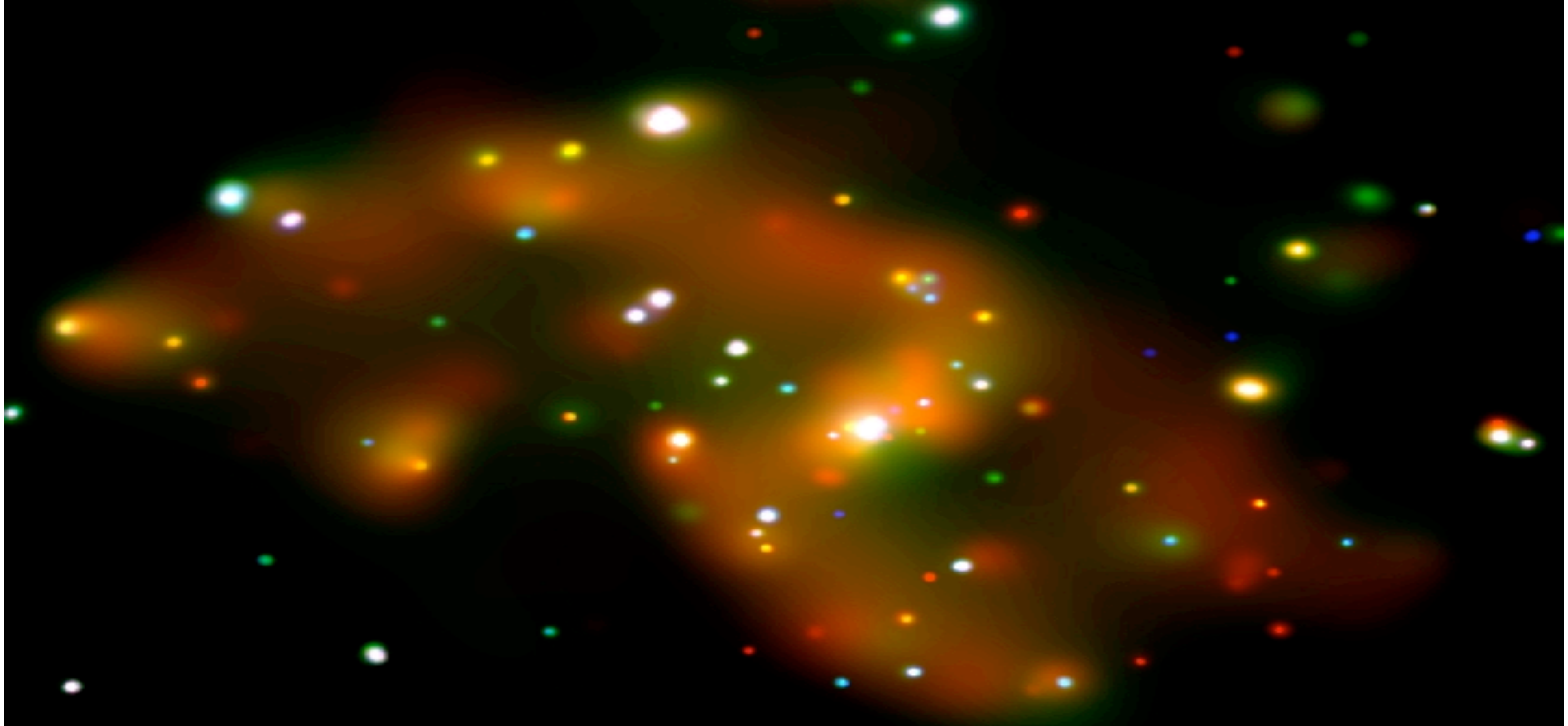
Young X-ray pulsars and ULXs



Roberto Soria *(MSSL)*

Thanks also to: **Rosalba Perna** *(JILA-Boulder)*
Luigi Stella *(INAF-Rome)*

Content

- What are the most luminous non-nuclear X-ray sources in galaxies?
(Ultraluminous X-ray sources = ULXs)

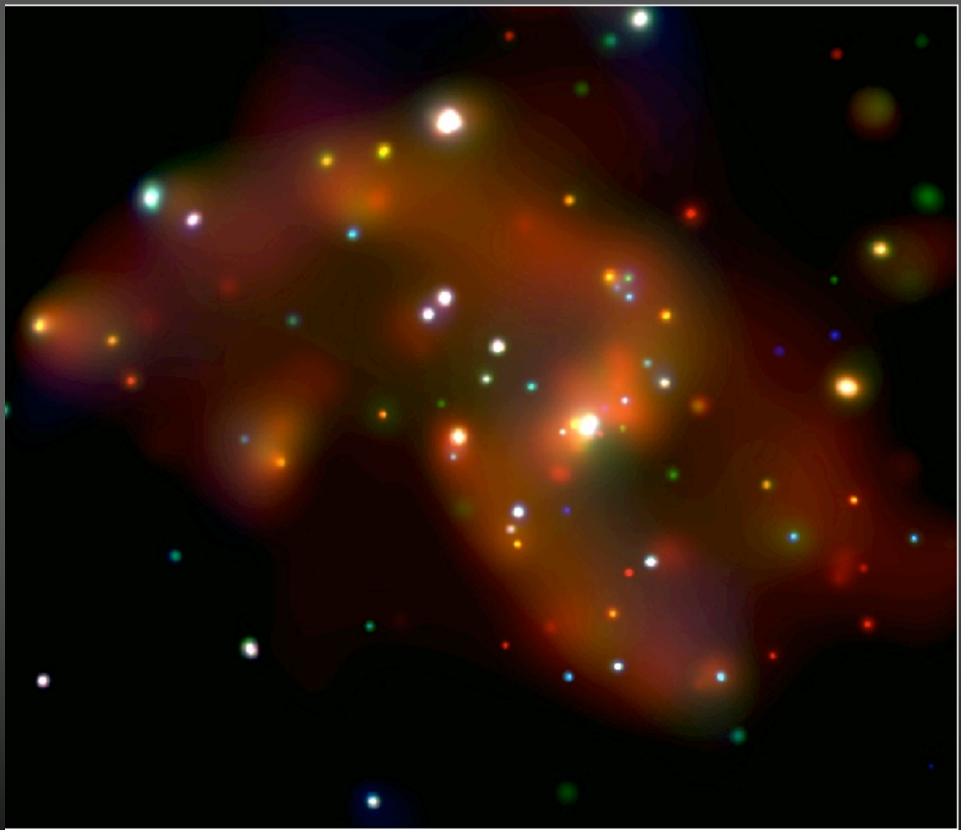
Black hole X-ray binaries powered by accretion?

Young neutron stars powered by spin-down?

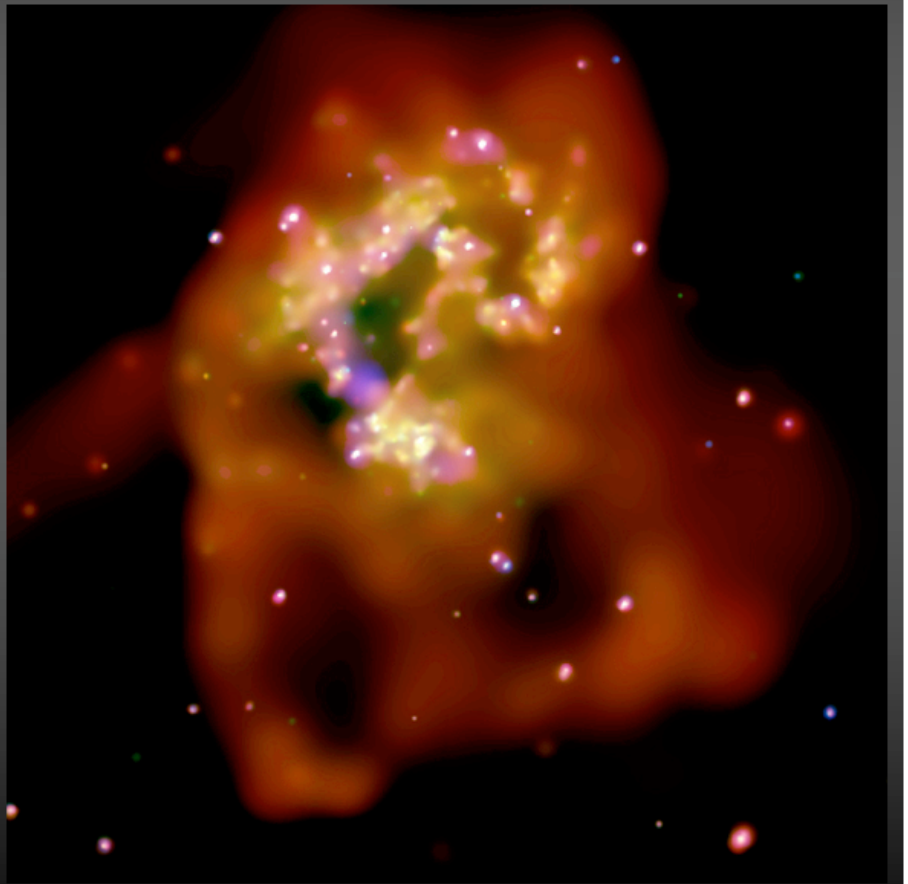
- Search for luminous young X-ray pulsars in the Milky Way and nearby galaxies
- Constraints to the initial NS spin distribution

What are ultraluminous X-ray sources (ULXs)

Non-nuclear X-ray sources
with apparent $L_x \sim 10^{39}$-10^{40} erg/s



NGC6946 (d ~ 6 Mpc)



Antennae (d ~ 20 Mpc)

What are ultraluminous X-ray sources (ULXs)

Non-nuclear X-ray sources
with apparent $L_x \sim 10^{39}$-10^{40} erg/s

Most luminous X-ray source in the Milky Way:
GRS 1915+105: $L_x \sim 1 \times 10^{39}$ erg/s

Peak luminosity of MW X-ray binaries in outburst
$L_x \sim 0.5$-1×10^{39} erg/s

Eddington luminosity for "typical" stellar-mass BHs:
$L_x \sim 1 \times 10^{39}$ erg/s

What are ultraluminous X-ray sources (ULXs)

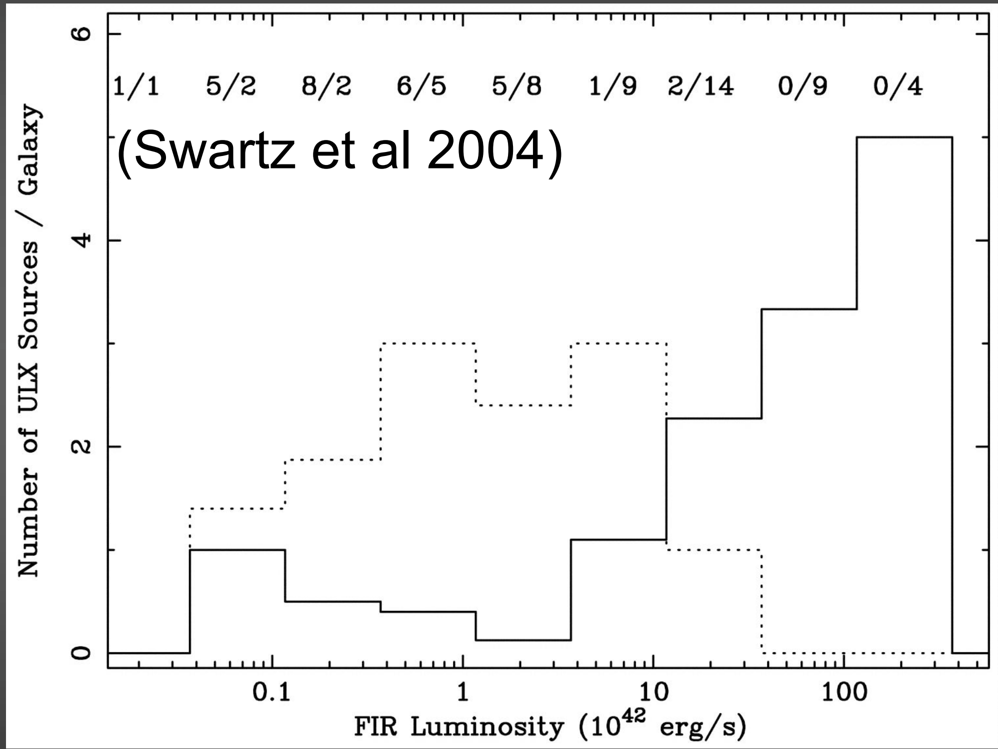
Non-nuclear X-ray sources
with apparent $L_x \sim 10^{39}$-10^{40} erg/s

If ULXs are powered by accretion, they require either:

- Higher BH masses (100 M_{sun}? 1000 M_{sun}?)
- Moderately beamed emission
- Super-Eddington luminosity

But no such problem (no Eddington limit)
if ULXs are not powered by accretion

Most luminous X-ray sources ($L_x \sim 10^{40}$ erg/s) found in starburst, starforming or colliding galaxies *(not in massive ellipticals)*



