Radio emission from supernova remnants in the Magellanic Clouds as a probe of particle acceleration*

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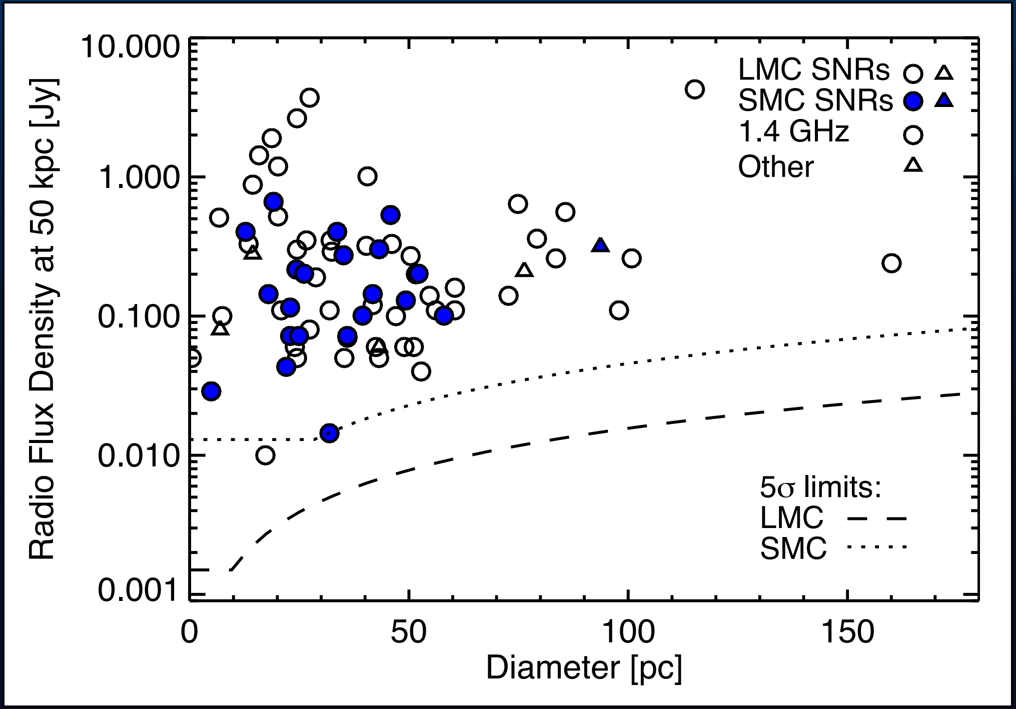
Radio supernova remnants (SNRs)

Radio SNR emission: Synchrotron emission from the SN blast wave as SN ejecta interacts with external medium

Many radio SNRs have been detected in our Galaxy → Uncertain distances

Magellanic Clouds (MC) provide a (almost) complete sample to study at a known distance (~80 SNRs).



Badenes et al. (2010)

