Magnetosfere di stelle di neutroni in accrescimento e di magnetars

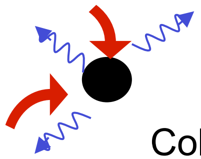
Luigi Stella

INAF – Osservatorio Astronomico di Roma

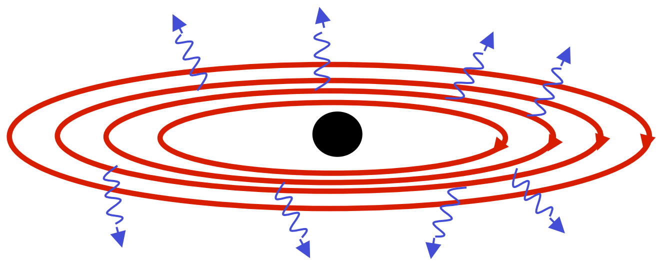
Accretion into collapsed objects

Matter accretion toward collapsed stars:

→ Energy production with high efficiency!



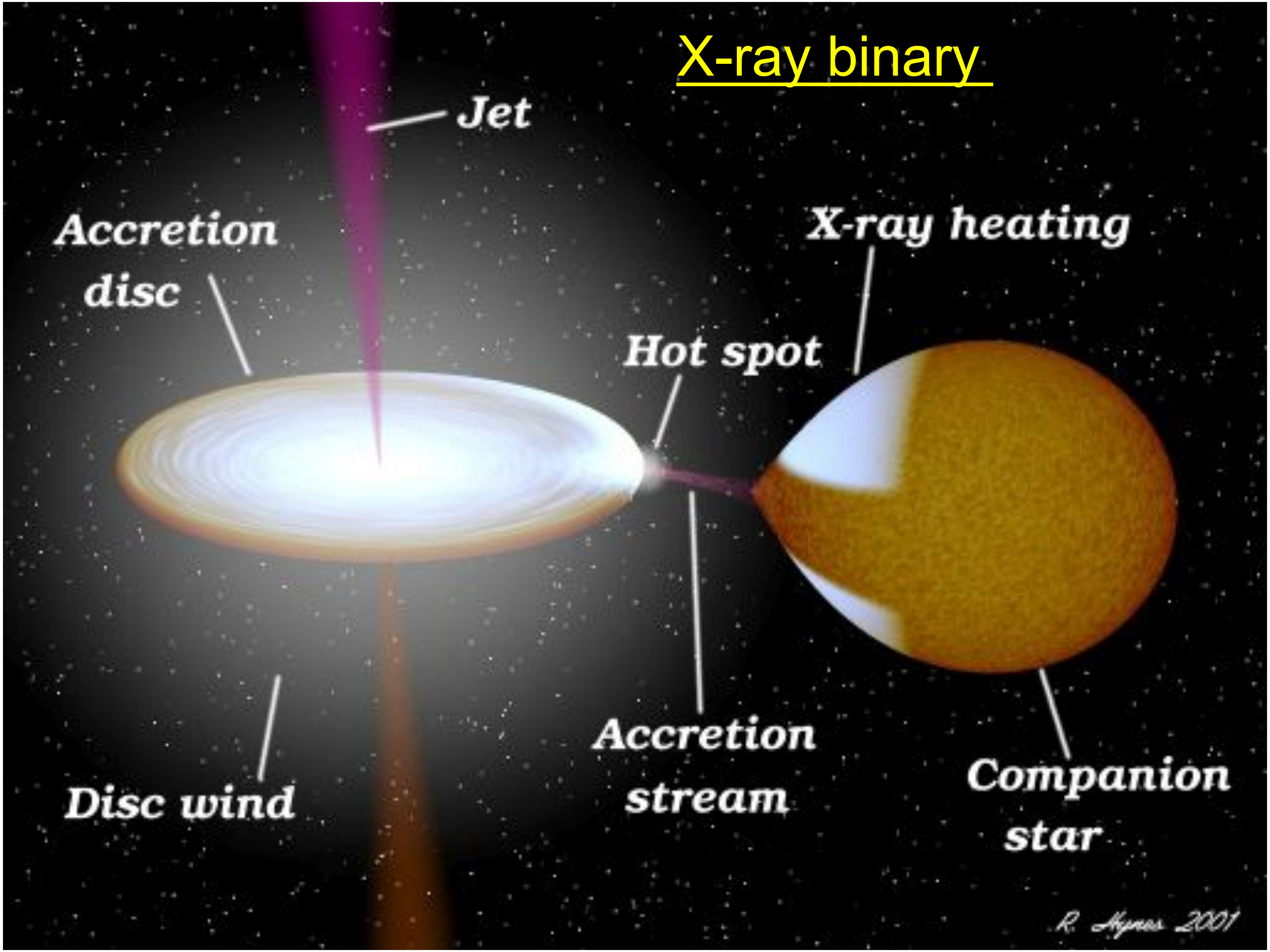
If matter has enough $\vec{L}$ an accretion disk forms:



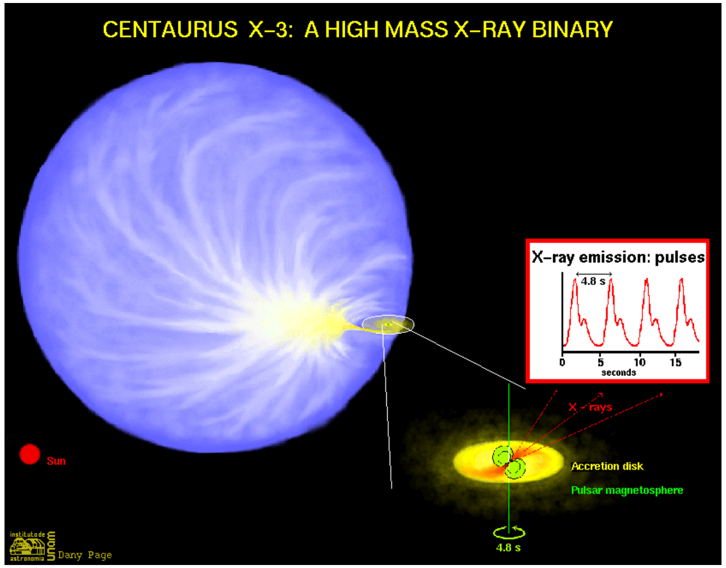
efficiency: ~ 0.1 – 0.5

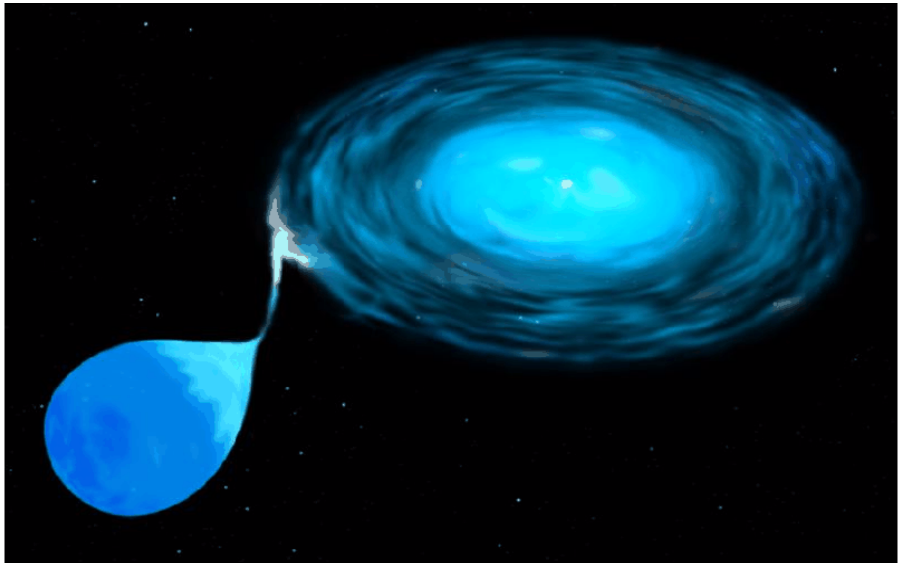
Regions of strong gravitational field accessible to study.

Systems are not "clean": a variety of effects (plasma, radiative transfer, fluidodynamics, MHD) complicate matters.


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

High Mass XRB vs. Low Mass XRB





- HMXB : companion mass $M_2 > M_\odot$
- Luminous, young, early type (O, B)
- Stellar wind fed systems
- Often contains an X-ray pulsar

- LMXB : companion mass $M_2 \leq M_\odot$
- Faint, old, late spectral type (K, M)
- Roche-Lobe / Disk fed systems
- Often transient system

ALSO

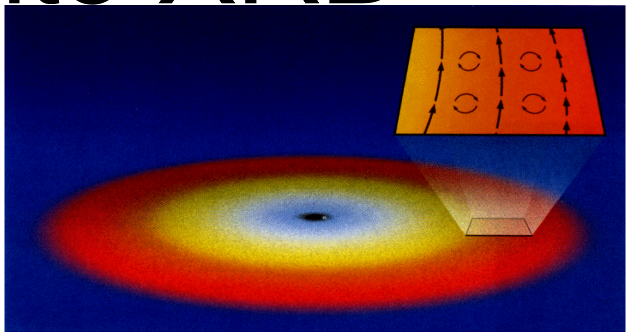
Neutron Star XRB vs. Black Hole XRB

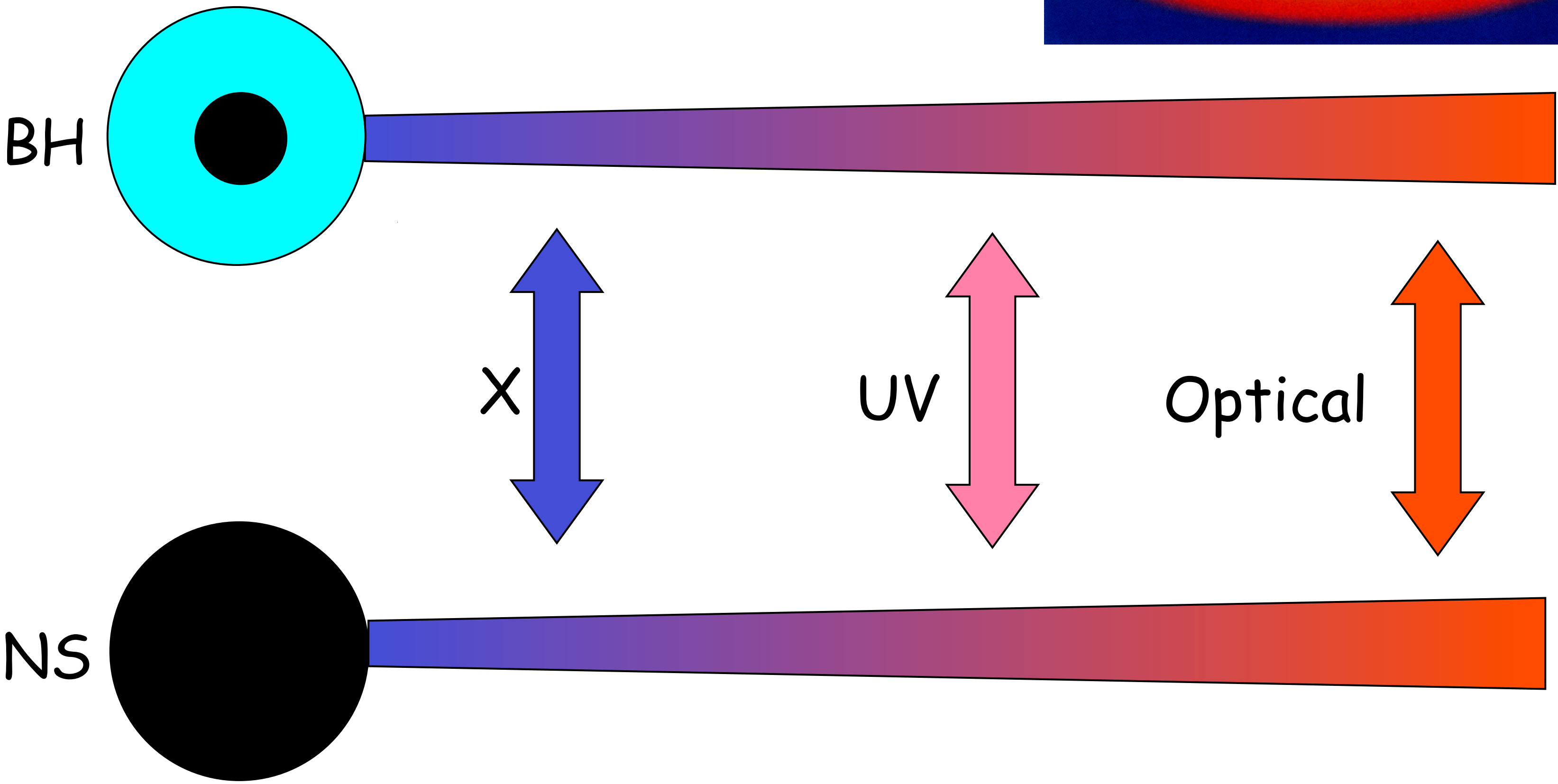
Disk accretion onto XRB

Accretion disk structure

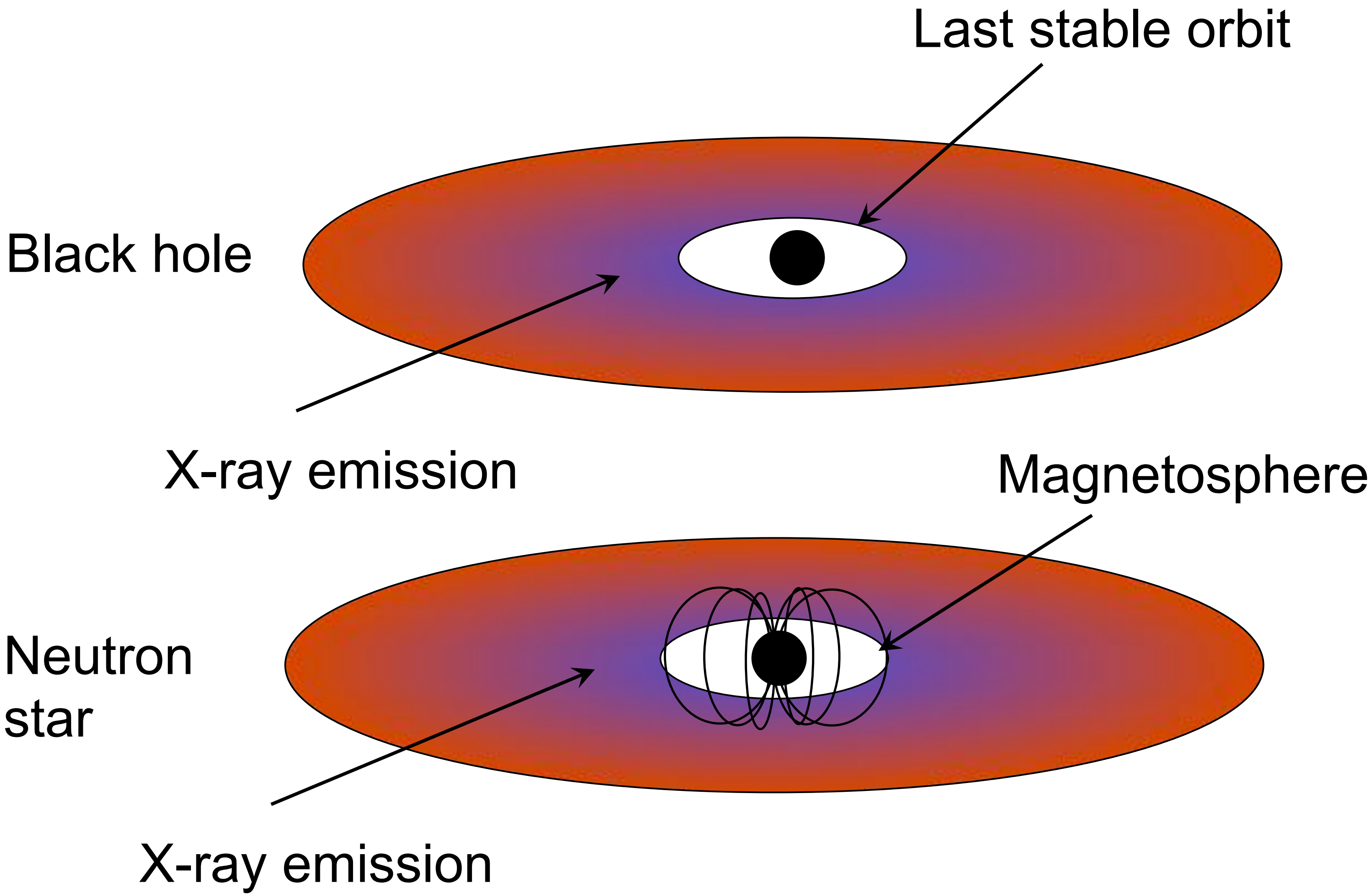
No ordered B field in BH

BH or NS?



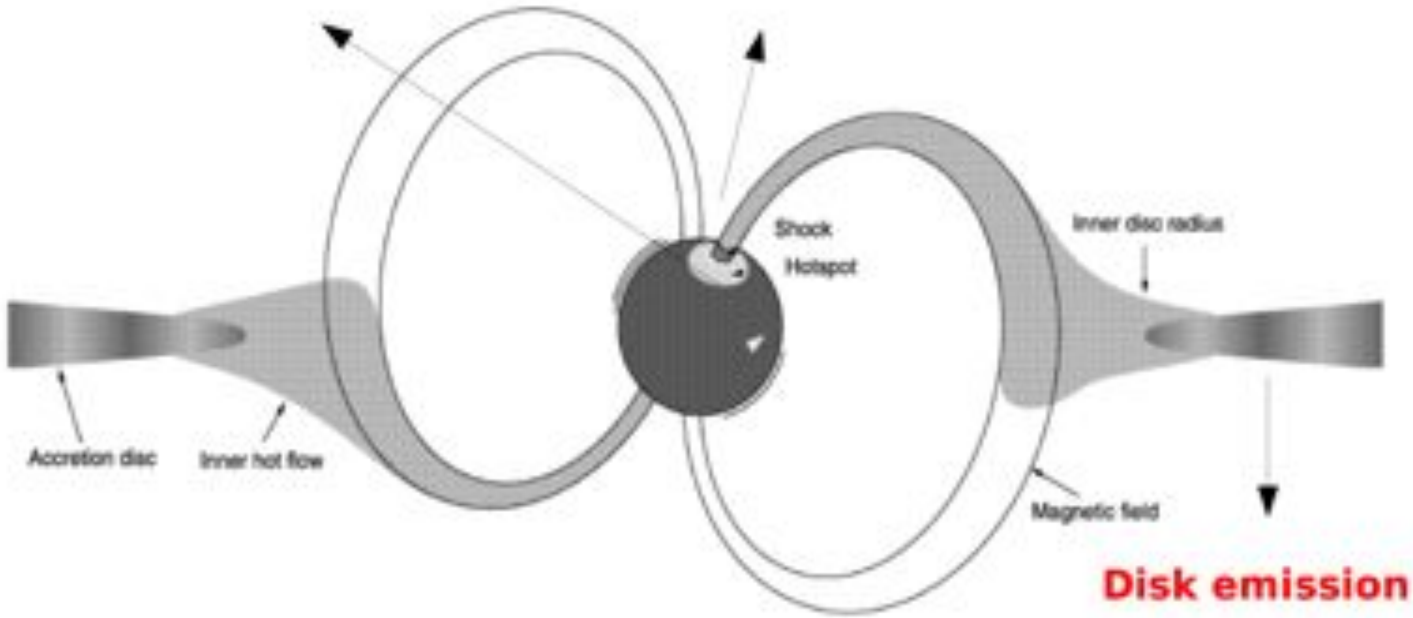


BH vs. NS


Last stable orbit
Black hole
X-ray emission
Magnetosphere
Neutron star
X-ray emission

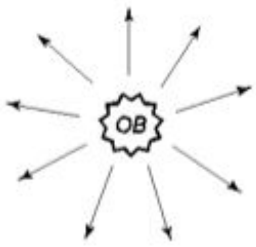
Hot spots – Reprocessing of the Irradiating hard photons into thermal radiation

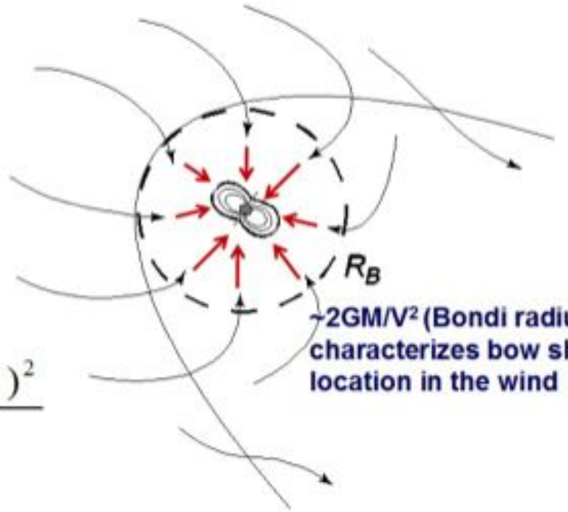
Accretion Column – Accreting plasma heated above NS surface → Comptonization of soft photons from the surface



