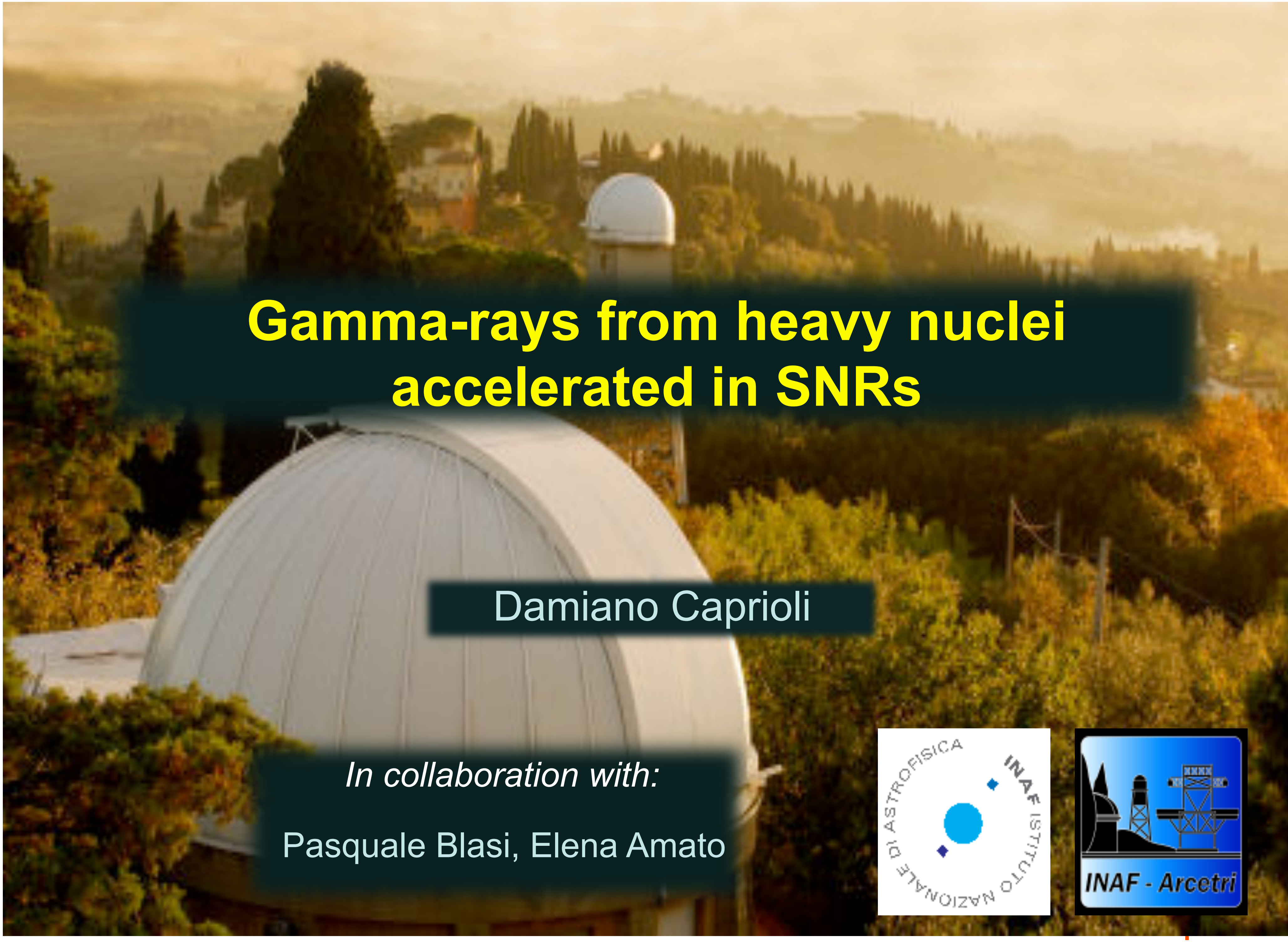

Gamma-rays from heavy nuclei accelerated in SNRs

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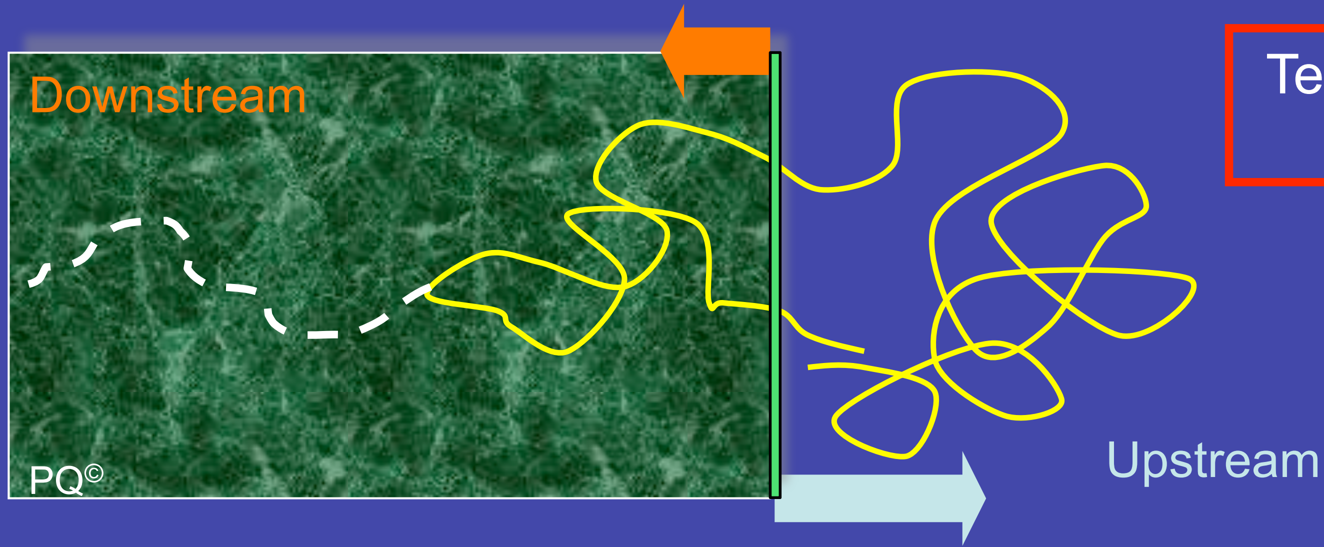
Accelerating particles

