X-ray observations of supernova remnants
- environment study of acceleration sites -

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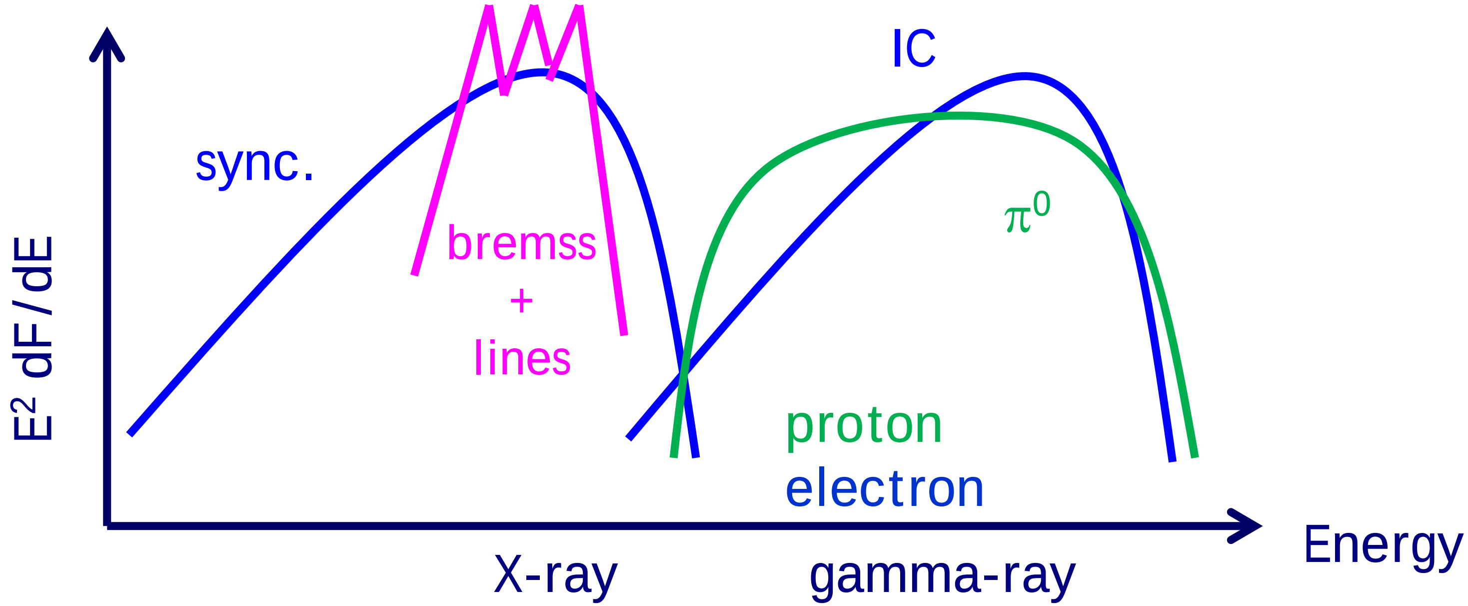
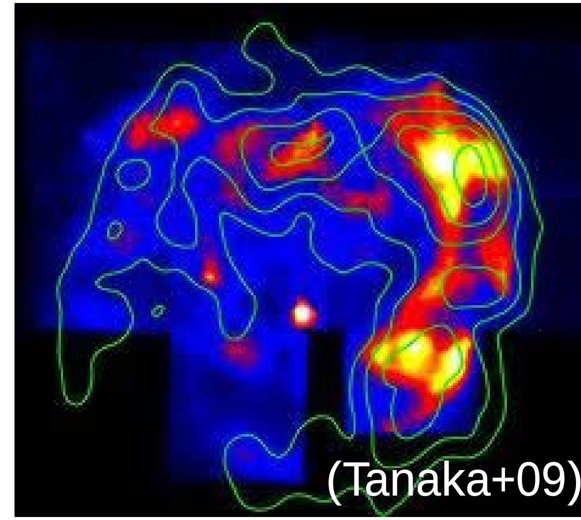
0. Acceleration sites and X-ray observations



X-ray:	synchrotron from e	→	info. on accelerated e
	thermal emission		info. on environment density, kT, time scale ...
gamma-ray:	IC emission from e emission from pi-on		info. on accelerated e/p

X-ray observations are a strong tool
to understand the environment of acceleration sites

Unresolved problems of environments (1): dense ? thin ?


(Tanaka+09)

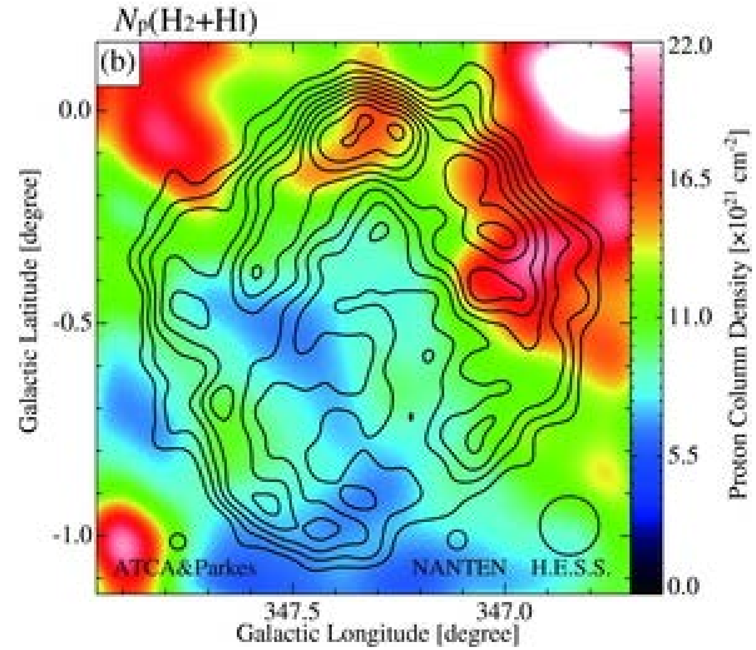
Information from X-ray observations

VHE gamma-ray SNRs show only nonthermal X-rays

RXJ1713 (Koyama+97), Vela Jr. (Tsunemi+00), HESSJ1731 (Bamba+12)

Weak thermal X-rays (bremss) -> low density plasma

-> acceleration happens in low density ISM ?



(Fukui+12)

Information from molecular cloud observations

VHE gamma-ray SNRs are surrounded by molecular clouds (MCs)

Gamma-rays are emitted from MC regions

-> acceleration happens in high density ISM ?

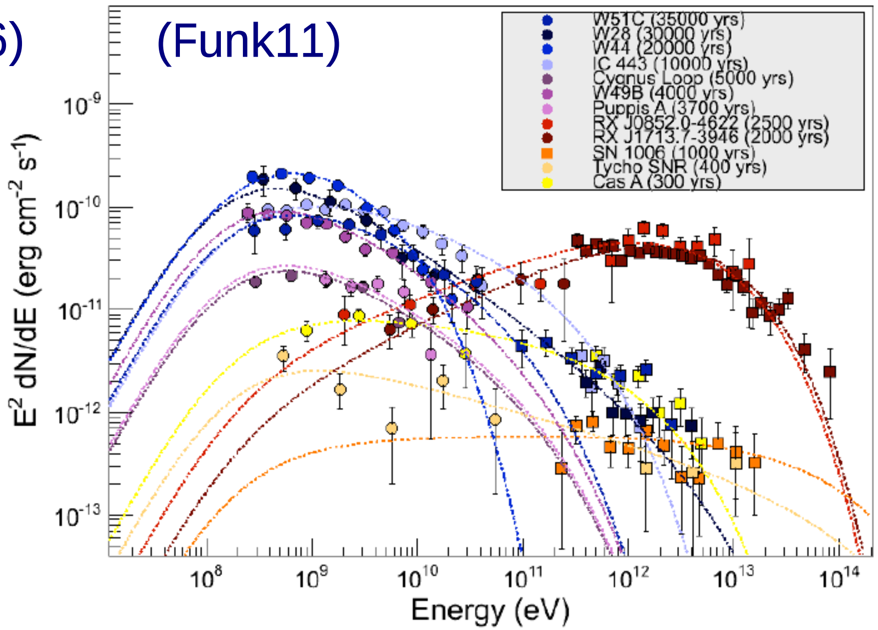
Which is correct ? -> topic 1

Unresolved problems of environments (2): escape sites ?

GeV SNRs have cut-off around 10 GeV

(Acero+16)

-> escape ?



The escape site environment is
still unknown

Typical GeV SNRs:

surrounded by molecular clouds

X-ray information ?

any difference from VHE gamma-ray SNRs ?

-> topic 2

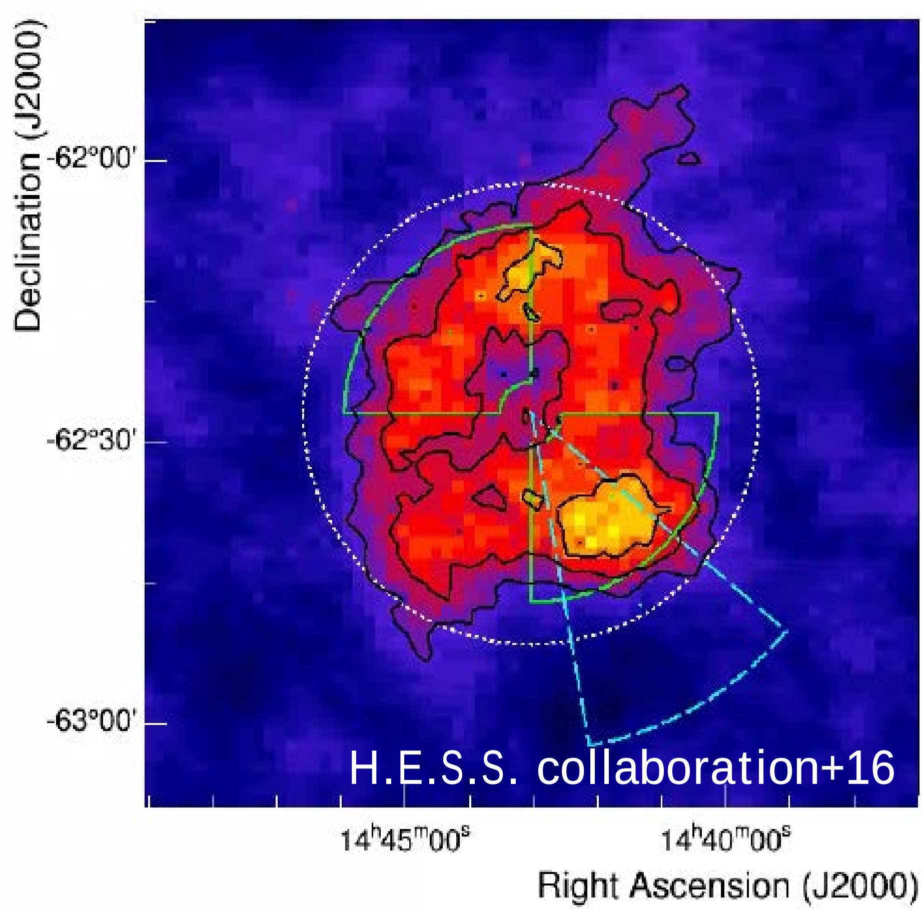
topic 1:
Environment study of VHE gamma-ray SNRs without thermal X-rays

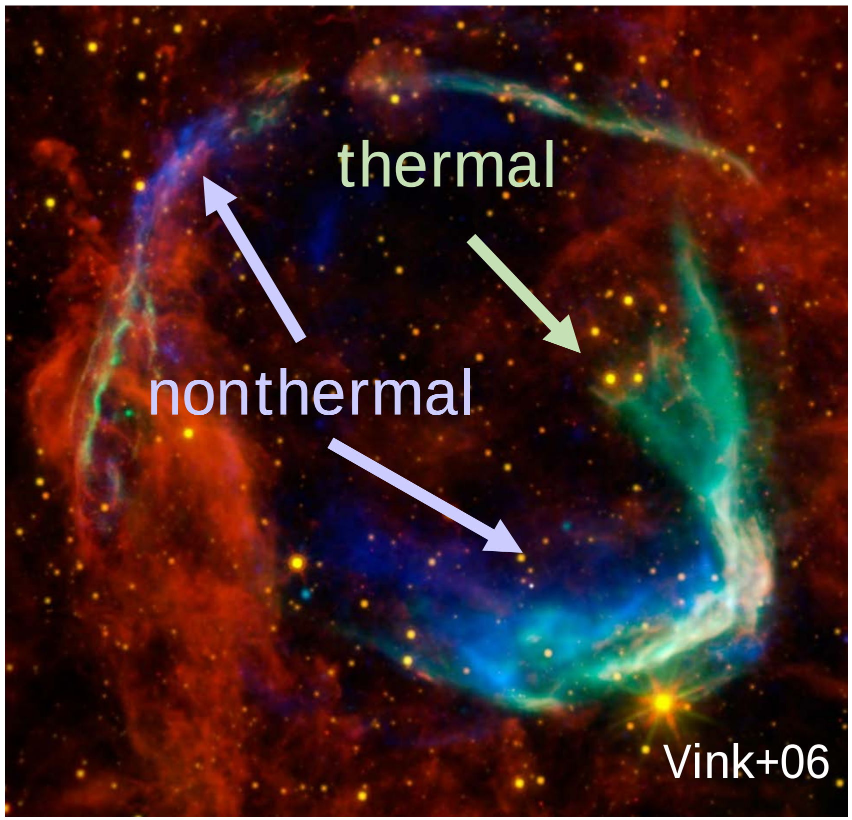
1.1. ideal target for the study of environment: RCW86

Typical VHE gamma-ray shell-type SNR (H.E.S.S.+16)

Both nonthermal and thermal X-rays

different spatial distribution -> which environment is strong sync. X-ray emitter ?



