Gamma-ray and X-ray study of possibly oldest GeV supernova remnant G298.6−0.0

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Related publication:
Yeung et al. in preparation (to be submitted to PASJ)

High-energy properties of SNRs revealed by gamma-ray observations

- No. of gamma-ray sources identified as or associated with SNRs:
  — ≥33 are detected by HESS, MAGIC, VERITAS in TeV
  — ≥40 are detected by Fermi-LAT in GeV

- Observations+Theories: SNRs can generate cosmic rays responsible for observed gamma-rays
  — hadronic-to-leptonic ratio is generally ~100

- ≥11 gamma-ray-bright SNRs are interacting with molecular clouds (SNR-MC sources)

- GeV spectra: Broken-Power-Law: $\frac{dN}{dE} = N_0 \times \begin{cases} (E/E_b)^{\gamma_1} & \text{if } E < E_b \\ (E/E_b)^{\gamma_2} & \text{otherwise} \end{cases}$
  $|\gamma_2| > |\gamma_1|$

Correlation of γ-ray spectrum with SNR age

The time-evolution of **CR-acceleration** energetics.

CR-escape develops with time, from high to low energies

- The time-evolution of SNR gamma-ray spectra: Flux+Shape
- "Gamma-ray spectrum vs. Age" relation
  — as a stopwatch for the escape of CRs from SNRs

Thermal X-rays of SNRs

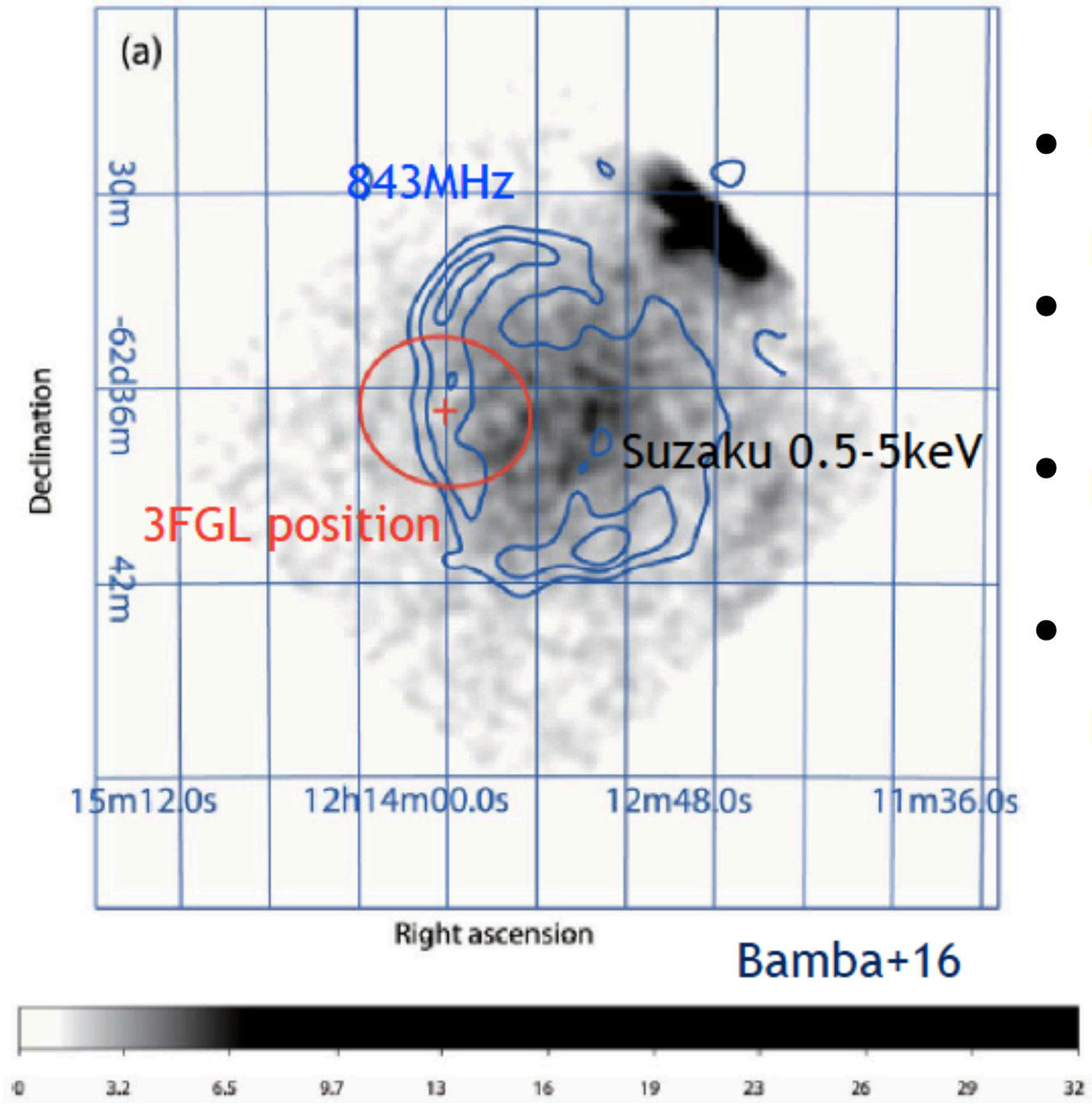
- Ionising Plasma (IP):
  electron temperature (T_e) > ionisation temperature (T_z);
  timescale > 10 kyr

- Recombining Plasma (RP): $T_e < T_z$ (timescale > 10 kyr)

- Plasma in Collisional Ionisation Equilibrium (CIE): $T_e = T_z$

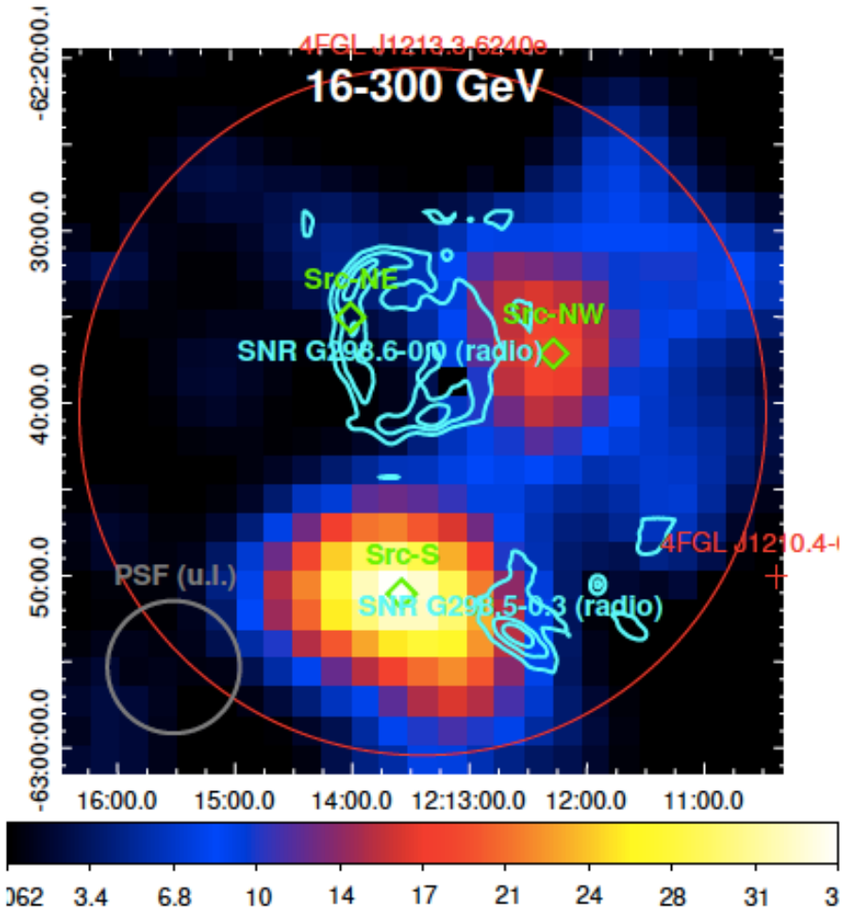
- Possible evolutionary routes of SNRs:
  IP domination ==> CIE; or
  IP domination ==> RP domination ==> CIE

Why studying SNR G298.6-0.0?

