A rotationally powered magnetar nebula around Swift J1834.9–0846

(The effect of reverberation on pulsar wind nebulae of pulsars with low spin-down power)

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Discovery of Swift J1834.9–0846

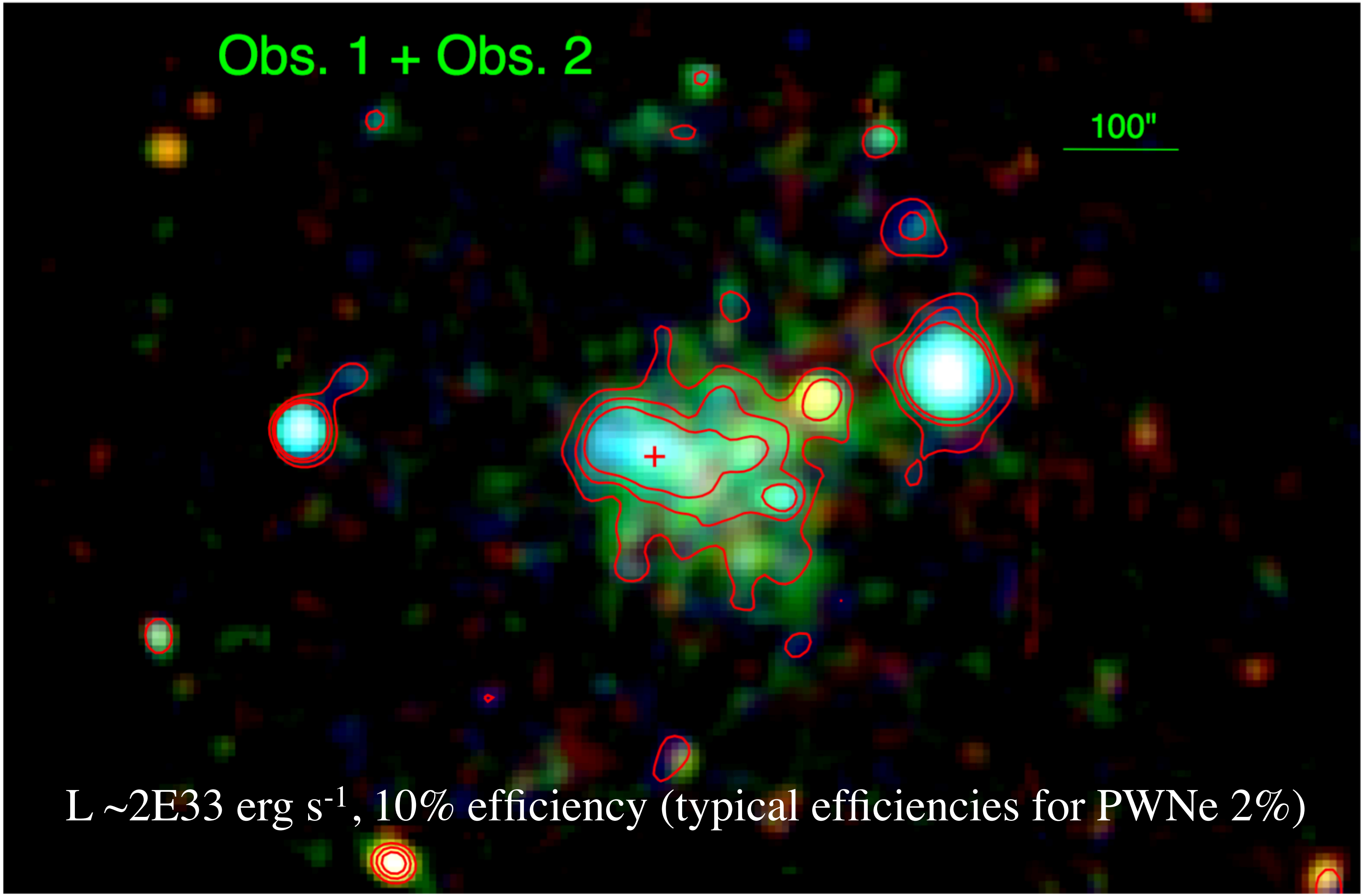
- Found by Swift X-ray satellite on 2011 August 7, via a short X-ray burst (D'Elia et al. 2011). A few hours later, another burst was detected by the Fermi GBM; and a third burst appeared days after (on August 29; Hoversten et al. 2011, Kargaltsev et al. 2012). Distance of 4kpc (Esposito et al. 2012)

- Follow up observations revealed it has a spin period P = 2.48 s and a dipolar magnetic field in the magnetar range (B=1.1E14 G, Gogus & Kouvellioutou 2011, Kargaltsev et al. 2012).

- The spin-down power derived from these timing parameters is relatively high for magnetars (2E34 erg s^{-1}), although not unique.

- Observations in quiescence revealed it is surrounded by extended X-ray emission (Kargaltsev et al. 2012, Younes et al. 2012).

Younes et al. (2016): First magnetar nebula



L ~2E33 erg s^{-1}, 10% efficiency (typical efficiencies for PWNe 2%)

What else, other than a wind nebula, can power this emission?

- Younes et al. (2016) report on new deep XMM-Newton observations done 2.5 and 3.1 years after the burst.

- They still find an extended emission centered at the magnetar, slightly asymmetrical, and non-variable (2005-2015).

- Scattering of soft X-ray photons by dust is unfavored due to the constancy of the flux and the hardness of the X-ray spectrum ($\Gamma = 1 - 2$).
    - The latter is at odds with what is expected as a result of a dust scattering of a soft burst emission (when the index was measured to be $\Gamma = 3 - 4$)

→ First magnetar nebula

A nebula surrounding a magnetar: Is it that weird?

- We know low-field magnetars (e.g., Rea et al. 2010, 2014),
- …and radio emission from magnetars (e.g., Camilo et al. 2006, 2007; Anderson et al. 2012)
- We detected a magnetar-like burst from the normal pulsar J1119-6127 (Kennea et al. 2016), which has a PWN.
- The magnetar's radio emission can be powered by the same physical mechanism responsible for the radio emission in other pulsars (Rea, Pons, DFT & Turolla 2012).
- The existence of a rotationally-powered magnetar nebula would only emphasize the connection between all pulsar classes.

Still... A nebula that powerful and that large, from a pulsar that dim?

- Tong (2016) has proposed that the nebula can only be interpreted in the wind braking scenario.

- Granot et al. (2016) proposed that nebula is powered via a transfer of magnetic power into particle acceleration.
  - What mechanism is foreseen for this to happen?

- But, what about a normal nebula? Is it really ruled out?

Full time-dependent PWNe with a detailed expansion model

Radius, Mass, Velocity of the PWN shell

$$\frac{dR(t)}{dt} = v(t),$$

$$M(t)\frac{dv(t)}{dt} = 4\pi R^2(t)\left[P(t) - P_{ej}(R,t)\right],$$

$$\begin{aligned}\frac{dM(t)}{dt} &= 4\pi R^2(t)\rho_{ej}(R,t)(v(t) - v_{ej}(R,t)). && \text{if } v_{ej}(R,t) < v(t)\\ &= 0. && \text{if } v_{ej}(R,t) > v(t)\end{aligned}$$

Particle evolution

$$\frac{\partial N(\gamma,t)}{\partial t} = Q(\gamma,t) - \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma,t)N(\gamma,t)\right] - \frac{N(\gamma,t)}{\tau(\gamma,t)}$$

Energy in particles

$$E_p(t) = \int_{\gamma_{min}}^{\gamma_{max}} \gamma m_e c^2 N(\gamma,t)\mathrm{d}\gamma.$$

Pressure of the PWN

$$P_p(t) = \frac{3(\gamma_{pwn} - 1)E_p(t)}{4\pi R(t)^3} \qquad P_B(t) = \frac{B^2(t)}{8\pi} \qquad P(t) = P_p(t) + P_B(t)$$

The model has: Similarities with Gelfand et al. 2009 + Particle radiation taken into account in the expansion + Considered one bounce only, then Sedov

More detailed model description: Martin, DFT, Pedaletti 2016 MNRAS

Profiles for the ejecta

v_{ej}, ϱ_{ej} and P_{ej} correspond to the values of the velocity, density, and pressure of the SNR ejecta at the position of the PWN shell.

unshocked ejecta

$R < R_{rs}$

shocked ejecta

$R_{rs} < R < R_{snr}$

Using prescriptions for a type II SN by
Truelove & McKee 1999
Bandiera 1984

After the compression the PWN bounces, and starts the Sedov phase when its pressure reaches the pressure of the SNR's Sedov solution.

$$R^4(t_{Sedov})P(t_{Sedov}) = R^4(t)P(t),$$

$P(t) = \rho_{ism} v_{fs}^2 / (\gamma_{snr} + 1)$ is the pressure in the forward shock.