Spherical accretion model

Accretion Bondi-Hoyle-Littleton

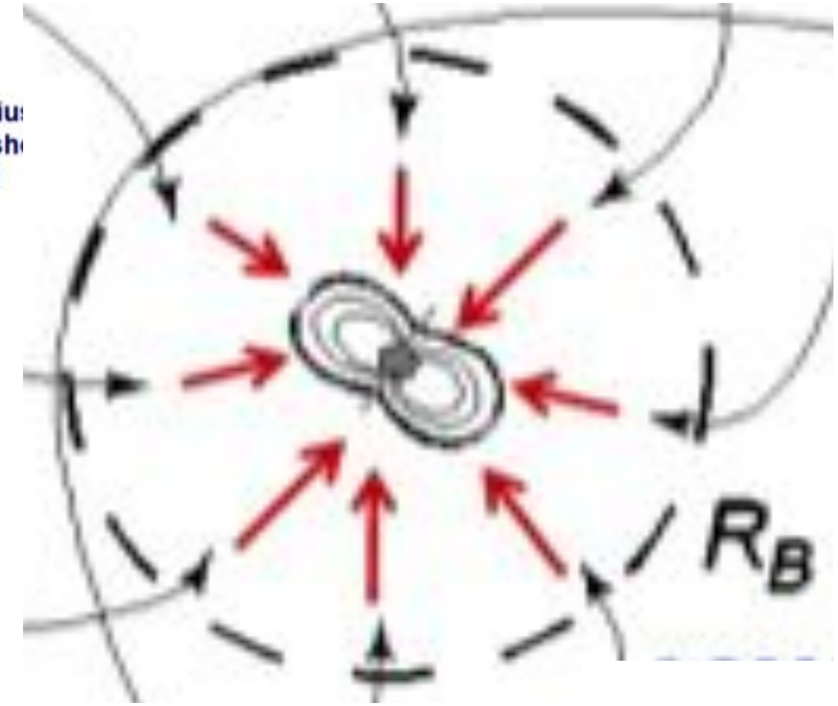




$$t_{cool} << t_{freefall}$$

$$\dot{M} \approx \rho v R_B^2 \sim \rho \frac{(2GM)^2}{v^3}$$

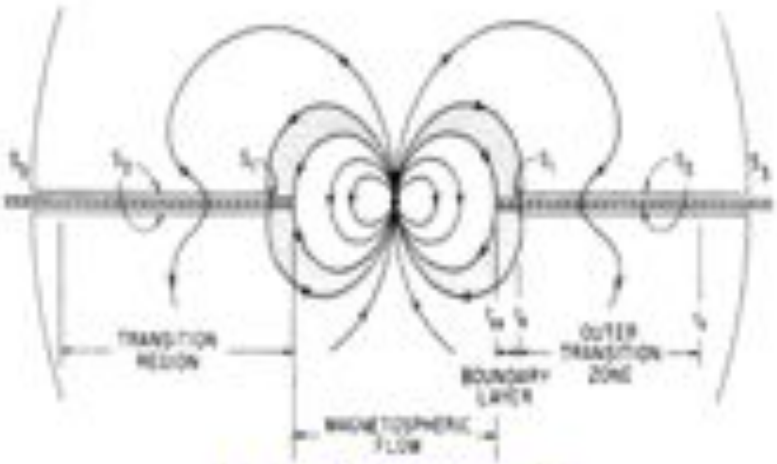
$$R_B = \frac{2GM}{v^2}$$



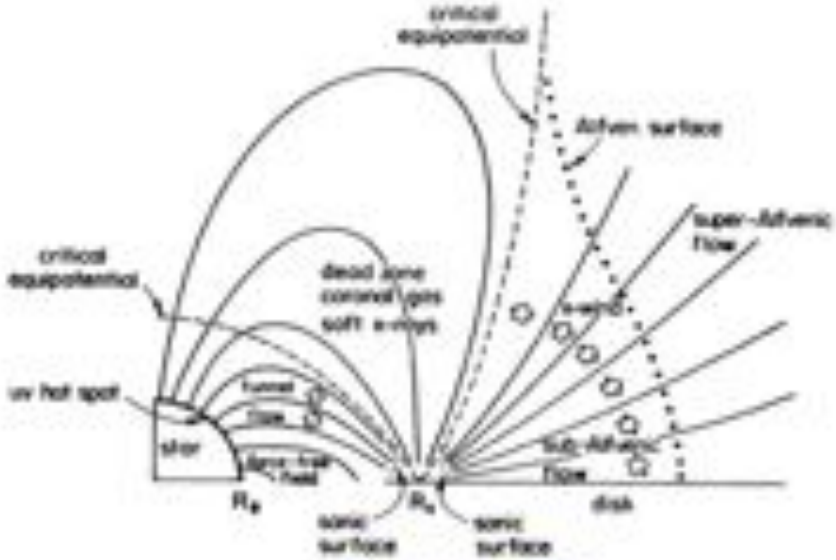
To work out Rm set:
Ram pressure = Magnetic pressure

$$r_A = \left(\frac{\mu^4}{2 G M \dot{M}^2}\right)^{1/7}$$

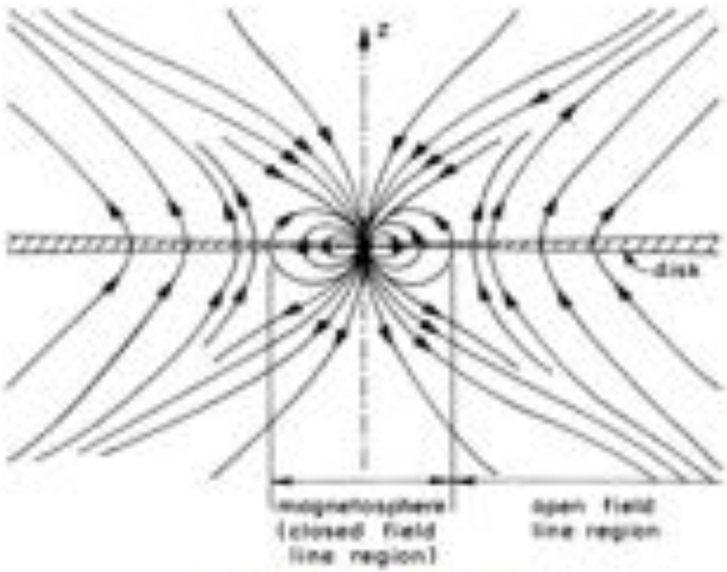
$$r_{cor} = \left(\frac{G M P^2}{4 \pi^2}\right)^{1/3}$$



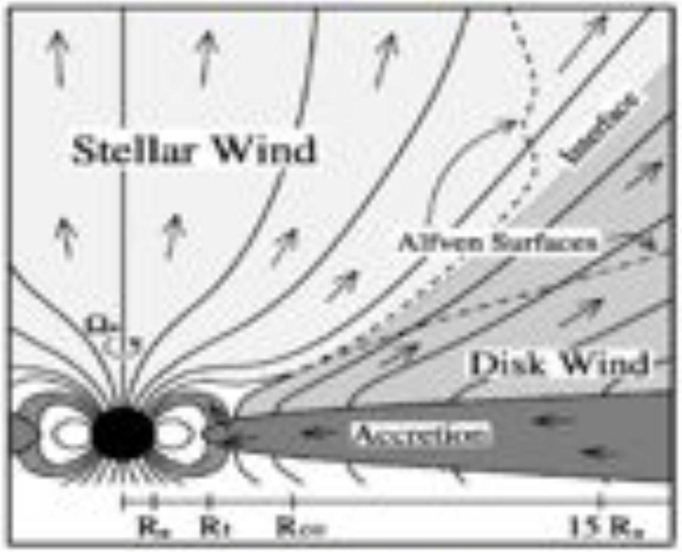
Ghosh & Lamb 1979



Shu et al. 1994



Lovelace et al. 1995



Matt & Pudritz 2005

$$r_{\rm cor} = \left(\frac{G\,M\,P^2}{4\,\pi^2}\right)^{1/3}$$

- For disk accretion neutron star, the spin will reach a equilibrium spin period when the co-rotation radius equal the magnetosphere radius.

$R_m > R_c$ spin down propeller phase

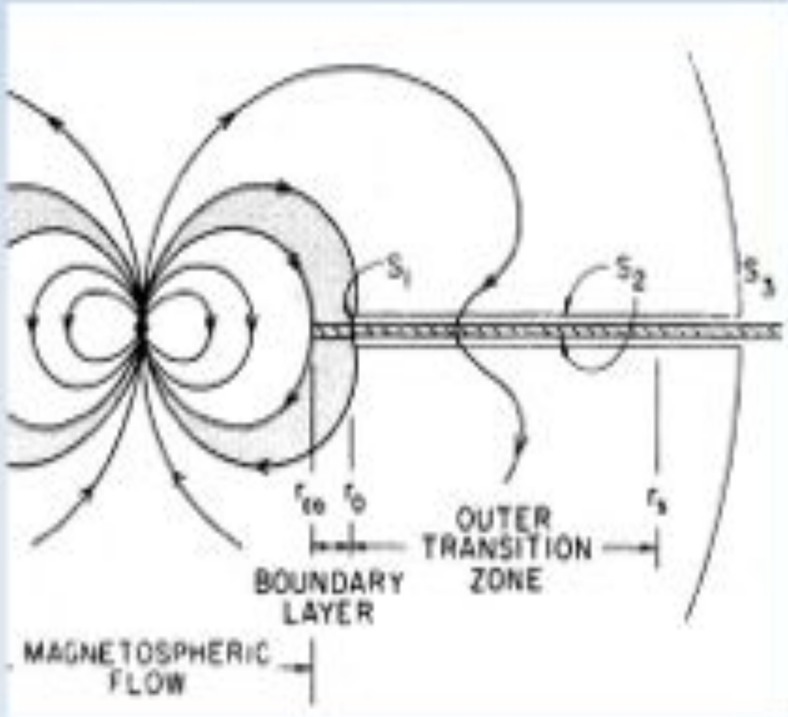
$R_m < R_c$ spin up accretion phase

$$R_m = \left[\mu^4 / 2GM_n \dot{M}^2\right]^{1/7}$$

$$R_c = \left[GM_n P_s^2 / 4\pi^2\right]^{1/3}$$

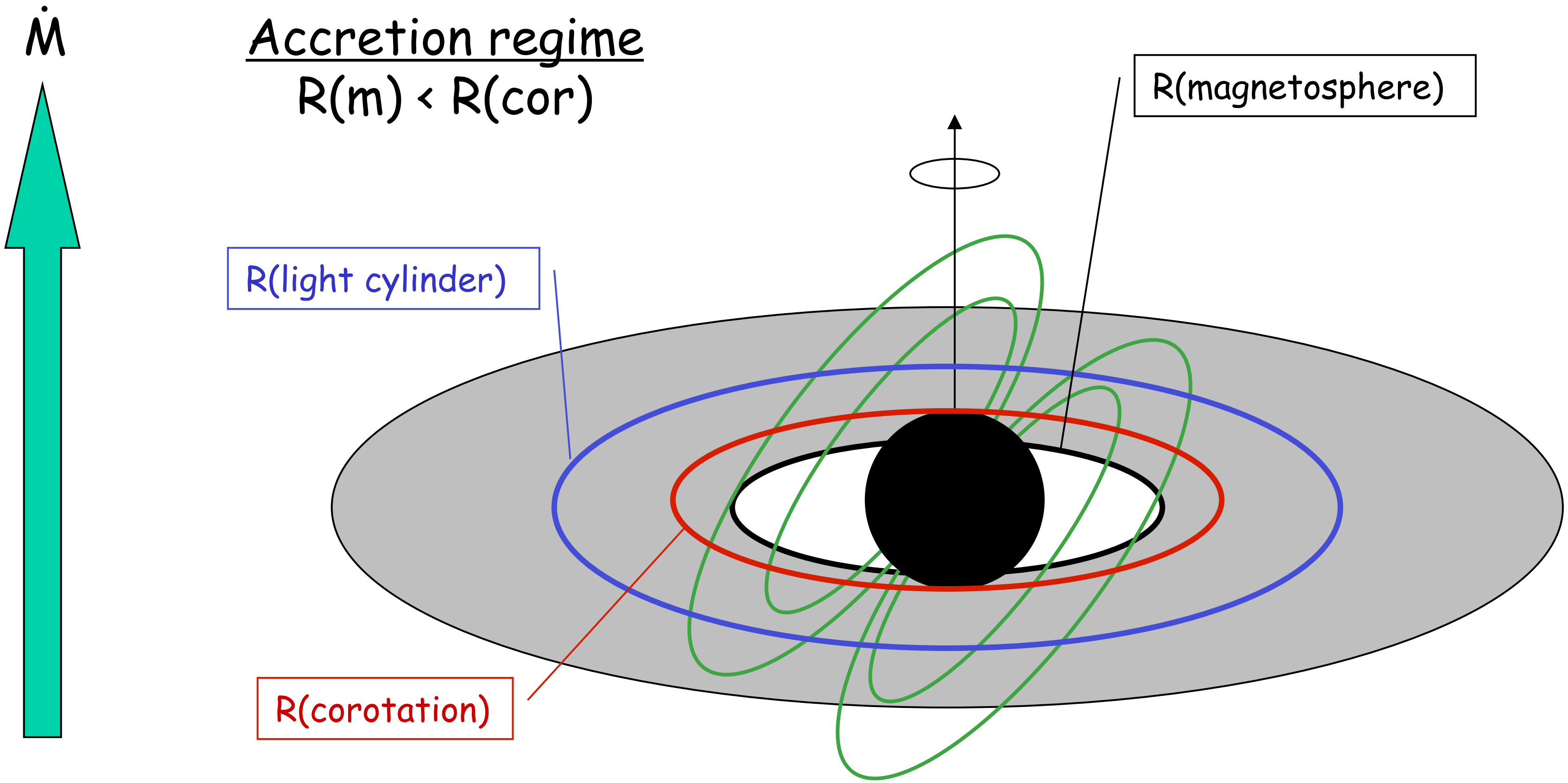
$R_m \sim R_c$

$$P_{eq} = 2\pi\sqrt{2}\,\mu^{6/7}(2GM_n)^{-5/7}\dot{M}^{-3/7}$$



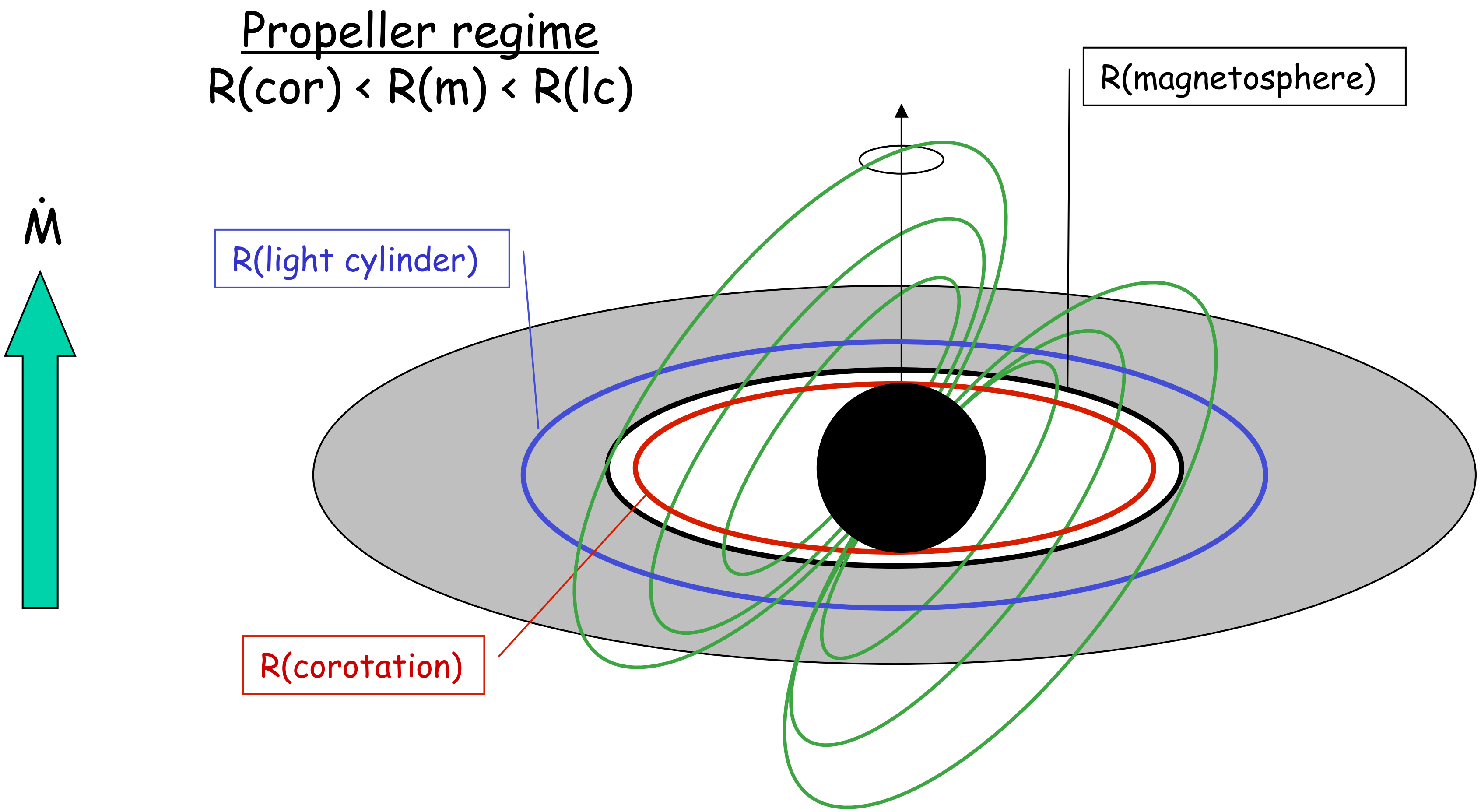
Different regimes for a rotating magnetic NS: 1

(Illarionov & Sunyaev 1975)



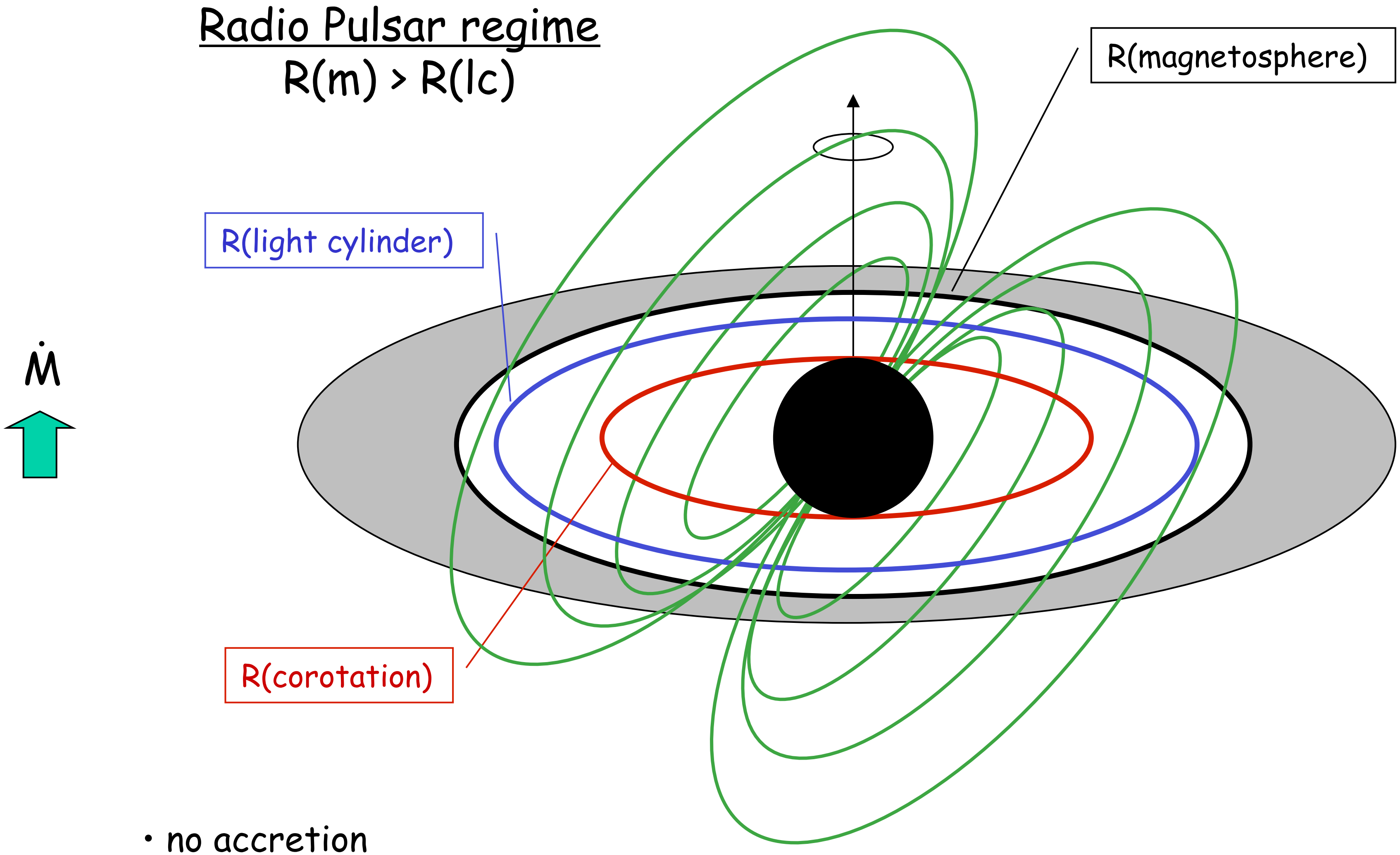
- accretion onto NS surface (magnetic poles)
- energy release L=GMM(dot)/R*

Different regimes for a rotating magnetic NS: 2



- centrifugal barrier closes (B-field drag stronger than gravity)
- matter accumulates or is ejected from R(m)
- accretion onto R(m): lower gravitational energy released

Different regimes for a rotating magnetic NS: 3



- no accretion
- disk matter swept away by pulsar wind and pressure

Why are X-ray transients important ?

