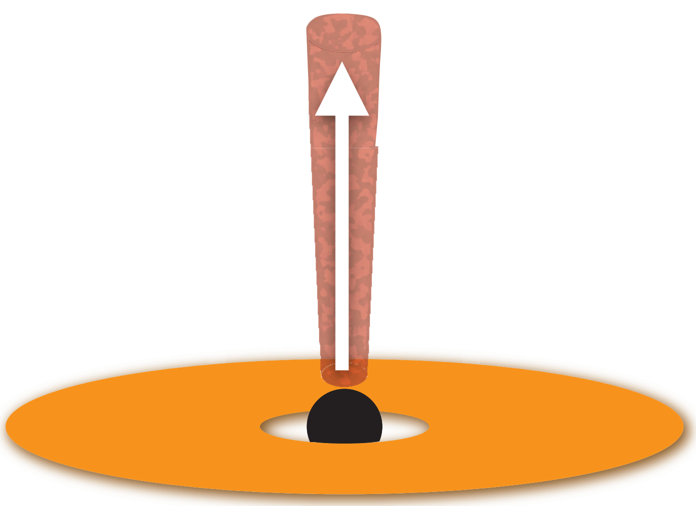
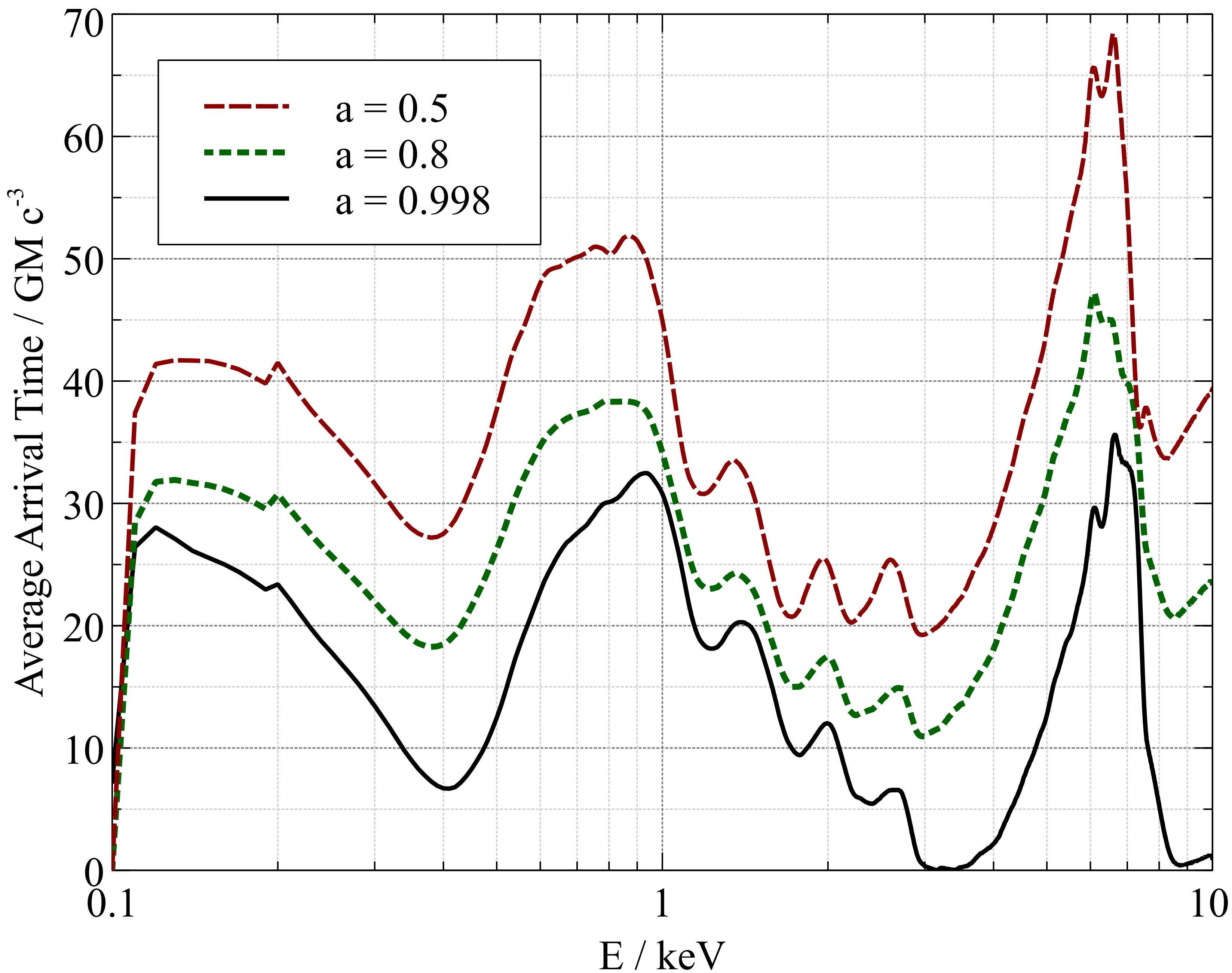
What is the dup at 3keV?

