UNIVERSITY OF CAMBRIDGE

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Probing Black Holes with X-ray Reverberation – New observational tools?

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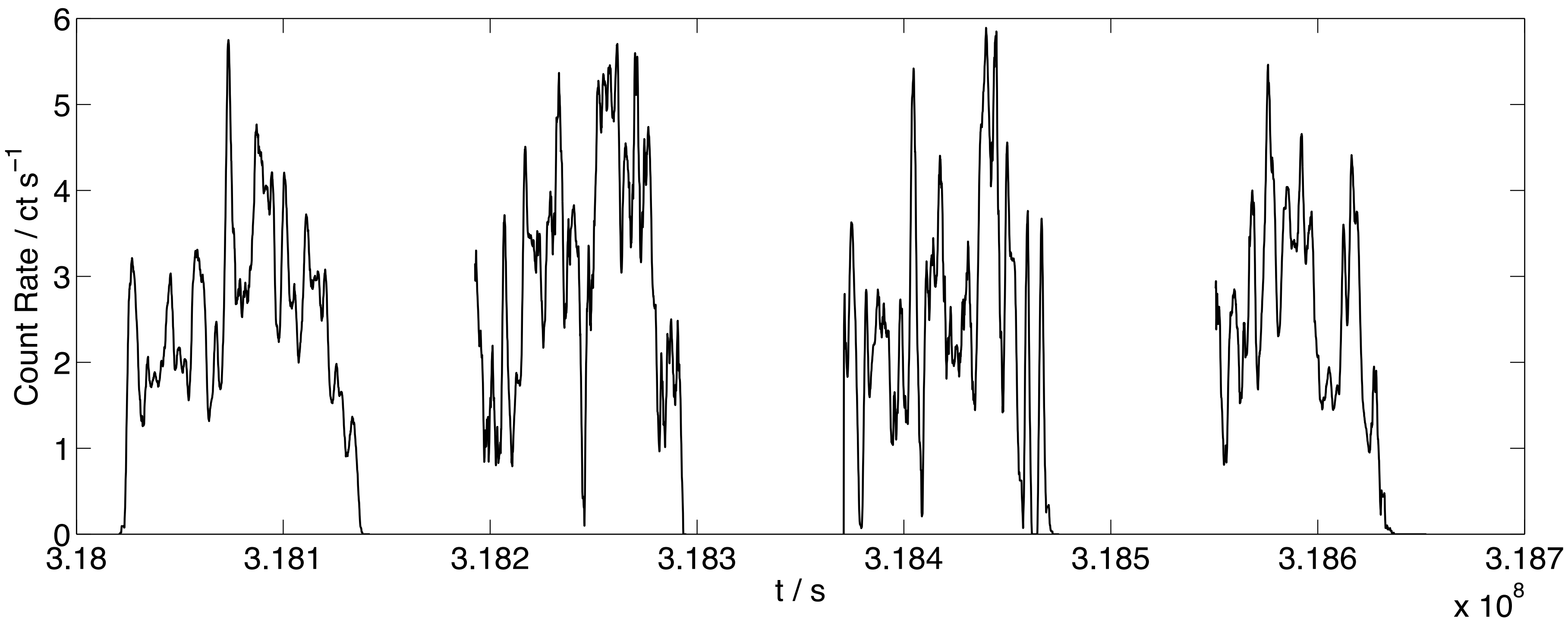
with Andy Fabian, Erin Kara, Phil Uttley, Ed Cackett

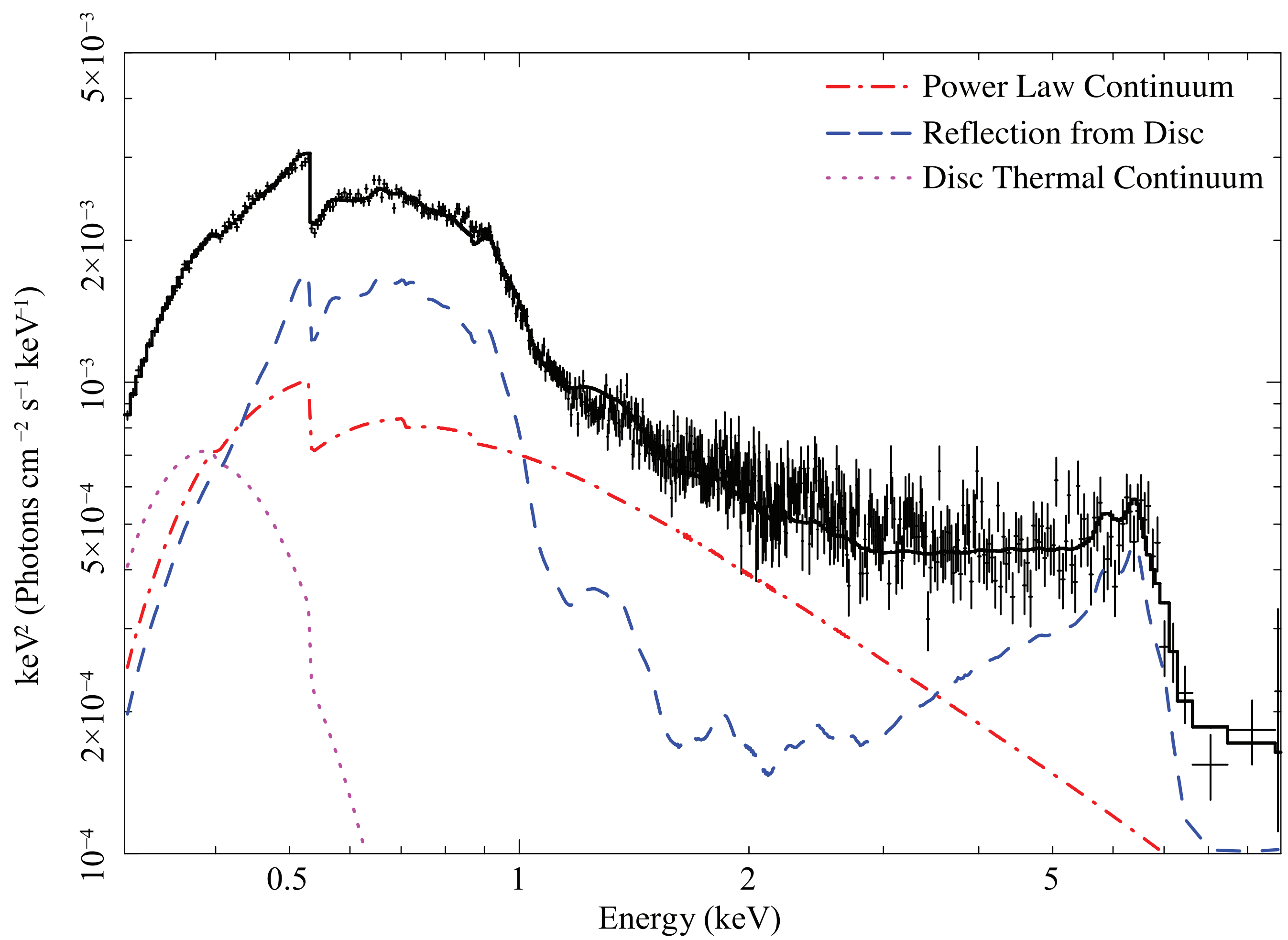
LOFT UK Science Meeting – RAS, June 2013

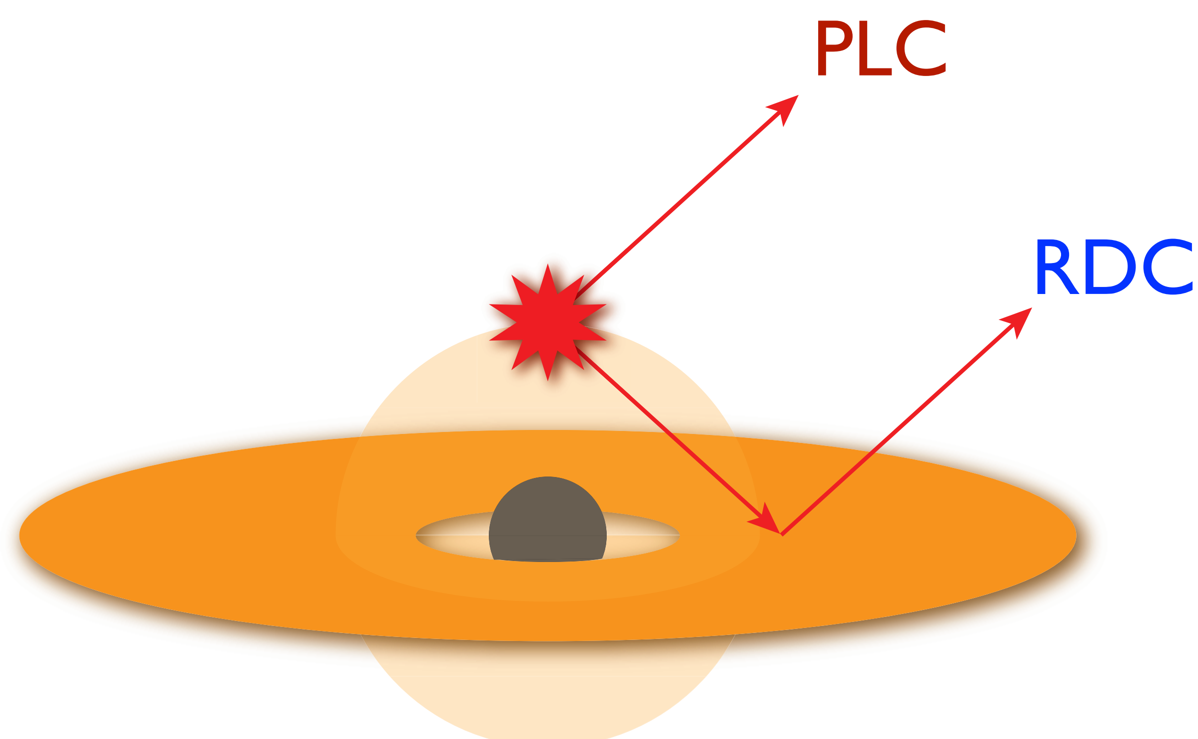
Cambridge X-Ray Astronomy

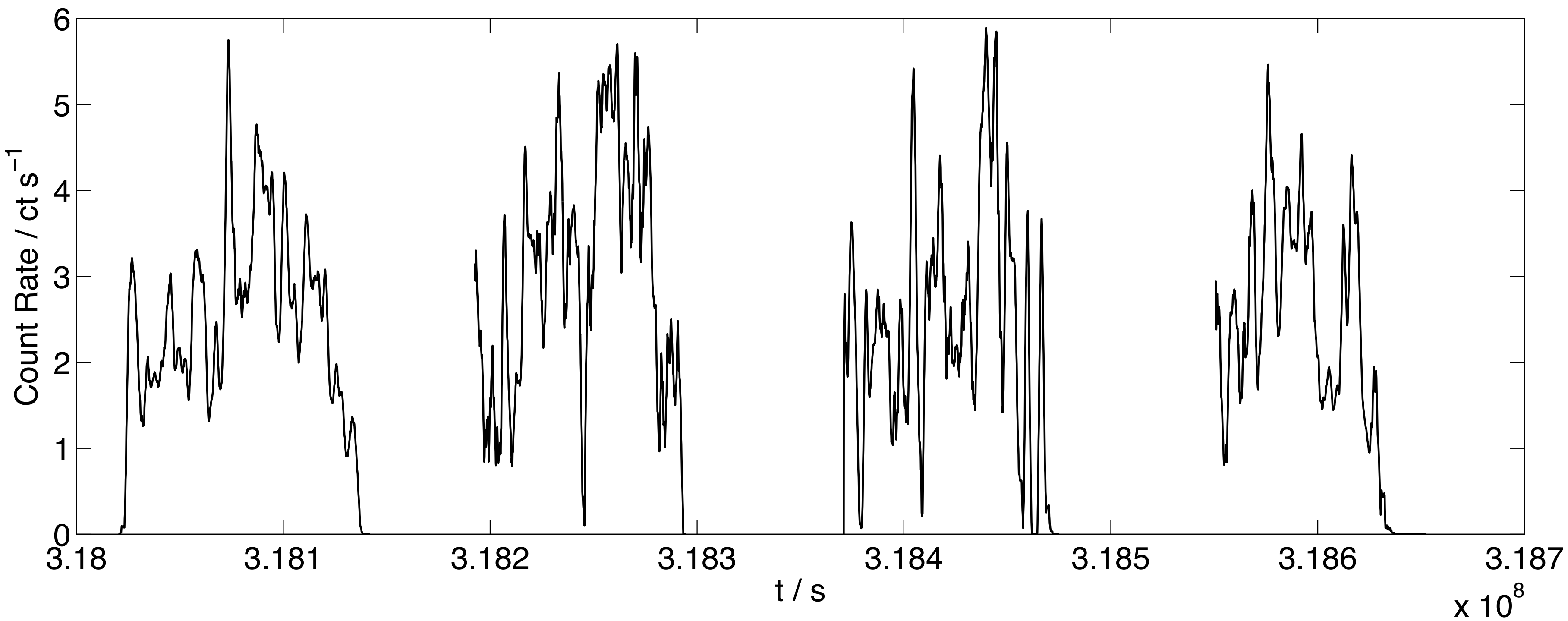
Outline

1. Current results from (separate) energy and timing analysis
2. Energy dependence of lags
3. Predicting lag/energy spectra
4. Simultaneous lag/energy fitting as an observational tool


Count Rate / ct s^{-1}
0
1
2
3
4
5
6
3.18
3.181
3.182
3.183
3.184
3.185
3.186
3.187
t / s
x 10^{8}


Power Law Continuum
Reflection from Disc
Disc Thermal Continuum
keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
10^{-4}
2×10^{-4}
5×10^{-4}
10^{-3}
2×10^{-3}
5×10^{-3}
0.5
1
2
5
Energy (keV)


