Compact Binaries

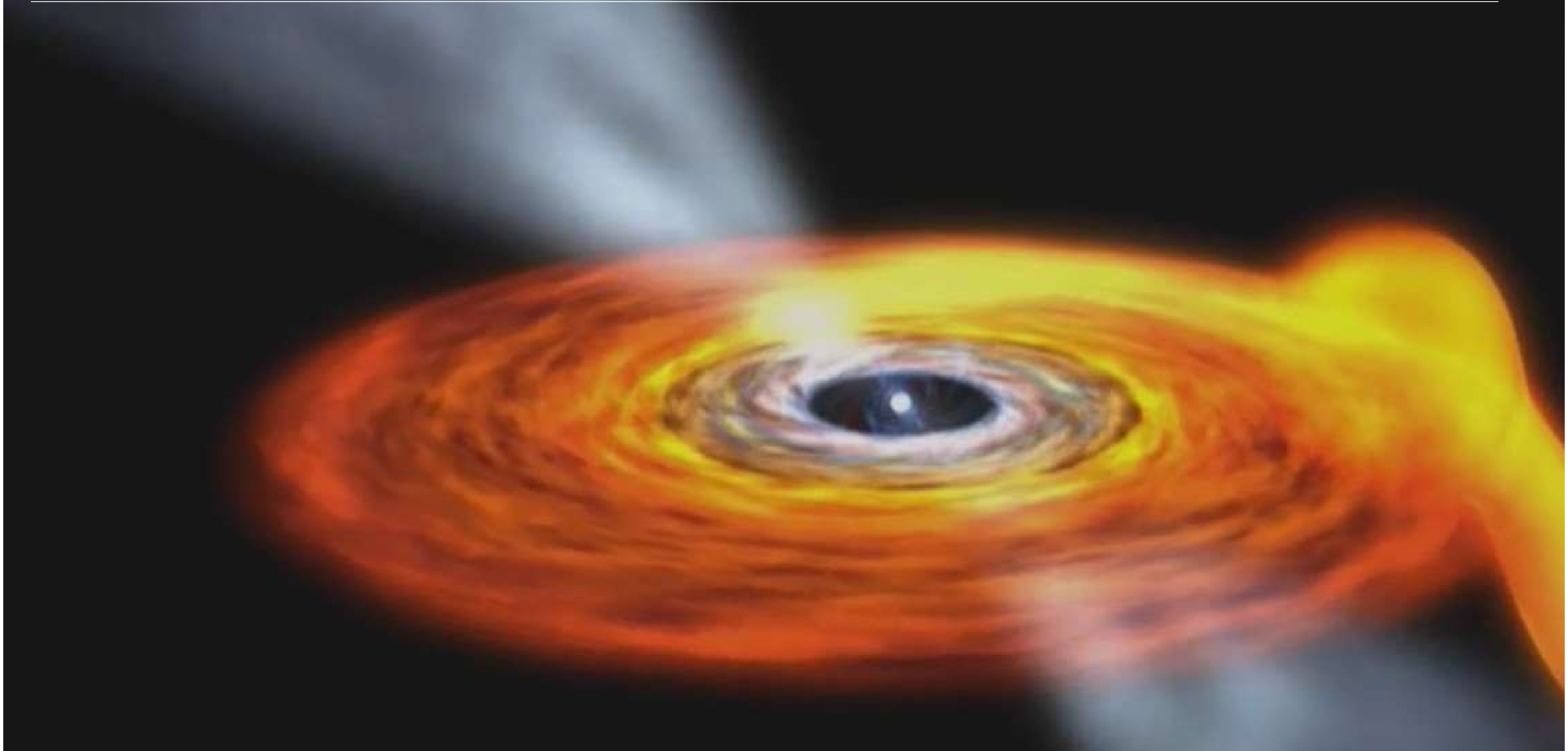
Lecture 4

Pulsars, Accreting Millisecond Pulsars and Transitional Millisecond Pulsar

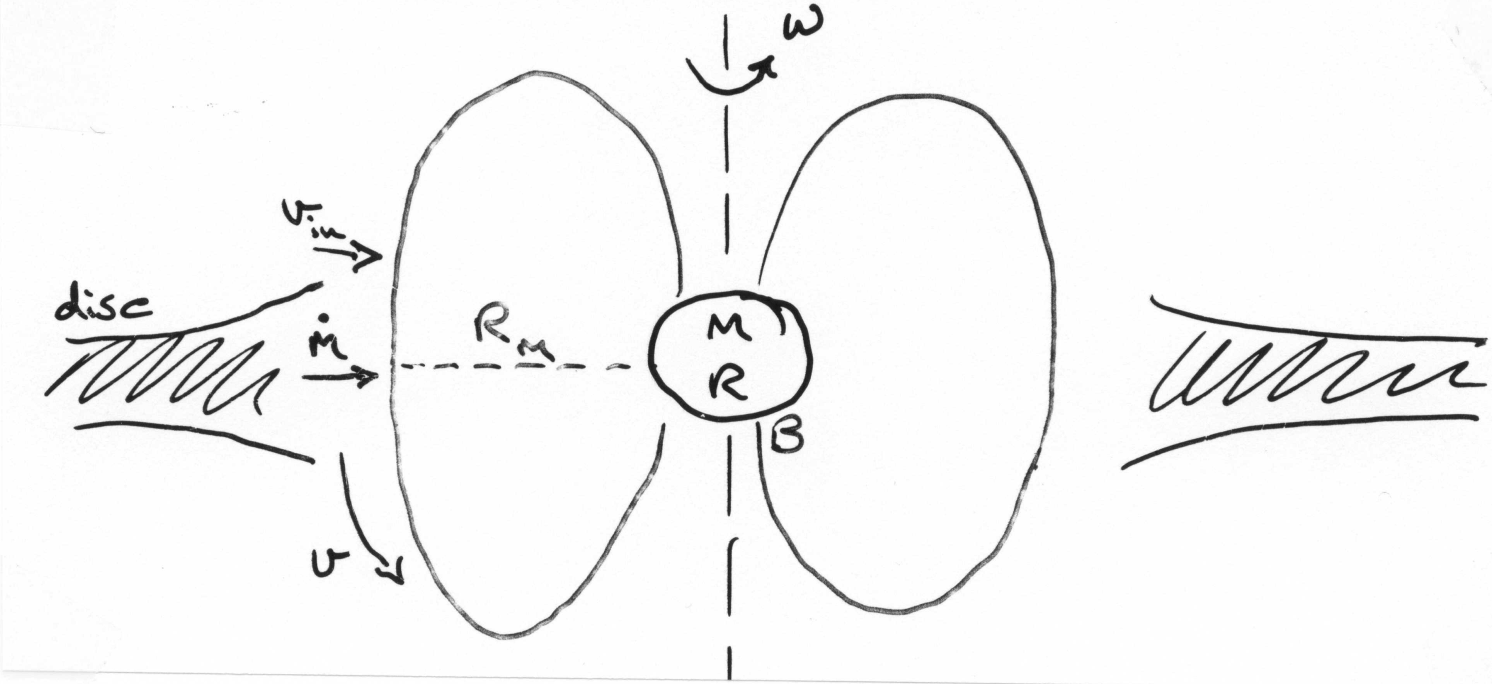
David Buckley
(dibnob@saao.ac.za)

South African Astronomical Observatory
Department of Astronomy UCT
Department of Physics UFS

Rotation and accretion power in binary millisecond pulsars

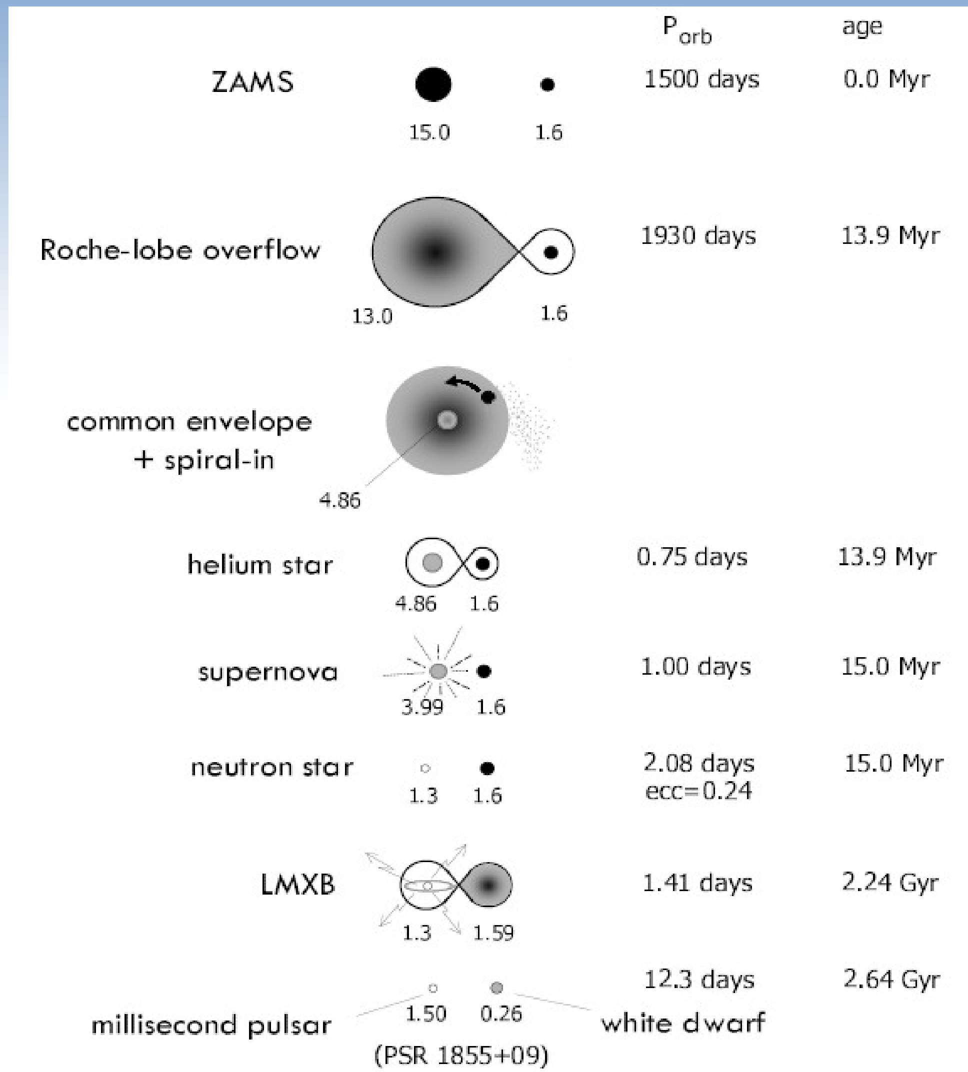


ACCRETION ONTO A MAGNETIC, SPINNING OBJECT



- compact object has magnetic field B
- at R_M
  - disc ram pressure $\simeq$ magnetic pressure
  - MAGNETOSPHERIC (or Alfvén) RADIUS
- material in disc has angular momentum, what is effect on spin of compact object? SPINS UP.

Evolution of Low Mass X-ray Binary Evolution

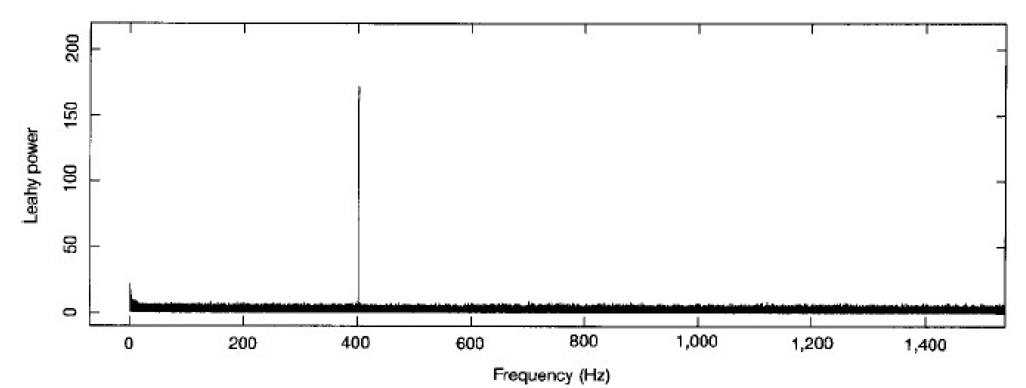


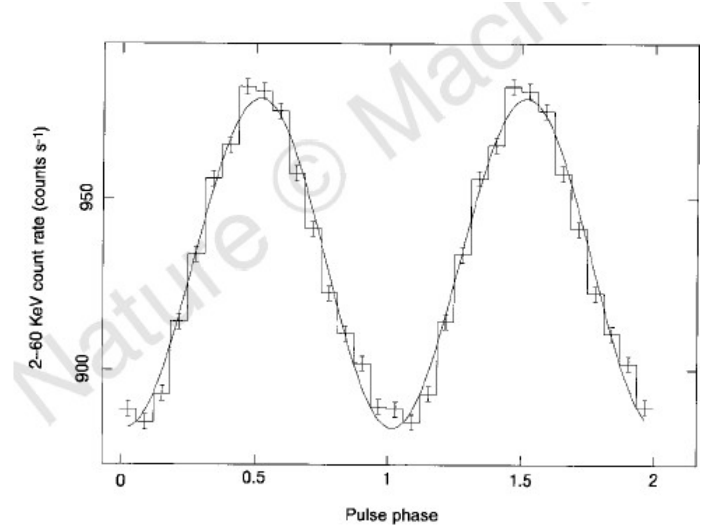
Discovery of accreting millisecond pulsars

letters to nature

A millisecond pulsar in an X-ray binary syste

Rudy Wijnands* & Michiel van der Klis*†





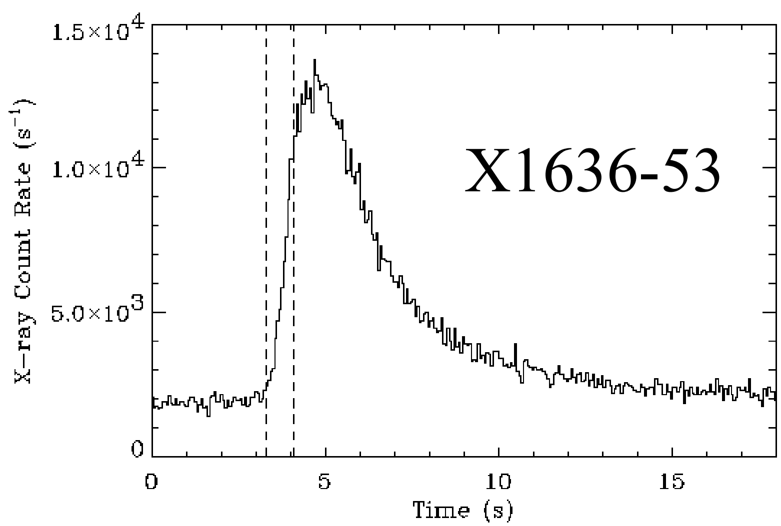
The expected end-points of Low Mass X-ray Binary Evolution

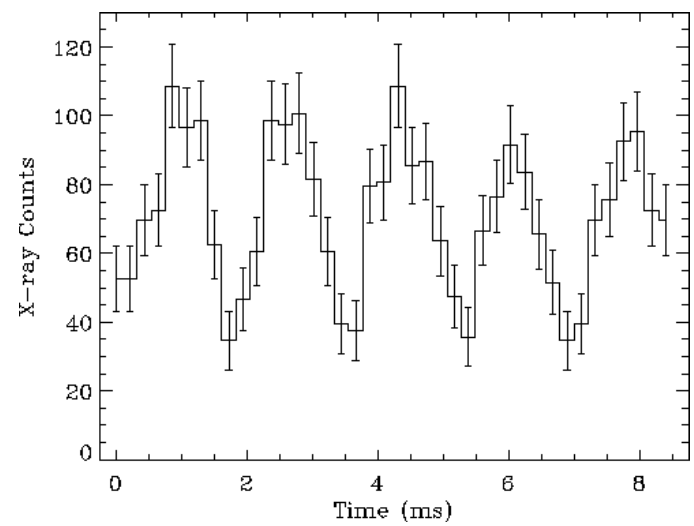
LMXBs are thought to be progenitors of Millisec Pulsars where NS have been spun-up through sustained accretion of matter with high angular momentum.

