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2013」
2013年9月4日(火) 東京大学 柏キャンパス

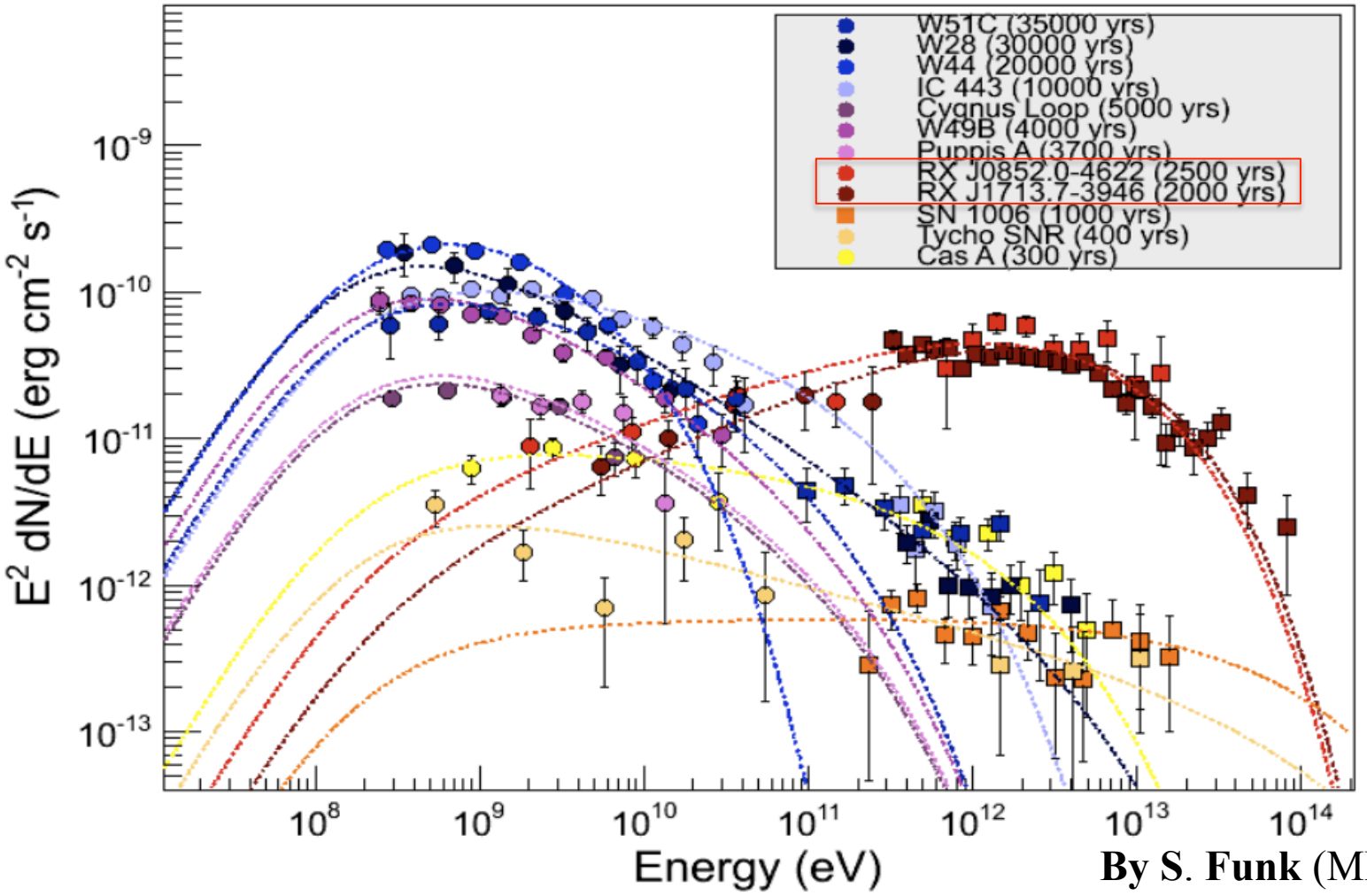
NANTEN2 と Suzaku 衛星による若いTeVガンマ線SNRの研究

佐野 栄俊（Hidetoshi SANO; 名大理 D3）

共同研究者：福田達哉，吉池智史，鳥居和史，早川貴敬，山本宏昭，立原研悟，犬塚修一郎，福井康雄 (名大理)，田中孝明 (京大理)，松本浩典 (名大KMI)，内山泰伸 (立教大理)，井上剛志，山崎了 (青山学院大理)，河村晶子，水野範和 (NAOJ)，水野亮 (名大STE)，西村淳，大西利和 (大阪府立大理)，他NANTENチーム

SNR as Cosmic-ray Accelerator

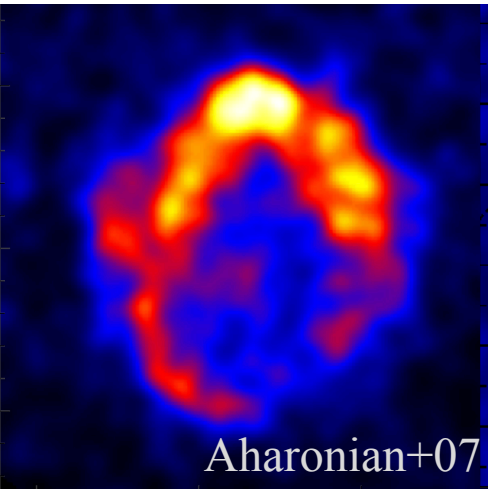
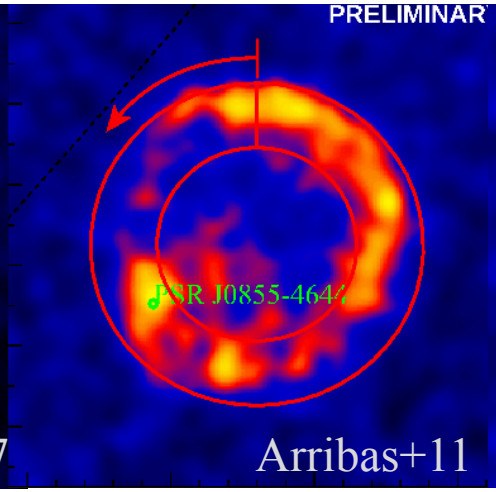
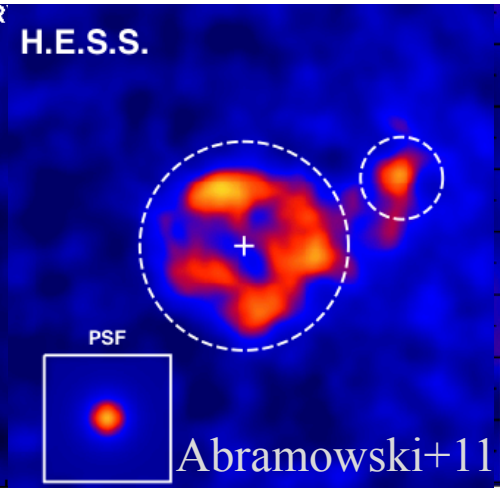
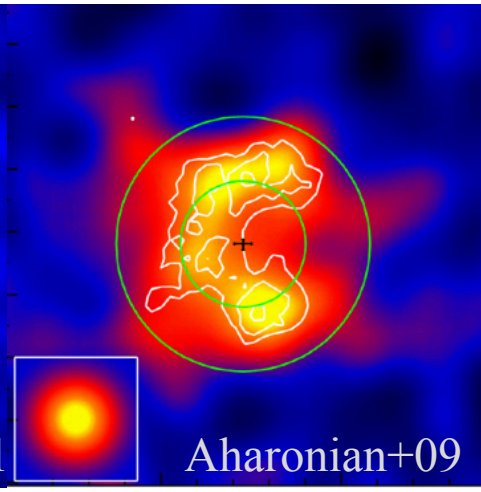
- SNRにおける Cosmic-Rays (CRs) の加速は, ほぼ揺るぎないものに (e.g., Fermi results)
  →しかし, 本当に Knee energy 付近まで CRs は加速されているのか？



- 若く(~2000yr) TeVガンマ線で明るいSNRが, 現段階ではこの鍵を握る最有力ターゲット

Four TeV Gamma-ray SNRs

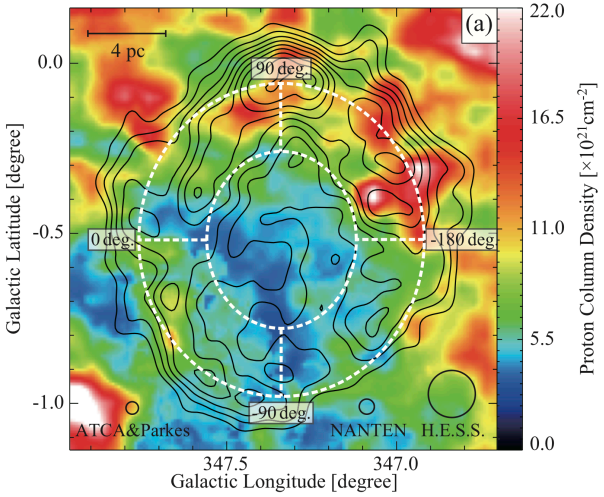
- 年齢2000年程度の4つのTeVガンマ線SNRs
  → どの天体もISM (Interstellar Medium) との相互作用が確認

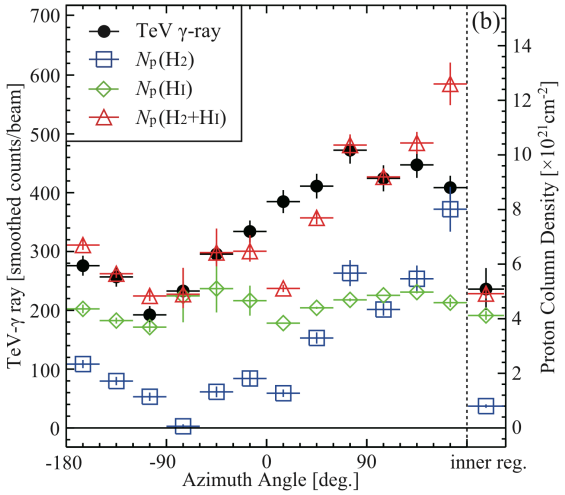
RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
			
Aharonian+07	Arribas+11	Abramowski+11	Aharonian+09
視直径: ~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
年齢: ~1600 yr	~1700−4300 yr	~3600−7200 yr	~1800 yr
ISM: rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays: pure synchrotron	pure synchrotron ?	pure synchrotron	thermal + non-thermal

- これらの高エネルギー放射起源や効率の良い CRs 加速と, ISMが密接に関係

Four TeV Gamma-ray SNRs

- RXJ1713, Vela Jr. HESSJ1731 のTeV γ線とISMの相関





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

W_p ..... Total energy in accelerated protons
n ..... Target ISM proton density
d ..... Distance to the SNR