PLC
RDC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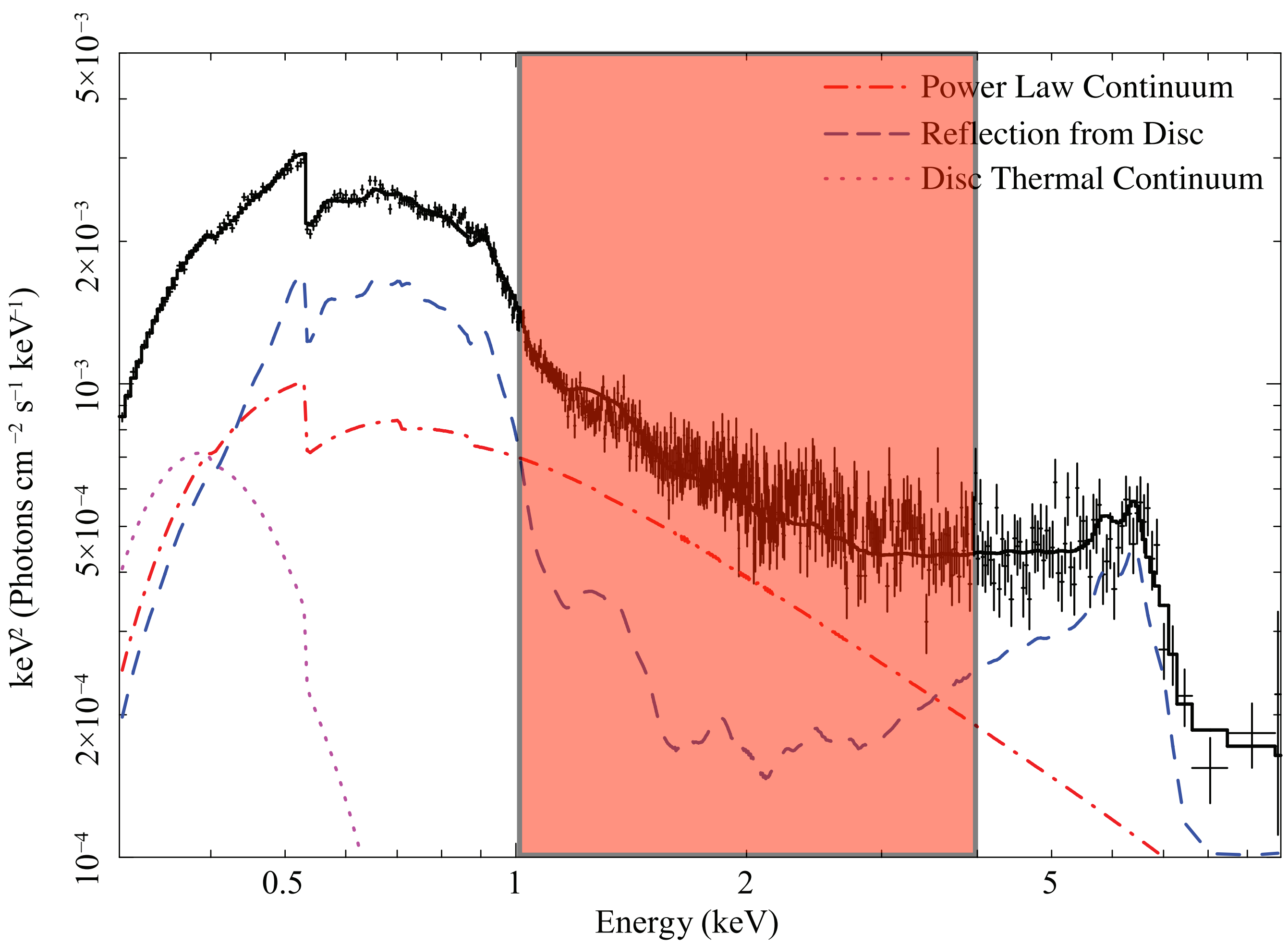
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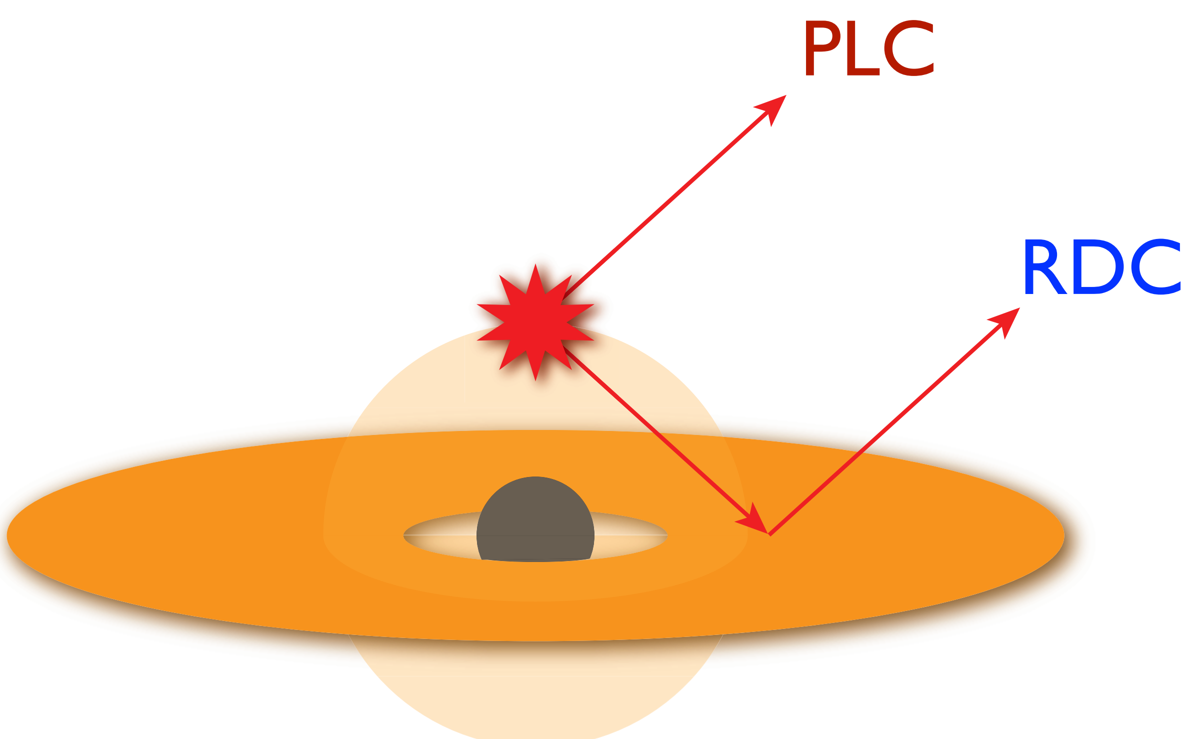
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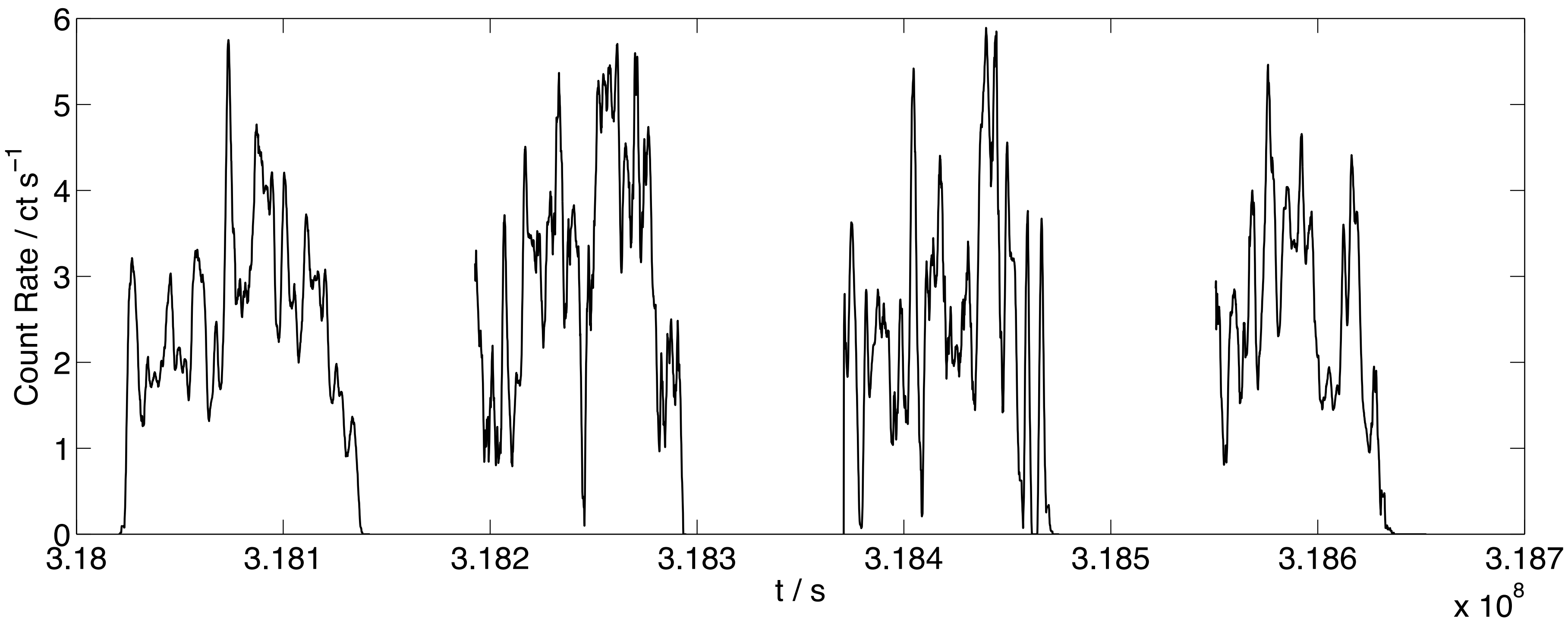
RDC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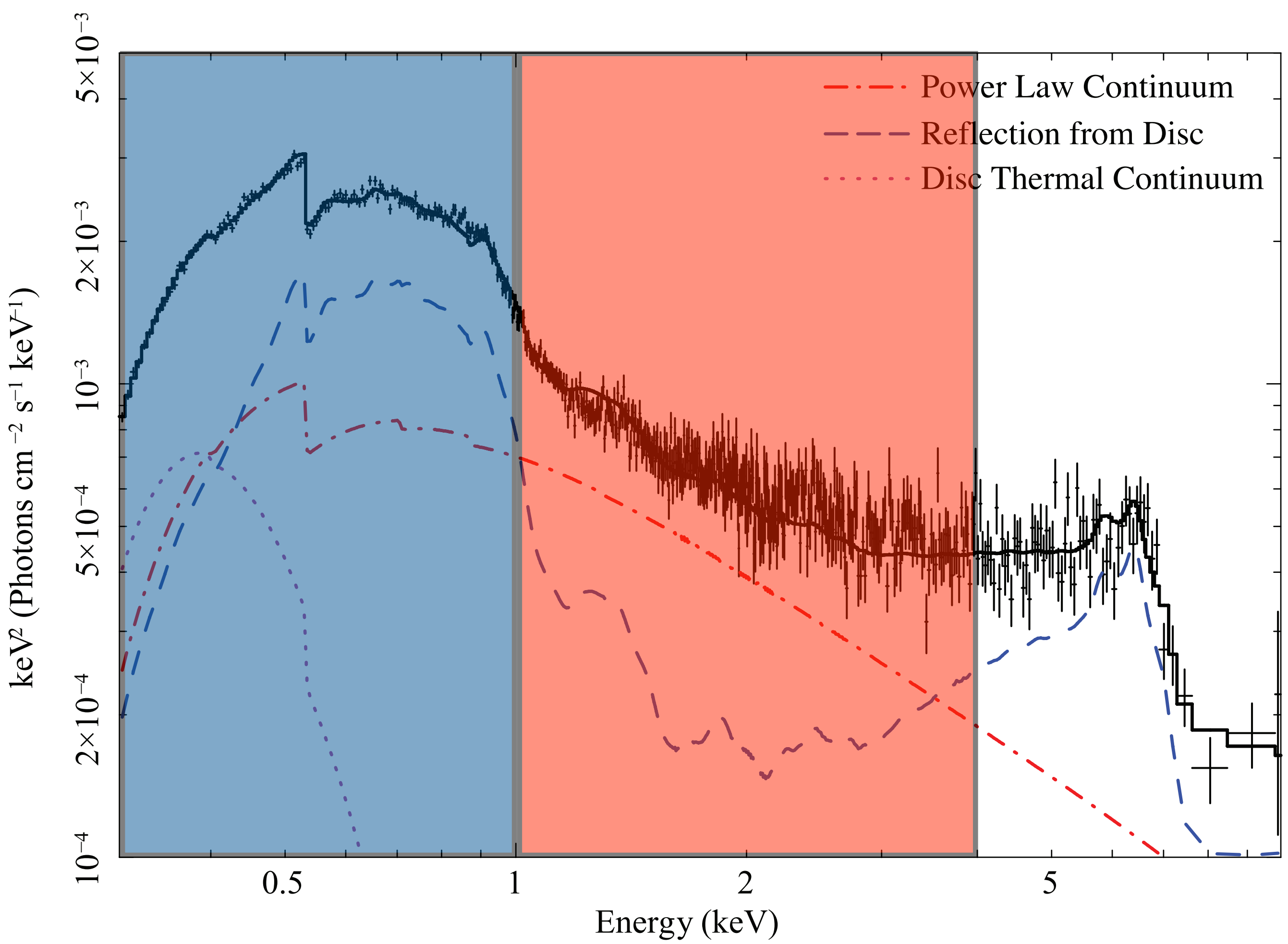
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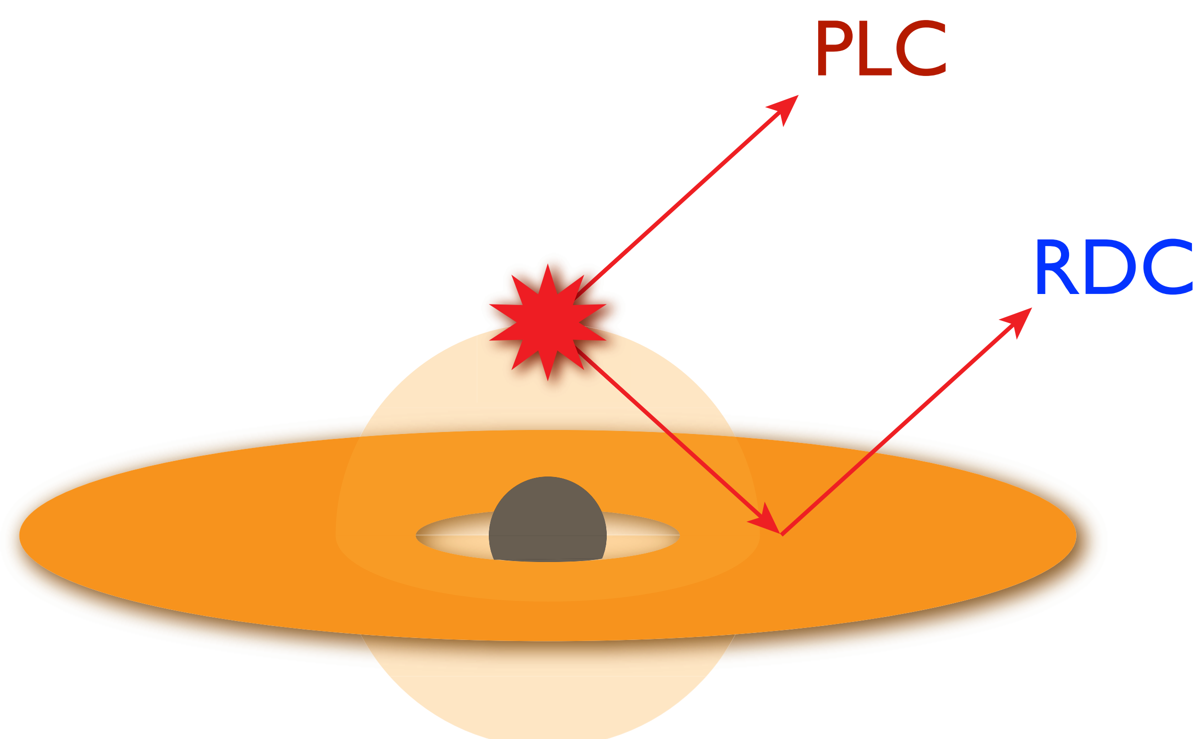
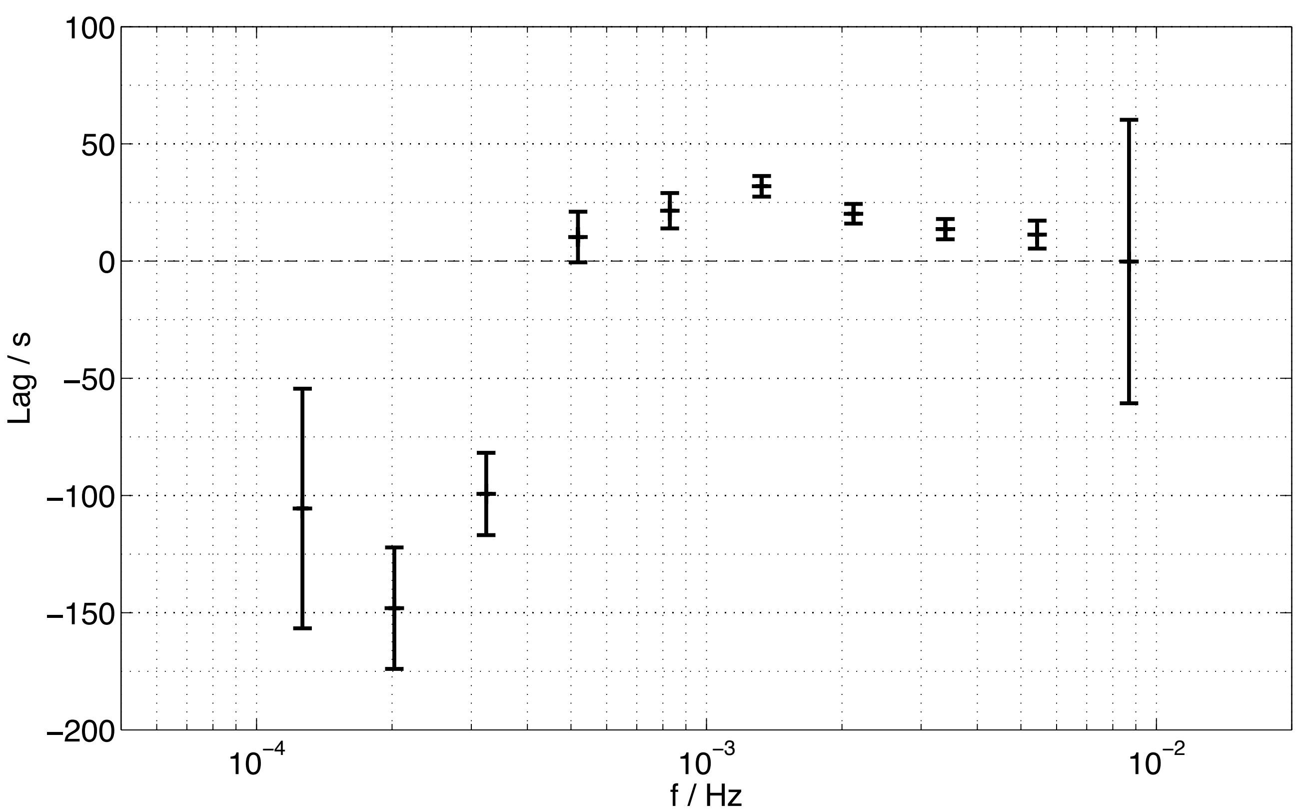
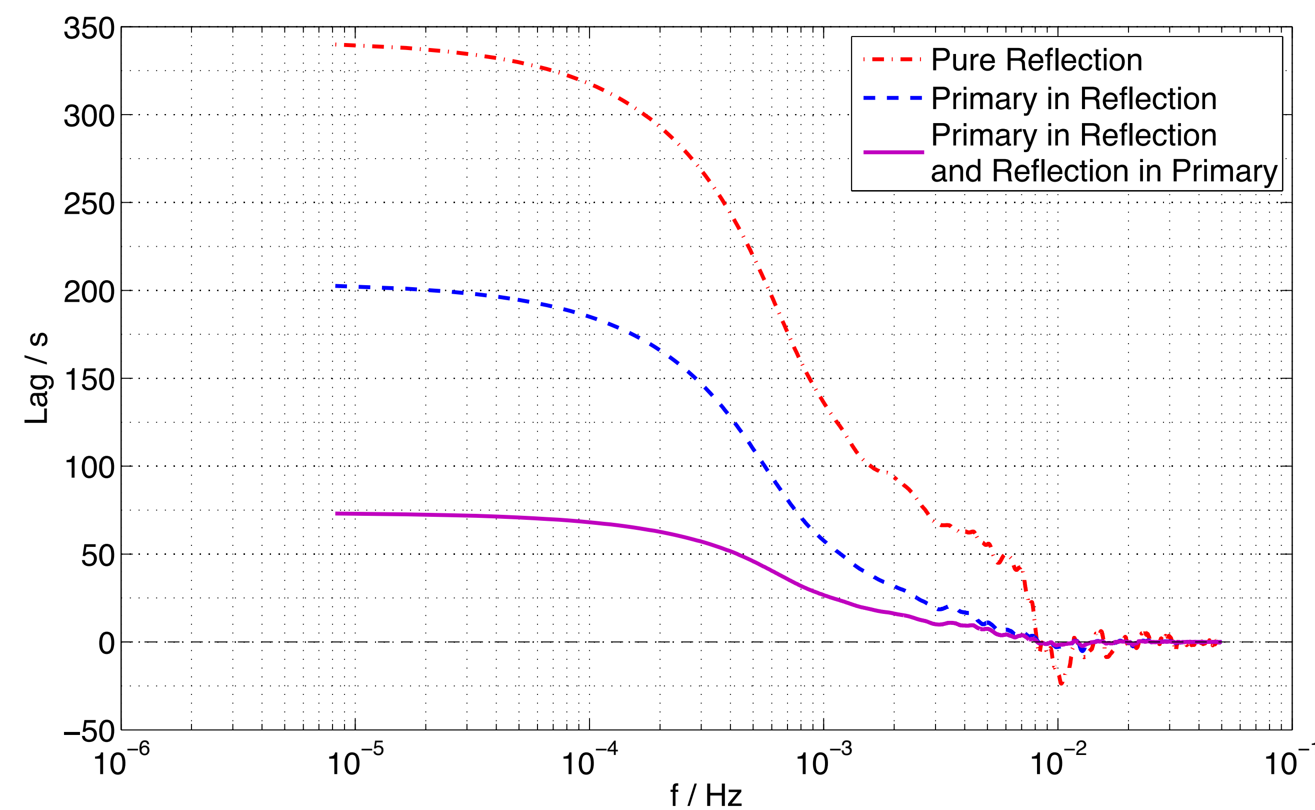

PLC
RDC

We found reverberation lags...

