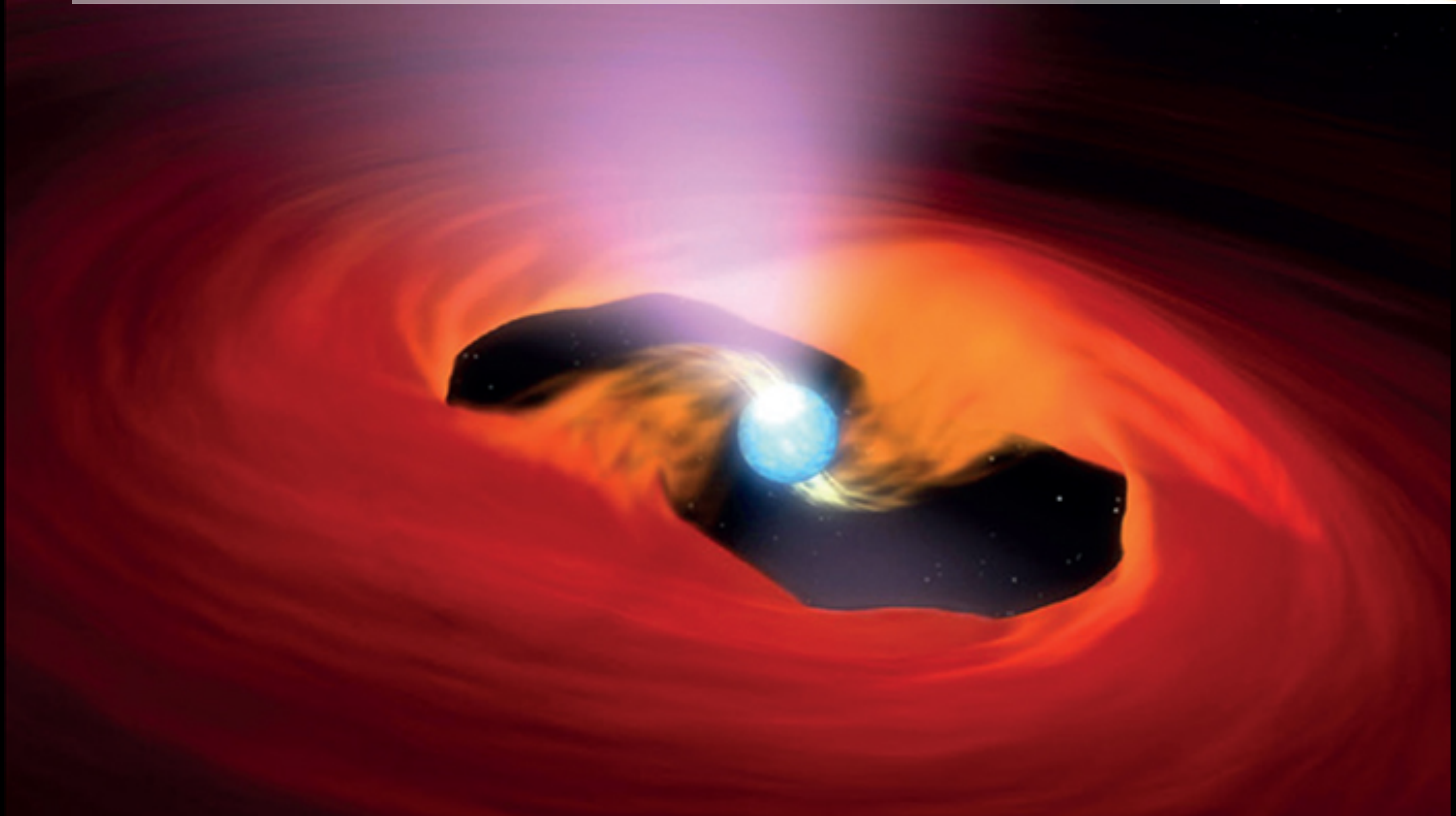
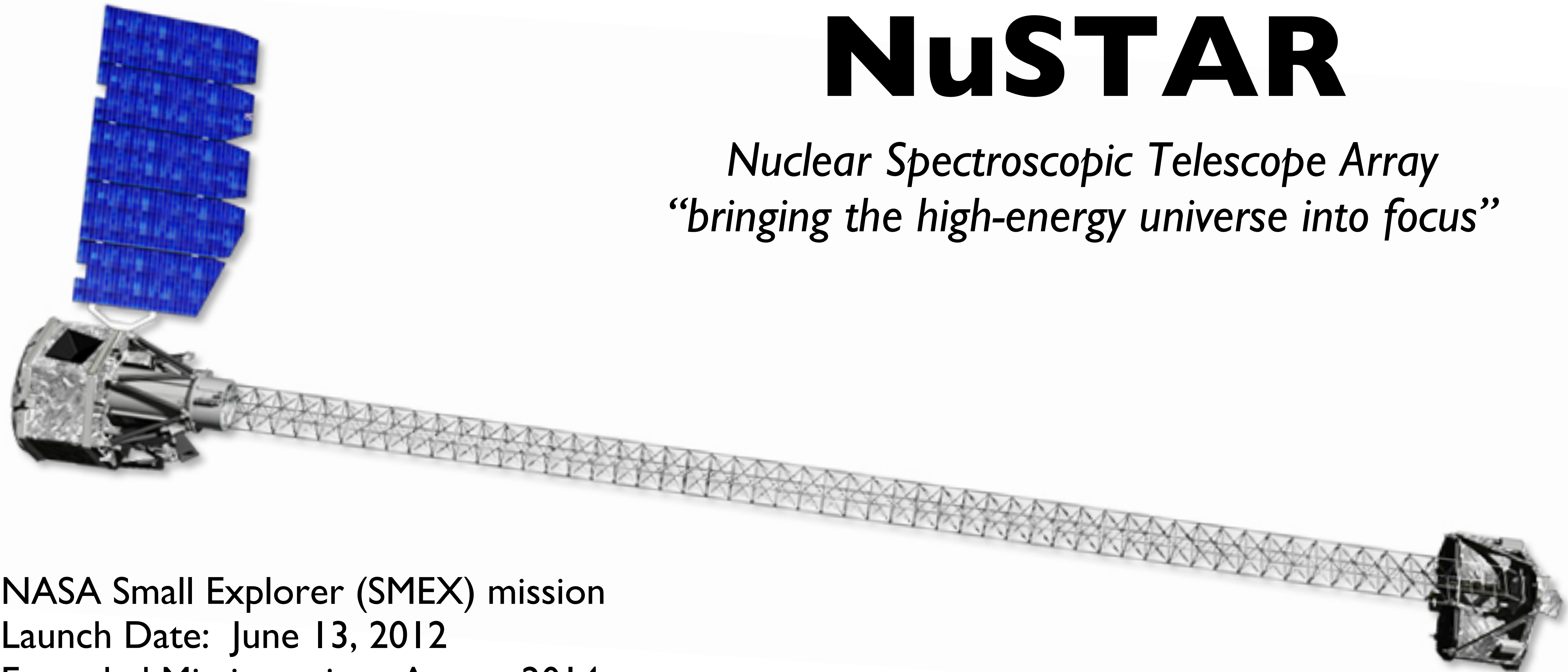
NuSTAR and Super-Eddington Accretion onto Neutron Stars



Murray Brightman, Fiona Harrison, Matteo Bachetti, Felix Fuerst, Daniel Stern, Matthew Middleton, Andy Fabian, Dom Walton, Didier Barret

NuSTAR

Nuclear Spectroscopic Telescope Array
“bringing the high-energy universe into focus”

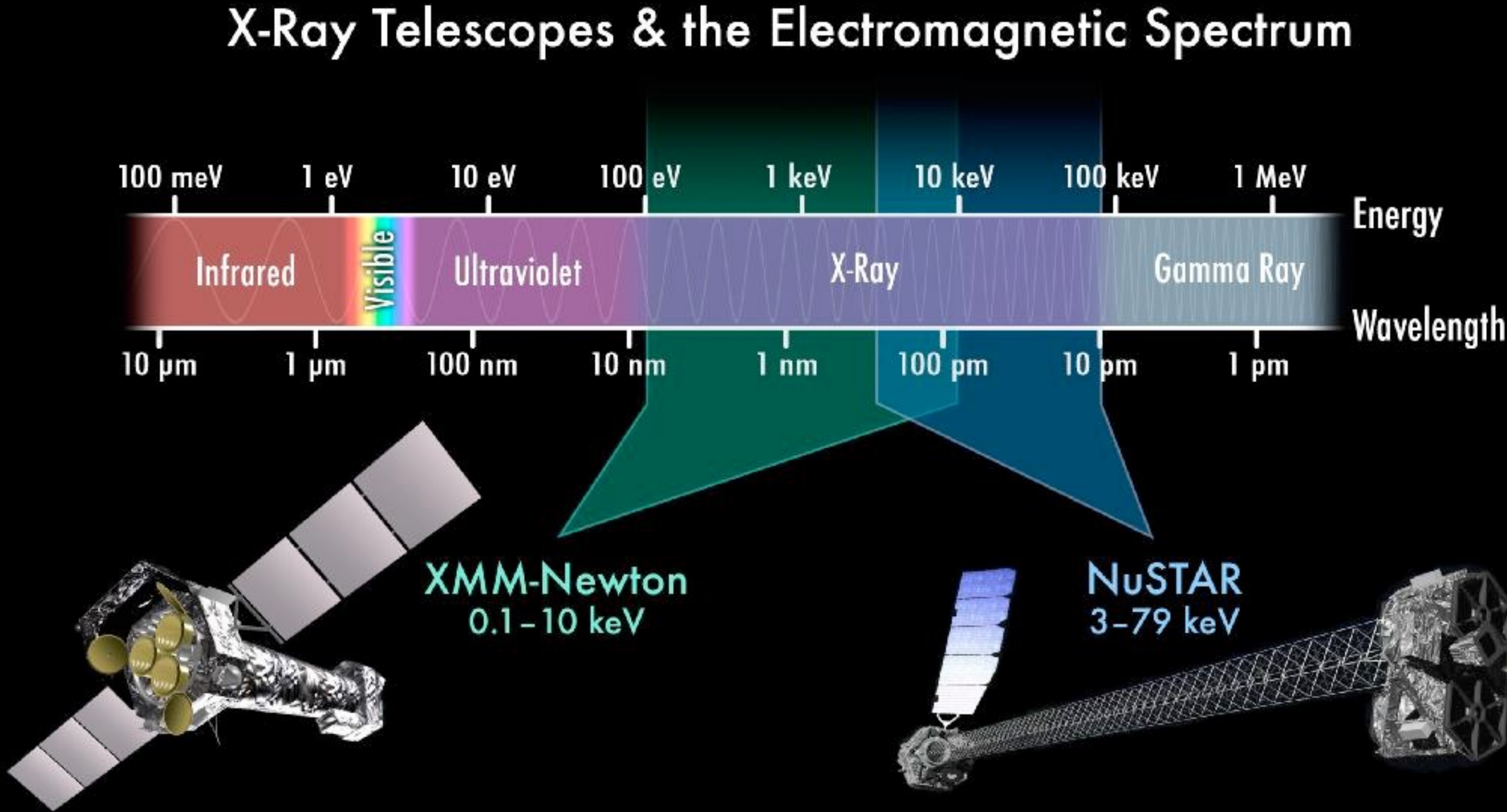


NASA Small Explorer (SMEX) mission
Launch Date: June 13, 2012
Extended Mission: since August 2014

Principal Investigator (P.I.): Fiona Harrison (Caltech)
Project Scientist: Daniel Stern (JPL/Caltech)

http://www.nustar.caltech.edu/

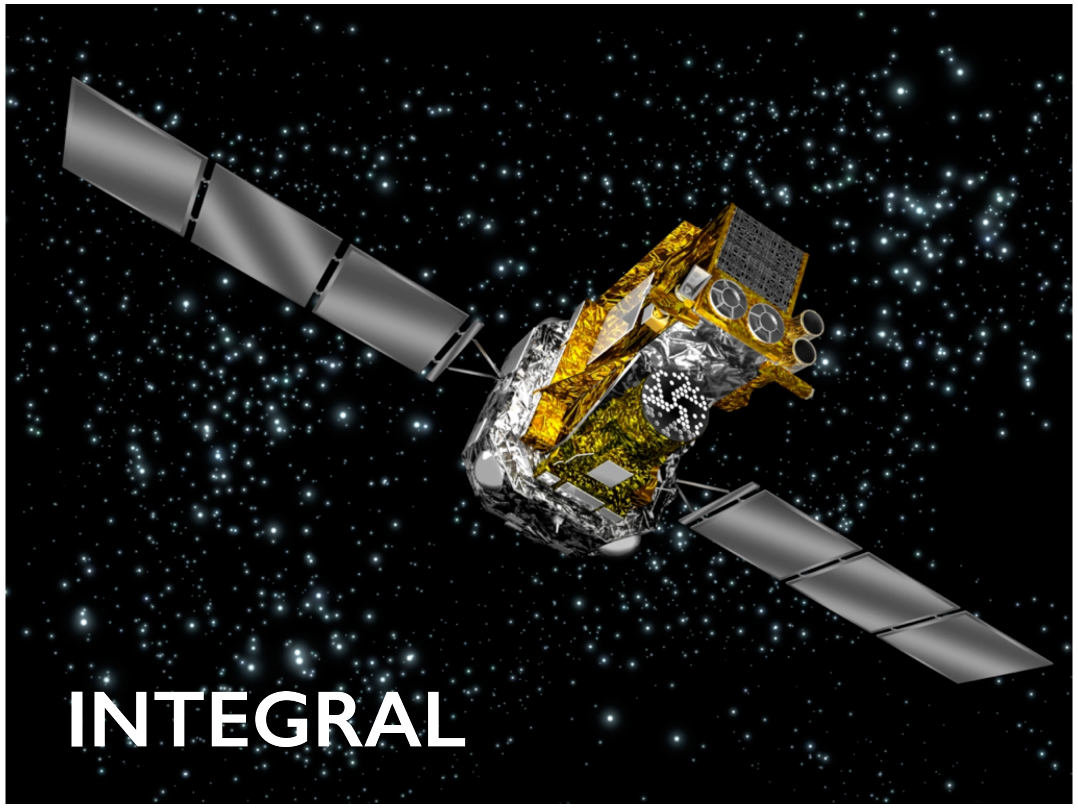
JPL · DTU Space National Space Institute · ATK Space · Orbital · agenzia spaziale italiana

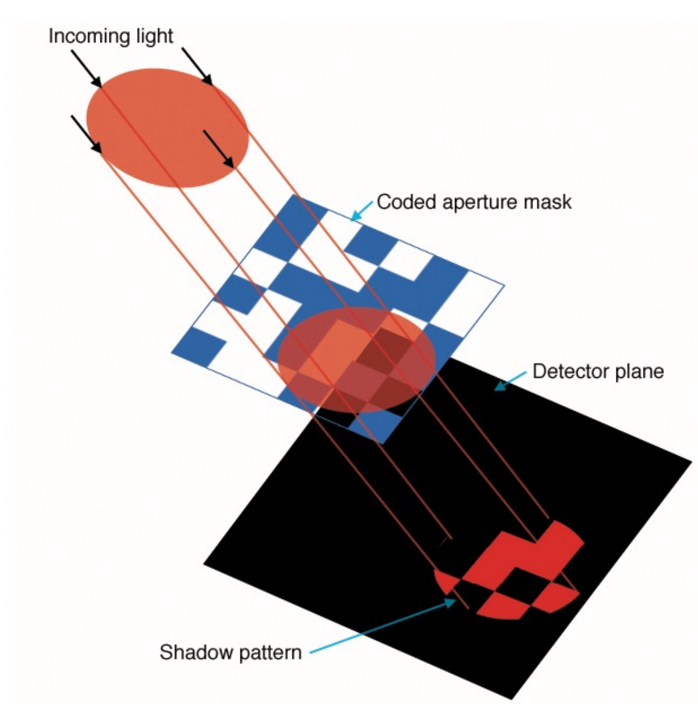


low-energy X-rays
"soft" X-rays

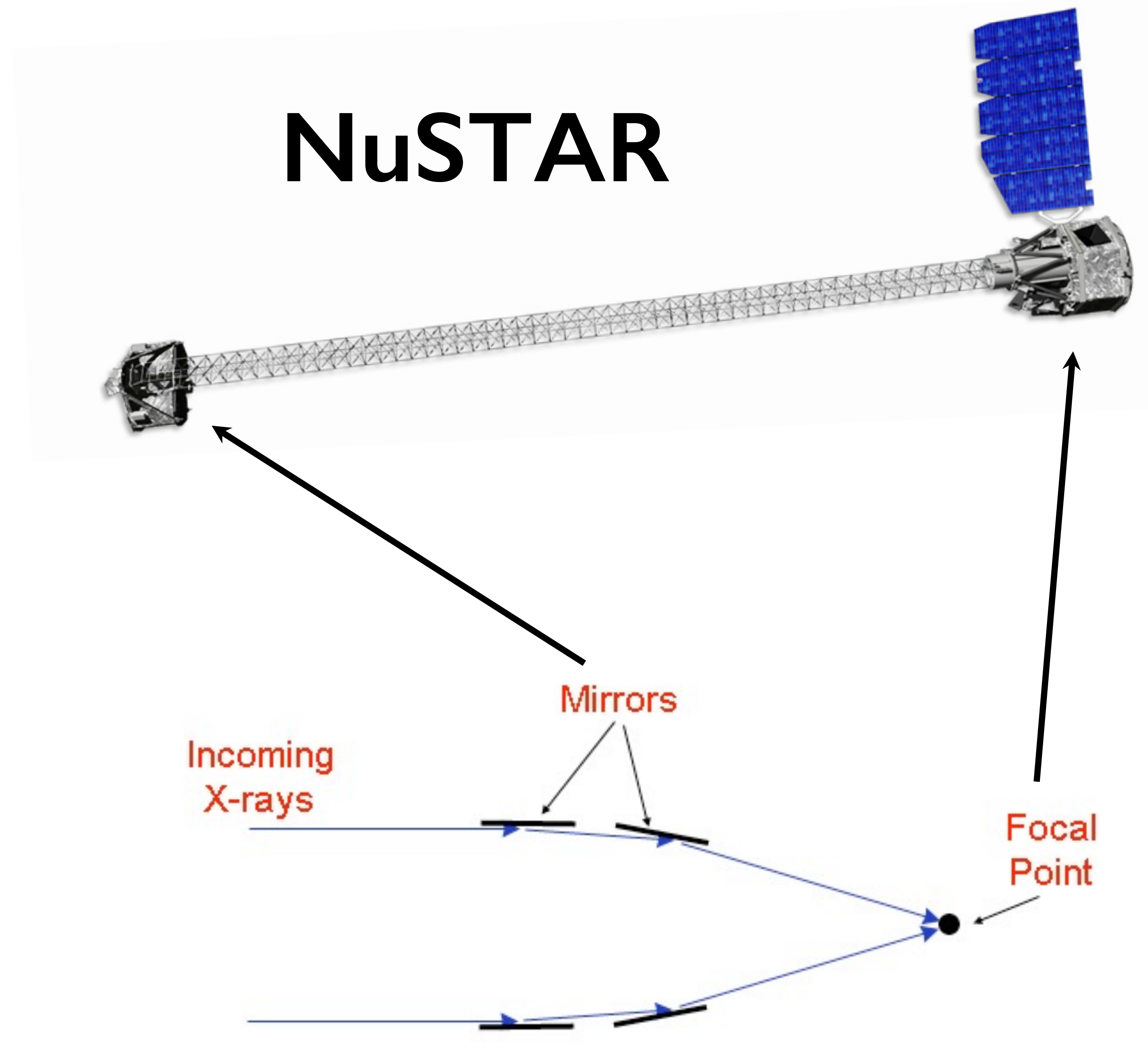
high-energy X-rays
"hard" X-rays

NuSTAR is the **first** focusing hard X-ray satellite





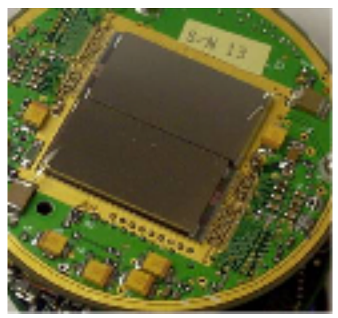
Coded Aperture Optics:
high background, large detector, blurry images



