Discovery of a hard X-ray spectrum from the mixed morphology SNR W28 with XMM-Newton

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Gerd Pühlhofer, Stefan J. Wagner

Introduction

Supernova Remnant (SNR) :

Candidate of the cosmic-ray accelerator

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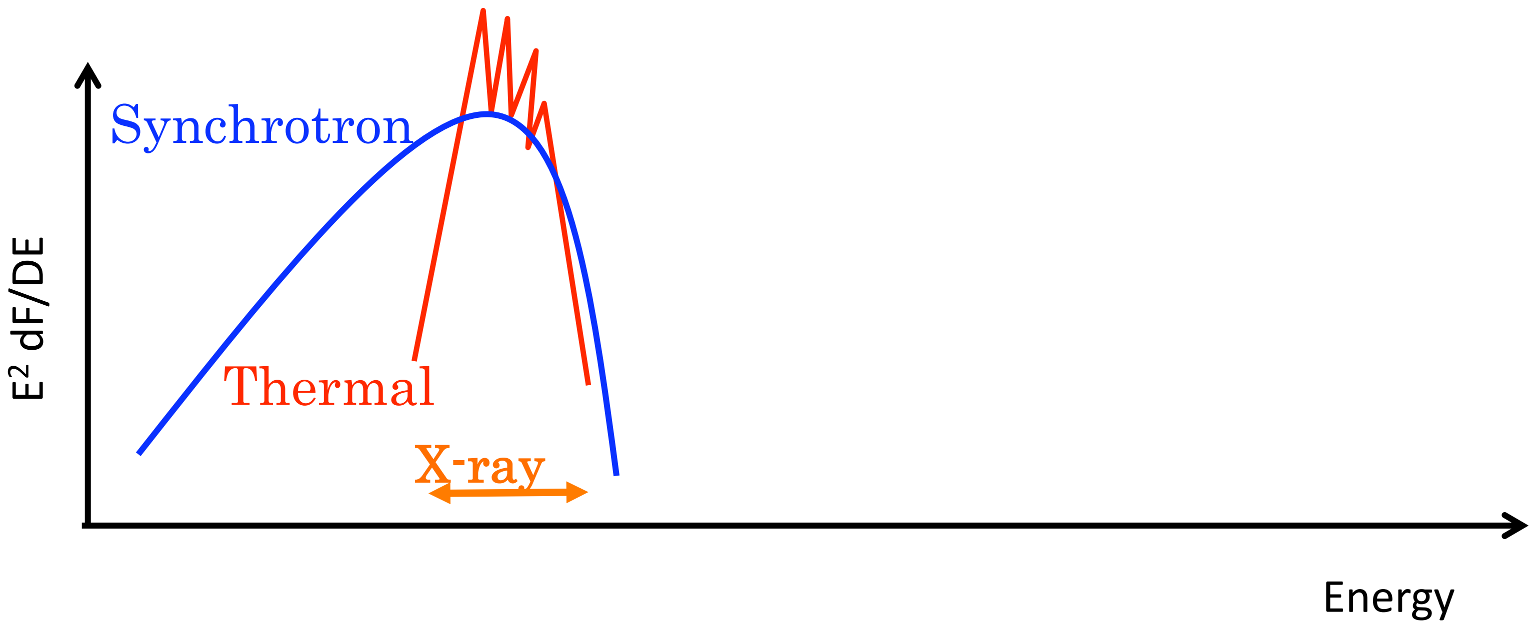

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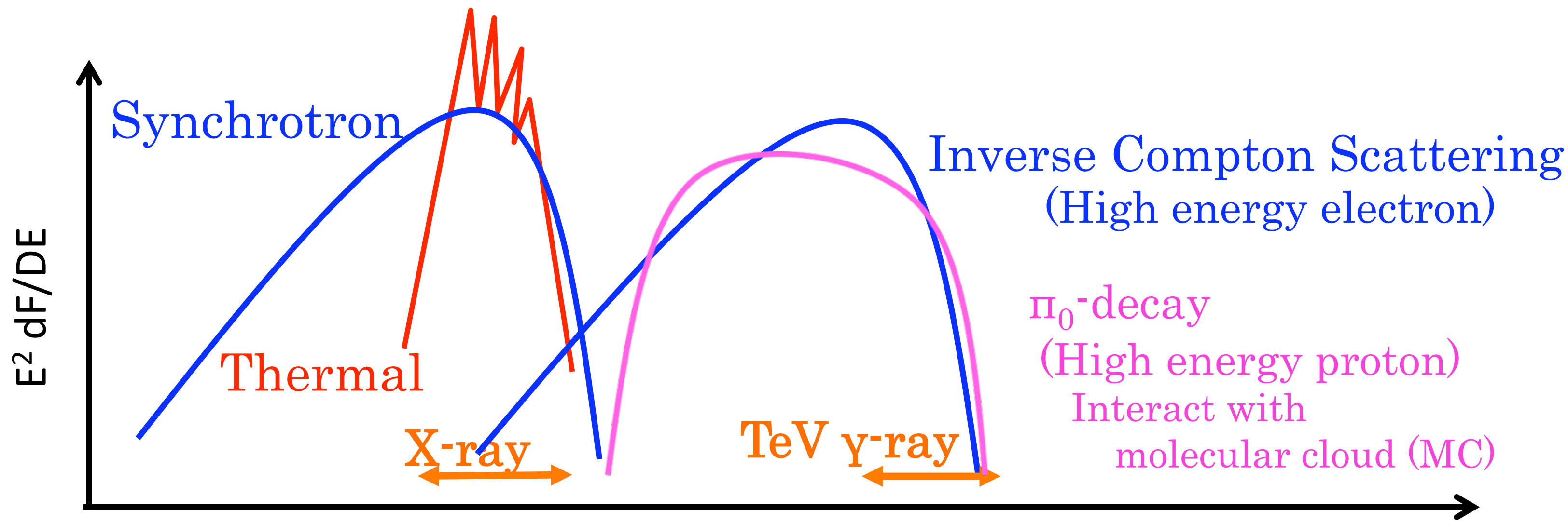

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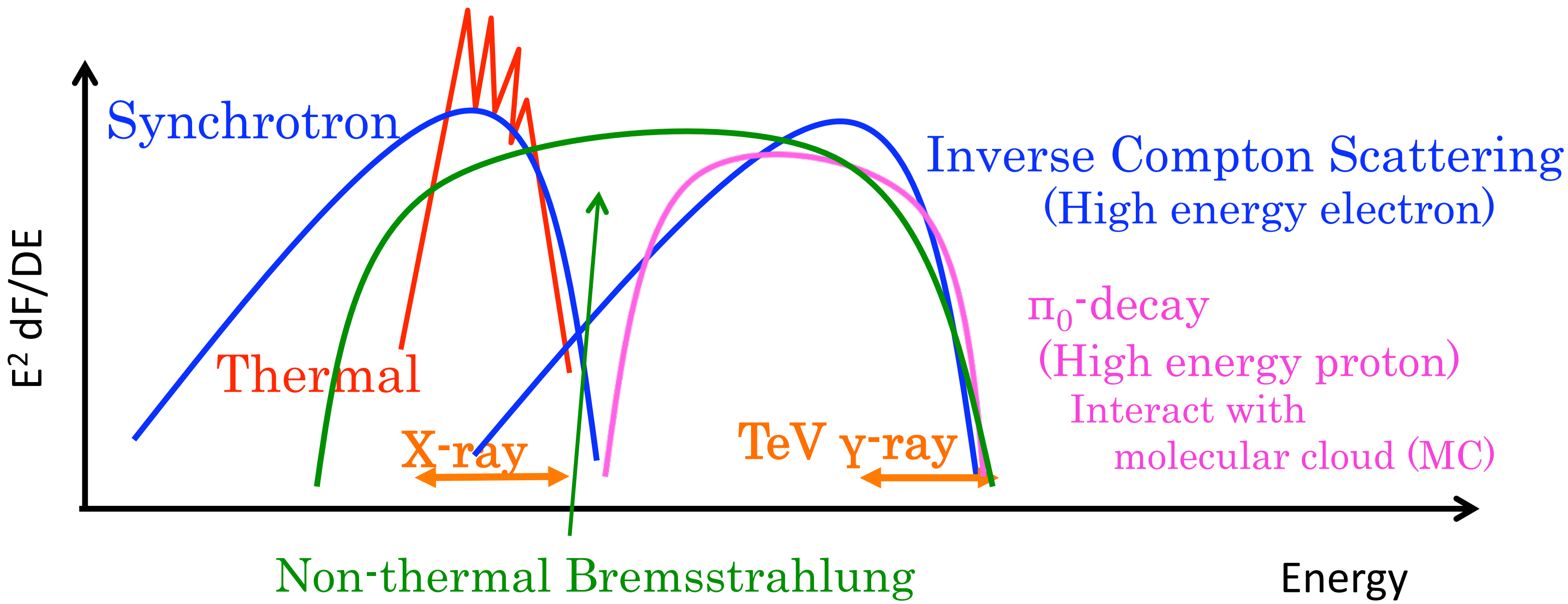

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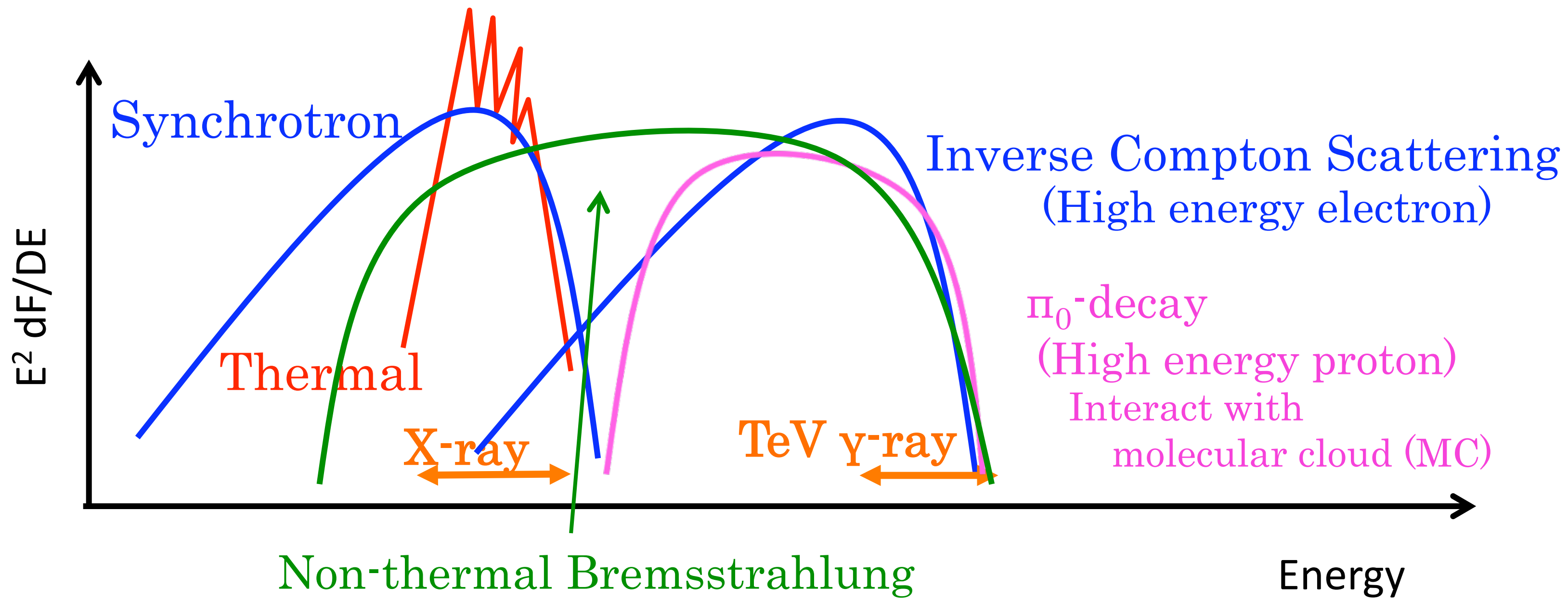

X-ray

・Thermal emission (Line + Bremss) ;
The environment and condition of the SNR (The age, The electron density, etc.)

・Non-thermal emission (Synchrotron X-ray or Non-thermal Bremss)

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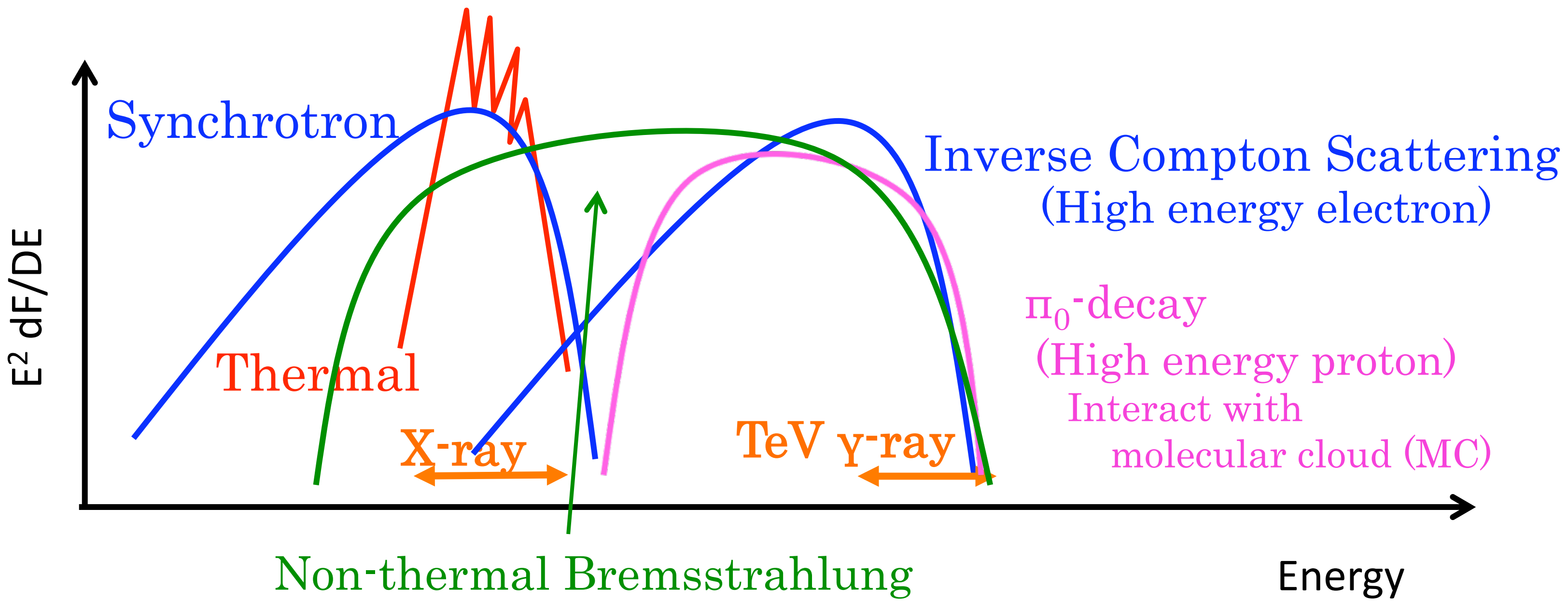

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TeV γ-ray

・IC
・Non-thermal Bremss } Electron
・π_0-decay Proton

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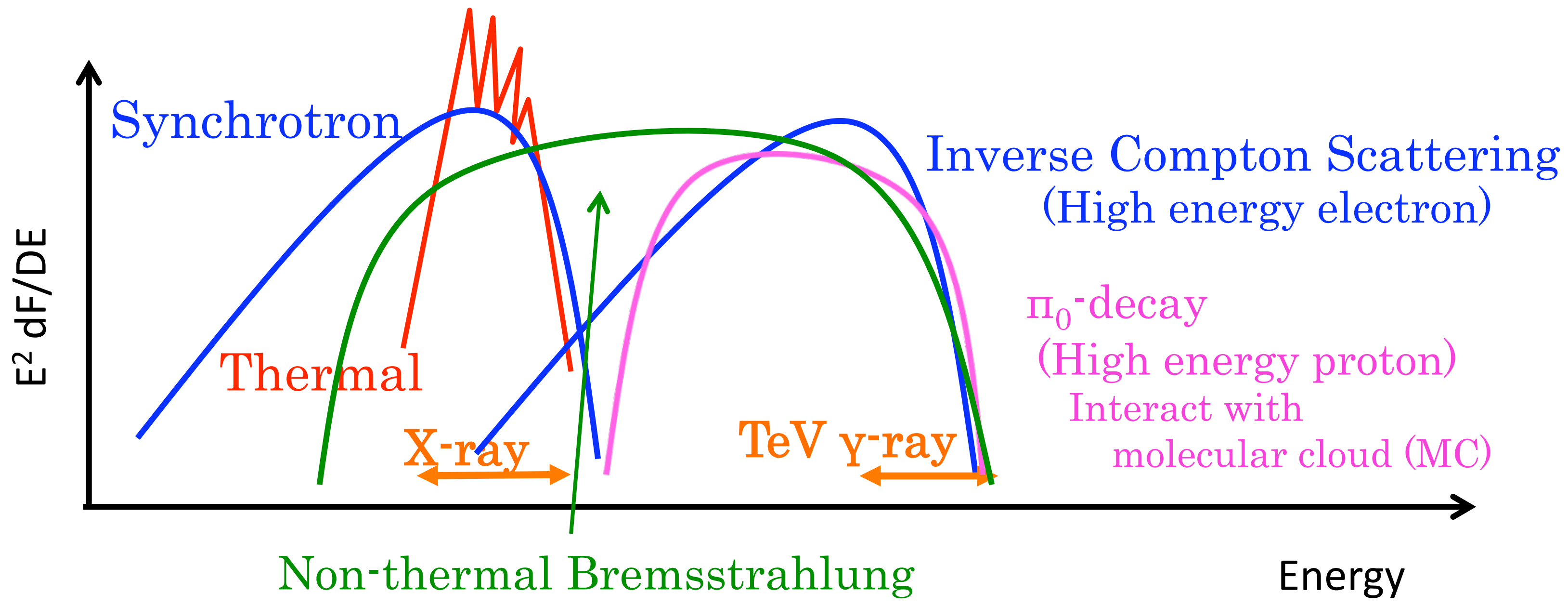

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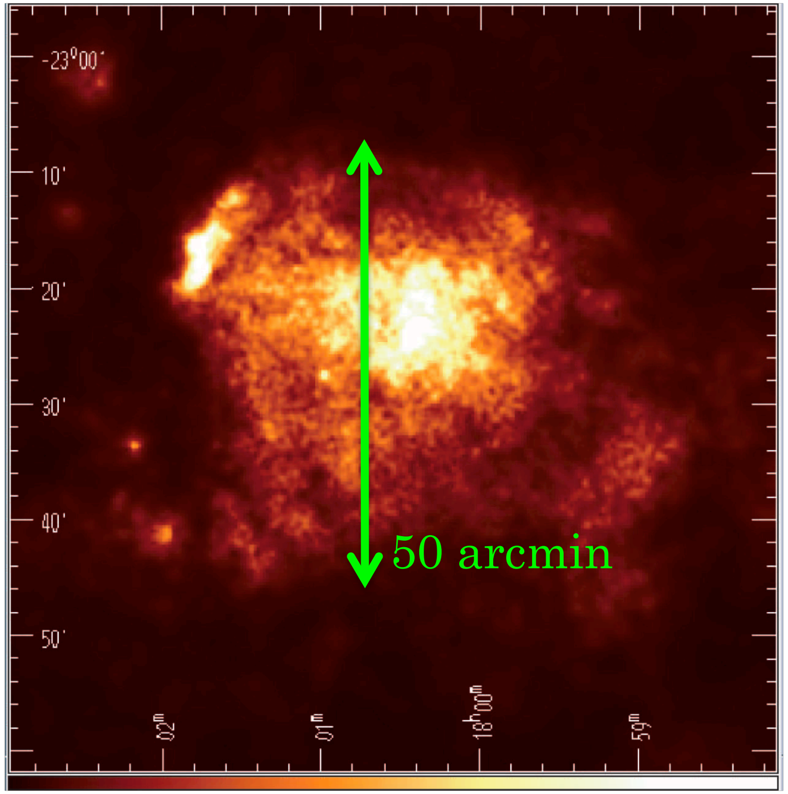
The mechanism of cosmic-ray acceleration (The maximum electron energy, The magnitude of the magnetic field, etc.)

