Neutron star radius-to-mass ratio from accretion disc occultation

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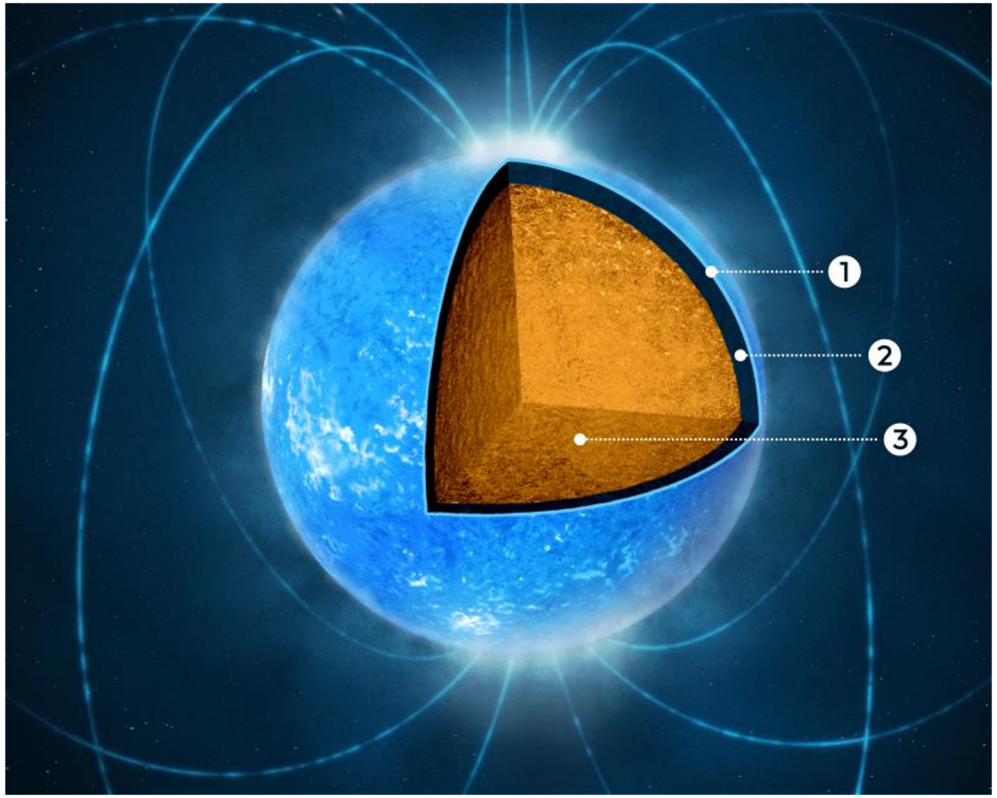
Neutron stars and their EoS

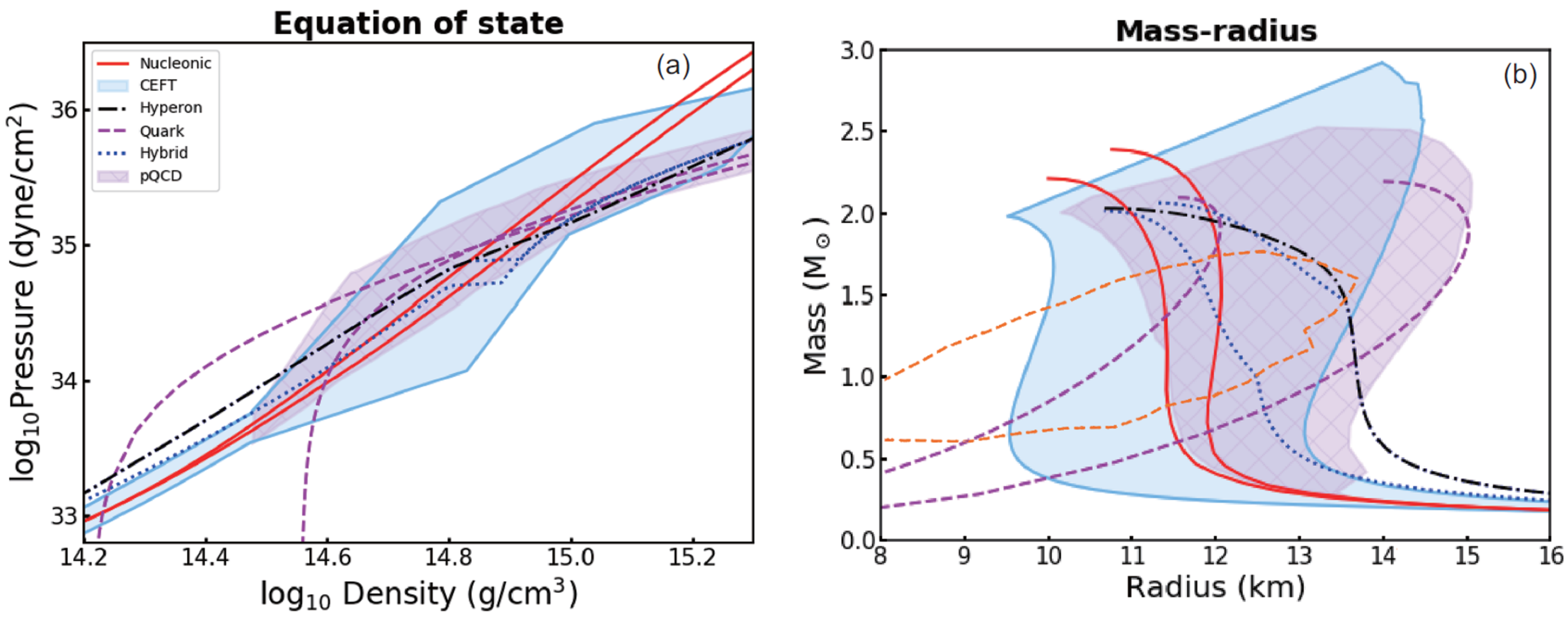


[Watts et al., 2016]

- $M \sim 1\text{-}2\ M_{Sun}$
- $R \sim 15$ km $\sim 7\ GM/c^2$
- $B \sim 10^{12}\text{-}10^{15}$ G
- $P_{rot} \sim 10^{-3}\text{-}30$ s
- $\varrho_{core} \gtrsim 10^{14}$ g/cm^3

Outer crust: nuclei + e^-
Inner crust: nuclei + n + e^-
Core: n + p + μ + e^- (maybe)

