Thermal X-ray Studies on Escaping of Accelerated Protons from SNR Shocks

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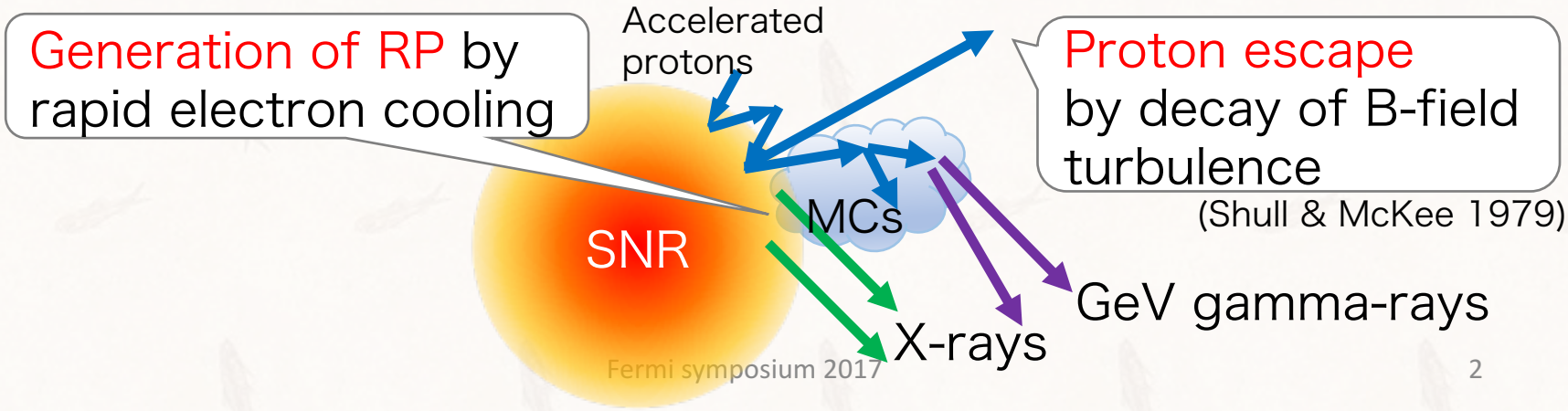
1. Escaping scenario of accelerated protons

- **Difficulty in cosmic ray escaping from SNR shocks**
  - **Fermi detections** of hadronic GeV emission from SNRs
    → Evidence for proton acceleration (e.g. W44, IC443; Ackermann et al. 2013)
  - Amplified magnetic field (B-field) (Bamba et al. 2005)
    → Protons are confined
  - How can protons escape to be cosmic rays ?

- **Common properties of GeV SNRs in other wavelength**
  - Interaction with molecular clouds (MCs)
  - Many have recombining plasma (RP; $kT_e < kT_{ionization}$)

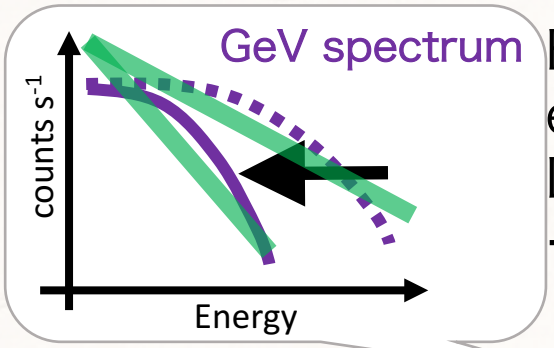
  } Same origin ?