- Fermi mechanism (1954): particle scattering against magnetic irregularities leads (on average) to an energy gain
- At SN shocks: Diffusive Shock Acceleration (Krimskii 1977, Bell 1978, Blandford & Ostriker 1978)



Test-particle Theory

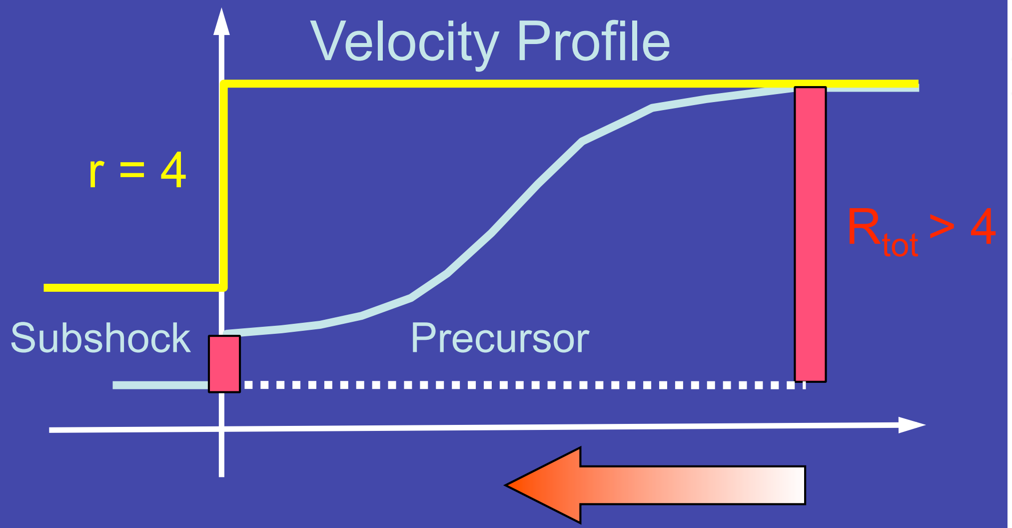
- Balance between energy gain and escape probability provides a power law spectrum whose index depends only on the compression ratio

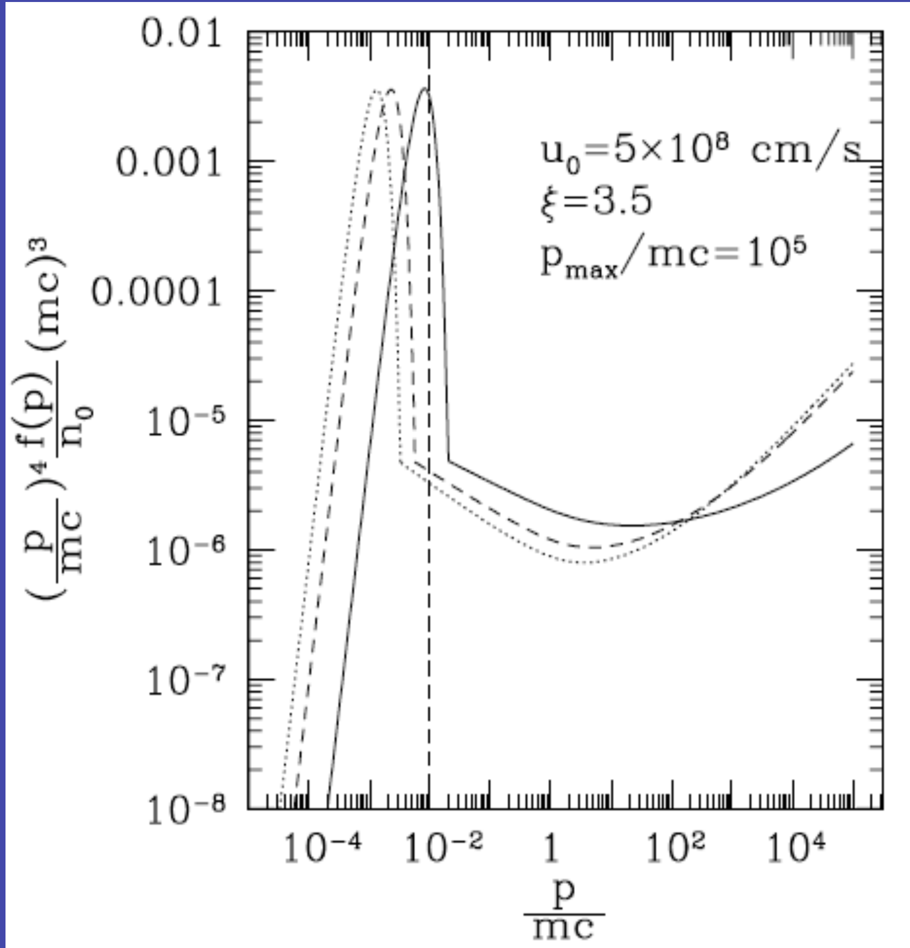
$$N(E) \propto \left(\frac{E}{E_0}\right)^{-\gamma} \qquad \gamma = \frac{R+2}{R-1}$$

- For strong shocks (M>>1): $R = 4 \Rightarrow N(E) \propto E^{-2}$

CR-modified shocks

- CR pressure around the shock: the upstream fluid is slowed down and becomes more compressible

