# Distance determination of Galactic Supernova Remnants

M. Andjelić

Department of Astronomy, Faculty of Mathematics,
University of Belgrade

# Why do we need the distance?

**Main observable**

Angular size

Distance converts observables into physical quantities.

- $D = d\,\theta$

- ► Physical radius and morphology
- ► Radio / X-ray luminosity
- ► Explosion energy and ambient density
- ► Shock velocity
- ► evolutionary stage

- ► Galactic distribution of SNRs

# The Galactic SNR population

**310 Galactic SNRs**

Green's catalogue (Green 2025)

92% detected in radio regime

46% X ray

32% optical

Majority are identified primarily through radio emission.

Distance estimates span a wide range of methods and uncertainties.

A substantial fraction still lack precise, independently confirmed distances.

Complex Galactic structure makes line-of-sight inference difficult.

We are “lacking” a few thousands of Galactic SNRs  - Ranasinghe & Leahy (2022)

# Why are SNR distances difficult?

Extended objects rather than point-like standard candles

Strong extinction, especially near the Galactic plane

Complex and clumpy interstellar medium

Projection effects and uncertain physical associations

Different tracers can probe different shock structures

# How can we determine an SNR distance?

**Geometrical**

proper motion + shock velocity

**Kinematic**

H I absorption • CO • OH 1720 MHz masers

**Association**

Pulsars • neutron stars • stellar populations • molecular clouds

**Extinction / models**

Optical extinction • X-ray $N_H$ • Sedov–Taylor • Σ-D

**Central principle: the most reliable distances usually come from independent methods that converge.**

# Proper motion

A geometrical distance from angular and physical expansion.

$$d = \frac{v_{exp}}{\dot{\theta}}$$

Measure the angular expansion rate between epochs.

Measure the corresponding physical expansion velocity spectroscopically.

Combine the two measurements for a distance.

**Advantages**

Geometrically motivated; independent of Galactic rotation.

**Limitations**

Requires a measurable shock velocity (OPTICAL usually) and matching expansion tracer.

Expansion rate measurement need variable time epochs – further the SNR, the longer epoch needed.

Projection effects

Angular motion and spectroscopic velocity should refer to the same physical shock.

# H I absorption

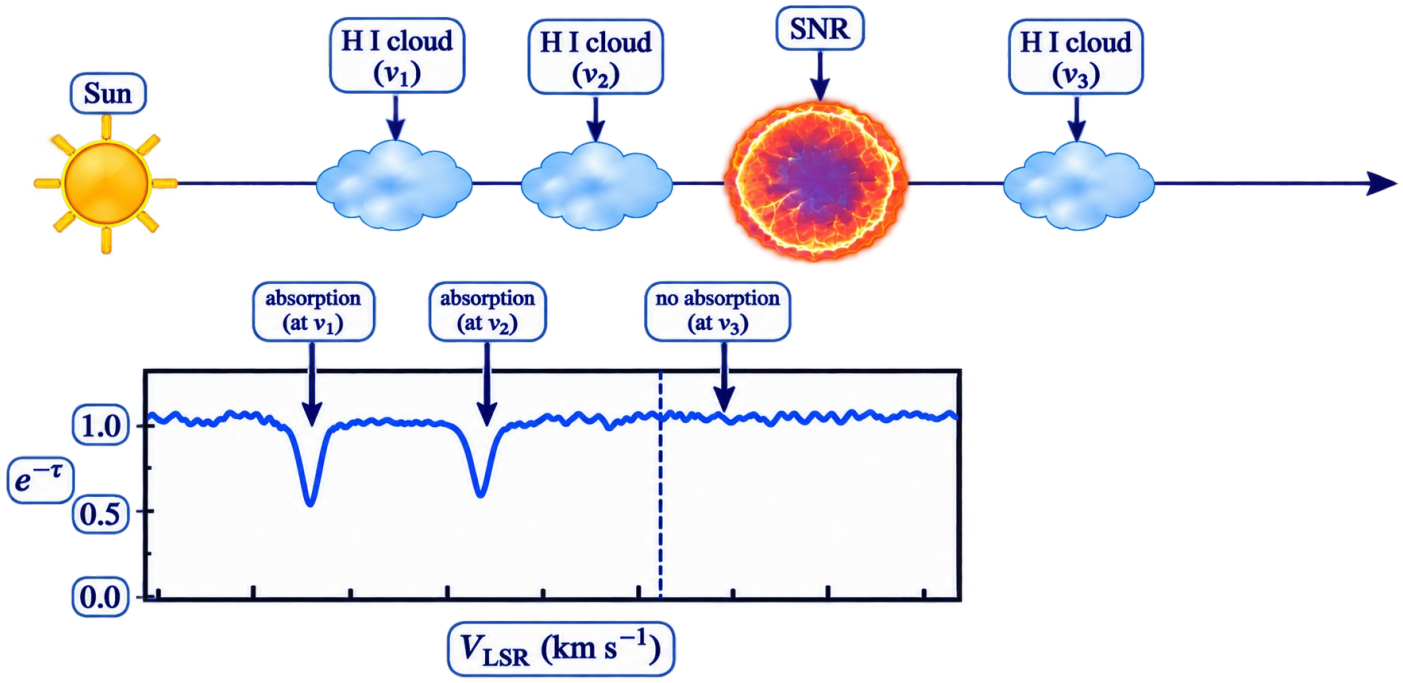
A principal kinematic tool for Galactic SNRs

SNR radio continuum emission provides a bright background source.

Foreground H I cloud can absorb the continuum at its Local Standard of Rest (LSR) velocity.

Detection of absorption places the SNR behind that gas.

The highest absorption velocity can constrain the SNR location.



# H I absorption method in more details

Needed observations:

- 20cm continuum observations

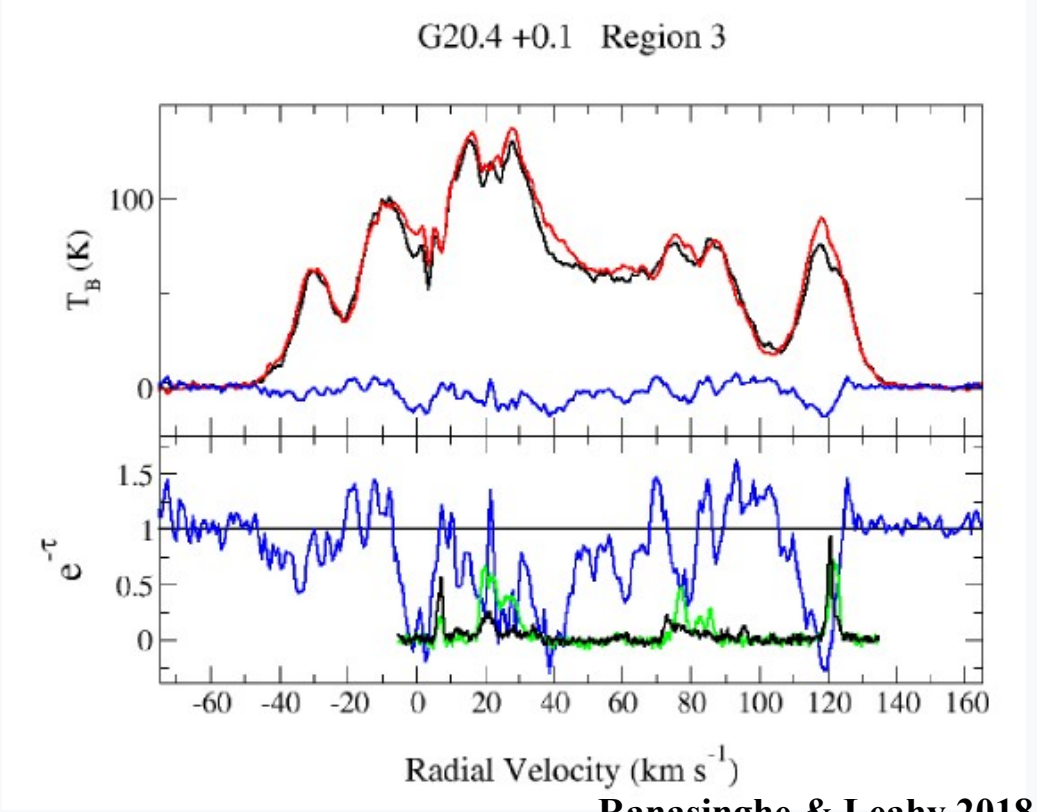
- H I line observations

- To construct the H I “cube”, the continuum component from SNR must be subtracted