$h = 5r_g$ $h = 1.5r_g$

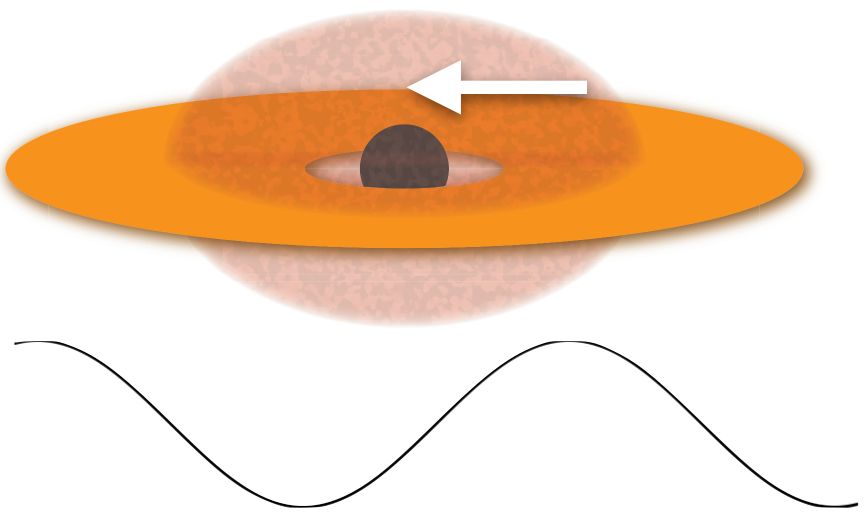


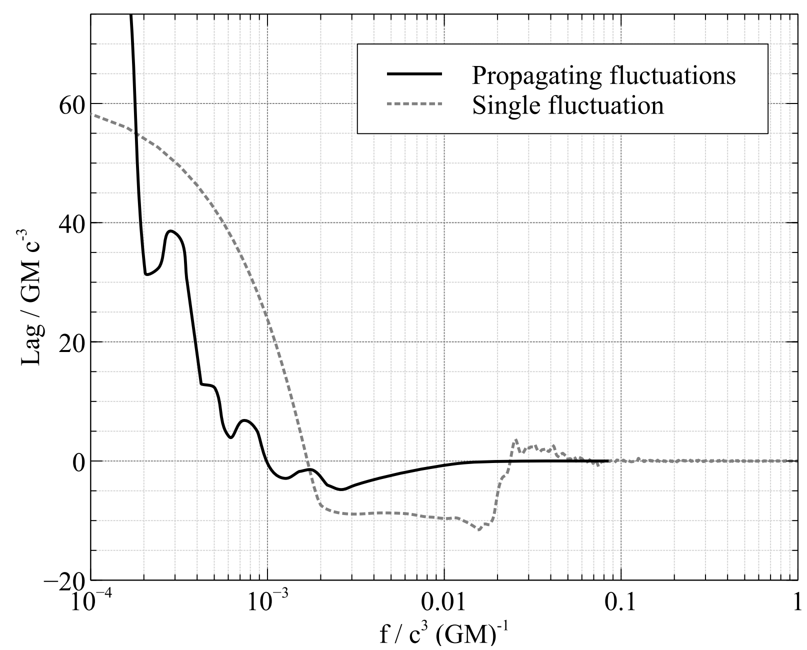
Black Hole Spin

