Durham University

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P Chris Fragile
Piotr Życki

20th July 2011

A physical model for the variability properties of black hole binaries

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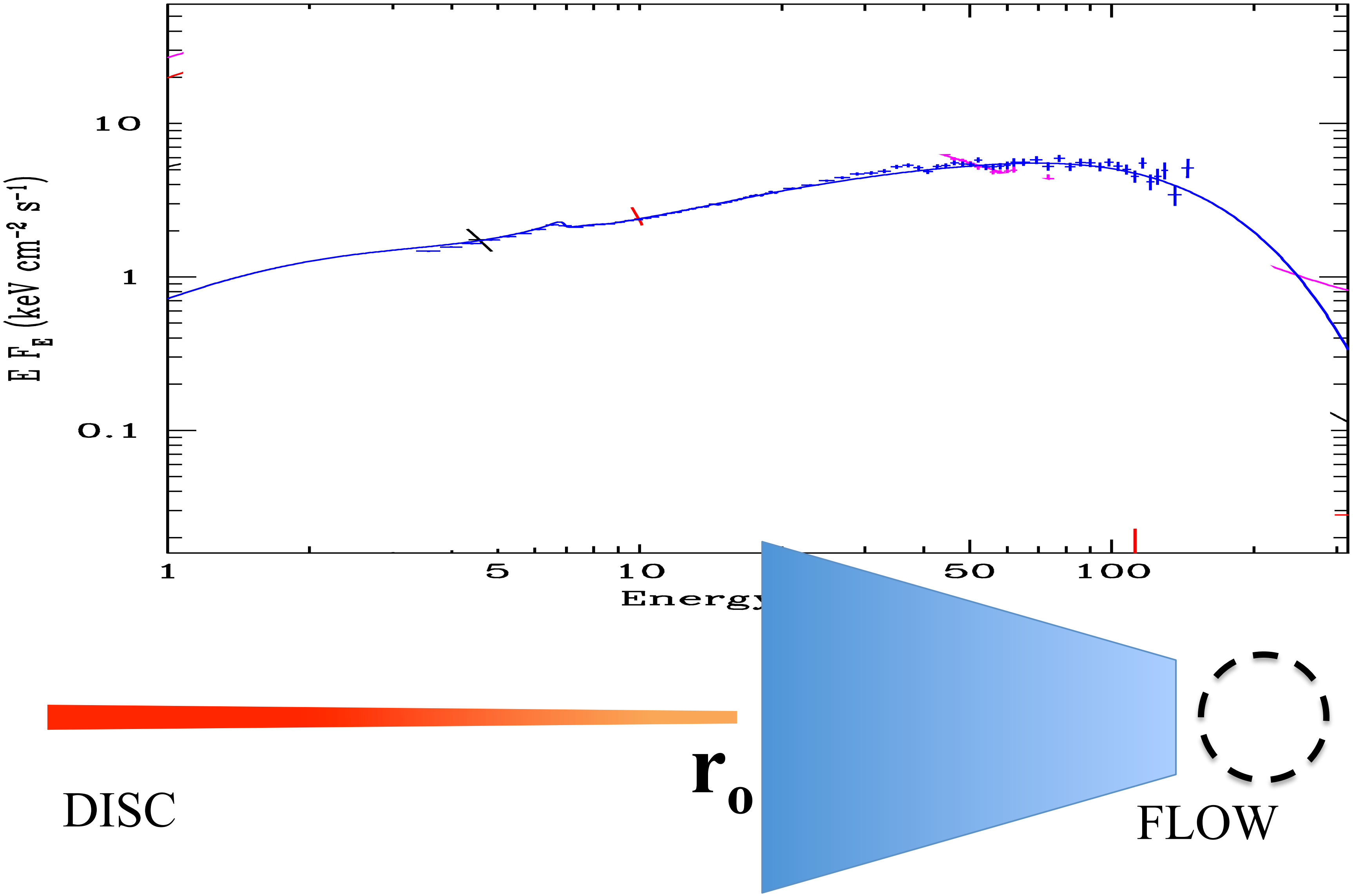
Overview

- The truncated disc model as a spectral model
- The truncated disc model as a power spectral model
- Fitting the power spectrum of XTE J1550-564
- Other properties of both model and data

Truncated disc model



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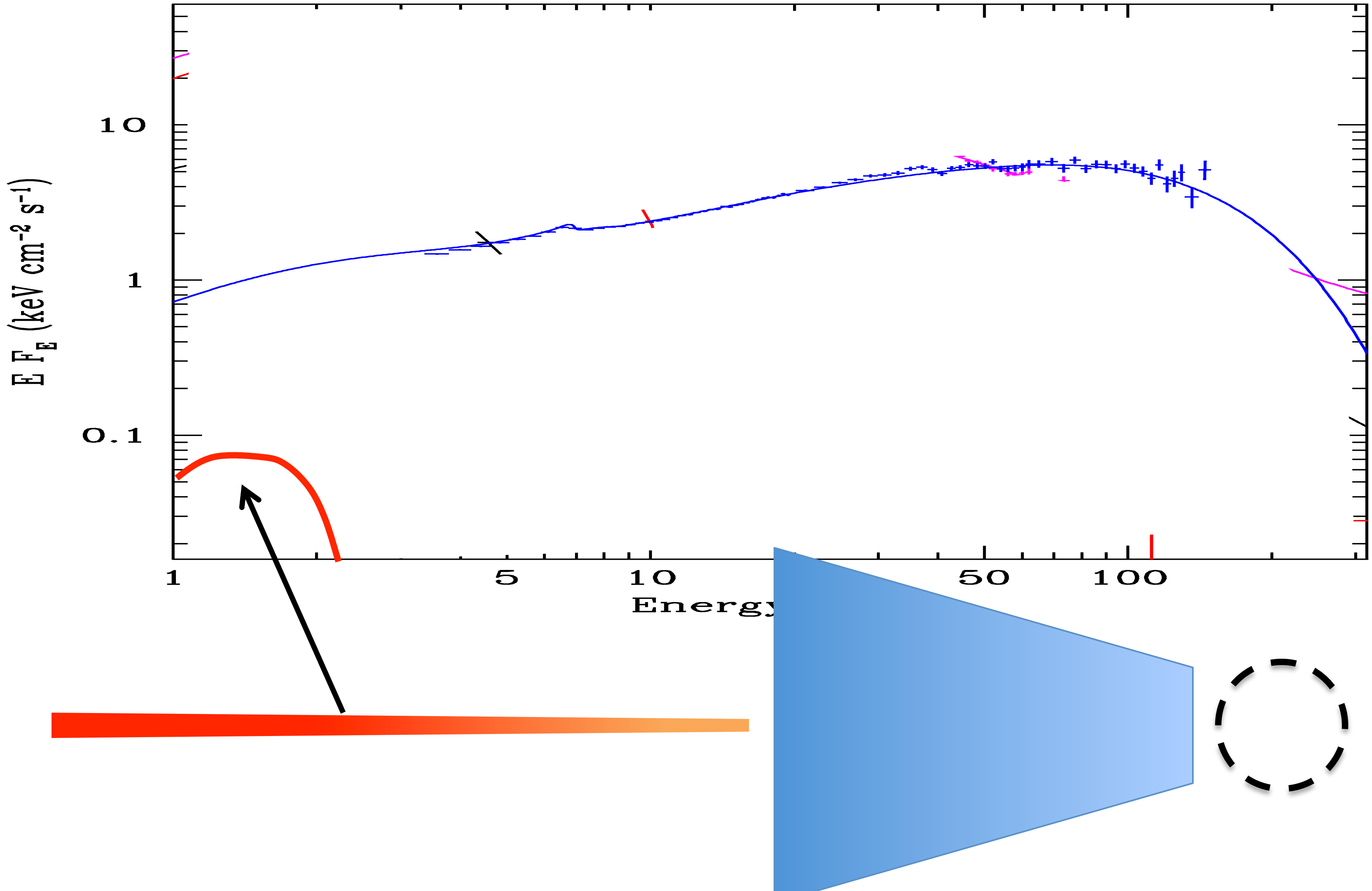

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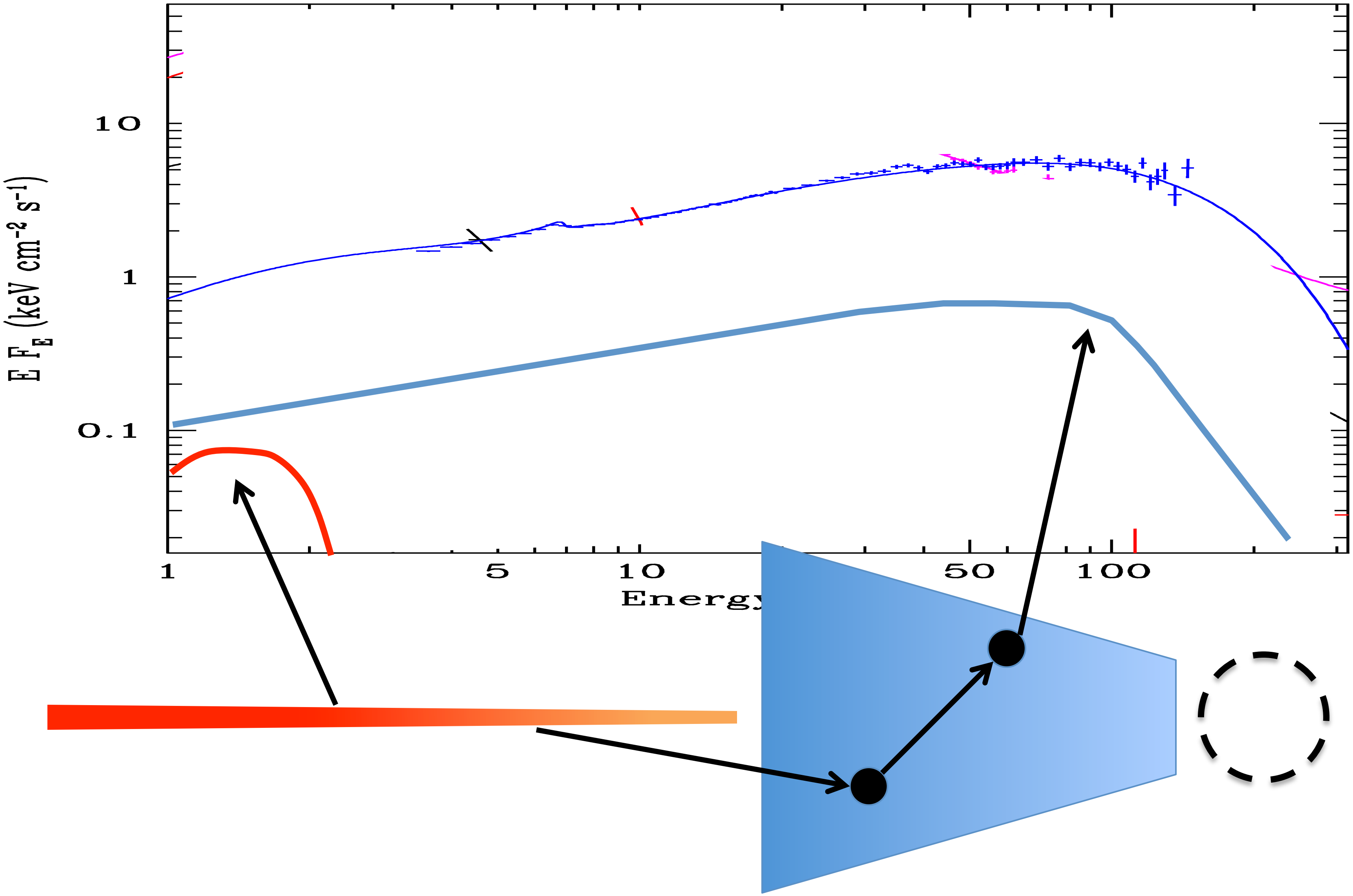

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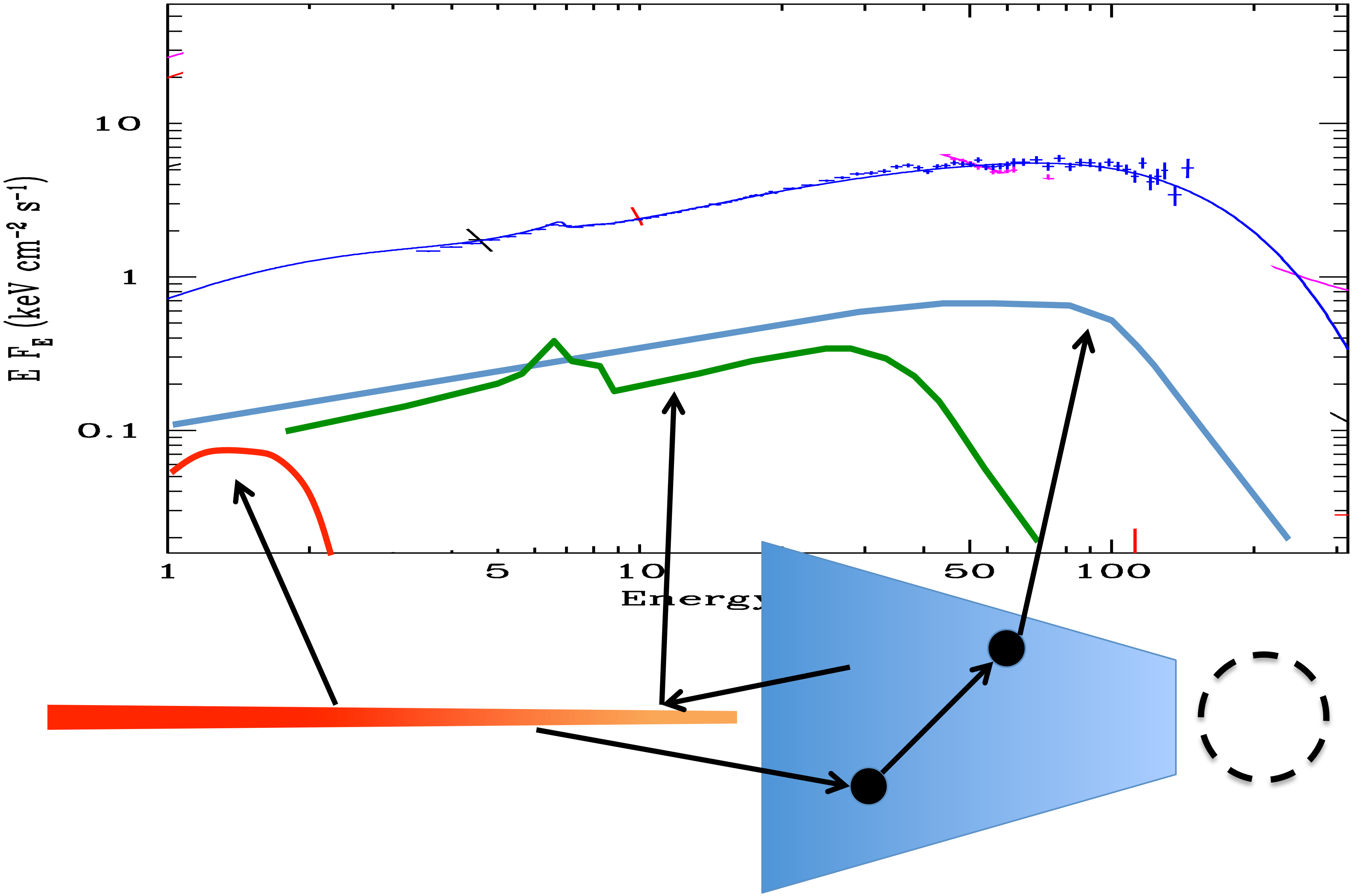
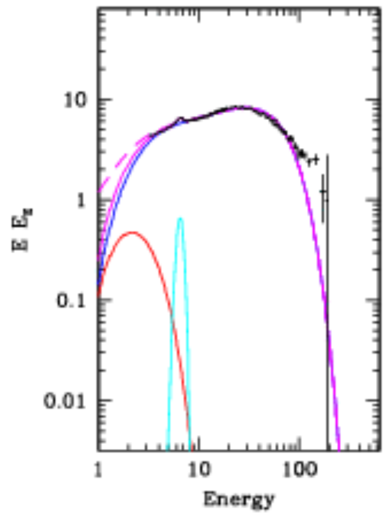
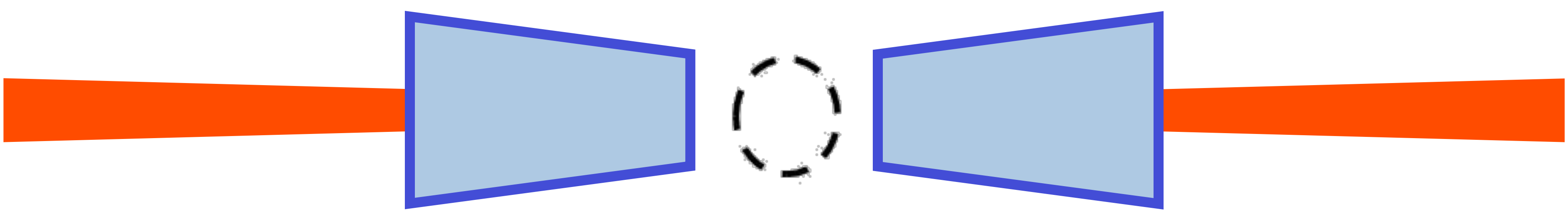


The truncated disc model



XTE J1550-564



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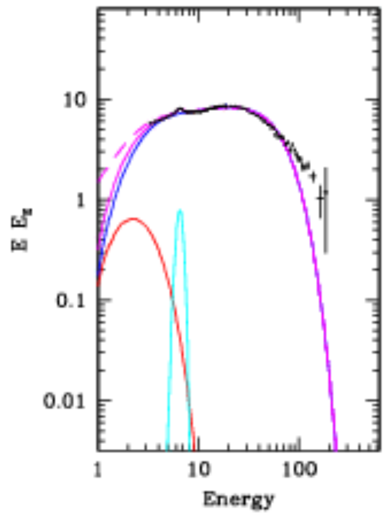

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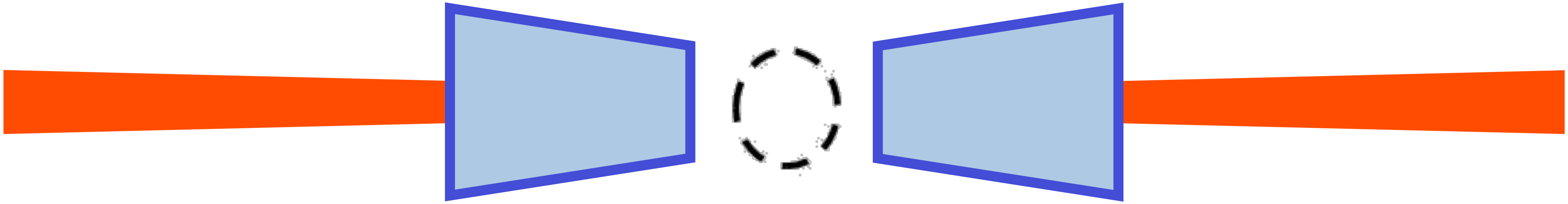

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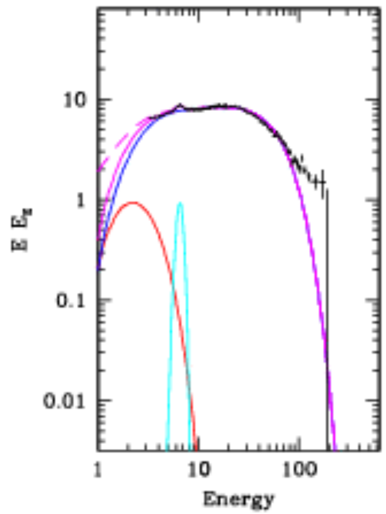

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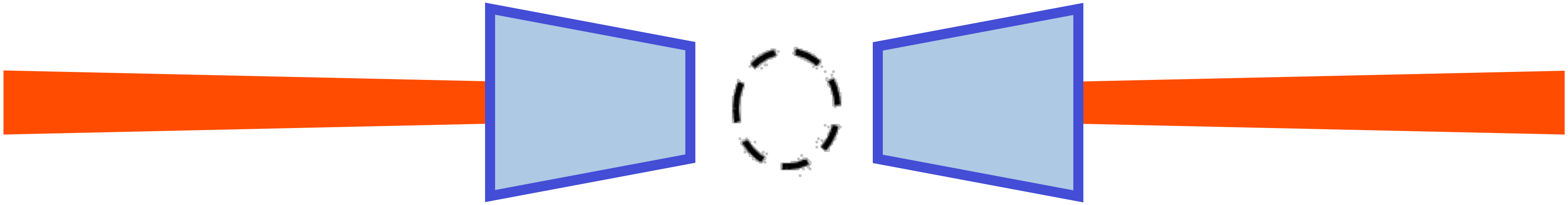

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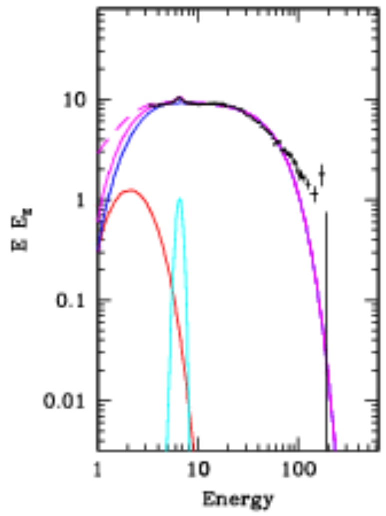

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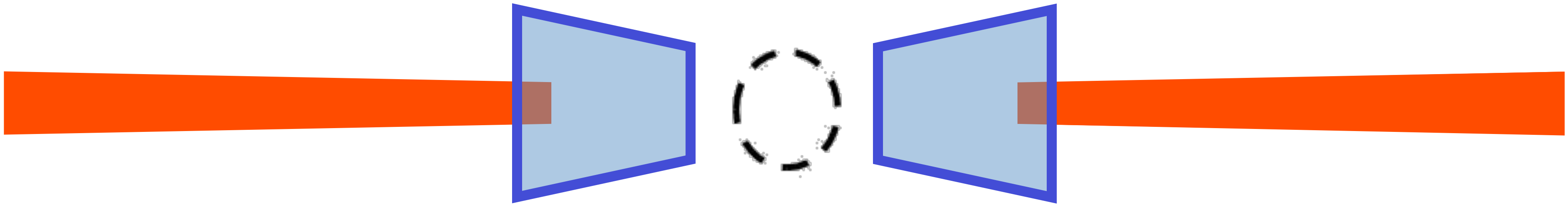

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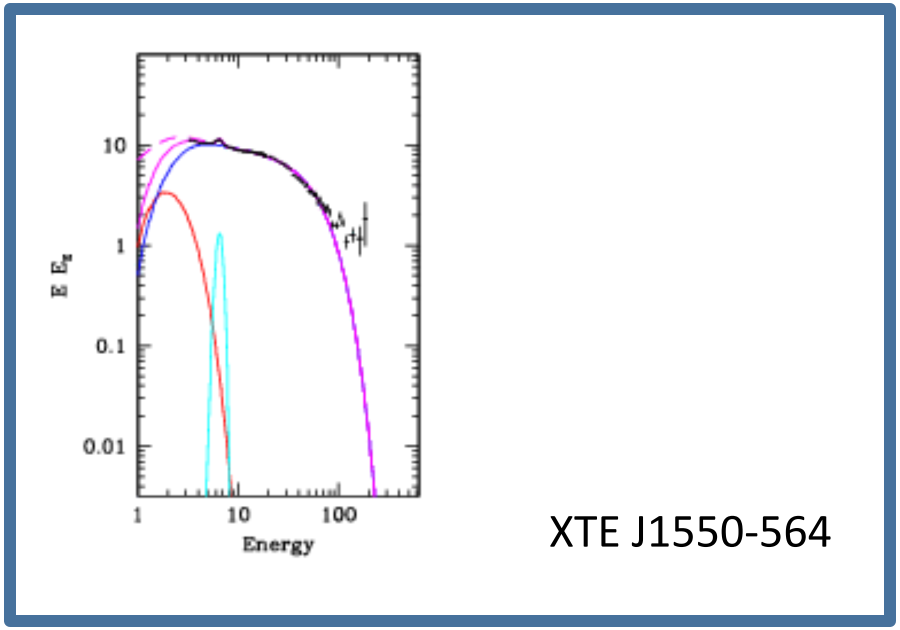

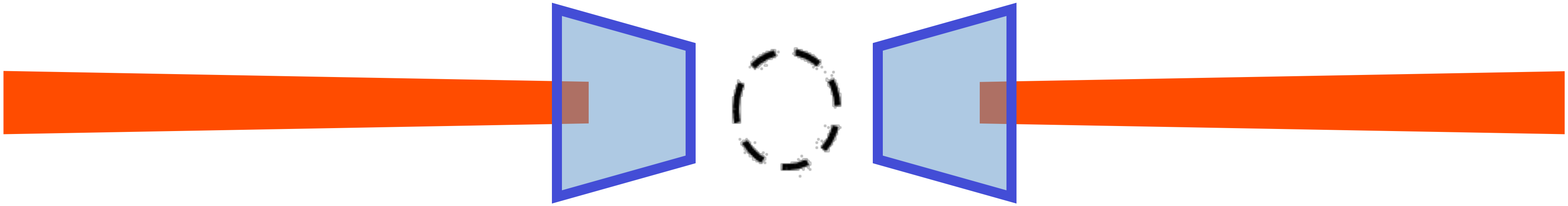

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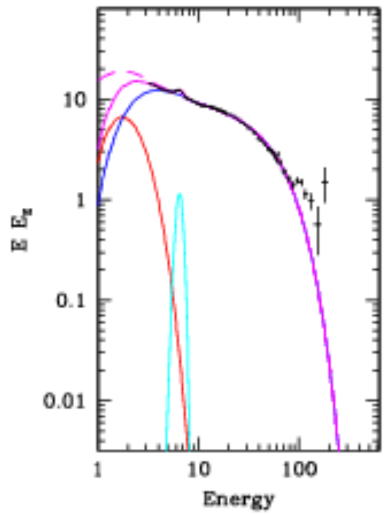

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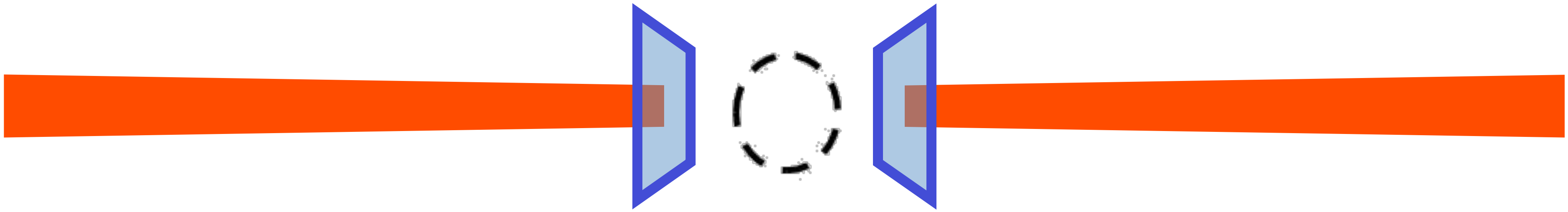

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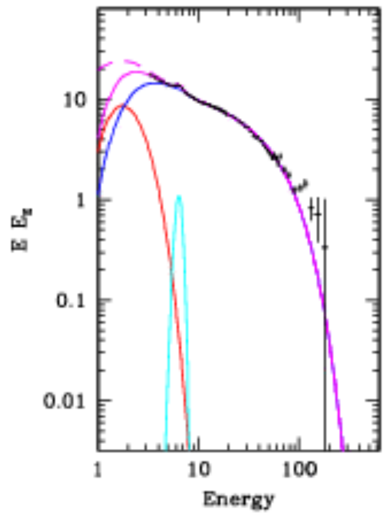

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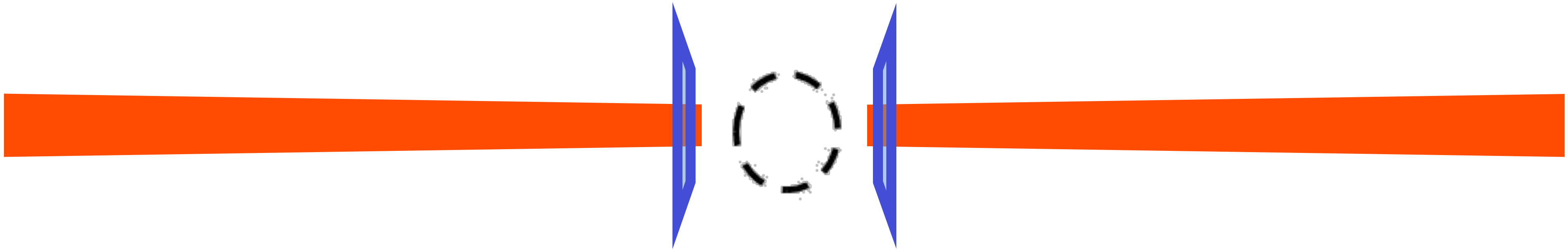

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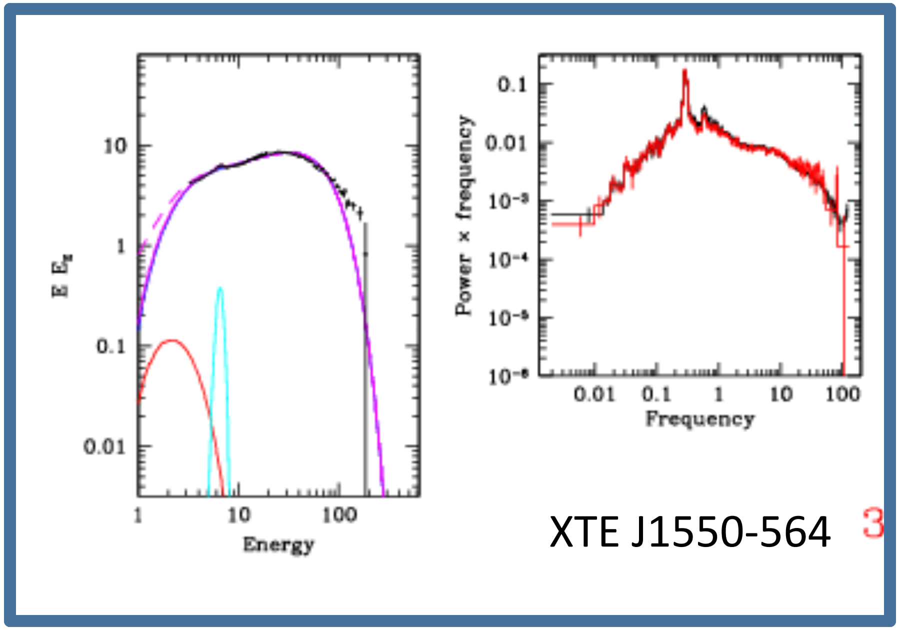
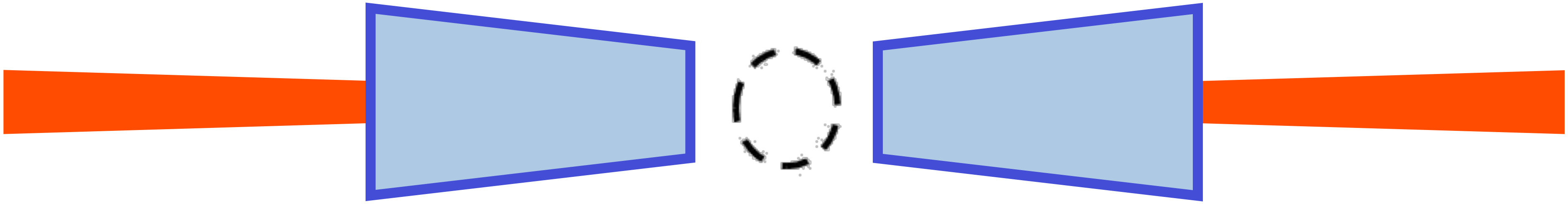
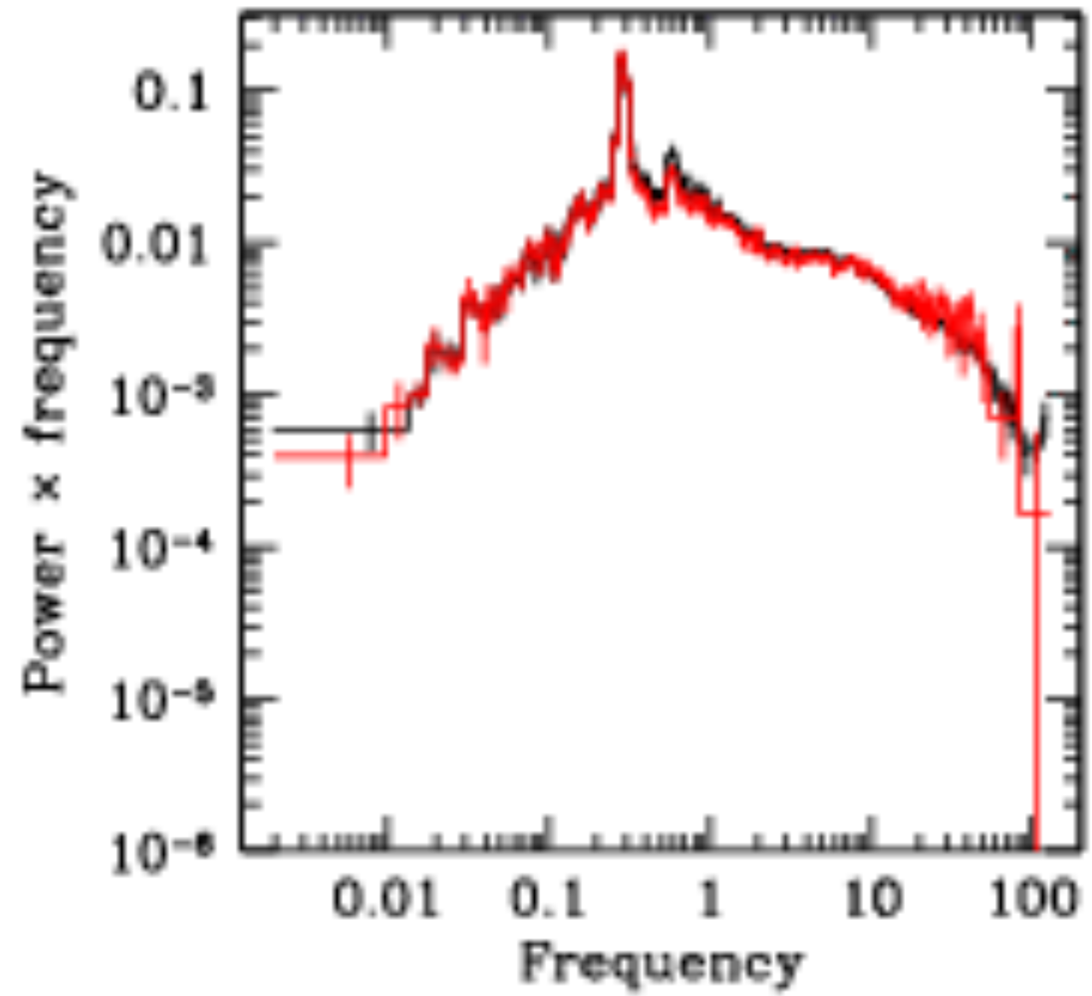
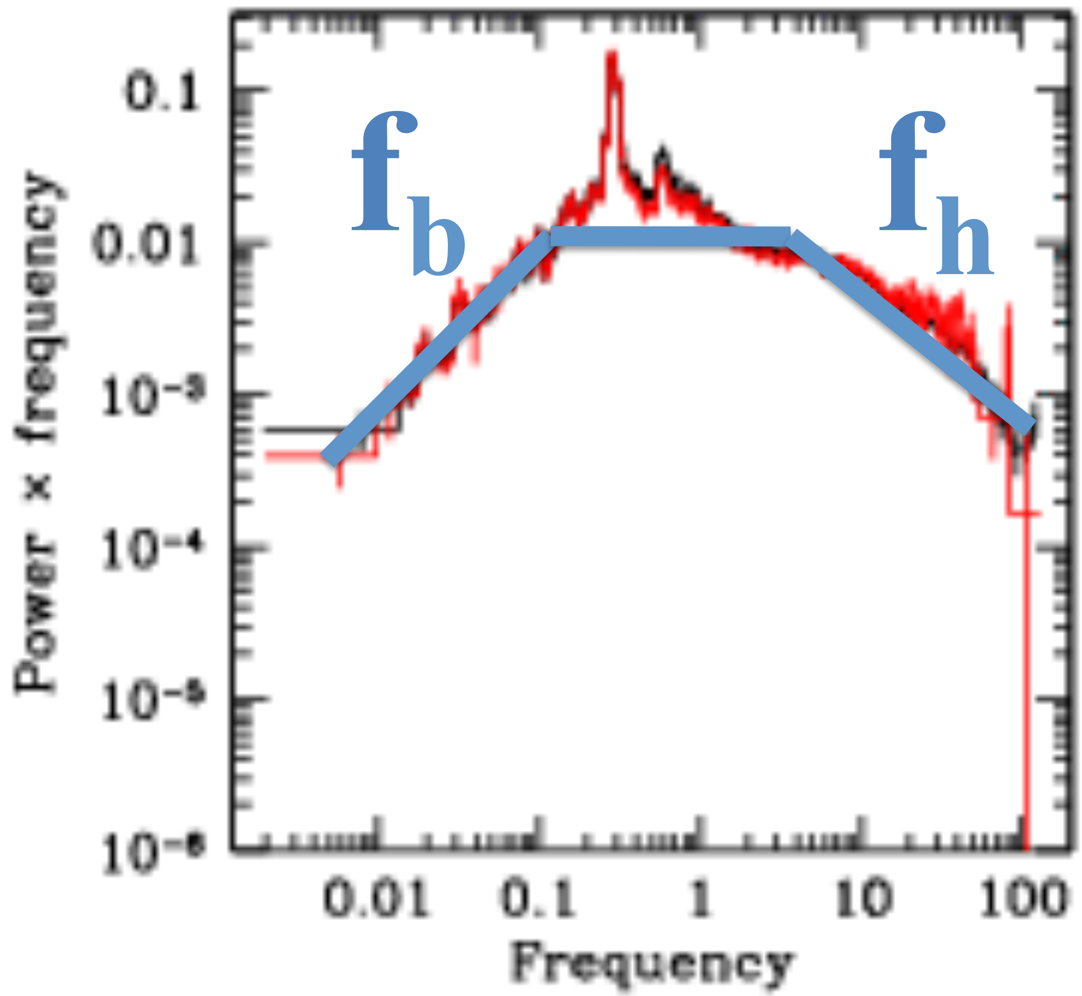




The


0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Power × frequency
0.01
0.1
1
10
100
Frequency

The



0.1
0.01
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.01
0.1
1
10
100
Frequency
Power × frequency
f_b
f_h

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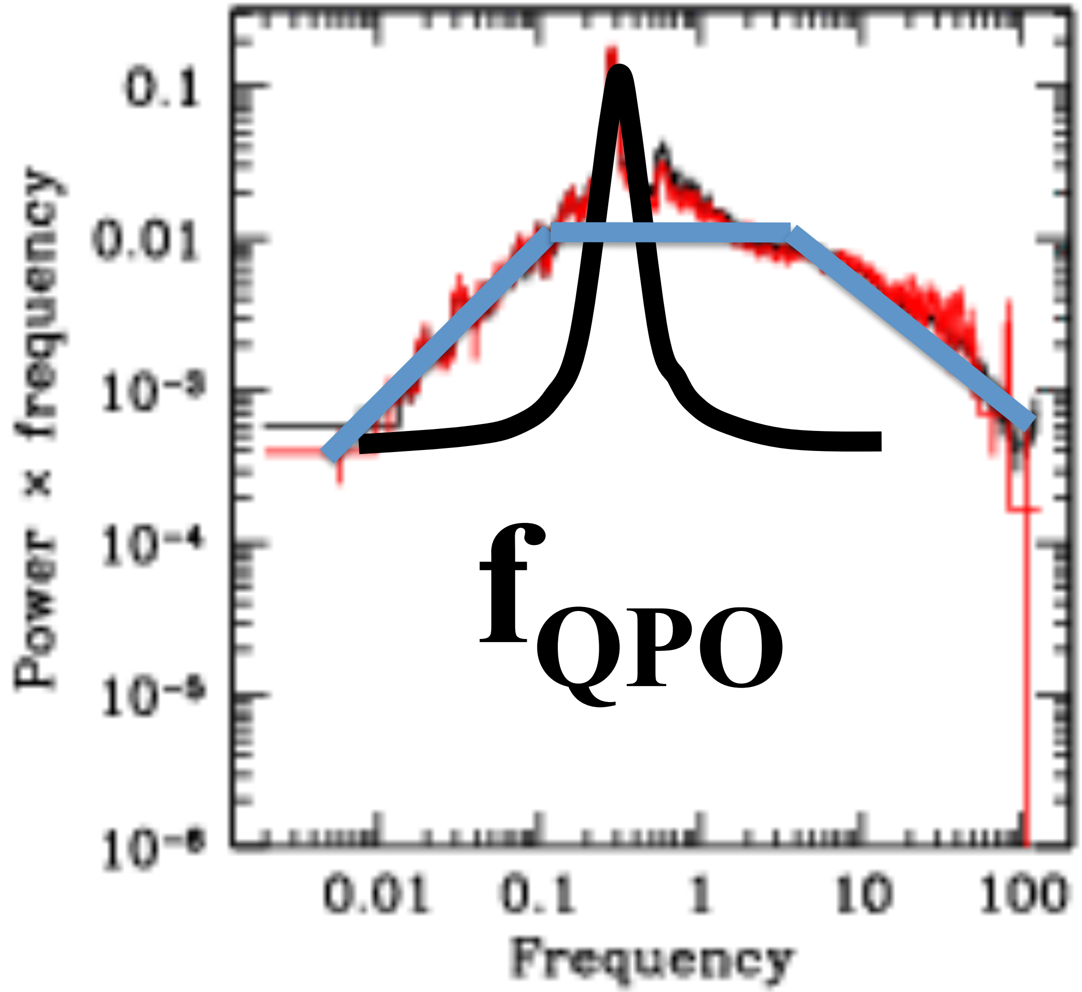
The



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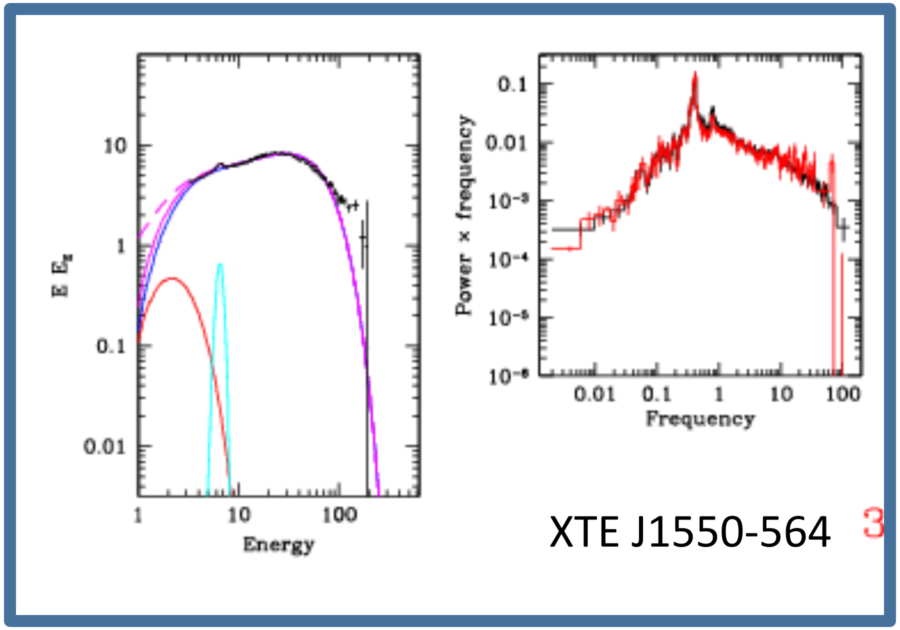

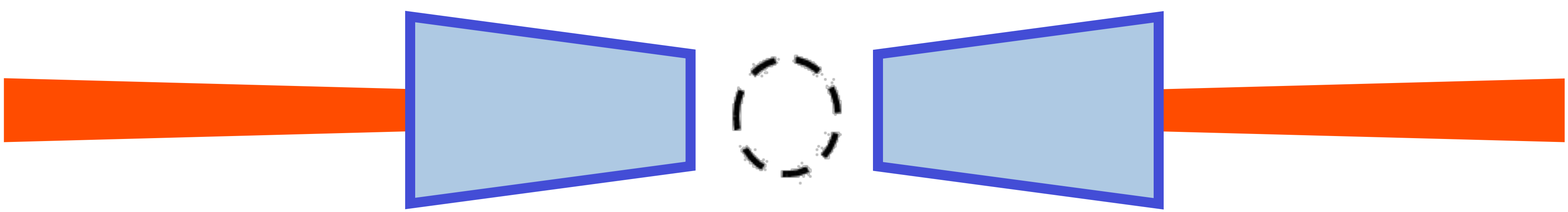

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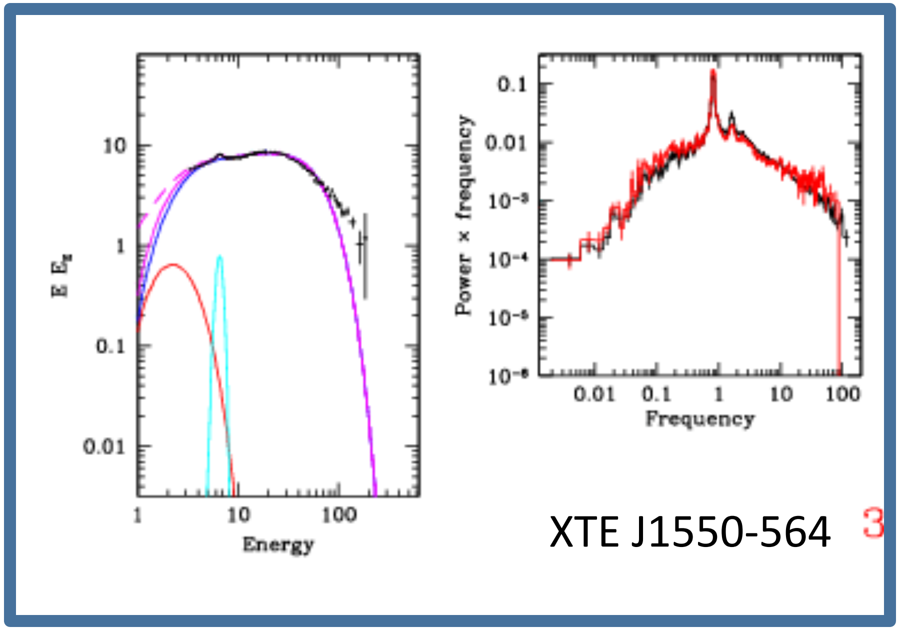