(One bounce considered, for a more realistic situation)

Consistently solving too the magnetic field equation

$$W_B = \frac{4\pi}{3} R^3_{PWN}(t) \frac{B^2(t)}{8\pi}.$$

Energy in Magnetic field

$$(dW_B/dt) = \eta L - W_B (dR_{PWN}/dt)/R_{PWN},$$

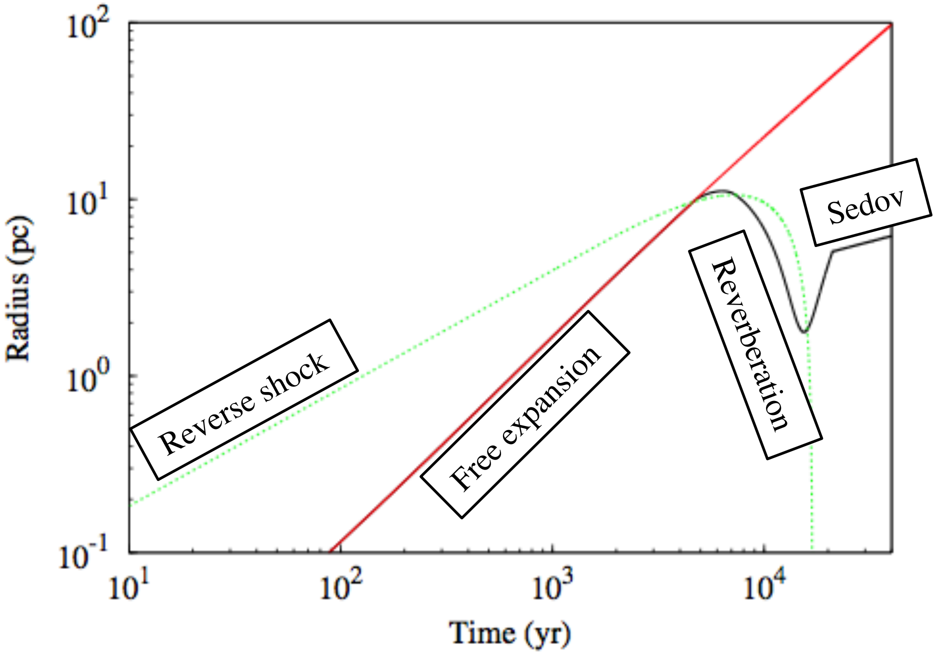
η, magnetization: Fraction of spin-down powering the field

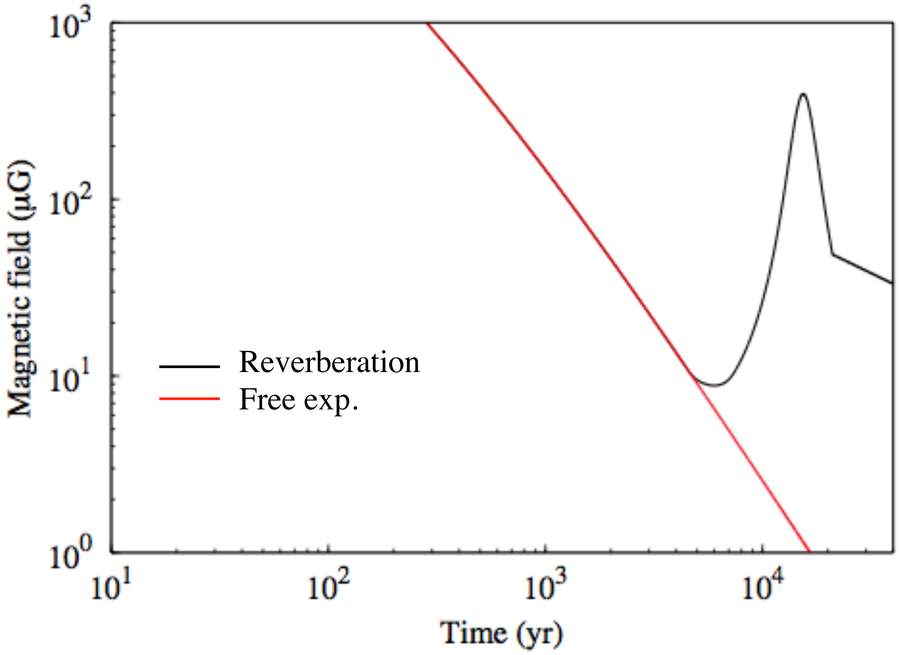
Energy loss due to nebula expansion

$$\int_0^t \eta L(t') R_{PWN}(t') dt' = W_B \, R_{PWN},$$

Numerical expression for the time evolution of B

Radius and magnetic field, generic example with a 40 kyr PWN





- The age at which the transition between different stages of the evolution occurs varies with the energy of the SN explosion, the ejected mass, and the initial profiles of the SNR ejecta.

- Reverberation: when the PWN shell goes into the shocked medium of the remnant and starts the compression. During this phase, the magnetic field and the internal pressure increases

Analyzing the size of the magnetar PWN

- The size constraint (2.9 pc) implies constraints on the age (take the characteristic age of 4.9 kyr as scale). We consider 0.6, 1.0, 1.6 τ_c

