Deep *Chandra* Studies of Millisecond Pulsars in Globular Clusters

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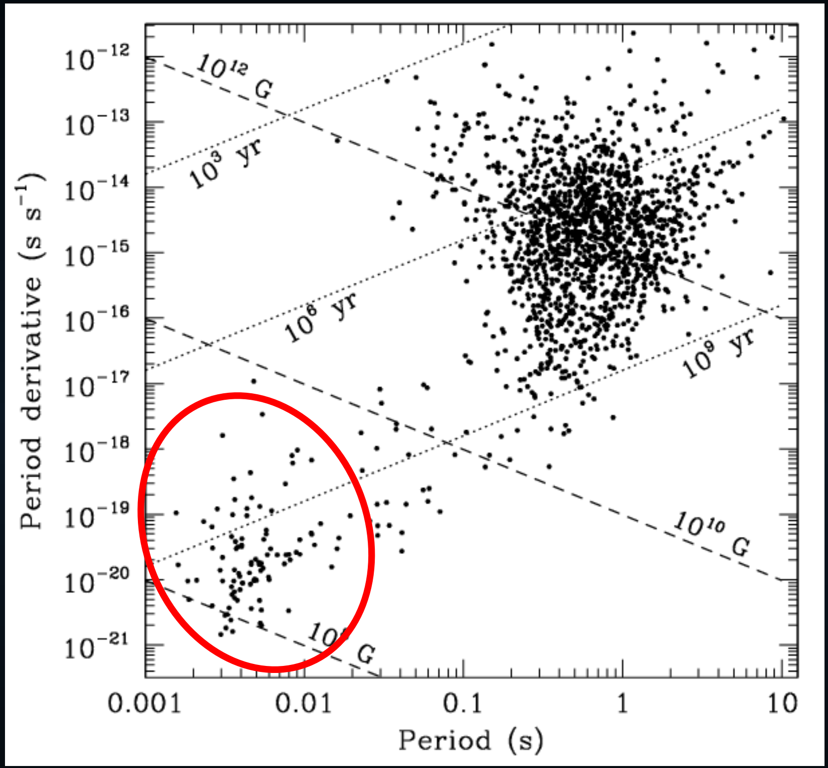
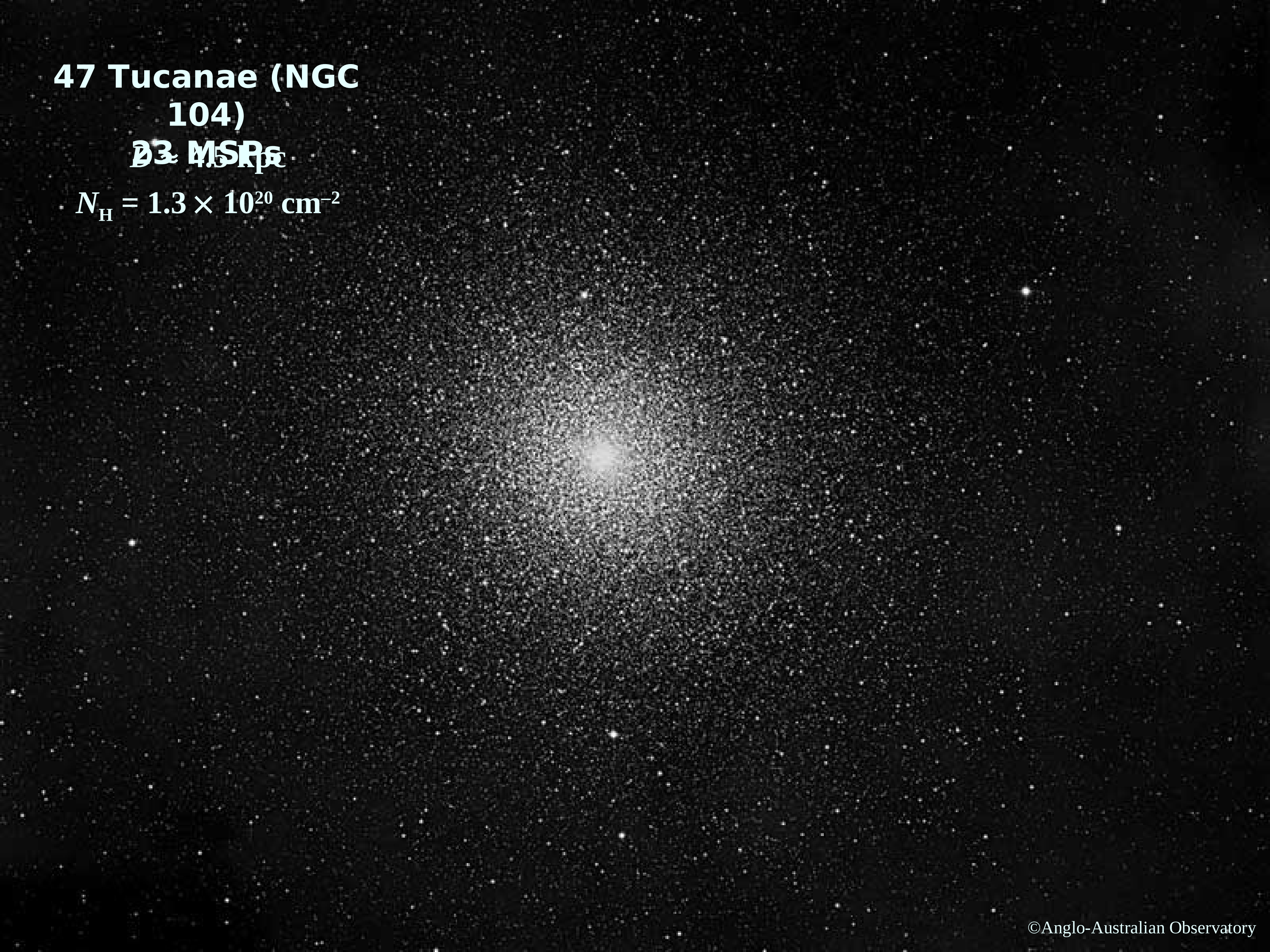
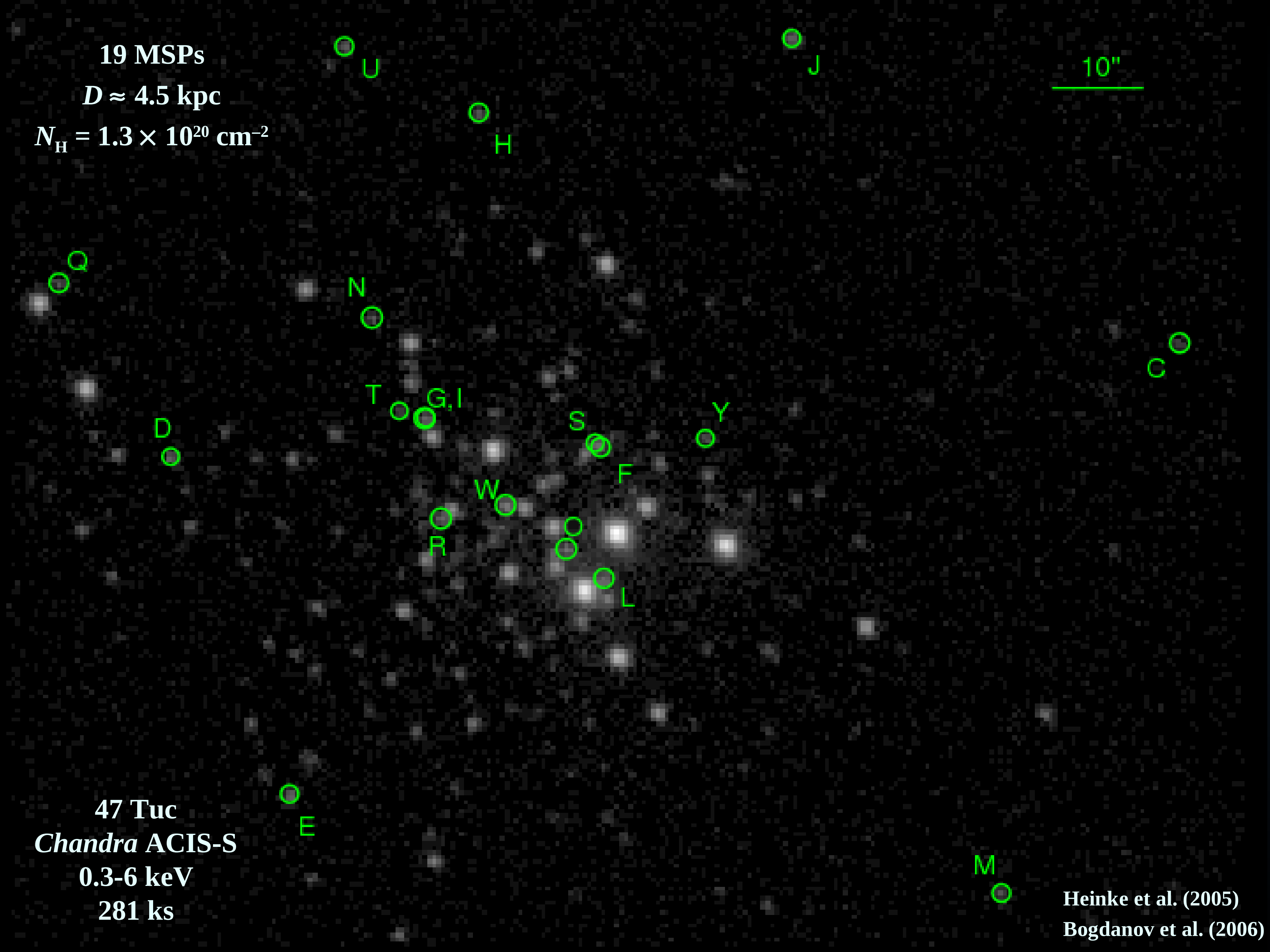
Rotation-powered ("recycled") millisecond pulsars

- Spun-up by accretion in NS LMXBs
- Abundant in globular clusters
  (~140 GC MSPs known; see www.naic.edu/~pfreire/GCpsr.html)
- Most are in binaries with WD or very low-mass (~0.03 M) companions
- Very faint X-ray sources
  ($L_X \leq 10^{33}$ ergs s^{-1}, typical: $L_X \approx 10^{30-31}$ ergs s^{-1})
  ⇒ require very deep exposures (>100 ks)
- Studies of cluster MSPs not possible before *Chandra*
- Today, MSPs account for ~1/3 of X-ray—detected pulsars thanks to deep globular cluster studies with *Chandra*

