The Zoo of Neutron Stars in Supernova Remnants (SNR):
An X-ray View

Neutron Stars Diversity ⟷ SNR connection

Birth and evolution (part I)
SN Progenitors (part II)

IAU Honolulu
Division D, Aug (2015)

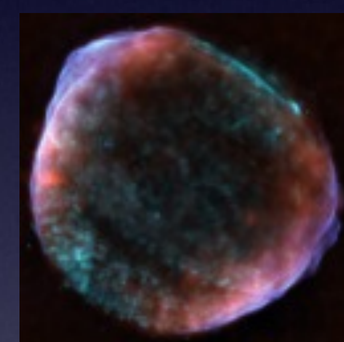
S. Safi-Harb

University of Manitoba

- **Our Galaxy's dynamics and magnetism (ENERGY)**

  - The non-thermal Universe *(see talk by Emma de Ona Wilhelmi)*
  - Galactic B-field

    (see talk by Jennifer West)

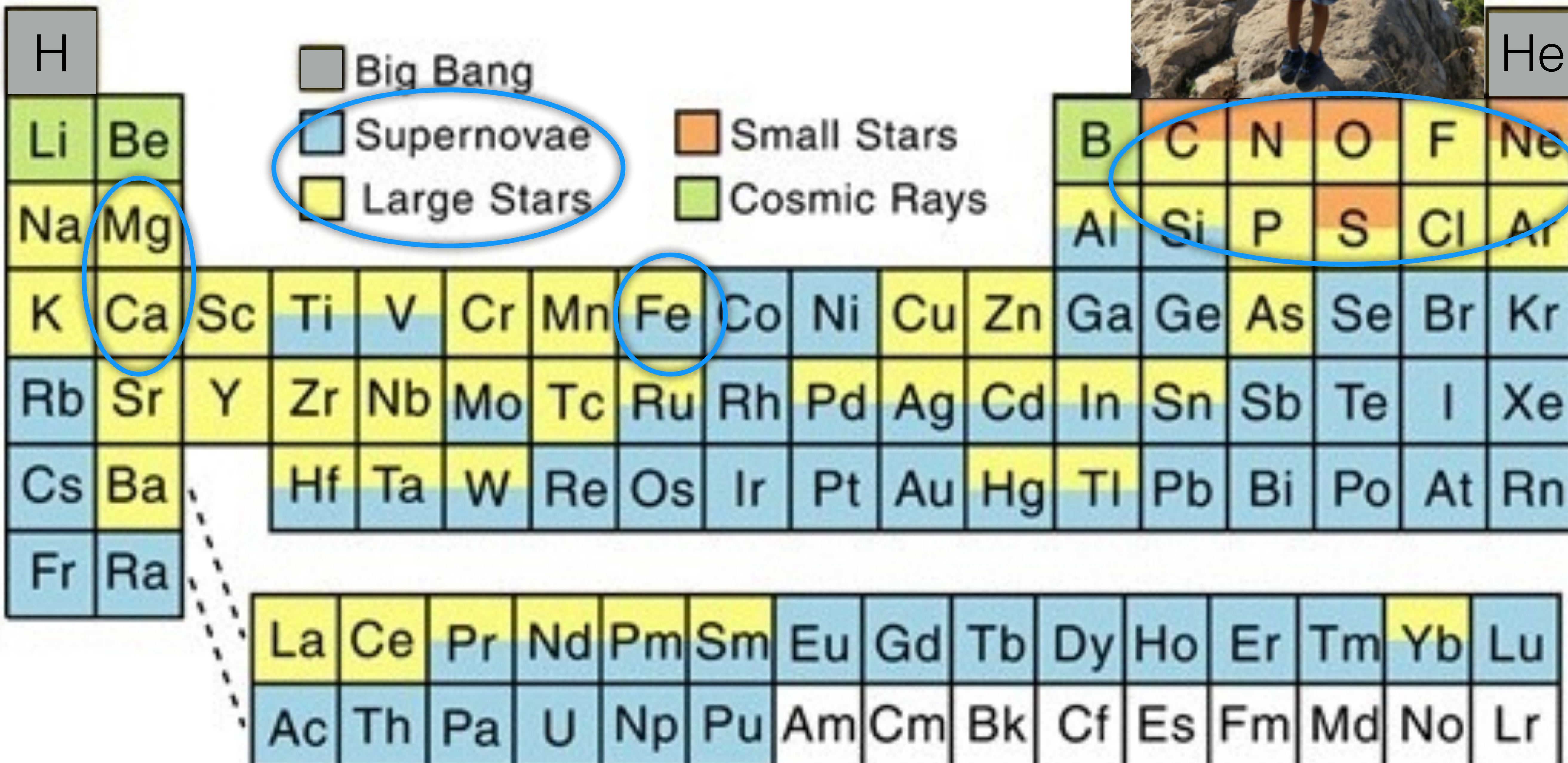


Supernova Remnants
The Big Picture

- **Our Galaxy's dynamics and magnetism (ENERGY)**
  - *The non-thermal Universe*
- **Nucleosynthesis (MATTER)**
  —the thermal Universe
  - *SN progenitors (this talk)*
  - *See also talk by Paolo Mazzali*

Supernova Remnants
Our Cosmic Connection to the Elements

Nucleosynthesis (MATTER)



adapted, credit: NASA (+ personal photos)

Supernova Remnants
The Big Picture

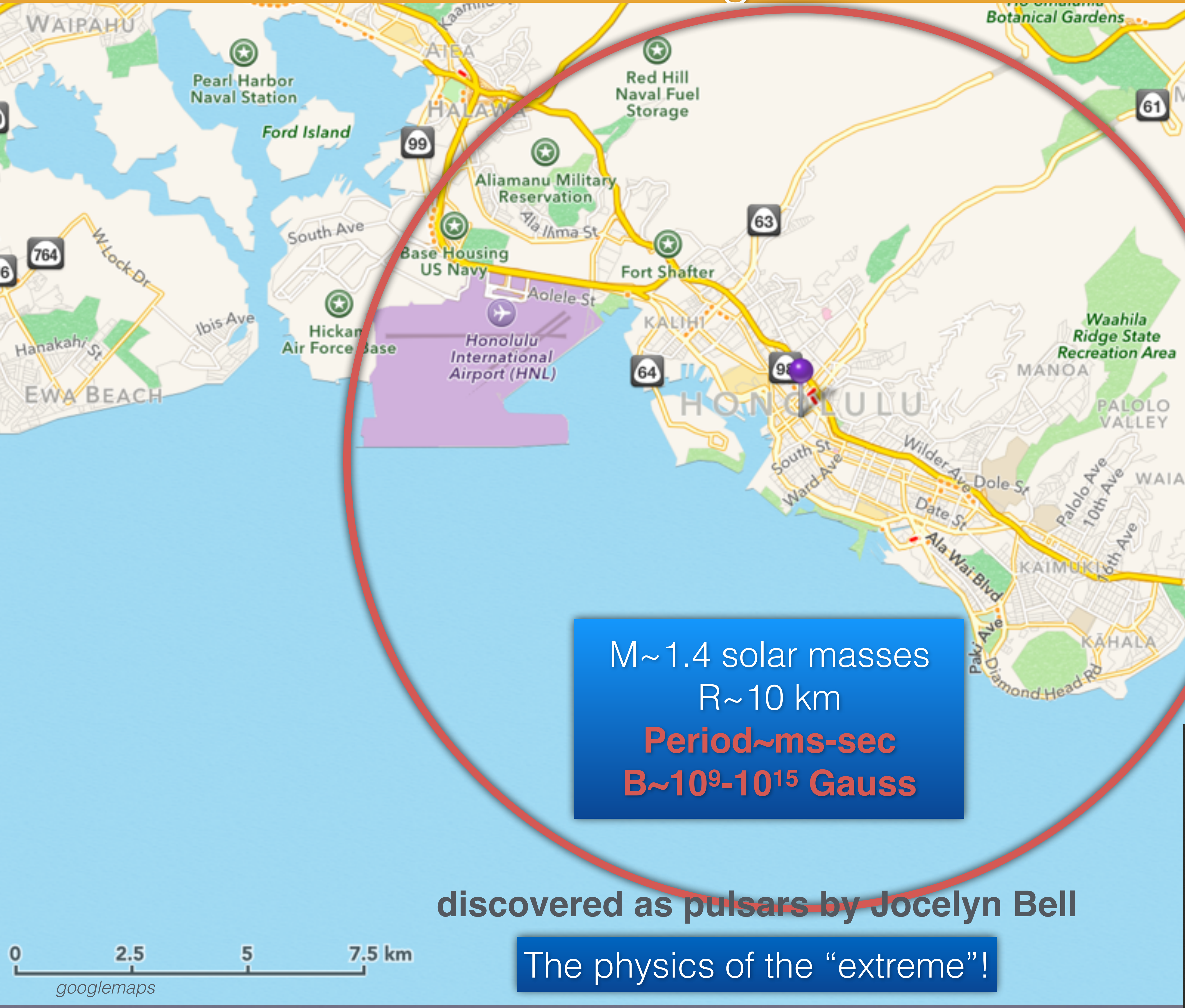
- **Our Galaxy's dynamics and magnetism**

- **Nucleosynthesis (MATTER)**
  —the thermal Universe

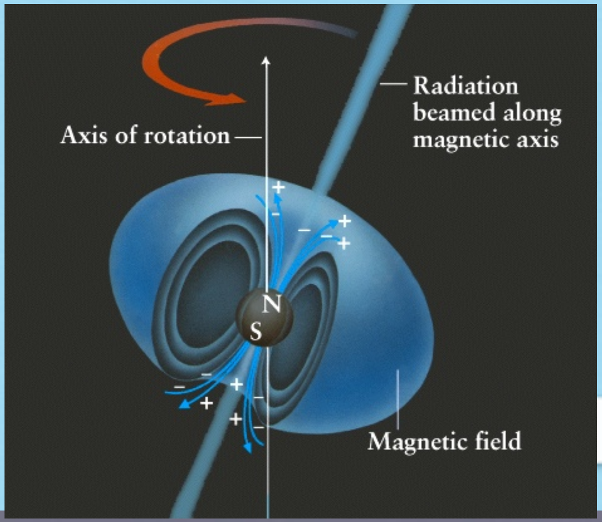
- **Nearby Laboratories for Extreme Physics**
  - Link to GRBs (*see N. Gehrels' and P. Mazzali's talks*)
  - **Neutron Stars** *(this talk; see also GianLuca Israel's talk)*

Their magnetic fields:
formation and evolution through SNR studies!

Neutron Stars:
The Big Picture



M~1.4 solar masses
R~10 km
Period~ms-sec
B~10^9-10^{15} Gauss



discovered as pulsars by Jocelyn Bell

The physics of the "extreme"!

Pulsars' Intrinsic Properties

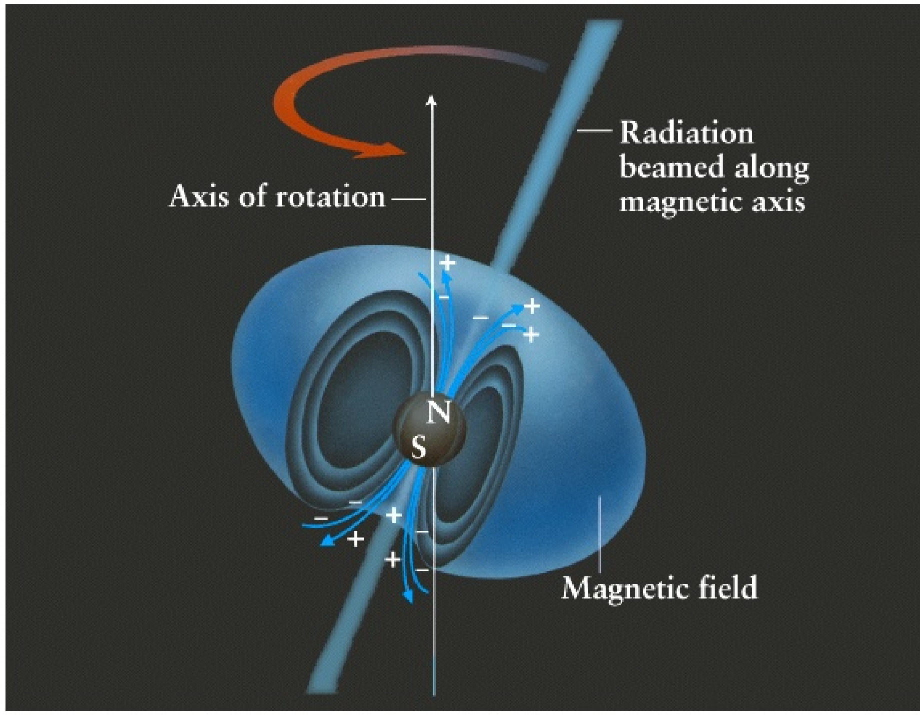
Spin (P), Spin down (Pdot)=> **Magnetic Field (B) and "Age"**

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = I \cdot \Omega \cdot \dot{\Omega}$$

$$= \frac{2}{3c^3} |m|^2 \Omega^4 \sin^2 \alpha$$

surface dipole magnetic field

$$B = \sqrt{\frac{3c^3}{8\pi^2} \frac{I}{R^6 \sin^2 \alpha} P \dot{P}} = 3.2 \cdot 10^{19} \sqrt{P \dot{P}} \text{ Gauss}$$



Credit: Pearson Prentice Hall, Inc.

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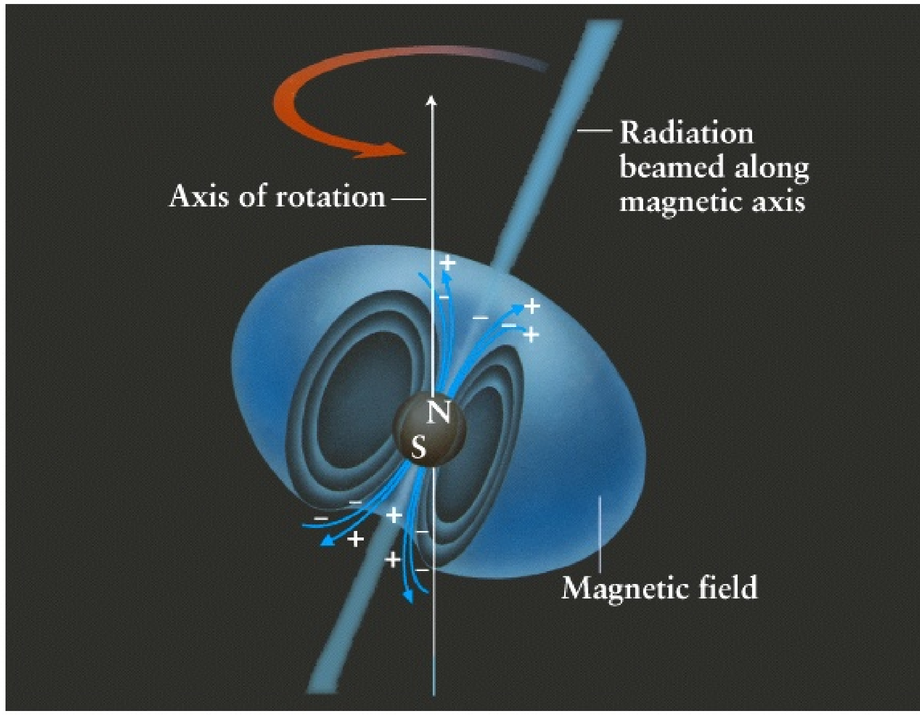

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"True" age

$$\dot{\Omega} = -k\Omega^n \quad \Rightarrow \quad \tau = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P}\right)^{(n-1)}\right]$$

n=braking index (=3: dipole)

$$n = \nu\ddot{\nu}/\dot{\nu}^2$$

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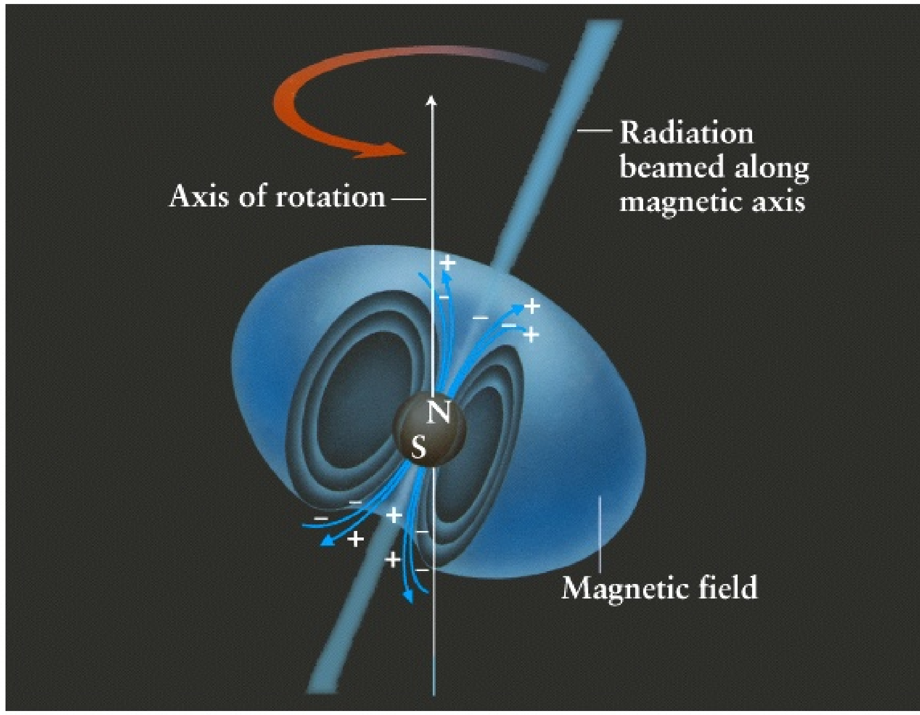

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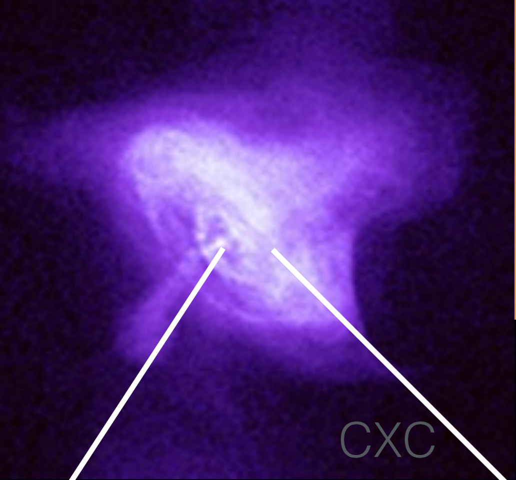
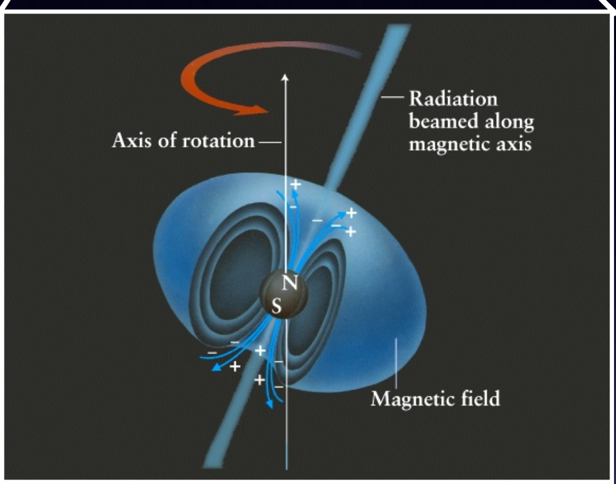
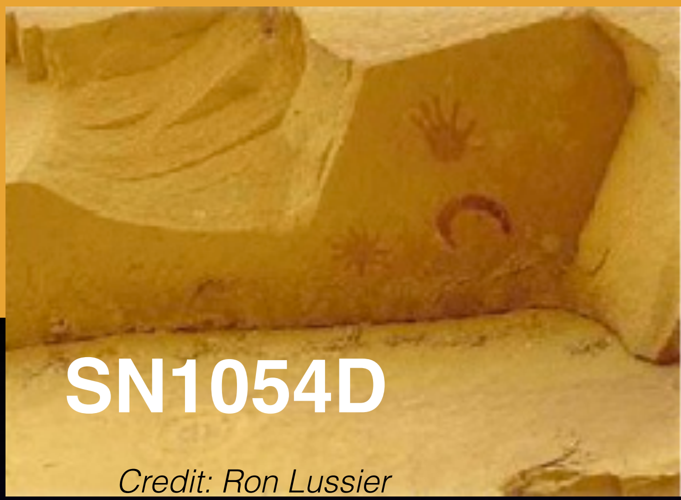
"characteristic" age

(assumes constant B, Magnetic Dipole, and P0<<P)

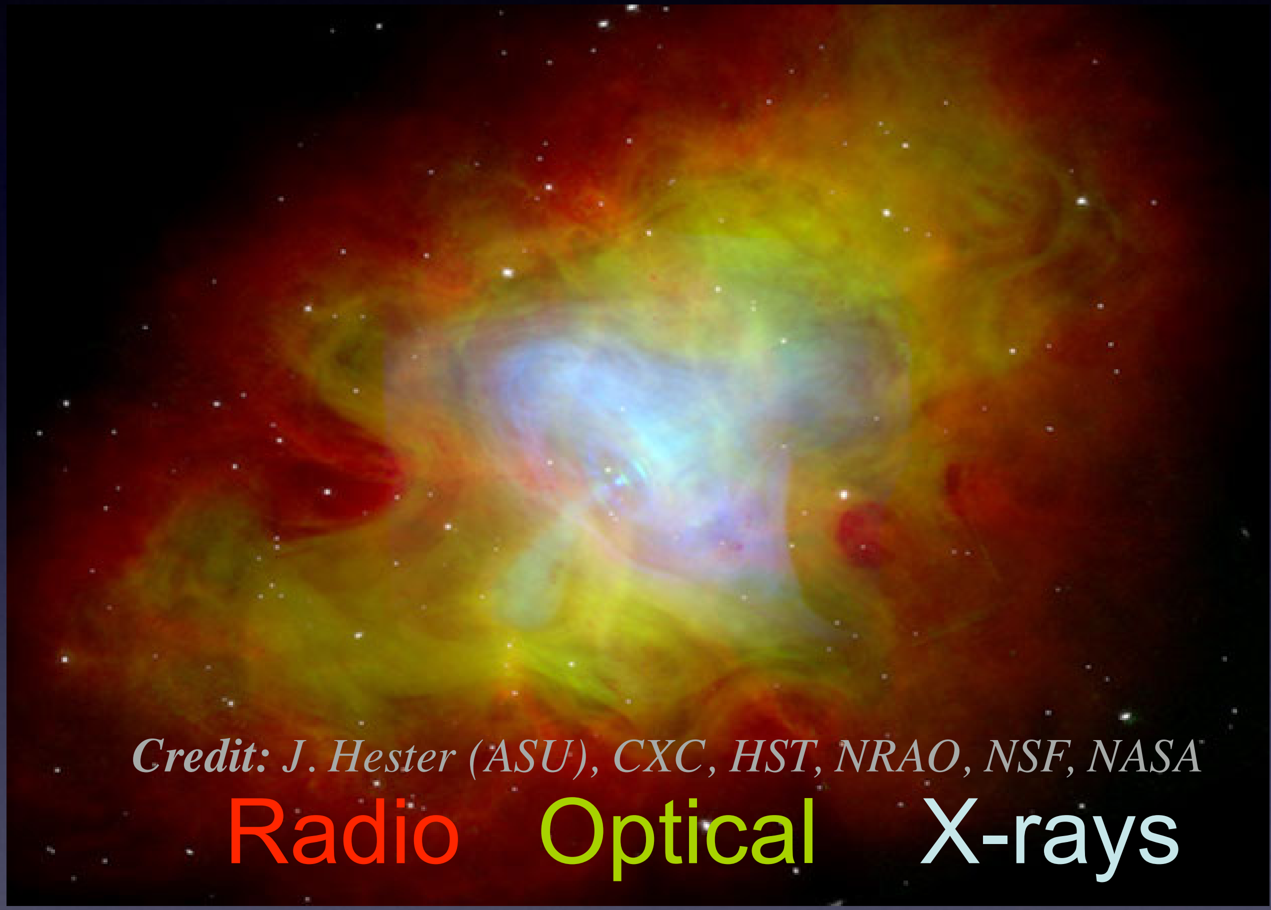
The Crab
PSR-SNR association







P=33 ms
Slows down with time:
dP/dt~1.3 ms/century!



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

Rotation-powered Pulsar (RPP)

powering a Pulsar Wind Nebula (PWN)=non-thermal synchrotron

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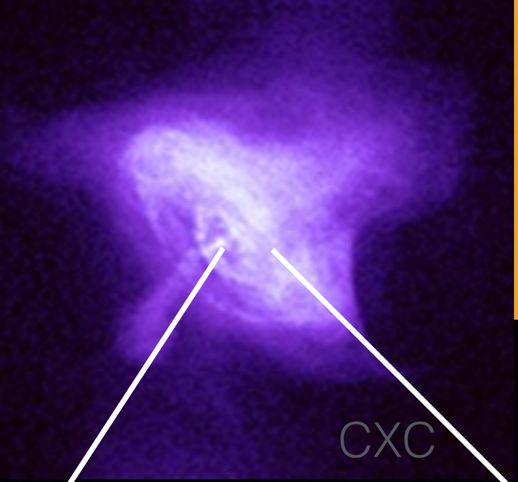

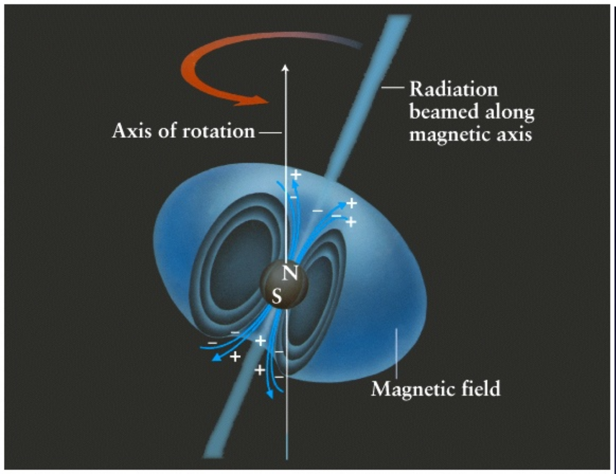

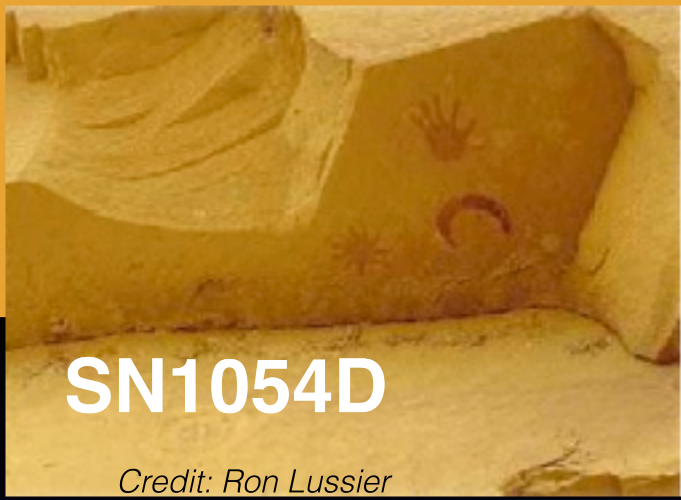

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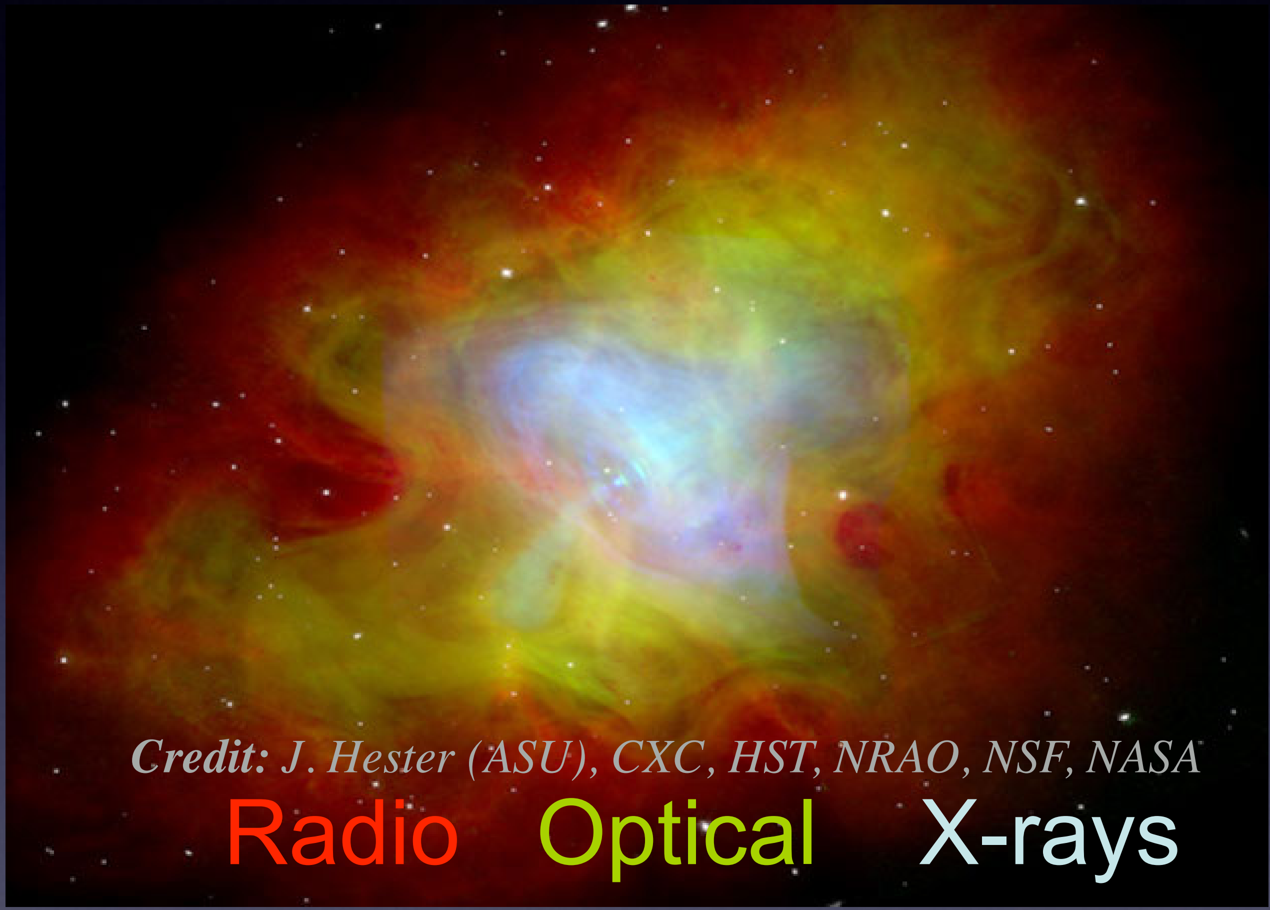

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B~**5 x 10^{12} Gauss**
Spin Down age~**1.3 kyr**
comparable to **961 yr (SN1054)**

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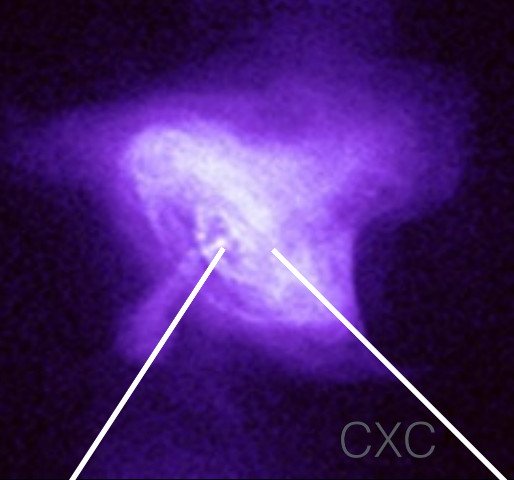

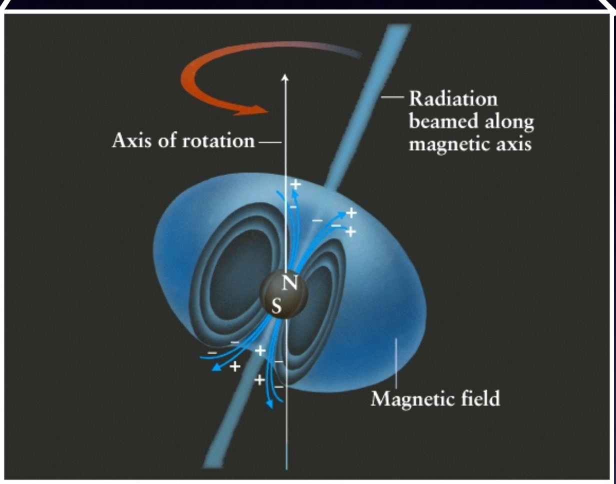

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(RPP)
al synchrotron

A “shell-less” or “Naked” SNR!

