

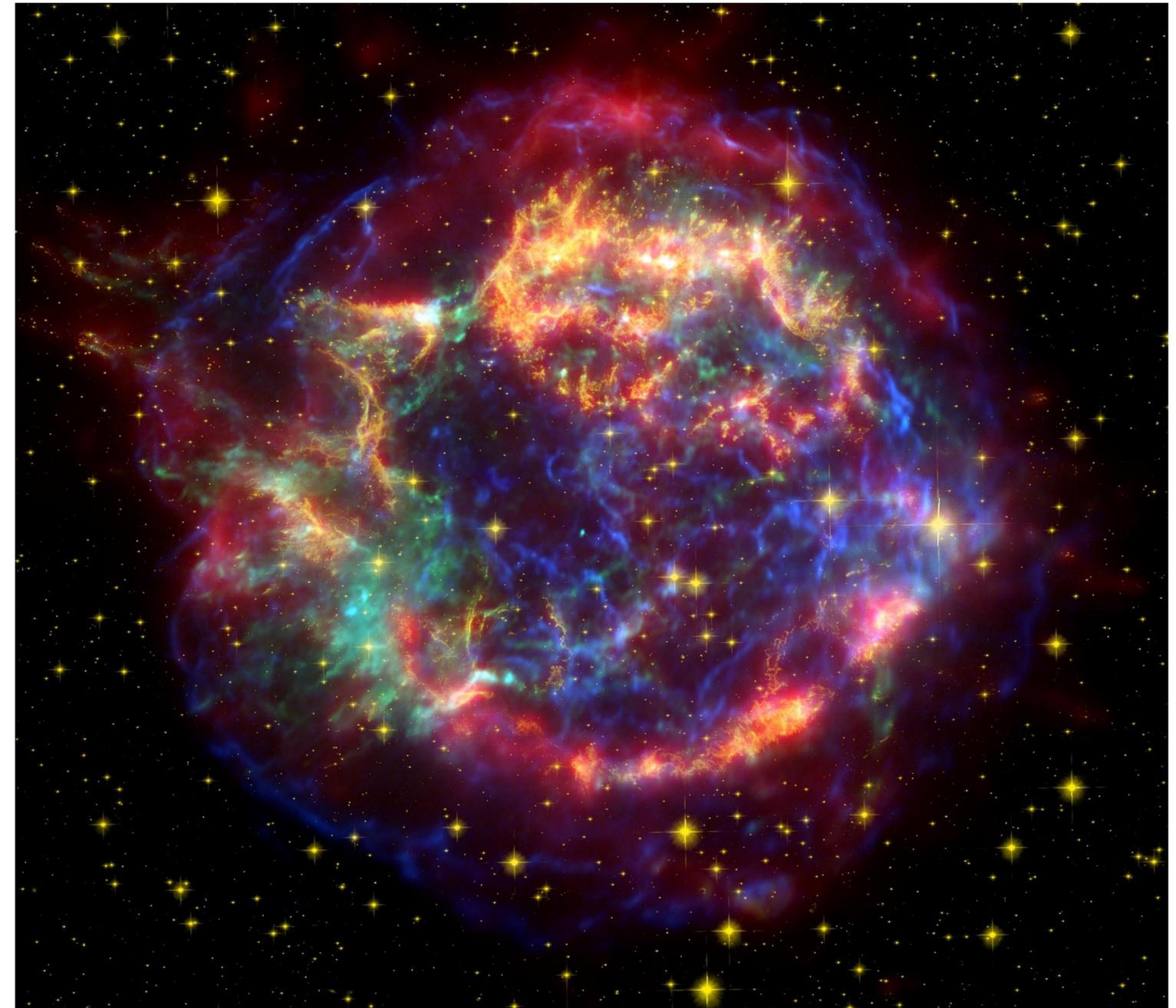
Molecular observations toward Cassiopeia A

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Cas A - prototype SNR

- Remnant of a Type IIb SN in AD 1681 \pm 19
- Best-observed SNR
- Prototype for many aspects of SNR study
 - Explosion mechanism
 - **CR acceleration (shock, gas density...)**
 - SNR evolution
 - ...

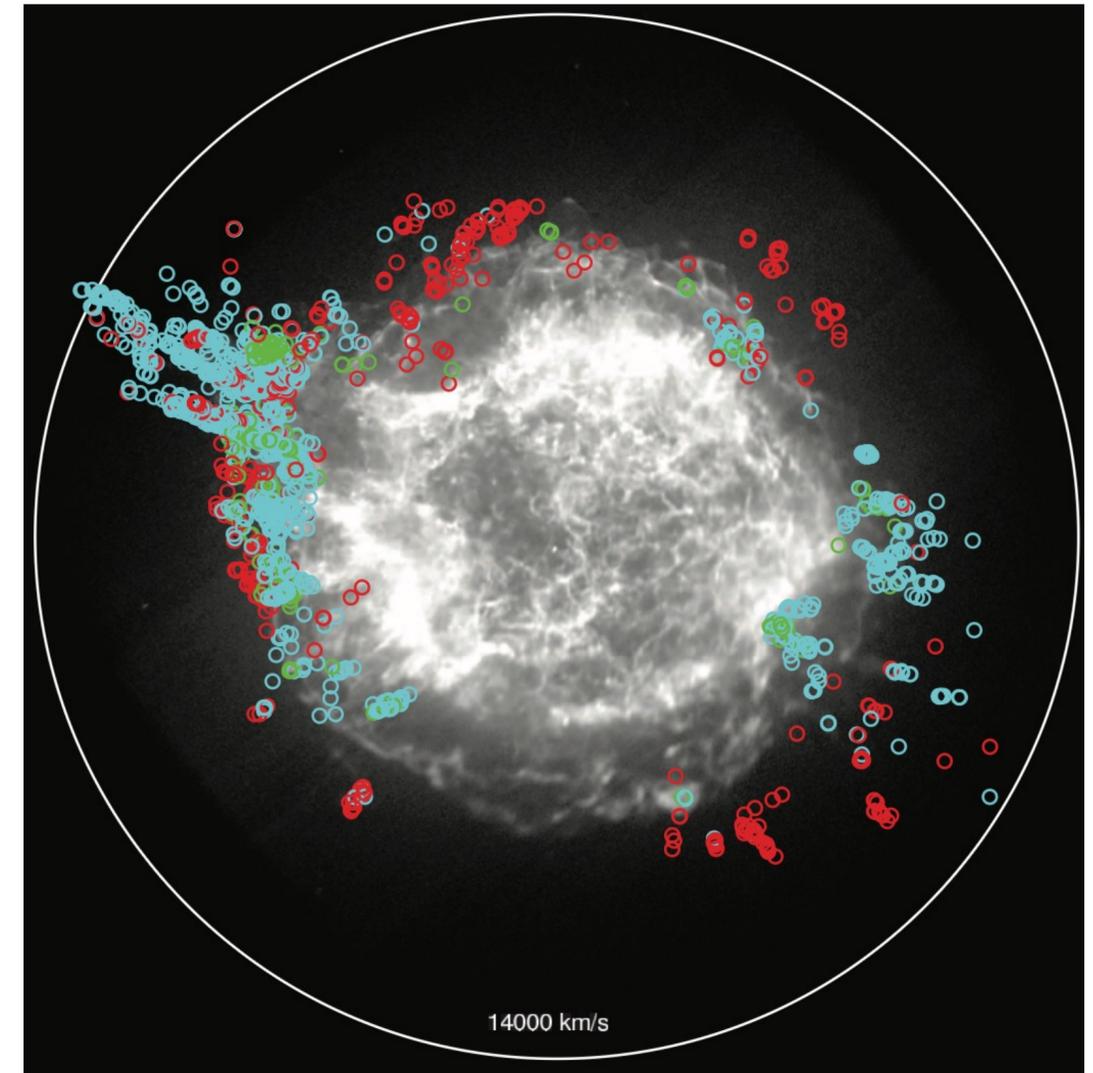
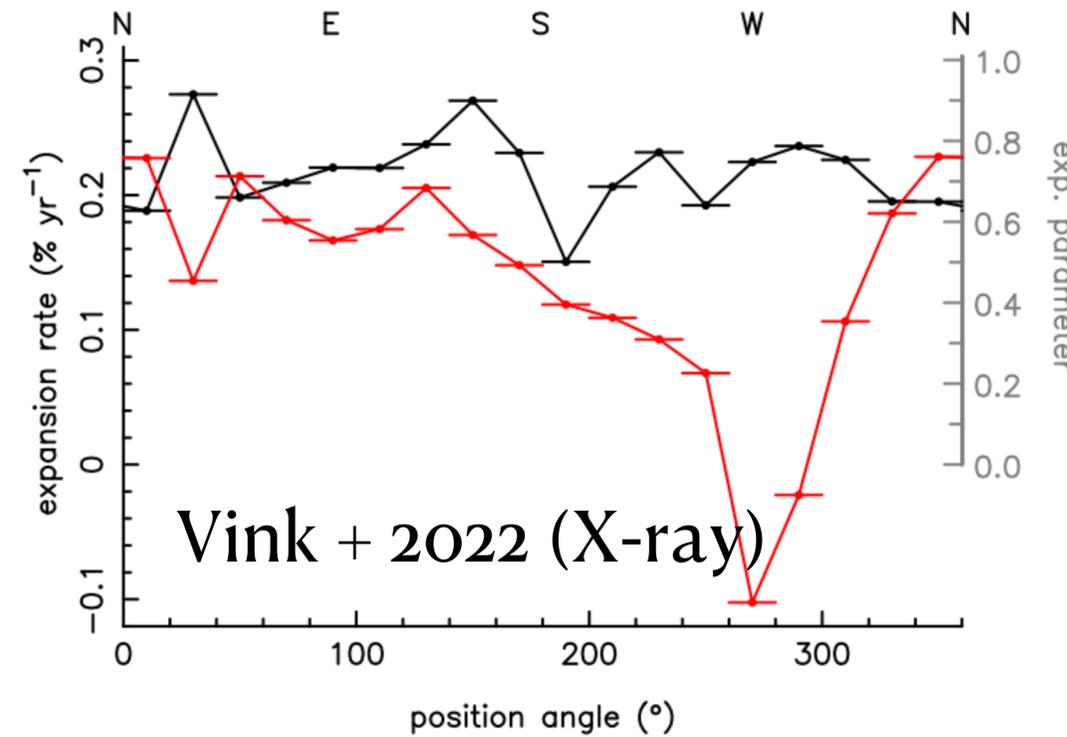
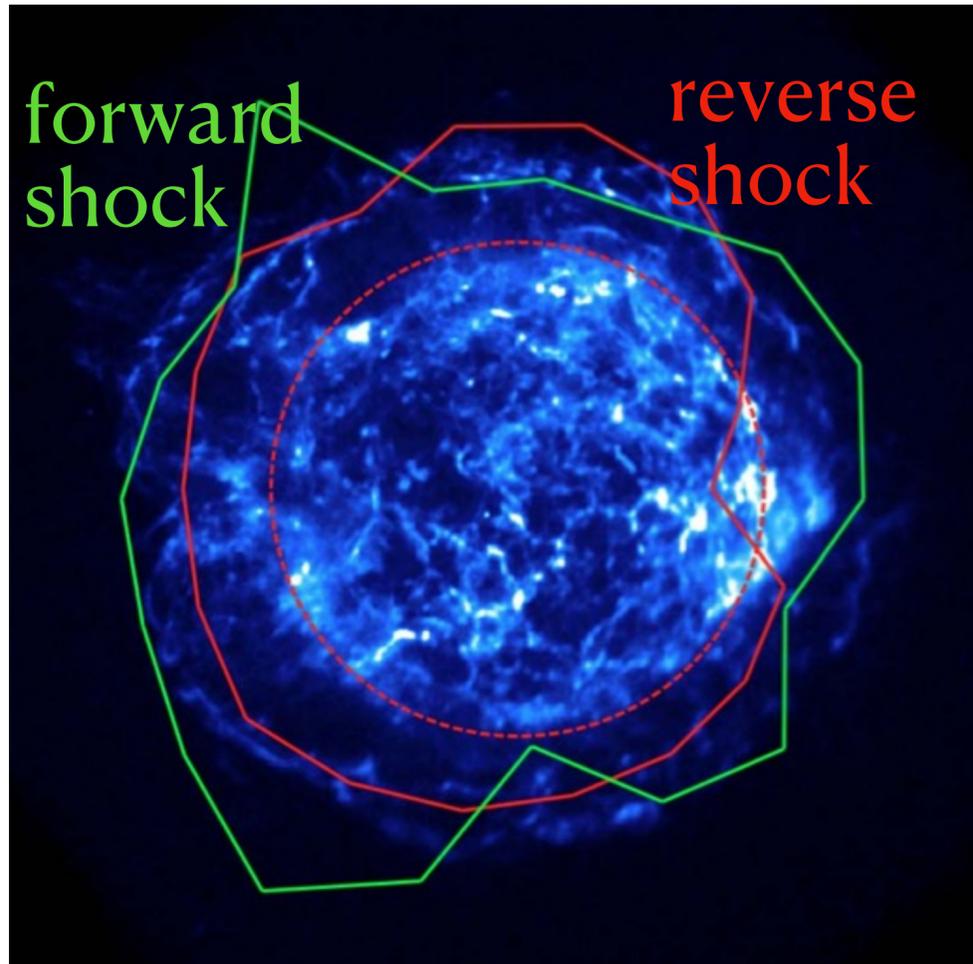