Outburst X-ray luminosities: $L_x \sim 10^{37-39}$ erg/s,

Quiescent X-ray luminosities: $L_x \sim 10^{31-33}$ erg/s

- Physics of accreting collapsed stars over a very large range of mass inflow rates, which is not accessible to persistent sources

Different regimes in Hard XRTs

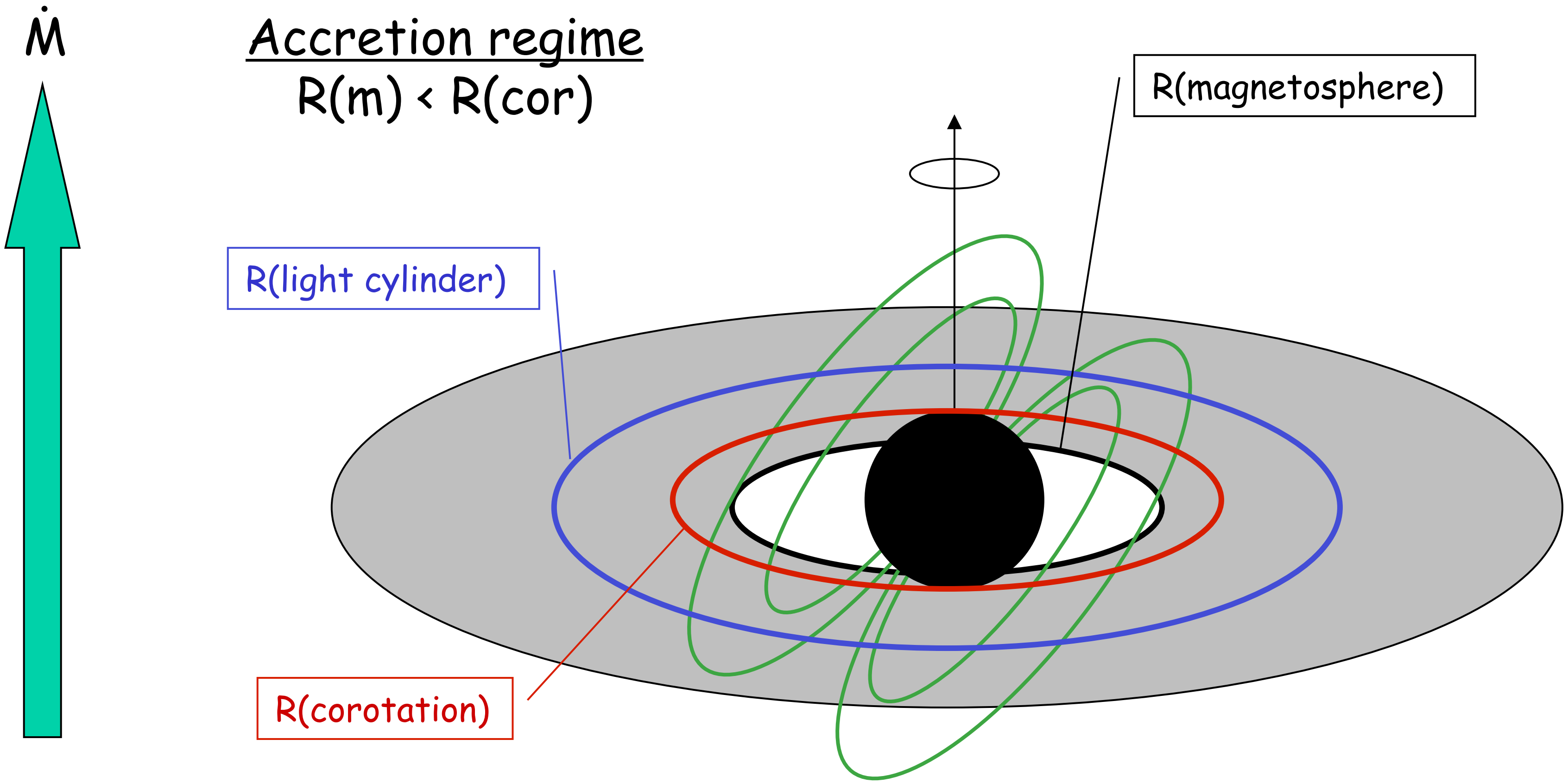
(X-ray pulsar/ Be star binaries)

(Stella, White & Rosner 1986)

- Centrifugal barrier likely closes close to an outburst end: X-ray flux decay should steepen suddenly
- Self-consistency check of interpretation, if P(spin), B and distance are measured

Different regimes for a rotating magnetic NS: 1

(Illarionov & Sunyaev 1975)



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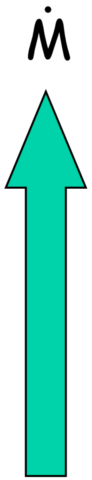
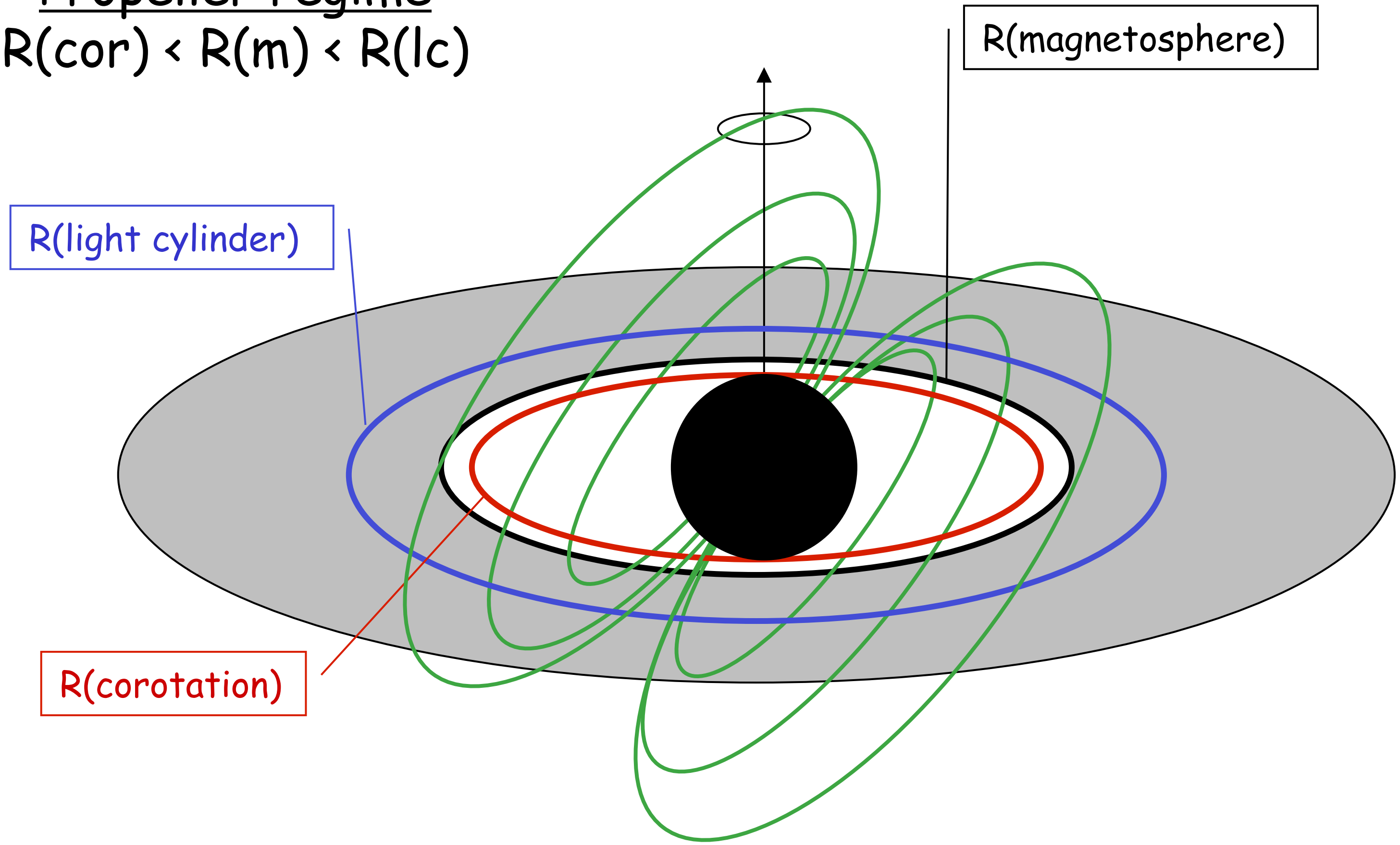
Different regimes for a rotating magnetic NS: 2

Propeller regime

R(cor) < R(m) < R(lc)





- centrifugal barrier closes (B-field drag stronger than gravity)
- matter accumulates or is ejected from R(m)
- accretion onto R(m): lower gravitational energy released

Onset of centrifugal barrier in Hard XRTs

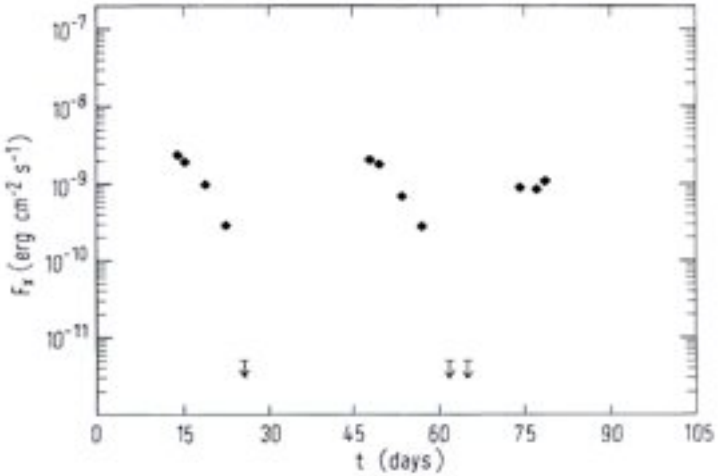
Very sharp X-ray luminosity decrease close to outburst end

V0332+53

P=4.4 s, B_{cyc}~10^{12} G

L(min)~10^{35} erg/s

(Stella, White & Rosner 1986)

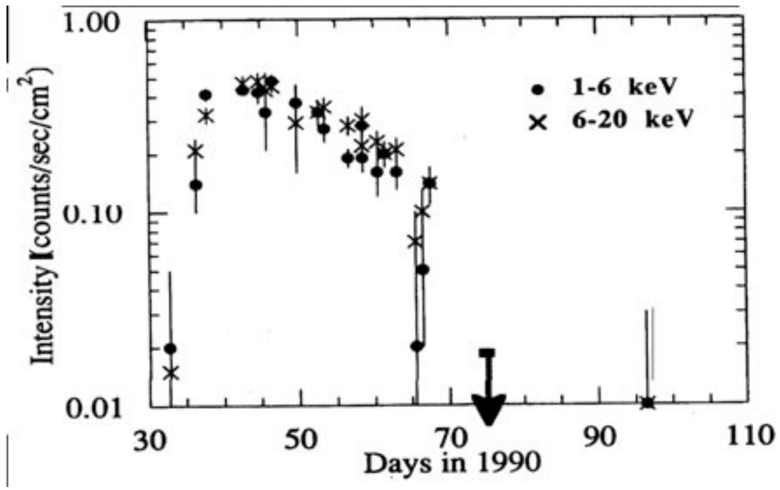


4U0115+63

P=3.6 s, B_{cyc}~10^{12} G

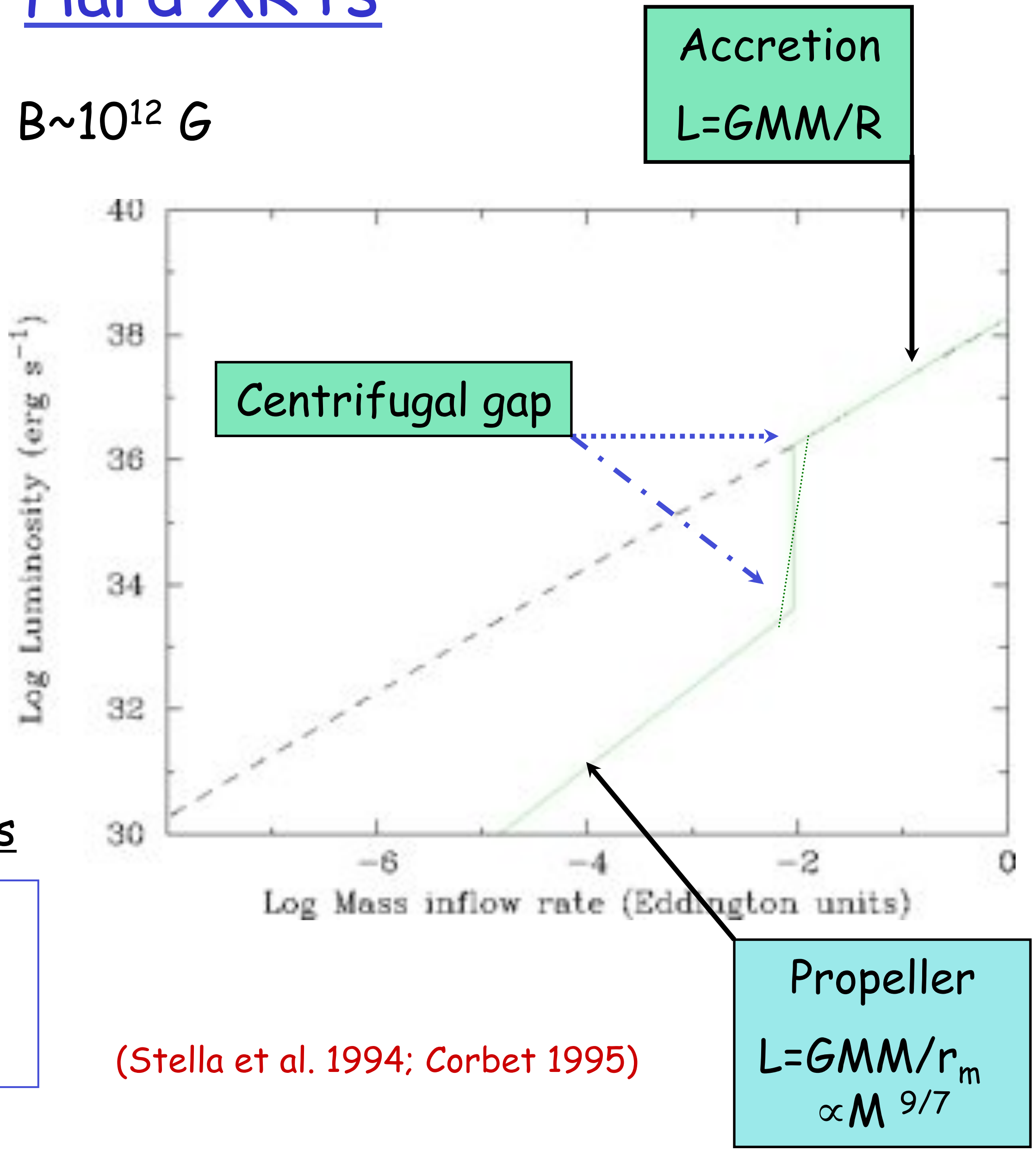
L(min)~10^{36} erg/s

(Tamura et al. 1992)



Expected mass-energy conversion efficiency in Hard XRTs

X-ray pulsar with P~4 s B~10^{12} G



Centrifugal gap expectations

- factor of ~400 jump in Lx
- very steep dependence on M(dot) (not step-like)

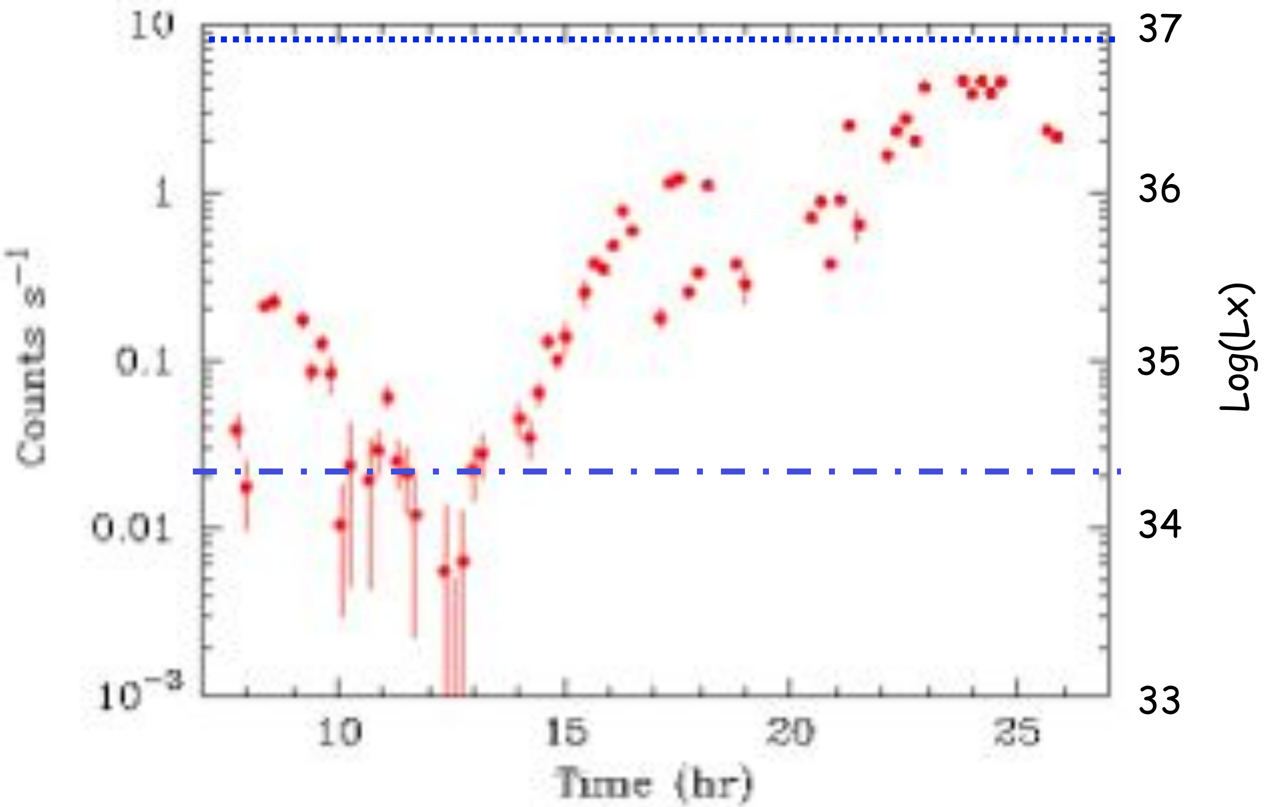
(Stella et al. 1994; Corbet 1995)

BeppoSAX observation 4U0115+63 in quiescence

(Campana et al. 2000)

Expected range of centrifugal gap, based on measured P, B and distance

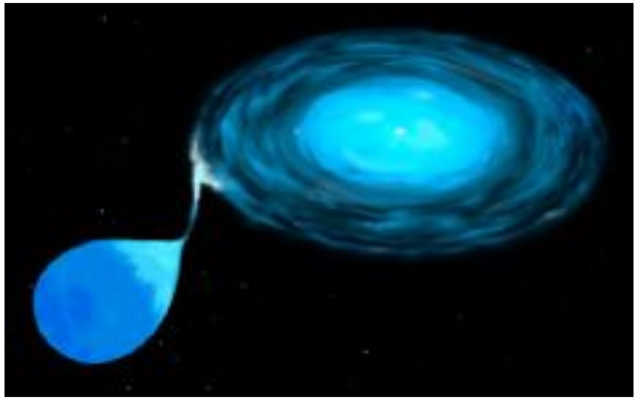
- Observed Lx within centrifugal gap !
- Very Large (factor of ~250) Lx variations!
- 3.6 s pulsations present
- No substantial pulsation amplitude and spectral variations



- Factor of < 3 variations in M(dot) expected at the most: imply a very steep dependence of Lx on M(dot) (power law slope of > 5)
- In the centrifugal gap some matter must leak through the barrier and accrete onto the NS surface

→ First evidence for centrifugal gap !

Soft XRTs: the missing link ?



Spin-up by accretion paradigm:
Soft XRTs (like NS low mass X-ray binaries) contain old, weakly magnetic NS with millisecond periods

Soft XTRs should be among the progenitors of ms radio pulsars

Quiescent Soft XRTs: Lx~ 10^{33} erg/s

Are there signs of a turned-on rotation powered pulsar in quiescent Soft XRTs, when the mass inflow rate is very low ?

