Comparison of the expected and observed supernova remnant counts with Fermi/LAT

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Supernova remnants

Age

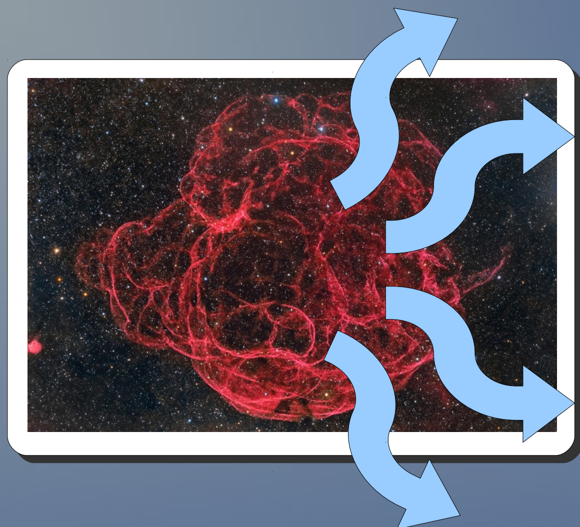
SN 1987A
Image Credit: Jason Pun (NOAO) and SINS Collaboration

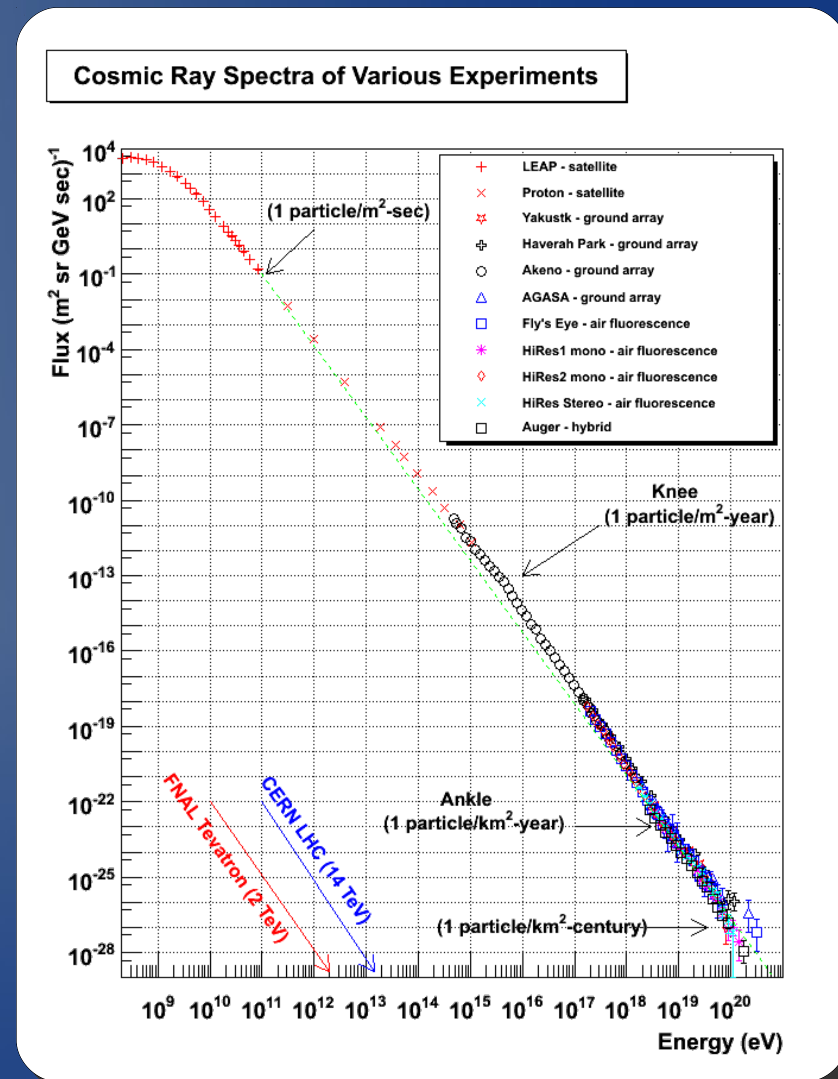
SNR 0509-67.5
Image Credit: X-ray: NASA/CXC/SAO/J.Hughes et al, Optical: NASA/ESA/Hubble Heritage Team (STScI/AURA)

Simeis 147
Autor: Maurizio Cabibbo

<u>Age</u>: from 0 to ~100 000 yeas (dissipation in the ISM)
<u>Typical kinetic energy</u>: 10^{51} ergs
<u>Total number of known in the Galaxy</u>: ~270 (Green '09)

SNRs and CRs





Supernova shocks are very suited places for the particle acceleration.

