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Observational Evidence for Magnetic Field Amplification in SN 1006

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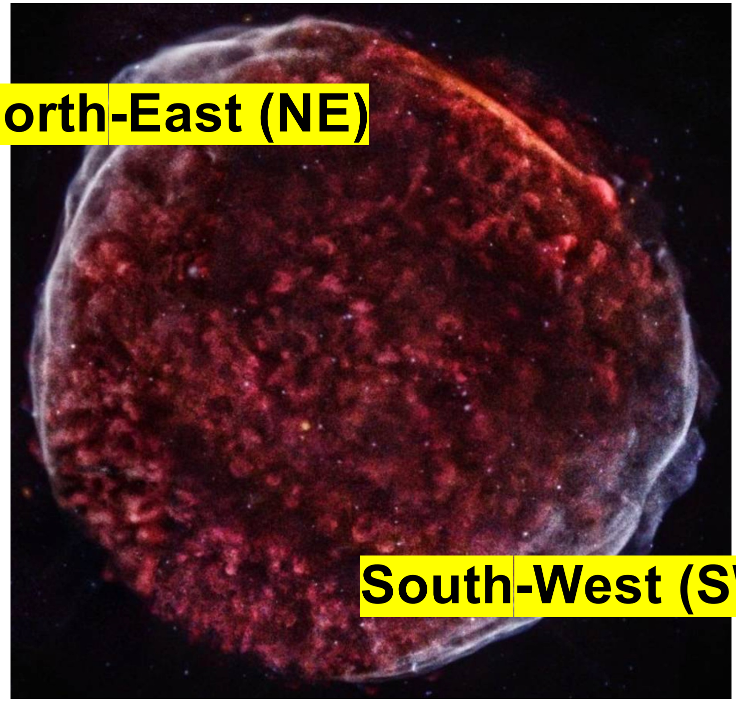
Tao et al. 2024 ApJL

Supernova remnant SN 1006



Chandra image of SN 1006 (ⒸNASA)

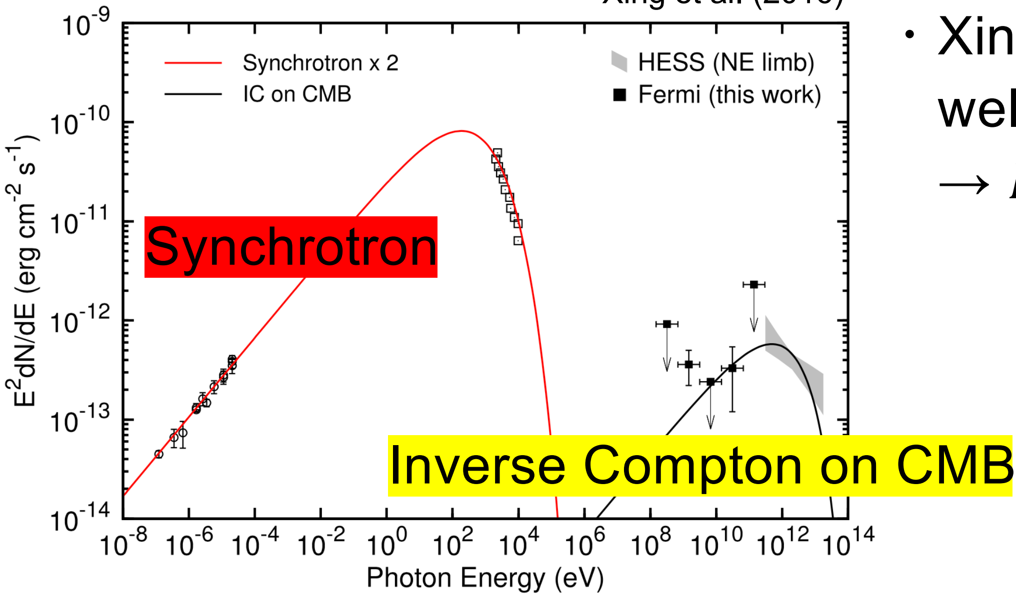
SN 1006
- Distance : 1.8 kpc
- Radius : 15 arcmin
- Type Ia

・Koyama et al. (1995) discovered synchrotron X-rays from the NE / SW shells
→ Indication of ≥ 100 TeV electrons
→ Cosmic ray accelerator

・accelerate particles up to “knee” energy at 10^{15} eV
→ strong magnetic field of ≥ $100\mu G$ are required

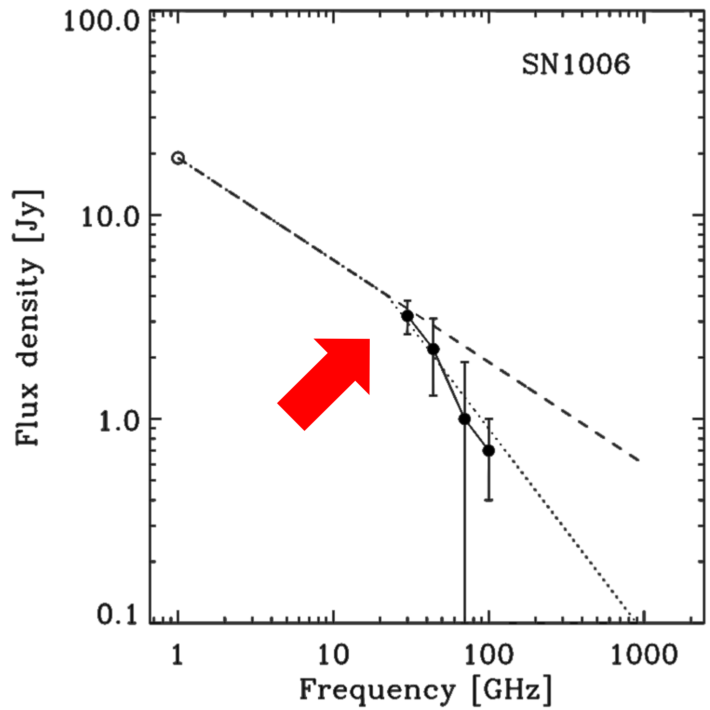
Broadband SED of SN 1006

Xing et al. (2016)