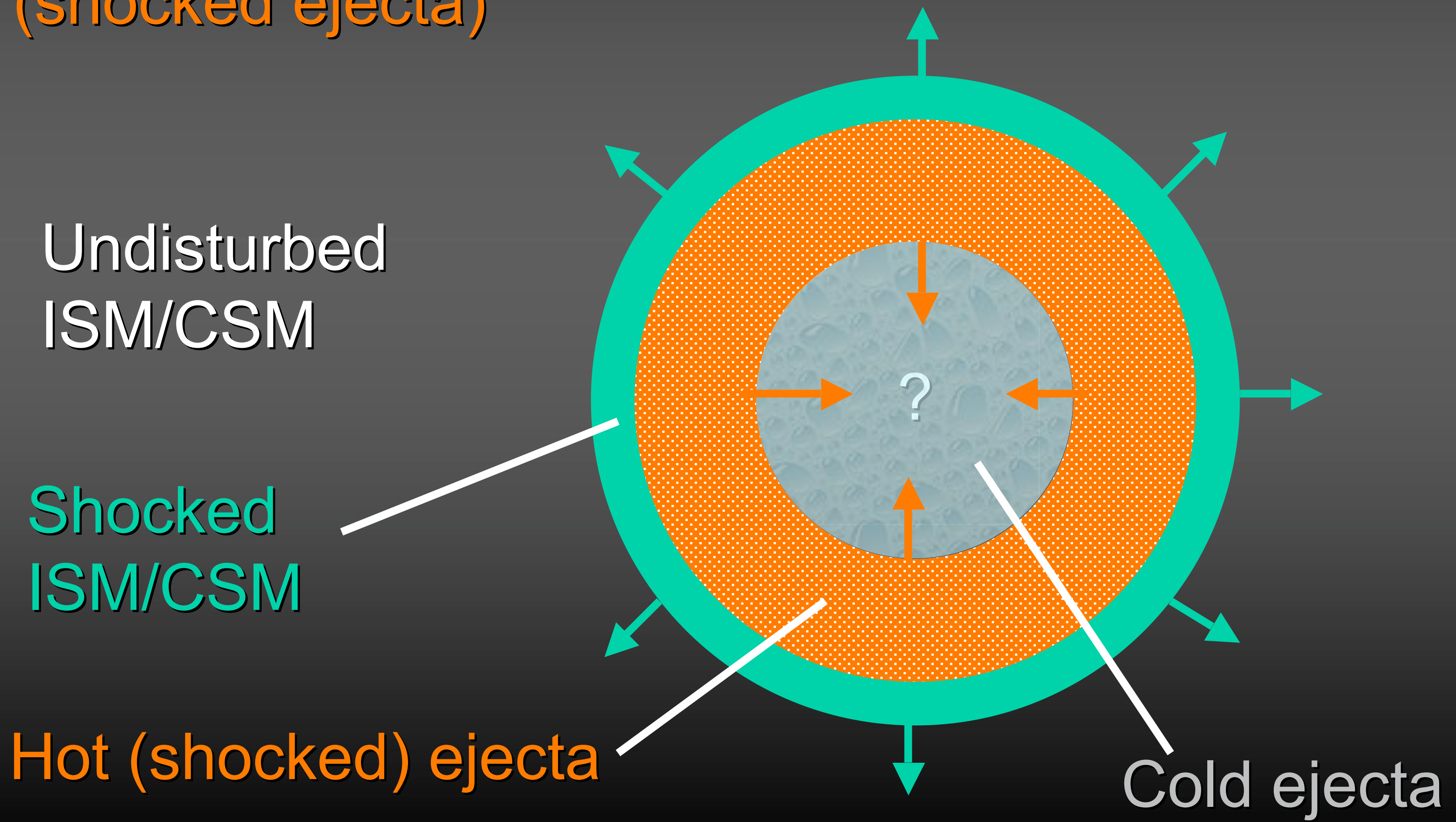
High-mass X-ray binaries?

Supernovae, young supernova remnants?

Young pulsars?

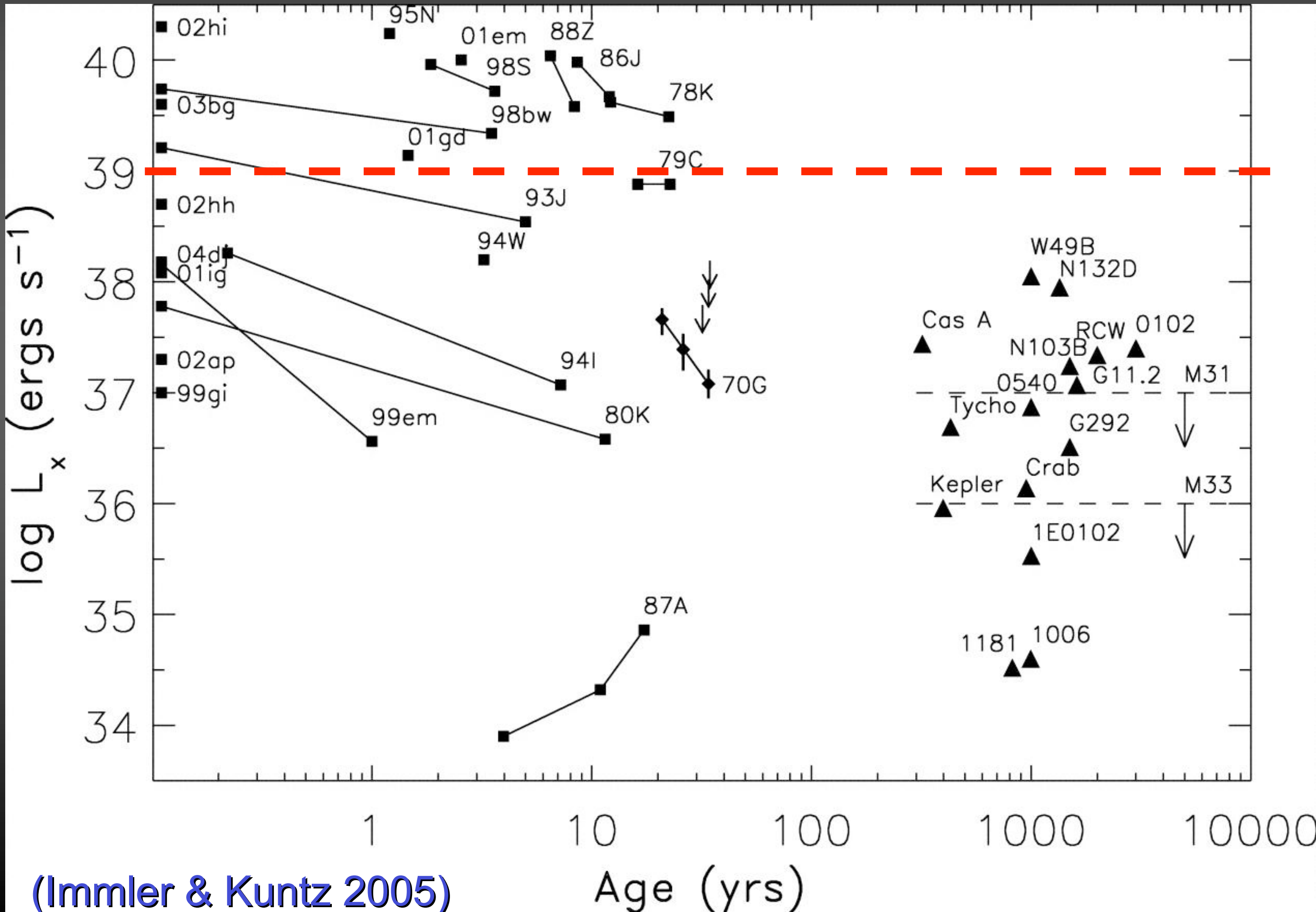
X-ray emission from supernovae

Supernovae produce (mostly) thermal emission from shocked gas after the *reverse shock* (shocked ejecta)

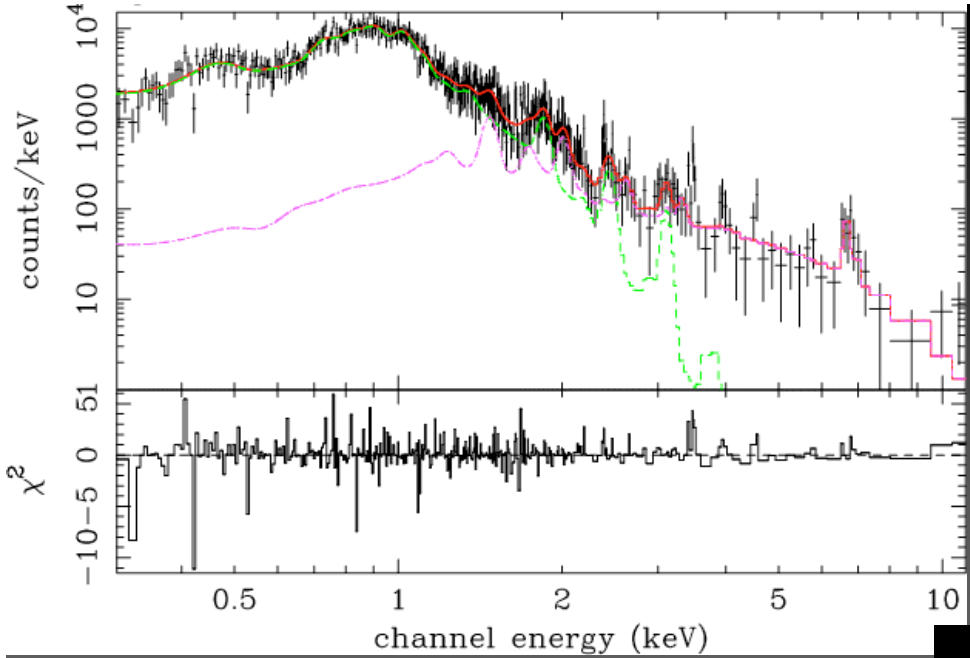


Young SNe can have $L_x \sim 10^{39} - 10^{41}$ erg/s

But steady decline over ~ 1000 yr



(Immler & Kuntz 2005)



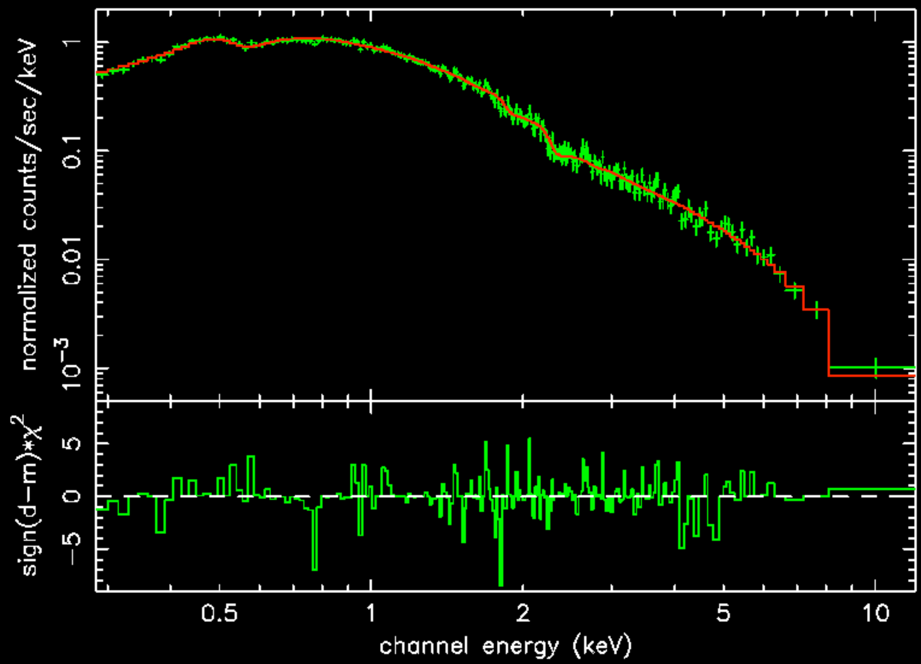
SN1993J in M81

(Zimmermann & Aschenbach 2003)