As SNR is becoming older, these high-energy particles escape it and get to the ISM.

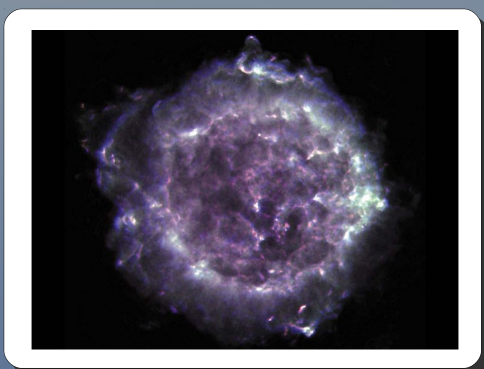
The overall quantity and energy budget of SNRs makes them vary plausible sources for the observed Galactic cosmic rays (up to 10^{15} eV)

Other possible sources of CR: pulsars and PWN (Neronov & Semikoz '12), OB assiciations (e.g. Bykov & Fleishman '92, Parizot et al. '04)

Evidences for acceleration in SNRs

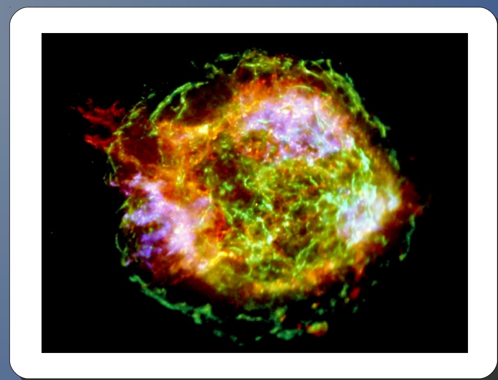
Cas A

Radio



Credit: NROA/VLA

X-rays



Credit: NASA/CXC/GSFC/ U.Hwang et al.

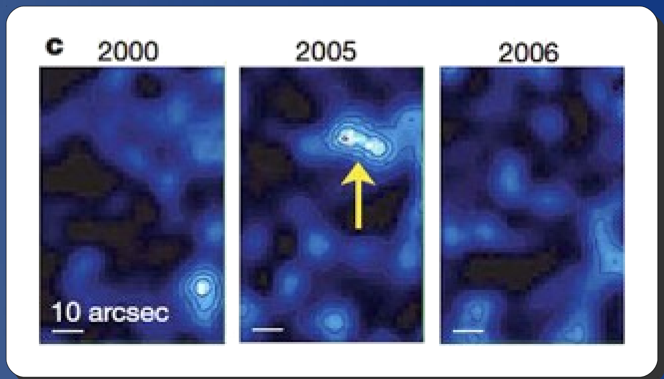
Similarities in radio and X-ray morphology show that the emission is due to the synchrotron radiation of the high-energy electrons.

Sometimes the hot spots are seen appearing and disappearing, indicating fast acceleration of particles in SNR shells.

Similarities in X- to gamma-ray morphology suggest that the VHE emission is of the Inverse Compton origin.

