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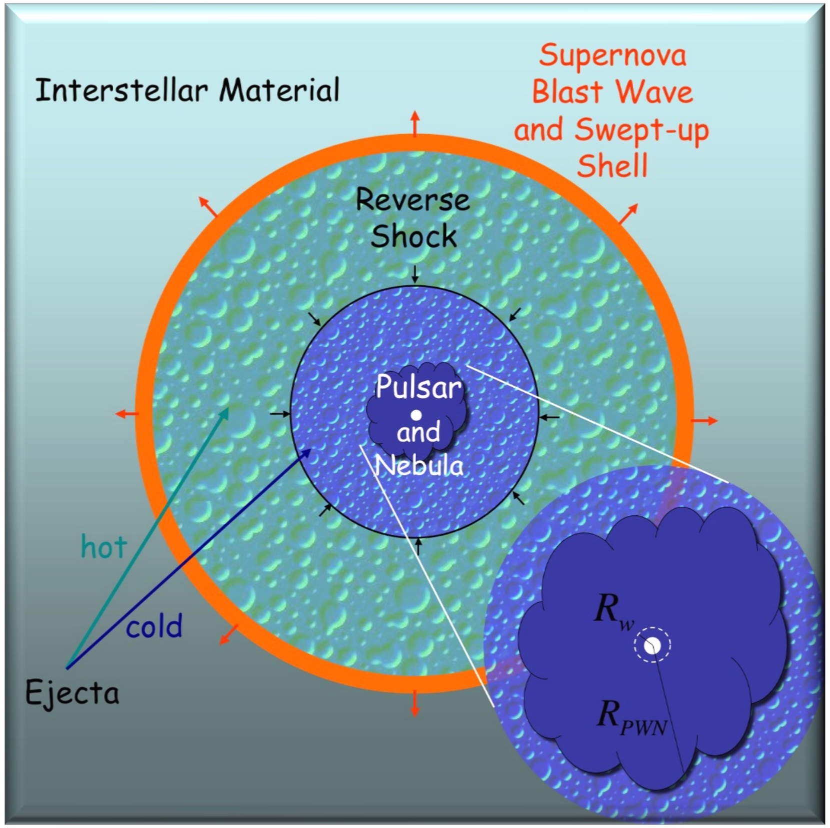
ICREA

Pulsar wind nebulae beyond reverberation

Diego F. Torres
with R. Bandiera, N. Bucciantini, B. Olmi

PWNe in the context of SNRs: the basic idea



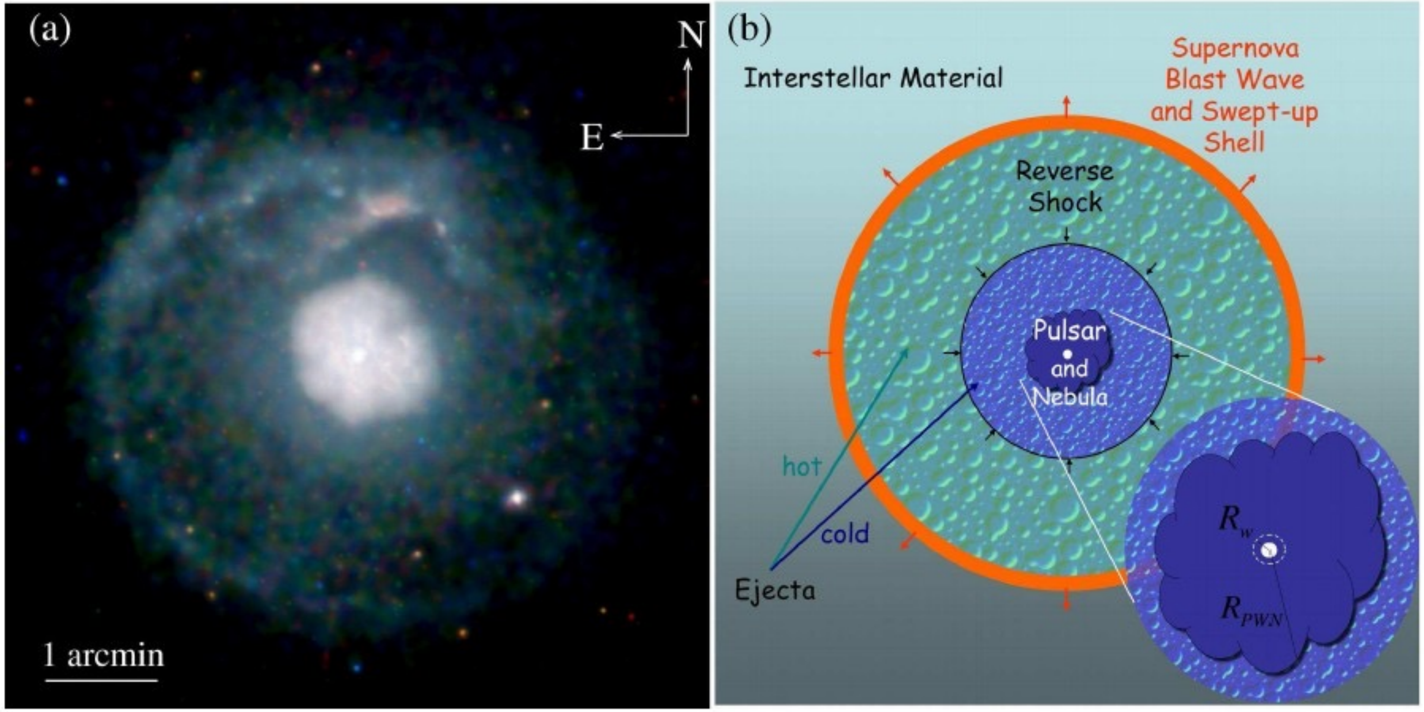
Plot from Gaensler & Slane 2006

- The pulsar wind sweeps up the ejecta; the shock decelerates the flow & accelerates particles; and a PWN forms

- PWN: hot bubbles (a.k.a., plerions) of particles and magnetic field, emitting non-thermal radiation (via synchrotron – inverse Compton) from radio to TeV γ-rays

- The Supernova Remnant sweeps up the ISM; and a reverse shock heats the ejecta; and for older PWN, ultimately compresses it