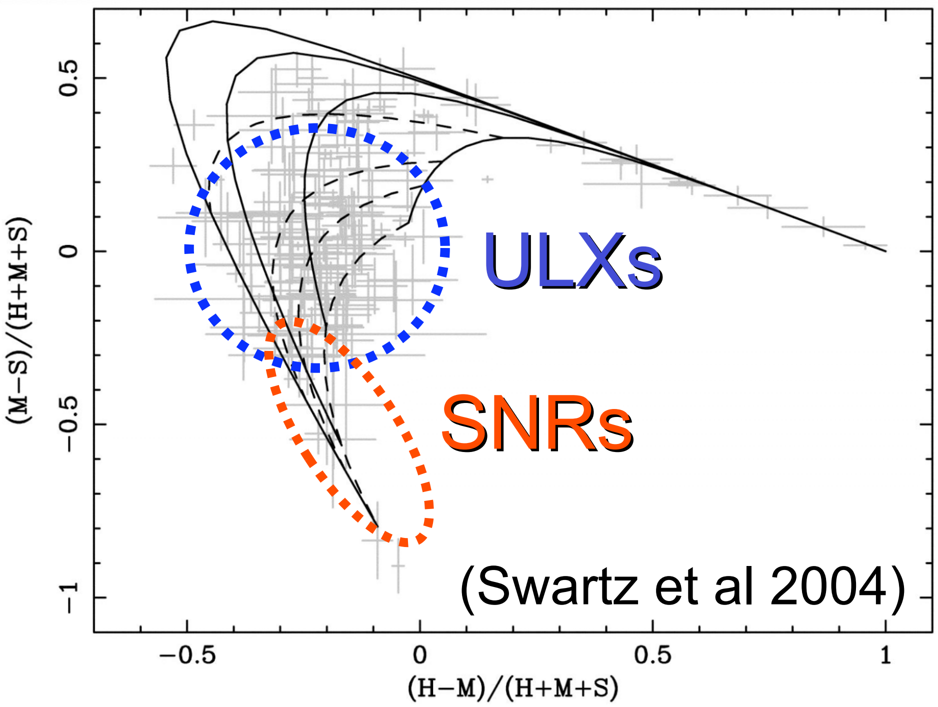
Mekal spectrum

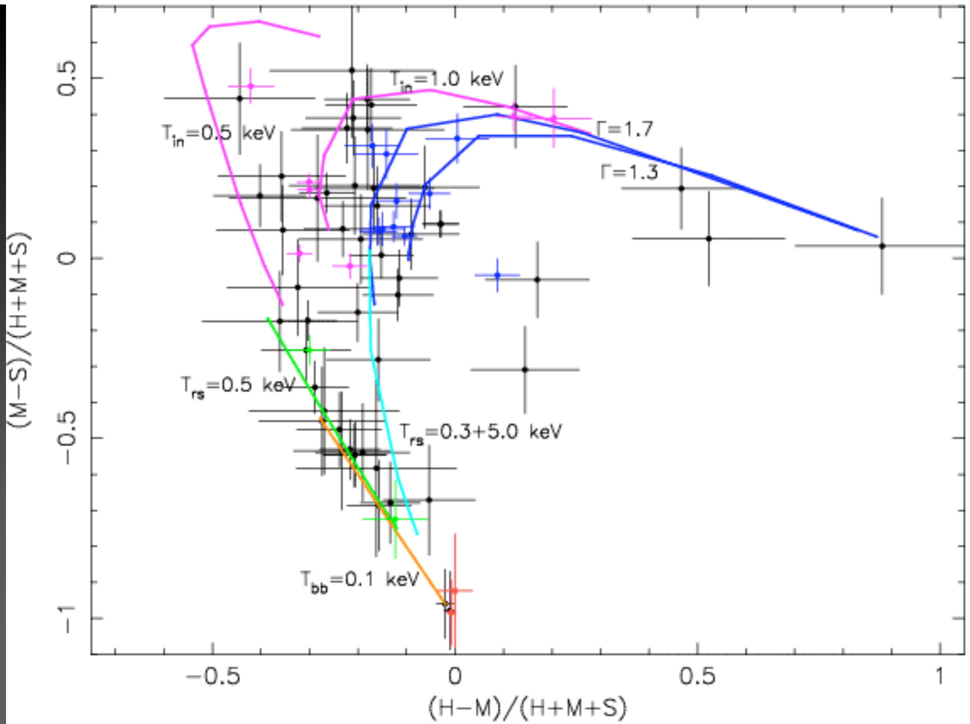
ULX in Holmberg II

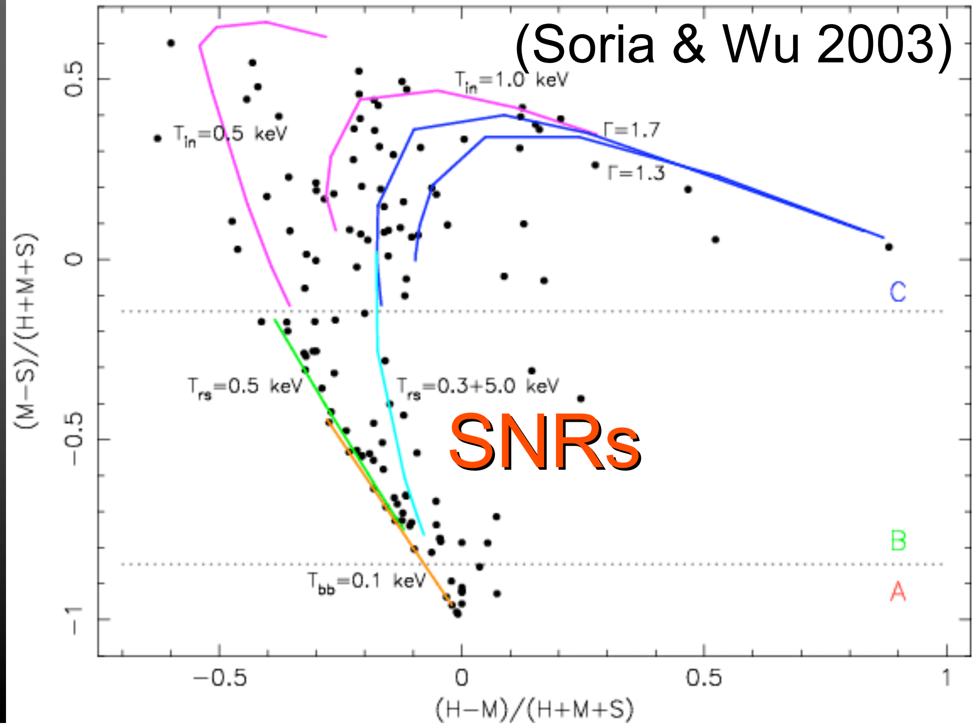
Power-law + diskbb



Young supernovae cannot explain ULXs (= power-law-dominated X-ray spectra)



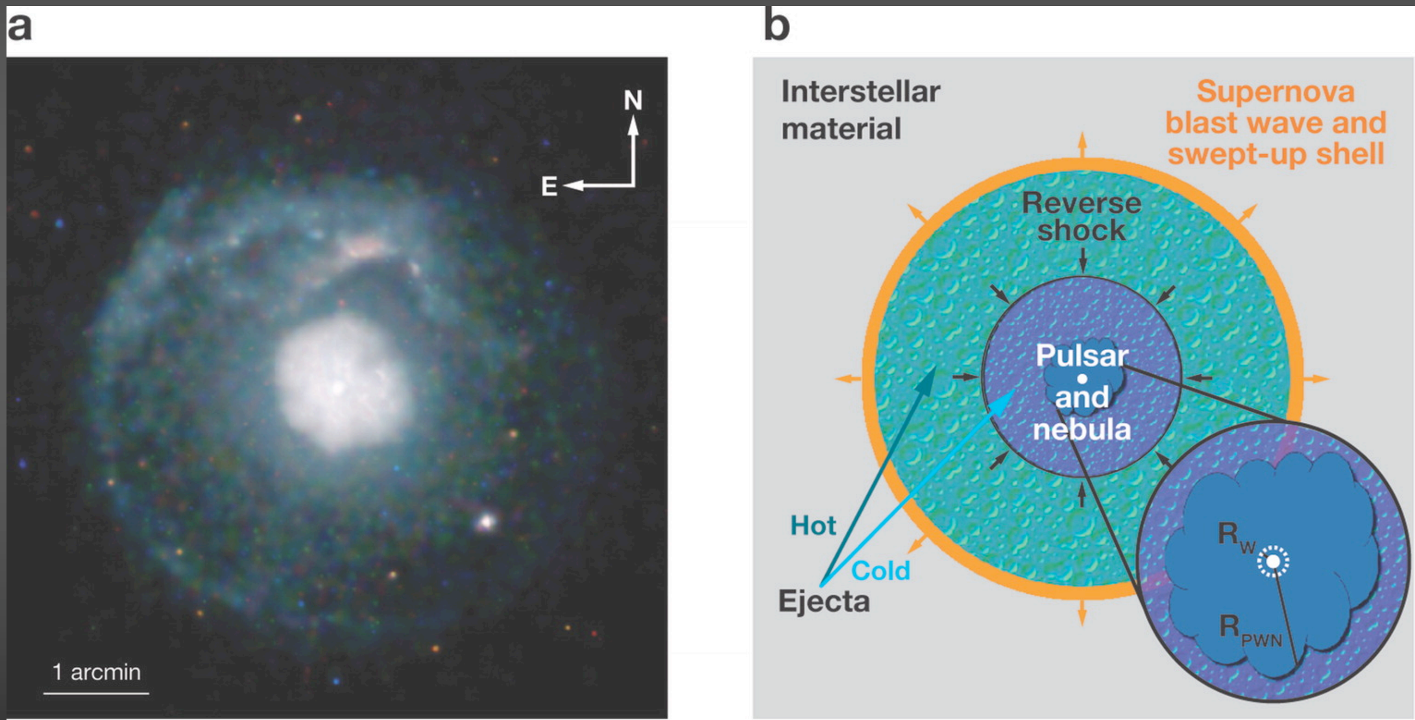




SNe and SNR have softer X-ray colours than ULXs, X-ray pulsars and XRBs

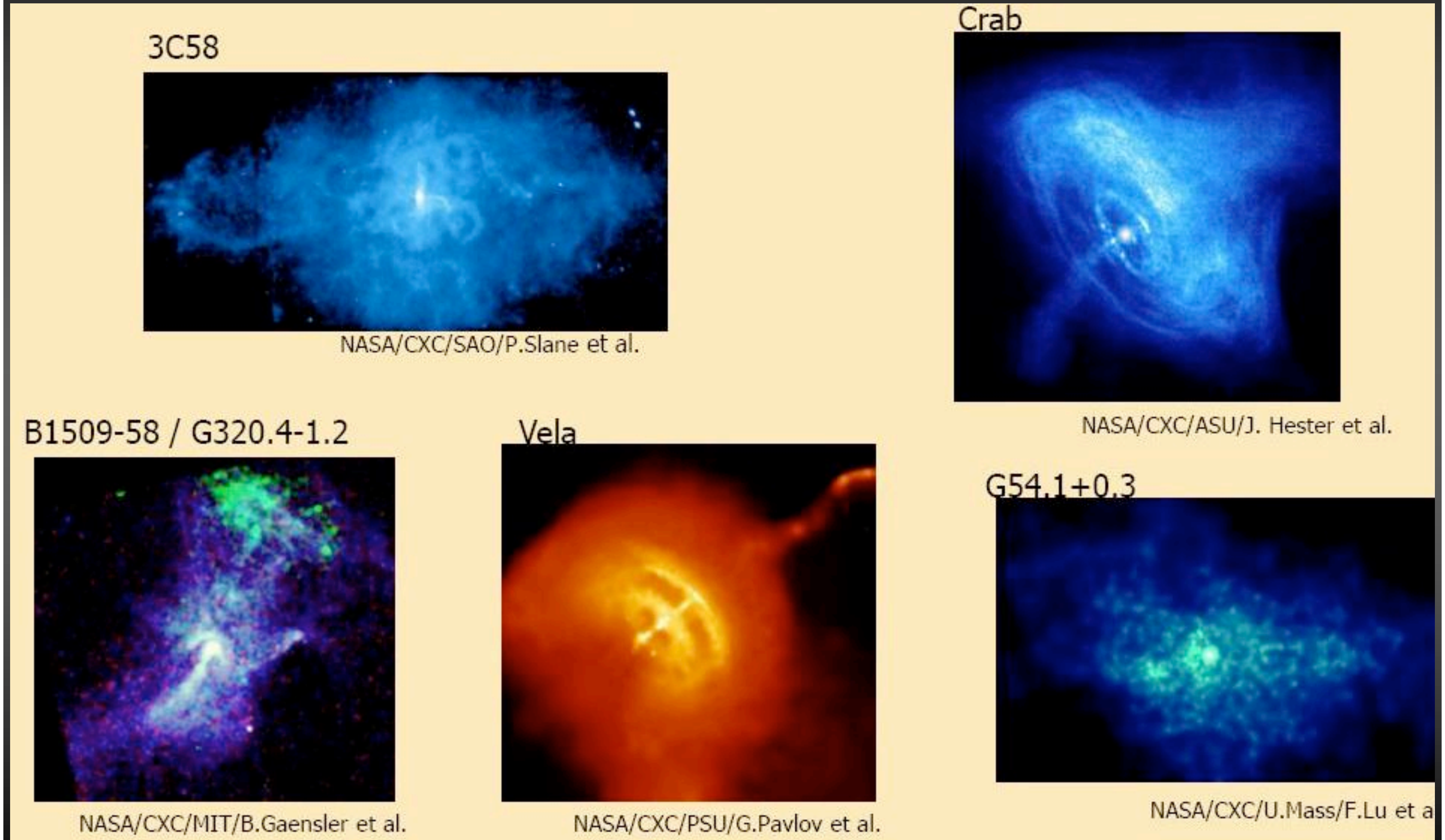
Composite supernova remnants:

fast-spinning pulsar and pulsar wind nebula inside the expanding SN remnant



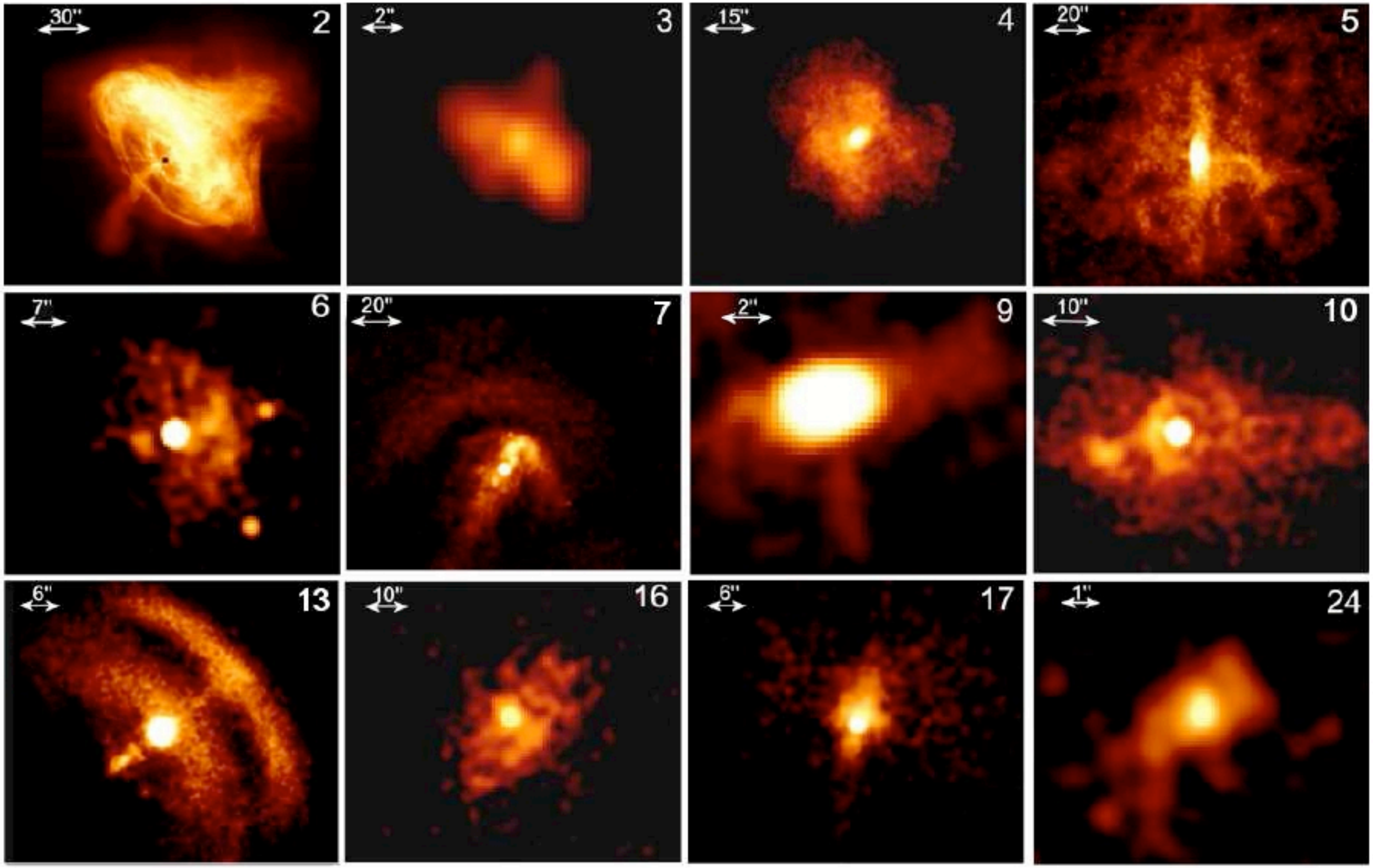
Gaensler BM, Slane PO. 2006.
Annu. Rev. Astron. Astrophys. 44:17–47