→ Nature of quiescent emission of Soft XTRs

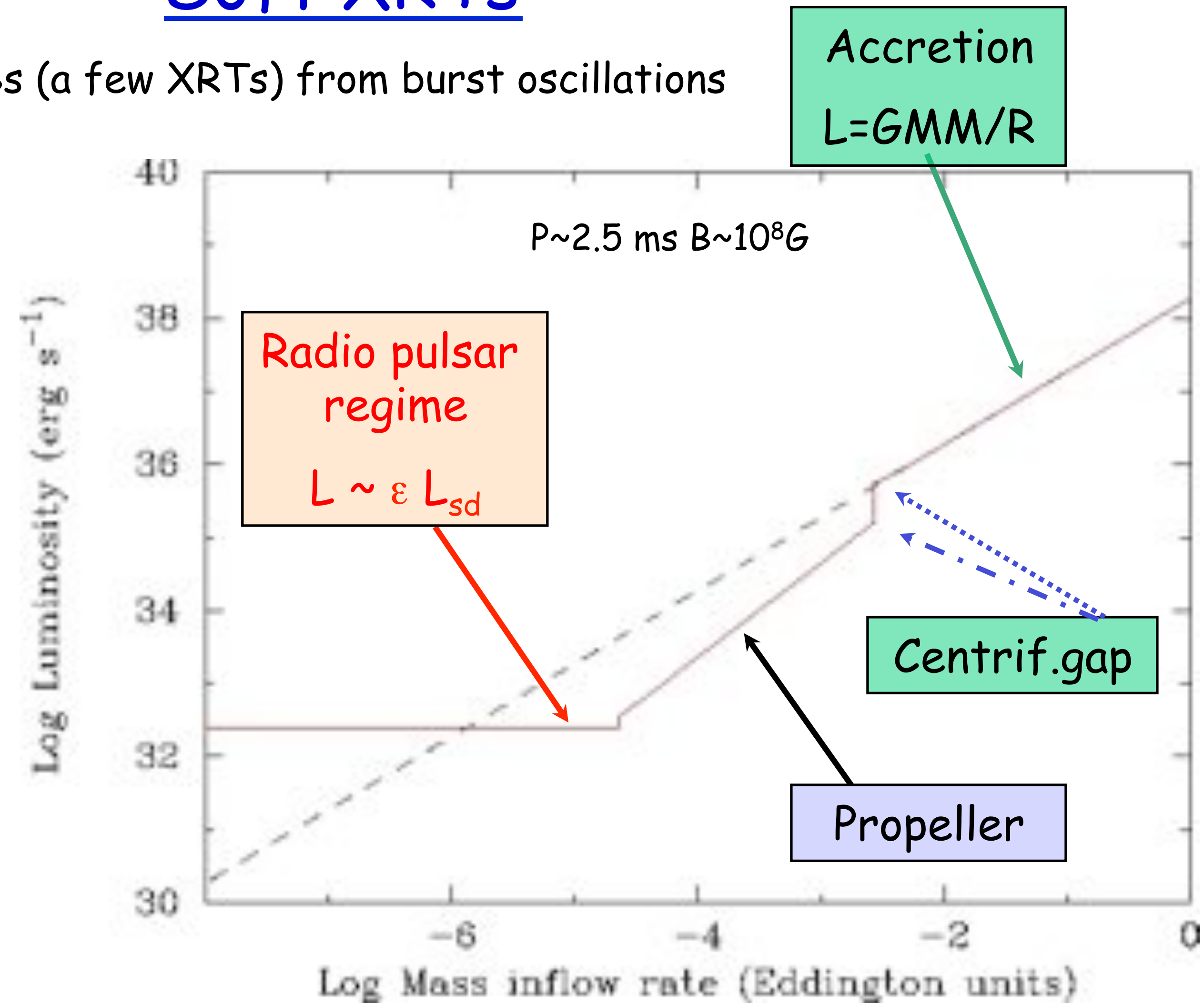
(Callanan 1989, Kulkarni et al. 1992, Stella et al. 1994)

Expected mass-energy conversion efficiency in Soft XRTs

P~ 1.6-4 ms in ~10 LMXRBs (a few XRTs) from burst oscillations

Basic expectations

- small centrifugal gap
- propeller regime over a range of ~100 in M(dot)
- radio pulsar regime for very low mass inflow rates: shock emission



(Stella et al. 1994, Campana et al .1998)

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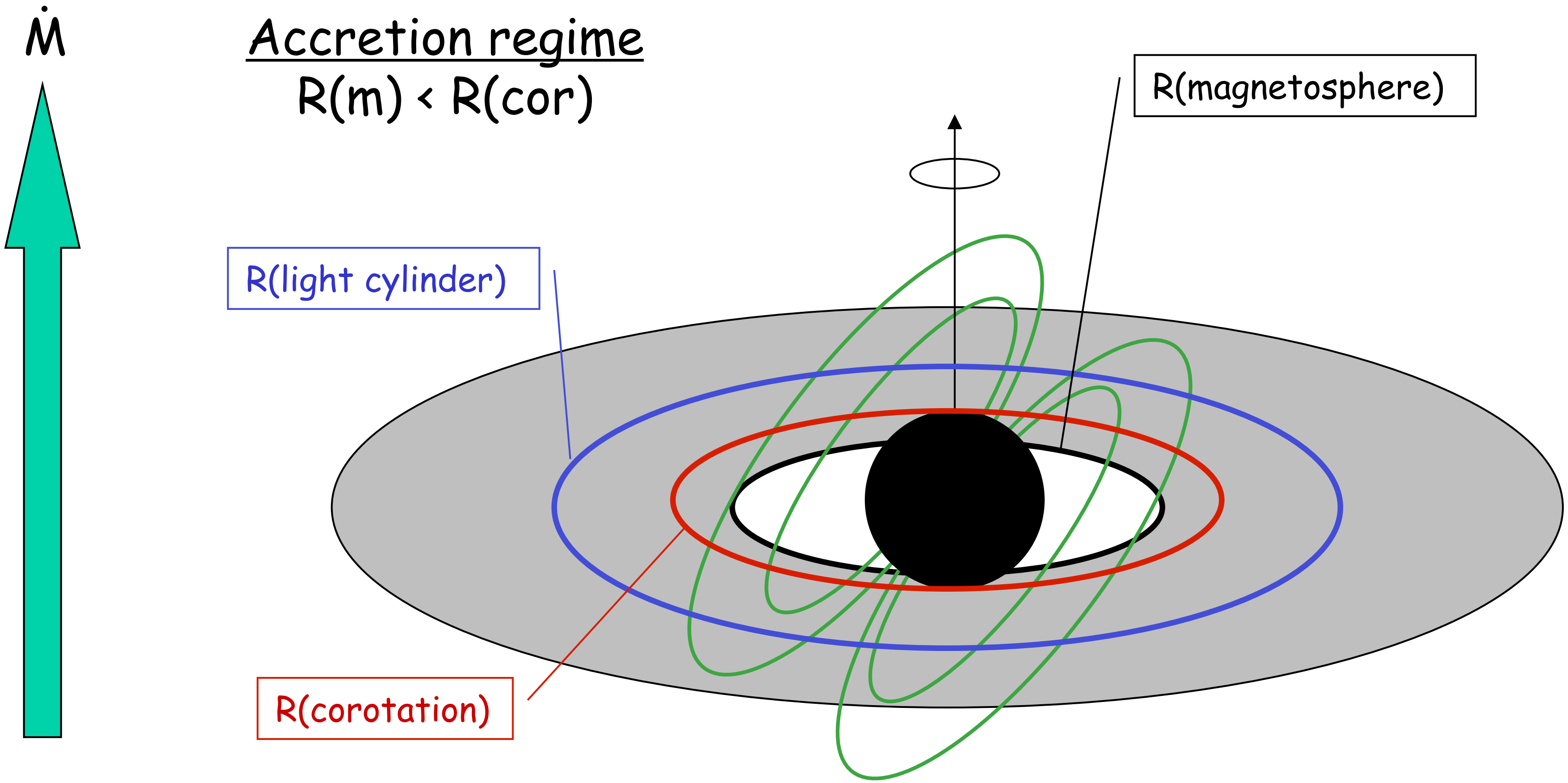

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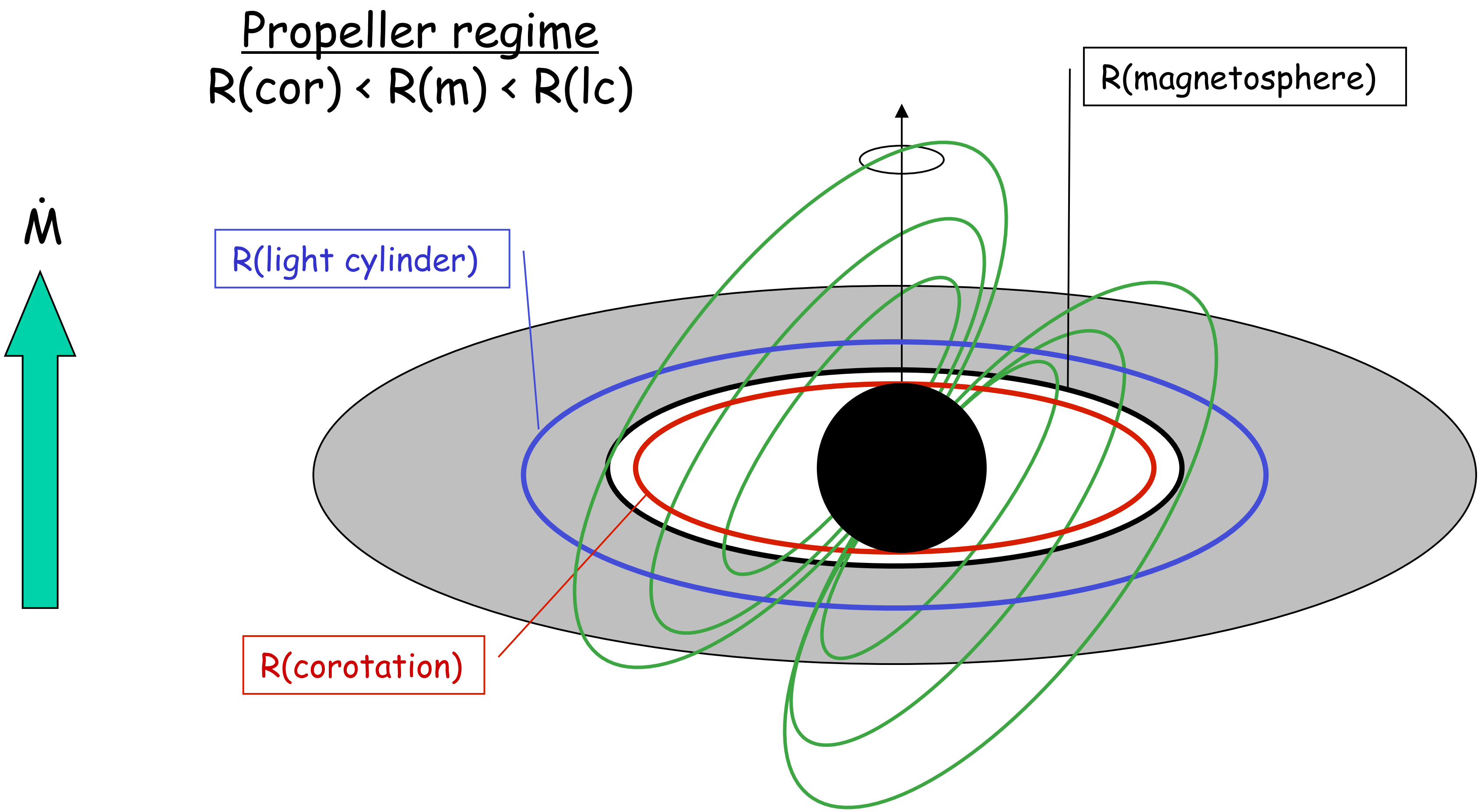
- energy release L=GMM(dot)/R*

Different regimes for a rotating magnetic NS: 2



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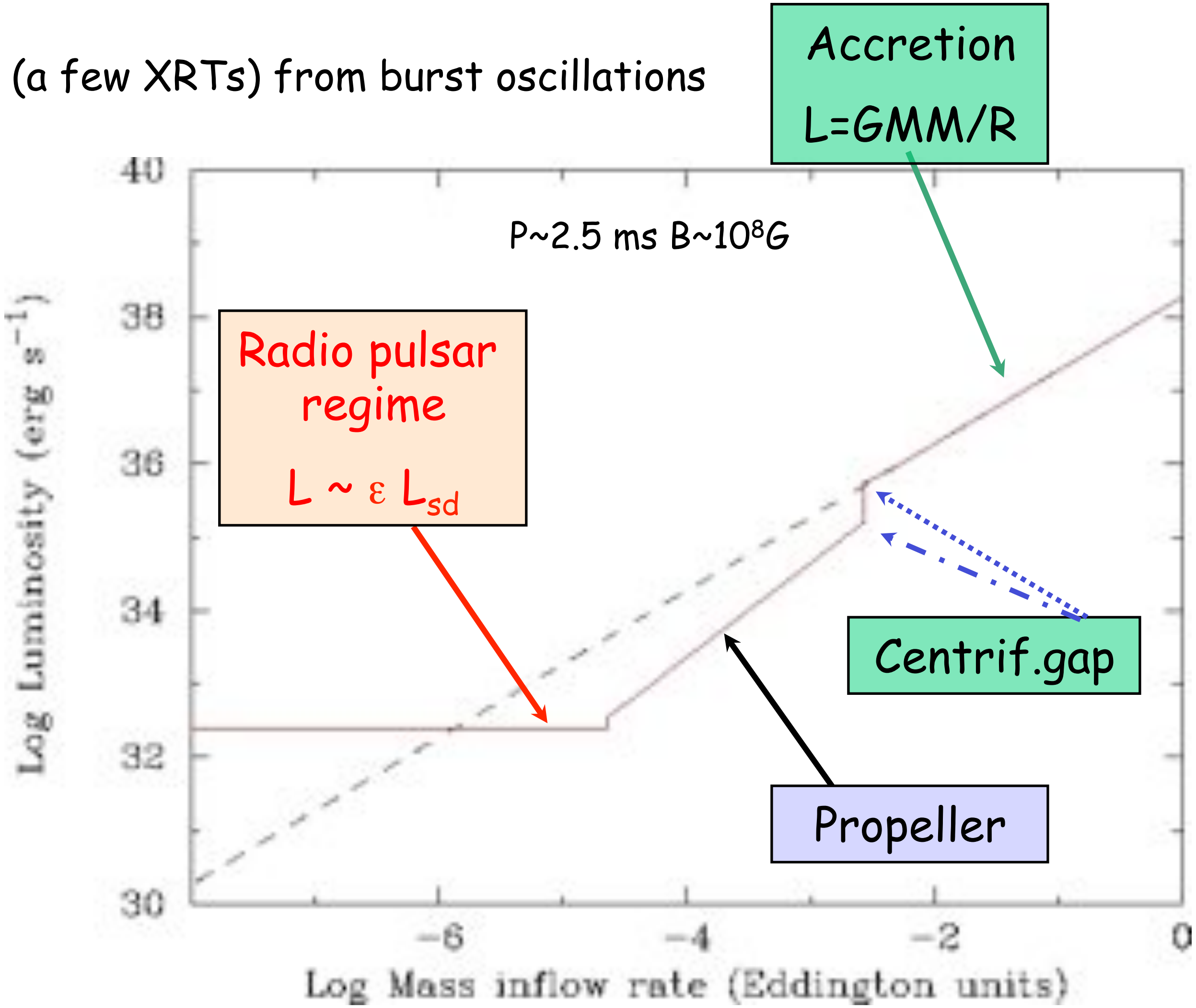

(Stella et al. 1994, Campana et al .1998)

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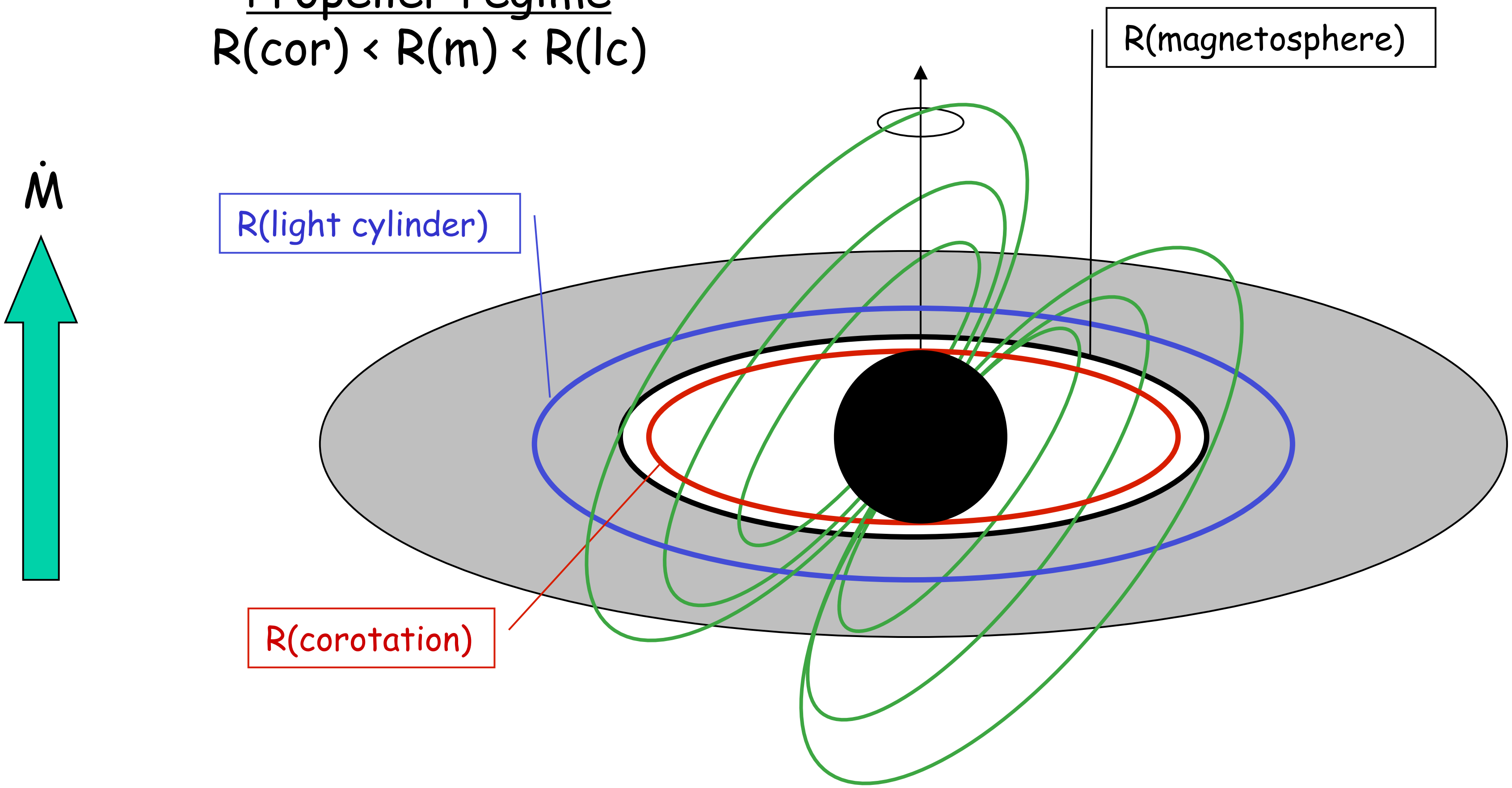

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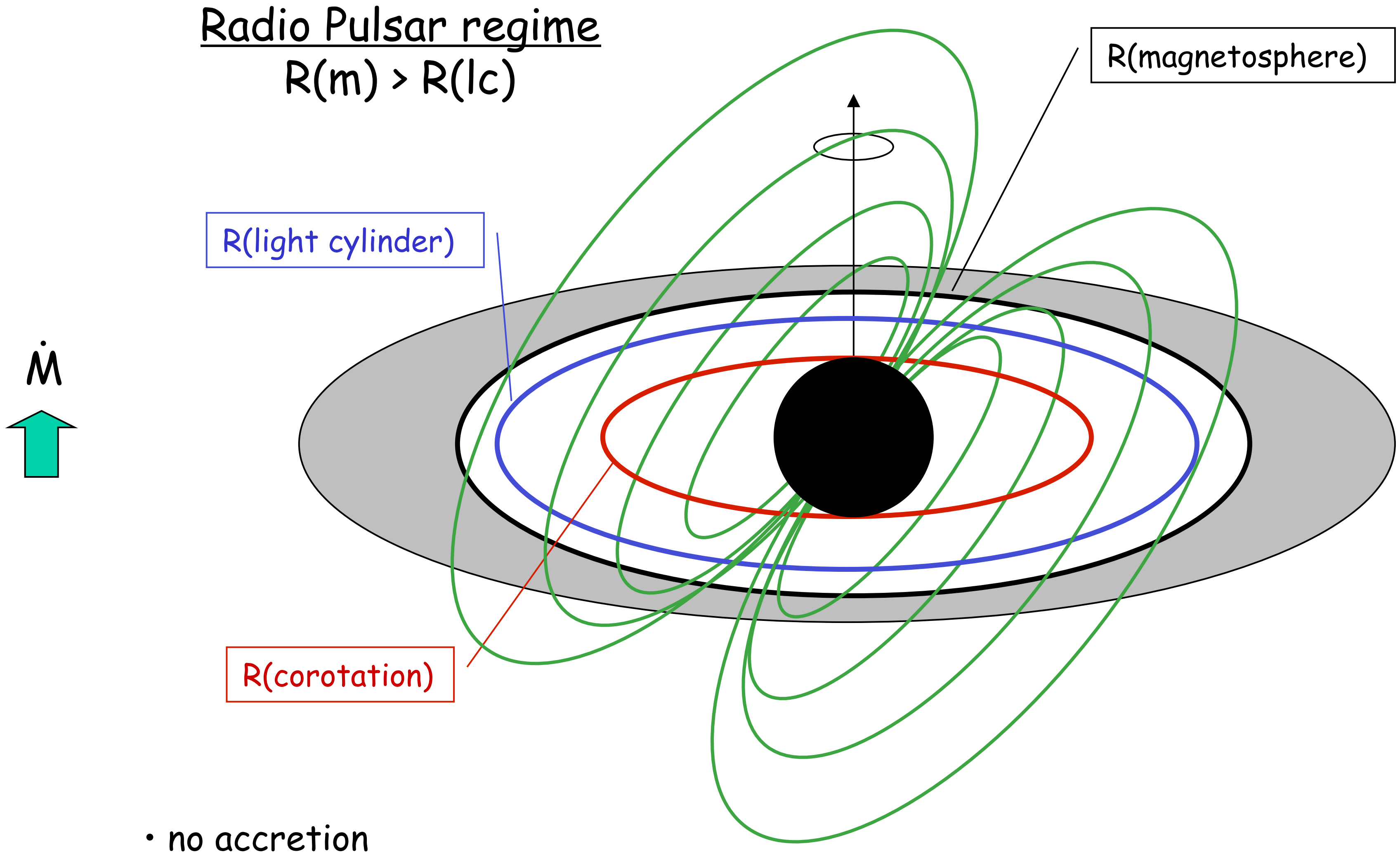


- no accretion
- disk matter swept away by pulsar wind and pressure

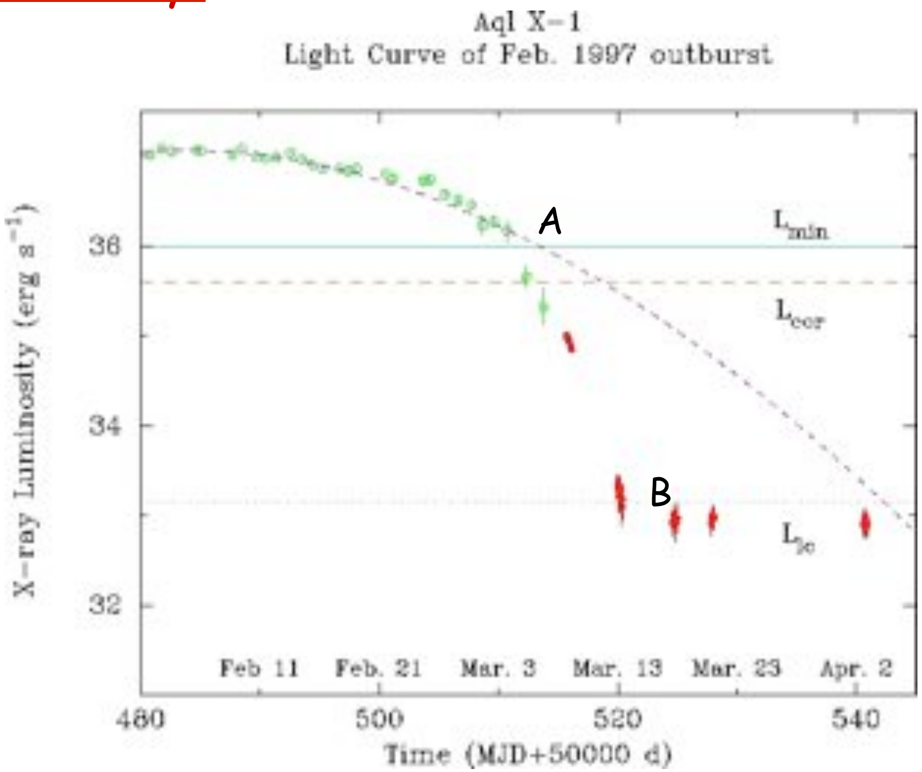
Soft XRTs: Aql X-1 from outburst to quiescence