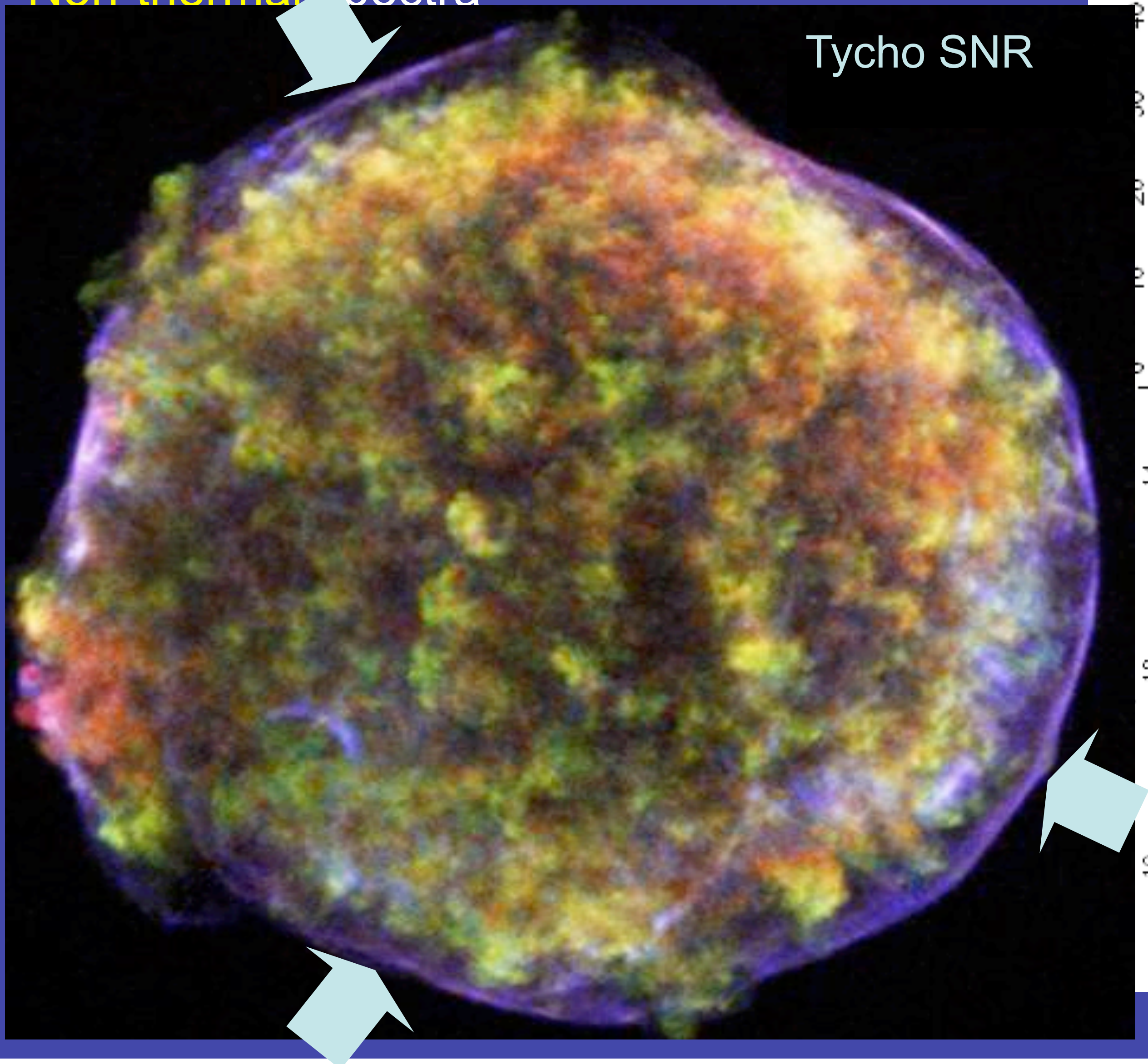


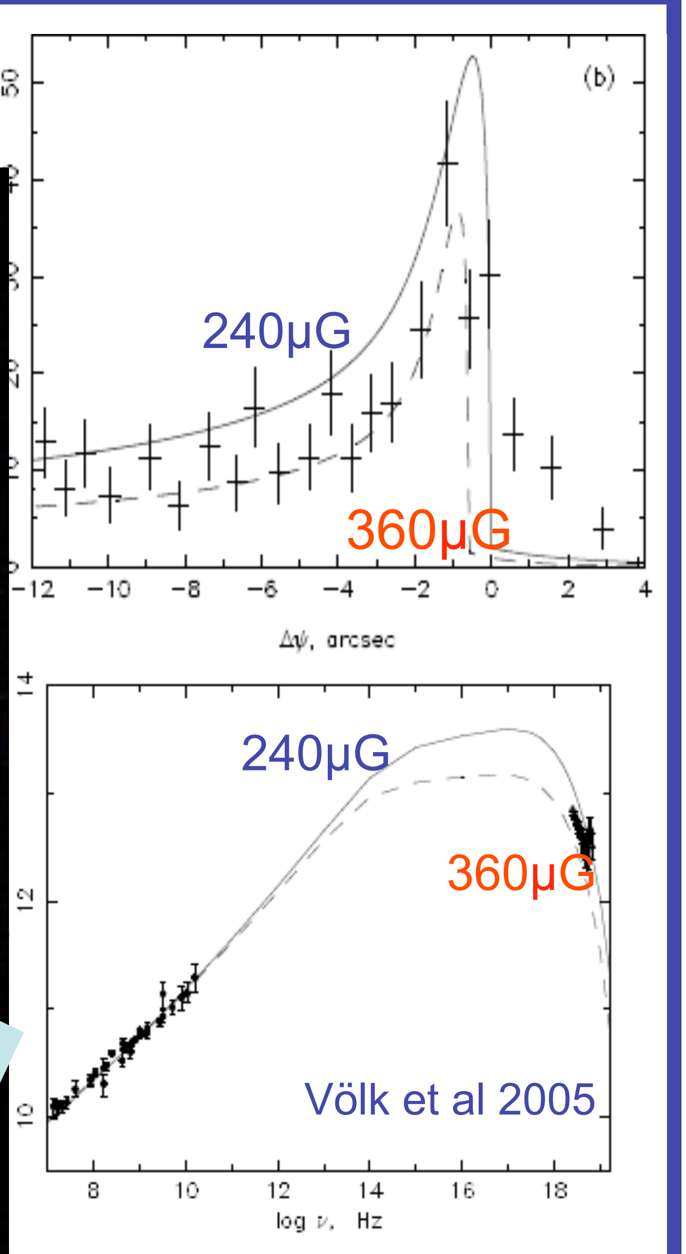


- Acceleration may be very efficient (R_{tot}~10)
- The downstream is heated less efficiently
- The spectra of accelerated particles become rather concave

X-ray observations of young SNRs

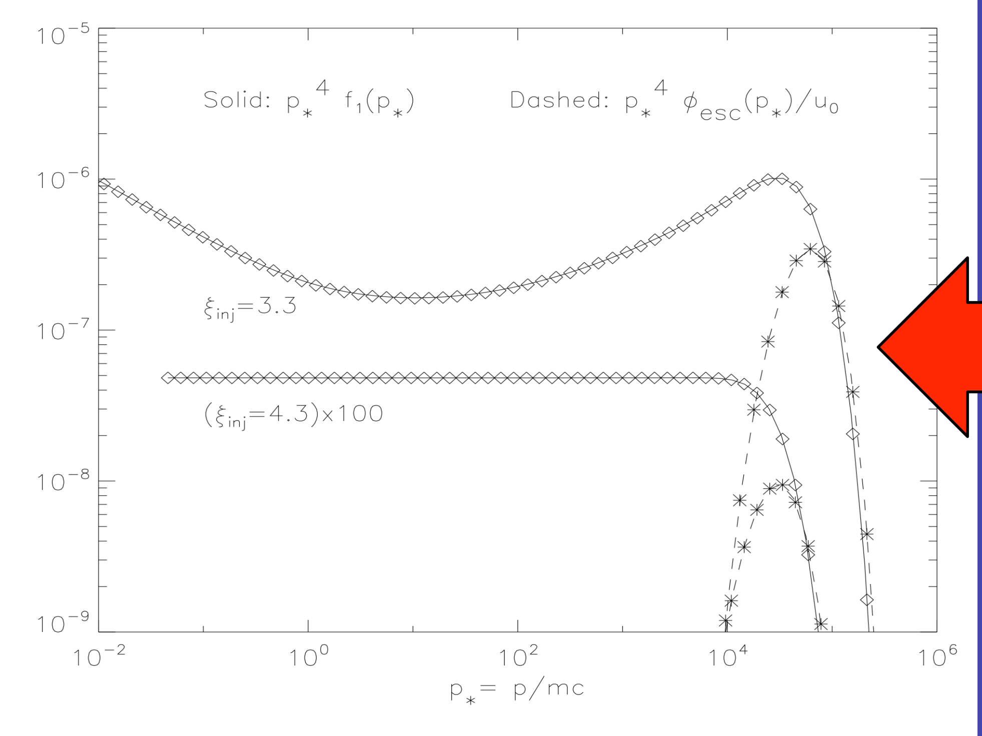
- Bright narrow rims at the blast wave
- Non-thermal spectra





The escape flux

- Ejecta dominated stage: P_{max} and magnetic turbulence increase with time
- Sedov-Taylor stage: V_{sh} and δB decrease, and the SNR confining power too
  - Particles with momentum close to P_{max} escape the system from upstream



Escape spectrum is no way related to E^{-2} Fermi's prediction for the acceleration one!

DC, Amato & Blasi, 2010b

- And the *back of the envelope* spectrum of escaping particles?

$$d\mathcal{E}(t) = \mathcal{F}_{esc}(t)\frac{1}{2}\rho V_{sh}^3(t)4\pi R_{sh}(t)^2dt$$

$$d\mathcal{E}(p) = 4\pi p^2 N_{esc}(p)pcdp$$

$$N_{esc}(p) \propto p^{-4}t^{5\nu-2}\mathcal{F}_{esc}(t)$$

$$R_{sh}(t) \propto t^{\nu}$$

$$N_{esc}(p) \propto p^{-4}$$

Semi-analytical NLDSA

- Solution the diffusion-convection equation (+ hydrodynamics) in a recursive way (Amato, Blasi 2005; 2006; DC, Amato, Blasi 2010a)

- Physical ingredients:
  - Analytical SNR evolution (Truelove, McKee 1999)
  - Injection of particles from the thermal bath (Blasi, Gabici, Vannoni 2005)
  - Escape of particles during the Sedov phase (DC, Amato, Blasi 2010a)
  - Back-reaction of the CRs
  - Amplification of the magnetic field via streaming instability
  - Back-reaction of the magnetic turbulence (DC et al. 2008; 2009)
  - Presence of nuclei heavier than Hydrogen (DC, Blasi, Amato, astroph:/1007.1925)