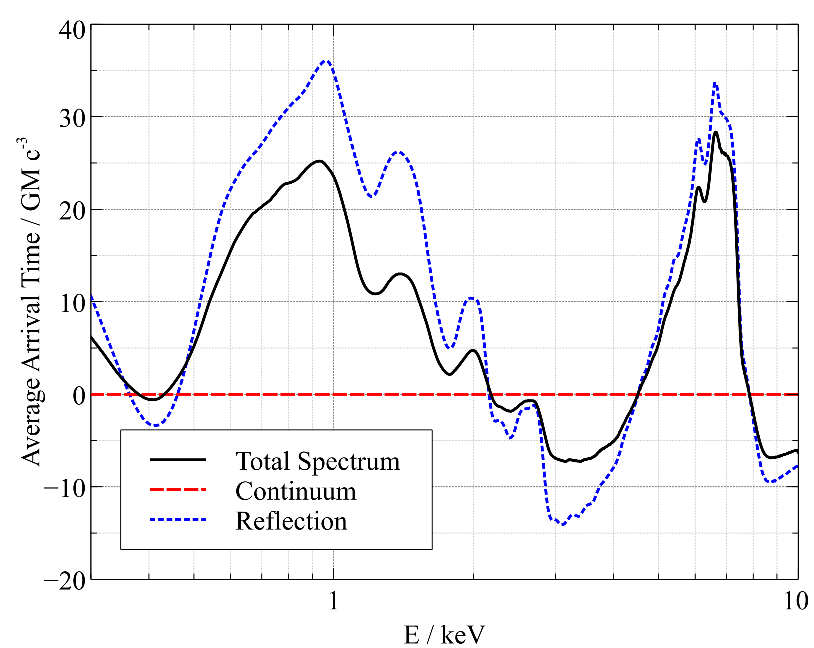


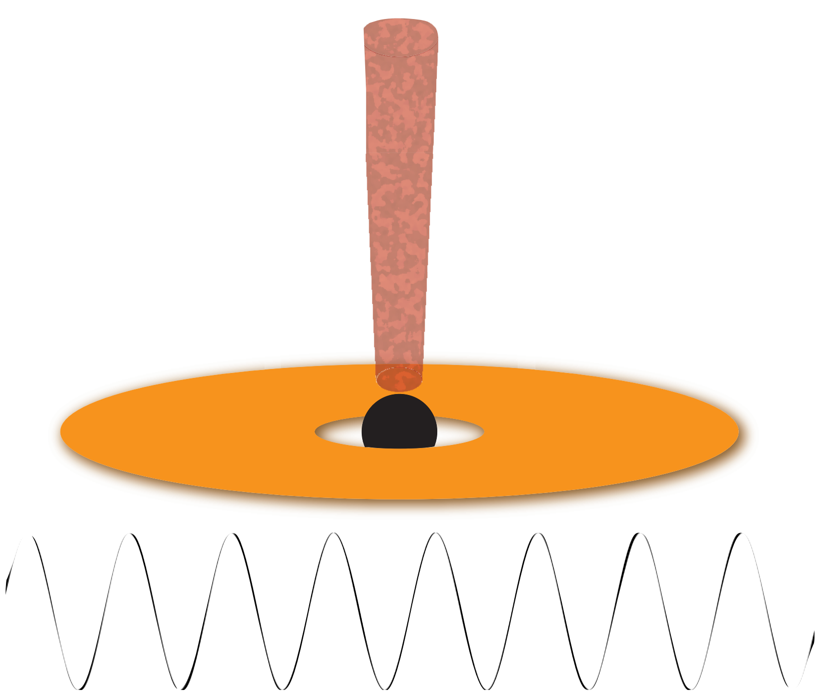


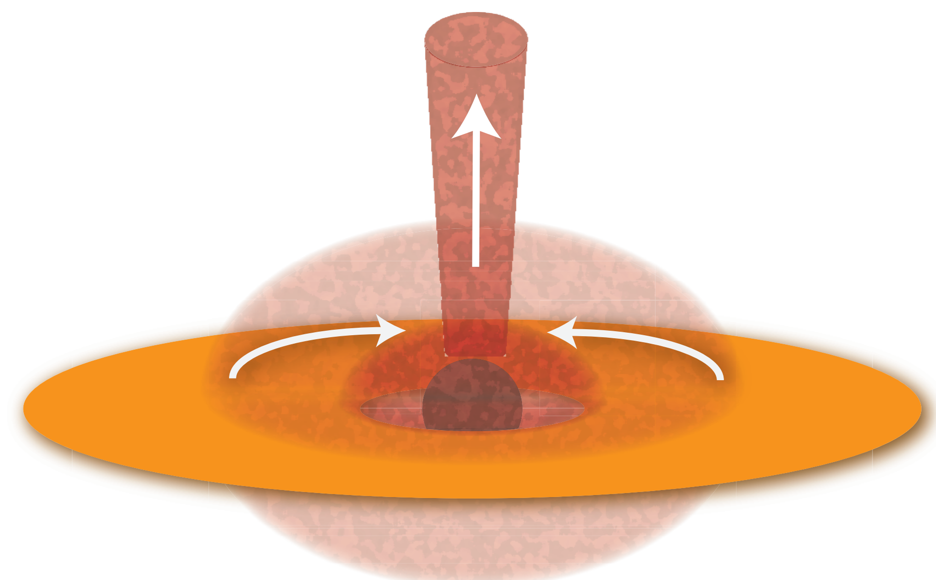
A tale of two coronae?



