On magnetars and their nebulae

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(Based on "A rotationally powered magnetar nebula around Swift J1834.9–0846",
DFT
ApJ 835, 54, 13 pp. (2017). arXiv:1612.02835)

With the support of

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Discovery of Swift J1834.9–0846 (the magnetar itself)

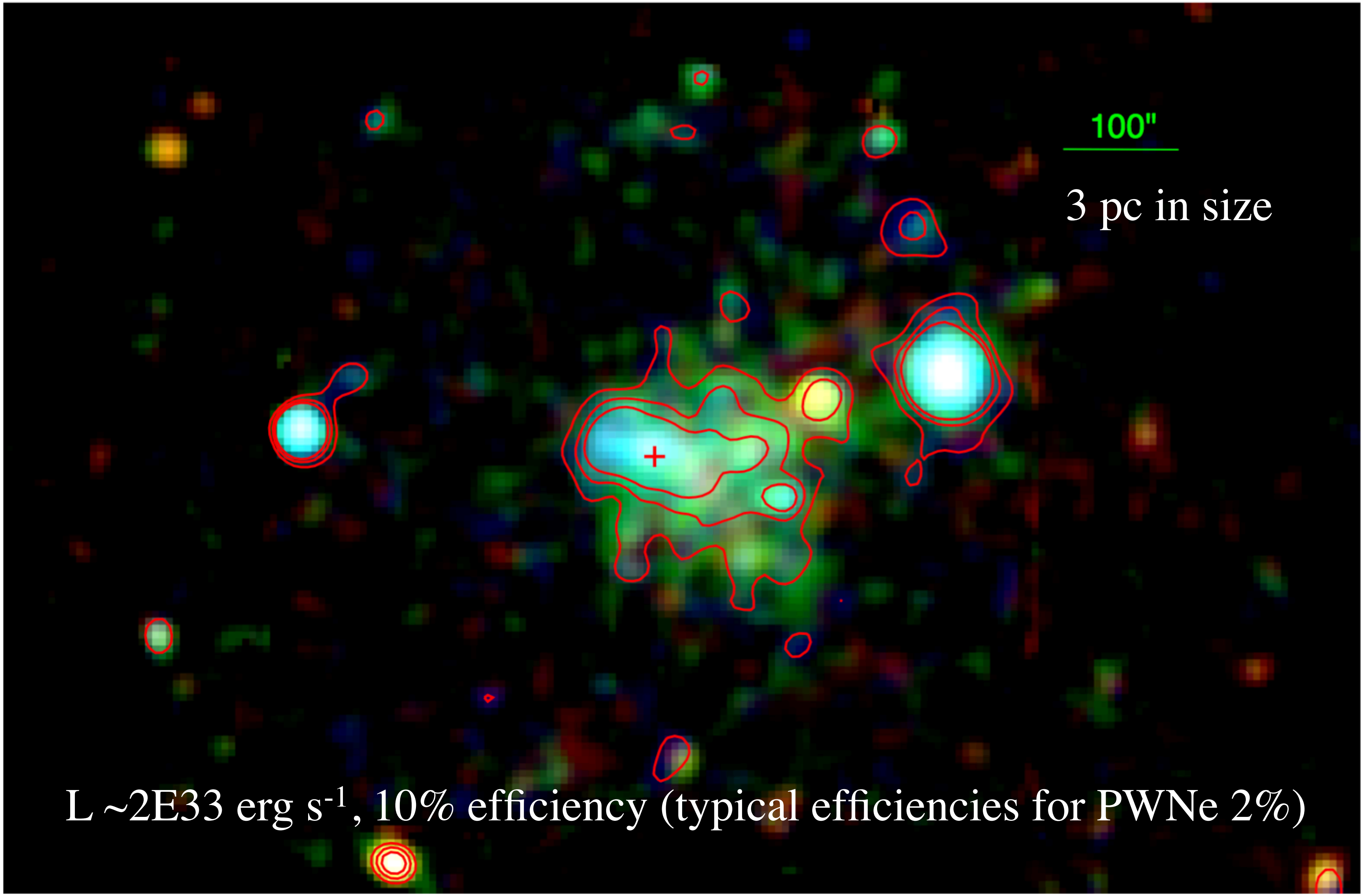
- Found by Swift X-ray satellite on 2011 August 7, via a short X-ray burst (D'Elia et al. 2011). A few hours later, another burst was detected by the Fermi GBM; and a third burst appeared days after (on August 29; Hoversten et al. 2011, Kargaltsev et al. 2012). Distance of 4kpc (Esposito et al. 2012)

- 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 (stable, hard emission)



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 (is it always?) 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.

A nebula surrounding a magnetar

- Why not?

Well… A nebula that powerful and that large, from a pulsar that dim?

- Are 2E34 erg/s of total energy reservoir enough to power a nebula 3 pc in size that emits 2E33 erg/s only in X-rays?

- Tong (2016) says no. He has proposed that the nebula can only be interpreted in the wind braking scenario. But his argument is wrong.

- Granot et al. (2016) proposed that nebula is powered via a transfer of magnetic power into particle acceleration.
  - Lots of freedom.. no spectral prediction
  - What mechanism is foreseen for this to happen? Is it continuous? Related to the flare? Why does it dominate?

- What about a 'normal' nebula?
- Is it really ruled out? If so, why?

Full time-dependent PWNe with a detailed expansion model

Radius, Mass, Velocity of the PWN shell

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

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

$$\frac{dM(t)}{dt} = 4\pi R^2(t)\rho_{ej}(R,t)(v(t) - v_{ej}(R,t)). \qquad \text{if } v_{ej}(R,t) < v(t)$$

$$= 0. \qquad \text{if } v_{ej}(R,t) > v(t)$$

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

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

For the experts: — The model has: Similarities with Gelfand et al. 2009 + Particle radiation taken into account in the expansion + Considers 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