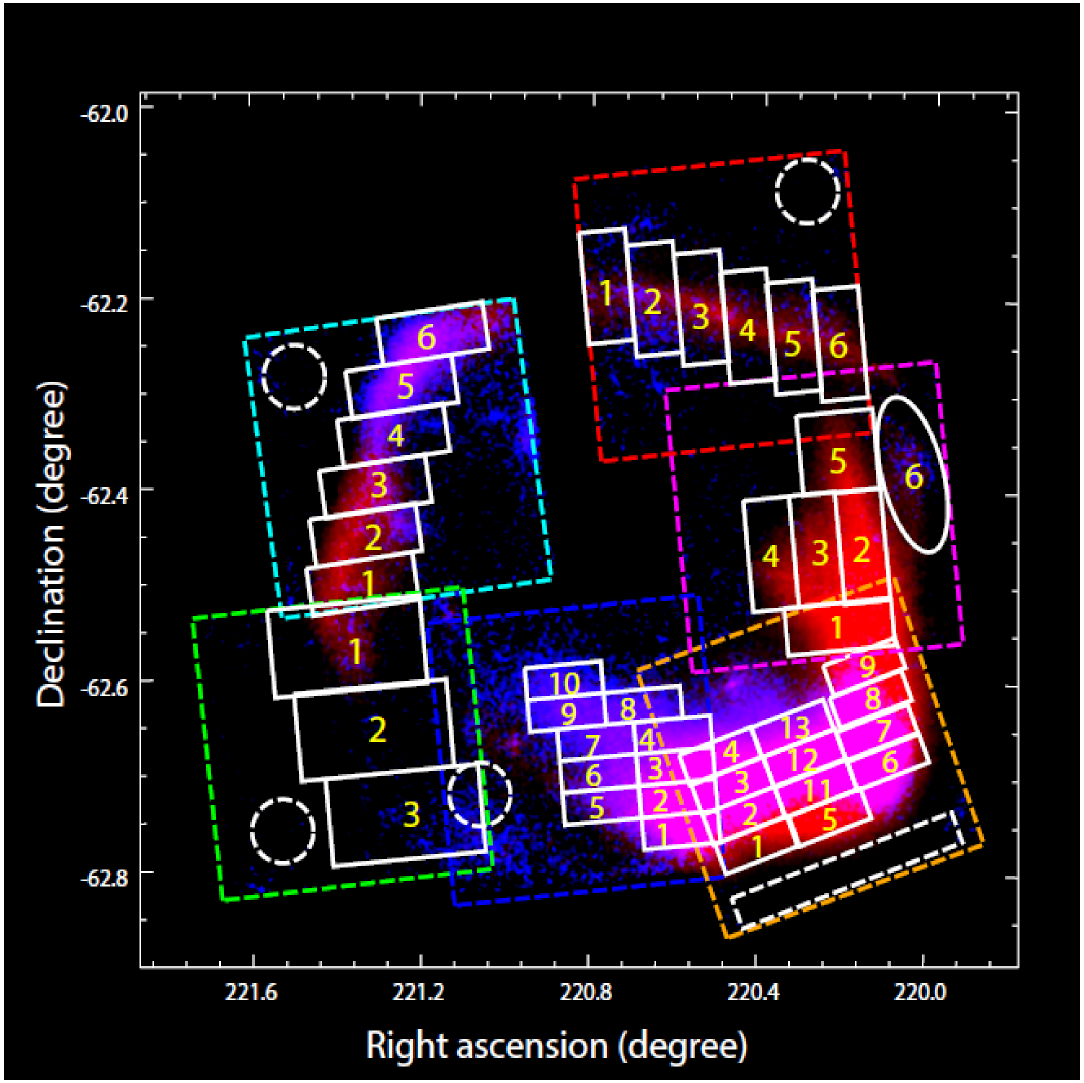


1.2. Suzaku observations and analysis of RCW86

Suzaku mapped entire RCW86

different hardness ratio
among regions

this work (Tsubone+, submitted):
We divided the remnant
into many pieces
Compared the characteristics
of each region