Fabian+2009, Zoghbi+2010, Kara+2012, Wilkins & Fabian 2013





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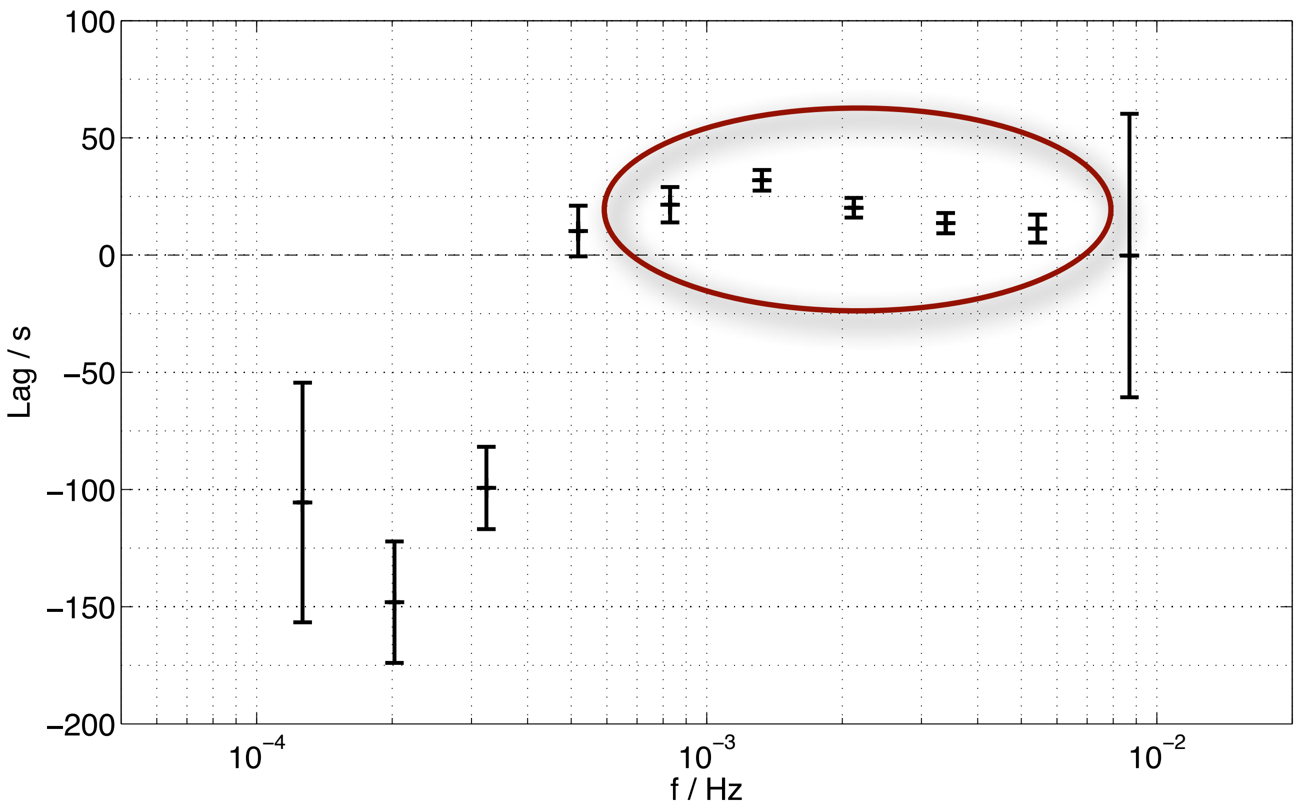

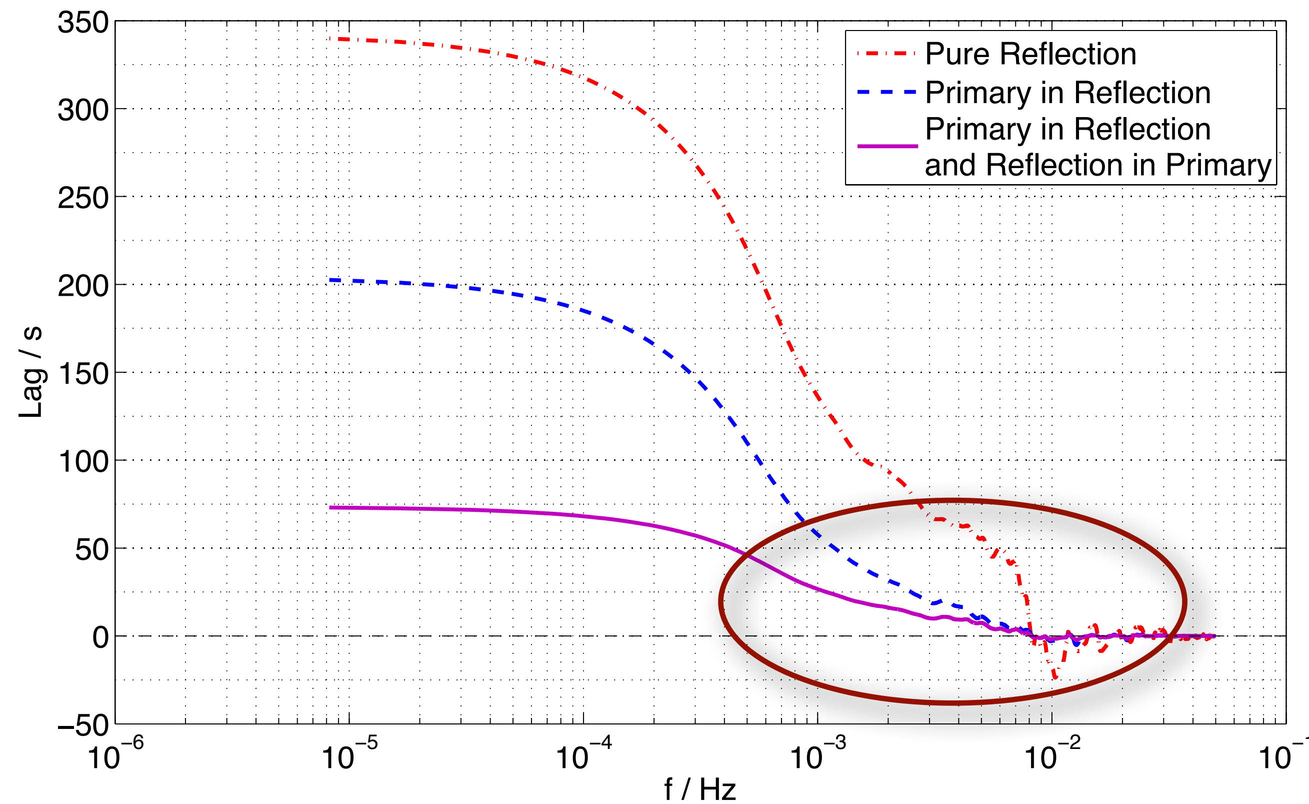

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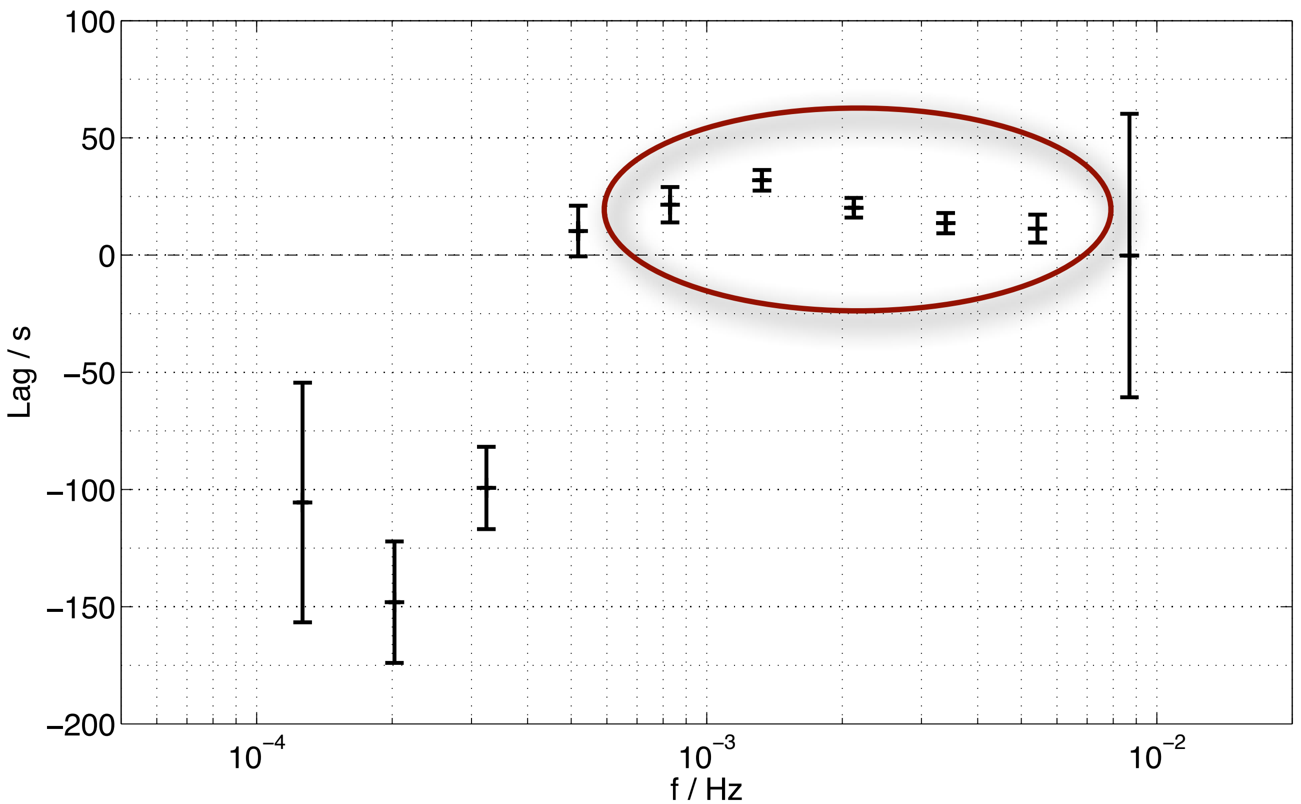
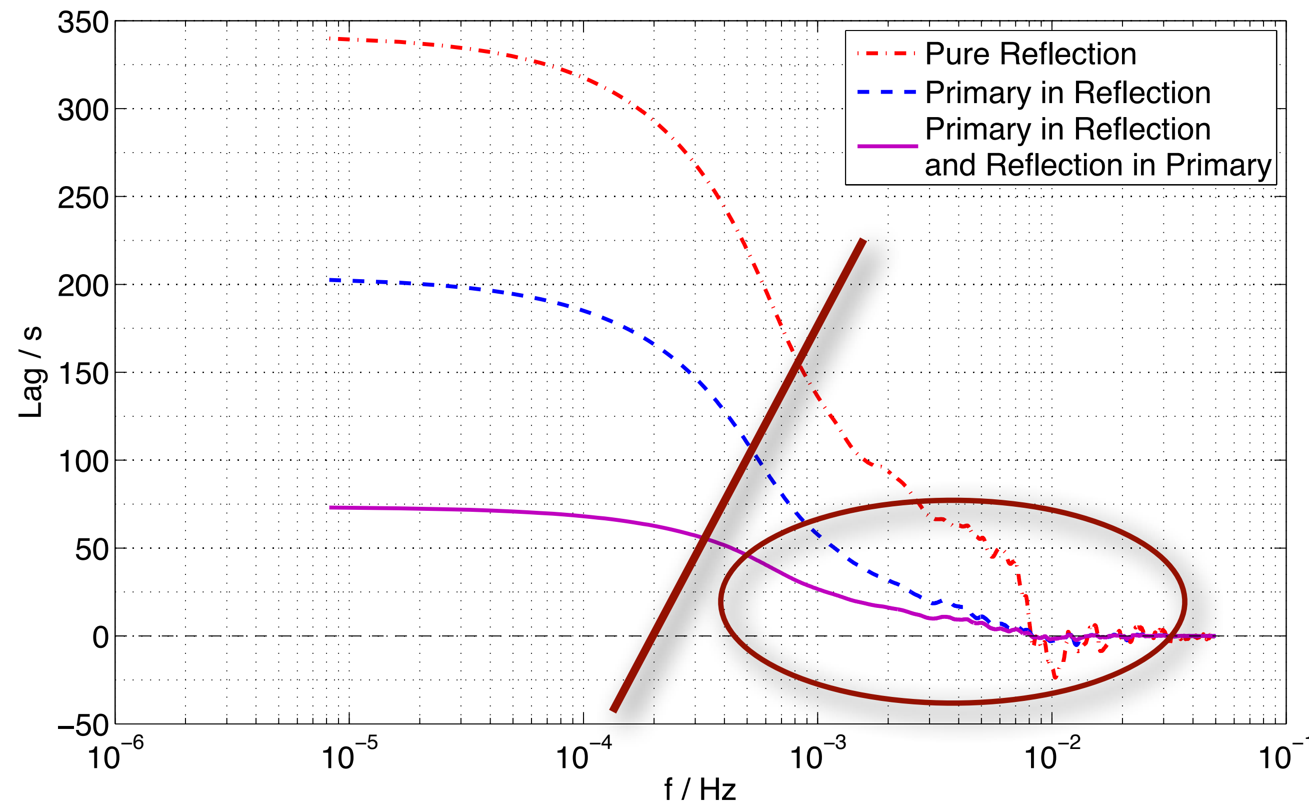
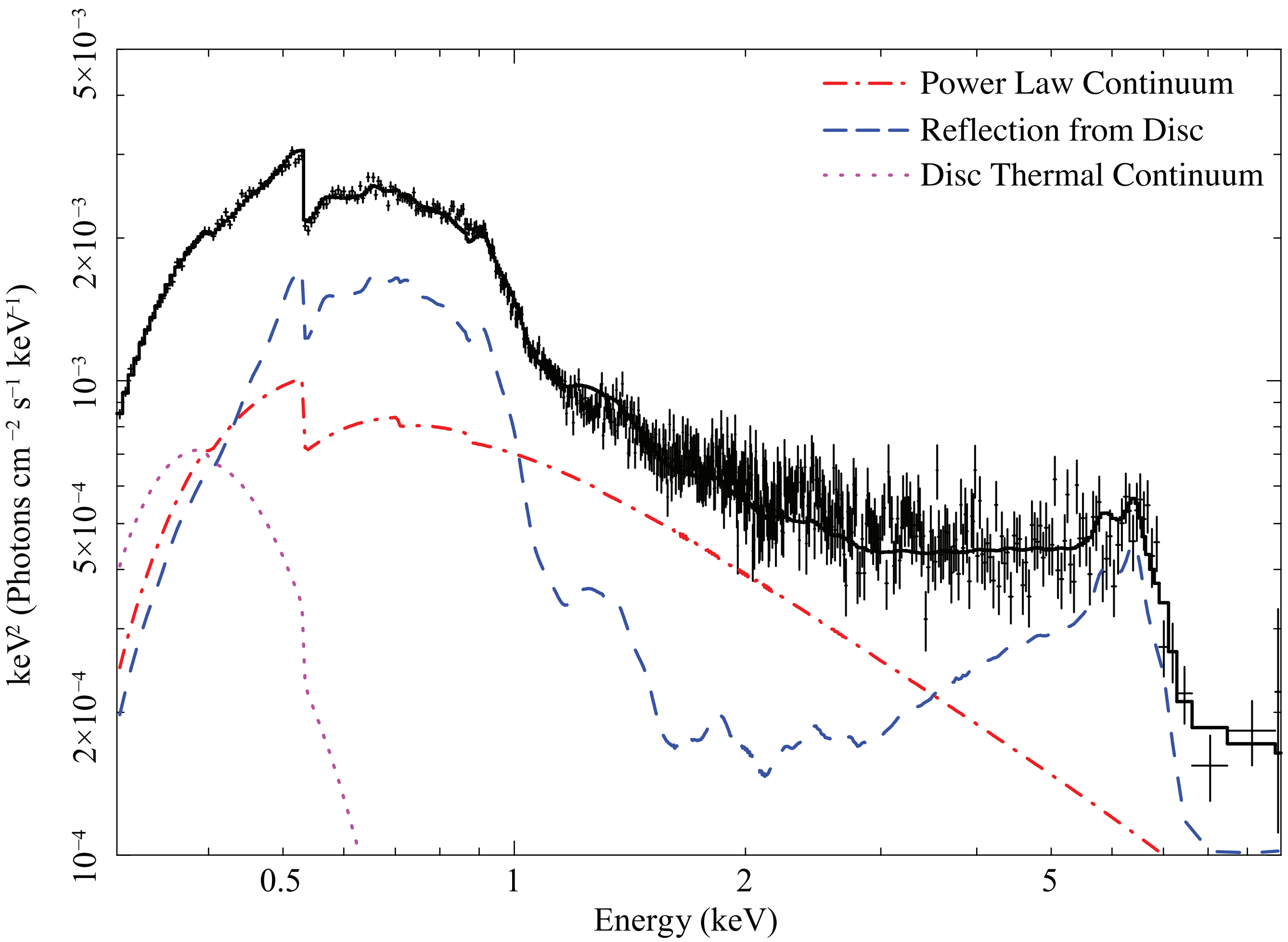
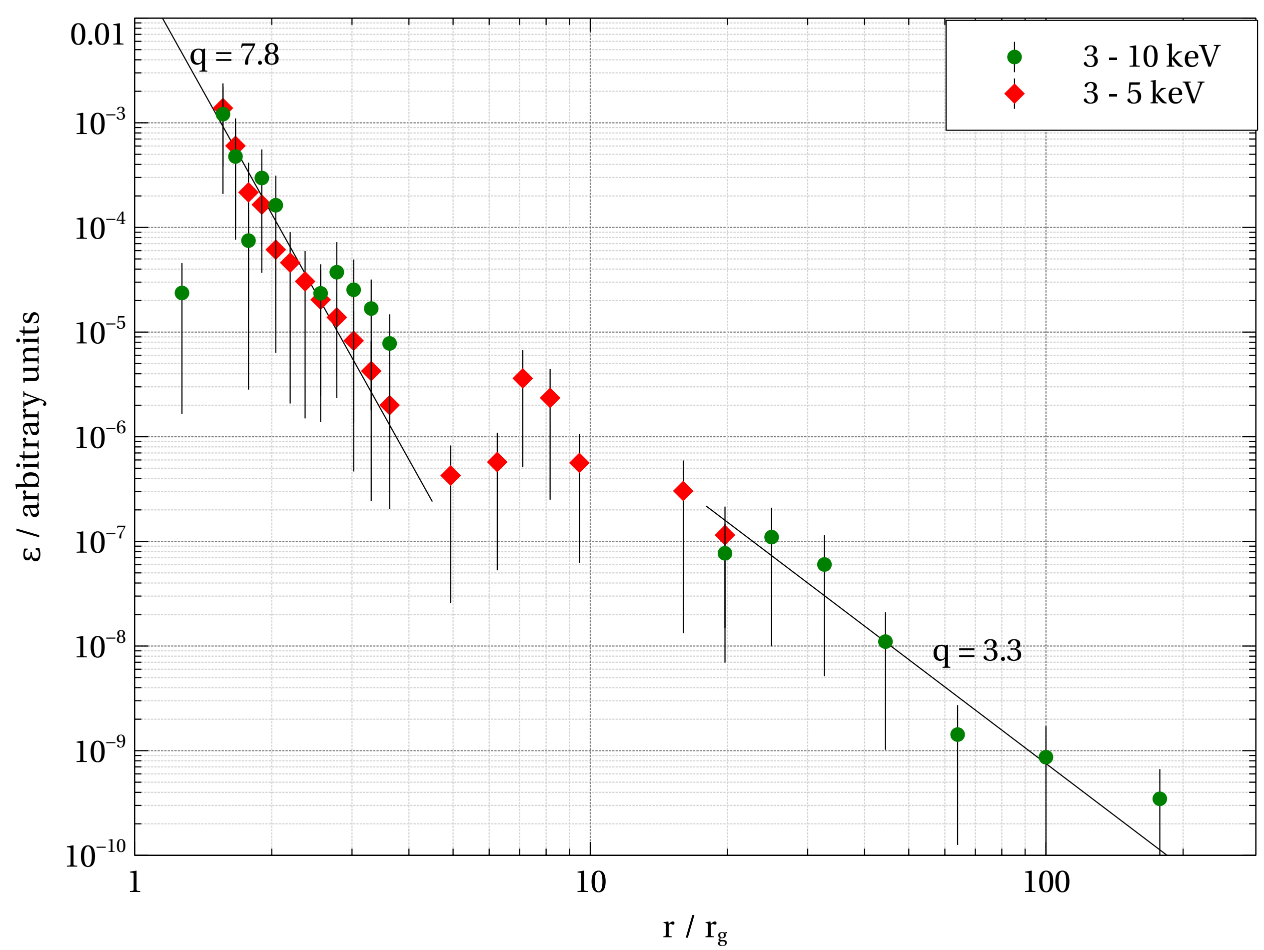




