Lighthouses in the Centres of Galaxies

Image credit: NASA/JPL-Caltech

University of Southampton

Fiona Redmen
Matthew Middleton, Adam Ingram

UAB Universitat Autònoma de Barcelona

Image credit:
NASA/JPL-Caltech

Geometry of corona and disk in AGN

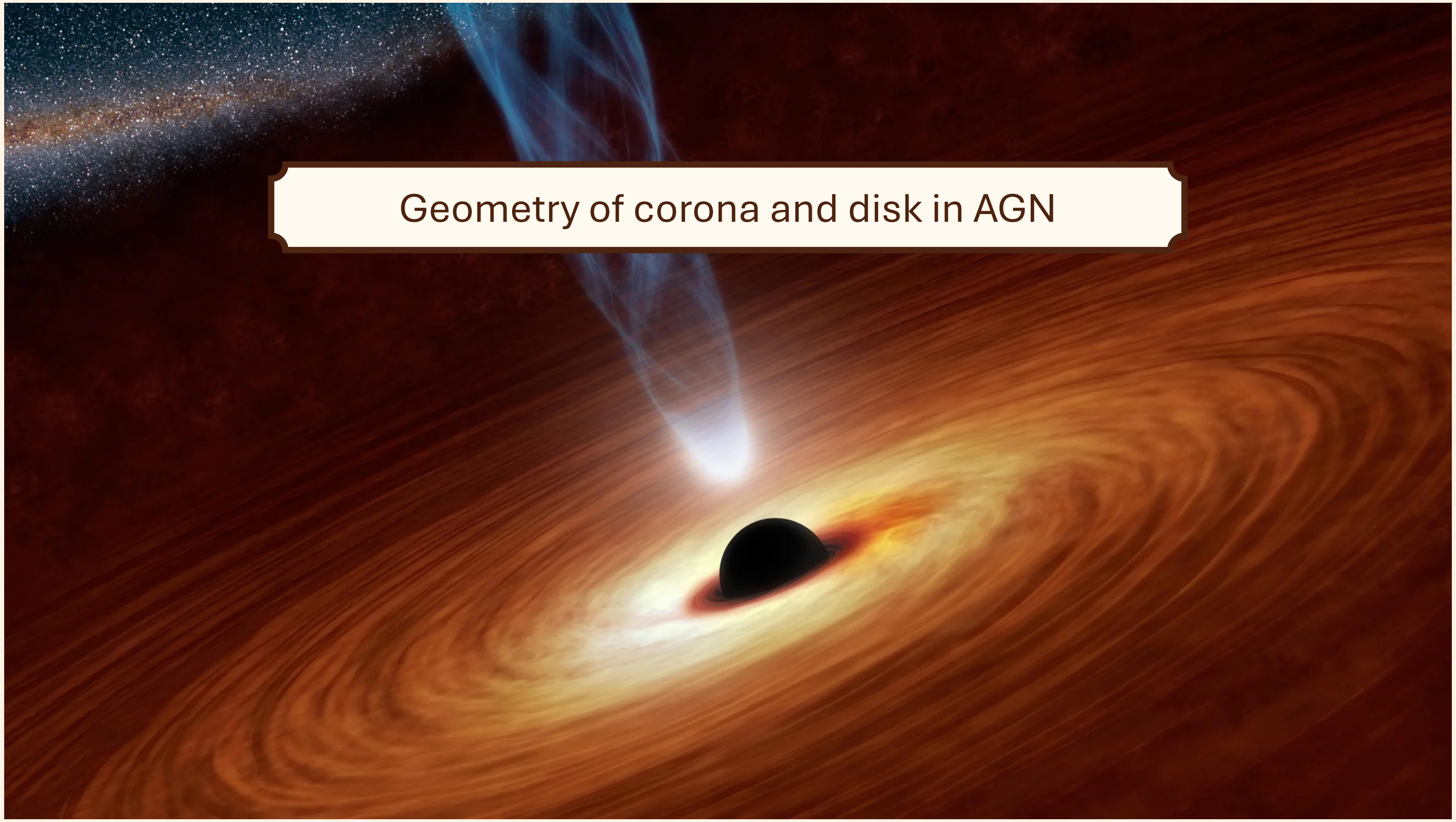


Image credit:
NASA/JPL-Caltech

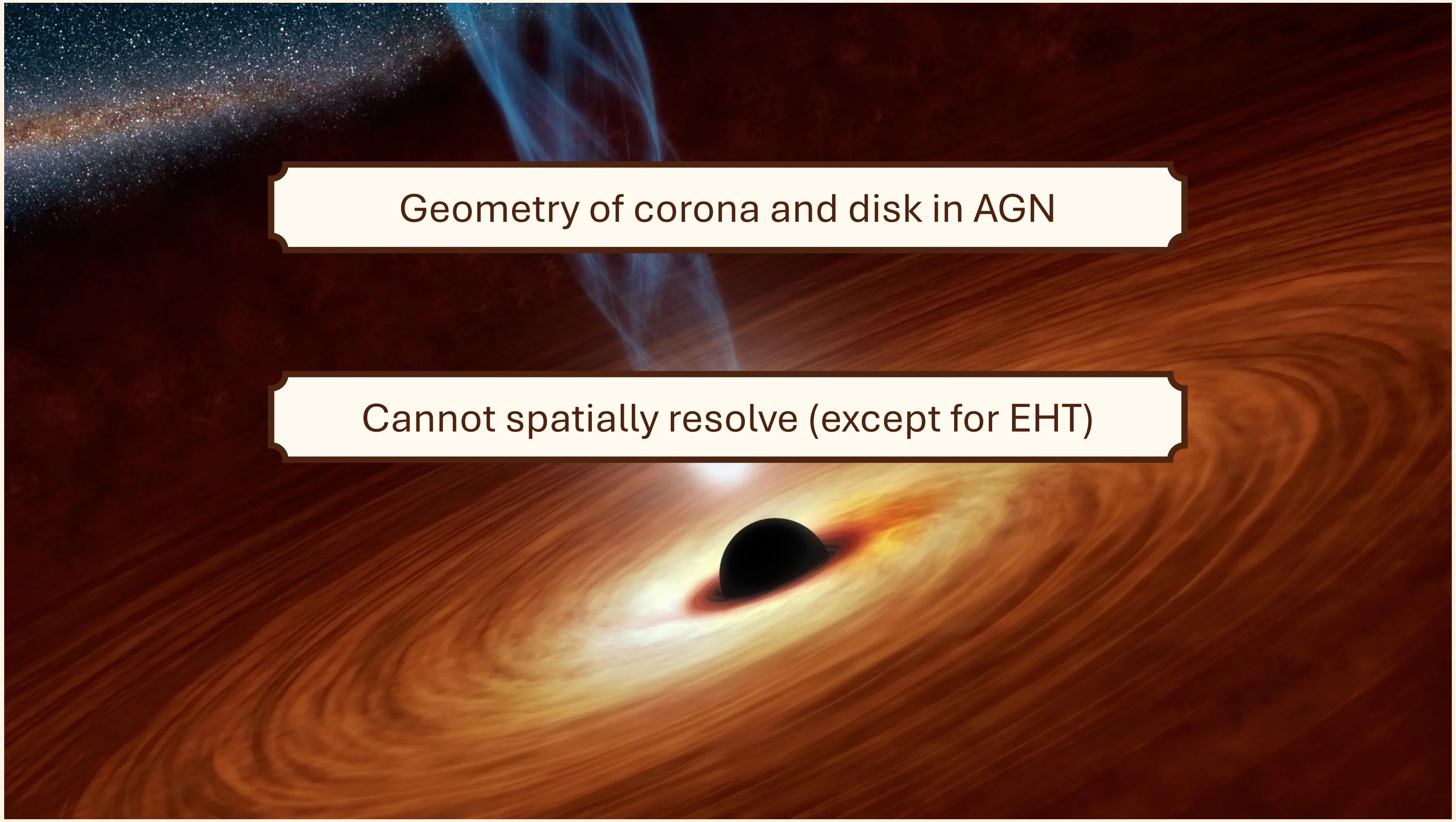
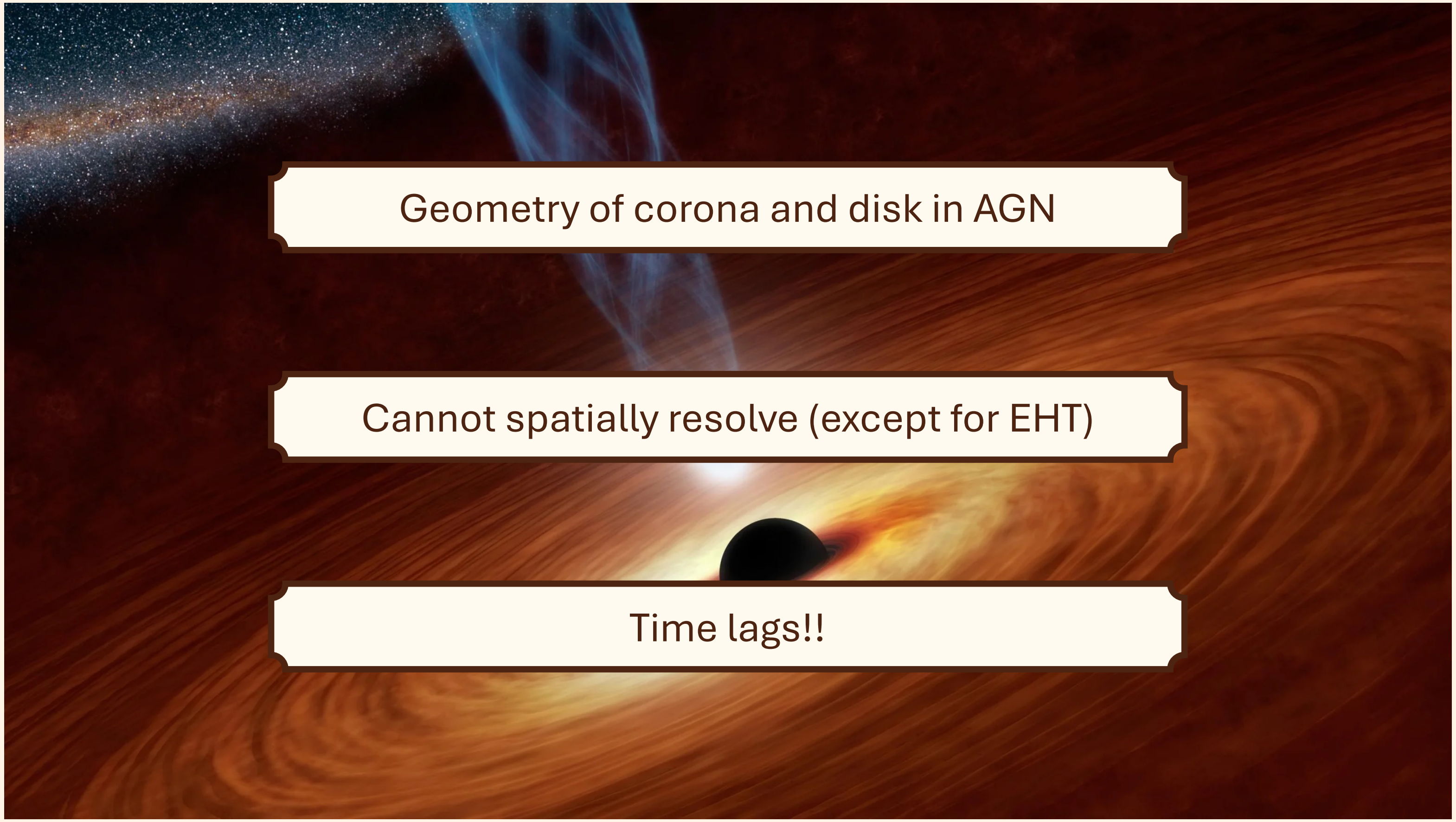


Image credit:
NASA/JPL-Caltech



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

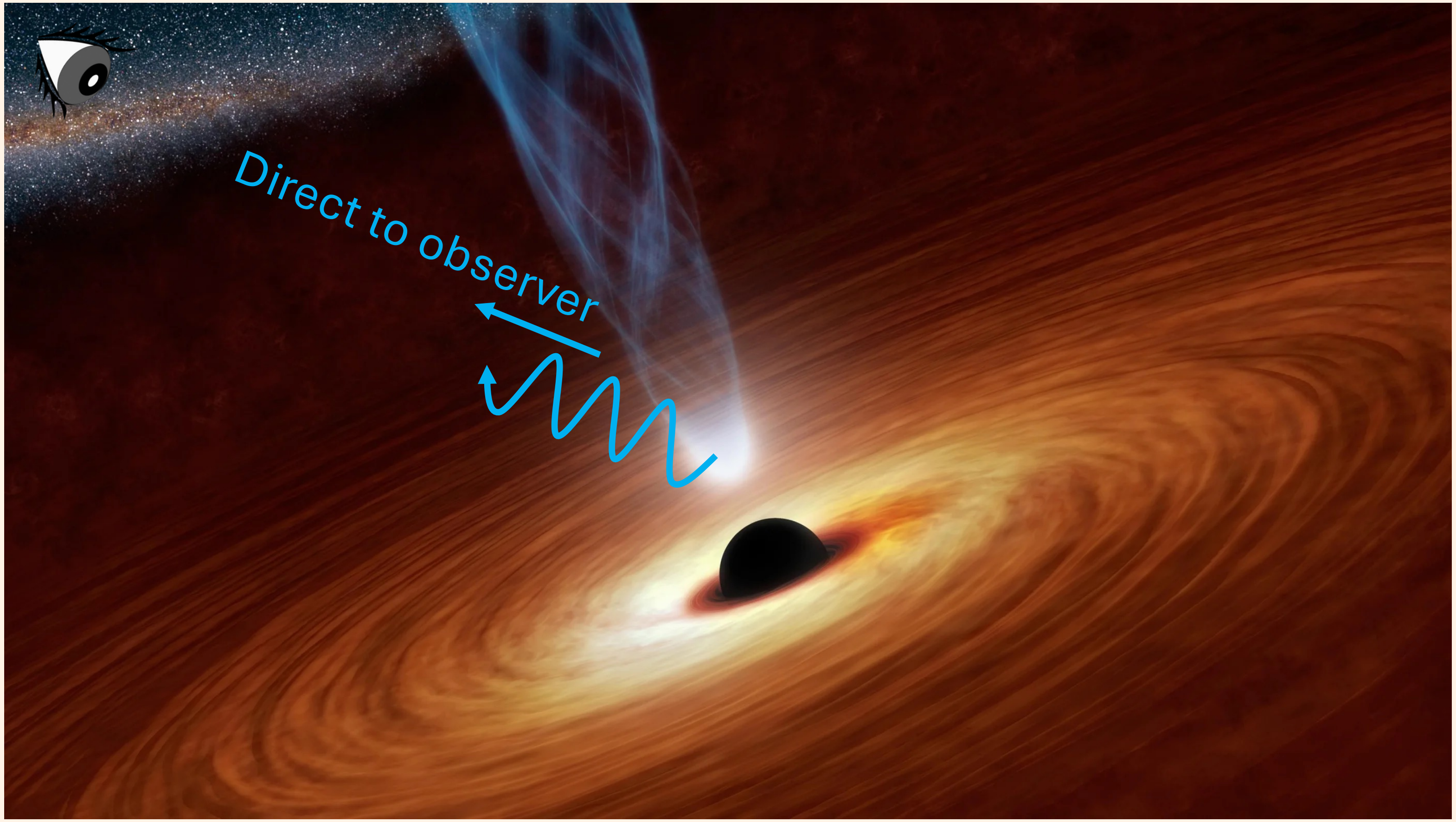


Image credit:
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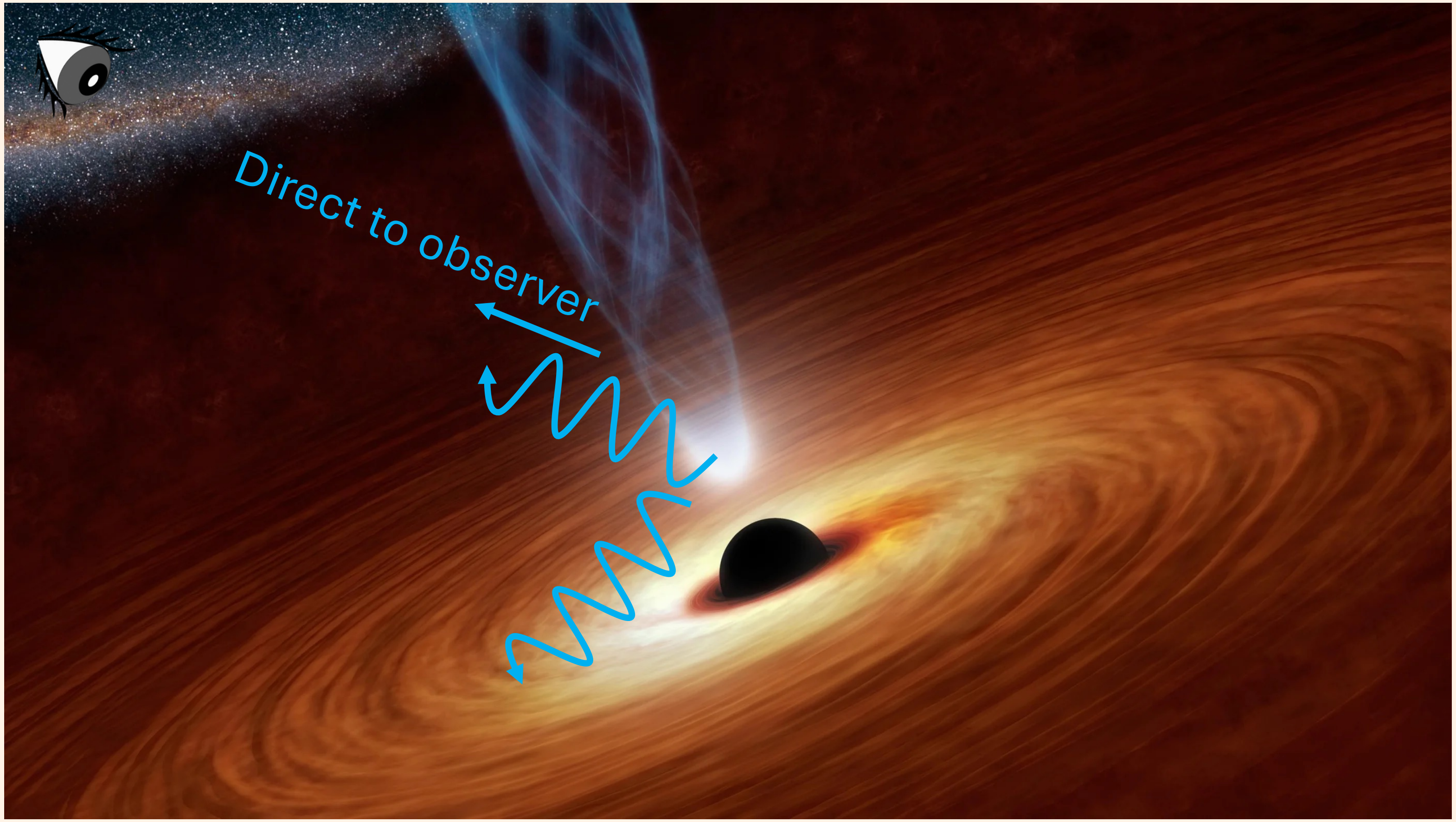
Time Lags



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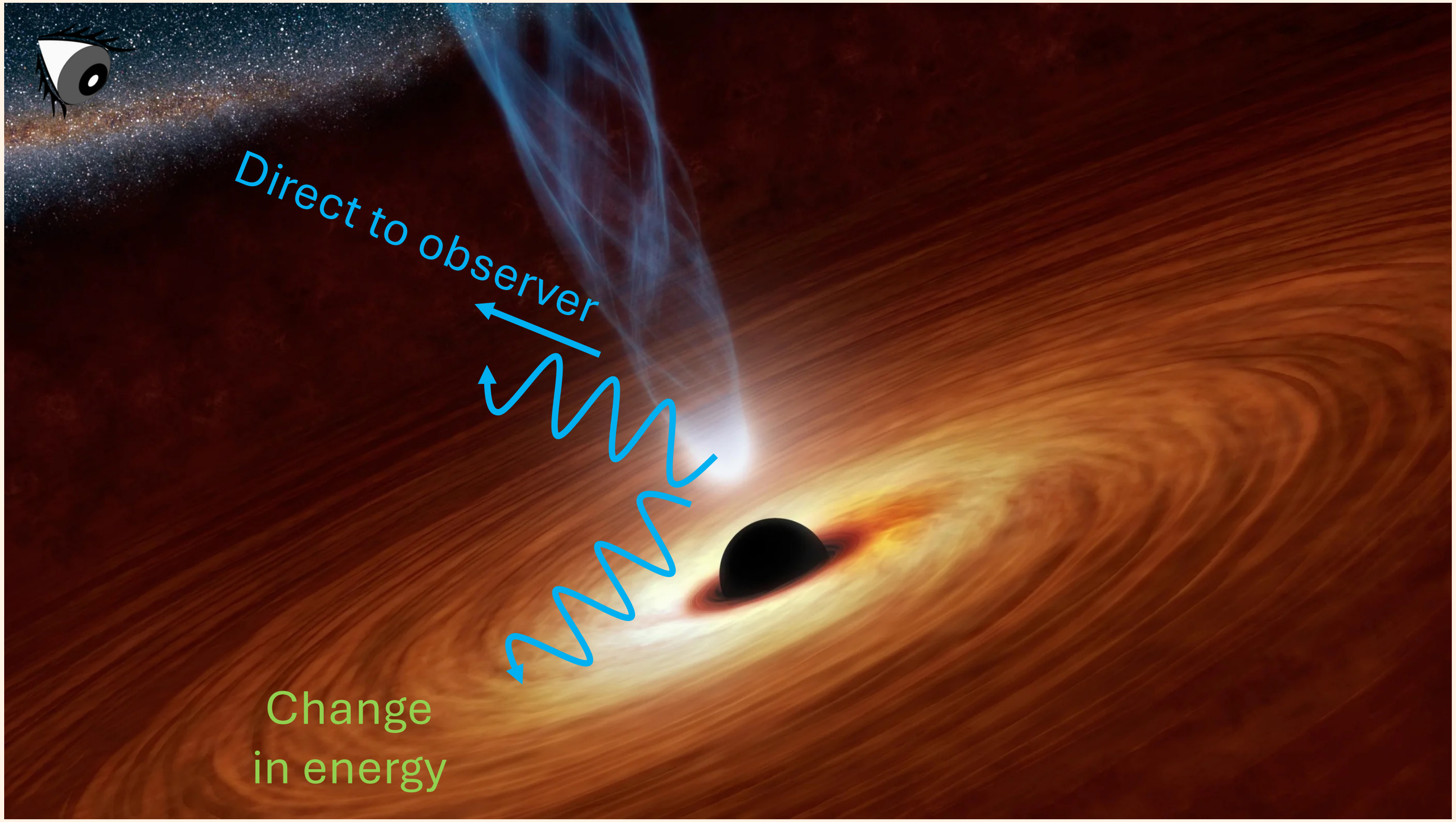
Time Lags