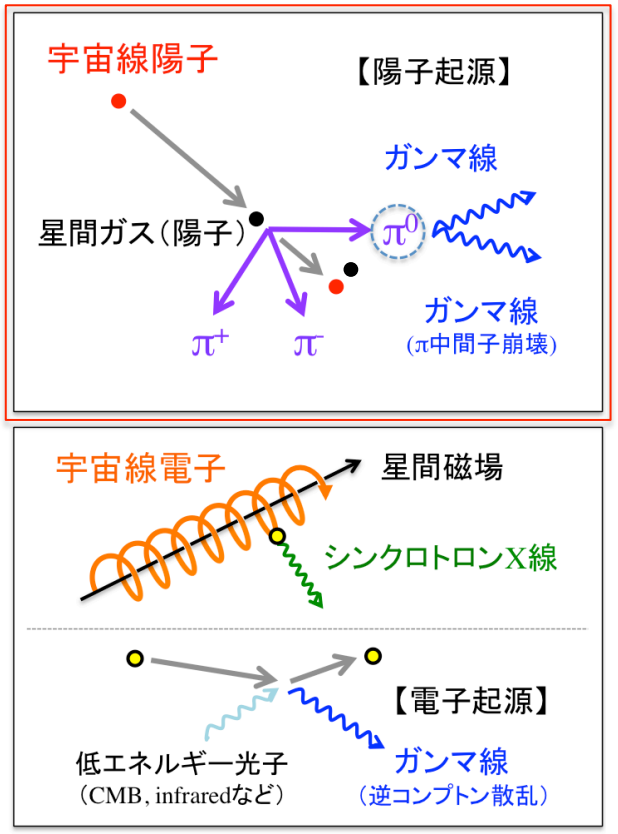


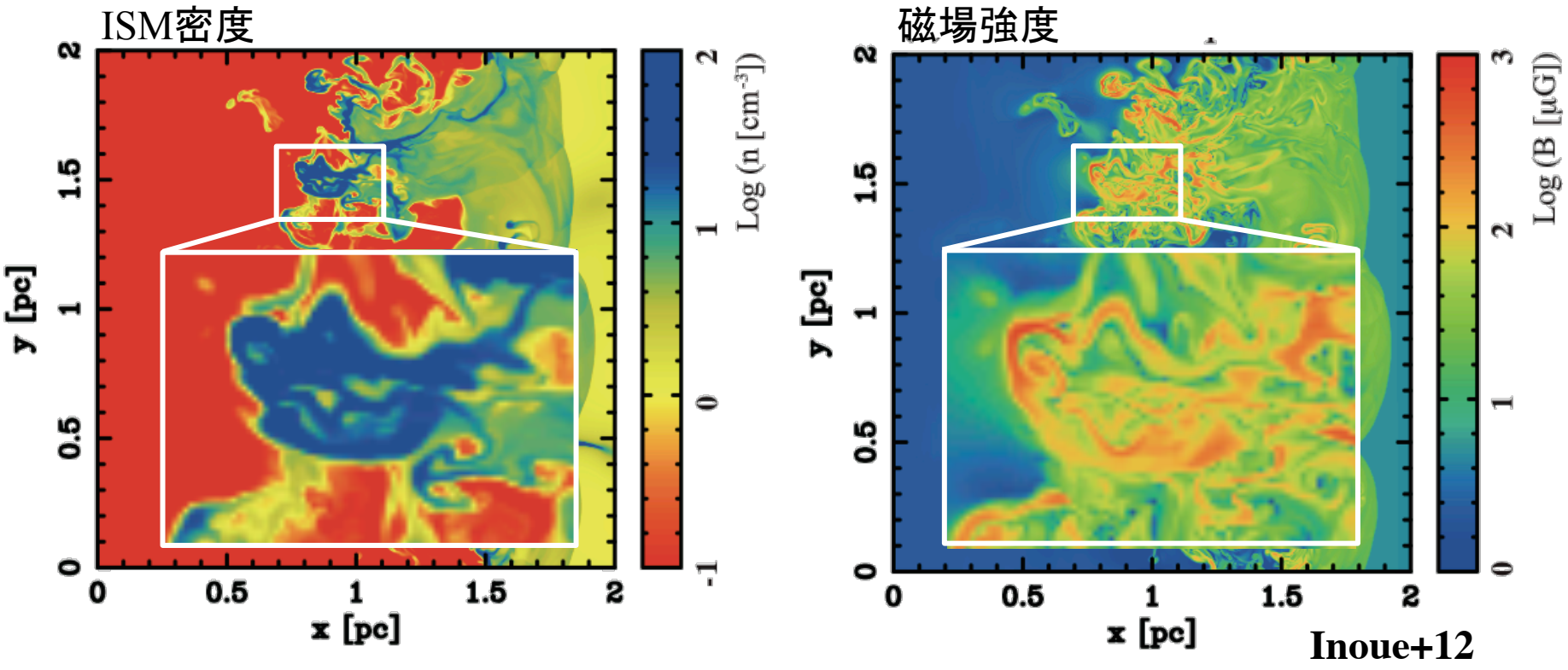
図1：宇宙線起源の高エネルギー放射模式図

↑ e.g., RXJ1713 **(Fukui, Sano et al. 2012)** 高度に非一様なISM分布
CRs proton の加速効率は ~0.1 % (~10^{48} erg)

- しかしながら, この空間分解能で議論できるのは視直径の大きなSNRに限られる.
→ CTA時代まで待つか, いま我々が他にできることは?

Shock-cloud interaction

- SNR shock waves と ISM の相互作用 (Shock-cloud interaction)
  ⇒ ISM clump 周辺で乱流励起 + 磁場増幅
  ⇒ 観測的には clump 周辺のX線増光として確認できる



高空間分解能 / 高統計のX線データ ＋ SNR と相互作用する ISM

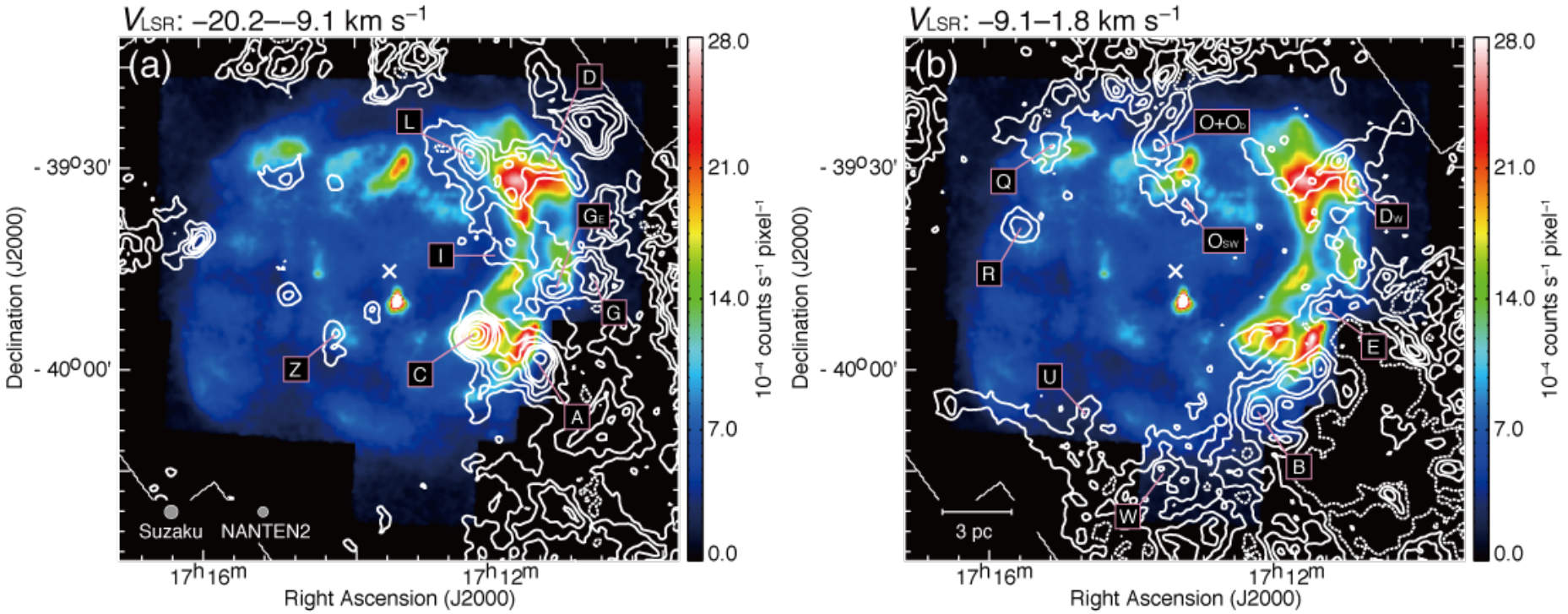
CR electron acceleration についての知見を深める

RXJ1713: Morphology (pc scale correlation)

- TeV ガンマ線 SNRの中でも最も重要なターゲットの１つ
  ⇒ Rich CO + Cold HIとの相互作用, Pure Synchrotron X-rays, 視直径 ~1 deg.

NANTEN2 CO …… HPBW ~1.5−3 arcmin
Suzaku X-rays ……. HPD ~2 arcmin
ATCA & Parkes HI ….. HPBW ~2.2 arcmin