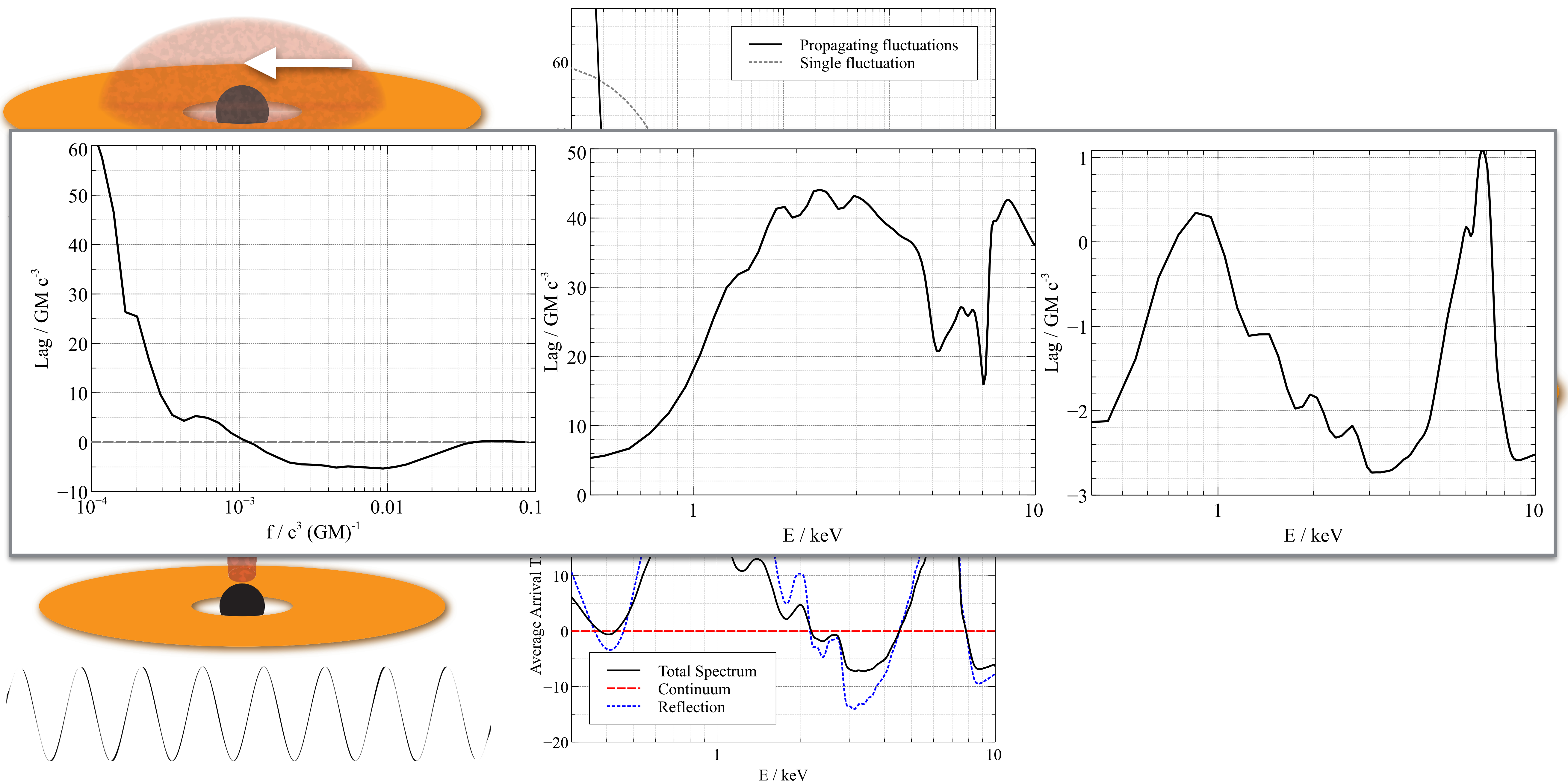








A tale of two coronae?



