Observational gamma-ray and X-ray study on cosmic-ray escape from supernova remnants

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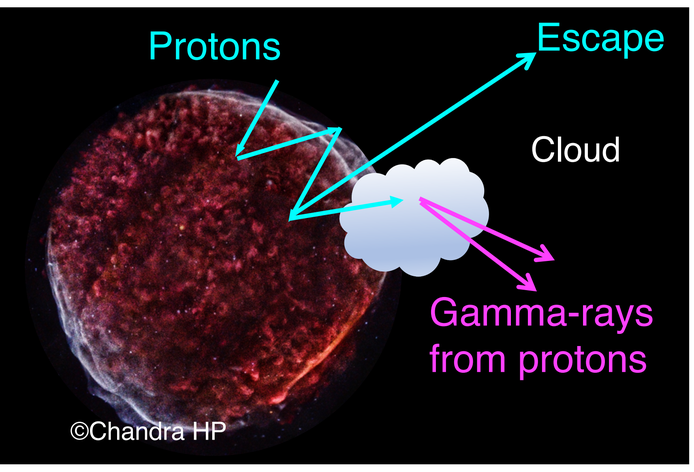
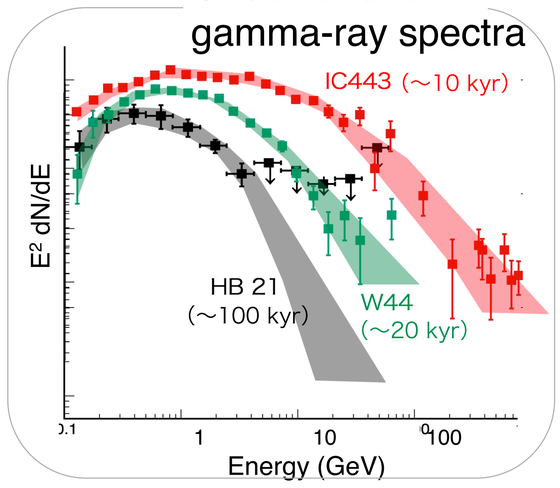
Introduction

- **Problem:** On which timescale accelerated particles escape from supernova remnants (SNRs) and become cosmic rays ?
- **Particle escape have developed well in old SNRs**
  - Theories: escape from higher-energy particles (e.g., Ptuskin+03,05; Ohira+10,11)
    = Spectrum becomes softer with particle escape
  - Observations: softer gamma-rays in older SNRs
    = Escape developed more in old SNRs
    -> Timescale of particle escape ?
    Dependence on environments ?



Observational gamma-ray spectra



Purpose & Method

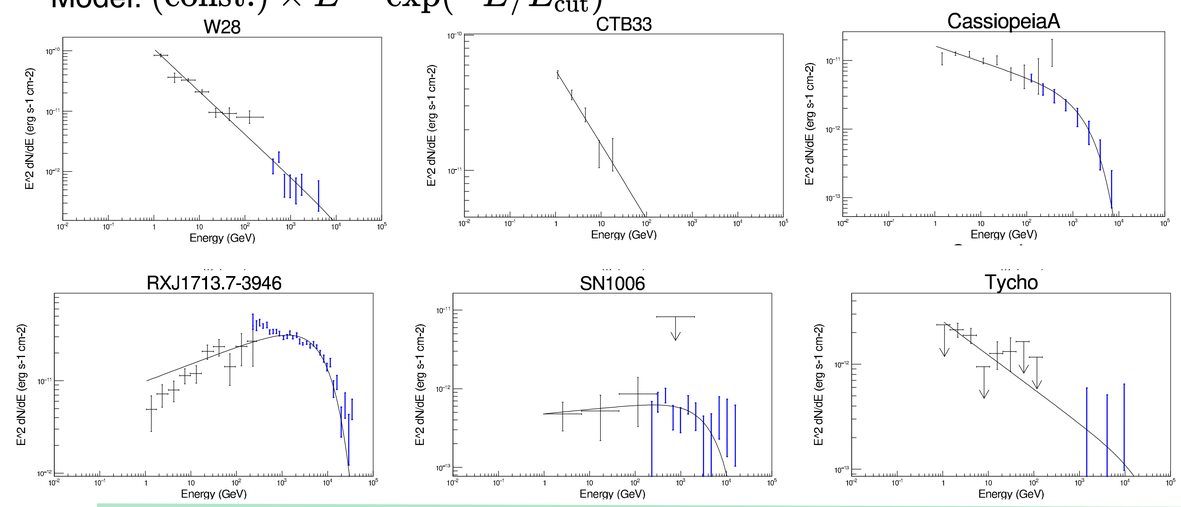
- **Purpose**: Measure particle escape timescale and its variety among SNRs
- **Analysis 1:** Extract indicators of particle escape from gamma-ray spectra
  -> See average temporal evolution of particle escape
  - SNR age: historical, dynamical, plasma age, etc. (Suzuki+ in prep. on reliability of ages)
  - Indicators of escape from gamma-ray spectrum:
    - Cutoff/Break energy (E_{cut}/E_{br}) ~ E_{max} of acceleration
    - Hardness ratio
    - Normalized luminosity
      ~ Total energy of confined protons normalized by spectral height@1 GeV
- **Analysis 2:**
  Compare observables to general analytical model of particle escape -> Constrain physical parameters of particle escape and thier variety