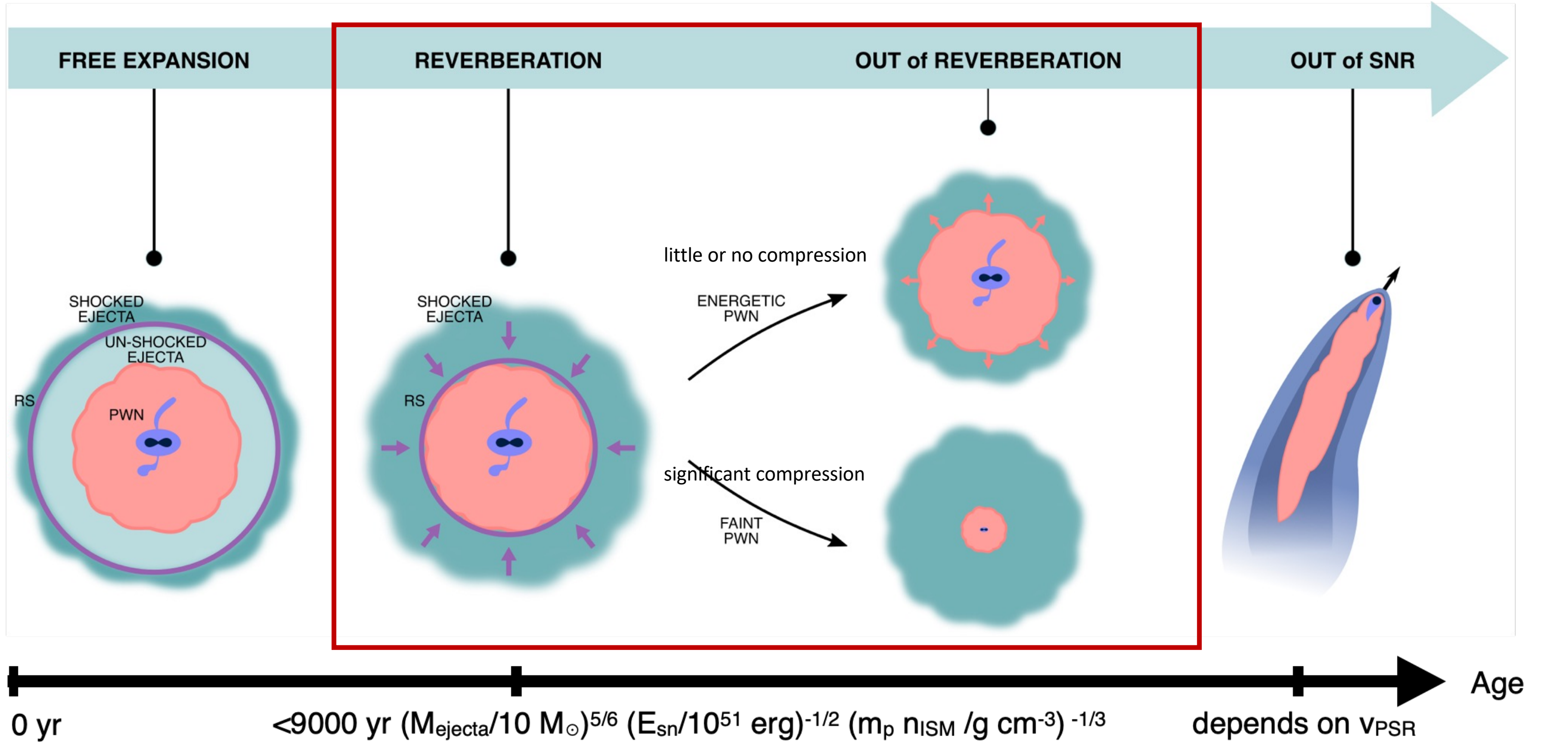
This simple concept works well for some PWN



Plot from Gaensler & Slane 2006 + observations of G21.5-0.9 with Chandra

A young PWN in an isotropic environment

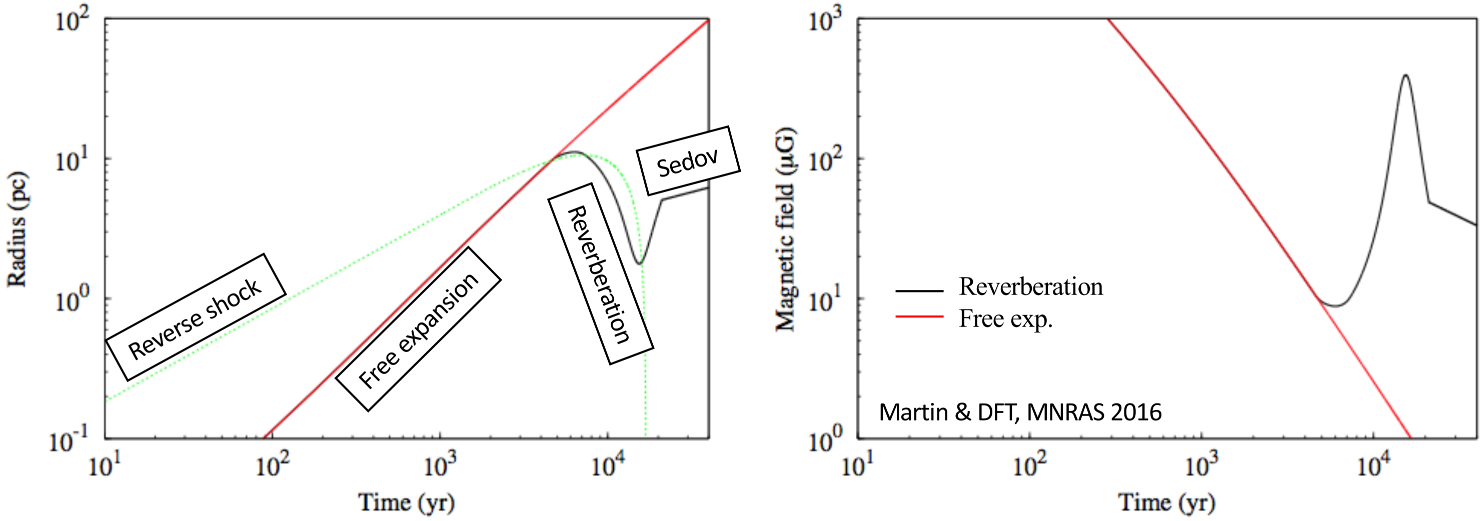
Reverberation phase, the great unknown



Plot from Olmi & Bucciantini 2023

Free expansion proceeds until the PWN reaches the reverse shock (RS). After that time, the shell experiences a strong deceleration, which in many cases leads to a compression of the PWN. Only when due to compression the PWN internal pressure becomes high enough, the PWN bounces and re-expands again. Reverberation (compression-bounce) last for a few kyrs or less

