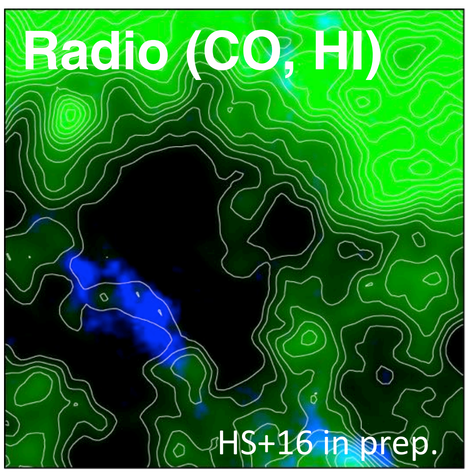
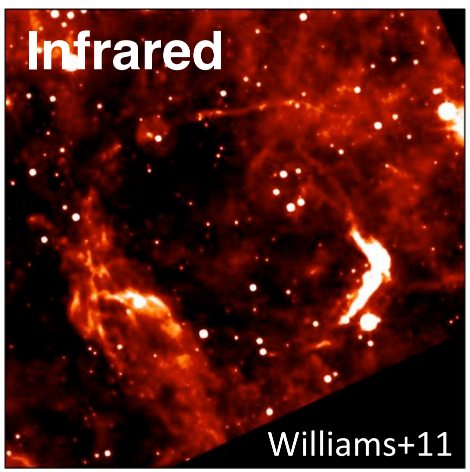
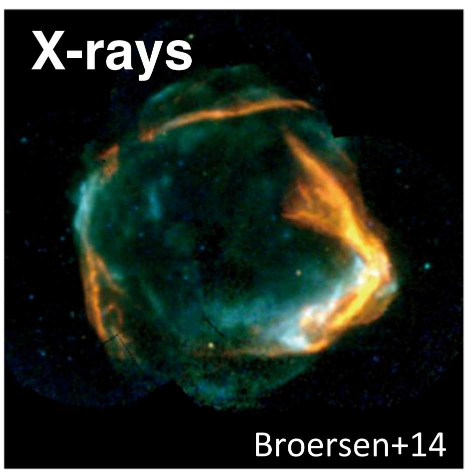
特別推進研究研究会・宇宙線研究所共同利用研究会
「高エネルギーガンマ線でみる極限宇宙2015」
"The extreme Universe viewed in very-high-energy gamma-rays 2015"

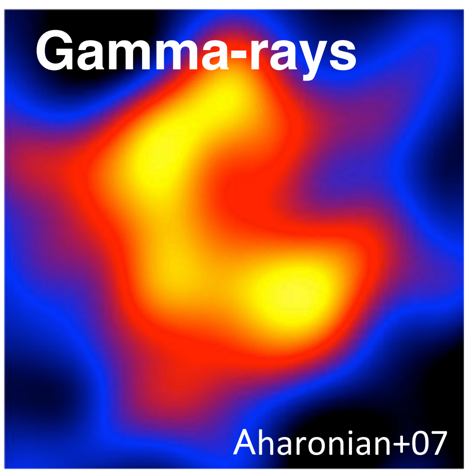
A multi-messenger search for the origin of cosmic-rays

Hidetoshi SANO (Nagoya Univ.)







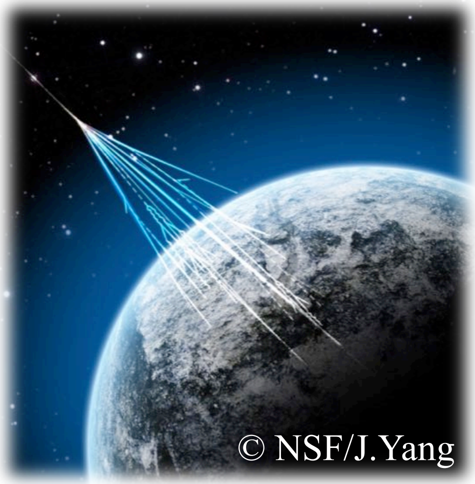


Revealing the origin of cosmic rays

- Cosmic rays: relativistic protons (90%), He (10%), electrons + nuclei (<1%)
  → They have a significant influence on the interstellar space

Heating the interstellar gas

Galaxy evolution



Earth environment

→ Revealing the origin of cosmic-rays is essential to understand the universe

SNRs are thought to be the primary sources for the bulk of Galactic cosmic-rays
However, the acceleration site of protons is still being debated…

Outstanding issues & solutions

[1] Origin of gamma-rays (hadronic and/or leptonic)

→ ◎ Spatial comparison between the ISM and gamma-rays

[2] Acceleration models including more realistic conditions

→ ◎ Shock-cloud interaction model

→ ○ Other acceleration mechanisms ?

(non-liner, 2nd order Fermi, magnetic reconnection etc…)

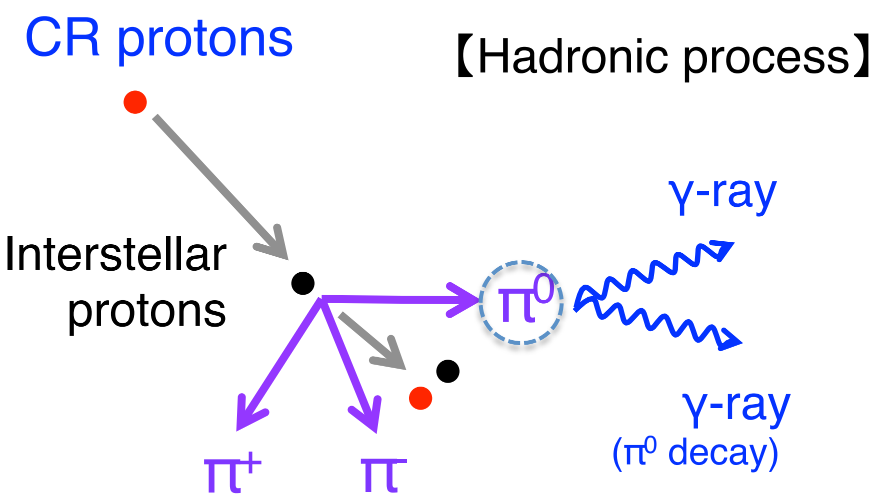
[3] Gamma-ray obs. with high sensitivity + angular resolution

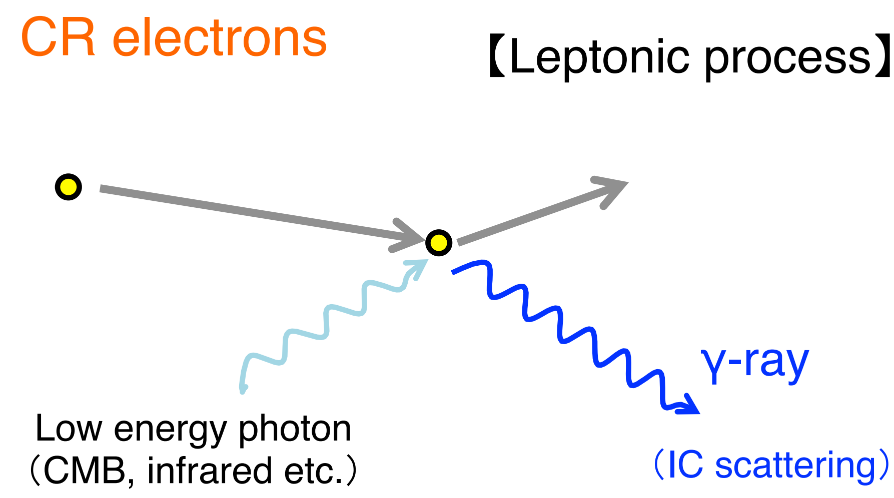
→ ◎ Cherenkov Telescope Array (CTA)

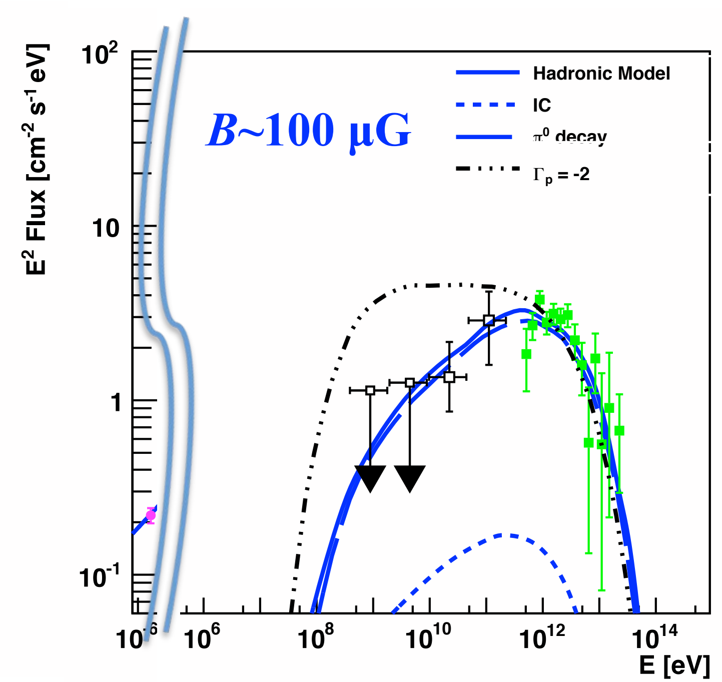
[4] To reveal an universality

→ ◎ Extend to the distant sources including the LMC SNRs

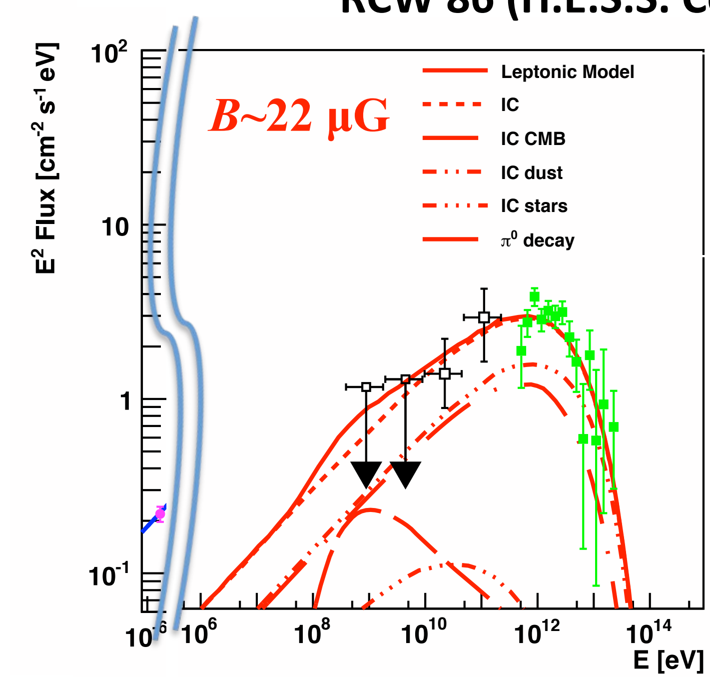
[1] Origin of gamma-rays (hadronic and/or leptonic)





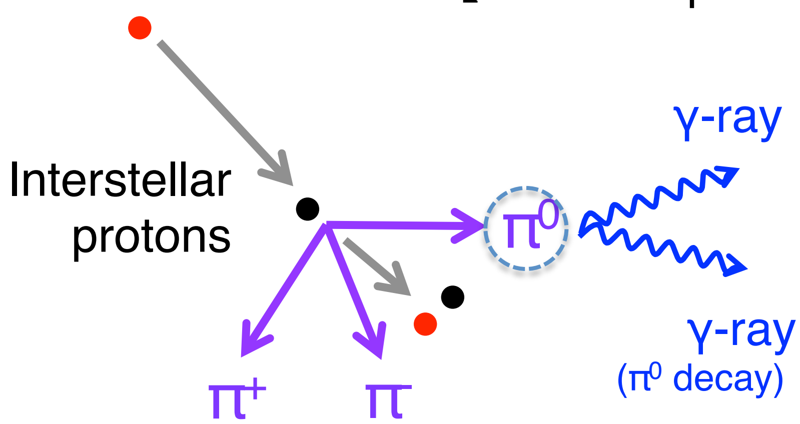


RCW 86 (H.E.S.S. Col.+15)