Target：W28

X-ray image (ROSAT 0.5-2.4 keV)



(Ryo and Borkowski 2002)

(l , b) = (6.4°, -0.1°)

Distance：1.9 kpc
Diameter：50 arcmin (= 27 pc) (Green 2006)
Age：Several times 10^4 yr
(Rho & Borkowski 2002)

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- Optical
- X-ray
- TeV γ-ray

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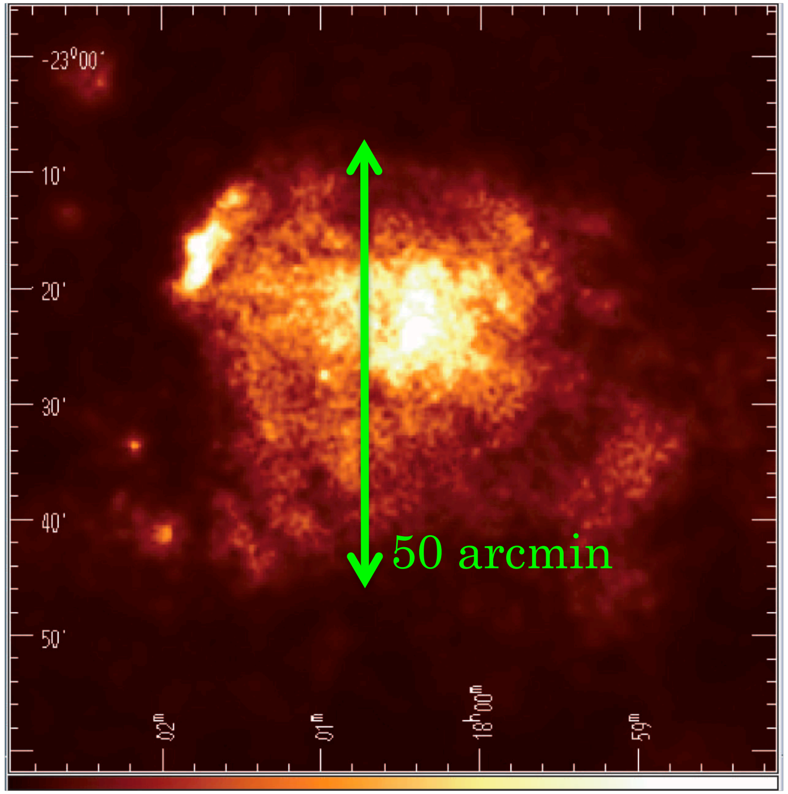

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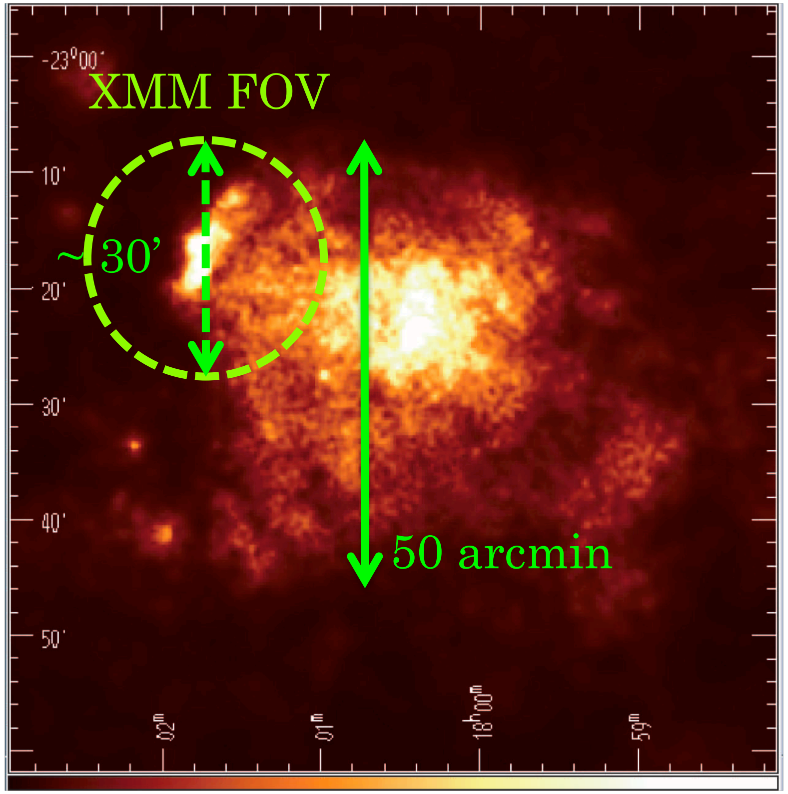

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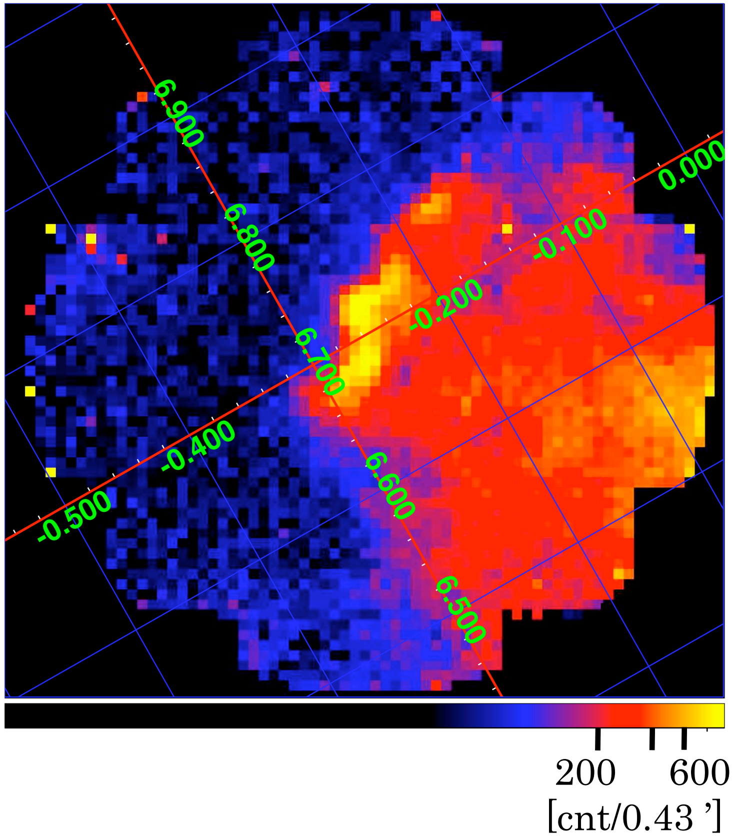
TeV γ-ray :
π_0-decay by the accelerated proton?

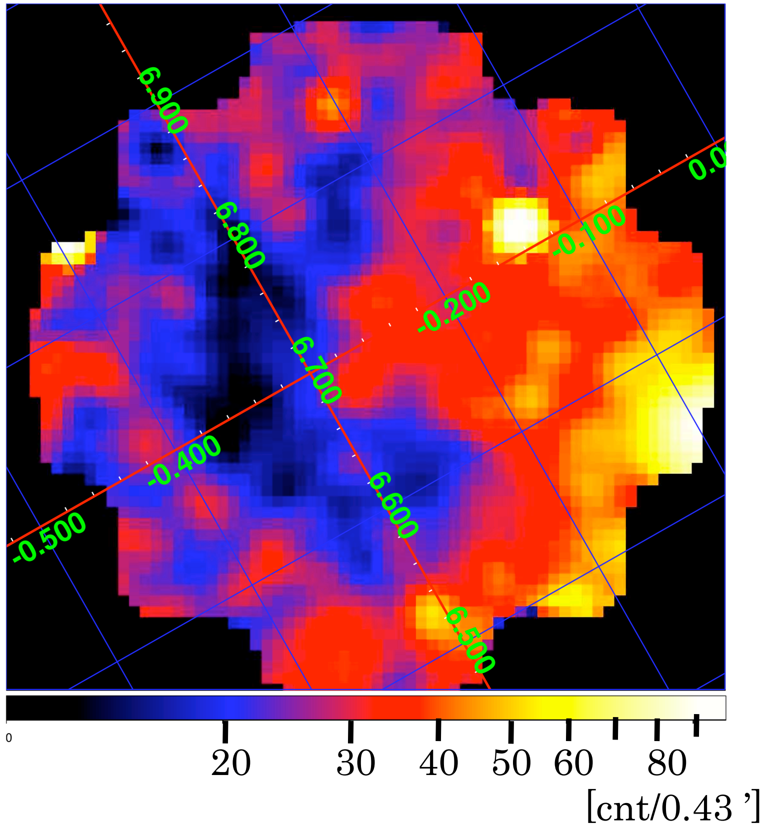
XMM–Newton observation (TeV γ-ray was detected region)
Exposure time : 52 ksec

Image

0.3 – 2.0 keV



2.0 – 10.0 keV



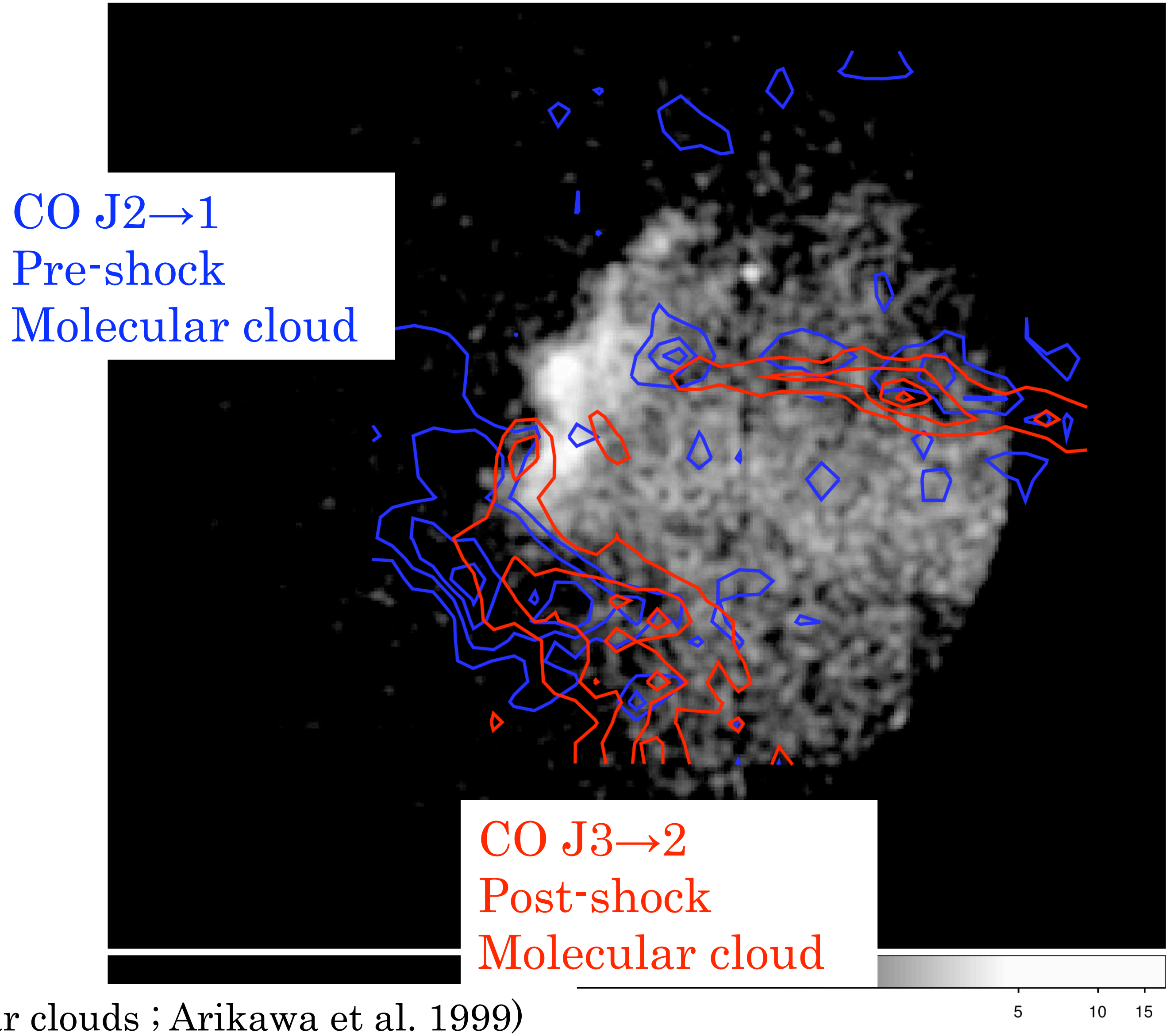
Low energy band (0.3-2.0 keV):

- Northeast shell is most bright.
- The shape is distorted.
- Inner region is also bright.

High energy band (2.0-10.0 keV):

- Inner region is bright.

Image



(Molecular clouds ; Arikawa et al. 1999)
(OH Masers ; M. J. Claussen 1997)

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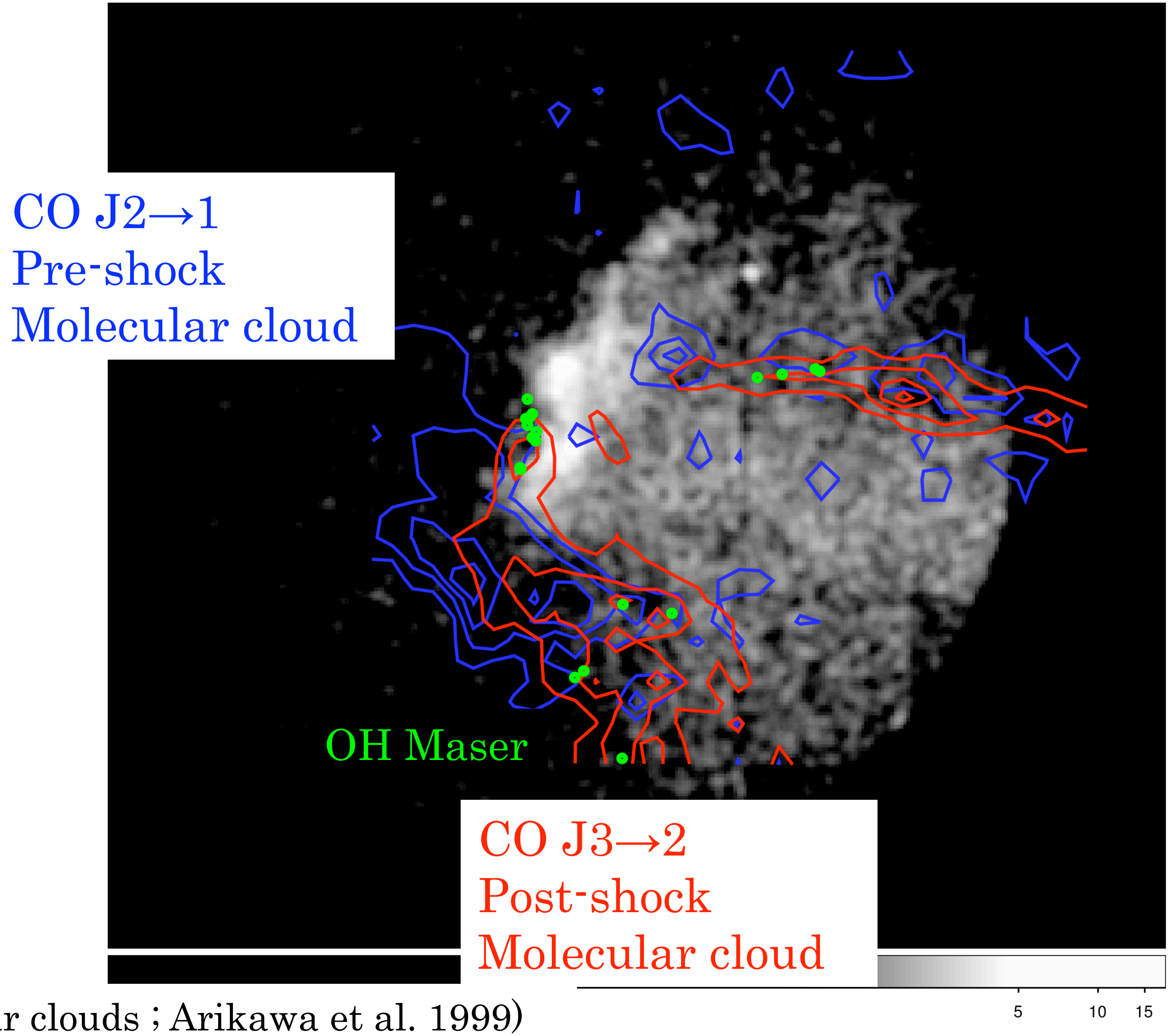