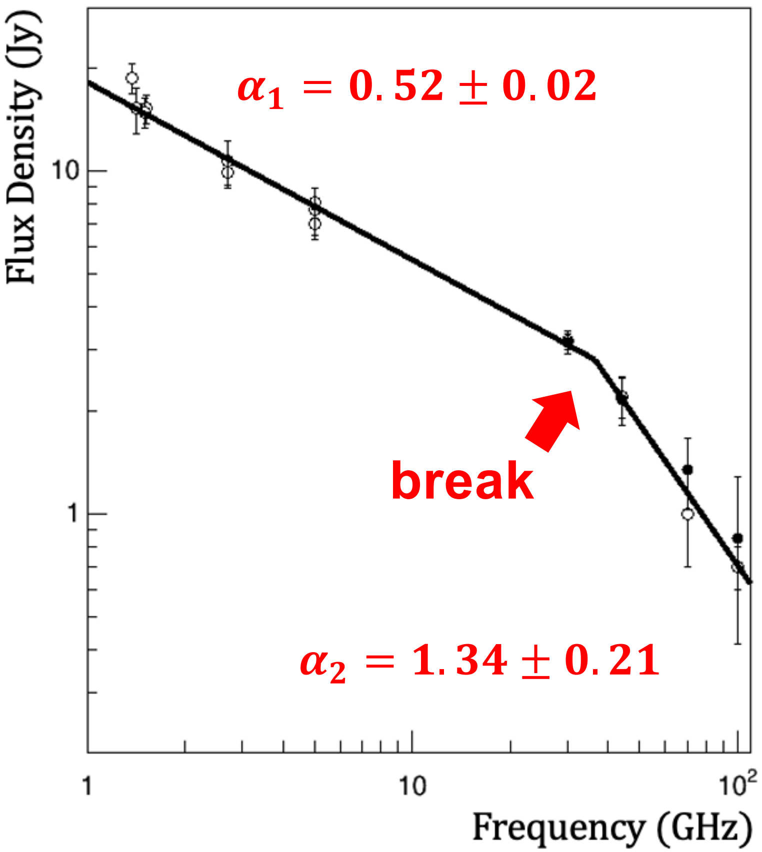
・Xing et al. (2016) suggested that the SED was well represented by one-zone leptonic model.
→ $B_{\mathrm{SED}} \approx 24\mu\mathrm{G}/30\mu\mathrm{G}$ (NE/SW)

Arnaud et al. (2016)

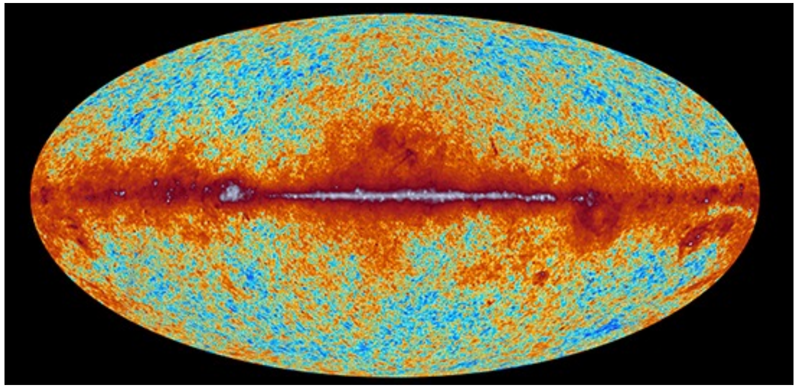


・Recent Planck observations indicated a spectral break above 10 GHz.
→ The radio-to-X-ray spectrum may not connect?

Broadband Radio Spectrum



Planck 30 GHz all sky map (ⒸESA)



Analyzed the Planck data (30, 44, 70, and 100 GHz)

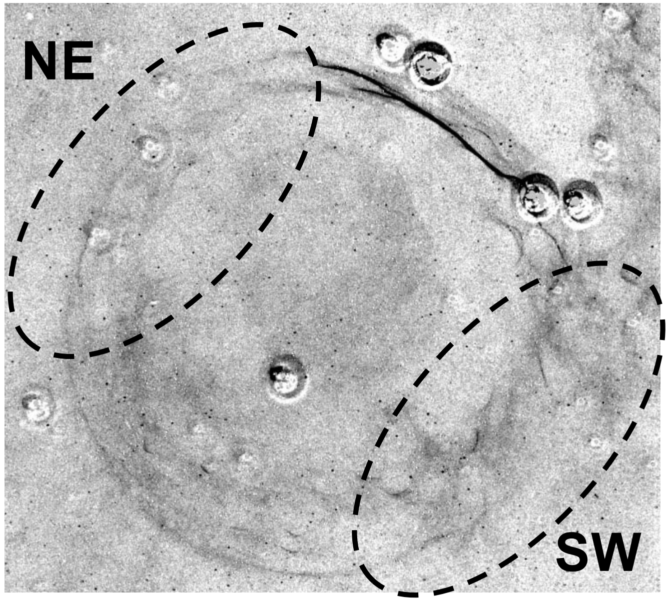
+

Archival radio flux densities

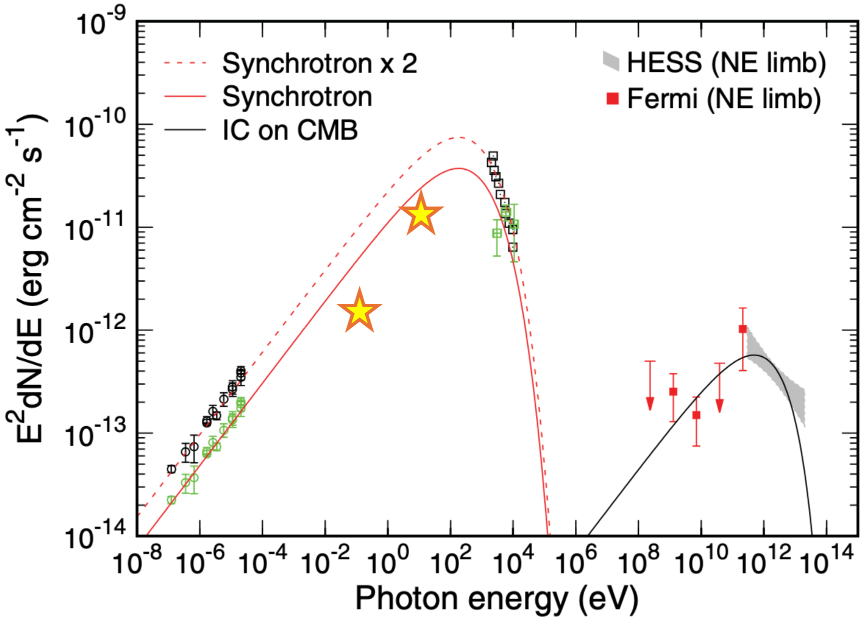
⬇

The spectrum can be well represented by a broken power law with a **break frequency $\nu_{brk} = 36 \pm 6$ GHz**.

