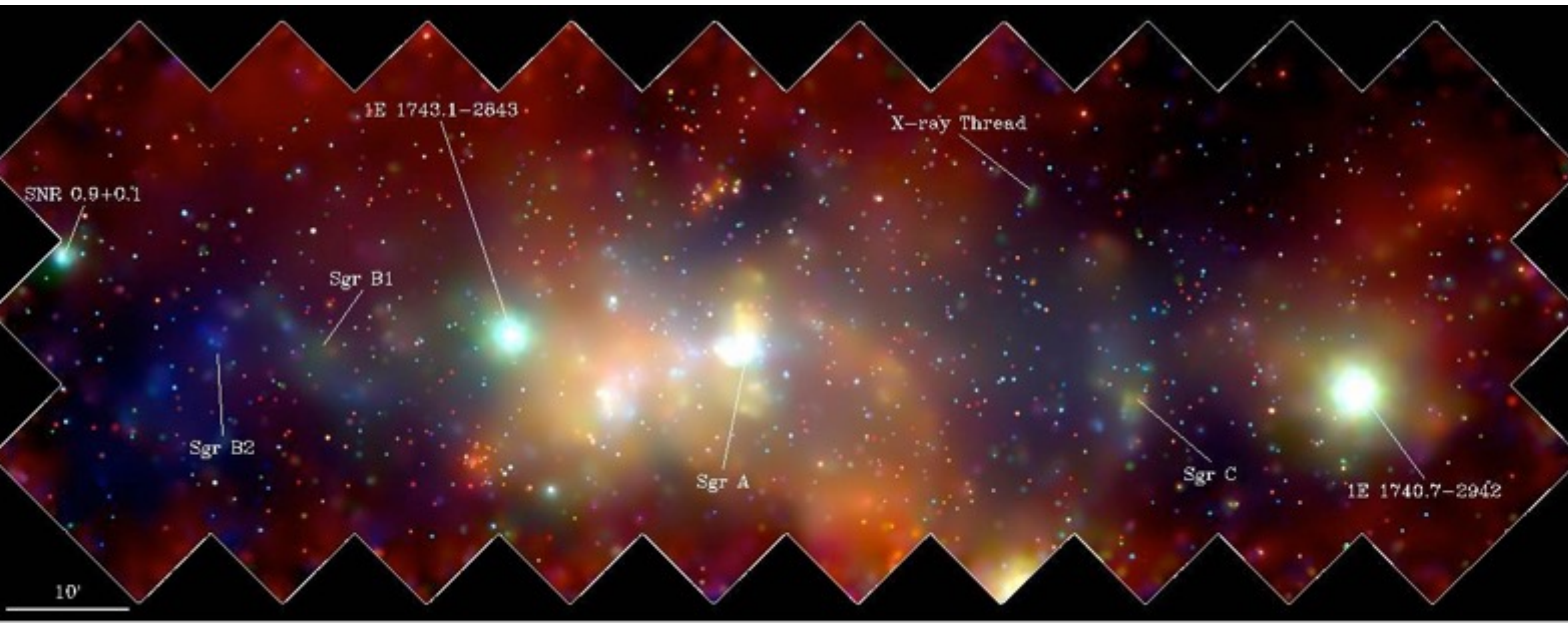
The Astrophysics of Stellar Mass Compact Objects

- Observational Properties
- Formation of Stellar Compact Objects
- Compact Objects as Cosmic Laboratories
- Future Work

GALACTIC CENTER IN X-RAYS



Wang et al

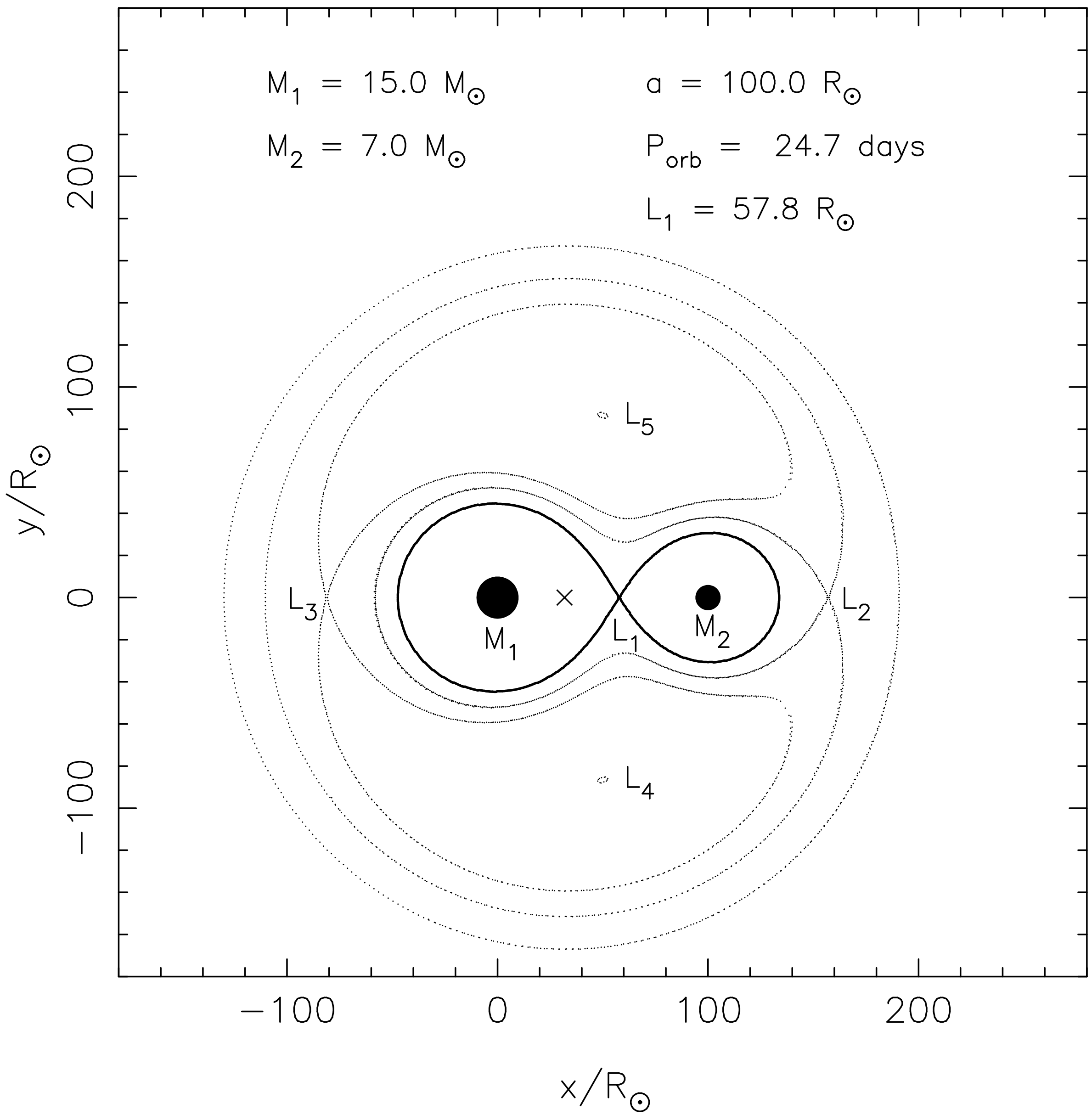
Main Categories of Compact Binary Systems

- Stellar Binary X-ray Sources (Black Holes/ Neutron Stars with a Companion)
- Cataclysmic Variables (White Dwarf with a Companion)
- Binary Radio Pulsars (Neutron Star/Neutron Star or Neutron Star/White Dwarf Star)