[1] Origin of gamma-rays (hadronic and/or leptonic)

CR protons 【Hadronic process】

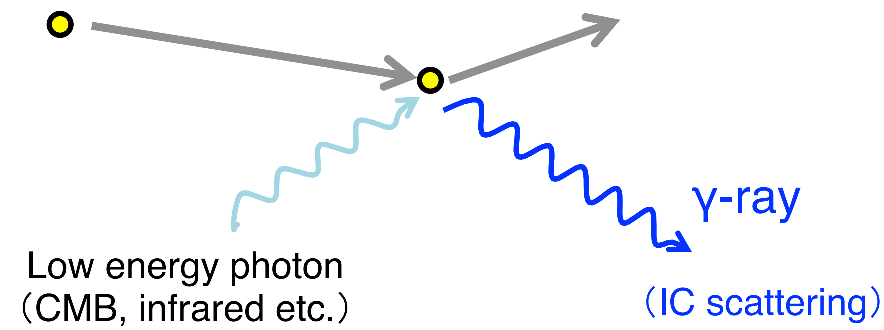


$$F \propto \frac{W_p n}{d^2}$$

W_p: total energy in accelerated proton
n: ISM gas density
d: distance to the SNR

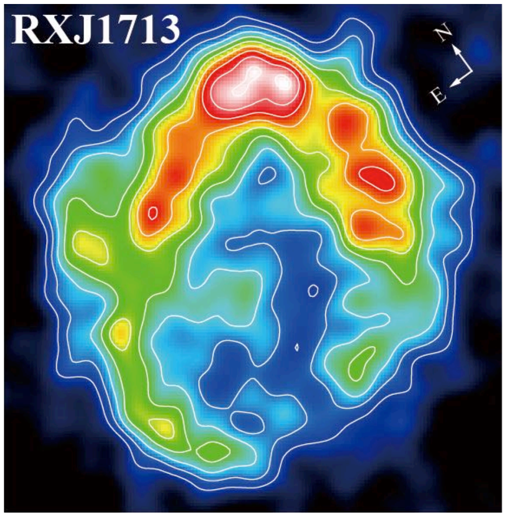
Gamma-rays distribution ∝ ISM gas distribution

CR electrons 【Leptonic process】

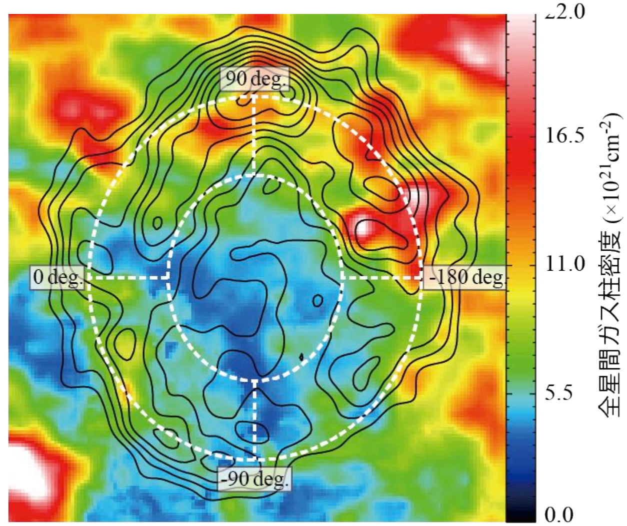


Evidence for the CR proton accelerations (Fukui+)

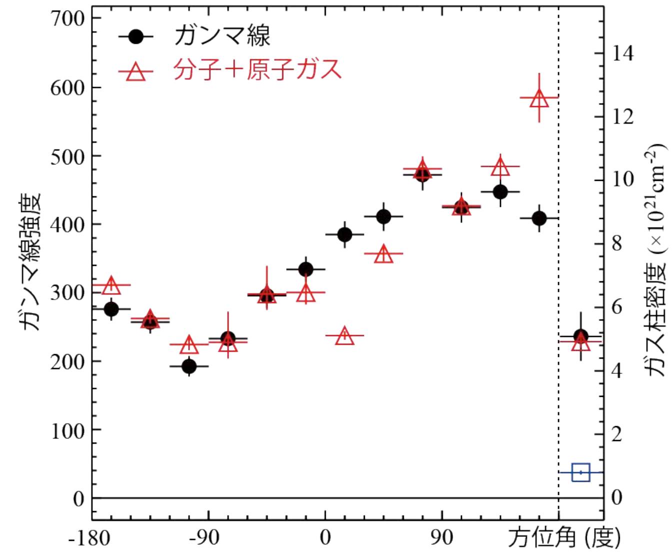
TeV Gamma-rays

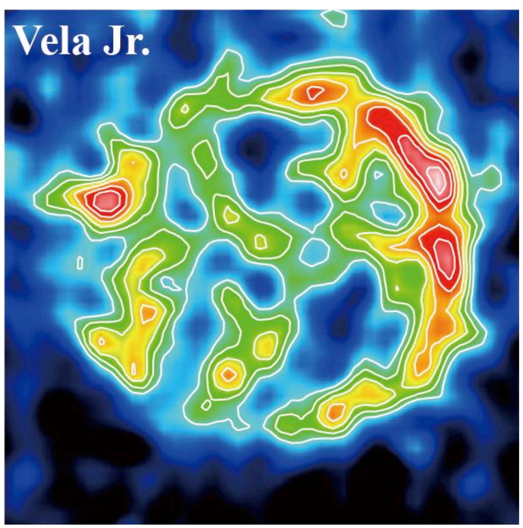


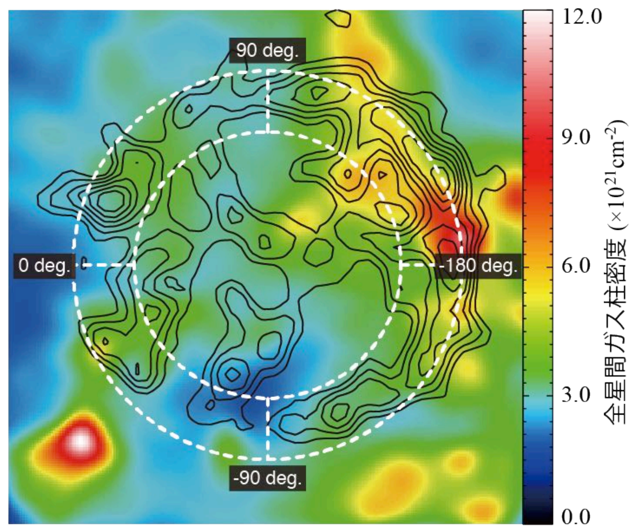
Total ISM

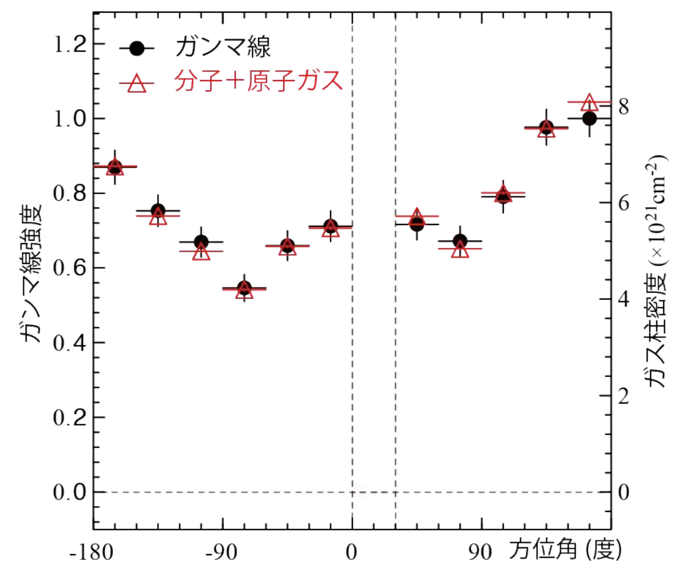


Acceleration efficiency ~0.1 %









(upper panels) Fukui, HS+12, (lower panels) Fukui, HS+16 in prep.

[2] Acceleration models including more realistic conditions

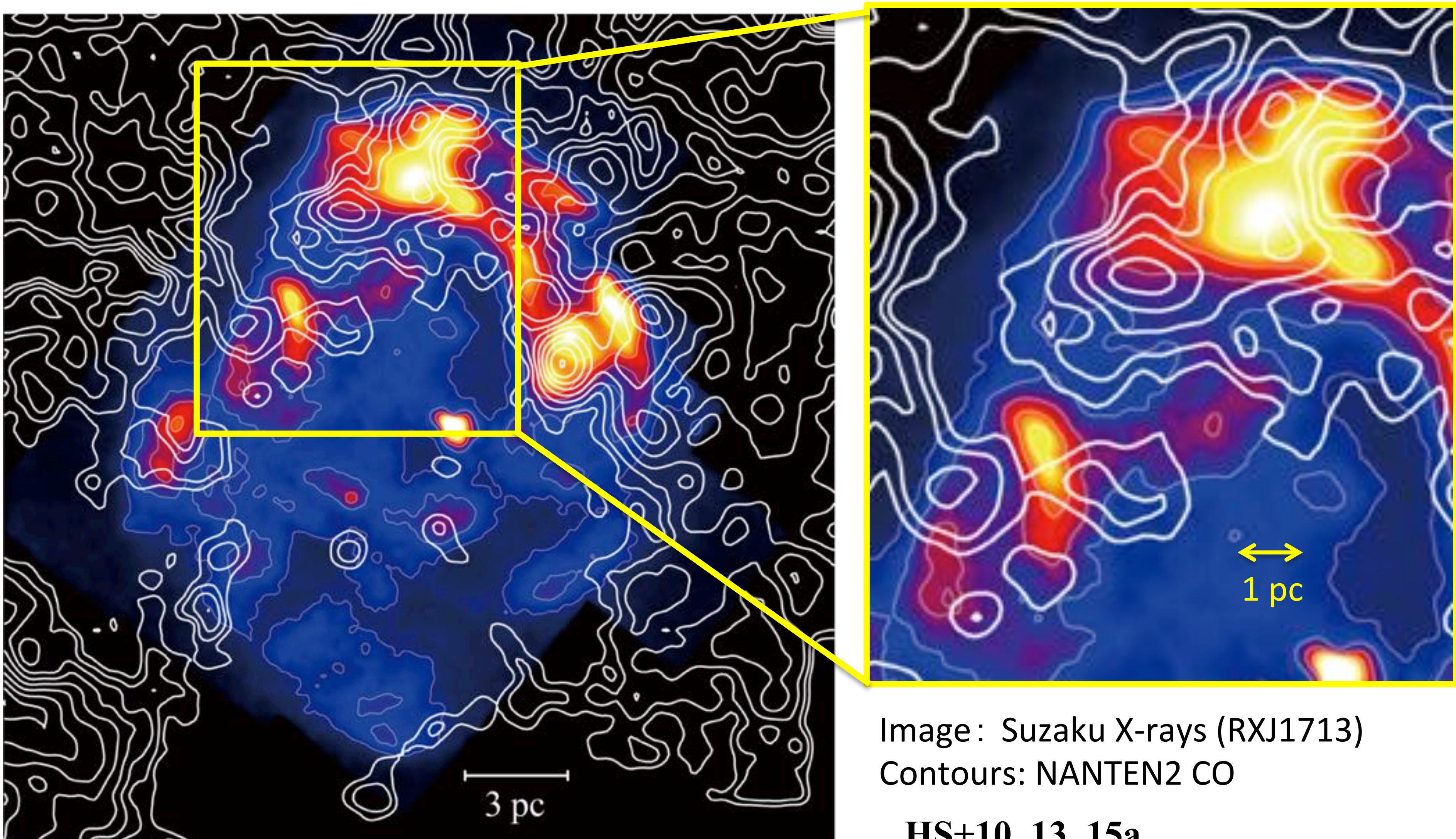
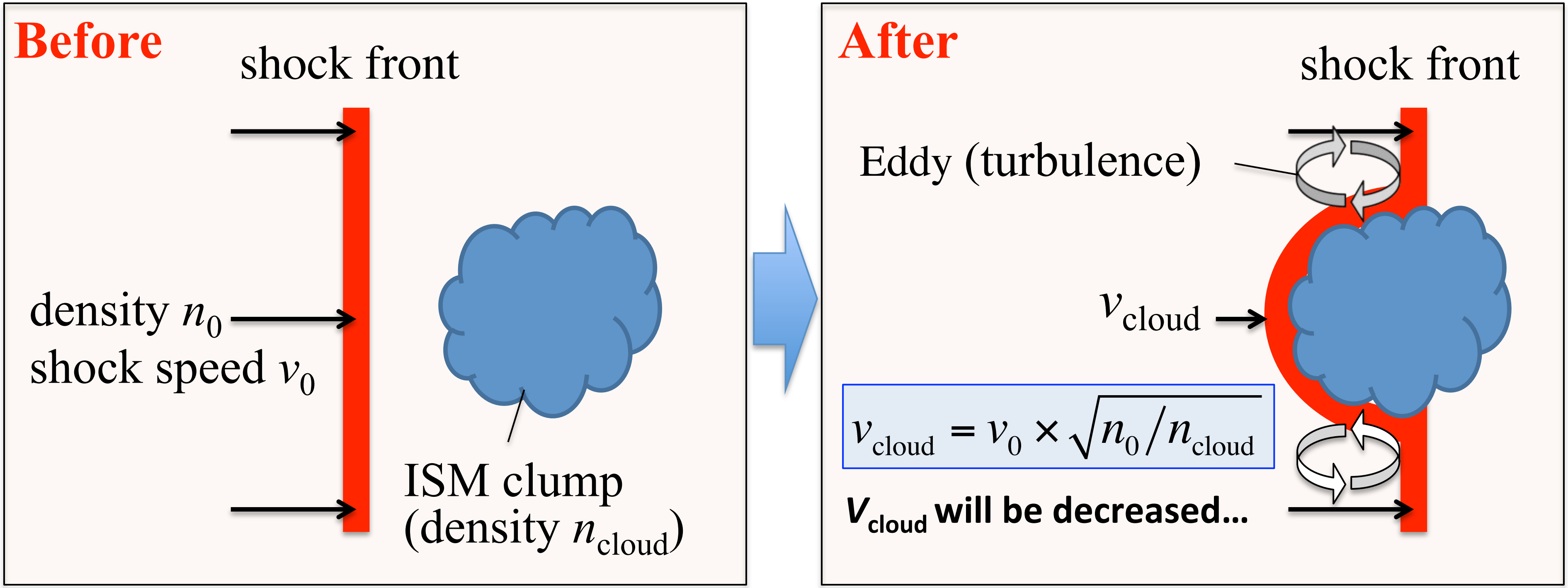