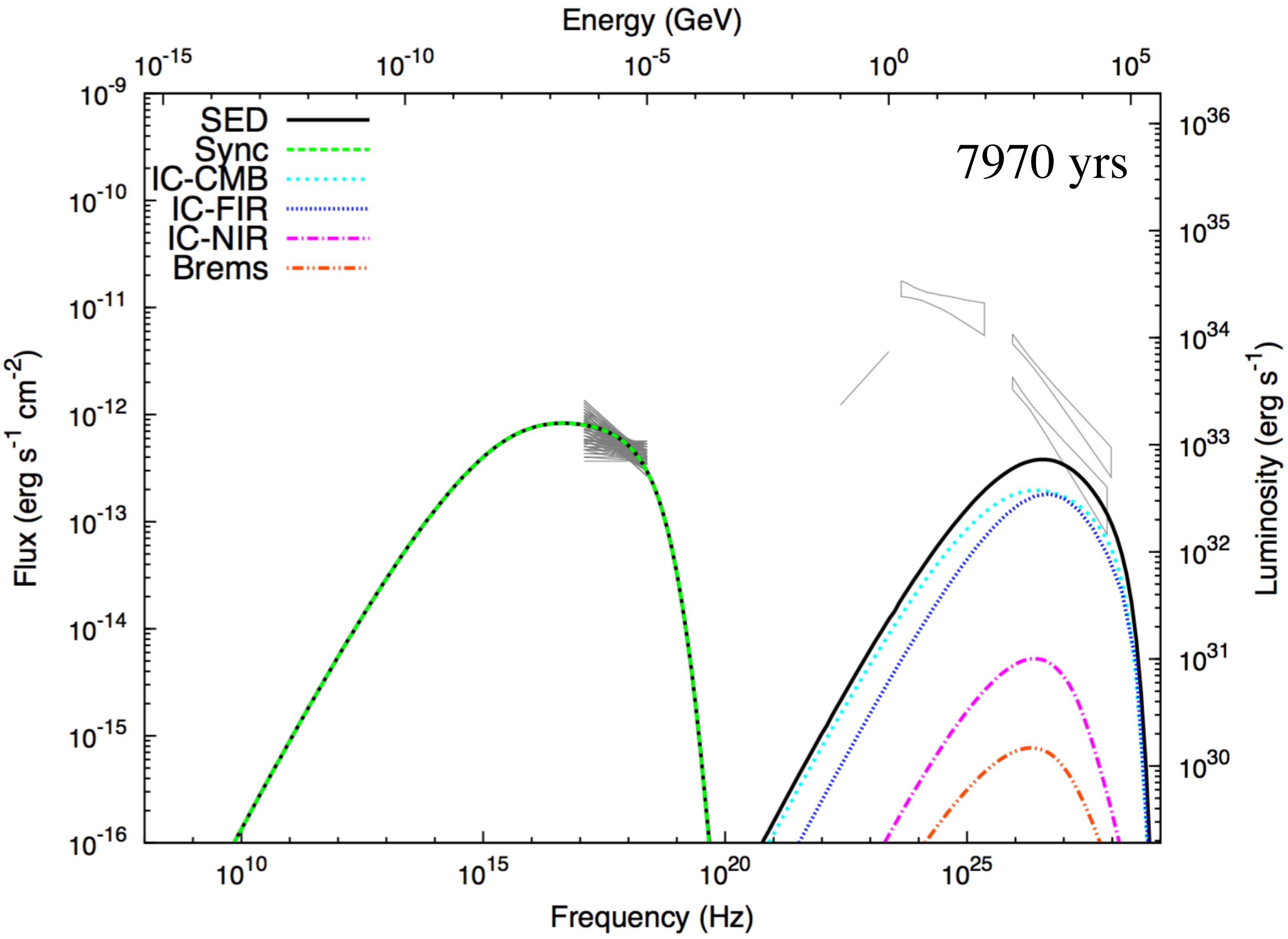
- **If the age is too small** (0.6, 1.0 τ_c), the pulsar would be too young to be free-expanding a rotationally-powered nebula up to the size detected;

- **If the age is too large** (>1.6 τ_c), the PWN expansion would have been already stopped by the medium and even when re-expanding, its size would be smaller than detected. [And other problems would appear.]

- Solutions possibly matching the nebula radius are those having an age around 1.6 τc, at the end of the free expansion phase or the beginning of the compression phase, where the nebula has not yet time to be compressed too much by the reverberation process.

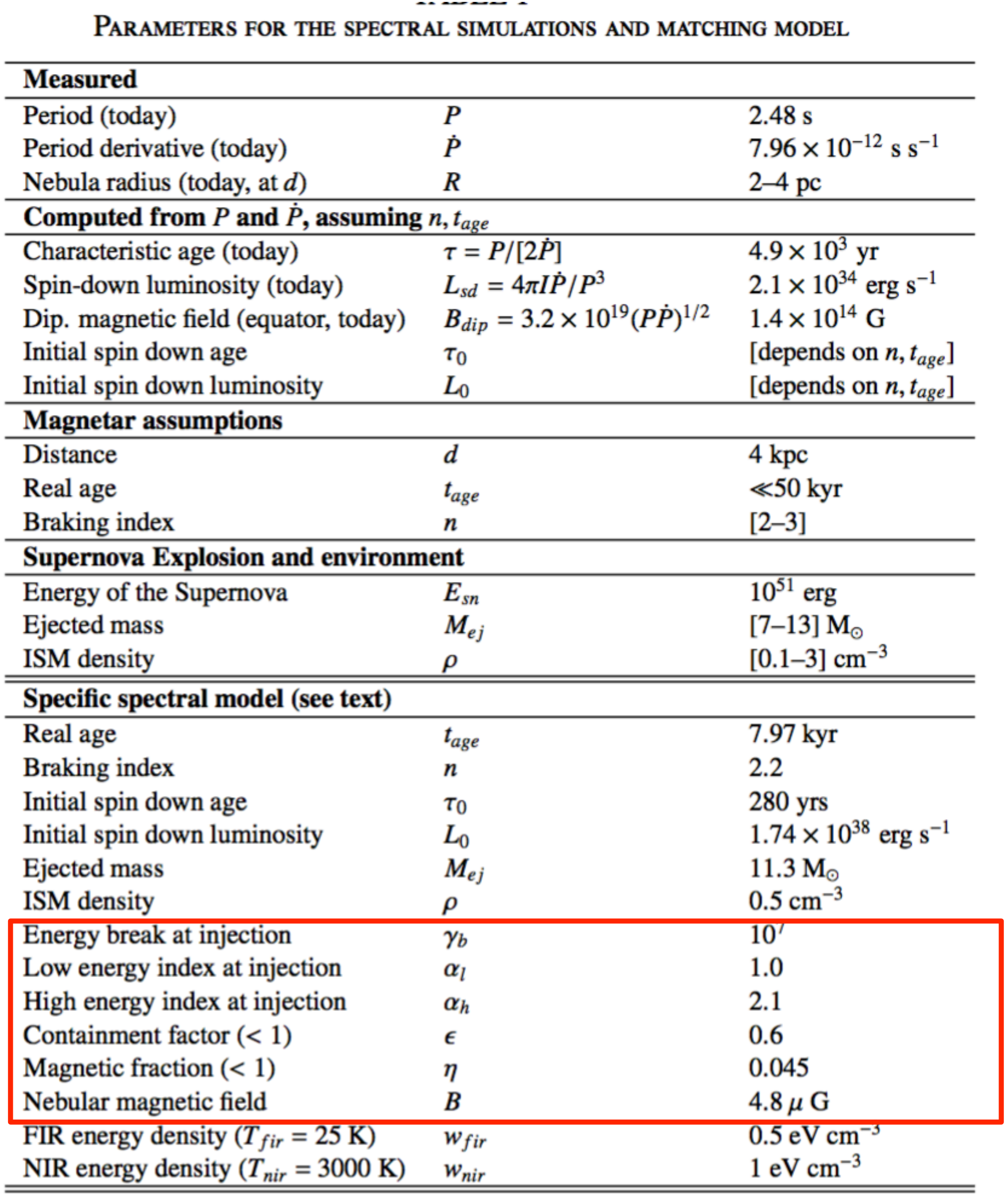
- Can some of these lead to a good spectral matching?