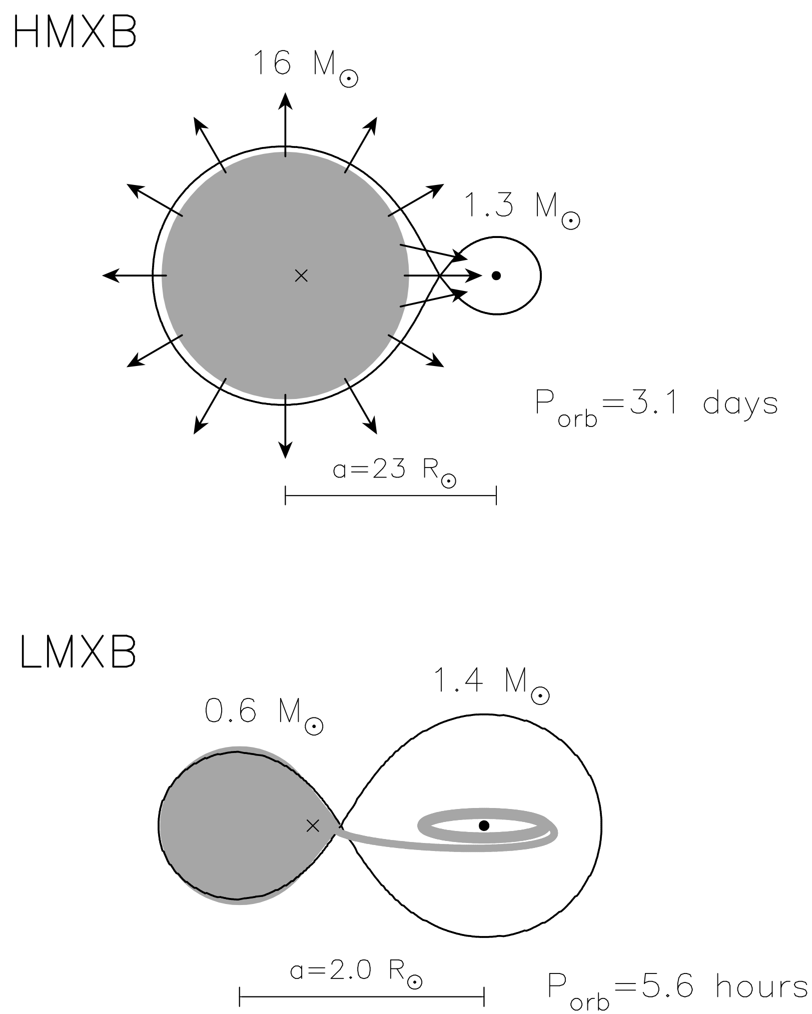
MAIN CLASSES OF X-RAY BINARY SOURCES

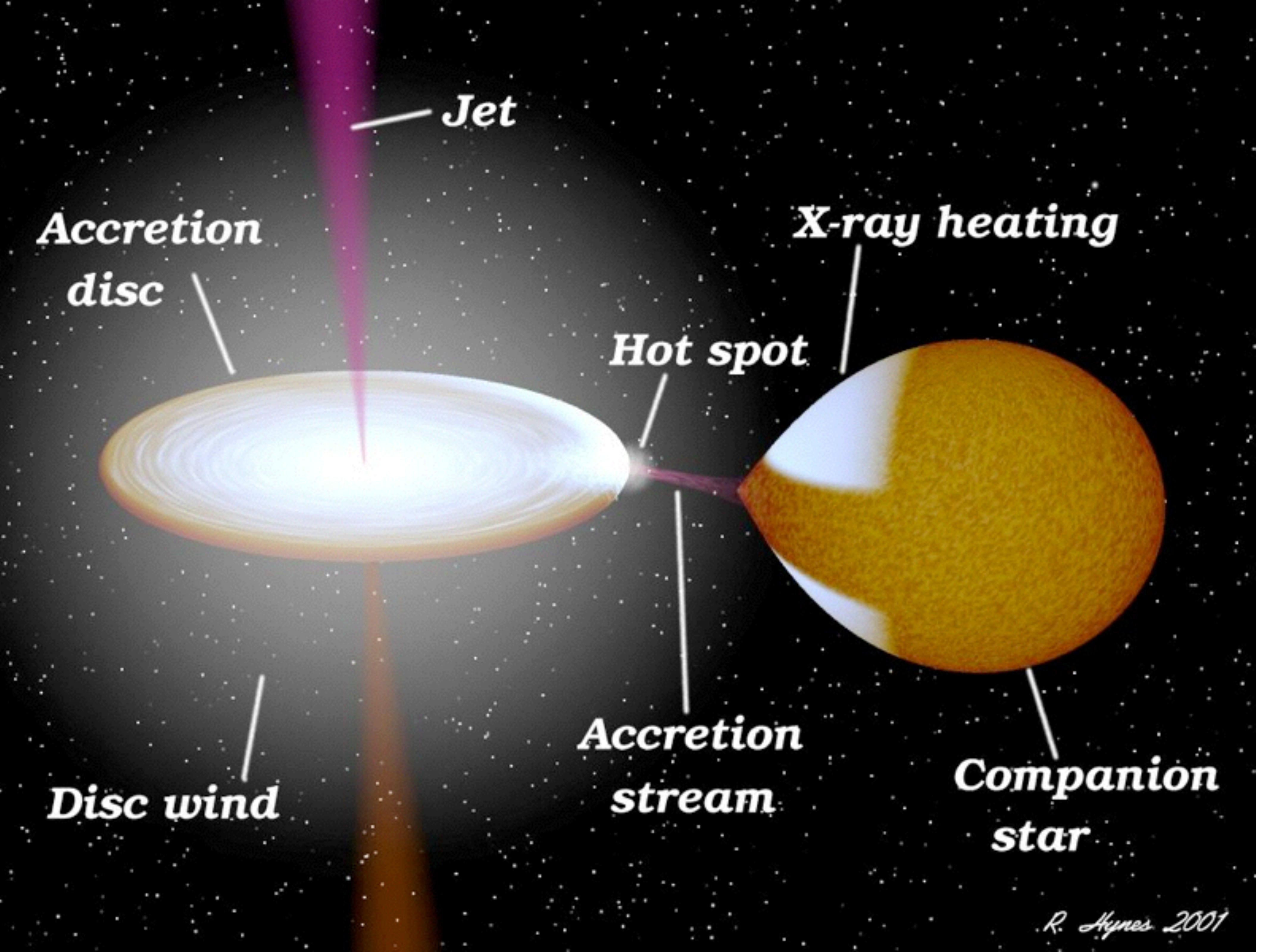
	HMXB	LMXB
X-ray Spectra	Hard (>10 keV)	Soft (<10 keV)
Accreting Star	High B field NS or BH	Low B field NS or BH
Accretion Process	Wind	Roche lobe overflow
Companion Star	High Mass	Low Mass

Binary Evolution - Roche Geometry



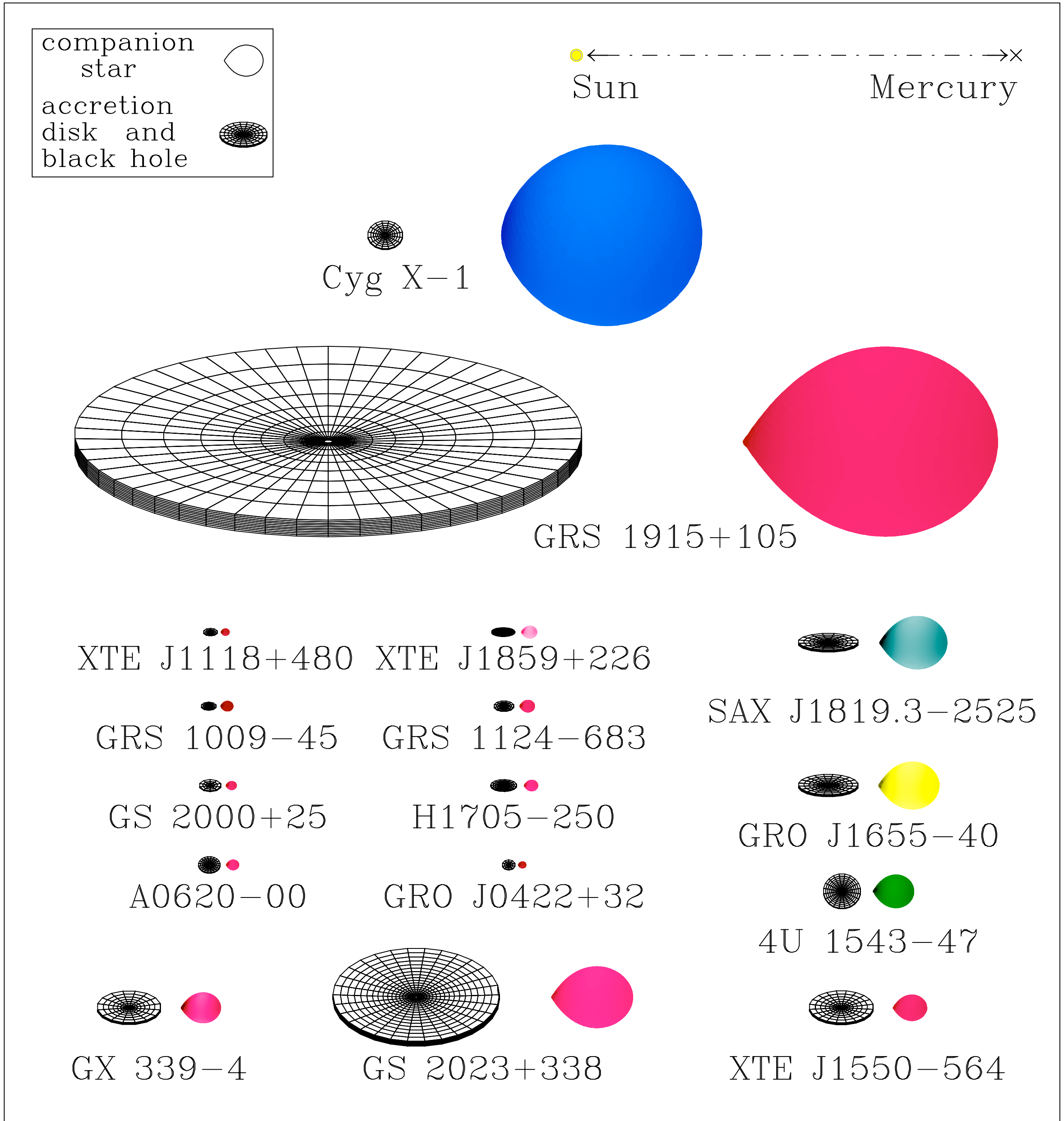
Examples of Typical Binary X-ray Sources

