Linking supernovae and supernova remnants
Time-dependent injection in SN1987A and γ-ray spectrum of IC443

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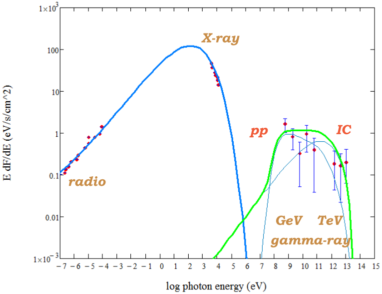
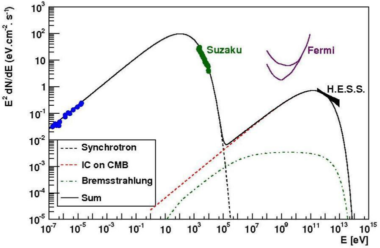
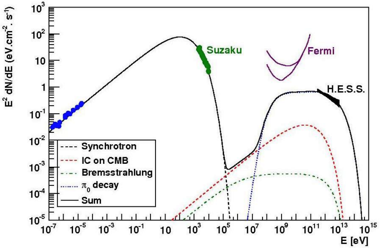
"SN 1987A, 30 years later" (20-24 February 2017, La Reunion Island)

- 294 known Galactic SNRs (Green 2014)
  - radio from accelerated electrons
- X-rays: 100+ SNRs
  - mostly the thermal emission



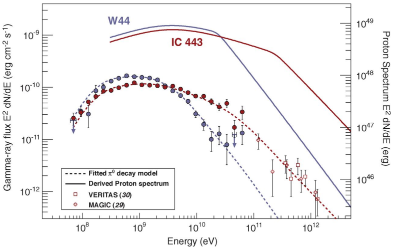
- X-rays nonthermal: 30+ SNRs (since 1995)
  - synchrotron from accelerated electrons
- GeV γ-rays: 20+ SNRs (since 2009)
  - from accelerated electrons or/and protons
- TeV γ-rays: 20+ SNRs (since 2004)
  - from accelerated electrons or/and protons



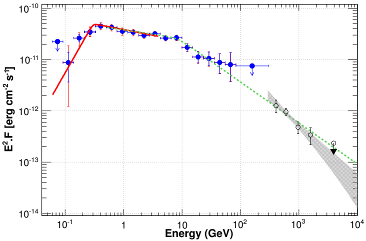


SN1006 (HESS Collaboration 2010)

- There are manifestations of accelerated electrons in SNRs
- The only way "to see" protons in the accelerator is the pion-decay γ-rays
- In many SNRs, γ-rays spectrum may be fitted as being from e or p
- **The problem**: to find SNR with a sign of accelerated protons
- **The question**: what kind of particles emit γ-rays in a given SNR?



(Ackermann et al. 2013)



W49B (Abdalla et al. 2016)

Essential properties of the γ-ray emission from protons

- Low-energy cutoff: γ-ray flux decreases below $E_\gamma \sim 300$ MeV
- There are 4 SNRs with such a cutoff: IC443, W44 (Ackermann et al. 2013); W51C (Jogler & Funk 2016); W49B (Abdalla et al. 2016)
- All these SNRs have also a spectral break around $E_\gamma \sim 30 - 90$ GeV
- Models for this break (e.g. Uchiyama et al. 2010; Cardillo et al. 2016) as well as for the particle spectrum assumes the stationary acceleration

Is acceleration in SNRs in the steady-state regime?

Time-dependent acceleration of cosmic rays

Non-stationary equation of the diffusive shock acceleration

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + Q \qquad (1)$$

Injection term

$$Q(t,x,p) = \frac{\eta n_1 u_1}{4\pi p_{\rm i}^2}\delta(p-p_{\rm i})\delta(x)Q_{\rm t}(t), \qquad (2)$$

Solution of equation (Forman & Drury 1983, Petruk & Kopytko 2016)

$$f_{\rm o}(t,p) = {\rm f}_{\rm o}(p)\int\limits_0^{\tau} Q_{\rm t}(\tau-\tau')\varphi_{\rm o}(\tau')d\tau'. \qquad (3)$$

where

$${\rm f}_{\rm o}(p) = \frac{\eta n_1}{4\pi p_{\rm i}^3}\frac{3\sigma}{\sigma-1}\left(\frac{p}{p_{\rm i}}\right)^{-s_{\rm f}}, \quad s_{\rm f} = 3\sigma/(\sigma-1) \qquad (4)$$

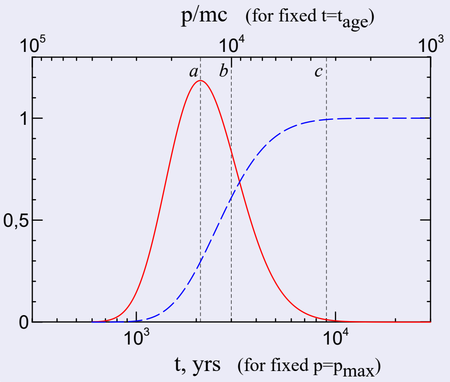
is the solution of the stationary equation, $\varphi_{\rm o}(\tau)$ a known function.

