Multiwavelength studies of gamma-ray supernova remnants

Aya Bamba

(Aoyama Gakuin University)

0.1. Why are we interested in Suprenova Remnants (SNRs) ?

Most plausible Galactic cosmic ray accelerators !
Distributing heavy elements
Energy input into interstellar medium

Main contributor of the diversity of the universe !

It is still unknown ...

- how efficient SNRs can accelerate particles ?
- what determines the efficiency of acceleration ?
- how accelerated particles become cosmic rays ?

0.2. New questions of Supernova Remnants with Fermi

young SNRs have large photon index Γ !!

Cas A: Γ =2.17 (Yuan+13)

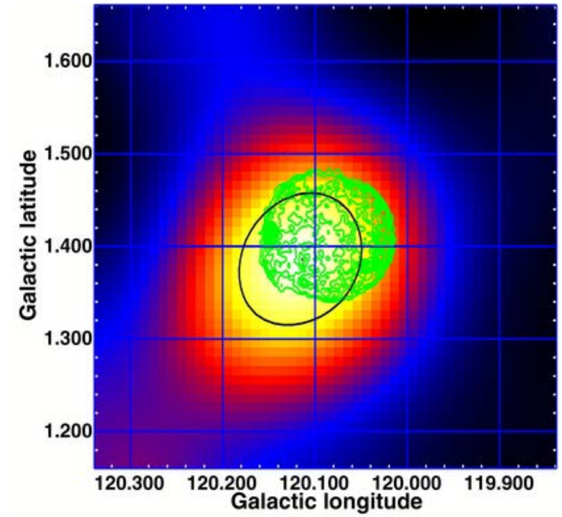
Tycho: Γ=2.3 (Giordano+12)

-> index of particle p > 2.0

<-> a problem of standard theory of CR acc.

which predicts p=2.0

-> Section 1



Tycho: Giordano+12

~10 GeV cut-off in old SNRs !!

They does not have

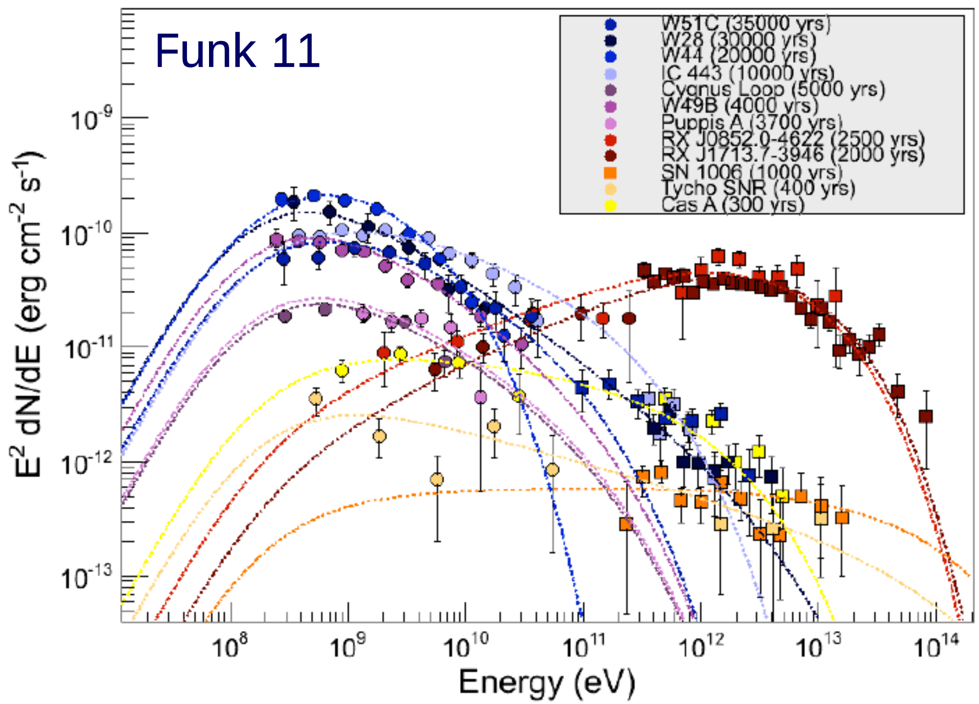
knee E particles !!

escaping particles

from shocks of SNRs ?

(particles can be cosmic rays)

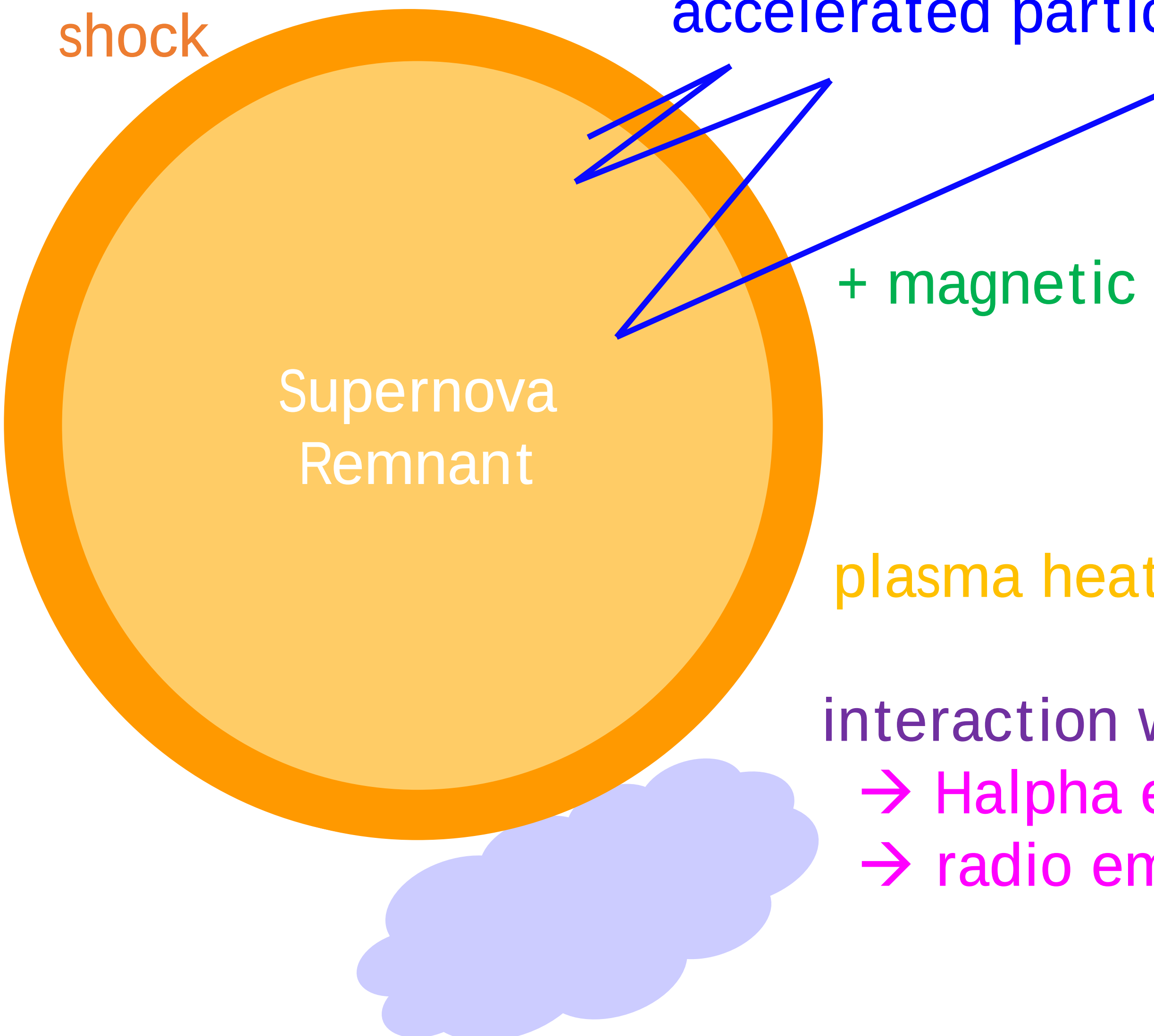
-> Section 2



To solve these new questions,

we need friends !