Chandra X-ray + Spitzer IR + HST optical

Kinematic measurements

Asymmetric expansion (explosion \checkmark environment?)

Asymmetric explosion



Average forward shock velocity $\sim 5800 \text{ km/s}$

Reverse shock $> 3000 \text{ km/s}$, peaking at 8000 km/s

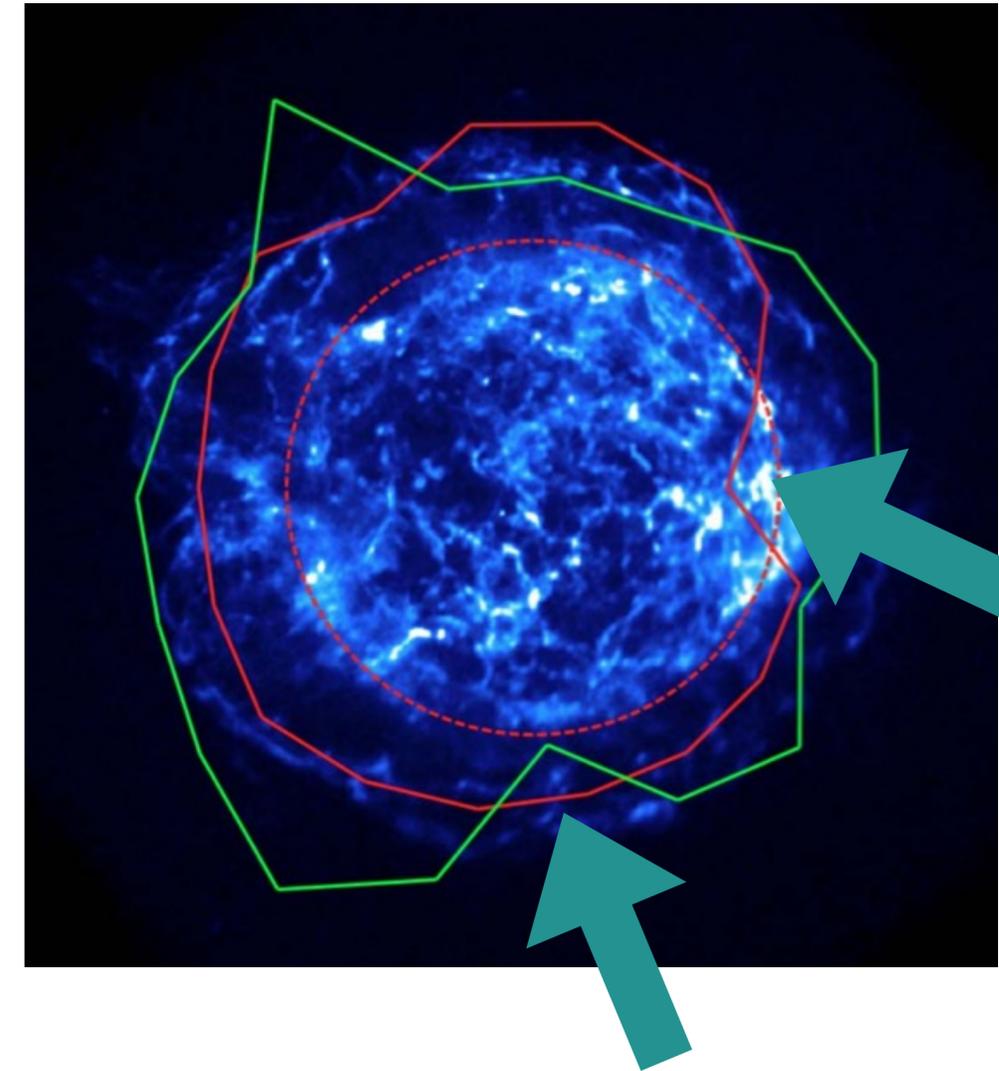
transverse velocity of outlying ejecta knots
 $5500 - 14500 \text{ km/s}$

Fesen + 2006 (optical)

Environment of Cas A

CSM (+ ISM?)