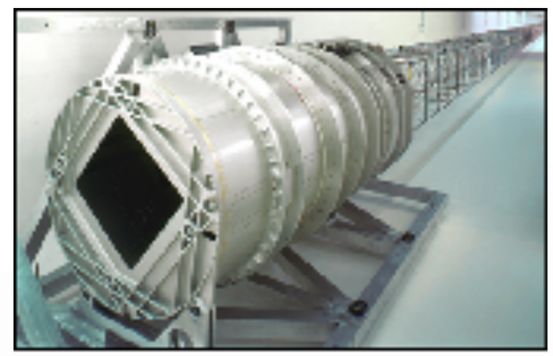
Grazing Incidence Optics:
low background, compact detector, sharp images

Three Key Technologies

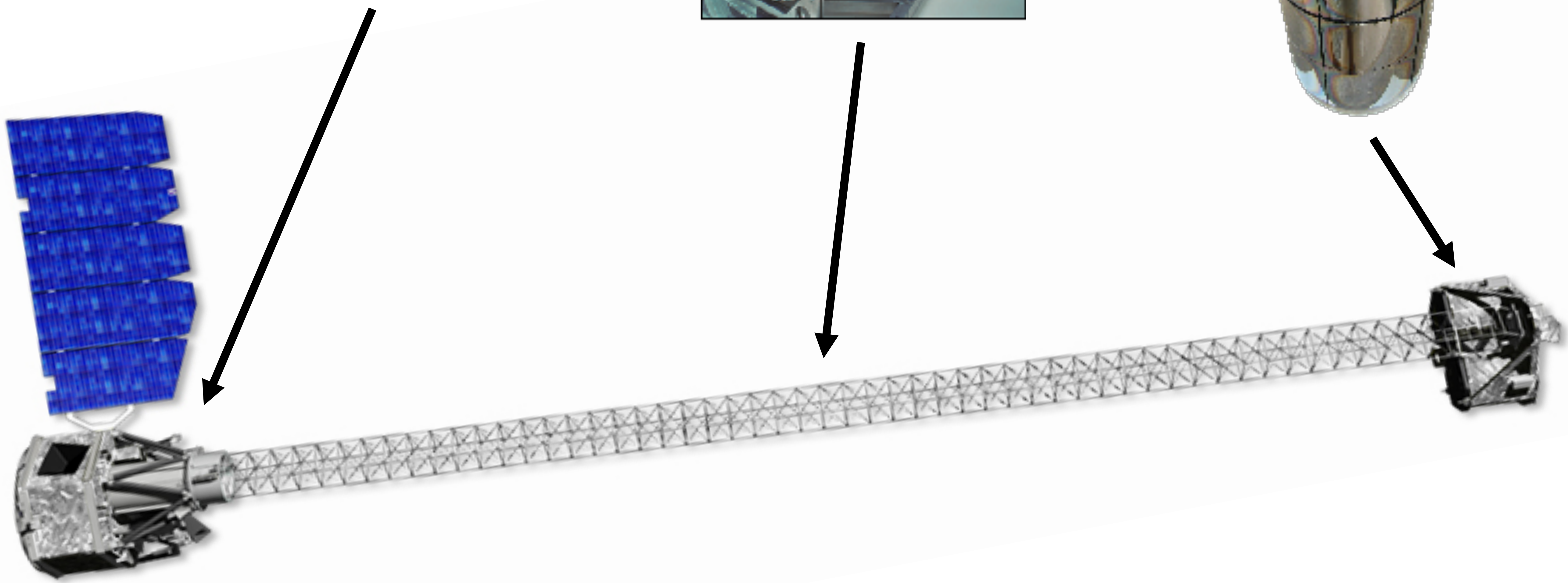
CdZnTe detector
(HEFT)



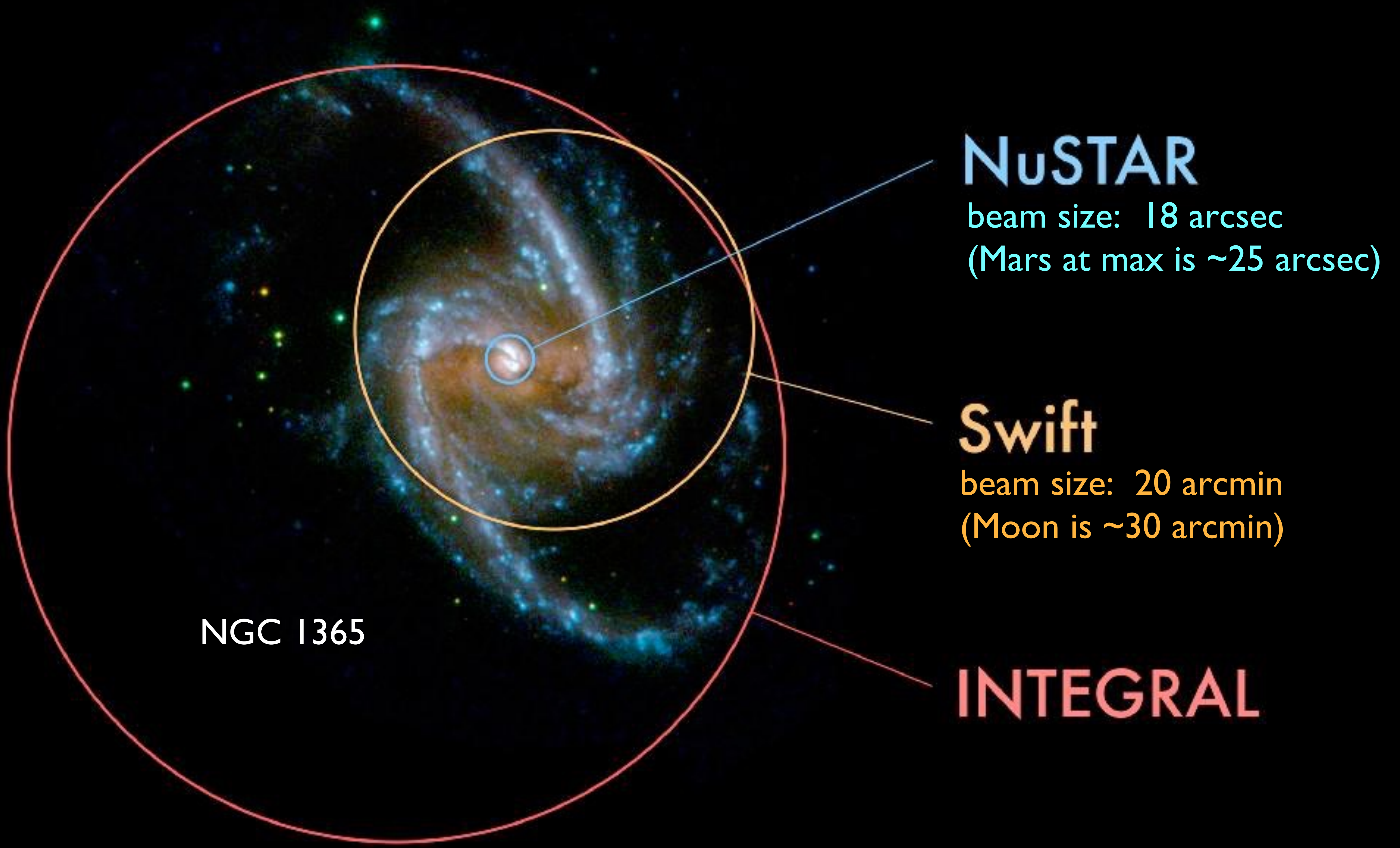
deployable mast
(SRTM: Shuttle Radar
Topography Mission)



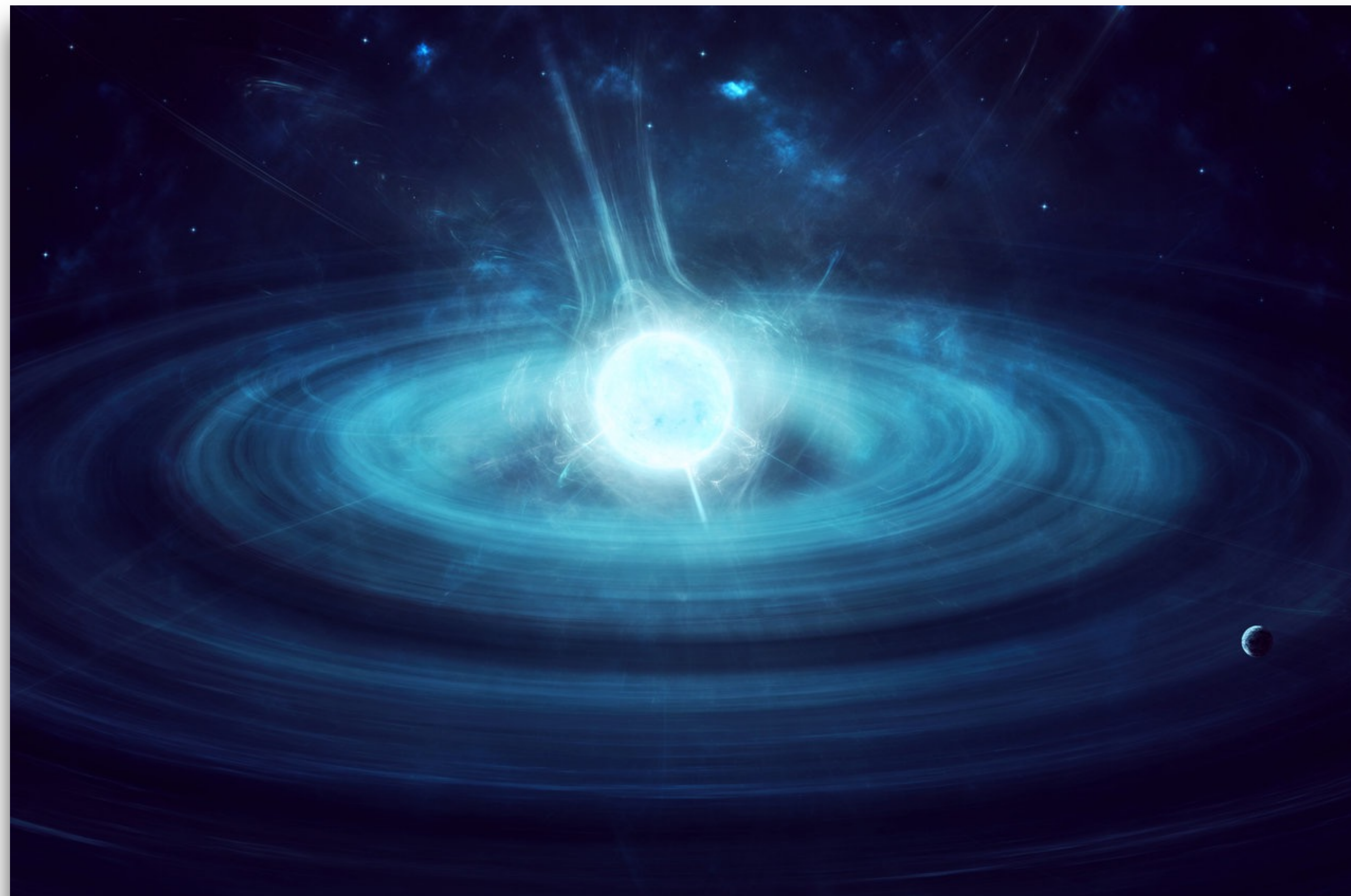
hard X-ray optics
(HEFT: High-Energy
Focusing Telescope)



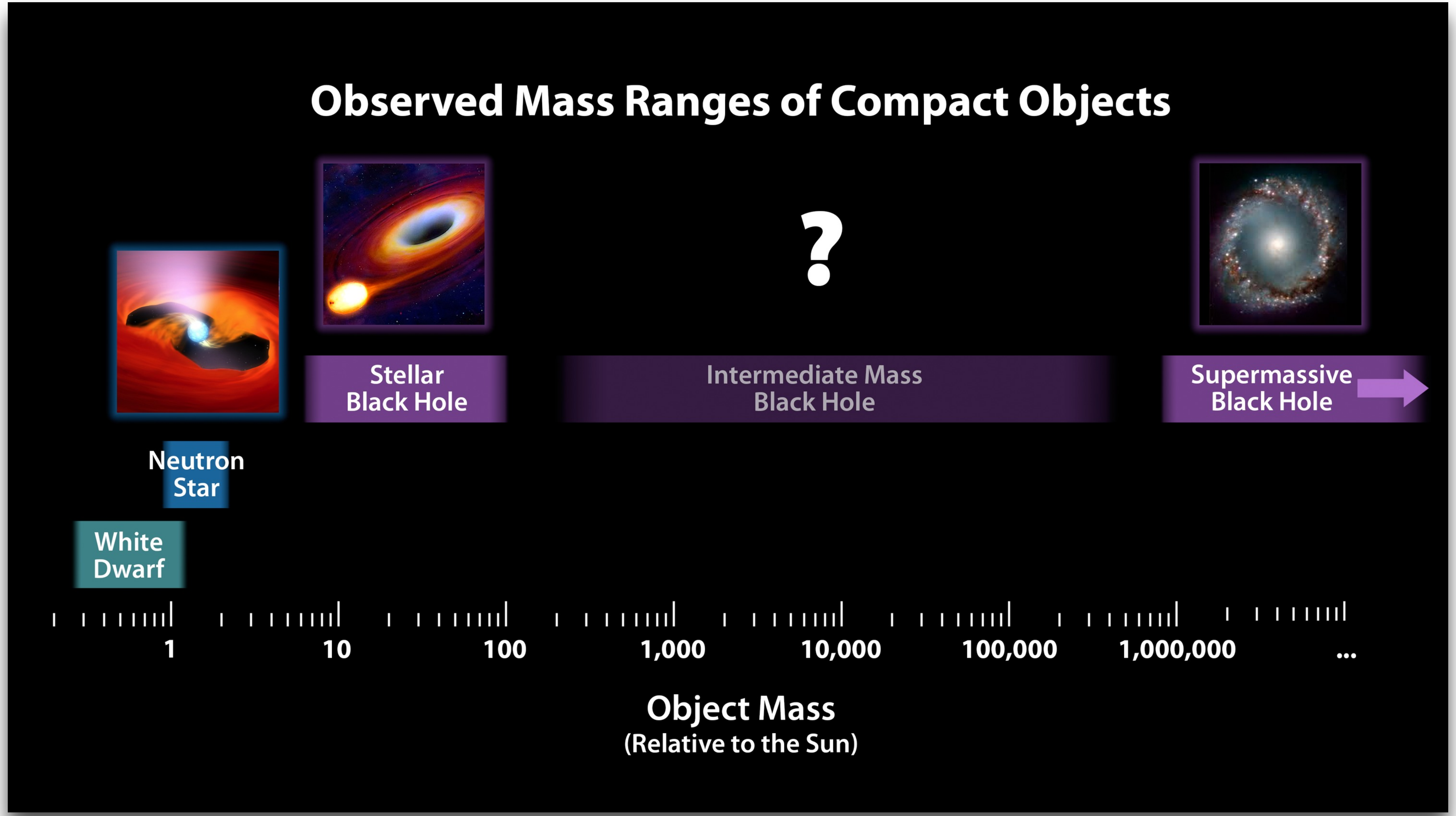
High-Energy Missions in Orbit:
angular resolution comparison