Time-dependent acceleration of cosmic rays

$$f_{\rm o}(t,p) = {\rm f}_{\rm o}(p) \int_0^{\tau} Q_{\rm t}(\tau-\tau')\varphi_{\rm o}(\tau')d\tau'$$

$\varphi_{\rm o}\big(\tau(t,p)\big)$ is the 2D probability distribution: $\mathcal{P}\big((p_{\rm i},t_{\rm i}) \to (p,t)\big)$

Probability $\varphi_{\rm o}$ (red line) and the integral (blue line): the case of IC443



– Most particles (a) are accelerated to $p_{\rm max}$ at $t < t_{\rm age}$

– The time-scale for steady acceleration (c) to $p_{\rm max}$ **is larger** than a SNR age (b).

[the plot is for $Q_{\rm t} = 1$]

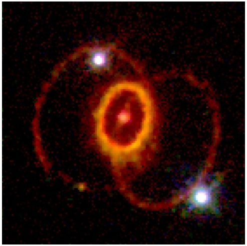
How to model the non-stationary spectra?

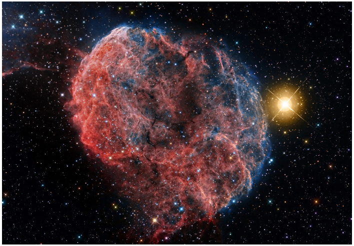
Our idea: to link an SN and an SNR

$$f_{\rm o}(t,p) = {\rm f_o}(p) \int_0^{\tau} Q_{\rm t}(\tau - \tau')\varphi_{\rm o}(\tau')d\tau'$$

1. We use the time-dependent solution to explain the time variation of the radio index $\alpha_{\rm r}$ in SN987A.
   The fit of the observed $\alpha_{\rm r}(t)$ gives us the unknown function $Q_{\rm t}(t)$.
2. We use this $Q_{\rm t}(t)$ in the solution to calculate the spectrum of protons in IC443 and, then, their γ-ray emission.

We couple SN1987A and IC443: they both are of the same type II SN





Factors affecting the radio index α_{r}

- **TP stationary equation**: *the shock compression*

$$\alpha_{\mathrm{r}} = -\frac{3}{2} + \frac{1}{2} \cdot \frac{3\sigma}{\sigma - 1}$$

- **NLA stationary equation**: *the modified shock compression*

$$\alpha_{\mathrm{r}} = -\frac{3}{2} + \frac{1}{2} \cdot \frac{3\sigma(p)}{\sigma(p) - 1} \left(1 + \frac{1}{3} \frac{d \ln \sigma(p)}{d \ln p}\right)$$

- **TP time-dependent equation**: *the time-dependence of injection*

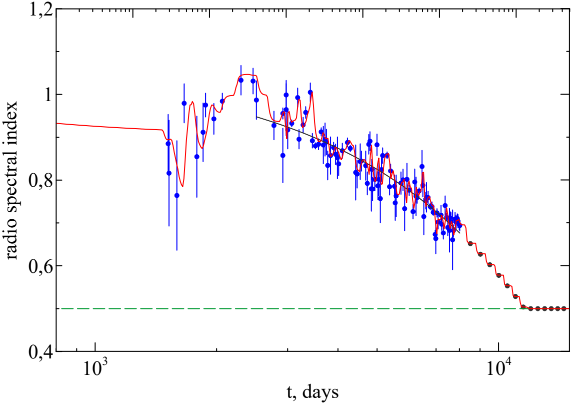
$$\alpha_{\mathrm{r}} = -\frac{3}{2} + \frac{1}{2} \cdot \left(\frac{3\sigma}{\sigma - 1} - \frac{d \ln}{d \ln p} \int_0^{\tau} Q_{\mathrm{t}}(\tau - \tau') \varphi_{\mathrm{o}}(\tau') d\tau'\right)$$

In particular, if $Q_{\mathrm{t}} \propto t^{\beta}$ and $D \propto p^{\alpha}$ then

$$\alpha_{\mathrm{r}} = -\frac{3}{2} + \frac{1}{2} \cdot \left(\frac{3\sigma}{\sigma - 1} + \alpha\beta\right)$$

It is much simpler to model the radio index evolution than the radio flux.