- **Our escaping scenario :**
  Escaping & Recombination start simultaneously



2. What happens by shock-cloud interaction ?

Collision to MCs make B-field turbulece decay
→ **Start escaping**



Higher-E protons easily escape due to larger Larmor radius (Ohira et al. 2011)
→ Lower GeV braking energy
= Softer spectrum

Supernova explosion

Time

Rapid cooling of electrons
→ **Start recombination**

Recombination gradually converge to approach ionization equilibrium

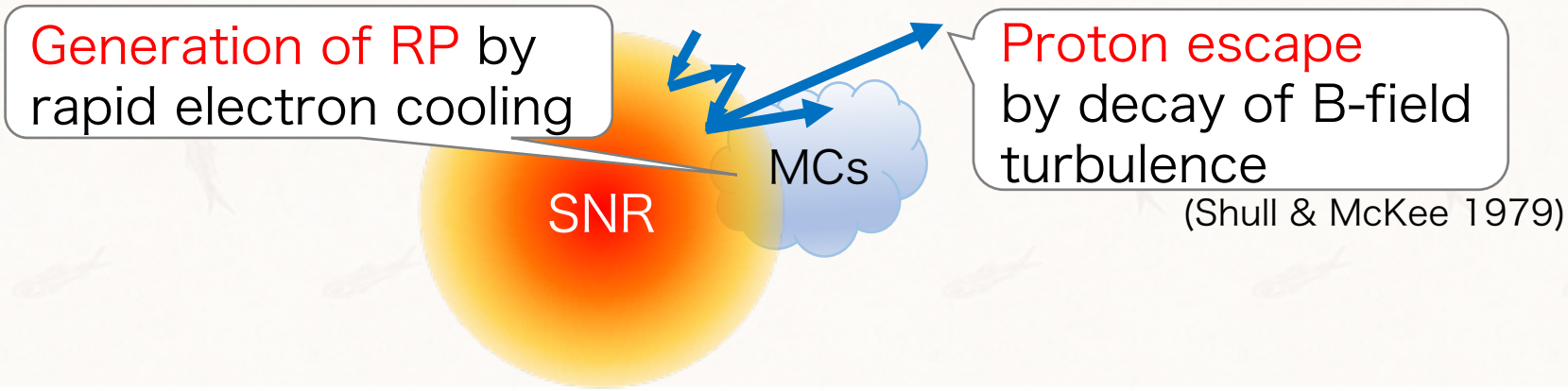