0.3. How to answer these new questions ?



accelerated particles → Gamma-rays

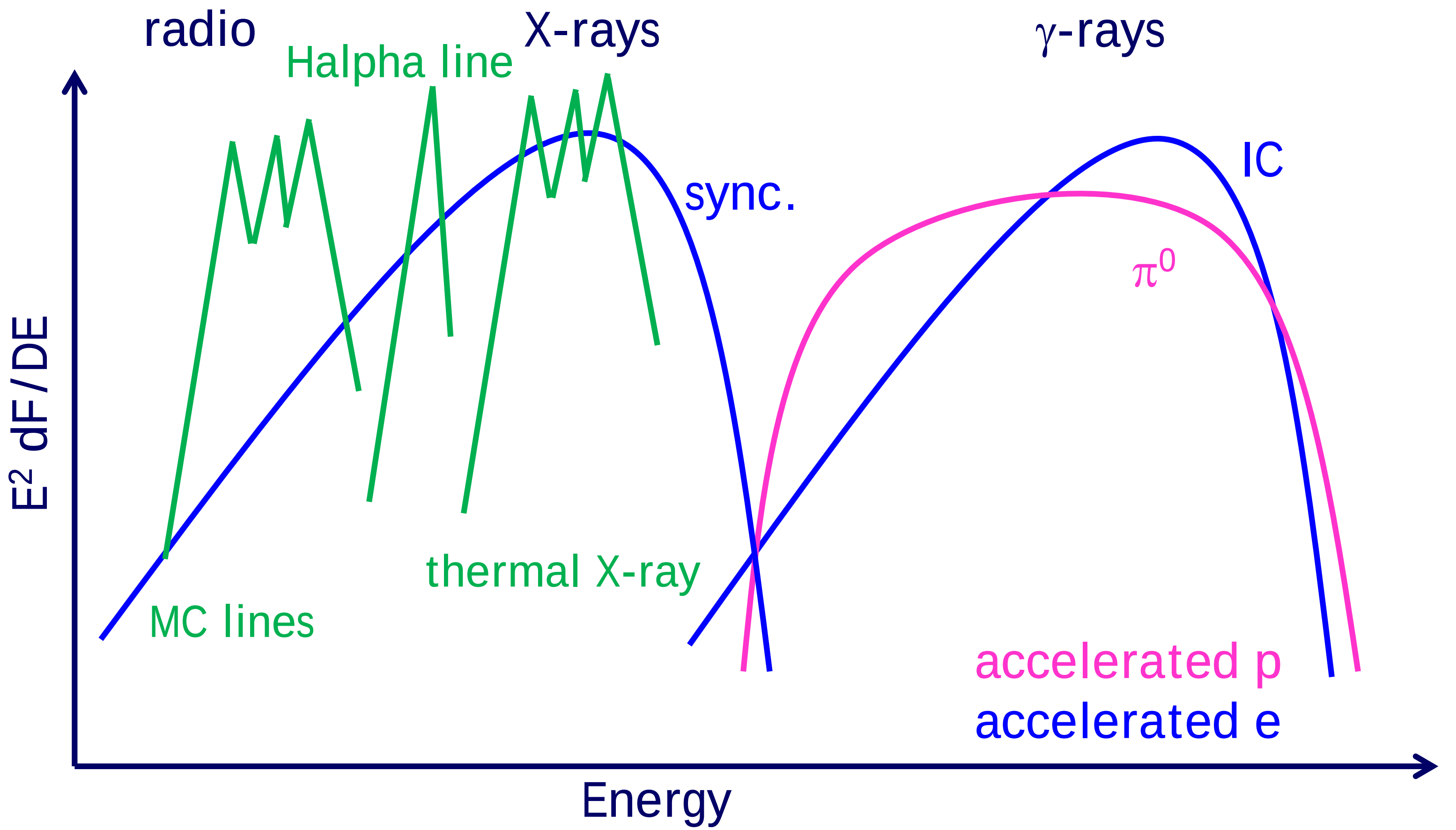
+ magnetic field → synchrotron radio – X-rays

plasma heating → thermal X-rays

interaction w. material
→ Halpha emission
→ radio emission from molecular cloud

Information from other wavelengths is very important !!

Wide-band emission from SNRs



thermal X-rays -> temperature, density, ionization state of background plasma

Halpha line -> ambient matter density, proper motion

MC lines -> ambient matter density, total mass, ...

Information of the background of the acceleration sites

1. Why $p > 2.0$ in young SNRs ?

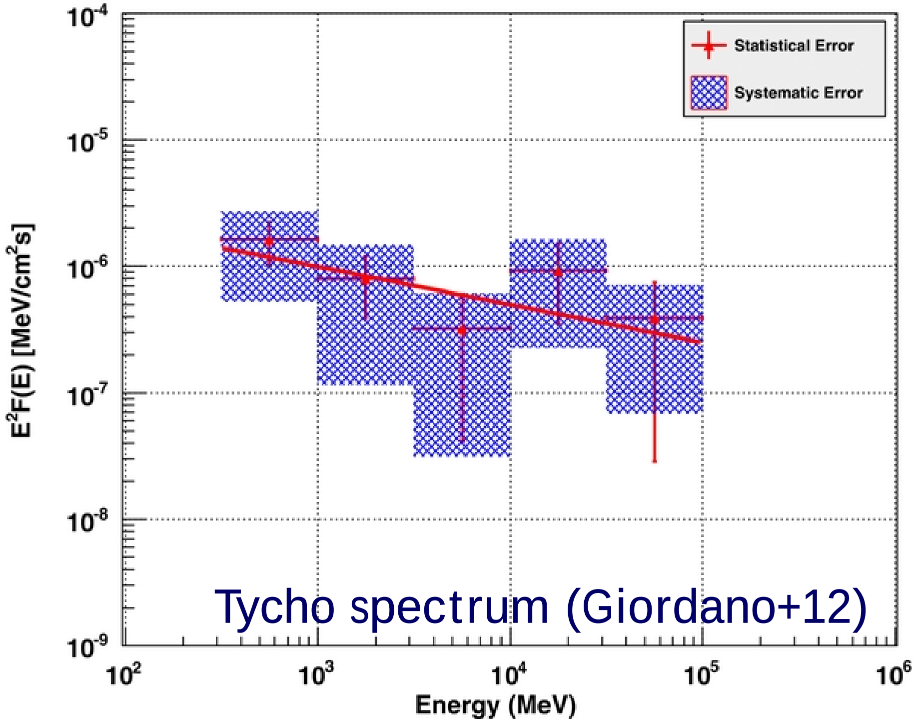
1.1. What is the problem on p > 2 spectrum ?