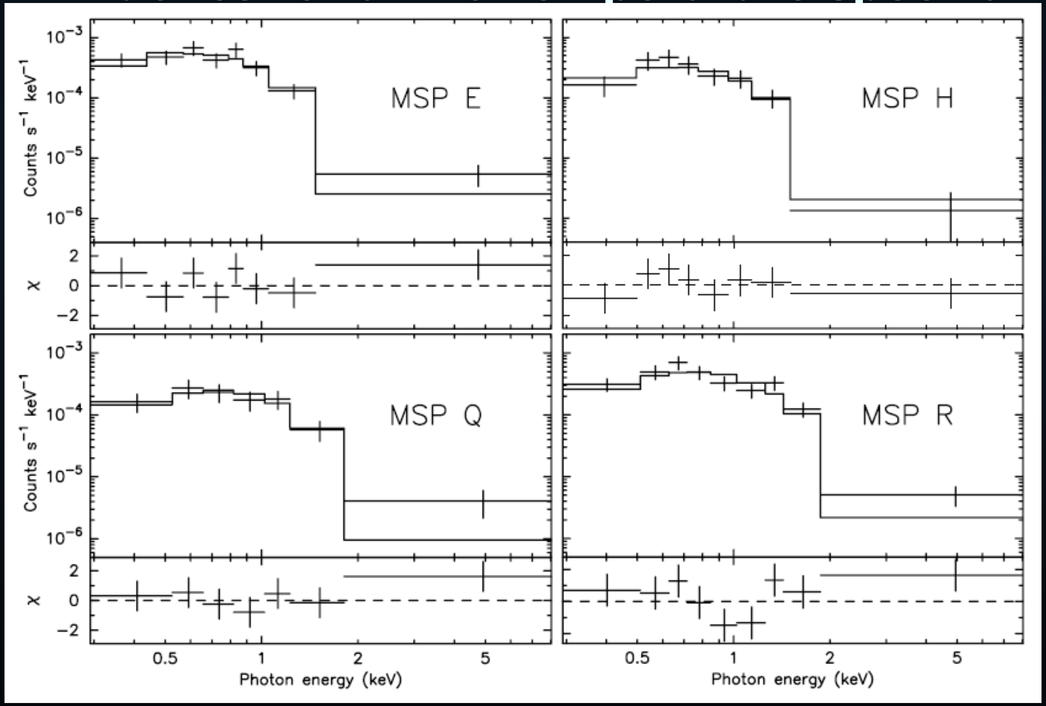



47 Tucanae (NGC 104)
23 MSPs
$D \approx 4.5$ kpc
$N_H = 1.3 \times 10^{20}$ cm^{-2}
©Anglo-Australian Observatory

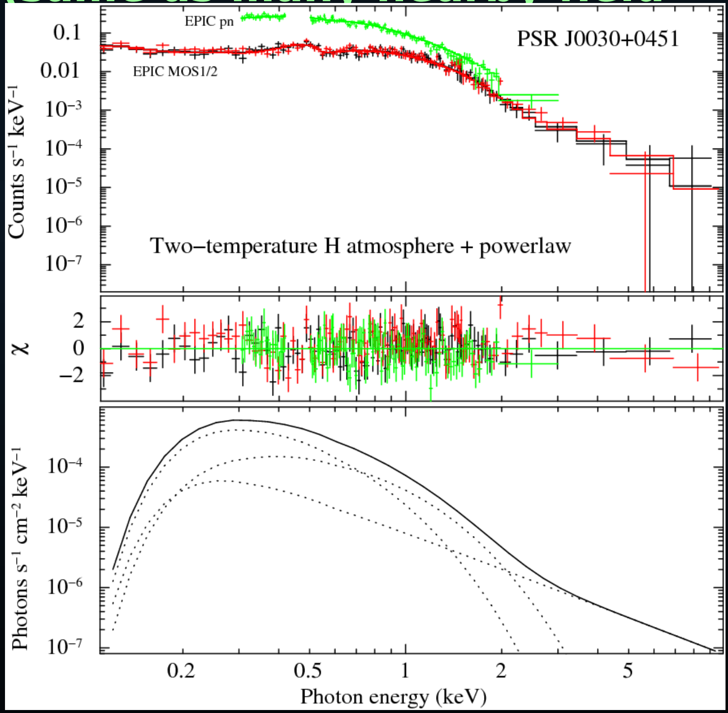

19 MSPs
D ≈ 4.5 kpc
N_H = 1.3 × 10^20 cm^-2
U
J
H
10"
Q
N
C
T
G,I
Y
D
S
F
W
R
L
E
M
47 Tuc
Chandra ACIS-S
0.3-6 keV
281 ks
Heinke et al. (2005)
Bogdanov et al. (2006)

Deep *Chandra* ACIS-S Observations of 47 Tuc

- ***All*** **19 known MSPs detected (typical count rate ≈ 1 photon/hour)**
- **16 out of 19 MSPs show faint, soft, thermal X-ray emission**
  - $T_{\rm eff} \sim 10^6$ K, $R_{\rm eff} \sim 0.1 - 2$ km ⇒ **hot polar caps**
  - $L_X \sim 10^{30-31}$ ergs s^{-1} (0.3 – 8 keV)
- **Evidence for a two-temperature spectrum (same as many nearby field**



Bogdanov et al. 2006, ApJ, 646, 1104



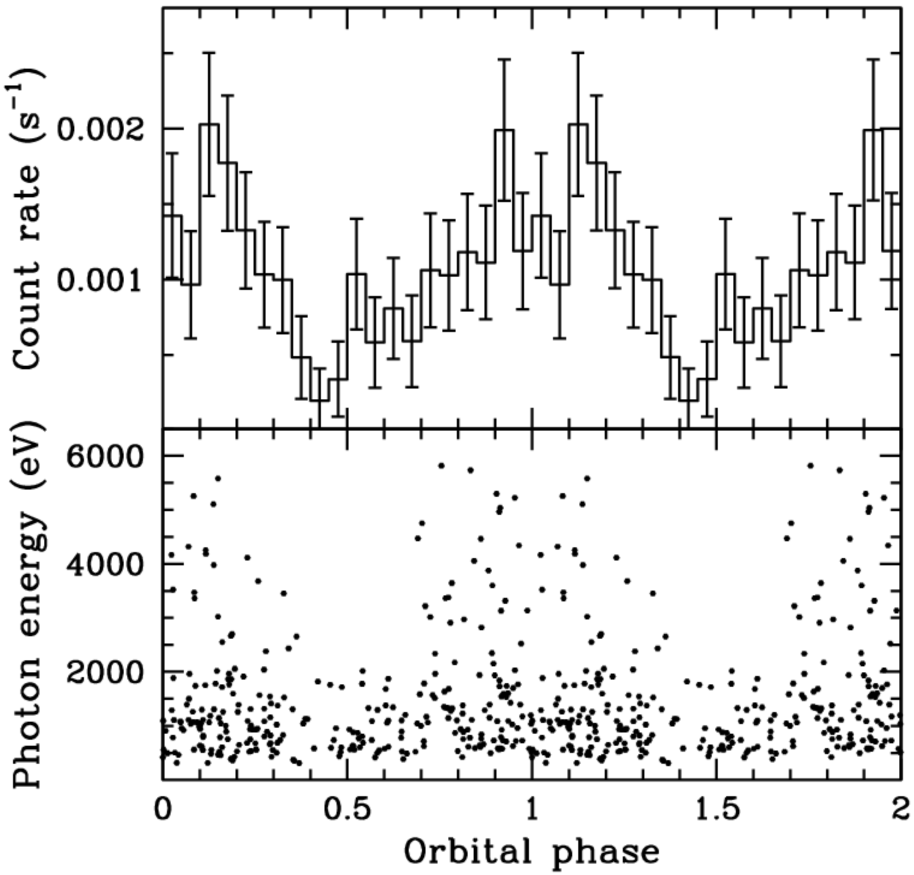
Bogdanov et al. 2009, ApJ, 689, 407

Conclusion: **most MSPs should have hot polar caps (thermal X-ray spectra**

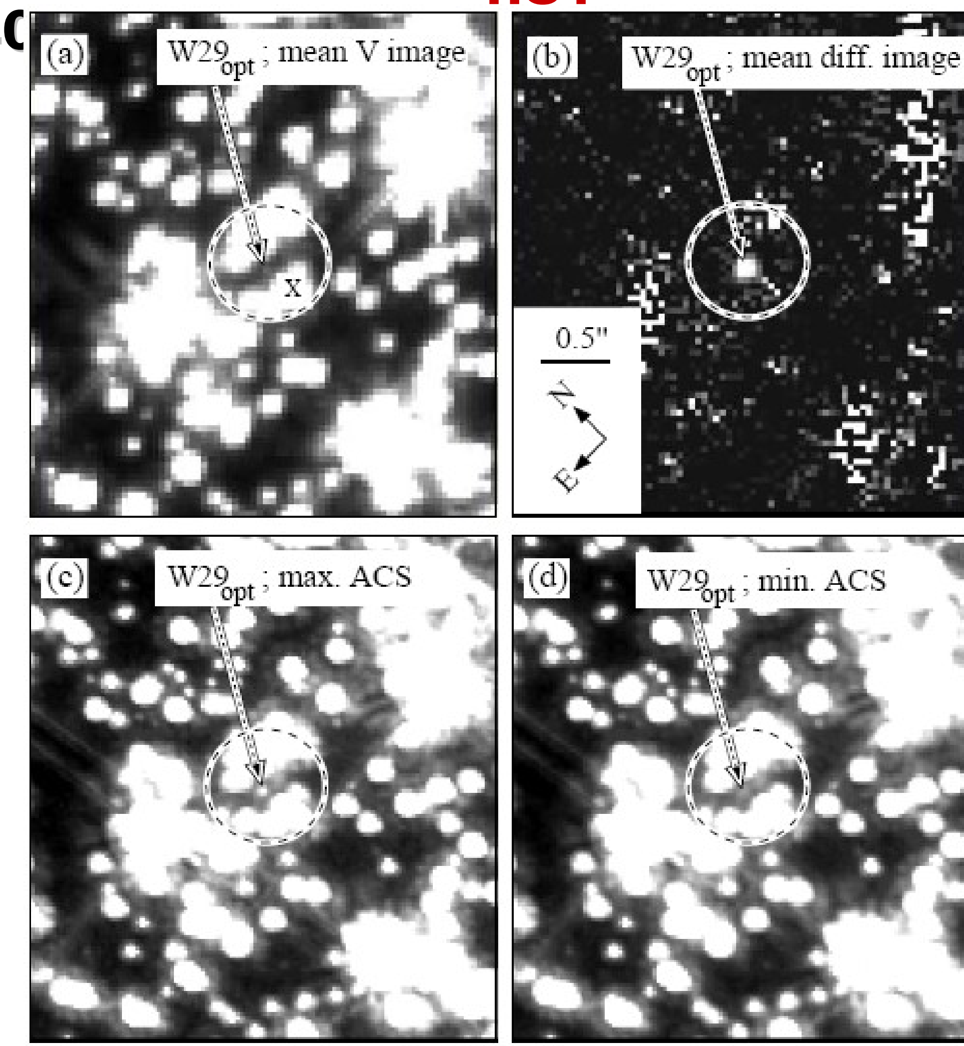
PSR J0024–7204W (aka "W")

- Binary MSP (P_b=3.2 h) with "**main sequence"** (!) companion ($m_c \geq 0.15$ M砿)
- In radio, MSP eclipsed for ~40

