Constraining the Dense Matter Equation of State
with Lynx Observations of
Globular Cluster X-ray Binaries

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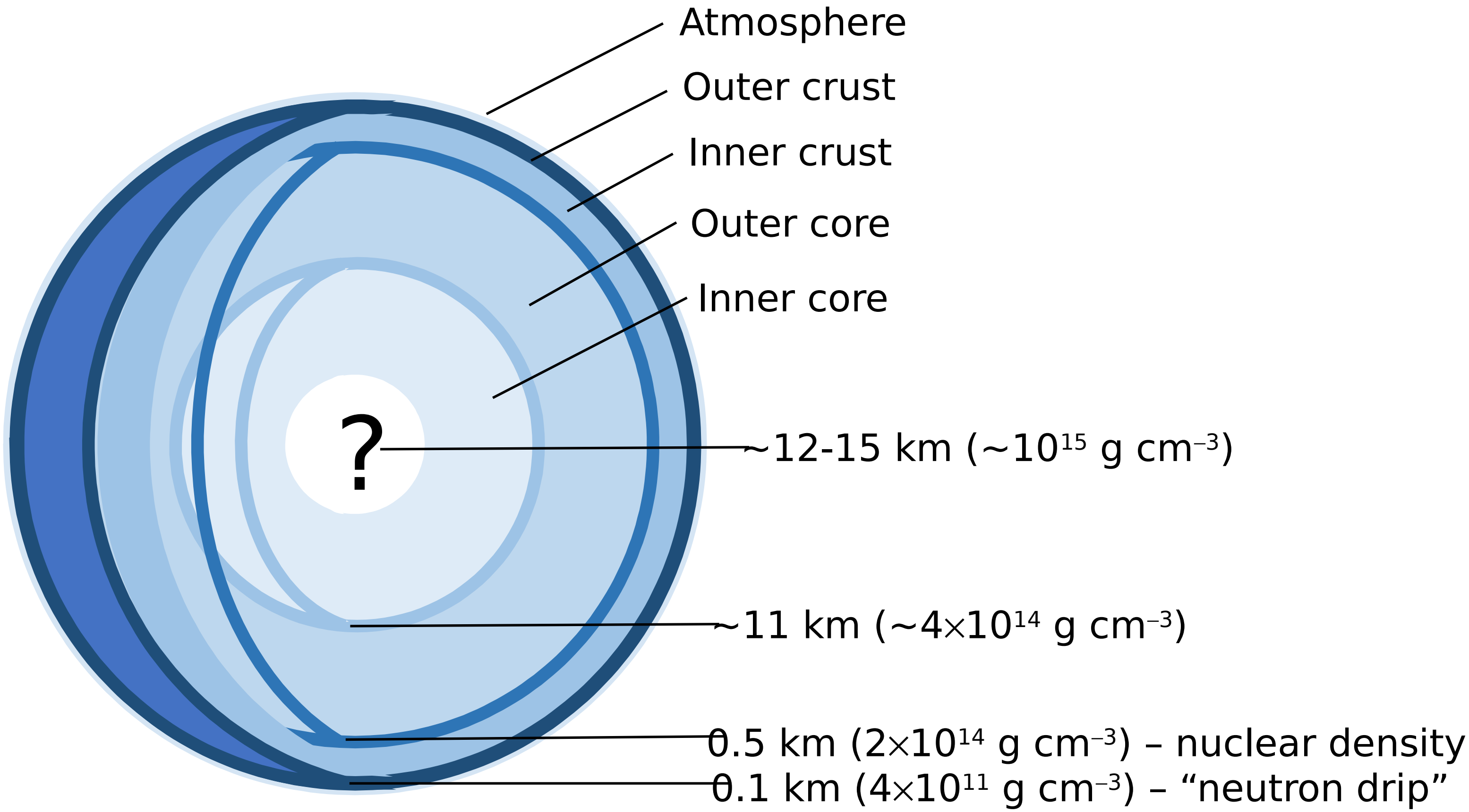
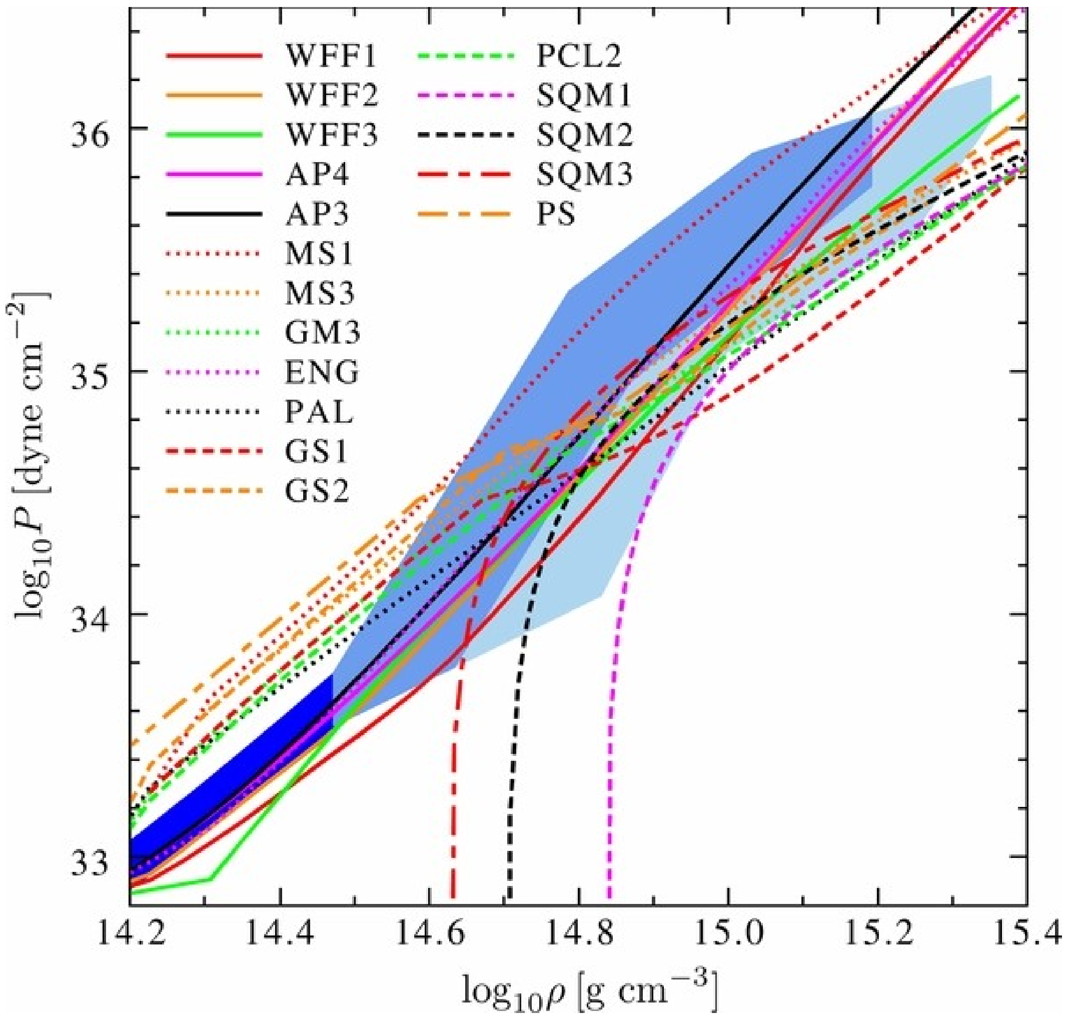
The interior structure of neutron stars is unknown

