

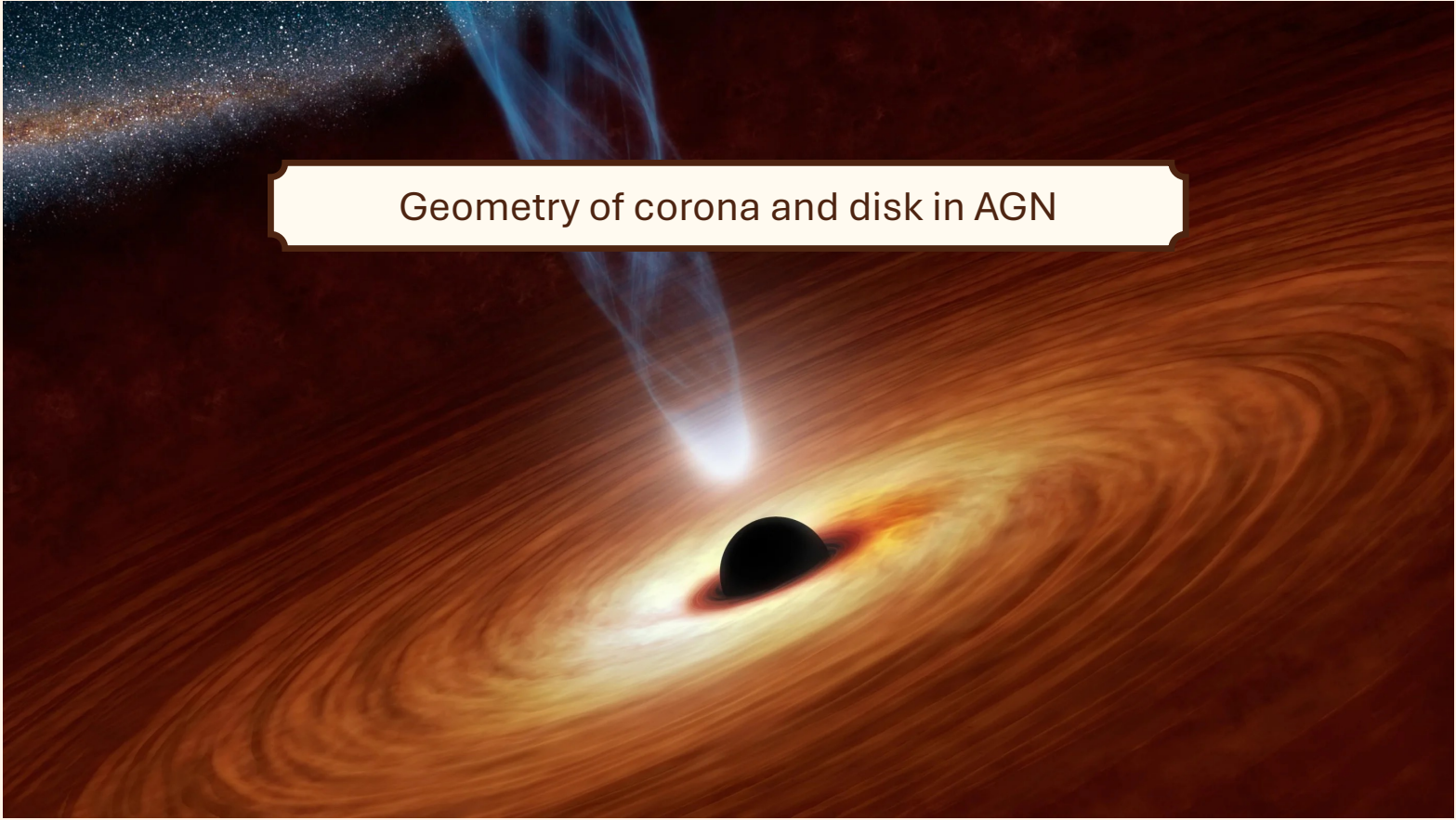
# Lighthouses in the Centres of Galaxies



Image credit:  
NASA/JPL-Caltech

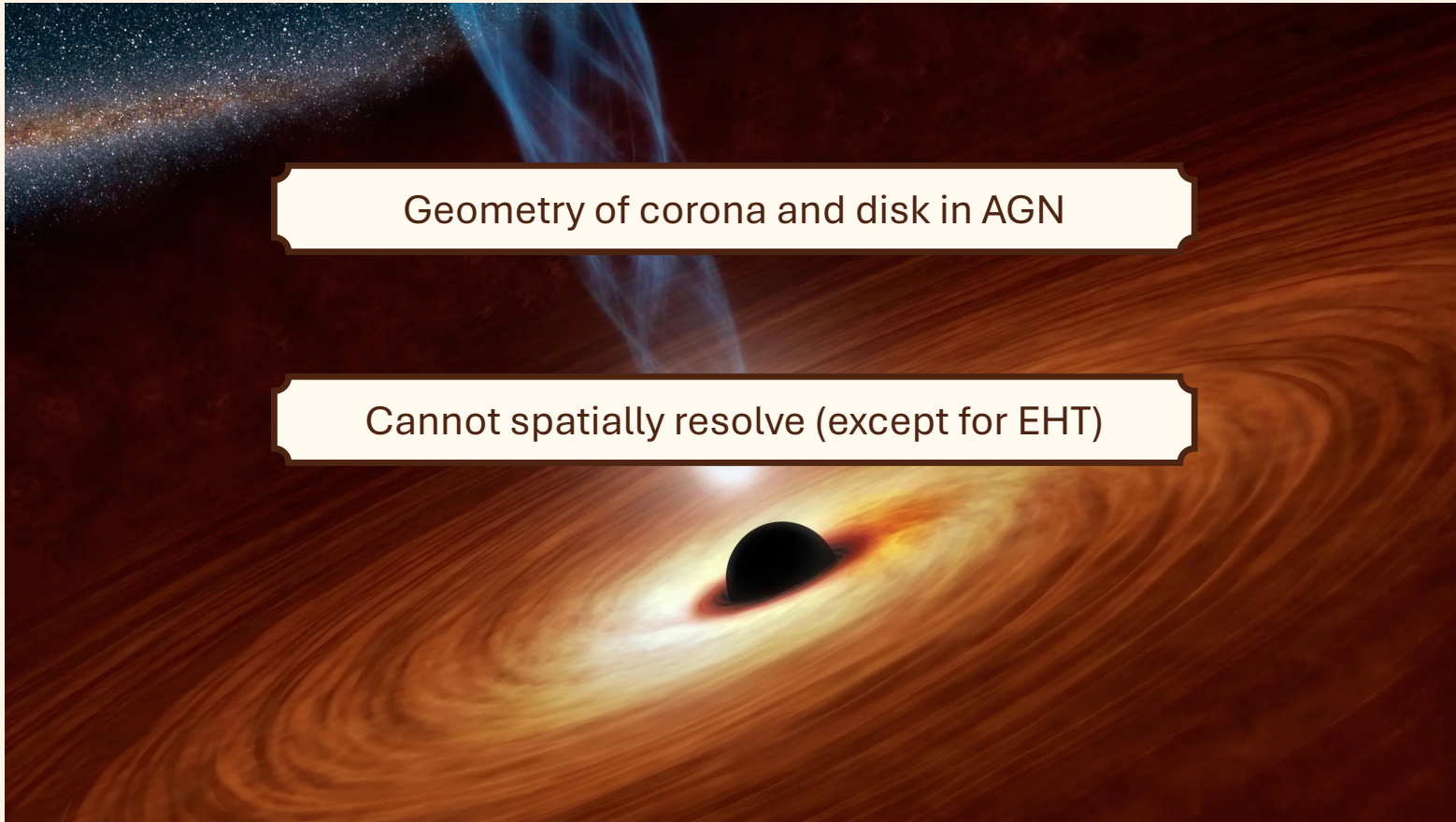


Image credit:  
NASA/JPL-Caltech

An artistic rendering of an active galactic nucleus (AGN). At the center is a black hole, depicted as a dark sphere. Surrounding it is a glowing accretion disk, shown as a series of concentric rings of light, transitioning from yellow and orange near the center to red and dark brown further out. Above the black hole, a bright, blue, elongated structure represents the corona, which is emitting a powerful jet of light. The background is a dark, starry space with a faint, glowing band of stars, possibly representing the galaxy's spiral arm.

Geometry of corona and disk in AGN

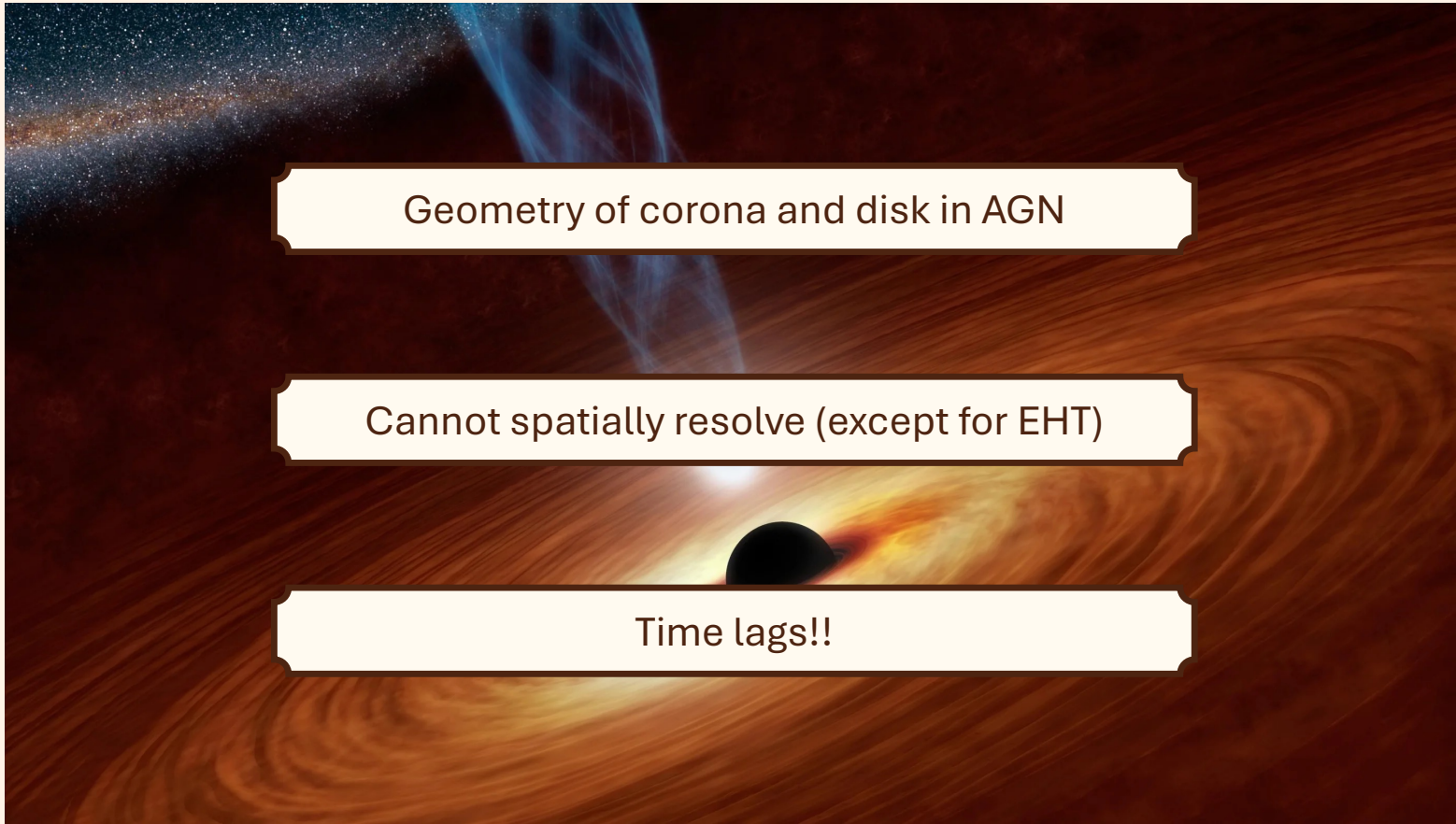
Image credit:  
NASA/JPL-Caltech



Geometry of corona and disk in AGN

Cannot spatially resolve (except for EHT)

Image credit:  
NASA/JPL-Caltech



Geometry of corona and disk in AGN

Cannot spatially resolve (except for EHT)

Time lags!!