Analysis & Results

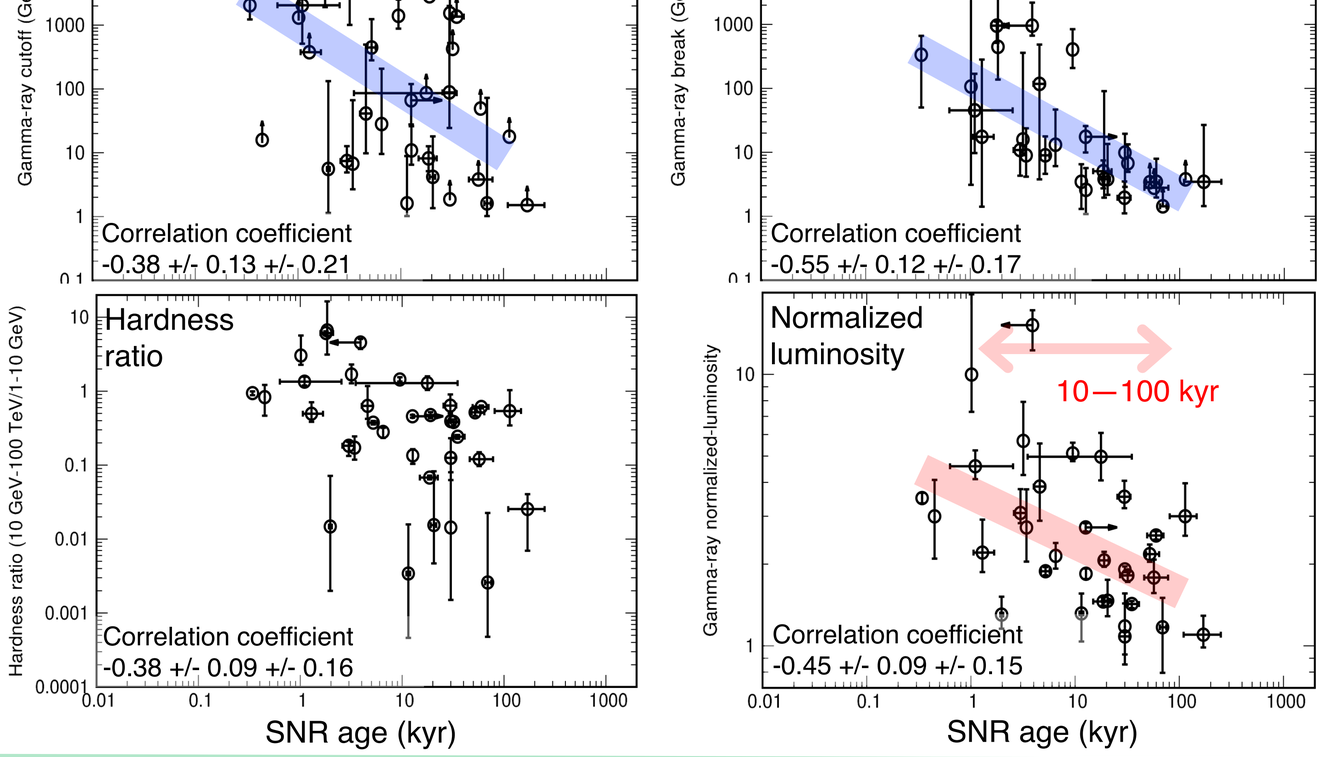
- **Sample selection** (Acero+16; Zeng+19)
  - From 1st Fermi SNR catalog & preceding systematic gamma-ray study: 38 SNRs
  - Gamma-ray spectra: our analysis on Fermi (15 SNRs) or literatures (23 SNRs) (Suzuki PhD thesis in prep.)
- **Analysis 1: Gamma-ray spectral modeling:** (Suzuki PhD thesis in prep.)
  - Markov-Chain Monte-Carlo method is used
  - Cutoff / Broken power-law models assumed

ex.) Cutoff power-law modeling results
Model: $(\mathrm{const.}) \times E^{-\Gamma} \exp(-E/E_{\mathrm{cut}})$