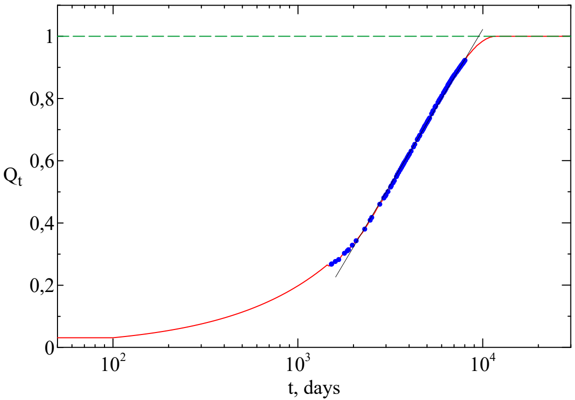
Time evolution of the radio index in SN1987A



Radio index as from Zanardo et al. (2010), during 1517 - 8014 days (filled circles with errors). Black circles are extrapolation of the linear fit (black line; from the same reference) up to the value $\alpha_r = 0.5$; then α_r is constant.

Red solid line represents the spectral index calculated with the adopted function $Q_t(t)$ (it is approximately $f_o(t,p) \propto p^{-3\sigma/(\sigma-1)} \cdot p^{-\beta(t)}$ for the radio emitting electrons). Green dashed line represents the case of the steady-state injection.

Time-dependence of the injection term $Q_{\rm t}(t)$

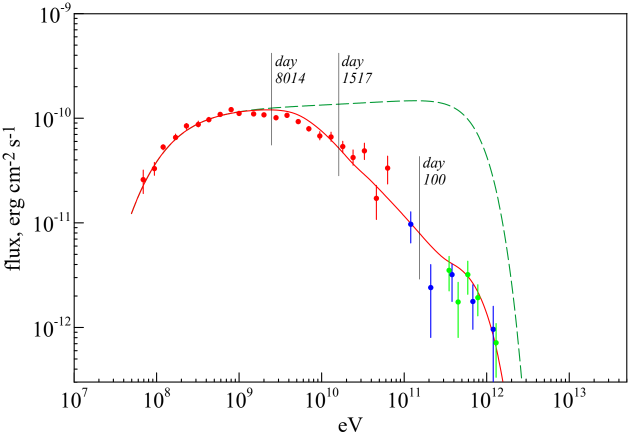


Time dependence of the injection term (red line). Blue circles correspond to the radio observations. We adopt a simple approximation $Q_{\rm t} \propto t^{-\beta}$ with $\beta = 0.8$ before the day 1517 and $Q_{\rm t} = \rm const$ before the day 100.

Black solid line is a function $Q_{\rm t} = \lg(t/950)$.

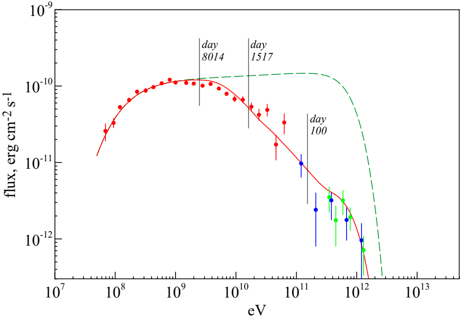
Green dashed line represents the case of the steady-state injection.

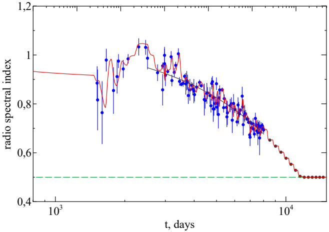
Gamma-ray spectrum of IC443

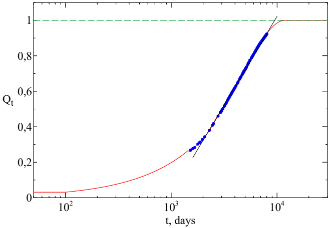


Gamma-ray spectrum of IC443: FERMI red (Ackermann+ 2013), MAGIC blue (Albert+ 2007), VERITAS green (Acciari+ 2009). Our fit is shown by the red line. The green line represents the case of the steady-state injection. $E_{\mathrm{p,max}} = 10$ TeV

Gamma-ray spectrum of IC443







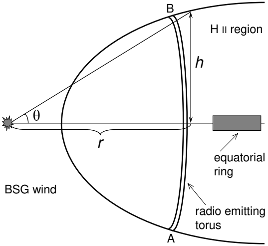
Conclusions...