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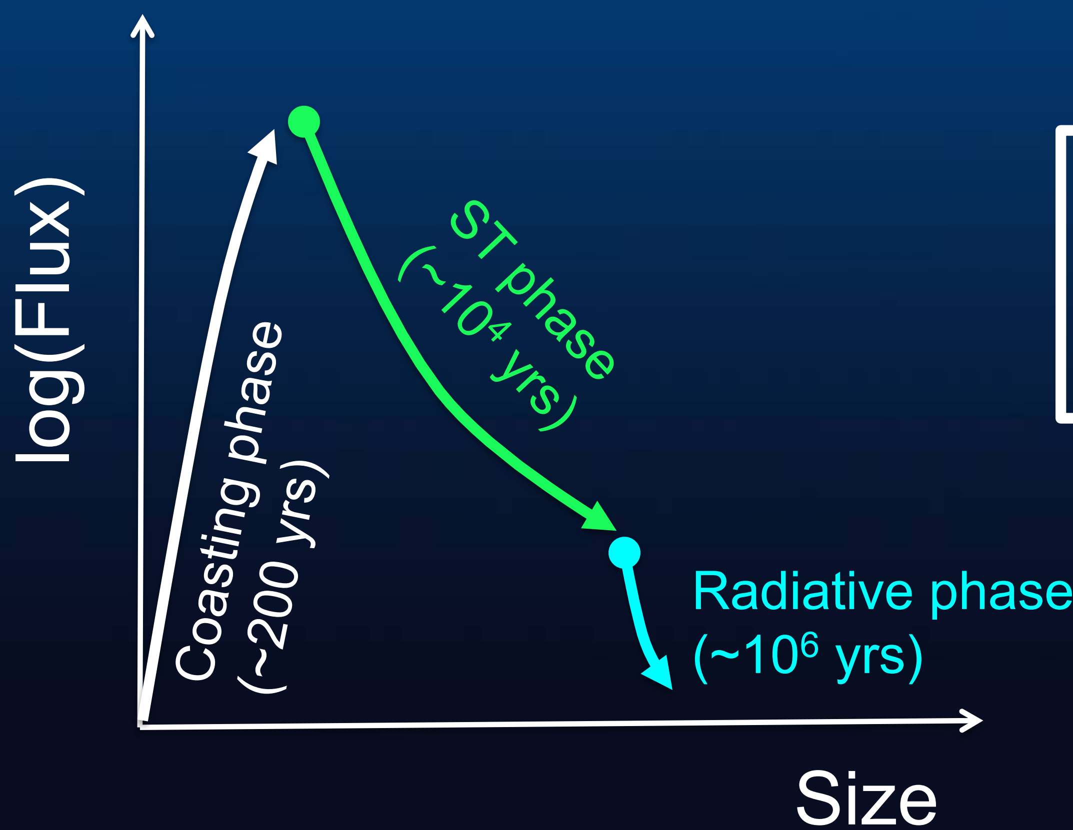
SNR stages

Supernova rate in both clouds:
1 SN every ~300 yrs (e.g., Maoz & Badenes 2010)



Coasting phase:
- Constant velocity
- Expected: ~1 SNRs

Sedov-Taylor (ST) phase:
- Decelerating (adiabatic)
- Expected: ~100 SNRs

Radiative phase:
- Decelerating (radiative)
- Expected: ~10^4 SNRs

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ST phase emission

Blast wave velocity (ST solution):

$$v \propto E^{1/5} n^{-1/5} t^{-3/5}$$

E → Kinetic energy of SN ejecta
n → Density of external medium
t → Time since explosion

Particle distribution:

Theory of Fermi acceleration in non-relativistic shocks (e.g., Bell 1978; Blandford & Ostriker 1978; Blandford & Eichler 1987)

Power-law distribution in momentum with slope *p*: $2 < p < 3$

Minimum electron Lorentz Factor: $\gamma_m - 1 \propto v^2$

	Most electrons by:	
	Number	Energy
$\gamma_m - 1 >> 1$	γ_m	γ_m
Our case → $\gamma_m - 1 << 1$	γ_m	~ 2

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ST phase

Radio flux (e.g., Chevalier 1982; … ; Granot et al. 2006; Sironi & Giannios 2013):

$$F \propto \varepsilon_e \varepsilon_B E \ n^{1/2} t^{-1}$$

ε_e , ε_B → Fraction of shocked fluid energy in electrons and magnetic fields

For $\nu_m < \nu_{obs} < \nu_c$

Size of the SNR:

$$R \propto E^{1/5} n^{-1/5} t^{2/5}$$

Flux is independent of density and time since explosion (BarniolDuran & Giannios 2015):