Gallery of X-ray bright pulsar wind nebulae



(Gaensler & Slane 2006)

Gallery of X-ray bright pulsar wind nebulae

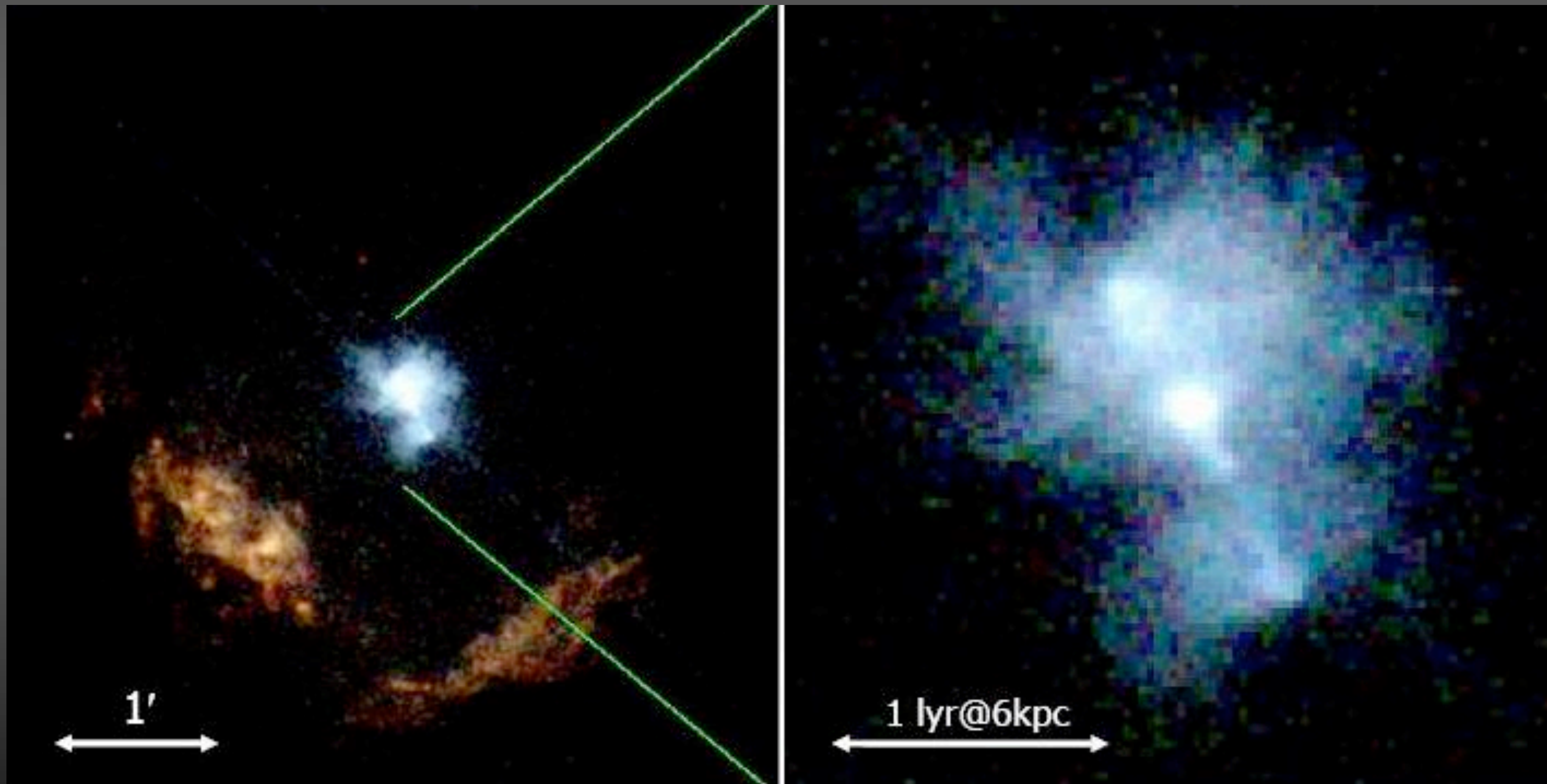


(Kargaltsev & Pavlov 2008)

Pulsar J1846-0258 (Kes 75)

Age ~ 900 yr
P = 324 ms
B = 5E13 Gauss

D = 6 kpc
Edot ~ 1E37 erg/s
L_x ~ 2E36 erg/s



155ks Chandra observation from 2006, Ng et al (2008)

Magnetospheric emission + wind nebula powered by pulsar spin-down

$$\dot{E}_{rot} = \frac{4\pi^2 \dot{P}}{P^3} = \frac{B^2 \sin^2\theta\, \Omega^4 R^6}{6c^3} \sim B^2 P^{-4}$$

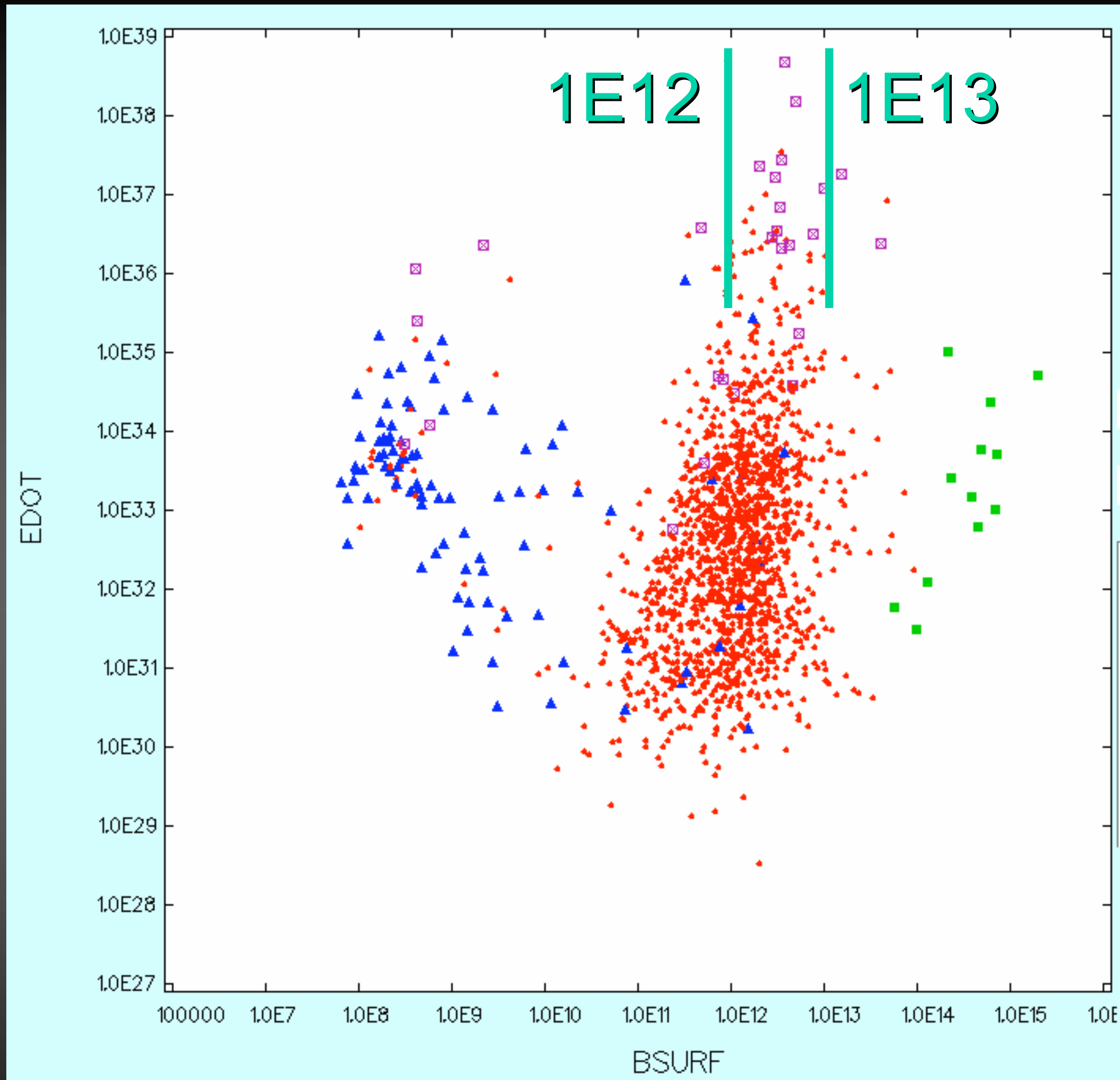
$$B \approx 6.4\times 10^{19} (P\dot{P})^{1/2}\ \mathrm{G}$$

From radio pulsar measurements and evolution models: magnetic field at birth

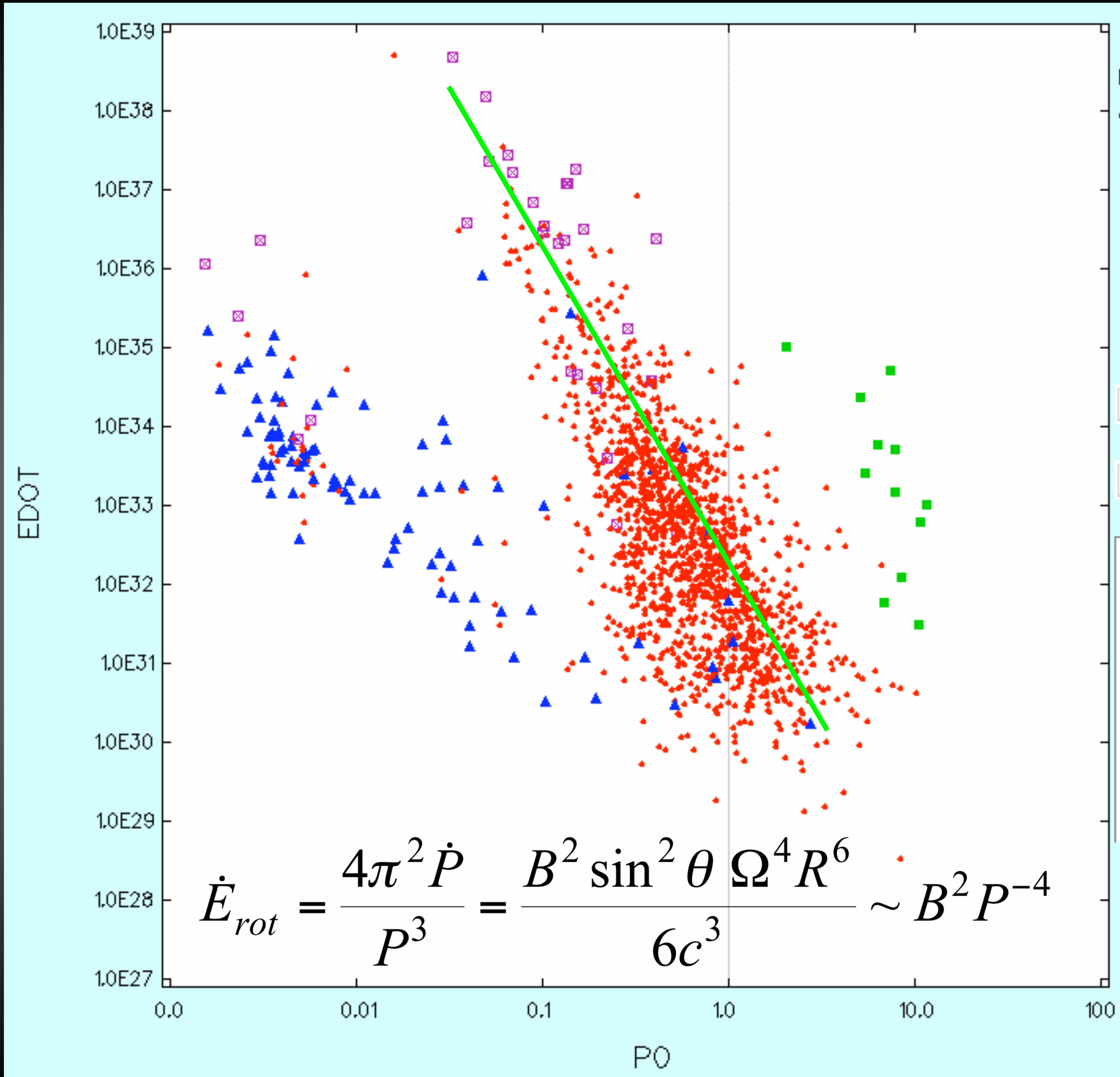
$\log B_0(\mathrm{G}) \approx 12.35 \pm 0.40$ (Arzoumanian et al 2002)