Two transitions observed in outburst decay:

A - Lx~ 10^{36} erg/s, decay ~ 1 d,
spectrum hardens

B - Lx~ 10^{33} erg/s, levels off,
power law component
decreases and flattens

P = 1.8 ms during bursts



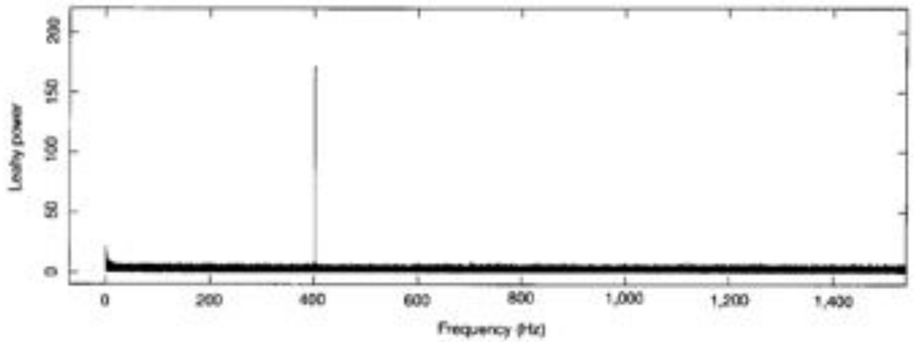
(Campana et al. 1998)

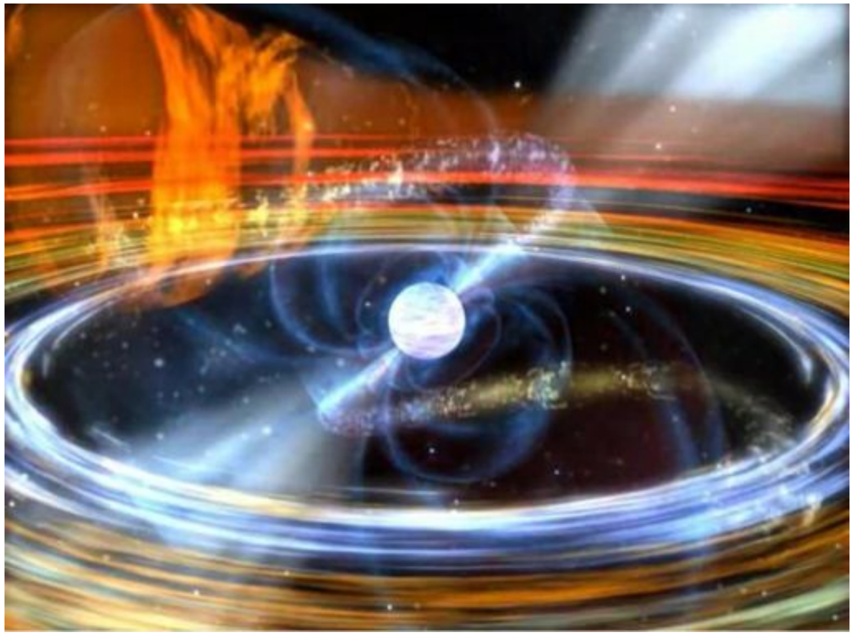
Discovery of accreting Millisecond pulsars

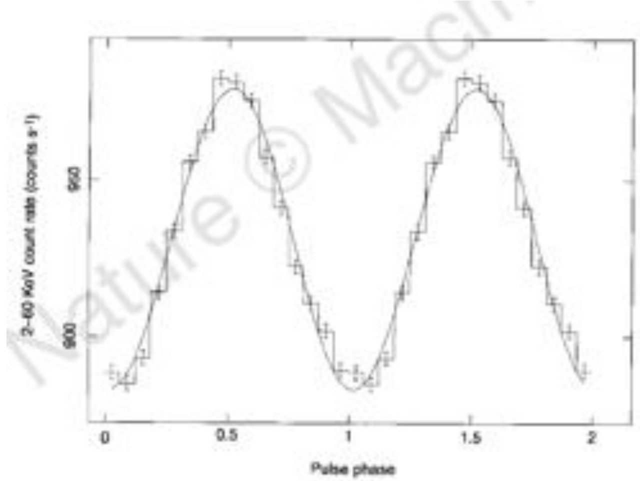

letters to nature

A millisecond pulsar in an X-ray binary syste

Rudy Wijnands* & Michiel van der Klis*†







Discovery of accreting Millisecond pulsars

The two-hour orbit of a binary millisecond X-ray pulsar

Deepto Chakrabarty & Edward H. Morgan

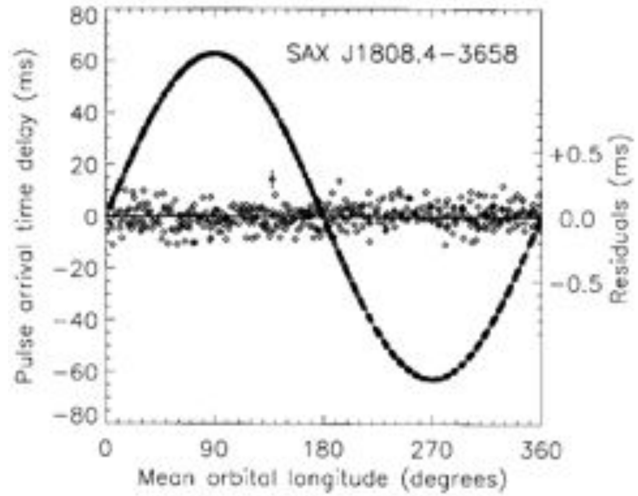
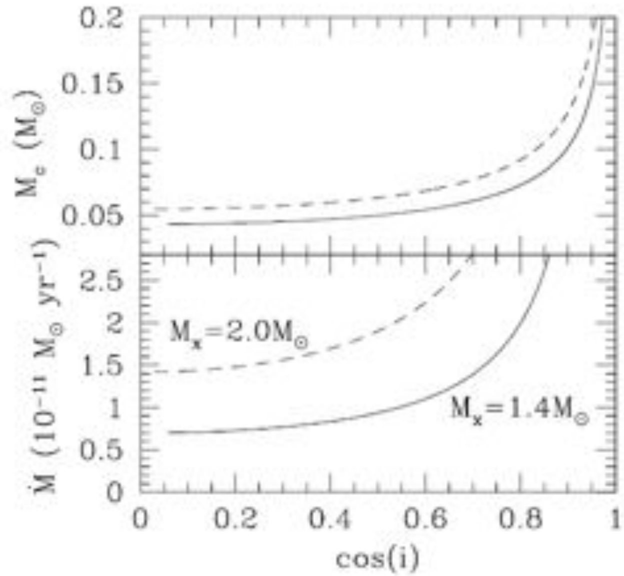


Table 1 Observed parameters of SAX J1808.4-3658

Barycentric pulse frequency, ν_0 (Hz)	400.9752106(8)
Pulse frequency derivative, $\|\dot{\nu}\|$ (Hz s^{-1})	$< 7 \times 10^{-13}$
Projected semimajor axis, $a_1 \sin i$ (light ms)	62.809(1)
Orbital period, P_{orb} (s)	7249.119(1)
Epoch of 90° mean longitude, $T_{\pi/2}$ (MJD)	50914.899440(1)
Eccentricity, e	$< 5 \times 10^{-4}$
Pulsar mass function, f_1 ($M_\odot$)	$3.7789(2) \times 10^{-5}$

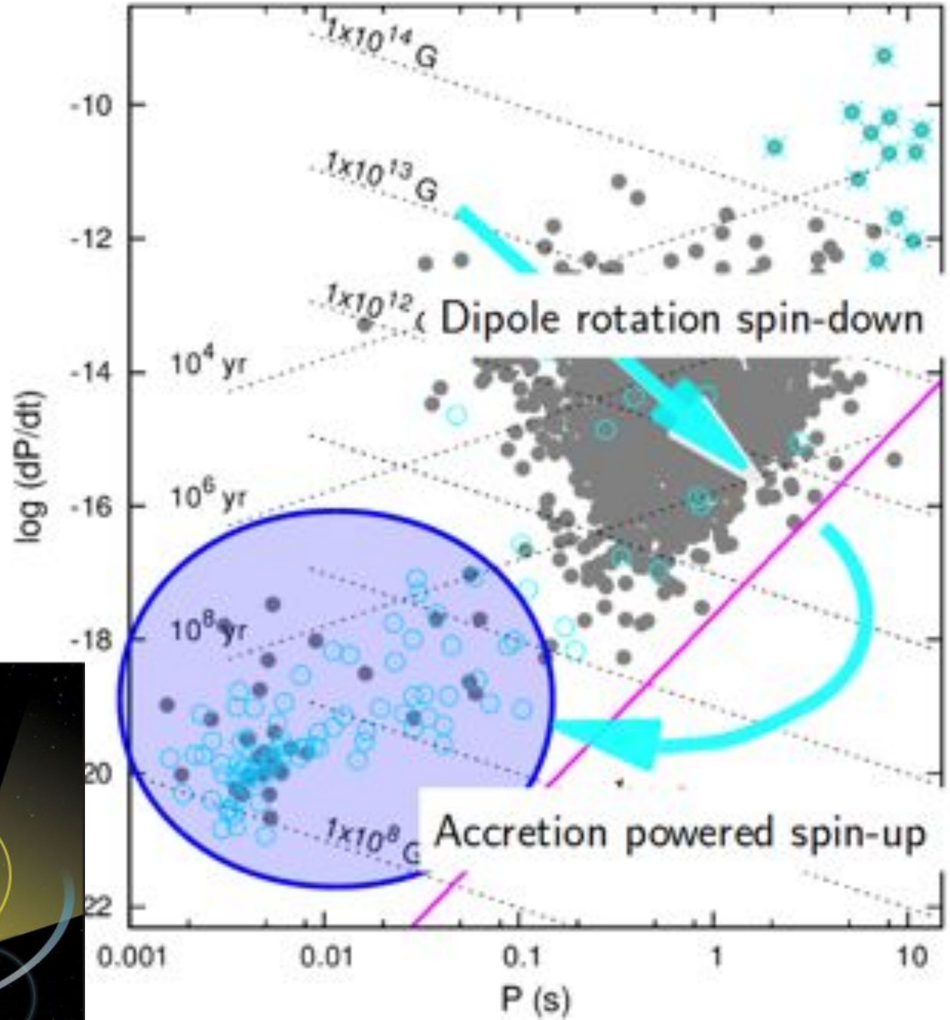
Modified Julian date MJD = JD − 2400000.5. Numbers in parentheses are the 1σ uncertainties in the last significant figure, and upper limits are quoted at the 2σ level. The $\dot{\nu}$ limit refers to the magnitude, independent of sign. Epochs are given in Barycentric Dynamical Time (TDB).

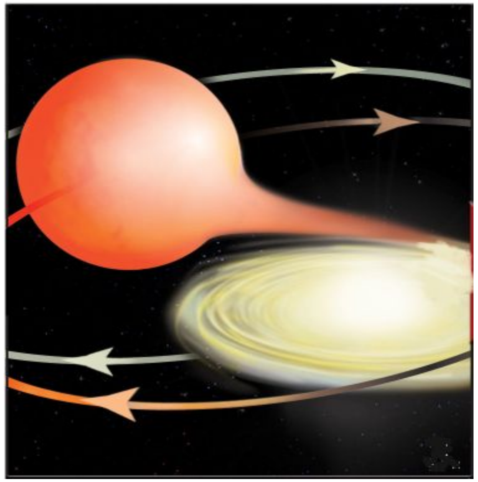


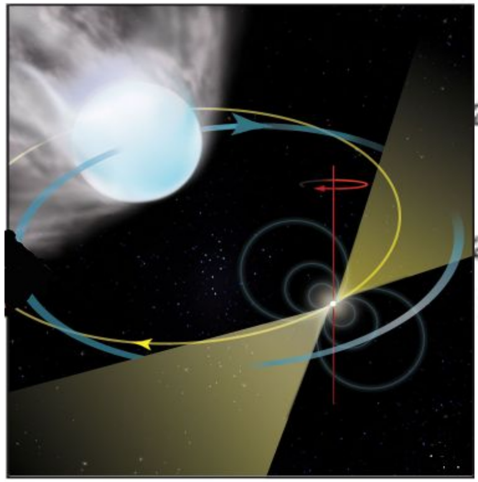
The fundamental plane of pulsars

Accreting ms pulsars show that NS in low mass X-ray binaries are spun up to ms periods.

Do Accreting ms pulsars turn on as radio pulsars during quiescence?





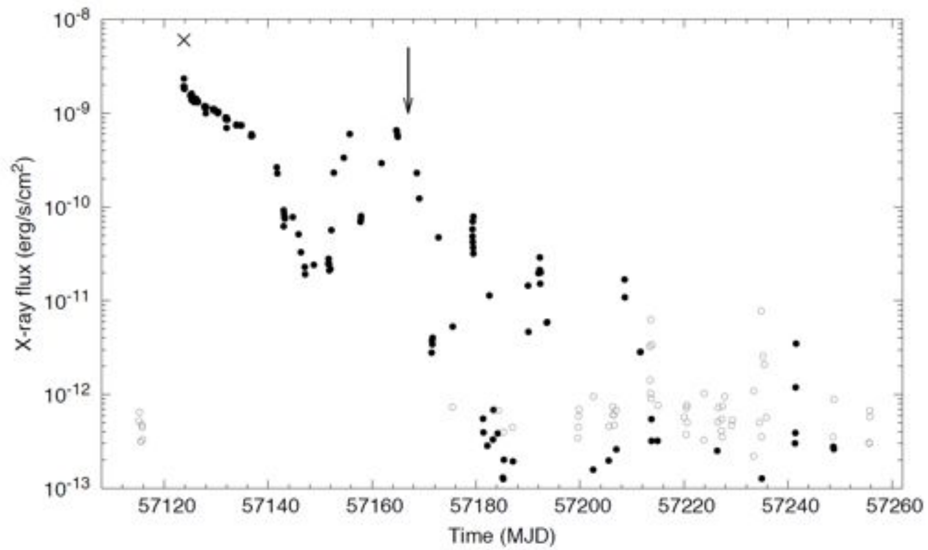


A radio pulsar turning on in quiescence?

Ps=1.5 ms

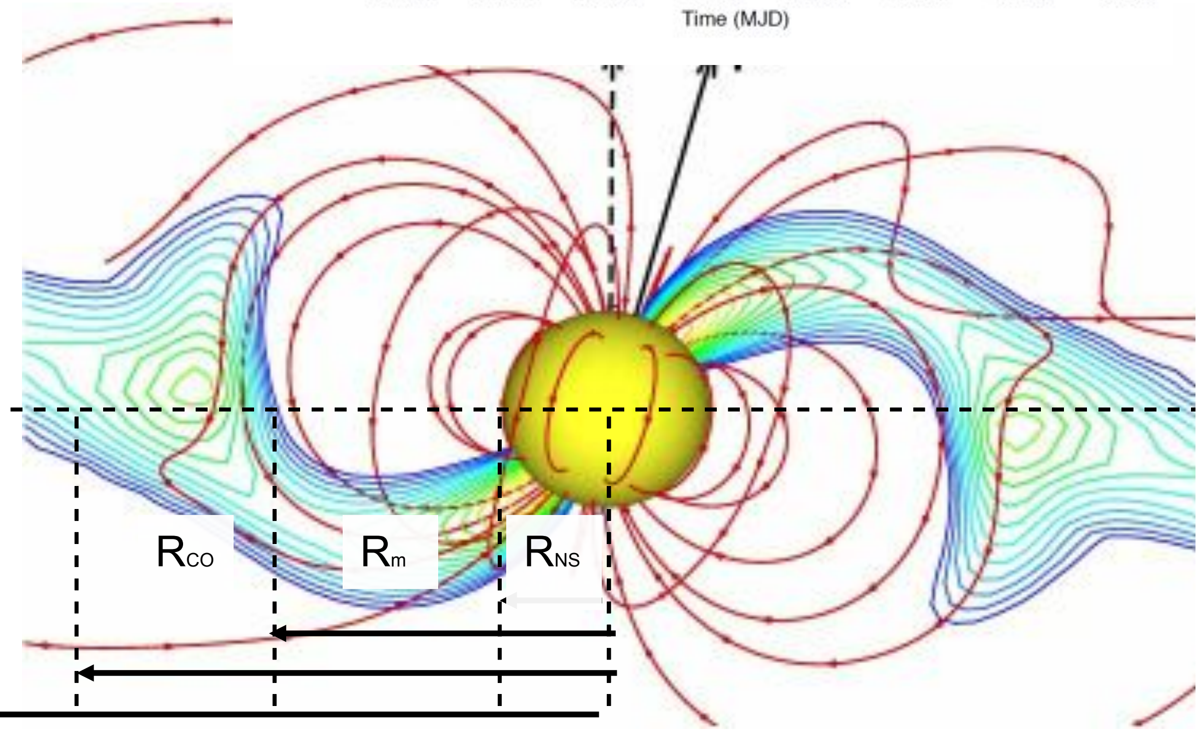
$R_{co} = [GM(P_s/2\pi)^2]^{1/3} = 22 km$

For B~10^8 G → μ~10^{26} G cm^3,
L_X=10^{37}erg/s → Mdot=5E16 g/s



$R_m = \xi \mu^{4/7} / M^{2/7} (GM)^{1/7} = 20 km$

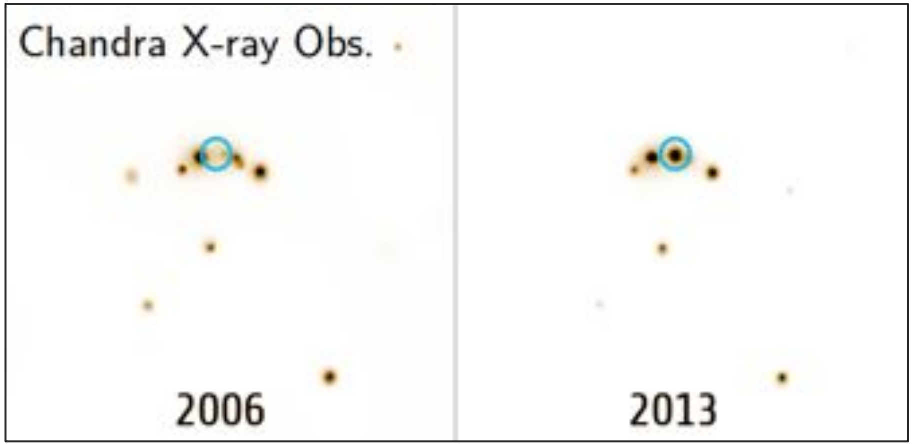
$R_{lc} = cP_s / 2\pi = 72 km$

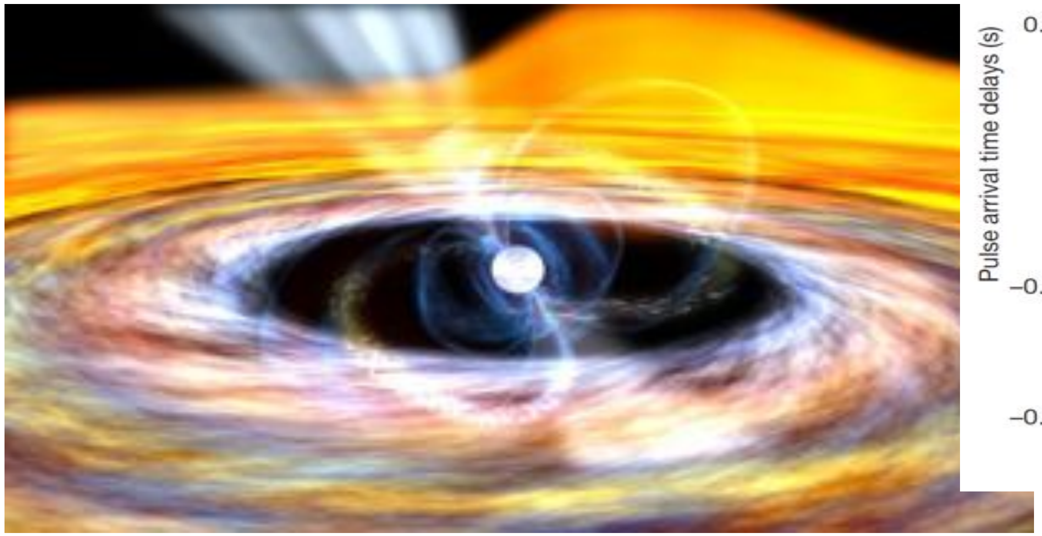


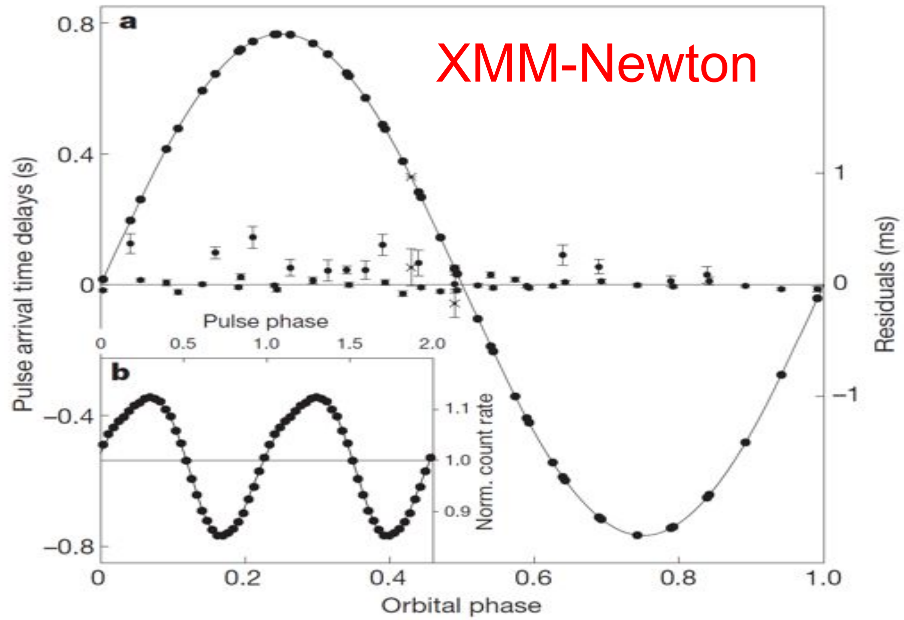
Rlc

An accreting ms pulsar in the globular cluster M28

IGR J18245-2452
L(X-rays) ~ 5 x 10^{36} erg/s
Pspin = 3.9 ms
Porb = 11 hr







LETTER

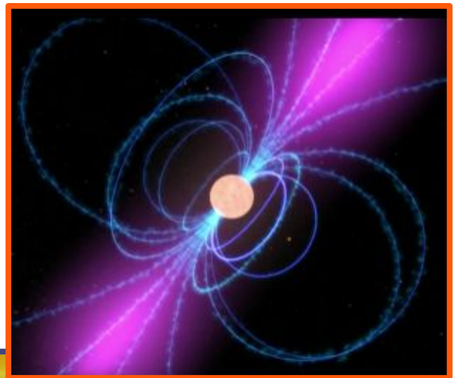
doi:10.1038/nature12470

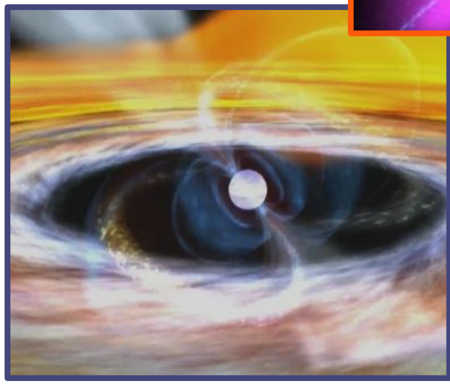
Swings between rotation and accretion power in a binary millisecond pulsar