- we need observations ON and OFF line-of-sight

$$e^{-\tau_v} - 1 = \frac{T_{B,on}(v) - T_{B,off}(v)}{T^C_{B,on} - T^C_{B,off}}$$

- method from Leahy & Tian 2010



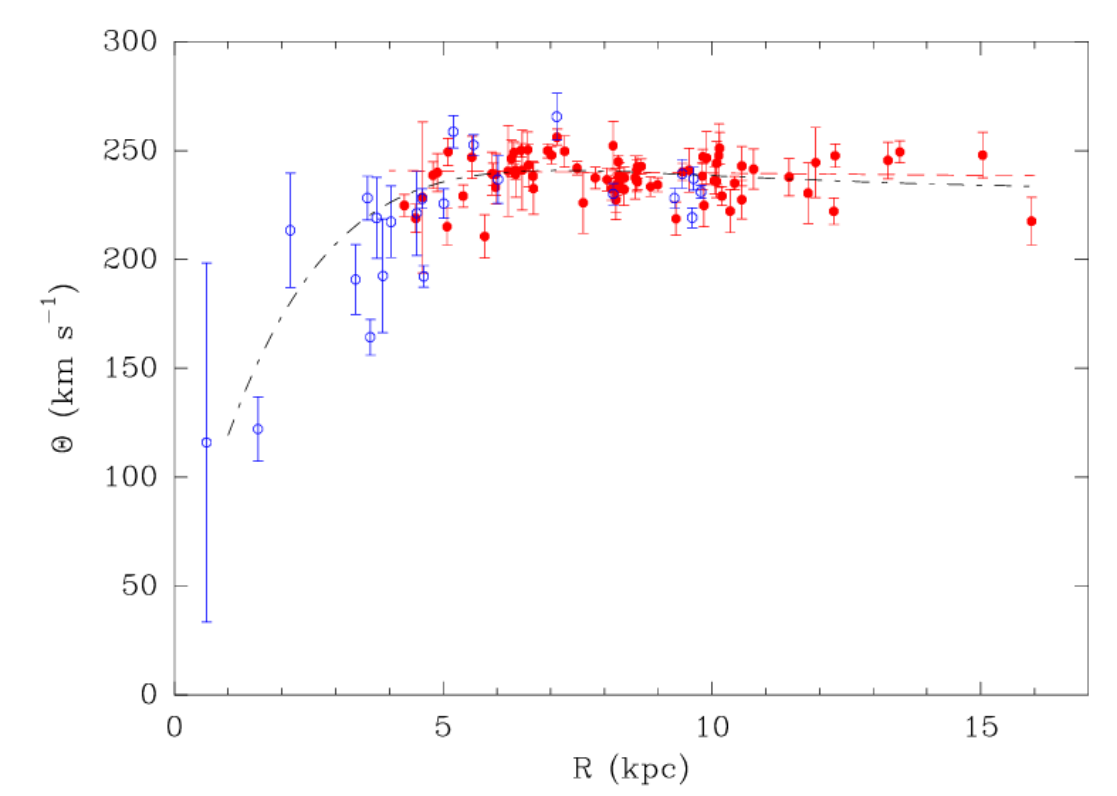

**Ranasinghe & Leahy 2018**

Black: SNR – ON source
Red: background – OFF source
Blue: difference, HI absorption
Green: CO emission

# Galactic rotation

Radial velocity can be converted to a Galactocentric distance $R$ using a Galactic rotation model (circular rotation model).

$$V_r = R_0 \sin(l) \left( \frac{V(R)}{R} - \frac{V_0}{R_0} \right)$$




The rotation curve - $V(R)$ Reid et al. 2014
$R_0$=8.34 kpc, $V_0$=240 km s$^{-1}$

# Galactic rotation and the near/far ambiguity

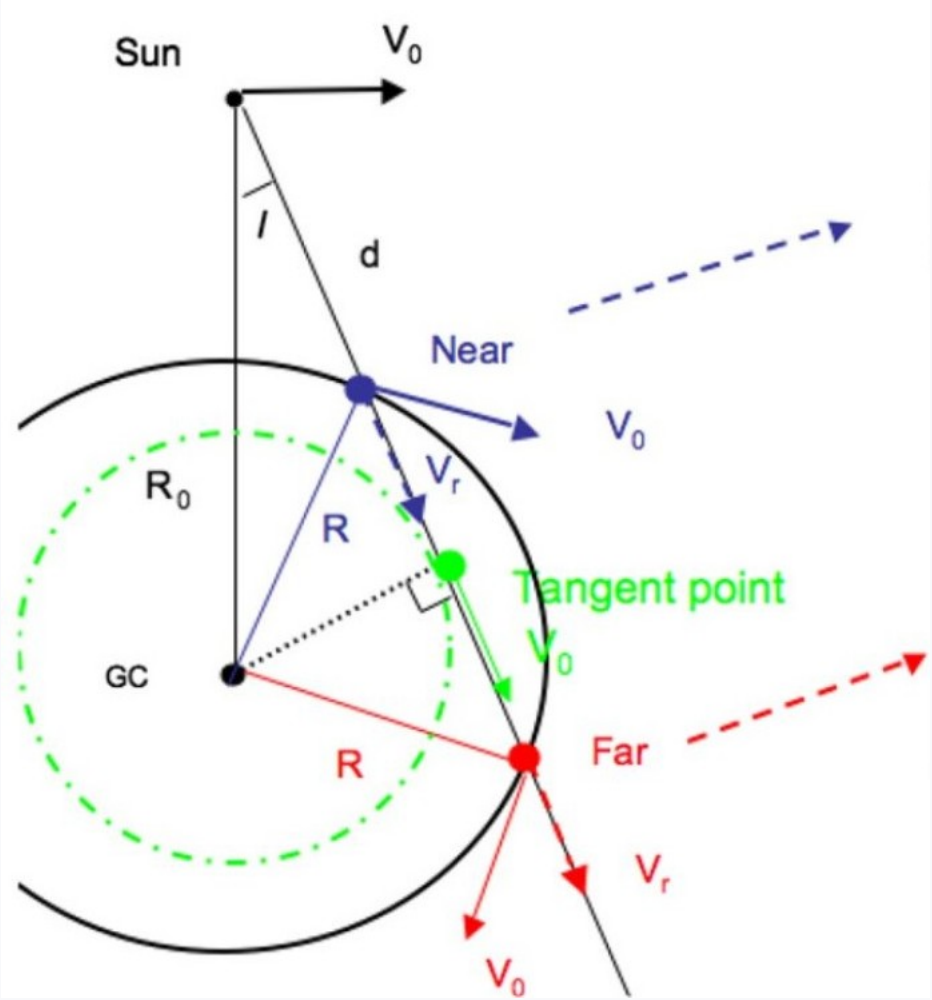
$$R^2 = R_0^2 + d^2 - 2R_0 d\cos(l)$$

-For many sightlines inside the Solar circle, one velocity corresponds to two distances.

$$d = R_0\cos(l) \pm \sqrt{R^2 - R_0^2\sin^2(l)}$$

-Near and far solutions must therefore be distinguished with additional evidence.