$\log B_0(\mathrm{G}) \approx 12.65 \pm 0.55$ (Faucher-Giguere & Kaspi 2006)

$$L_X \approx a\dot{E}_{rot}^{1.34} \sim B^{2.7} P^{-5.4}$$



On-line pulsar catalog
from the Australia Telescope National Facility



$$\dot{E}_{rot} = \frac{4\pi^2 \dot{P}}{P^3} = \frac{B^2 \sin^2\theta\ \Omega^4 R^6}{6c^3} \sim B^2 P^{-4}$$

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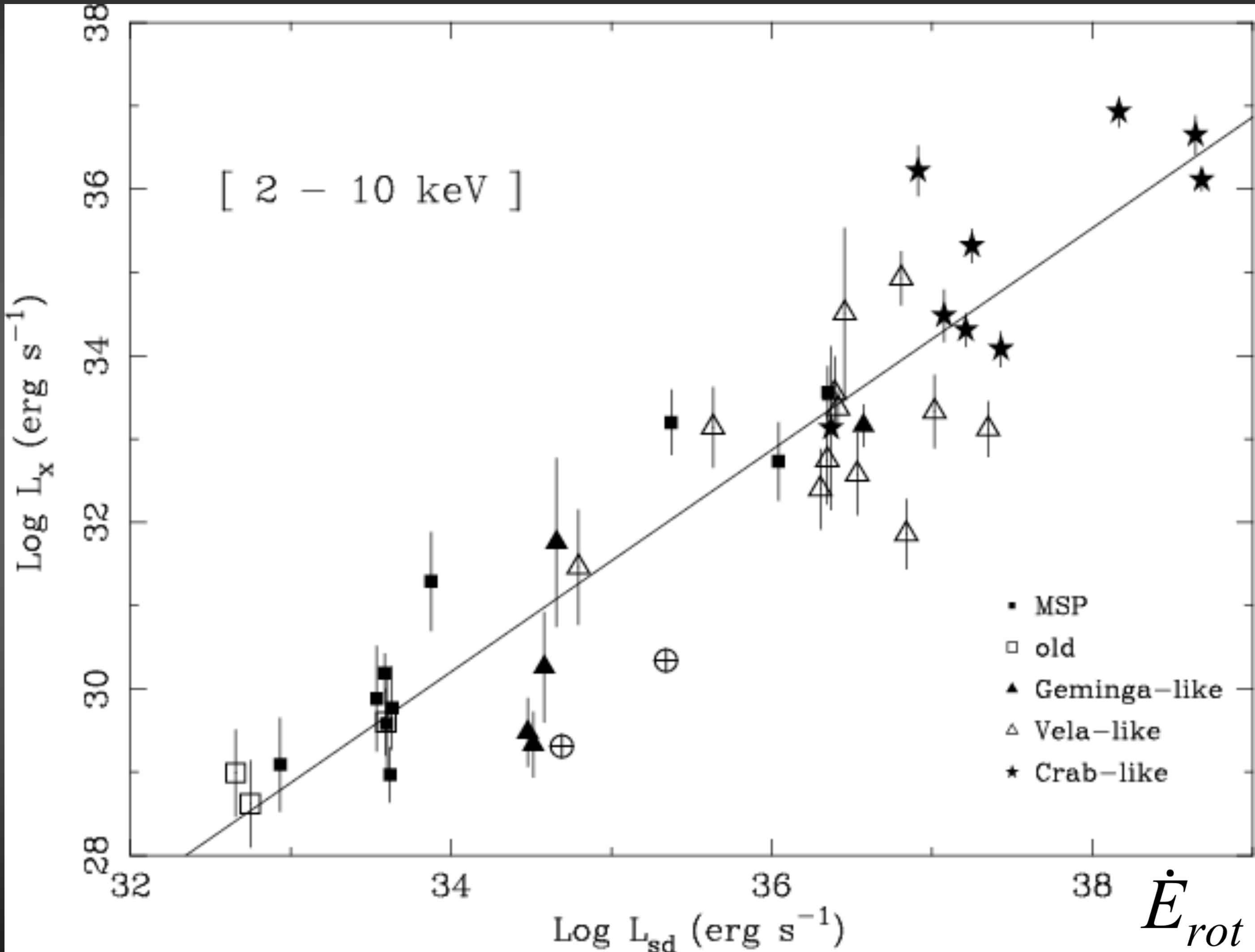
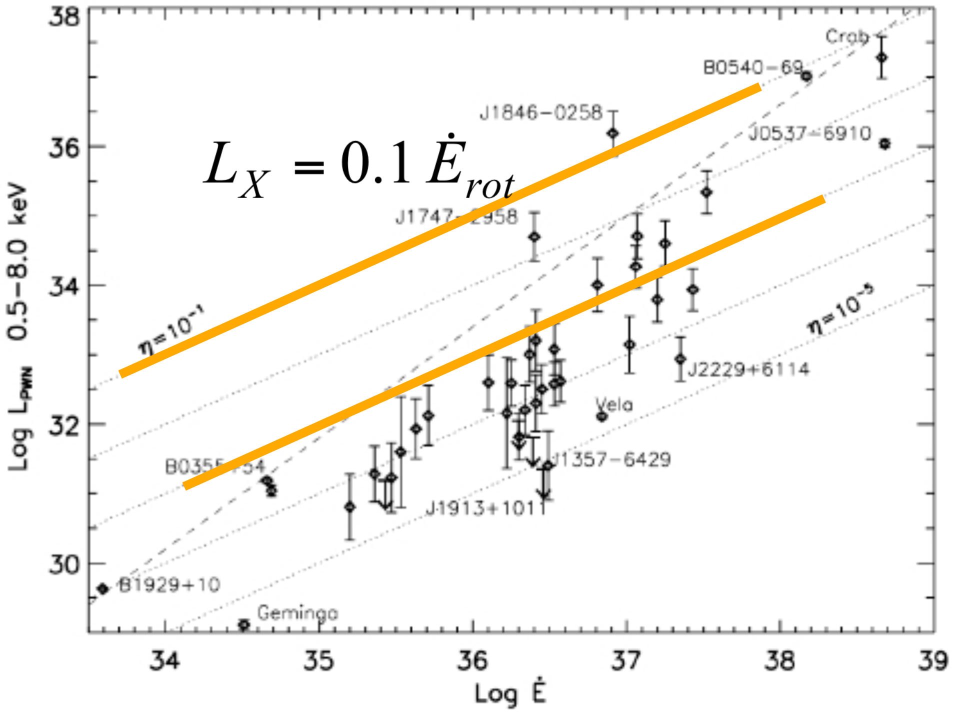
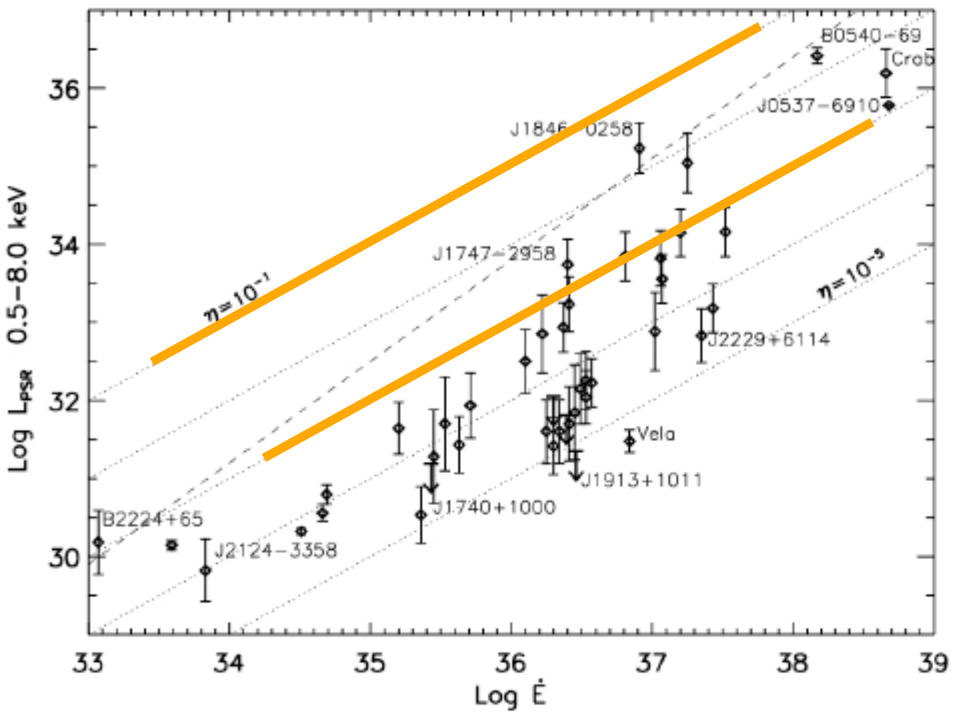


Possenti et al (2002)





$$L_X(psr) \approx a\dot{E}_{rot}^{1.6}$$

$$L_X(pwn) \approx a\dot{E}_{rot}^{1.3}$$

$$L_{X,obs} = L_X(psr) + L_X(pwn)$$

Kargaltsev & Pavlov (2008)
based on Chandra data

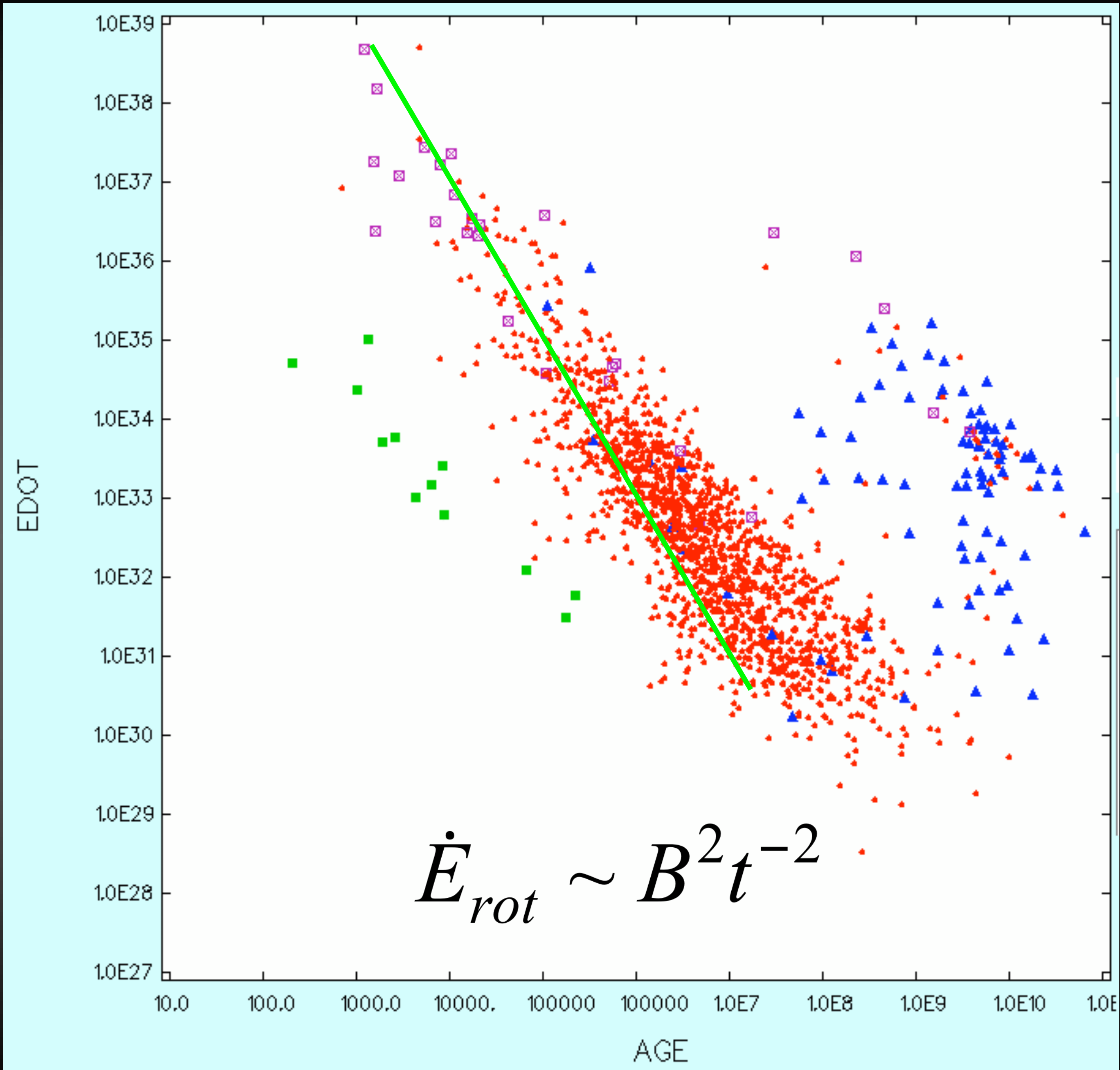
Maximum luminosity limited only
by initial NS spin and magnetic field
(no Eddington limit)

Then L_x declines with time, after a timescale ~ 10^3 yr

$$P(t) = \left[P_0^2 + \left(\frac{16\pi^2 R^6 B^2}{3Ic^3} \right) t \right]^{1/2} \sim (a+bt)^{1/2}$$

$$\dot{E}_{rot} \sim B^2 (a+bt)^{-2}$$

$$L_X \sim B^{2.7} (a+bt)^{-2.7}$$



1.0E39
1.0E38
1.0E37
1.0E36
1.0E35
1.0E34
1.0E33
1.0E32
1.0E31
1.0E30
1.0E29
1.0E28
1.0E27
EDOT
10.0
100.0
1000.0
10000.
100000
100000
1.0E7
1.0E8
1.0E9
1.0E10
AGE
$\dot{E}_{rot} \sim B^2 t^{-2}$

Different X-ray components

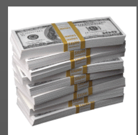
$\dot{E}_{rot}$

P-L synchrotron emission
from pulsar magnetosphere

+

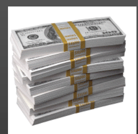
BB emission from polar cap
(heated by polar-gap current)

+



BB emission from polar cap
(heated by outer-gap current)