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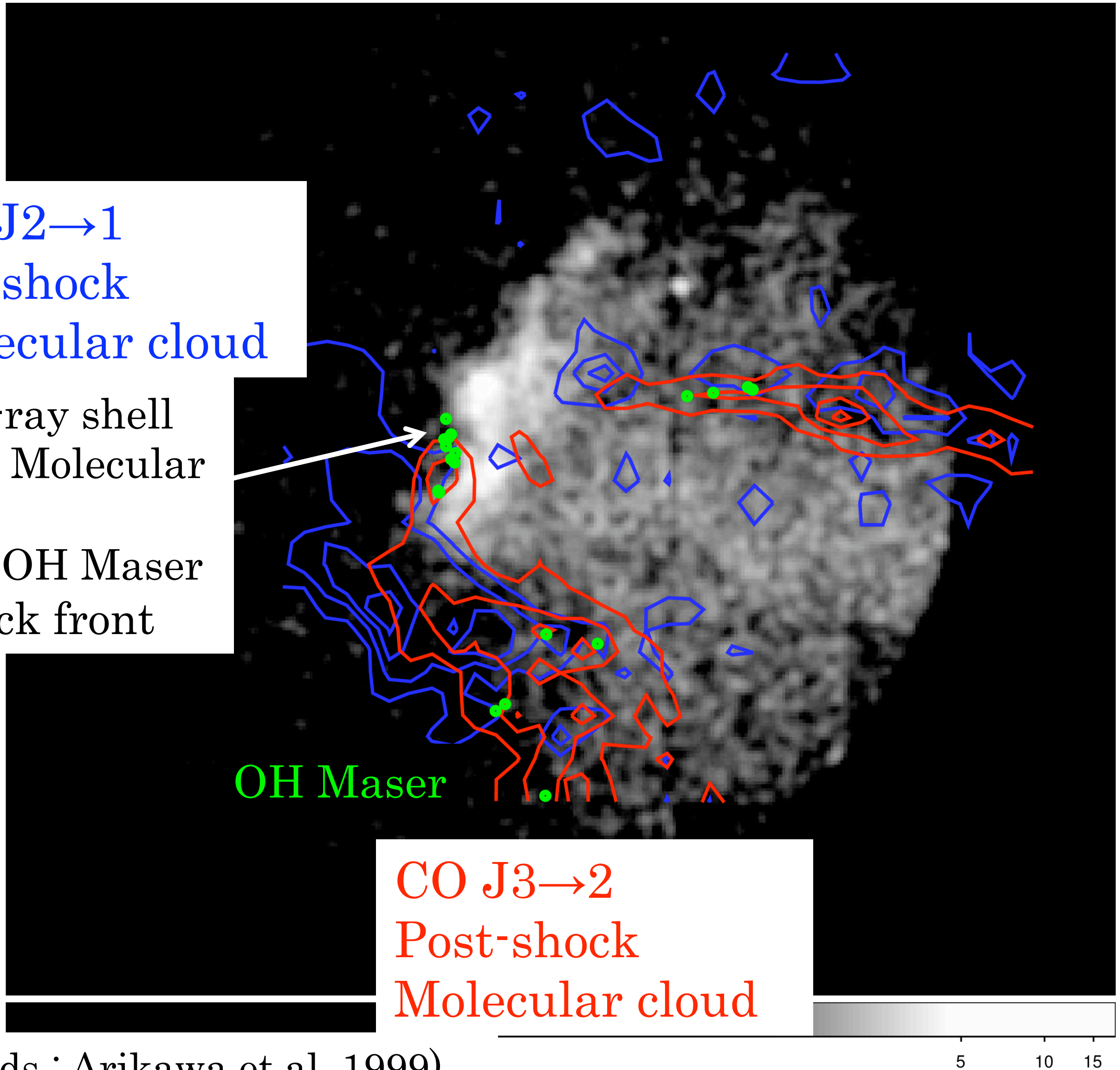

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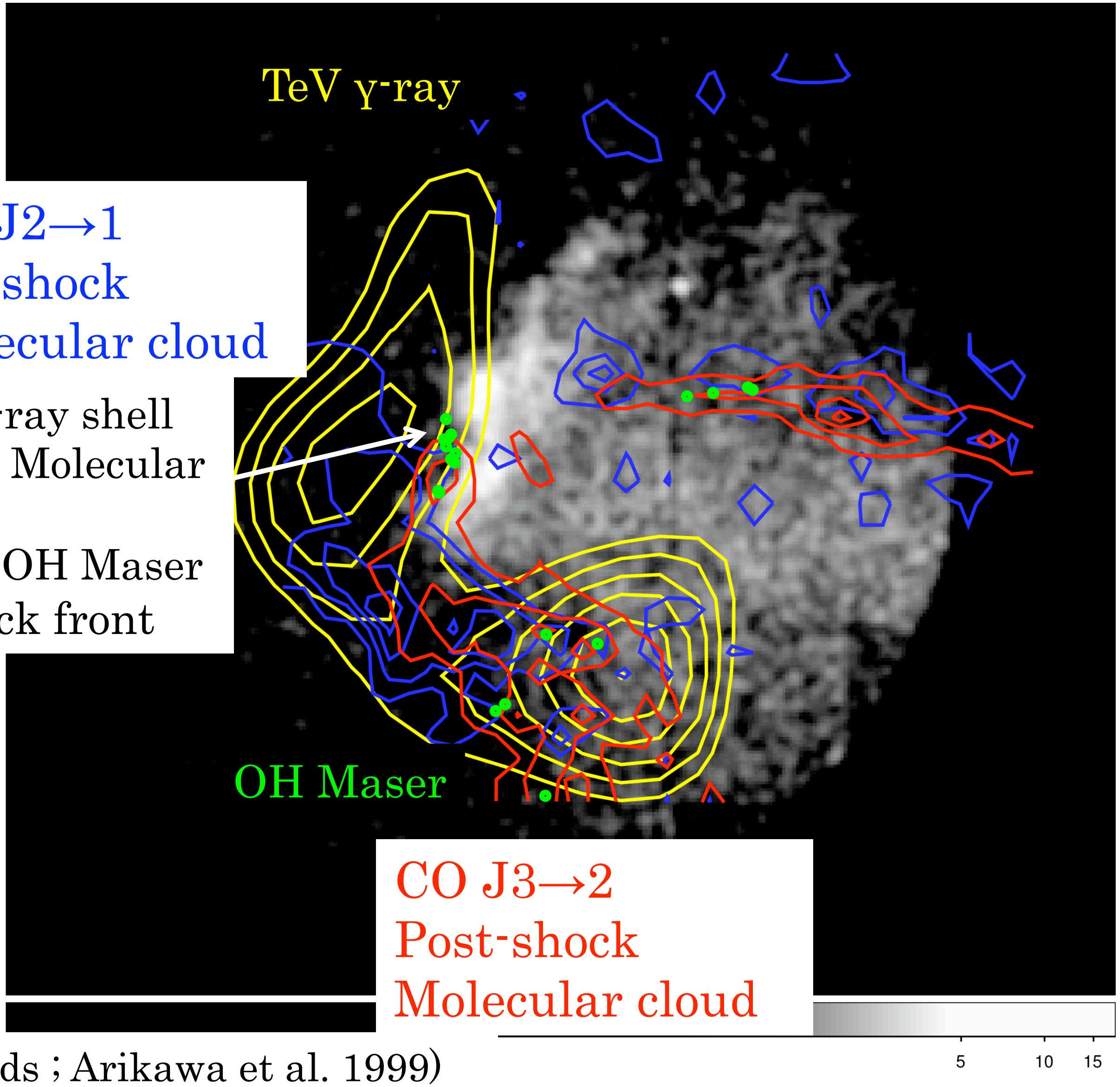


The shape of X-ray shell
The edge of the Molecular cloud
The position of OH Maser
→ Shock front

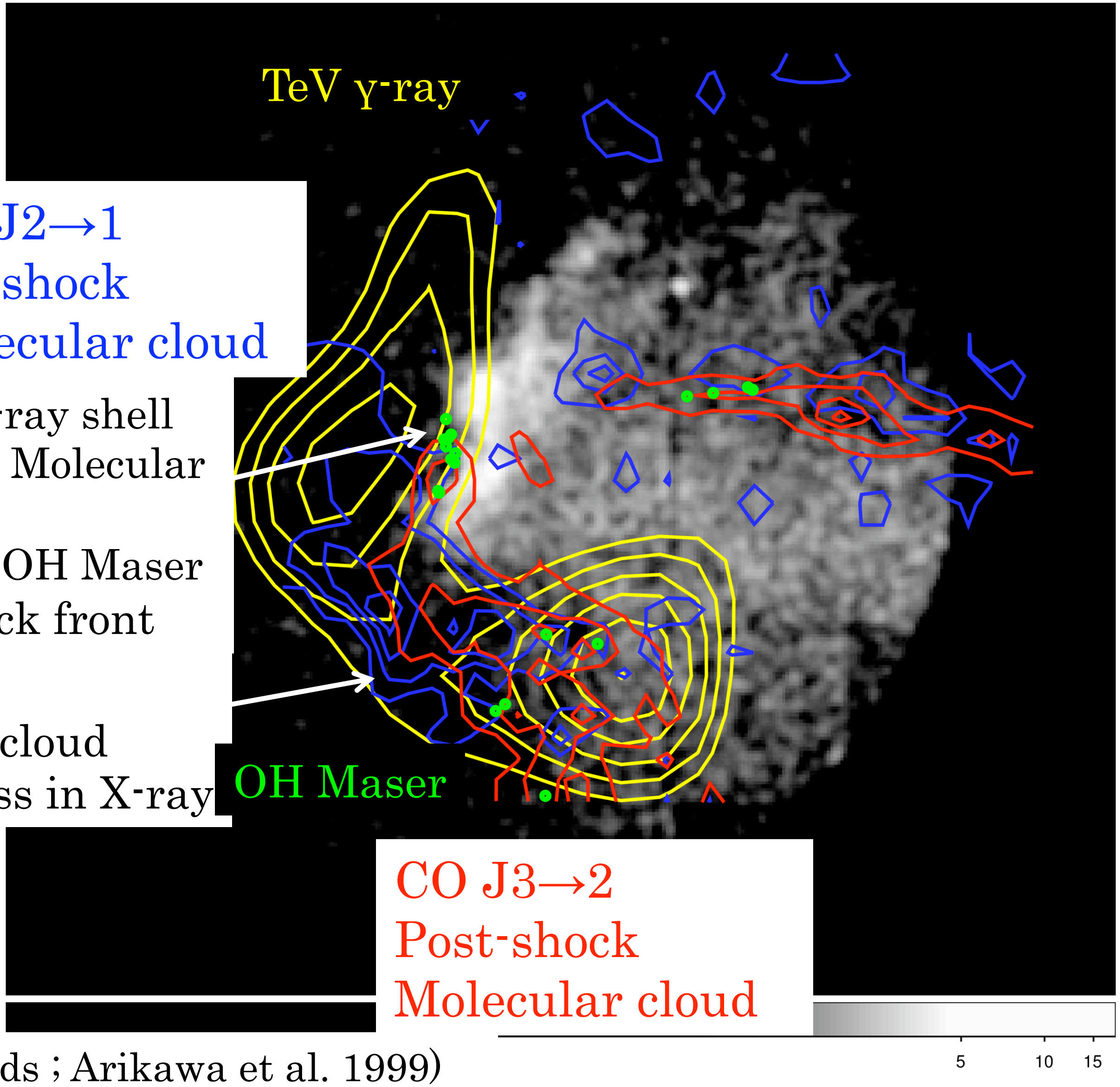
(Molecular clouds ; Arikawa et al. 1999)
(OH Masers ; M. J. Claussen 1997)

Image

CO J2→1
Pre-shock
Molecular cloud

The shape of X-ray shell
The edge of the Molecular cloud
The position of OH Maser
→ Shock front

TeV γ-ray
= Molecular cloud
Low brightness in X-ray



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Spectral fitting

Topic

1. Determine the X-ray flux of TeV γ-ray intensive region.
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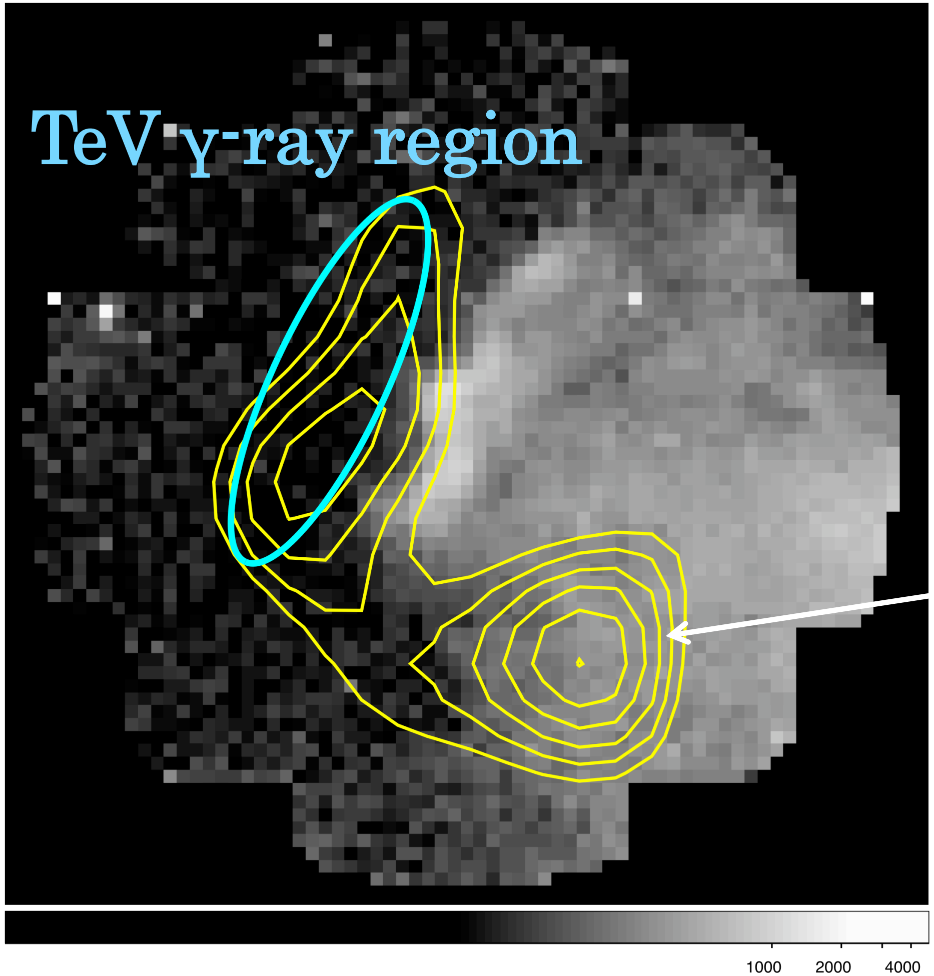

Analysis is difficult because of the thermal contamination from W28

Spectral fitting

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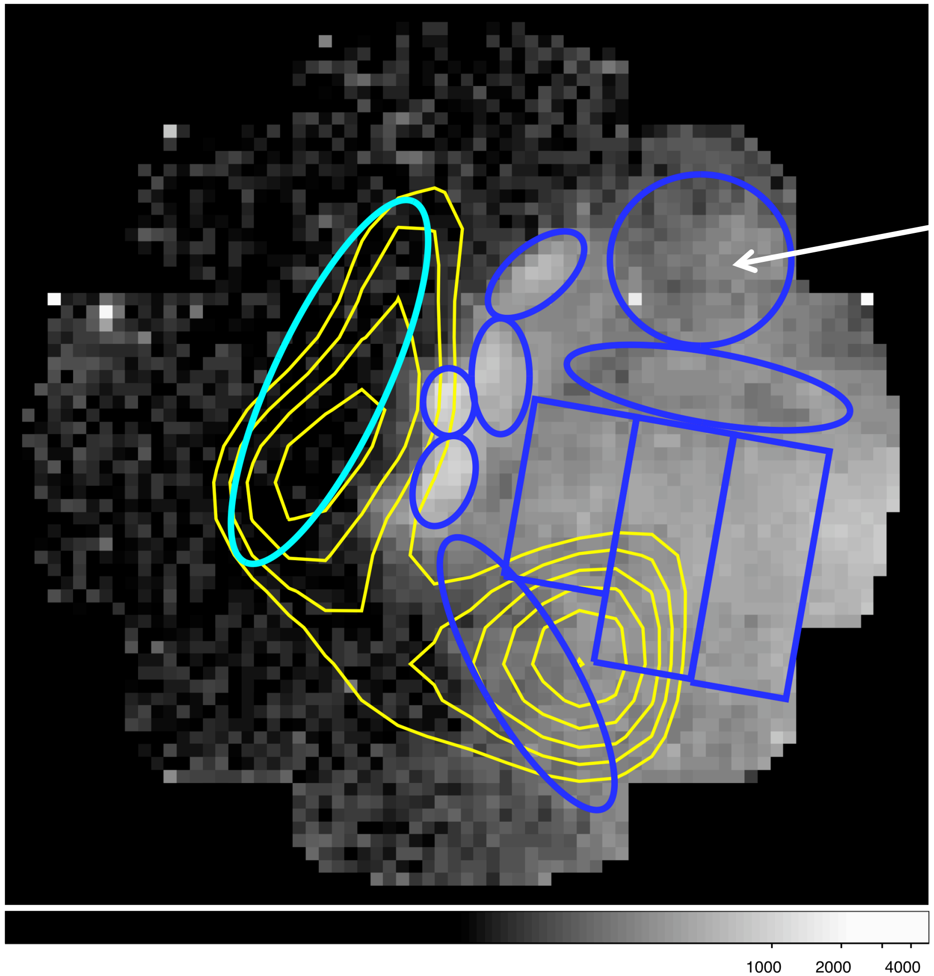