- from the longitude of an SNR and assumed Galactic rotation curve "**the tangent point distance**" can be obtained – distance to the point with the highest radial velocity

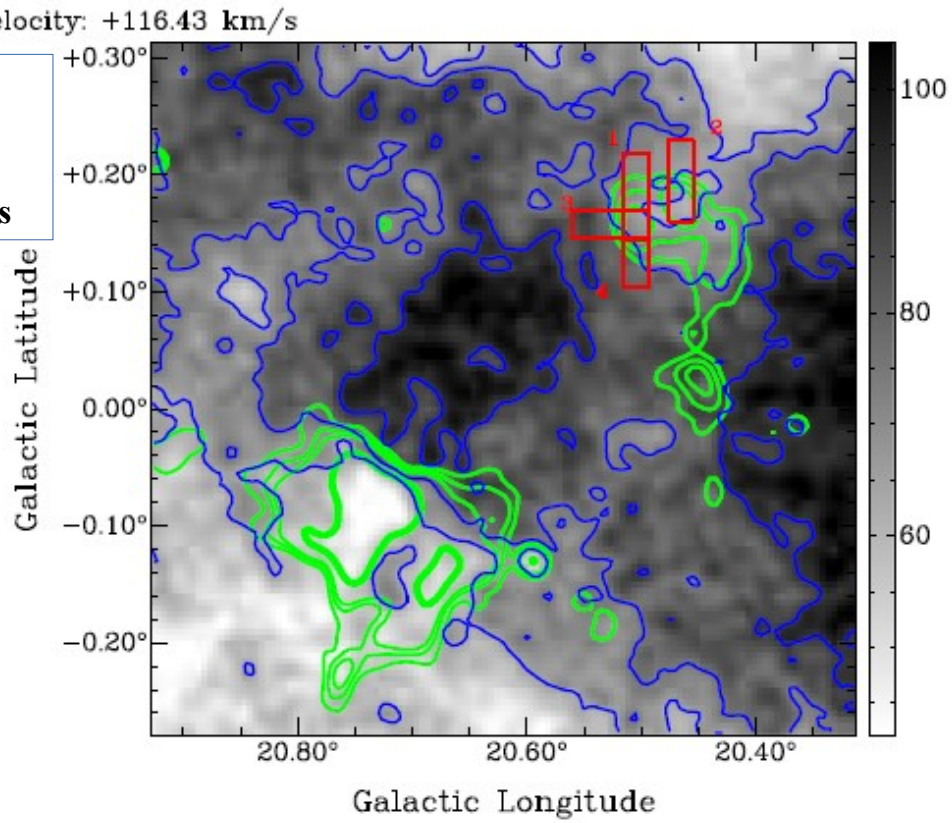


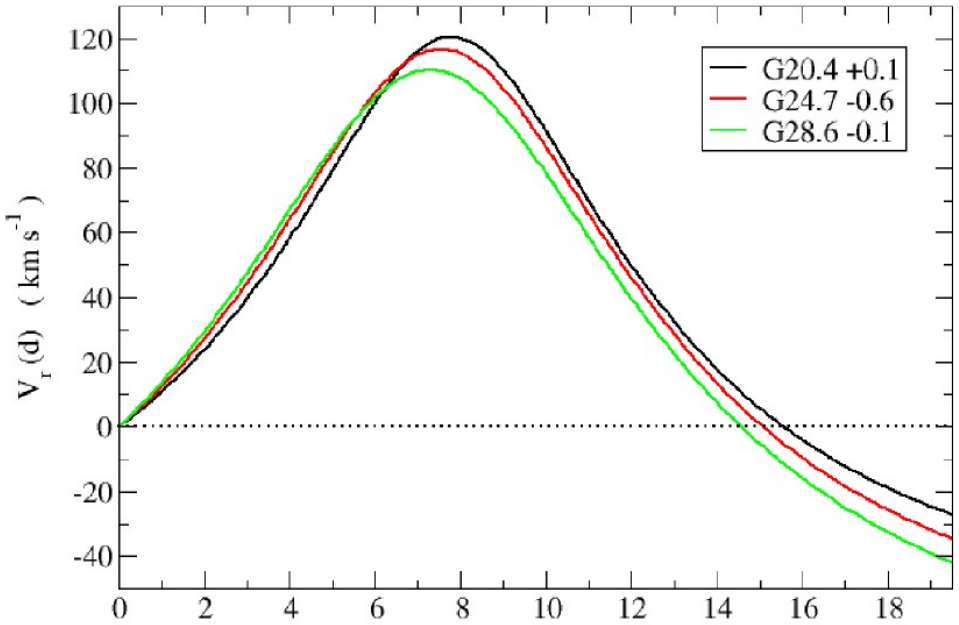
# Galactic rotation and the near/far ambiguity

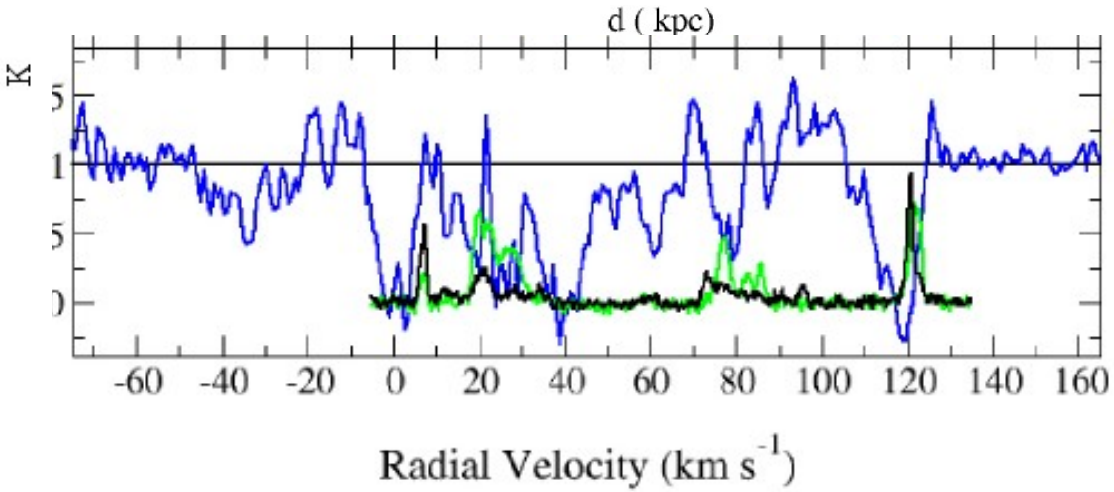
- If the SNR is at the near distance, it should not have H I absorption from clouds located beyond it

- Therefore, absorption at velocities corresponding to gas beyond the near-distance solution can indicate that the SNR is actually at the far distance

**SNR G20.4 + 0.1**
**1420 MHz image,**
**green contours**
**HI map blue contours**

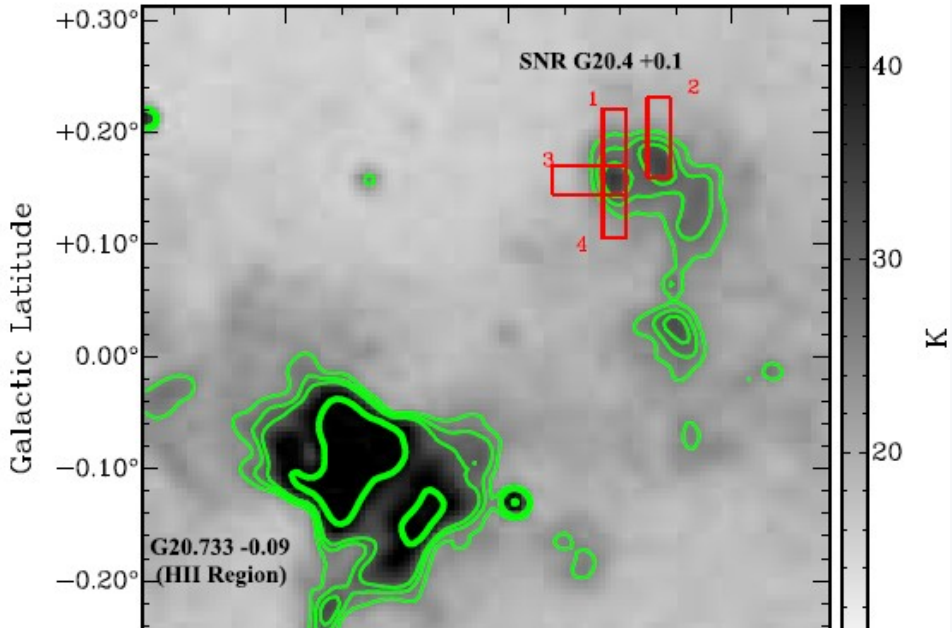


# CO and molecular clouds

**SNR G20.4 + 0.1**
**1420 MHz image, green contours at 25, 28, 31, 50K.**




CO observations trace molecular gas associated with dense clouds.