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

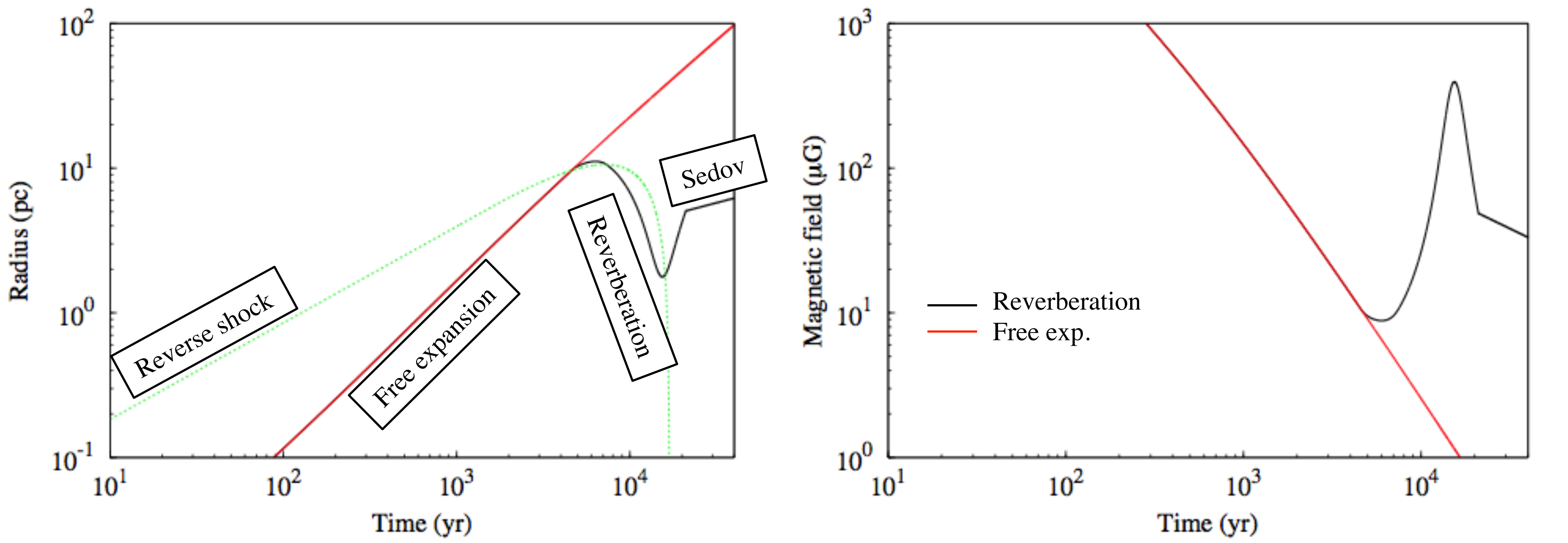
η, magnetization: Fraction of spin-down powering the field

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 (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

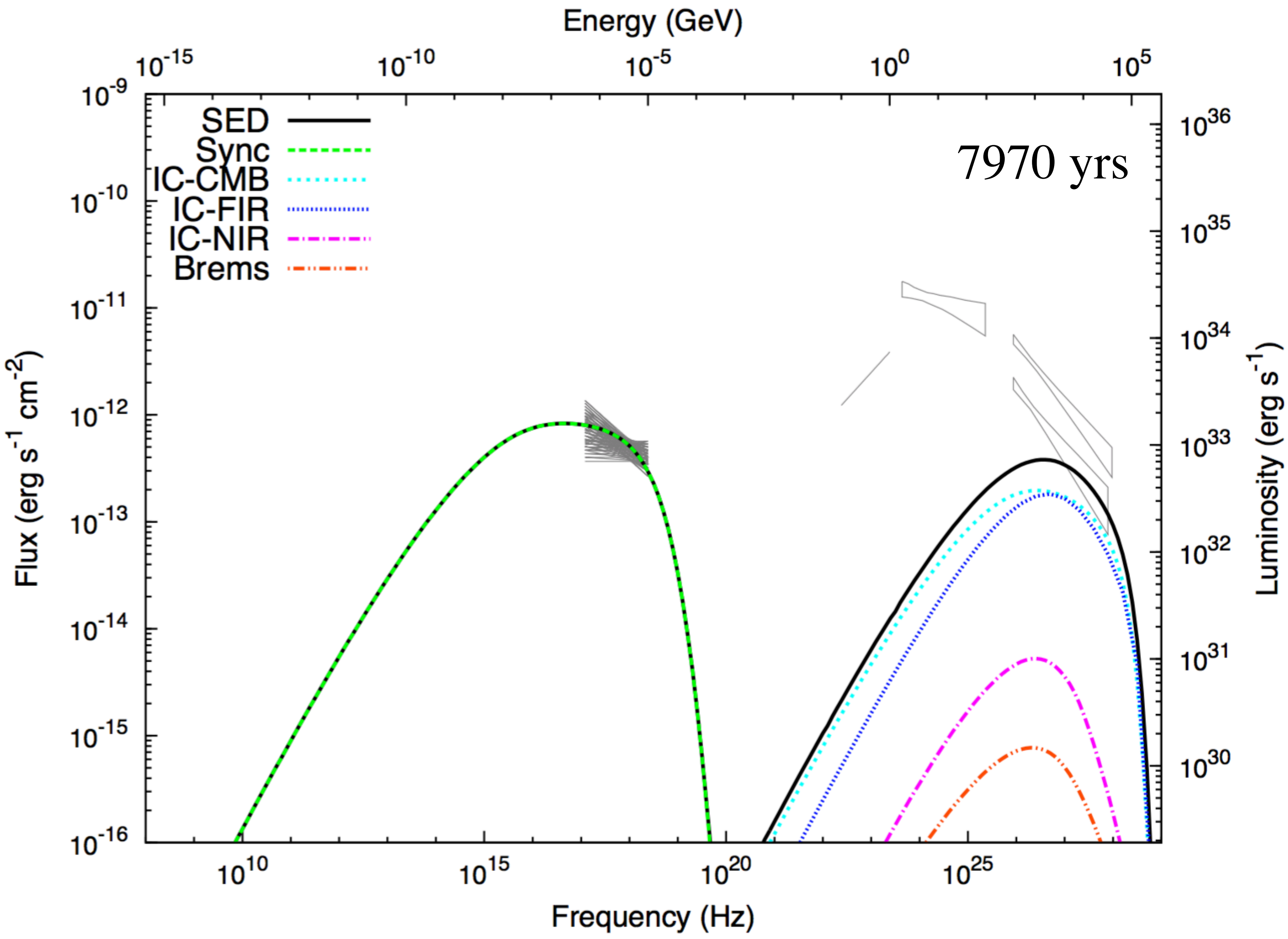
- **If the age is too small** (0.6, 1.0 τ_c), the pulsar would be too young to be free-expanding a rotationally-powered nebula up to the size detected;

- **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: low numbers of high energy electrons are left alive.]