Combined with the Spectrum...

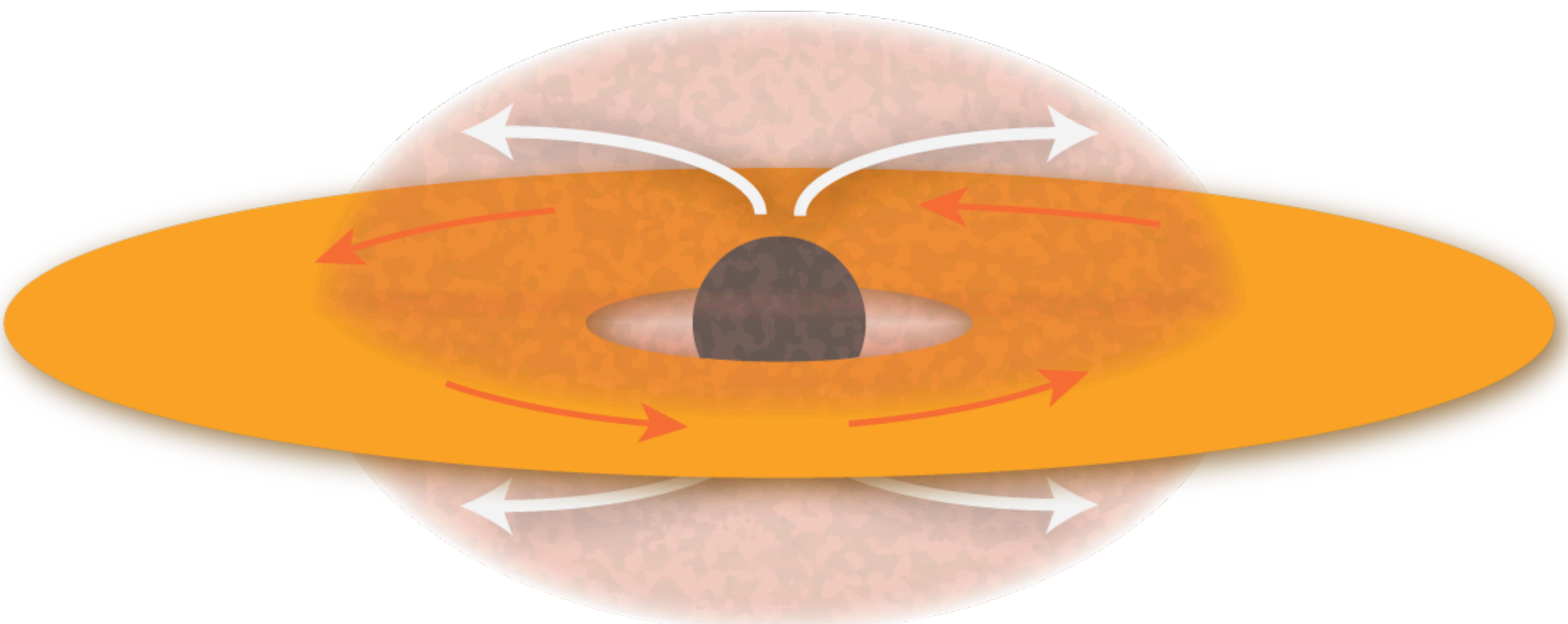
Wilkins & Fabian 2011, 2012





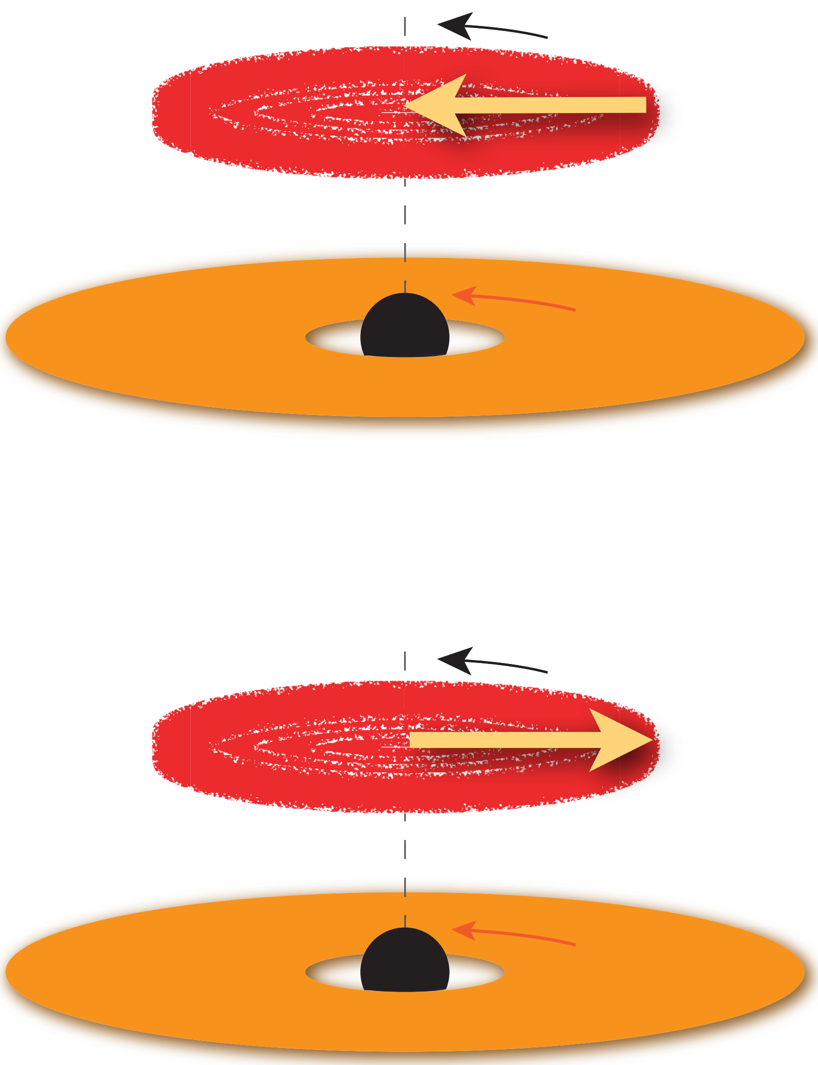
...we found the corona!

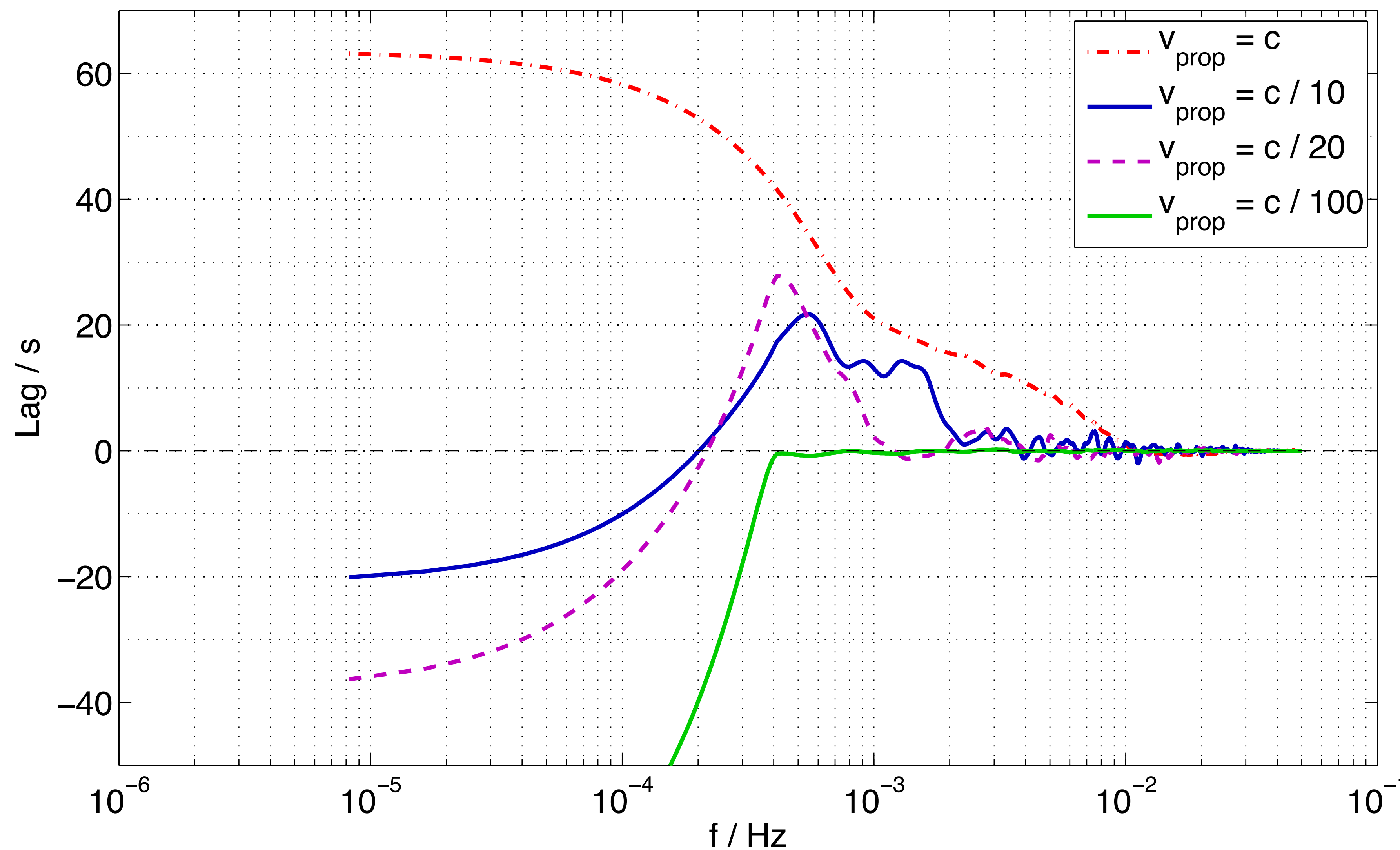
Wilkins & Fabian 2012, 2013



Propagation Effects

Wilkins & Fabian 2013, Arévalo & Uttley 2006

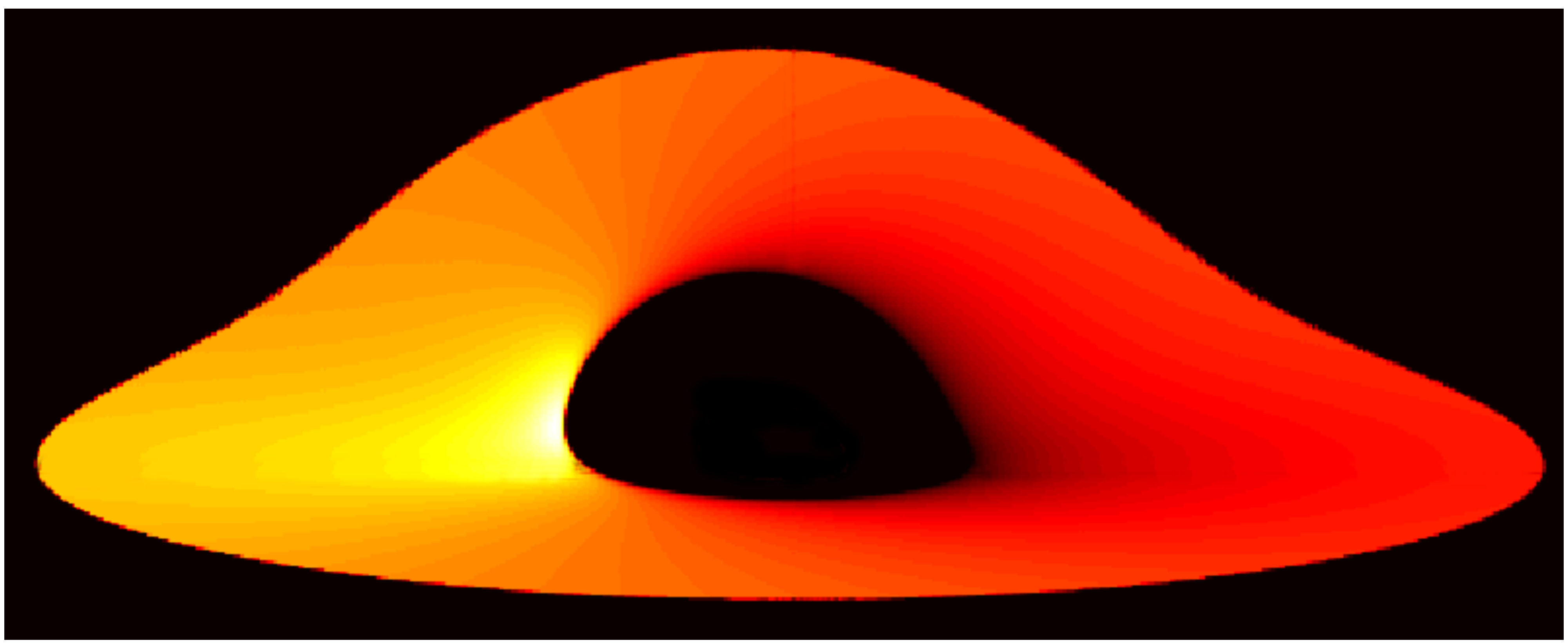




Can we do better?