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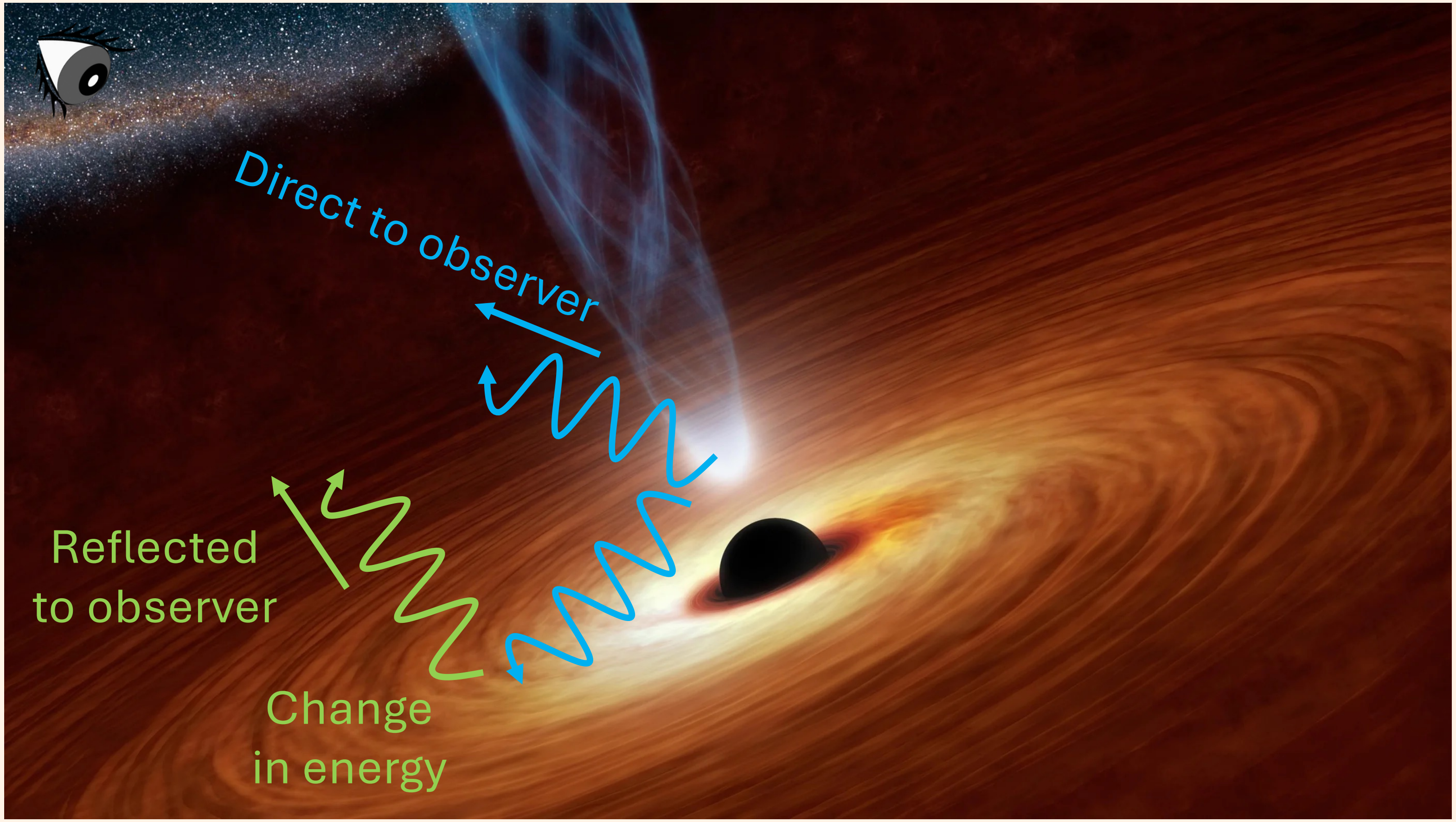
Time Lags



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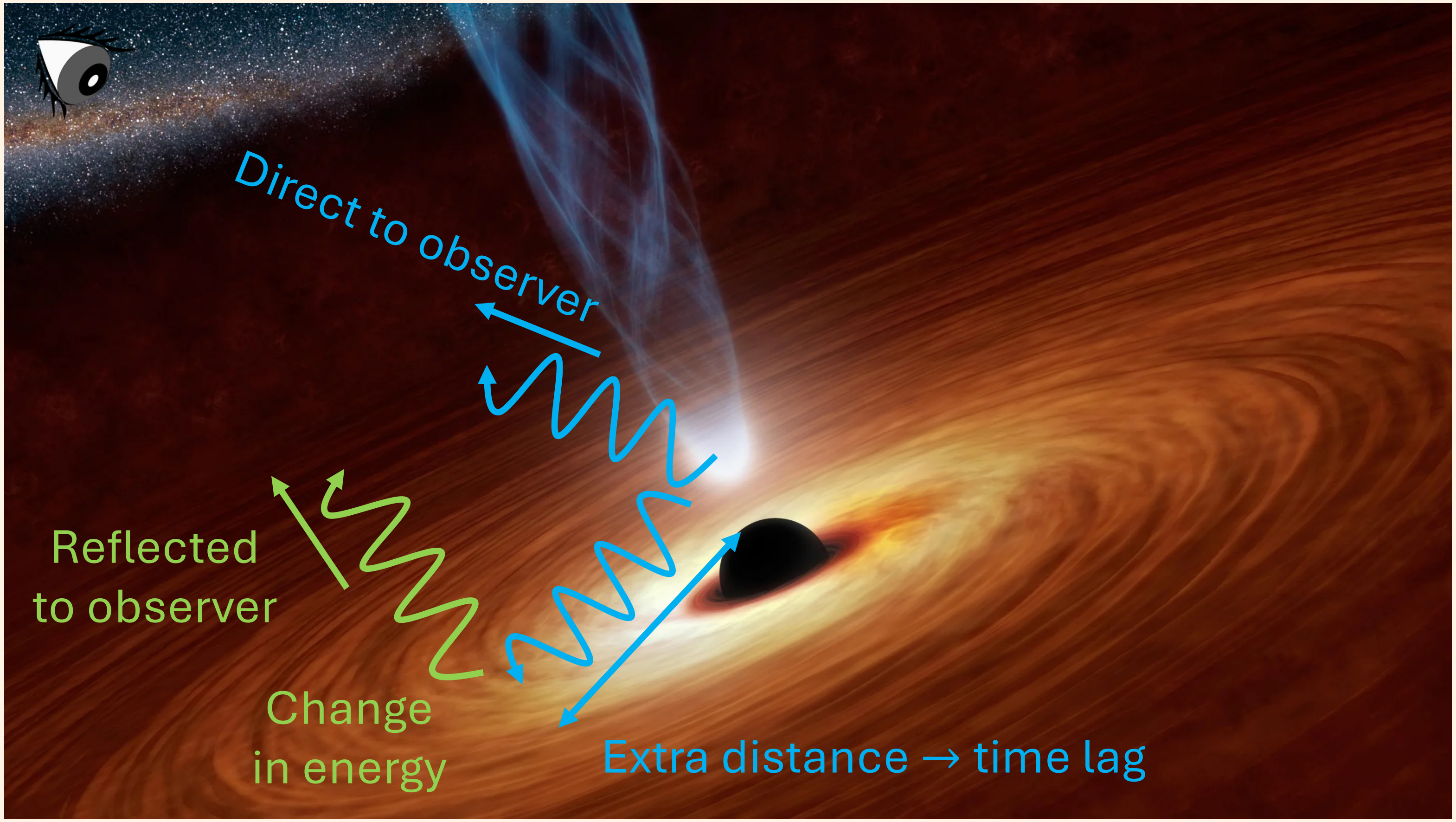
Time Lags



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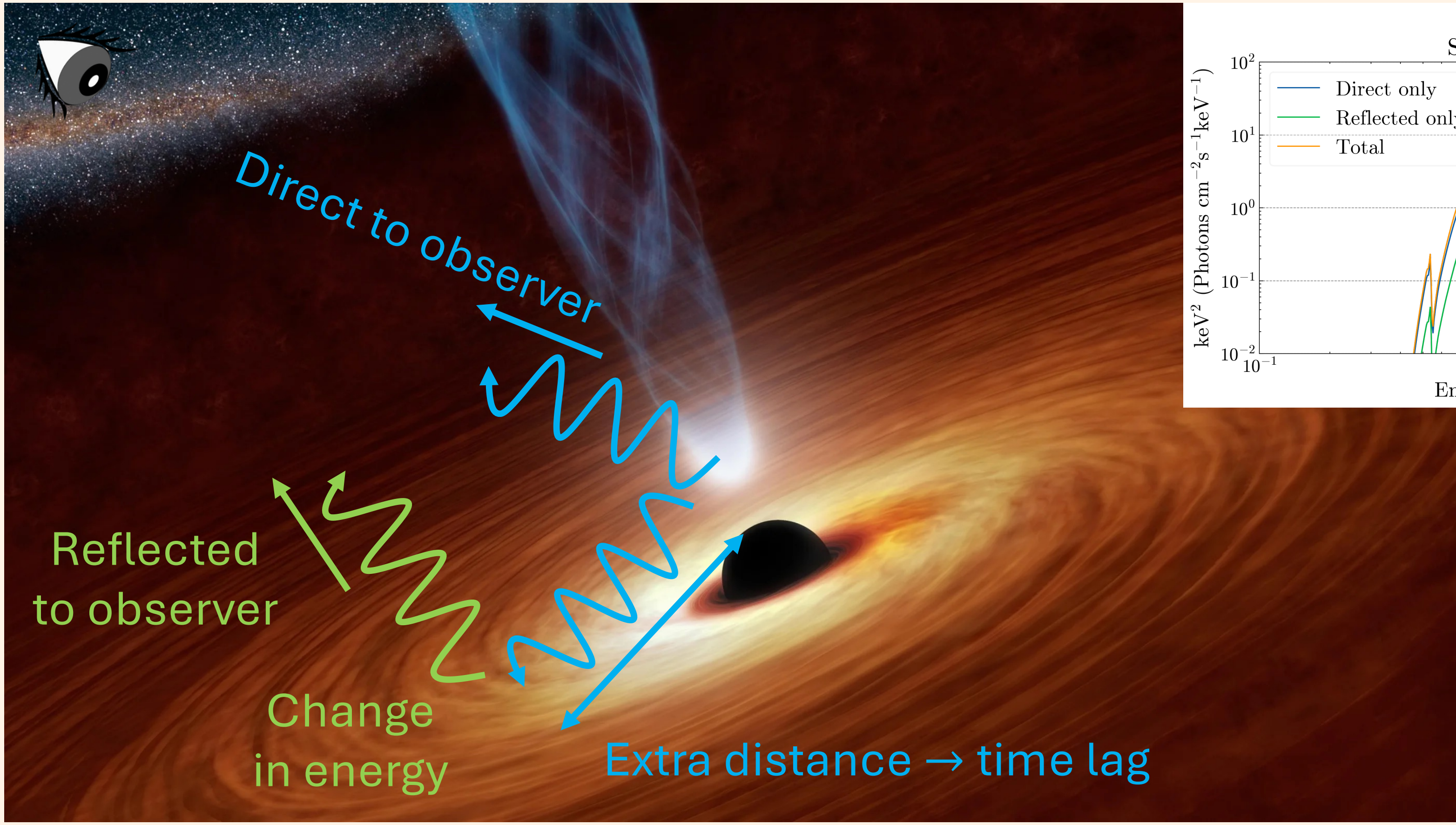

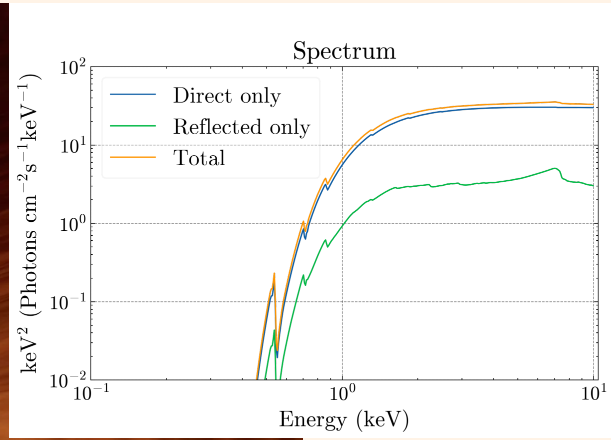

Image credit:
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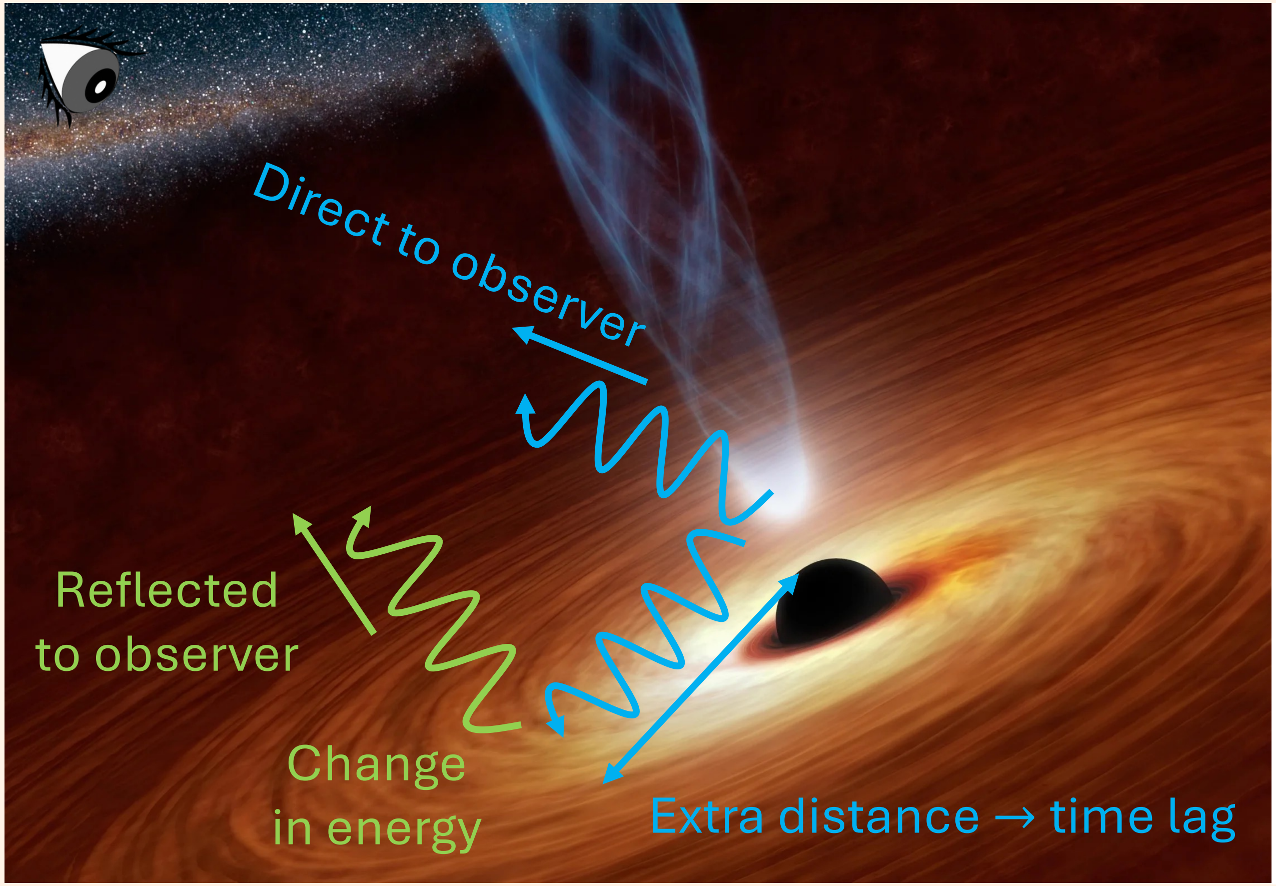

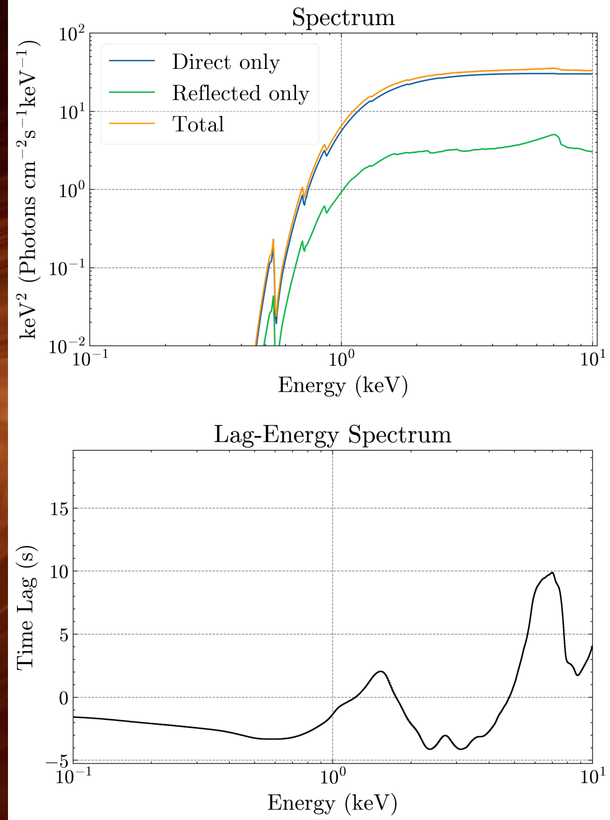

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NASA/JPL-Caltech

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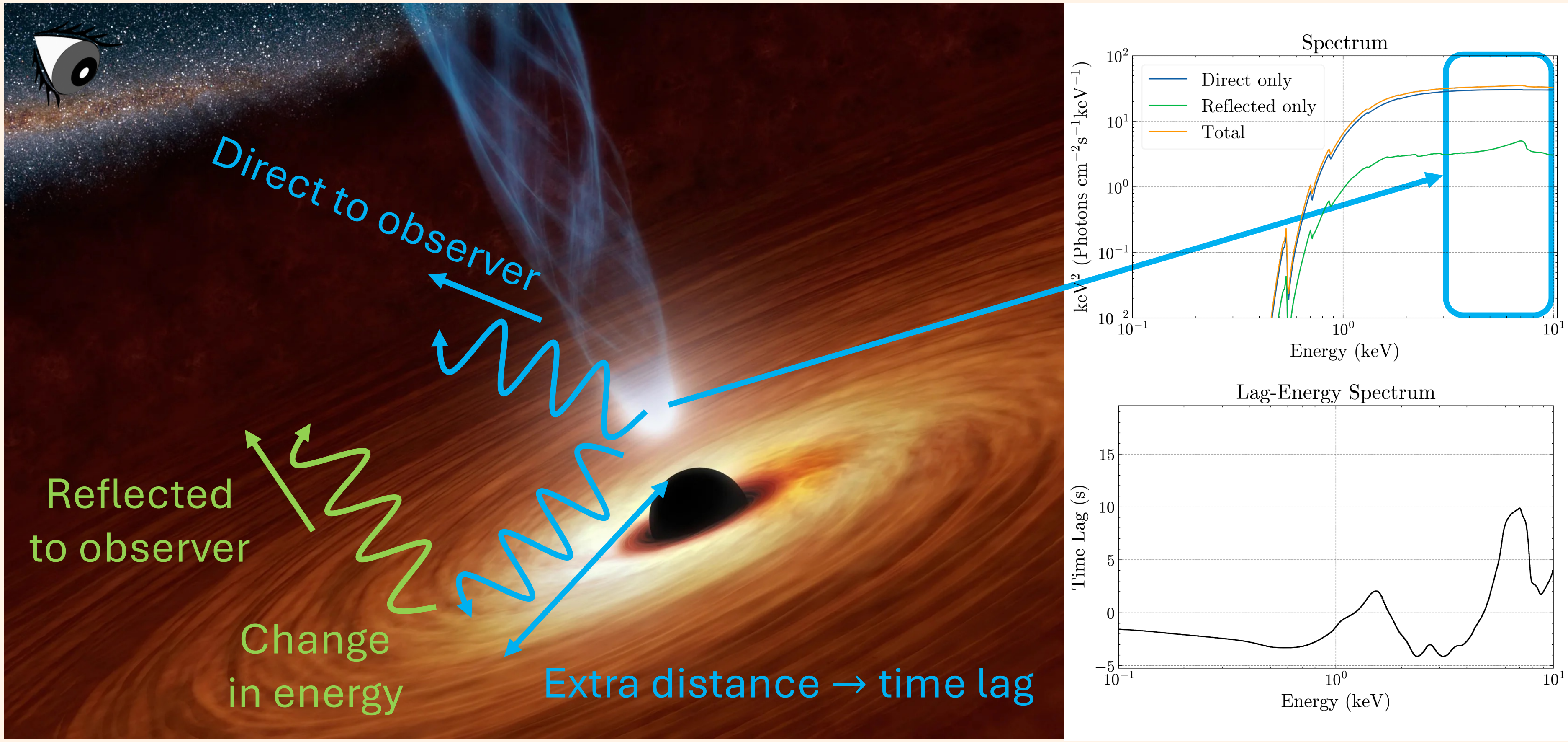