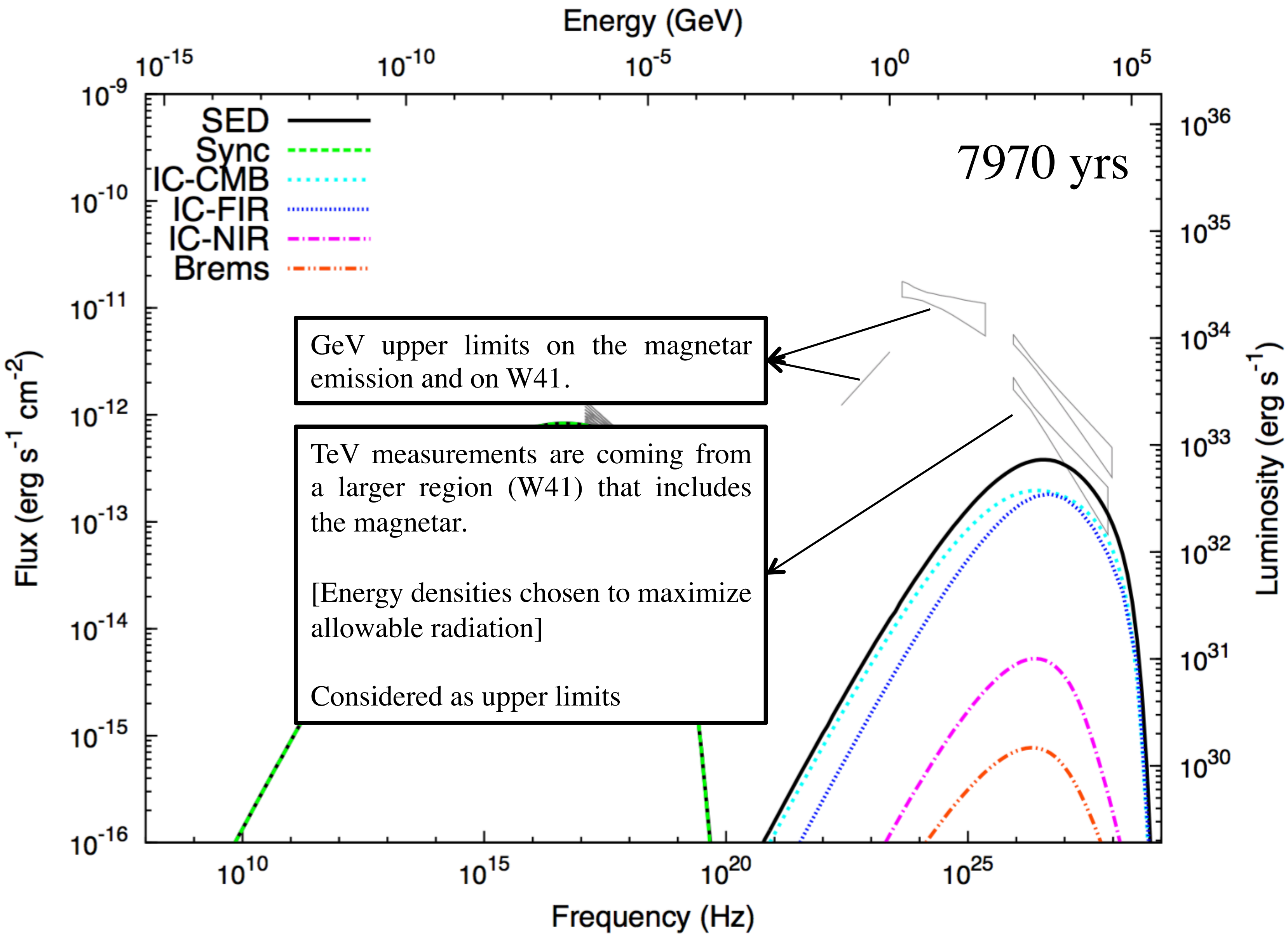
- Solutions matching the nebula radius have an age ~1.6 τ_c, at the end of the free expansion or the beginning of the compression phase, where the nebula has not yet time to be compressed too much by the reverberation process.

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

Yes, this is an spectrally matching model



Yes, this is an spectrally matching model



And it has usual PWNe parameters, nothing too unusual

In line with all other PWNe known

PARAMETERS FOR THE SPECTRAL SIMULATIONS AND MATCHING MODEL

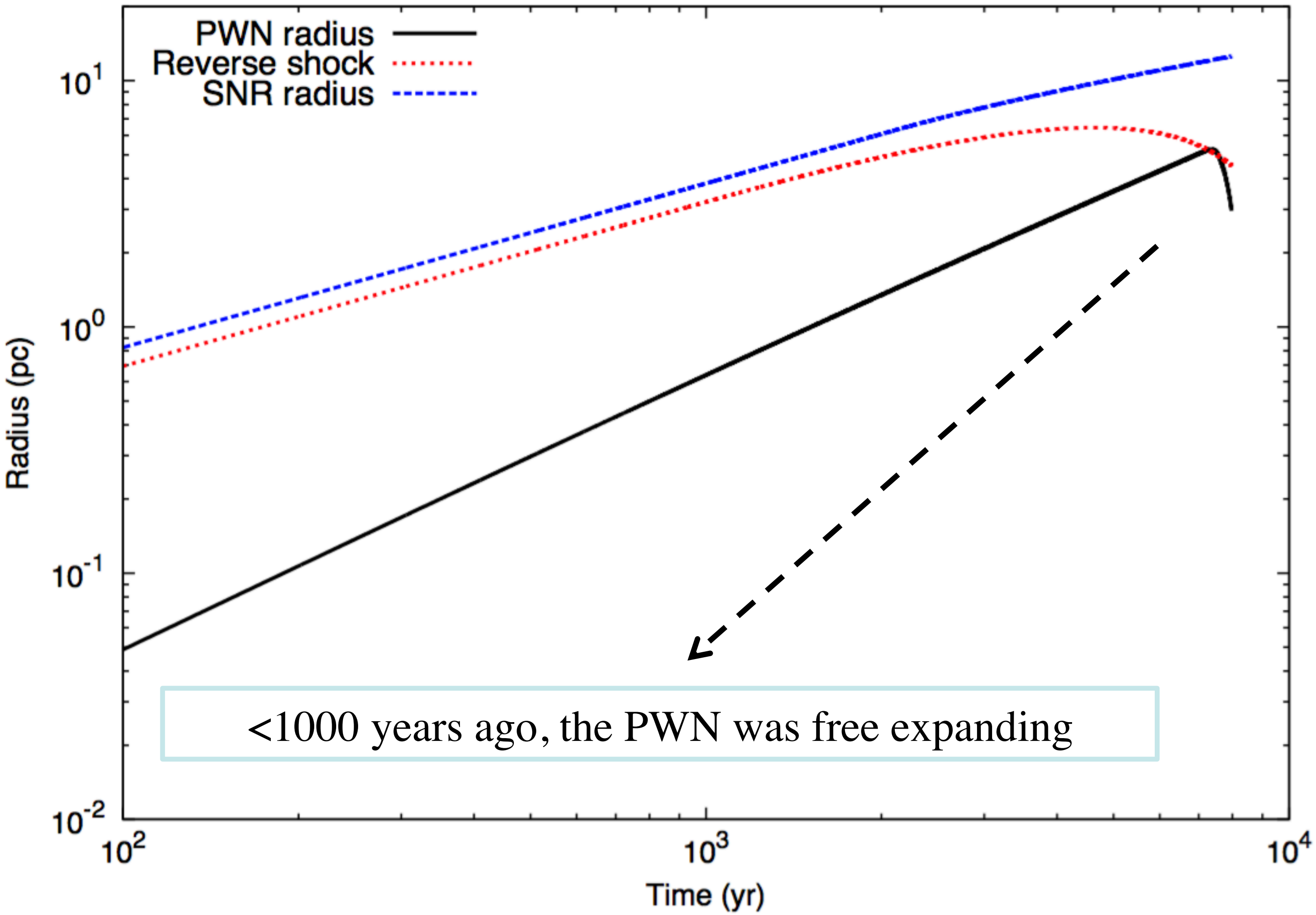
Measured		
Period (today)	P	2.48 s
Period derivative (today)	$\dot{P}$	7.96×10^{-12} s s^{-1}
Nebula radius (today, at d)	R	2–4 pc
Computed from P and $\dot{P}$, assuming n, t_{age}		
Characteristic age (today)	$\tau = P/[2\dot{P}]$	4.9×10^3 yr
Spin-down luminosity (today)	$L_{sd} = 4\pi I\dot{P}/P^3$	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}