Yes, this is an spectrally matching model



And it has usual PWNe parameters, no extremes

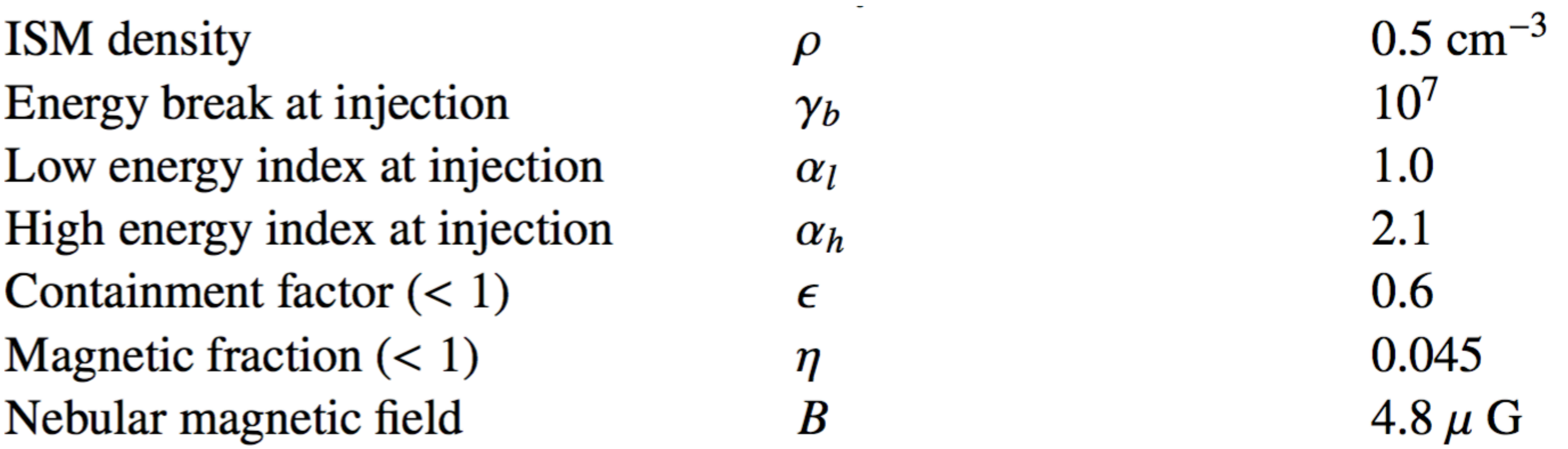
In line with
all other PWNe
known



PARAMETERS FOR THE SPECTRAL SIMULATIONS AND MATCHING MODEL

Measured		
Period (today)	P	2.48 s
Period derivative (today)	$\dot{P}$	7.96×10^{-12} s s^{-1}
Nebula radius (today, at d)	R	2–4 pc
Computed from P and $\dot{P}$, assuming n, t_{age}		
Characteristic age (today)	$\tau = P/[2\dot{P}]$	4.9×10^3 yr
Spin-down luminosity (today)	$L_{sd} = 4\pi I\dot{P}/P^3$	2.1×10^{34} erg s^{-1}
Dip. magnetic field (equator, today)	$B_{dip} = 3.2 \times 10^{19}(P\dot{P})^{1/2}$	1.4×10^{14} G
Initial spin down age	τ_0	[depends on n, t_{age}]
Initial spin down luminosity	L_0	[depends on n, t_{age}]
Magnetar assumptions		
Distance	d	4 kpc
Real age	t_{age}	$\ll$50 kyr
Braking index	n	[2–3]
Supernova Explosion and environment		
