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

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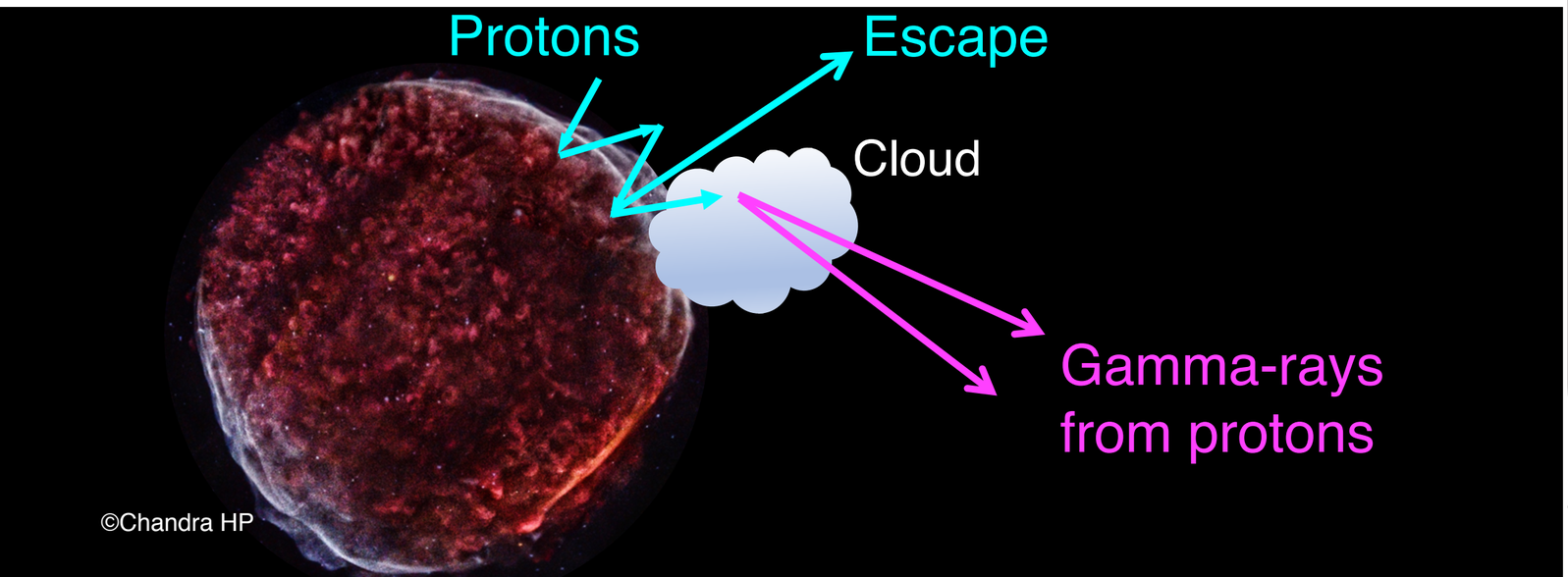
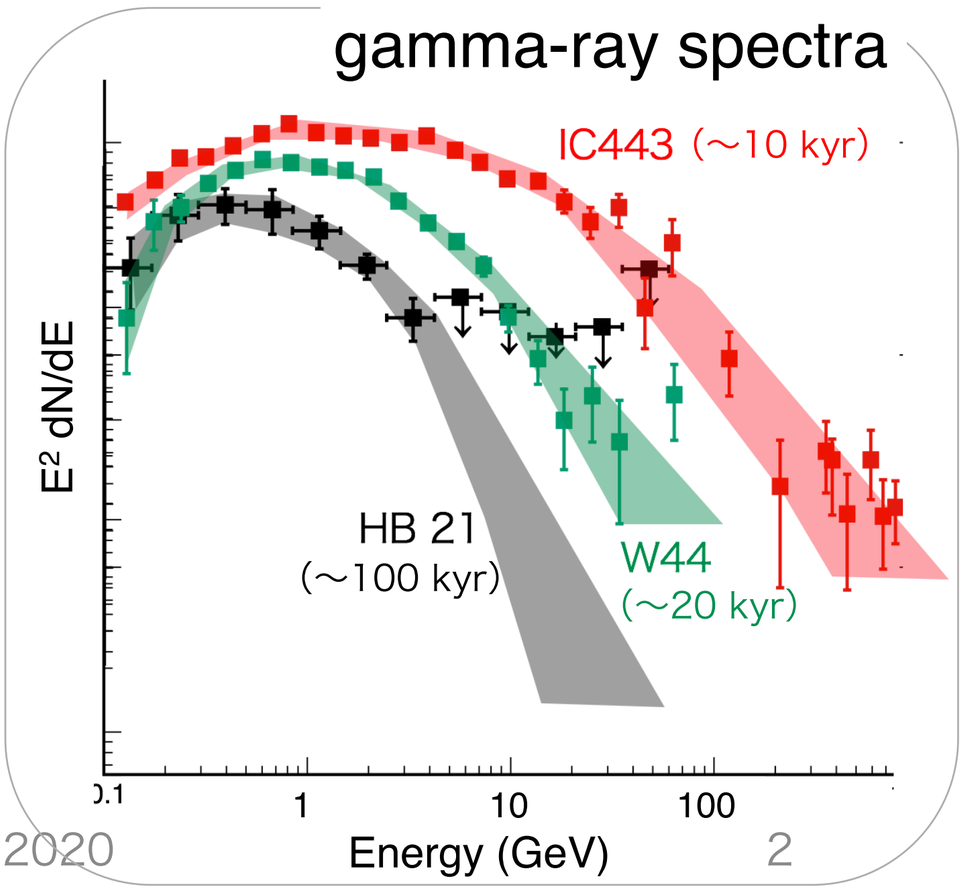
Particle escape from supernova remnants

- **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 ?