Estimation of the Optical and UV fluxes



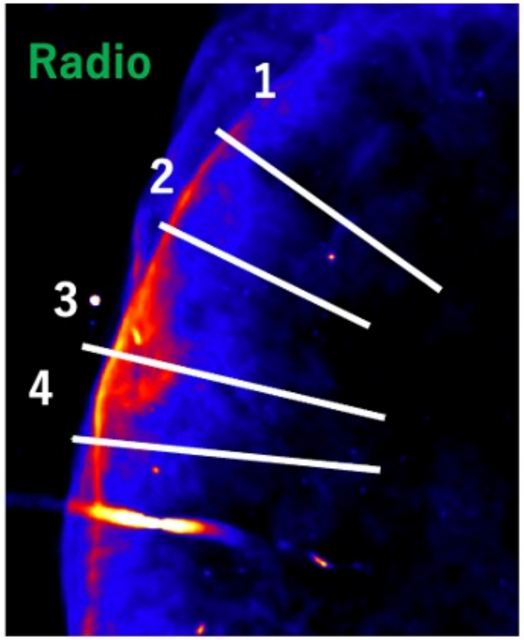
Deep H_α image of SN 1006 (Winkler et al. (2003))



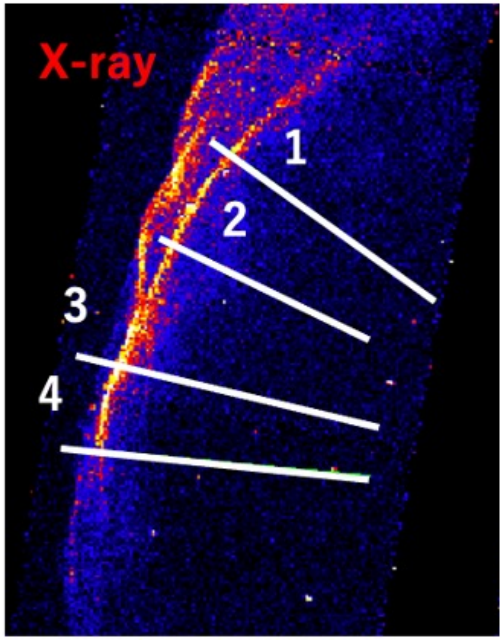
- The optical emission of SN 1006 is extremely faint except for the bright NW shell. The flux of NE would be $\approx (1.6 - 2.5) \times 10^{-12} \mathrm{erg\ cm^{-2}\ s^{-1}}$.
- The UV flux is also faint ($(1.1 - 2.2) \times 10^{-11} \mathrm{erg\ cm^{-2}\ s^{-1}}$).

→ The radio-to-X-ray spectrum may not connect?

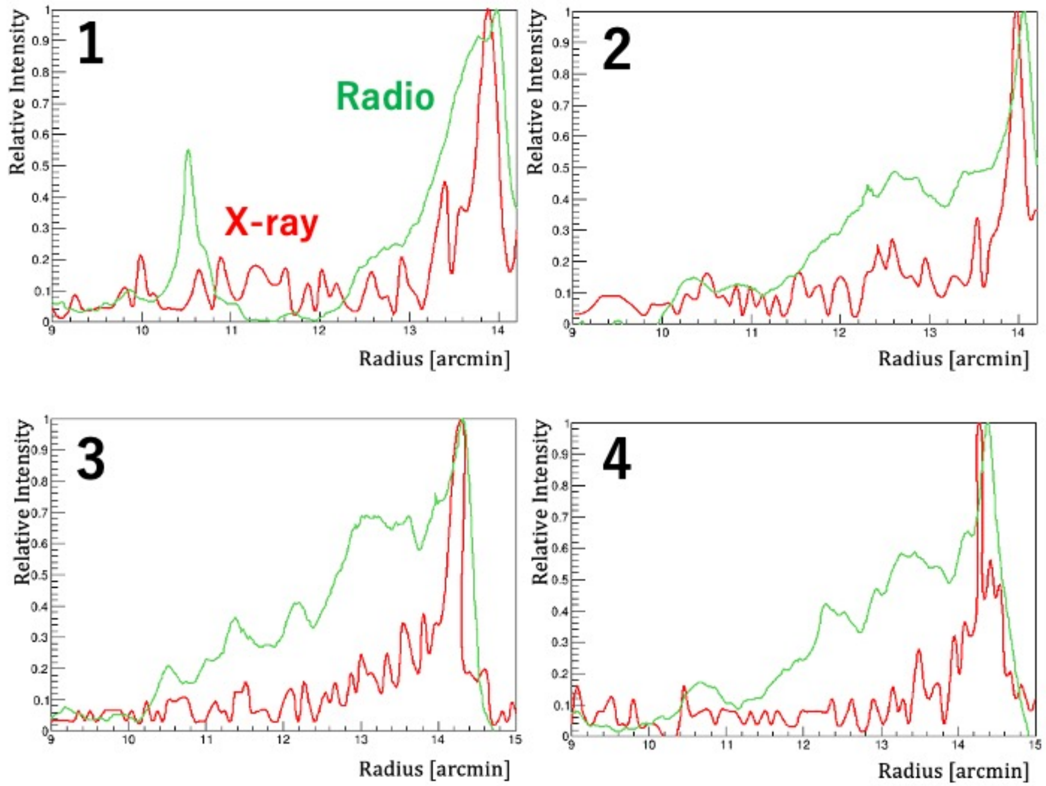
Direct Comparison of radio / X-ray shells



1335 MHz ; MeerKAT
$\Delta\theta = 8''$



2.0-7.0 keV ; Chandra
$\Delta\theta = 0.5''$



・The width of the radio shells was broader than that of the X-ray by a factor of only 3-23.

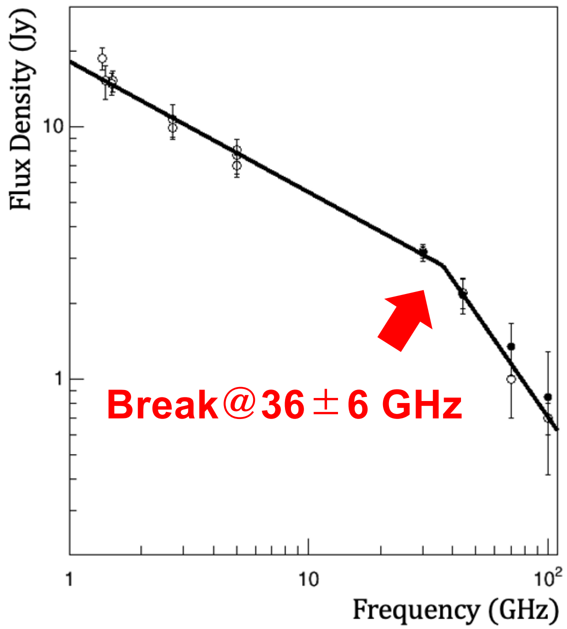
Estimation of the magnetic field strength

- The spectral break：a result of **synchrotron losses**
- Cooling time：$t_{cool} \sim 5.1\times10^{8} B_{\rm cool}{}^{2} \gamma_{\rm brk}{}^{-1}$

  $B_{\rm cool}$: magnetic field

  $\gamma_{\rm brk}$: Lorentz factor ($\nu_{\rm brk} \sim 1.2\times10^{6} B_{\rm cool} \gamma_{\rm brk}{}^{2}$)

$$\rightarrow \quad B_{\rm cool}[\mu G] = 6.8\times10^{3} t_{\rm cool}\,[{\rm kyr}]^{-\frac{2}{3}} \nu_{brk}[{\rm GHz}]^{-\frac{1}{3}}$$