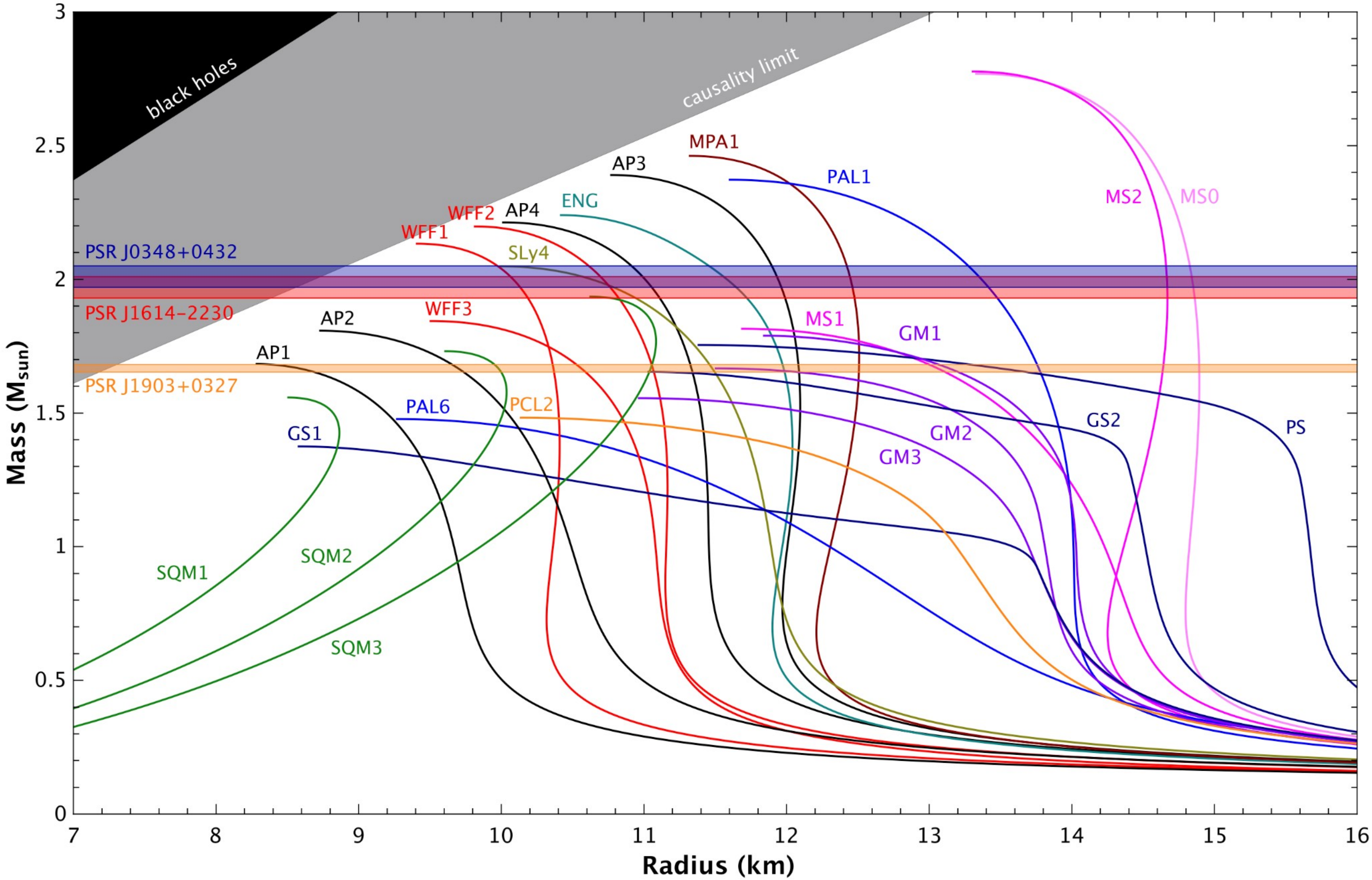


The state of cold, supranuclear matter is unknown

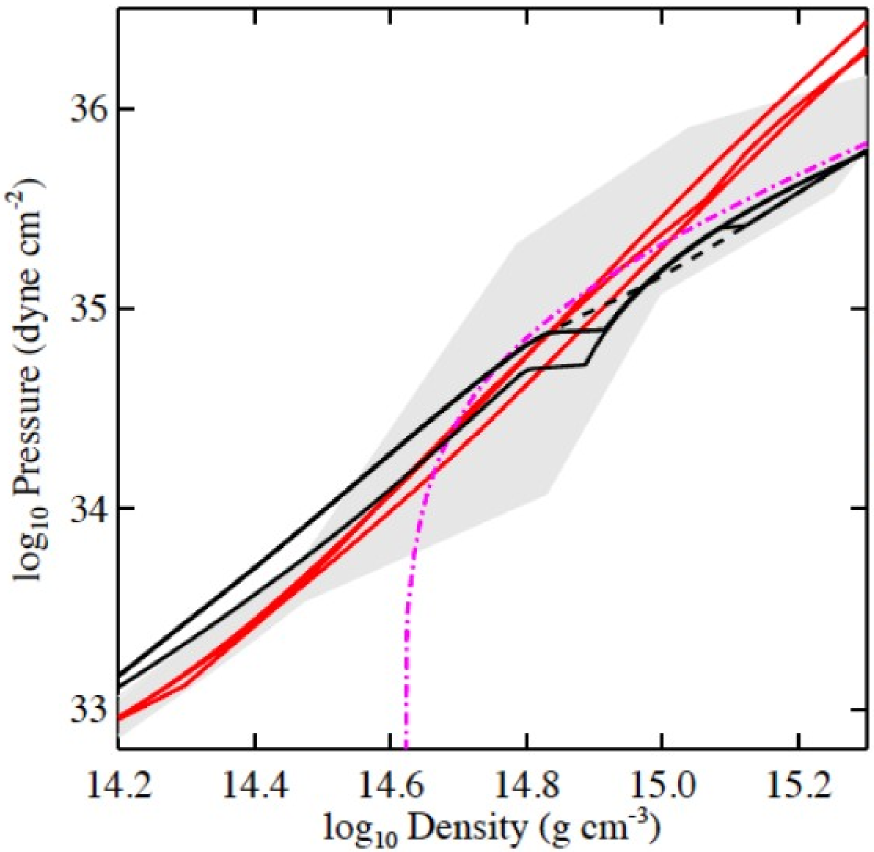


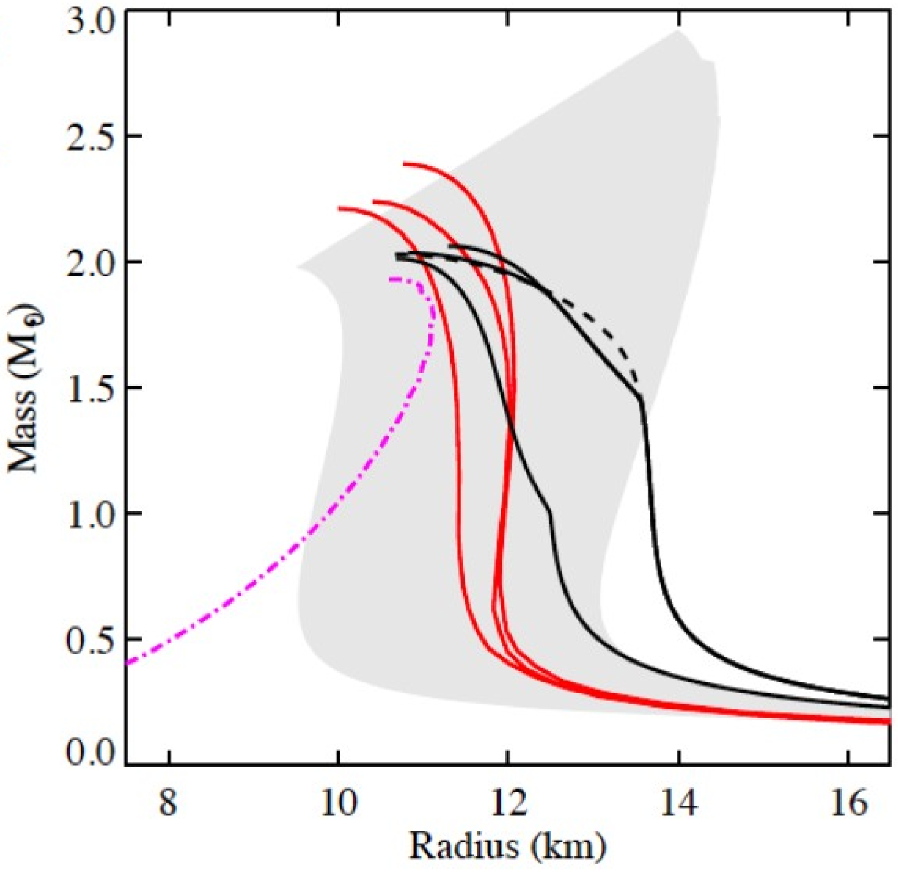
Hebeler et al. ApJ, 773, 11 (2013)

The neutron star mass-radius relation



Mapping between P-ρ and M-R





Observational methods for dense matter equation of state constraints using neutron stars