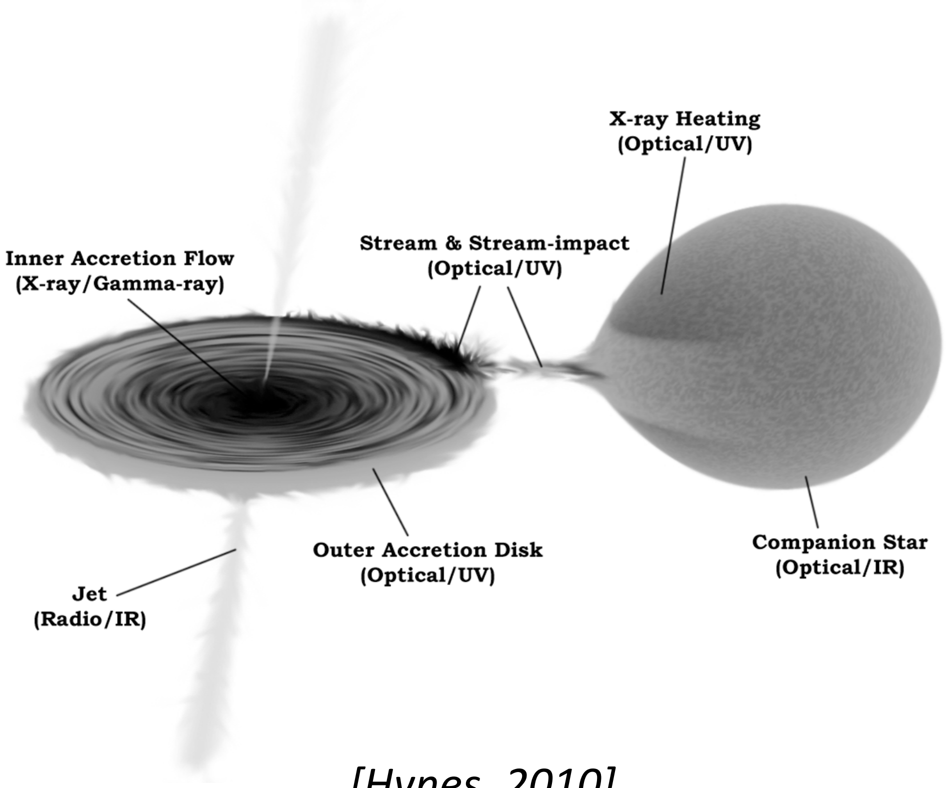
Neutron stars and their EoS



[Watts et al., 2019]

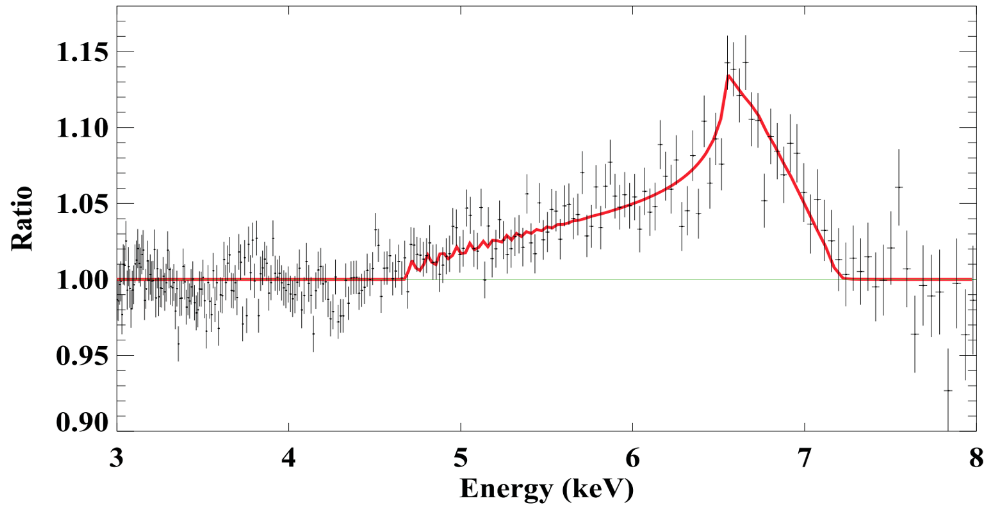
We can derive tight constraints on the equation of state (EoS) through observations of NSs by measuring M and R with precision better than ~5% (currently ~9%)

Iron K-α lines in accretion disks



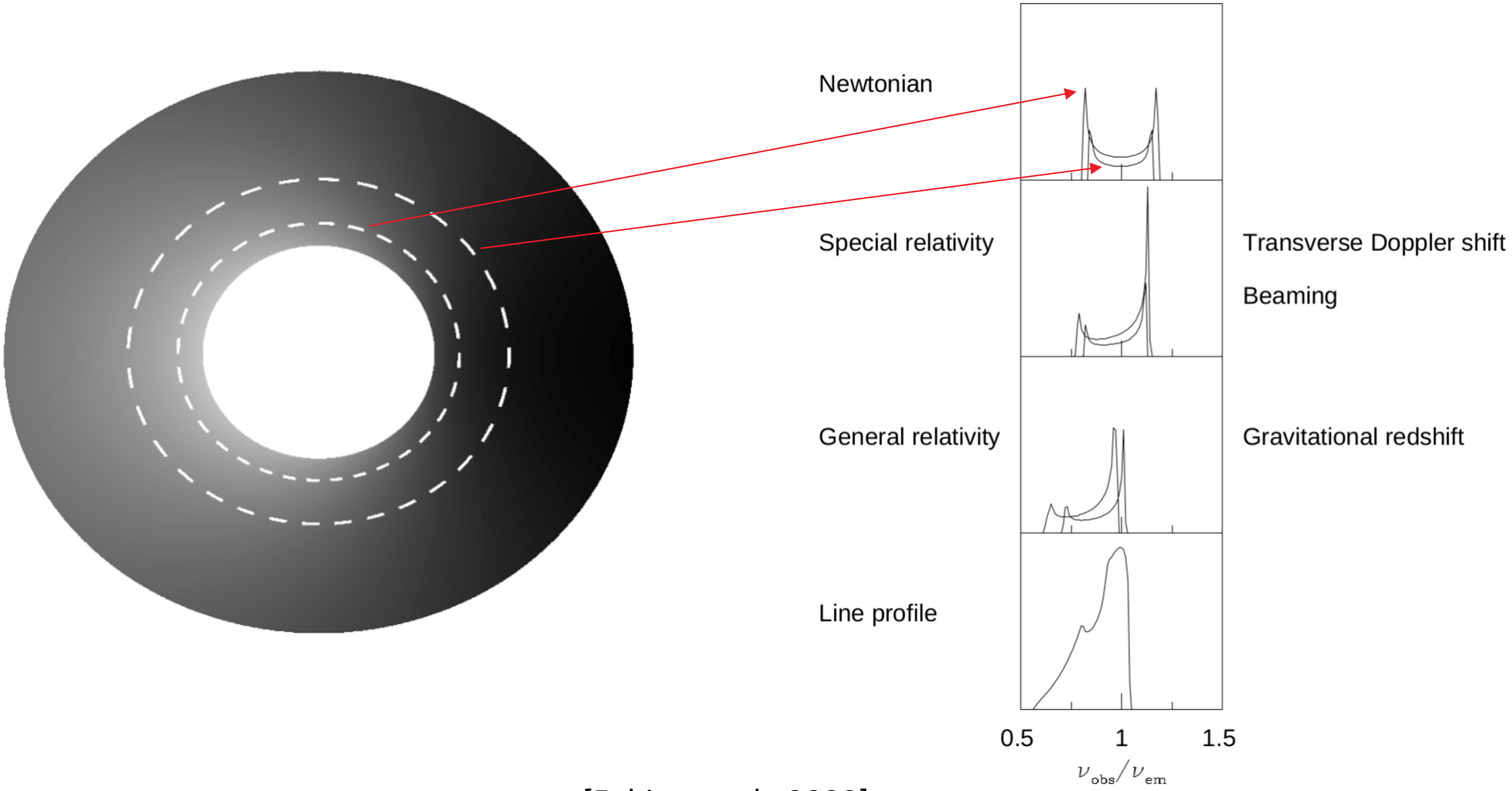
[Hynes, 2010]