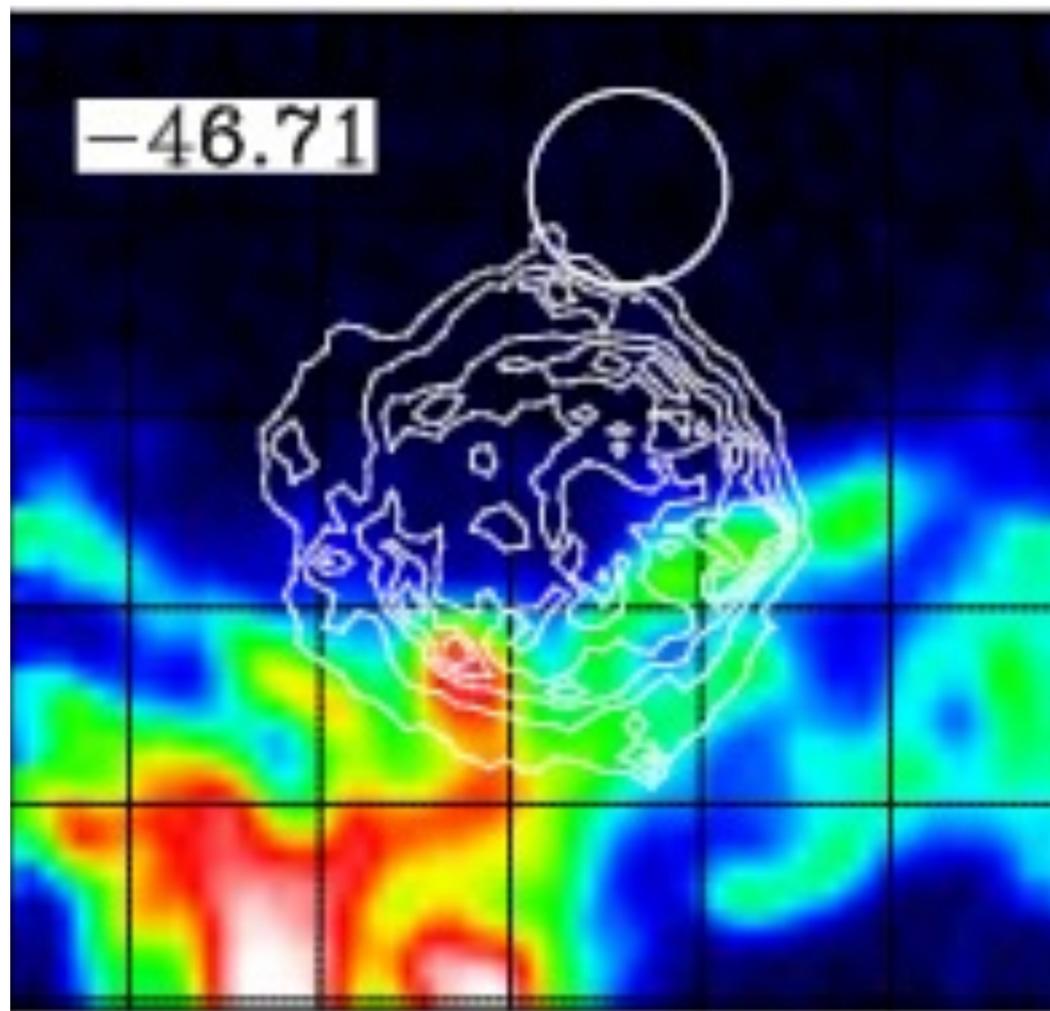
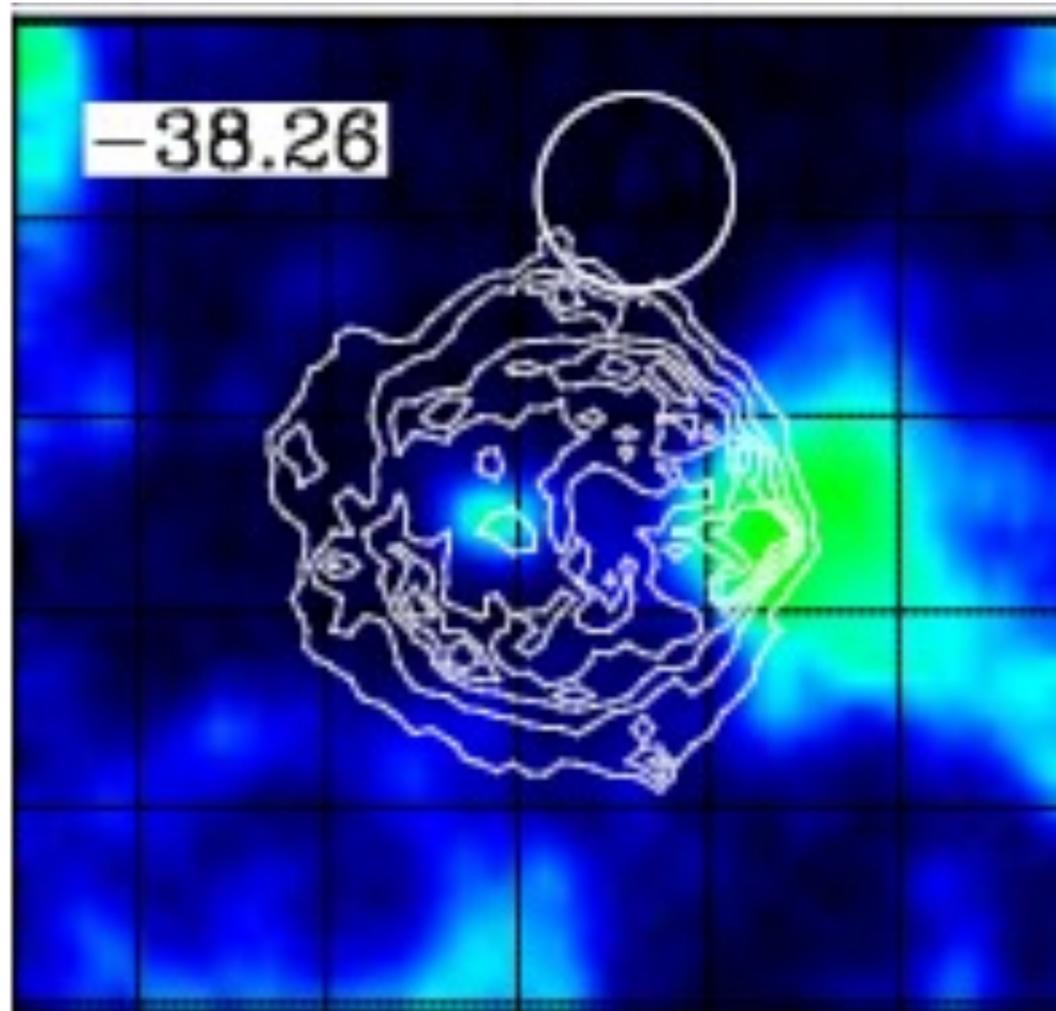
- Dense winds by the progenitor star
 - SN IIb — strong pre-SN mass-loss (Krause + 2008, Rest + 2011)
 - Expansion evolution follows $R \propto t^{0.7}$, consistent with that predicted by the wind cavity explosion (Koralesky + 1998, Vink + 1998)
 - $n_{\text{H}} \sim 0.9 \text{cm}^{-3}$ at the rim
 - The mass-loss was aspherical, influencing the SNR morphology (Orlando + 2021)
- Dense ISM near Cas A?
 - may influence Cas A's evolution and gamma-ray emission



Vink + 2022 (X-ray)

Are there dense clouds near Cas A?

Molecular gas distribution along the line of sight of Cas A

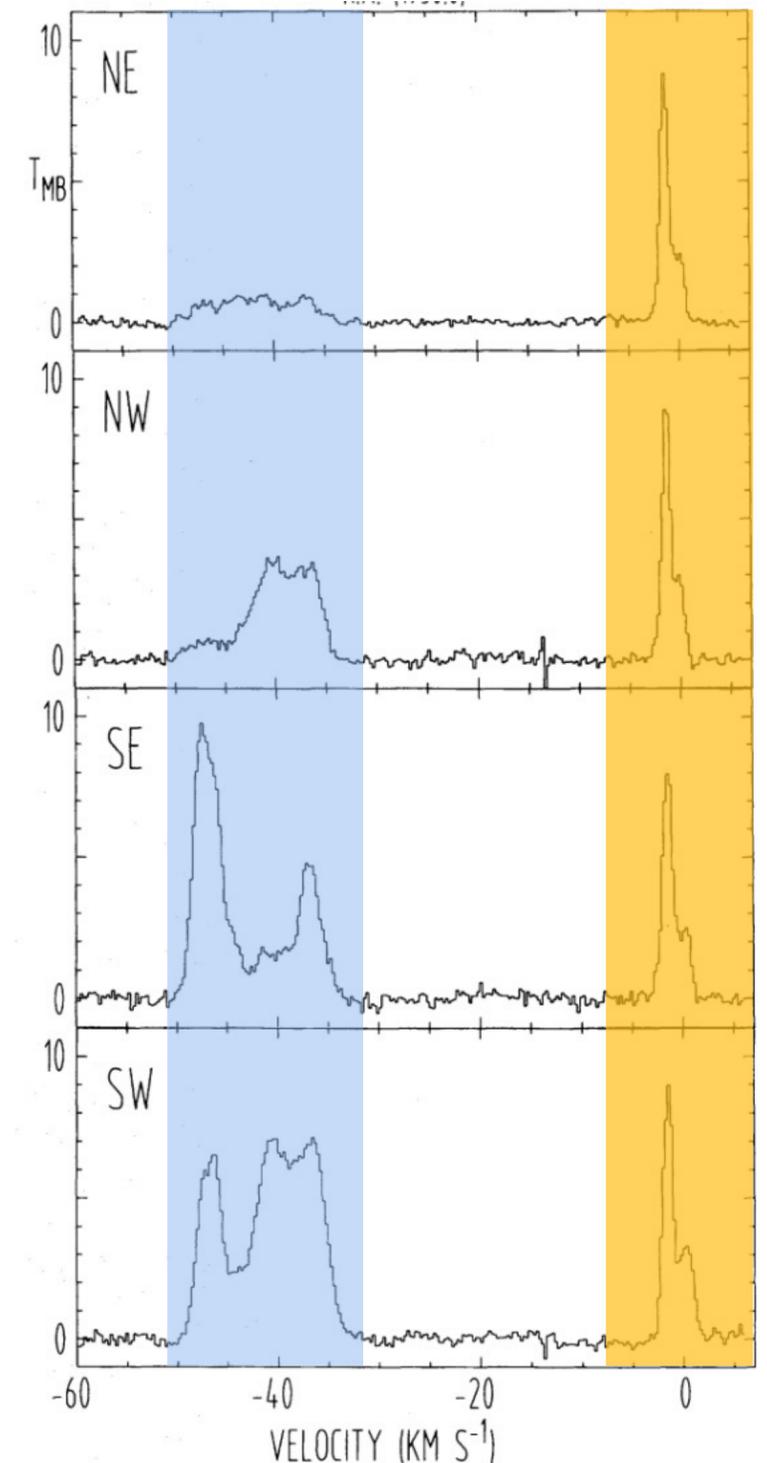


Kilpatrick + 2014 (SMT 12m telescope, CO J=2-1)

CO spectra

Perseus arm

near the Sun
Orion spiral arm

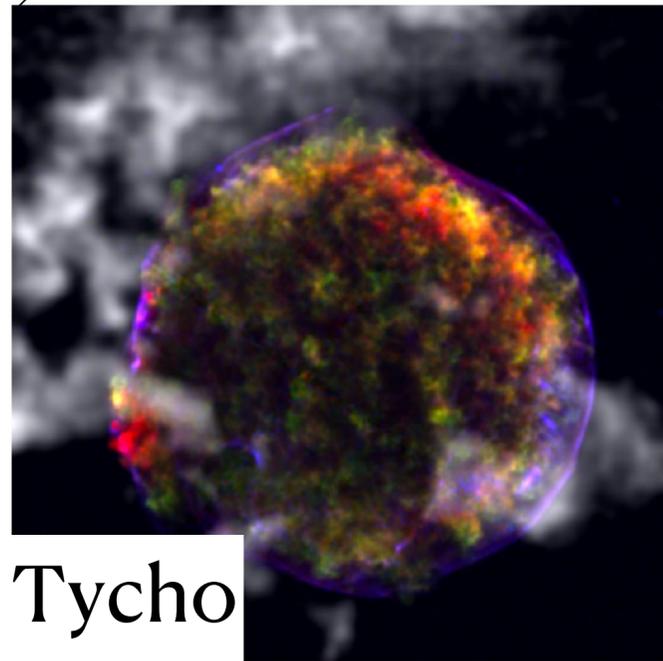
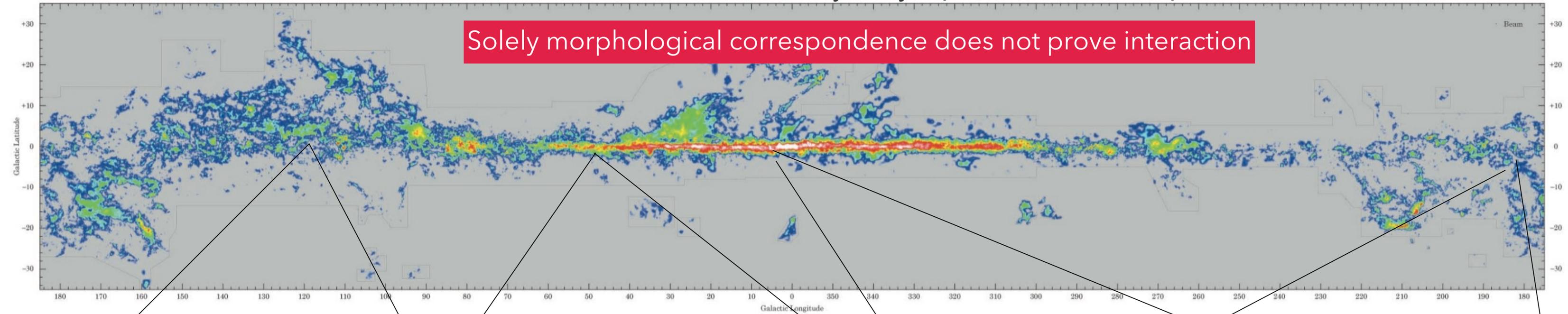