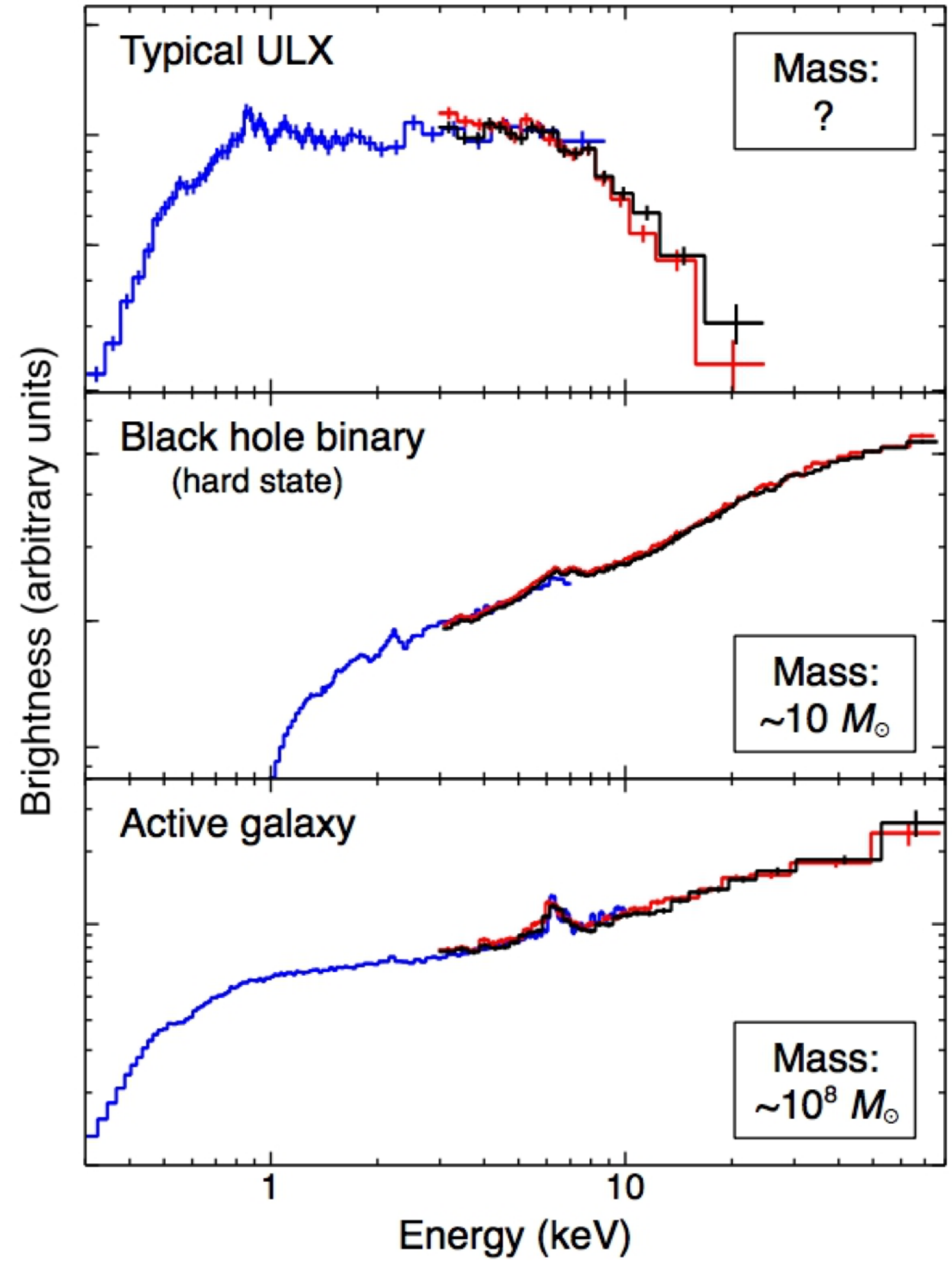


Ultraluminous X-Ray Sources



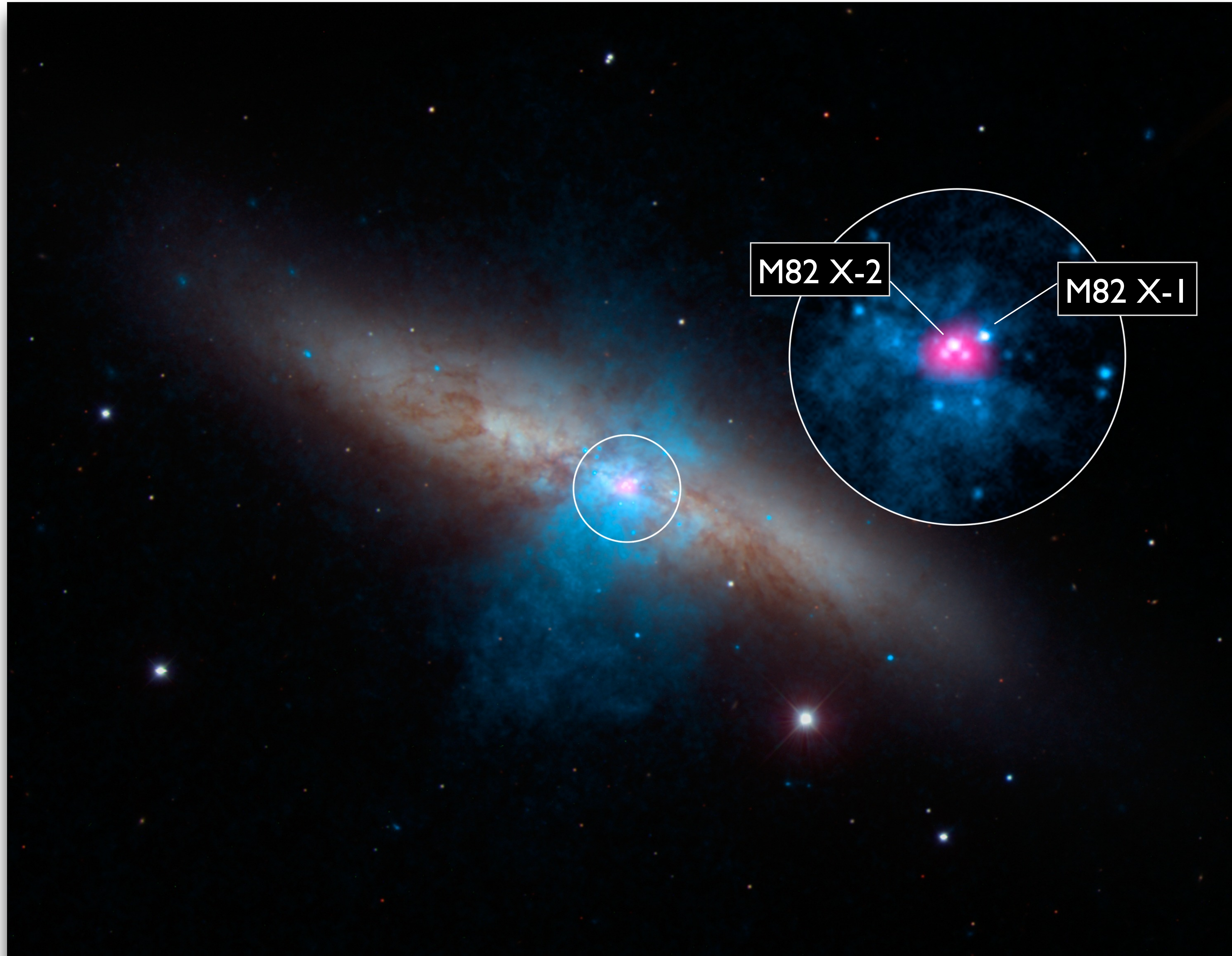
- large black holes, ~1000x the mass of the sun, feeding at typical rates?
- stellar mass black holes feeding at prodigious rates?
- something else?


Observed Mass Ranges of Compact Objects
?
Stellar Black Hole
Intermediate Mass Black Hole
Supermassive Black Hole
Neutron Star
White Dwarf
1
10
100
1,000
10,000
100,000
1,000,000
...
Object Mass
(Relative to the Sun)



- large black holes, ~1000x the mass of the sun, feeding at typical rates?
- stellar mass black holes feeding at prodigious rates?
- something else?

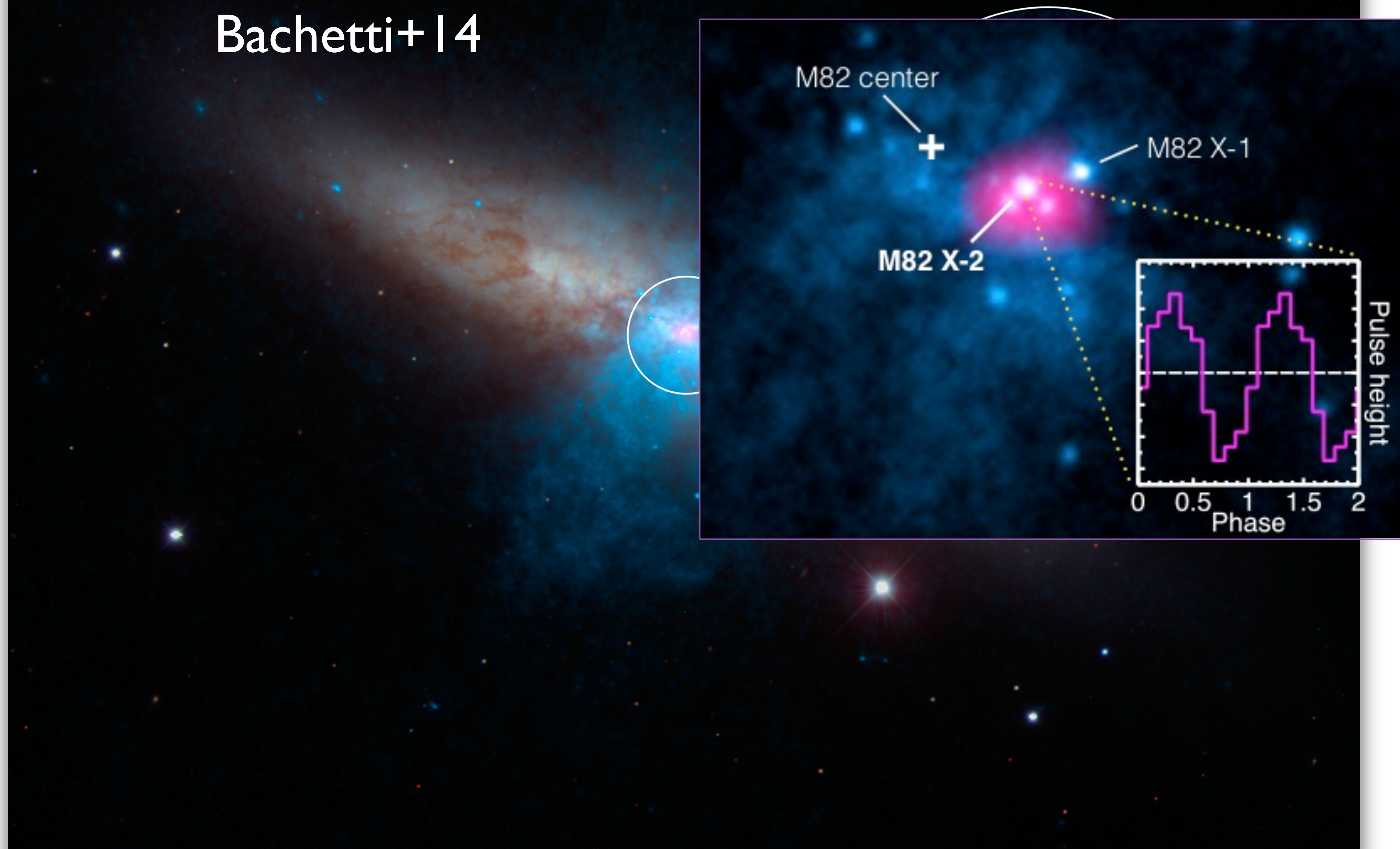
Messier 82 (AKA M82, or the "Cigar Galaxy")



M82 X-2
M82 X-1

NuSTAR detects coherent pulsations from an ultraluminous X-ray source

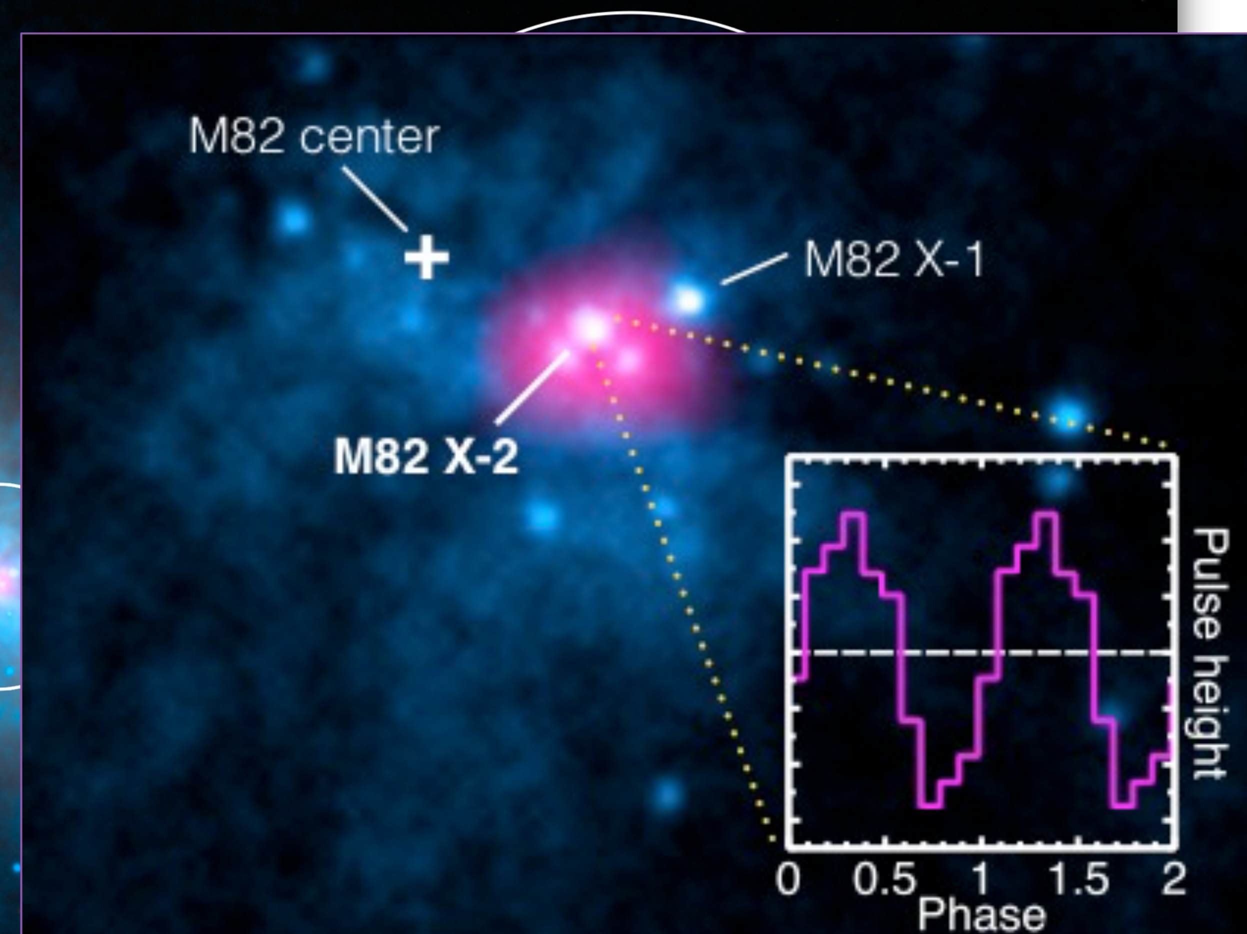
Bachetti+14



NuSTAR detects coherent pulsations from an ultraluminous X-ray source

Bachetti+14

Can only be produced by a rapidly spinning, magnetized neutron star (black holes cannot produce these)



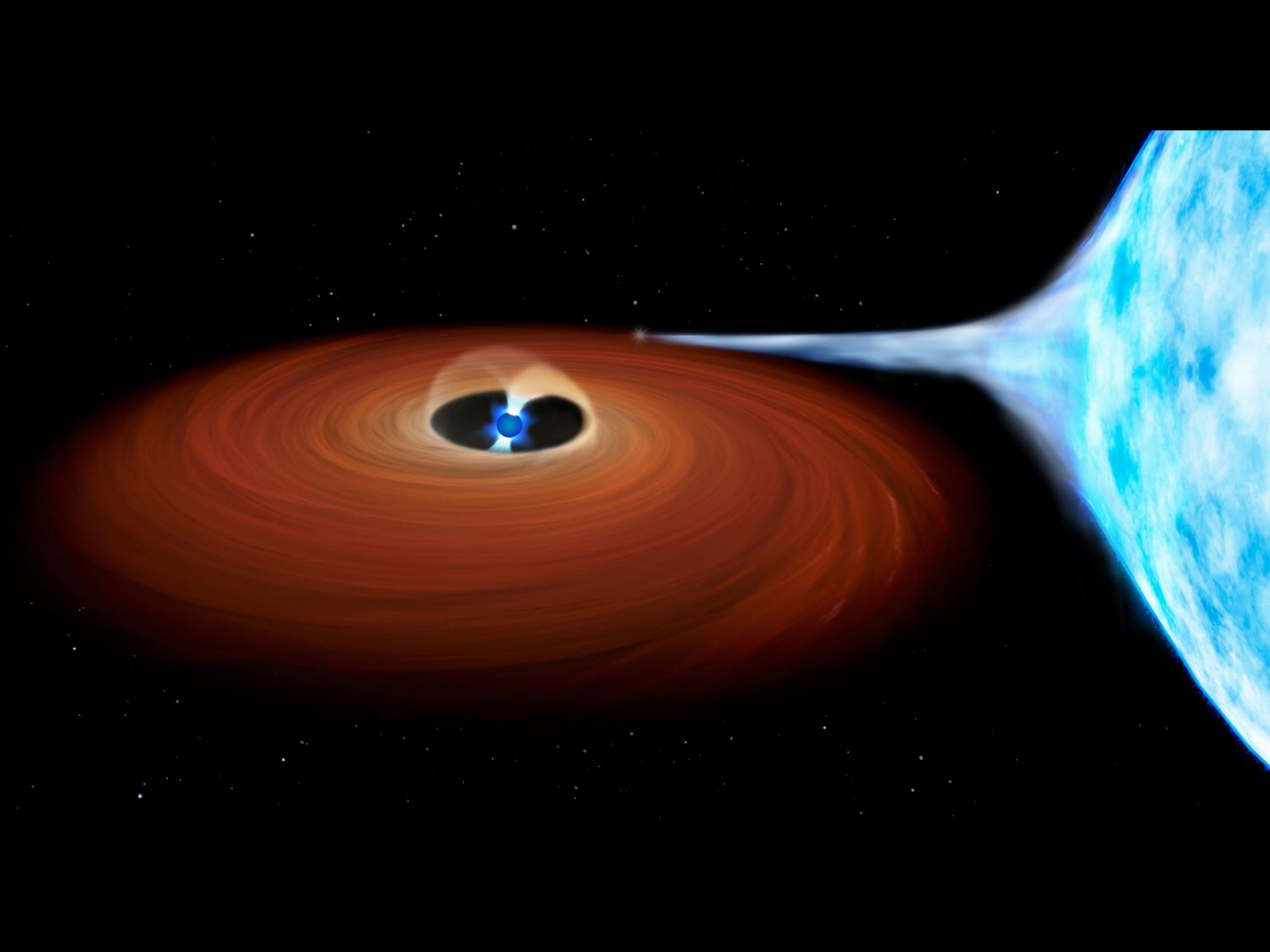
1.37-s period,
-2×10^{-10} s s^{-1} variable period derivative
2.5-day orbital period
5.2-M_{sol} minimum mass companion