Image credit:  
NASA/JPL-Caltech

# Time Lags



Image credit:  
NASA/JPL-Caltech

# Time Lags

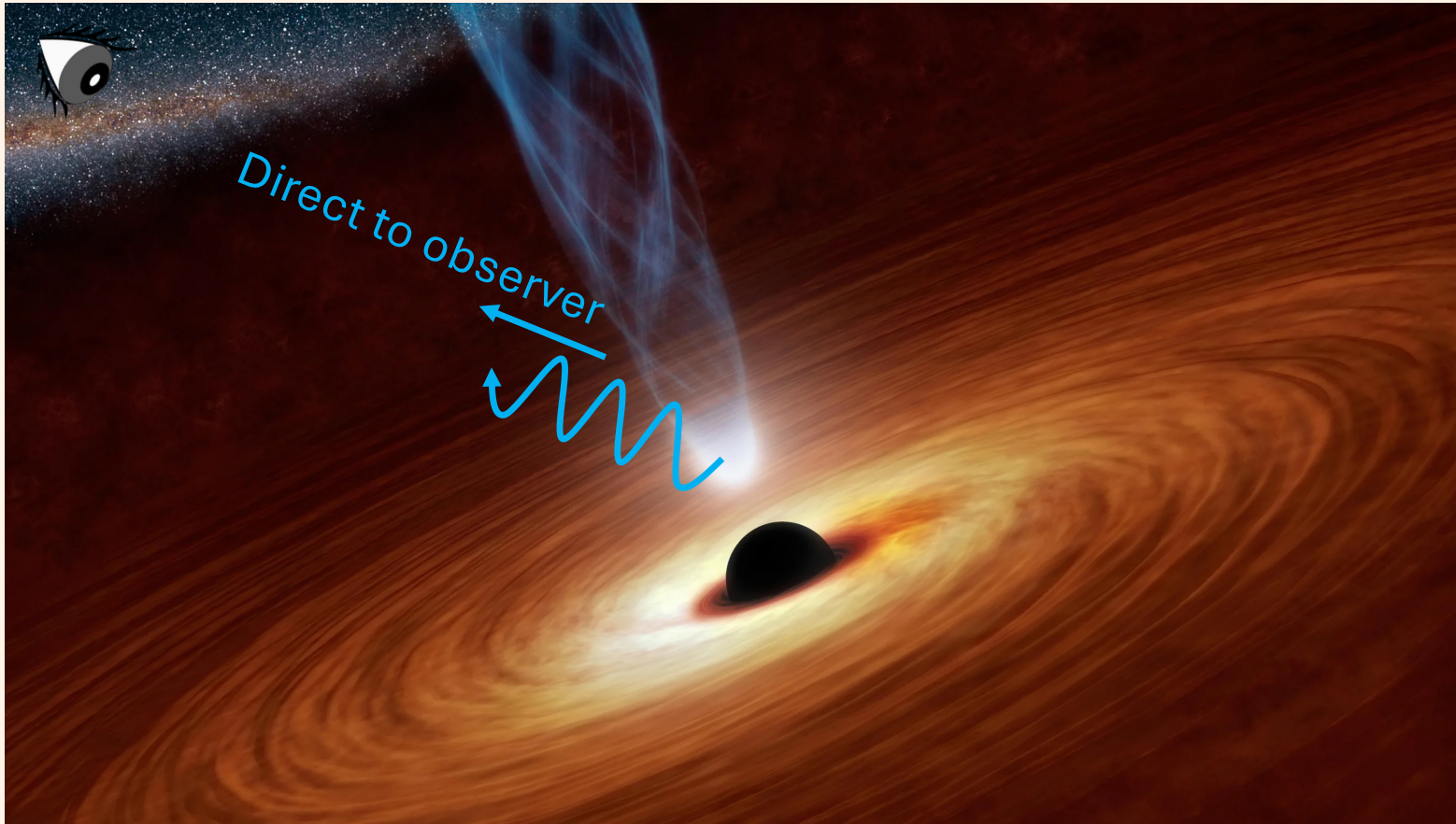


Image credit:  
NASA/JPL-Caltech

# Time Lags

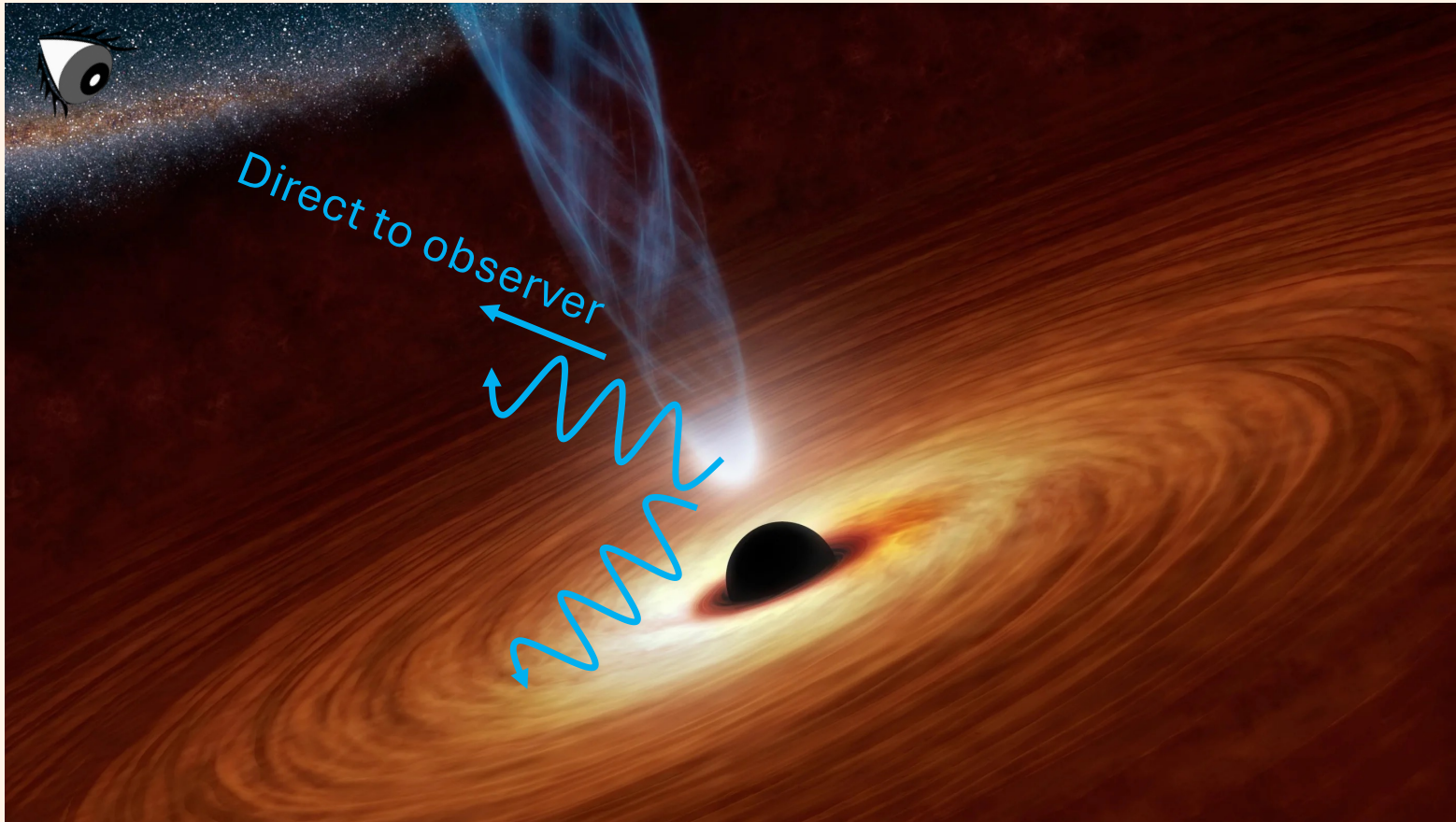


Image credit:  
NASA/JPL-Caltech

# Time Lags

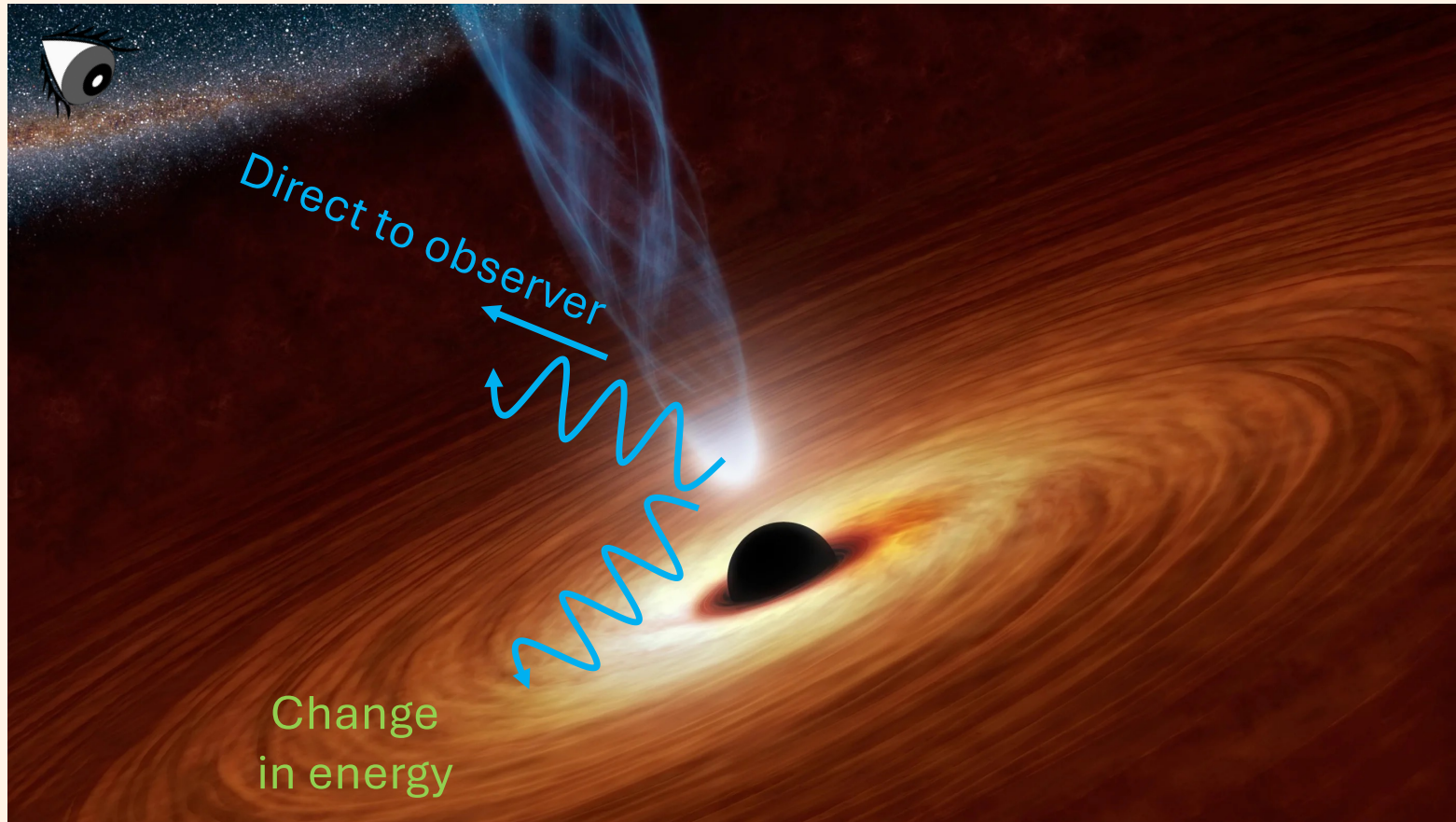


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NASA/JPL-Caltech

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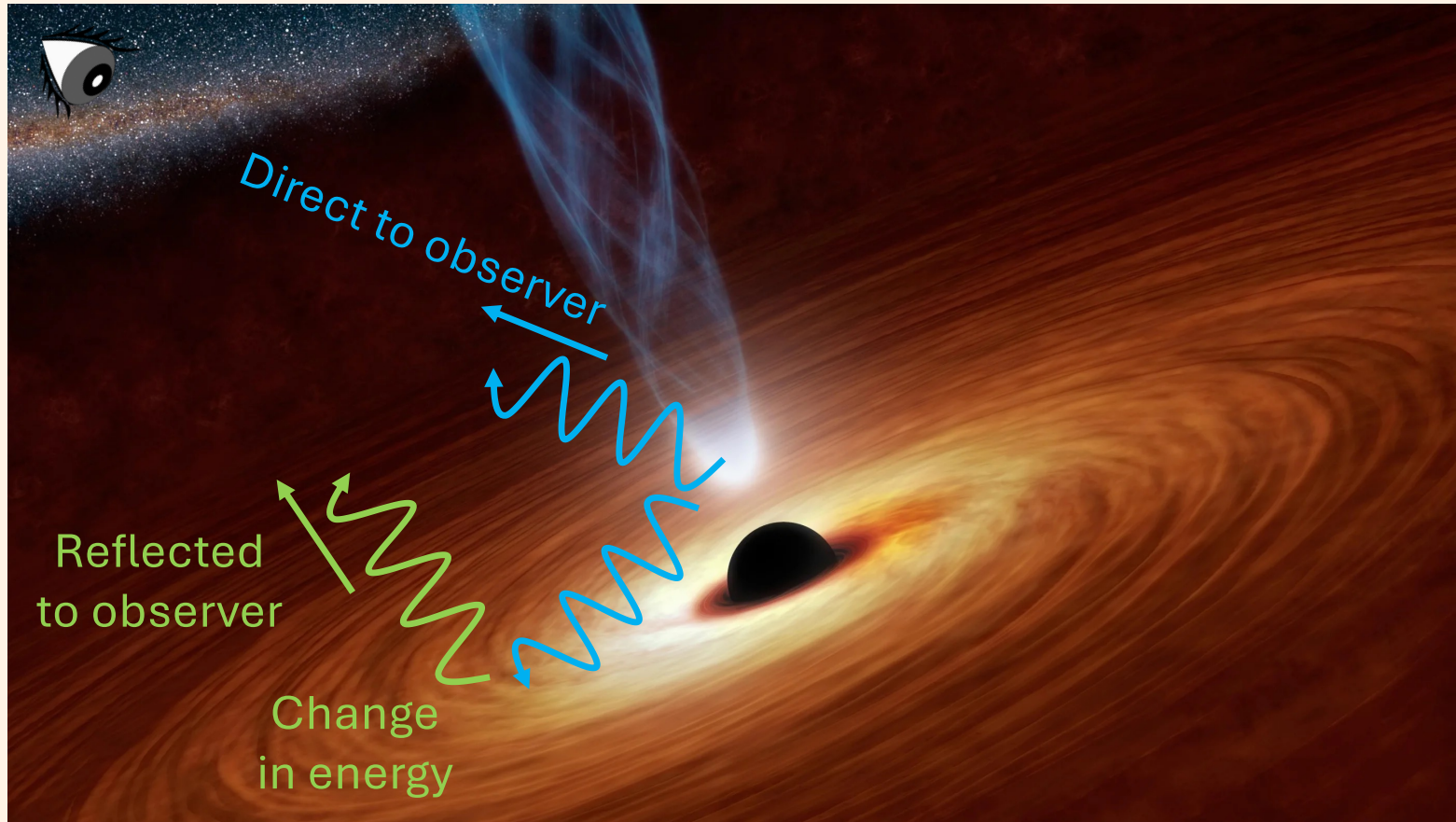


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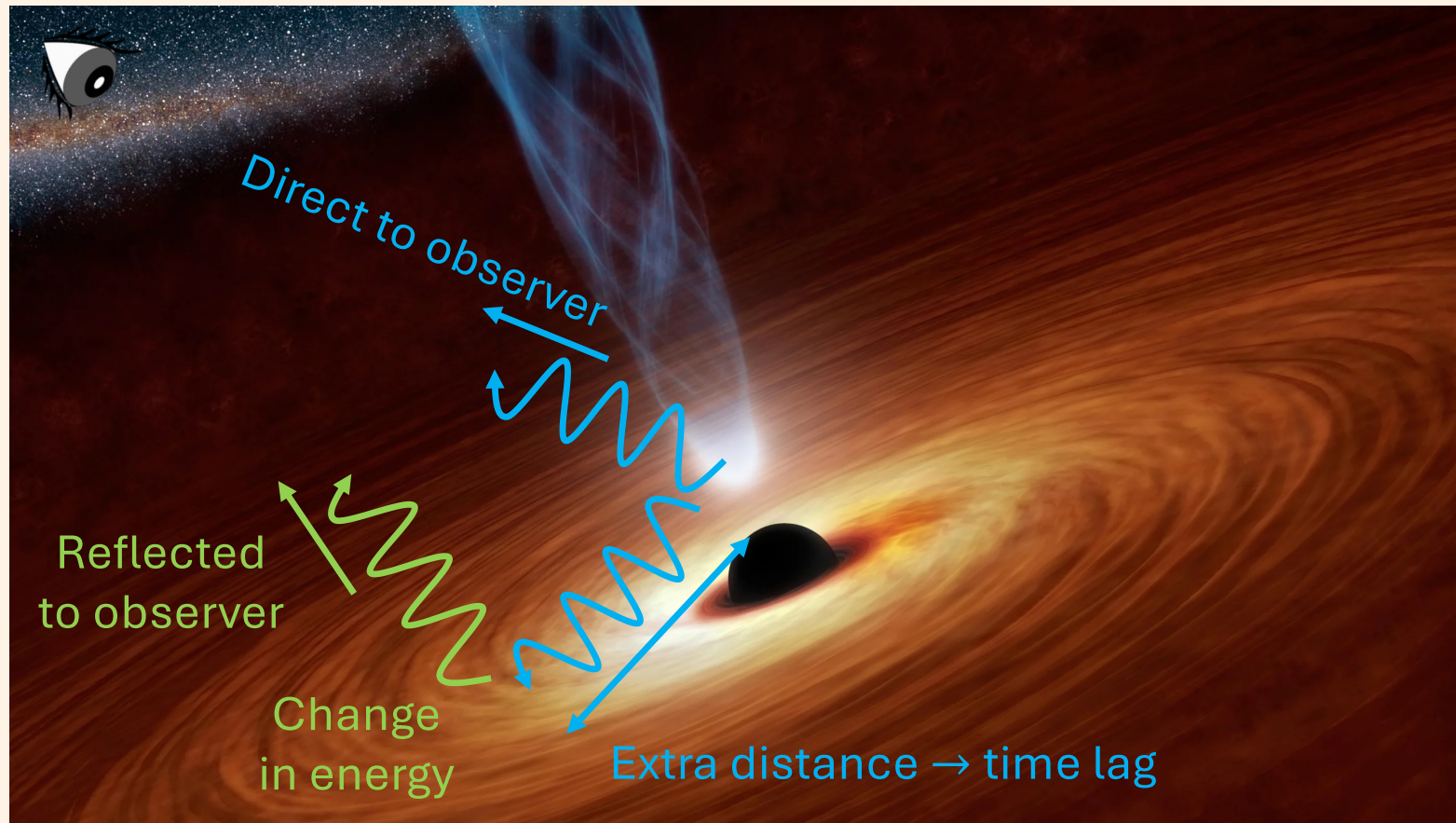


Image credit:  
NASA/JPL-Caltech

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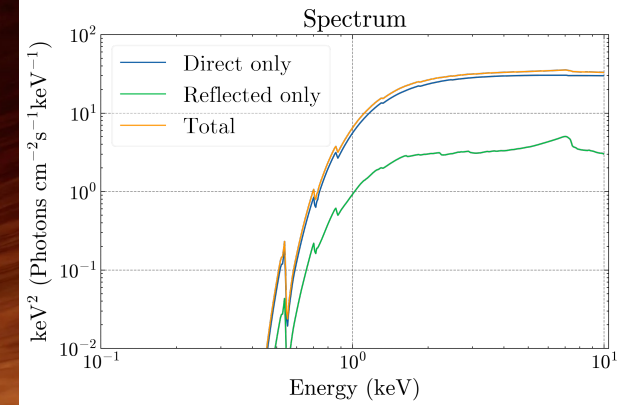
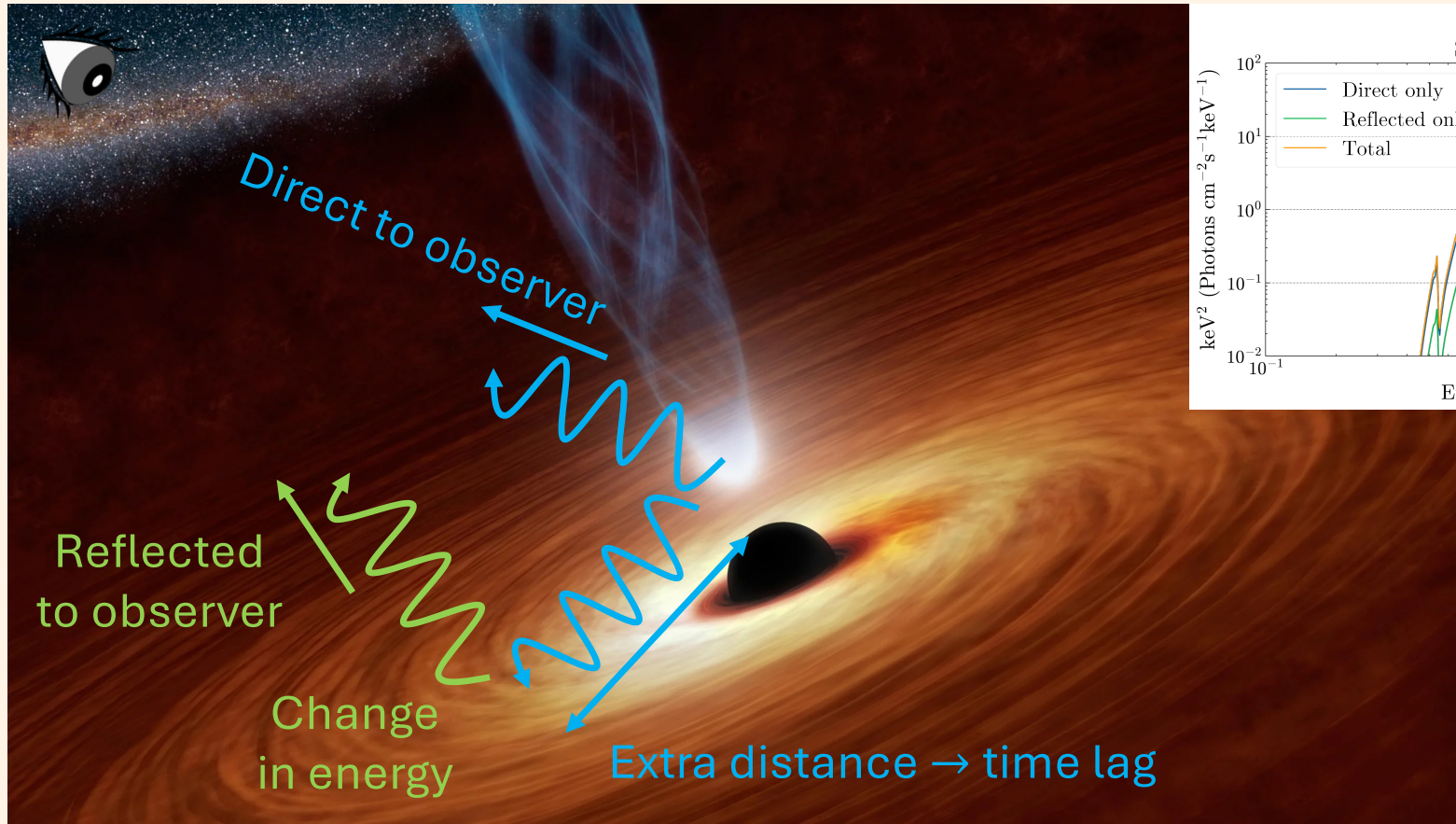


Image credit:  
NASA/JPL-Caltech

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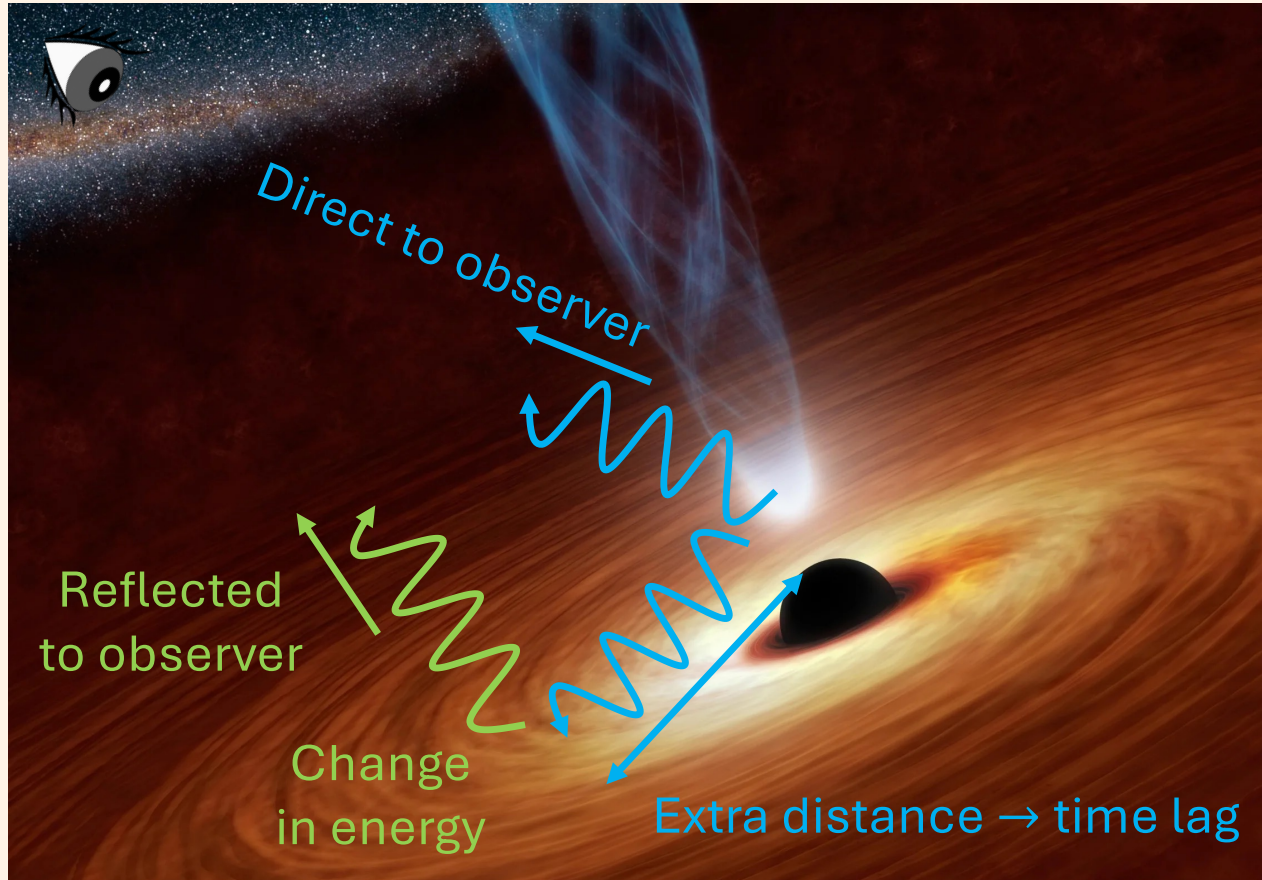
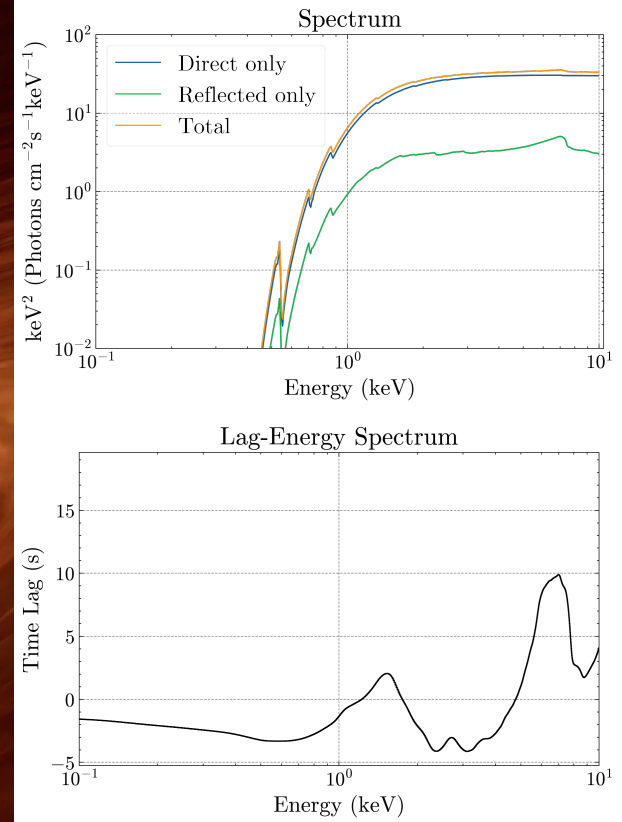


Image credit:  
NASA/JPL-Caltech



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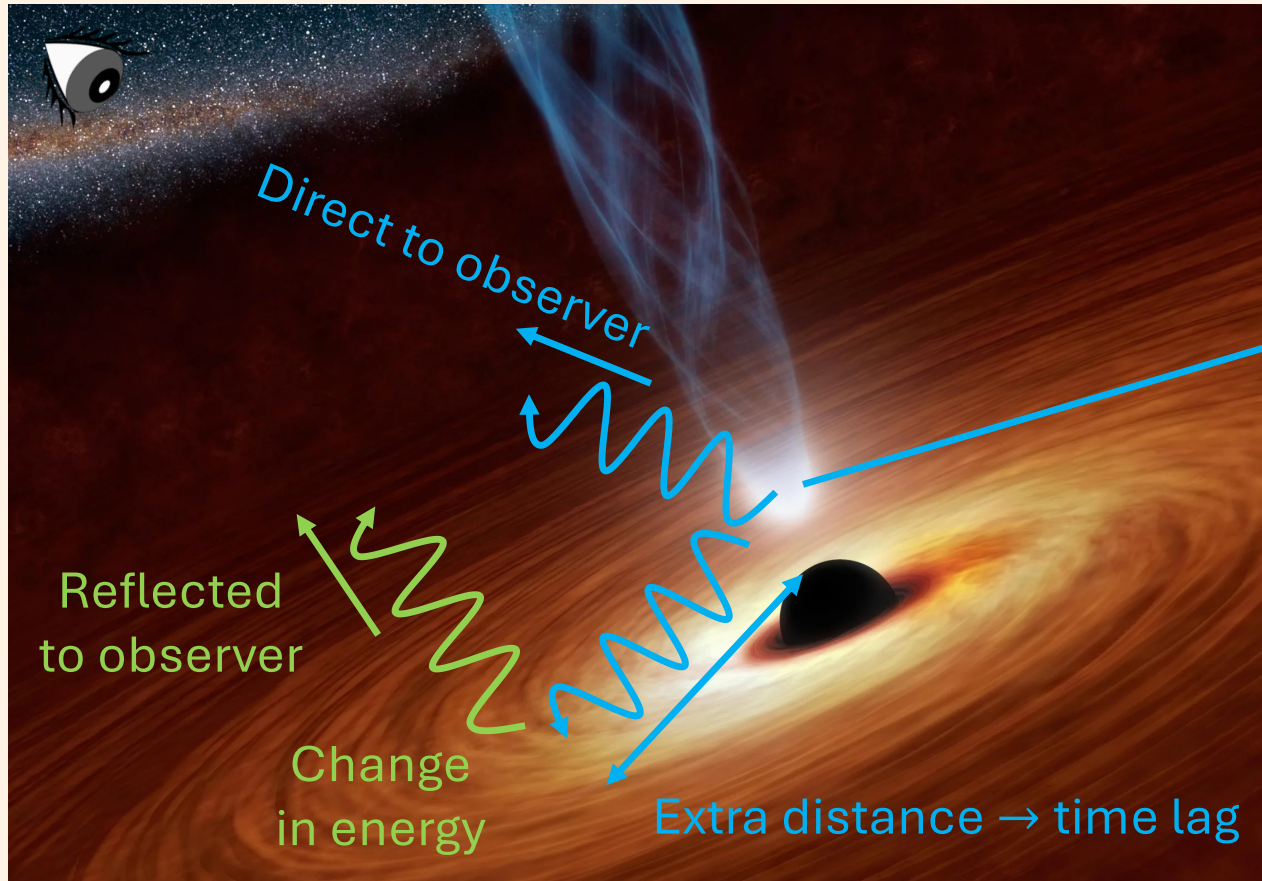
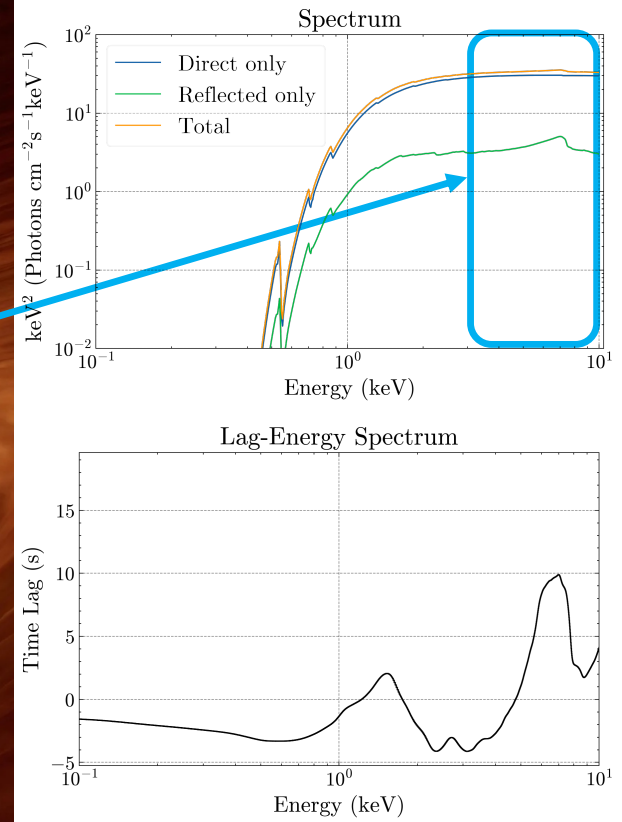