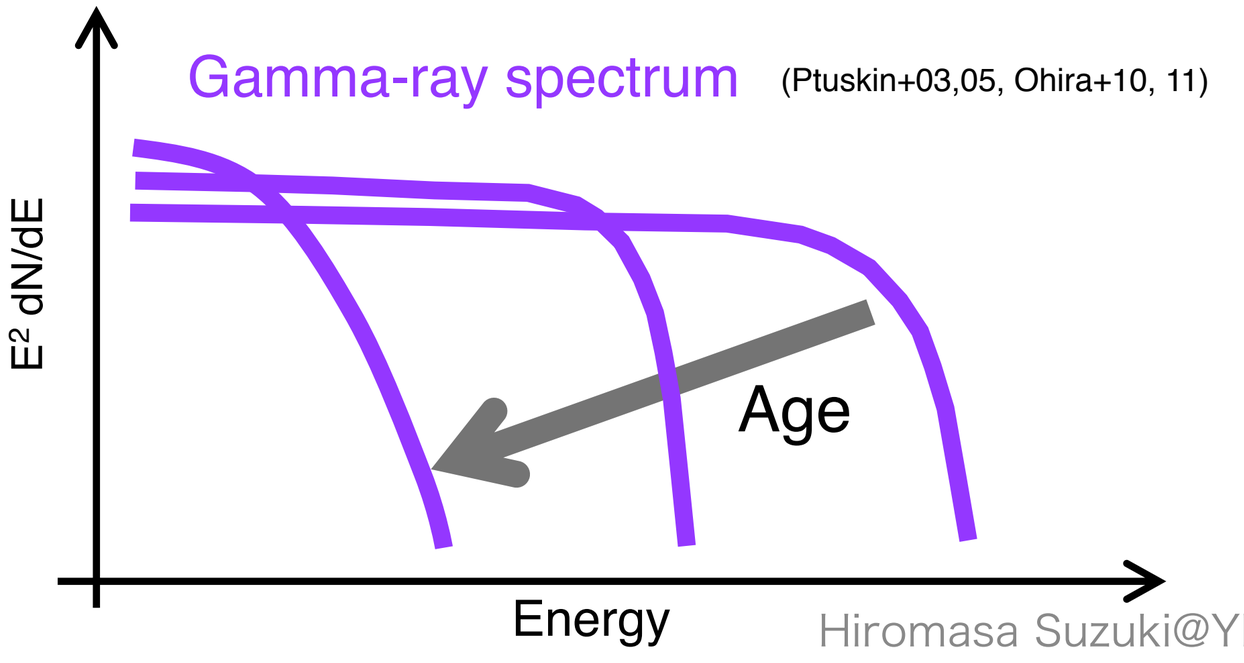
Observational gamma-ray spectra

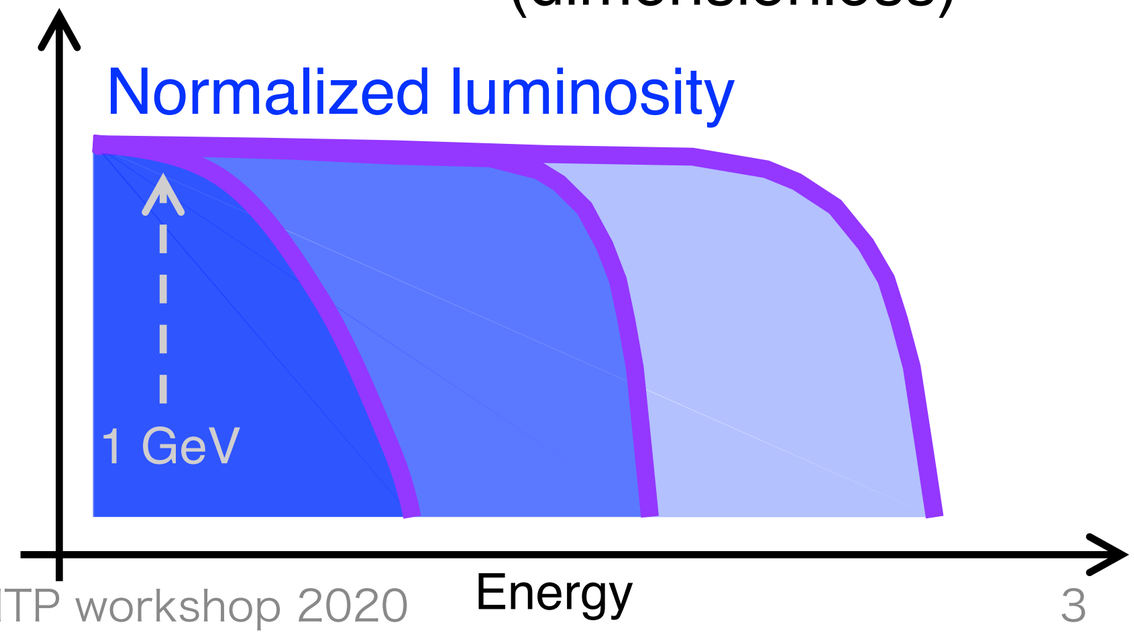


Purpose and method of this work

- **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 taken from gamma-ray spectrum:
    - Cutoff/Break energy (E_{cut}/E_{br}) ~ Maximum energy of acceleration E_{max}
    - Hardness ratio
    - Normalized luminosity ~ Total energy of confined protons normalized by spectral height (dimensionless)