-unseen cold ejecta/CSM far out?
-low-energy (<~1e50 ergs) explosion of 8-10 Mo progenitor with early dense CSM interaction (type IIn-P)? *Smith+13*

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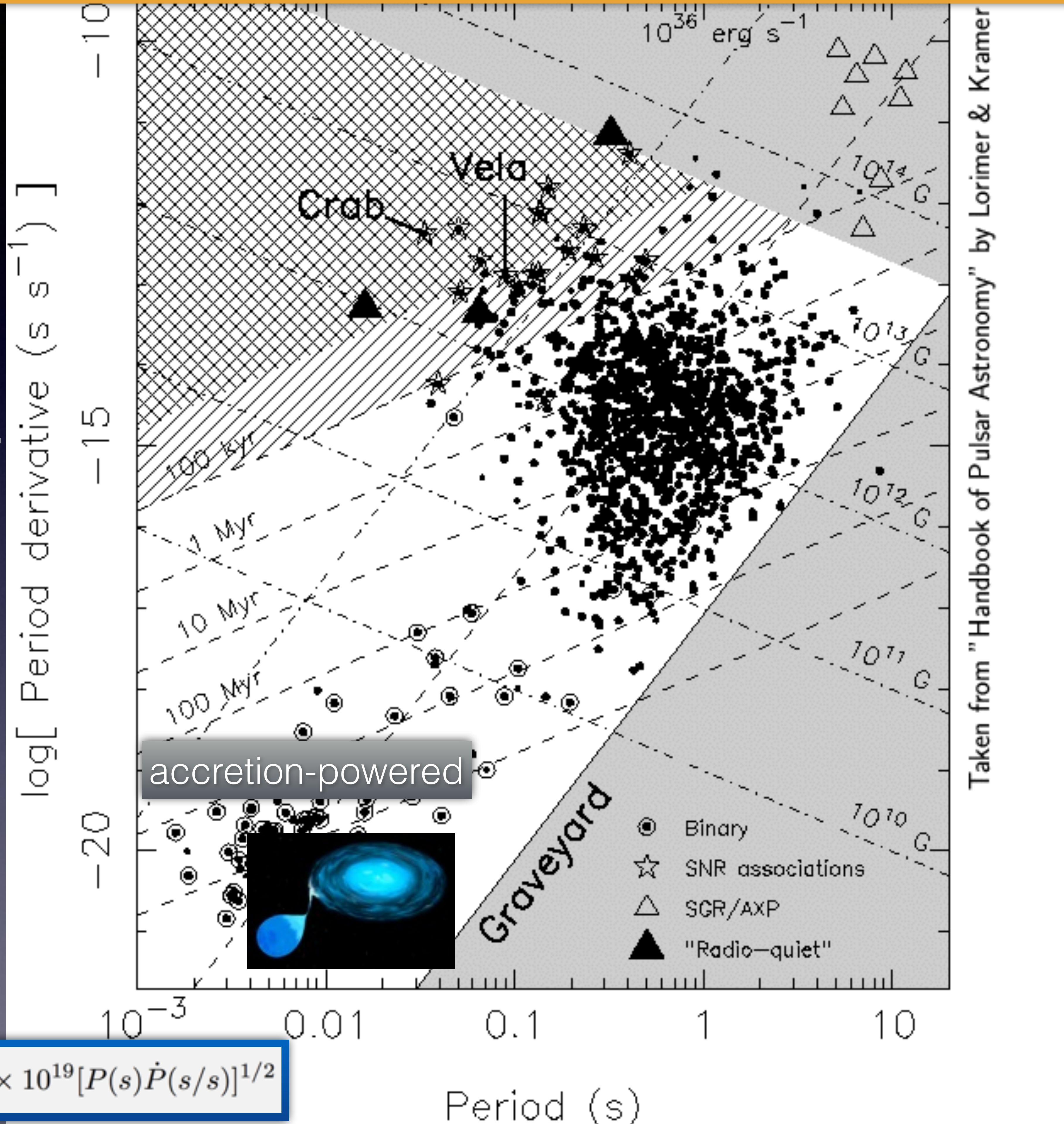
comparable to **961 yr (SN1054)**

“P-Pdot" Diagram of Pulsars=> Neutron Stars Diversity (Zoo)

“Isolated”:
RPP
Magnetars
HBPs
CCOs

- XDINSs (INS),
- RRATs…



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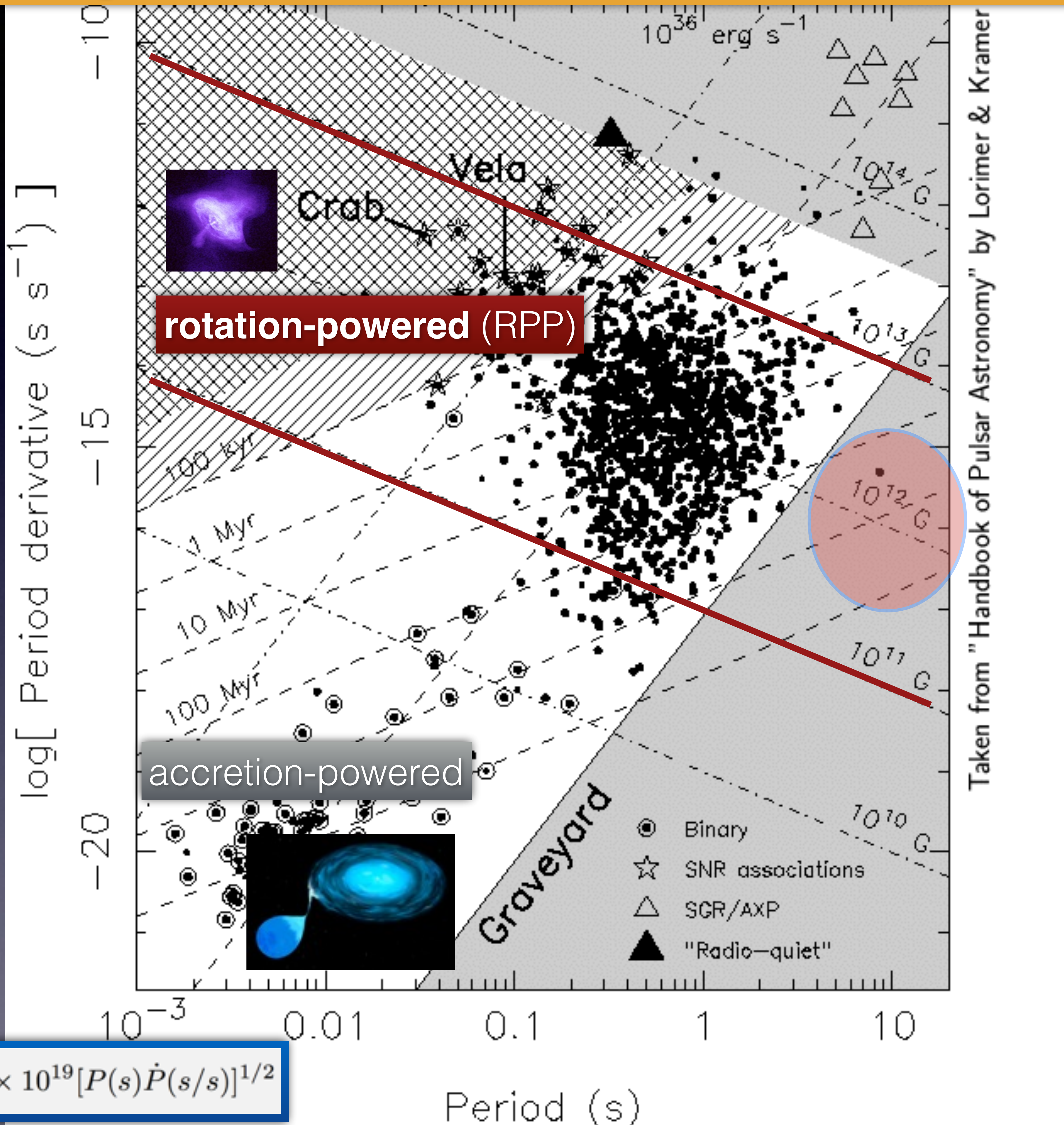

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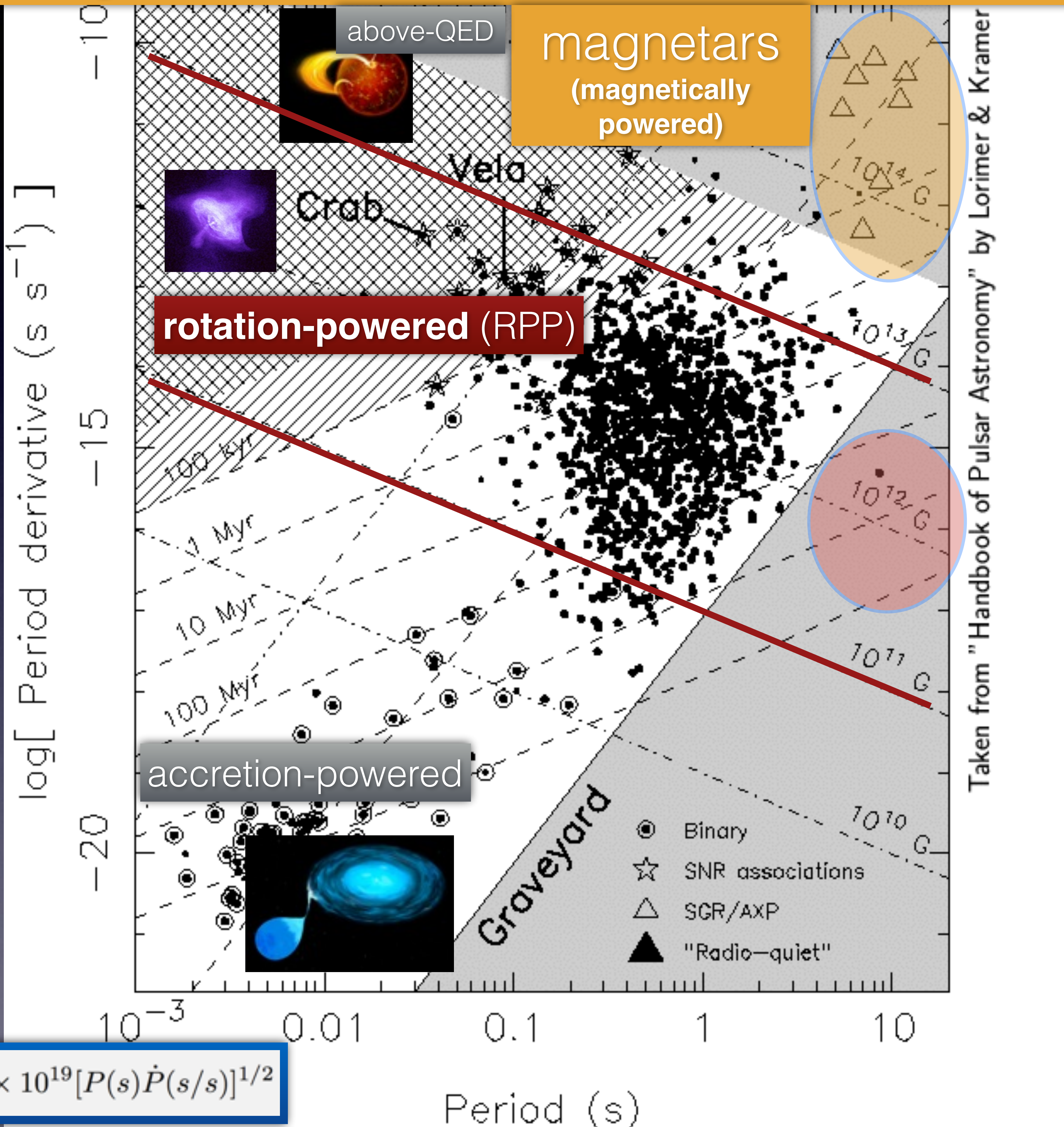

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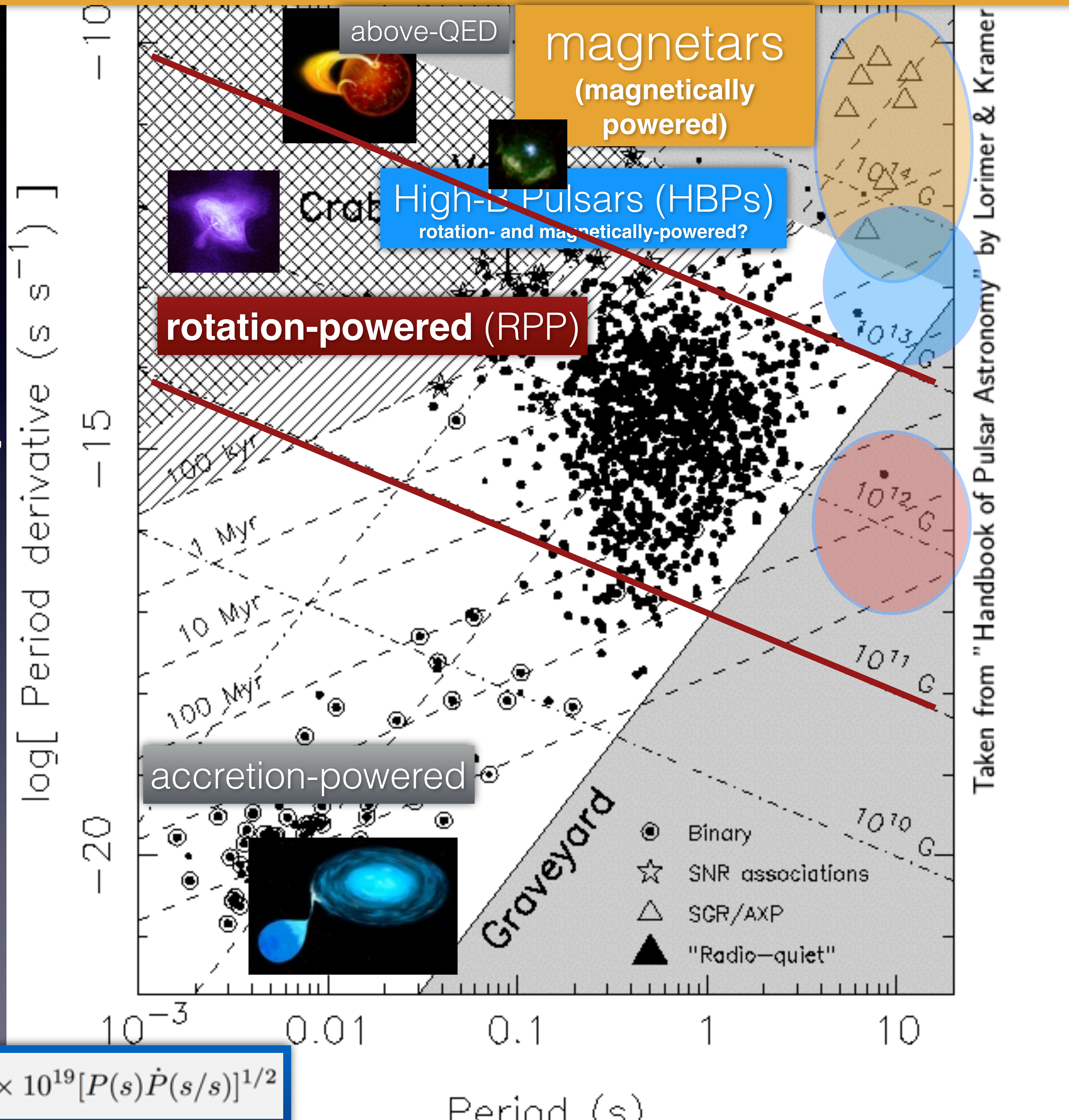

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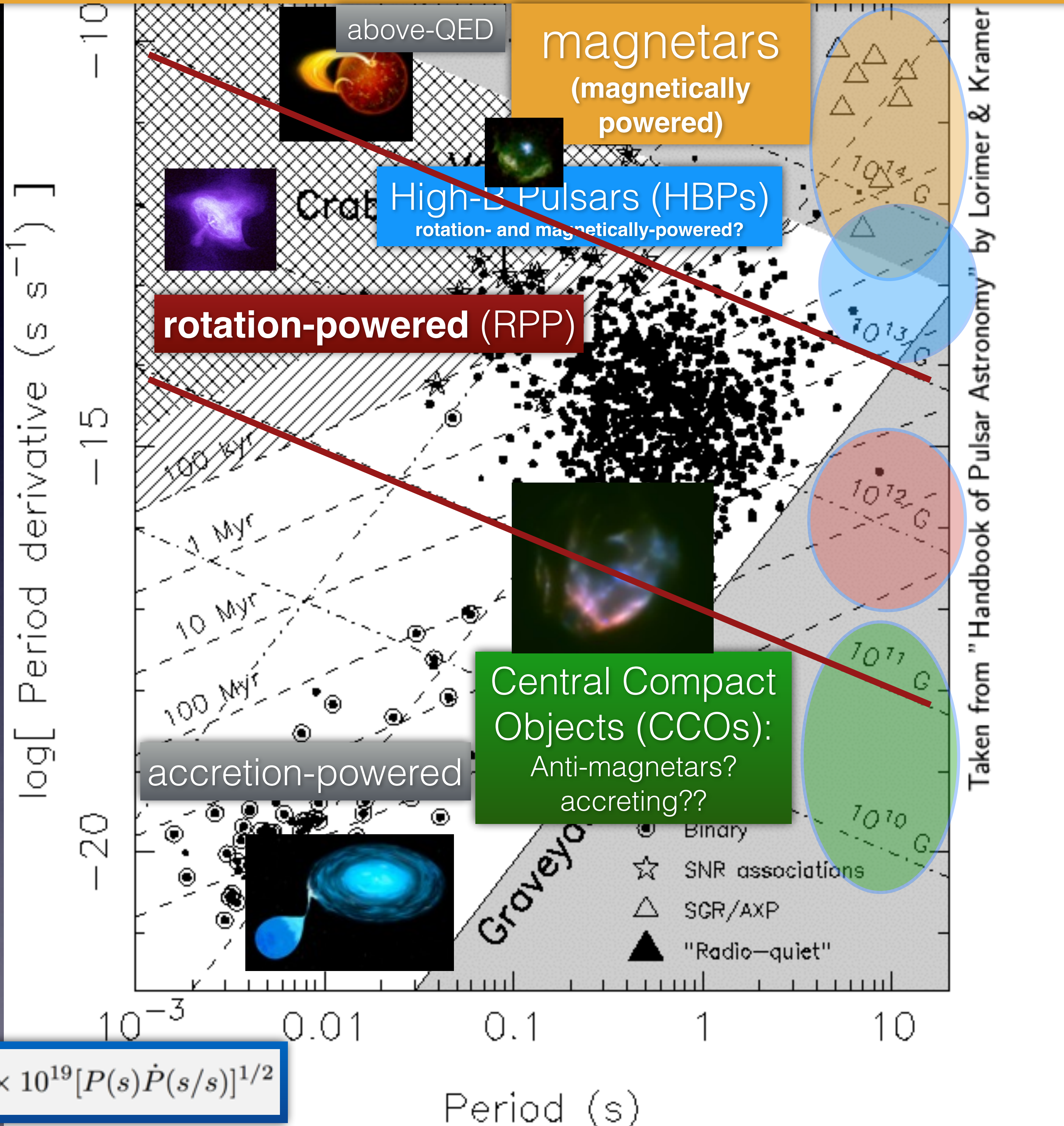

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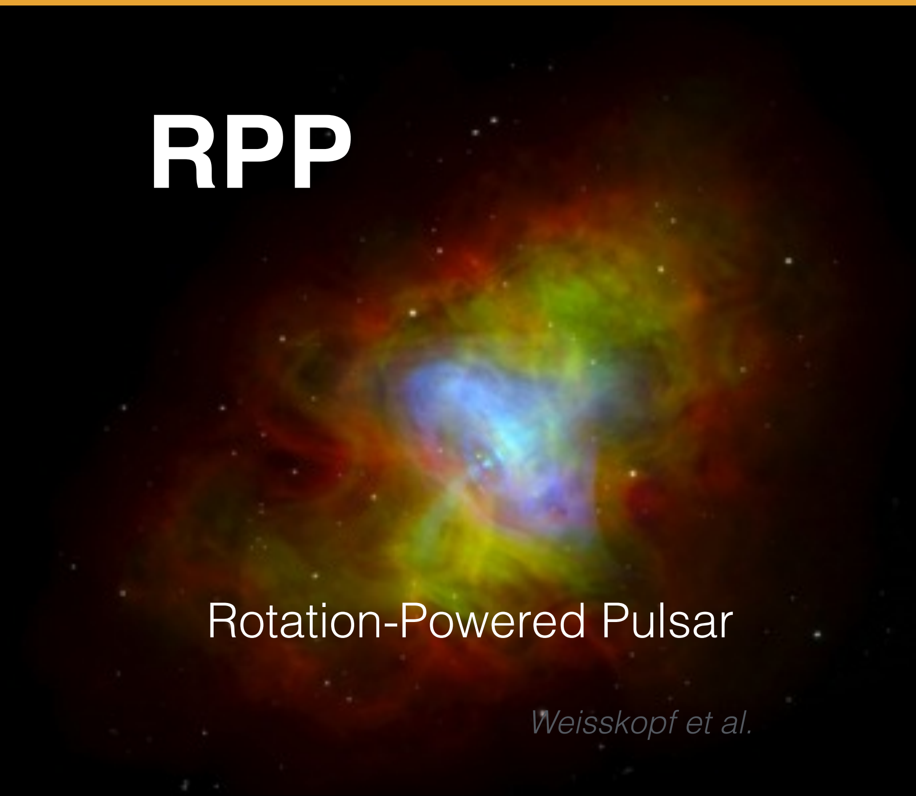
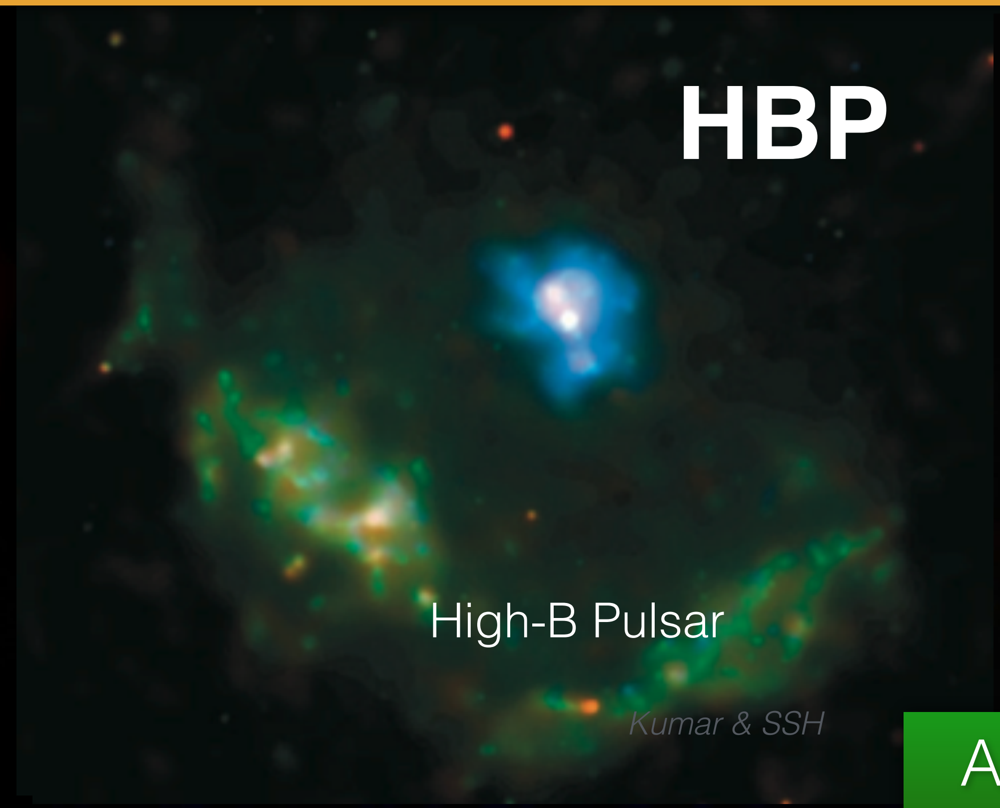
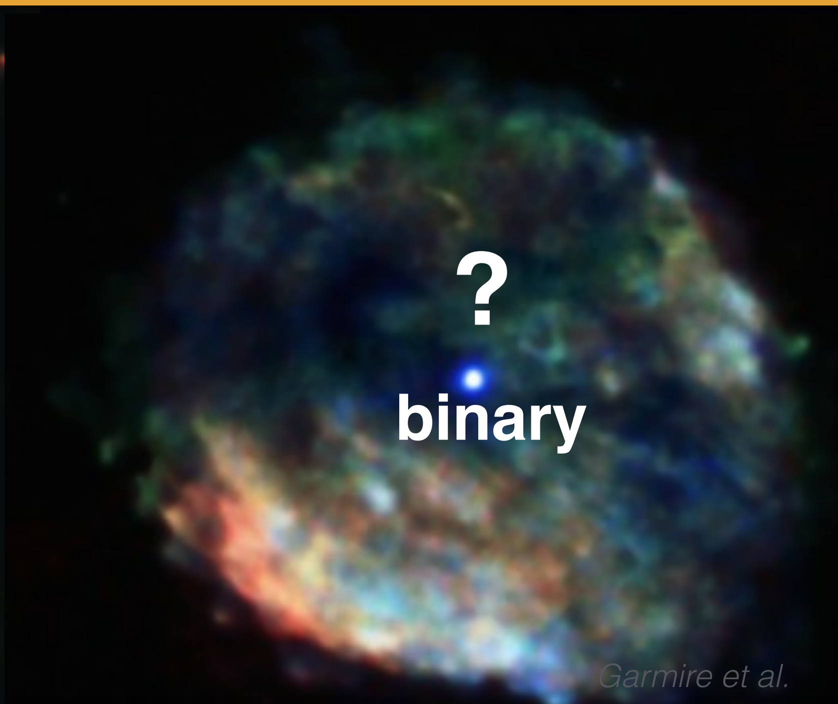
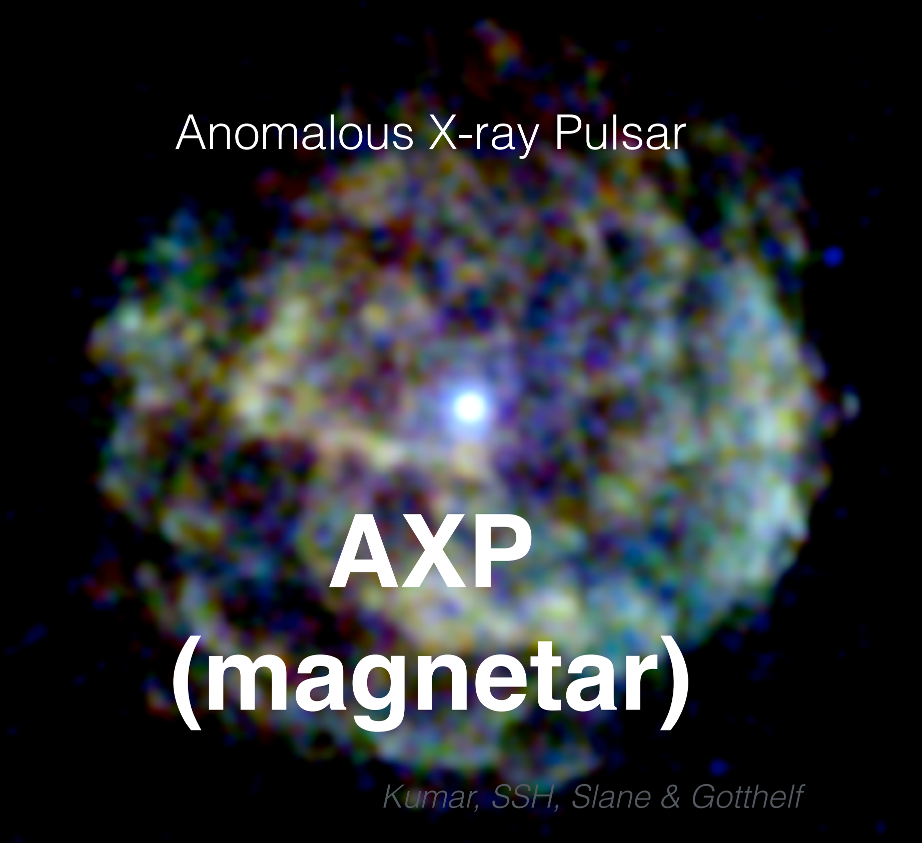
The many "faces" of Neutron Stars in Supernova Remnants

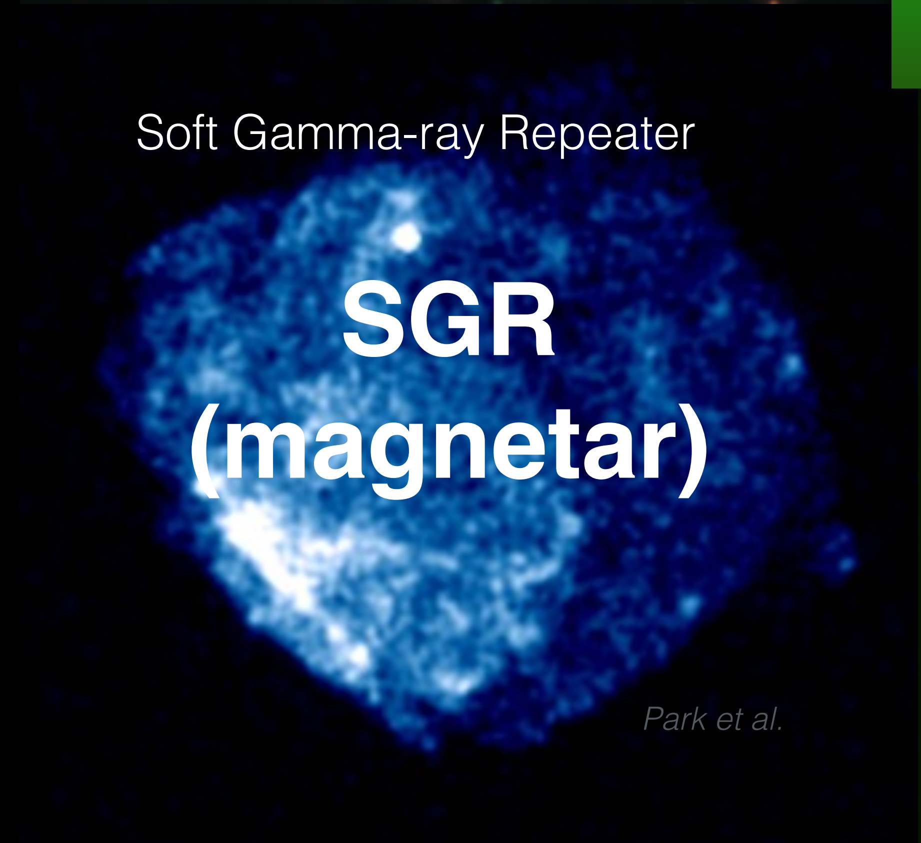






AXPs (magnetars) and CCOs are exclusively X-ray objects!