Extracted and analyzed several region spectra

Spectral fitting

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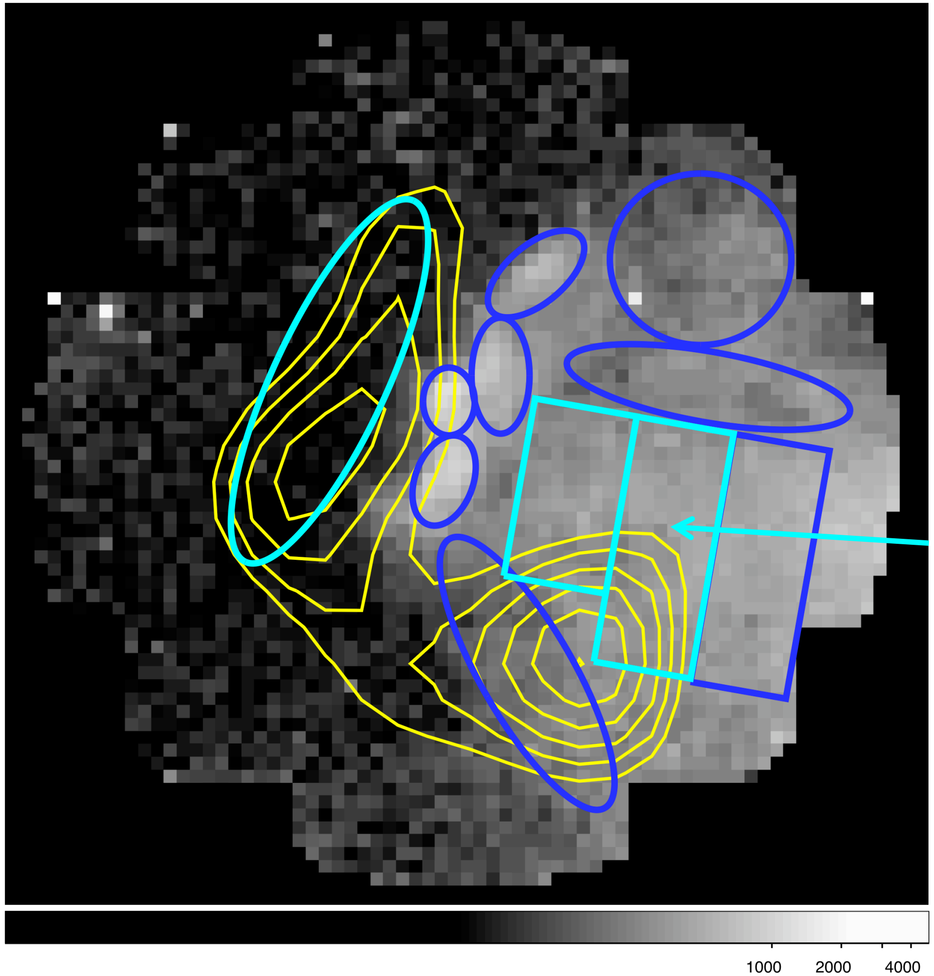
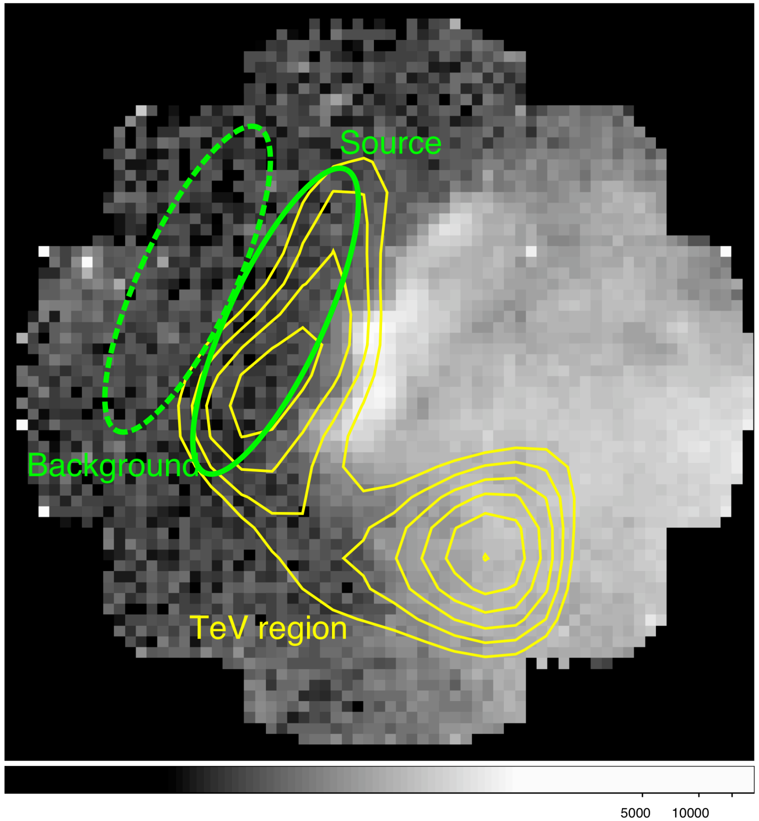
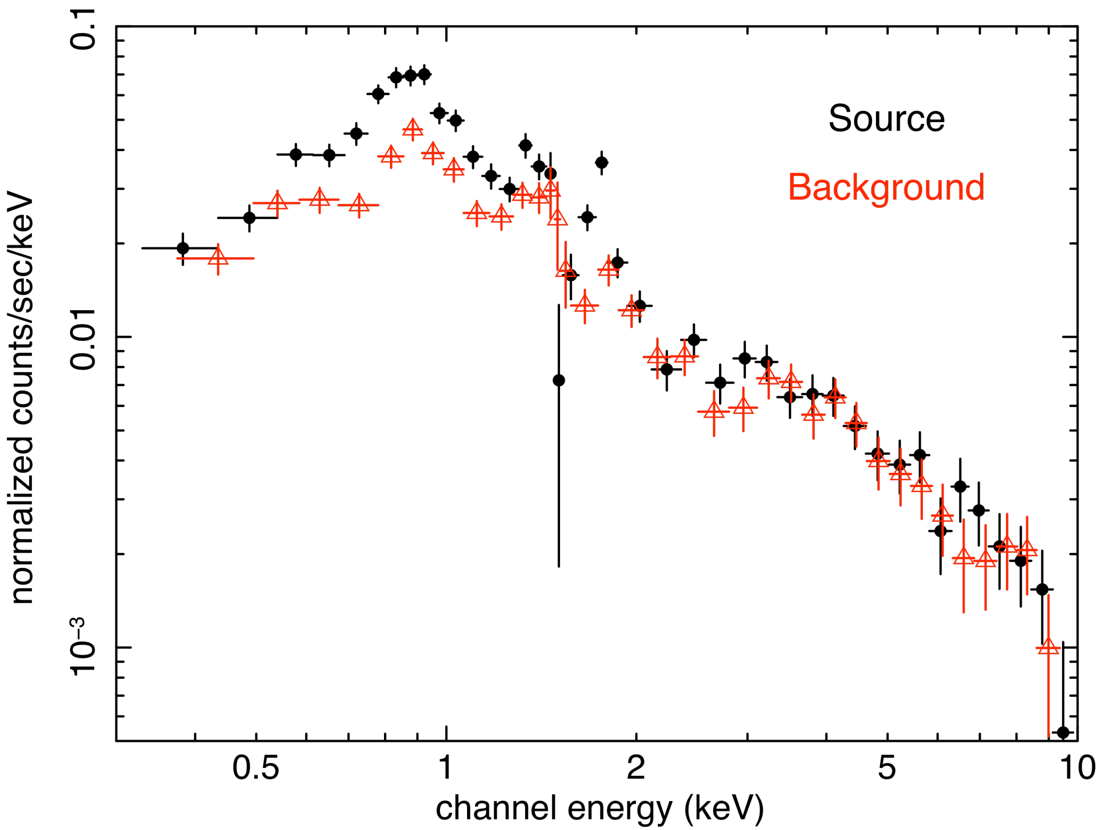


We discovered non-thermal X-ray from 2 regions.

1. TeV γ-ray region





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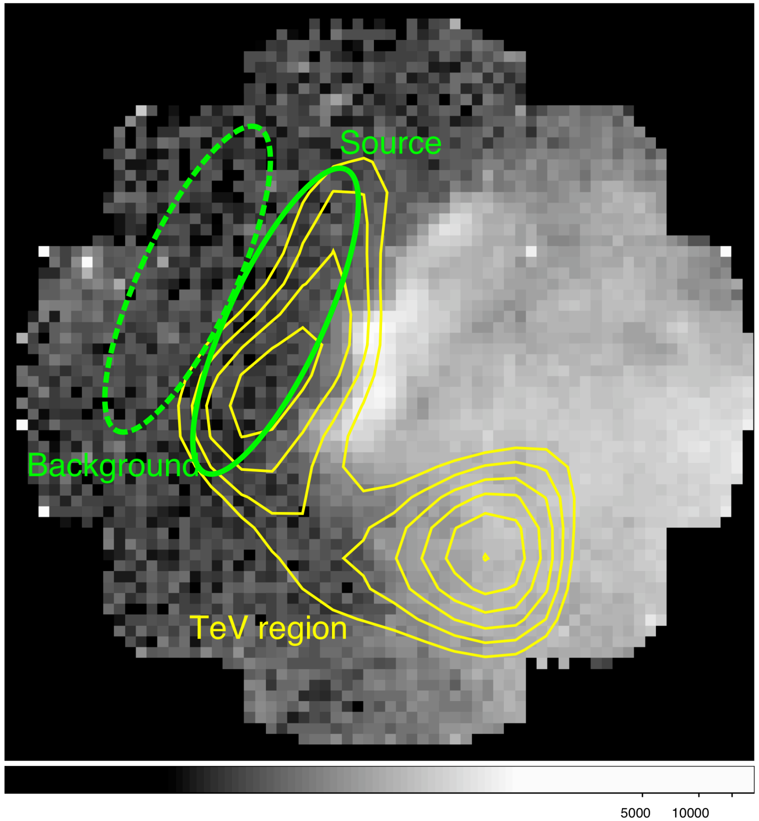

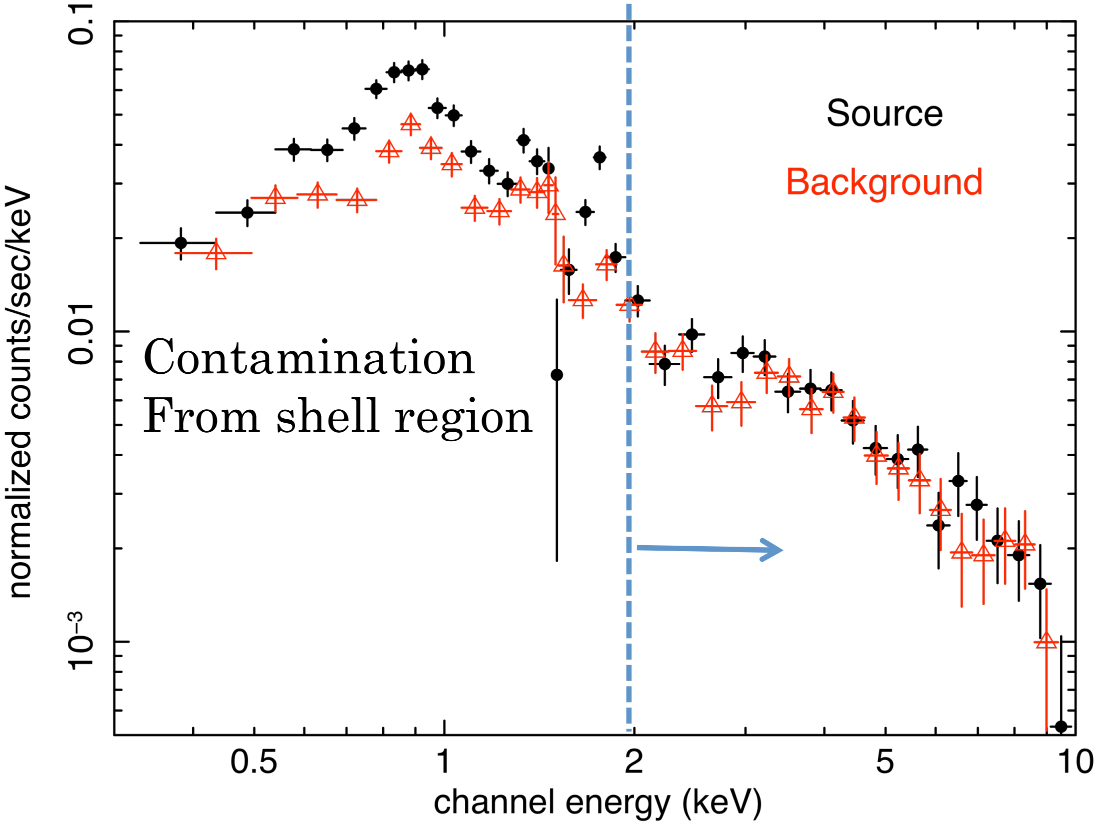

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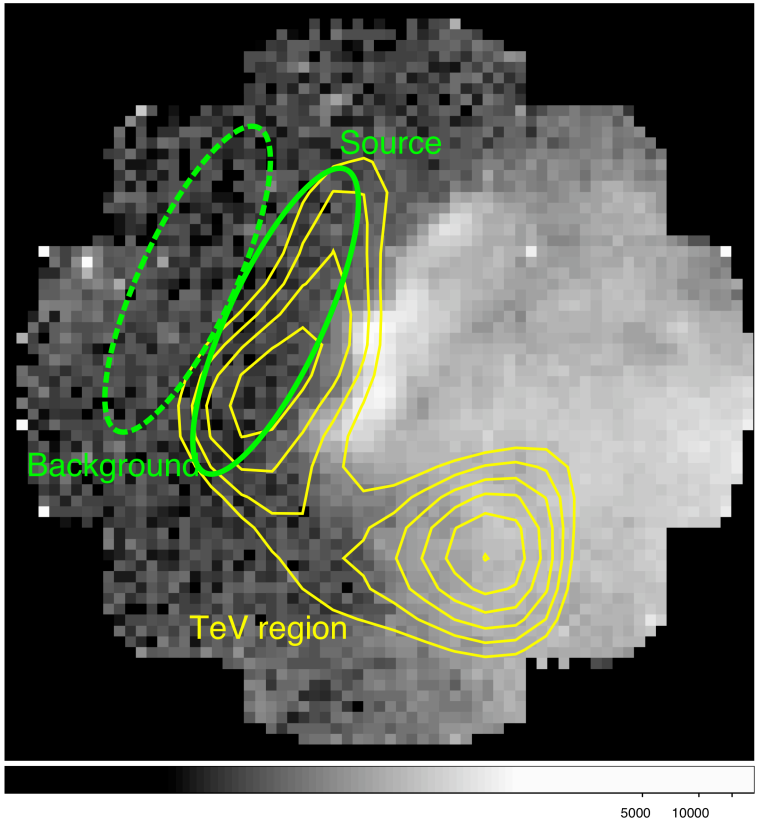
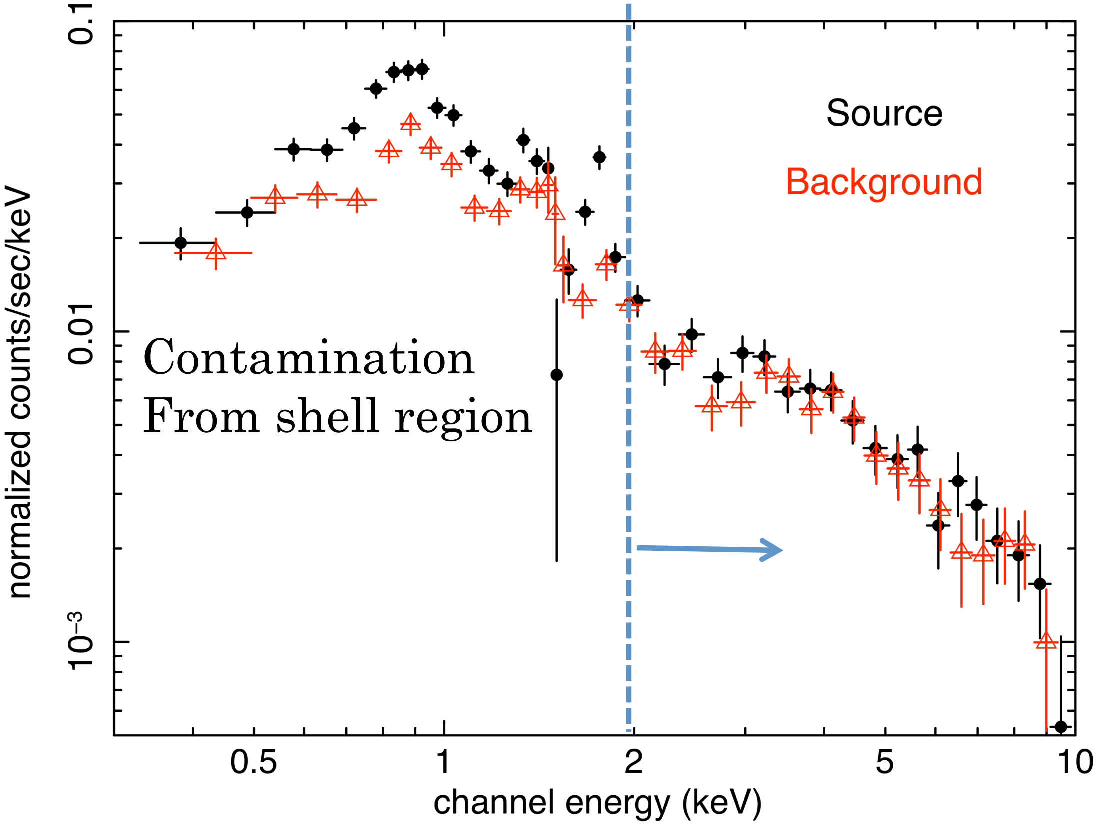