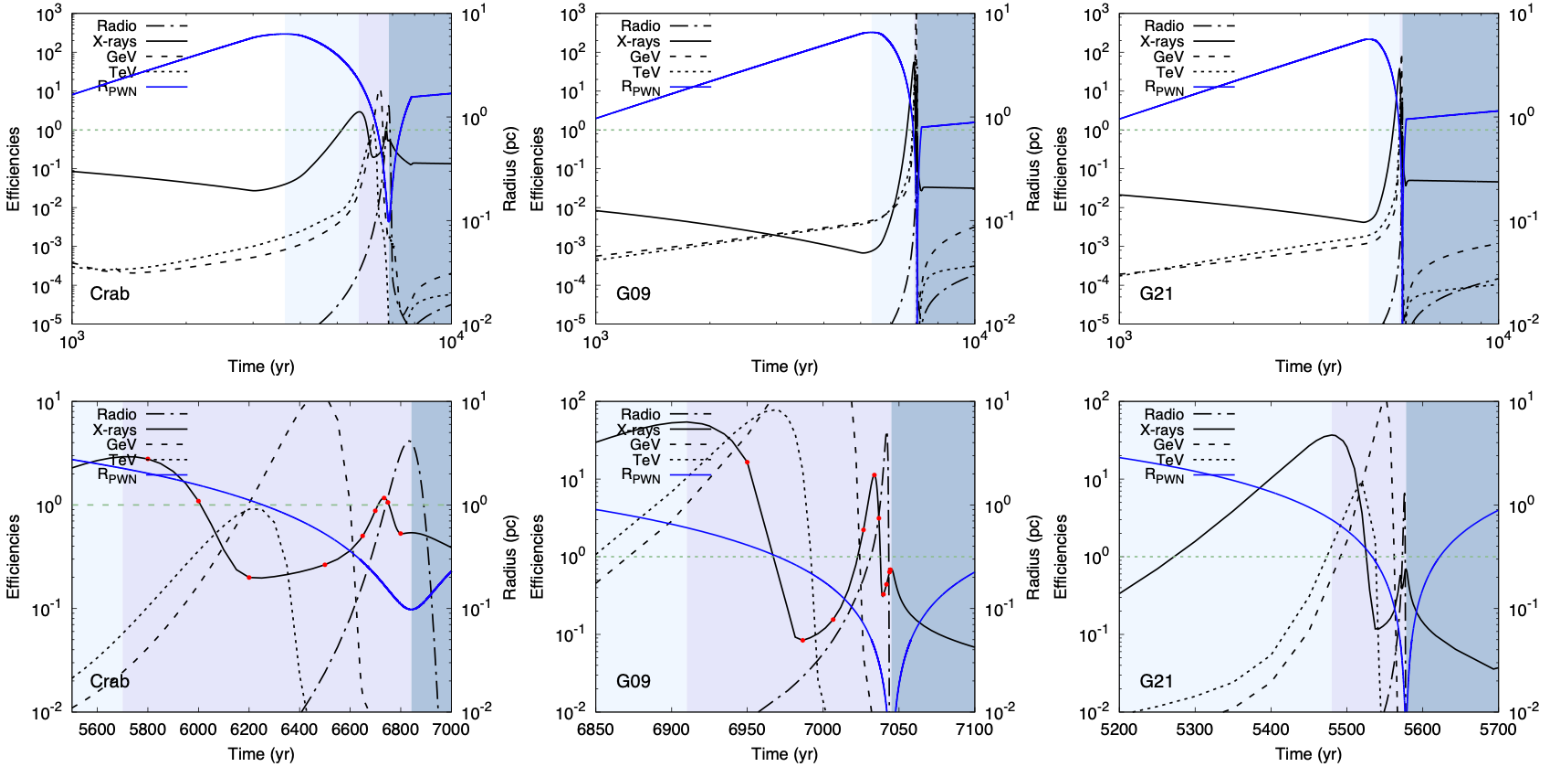
Why do we care? Reverberation may produce a significant re-distribution of particle energies



Martin & DFT, MNRAS 2016

- During reverberation the energy reservoir is no longer the pulsar spin-down power
- The environment may be giving energy to the nebula due to its compression
- Such compression will significantly increase the magnetic field, and thus the losses of particles.
- The particle population is drastically changed, or burnt, with their energies reshuffled.
- PWN could be super-efficient: e.g., $L_x > L_{sd}$ at the time

Now, why do we care? Reverberation may produce a significant re-distribution of particle energies



DFT & Lin, ApJ 2018

See discussion also in

DFT, ApJ 2017
DFT, Lin & Coti-Zelati MNRAS 2019

At the maximum compression the emitted luminosity may exceeds L_{PSR} at all frequencies.

Periods of super-efficiency may be possible, and even common (although short).

Even in the cases of no super-efficiency, all models and population studies beyond reverberation will be severely affected: the population features of middle-age PWN depend on understanding reverberation.

Comparing 1D-HD (no radiation) with radiative models: up to x20 differences in compression factors

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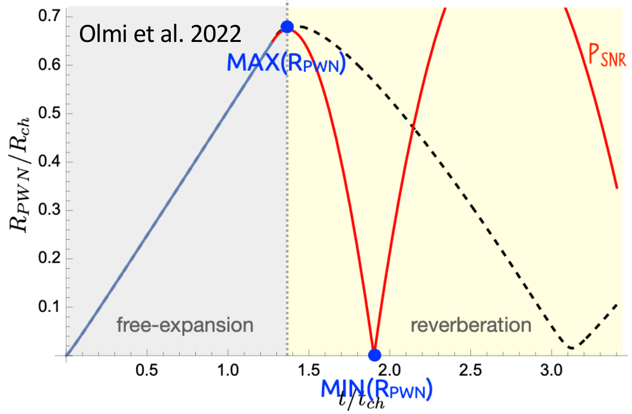
Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023a

Comparison between a 1-zone model and a 1D HD simulation



CF=MAX(R_PWN)/MIN(R_PWN)

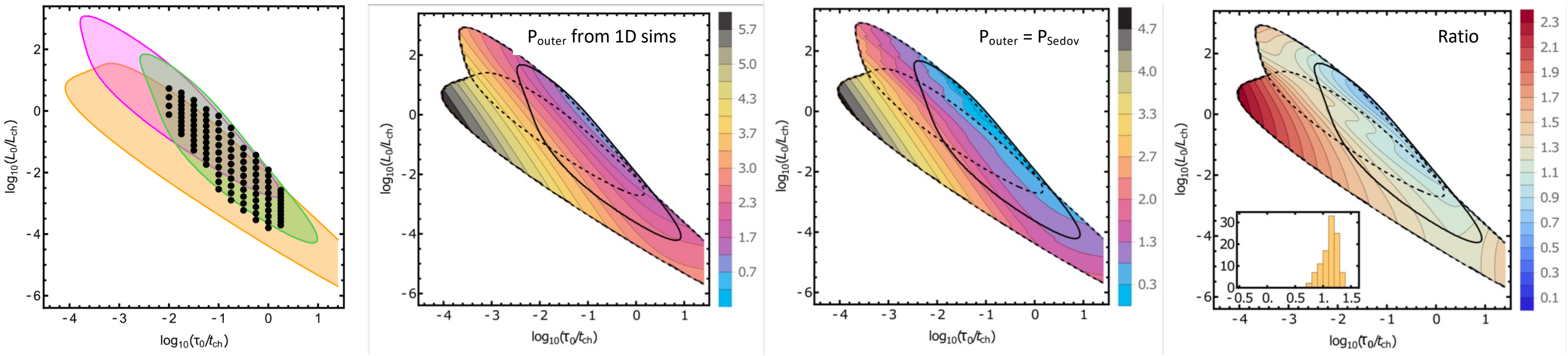
Rad. Model
P_SNR ~ P_Sedov – 0.67/0.0007~960

1D –HD Model
(no radiation) – 0.67/0.015~45

factor 20 difference!