Serpens X-1



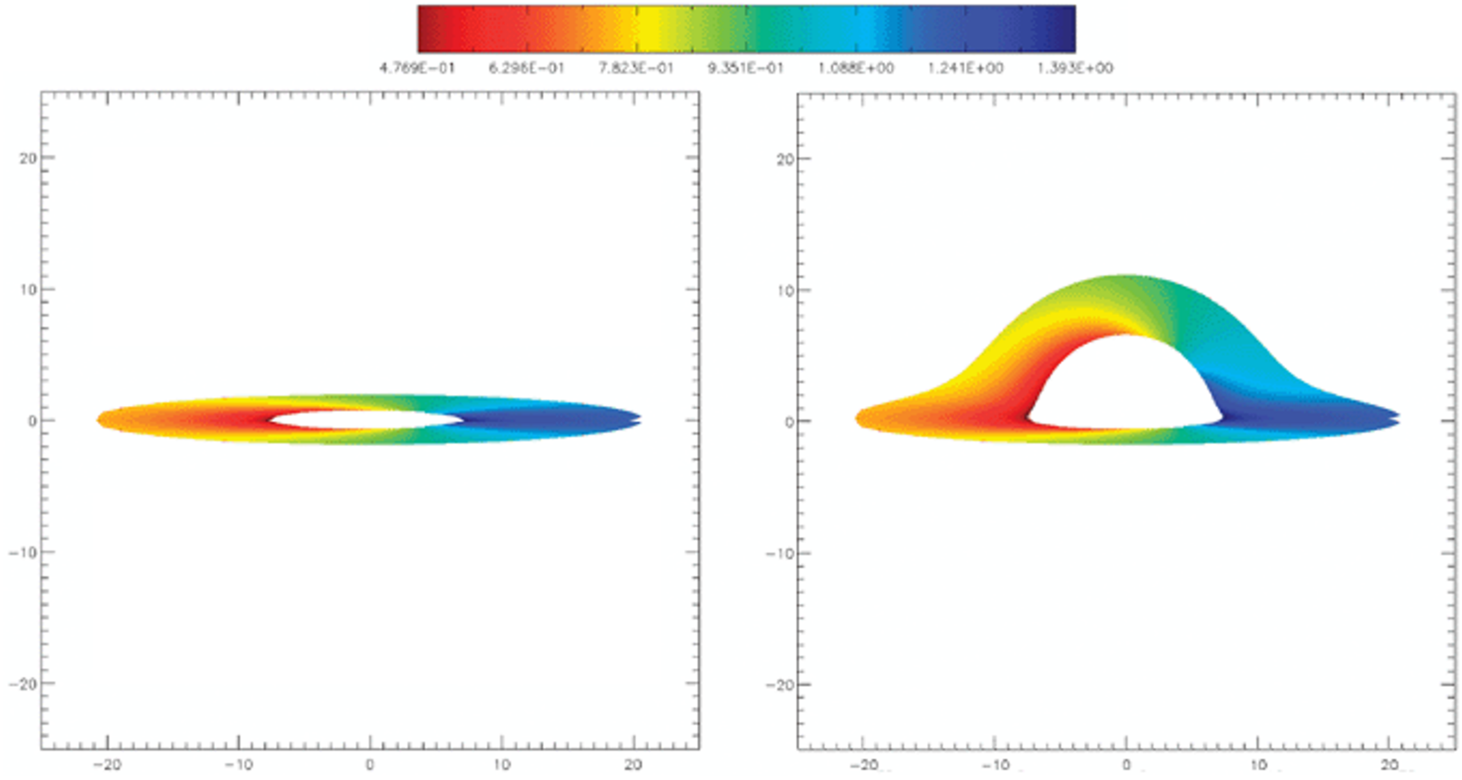
[Chiang et al., 2016]

Iron K-α lines in accretion disks



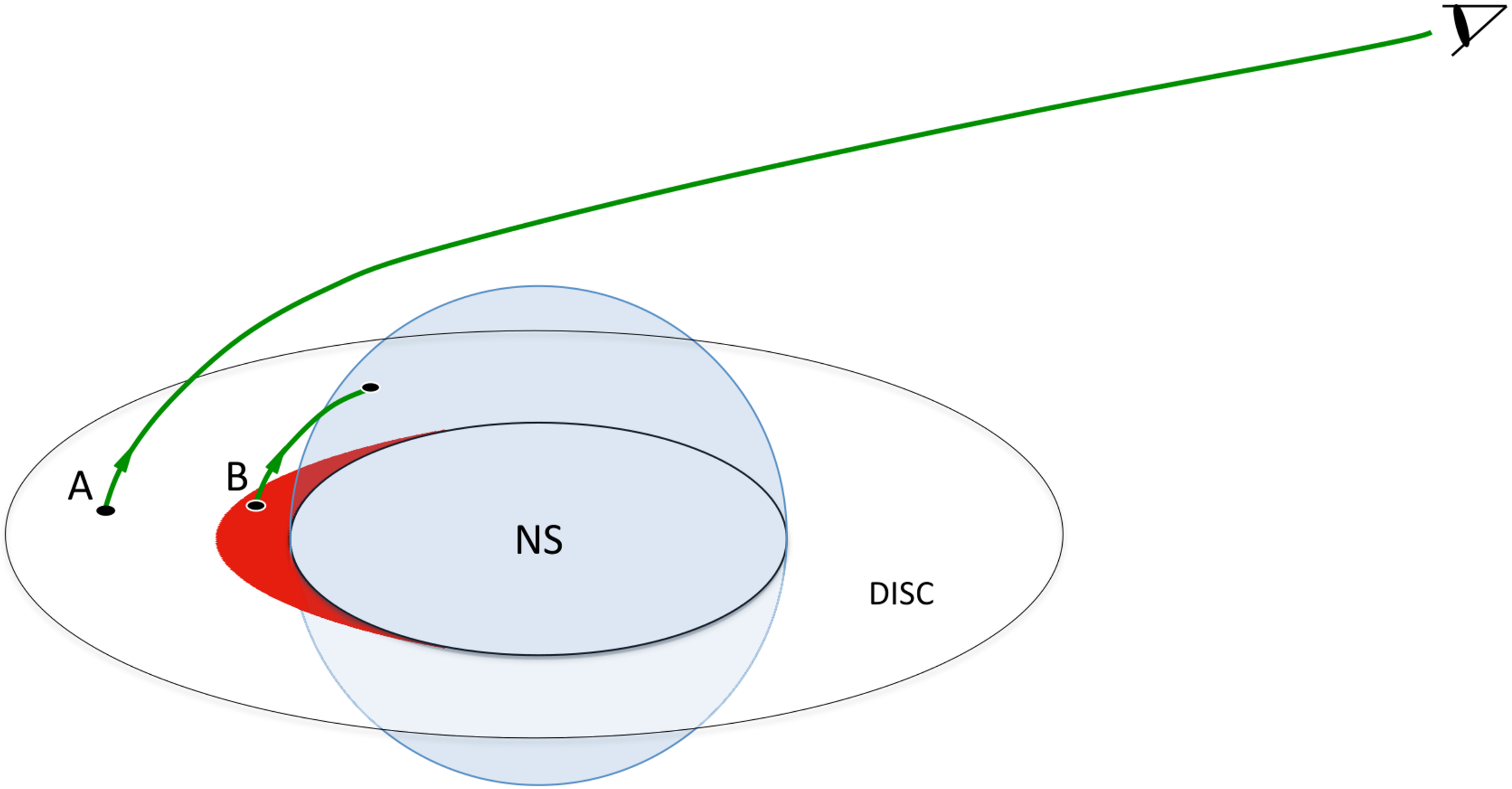
[Fabian et al., 2000]