In standard theory:

$$N(E) \propto E^{-p}, \qquad p = \frac{r+2}{r-1}$$

r: compression ratio

r -> 4, p -> 2 when Mach number of shock -> infinity



p=2.3 (Fermi Result)

-> Mach number should be ~ 4

<-> In reallity,

Mach number > 100

Standard theory cannot reproduce soft spectrum in young SNRs !

1.2. How to make soft spectrum ?

A. Magnetic field effect (Nonlinear model)

amplified magnetic field can makes

apparent compression ratio lower (Bell77, Terasawa+08)

B. Effect of Neutral particles

Hα observations suggest existence of neutral particles

(Ghavamian+00,02)

charge exchange -> instability of B amplification (Ohira+09)

-> Anyway, amplified B and efficient acceleration is predicted

C. Escaping effect ?

high energy particles are already escaped

which makes softer spectrum? (Ohira+09)

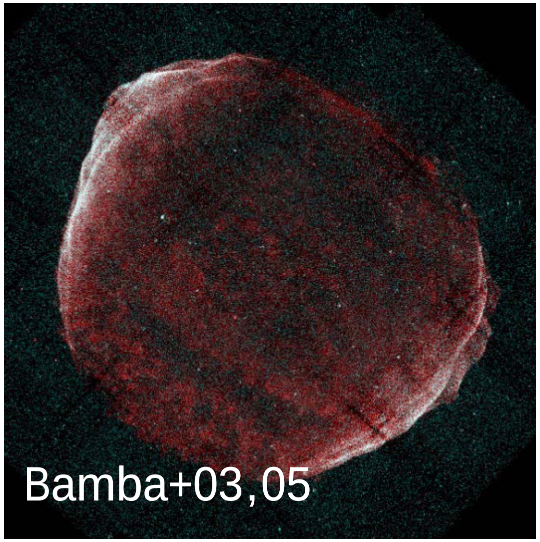
Fast escape even in a few 100 years !

Knee particles are already made and escaped ?

-> fast (efficient) acceleration is predicted

1.3. Observational evidences of amplified magnetic field

sync. emission -> information of magnetic field



thin filament

-> small diffusion and gyro radius

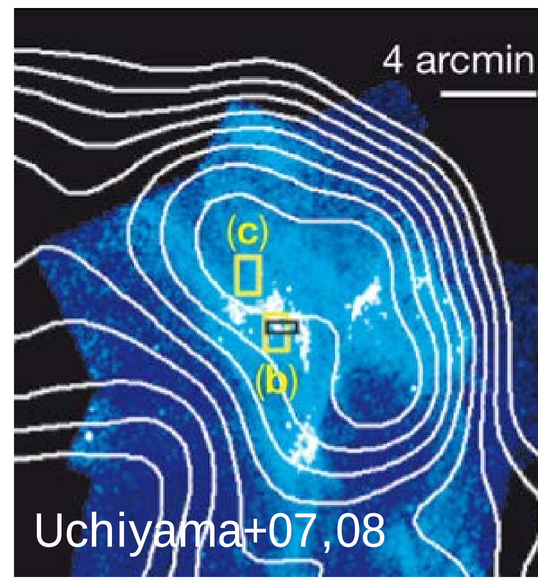
-> amplified B ~ a few 100 uG
   turbulent B up to Bohm limit

-> high acceleration efficiency

year-scale time variation of
X-ray emitting knots

year-scale acceleration
and synchrotron loss!

B ~ mG! (a part of remnants)



X-ray observations shows amplified and turbulent B

1.4. More information of magnetic field turbulence

Radio polarization of SN1006

SE and NW (no sync. X-rays): very strong polarization (60%)

-> aligned magnetic field

NE and SW (w. sync. X-rays): rather weak polarization (20%)

-> turbulent magnetic field

Efficient acceleration makes magnetic field turbulent

Direction of B in NE and SW:

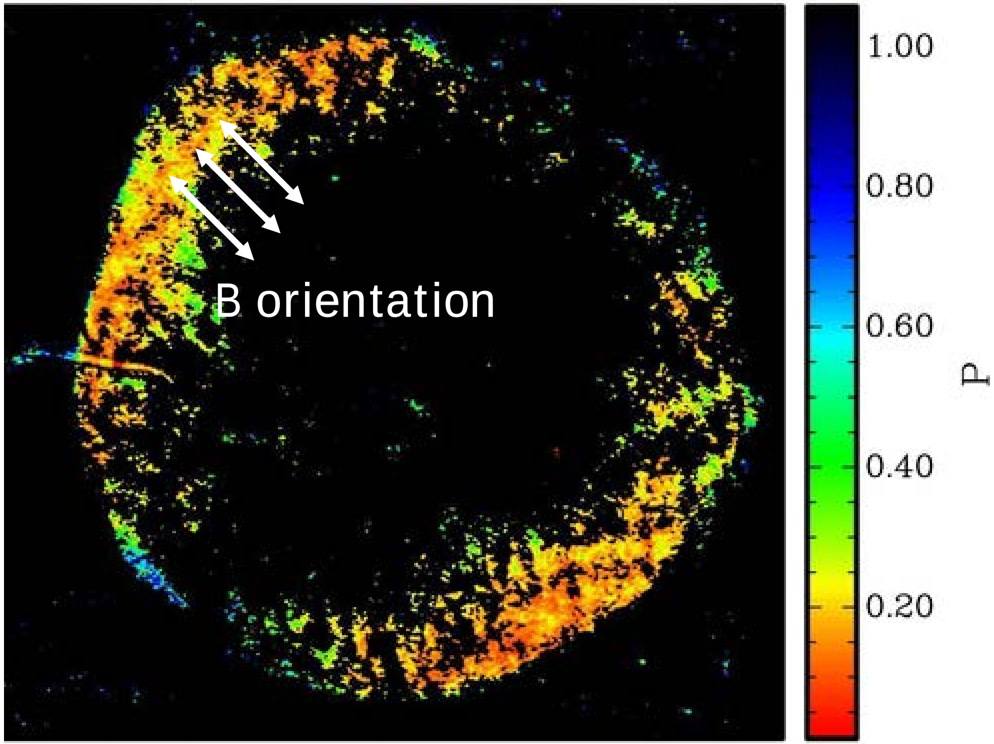
nearly parallel to

the shock normal

-> efficient acc.

in parallel B ??