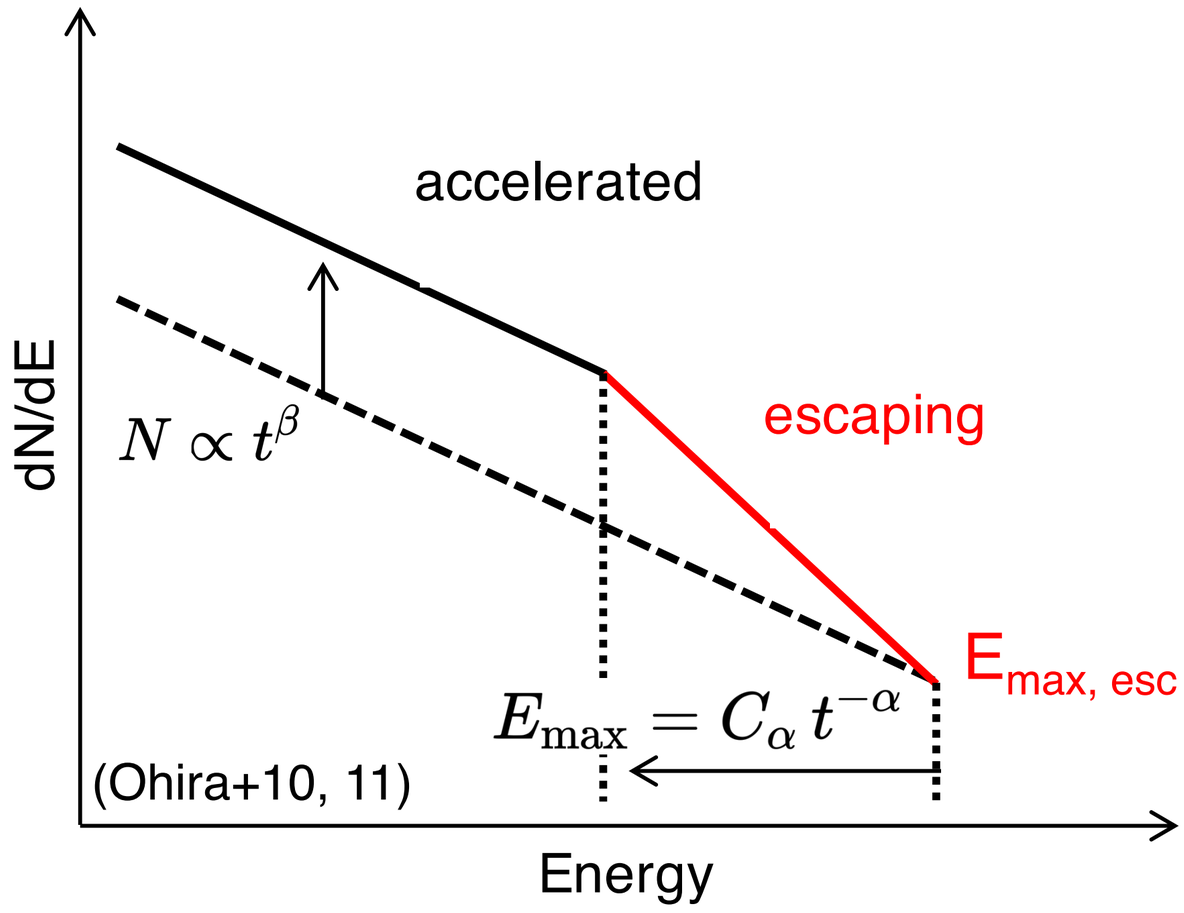




Purpose and method of this work

- **Purpose**: Measure particle escape timescale and its variety among SNRs

- **Analysis 2:**
  Compare observables to general analytical model of particle escape (Ohira+10,11)
  -> Constrain physical parameters of particle escape and thier variety



Sample selection & Analysis 1: gamma-ray spectral modeling

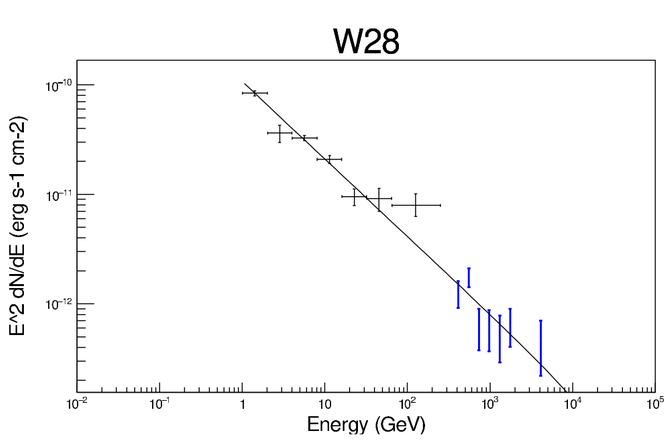
- **Sample selection**
  - From 1st Fermi SNR catalog & preceding systematic gamma-ray study : 38 SNRs (Acero+16; Zeng+19)
  - Gamma-ray spectra: our analysis on Fermi (15 SNRs) or literatures (23 SNRs) (Suzuki PhD thesis in prep.)
- **Analysis 1: Gamma-ray spectral modeling:** (Suzuki PhD thesis in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