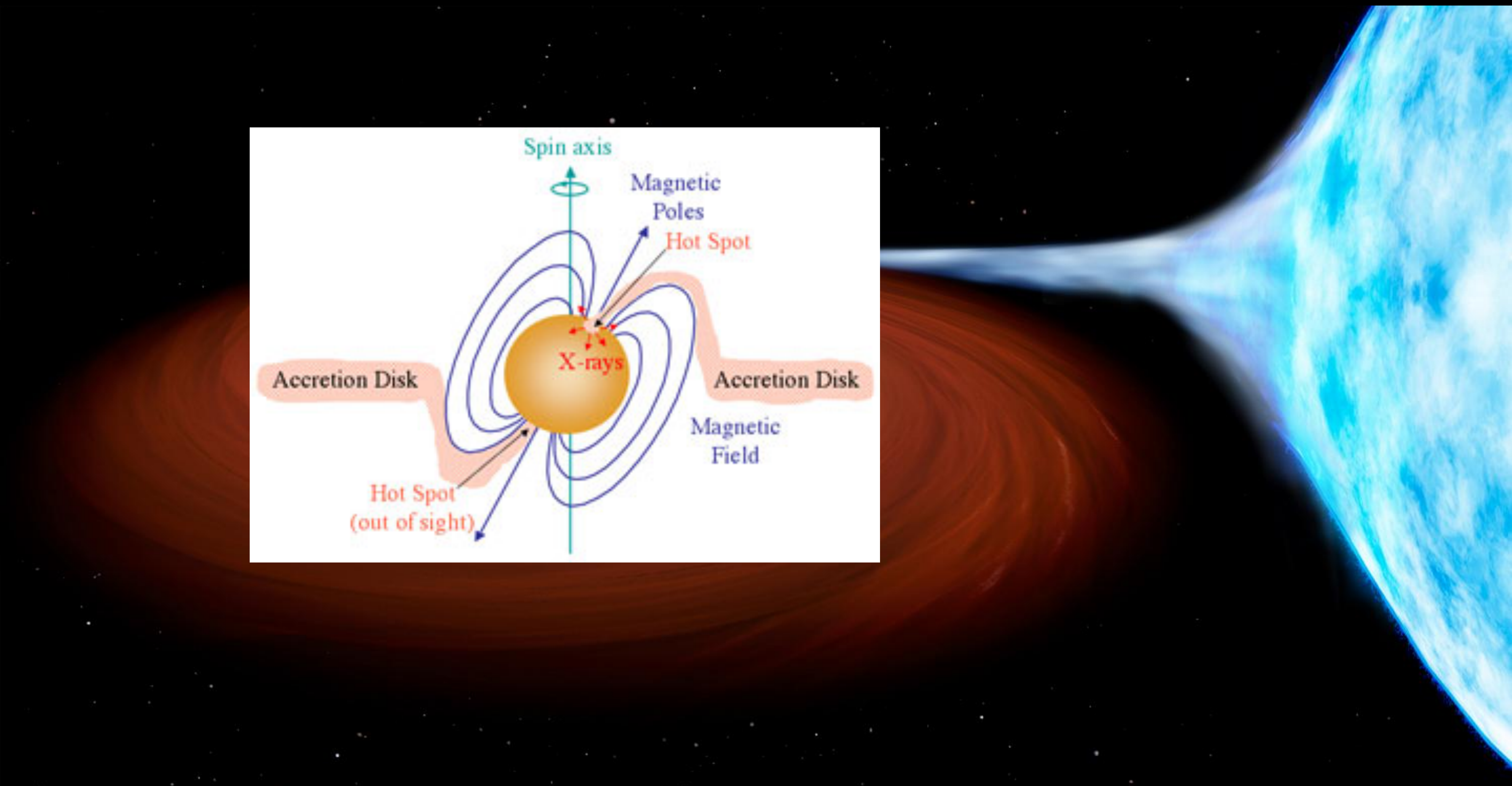
Eddington limit

$$L_{\mathrm{Edd}} = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{T}}}$$

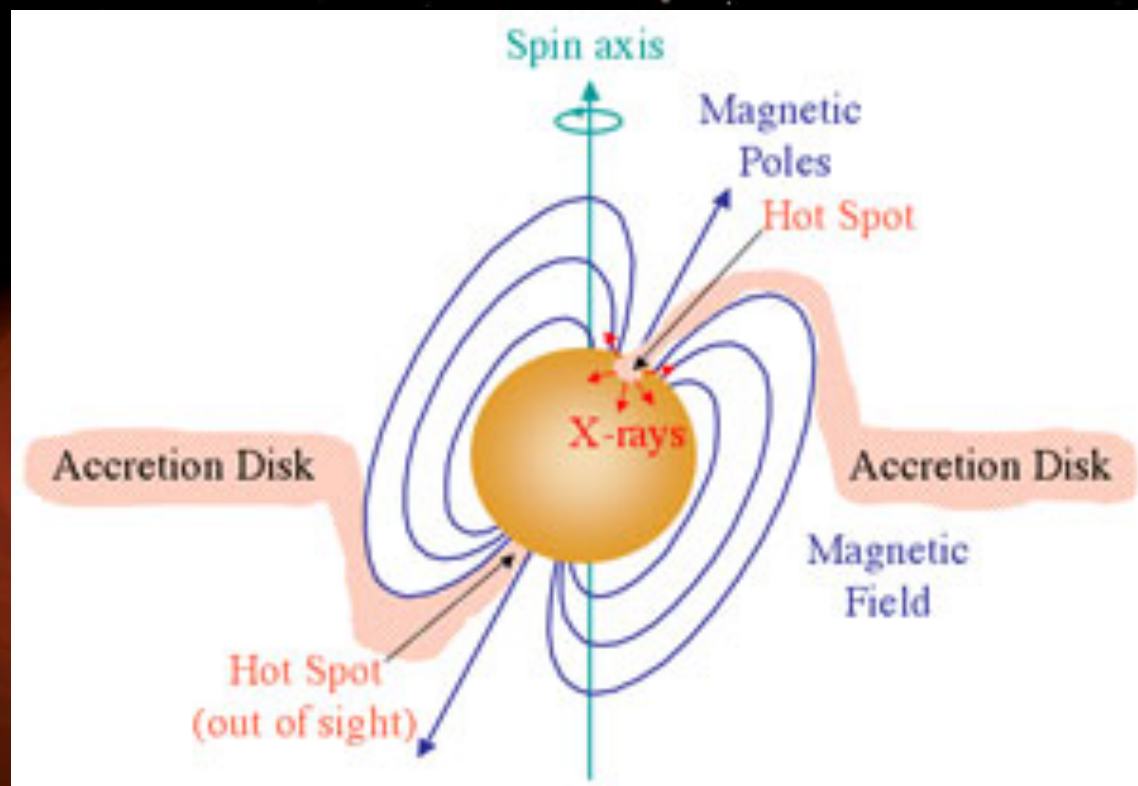
$$\cong 1.26 \times 10^{31} \left(\frac{M}{M_{\odot}} \right) \mathrm{W}$$

$$1.26 \times 10^{38} \left(\frac{M}{M_{\odot}} \right) \mathrm{erg/s}$$





Spin axis
Magnetic
Poles
Hot Spot
X-rays
Accretion Disk
Accretion Disk
Magnetic
Field
Hot Spot
(out of sight)



High B-field ($B>10^{12}$G) pulsars can theoretically exceed limit…
(e.g. Basko & Sunyaev 1975)
…by factors of ~a few

M82 X-2 reaches100x Eddington limit for a 1.4 M_{sol} compact object!!

Magnetic field strength of the ultraluminous pulsar

High magnetic field strength (10^{13} G)

- Dall'Osso et al (2015) explains high L_X and variation in dP/dt
- Eksi et al. (2015) based on torque equilibrium.

Typical magnetic field strength (10^{12} G)

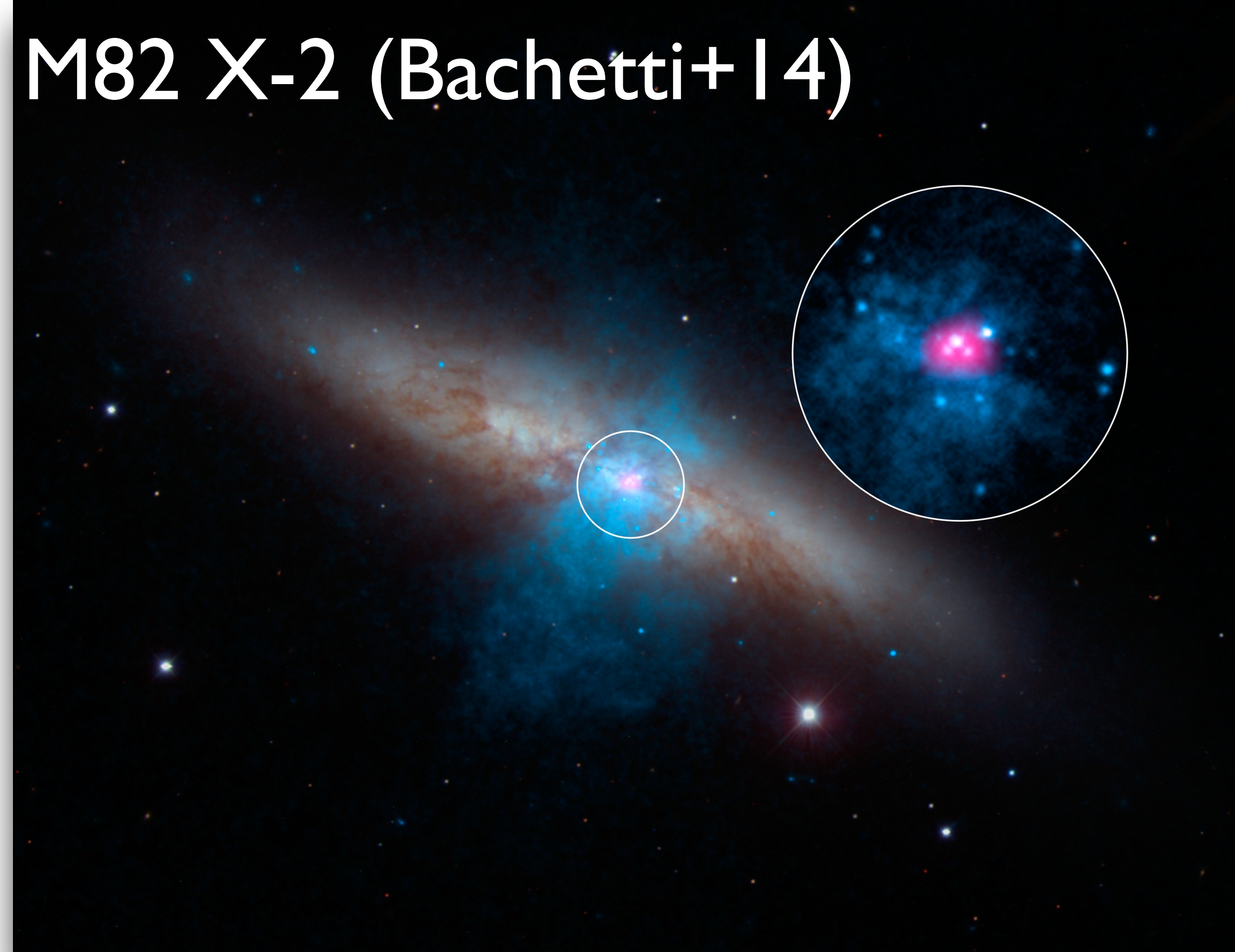
- Christodoulou et al. (2014) the observed luminosity can be accounted for by geometric beaming.

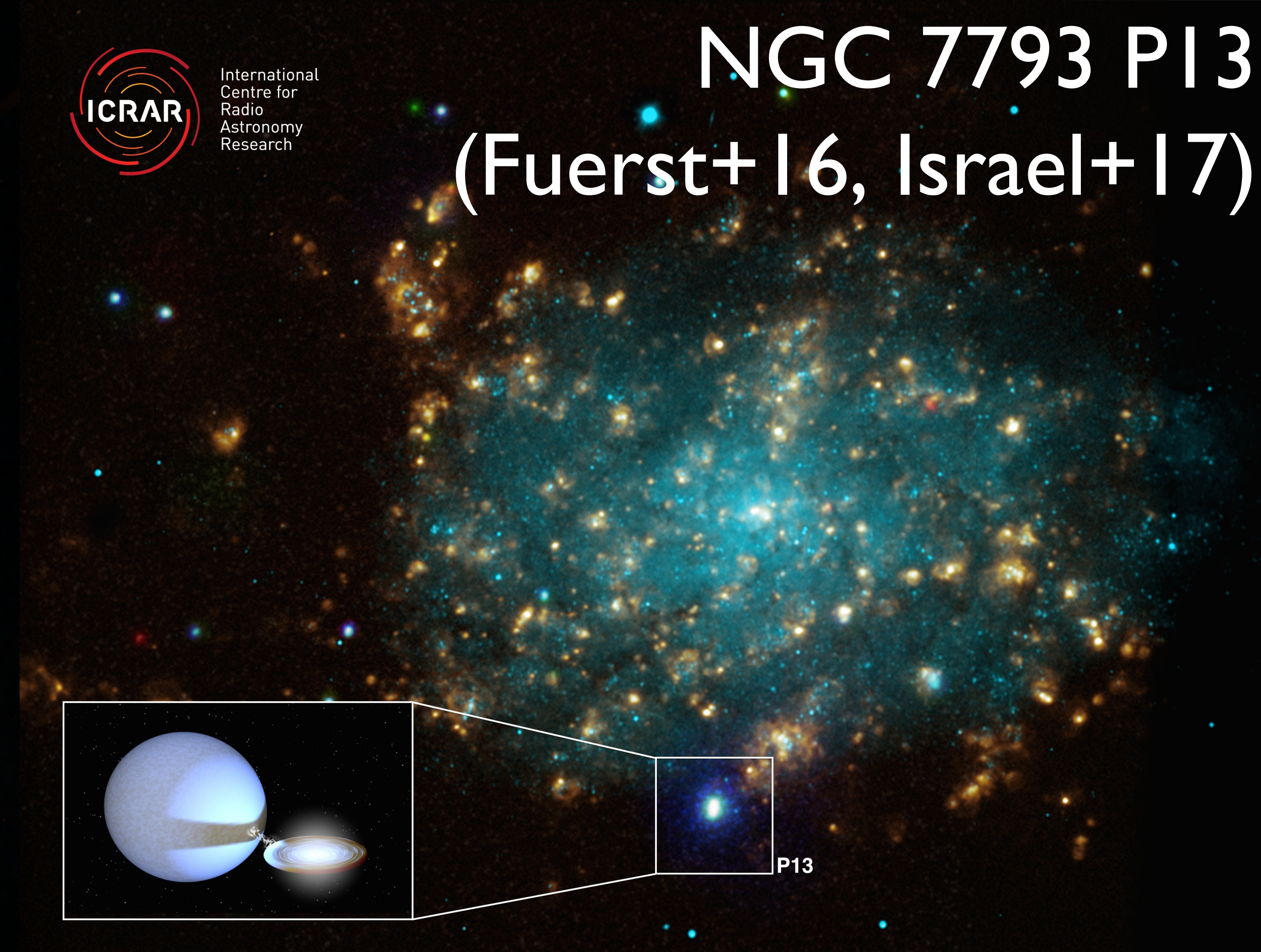
Low magnetic field strength (10^{9} G)

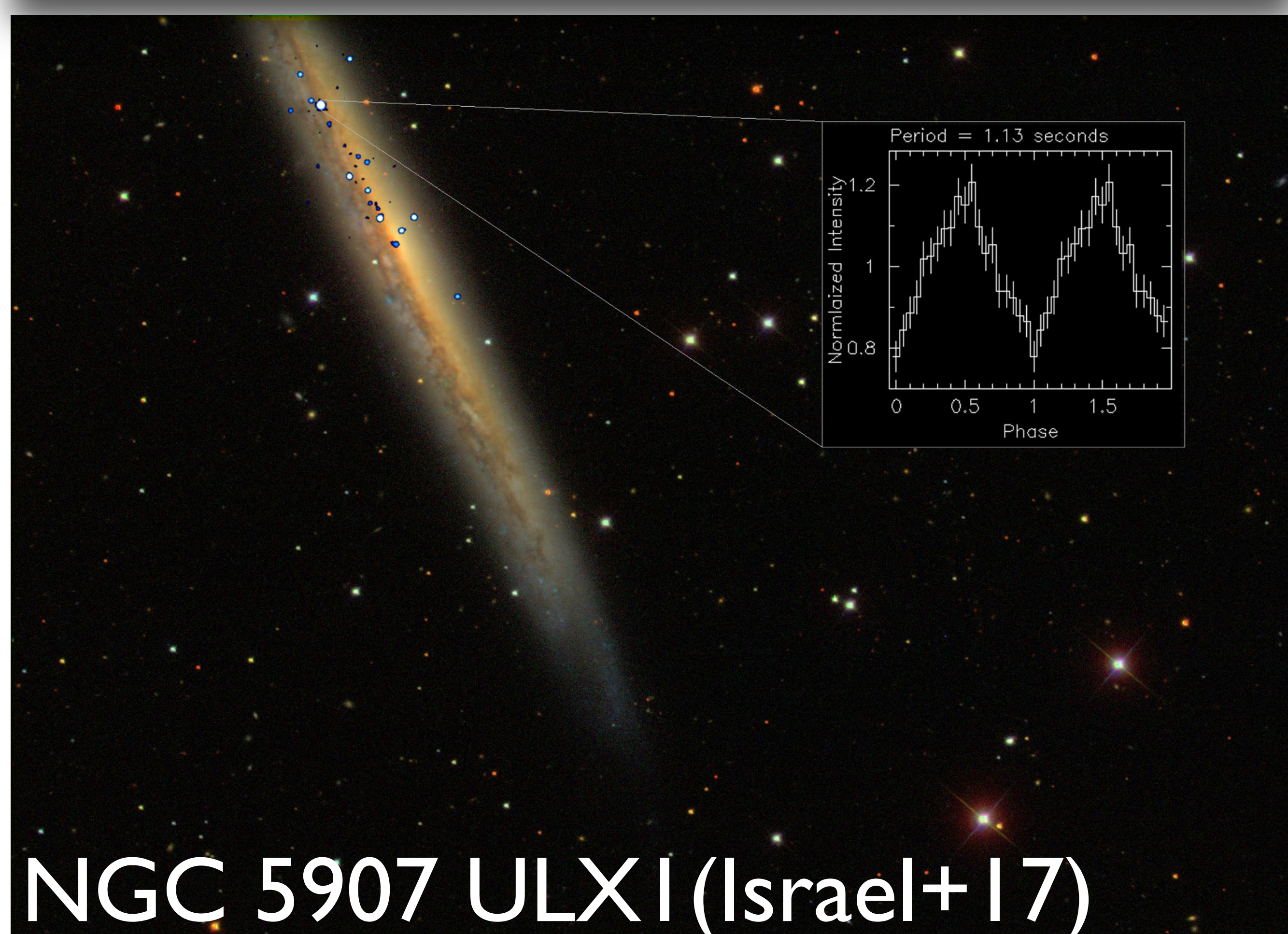
- Kluzniak & Lasota (2015) based on ratio of spin-up to luminosity.