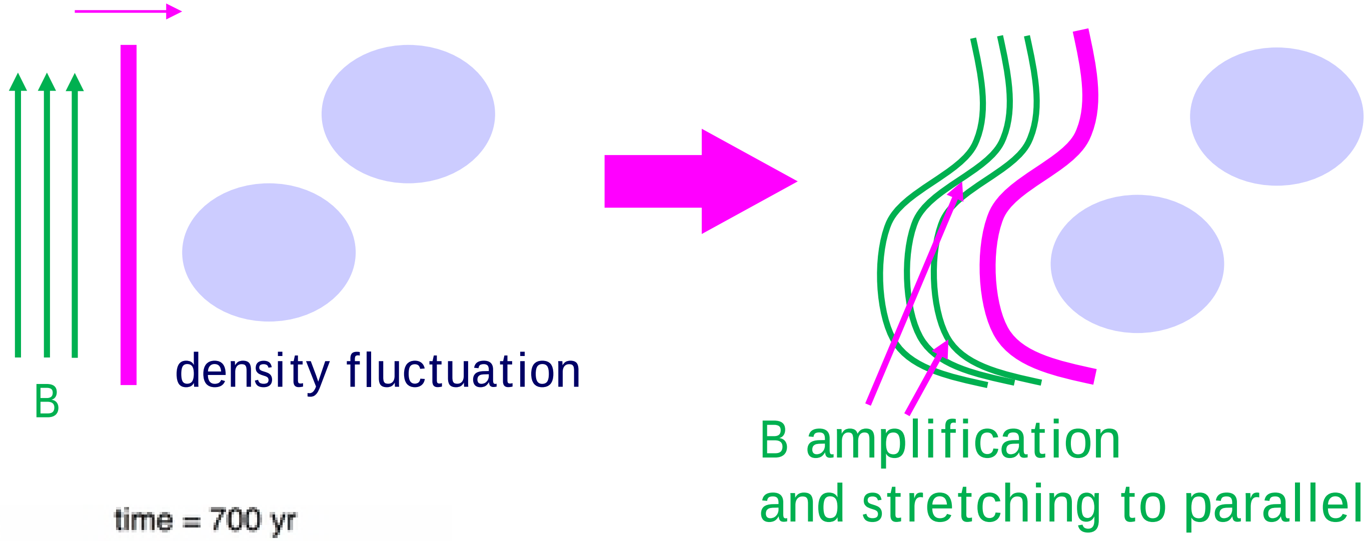
SN1006

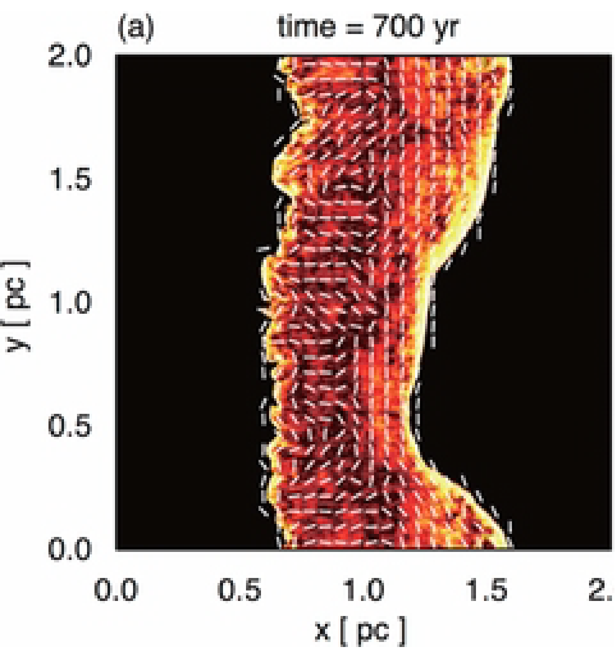


(Reynoso+13)

1.5. efficient acc. in parallel magnetic field ?

B field was originally parallel or became parallel
in efficient acceleration sites ?



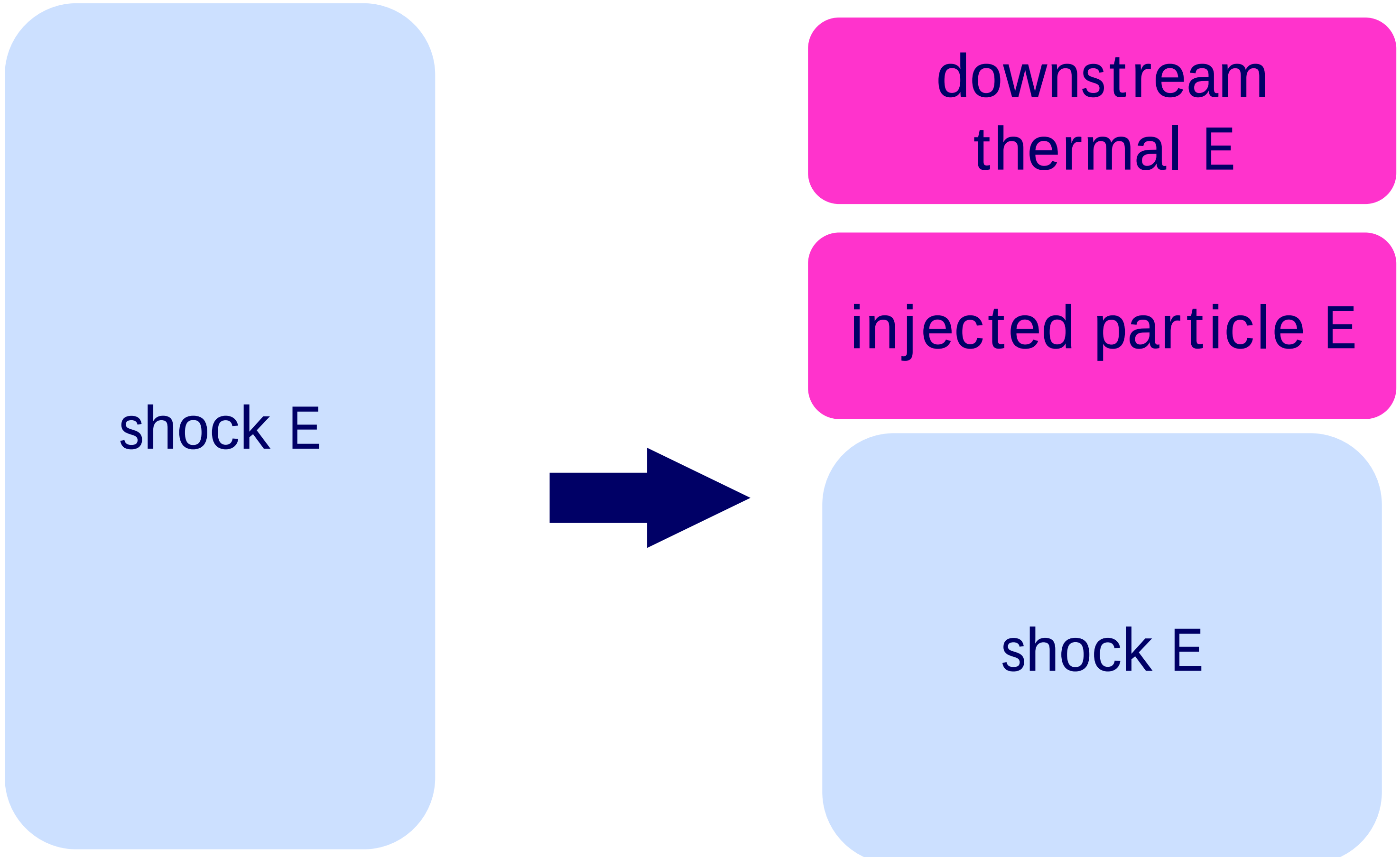


3D simulation reproduced parallel B
(Inoue+13)

Origin of density fluctuation:
- turbulence of ISM ?
- Drury instability
  in the cosmic-ray modified shock?
- nonlinear feedback of
  the cosmic-ray streaming instability?