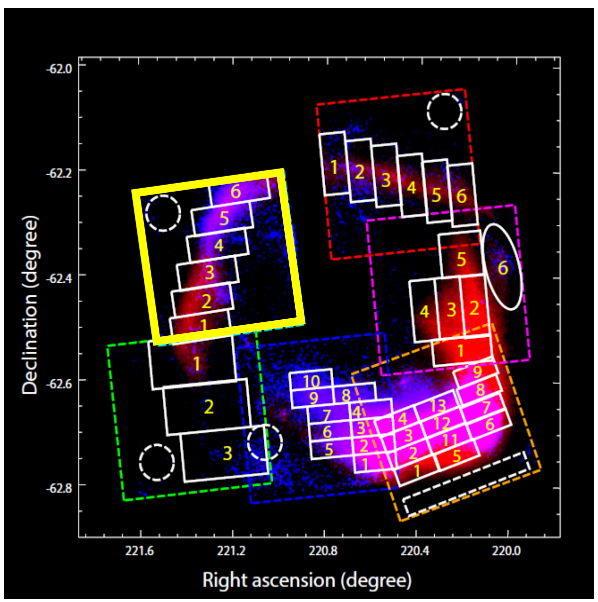


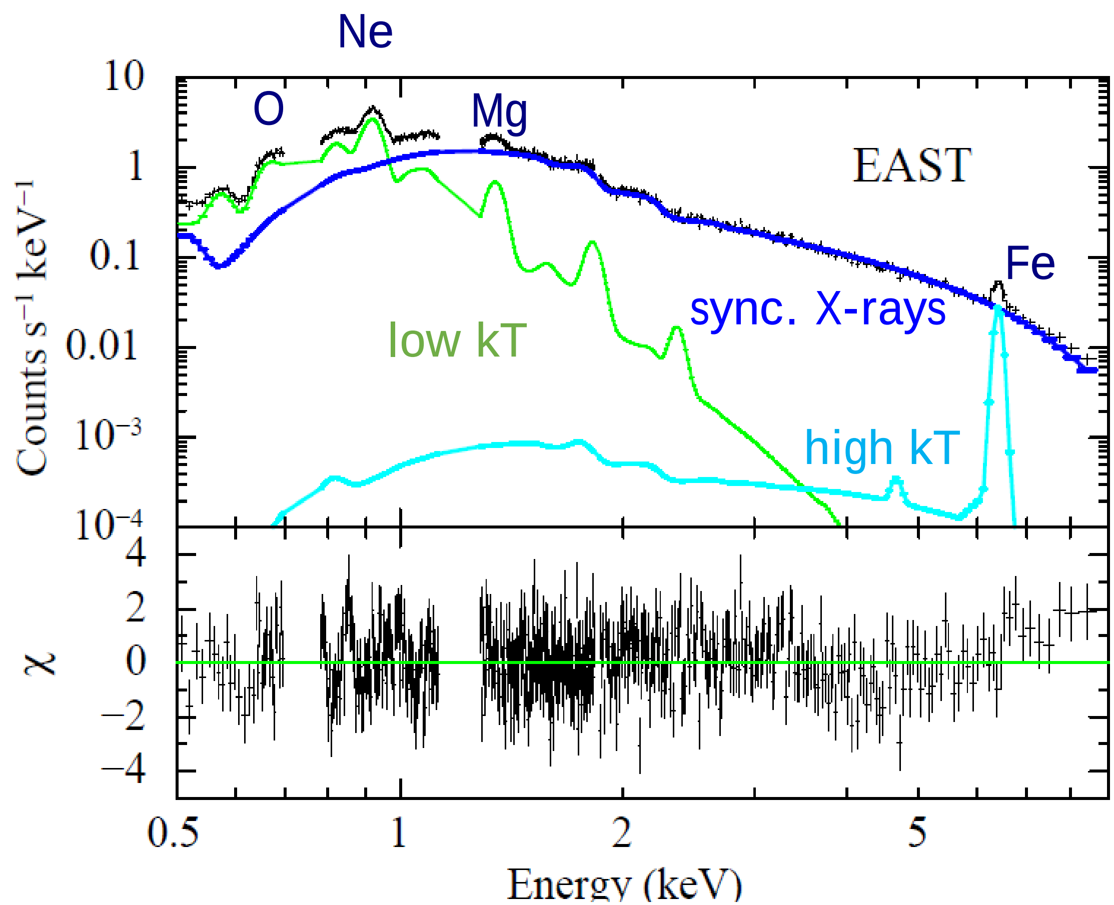
Spectrum analysis of each region

Yamaguchi+08, 11 resolved the spectrum components of

- low kT comp. (heated ISM)
- high kT comp. (Fe ejecta)
- sync. X-ray emission

example



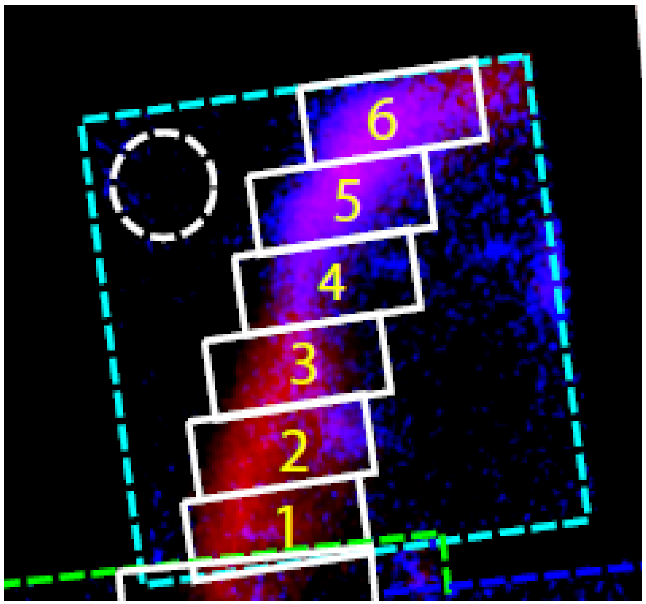


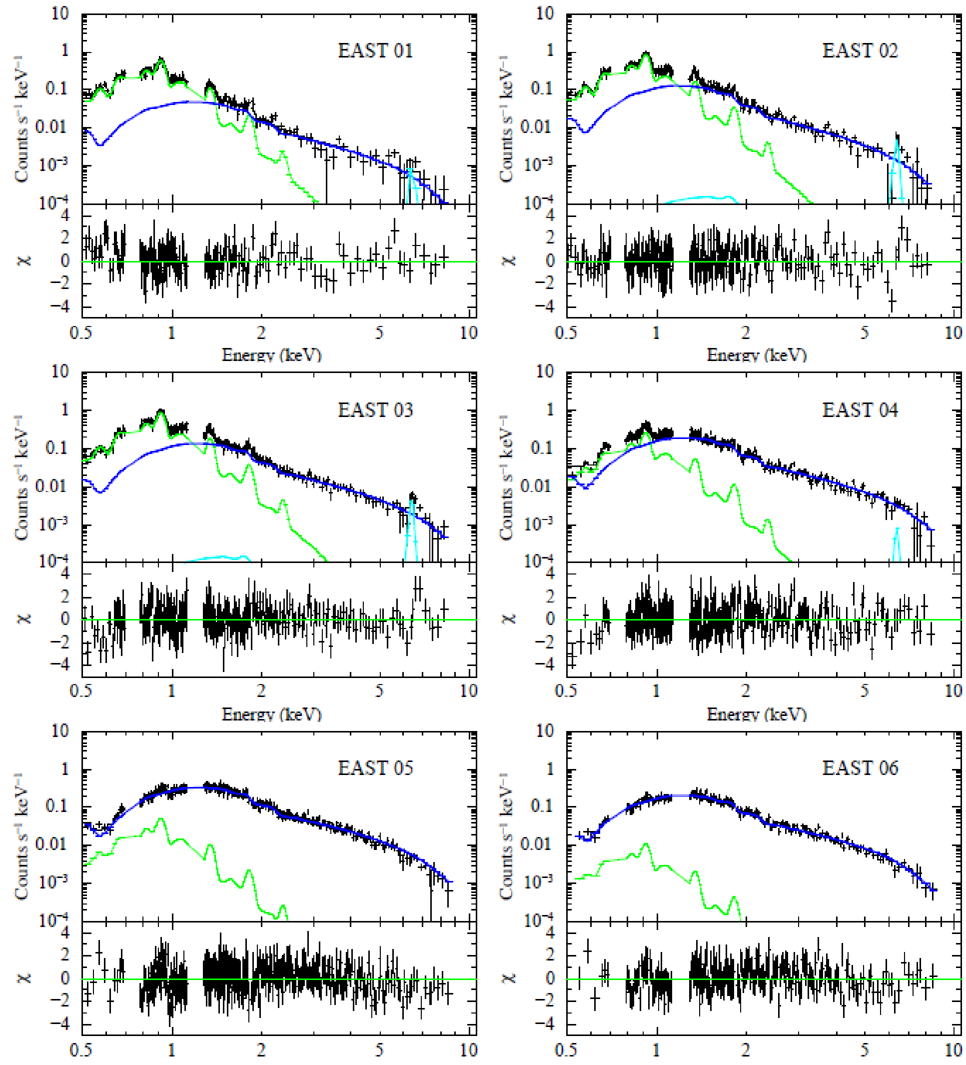
Parameters for small regions

free parameters: emission measure of thermal components

photon index and surface brighteness of sync. X-rays

-> rough characterization of the emission





east region:

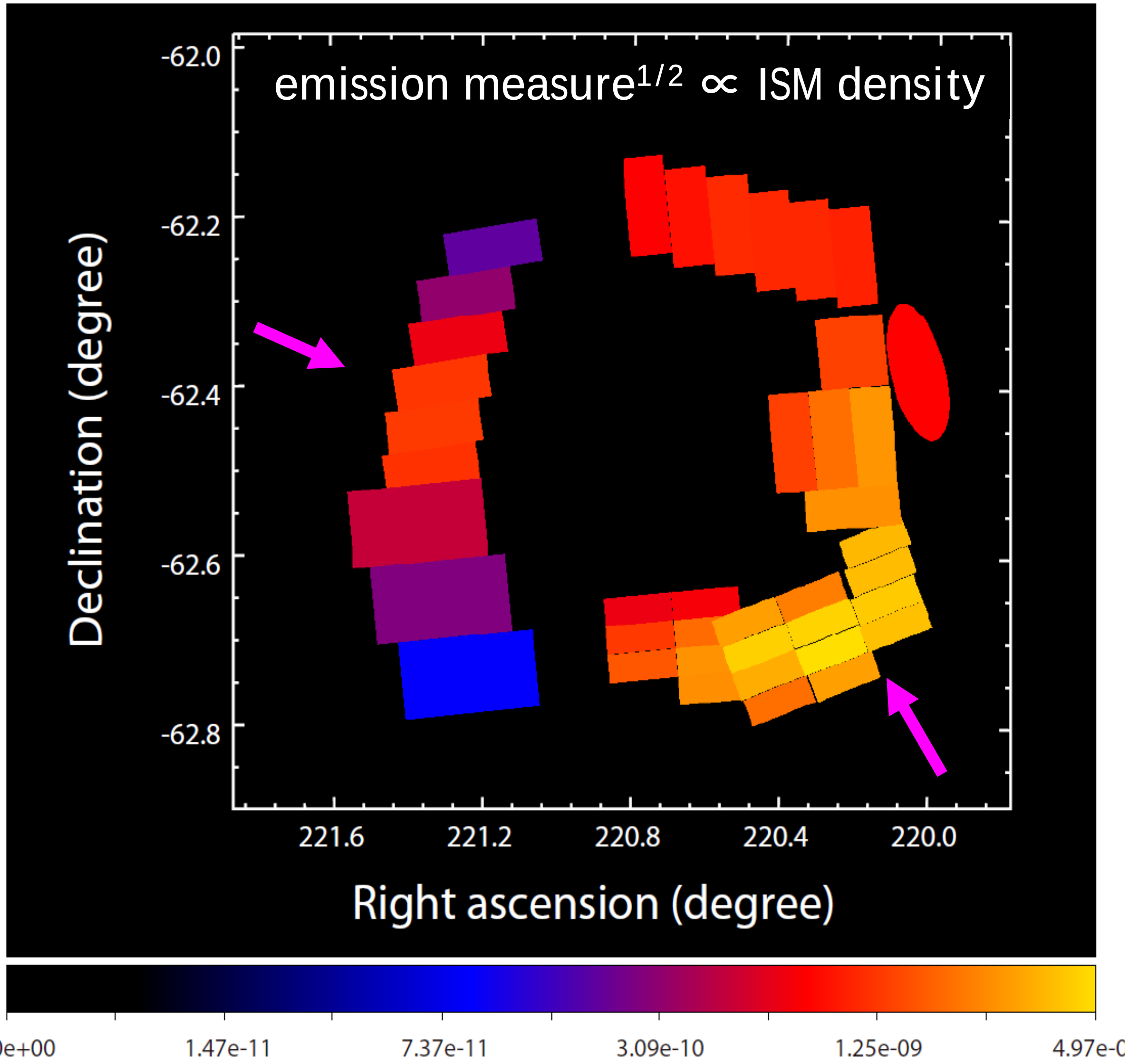
sync. comp. is bright in the north

ISM comp. is bright in the south

1.3. Parameter maps

emission measure (E.M.) of the ISM component ∝ ISM density^2

(emission measure ∝ n_e^2V)

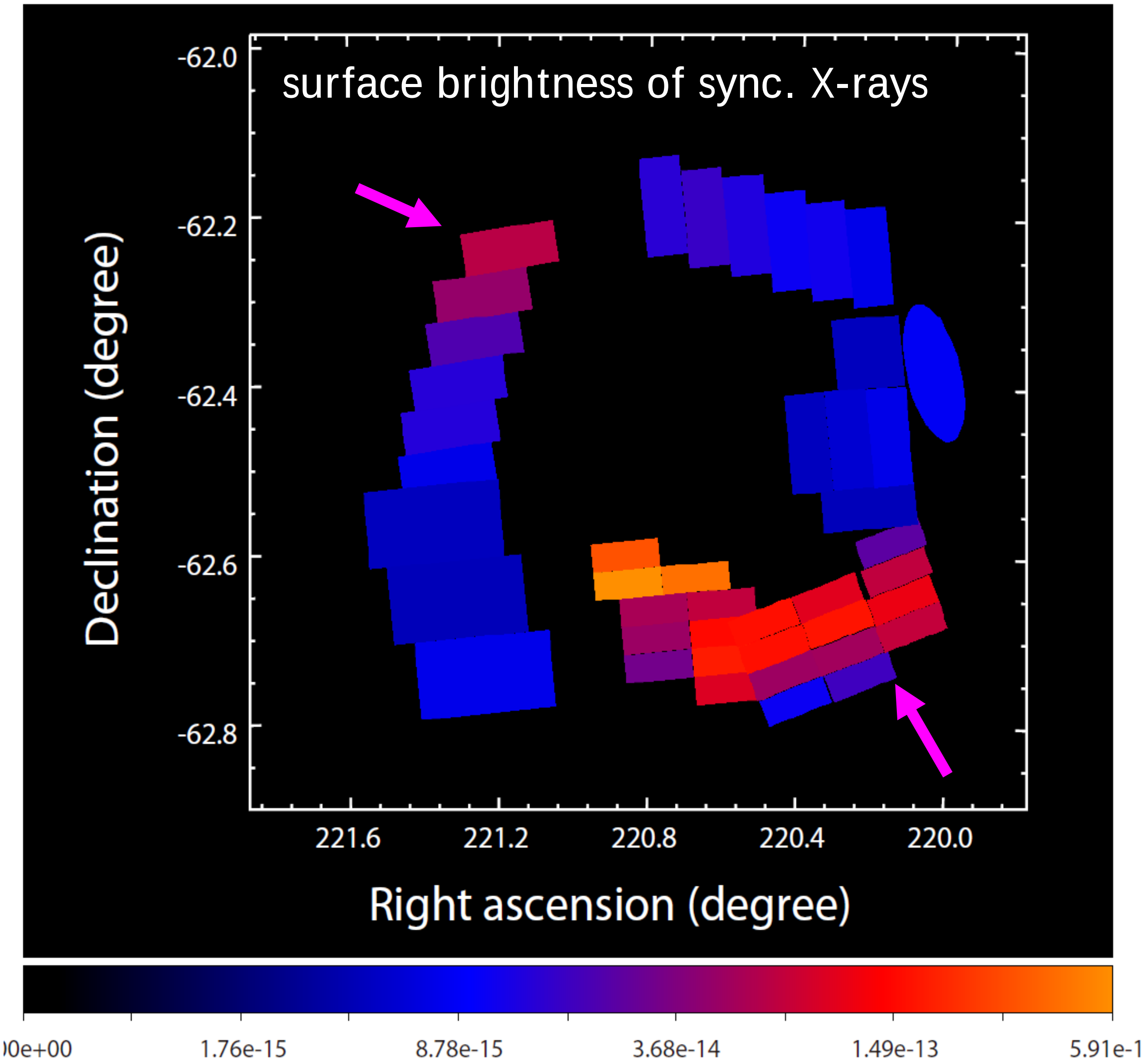


West and east have bright E.M.