Plasma temperature

$kT_{\mathrm{ionization}}$

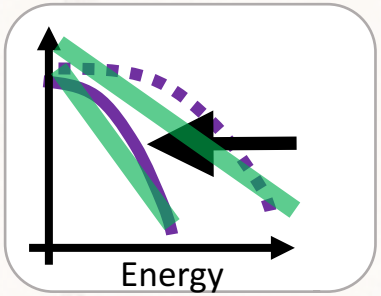
kT_{electron}

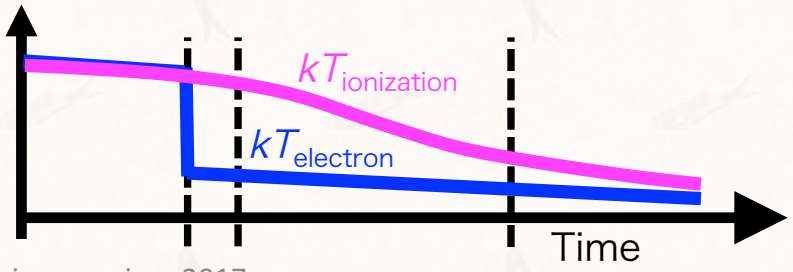
Time

3. Aim of this study



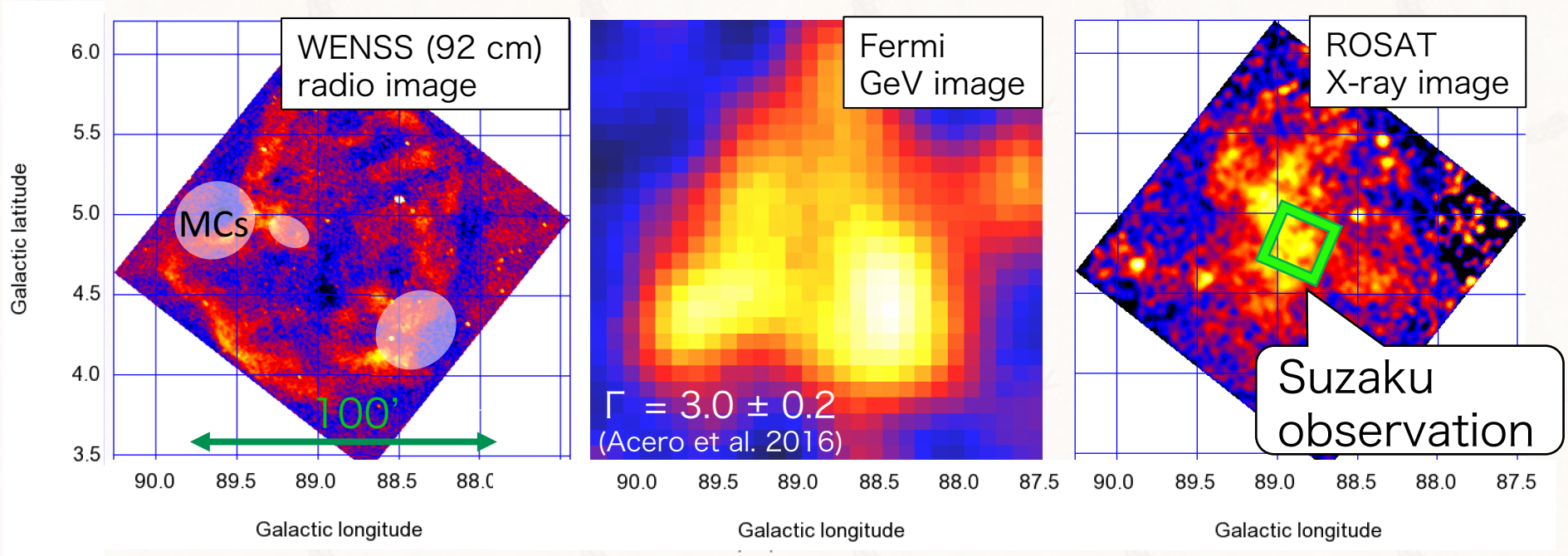
- According to our escaping scenario, we prospect SNRs with **softer GeV spectrum** have **older RP**
- We investigated the correlation between "GeV spectral index" (= progress of escaping of protons) and "Age of RP" (= time after rapid cooling of the plasma)