Gravitational light bending

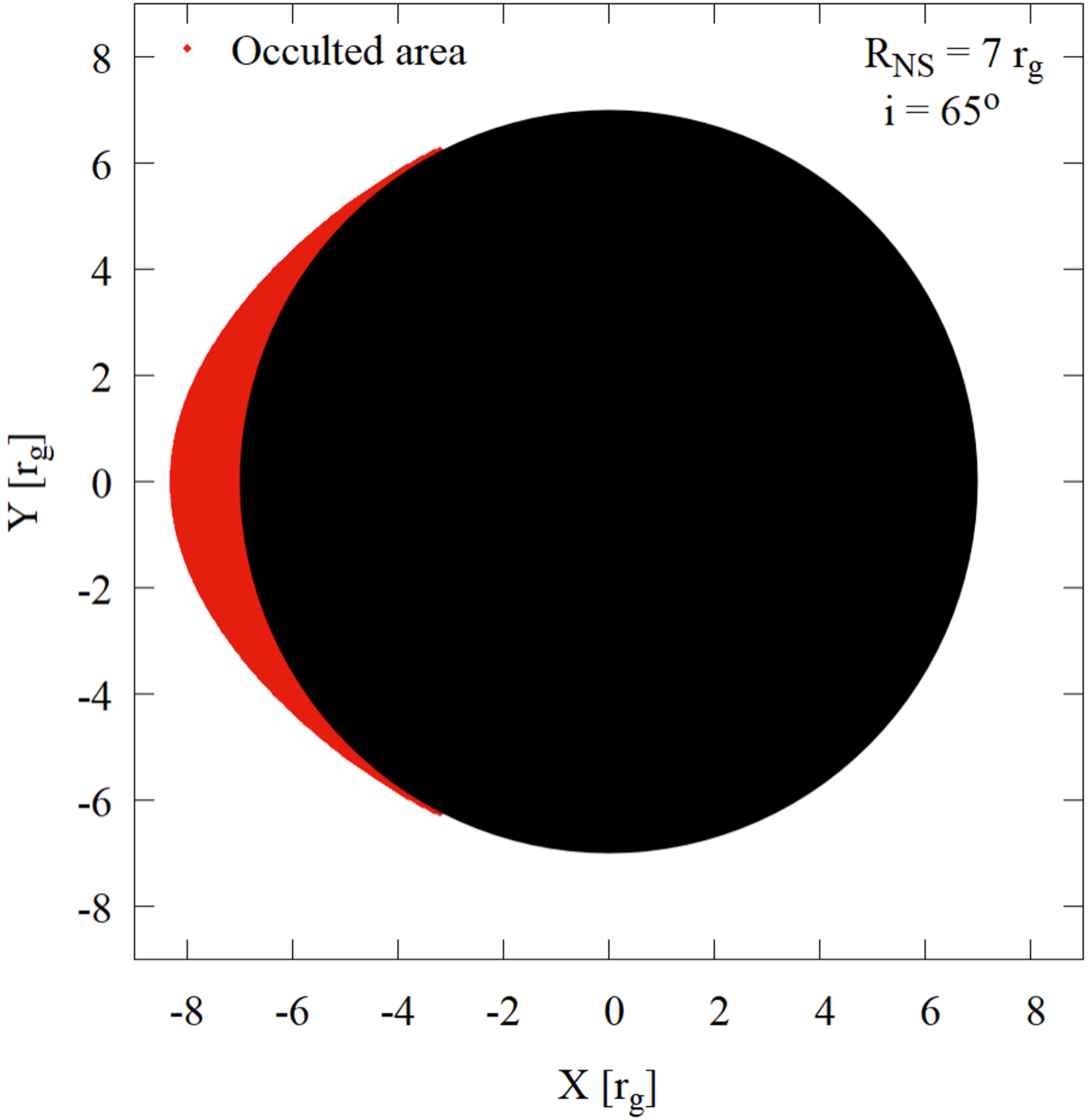


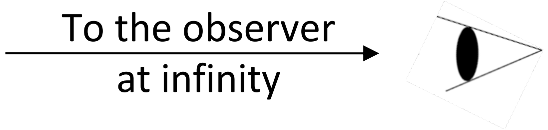
[adapted from Beckwith & Done, 2004]

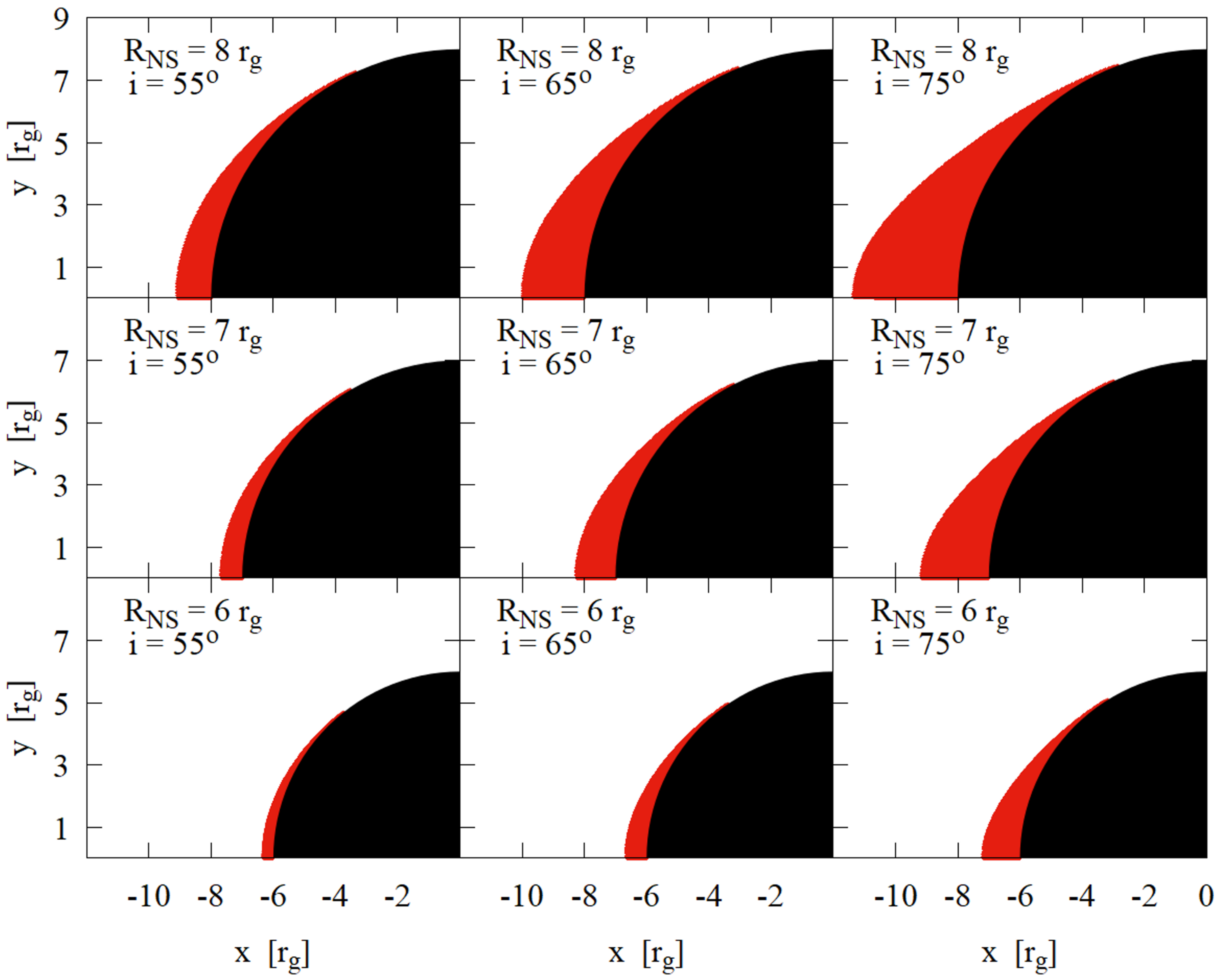
Occultation



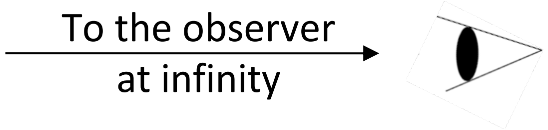
(Drawing not in scale)


Occulted area
$R_{NS} = 7\ r_g$
$i = 65^o$
Y [r_g]
X [r_g]
8
6
4
2
0
-2
-4
-6
-8
-8
-6
-4
-2
0
2
4
6
8