But detection of millisecond pulsars in LMXBs elusive for 20 yrs

Since 1996 XTE has discovered :

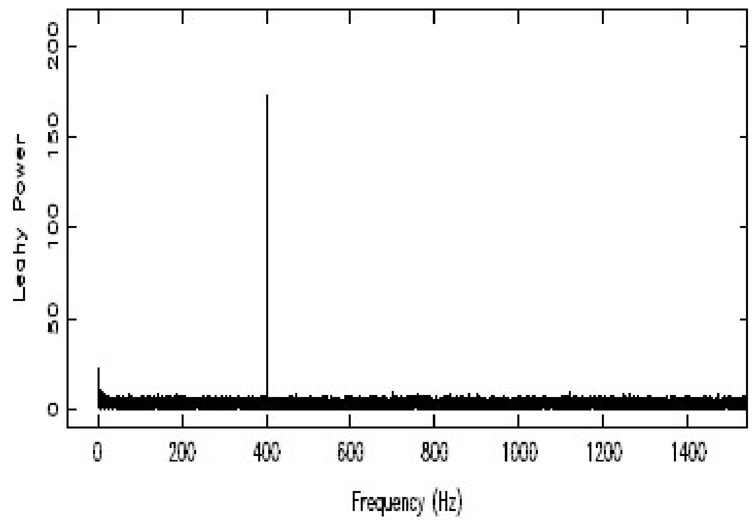
- 5 millisecond Pulsars in transient LMXBs, with ν_{spin}=185-435 Hz
- Coherent oscillations during X-ray bursts in 13 LMXBs

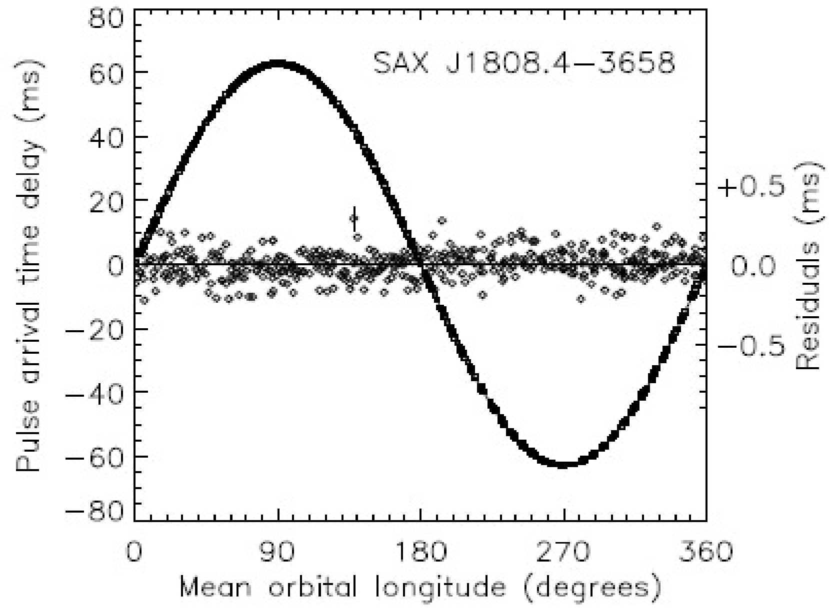




In SAX J1808.4-3658 & XTE J1814-338: confirms burst oscillation modulated by the NS spin (Chakrabarty et al. 2003 Nature 424 42; Strohmayer et al. 2003 ApJ 596 67)

Expect to find most rapidly spinning pulsars in LMXBs





Pulsars in a binary will show Doppler related pulse timing delays over the orbit

- will need to know the orbit to resolve pulses (smearing of peaks)

Table 1.3. *Observed Properties of Millisecond Accreting Pulsars*[a]

Source	f_s (Hz)	P_{orb} (m)	a (lt-ms)	f ($M_\odot$)
SAX J1808.4−3658[b]	401.0	120.9	62.809	3.78×10^{-5}
XTE J0929−3314[c]	185.1	43.6	6.290	2.7×10^{-7}
XTE J1751−305[d]	435.3	42.4	10.1134	1.278×10^{-6}
XTE J1807−294[e]	190.6	40.1	4.80	1.54×10^{-7}
XTE J1814−338[f]	314.3	256.5	390.3	2.016×10^{-3}

Rotation and accretion powered millisecond pulsars

- The quickest spinning rotation powered radio pulsars
  - The most accurate clocks probe General Relativity

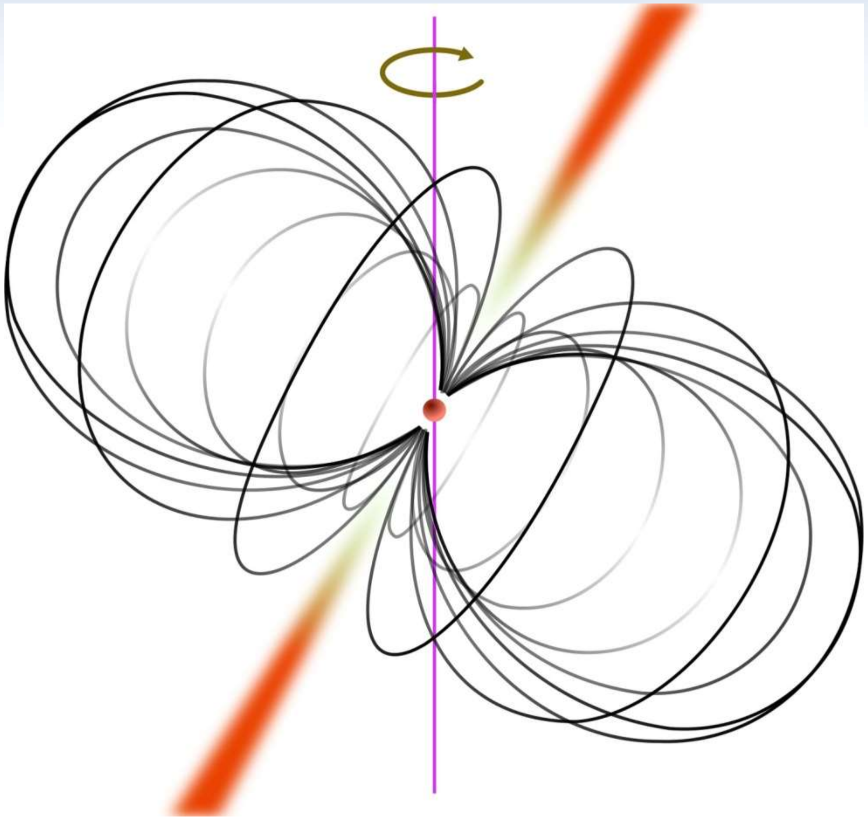
- Evolutionary scenarios: recycling neutron stars
  - Discovery of accreting millisecond pulsars
  - Properties of accreting MSP

    (magnetic field, X-ray spectrum, spin evolution)
  - The spin distribution of accreting MSP

- Transitional millisecond pulsars
  - Swinging back and forth radio and X-ray pulsar states

Rotation-powered pulsars

- Neutron stars (isolated/binary/triple/planetary systems)
- Spin periods between ~ms and ~10s
- Highly magnetized (B~10^8 – 10^{14} G)
- Pulsed emission observed throughout the EM spectrum:
  - radio
  - optical
  - X-rays
  - gamma-rays



Rotation-powered pulsars – main observables

- Spin period, Ps
- Spin period derivative, dP/dt<0 (spin-down)

$$L_{\dot{\nu}_s} = -4\pi^2 I \nu_s \dot{\nu}_s$$

Dipole spin-down luminosity:
Powers non-thermal emission

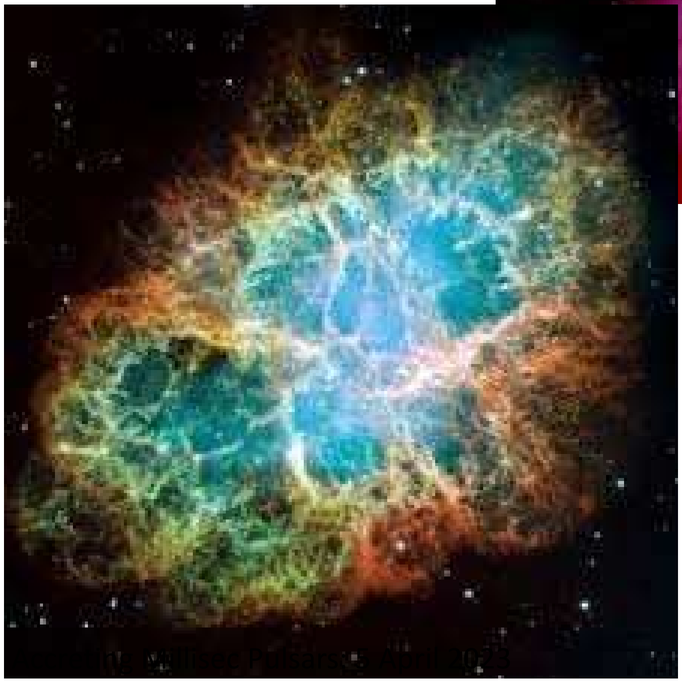
e.g. Crab PSR

$$P_s = 33\,ms;\ \dot{P}_s = -4.2\,x\,10^{-13}$$

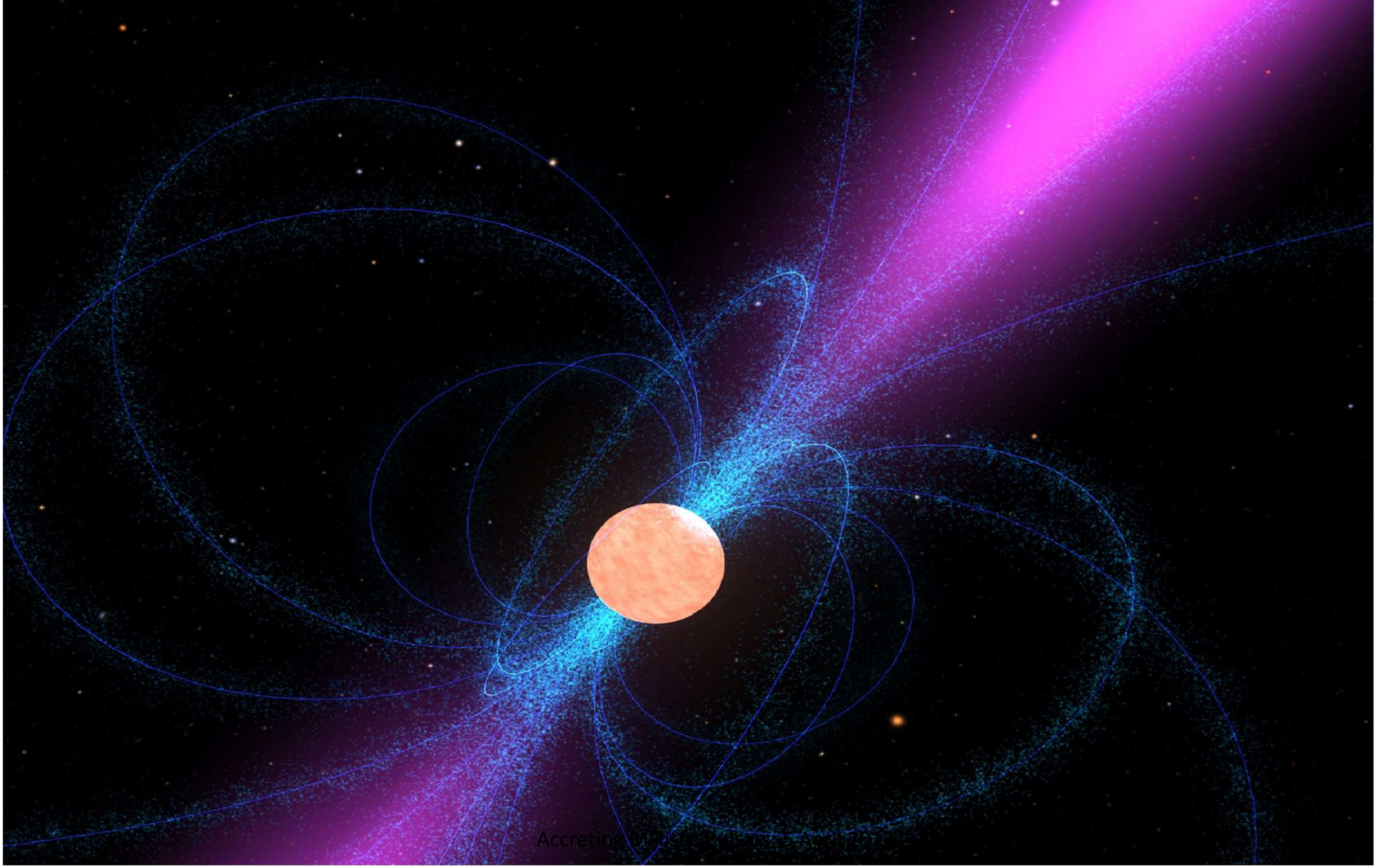
$$I = 10^{45}\,g\,cm^2$$

$$dE/dt = 4.5\,x\,10^{38}\,erg/s$$

Enough to power the observed nebular emission



Millisecond Radio (rotation-powered) pulsars

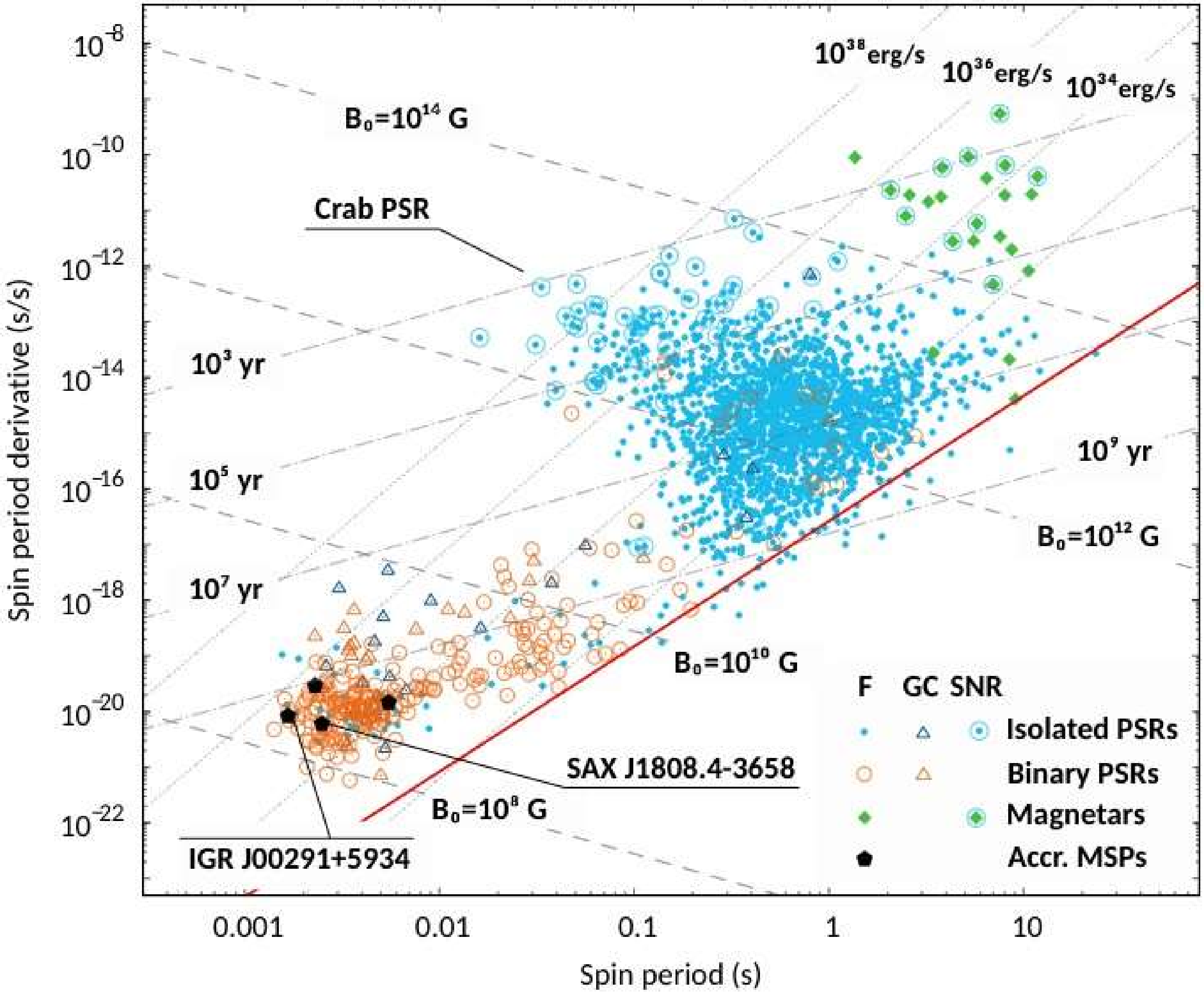


Rotation-powered pulsars

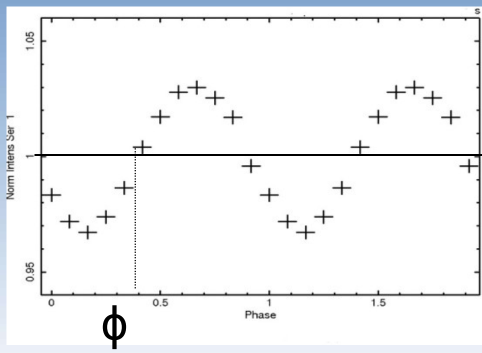
$$B_s = 3.2 \times 10^{19} (P_s(s) \dot{P}_s)^{1/2} G$$