Wilson+1993 (IRAM 30m, CO)

Tens of SNRs are associated with molecular clouds

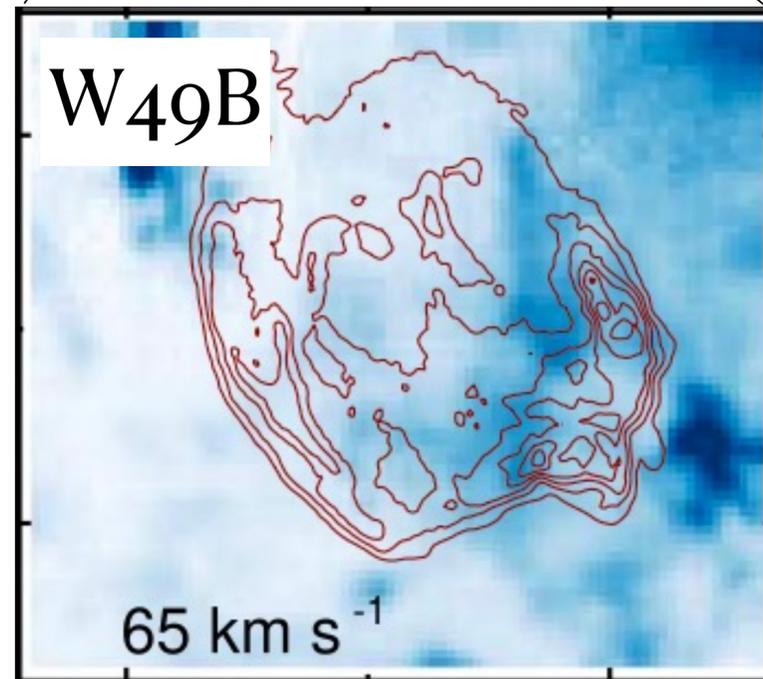
CO emission of the Milky Way (Dame et al. 2001)

Solely morphological correspondence does not prove interaction



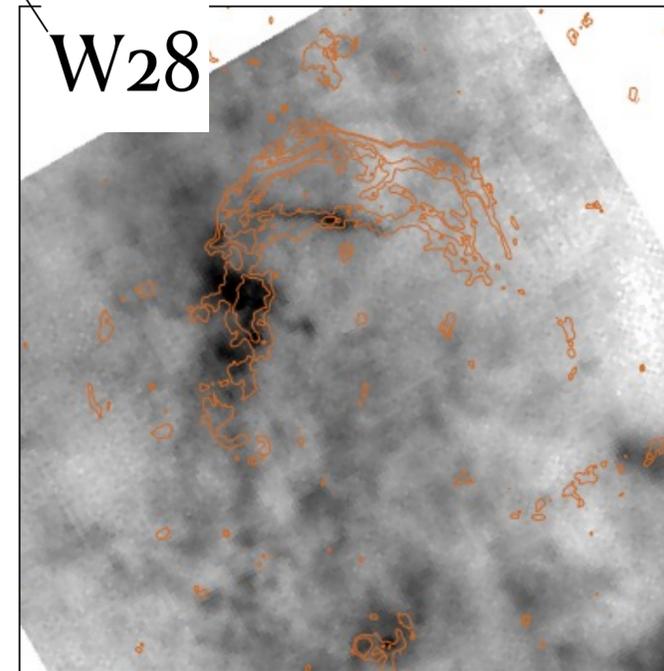
Tycho

Zhou + 2016



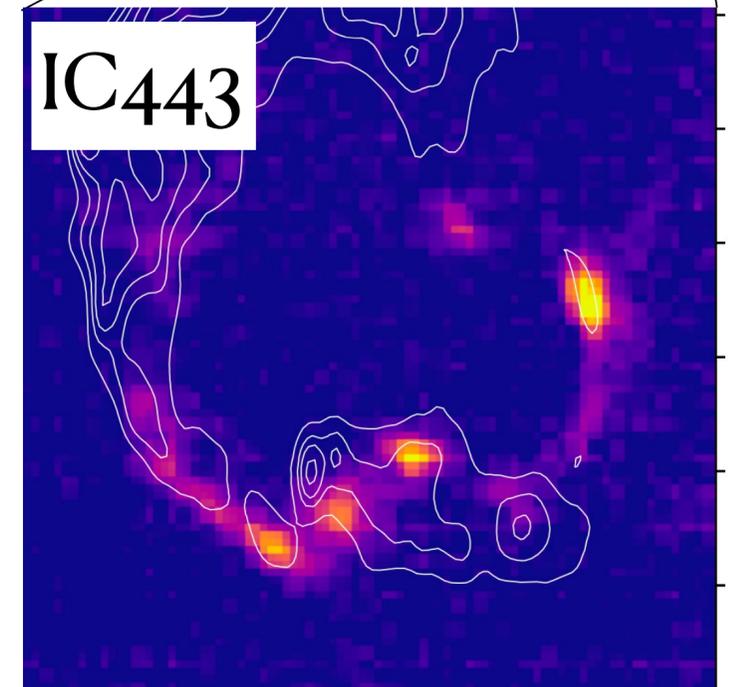
W49B

Zhou + 2022



W28

by Tianyu Tu+2024

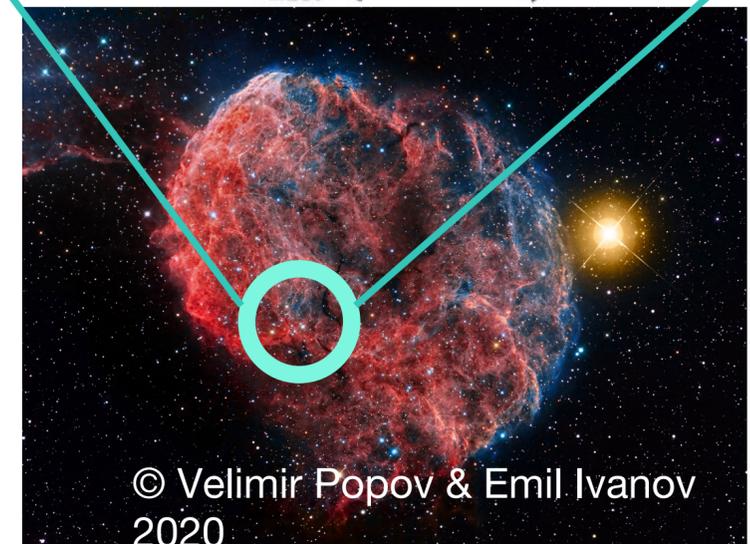
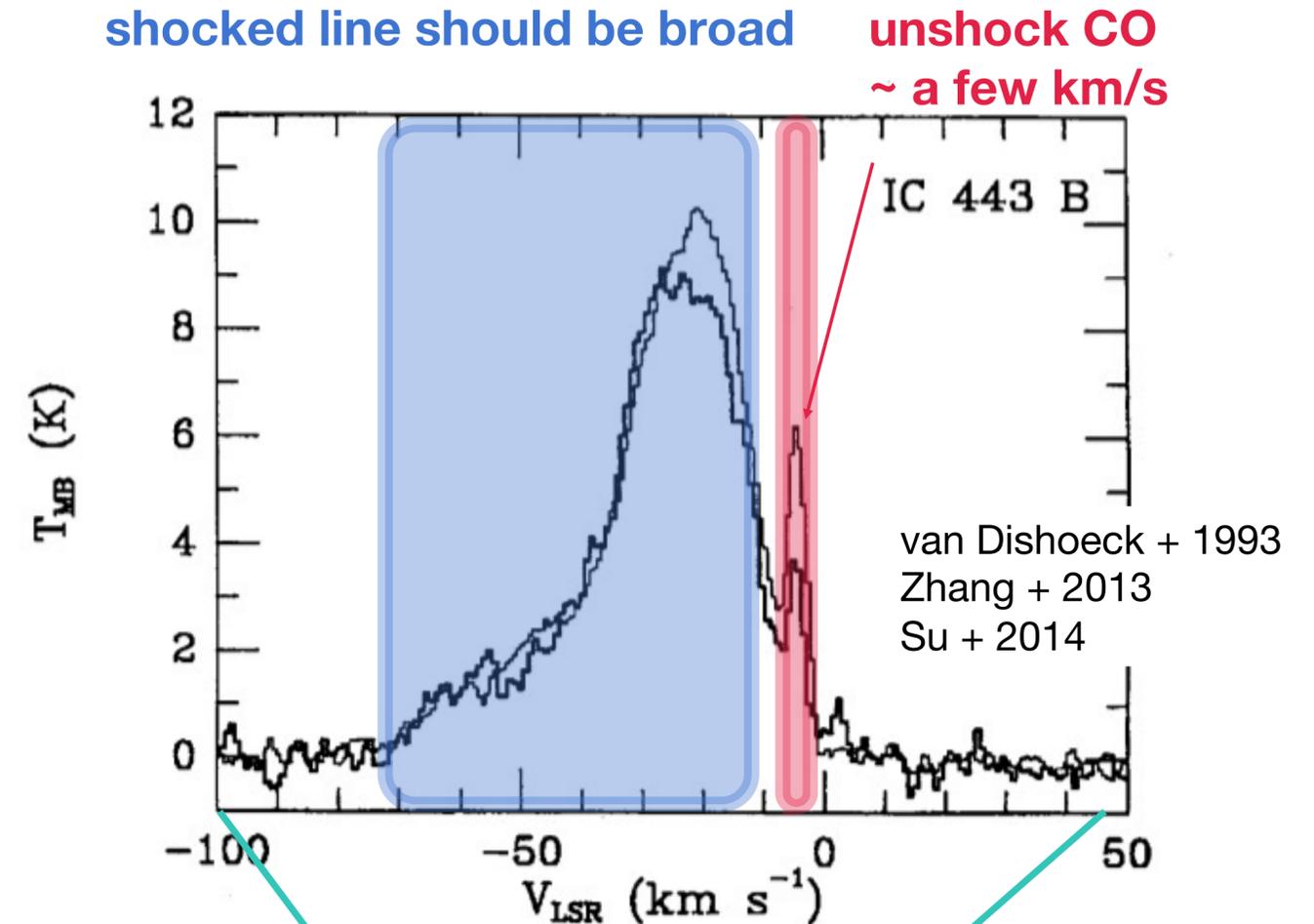