+



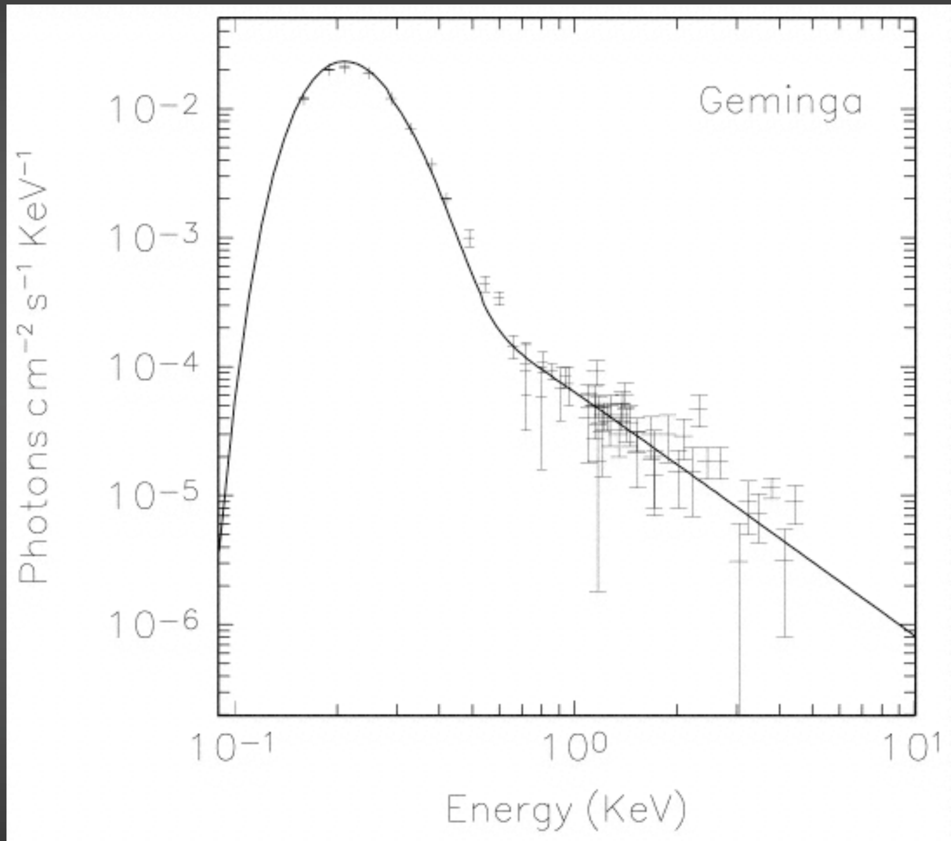
P-L synchrotron emission
from wind nebula
(jet, torus, termination shock)

L_X

Spatially unresolved
in other galaxies

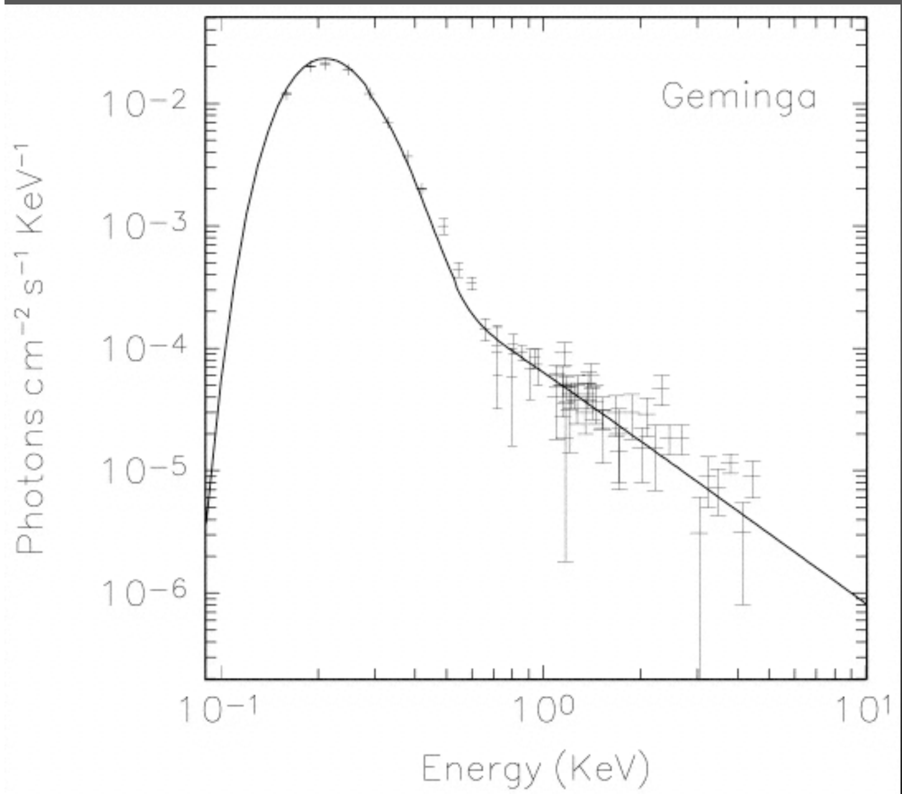
Expected spectral appearance:

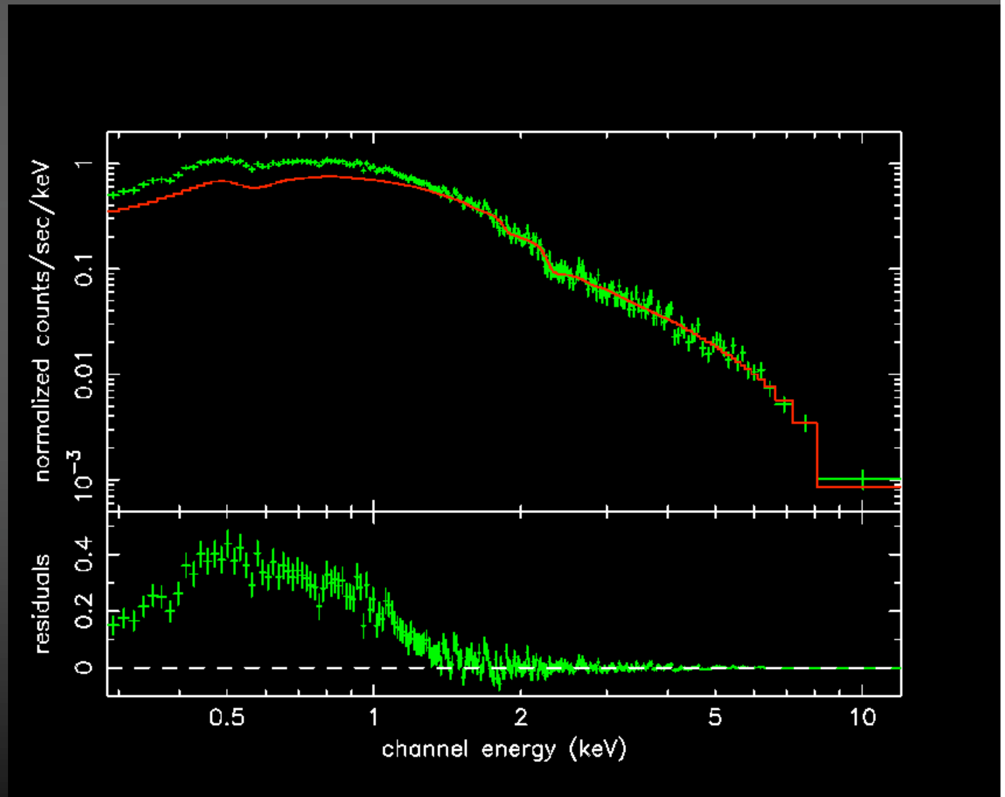
Power-law (photon index ~ 2)
+ soft bb component (T ~ 0.2 keV)

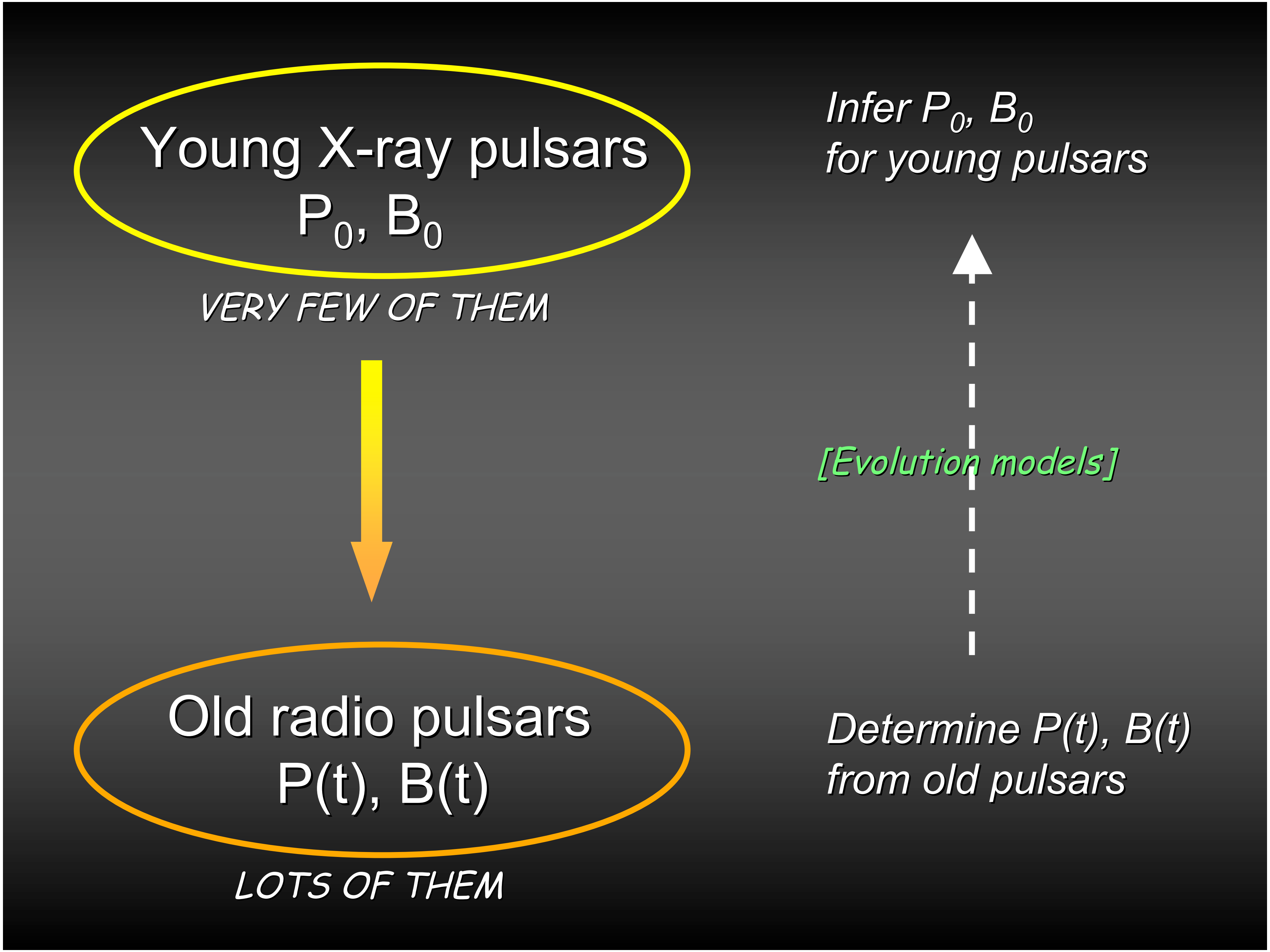


(possibly in addition to optically-thin thermal-plasma emission from the surrounding SNR)

Pulsar+PWN X-ray spectra may look similar to the X-ray spectra of ULXs. Just a coincidence?






Young X-ray pulsars
P_0, B_0
VERY FEW OF THEM
Old radio pulsars
P(t), B(t)
LOTS OF THEM
Infer P_0, B_0
for young pulsars
[Evolution models]
Determine P(t), B(t)
from old pulsars