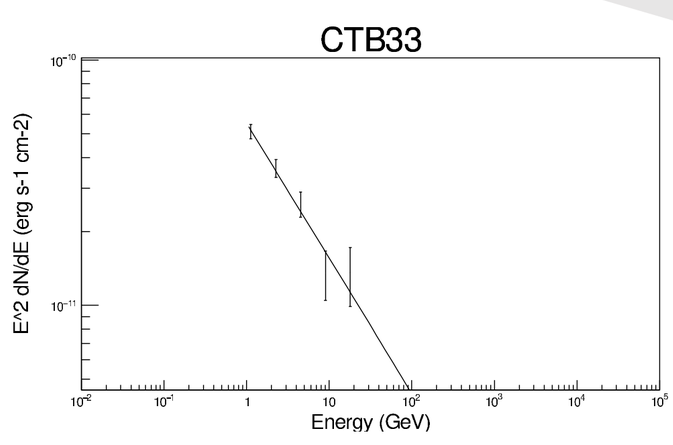
ex.) Cutoff power-law modeling results

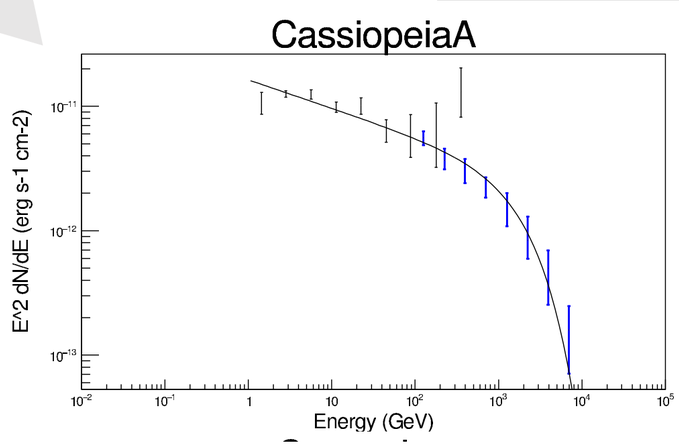
Model: $(\mathrm{const.}) \times E^{-\Gamma} \exp(-E/E_{\mathrm{cut}})$

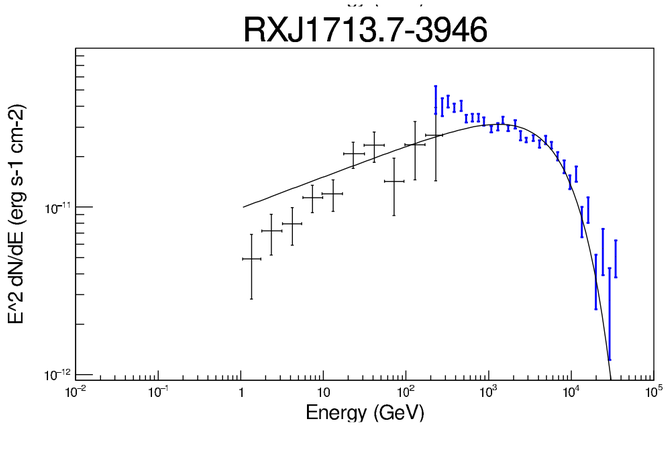
Good fit for almost all w/ this simple model