IC443

by Qianqian Zhang+

Observational evidence of SNR-MC interaction

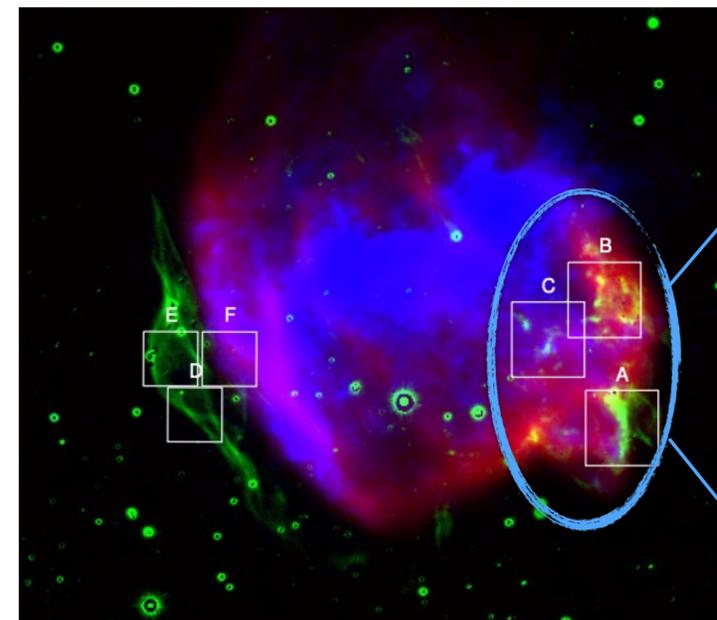
- OH 1720 MHz maser (shock)
- **molecular line broadening (shock)**
- $^{12}\text{CO } 2-1/1-0 \gg 1$ (heating)
- H₂ near-IR emission (heating)
- Shock, CR or X-ray induced chemistry, e.g, HCO⁺/CO enhancement
- Neutral Fe K α fluorescence line (interaction between CRs/hard X-ray emission with dense gas)
- ...



Observational evidence of SNR-MC interaction

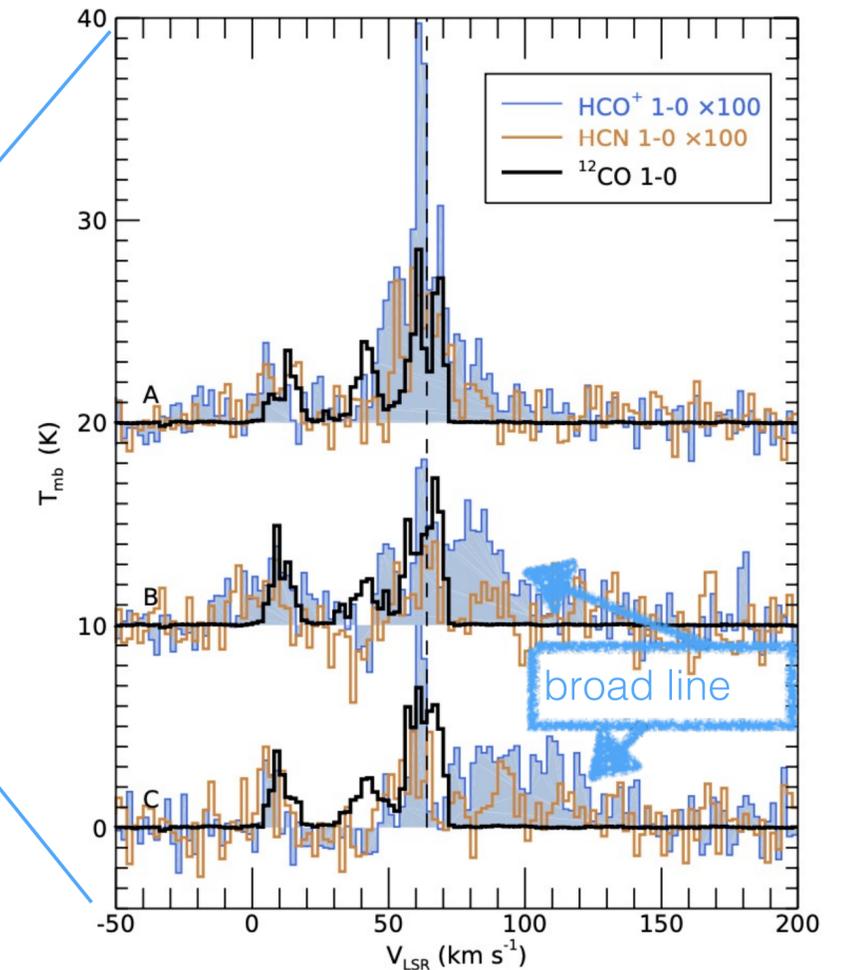
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W₄₉B (Zhou et al. 2022)



radio, 2.12 μm H₂, X-ray

Broad HCO⁺ line



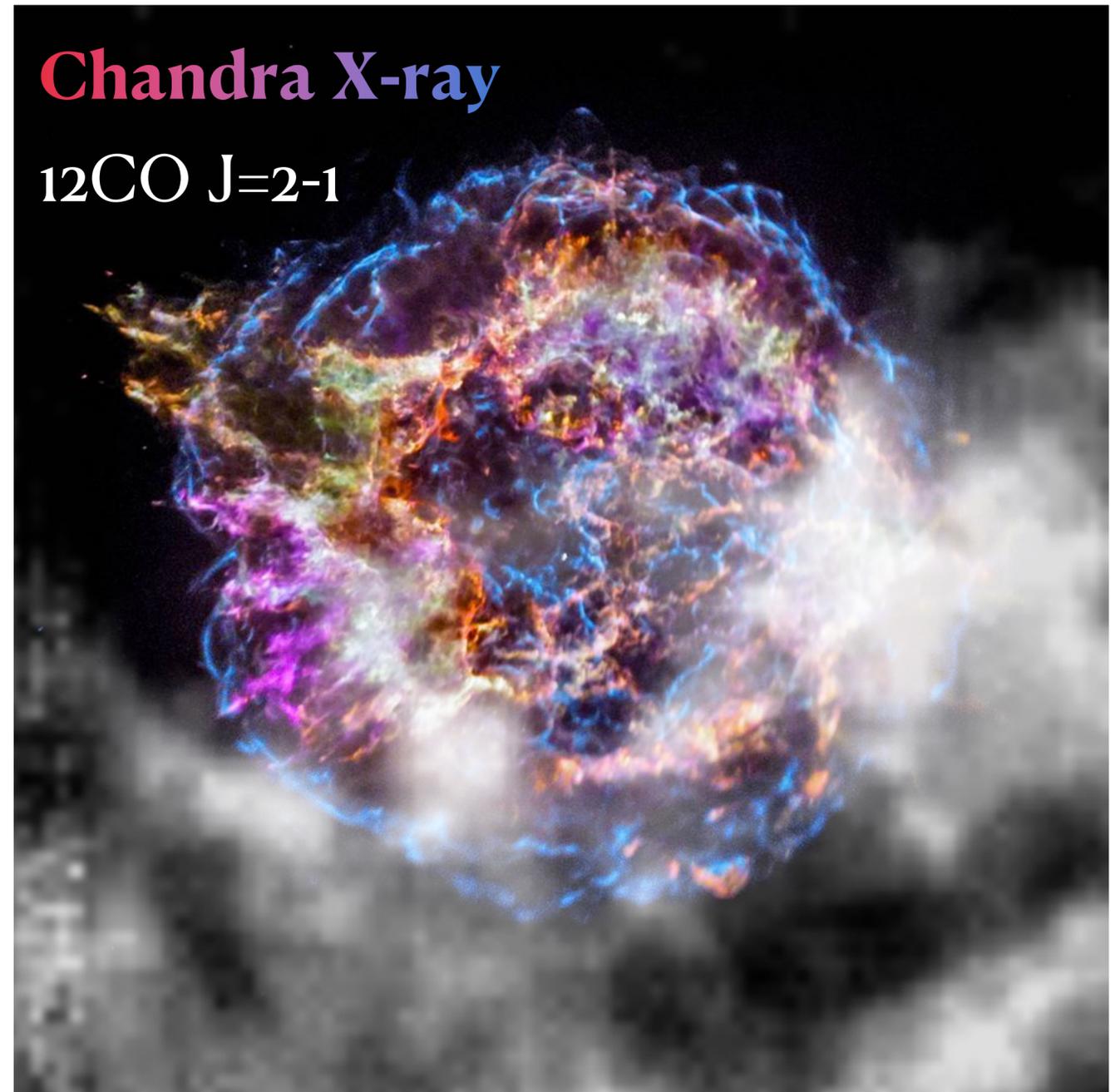
Unusually high CO⁺/CO intensity ratio ~ 1 ,
> 10x than ISM value

New molecular observations toward Cas A

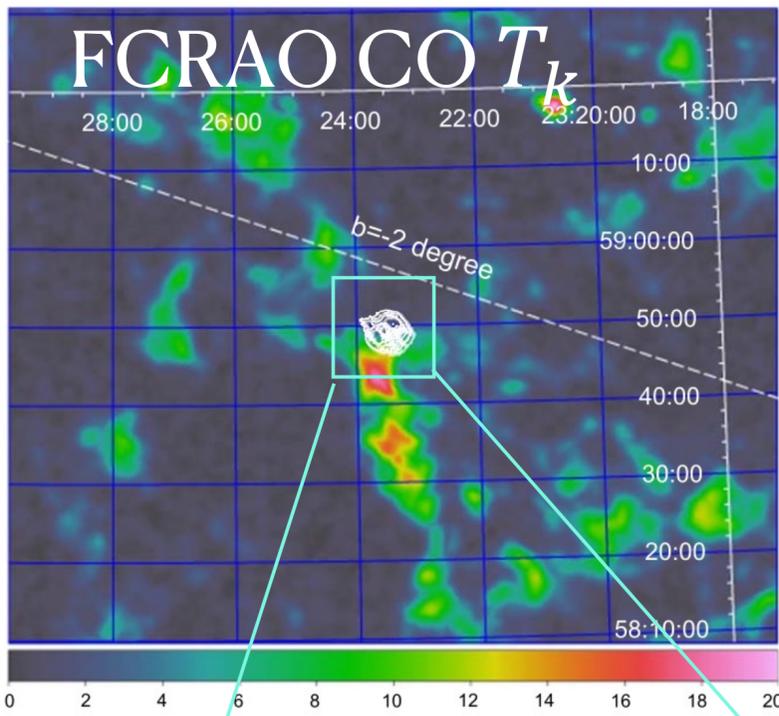
- IRAM 30m observations
 - mapping: 4 CO transitions
 - line survey: a few positions
 - angular resolution: 11" for CO 2-1
- Aim: test if the MCs are associated with Cas A
 - search for broad lines indicative of shock
 - search for high temperature (and CO J=2-1/1-0 ratio) that are indicative of heating