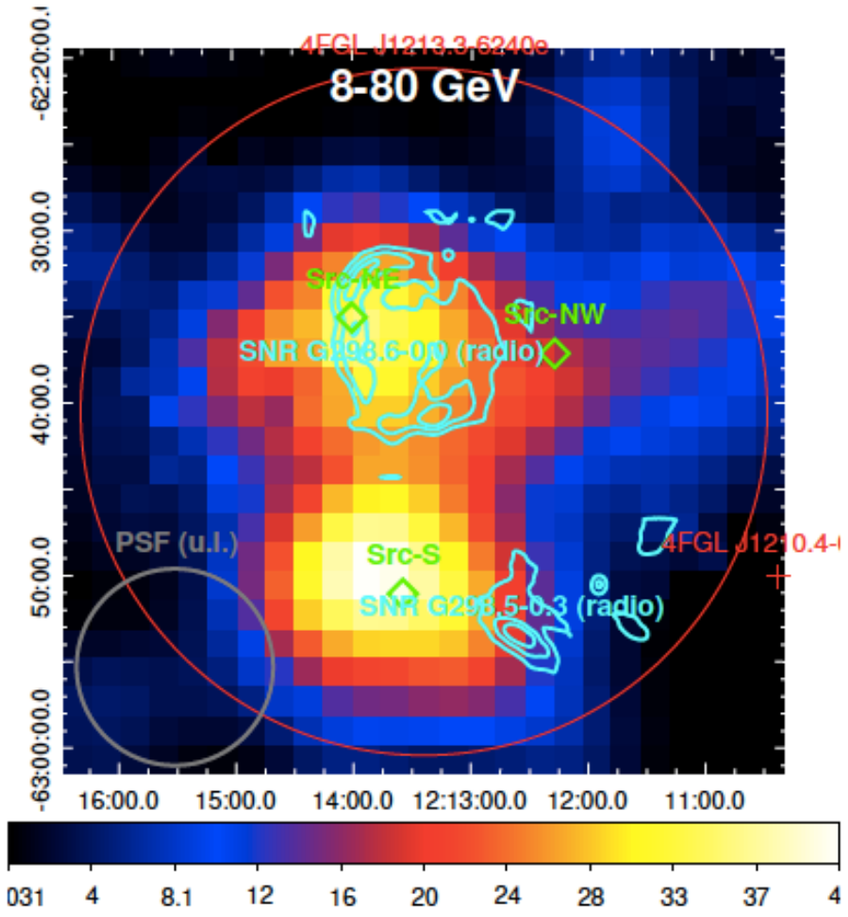


- Mixed-Morphology SNR
- Molecular-cloud interaction
- CIE X-ray spectrum (Suzaku)
- Our observational efforts:
  - Fermi-LAT data (13.7 yr)
  - Chandra data (20 ks)

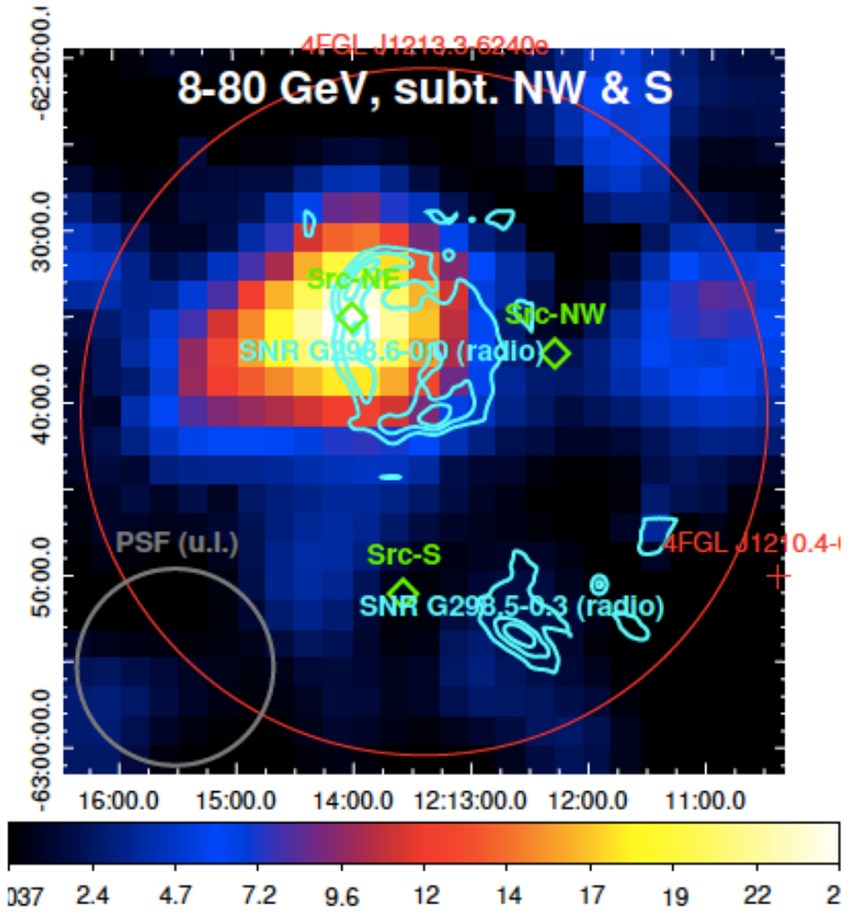
Fermi-LAT Spatial Morphologies



Src-NW & Src-S detected at >16 GeV



Additional component: Src-NE detected at >8 GeV



Subtract NW & S to localise NE

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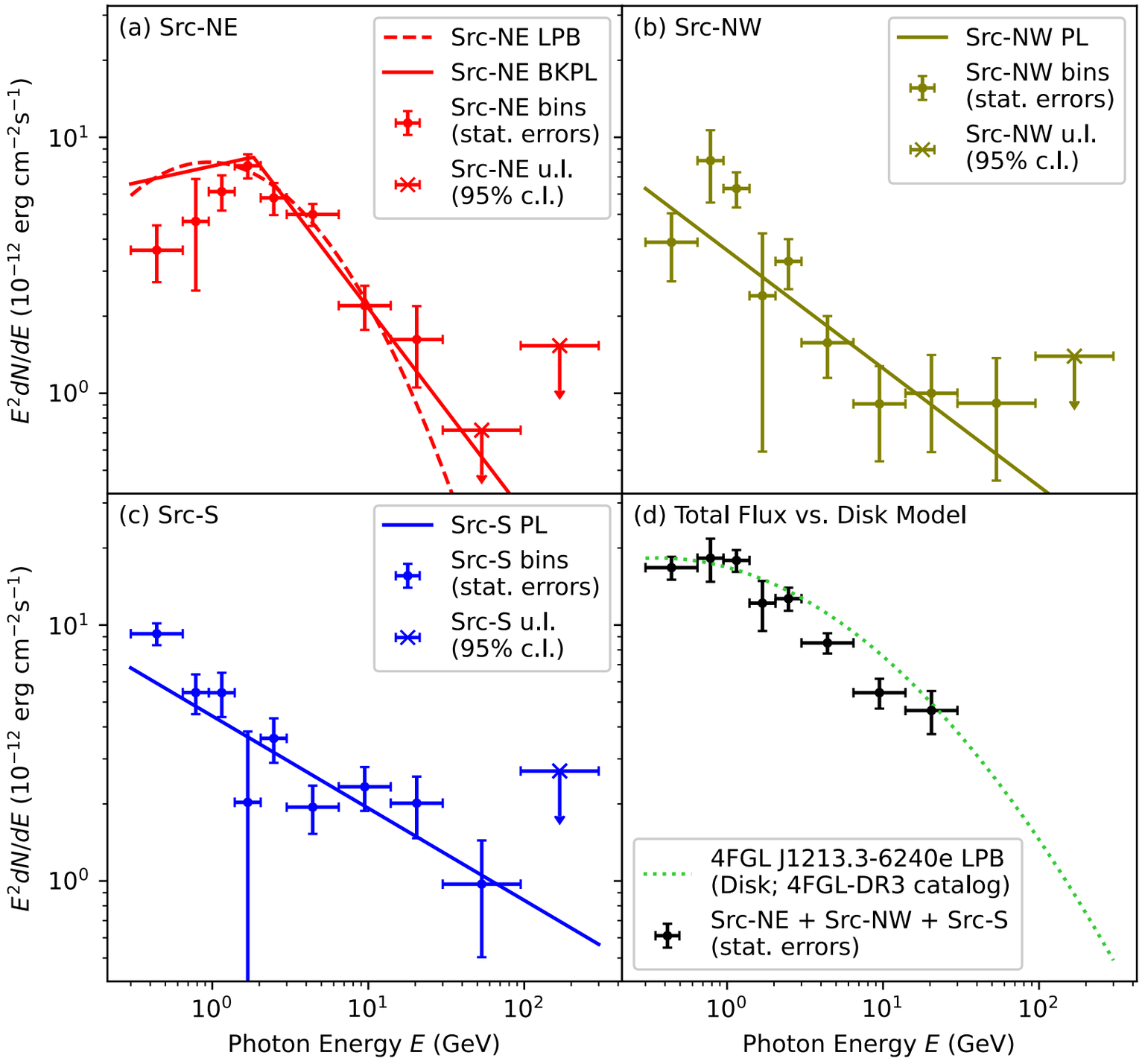
Fermi-LAT Spectral Energy Distributions