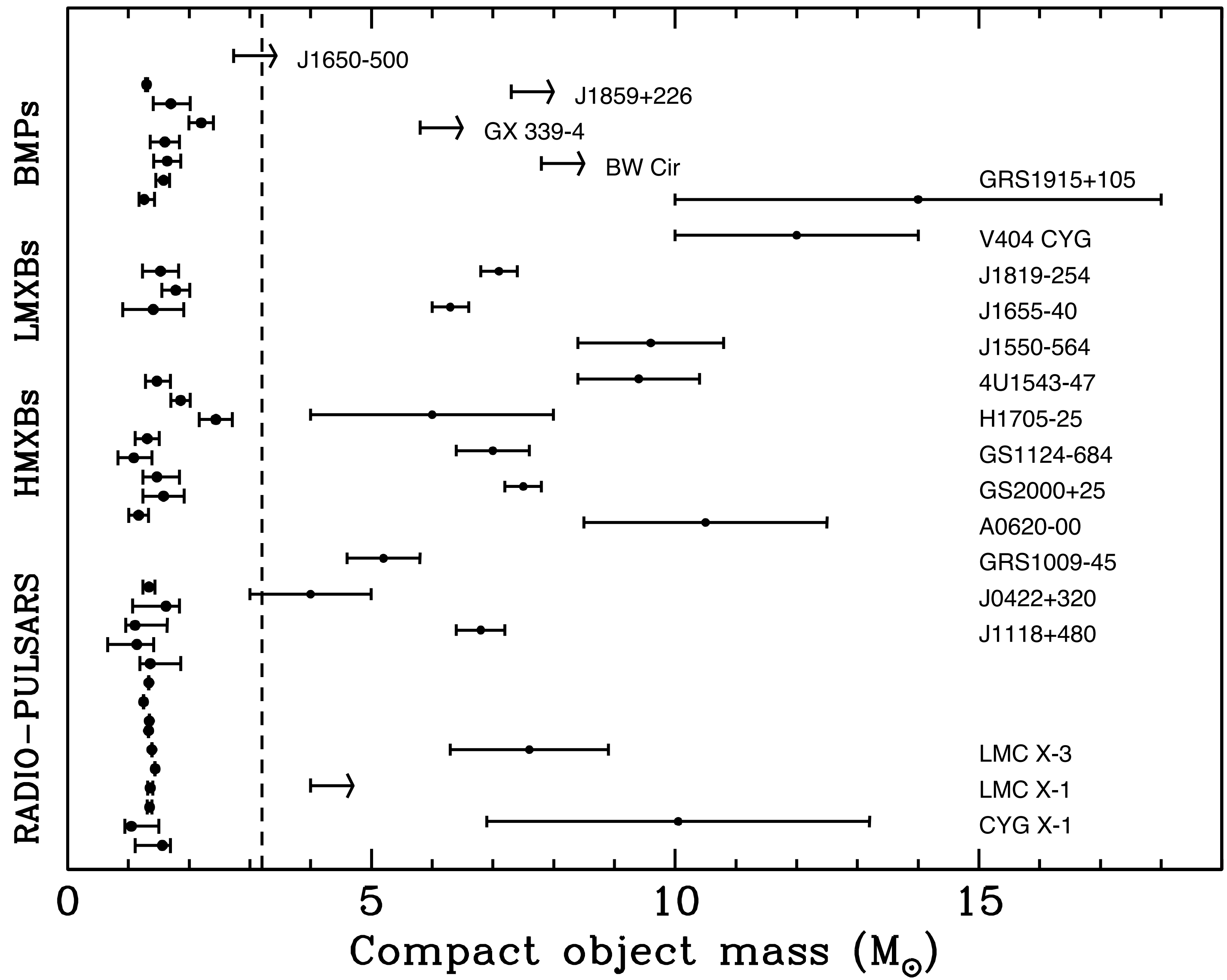




Jet
Accretion disc
X-ray heating
Hot spot
Accretion stream
Companion star
Disc wind
R. Hynes 2001

Black Hole Binaries in the Milky Way





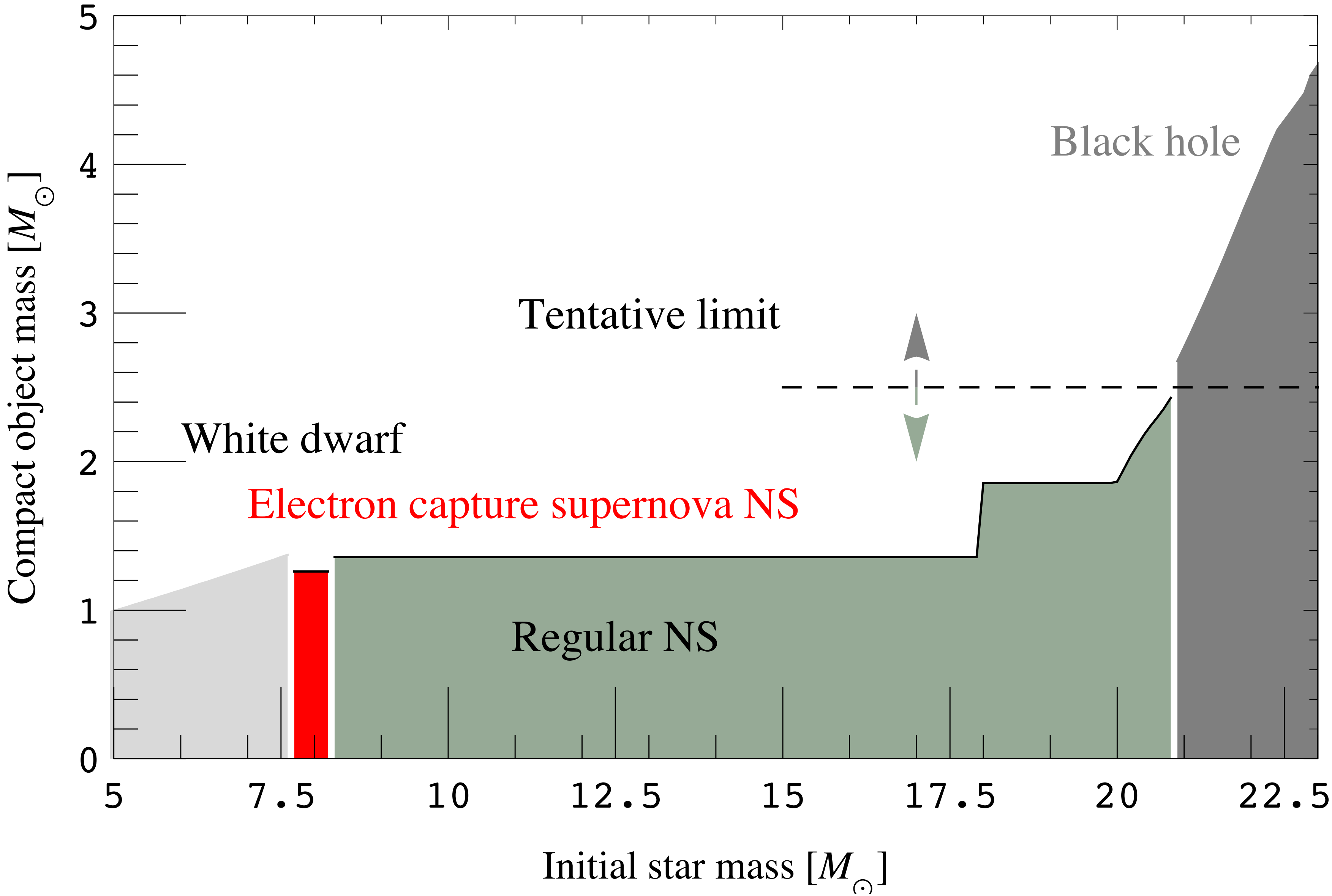
BMPs
LMXBs
HMXBs
RADIO-PULSARS
J1650-500
J1859+226
GX 339-4
BW Cir
GRS1915+105
V404 CYG
J1819-254
J1655-40
J1550-564
4U1543-47
H1705-25
GS1124-684
GS2000+25
A0620-00
GRS1009-45
J0422+320
J1118+480
LMC X-3
LMC X-1
CYG X-1
0
5
10
15
Compact object mass ($M_\odot$)

Casares

ENERGY EFFICIENCIES

Star	Radius (km)	GM/Rc^2
Sun	700,000	0.000002
White Dwarf	10,000	0.0002
Neutron Star	10	0.15
Black Hole	>3	0.1 - 0.4

Formation of Compact Objects



Counter example: Westerlund 1

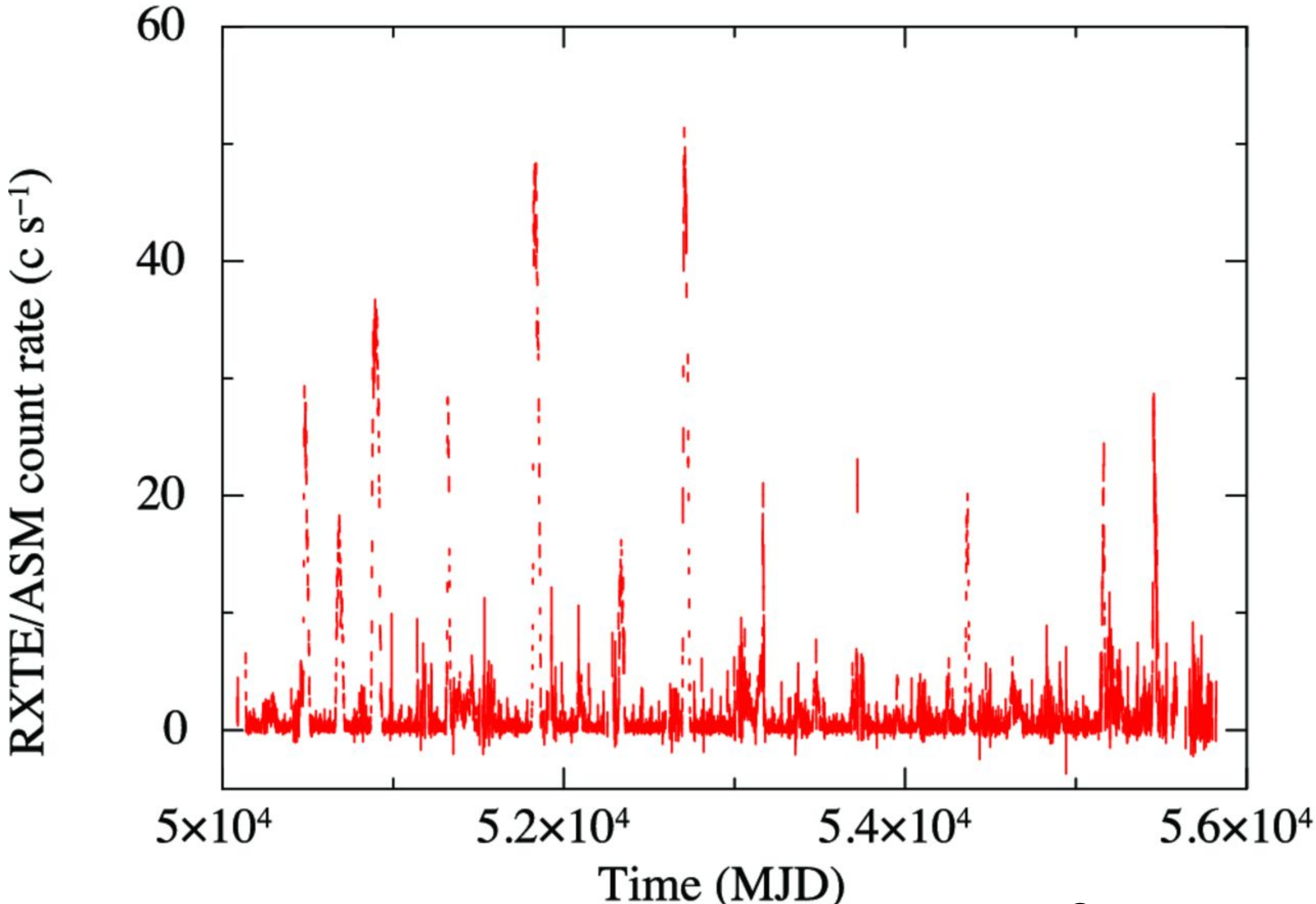
- Young stellar cluster ~ 3-5 Myr with a turnoff mass ~ 35 solar masses
- Existence of a slowly rotating neutron star: CXO J164710.2-455216 (10.6 s) radiating at a luminosity of ~ solar luminosity in X-rays
- Very high observed fraction of binaries (~70%) amongst the high mass population