Line
$^{12}\text{CO } J = 2-1$
$^{13}\text{CO } J = 2-1$
$^{12}\text{CO } J = 1-0$
$^{13}\text{CO } J = 1-0$
$\text{HCO}^+ J = 1-0$

CO emission towards Cas A

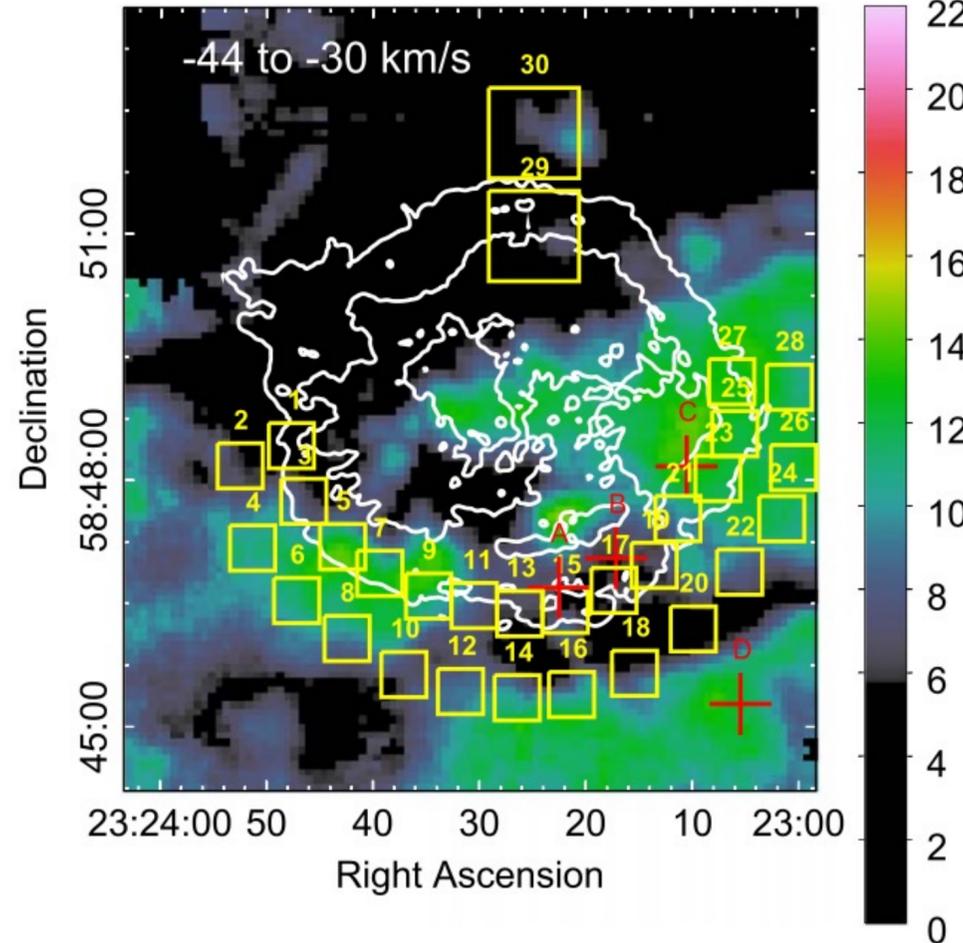
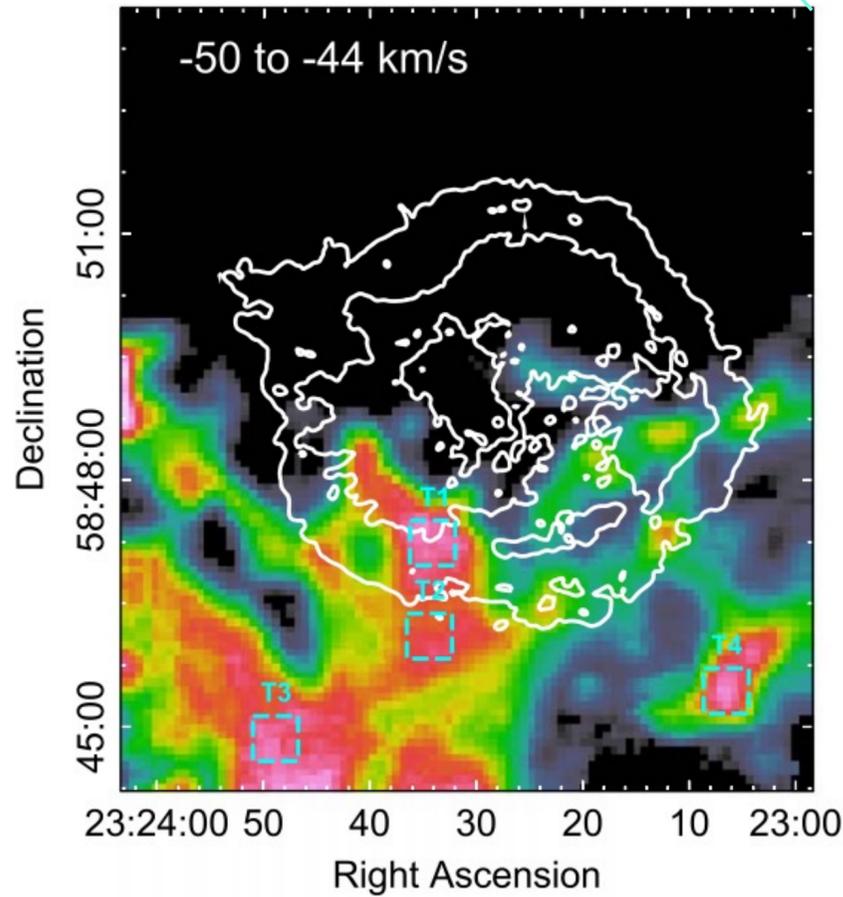


Temperature of the MCs



$T_k \leq 22\text{K}$

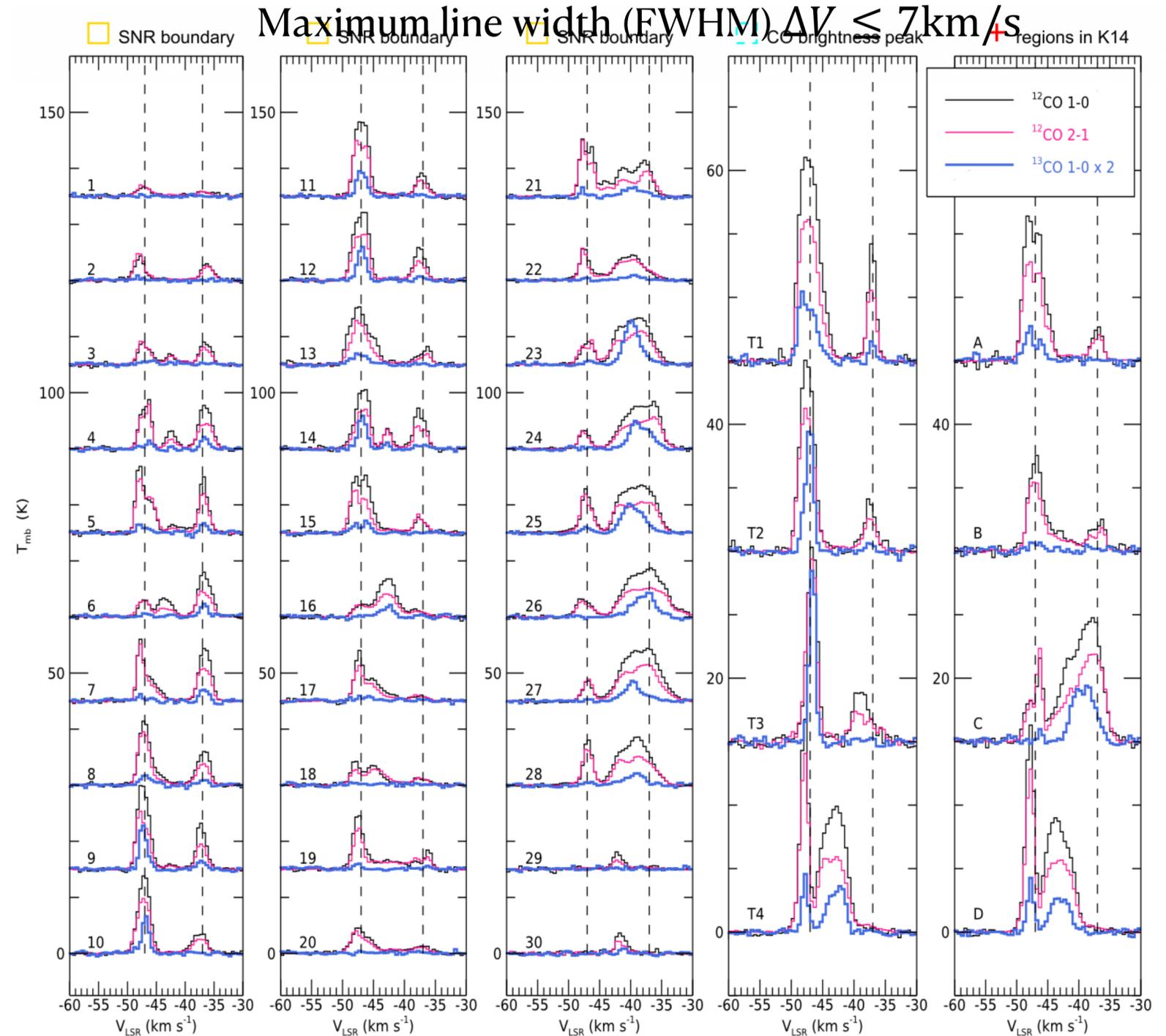
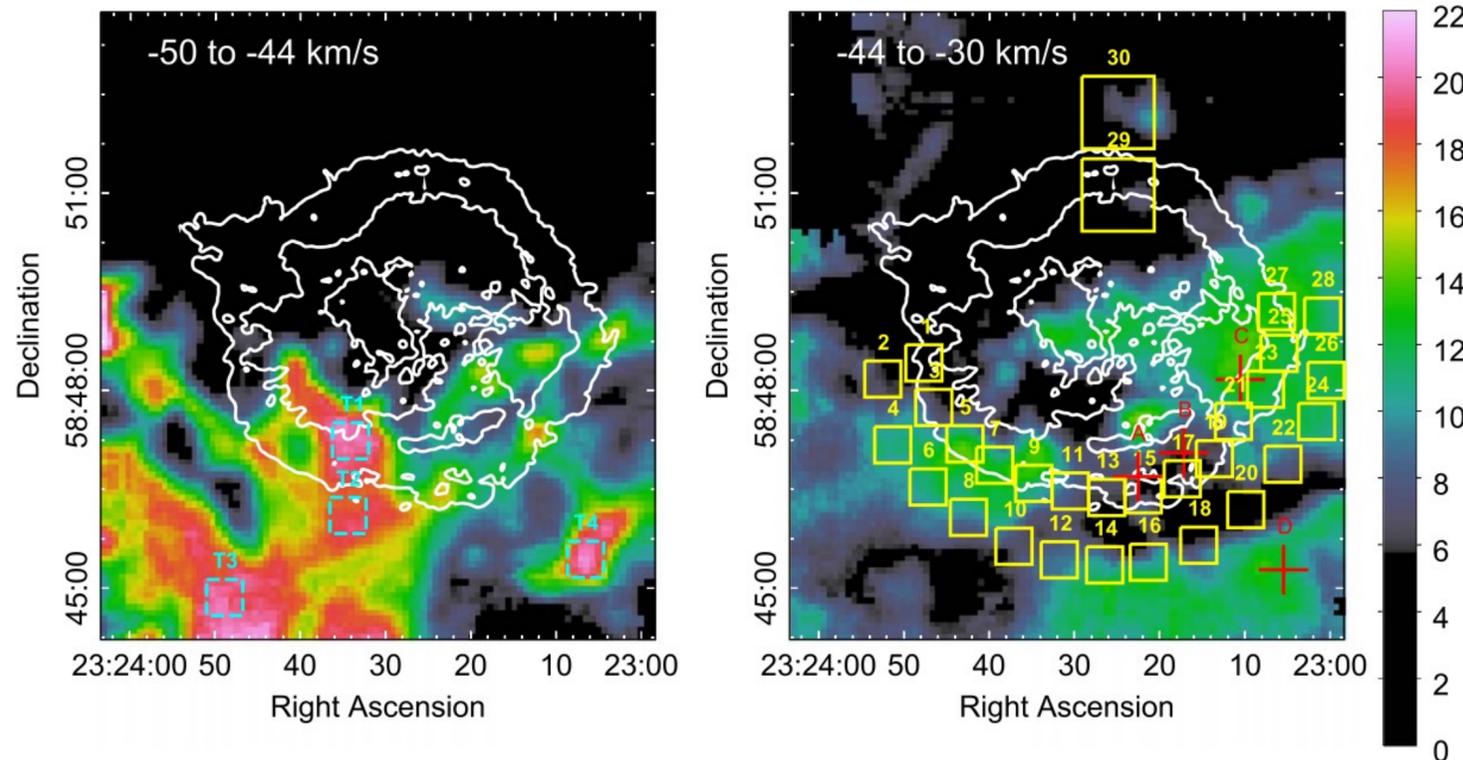
$T_k \leq 15\text{K}$



