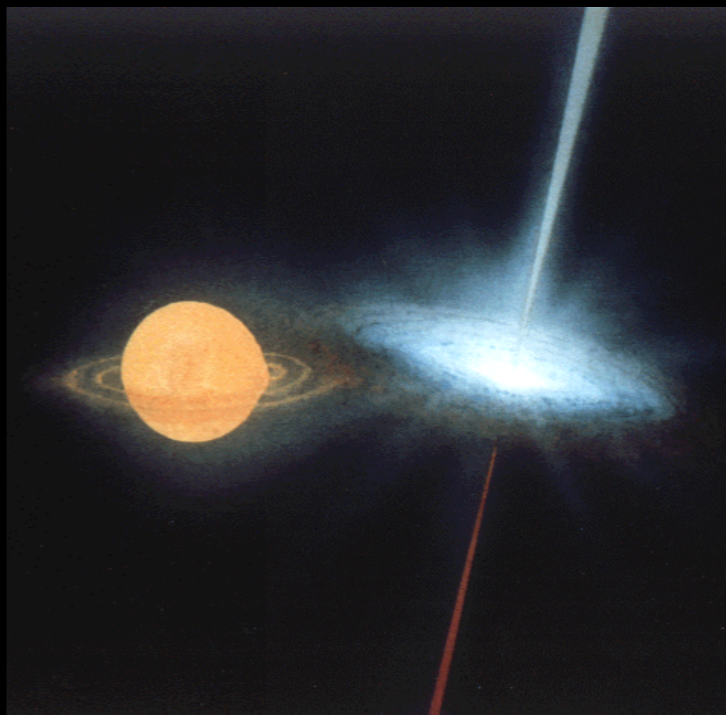
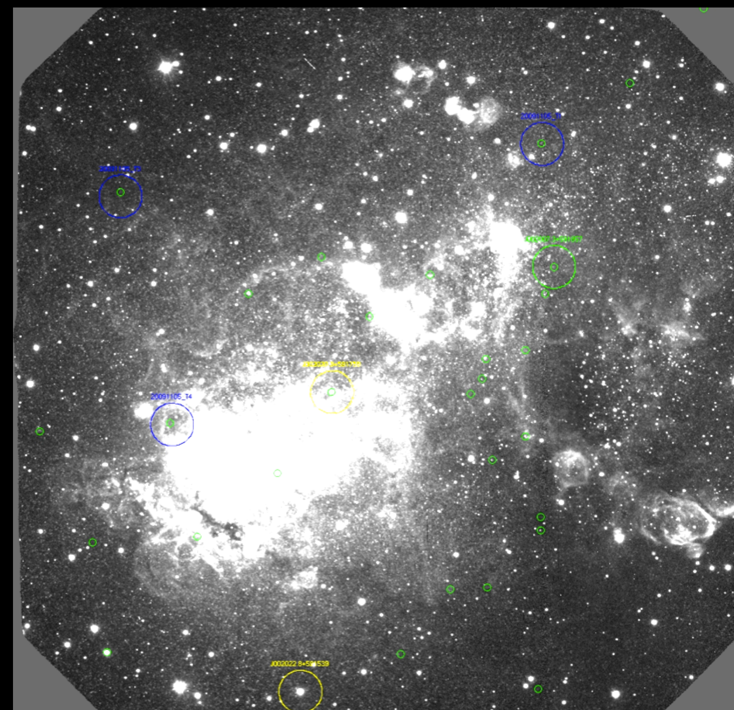
X-ray Binaries and Black Holes as Astrophysical Probes – a Talk for UML CAR

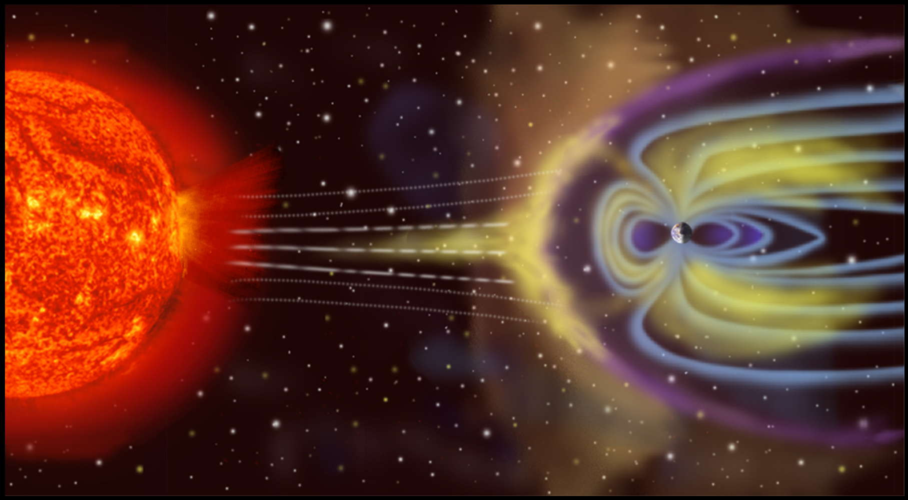


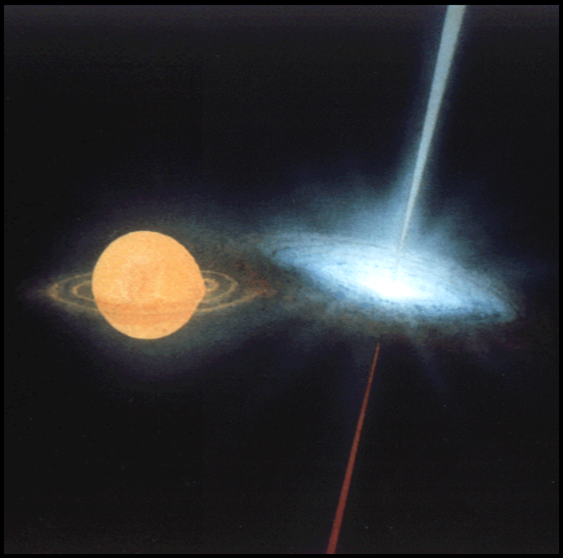


Silas Laycock (Dec 12, 2012

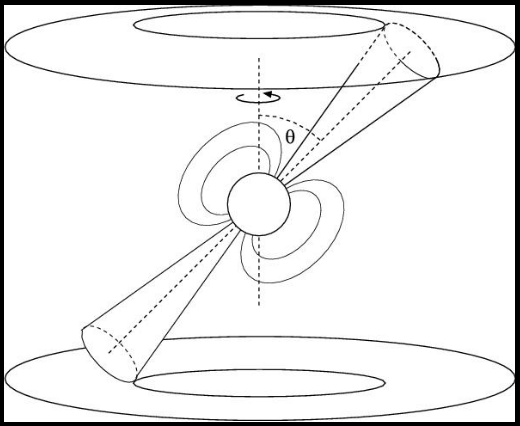
Colleen Wilson, Choni Camero (NASA/MSFC), Jaesub Hong (CfA), Andreas Zezas (Crete/CfA), Vallia Antoniou (Iowa), Robin Corbet (NASA/GSFC), Ben Williams (Washington), Jose Galache, Malcolm Coe (Southampton), Andrea Prestwich (CfA), Roy Kilgard (Wesleyan), Josh Grindlay (Harvard)

The Sun-Earth and X-ray Binaries are both examples of Accretion on a rotating Magnetosphere





Maybe some differences in the physical parameters?



Black holes, neutron stars -the relics of the most massive and short lived stars.