Parameter	IGR J18245–2452	PSR J1824–2452I
Right Ascension (J2000)	$18^h\ 24^m\ 32.53(4)^s$	
Declination (J2000)	$-24°\ 52'\ 08.6(6)''$	
Reference epoch (MJD)	56386.0	
Spin period (ms)	3.931852641(2)	3.93185(1)
Spin period derivative	$< 2 \times 10^{-17}$	
RMS of pulse time delays (ms)	0.1	
Orbital period (hr)	11.025781(2)	11.0258(2)
Projected semi-major axis (lt-s)	0.76591(1)	0.7658(1)
Epoch of zero mean anomaly (MJD)	56395.216889(5)	

Papitto et al. 2013, Nature

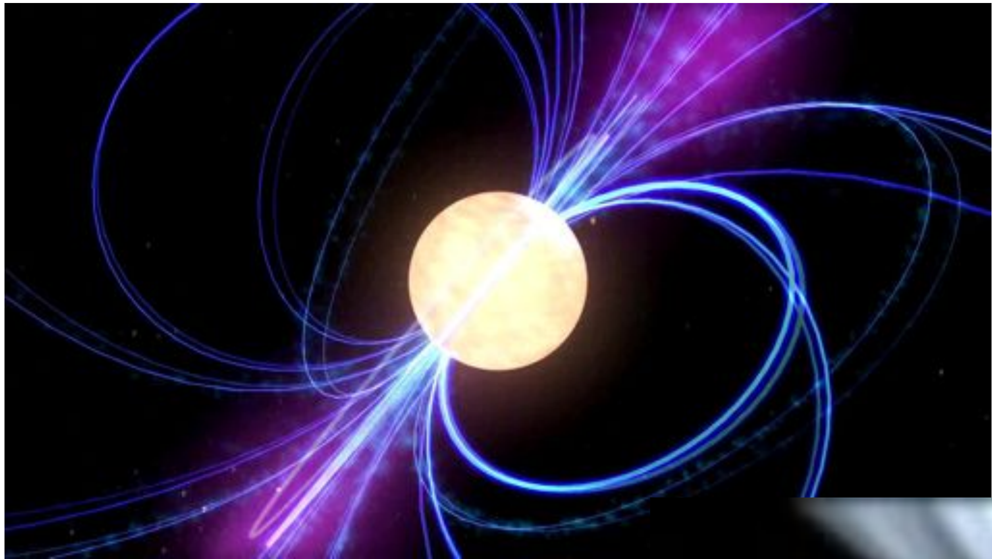
Rotation powered **Radio PSR**



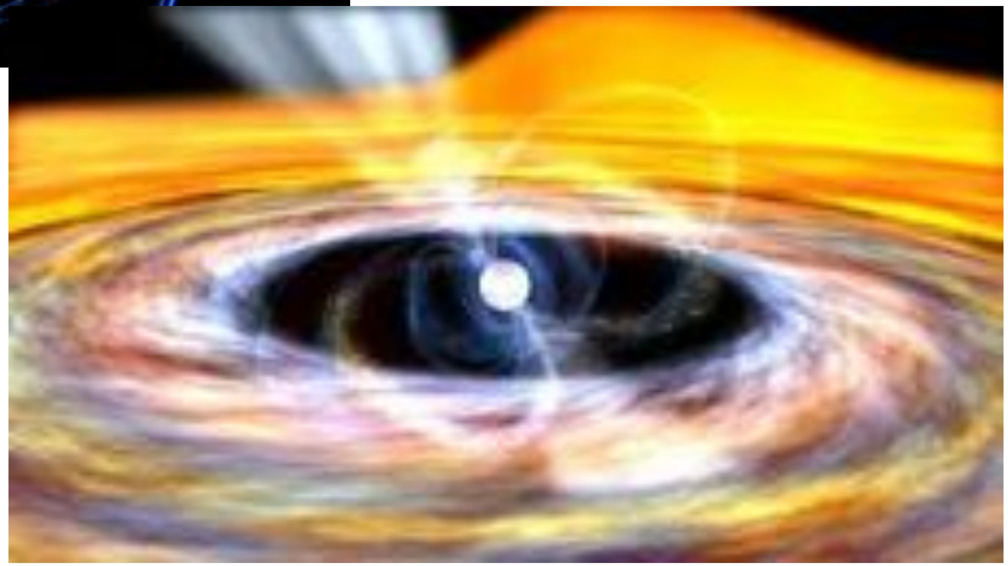


Xray PSR accretion powered

Transitional Millisecond Pulsars

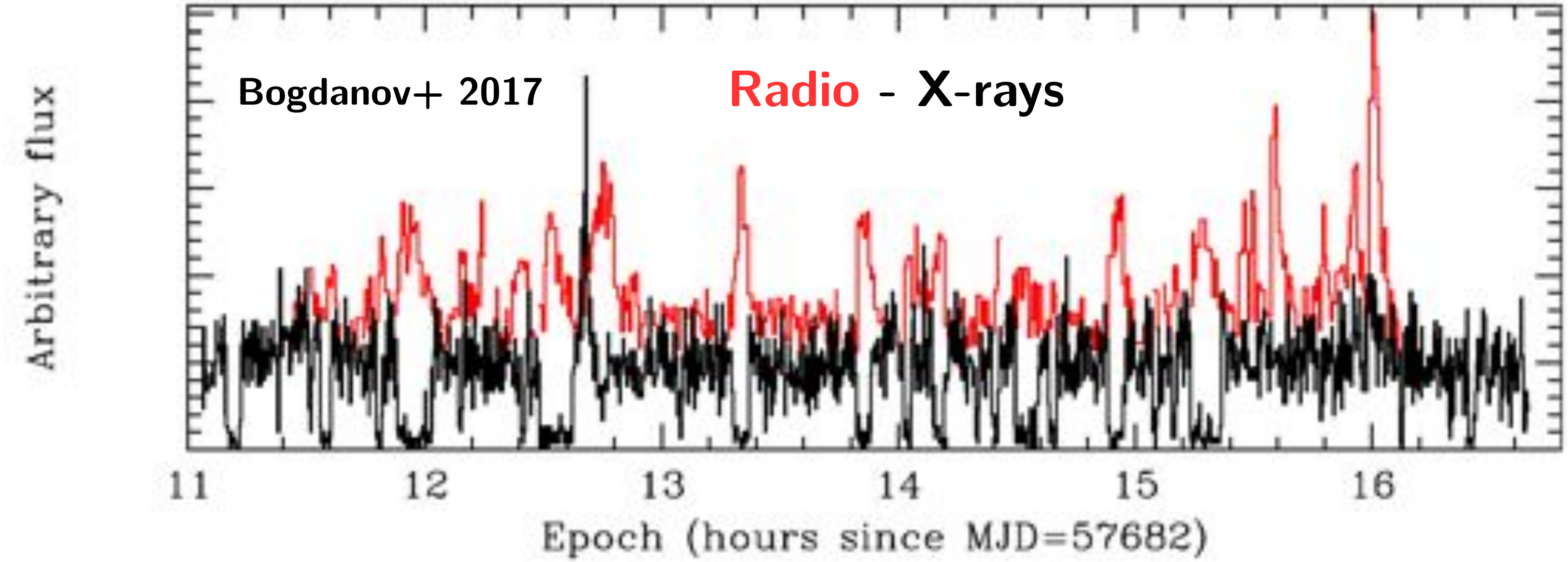


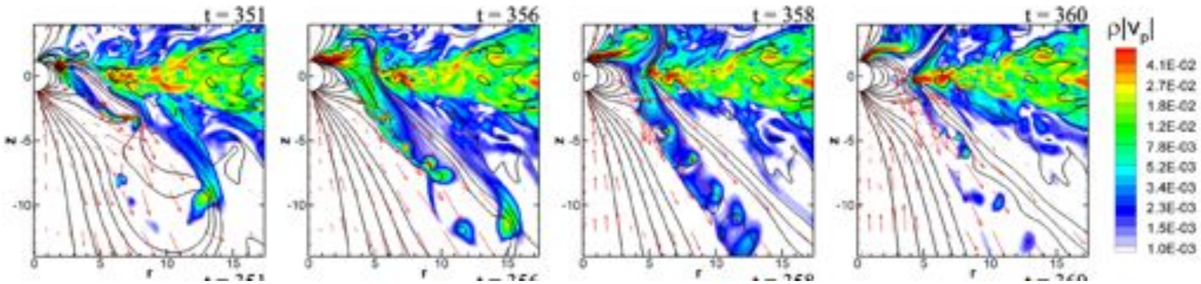
Rotationally-powered (radio, gamma-ray) pulsars



Accretion-powered (X-ray) pulsars

Plasma ejection events





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LETTERS
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Optical pulsations from a transitional millisecond pulsar

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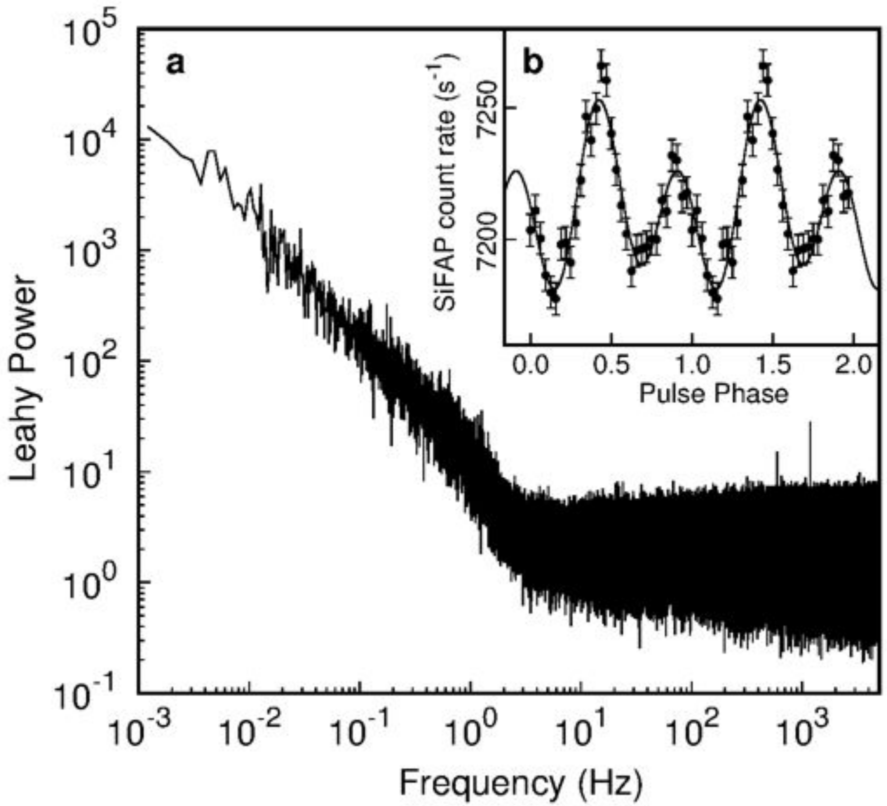
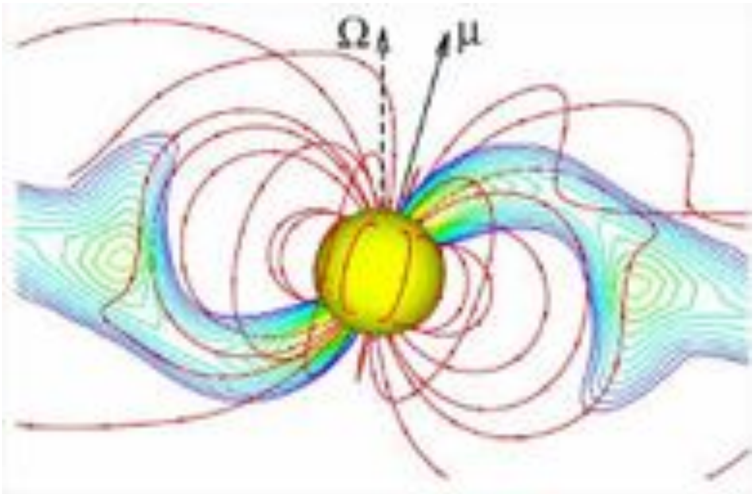
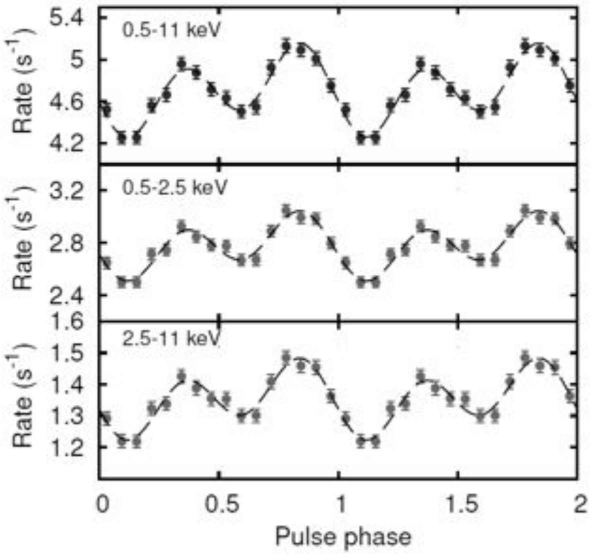
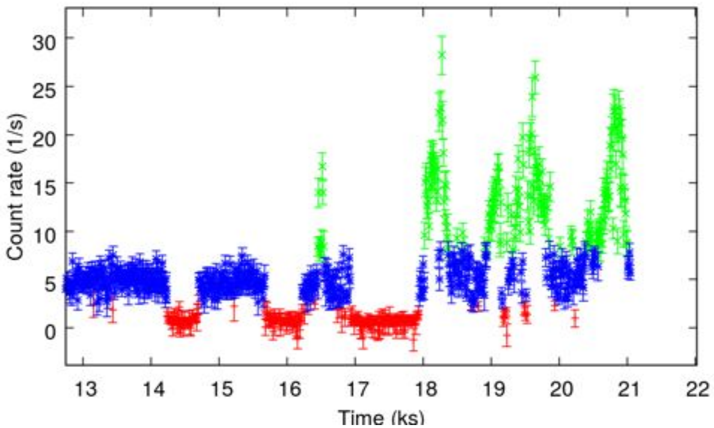


Coherent X-ray pulsations. Accretion power?

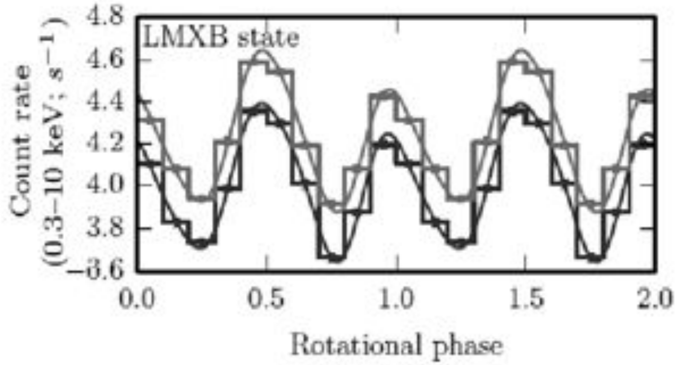


XSS J12270-4859 [Papitto+ 2015, MNRAS]

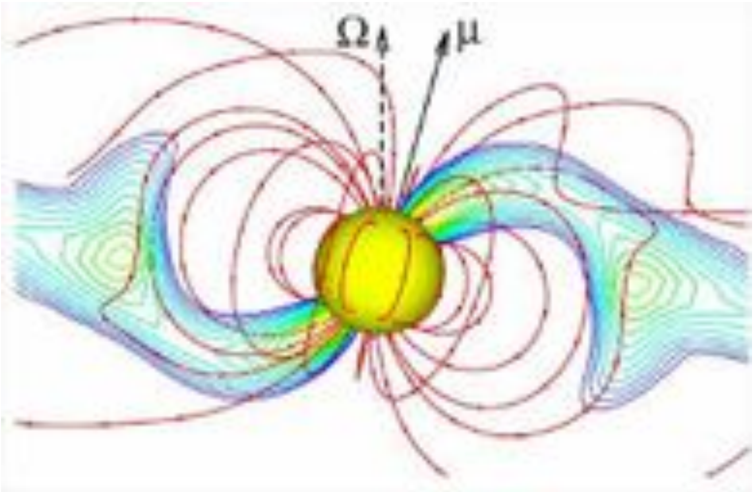


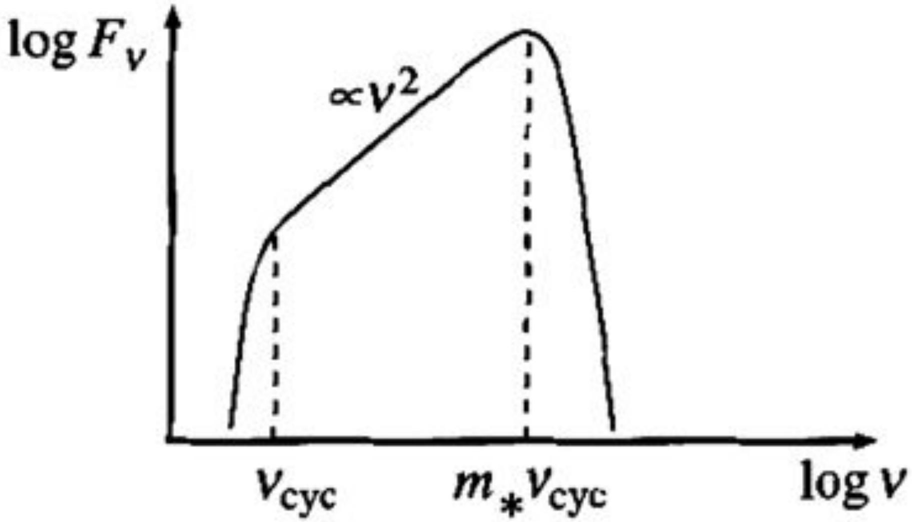


PSR J1023+0038 [Archibald+ 2015, ApJ]



Cyclotron emission from the hot-spots?