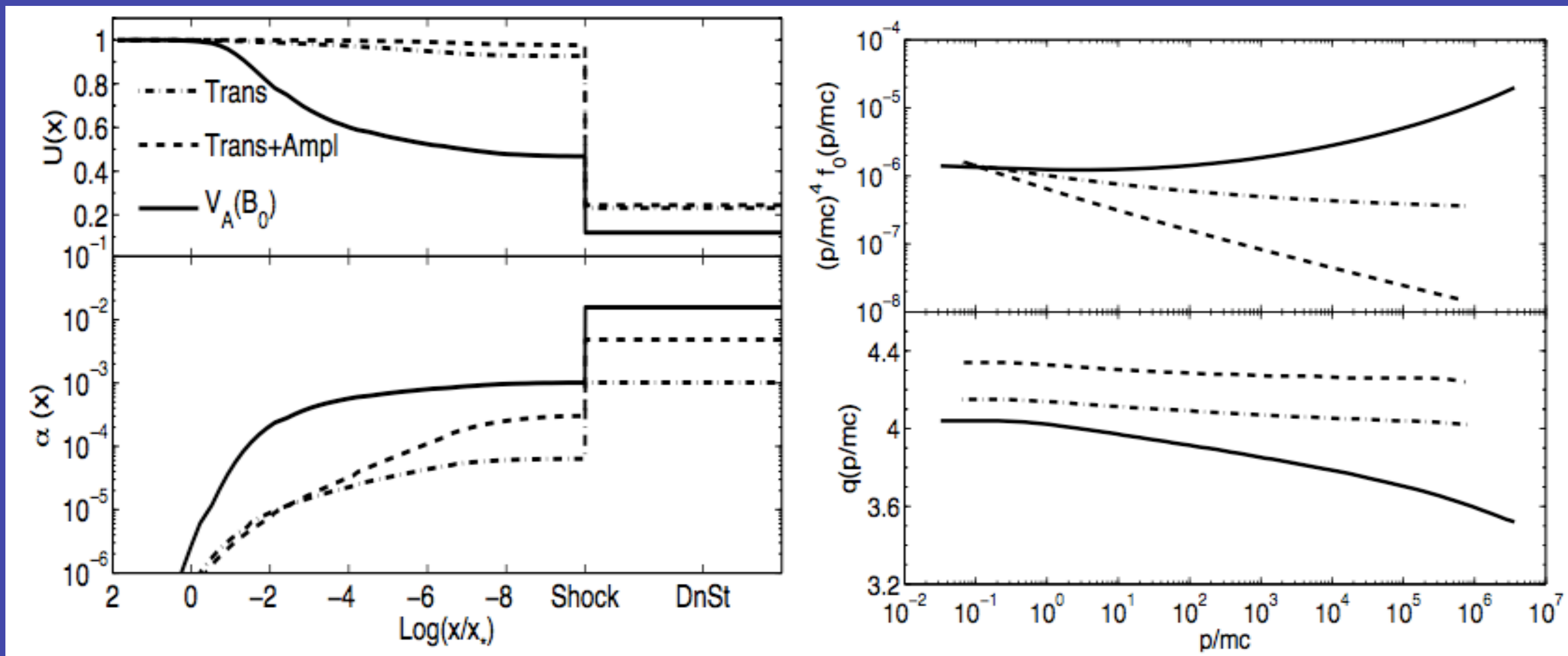
- The method is:
  - computationally very fast
  - flexible in implementing new pieces of Physics
  - in perfect agreement with Monte-Carlo and fully numerical solutions (DC, Kang, Jones, Vladimirov 2010)

The velocity of the scattering centers

- CRs do not scatter on the fluid, but on magnetic irregularities!
  - The compression ratio CRs actually feel is $R_{CR} = \frac{(u + v_w)_{ups}}{(u + v_w)_{downs}} \neq 4$

What is v_W? It depends on the nature of the turbulence!

- Assuming an effective Alfvén velocity in the amplified B spectra are steeper! (see Bell 1978) $v_w = -v_A = -\frac{\delta B}{\sqrt{4\pi\rho}} \approx -(0.01 - 0.1)u$