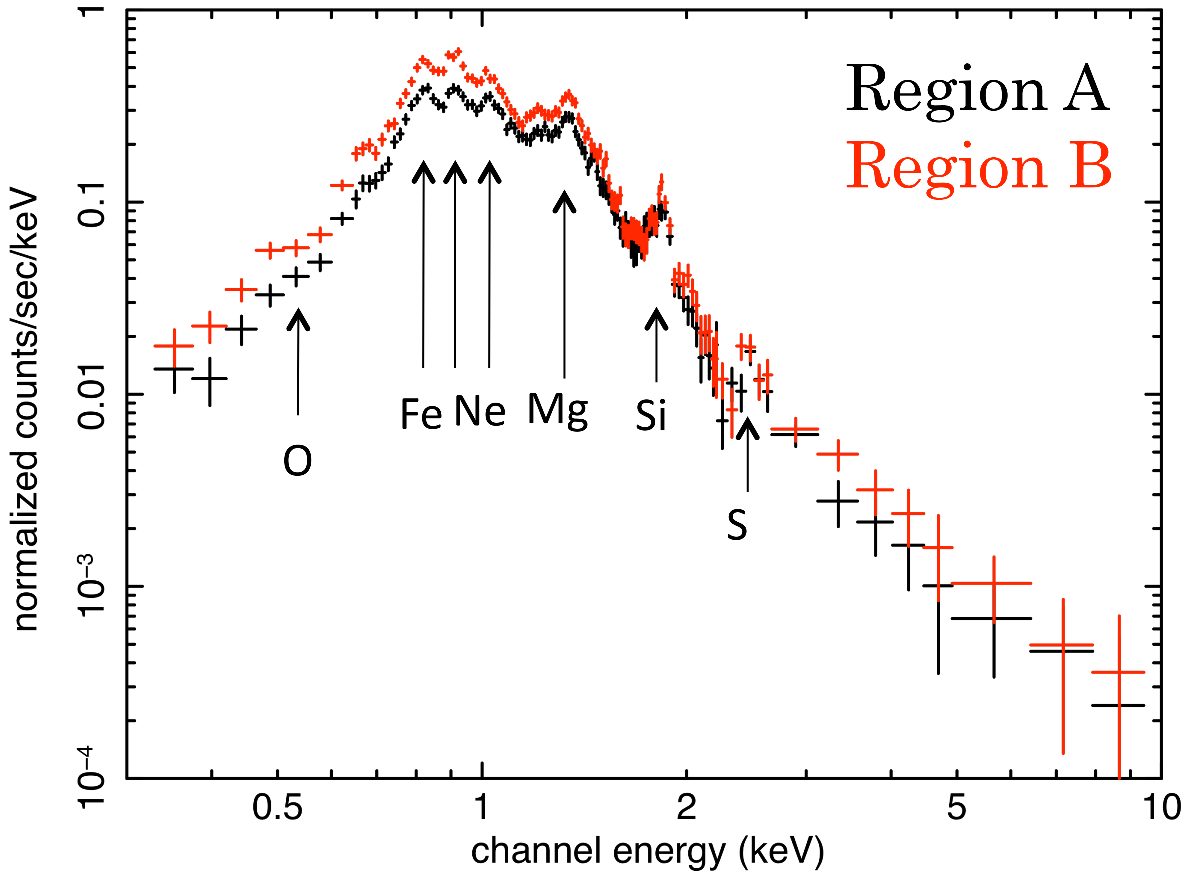


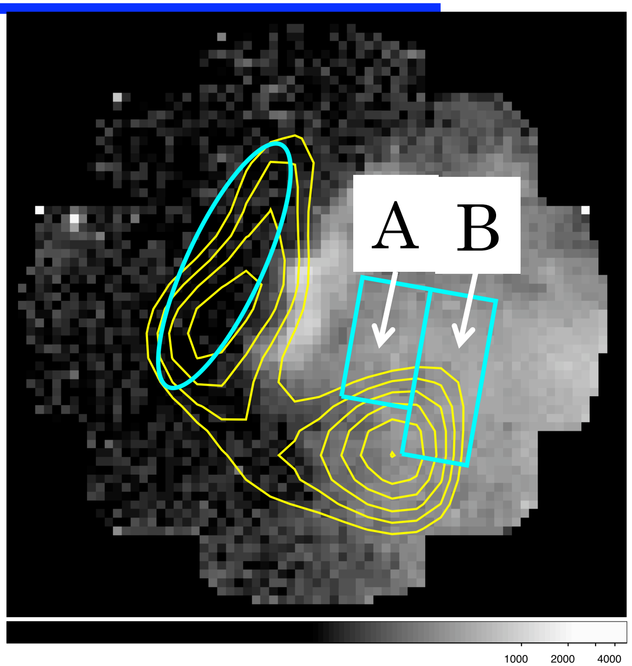
Power-law model fitting

Photon index was fixed of 2.66(from TeV γ-ray spectrum)

2- 10 keV Flux $\leq 2.1 \times 10^{-14}$ ergs/cm^{2}s

2. Non-thermal X-ray emission





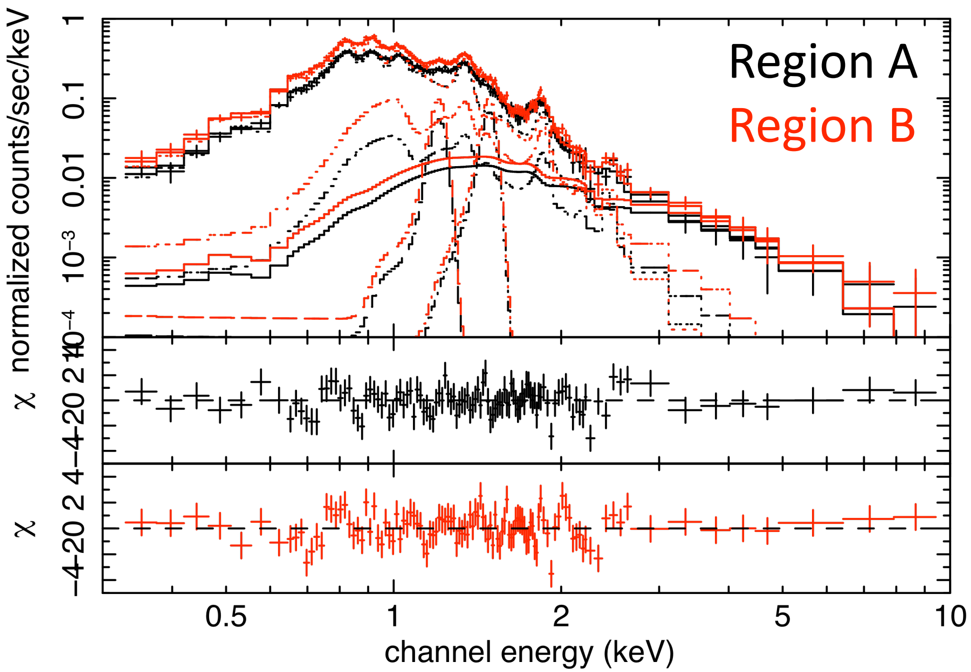
2 temperature NEI model

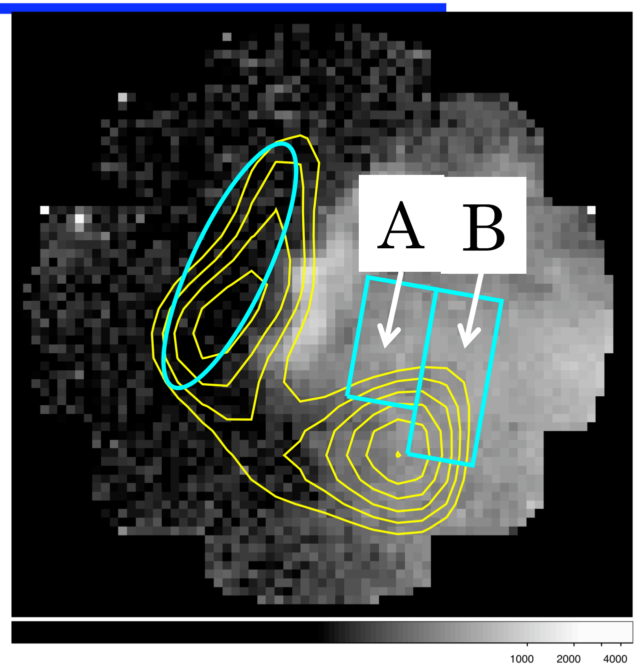
(non-equilibrium ionization collisional plasma model)

+

Power-law model

2. Non-thermal X-ray emission





2 NEI + Power-law model

	Region A + B
kT_1	~ 0.3 keV
kT_2	~ 0.9 keV
Electron density	~ 1 /cm^3
Photon index	2.4 (2.1-2.8)
2-10 keV Flux	5.8 (4.2-7.0) x 10^{-13} erg/cm^2s
χ^2 / d.o.f	507/519 (0.98)

Thermal emission

Non-thermal emission

Discussion (1. TeV γ-ray region)

2- 10 keV Flux $\leq 2.1 \times 10^{-14}$ ergs/cm^{2}s

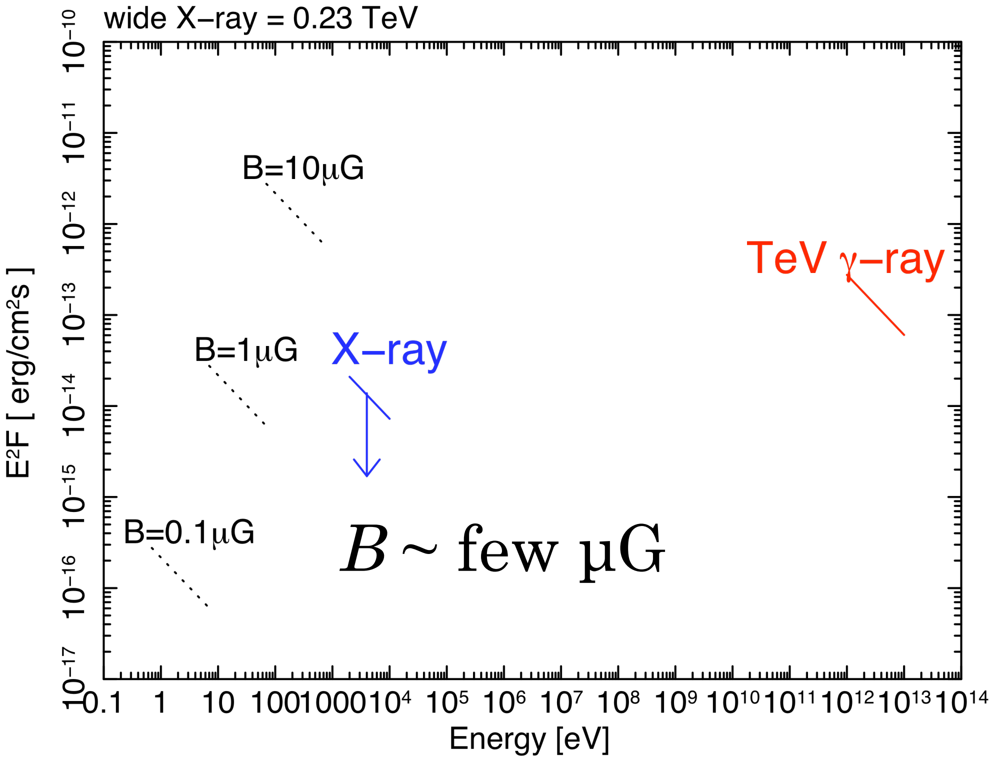
1-Zone Inverse Compton (IC)

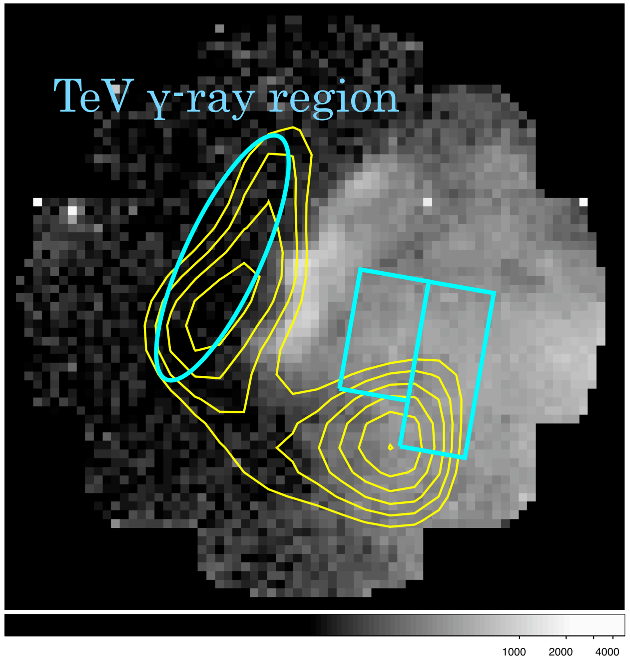
$$\varepsilon \approx 0.07\left(\frac{E}{1TeV}\right)\left(\frac{B}{10\mu G}\right)$$

$$f_X \approx 10 f_{TeV}\left(\frac{B}{10\mu G}\right)^2$$

ε : Synchrotron photon energy [keV]

E : IC energy [TeV]





Consistency of TeV γ-ray and MC

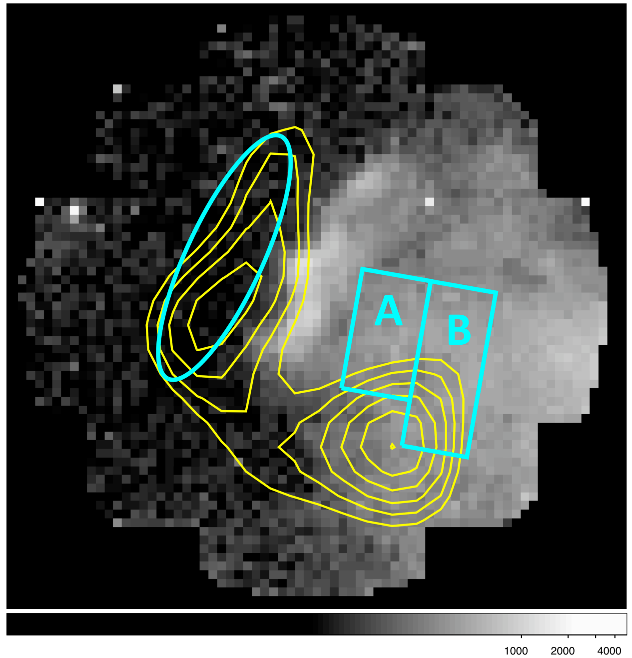
Low brightness in X-ray

→π_0-decay by high energy proton

Discussion (2.Non-thermal X-ray emission)

<u>Non-thermal emission was discovered from inner region</u>

What is the emission mechanism?



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  - ➢Primary
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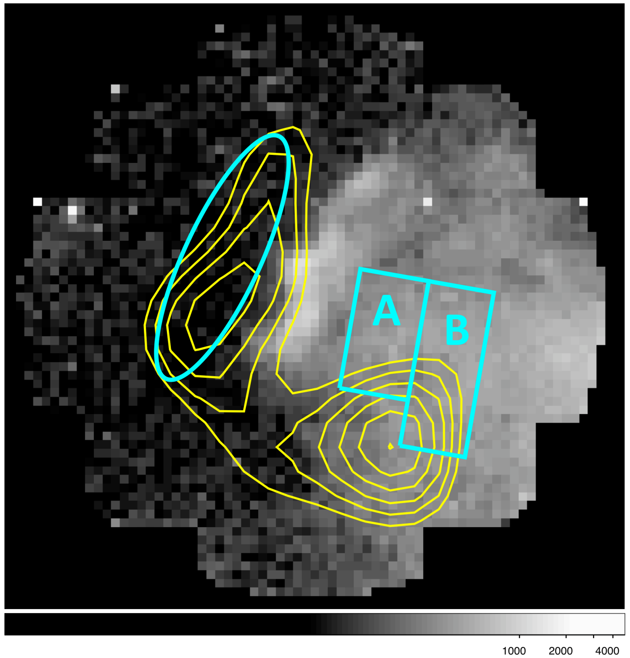

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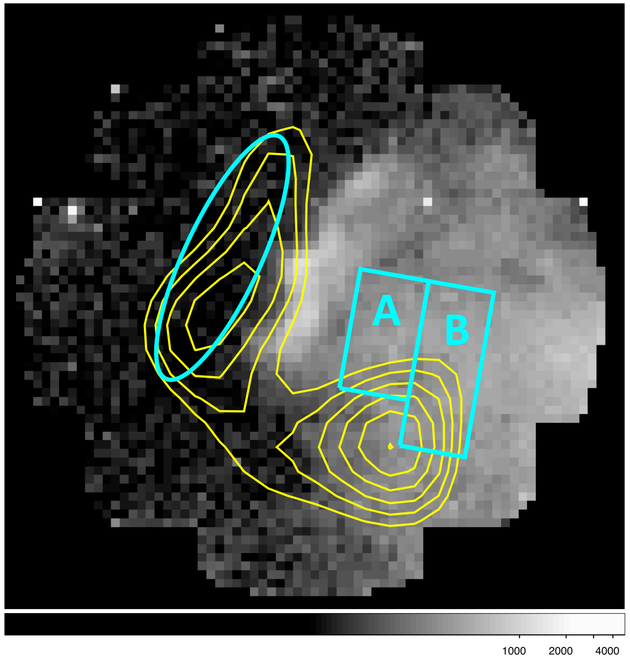

What is the emission mechanism?

- Synchrotron X-ray
  - Primary
  - ~~Secondary~~
    ~~produced by the decay of π_0 mesons~~

Unlikely because of the discrepancy of region between non-thermal X-ray and TeV γ-ray emission.