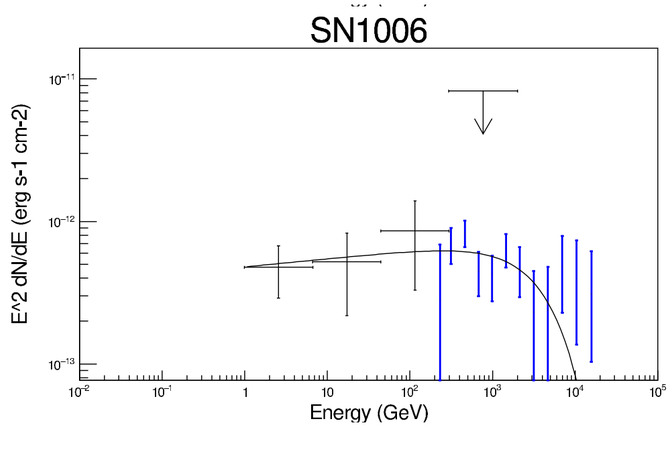
Fermi
HESS/ MAGIC/ VERITAS

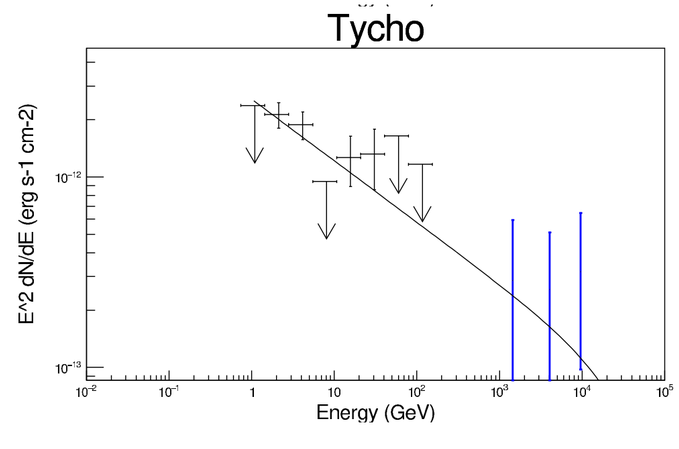






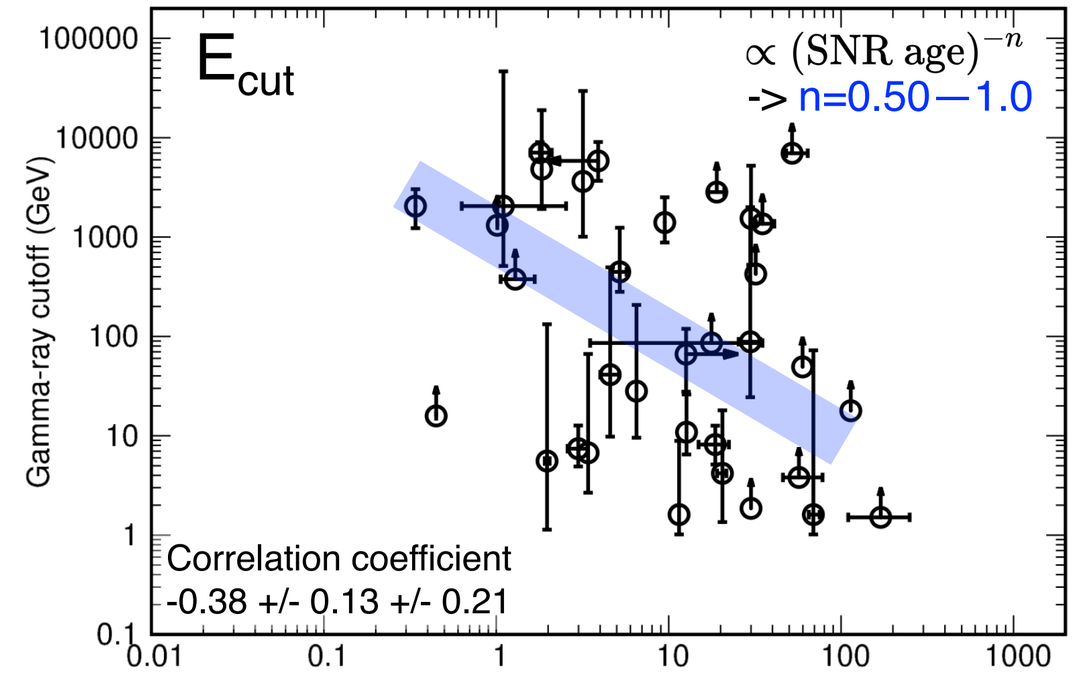


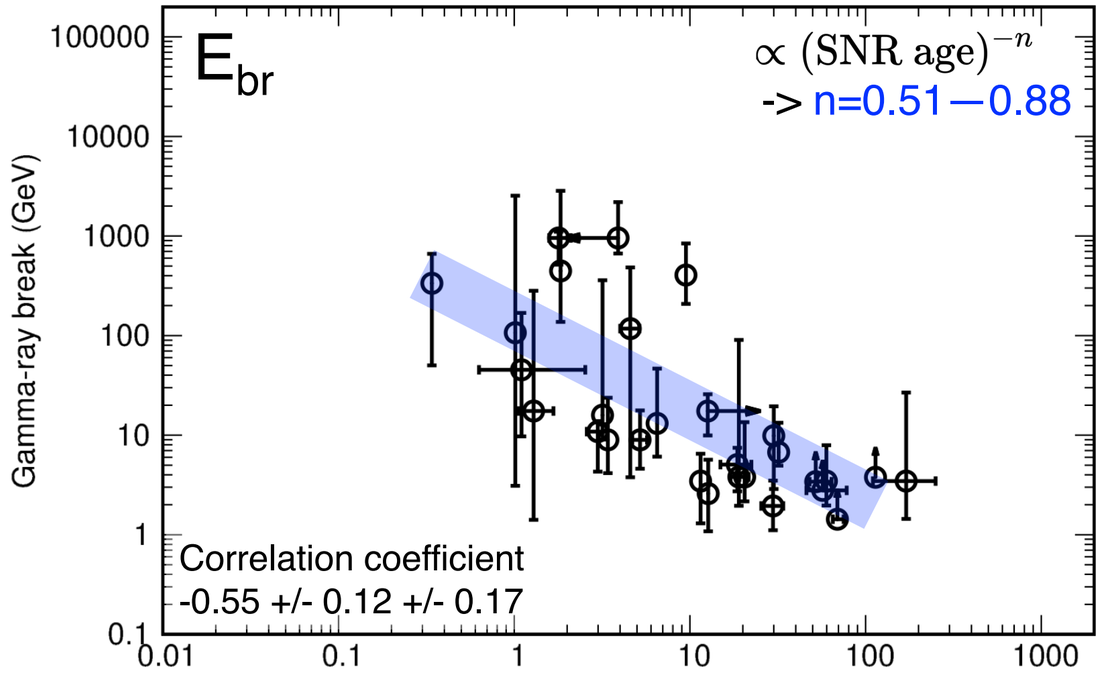


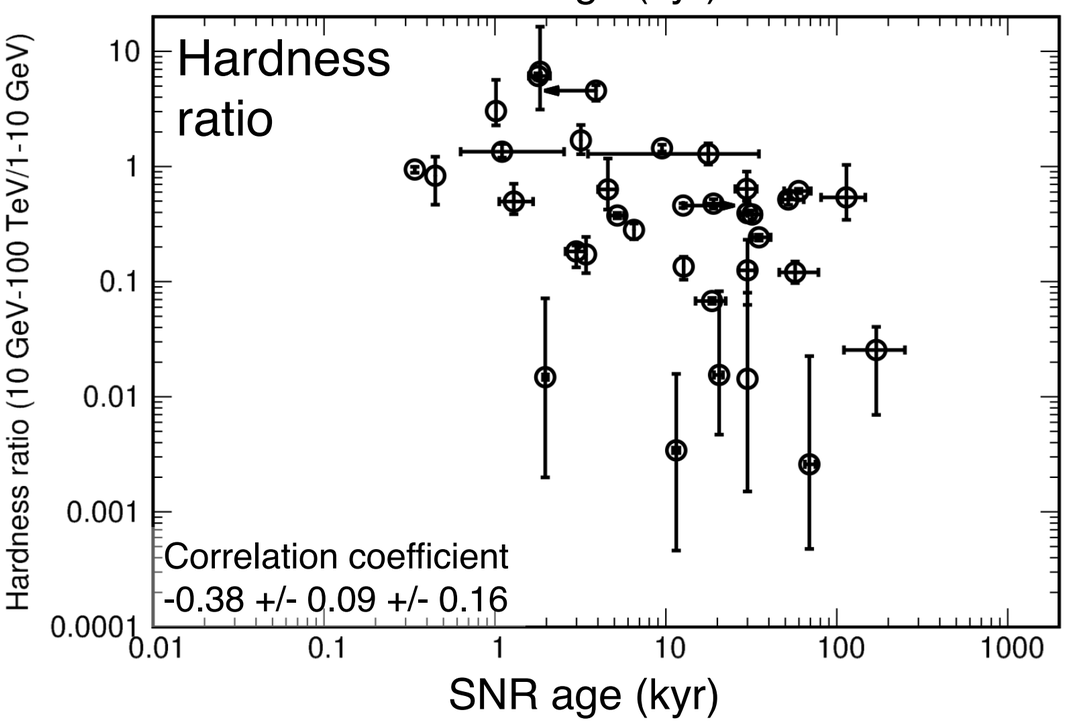


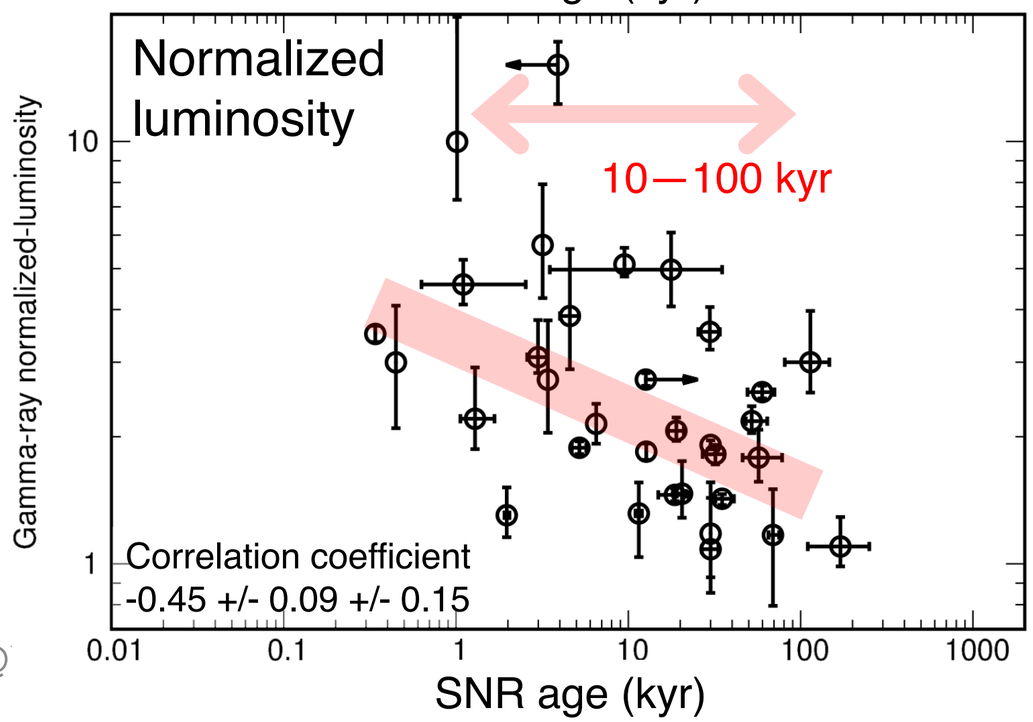
Result 1: average trend of observational parameters

- All parameters below show decreasing trends with age
- Average escape timescale (of total energy of confined protons): 10—100 kyr