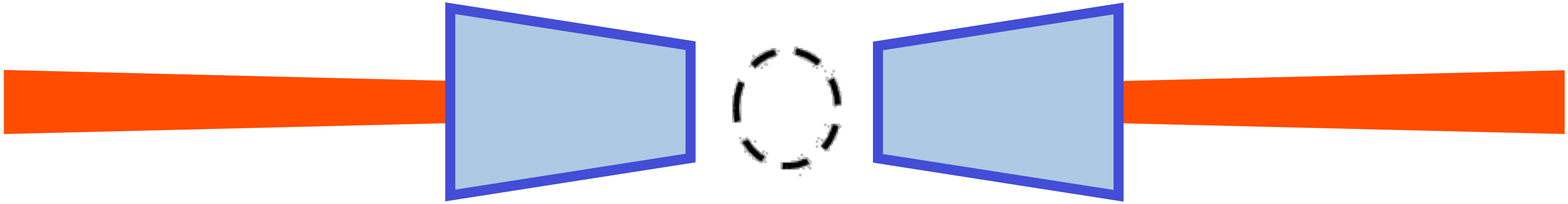

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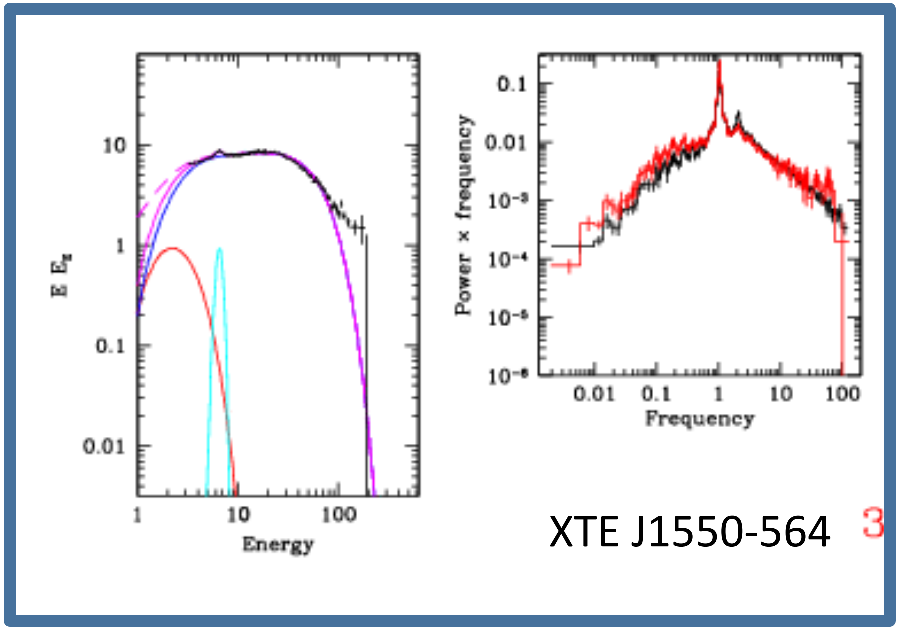

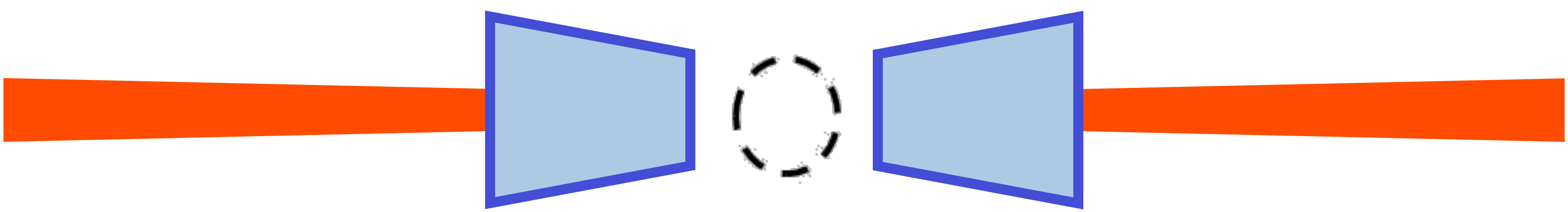

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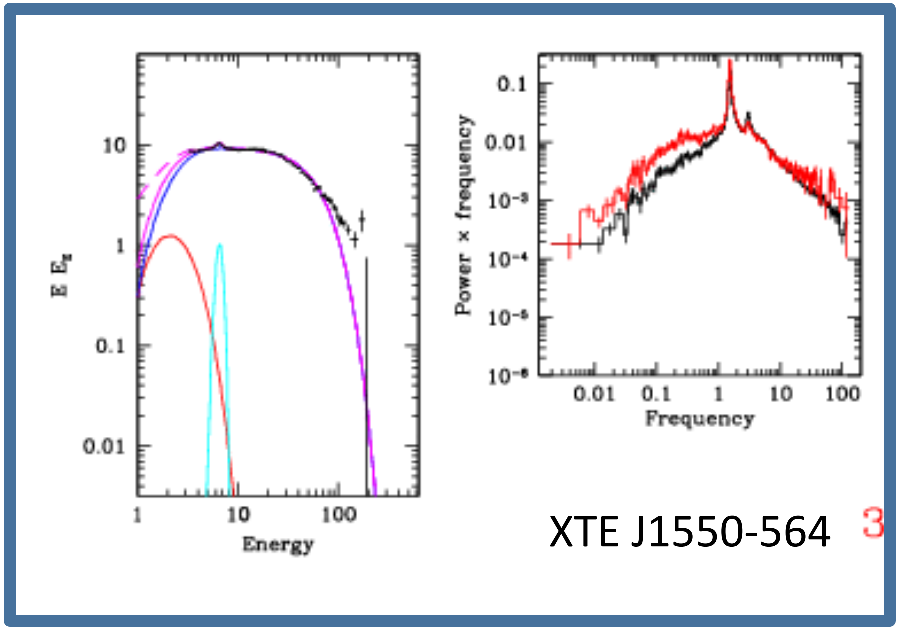

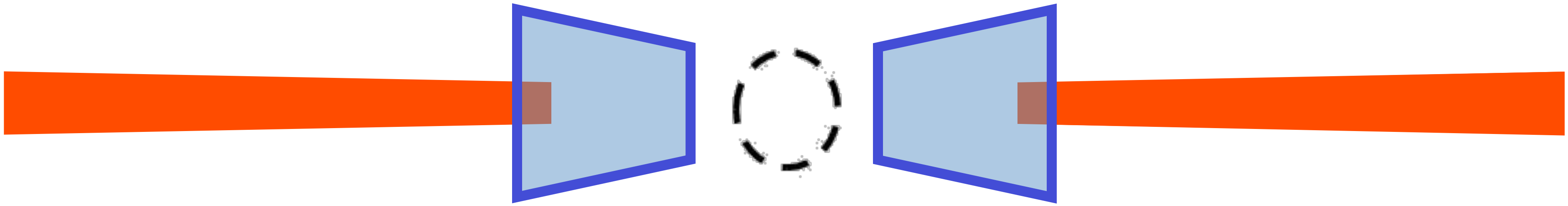

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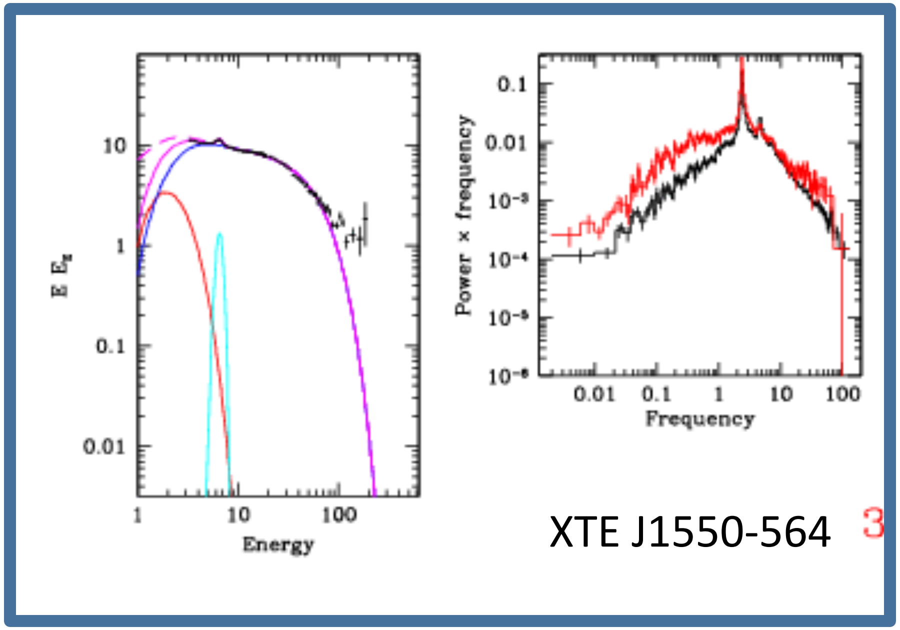

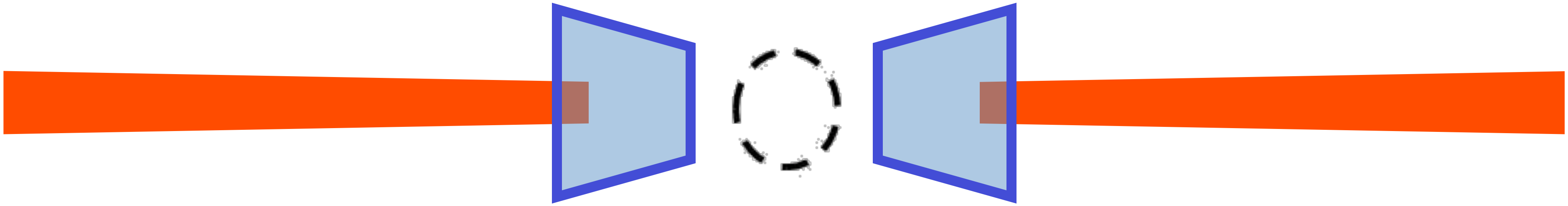

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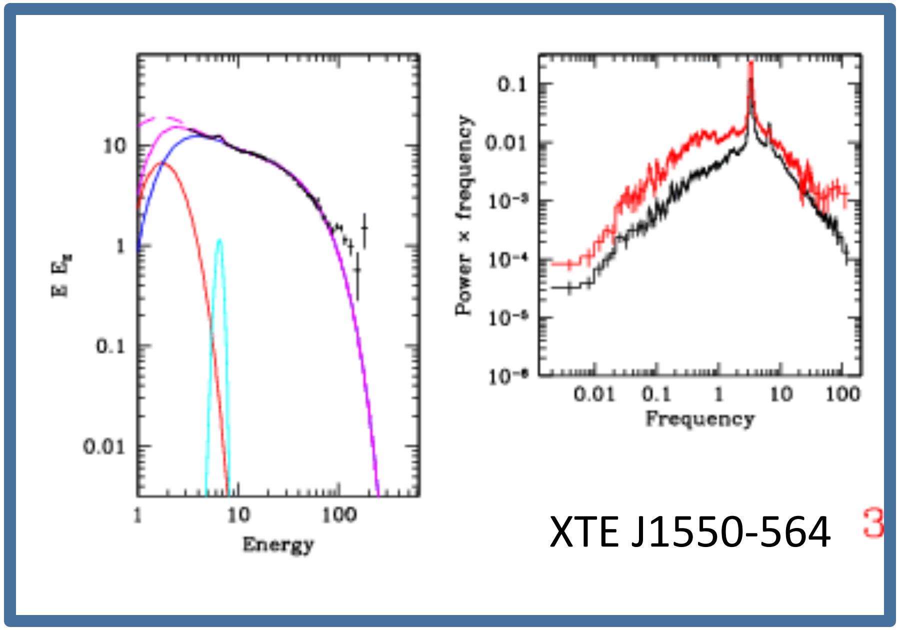

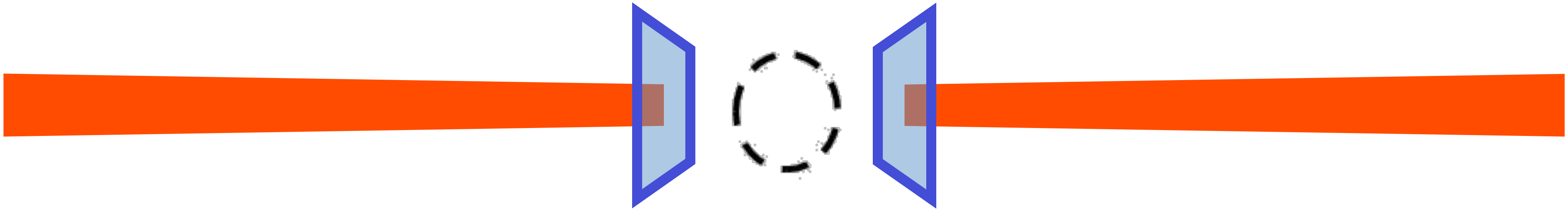

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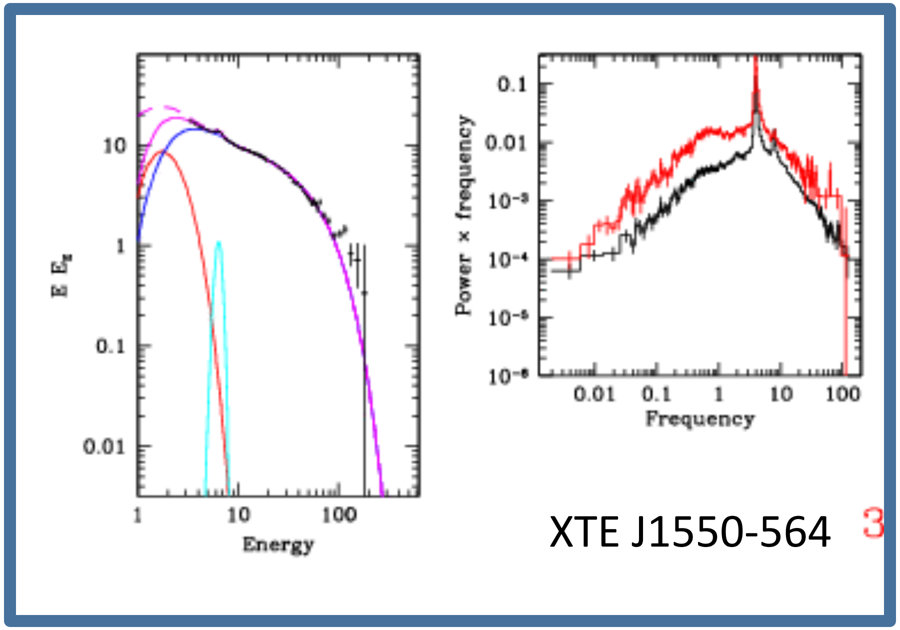
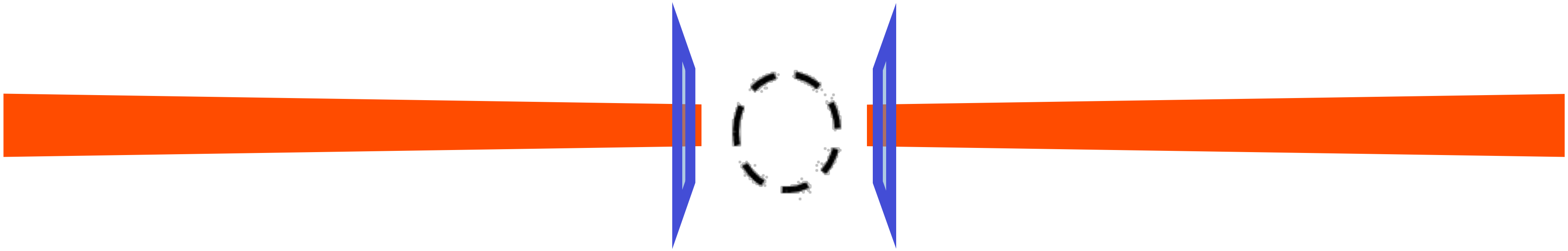


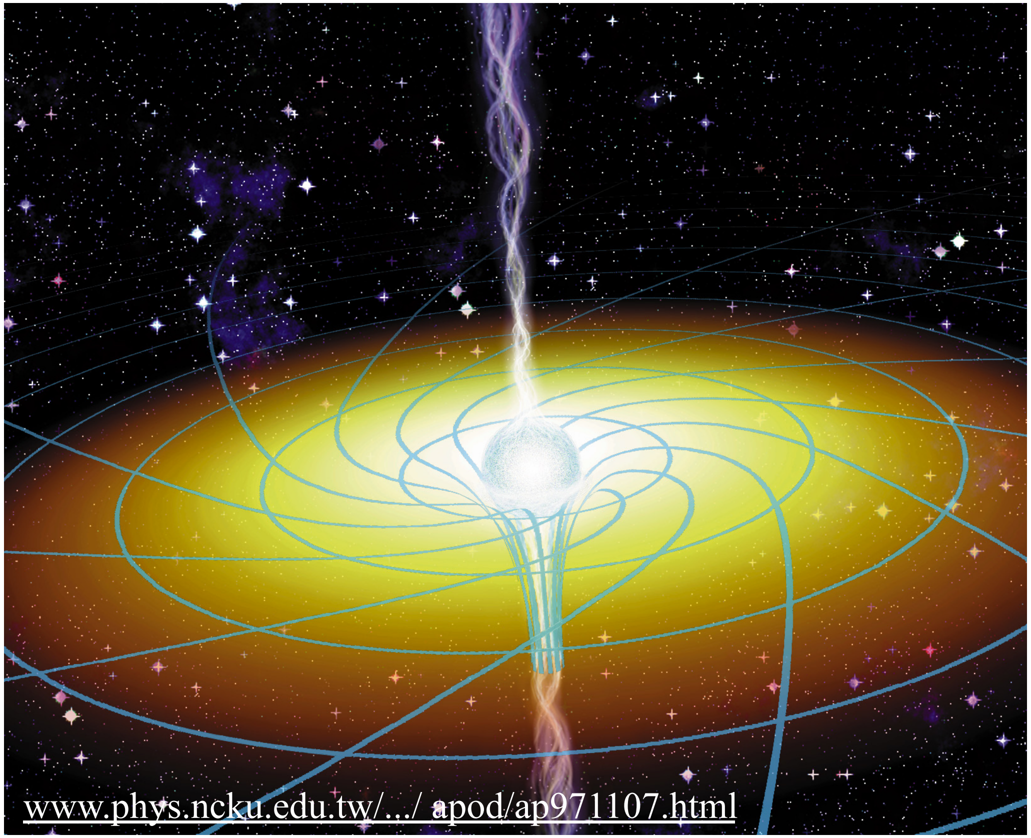


…so what is the QPO?
what is the broadband noise?

QPO?

Stella & Vietri 1998: Lense-Thirring precession?

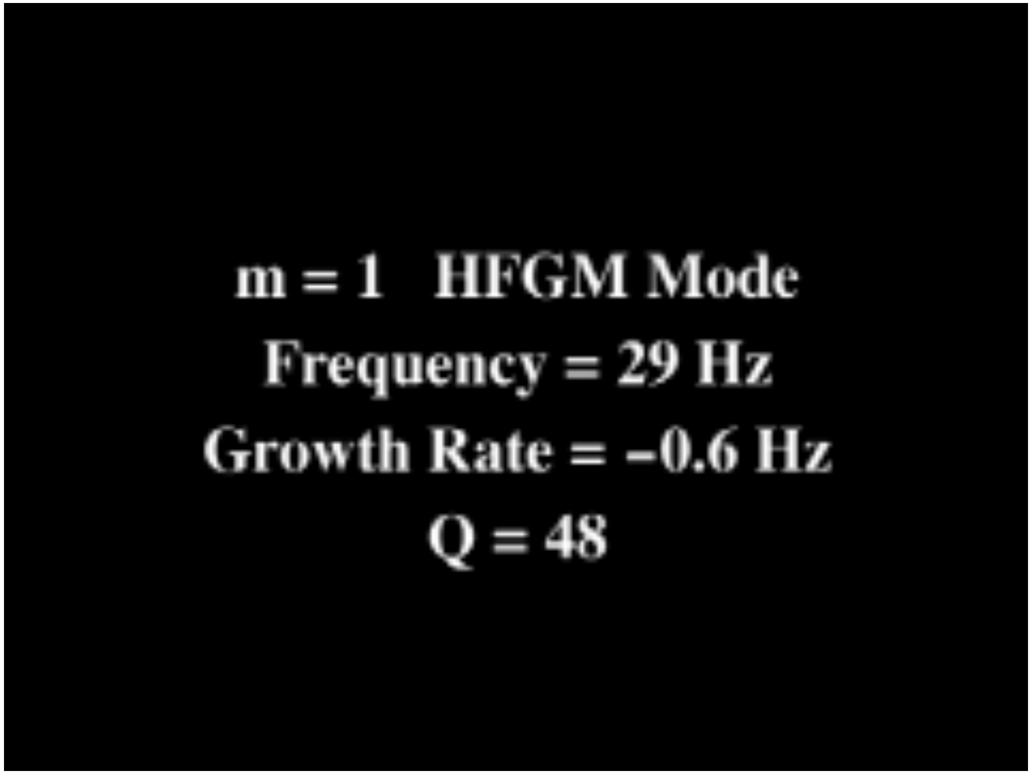
Lense-Thirring precession



- Asymmetric potential => precession of particle orbits

  …Lense-Thirring precession

Lense-Thirring precession



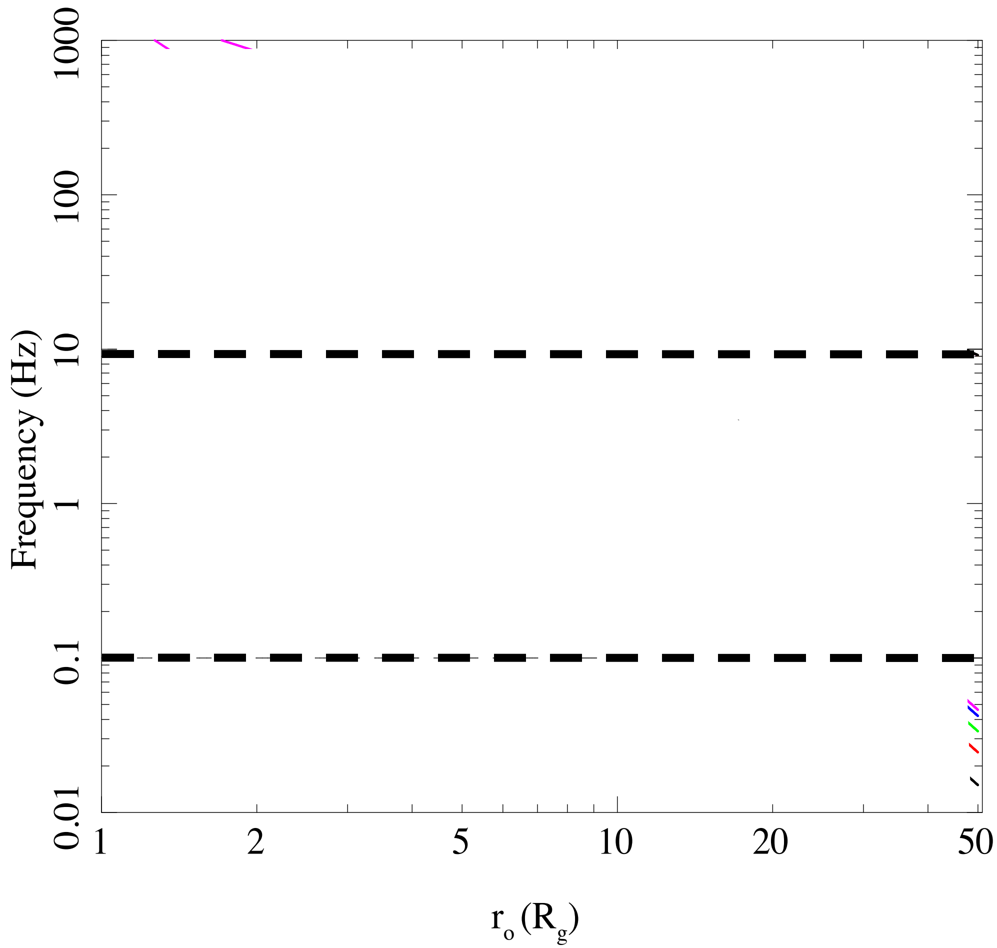
- Asymmetric potential => precession of particle orbits

…Lense-Thirring precession

Marković, Lamb, Duez, Engelhard, Fregeau & Huffenberger

Lense-Thirring precession

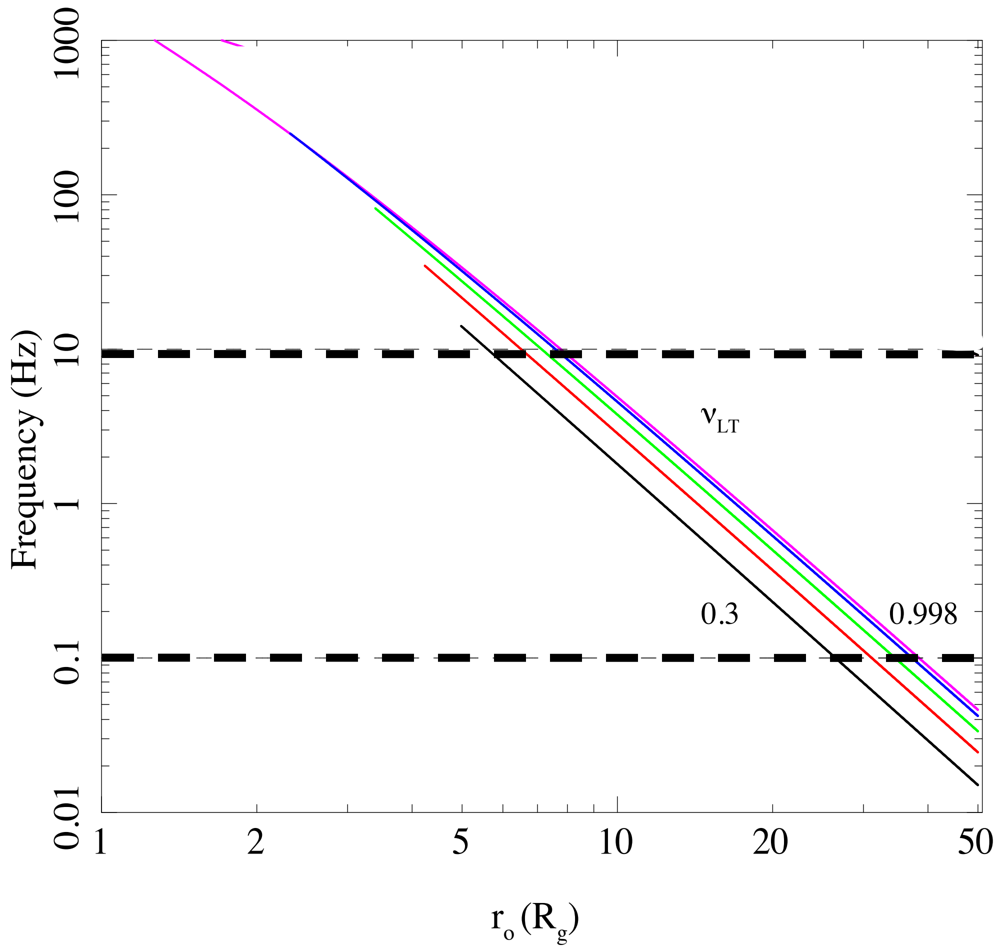
Lense-Thirring precession? – test mass at r_o



Ingram, Done & Fragile 2009

Lense-Thirring precession

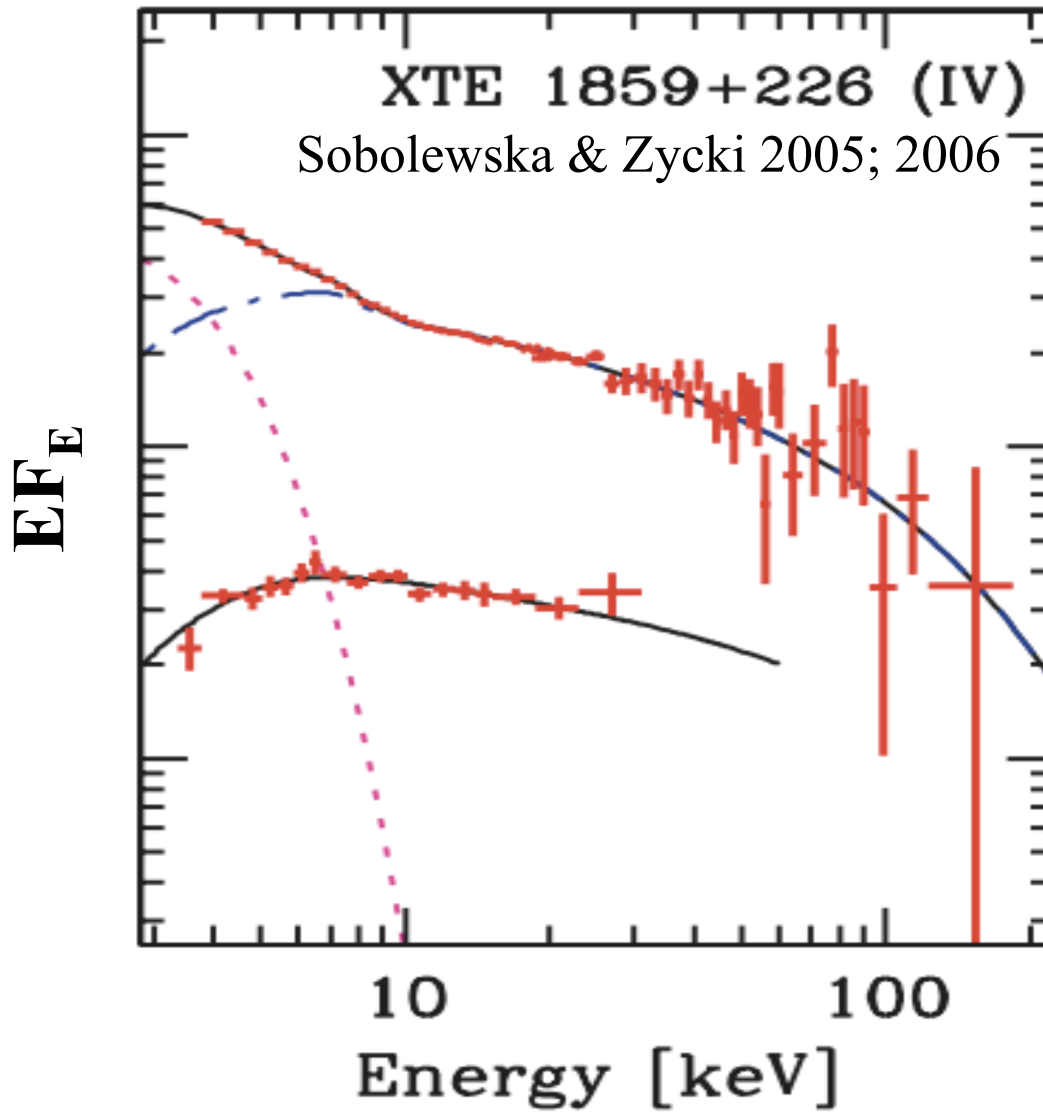
Lense-Thirring precession? – test mass at r_o



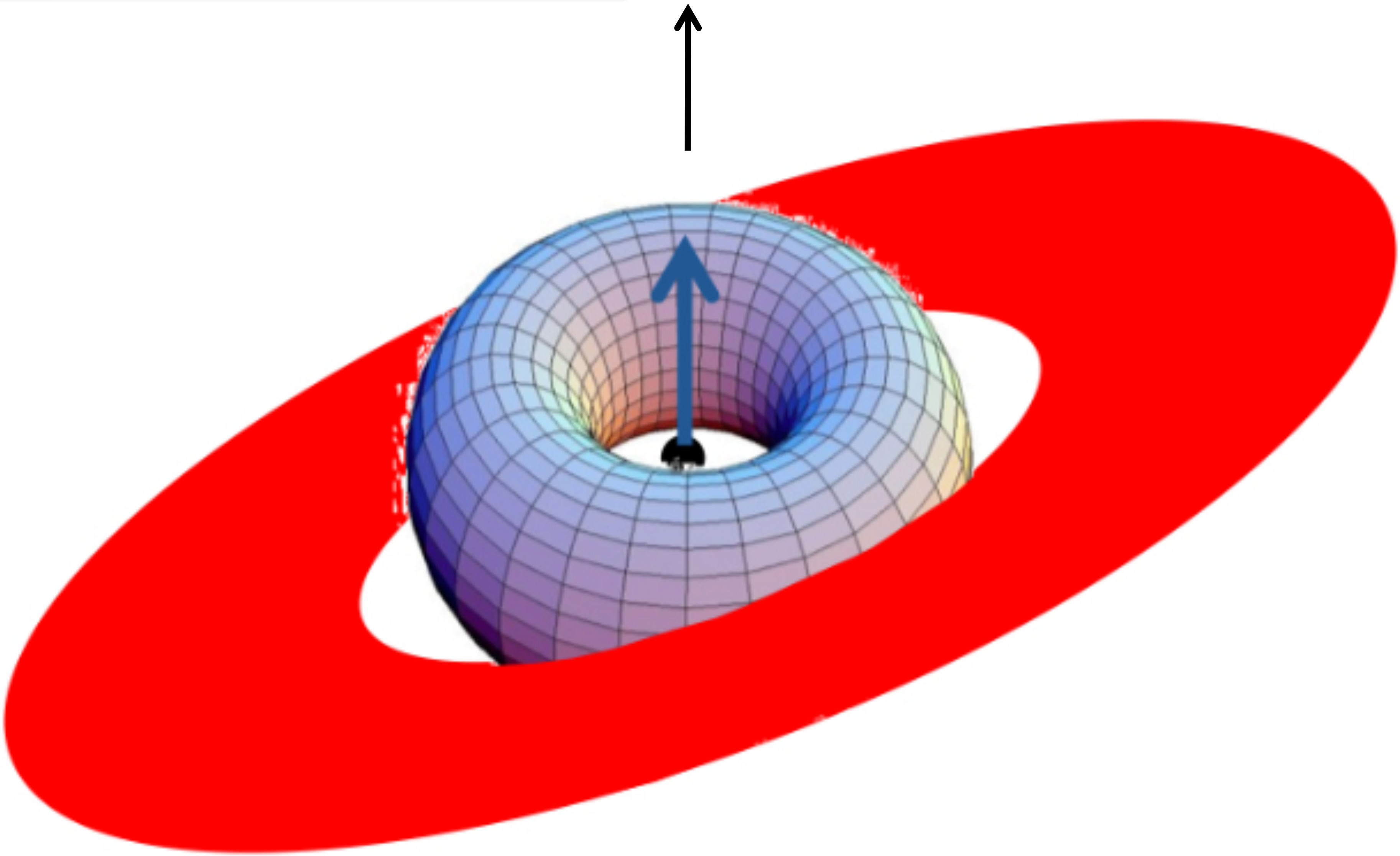
Ingram, Done & Fragile 2009

Lense-Thirring precession

- QPO is observed in the Comptonized tail
- Need a model that ties the QPO to the tail



Lense-Thirring precession



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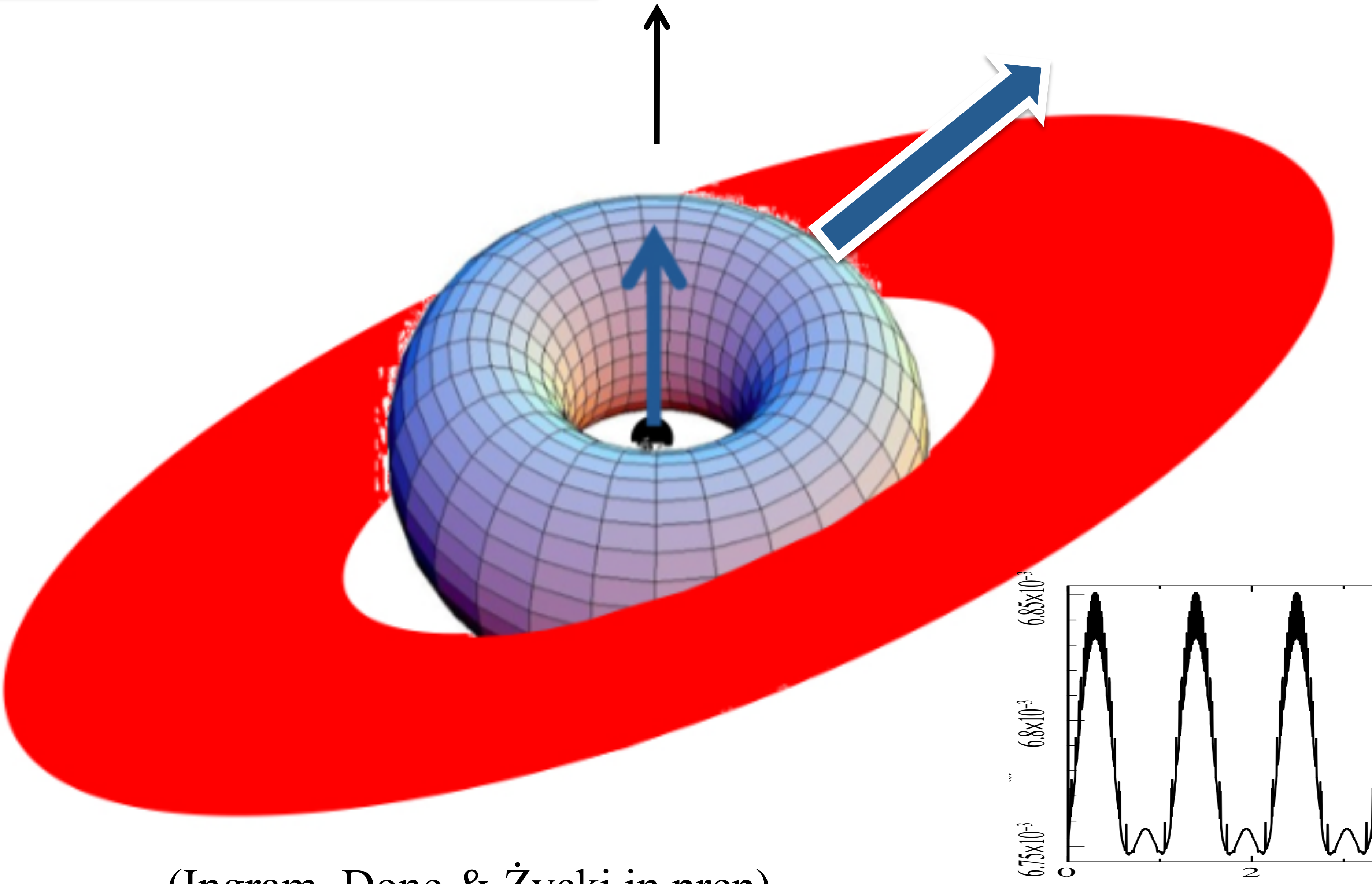
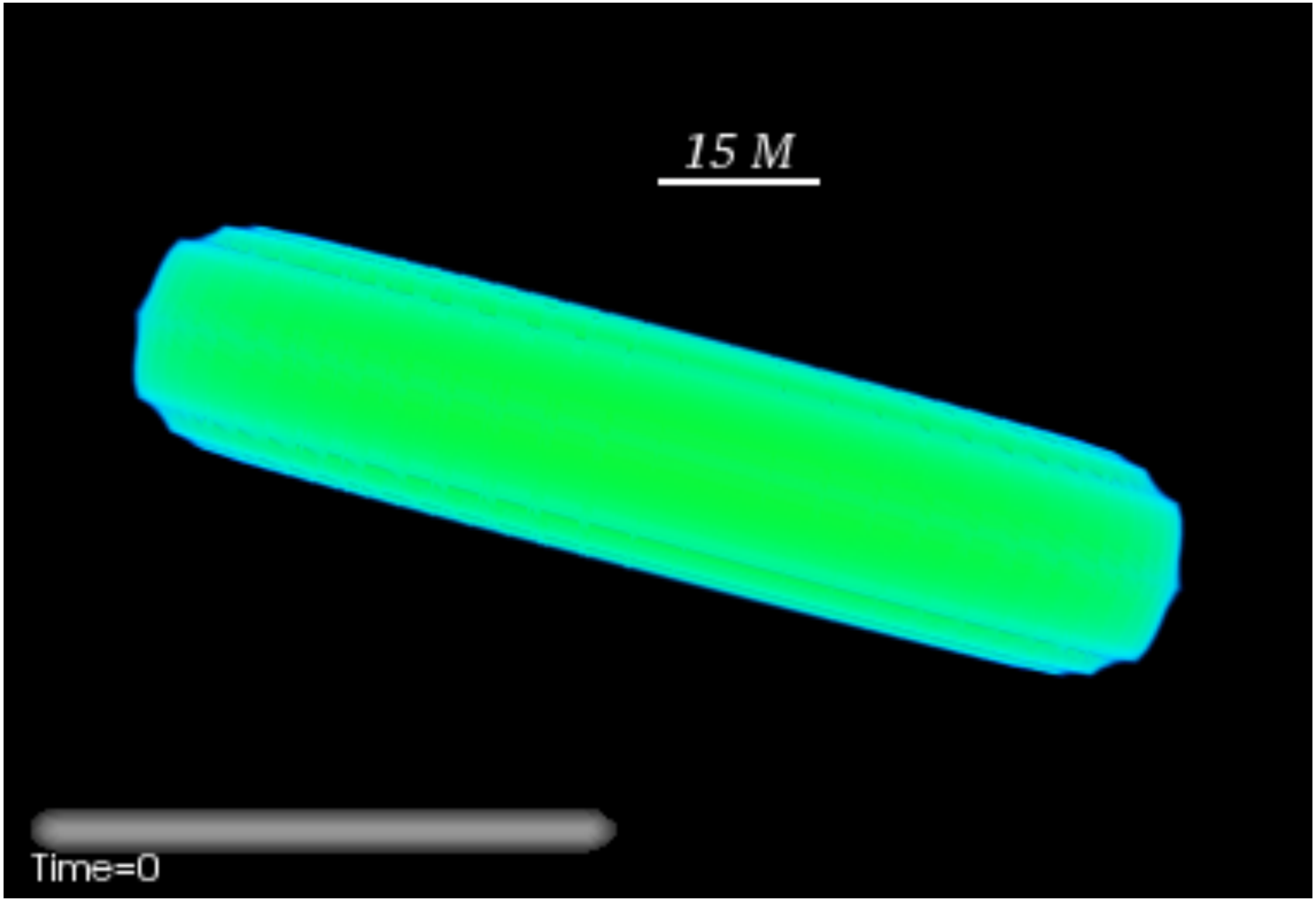


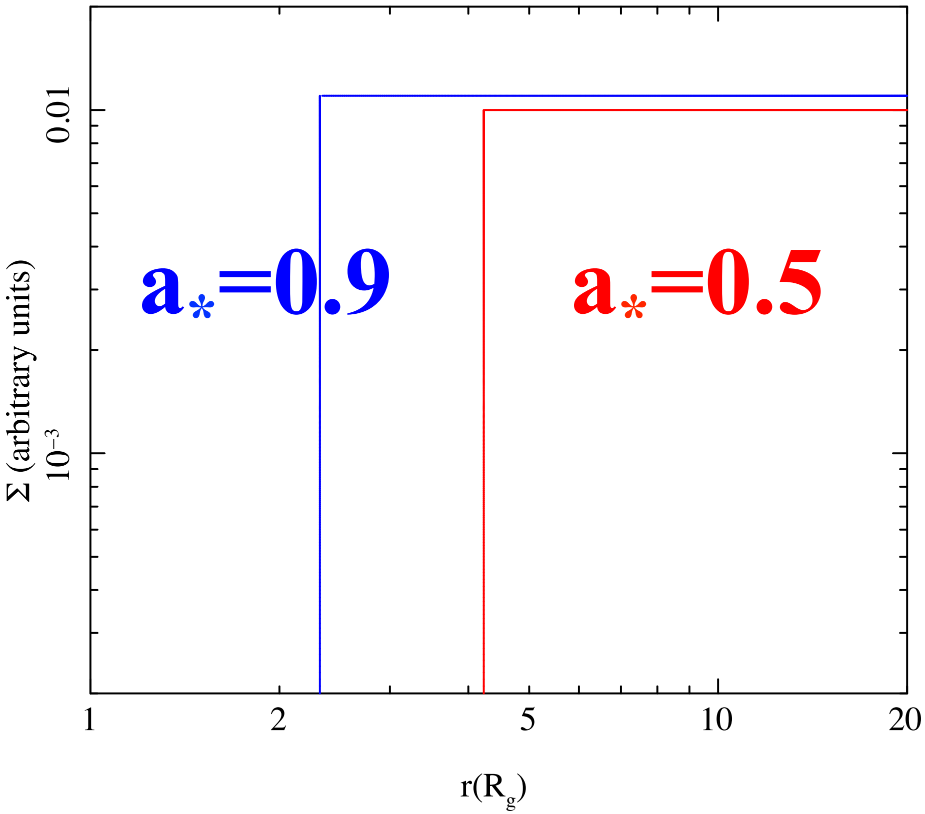
(Ingram, Done & Życki in prep)