Image credit:  
NASA/JPL-Caltech



# Time Lags

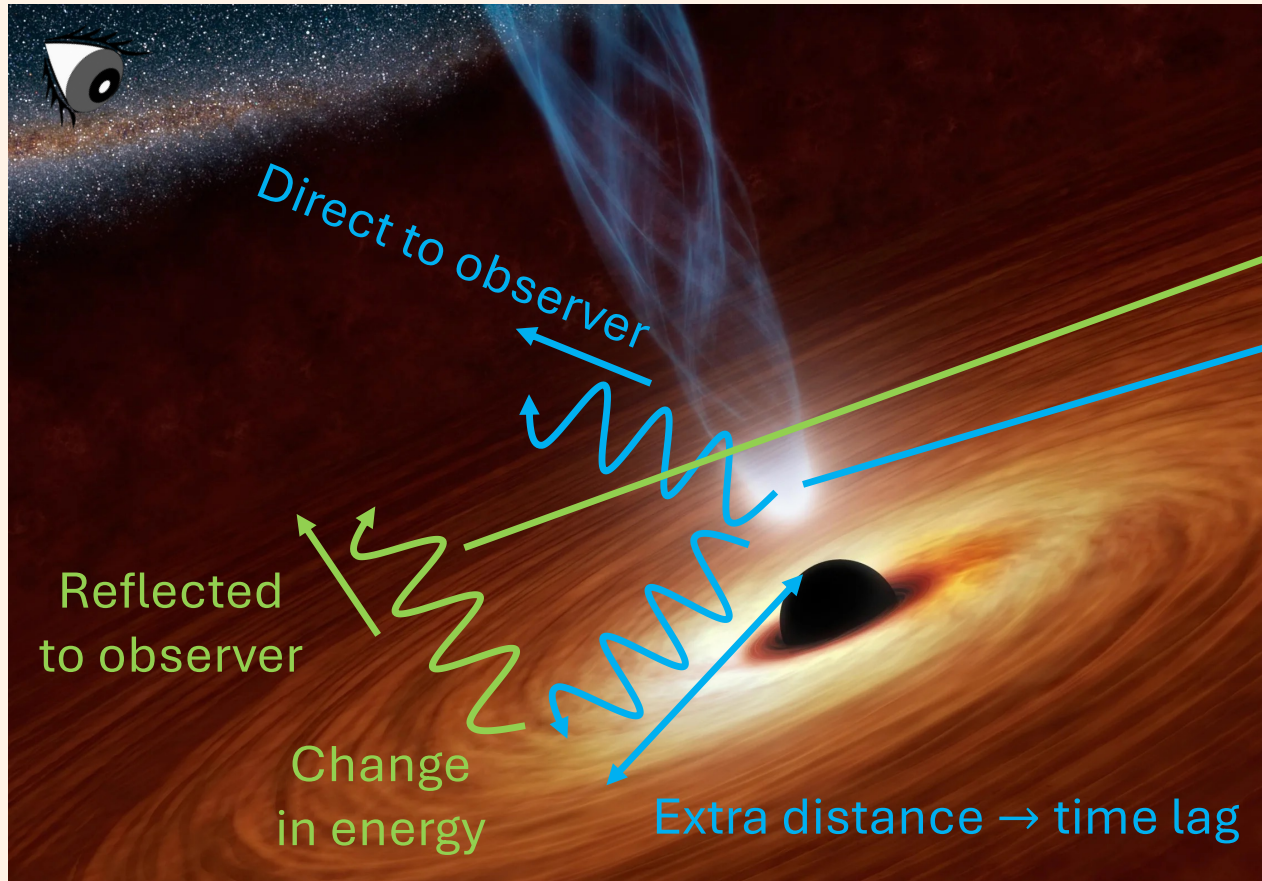
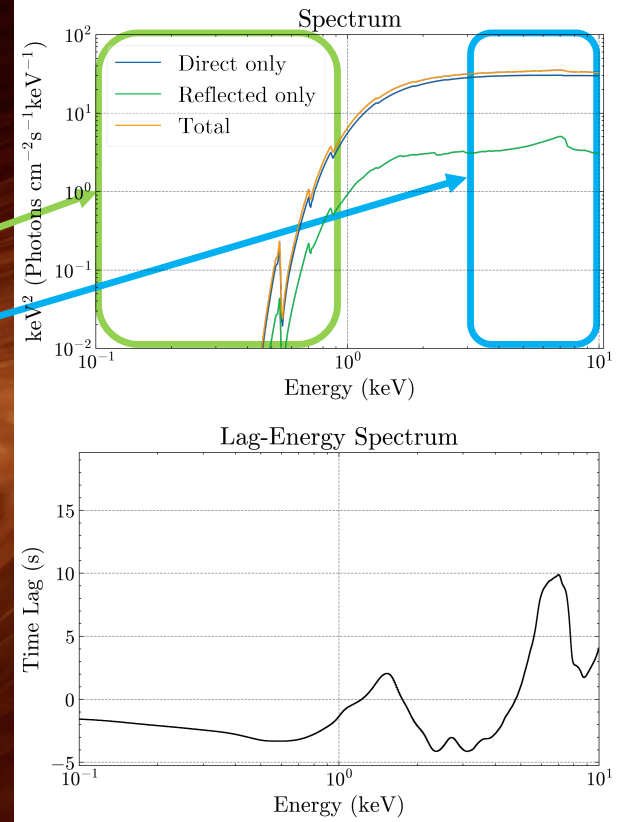


Image credit:  
NASA/JPL-Caltech



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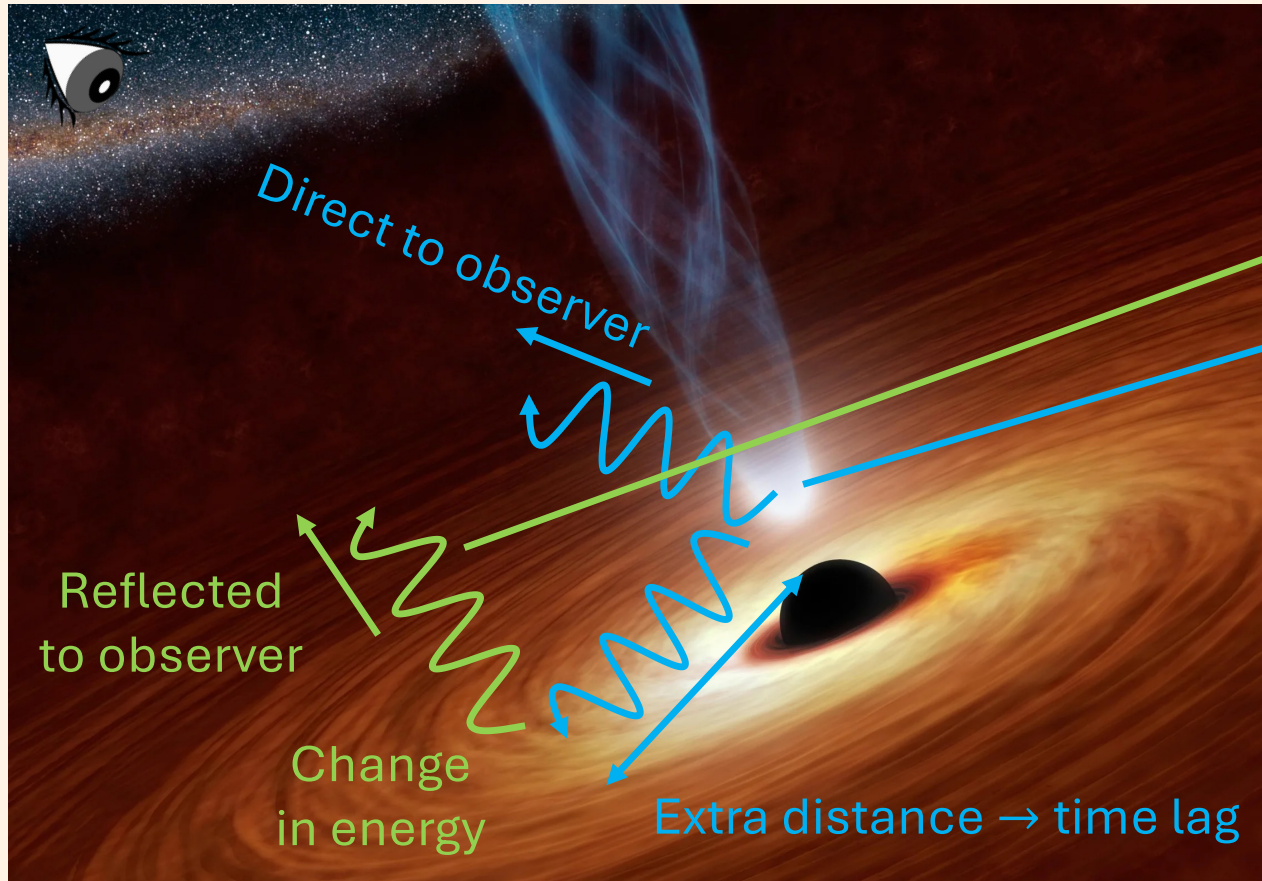
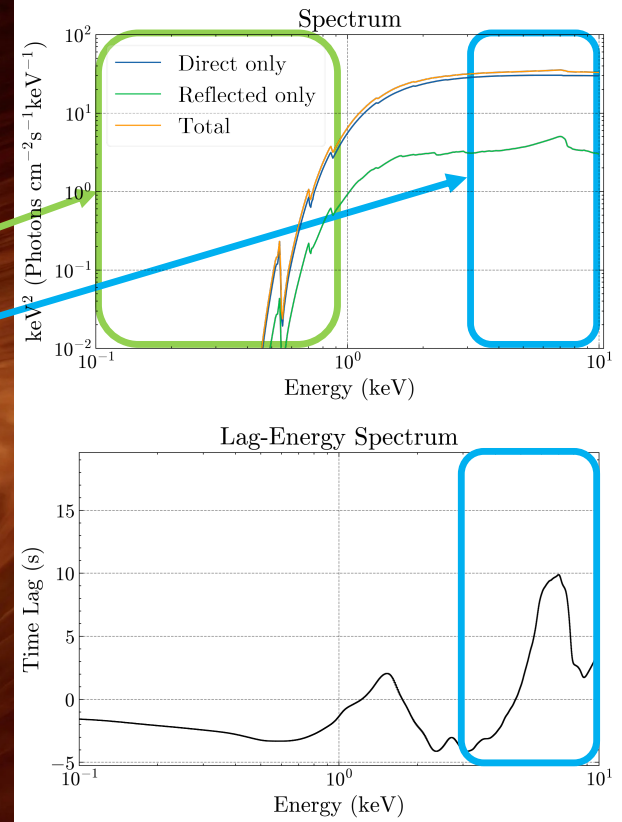


Image credit:  
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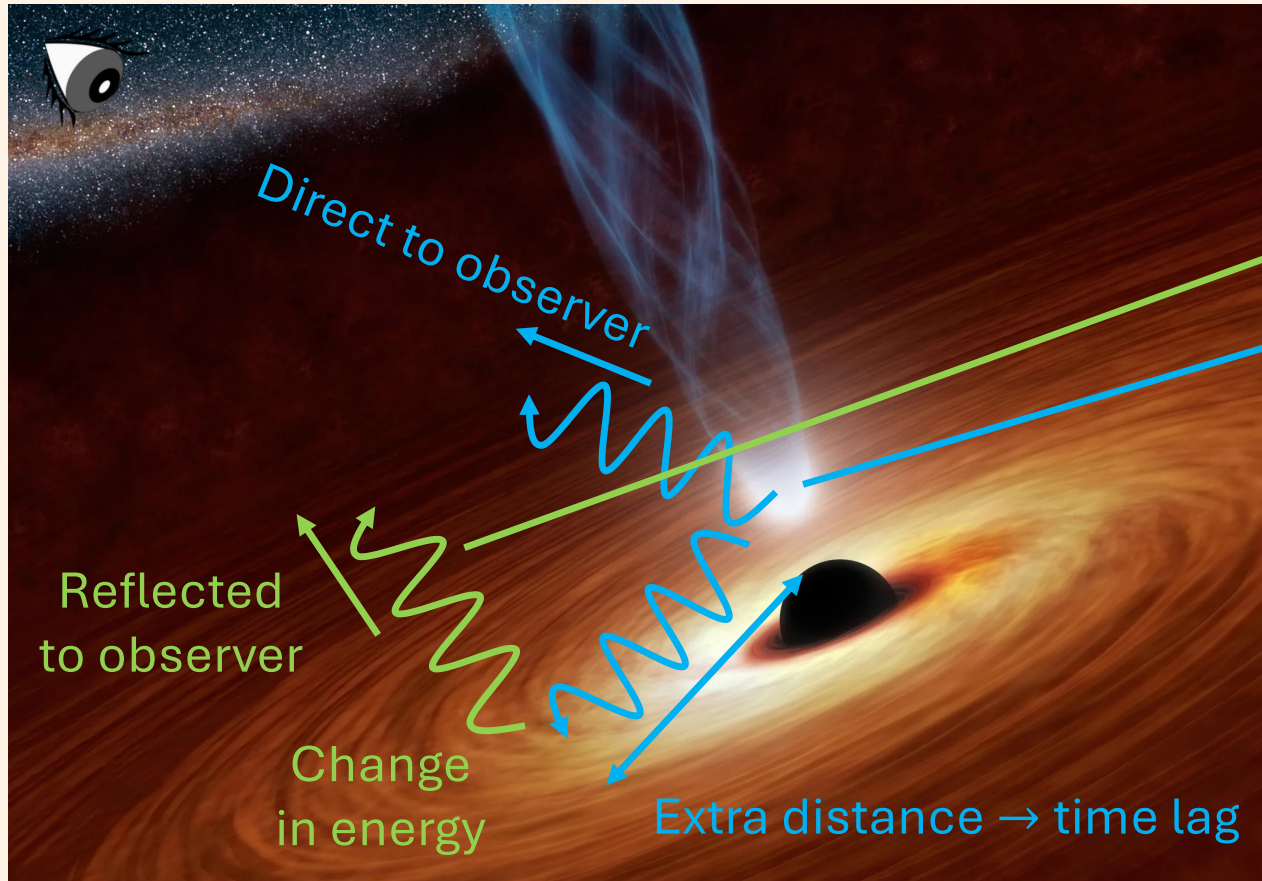
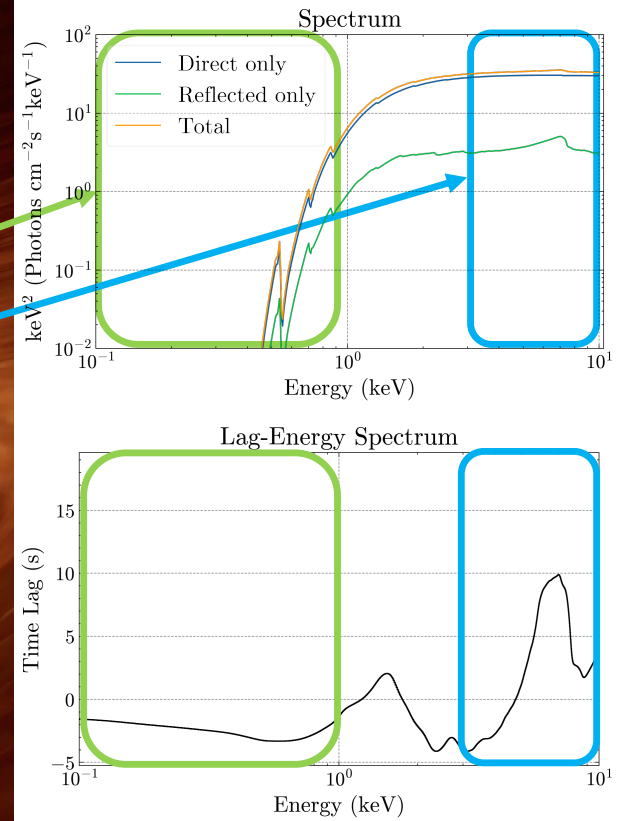


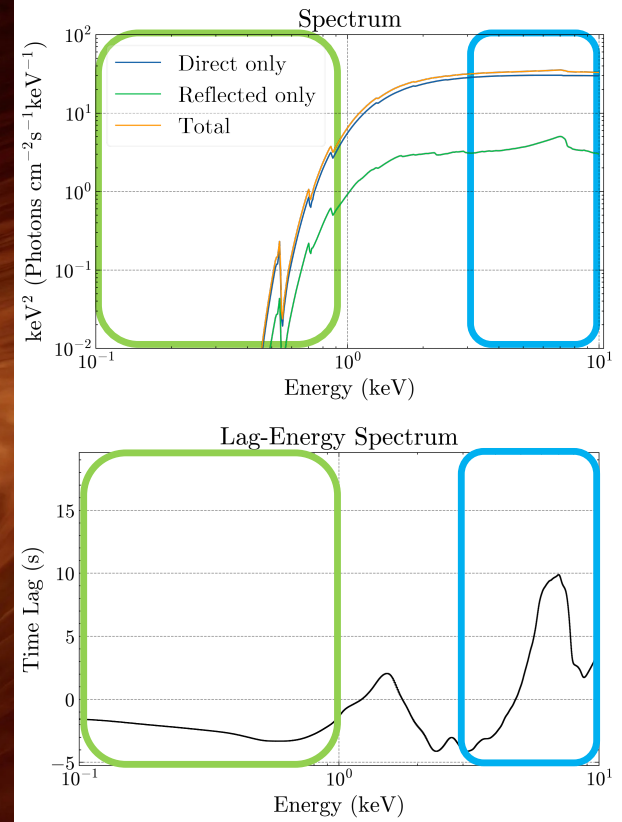
Image credit:  
NASA/JPL-Caltech



# Time Lags



Image credit:  
NASA/JPL-Caltech



+ reltrans

(Relativistic transfer model)

# Time Lags

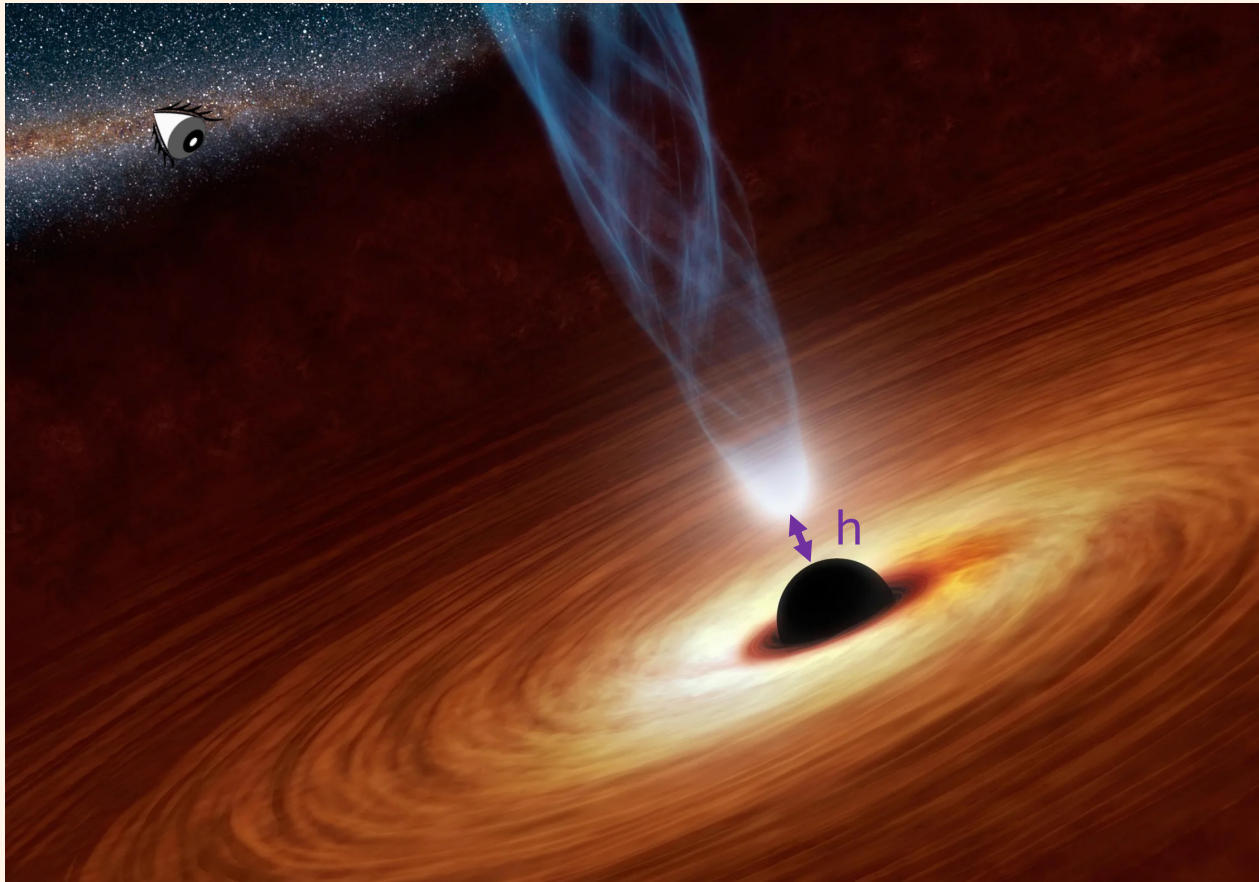
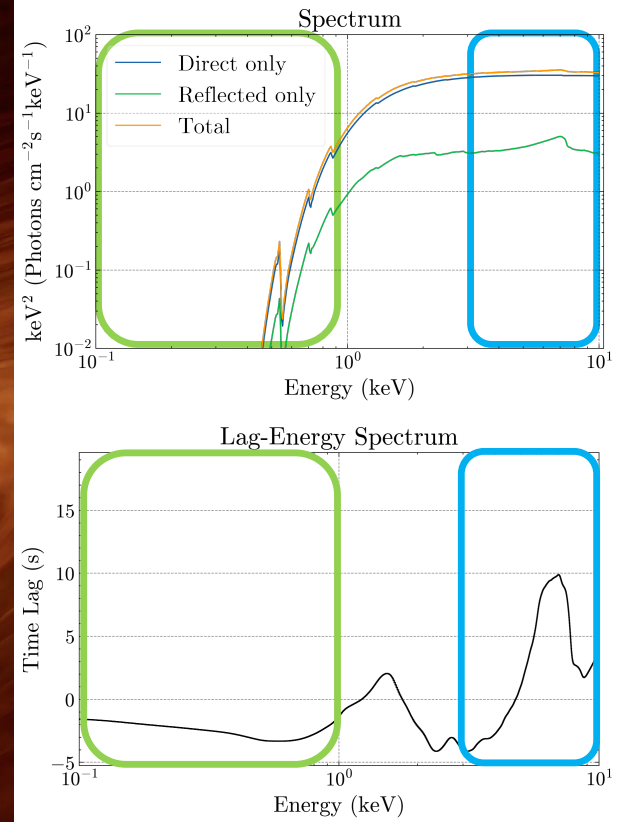


Image credit:  
NASA/JPL-Caltech



+ reltrans = h,  
(Relativistic transfer model)