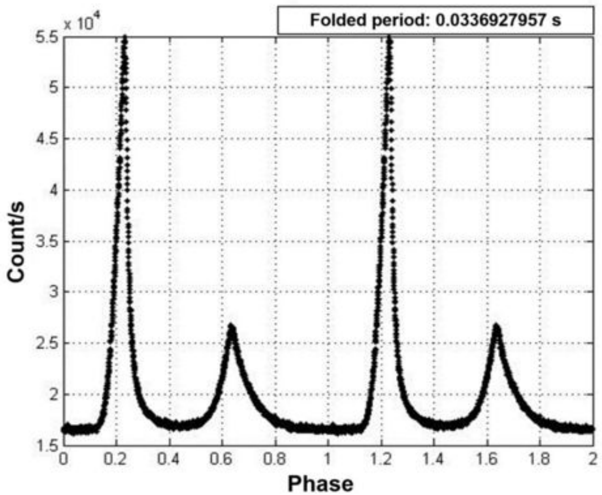


$$E_{cyc} \simeq 1\,(B_s/10^8\,\mathrm{G})\;\mathrm{eV}$$

$$L_{cyc} \simeq 3 \times 10^{29} \left(\frac{A}{100\,\mathrm{km}^2}\right) \left(\frac{kT_{el}}{100\,\mathrm{keV}}\right) \mathrm{erg\ s^{-1}}$$

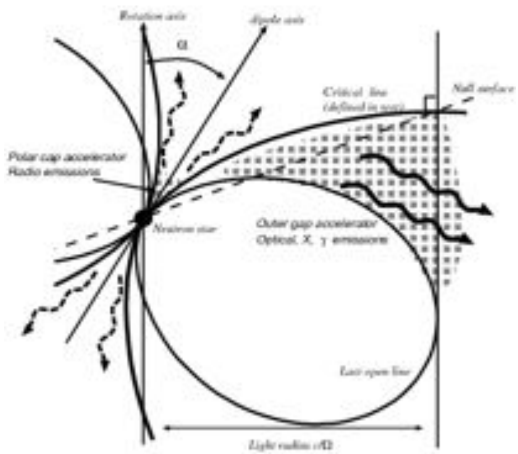
$\sim$30 times lower than observed luminosity even for very large spots

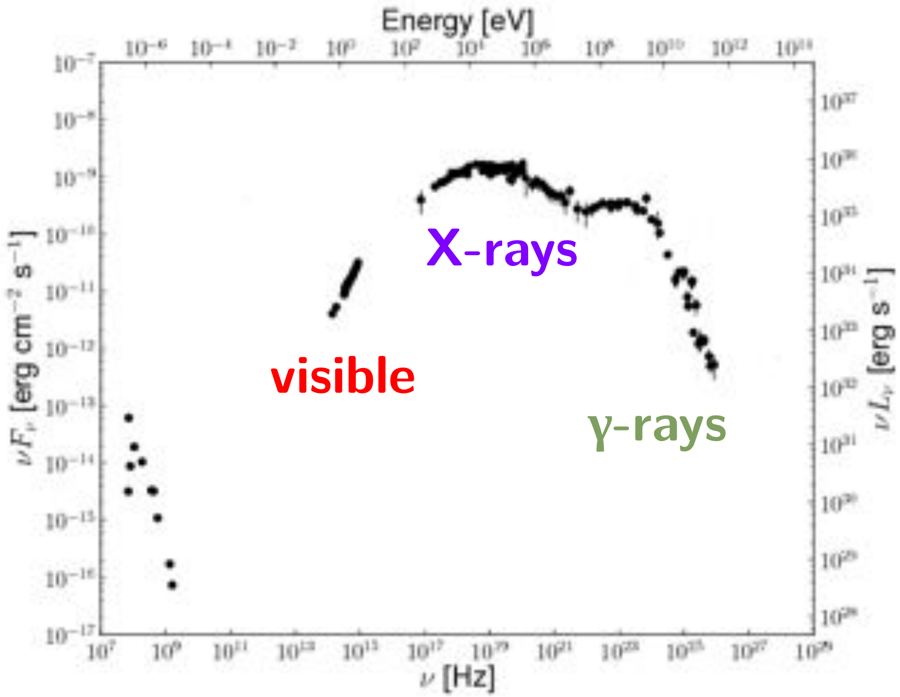
Rotationally-powered optical pulsations



Crab/Vela/Geminga

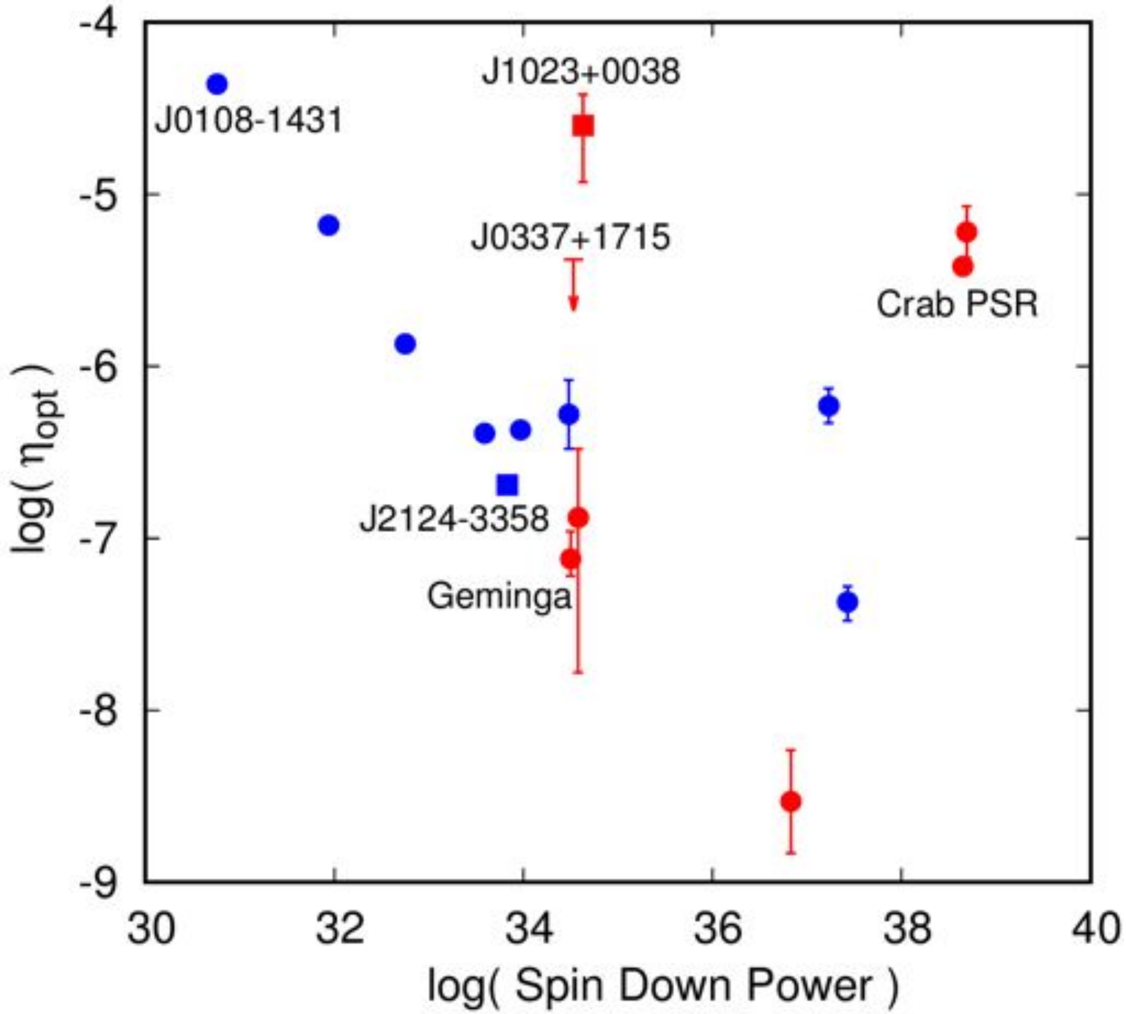
Synchrotron emission of $\sim$ MeV electrons





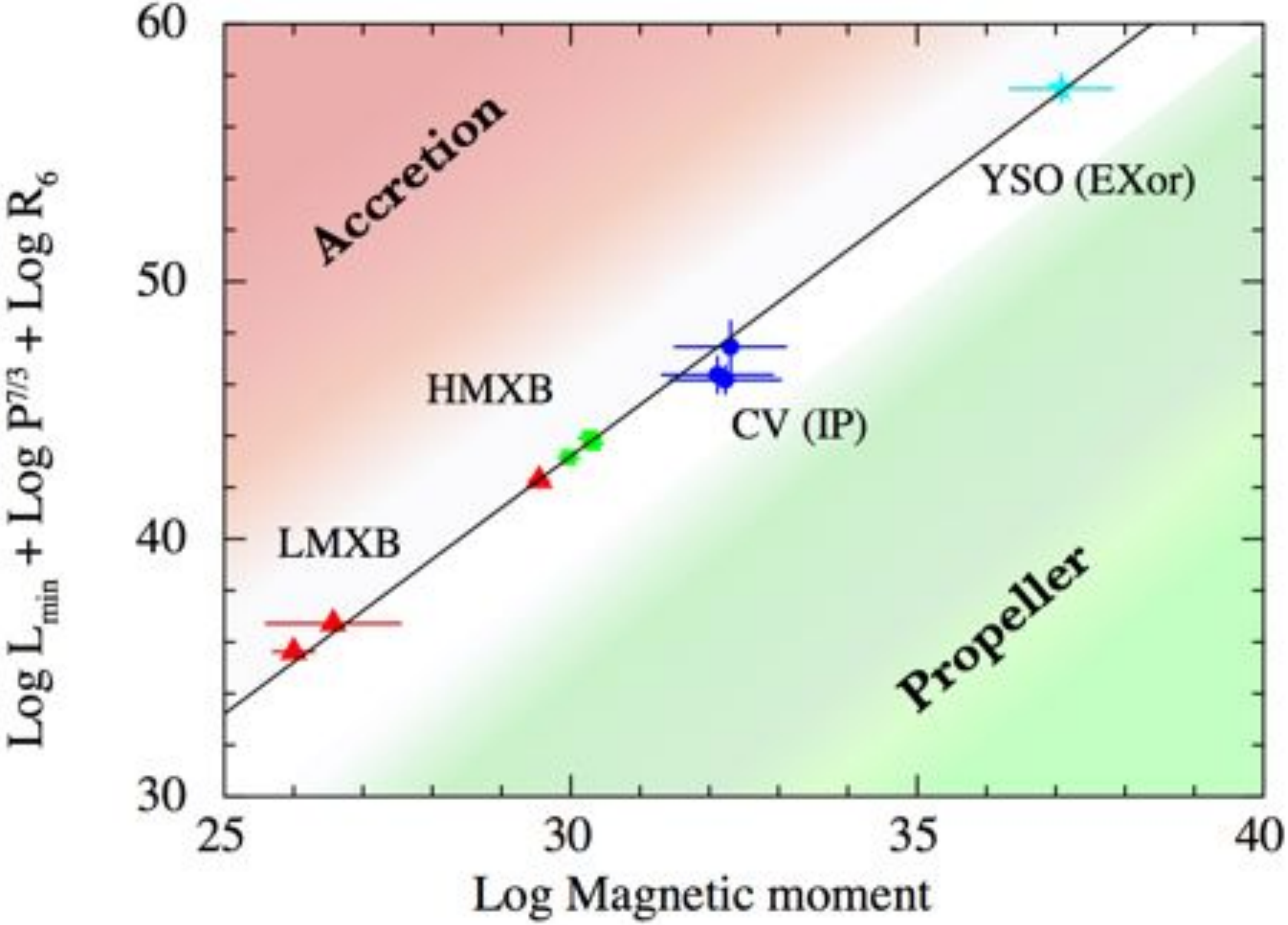
A very efficient optical rotationally-pwd pulsar

L(B-band)/Lspin-down = 5×10^{-4}



Optical pulsars

Non-pulsed optical emission


Accretion
Propeller
LMXB
HMXB
CV (IP)
YSO (EXor)
60
50
40
30
25
30
35
40
Log Magnetic moment
Log L_min + Log P^7/3 + Log R_6

Propeller Onset

Simple theory

$$L_{\rm lim} \sim 1.97 \times 10^{38}\, \xi^{7/2}\, \mu_{30}^{2}\, P^{-7/3}\, M^{-2/3}\, R_6^{-1}$$

From observations

$$r_{\rm m} = k\,(\mu^{\alpha}\, L^{-\gamma}\, R^{-\gamma})^{\frac{2}{3\beta}}\,, \qquad (5)$$

which is independent of the central mass object. For standard accretion theory values $\alpha = 2, \beta = 7/3$, and $\gamma = 1$ we derive

$$r_{\rm m} = (3.3 \pm 0.5) \times 10^{8} \left(\mu_{30}^{4}\, L_{36}^{-2}\, R_6^{-2}\, M\right)^{\frac{1}{7}} \ {\rm cm}, \qquad (6)$$

with L_{36} the accretion luminosity in units of 10^{36} erg s^{-1}. Eq. (3) instead becomes

$$L_{\rm lim} \sim 1.65^{+0.94}_{-0.60} \times 10^{37}\, \mu_{30}^{2}\, P^{-7/3}\, M^{-2/3}\, R_6^{-1} \ {\rm erg\ s^{-1}}. \qquad (7)$$

Need an advanced theory of disk–magnetosphere interaction

Two classes of high energy sources contain magnetars

(They are in highly absorbed regions in the galactic plane)

	Soft Gamma Repeaters SGRs (1987)	Anomalous X-ray Pulsars AXPs (1995)
• No. of sources	~10	~10
• Spin Period	2-8 s	2-12 s
• Period Derivative	$\sim 10^{-11}$ s/s	$\sim 10^{-11}$-5×10^{-13} s/s
• Isolated	yes	yes
• Recurrent Bursts	$\sim 10^{38}$-10^{41} erg/s	$\sim 10^{37}$-10^{38} erg/s
• Giant Flares	yes	no
• Persistent emission	$\sim 10^{35}$ erg/s	$\sim 10^{34}$-10^{35} erg/s
• Association to SNRs	?	in some cases
• Radio pulsations	?	in some cases

SGR Bursts

- Concentrated in time ("outbursts")
- Relatively simple profiles (faster rise than decay)
- Broad distribution of wait times (~7 decades) : similar to that of earthquakes; no waiting-time correlations
- Energy distribution $dN/dE \sim E^{-5/3}$: similar to earthquakes
- Most bursts release ~10^{38}-10^{41} ergs

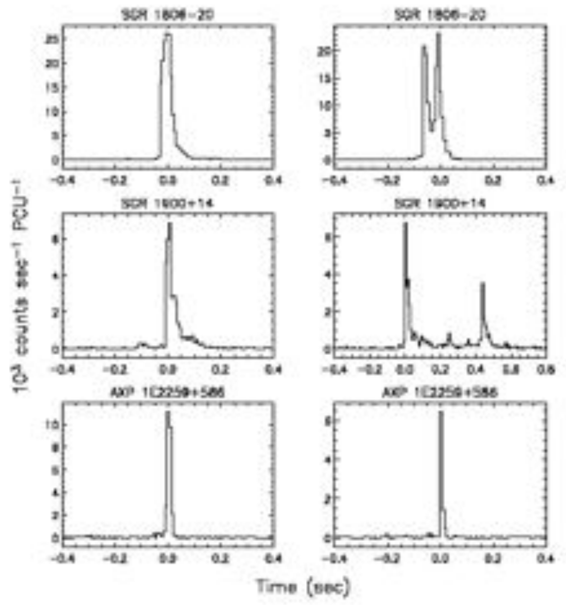
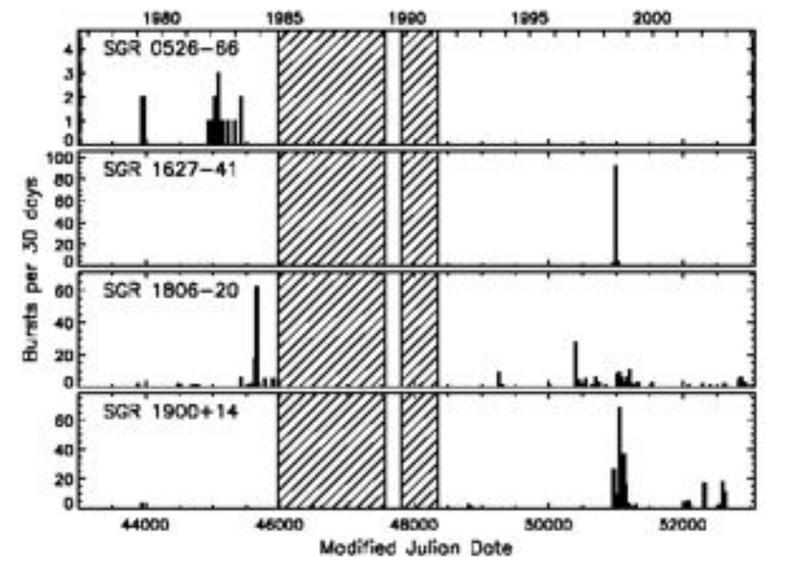
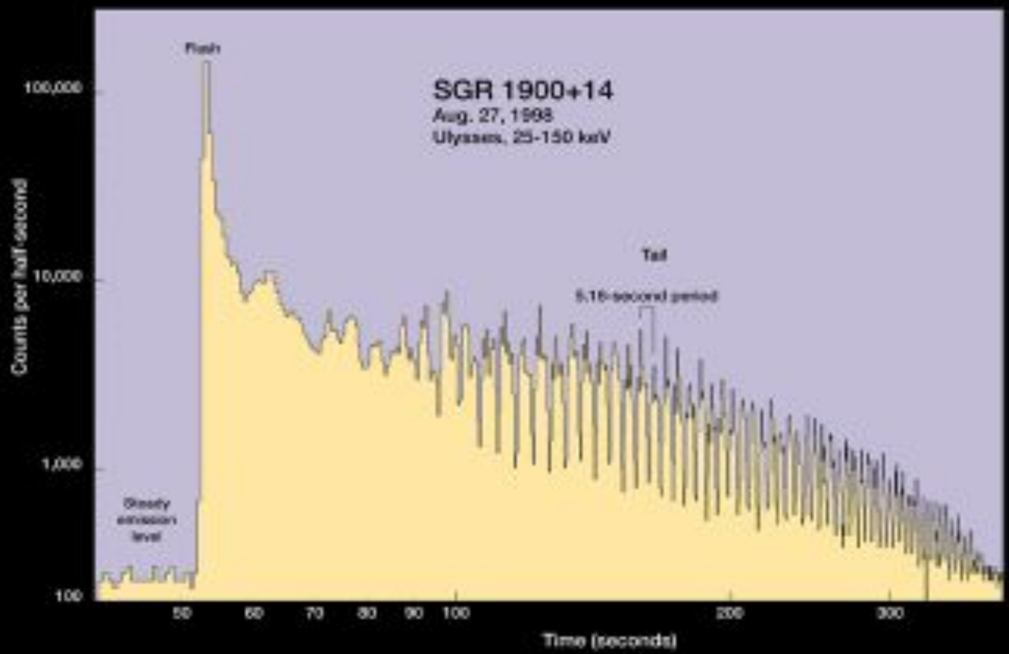


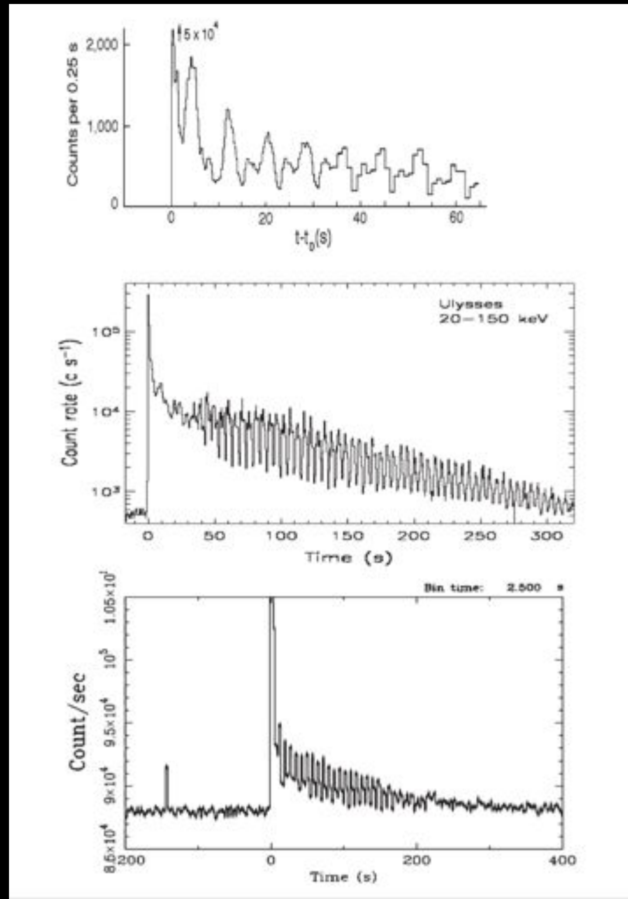
Fig. 14.1. A selection of common burst morphologies recorded from SGR 1806−20, SGR 1900+14 and 1E 2259+586, as observed with the *RXTE* PCA. All light curves display counts in the energy range 2−20 keV, with a time resolution of 7.8 ms. See text for further details.