Lense-Thirring precession

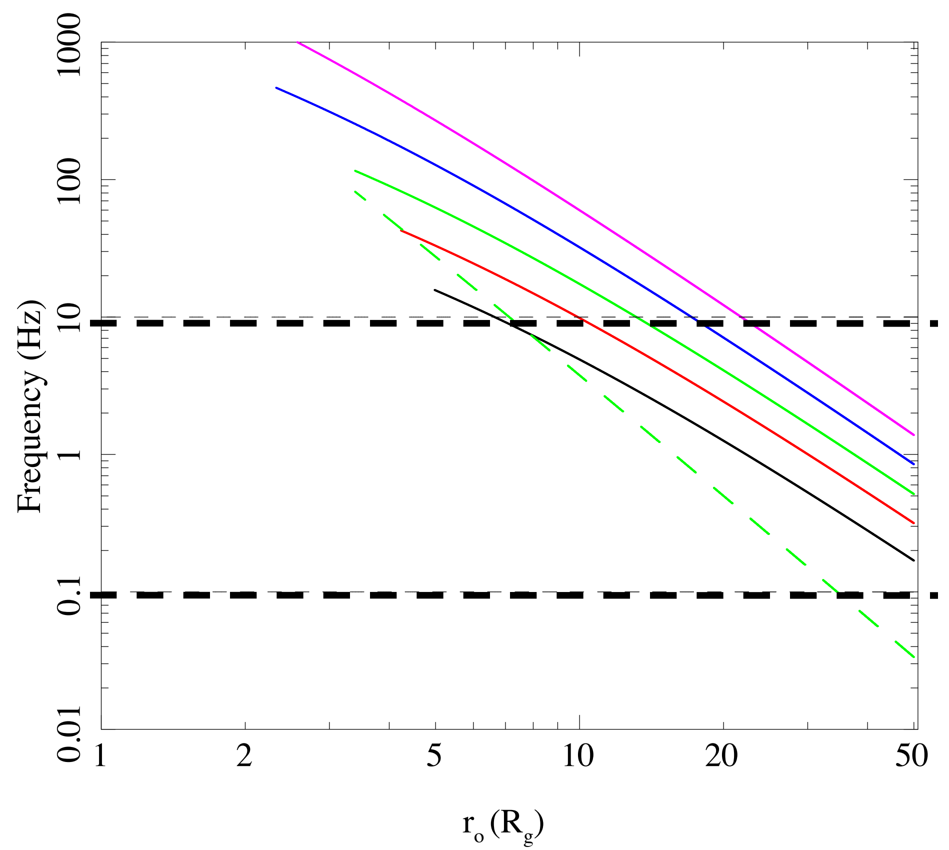


Fragile et al 2007

Lense-Thirring precession



Ingram, Done & Fragile 2009



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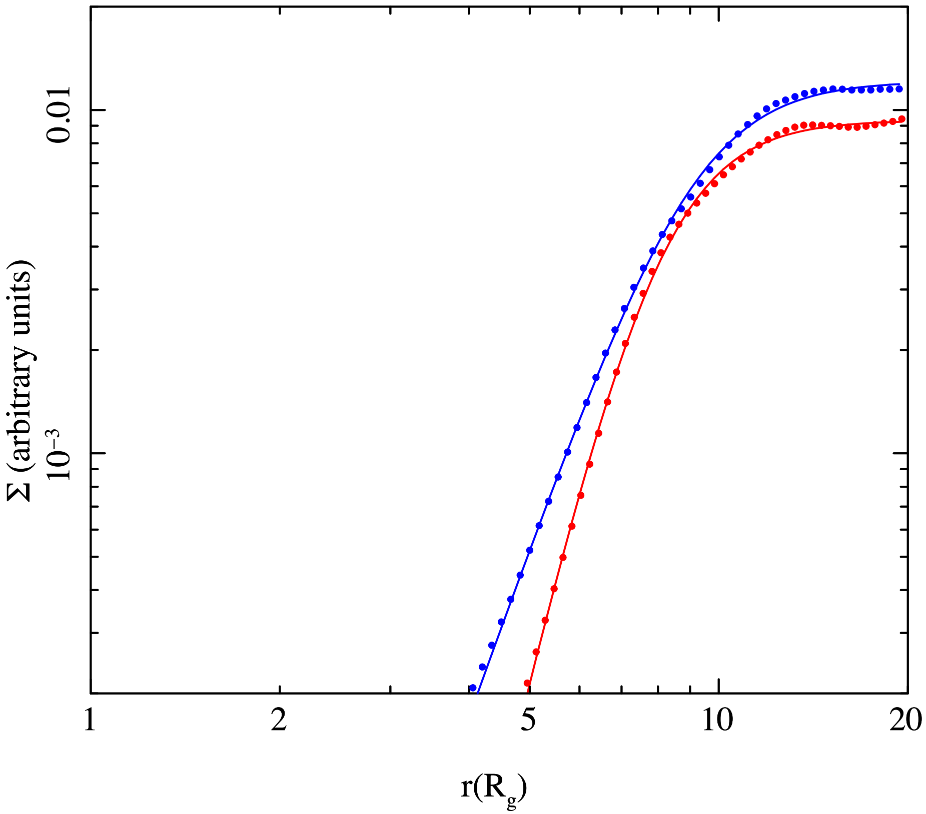
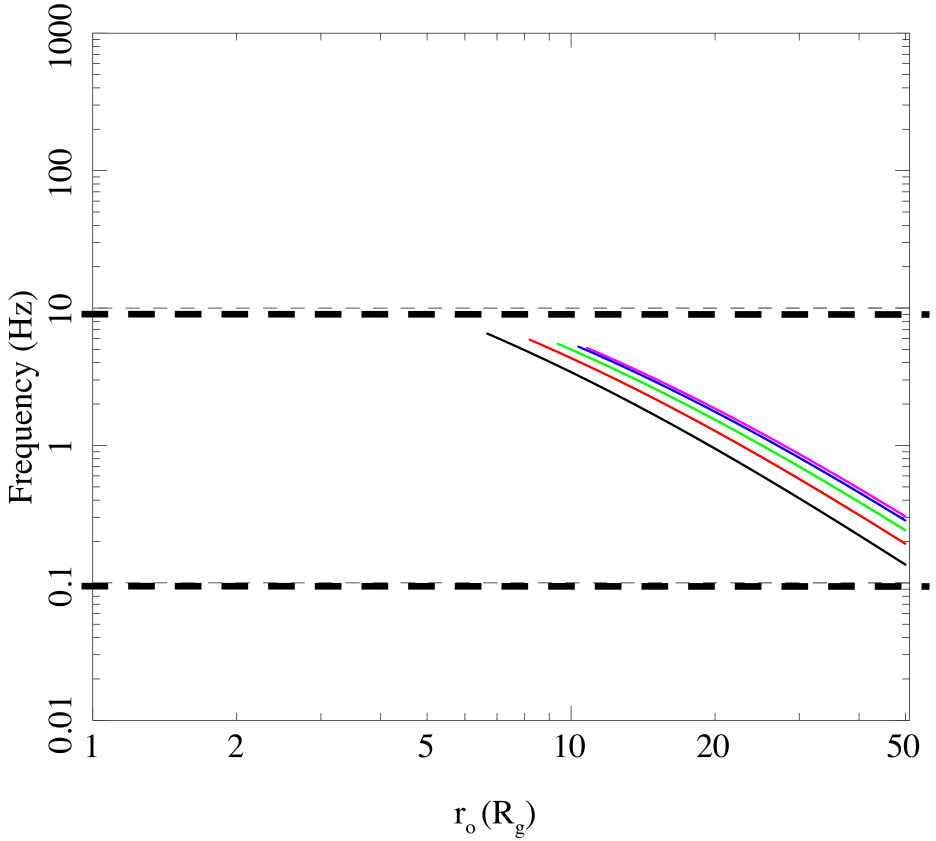
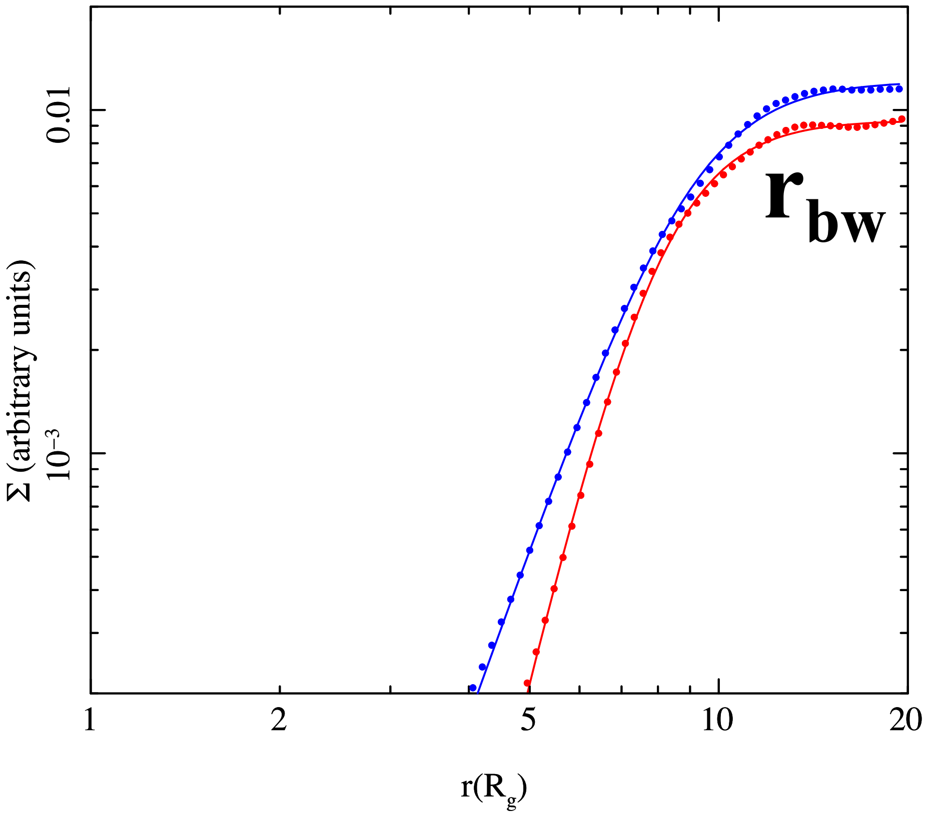


Ingram, Done & Fragile 2009
Fragile et al 2007

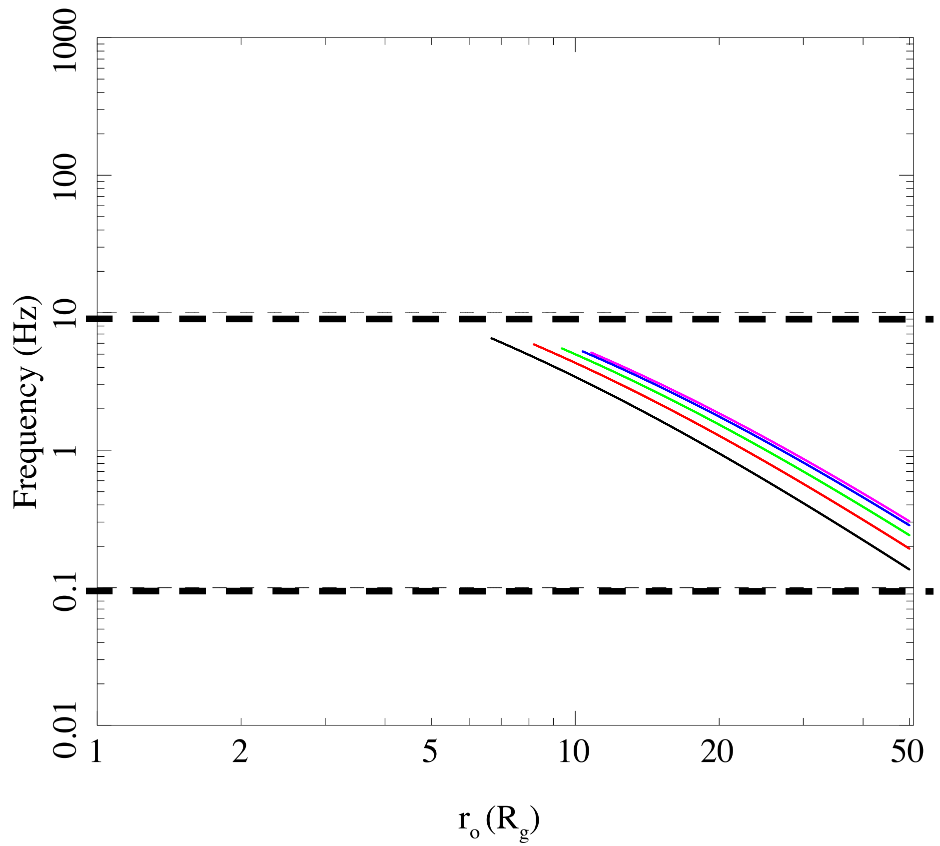


Lense-Thirring precession



$$r_{bw}=3(h/r)^{-4/5}a_*^{2/5}$$

Ingram, Done & Fragile 2009
Fragile et al 2007
Lubow & Ogilvie 2001



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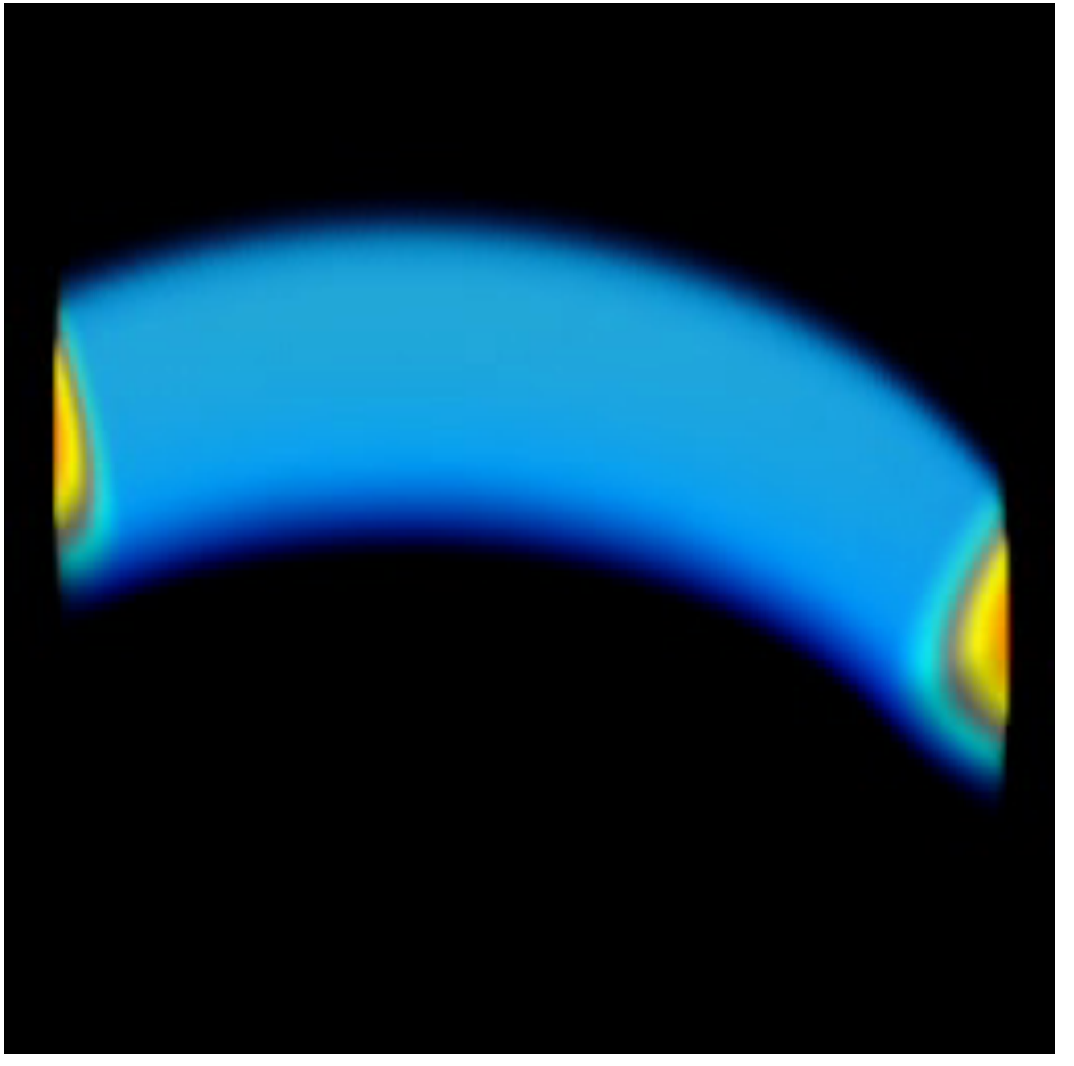
Broadband noise?

MRI

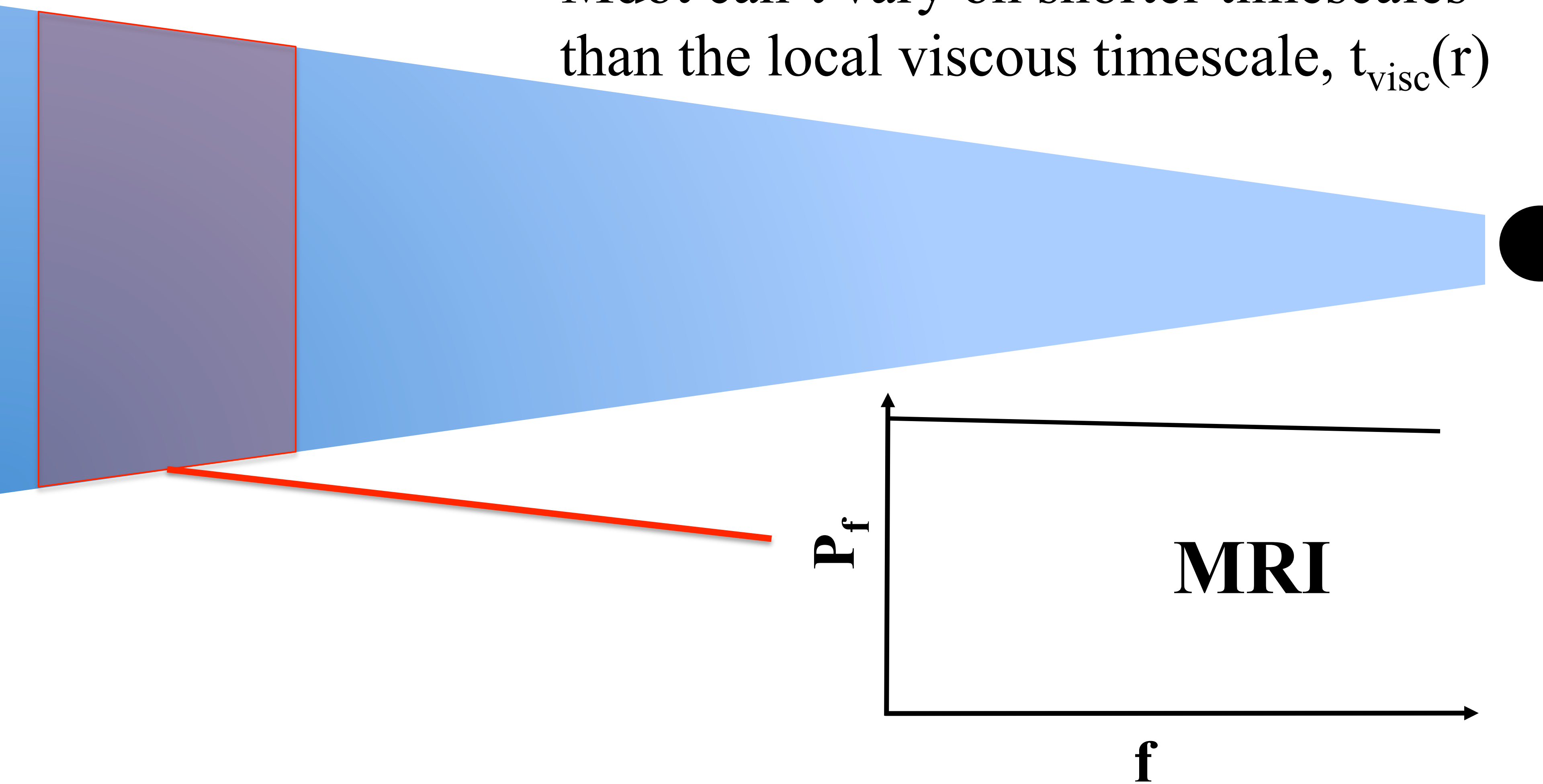
- Magneto Rotational Instability
- Underlying source of viscosity
- Underlying source of variability
- Variability up to very short timescales (~white noise)



Krolik, de Villiers & Hawley

Propagating fluctuations

- But emission depends on Mdot
- Mdot can't vary on shorter timescales than the local viscous timescale, $t_{visc}(r)$



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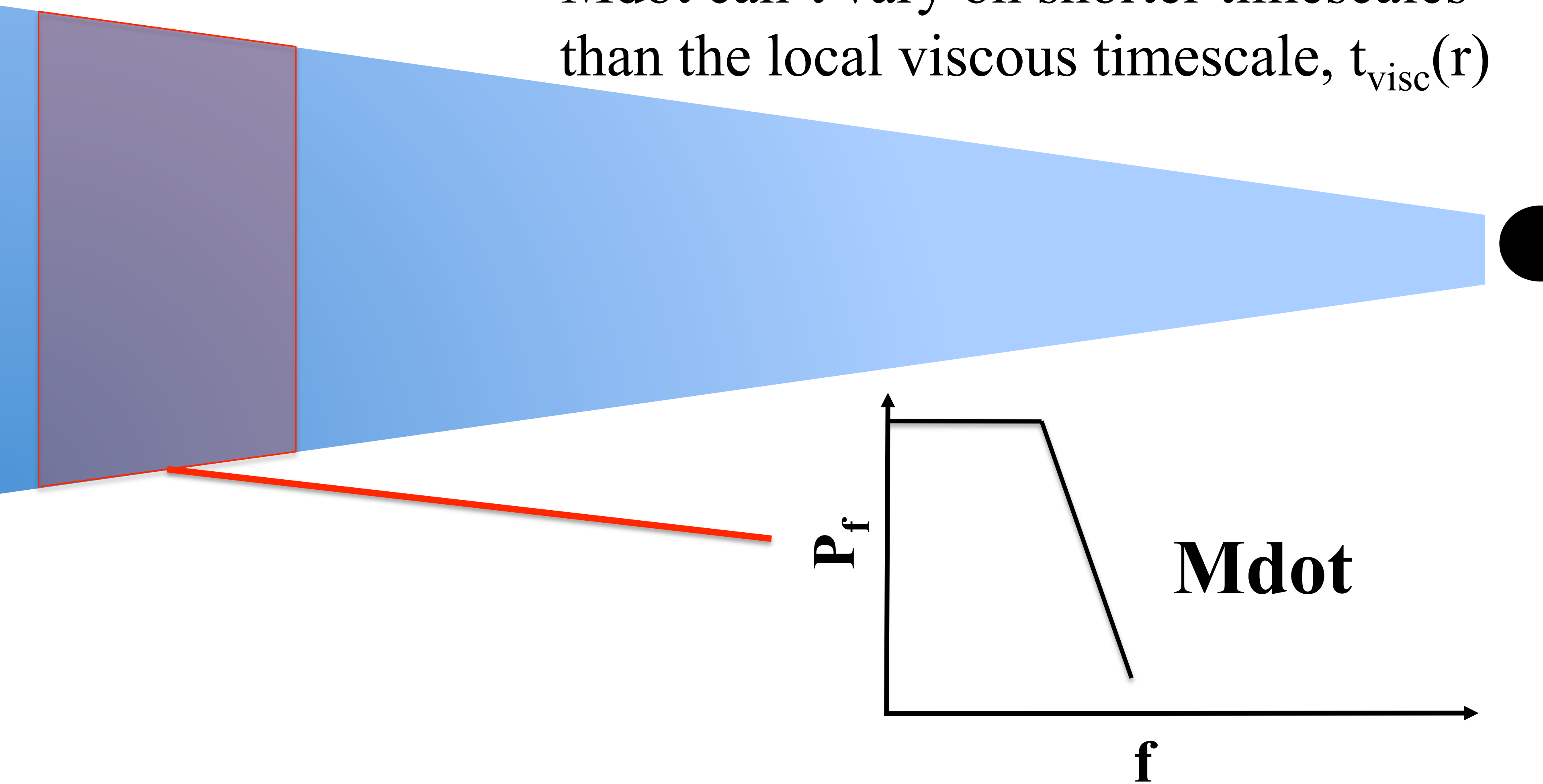

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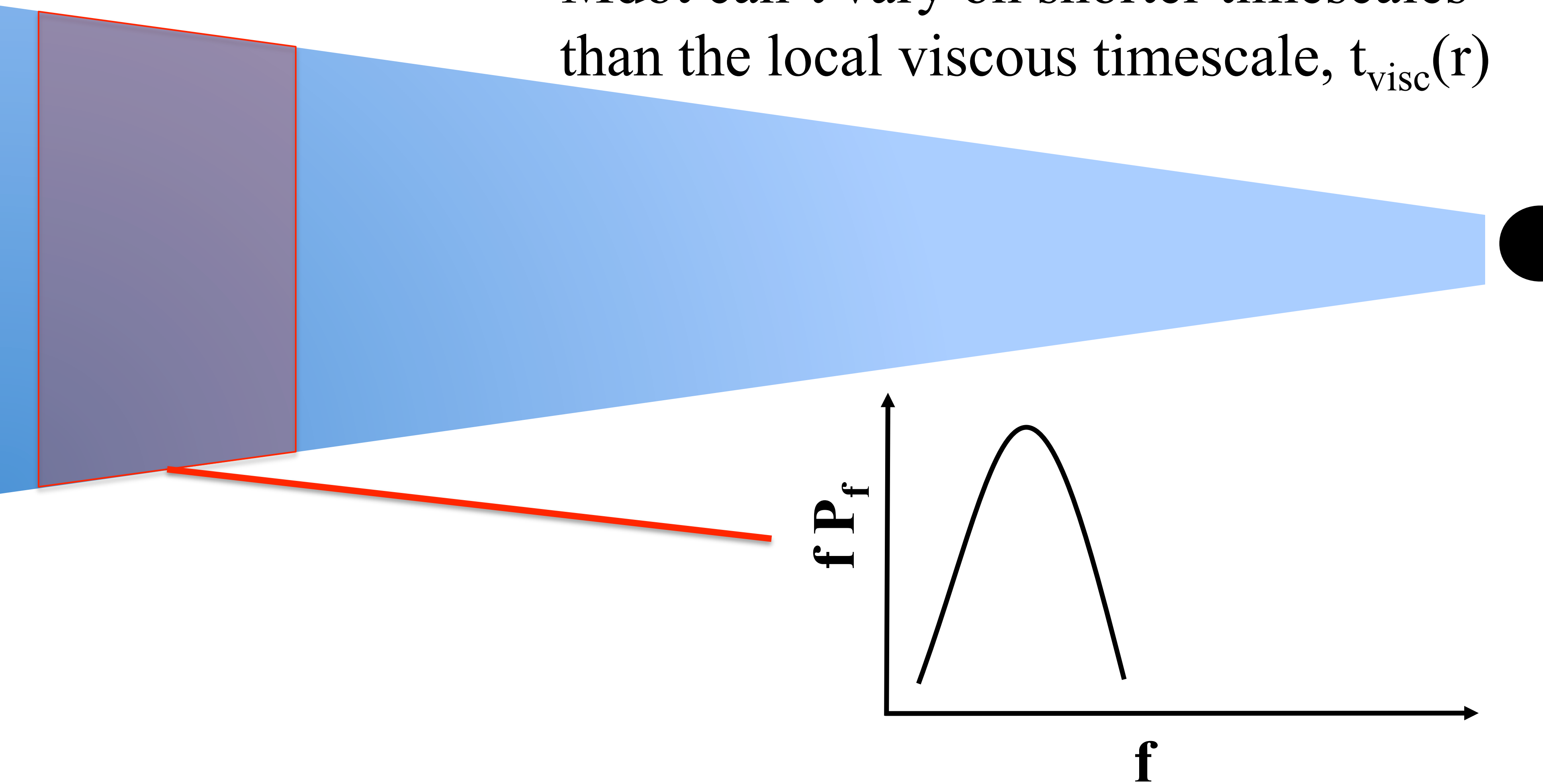

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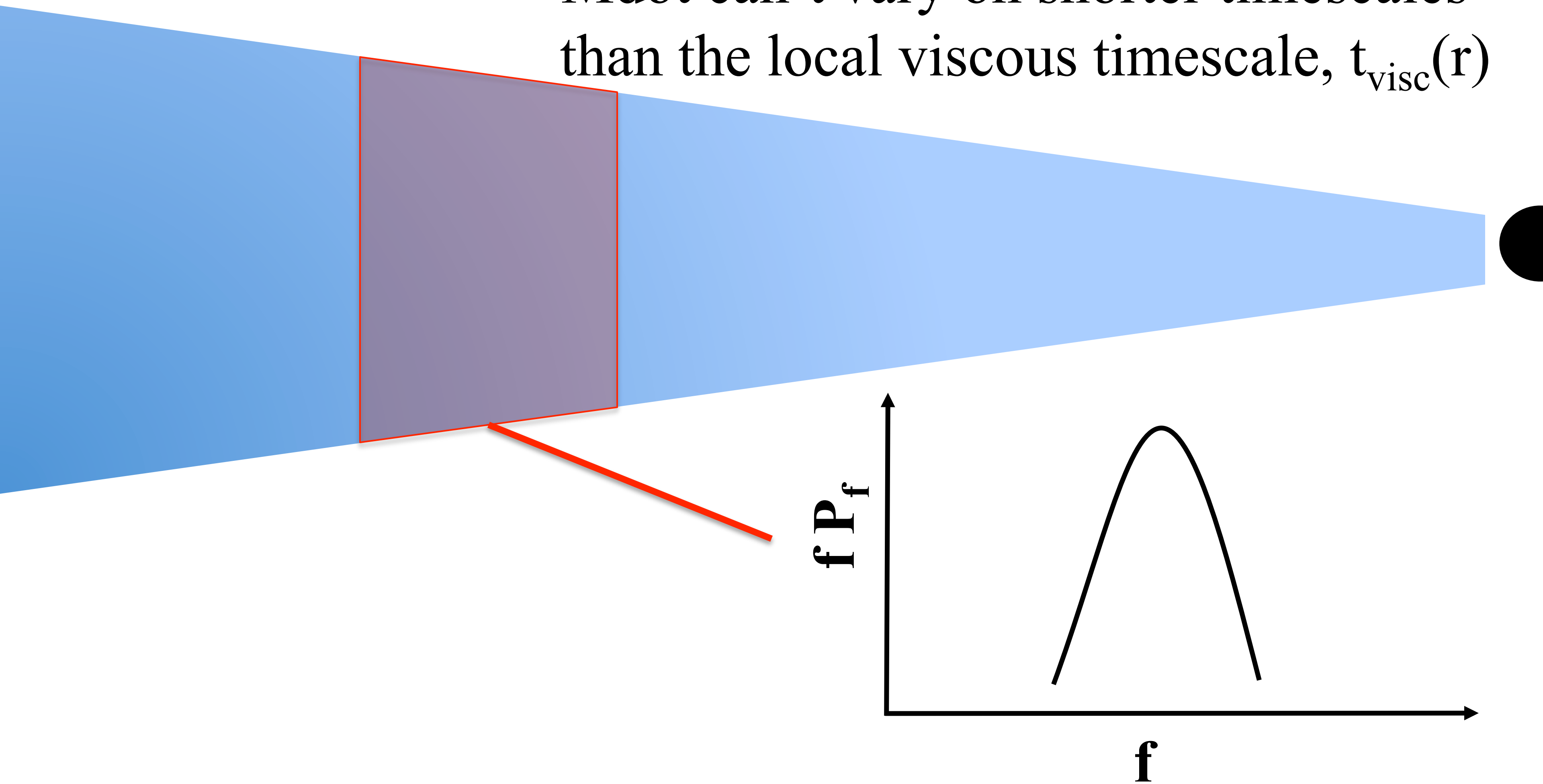

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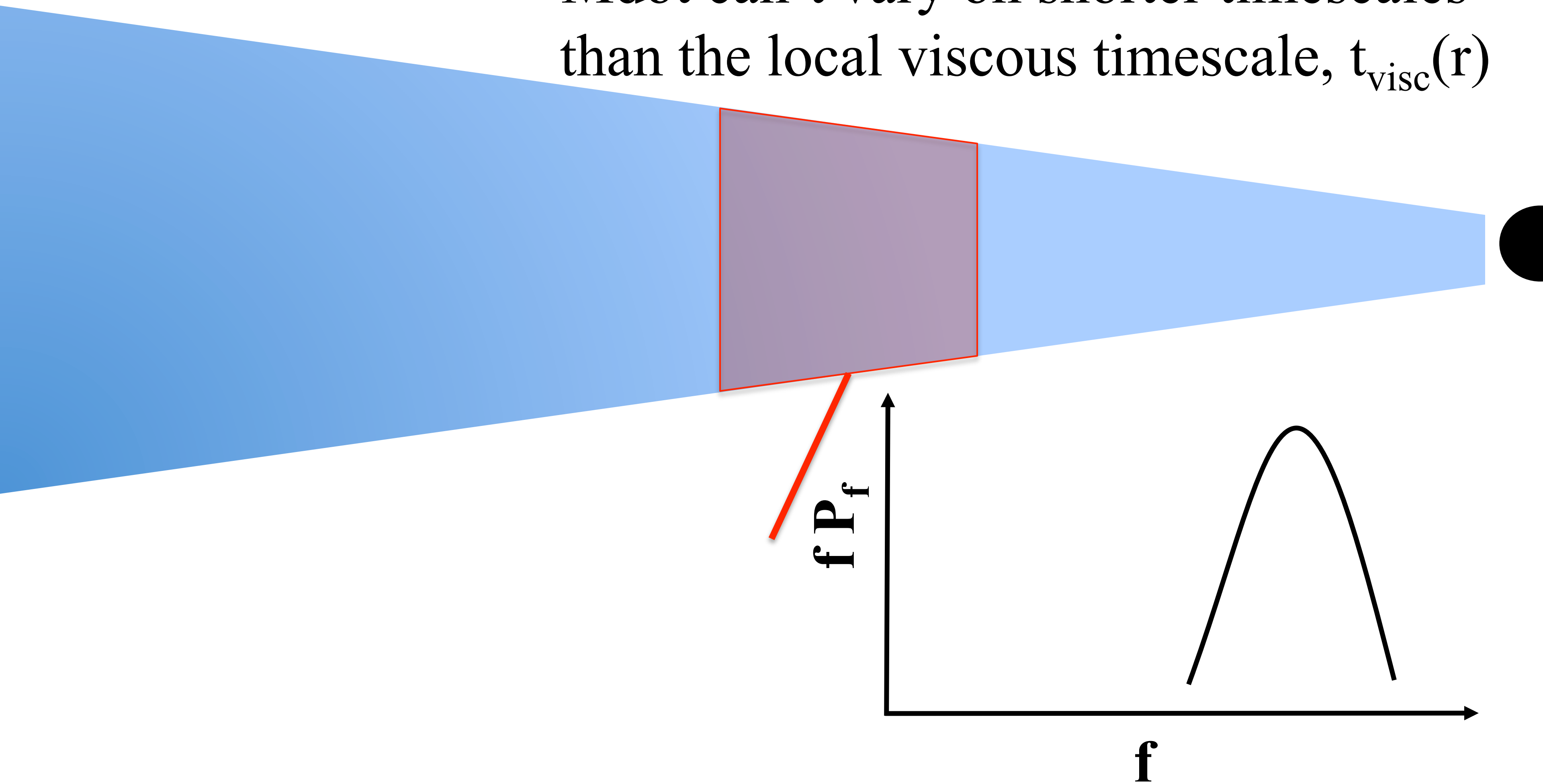

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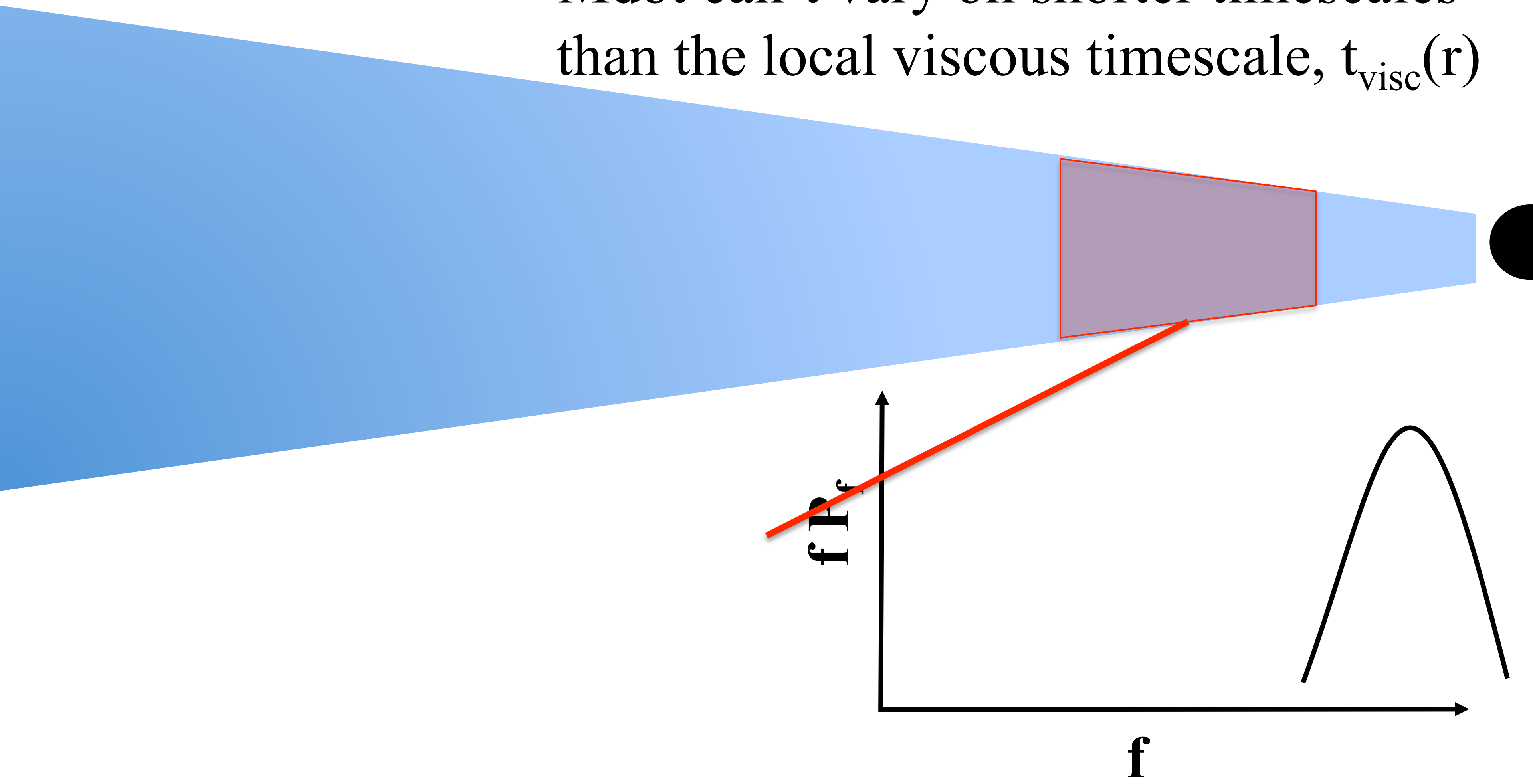
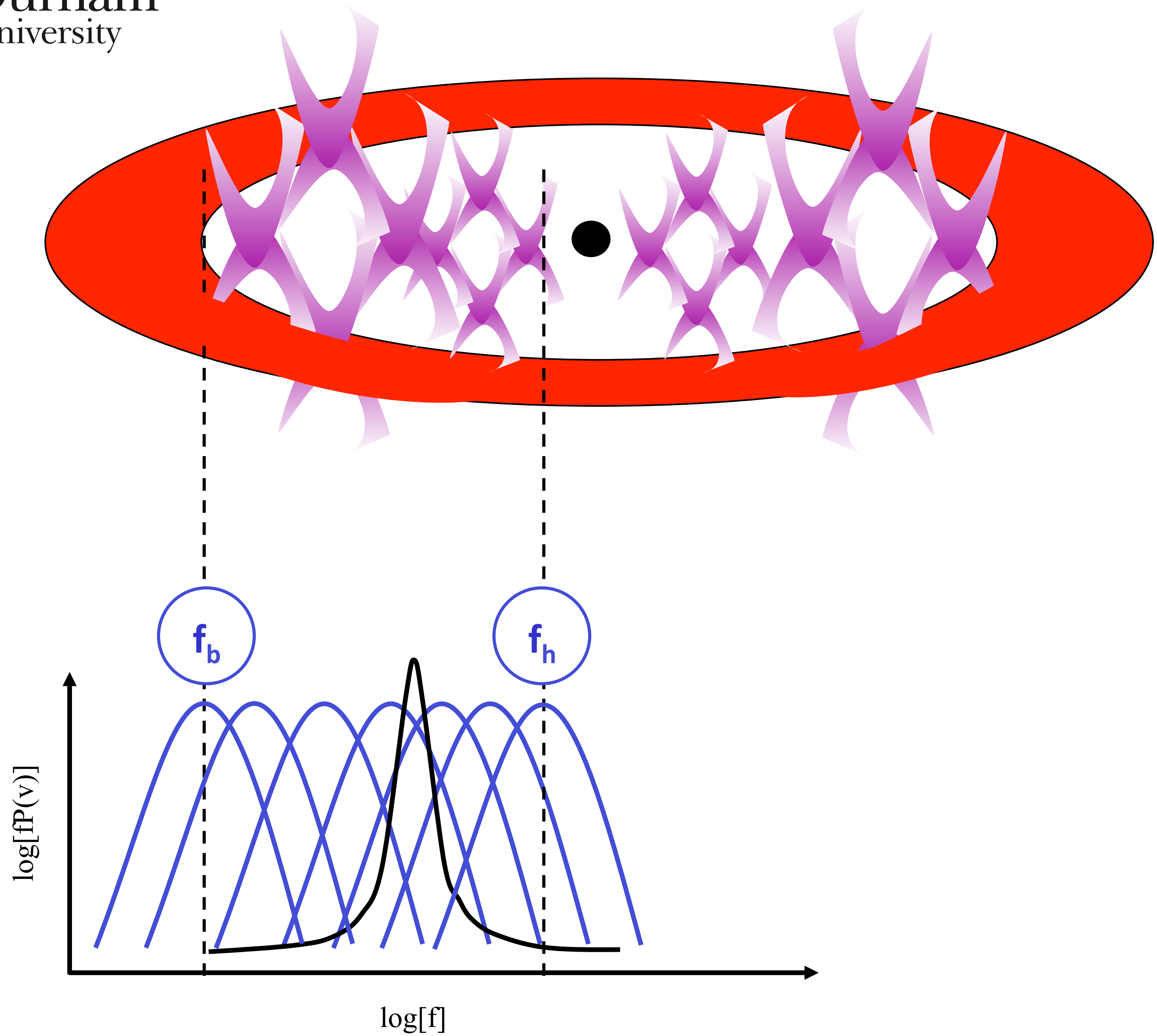
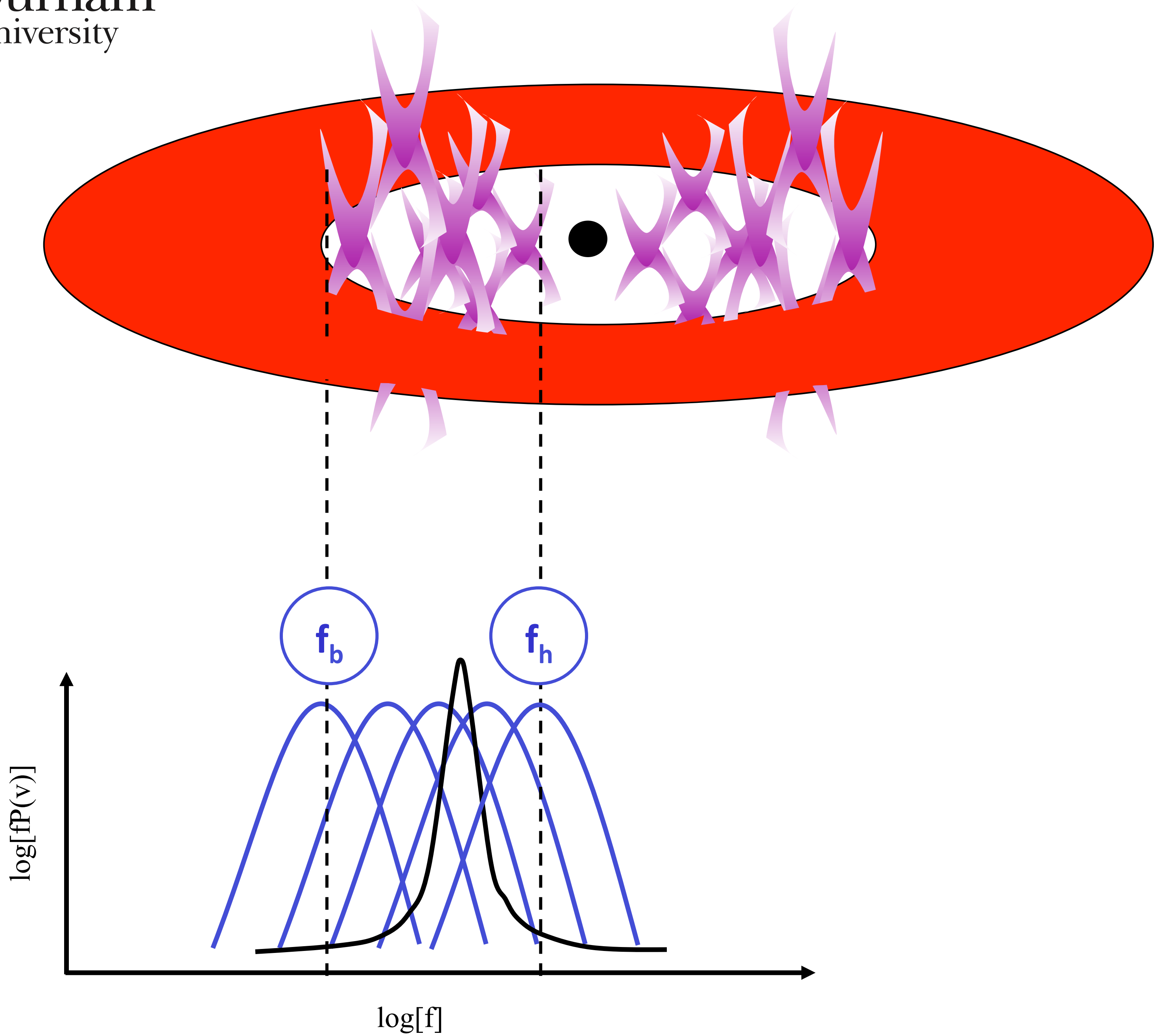
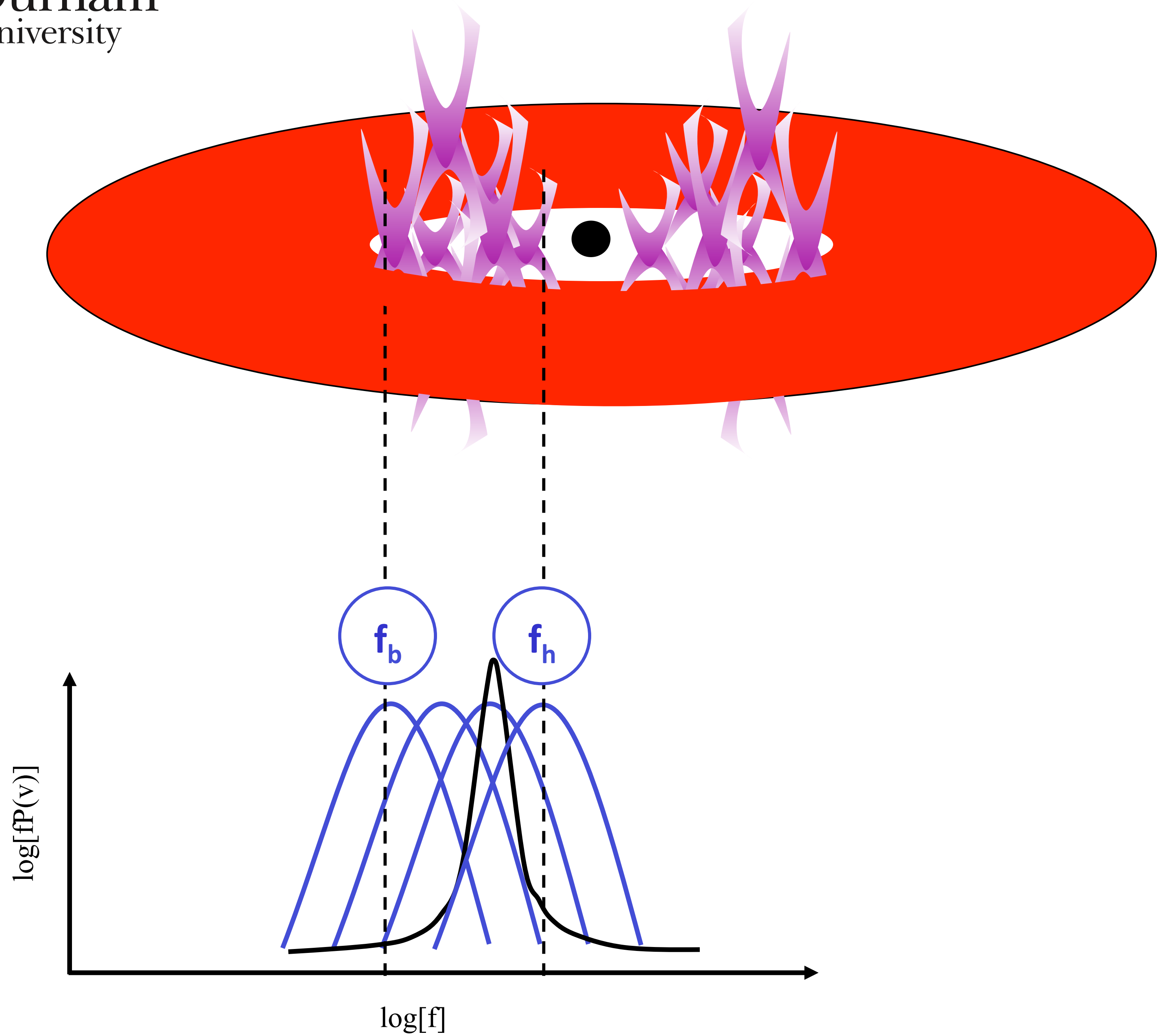




f_b
f_h
log[fP(v)]
log[f]