# Time Lags

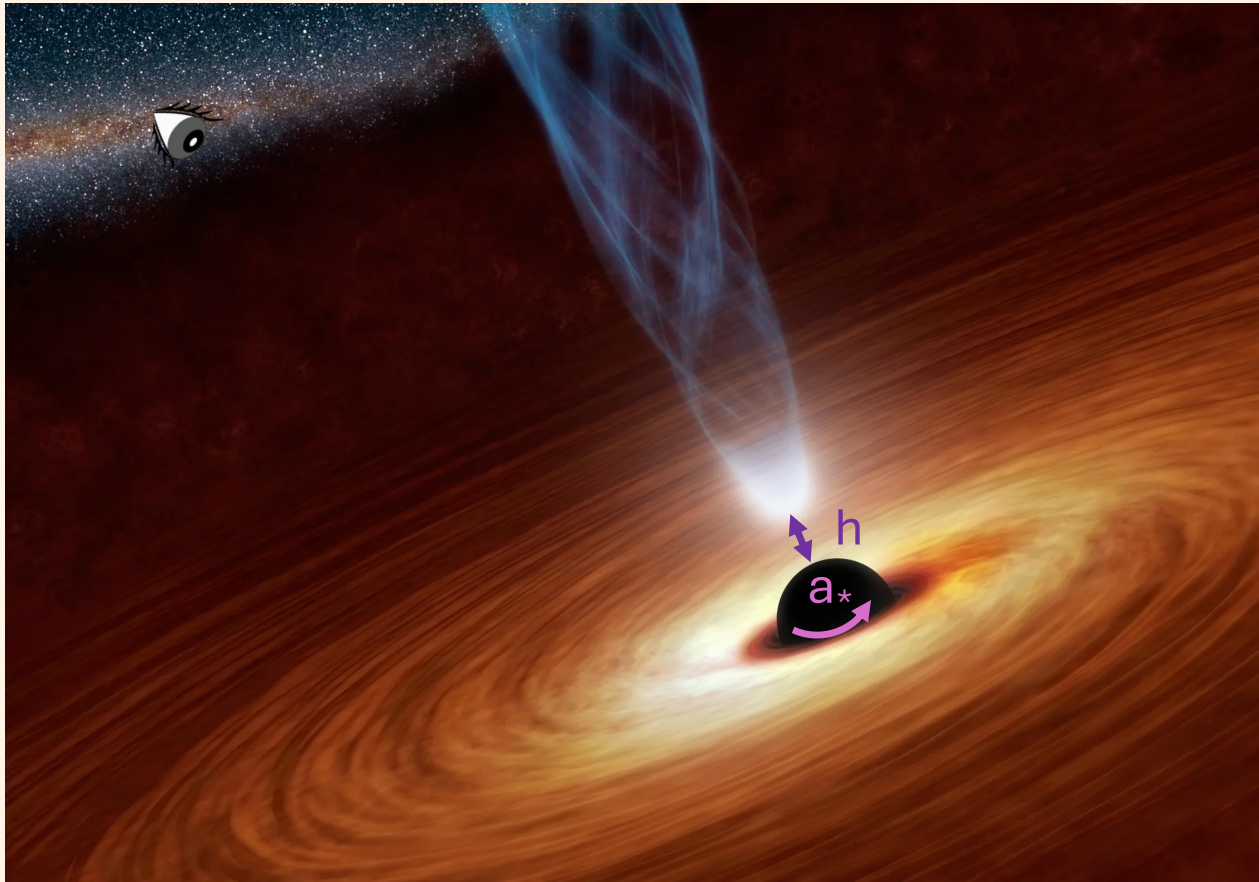
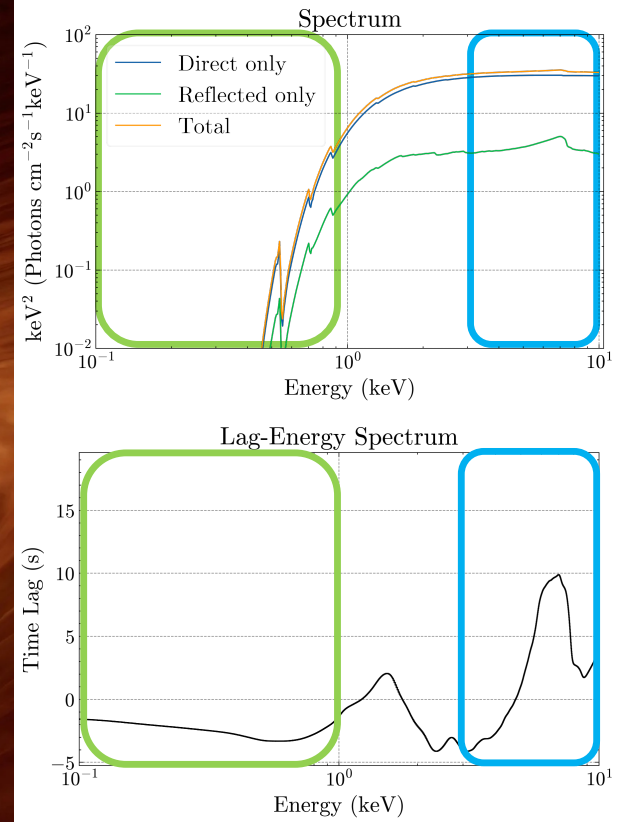


Image credit:  
NASA/JPL-Caltech



+ reltrans =  $h$ ,  $a_*$ ,  
(Relativistic transfer model)

# Time Lags

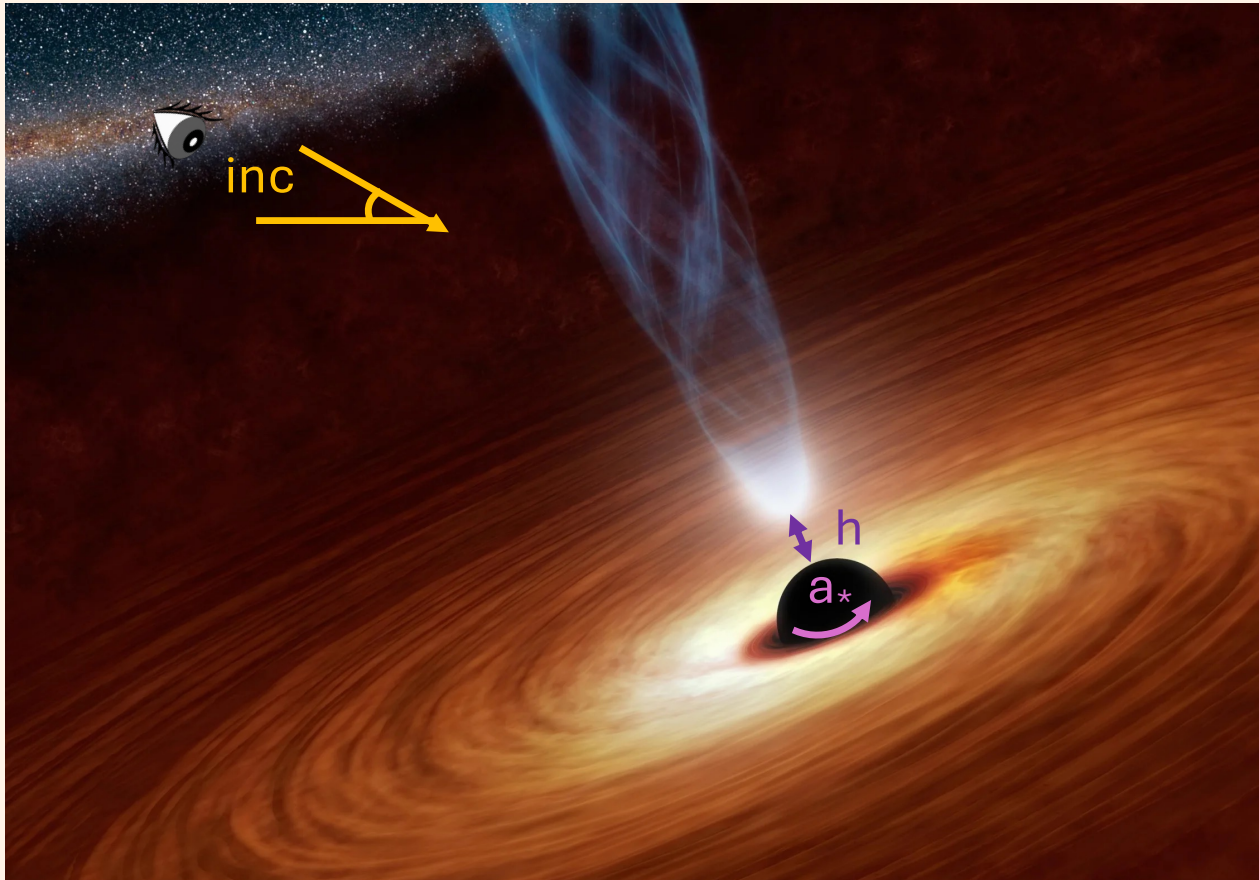
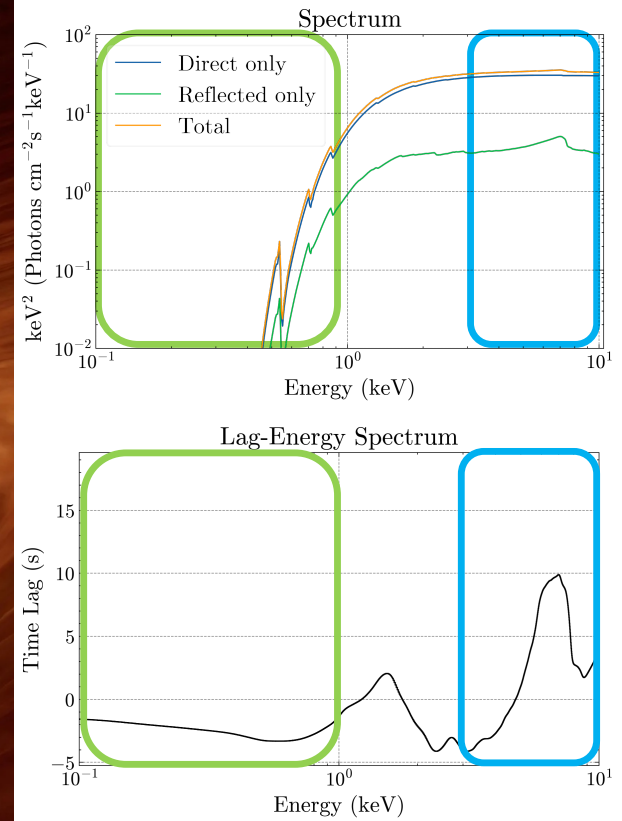


Image credit:  
NASA/JPL-Caltech



+ reltrans =  $h$ ,  $a_*$ ,  $inc$ , ...  
(Relativistic transfer model)

# Time Lags

**Problem!**  
Intrinsic white noise reduces coherence between energy bands

→ Lag – energy have high errors

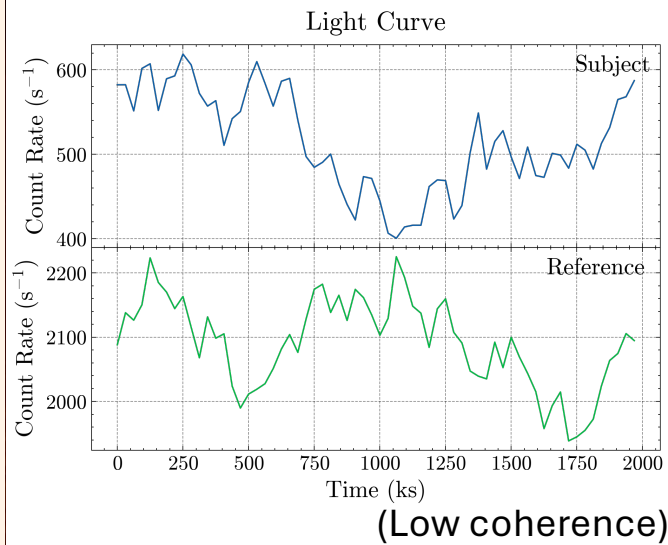
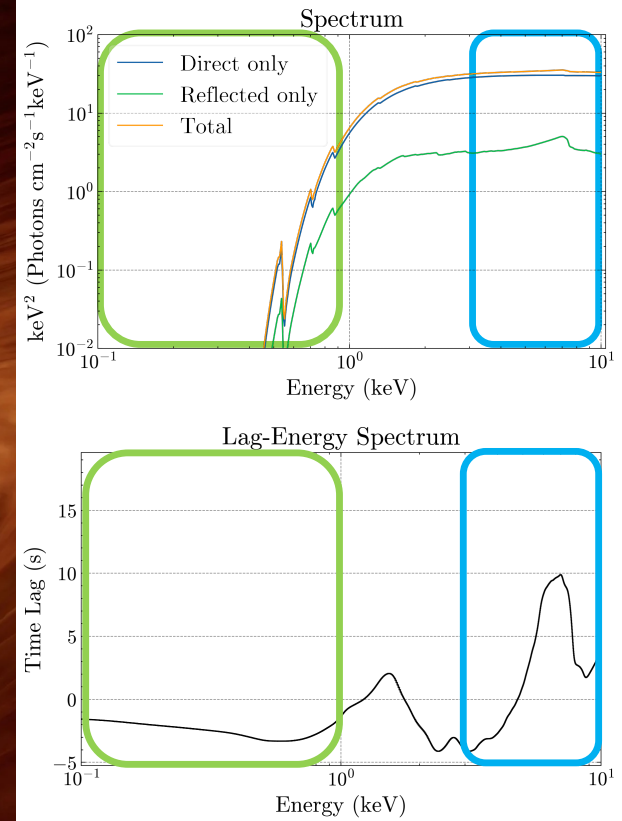


Image credit:  
NASA/JPL-Caltech



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(Relativistic transfer model)

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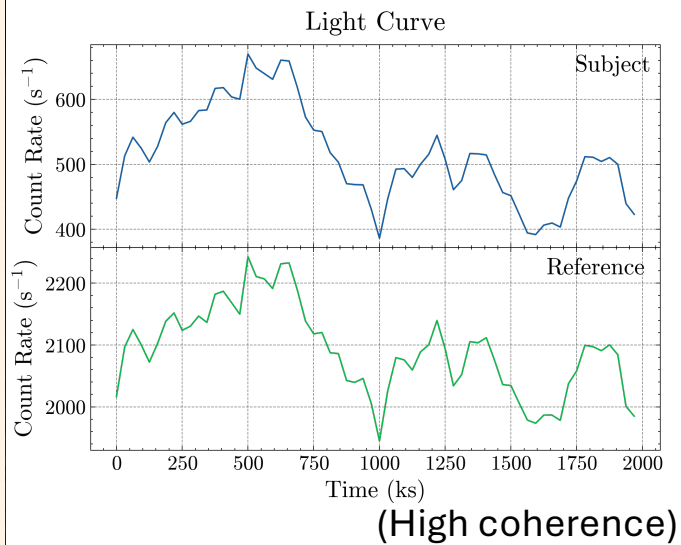
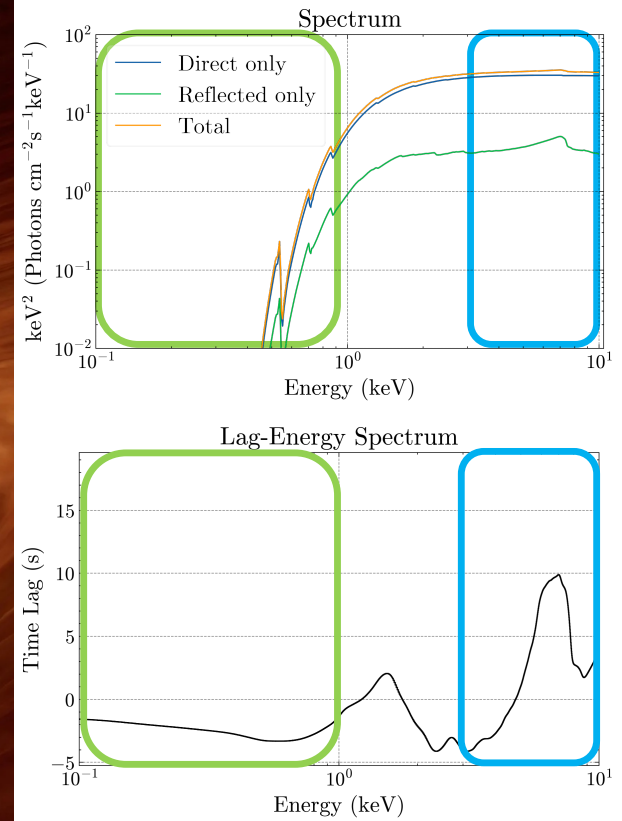
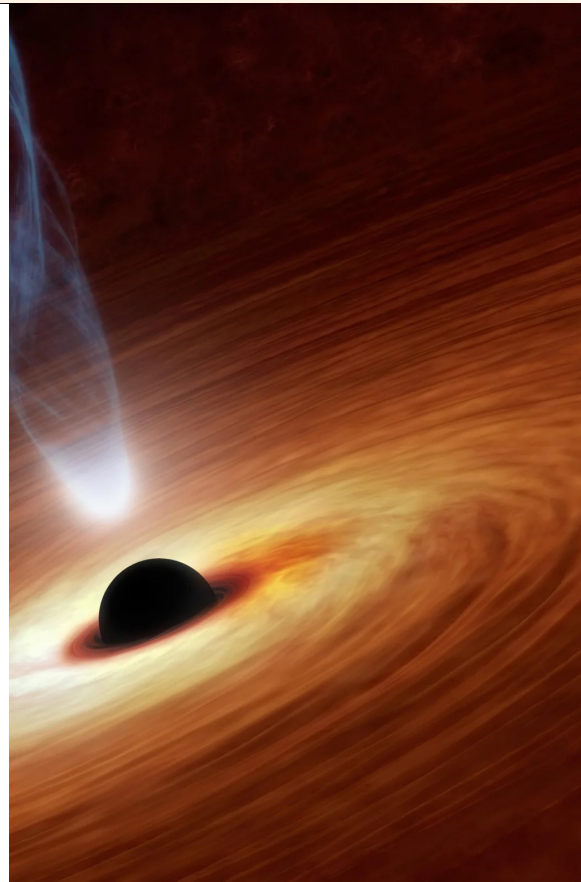


Image credit:  
NASA/JPL-Caltech



+ reltrans = h,  $a_*$ , inc, ...  
(Relativistic transfer model)

# Time Lags

Problem!  
 Intrinsic white noise reduces  
 coherence between energy bands

→ Lag – energy have high errors

Proposed solution: high-freq QPOs

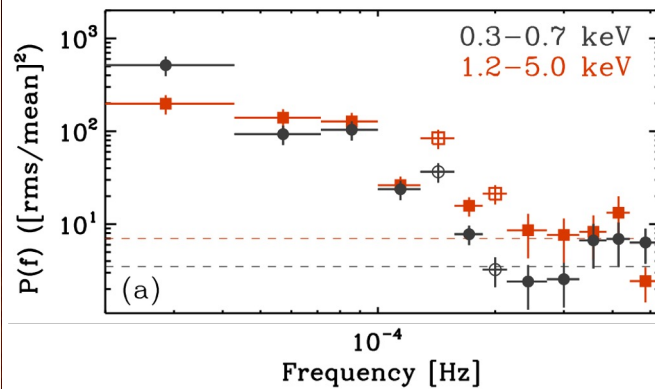
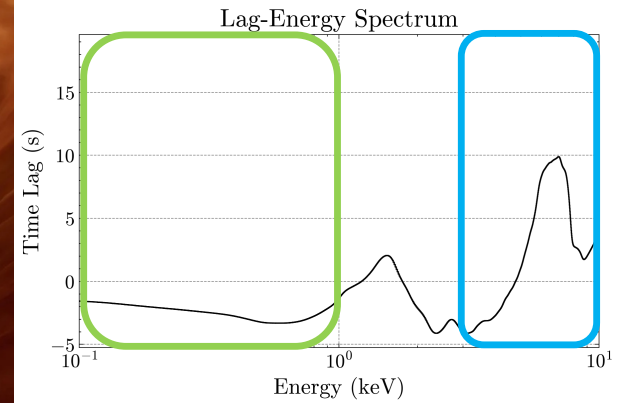
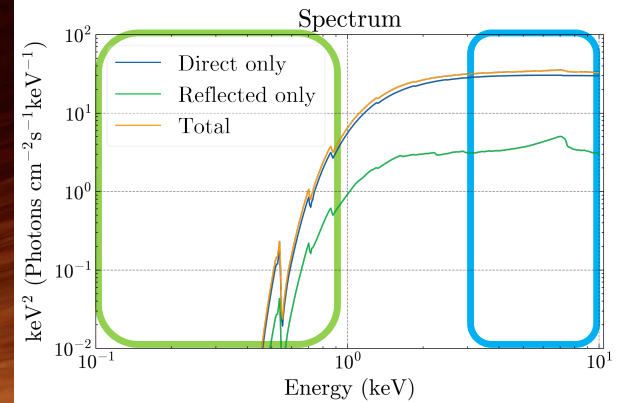
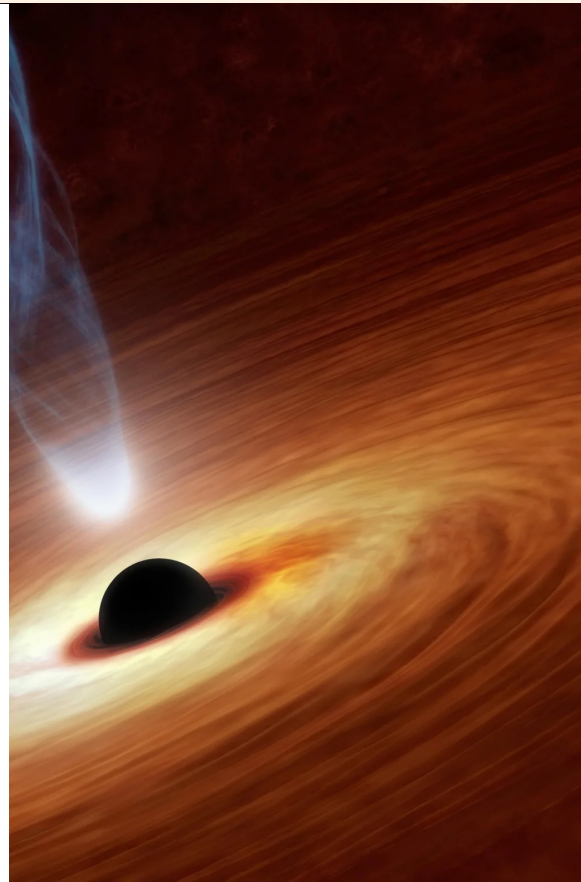