...could be here but

there are two additional points to consider.

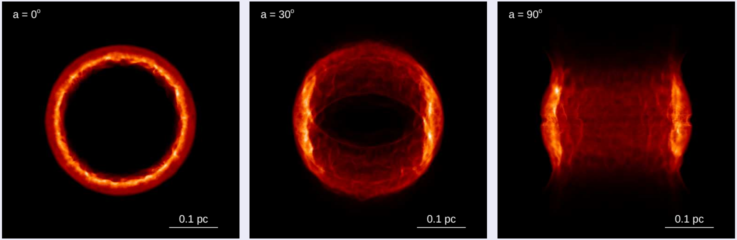
- What could be a reason for varying injection in SN1987A?
- Could SN1987A be visible in γ-rays?

What could be a reason for varying injection in SN1987A?



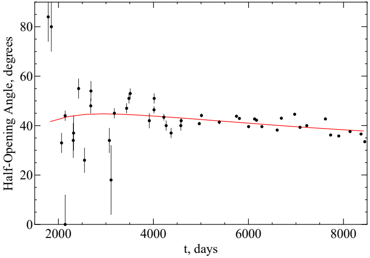
The structure of the ambient medium around SN1987A
(e.g. Potter+ 2014; Orlando+ 2015).
θ is the half-opening angle (Ng+ 2013).

Our 3-D model of SN1987A (Orlando+ 2015)



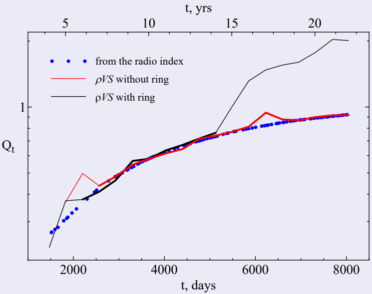
3D rendering of the density, at 15 years (around Day 5500).

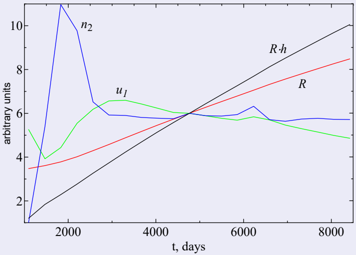
What could be a reason for varying injection in SN1987A?



Half-opening angle θ
– dots: the Fourier analysis of the radio observations (Ng+ 2013)
– red line: our 3-D model.

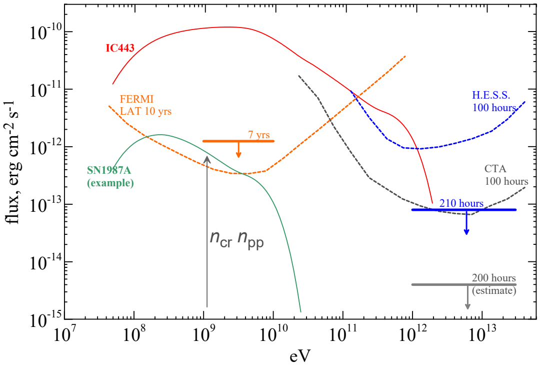
$Q_t \propto \rho \cdot V \cdot S$ – as from our 3-D model





Could SN1987A be visible in (hadronic) γ-rays?

If acceleration rate in SN1987A is the same as in IC443



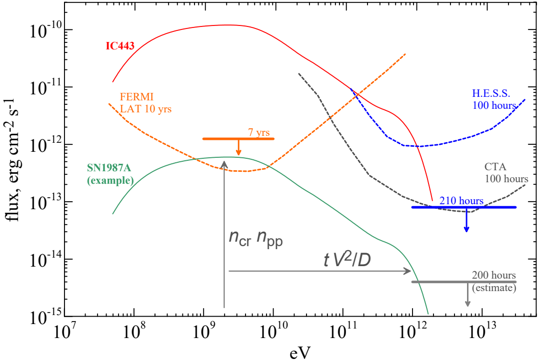
sensitivities:
Funk+ 2013
upper limits for SN1987A:
FERMI collabor. 2016
HESS collabor. 2015

- The amplitude is proportional to $n_{\rm cr} n_{\rm pp}$. No dense cloud to illuminate? An 'optimistic' value $n_{\rm Hii,sn1987a} \sim 0.03 \cdot n_{\rm mc,ic443}$ is used here.
- The age of SN1987A is $t_{\rm sn1987a} \sim 0.01 \cdot t_{\rm ic443}$

No chance to see hadronic TeV γ-rays from SN1987A,
even if FERMI detects it in the next few years.