Energy of the Supernova	E_{sn}	10^{51} erg
Ejected mass	M_{ej}	[7–13] $M_\odot$
ISM density	ρ	[0.1–3] cm^{-3}
Specific spectral model (see text)		
Real age	t_{age}	7.97 kyr
Braking index	n	2.2
Initial spin down age	τ_0	280 yrs
Initial spin down luminosity	L_0	1.74×10^{38} erg s^{-1}
Ejected mass	M_{ej}	11.3 $M_\odot$
ISM density	ρ	0.5 cm^{-3}
Energy break at injection	γ_b	10^7
Low energy index at injection	α_l	1.0
High energy index at injection	α_h	2.1
Containment factor (< 1)	ϵ	0.6
Magnetic fraction (< 1)	η	0.045
Nebular magnetic field	B	4.8 μ G
FIR energy density (T_{fir} = 25 K)	w_{fir}	0.5 eV cm^{-3}
NIR energy density (T_{nir} = 3000 K)	w_{nir}	1 eV cm^{-3}

Main parameters and resulting values



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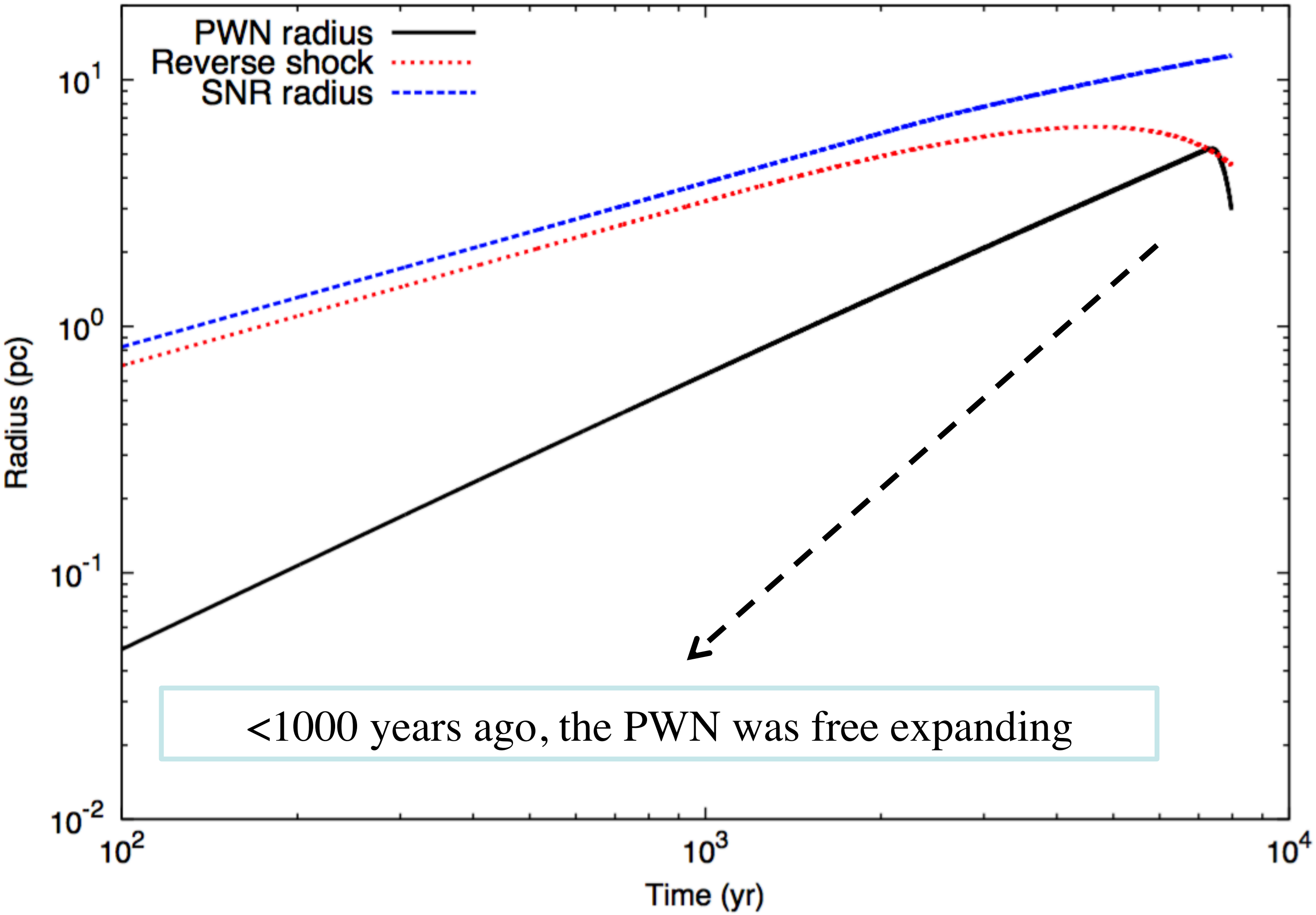
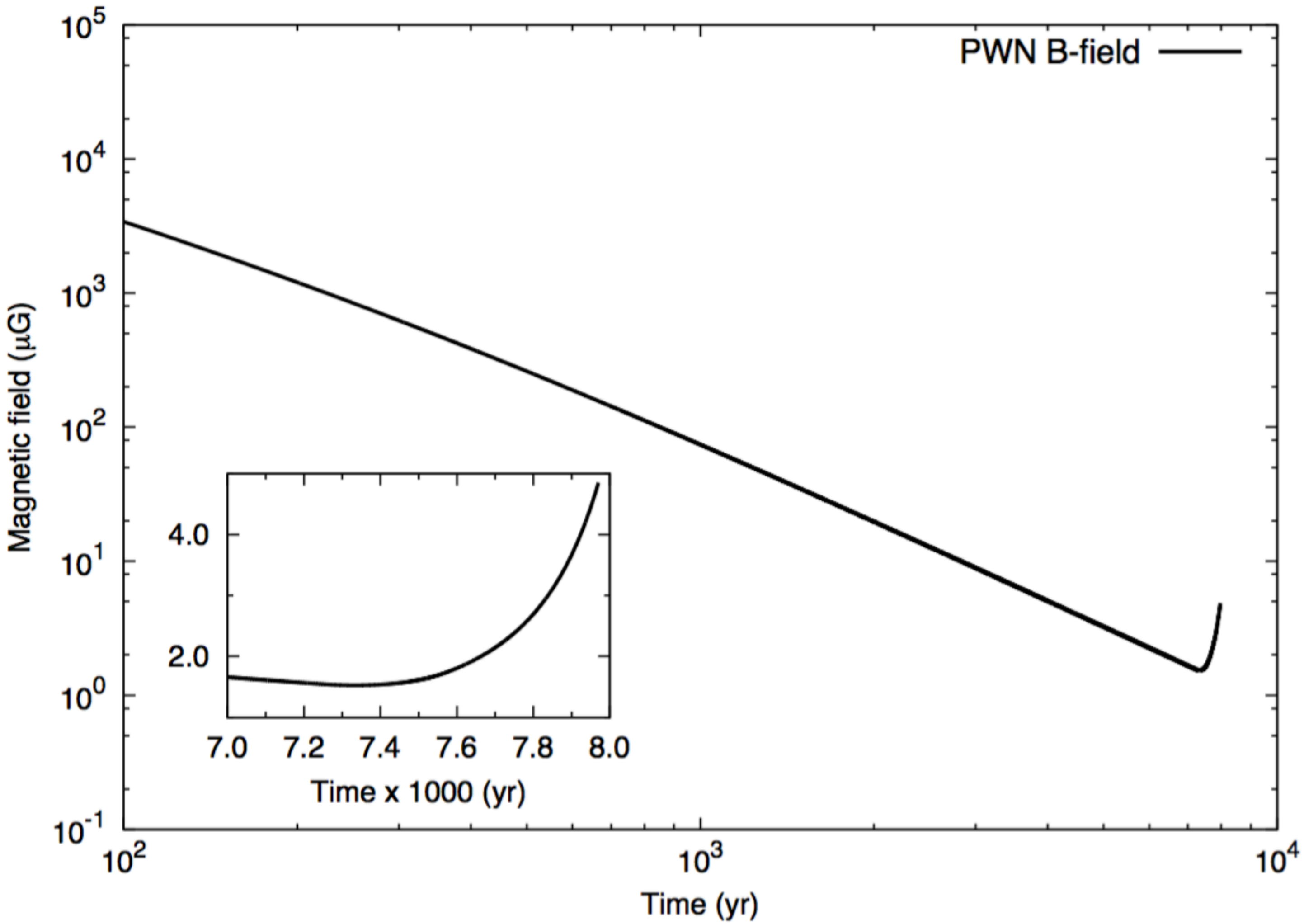
So, where is the trick? Yes.. The PWN is entering reverberation…