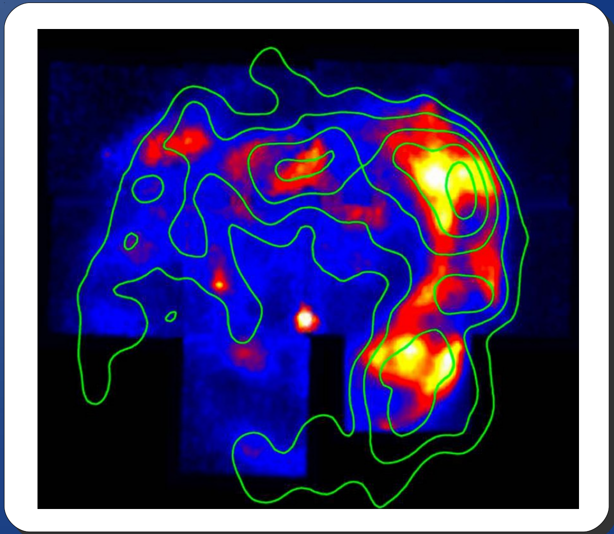
RX J1713.7-3946

X-rays



Credit: CXC/Yasunobu Uchiyama/HESS/Nature

X- to gamma rays



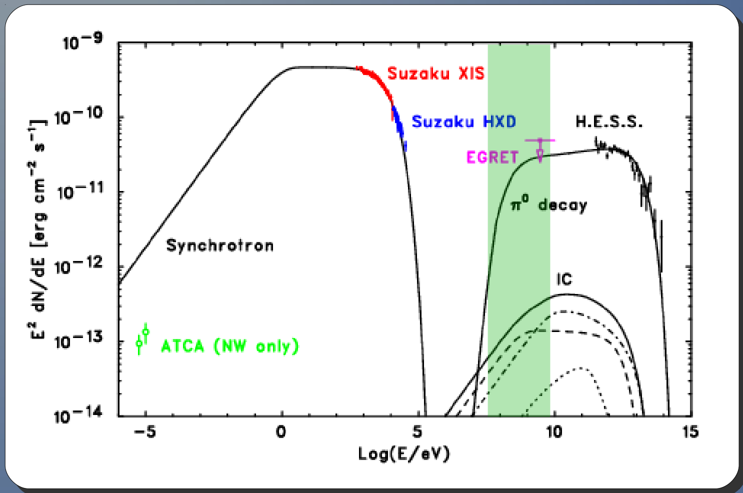
Credit: JAXA/ Takaaki Tanaka/HESS

Detection of CRs in SNRs: protons

Different models

Pion feature detected

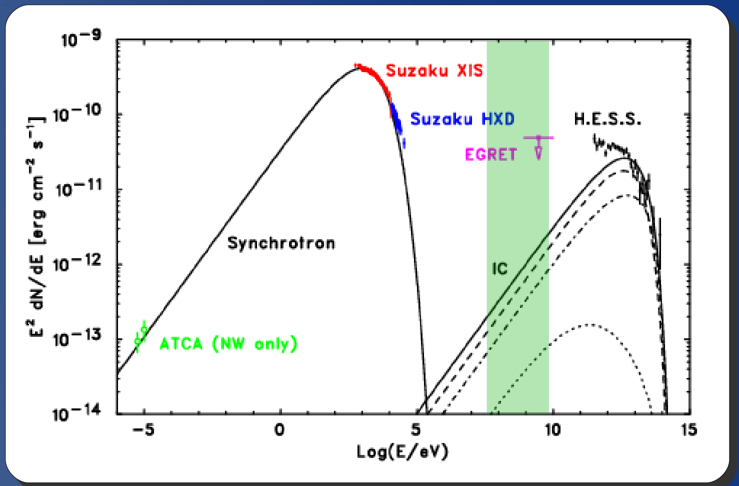
RX J1713.7-3946: hadronic origin

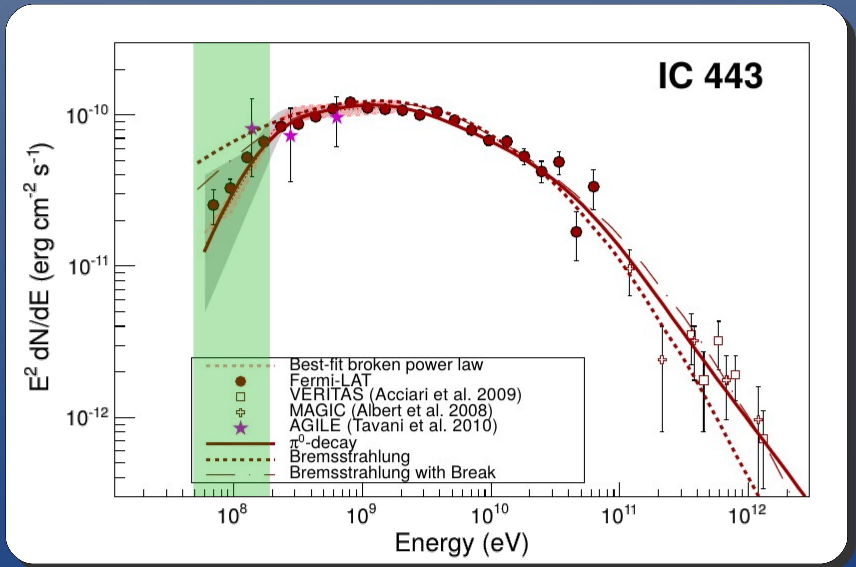


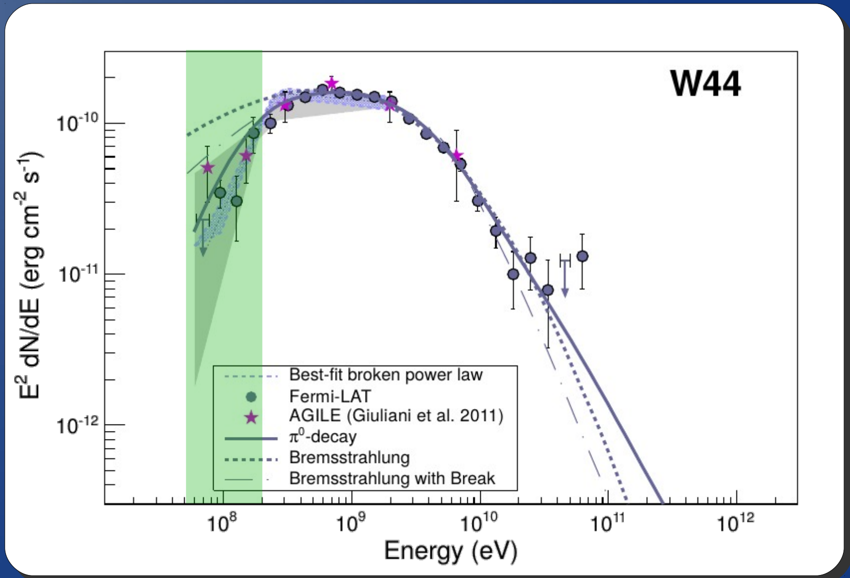
Tanaka+ '08

?

RX J1713.7-3946: leptonic origin







Ackermann+ '13

What about the rest of SNRs?

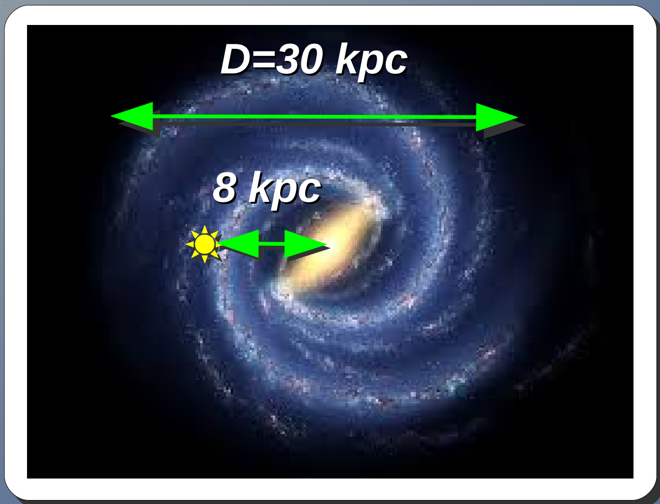
The majority of SNRs lack the detection of the pion feature – or even detection in the gamma-ray band at all.
The 1st LAT SNR catalogue (Hewitt+ '13) lists 44 objects, among which only 19 are firm detections.

However, if SNRs are the sources of CR, their number should be in balance with the CR amount and leakage from the Galaxy.

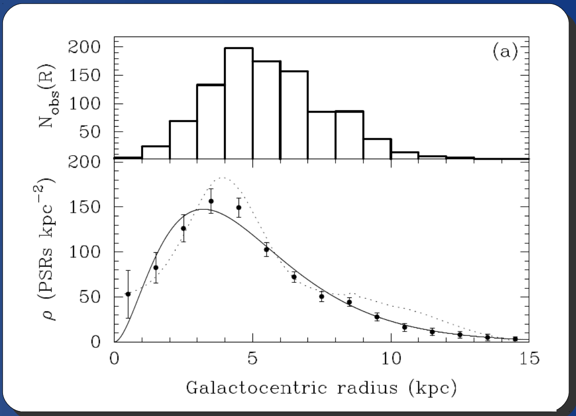
Based on this we can predict how many SNRs we should see the gamma-ray band and compare with the observations.

Rather than analyzing sources one by one, we will use a statistical approach here.