For instance

ISM density	ρ	$0.5\ \mathrm{cm}^{-3}$
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	$4.8\ \mu$ G

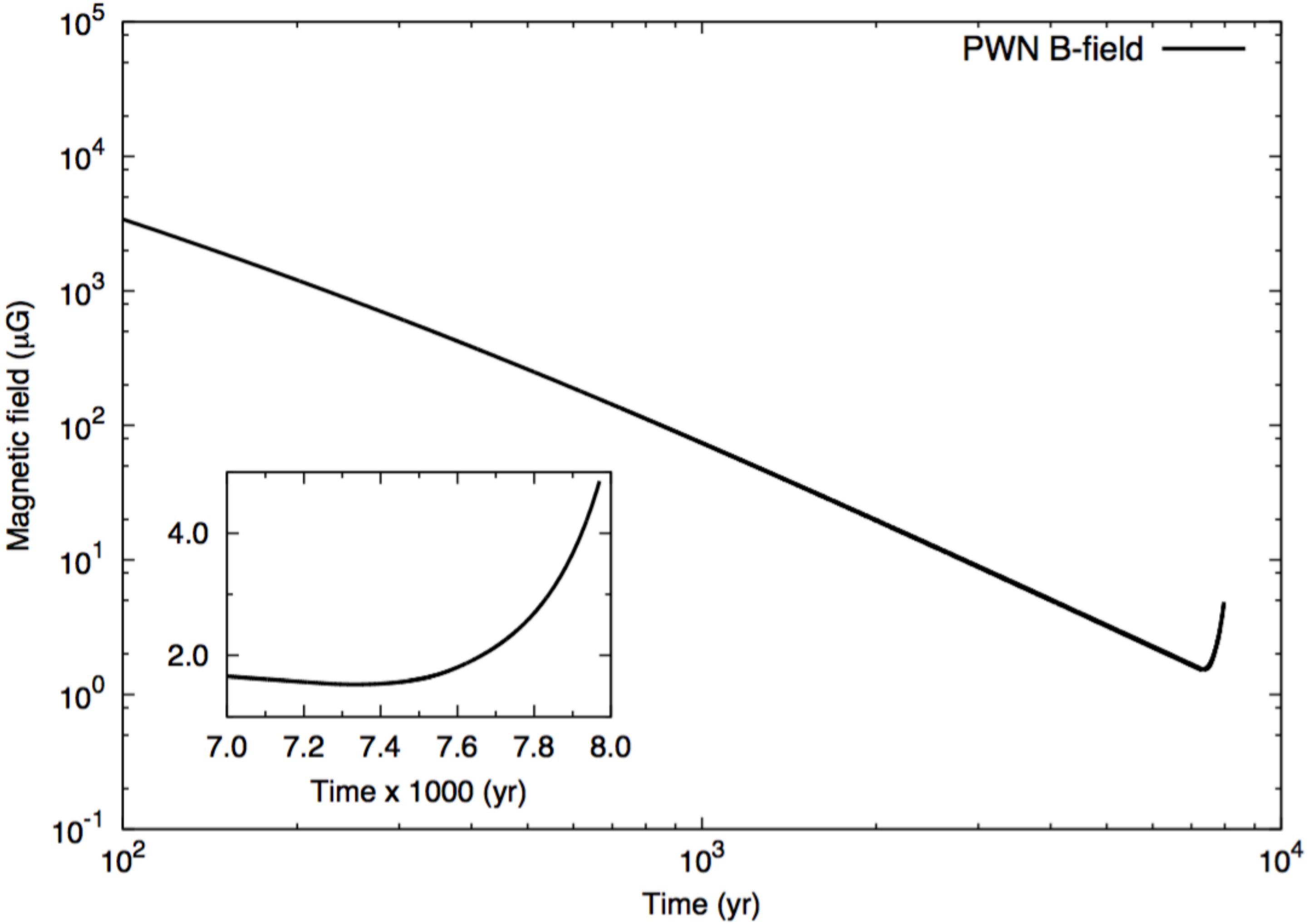
So, where is the trick?