<1000 years ago, the PWN was free expanding

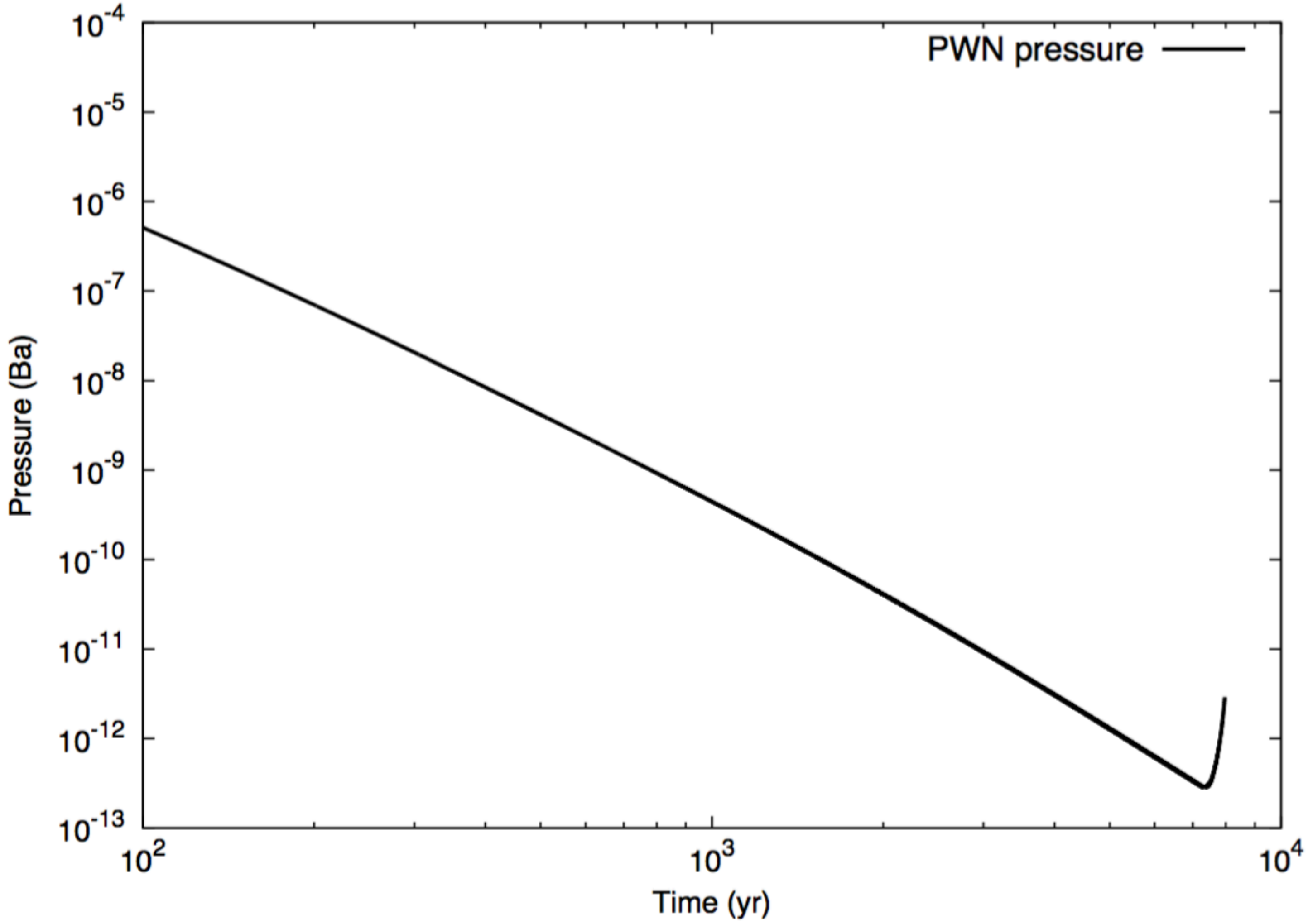
The PWN size is quickly decreasing

The PWN is entering reverberation



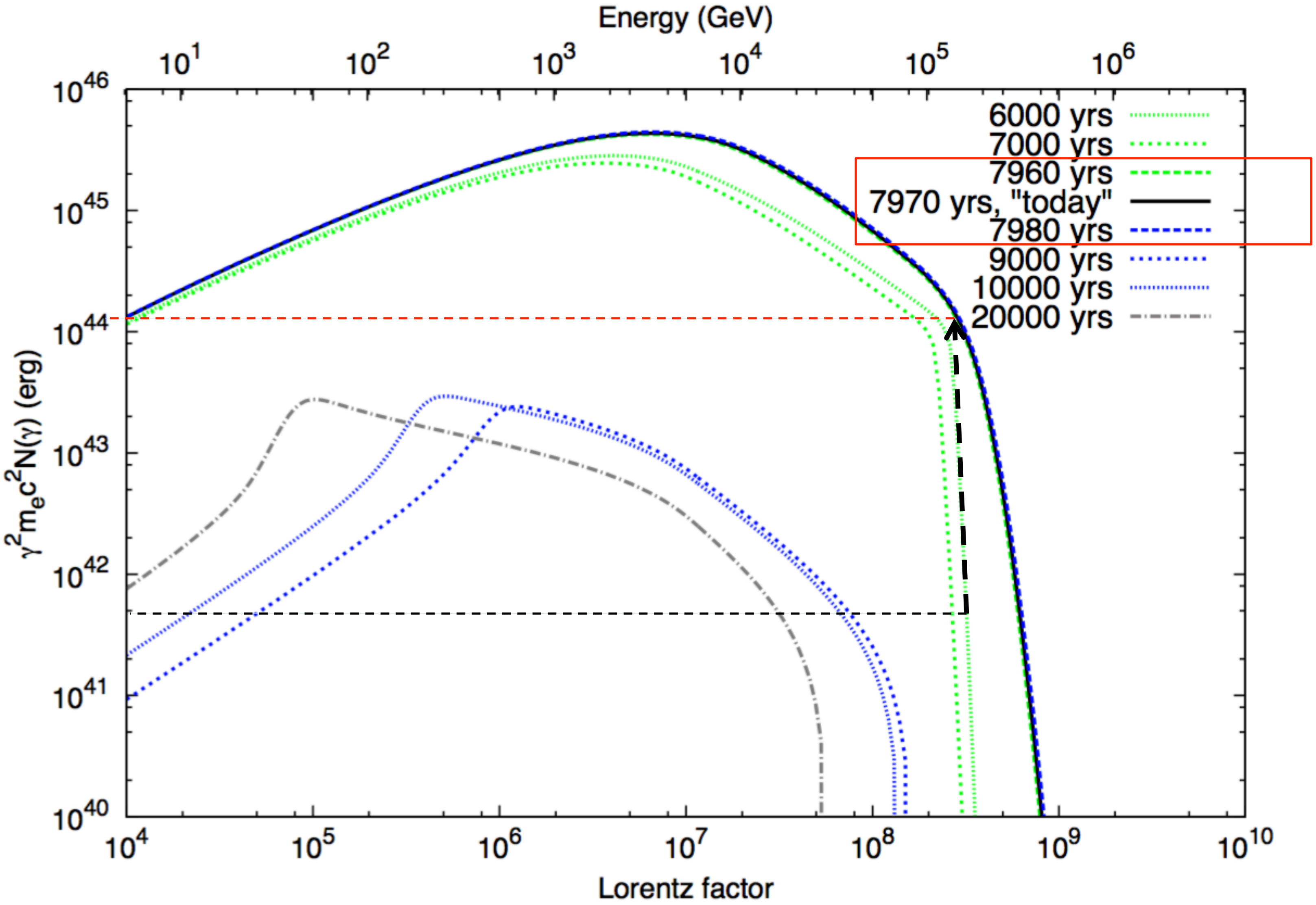
The B field is quickly increasing

The PWN is entering reverberation

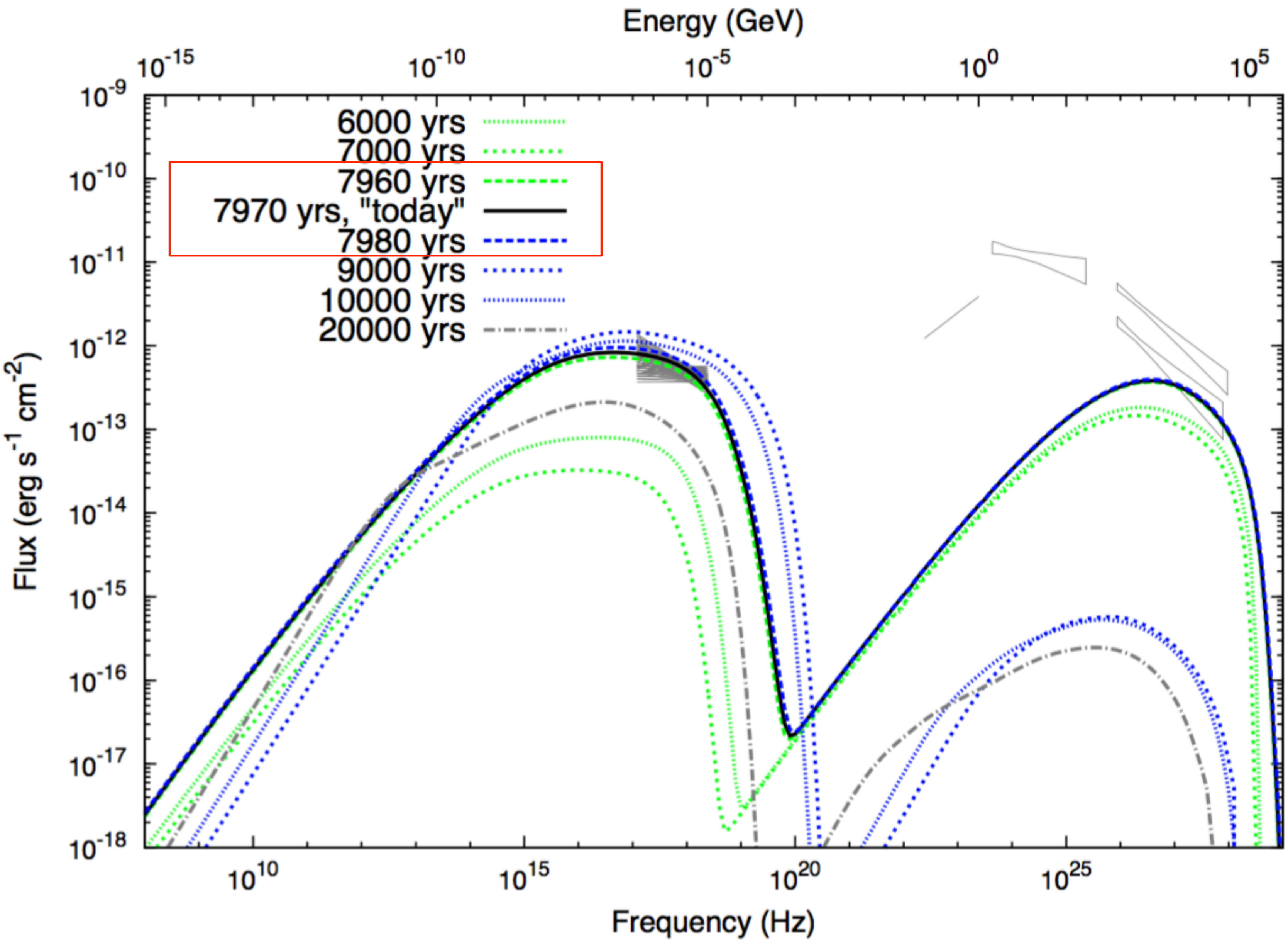


The PWN pressure is also quickly increasing

There is a huge increase of the high-energy particle population



... that reflects in the spectral energy distribution



Why in hell this happens?