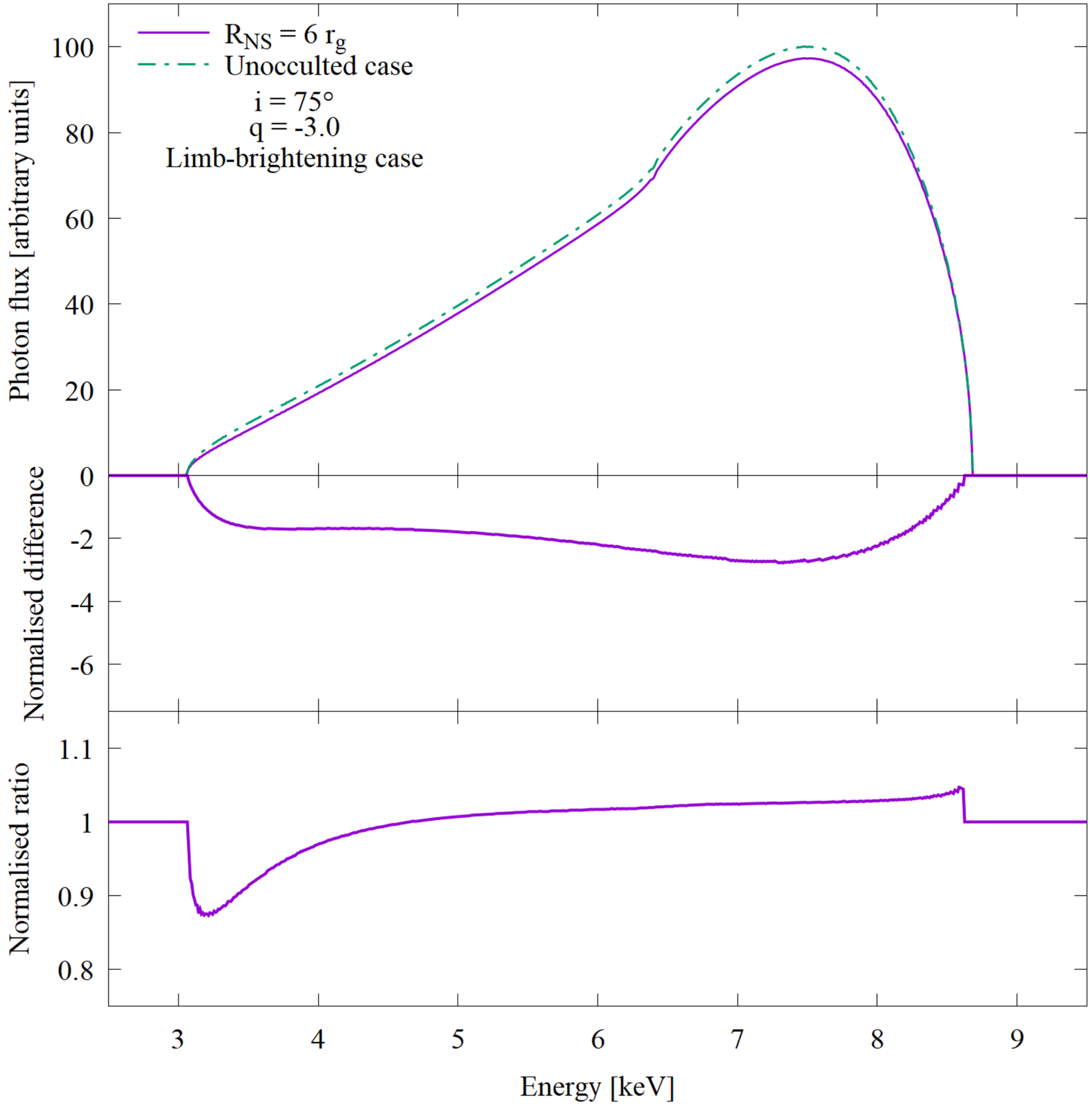

To the observer
at infinity

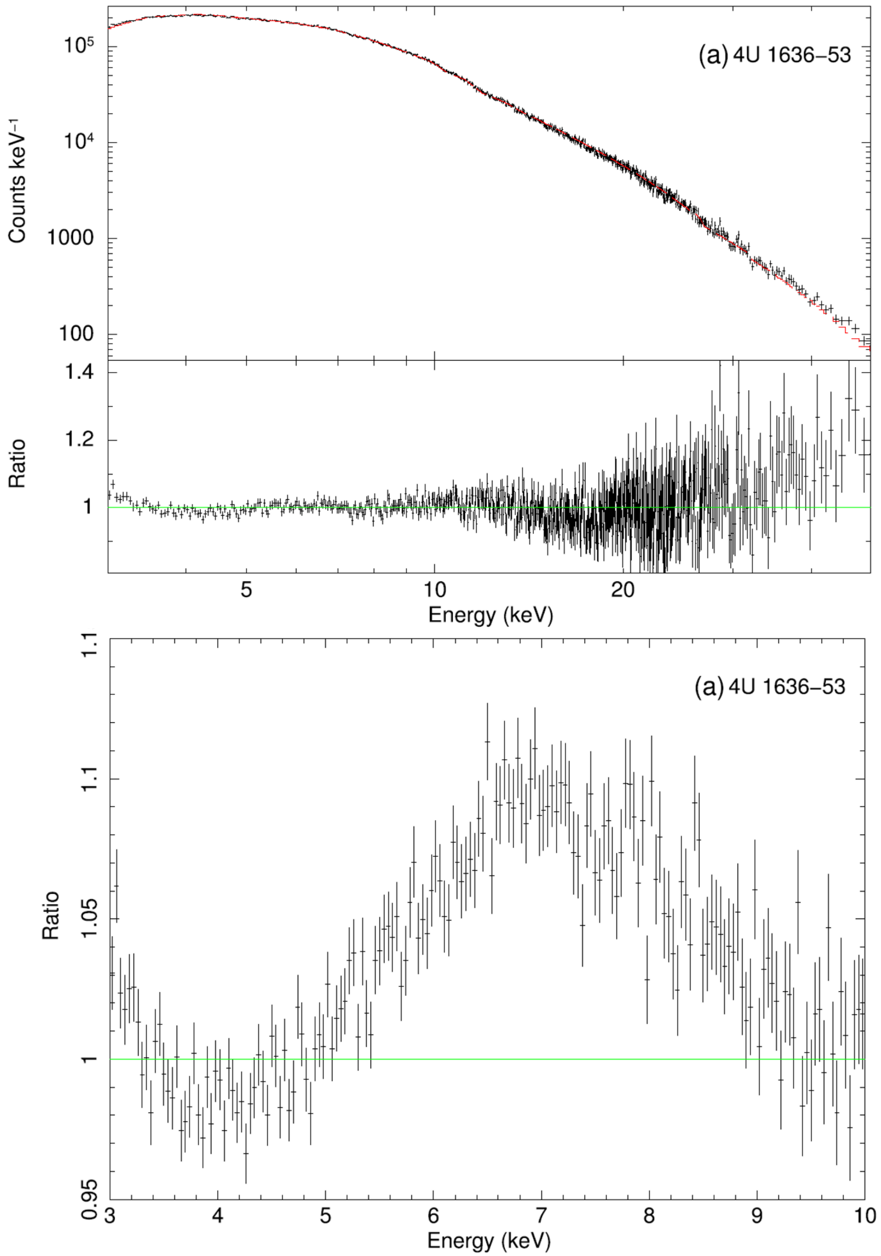


$R_{NS} = 8\ r_g$
$i = 55^o$
$R_{NS} = 8\ r_g$
$i = 65^o$
$R_{NS} = 8\ r_g$
$i = 75^o$
$R_{NS} = 7\ r_g$
$i = 55^o$
$R_{NS} = 7\ r_g$
$i = 65^o$
$R_{NS} = 7\ r_g$
$i = 75^o$
$R_{NS} = 6\ r_g$
$i = 55^o$
$R_{NS} = 6\ r_g$
$i = 65^o$
$R_{NS} = 6\ r_g$
$i = 75^o$
y $[r_g]$
x $[r_g]$