Fermi
HESS/ MAGIC/ VERITAS

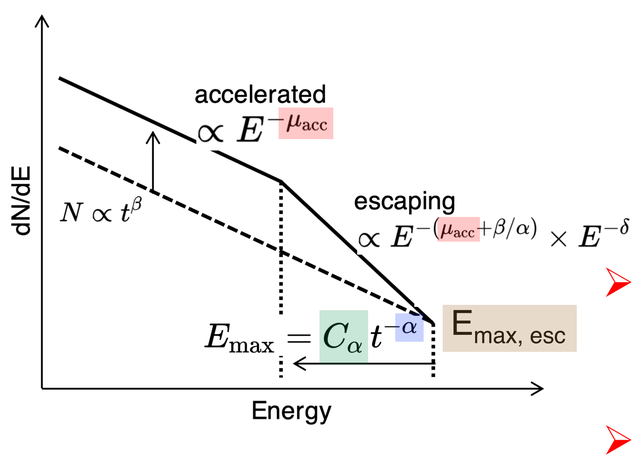


- **Result 1**
  - All parameters below show decreasing trends with age
  - Average escape timescale (of total energy of confined protons): 10—100 kyr
  - Large dispersion of observables of ≲ three orders of magnitude

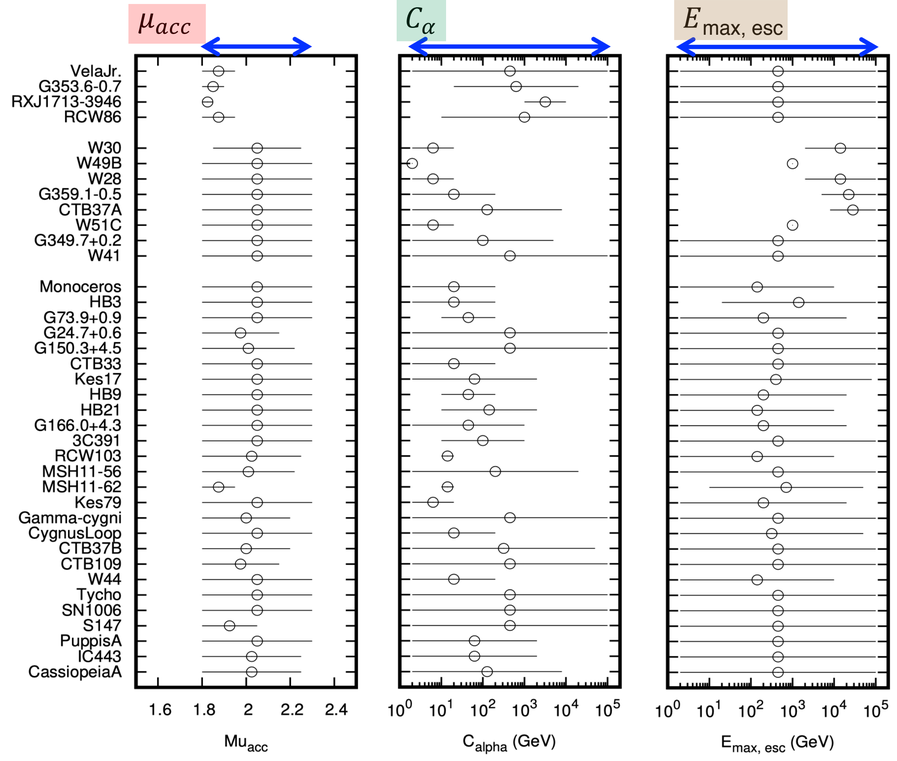


- **Analysis 2: Compare observables to analytical model to constrain physical parameters** (Ohira+10, 11)
  - Free parameters of the model:
    - μ_{acc}: spectral index of accelerated particles
    - α: determines escape timescale
      = 0.5—1.0 (common among SNRs) from decreasing trends of E_{cut} & E_{br} (Result 1)
    - C_α (GeV): E_{max} of acceleration@1 kyr
    - $E_{max,\,esc}$ (GeV): E_{max} of emission from escaping particles
    - δ, β: determine spectral index of escaping particles
  - Observables compared between obs. and models:
    - Age
    - Fitted Γ
    - Fitted E_{cut}
    - Hardness ratio
    - Normalized luminosity

Model spectra are fitted in same way as done for obs. spectra



- **Result 2:** accepted parameter ranges for each SNR



- C_α (∝ E_{max} in lifetime), $E_{max,\,esc}$ significantly vary among objects = First quantitative evidence for variety of E_{max} during lifetime and environment of escaping particles
- $C_\alpha \propto \xi_{CR}^{1-2}\, E_{SN,kin}^{0.6-1.6}\, n^{-(0.6-1.6)}\, B_0^{-(0-3)}$ -> large dispersion of observables possibly due to variety of these params. (Ptuskin+03)