Could SN1987A be visible in (hadronic) γ-rays?

However, what if acceleration is faster in SN1987A?



sensitivities:
Funk+ 2013
upper limits for SN1987A:
FERMI collabor. 2016
HESS collabor. 2015

$n_{\mathrm{Hii,sn1987a}} \sim 0.005 \cdot n_{\mathrm{pp,ic443}}$ is used here

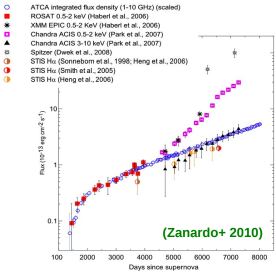
- Right-hand portion scales with $t/t_{\mathrm{acc}} \propto tV^2/D$
- There should be $\frac{t_{\mathrm{sn1987a}}}{t_{\mathrm{ic443}}} \frac{V^2_{\mathrm{sn1987a}}}{V^2_{\mathrm{ic443}}} \frac{D_{\mathrm{ic443}}}{D_{\mathrm{sn1987a}}} \geq 1.$ (smaller D, larger V)

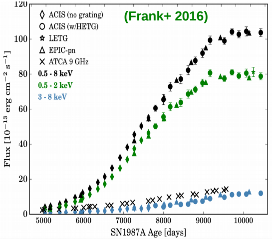
If FERMI detects SN1987A in few years and $t_{\mathrm{acc,sn1987a}} \leq 0.01 \cdot t_{\mathrm{acc,ic443}}$ then SN1997A should be visible to CTA.

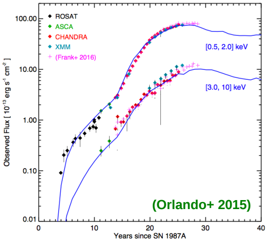
Conclusions

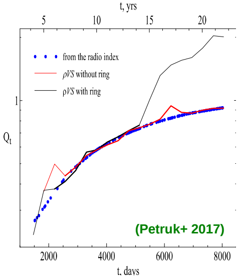
- The time-scale for the steady acceleration to $p_{\max}$ **is larger** than an SNR age.
- It is obligatory therefore to consider the **non-stationary** particle spectrum for models of the γ-**ray emission**.
- Variation of the injection during the **early times** after the SN explosion is critical for interpretation of the TeV γ-ray spectra of SNRs
- **Radio observations of SNe** may be used to track the injection behavior
- The main reason of the injection variation in SN is the **surface increase**
- In this approach, we successfully fitted the GeV-TeV γ-ray spectrum of IC443, using SN1987A as a proxy of the parent SN
- The **break** in the proton spectrum is a natural consequence of the time-dependent particle injection.

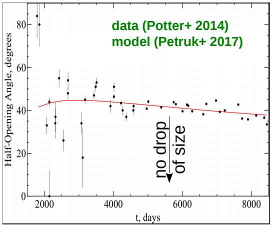
SN1987A: no radio flux from the ring?

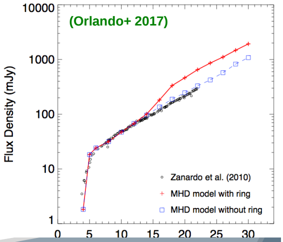


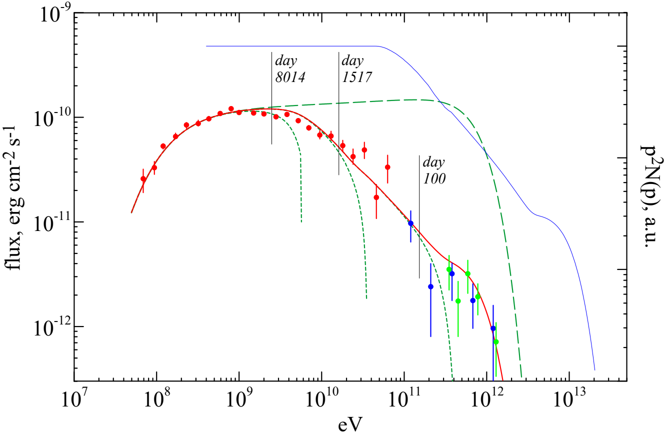












Gamma-ray spectrum of IC443 (FERMI red, MAGIC blue, VERITAS green), our fit (red line) and the energy distribution of the parental protons (blue line). The green dotted lines represent the spectra with $Q_t = 0$ before the day 100, before the day 1517 and before the day 8014.