Probing the Origin of NPS by Broadband Radio Observation：
New Insight into Future X-ray and Gamma-ray Observations

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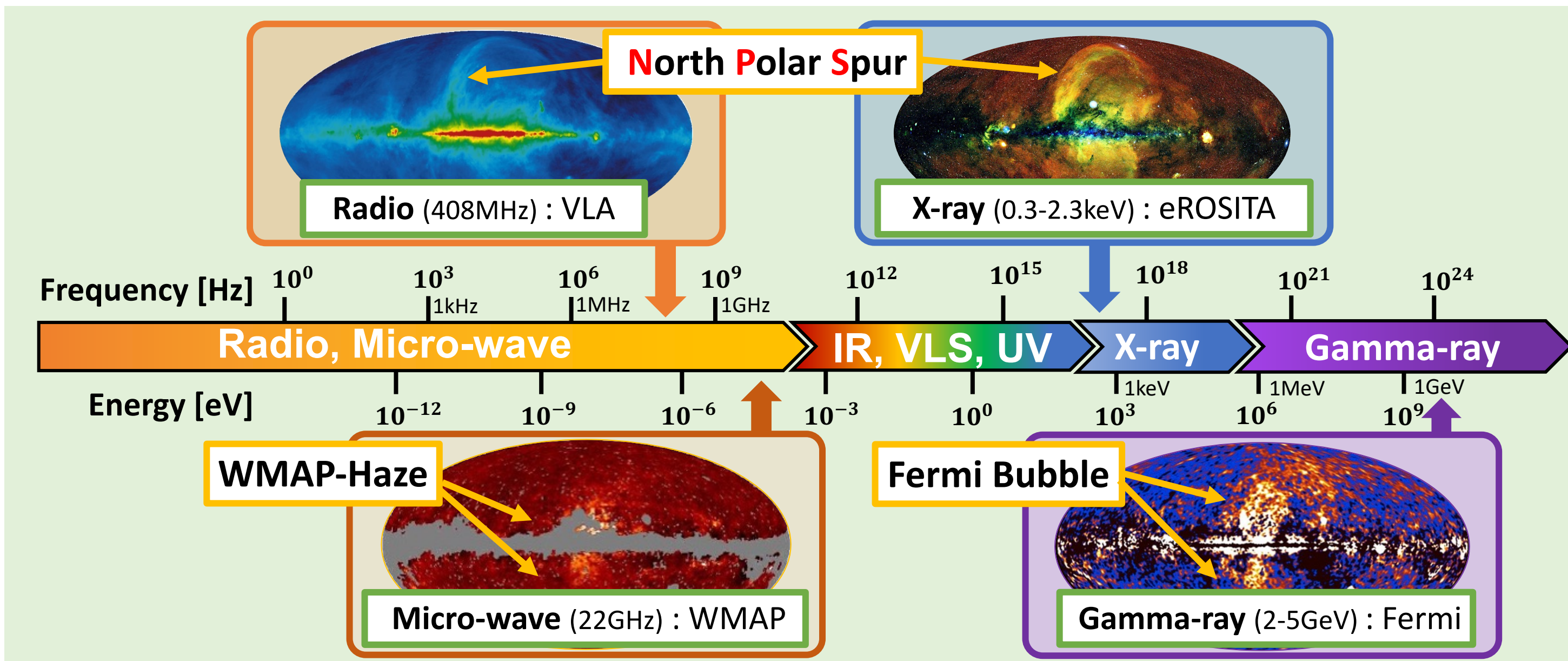
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Abstract