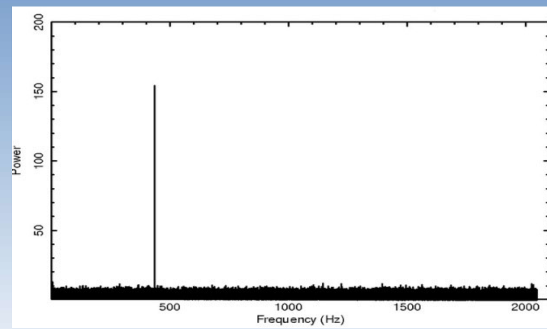
$$\tau_{sd} = \frac{P_s}{2\dot{P}_s}$$

Spin-down time scale



Millisecond pulsars as clocks, timing techniques





Fourier techniques to detect a coherent periodicity

$\delta\nu = \dfrac{1}{\Delta t_{obs}}$ $\delta P = \dfrac{P^2}{\Delta t_{obs}}$ ~0.3 ns (2×10^{-10} s) accuracy reached over Δt_{obs}~hour

A better precision is achieved through phase fitting

$\delta\nu = \dfrac{\delta\phi}{\Delta t_{obs}}$ $\delta P = \dfrac{P^2\,\delta\phi}{\Delta t_{obs}}$ ~10 ps (10^{-11} s) accuracy reached over Δt_{obs}~hour

If the frequency evolution is 'stable', observations spanning large intervals can be tied together

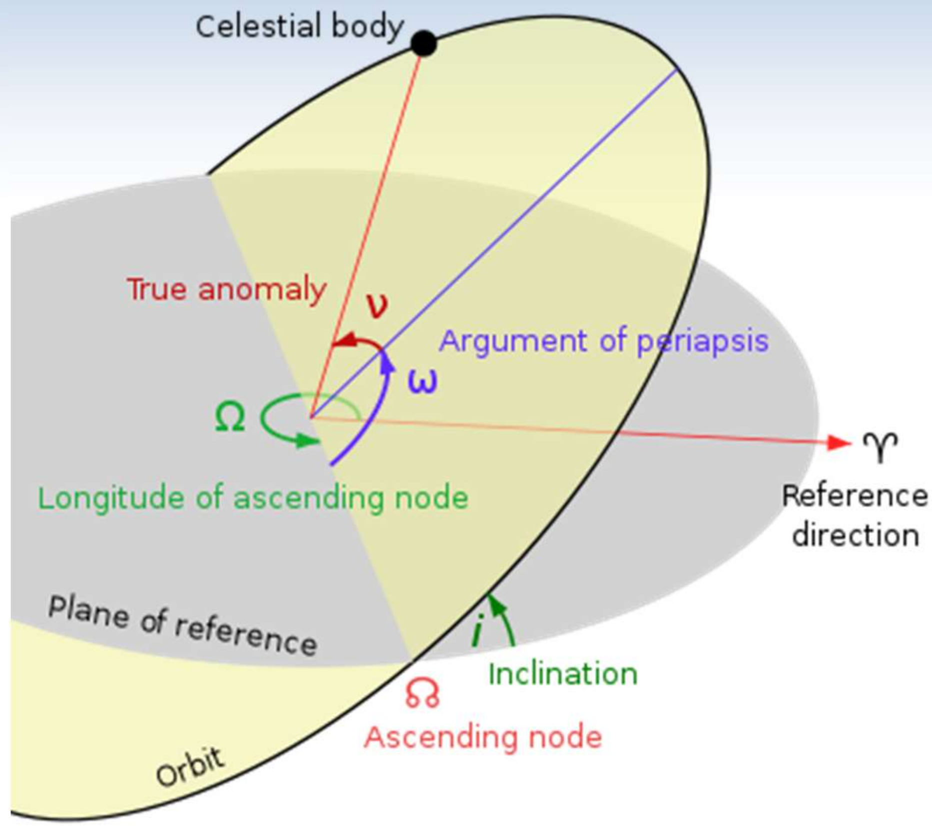
$\delta\nu = \dfrac{\delta\phi}{\Delta t_{span}}$ $\delta P = \dfrac{P^2\,\delta\phi}{\Delta t_{span}}$ ~1 fs (10^{-15} s) accuracy reached over Δt_{span}~year

Millisecond pulsars in binary systems

A MSP in a binary system is a clock falling in the gravitational field of the companion.

Keplerian parameters

- orbital period
- projected size of pulsar orbit
- orbital phase
- eccentricity
- longitude of periastron



Post-Keplerian parameters

- rate of periastron advance
- orbital period decay
- Einstein delay
- Shapiro delay & shape

Position and motion

Millisecond pulsars in relativistic binary systems

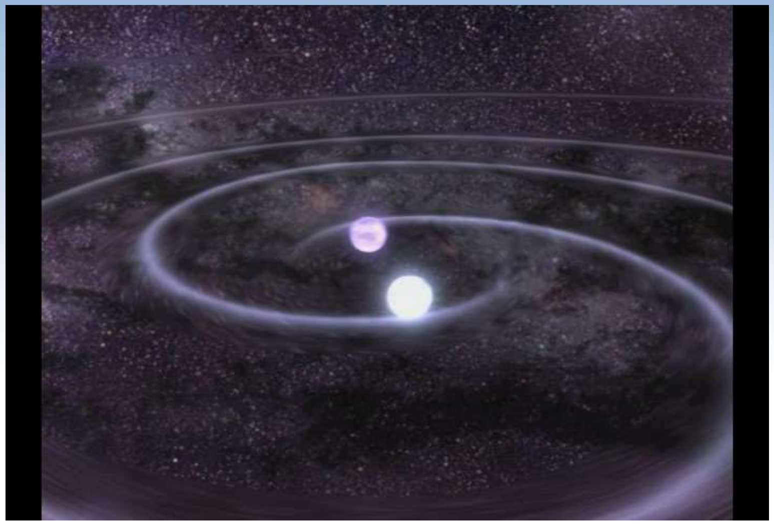
Probe the orbital motion of a pulsar in the grav. field of another neutron star

Post Keplerian parameters depend on M_1, M_2 and

Keplerian parameters

→ 2 PK parameters measure masses

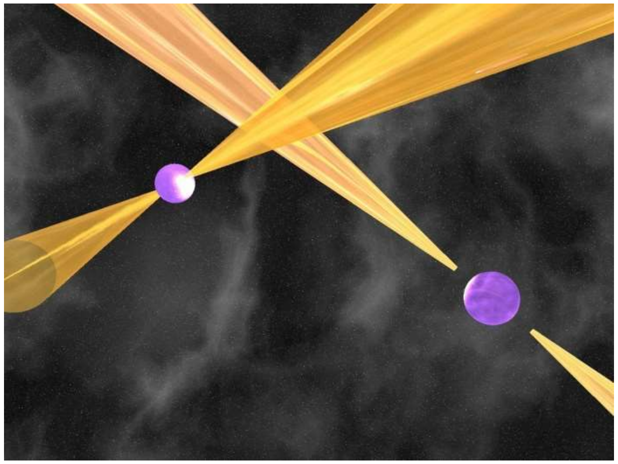
→ 2+ PK parameters test GR



Hulse & Taylor binary pulsar B1913+16 (Nobel prize in 1993)

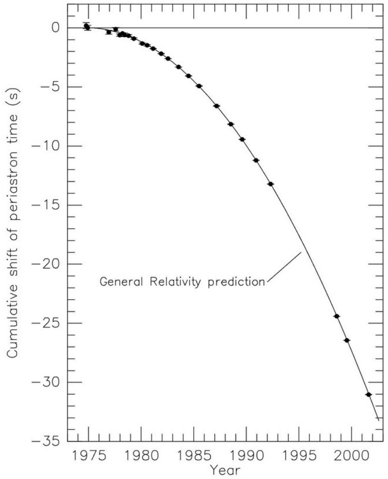
PSR J0737−3039A, B

- 2 pulsars (one is a ms pulsar)
- shorter Porb (~2.4 hr)



5 PK parameters + mass ratio

Masses measured with 0.01% acc.

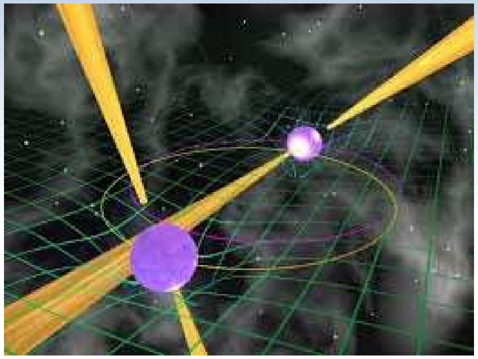


Utility of millisecond pulsar clocks

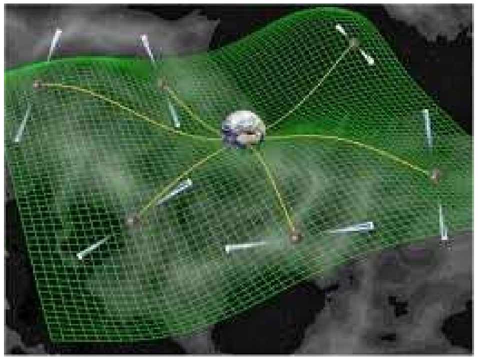
Test General Relativity in the weak field regime (but stronger than in Solar System)

Test strong equivalence principle (grav mass = inertial mass)

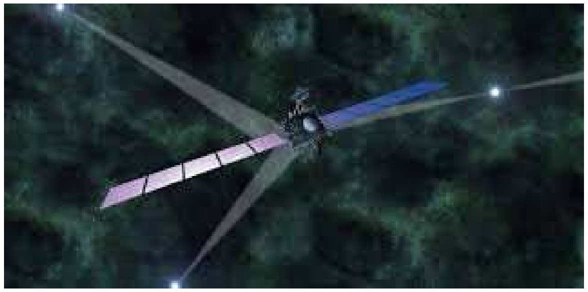
- pulsar + white dwarf binaries in the Galaxy grav. Field
- pulsar in a triple system (e.g. Ransom et al. 2014)



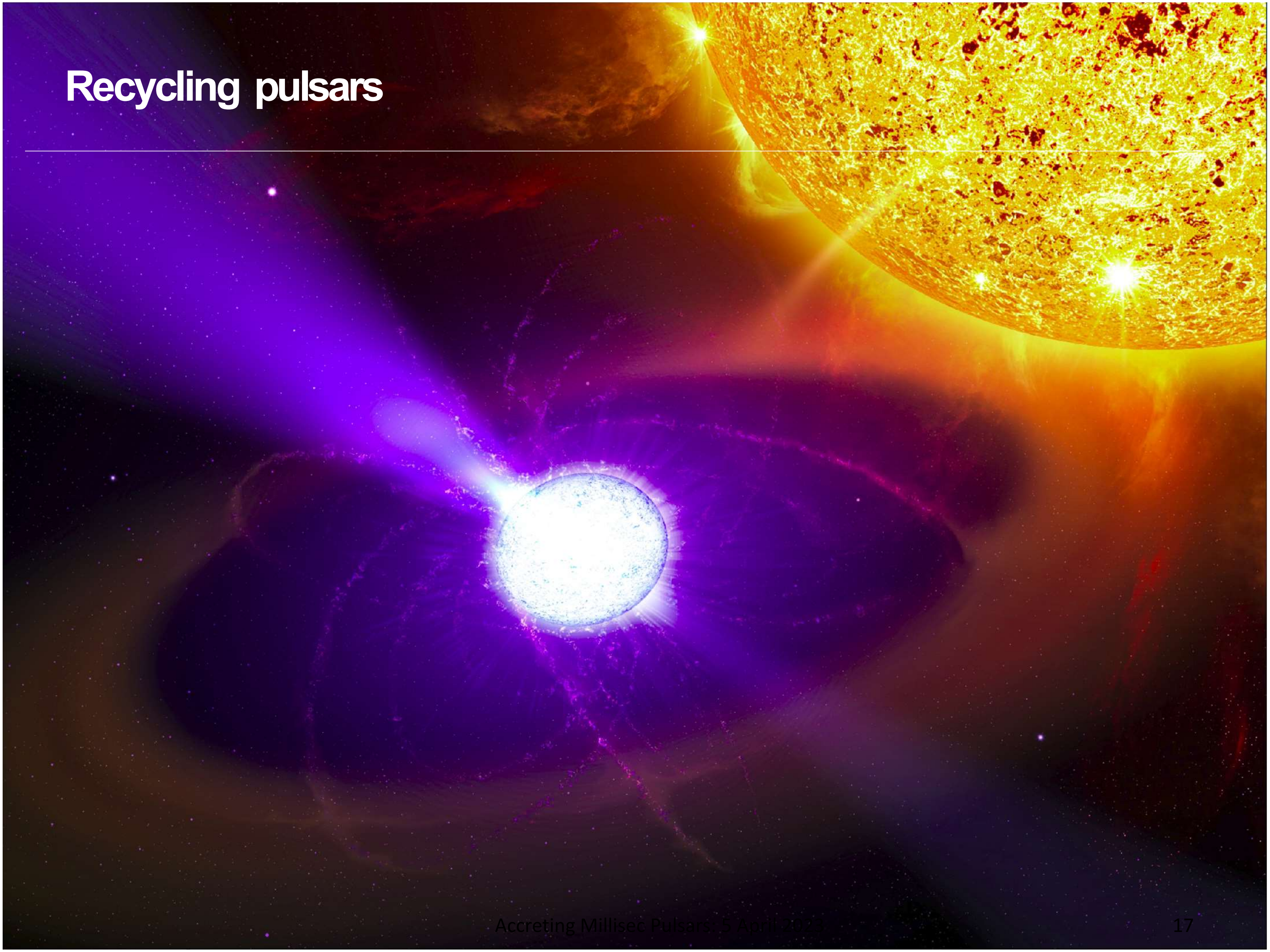
Detect gravitational waves (→ Pulsar Timing Array)



Deep space pulsar navigation



Recycling pulsars



Origin of Millisecond pulsars

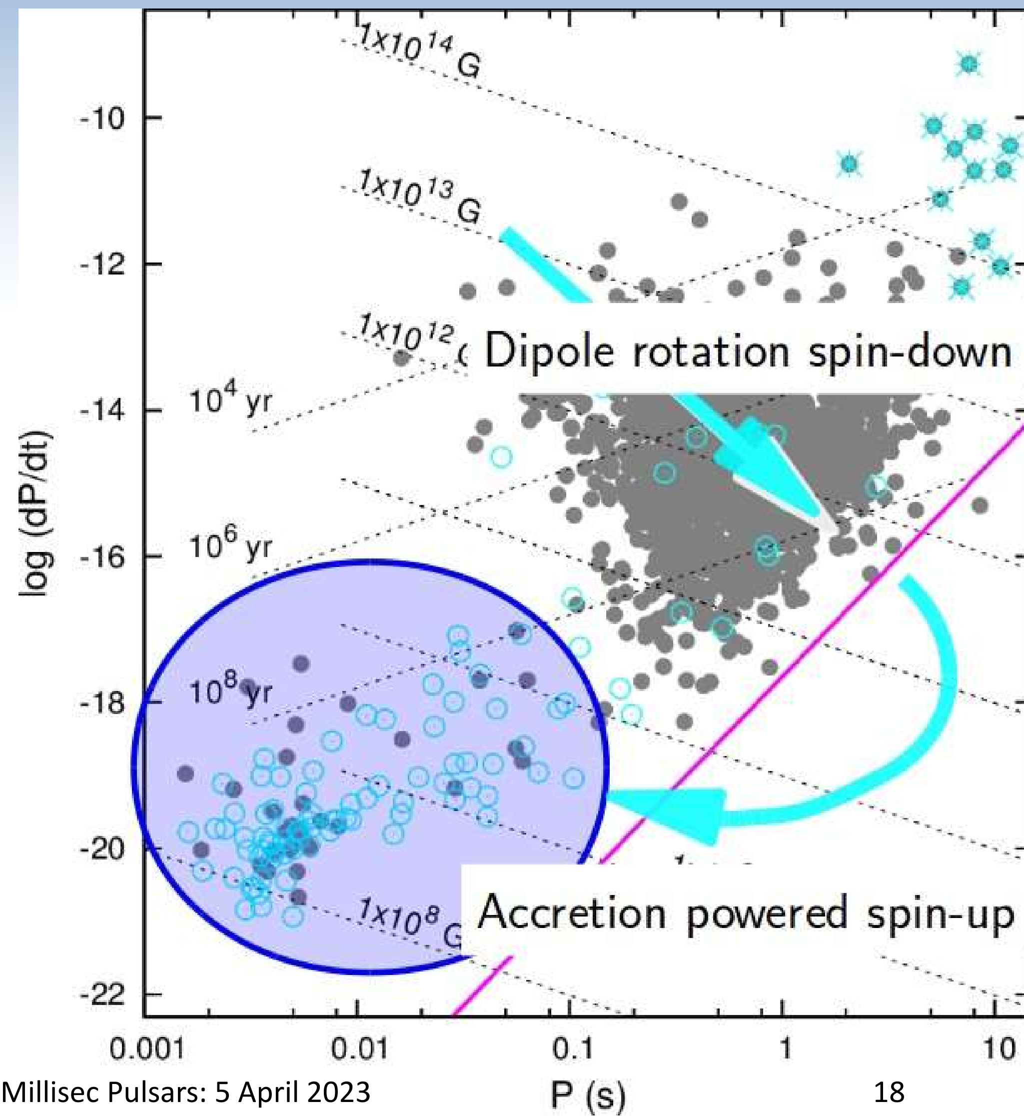
Millisecond pulsars

[Backer+ 1982 Nature]