To the observer
at infinity


$R_{NS} = 6\ r_g$
Unocculted case
$i = 75°$
$q = -3.0$
Limb-brightening case
Photon flux [arbitrary units]
Normalised difference
Normalised ratio
Energy [keV]
100
80
60
40
20
0
-2
-4
-6
1.1
1
0.9
0.8
3
4
5
6
7
8
9



[Ludlam et al., 2017]

4U 1636-53: a good candidate

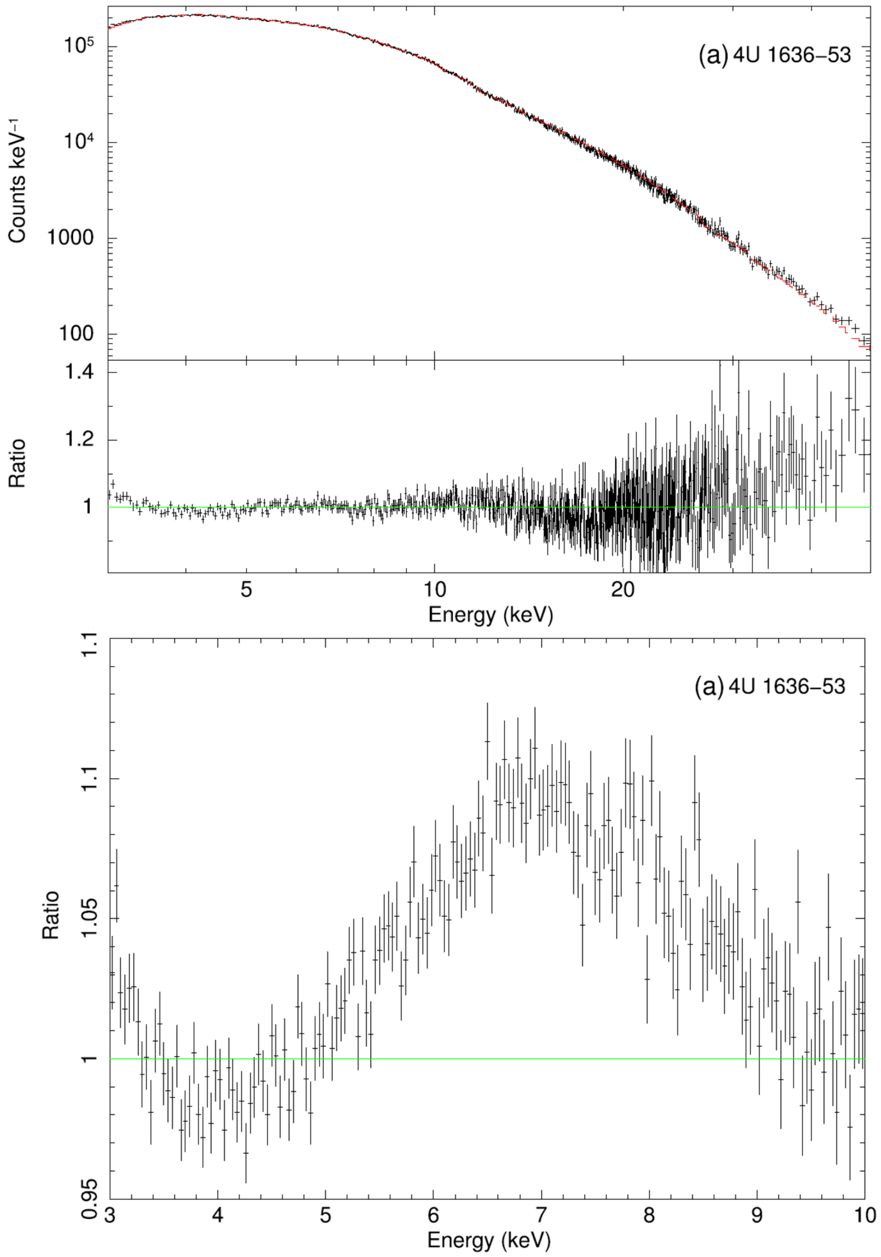
Inclination consistently reported to be high

Inner disc radius close to/reaching the ISCO

X-ray flux usually around 120 mCrab

Broad iron Kα line, with ~0.19keV EW

[Pandel et al, 2008; Cackett et al, 2010; Sanna et al, 2013; Lyu et al, 2014; Ludlam et al, 2017]



[Ludlam et al., 2017]

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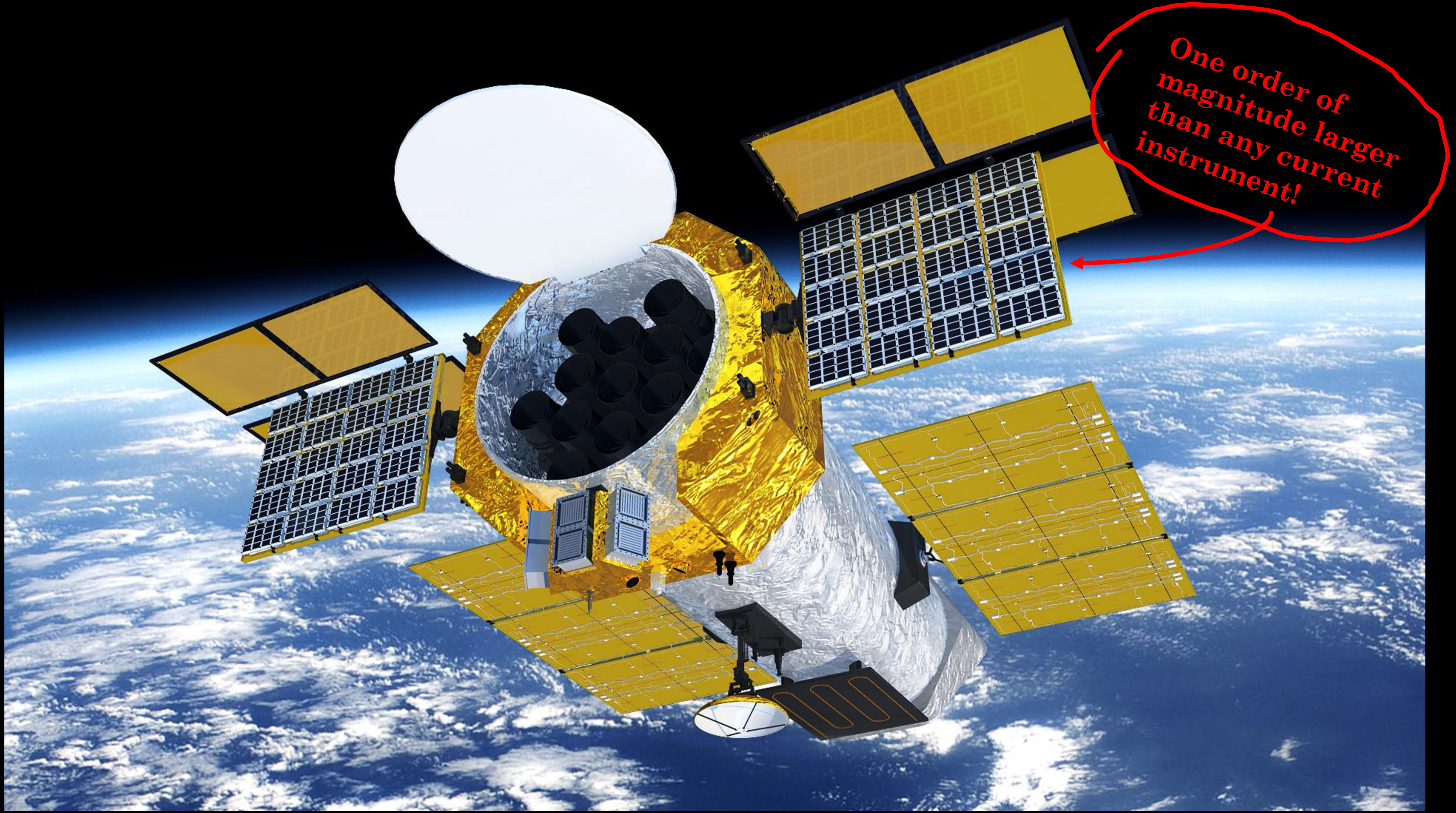
Yet unfortunately we lack the necessary S/N ratio