Image: Suzaku X-rays (RXJ1713)
Contours: NANTEN2 CO

HS+10, 13, 15a

- Synchrotron X-rays are enhanced around CO clumps in 0.1 pc scale

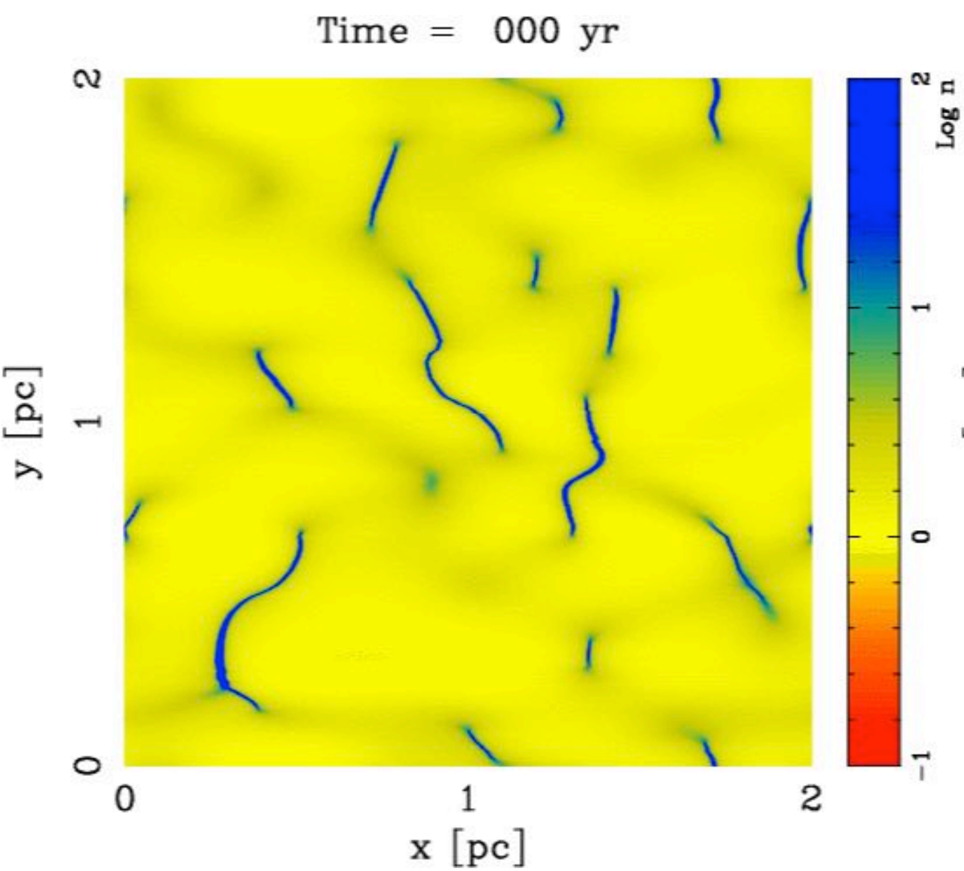
Shock cloud interaction model: schematic view

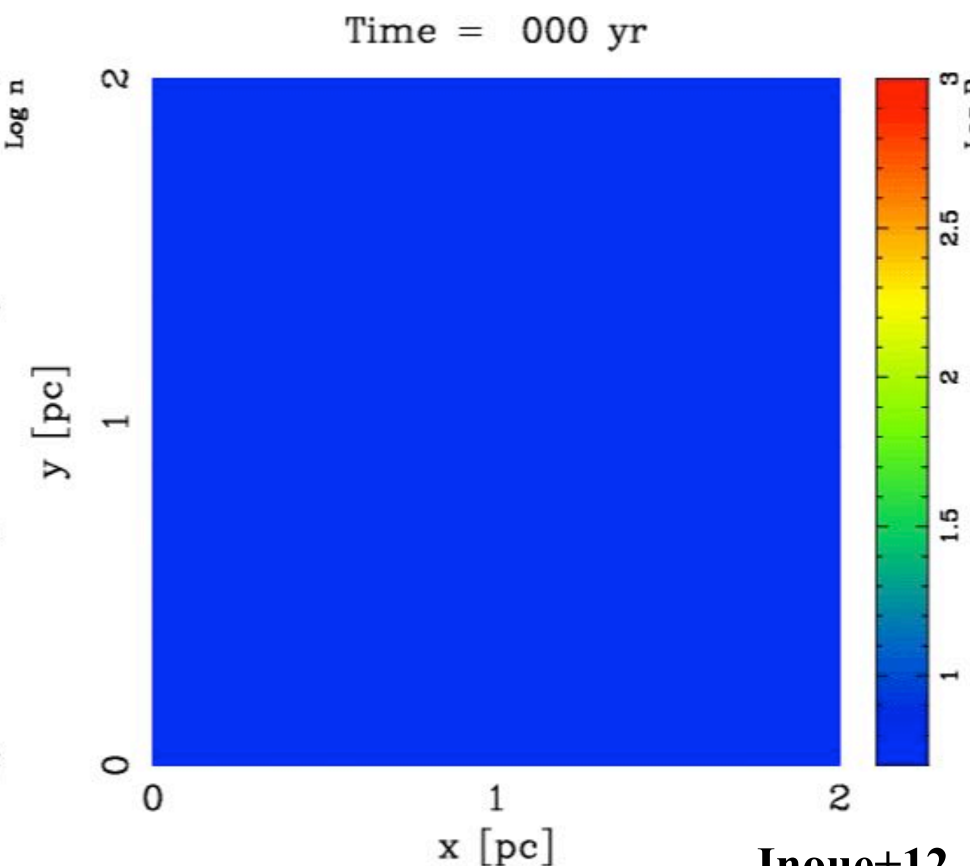


- Shock cloud interaction generates turbulence around the ISM clumps
  - [1] rotational current + dynamo effect → magnetic field amplification
  - [2] Synchrotron X-rays are enhanced around the ISM clumps