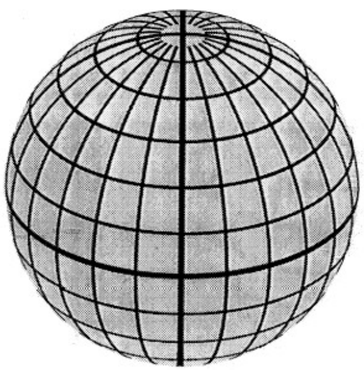
- Mass measurements from radio pulsar timing
  - e.g. $\sim 2M_{\odot}$ NSs; Demorest et al. *Nature*, 467, 1081 (2010); Antoniadis et al. *Science*, 340, 448 (2013)
- Maximum spin rate of neutron stars
  - e.g. 716 Hz pulsar; Hessels et al. *Science*, 311, 1901 (2006)
- kiloHertz quasi-periodic oscillations (QPOs)
  - e.g. Miller et al. *ApJ*, 509, 793 (1998)
- Cooling rates of neutron stars
  - e.g. Page et al. *NuPhA*, 777, 497 (2006)
- Photospheric radius expansion in thermonuclear bursts
  - Joss *Nature*, 270, 310 (1977); Özel et al. (2009); Steiner et al. (2010); etc…
- Pulse profile/waveform/light curve modeling of accreting and "recycled" MSPs
  - e.g., Pechenick et al. (1983); Poutanen & Gierlinski (2003); Bhattacharyya et al. (2005); Morsink & Leahy (2011); Bogdanov (2013); Lo et al. (2013); etc...
- **Radius measurements via X-ray spectroscopy of quiescent LMXBs**
  - e.g., Rutledge et al. (2001); Heinke et al. (2006,2014); Guillot et al. (2013); etc…

Neutron Star Radius Measurements from Spectroscopy
Quiescent Low-Mass X-ray Binaries

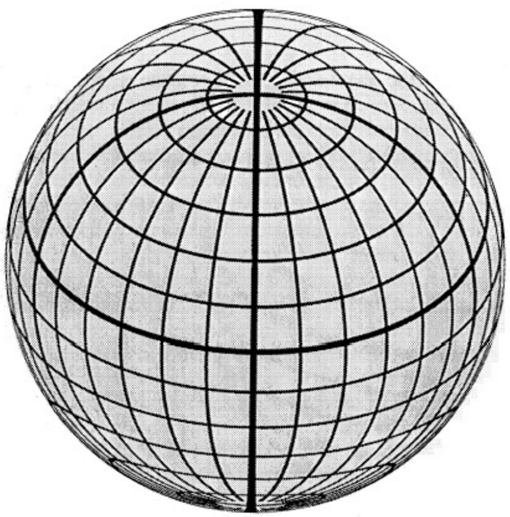
$$R_\infty \equiv (1+z)\, R_{NS} \qquad T_\infty = \frac{T_{\rm eff}}{1+z} \qquad 1+z = (1 - R_S/r)^{-1/2} \qquad R_S = 2GM/c^2$$

- Flux measured by a distant observer:

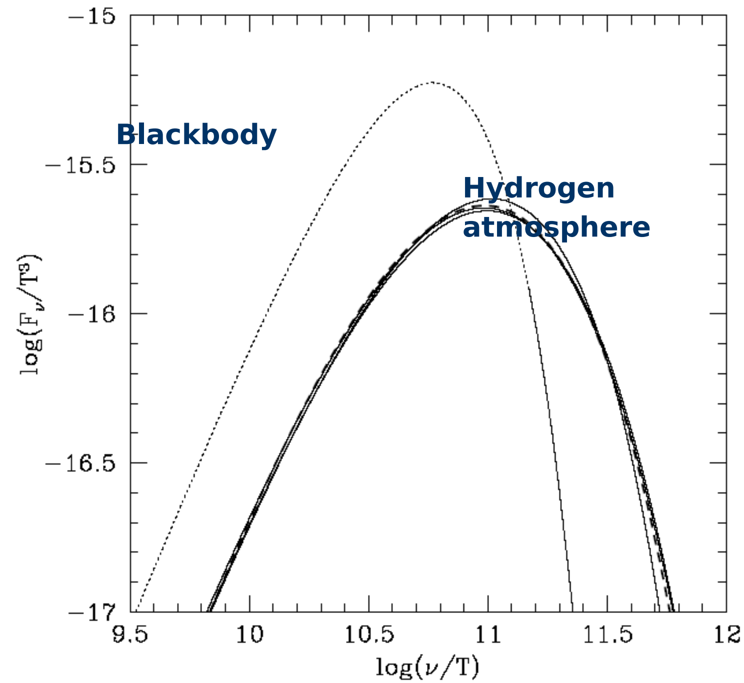
$$F(r_{\rm obs},\ \nu_{\rm obs}) = (1+z)^{-1} \frac{r^2}{r_{\rm obs}^2} F[r,\ (1+z)\nu_{\rm obs}]$$