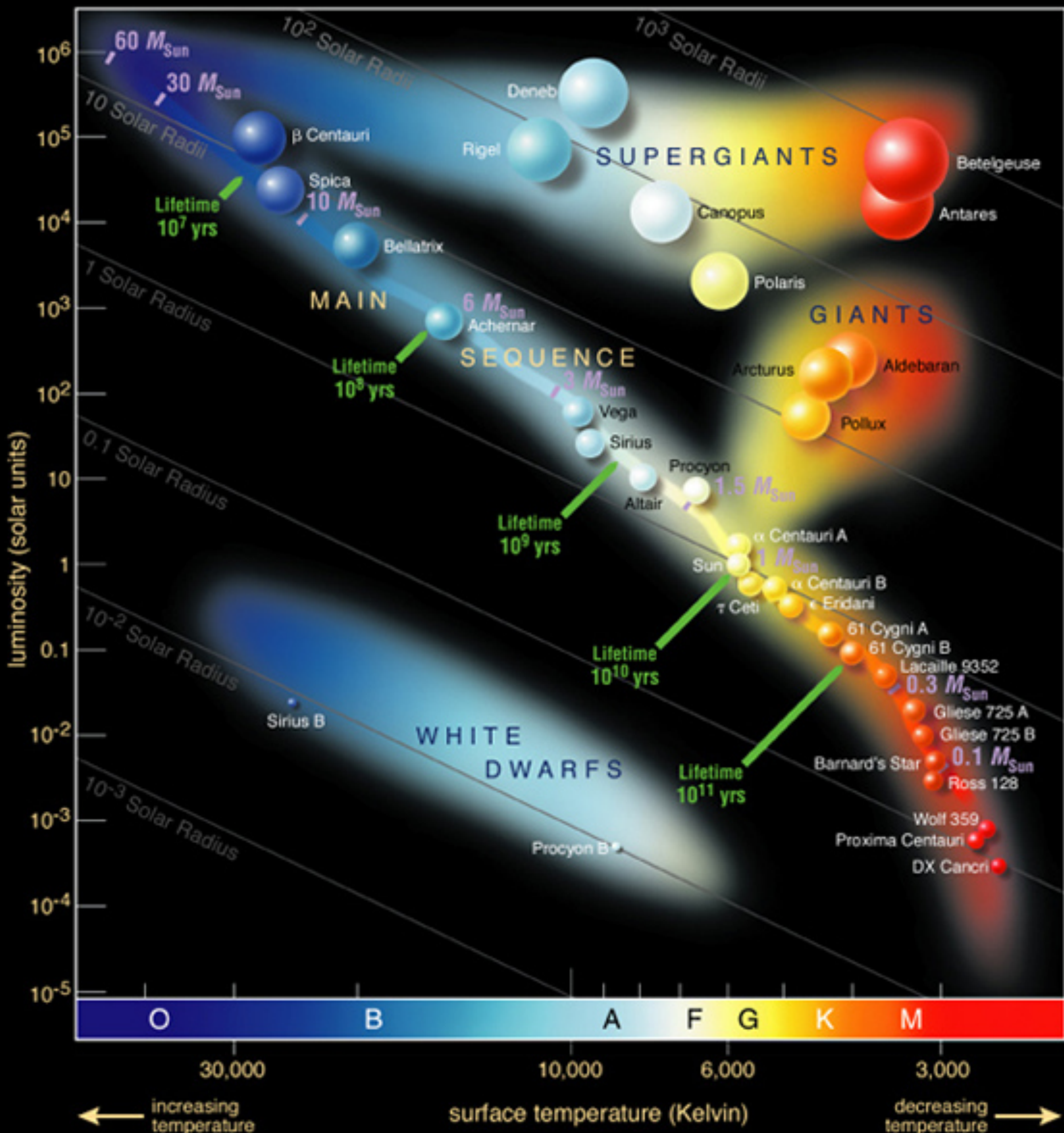
- Lifetimes and evolution of the massive progenitors are not well known. [Marcolino et al 2009]
- Main observational differences:

    NS: surface, B-field, rotation-pulsars.

    BH: No surface, GR
- Visibility – *X-ray, Optical, IR, *Radio
- Astrophysical parameters
- Population synthesis [Belczynski et al., 2008, ApJS, 174, 223]

At the one end of the scale X-ray binaries probe extreme physics,
while at the other end, they probe stellar populations during their most tumultuous years.

Quick Recap on Stars: The HR Diagram



Lifetime and evolution governed by initial mass:

Sun ~ 10^{10} yrs

->White Dwarf

$10M_{sun}$ ~ 10^6 yrs

-> Supernova

-> NS/BH

History of NS & BH

- 1783- Dark stars proposed by John Mitchell
- 1915- Schwartzchild, Einstein, GR
- 1926 Degenerate matter (Fowler)
- 1931- Chandrasekhar –applies idea to stellar evolution.
  - Chandrasekhar Limit for White dwarf < 1.44 M_{sun}
- 1933 Discovery of the Neutron (Chadwick)
- 1934 Prediction of Neutron Stars (Baade & Zwicky)
- 1939 – Calculation of NS mass and EoS (Oppenheimer)
  - Neutron Star < 2.5M_{sun}
  - BH > 3 Msun
- 1965 – Compact radio source in Crab Nebula (a SNR)
- 1967 -Discovery of Pulsars (Burnell & Hewish)
- 1967 – Hard X-rays from Sco X-1
- 1971- X-ray pulsations (4.8s) in Cen X-3(Giacconi)
- 1971 Cygnus X-1 –first dynamical BH
- 1999- Chandra X-ray Observatory revolutionizes X-ray astronomy.
- 2007 – First optical detection of a NS
- Now: >10^3 Radio Pulsars, >100 X-ray pulsars, >10 stellar BHs

GR and Neutron stars

- Gravitational light deflection at a neutron star. Due to relativistic light deflection more than half of the surface is visible (each chequered patch here represents 30 degrees by 30 degrees).

Degeneracy pressure

Chandrasekar Mass ~ 5.6 M_{sun}

Tolman-Oppenheimer-Volkov limit ~ 2.5 M_{sun}

Conservation of Momentum

At birth:

$$\omega = \omega_o (r_1/r_2)^2 \sim 1\text{ms}$$

Equatorial speed of NS sufficient to breakup all but NS

<u>Gravitational Binding energy</u>

Compare:

$$E_G = GMm/r$$

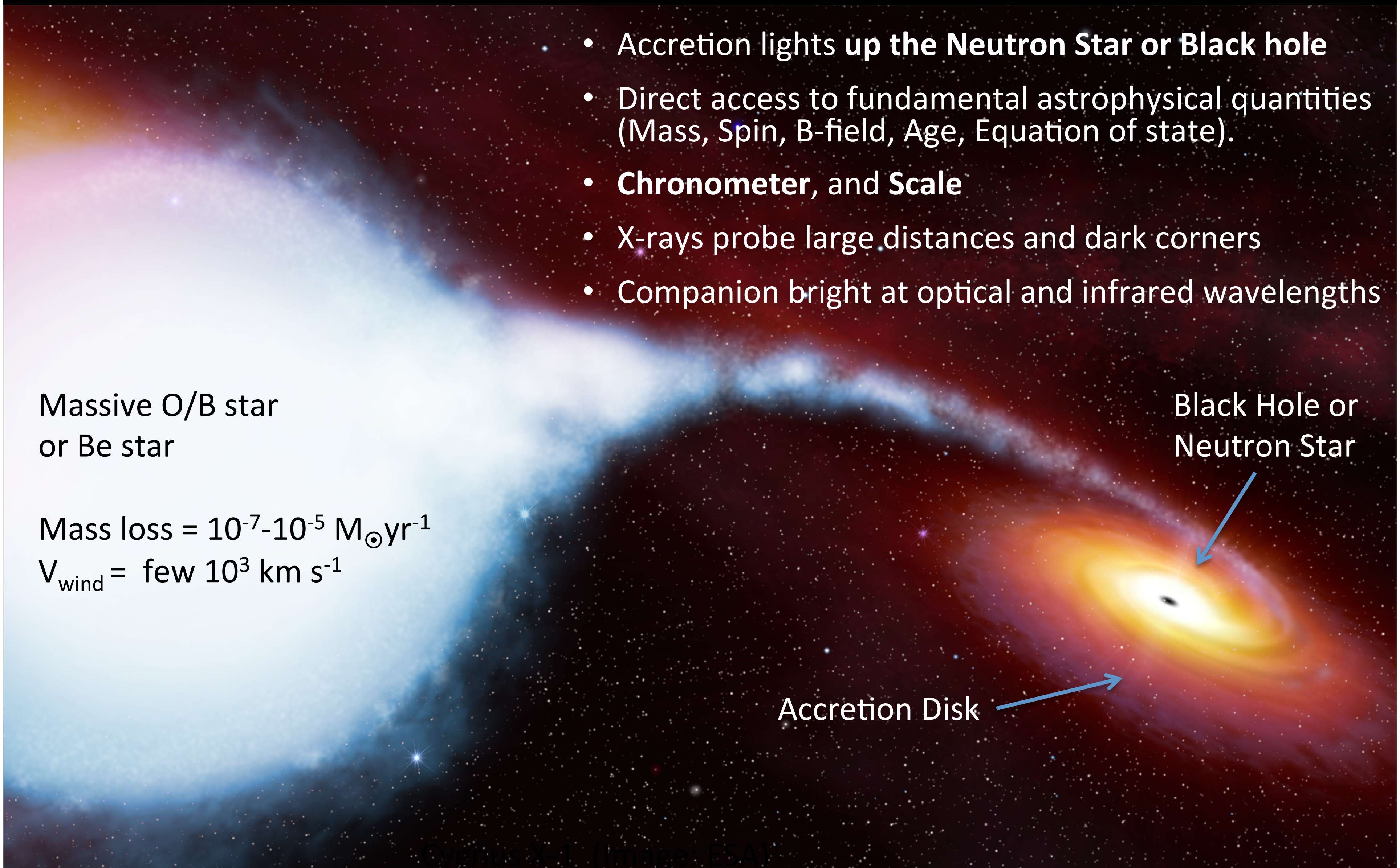
$$E_{rest\ mass} = mc^2$$

$$E_G/E_{rm} = GM/rc^2 \sim 0.2$$

<u>Magnetic Field</u> ~ 10^{12} gauss

Black holes, Neutron stars -relics of the most massive and short lived stars.

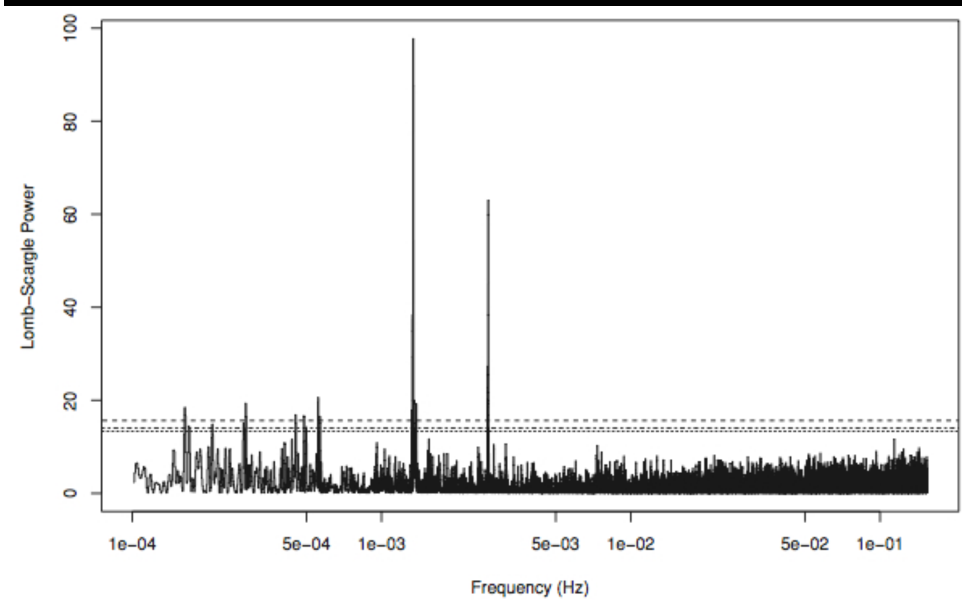
- Accretion lights **up the Neutron Star or Black hole**
- Direct access to fundamental astrophysical quantities (Mass, Spin, B-field, Age, Equation of state).
- **Chronometer**, and **Scale**
- X-rays probe large distances and dark corners
- Companion bright at optical and infrared wavelengths

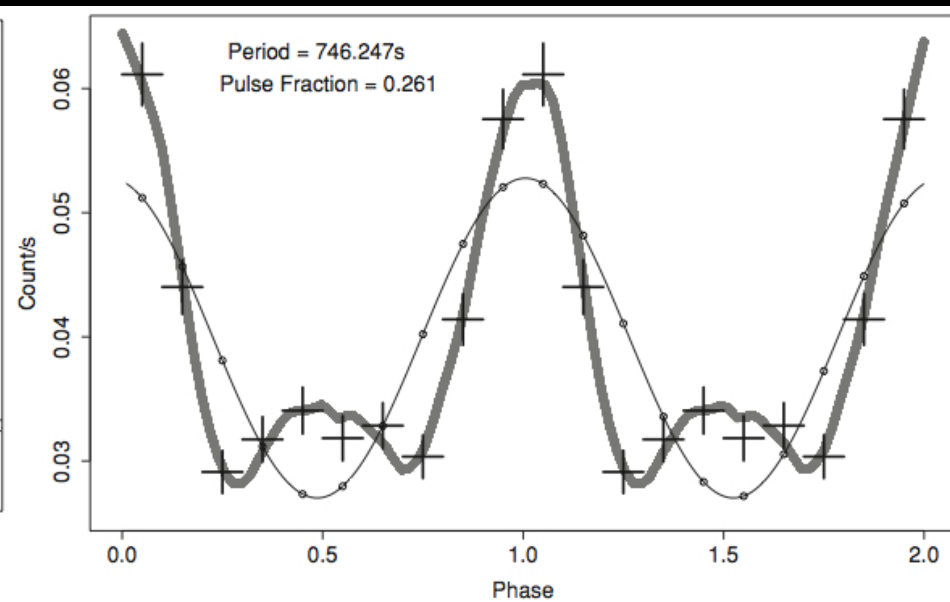


Cygnus X-1 (Image: ESA)

From Pulsar Lightcurves to Astrophysical Parameters:

Frequency Spectrum → Pulse Profile

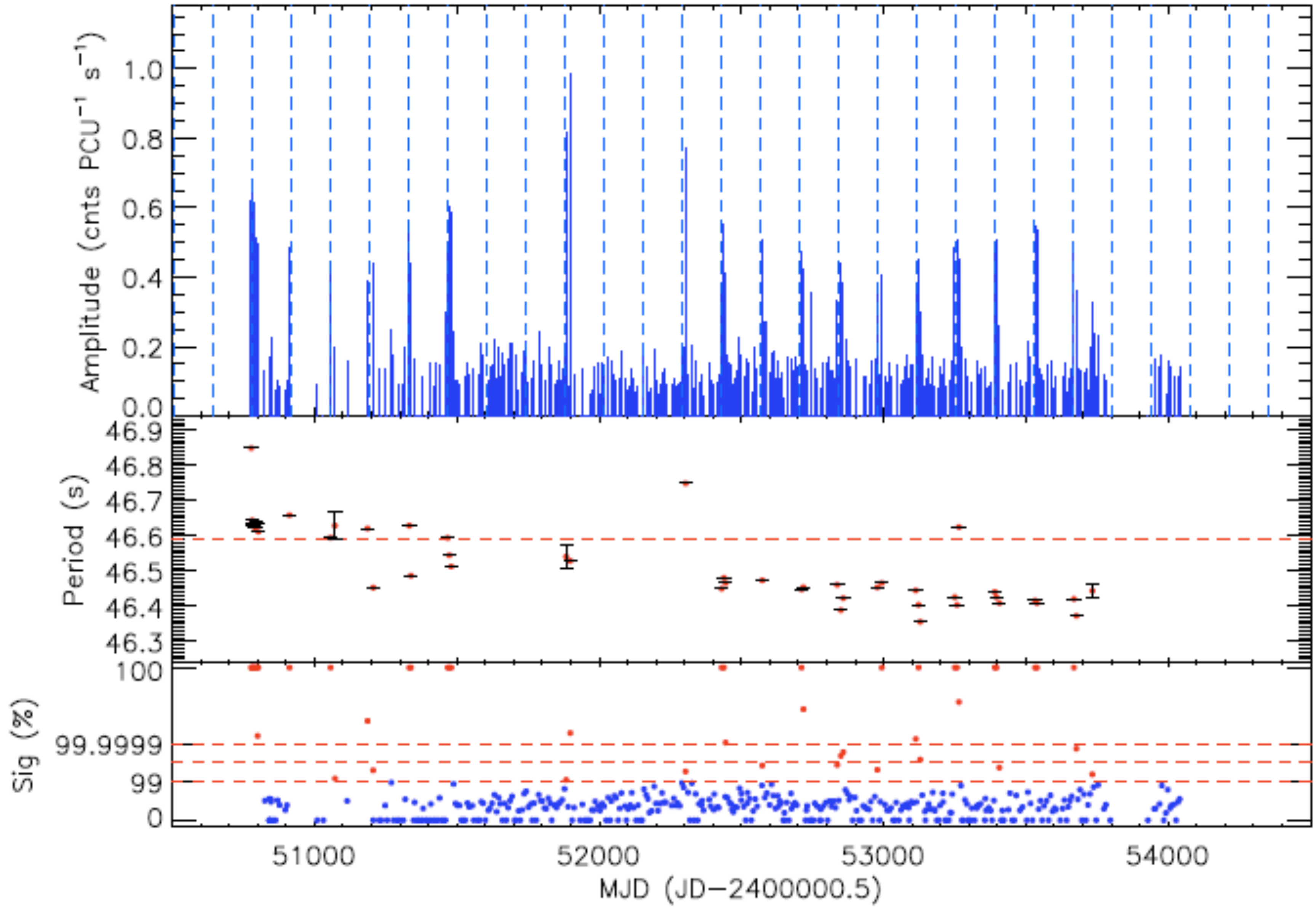




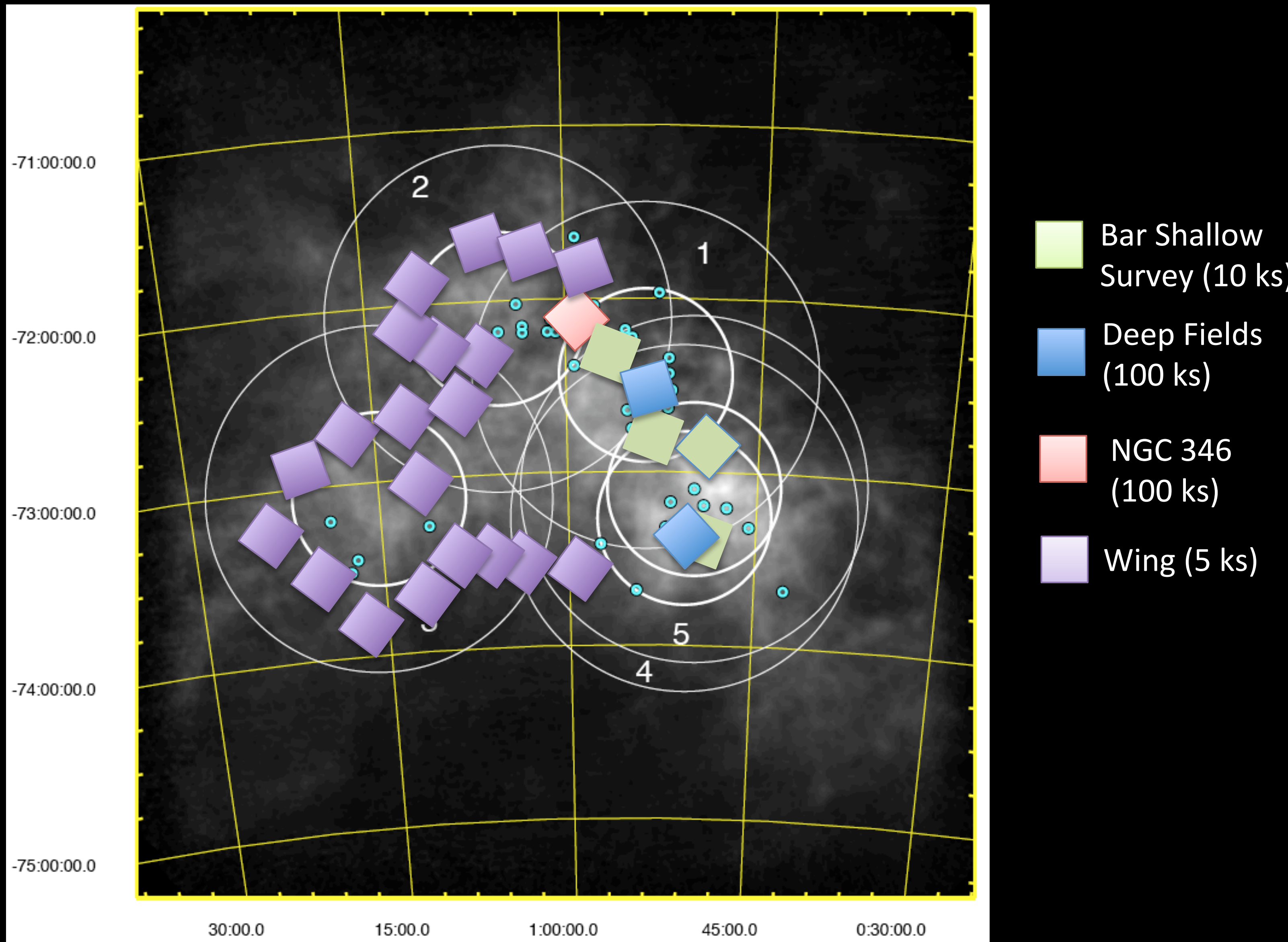
- 60 Pulsars in the Small Magellanic Cloud – Monitored for a decade – Still going!
- Spin Period and Orbital Period Distributions
- Pulse Profiles reveal the Polar Cap Structure