ISM density

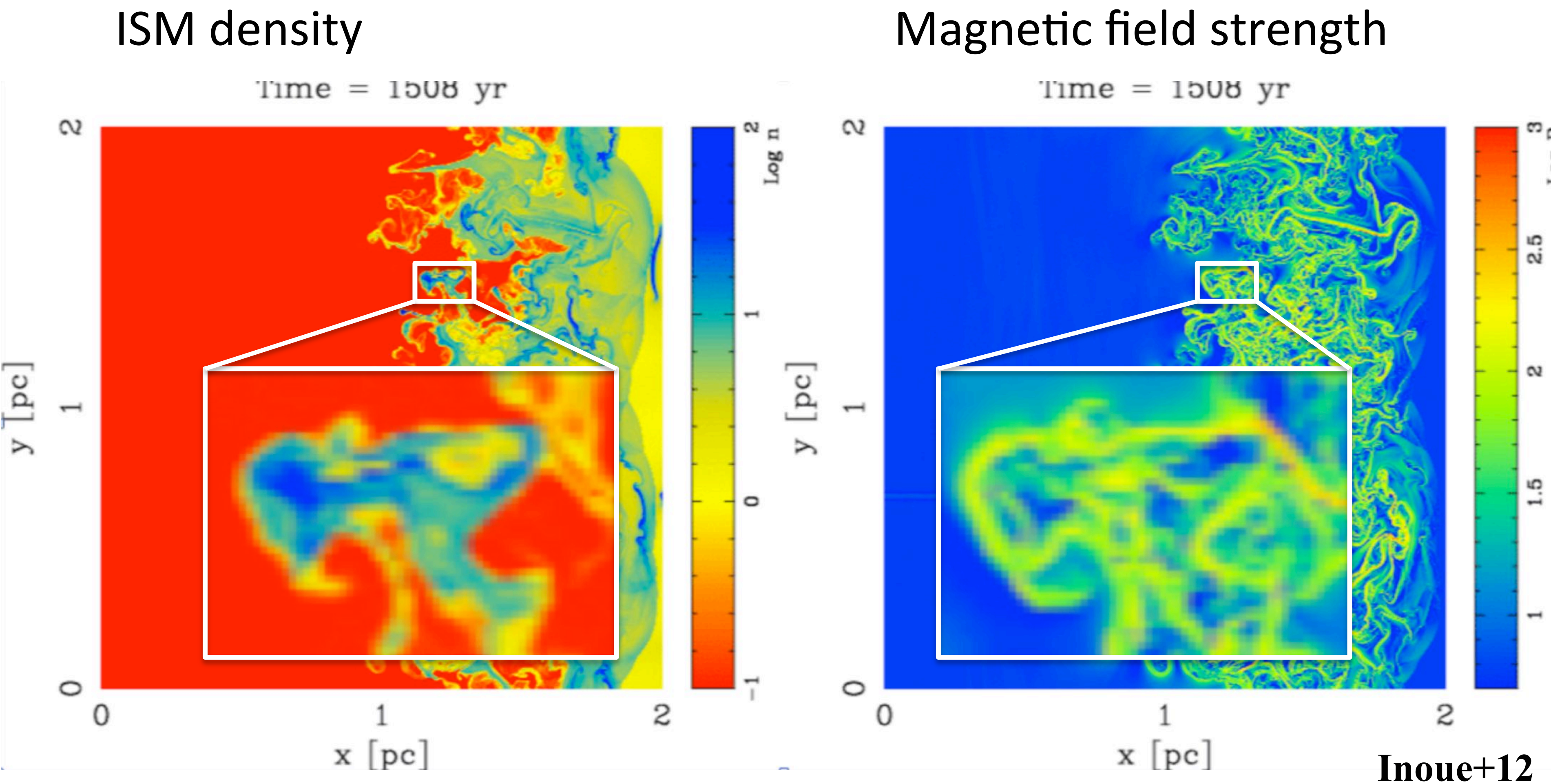
Magnetic field strength





Inoue+12

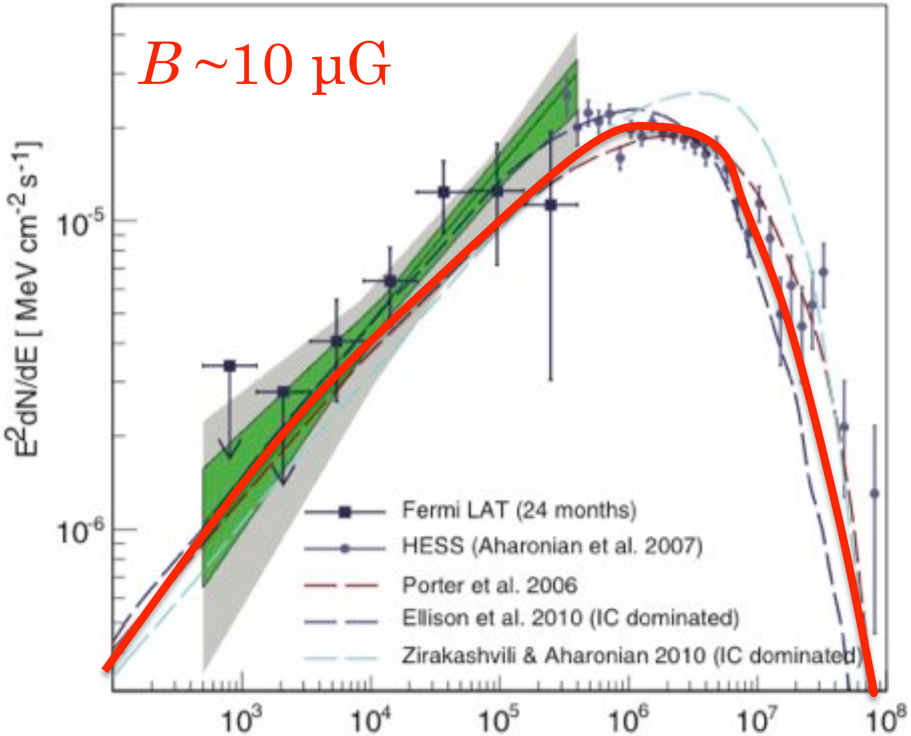
Shock cloud interaction model: HMD simulation (Inoue+12)



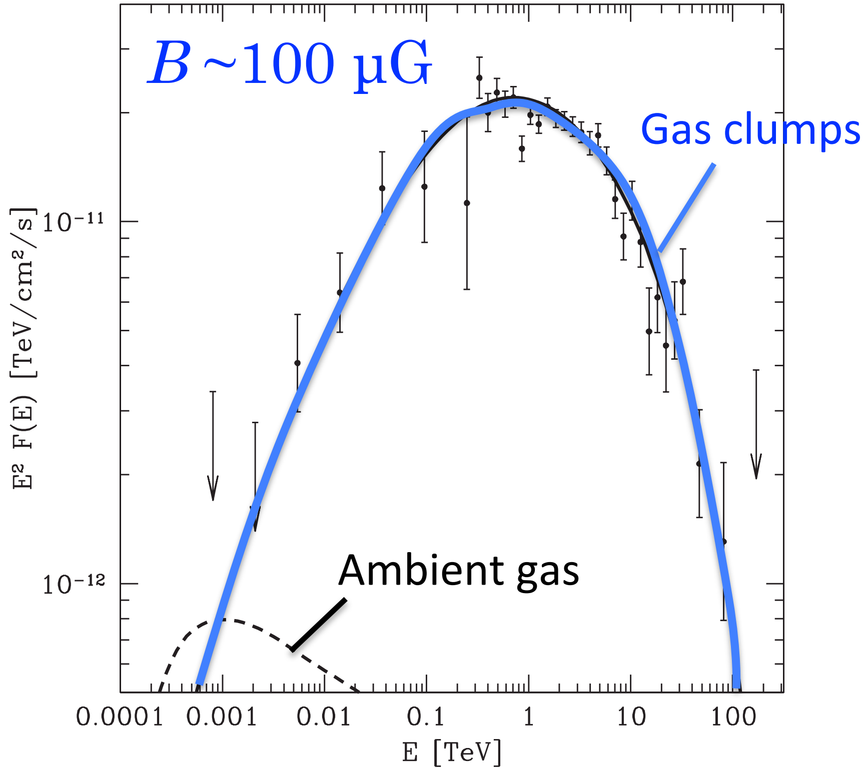
Gas clumps are rim-brightened in synchrotron X-rays.
→ strong turbulence + *B* field may accelerate the CRs (e.g., HS+15)

Shock cloud interaction model: Gamma-ray spectrum

Leptonic model
(Abdo+11)



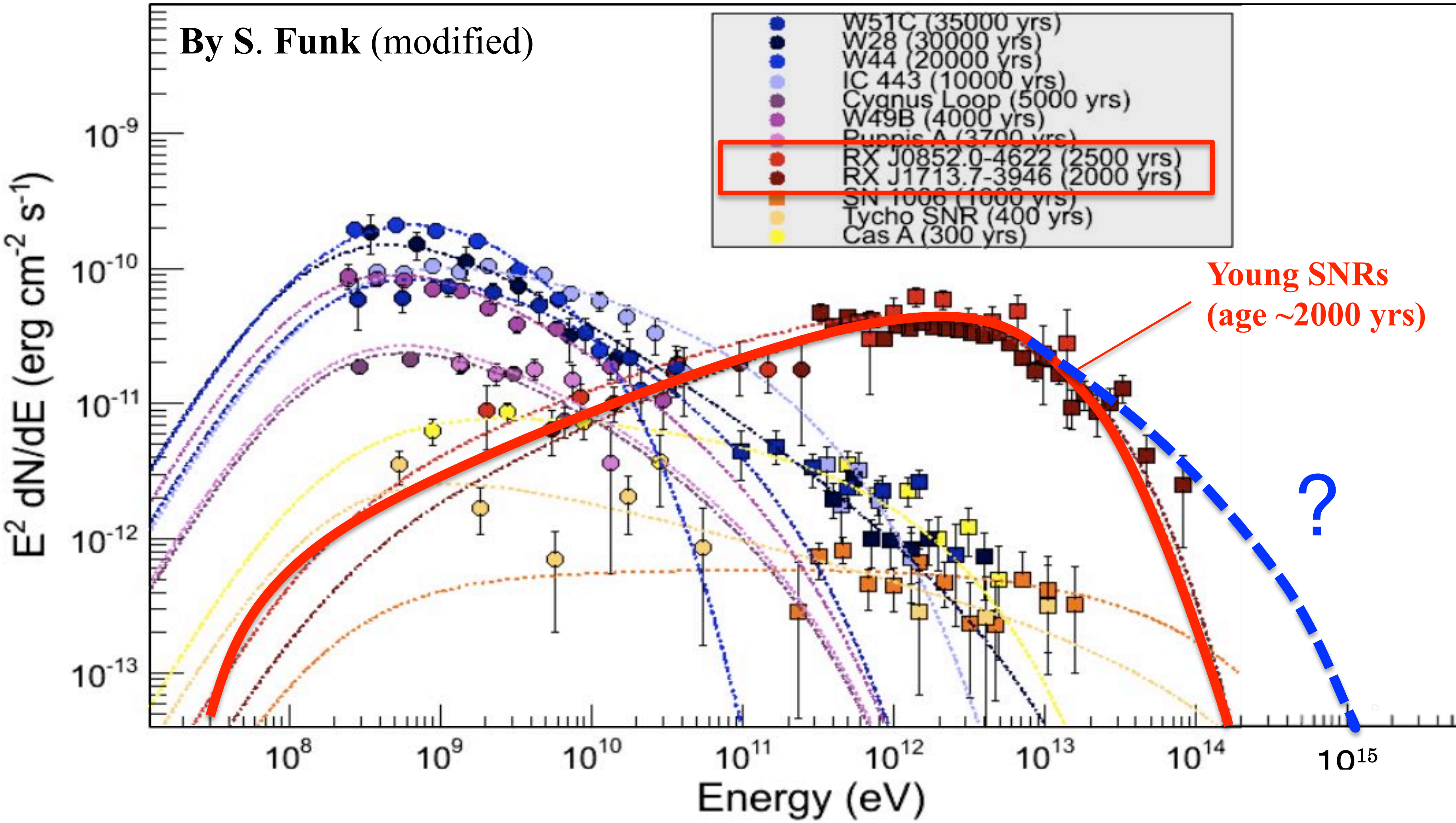
Hadronic model
(Gabici & Aharonian 14)



$$l_{\rm pd} \simeq (\kappa_{\rm d}\, t)^{1/2} = 0.1\, \eta^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2} \left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2} {\rm pc},$$