Chandra

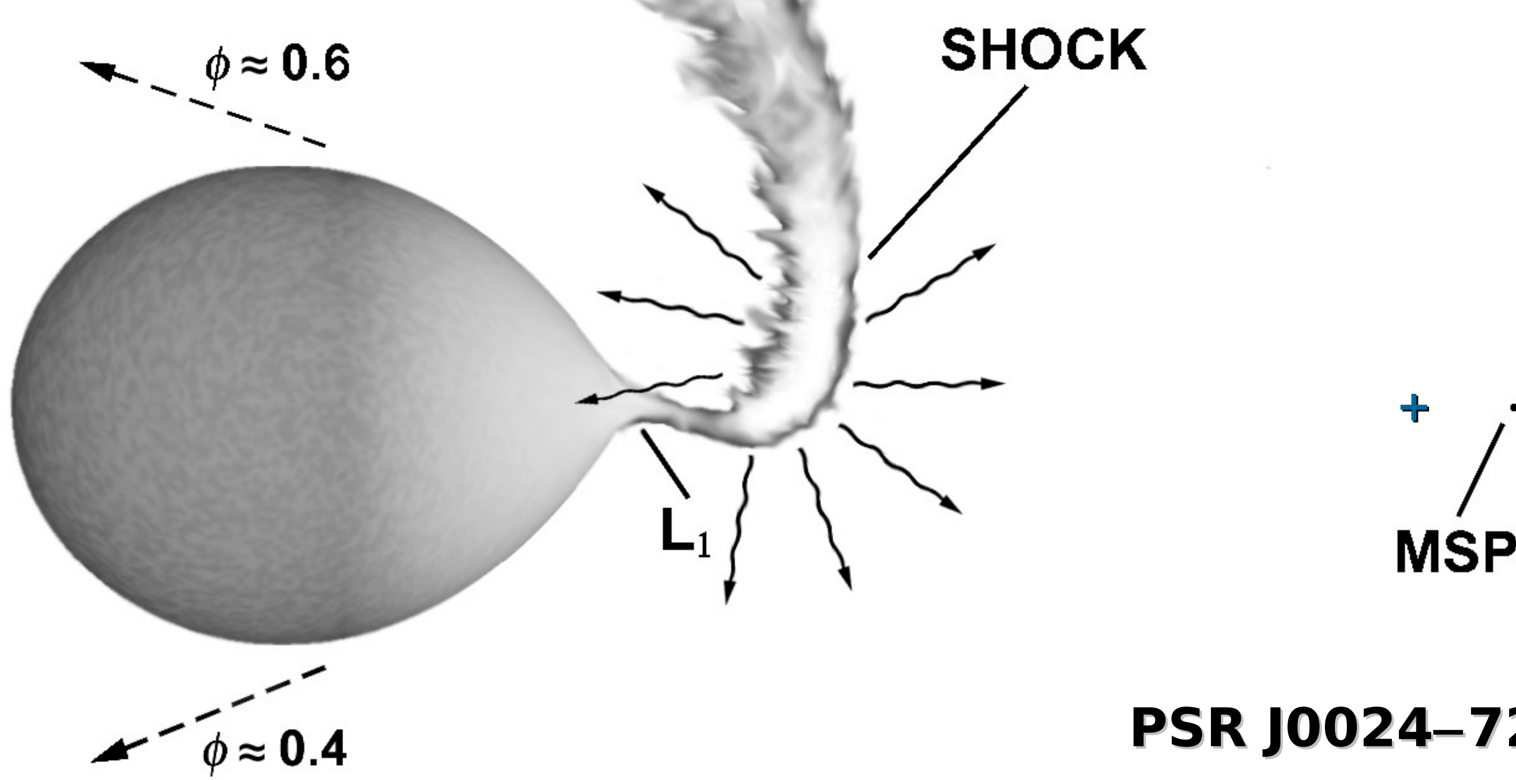


HST

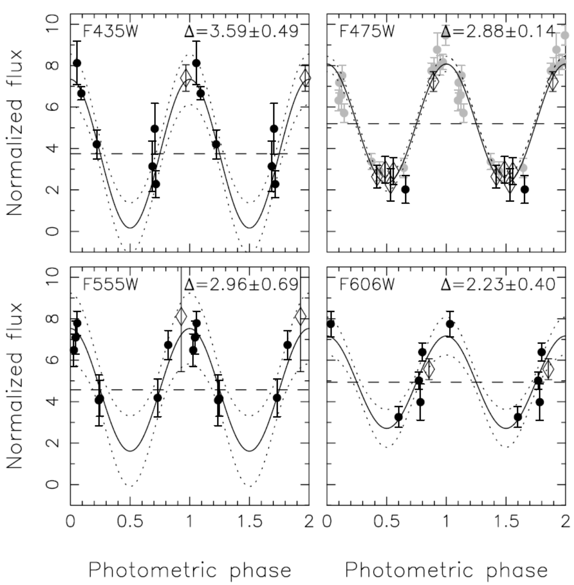


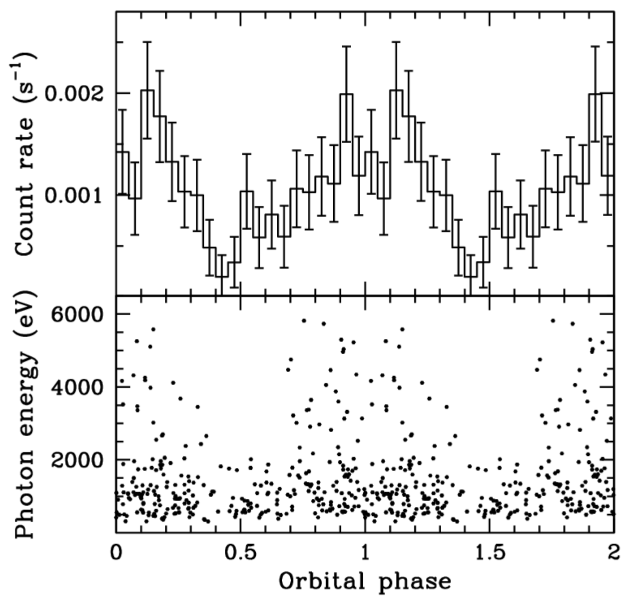
Bogdanov, Grindlay, & van den Berg (2005)

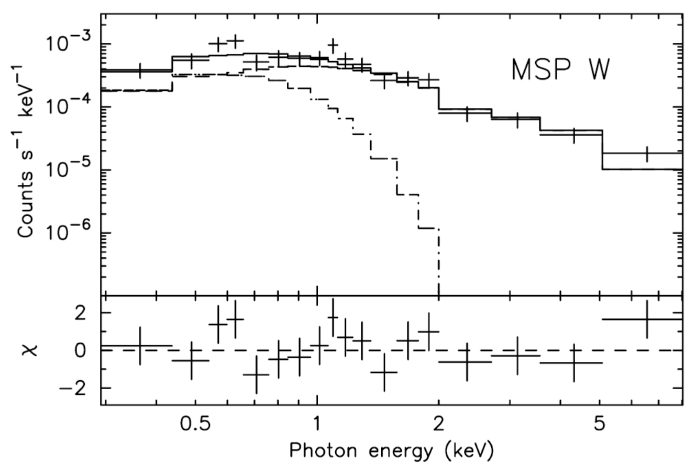
Edmonds et al. (2003)



PSR J0024–7204W



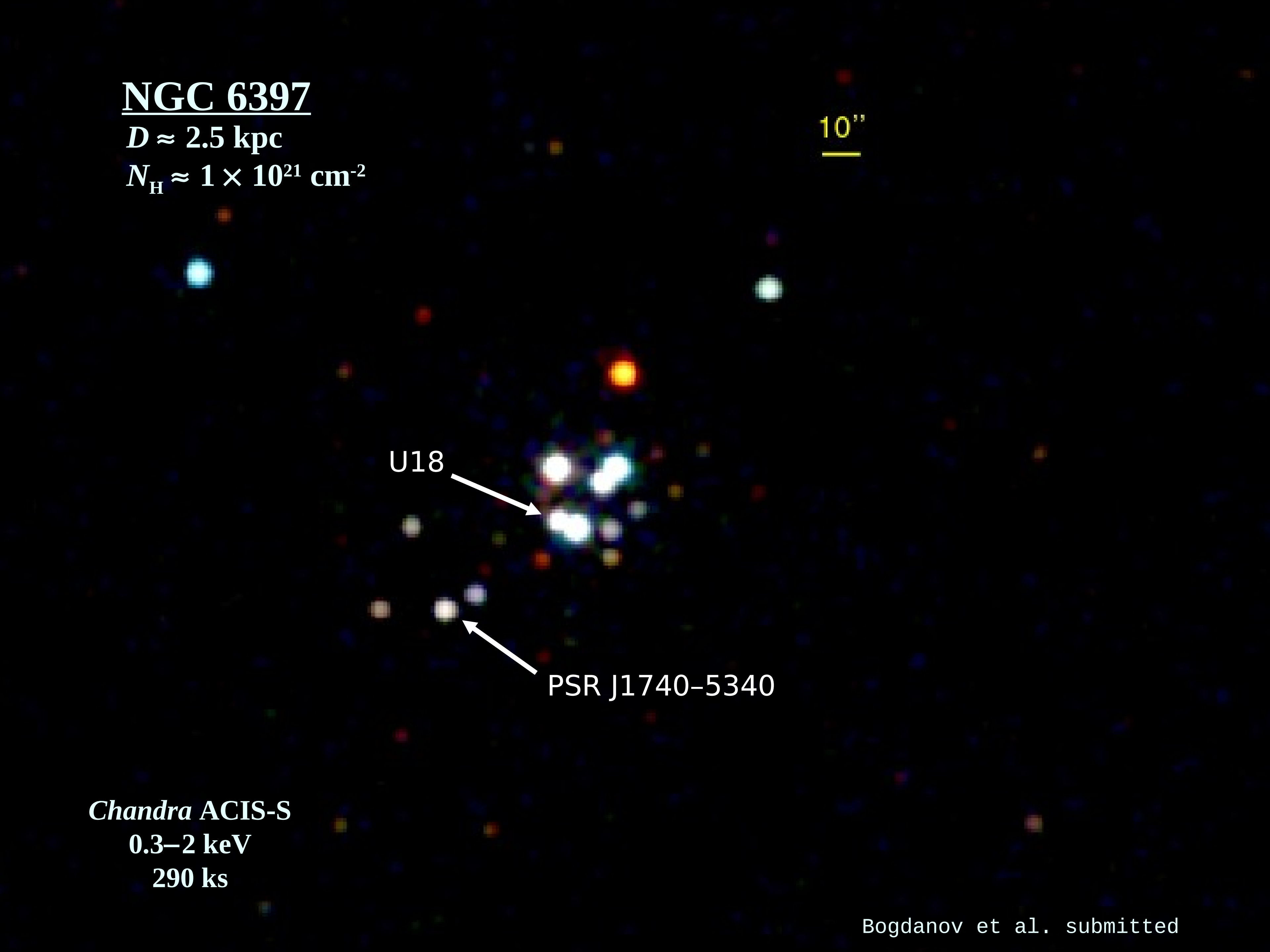




Bogdanov, Grindlay, & van den Berg (20

Globular Cluster NGC 6397

Hubble Heritage


NGC 6397
D ≈ 2.5 kpc
N_H ≈ 1 × 10^21 cm^-2
10''
U18
PSR J1740–5340
Chandra ACIS-S
0.3–2 keV
290 ks
Bogdanov et al. submitted

PSR J1740–5340 in NGC 6397

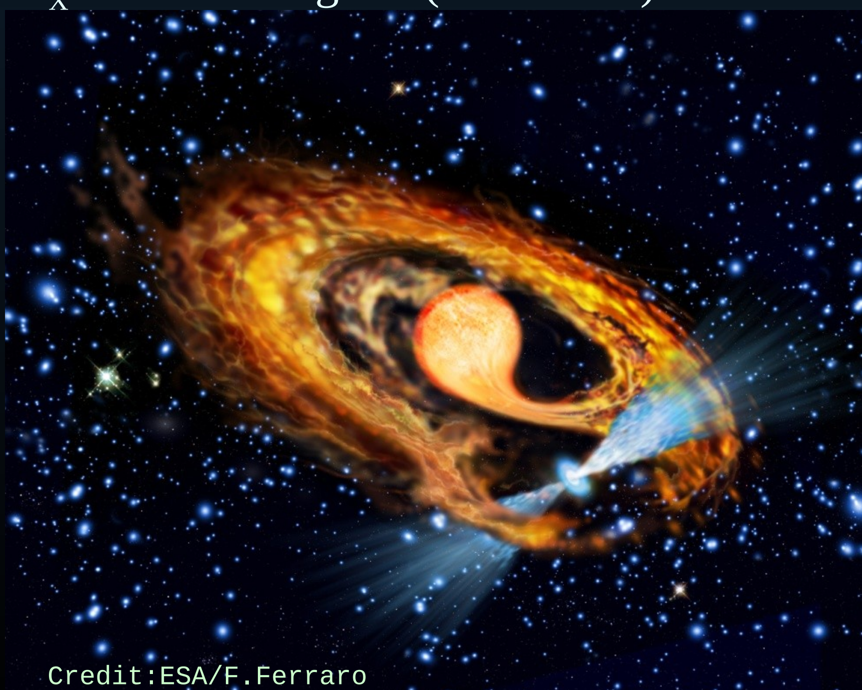
P = 3.56 ms
P_b = 32 h
$m_c \approx 0.3\ M_{\odot}$ "red straggler/sub-subgiant"