Yes.. The PWN is entering reverberation…



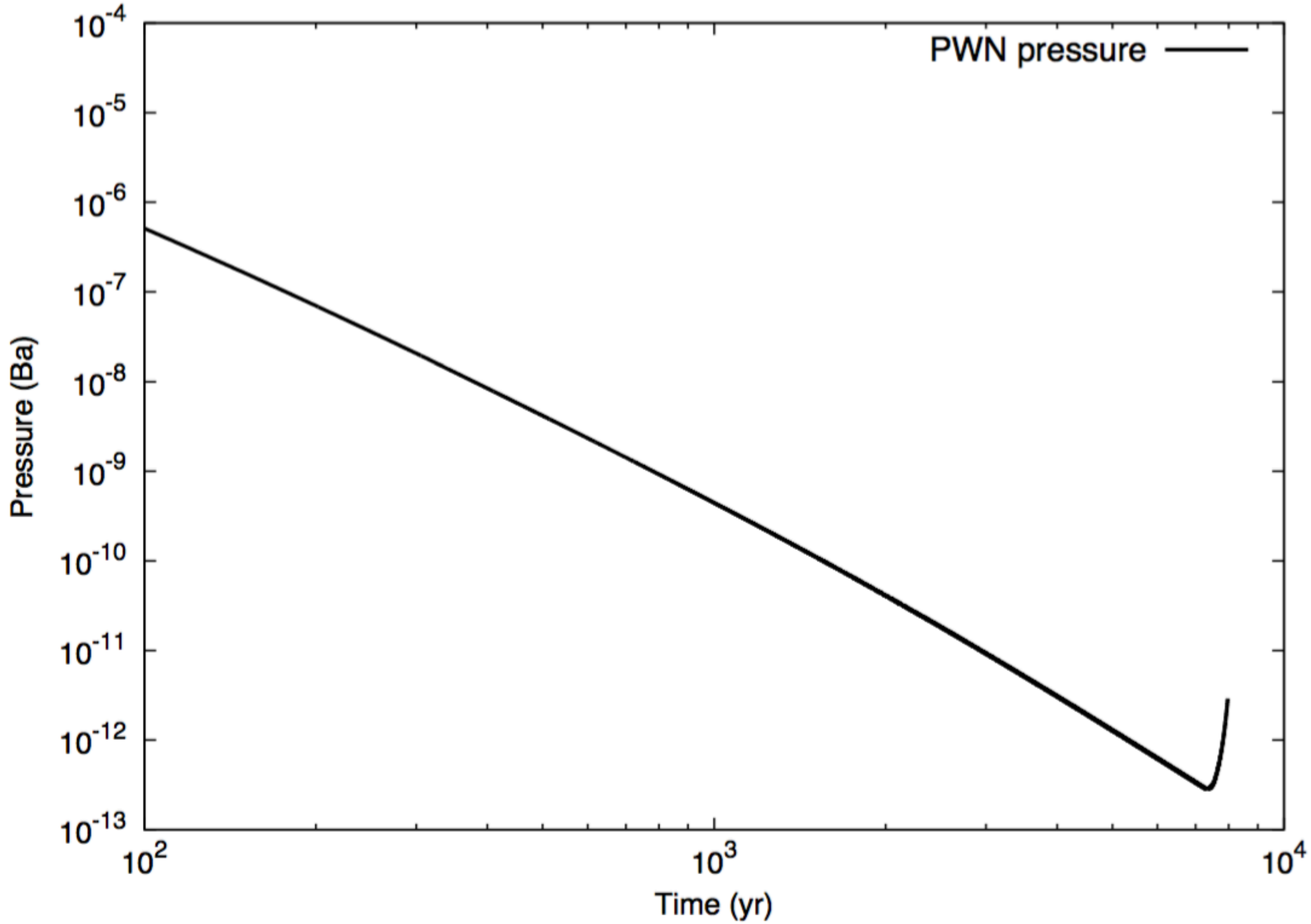
The PWN size is quickly decreasing

The PWN is entering reverberation



The B field is quickly increasing

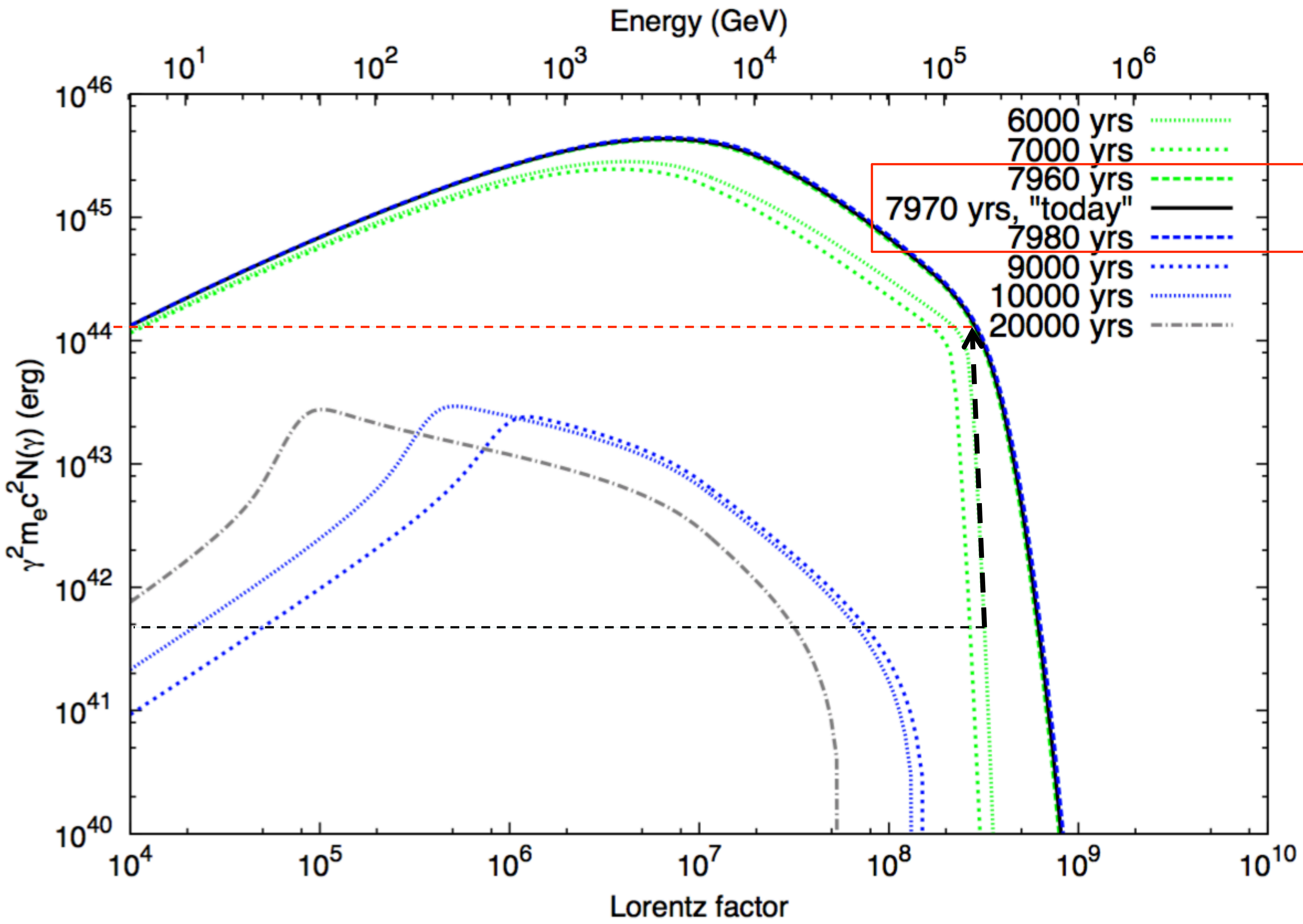
The PWN is entering reverberation



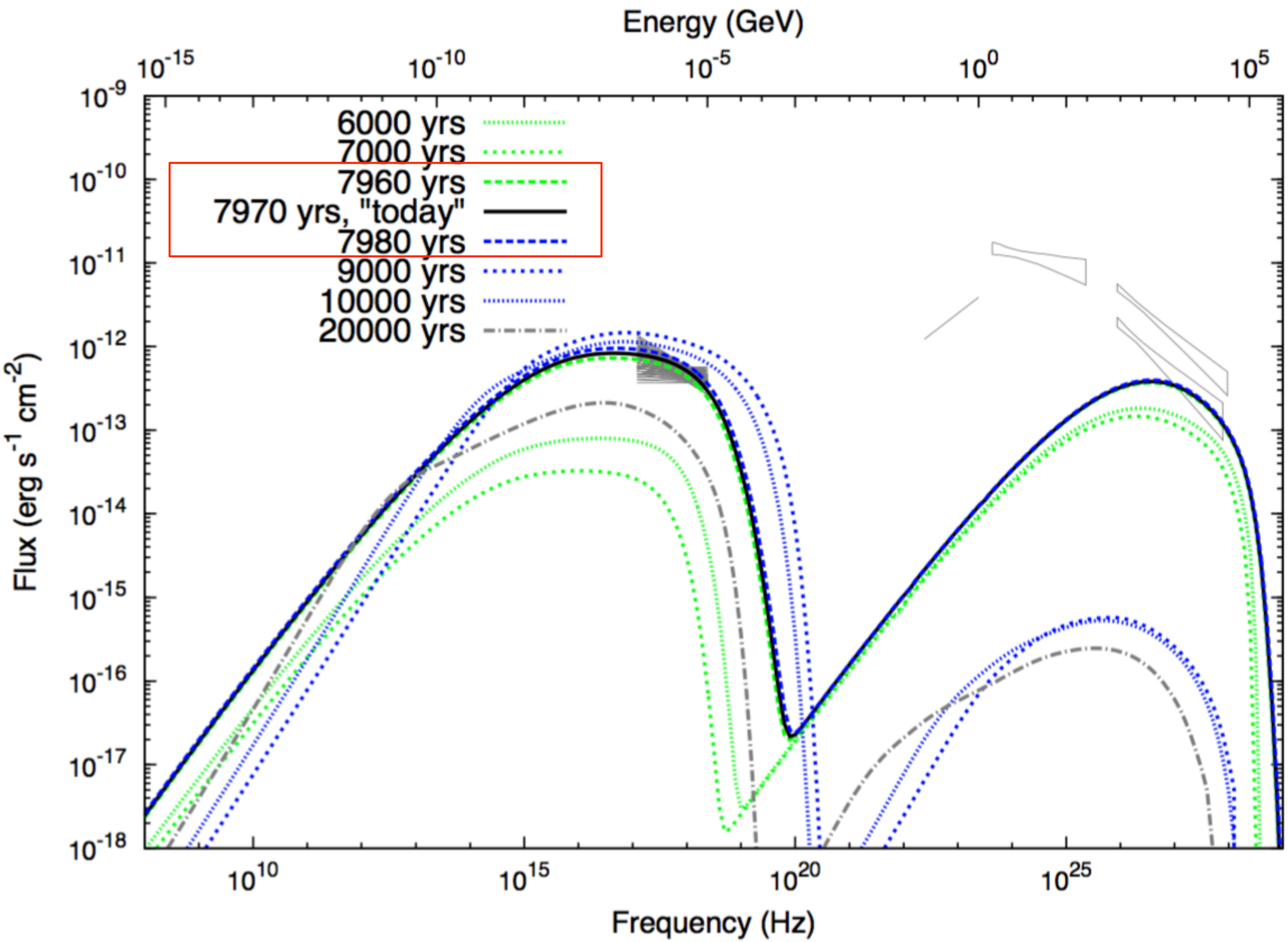
The PWN pressure is also quickly increasing

All this is expected in all reverberation processes