Simulation of the SNR population



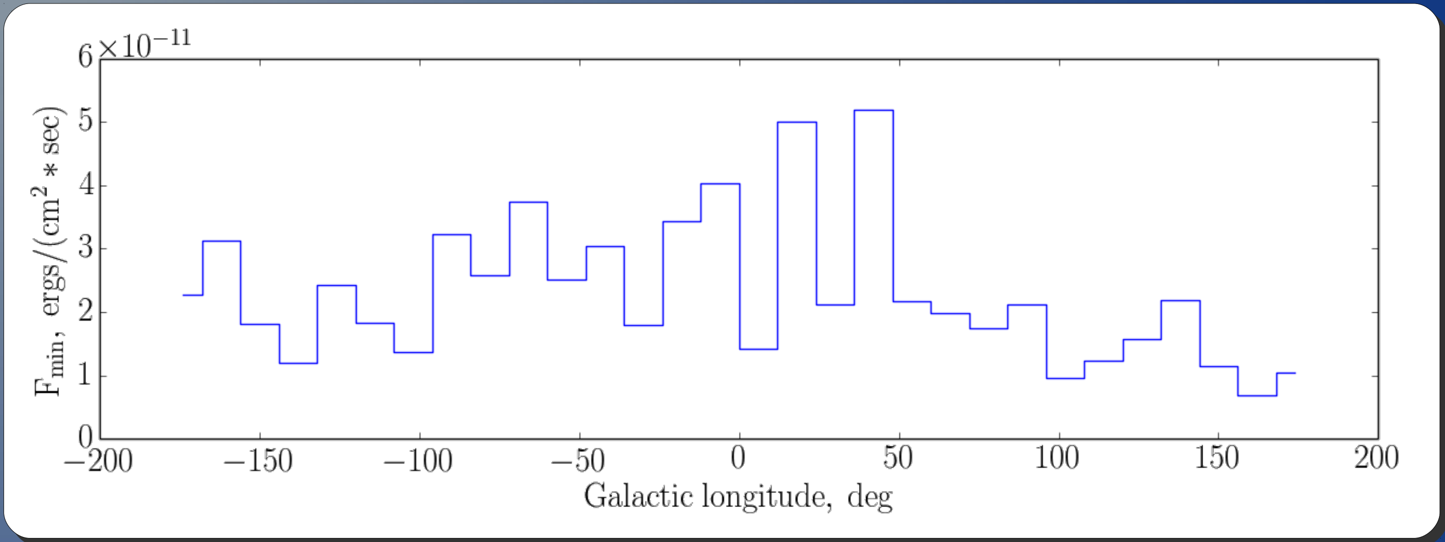
Lorimer+ '06
pulsar distribution profile



Procedure

- *characterize a single typical SNR*
- *calculate the total number of the SNR in the Galaxy*
- *distribute this number of SNRs according to their expected*
- *spatial distribution in the Galaxy*
- *estimate the sensitivity of the γ-ray instrument in our possession*
- *calculate the fraction of the SNR population that can be observed with the available γ-ray telescope*

Fermi/LAT sensitivity in the Gal. plane



To estimate the sensitivity, we took the 2FGL catalogue and looked for the weakest detected sources (TS>25, ≈4σ) in the b=[-5,+5] range.

This we then rescaled by $\sqrt{(t_{SNR\ cat.} / t_{2FGL})}$ ***to compensate for the different exposures in the catalogues.***

Basic expressions

number of explosions over the CR diffusion time scale

fraction of SNR that will stay alive

$$N_{SNR} = \frac{CR_{diff}}{\Delta T_{SN}} \frac{T_{life}}{CR_{diff}} = \frac{T_{life}}{\Delta T_{SN}} \approx 1000 \left(\frac{T_{life}}{10^5\ \mathrm{yr}}\right)\left(\frac{100\ \mathrm{yr}}{\Delta T_{SN}}\right)$$

$$t_{pp} = \lambda_{pp}/(fc) = 1/(n_0 \sigma_{pp} f c) \approx 6 \times 10^7 \left(\frac{1\ \mathrm{cm}^{-3}}{n_0}\right)\ \mathrm{yr}$$

Typical cooling time of a proton

$$E_{CR} = L_{CR} \times \Delta T_{SN} \approx 3 \times 10^{50} \left(\frac{\Delta T_{SN}}{100\ \mathrm{yr}}\right)$$