- Src-NE: Log-Parabola / Broken-Power-Law
  - E_{break} ~ 1.8 GeV
  - Curvature/Break is robust against statistical & systematic errors
- >2 GeV: NE is much softer than S

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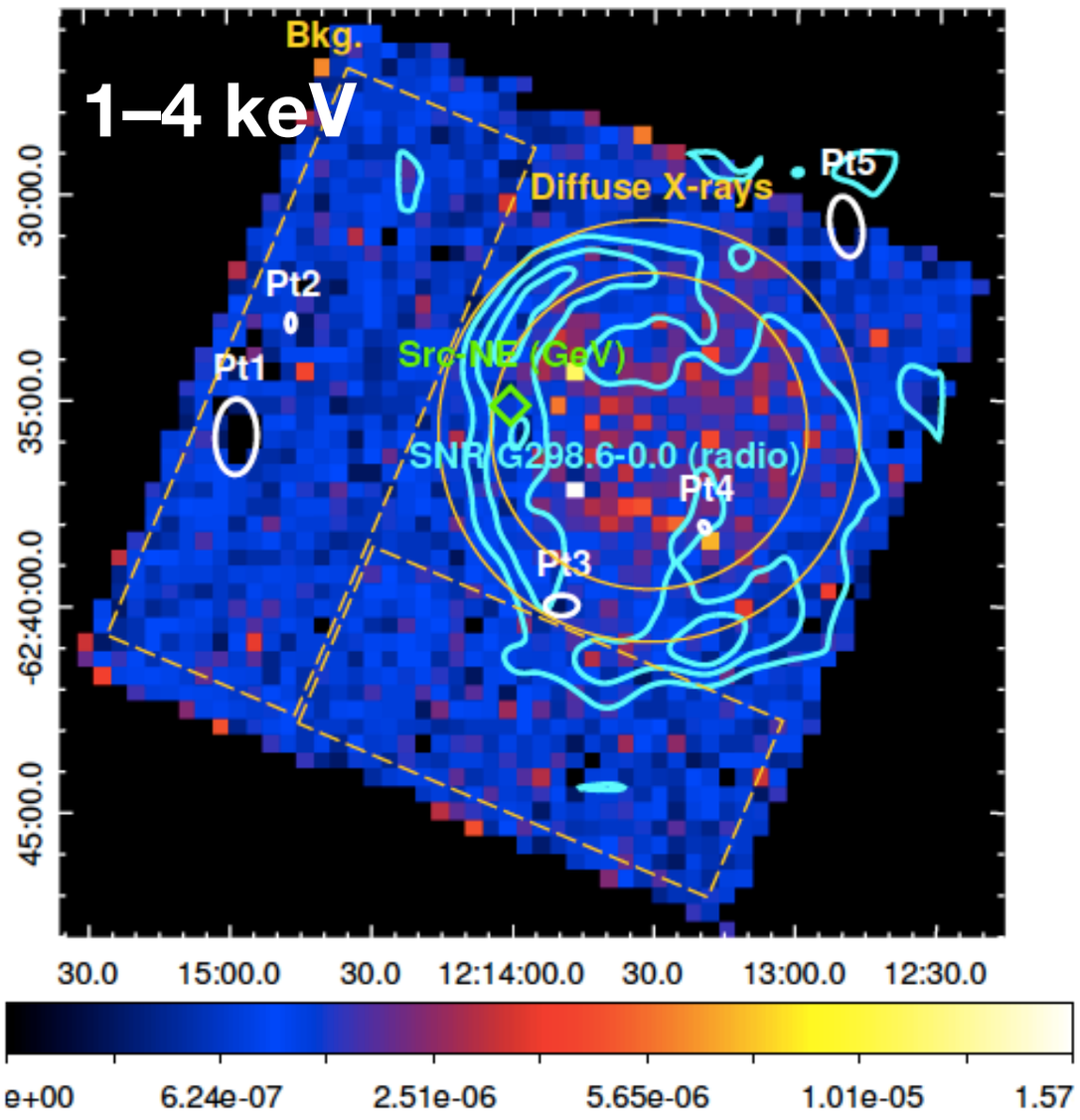
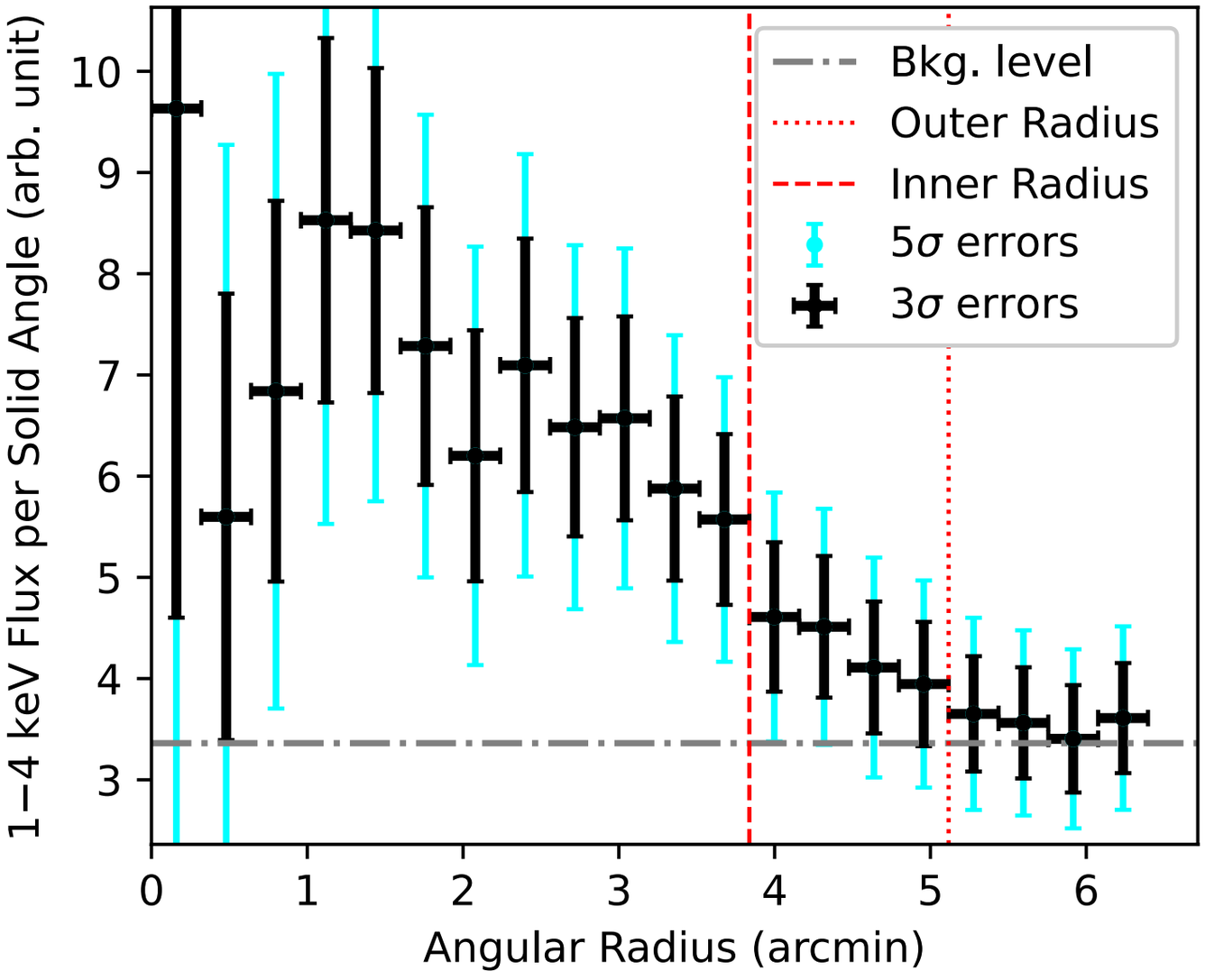
Chandra-ACIS Spatial Morphology