Here there is a huge increase of the high-energy particle population



... that reflects in the spectral energy distribution



Why does this happen?

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

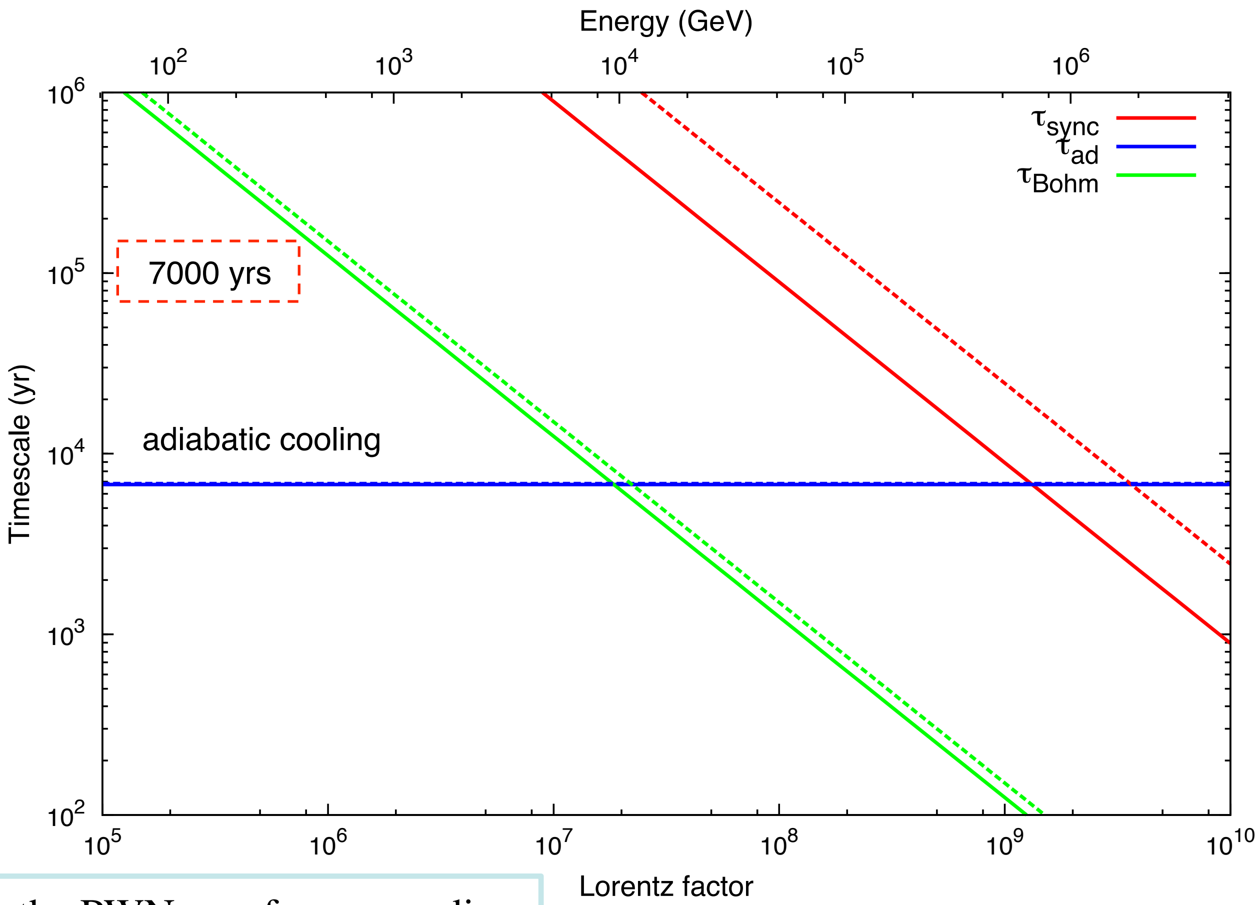
Comparison of timescales for relevant particle losses

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.

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

What makes for more high-E particles?