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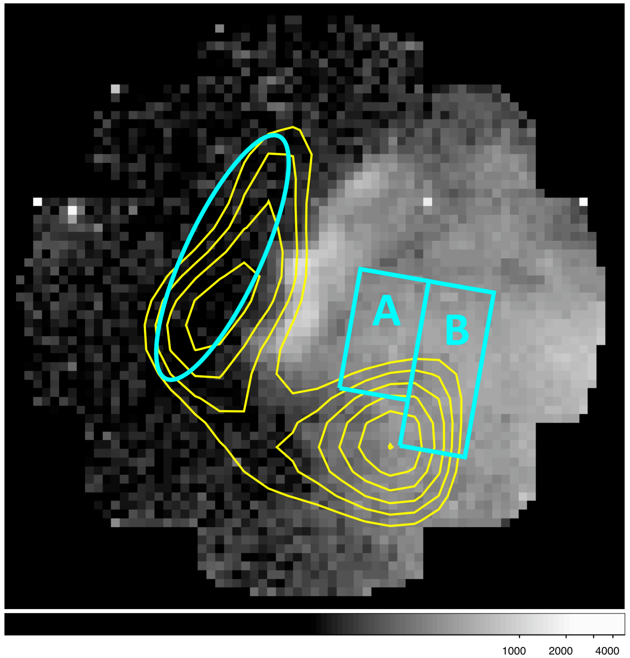

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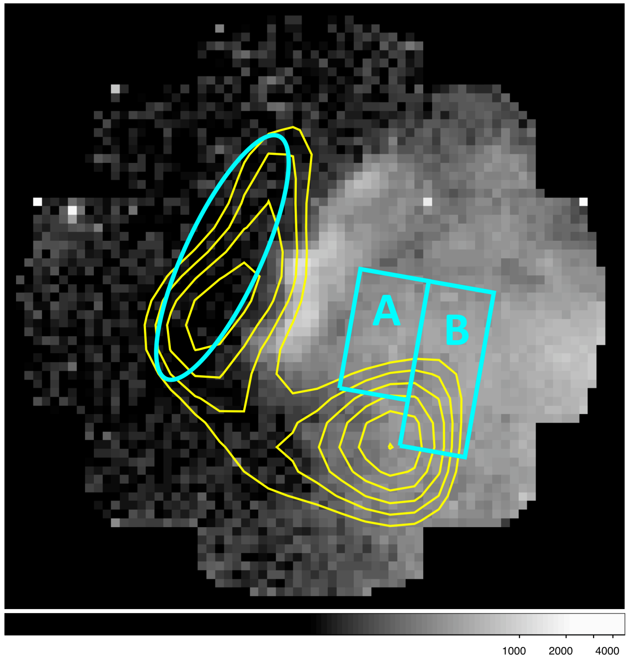

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Discussion (Synchrotron X-ray)

Power of synchrotron X-ray

$$P = \frac{4}{3}\sigma_T c\beta^2\gamma^2 \frac{B^2}{8\pi}$$

$$\approx 1.6\times 10^{-3} E_e{}^2 B^2 \text{[ergs/sec]}$$

Cooling time t_{cool}

$$t_{\text{cool}} = \frac{E_e}{P} = 6.3\times 10^2 E_e{}^{-1}B^{-2}\text{[sec]}$$

Synchrotron photon energy ε

$$\varepsilon \approx 1.2\times 10^{-4}\left(\frac{B}{1\mu G}\right)\left(\frac{E_e}{1TeV}\right)^2 \text{[keV]}$$

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$B = 1\mu\mathrm{G}$

$\varepsilon = 1\mathrm{keV}$

$t_{\mathrm{cool}} = 4.7 \times 10^4$ [yr]

Consistent with few μG magnetic field

$B \approx$ few μG OK

Discussion (Non-thermal Bremss)

Photon spectrum $N_{\text{theory}}(\varepsilon)$

$$N_{\text{theory}}(\varepsilon) = 1.47\times10^{-17} Z^2 \frac{(p-2)}{(p-1)} \frac{n_{\text{p}}}{E_{\text{min}}^{\,2-p} - E_{\text{max}}^{\,2-p}} \ln\left(\frac{192}{Z^{\frac{1}{3}}}\right) \rho_{\text{e}}^{\text{NT}} \varepsilon^{-p}$$

[ph / cm³ s erg]

ε : Photon energy
p : Electron nuber index
n_{p} : Proton density
$E_{\text{min / max}}$: Electron minimum / maximum energy
$\rho_{\text{e}}^{\text{NT}}$: Non-thermal electron energy density (Logner 1992)

Observed spectrum $N_{\text{observe}}(\varepsilon)$

$$N_{\text{observed}}(\varepsilon) = \frac{Flux_{2\text{–}10\text{keV}} \times (p-2)}{2^{2-p} - 10^{2-p}} \frac{4\pi d^2}{V} \varepsilon^{-p}$$

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$p = 2.4$
$Flux = 5.8 \times 10^{-13}$ [erg/cm²s]
$n_{\rm p} = 1$ [cm⁻³]
$E_{\rm min} = 1$ [keV]
$V = 10^{58}$ [cm³]

$$\rho_{\rm e}{}^{\rm NT} = 1.4\times10^{-9} [{\rm erg/cm^3}]$$

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$$\rho_{\mathrm{e}}^{\mathrm{NT}} = 1.4 \times 10^{-9} [\mathrm{erg/cm^3}]$$

Thermal electron energy density $\rho_{\mathrm{e}}^{\mathrm{T}} = 3/2 n_{\mathrm{e}} \mathrm{k} T_{\mathrm{e}} = 1.2 \times 10^{-9}$ [erg/cm^3]

Discussion (Non-thermal Bremss)

Photon spectrum $N_{\mathrm{theory}}(\varepsilon)$

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n_{p} : Proton density
$E_{\mathrm{min/max}}$: Electron minimum / maximum energy
$\rho_{\mathrm{e}}{}^{\mathrm{NT}}$: Non-thermal electron energy density (Logner 1992)

Observed spectrum $N_{\mathrm{observe}}(\varepsilon)$

$$N_{\mathrm{observed}}(\varepsilon) = \frac{Flux_{2-10\mathrm{keV}} \times (p-2)}{2^{2-p} - 10^{2-p}} \frac{4\pi d^2}{V} \varepsilon^{-p}$$

[ph / cm² s erg]

$p = 2.4$
$Flux = 5.8 \times 10^{-13}$ [erg/cm²s]
$n_{\mathrm{p}} = 1$ [cm⁻³]
$E_{\mathrm{min}} = 1$ [keV]
$V = 10^{58}$ [cm³]

$$\rho_{\mathrm{e}}{}^{\mathrm{NT}} = 1.4 \times 10^{-9} [\mathrm{erg/cm^3}]$$

same

Thermal electron energy density $\rho_{\mathrm{e}}{}^{\mathrm{T}} = 3/2 n_{\mathrm{e}} \mathrm{k} T_{\mathrm{e}} = 1.2 \times 10^{-9}$ [erg/cm³]

Discussion (Non-thermal Bremss)

Photon spectrum $N_{\mathrm{theory}}(\varepsilon)$

$$N_{\mathrm{theory}}(\varepsilon) = 1.47 \times 10^{-17} Z^2 \frac{(p-2)}{(p-1)} \frac{n_{\mathrm{p}}}{E_{\mathrm{min}}^{\;2-p} - E_{\mathrm{max}}^{\;2-p}} \ln\left(\frac{192}{Z^{\frac{1}{3}}}\right) \rho_{\mathrm{e}}^{\mathrm{NT}} \varepsilon^{-p}$$

[ph / cm³ s erg]

ε : Photon energy
p : Electron nuber index
n_{p} : Proton density
$E_{\mathrm{min\,/\,max}}$: Electron minimum / maximum energy
$\rho_{\mathrm{e}}^{\mathrm{NT}}$: Non-thermal electron energy density (Logner 1992)

Observed spectrum $N_{\mathrm{observe}}(\varepsilon)$

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same

Thermal electron energy density $\rho_{\mathrm{e}}^{\mathrm{T}} = 3/2 n_{\mathrm{e}} k T_{\mathrm{e}} = 1.2 \times 10^{-9}$ [erg/cm³]

Typical SNR $\rho_{\mathrm{e}}^{\mathrm{NT}} \approx \frac{1}{100} \rho_{\mathrm{e}}^{\mathrm{T}}$

$\rho_{\mathrm{e}}^{\mathrm{NT}}$ is large → Unlikely

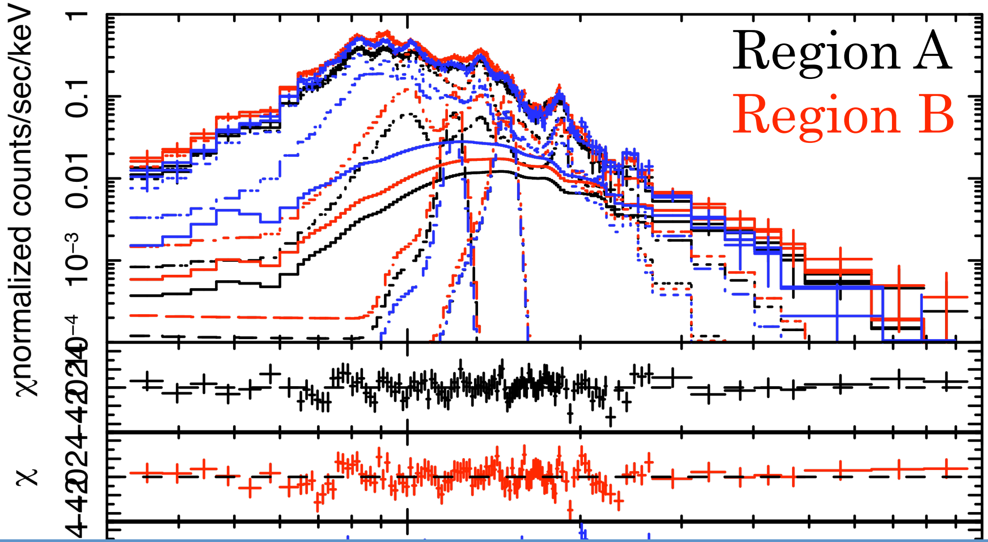
Conclusion

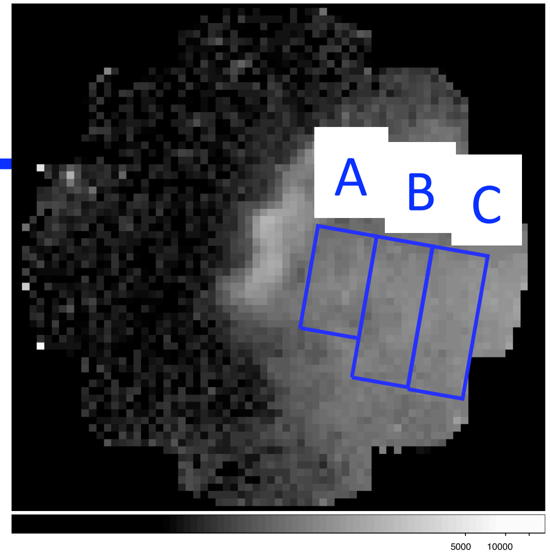
- XMM-Newton observed northeast of W28
- The shape of the bright shell in X-ray coincide with OH masers and the molecular cloud
- TeV γ-ray and MC are also coincident.
- We analyzed the spectra of inner and TeV γ-ray region.

- The 2-10 keV upper limit flux of TeV γ-ray region can be determined to be 2.1×10^{-14} ergs/cm^{2}s
- TeV γ-ray is probably due to π_0-decay by high energy protons.
- We discovered non-thermal emission from inner region with the photon index of 2.4.
- This non-thermal emission is likely a synchrotron X-ray emission.

ここまで

Inner region





3VNEI

2VNEI + Power-law

	Region A	Region B
kT [keV]	3.7 (2.8-5.0)	4.3 (2.5-6.6)
Fe	8.0E-11 (<0.49)	1.5E-04 (<0.46)
χ^2 / d.o.f	230/259 (0.89)	267/259 (1.03)
Γ	2.4 (1.7–2.9)	2.4 (1.7-2.7)
2-10 keV Flux [10^{-13} erg/cm^{2}s]	2.0 (1.3-2.7)	3.7 (2.8-4.8)
χ^2 / d.o.f	234/259 (0.90)	273/259 (1.05)

→ Too high temp. for old SNR

Non-thermal emission

Discussion (Non-thermal Bremss)

Emissivity of photon J

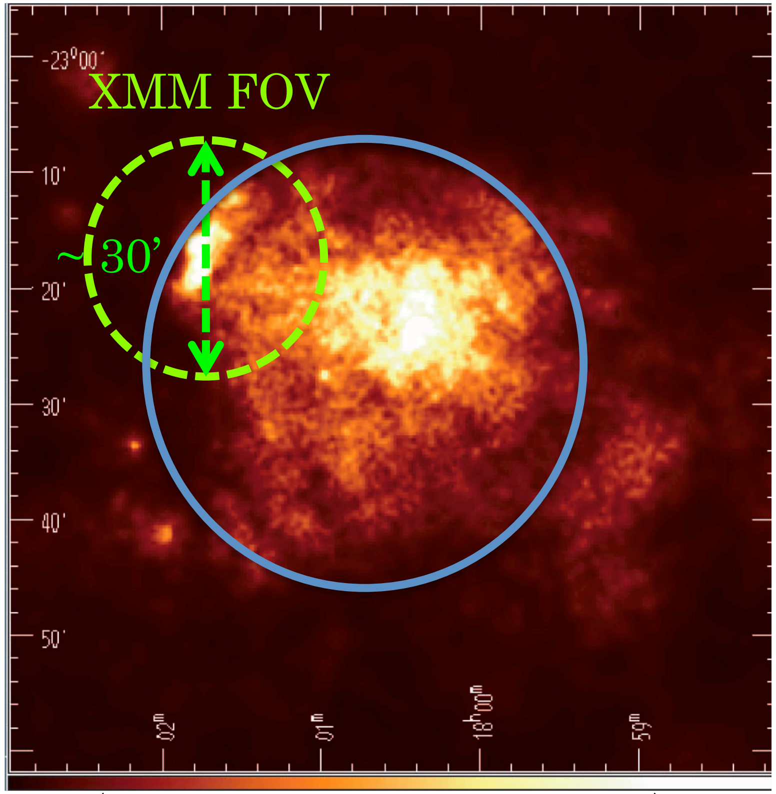
$$J = 1.47 \times 10^{-17} Z^2 \frac{(p-2)}{(p-1)^2} \frac{\varepsilon^{1-p}}{E_{\mathrm{min}}{}^{2-p} - E_{\mathrm{max}}{}^{2-p}} \ln\left(\frac{192}{Z^{\frac{1}{3}}}\right) n_{\mathrm{p}} \rho_{\mathrm{e}}{}^{\mathrm{NT}}$$

[ph / cm^3 s]

p : Electron nuber index
ε : Photon energy
$E_{\mathrm{min/max}}$: Electron minimum / maximum energy
n_{p} : Proton density
$\rho_{\mathrm{e}}{}^{\mathrm{NT}}$: Non-thermal electron energy density (Logner 1992)

Target：W28

X-ray image (ROSAT 0.5-2.4 k

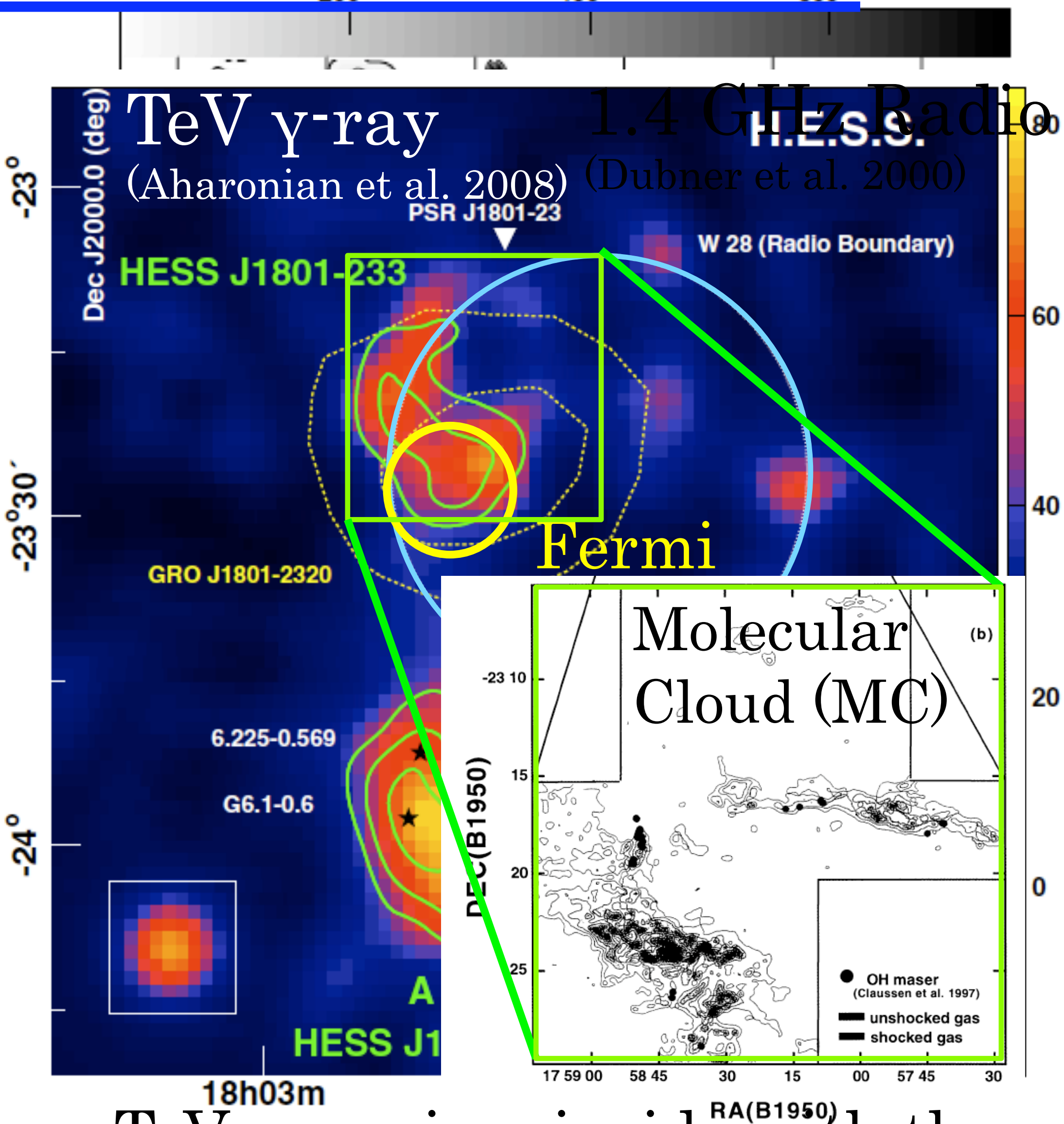


(Ryo and Borkowski 2002)

X-ray：Center Filled

Radio：shell

52ksec observation (2002, 2003)