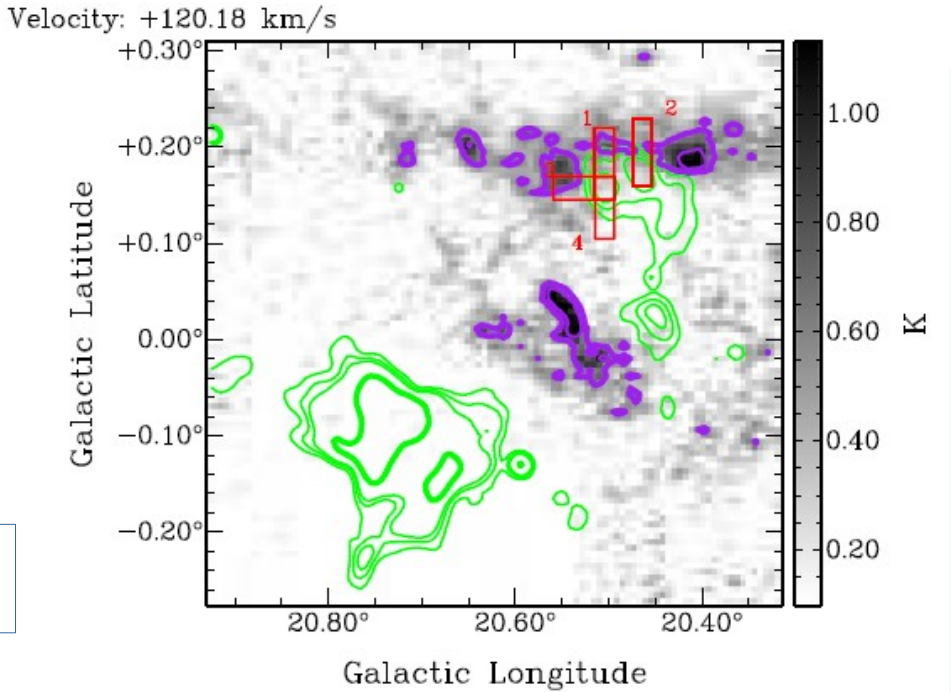
If the SNR physically interacts with a cloud, their velocities should be consistent.

Evidence of shock-interaction (e.g. broadened CO line wings).

Cloud velocity → Galactic rotation model → kinematic distance.

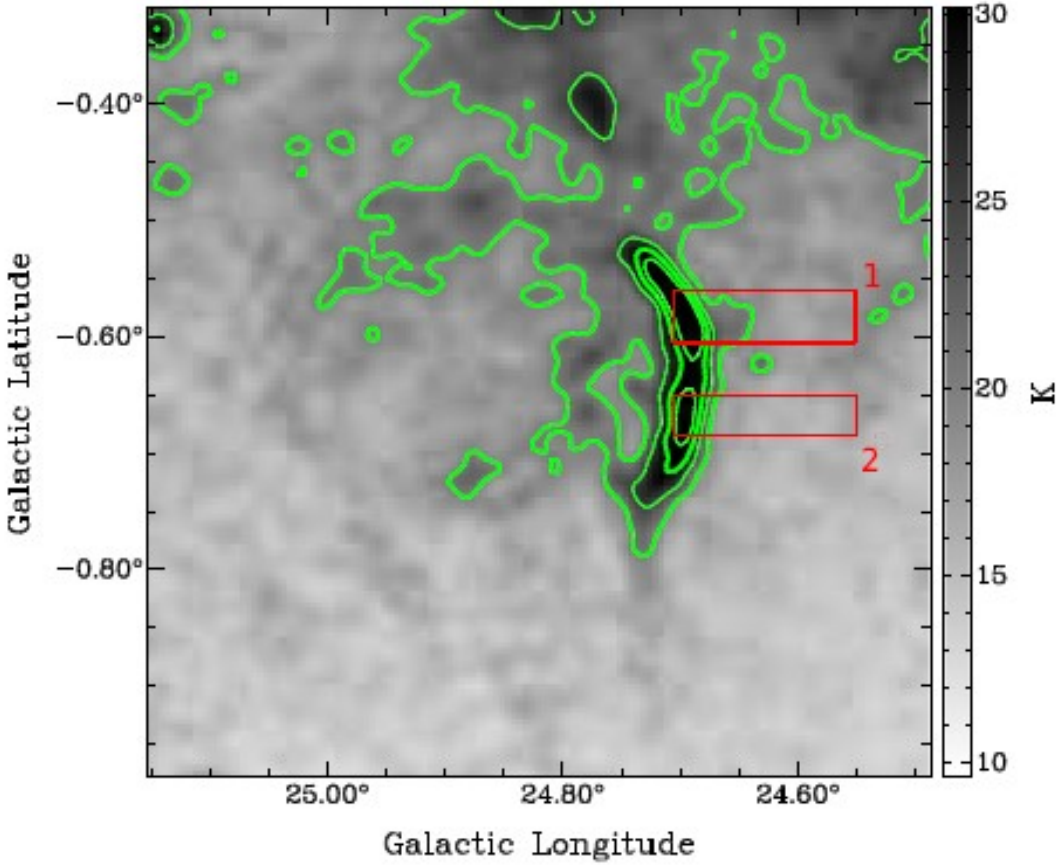
Spatial coincidence alone is not sufficient: velocity evidence matter.

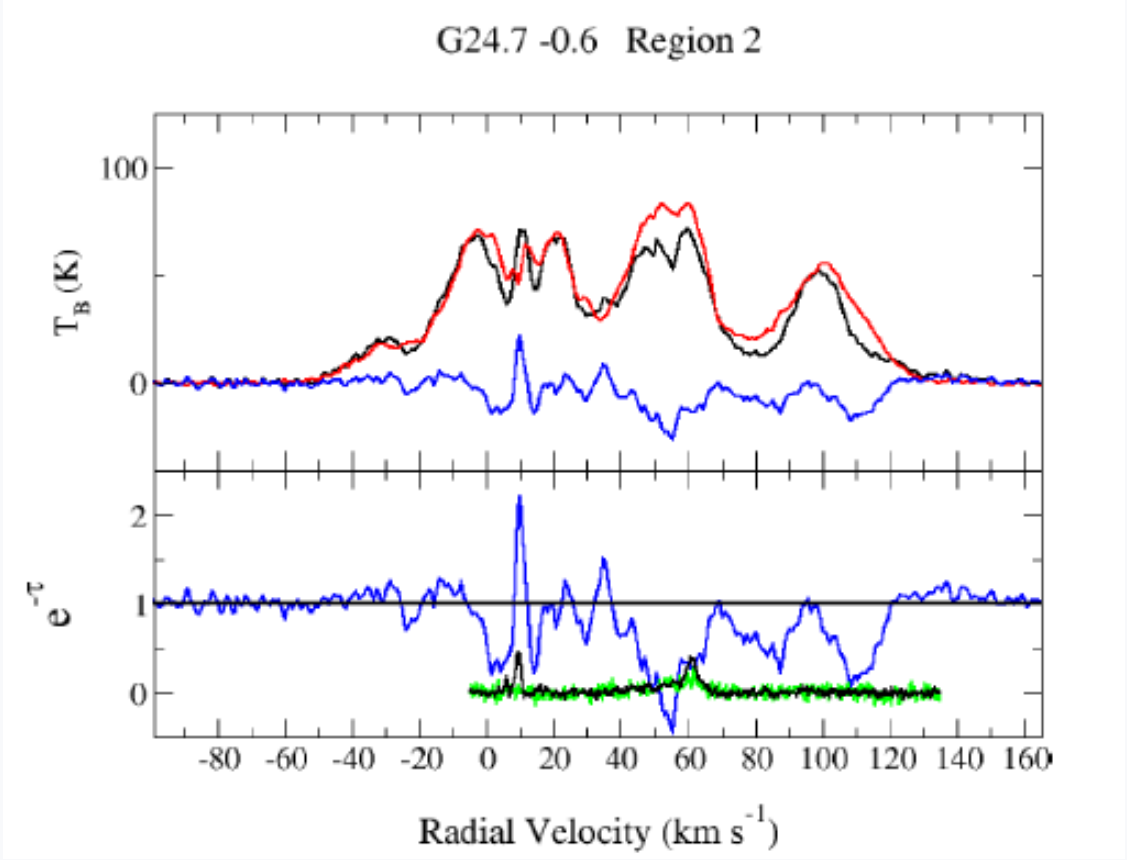
**G20.4 + 0.1 $^{13}$CO channel maps +120.6**