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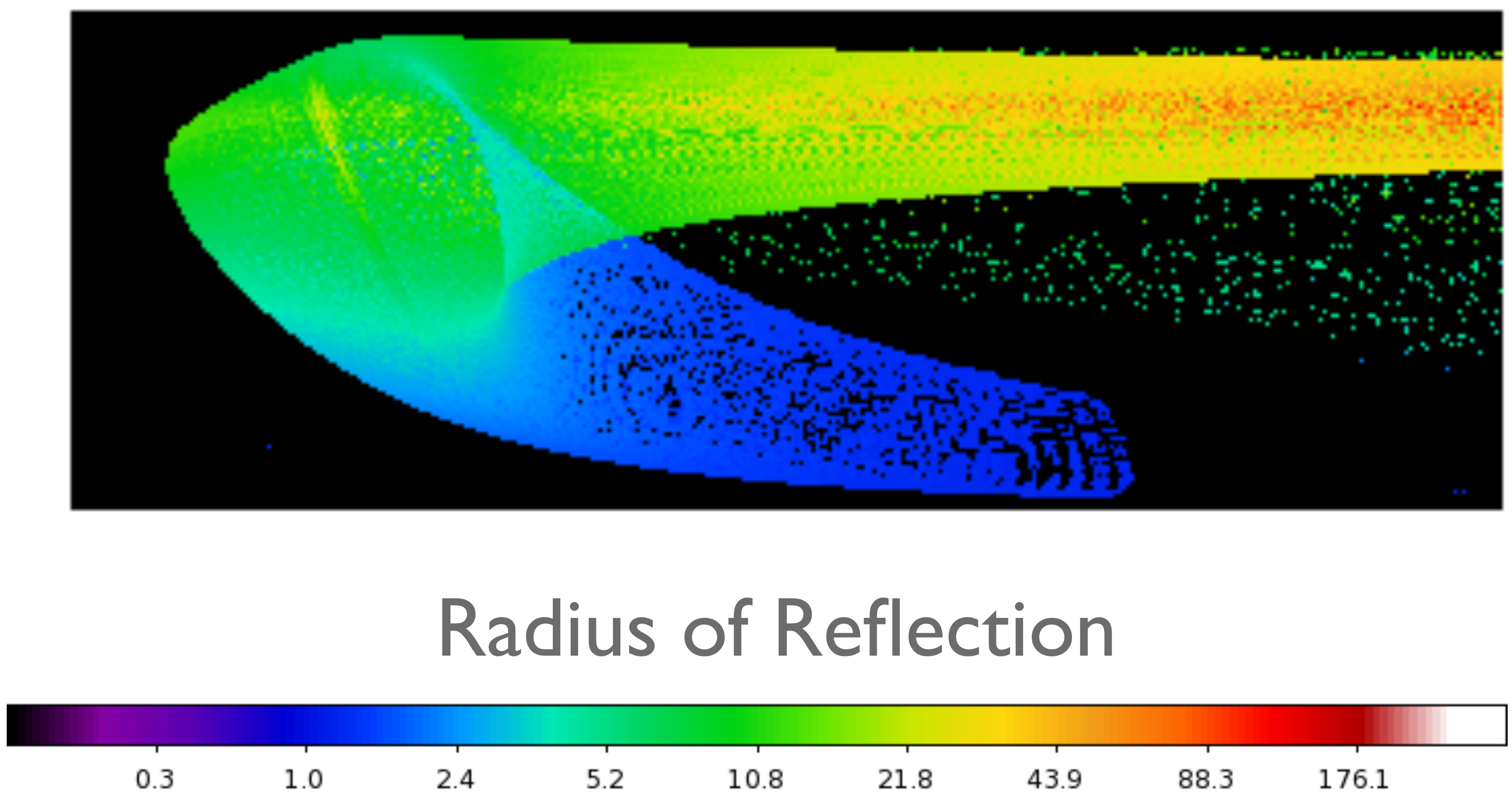
Looking Ahead