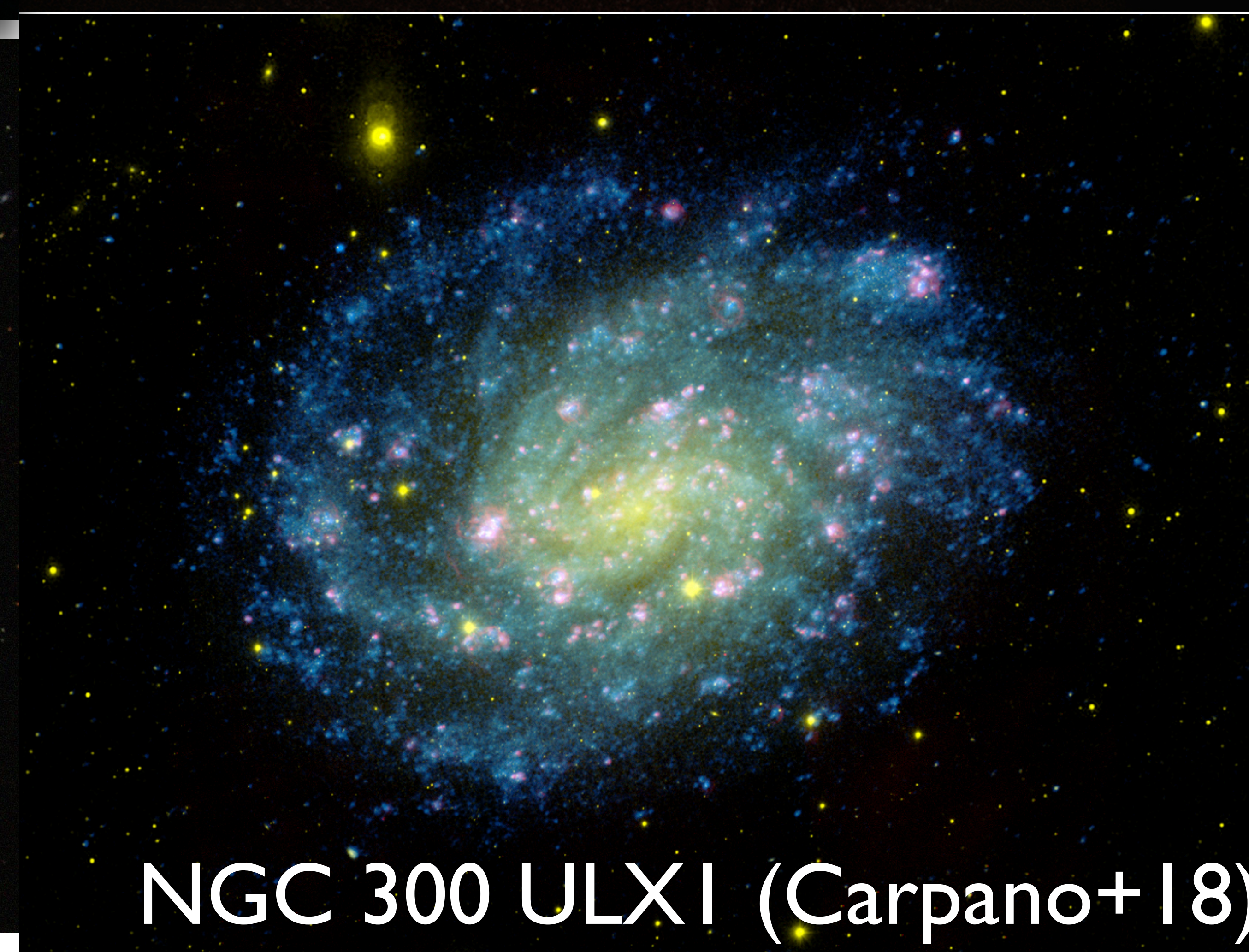
…and many others

Further observational evidence required…


M82 X-2 (Bachetti+14)

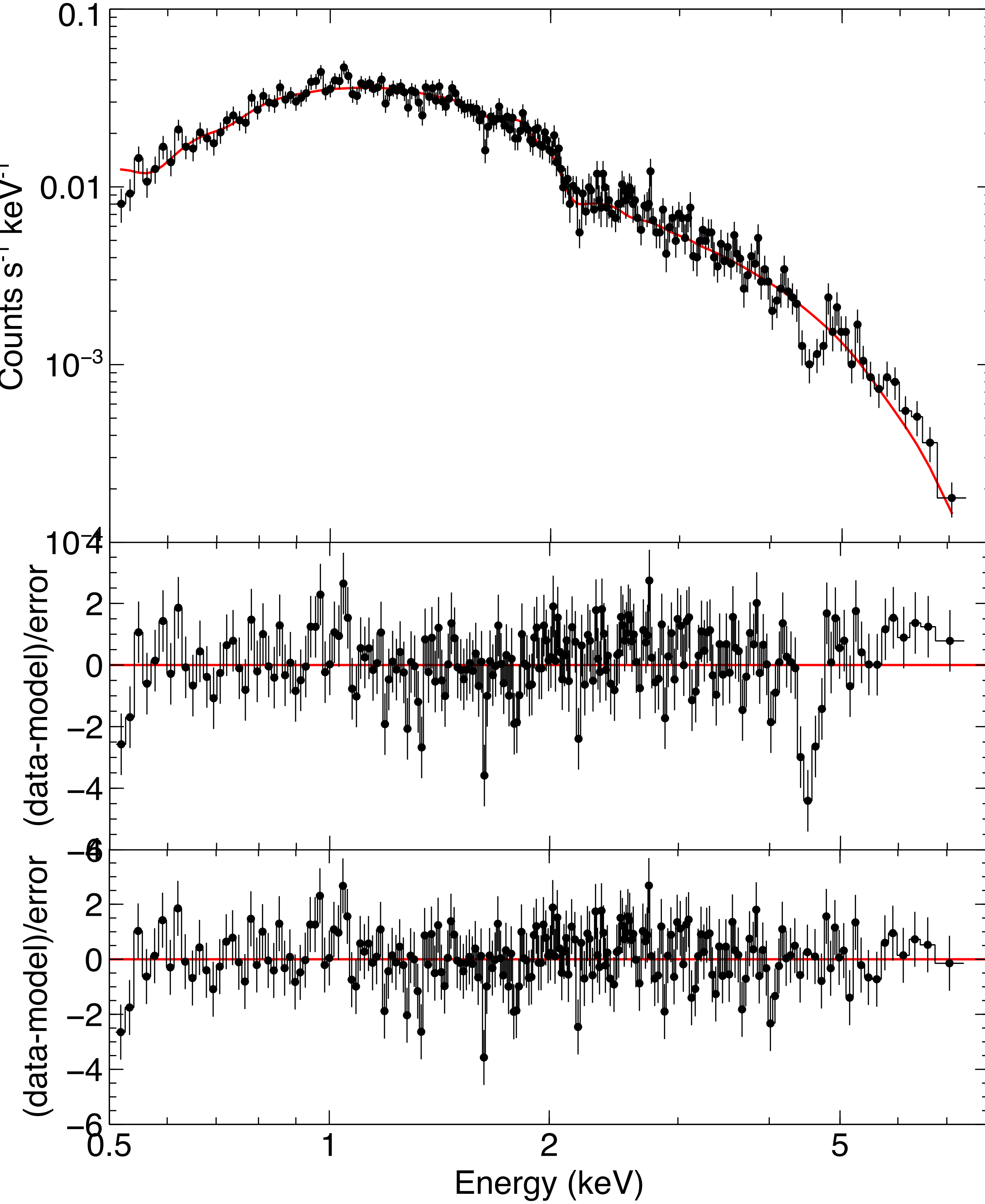

NGC 7793 P13
(Fuerst+16, Israel+17)
ICRAR
International Centre for Radio Astronomy Research
P13


Period = 1.13 seconds
Normalized Intensity
1.2
1
0.8
0
0.5
1
1.5
Phase
NGC 5907 ULX1(Israel+17)


NGC 300 ULX1 (Carpano+18)