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Time Lags

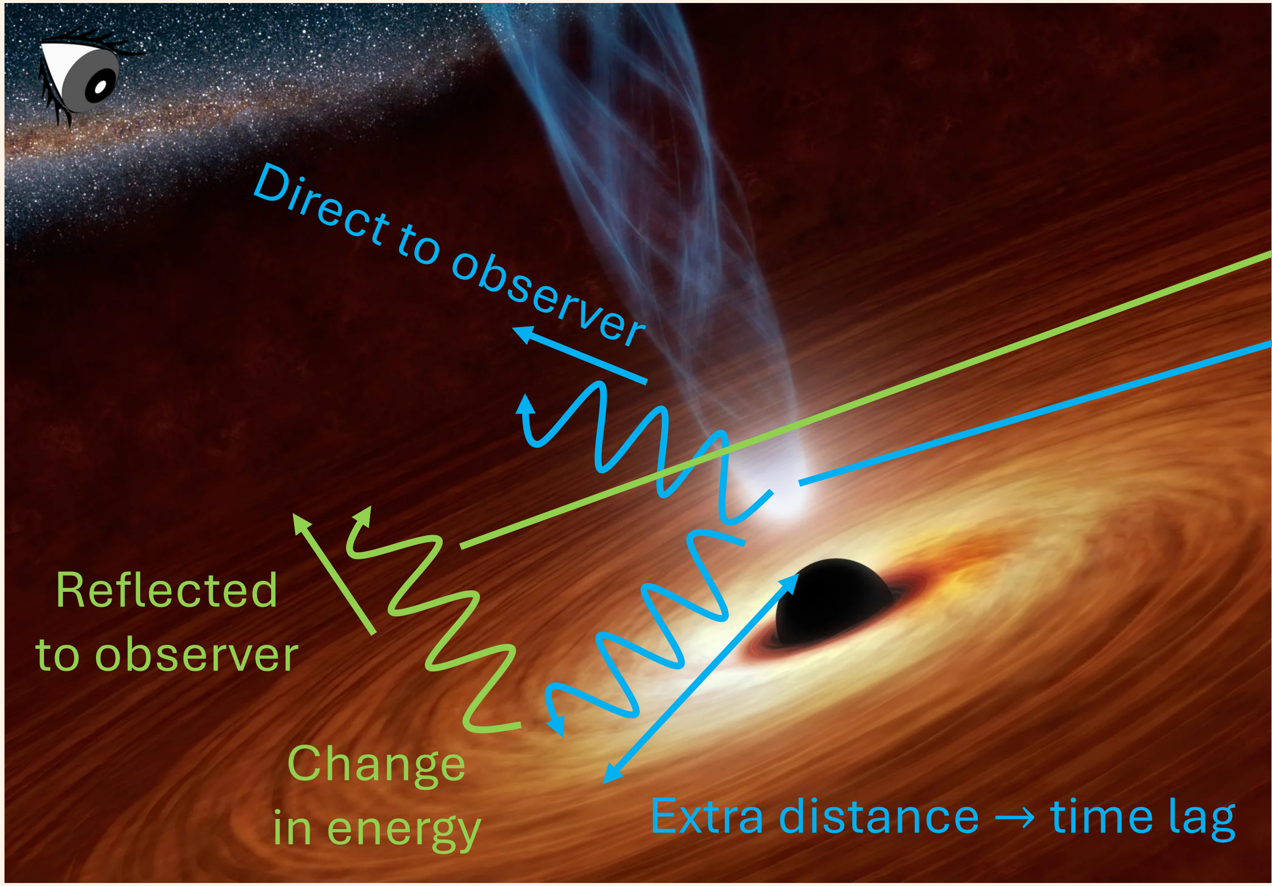

Image credit:
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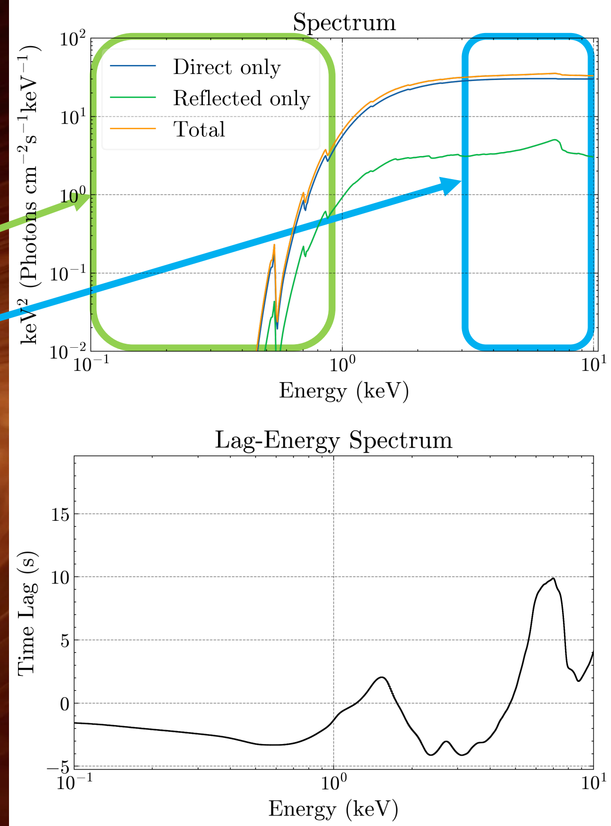
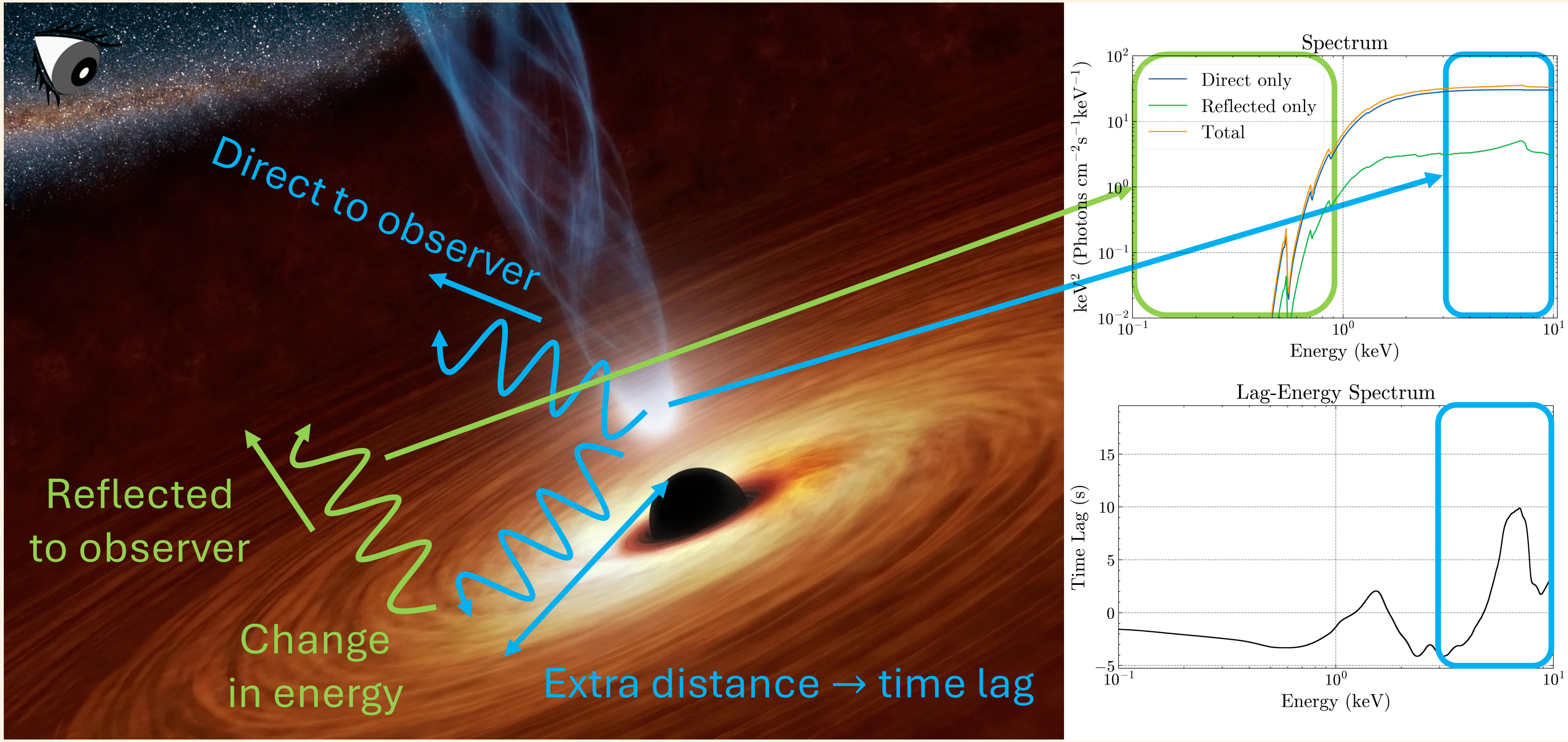


Time Lags



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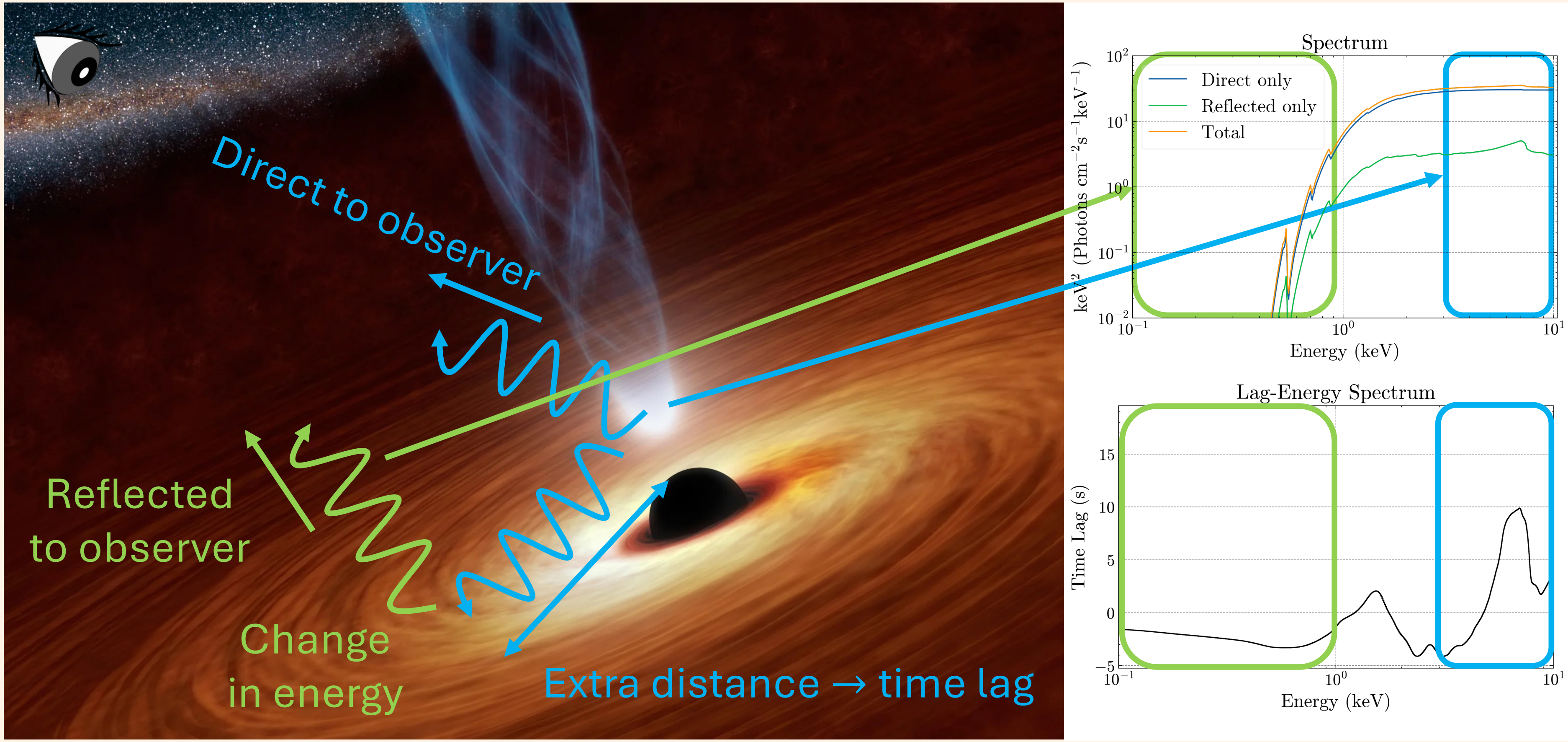
Time Lags



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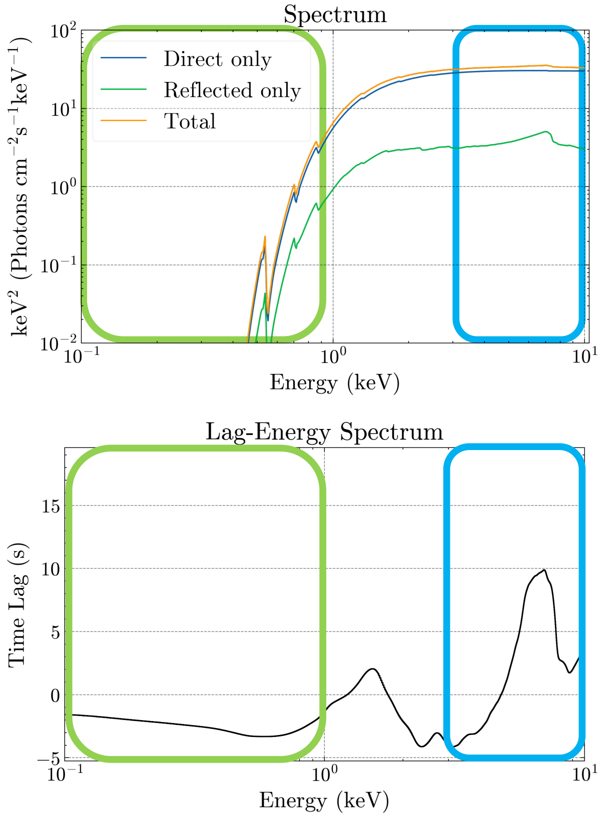


+ reltrans

(Relativistic transfer model)

Time Lags

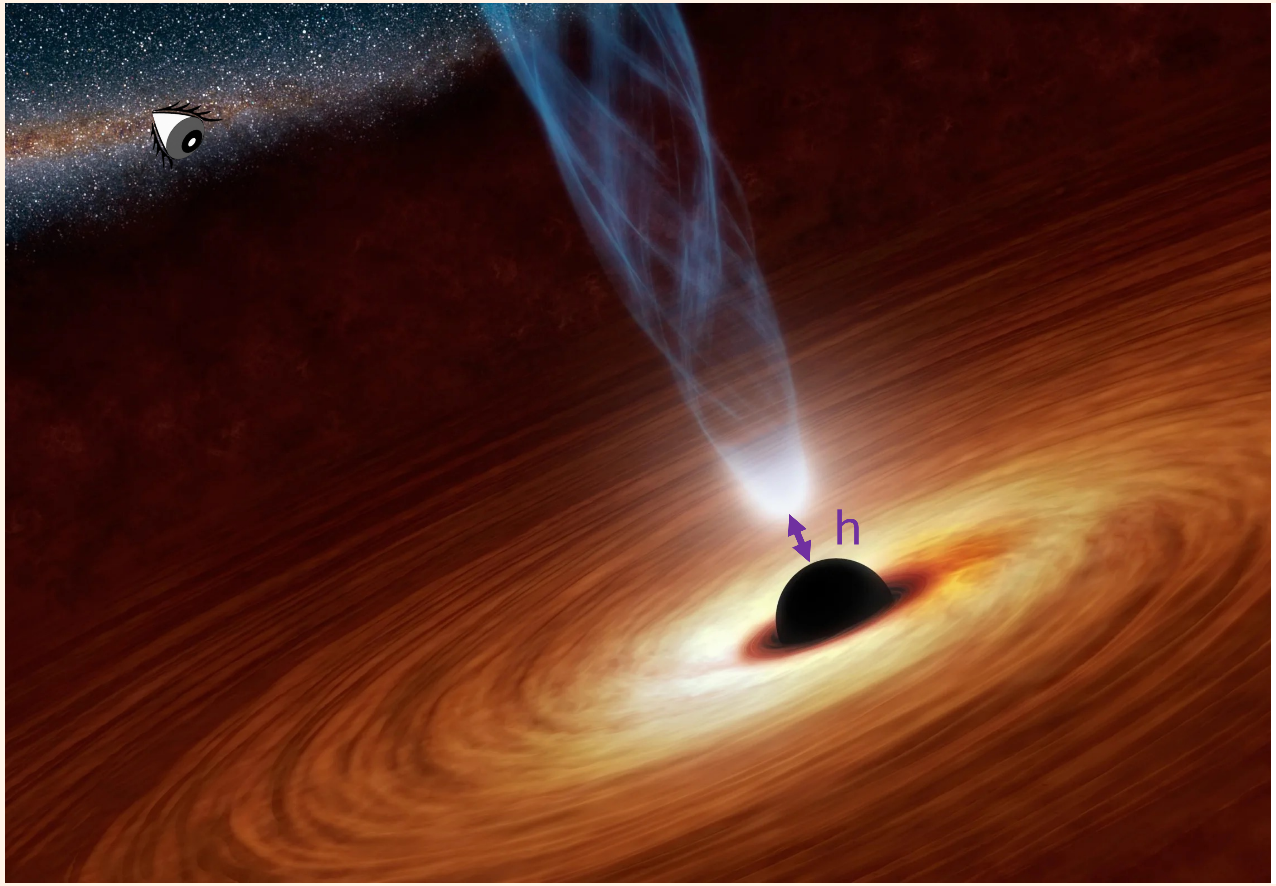
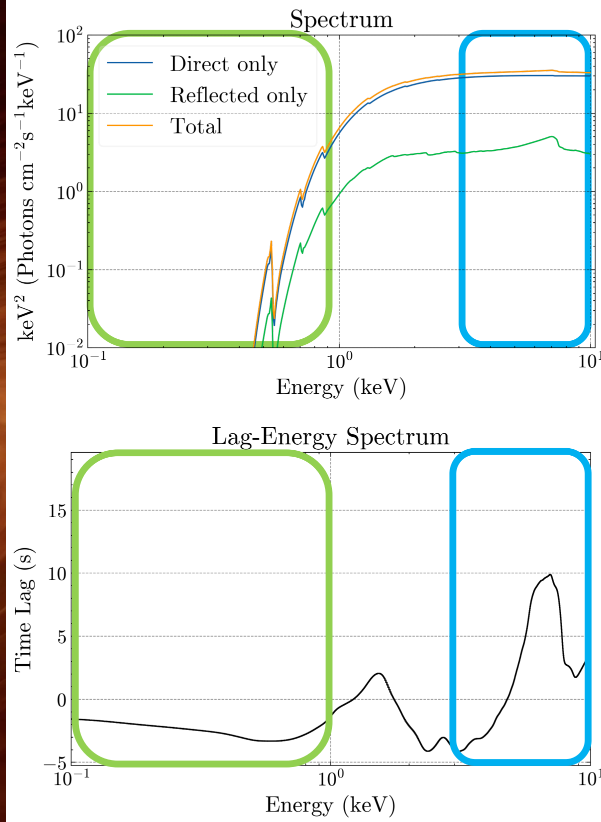


Image credit:
NASA/JPL-Caltech



+ reltrans = h,

(Relativistic transfer model)

Time Lags

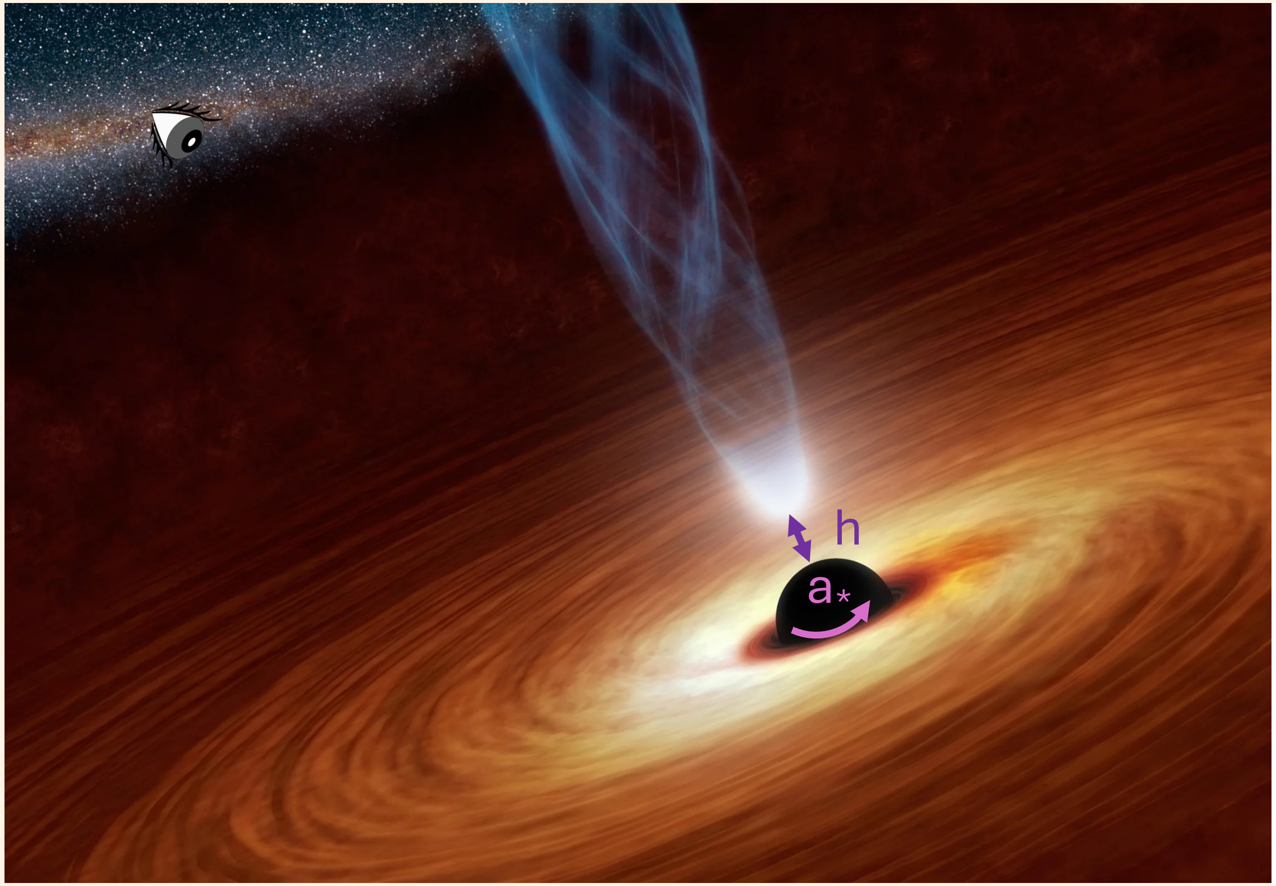
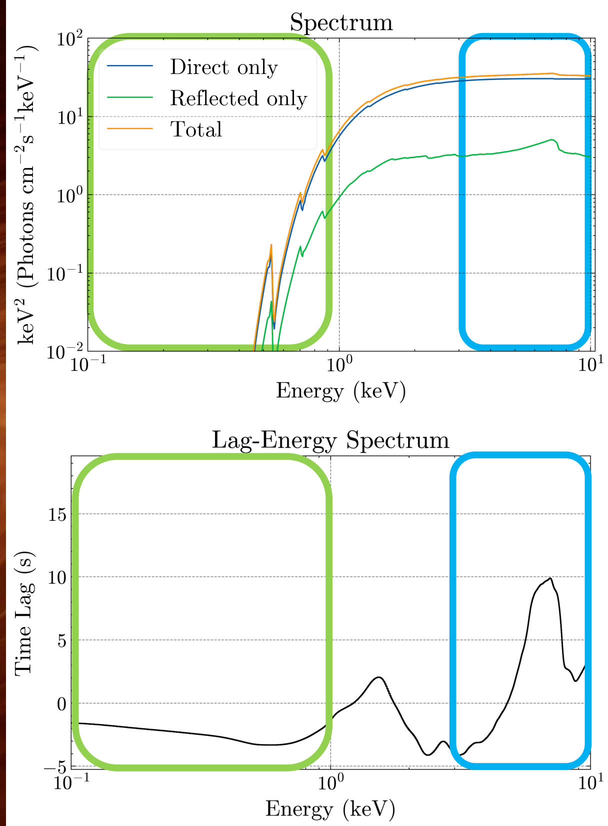