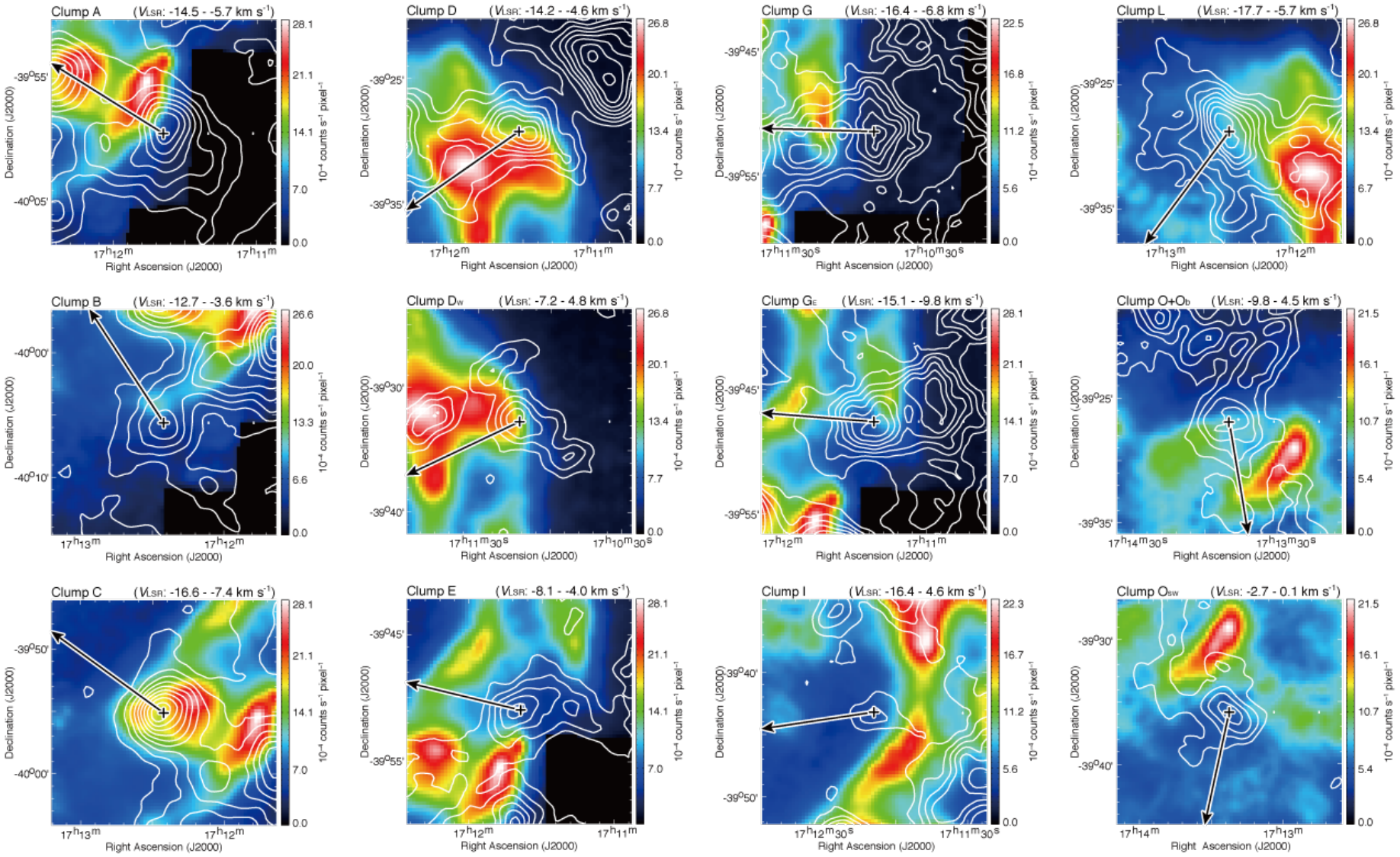
Sano+13a arXiv: 1304.7722



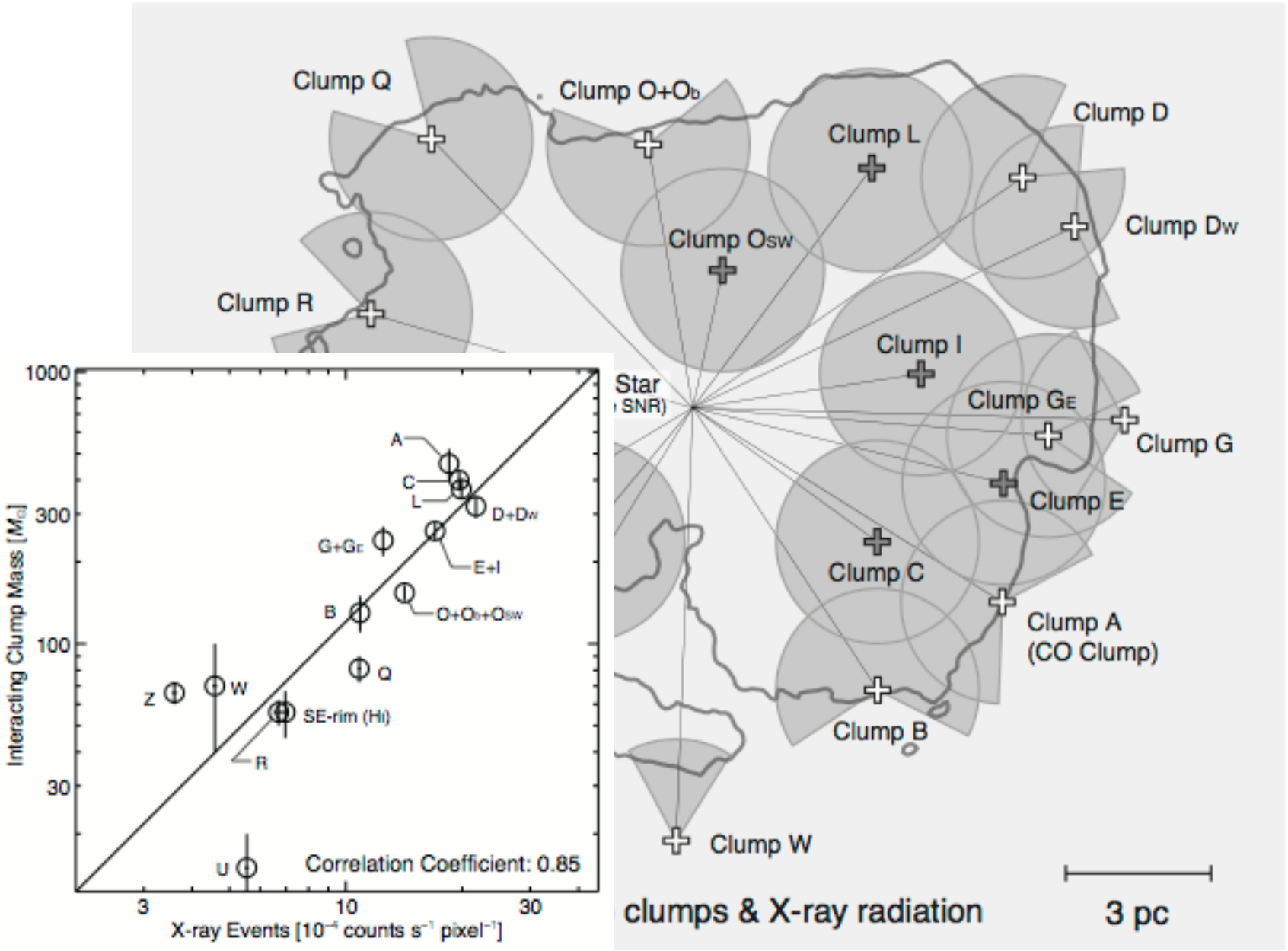
images: *Suzaku* 1–5 keV mosaics, contours: ^{12}CO(J=2–1) integrated intensity (two velocity ranges)

RXJ1713: Morphology (sub pc scale anti-correlation)

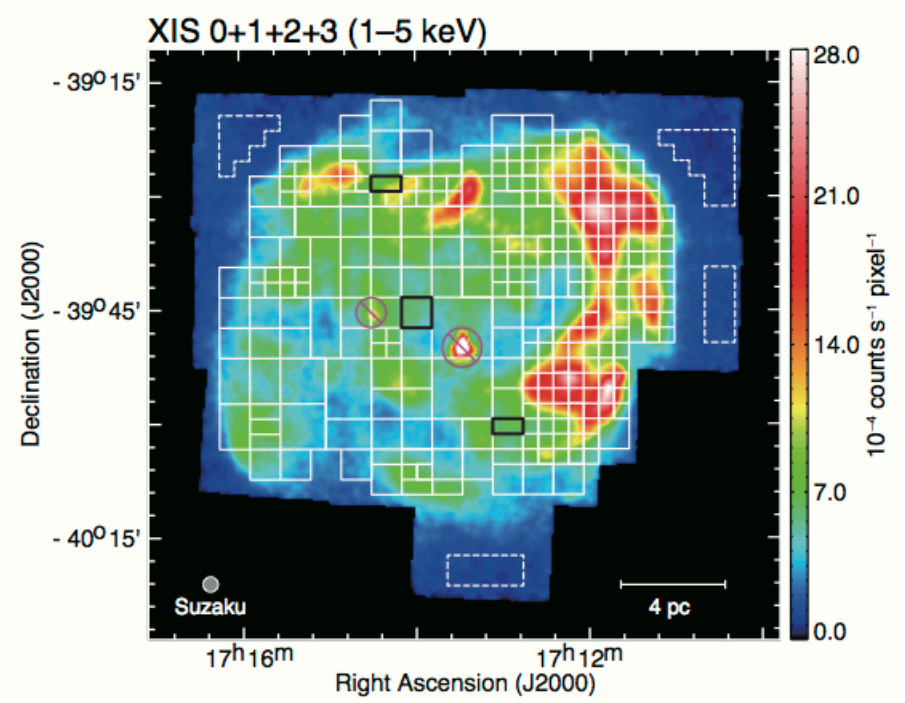
- 17 clumps 全てで, CO と X-ray の anti-correlation がみえている

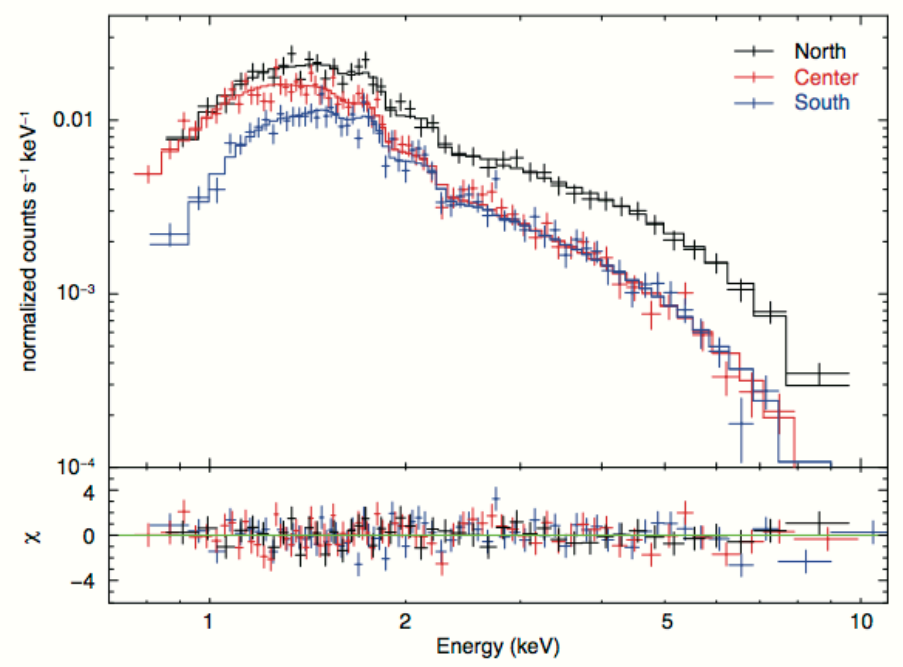


RXJ1713: Schematic image



X-ray Spectroscopy: Regions and Models





↑ Image: *Suzaku* XIS (1—5 keV) mosaic
Solid boxes: source regions
Dashed boxes: background regions