- X-ray centroid is slightly tilted to **northeast** part of SNR
- No X-rays at southwest edge of SNR

- Beyond the **inner** region, flux – bkg ≲ 5σ
- Beyond the **outer** region, flux – bkg << 3σ

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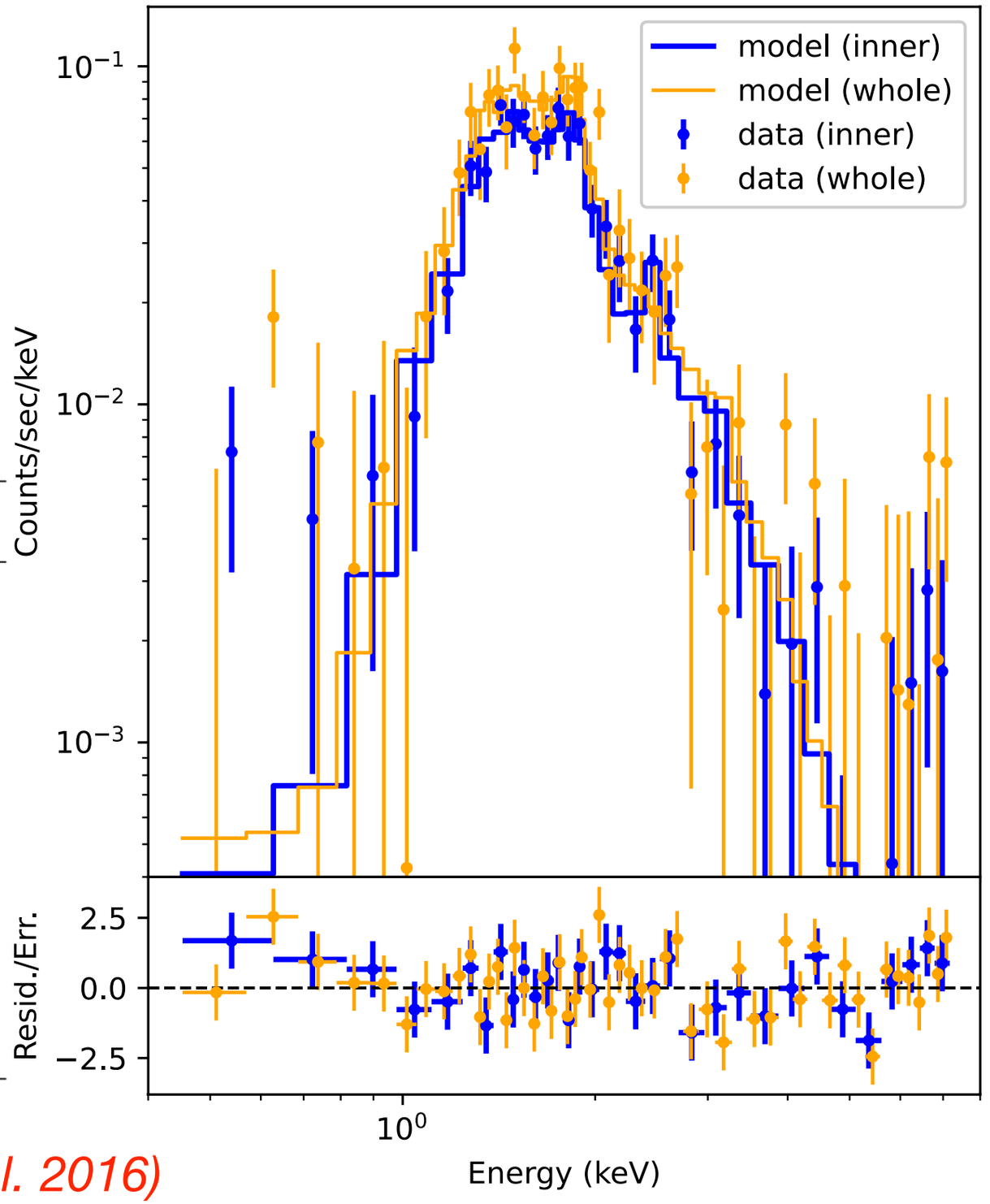
Chandra-ACIS Spectroscopy

- Model: *VAPEC×PHABS*
  - VAPEC: Plasma in Collisional Ionisation Equilibrium
  - PHABS: Photoelectric absorption along line of sight

	Inner Region	Whole Region
$N_{\rm H}$ (10^{22} cm^{-2})	1.93 ±0.27	2.25 ±0.55
kT (keV)	0.71 ±0.10	0.64 ±0.11
Mg	0.45 ±0.25	0.48 ±0.32
Si	0.27 ±0.11	0.26 ±0.10
S	0.41 ±0.22	0.02 ±0.17
Fe	0 ±0.04	0.18 ±0.24
EM (cm^{-5})*	8.9 ±3.8	15.8 ±8.7
$\chi^2/d.o.f.$	30.1 / 26	63.3 / 45