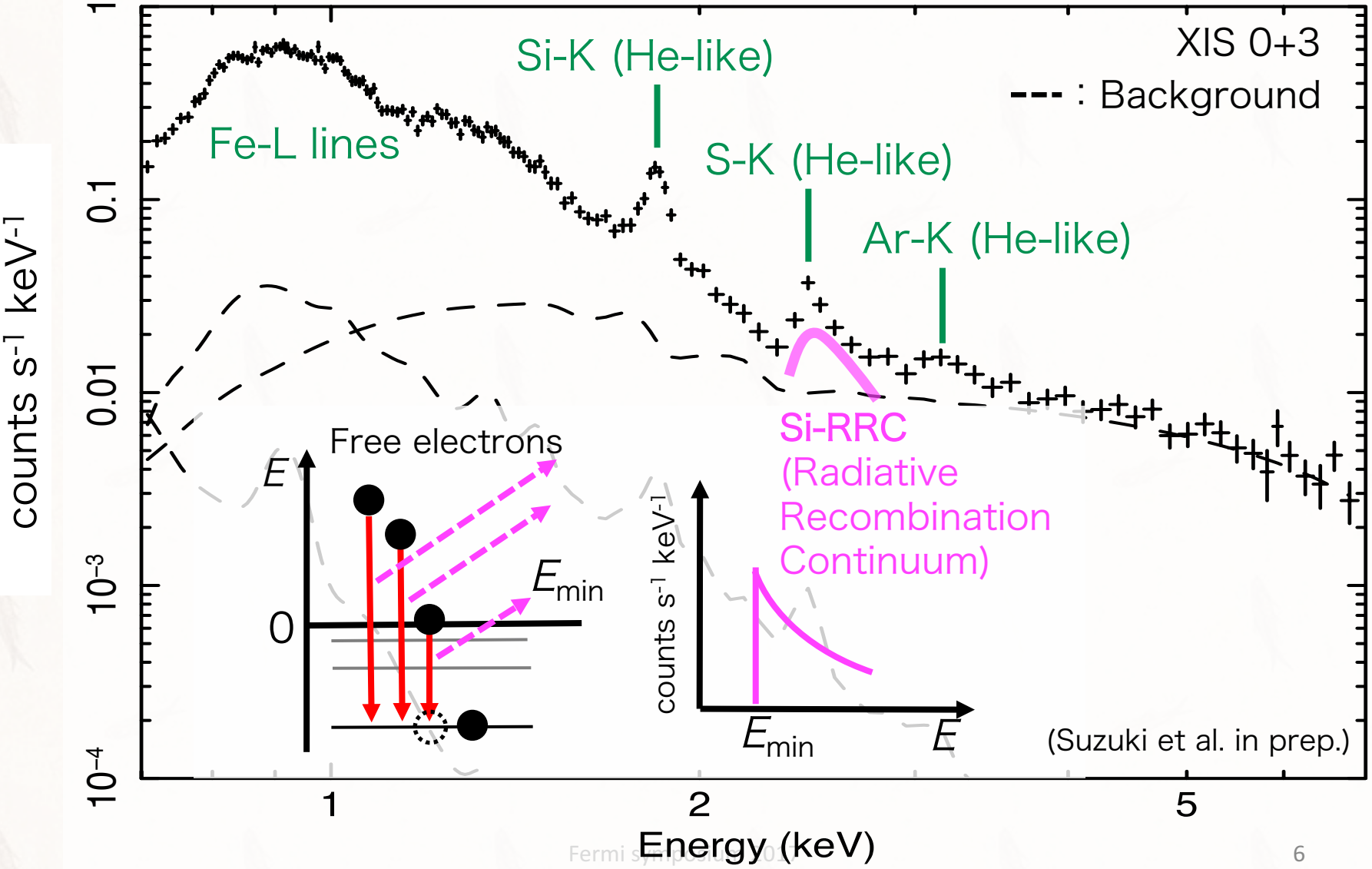
4. Faintest & softest GeV SNR HB 21

- GeV SNR **HB 21**
  - **Faintest & softest** in GeV band among known GeV SNRs (Pivato et al. 2013; Acero et al. 2016)
  - Interacting with MCs (Tatematsu et al. 1990; Koo et al. 2001; Byun et al. 2006)
- **Suzaku** X-ray observation
  - Suitable with low + stable background & accurate E calibration
  - 133 ksec observation with X-ray CCDs (XIS)
  - Investigated whether HB 21 also has RP, and RP is old ?