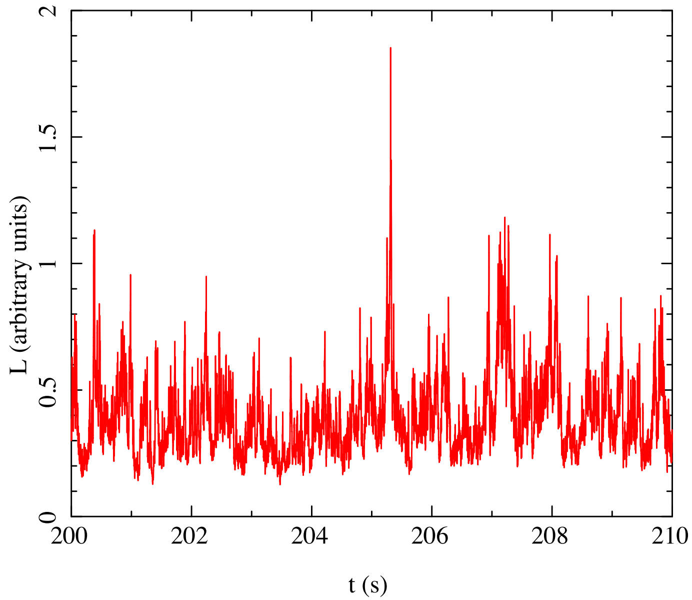


f_b
f_h
log[fP(v)]
log[f]



f_b
f_h
log[fP(ν)]
log[f]

Sigma-flux relation



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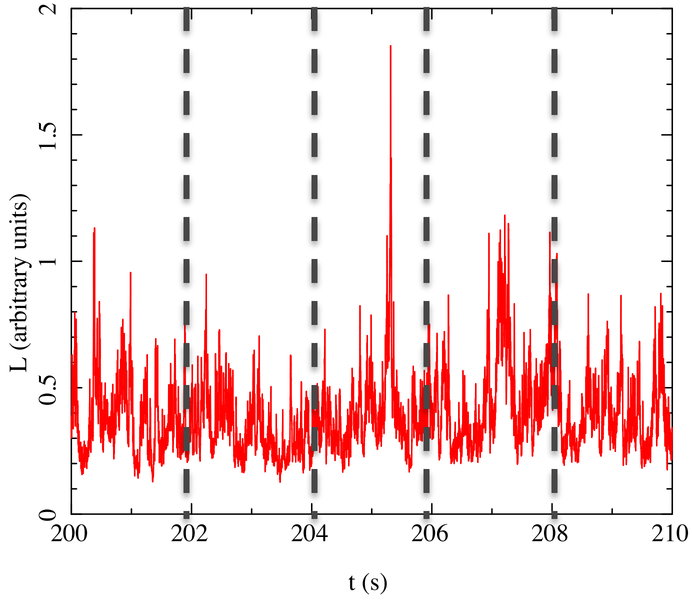
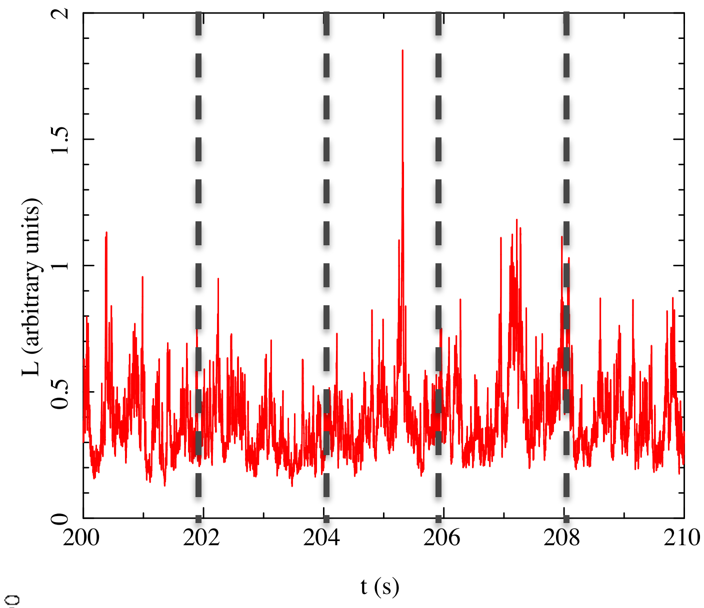
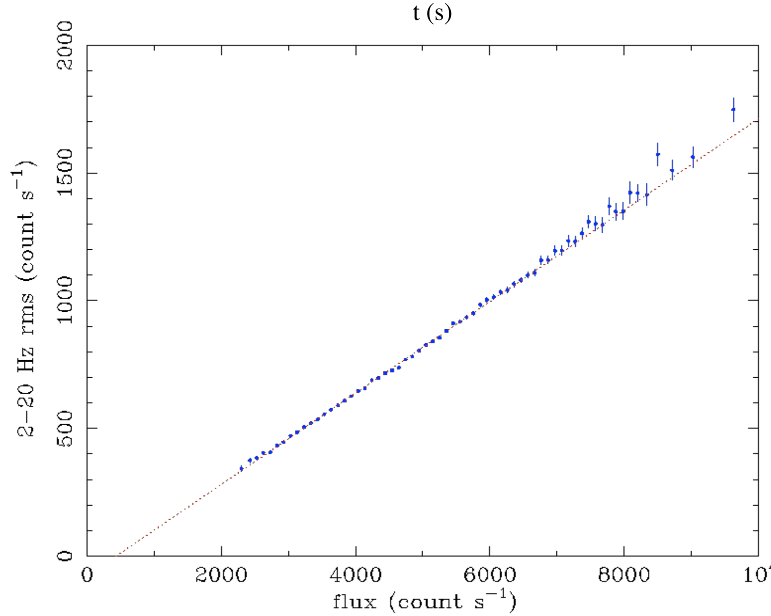


Sigma-flux relation

Plot the standard deviation of a segment against the mean of that segment then bin

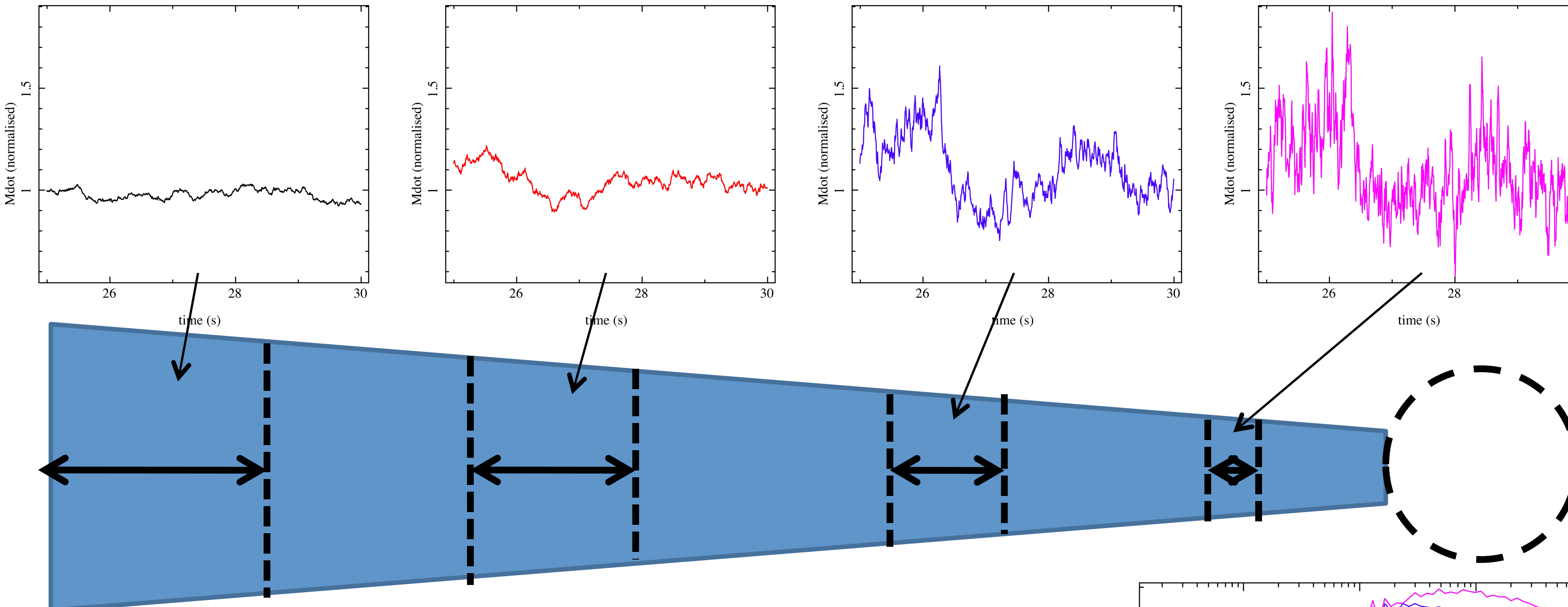


Rules out simple shot noise models – need causal connection between frequencies

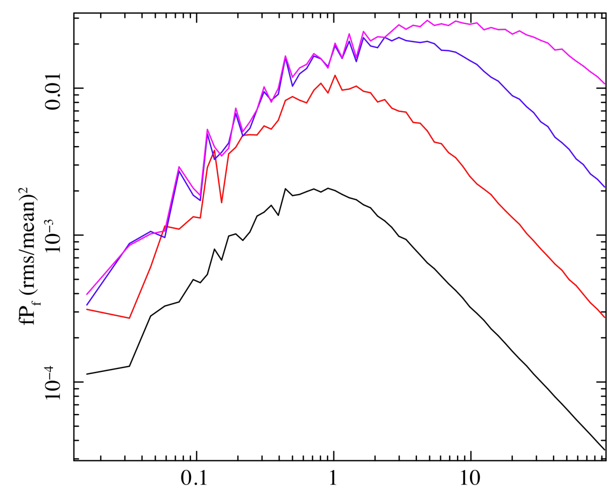


Uttley & McHardy (2001);
Uttley, McHardy & Vaughan (2005)

Propagating fluctuations

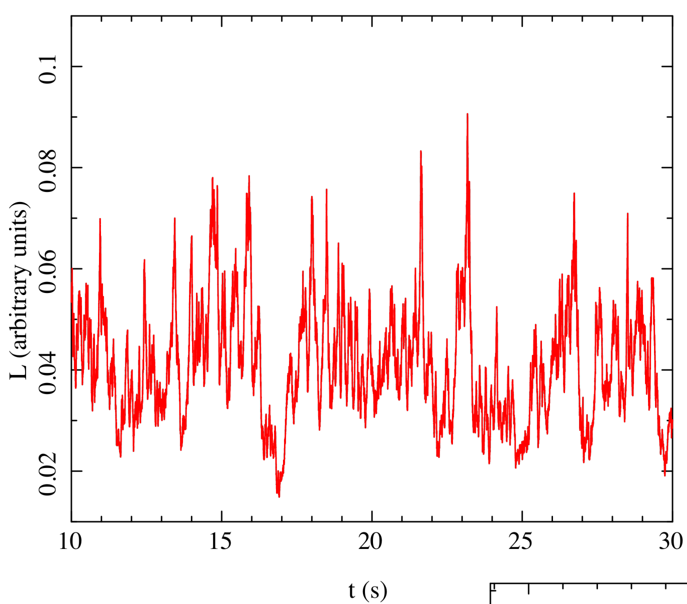


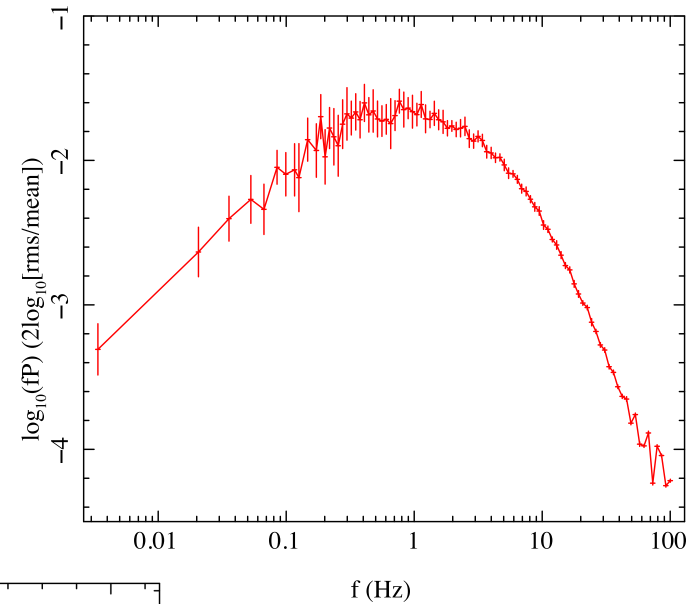
This gives the noise spectrum EMMITED at each annulus

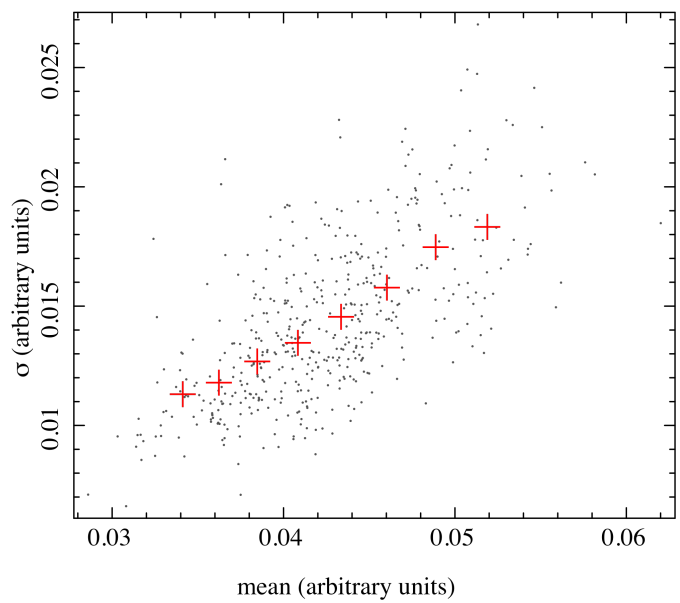


Lyubarskii 1997; Arevalo & Uttley 2006, Kotov et al 2001

Propagating fluctuations



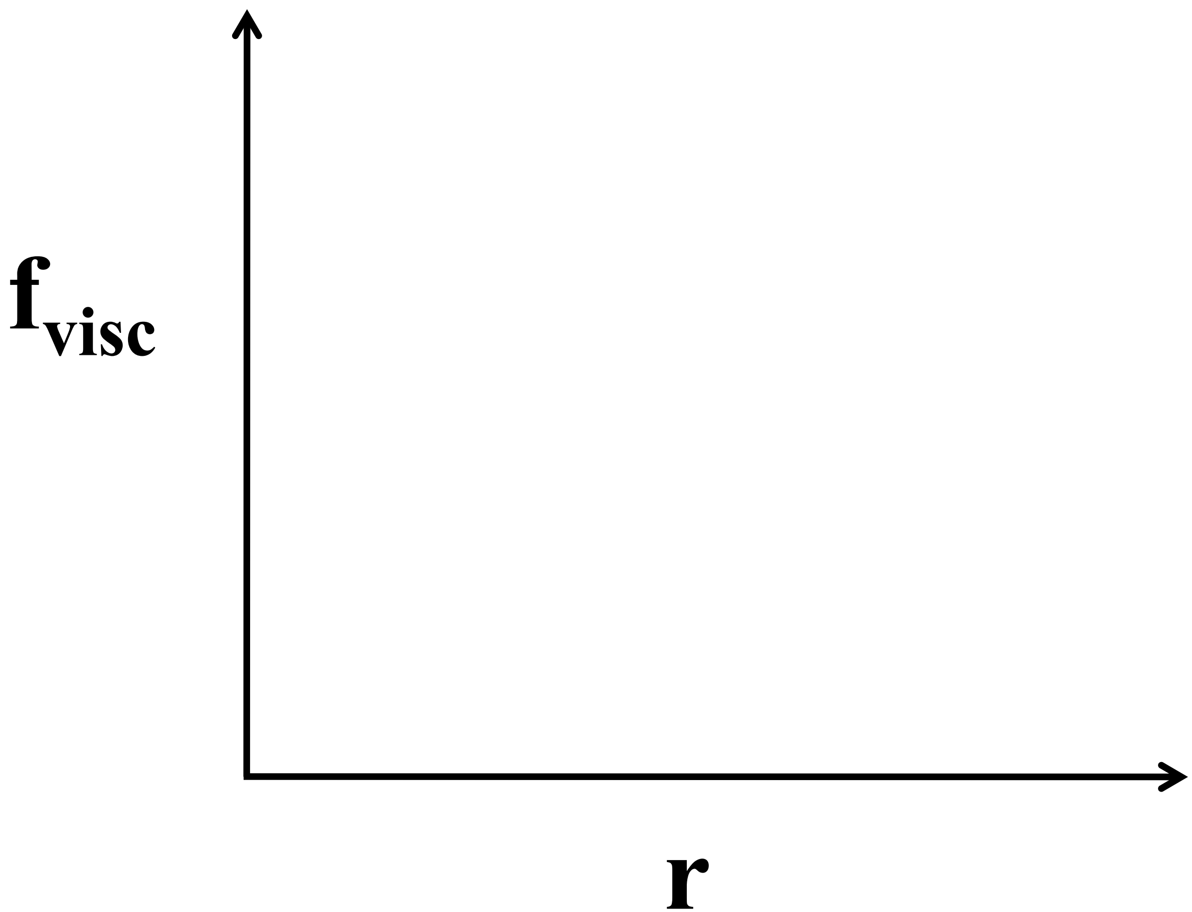




Arevalo & Uttley 2006
Ingram & Done 2011 (a & b)

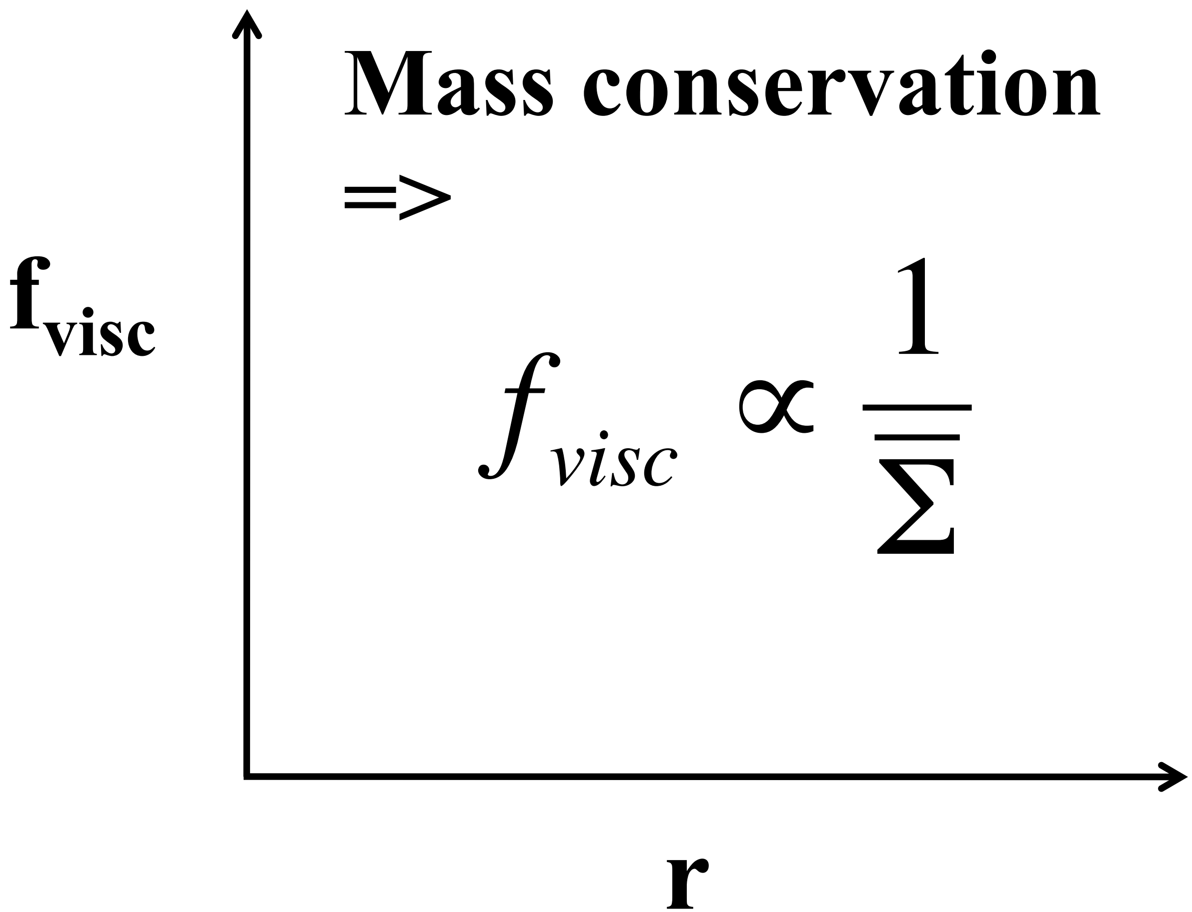
Durham University

Propagating fluctuations



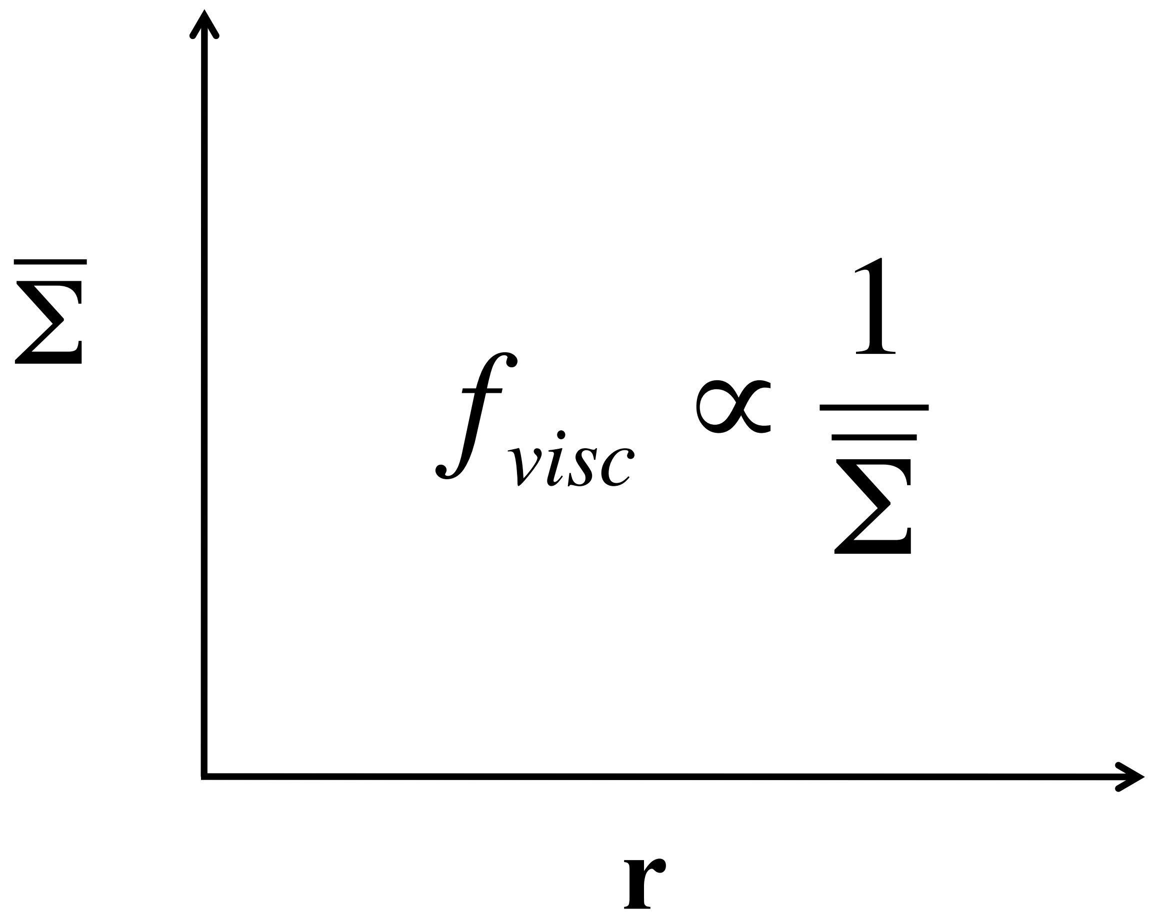
Ingram & Done 2011b

Propagating fluctuations



Ingram & Done 2011b

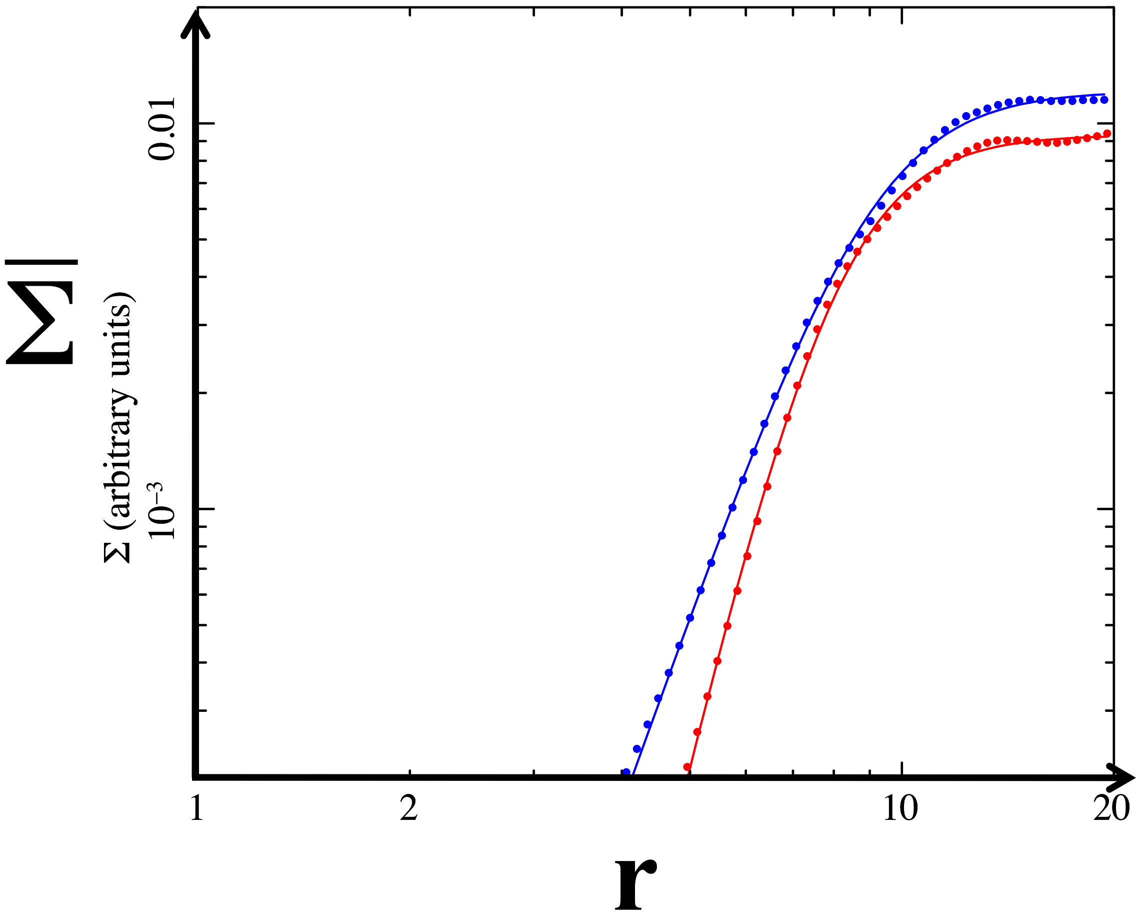
Propagating fluctuations



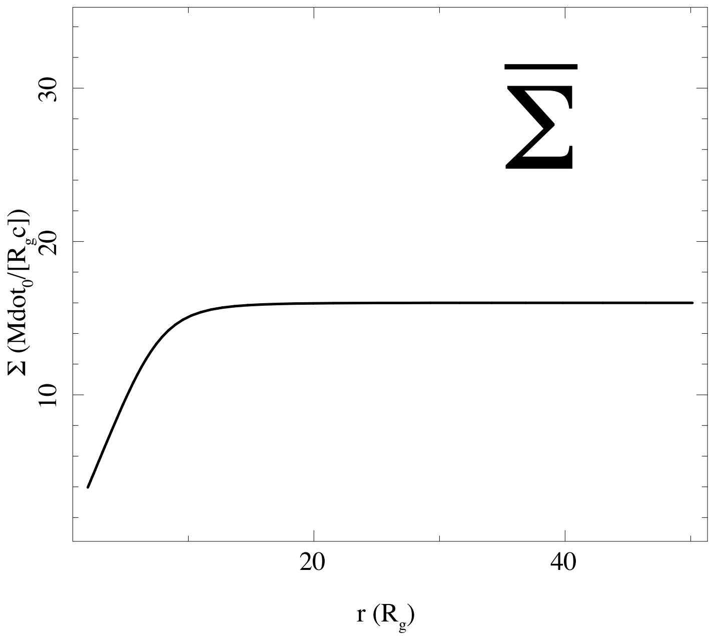
$$f_{visc} \propto \frac{1}{\overline{\Sigma}}$$

Ingram & Done 2011b

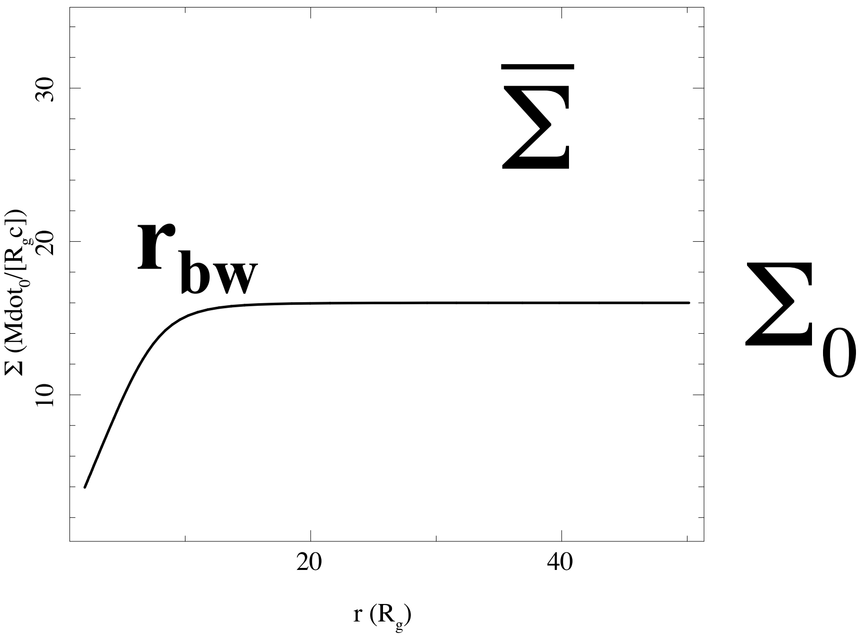
Propagating fluctuations



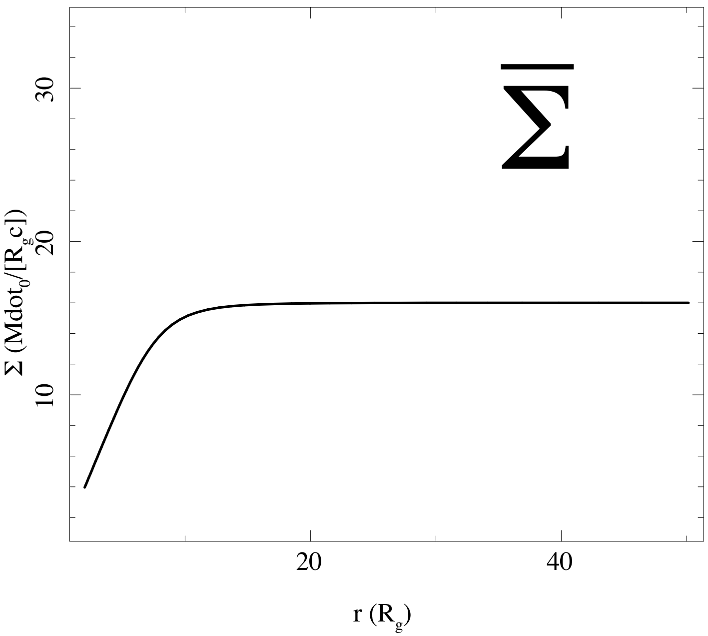
Ingram & Done 2011b



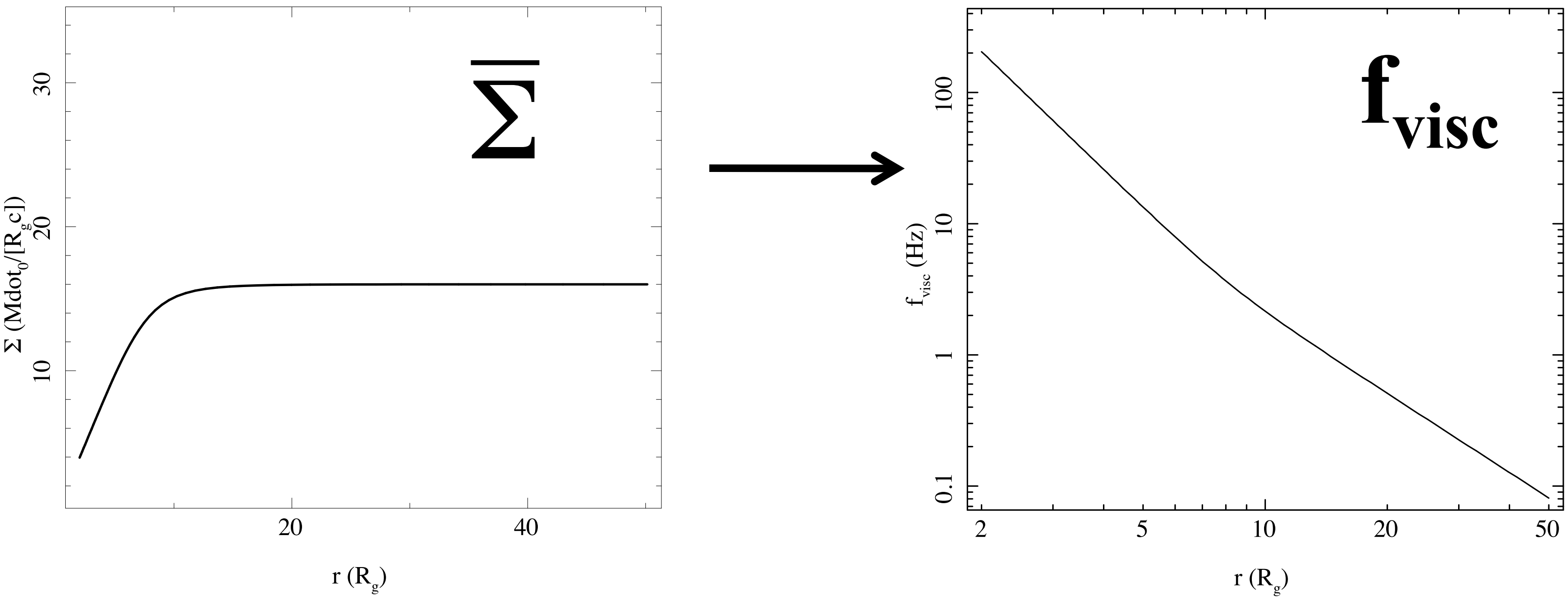
Σ̄
Σ (Mdot0/[Rgc])
10
20
30
20
40
r (Rg)



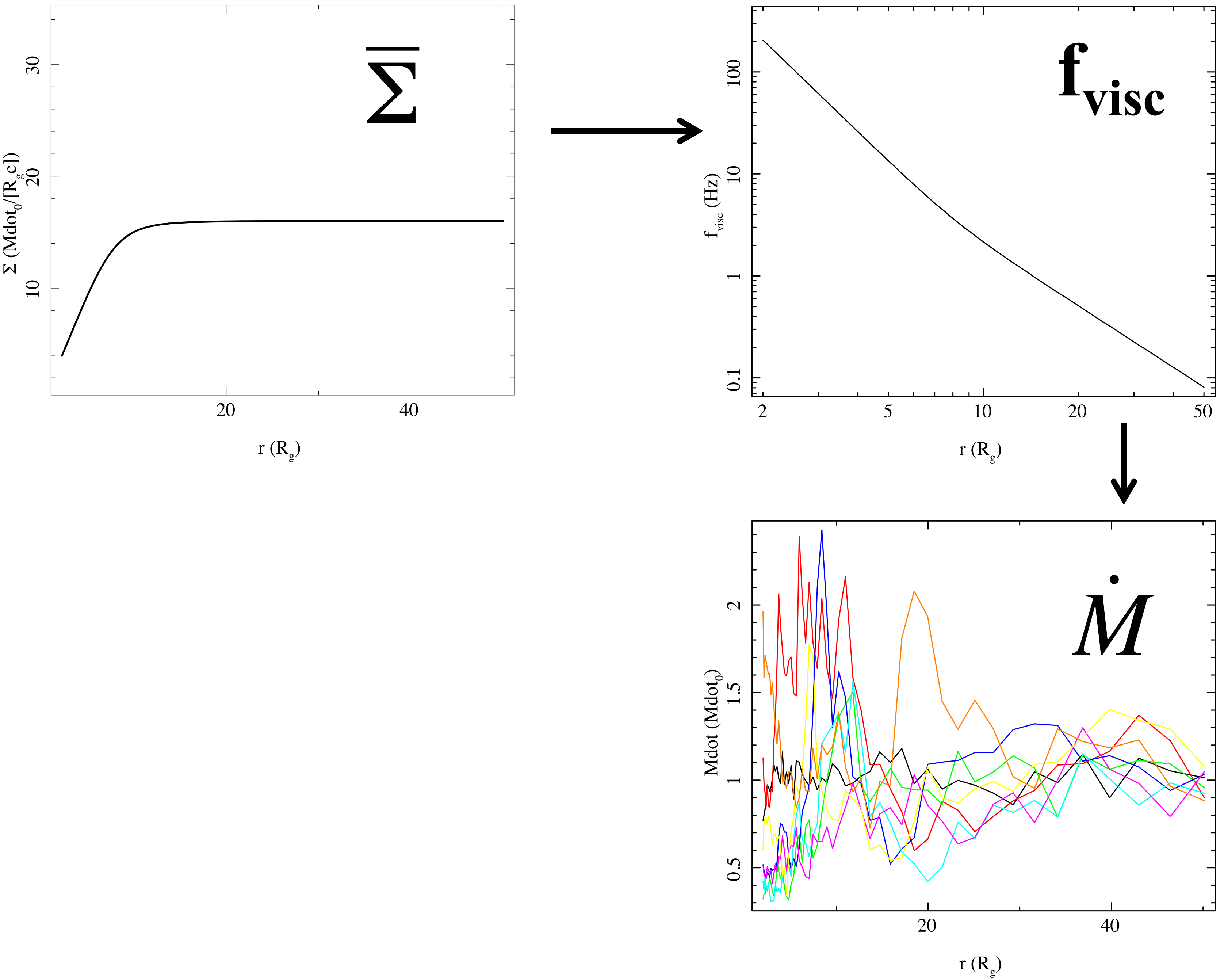
30
20
10
Σ (Mdot0/[Rgc])
20
40
r (Rg)
Σ̄
rbw
Σ0



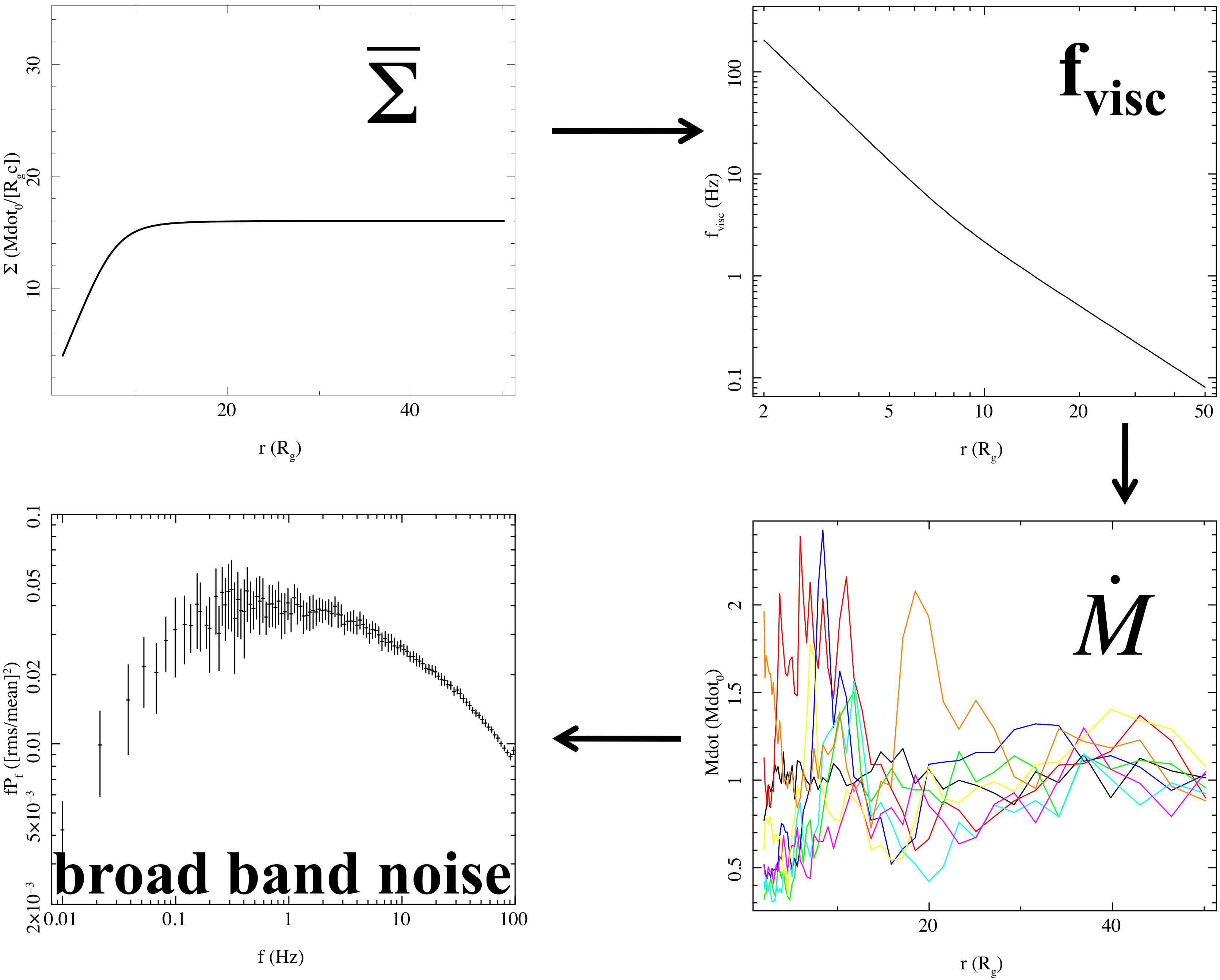
$$\longrightarrow \quad \mathbf{f_{prec}=f_{QPO}}$$