Image credit:  
 NASA/JPL-Caltech



Alston et al. 2015

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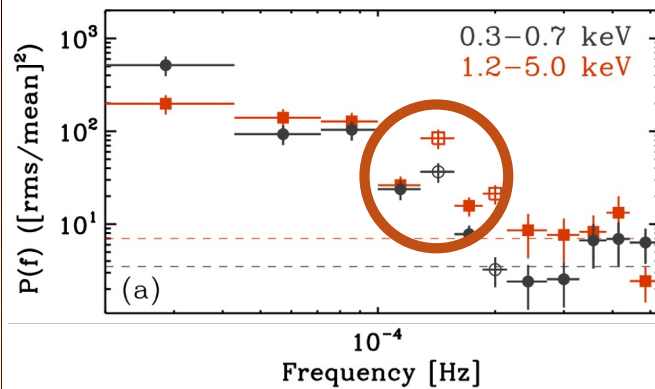
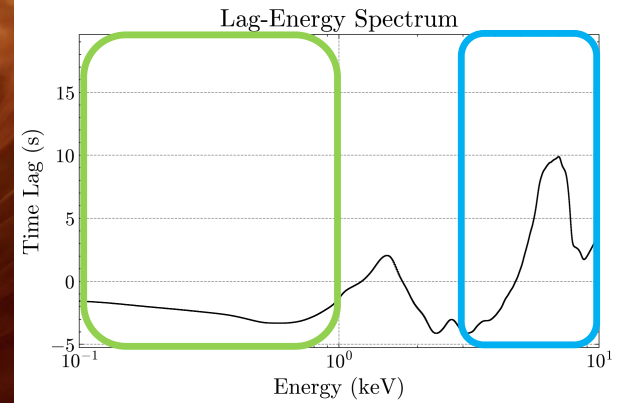
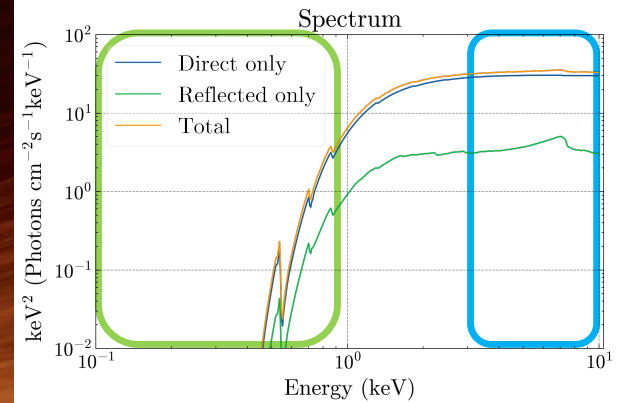
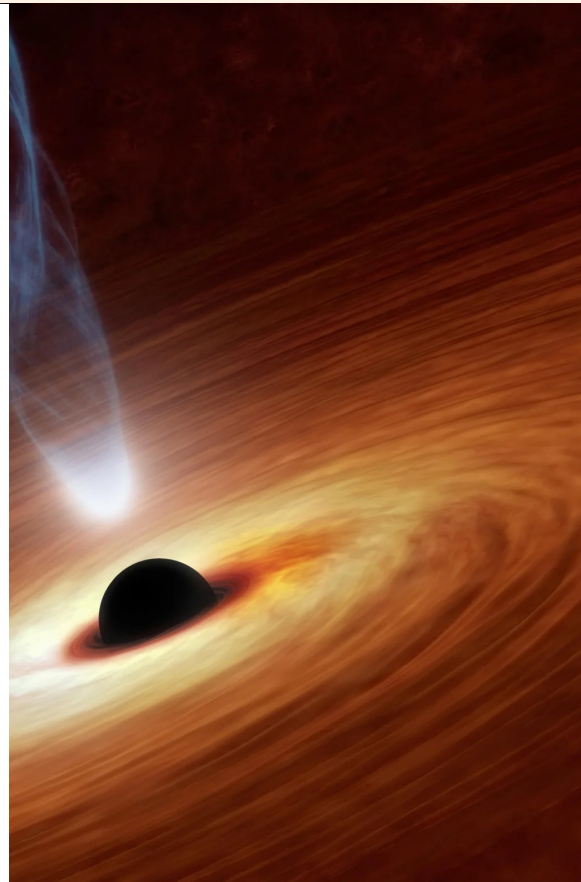


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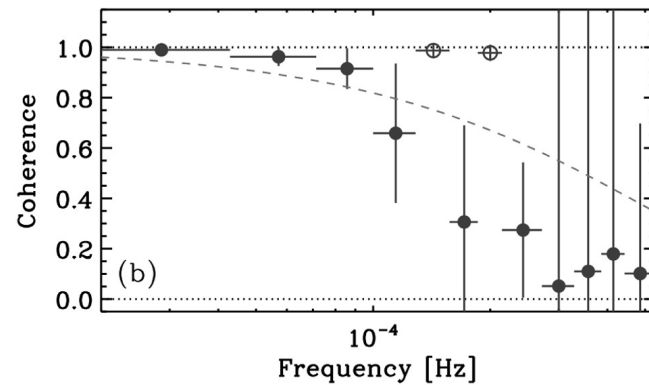
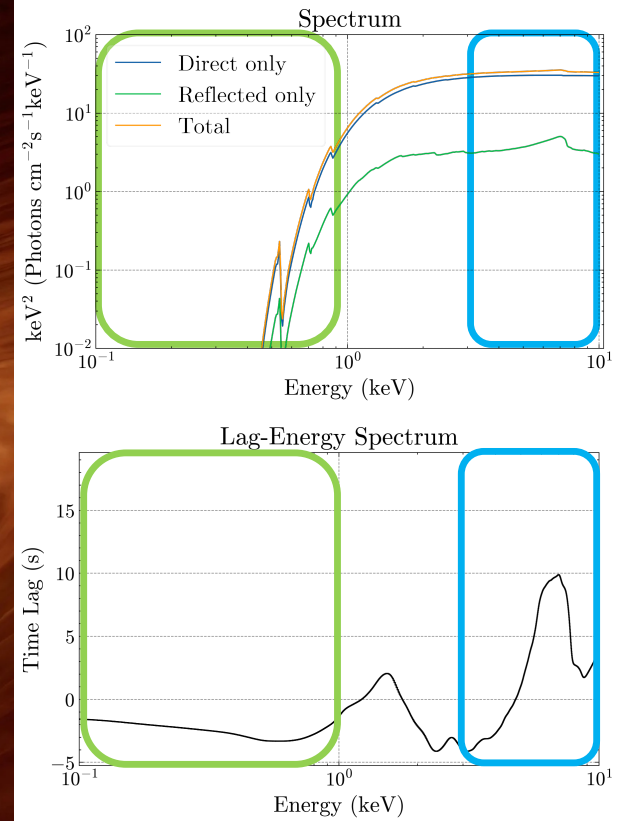
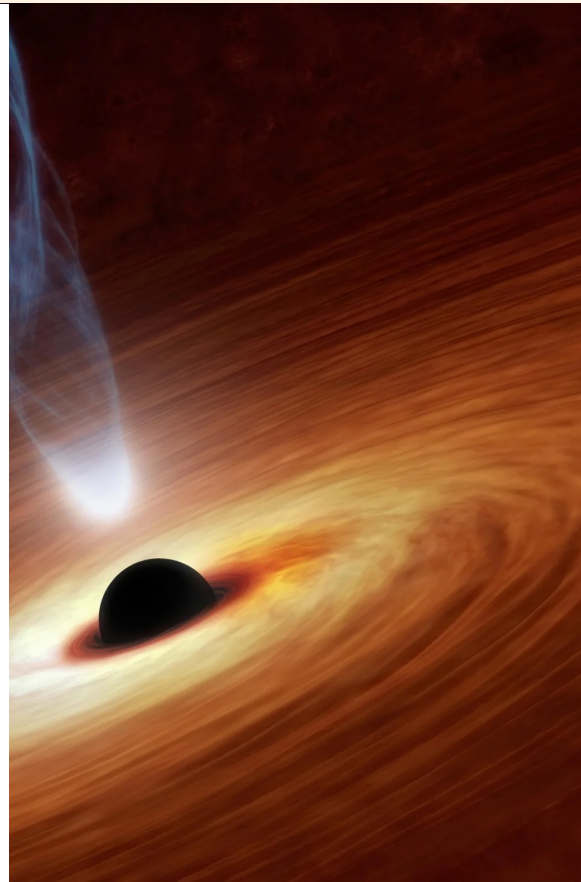


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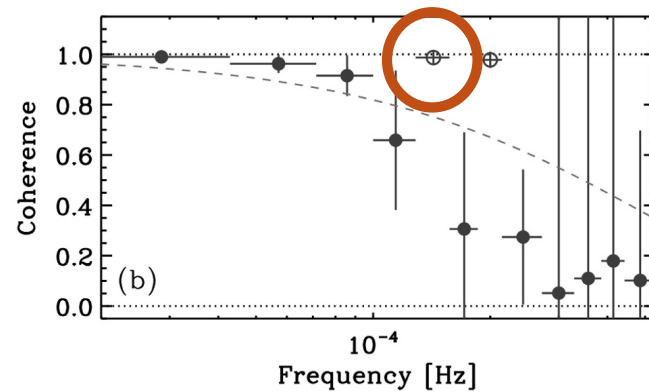
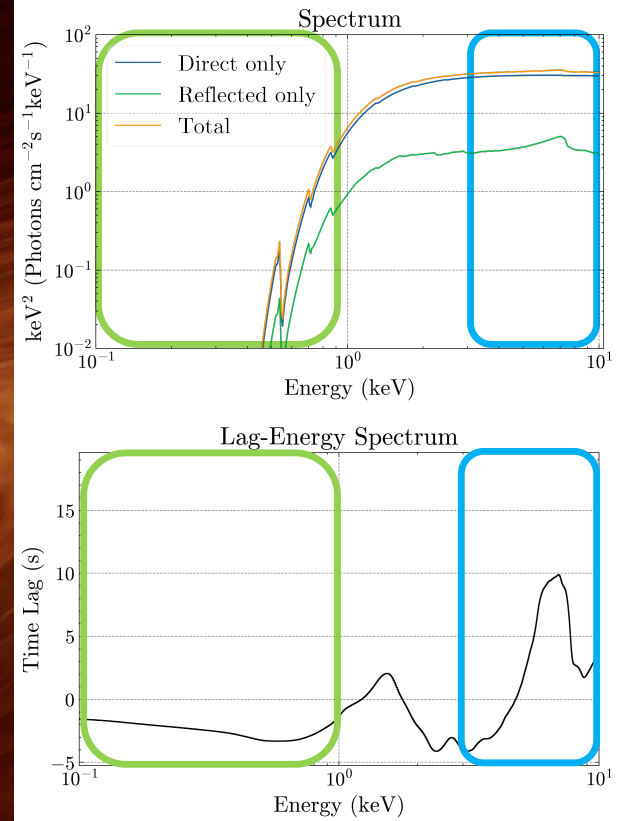
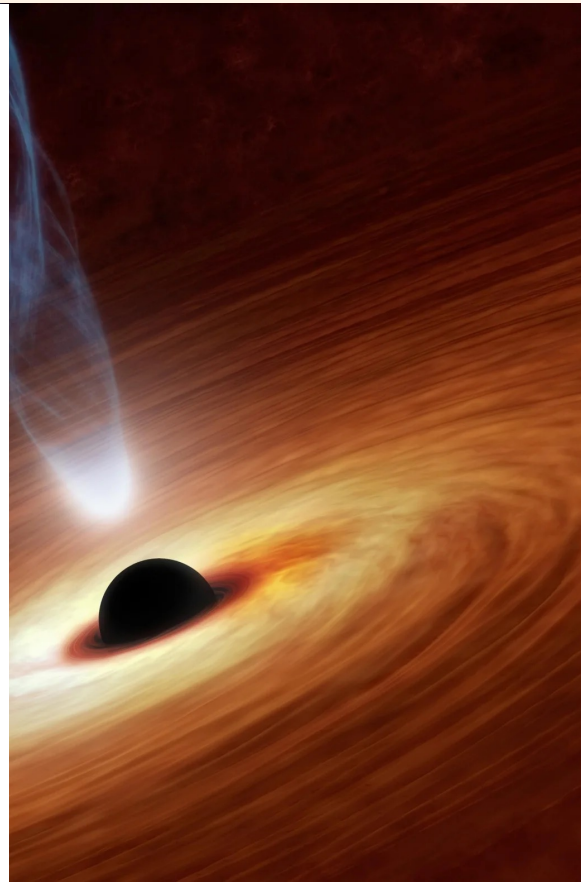


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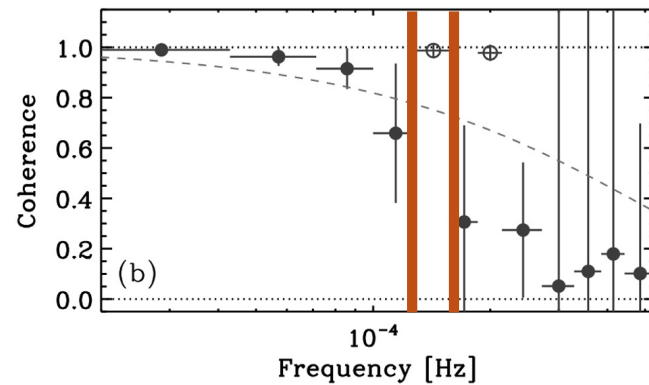
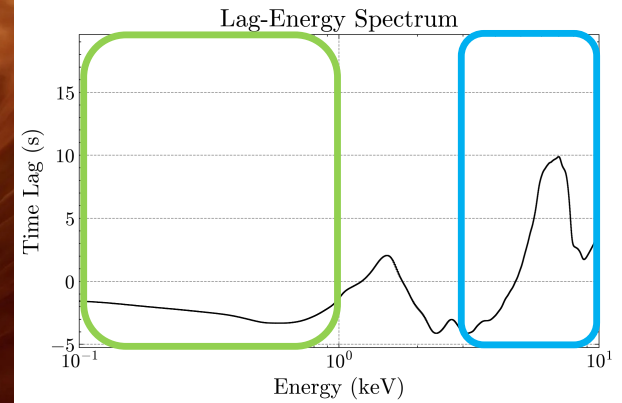
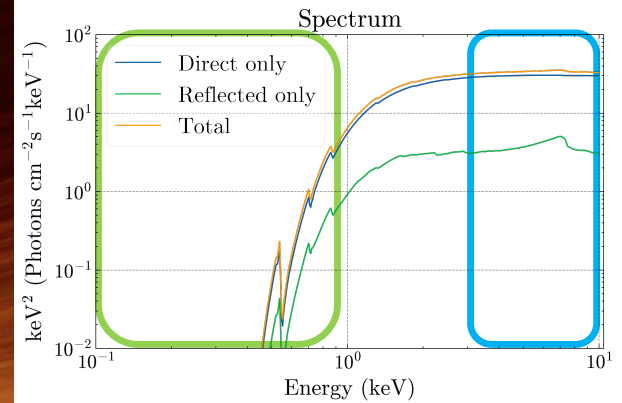


Image credit:  
 NASA/JPL-Caltech

Alston et al. 2015



+ reltrans = h,  $a_*$ , inc, ...  
 (Relativistic transfer model)