— **Consistent with each other**

— **Consistent with Suzaku results** *(Bamba et al. 2016)*

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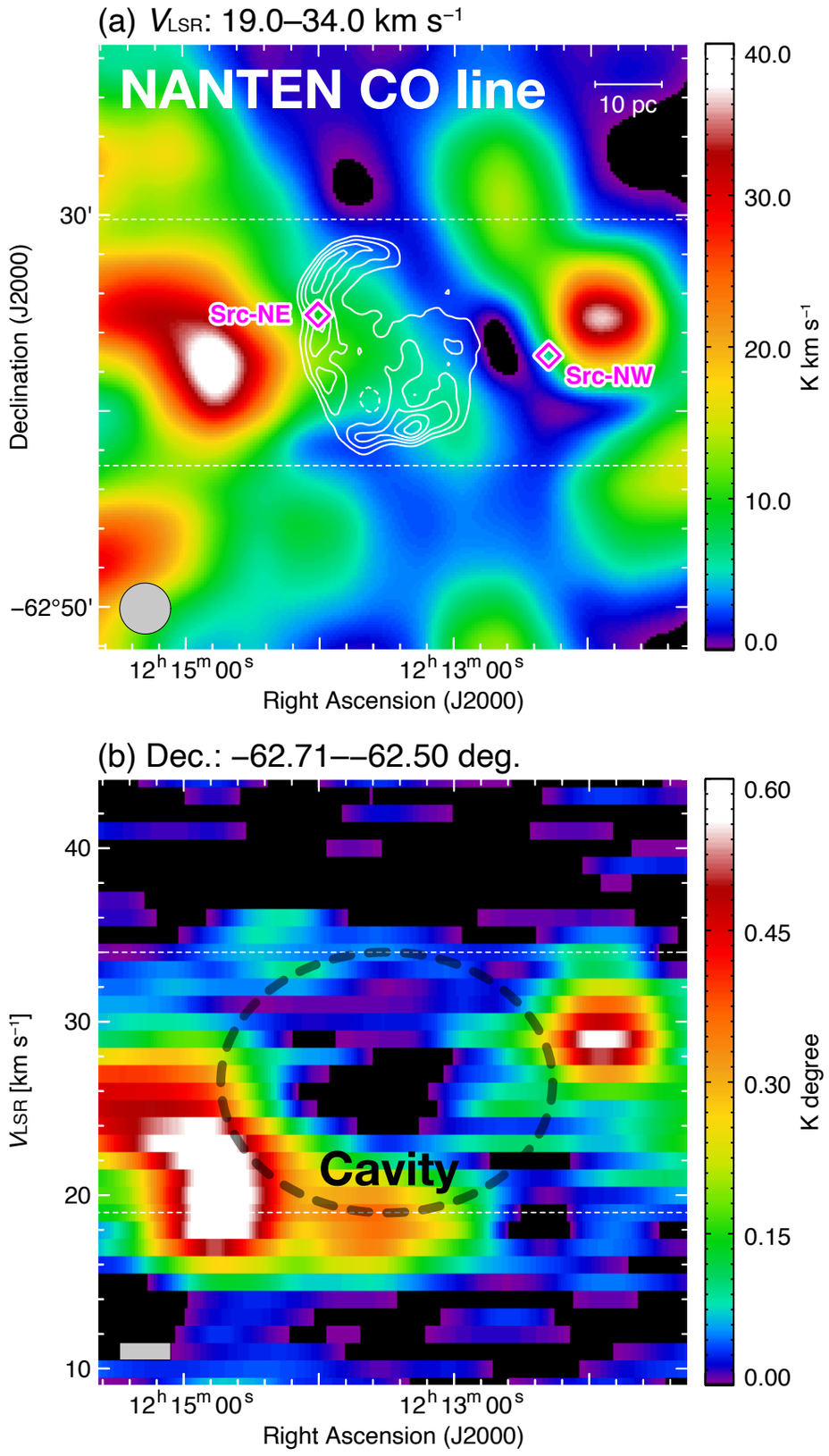
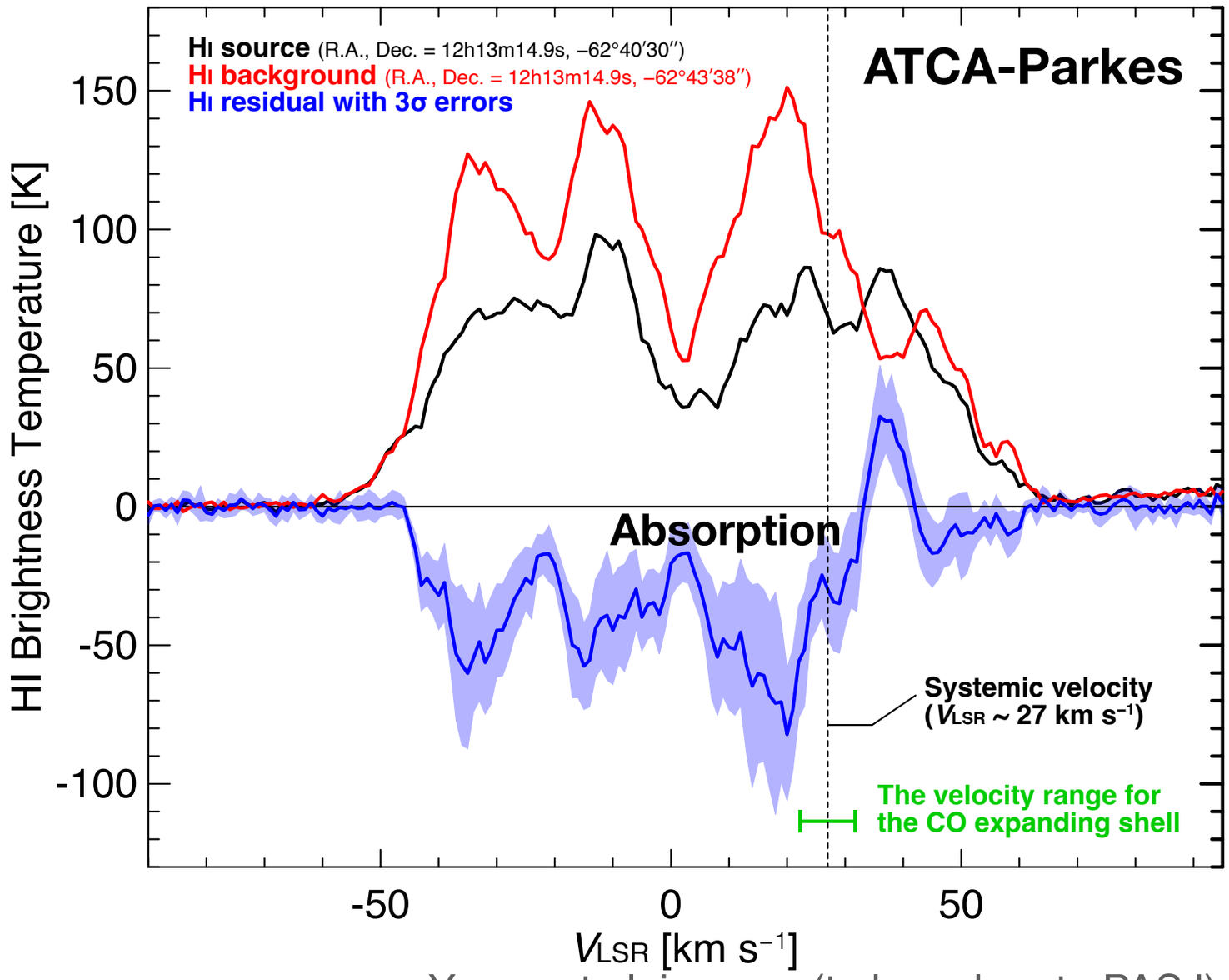
CO & HI Lines



- Tracers of molecular clouds (MCs) and dense media: ^{12}CO(J=1–0) (115 GHz) & HI (1.4 GHz) emission lines



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CO & HI Lines

- At V_{LSR}~27 km/s, towards SNR G298.6-0.0,
  CO: cavity; HI: absorption

  ==> Expanding gas motion (Wind-blown bubble)

  ==> Proofs of **shock-cloud interaction**

- V_{LSR}~27 km/s corresponds to
  kinematic distance ~ 10.1 kpc (∵ Galactic rotation curve)

- 3 MC clumps (CO) surrounding the SNR:
  East clump <—> Src-NE
  North-front clump <—> Src-NE
  West clump <—> Src-NW