Compact Objects as Cosmic Laboratories

- X-ray Transients - Neutron Stars
- X-ray Transients - Black Holes

X-ray Transients - Neutron Stars

- X-ray variability correlates with mass transfer rate: H/He disk stability model predicts various states
- X-ray bursts (active and quiescent states)

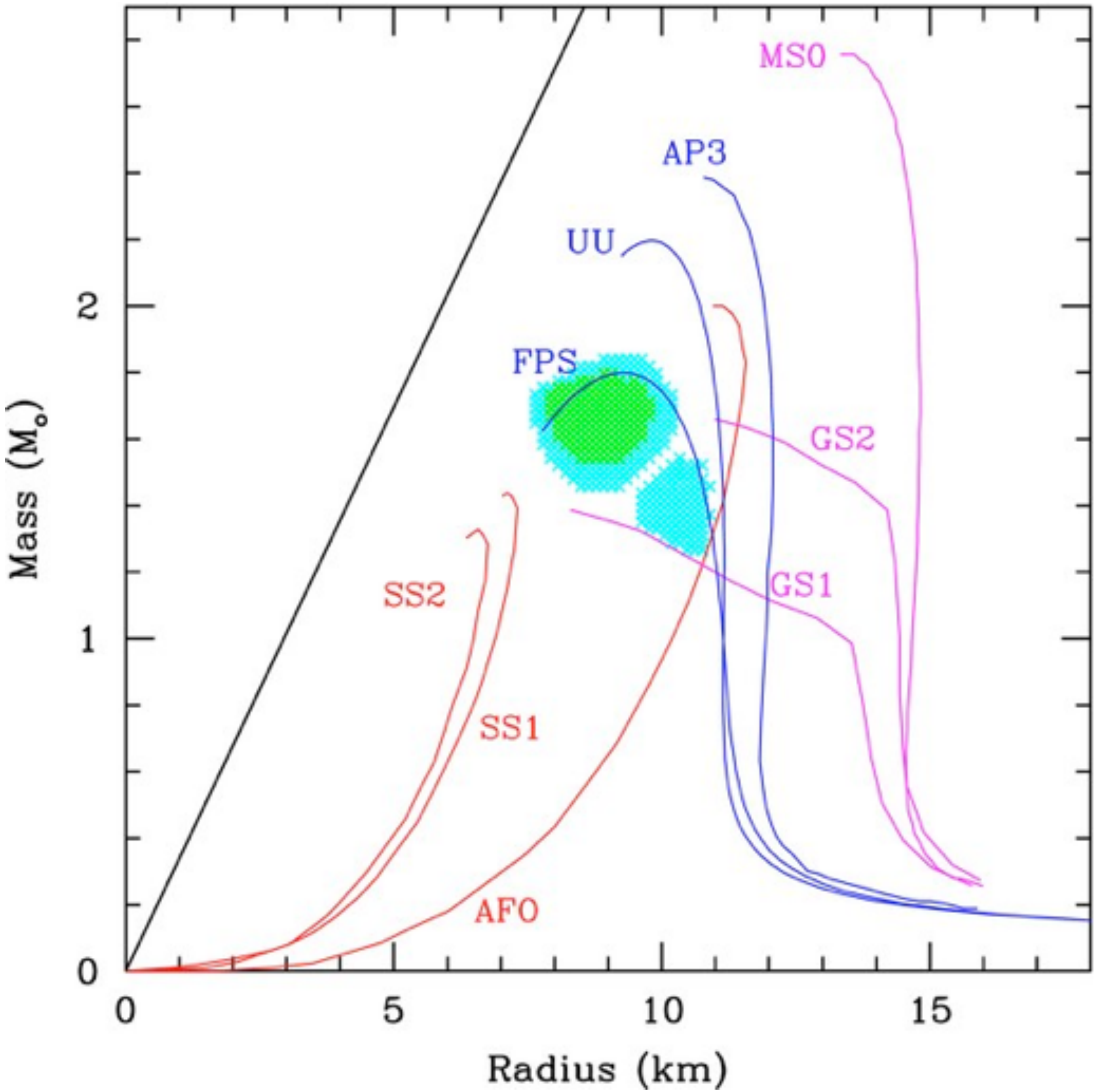


Campana et al

Constraints on Dense Matter

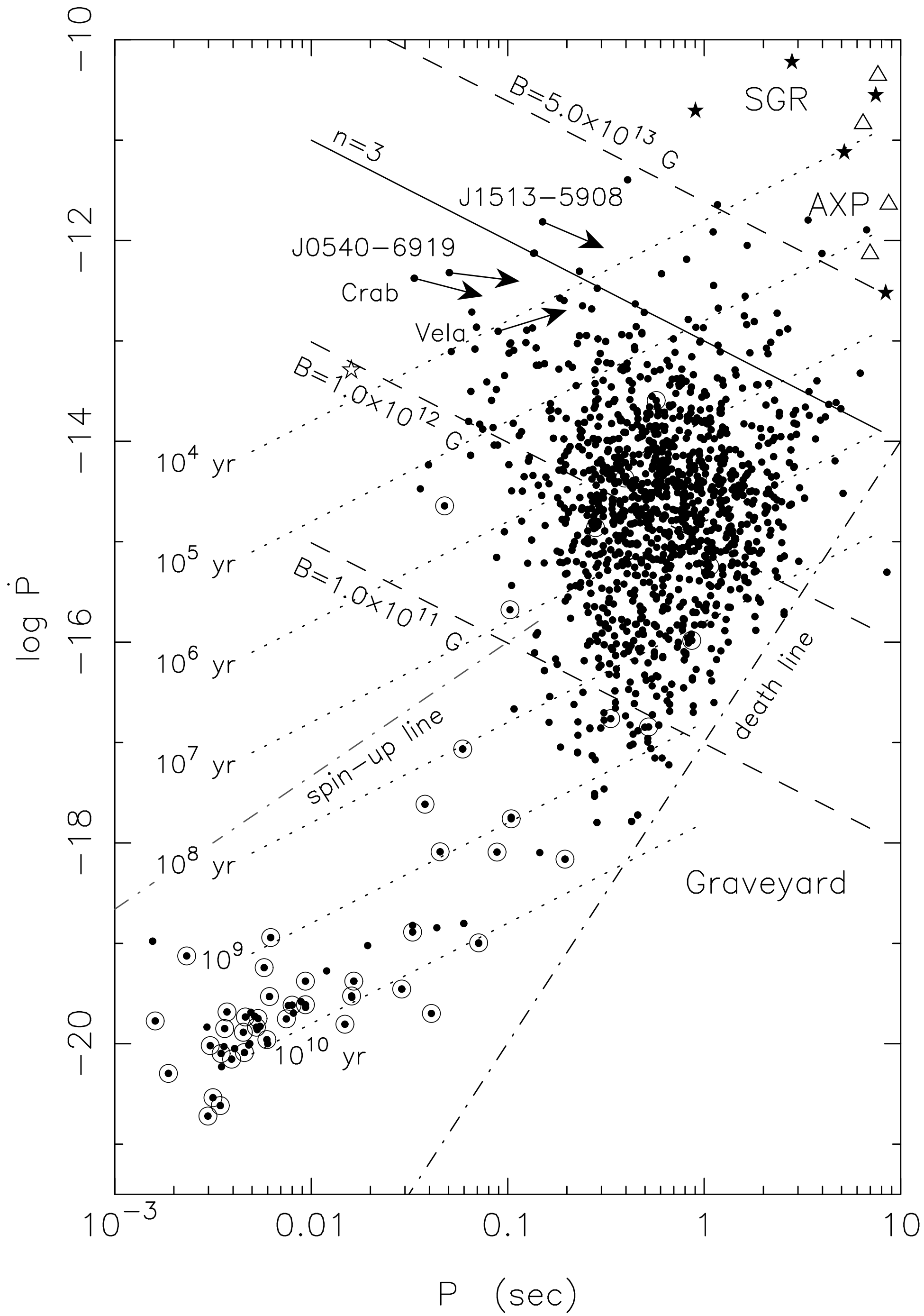
- Equation of state: radius constraints from fitting model atmospheres (flux, temperature, and distance must be known); gravitational redshift; mass and its maximum value
- Thermal state of neutron stars