Simplified pressure structure beyond the RS (constant); reduction in more complex descriptions?

But estimates accounting for the loss of internal pressure due radiative losses show that this can increase 5 to 10x for the least energetic cases.



$$
\begin{aligned}
R_{\rm ch} &= M_{\rm ej}^{1/3}\rho_0^{-1/3},\\
t_{\rm ch} &= E_{\rm sn}^{-1/2}M_{\rm ej}^{5/6}\rho_0^{-1/3},\\
L_{\rm ch} &= E_{\rm sn}^{1/2}M_{\rm ej}^{-5/6}\rho_0^{1/3} = E_{\rm sn}/t_{\rm ch},
\end{aligned}
$$

PWN 1-zone-models: literature either ignores reverberation at all, or treats it in simplified ways

In the latter case, there are 3 main assumptions:

1. The PWN is a **uniform** (one-zone) bubble of particles and field
2. The shell at the PWN boundary is **thin** ($R_{\rm shell} \sim R_{\rm pwn}$; $\Delta R_{\rm shell} << R_{\rm pwn}$)
3. The **pressure outside** the PWN is **equal to or a constant fraction of** the pressure at the FS in the **Sedov** solution

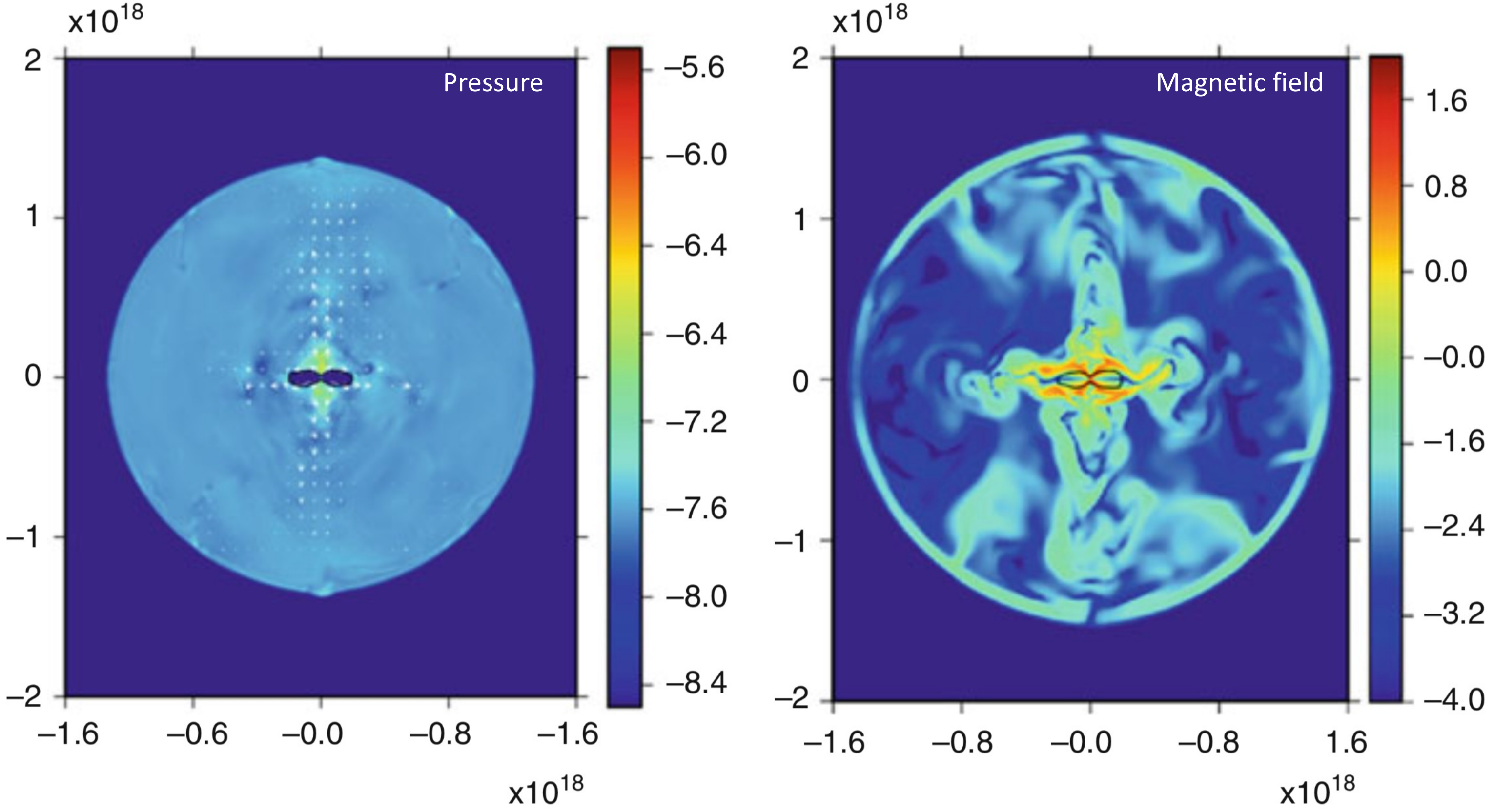
$$P_{\rm Sedov} = 0.1592 \left(\frac{t}{t_{\rm ch}}\right)^{-6/5} \frac{\rho_{\rm ISM} E_{\rm sn}}{M_{\rm ej}}$$

[Gelfand et al. 2009 - Fang & Zhang 2010 - Tanaka & Takahara 2010 - Martin et al. 2012 - Tanaka & Takahara 2013 - Vorster et al. 2013 - Torres et al. 2013-2014- 2017-2018-2019 - Gelfand et a. 2015-2017 - Bandiera et al. 2021 - Fiori et al. 2022]

First assumption… roughly ok, according to 3D MHD models

Porth et al. 2014
Crab @ 50 years

See also
Olmi et al. 2019



The PWN is a rather uniform (one-zone) bubble of particles and field.