Young X-ray pulsars
P_0, B_0

VERY FEW OF THEM

Old radio pulsars
$P(t)$, $B(t)$

LOTS OF THEM

Infer P_0, B_0
for young pulsars

Calculate X-ray luminosity
expected for those P_0, B_0

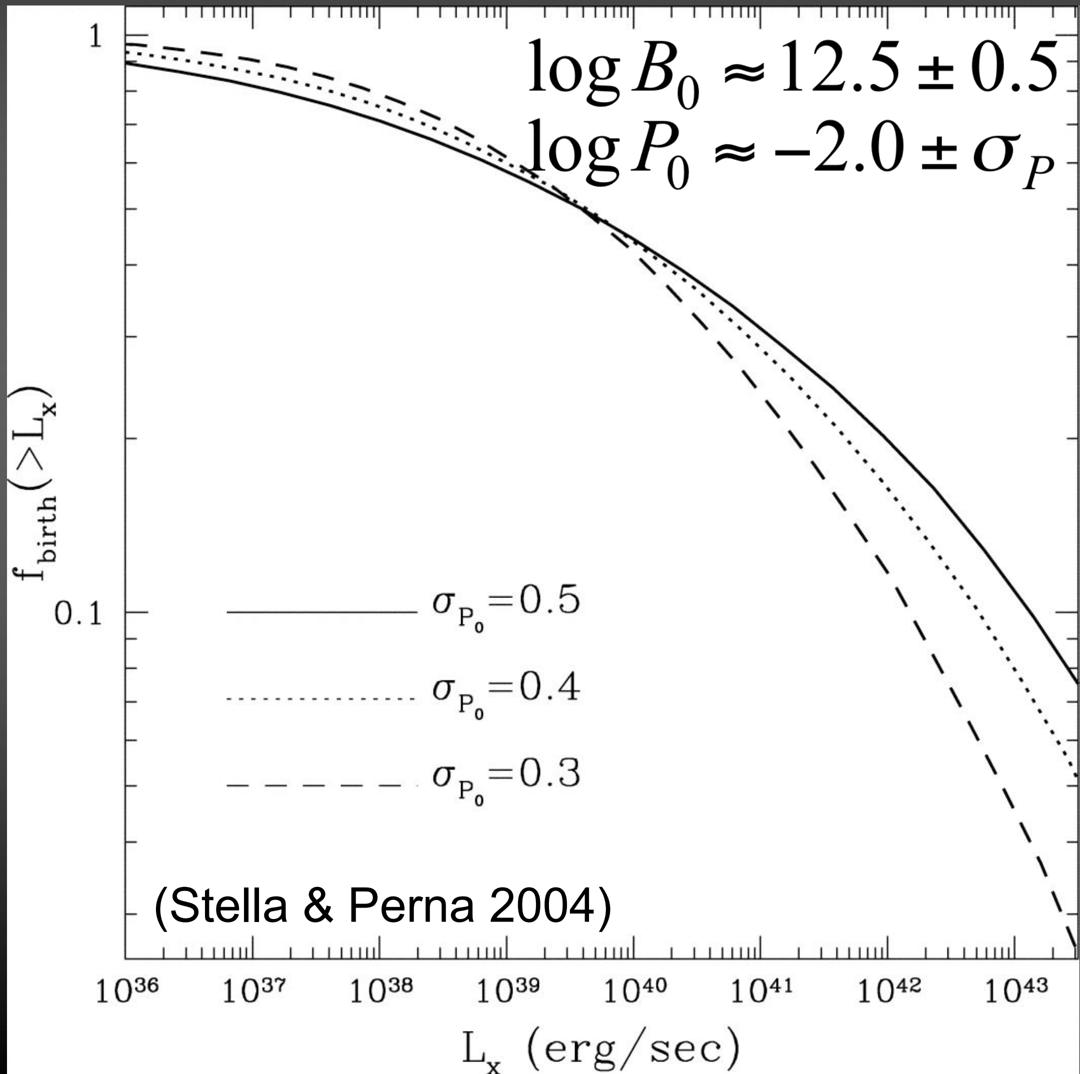
Measure X-ray luminosity
of young pulsars in nearby
galaxies

Direct way
to constrain P_0, B_0

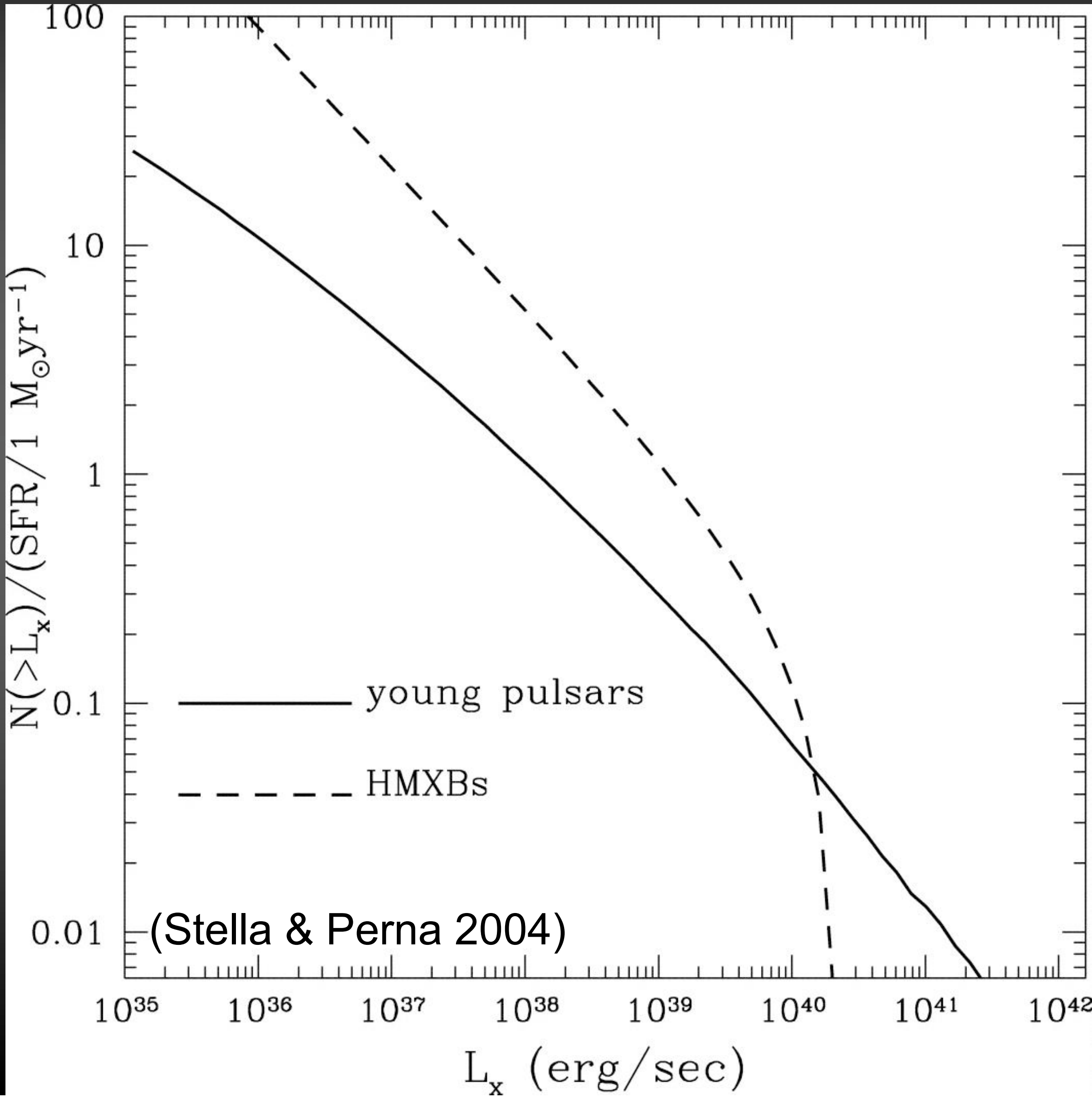
Observed distribution of old radio pulsars

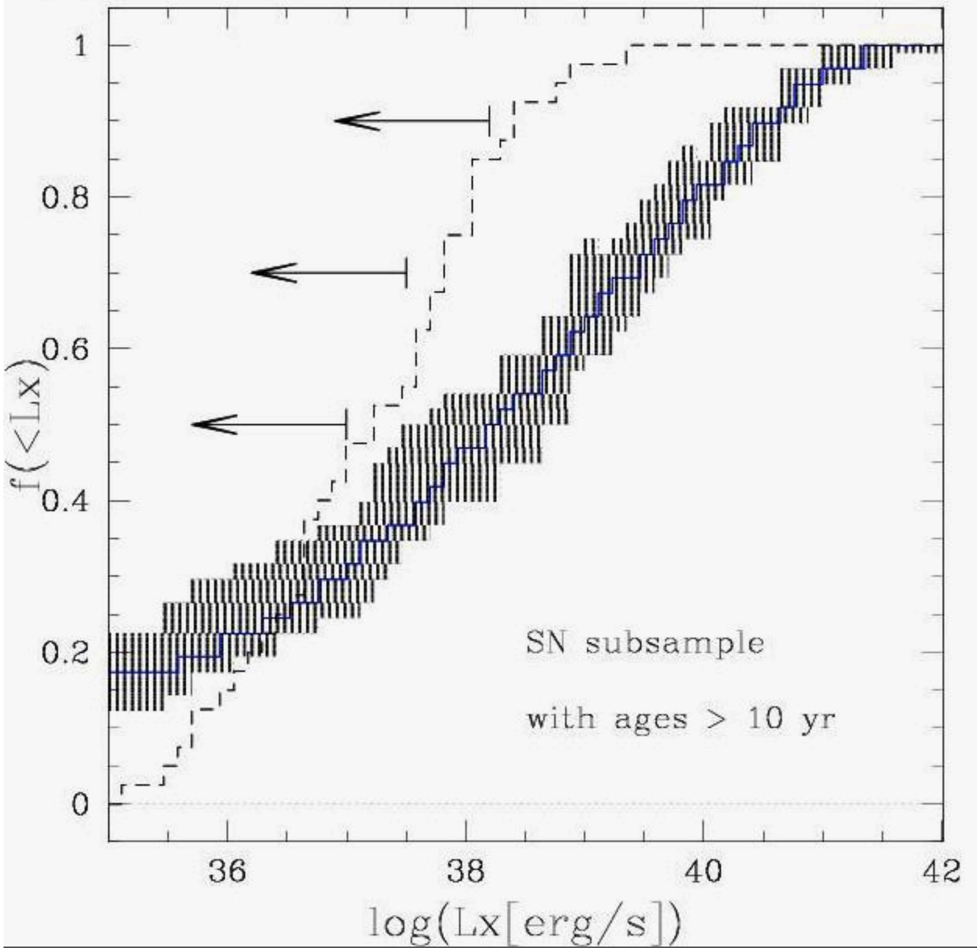
Evolution models by Arzoumanian et al. (2002)

Predicted X-ray luminosity of pulsars at birth



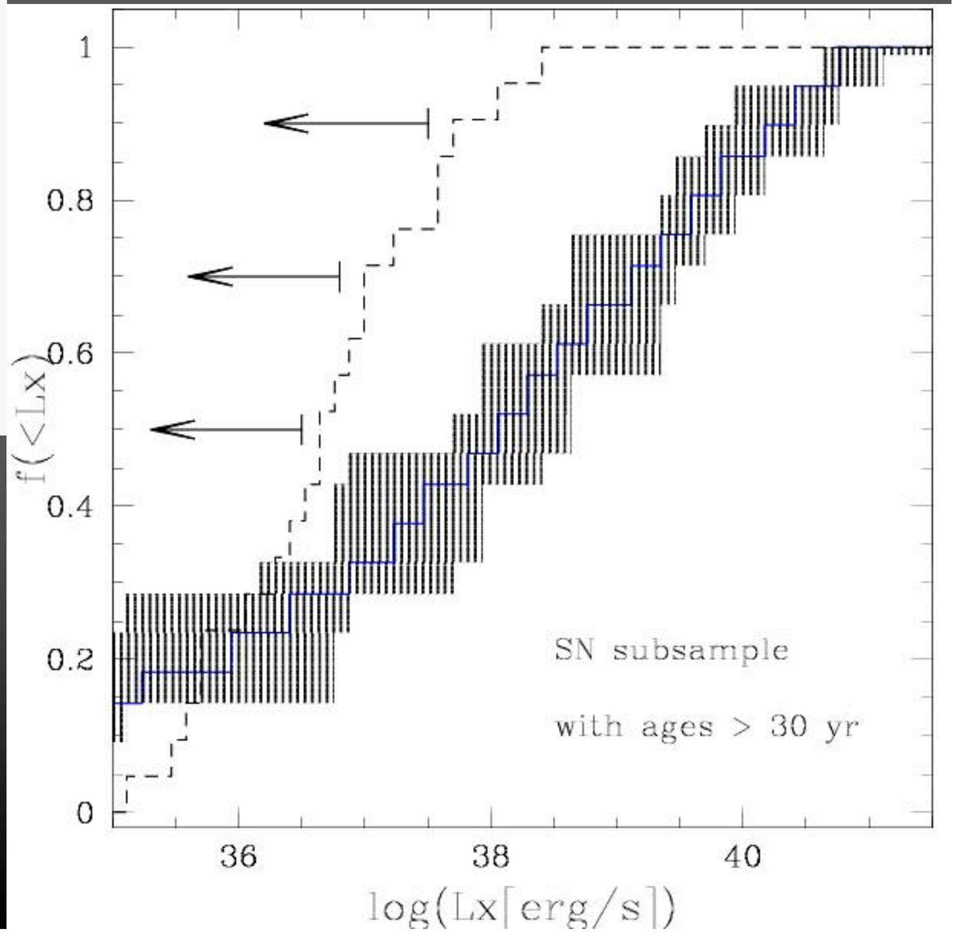
Predicted number of X-ray pulsars and high-mass X-ray binaries as a function of star-formation-rate





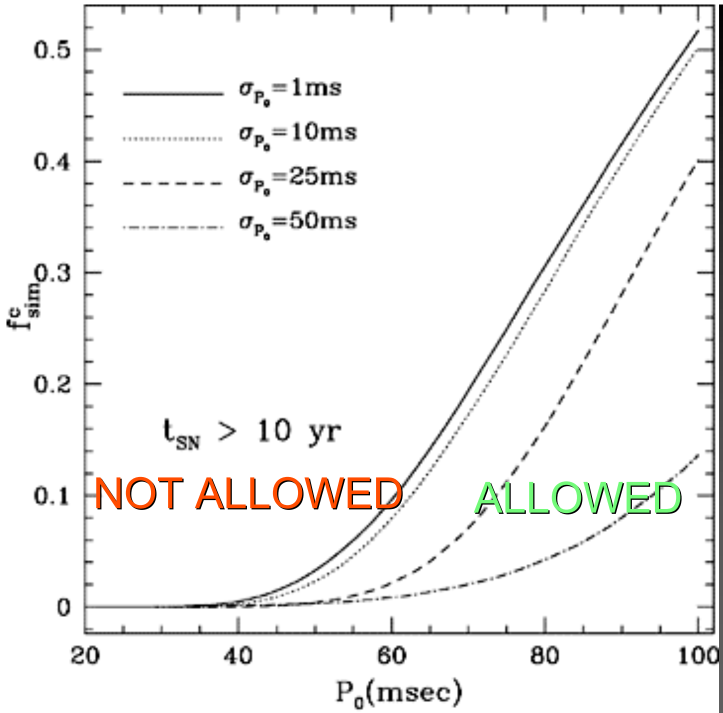
We measured or constrained the X-ray luminosity of ~ 100 historical SNe
with ages ~ 10-100 yrs