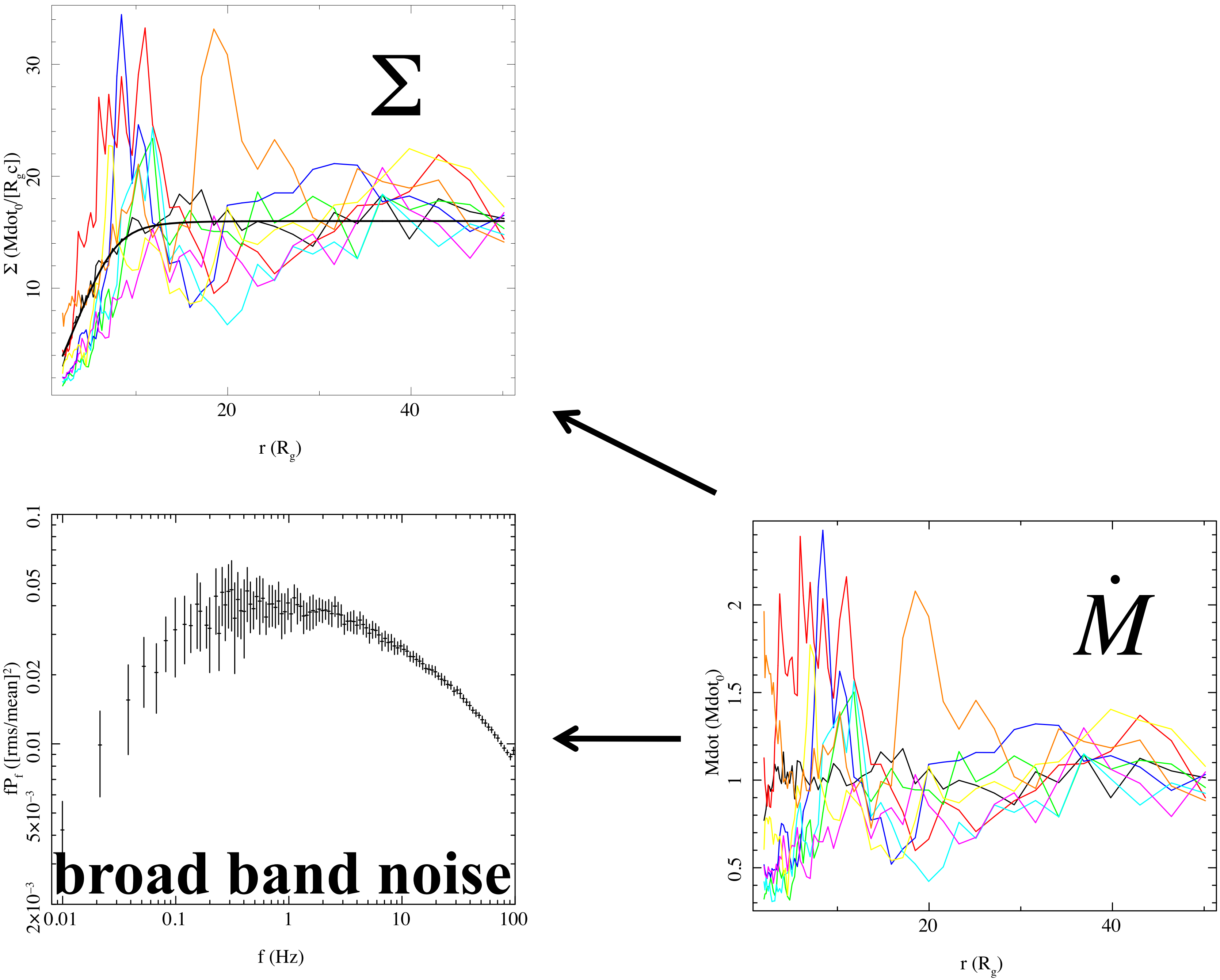
$\bar{\Sigma}$
Σ (Mdot$_0$/[R$_g$c])
30
20
10
20
40
r (R$_g$)
f_{visc}
f_{visc} (Hz)
100
10
1
0.1
2
5
10
20
50
r (R$_g$)



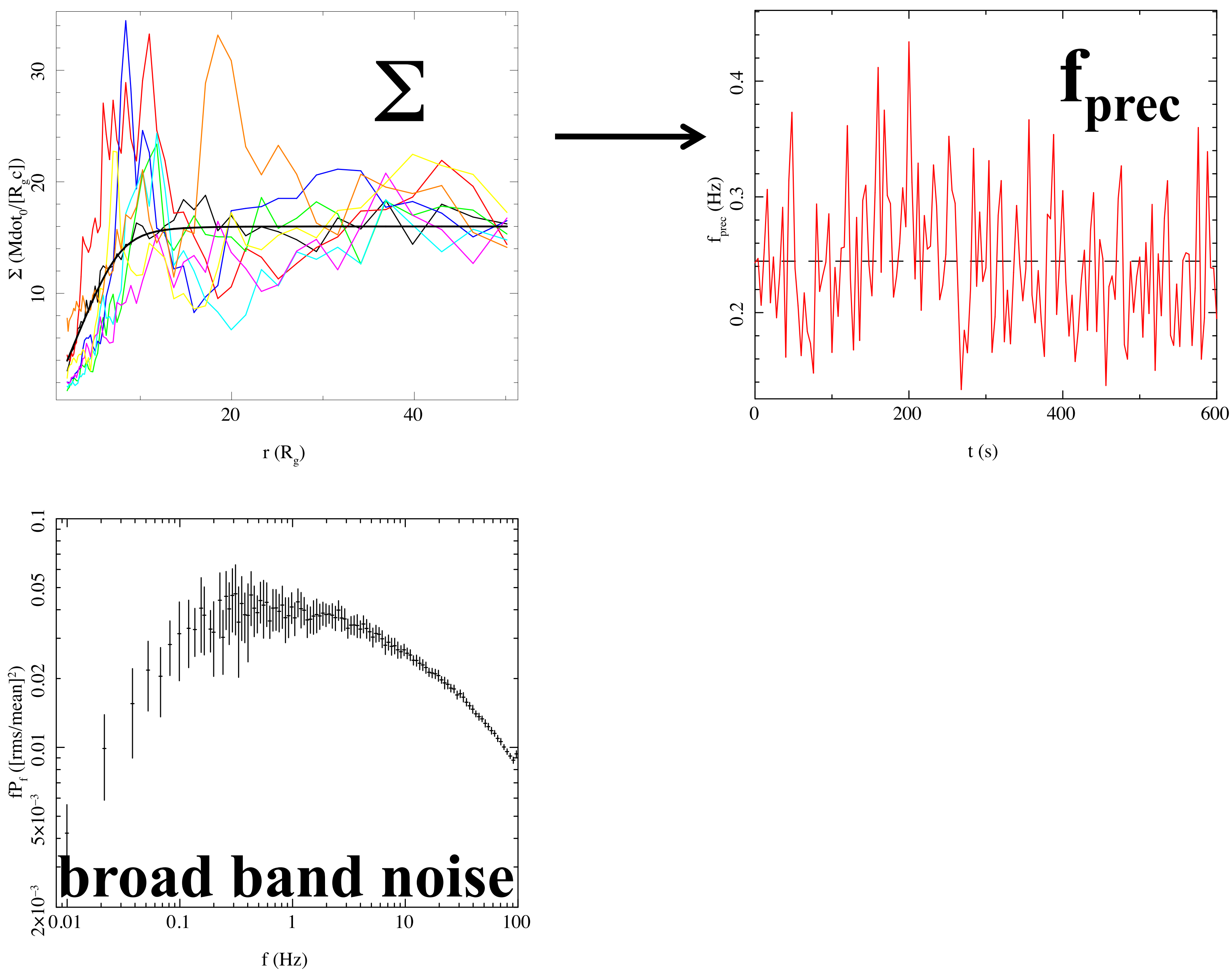
Σ̄
Σ (Mdot$_0$/[R$_g$c])
r (R$_g$)
f$_{visc}$
f$_{visc}$ (Hz)
r (R$_g$)
Ṁ
Mdot (Mdot$_0$)
r (R$_g$)



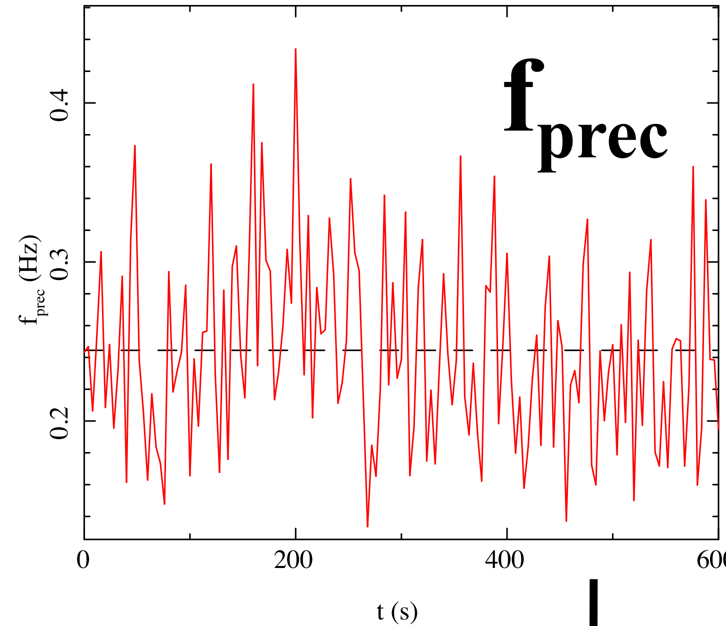
$\overline{\Sigma}$
Σ (Mdot$_0$/[R$_g$c])
10
20
30
20
40
r (R$_g$)
f$_{visc}$
f$_{visc}$ (Hz)
0.1
1
10
100
2
5
10
20
50
r (R$_g$)
$\dot{M}$
Mdot (Mdot$_0$)
0.5
1
1.5
2
20
40
r (R$_g$)
broad band noise
fP$_f$ ([rms/mean]^2)
2×10^{-3}
5×10^{-3}
0.01
0.02
0.05
0.1
0.01
0.1
1
10
100
f (Hz)

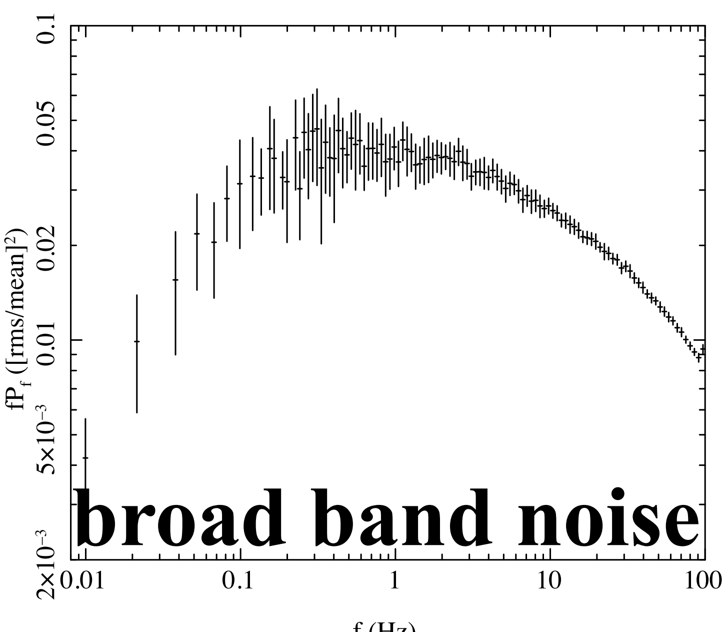


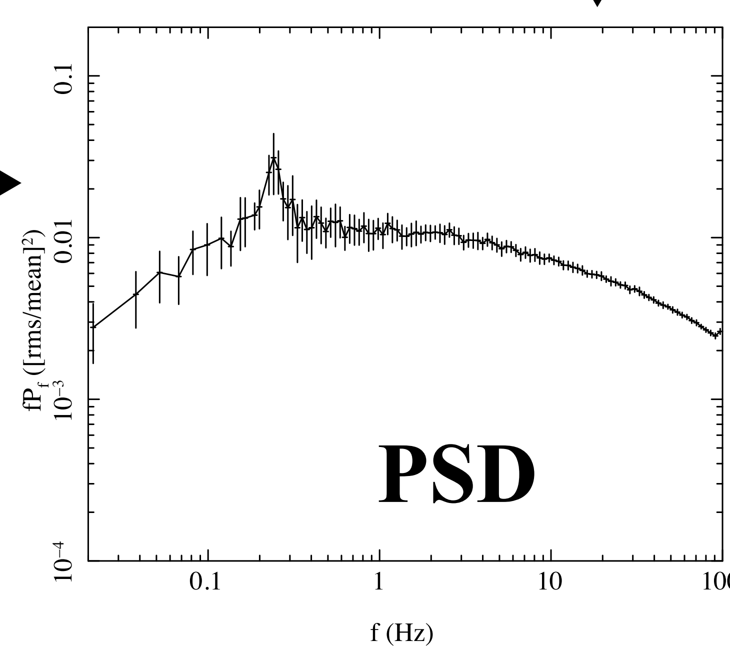
Σ
Σ (Mdot0/[Rgc])
r (Rg)
broad band noise
fPf ([rms/mean]2)
f (Hz)
Ṁ
Mdot (Mdot0)
r (Rg)

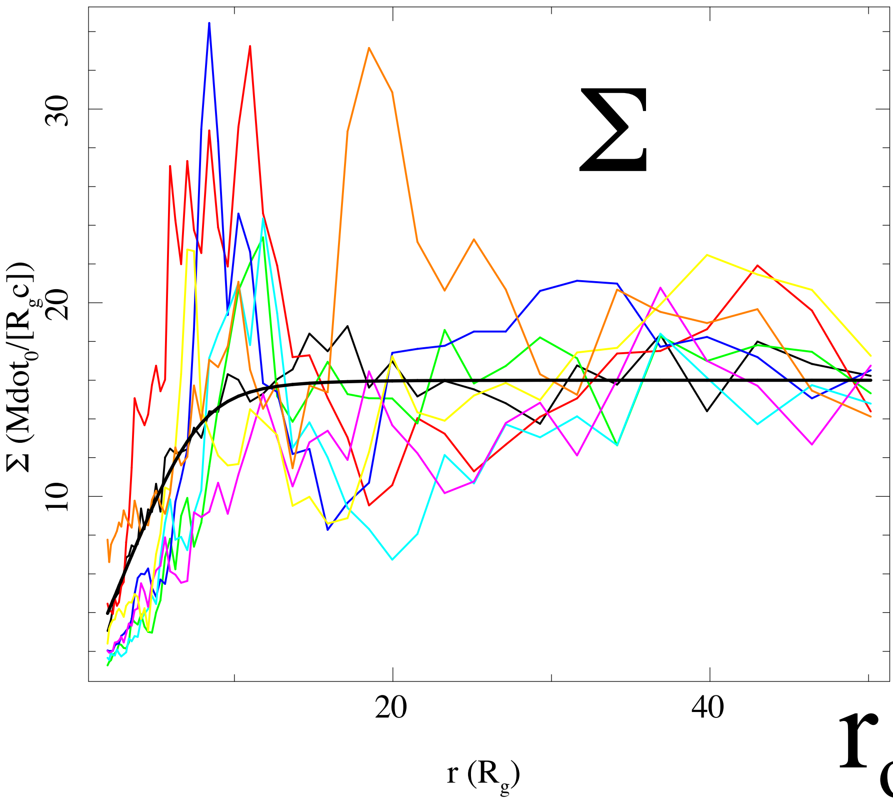

Σ
Σ (Mdot$_0$/[R$_g$c])
r (R$_g$)
10
20
30
20
40
f$_{prec}$
f$_{prec}$ (Hz)
t (s)
0.2
0.3
0.4
0
200
400
600
broad band noise
fP$_f$ ([rms/mean]^2)
f (Hz)
2×10^{-3}
5×10^{-3}
0.01
0.02
0.05
0.1
0.01
0.1
1
10
100

Model for the entire power spectrum!

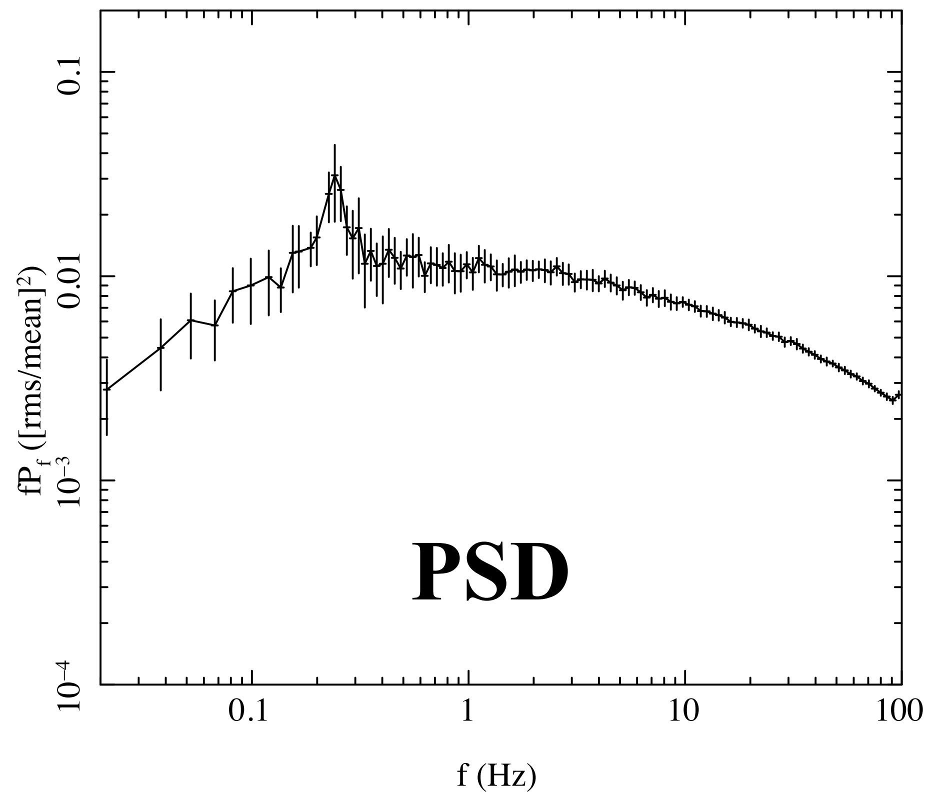


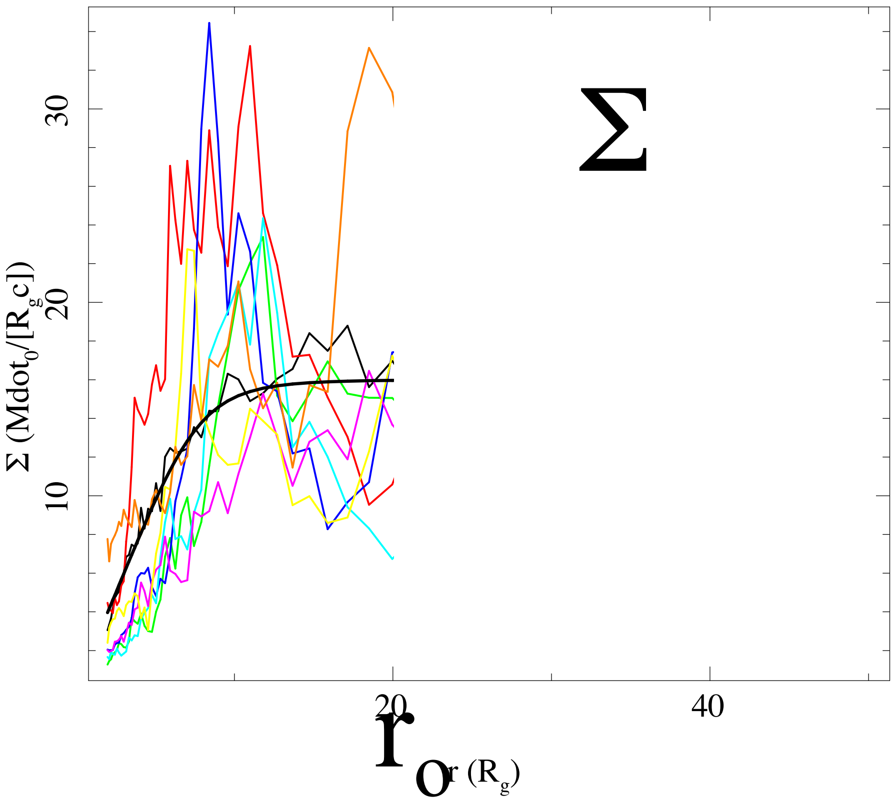


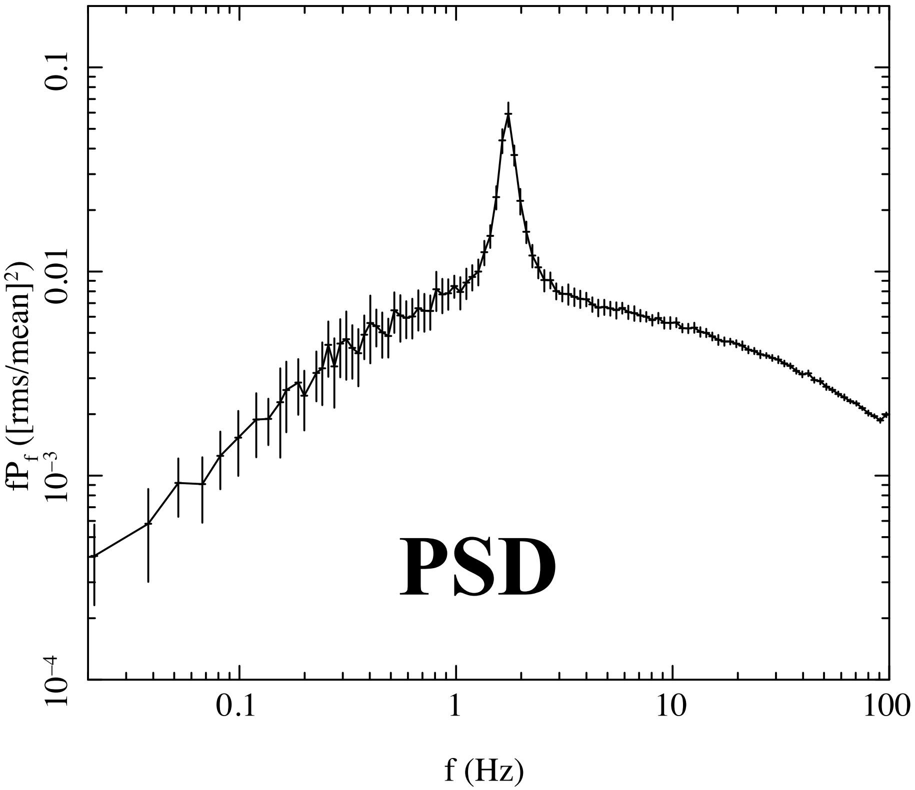


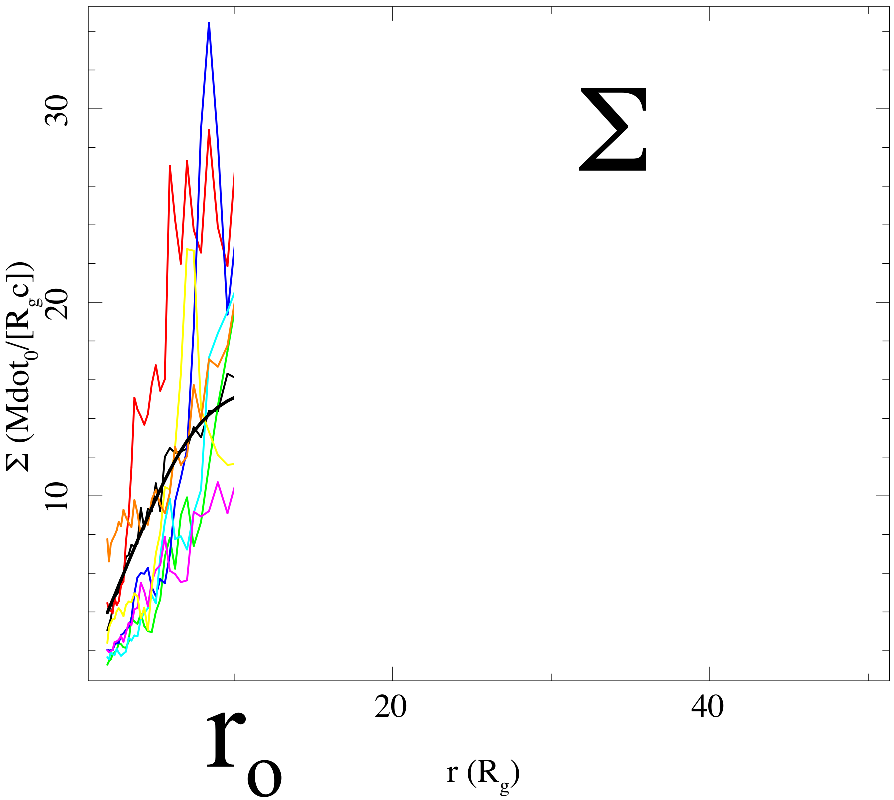

Σ
30
20
10
Σ (Mdot0/[Rgc])
20
40
r (Rg)

r_o

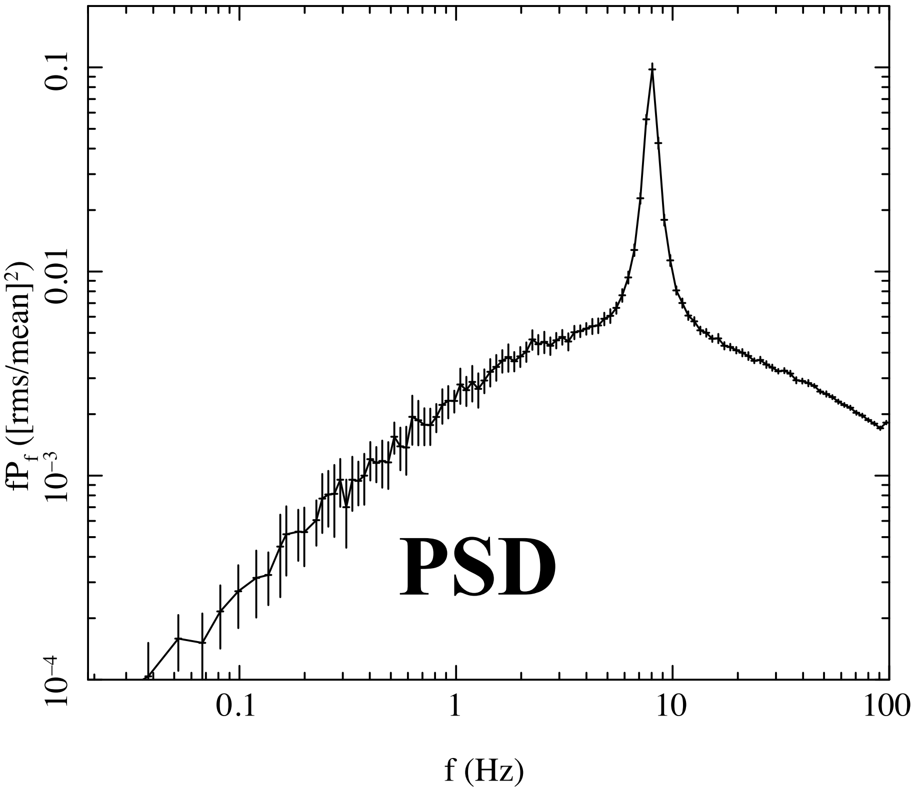

0.1
0.01
10−3
10−4
fPf ([rms/mean]2)
PSD
0.1
1
10
100
f (Hz)


Σ
Σ (Mdot$_0$/[R$_g$c])
30
20
10
20
40
r (R$_g$)
r$_o$


PSD
fP$_f$ ([rms/mean]^2)
0.1
0.01
10^{-3}
10^{-4}
0.1
1
10
100
f (Hz)



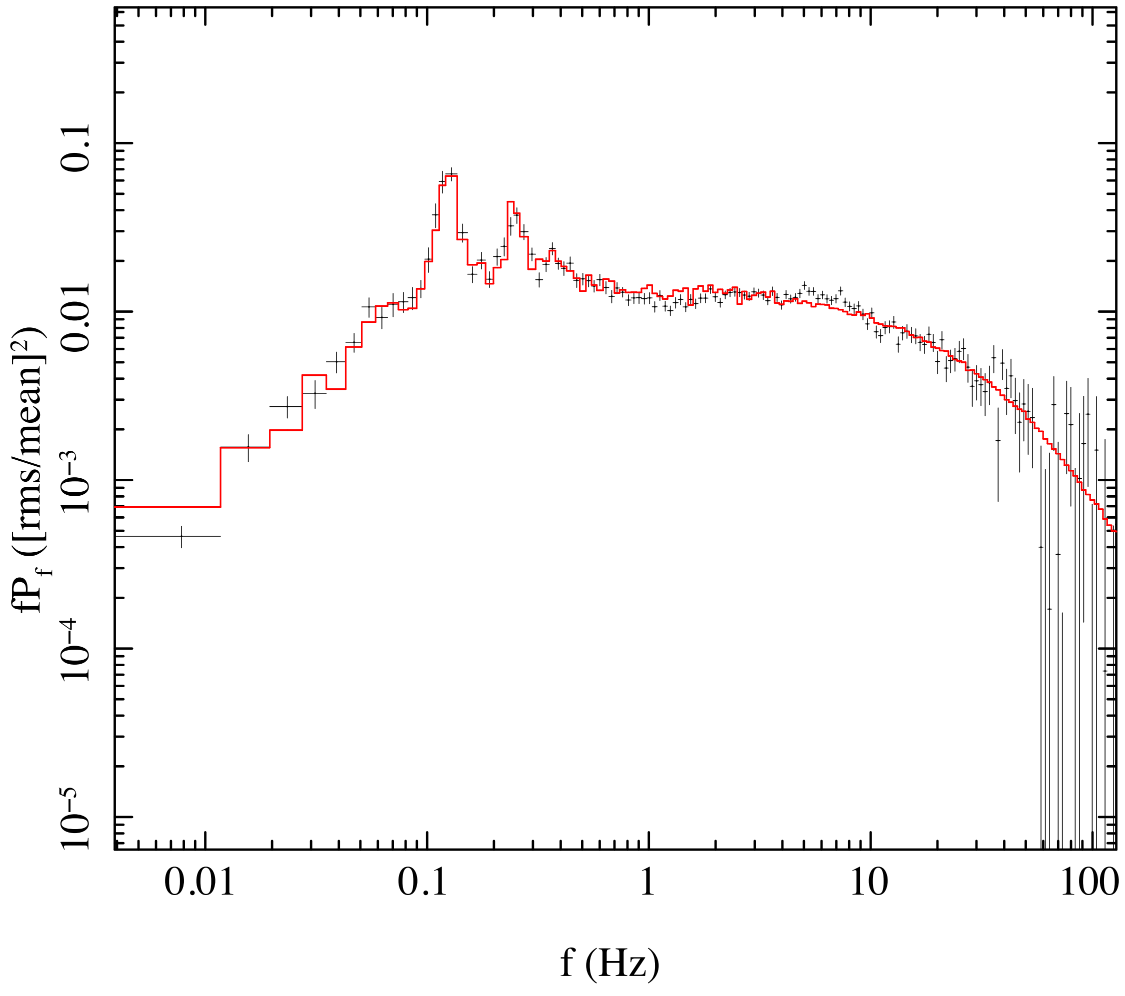
Σ
30
20
10
Σ (Mdot0/[Rgc])
20
40
r (Rg)
ro