EXO 1745-248



Ozel et al

RADIO PULSAR DIAGRAM



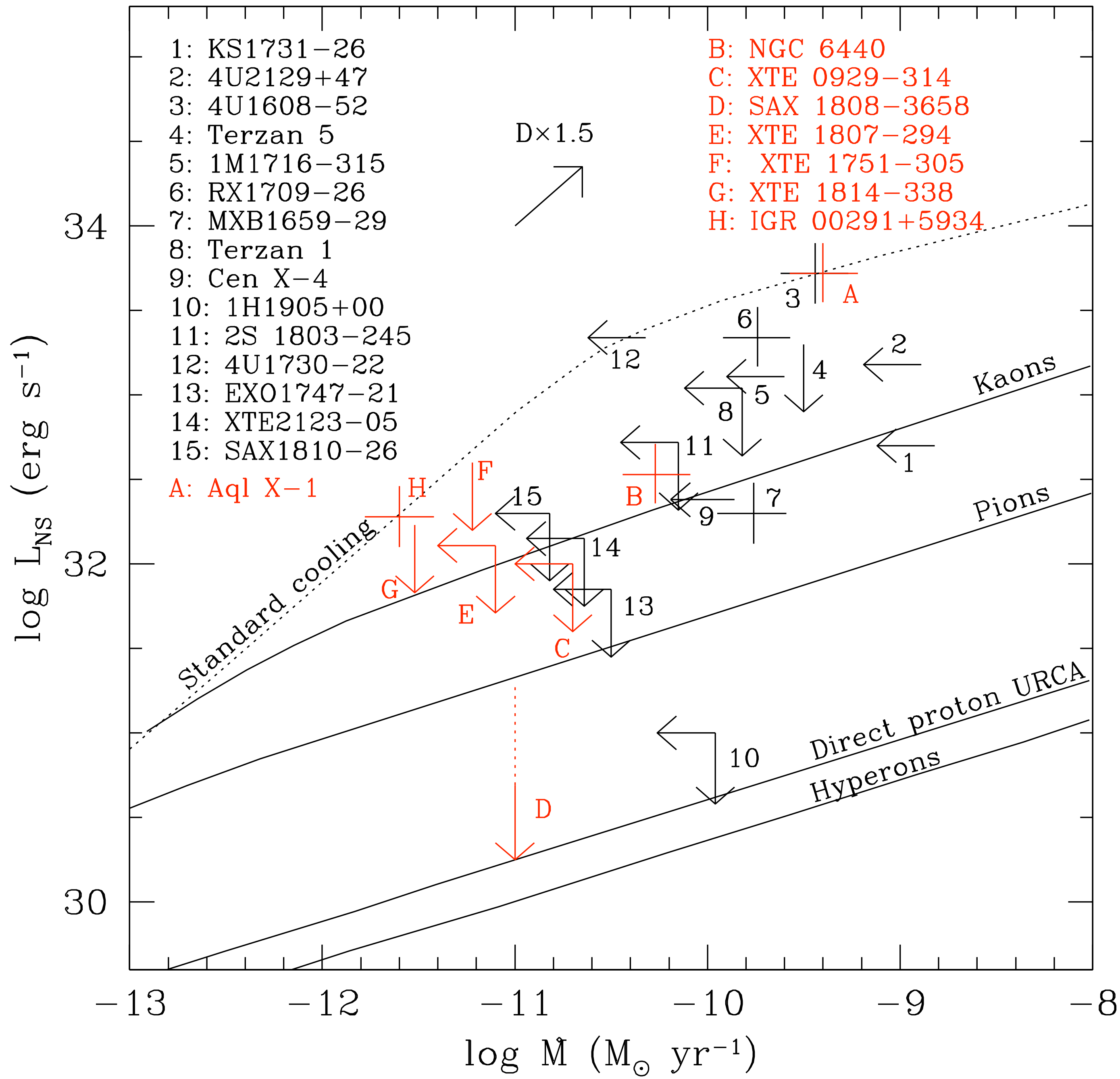
- Mass measurements of pulsars J 1614-2230 (Demorest et al 2010) and J 0348+ 0432 (Antoniadis et al. 2013) yield masses of 1.97 and 2.01 solar masses respectively with uncertainties of 0.04 solar masses
- Rules out most condensate, hyperon, and quark models

Case Study: SAX 1808.4-3658

- First accreting millisecond pulsar discovered (2.5 ms)
- Regular outbursts ~ 2 years
- Distance ~3.4-3.6 kpc, implying mean mass transfer rate is known

- Prediction on quiescent flux
- X-ray spectrum during quiescent state is well fit by a power law without a black body component (kT < 35 eV)

$$L_{NS} < 10^{31} \text{ergs/s}$$



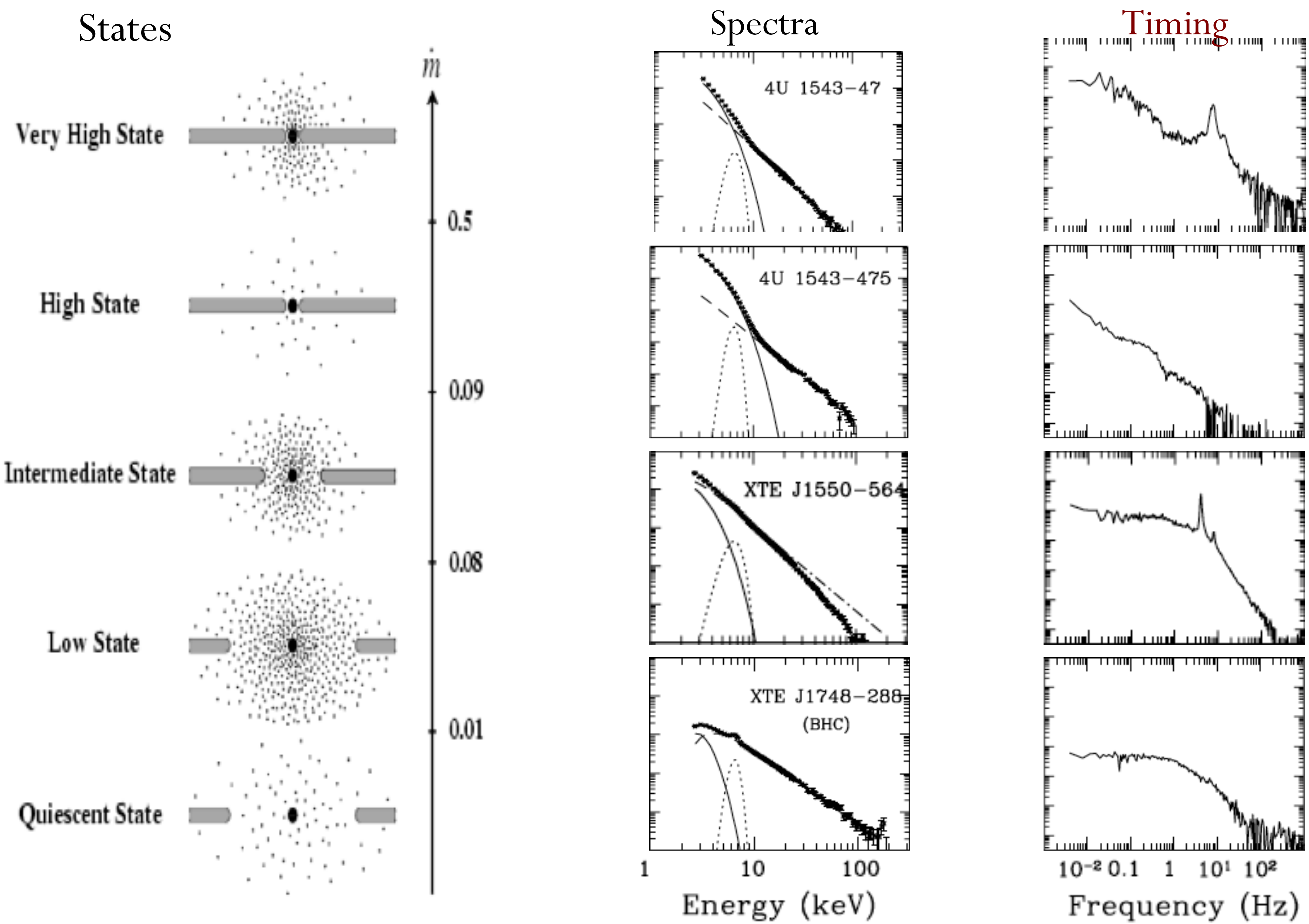
1: KS1731−26
2: 4U2129+47
3: 4U1608−52
4: Terzan 5
5: 1M1716−315
6: RX1709−26
7: MXB1659−29
8: Terzan 1
9: Cen X−4
10: 1H1905+00
11: 2S 1803−245
12: 4U1730−22
13: EXO1747−21
14: XTE2123−05
15: SAX1810−26
A: Aql X−1
B: NGC 6440
C: XTE 0929−314
D: SAX 1808−3658
E: XTE 1807−294
F: XTE 1751−305
G: XTE 1814−338
H: IGR 00291+5934
D×1.5
Standard cooling
Kaons
Pions
Direct proton URCA
Hyperons
log L_{NS} (erg s^{-1})
log $\dot{M}$ ($M_\odot$ yr^{-1})