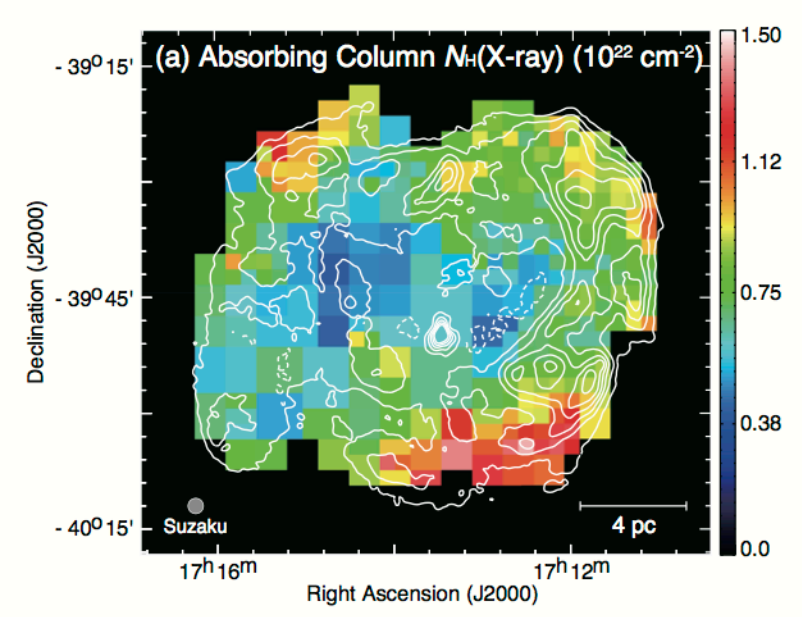
Typical X-ray spectra ↗
and best fit parameters →

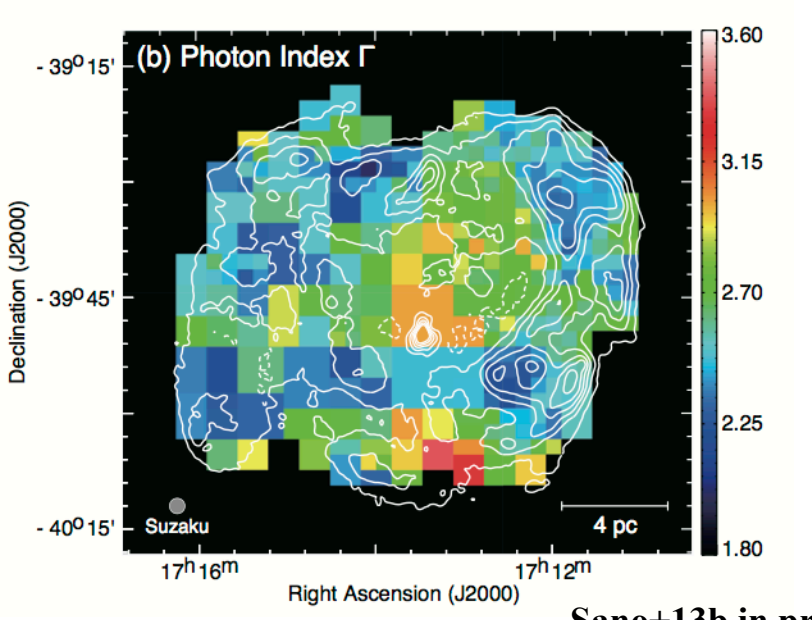
Region	$N_{\rm H}$ (X-ray)	Γ
North	$0.6^{+0.1}_{-0.2} \times 10^{22}$ cm^{-2}	2.1±0.1
Center	$0.50^{+0.06}_{-0.05} \times 10^{22}$ cm^{-2}	2.7±0.1
South	$0.89 \pm 0.09 \times 10^{22}$ cm^{-2}	2.7±0.1

- Source grid size 2′−8′, 計315領域からスペクトルを抽出 (FI CCDs only).
  → Absorbing column density $N_{\rm H}$ (X-ray) の relativistic error < 30 % となるように調整.
- Absorbed power-low model で fitting (at least ~100 counts / bin).

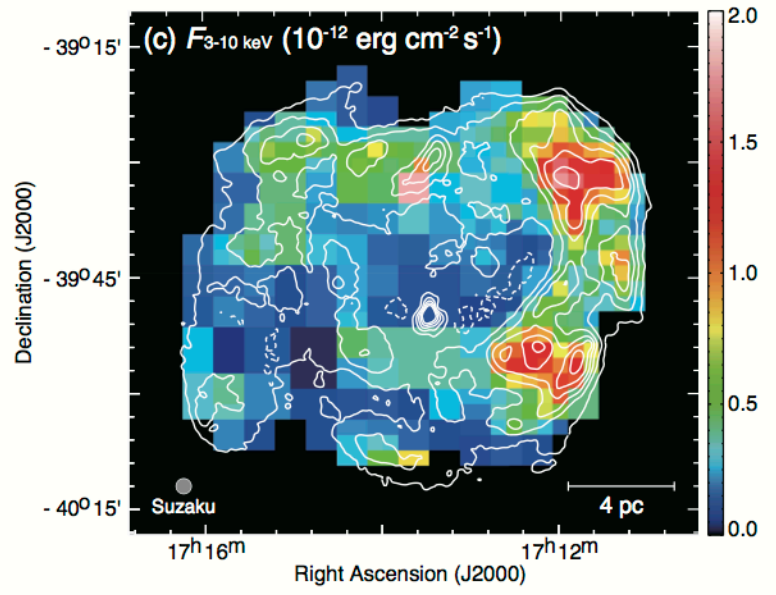
Sano+13b in prep.

X-ray Spectroscopy: Spatial and spectral characterization





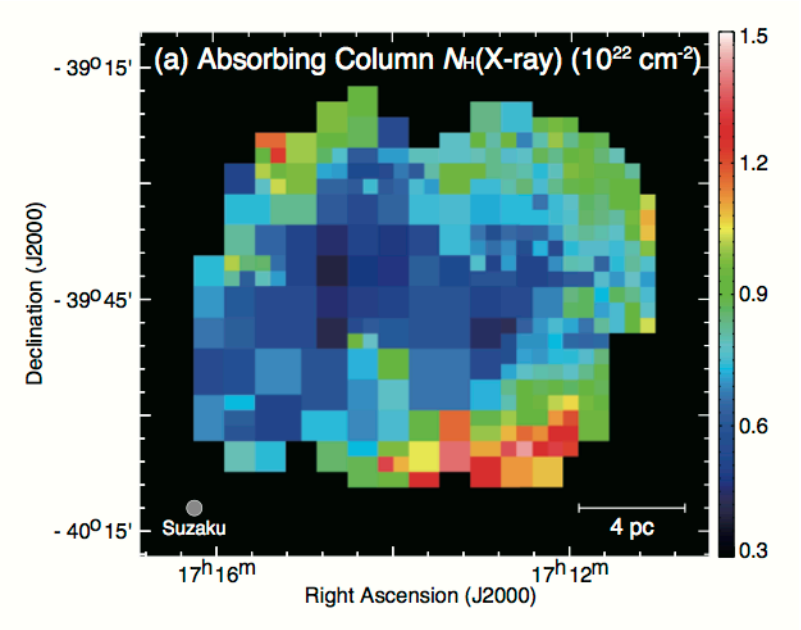
Sano+13b in prep.

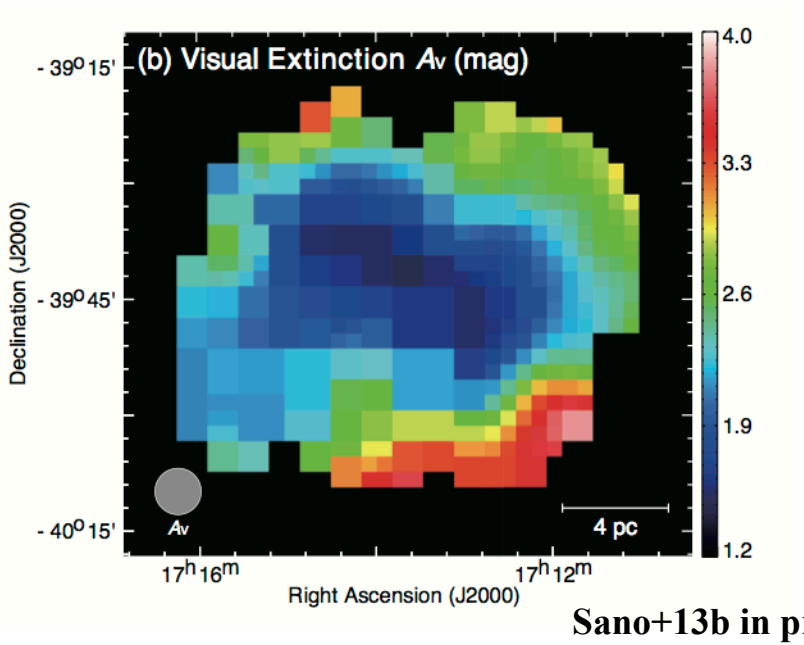


○ Maps of the Best-fit parameters
(a) absorbing column N_H(X-ray)
(b) photon index Γ
(c) absorption-corrected X-ray flux (3−10 keV)
(contours indicate the smoothed XIS 1−5 keV image)

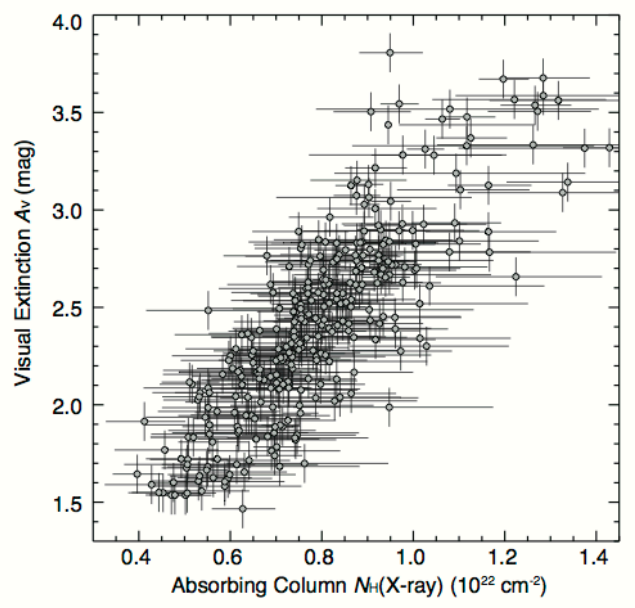
○ Relative error (90% confidence level)
N_H(X-ray)… ~14 % (max 30%)
Γ …… ~6 % (max 13%)
Flux…… ~7 % (max 23%)

Absorbing column & Visual extinction





Sano+13b in prep.