TeV γ-ray is coincide with the molecular cloud

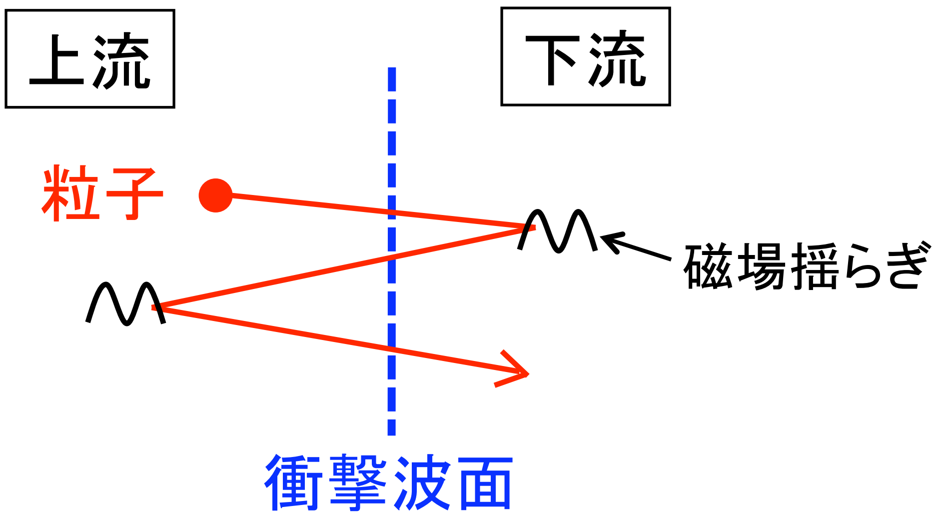
宇宙線とは

宇宙線 : 宇宙を飛び交う高エネルギー粒子

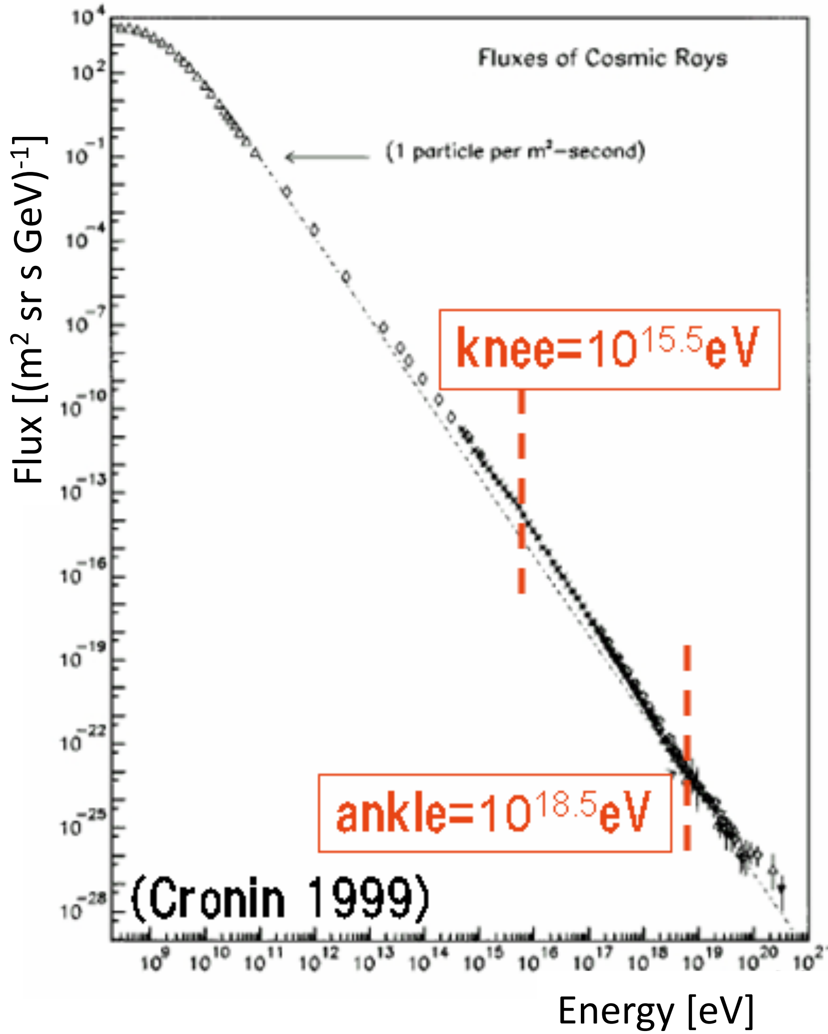
エネルギー密度 ~ 1 eV/cc

加速機構
加速現場 } まだわかっていない

→Diffusive shock acceleration



衝撃波面を往復することでエネルギーを得る。



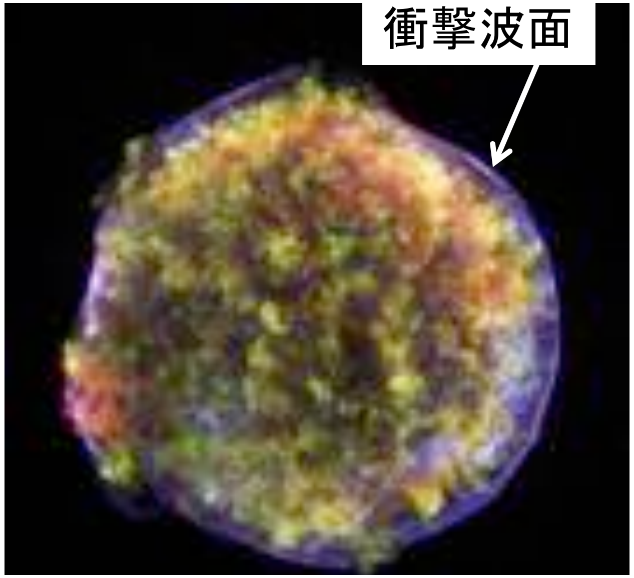
超新星残骸

超新星残骸(SNR) : 最も有力な宇宙線加速現場候補

- 星が一生の最後に起こす超新星爆発によってできる
- 爆発による噴出物が外に広がる
- 衝撃波が形成される

knee energy (10^{15} eV) までの宇宙線は
超新星残骸衝撃波面で加速

今見つかっている宇宙線加速源
我々の銀河系で～ 10 / 270



Tycho SNR X-ray image
detected with *Chandra*

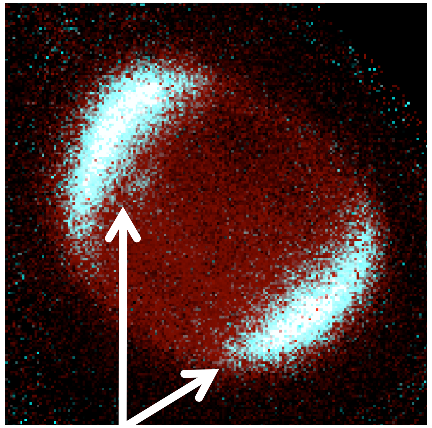
X線、TeV γ線によるSNRの観測

衝撃波が噴出物、星間物質を加熱
～1.0 x 10^6 K (～ 0.1 keV)

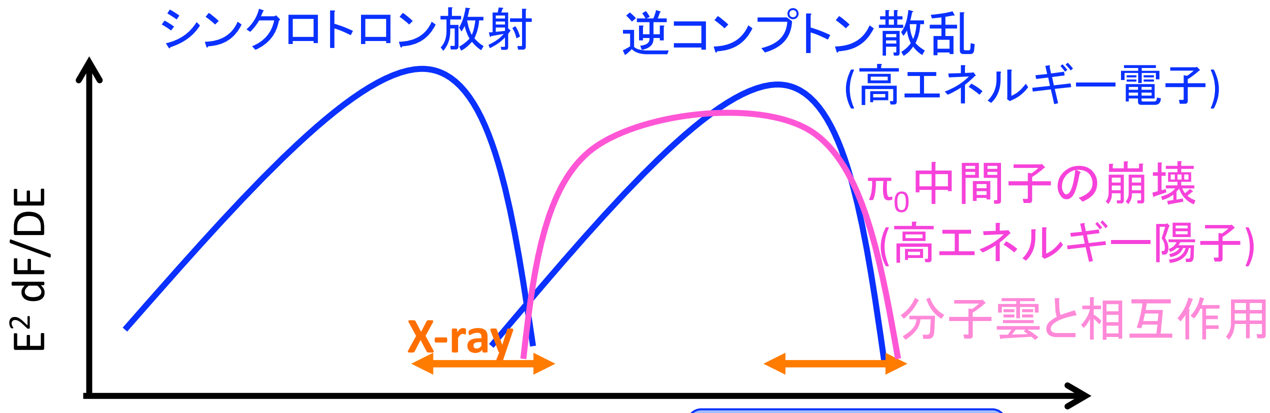
⇒ **熱的X線放射**
(line + thermal bremss)

SNRの環境、状態 (年齢、電子密度、爆発の型など)

SN1006 (X-ray)



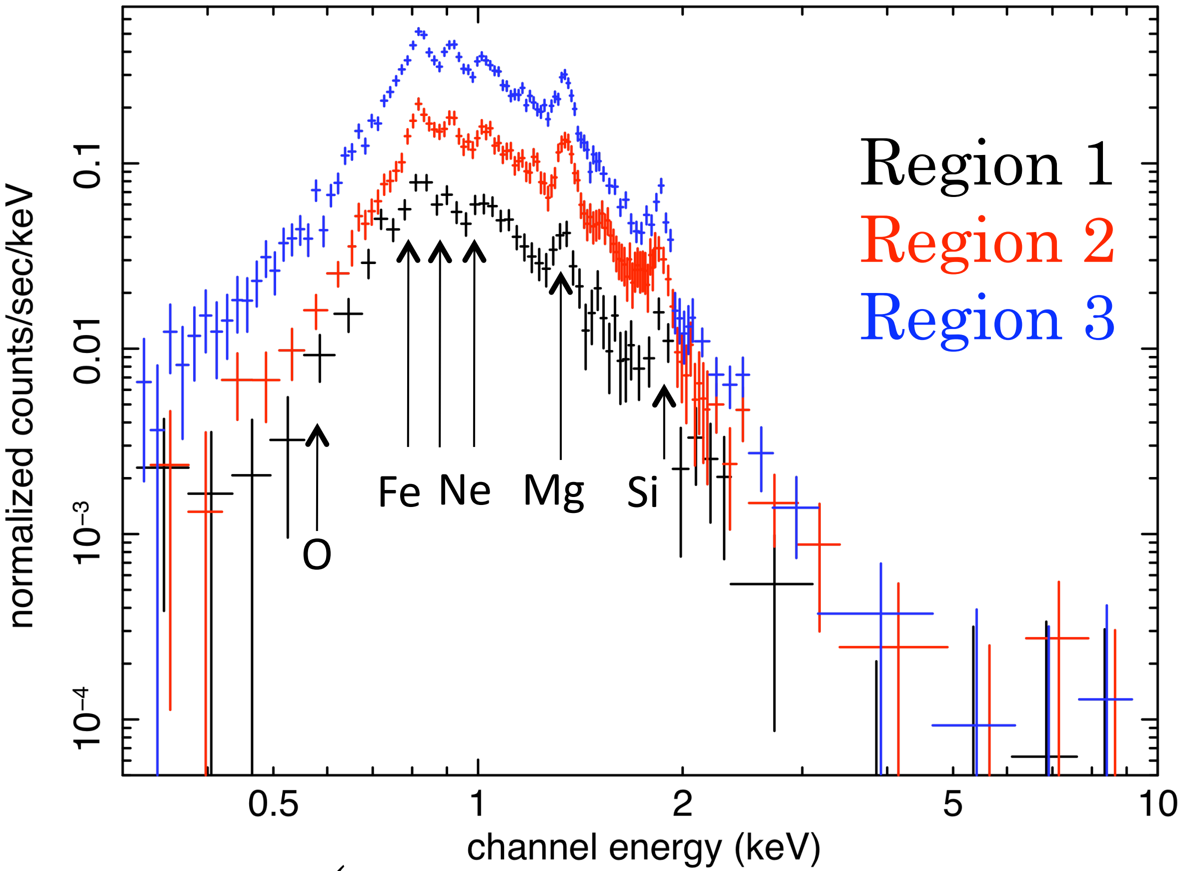
高エネルギー電子による
シンクロトロンX線放射
(Koyama et al. 1995)

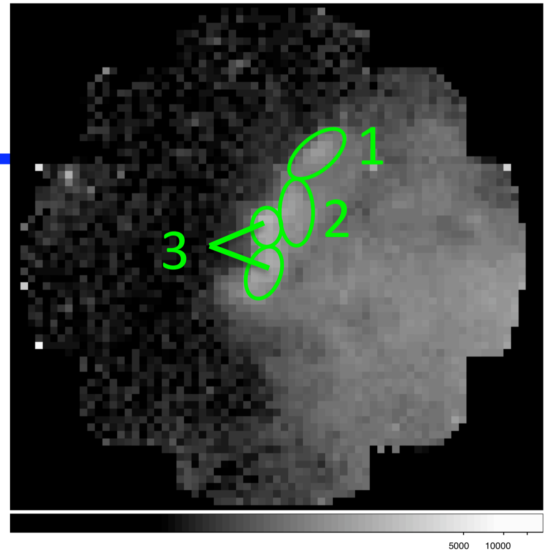


TeV γ線放射

宇宙線加速機構の解明
（電子の最高エネルギー、磁場など)

Shell region





NEI Model (non-equilibrium ionization collisional plasma model)

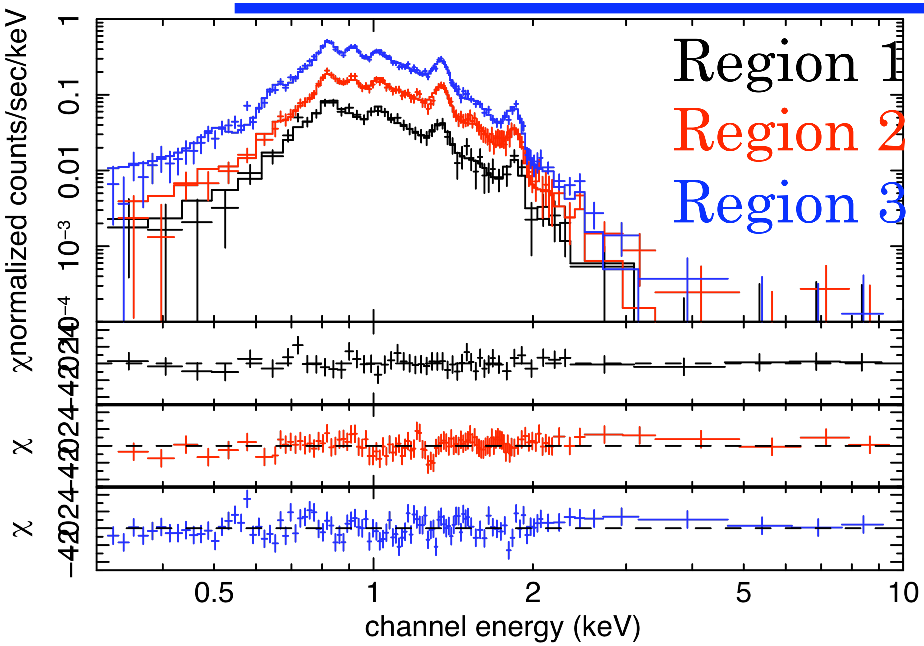
→Ionization parameter $n_e t \sim 10^{13}$ s/cm^3 →Ionization equilibrium

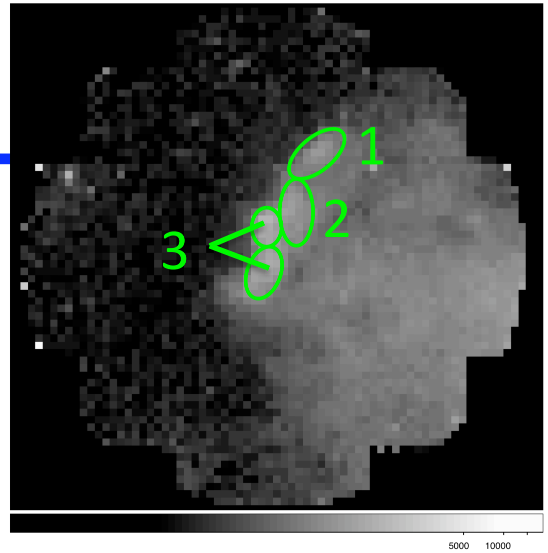
APEC Model (ionized thin-thermal plasma model)

Abundance：Anders & Grevesse, 1989

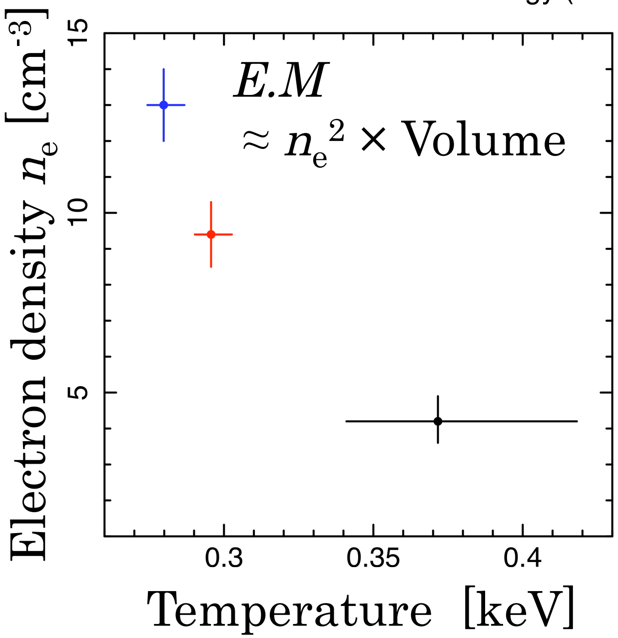
O, Ne, Mg, Si, Fe set to free, others are set to solar abundances.vv