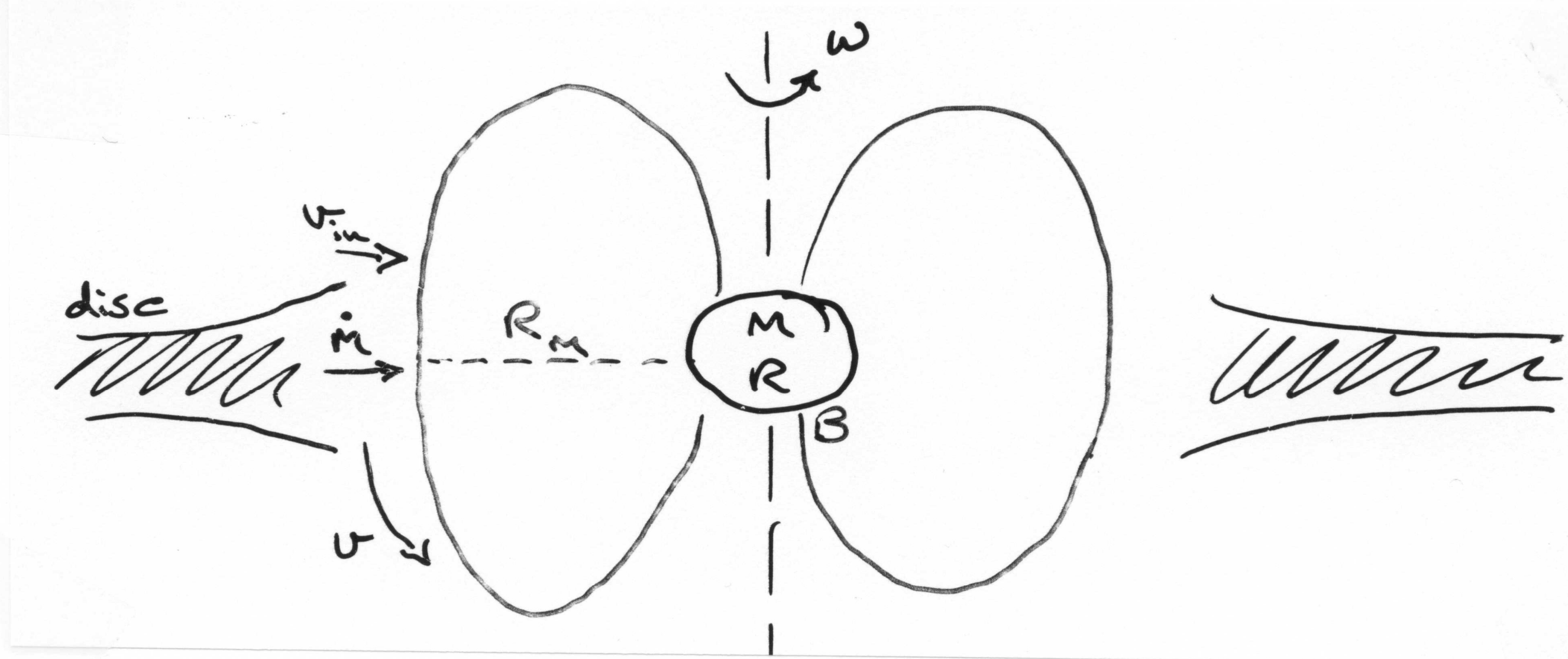
- weakly magnetized
- often found in globular clusters
  → old systems
- often in **binaries**

Neutron stars recycling

[Bisnovatyi-Kogan & Komberg 1974, Alpar+, Radhakrishnan+ 1982]



Accretion Torque Spin-up



- compact object has magnetic field $\underline{B}$
- at R_M
  - disc ram pressure $\simeq$ magnetic pressure
  - MAGNETOSPHERIC (or Alfvén) RADIUS
- material in disc has angular momentum, what is effect on spin of compact object? SPINS UP.

Angular Momentum Transfer

Flux of angular momentum across R_M is $J = \dot{M} v R_M$

$v^2 = \dfrac{GM}{R_M}$ therefore $J = \dot{M}(GMR_M)^{1/2}$

transferred to an object already spinning at $\omega\left(=\frac{2\pi}{p}\right)$

$$\text{therefore } J = I\dot{\omega} \qquad \text{where } I = \frac{2}{5}MR^2$$

and so $\dfrac{2}{5}MR^2\dot{\omega} = \dot{M}(GMR_M)^{1/2}$

$$\Longrightarrow \dot{\omega} = 2.5\left(\frac{GR_M}{M}\right)^{1/2}\frac{\dot{M}}{R^2} \qquad \text{But } \dot{\omega} = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{2\pi}{\mathrm{P}}\right) = -2\pi\frac{\dot{\mathrm{P}}}{\mathrm{P}^2}$$

$$\text{therefore} \qquad \frac{\dot{P}}{P} = -\frac{2.5\sqrt{G}}{2\pi}P\dot{M}R_M^{1/2}M^{-1/2}R^{-2} \qquad (1)$$

Angular Momentum Transfer

Estimate R_M by equating ram and magnetic pressure.

$$P_B = \frac{B_M^2}{8\pi} = \frac{B^2}{8\pi}\left(\frac{R}{R_M}\right)^6 \qquad \text{assuming } \mathrm{B_M} = \mathrm{B}\left(\frac{\mathrm{R}}{\mathrm{R_M}}\right)^3$$

$$P_{\text{gas}} = \rho v_{\text{in}}^2 = 2\rho\frac{GM}{R_M}$$

For ρ assume $\dot{M}$ uniformly spread over R_M i.e. $\dot{M} = 4\pi R_M^2 \rho v_{\text{in}}$

$$= \frac{2GM}{R_M}.\frac{\dot{M}}{4\pi R_M^2 v_{\text{in}}} \qquad \text{and since } v_{\text{in}}^2 = \frac{2GM}{R_M}$$

$$= \frac{1}{2\pi}\left(\frac{G}{2}\right)^{1/2} M^{1/2}\dot{M}R_M^{-5/2}$$

Equating P_{gas} to $P_B \longrightarrow$

$$R_M = 2^{-3/7}G^{-1/7}\left\{\frac{B^2R^6}{\dot{M}M^{1/2}}\right\}^{2/7}$$

Spin Up of Accreting Neutron Star

substitute back into (1) $\longrightarrow$

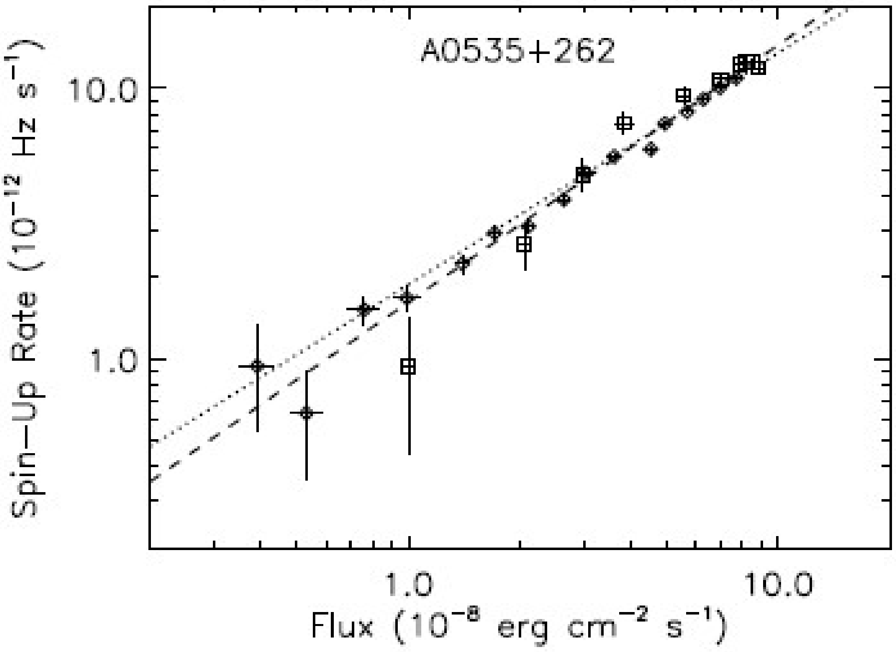
$$\frac{\dot{P}}{P} = -\frac{2.5\sqrt{G}}{2\pi} P \dot{M}^{6/7} 2^{-3/14} G^{-1/14} \left\{ \frac{B^2 R^6}{M^{1/2}} \right\}^{1/7} M^{-1/2} R^{-2}$$

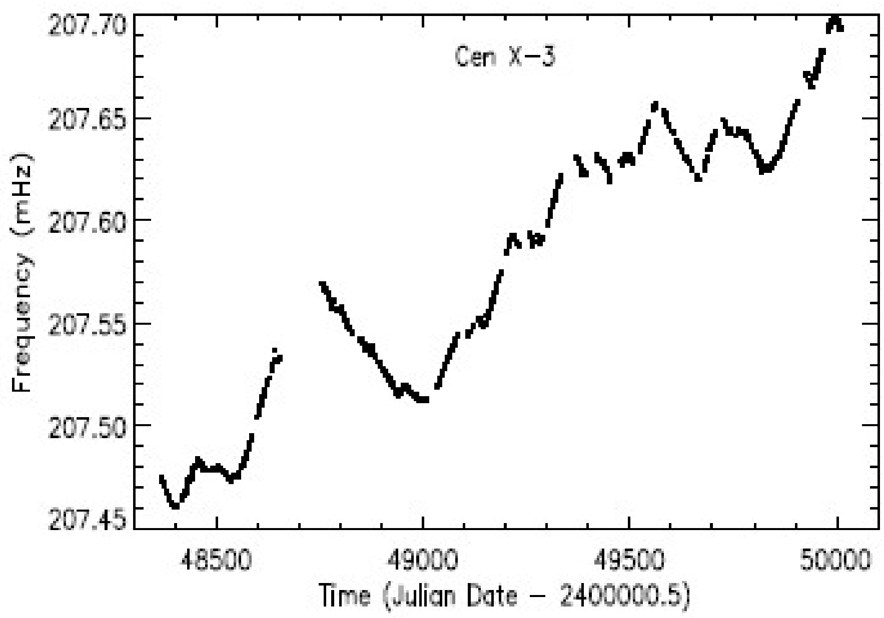
and since $L_x = \dfrac{G M \dot{M}}{R}$ then

$$\boxed{\frac{\dot{P}}{P} = -\frac{2.5}{2\pi} \frac{2^{-3/14}}{G^{3/7}} P L_x^{4/7} M^{-10/7} B^{2/7} R^{-2/7}}$$

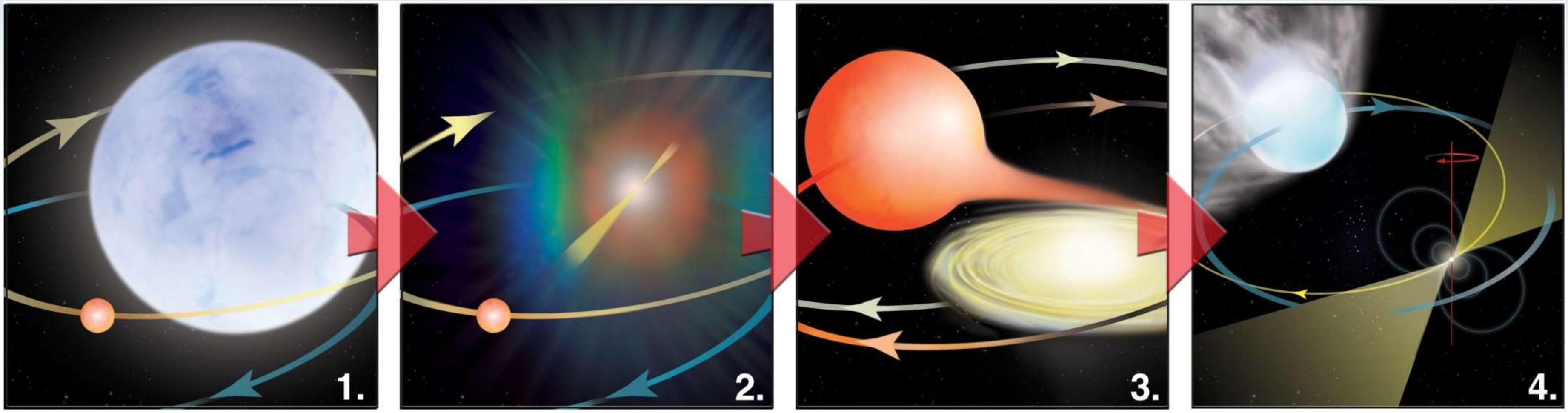
$$\text{or } -\frac{P}{\dot{P}} = 49 \left(\frac{200 \text{ s}}{P} \right) \left(\frac{10^{37} \text{ erg s}^{-1}}{L_x} \right)^{6/7} \left(\frac{M}{M_\odot} \right)^{10/7} \left(\frac{10^{12} G}{B} \right)^{2/7} \left(\frac{R}{10 \text{ km}} \right)^{2/7} \text{yrs}$$

X-ray pulsars spinning up "steadily"





Progenitors of Millisecond pulsars



The quest for spin frequencies of LMXB

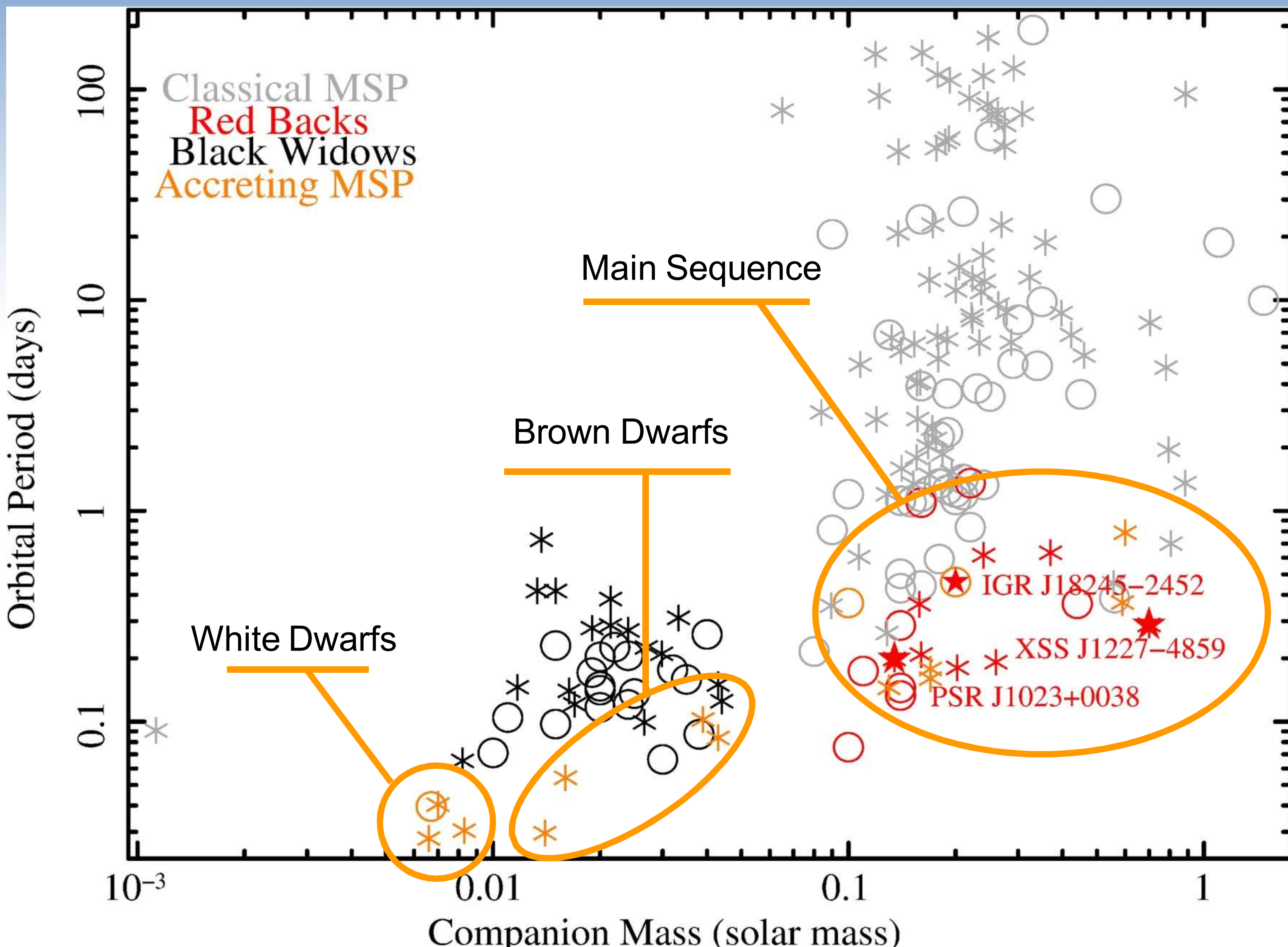
No pulsating Low mass X-ray binary known for decades

$$P \sim N_\gamma A^2 \sim A_{eff} T_{obs} L_{source} A^2_{sky}$$

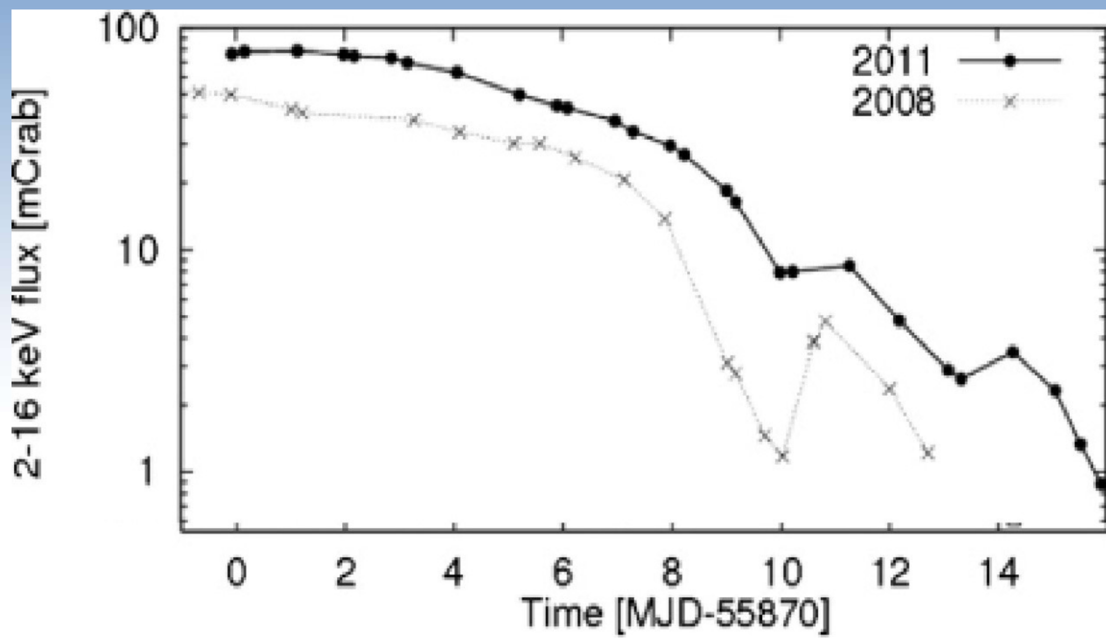
T_{obs} limited by orbital Doppler shifts in LMXB
(P_{orb} < 1 day)