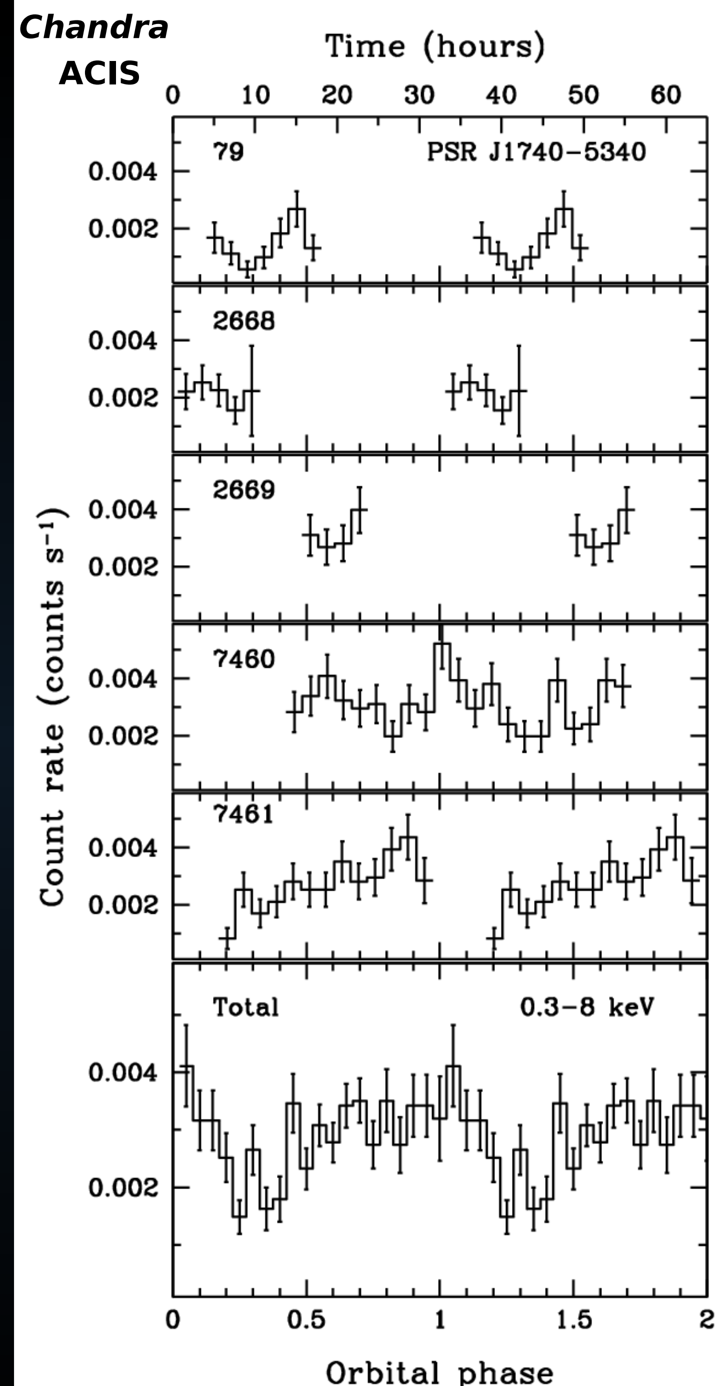
- random & irregular radio eclipses

- Roche lobe-filling companion

- variable, hard non-thermal X-ray emission
  ⇒ **synchrotron from intrabinary shock**

$L_X = 2 \times 10^{31}$ ergs s^{-1} (0.3–8 keV)





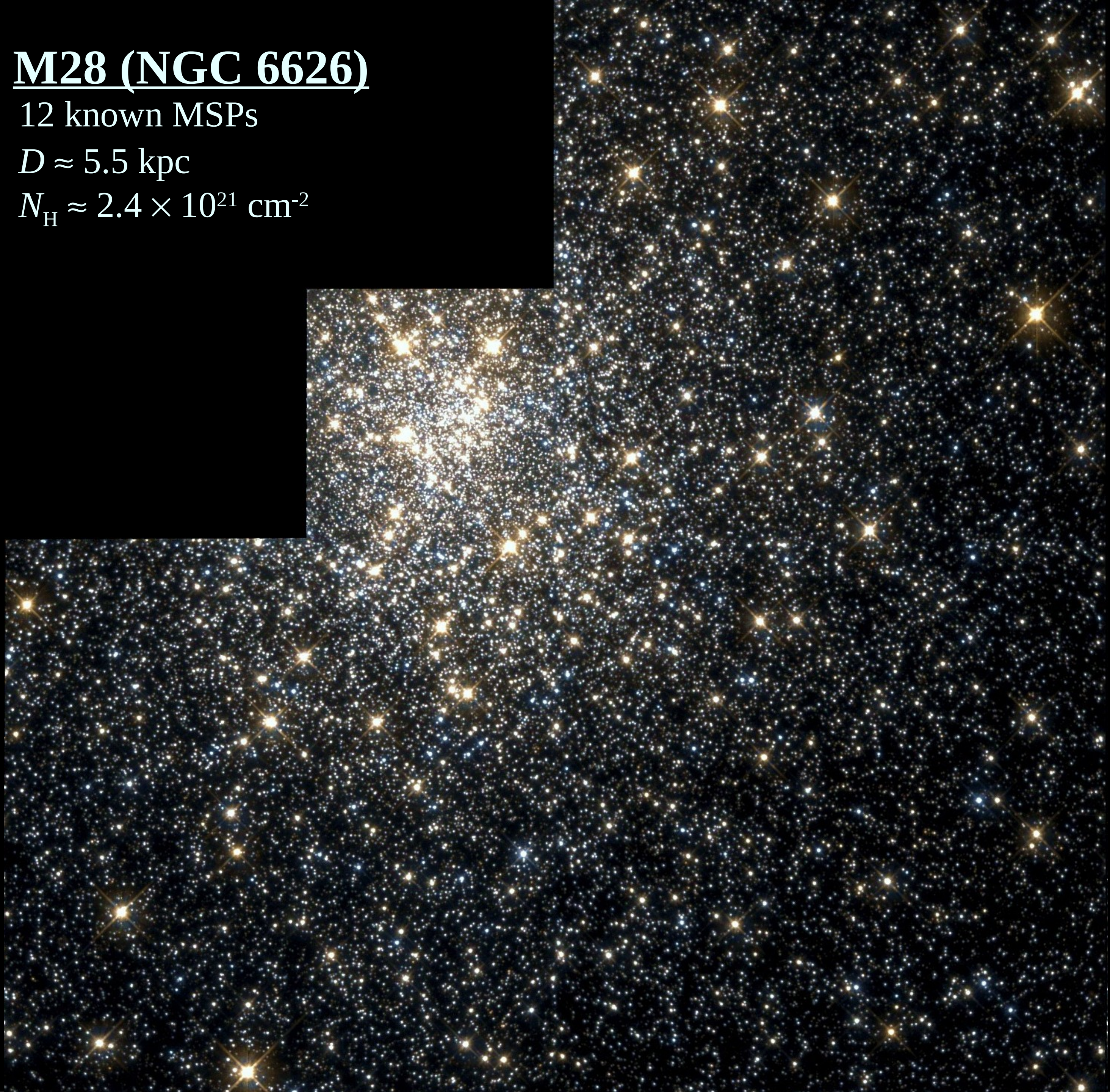
Bogdanov et al. submitted

M28 (NGC 6626)

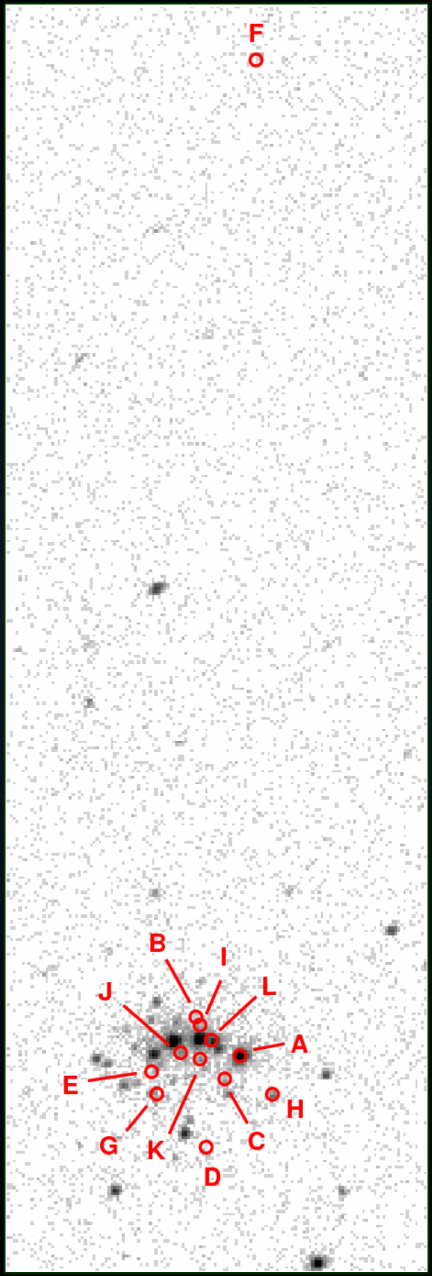
12 known MSPs

$D \approx 5.5$ kpc

$N_H \approx 2.4 \times 10^{21}$ cm^{-2}



M28 (NGC 6626)