Heinke et al

X-ray Transients - Black Holes

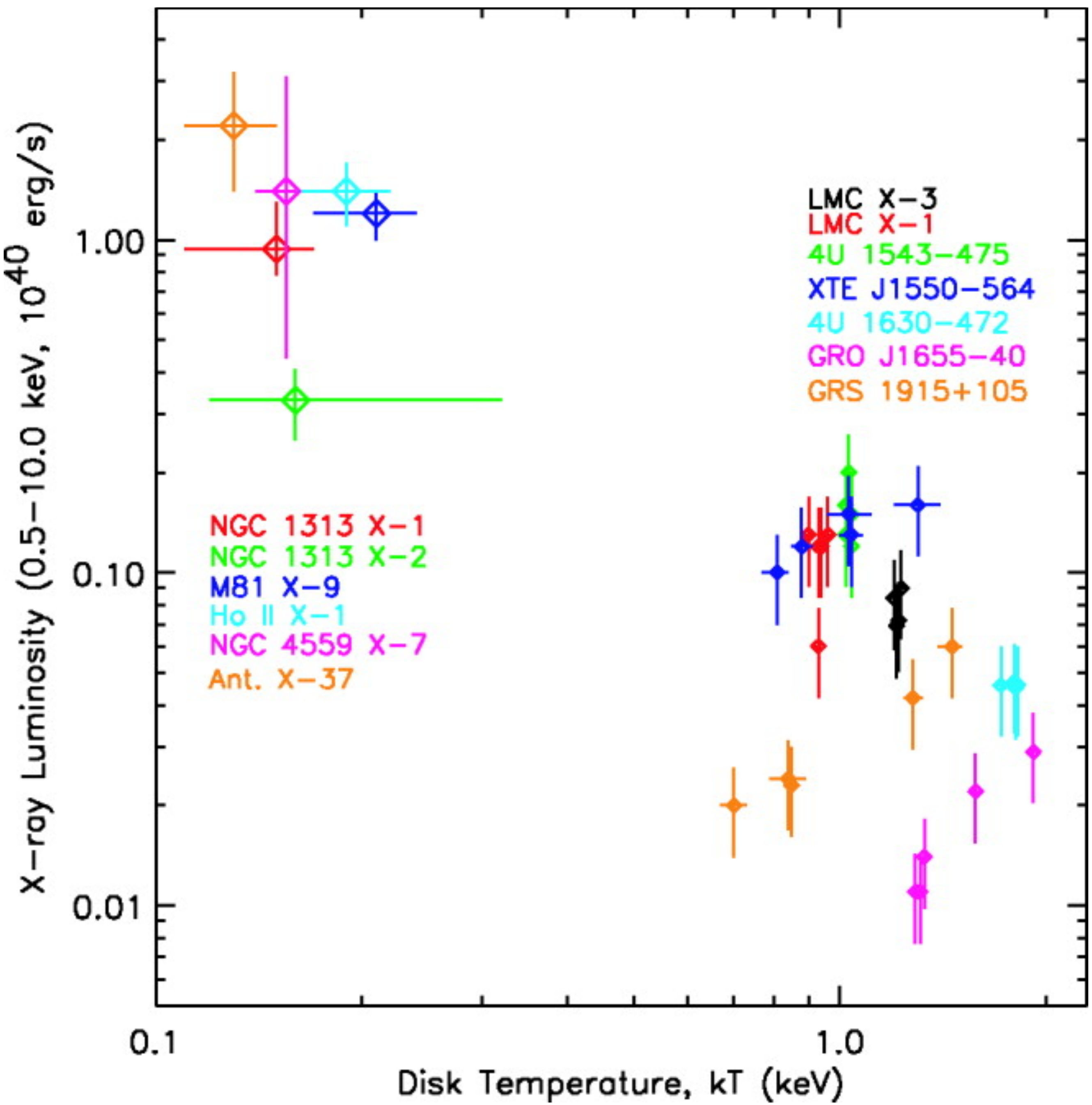
- High luminosity states characterized by a soft thermal component
- Low luminosity states characterized by power law with photon index ~1.7
- Hard states with the presence of cool gas: soft thermal and reflection component; evidence of iron features

X-ray properties



Ultra-luminous X-ray Sources

- very soft spectra (< 0.2 keV)
- luminous $\sim 10^{39} - 10^{42} \mathrm{ergs/s}$
- stellar mass black holes accreting super critically?
- intermediate mass black holes (100 - 1000 solar masses) accreting sub critically?

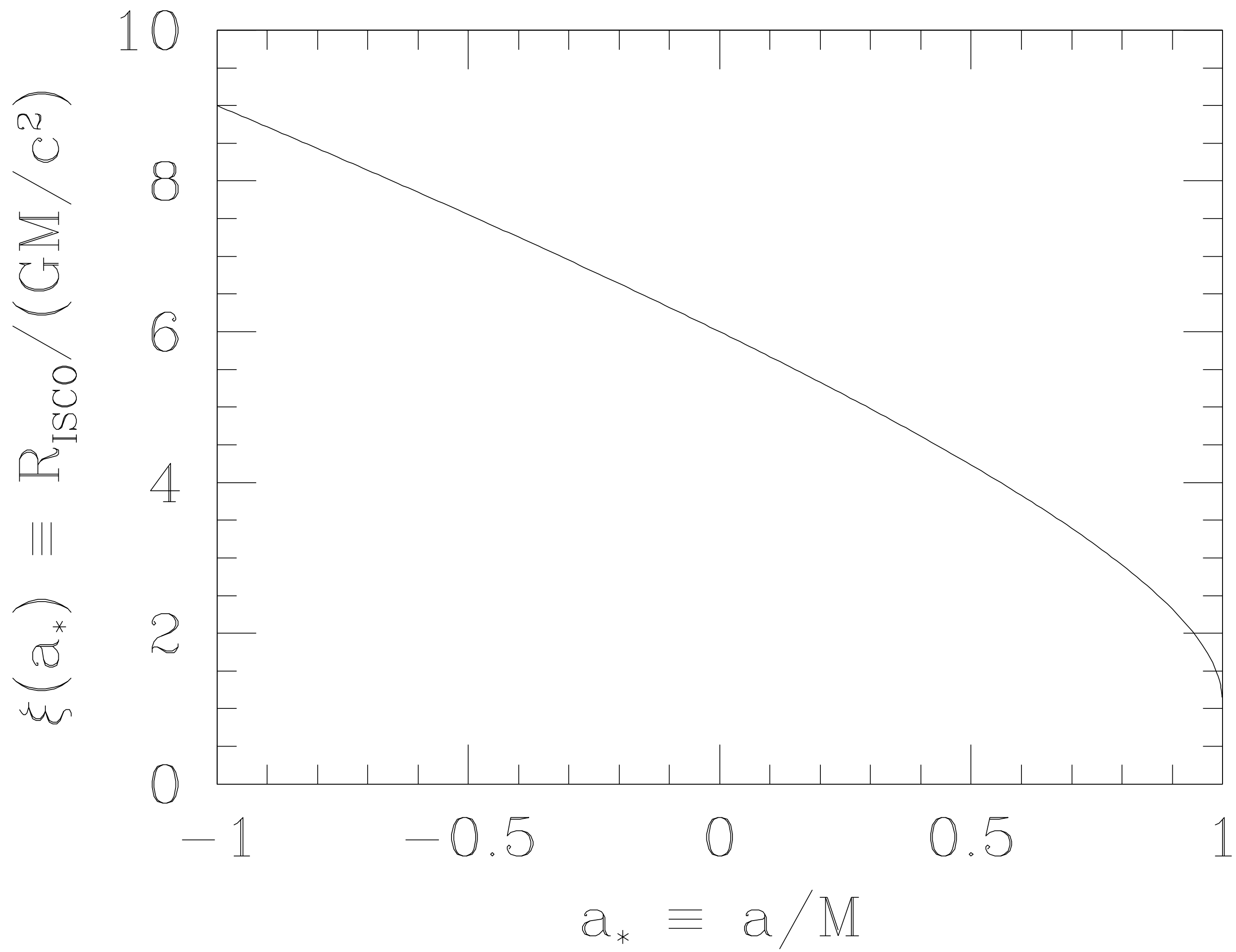


X-ray Luminosity (0.5–10.0 keV, 10^{40} erg/s)
1.00
0.10
0.01
0.1
1.0
Disk Temperature, kT (keV)
LMC X-3
LMC X-1
4U 1543-475
XTE J1550-564
4U 1630-472
GRO J1655-40
GRS 1915+105
NGC 1313 X-1
NGC 1313 X-2
M81 X-9
Ho II X-1
NGC 4559 X-7
Ant. X-37