- Gas at $V_{\text{LSR}} = -50 \sim -44\text{km/s}$ is warmer
- Gas temperature is similar to that of quiescent giant MCs (10–20 K)
- The relatively high temperature is also seen far outside of the SNR boundary (shock heating should predict a higher temperature near or within the SNR)

$$T_k = \frac{5.53}{\ln\{1 + 5.53/[T_{\text{mb}}(^{12}\text{CO})/f + 0.84]\}} \text{K}$$

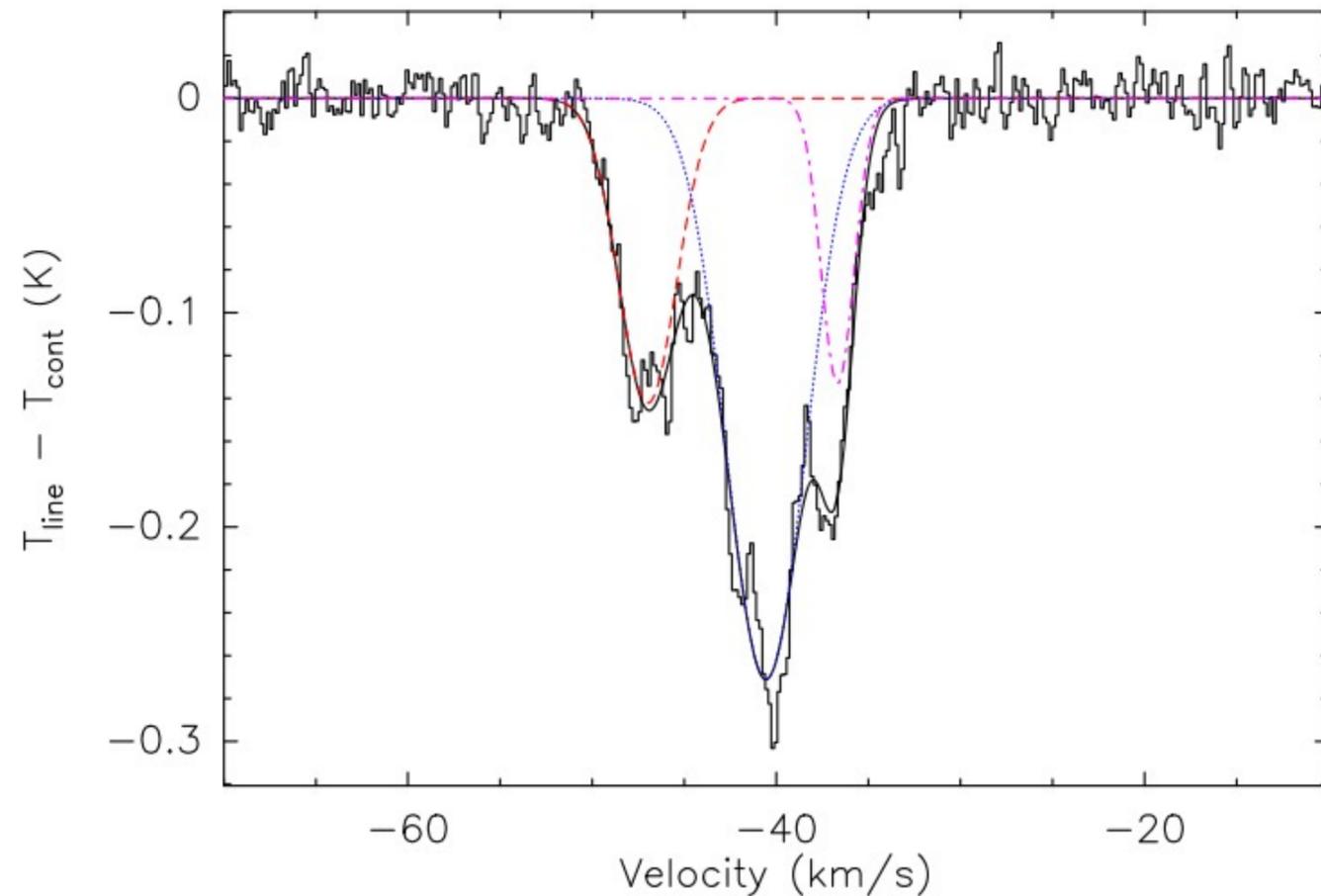
CO spectra \longrightarrow no evident line broadening



- CO lines are narrow
- CO line profiles at around the SNR boundary are similar to those far away from the SNR
- $^{12}\text{CO } J=2-1/1-0$ ratio ≤ 1 (no extra heating)

These MCs are foreground gas

HCO⁺ absorption lines toward
the radio peak of Cas A



- Foreground HCO⁺ gas can absorb the radio continuum emission of Cas A at specific frequencies
- Cas A is behind the MCs
- $N(\text{HCO}^+) \sim 5.7 \times 10^{11} \text{ cm}^{-2}$
- $N(\text{HCO}^+)/N(\text{CO}) \sim 10^{-6}$ (interstellar MCs: $10^{-6} \sim 10^{-4}$)
- In contrast, CR-heated gas shows high $N(\text{HCO}^+)/N(\text{CO})$

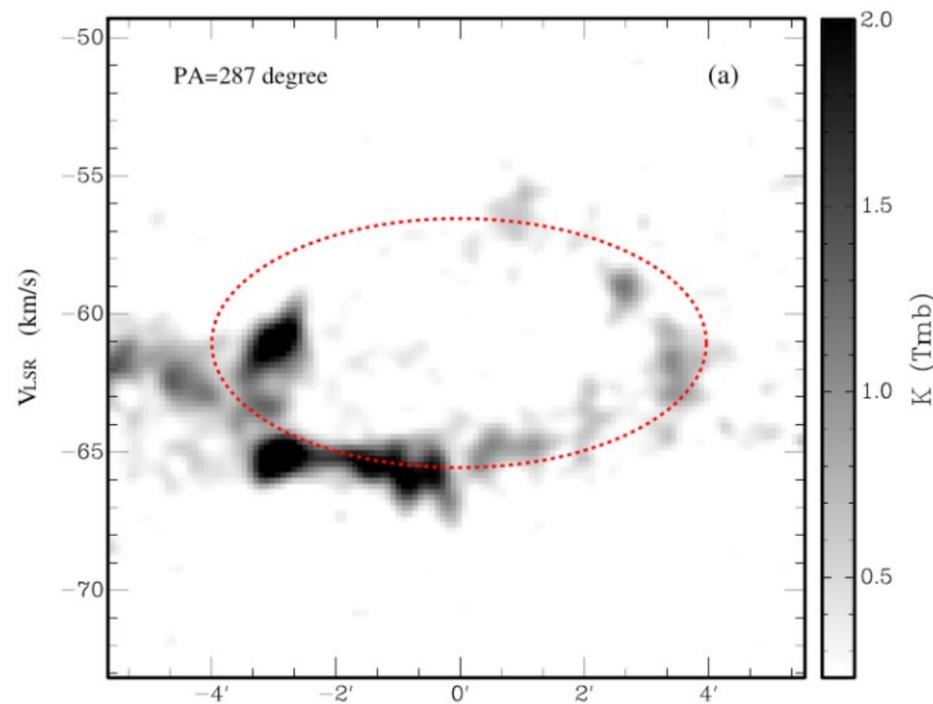
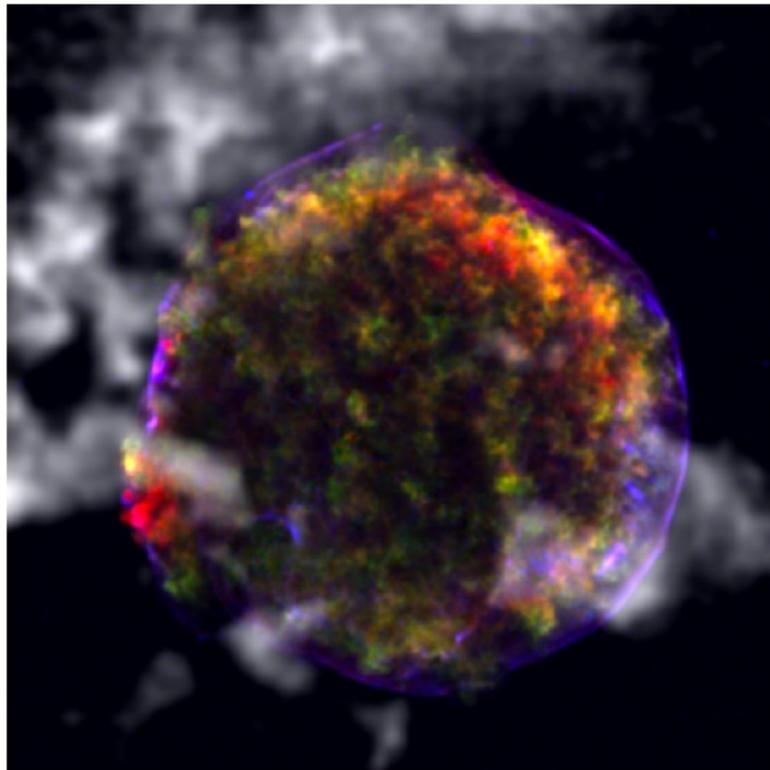
No interaction \neq no association