- Model fitting - robust parameter estimates
- Data quality required
- Best fitting strategy
  - Fit lag/frequency, lag/energy or cross-spectrum
  - Use all the spectral & timing information!
- Degeneracies

Resolving the Disc



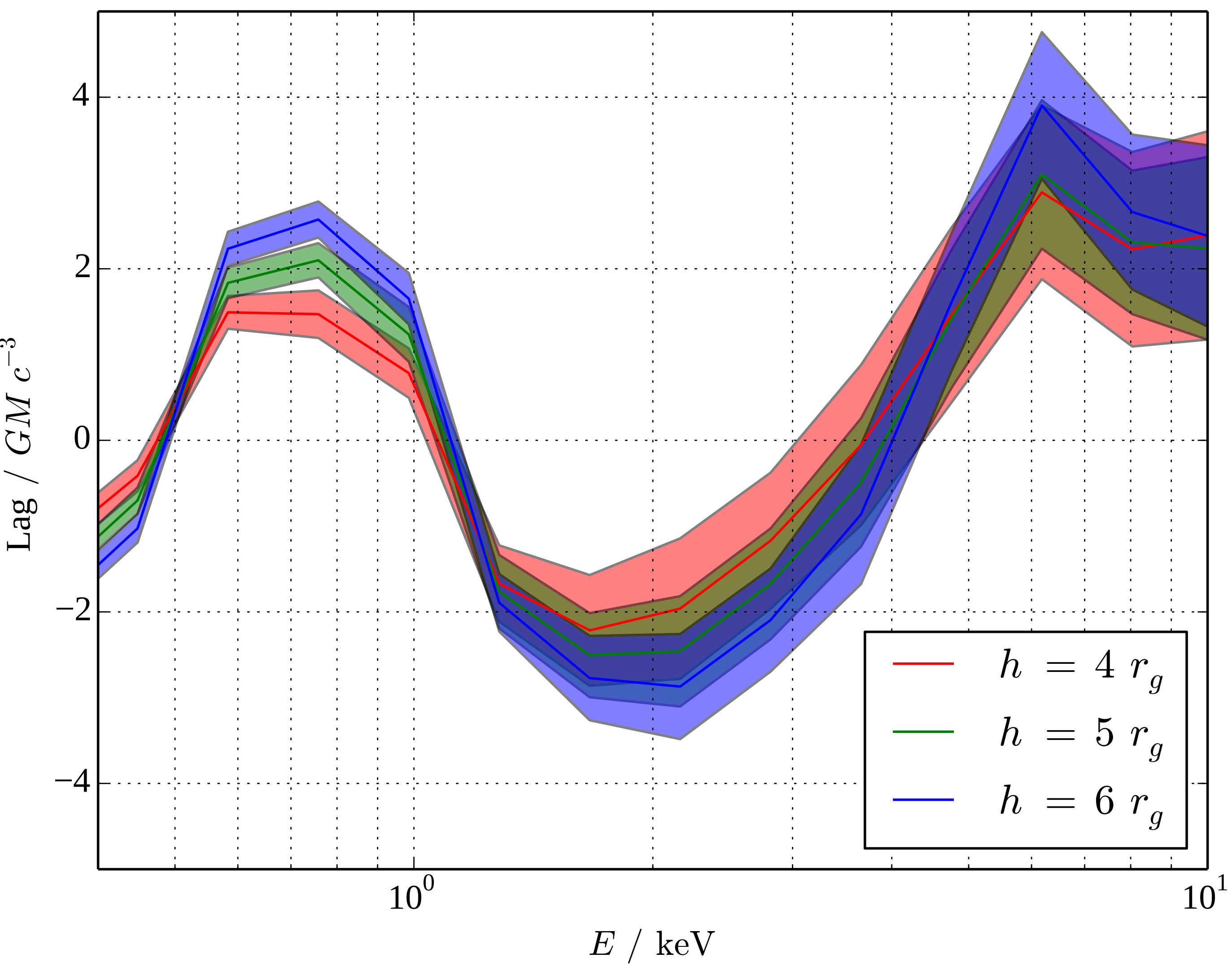
E-mail: drw@ap.smu.ca
arXiv: 1602.00022

Conclusions

- General relativistic ray tracing enables modelling of X-ray reverberation
- X-ray reverberation gives us a complimentary probe of the corona and geometry of the inner regions
- Point source models struggle to reconciling reverberation with hard lags and explain features of lag/energy spectrum
- Can already constrain broad features of the corona. Hints of more complex structures within the corona, giving clues to the physics powering the X-ray source