Second and third assumption, too simplistic

equations for the evolution:

1. conservation of shell mass

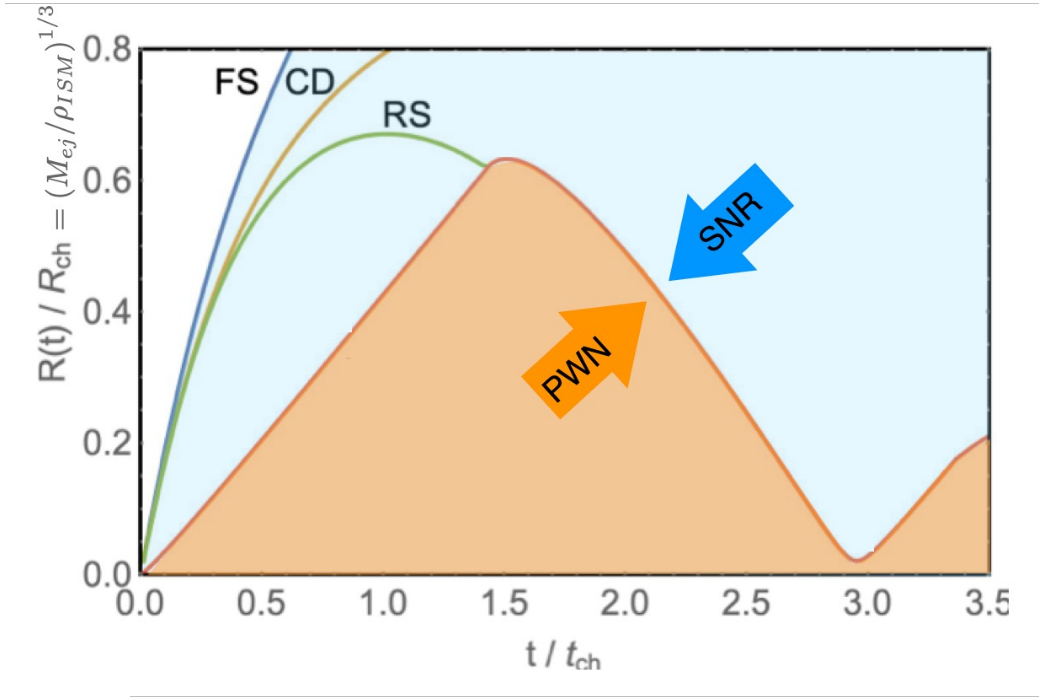
$$\frac{dM(t)}{dt} = 4\pi R^2 \rho_{\rm ej}(R,t)\left[\frac{dR}{dt} - v_{\rm ej}(R,t)\right]$$

2. conservation of shell momentum

$$\frac{\mathrm{d}\left(M_{\rm sh}(t)\dot{R}_{\rm sh}(t)\right)}{\mathrm{d}t} = 4\pi P_{\rm pwn}(t)\, R^2_{\rm sh}(t) + \frac{\mathrm{dM_{sh}(t)}}{\mathrm{dt}}\,\frac{R_{\rm sh}(t)}{t}$$

3. evolution of internal energy

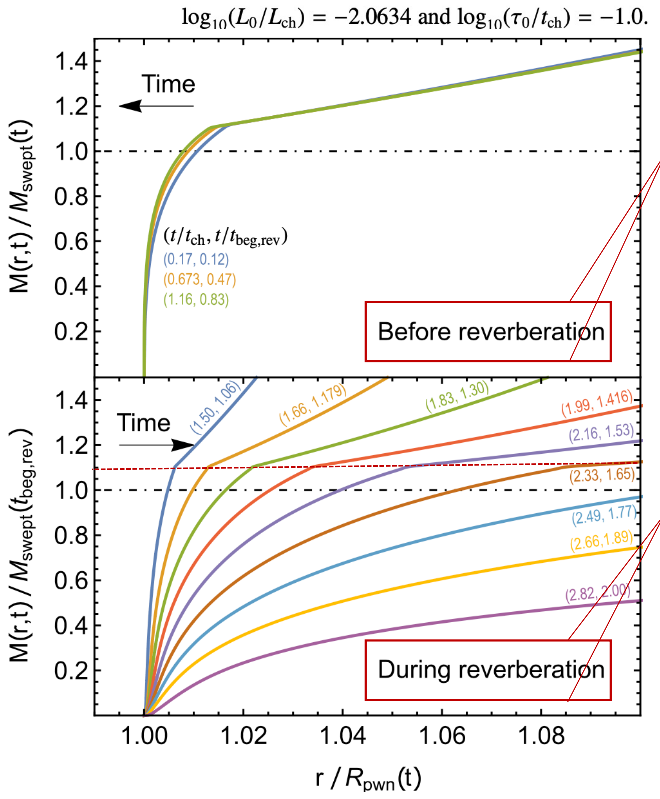
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(4\pi R_{\rm sh}(t)^3 P_{\rm pwn}(t)\right) = L_{\rm psr}(t) - 4\pi R_{\rm sh}(t)^2 \dot{R}_{\rm sh}(t) P_{\rm pwn}(t) - J(t)$$



The evolution is determined by the balance between internal (PWN) and outer (SNR) pressure. And it is very sensitive to it.

The thin-shell… well… is not always thin

Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023a



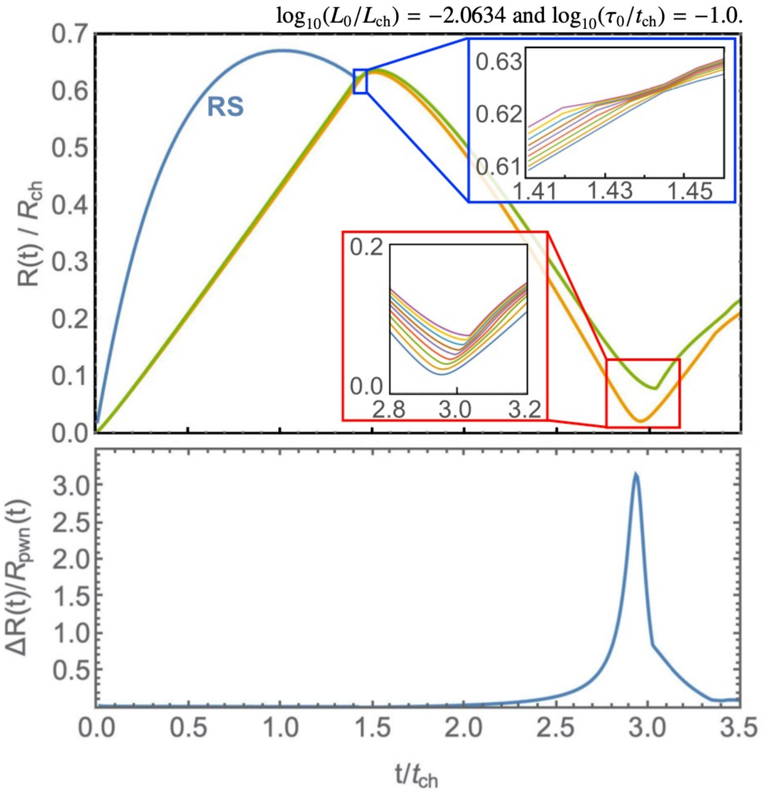
- For a scaled radius ranging between 1 and about 1.02, the profiles are related to the density profile inside the shell.
- They are superimposed, meaning that the density preserves its profile, apart from a slight decrease with time of the shell relative width.
- The sharp break in the profiles (reflecting a density jump) indicates the position of the shock at the outer boundary of the shell;
- The scaled mass slightly higher than unity means that the real swept-up mass is that within the outer boundary of the shell, rather than within $R_{pwn}(t)$.