# Kinematic distance

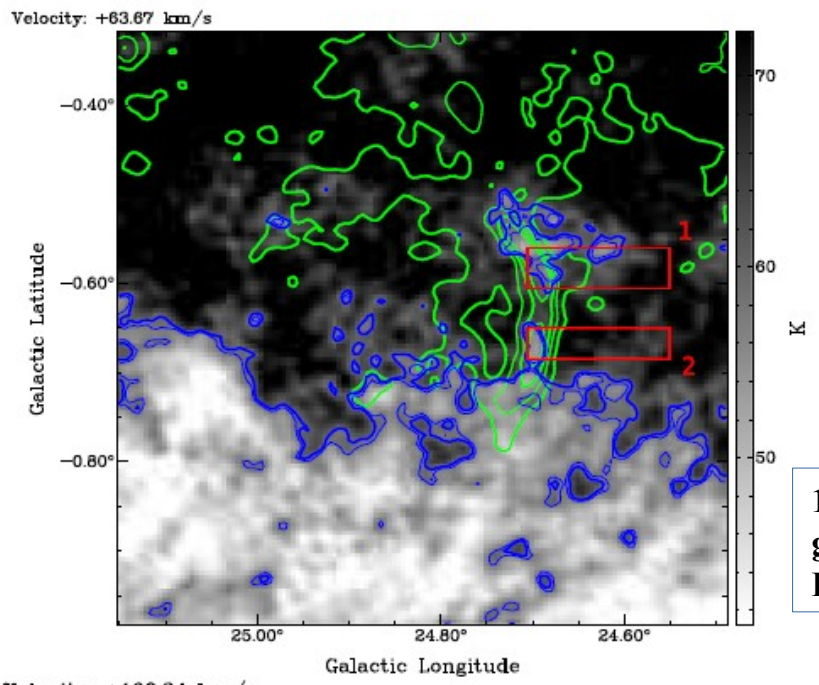
Example: SNR G24.7 − 0.6: absorption up to the tangent point ~110 km $s^{-1}$

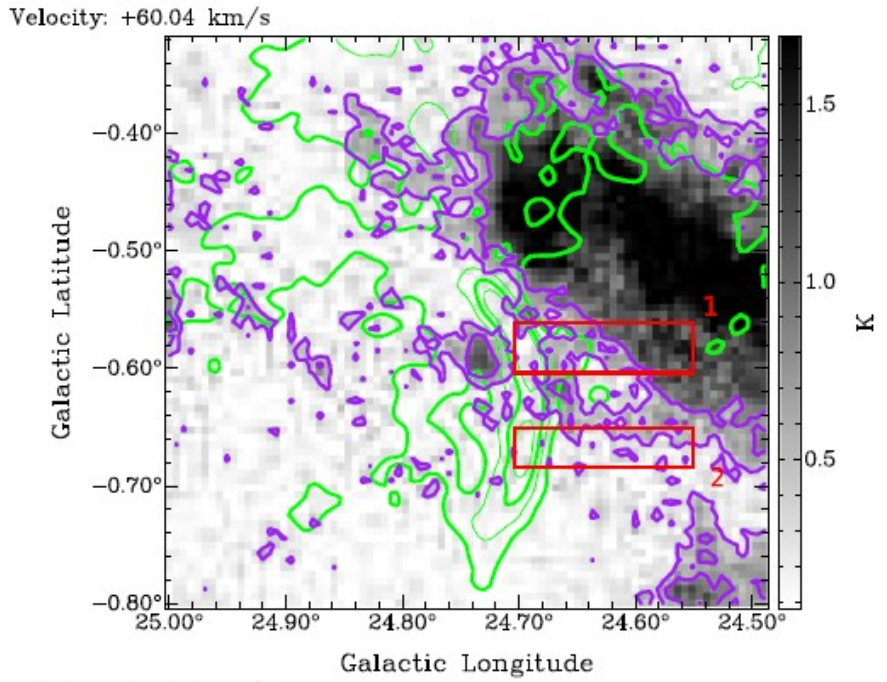


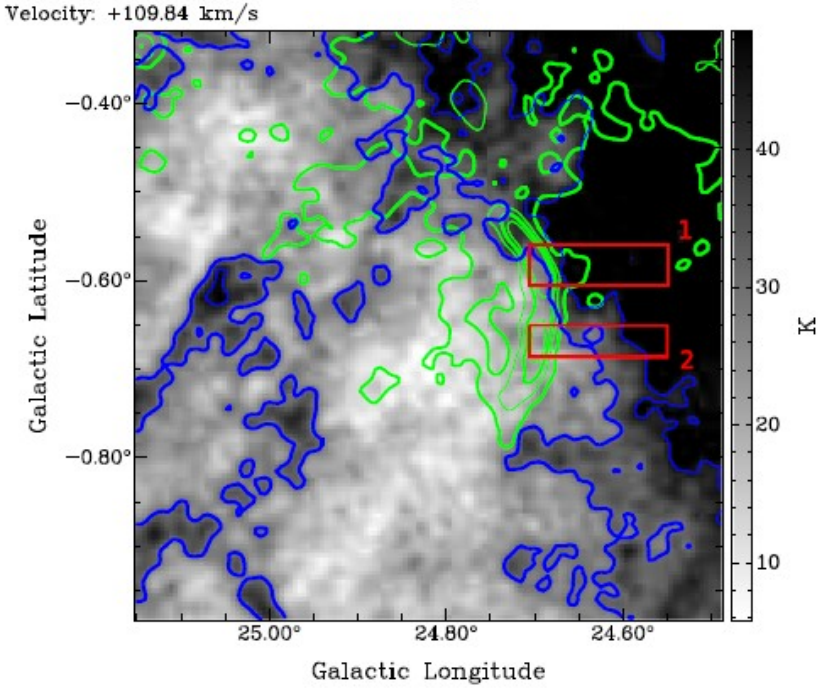

**1420 MHz image, green contours**

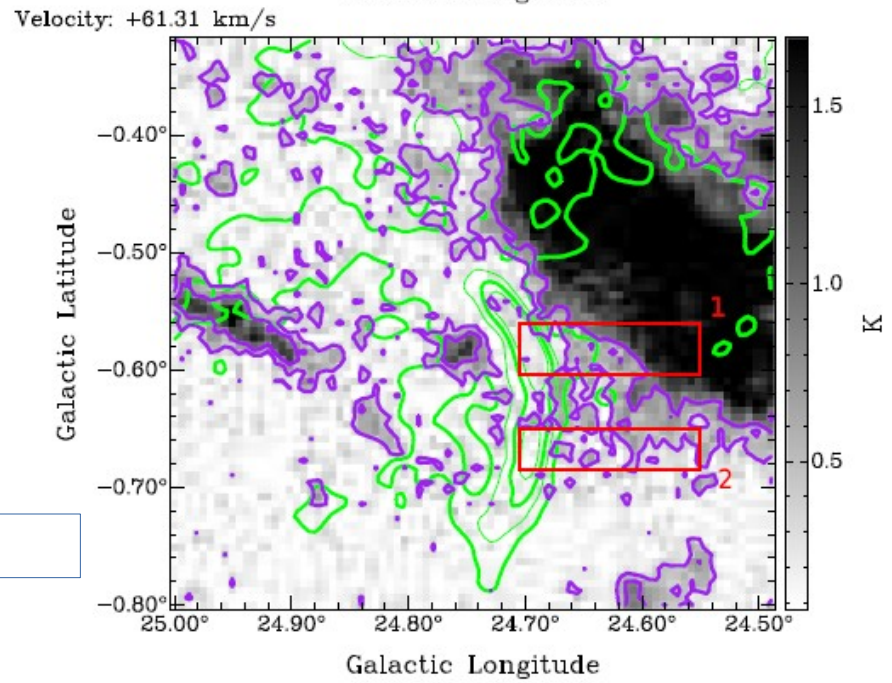
# SNR G24.7 − 0.6




**1420 MHz image,**
**green contours**
**HI map blue contours**




**$^{13}$CO channel maps**

# OH 1720 MHz masers

A strong tracer of some SNR–molecular-cloud interactions

**Observed**

1720 MHz OH maser emission can arise in shocked molecular gas.

**Inference**

Maser ↔ shocked cloud ↔ SNR interaction

Strong physical association can make the kinematic distance compelling.