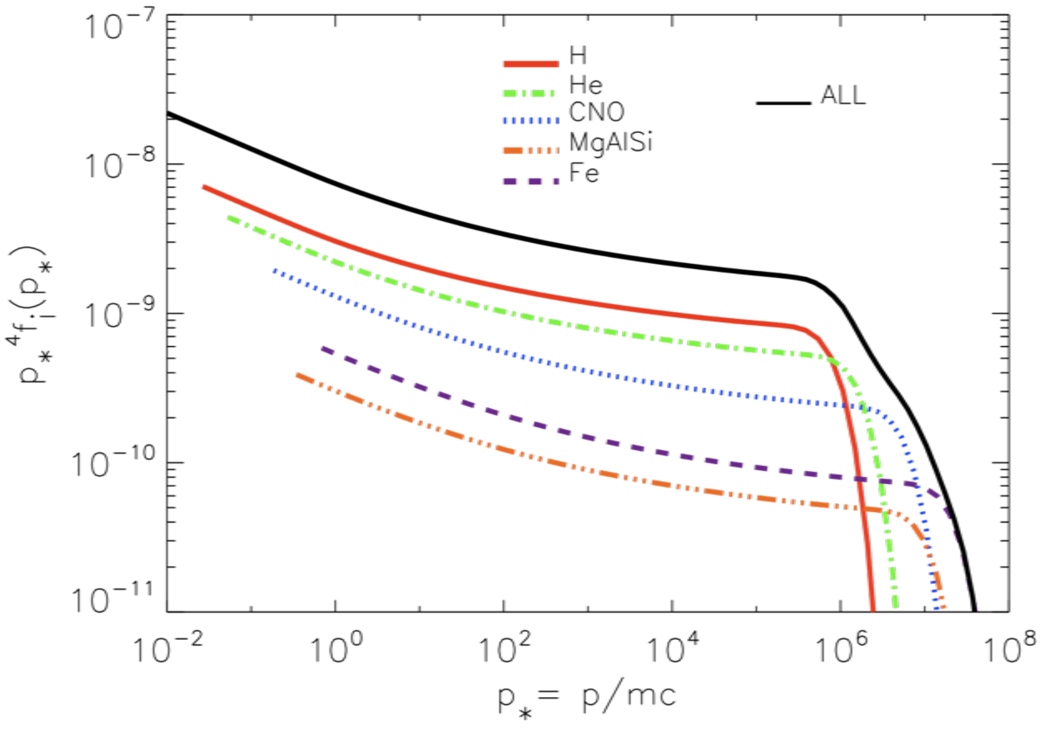


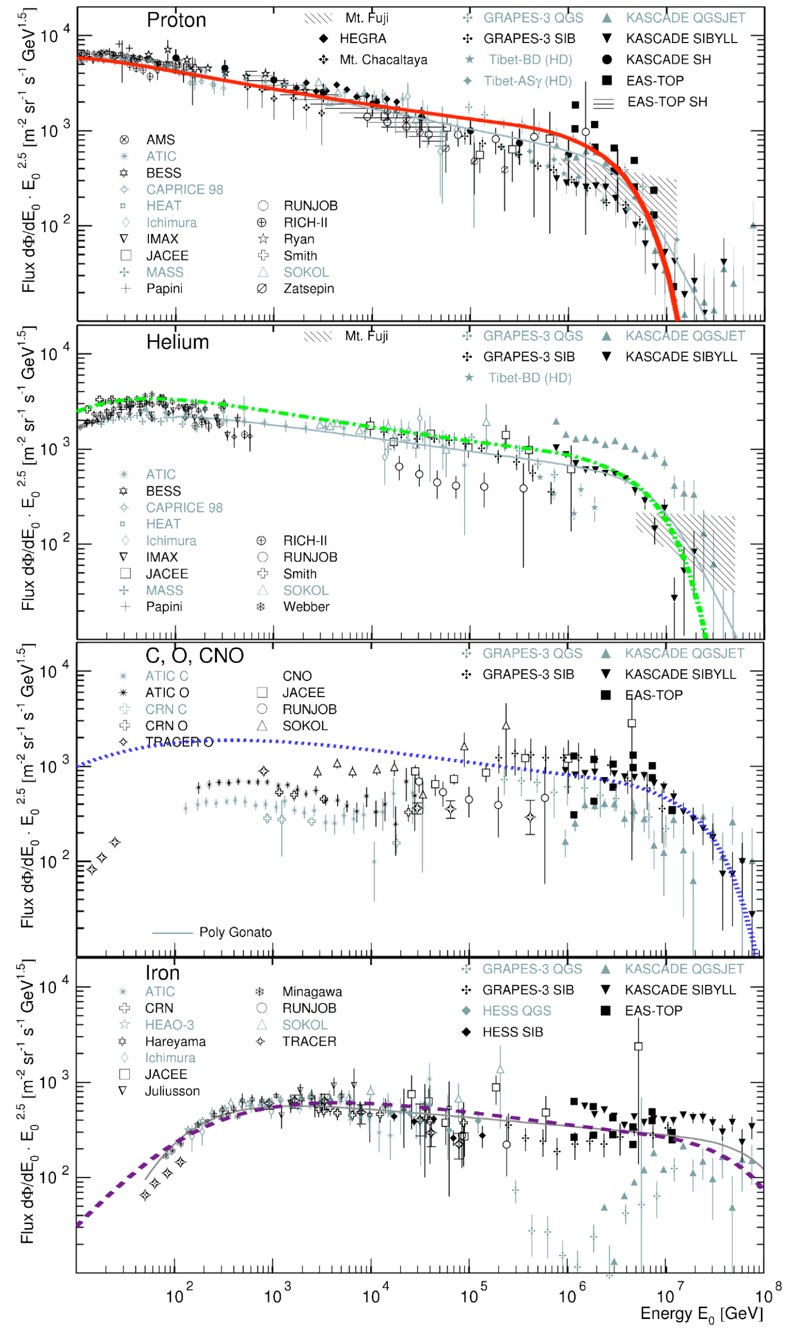
DC, Blasi, Amato & Vietri 2009

Results

- We take a benchmark SNR accounting for the CR spectrum measured at Earth
- At the beginning of the Sedov stage:

DC, Blasi, Amato astroph:/1007.1925

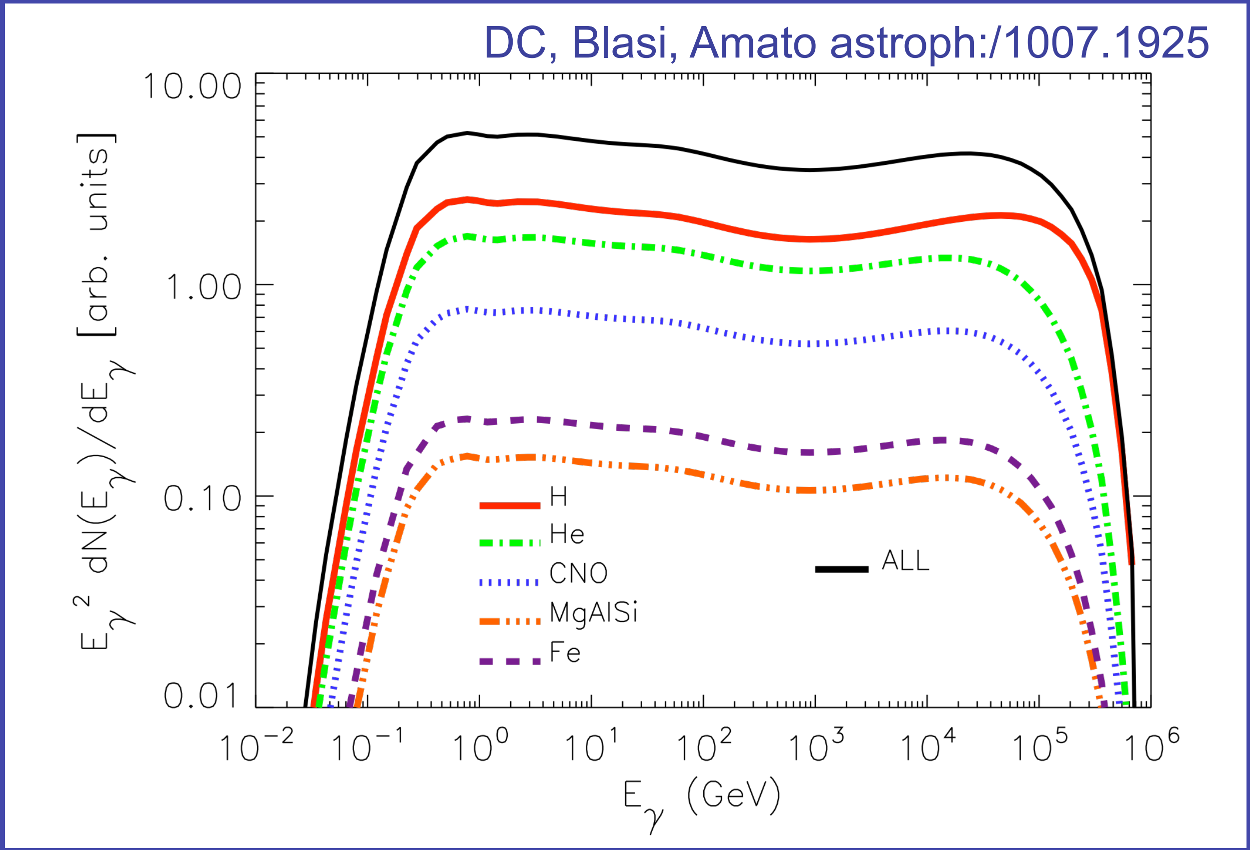




- Instantaneous *concave* spectrum
- Heavy nuclei (HN) are not negligible in the shock dynamics

Hadronic Gamma rays

- With the same HN abundances adopted above:

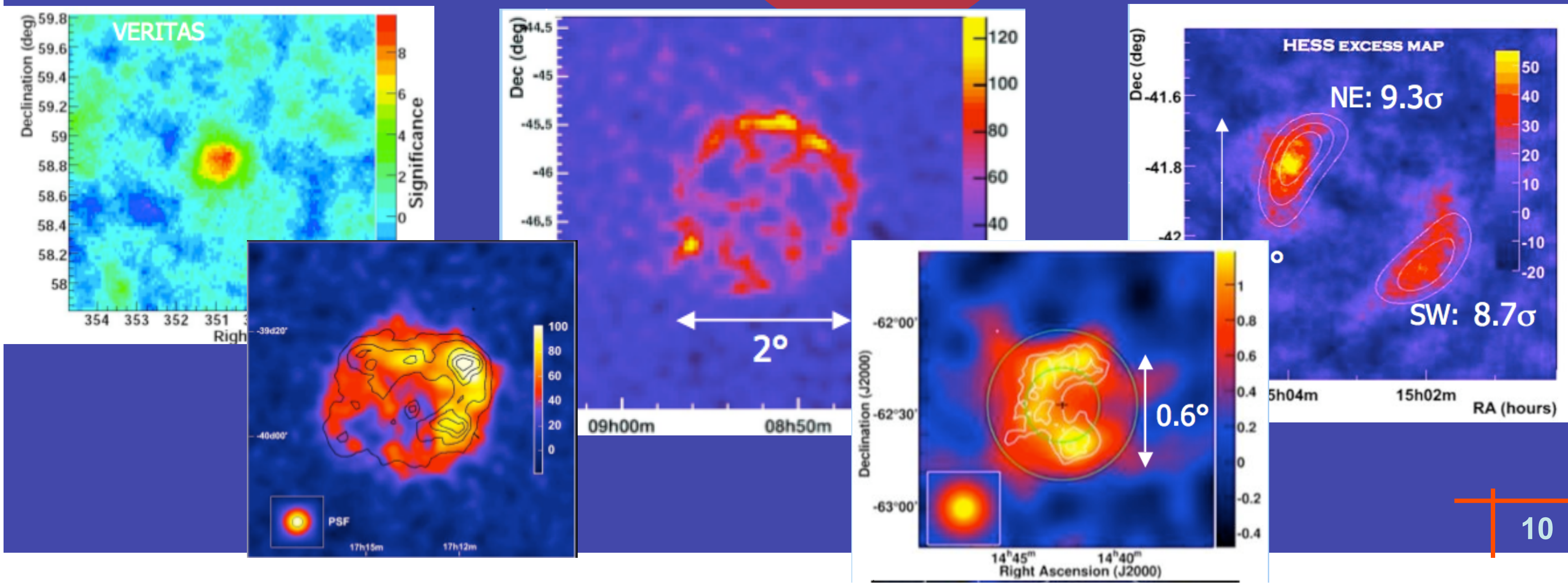


- HN contribute as much as protons (maybe more in HN-rich environments!)
- The cut-off shape is affected by nuclei
- The circumstellar density may be significantly lower than standard estimates
  - Effects on the SNR evolution and on the thermal emissivity

Observational facts

- SNRs with SHELL MORPHOLOGY:

SNR	Detected by	Slope	Age (yr)	Distance (kpc)
Cas A	MAGIC/VERITAS	2.3 ± 0.2	330	3.4
RX J1713.4-3047	HESS+Fermi	2.04 ± 0.04	1600	1
Vela Jr.	HESS	2.24 ± 0.04	600-4000	0.2-0.8
RCW 86	HESS	2.54 ± 0.12	1800	2.5
SN 1006	HESS	2.34 ± 0.22 SW 2.54 ± 0.15 NE	1004	2.2



Escape flux and MCs

- If a source is close to a Molecular Cloud, the number of targets for p-p collisions drastically increases:
  - The cloud may look like a γ-ray source (Issa, Wolfendale 1981; Aharonian 1991)
  - Many SNRs/MCs detected both in TeV (IC 443, W51, W28…) with HESS, VERITAS and MAGIC and in GeV with Fermi, with slope in the range 2.1-2.9