1998 - Rossi X-ray Timing Explorer
- proportional counters A~6250 cm^2
- time resolution ~ 1 μs
- energy range 2-60 keV

Binary properties of accreting millisec pulsars



Accretion driven X-ray emission



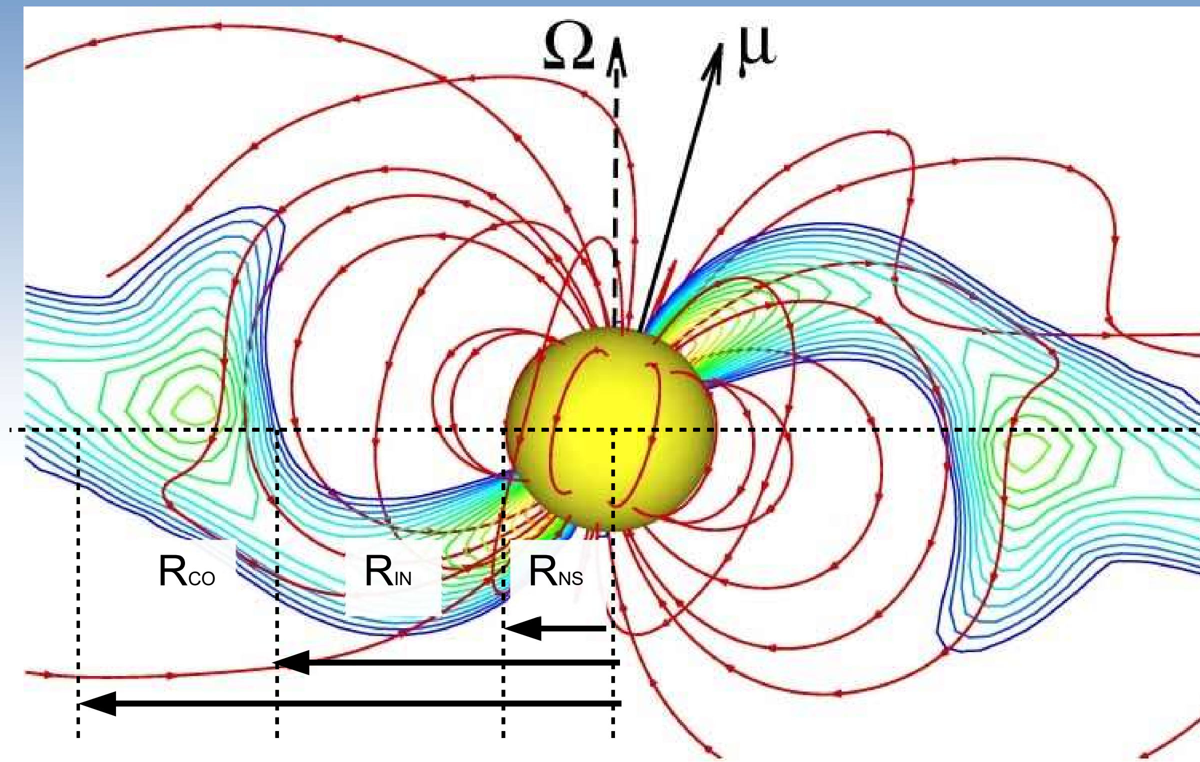
All AMSPs are X-ray transients

Peak X-ray luminosity ~ few x 10^{36} erg/s ~ 0.01 Eddington rate

Outburst duration ~ a few weeks/months

Pulsations detected down to ~10^{35} erg/s

Magnetic field estimate

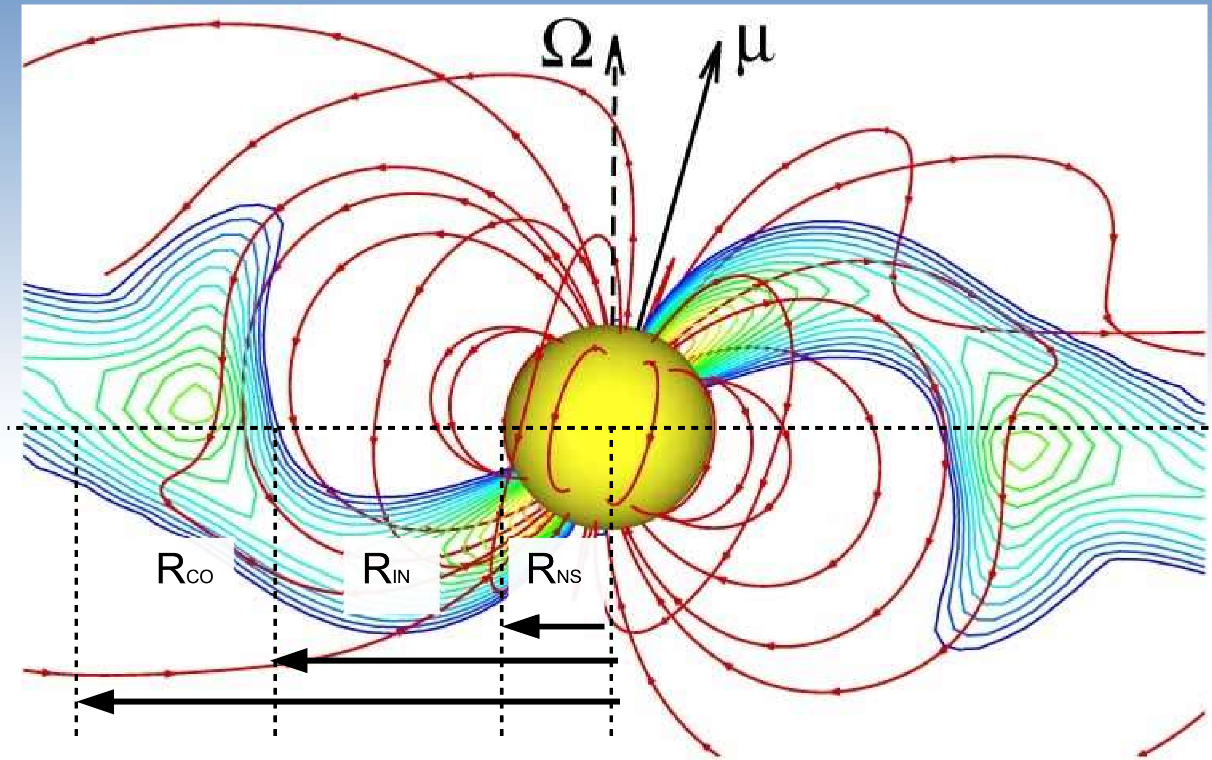


Corotation radius – Rco = 35 $(P/3ms)^{-2/3}$ km
Inner disk radius – Rin ~ $[\mu^4/2\ GM\ (dM/dt)^2] \sim \mu^4/L_X$ 2

To have Rco ≥ Rin ≥ Rns for $L_X \sim 10^{36}$ erg/s → $\mu = 10^{26}$-10^{27} G cm^3

B_{ns} = 10^8-10^9 G

Why so few AMSPs?

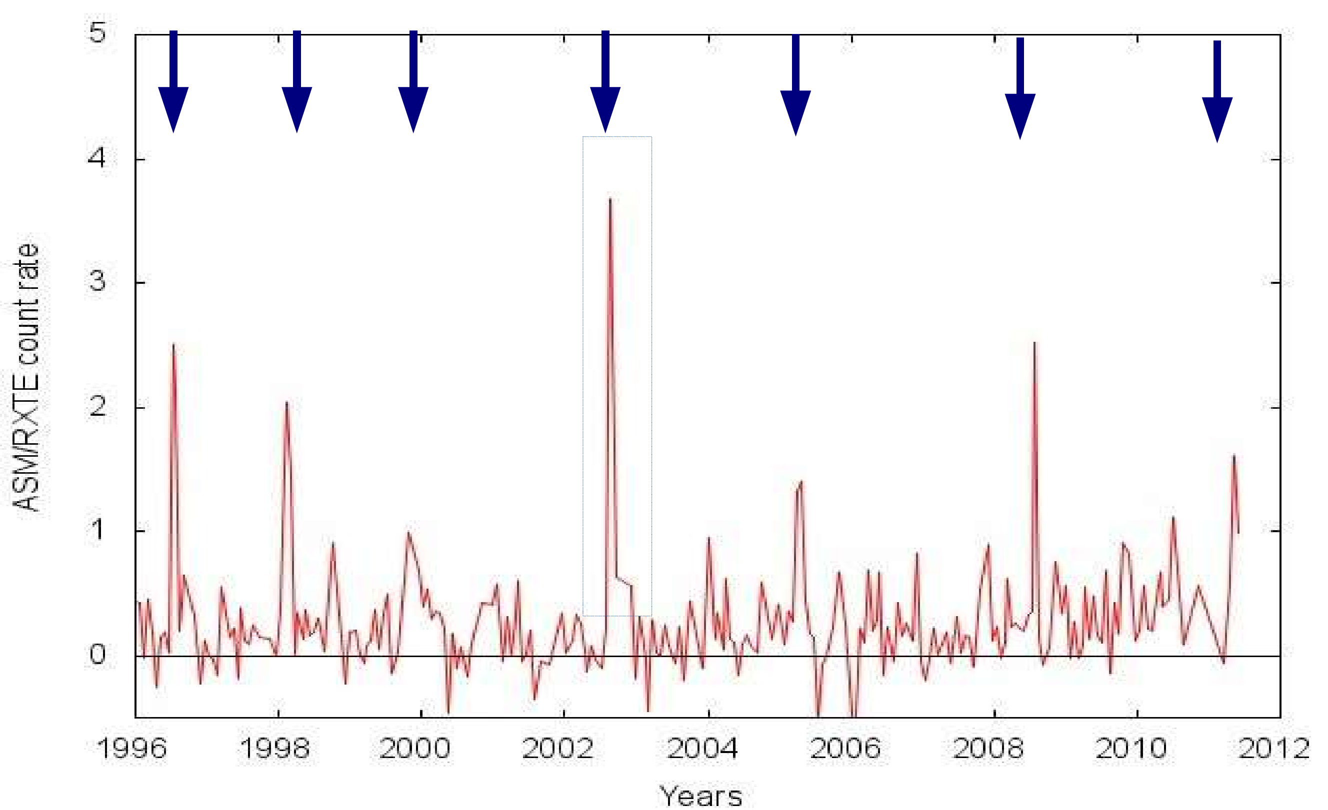


Inner disk radius – Rin ~ [μ^4/G M $(dM/dt)^2$] ~ μ^4/L_X^2

At a larger mass accretion rate (X-ray luminosity):

- the disk extends down to the NS surface
- the field is screened by accreting unmagnetized matter [Cumming+ 2008]
- Rayleigh-Taylor instabilities allow equatorial accretion [Romanova+ 2007]

Recurrence times



SAX J1808.4-3658 – one outburst every ~2.5 years (one more in 2015)

Other systems seen only once in ~15 years

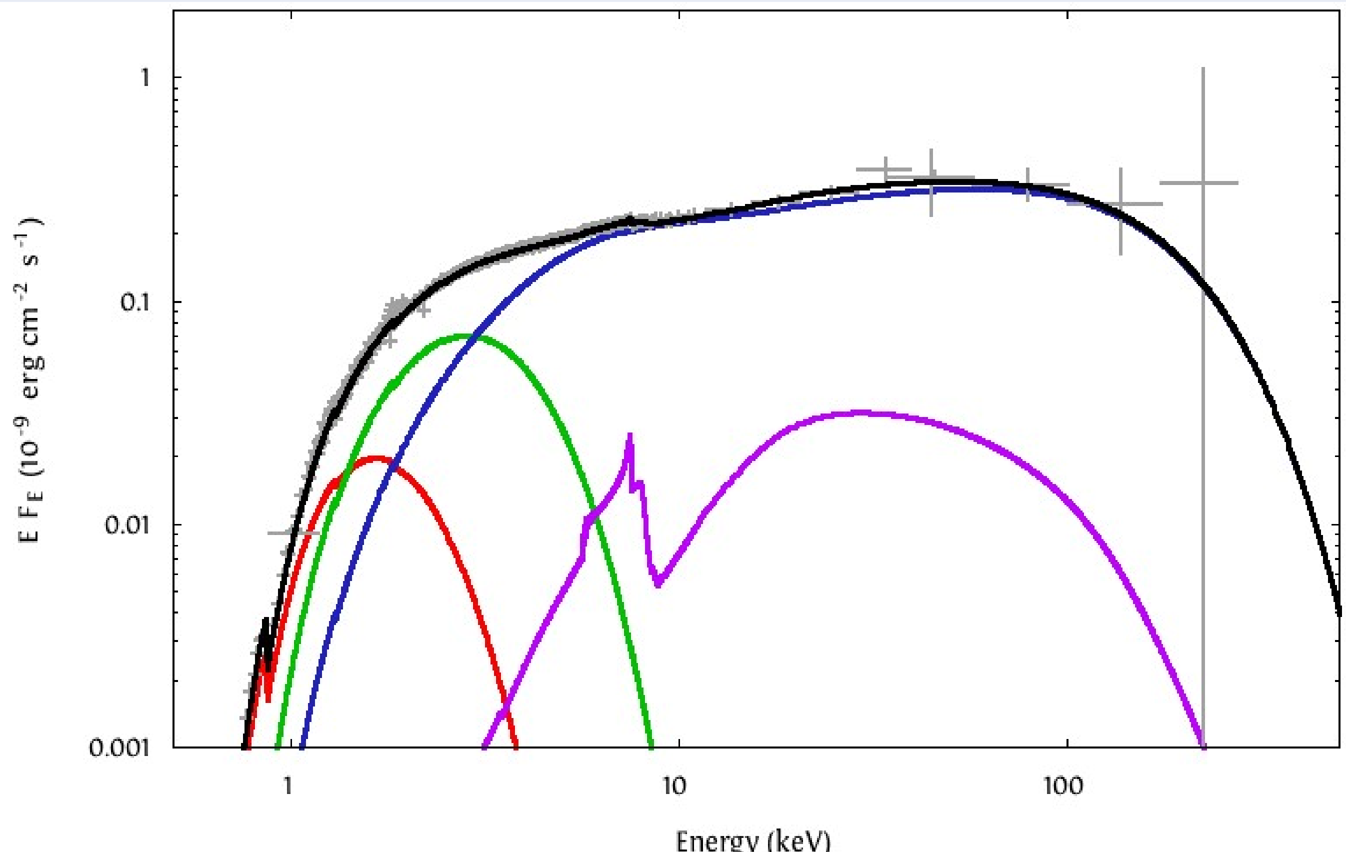
X-ray Spectral properties

AMSPs are always in a hard state.