Not universal: only a subset of SNRs show suitable masers.

# Pulsars and neutron stars

Associated compact objects can provide independent constraints.

- Parallax to the pulsar or neutron star: direct geometrical distance when available.
- Dispersion measure: integrated free-electron column.
- Association can be tested using position, compatible age of compact object and SNR, proper motion and distance.
- Projection alone does not prove physical association.

# Optical extinction as a distance indicator

## Red clump stars

- Measure stellar extinction and distance toward SNR.

- Construct an extinction–distance relation.

(*Shan et al. 2018, 2019*)

- Compare with SNR extinction.

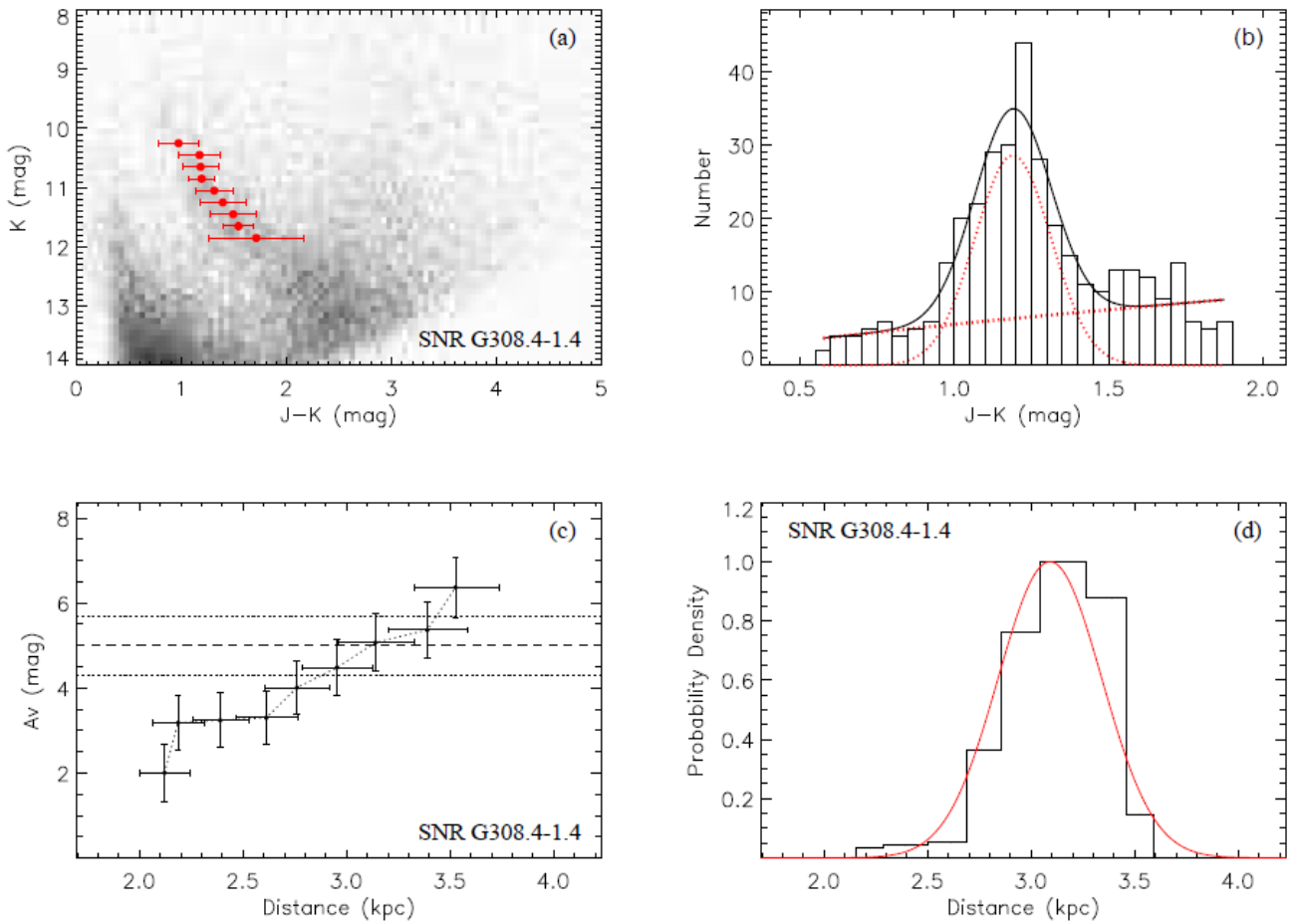



Fig. 1: (a) The CMD in the direction of G308.4-1.4 within 0.5 deg$^2$, the red dot and lines show the fitted location of the RC peak density and its extent with $1\sigma$. (b) Histogram of the J – K values of the selected stars in the $10.6 < K < 11.1$. The black curve is the best fit to this histogram. The red dotted curves are the Gaussian and power-law components, respectively. (c) The $A_V$-D relation in the direction of G308.4-1.4. The dashed line is $A_v$ value of this SNR. The dotted lines are the uncertainties of $A_v$. (d) Probability distribution over distance to the SNRs and the best-fit Gaussian model.

**Shan et al. 2019**

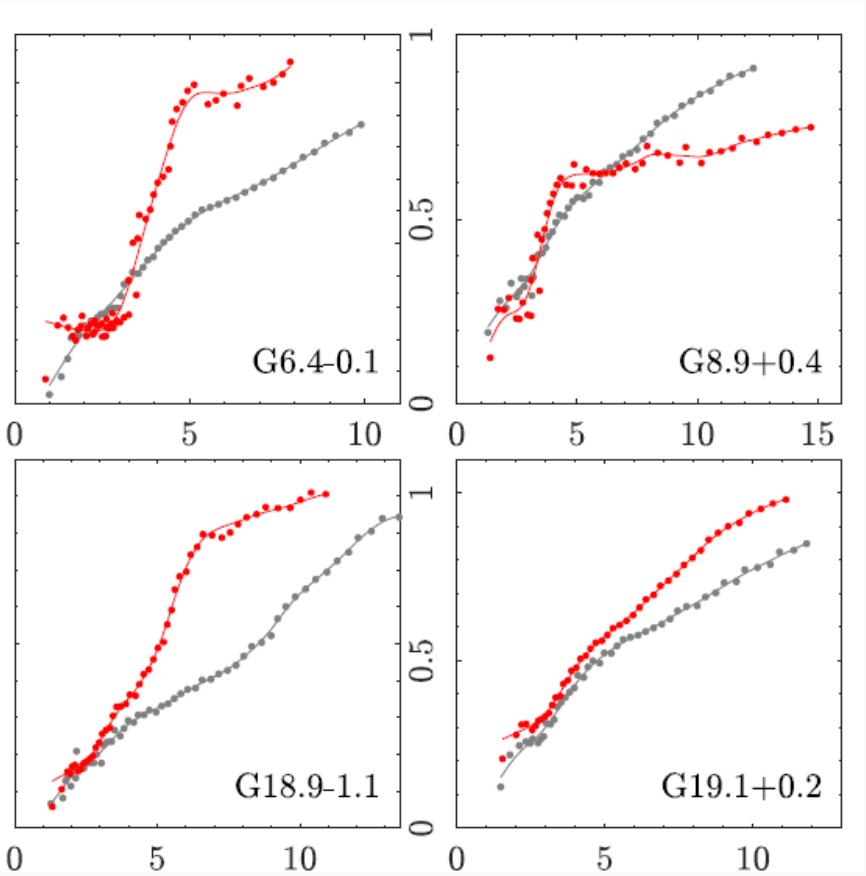
# Optical extinction as a distance indicator

Use stars as distance markers along the line of sight.

- Measure stellar extinction and distance.
- Construct an extinction–distance relation.

(*B. Q. Chen et al. 2017; H. Zhao et al. 2018, 2020; B. Yu et al. 2019*)

- If extinction increases at a particular distance along the line of sight, that can indicate the location of the SNR.
- Gaia parallaxes make this approach  feasible for nearby remnants.




Wang et al. 2020

# Optical extinction as a distance indicator

Use stars as distance markers along the line of sight.