-> these have high density

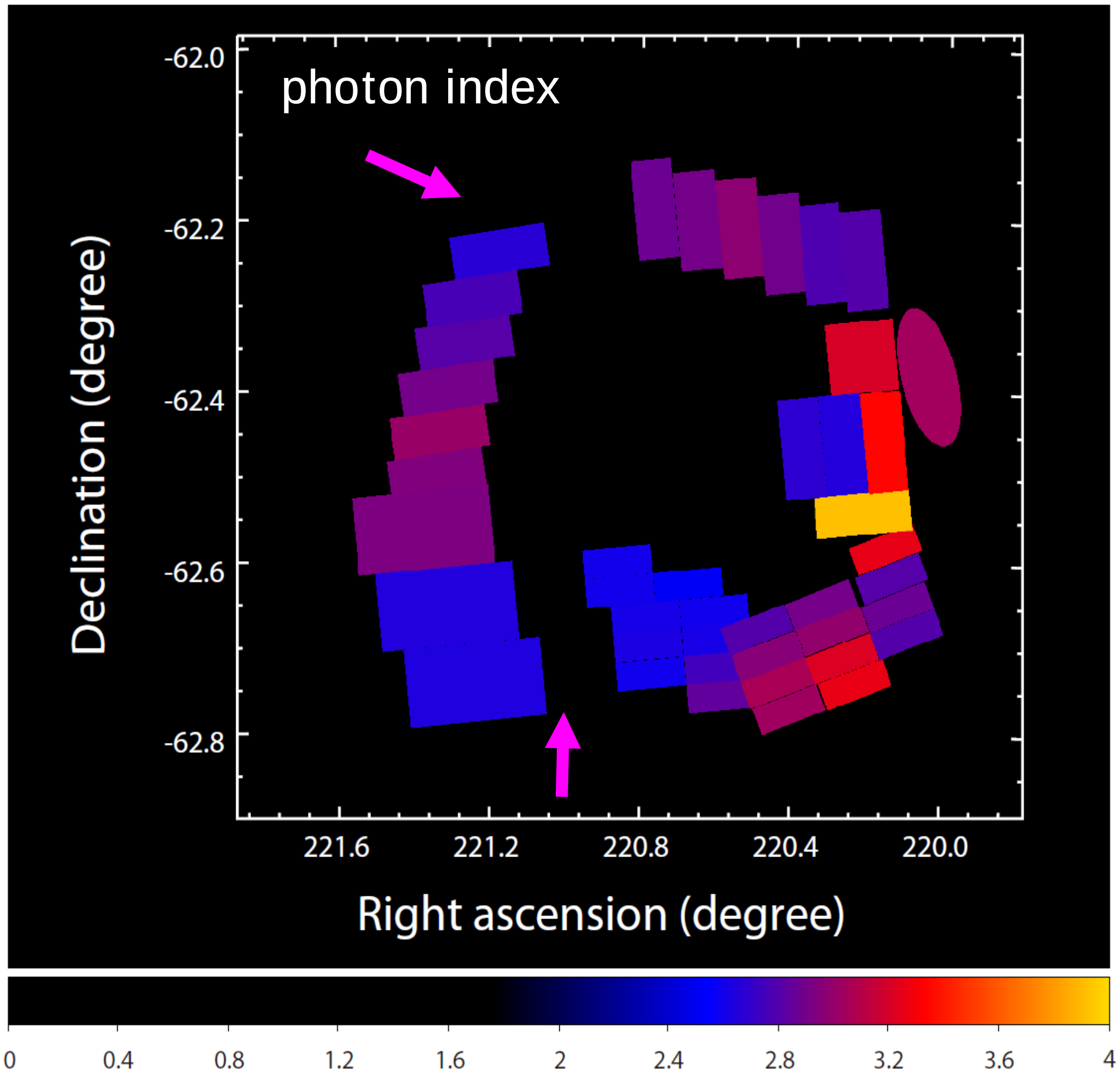
surface brightness of sync. X-rays

$\propto$ density of acc. e x magnetic field^2



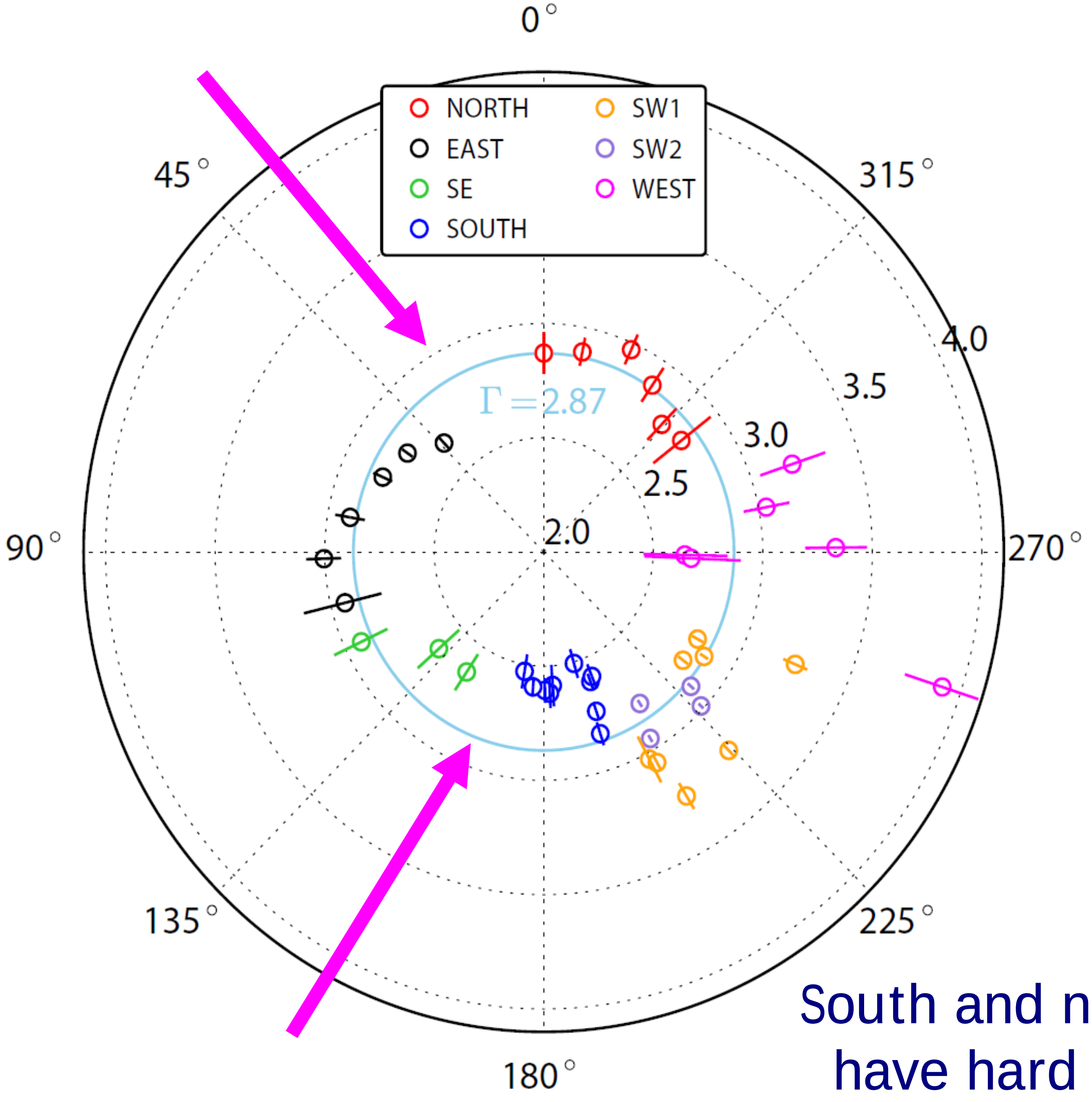
south and northeast contain strong sync. X-rays

photon index ~ E_{max} of accelerated electrons



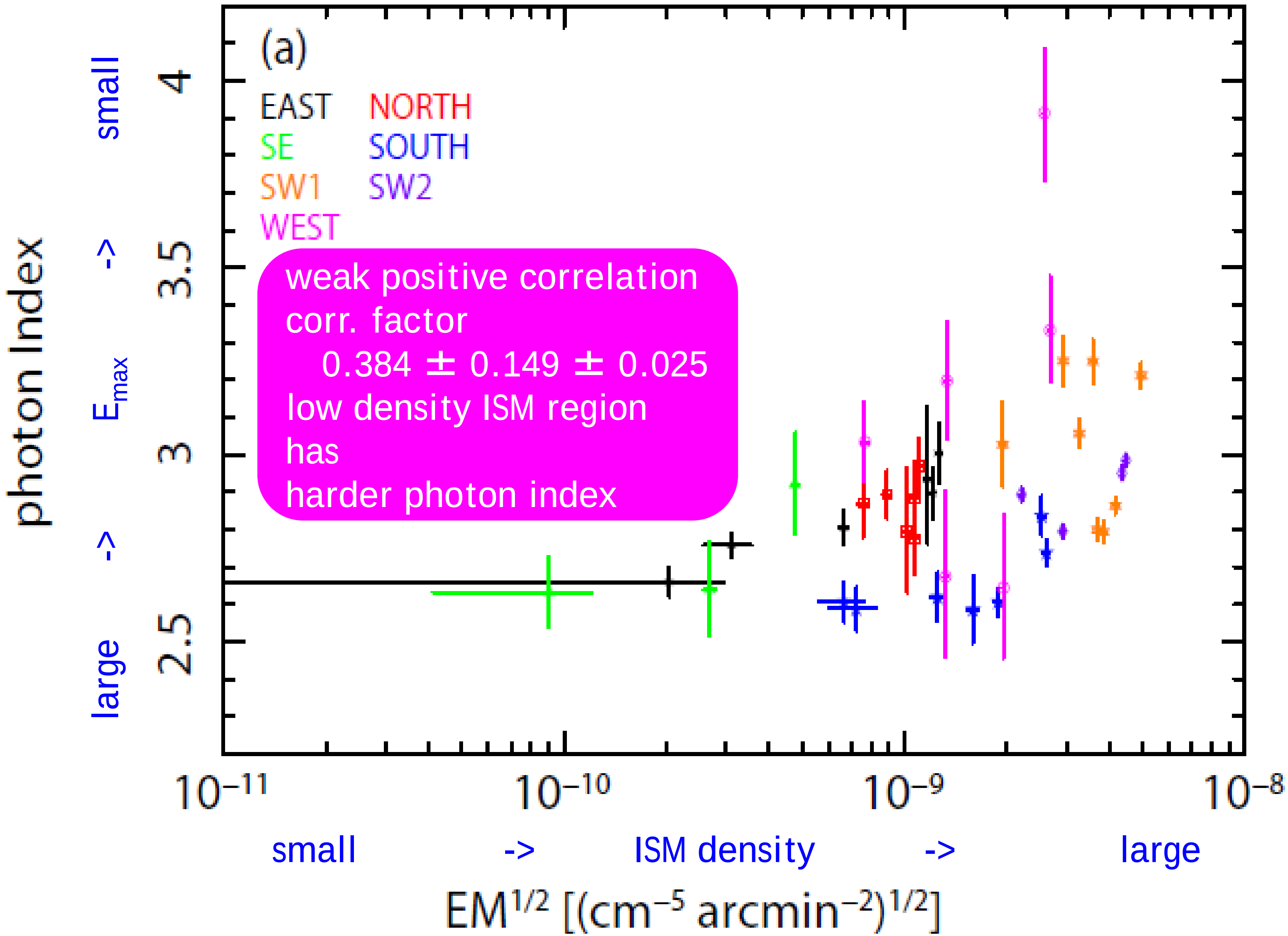
South and northeast have hard sync. X-rays