- After $t_{beg,rev}$ the mass within the shell, now scaled with the swept-up mass at $t_{beg,rev}$, does not change with time, as it can be inferred from the constancy of the vertical coordinate of the break
- The relative width of the shell increases with time, partly reflecting its physical broadening, and partly as a consequence of a decreasing of its size.

This figure justifies the assumption of a fixed shell mass during reverberation and that when the PWN has been compressed, the needed conditions for treating the shell as a thin-shell may no longer be valid.

The thin-shell… well… is not always thin

Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023a



For $t < t_{beg,rev}$ the shell boundaries are very close each other, meaning that the thin-shell approximation is well satisfied.

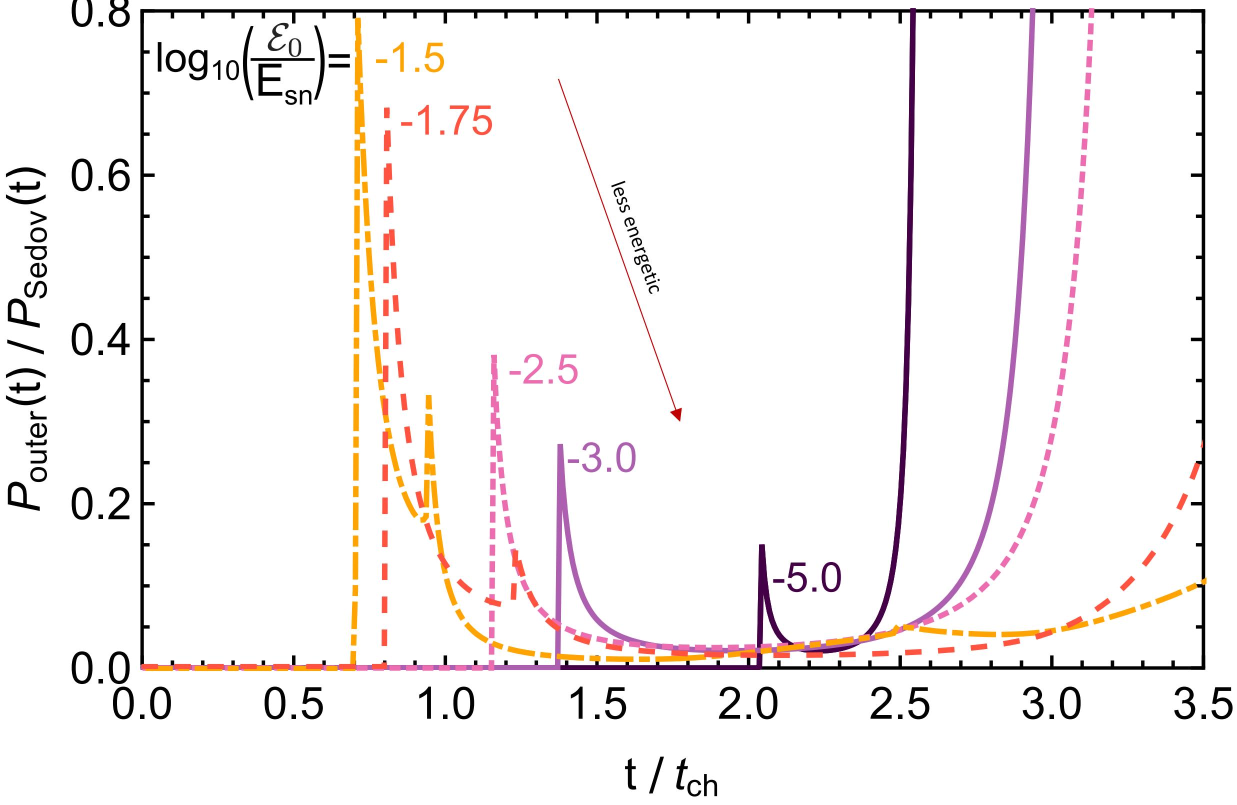
But especially close to the maximum compression, the shell boundaries separate, and the combination of a higher shell thickness and a smaller shell size implies that a thin-shell approach is no longer justified.

During the reverberation phase, the outer edge of the shell is defined by the mass collected before $t_{beg,rev}$ and one may clearly see that the shell becomes thicker, and as the PWN starts to contract the shell inflates progressively

The outer pressure…well… is not constant

Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023a

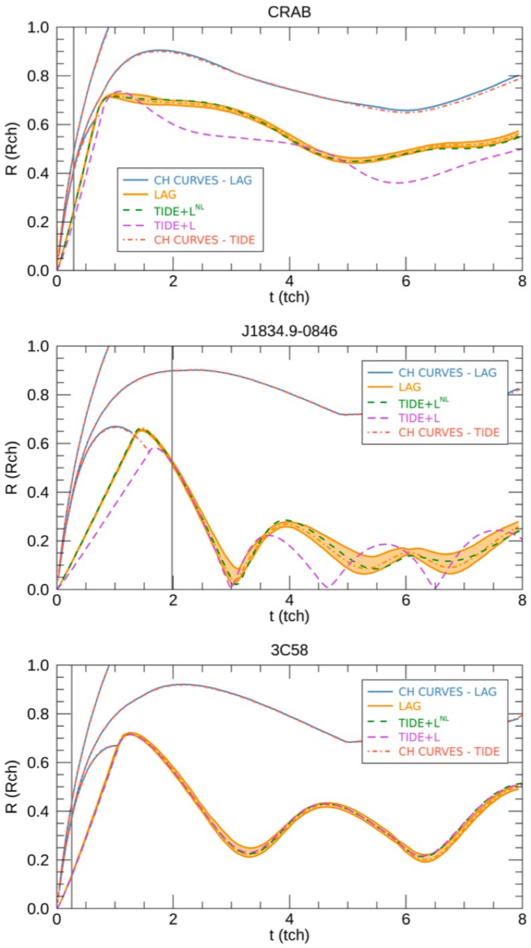
$\varepsilon_0 = L_0\,\tau_0$ is the PWN energetics



For a large part of the evolution P_{outer} is smaller than the Sedov pressure, and is different from a constant.

How to model middle age systems? Radius

Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023b



TIDE+L:

Hybrid radiative – HD model

- Radiative model until reverberation, with dynamics incoporated
  - then use this stage just before reveberation as input for a...
- Lagrangian model thereafter, with radiation incorporated

Correctly converges to the Lagrangian model all along when no losses are considered.
Correctly matches at the interface between the two approaches.