# Overview



Image credit:  
NASA/JPL-Caltech

# Overview

Decide Geometry

for our example case

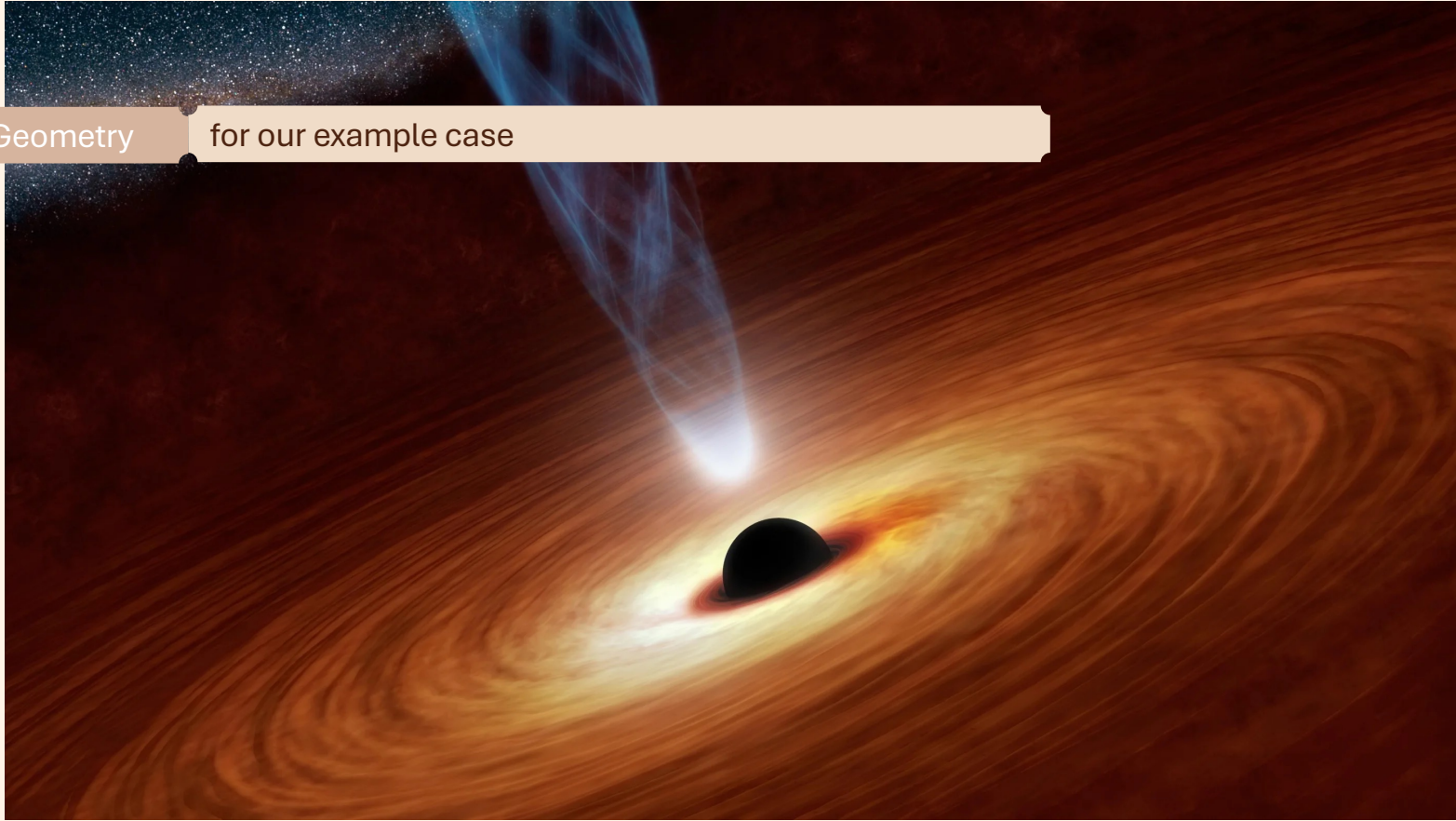


Image credit:  
NASA/JPL-Caltech

# Overview

Decide Geometry

for our example case

Simulate Light Curve

in multiple energy bands from given spectrum

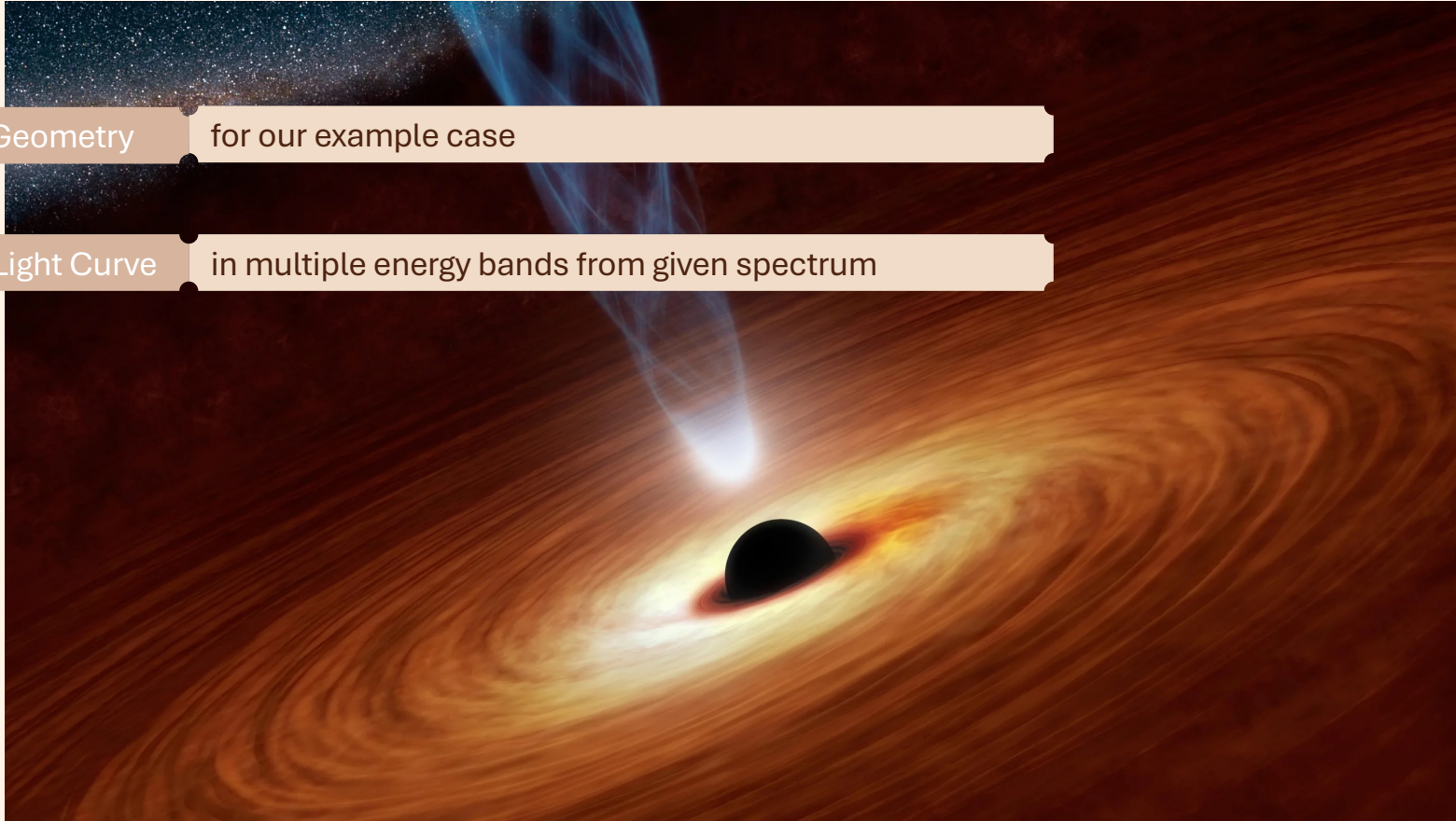


Image credit:  
NASA/JPL-Caltech

# Overview

Decide Geometry

for our example case

Simulate Light Curve

in multiple energy bands from given spectrum

Fourier Analysis

in each energy band to get lag-energy for QPO and BBN

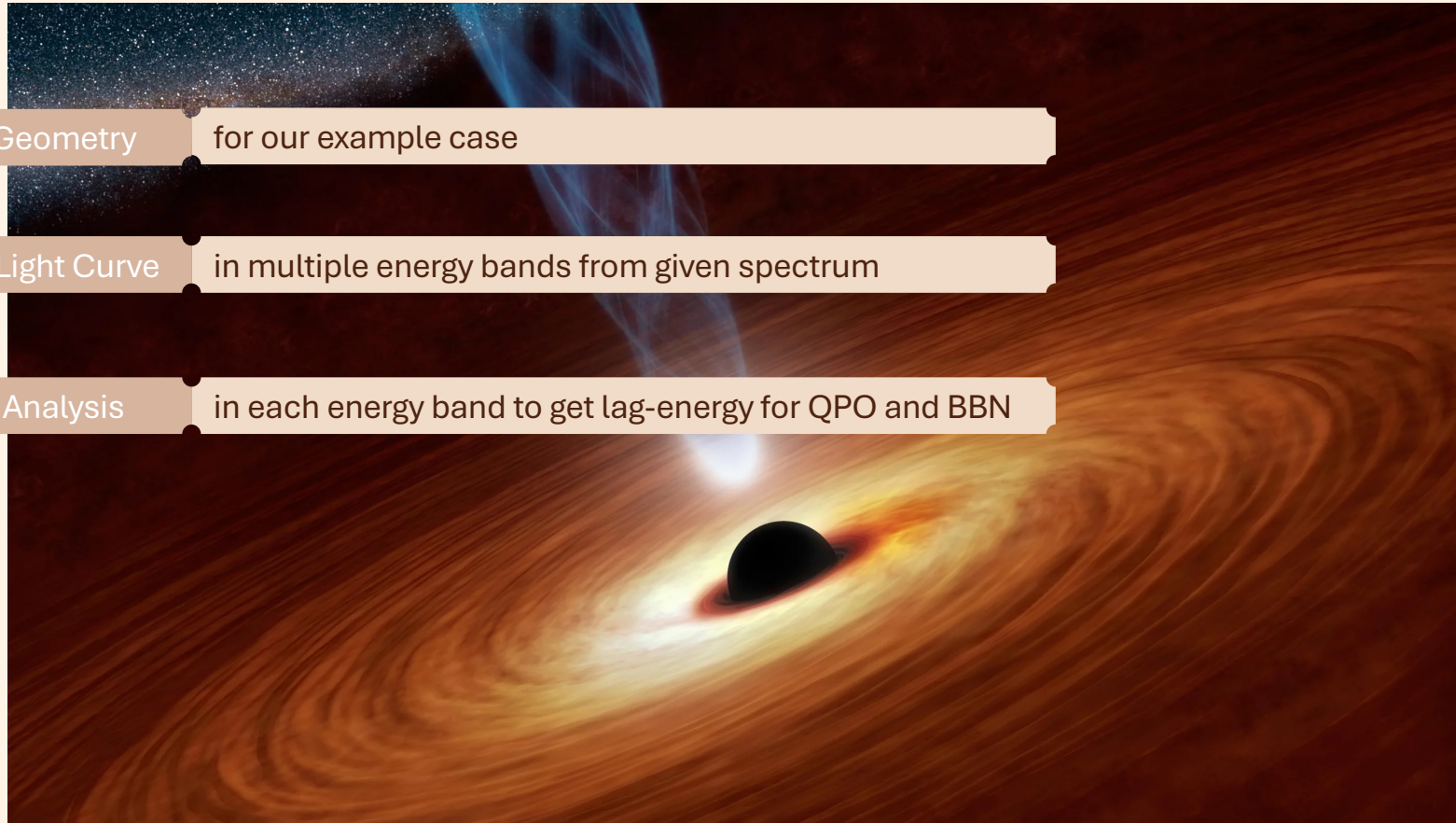


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NASA/JPL-Caltech

# Overview

Decide Geometry

for our example case

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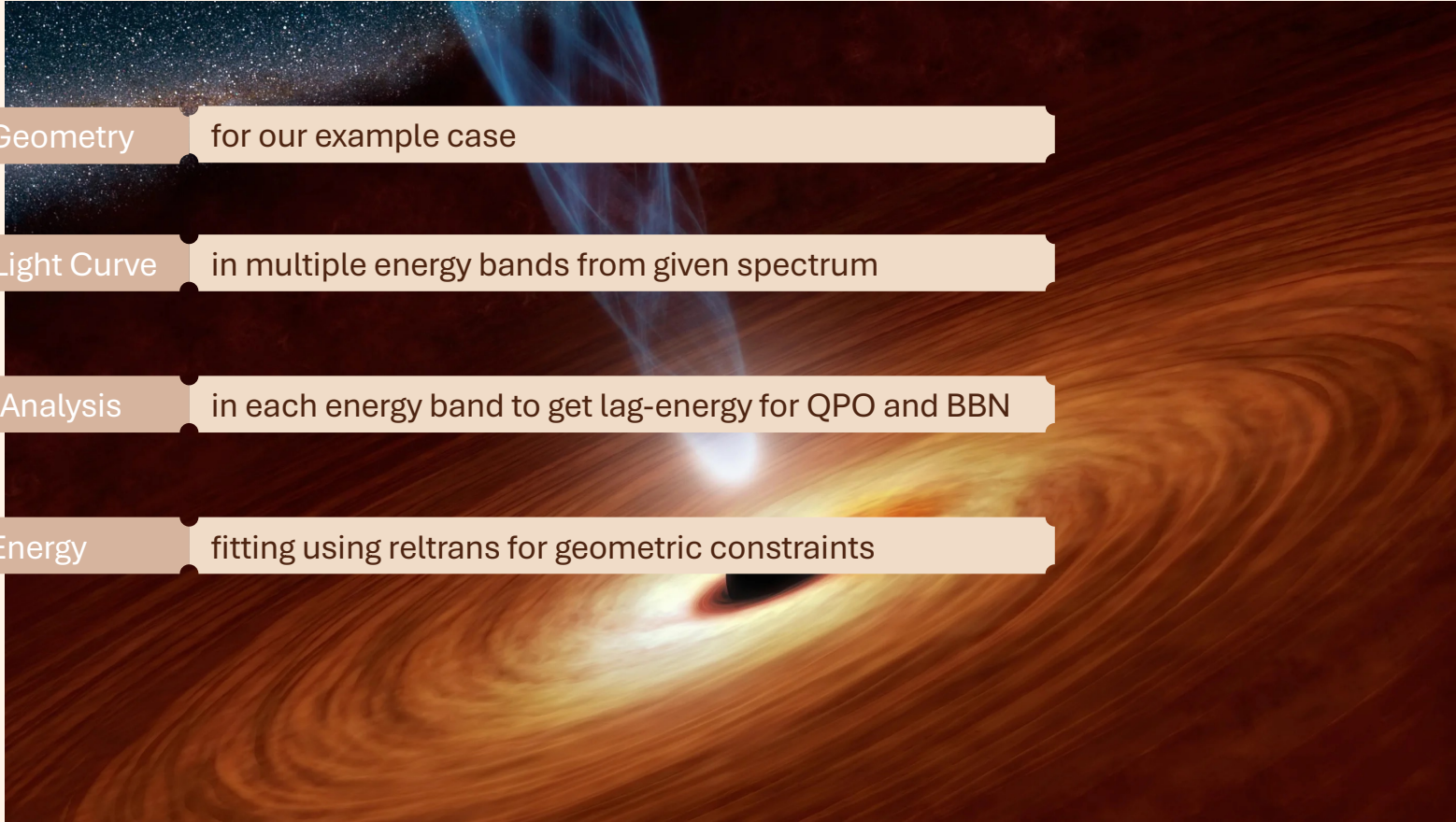
Fourier Analysis

in each energy band to get lag-energy for QPO and BBN

Lag-Energy

fitting using reltrans for geometric constraints

Image credit:  
NASA/JPL-Caltech



# Overview



Image credit:  
NASA/JPL-Caltech

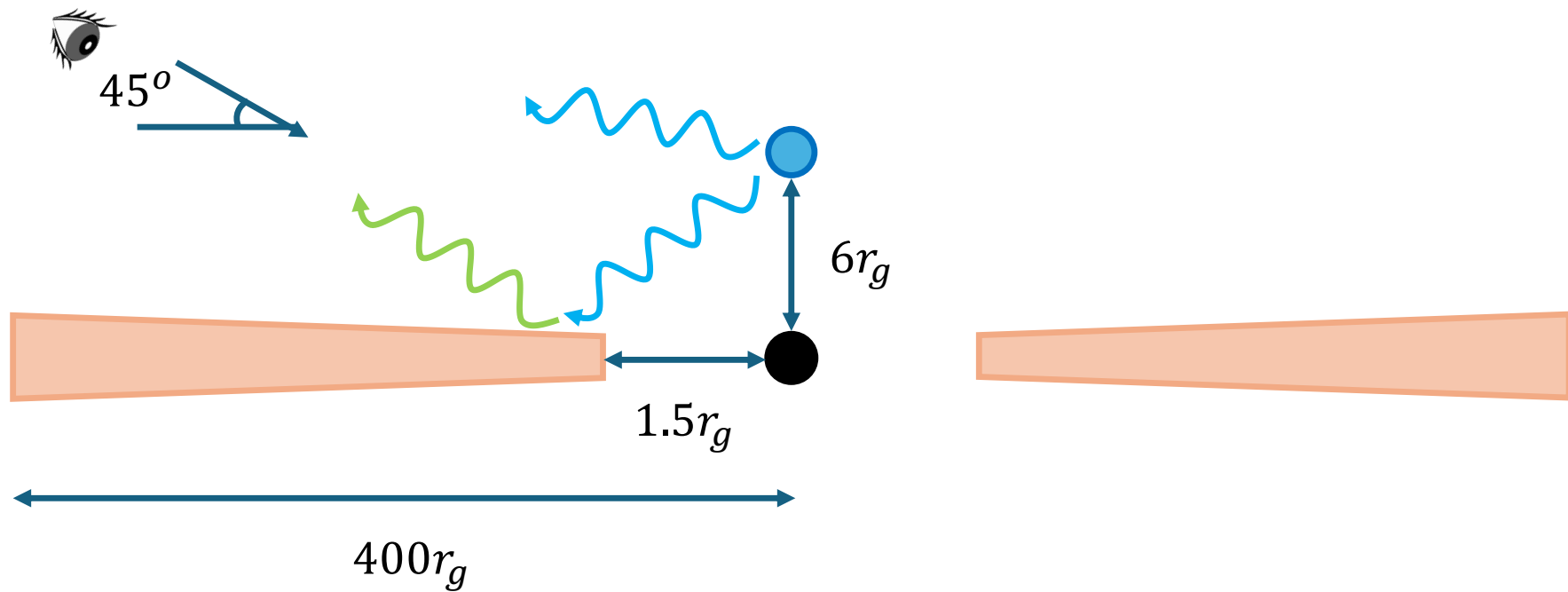
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Decide Geometry



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

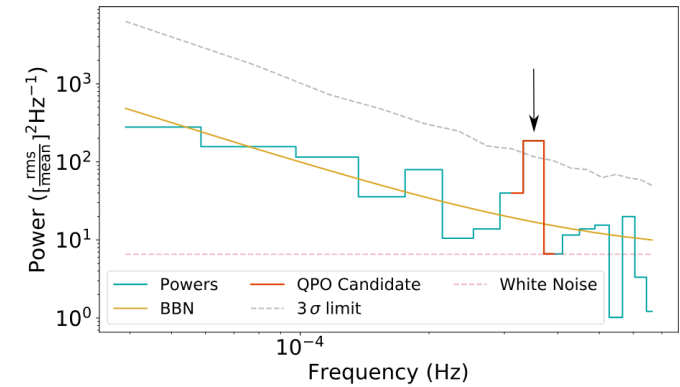
# Simulate light curve

Simulate light curve in each energy band

Require energy-dependent parameters:

Quantity	Use
$\beta$ - values	Slope of red noise in Fourier space
Mean count rate	Poisson noise
Reflection fraction (direct/reflected)	Modulates effect of transfer function

Ashton & Middleton 2020



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Simulate light curve

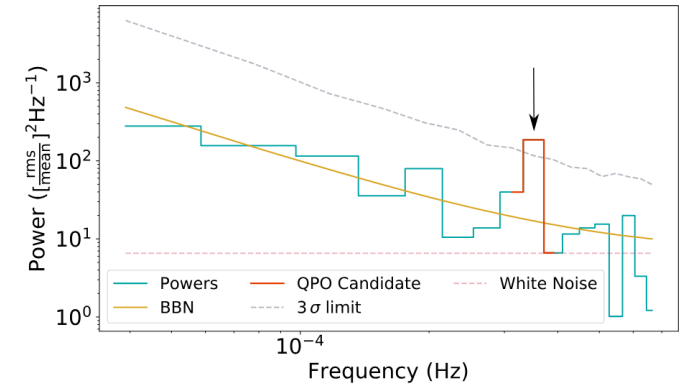
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Ashton & Middleton 2022

Ashton & Middleton 2020



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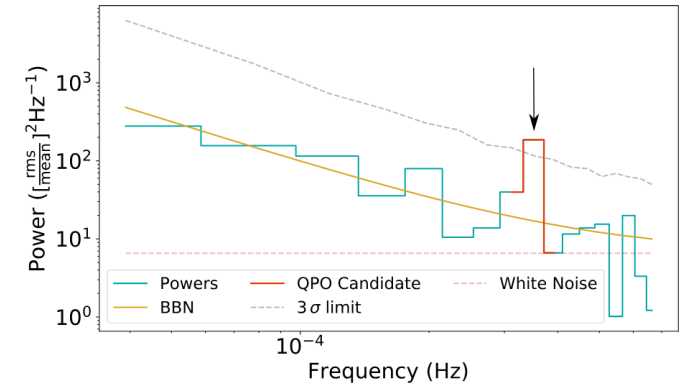
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Ashton & Middleton 2022

Require total spectrum

Ashton & Middleton 2020



Decide Geometry

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Fourier Analysis

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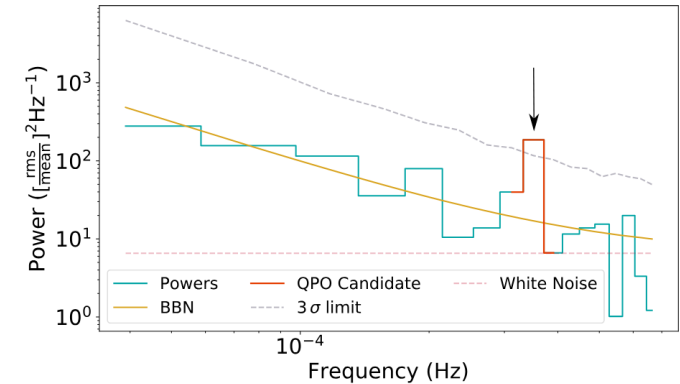
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Ashton & Middleton 2022

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Require direct and reflected spectra

Ashton & Middleton 2020



Decide Geometry

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Fourier Analysis

Lag-Energy

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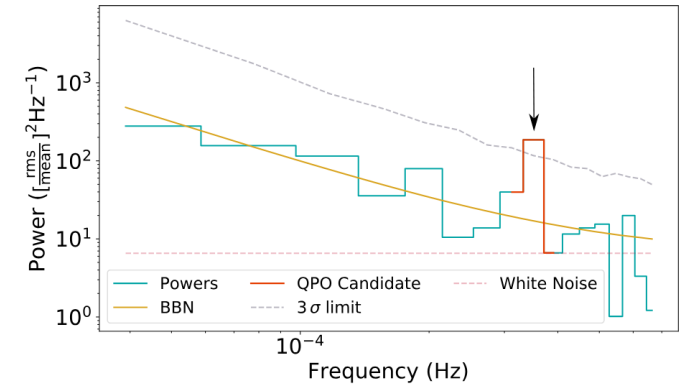
Ashton & Middleton 2022

Require total spectrum

Require direct and reflected spectra



Ashton & Middleton 2020



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

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Simulate light curve in each energy band

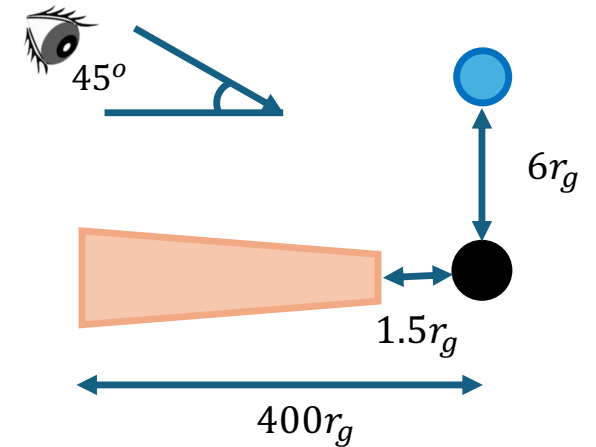
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Ashton & Middleton 2022

Require total spectrum

Require direct and reflected spectra



TBabs(relxillp)