Laycock et al., 2005., ApJS, 161,96 , Galache et al., 2008, ApJS, 177, 189

X-ray Pulsar Spin Periods Change…



Getting a BIG sample: The Small Magellanic Cloud



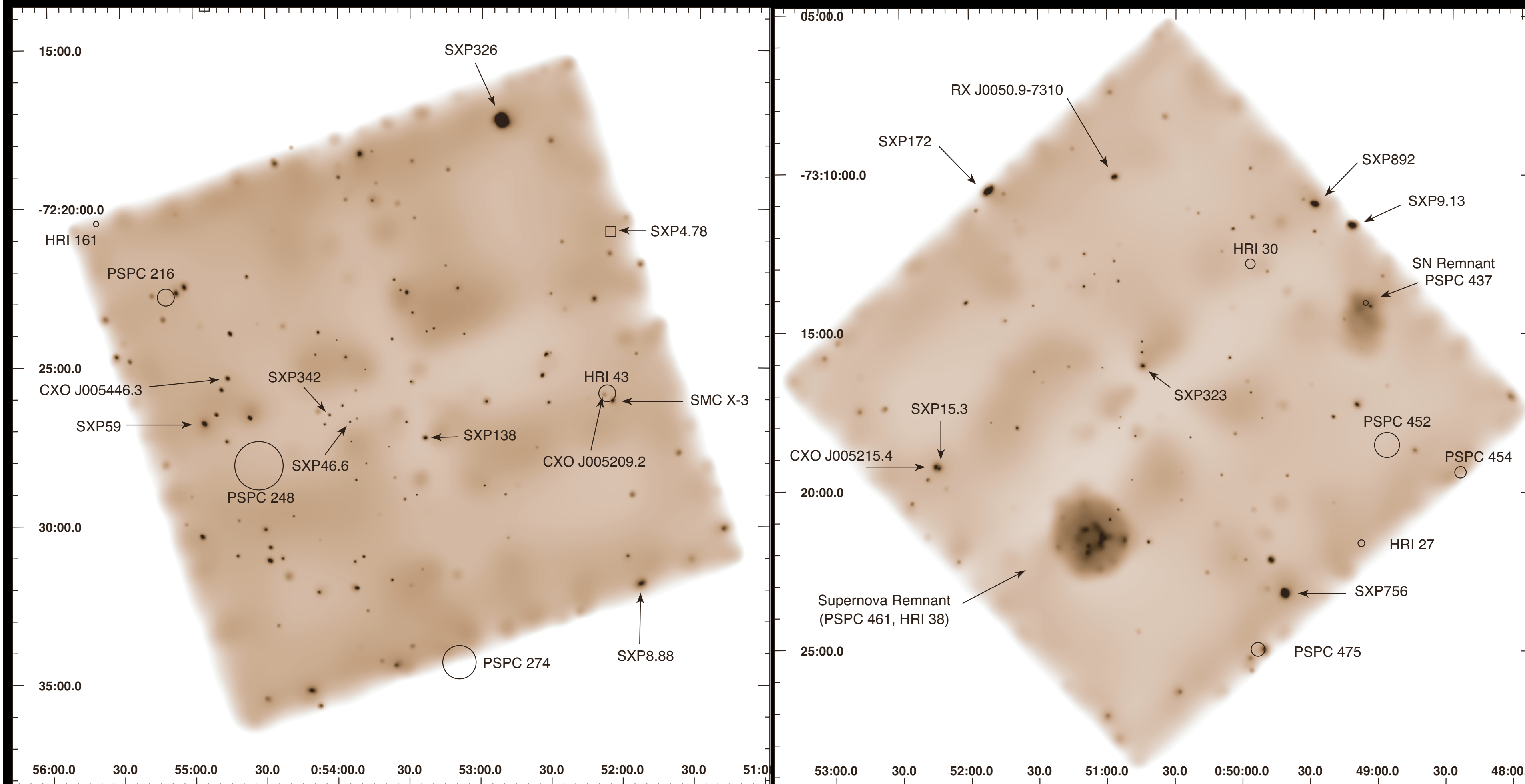
RXTE: Laycock et al., 2005, ApJS, 161, 96, Galache et al., 2008, ApJS, 177, 189, Wing: McGowan et al., 2008, MNRAS, 383, 330, NGC 346: Naze et al, Deep Fields: Laycock et al., 2010, ApJ, Bar: Antoniou et al., 2009/10

Probing the Faintest X-ray Fluxes: SMC Deep Fields

Chandra goes 1000X fainter, and brings ~1 arcsec spatial resolution

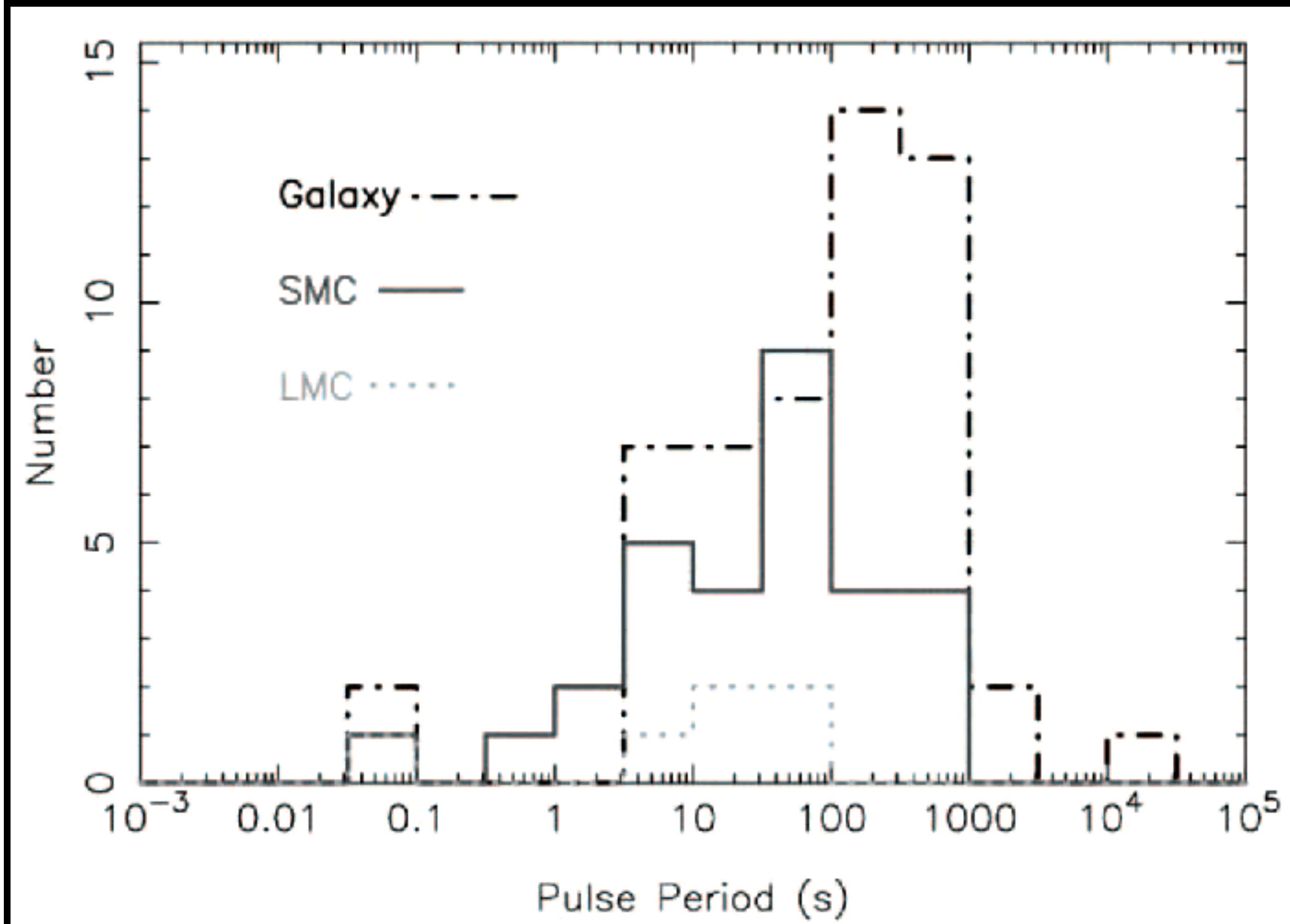
394 sources, 15 pulsars, How Many HMXBs? interesting…..