How to model middle age systems? Spectra

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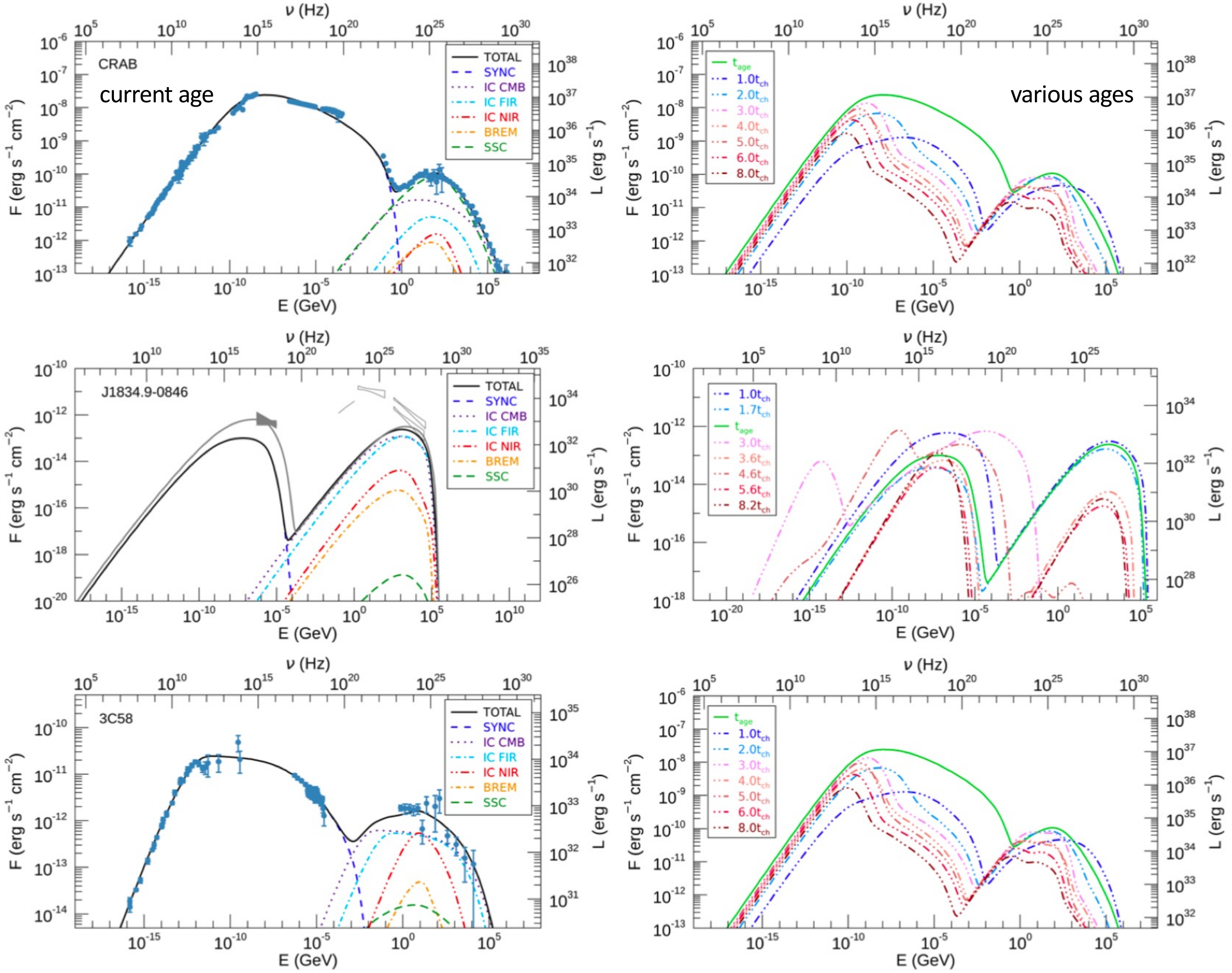
Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023b



- Significant spectral variability as time goes by confirmed.

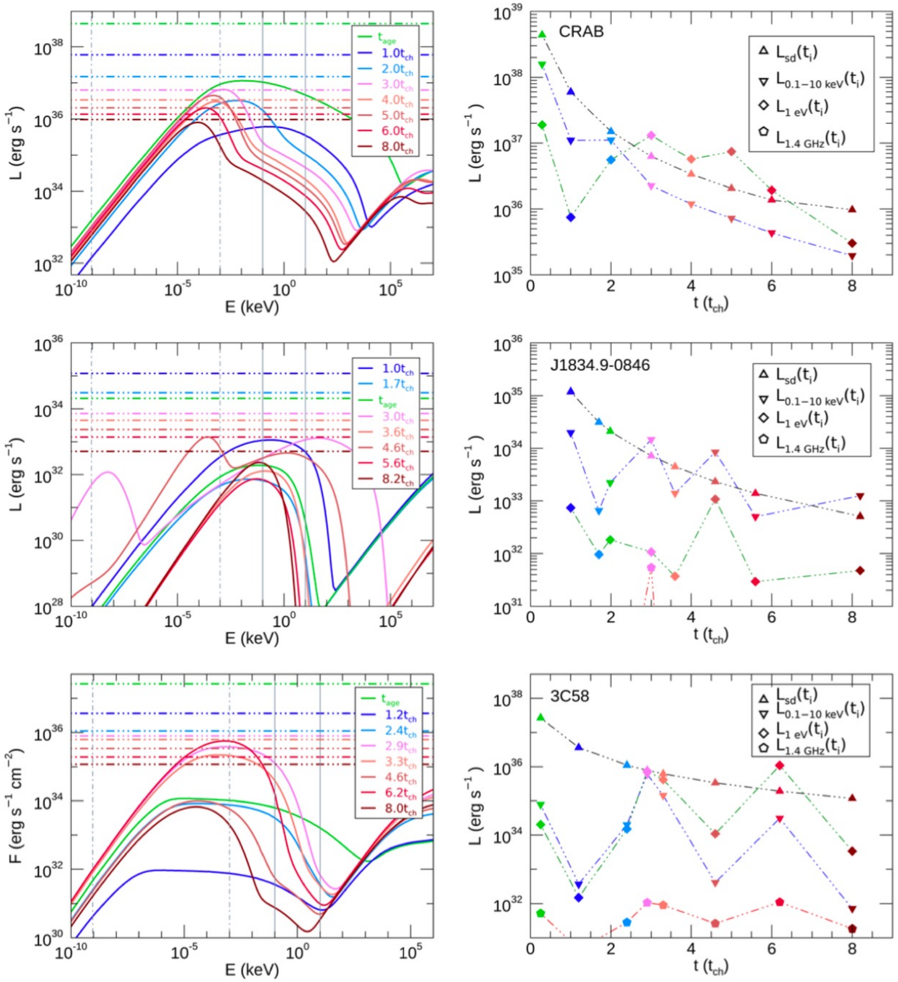
To be studied in detail both for particular cases and population analysis.

