Observational constraints on the maximum energies of accelerated particles in supernova remnants

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1. Particle released from supernova remnants

- **Galactic cosmic rays (< 3 PeV)**
  - Most plausible sources: supernova remnants (SNRs)
  - > 10 TeV particles are in fact accelerated (e.g., Ahnen+17)
  - Softer spectra for older SNRs: gradual particle release
- **Question: properties of released particles**
  - energy spectrum: index, maximum energy
  - release timescal
  - Big problem as the supply process of Gaactic. cosmic rays

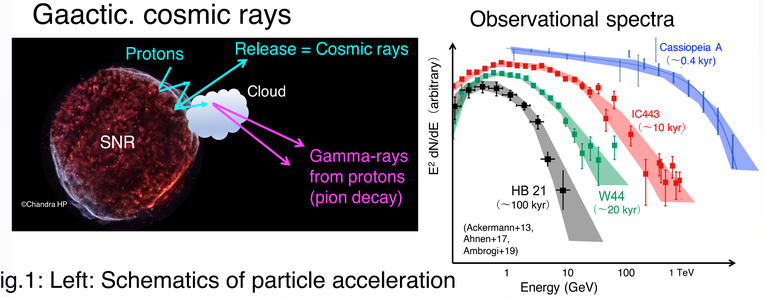
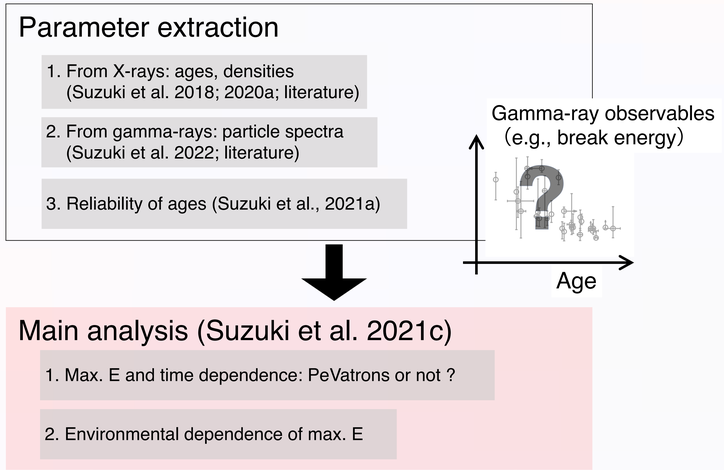


Fig.1: Left: Schematics of particle acceleration and release in SNRs. Right: Spectral difference of SNRs with different ages

2. Purpose and method

- Purpose: energy spectra of released particles and their evolution
- Method: systematic study for 38 gamma-ray emitting SNRs



3. Parameter extraction (1)

- Purpose: Get ages based on thermal X-ray plasma properties (density, temperature, ionization state) (Sedov+59, Itoh&Masai+89, Zhang+19)
- Method & Results: ① 2 SNR analyses: HB 21 & G359.1-0.5
  ② 36 others: ages based on the literature

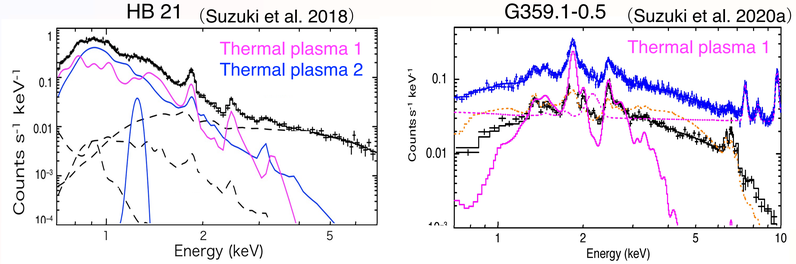


Fig.2: X-ray spectra and the best-fit models for two SNRs

3. Parameter extraction (2)

- Purpose: Get gamma-ray spectral parameters (luminosity, cutoff, break, hardness ratio, ...)
- Method & Results: ① Fermi spectral extraction for 15 SNRs
  ② Spectral modeling for all the 38 SNRs