5-1. X-ray spectrum : signature of RP

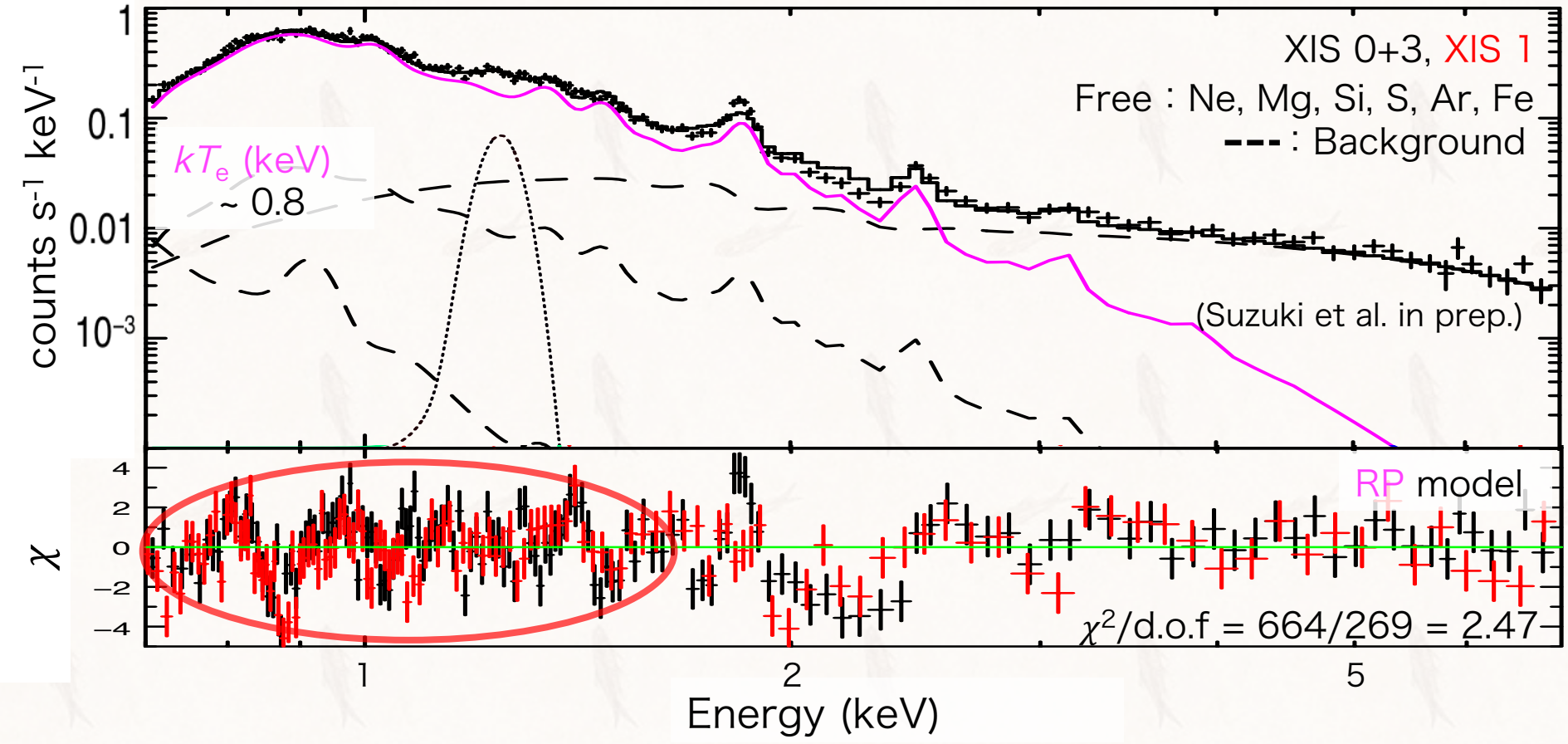
- We detected thermal plasma emission



5-2. X-ray spectroscopy : discovery of RP

(Suzuki et al. in prep.)