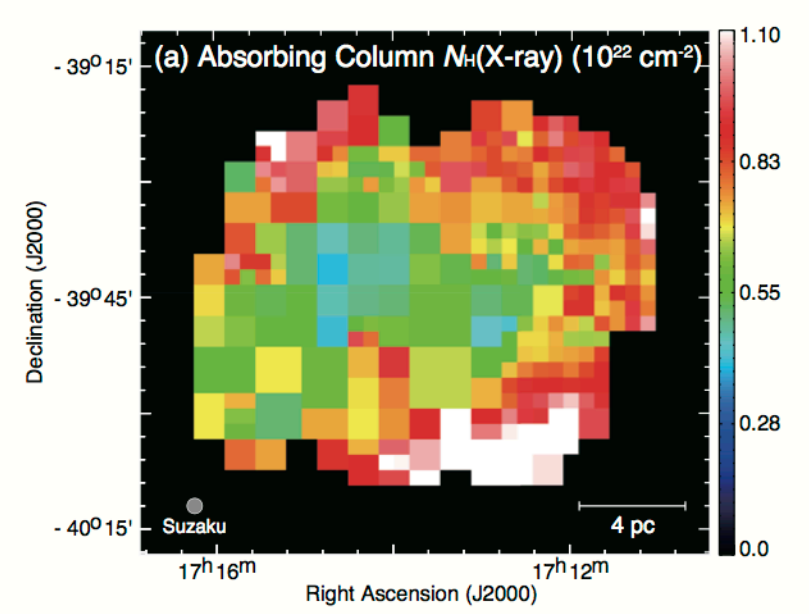
↖↑Maps of N_H(X-ray) and visual extinction (Dobashi+05)

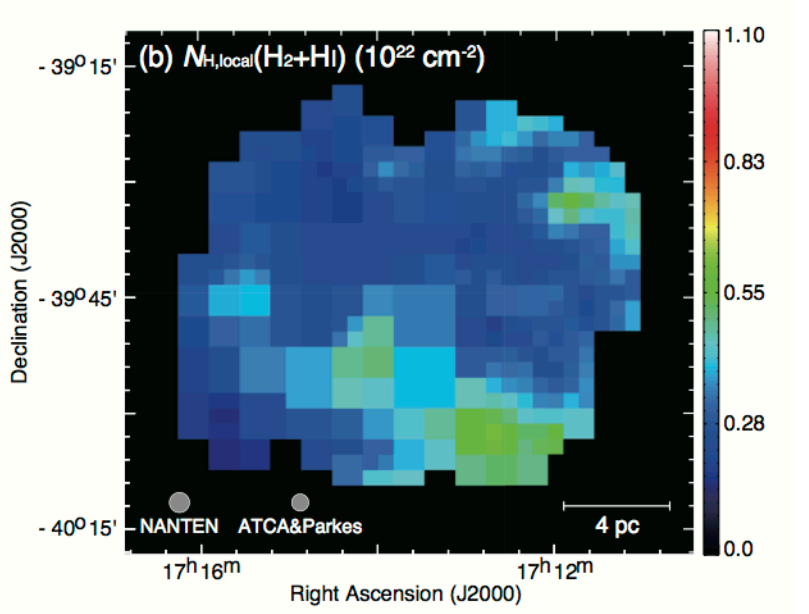
← Correlation plot
- correlation coefficient: ~0.83
- N_H(X-rays) (cm^{-2}) = 3.0×10^{21}・Av (mag.)

cf. N_H (cm^{-2}) = 2.5×10^{21}・Av (mag.) (Jenkins & Savage+74)

- N_H(X-rays) ~0.4−1.4×10^{22} cm^{-2} の範囲で変化
  → Cassam-Chenai+04の傾向とconsistent
- N_H(X-rays) と Visual Extinction の非常に良い相関

Absorbing column – Foreground component





○ Foreground component $N_{H,\,local}$(H_2+HI) is identified by Moriguchi+05 with NANTEN and *ROSAT* data.

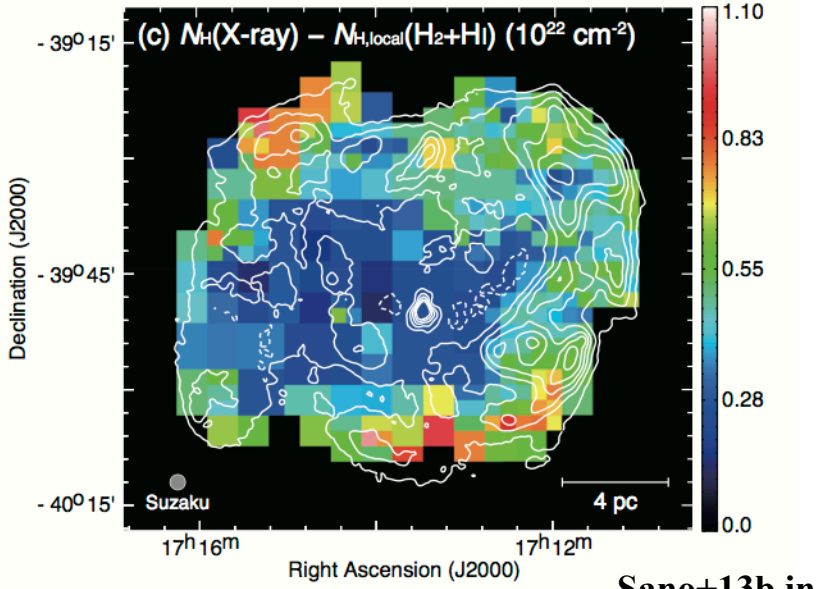
○ ISM proton column density estimation

□ N_H (H_2+HI) = 2×N(H_2) + N_H(HI).

□ N(H_2) (cm^{-2}) = X_{CO} (cm^{-2} (K km s^{-1})$^{-1}$) ×W(CO) (K km s^{-1}).

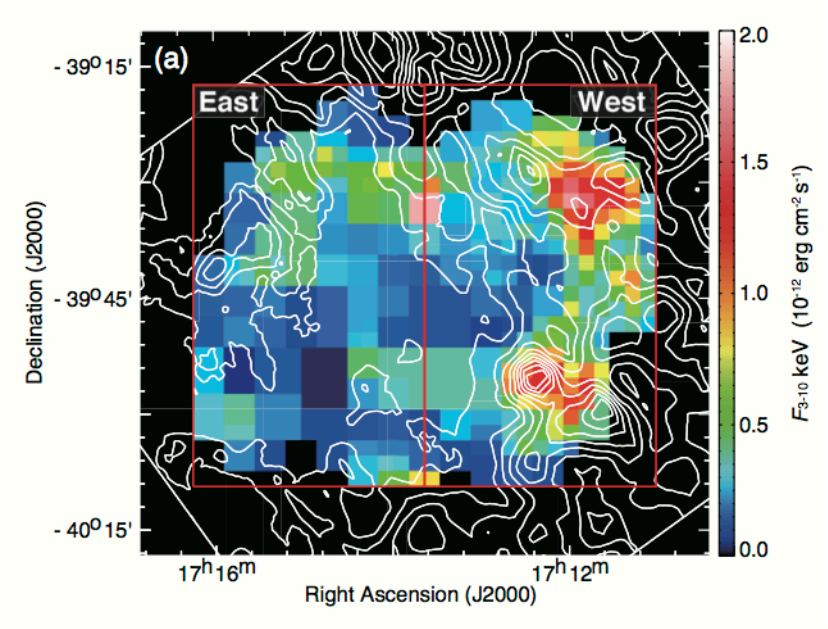
□ X_{CO} = 2 × 10^{20} (cm^{-2} (K km s^{-1})$^{-1}$) (Bertsch+93).

■ Foreground (local) ISM による吸収量を推定, N_H(X-ray) から差し引く (=SNRとの相互作用分).
→ X-ray shell に沿った構造が明らかになった.



Sano+13b in prep.

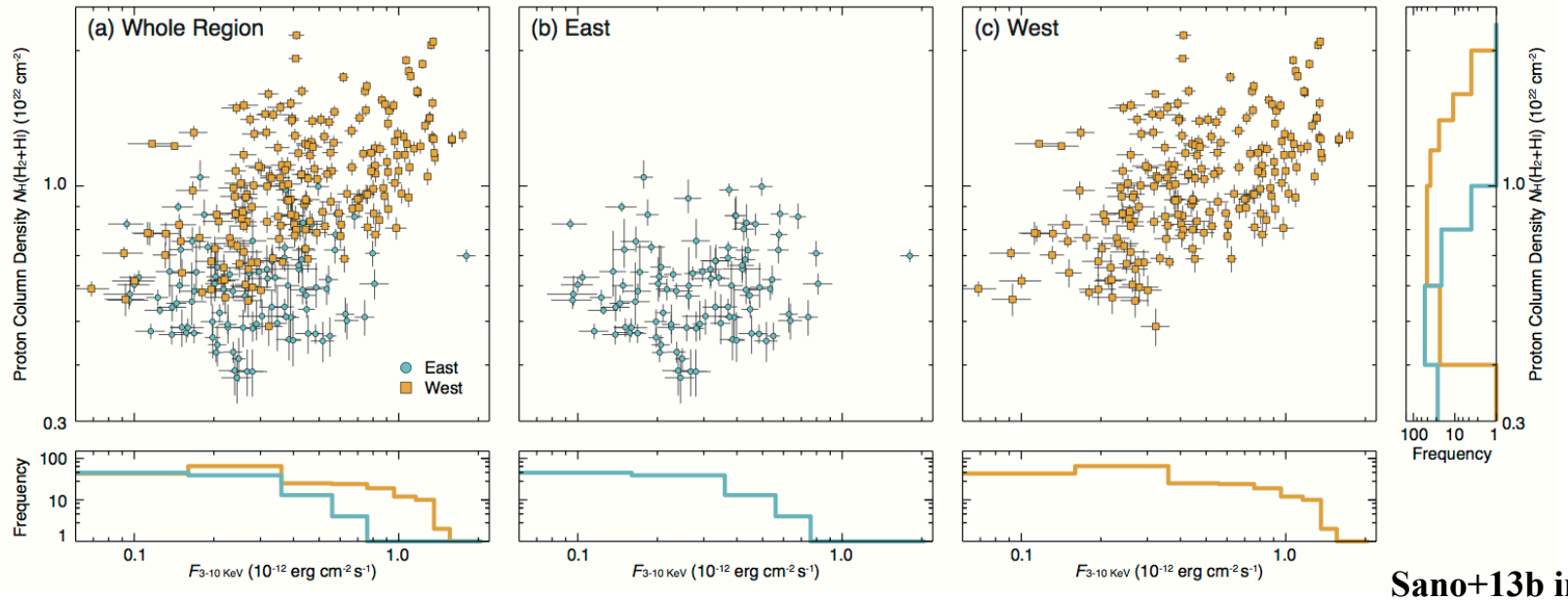
X-ray Flux & ISM proton column density



← Image: absorption-corrected X-ray flux (3−10 keV)
Contours: ISM proton column density $N_H(H_2+HI)$