SNR	GeV	TeV
Cassiopeia A (G111.7−2.1)	○	○
CTB 109 (G109.1−1.0)	△	—
CTB 37 B (G348.7+0.3)	○	○
Cygnus loop (G74.0−8.5)	△	—
G349.7+0.2	○	○
Gamma-cygni (G78.2+2.1)	○	○
Kes 79 (G33.6+0.1)	○	○
MSH 11-62 (G291.0−0.1)	△	—
MSH 11-56 (G336.3−01.8)	△	—
Puppis A (G260.4−3.4)	○	upper limit
RCW 103 (G332.4−0.4)	○	○
RCW 86 (G315.4−2.3)	○	○
RX J1713-3946 (G347.3−0.5)	○	○
SN 1006 (G327.6+14.6)	○	○
Tycho (G120.1+1.4)	△	○
W 51 C (G49.2−0.7)	○	○
3C 391 (G31.9+0.0)	△	○
CTB 37 A (G348.5+0.1)	○	○
G166.0+4.3	△	—
G359.1−0.5	○	○
HB 21 (G89.0+4.7)	△	—
HB 9 (G160.9+2.6)	○	—
IC 443 (G189.1+3.0)	○	○
Kes 17 (G304.6+0.1)	△	○
W 28 (G6.4−0.1)	○	○
W 44 (G34.7−0.4)	○	○
W 49 B (G43.3−0.2)	○	○
CTB 33 (G337.0−0.1)	○	—
G150.3+4.5	○	—
G24.7+0.6	○	—
G353.6−0.7	○	○
G73.9+0.9	○	—
HB 3 (G132.7+1.3)	○	—
Monoceros nebula (G205.5+0.5)	△	—
Vela Jr. (RX J0852.0−4622; G266.2−1.2)	○	○
S 147 (G180.0−1.7)	△	—
W 30 (G8.7−0.1)	○	○
W 41 (G23.3−0.3)	○	○

Table 1: Gamma-ray emitting SNRs used in this work

Suzuki et al. 2022, ApJ

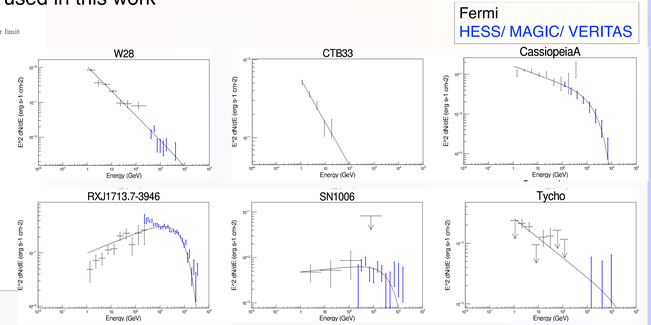


Fig.3: Gamma-ray spectra and the best-fit exponential cutoff PL models

5. Conclusion

- A systematic study on gamma-ray spectra of 38 SNRs is performed
- We find low maximum energies (but may reach PeV at 10 yr) & large variety (1–2 orders of magnitudes)

For more details...
Suzuki et al. 2018, PASJ; 2020a, ApJ; 2020c, PASJ; 2021a, ApJ; 2022, ApJ

3. Parameter extraction (3)

- Purpose: Calibration of SNR age
- Method & Results: Use the systems where reliable age estimation is possible (historical, light-echo, ejecta motion, kinematics of neutron star)
- Result: two general age estimates are reliable within a factor of 4

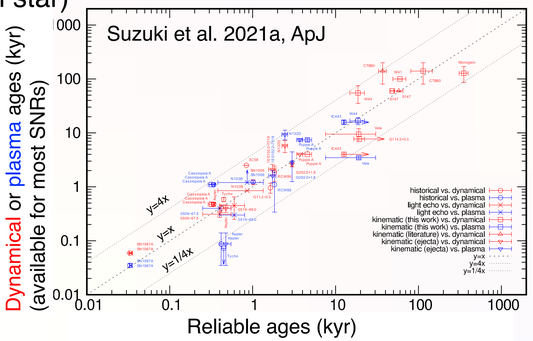


Fig.4: Relation between the reliable age and two general age estimates for SNRs

4.Main analysis

- Maximum E candidates: E_{cut}, E_{br} are < PeV
- Modeled evolution : $E_{cut} = 1.3\ (0.67\text{–}2.4)\ \mathrm{TeV}\ (t_b/1\ \mathrm{kyr})^{-0.81\pm0.24}$
  $E_{br} = 270\ (140\text{–}510)\ \mathrm{GeV}\ (t_b/1\ \mathrm{kyr})^{-0.77\pm0.23}$
- Large variety of E_{cut}, E_{br}: 1–2 orders of magnitude
  → dependence on environments

Suzuki et al. 2022, ApJ

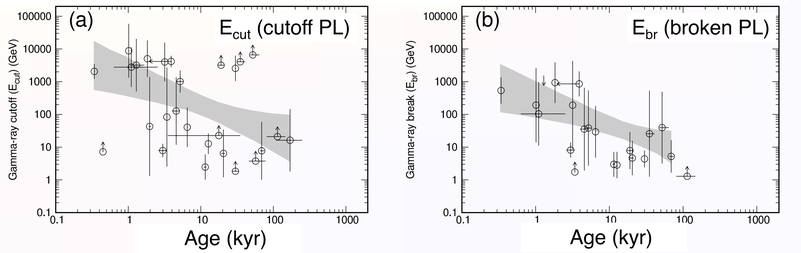


Fig.5: Gamma-ray parameters as a function of age