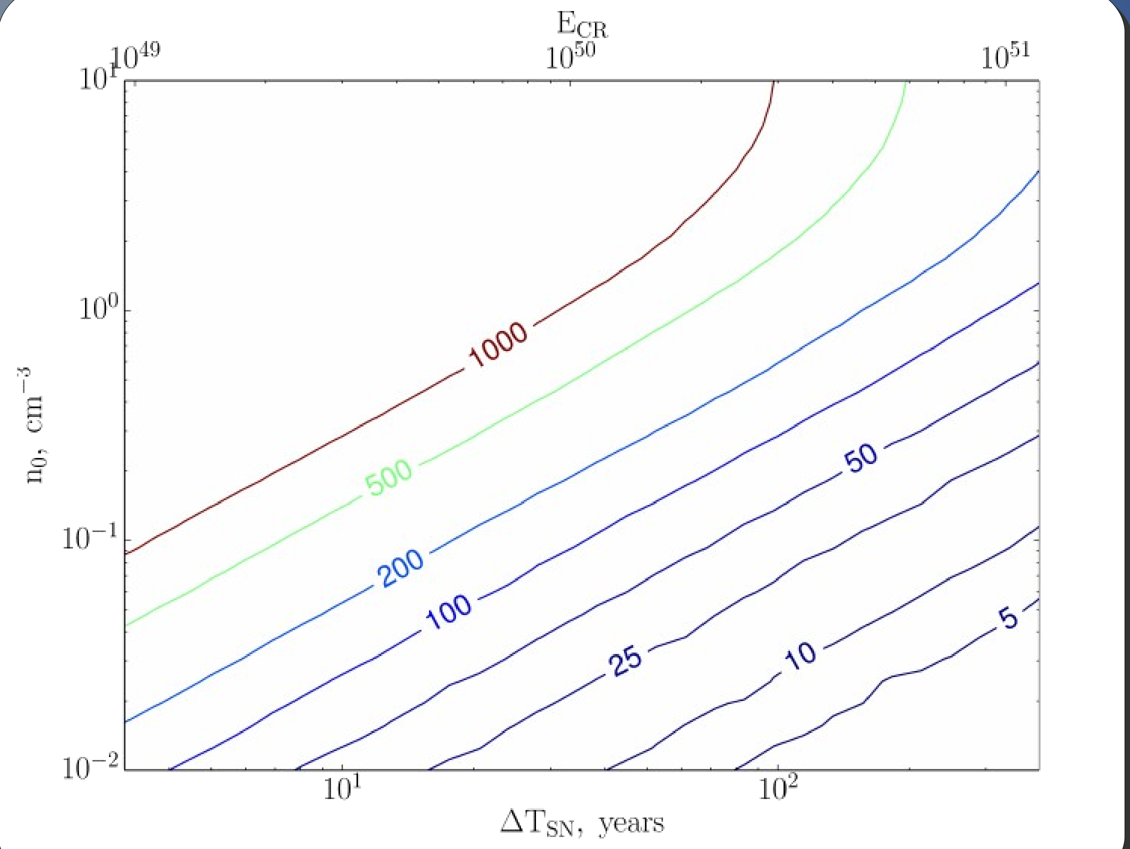
CR energy budget of an SNR (L_{CR} is the CR leakage flux from the Galaxy)

$$L_{SNR} = E_{CR}/t_{pp} \approx 2 \times 10^{35} \left(\frac{\Delta T_{SN}}{100\ \mathrm{yr}}\right)\left(\frac{n_0}{1\ \mathrm{cm}^{-3}}\right)\ \mathrm{erg/s}$$

Typical luminosity of an SNR

N of observable SNRs in Galaxy

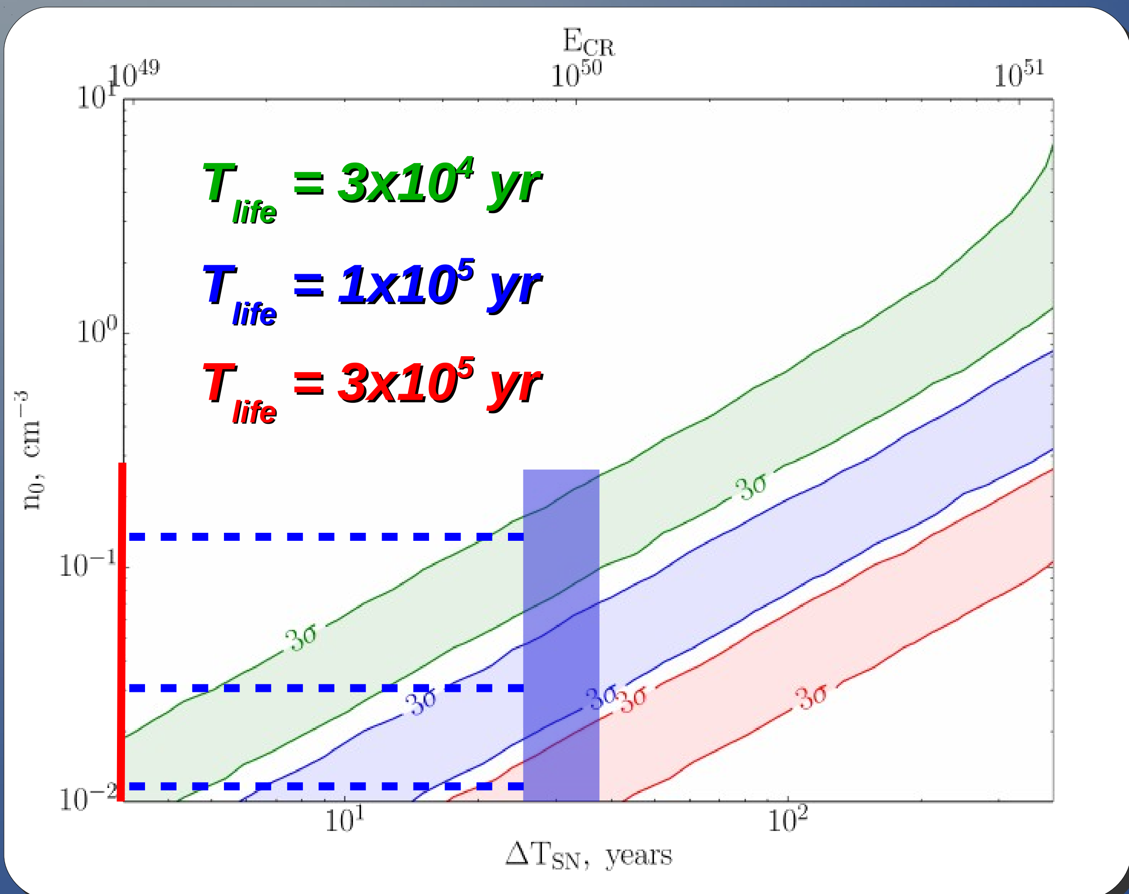
$$N_{SNR}^{obs} \sim L_{SNR} N_{SNR} \sim n_0 / \Delta T_{SN}$$