1.4. azimuth map of photon index

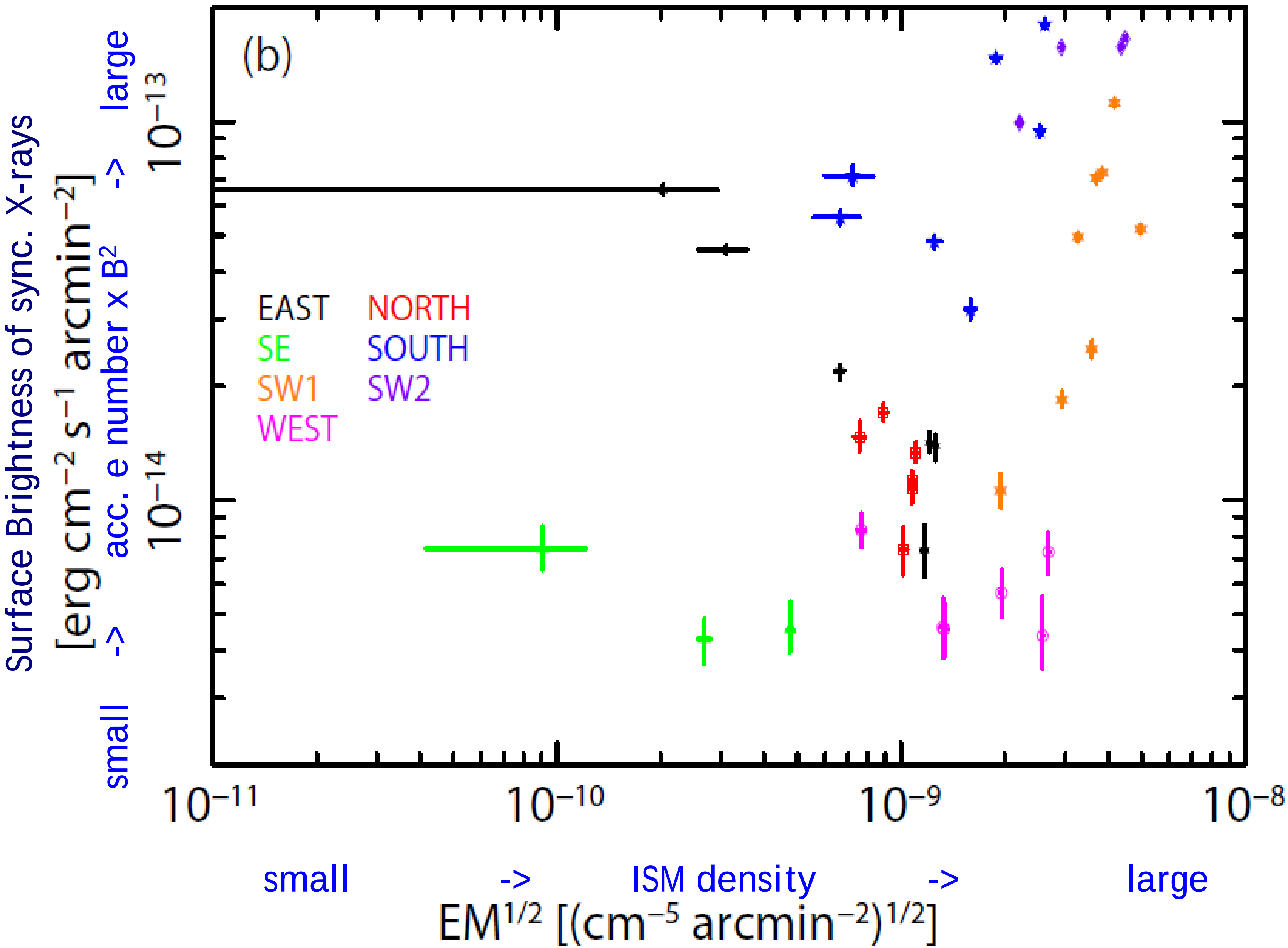


South and northeast have hard sync. X-rays

1.4. Correlation among parameters



no correlation



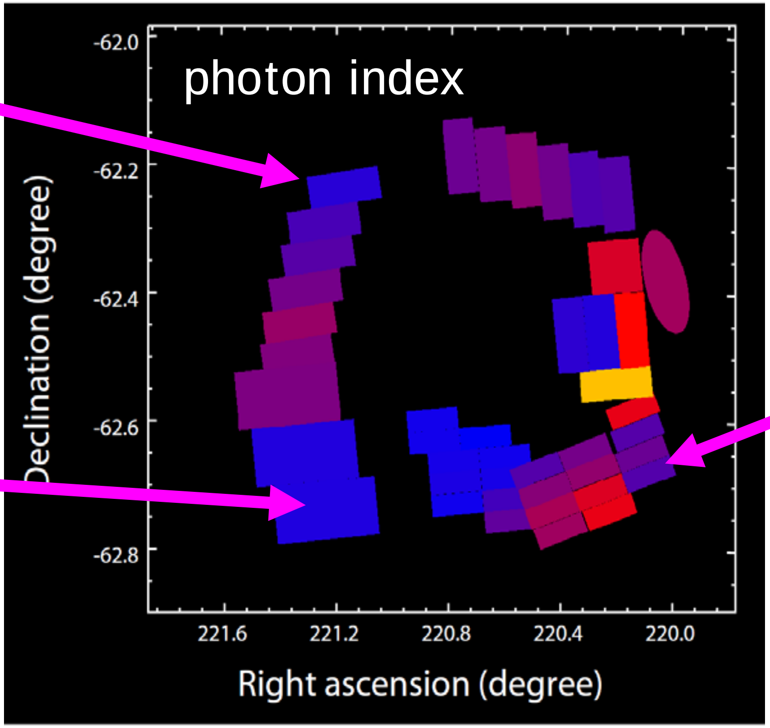
1.5. Discussion

low ISM density region has
harder sync. X-rays = large E_{max} for acc. electrons ?

When E_{max} is determined by sync. loss limit:
cut-off E of sync. X-rays $\propto$ shock velocity^2
(Yamazaki+06, Aharonian & Atoyan 1999)
low ISM density <-> shock keeps large velocity <-> large E_{max}

north-east
v_s = 1200 +- 200 km/s
(Helder+13)

South
no info. of v_s



south-west
v_s = 562 +- 18 km/s
(Ghavamian+01)

no correlation between ISM density and number of acc. e and B

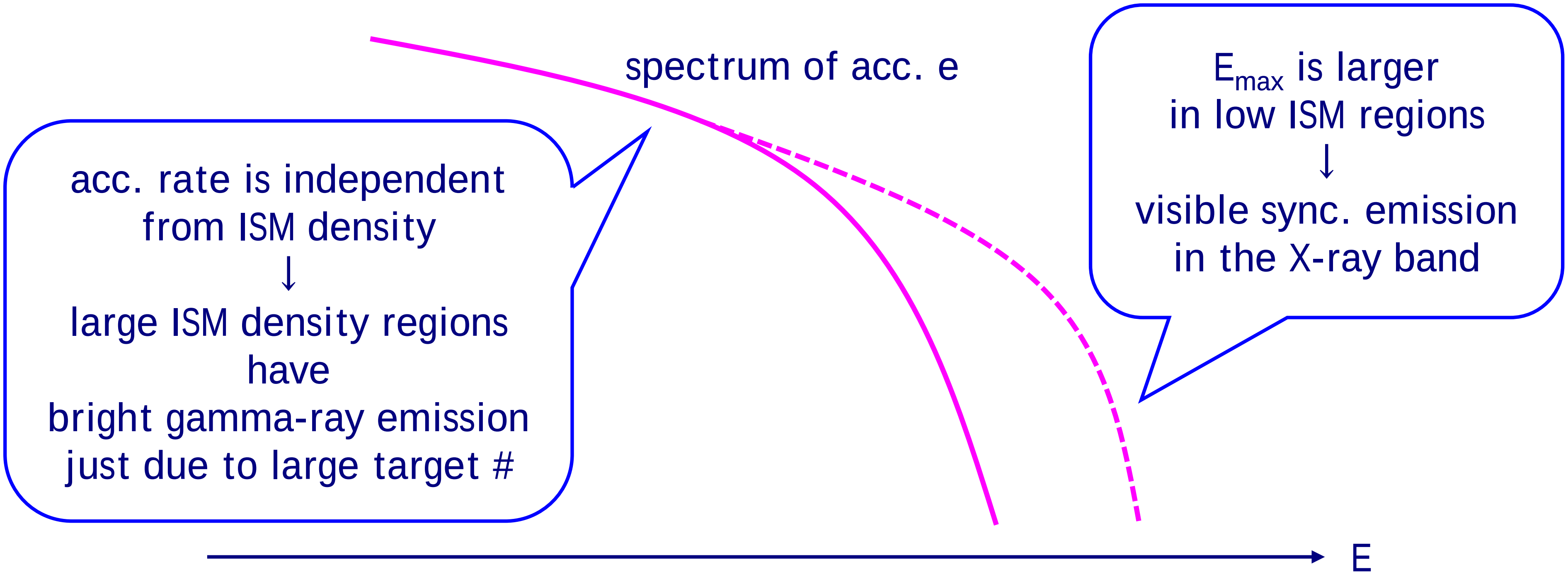
Injection rate can be independent from ISM density ?

B amplification can be also independent from ISM density ?

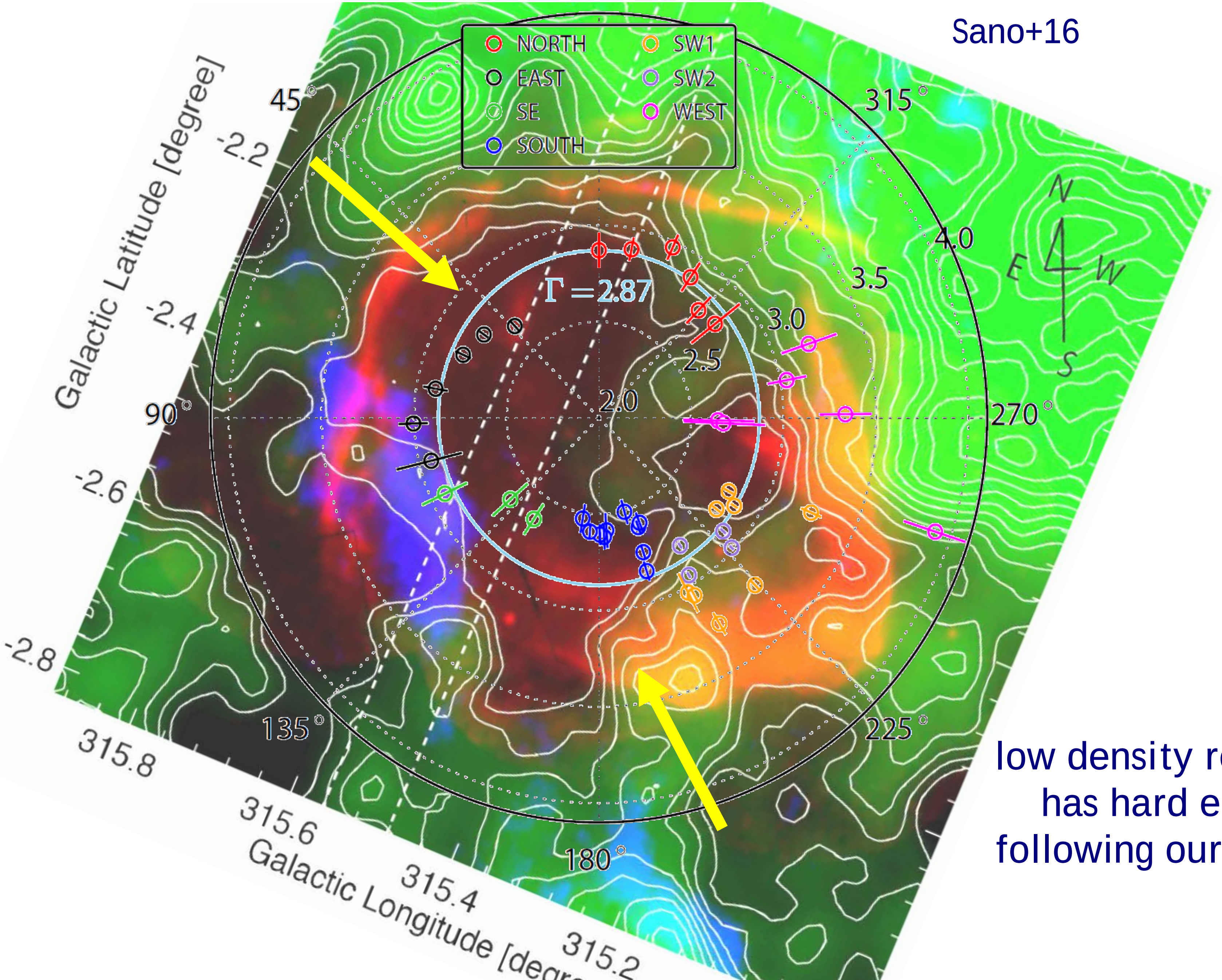
or we should check it in smaller scale ? (Inoue+12)