The **North Polar Spur** (**NPS**) is a giant structure that clearly shows up both in the **radio** and **X-ray** all-sky maps. Even though a half century has passed since its discovery, **two competing ideas** are actively debated to postulate its origin; one is a **local super-bubble near the solar system**, and the another is a **remnant of AGN and/or starburst outflow from the Galactic Center (GC)** over 10Myr ago. In this context, recent discovery of **gamma-ray Fermi Bubbles** as well as even larger **X-ray eROSITA bubbles** may suggest **possible connection between NPS and these huge structures**. In this study, we analyzed a **broad-band radio observations** covering from **22MHz (VLA)** to **70GHz (Planck)** for the first time to provide a systematic analysis of thermal/non-thermal emission associated with the NPS. We show that the radio emission from **NPS is composed of (1) Synchrotron radiation (2) free-free radiation** and **(3) dust emission**, but the synchrotron emission dominates over other emissions at high galactic latitude. In most regions, the electron spectrum indicates a power-law with its index (s of $N(\gamma) \propto \gamma^{-s}$) of 2.2-3.0, moderated by a high-energy turnover cutoff around $\gamma \sim 10^4 (E \sim 10$ GeV), indicating that **radio emitting electrons are already cooled in the NPS**. The cooling time, assuming a typical magnetic field strength B ~5 uG, leads to **~10Myr**, which provides additional **supports that the NPS is a structure in the GC**. We estimated the non-thermal energy stored in the NPS to be $\sim 2.6 \times 10^{55}$ [erg] in case of the GC. We also estimated that gamma-ray emission associated with the NPS, though the inverse comptonization of the CMB, peaks around 100-1000keV with a flux of $\sim 10^{-9}$ [erg/cm^2/s /str], that may be a good candidate of future detection by X-ray observatory.

Introduction

▶ North Polar Spur (NPS) ~ *Radio* and *X-ray* ~

NPS Origin ⇒ still under debate
1. **Supernova Remnant (SNR)** near the **solar system**
2. **AGN and/or starburst outflow** from the **Galactic Center (GC)**

North Polar Spur
Radio (408MHz) : VLA
X-ray (0.3-2.3keV) : eROSITA
WMAP-Haze
Micro-wave (22GHz) : WMAP
Fermi Bubble
Gamma-ray (2-5GeV) : Fermi

NPS Radiation mechanism

X-ray：**Thermal Radiation**
- ✓ Local Bubble and SWCX
- ✓ thermal emission and Galactic Halo
- ✓ cosmic X-ray background   *Kataoka et al.2013*