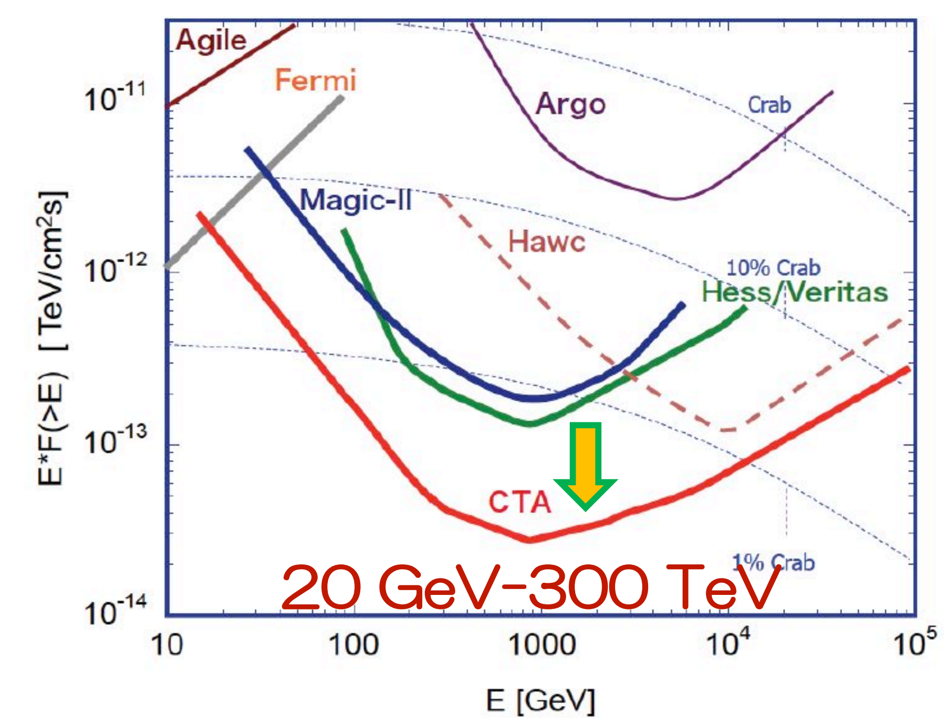
Inoue+12

[3] Gamma-ray obs. with high sensitivity + angular resolutions



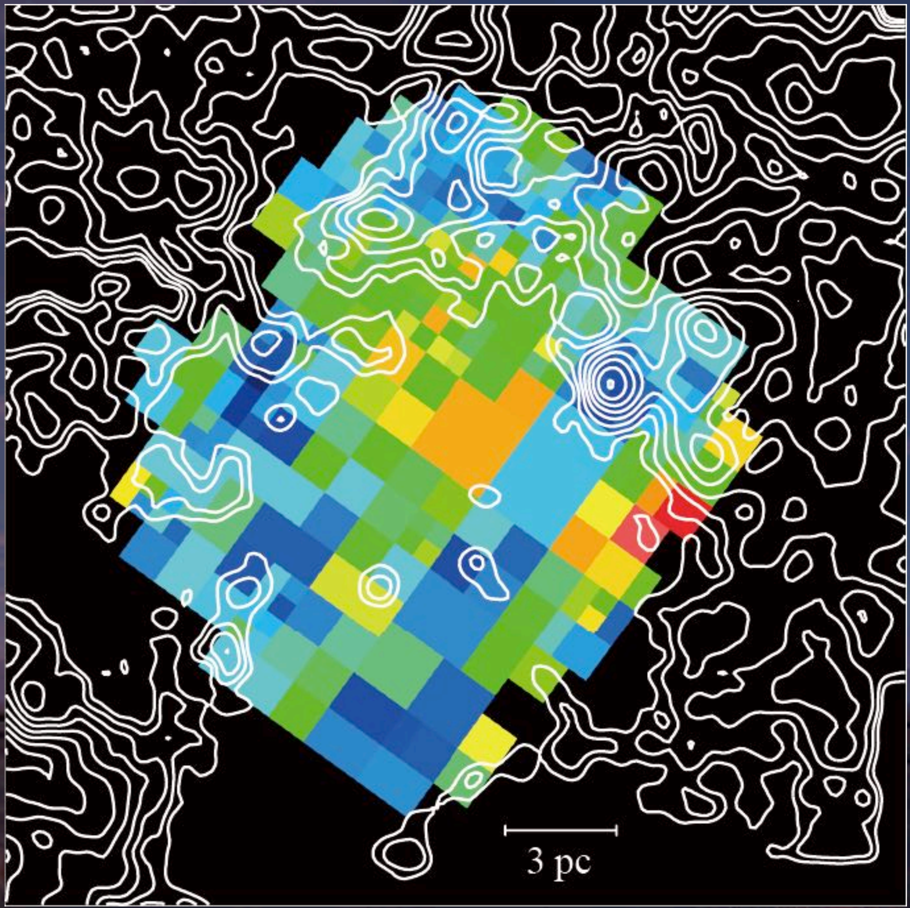
Current observations could not determine the spectra shape E > 100 TeV

Cherenkov Telescope Array (CTA)



HS+15

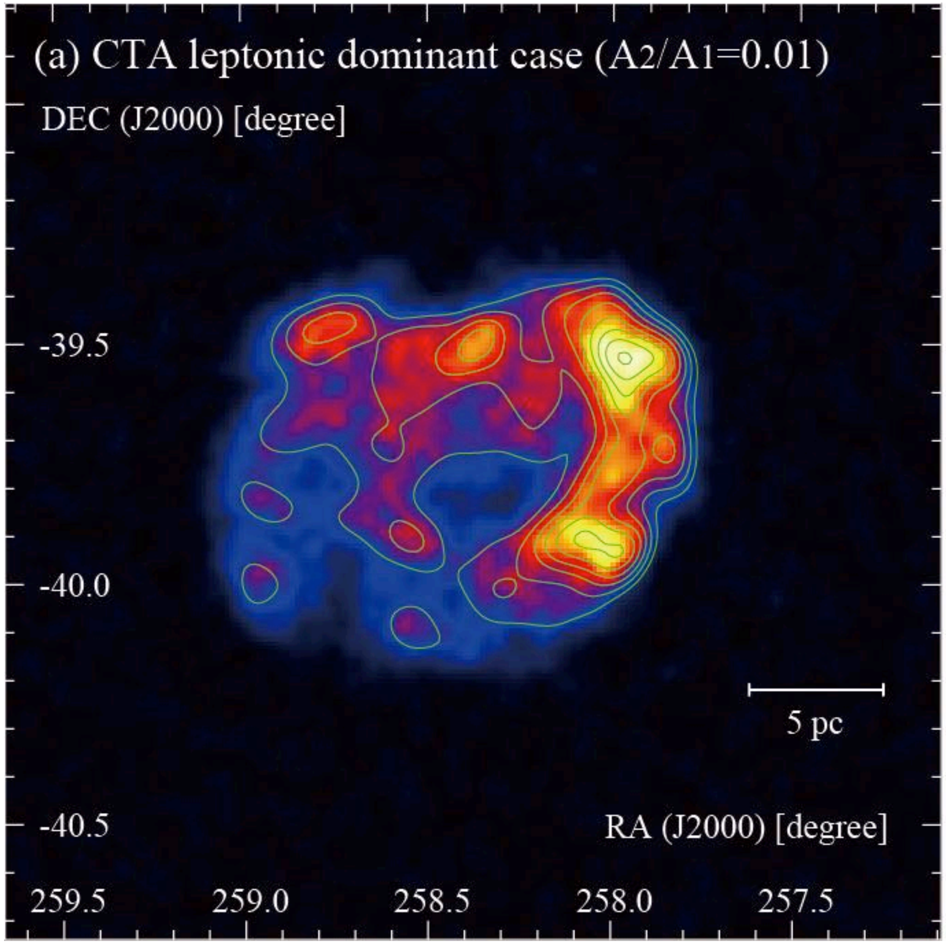
X-ray photon index map (RXJ1713)



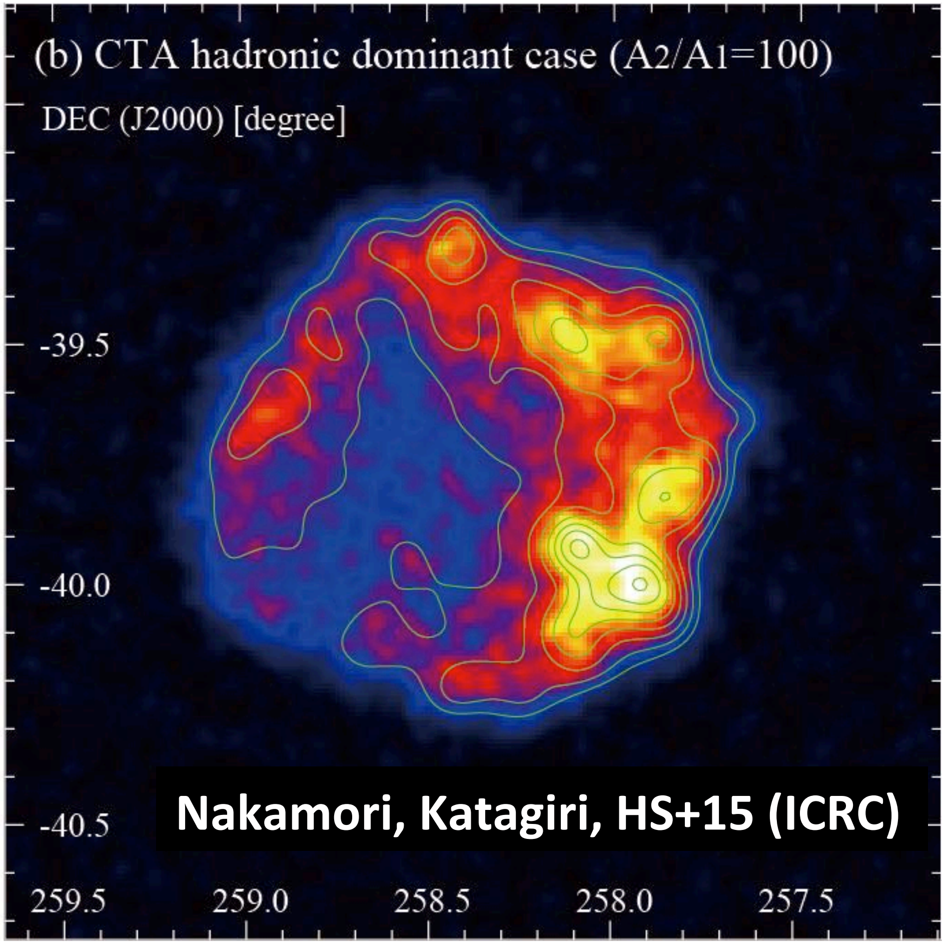
We will be able to determine the spectral shape $E > 100$ TeV by using CTA!

Cherenkov Telescope Array (CTA): imaging simulations

Leptonic origin



Hadronic origin

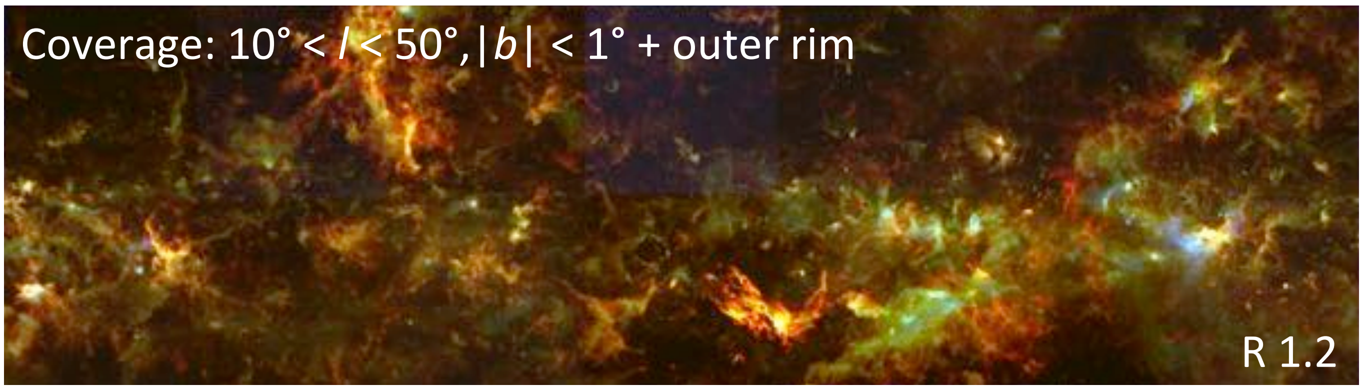


The origin of gamma-rays can be distinguished by morphological studies

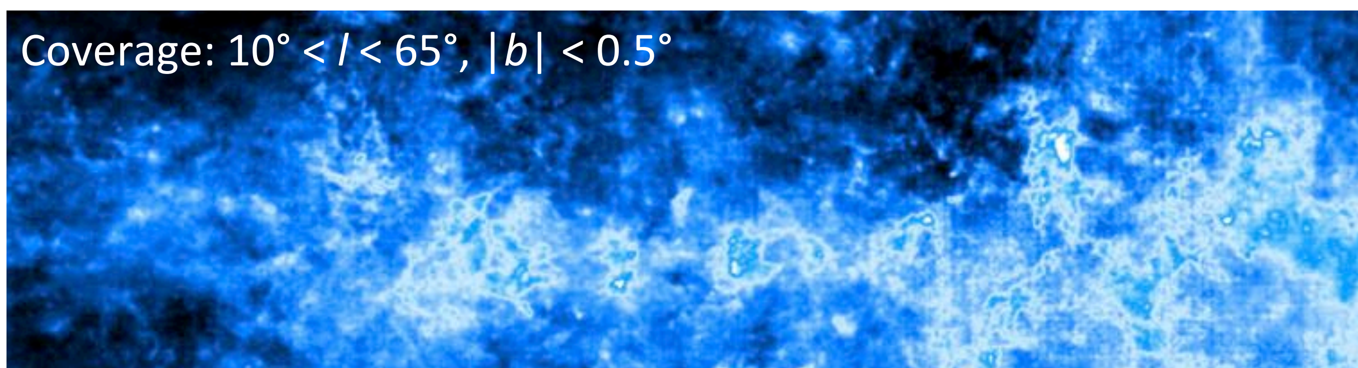
[4] To reveal an universality

We are extending our comparative studies (ISM, X-rays, Gamma-rays) for the distant SNRs by using high-angular resolution CO data ($\Delta\theta$~20")