Image credit: NASA/JPL-Caltech



+ reltrans = h, a*,

(Relativistic transfer model)

Time Lags

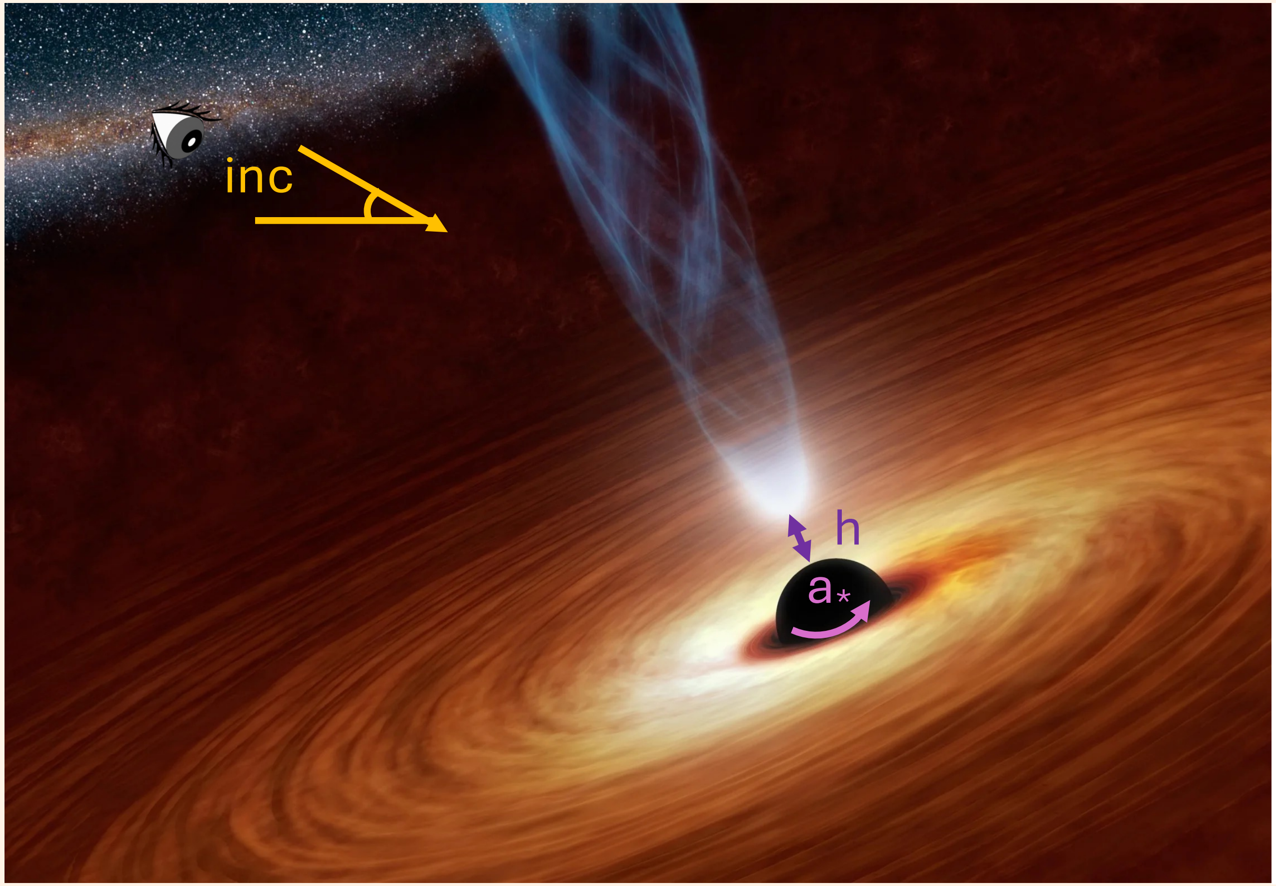
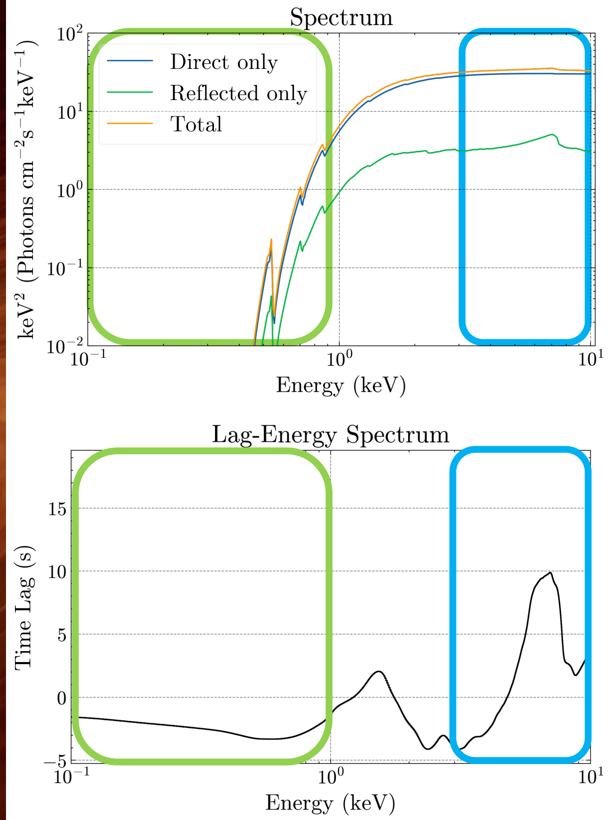


Image credit: NASA/JPL-Caltech



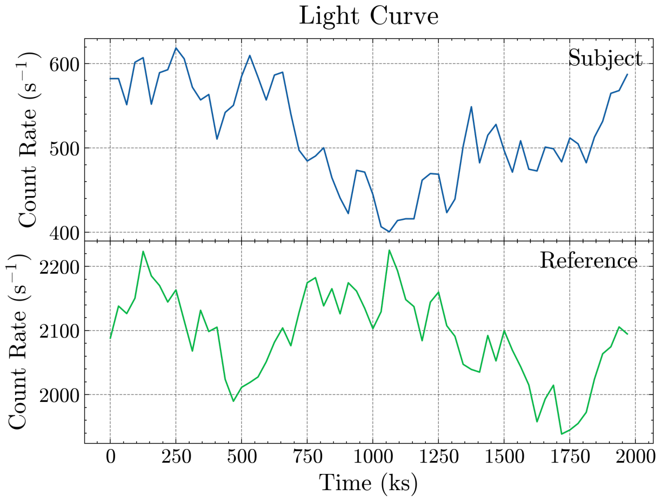
+ reltrans = h, a*, inc, ...

(Relativistic transfer model)

Time Lags

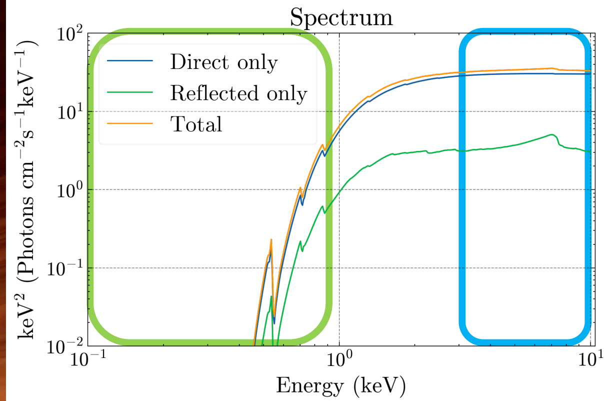
Problem!
Intrinsic white noise reduces coherence between energy bands

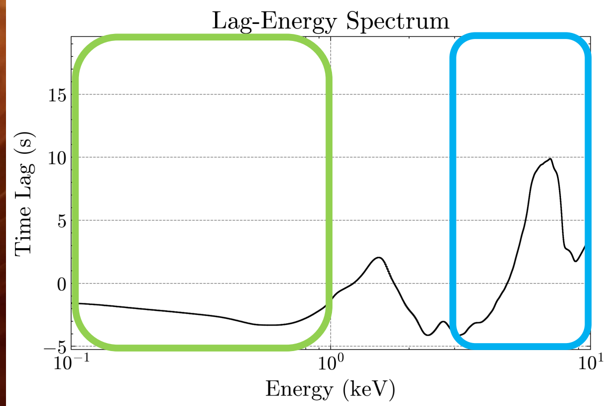
→ Lag – energy have high errors



(Low coherence)

Image credit:
NASA/JPL-Caltech





+ reltrans = h, a_*, inc, ...

(Relativistic transfer model)

Time Lags

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Intrinsic white noise reduces coherence between energy bands

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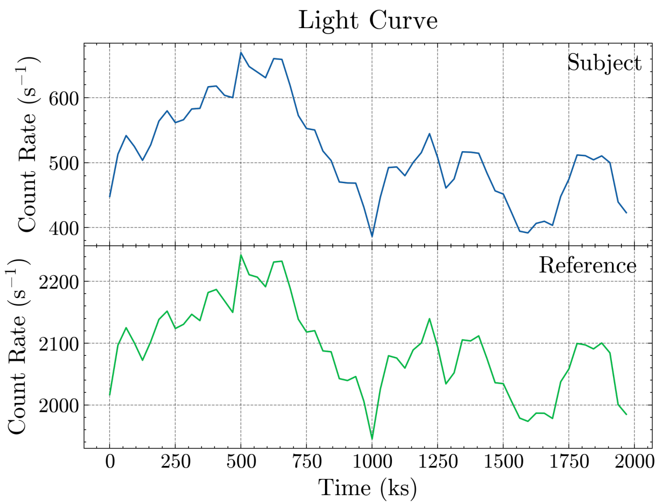
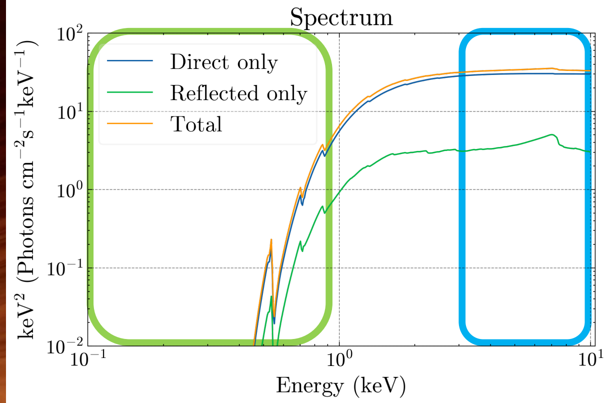
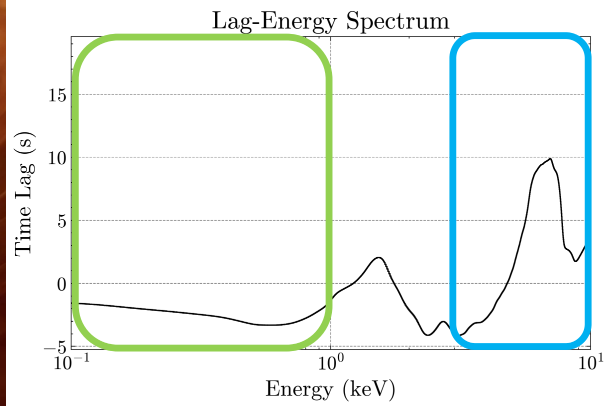


(High coherence)

Image credit:
NASA/JPL-Caltech





+ reltrans = h, a_*, inc, ...

(Relativistic transfer model)

Time Lags

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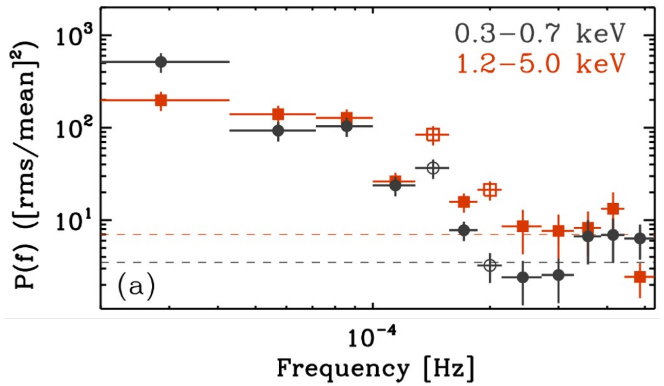
Intrinsic white noise reduces coherence between energy bands

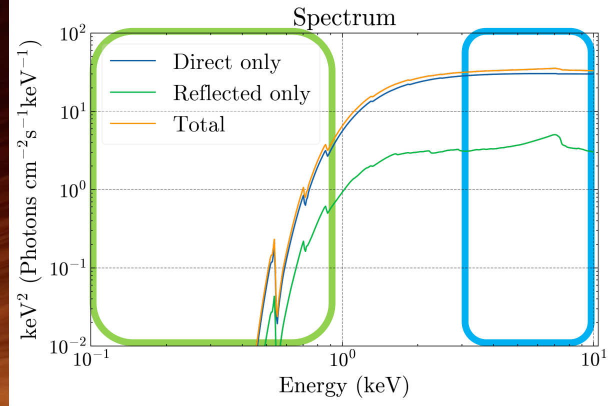
→ Lag – energy have high errors

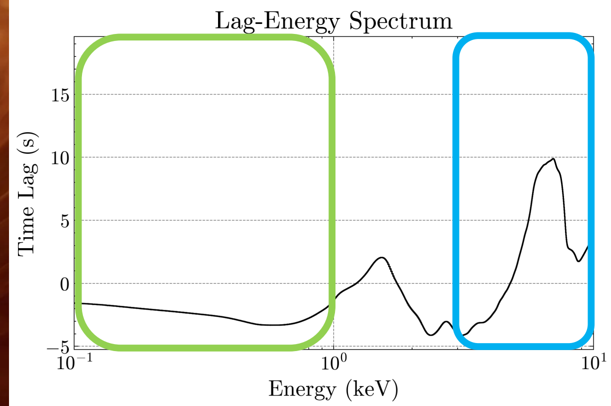
Proposed solution: high-freq QPOs



Alston et al. 2015

Image credit:
NASA/JPL-Caltech





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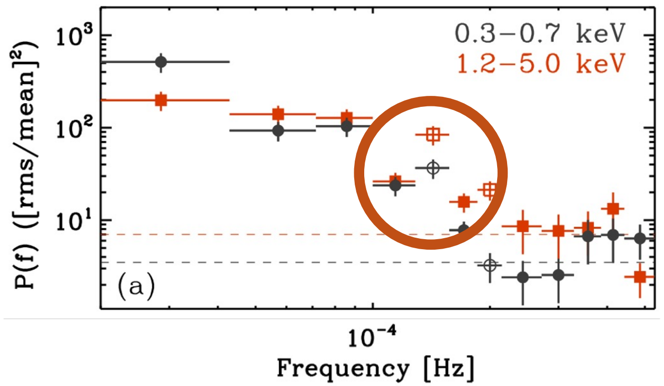

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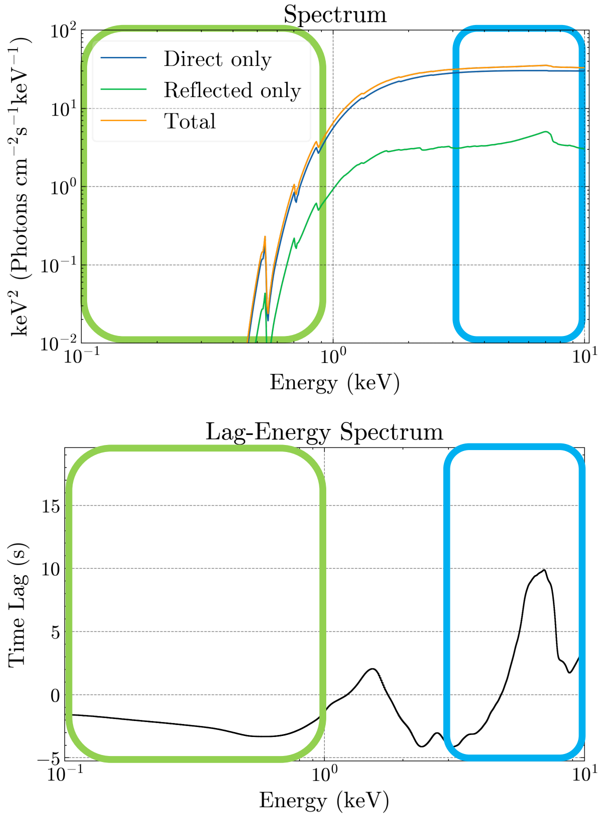

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(Relativistic transfer model)

Time Lags

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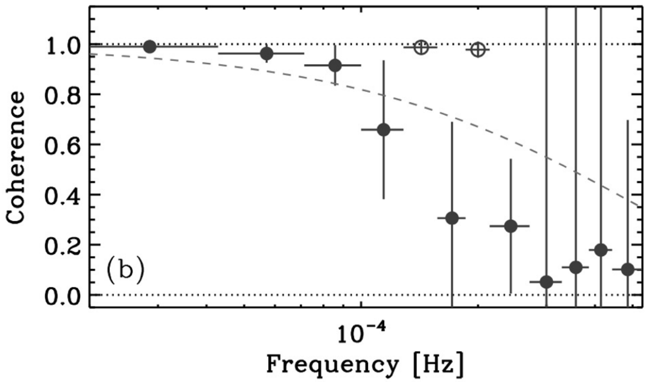

Alston et al. 2015

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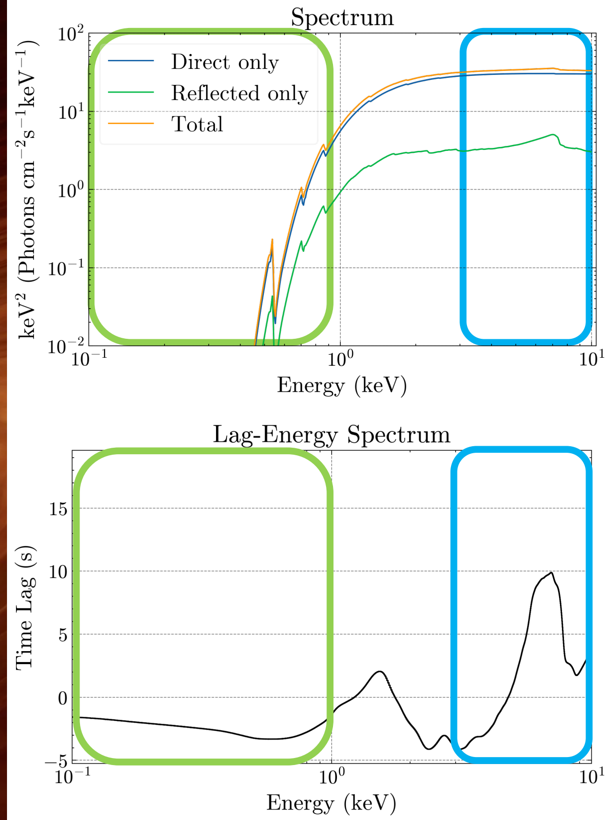
NASA/JPL-Caltech



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(Relativistic transfer model)

Time Lags

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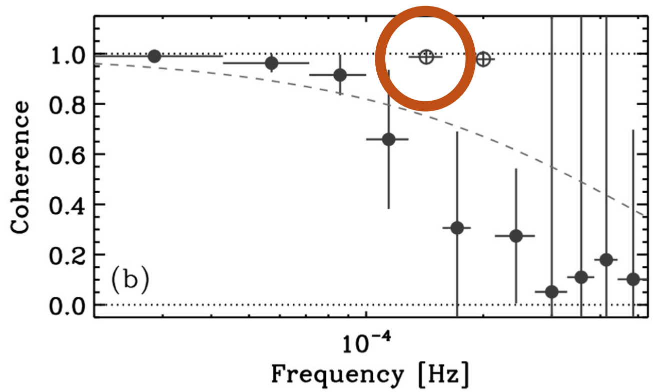