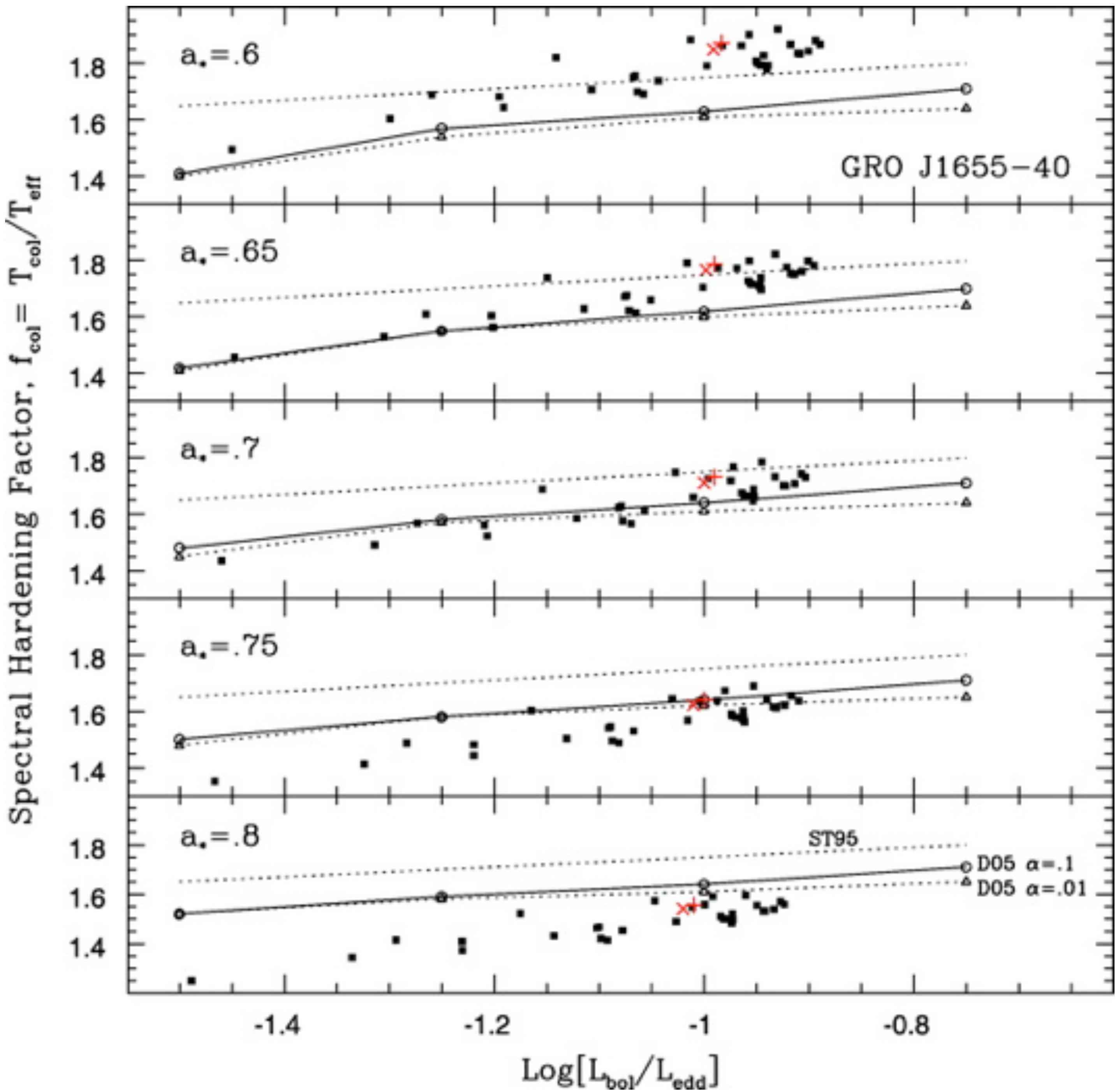
Miller et al

X-ray Transients - Black Hole Spin

- Thermal continuum spectrum from the accretion disk
- Broad and skewed fluorescent iron line emission from the disk
- High frequency quasi-periodic oscillations (trapped g-modes, parametric resonances, Lense-Thirring precession)



10
8
6
4
2
0
−1
−0.5
0
0.5
1
$\xi(a_*) \equiv R_{ISCO}/(GM/c^2)$
$a_* \equiv a/M$

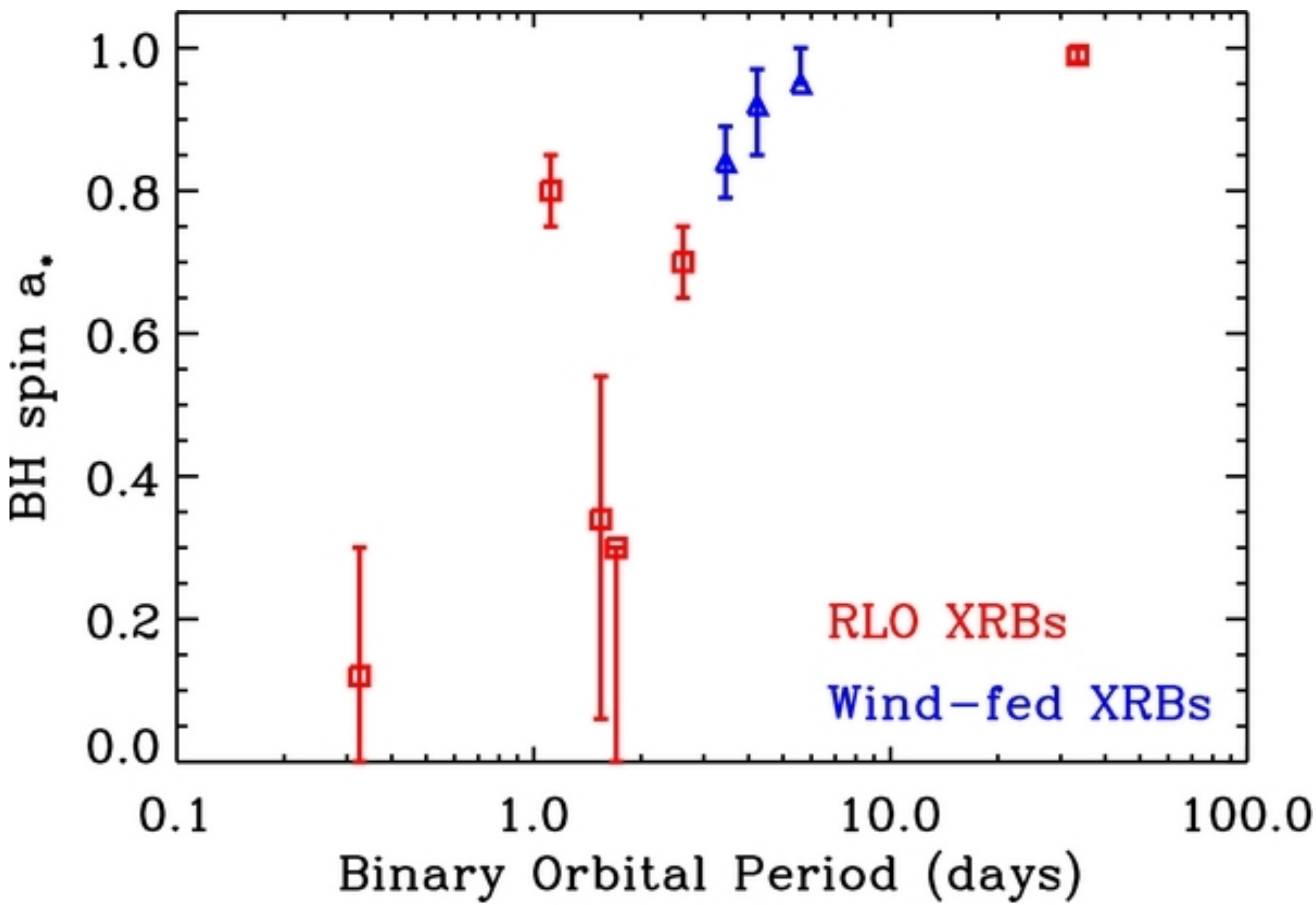


a*=.6
GRO J1655-40
a*=.65
a*=.7
a*=.75
a*=.8
ST95
D05 α=.1
D05 α=.01
1.8
1.6
1.4
-1.4
-1.2
-1
-0.8
Spectral Hardening Factor, $f_{col}= T_{col}/T_{eff}$
$Log[L_{bol}/L_{edd}]$

Shafee et al

Summary of Spin Estimates

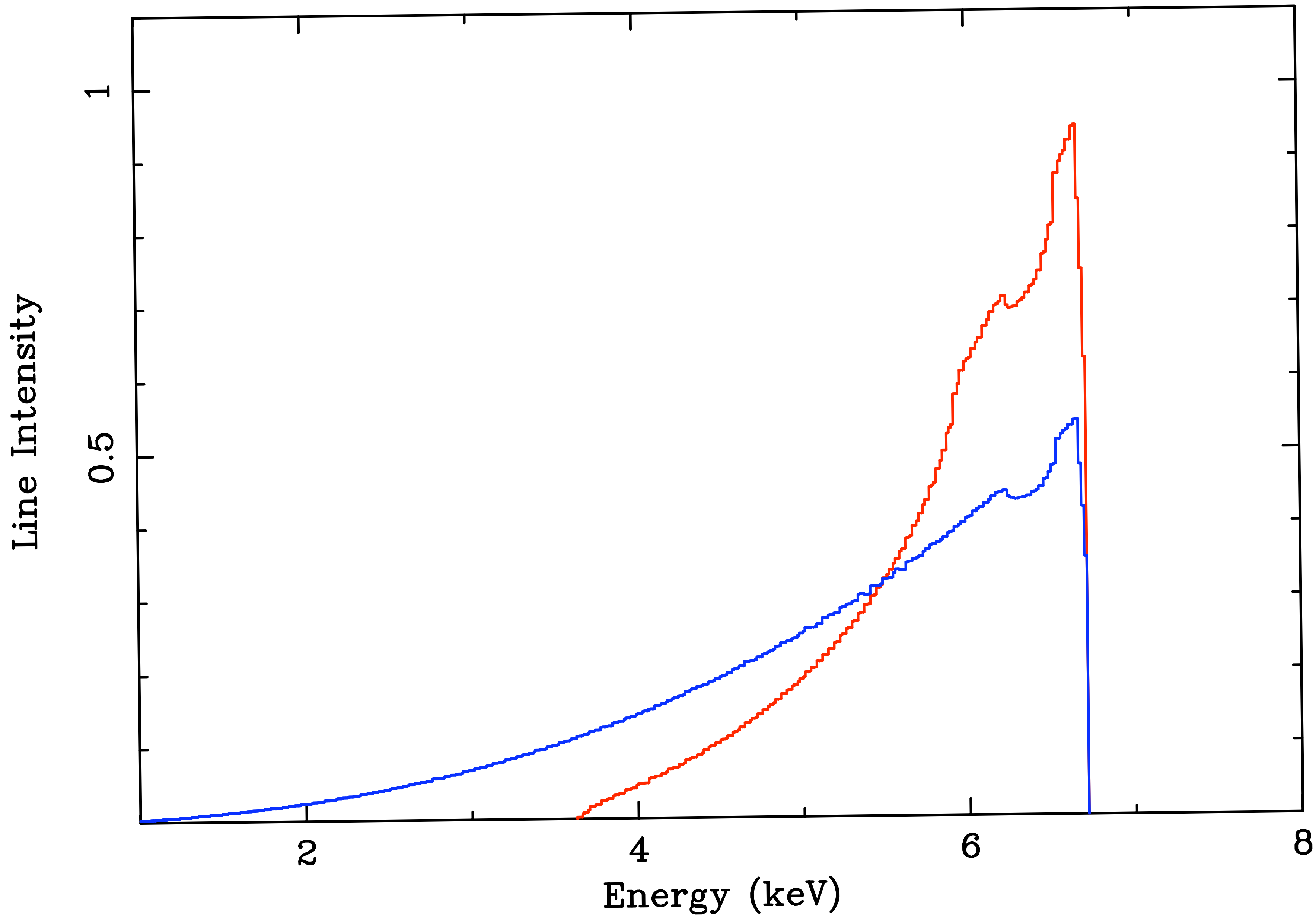
Source	M	a/M
A0620-00	6.3-6.9	0.13-0.44
LMC X-3	5.9-9.2	0.09-0.38
11550-564	8.5-9.7	0.06-0.54
11655-40	6.0-6.6	0.65-0.75
4U1543-47	8.4-10.4	0.79-0.89
M33 X-7	14.2-17.1	0.81-0.89
LMC X-1	9.4-12.4	0.85-0.97
Cyg X-1	13.8-15.8	> 0.98
1915+105	10-18	> 0.98