- Spectral fittings with RP model

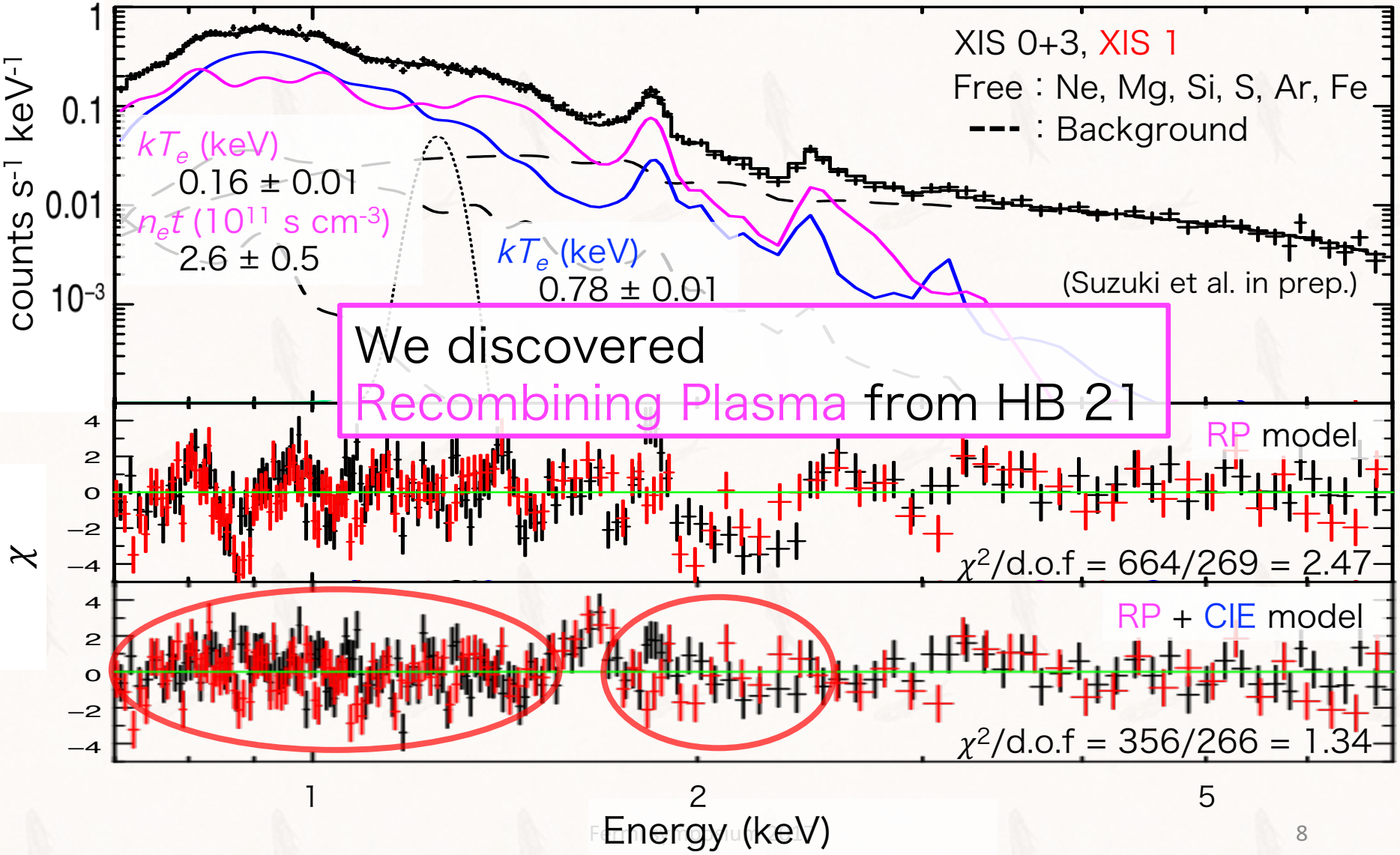


→ Spectra require another kT_e component

5-2. X-ray spectroscopy : discovery of RP

(Suzuki et al. in prep.)

- Spectral fittings with RP + Collisional Ionization Equilibrium (CIE)