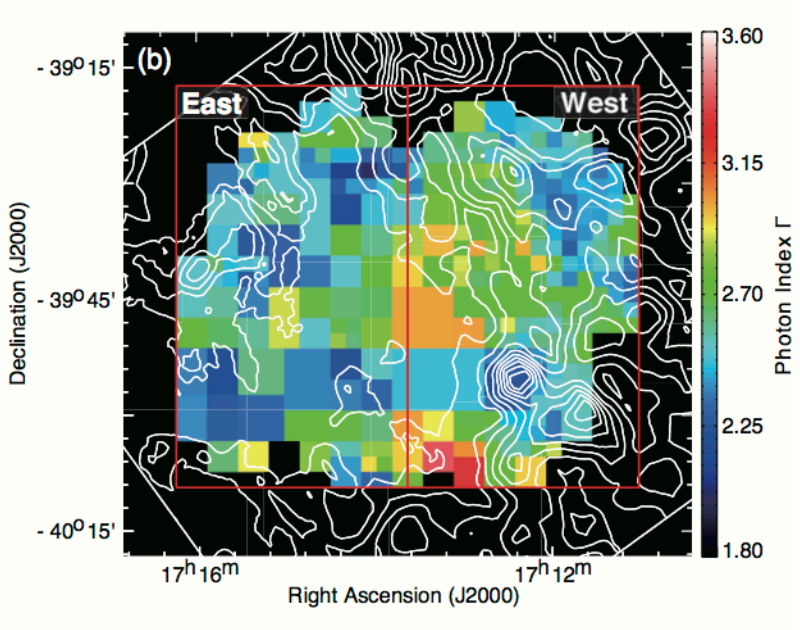
↓ Correlation plot between the Flux and $N_H(H_2+HI)$
(a) whole, (b) East and (c) West region.
Correlation coefficient: ~0.54 (whole region)

- ISMは西側で clumpy, 東側では diffuse に分布.
- ISM の多い領域で X-ray enhance (特に西側)
- 弱いながらも $N_H(H_2+HI)$ と flux は相関



Sano+13b in prep.

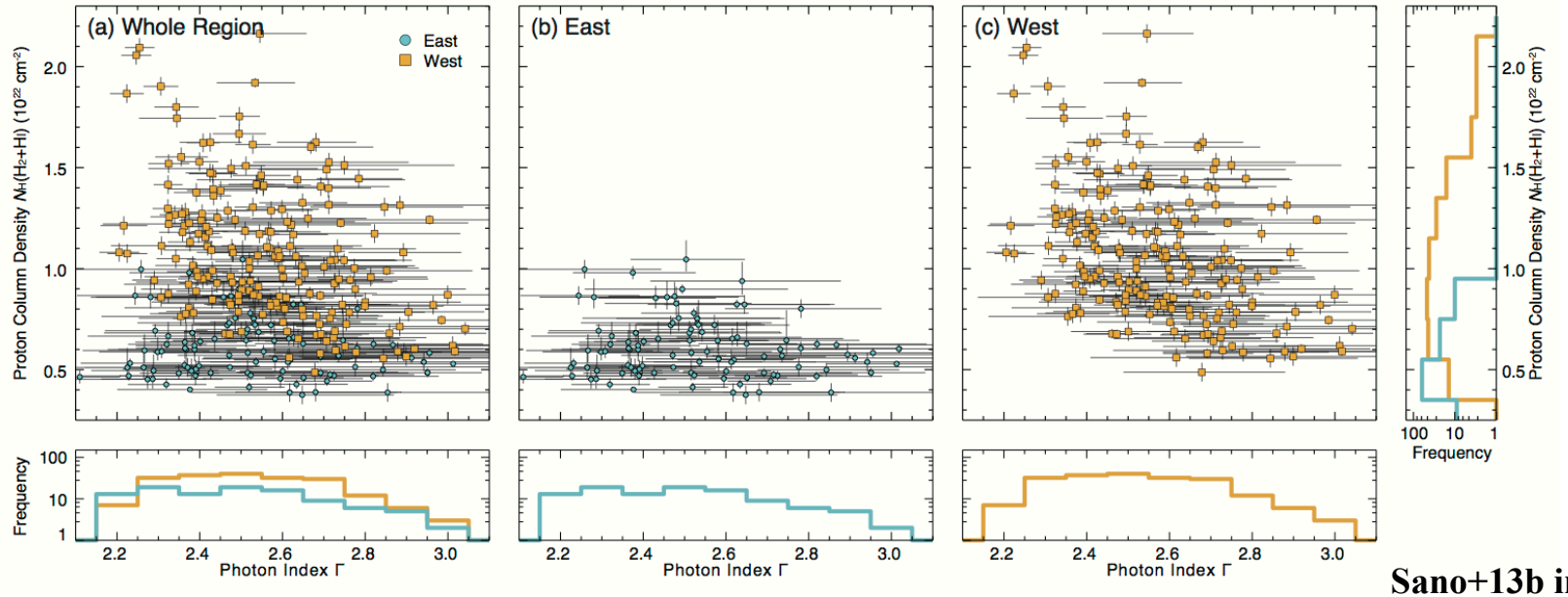
Photon index & ISM proton column density



← Image: Photon index Γ
Contours: ISM proton column density $N_H(H_2+HI)$

↓ Correlation plot between the Γ and $N_H(H_2+HI)$
(a) whole, (b) East and (c) West region.

- SNR 全体に渡って, photon index Γ の小さな領域がいくつか存在している.
- ISM rich な西側は $N_H(H_2+HI)$ と Γ が反相関, 東側では, 両者の顕著な相関は見られない



Sano+13b in prep.

Discussion: Efficient cosmic-ray acceleration

- We interpret the photon index variation as difference of cut-off energy ε_0.
  → The cutoff-energy become large (small) when the value of photon index is small (large).
  The cutoff-energy ε_0 is expressed as (Zirakashvili & Aharonian 07),

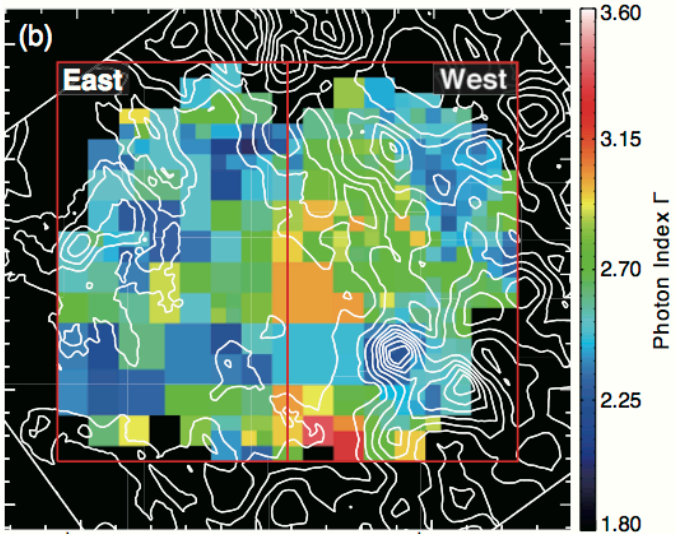
$$\varepsilon_0 = 0.55 \times (v_s / 3000 \text{ km s}^{-1})^2 \eta^{-1} \text{ keV}.$$

  where v_s is shock velocity, η is the degree of magnetic field fluctuations (gyro-factor).
  Here, the shock velocity in the dense clump became $v_{s,clump} = v_{s,ambient}\ (n_{ambient}/n_{clump})^{0.5}$,
  where the ambient gas density $n_{ambient} = 1$ cm^{-3} and clump density $n_{clump} = 10^2$–10^3 cm^{-3}.

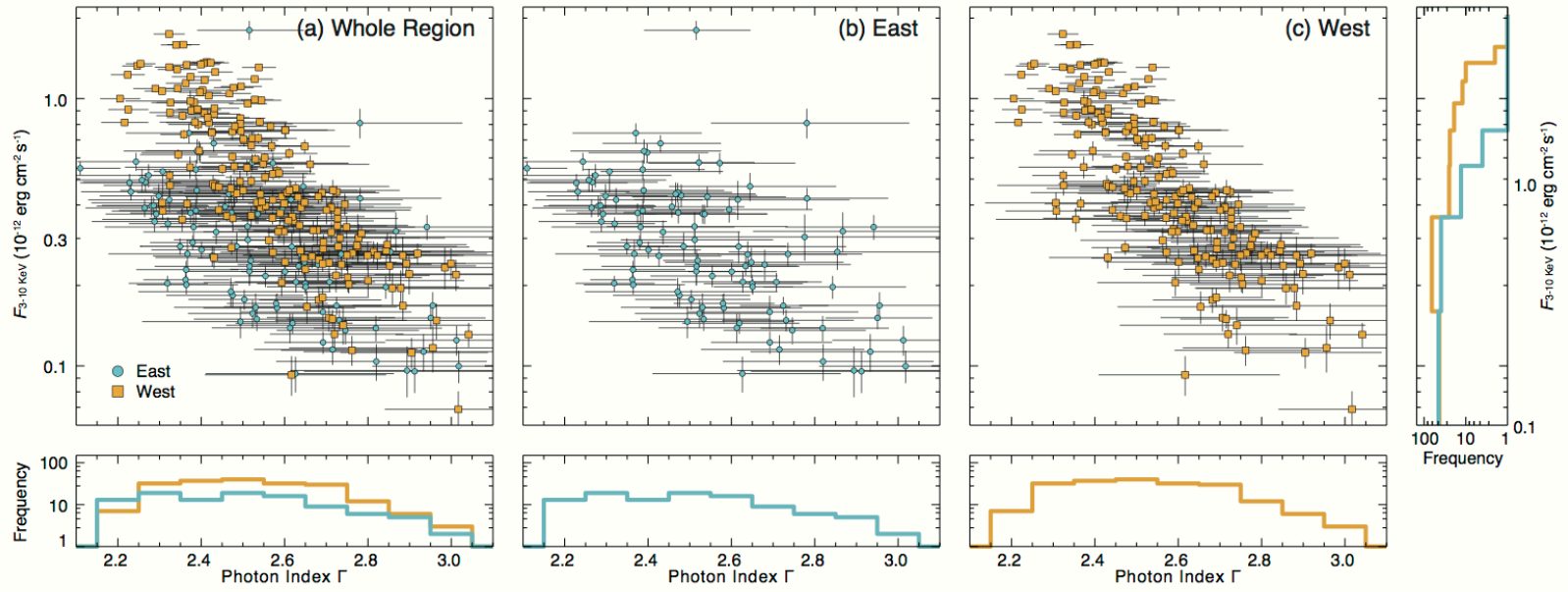
- In the west region: clumpy and rich ISM
  (shock waves will be stalled + strong turbulence)
  ⇒ small shock speed and small η (η~1; Uchiyama+07)

  In the east region: diffuse and poor ISM
  (shock waves will be little decelerated)
  ⇒ large shock speed and large η

  Therefore, photon index Γ can be small in both regions.
  However, the flux excess cannot describe only this scenario.