Because the reverberation process transfers energy to particles via adiabatic heating, and its timescale is few 100 years

Comparison of timescales for relevant particle losses

Shown are **models** with dynamical evolution **without (dashed lines) and with (solid lines) reverberation** being considered. Subdominant bremsstrahlung and inverse Compton timescales are not shown for clarity but also considered in the computation.

$$t_i = \frac{\gamma}{\dot{\gamma}_i(\gamma, t)}, \qquad t_{ad} \sim \frac{R(t)}{v(t)}, \qquad t_{\mathrm{Bohm}} \sim \frac{qB(t)R(t)^2}{2m_e c^3 \gamma}, \qquad t_{\mathrm{Sync}} \sim \frac{\gamma}{\frac{4}{3}\frac{\sigma_T}{m_e c} U_B(t)\gamma^2},$$

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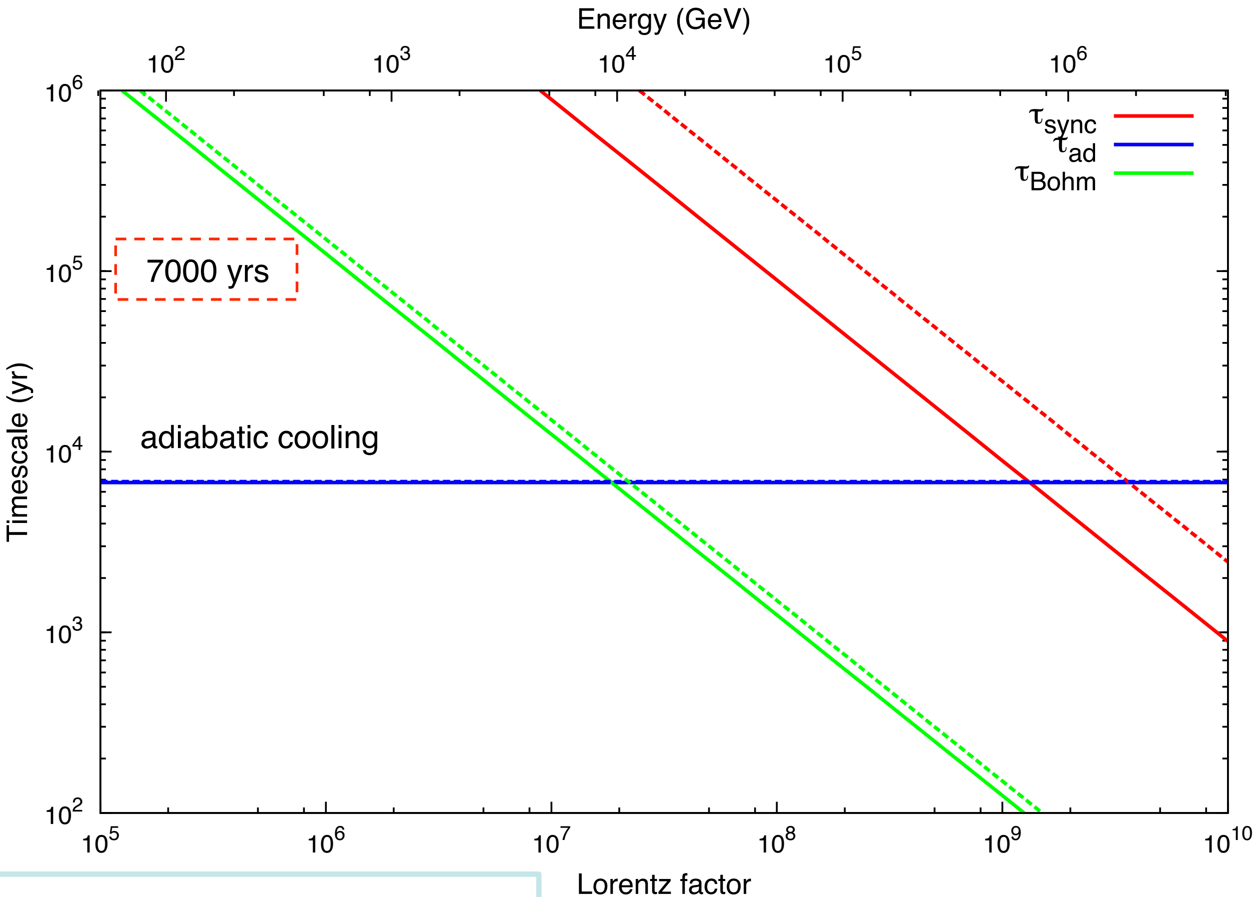

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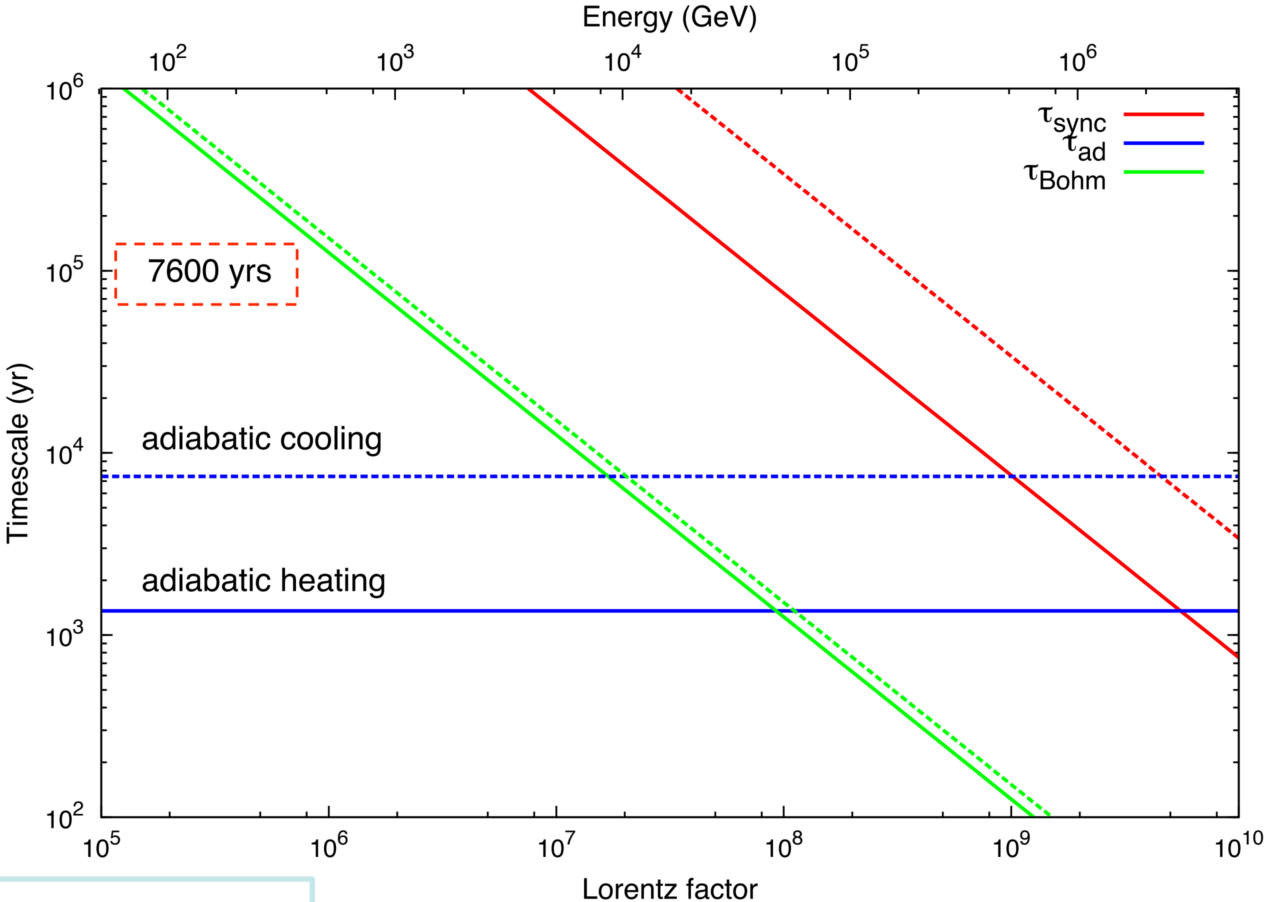
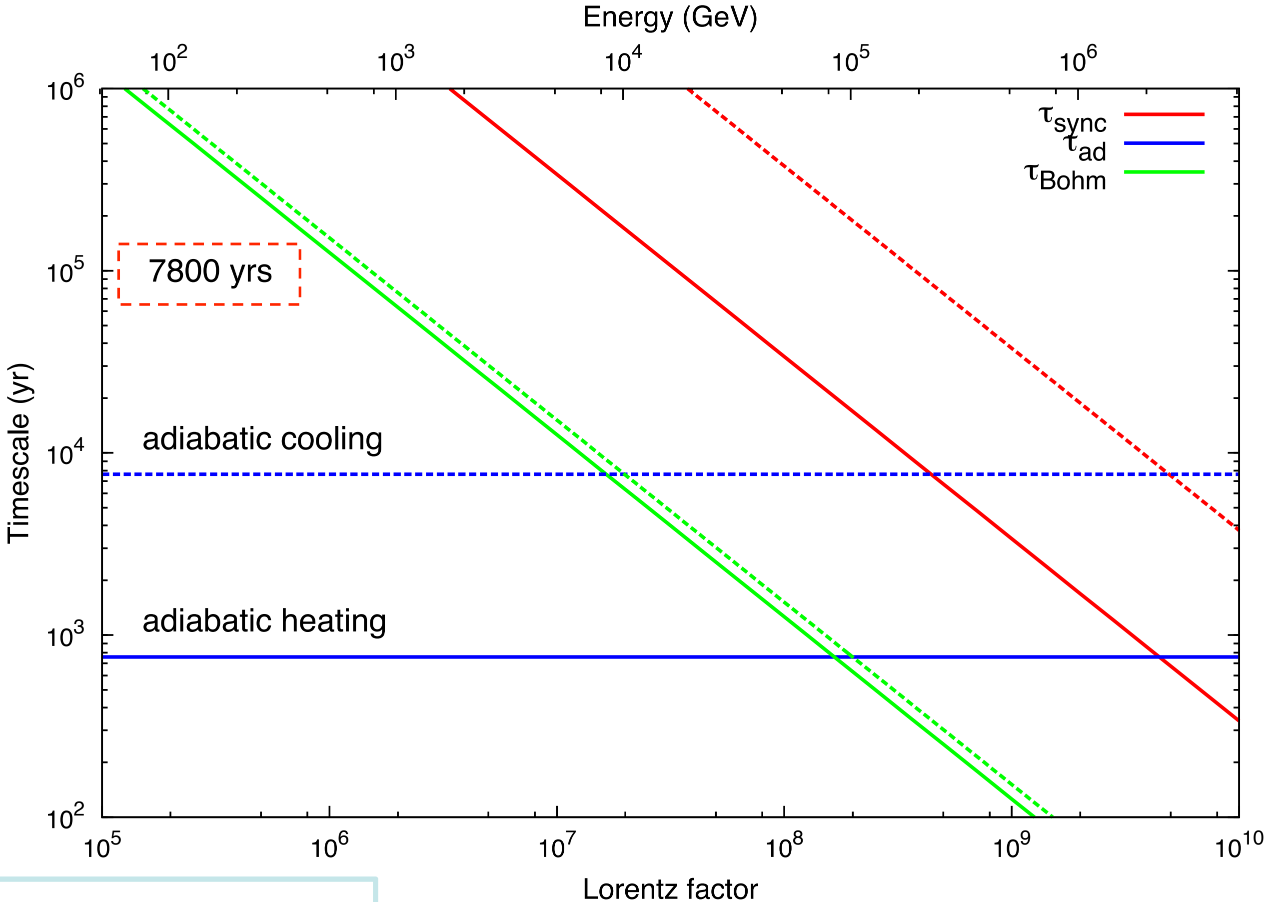