$$\Rightarrow F \propto \varepsilon_e \varepsilon_B E^{1.5} R^{-5/2}$$

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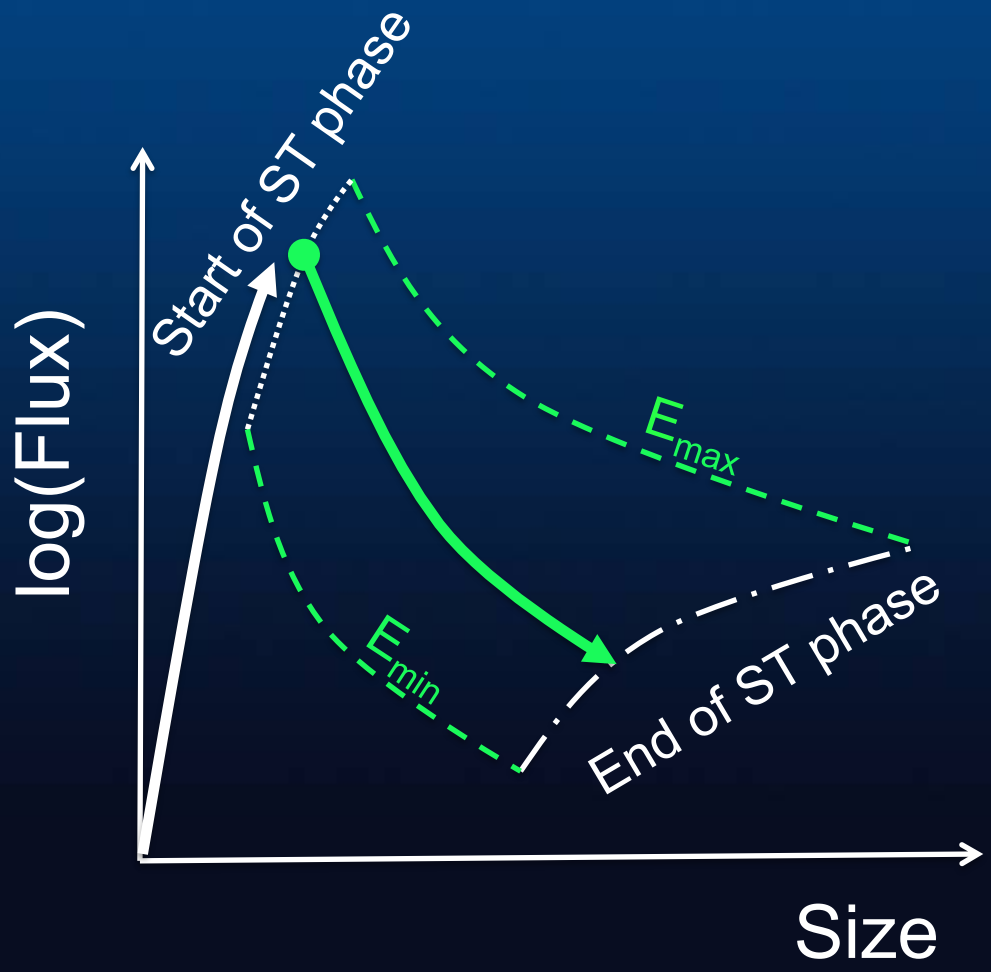
ST phase



For fixed ε_e and ε_B, the ST flux only depends on SN energy.

Kinetic energy of SNe (e.g., Hamuy 2003) :