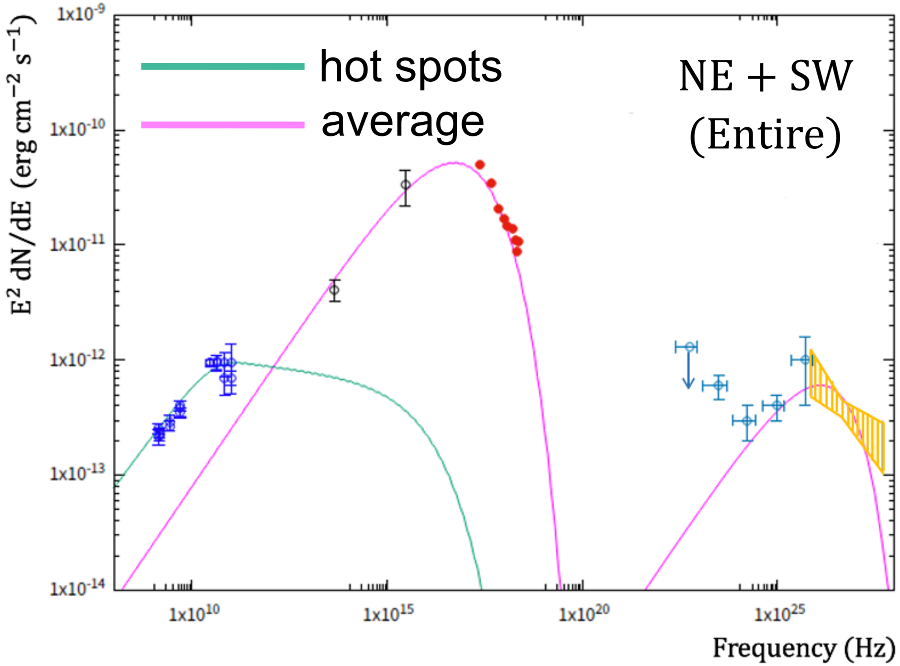
- Substituting the age of SN 1006 for $t_{\rm cool}$, we obtain

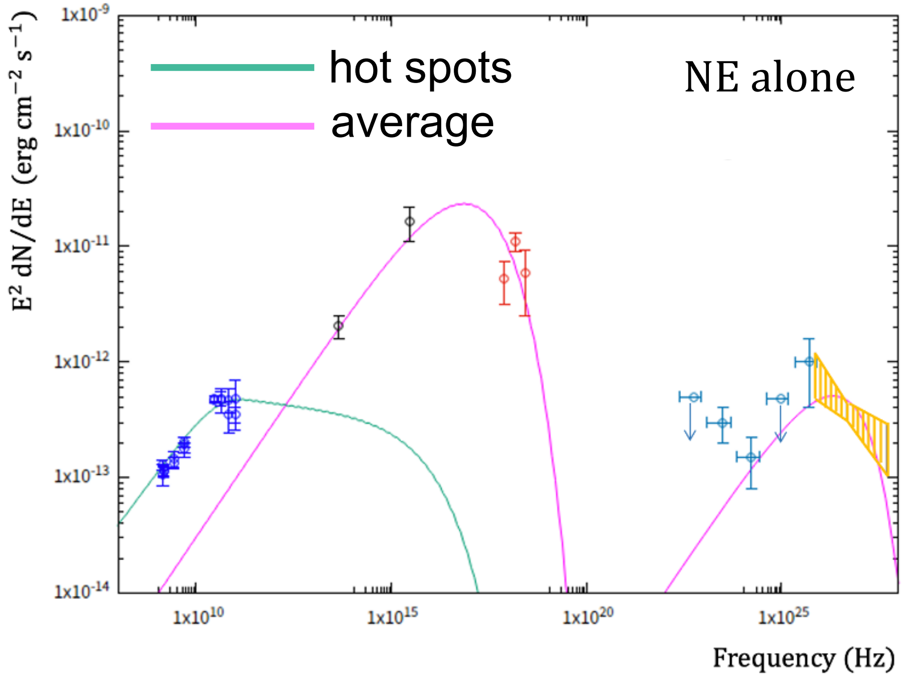
Lower limit : $B_{cool} \geq 2{\rm mG}$

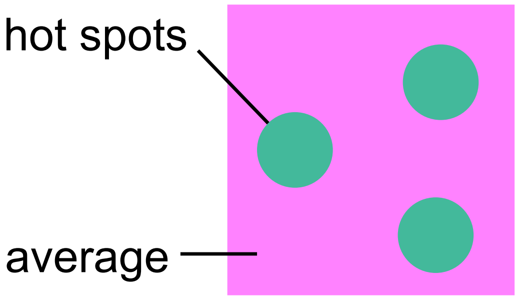
- The magnetic field estimated from equipartition, we obtain $B_{\rm min}$ ~ 5-10 μG