Giant Flares

- 1979 March 5 from SGR 0526–66: energy released ~10^{44} ergs
- 1998 August 27 from SGR1900+14: energy released ~10^{44} ergs
- Main peak ~0.2 s; variability down to ms, hard BB-like spectrum (kT~ 100 keV)
- 2-3 min long ringing tail: (nearly) exponential decay
  pulsations at 5-8 s (spin period)
  TB temperature of ~30-50 keV.
- In Magnetar model: GFs due to large scale rearrangements of core B-field

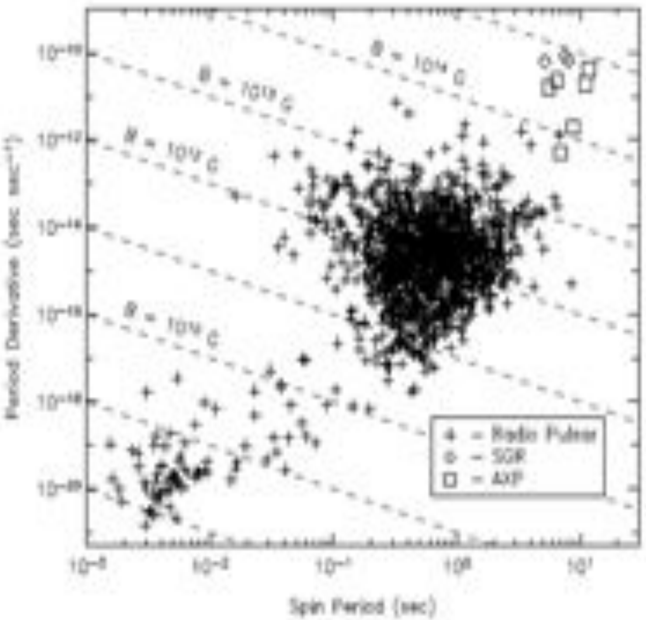




- Period range: 5-12 s
- Characteristic ages: 10^3-10^5 yr

RAPID SPIN DOWN

- Estimated B ~ 10^{14} - 10^{15} G (see table)

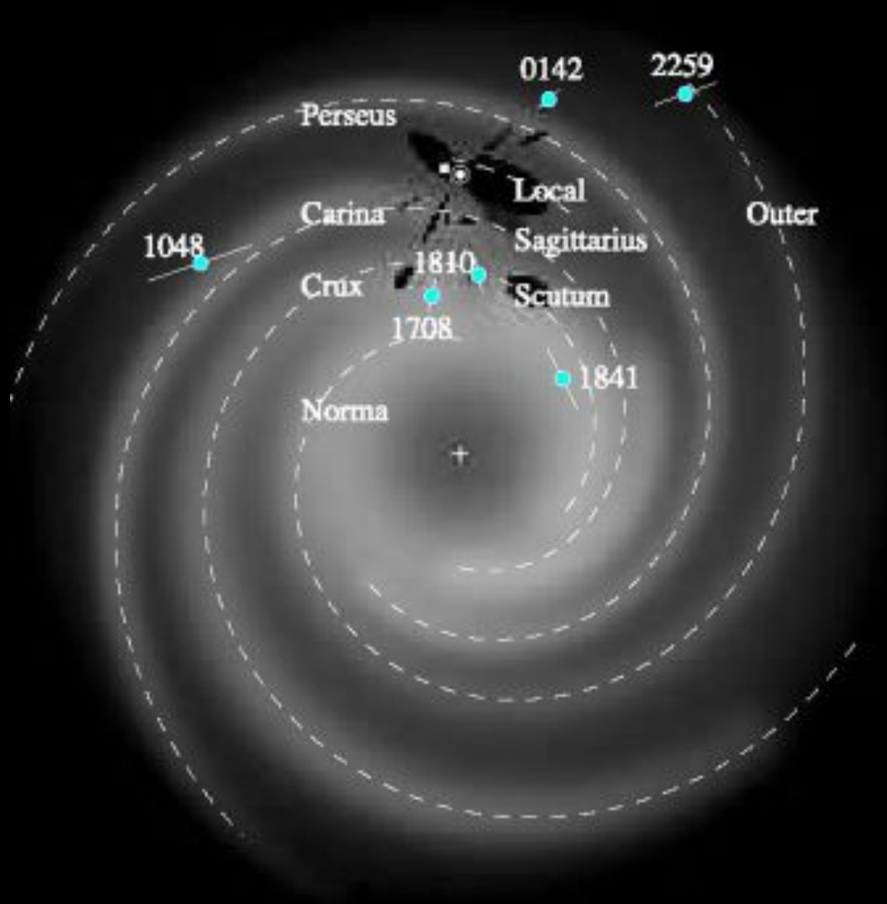


Source	Period (s)	Period Derivative (10^{-11} s s^{-1})	Magnetic Field[a] (10^{14} Gauss)	Spin down Age[b] (10^3 years)
SGR 0526−66	8.0	6.6	7.4	1.9
SGR 1627−41	6.4?	–	–	–
SGR 1806−20	7.5	8.3−47	7.8	1.4
SGR 1900+14	5.2	6.1−20	5.7	1.3
CXOU 010043.1−721134	8.0	–	–	–
4U 0142+61	8.7	0.20	1.3	70
1E 1048.1−5937	6.4	1.3−10	3.9	4.3
1RXS J170849−400910	11.0	1.9	4.7	9.0
XTE J1810−197	5.5	1.5	2.9	5.7
1E 1841−045	11.8	4.2	7.1	4.5
AX J1844−0258	7.0	–	–	–
1E 2259+586	7.0	0.048	0.60	220

– $B_{dipole} = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G (the mean surface dipole field)

– Characteristic age of pulsar spinning down via magnetic braking ($P/2\dot{P}$)

Magnetars in our Galaxy



Magnetars: Neutron Stars powered by magnetic energy

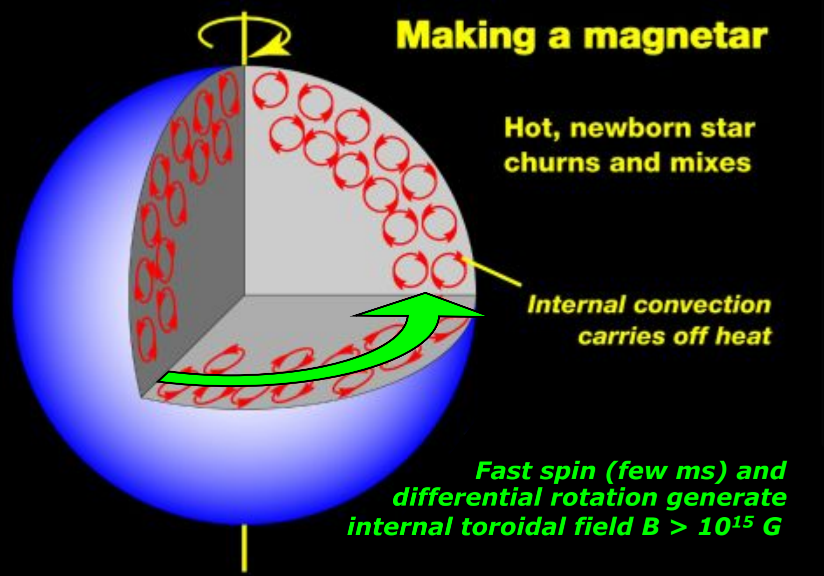
- "Magnetars" (MAGNEtic sTARS): neutron stars with very high magnetic fields ($B > 10^{14}G$)
  Why magnetic energy ? (Magnetic energy propagating through fractures in the crust)

Persistent luminosity 10-100 times higher than spin down power

-> rotational energy ruled out

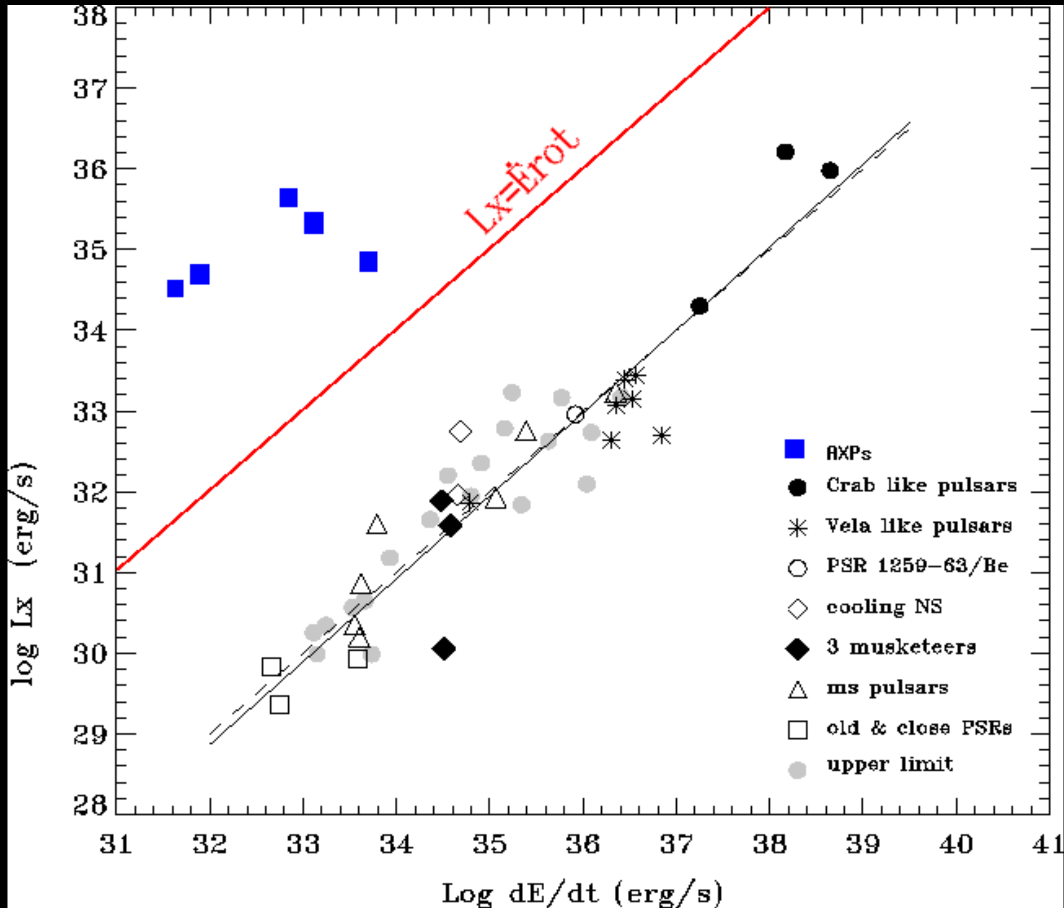
Recurrent flares reach 10^{41} erg/s ~ 1000 L_{Edd} , giant flares 10^{44} erg/s ~ 10^6 L_{Edd}

-> accretion energy ruled out



Persistent X-ray emission of AXPs

Rotational energy losses are orders of magnitudes smaller (10^{32-33} erg/s) than observed L_x!!



$\dot{E}_{rot} = I\Omega\dot{\Omega} = 4\pi^2 I\dot{P}P^{-3}$

Magnetars: Neutron Stars powered by magnetic energy

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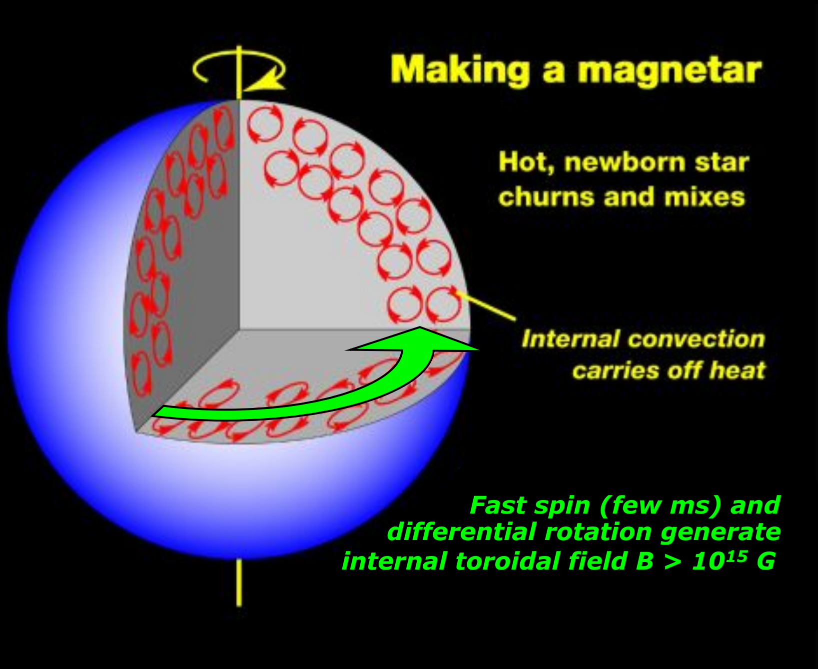
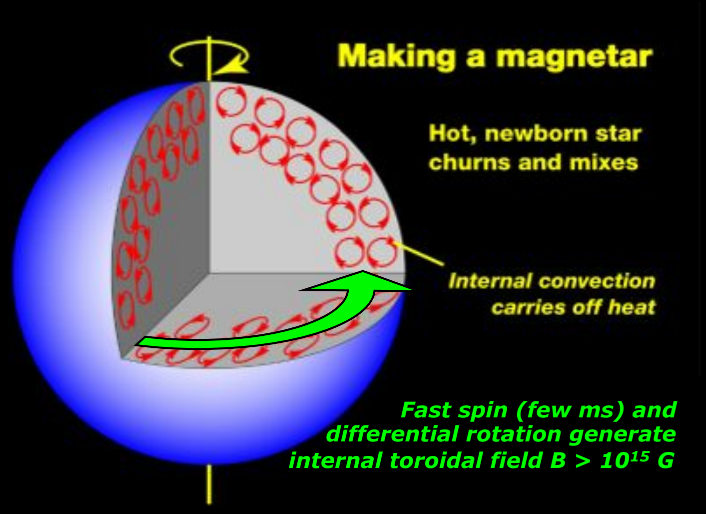
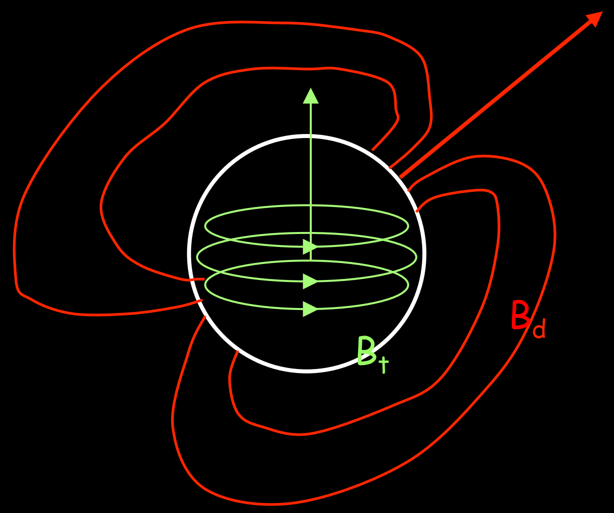


The B-field of Magnetars

Very strong internal *B*-fields in a newborn differentially rotating fast-spinning neutron star

For initial spin periods of P_i~1–2 ms, differential rotation can store ~$10^{52}(Pi/1\ ms)^2$ ergs, that can be converted into a magnetic field of up to $3x10^{17}\ (P_i/1ms)^{-1}$ G.
(efficient dynamo might be limited to ~$3x10^{16}$ G) (Duncan & Thompson 1992)





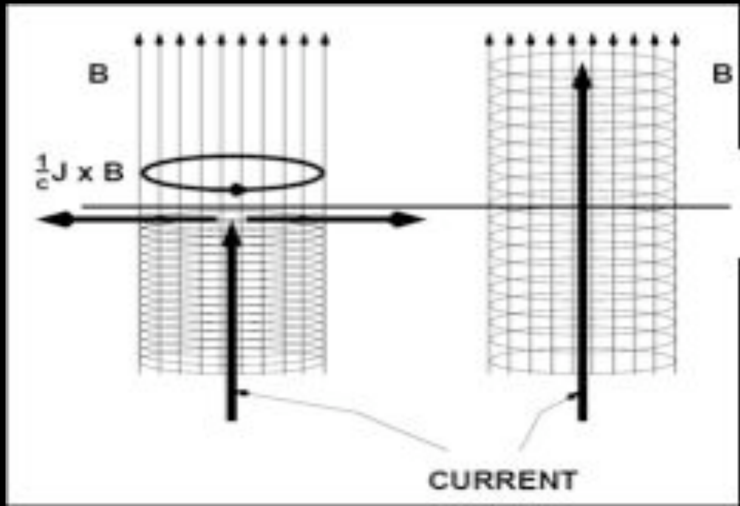
B_d ~ $10^{14\text{-}15}$ G outer dipole field (spin-down, pulsations)
inferred from spin-down rate (and confirmed through the energetics and fast variability properties of the "ringing tail" of Giant Flares from SGRs)

B_t > 10^{15} G inner toroidal field (energy reservoir):
lower limit from: L(persistent) x age ~ 10^{47} ergs

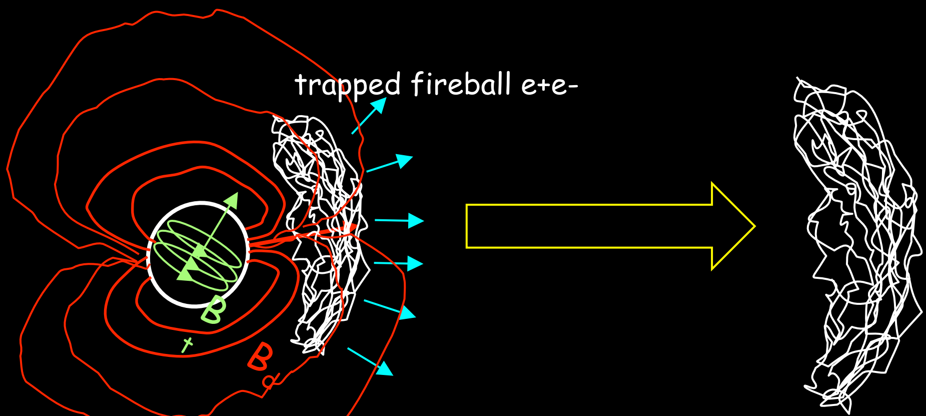
Bursts/Giant Flares in the Magnetar Model

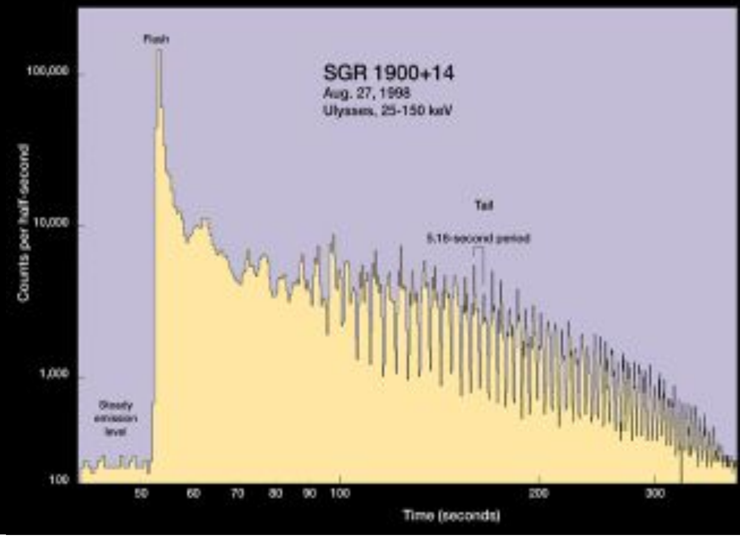
Internal field evolves through ambipolar diffusion, building up magnetic stresses below NS crust

- Magnetic elicity fed to NS magnetosphere by local crustquakes of various amplitude, giving rise to **Recurrent bursts**

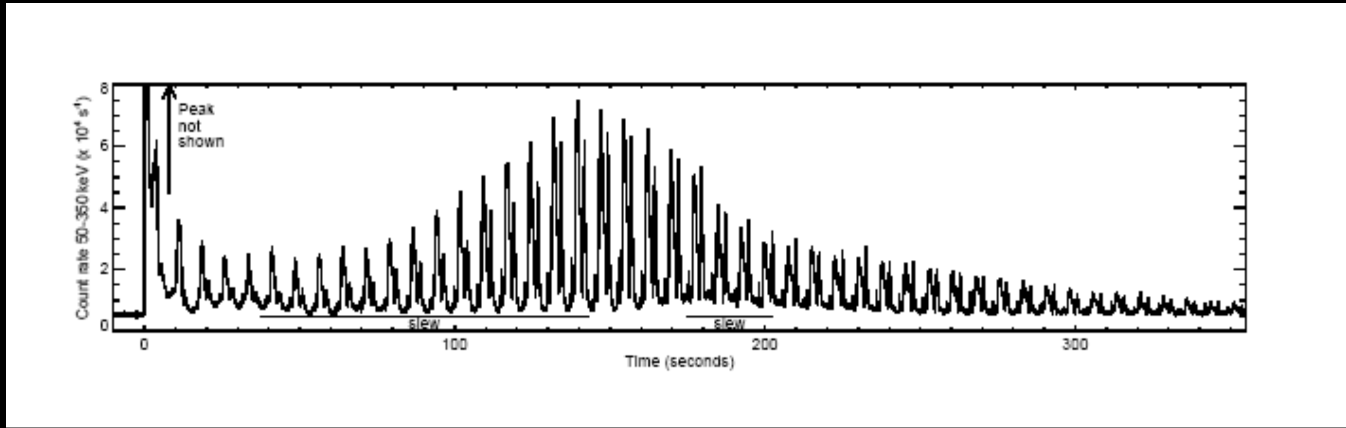


- **Giant flares** result from large-scale rearrangements of the core magnetic field:
- crustal yield strain is overcome, large-scale fracturing occurs that leads to sudden release of very large amounts of energy into the magnetosphere
- fireball of pair-dominated plasma expanding at ~ c -> Initial subsecond Spike of Giant Flares
- trapped fireball gives rise to ~300 s oscillating tail

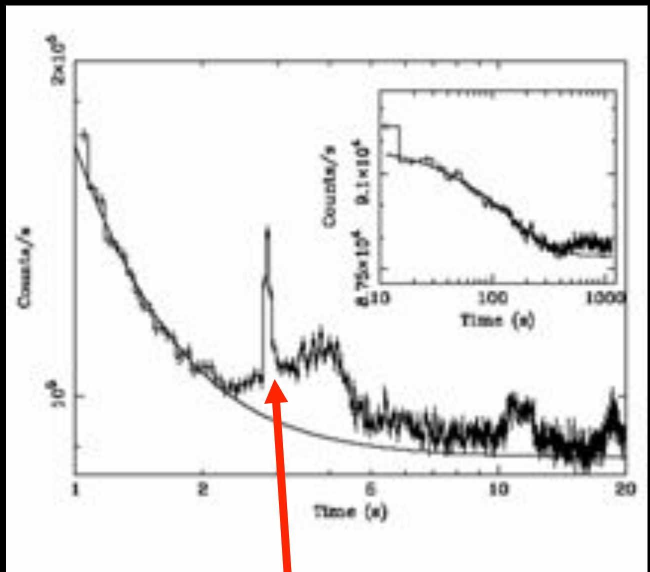




SGR 1806-20: Giant Flare of 2004 Dec 27



(Palmer et al. 2005
Hurley et al. 2005)



Moon reverberation seen !

Giant Flare Source Assumed distance	March 5, 1979 SGR 0526-66 55 kpc	August 27, 1998 SGR 1900+14 10 kpc	December 27, 2004 SGR 1806-20 15 kpc
Initial Spike			
Duration (s) Peak luminosity (erg s^{-1}) Fluence (erg cm^{-2}) Isotropic Energy (erg)	$\sim$0.25 3.6 10^{44} 4.5 10^{-4} 1.6 10^{44}	$\sim$0.35 >3.7 10^{44} >5.5 10^{-3} >6.8 10^{43}	$\sim$0.5 (2÷5) 10^{47} 0.6÷2 (1.6÷5) 10^{46}
Pulsating tail			
Duration (s) Fluence (erg cm^{-2}) Isotropic Energy (erg) Spectrum Pulse Period (s)	$\sim$200 1 10^{-3} 3.6 10^{44} kT$\sim$30 keV 8.1	$\sim$400 4.2 10^{-3} 5.2 10^{43} kT$\sim$20 keV 5.16	$\sim$380 5 10^{-3} 1.2 10^{44} kT$\sim$15-30 keV 7.56

(Mereghetti et al. 2005)