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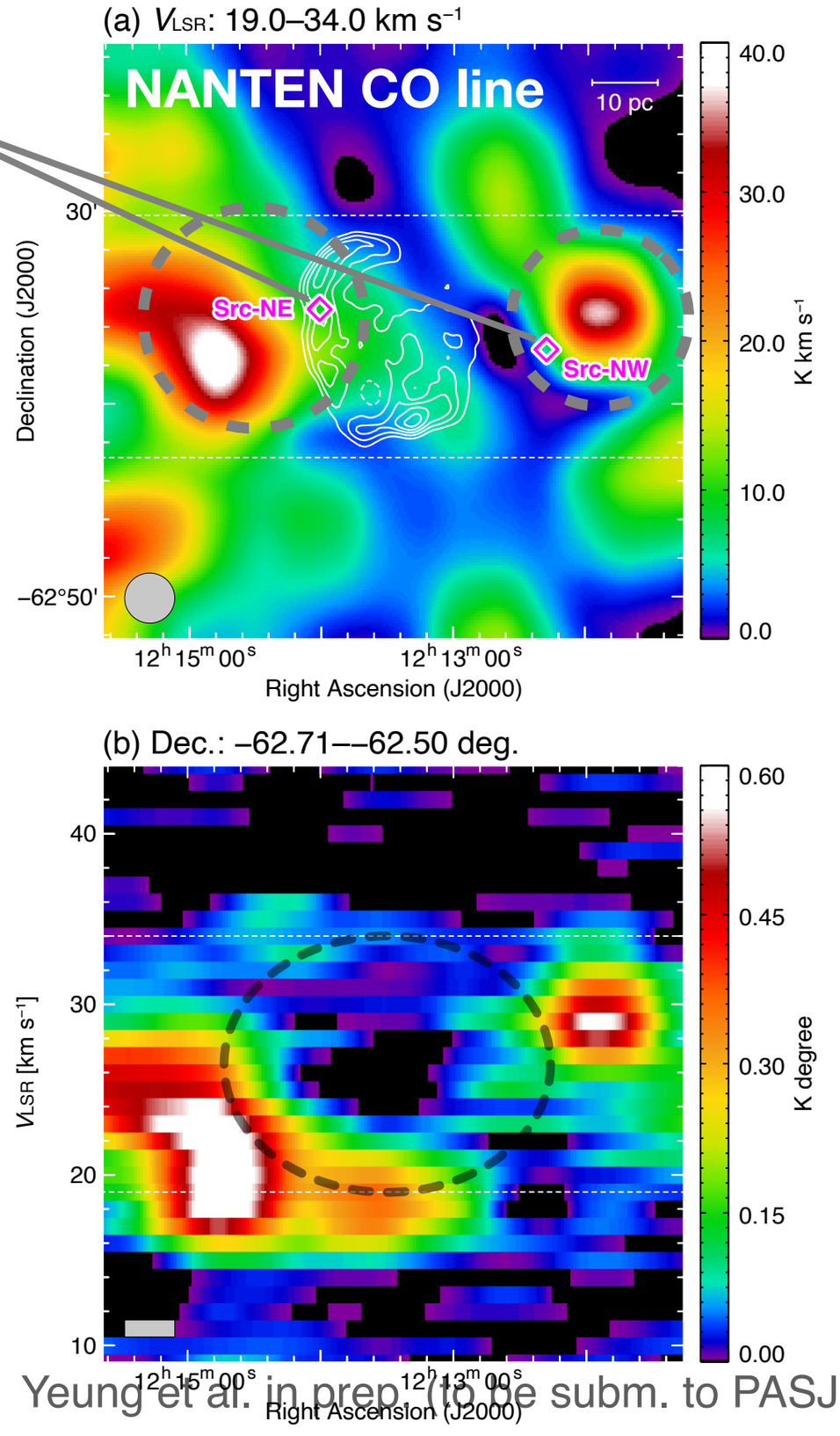
MCs as actual gamma-ray emitters

- The gamma-ray centroids are more coincident with the MC distribution than with the dimension of SNR G298.6-0.0. Why?

- Because pion-decays occur at proton collision sites (MCs) rather than the proton acceleration site (SNR).

- More accurately speaking, the actual gamma-ray emitting sources are the MCs impacted by the SNR-accelerated cosmic-ray particles, instead of the SNR itself.



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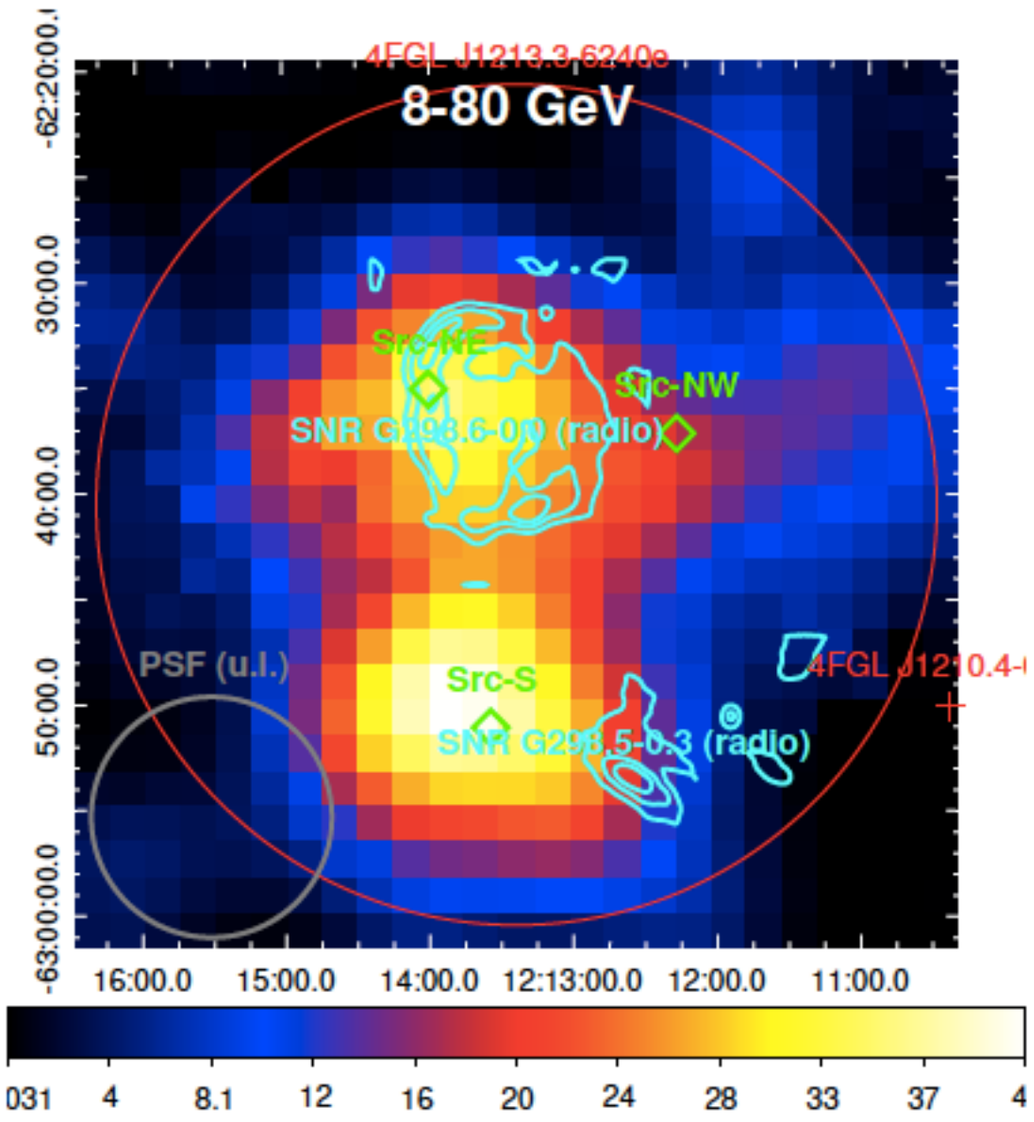
Major Orientation of SNR-MC Interaction

- Gamma-ray: Src-**NE** is much brighter than Src-NW

- X-ray: Diffuse emission is slightly more concentrated in **northeast** part of SNR

- CO line: MCs in SNR's **northeast** vicinity are larger, denser & closer to SNR