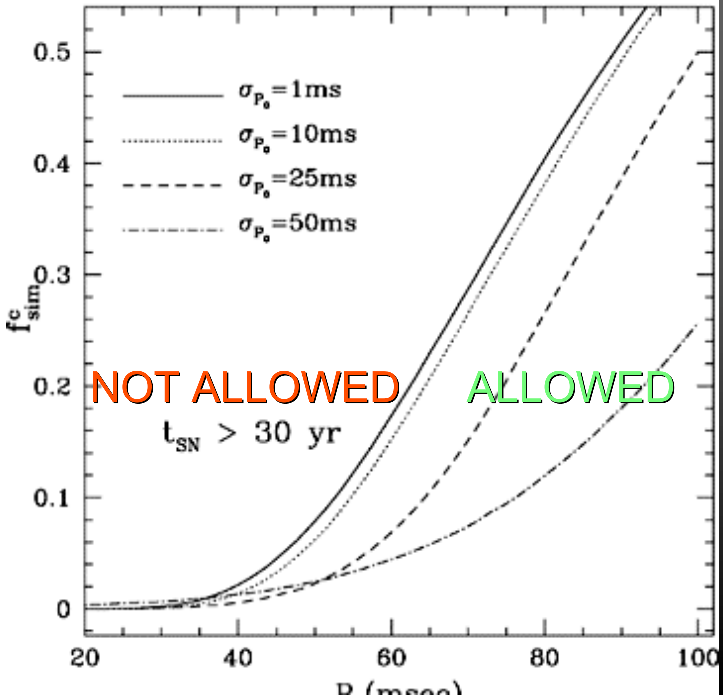
(Chandra, XMM, Swift data)



We found fewer (fainter)
X-ray pulsars than predicted

(Perna et al 2008)





Assuming we know birth rate and magnetic field

Constraints on birth period

For a log-normal distribution,

$$\langle P_0 \rangle > 50 \text{ ms}$$

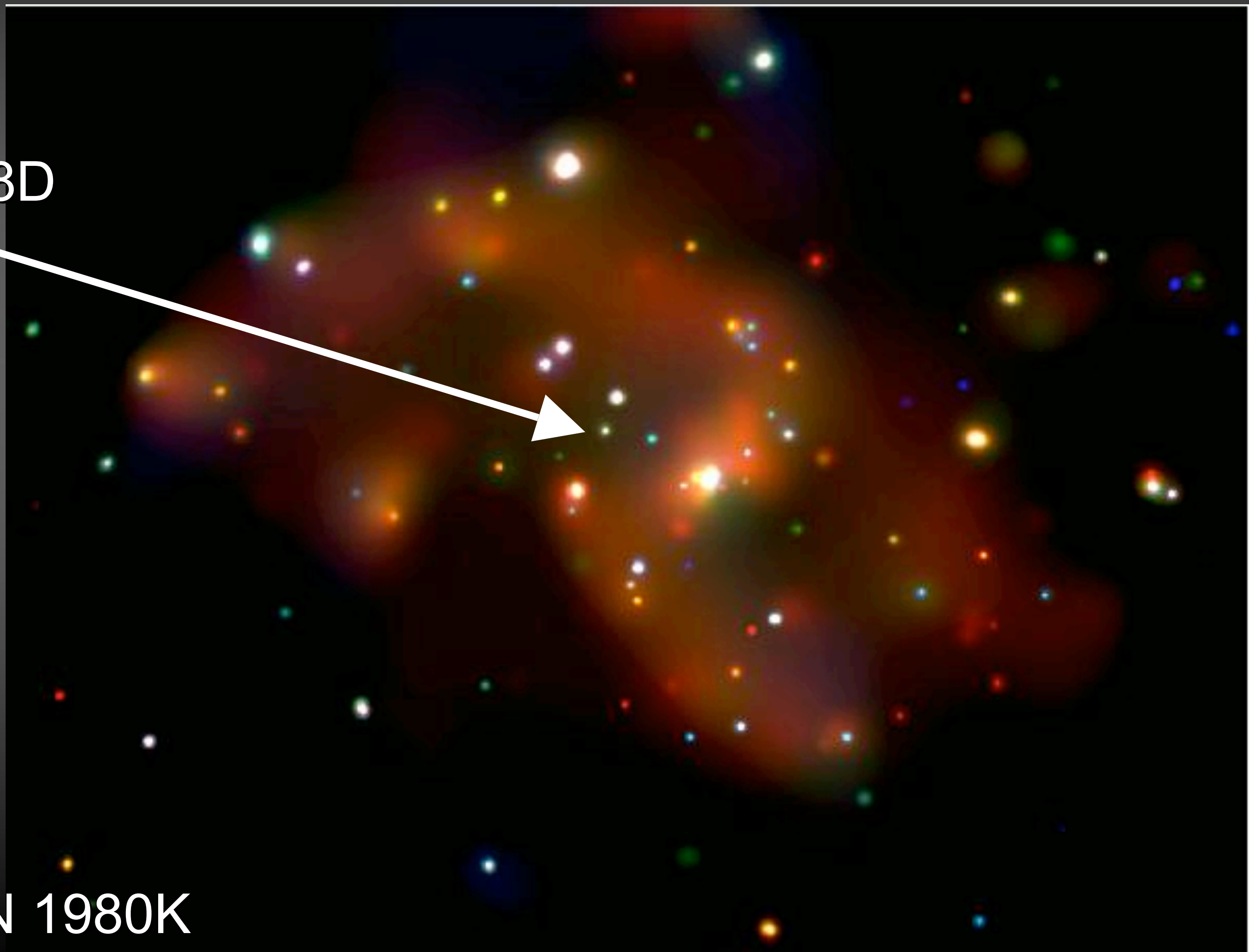
(Perna et al 2008)

X-ray luminosity associated with every core-collapse SN from 1900-1970 in galaxies at distances <= 15 Mpc

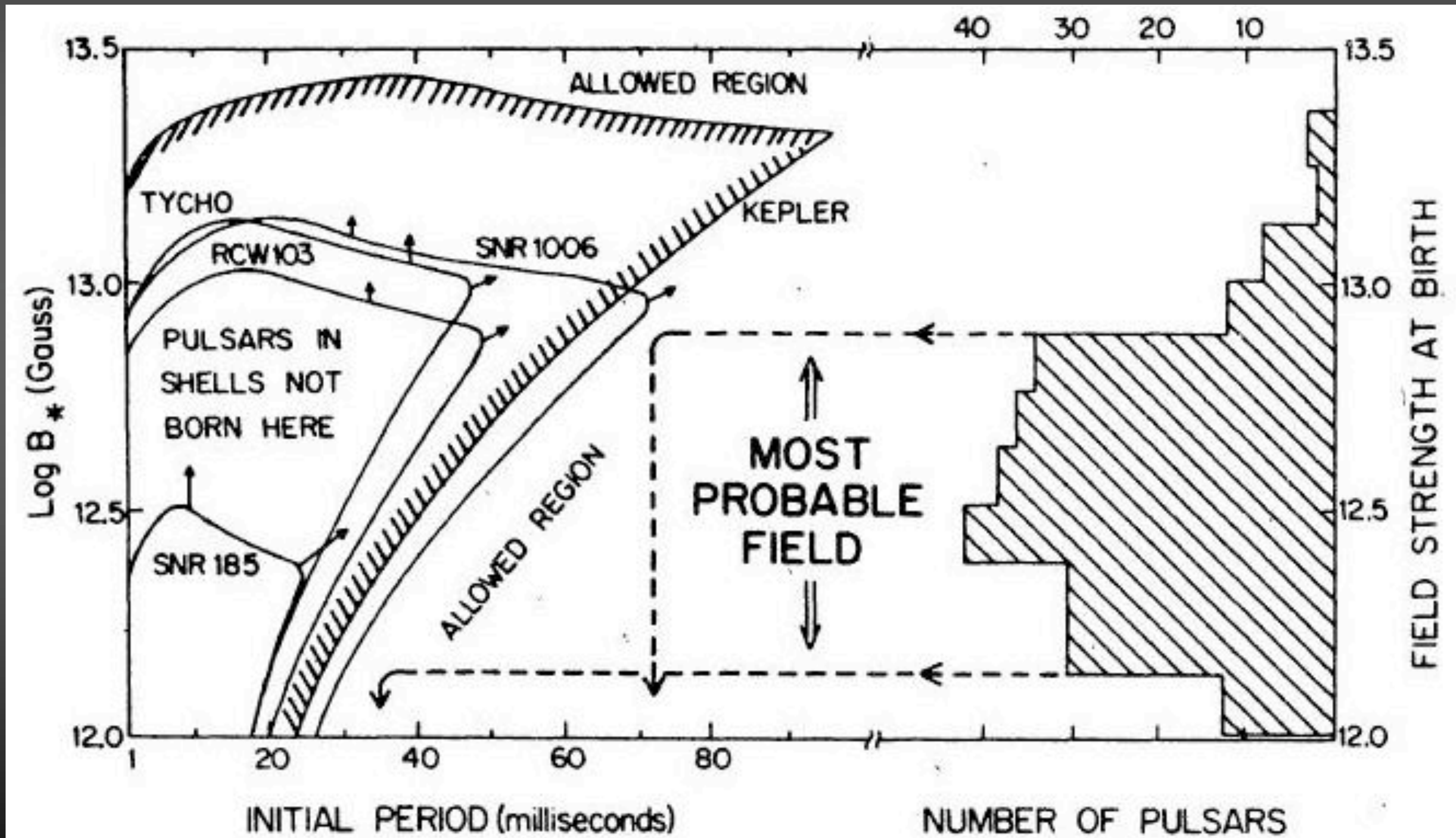
SN ID	Type	Galaxy	Distance (Mpc)	*Chandra* time available (ks)	*Chandra* time requested (ks)	X-ray SN?	$L_{0.3-8}$ (erg s^{-1})
1909A	II	M101	7.4	100	-	-	$< 5 \times 10^{36}$
1917A	II	N6946	5.5	180	-	-	$< 2 \times 10^{36}$
1921B	II	N3184	8.7	65	-	-	$< 10^{37}$
1923A	IIP	M83	4.5	50	-	-	$< 3 \times 10^{36}$
1937A	IIP	N4157	15	-	-	-	$(< 3 \times 10^{37})^{a}$
1937F	IIP	N3184	8.7	65	-	-	$< 10^{37}$
1940A	IIL	N5907	13	-	-	-	$(< 2 \times 10^{37})^{a}$
1940B	IIP	N4725	13	25	-	-	$< 3 \times 10^{37}$
1941A	IIL	N4559	10	23	-	-	$< 2 \times 10^{37}$
1941C	**II**	**N4136**	**10**	**39**	**30**	$\mathbf{Y}^{b}$	5×10^{37}
1948B	IIP	N6946	5.5	180	-	-	$< 2 \times 10^{36}$
1951H	II	M101	7.4	100	-	-	$< 5 \times 10^{36}$
1954A	Ib	N4214	3.0	85	-	-	$< 5 \times 10^{35}$
1959D	**IIL**	**N7331**	**15**	**30**	**40**	$\mathbf{Y}^{b}$**?**	4×10^{37}
1961U	**II**	**N3938**	**12**	**-**	**30**	?	?
1961V	IIn	N1058	9.1	20	-	-	$< 3 \times 10^{37}$
1962L	**Ic**	**N1073**	**15**	**6**	**35**	?	$(< 2 \times 10^{38})$
1962M	IIP	N1313	4.0	50	-	-	$< 2 \times 10^{36}$
1964H	**II**	**N7292**	**15**	**-**	**40**	?	?
1964L	**II**	**N3938**	**12**	**(5)**[c]	**30**	?	?
1966J	Ib	N3198	12	(62)[c]	-	?	?
1968D	II	N6946	5.5	180	-	Y^{b}	2.4×10^{37}
1968L	IIP	M83	4.5	50	-	-	$< 3 \times 10^{36}$
1969B	IIP	N3556	14	60	-	-	$< 3 \times 10^{37}$
1969L	IIP	N1058	9.1	20	-	-	$< 3 \times 10^{37}$
1970A	**II**	**IC3476**	**10**	-	**30**	?	?
1970G	IIL	M101	7.4	140	-	Y^{d}	$\approx 10^{37}$

One of the very few Crab-like young pulsar candidates, at the location of SN 1968D in NGC 6946 ($L_x \sim 10^{37}$ erg/s)

(Soria & Perna 2008)



Our X-ray survey result agrees with the pioneering study of Srinivasan et al (1984), based on X-ray and radio luminosity of young Galactic SNRs



Low angular parameter at birth:

$$a / M \approx 0.015 \left(\frac{50\,\mathrm{ms}}{P} \right)$$

consistent with Spruit & Phinney's (1998) model,
initial spin ~ kick velocity

Not enough energy at birth to power a hypernova

$$E_{rot} \approx 10^{49} \text{ erg for } P = 50 \text{ ms}$$
$$E_{rot} \approx 3 \times 10^{52} \text{ erg for } P = 1 \text{ ms}$$

Consistent with Vink & Kuiper's (2006)
study of magnetar/SNR associations

Implies pre-collapse Fe core *P* ~ 50-100 s

(Ott et al 2006)

Main result of our X-ray survey

Almost all NS pulsars born with P> 40 ms

Why? Is it true also for stellar BHs?
Are BHs born with angular parameter a ~ 0.01?

High-energy pulsars are a small fraction of X-ray population (Crab-like systems are rare)

Alternative possibility:

Is the NS birth rate overestimated?

Perhaps a larger fraction of core-collapse SNe forms BHs or leaves no remnant?

Do many SNe produce quark stars (expected to be X-ray fainter) instead of neutron stars?

Ultraluminous X-ray sources (ULXs) cannot be high-energy pulsars

ULXs = accreting X-ray binaries with BH + donor star

- $L_x \sim 10^{37}$ — Young pulsars
- $L_x <\sim 3\ 10^{38}$ — NS XRBs
- $L_x <\sim 10^{39}$ — Stellar BH XRBs
- $L_x \sim 10^{40}$ — ULXs

ULXs →
- Higher BH masses (100 M_{sun}? 1000 M_{sun}?)
- Beamed emission
- Super-Eddington emission