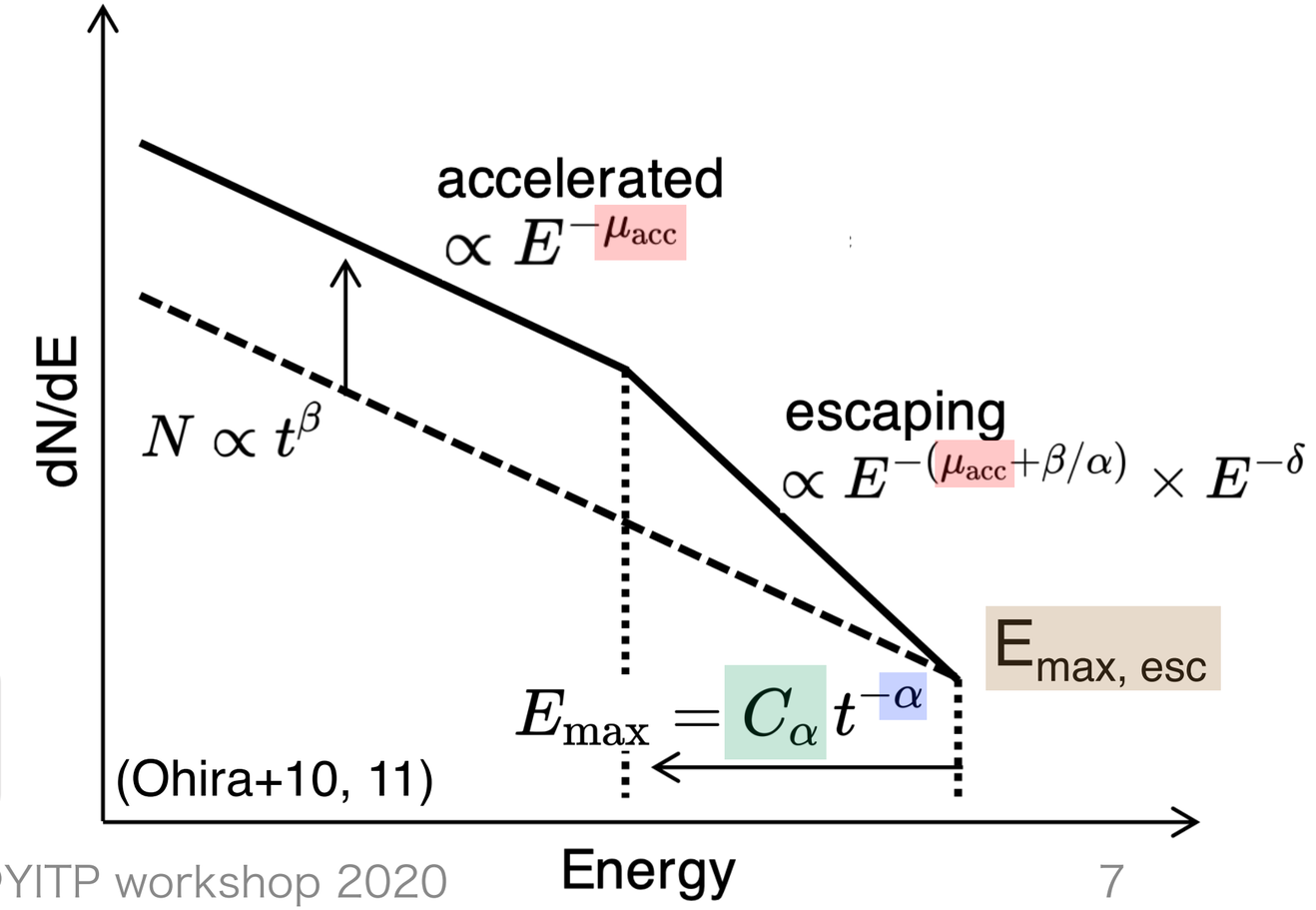


Analysis 2: Constraint on particle escape parameters

- **Compare observables to analytical model to constrain physical parameters**
  - Free parameters of the model: (Ohira+10, 11)
    - μ_{acc}: spectral index of accelerated particles
    - α: determines escape timescale
      = 0.5—1.0 (common) 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