0.1
0.01
10−3
10−4
fPf ([rms/mean]2)
0.1
1
10
100
f (Hz)
PSD

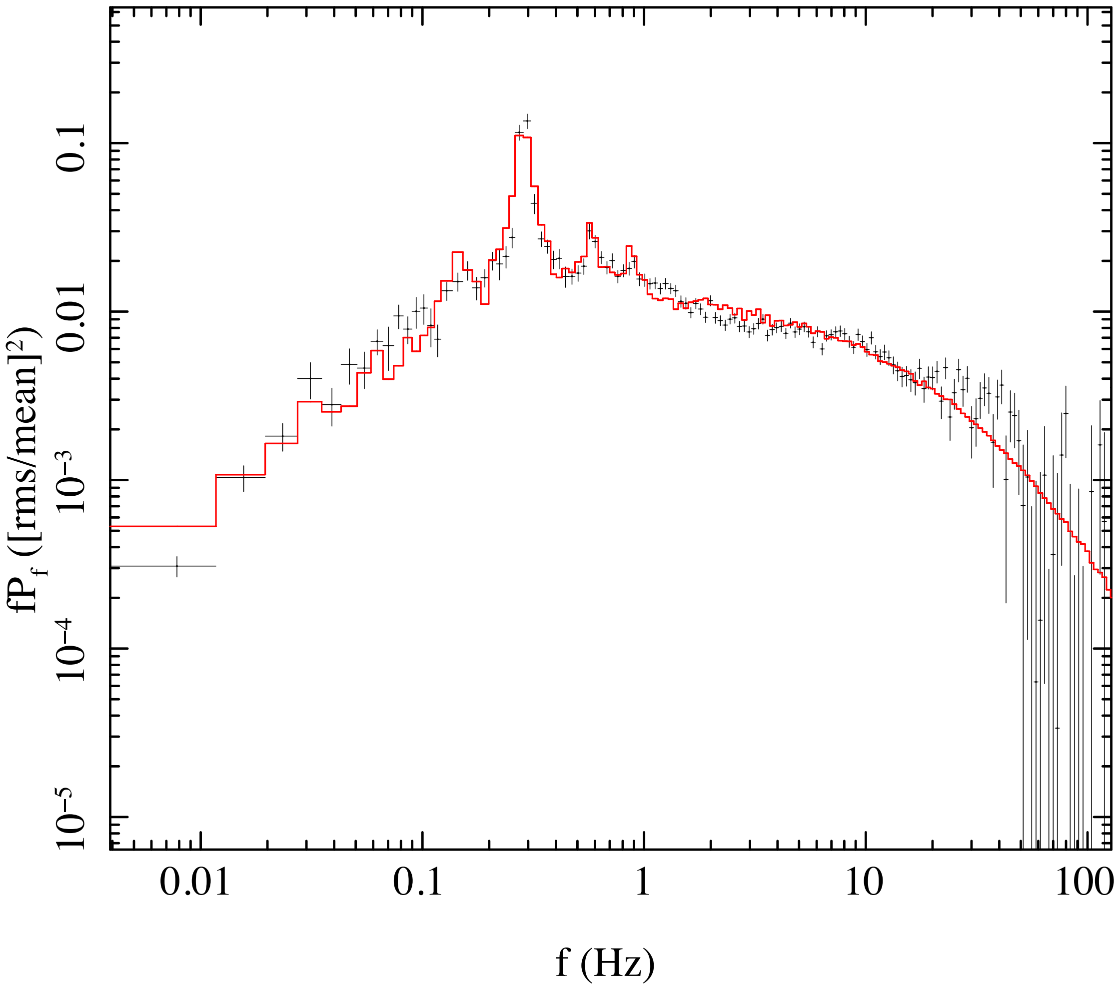
Fitting to XTE J1550-564

r_o=68.0



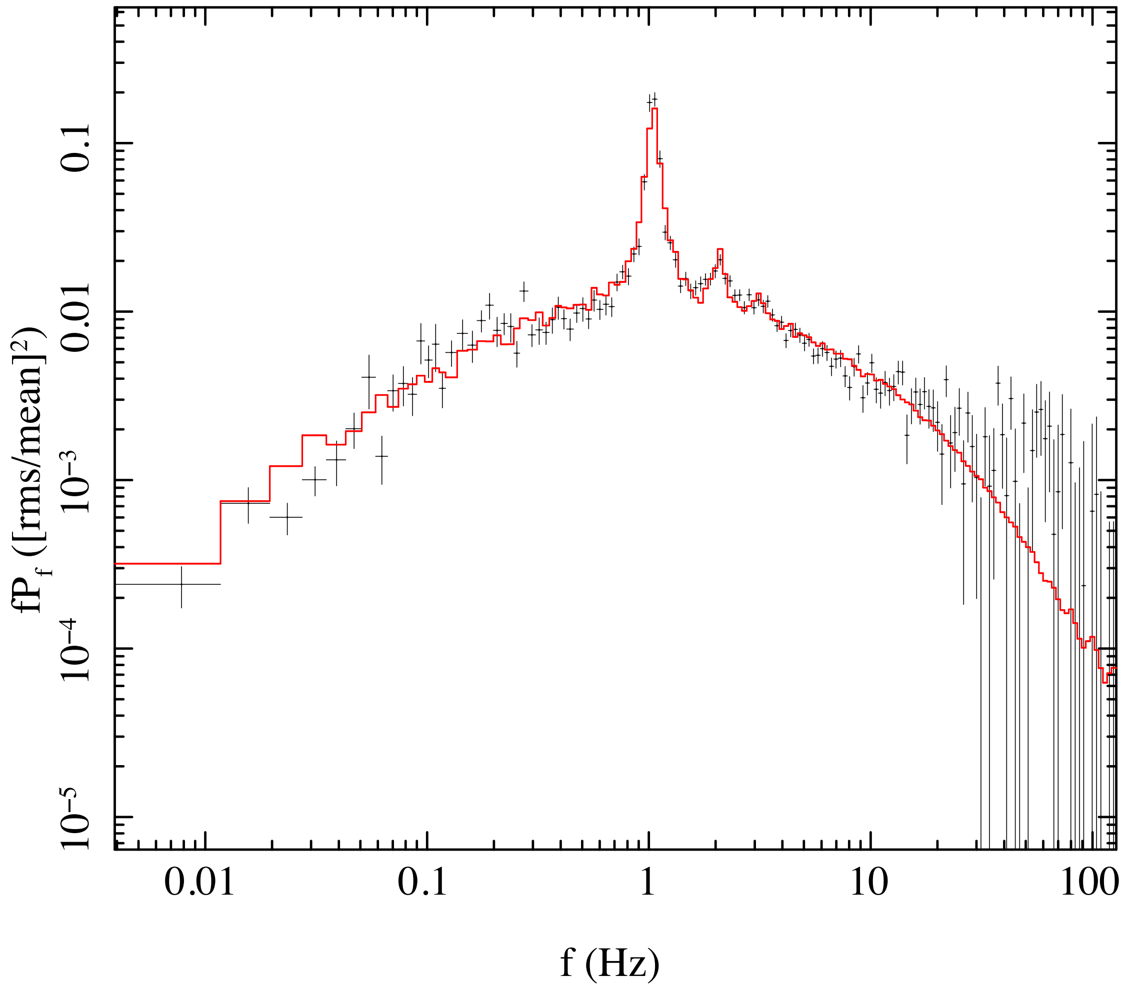
Fitting to XTE J1550-564

r_o=45.7



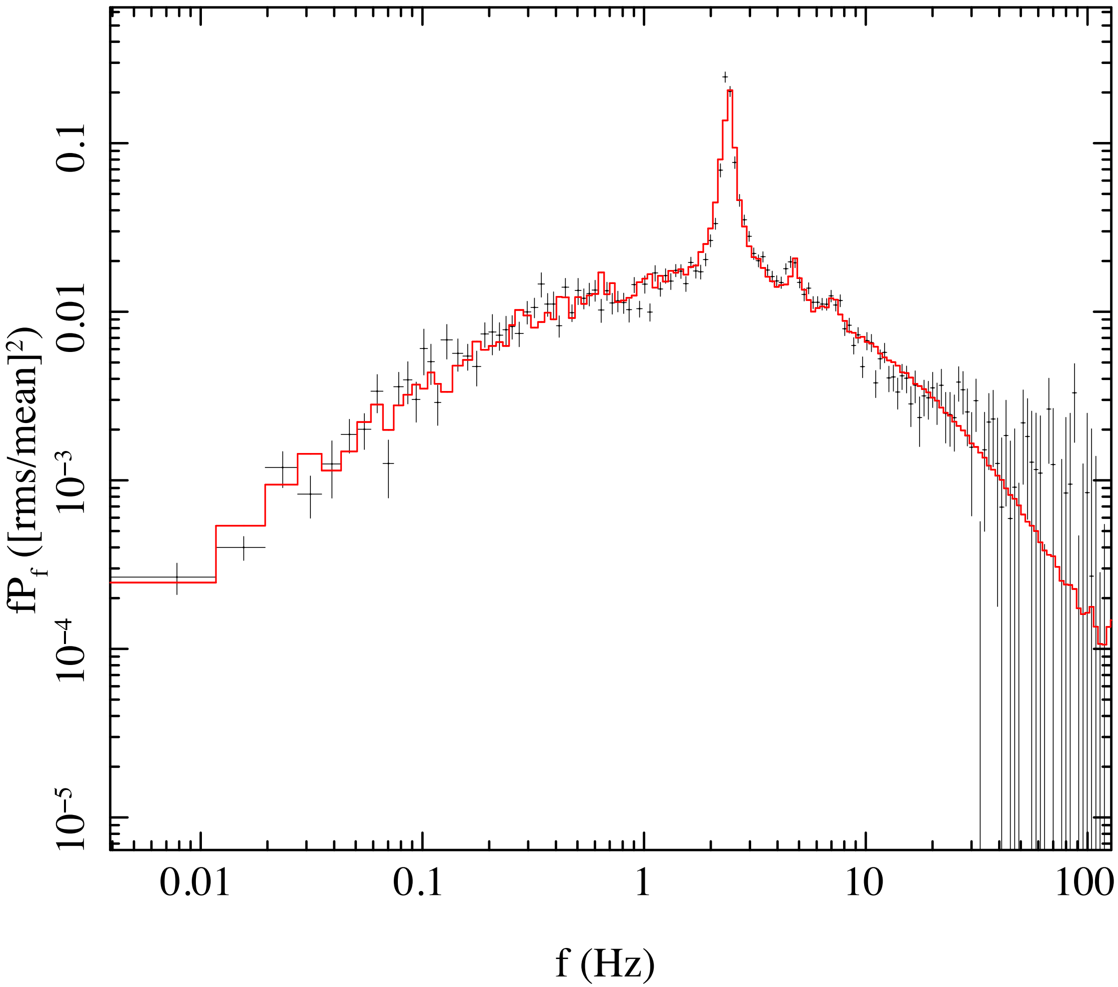
Fitting to XTE J1550-564

r_o=25.0



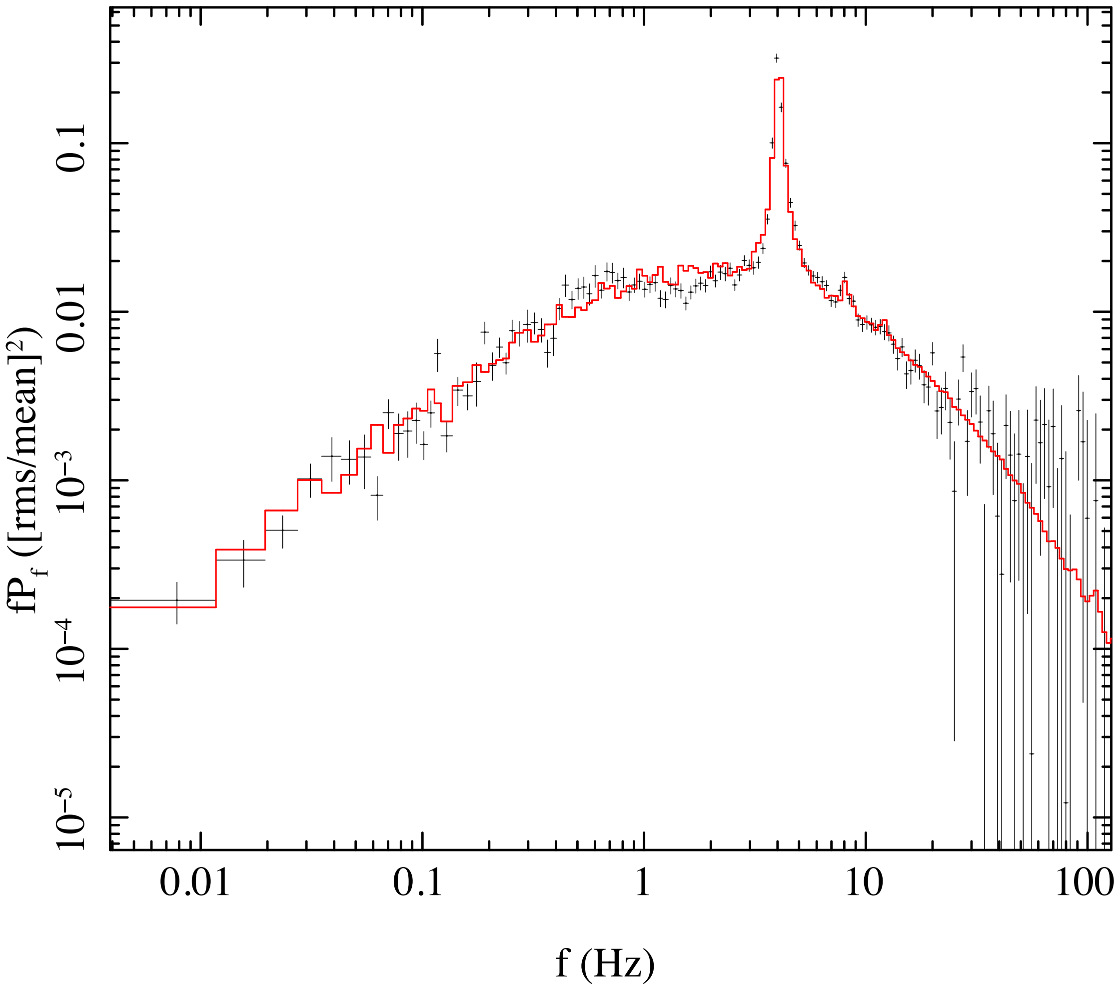
Fitting to XTE J1550-564

r_o=16.3



Fitting to XTE J1550-564

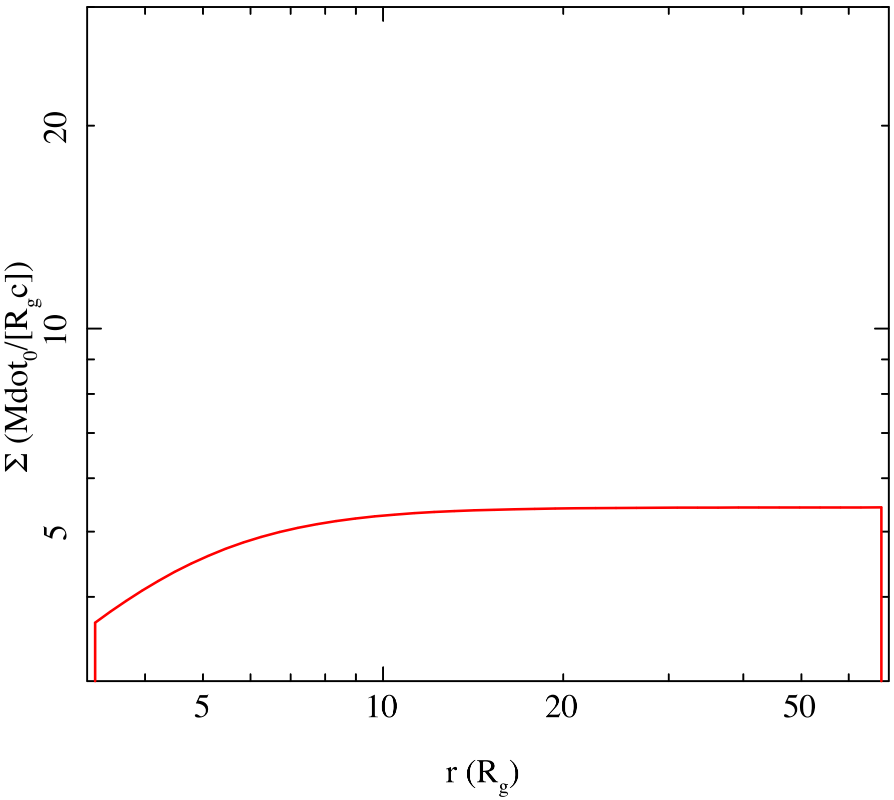
r_o=12.8

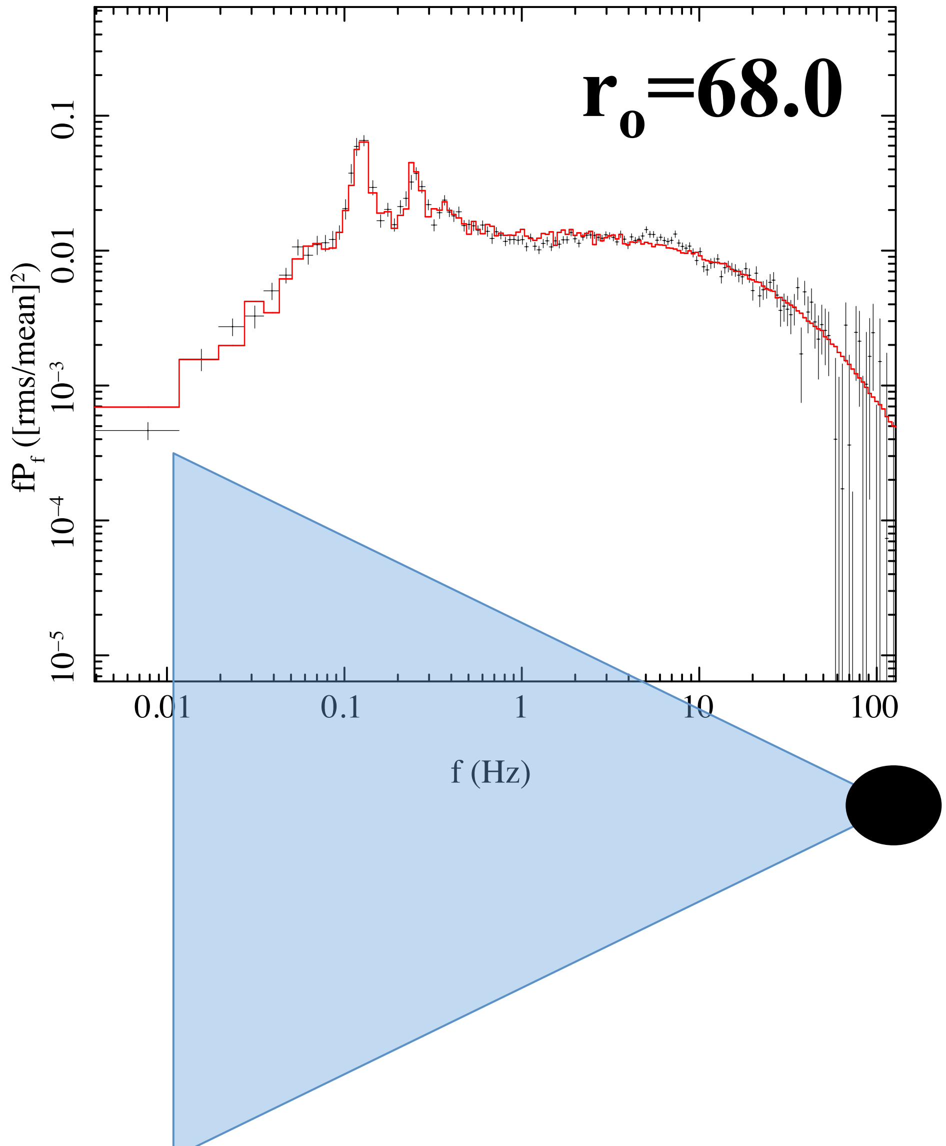


Ingram & Done 2011 a & b

Durham University

Fitting to XTE J1550-564



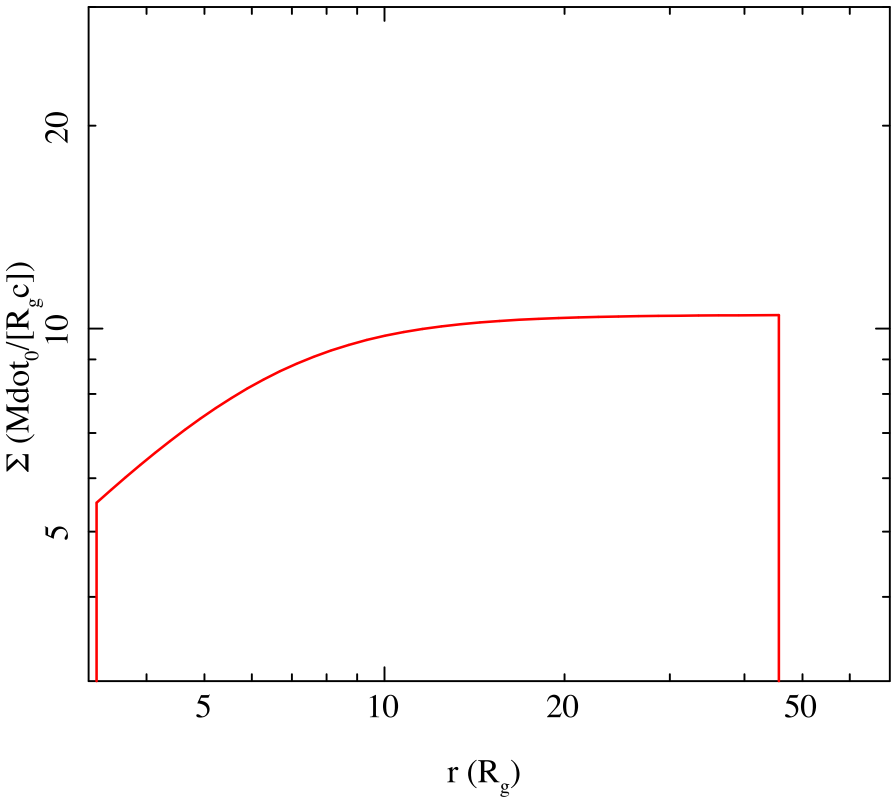


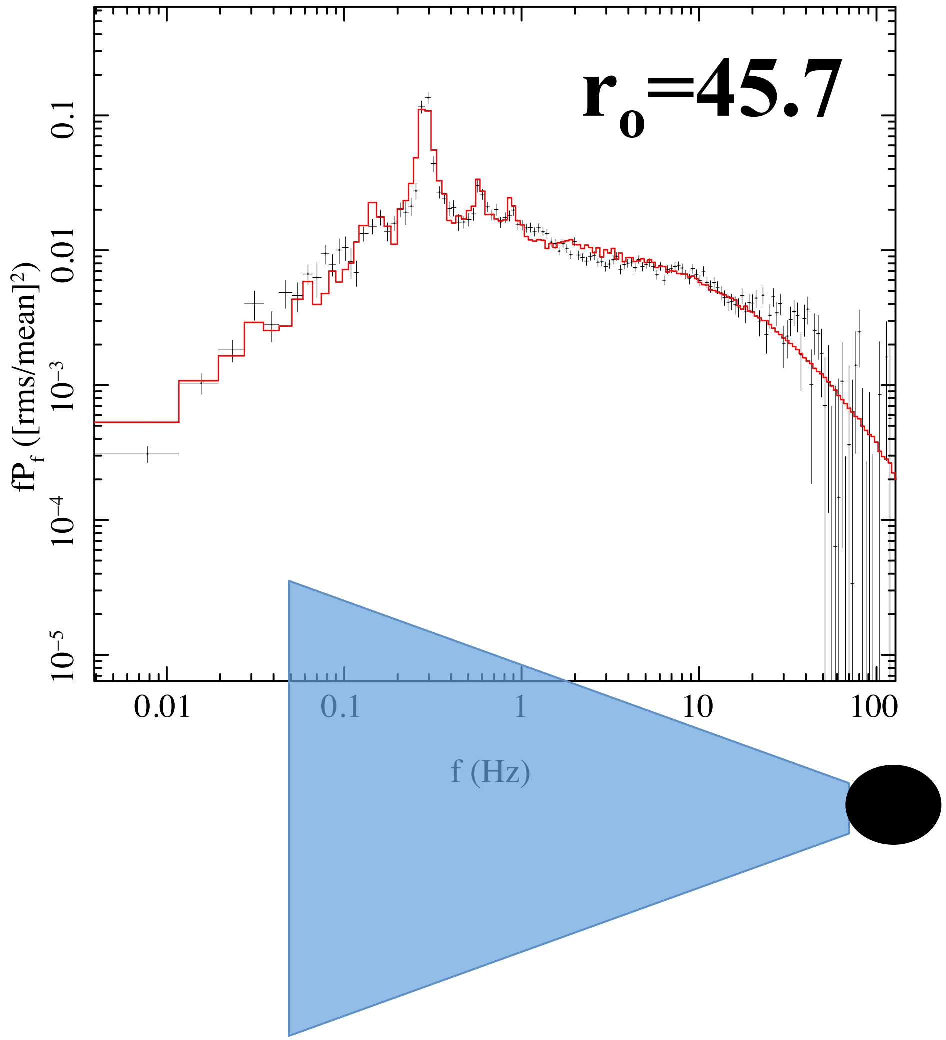
r_{bw}=4.6

h/r=0.41

Σ_0 =5.4

Fitting to XTE J1550-564





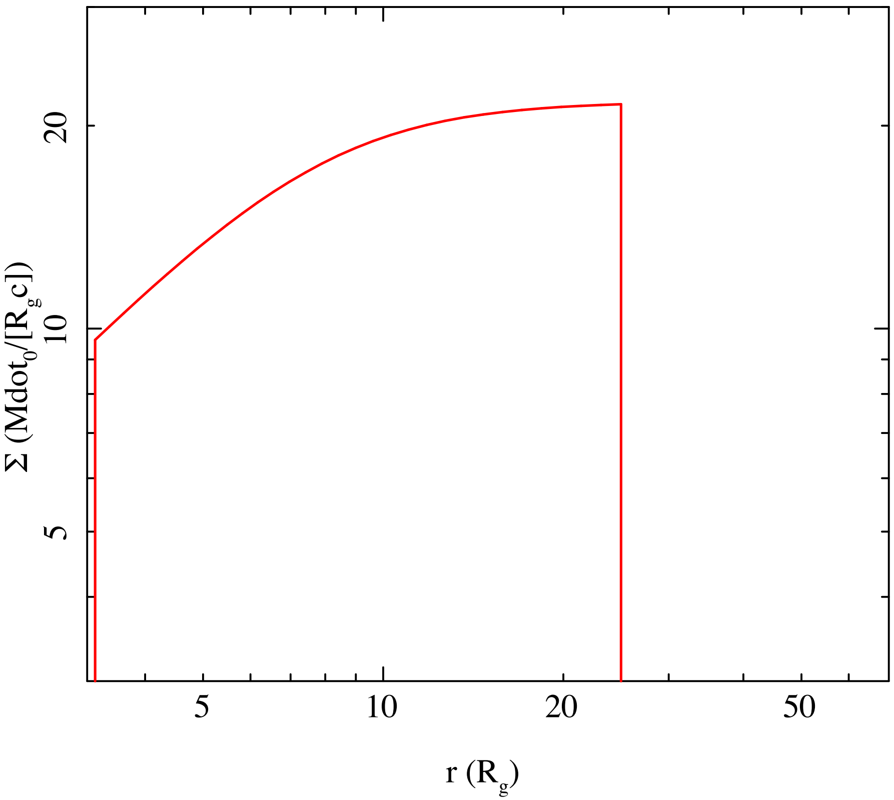
r_o=45.7

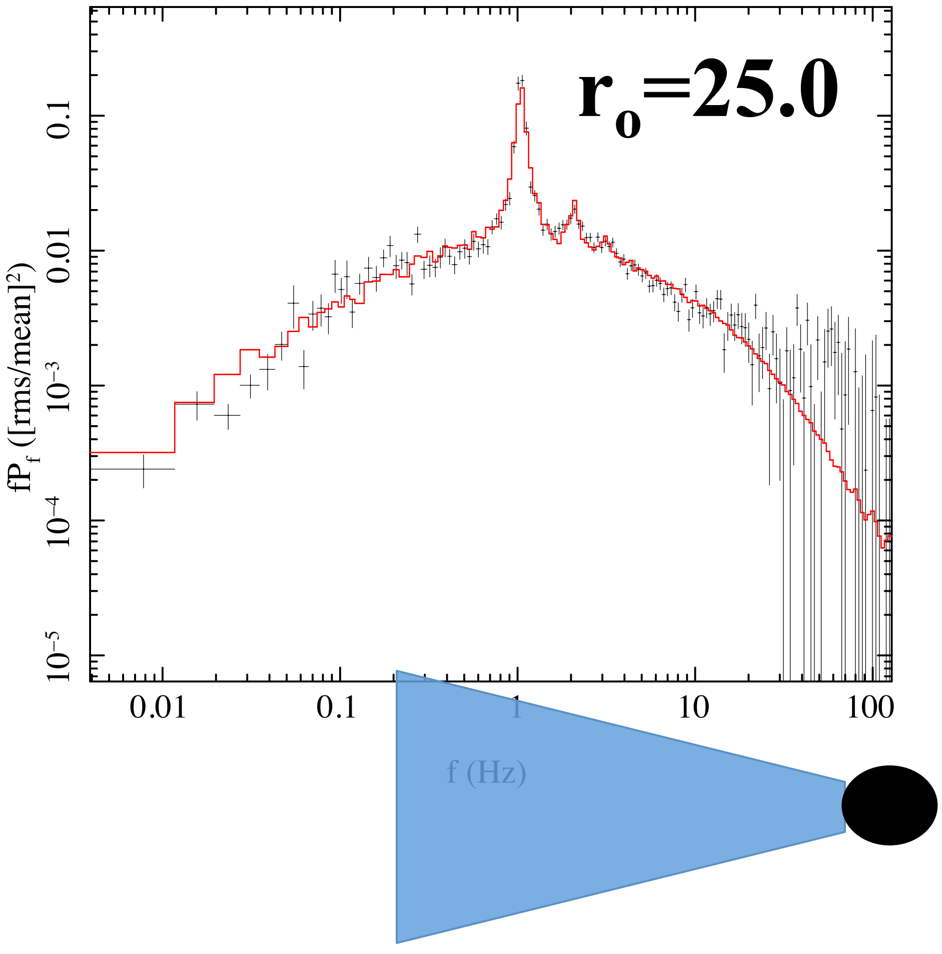
r_{bw}=6.5

h/r=0.27

Σ_0 =10.5

Fitting to XTE J1550-564





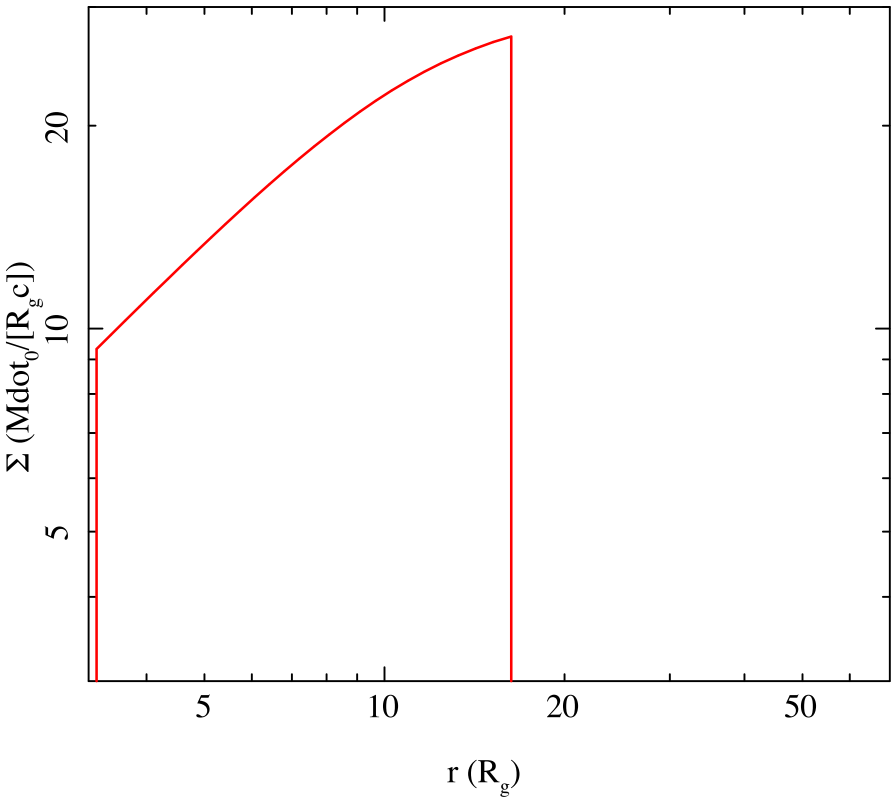
r_o=25.0

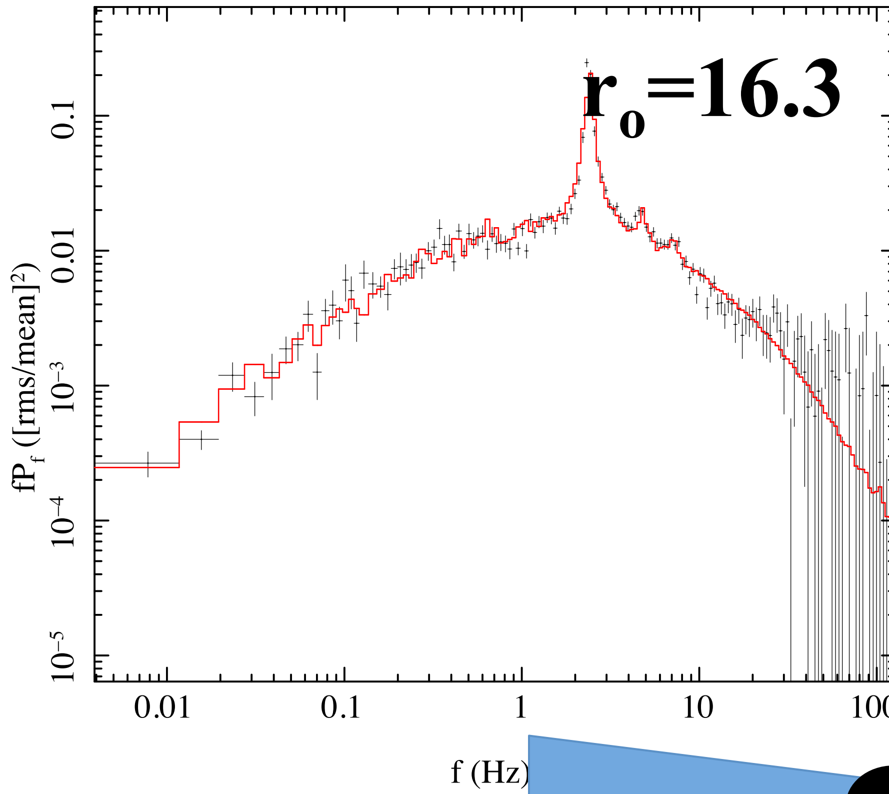
r_{bw}=8.0

h/r=0.21

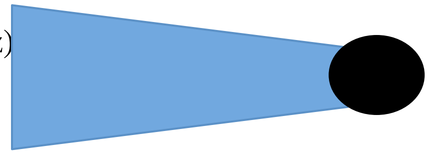
Σ_0 =21.7

Fitting to XTE J1550-564





r_o=16.3

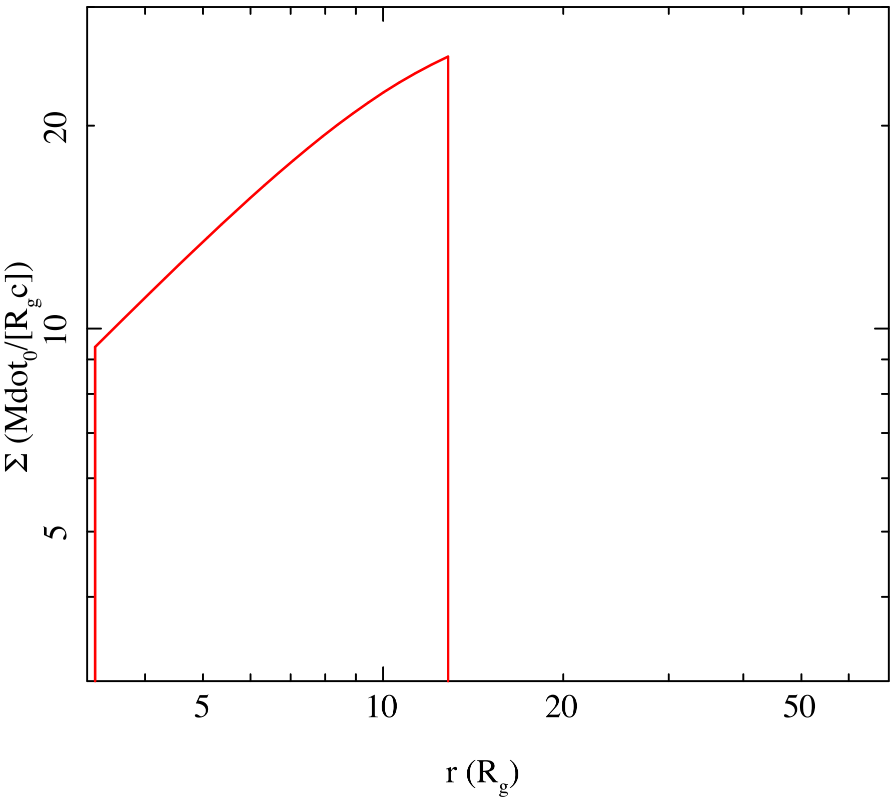


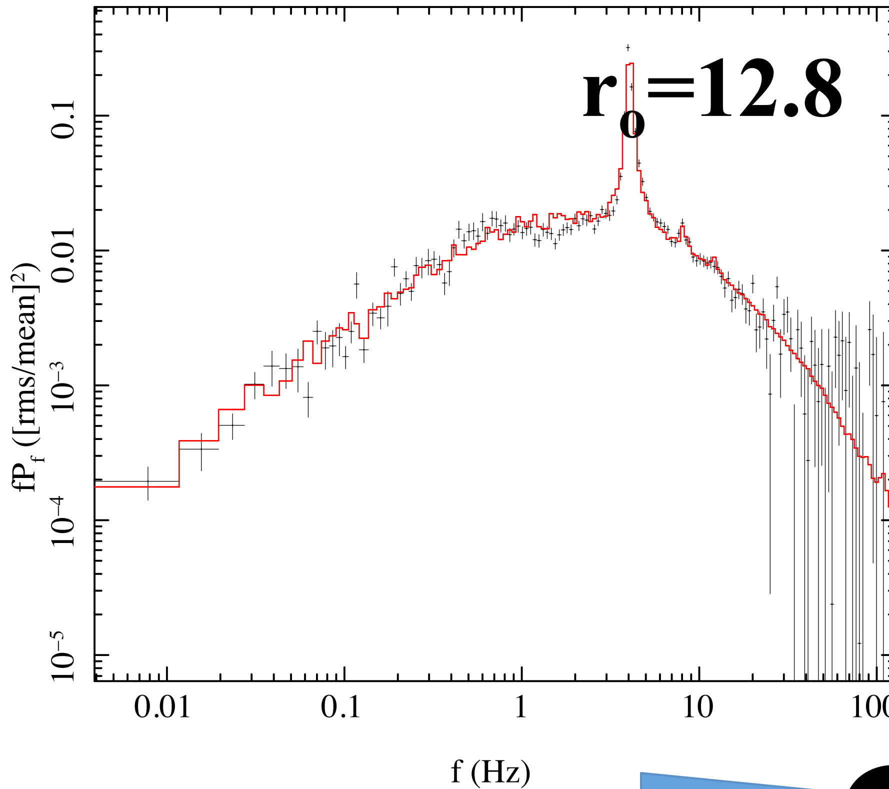
r_{bw}=12.0

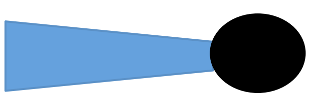
h/r=0.13

Σ_0 =30.0

Fitting to XTE J1550-564







r_{bw}=12.1

h/r=0.12

Σ_0 =30.4

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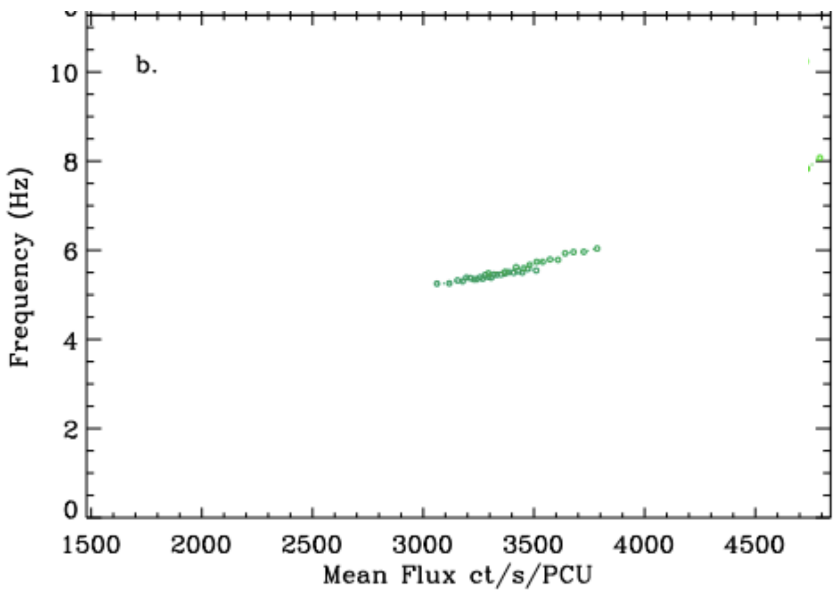
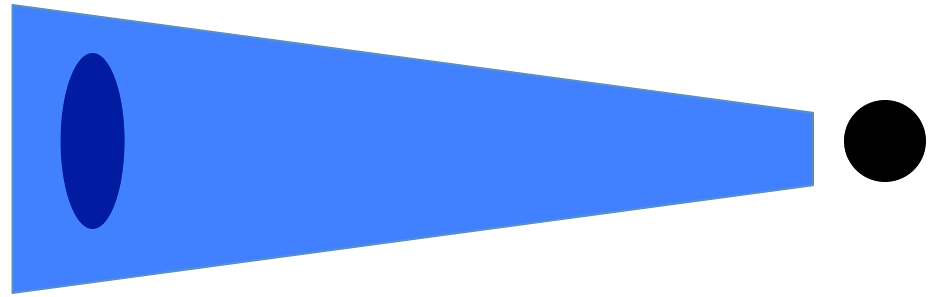
Conclusions

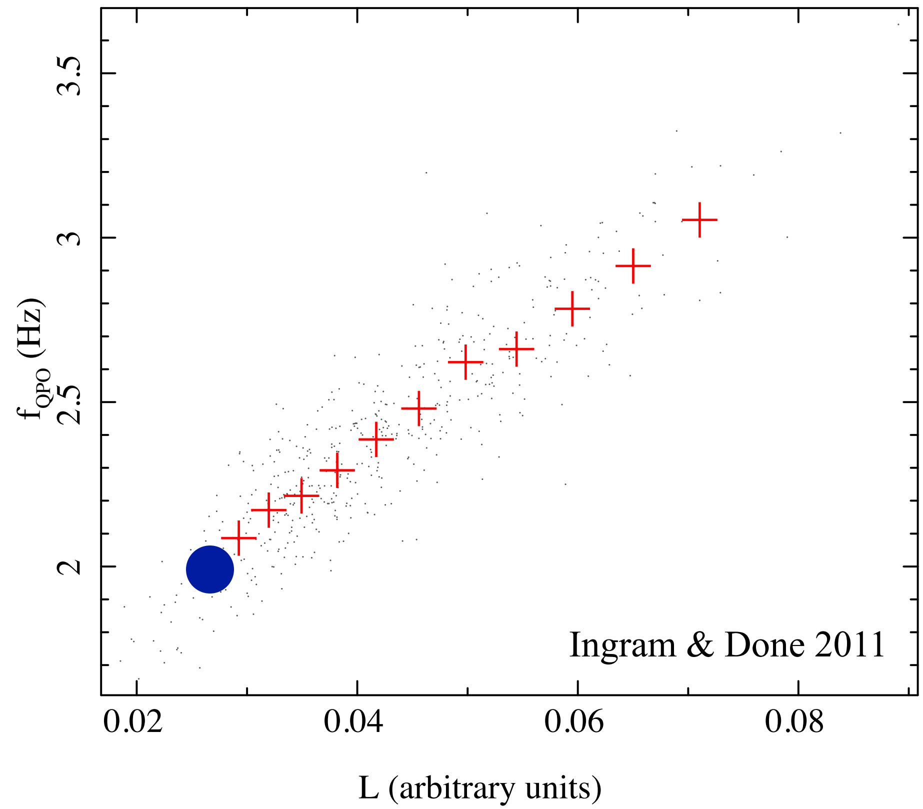
- Propagating fluctuations model can predict broadband noise shape
- Lense-Thirring precession model can predict QPO frequencies from SAME accretion flow model
- This allows us to fit a physical model to the power spectrum of a black hole for the 1st time
- The evolution of model parameters is self-consistent
- The model also has the capability to explain many other properties …e.g. frequency jitter, lags, sigma-flux relation, frequency resolved rms spectrum

Frequency jitter

Heil, Vaughan & Uttley 2011







- On short timescales (3s segments), the QPO frequency correlates with the source flux
- Our model *predicts* this because both precession frequency and flux depend on mass accretion rate

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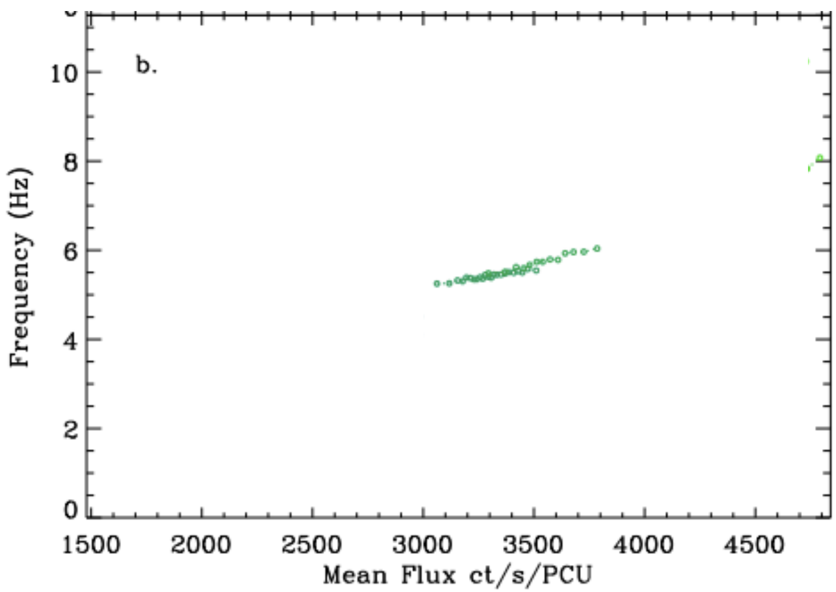
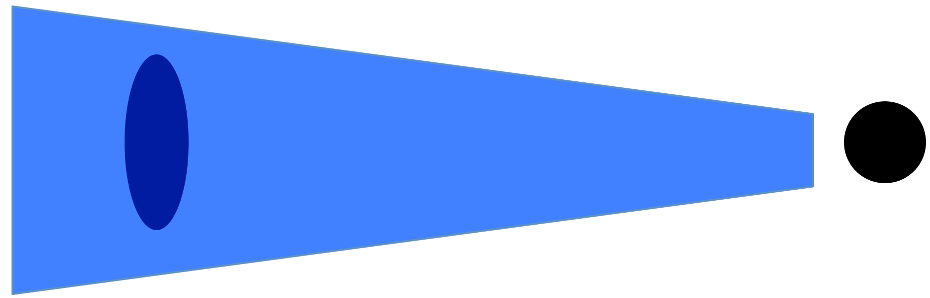
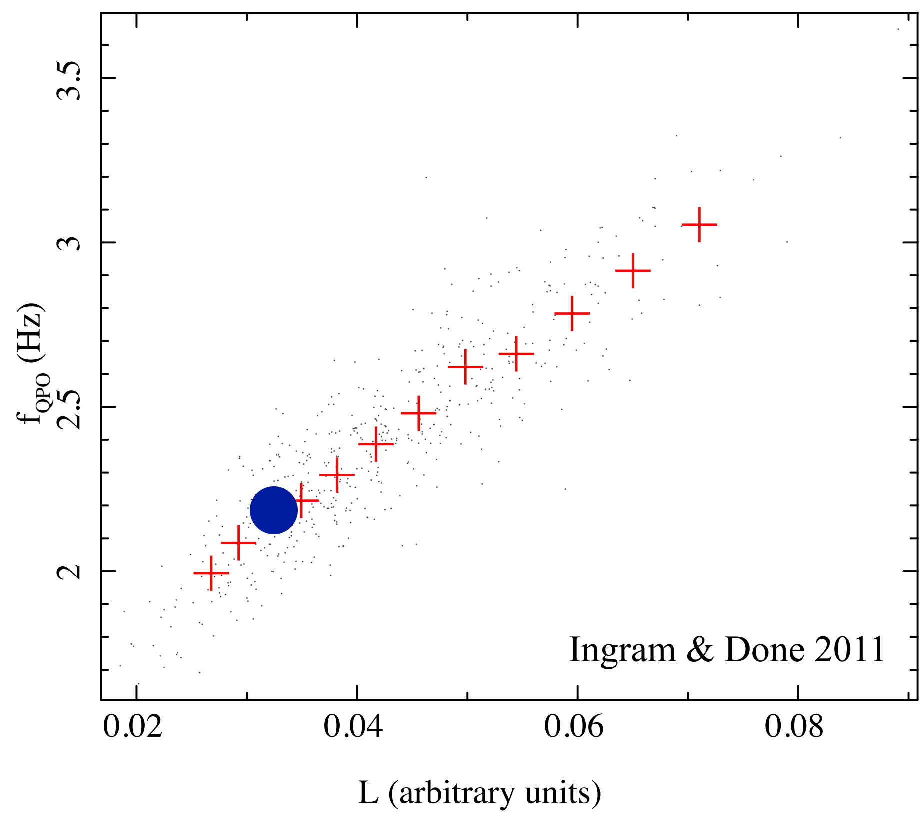
Frequency jitter

Heil, Vaughan & Uttley 2011







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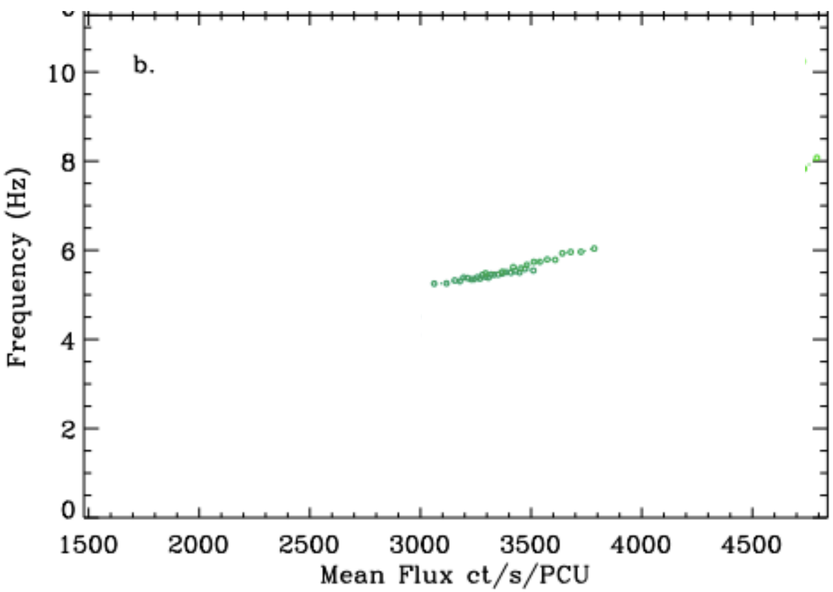
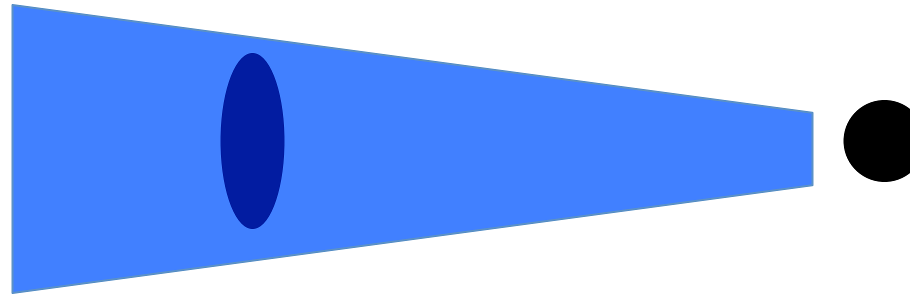
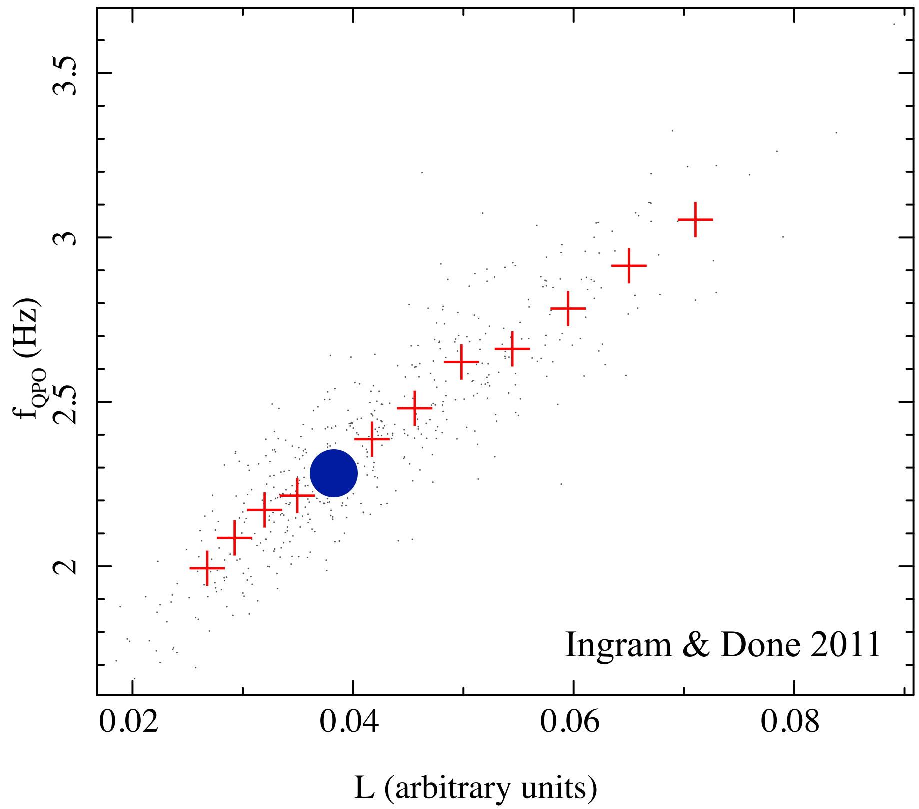
Frequency jitter

Heil, Vaughan & Uttley 2011







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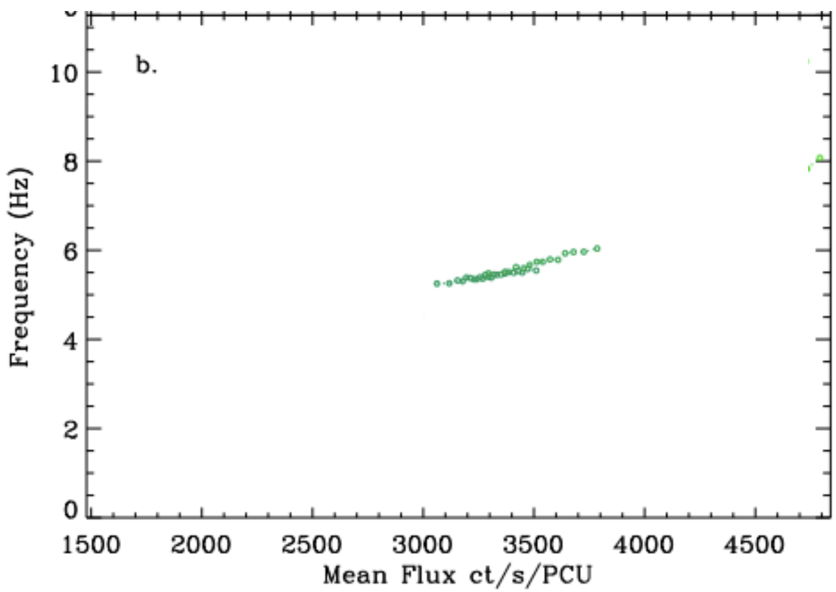
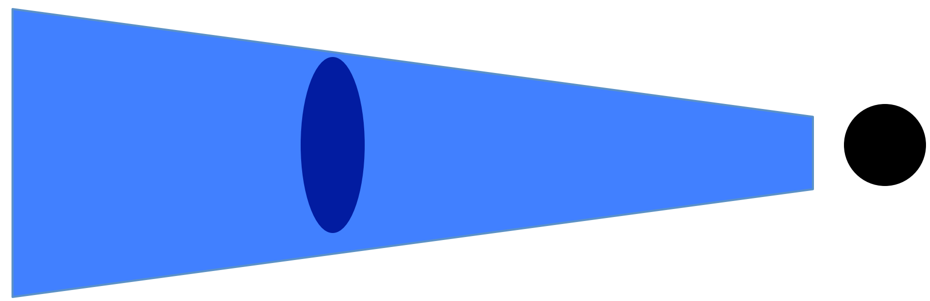
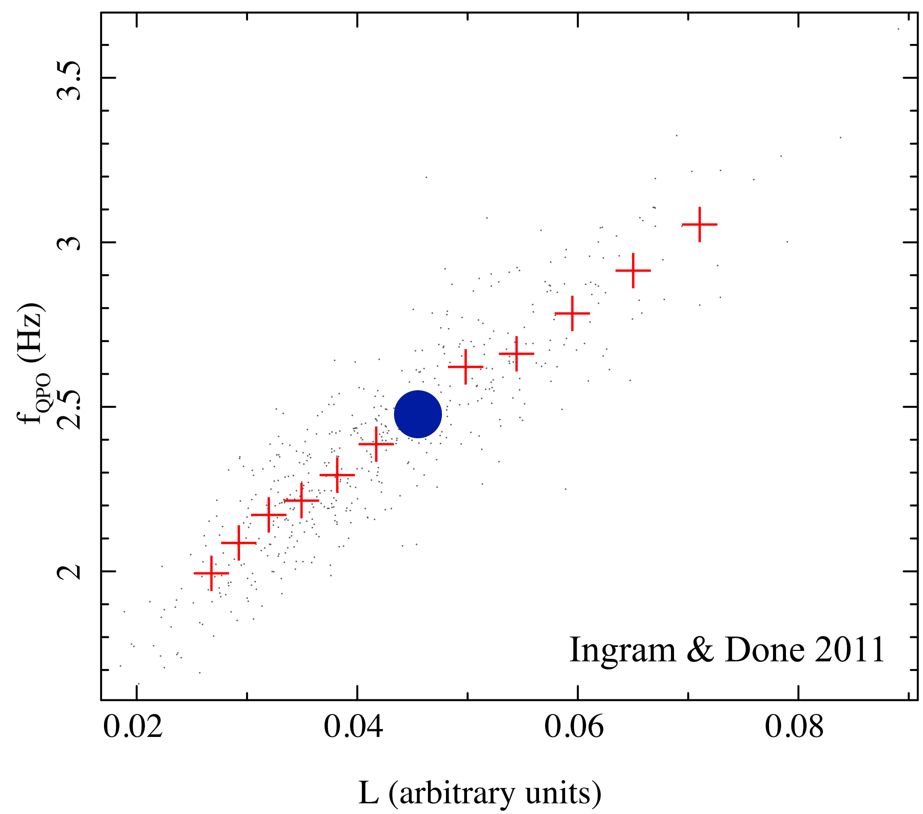
Frequency jitter