Radio：**Nonthermal Radiation??**
- ✓ presumed to be Synchrotron Radiation

Discovery of Galactic Bubble

Gamma-ray：Fermi Bubble
micro-wave：WMAP-Haze
→ **Extending along the NPS**

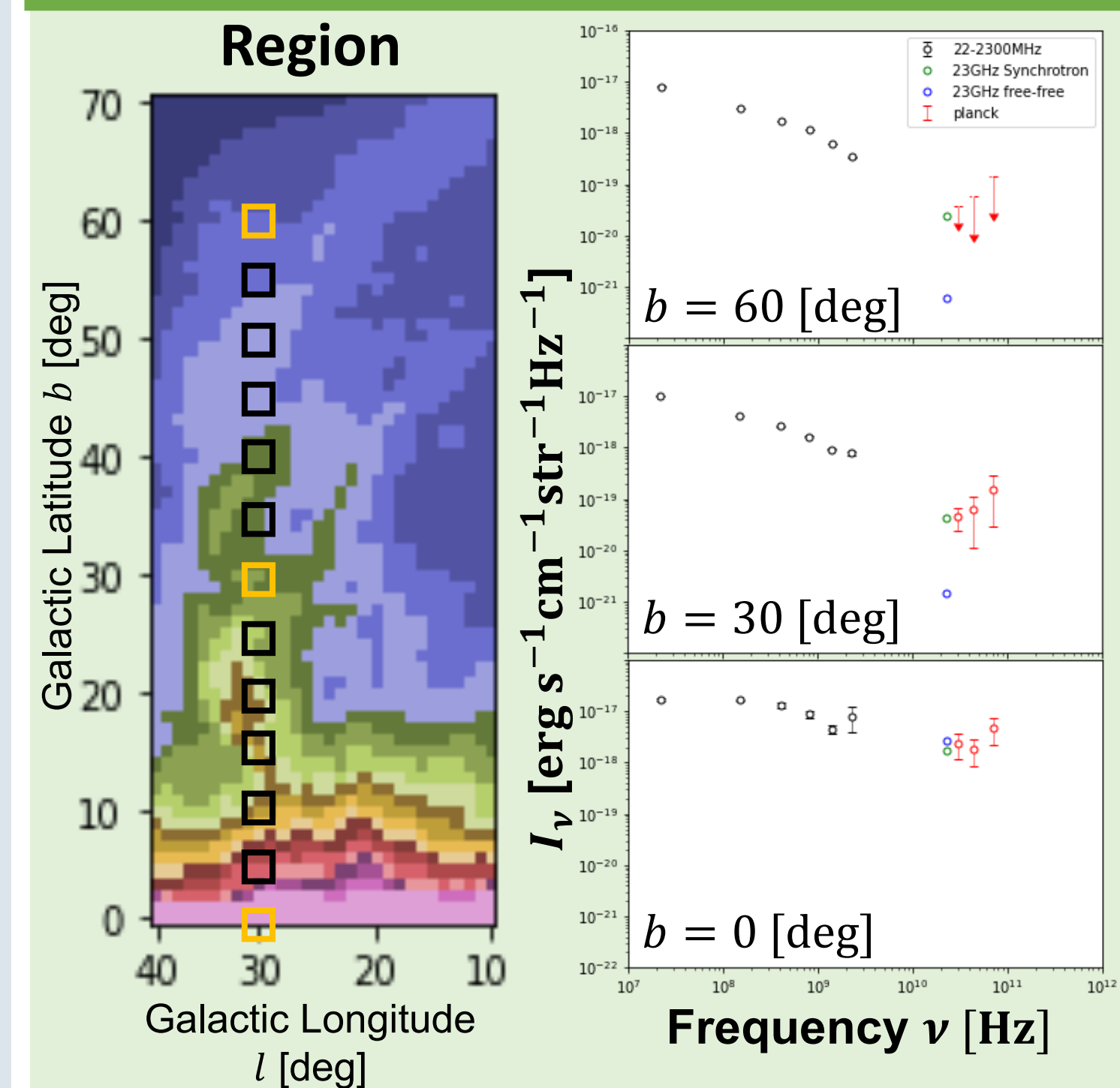**Existence of High-Energy radiation due to Inverse Compton scattering??**

Broad-Band observations covering from 22MHz (VLA) to 70GHz (Planck)

Analysis & Discussion

### ▶ Radio NPS spectrum @22MHz ~ 70GHz

1Region
1 [deg] × 1 [deg]
l = 30 [deg] (Fix)
→ **Galactic Latitude dependency**

NPS Radiation @ Radio

(1) **Synchrotron Radiation** ($I_\nu \propto \nu^{-\alpha_{syn}}$)
- ✓ Cut-off at ~1GHz
- ✓ Dominant at low Frequency (~GHz)

(2) **free-free Radiation** ($I_\nu \propto \nu^{-\alpha_{ff}}; \alpha_{ff} \sim 0.1$)
- ✓ High emissivity at low Galactic Latitude
- ✓ High radiation at high Frequency (GHz~)

(3) **Dust emission** ($I_\nu \propto \nu^2$)
- ✓ Dominant at several tens of GHz
- ✓ Black-Body modified by optical thickness