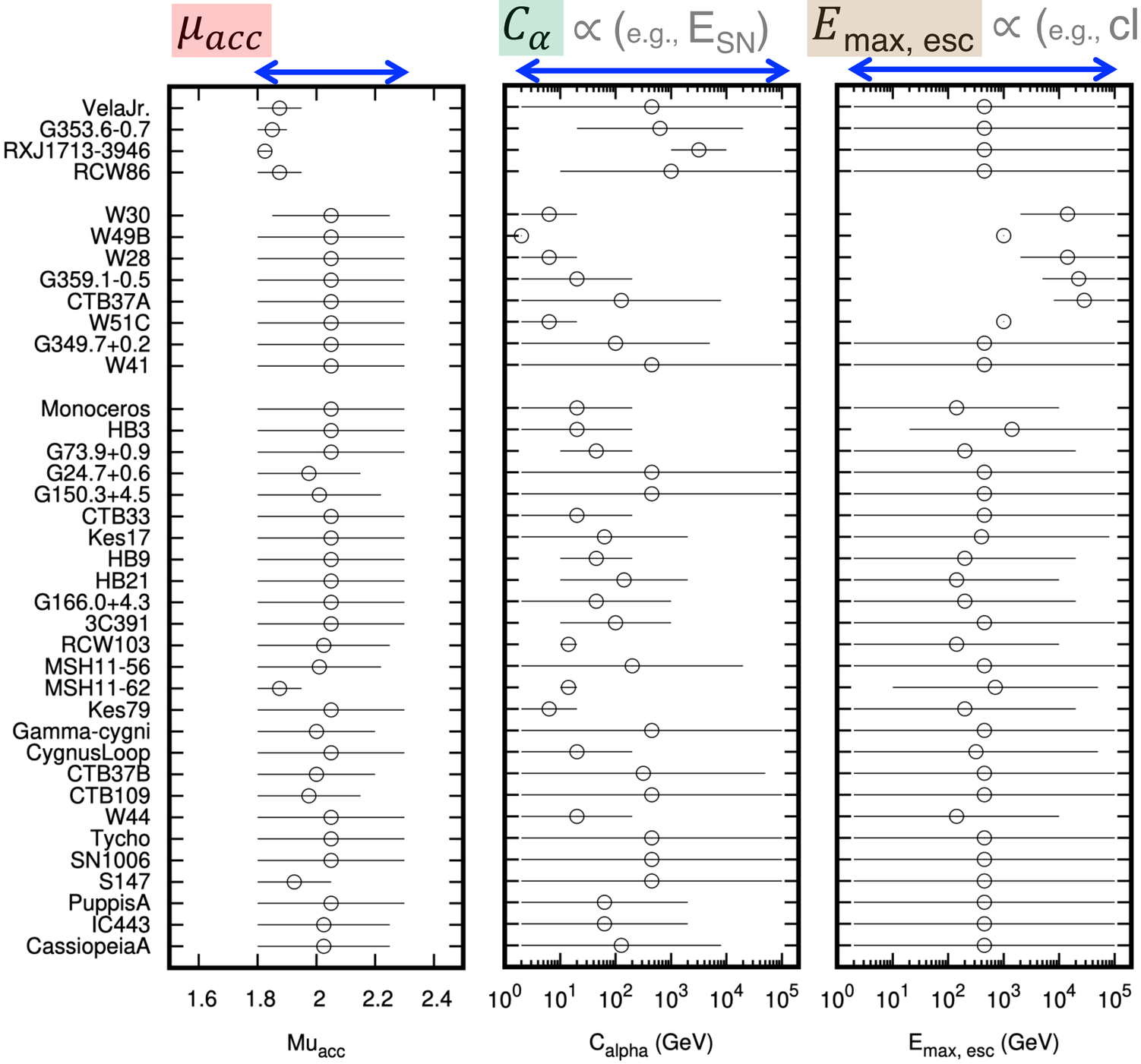
- Observables compared between obs. and models:
  - Age
  - Fitted Γ
  - Fitted E_{cut}
  - Hardness ratio
  - Normalized luminosity