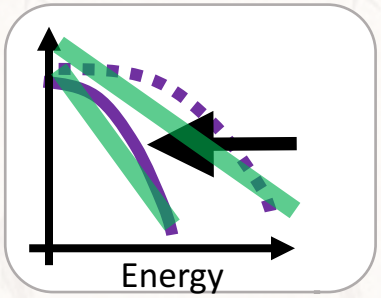
6. Oldest RP from HB 21

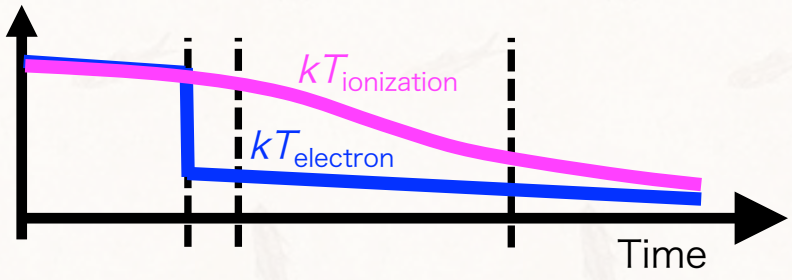
- **Faintest & softest** in GeV band among GeV SNRs
  ($(3.3 \pm 0.6)\times10^{34}$ erg s^{-1}, $\Gamma = 3.0 \pm 0.2$; Pivato et al. 2013, Acero et al. 2016)
- We found RP from X-ray analysis
- The RP is **oldest** among recombining SNRs

Recombination timescale : $n_e t$
$n_e \propto$ Luminosity$^{0.5}$ $V^{-0.5}$

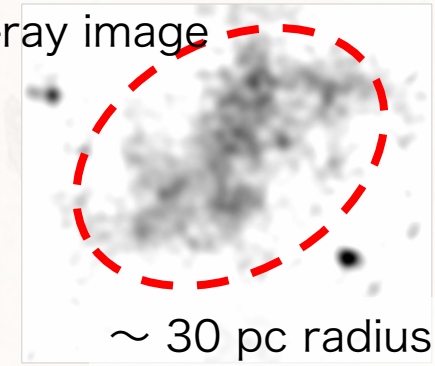
$n_e t \sim 3 \times 10^{11}$ s cm^{-3}
$n_e \sim 0.09$ cm^{-3}
→ $t \sim$ 100 kyrs