$E_{min} \sim 5 \times 10^{50}$ erg

$E_{max} \sim 8 \times 10^{51}$ erg

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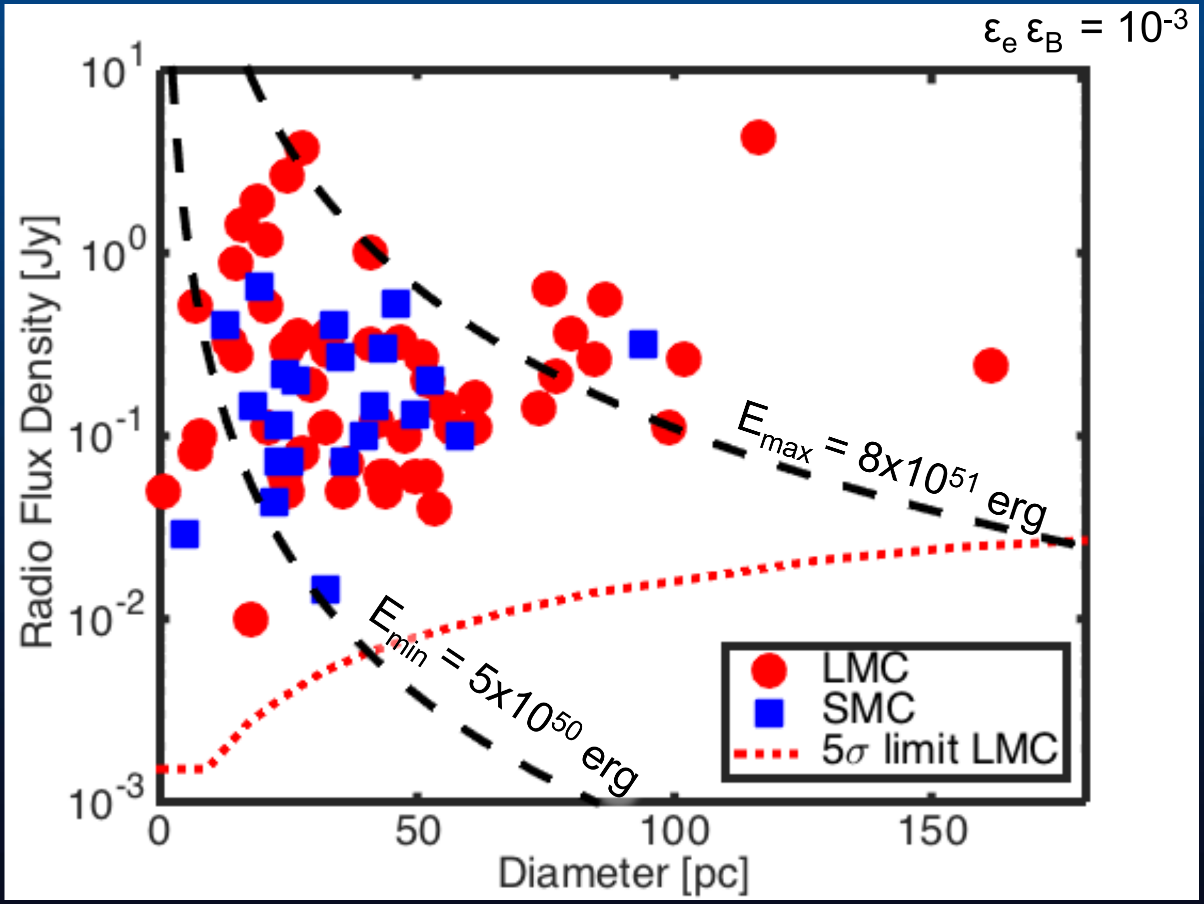
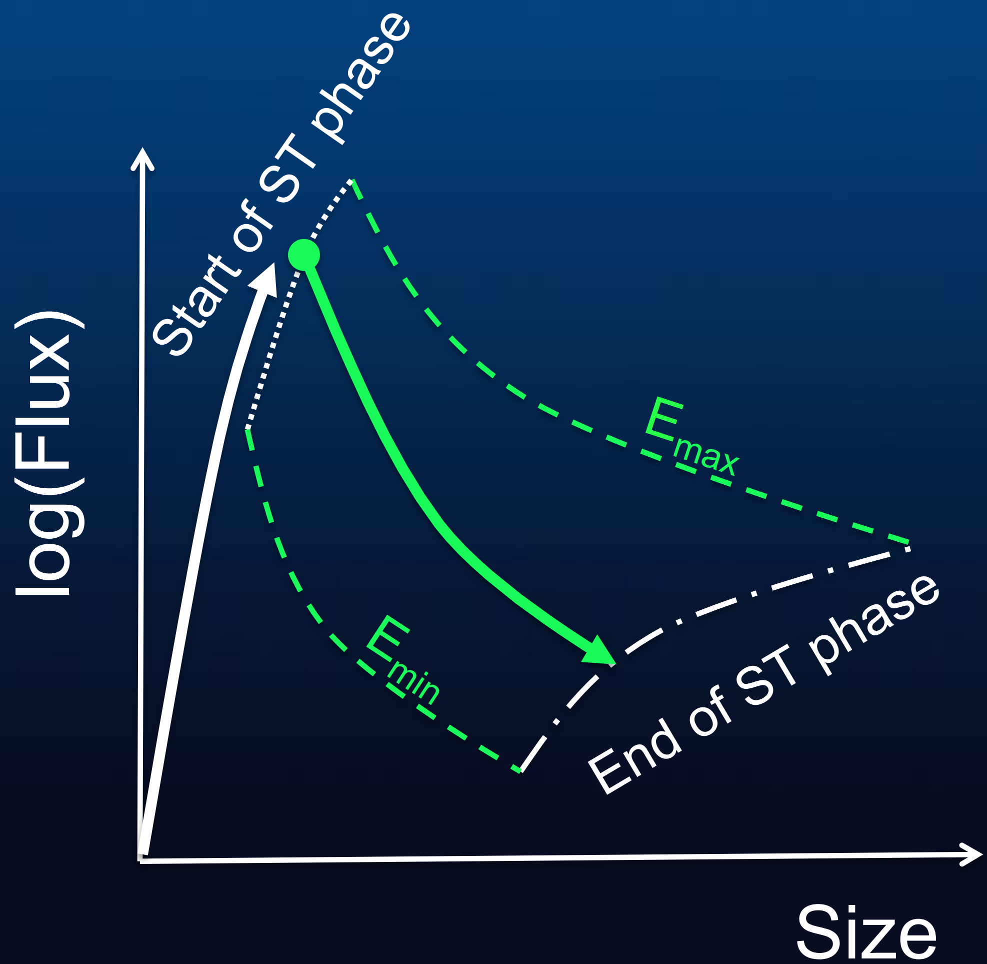
Application to MC SNRs