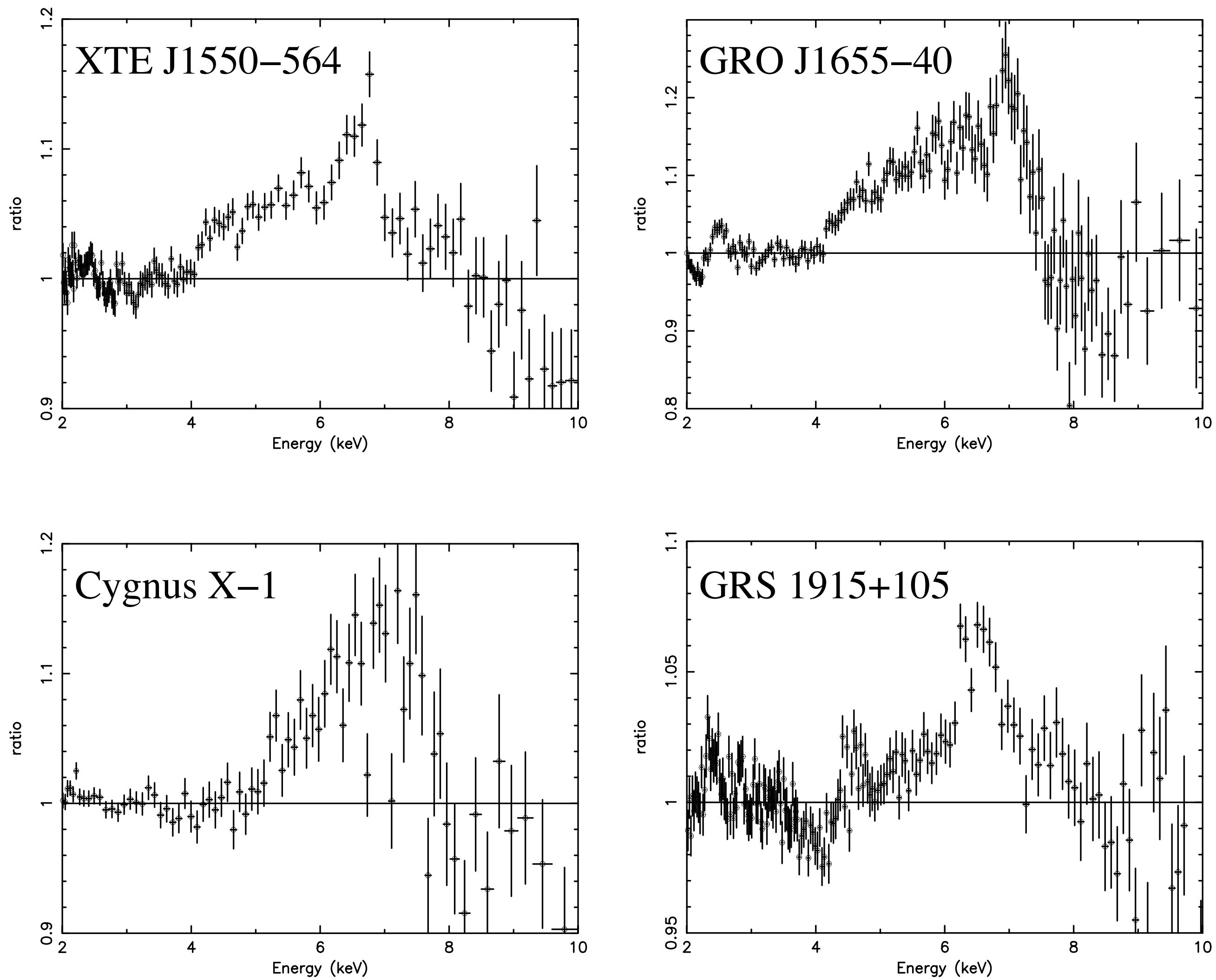


BH spin a*
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1.0
10.0
100.0
Binary Orbital Period (days)
RLO XRBs
Wind-fed XRBs

Fragos et al

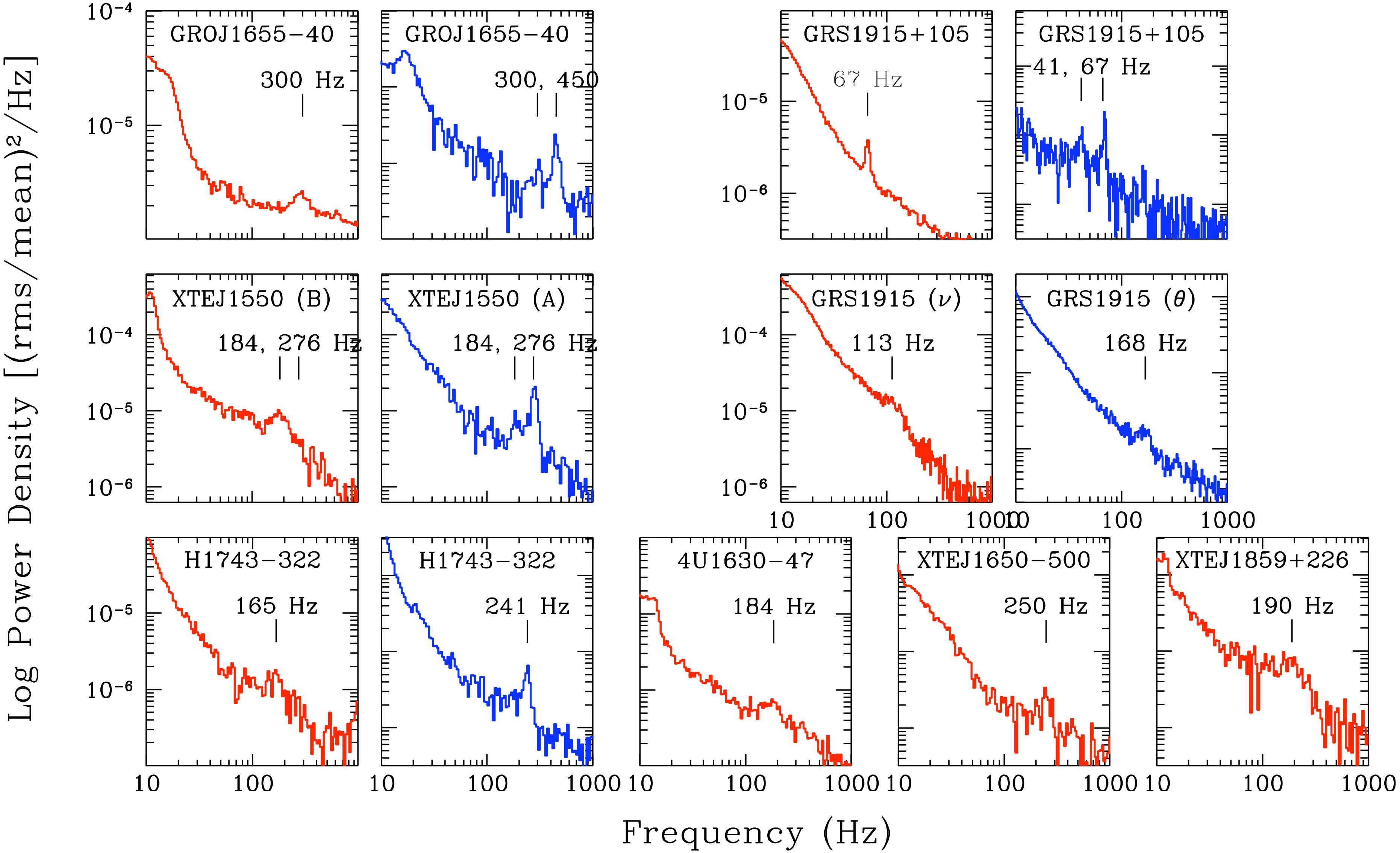
Relativistic Fe line profiles




XTE J1550−564
GRO J1655−40
Cygnus X−1
GRS 1915+105
ratio
Energy (keV)
2
4
6
8
10
0.9
1
1.1
1.2
0.8
0.95
1.05

Miller

High frequency quasi periodic oscillations



Remillard et al

Future Studies

- Probes of dense matter through neutron star properties
- Formation and evolution of black holes in different systems and environments
- Disk physics - investigation of turbulent viscosity & resistivity: importance for disk structure and its variability especially the inner region