expanding bubbles discovered in SNRs – progenitor winds

CO expansion motion for G106

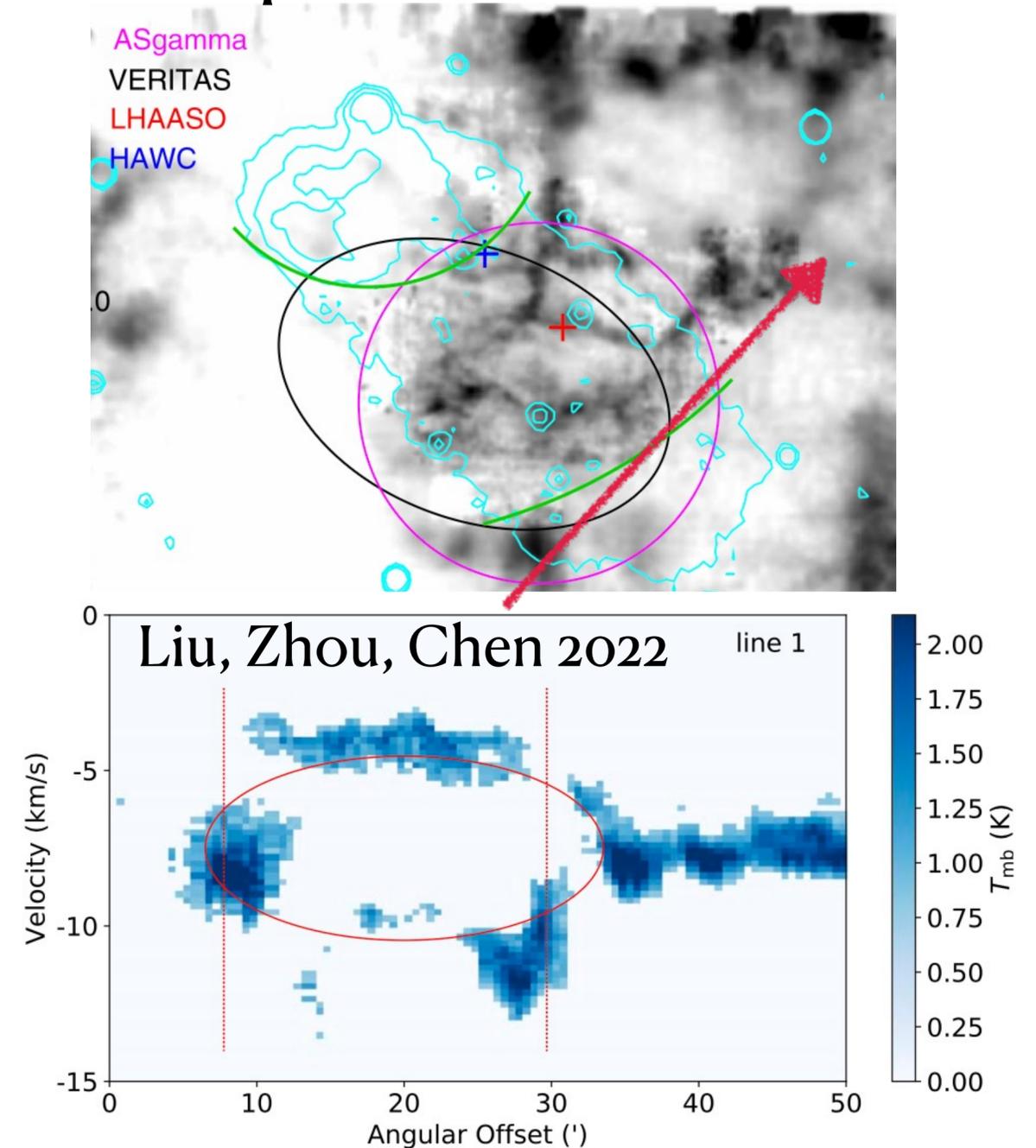
CO (white) near Tycho

5 km/s spherical expansion



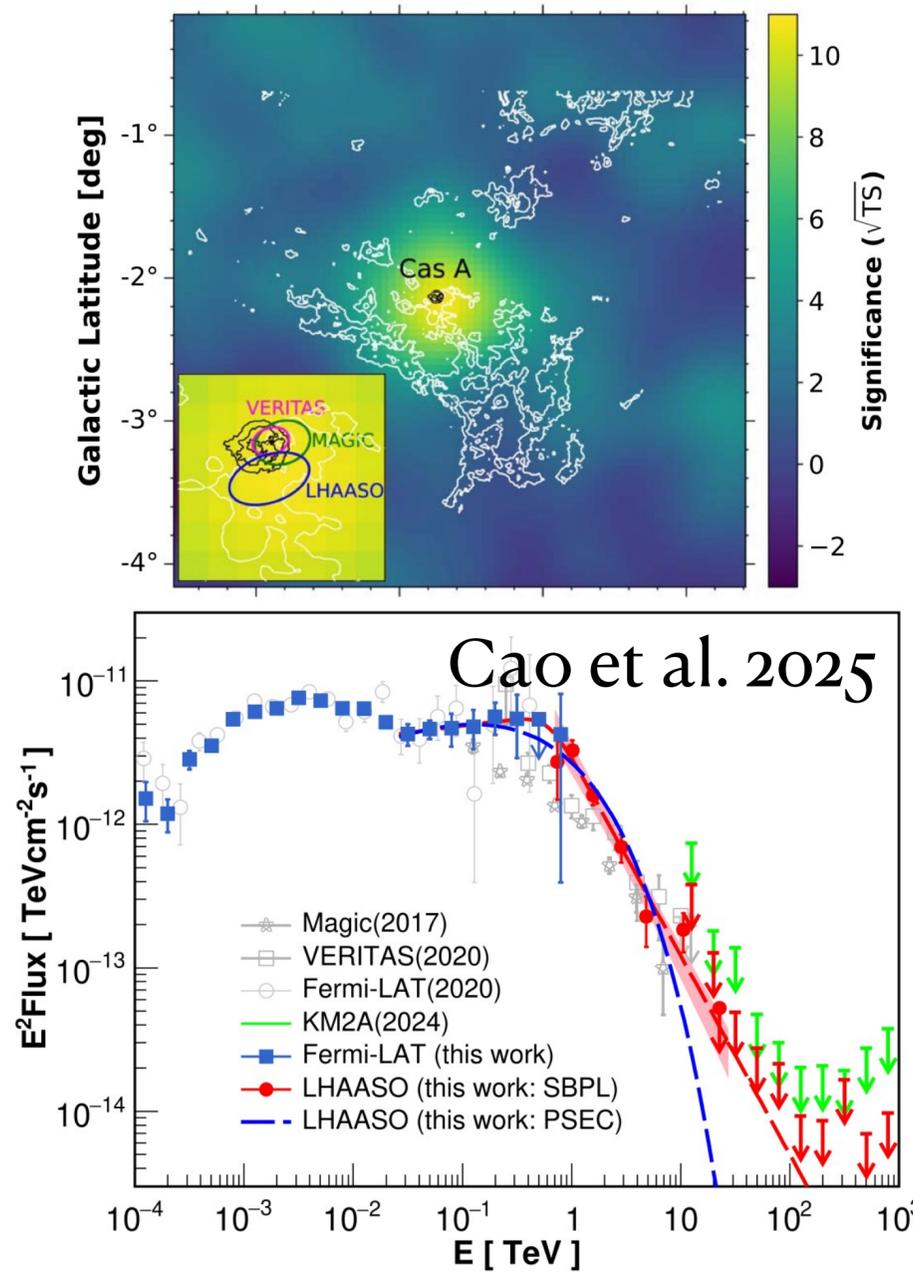
Zhou et al. 2016

SNR-MC interaction started in recent years



Are there MCs near Cas A but not shocked?

LHAASO TS 0.9–25 TeV map
contours: MCs along the line of sight



- Cas A distance $3.4_{-0.1}^{+0.3}$ kpc (Reed+98)
- MC distance ($V_{\text{LSR}} \sim -47 \text{ km s}^{-1}$) : $4.1_{-0.9}^{+0.8}$ kpc
- MCs are foreground: \rightarrow 3.2-3.7 kpc (MC-SNR distance < 500 pc)
- Extinction measurement may refine the MC distance
- Perseus arm distance (SFRs near Cas A): $3.3_{-0.7}^{+1.2}$ kpc (Choi et al. 2014)

Summary and discussion: No clear evidence of an interaction between Cas A and MCs

- MCs are cold ($T \leq 22$ K)
- MCs are not shocked (^{12}CO line width $\Delta V \leq 7$ km/s)
- No evidence of high HCO^+/CO ratio due to CR-ionization
- Support from other studies:
 - no near-IR H_2 emission (Koo et al. 2018)
 - gas density at the forward shock region is low (1cm^{-3}), significantly lower than that of MCs ($\gtrsim 10\text{cm}^{-3}$)
- Are these clouds near Cas A? Maybe, but physical evidence is lacking.

Cas A behind MCs