Distinction between magnetars and the other classes has been blurred with the discovery of….

- **Magnetar-like behaviour** from a high-B pulsar (**HBP**) thought to be rotation-powered (Crab-like)

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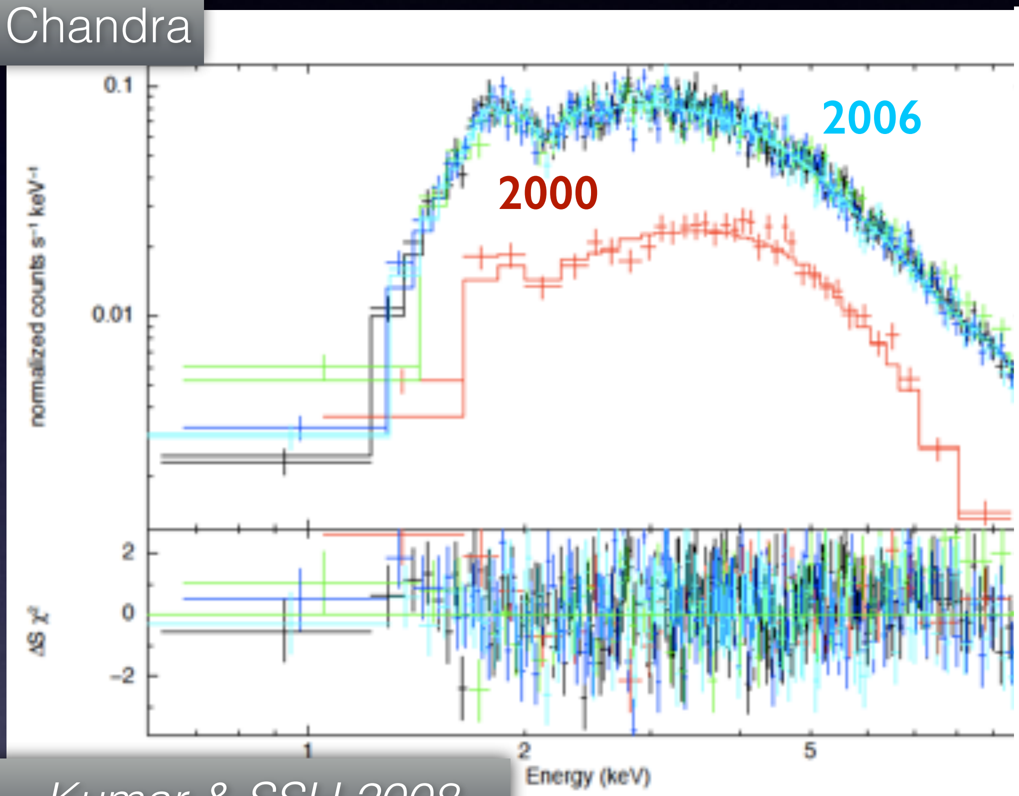
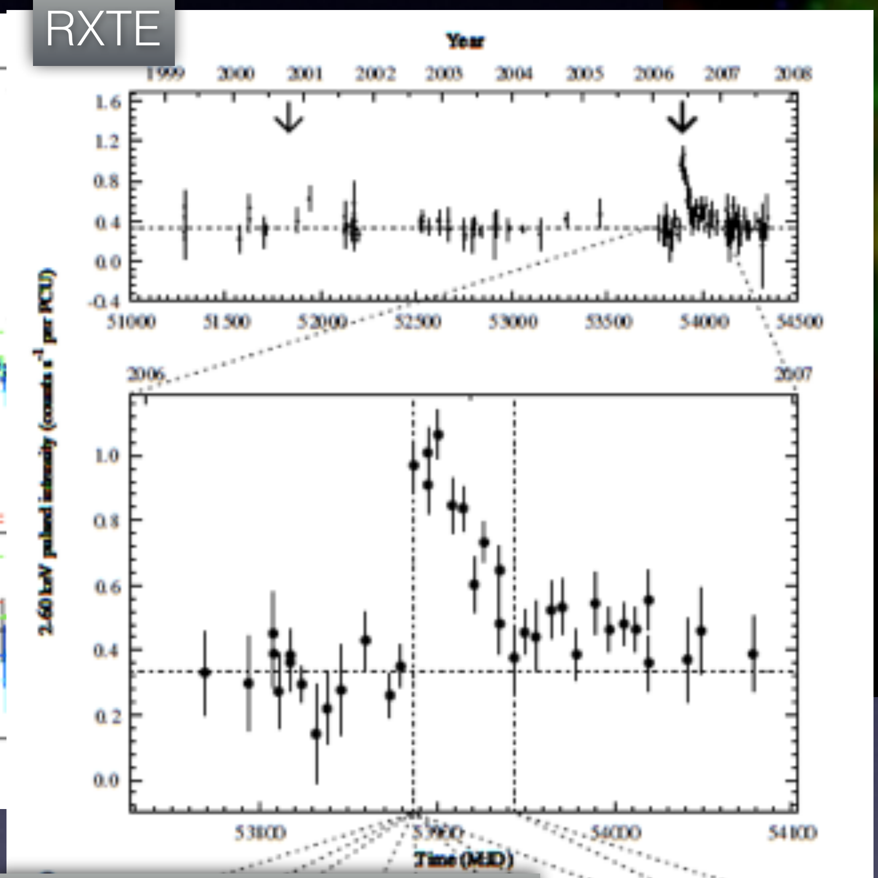
Chandra



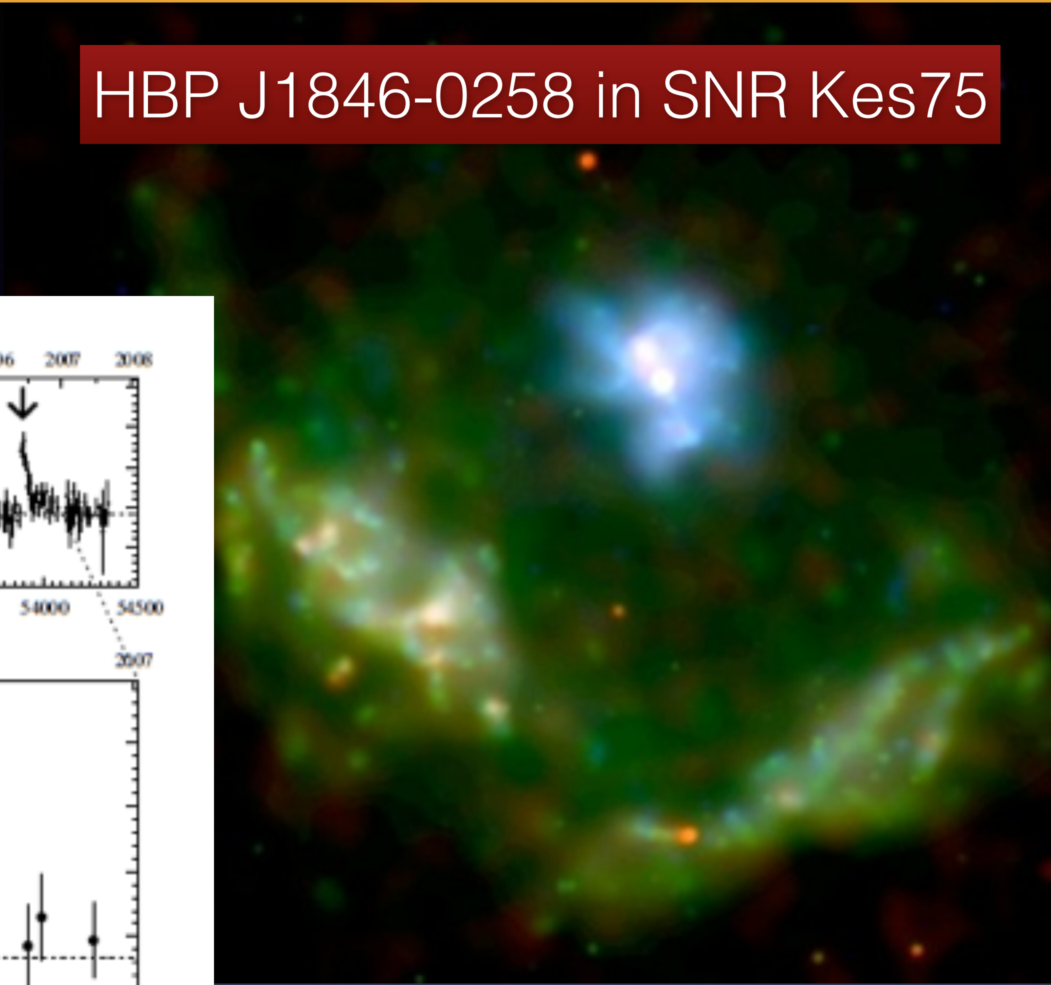
Kumar & SSH 2008

RXTE



Gavriil et al. 2008

HBP J1846-0258 in SNR Kes75



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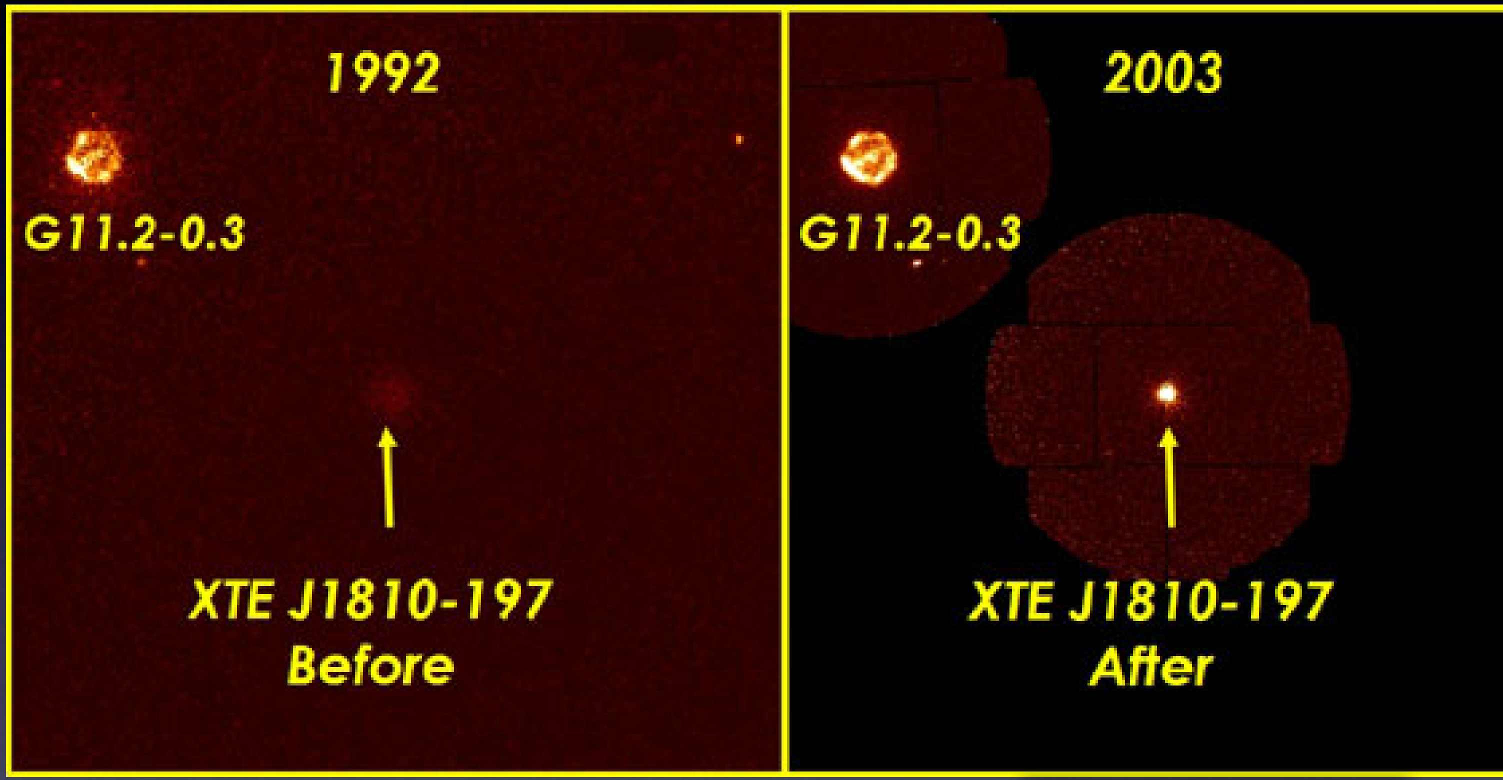
- Discovery of **transient magnetars** (e.g. *Ibrahim et al. 2003*)



NASA/RXTE/Ibrahim et al.

- Discovery of radio emission from transient magnetars (*Camilo et al. 2006)*

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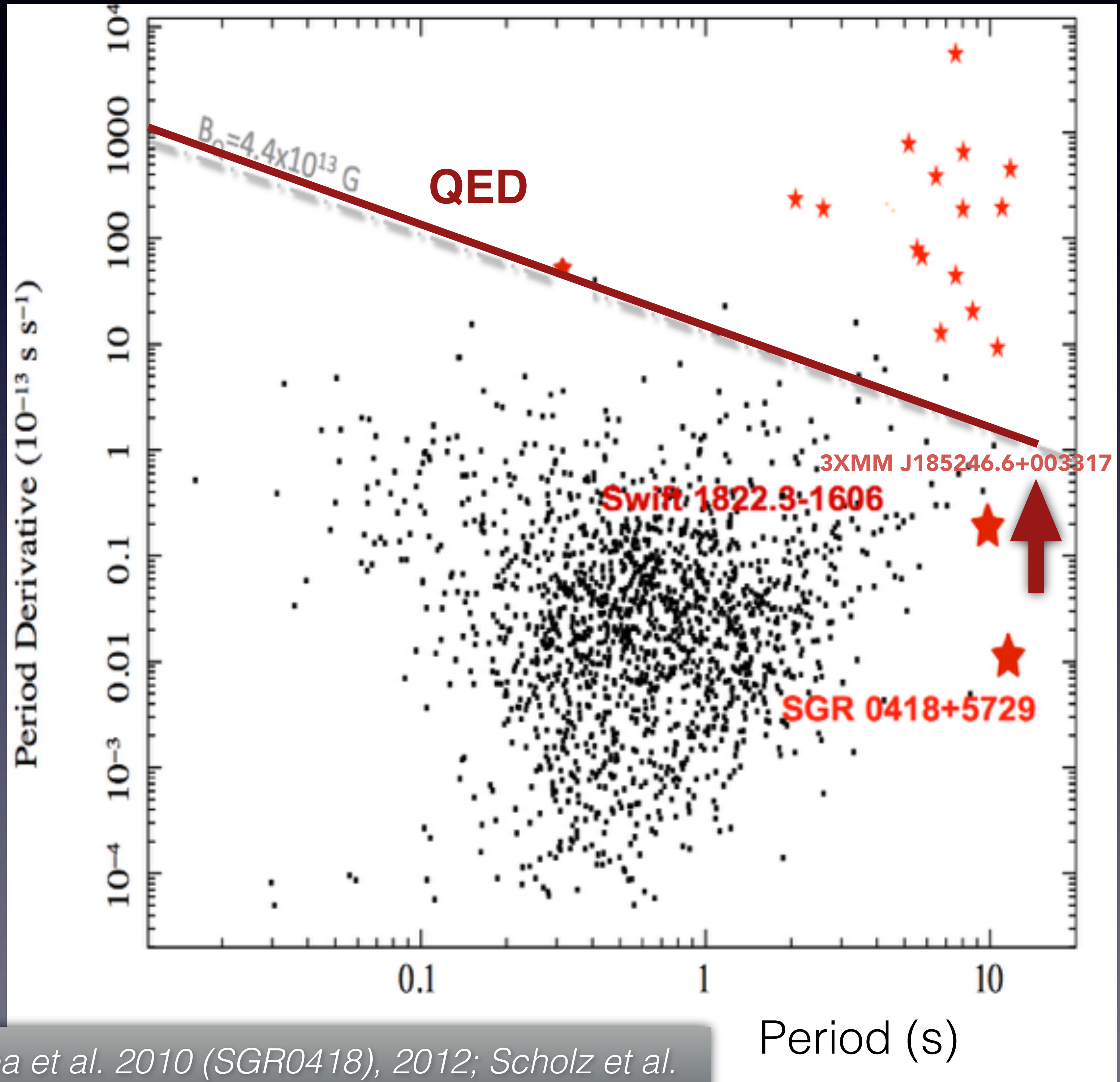
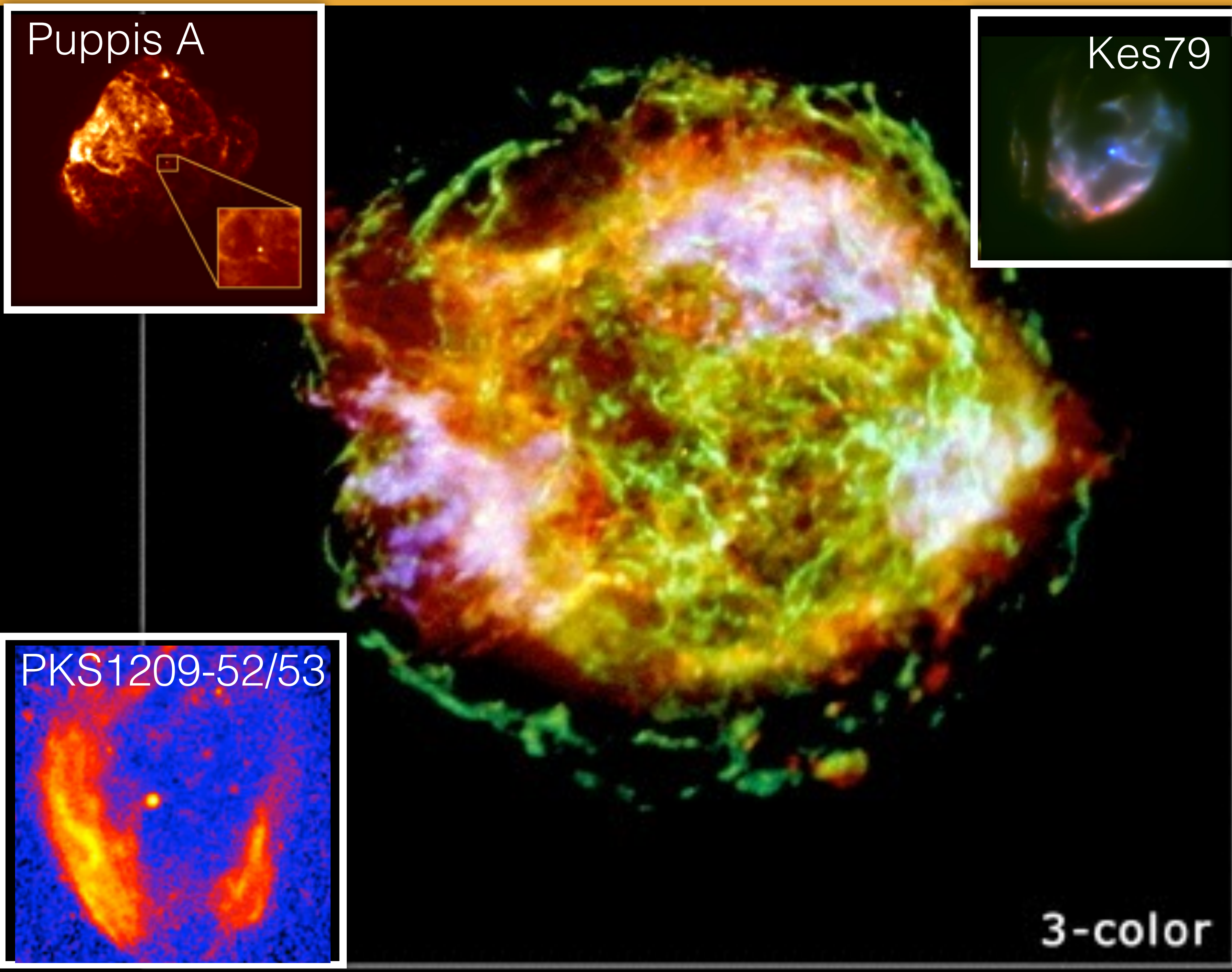
- Discovery of "**low-B**" (below QED) magnetars!



adapted from Rea et al: Rea et al. 2010 (SGR0418), 2012; Scholz et al. 2012 (Swift source), Zhou et al. 2014 (3XMM source near SNR Kes79)

How about the **CCOs (Central Compact Objects)**
Anti-magnetars?



- Central Compact Objects (~**15 known** in SNRs)
- **X-ray** emitters ONLY
- **No pulsar wind nebulae**
- L_X>Edot, steady, thermal
- quiescent magnetars? cooling? accreting?
- X-ray pulsations (3 objects):
  - 105 ms, 112 ms, 424ms
  - B=3.1/2.9/9.8 x 10^{10} G ($<10^{11}$ G)

  => "anti-magnetars"!
  - **PSR ages>>> SNR ages**

How connected to the other neutron star classes?
Are they "low" or "high" B-field neutron stars?

e.g. Gotthelf & Halpern'13, '09 (timing); Ho & Heinke'09 (spectroscopy of CasA CCO); Gotthelf+13, Bogdanov+14, Luo+15 (Descendants of CCOs); Ho 2011, Bernal & Page 11 (B growing/submerged); De Luca+08, Pavlov+08 (reviews)

Neutron Stars Diversity

The age and braking index "problem"<=> SNR association

secure associations only with known SNR age

Observed properties of NSs

PSR	P s	$\dot{P}$ $10^{-11} s\ s^{-1}$	n braking index	τ_{PSR} kyr	SNR	τ_{SNR-} kyr	τ_{SNR+} kyr
AXPs							
AXP 1E 1841–045	11.783	3.930		4.750	G27.4+0.0 (Kes 73)	0.750	2.100 [1]
AXP 1E 2259+586	6.979	4.843e – 2		228.317	G109.1-01.0 (CTB 109)	10.000	16.000 [2]
CXOU J171405.7–381031	3.825	6.400		0.947	G348.7+00.3	0.350	3.150 [3]
SGRs							
SGR 0526–66	8.054	3.800		3.358	N49	–	4.800 [4]
SGR 1627–41	2.595	1.900		2.164	G337.3–0.1	–	5.000 [5]
HBPs							
HBP J1119–6127	0.408	0.400	2.684 ± 0.002 [14]	1.616	G292.2–0.5	4.200	7.100 [6]
HBP J1734–3333	1.170	0.228	0.9 ± 0.2 [15]	8.131	G354.8–0.8	1.300	– [7]
HBP J1846–0258 A	0.325	0.709	2.64 ± 0.01 [16]	0.726	G029.7–0.3 (Kes 75)	0.900	4.300 [8]
HBP J1846–0258 B	0.326	0.708	2.68 ± 0.03 [16]	0.729			
HBP J1846–0258 C	0.327	0.711	2.16 ± 0.13 [17]	0.728			
RPPs (also studied by Ho 2015)							
PSR J0537–6910	0.016	0.518	-1.5 ± 0.1 [18]	4.925	N157B	1.000	5.000 [9]
PSR B0833–45	0.089	1.250	1.4 ± 0.2 [19]	11.319	G263.9–03.3 (Vela)	5.400	16.000 [10]
CCOs							
RX J0822.0–4300	0.112	8.300e – 4		213.799	G260.4–3.4 (Puppis A)	3.700	5.200 [11]
1E 1207.4–5209	0.424	6.600e – 6		1.018e5	G296.5 +10.0 (PKS 1209–51/52)	2.000	20.000 [12]
CXOU J185238.6+004020	0.105	8.680e – 7		1.917e5	G033.6+00.1 (Kes 79)	5.400	7.500 [13]

See Poster DDp.2.50 (*Rogers & SSH*)

SNR ages in SNRcat
www.physics.umanitoba.ca/snr/SNRcat

Neutron Stars Diversity

The age and braking index “problem”<=> SNR association

secure associations only with known SNR age

Observed properties of NSs

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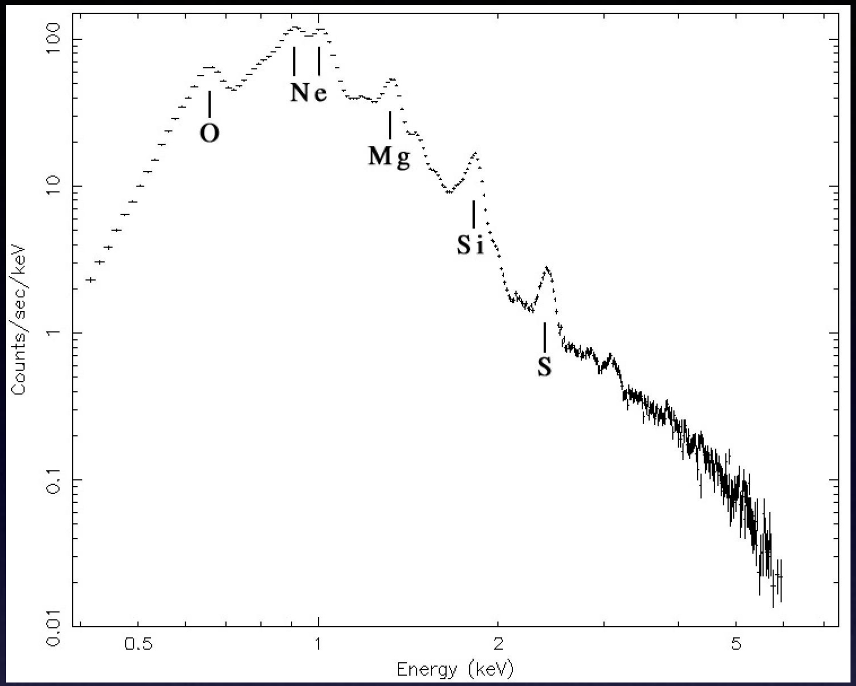