→ Support our escaping scenario





X-ray image



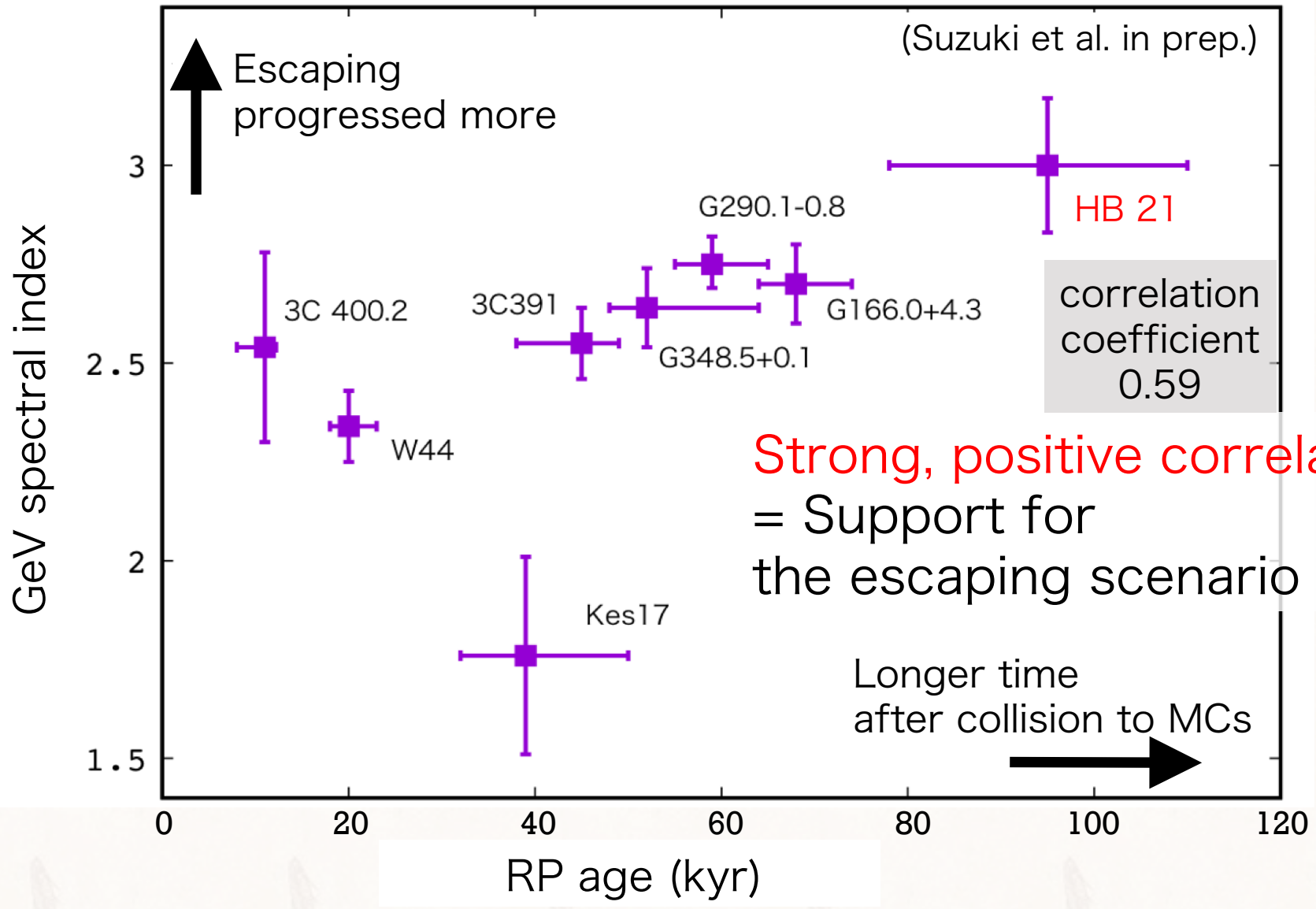
7. Other recombining GeV SNRs

- Compilation of published results
- First systematic study connecting **thermal X-ray** with **GeV gamma-ray** properties

Name	n_e (cm^{-3})	RP age (kyr)	GeV spectral index	References
IC443	2	?	2.34 (2.25-2.43)	Yamaguchi+09, Acero+16
W49B	7	?	2.36 (2.31-2.41)	Ozawa+09, Acero+16
G359.1-0.5	0.4	?	2.34 (2.25-2.43)	Ohnishi+11, Acero+16
W28	0.8	?	2.64 (2.60-2.68)	Sawada & Koyama+13, Acero+16
W44	1	20 (18-23)	2.34 (2.25-2.43)	Uchida+12, Acero+16
3C391	0.9	45 (38-49)	2.55 (2.46-2.64)	Sato+14, Ergin+14, Acero+16
Kes17	0.9	39 (32-50)	1.76 (1.51-2.01)	Washino+16, Acero+16
G290.1-0.8	0.7	59 (55-65)	2.75 (2.69-2.82)	Kamitsukasa+15, Auchettl+15
G348.5+0.1	0.8	52 (48-64)	2.64 (2.54-2.74)	Yamauchi+14, Acero+16
G166.0+4.3	0.9	68 (64-74)	2.70 (2.60-2.80)	Matsumura+17, Araya+13
3C400.2	0.5	11 (8.0-12)	2.54 (2.30-2.78)	Ergin+17
HB 21	0.09	95 (78-110)	3.00 (2.83-3.17)	This work, Acero+16

Selected these 8

8. RP age vs. GeV spectral index for 8 SNRs



9. Summary

- We propose an escaping scenario of accelerated protons from SNR shocks caused by collision to MCs.
- We conducted an X-ray analysis on the **faintest & softest** GeV SNR HB 21, and found the **oldest** Recombining Plasma (RP) among recombining SNRs.
- We compared "**RP age**" with "**GeV spectral index**" for 8 recombining GeV SNRs to get the evidence for the escaping scenario.
- We found a strong, positive correlation, which means at SNRs with **longer time after rapid cooling** of the plasma, **higher energy protons almost escaped** which supports the escaping scenario.