  $\rightarrow \boldsymbol{B_{\rm min} \ll B_{cool}}$

Implication from SED







Magnetic field	NE+SW	NE alone
hot spots	2.5 mG	2.5 mG
average	25 μG	18 μG

amplification factor

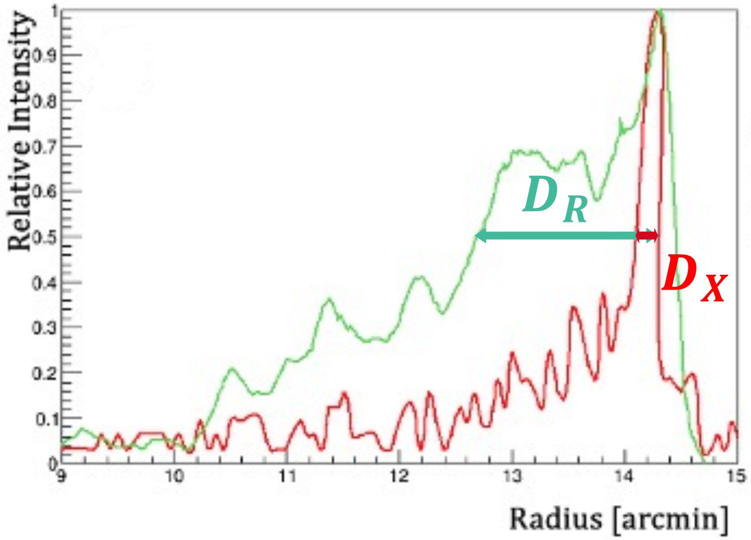
a ~ 100

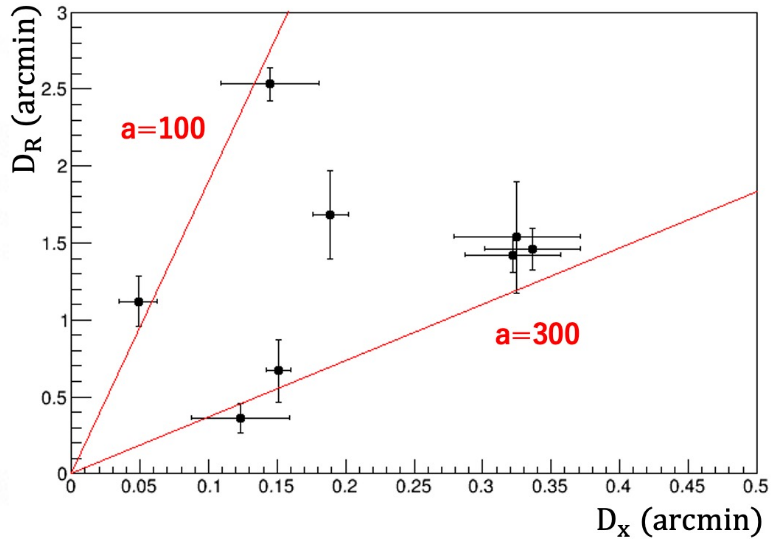
Comparison between Radio/X-ray of the shells

$$D \sim v_{\mathrm{shock}} t_{\mathrm{cool}}$$

$$\downarrow$$

$$\frac{D_{\mathrm{R}}}{D_{\mathrm{X}}} = \left(\frac{B_{\mathrm{R}}}{B_{\mathrm{X}}}\right)^{-\frac{3}{2}} \left(\frac{\nu_{\mathrm{R}}}{\nu_{\mathrm{X}}}\right)^{-\frac{1}{2}}$$

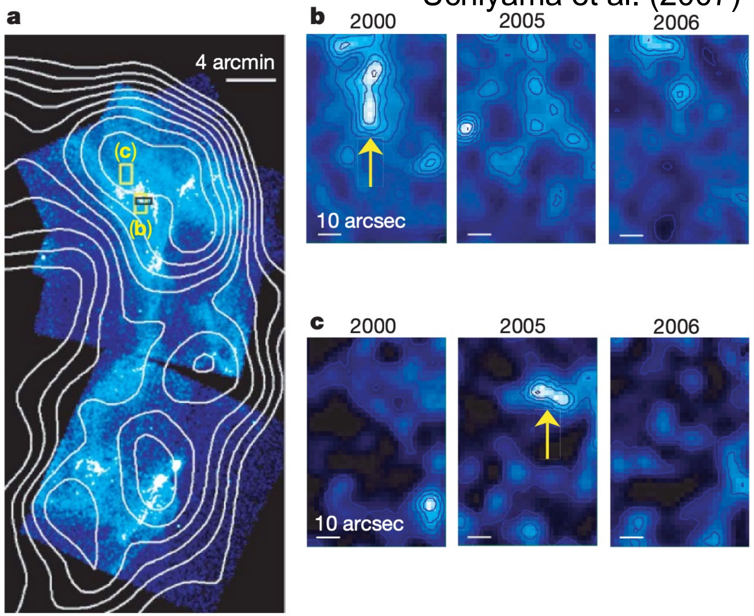




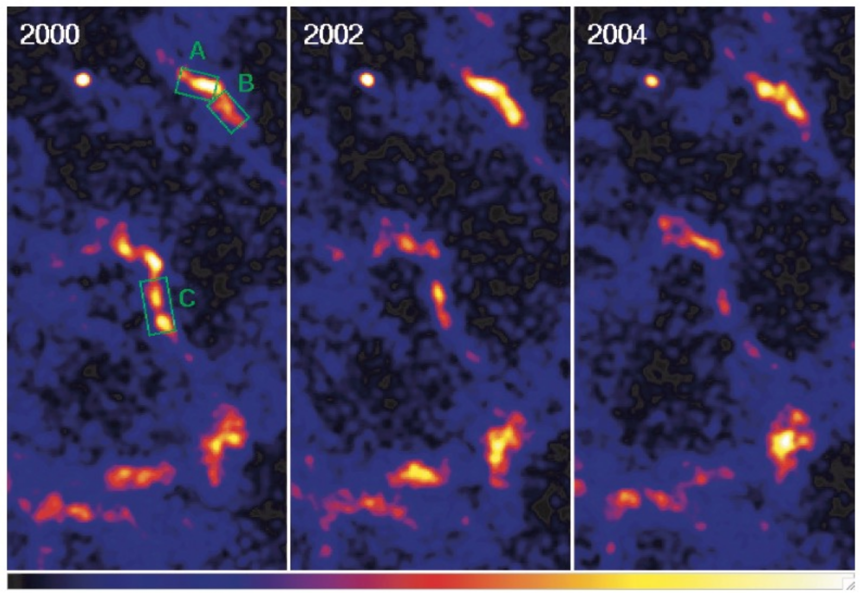
- If the magnetic field for radio and X-ray emissions are the same, $D_{\mathrm{R}}/D_{\mathrm{X}} \approx 2\times10^{4}$.
  → Magnetic fields, which contributed to the radio and X-ray emissions, **can't be the same**
- The observed ratio of $3 \leq D_{\mathrm{R}}/D_{\mathrm{X}} \leq 23$, can be converted to the amplification factor of the magnetic field as $88 \leq a \leq 348$.
  → **consistent with the magnetic field amplification in the hot spot (a ~ 100)**

Comparison with other SNRs

Uchiyama et al. (2007)



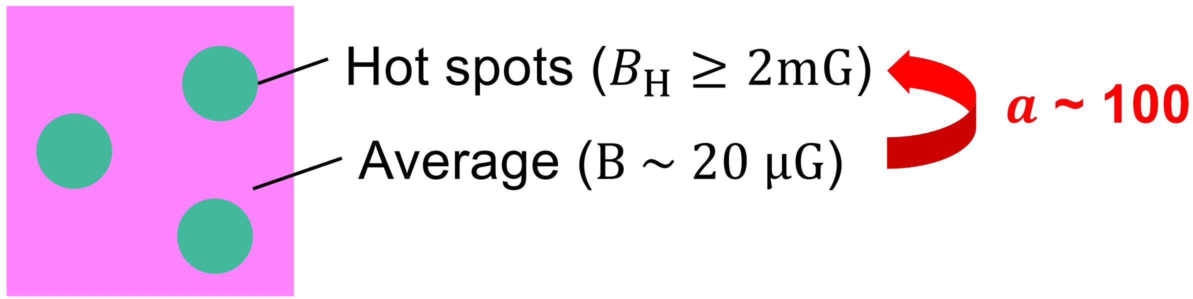
Uchiyama & Aharonian (2008)



- The short time variability on a 1yr timescale was found in RX J1713.7-3946 and Cassiopeia A.
  → hot spots with a strong magnetic field ($B_{\mathrm{H}} \sim 1\mathrm{mG}$)
- The X-ray emission from the hot spot is less than ~100 of that of the entire SNR.