Reverberation starts energization

Why in hell this happens?

Because the reverberation process transfers energy to particles via adiabatic heating, and its timescale is few 100 years



L_sd is small, so reveberation is fast

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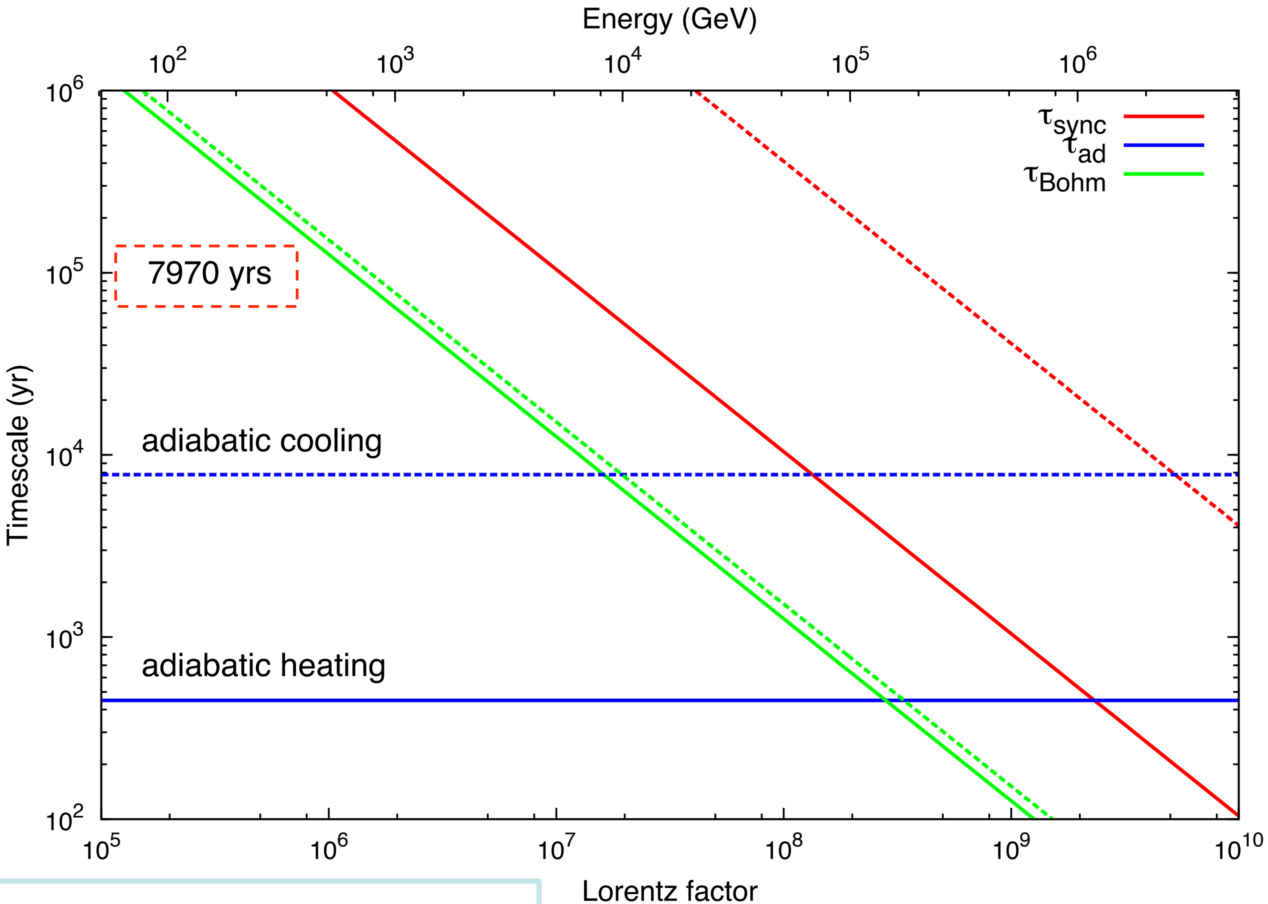

Reaching a timescale of only few 100 yrs

Assessment

- the adiabatic timescale along reverberation is no longer representing losses, but energization of particles: the environment is transferring energy to the PWN.

- An smaller adiabatic timescale makes for quick and significant energization of particles that would immediately participate in enhancing the synchrotron spectrum.

- At the relevant energies for X-ray production, around $\gamma \sim$ 1E8 and beyond, the losses are dominated by diffusion before reverberation, and the adiabatic heating timescale when reverberation is ongoing.

- Given that the timescale for heating is of the order of the duration of the compression, more and more particles participate in generating the X-ray yield.

Conclusions

- A rotationally powered PWN can power the magnetar nebula!
- But reverberation (a detailed study of the dynamics of the evolution) is critical to get this result
  - Would not appear otherwise!
- We should forget about the spin-down (and related) parameters as markers of the PWN detectability, you need much more…
- Explains why we have seen only one PWN in all 20 magnetars.
- Establish constraints on the magnetar age

A lot more in the original paper: DFT, ApJ 835, article id. 54 (2017)