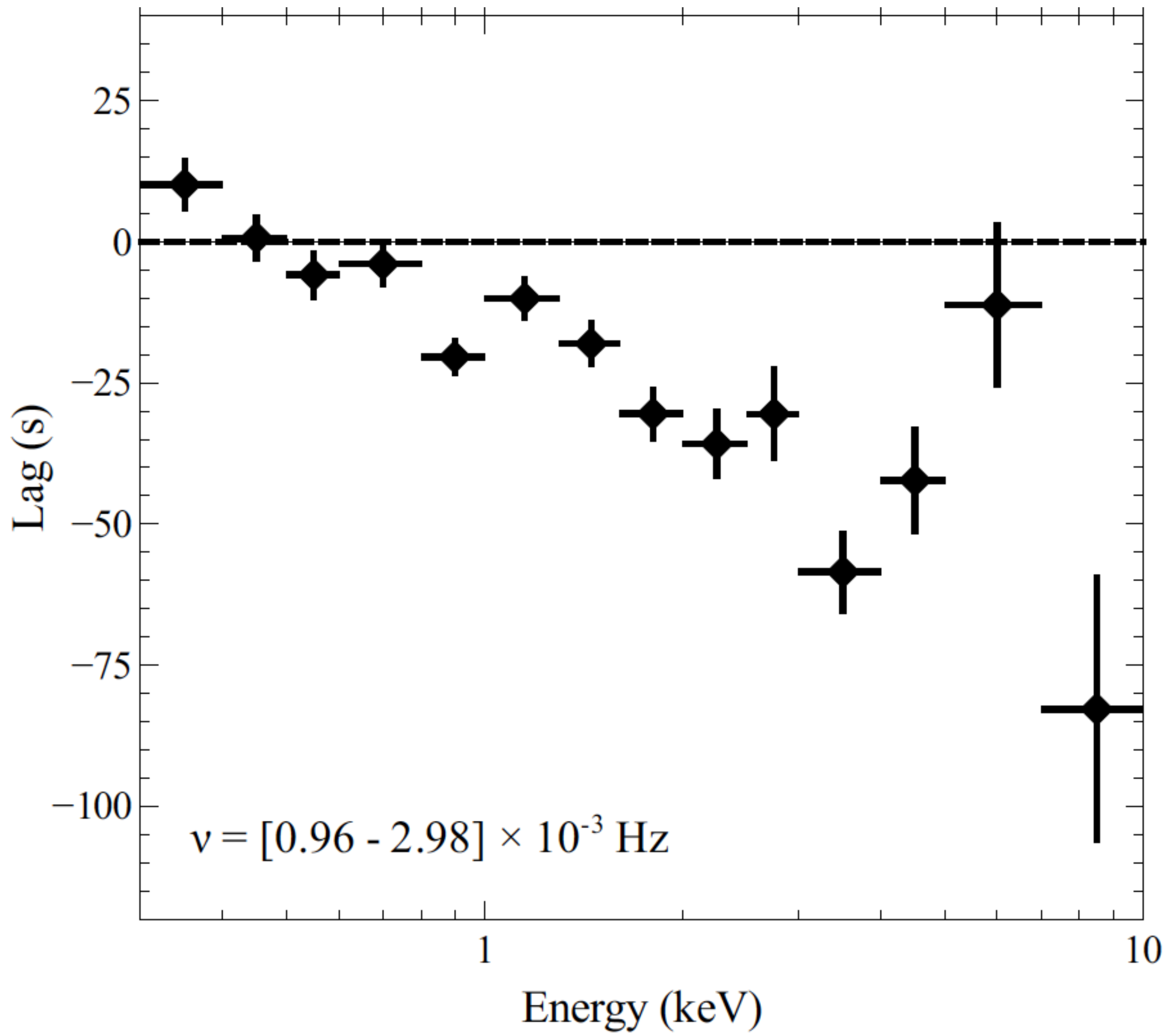
- Treated the energy spectrum and variability/reverberation separately
  - Signal to noise
- They are predicted by the same model
- Should be able to fit them simultaneously!
  - Better constraints on models rather than iterative best fitting between data sets
  - Breaks degeneracies