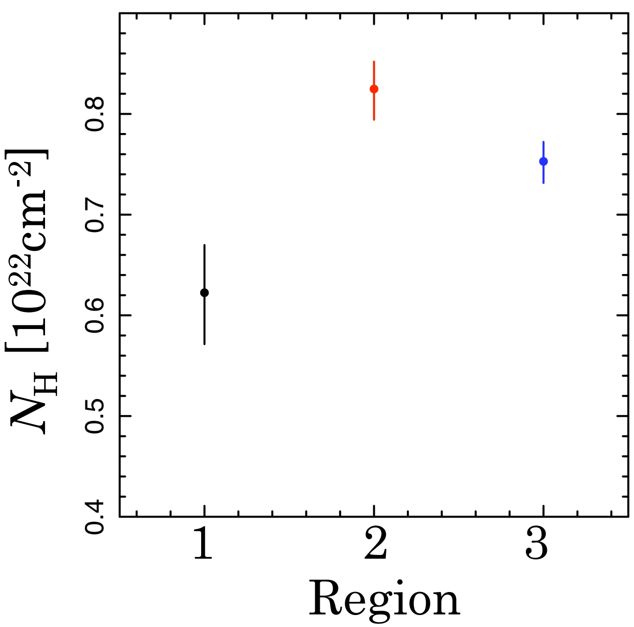
Shell region

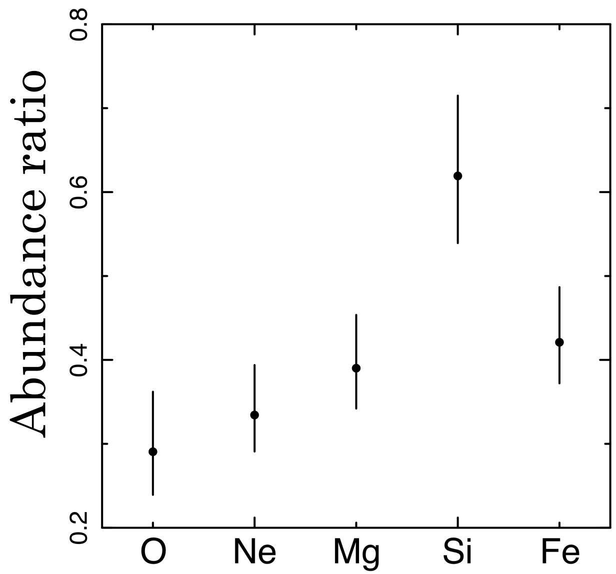




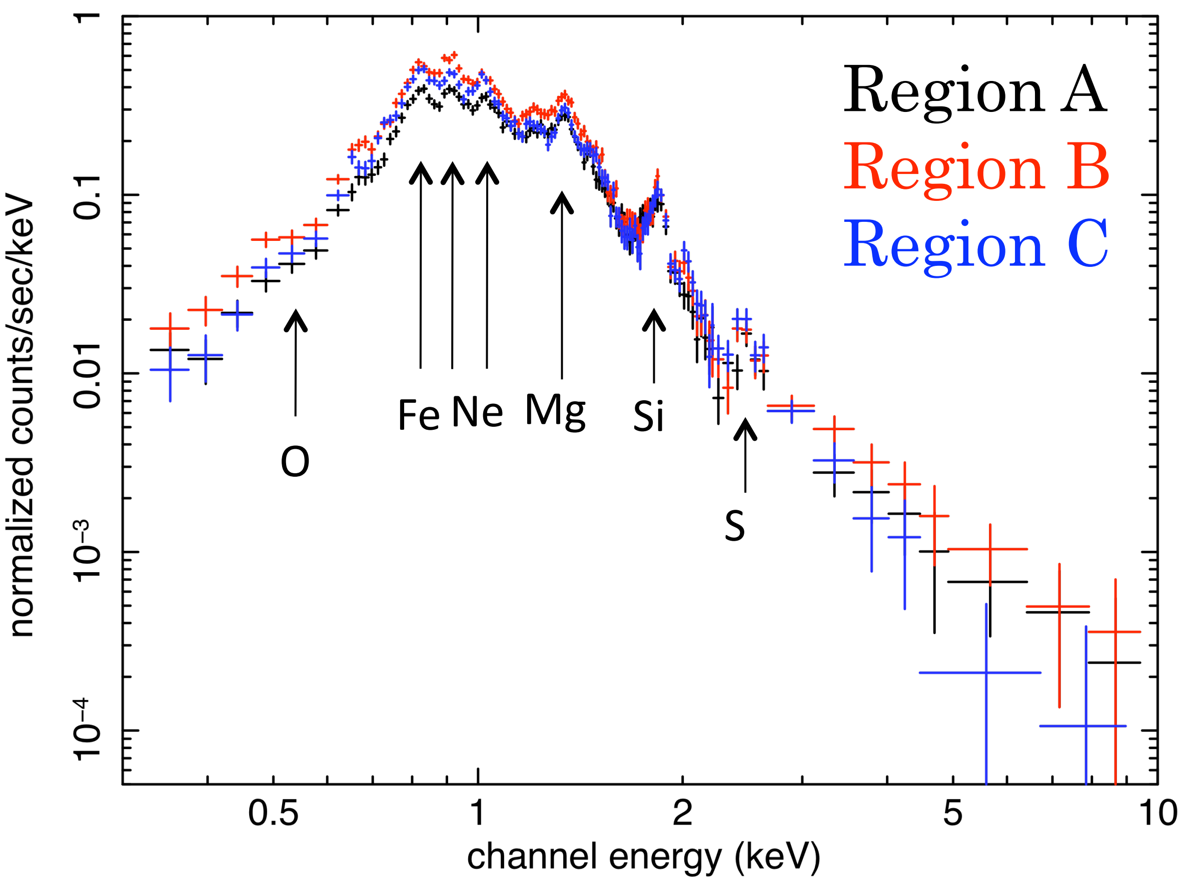
1 temperature VAPEC Model

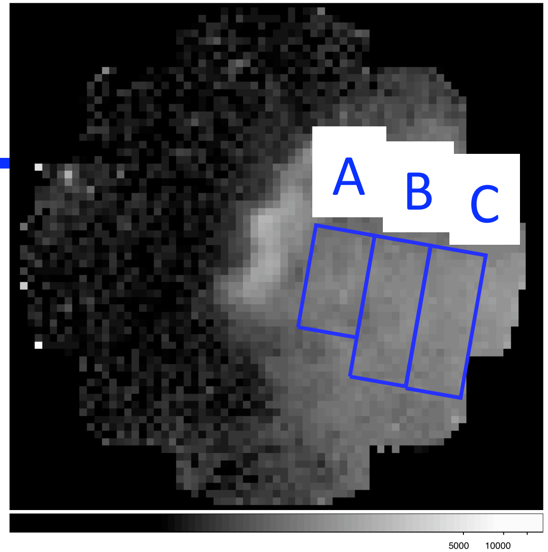






Inner region





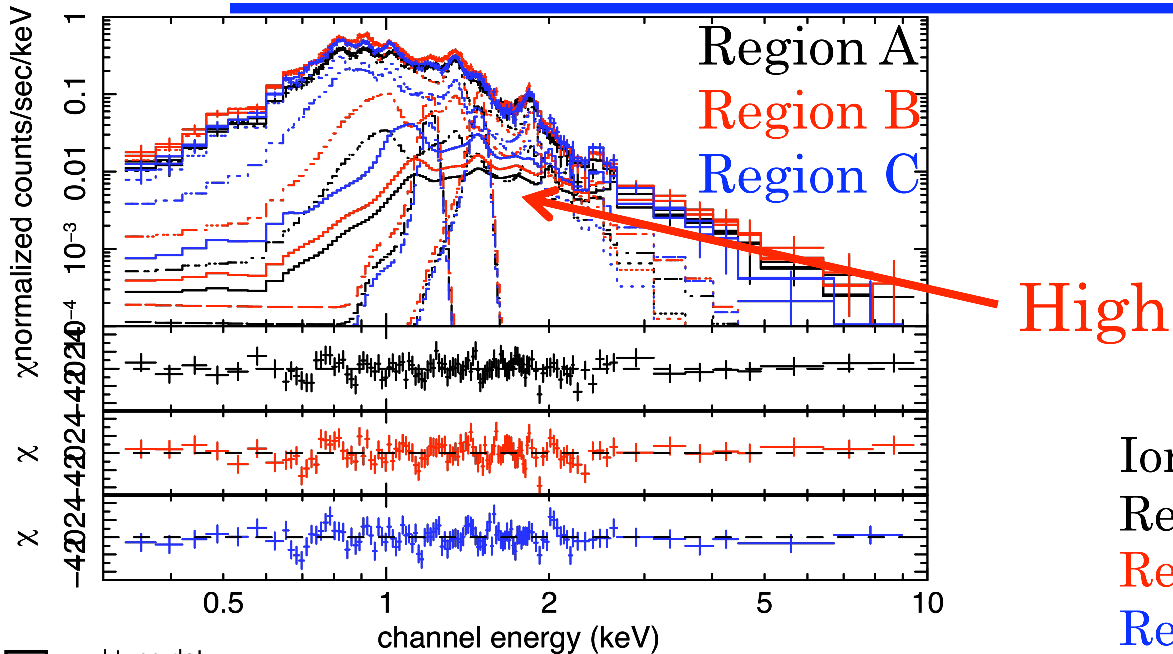
3 temperature NEI model

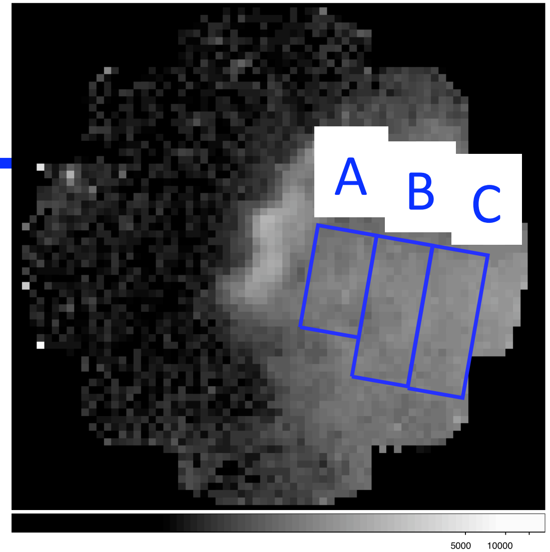
(non-equilibrium ionization collisional plasma model)

Abundance：Anders & Grevesse, 1989

O, Ne, Mg, Si, S, Fe are set to free, others are fixed as solar.

Inner region



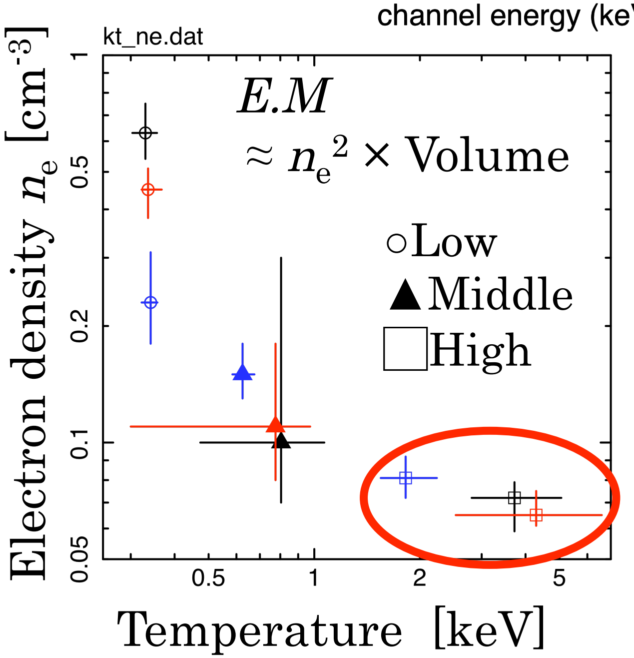


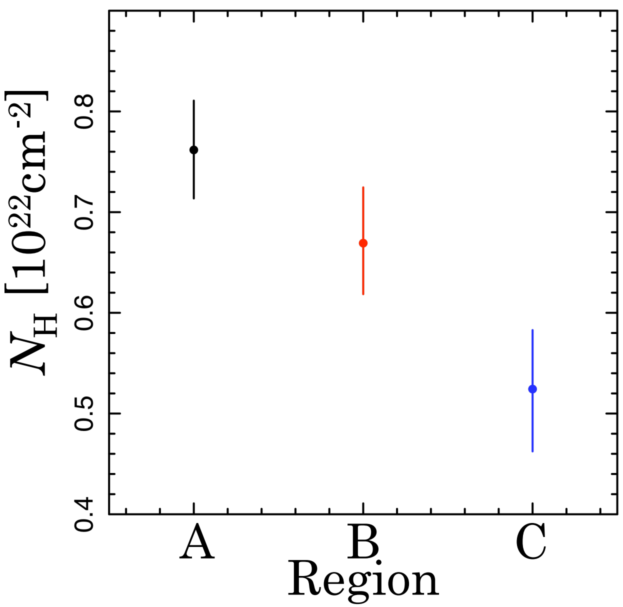
Ionization parameter $n_e t$

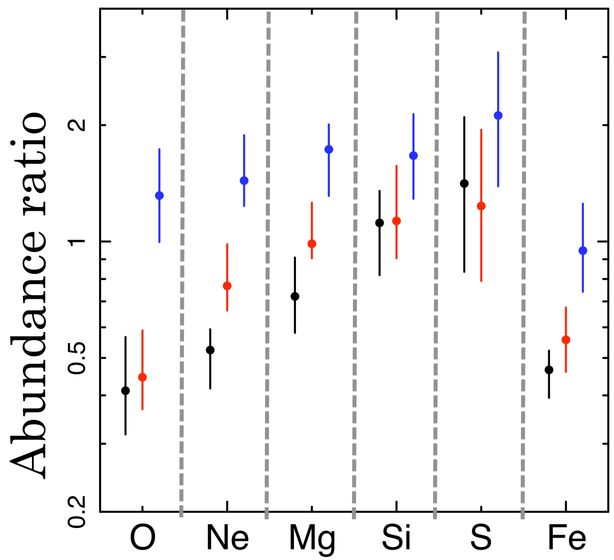
Region A : 3.9 (2.6-6.5) × 10^{11} s/cm^3

Region B : 3.0 (2.0-5.0) × 10^{11} s/cm^3

Region C : 93 (>3.8) × 10^{11} s/cm^3

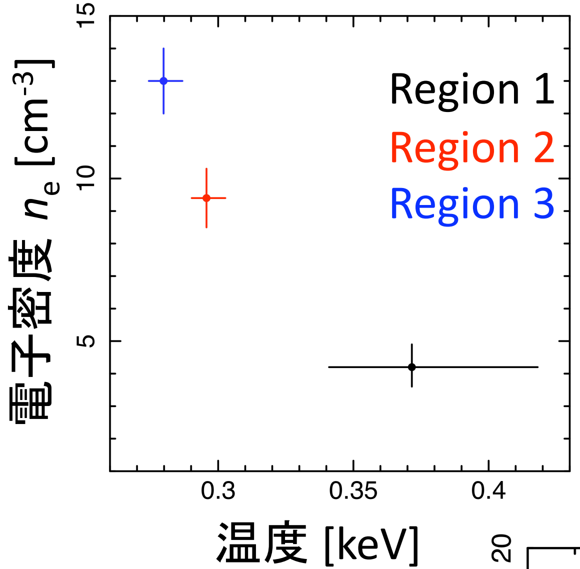




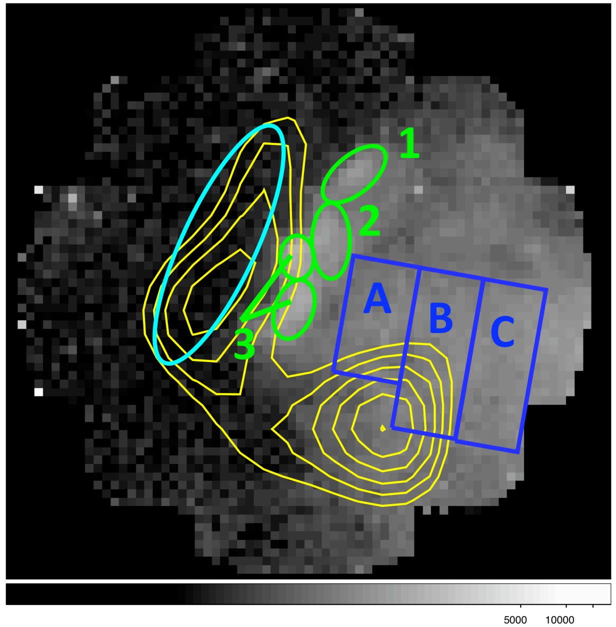


Discussion (熱的X線放射)

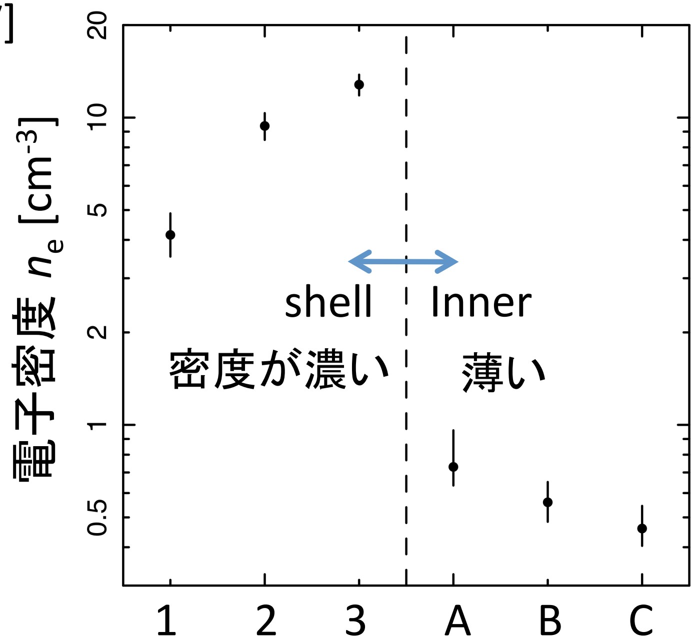
Shell region



分子雲・OHメーザーに近いShell 2. 3→
密度の濃いガスにぶつかって衝撃波が減速、
断熱膨張で冷えている。



電子密度



Shell : 〜 10 コ/cc

Inner : < 1 コ/cc

Discussion (熱的X線放射)

領域	体積 [cm^3]	温度 [keV]	電子密度 [cm^{-3}]	質量 [$M_\odot$]	熱エネルギー [10^{48}ergs]
Region 1	1.3×10^{55}	0.37 (0.34-0.42)	4.2 (3.6-4.9)	0.04 (0.03-0.05)	0.09 (0.08-0.11)
2	1.4×10^{55}	0.30 (0.29-0.32)	9.4 (8.5-10)	0.11 (0.10-0.12)	0.18 (0.16-0.20)
3	1.7×10^{55}	0.28 (0.27-0.29)	13 (12-14)	0.17 (0.16-0.18)	0.27 (0.25-0.29)
A	3.0×10^{57}	0.33 (0.30-0.36)	0.63 (0.54-0.75)	1.5 (1.3-1.8)	2.8 (2.3-3.4)
		0.80 (0.47-1.1)	0.10 (0.07-0.30)	0.24 (0.17-0.72)	1.1 (0.6-3.3)
B	5.6×10^{57}	0.34 (0.33-0.37)	0.45 (0.38-0.51)	2.0 (1.7-2.3)	3.8 (3.2-4.4)
		0.78 (0.30-0.98)	0.11 (0.08-0.18)	0.52 (0.37-0.82)	2.2 (0.7-3.6)
C	6.0×10^{57}	0.34 (0.32-0.36)	0.23 (0.41-0.55)	1.1 (0.9-1.5)	2.1 (1.6-2.8)
		0.62 (0.58-0.67)	0.15 (0.13-0.18)	0.72 (0.61-0.88)	2.5 (2.2-2.9)
		1.8 (1.5-2.4)	0.08 (0.07-0.09)	0.39 (0.35-0.44)	4.0 (2.3-6.6)
合計	1.5×10^{58}	温度 [keV]		8.5	26
	3.0×10^{59}	0.37 (0.34-0.42)		170	520

20倍

星間空間の密度 1コ/cc → 掃き集めた質量～ 200 $M_\odot$

X線で光っているのはISM