Flat



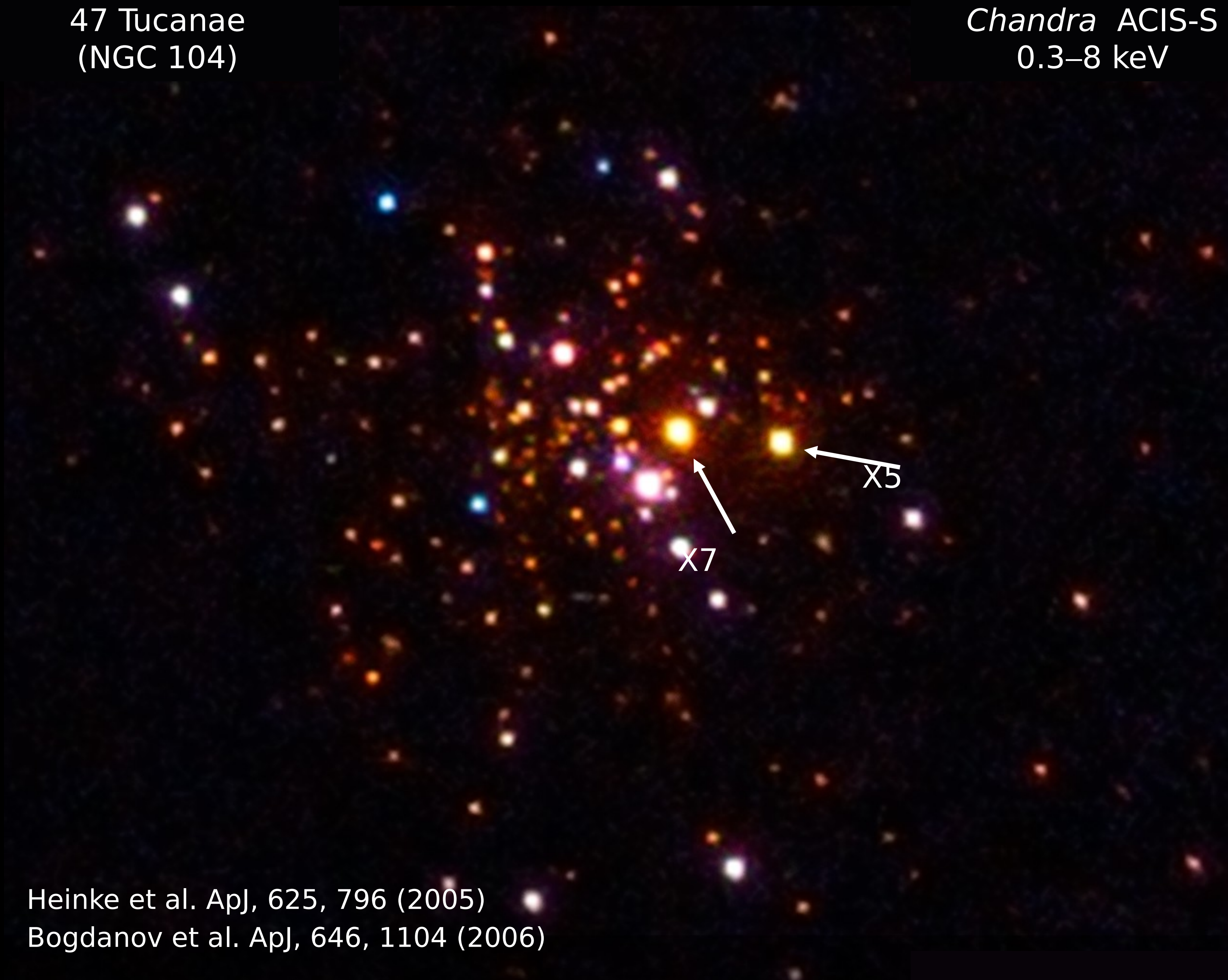
Schwarzschild



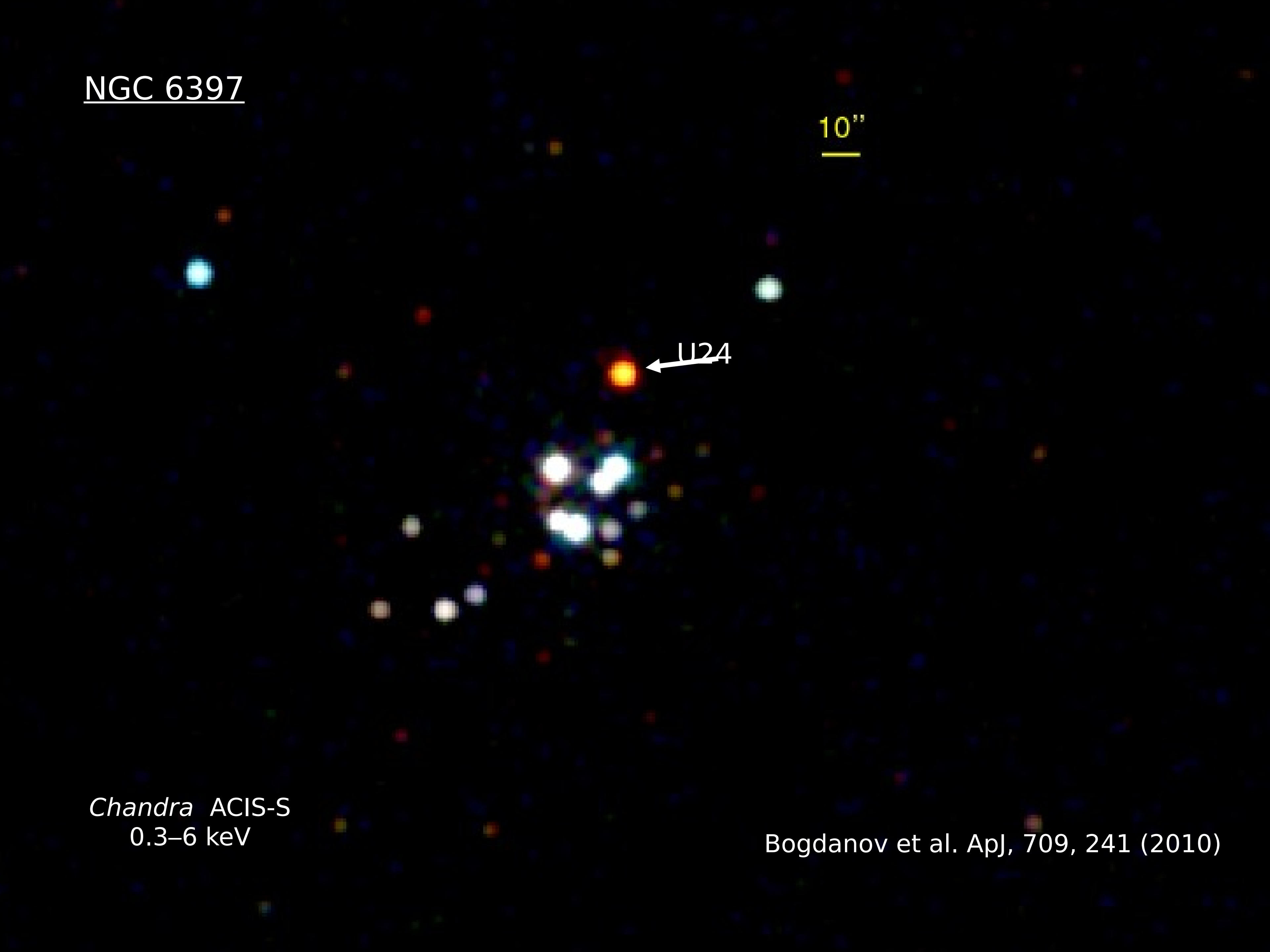
- **Measurement relies on correct emission model and precise distance to source**

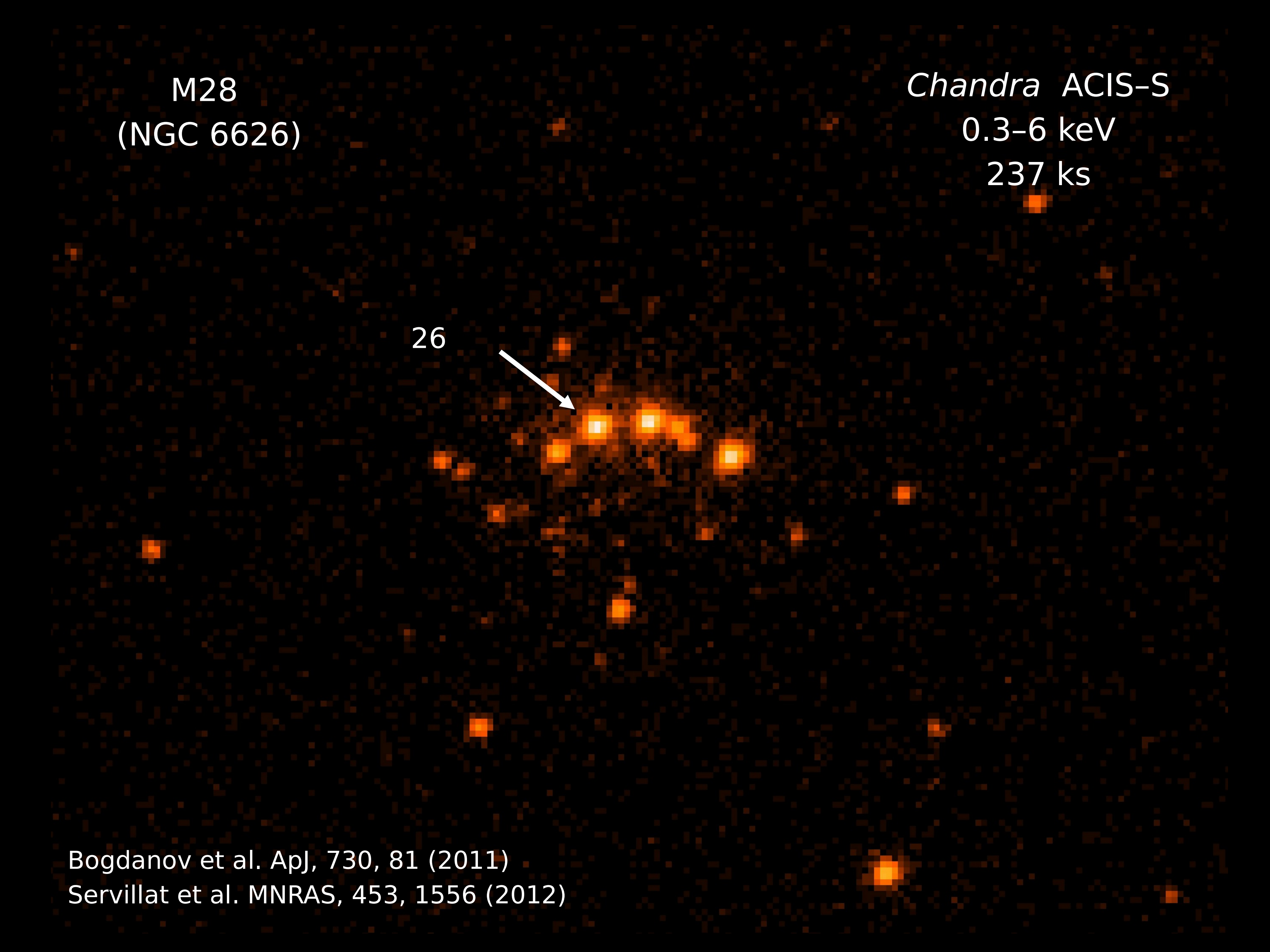
47 Tucanae
(NGC 104)