F
B
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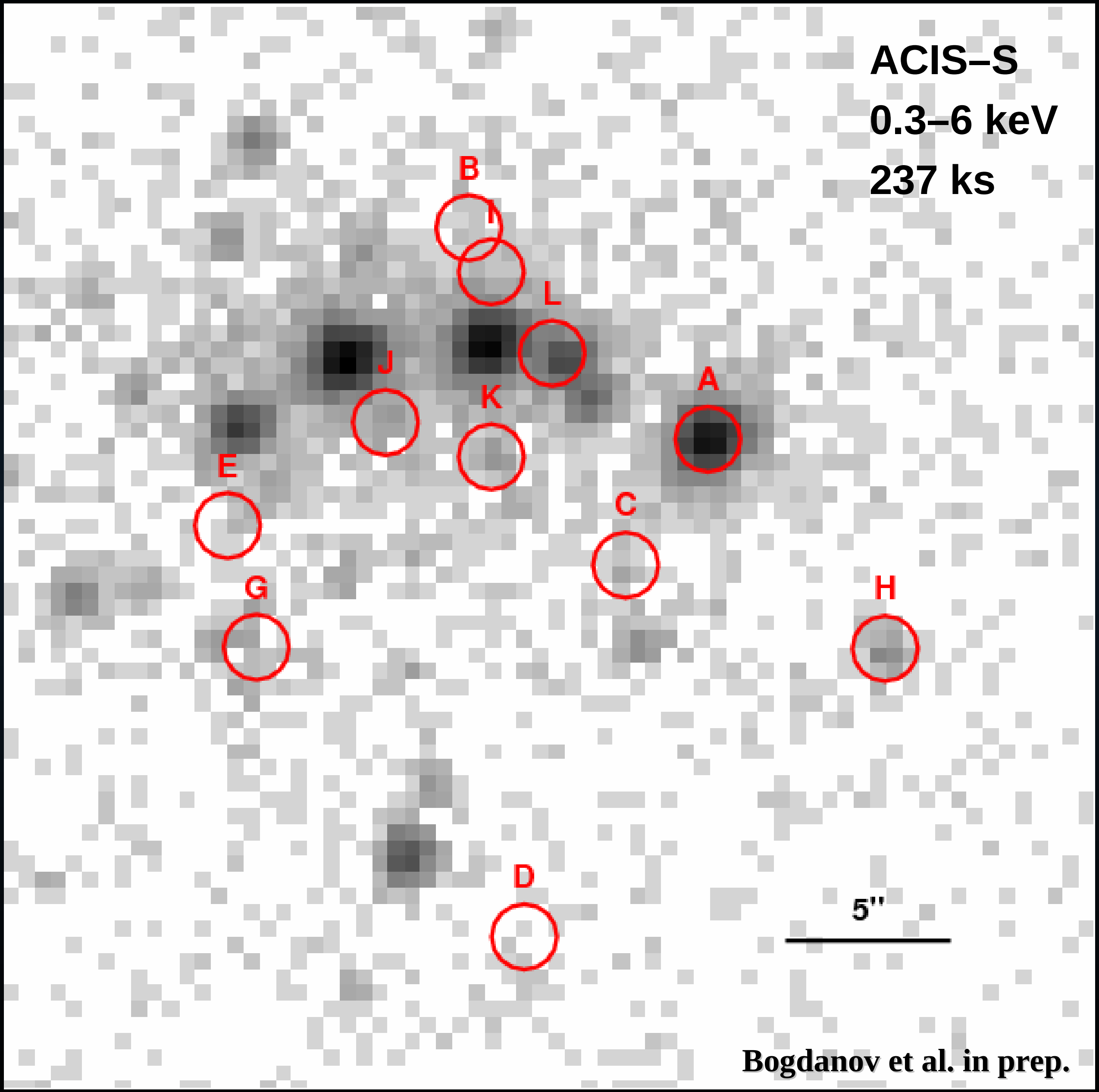
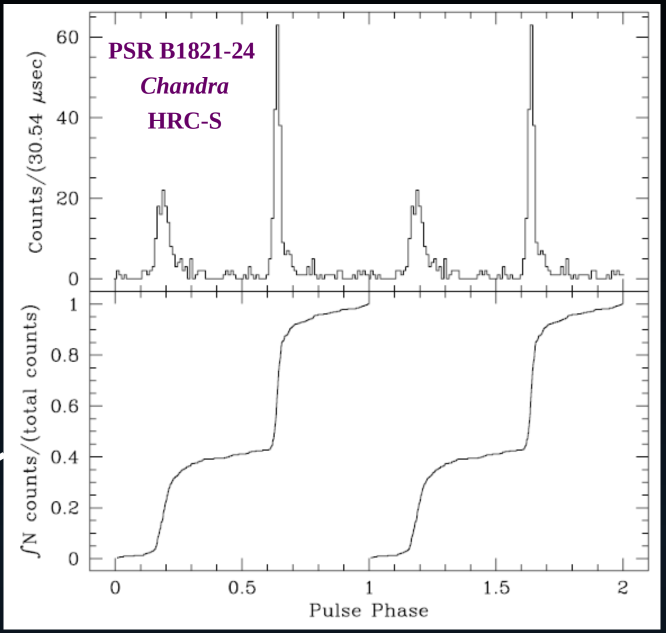
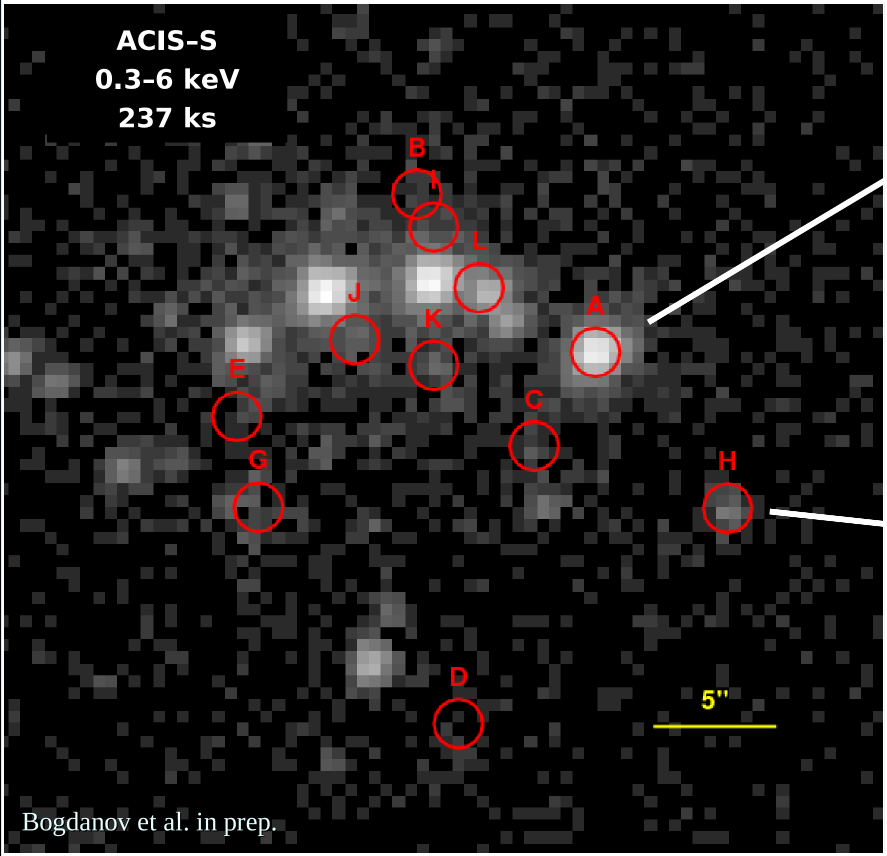

ACIS–S
0.3–6 keV
237 ks
B
I
L
J
K
A
E
C
G
H
D
5''
Bogdanov et al. in prep.

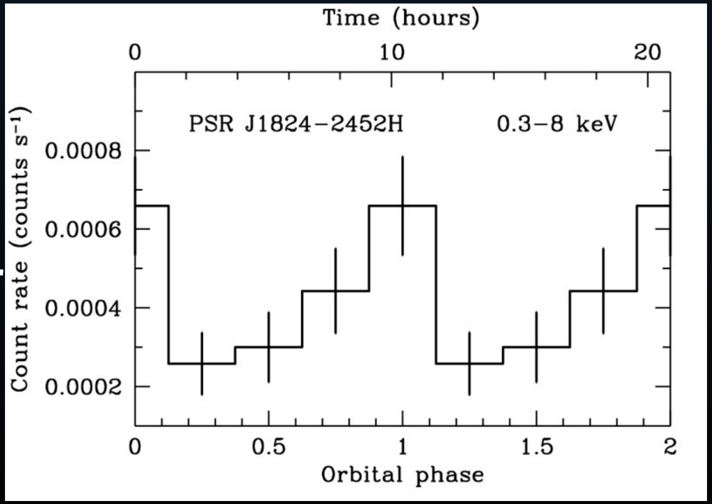
M28 (NGC 6626)

- **PSR B1821–24** (first GC MSP, Lyne et al. 1987)
  Most energetic and luminous MSP known
  ($\dot{E} \approx 2 \times 10^{36}$ ergs s^{-1}, $L_X \sim 10^{33}$ ergs s^{-1}) strongly pulsed, hard non-thermal X-ray emission
- **PSR J1824–2452H**
  Binary MSP with "main-sequence-like" companion
  hard spectrum + possible varibility

Rutledge et al. (2004)







Bogdanov et al. in prep.

Chandra X-ray detections of globular cluster MSPs

- **19 in 47 Tuc**
- **1 in NGC 6397 (+ 1 candidate)**
- **6 in M28 (+ 3 possible detections)**
- 2 in Ter 5 (PSRs J1748–2446P and J1748–2446ad, Heinke et al. 2006)
- **1** in M4 (PSR 1620–26, D'Amico et al. 2002)
- **1** NGC 6752 (PSR J1911–6000C, Bassa et al. 2004)
- **1** in M71 (PSR J1953+1846A, Elsner et al. 2008) – "black widow"

31 MSPs to date

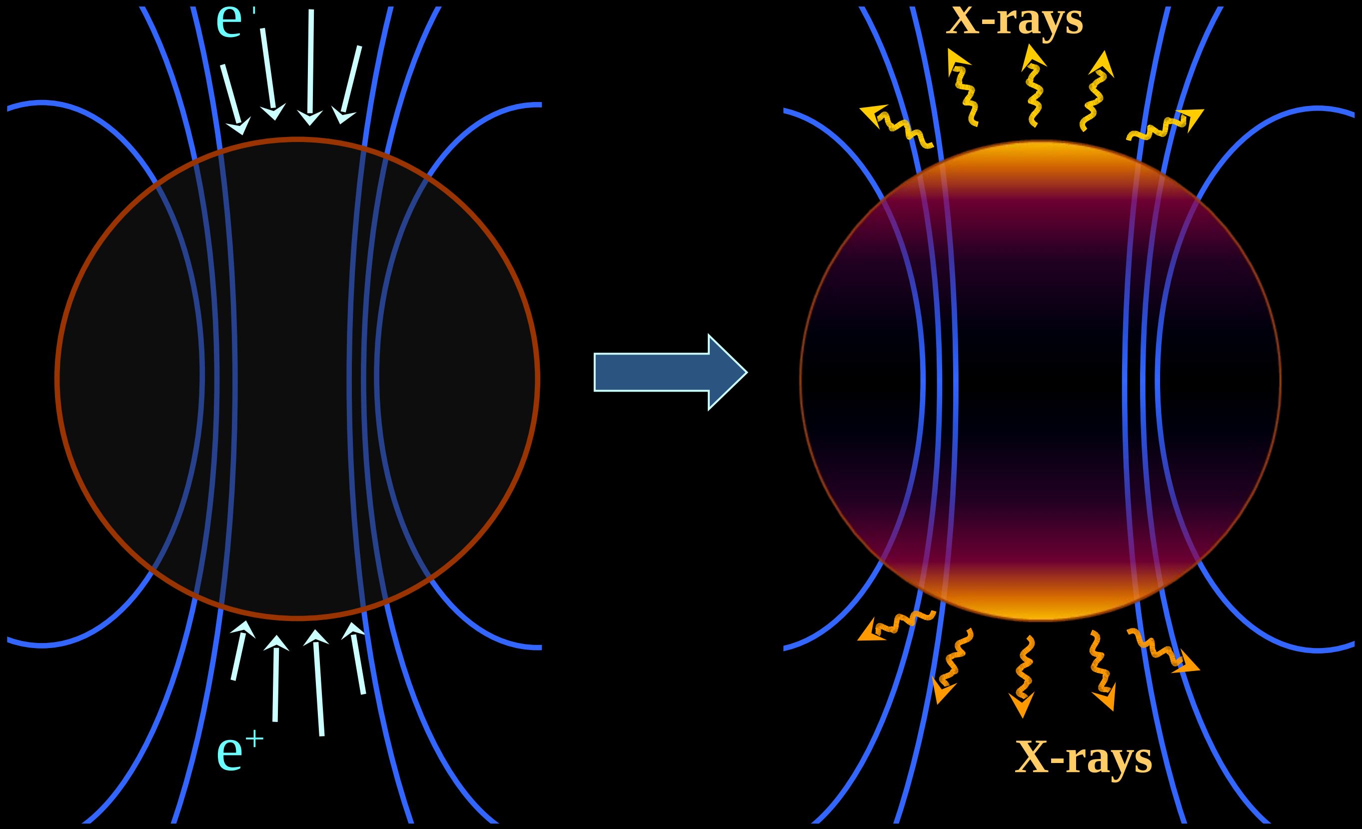
- **Most MSPs have soft thermal spectra**

$T_{eff} \sim 10^6$ K, $R_{eff} \sim$ 2 km, $L_X \sim 10^{30-31}$ ergs s^{-1} (0.3 – 8 keV)

- Some "black widow" systems have non-thermal spectra

- MSP-"main-sequence" binaries have non-thermal (variable) spectra

- Thermal X-ray emission is due to polar cap heating by relativistic particles from pulsar magnetosphere (see, e.g., Harding & Muslimov 2002, ApJ, 568, 862)



Modeling thermal X-ray emission from MSPs

- Ingredients:_

- rotating neutron star

- two X-ray emitting hot spots

- general & special relativity

  * Schwarzschild metric
  * Doppler boosting/aberration
  * propagation time delays