NRO 45-m Galactic plane survey (FUGIN): ^{12}CO, ^{13}CO, C^{18}O J = 1–0



JCMT Galactic plane survey: ^{12}CO J = 3–2



SNR distributions toward the survey area

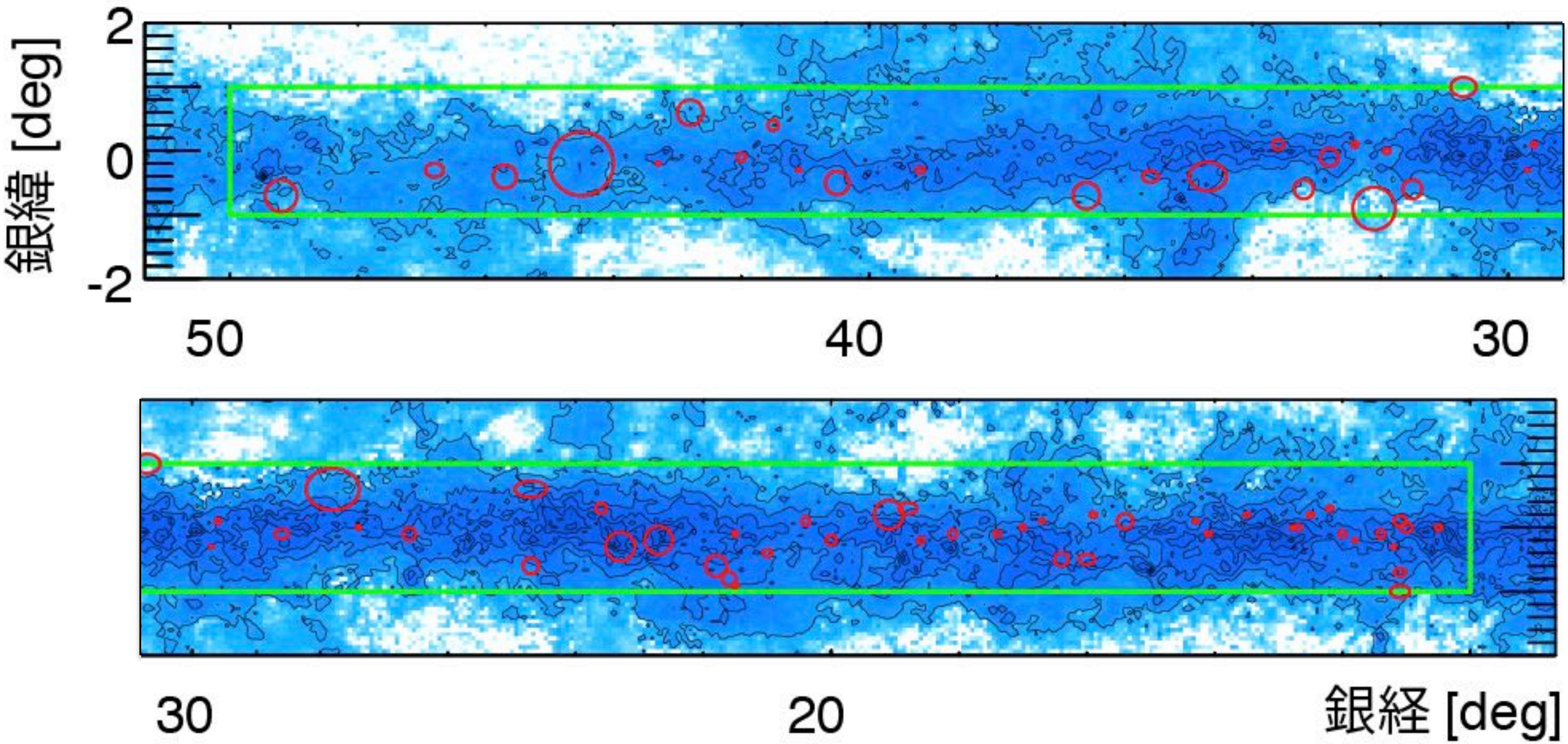


Image: NANTEN GPS (Mizuno & Fukui 2004), Red: SNR boundary, Green: FUGIN area

- 67 SNRs are located within the FUGIN survey area
  → 40 % of SNRs are emitted by diffuse X-rays

Preliminary results of ^{12}CO $J = 3$–2

Preliminary Result…

Preliminary Result…

Image： JCMT ^{12}CO J = 3–2 integrated intensity, Contours: *Chandra* broad band X-rays

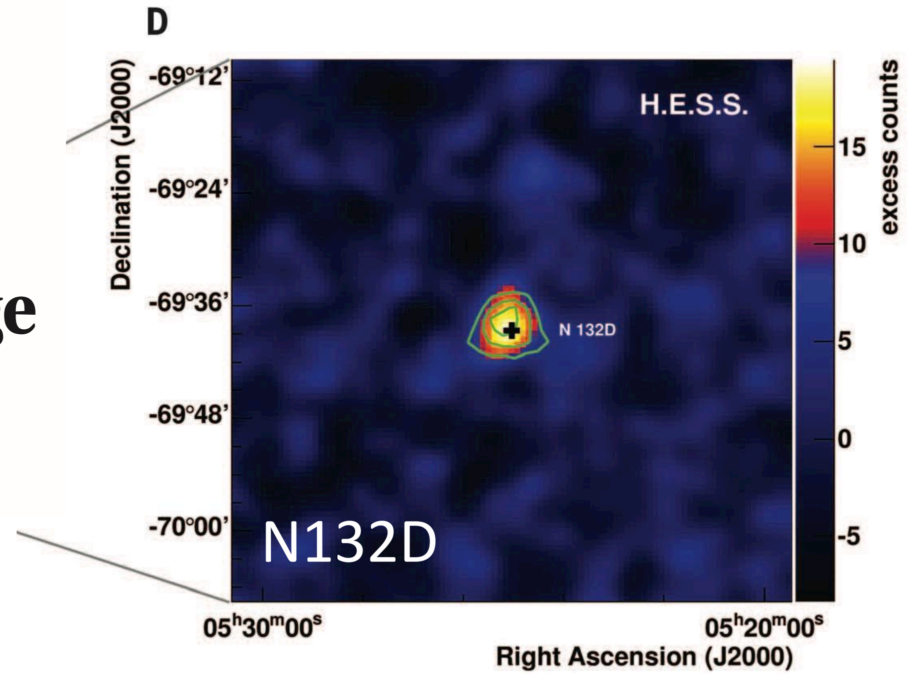
- These SNRs are ~10 times smaller than RX J1713 (size ~ 60 arcmin), while we could identify the interacting molecular clouds

REPORTS

ASTROPHYSICS

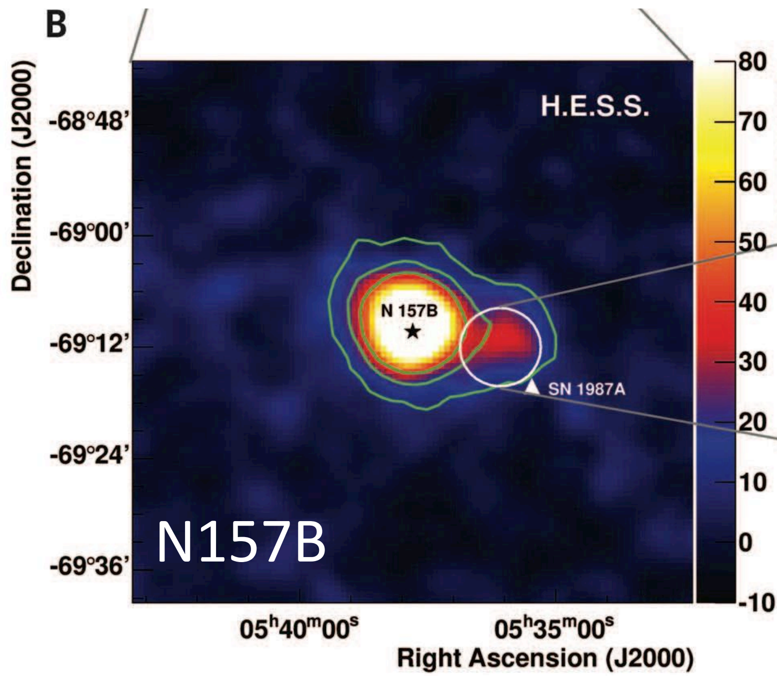
The exceptionally powerful TeV γ-ray emitters in the Large Magellanic Cloud

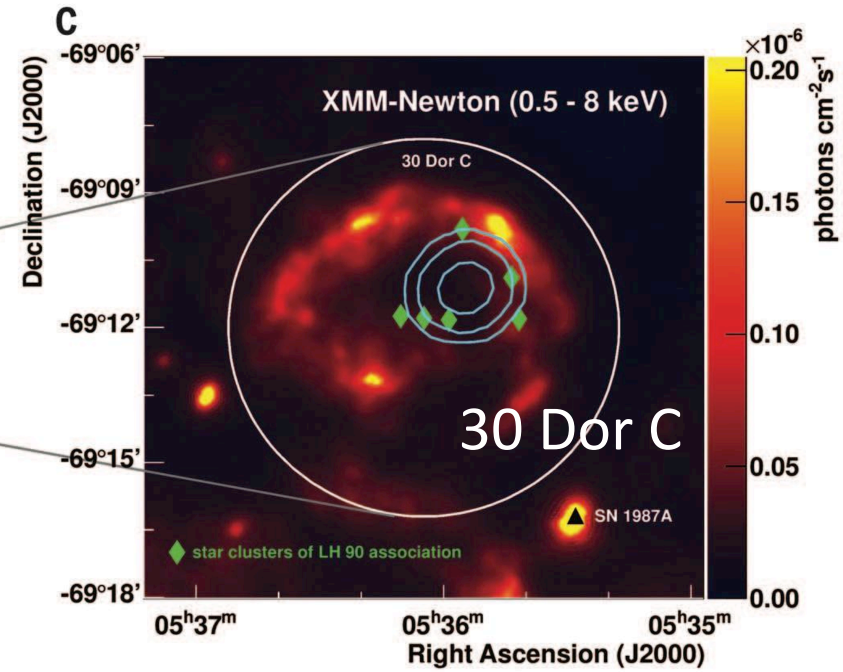
The H.E.S.S. Collaboration*†



Next targets

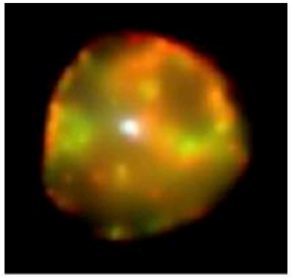
Magellanic SNRs & Superbubbles

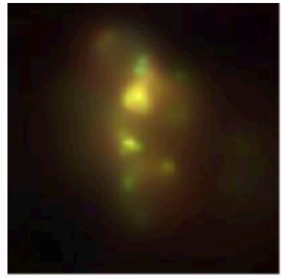


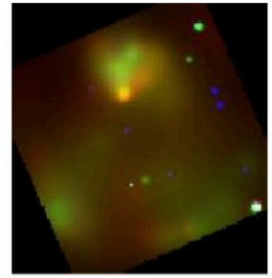


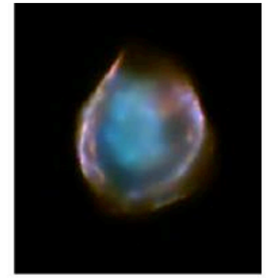
Chandra X-ray 3 color Images

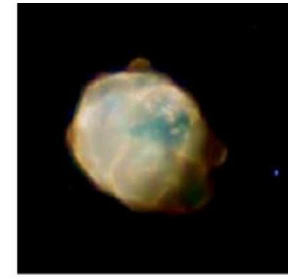

例: SNR J0525.1−6938 (N132D)