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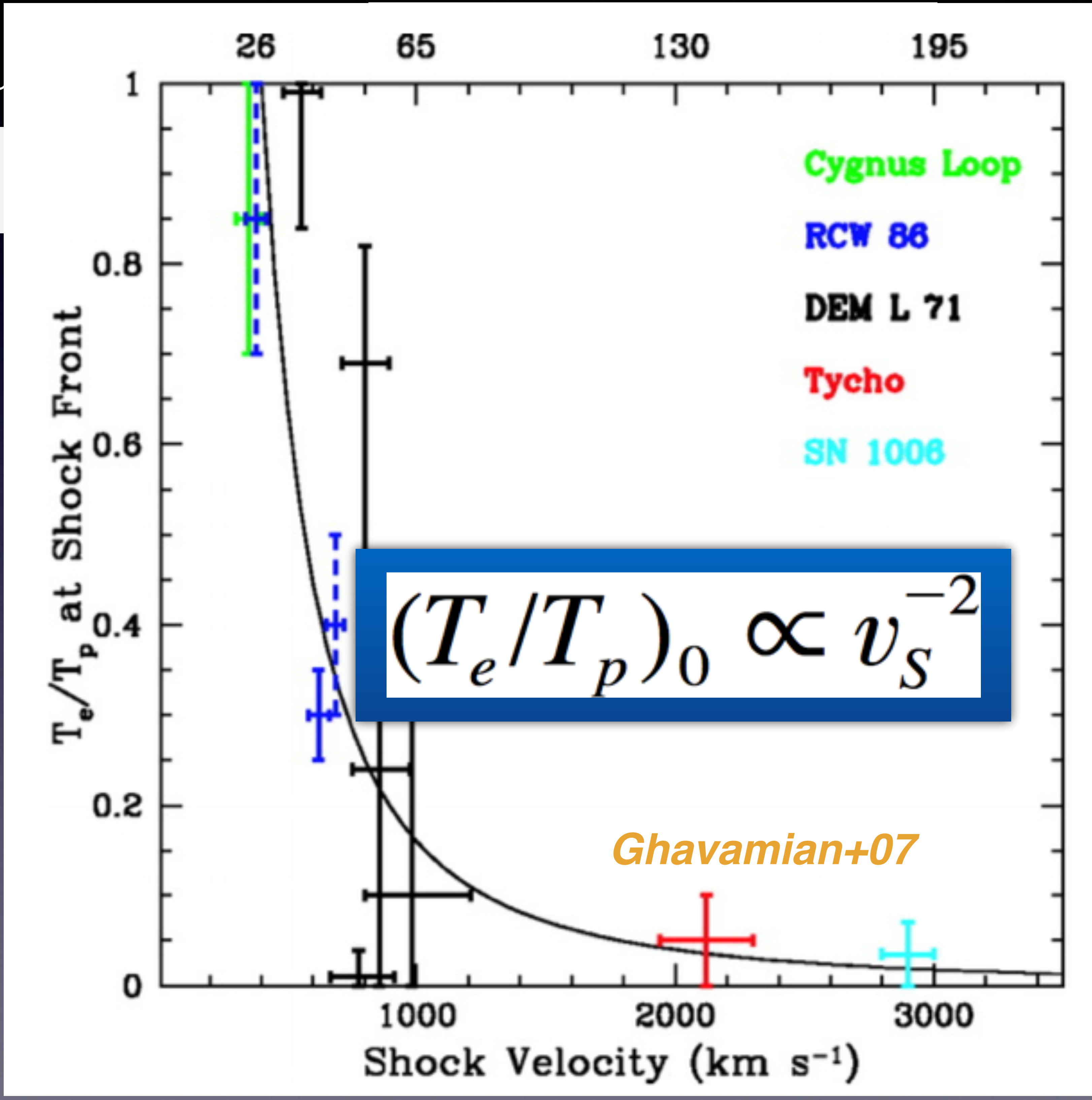

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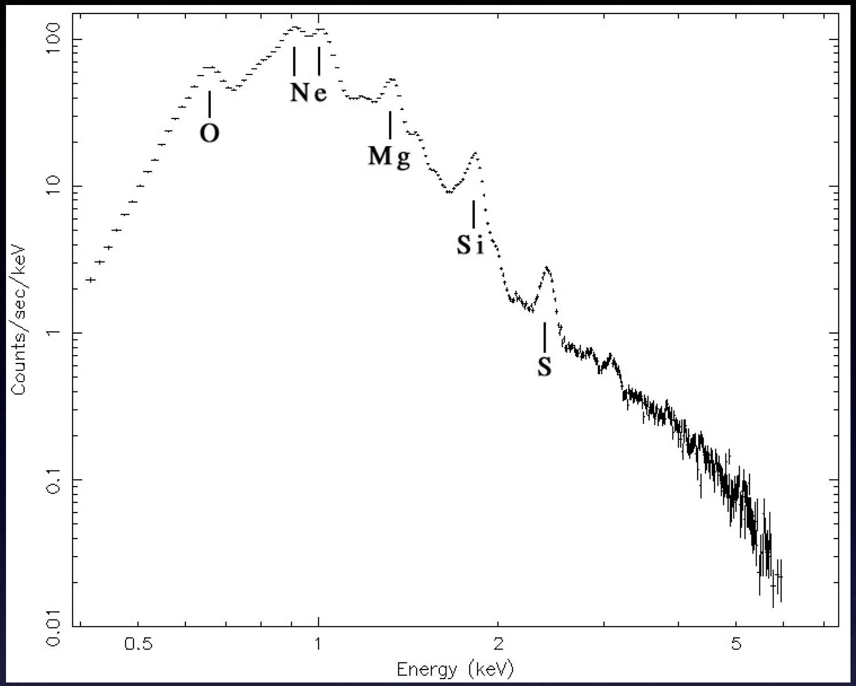

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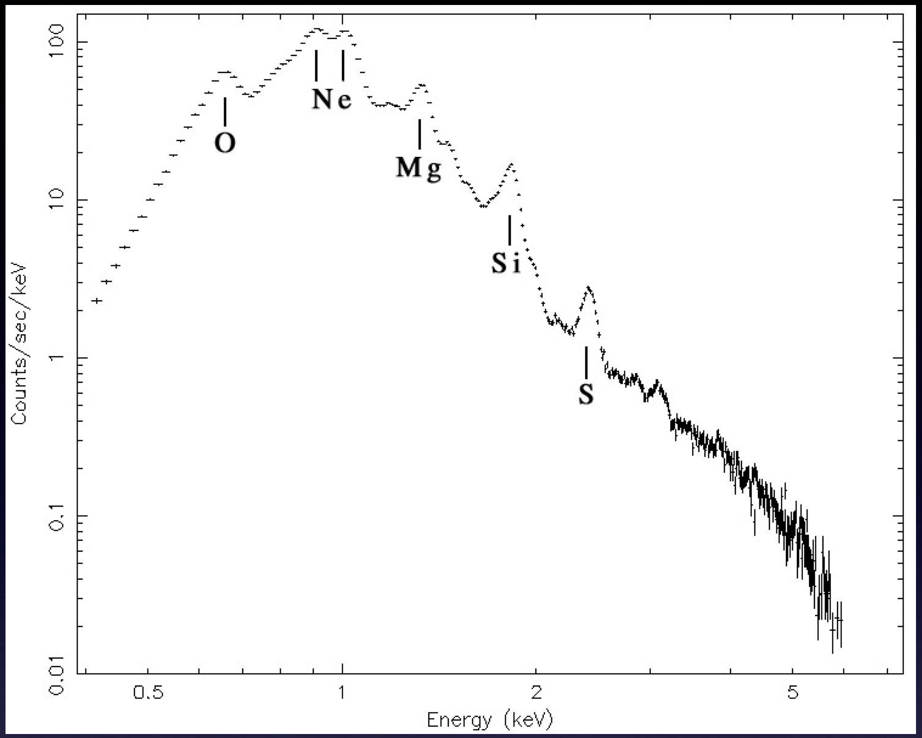

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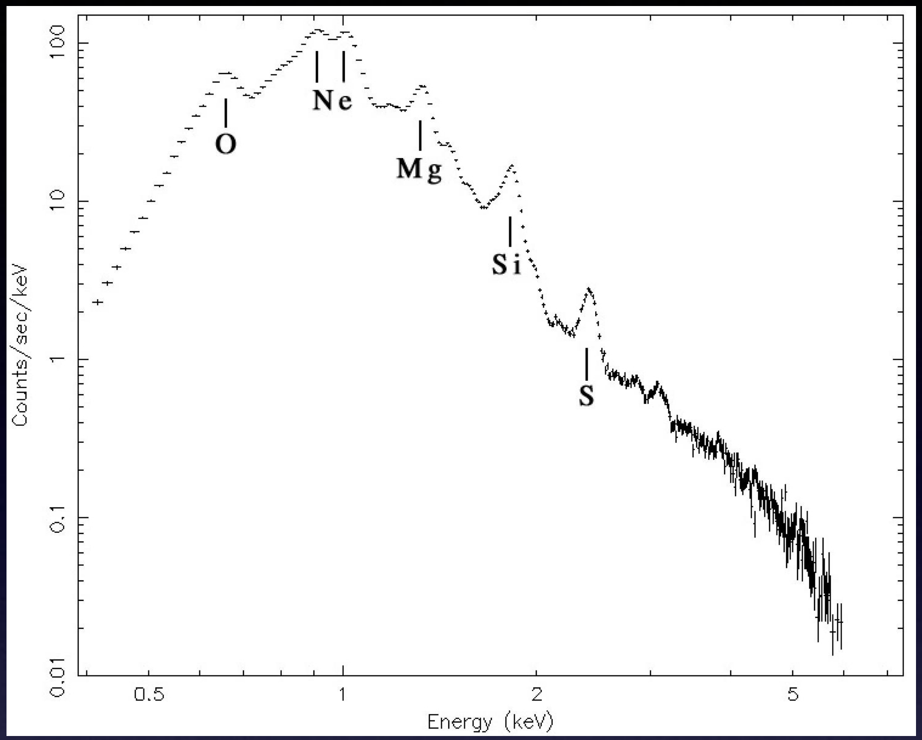

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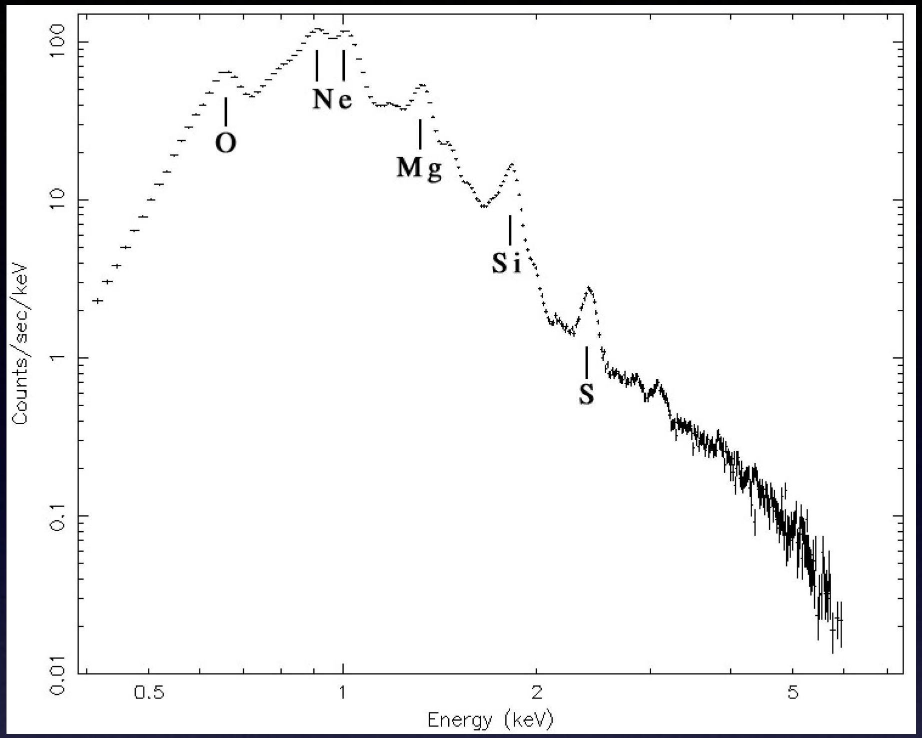

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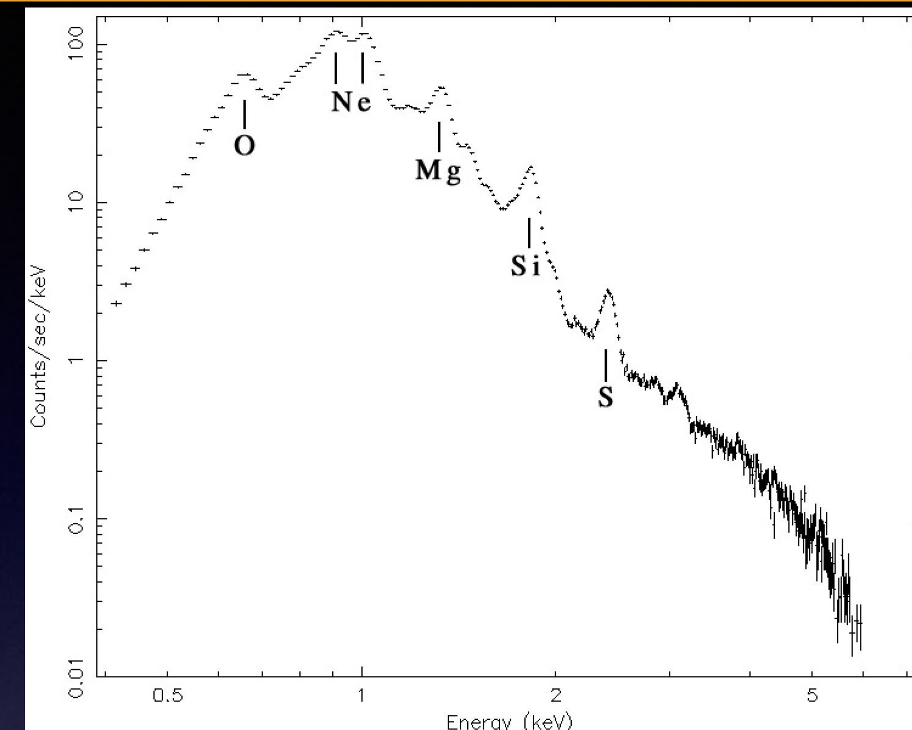

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Ionization timescale: n_e t (another handle on "age", t)

Solving the PSR-SNR age discrepancy

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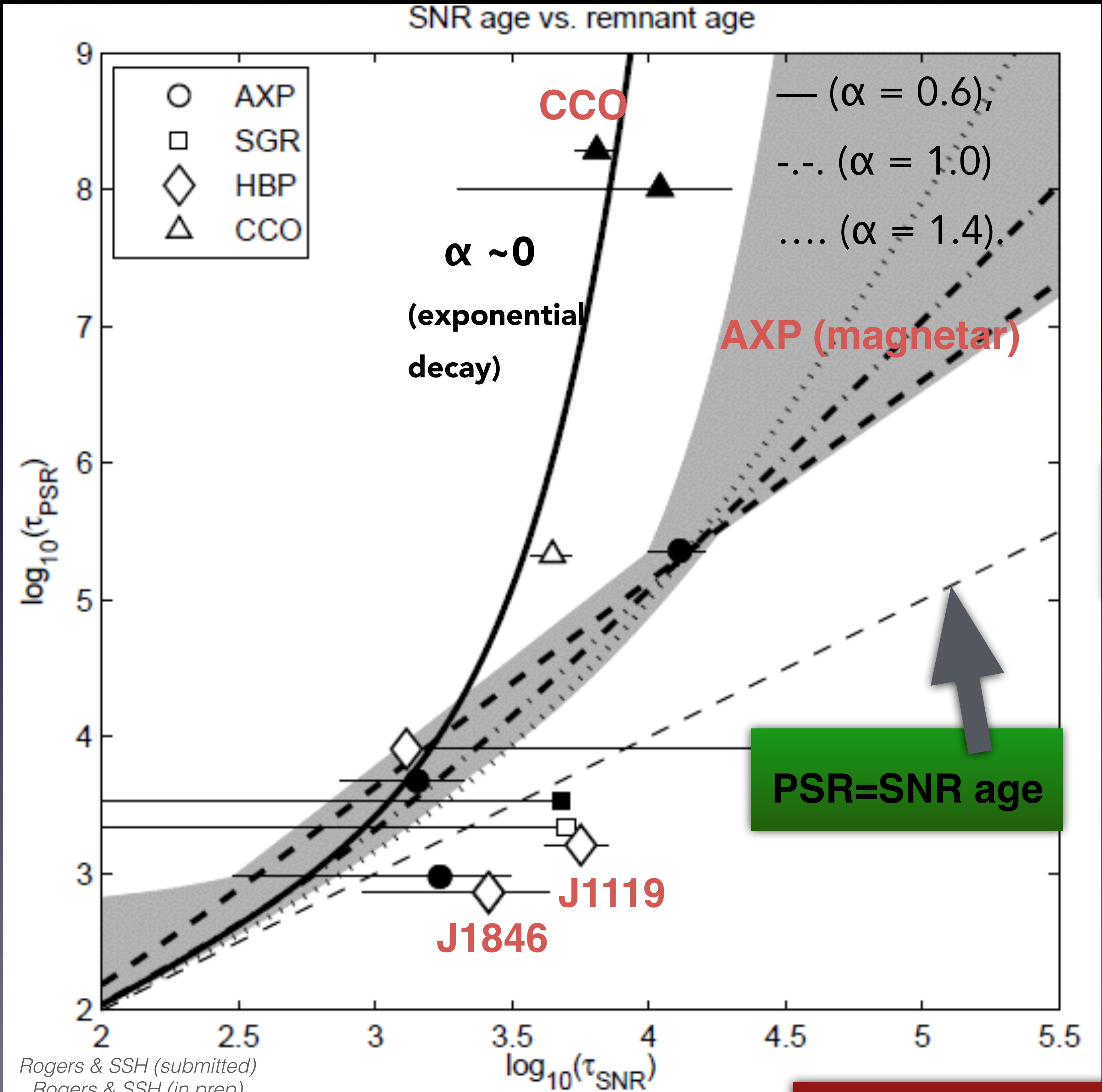

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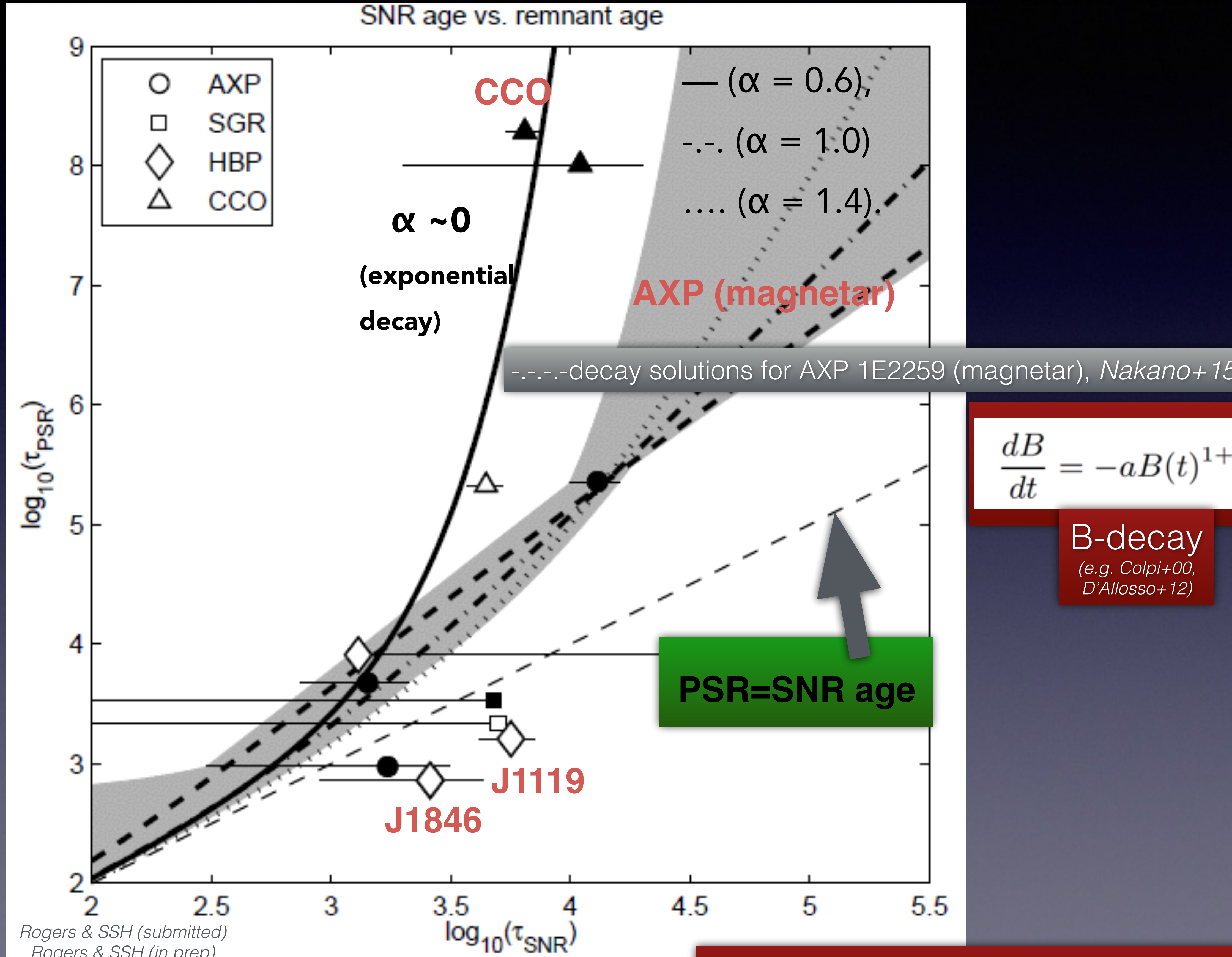

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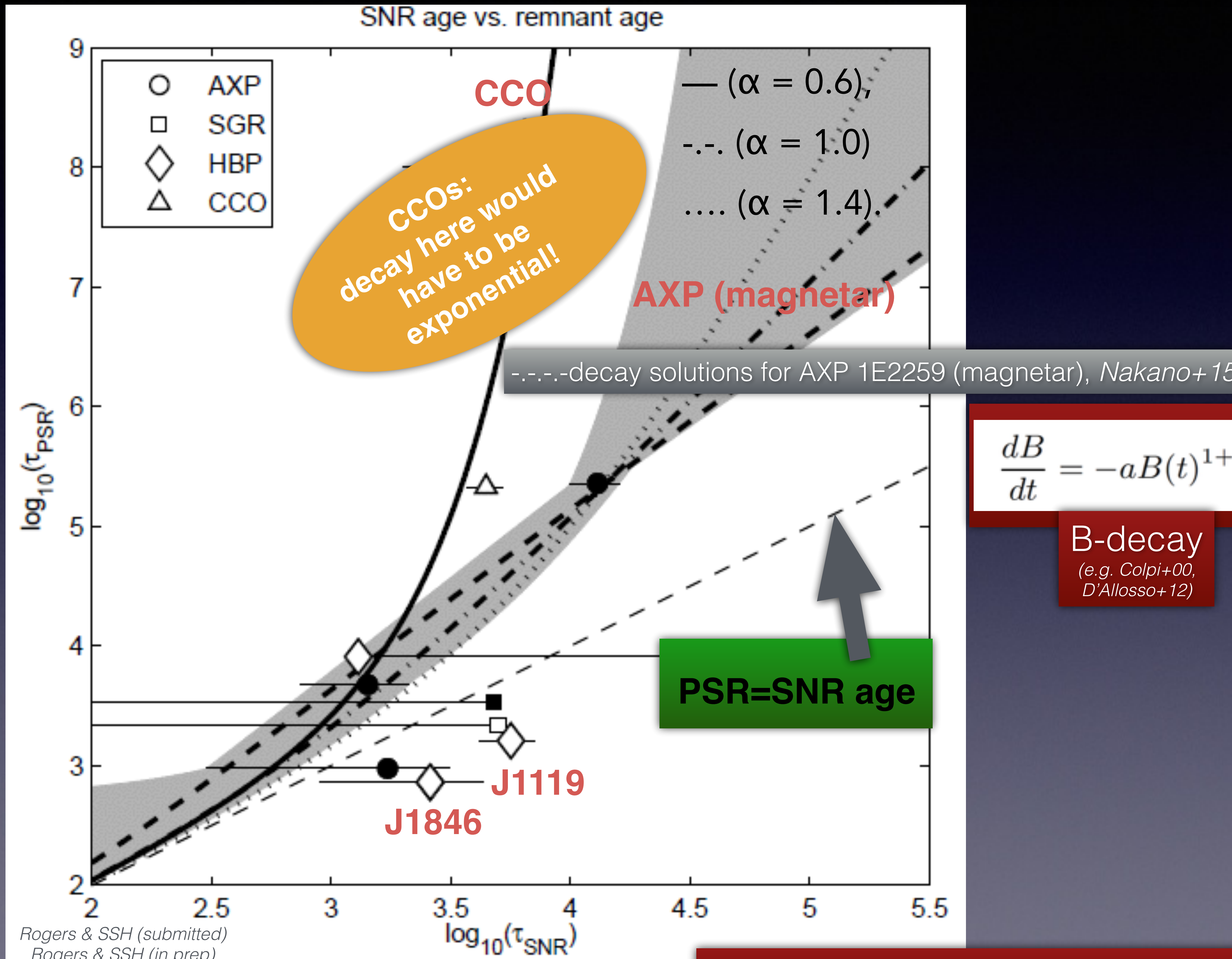

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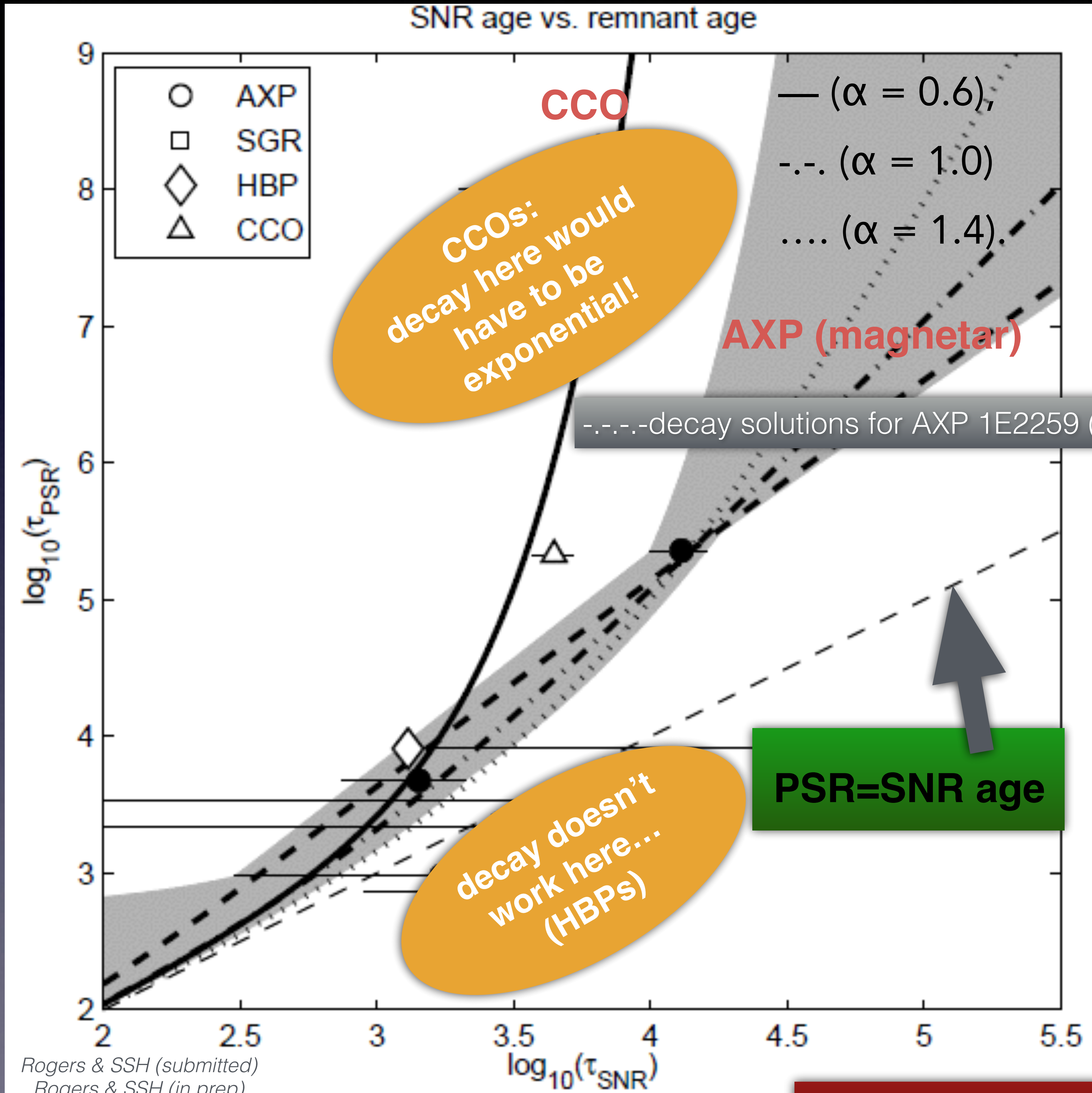

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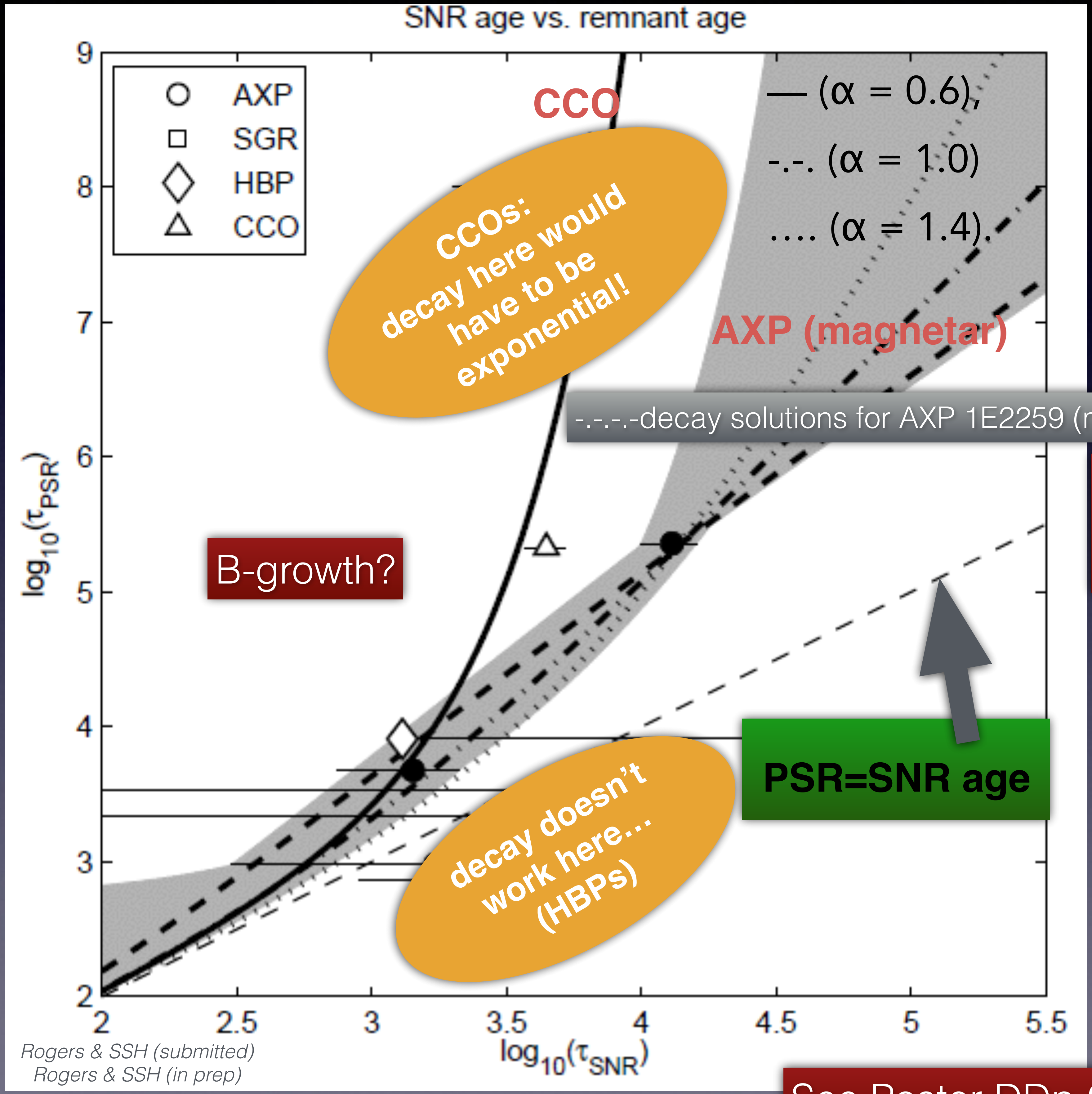