Cut-off above ~50 keV

One or two thermal components detected below 1 keV

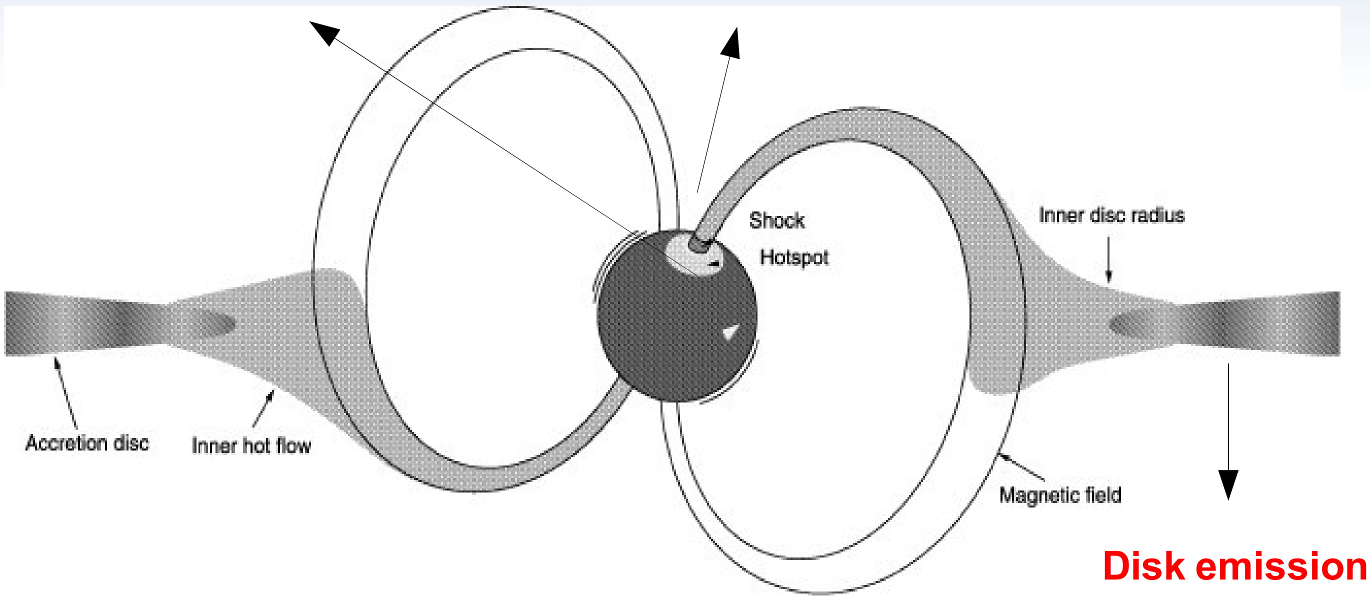
Signature of disk reflection component



Model

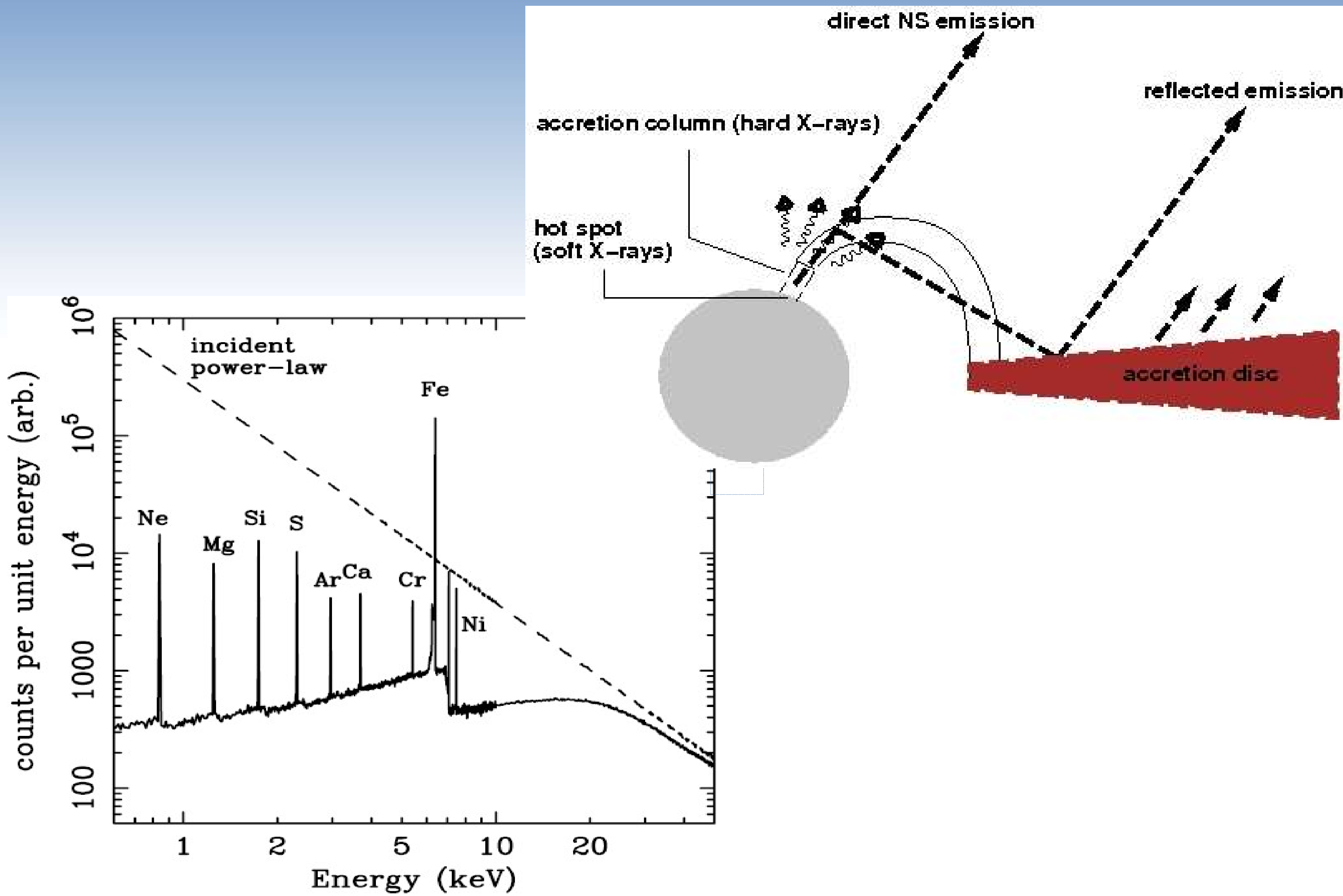
Hot spots – Reprocessing of the Irradiating hard photons into thermal radiation

Accretion Column – Accreting plasma heated above NS surface → Comptonization of soft photons from the surface



Such a picture not only best fits the observed spectra, but also explains the spectral properties of the pulse profiles [Gierlinski, Done & Barret 2002, Gierlinski+ 2005, Falanga+ 2005, Papitto+ 2010]

Reflection component

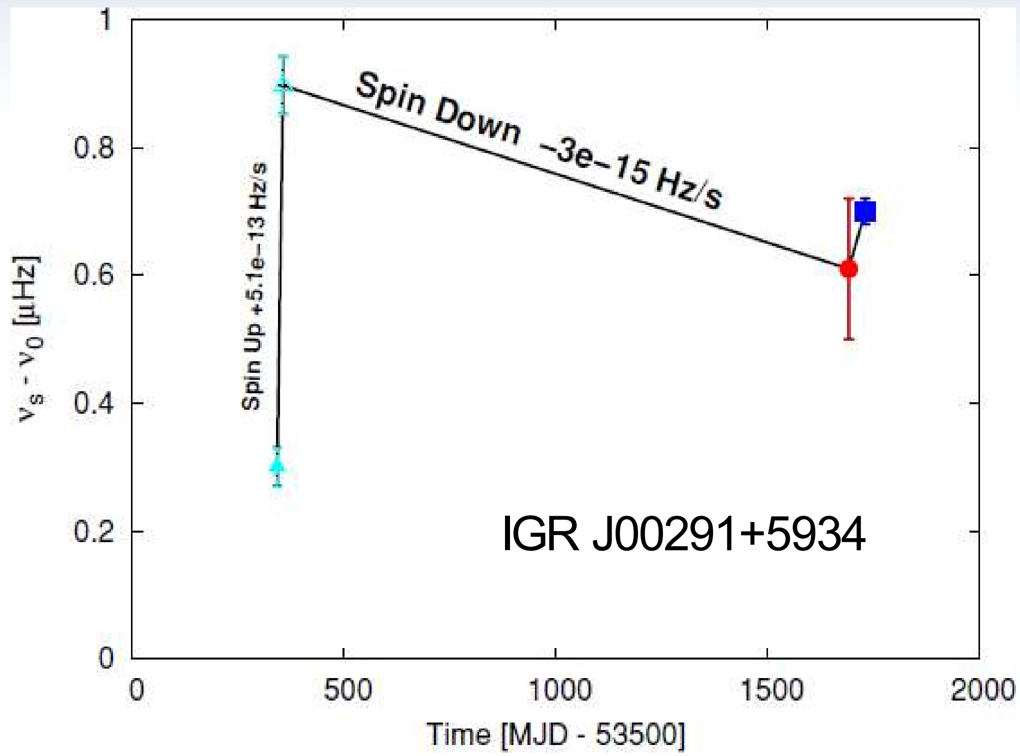


Spin evolution during quiescence

Spin down at a rate comparable to rotation powered ms radio pulsars

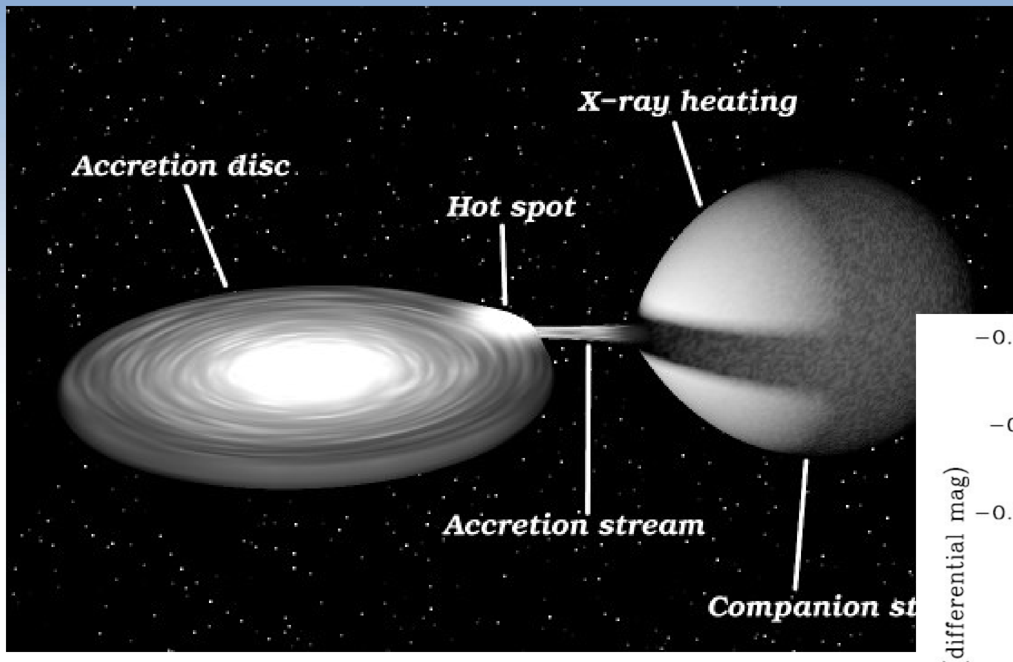
Used to set tight upper limits on NS mass quadrupole & GW emission rate ($Q<10^{36}$ g cm^2)

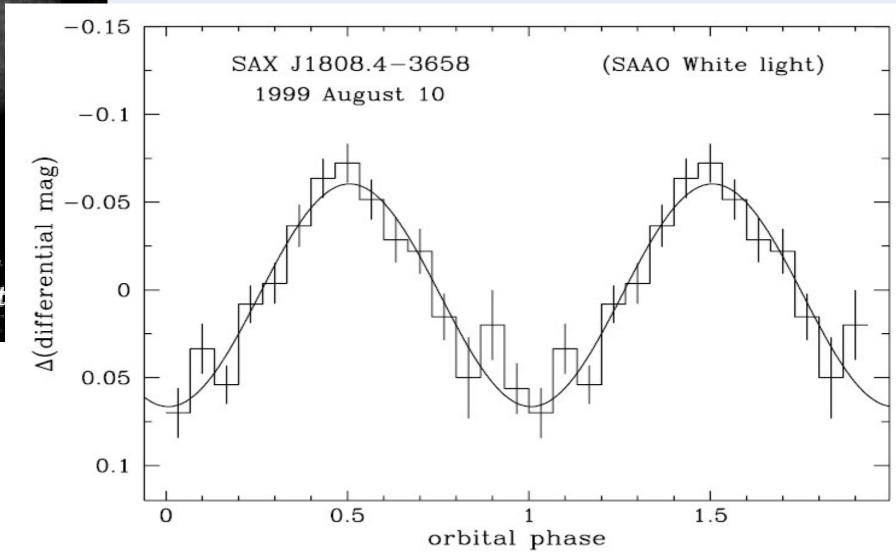
→ AMSPs unlikely to be detected by current generation of GW detectors (→ Einstein Telescope)



[Hartman+2008; Hartman+2009; Papitto+ 2010; Hartman+ 2010]

Irradiation of the companion

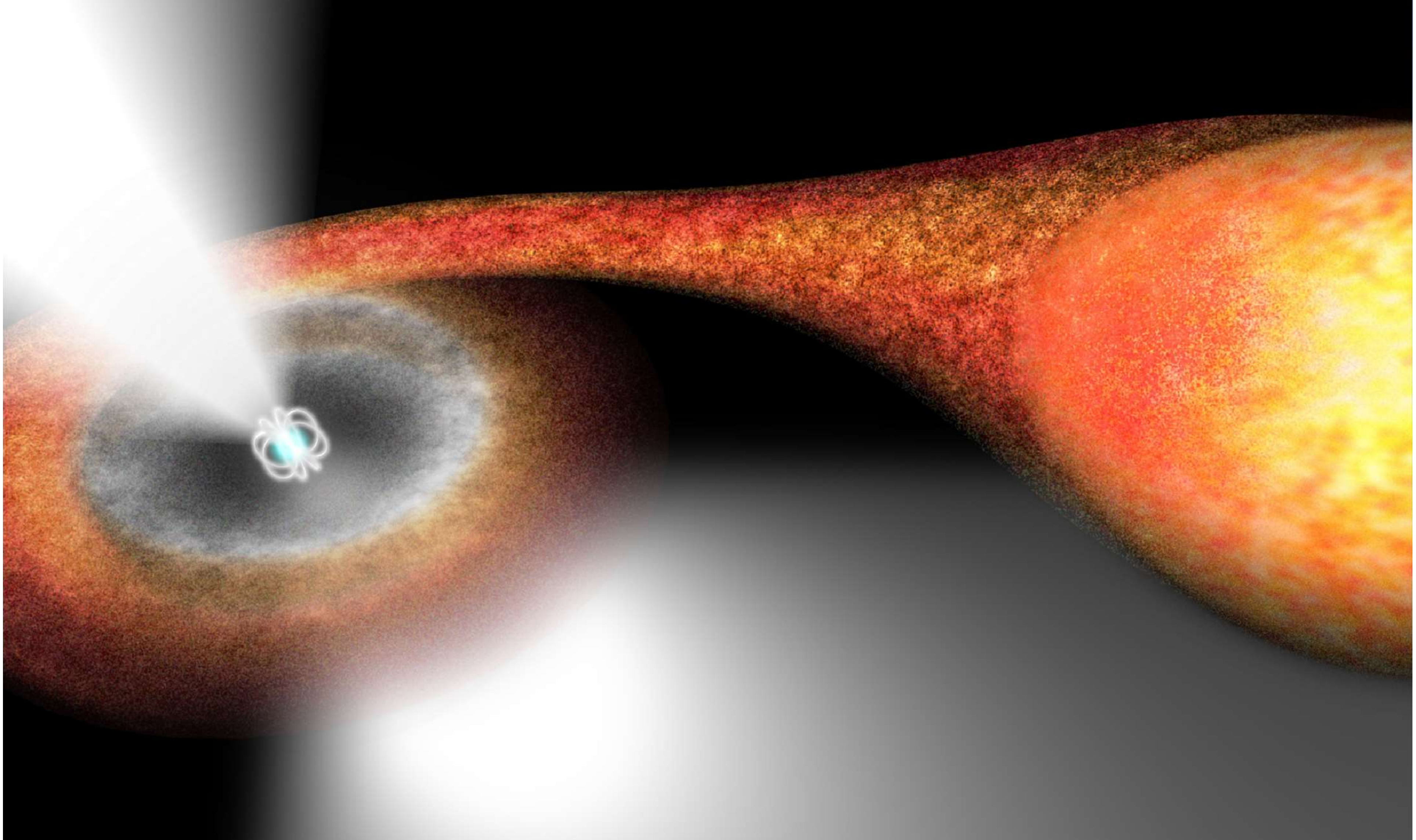




The spin down power of a radio pulsar illuminates the companion

[Burderi+2003; Campana+2004, D'Avanzo+ 2009,2011; Cornelisse+ 2009]