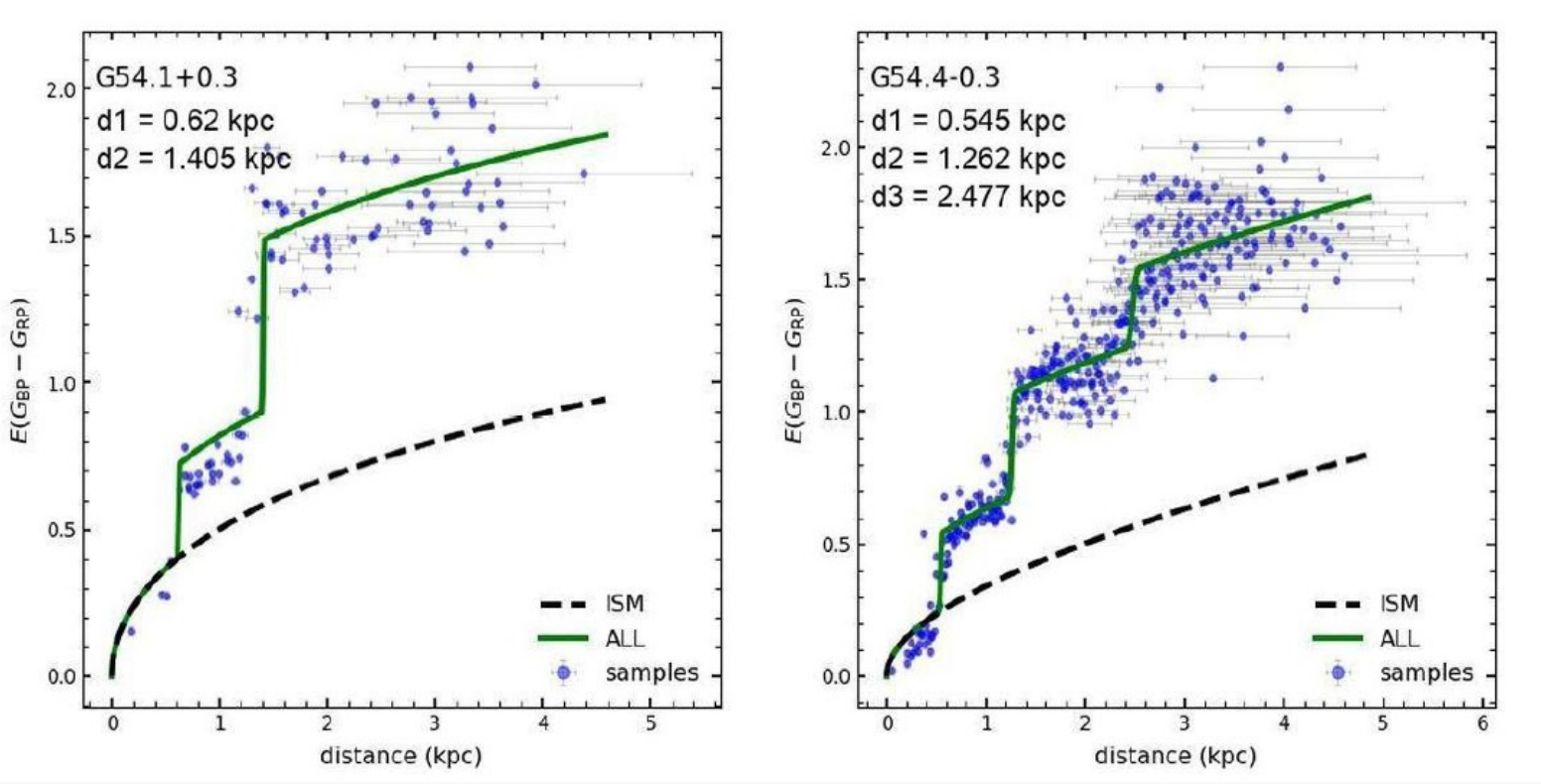
- Gaia parallaxes make this approach  feasible for larger number of SNRs.

-Multiple distance estimates.

-CO interaction.

**Modern combination**

Gaia + optical/IR photometry + 3D dust maps




Chen et al. 2025

# X-ray absorption

$$N_{\mathrm{H}} = \int_0^d n_{\mathrm{H}}(l)\, dl$$

Fit the X-ray spectrum to estimate N_H.

Compare with the Galactic gas distribution.

Can be valuable when optical extinction is severe.

Model assumptions enter through abundances, spectral components and gas distribution.

**Important**

N_H is not a direct distance measurement.

# Sedov–Taylor modelling

Useful physics — **but explicitly model dependent**

$$R = \xi \left( \frac{E_0 t^2}{\rho_0} \right)^{1/5}$$

Estimate a physical radius from an assumed explosion energy, age and ambient density.

Then compare with the angular radius:

$$d = \frac{R}{\theta}$$

The result is sensitive to assumptions about evolutionary stage, age and ambient conditions.

# Radio surface brightness–diameter relation

**An empirical statistical approach**

$$\Sigma = AD^{\beta} \qquad d = \frac{D}{\theta}$$

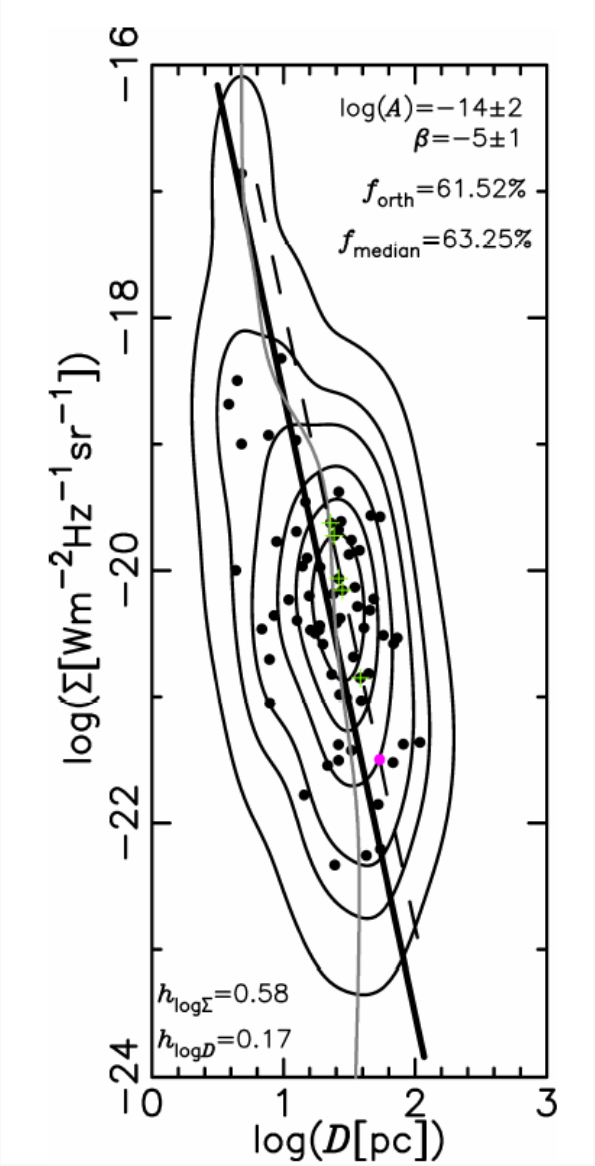
$$\Sigma = \frac{L}{4\pi d^2 \Omega} = \frac{S}{\Omega} \qquad \Omega = \frac{\pi}{4}\left(\frac{D}{d}\right)^2$$

- $\beta$ dependent on a spectral index

- $A$ characterizes properties of a SN explosion coupled with the density and magnetic field strength of the SNR environment.

$$\Sigma\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}\ \mathrm{sr}}\right] = 1.505 \times 10^{-19}\frac{S[\mathrm{Jy}]}{\theta[']^2}$$

# Radio surface brightness–diameter relation




Urošević et al. 2025

69 SNRs used as Sigma-D calibrators

matrix that describes the data points density in the Sigma-D plane

Useful for population studies

Large intrinsic scatter arises from differences in explosion energy, density, magnetic field and acceleration efficiency