Conclusion:

low ISM density leads no de-acceleration of shock velocity and high E_{max}



Comparison with molecular clouds

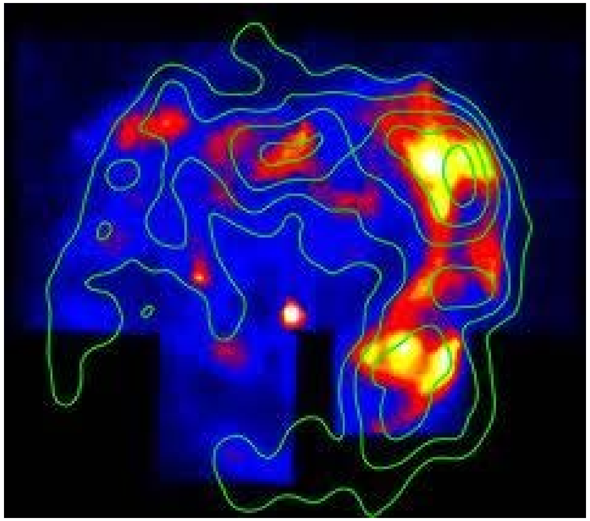


Sano+16

low density region
has hard emission
following our scenario

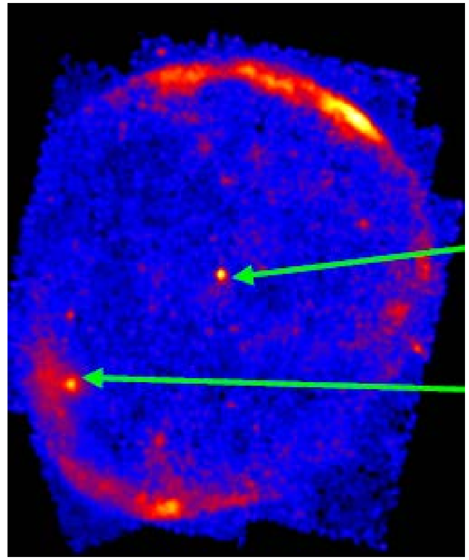
Relation to other VHE gamma-ray SNRs

RX J1713-3946



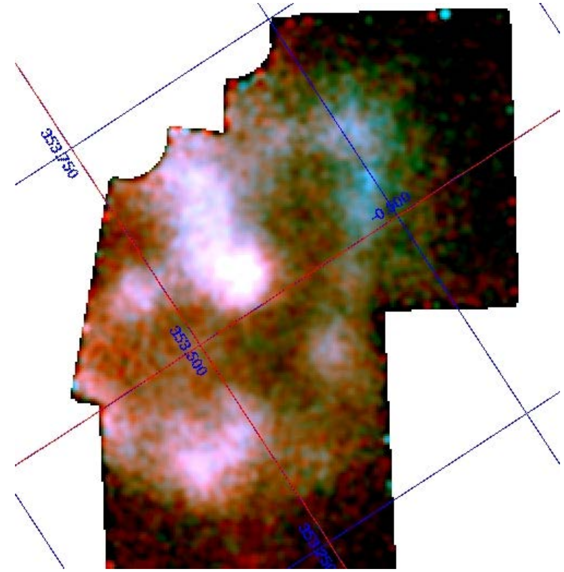
(Koyama+97, ...)

Vela Jr.



(Slane+00, ...)

HESS J1731-347

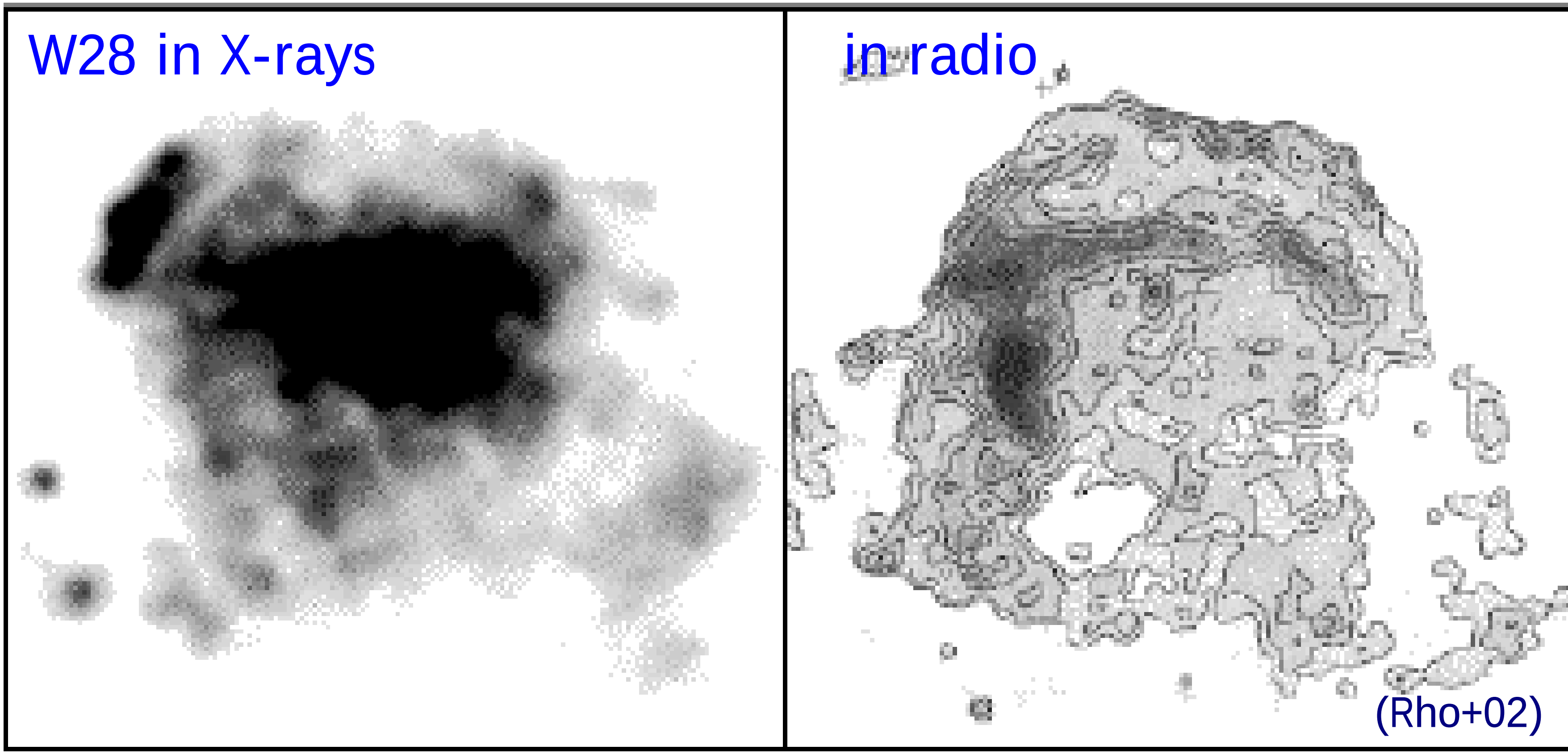


(Bamba+12, ...)

VHE gamma-ray SNRs does not have significant thermal X-rays
-> small ISM density
-> bright sync. X-rays due to the large shock velocity

topic 2:
X-ray study of environment of particle escape site of SNRs

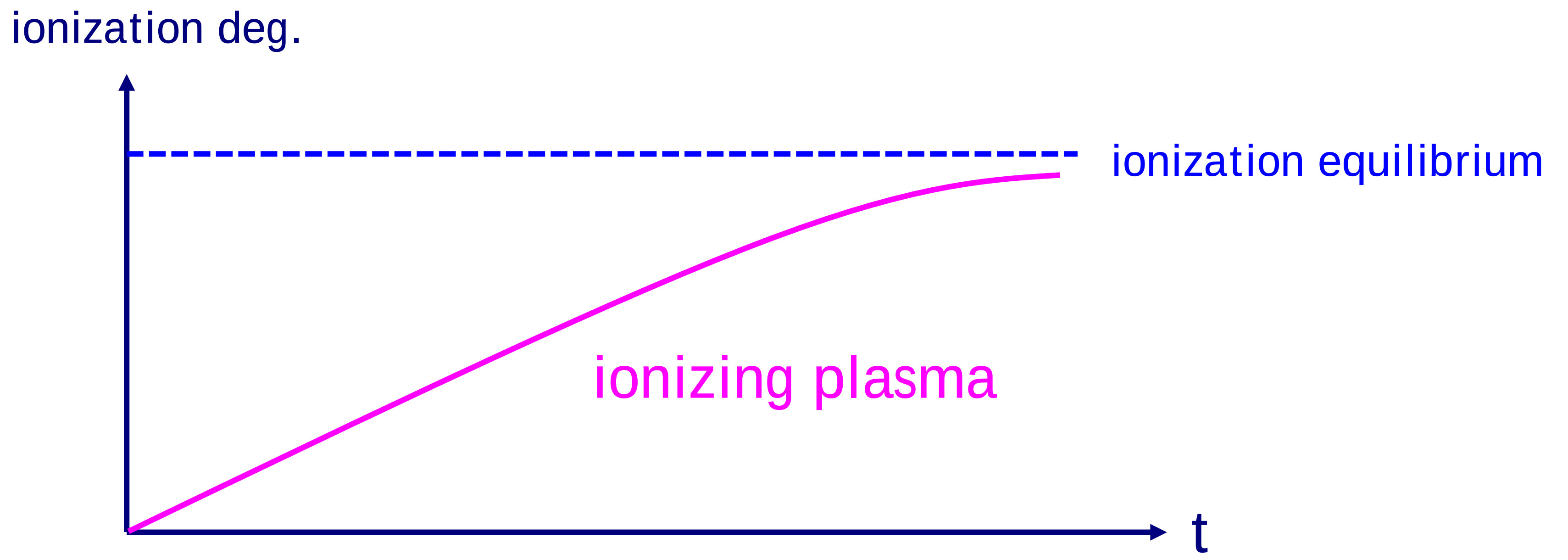
2.1. X-ray characteristics of GeV SNRs



Thermal X-ray emission from central region of the SNR
“mixed morphology (MM) type”
shocks are already cooled down due to the expansion ?

Thermal plasma condition

The density of thermal plasma in SNRs is very LOW
-> it takes time to be ionization equilibrium