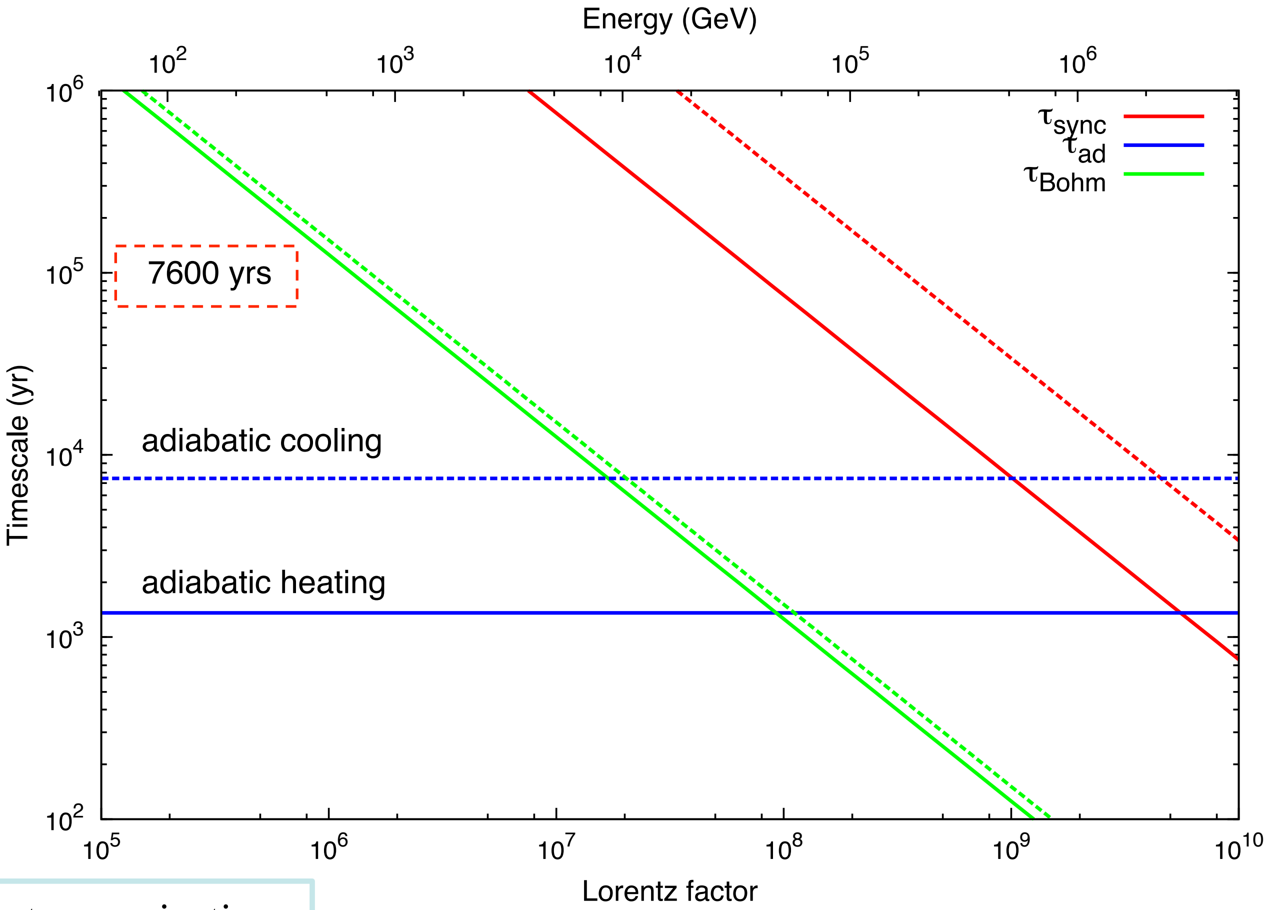
The reverberation process transfers energy to particles via adiabatic heating, and its timescale is few 100 years



<1000 years ago, the PWN was free expanding

What makes for more high-E particles?

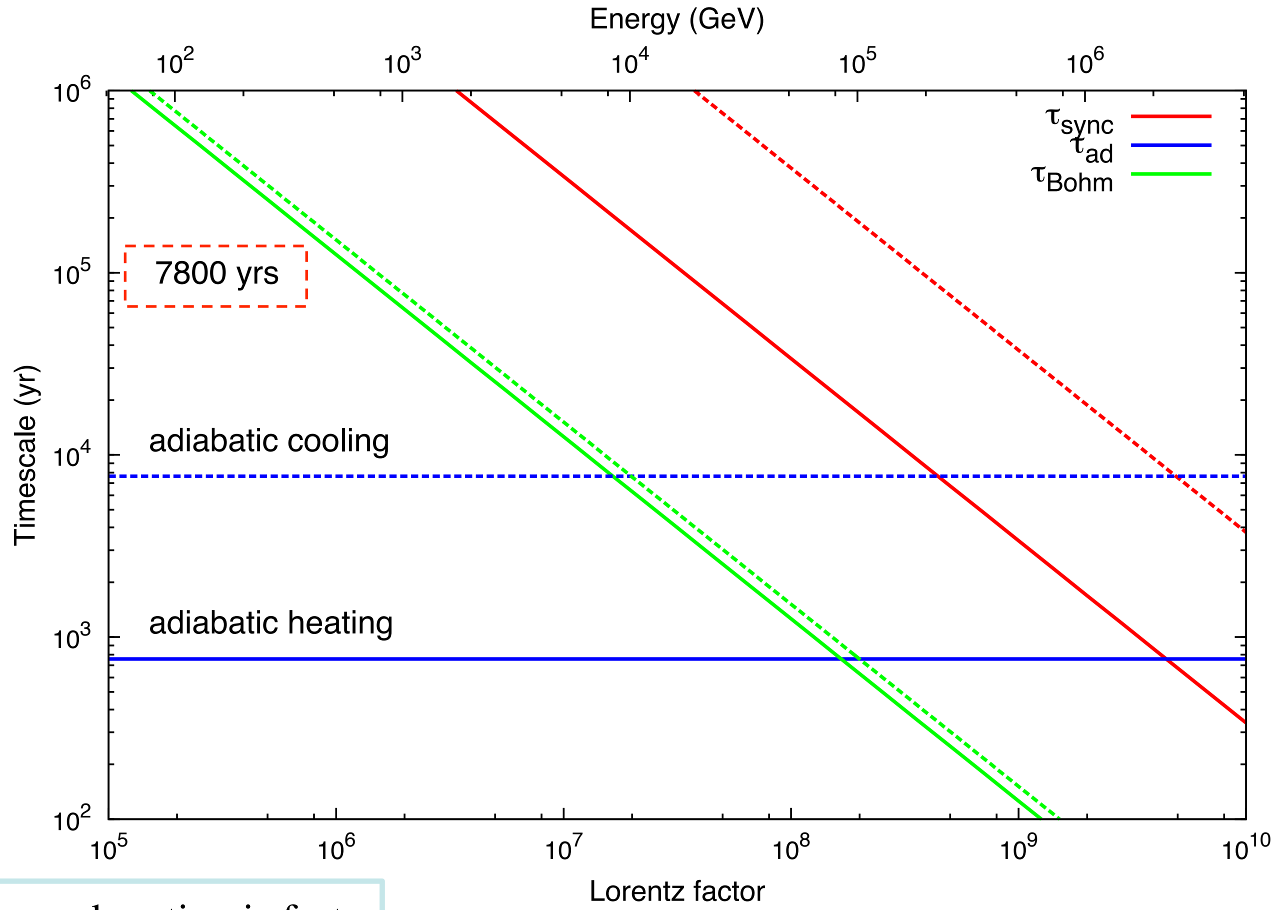
The reverberation process transfers energy to particles via adiabatic heating, and its timescale is few 100 years



Reverberation starts energization

What makes for more high-E particles?