1.6. Acceleration efficiency measurements

From Rankine-Hugoniot relation



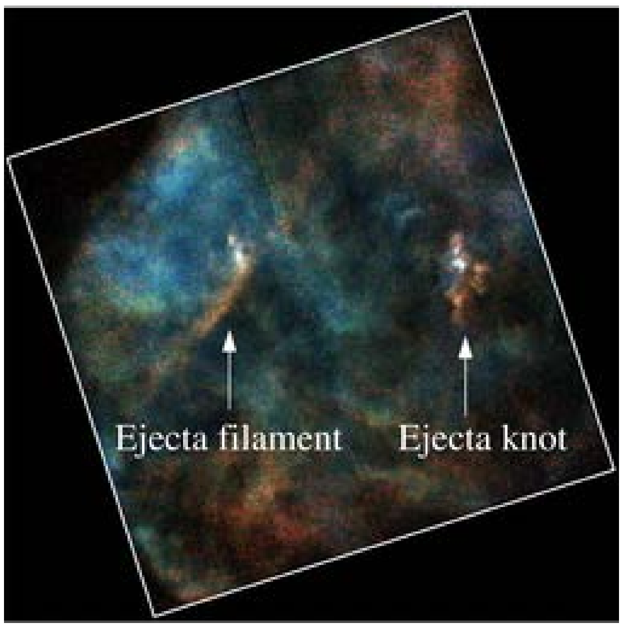
efficient particle acceleration steal energy
from the thermal energy of downstream plasma
We need excellent spectral resolution to measure ion kT
in X-ray band

Injection efficiency

measured from ion kT

obs. of ejecta knots in SNRs

-> Dopp. shift + thermal broard



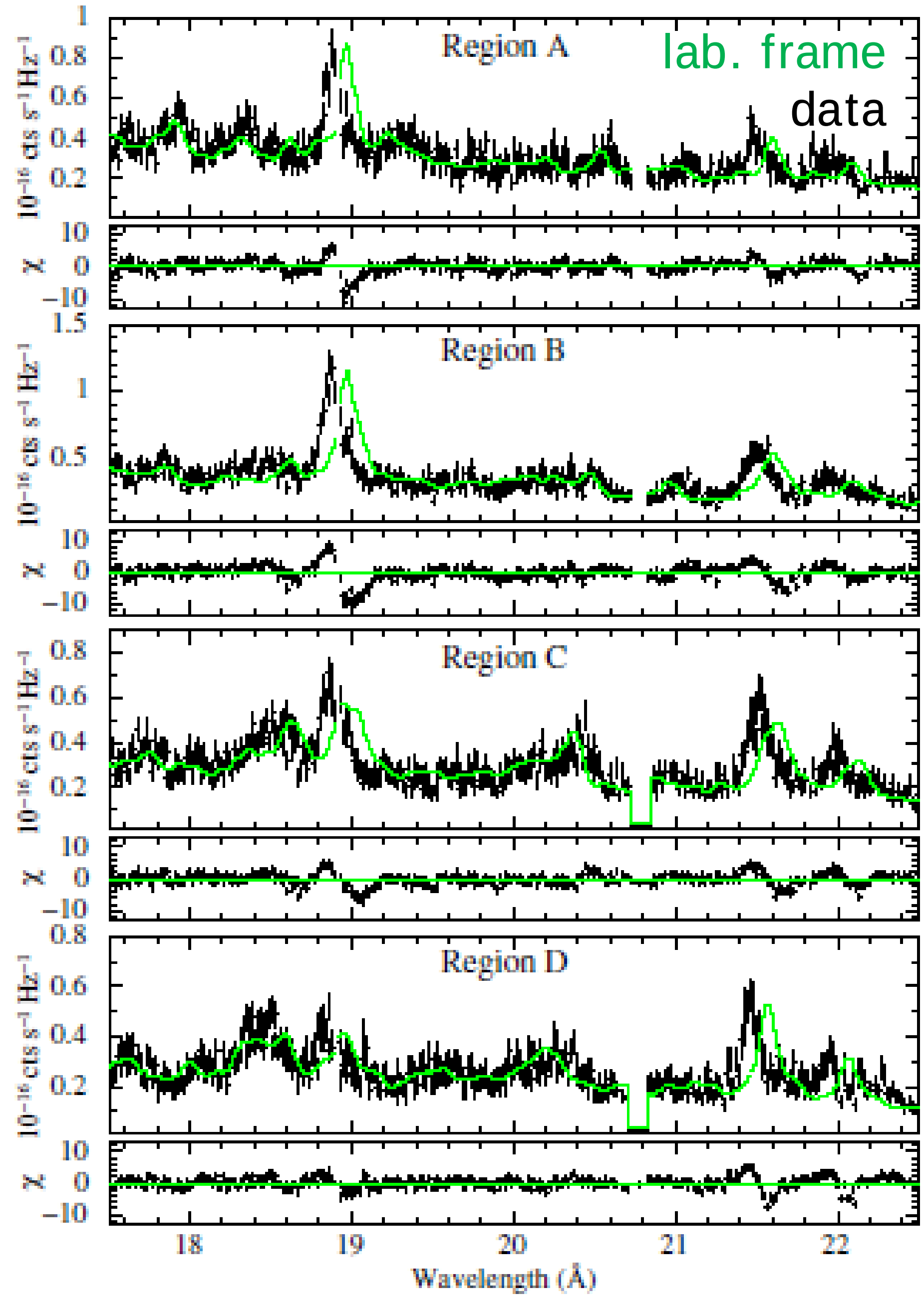
In the case of Puppus A Oxygen

Doppler v ~ 1500km/s

expected O kT ~ 130 keV

<-> observed O kT < 30 keV

(XMM RGS; Katsuda+13)



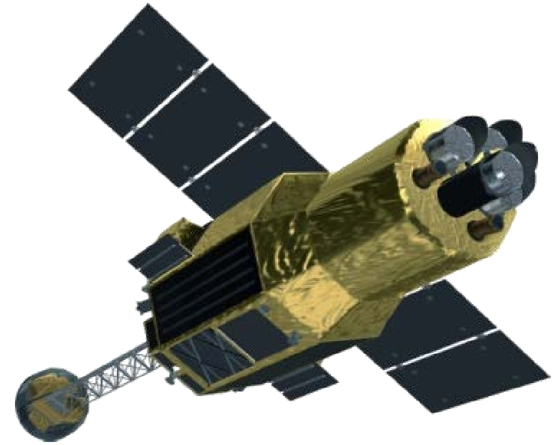
(Katsuda+13)

due to non-equilibrium? or energy injection ?