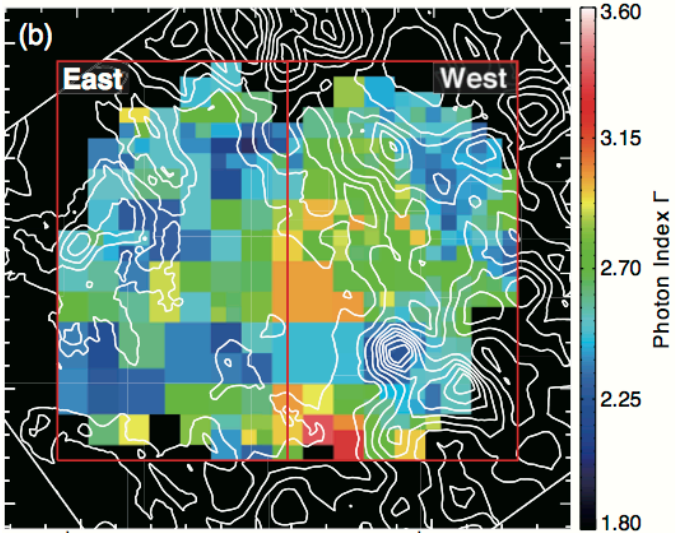
Discussion: Efficient cosmic-ray acceleration



- In the west region: clumpy and rich ISM
  (shock waves will be stalled + strong turbulence)
  ⇒ small shock speed and small η (η~1; Uchiyama+07)

  In the east region: diffuse and poor ISM
  (shock waves will be little decelerated)
  ⇒ large shock speed and large η

  Therefore, photon index Γ can be small in both regions.
  However, the flux excess cannot describe only this scenario.
  → Perhaps the additional particle acceleration mechanism
  is working in the ISM rich and clumpy region (e.g., Hoshino+12)

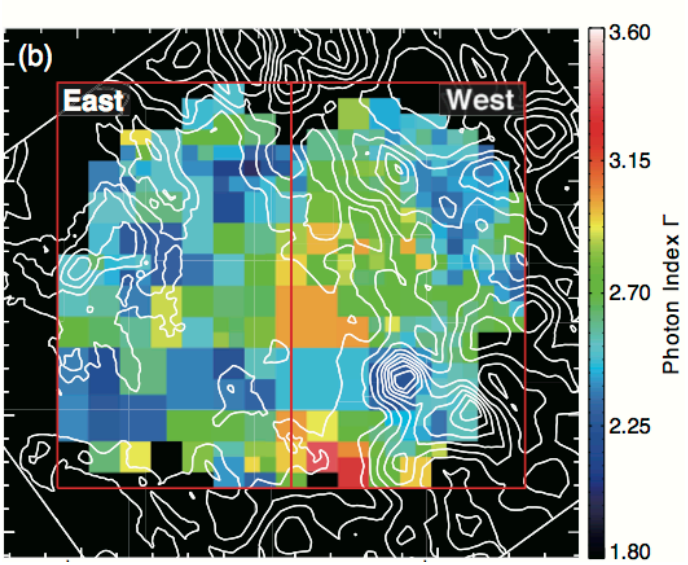


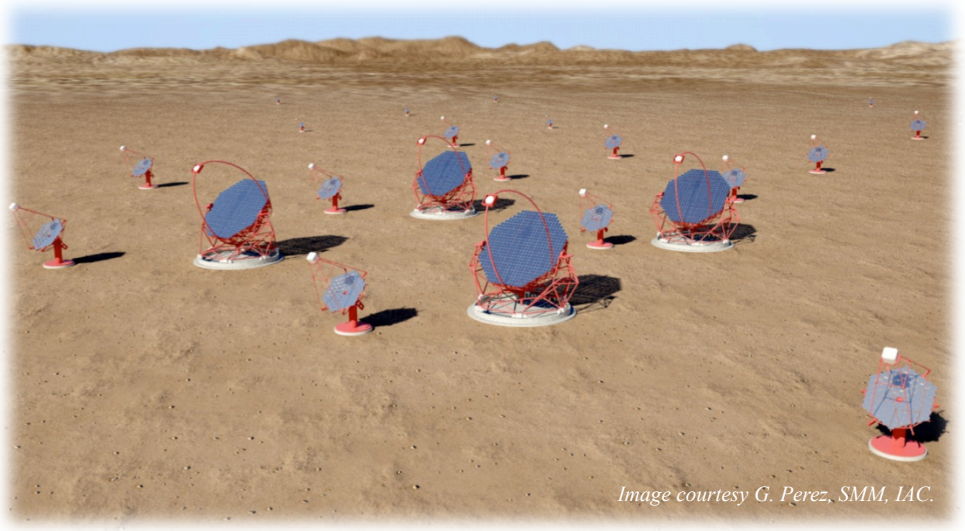
Summary

- X-ray spectroscopy for the young TeV γ-ray SNR RXJ1713
  − We reveal the N_H(X-ray), Γ and flux maps (+comparing with the ISM)

- Efficient cosmic-ray acceleration
  − We can describe the photon index variation as difference of the cut-off energy.
  − The additional particle acceleration mechanism is working in the ISM rich and clumpy region.
  − The interacting ISM with SNR is crucial play a role to understanding the efficient CR acceleration. (NANTEN/NANTEN2 CO and *Suzaku* X-ray datasets make a very strong combination!)

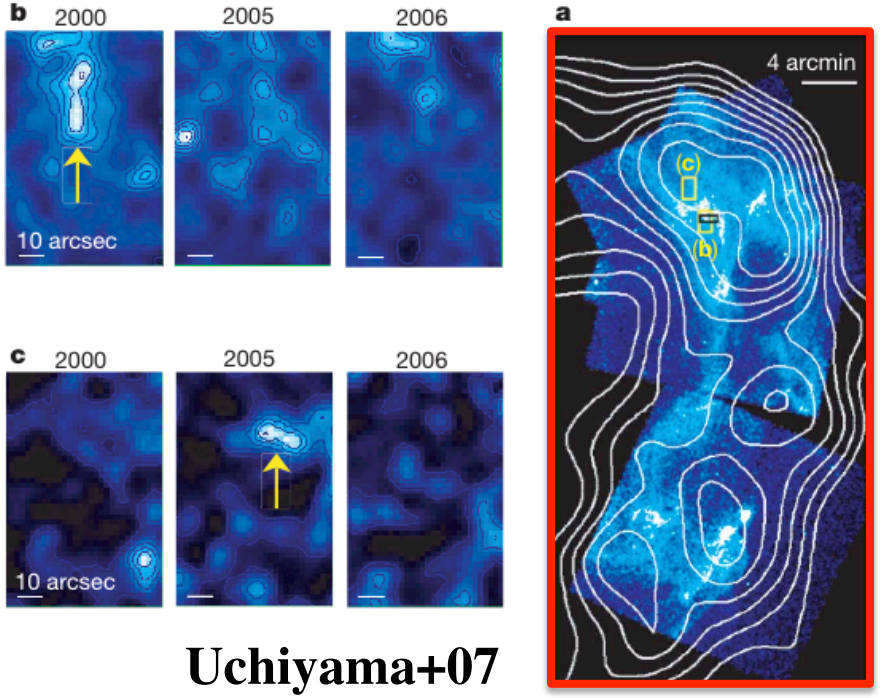
- CTA will provide more detail information (high angular resolution images, photon index distribution, etc…) and reveal the relationship between the efficient CR acceleration and the ISM distribution.



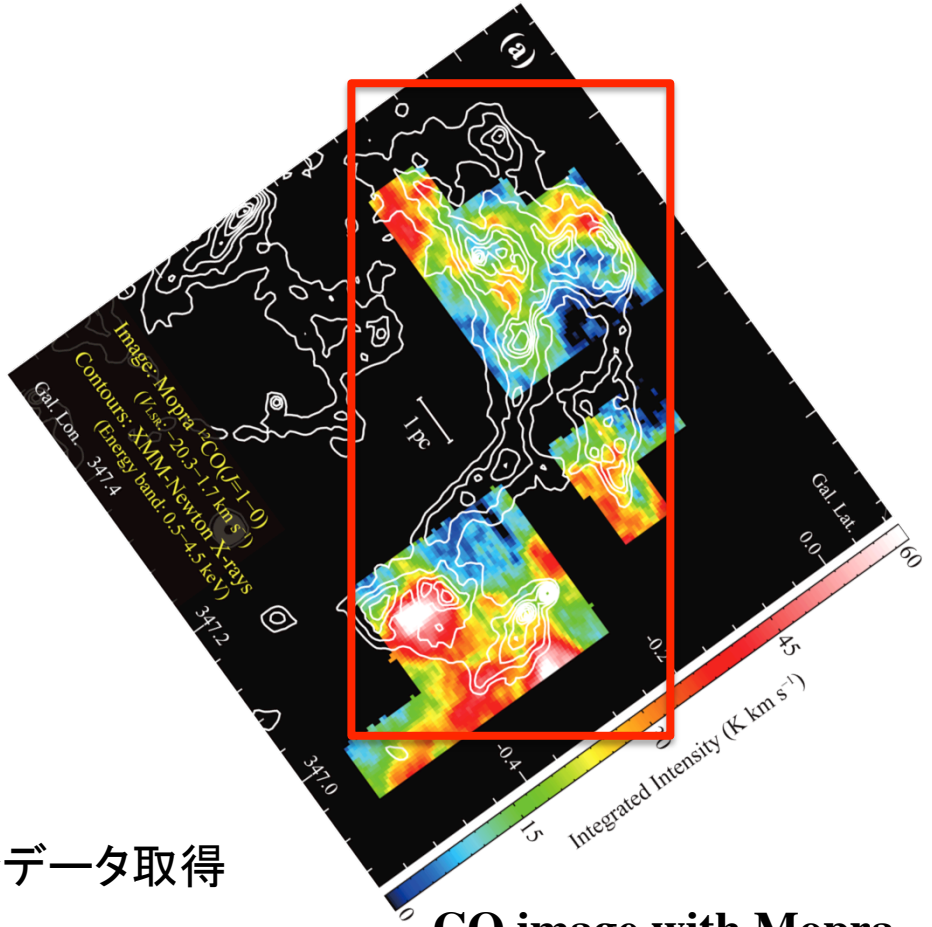


Future work (1)

- RXJ1713 の X-ray filamentary structure と ISM
  - MHD 計算の磁場増幅 scale は, ~0.05 pc (Inoue+12).
  - RXJ1713 で確認されているX線の short time variability (~0.05 pc: Uchiyama+07)