Alston et al. 2015

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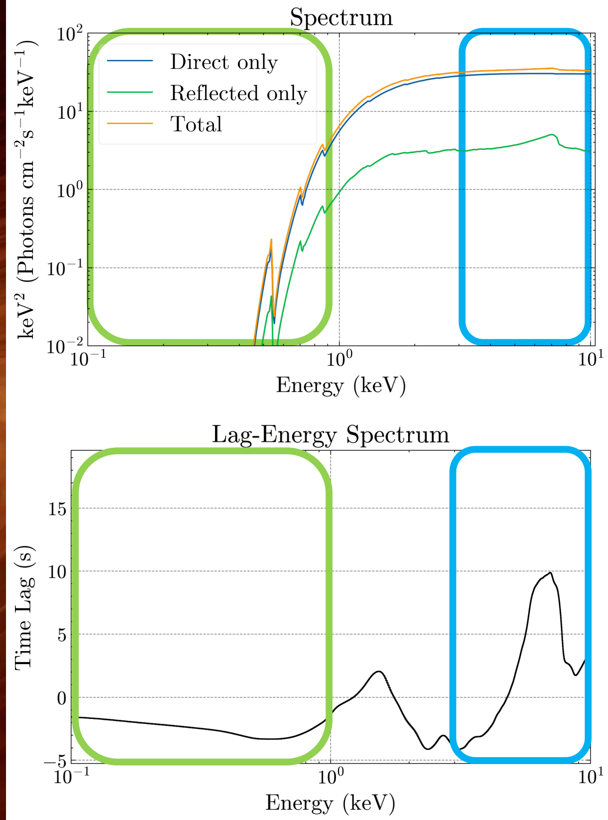

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(Relativistic transfer model)

Time Lags

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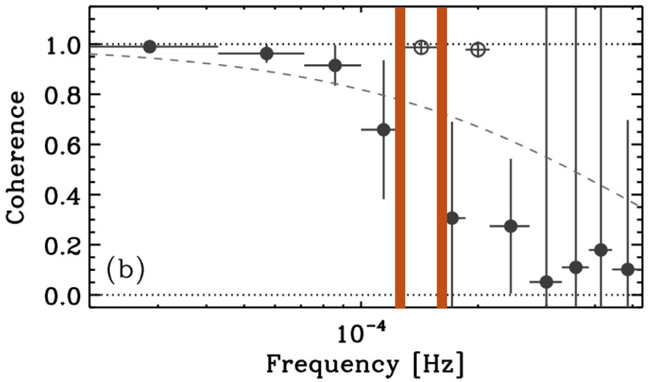
Proposed solution: high-freq QPOs



Alston et al. 2015

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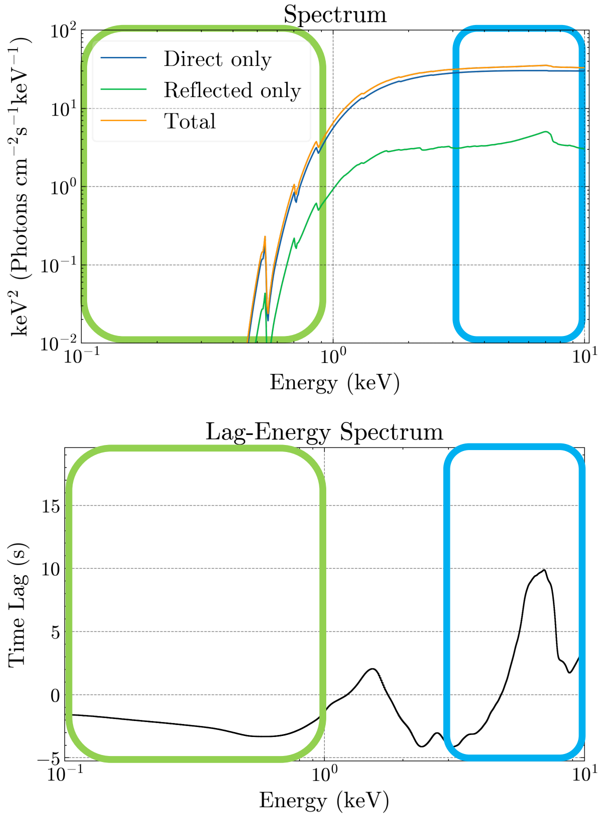


+ reltrans = h, a_*, inc, ...

(Relativistic transfer model)

Overview

Image credit:
NASA/JPL-Caltech

Overview

Decide Geometry for our example case

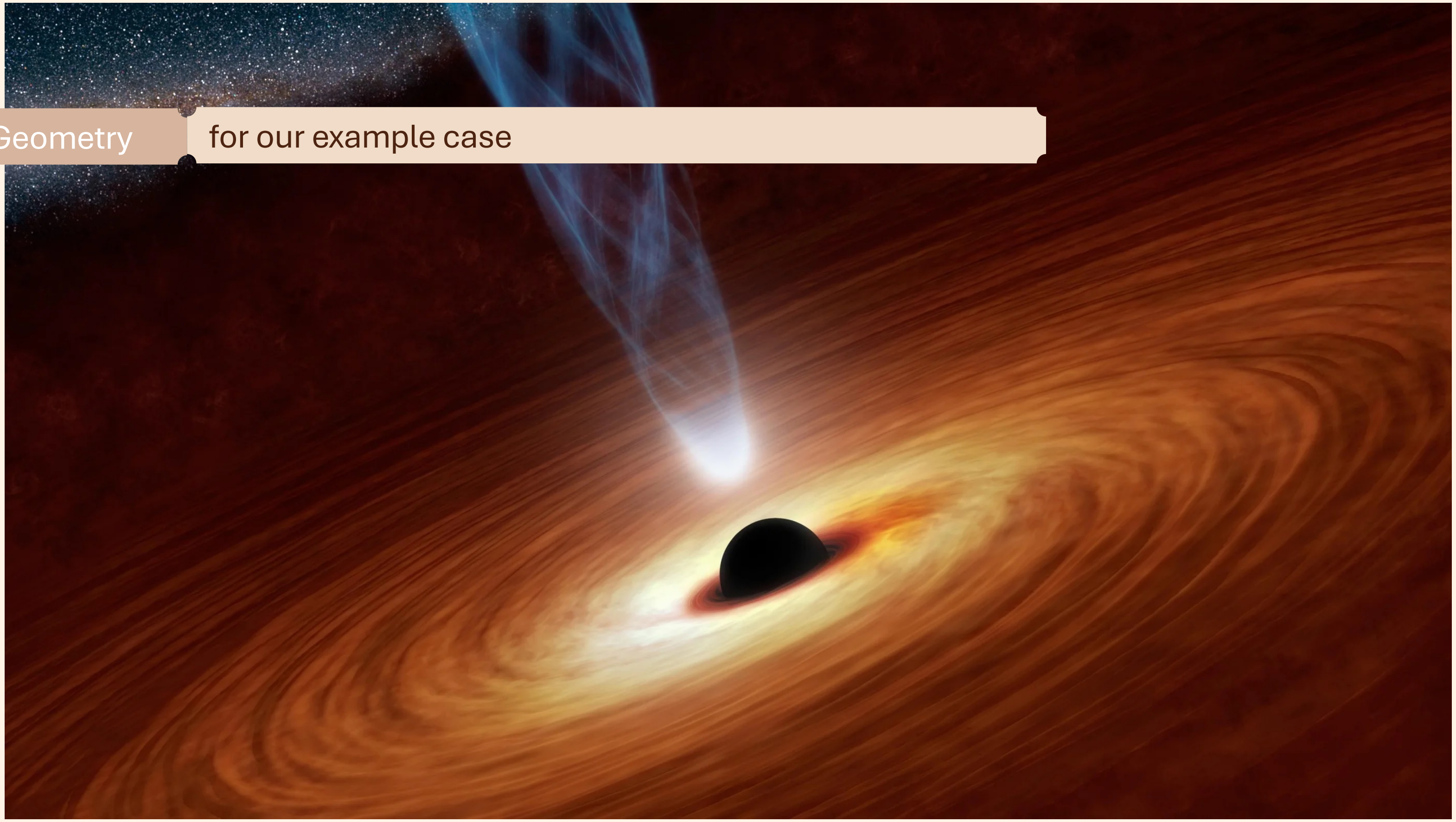
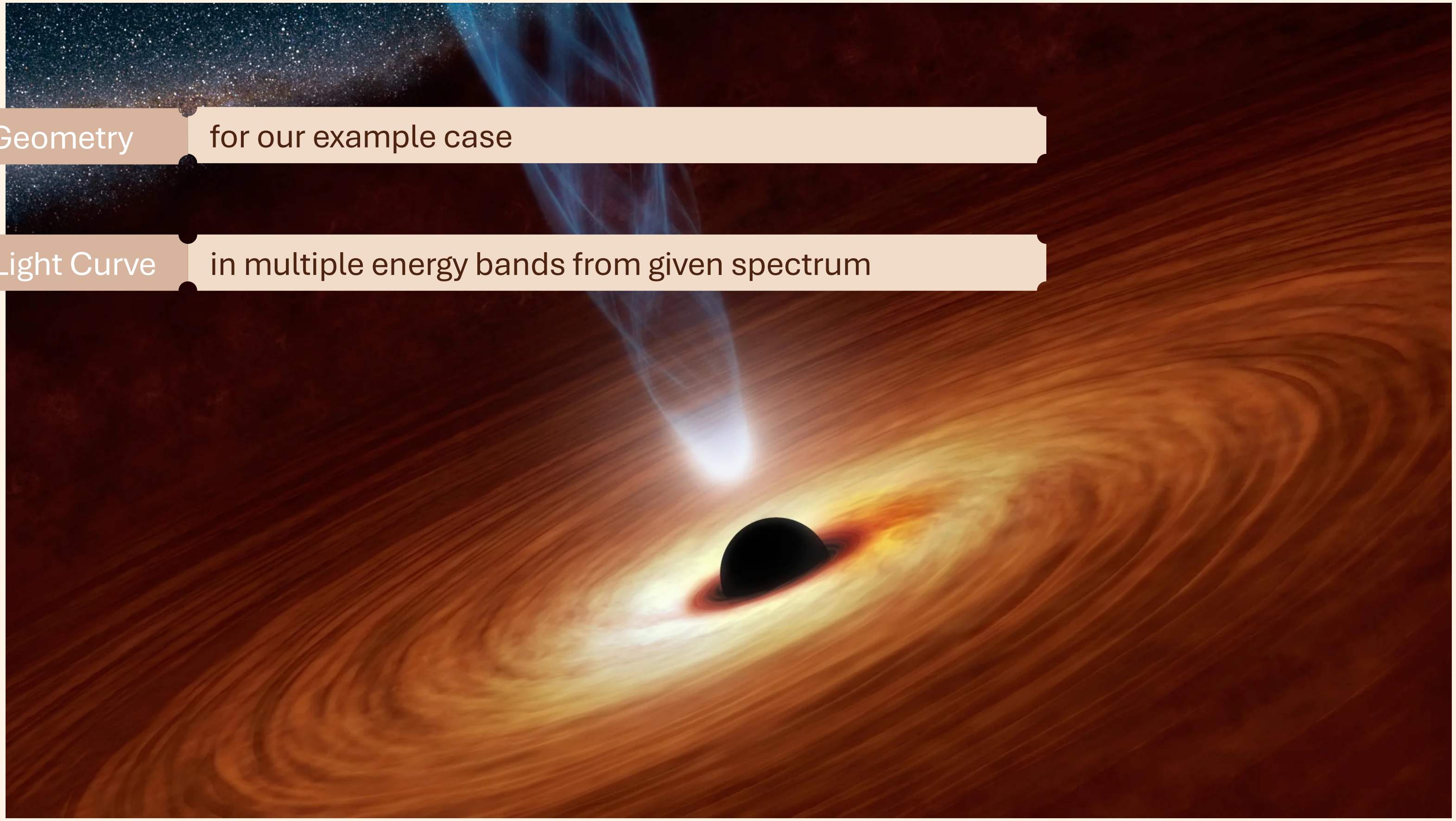


Image credit:
NASA/JPL-Caltech

Overview

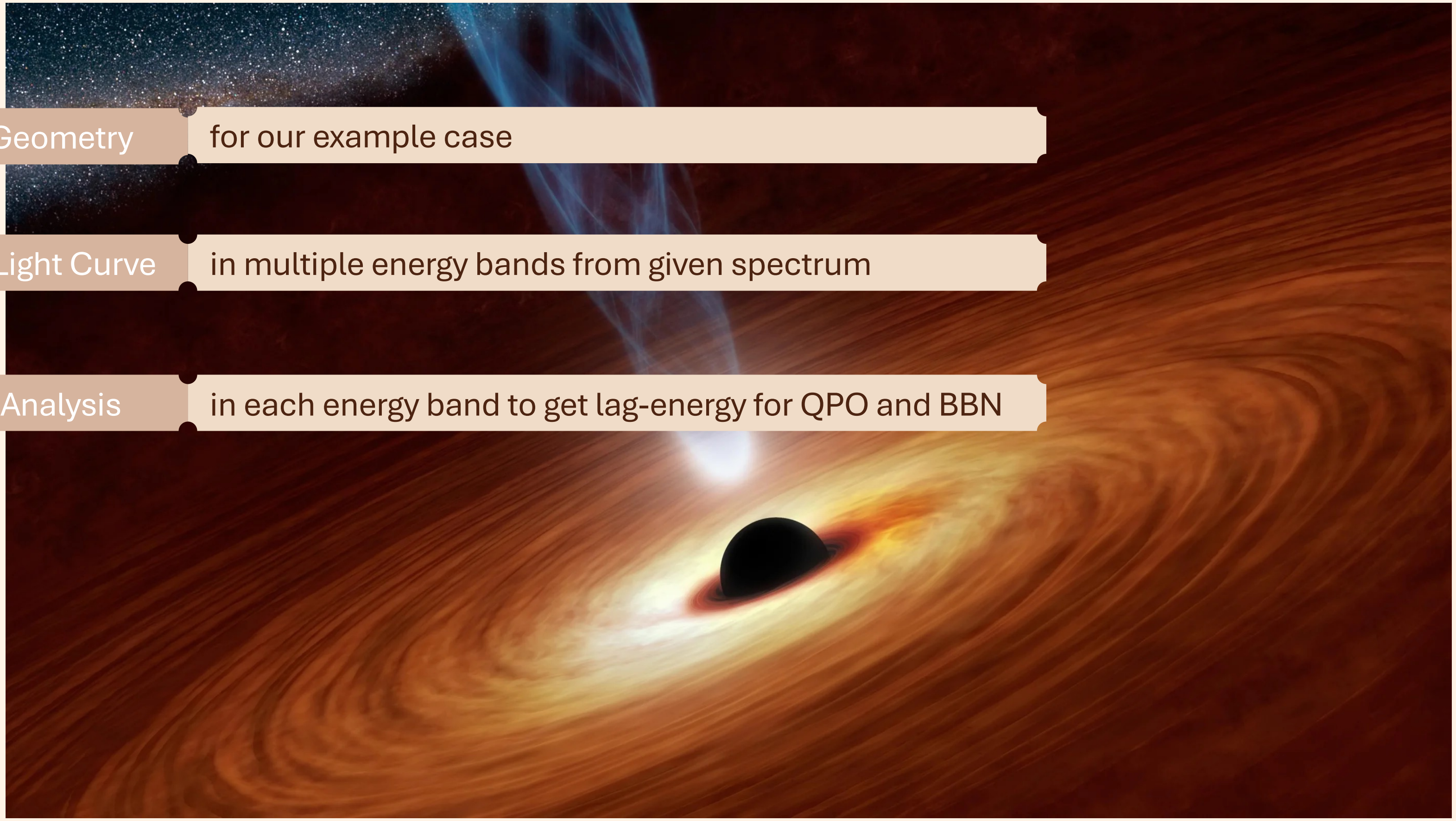


Decide Geometry — for our example case

Simulate Light Curve — in multiple energy bands from given spectrum

Image credit: NASA/JPL-Caltech

Overview



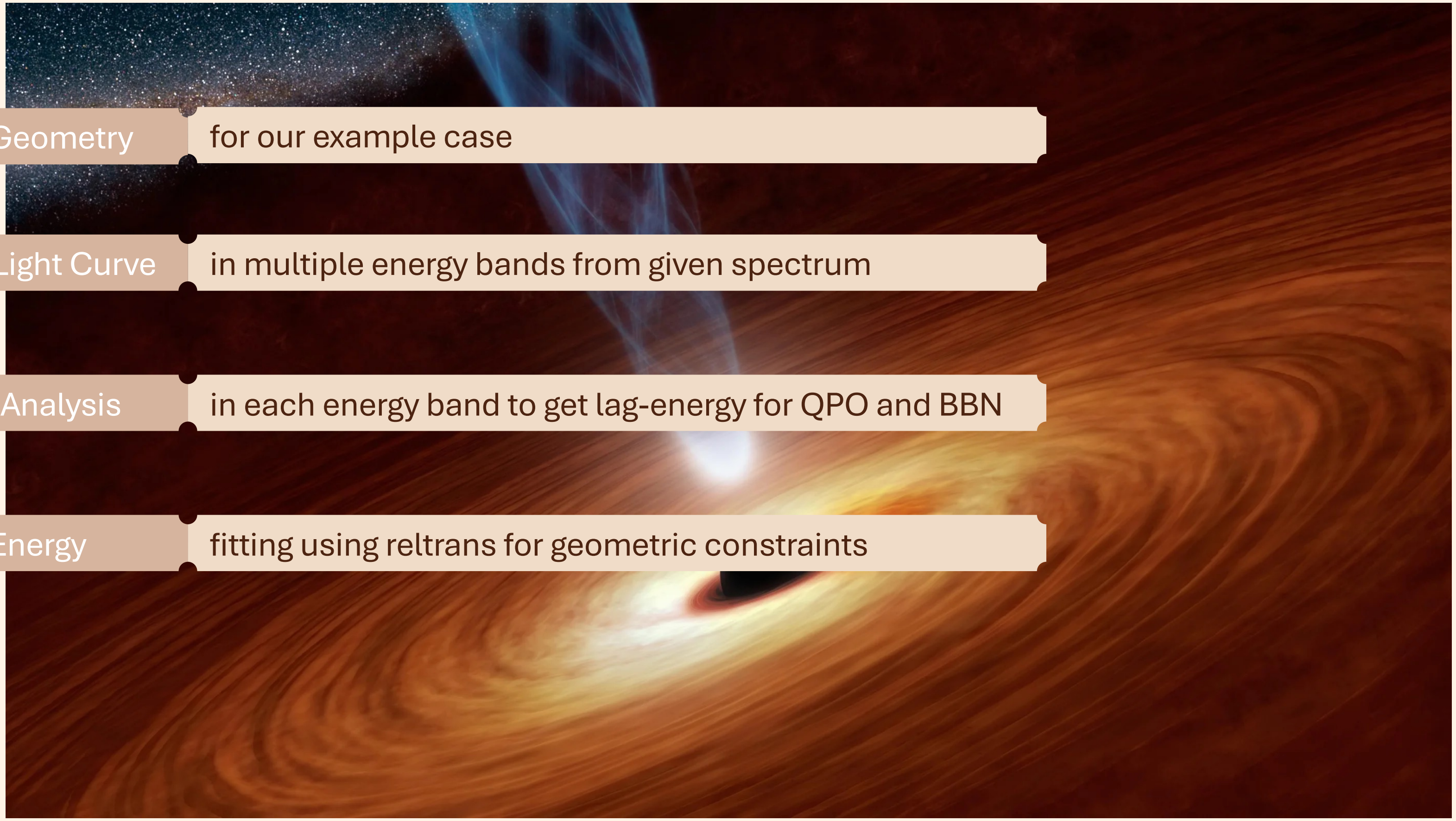
Decide Geometry — for our example case

Simulate Light Curve — in multiple energy bands from given spectrum

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

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
- **Lag-Energy** fitting using reltrans for geometric constraints

Image credit: NASA/JPL-Caltech

Overview

Image credit: NASA/JPL-Caltech

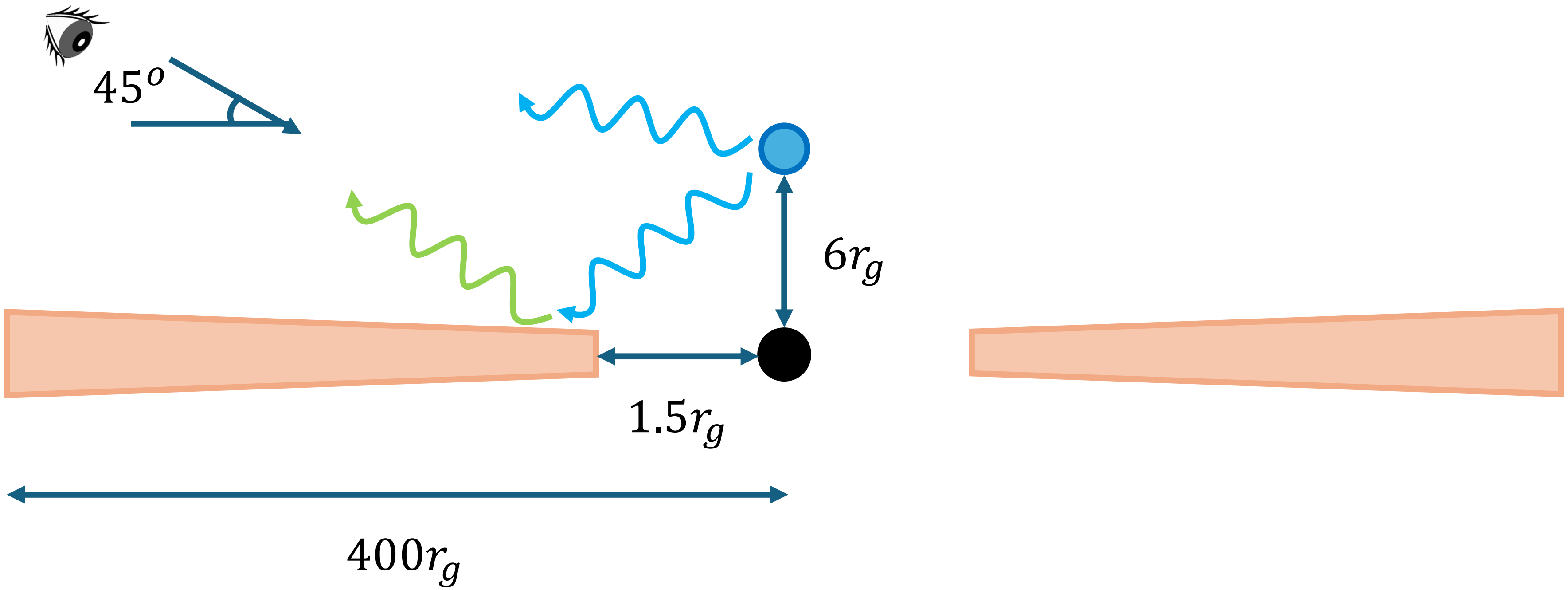
Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