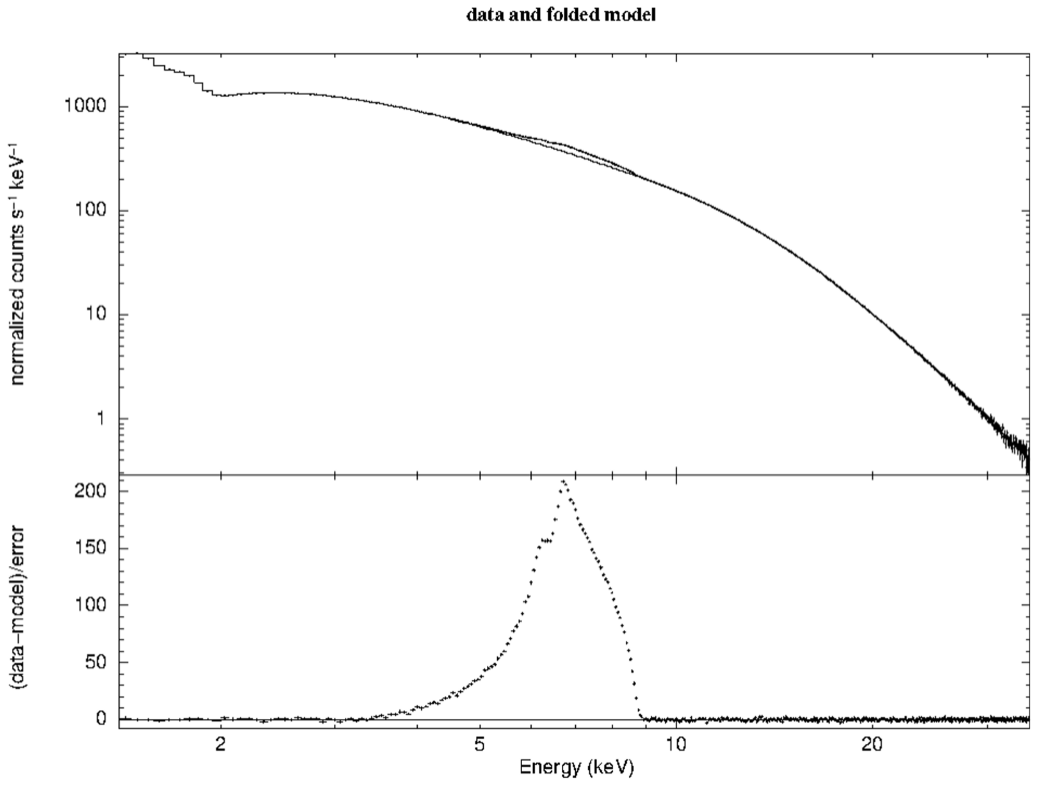
eXTP: coming to your favourite orbit in ~~2025~~ 2028

[Credits to: https://www.isdc.unige.ch/extp/]

eXTP: coming to your favourite orbit in ~~2025~~ 2028



[Credits to: https://www.isdc.unige.ch/extp/]


data and folded model
normalized counts s⁻¹ keV⁻¹
1000
100
10
1
(data−model)/error
200
150
100
50
0
2
5
10
20
Energy (keV)

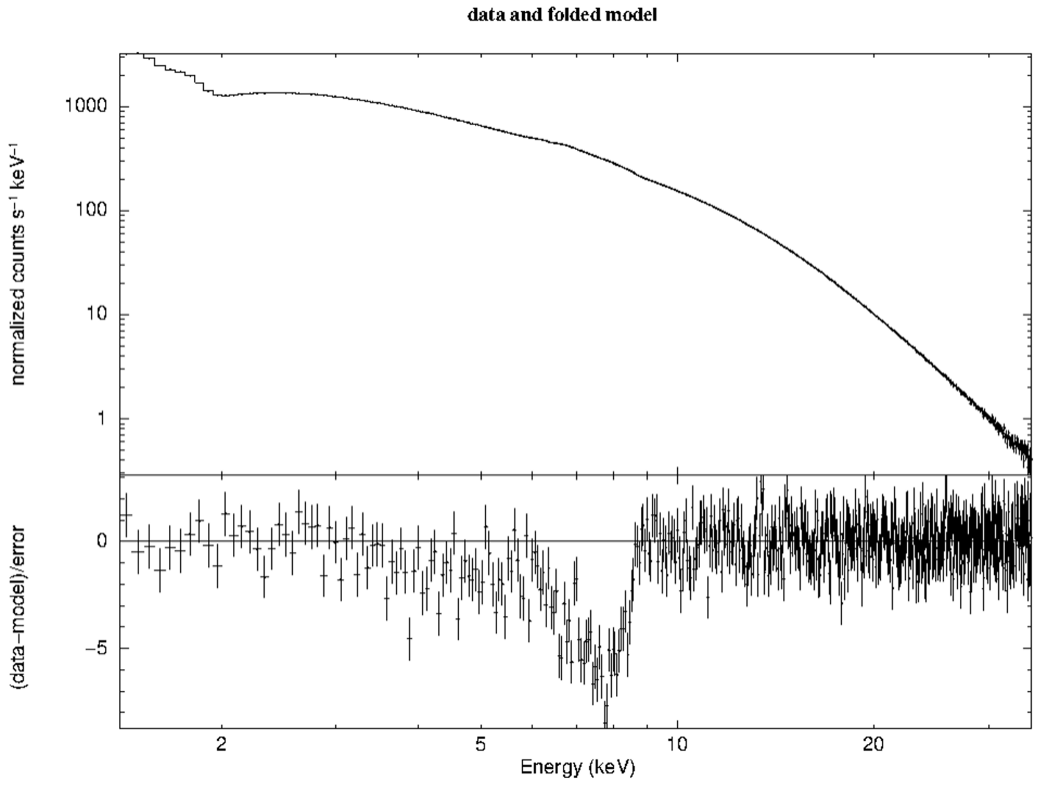

data and folded model
normalized counts s⁻¹ keV⁻¹
1000
100
10
1
(data−model)/error
0
−5
2
5
10
20
Energy (keV)