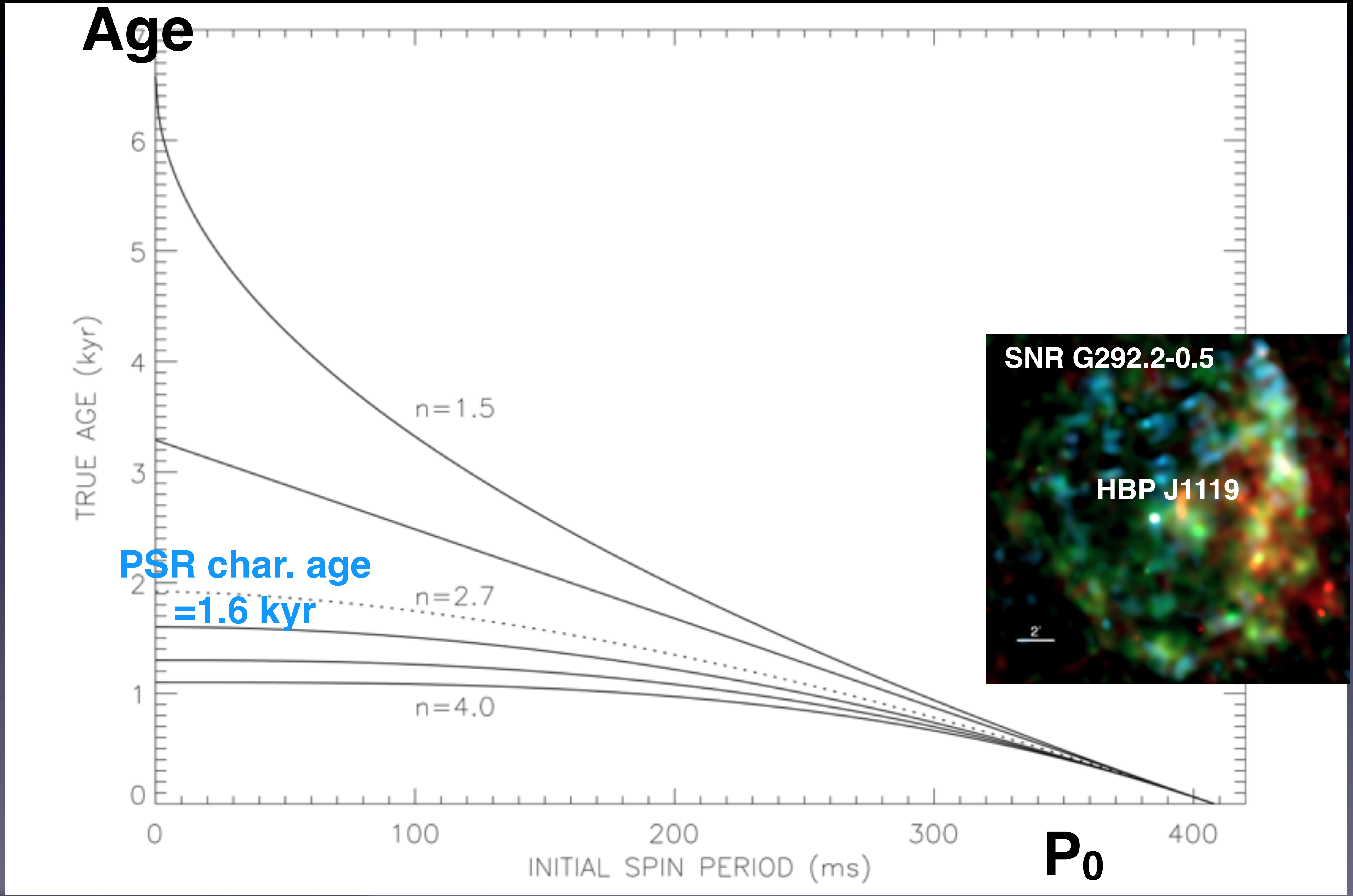
$$\frac{dB}{dt} = -aB(t)^{1+\alpha}$$

B-decay

(e.g. Colpi+00, D'Allosso+12)

See Poster DDp.2.50 (Rogers & SSH)

HBP J1119-6127 in G292.2-0.5



$$\tau = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{(n-1)}\right]$$

Kumar, SSH & Gonzalez 2012
Weltevrede et al. 2011

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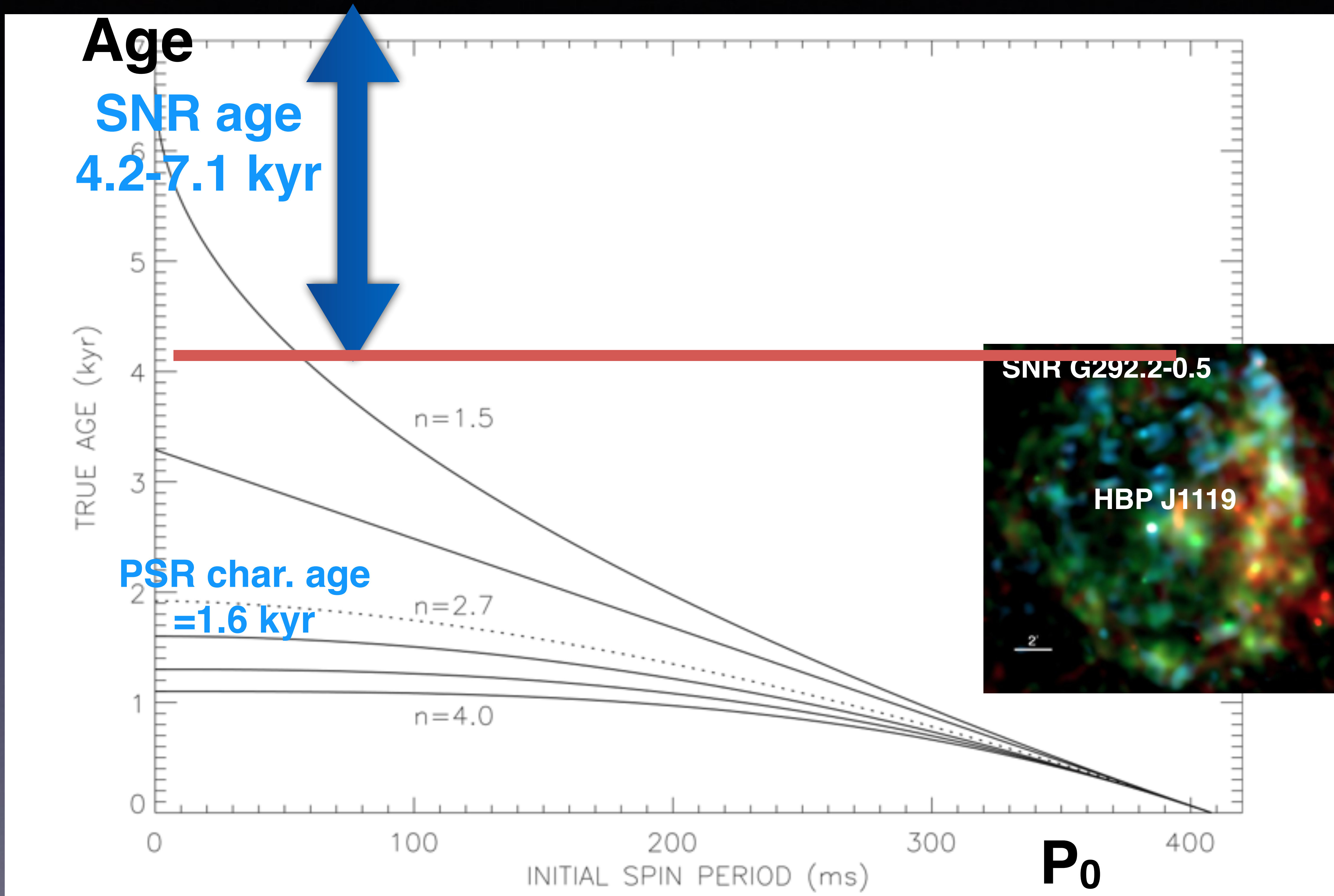

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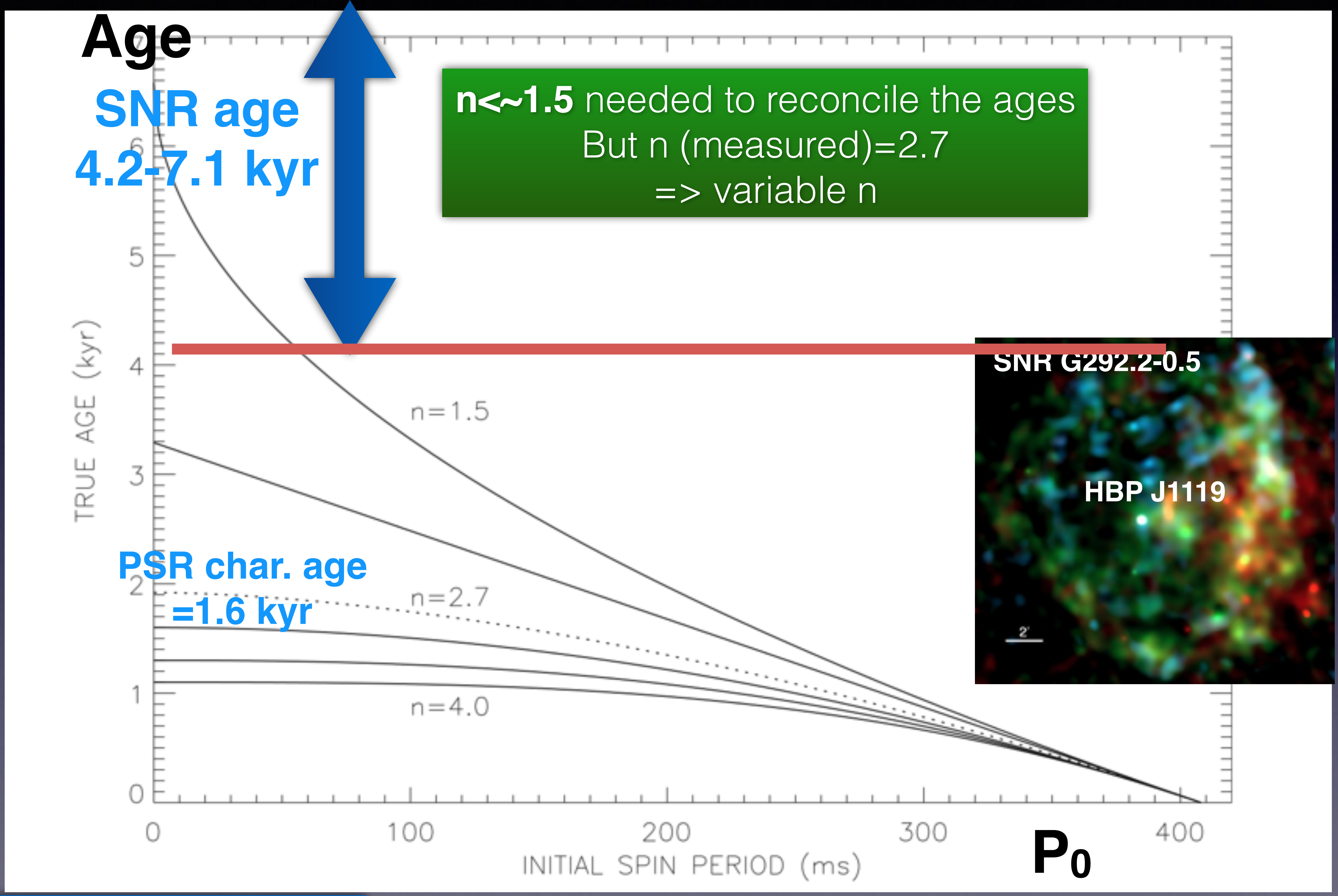

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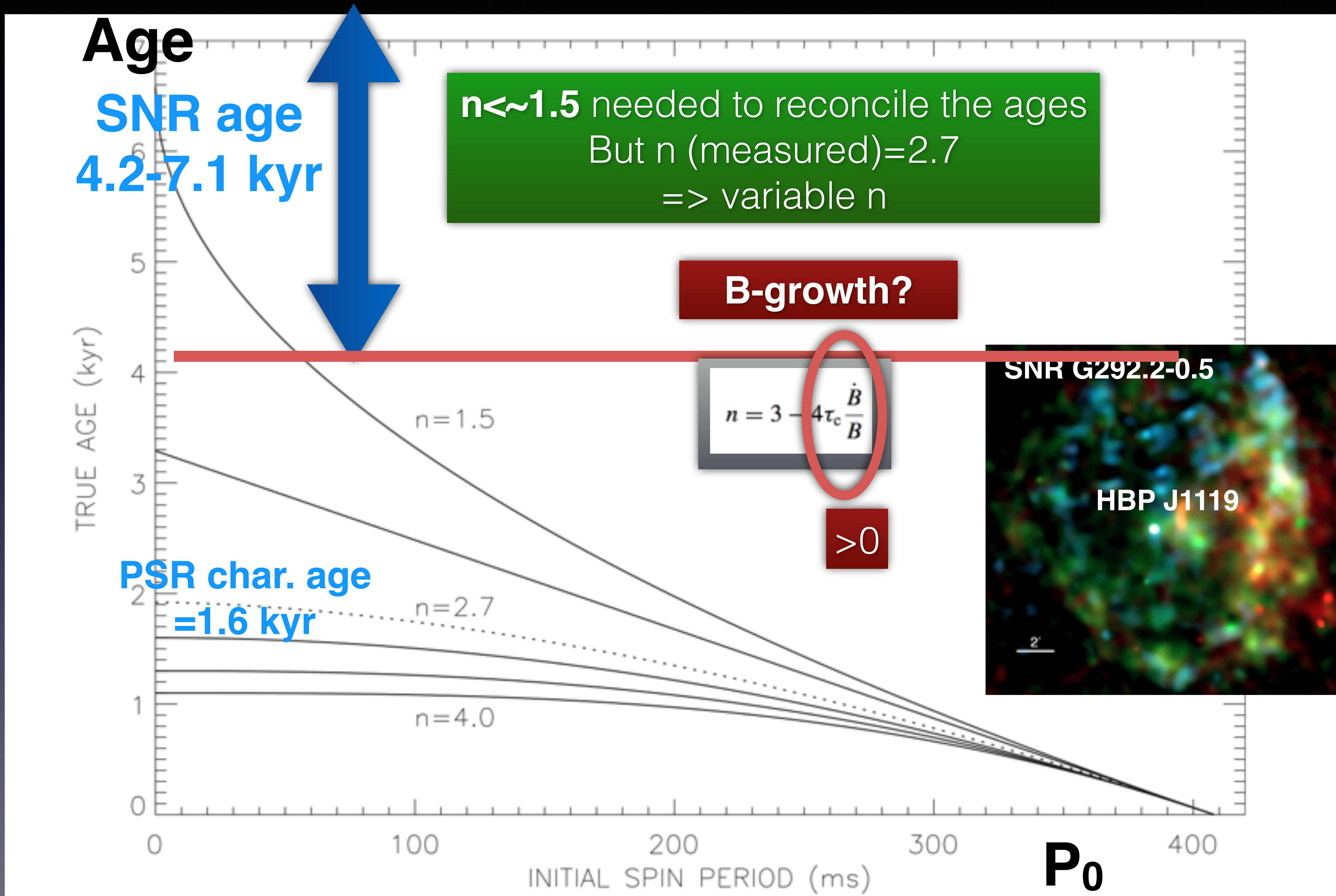

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B "submerged" in CCOs?

a way around the age and B measurement?

CCO
P=105 ms
B=3.1e10 Gauss
(*Seward et al; Gotthelf et al.*)

Kes 79
Zhou et al. 2014

SNR age: 5.4-7.5 kyr
(see new study: *Zhou et al.* **Poster DDp.2.37**)
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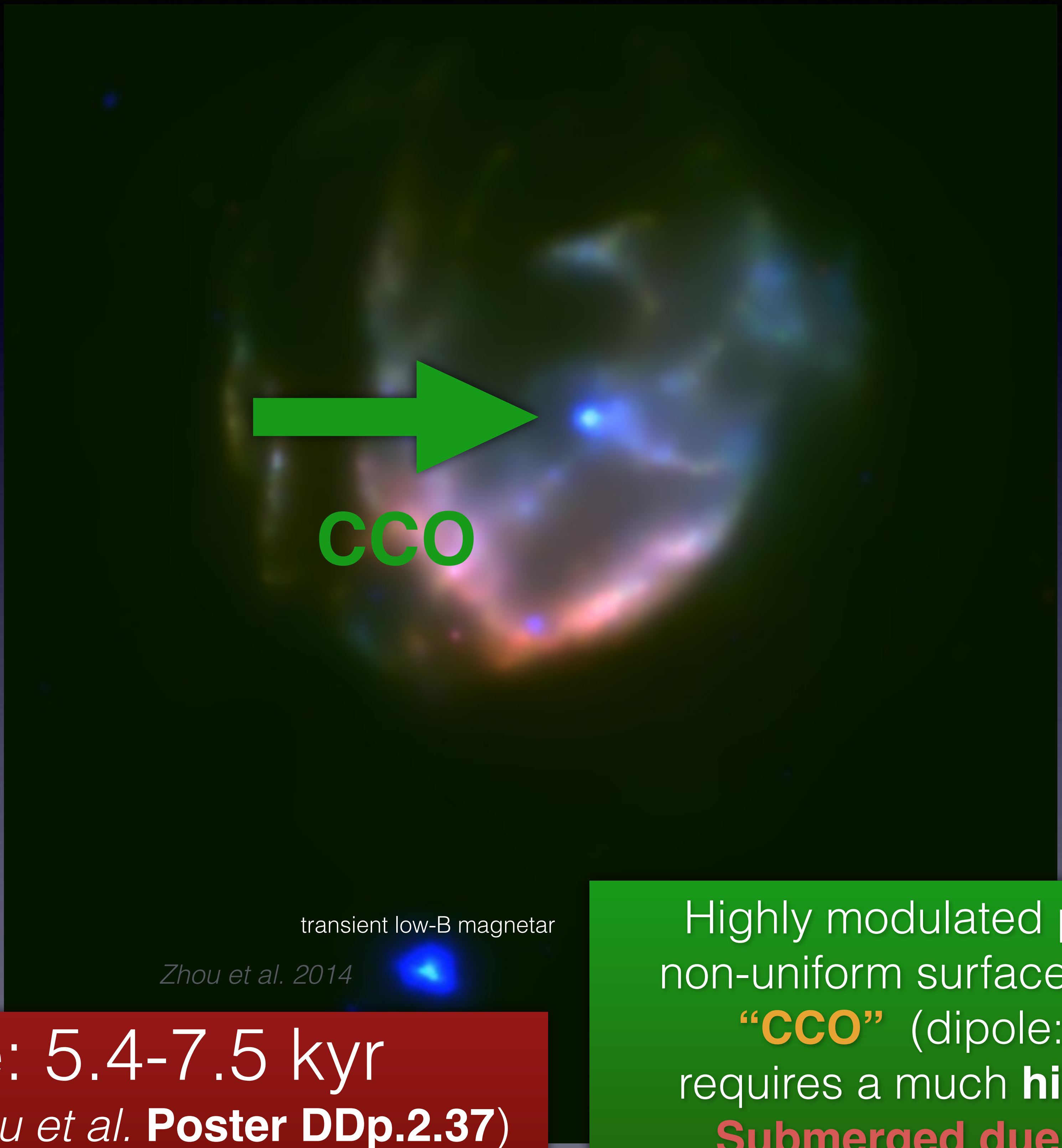

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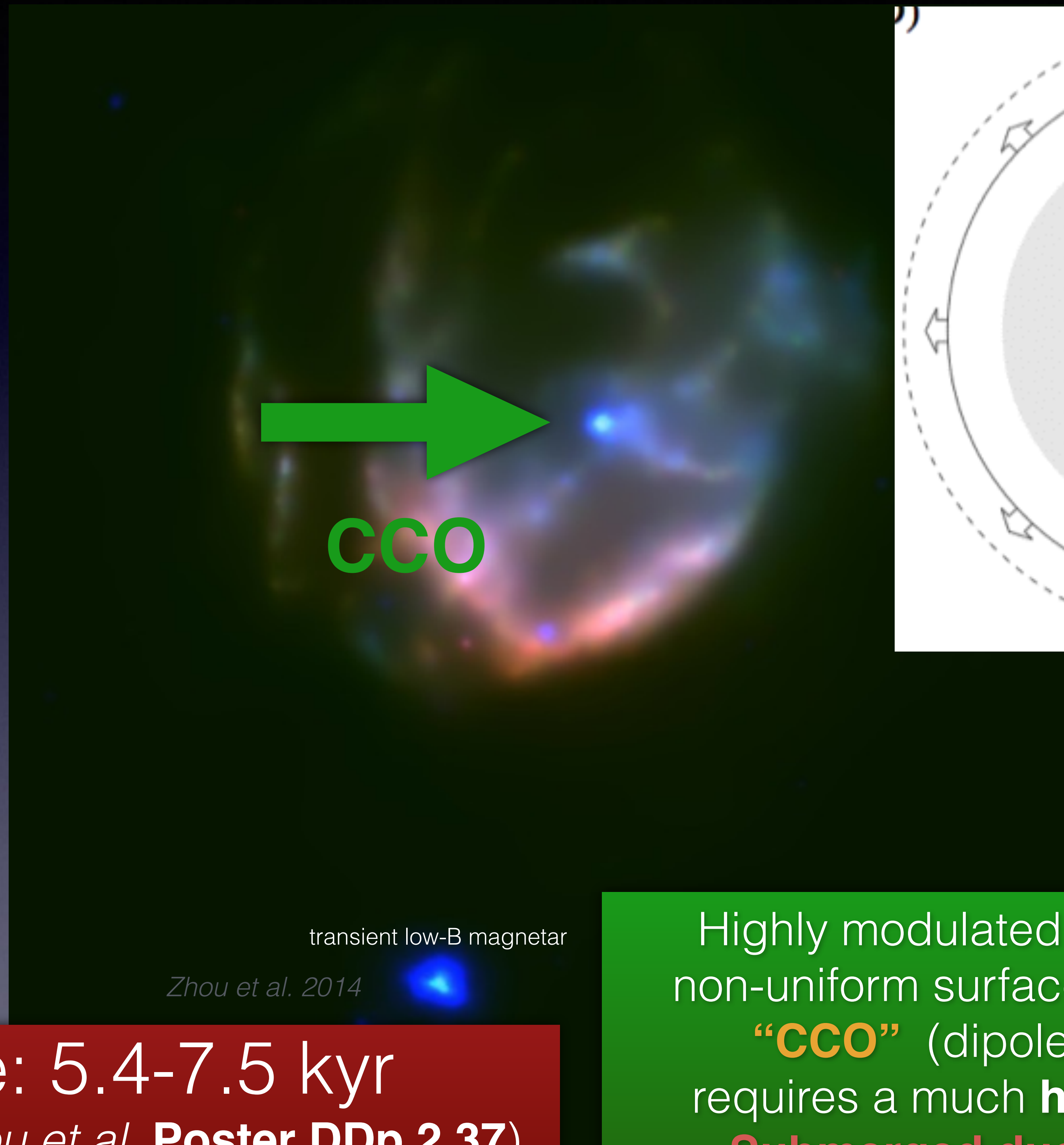

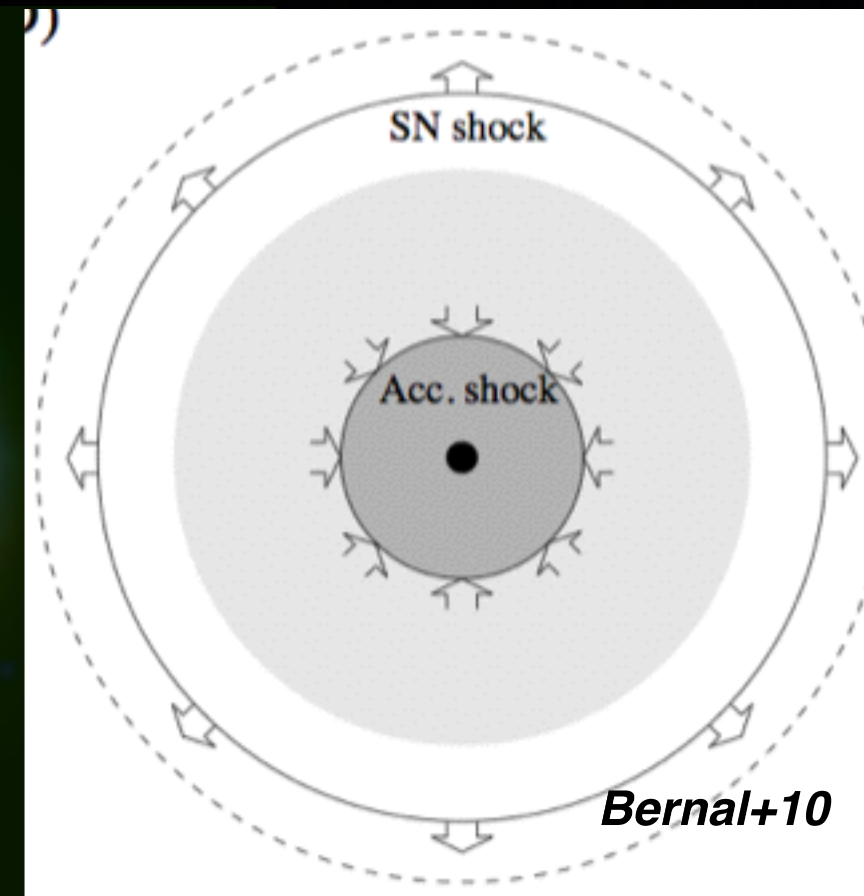

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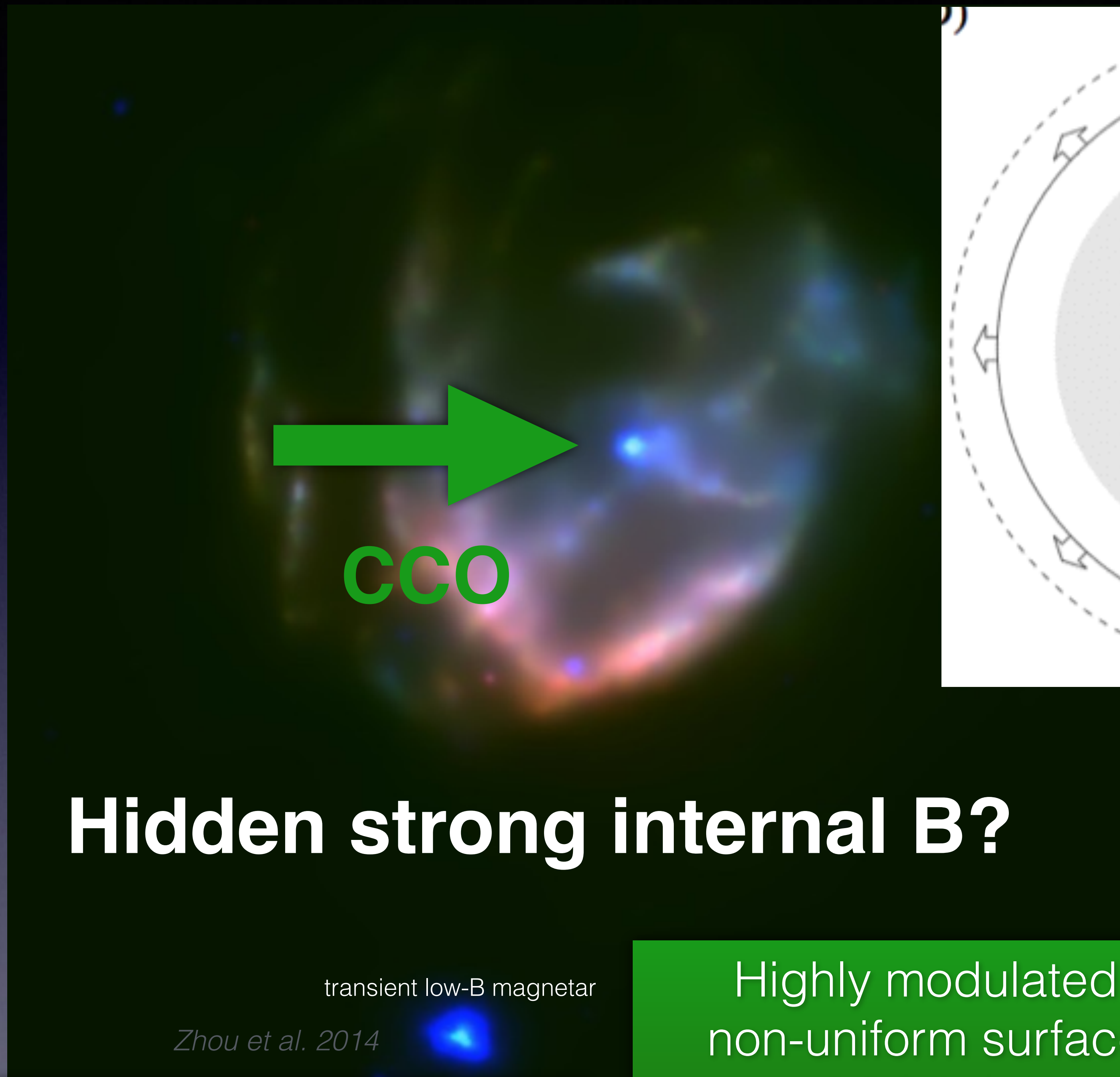