Decide Geometry



Decide Geometry

Simulate Light Curve

Fourier Analysis

Lag-Energy

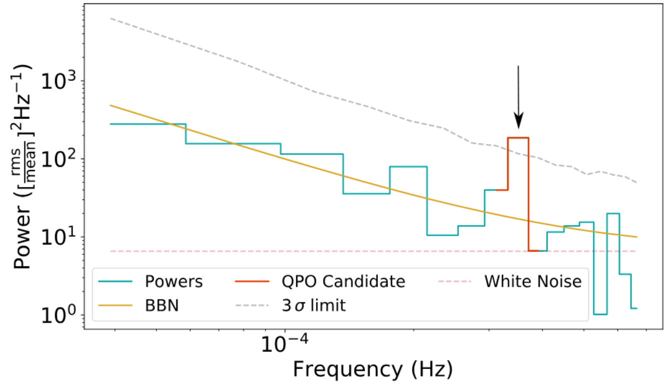
Simulate light curve

Ashton & Middleton 2020

Simulate light curve in each energy band

Require energy-dependent parameters:

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



Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve

Ashton & Middleton 2020

Simulate light curve in each energy band

Require energy-dependent parameters:

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β- values	Slope of red noise in Fourier space
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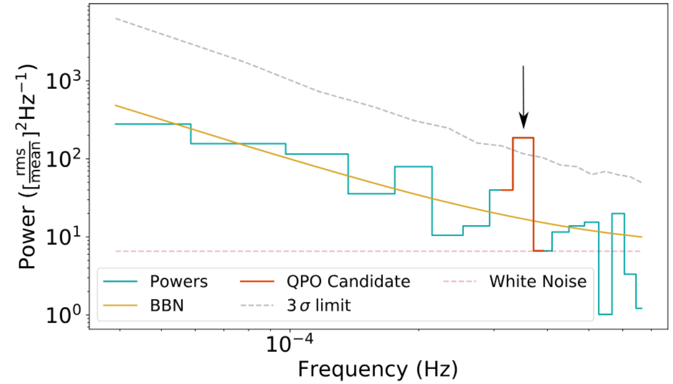
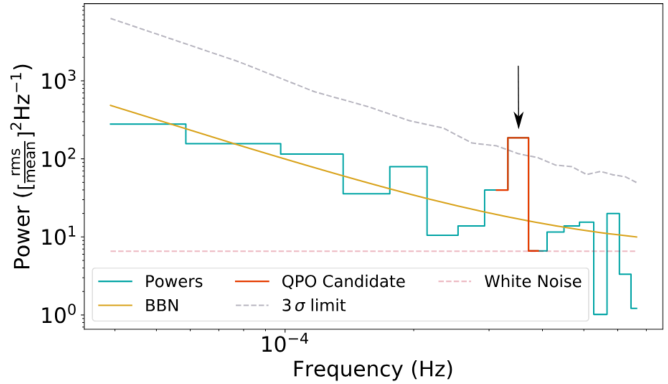
Ashton & Middleton 2022



Simulate light curve

Ashton & Middleton 2020



Simulate light curve in each energy band

Require energy-dependent parameters:

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

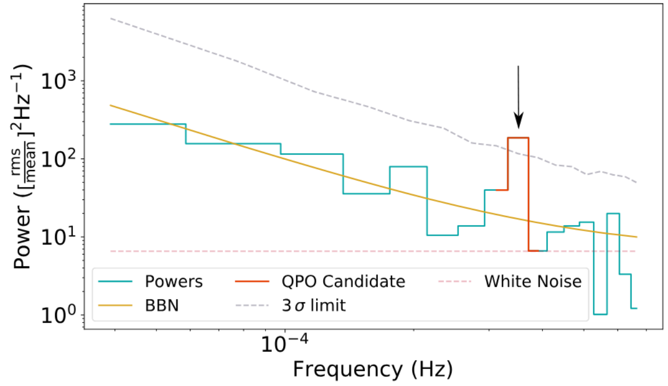
Ashton & Middleton 2022

Require total spectrum

Decide Geometry | **Simulate Light Curve** | Fourier Analysis | Lag-Energy

Simulate light curve

Ashton & Middleton 2020



Simulate light curve in each energy band

Require energy-dependent parameters:

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

Ashton & Middleton 2022

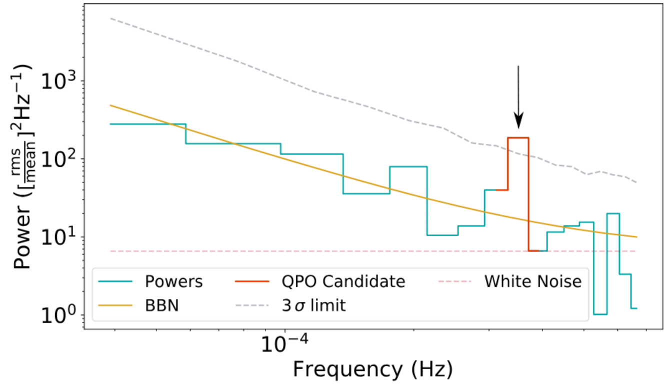
Require total spectrum

Require direct and reflected spectra

Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve

Ashton & Middleton 2020



Simulate light curve in each energy band

Require energy-dependent parameters:

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

Ashton & Middleton 2022

Require total spectrum → TBabs(relxilllp)

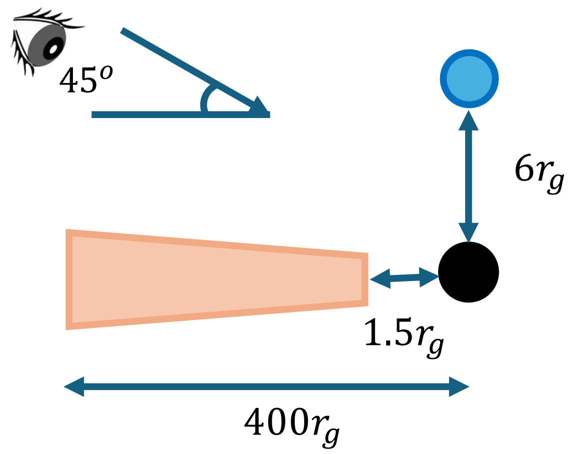
Require direct and reflected spectra → TBabs(relxilllp)

Simulate light curve

Simulate light curve in each energy band

Require energy-dependent parameters:

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



Ashton & Middleton 2022

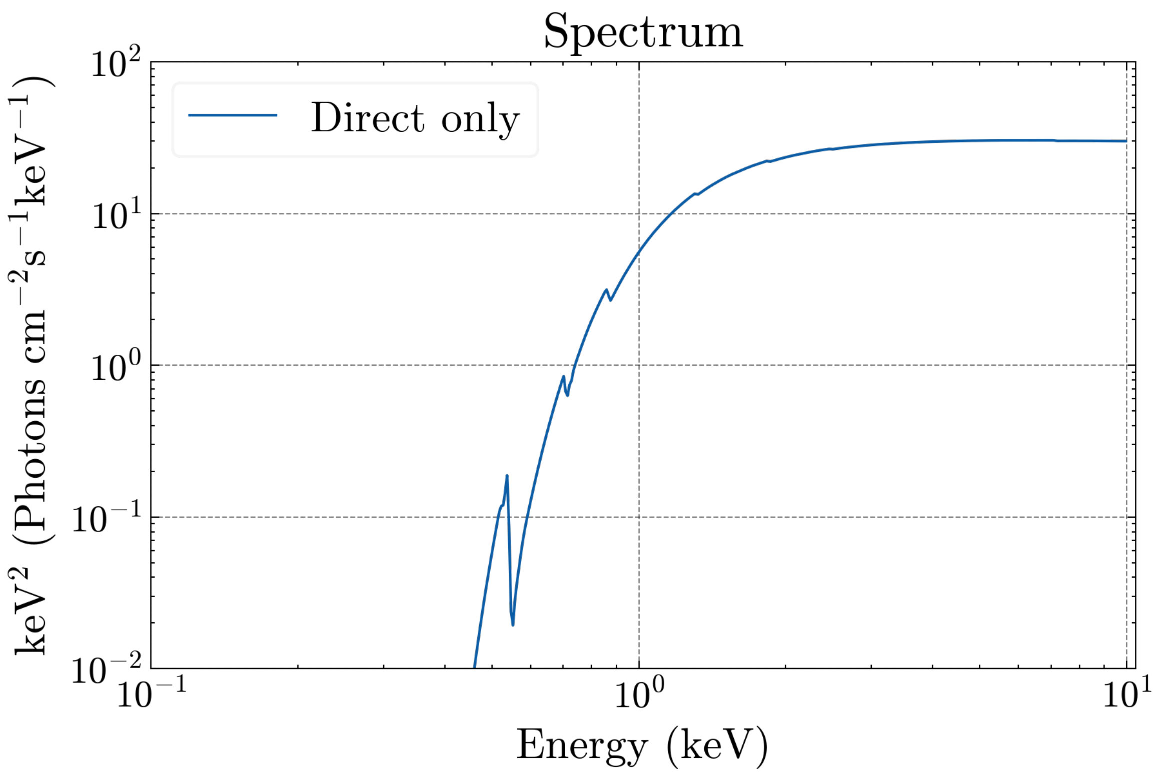
Require total spectrum → TBabs(relxilllp)

Require direct and reflected spectra → TBabs(relxilllp)

Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve: spectra

Direct: TBabs (relxilllp) refl_frac = 0

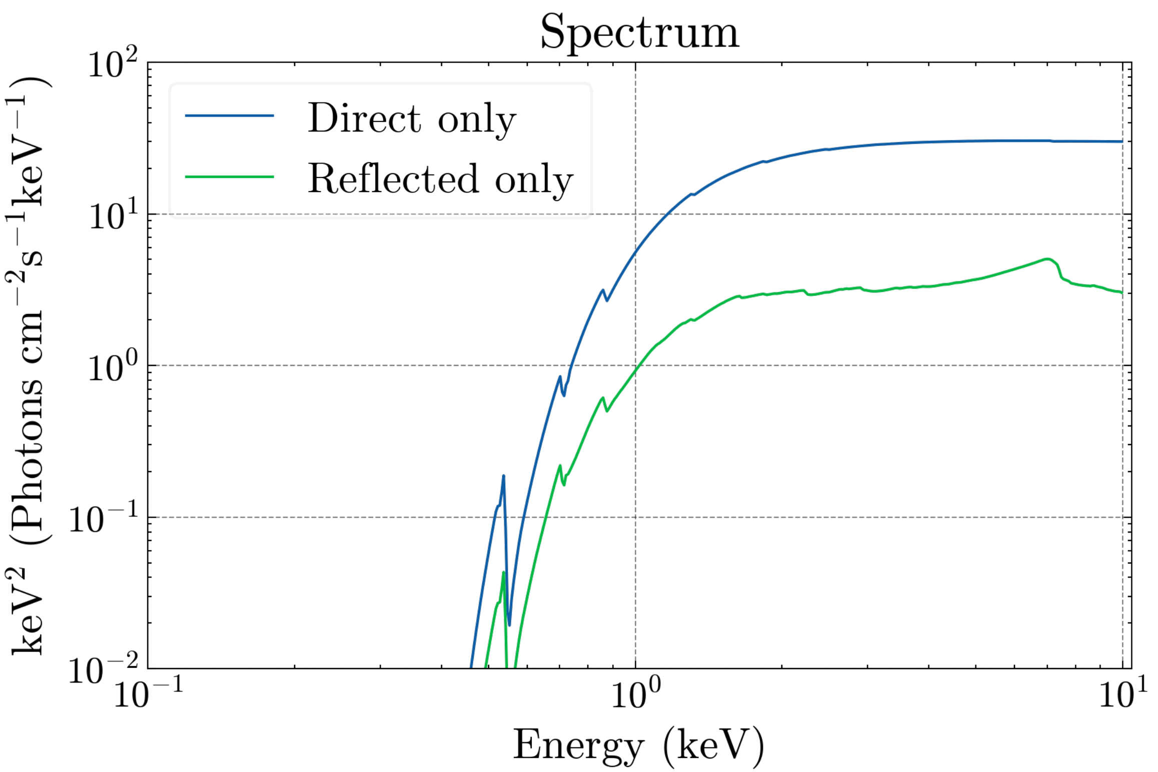


Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve: spectra

Direct: TBabs (relxilllp) refl_frac = 0

Reflected: Tbabs (relxilllp) refl_frac = -0.25



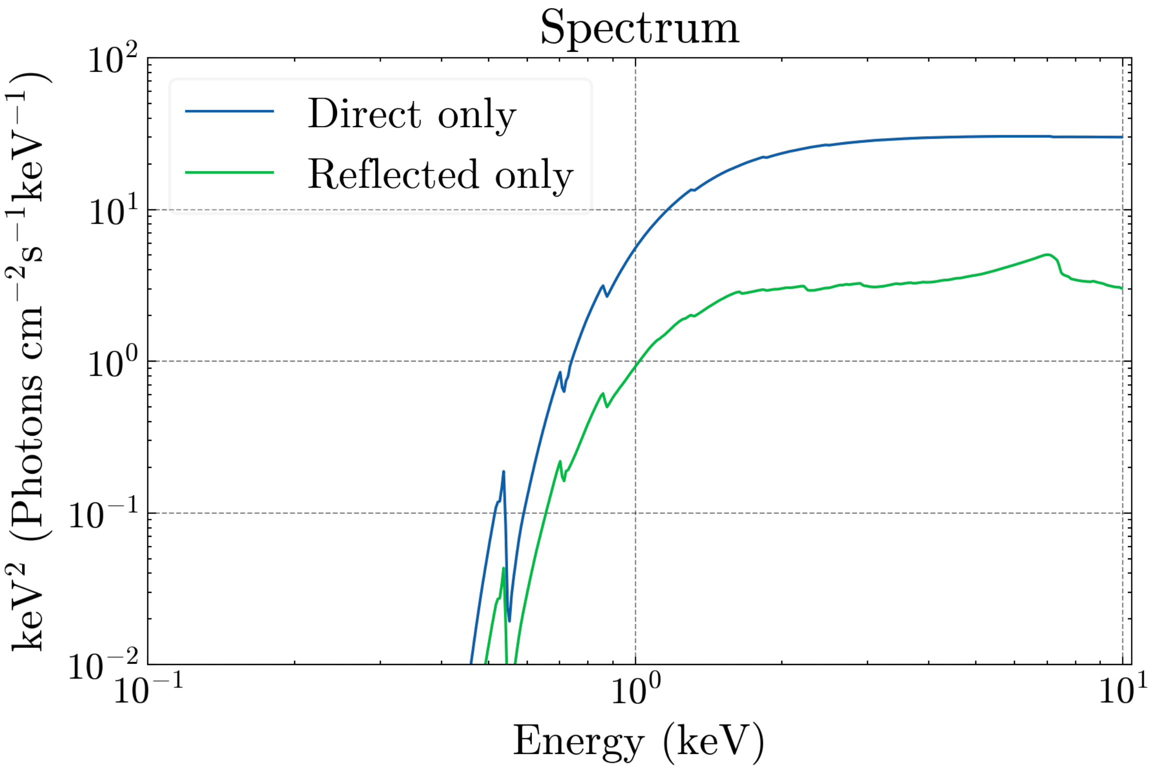
Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve: spectra