Barniol Duran, Whitehead, Giannios (2016)

Quite encouraging! Need external density to determine SNR location in plot.

ST phase



The start and end of the ST phase do depend on density.

Badenes et al. (2010) find that density follows a probability function:

$$P(n) \propto n^{-1}$$

Use Monte Carlo scheme to simulate history of the SNR in the Clouds.

Use log-normal distribution for kinetic energy of SN.

Fix $\epsilon_e \, \epsilon_B = 10^{-3}$

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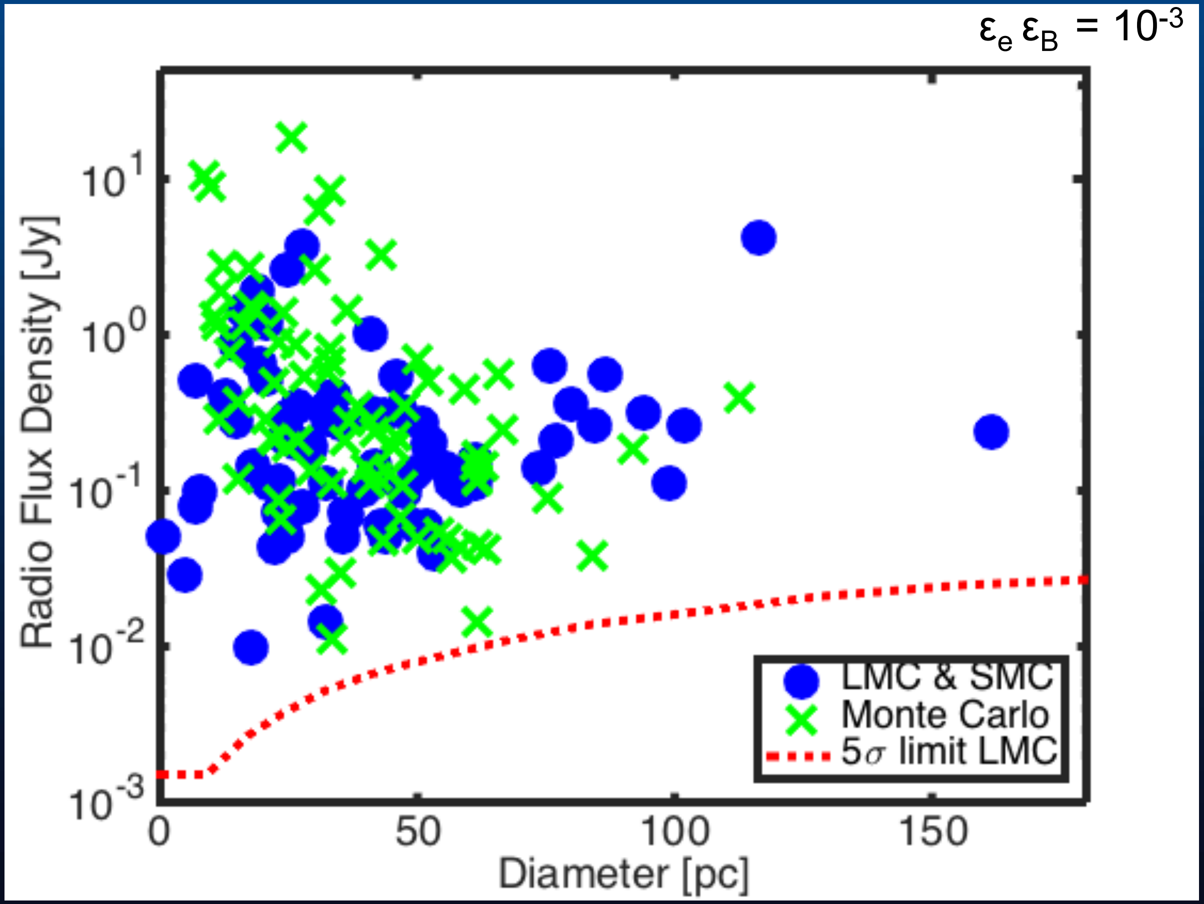
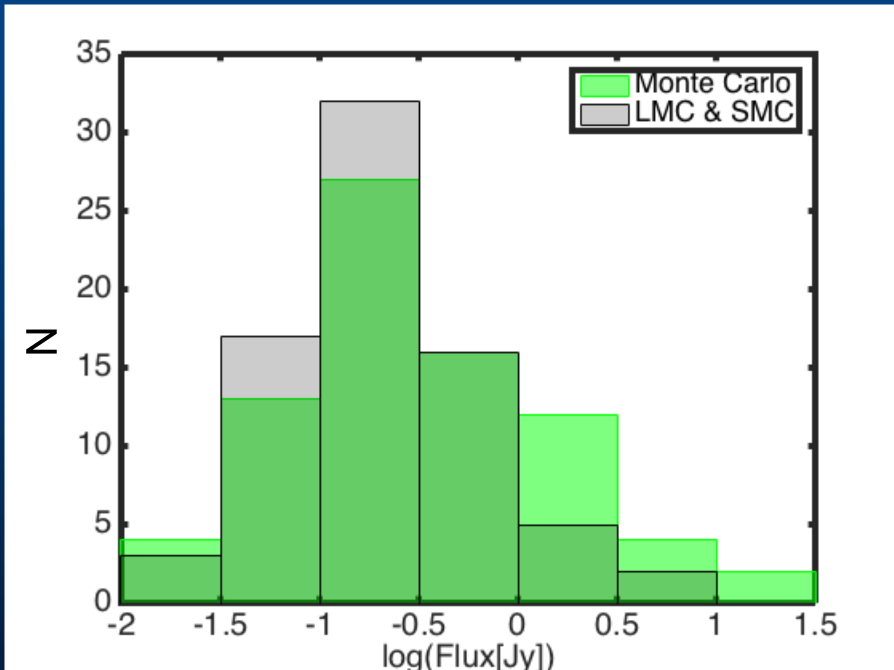
Monte Carlo results