ASTRO-H measurement of acceleration efficiency

ASTRO-H (planned to launch FY2015)

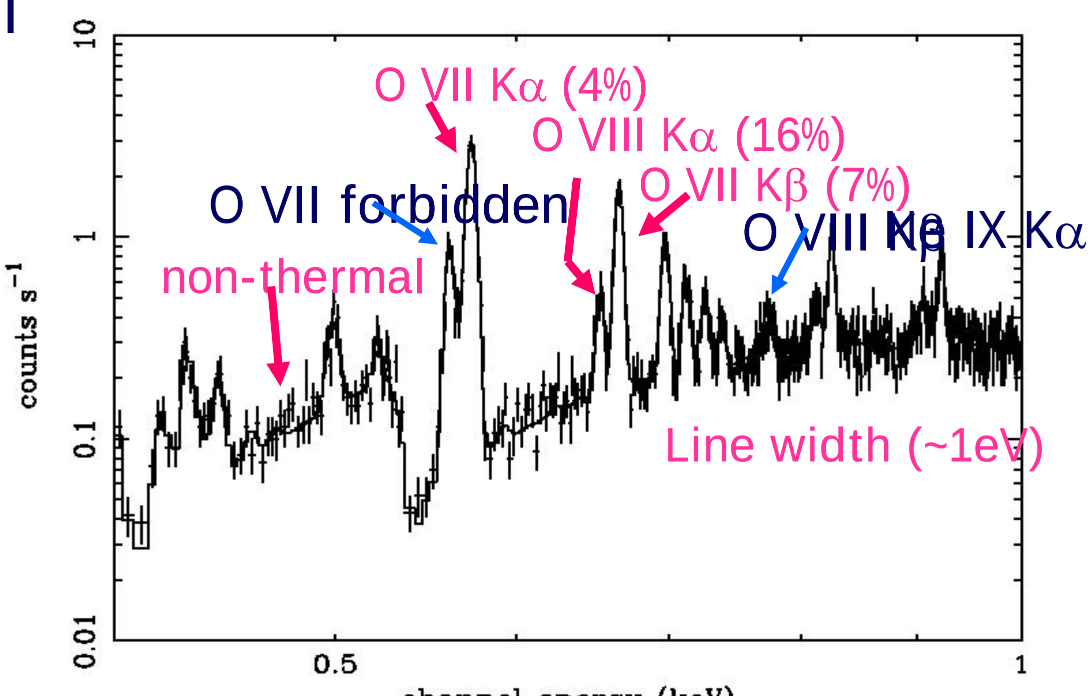
- excellent spectral resolution for extended sources
- wideband spectroscopy from 0.2-600 keV
- imaging capability in 0.2-80 keV like NuSTAR



Resolving a lot of emission lines
-> determine the ratio of kT for several elements

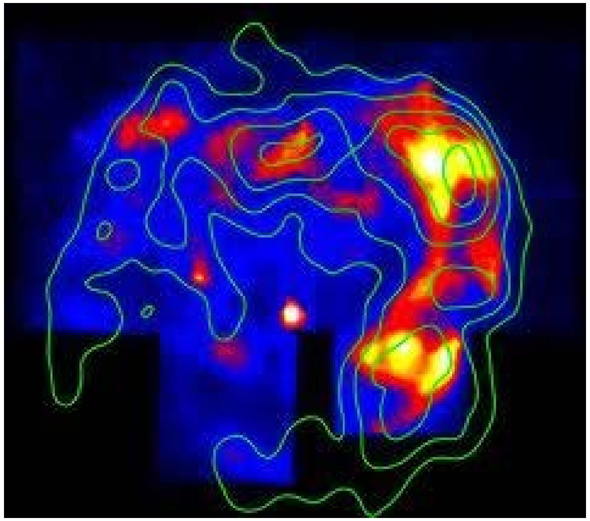
-> measure the E injection

SN1006 NE shell 80ks simulation



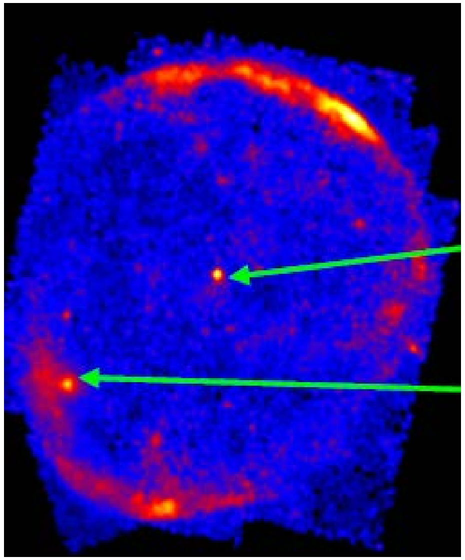
1.7. Non-thermal X-ray dominated SNRs

RX J1713-3946



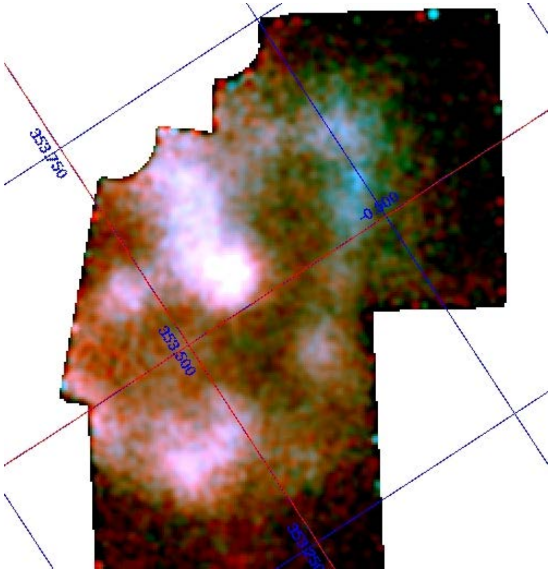
(Koyama+97, ...)

Vela Jr.



(Slane+00, ...)

HESS J1731-347



(Bamba+12, ...)

Bright TeV SNRs have no significant thermal X-rays

thermal X-ray luminosity ~ n_e^2

-> background plasma is thinner than average ??

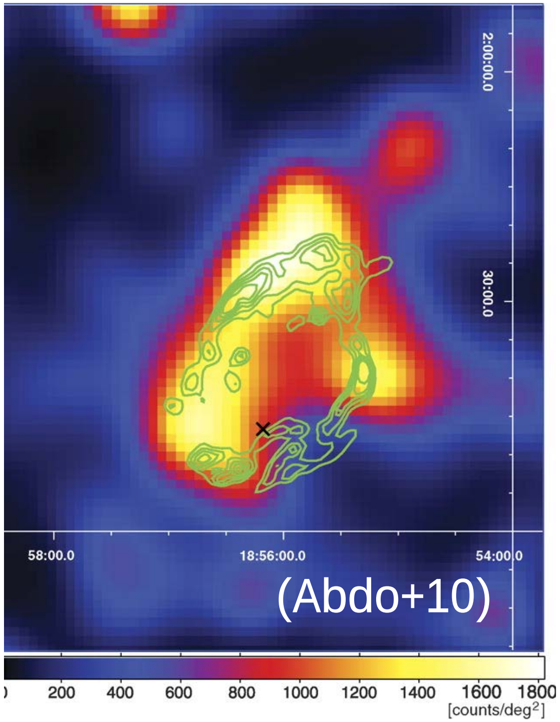
no information on the background of such sources

ASTRO-H will detect emission lines from these SNRs and measure the background condition of such efficient accelerators