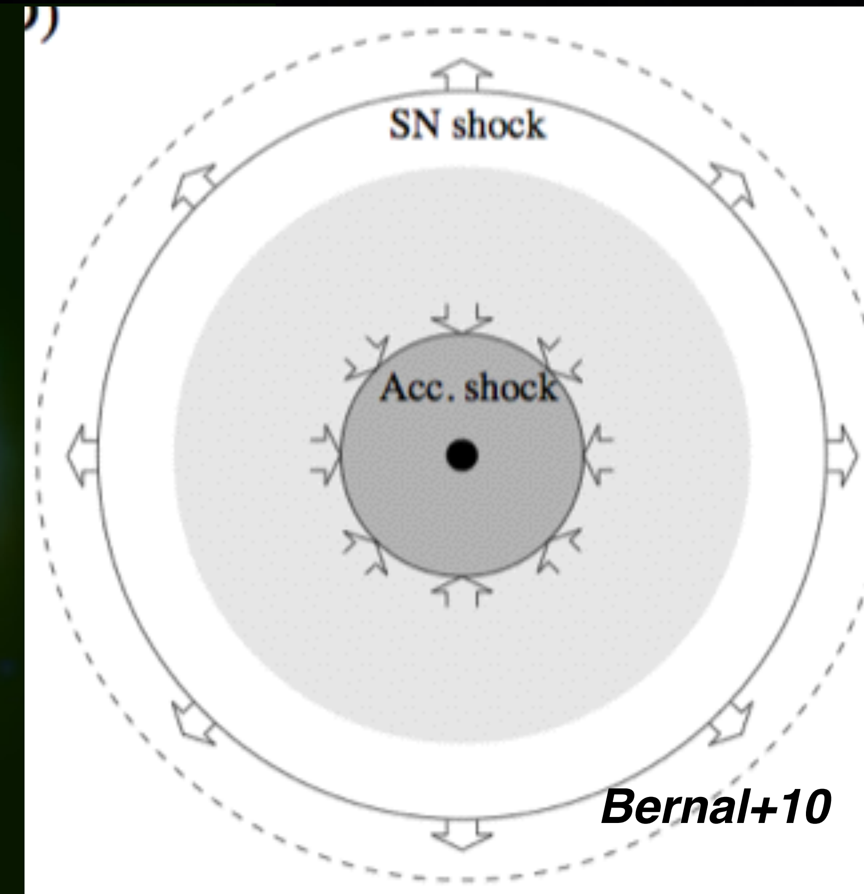

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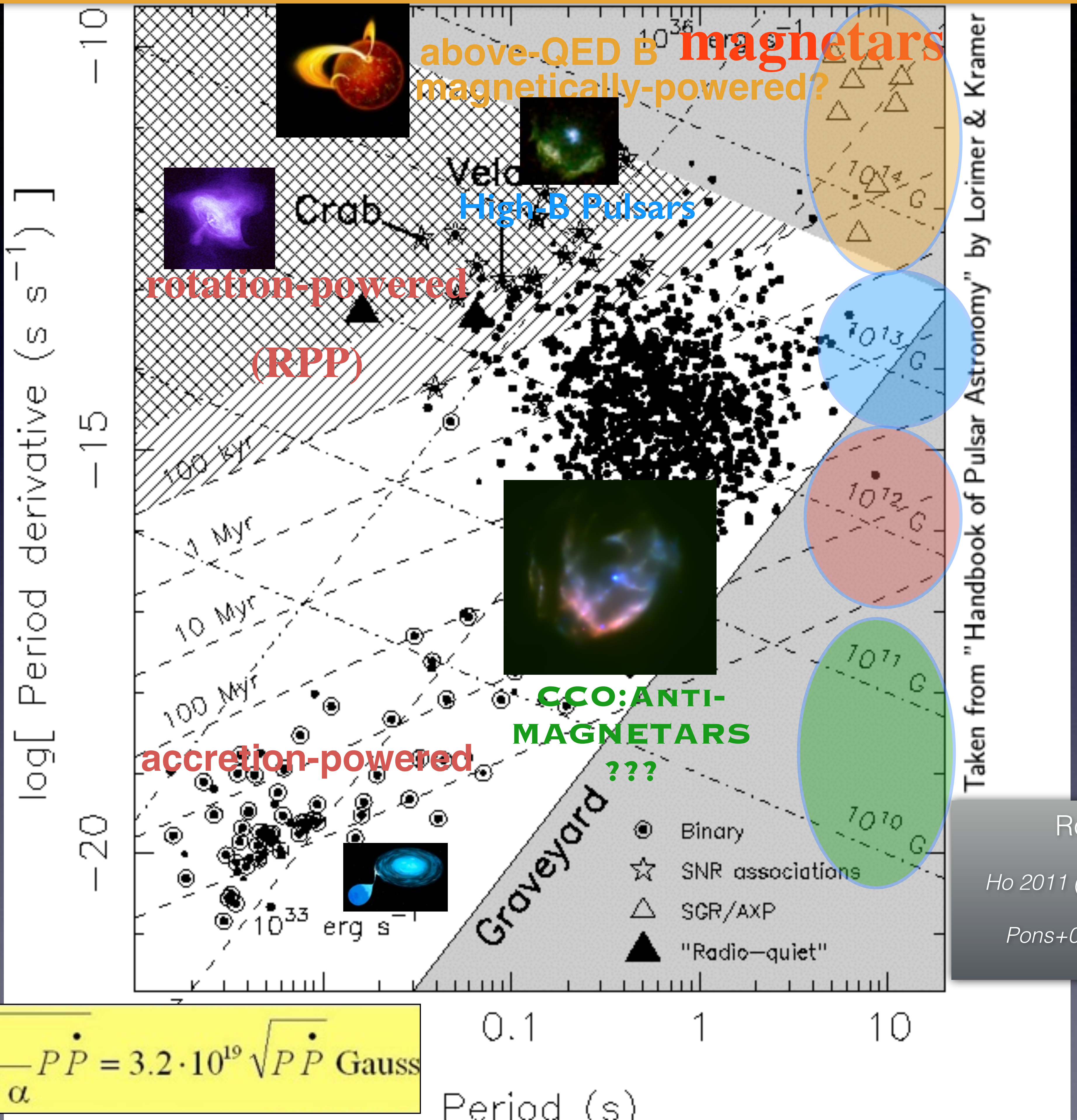
Connecting the Neutron Stars **Diversity** through **B-evolution?**

"Isolated":
RPP
Magnetars
HBPs
CCOs



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Rogers & SSH
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$$B = \sqrt{\frac{3c^3}{8\pi^2}\frac{I}{R^6 \sin^2\alpha} P\dot{P}} = 3.2\cdot 10^{19}\sqrt{P\dot{P}}\ \text{Gauss}$$

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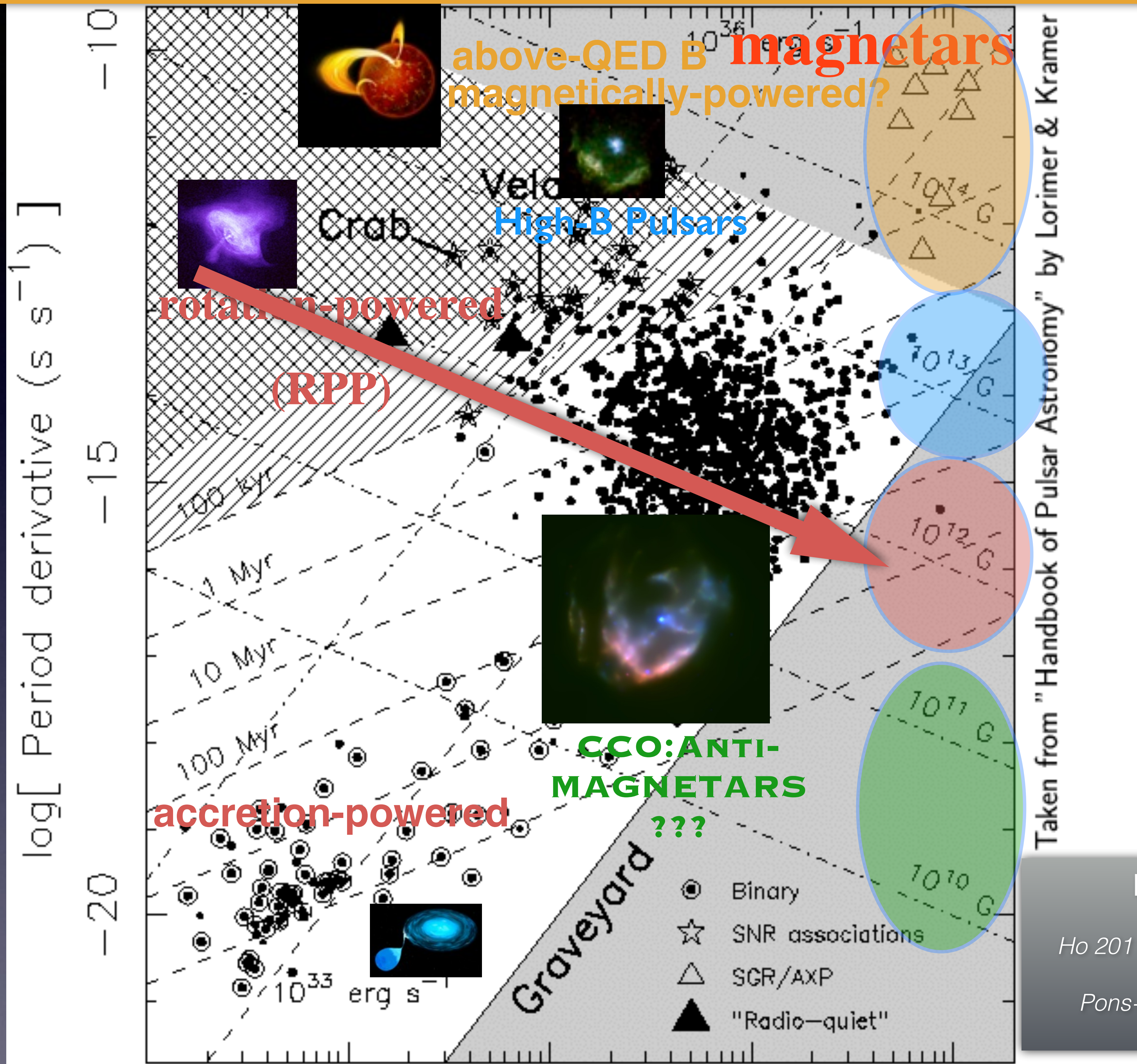

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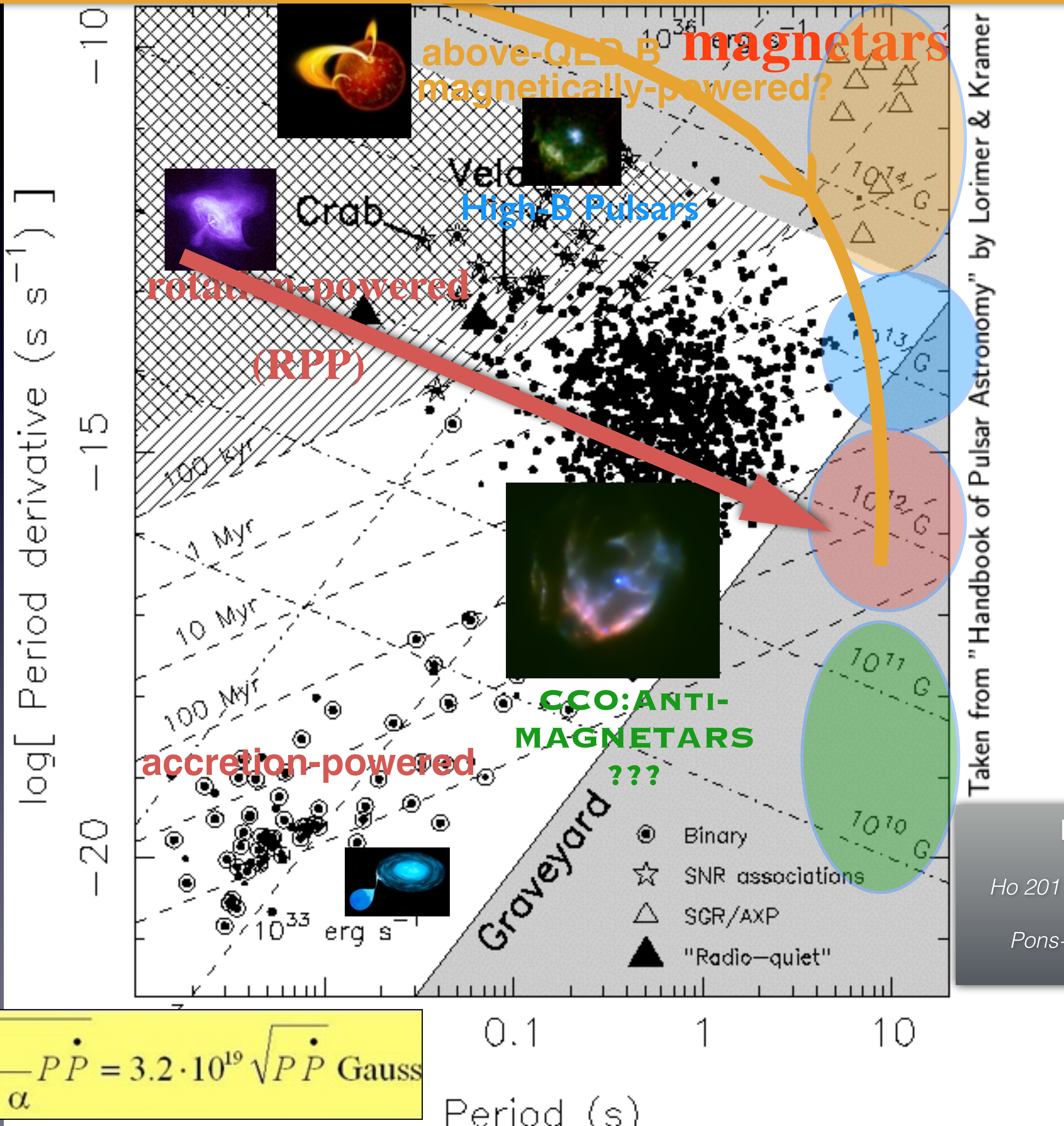

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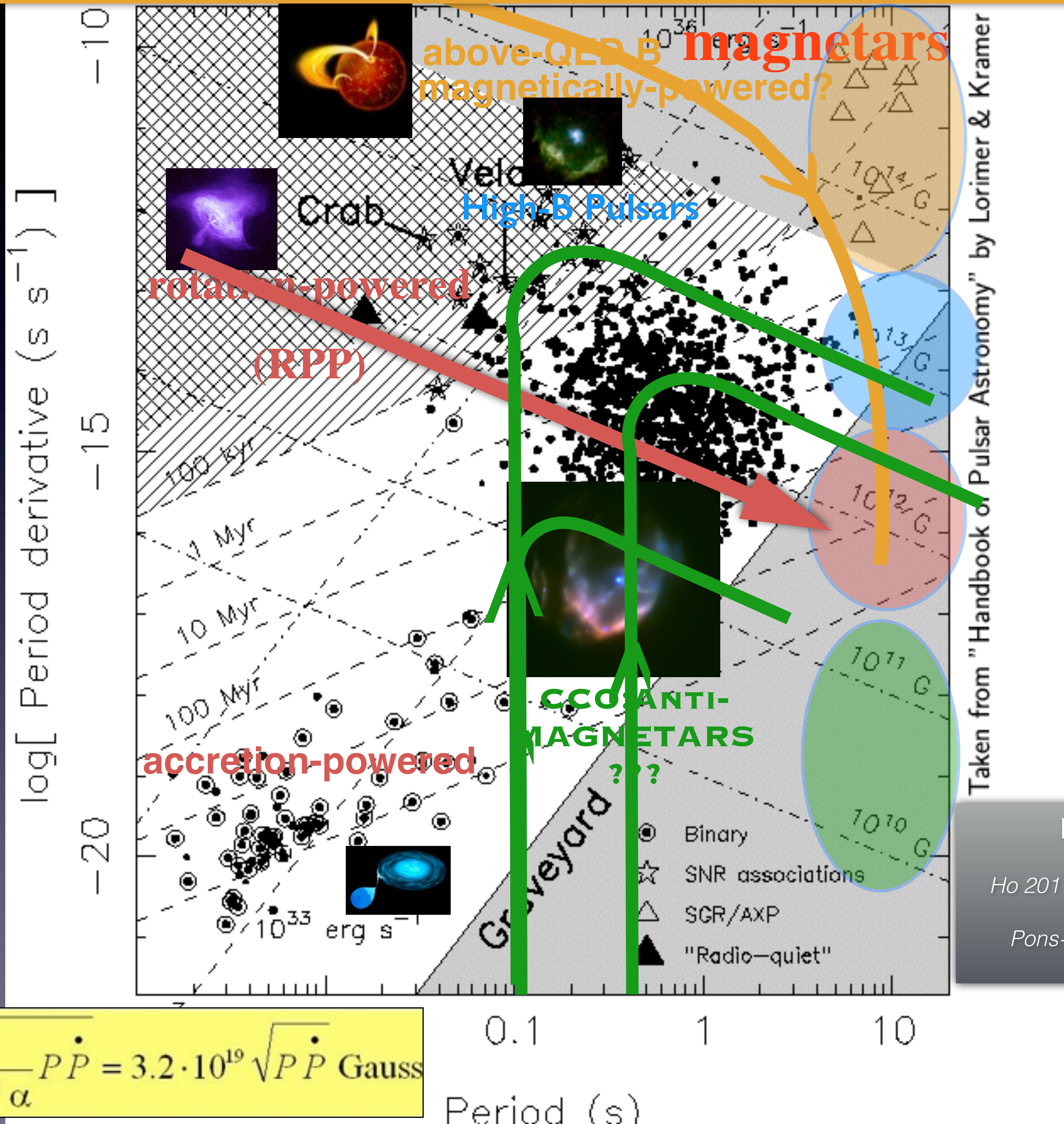

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Conclusion (part I):

SNR ages are better indicators for the “true” ages:

The zoo can be attributed (at least partly) to B-evolution

B-evolution (growth) still under hot debate!

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On their **Progenitors**

and environment

(for the highly magnetized neutron stars)

II. On their Progenitors
(Linking SNRs to their SN progenitors in X-rays)

- Ia vs core-collapse, SN typing:
  - SNR morphology (e.g. *Lopez+2009, 2011*)

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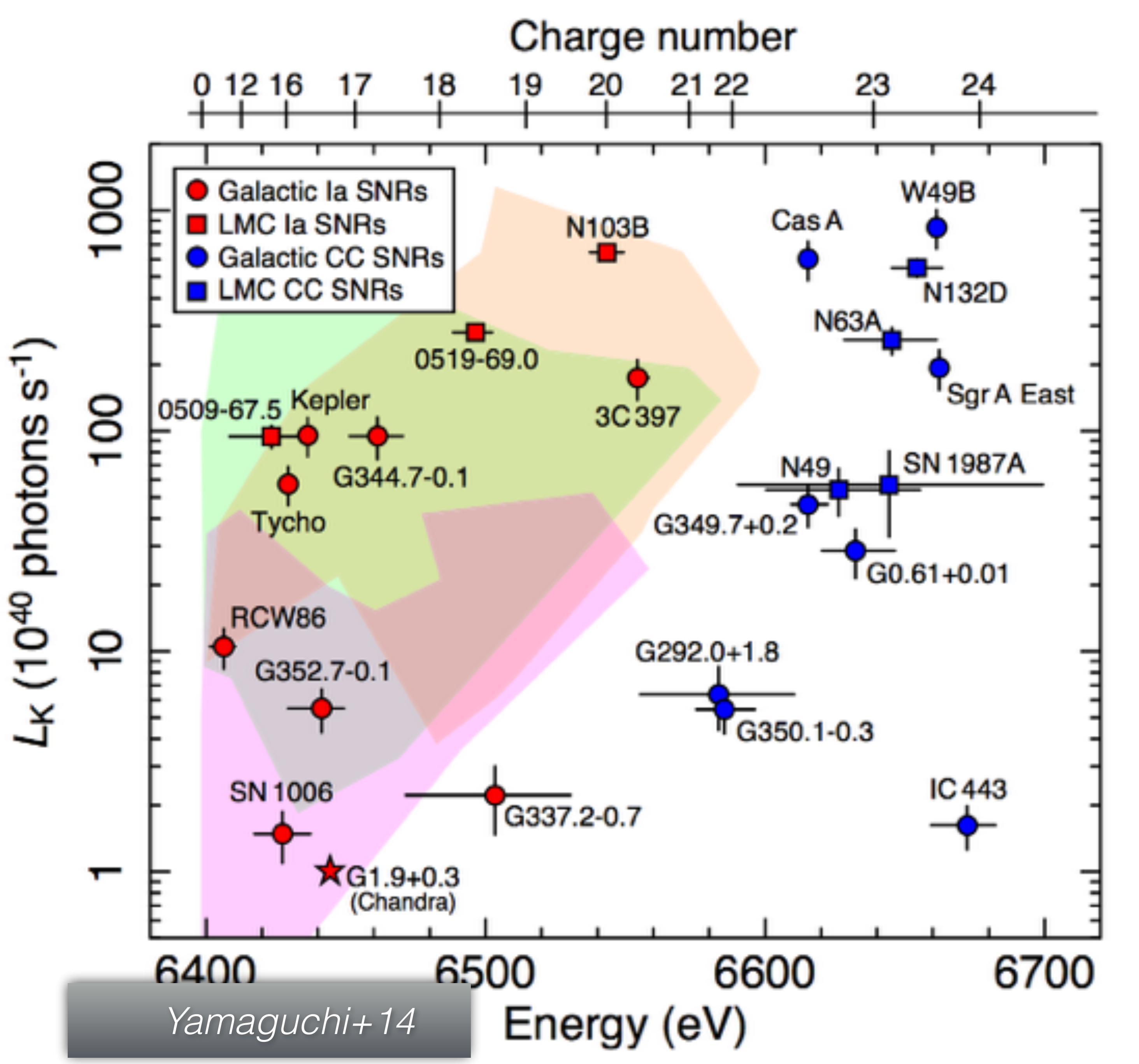

Yamaguchi+14

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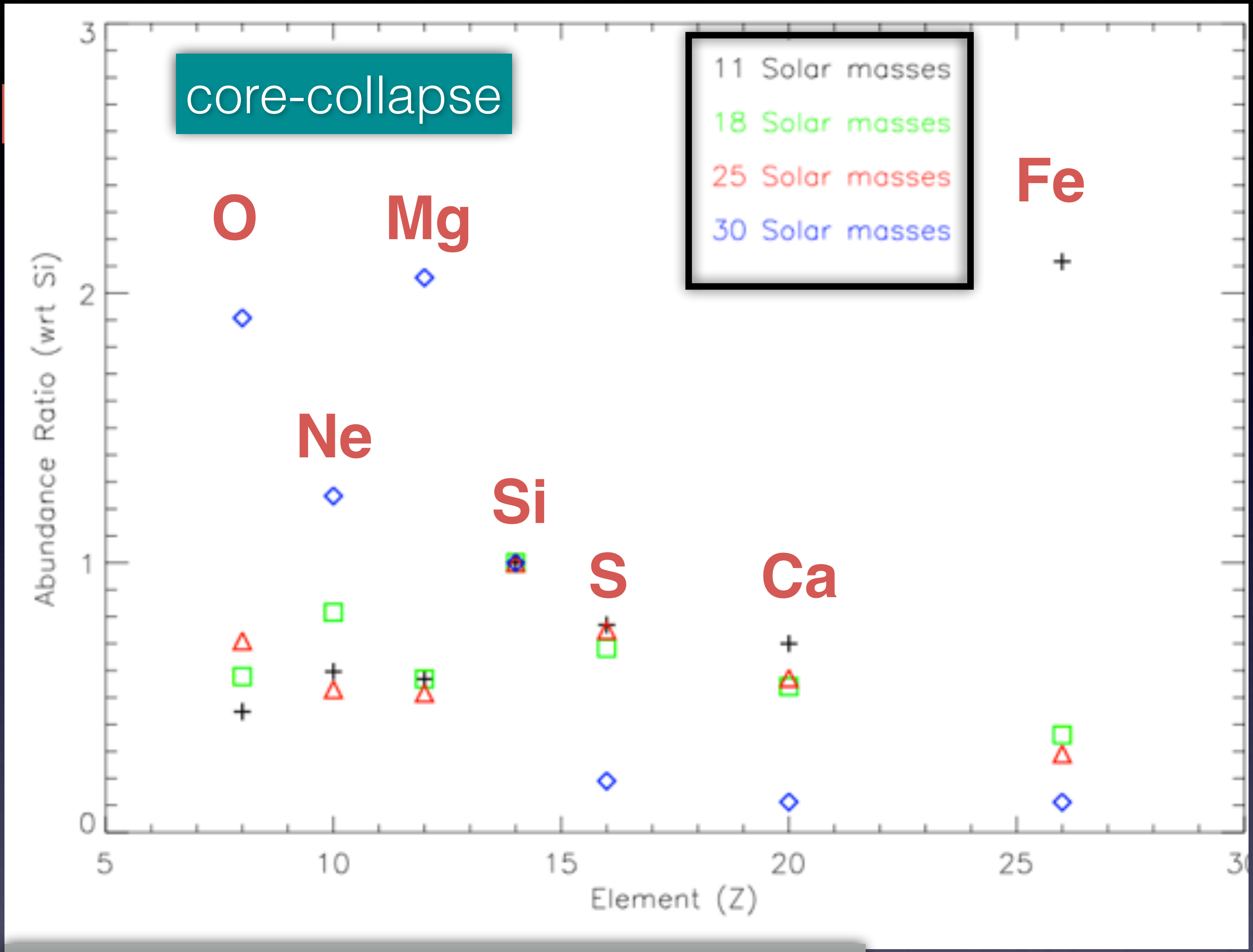

e.g. using Woosley & Weaver 1995 yields

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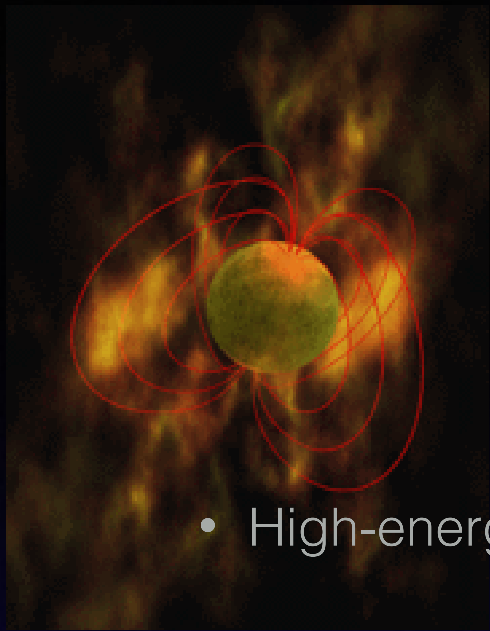
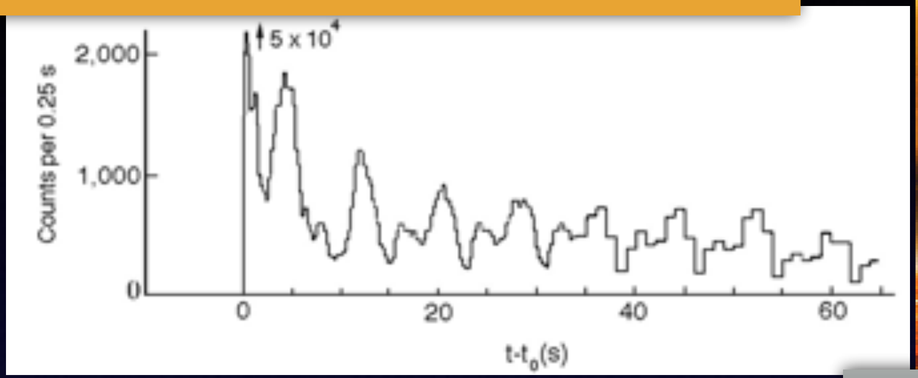


Magnetars

$B \sim 10^{14}$-10^{15} Gauss



Kouveliotou, Duncan, Thompson (Scientific American)

- High-energy sources (AXPs, SGRs)
  - **burst, P~2-12 s**
- **L_x > Edot (spin-down energy)**
  - **can NOT be powered by rotation**
    - Decay of their super-strong B (
    - accretion (
    - quark stars? (
- B > B_{QED} (4.3e13 Gauss)
  - although we now know of 3 "low-B" magnetars
  - Proton Cyclotron Features?