Decide Geometry

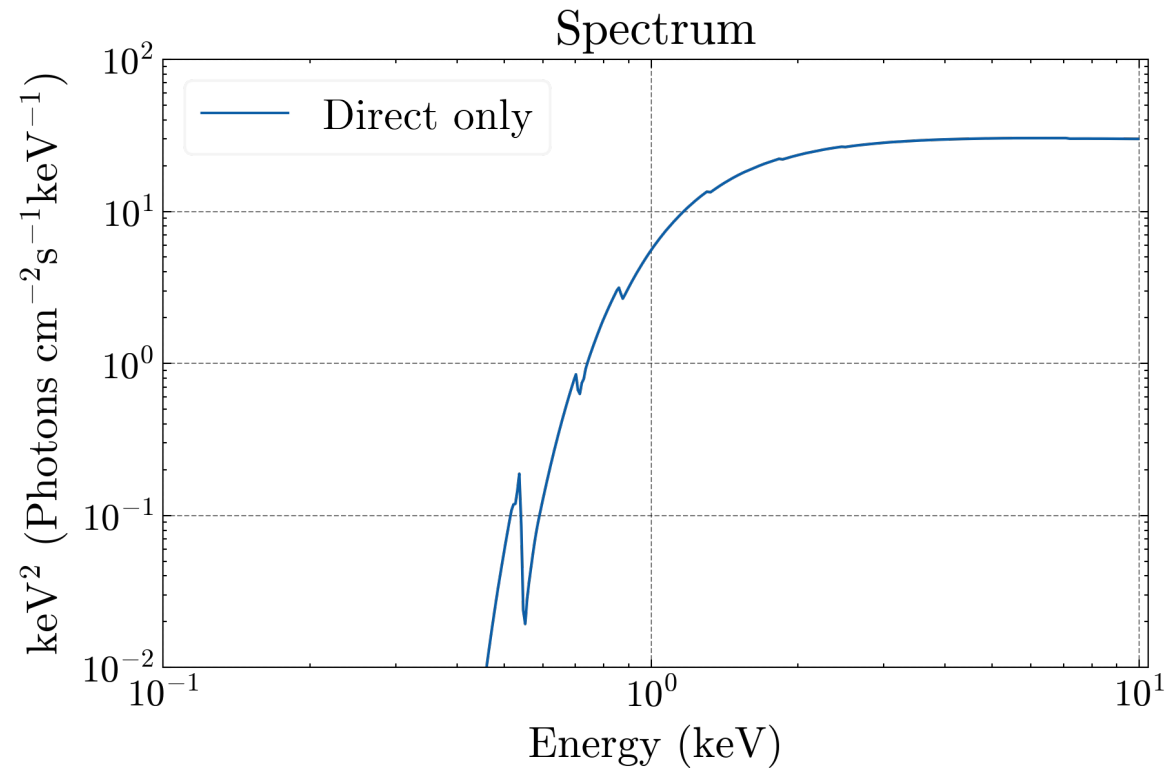
Simulate Light Curve

Fourier Analysis

Lag-Energy

# Simulate light curve: spectra

Direct: TBabs (relxillp) refl\_frac = 0



Decide Geometry

Simulate Light Curve

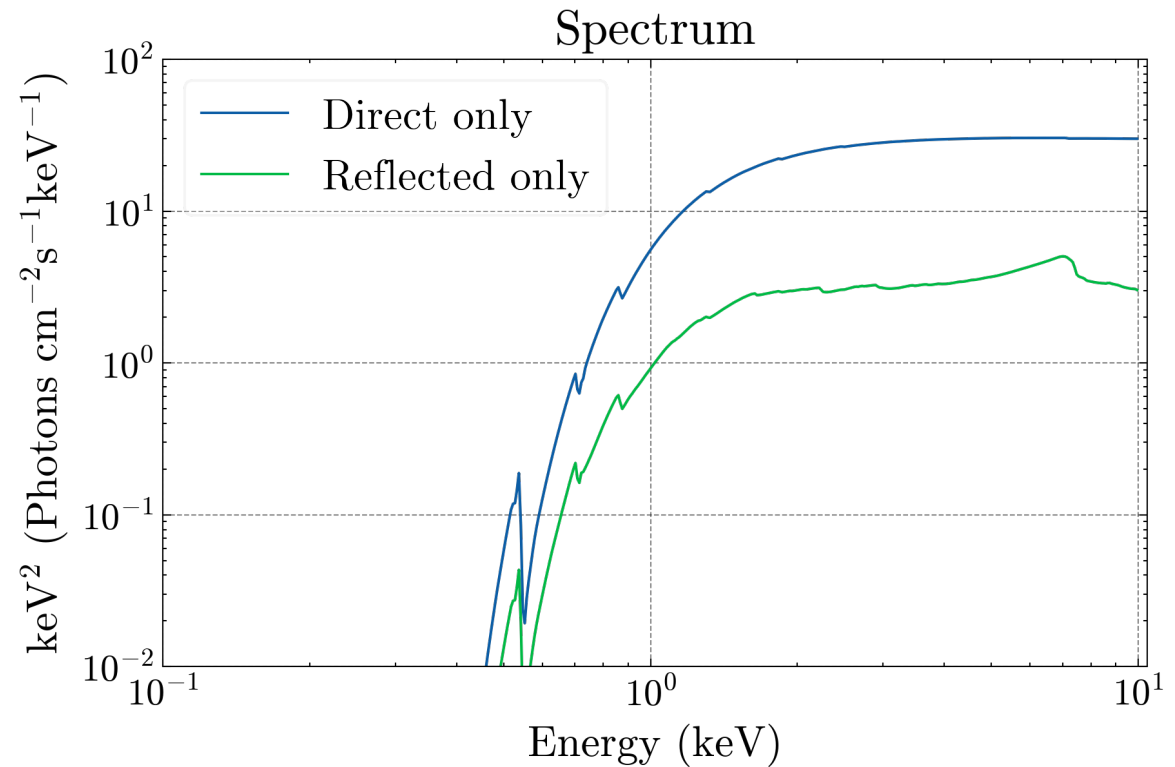
Fourier Analysis

Lag-Energy

# Simulate light curve: spectra

Direct: TBabs (relxillp) refl\_frac = 0

Reflected: Tbabs (relxillp) refl\_frac = -0.25



Decide Geometry

Simulate Light Curve

Fourier Analysis

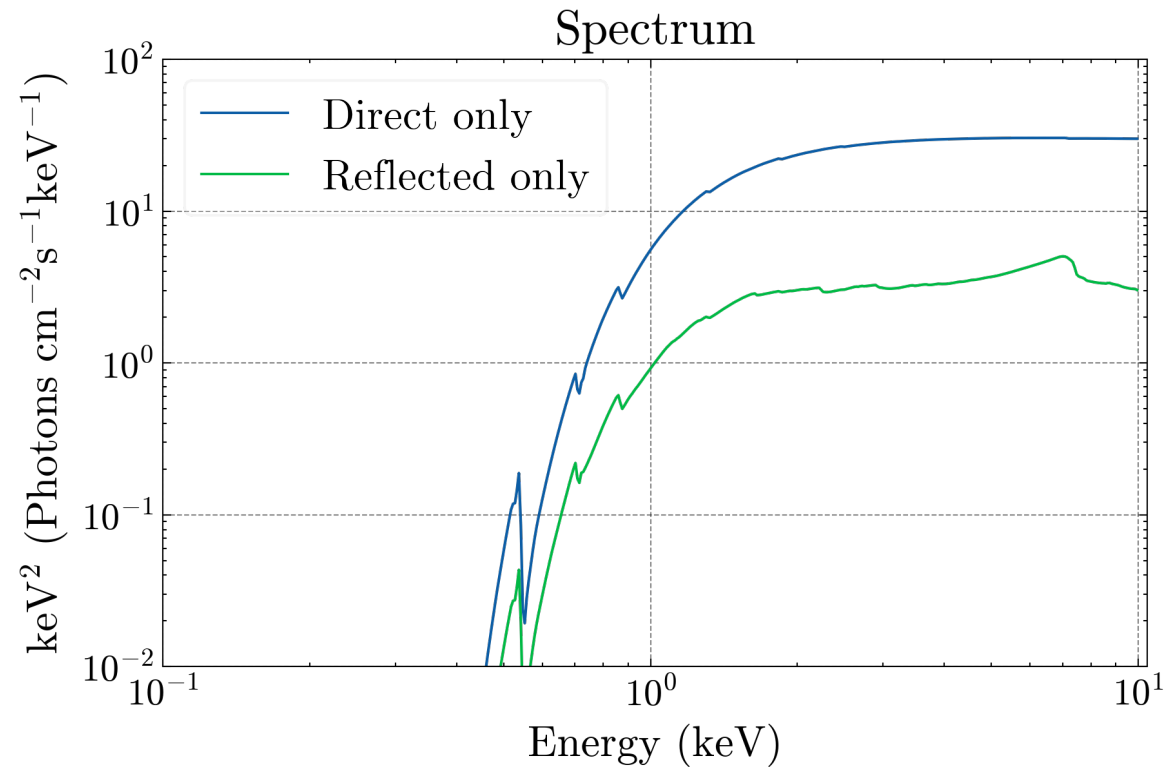
Lag-Energy

# Simulate light curve: spectra

Direct: TBabs (relxillp) refl\_frac = 0

Reflected: Tbabs (relxillp) refl\_frac = -0.25

↑  
Isolates  
reflection



Decide Geometry

Simulate Light Curve

Fourier Analysis

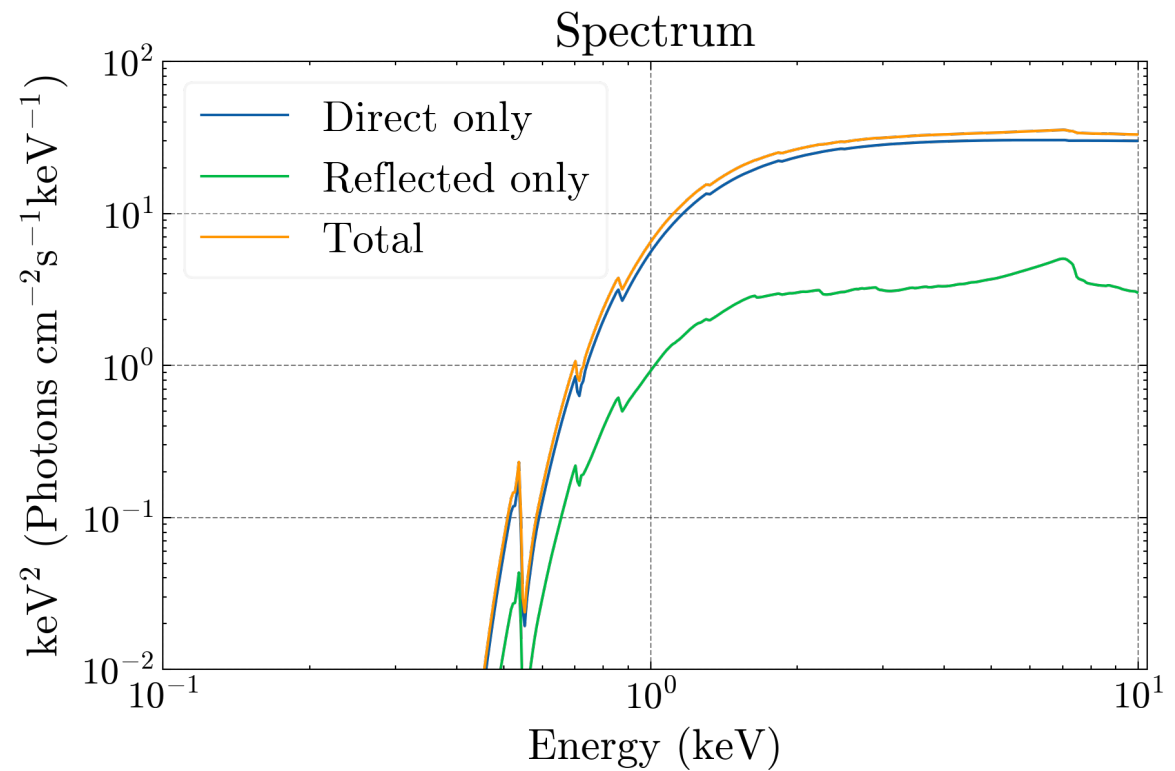
Lag-Energy

# Simulate light curve: spectra

Direct: TBabs (relxillp) refl\_frac = 0

Reflected: Tbabs (relxillp) refl\_frac = -0.25

Total = Direct + Reflected



Decide Geometry

Simulate Light Curve

Fourier Analysis

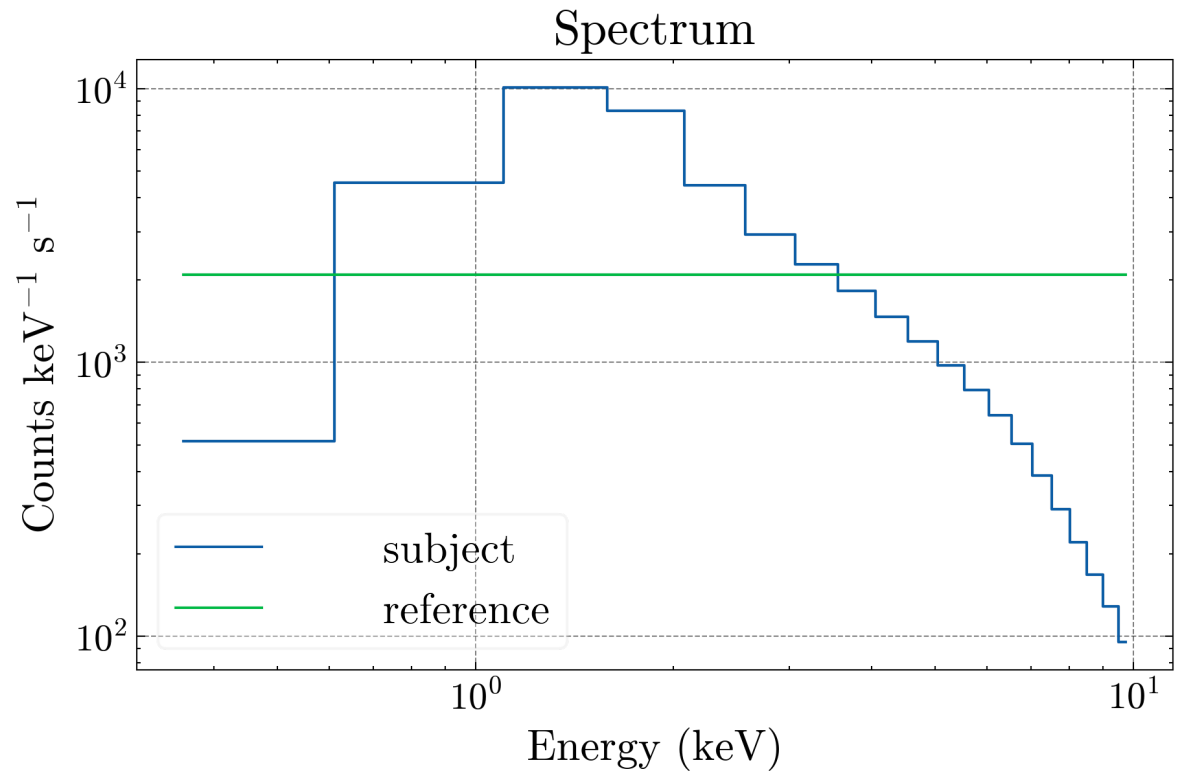
Lag-Energy

# Simulate light curve: spectra

Reference : 0.3 – 10 keV

Subject : 20 bins

Quantity	Used to
$\beta$ - values	Slope of red noise in Fourier space
Mean count rate	Generate Poisson noise
Reflection fraction (direct/reflected)	Apply transfer function



Decide Geometry

Simulate Light Curve

Fourier Analysis

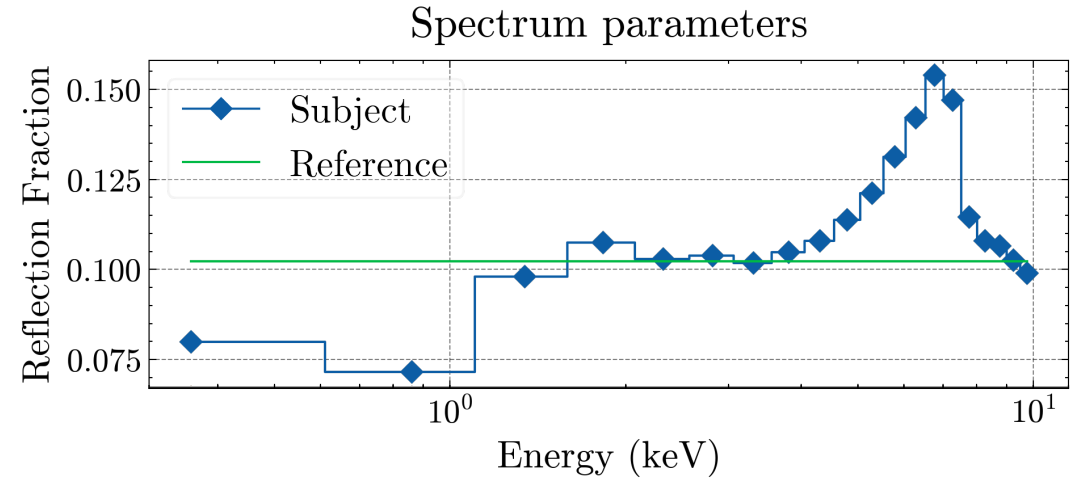
Lag-Energy

# Simulate light curve: spectra

Reference : 0.3 – 10 keV

Subject : 20 bins

Quantity	Used to
$\beta$ - values	Slope of red noise in Fourier space
Mean count rate	Generate Poisson noise
<b>Reflection fraction</b> (direct/reflected)	Apply transfer function



Decide Geometry

Simulate Light Curve

Fourier Analysis

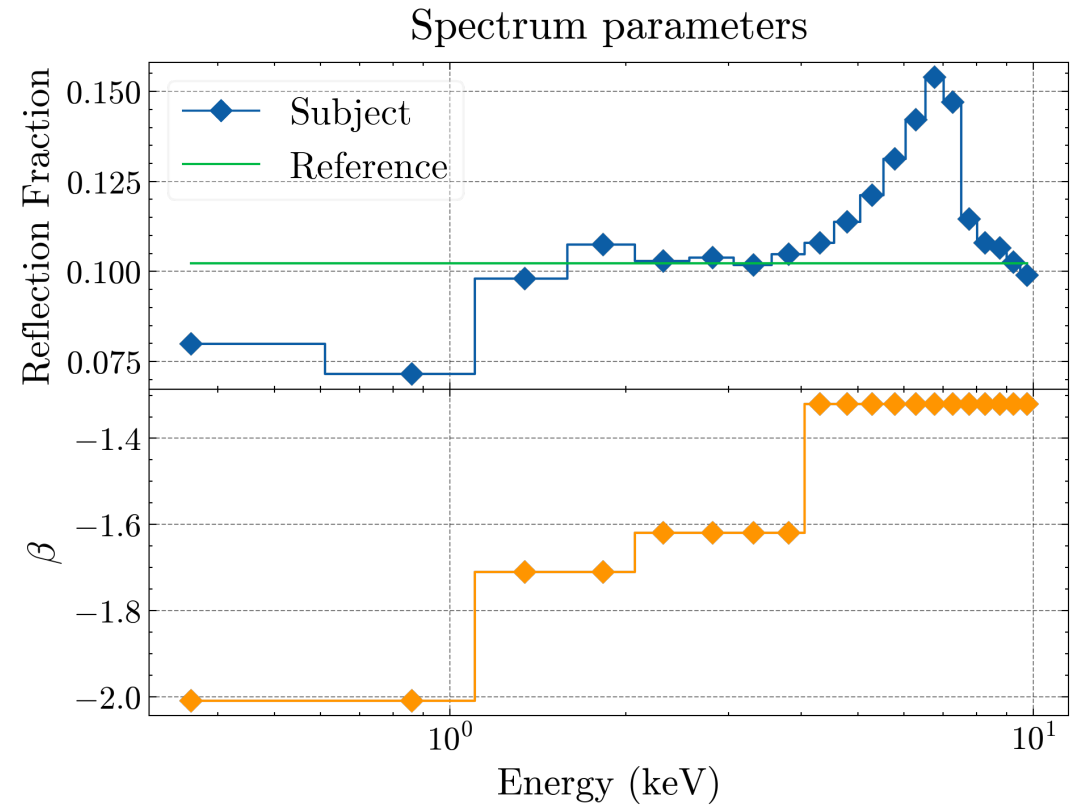
Lag-Energy

# Simulate light curve: spectra

Reference : 0.3 – 10 keV

Subject : 20 bins

Quantity	Used to
$\beta$ - values	Slope of red noise in Fourier space
Mean count rate	Generate Poisson noise
Reflection fraction (direct/reflected)	Apply transfer function



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Simulate light curve

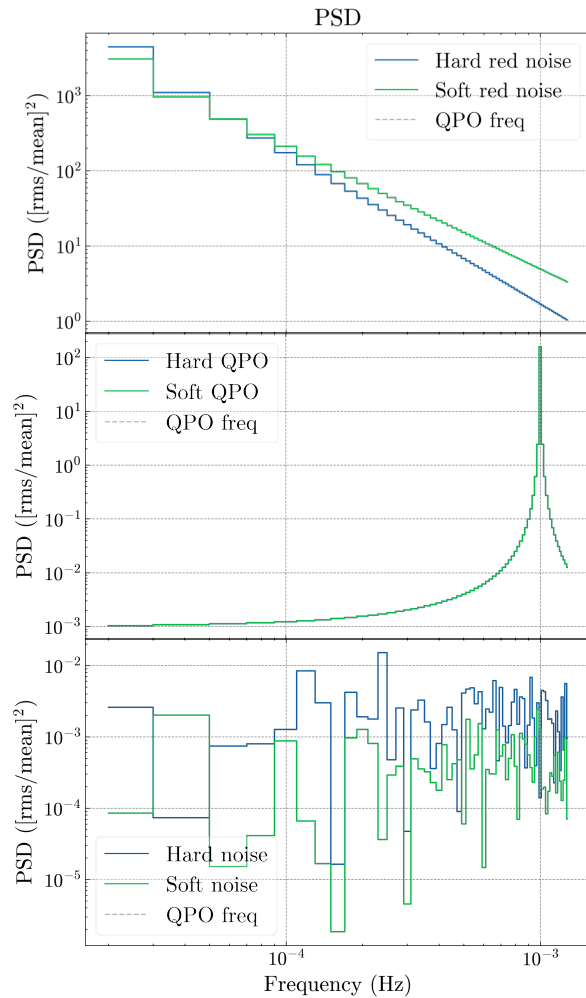
Red noise

+

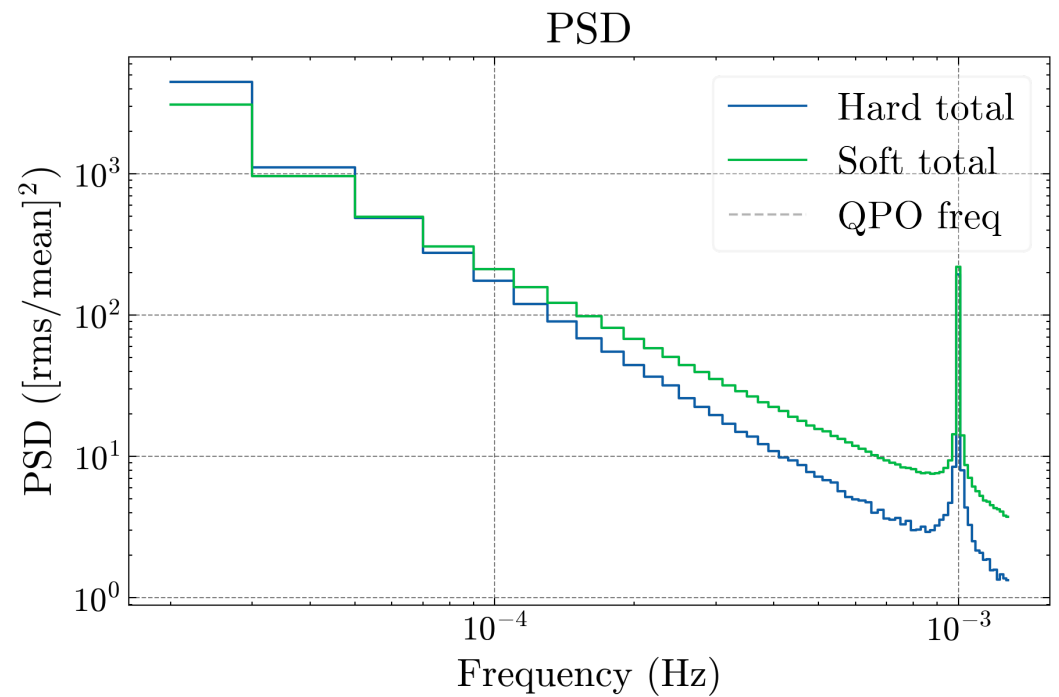
QPO

+

White noise



$\Rightarrow$



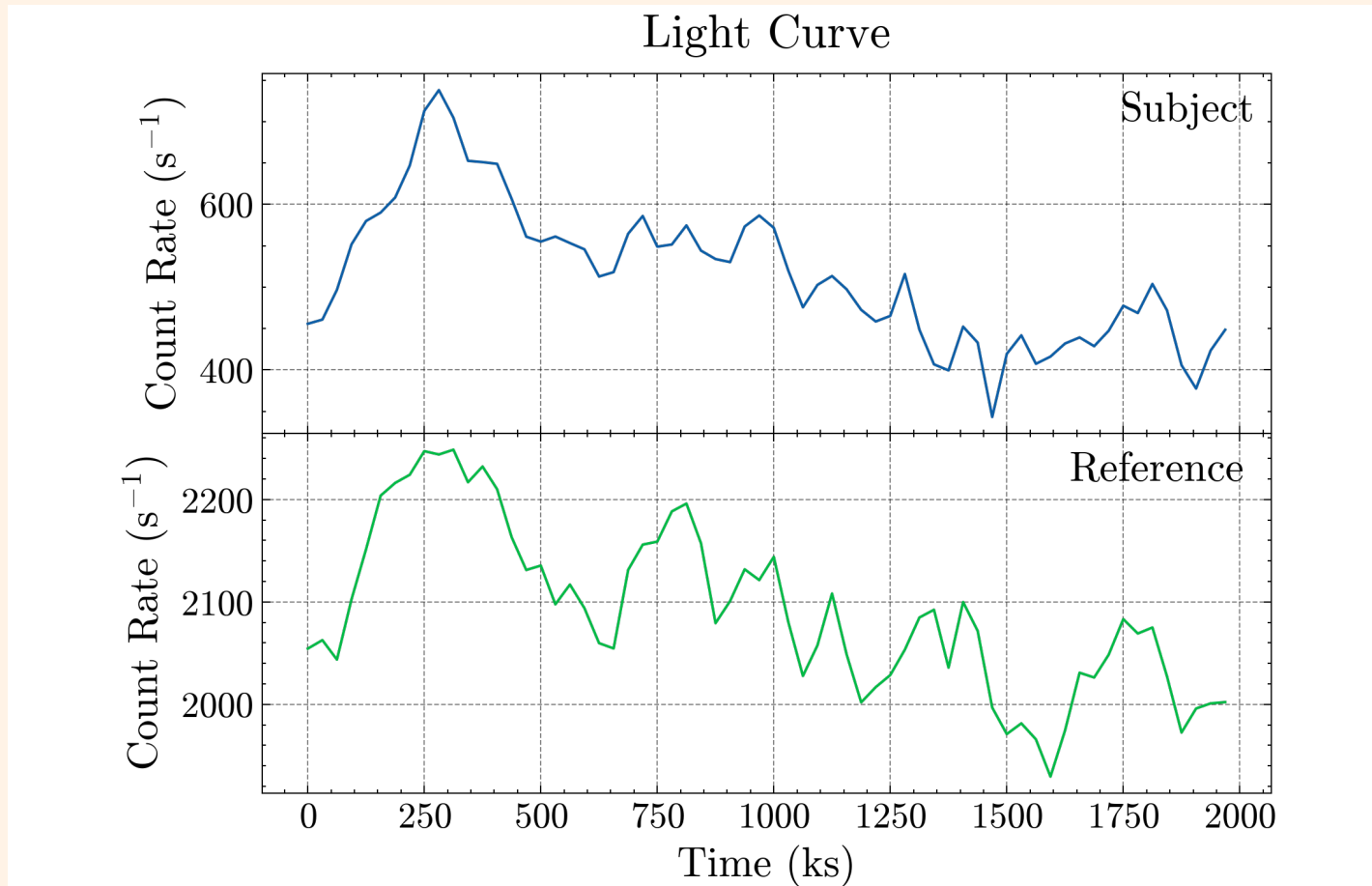
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Simulate light curve



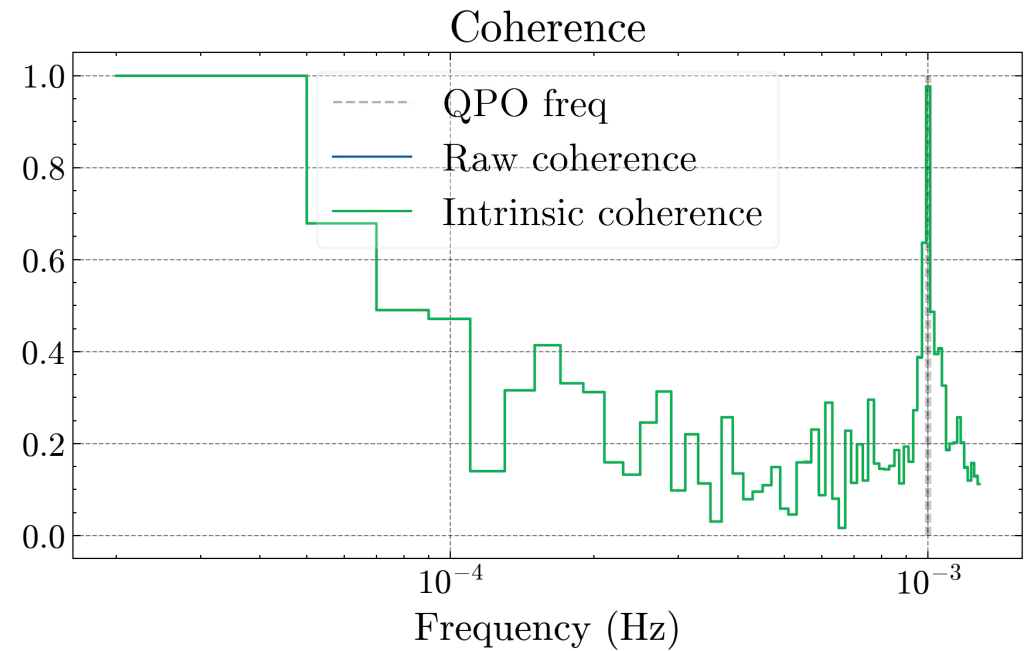
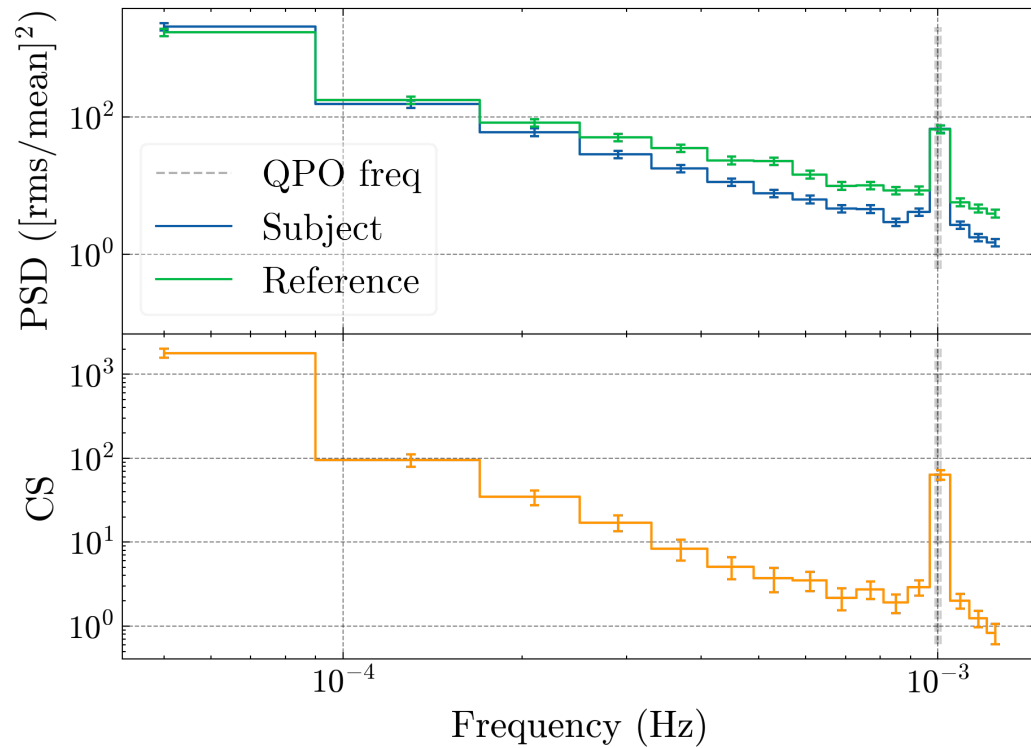
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Fourier analysis