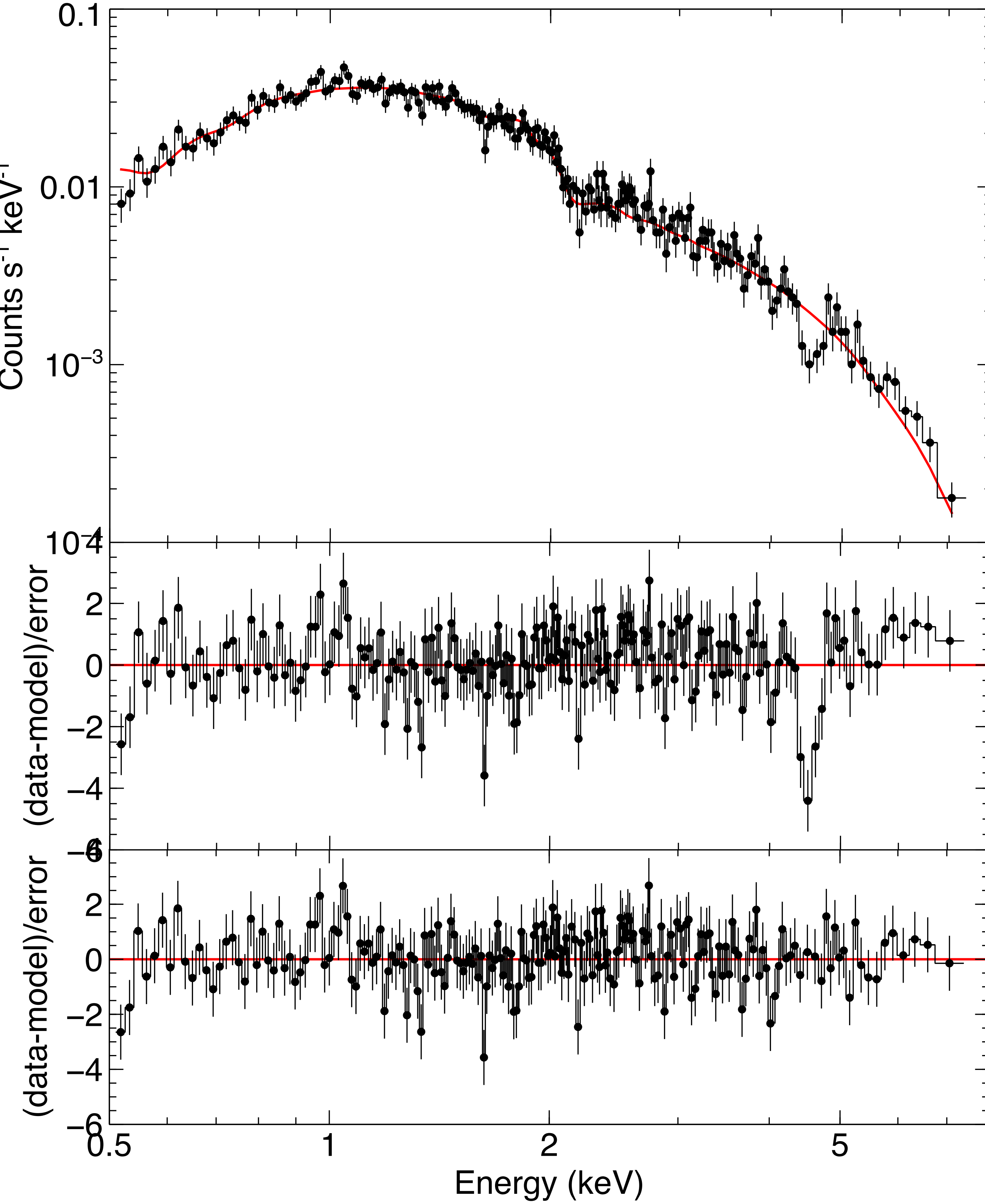

M51, the Whirlpool Galaxy
ULX8

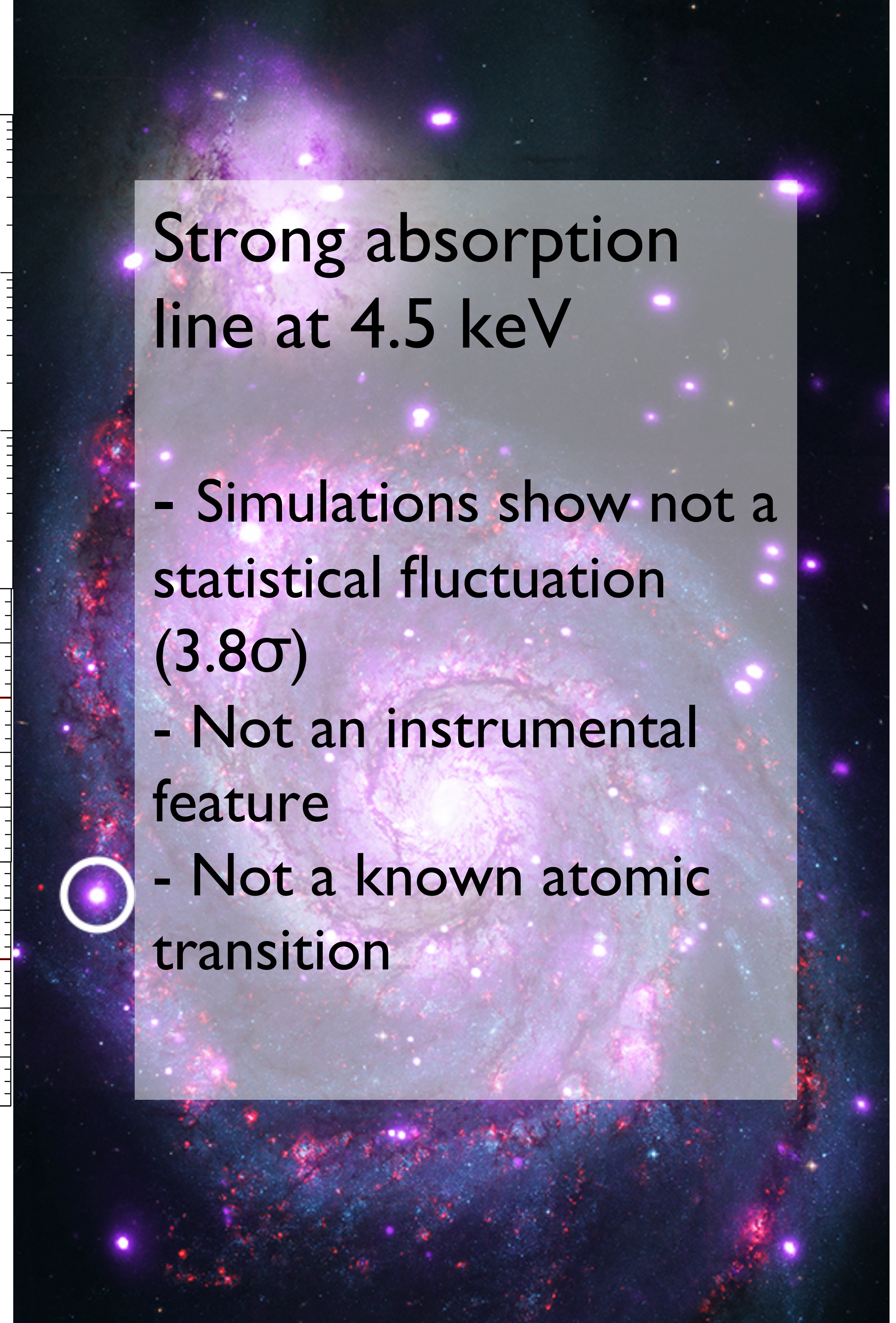
Brightman+18



M51, the Whirlpool Galaxy

Brightman+18

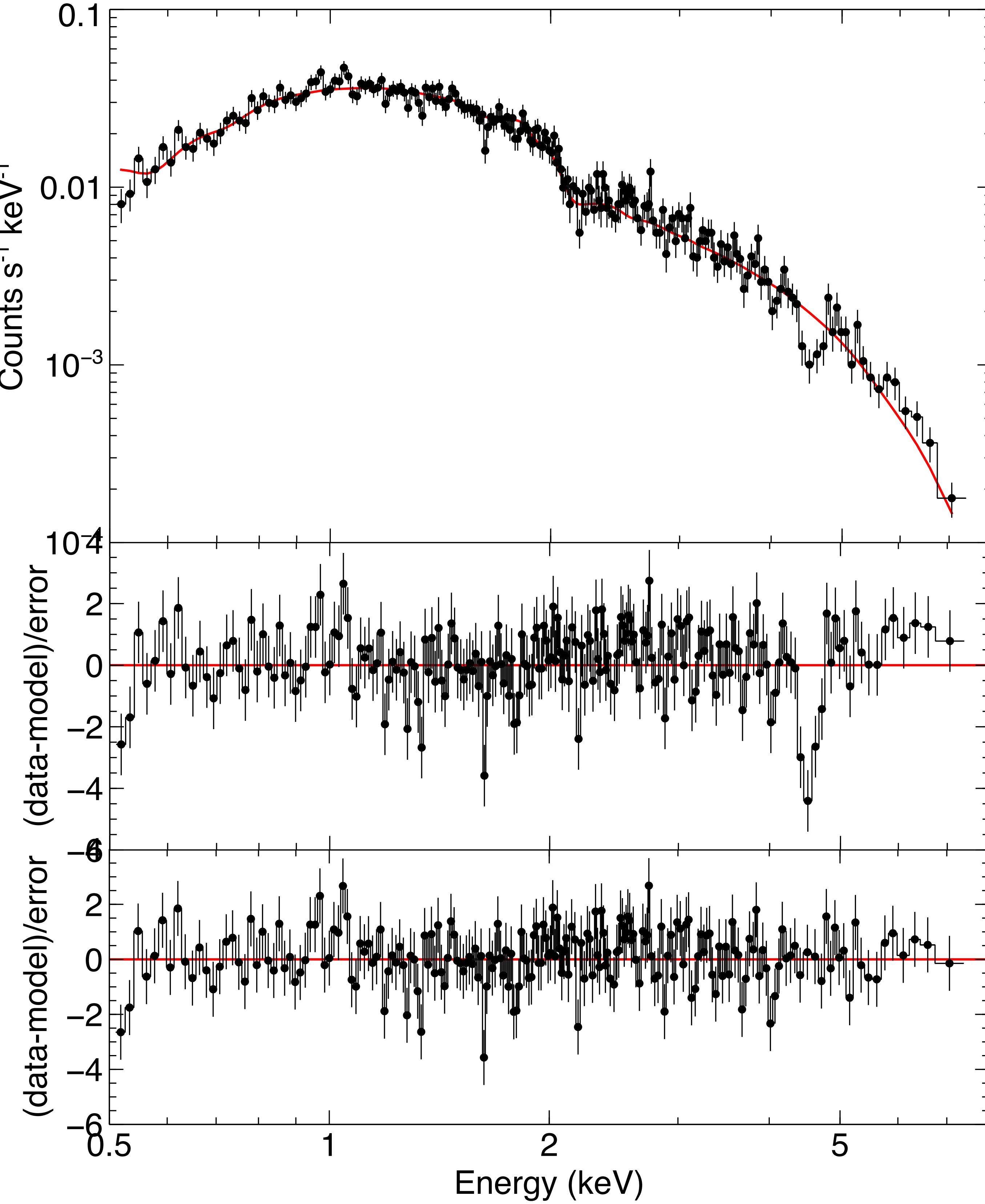


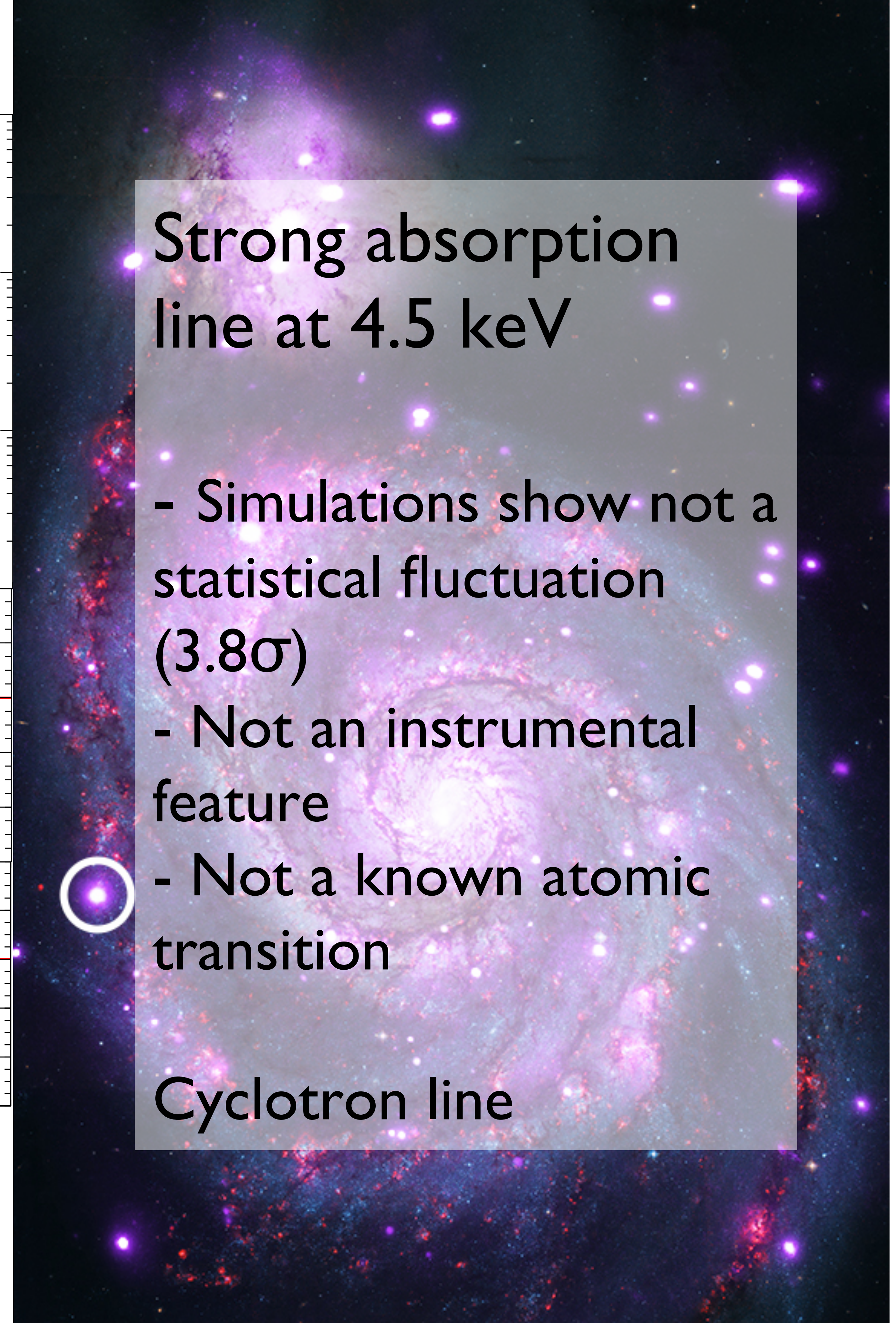


Strong absorption line at 4.5 keV

- Simulations show not a statistical fluctuation (3.8σ)
- Not an instrumental feature
- Not a known atomic transition

Brightman+18





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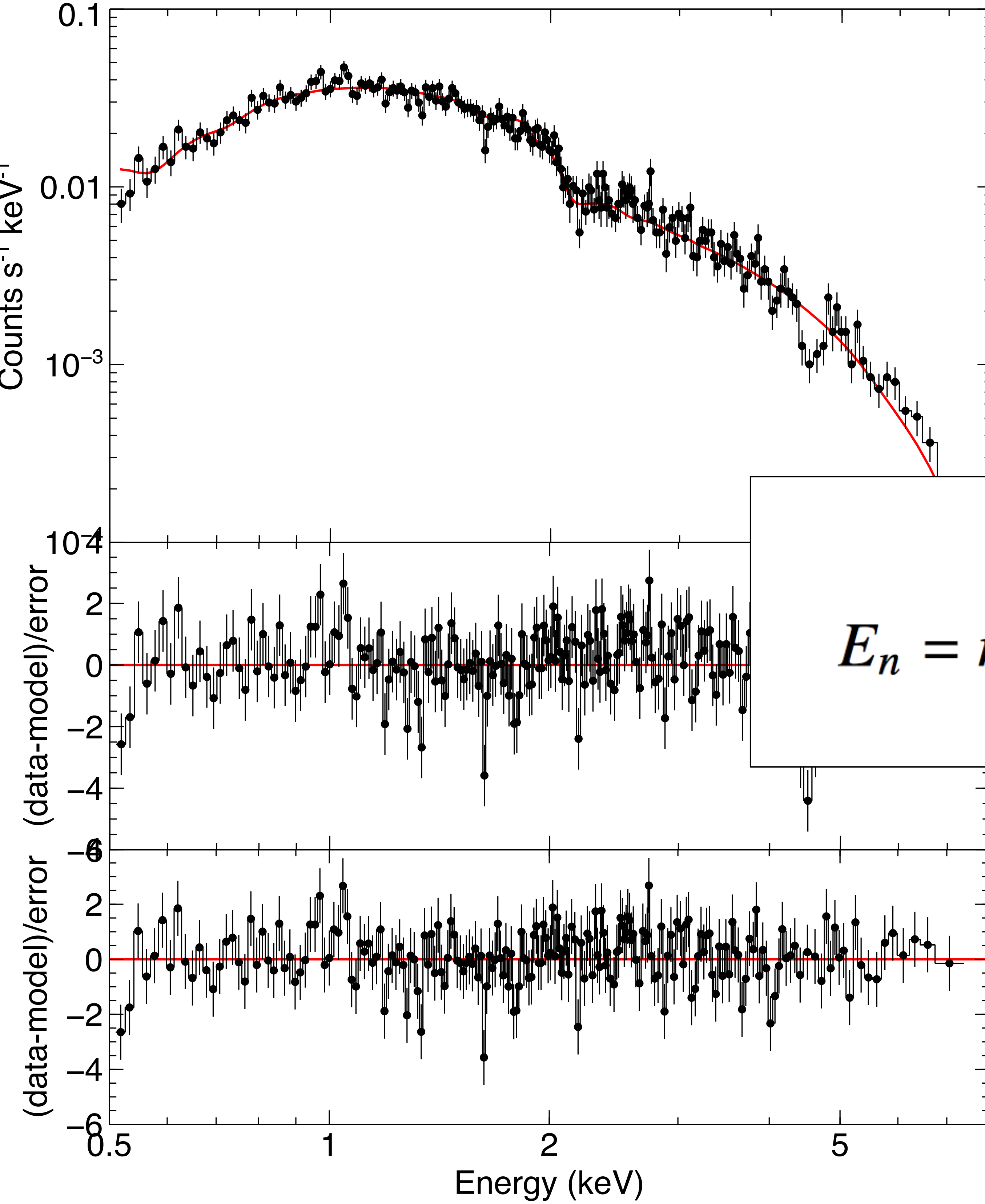
Cyclotron line

Brightman+18



Cyclotron lines:

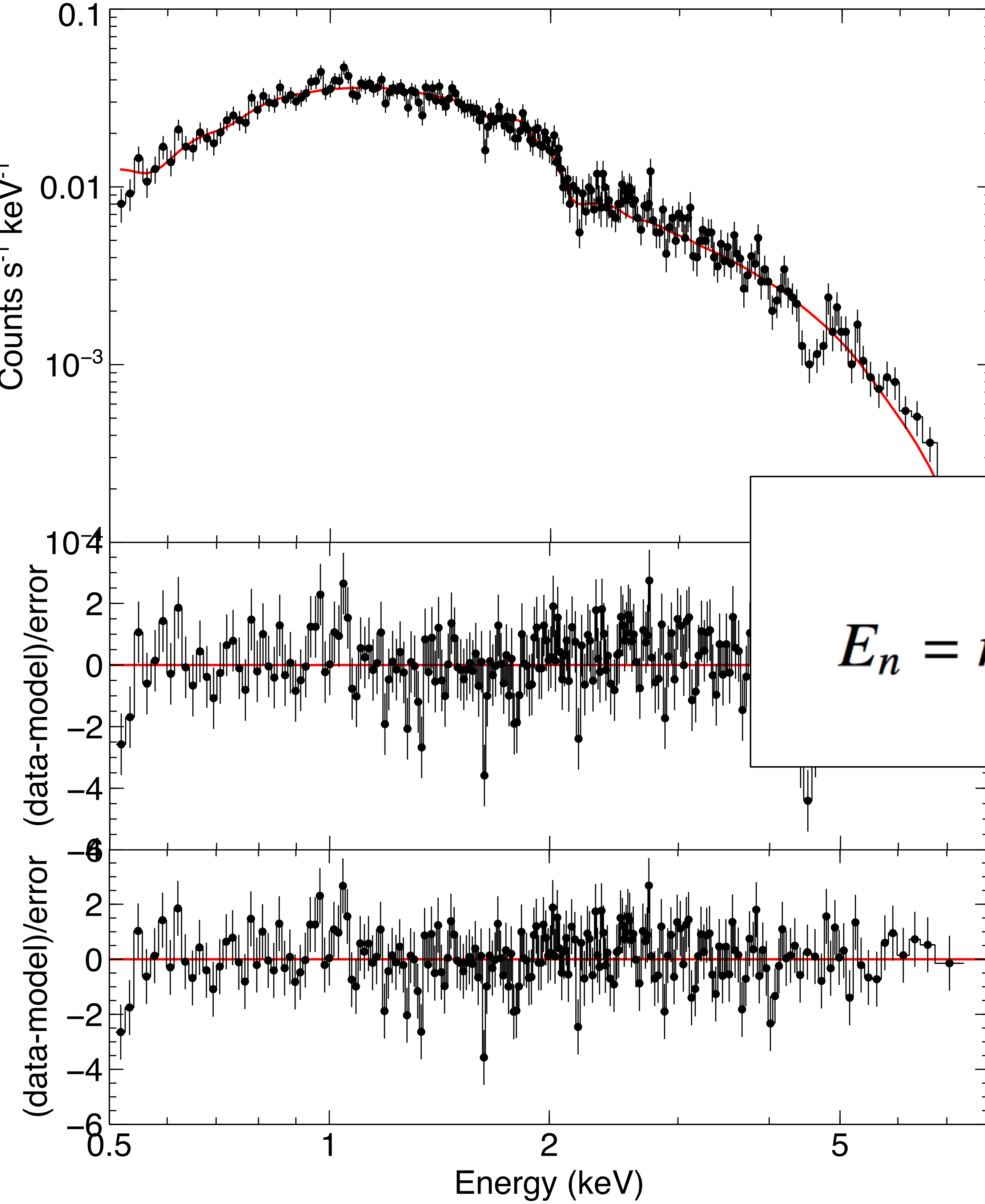
Cyclotron resonance scattering features (CRSF). Caused by the transition of charged particles between Landau levels produced by a magnetic field.

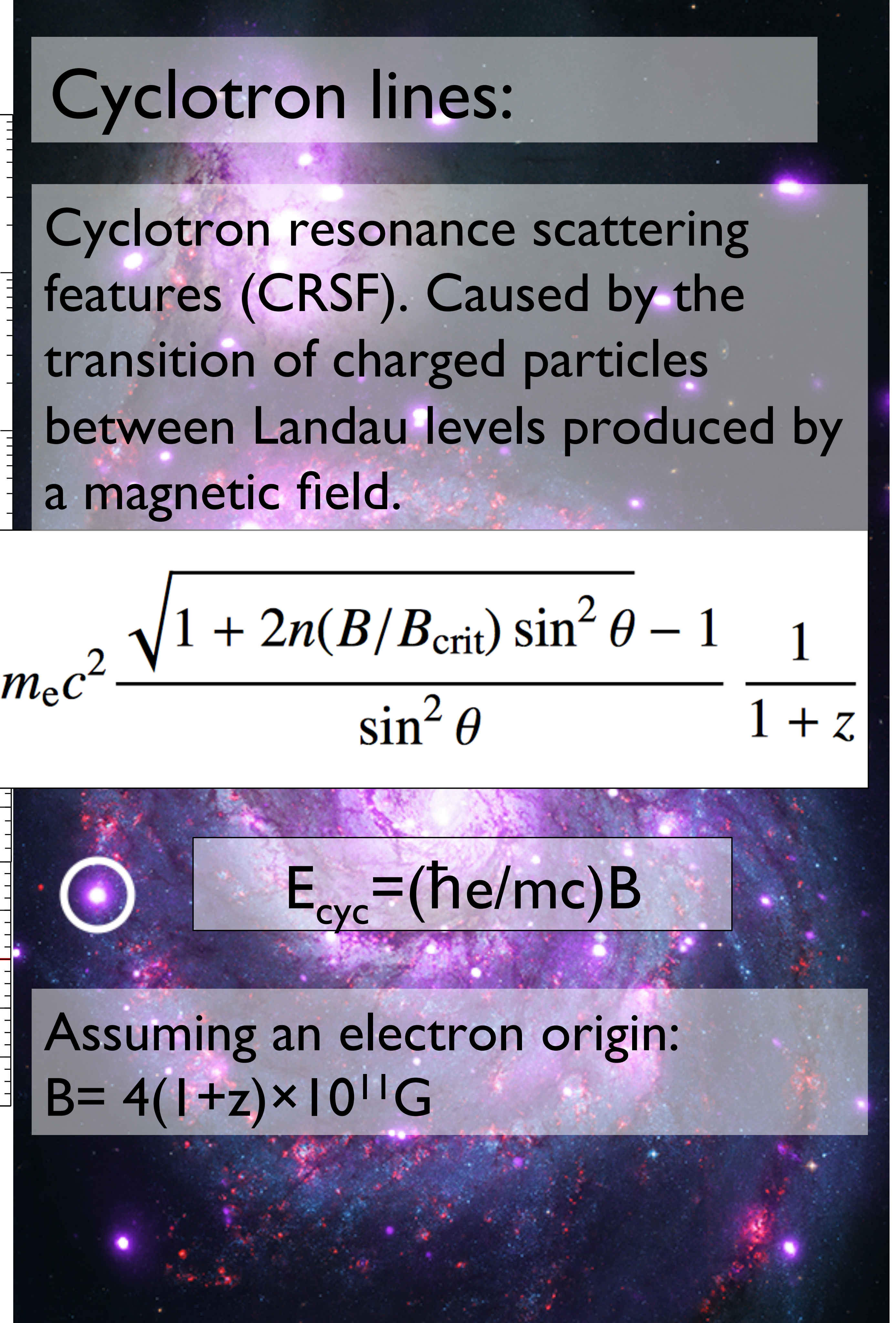
$$E_n = m_e c^2 \frac{\sqrt{1 + 2n(B/B_{\rm crit})\sin^2\theta} - 1}{\sin^2\theta} \frac{1}{1+z}$$

$$E_{cyc} = (\hbar e/mc)B$$

Not only implies the presence of a neutron star, but gives a direct measurement of its magnetic field strength.