==> SNR-MC interaction occurs mainly in **northeast** direction



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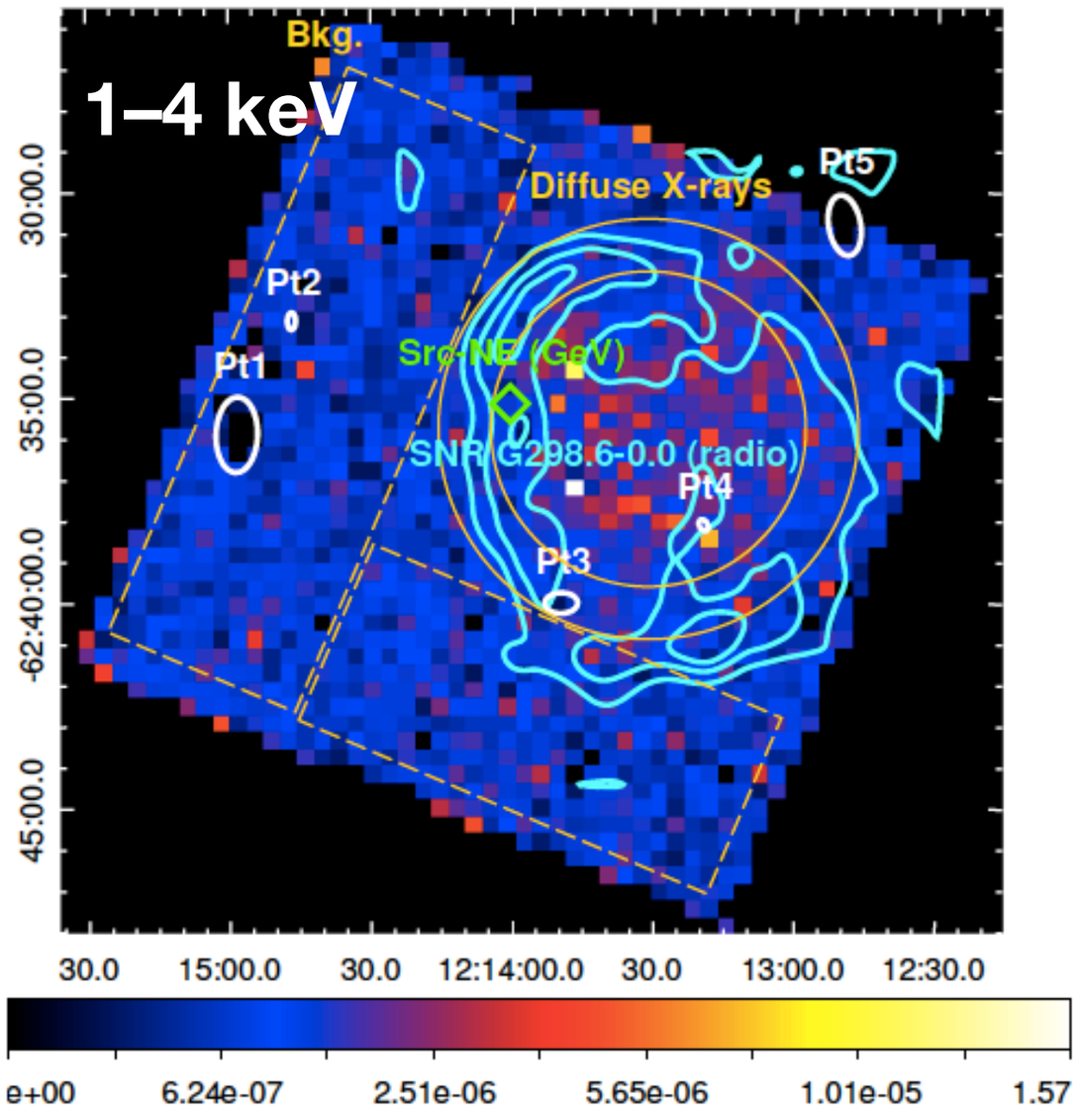

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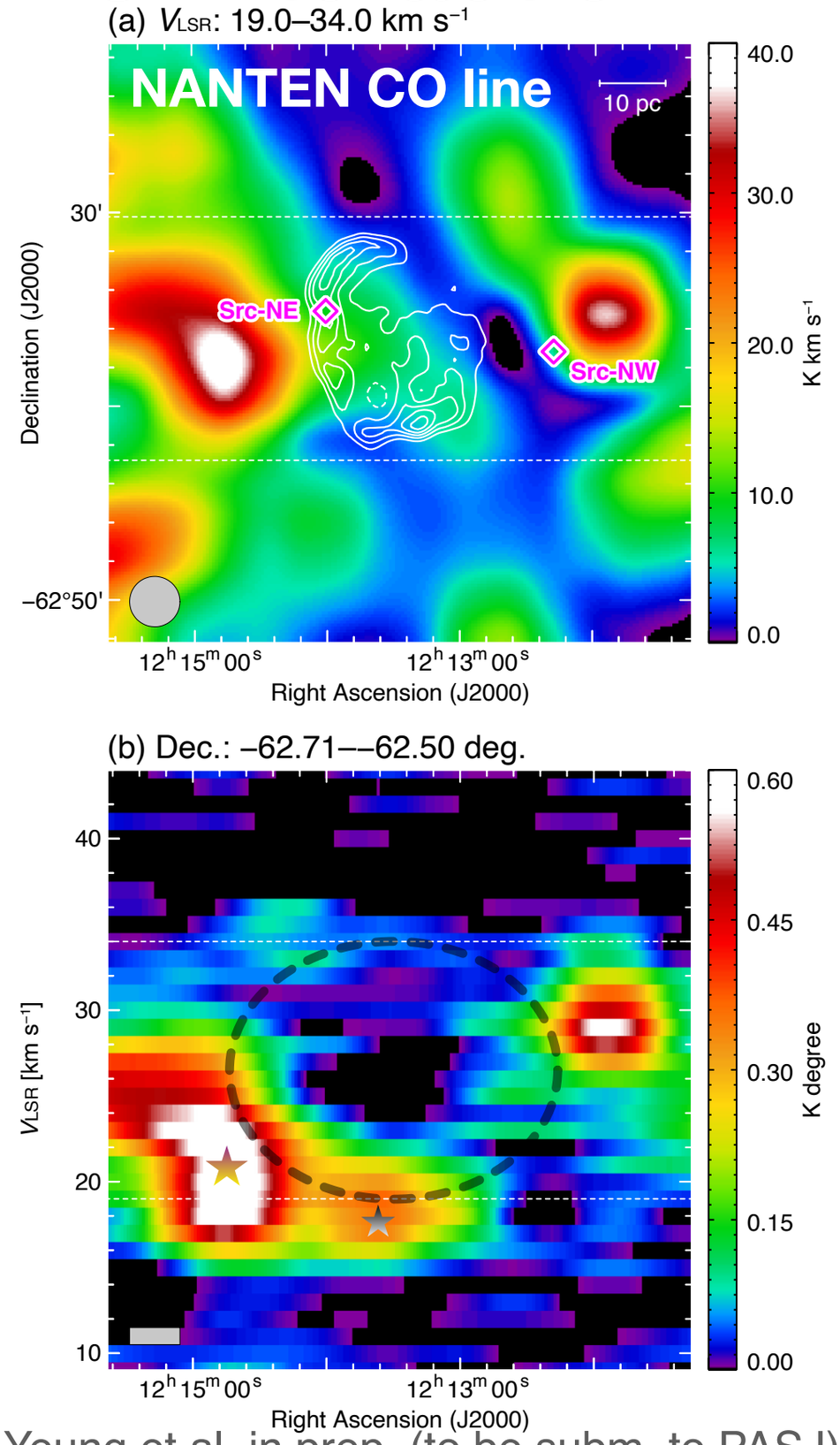