$I_{syn} \propto \nu^{-\alpha}$ cut-off $I_{dust} \propto \nu^2$
$I_{ff} \propto \nu^{-0.1}$ Low-latitude   High-latitude
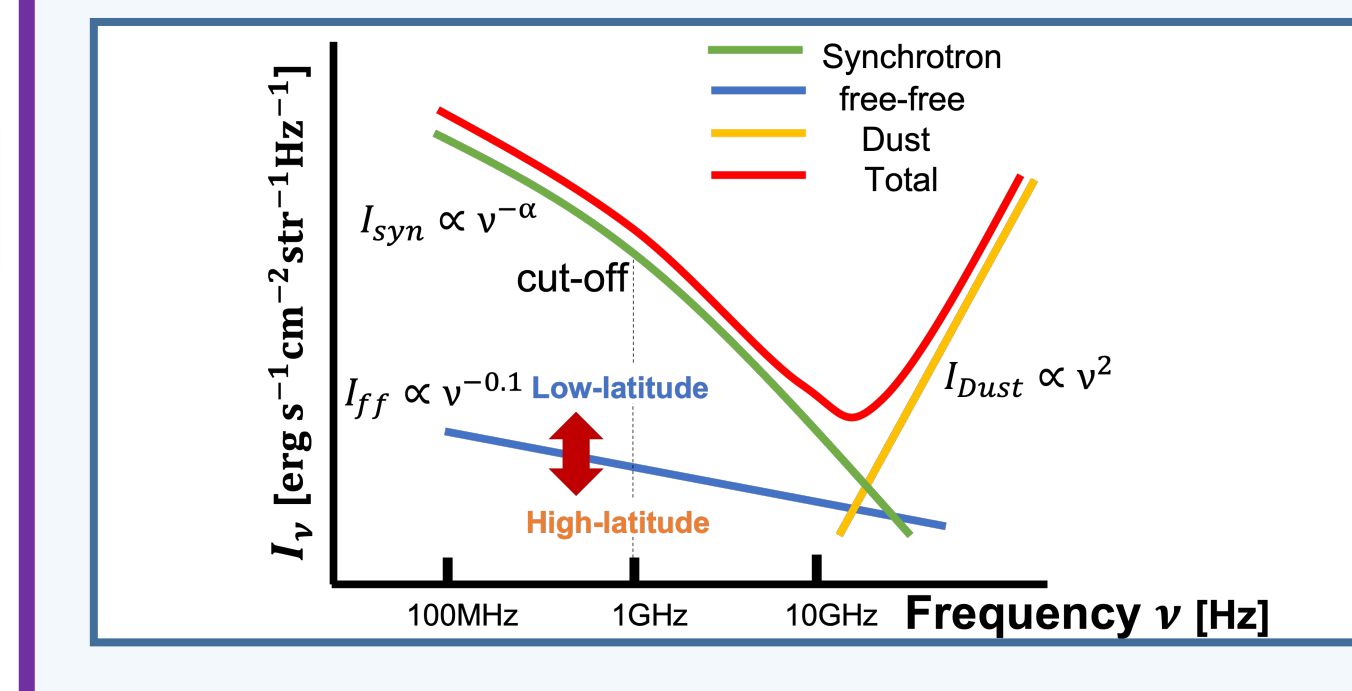
Synchrotron radiation dominates at high latitudes ➡ **SED Fitting**
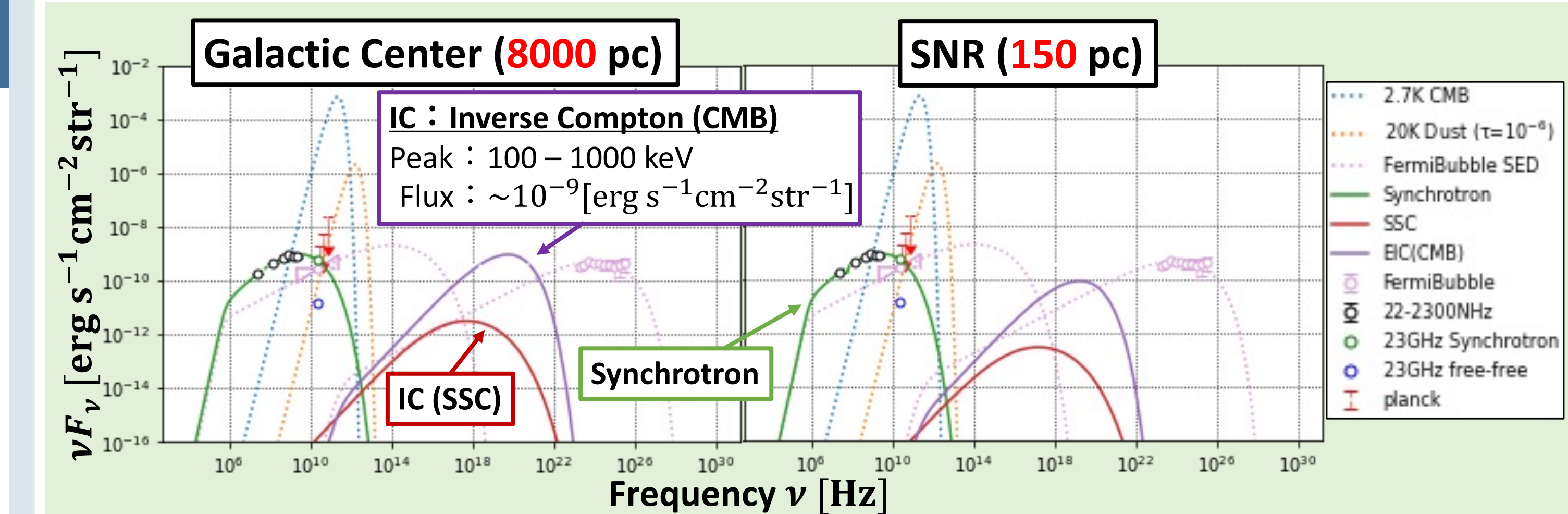
▶ Spectral Energy Distribution (SED)