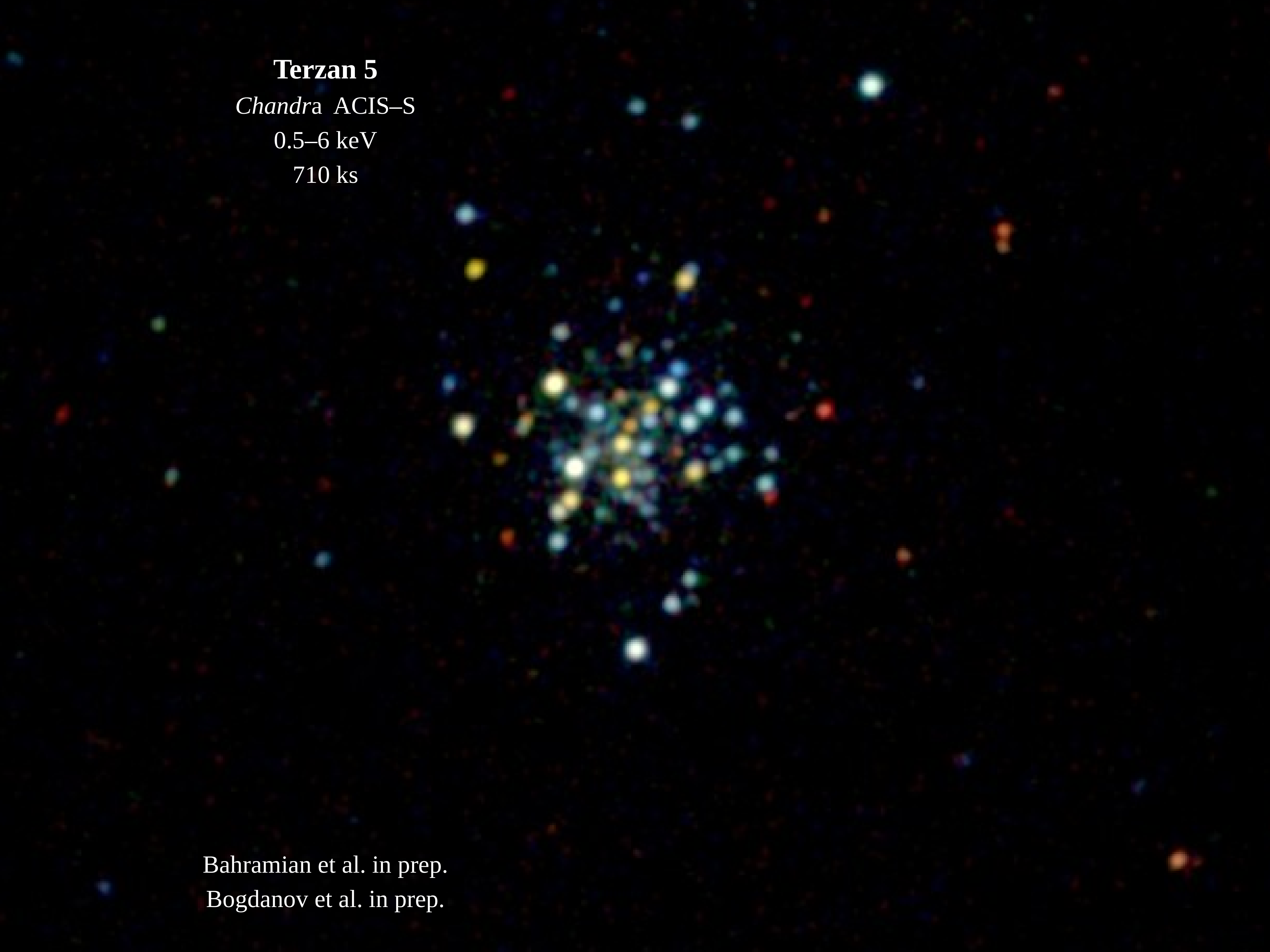
Chandra ACIS-S
0.3–8 keV



Heinke et al. ApJ, 625, 796 (2005)
Bogdanov et al. ApJ, 646, 1104 (2006)

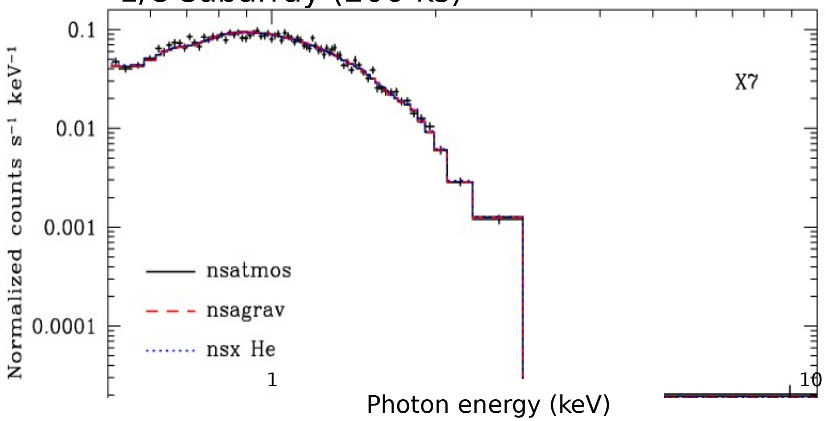

NGC 6397
10''
U24
Chandra ACIS-S
0.3–6 keV
Bogdanov et al. ApJ, 709, 241 (2010)

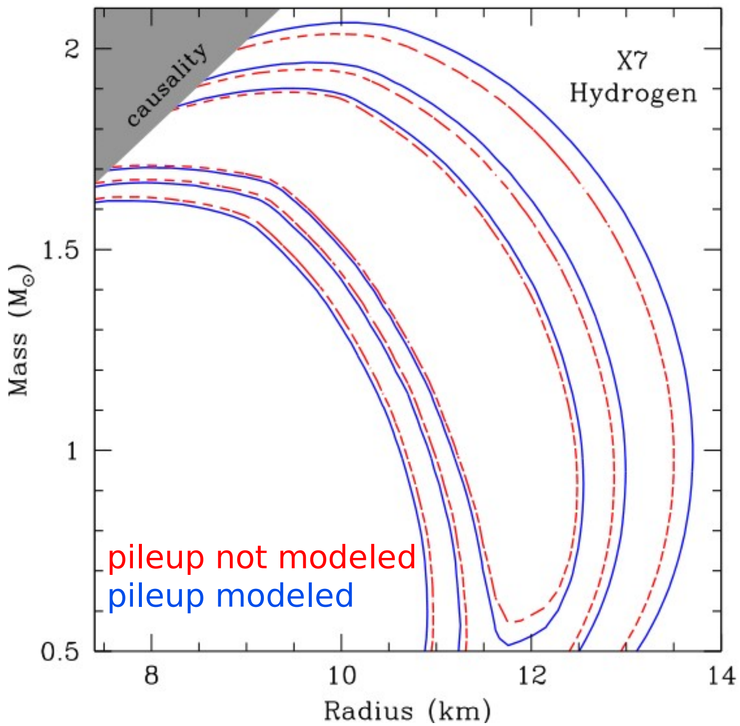

M28
(NGC 6626)
Chandra ACIS–S
0.3–6 keV
237 ks
26
Bogdanov et al. ApJ, 730, 81 (2011)
Servillat et al. MNRAS, 453, 1556 (2012)


Terzan 5
Chandra ACIS–S
0.5–6 keV
710 ks
Bahramian et al. in prep.
Bogdanov et al. in prep.

Spectroscopy of quiescent low-mass X-ray binaries

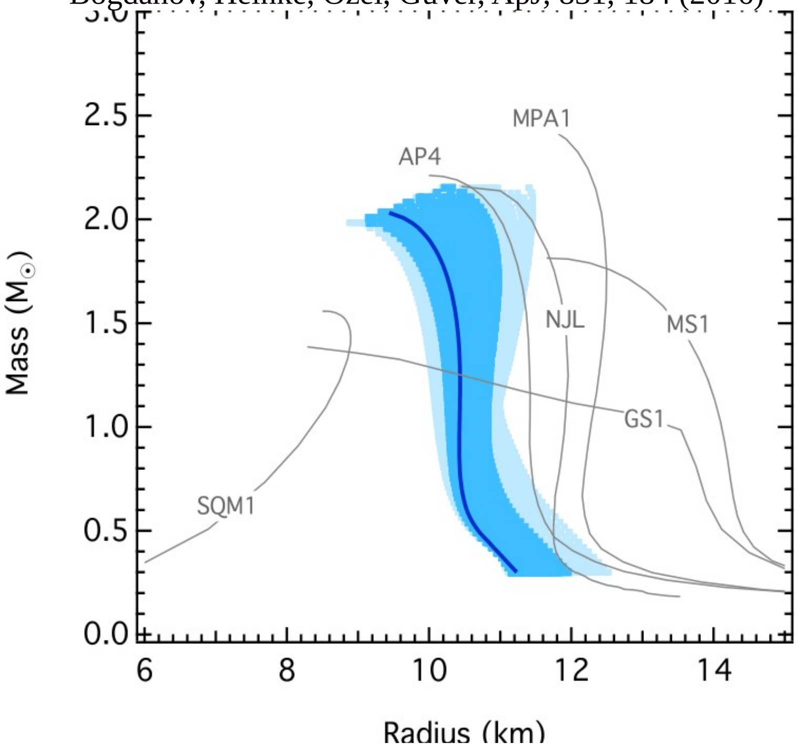
Chandra ACIS-S
1/8 subarray (200 ks)