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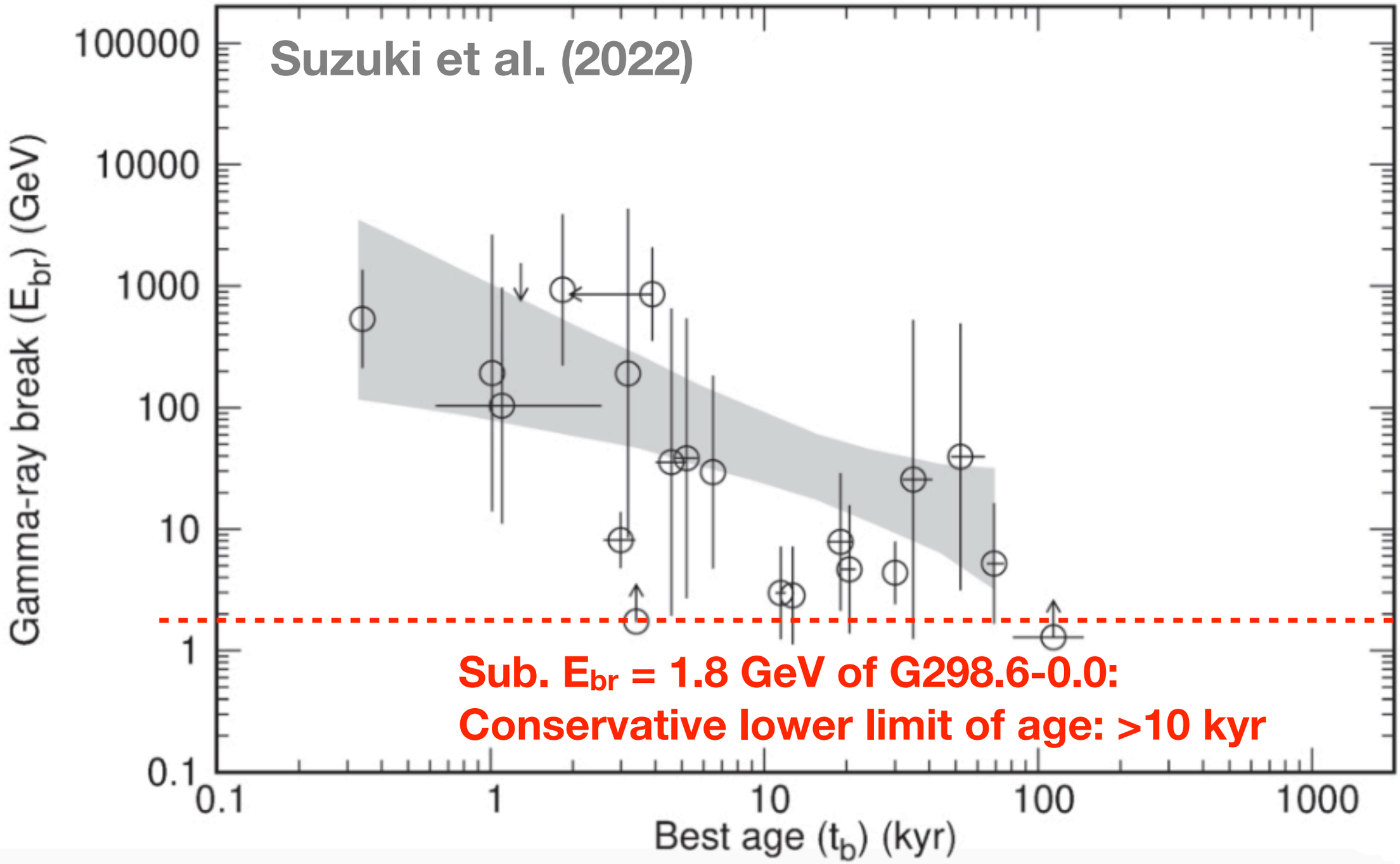
Estimated age of SNR G298.6-0.0

- Relation between SNR gamma-ray spectrum and SNR age



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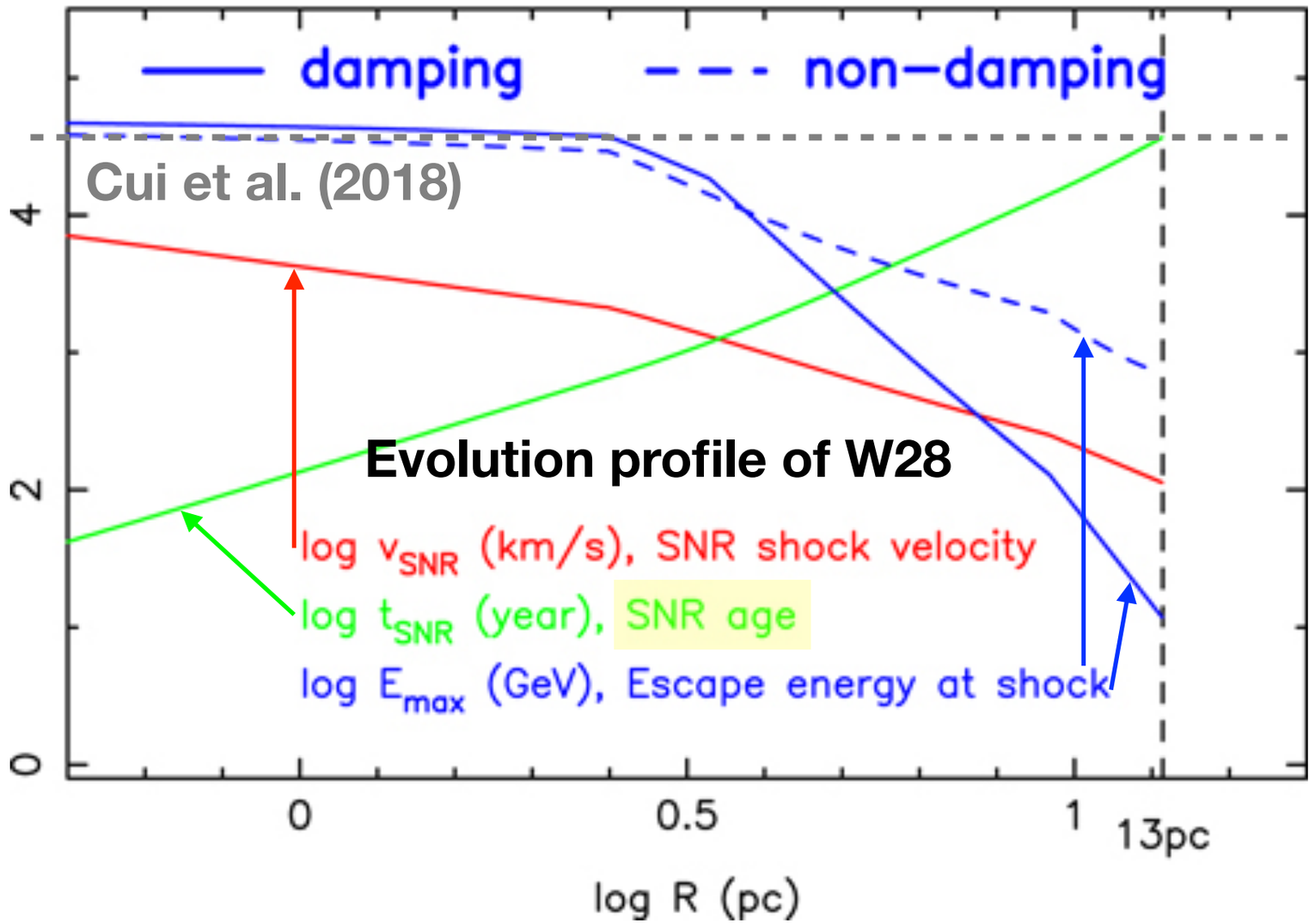
Estimated age of SNR G298.6-0.0

- Kinematic distance (CO & HI) of G298.6-0.0 from us : ~10.1 kpc
- Angular radius (radio) of G298.6-0.0 ~ 5.3’
  <==> Physical radius ~ 15.5 pc
- Size is prop. to Age
- SNR W28: Age > 30 kyr;
  R ~ 13.1 pc
- Conservative lower limit of G298.6-0.0 age:
  >10 kyr



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Estimated age of SNR G298.6-0.0

- Satisfactory fit of *VAPEC*×*PHABS* model to X-ray spectrum

==> Collisional Ionisation Equilibrium (CIE)

==> IP-domination (>10 kyr) had passed

==> Further supports an old age

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Kind Reminders

- In hadronic model, the actual gamma-ray emitting sources are the molecular clouds impacted by the SNR-accelerated cosmic-ray particles, instead of the SNR itself.

- The gamma-ray spectral shape of an SNR is somewhat correlated with the SNR age, but it is also affected by the surrounding environment.

Keep Calm & Investigate Supernova Remnants

Crab Nebula observed by *Hubble*
Credits: NASA/ESA