- optically-thick, non-magnetized ($B = 10^8$ G ≈ 0) hydrogen atmosphere___

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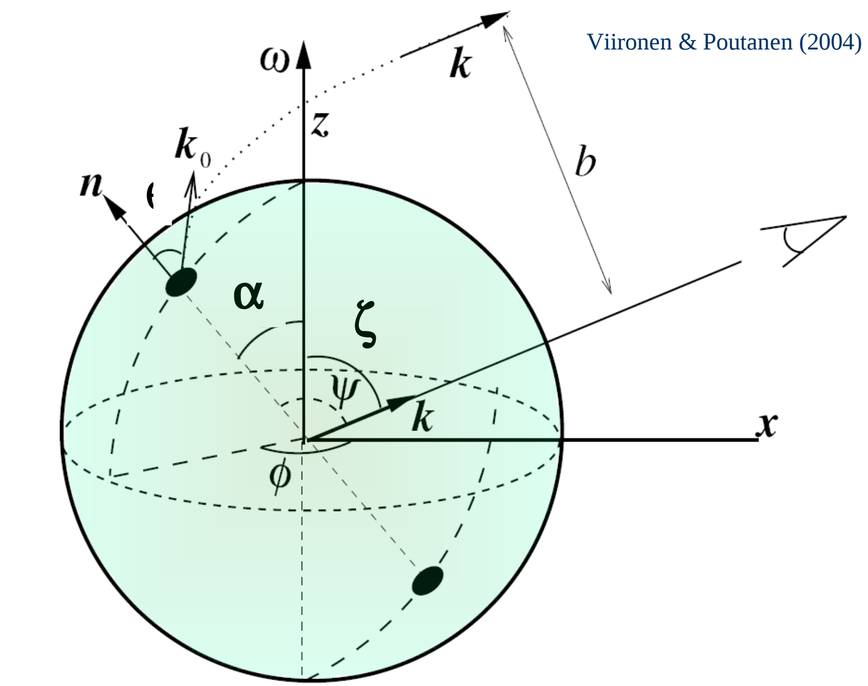


α = pulsar obliquity

ζ = ∠ b/w line of sight & pulsar spin axis

$\phi(t)$ = rotational phase

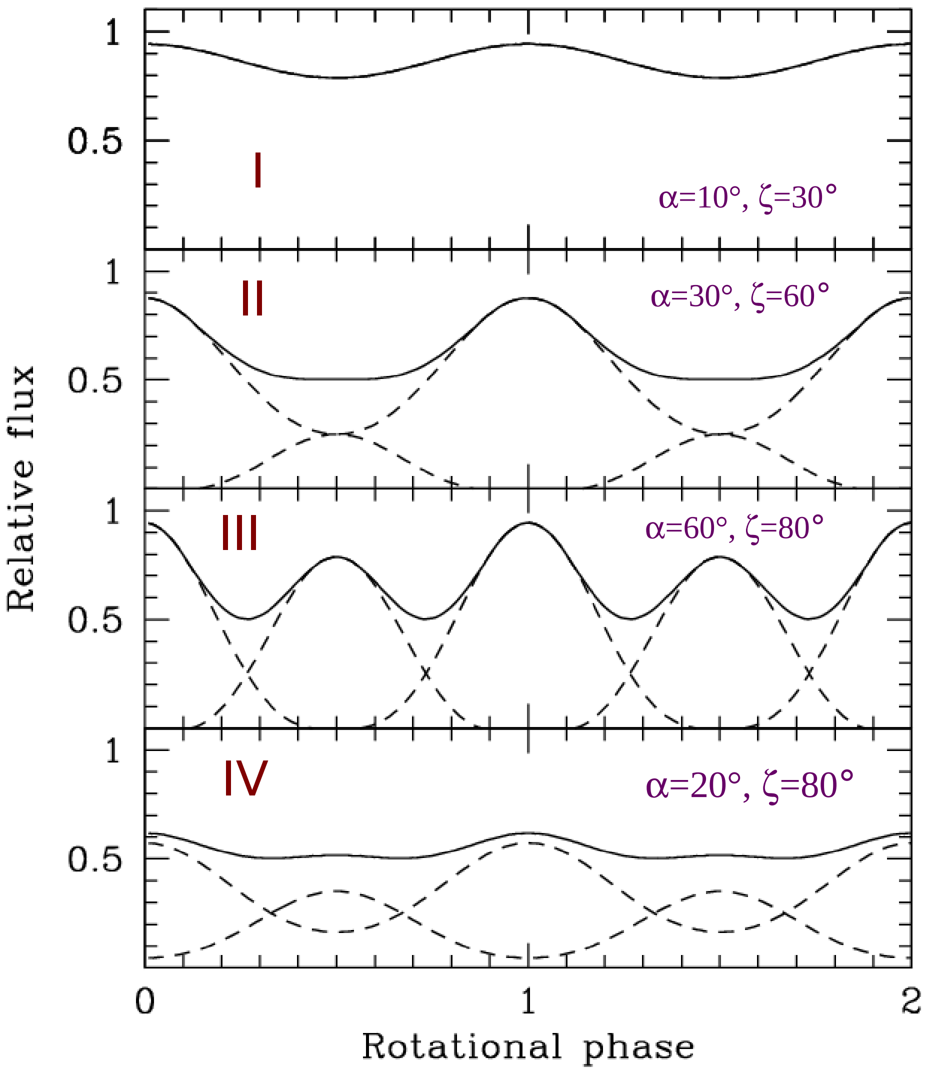
θ = photon ∠ w.r.t surface normal

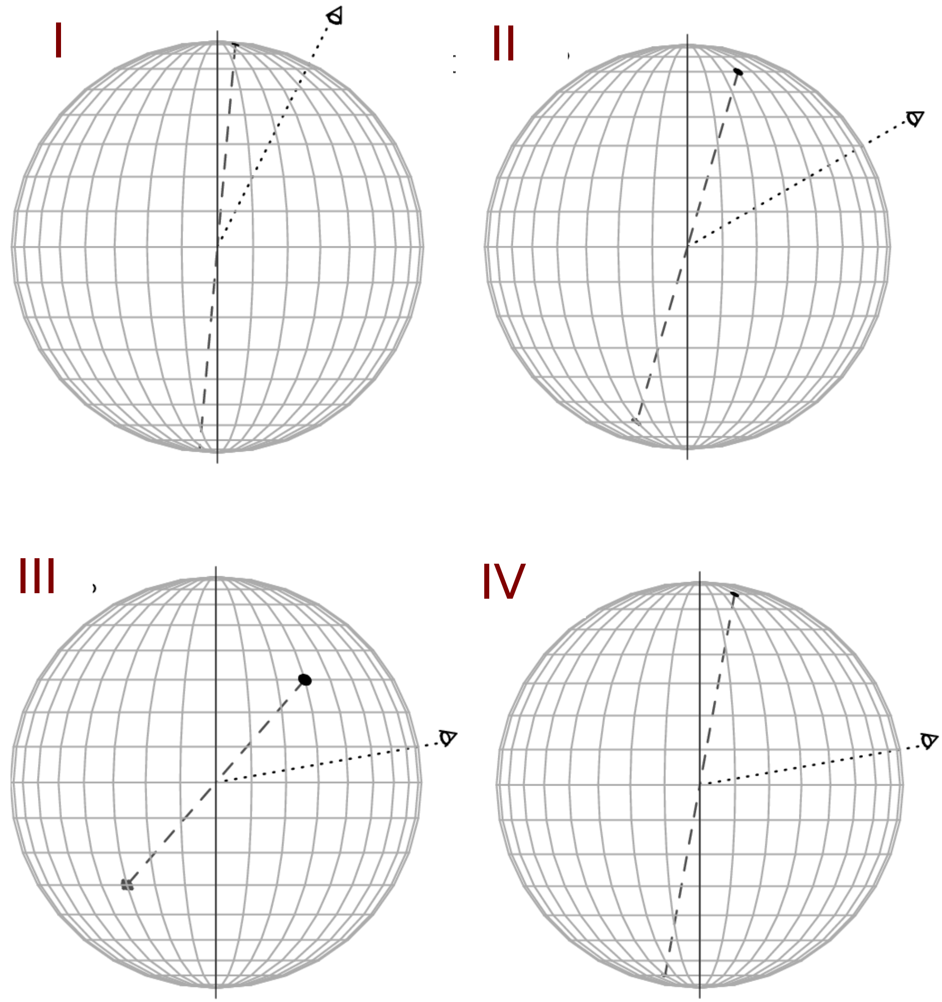
ψ = photon ∠ at infinity

b = photon impact parameter at infinity

ynthetic MSP X-ray pulse profiles

- R = 10 km, M = 1.4 $M_\odot$
- $T_{eff} = 2 \times 10^6$ K (H atmosphere)
- 2 antipodal, point-like polar caps

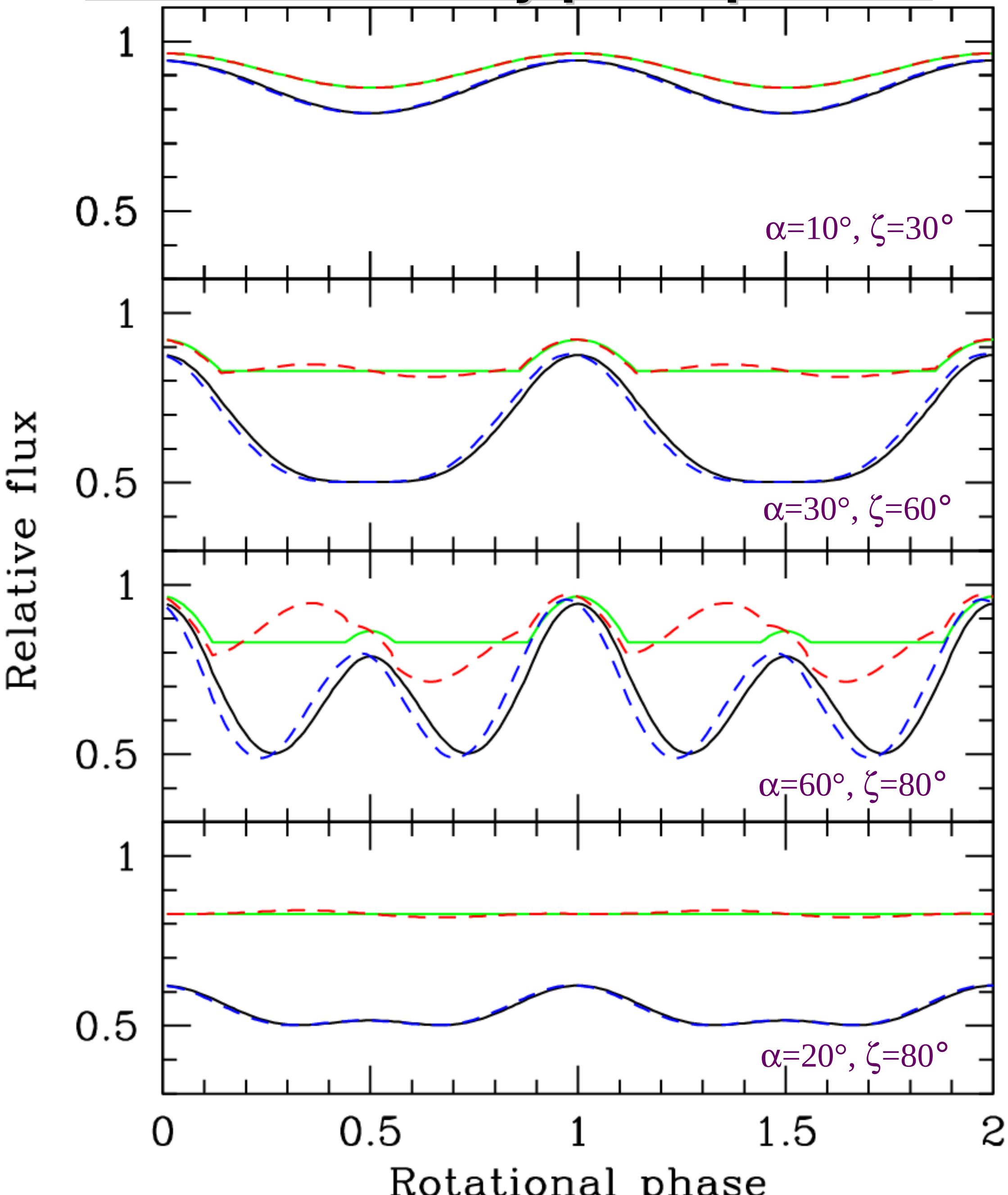




Thermal X-ray emission is observable for all (α, ζ)