Selection effects are largely present

The only distance estimate for majority of SNRs

# Comparing the distance methods

| Method | Primary observable | Main limitation |
|---|---|---|
| | | |
| **Proper motion** | Angular + physical velocity | Tracer matching |
| **H I absorption** | Gas in front of SNR | Near/far ambiguity |
| **CO / OH** | SNR–cloud kinematics | Association |
| **X-ray N_H** | X ray spectra | Spectral/ISM model |
| **Gaia + extinction** | Dust vs. distance | Suitable background stars |
| **Sedov** | Physical model | Evolutionary assumptions |
| **Σ-D** | Radio emission | Large scatter |

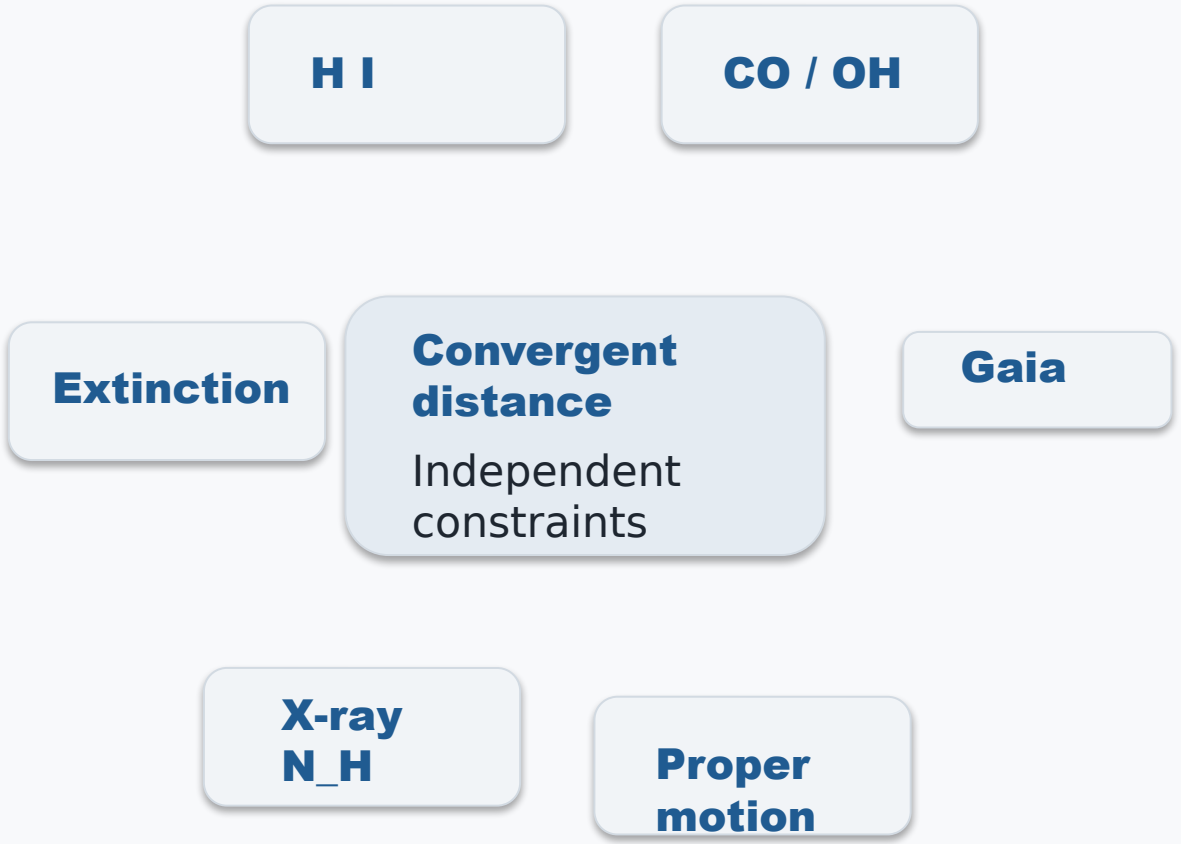
# The multi-wavelength approach

**Do not ask only:**

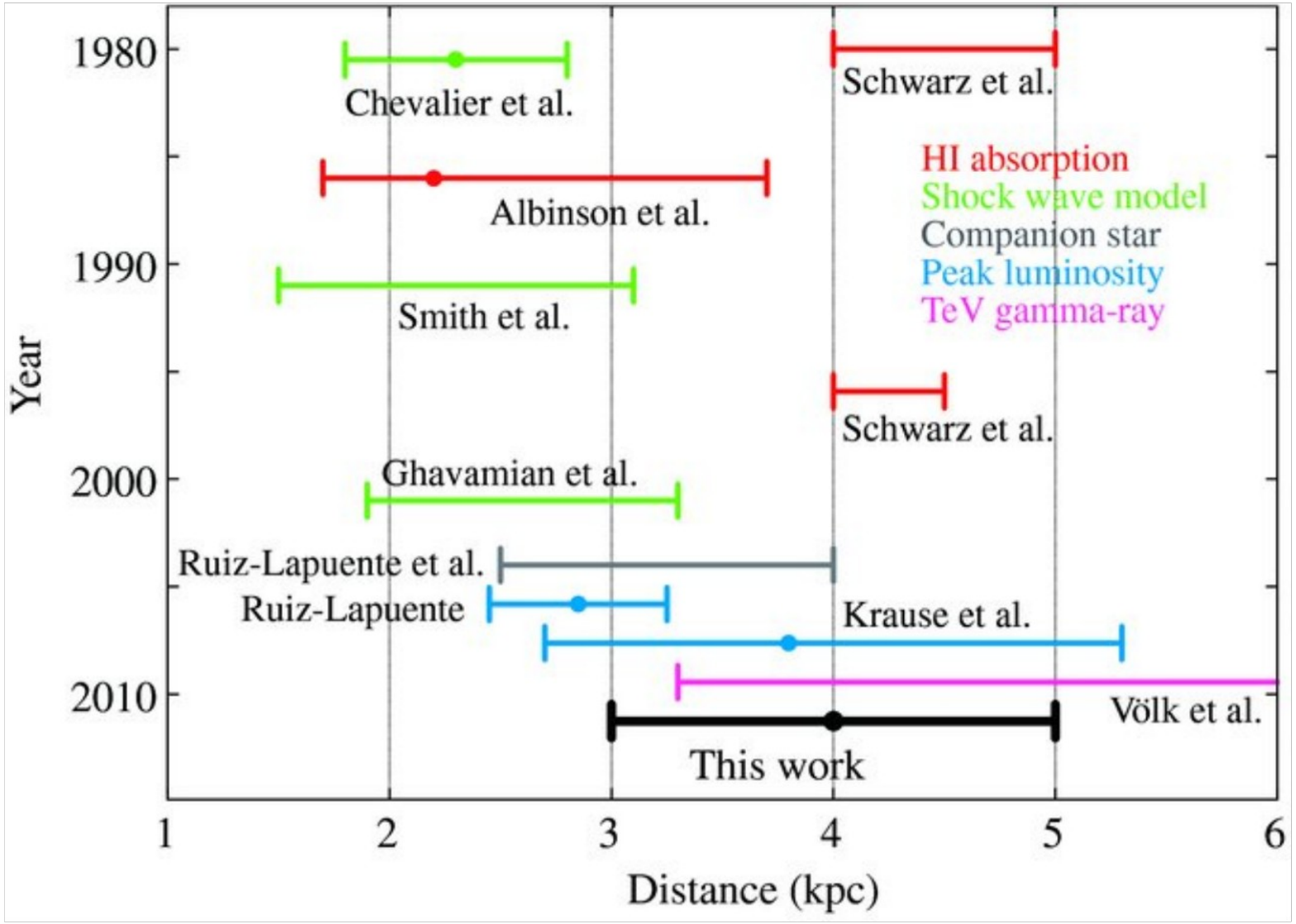
**“What distance does method *x* give?”**

**Ask instead:**

**“Which independent observations constrain the distance — and are they consistent?”**



Copyright is not claimed for this article. All rights reserved.




**Tycho** distance chart
Hayato et al. 2010
X-ray proper motion

# Conclusions

Distance is fundamental to interpreting SNR physical properties.

No single method is universally applicable.

Kinematic methods remain central for Galactic remnants, but require careful interpretation.

Gaia and extinction–distance methods provide powerful new constraints.

The most convincing distances come from independent, multi-wavelength observations.

**Reliable distance =**
**multiple constraints + physical consistency**