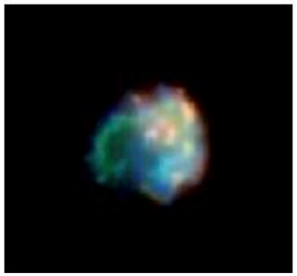

SNR J0453.6−6829 (B0453−685)


SNR 0454.4−6713 (N9)


SNR J0459.9−7008 (N186D)

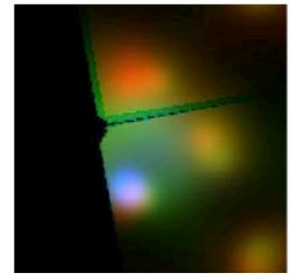

SNR J0505.7−6752 (DEM L71)

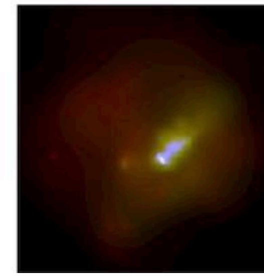

SNR J0535.7−6602 (N63A)

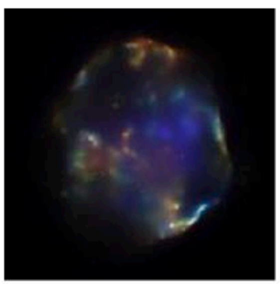

SNR J0509.0−6843 (N103B)

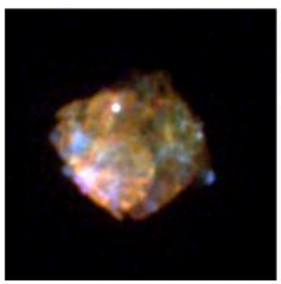

SNR J0509.5−6731 (B0509−67.5)

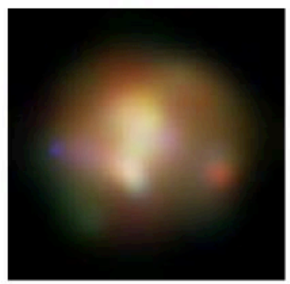

SNR J0519.5−6902 (B0519−

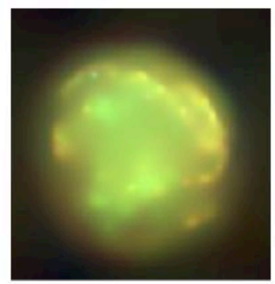

SNR J0523.0−6753 (N44)

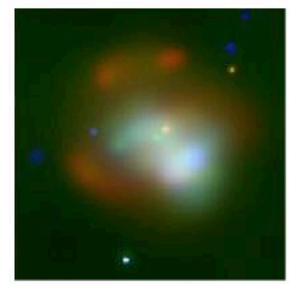

SNR J0537.8−6910 (N157B)

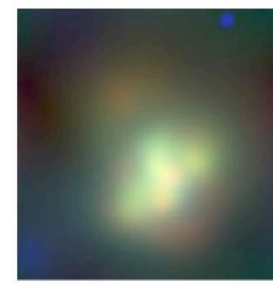

SNR J0525.4−6559 (N49B)

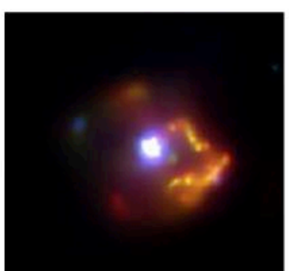

SNR J0526.0−6604 (N49)


SNR J0531.9−7100 (N206)

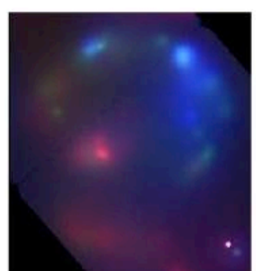

SNR J0534.0−6955 (B0534−69.9)


SNR J0534.2−7033 (DEM L238)

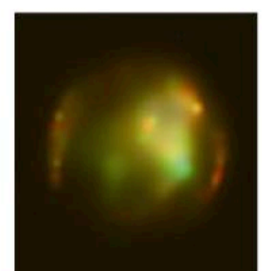

SNR J0536.1−7038 (DEM L249)

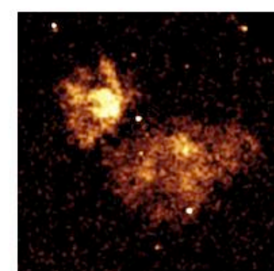

SNR J0540.1−6919


SNR J0535.7−6918 (Honeycomb)


SNR J0536.0−6912 (N157C)


SNR J0535.9−6733 (DEM L241)


SNR J0547.8−7024 (B0548−704)


SNR J0547.0−6943 (DEM L316B)

Preliminary Results…

Images:
Mopra CO 1-0

Contours:
Chandra X-ray

例: SNR J0525.1−6938 (N132D)	SNR J0453.6−6829 (B0453−685)	SNR 0454.4−6713 (N9)	SNR J0459.9−7008 (N186D)	SNR J0505.7−6752 (DEM L71)	SNR J0535.7−6602 (N63A)
	SNR J0509.0−6843 (N103B)	SNR J0509.5−6731 (B0509−67.5)	SNR J0519.5−6902 (B0519−	SNR J0523.0−6753 (N44)	SNR J0537.8−6910 (N157B)
SNR J0525.4−6559 (N49B)	SNR J0526.0−6604 (N49)	SNR J0531.9−7100 (N206)	SNR J0534.0−6955 (B0534−69.9)	SNR J0534.2−7033 (DEM L238)	SNR J0536.1−7038 (DEM L249)
SNR J0540.1−6919	SNR J0535.7−6918 (Honeycomb)	SNR J0536.0−6912 (N157C)	SNR J0535.9−6733 (DEM L241)	SNR J0547.8−7024 (B0548−704)	SNR J0547.0−6943 (DEM L316B)

Magellanic SNR N132D (Mopra CO1-0, HS+15b)

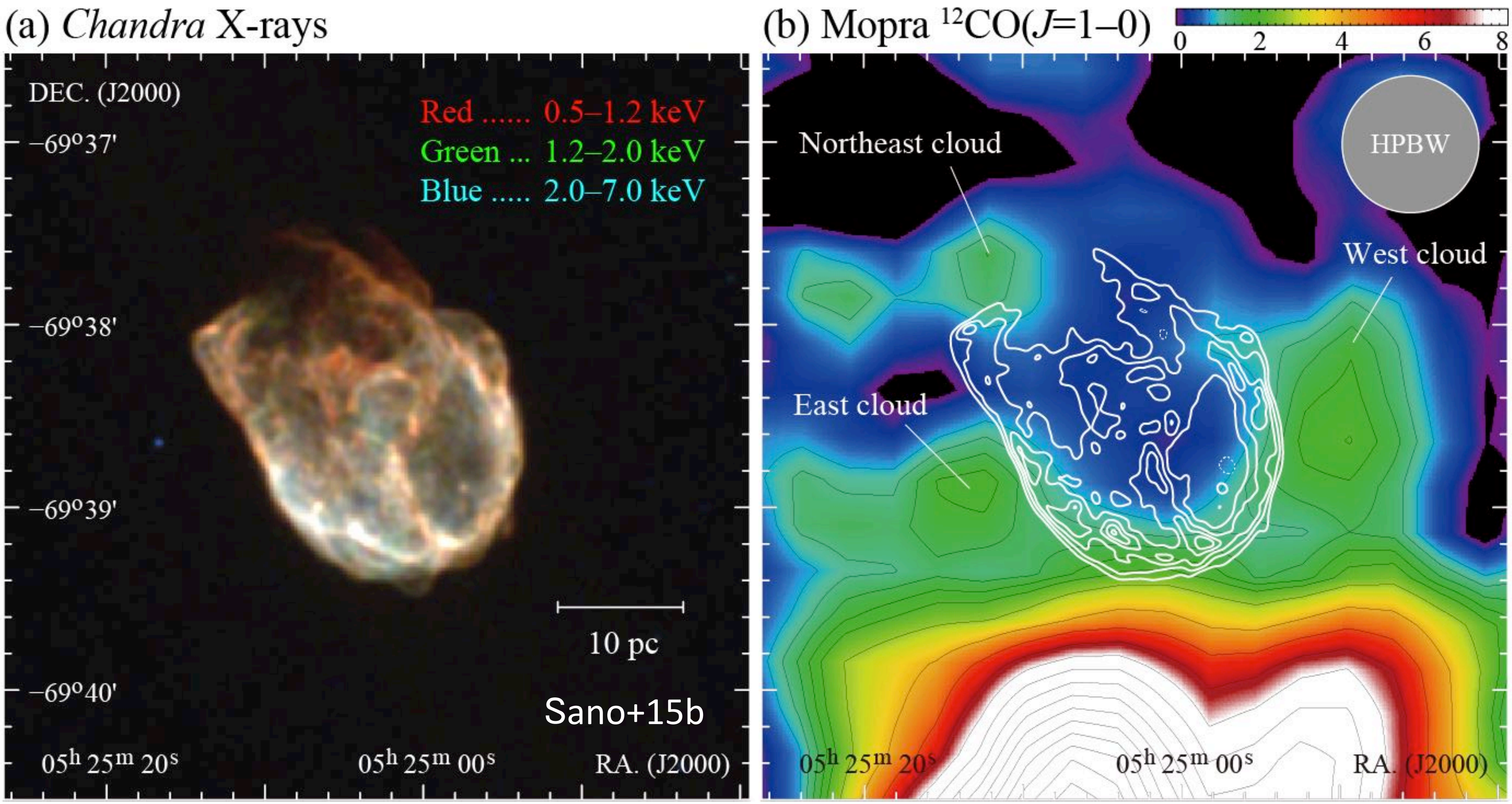
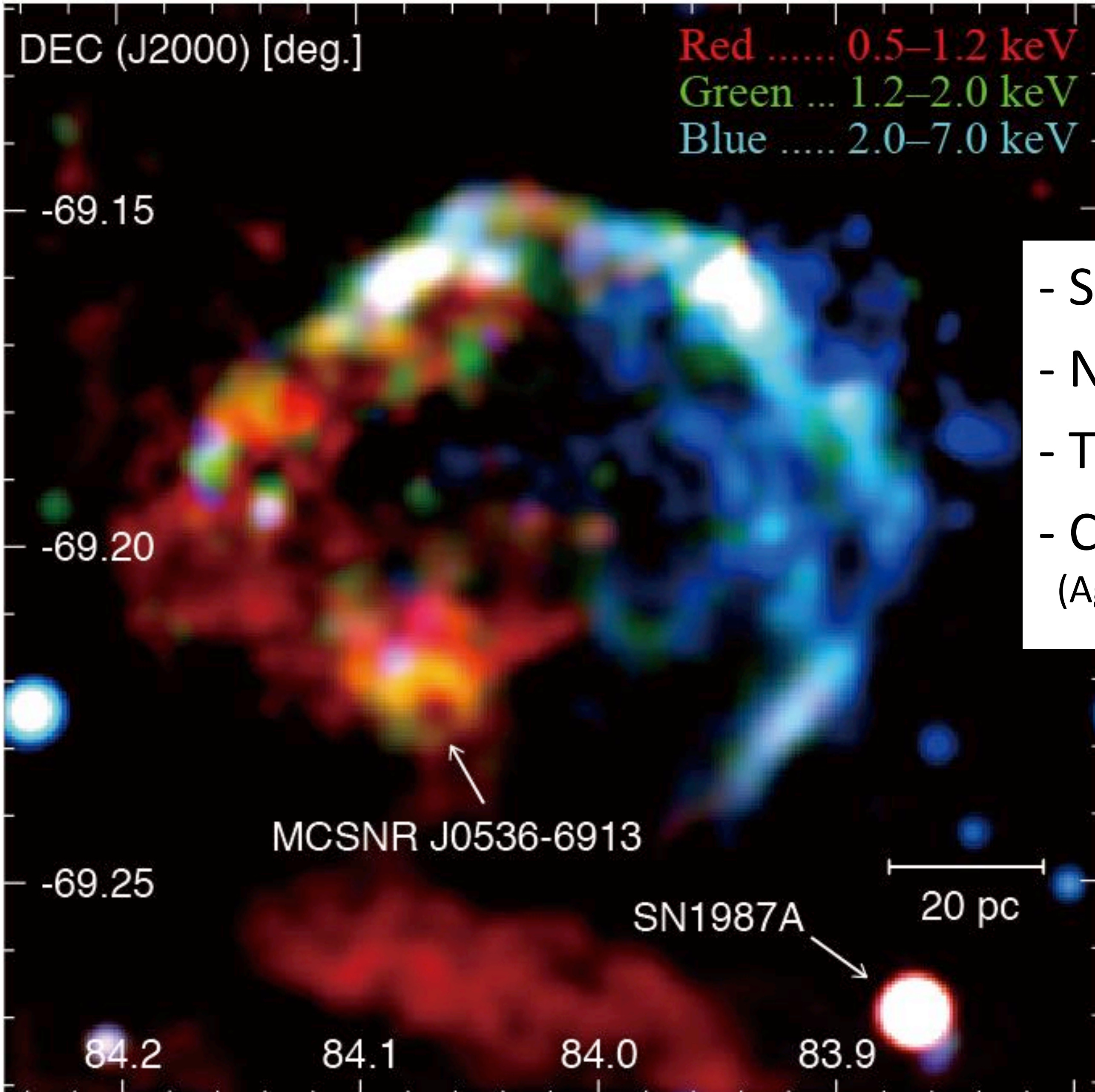