Bogdanov et al. (2008)

Model MSP X-ray pulse profiles



- P = 4 ms, R = 10 km, M = 1.4 $M_{\odot}$
- $T_{eff} = 2 \times 10^6$ K (H atmosphere)
- 2 antipodal, point-like polar caps

Blackbody

Blackbody + Doppler

H atmosphere

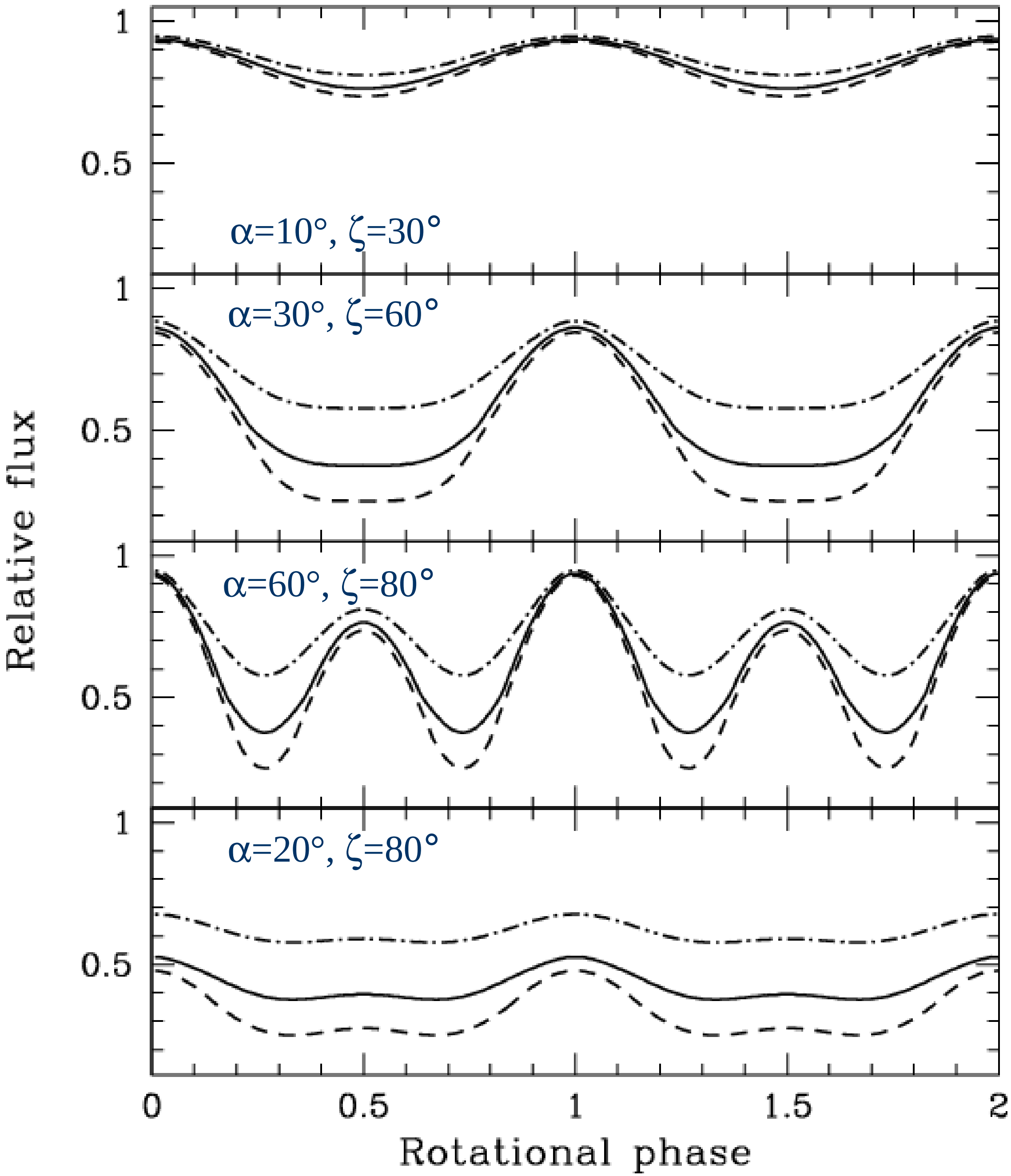
H atmospere + Doppler

- Can determine emission properties of NS surface (H atm. vs blackbody)

- Can constrain magnetic field and viewing geometries

Bogdanov, Rybicki, & Grindlay (2007)

Model MSP X-ray pulse profiles



* **Fits to X-ray pulse profiles of MSPs can be used to infer NS compactness**

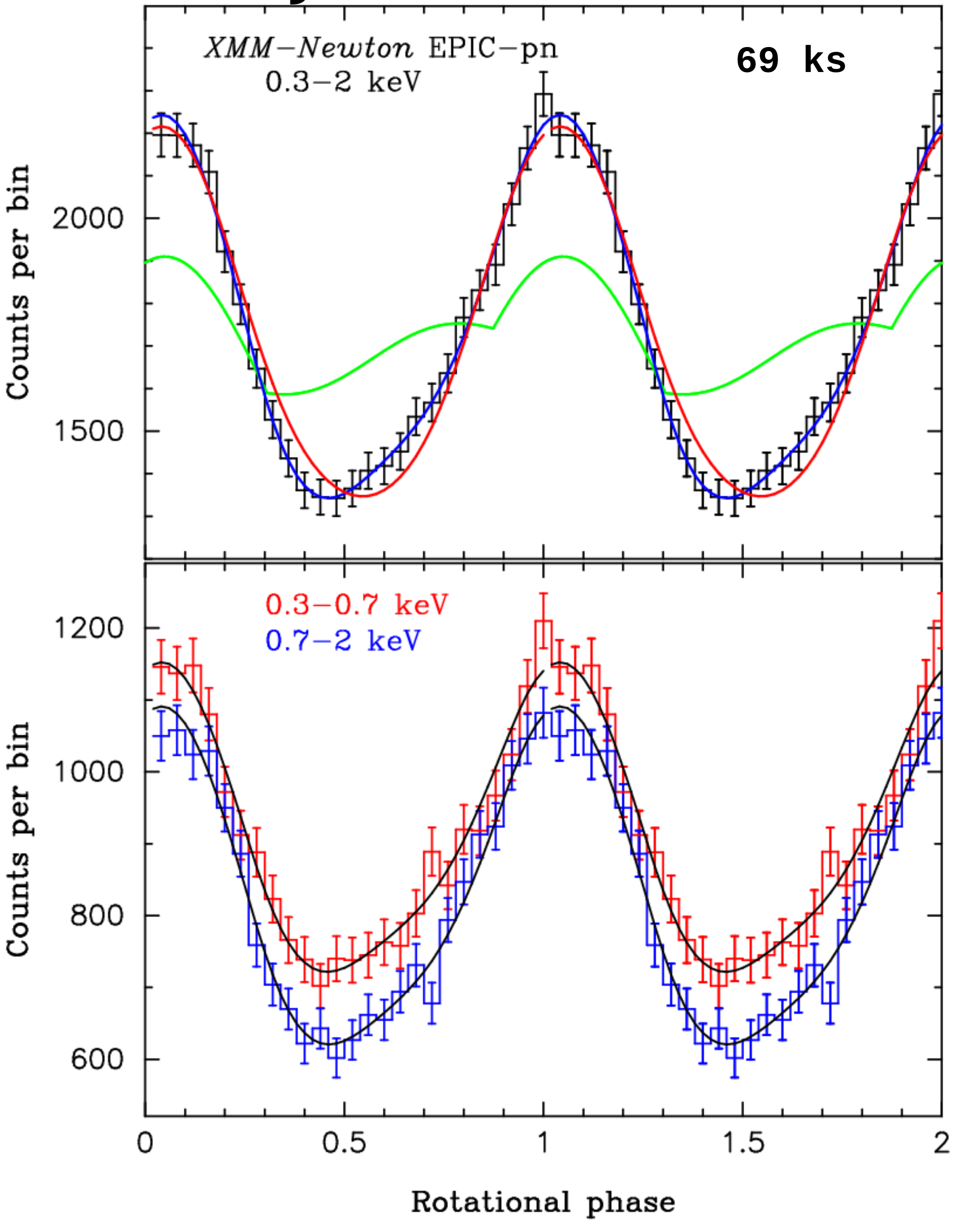
$$1 + z_g = (1 - 2GM/c^2R)^{-1/2}$$

⇒ constrain NS EOS (Pavlov & Zavlin 1997; Zavlin & Pavlov 1998)

-·-·- 9 km
—— 12 km
- - - 16 km
} for M = 1.4 M砿

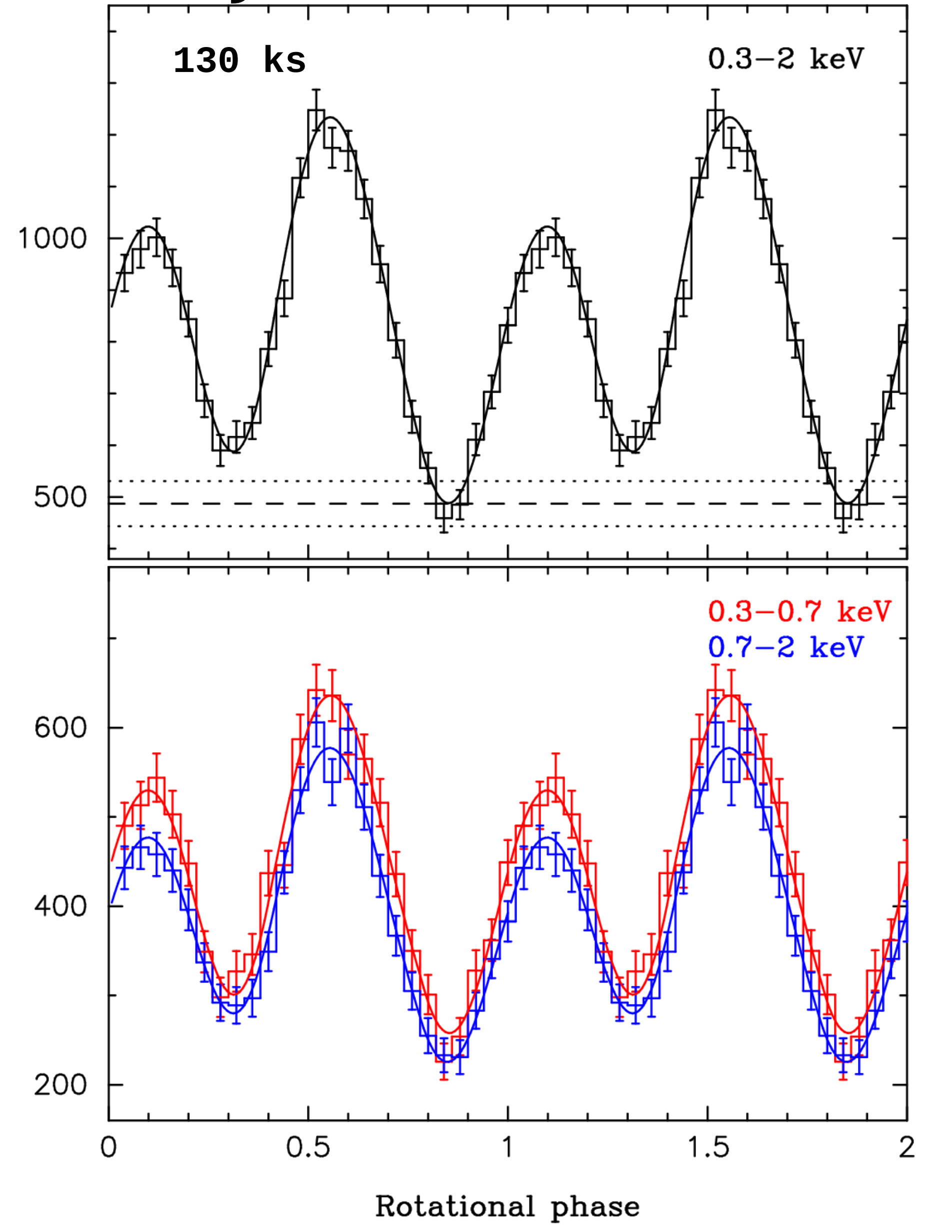
Bogdanov, Rybicki, & Grindlay (2007)