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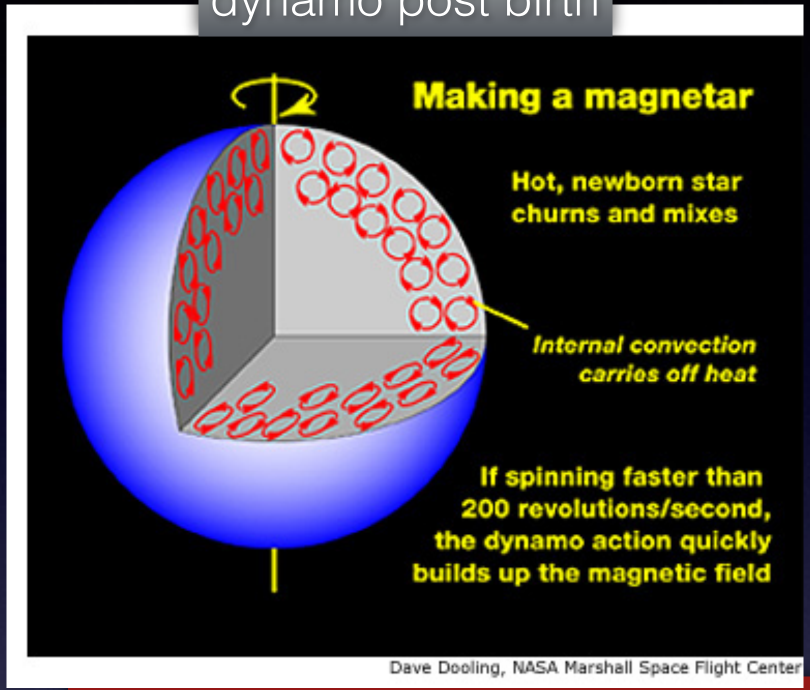
- **Big/Debated questions:**
  - **Link to other classes of neutron stars (part I)**
  - **What is the origin of their super-strong B field?**
  - **On their progenitors**

Magnetar Progenitors, origin of B

Two "competing"/popular models

Proto-Neutron-Star

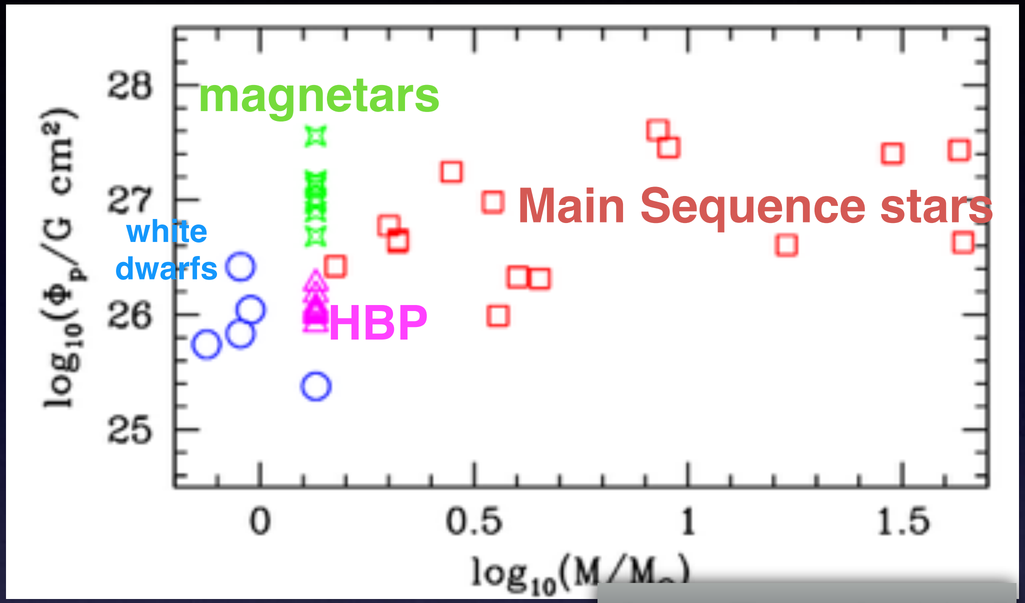
dynamo post birth



- Predict: P0<~3 ms
- super-energetic ($>>10^{51}$ ergs) SNRs
- *see e.g. Vink 2008*

Fossil-field hypothesis

magnetic flux conservation



from Ferrario 2015

Very massive (20-45 solar masses) progenitors

(Ferrario & Wickramasinghe 2008)

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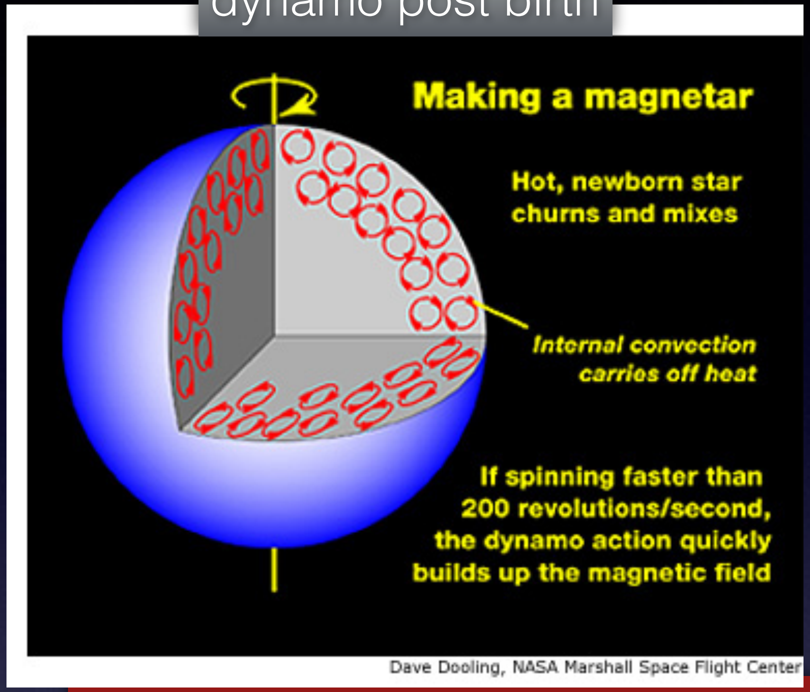

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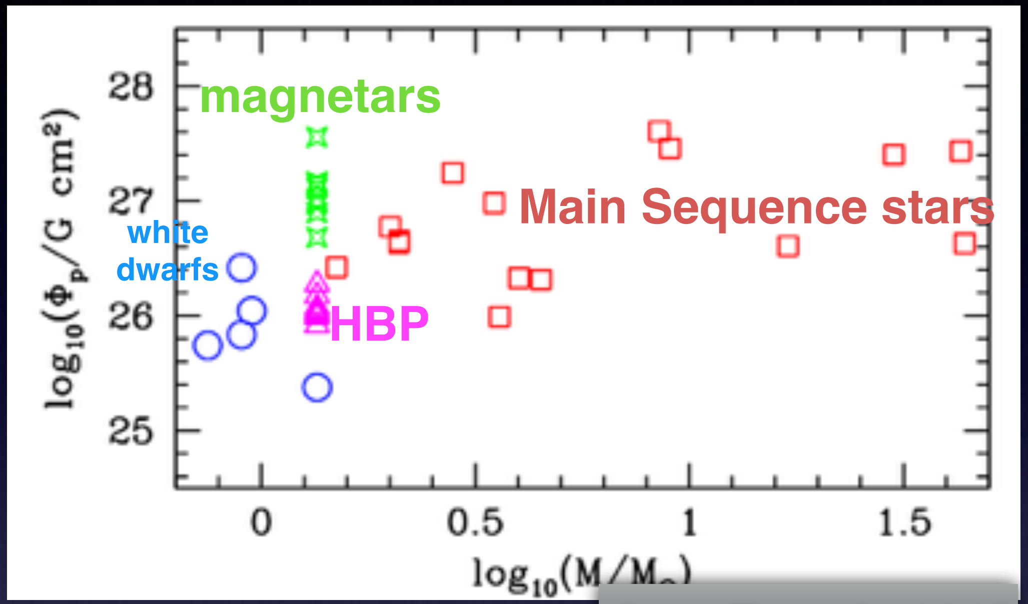

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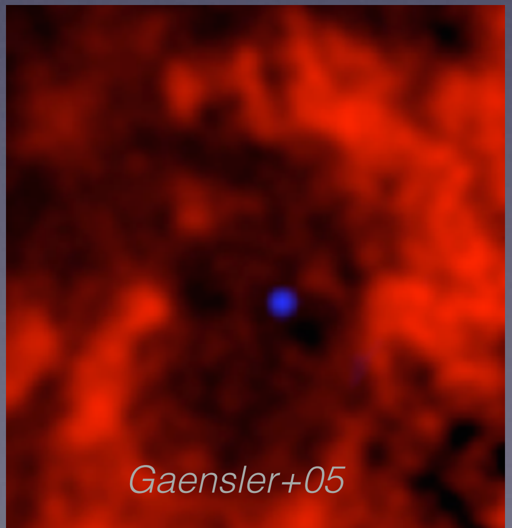

Multi-wavelength Observations:
<= HI bubble around an AXP
20-45 solar-mass progenitors=>

- **SGR** 1806-20 and magnetar CXO U J164710.2-455216 associated with **very massive star clusters**
- **Wolf-Rayet progenitor** inferred for the **HBP** J1846-0258/Kes 75
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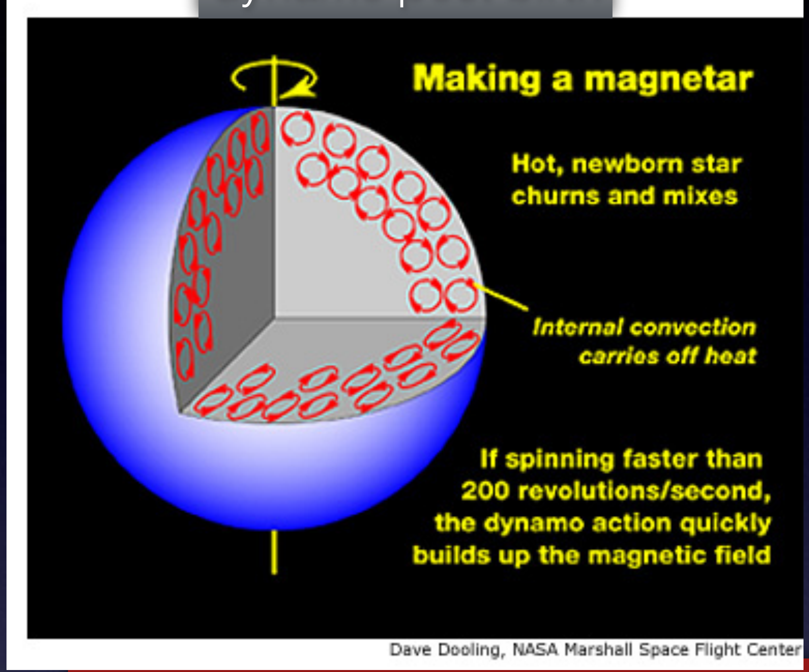

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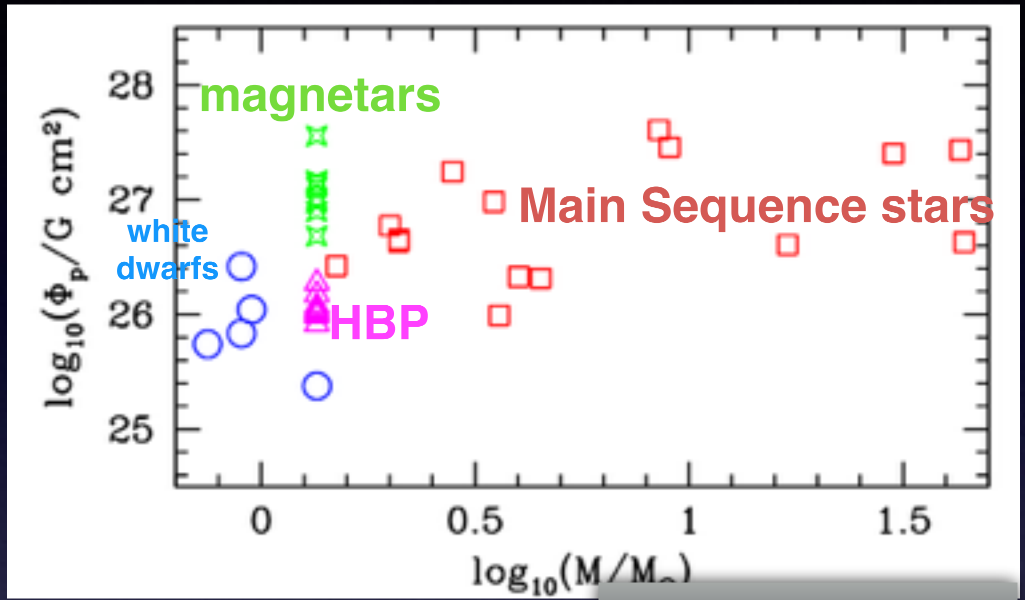

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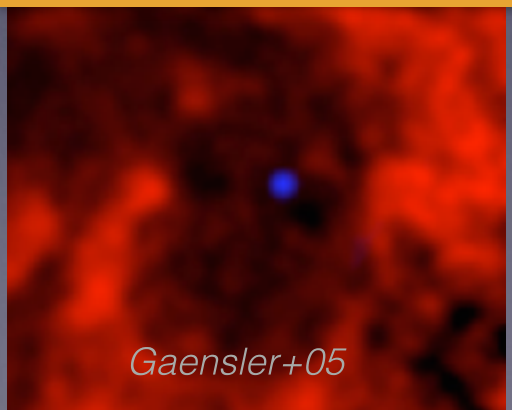
What can we learn from X-ray spectroscopy of associated SNRs (environment)?



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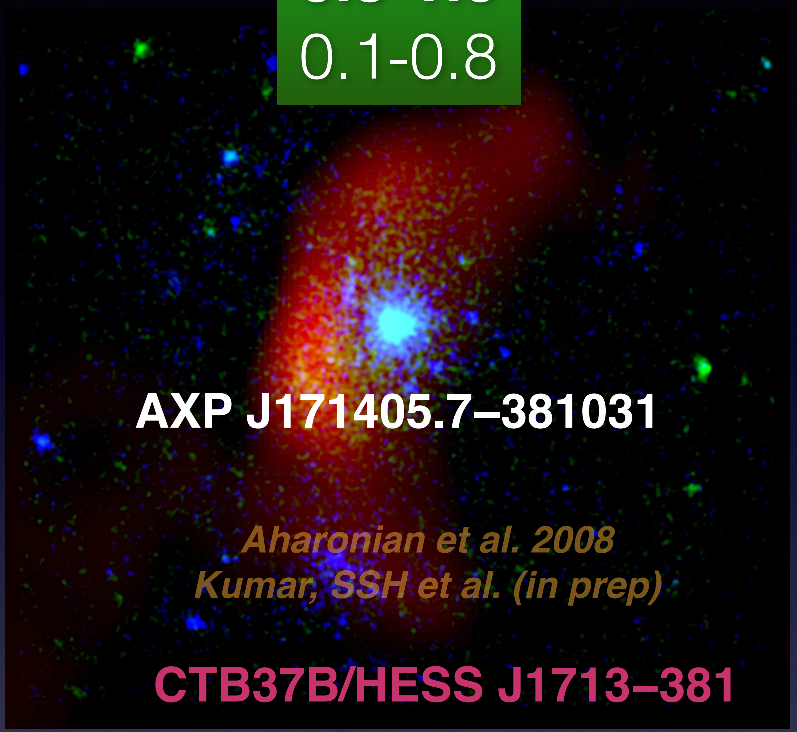
SN properties:

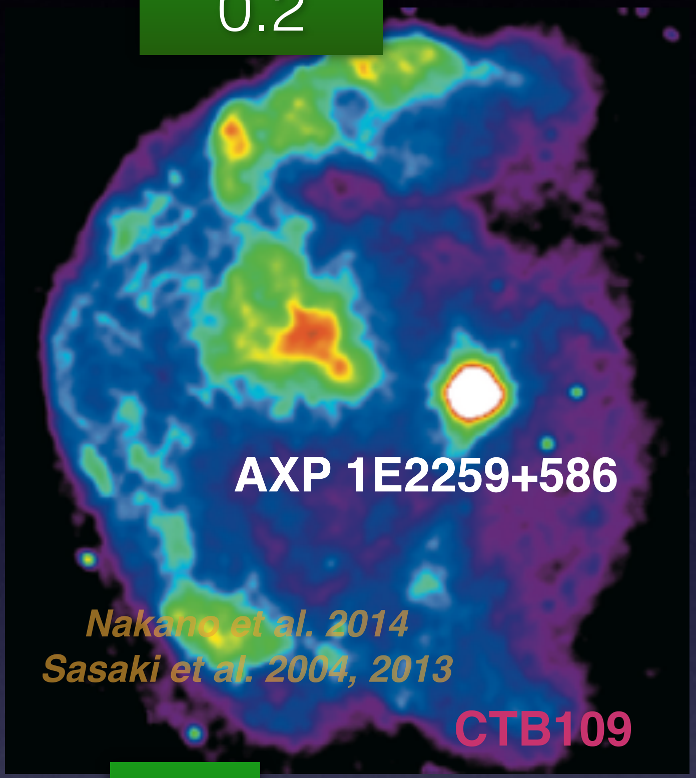
E (1e51 ergs)
n_0 (cm^{-3})

0.3-1.1
0.5

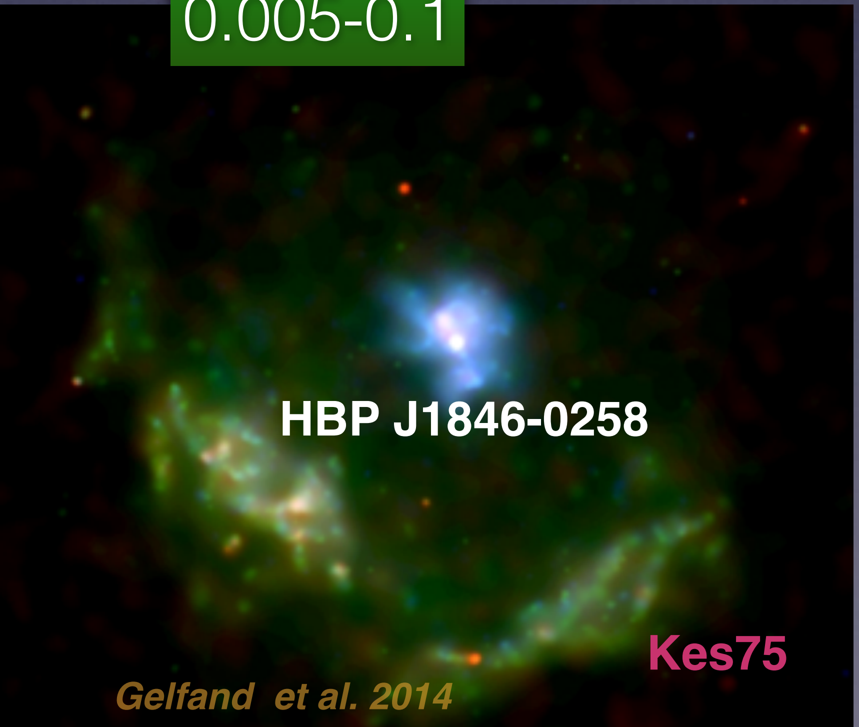
0.3-1.0
0.1-0.8



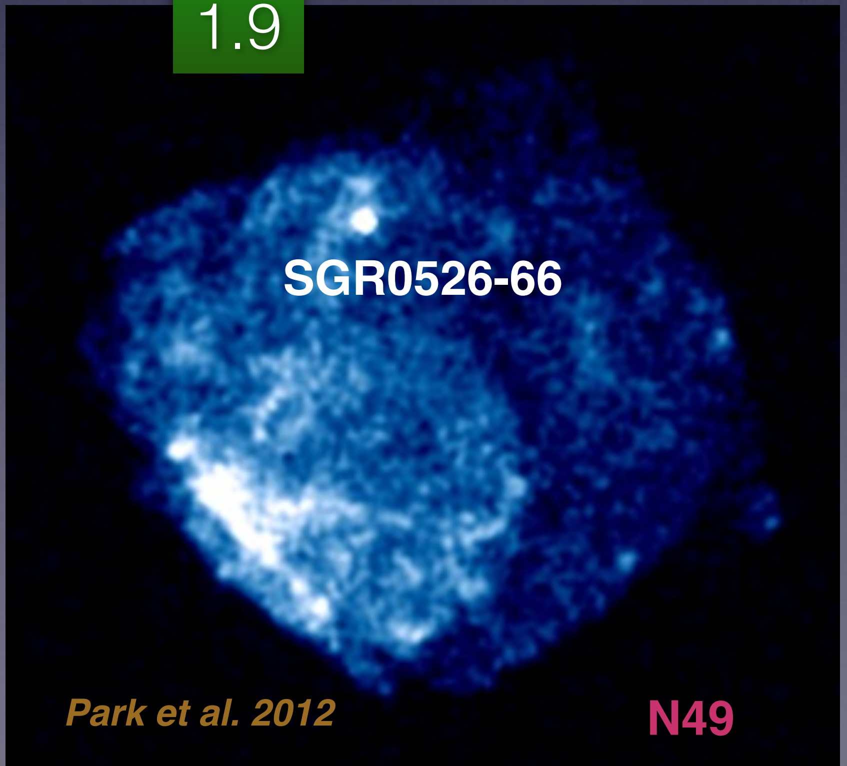
0.7-1.8
0.2



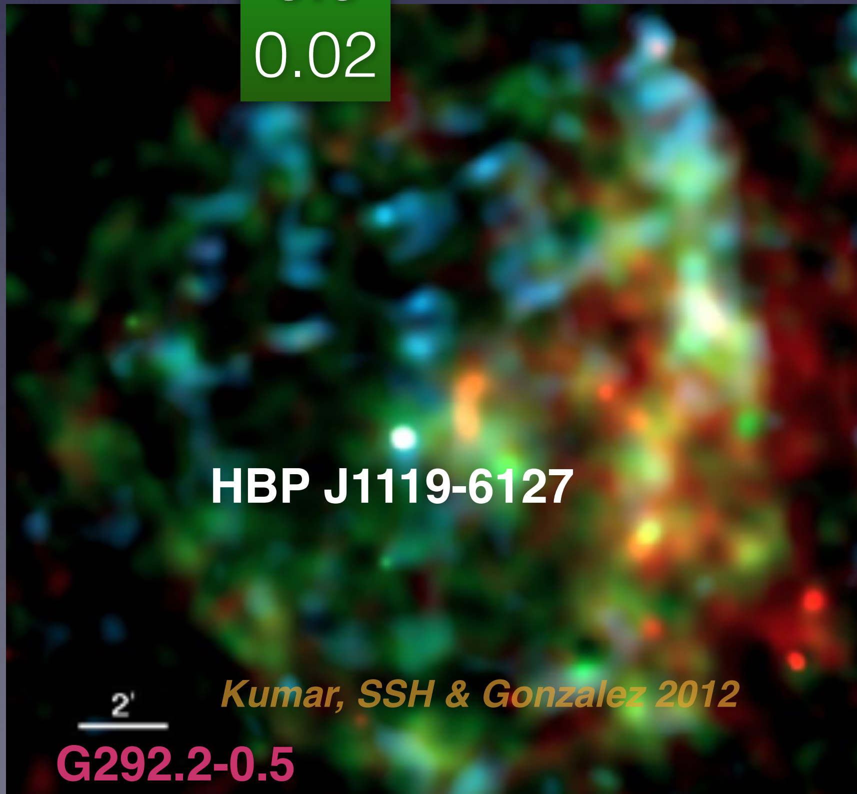
0.3-1.0
0.005-0.1



1.8
1.9



0.6
0.02



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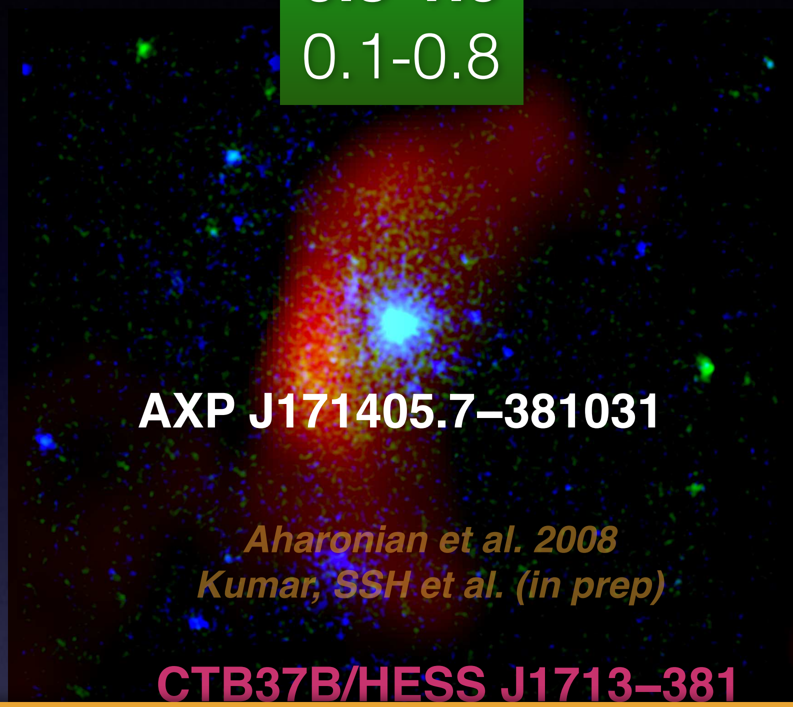

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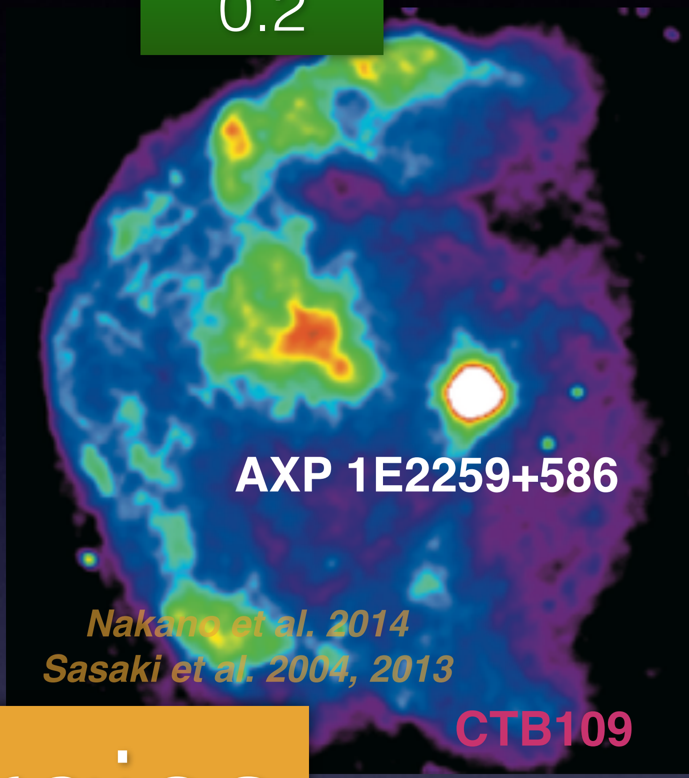
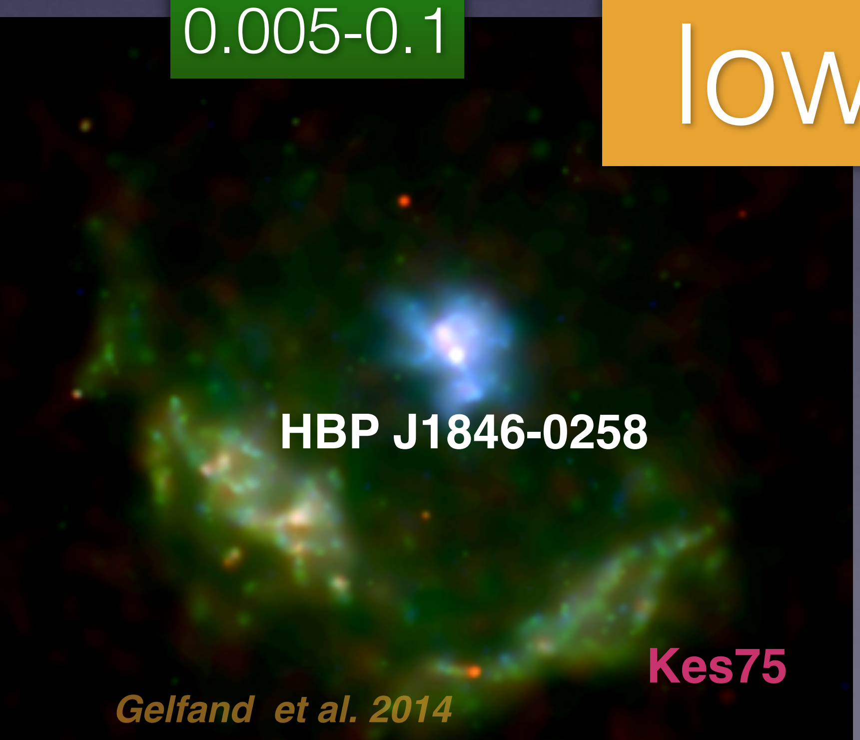
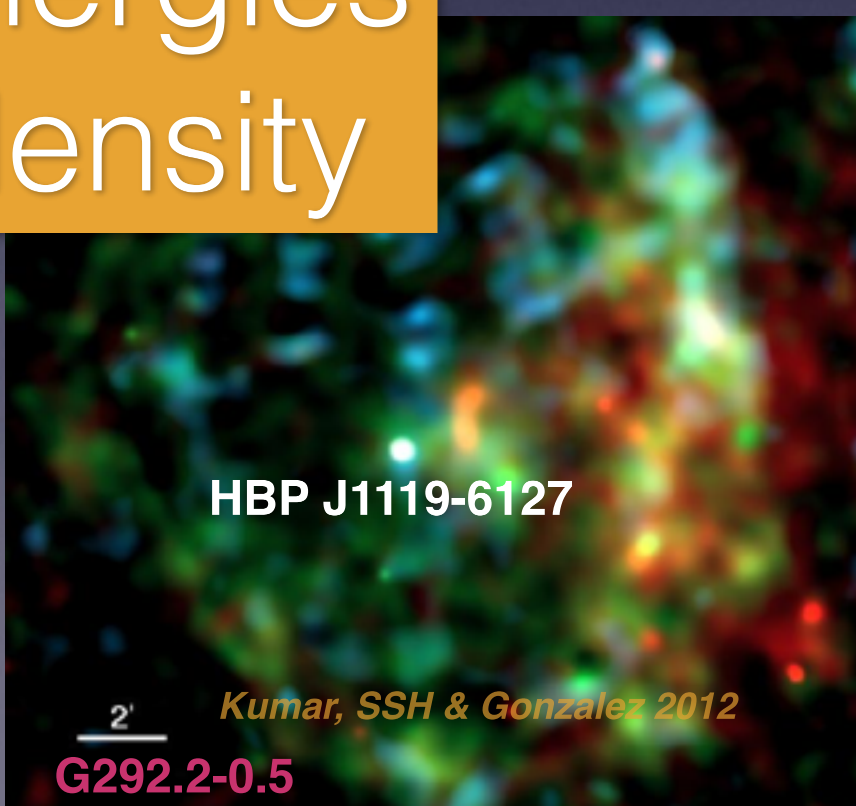