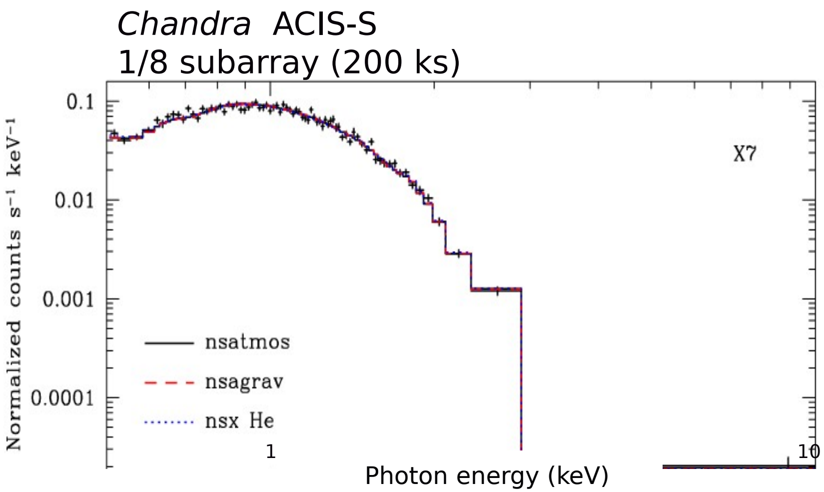


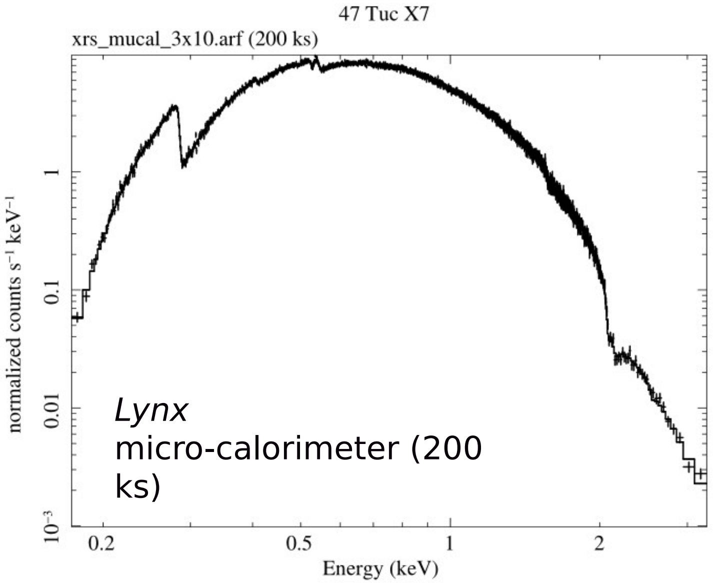
- NS M-R estimates from an ensemble of systems can provide stringent constraints on the dense matter EoS

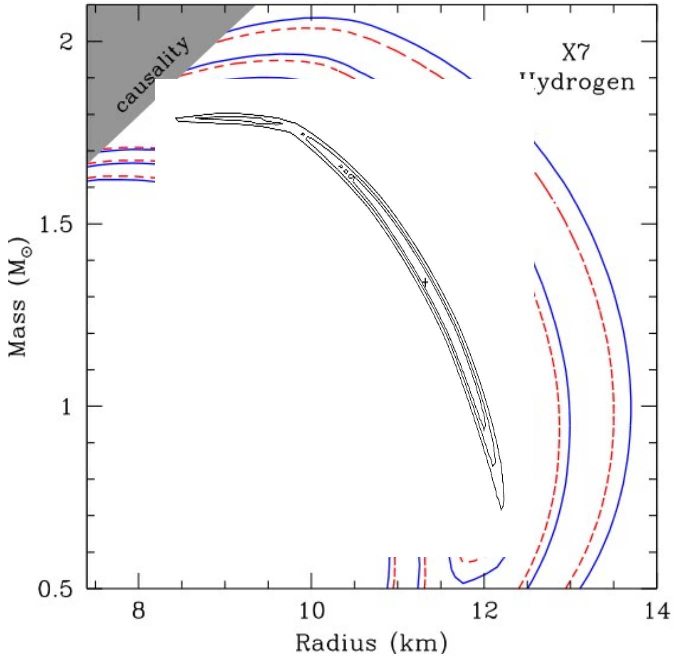
Bogdanov, Heinke, Özel, Güver, ApJ, 831, 184 (2016)