Table 2. CFs and related quantities as obtained, for the different sources considered in this work, with the pure lagrangian approach and the two versions of TIDE+L (the non radiative one indicated with TIDE+L^{NL}).

System	Code	$t_{beg,rev}$ [t_{ch}]	R^{MIN}_{pwn} [R_{ch}]	R^{MAX}_{pwn} [R_{ch}]	CF
CRAB	LAG	0.6852	0.4414	0.6385	1.447
	LAG(bary)	·	0.4499	0.7205	1.602
	TIDE+L^{NL}	0.6408	0.4489	0.7153	1.593
	TIDE+L	0.6633	0.3595	0.7357	2.047
J1834.9–0846	LAG	1.323	0.0198	0.6196	31.29
	LAG(bary)	·	0.0368	0.6629	18.01
	TIDE+L^{NL}	1.315	0.0205	0.6592	32.16
	TIDE+L	1.339	0.0024	0.5819	242.5
3C58	LAG	1.082	0.1915	0.6837	3.570
	LAG(bary)	·	0.2009	0.7232	3.600
	TIDE+L^{NL}	1.054	0.2128	0.7154	3.362
	TIDE+L	1.062	0.2161	0.7143	3.305

How to model middle age systems? Spectra

Bandiera, Bucciantini, Martin, Olmi & DFT, MNRAS 2023b



- Superefficient phases seem common in the UV-optical bands
- Superefficiency in X-rays appears for extremely compressive systems

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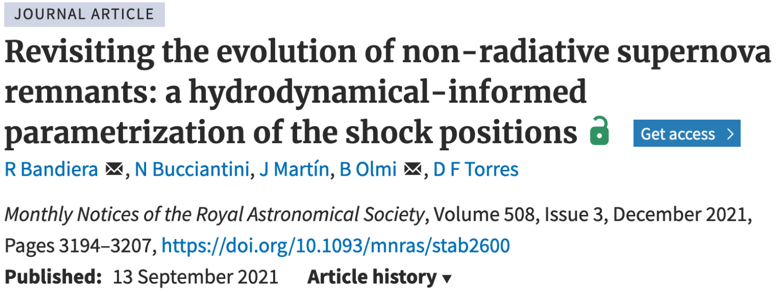

JOURNAL ARTICLE

Revisiting the evolution of non-radiative supernova remnants: a hydrodynamical-informed parametrization of the shock positions Get access ›

R Bandiera ✉, N Bucciantini, J Martín, B Olmi ✉, D F Torres

Monthly Notices of the Royal Astronomical Society, Volume 508, Issue 3, December 2021, Pages 3194–3207, https://doi.org/10.1093/mnras/stab2600

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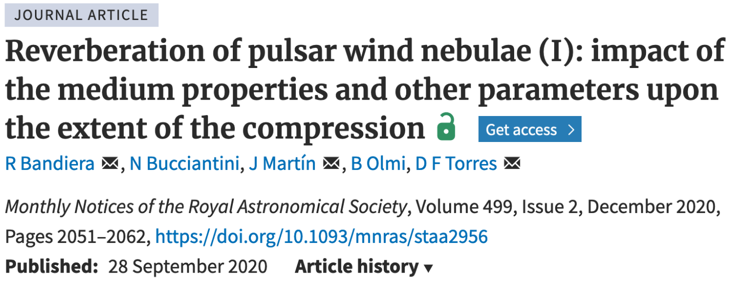

JOURNAL ARTICLE

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R Bandiera ✉, N Bucciantini, J Martín ✉, B Olmi, D F Torres ✉

Monthly Notices of the Royal Astronomical Society, Volume 499, Issue 2, December 2020, Pages 2051–2062, https://doi.org/10.1093/mnras/staa2956

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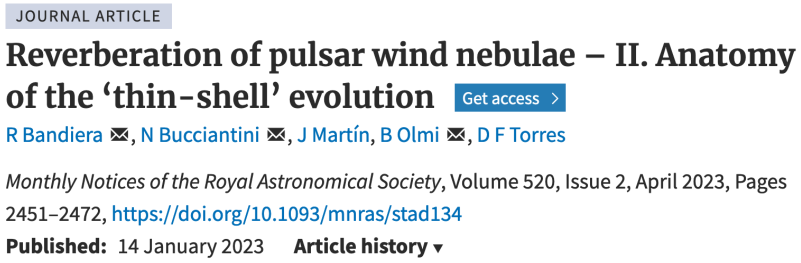

JOURNAL ARTICLE

Reverberation of pulsar wind nebulae – II. Anatomy of the 'thin-shell' evolution Get access ›

R Bandiera ✉, N Bucciantini ✉, J Martín, B Olmi ✉, D F Torres

Monthly Notices of the Royal Astronomical Society, Volume 520, Issue 2, April 2023, Pages 2451–2472, https://doi.org/10.1093/mnras/stad134

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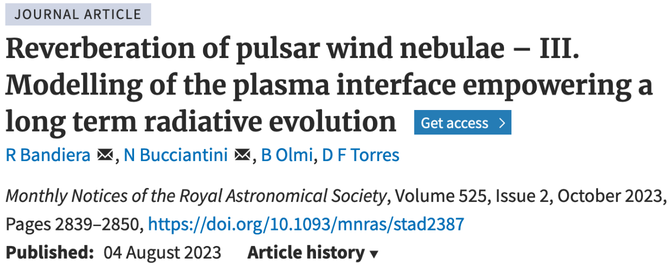

JOURNAL ARTICLE

Reverberation of pulsar wind nebulae – III. Modelling of the plasma interface empowering a long term radiative evolution Get access ›

R Bandiera ✉, N Bucciantini ✉, B Olmi, D F Torres

Monthly Notices of the Royal Astronomical Society, Volume 525, Issue 2, October 2023, Pages 2839–2850, https://doi.org/10.1093/mnras/stad2387

Published: 04 August 2023 **Article history** ▾

Conclusions

- Mixed one-zone/HD models solve the problems introduced by the pure thin-shell approximation in the treatment of the reverberation phase: they catch the global behavior and do not overestimate the PWN compression

- First relatively consistent numerical passage through reverberation for a radiative/HD model
  - Joins the best of both worlds!

- PWNe can reduce themselves in size by more than two orders of magnitude, at least in the 1D representation.

- Systems with large compression CF $\gg$ 100 are possible but rare, limited to the extremes of the known population of PWNe.

- As a result, superefficiency appears often at UV/optical, and less often in X-rays

- Understanding and correctly modelling reverberation is critical for population studies (e.g., how many PWN will we see in future surveys at different frequencies) and individual predictions / description of all middle-age systems

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