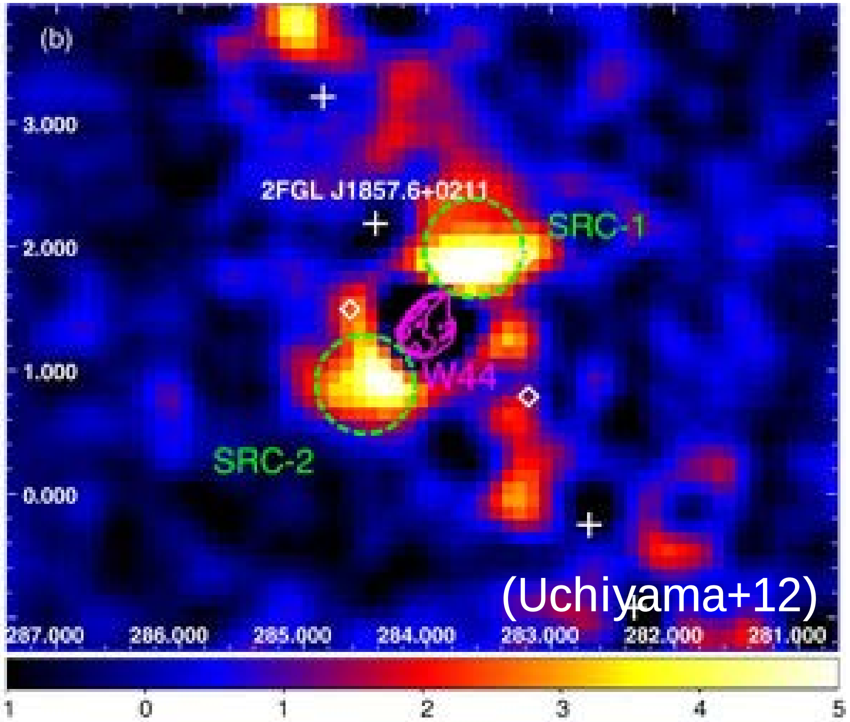
2. Escaping particles from SNRs

2.1. Particle escape from SNRs

W44



vicinity of W44



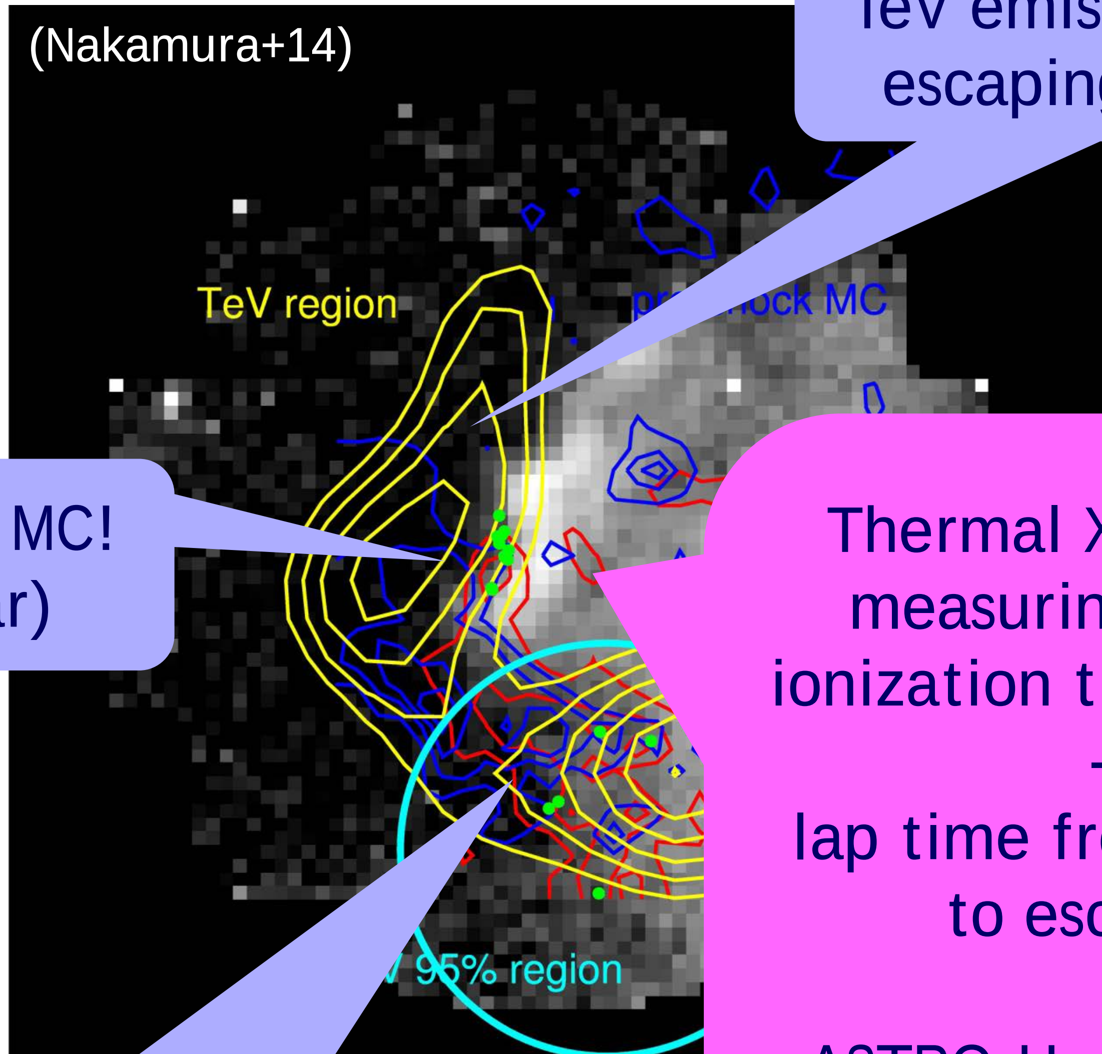
GeV emission from and vicinity of old SNRs

GeV cut-off of old SNRs

-> emission from escaping particles !

When particles can escape from acceleration site ?

2.2. Excellent example: NE shell of W28



TeV emission from MC escaping particles ?

colliding w. MC! (OH mesar)

Thermal X-ray knots measuring density, ionization timescale, …

->

lap time from collision to escape ??