Brightman+18





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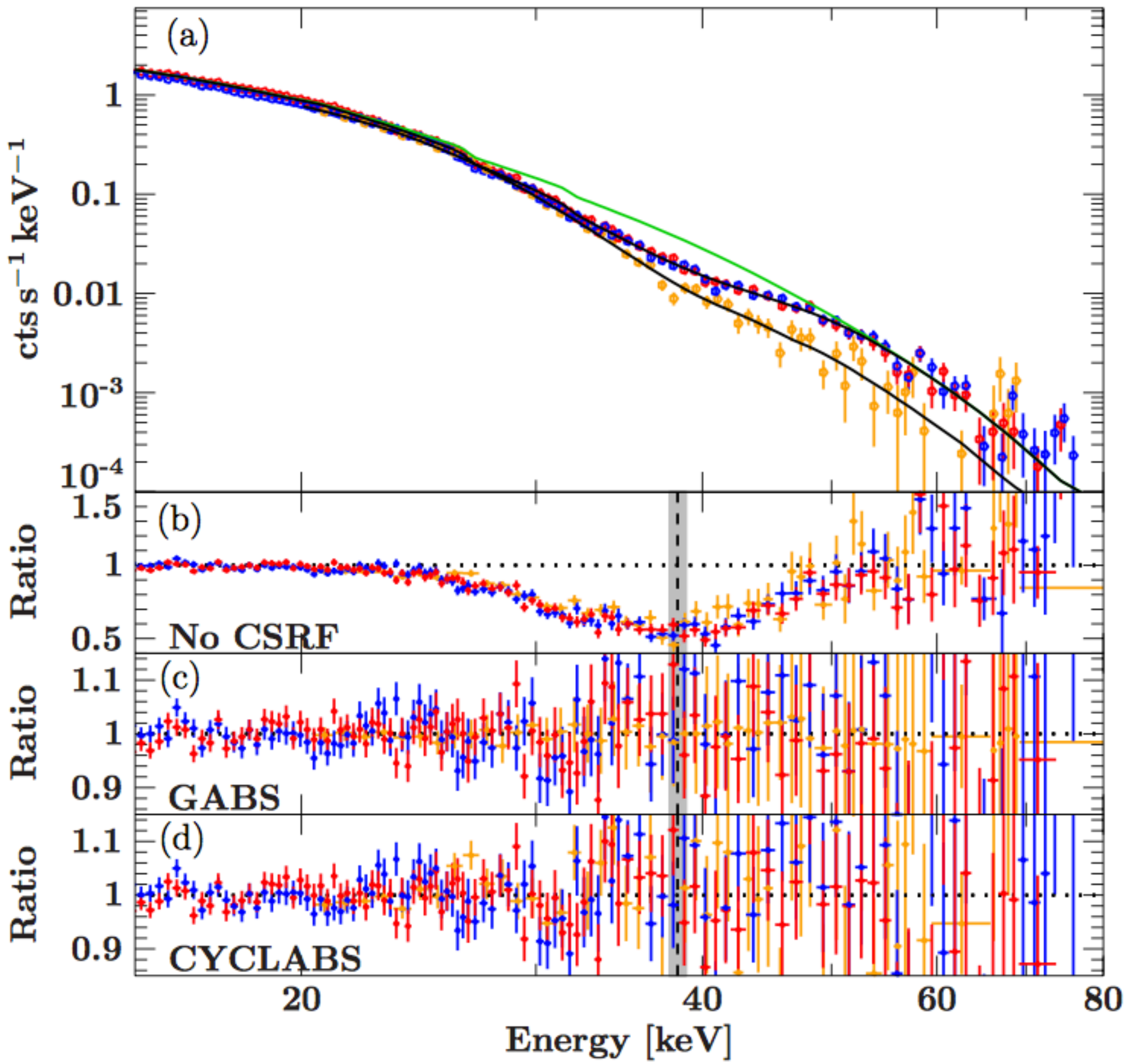
$$E_{cyc} = (\hbar e/mc)B$$

Assuming an electron origin:
$B = 4(1+z)\times10^{11}$G

Cyclotron lines:

Her X-1, Fuerst+13



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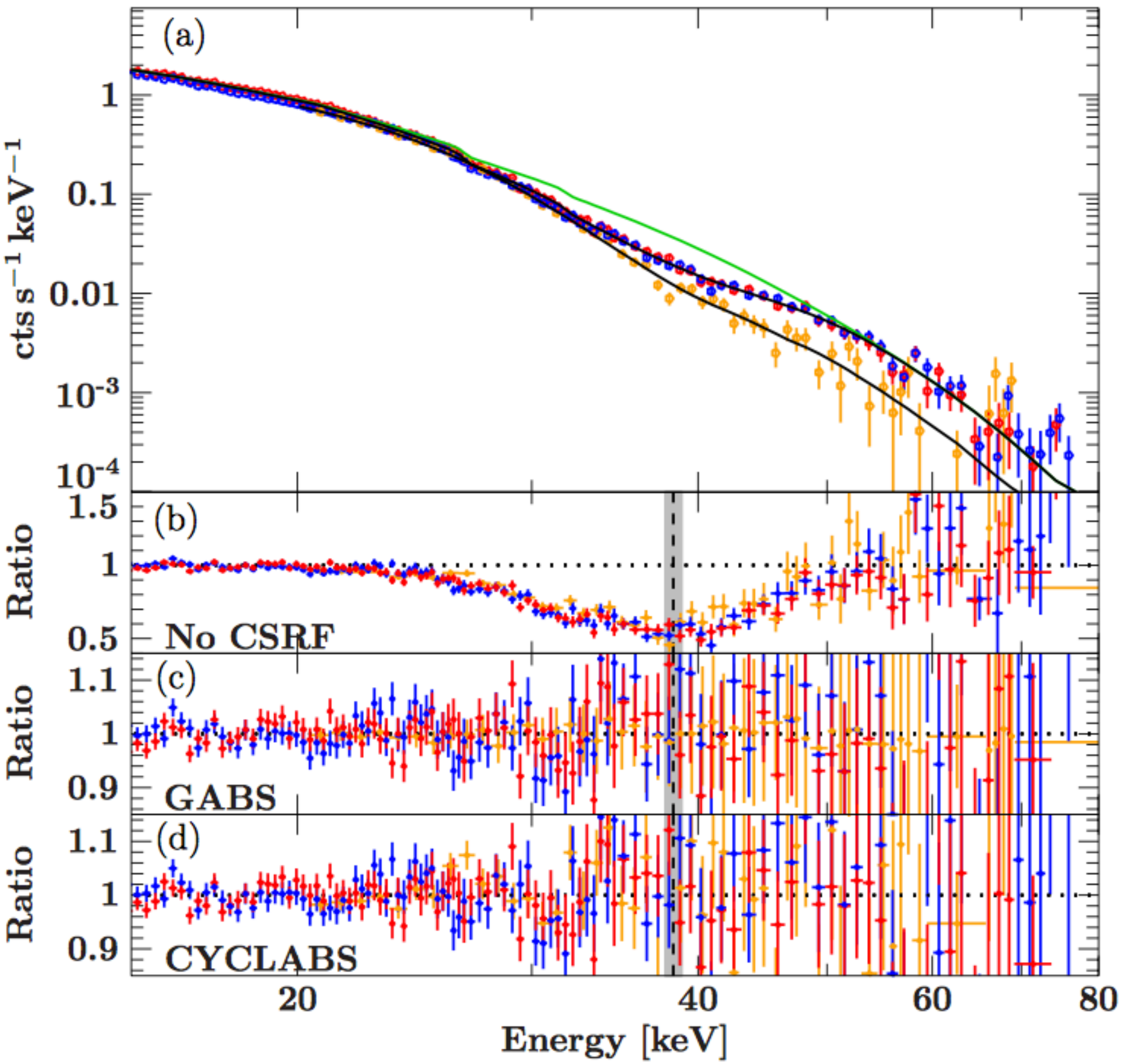
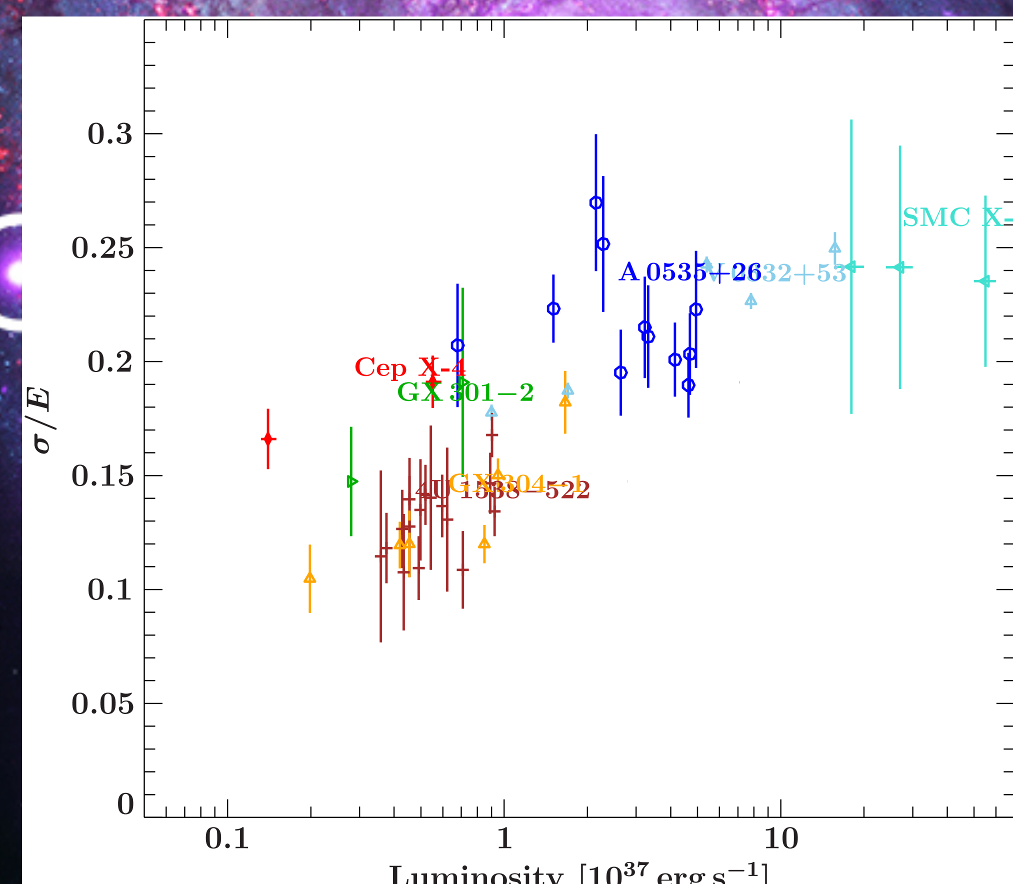
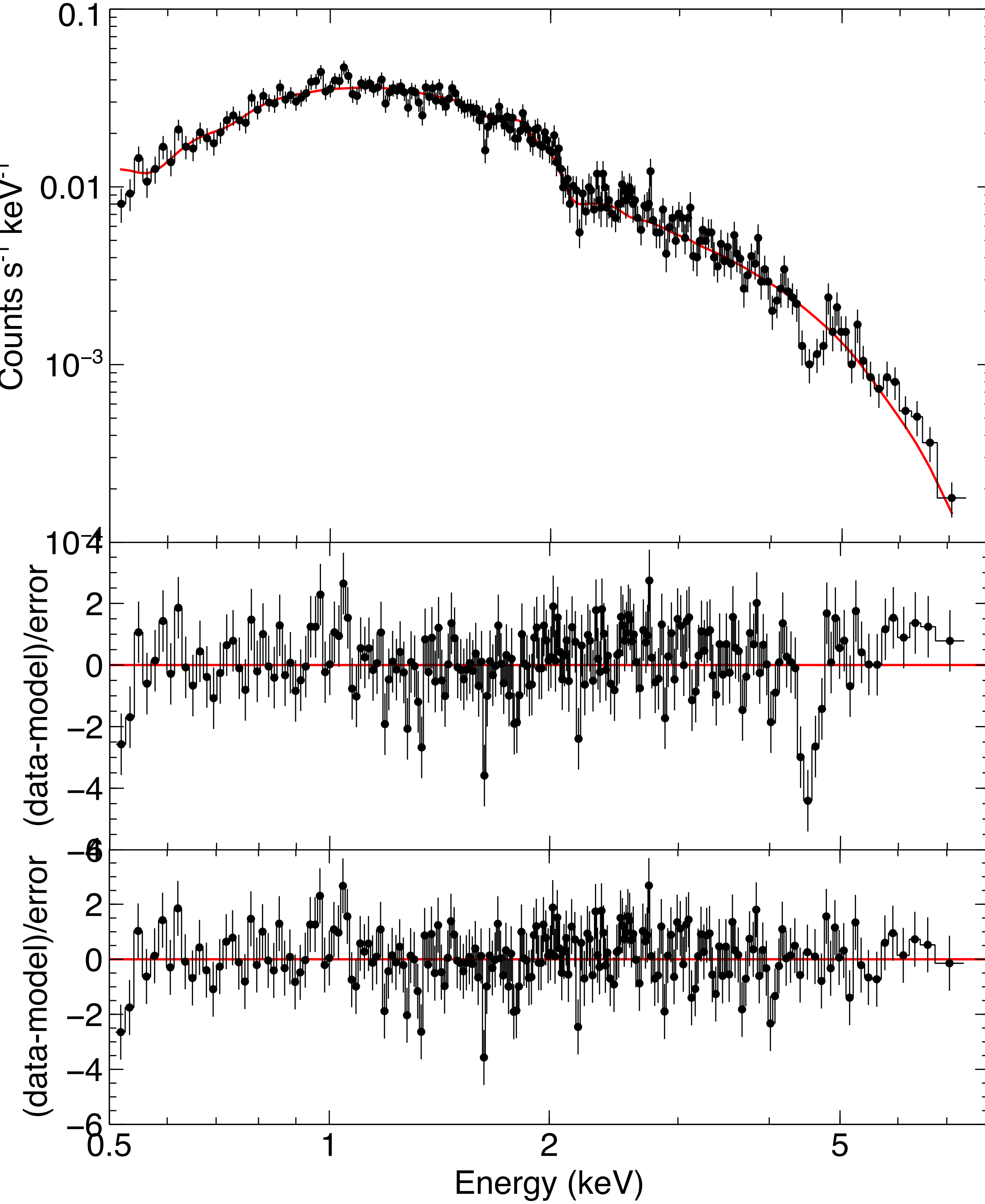


For electrons,
σ/E > 0.1

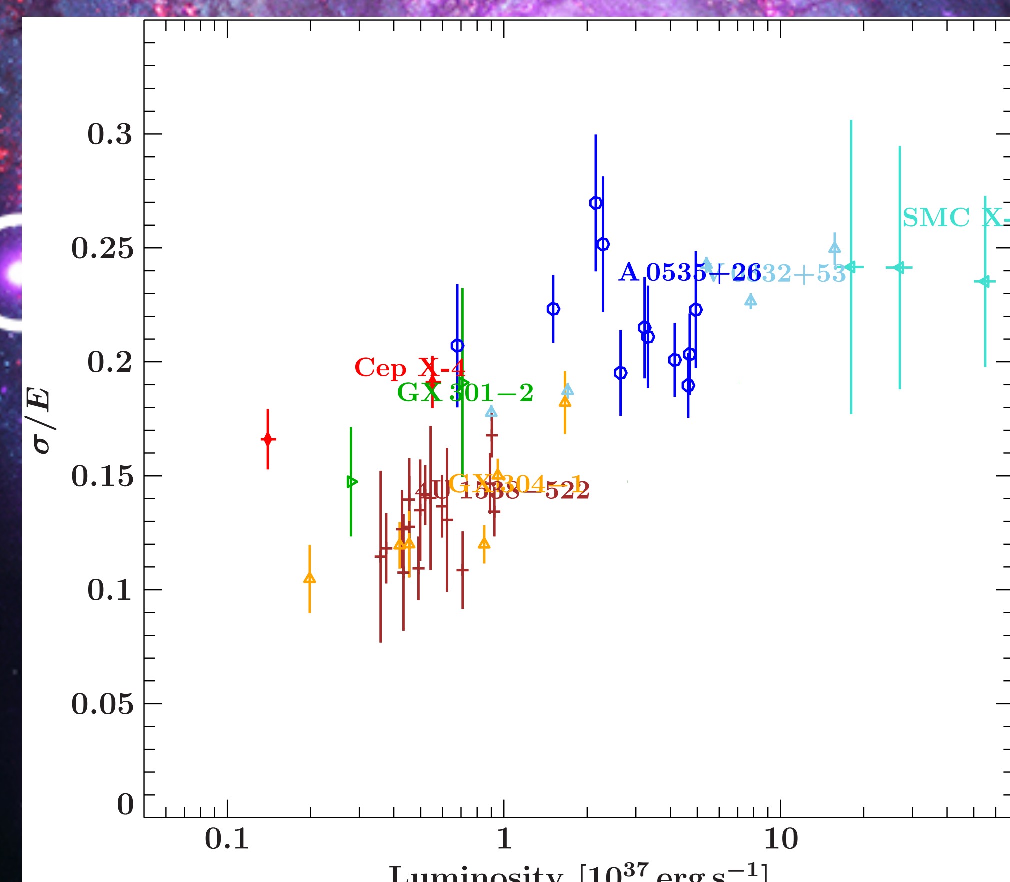


Brightman+18



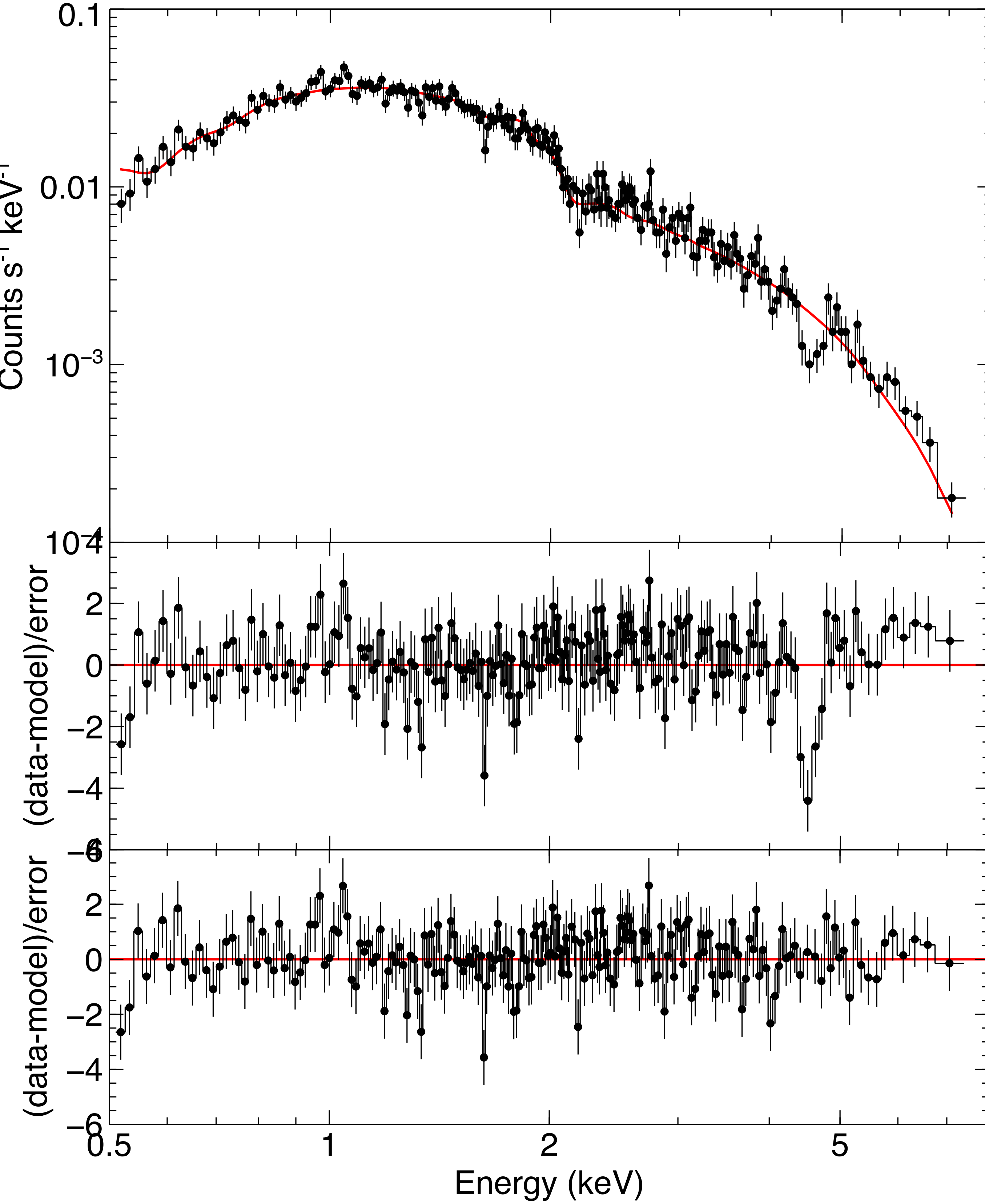
Cyclotron lines:

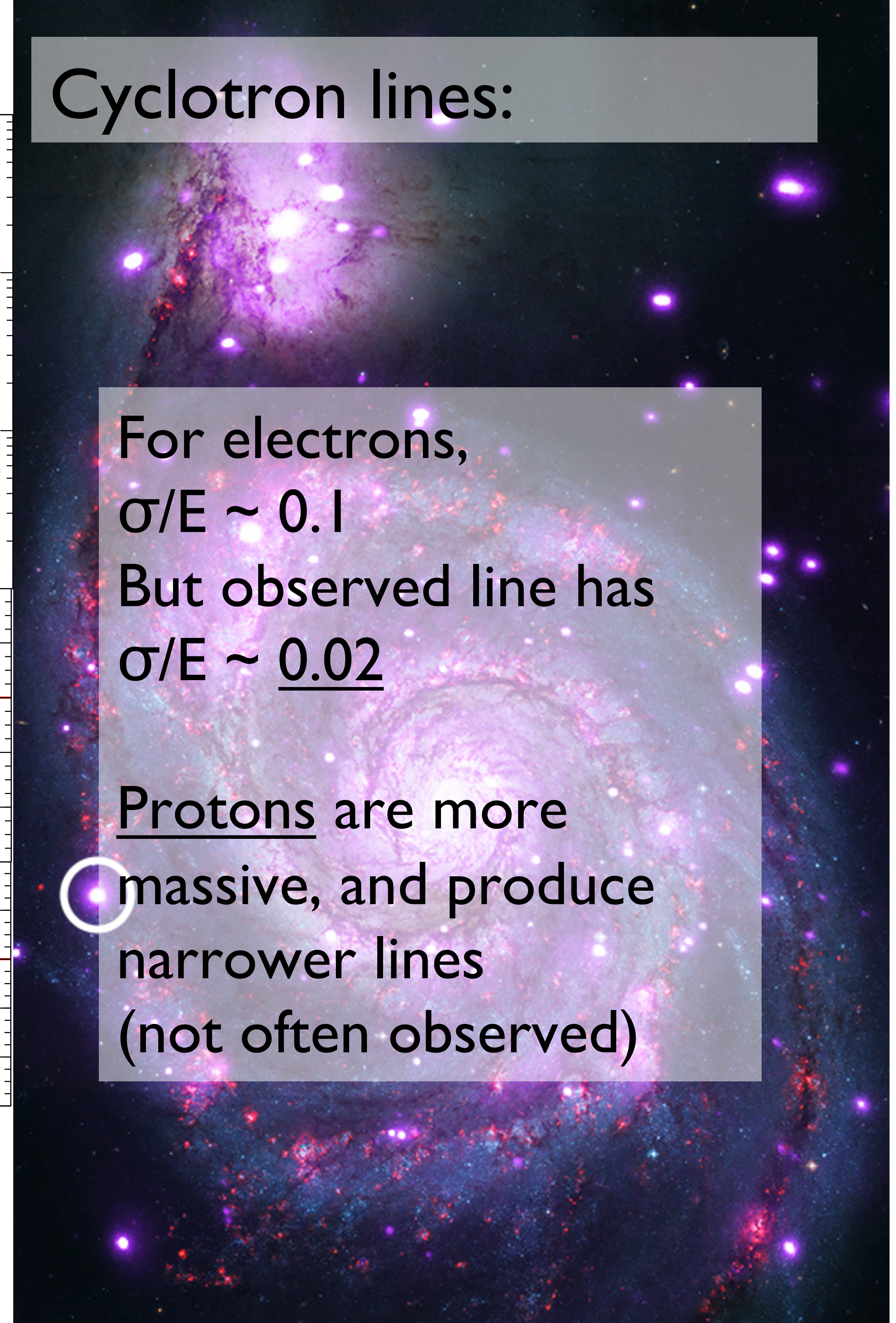
For electrons,
σ/E > 0.1
But observed line has
σ/E ~ <u>0.02</u>



ULX8

Brightman+18



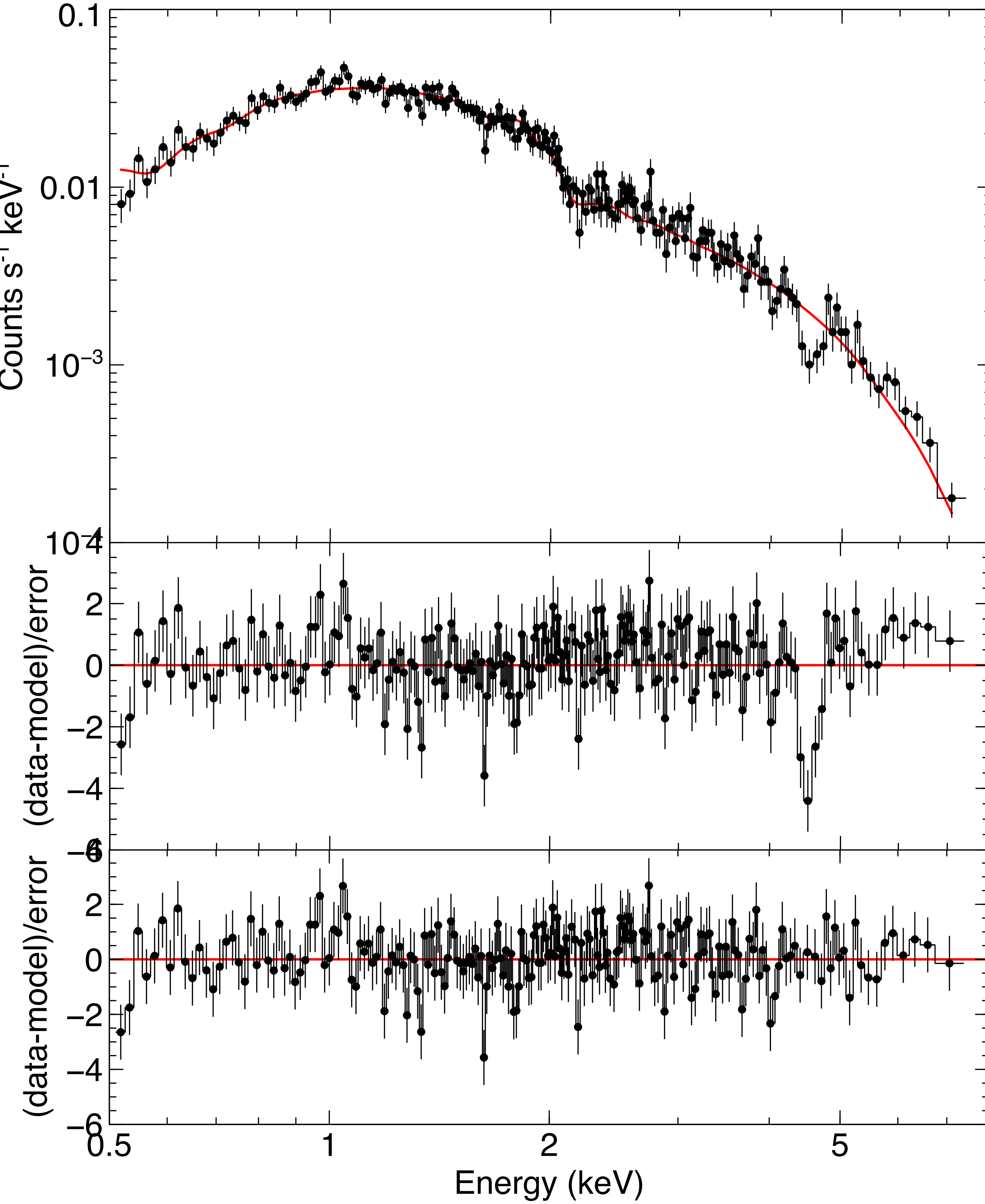


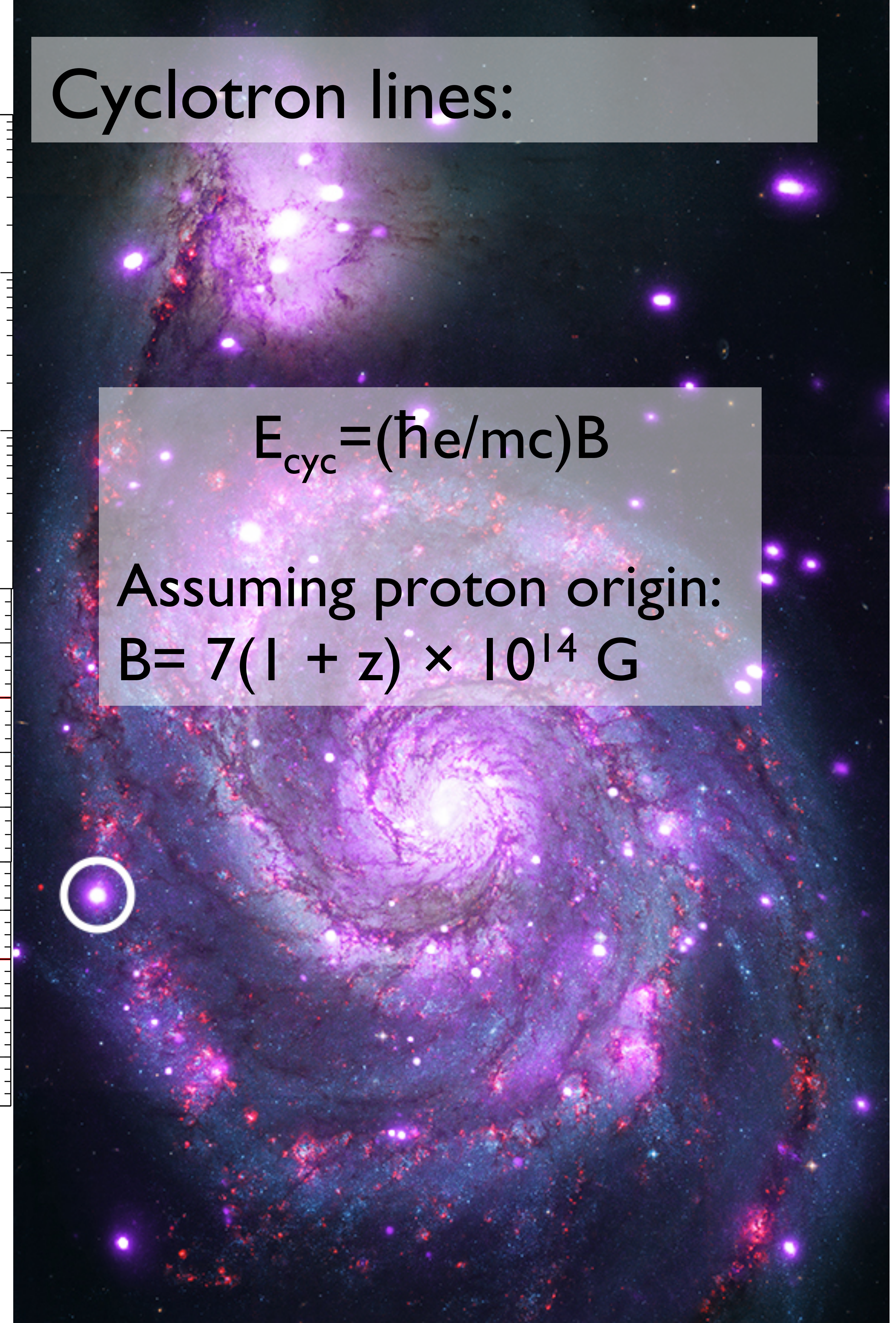
Cyclotron lines:

For electrons,
σ/E ~ 0.1
But observed line has
σ/E ~ 0.02

Protons are more massive, and produce narrower lines (not often observed)

Brightman+18





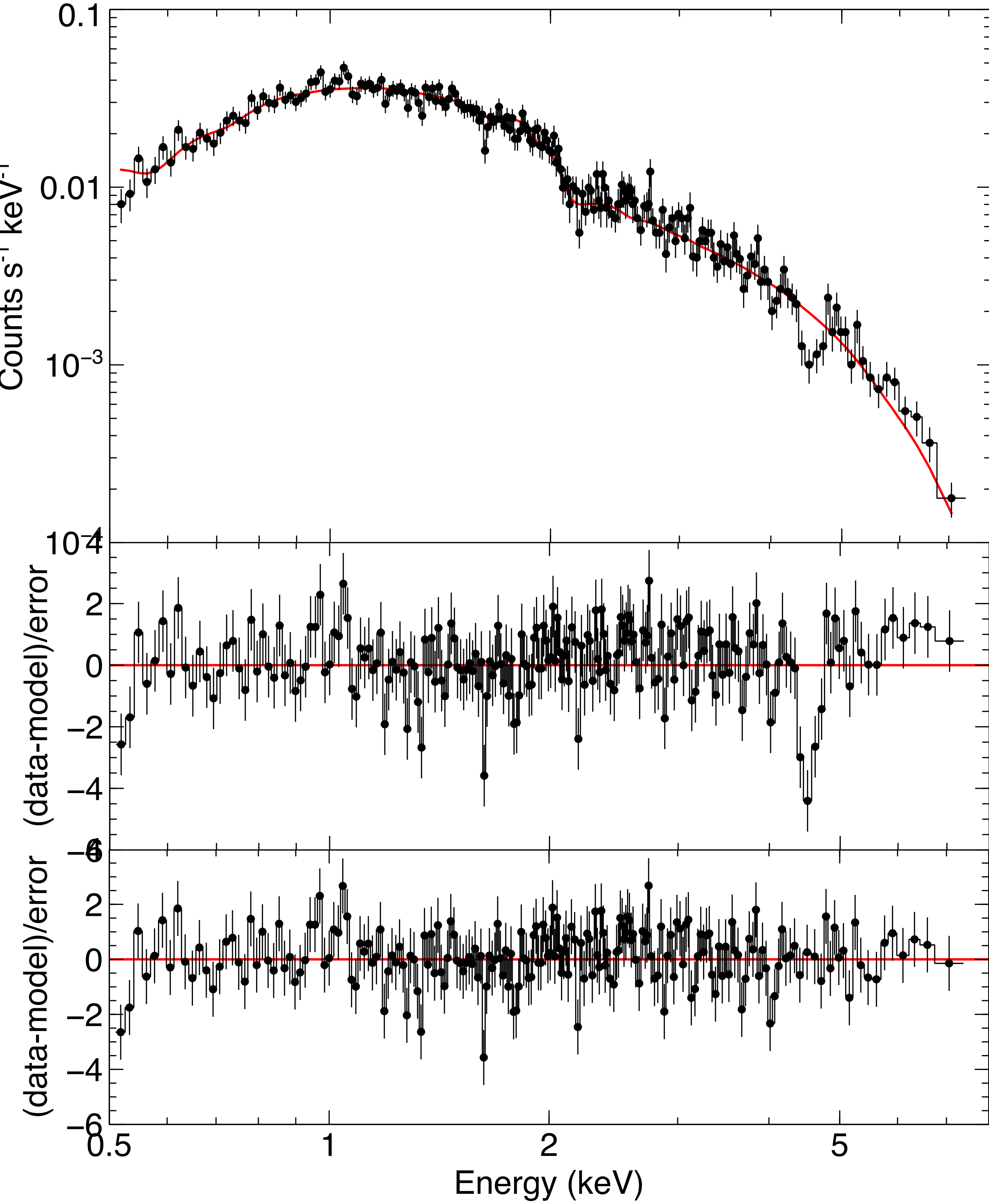
Cyclotron lines:

$E_{cyc}=(\hbar e/mc)B$

Assuming proton origin:

$B = 7(1 + z) \times 10^{14}$ G

Brightman+18



Proton CRSF at 4.5 keV?

- Implies an ultra-strong magnetic field strength close to the surface of the NS
- Would significantly reduce electron scattering cross-section ➔ Allow super-Eddington accretion

More data required

- Detect pulsations
- Detect harmonic lines

Summary:

NuSTAR discovery that M82 X-2 was powered by accretion onto a neutron star revolutionised the field of ultraluminous X-ray sources

Are all ULXs powered by neutron stars?

Do NS-ULXs harbour immense magnetic fields?