PSR J0437−4715



Bogdanov, Rybicki, & Grindlay (2007)

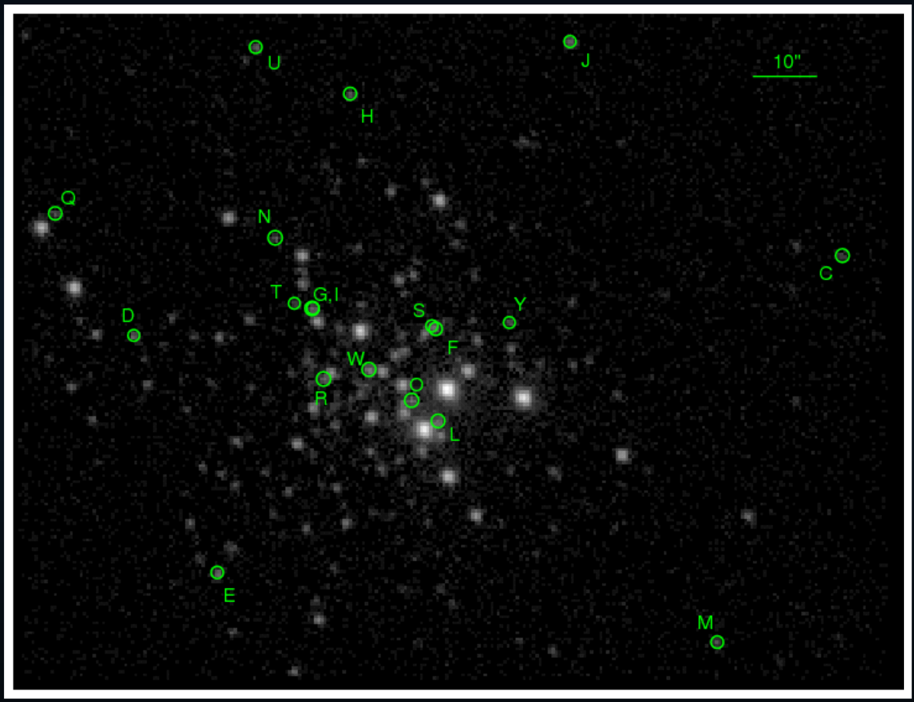
PSR J0030+0451



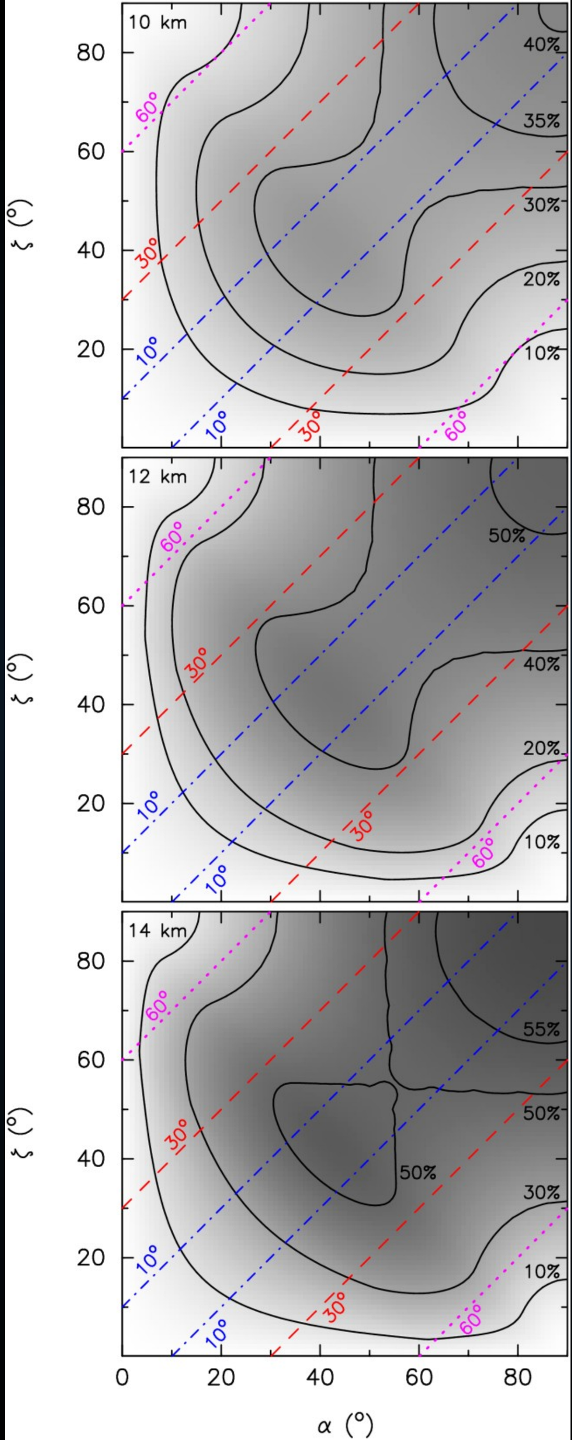
Bogdanov & Grindlay (2009)

Pulsed thermal X-ray emission is observable for *all* combinations of viewing angle (ζ) and pulsar magnetic inclination (α) due to light bending

Radio emission only observable for $\rho > |\alpha - \zeta|$

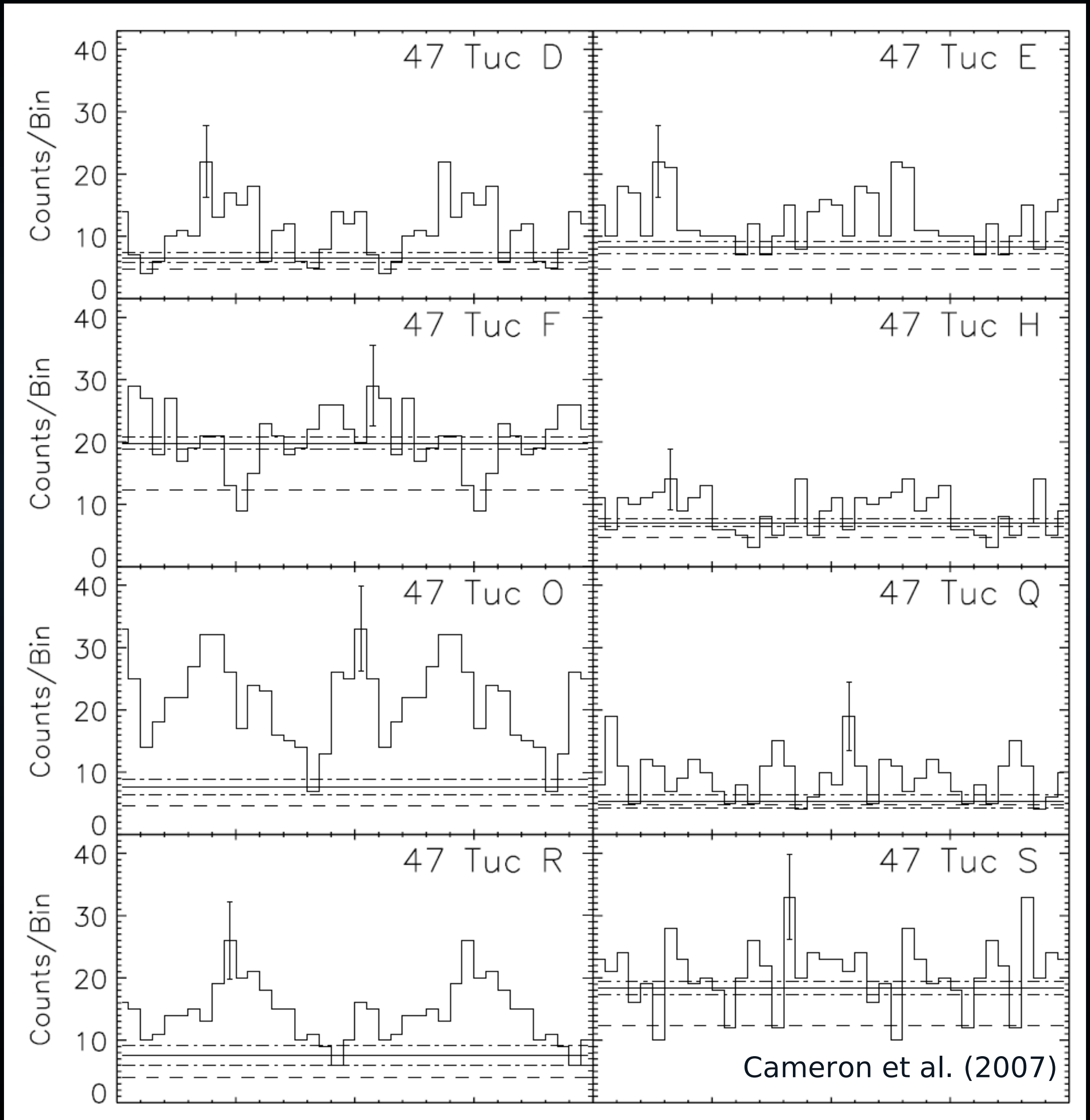


Blind X-ray timing searches could discover *all* MSPs in nearby globular clusters (with *Gen-X*?)



Bogdanov, Grindlay, & Rybicki (2008)

Deep *Chandra* HRC-S Timing Observation of 47 Tuc (833.9 ks)



“Exchanged”
Binary MSPs
PSR J1740–5340
NGC 6397
Credit:ESA/F.Ferraro

The Peculiar Binary PSRs J0024–7204W (47 Tuc), J1740–5340 (NGC 6397), J1824-2452H (M28),…

- Unusual ("main-sequence-like") binary companions
- Hard X-ray emission due to collisionless relativistic intrabinary shock

Original, evolved companion exchanged for current one in binary-binary close dynamical encounter?

or

System recently emerged from LMXB phase?

- Sites for studies of relativistic shocks & pulsar winds

- Optical/X-ray properties remarkably similar to accretion-powered X-ray MSP SAX J1808.4–3658 in quiescence
  ⇒ rotation-powered pulsar wind?

PSR J1023+0038: a similar system in the field of the Galaxy!
(see Archibald et al. 2009, Science, 324, 1411)
⇒ (86 ks Cycle 11 observation coming up)

Conclusions

- ~31 globular cluster MSPs detected in X-rays to date (19 in 47 Tuc alone) by *Chandra*
- Majority of radio MSPs have soft, thermal X-ray spectra due to heated magnetic polar caps ($T_{eff} \sim 10^6$ K)
- No systematic differences between MSPs in globular clusters and field of Galaxy
- *All* nearby MSPs should be detectable in X-rays (even those invisible in the radio due to unfavorable viewing geometry)
- Modeling thermal X-ray emission from MSPs – promising method for measuring important NS properties (EOS, B-field geometry, population)
- PSRs J0024–7204W, J1740–5340, etc:
  - Dynamically exchanged old MSPs or nascent MSPs?
  - Insight into neutron star systems transitioning from accretion to rotation power
  - Sites for studies of relativistic shocks & pulsar winds
- Ongoing radio pulsar timing searches ⇒ *Chandra* follow-up
- Future high angular (~0.1”) & time (~μs) resolution X-ray studies could reveal 100% of the MSP population of nearby globular clusters