Transitional Millisecond Pulsars in LMXBs

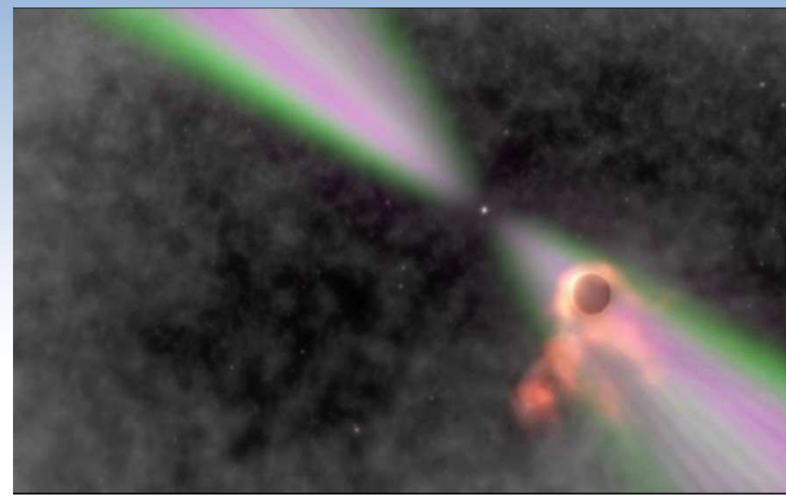


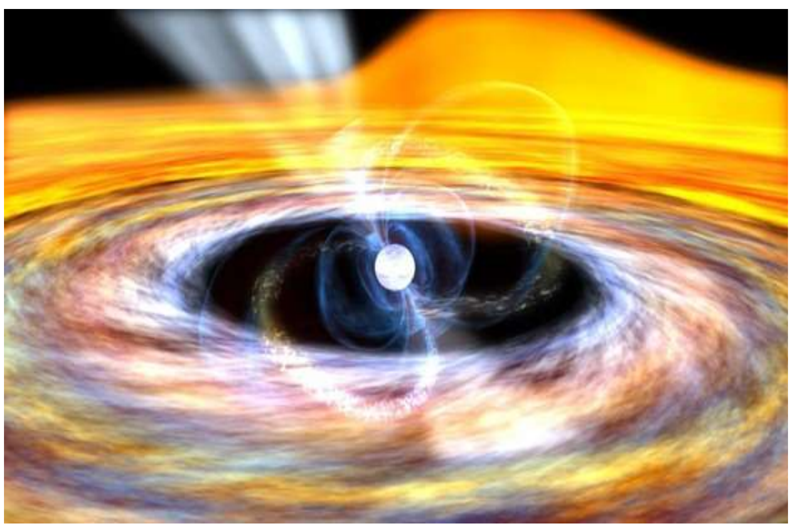
Swinging between accretion and rotation power

Mass in-flow rate drives the variability

Low Mass in-flow rate: Magnetic field dominates

→ rotation powered **Radio PSR**





High Mass in-flow rate: Gravity dominates

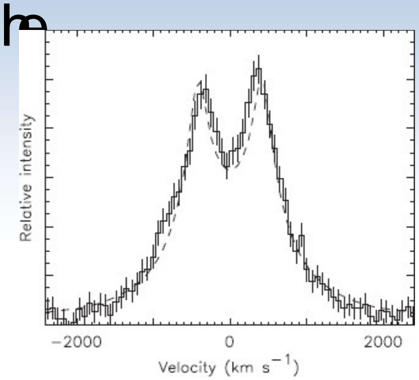
→ accretion powered **X-ray PSR**

Prototype: PSR J1023+0038

2000-01

Accretion disk

H a line



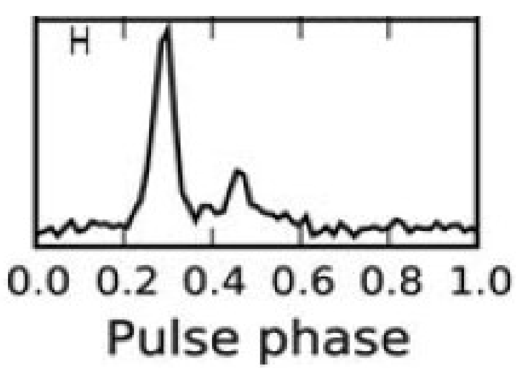
2009-13

Radio PSR (d=1.4kpc; P=1.7ms)

Irregular eclipses (a redback)

Also a gamma-ray pulsar

[Archibald+ 2009, Science]



2013 ...

Accretion disk Ha line

Brighter in X-rays and γ-rays (few x 10^{33} erg/s)

No radio pulses

[Patruno+ 2014, Stappers+ 2014, Bogdanov+ 2015]

XSS J12270-4859

2003-13

Accretion disk Hα line

X-rays (few x 10^{33} erg/s)

γ-rays (few x 10^{33} erg/s)

[De Martino+2010,2013; Saitou+2010; Hill+2011]

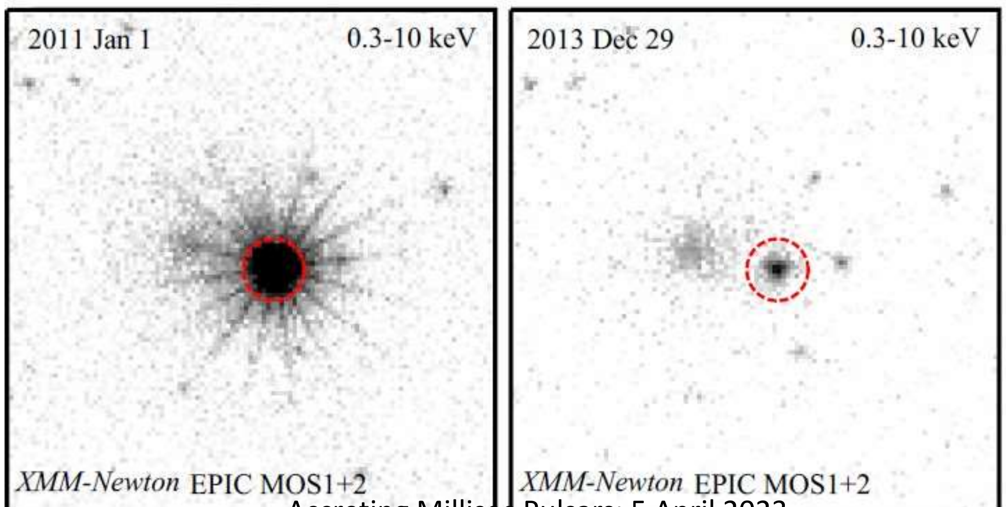
2013 ...

Radio PSR (P=1.7ms)

Irregular eclipses (a redback)

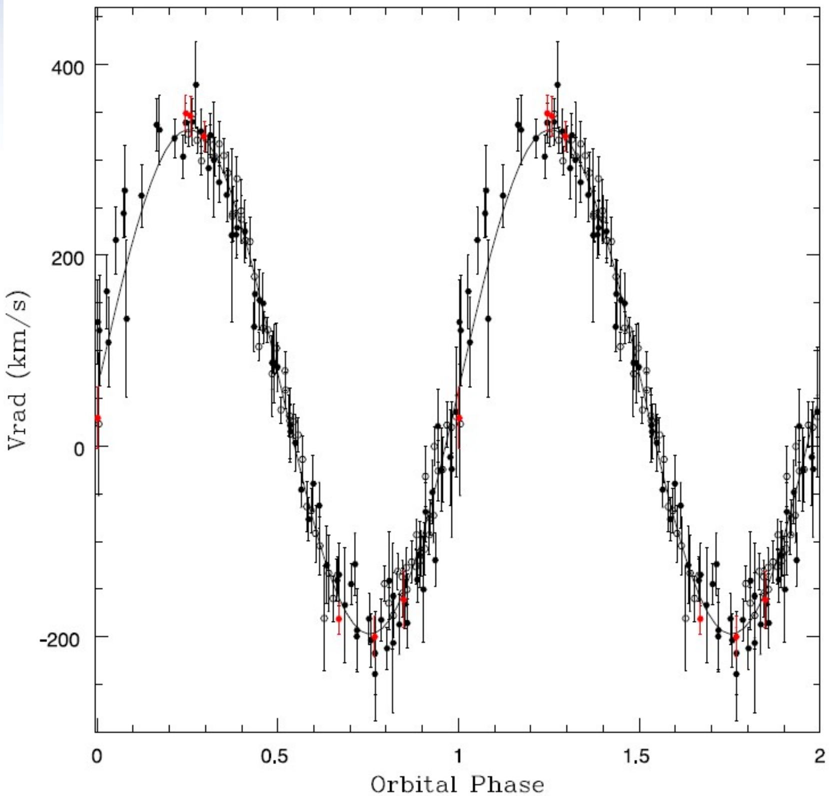
Also a gamma-ray pulsar

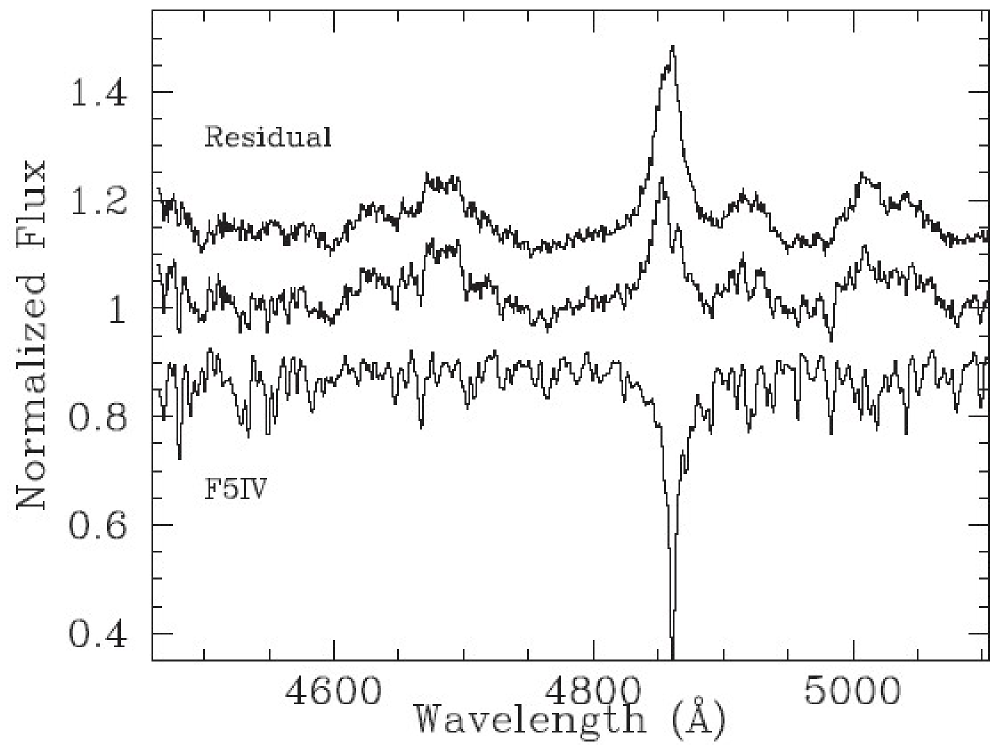
[Bassa+2014, Bogdanov+2014, Roy+ 2014]



XSS J12270-4859

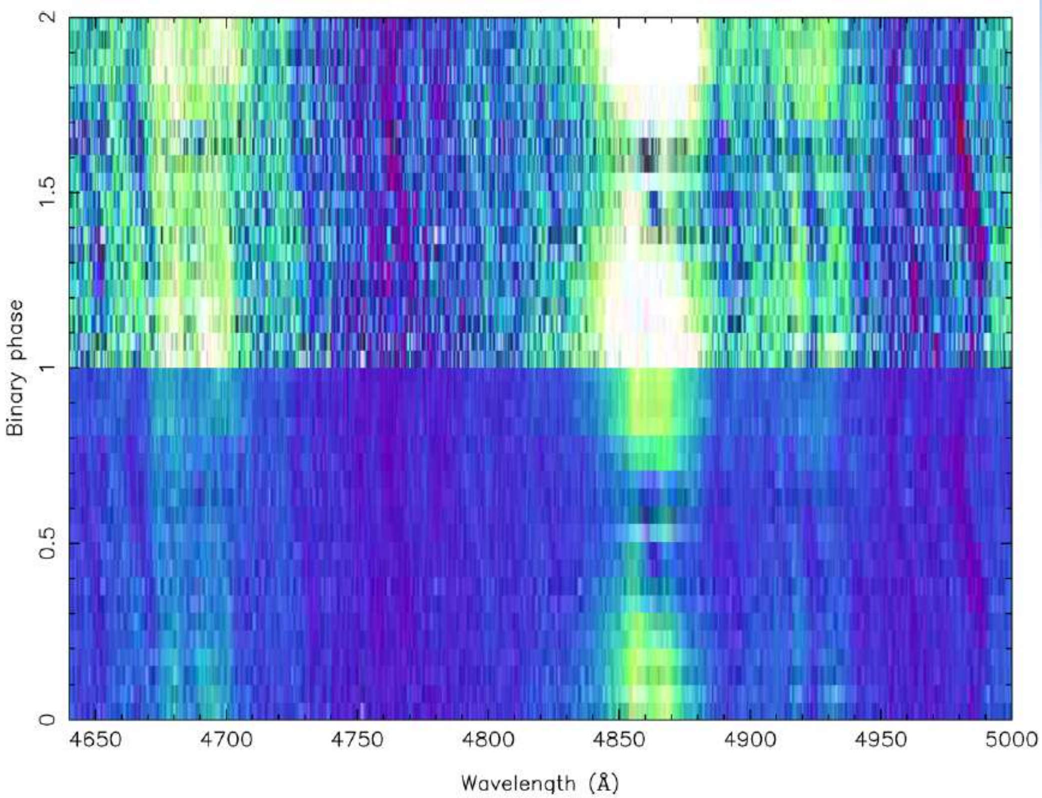
- 2012 observing campaign (SAAO/SALT, ESO)
  - Spectroscopy & photometry
- Radial velocity curve => 6.9 h orbital period
- F-type companion (under massive at 0.06 – 0.12 $M_{\odot}$)