Quiescence?, long $P_{spin?}$, limits of Lx?



Laycock, Zezas, Hong, Drake, Antoniou, 2010, ApJ, 716, 1217

Distribution of Pulsar Spin Periods



- Do not resemble neutron star birth spins
- Preference for ~100-200s
- Upper and lower limits?

- Both limits are driven by evolution and plasma physics

Laycock et al. 2005, ApJS, 161, 96

Spin-Orbit Equilibrium for X-ray Pulsars

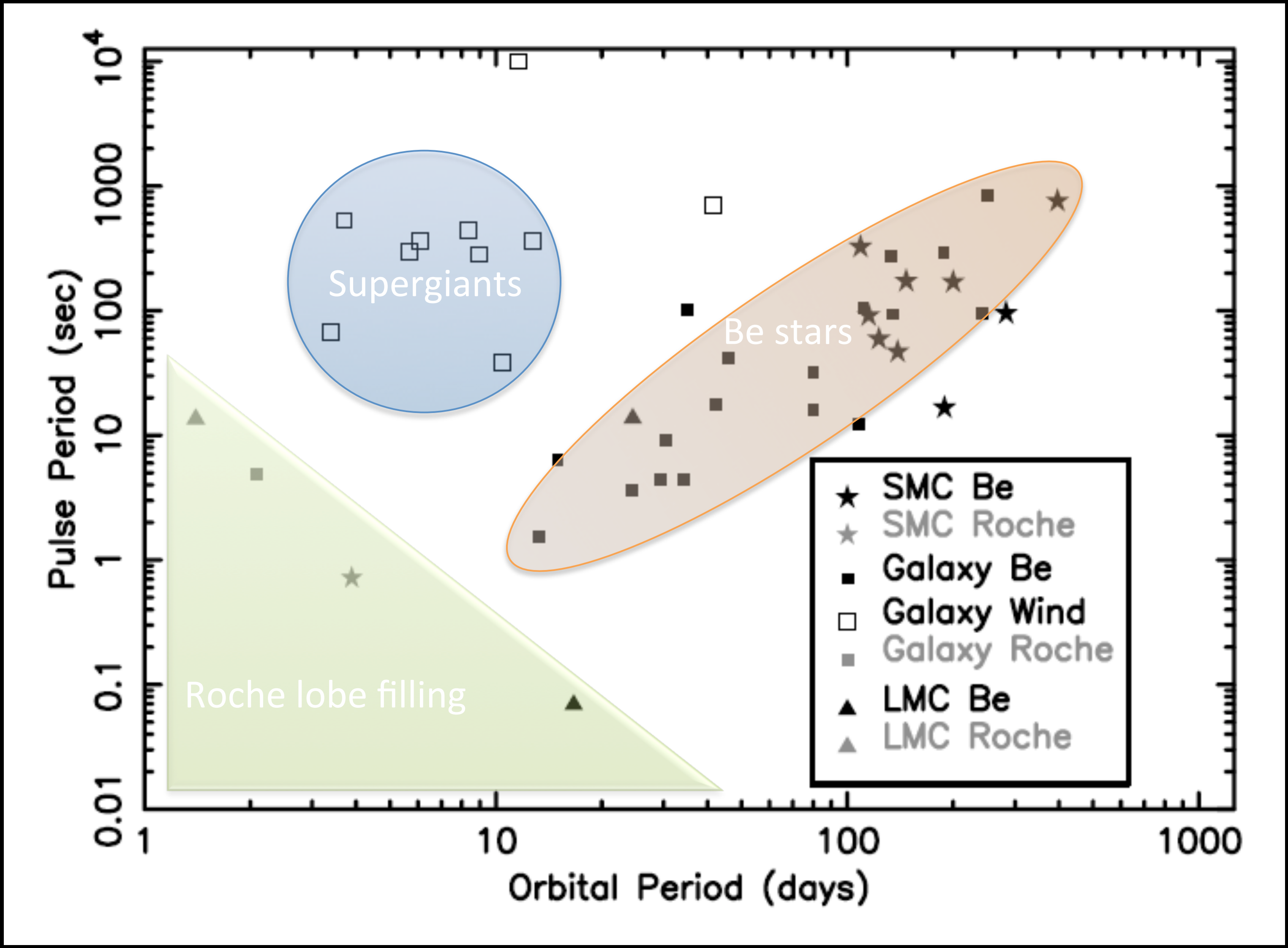
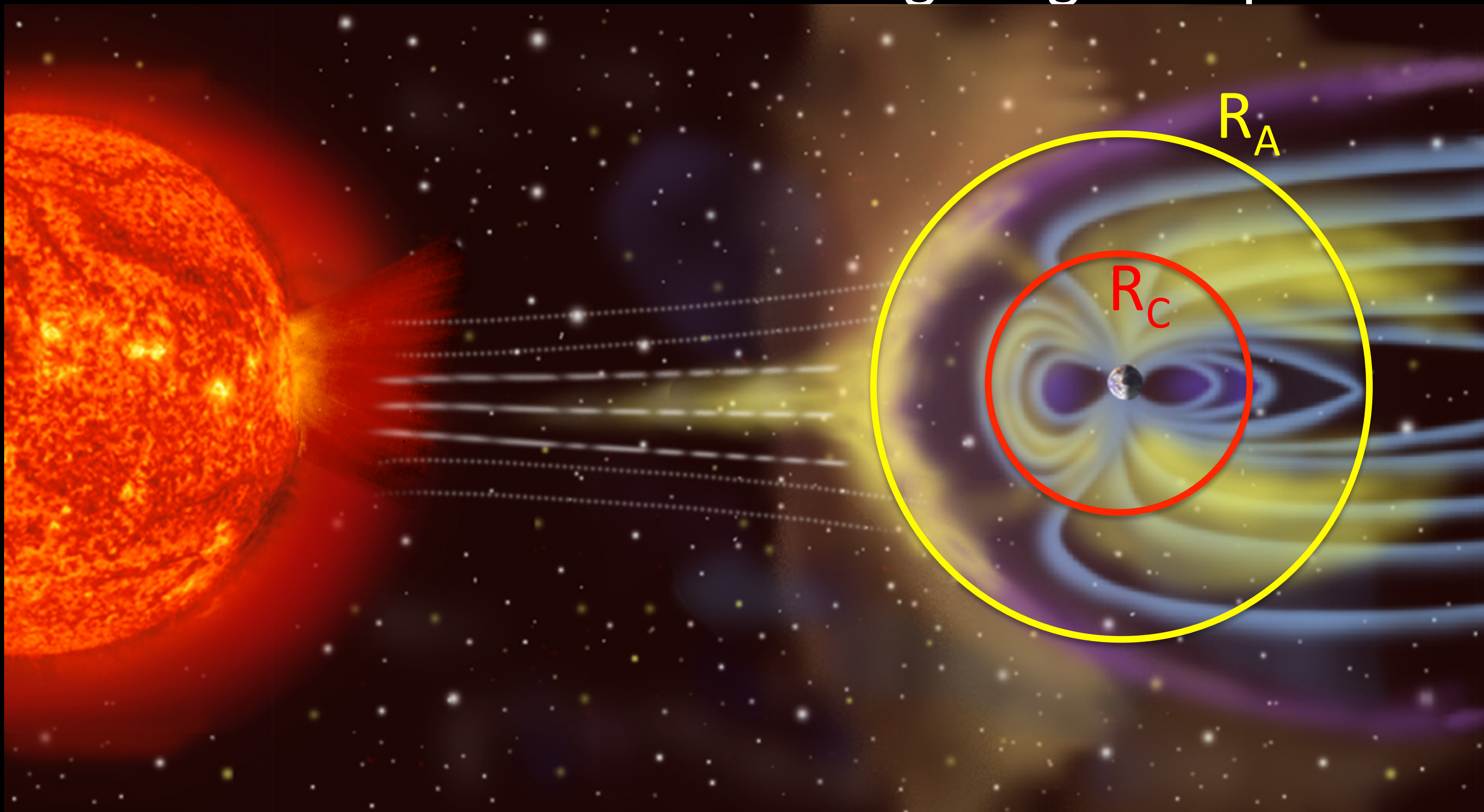