Summary

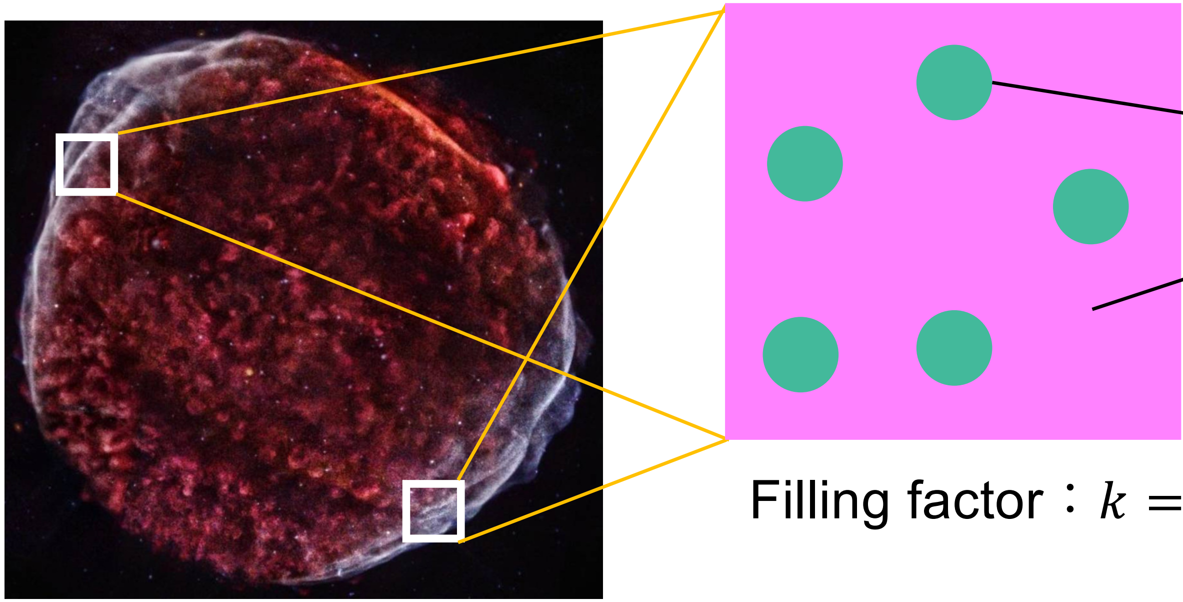
- The spectral break in the radio spectrum (due to synchrotron cooling)
  $\rightarrow B_{\rm cool} \geq 2{\rm mG}$
- The broadband SED (consider the radio break and faint optical/UV fluxes)
  → ‘double’ electron populations; hot spots and average region
- Comparison between Radio/X-ray of NE/SW shells ($3 \leq D_{\rm R}/D_{\rm X} \leq 23$)
  $\rightarrow 88 \leq a \leq 348$



- The manifestation of hot spots with a strong magnetic field of $B_{\rm H} \sim 1mG$ has been reported in similar young SNRs

Appendix

A Proposed scenario



Filling factor : $k = 2.5\times10^{-5}$

- The radio flux in the hot spots f_{HS} is expressed as $f_{\mathrm{HS}} \propto U_{\mathrm{e,HS}} U_{\mathrm{B,HS}} kV$.
- Assuming the radio emissions of hot spots is 10-100 times brighter than that of the average region of the SNR, $f \propto U_{\mathrm{e}} U_{\mathrm{B}} (1-k)V$, we obtain $f_{HS}/f \sim k\times a^3$ $\rightarrow 10^{-5} \leq k \leq 10^{-4}$.

Planck data analysis

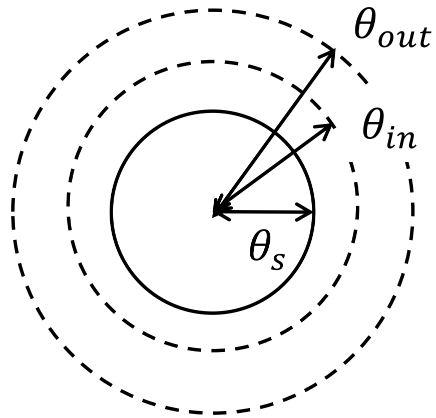
Planck data analysis is based on Arnaud et al. (2016)

Source size $\theta_s = 1.5\sqrt{{\theta_{SNR}}^2 + {\theta_{beam}}^2}$

Background inner radii $\theta_{in} = 1.5\theta_{src}$

Background outer radii $\theta_{out} = 2.0\theta_{src}$

(θ_s : spatial distribution of SN 1006 θ_b : Planck beam size)



- An aperture correction was applied to correct for the loss of flux density outside the aperture.
- The uncertainties for the flux densities were the root-sum-square of calibration uncertainty and propagated statistical errors.

- The confidence level that the broken power law is a better representation of the data than single power law is 99.9% (3.59σ) based on F-test.

Estimation of the Optical flux

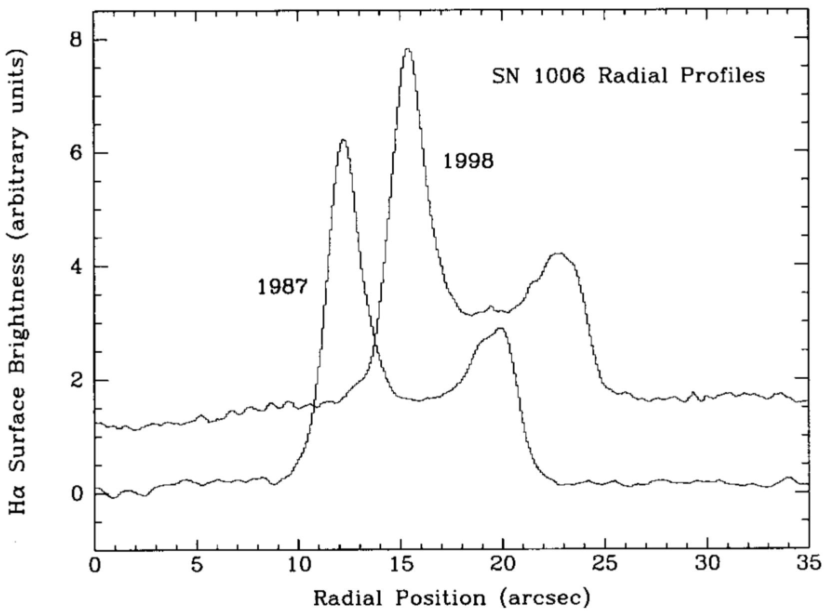


Fig.3 of Winkler et al. (2003)