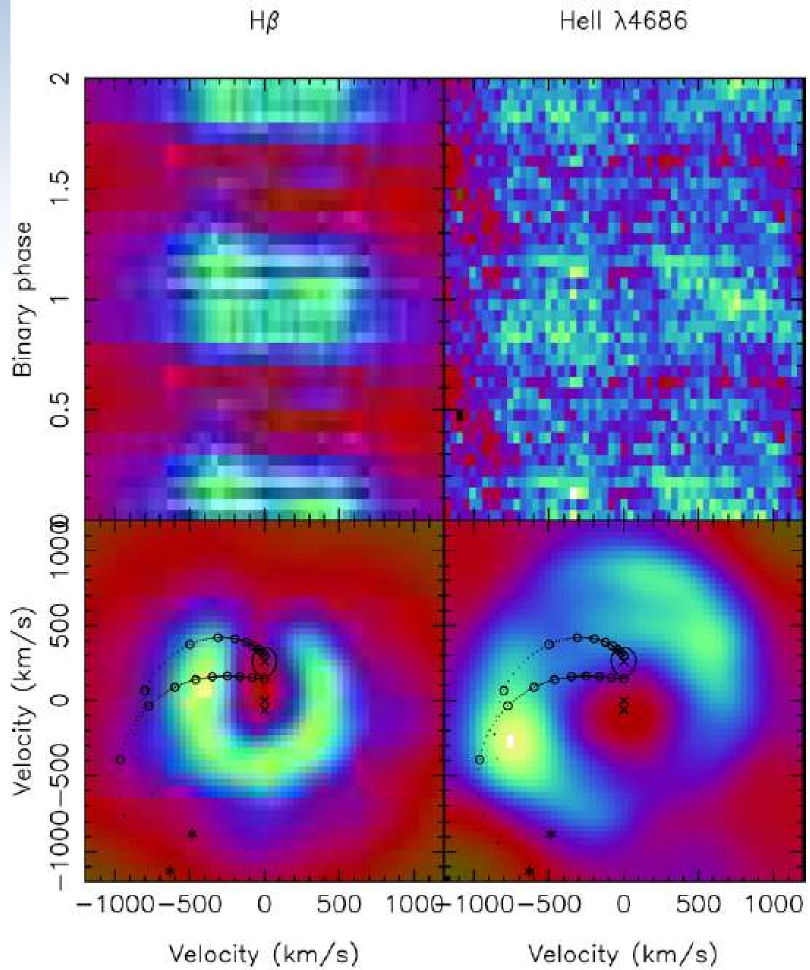




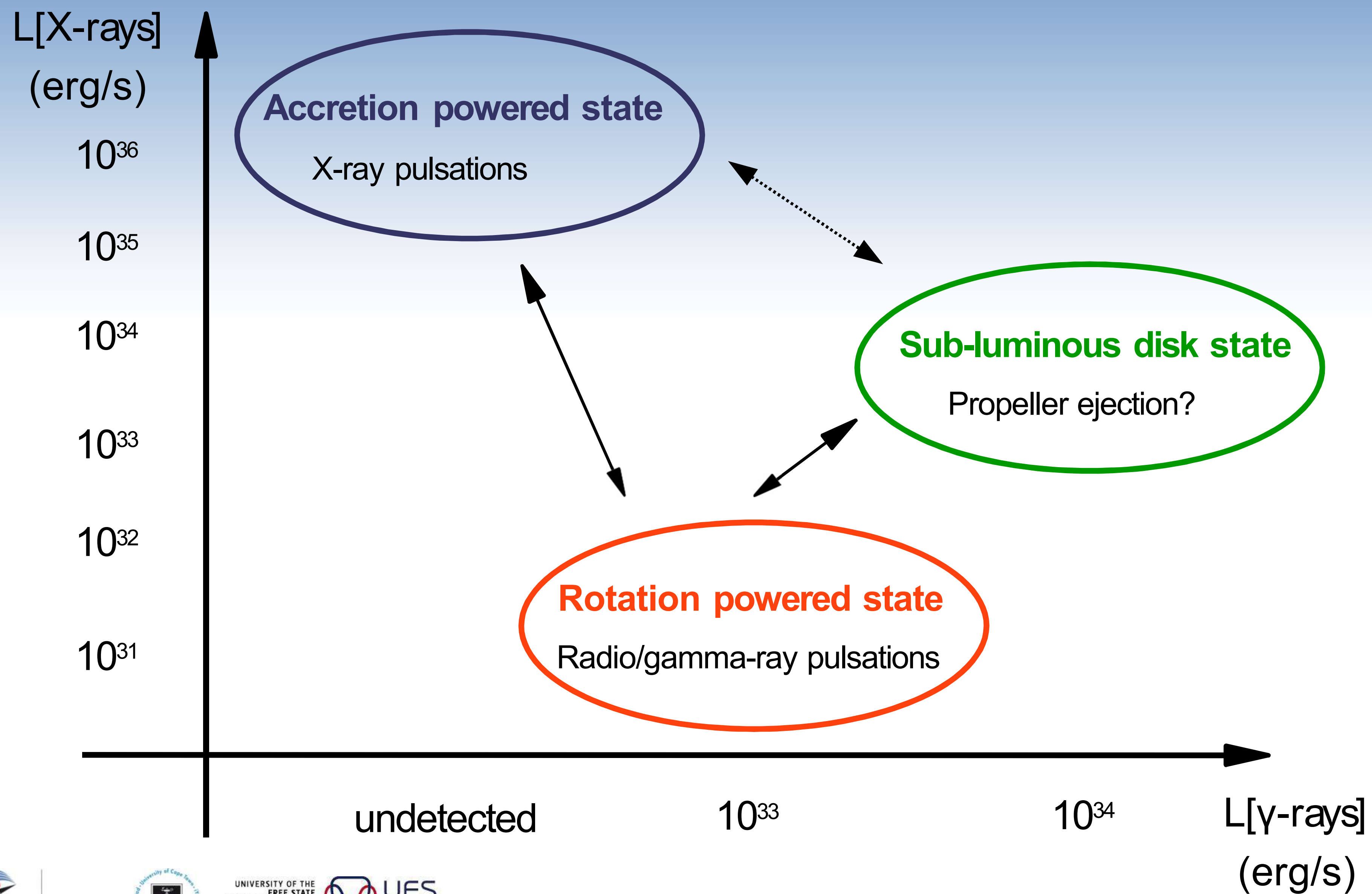
XSS J12270-4859

- Doppler tomography => accretion disk





The three states of transitional ms pulsars



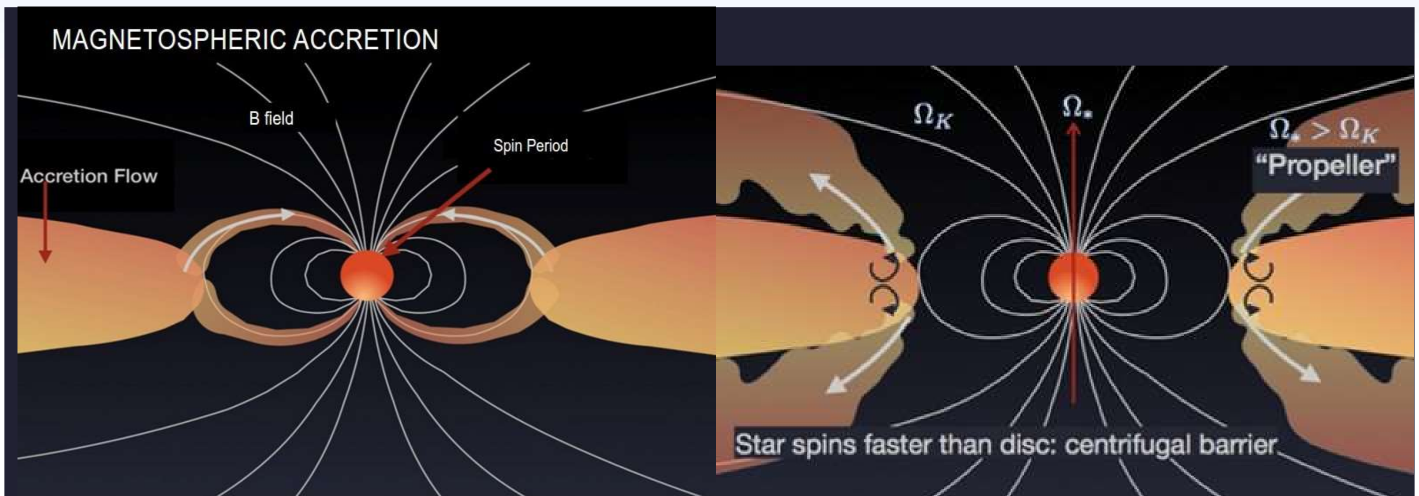
The enigma of the sub-luminous disk state

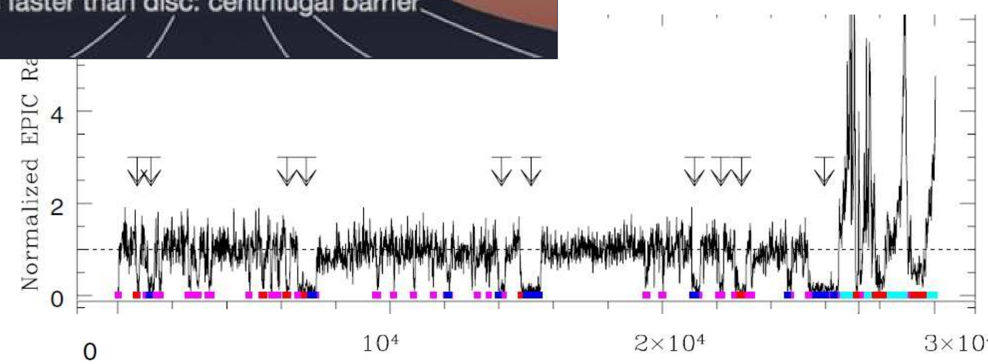
X-rays (L_X~$5x10^{33}$ erg/s)

Fainter than during outburst (→ propeller inhibition of accretion)

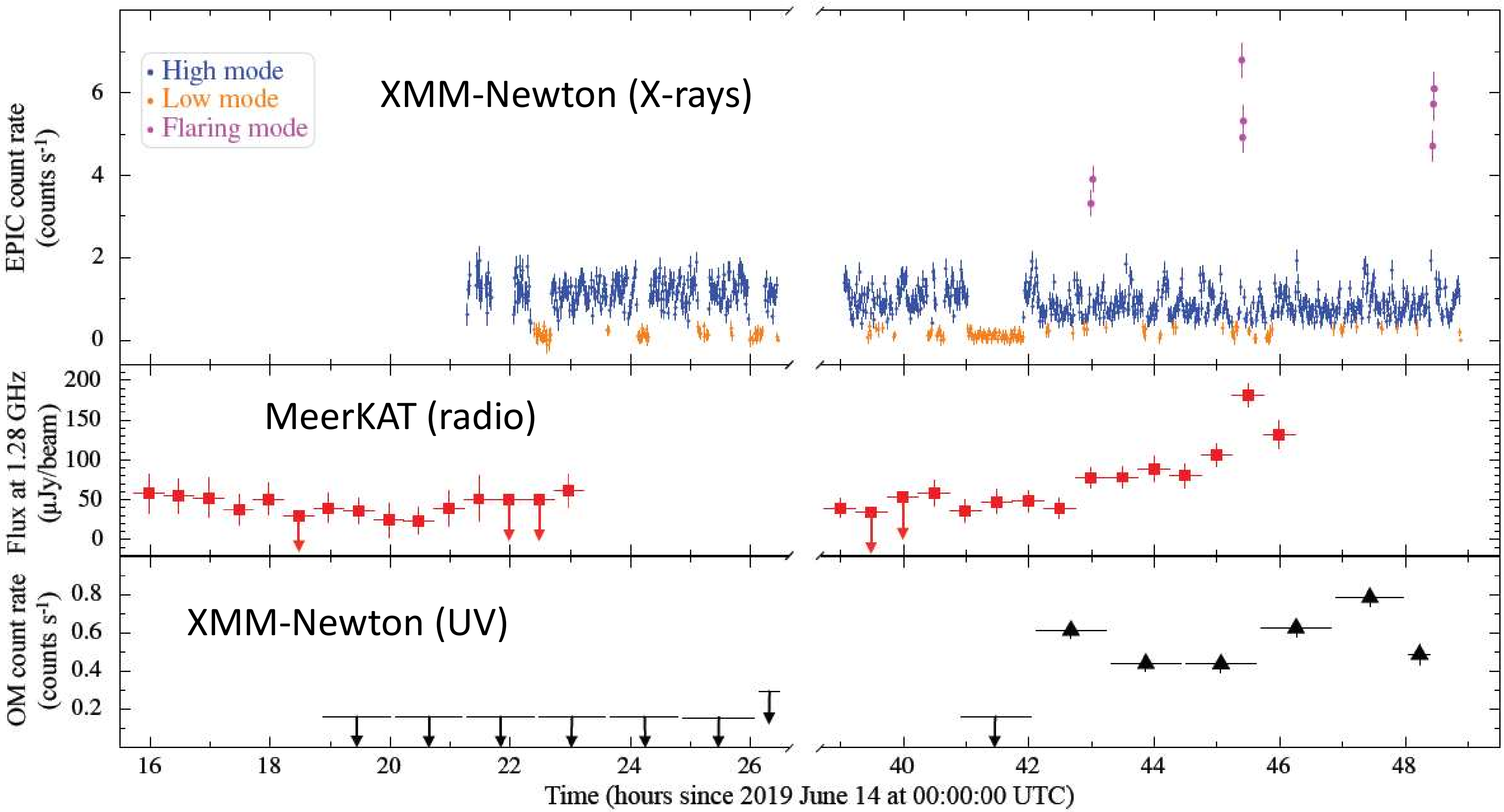
Peculiar variability [e.g. de Martino+ 2011, Ferrigno+ 2014, Bogdanov 2015]

Accretion powered X-ray pulsations [Archibald+ 2015, Papitto+ 2015]

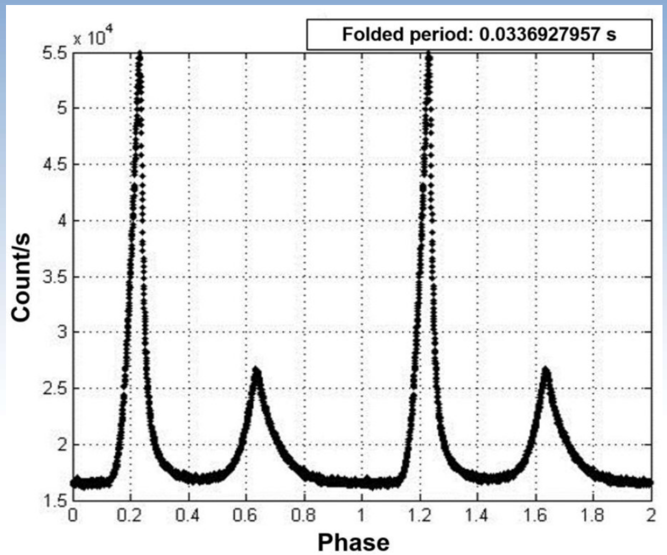




Recent observations of a new tMSP candidate CXOU J1109-6502



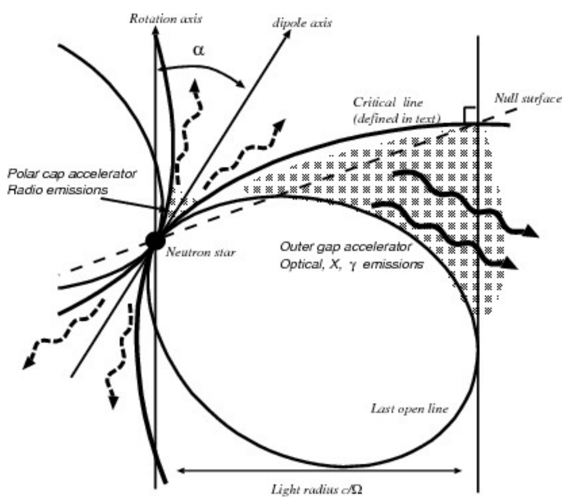
Rotationally-powered optical pulsations

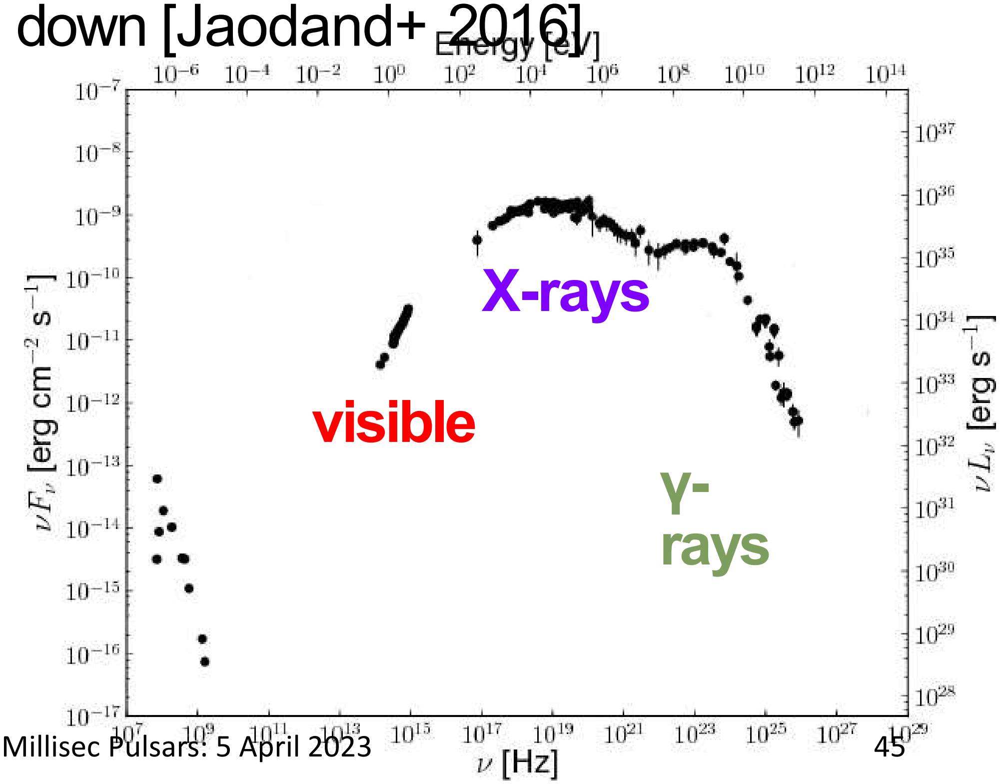


e.g the Crab PSR →

Synchrotron emission of ~ MeV electrons

Compatible with the observed spin-down [Jaodand+ 2016]





References: Rotation and accretion powered millisecond pulsars

Millisecond pulsars

- Lorimer 2008, https://arxiv.org/abs/0811.0762
- Kramer 2004, https://arxiv.org/pdf/astro-ph/0405178.pdf

Recycling scenario

- Verbunt ARA&A 1993, 31, 93
- Tauris & van den Heuvel 2003, astro-ph:0303456
- Bhattacharya & van den Heuvel 1991, Phys. Rep, 1, 124

Accreting ms pulsars

- Patruno & Watts 2012, arXiv:1206.2727
- Campana & Di Salvo 2018, arXiv: 1804.03422
- Di Salvo & Sanna 2020 arXiv: 2010.09005

Transitional ms pulsars

- Archibald et al. 2009, Science, arXiv:0905.3397
- Papitto et al. 2013, Nature, arXiv:1305.3884
- Papitto & de Martino 2020, arXiv: 2010.09060

Reference: White Dwarf pulsars

- Marsh, T. R. *et al*. A radio-pulsing white dwarf binary star. *Nature* ***537,*** 374–377 (2016). https://ui.adsabs.harvard.edu/link_gateway/2016Natur.537..374M/arxiv:1607.08265

- Buckley, D.A.H. *et al.* Polarimetric evidence of a white dwarf pulsar in the binary system AR Scorpii, *Nature Ast.,* ***1****,* 0029 (2017) *https://ui.adsabs.harvard.edu/link_gateway/2017NatAs...1E..29B/doi:10.1038/s41550-016-0029*

- Potter, S.B & Buckley, D.A.H. Time series photopolarimetry and modelling of the white dwarf pulsar in AR Scorpii, *MNRAS*, **418**, 2384 (2018). https://ui.adsabs.harvard.edu/link_gateway/2018MNRAS.481.2384P/arxiv:1809.01884

Acknowledgements

Some of these slides were provided courtesy of Tariq Shabhaz (IAC) & Alessandro Papitto (INAF)