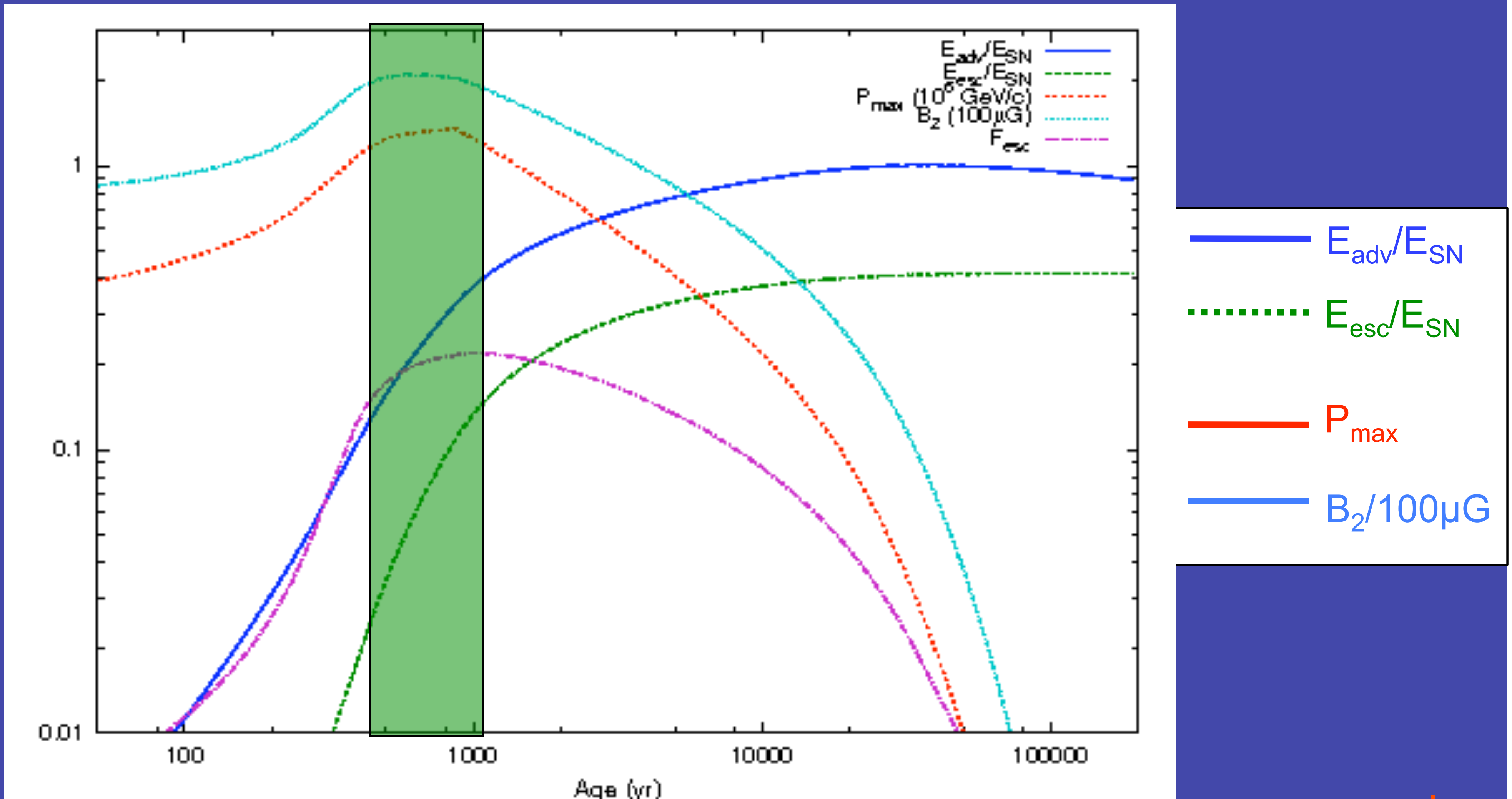
Name	Spatial R.A. (deg)	Decl. (deg)	r_{95} (deg)	Spectral Fit F(0.1-100 GeV) (10^{-7} photons cm^{-2} s^{-1})	Γ
G349.7+0.2	259.47	-37.50	0.03	0.58 ± 0.11	2.10 ± 0.11
CTB 37A	258.65	38.52	0.04	1.36 ± 0.15	2.19 ± 0.07
3C 391	282.26	-0.92	0.03	1.58 ± 0.26	2.33 ± 0.11
G8.7–0.1	271.33	-21.64	0.03	3.88 ± 0.42	2.40 ± 0.07

Castro, Slane 2010

- The spectrum may be related to the CR escape flux (e.g. Gabici, Aharonian, Blasi 2007; Gabici, Aharonian, Casanova 2009; Lee, Kamae, Ellison 2009)
- Unidentified TeV sources (20 over 80) may be associated with MCs illuminated by SNRs

SNRs and PeVatrons

- Why don't we see sources with $E_{max}>10^6$ GeV (i.e. $E^{\gamma}_{max}>300$ TeV)?
  - Best candidates are 500-1000 yr old SNRs (around T_{Sedov})
  - Assuming a lifetime of 70 kyr, less than 1% of the SNRs should be a PeVatron!



DC et al., in preparation

Conclusions

- Nuclei heavier than Hydrogen may contribute is a substantial way to the gamma emission from SNRs
  - Contribution to shock dynamics
  - Estimate of the circumstellar density
- Explaining the steep spectra so-far observed is a new challenge for NLDSA
  - Need for a better comprehension of the magnetic turbulence
  - Account consistently for the Galactic CR spectrum
  - Prediction of the physics of SNR/MCs interactions
- The lack of detection of PeVatrons is not at odd with theoretical expectations