Direct: TBabs (relxilllp) refl_frac = 0

Reflected: Tbabs (relxilllp) refl_frac = -0.25

↑ Isolates reflection

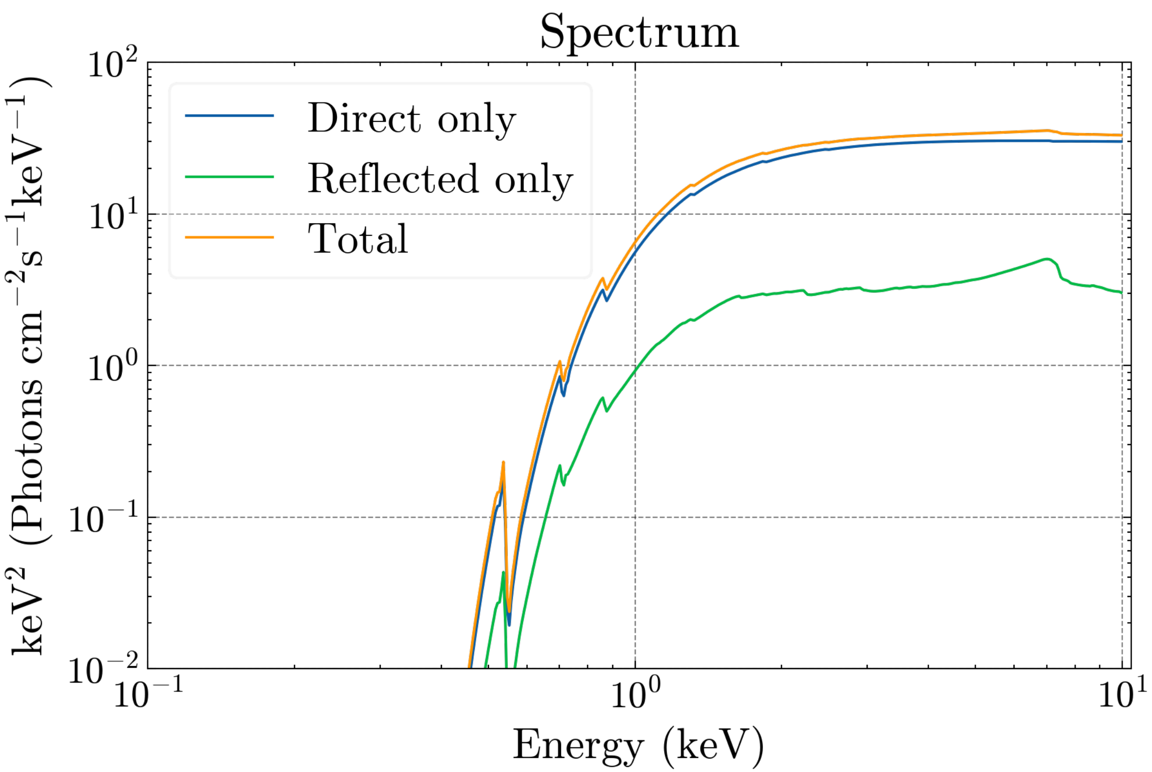


Simulate light curve: spectra

Direct: TBabs (relxilllp) refl_frac = 0

Reflected: Tbabs (relxilllp) refl_frac = -0.25

Total = Direct + Reflected



Decide Geometry

Simulate Light Curve

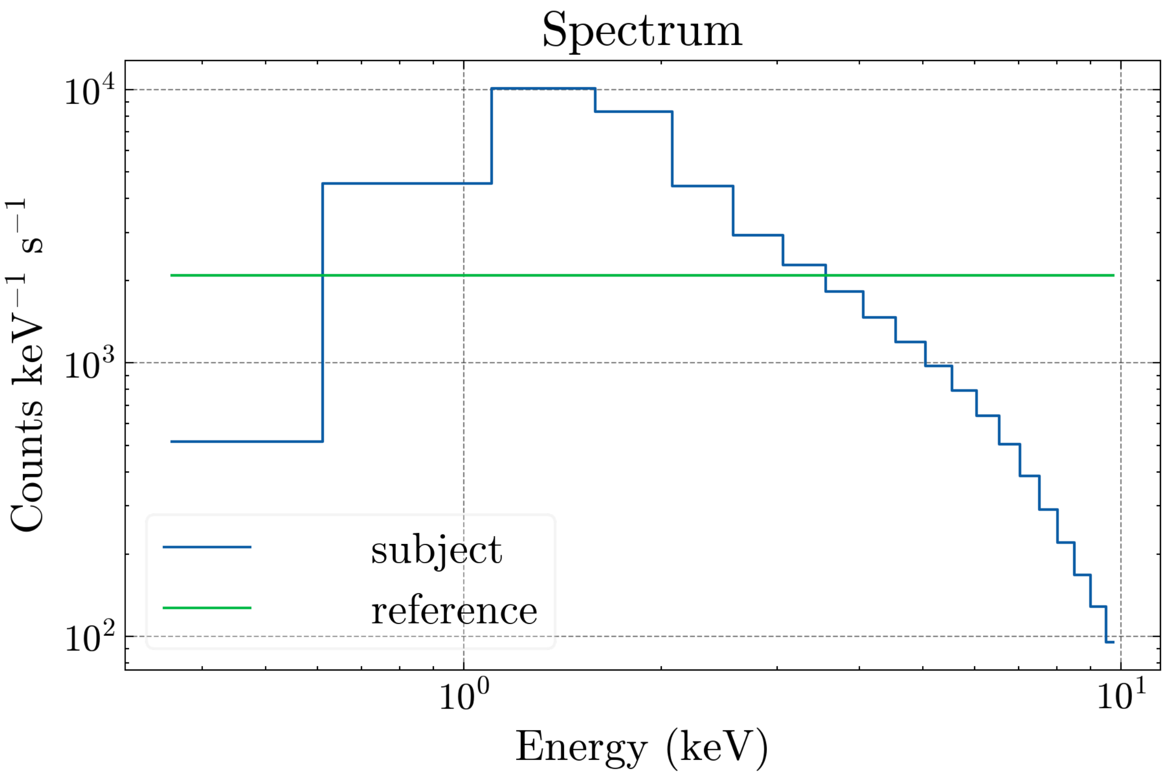
Fourier Analysis

Lag-Energy

Simulate light curve: spectra

Reference : 0.3 – 10 keV
Subject : 20 bins

Quantity	Used to
β- 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

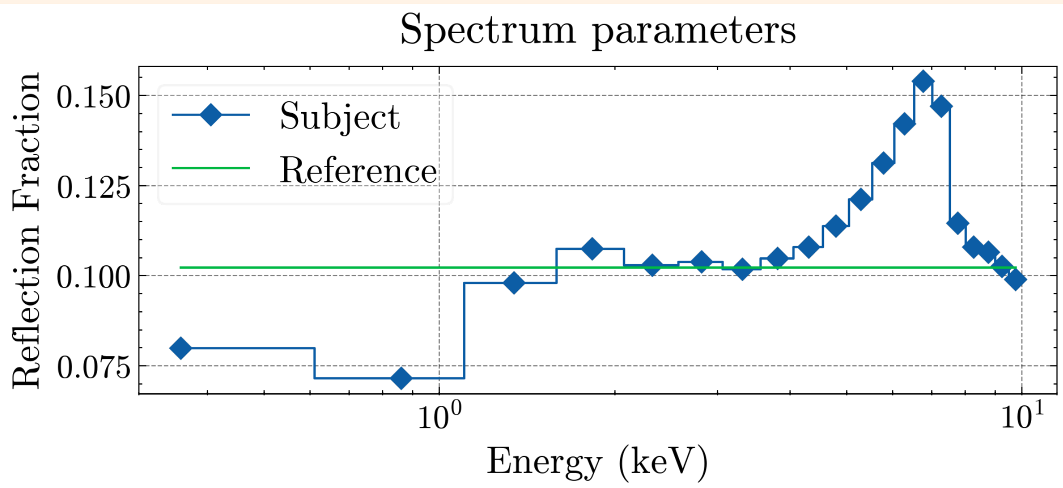
Fourier Analysis

Lag-Energy

Simulate light curve: spectra

Reference : 0.3 – 10 keV
Subject : 20 bins

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

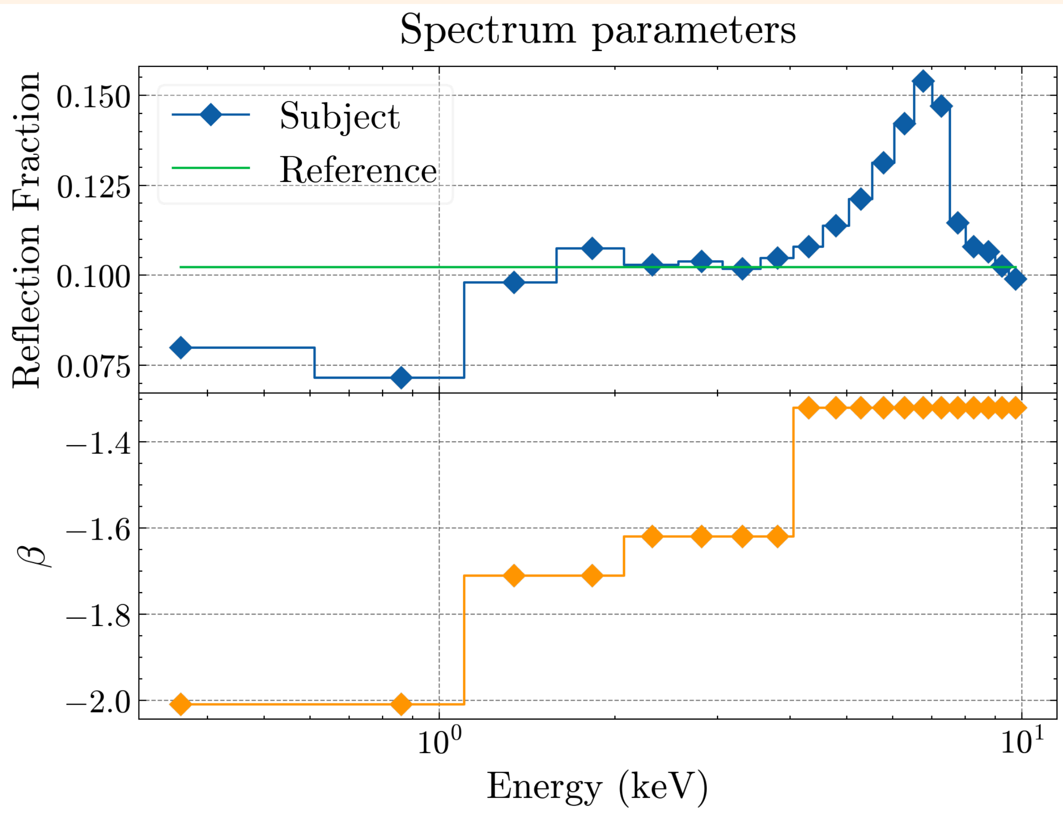


Decide Geometry | Simulate Light Curve | Fourier Analysis | Lag-Energy

Simulate light curve: spectra

Reference : 0.3 – 10 keV
Subject : 20 bins

Quantity	Used to
***β*- 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

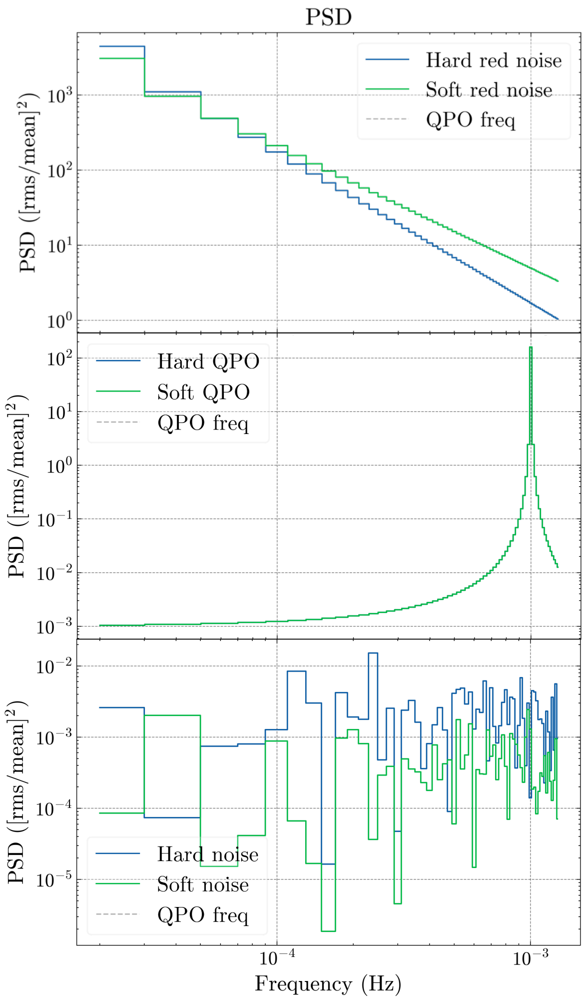
Red noise

+

QPO

+

White noise



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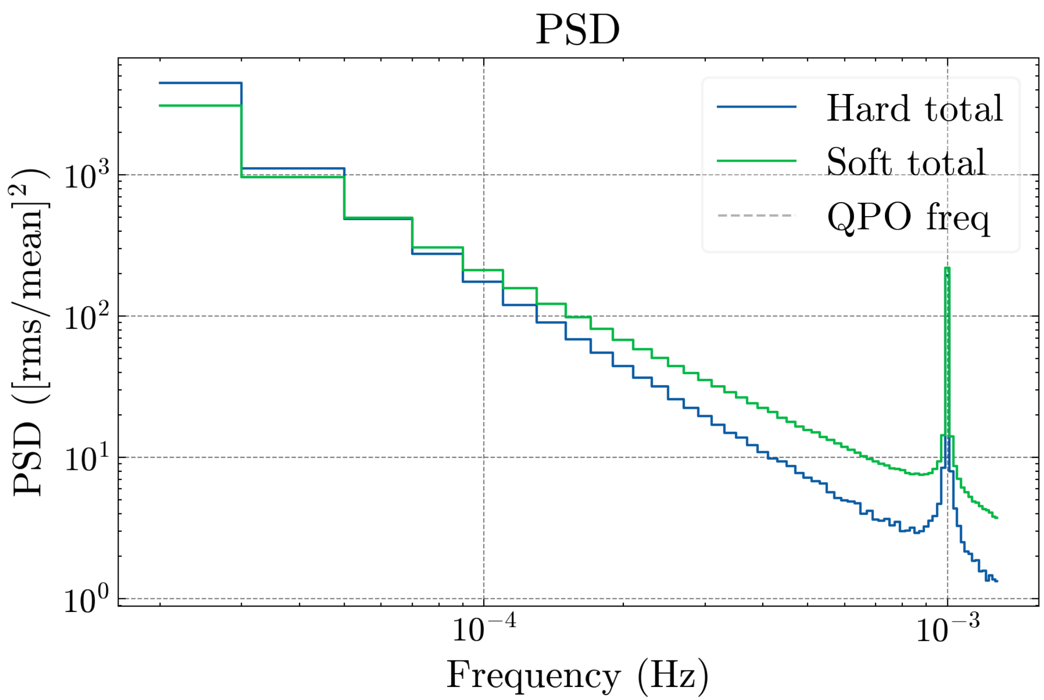
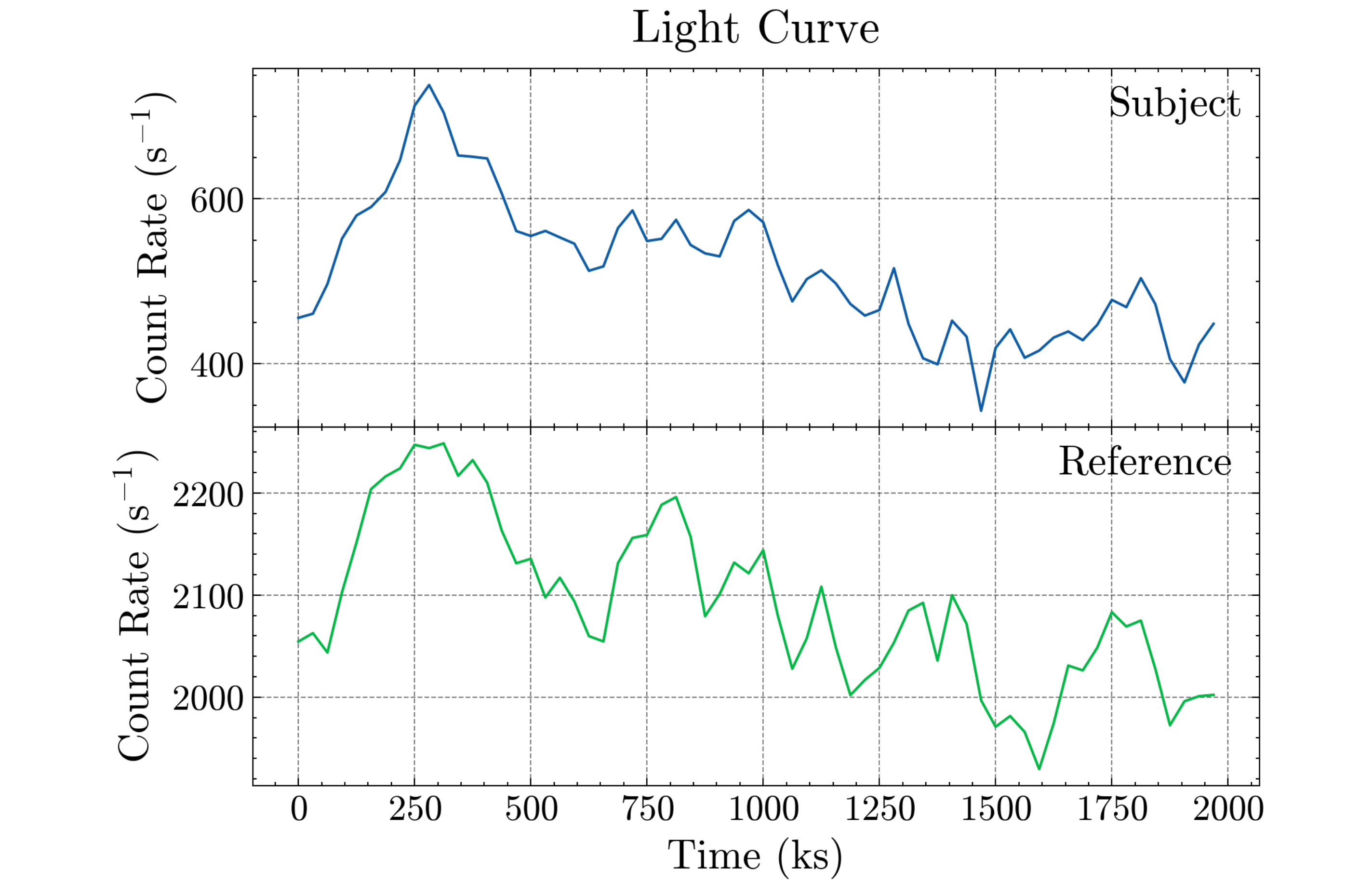
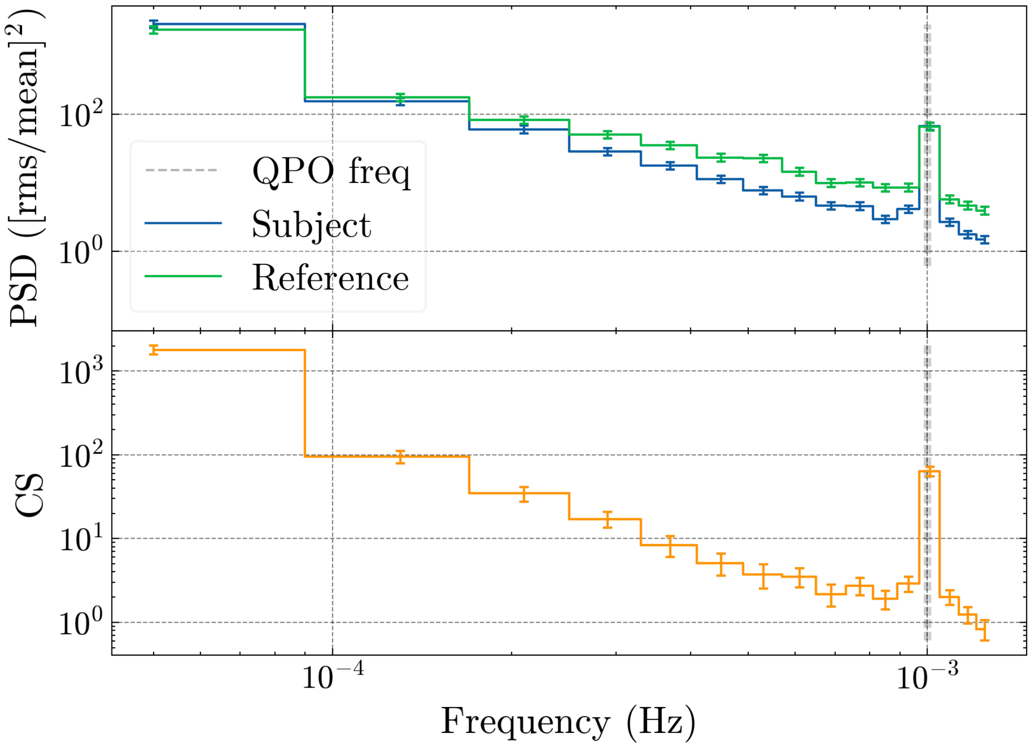
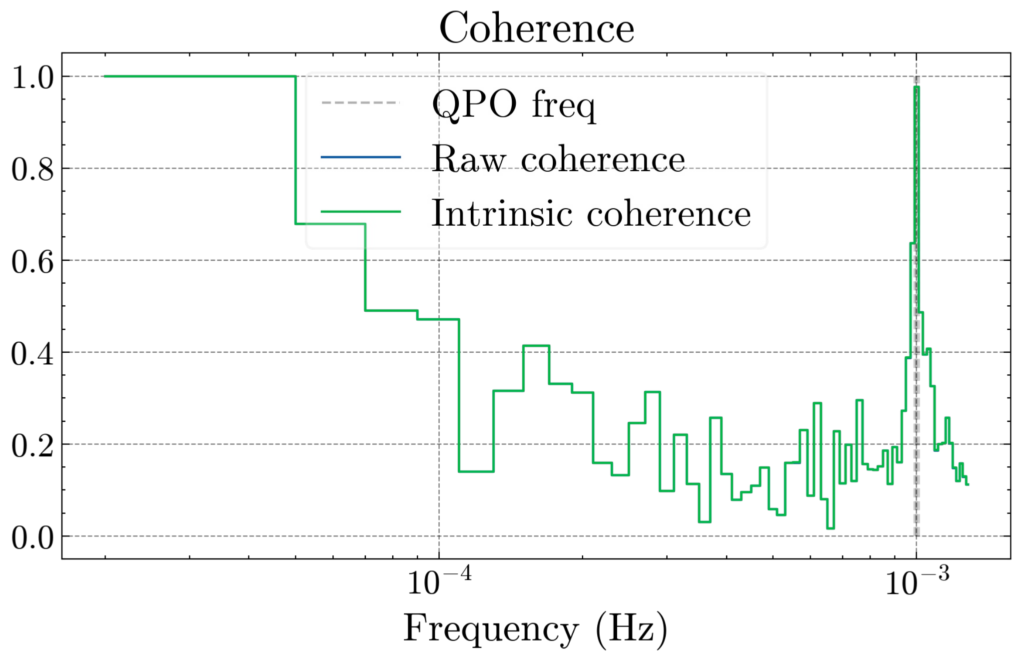


Simulate light curve

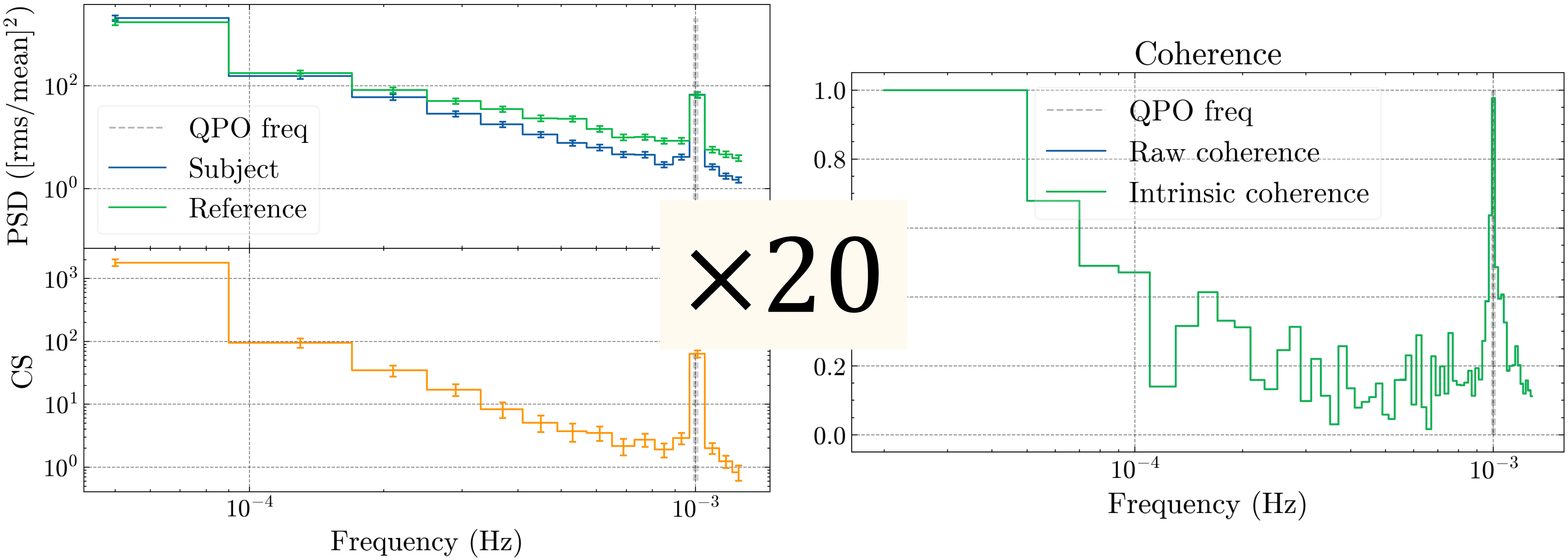


Fourier analysis



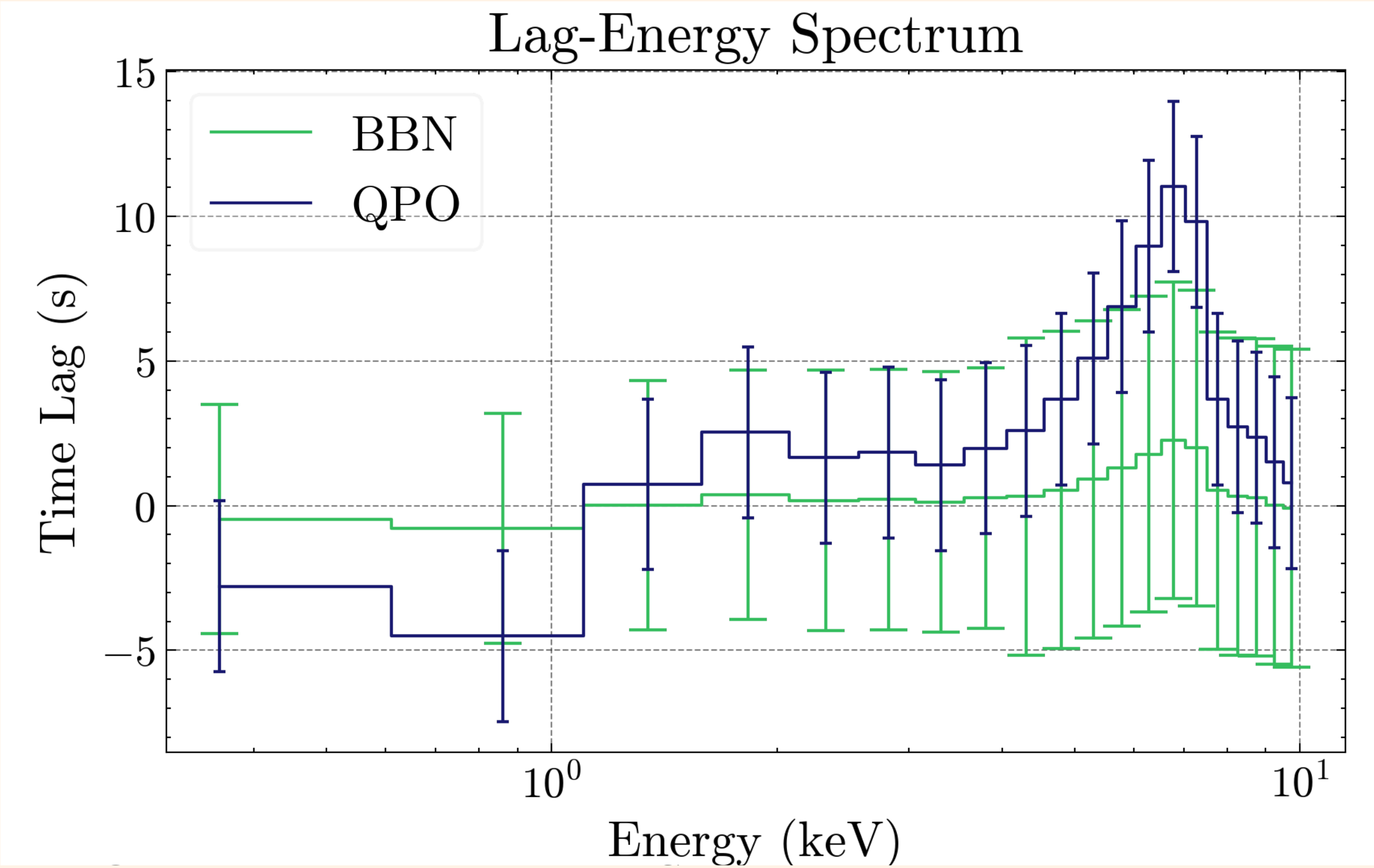


Fourier analysis



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      frozen
   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    -256.528     +/-  6048.05
   2    1   reltransDCpa                   0.997630     +/-  0.618348
   3    1   reltransDCpinc        deg      78.2067      +/-  390.824
   4    1   reltransDCprin        Rg/ISCO  -1.00000     frozen
   5    1   reltransDCprout       Rg       400.000      frozen
   6    1   reltransDCpz                   0.0          frozen
   7    1   reltransDCpGamma               1.40000      +/-  4.51429
   8    1   reltransDCplogxi               4.69593      +/-  11.2278
   9    1   reltransDCpAfe                 0.504932     +/-  10.7744
  10    1   reltransDCplogNe               15.0000      frozen
  11    1   reltransDCpkTe        keV      49.8289      +/-  494.341
  12    1   reltransDCpnH         10^22    277.913      +/-  573.771
  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                    0.23     using 20 bins.