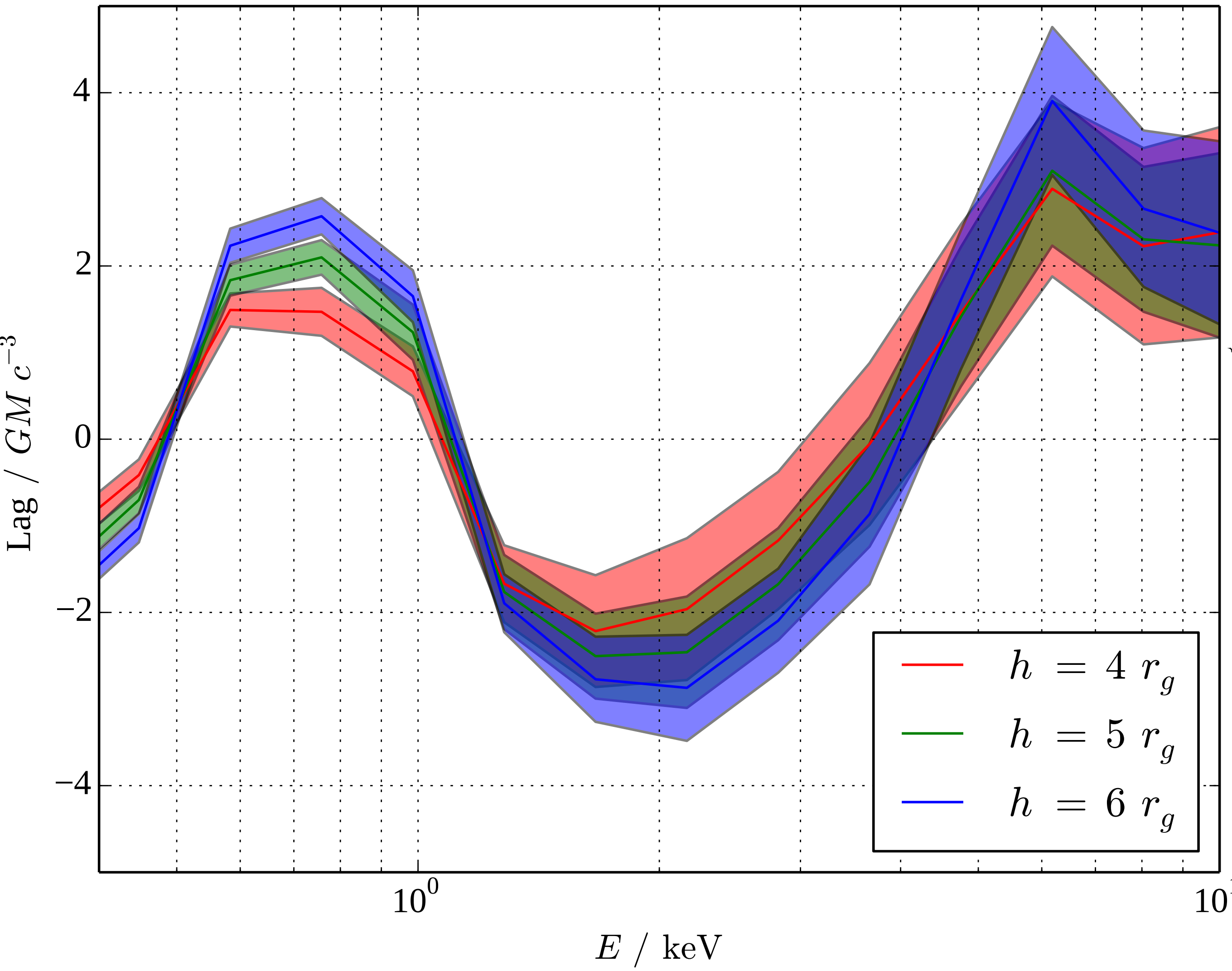
Data Quality and Model Fitting

XMM 1Ms



Data Quality and Model Fitting

XMM 1Ms



Athena 1Ms