Barniol Duran, Whitehead, Giannios (2016)

Monte Carlo results



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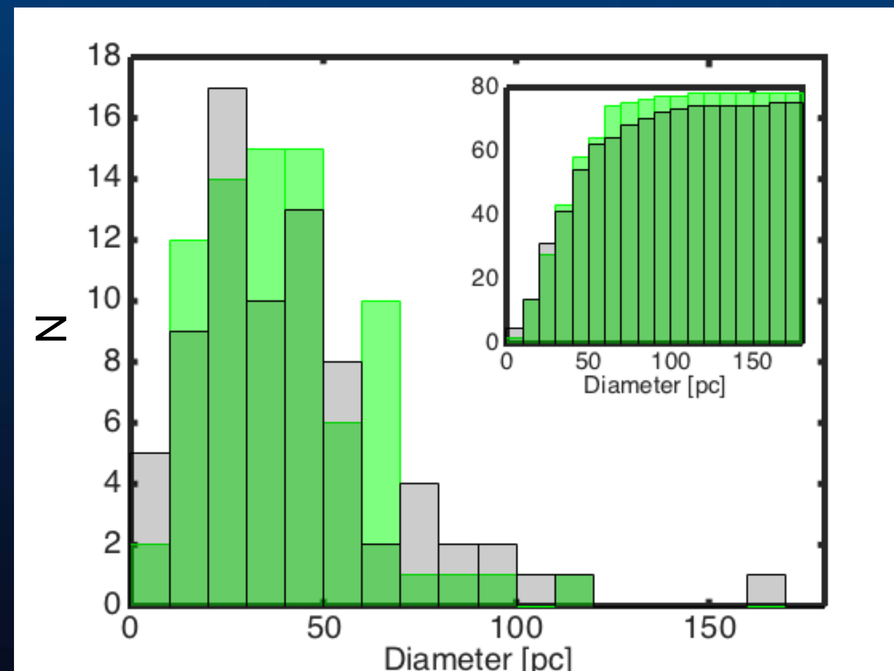

Nice agreement between Monte Carlo results and observations.

Similar range of ε_e and ε_B found in radio SNe early phases (< months).

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Implications of $\varepsilon_e \varepsilon_B = 10^{-3}$

1. $\varepsilon_e \sim \varepsilon_B \sim 0.03$ (Equipartition between electrons and B-field)

3 per cent of dissipated shock energy goes to ~1 MeV electrons

A smaller fraction $\varepsilon_e (m_e/m_p)^{p-2} \sim 10^{-3}$ goes to >GeV electrons

Assume $\varepsilon_p \sim 0.1$ of energy goes to non-thermal protons

Electron-to-proton injection ratio: $K_{ep} \sim 10^{-2}$ (consistent with observed cosmic ray composition at Earth at ≥ GeV, e.g., Meyer 1969; Picozza et al. 2013)

2. $\varepsilon_p \sim 0.2$, $\varepsilon_B \sim 0.2$ (Equipartition between protons and the B-field)

Constraint yields $\varepsilon_e \sim 0.004$, and $K_{ep} \sim 10^{-3}$
Consistent with PIC simulations (e.g., Park et al. 2015)

In both scenarios, B-field amplification is by a ~ few tens
Similar to that obtained in GRB relativistic shocks (e.g., Barniol Duran 2014; Santana, Barniol Duran & Kumar 2014).

Summary

Radio SNRs in the Magellanic Clouds are produced via synchrotron emission in the SN blast wave.

The radio SNRs in the Clouds are most likely in the Sedov-Taylor (adiabatic) phase.

The range of fluxes of the radio SNRs can be attributed to the spread in SN kinetic energies, while keeping the microphysical parameters constant.

We confirm the previous point using a Monte Carlo scheme.

We constrain the microphysics to be $\varepsilon_e \varepsilon_B = 10^{-3}$ for all radio SNRs in the Clouds (although this model might be over simplistic).