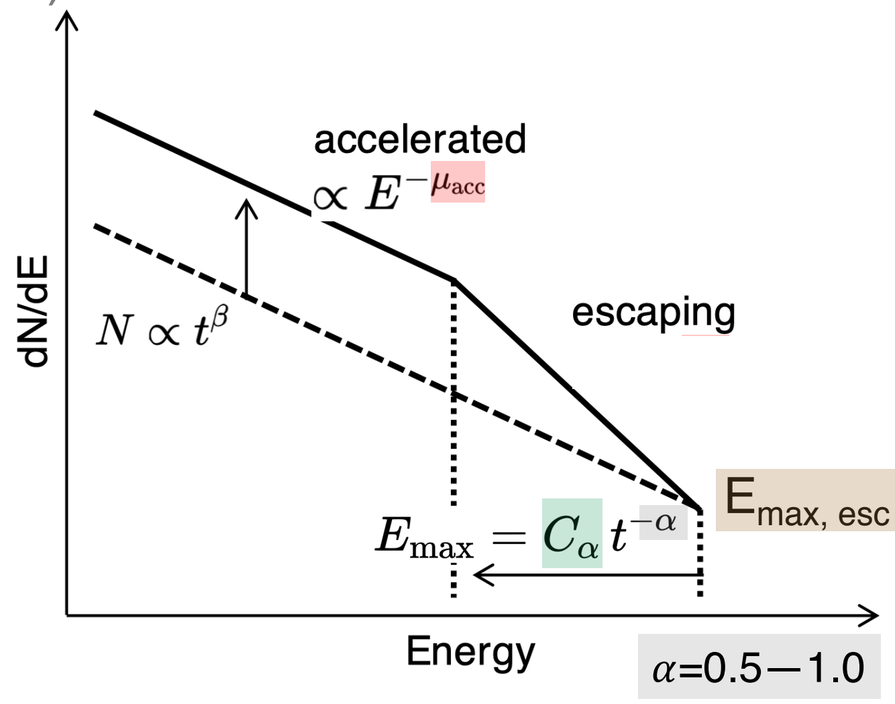
Model spectra are fitted in same way as done for obs. spectra

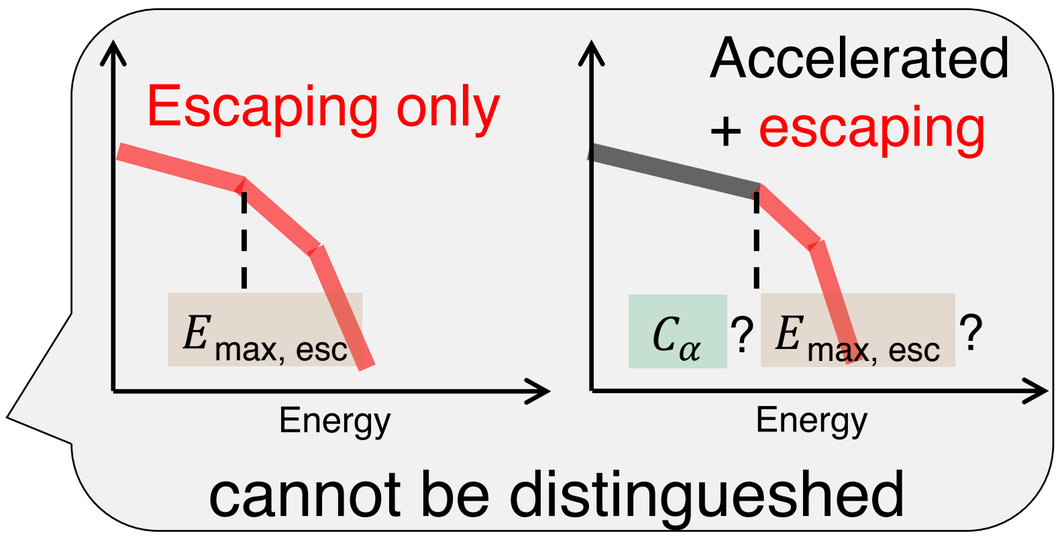


Result 2: Constraint on escape parameters

- Accepted model parameter ranges for each SNR (searched range)



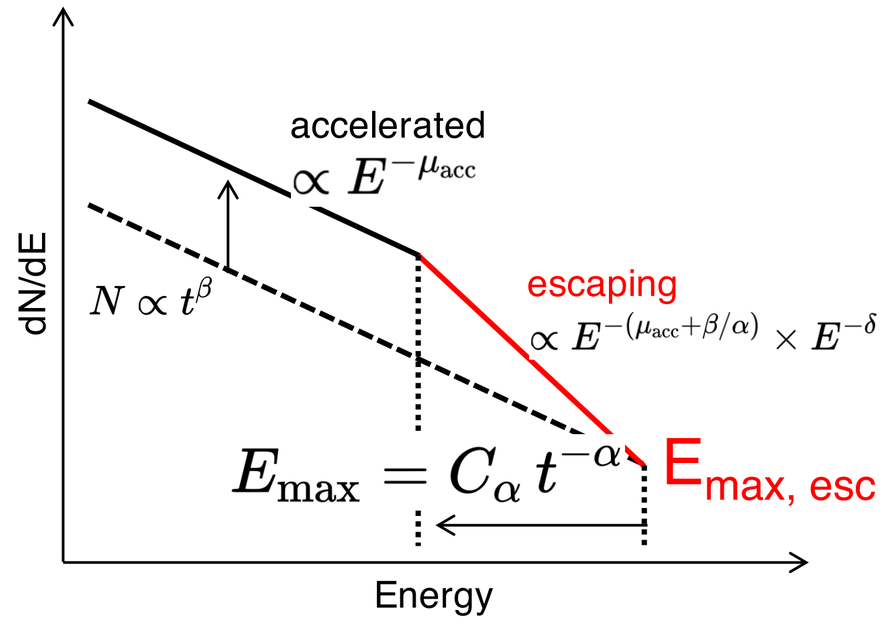




- C_α , $E_{max,\ esc}$ significantly vary among objects = First quantitative evidence for variety of E_{max} during lifetime and environment of escaping particles

Summary

- We are interested in particle escape timescale from SNRs and its dependence on environments
- We parameterized gamma-ray spectra and compared parameters to analytical model of particle escape
- Result 1:
  - E_{cut}, E_{br}, Hardness ratio, Normalized luminosity all show decreasing tendency with age
    -> Average escape timescale is 10—100 kyr
    Escape parameter α =0.5—1.0 assuming common value among SNRs
- Result 2:
  - C_α varies among SNRs
    = maximum energy of acceleration during lifetime varies
  - $E_{max,\ esc}$ varies among SNRs
    = environment of escaping particles varies



Publications (plans):
Suzuki et al., PASJ, 2020; Suzuki et al., ApJ, in prep.;
Suzuki PhD. thesis in prep.