- Compared with the maximum surface brightness for the filament, $2.0\times10^{-16}\mathrm{erg\ cm^{-2}\ s^{-1} arcsec^{-2}}$, the intensity of the diffuse emission associated with NE/SW shells of SN 1006 is fainter than a factor of 20-25. (see Fig.3 of Winkler et al. (2003))
- For the NE shell, the integrated flux would be $\approx (1.6-2.5)\times10^{-16}\mathrm{erg\ cm^{-2}\ s^{-1}}$. (Assuming a region size of 70 $\mathrm{arcmin^2}$)

Estimation of the UV flux

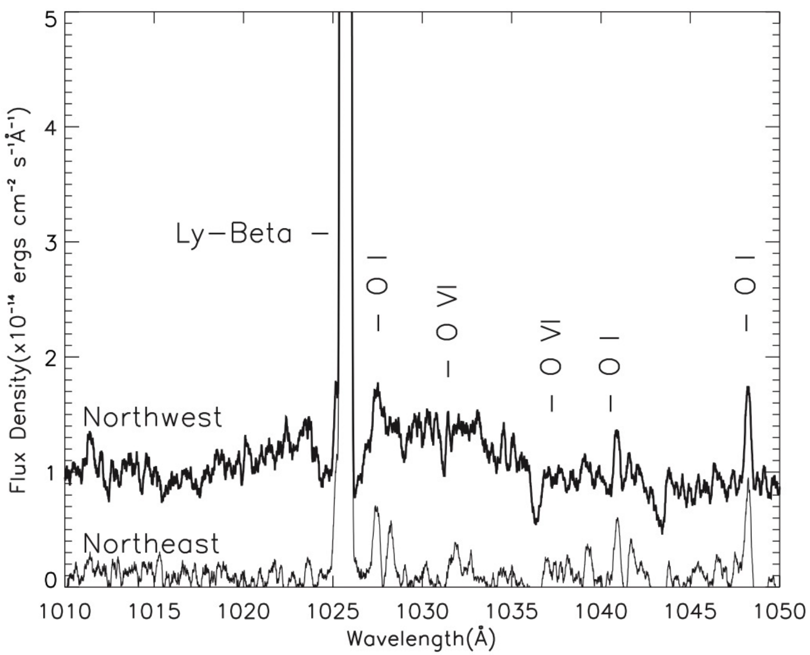


Fig.2 of Korreck et al. (2004)

- The flux density in the NE shell in the UV range is $\approx (1.6-2.5)\times 10^{-16}\mathrm{erg\ cm^{-2}\ s^{-1}\AA^{-1}}$ between 1010 and 1050 Å (see Fig.2 of Korreck et al. (2004)).
- Considering the relatively narrow field of view of FUSE, the integrated NE flux is estimated to be $(1.1-2.2)\times 10^{-16}\mathrm{erg\ cm^{-2}\ s^{-1}}$ for the assumed region.

The magnetic field estimated from equipartition

- Another way of estimating the magnetic field from the observed radio flux is to assume an equipartition (i.e., minimum energy) between the electron and magnetic field energy densities.

$$B_{min}[\mu\mathrm{G}] = 27\left(\frac{d[\mathrm{kpc}]^2 f_\nu[\mathrm{Jy}]}{V[\mathrm{pc}^3]}\right)^{\frac{2}{7}} \nu[\mathrm{GHz}]^{\frac{1}{7}}$$

(d and V : distance and volume of the SNR f_ν : flux density at frequency ν)

- η is the ratio of the energy stored in electrons and protons, where $\eta = 1$ for e^-- e^+ plasma. Consequently, we obtained $\mathrm{B_{min}} \approx 5\mu\mathrm{G}$. Instead, if we assume a typical CR composition, $\eta \approx 100$, $\mathrm{B_{min}} \approx 10\mu\mathrm{G}$ is obtained.

Implication from SED

- Filling factor k : the volume ratio of magnetically enhanced regions to the entire shell
- The radio flux in the hot spots f_{HS} is expressed as $f_{\mathrm{HS}} \propto U_{\mathrm{e,HS}} U_{\mathrm{B,HS}} kV$.
- Assuming the radio emissions of hot spots is 10-100 times brighter than that of the average region of the SNR, $f \propto U_{\mathrm{e,HS}} U_{\mathrm{B,HS}} (1-k)V$, we obtain $f_{HS}/f \sim k \times a^3 \sim 10\text{-}100$; thus, $10^{-5} \le k \le 10^{-4}$.

- As for an electron population in the hot spots, we assumed a broken power law function with an exponential cut-off,

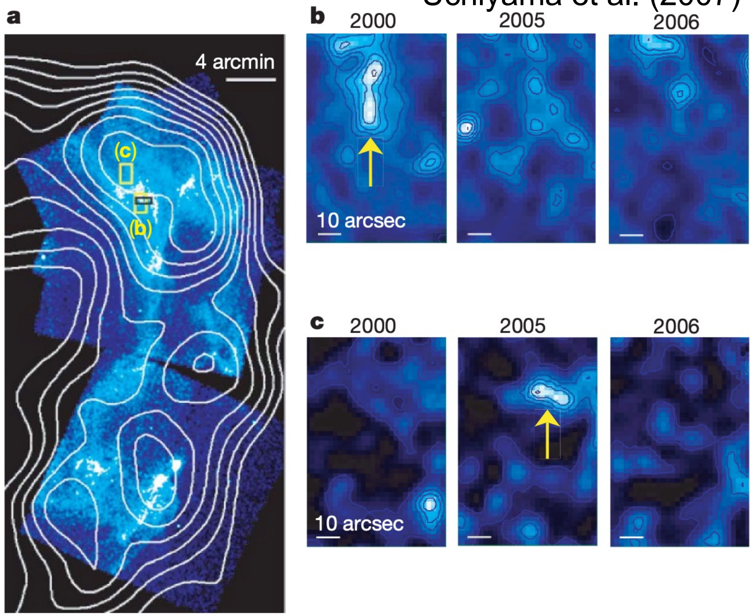
$$N_e(\gamma) = \begin{cases} N_0 \gamma^{-s} \exp(-\gamma/\gamma_{\mathrm{max}}) & (\gamma_{min} < \gamma < \gamma_{\mathrm{brk}}) \\ N_0 \gamma_{\mathrm{brk}} \gamma^{-(s+1)} \exp(-\gamma/\gamma_{\mathrm{max}}) & (\gamma_{\mathrm{brk}} < \gamma < \gamma_{\mathrm{max}}) \end{cases}$$

- For remaining average region, we assumed a simple power law function with an exponential cutoff,