ASTRO-H will show us the time scale of escape

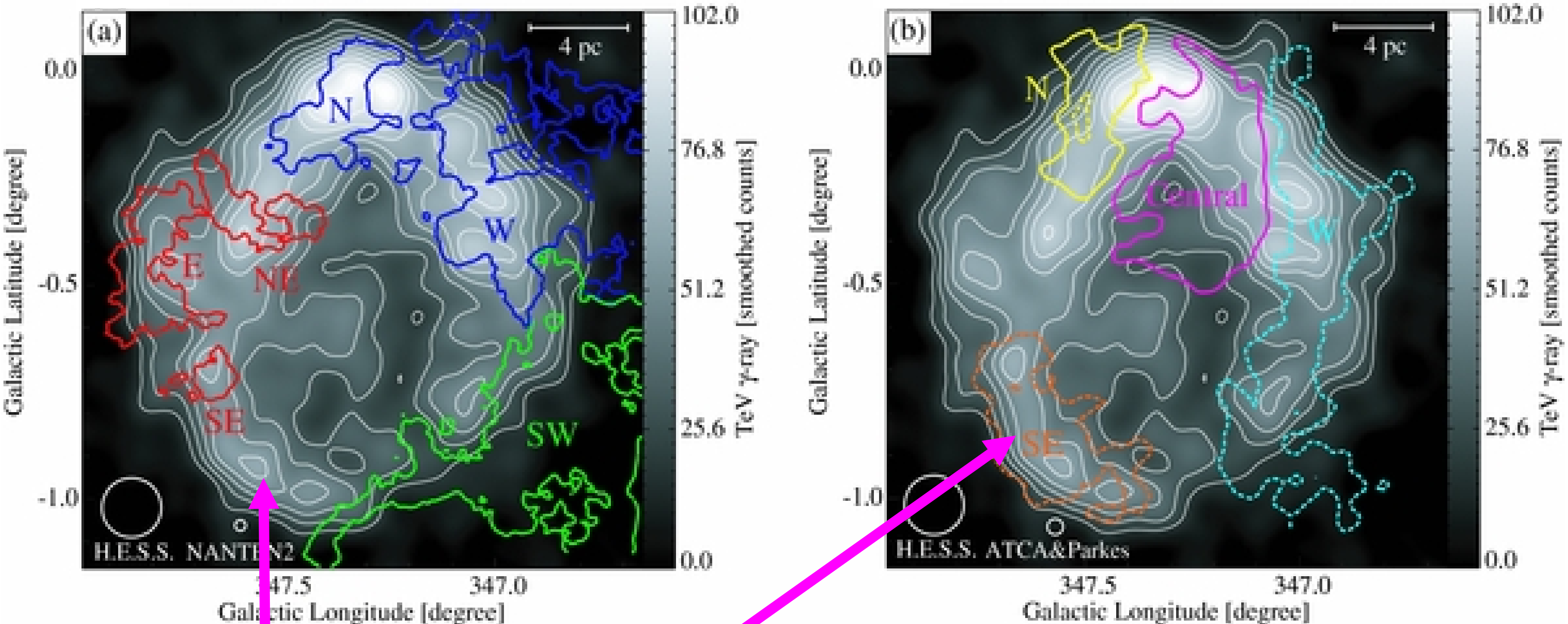
GeV+TeV from shocked MC softer particle escaping ?

2.3. Not only CO clouds

CO cloud is the most well-known target to see high E particles

RX J1713

CO HI



no CO cloud but HI gas !
main mass here is HI gas.

gray scale: TeV emission (Aharonian+07)
color: CO and HI distribution (Fukui+12)

We also need HI observations to know TOTAL matter around SNRs

2.4. Peculiar plasma condition in GeV emitting SNRs

plasma in SNRs is low density!

ionization degree of SNR plasma

slowly approaches to thermal equilibrium

time scale: $nt \sim 10^{13}$ cm^{-3}s

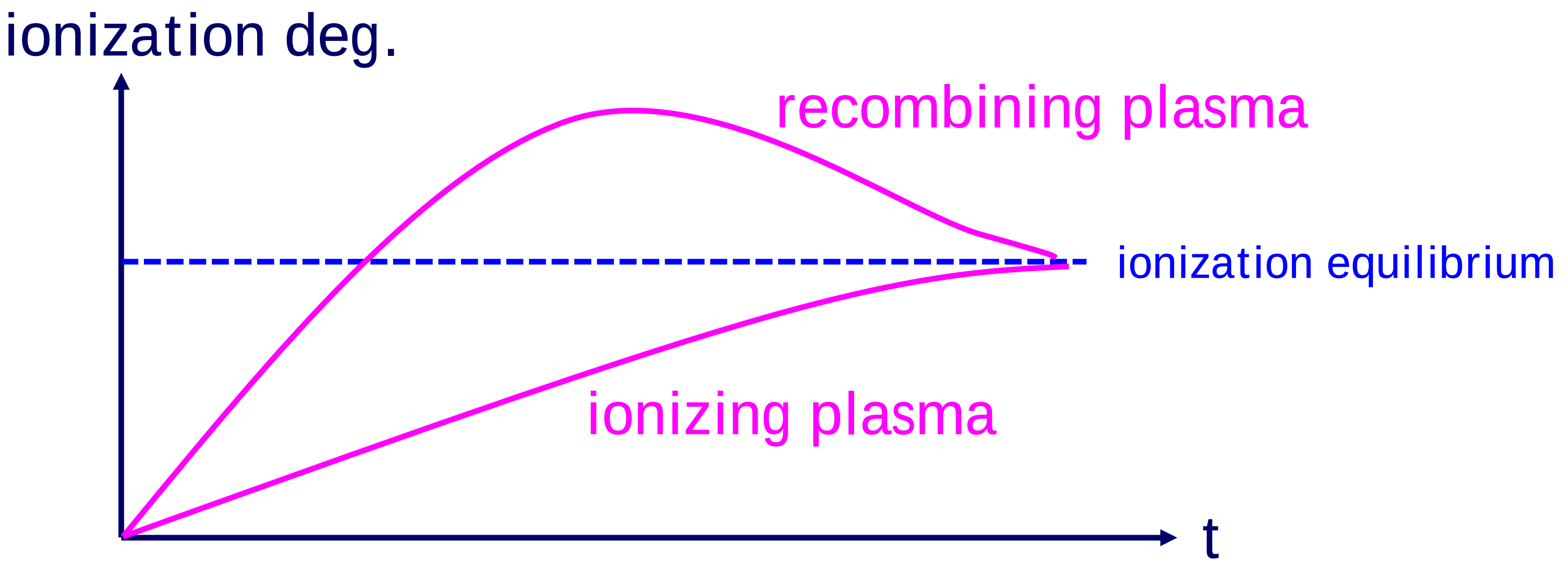
$t \sim 3\times10^{4}$ yrs with $n=1$ cm^{-3}

plasma of young SNRs should be still ionizing

Suzaku X-ray satellite discovered several SNRs

with over-ionized plasma !

Plasma in such SNRs is recombining -> "recombining plasma"



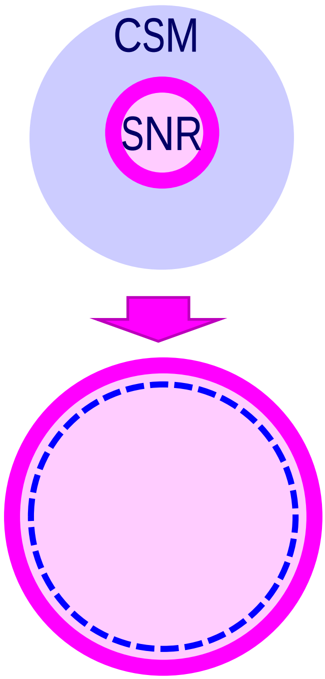
Recombining plasma SNRs are GeV SNRs

RP SNR lists:

IC443(Yamaguchi+09), W49B(Ozawa+09), G359.1-0.5(Ohnishi+11), W28(Sawada+12), W44(Uchida+12), G346.6-0.2(Yamauchi+13), 3C391(Sato+14)

GeV source, TeV source

6/7 sources are Gamma-ray emitters !



Possible scenario (Shimizu+14)

SNR exploded in circumstellar matter
-> shock breaks out CSM into ISM
-> higher shock velocity

higher efficient acc.
-> GeV-TeV gamma-rays ?

rapid expansion and cooling
-> recombining plasma ?

(Shimizu+14)

good tracer of GeV SNRs ??
We need more information on this relation

3. Summary

- Fermi showed us that SNRs are efficient accelerators and distribute particles into the space.
- We need multiwavelength observations to understand what makes such efficient acceleration and escape.
- X-ray and radio observations are good B tracers and showed amplified and turbulent magnetic field.
- X-ray diagnostics with ASTRO-H will measure the acceleration efficiency of particles.
- Radio observations need to know material distribution
- X-ray plasma diagnostics will show us the timescale of escape.