Figure from Laycock et al. 2005, see also Corbet 1984.

Pulsars: Accretion on a rotating Magnetosphere



- Centrifugal Barrier
- Propellor Effect

[Illurianov & Sunyaev 1975]

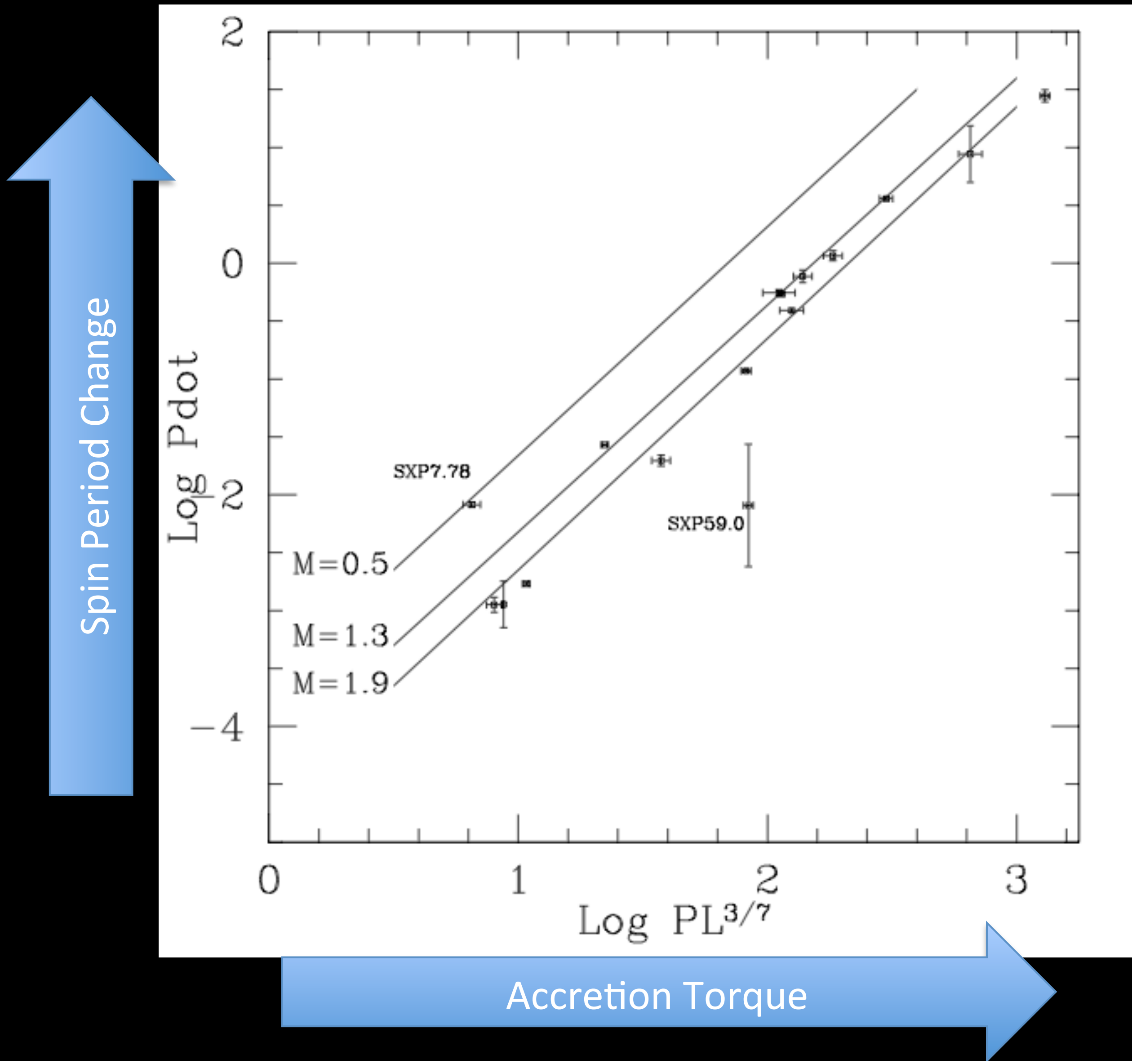
See the book "Accretion Power in Astrophysics" by Frank, King & Raine, 2003, CUP