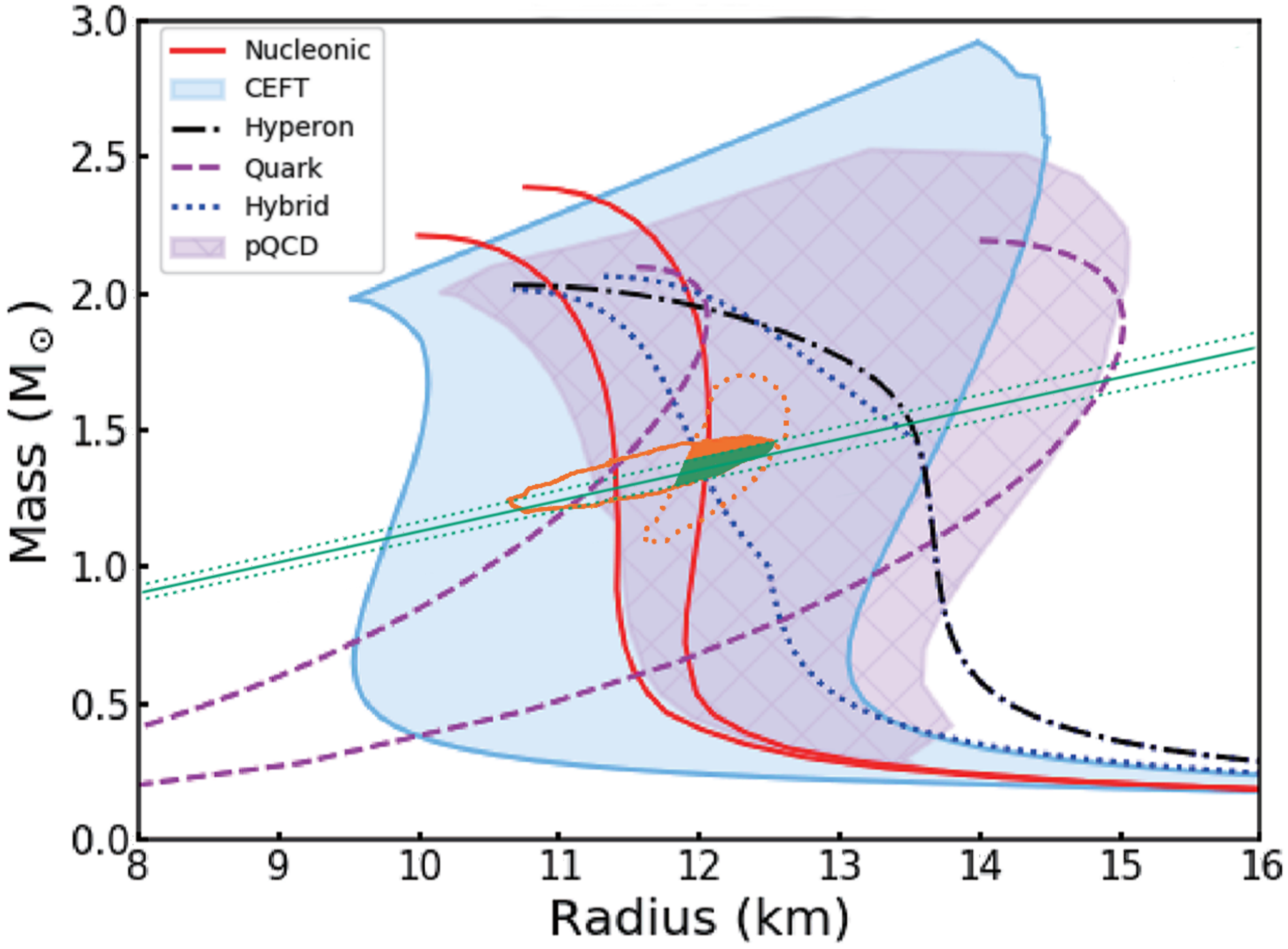
Table 2
Best-fit $r_{\rm in}$ and $R_{\rm NS}$ Parameters for the Simulations in which $r_{\rm in} = R_{\rm NS}$

	$R_{\rm NS} = 6\ r_g$		$R_{\rm NS} = 7\ r_g$		$R_{\rm NS} = 8\ r_g$	
i	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$
55°	…	…	…	…	$8.00^{+0.01}_{-0.02}$	$7.68^{+0.32}_{-0.21}$
60°	$6.00^{+0.01}_{-6.00}$	$5.90^{+0.11}_{-0.01}$	$7.01^{+0.01}_{-0.02}$	$6.85^{+0.16}_{-0.19}$	$8.00^{+0.01}_{-0.02}$	$8.00^{+0.01}_{-0.28}$
65°	$6.01^{+0.01}_{-0.01}$	$6.00^{+0.01}_{-0.23}$	$7.00^{+0.01}_{-0.01}$	$7.00^{+0.01}_{-0.15}$	$8.01^{+0.02}_{-0.01}$	$7.99^{+0.03}_{-0.30}$
70°	$6.00^{+0.02}_{-0.00}$	$5.96^{+0.04}_{-0.22}$	$7.00^{+0.01}_{-0.01}$	$7.00^{+0.02}_{-0.08}$	$8.00^{+0.02}_{-0.00}$	$7.88^{+0.17}_{-0.19}$
75°	$6.00^{+0.03}_{-6.00}$	$5.99^{+0.17}_{-0.13}$	$7.01^{+0.01}_{-0.03}$	$6.86^{+0.10}_{-0.15}$	$8.00^{+0.01}_{-0.04}$	$8.00^{+0.01}_{-0.10}$
80°	$6.00^{+0.01}_{-6.00}$	$5.94^{+0.06}_{-0.07}$	$6.99^{+0.03}_{-0.02}$	$6.98^{+0.16}_{-0.16}$	$8.00^{+0.03}_{-0.00}$	$7.99^{+0.02}_{-0.08}$

Table 3
Best-fit $r_{\rm in}$ and $R_{\rm NS}$ Parameters for the Simulations in which $r_{\rm in} = R_{\rm NS} + 1\ r_g$

	$R_{\rm NS} = 6\ r_g$		$R_{\rm NS} = 7\ r_g$		$R_{\rm NS} = 8\ r_g$	
i	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$	$r_{\rm in}^{\rm bf}$	$R_{\rm NS}^{\rm bf}$
60°	…	…	…	…	$9.00^{+0.02}_{-0.03}$	$8.13^{+0.23}_{-0.34}$
65°	…	…	$8.00^{+0.02}_{-0.03}$	$7.07^{+0.31}_{-7.07}$	$8.95^{+0.01}_{-0.01}$	$8.15^{+0.24}_{-0.40}$
70°	$7.00^{+0.01}_{-0.01}$	$5.99^{+0.82}_{-5.99}$	$8.00^{+0.02}_{-0.01}$	$7.16^{+0.18}_{-0.20}$	$8.97^{+0.03}_{-0.01}$	$7.82^{+0.27}_{-0.23}$
75°	$6.99^{+0.02}_{-0.01}$	$5.99^{+0.36}_{-5.99}$	$8.05^{+0.03}_{-0.03}$	$7.12^{+0.22}_{-0.22}$	$8.91^{+0.04}_{-0.04}$	$7.87^{+0.28}_{-0.32}$
80°	$7.00^{+0.01}_{-0.01}$	$6.05^{+0.20}_{-0.15}$	$7.97^{+0.01}_{-0.01}$	$7.06^{+0.14}_{-0.16}$	$8.95^{+0.02}_{-0.02}$	$8.07^{+0.18}_{-0.18}$

In all cases the 90% error bars on the NS radius are below 5% of the best-fit value (in most of them even below 3.5%), providing the precision required to constrain the EoS



[adapted from Watts et al., 2019]

Summary

- We have developed a new subroutine to fit relativistically broadened lines from accretion disks accounting for the occultation by a central body: this occultation imprints a signature on the line profiles which should be visible for high enough inclinations and close disks.

- Current instrumentation simply does not provide the necessary signal-to-noise ratio to detect occultation features. However, with near-future telescopes measuring the R/r_g ratio should be possible within ~1÷5% precision, which is the one required to put tight constraints on the EoS of NS matter together with other X-ray techniques: this opens a new window in the physics of ultradense, cold matter.

- Although we assume the metric to be described by the Schwarzschild case and the star to be spherical, the accuracy and precision of the model still holds for reasonably rotating, oblate NS.