Lags should be energy dependent



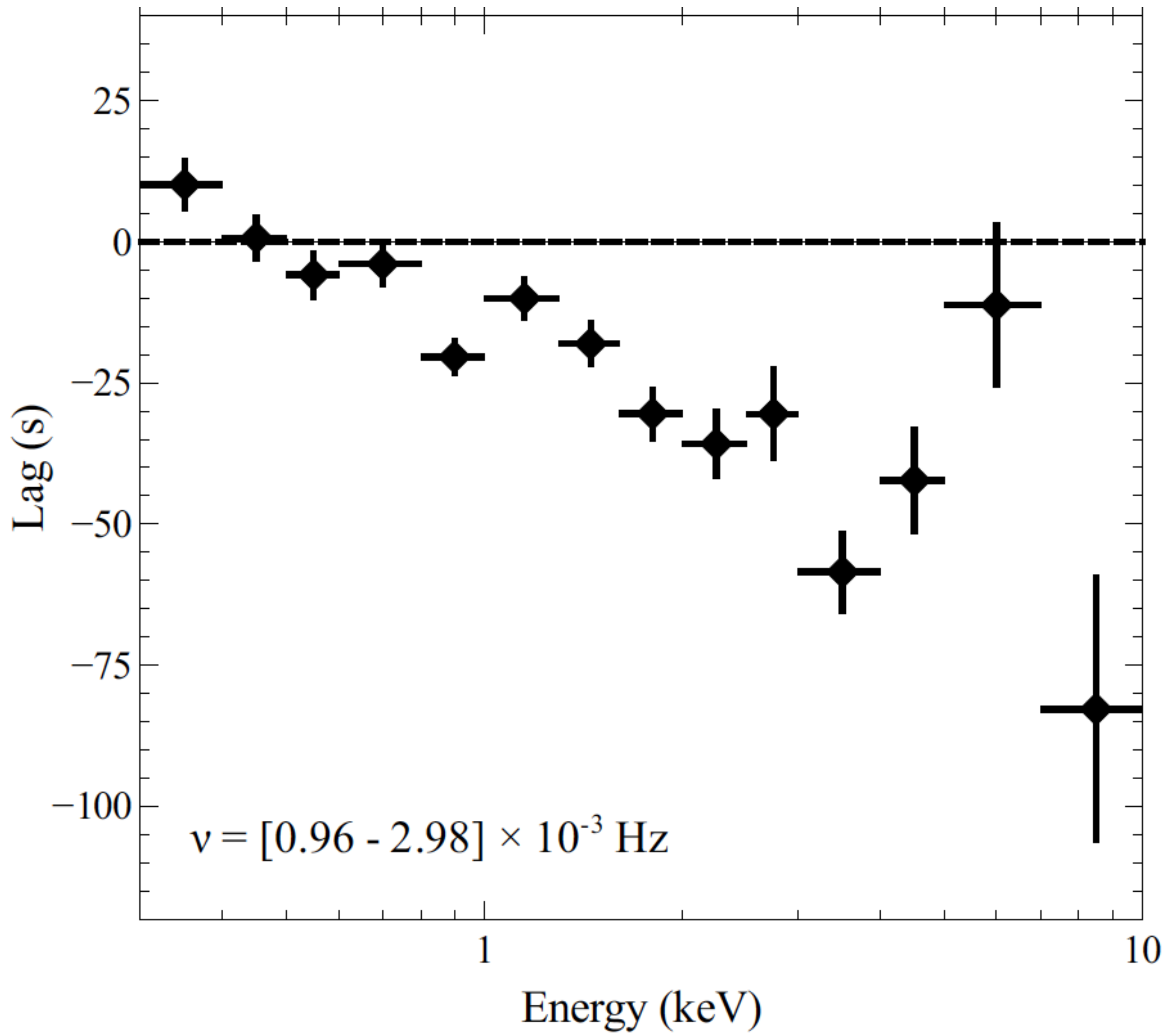
The Lag/Energy Spectrum

Kara+2012

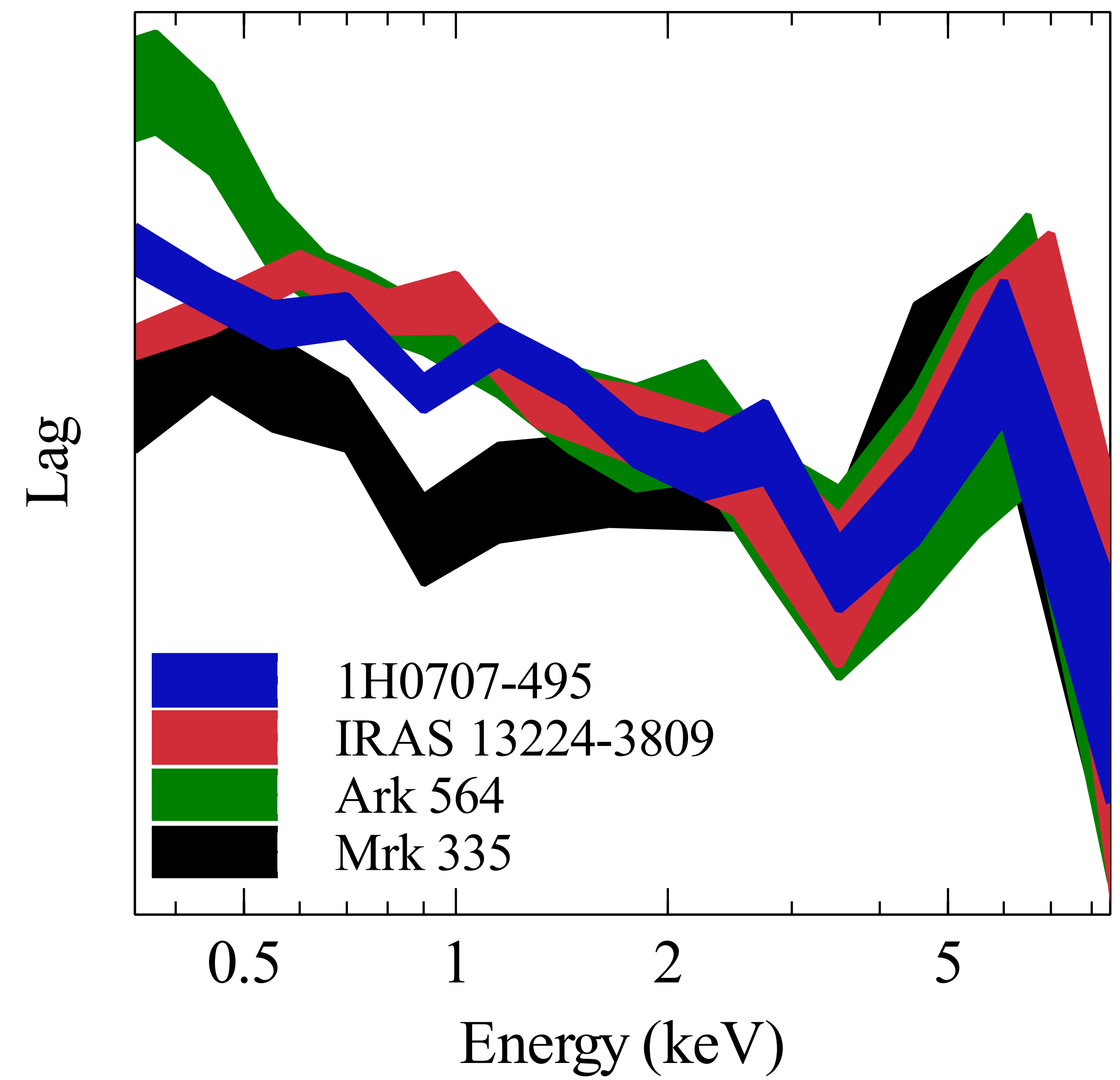


The Lag/Energy Spectrum

Kara+2012

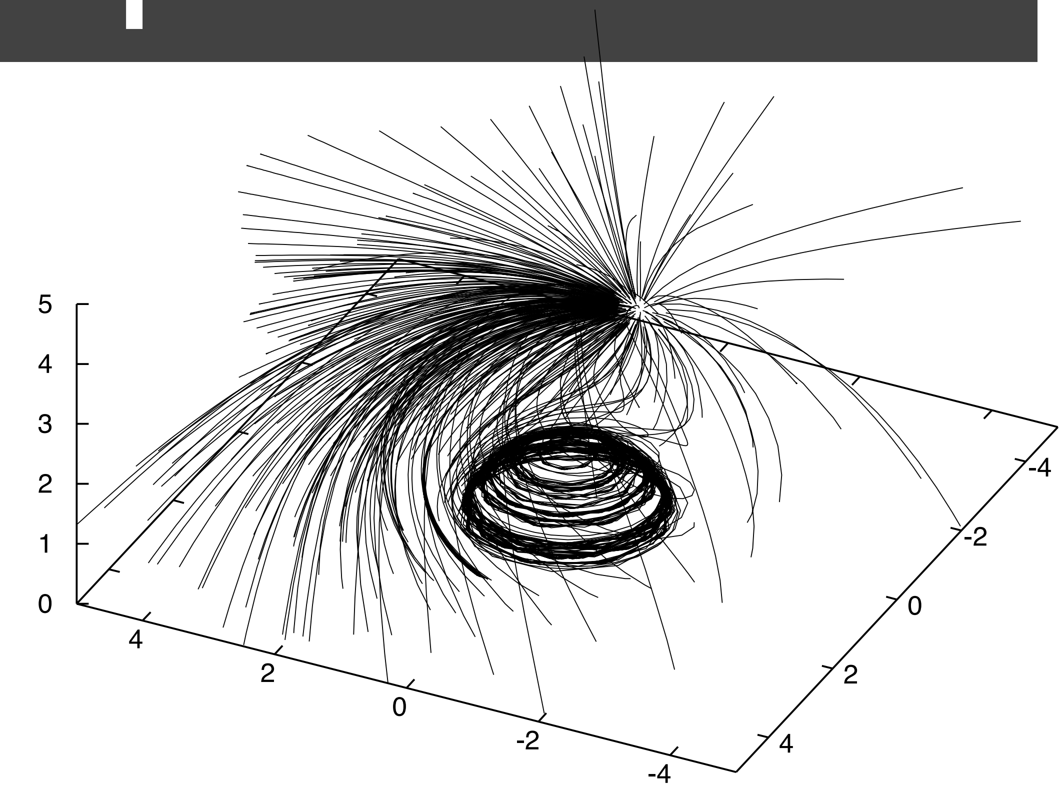


Kara+2013c

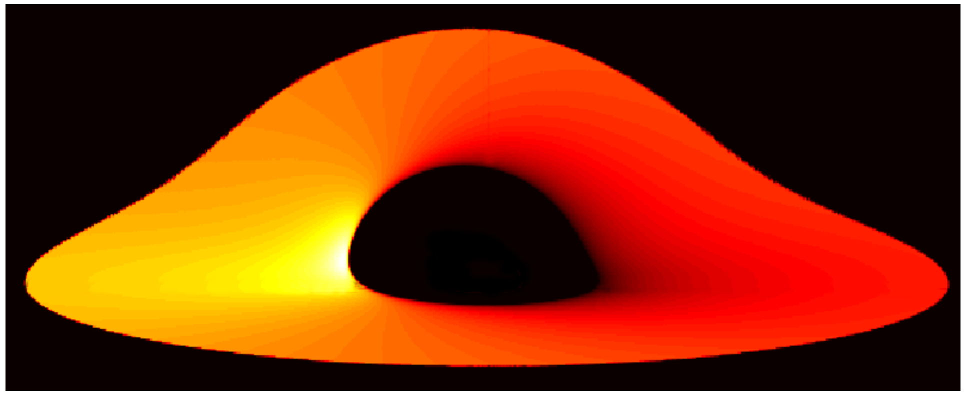


Predicting Lag-Energy Spectra

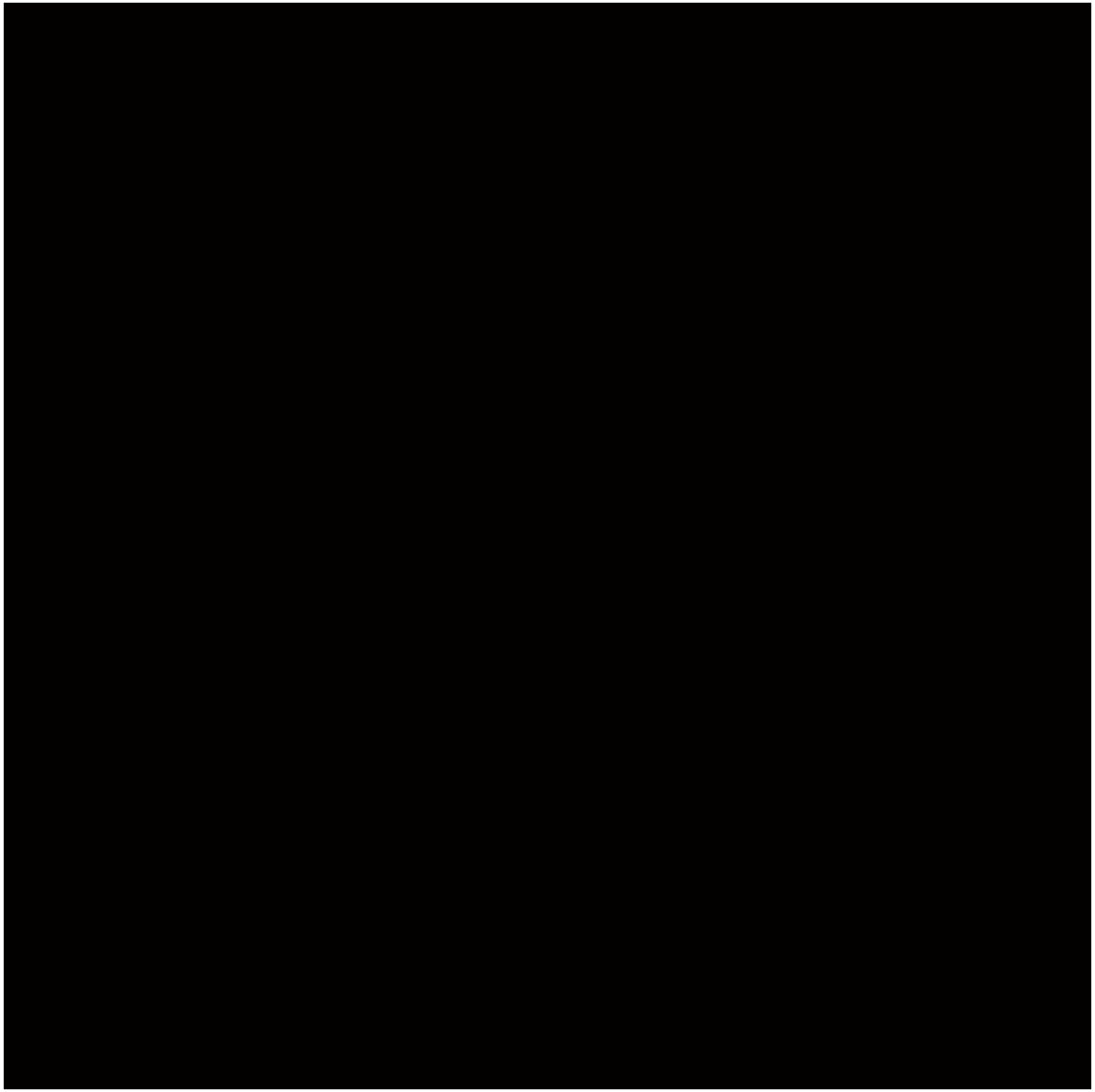
- Trace rays from source to disc

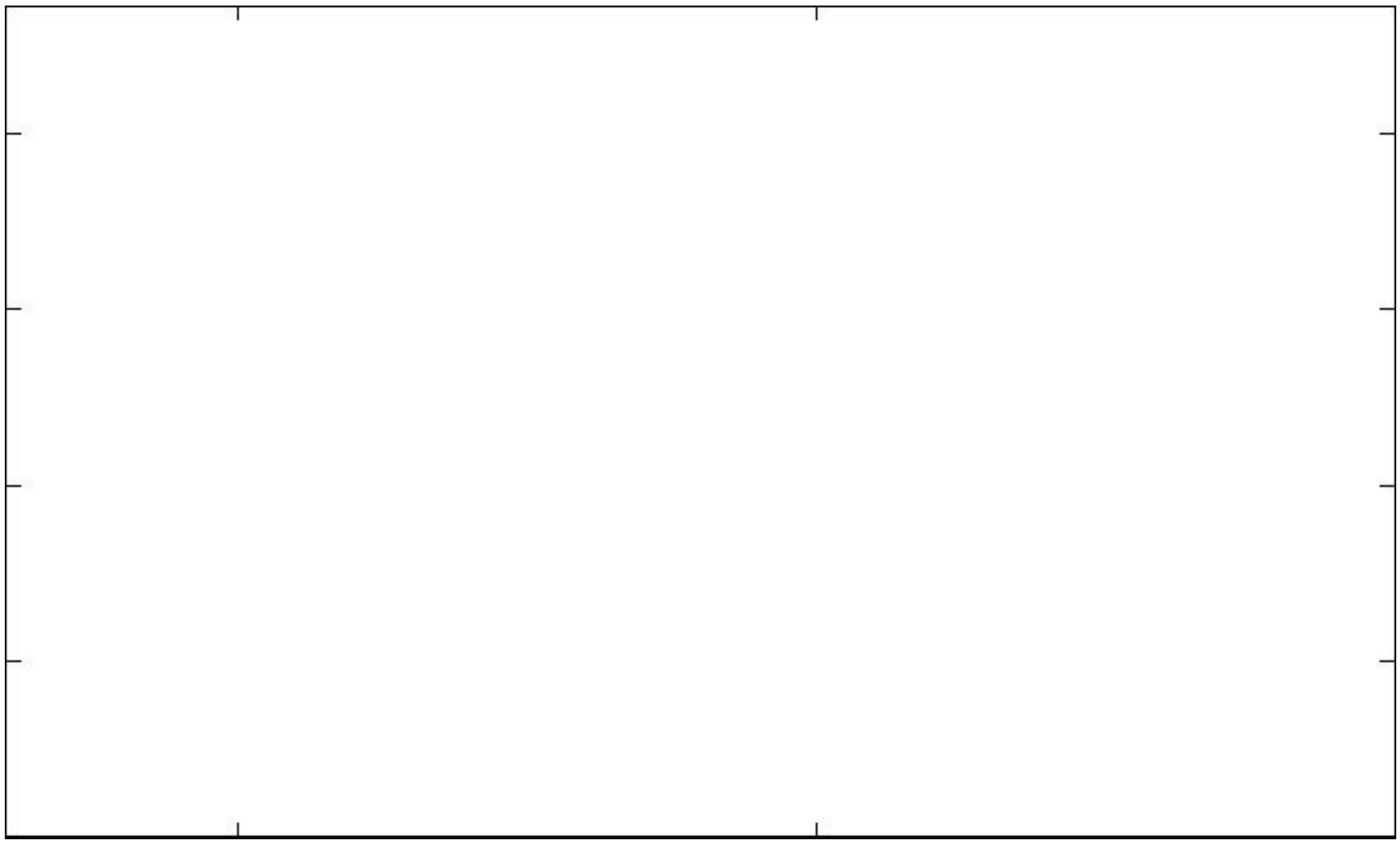


- Observe rays with telescope

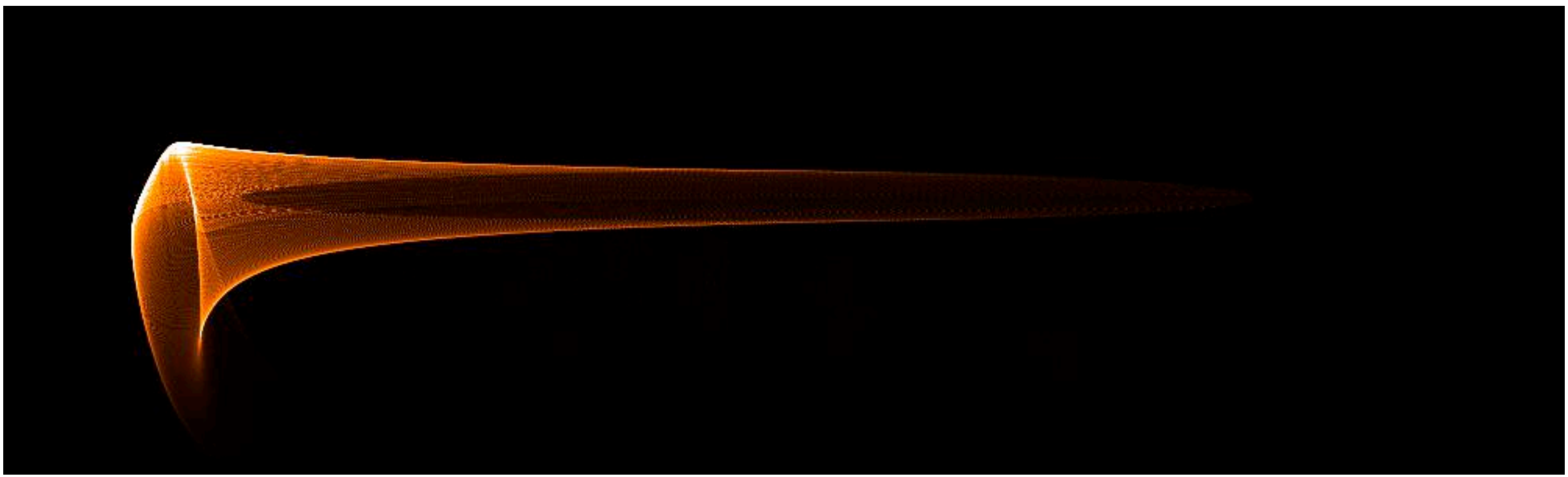


- For each, record its arrival time, redshift (energy) and intensity

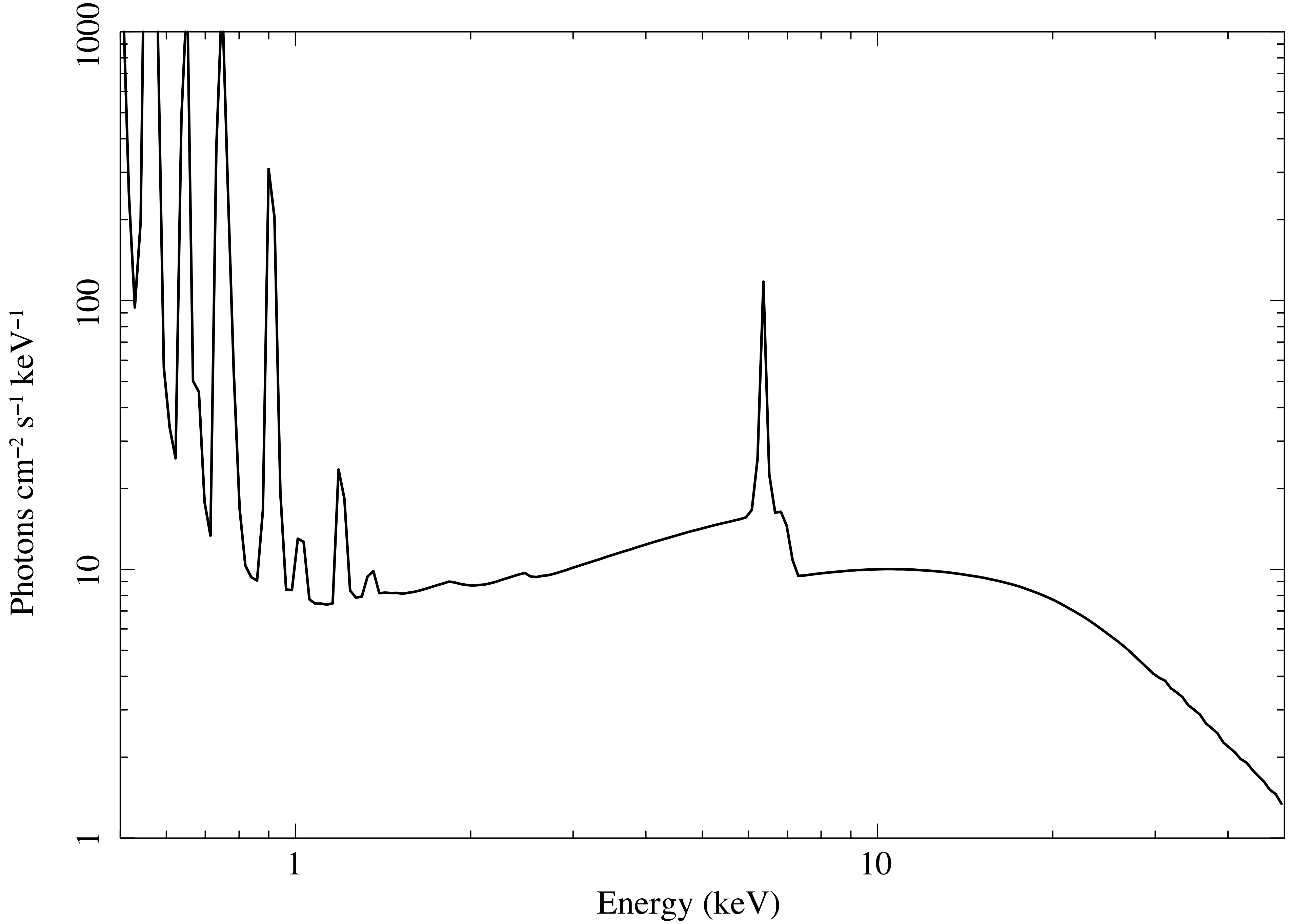




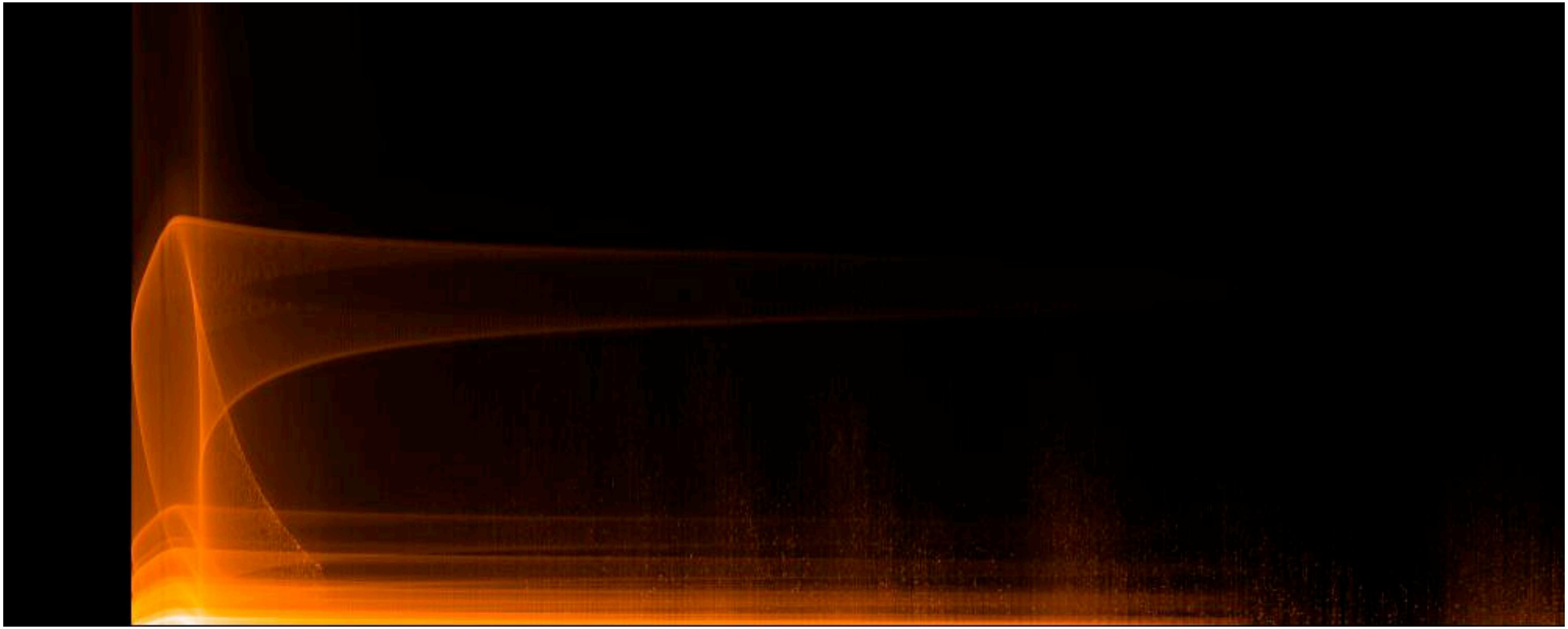
The Time-Energy Transfer Function



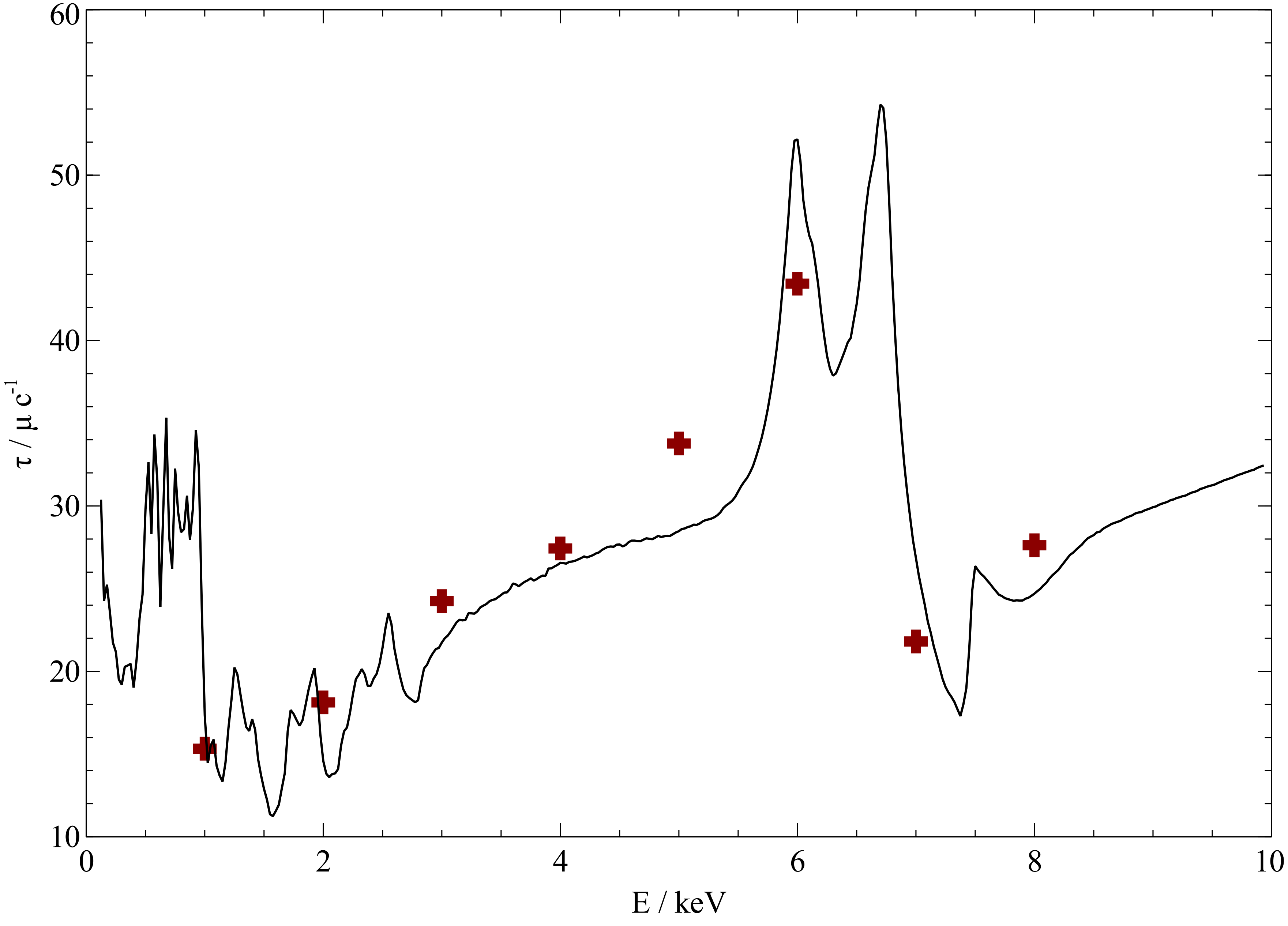
The Reflection Spectrum



Time-Resolved Reflection



Lag/Energy Spectrum v1

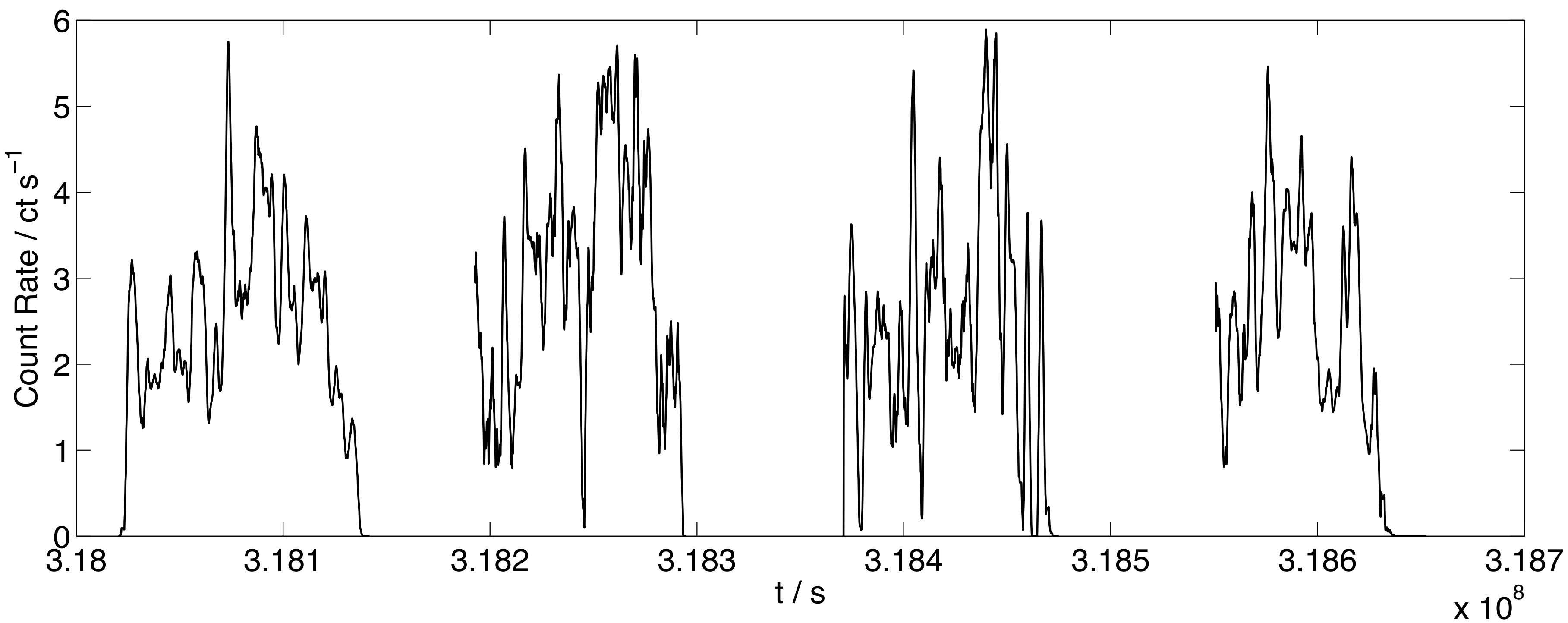


The Fourier Transform

$$F(t) = \int \tilde{F}(\omega) e^{i\omega t} d\omega$$

$$\tilde{F}(\omega) = \int F(t) e^{-i\omega t} dt$$

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



The Lag Spectrum

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

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

The Lag Spectrum