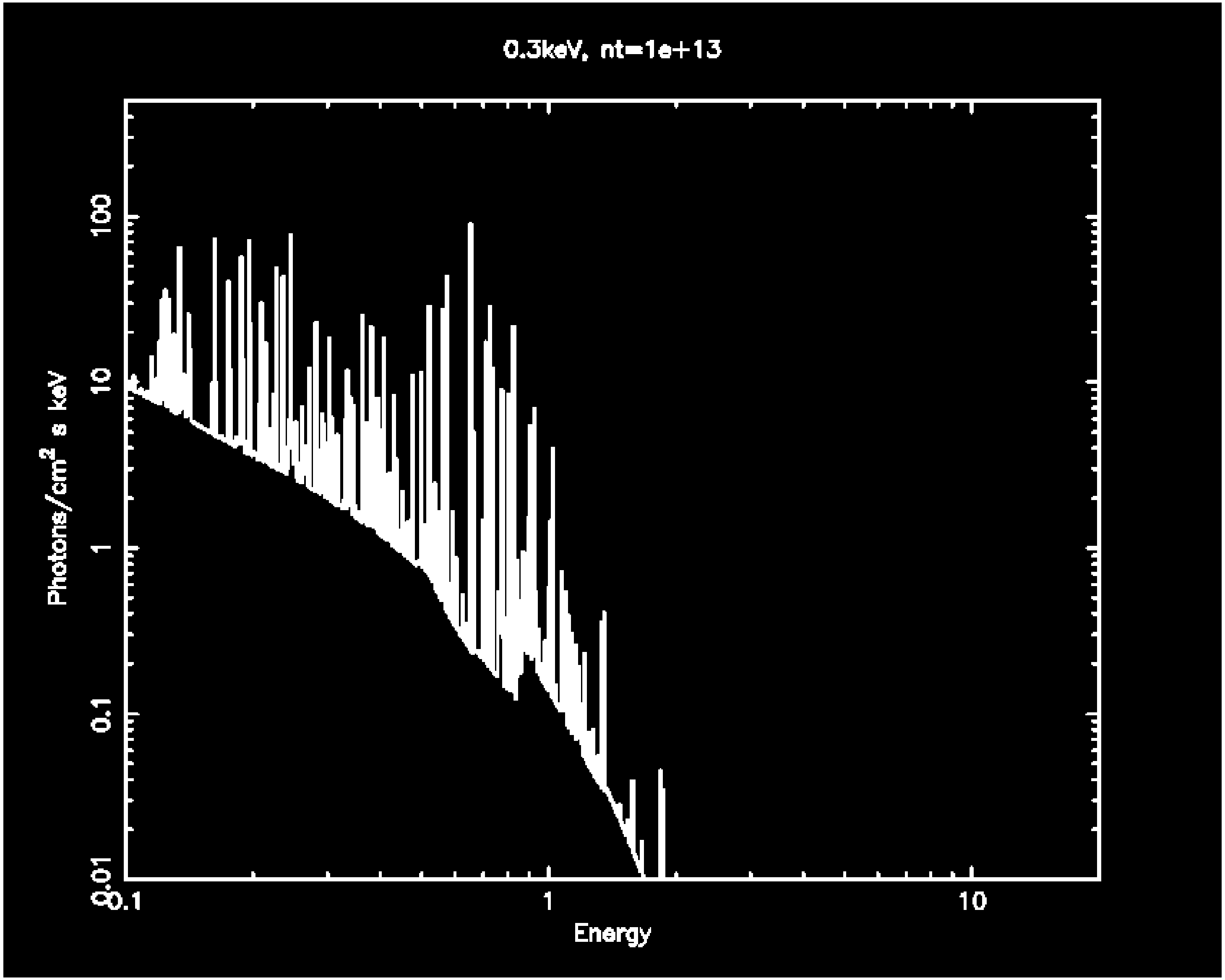


plasma age $\propto n_e t$

time scale for the equilibrium: $n_e t \sim 10^{12}$ $cm^{-3}s$

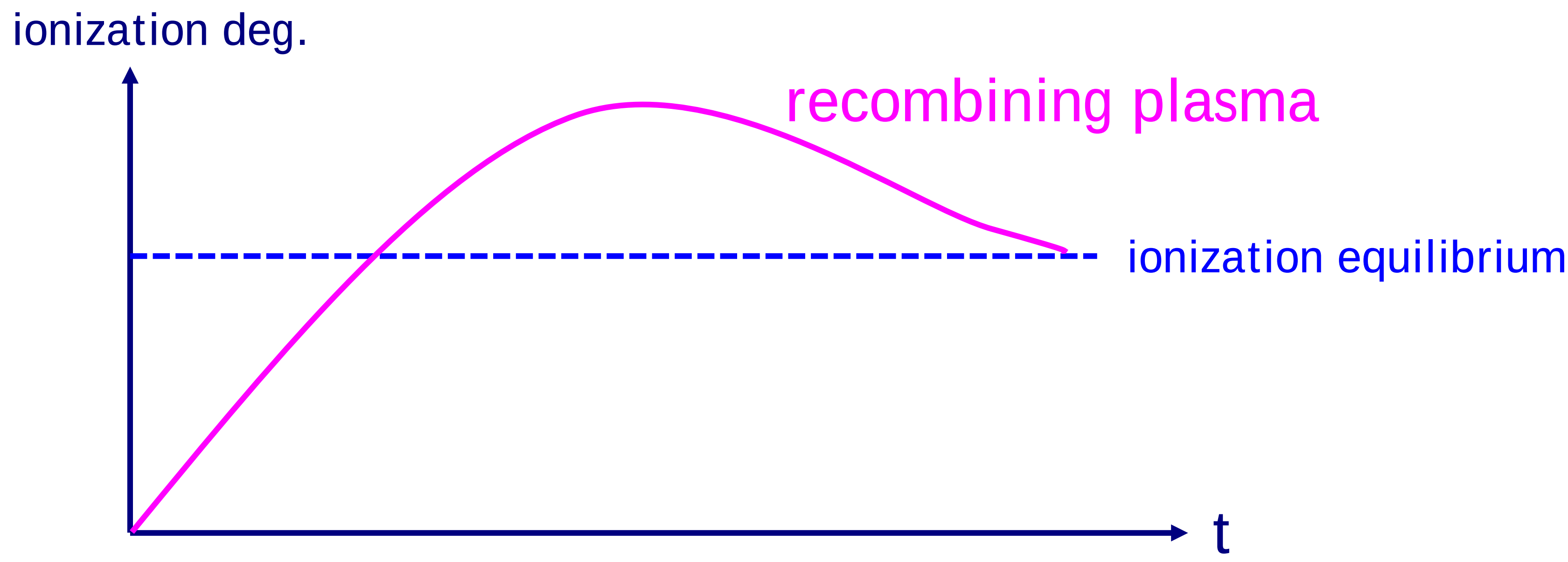
typical SNR: $n_e \sim 1$ cm^{-3} -> $\sim 10^4$ yrs for the equlibrium

How to measure the ionization time scale ?



more ionized -> more high E electrons, more lines

Plasma condition of GeV SNRs



ionization kT is higher than electron kT: over-ionized !

-> plasma is recombining (RP)

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

most of RP SNRs are gamma-ray emitters

2.2. What recombining plasma tells us ?

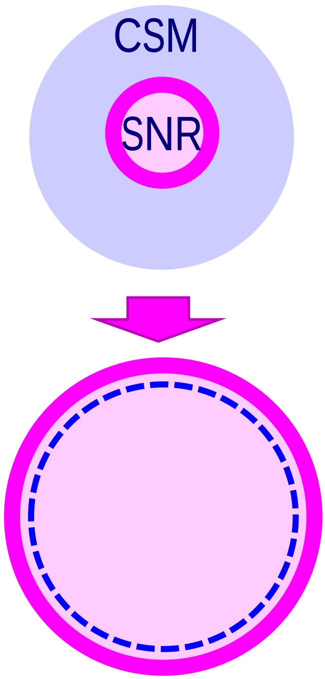
We need sudden cooling to make recombining plasma

- rapid expansion ?
- heat conduction with colliding molecular clouds ?

together with GeV gamma-rays

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

2.3. X-ray follow-up of GeV SNRs

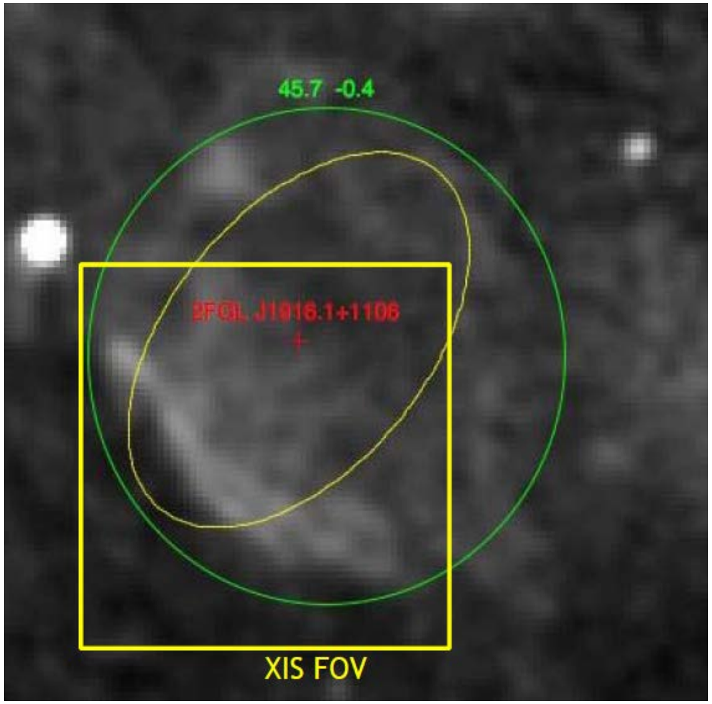
3FGL catalog (Acero+16): Many GeV SNR candidates

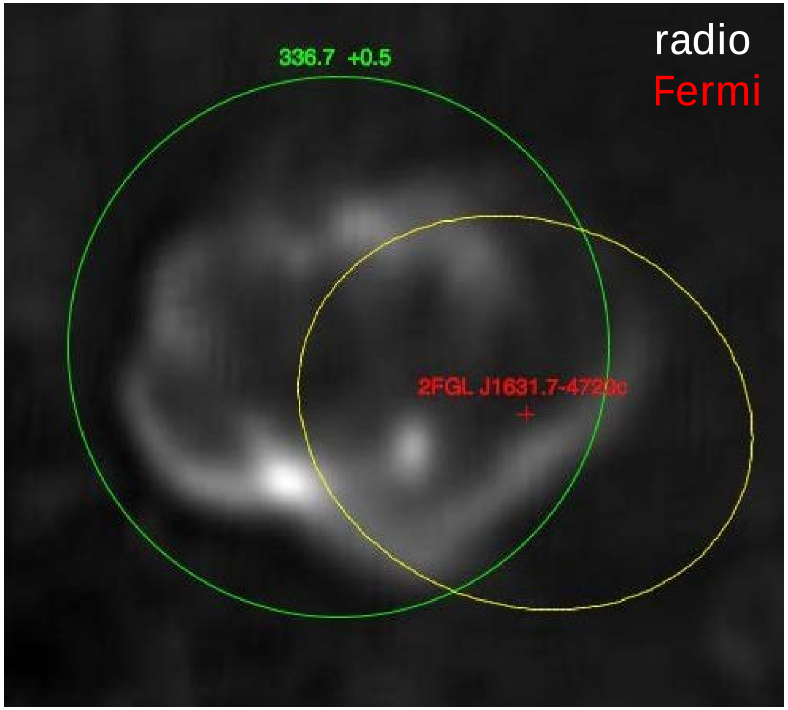
-> real counterpart or not? characteristics in X-rays?

mixed morphology, recombining plasma, …

Many GeV SNRs are rather old

-> Many have not observed in X-rays yet

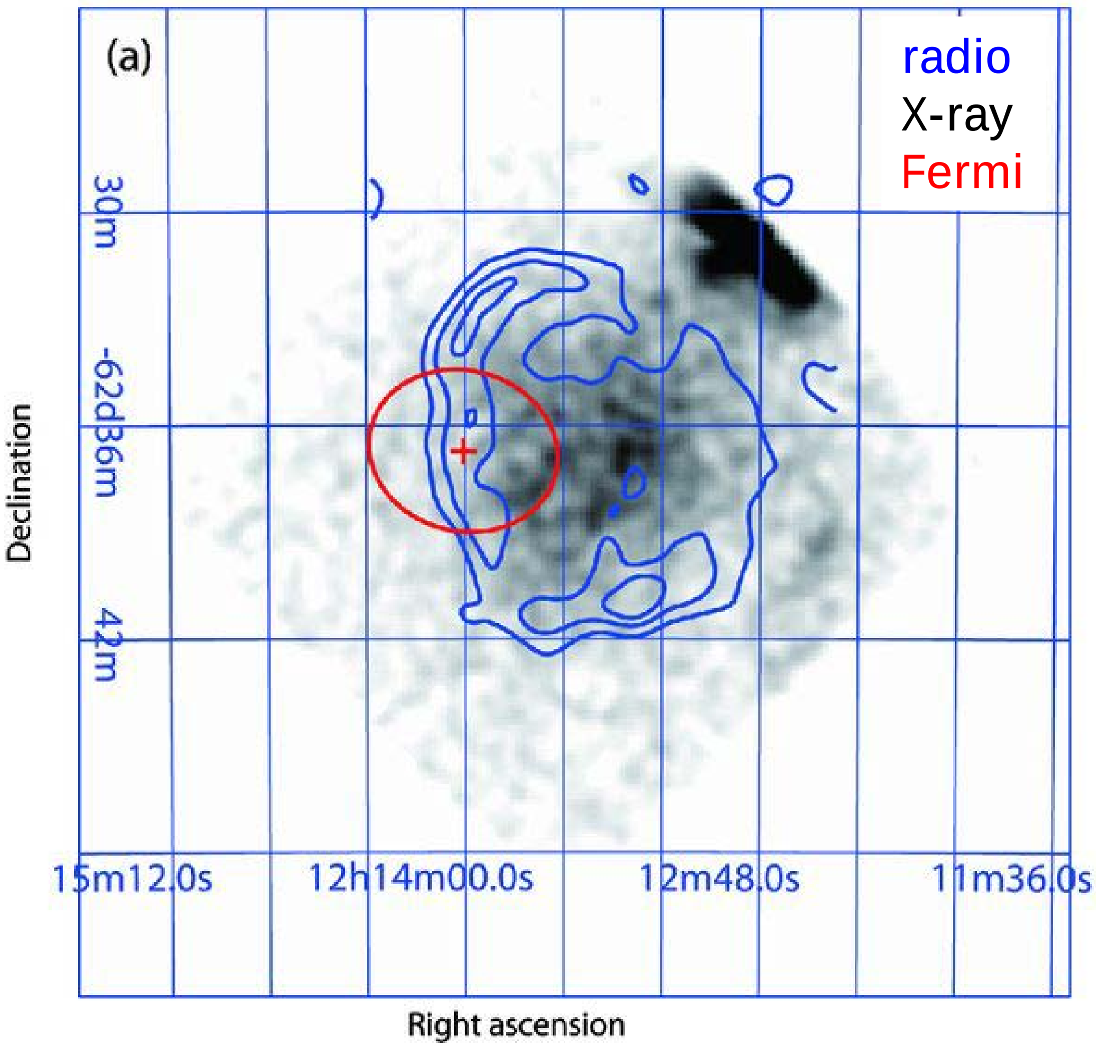




-> X-ray follow-up observations

follow-up example

G298.6-0.0 with Suzaku
upper-limit with ROSAT (Hwang & Markert 1994)