Heil, Vaughan & Uttley 2011







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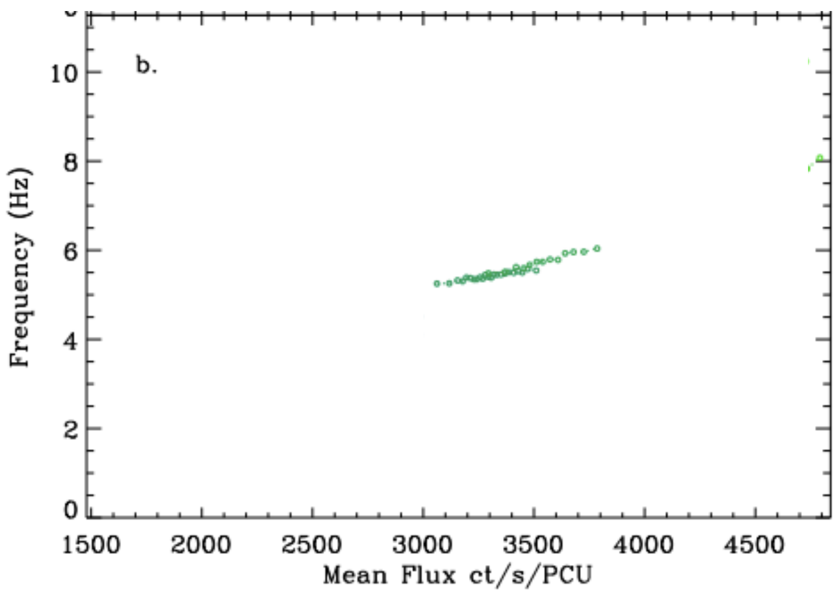
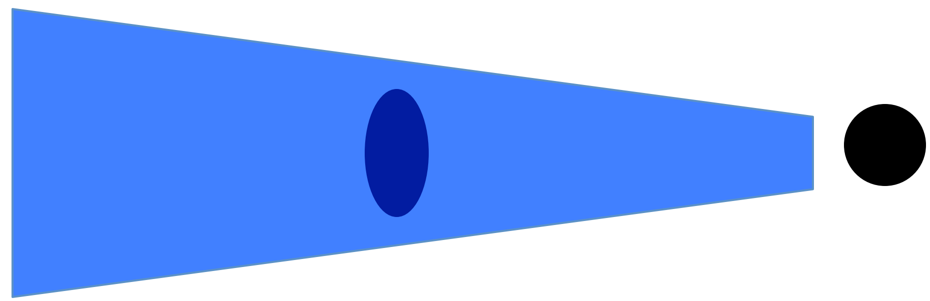
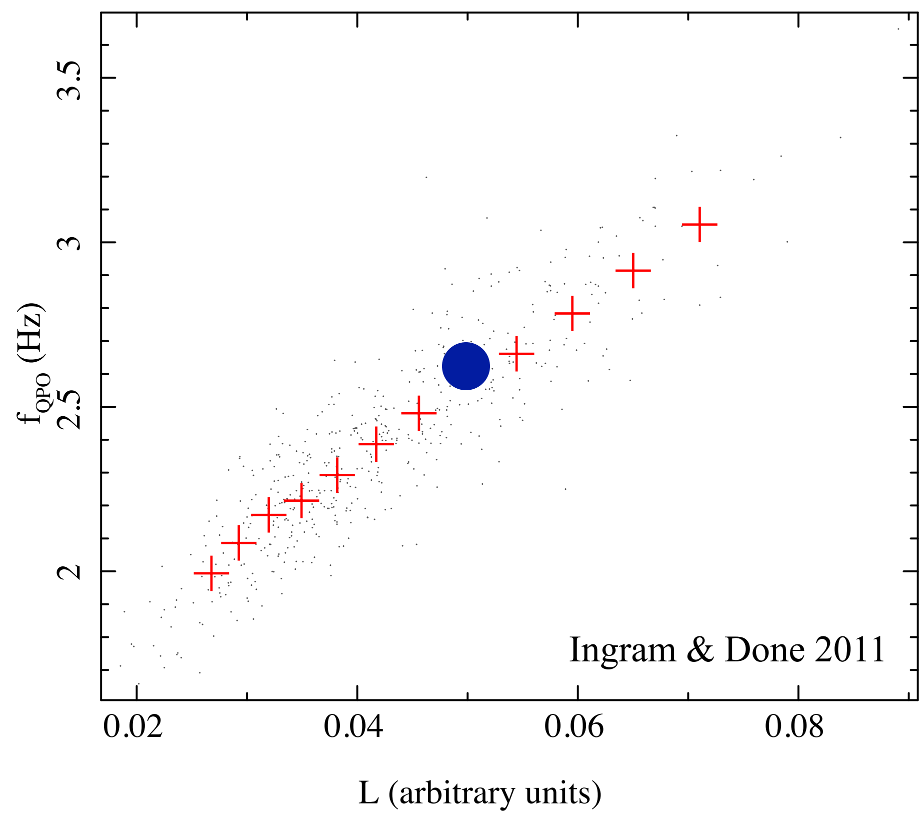
Frequency jitter

Heil, Vaughan & Uttley 2011







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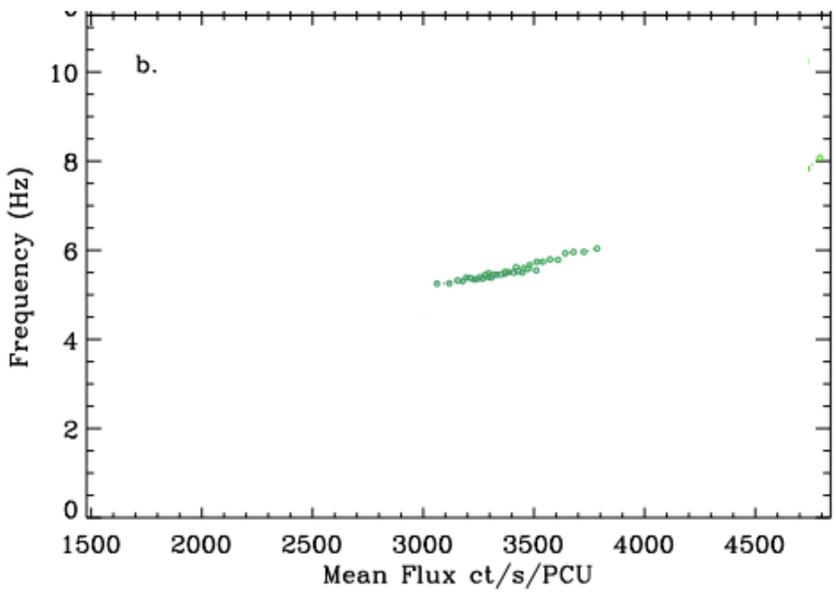
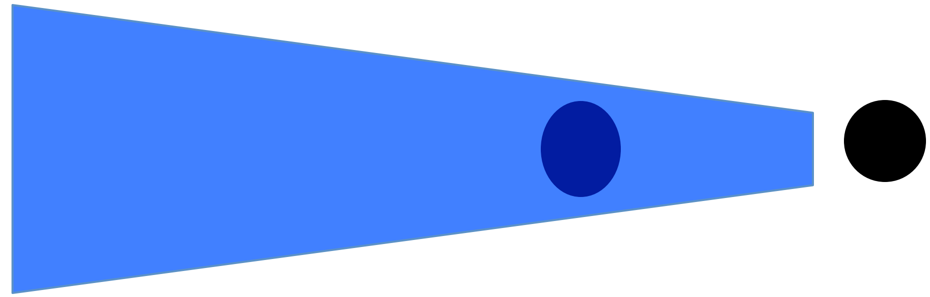
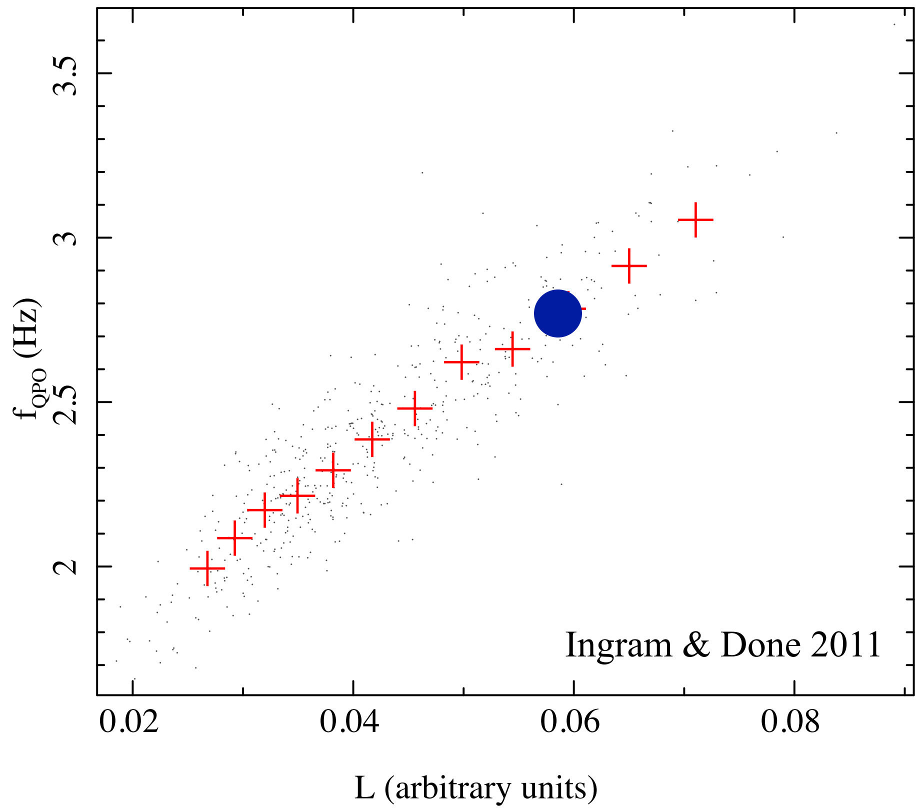
Frequency jitter

Heil, Vaughan & Uttley 2011



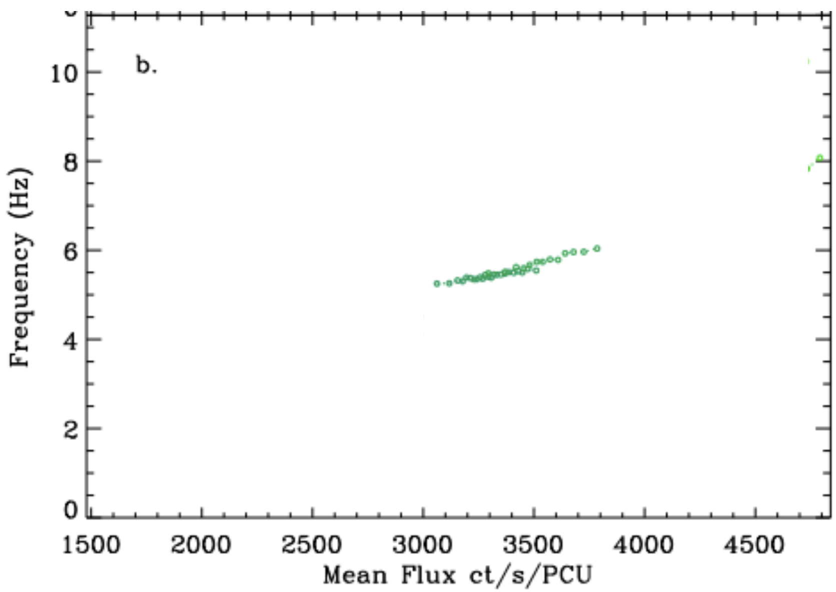


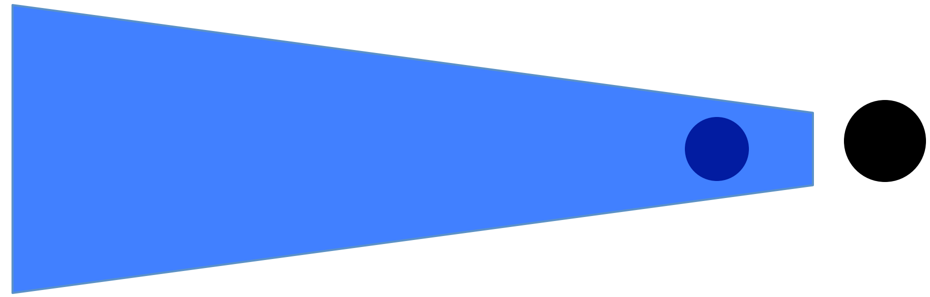


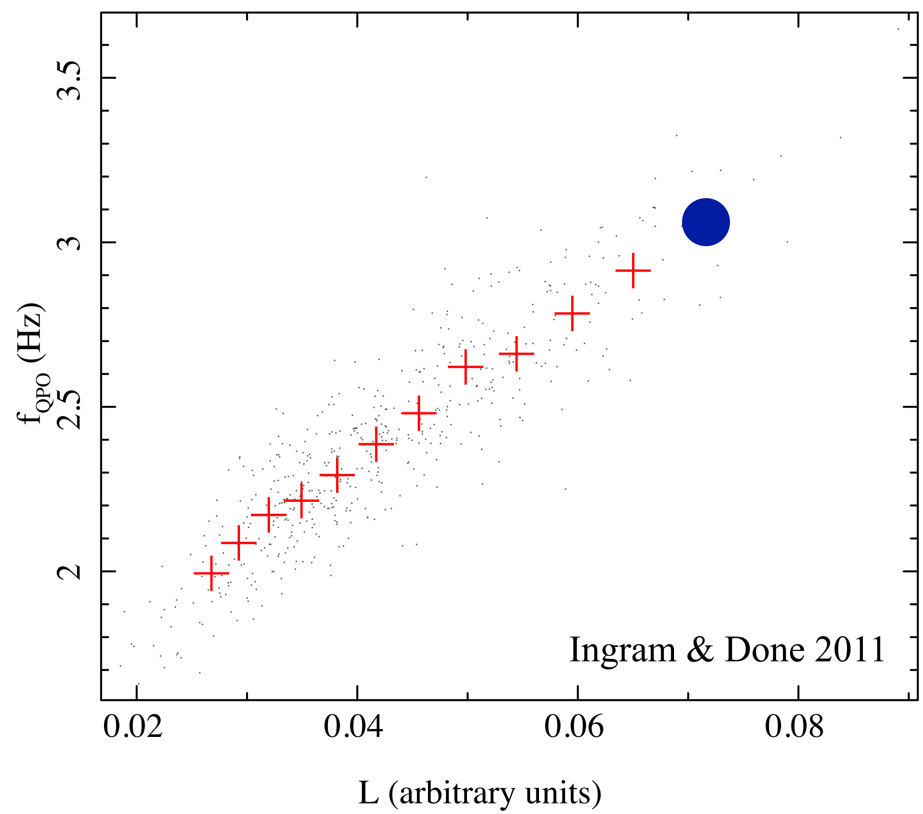
- On short timescales (3s segments), the QPO frequency correlates with the source flux
- Our model *predicts* this because both precession frequency and flux depend on mass accretion rate

Frequency jitter

Heil, Vaughan & Uttley 2011







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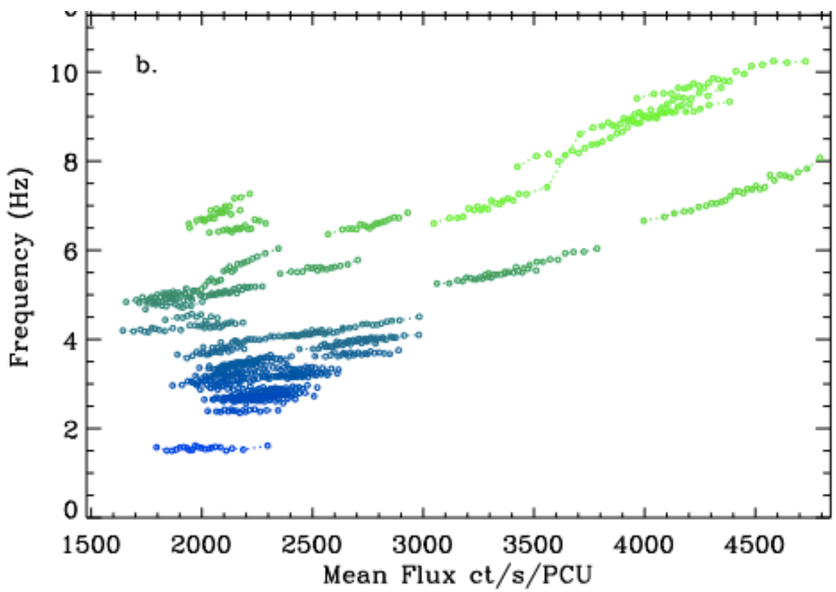
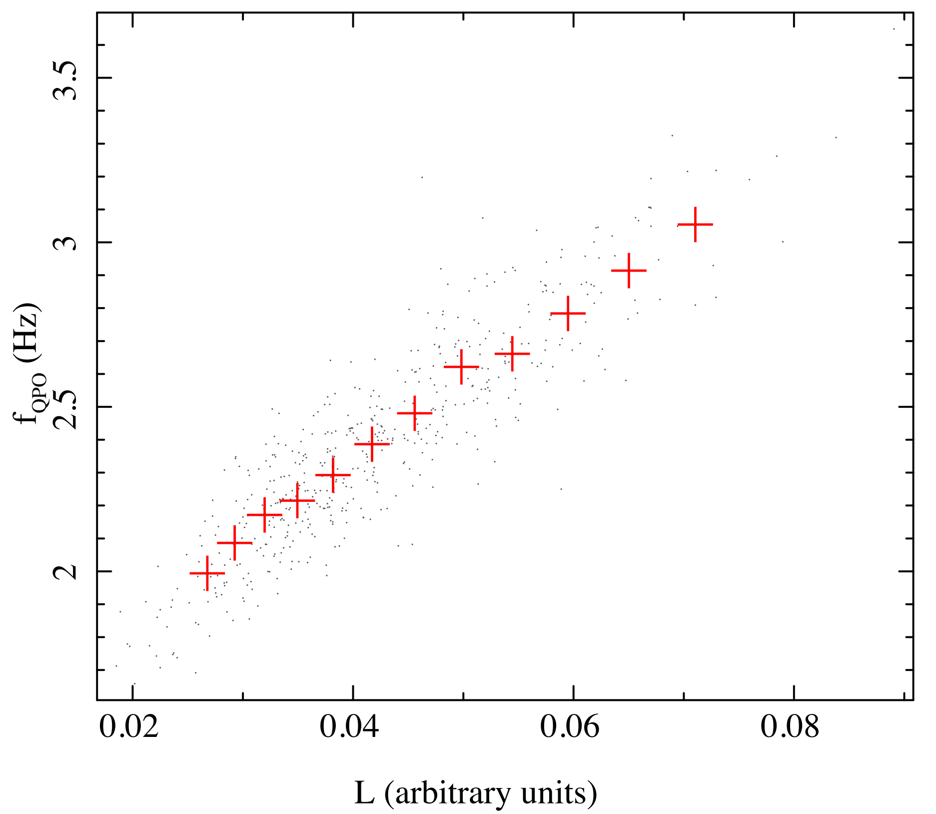
Frequency jitter



Heil, Vaughan & Uttley 2011

Ingram & Done 2011



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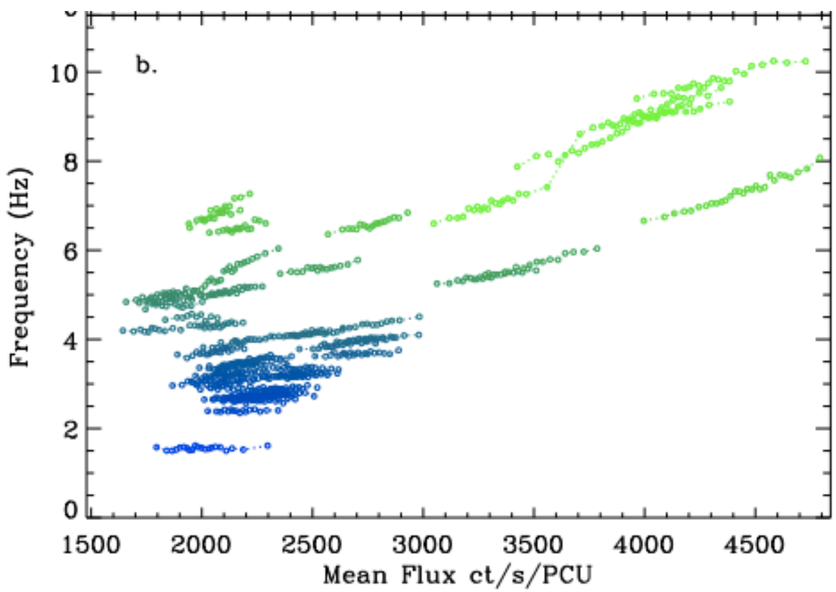
Frequency jitter



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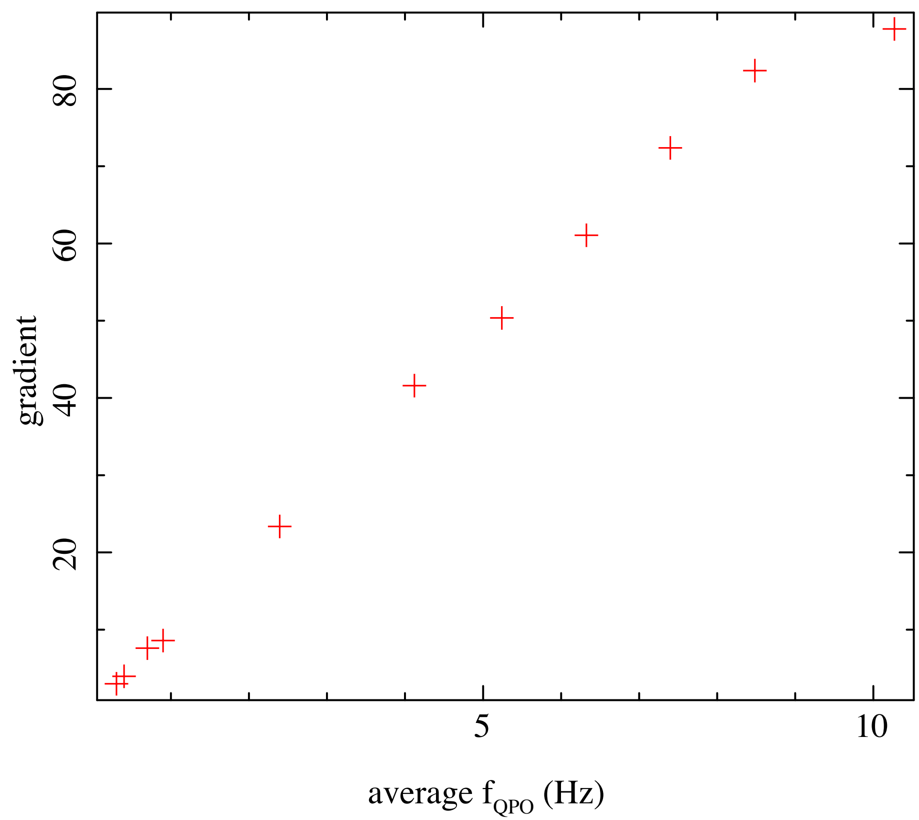

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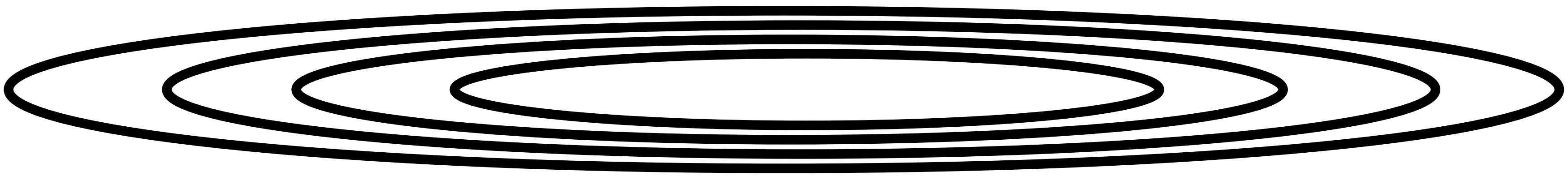
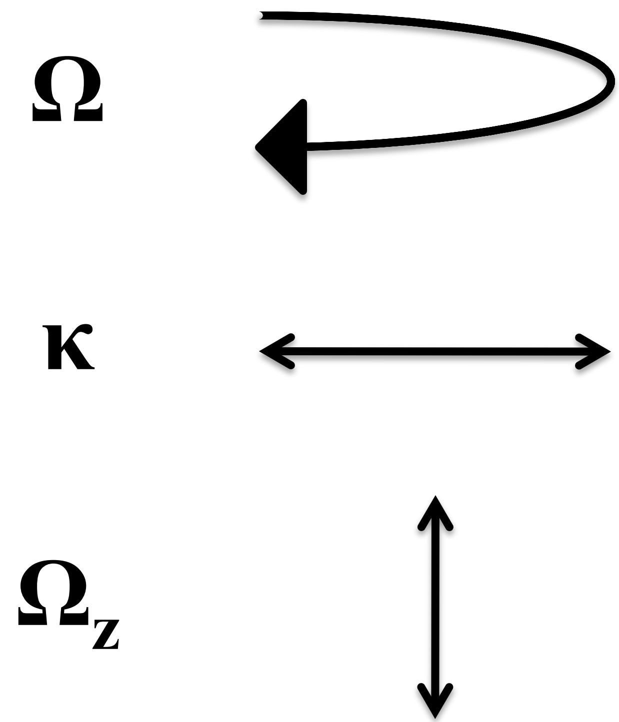
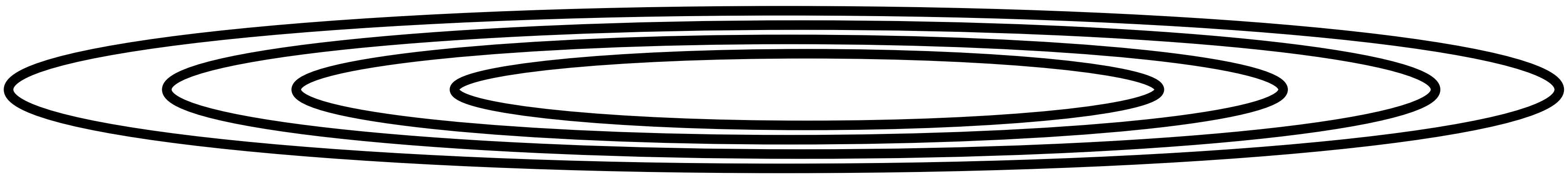
Warping



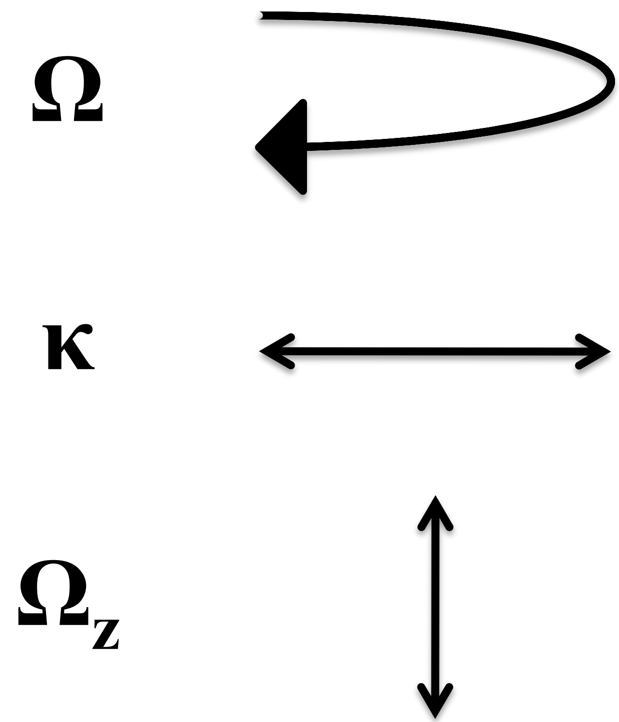
- All these frequencies depend strongly on radius
- If these rings didn't interact, there would be a huge warp
- But they interact via viscosity



Warping



- For large scale height flow, forms a steady shape that precesses
- What is this steady shape?



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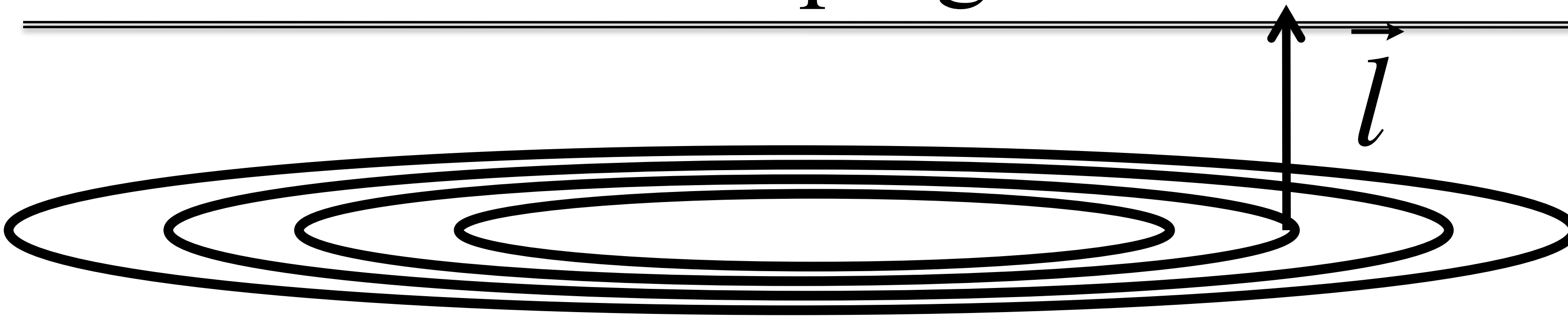
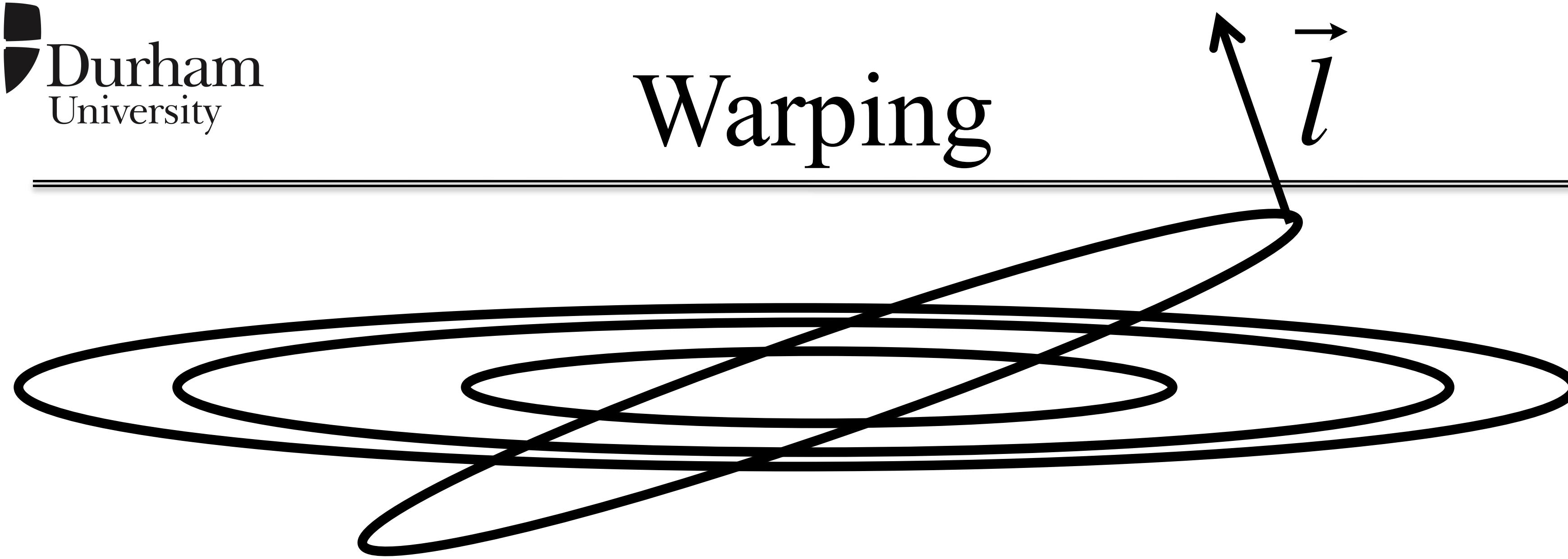
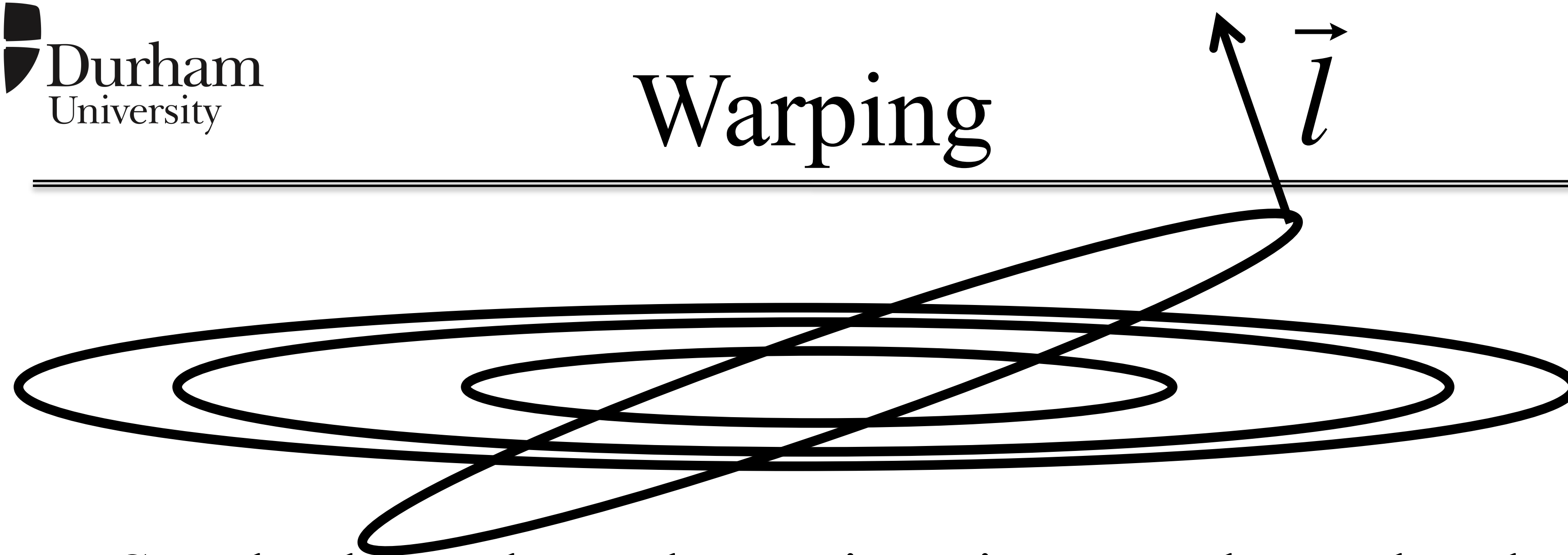
Warping



Warping



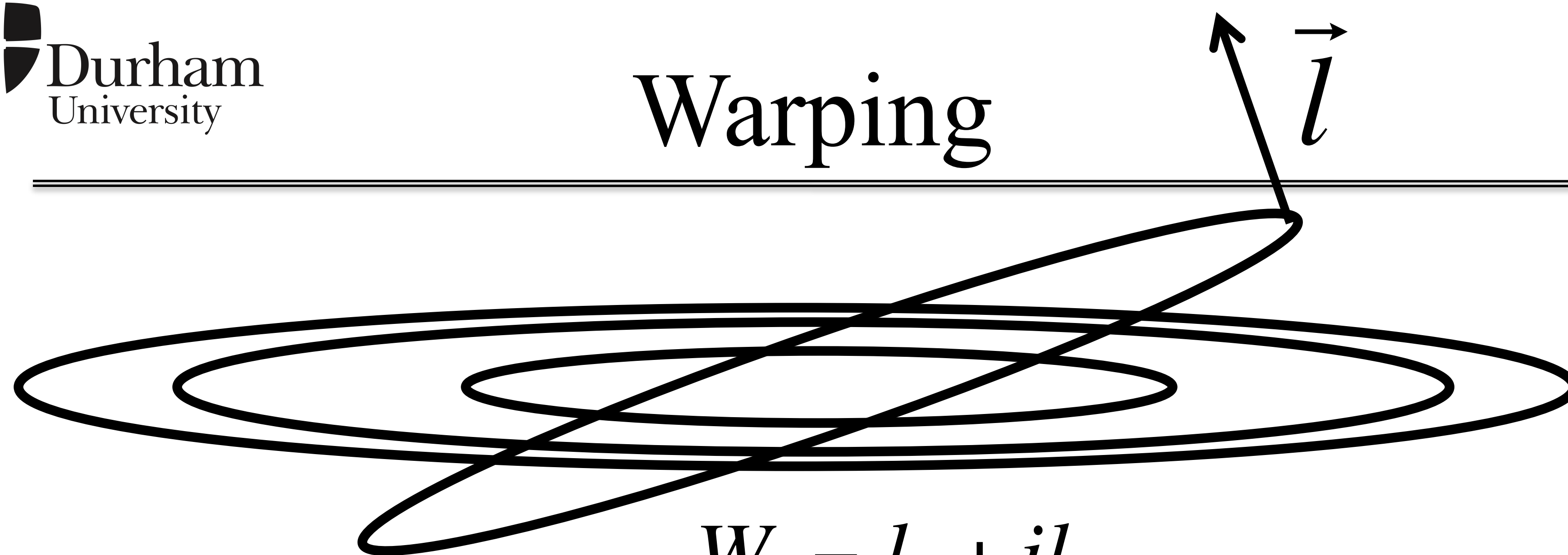
Warping



- Steady shape depends on viscosity, sound speed and the radial dependence of the three characteristic frequencie
- This means it is smooth for $r > r_{bw}$ and oscillatory for $r < r_{bw}$.

$$W = l_x + il_y$$

Warping

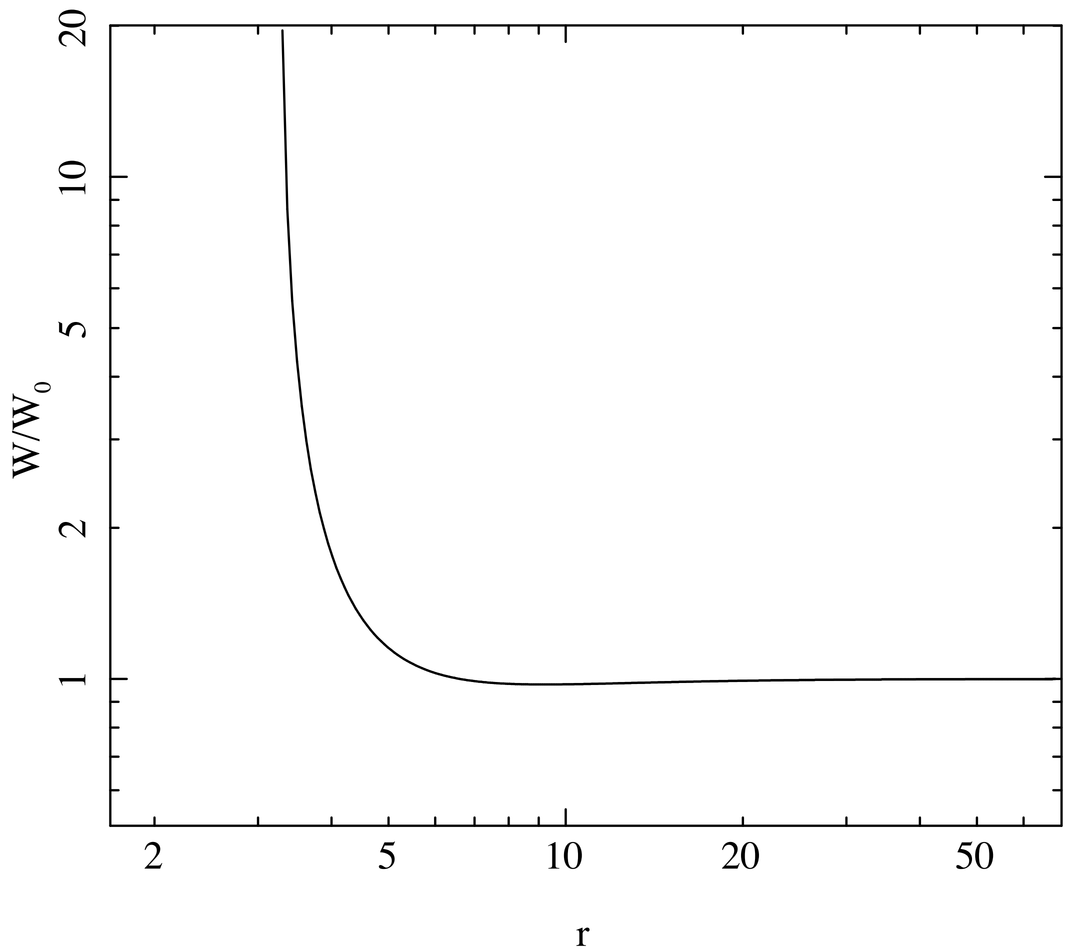


$$W = l_x + i l_y$$

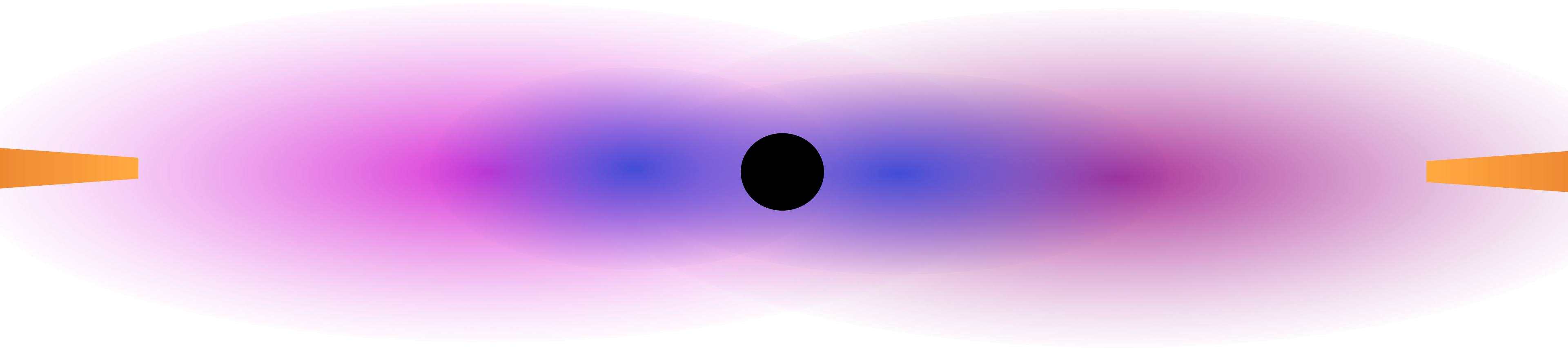
$$W \approx W_\infty(t)\frac{\cos(2\pi(r_i - r)/\lambda)}{\cos(2\pi r_i/\lambda)}$$

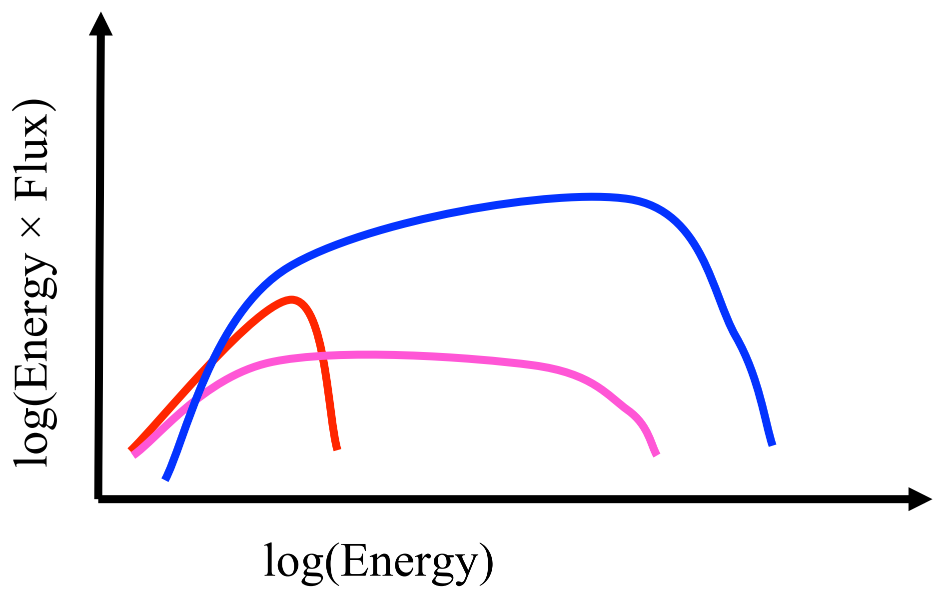
$$\lambda \approx \frac{5\pi}{4}\frac{(h/r)r^{9/4}}{(6a_*)^{1/2}}$$