These numbers also scale with T_{life} (the plot shows $T_{life}=10^5$ yr)

We could (should?) have seen a lot of SNRs...

SNR life time



Need low n_0 to match the observed number of SNRs (44)

The expected number of SNRs depends significantly on the SNR life time T_{life}

$$N_{SNR}^{obs} \sim N_{SNR} \sim T_{life}$$

CR escape time

$$t_{esc} = \frac{R_{SNR}}{v_a} \approx 1.4\times10^5 \left(\frac{R_{SNR}}{10\ \mathrm{pc}}\right)\left(\frac{B}{10\ \mu\mathrm{G}}\right)^{-1}\left(\frac{n_0}{0.1\ \mathrm{cm}^{-3}}\right)^{0.5}\ \mathrm{yr}$$

$$t_{radiative} = 8.9\times10^4 \left(\frac{E_0}{10^{51}\ \mathrm{ergs}}\right)^{0.24}\left(\frac{n_0}{0.1\ \mathrm{cm}^{-3}}\right)^{-0.52}\ \mathrm{yr}$$

SNR transition to radiative stage
(Cesarsky '80)

Some considerations

Though SNRs are generally believed to be the sources of the galactic CRs, only for very few of them there direct evidences for the presence of relativistic protons.
However, this does not necessarily mean that all SNRs accelerate CRs or do this with sufficient efficiency.