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

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

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

The Lag Spectrum

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

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

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

$$S(t) = H(t) \otimes T(t)$$

$$\tilde{S}(\omega) = \tilde{H}(\omega)\tilde{T}(\omega)$$

$$\tilde{C}(\omega) = |\tilde{H}|^2 |\tilde{T}| e^{i\varphi_T}$$

The Lag Spectrum

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

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

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

$$S(t) = H(t) \otimes T(t)$$

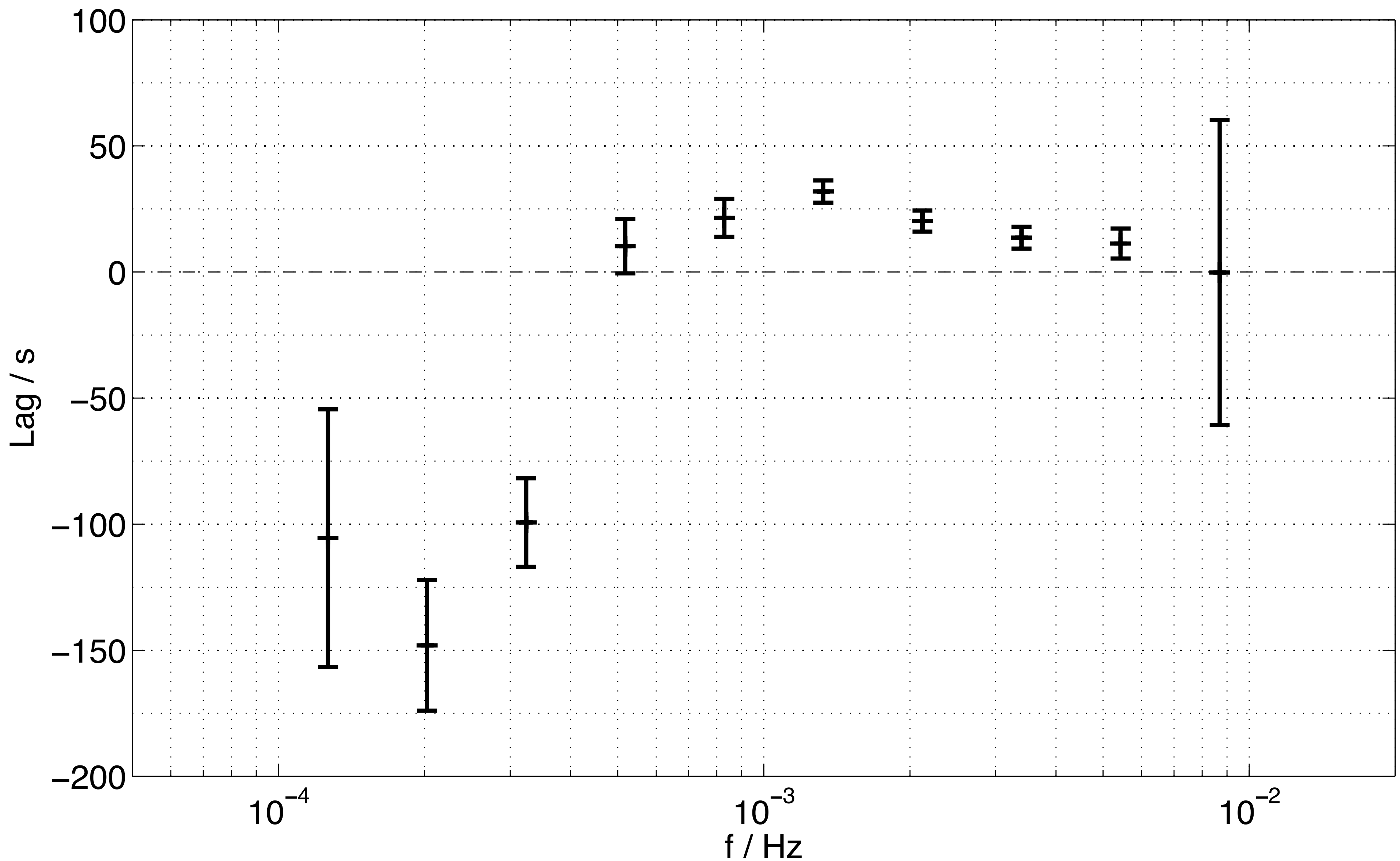
$$\tilde{S}(\omega) = \tilde{H}(\omega)\tilde{T}(\omega)$$

$$\tilde{C}(\omega) = |\tilde{H}|^2 |\tilde{T}| e^{i\varphi_T}$$

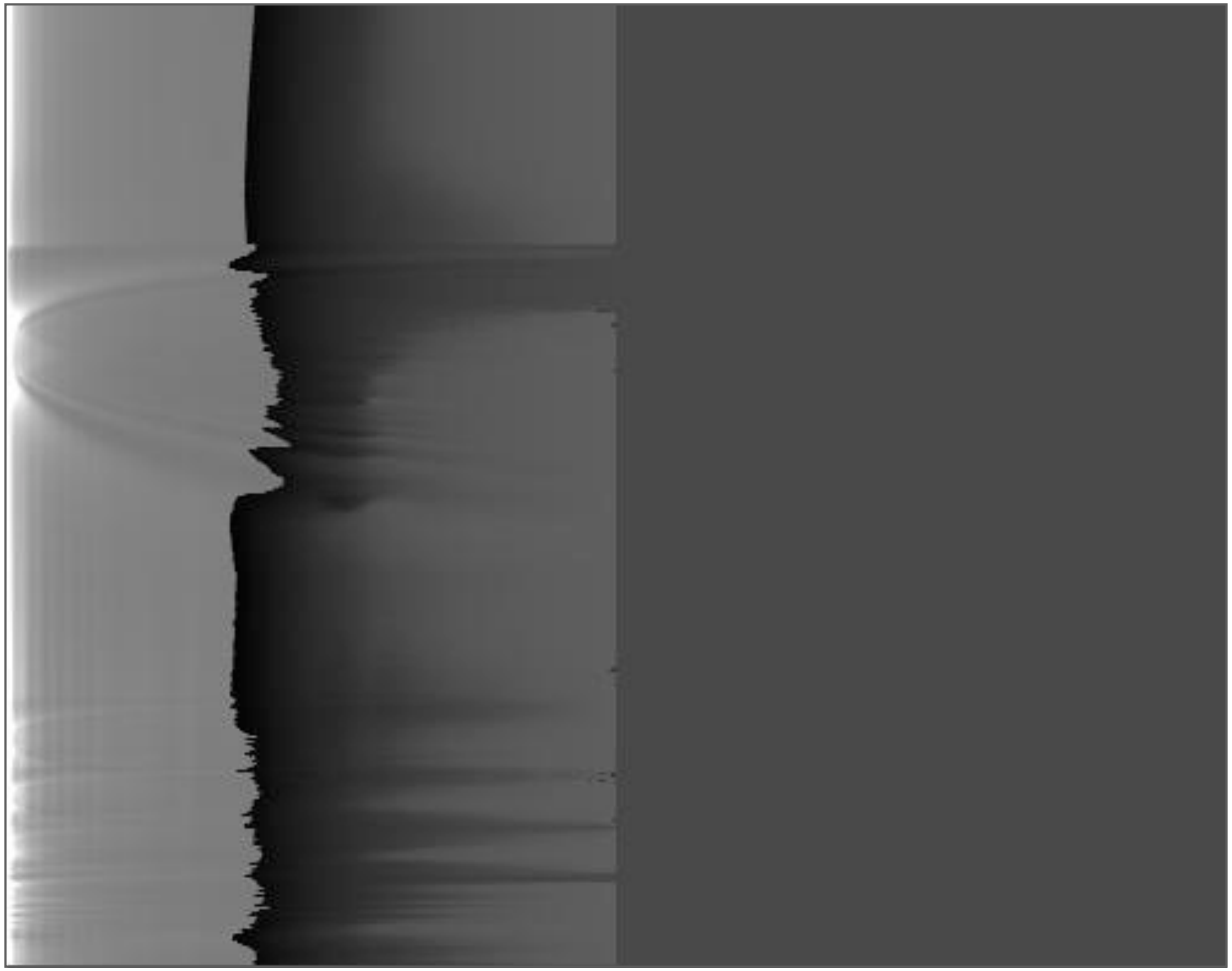
$$\varphi = \omega t$$

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

Lag/Frequency Spectrum



Lag/Energy/Frequency Spectrum



The Reference Band

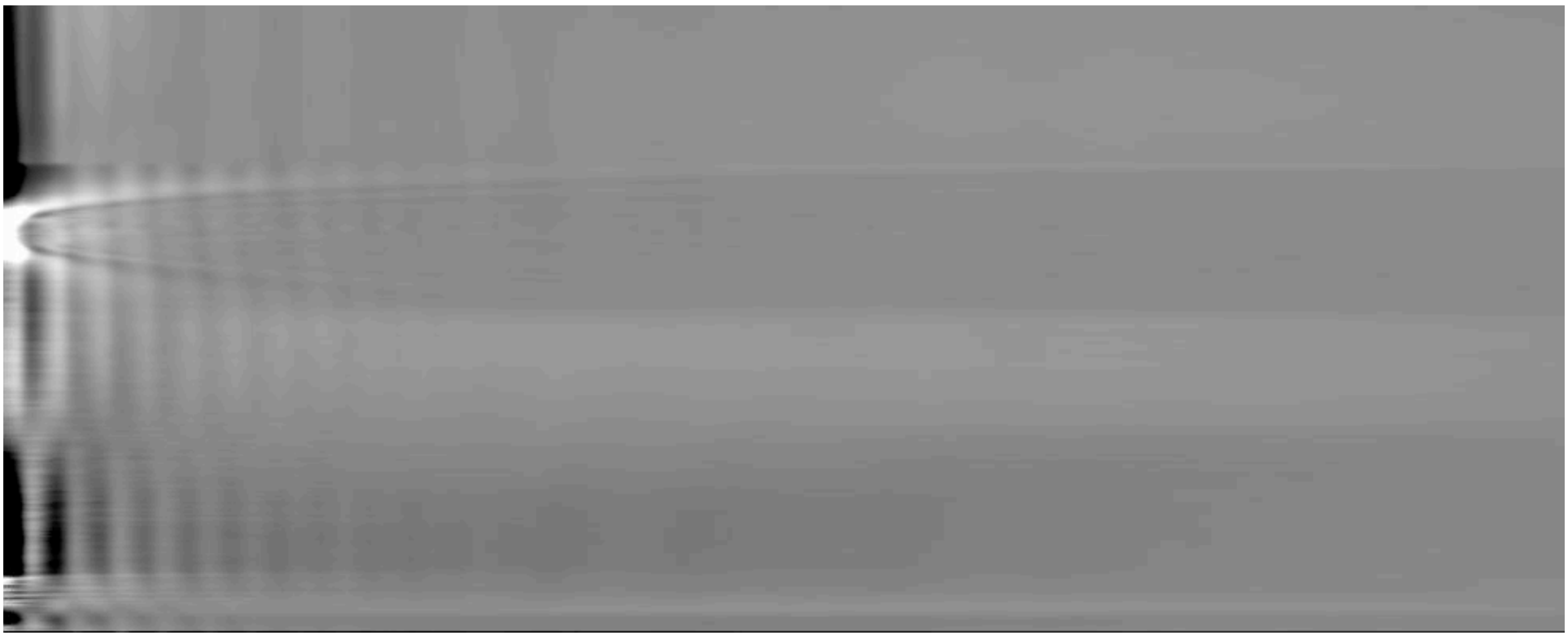
- Intrinsic variability of the source, S(t)
- Each energy band has its own transfer function