Fitting Data
Frequency：22MHz – 23GHz
Region：$(l, b) = (30°, 60°)$
1 [deg] × 1 [deg]

Assumption
Distance to NPS
SNR near the solar system：150 pc
Galactic Center：8000 pc

Galactic Center (8000 pc)   SNR (150 pc)
IC：Inverse Compton (CMB)
Peak：100 – 1000 keV
Flux：$\sim 10^{-9}$[erg s^{-1}cm^{-2}str^{-1}]
IC (SSC)   Synchrotron

electron cooling time

$$t_{cool} \sim \frac{5.1 \times 10^8}{B^2 \gamma} \text{ [s]}$$

Fitting Result
$B \sim 5 \mu G$
$\gamma \sim 10^4$

$t_{cool} \sim 10$ Myr

Age of SNR: ~10000 yr
➡ **NPS is not a single SNR**

Supporting a structure in the GC

Non-thermal Energy of NPS

Assumption
NPS：Spherical shell
$V \sim$ GC : 1.2×10^{67} [cm^3]
SNR : 7.9×10^{61} [cm^3]

Fitting Result
Energy density of electron/magnetic field

	U_e [erg cm^{-3}]	U_B [erg cm^{-3}]
GC	1.2×10^{-12}	9.9×10^{-13}
SNR	1.3×10^{-11}	1.0×10^{-11}

Non-thermal Energy
$$E_{n/th} = V \times (U_e + U_B)$$
SNR：$E \sim 1.8 \times 10^{51}$ [erg]
⇒ Too large as a SNR
GC：$E \sim 2.6 \times 10^{55}$ [erg]
⇒ Acceptable

Conclusion

➢ **Radio NPS spectrum**
- ✓ Synchrotron radiation
- ✓ free-free radiation
- ✓ Dust emission

Synchrotron radiation dominates at high latitudes

➢ **Spectral Energy Distribution**
- ✓ Inverse Compton(CMB) @GC ⎰ peak：100 - 1000 keV
  ⎱ Flux：$\sim 10^{-9}$ [erg s^{-1}cm^{-2}str^{-1}]
- ✓ Electron cooling time ⇒ **~10 Myr**
- ✓ Non-thermal Energy ⎰ SNR：1.8×10^{51} [erg]
  ⎱ GC：2.6×10^{55} [erg]

Supporting a structure in the GC