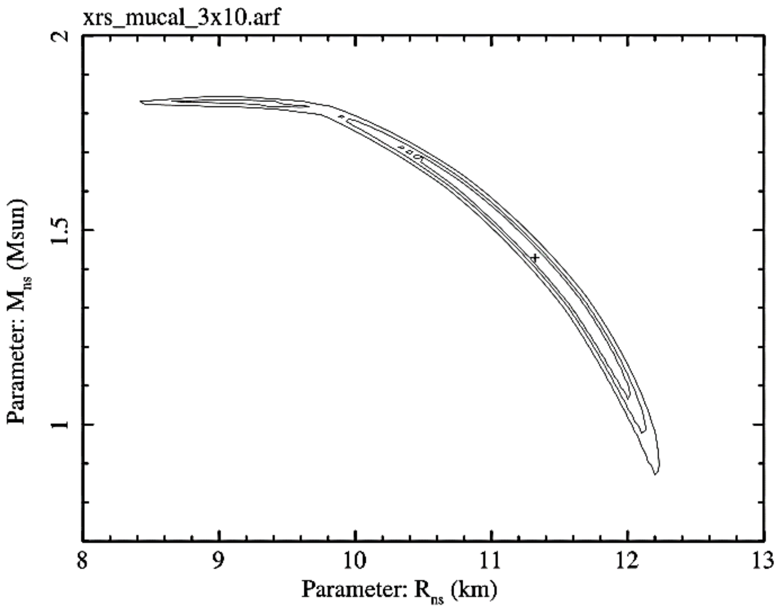


Neutron Star Mass-Radius Constraints with Lynx

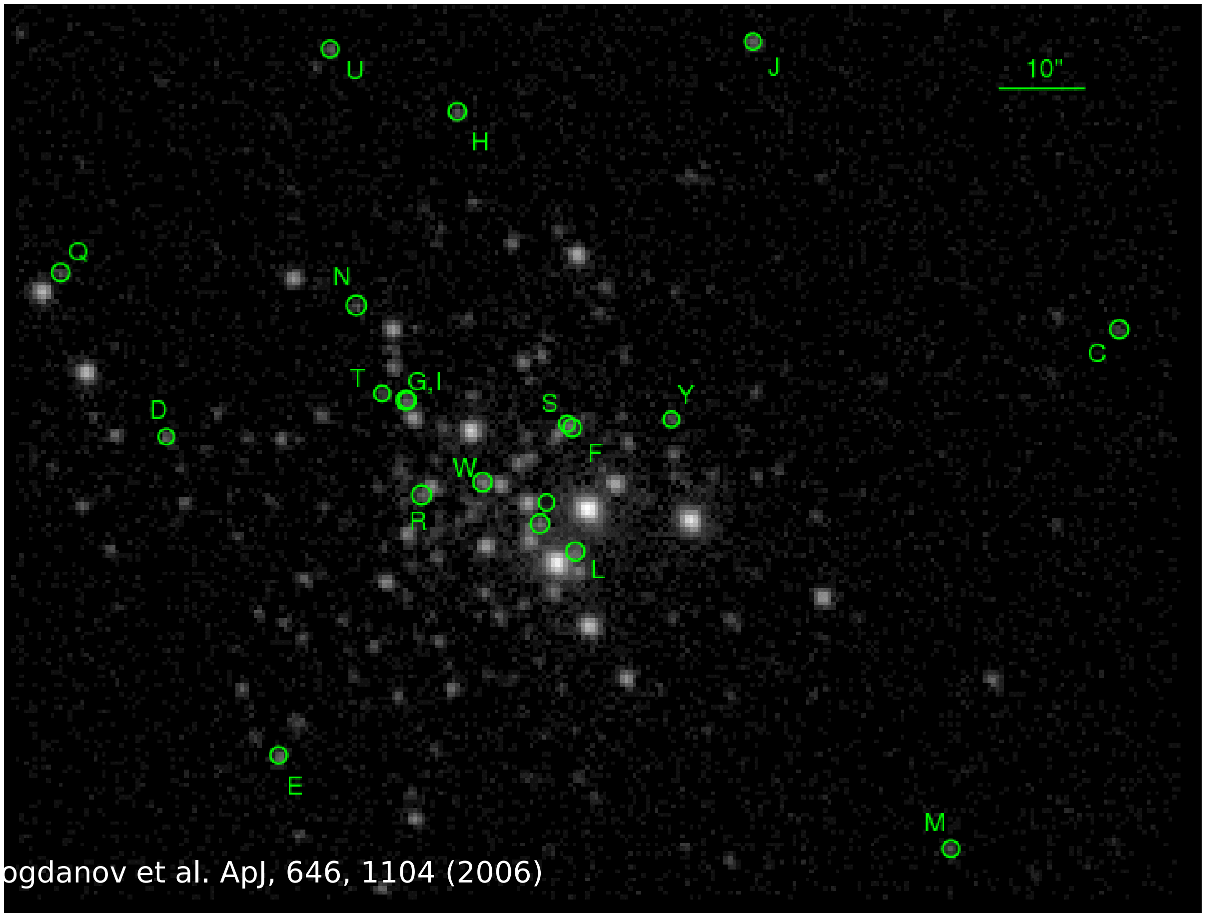




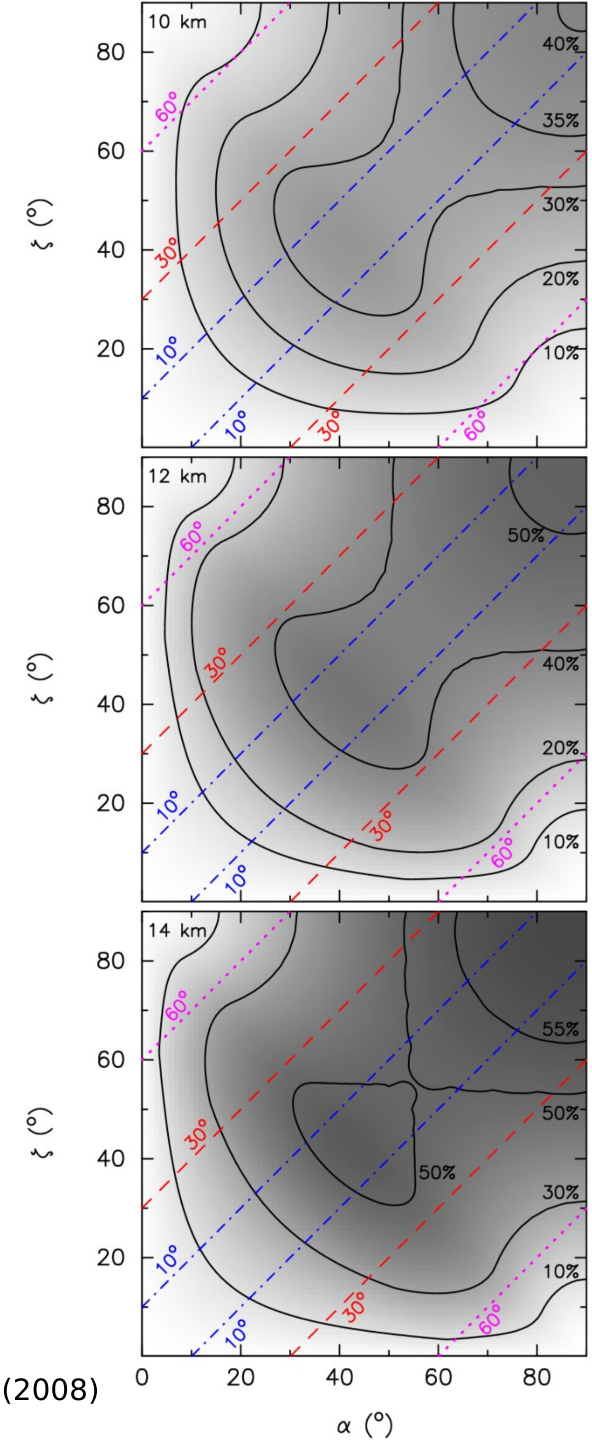




A complete census of rotation-powered MSPs
in globular clusters



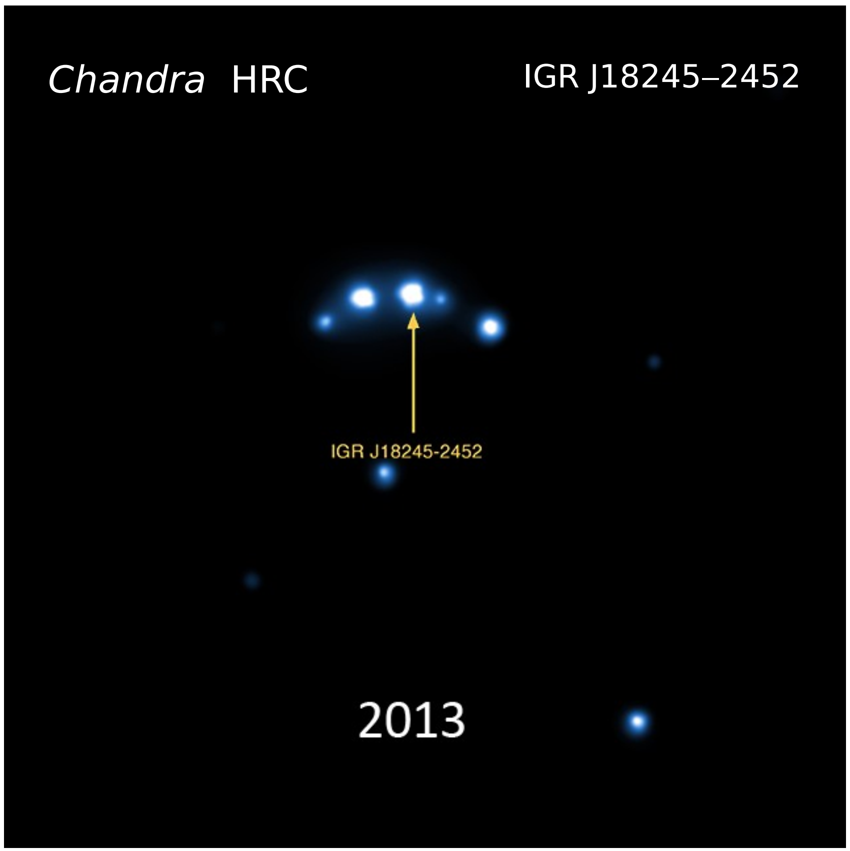
Blind X-ray timing searches could discover **all** MSPs in nearby clusters



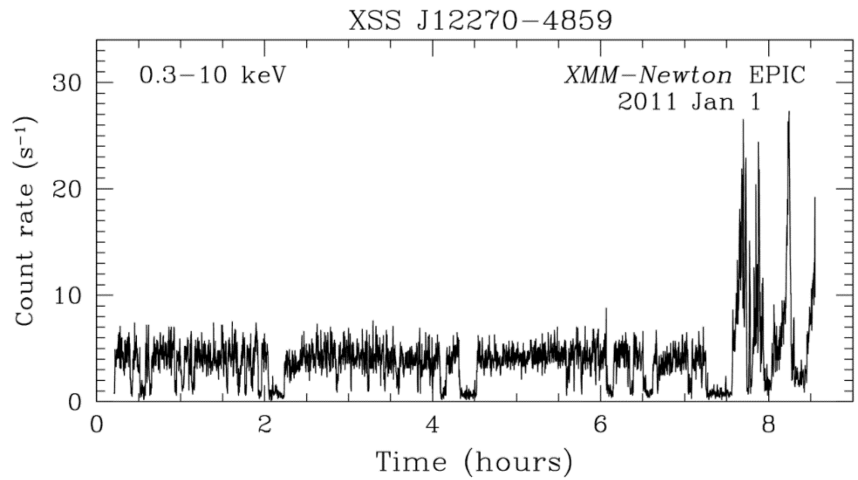
Bogdanov, Grindlay, & Rybicki, ApJ, 689, 407 (2008)