Uchiyama+07

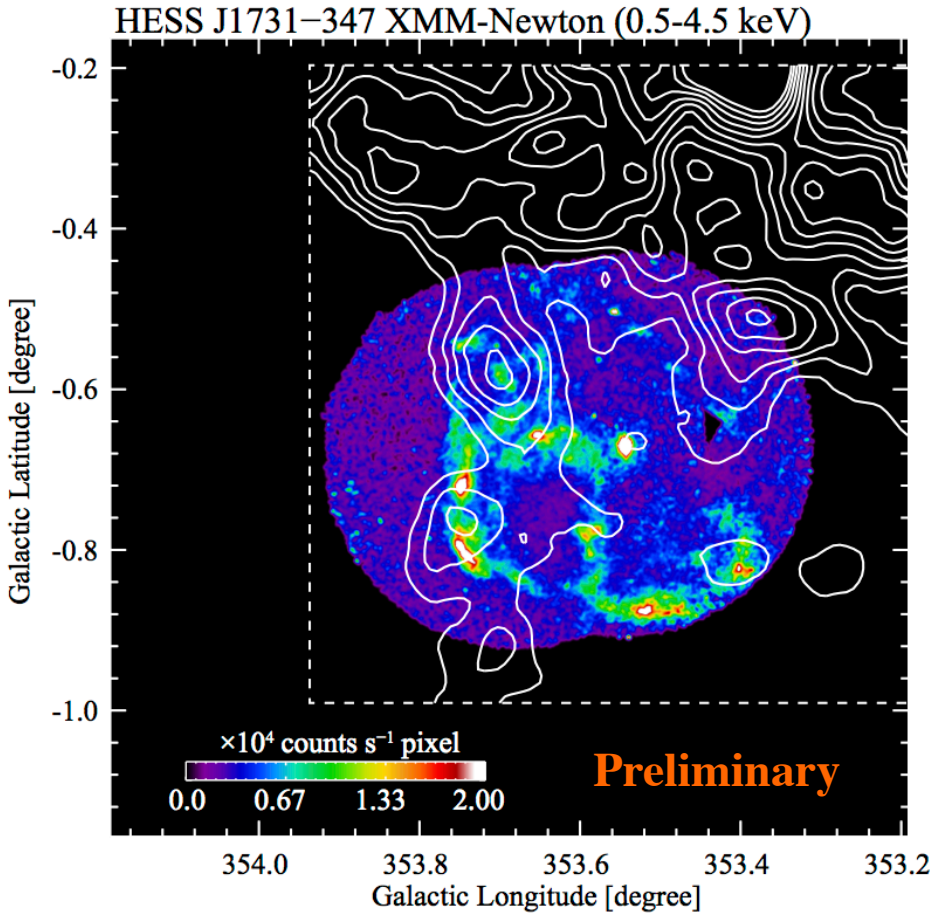


CO image with Mopra (Sano in prep.)

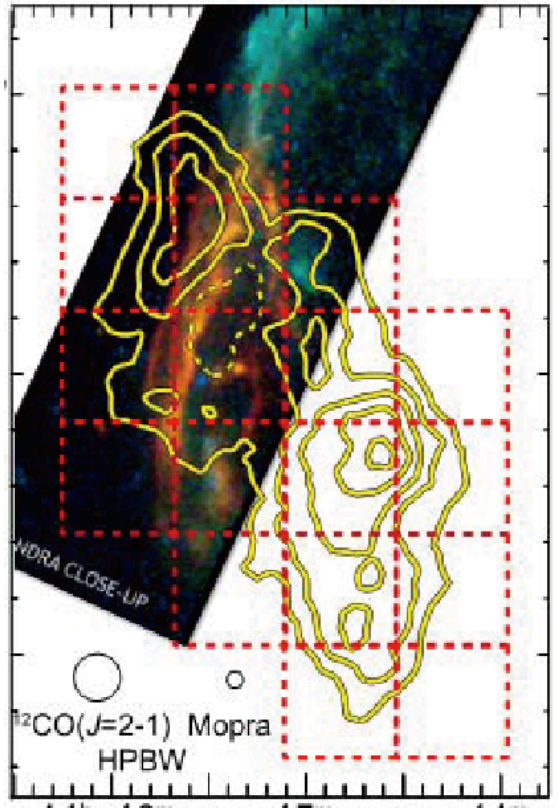
○ COについては, すでに ~0.15 pc の分解能でデータ取得
⇒ ALMAで ~0.05 pc へ迫る

Future work (2)

- 他のガンマ線 SNR と ISM の相互作用
  - RXJ1713 の結果の普遍性を探る (HESS J1731, RCW86 etc..)
  - Thermal X-rays や Hard X-rays と ISM の関係は？ (ASTRO-H SXS, HXI に期待)



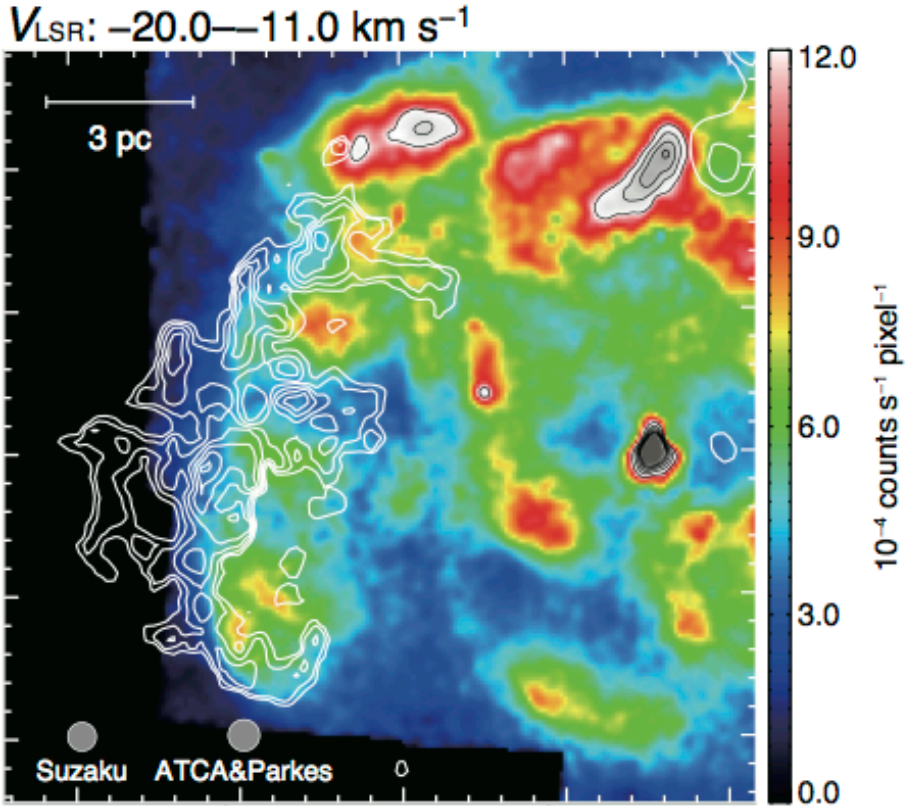
Contours: CO 1-0 (Fukuda+13 submitted to ApJ)



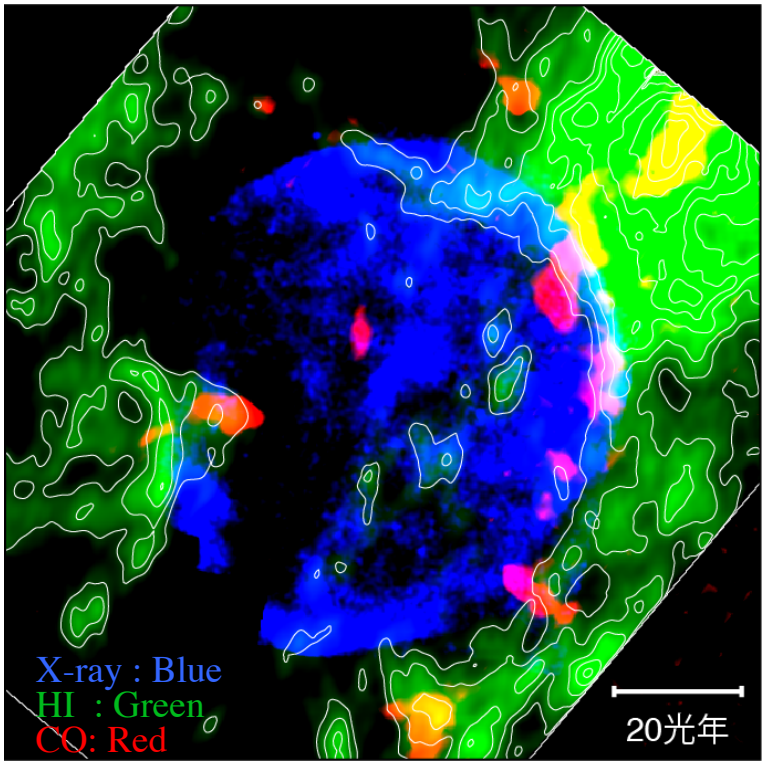
RCW86 X-ray image
+NANTEN2 CO contours

Future work (3)

- Interacting ISM としての HI の重要性
  - RXJ1713 SE-rim の cold HI や, Vela Jr. の HI シェルも重要な ISM 構成要素
    → SNR と相互作用する ISM の大半を占めたり, 100 個/cc を超えるものも存在

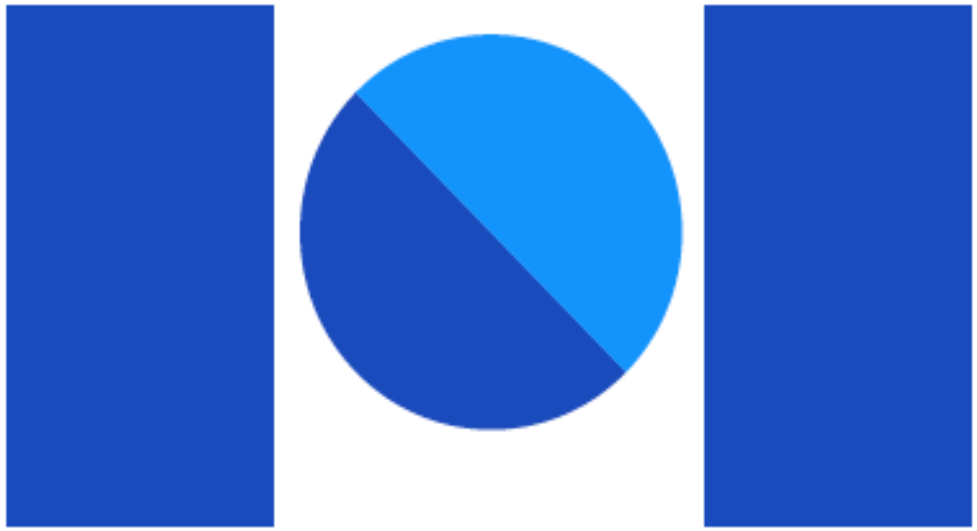


RXJ1713 East (Sano+13b in prep.)



Vela Jr. (Sano+13c in prep.)

多くのSNRについて付随する HI を特定, 物理量を明らかにしていくことが肝要



NANTEN

Submillimeter Observatory