Warping

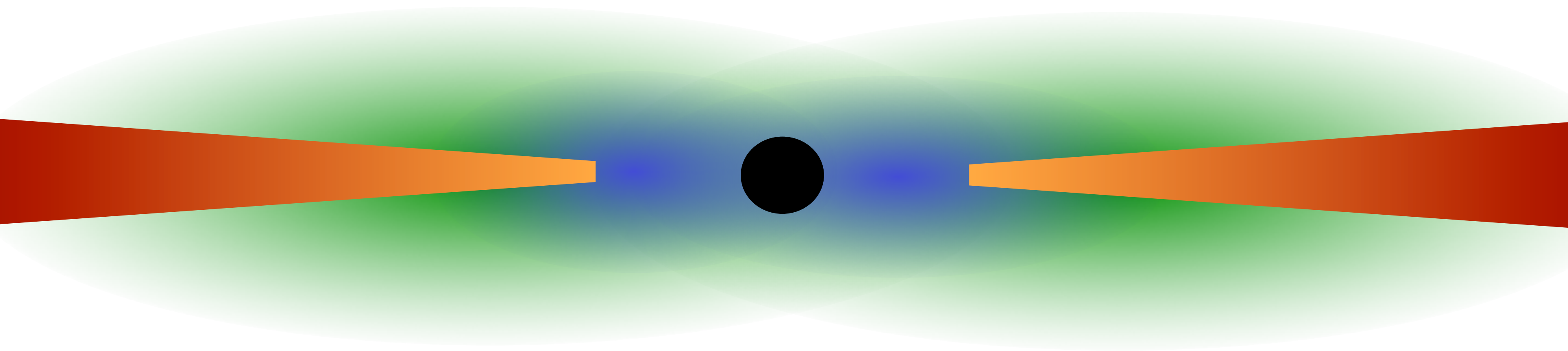


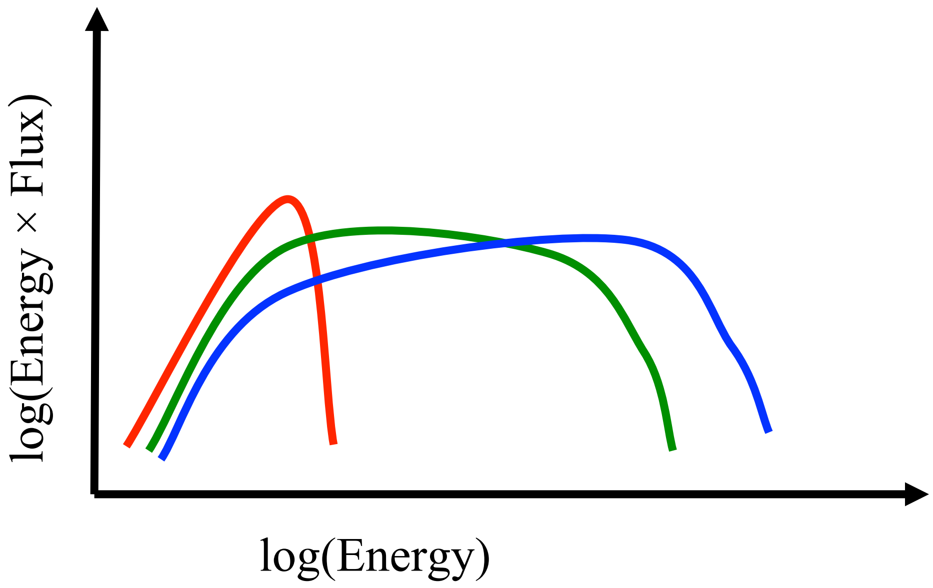
Inhomogeneous spectra

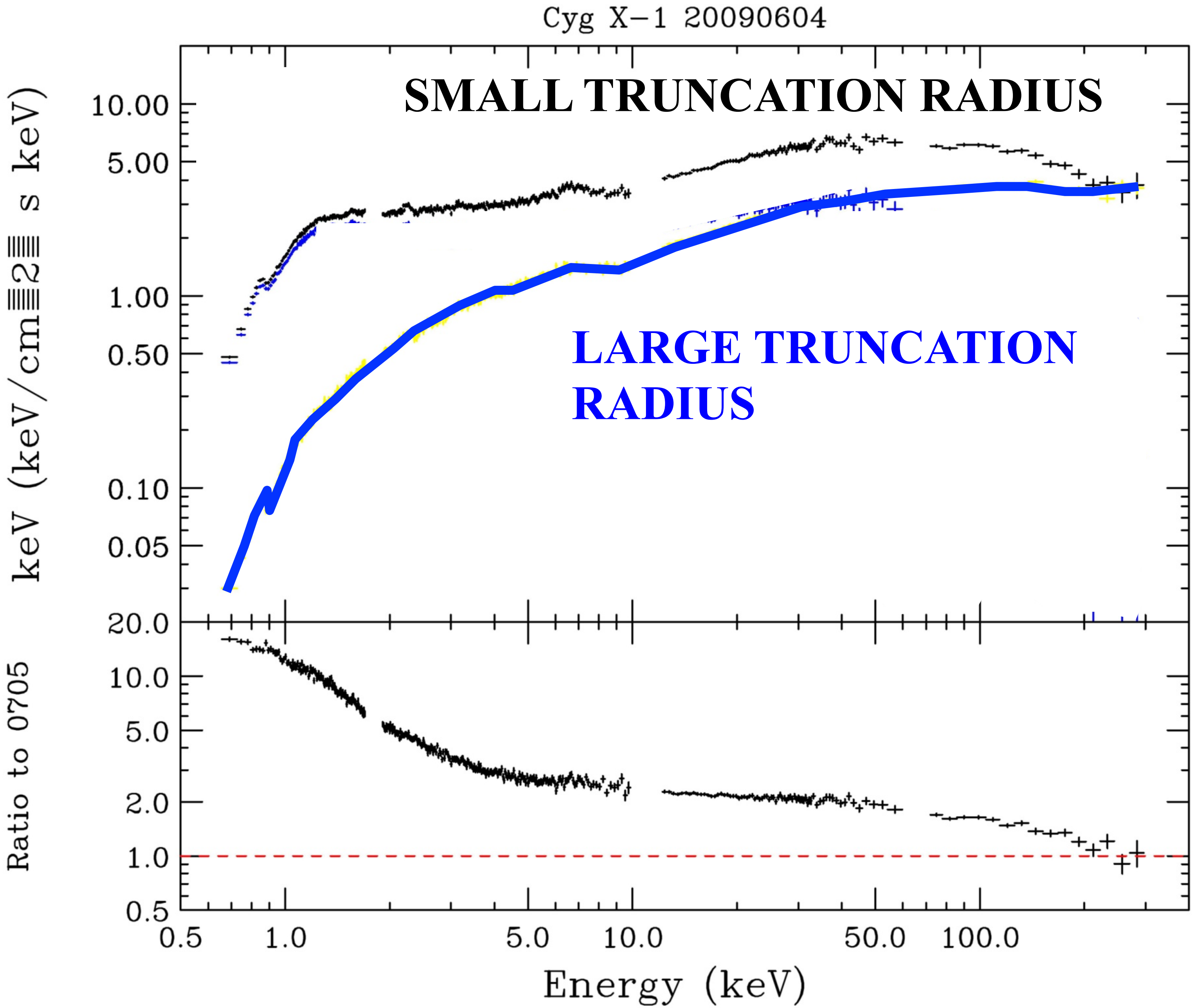




Inhomogeneous spectra



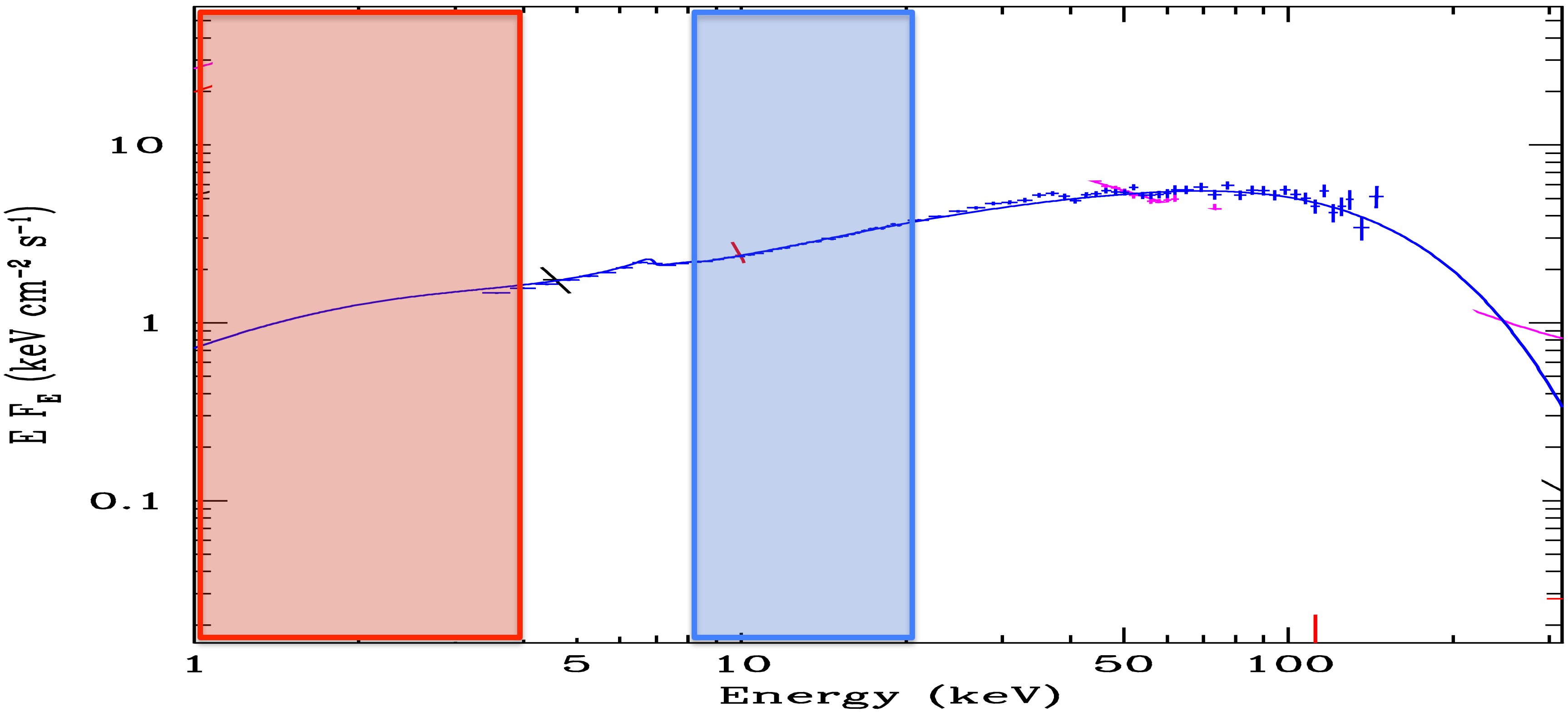




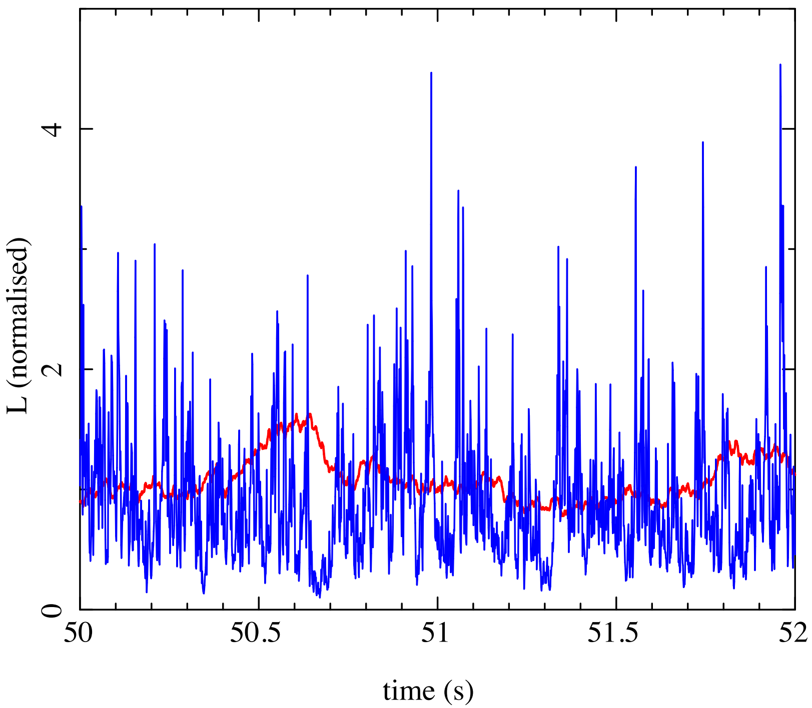
Makishima, Torii, Takahashi….

Comparing energy bands

S(t) **H(t)**

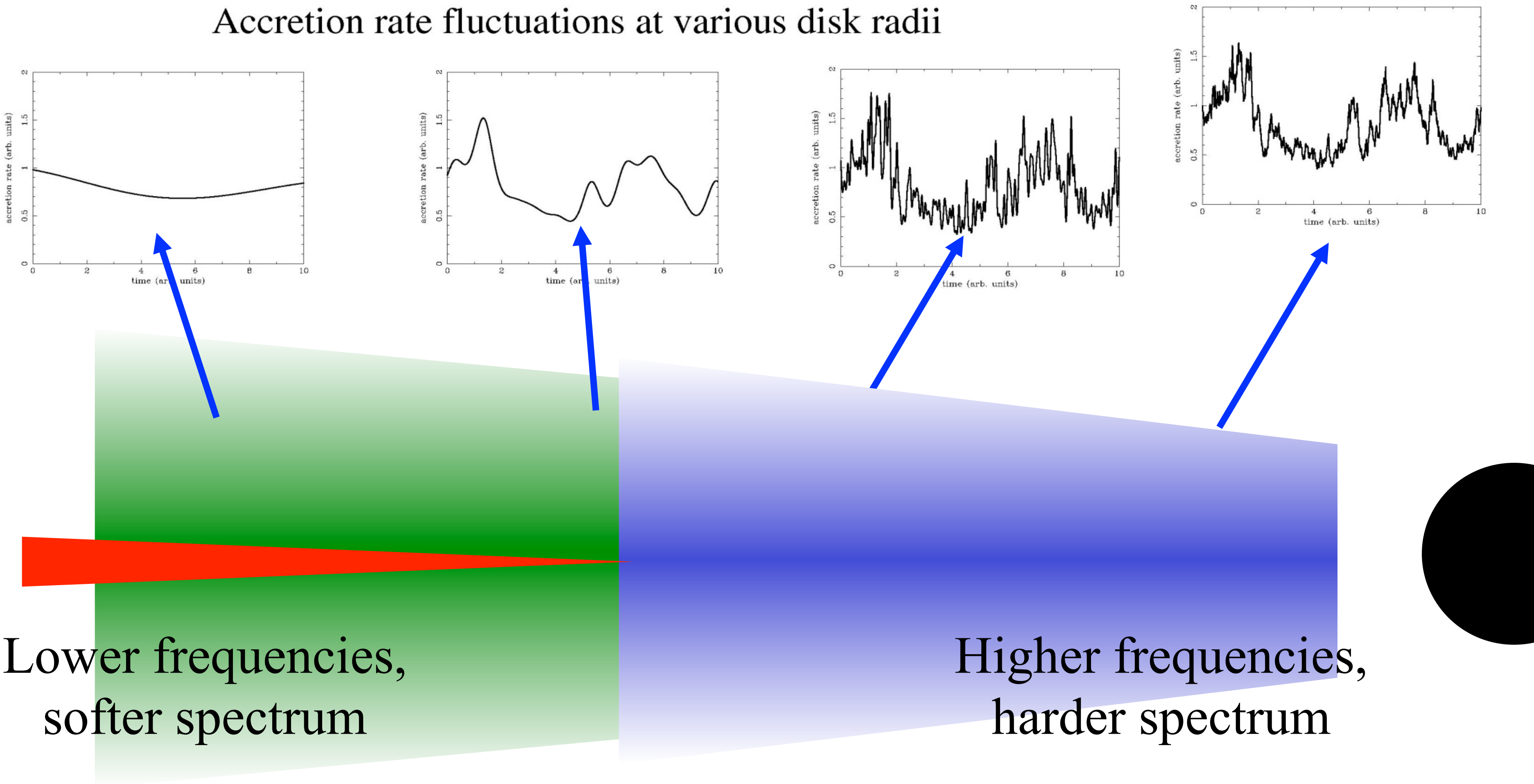


Comparing energy bands



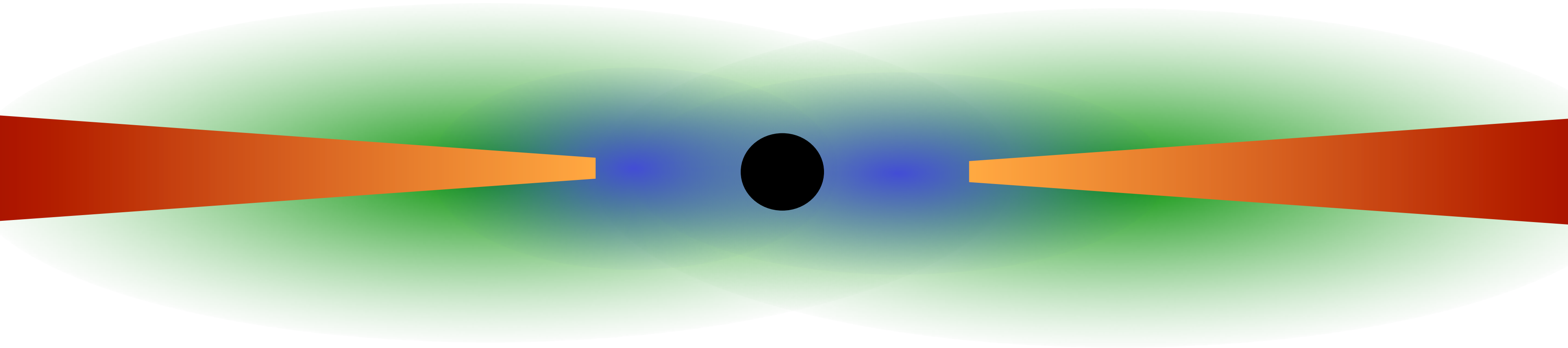
Clearly more high frequency variability in the hard band than in the soft band

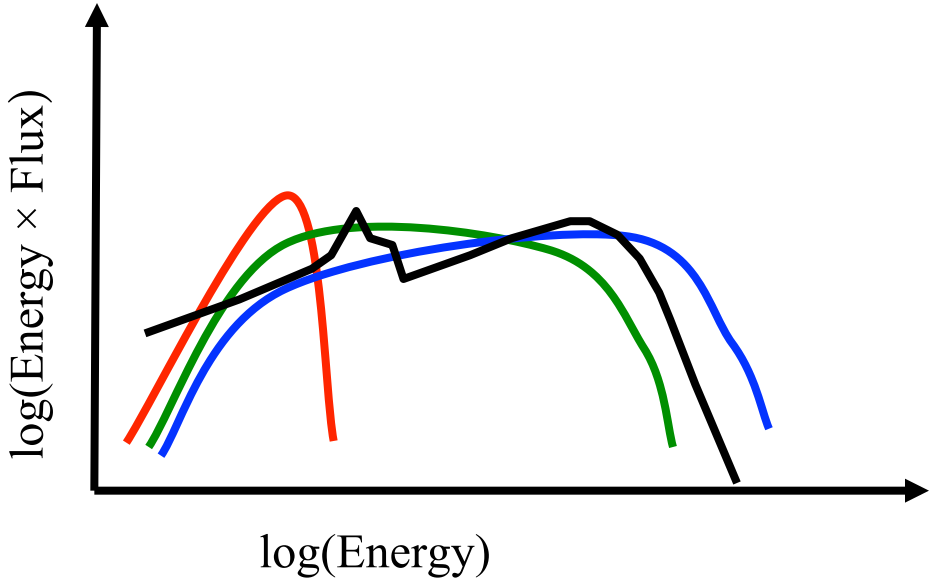
Comparing energy bands



Kotov et al 2001
Arevalo & Uttley 2006

Reflection





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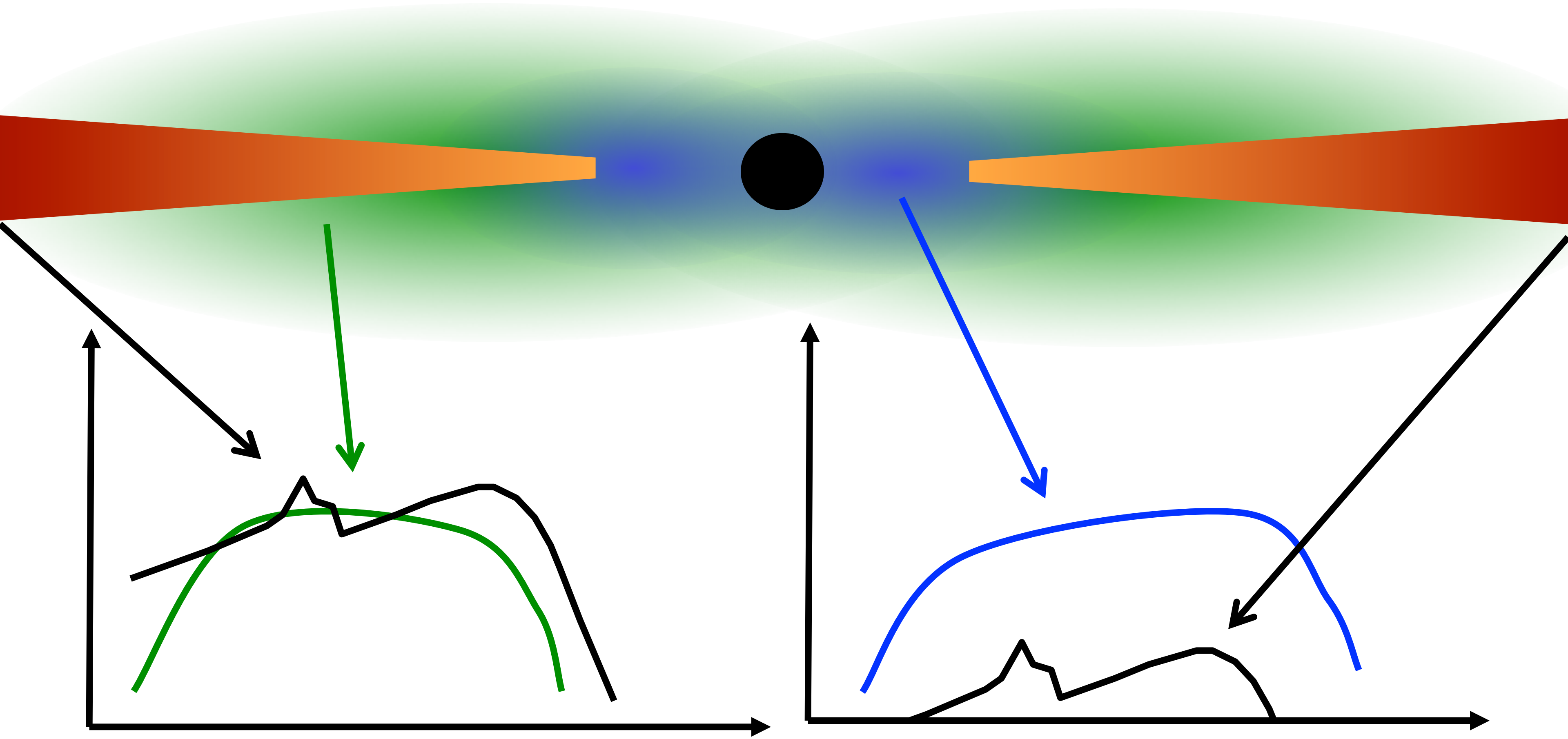
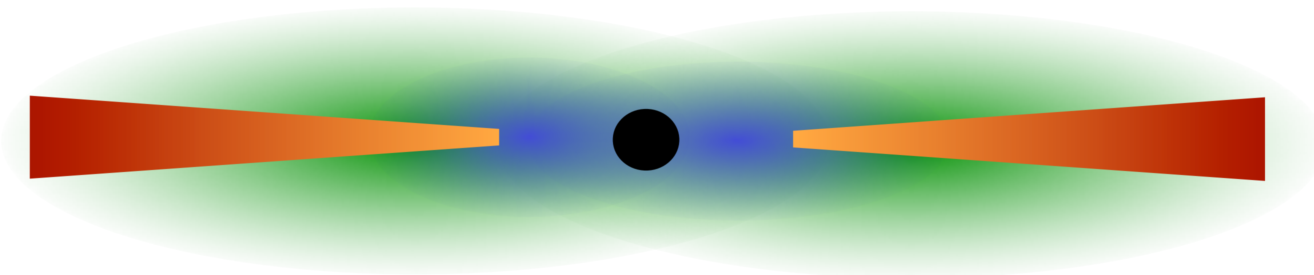
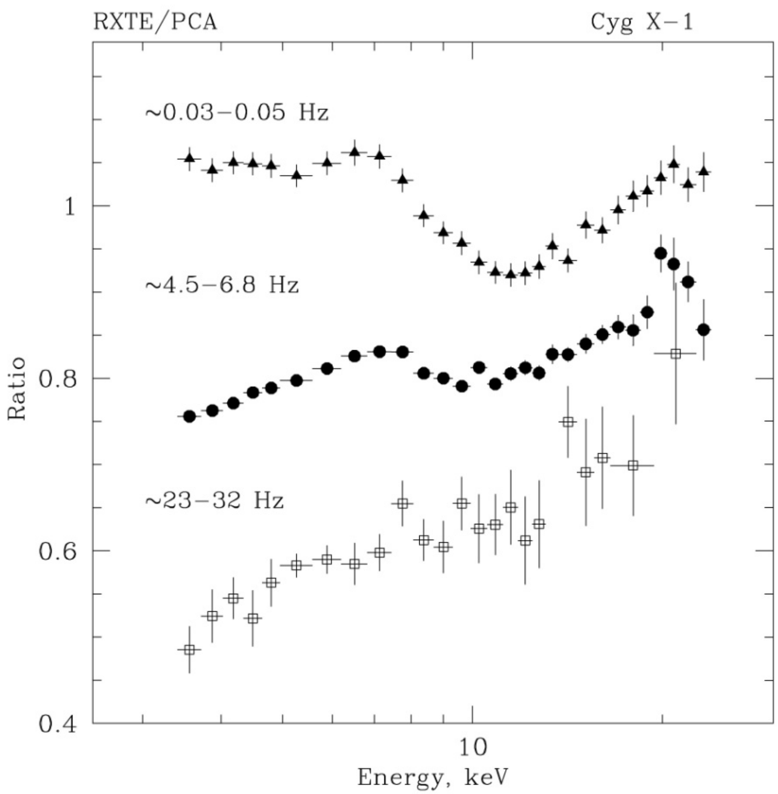


LOW FREQUENCIES **HIGH FREQUENCIES**

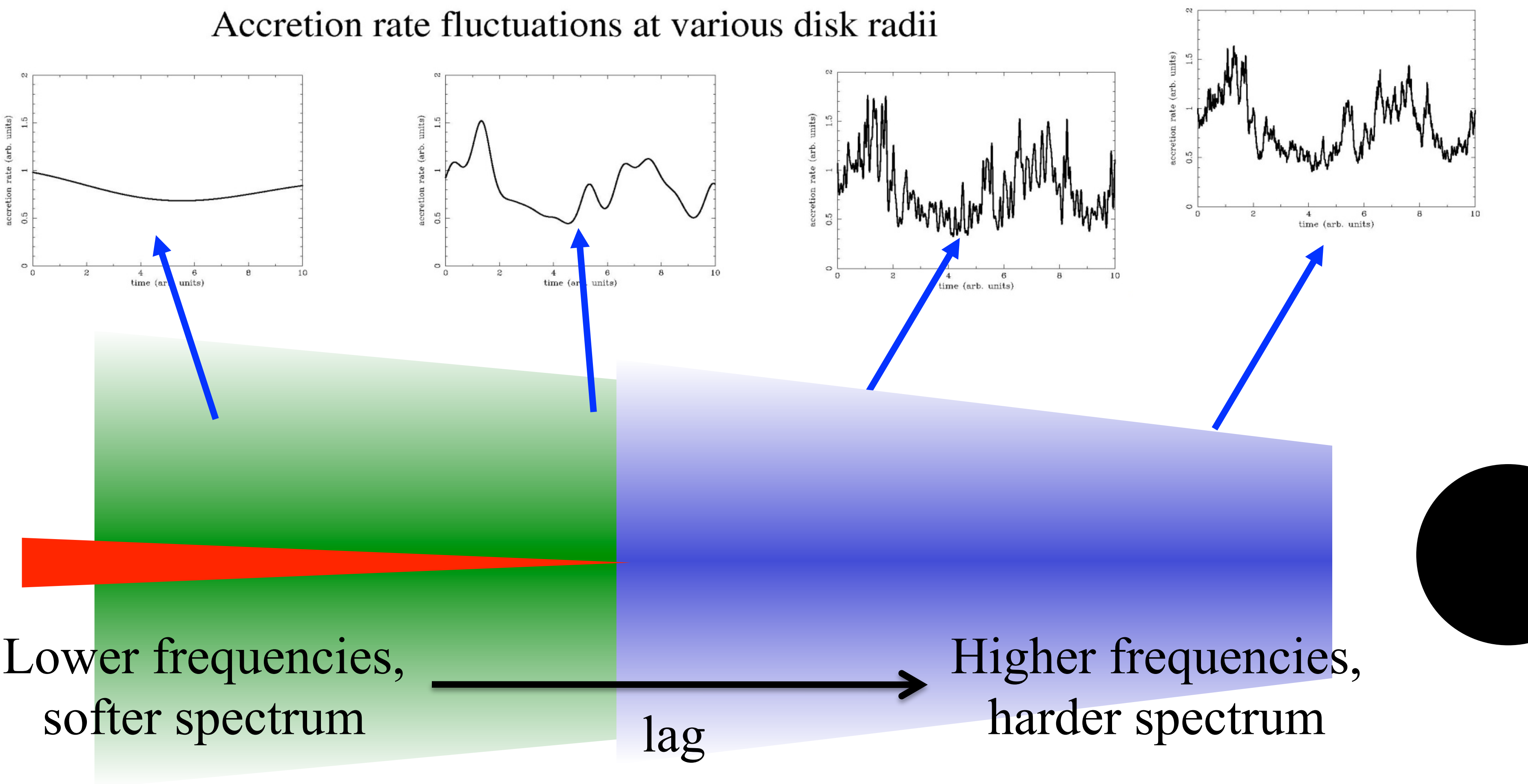
Fourier resolved spectroscopy





- Higher reflection fraction and softer spectrum for lower frequency bands – Revnivtsev et al 1999
- Large radius softer, and more reflection, slow variability
- In inner region, higher frequencies and fewer seed photons so harder spectrum and less reflection

Time lags



Kotov et al 2001
Arevalo & Uttley 2006

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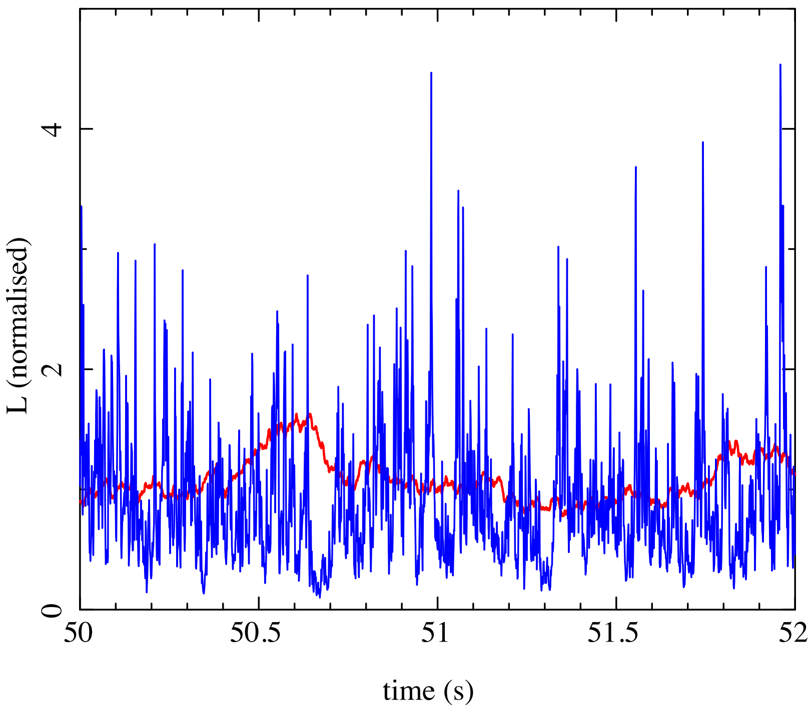
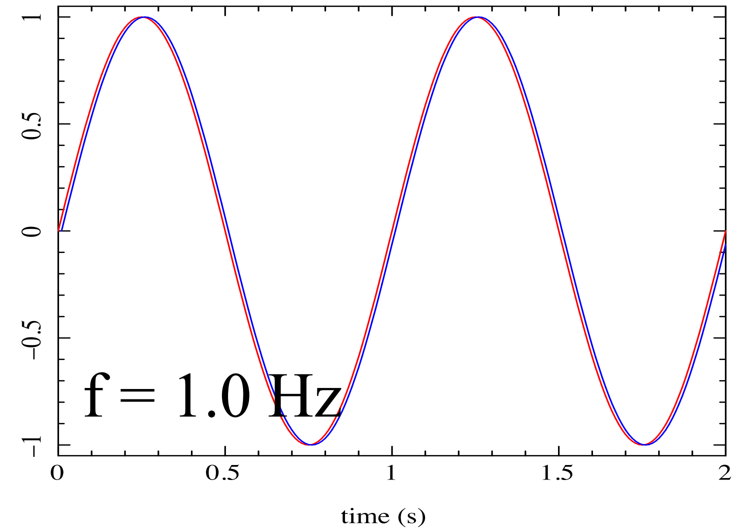
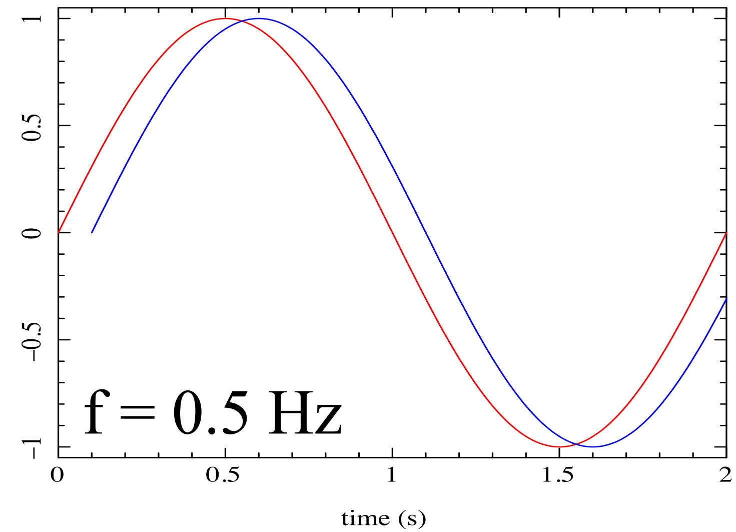
Time lags

Hard energy bands lag soft



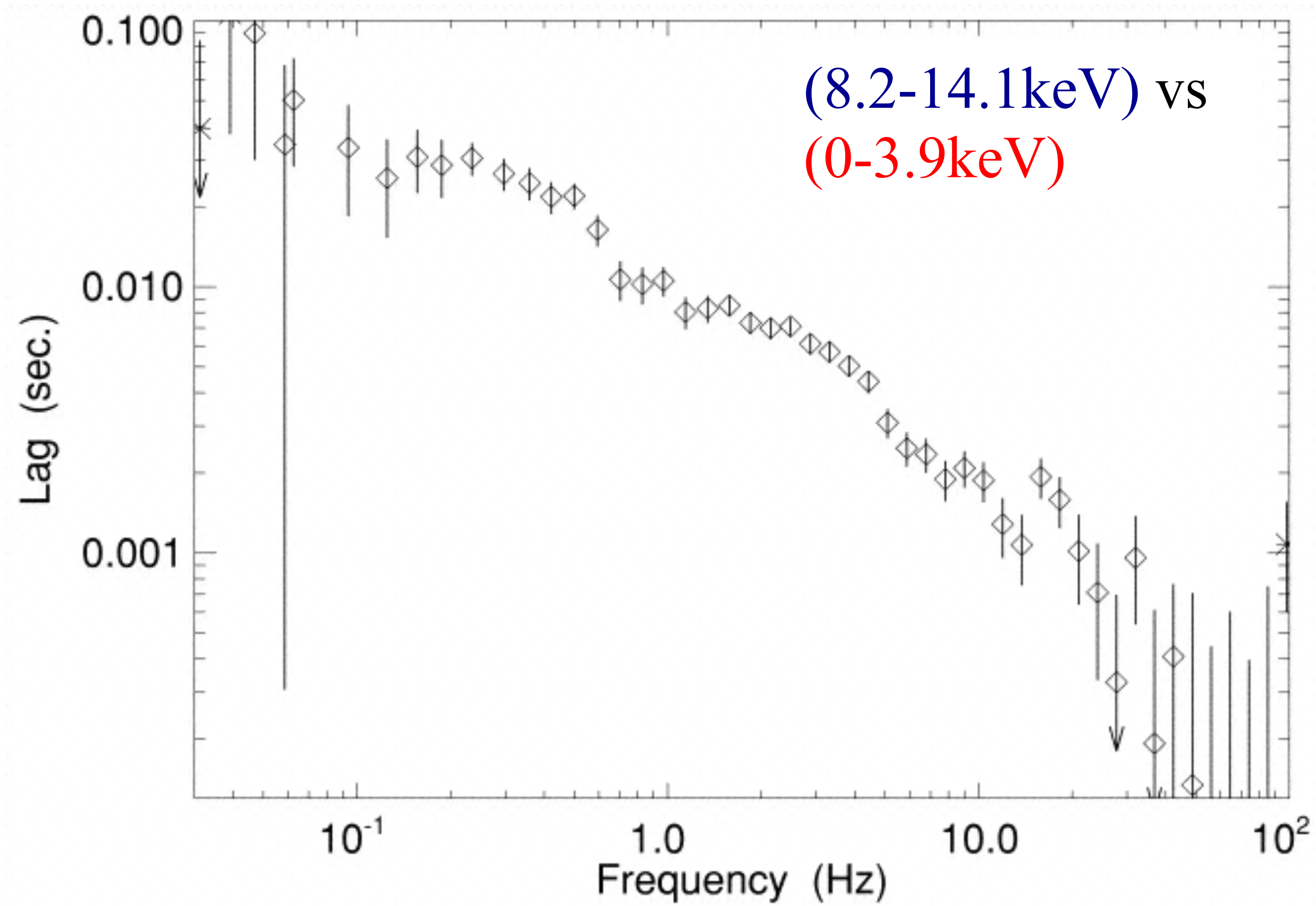




Miyamoto & Kitamoto 1988; Kotov et al 2001, Nowak et al 1999, Arevalo & Uttley 2006

Time lags

Hard energy bands lag soft



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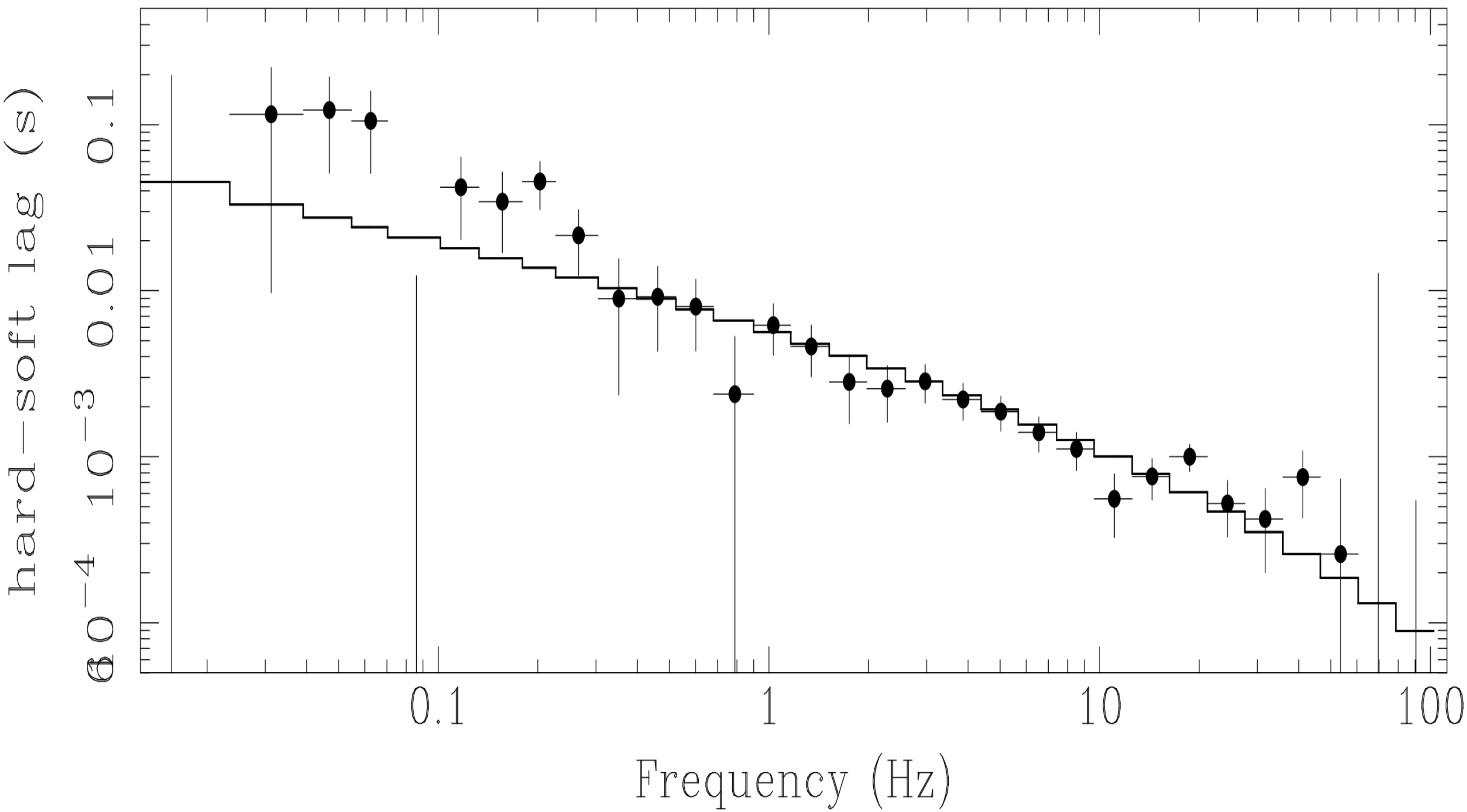
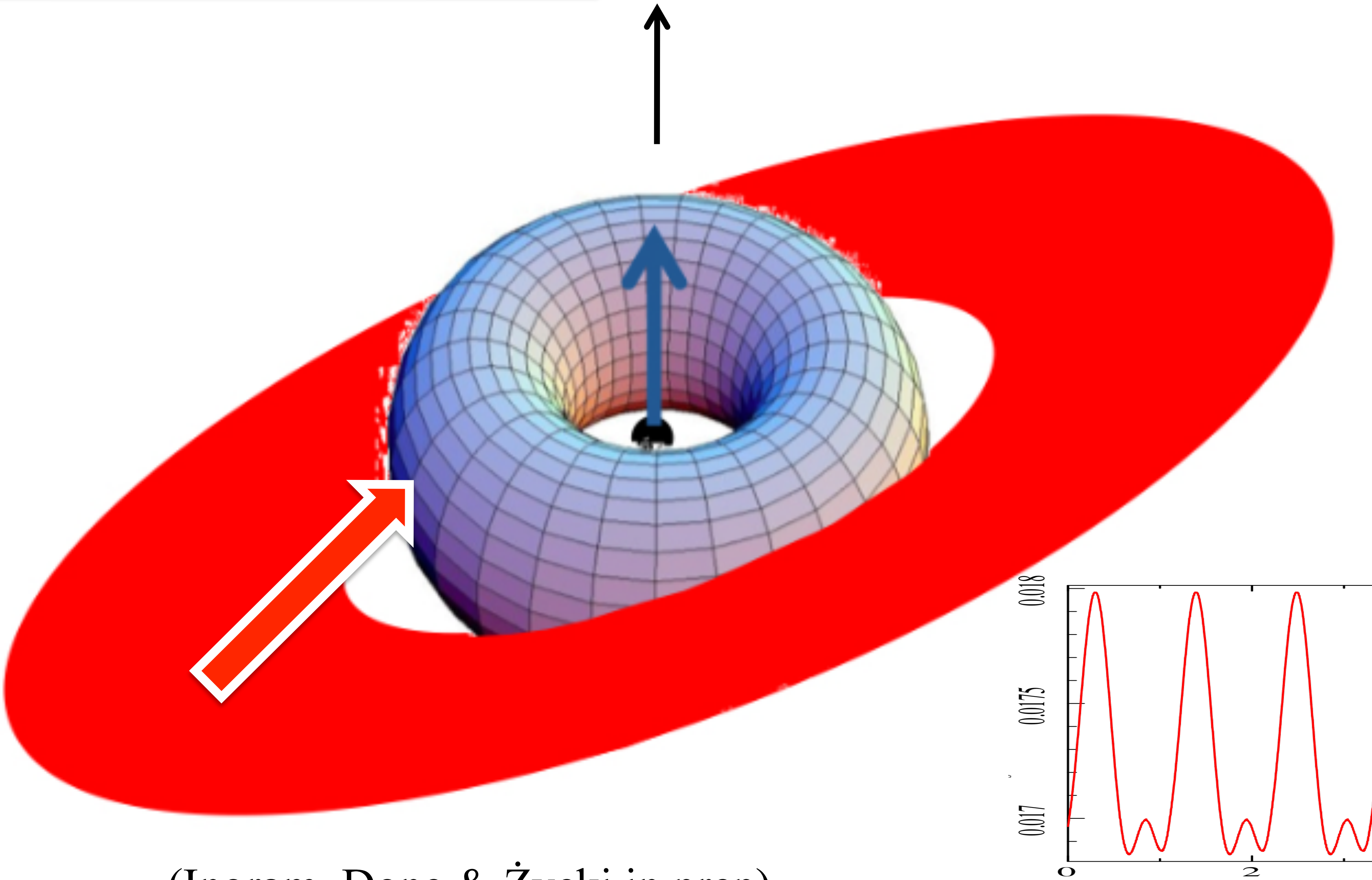
Time lags



CygX1 - Arevalo & Uttley 2006

Lense-Thirring precession



(Ingram, Done & Życki in prep)

Lense-Thirring precession