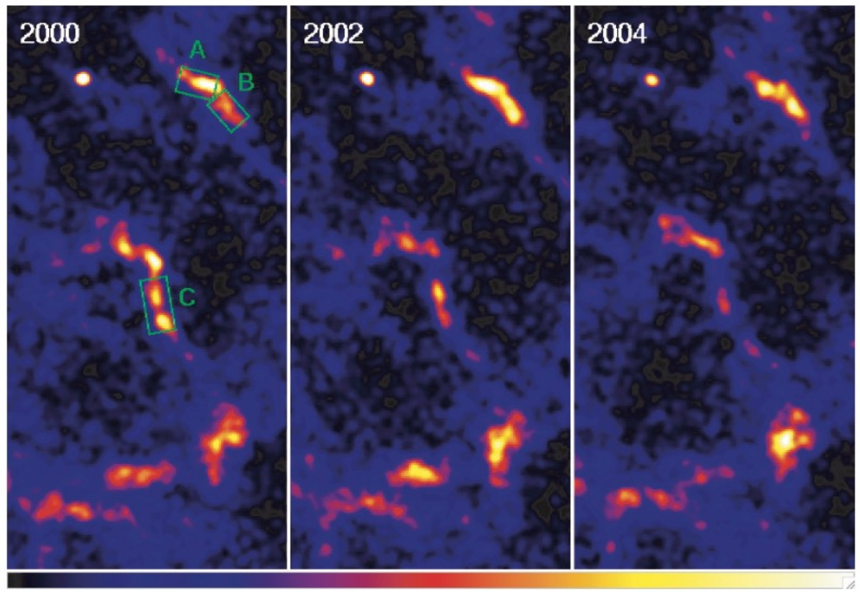
$$N_0 \gamma^{-s} \exp(-\gamma/\gamma_{\mathrm{max}})$$

Comparisons with similar young SNRs

Uchiyama et al. (2007)



Uchiyama & Aharonian (2008)



- The anticipated linear size of the hot spots would be $k^{\frac{1}{3}} = 2.9\times10^{-2}$ times smaller than the typical shell thickness of 10”
  → difficult to resolve even with Chandra

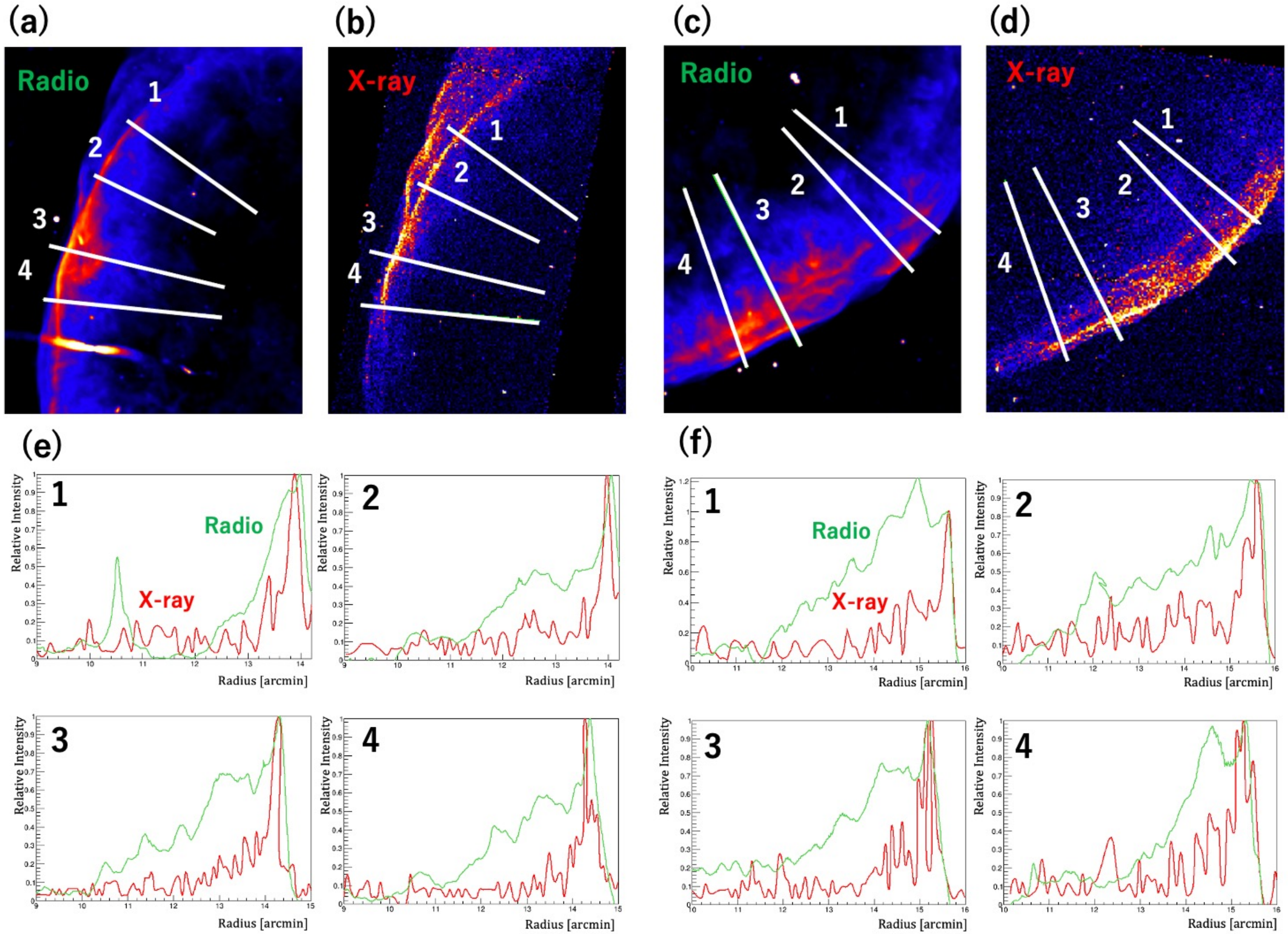
The physical mechanism of amplification

- In the standard theory of shock compression, $a = B_d/B_\mathrm{u} = U_d/U_\mathrm{u} = 4$. (d/u : down/up stream)
  → $a \sim 100$ is hardly explained by the classical shock theory

- For RX J1713.7-3946, such a strong magnetic field may be produced owing to the turbulent dynamo action through shock-cloud interaction. (Inoue et al. (2011))
  → However, this can not be the case for a relatively “clean” environment as in SN 1006 and Cas A

- In this context, some particle-in-cell simulations of nonrelativistic perpendicular shocks in the high-Mach number (M_A) suggest magnetic amplification of $a = 5.5(\sqrt{M_A} - 2)$. (Bohdan et al. (2021)).
  → $a \approx 100$ for $M_A \approx 400$ or $v_\mathrm{sh} \approx 4000\ \mathrm{km\ s^{-1}}$

- However, whether similar efficient amplification is possible even in parallel shocks is uncertain, as observed in SN1006.



(a)
Radio
1
2
3
4
(b)
X-ray
1
2
3
4
(c)
Radio
1
2
3
4
(d)
X-ray
1
2
3
4
(e)
1
Radio
X-ray
2
3
4
Relative Intensity
Radius [arcmin]
(f)
1
Radio
X-ray
2
3
4
Relative Intensity
Radius [arcmin]