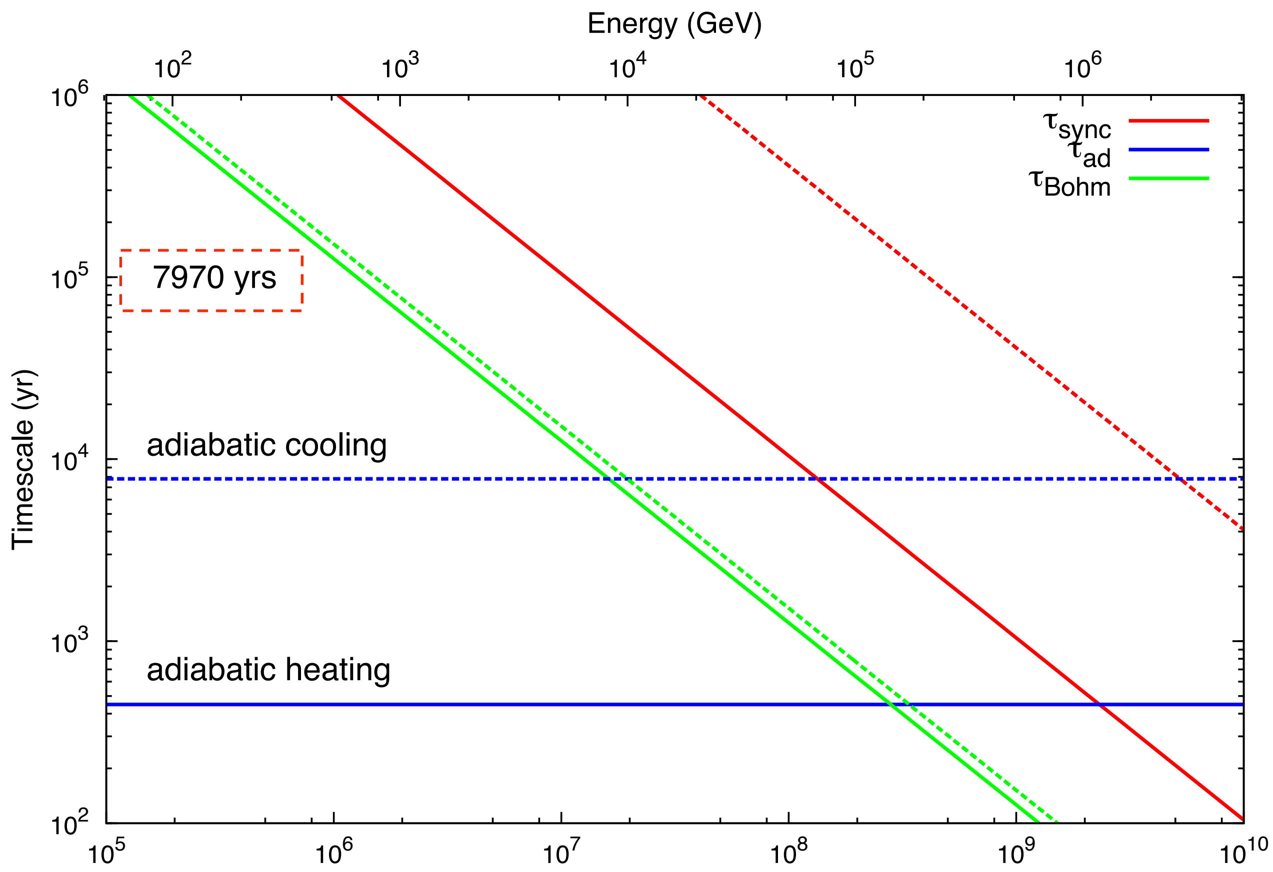
The reverberation process transfers energy to particles via adiabatic heating, and its timescale is few 100 years



L_sd is small, so reveberation is fast

What makes for more high-E particles?

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



Reaching a timescale 10+ times less than the duration of the reverberation process as a whole.

Such a high-dominance of the heating over the losses can only happen in pulsars of low spin down. Like a magnetar.

Higer L_{sd} pulsars don't allow for a reverberation process so fast. And usually, synchrotron losses dominate.

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
  - The nebula would not appear otherwise!
- We should forget about the spin-down (and related) parameters as markers of the PWN detectability, you need much more…
- The model explains why it is natural to 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)

Extra slides

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.

Reverberation process in pulsars of low spin-down

- Reverberation is more extreme in pulsars of low spin-down than in more energetic pulsars
- It is faster because there is less supporting pressure
- One is forced to take reverberation into account
    - Results with or without this effect being considered differ by several orders of magnitude
- The timescale for heating particles dominates any other timescale for losses along the reverberation process
- We can (and will, someday) see super-efficient nebulae in X-rays (i.e. nebula whose X-ray power exceeds the spin-down reservoir)*

**Subject of my next paper in the topic*

Extra slides

Other approaches: Tong (2016) [no spectral fitting]

- "Lsd is not enough to power the particle luminosity: if a small portion of the particle energy is converted to non-thermal X-rays, the particle luminosity of Swift J1834.9-0846 should be $>10^{35}$ erg s^{-1}, and is not."

- True **only** if there is no accumulation of electrons along the lifetime of the pulsar.
  - If there is, one can have an instantaneous income of electrons always limited by the spin-down power at the time of the injection, but many years for accumulating such electrons.

- The X-ray emission we see today should not be directly compared with the electron population injected today but by the burning of the accumulated pairs.

- Other issues: size considered is 3x smaller than measured, B, P are both very large (resulting from approximations), even larger than Crab's

Other approaches: Granot et al (2016) [no spectral fitting]

- ”..powered predominantly by outflows from the magnetar, whose main energy source is said to be the decay of the internal magnetic field.”
  - But "The conversion mechanism of this internal field into accelerated particles in a wind is not understood."

- Similarities: comparable B, η, R, and acceleration constraints (although we track all of this along the time evolution).

- Differences: much larger age (assuming a relation with W41, not proven, and need the magnetar velocity to be at most a few 10 km s^{-1}).

- The approaches to deal with reverberation… ours is relying in a direct, numerical solution of the dynamical set of equations.

- Granot et al do not include diffusion losses along most of their analysis. Without the latter, Sync losses dominate at high enough energies.

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,

- The emission is 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

Other approaches: Granot et al (2016) [no spectral fitting]

- Other smaller differences:

- We do not make any radiative approximations in our estimates of synchrotron emission, nor on the determination of B(t), nor on the dynamical evolution, nor on the detailed balance (which for us is searched by a numerical solution of the full diffusion-loss equation). The concurrency of the impact of all of these approximations is hard to track.