Image: (a) Chandra X-rays, (b) Mopra CO 1-0 (MAGMA: Wong+11)
Contours: Chandra X-rays (0.5-7.0 keV)

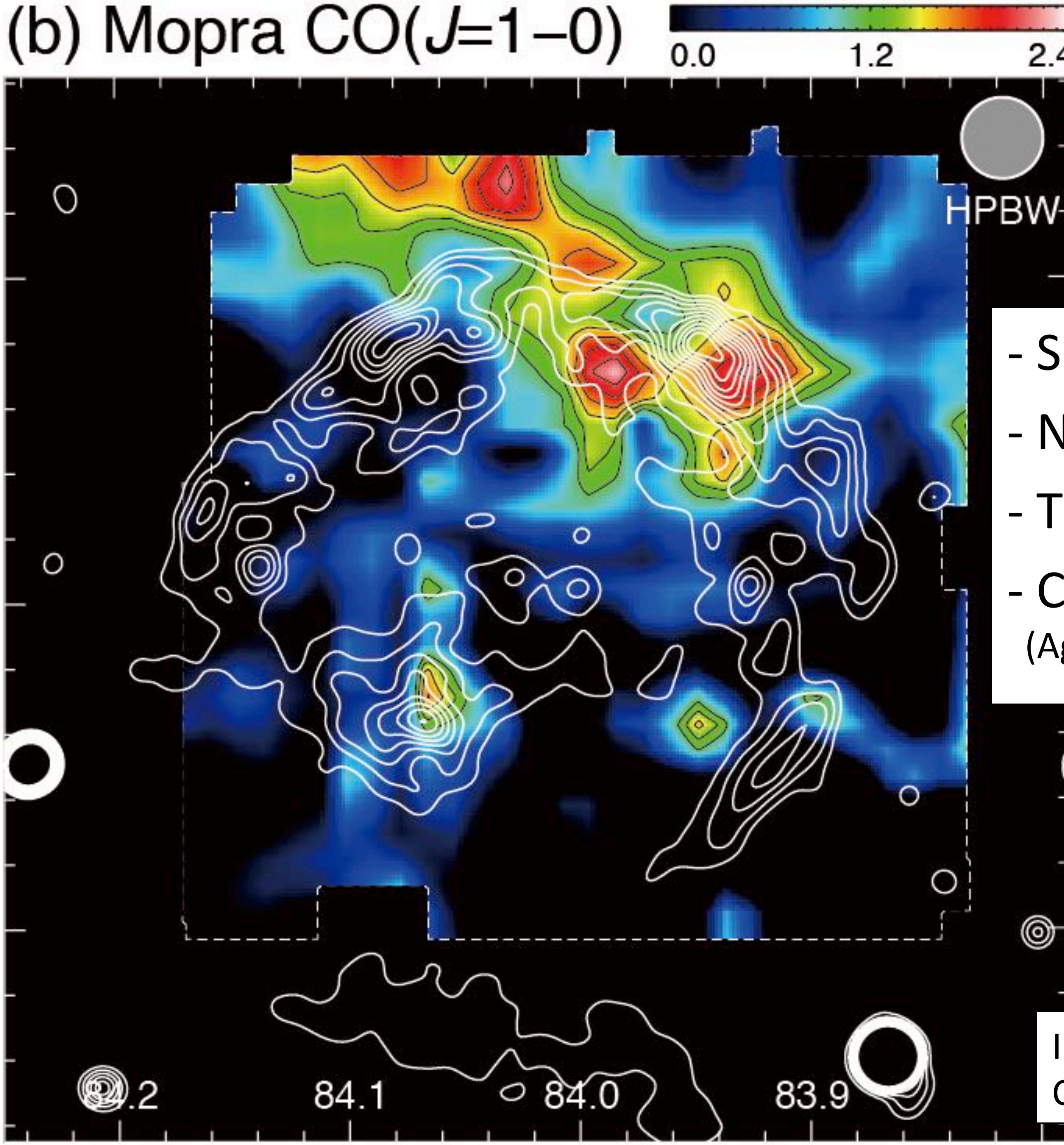
(a) Chandra X-rays



30 Dor C

- Superbubble in 30 Dor
- Non-thermal X-rays
- TeV Gamma-rays
- Containing young SNR
  (Age: 2.2–4.9 kyr, Kavanagh+14)

HS+16 in prep.

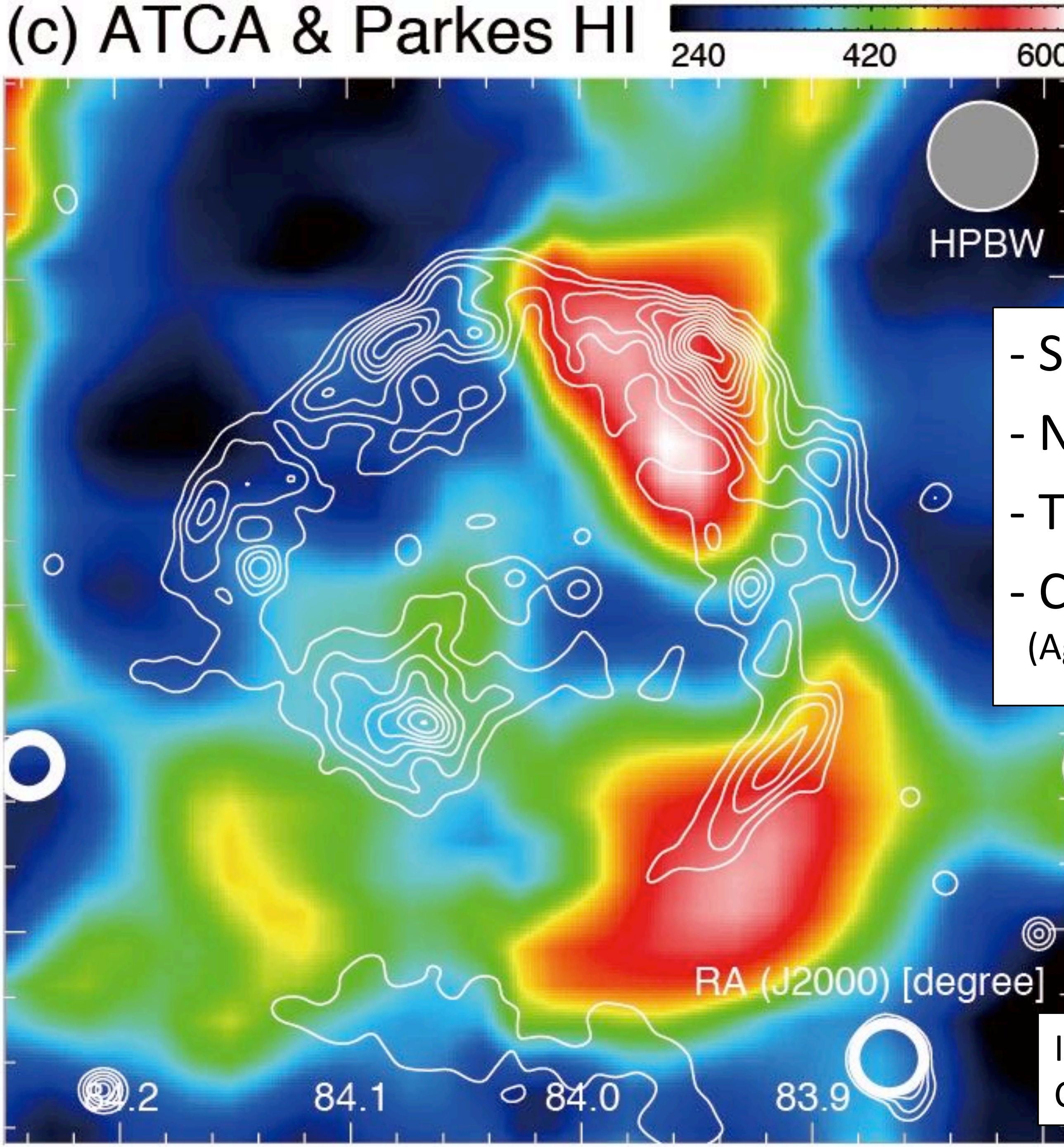


30 Dor C

- Superbubble in 30 Dor
- Non-thermal X-rays
- TeV Gamma-rays
- Containing young SNR
  (Age: 2.2–4.9 kyr, Kavanagh+14)

HS+16 in prep.

Image: CO
Contours : X-rays (0.5-7.0 keV)



30 Dor C

- Superbubble in 30 Dor
- Non-thermal X-rays
- TeV Gamma-rays
- Containing young SNR
  (Age: 2.2–4.9 kyr, Kavanagh+14)

HS+16 in prep.

Image: HI (Kim+03)
Contours : X-rays (0.5-7.0 keV)

ISM associated superbubbles

Preliminary Result…

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Summary: outstanding issues & solutions

[1] Origin of gamma-rays (hadronic and/or leptonic)

→ ◎ Spatial comparison between the ISM and gamma-rays

[2] Acceleration models including more realistic conditions

→ ◎ Shock-cloud interaction model

→ ○ Other acceleration mechanisms ?

(non-liner, 2nd order Fermi, magnetic reconnection etc…)

[3] Gamma-ray obs. with high sensitivity + angular resolutions

→ ◎ Cherenkov Telescope Array (CTA)

[4] To reveal an universality

→ ◎ Extend to the distant sources including the LMC SNRs

Multi-messenger search plays an essential role in understanding the origin of galactic cosmic-rays!