Typical Explosion Energies low ambient/CSM density

0.3-1.0
0.005-0.1





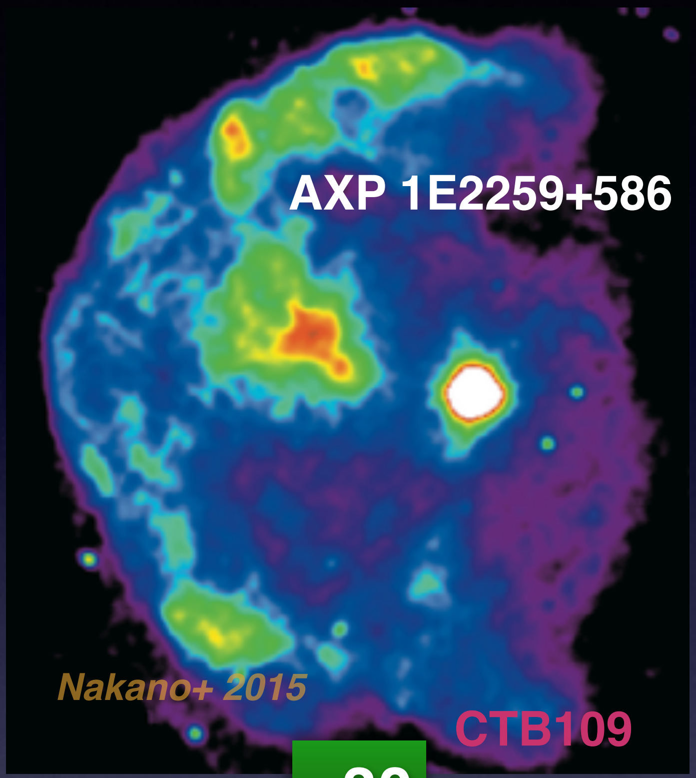
Progenitors of HBPs/Magnetars

M_{prog} (solar masses)

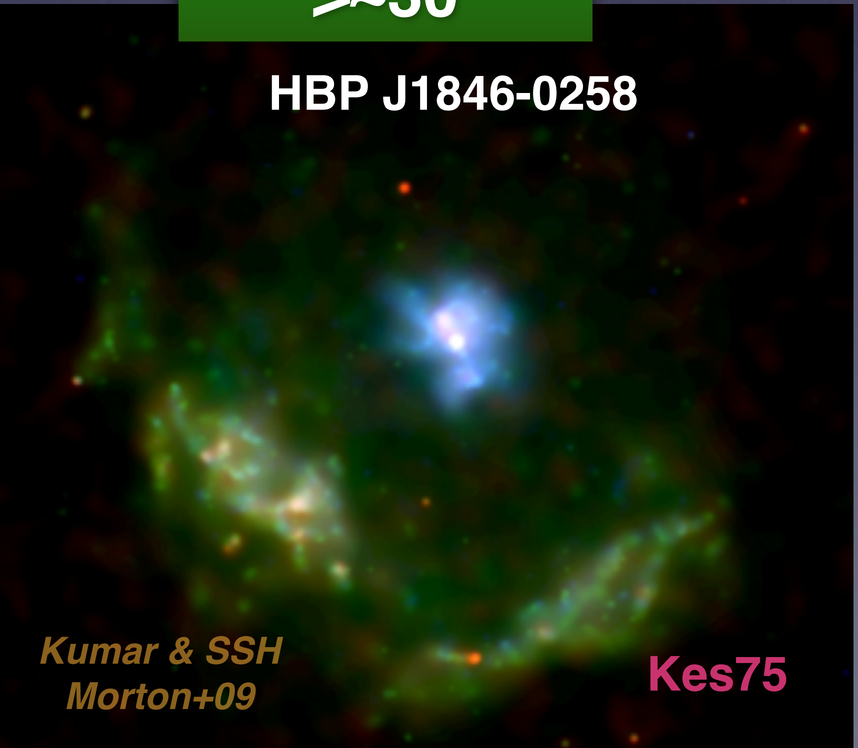
>20

WR bubble?
(no ejecta)

~40



Wolf-Rayet?
>~30



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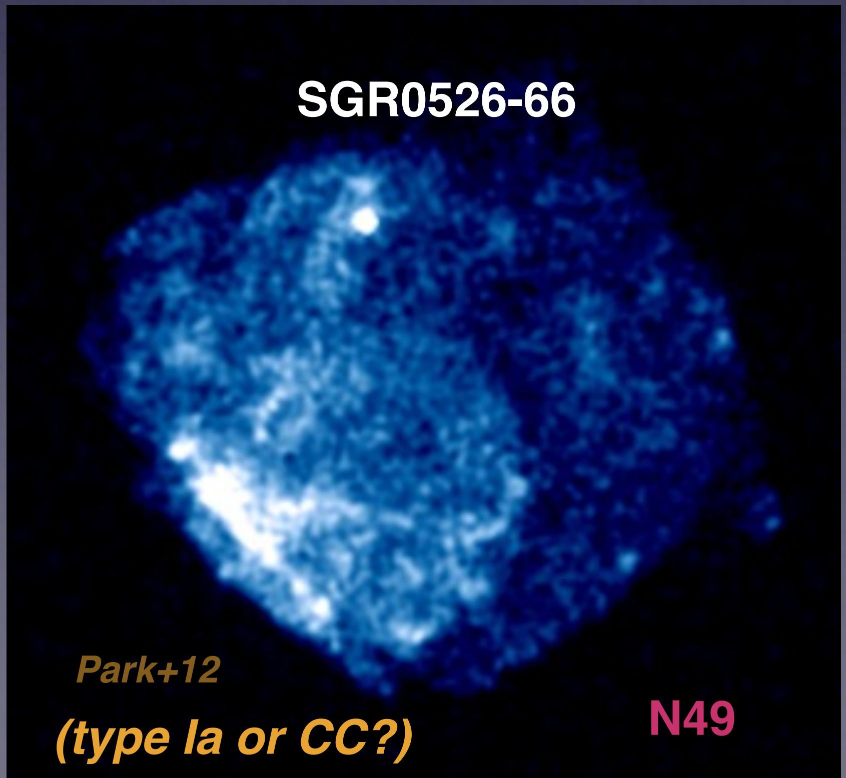
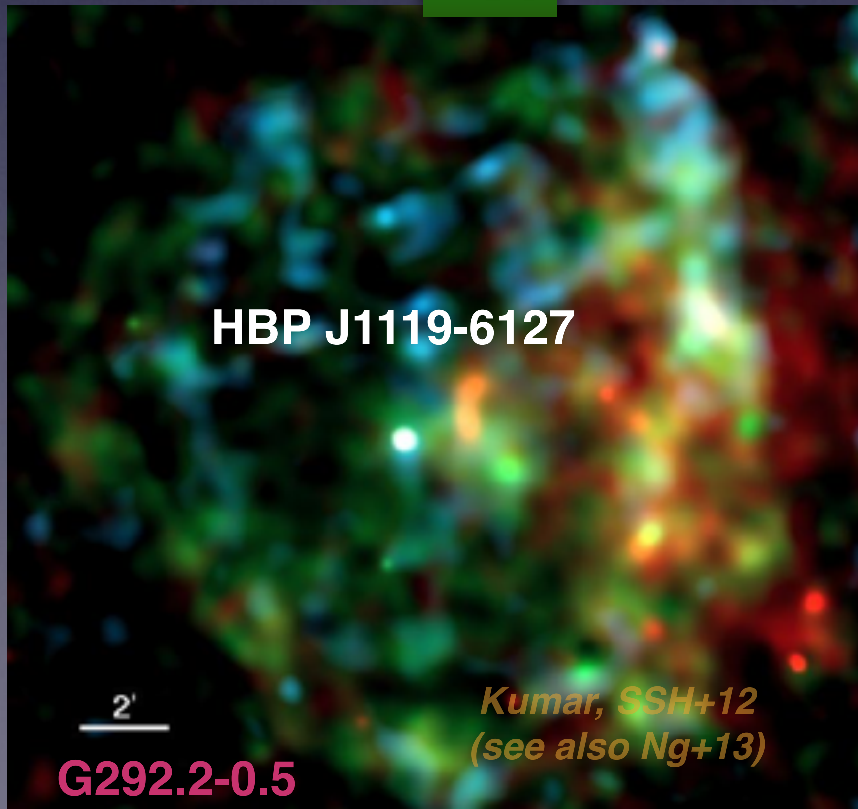


~30



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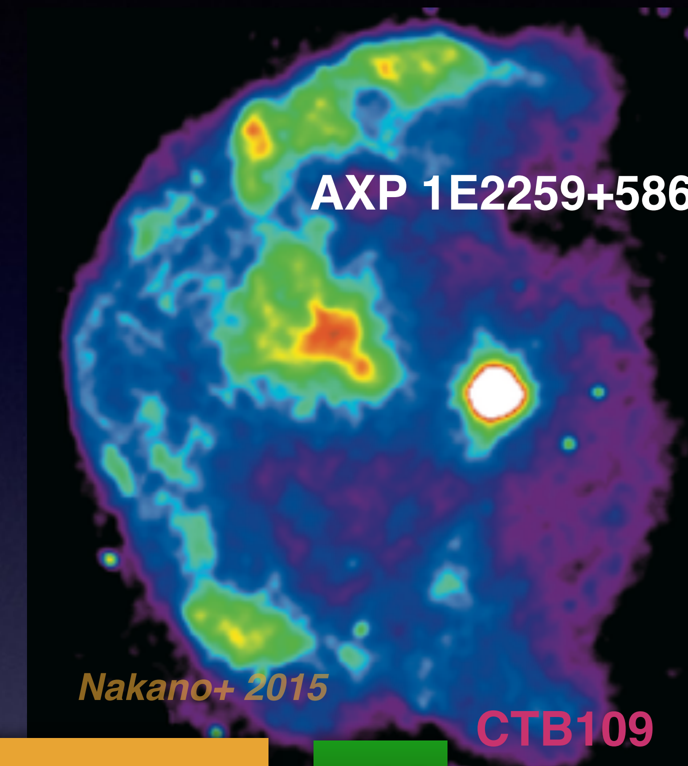

Wolf-Rayet?
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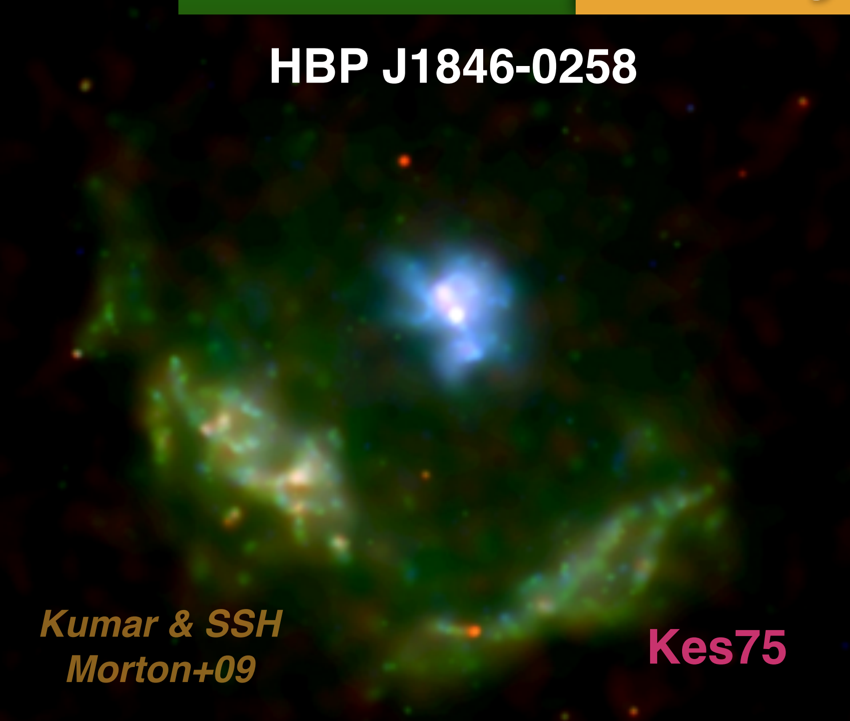
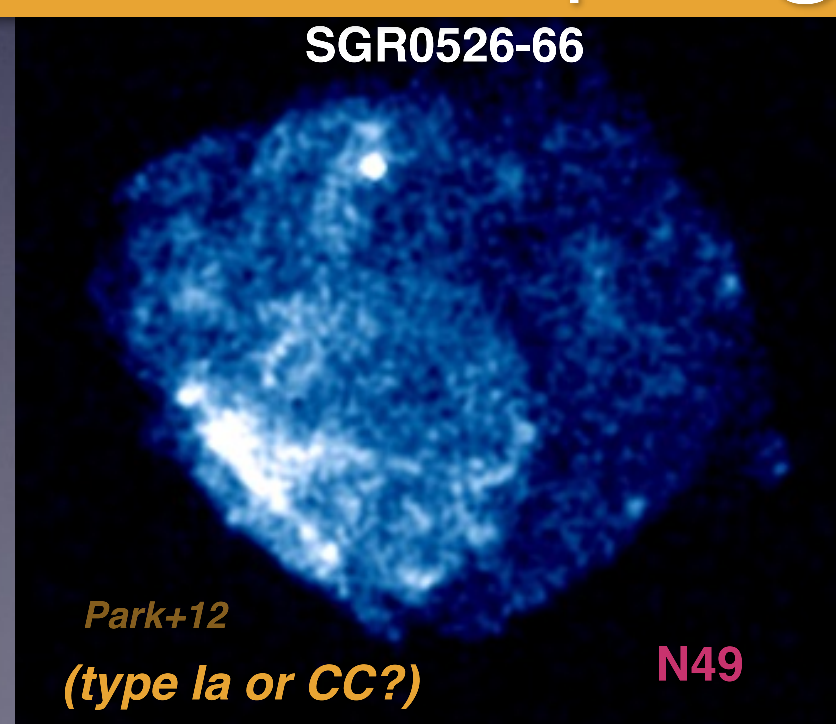
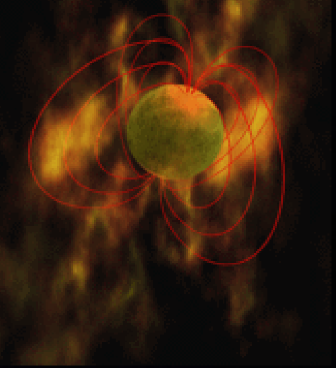
Very massive progenitors?

~30





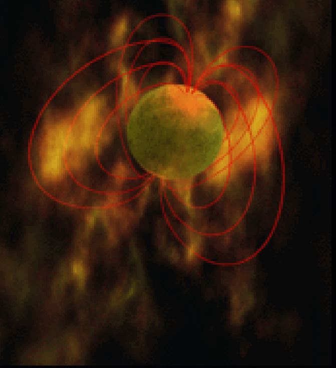


Summary for SN Progenitors & Energetics

Highly magnetized neutron stars (HBPs and magnetars):

While the SNR explosion energies appear to be "typical" (~e50-1e51 ergs), the progenitors appear to be very massive (or expanding into wind bubbles/very low-density medium)

✳**Supports the Fossil Field Model for highly magnetized NSs**



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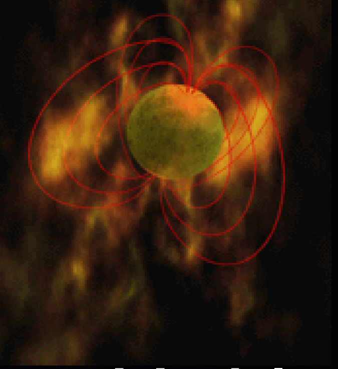

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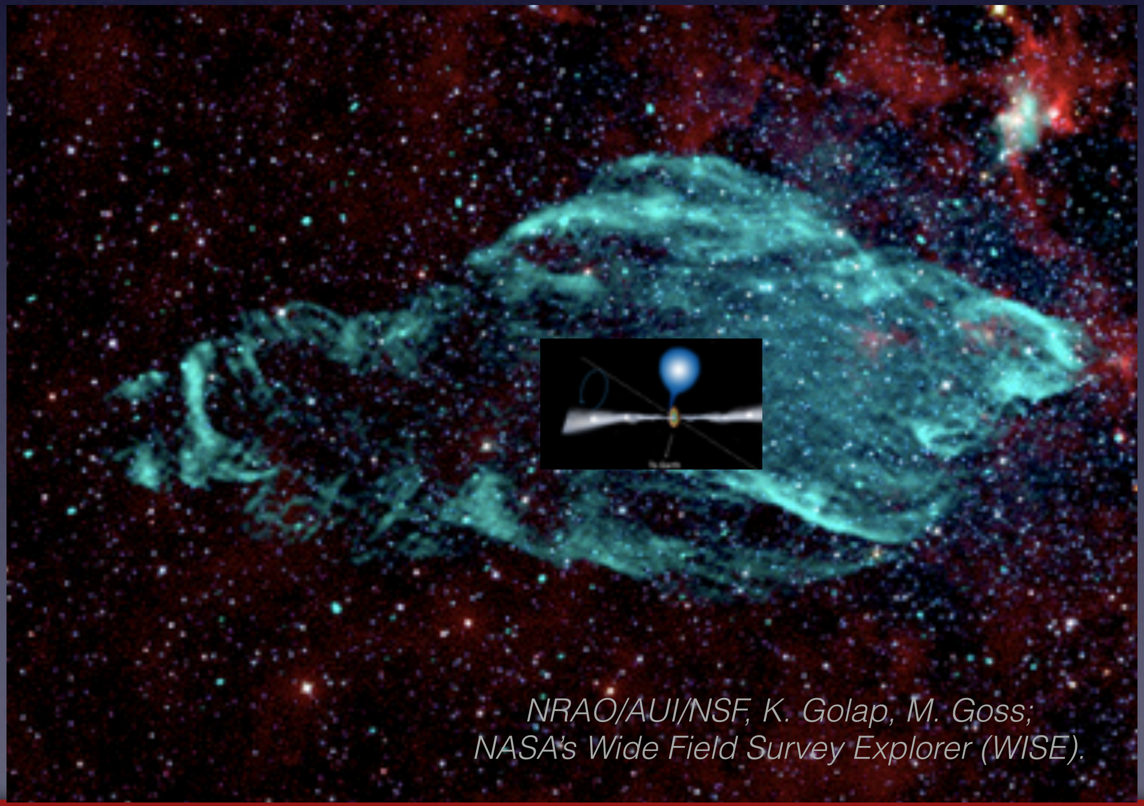

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The future with Astro-H (and Athena)
High-Resolution X-ray spectroscopy era

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Limitations:

a) **CCD-type spectra**

b) Different Nucleosynthesis models and yields

c) Energetics neglects gravitational radiation

d) Small Sample

e) (PSR ages not to be trusted) but SNR ages and shock velocities also need to be **accurately determined!**

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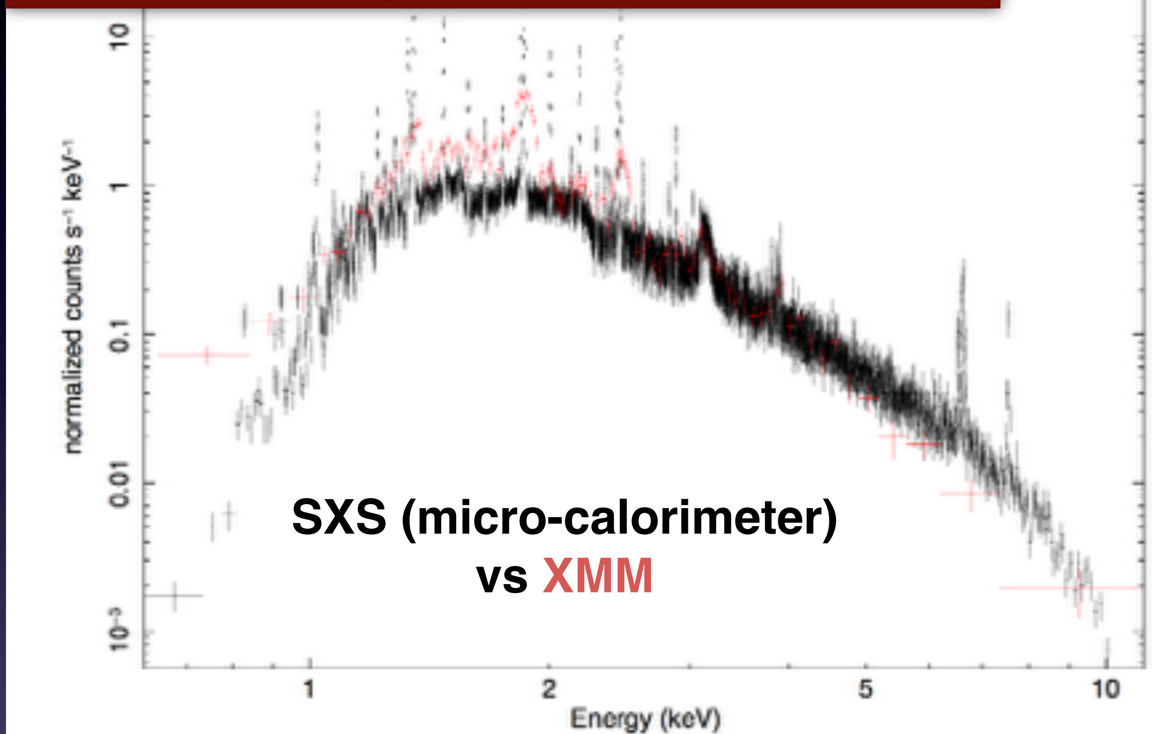
magnetar SNR=> abundance measurements (**line ratios**)



ASTRO-H will provide a leap in high-resolution X-ray spectroscopy:

1) **Progenitors** of the PSRs zoo, and other SNRs (SXS)
2) Accurate **SNR age and shock velocity** measurements (SXS)
3) **search for thermal emission in synchrotron dominated SNRs (e.g. shell-less PWNe)**
4) **direct measurement/origin of B** (SXS/SXI/HXI, broadband): cyclotron features

See "AstroH White papers" on SNRs and compact objects (arXiv:1412.1165/66/69/75)

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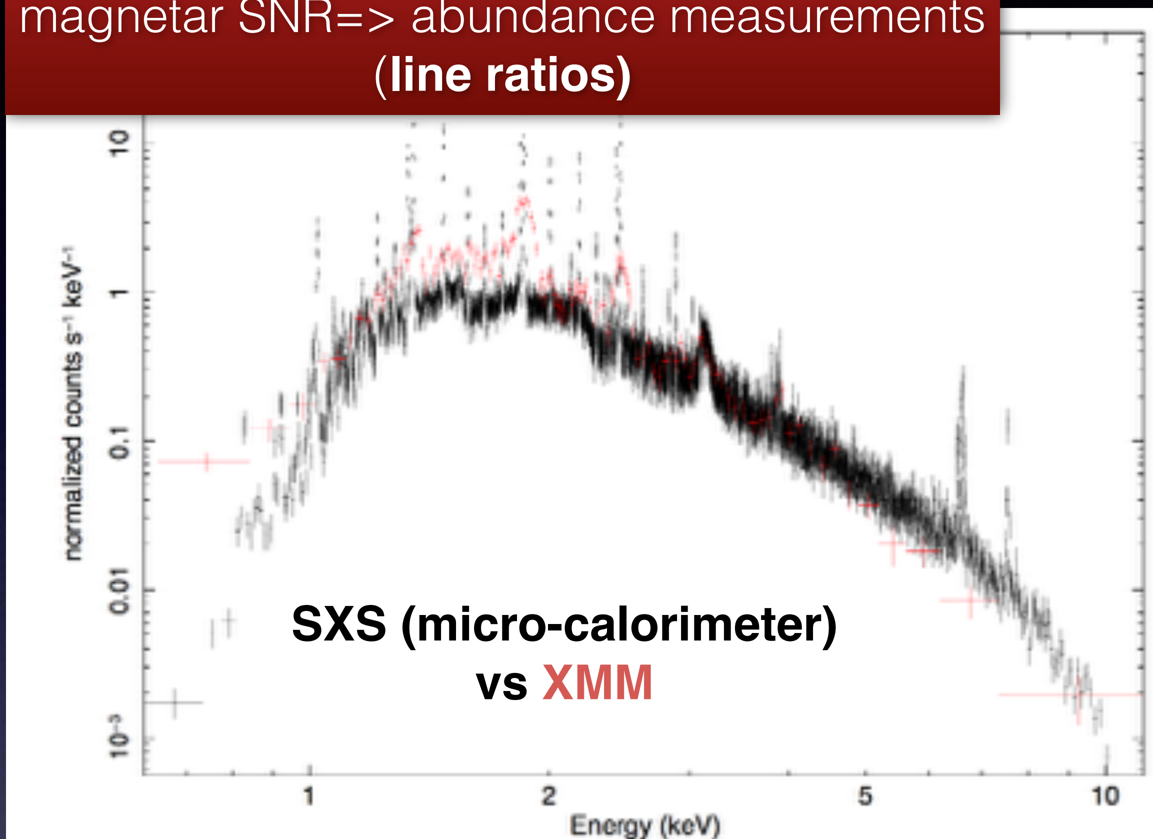

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Thermal broadening=> Ions temperature (**line widths**).
Line Centroids=> Doppler shift

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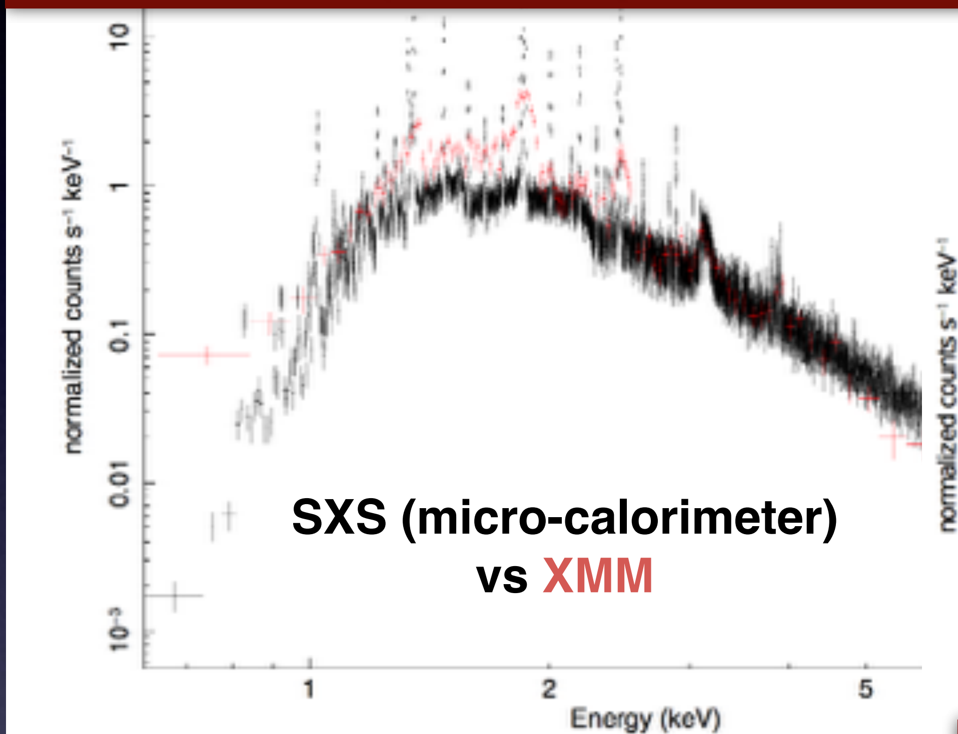

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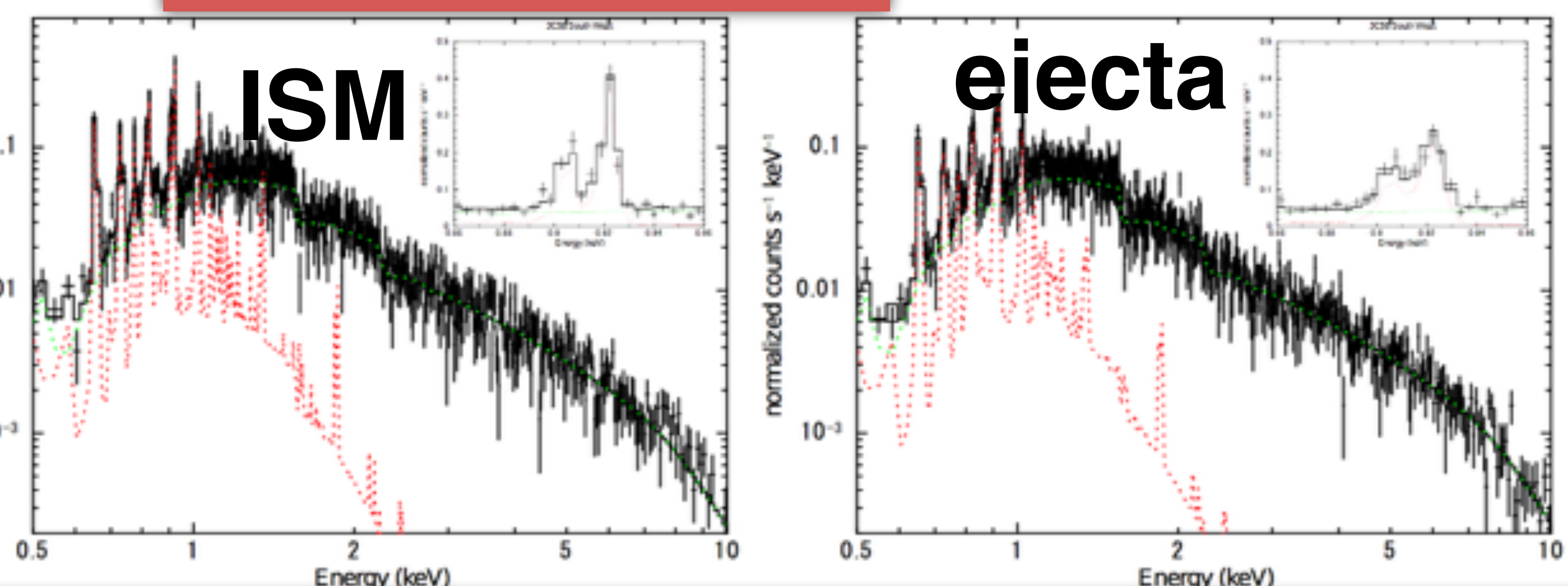

Shell-less/Naked SNRs (i.e. PWN) and synchrotron dominated SNRs=> search for **(missing) SNR thermal plasma**=>progenitors

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Summary:

SNRs offer laboratories to study the physics of exotic objects

-Age: **magnetic field evolution** linking the different faces of neutron stars

-SN progenitor/Energetics studies: **very** (?) massive progenitors for magnetars/HBPs

The future is promising for upcoming high-resolution X-ray spectroscopy

(soon, ASTRO-H: <7eV resolution, better sensitivity in Fe-K, broadband 0.5-600 keV; Late 2020's: Athena in synergy with other planned multi-wavelength missions)

Thank you!

(also with thanks for the SNR group members and collaborators)

NSERC CRSNG

Canada Research Chairs

IAU XXIX GENERAL ASSEMBLY Hawaii

CSA ASC

X-RAY OBSERVATORY ASTRO-H

Check out our on-line and regularly updated high-energy (X+γ) SNR catalogue (**SNRcat**):
http://www.physics.umanitoba.ca/snr/SNRcat
Comments, corrections, input … are welcome!