$$r_C = 1.7 \times 10^6 P_{spin}^{2/3}$$

$$r_A = r_C$$

$$L(\min) = 6.8 \times 10^{37} P_{spin}^{-7/3} ergs^{-1}$$

Pulsar-Timing and the NS Equation of State



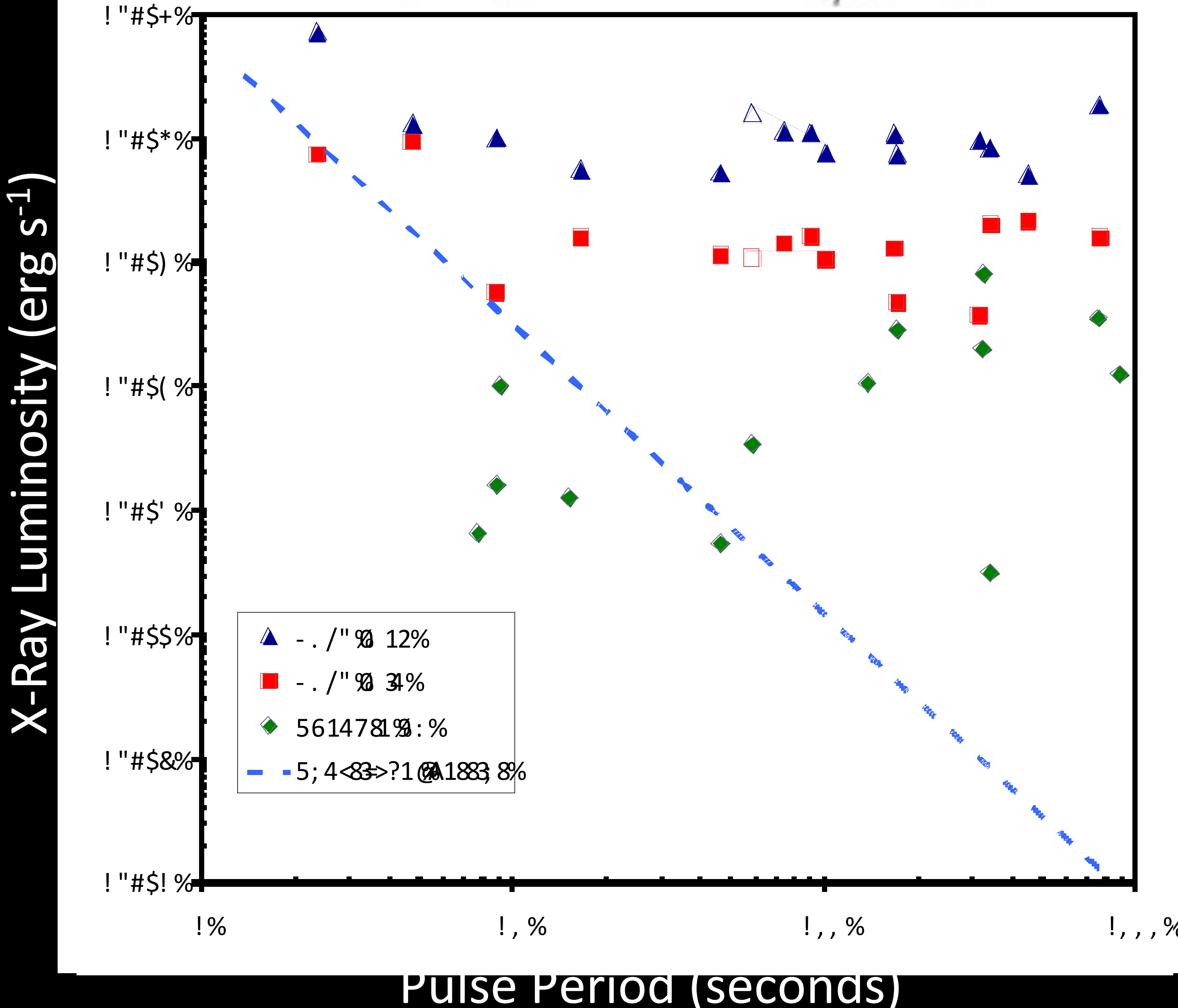
By measuring how the pulsars' spin periods change in response to accretion torques, we can measure their moment of inertia, yielding constraints on neutron star mass.

B-field and EoS (basically density/radius) are assumed constant among the sample.

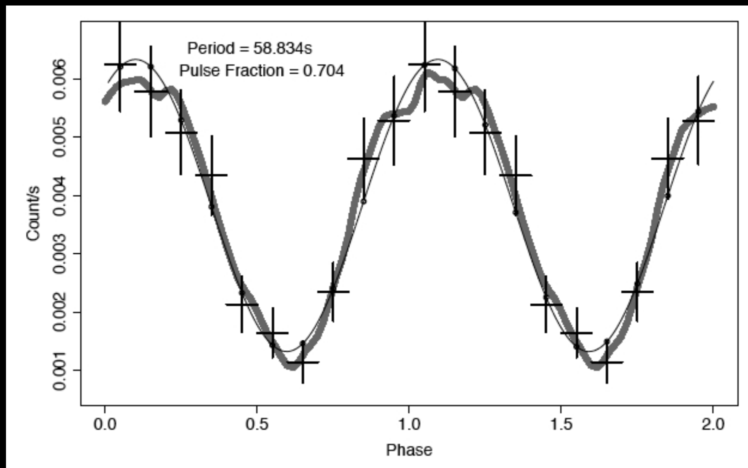
Observations:
(SMC) Coe, McBride & Corbet, 2010, MNRAS, 401, 252
(Galaxy) Bildsten et al, 1997, ApJ, 113, 367
Theory:
Ghosh & Lamb, 1979, ApJ, 234, 296

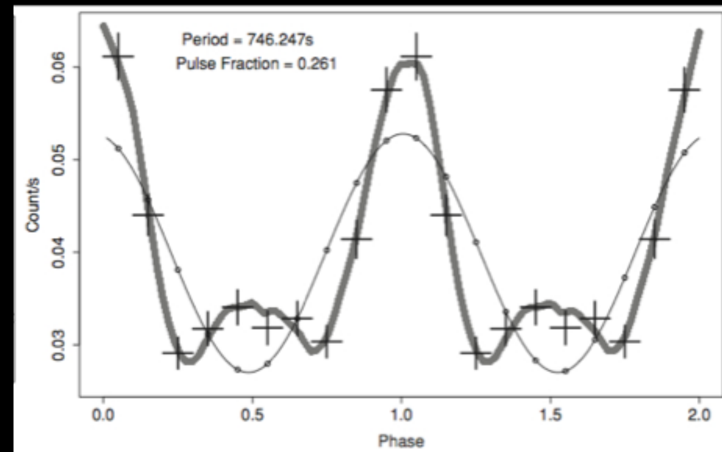
Pushing the Propellor : Limits of Magnetic Accretion

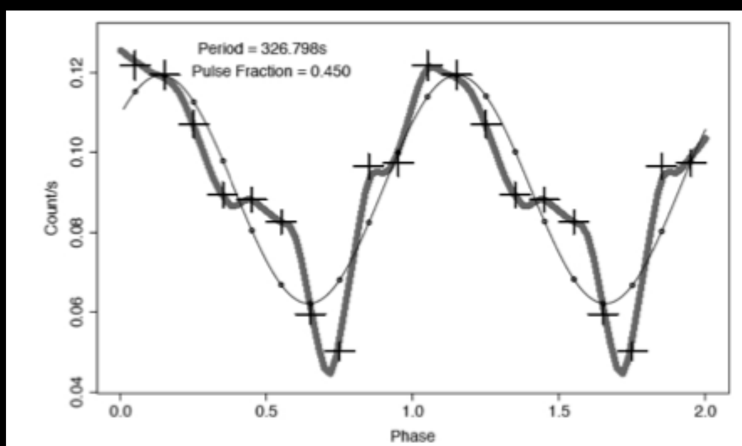
$$L(\min) = 6.8 \times 10^{37} P_{spin}^{-7/3} ergs^{-1}$$

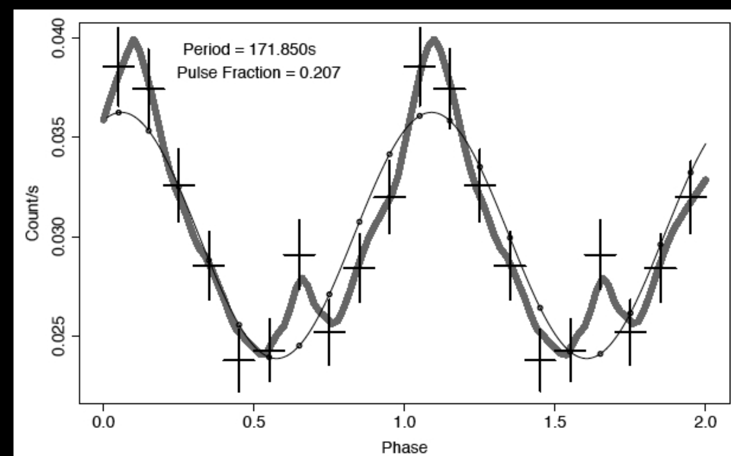


Wide diversity of X-Ray Pulse Profiles









It is hypothesized that pulse-profiles hold the key to modeling the polar-cap B-field geometry and the structure of the accretion column.

Profiles are energy-dependent and change with luminosity

Prospects for Space Physics

- X-ray Pulsar Beam Profiles- Modelling
- Accretion Flows and Accretion Cut-off
- Suppression of Fast Rotators
- SFXTs (Supergiant Fast X-ray Transients)
- Evolution of Slow Rotators
- Black-Hole Binary (ULX) Luminosity and orbit evolution