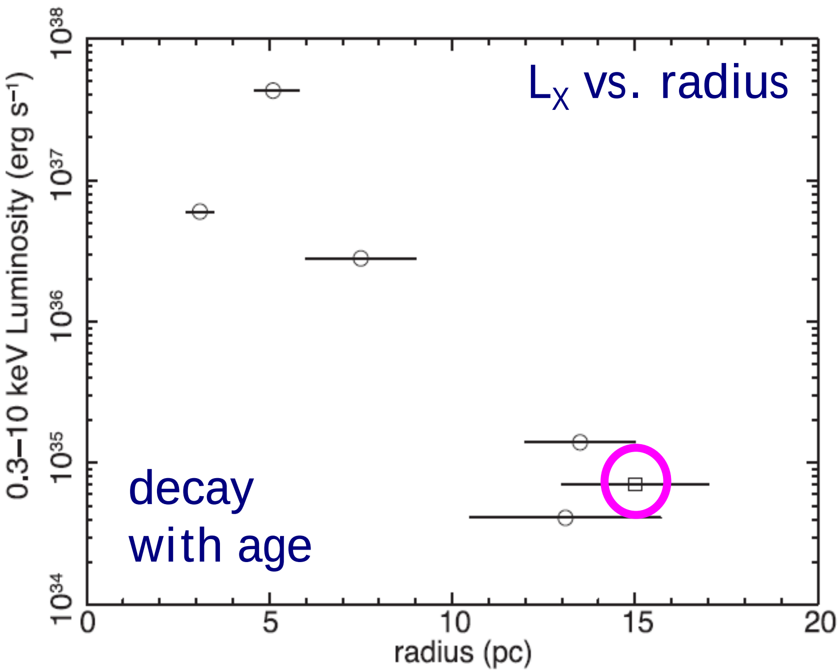
Bamba+16
discovery of thermal X-rays
mixed morphology

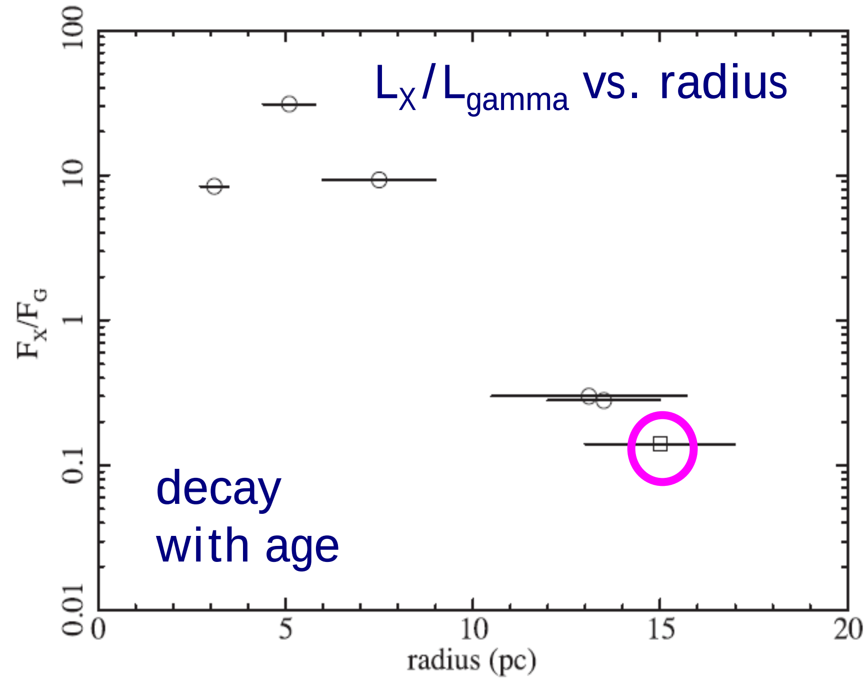
Good GeV SNR candidate !

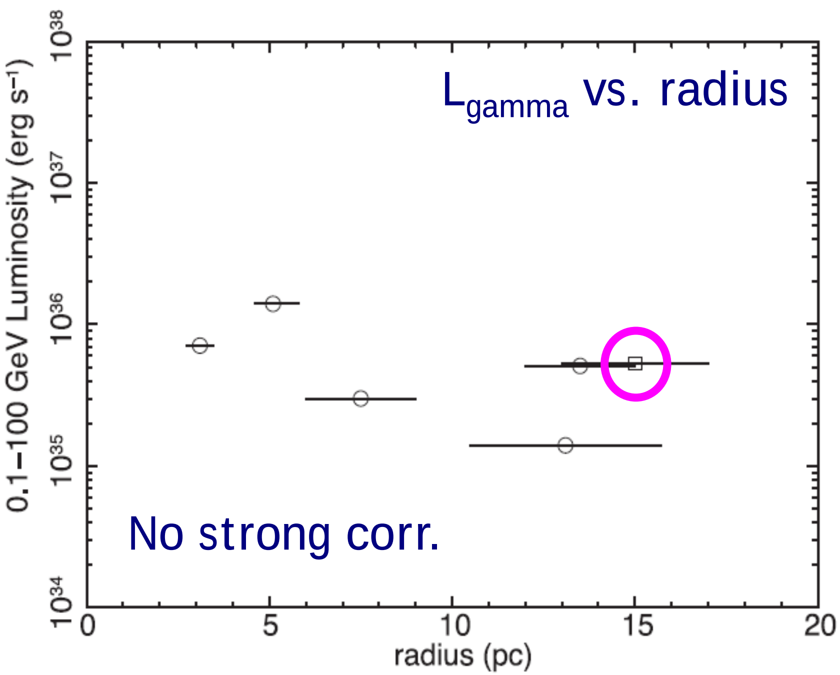
Too faint to resolve
plasma condition

Plan to further follow-ups
(XMM?)

2.4. Luminosity evolution of GeV SNRs (Bamba+16)







L_X/L_{gamma} decays with age
Plasma cooling is faster than particle escape ?

G298.6-0.0 is the most evolved sample ?

When they evolve further, do they become GeV inID srcs ?

2.5. Clue of escaped protons ?

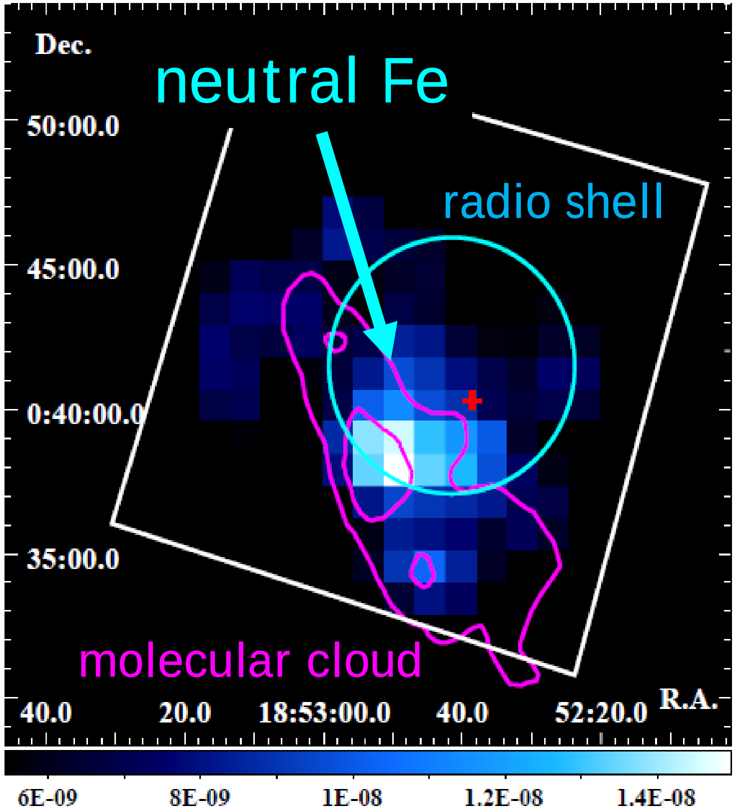
Kes 79 (Sato+16)

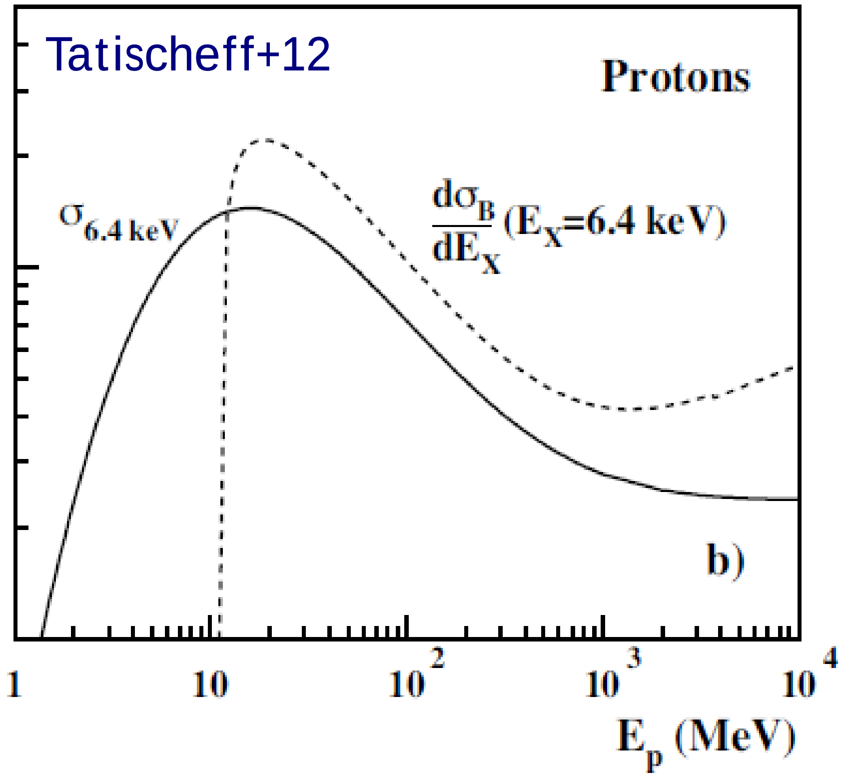
neutral Fe line from

Kes 79 interacting point with MC

clue of ~10 MeV protons

escaping from the SNR ?





Similar neutral Fe is found

in the Galactic center region

(Nobukawa+15)

We need more samples

3. Summary

- X-rays observations are a strong tool to understand environments of acceleration sites.

- Thermal X-rays are faint in regions with strong sync. X-rays.
  - electron E_{max} is higher in low ISM region ?

- GeV SNRs has recombining plasma, implying rapid cooling.
  - related to the CR escape ?