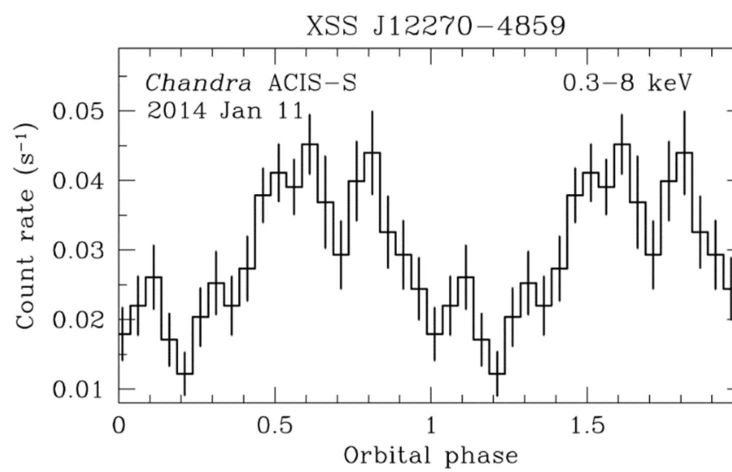
Transitional Pulsars

Rotation-powered (radio) MSPs □ Accretion-powered (X-ray) MSPs



Papitto et al. Nature, 501, 517 (2013)





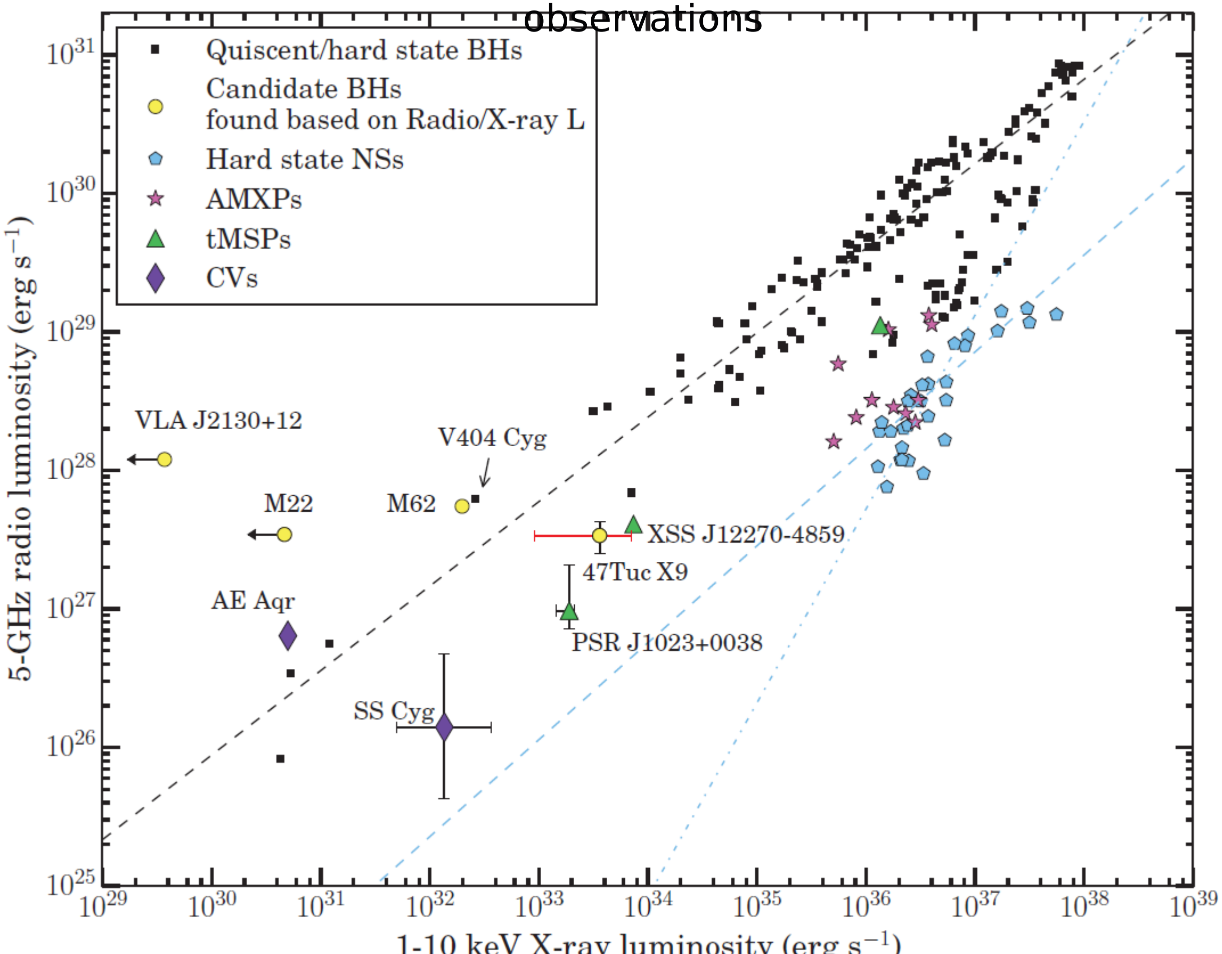
Bogdanov et al. ApJ, 789, 40 (2014


47 Tucanae
(NGC 104)
Chandra ACIS-S
0.3–8 keV
X9

47 Tuc X9: An Ultracompact Black Hole X-ray Binary

- A 28 minute binary with a C-O WD donor and BH accretor!

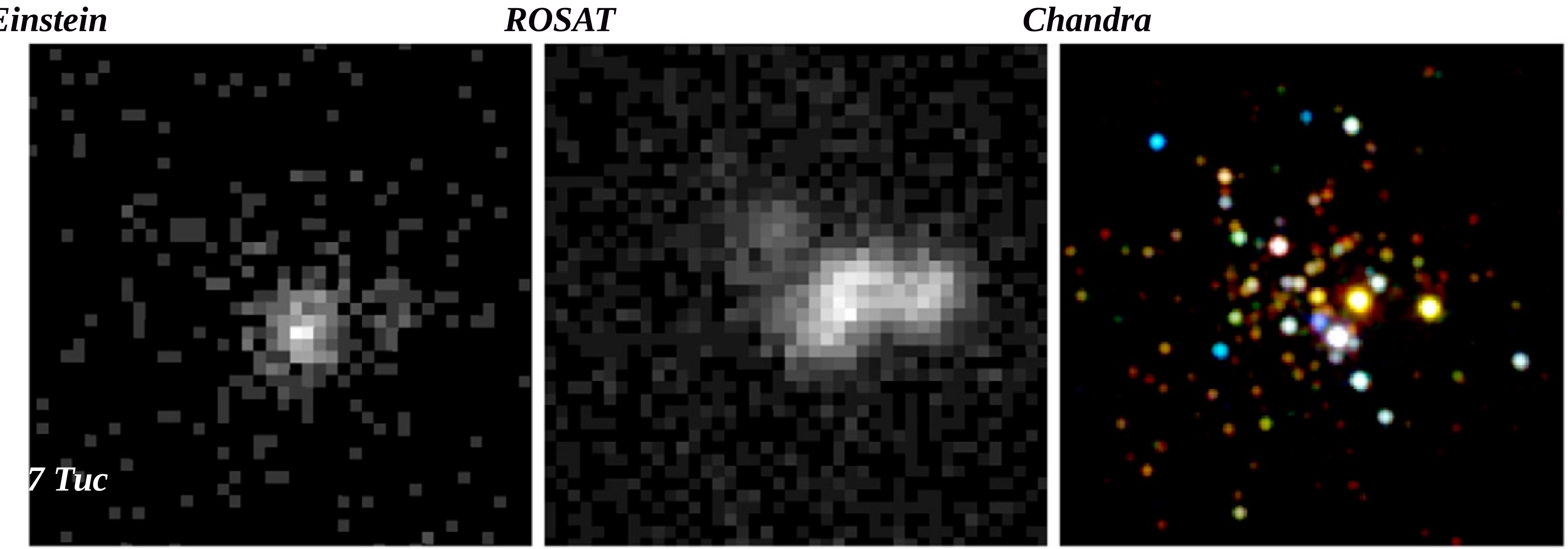
contemporaneous *Chandra* + *NuSTAR* + ATCA observations



Bahramian et al. MNRAS, 467, 2199 (201

Conclusions

- Lynx observations of NS qLMXBs in globular clusters can produce stringent dense matter EoS constraints
- Bonus science from the same observations: cataclysmic variables, chromospherically active binaries, radio millisecond pulsars, transitional pulsars, black hole LMXBs, etc.
- Sub-arcsecond angular resolution is essential!



Pooley, PNAS, 107, 7164 (2010