$$L_1(t) = S(t) \otimes T_1(t)$$
$$L_2(t) = S(t) \otimes T_2(t)$$

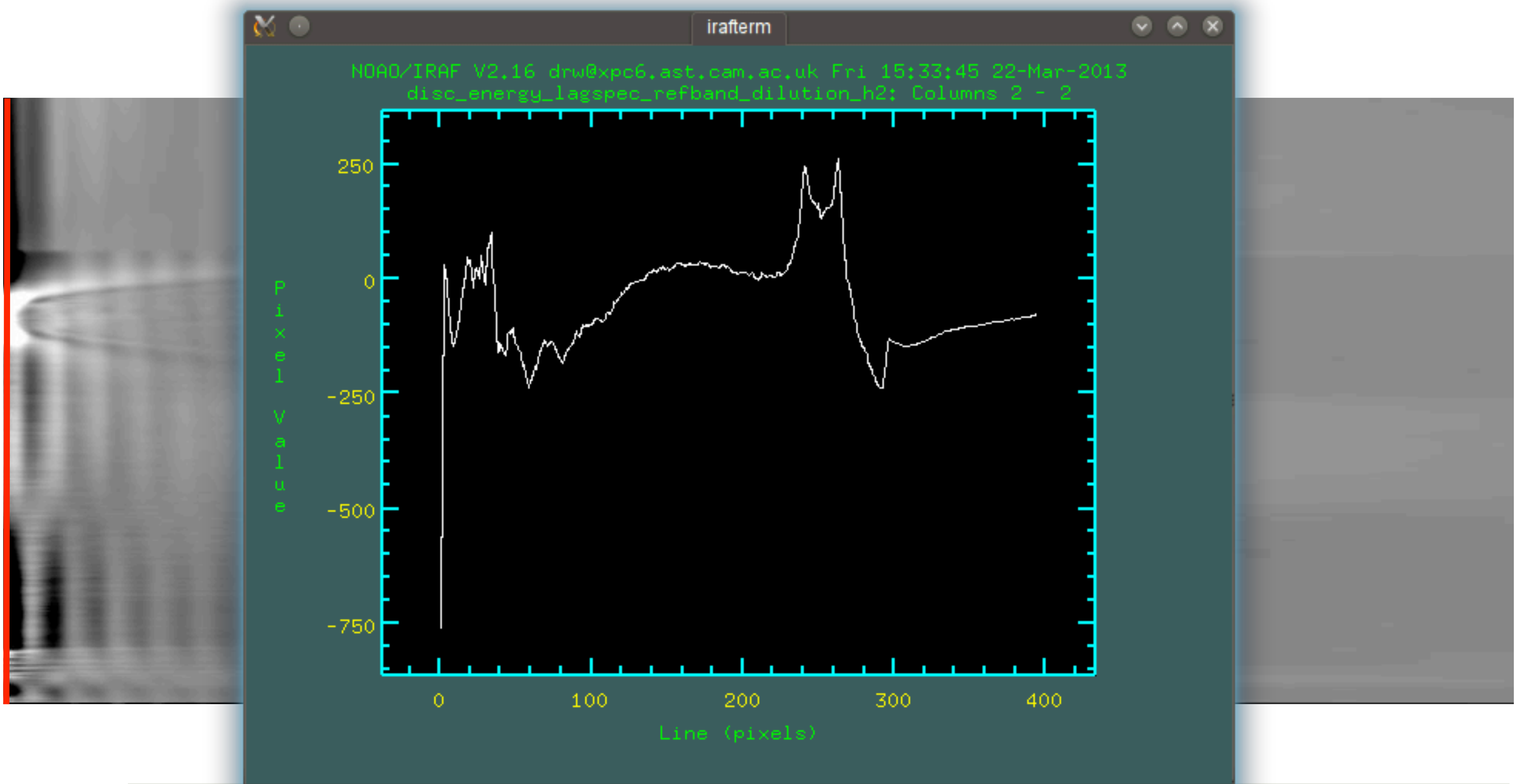
- Giving the cross spectrum

$$\tilde{C} = \tilde{L}_2^* \tilde{L}_1 = |\tilde{S}|^2 \tilde{T}_2^* \tilde{T}_1$$

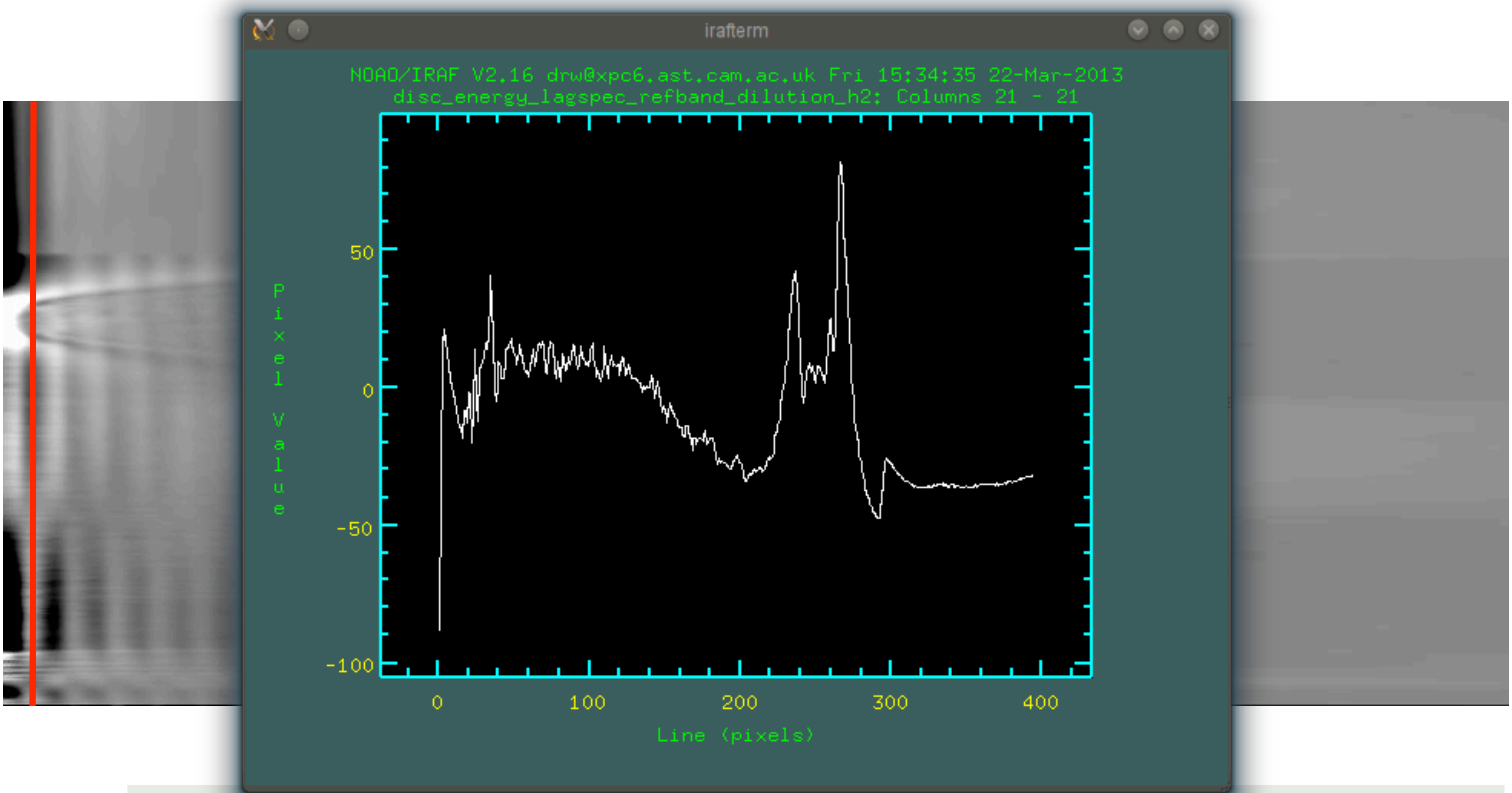
Lag/Energy/Frequency Spectrum



Lag/Energy/Frequency Spectrum



Lag/Energy/Frequency Spectrum



The Current State of Affairs

- Limited by number of counts and uncorrelated noise
- Limits energy and frequency resolution

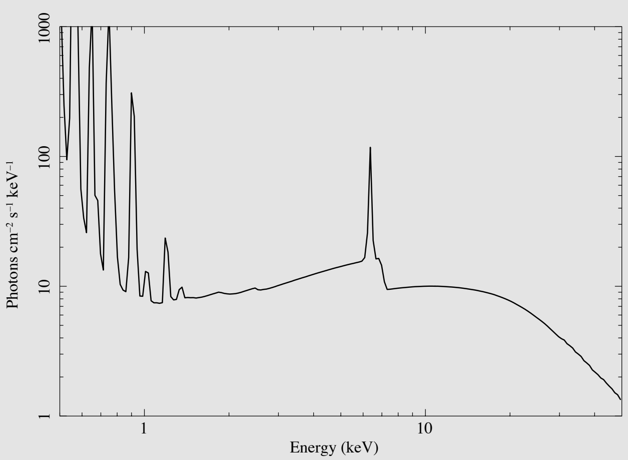
- Also lose the low energy part to the hard lag

Model

powerlaw

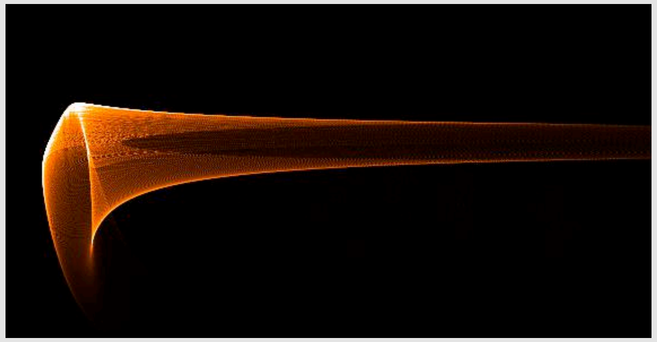
+

reflionx



⊗

Disc Response



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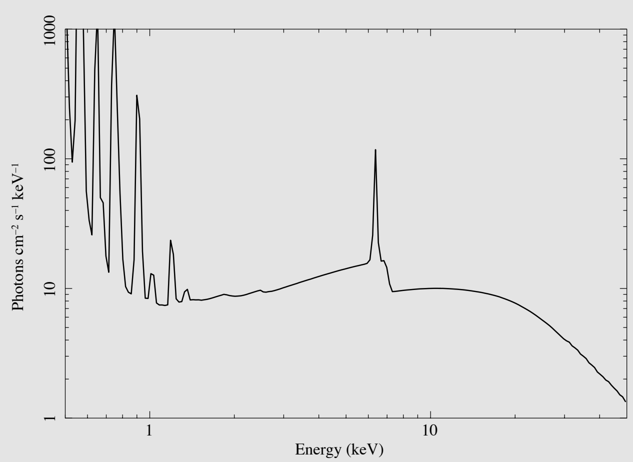

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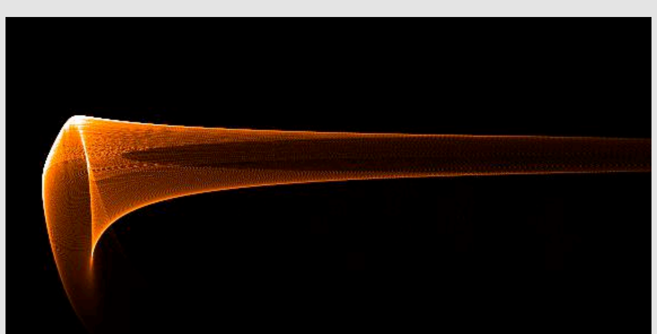
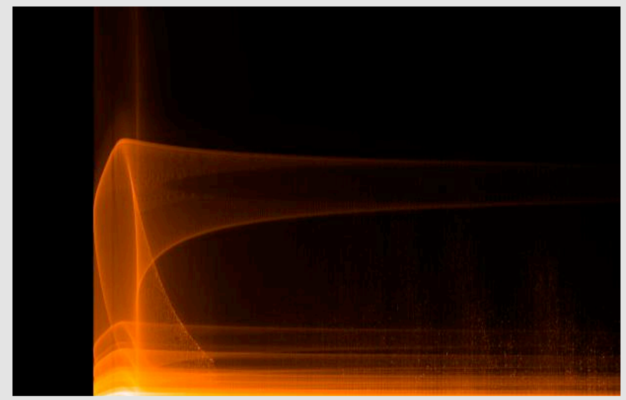


Instrument Response



*

ARF

⊗

RMF

⊗

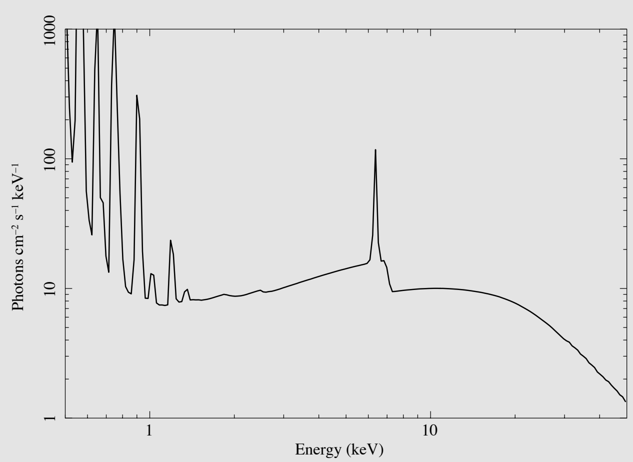
Timing Response

Model

powerlaw

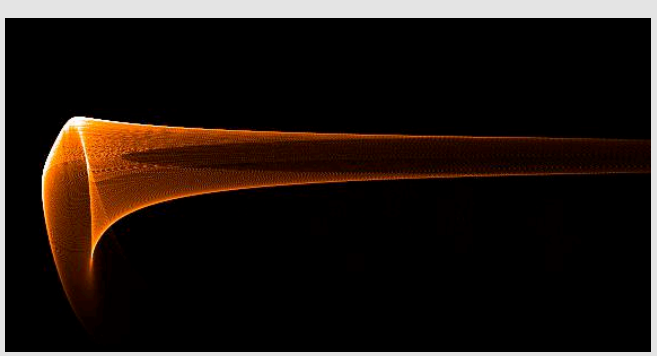
+

reflionx



$\otimes$

Disc Response



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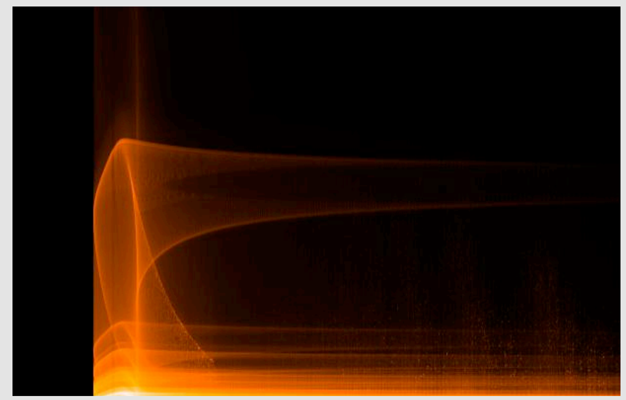


$*$

ARF

$\otimes$

RMF

$\otimes$

Timing Response

Cross Spectrum

Fourier Transform

$$\tilde{C} = \tilde{L}_2^* \tilde{L}_1 = |\tilde{S}|^2 \tilde{T}_2^* \tilde{T}_1$$

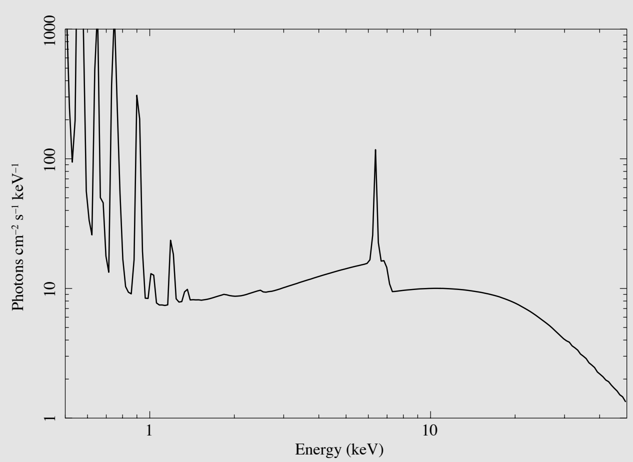
Fit to data (E, ν)

Model

powerlaw

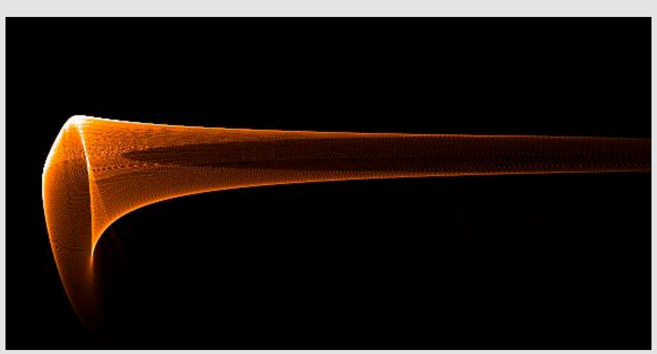
+

reflionx

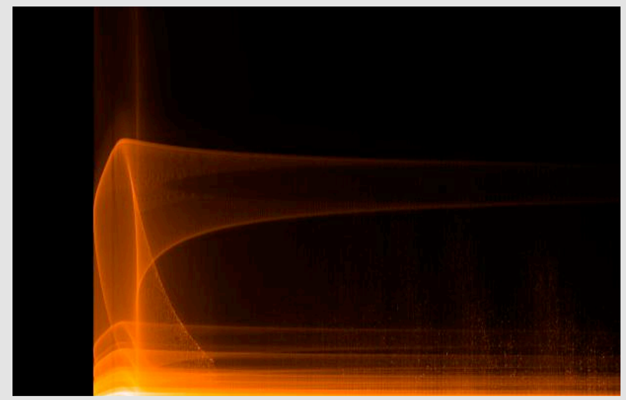


$\otimes$

Disc Response



Instrument Response



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ARF

$\otimes$

RMF

$\otimes$

Timing Response

Cross Spectrum

Fourier Transform

$$\tilde{C} = \tilde{L}_2^* \tilde{L}_1 = |\tilde{S}|^2 \tilde{T}_2^* \tilde{T}_1$$

Fit to data (E, ν)

Lag Spectra

$$T(\nu) = \frac{\arg C(\nu)}{2\pi\nu}$$

Conclusions

- Predicting lag/energy/frequency spectra for X-ray reverberation models from ray tracing simulations
- Need to understand what we are measuring and its frequency and energy dependence
- Can construct spectra from combinations of energy, (lag) time, frequency and counts
- Models must simultaneously fit all of these spectra