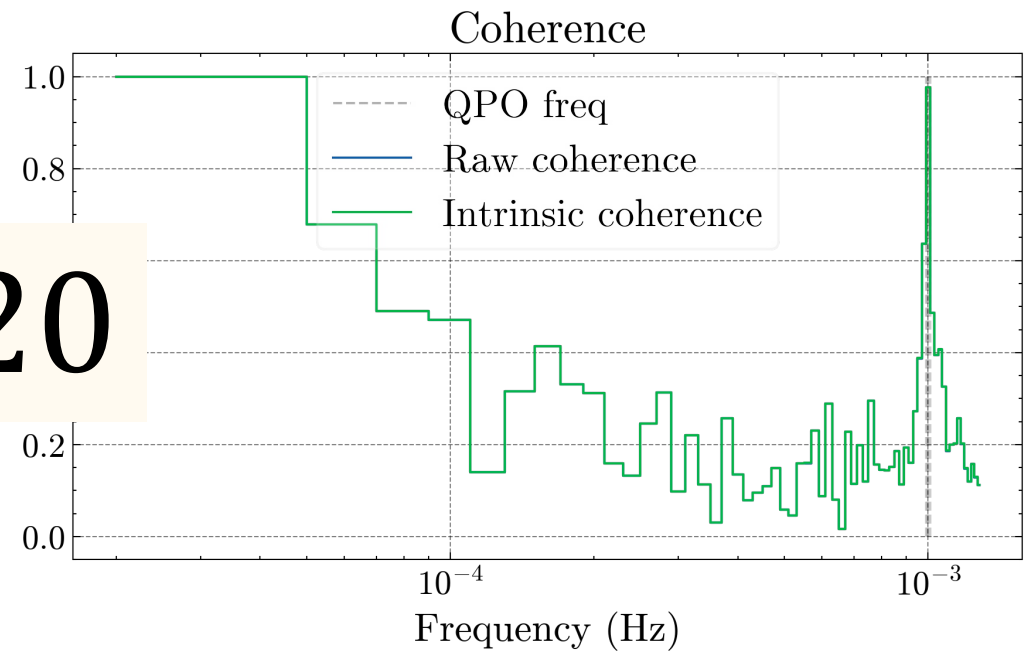
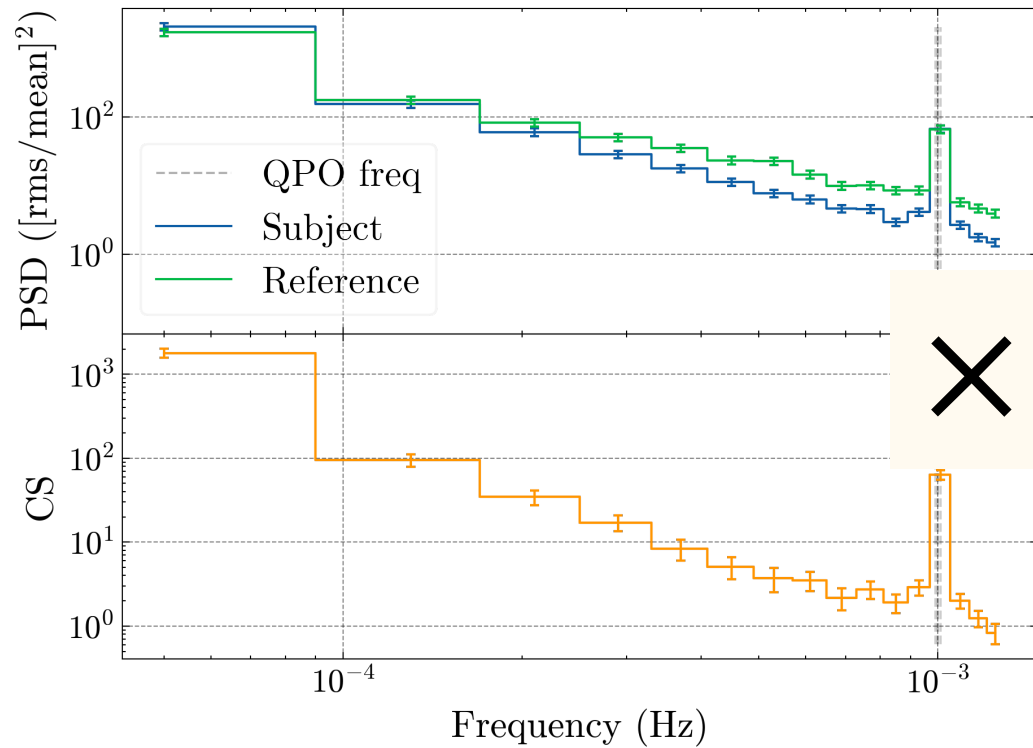
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Fourier analysis



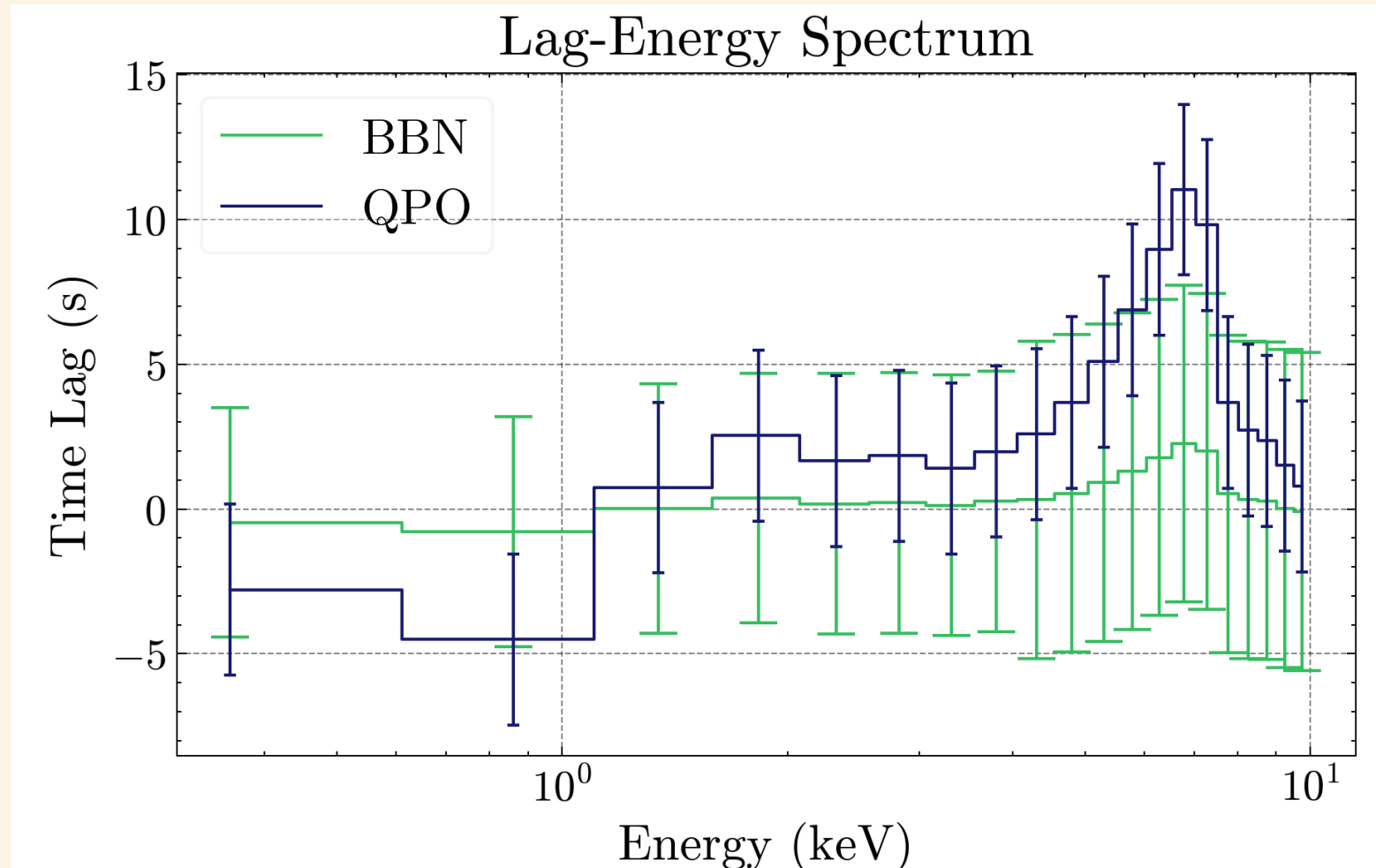
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Lag-energy errors lower and iron line more prominent for QPO



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Lag-energy: fit results

## QPO

```

=====
Model reltransDCp<1> Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
 1 1 reltransDCph Rg/Rh -1.50000 +/- 1.77886
 2 1 reltransDCpa 0.998000 +/- 7.27933E-02
 3 1 reltransDCpinc deg 51.1589 +/- 8.41071
 4 1 reltransDCprin Rg/ISCO -1.00000 frozen
 5 1 reltransDCprout Rg 400.000
 6 1 reltransDCpz 0.0 frozen
 7 1 reltransDCpGamma 2.24141 +/- 1.81286
 8 1 reltransDCplogxi 0.0 +/- 0.434690
 9 1 reltransDCpAfe 10.0000 +/- 17.5840
10 1 reltransDCplogNe 15.0000 frozen
11 1 reltransDCpkTe keV 194.218 +/- 279.366
12 1 reltransDCpnH 10^22 1.66615E-03 +/- 0.296474
13 1 reltransDCpboost 1.00000 frozen
14 1 reltransDCpMass Msun 1.00000E+06 frozen
15 1 reltransDCpfmin Hz 9.90000E-04 frozen
16 1 reltransDCpfmax Hz 1.01000E-03 frozen
17 1 reltransDCpReIm 6.00000 frozen
18 1 reltransDCpphiA rad 0.0 frozen
19 1 reltransDCpphiAB rad 0.0 frozen
20 1 reltransDCpg 0.0 frozen
21 1 reltransDCpRESP 1.00000 frozen
22 1 reltransDCpnorm 1.00000 frozen
=====

```

Using energies from responses.

Fit statistic : Chi-Squared 18.80 using 20 bins.  
 Test statistic : Chi-Squared 18.80 using 20 bins.  
 Null hypothesis probability of 9.36e-02 with 12 degrees of freedom

## BBN

```

=====
Model reltransDCp<1> Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
 1 1 reltransDCph Rg/Rh -697.758 +/- 4.04743E+04
 2 1 reltransDCpa 0.991258 +/- 3.98353
 3 1 reltransDCpinc deg 72.3528 +/- 589.143
 4 1 reltransDCprin Rg/ISCO -1.00000 frozen
 5 1 reltransDCprout Rg 400.000 frozen
 6 1 reltransDCpz 0.0 frozen
 7 1 reltransDCpGamma 2.33548 +/- 28.6757
 8 1 reltransDCplogxi 4.44265 +/- 242.762
 9 1 reltransDCpAfe 0.505206 +/- 20.6032
10 1 reltransDCplogNe 15.0000 frozen
11 1 reltransDCpkTe keV 499.604 +/- 1.30388E+06
12 1 reltransDCpnH 10^22 166.831 +/- 545.242
13 1 reltransDCpboost 1.00000 frozen
14 1 reltransDCpMass Msun 1.00000E+06 frozen
15 1 reltransDCpfmin Hz 2.00000E-05 frozen
16 1 reltransDCpfmax Hz 1.28000E-03 frozen
17 1 reltransDCpReIm 6.00000 frozen
18 1 reltransDCpphiA rad 0.0 frozen
19 1 reltransDCpphiAB rad 0.0 frozen
20 1 reltransDCpg 0.0 frozen
21 1 reltransDCpRESP 1.00000 frozen
22 1 reltransDCpnorm 1.00000 frozen
=====

```

Fit statistic : Chi-Squared 0.28 using 20 bins.  
 Test statistic : Chi-Squared 0.28 using 20 bins.  
 Null hypothesis probability of 1.00e+00 with 12 degrees of freedom

Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Lag-energy: fit results

## QPO

```

=====
Model reltransDCp<1> Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
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19 1 reltransDCpphiAB rad 0.0 frozen
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=====

```

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```

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Model Model Component Parameter Unit Value
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=====

```

Fit statistic : Chi-Squared 0.28 using 20 bins.  
 Test statistic : Chi-Squared 0.28 using 20 bins.  
 Null hypothesis probability of 1.00e+00 with 12 degrees of freedom

Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

# Summary



Image credit:  
NASA/JPL-Caltech

# Summary

Time lags help investigate corona and disk geometry of AGN



Image credit:  
NASA/JPL-Caltech

# Summary



Time lags help investigate corona and disk geometry of AGN

Low coherence in signals makes time lags harder to analyse

Image credit:  
NASA/JPL-Caltech

# Summary

An artistic rendering of an active galactic nucleus (AGN). It features a central black hole with a glowing accretion disk. Two blue jets of gas are shown being ejected from the poles of the black hole. The background shows a starry field with a prominent band of stars, likely representing the Milky Way galaxy.

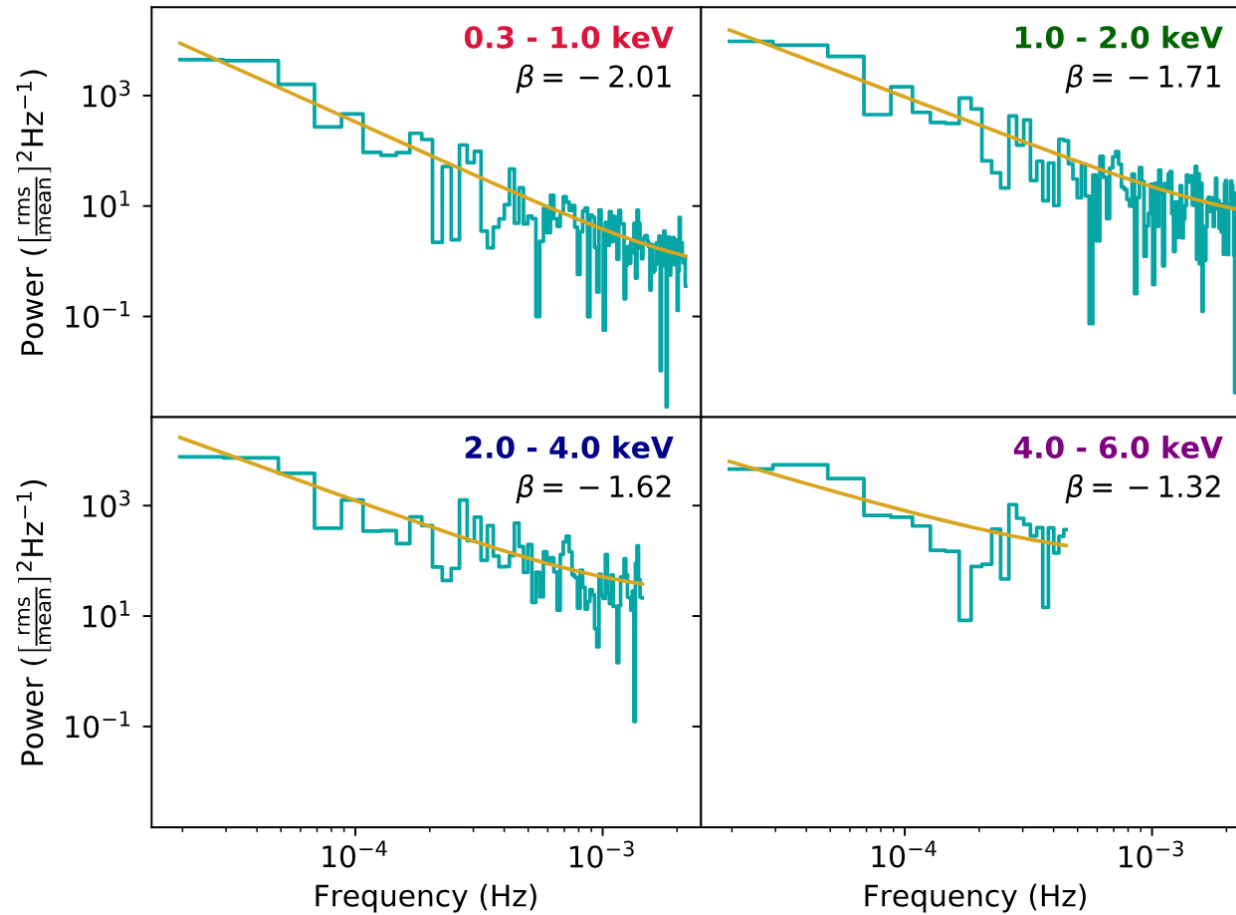
Time lags help investigate corona and disk geometry of AGN

Low coherence in signals makes time lags harder to analyse

QPOs are coherent and can improve geometric constraints

Image credit:  
NASA/JPL-Caltech

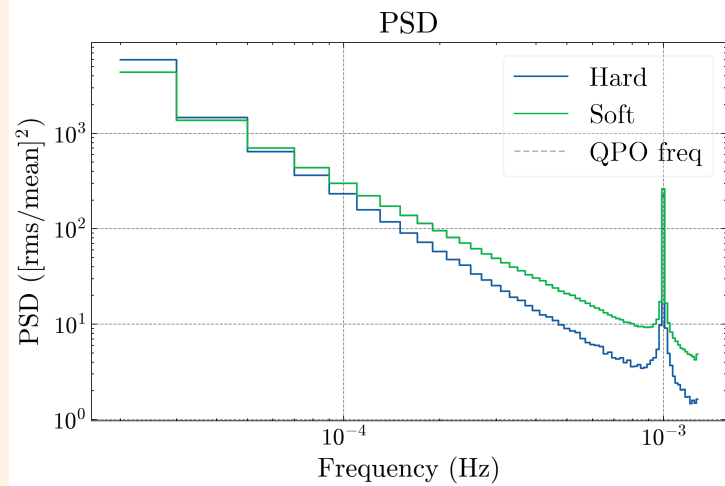
# Energy dependance of beta values



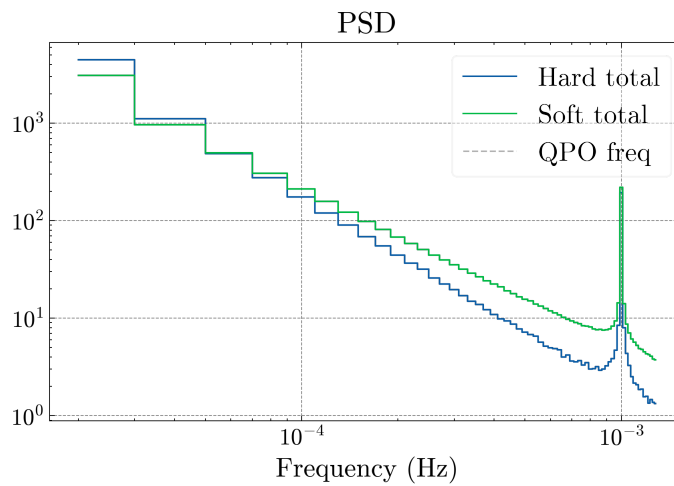
Ashton & Middleton 2022

# Simulate light curve

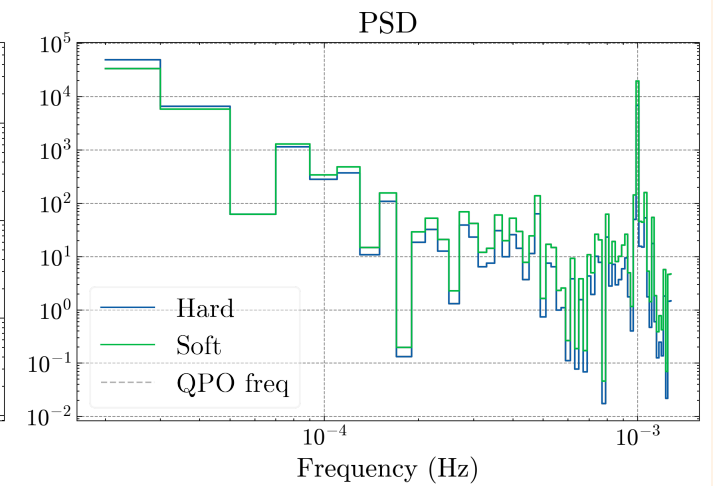
Total of components



+ Transfer function

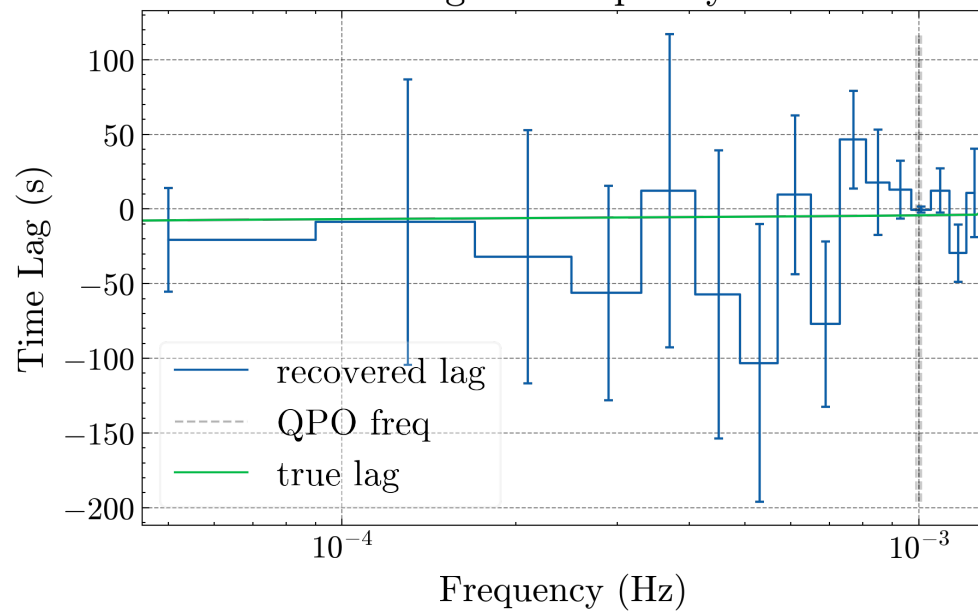


+ Coherence



# Fourier Analysis

Lag vs. Frequency



Coherence