Test statistic : Chi-Squared                    0.23     using 20 bins.
 Null hypothesis probability of 1.00e+00 with 12 degrees of freedom
```

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      frozen
  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
________________________________________________________________________

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BBN

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  3    1   reltransDCpinc         deg      78.2067      +/-  390.824
  4    1   reltransDCprin         Rg/ISCO  -1.00000     frozen
  5    1   reltransDCprout        Rg       400.000      frozen
  6    1   reltransDCpz                    0.0          frozen
  7    1   reltransDCpGamma                1.40000      +/-  4.51429
  8    1   reltransDCplogxi                4.69593      +/-  11.2278
  9    1   reltransDCpAfe                  0.504932     +/-  10.7744
 10    1   reltransDCplogNe                15.0000      frozen
 11    1   reltransDCpkTe         keV      49.8289      +/-  494.341
 12    1   reltransDCpnH          10^22    277.913      +/-  573.771
 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                    0.23      using 20 bins.

Test statistic : Chi-Squared                    0.23      using 20 bins.
 Null hypothesis probability of 1.00e+00 with 12 degrees of freedom
```

Summary

Image credit:
NASA/JPL-Caltech

Summary

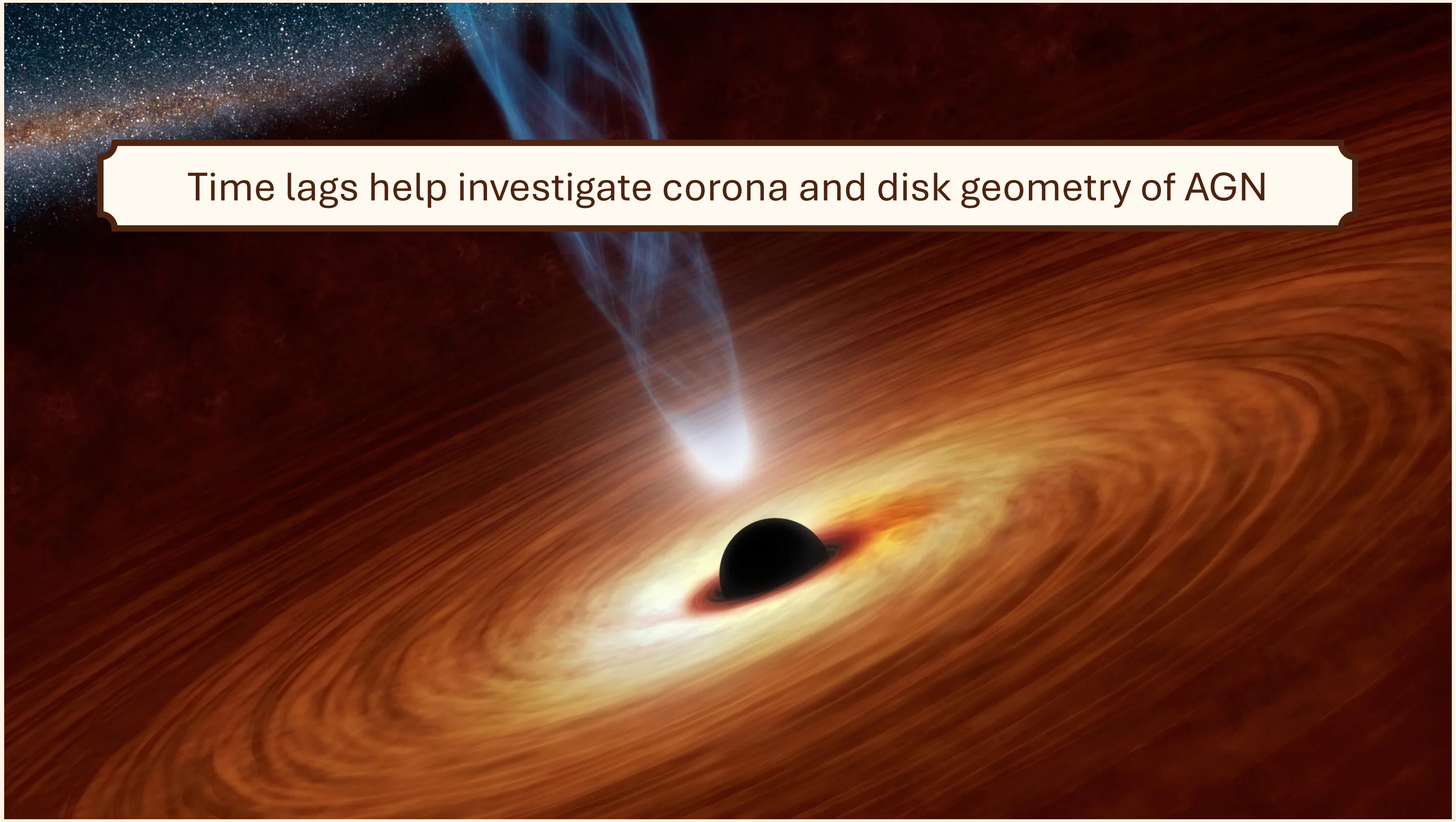


Image credit:
NASA/JPL-Caltech

Summary

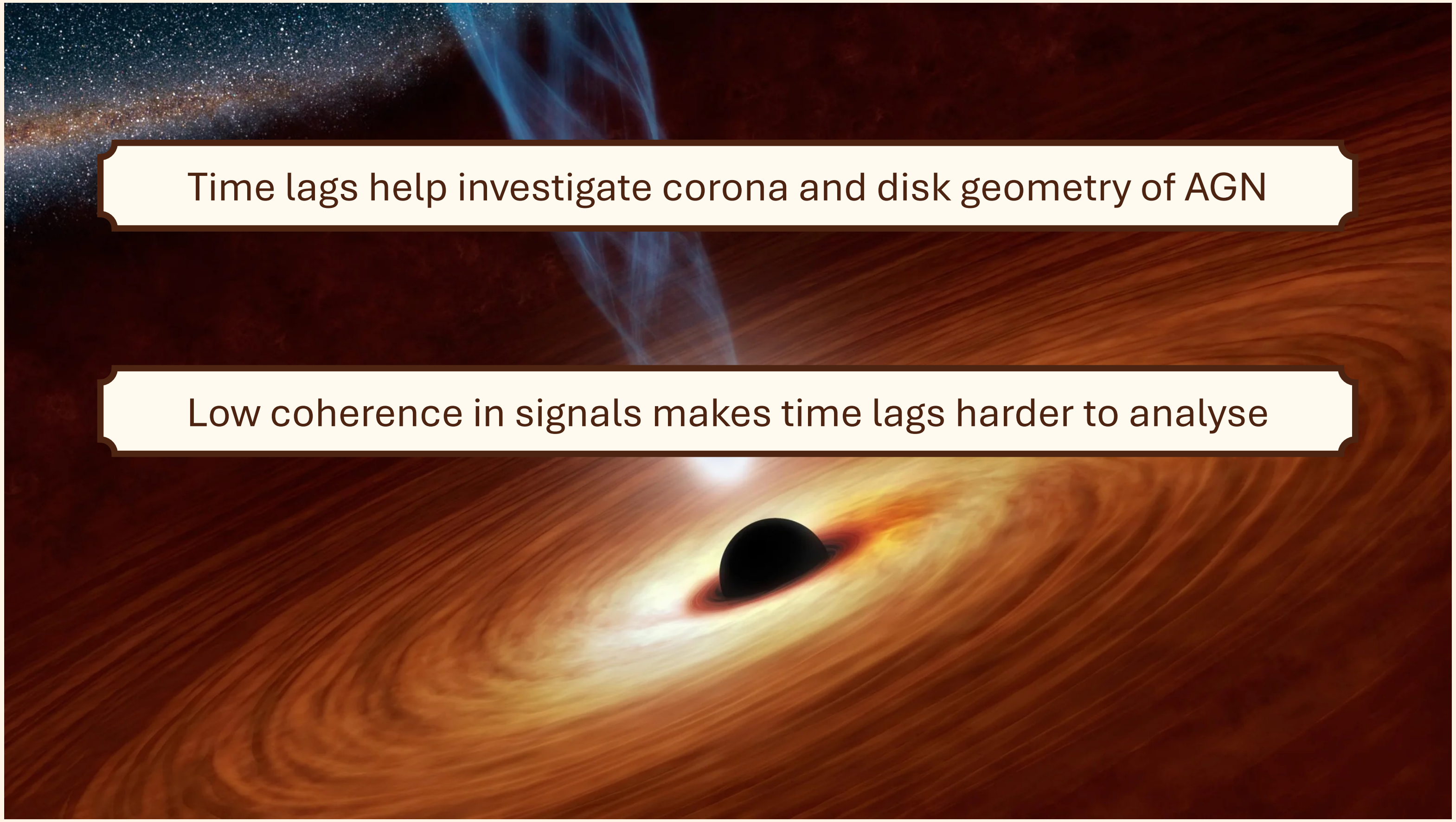
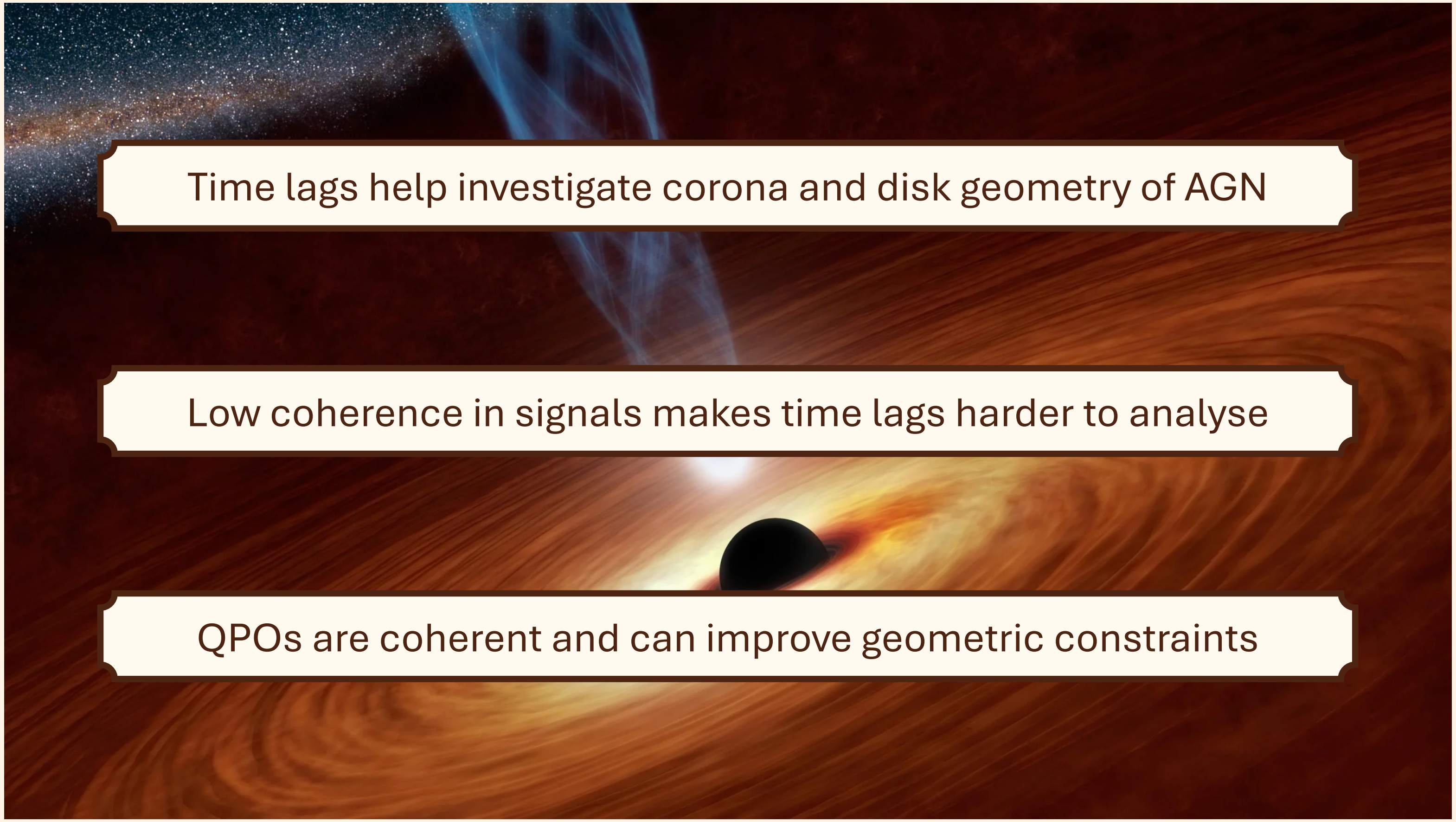


Image credit:
NASA/JPL-Caltech

Summary



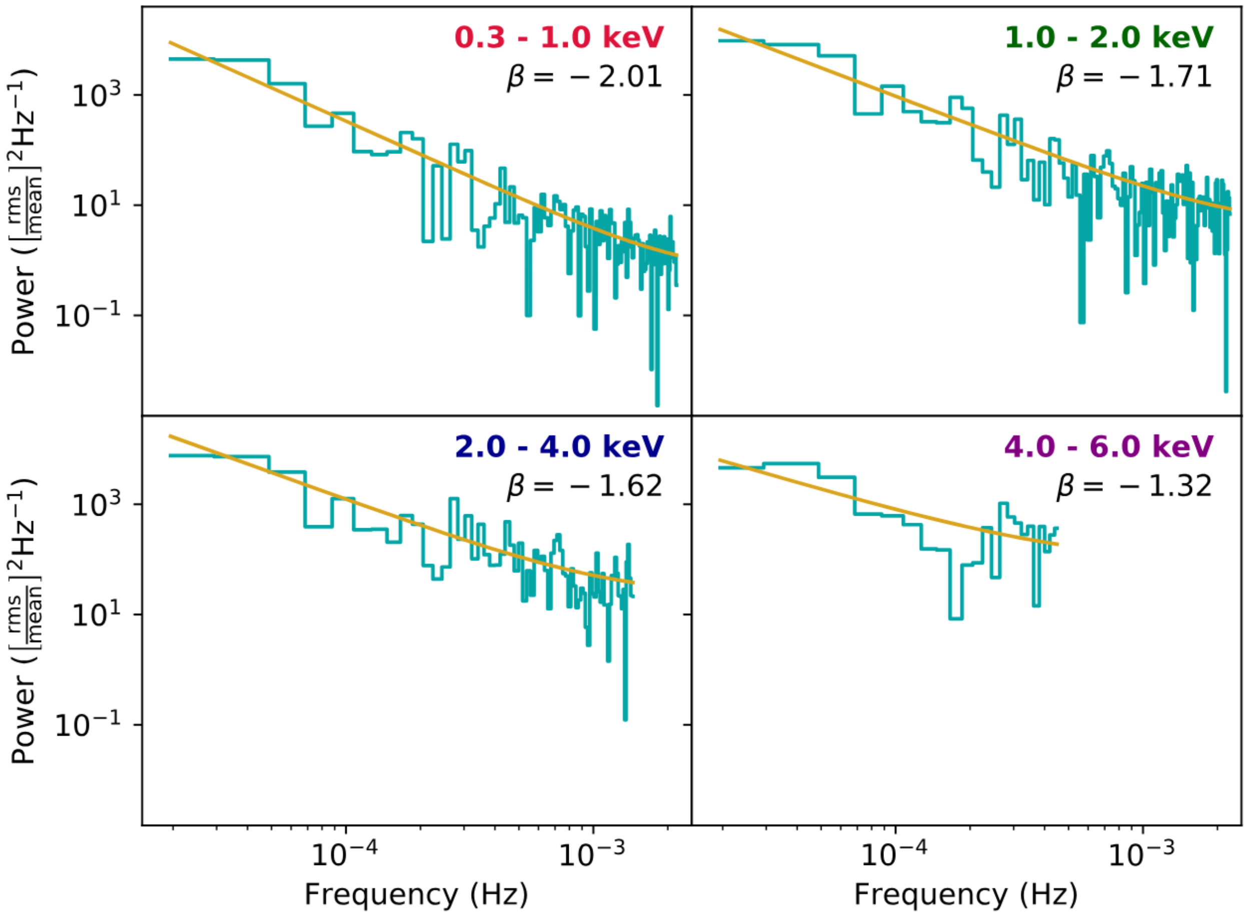
Time lags help investigate corona and disk geometry of AGN

Low coherence in signals makes time lags harder to analyse

QPOs are coherent and can improve geometric constraints

Image credit:
NASA/JPL-Caltech

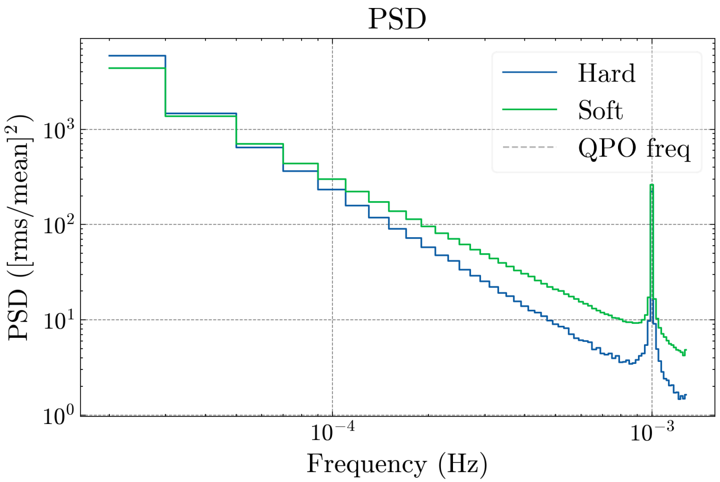
Energy dependance of beta values



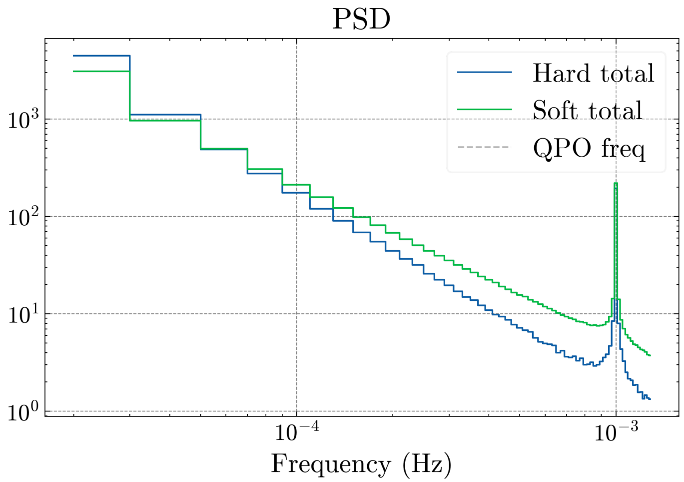
Ashton & Middleton 2022

Simulate light curve

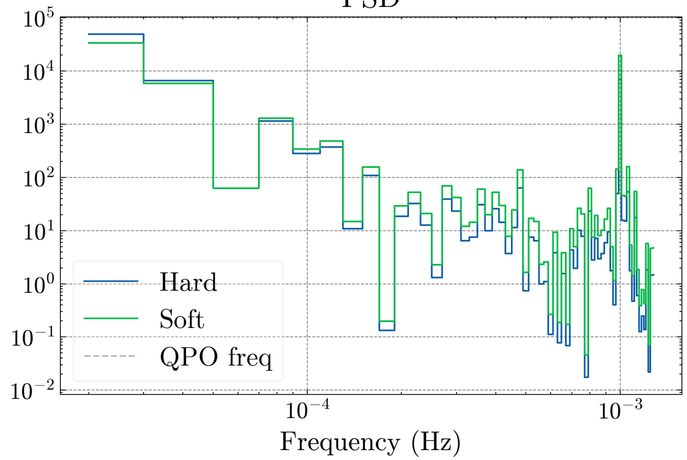
Total of components



+ Transfer function



+ Coherence



Fourier Analysis