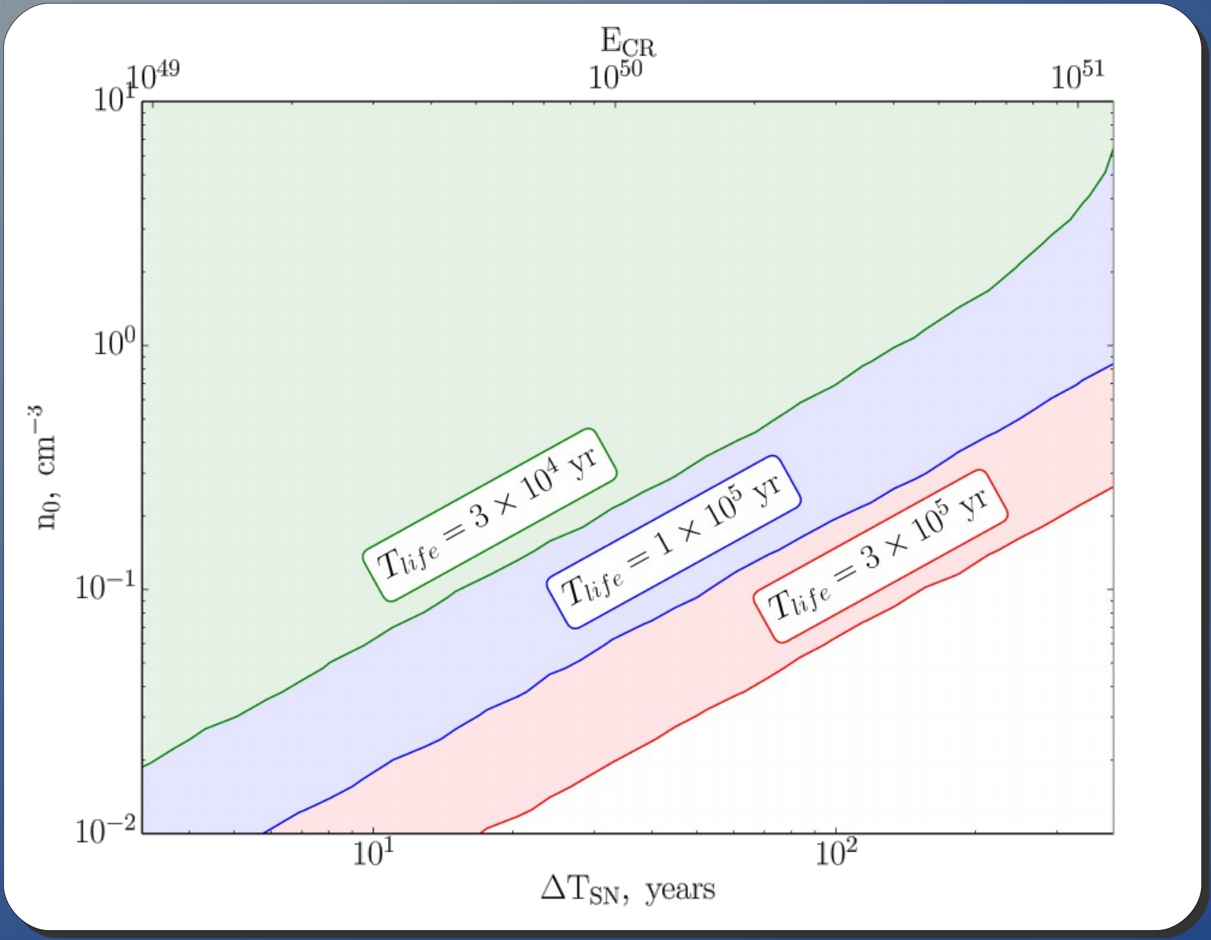
CRs have soft spectrum => most of the power is emitted at low energies => good for Fermi/LAT

Due to the modest resolution (1º @ 1GeV) LAT have problems identifying sources in crowded regions => Out of 44 catalogued SNRs only 19 are firm detections.

Some of the detected SNR might be shining through the Inverse Compton (electrons!)

→ ***The true number of the detected SNRs is <44 (<19)***

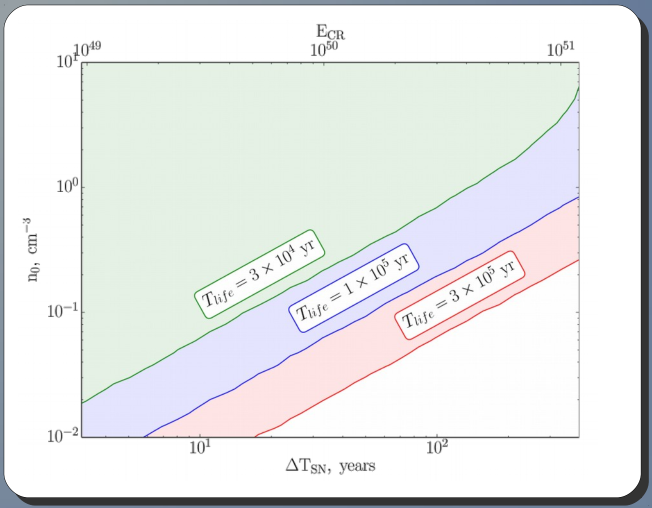
Resulting picture



The constraint on the number of detected SNRs transforms in the constraint on the n_0.

For a reasonable range of parameters we get $n_0 << 1$.

This is suggests that SN explode on average in under-dense regions – bubbles.



Summary

Here we try to attack the CR origin problem based on the statistical approach – SNR counts.

Our model gives a simplified description of a distribution of hadronic SNR, which is in balance with the CR leakage from the Galaxy.

We find, that a simple assumption of n_0=1 cm^{-3}, ΔT=30 yr, T_{life}=10^5 yr is disfavored by the data and a strong evidence for n_0<<1 cm^{-3} , suggesting that SN typically explode in the bubbles of the progenitor stars (~10^{-2} cm^{-3} expected).