LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

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Supernova remnants
A science case for AtLAST ?

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significant contribution from P. Dell'Ova, former PhD student

Outline

- Why study supernova remnants ?
- CO lines & Dust continuum
- Feedbacks
- Star formation
- Perspectives: towards cosmic ray science

Why study supernova remnants ?

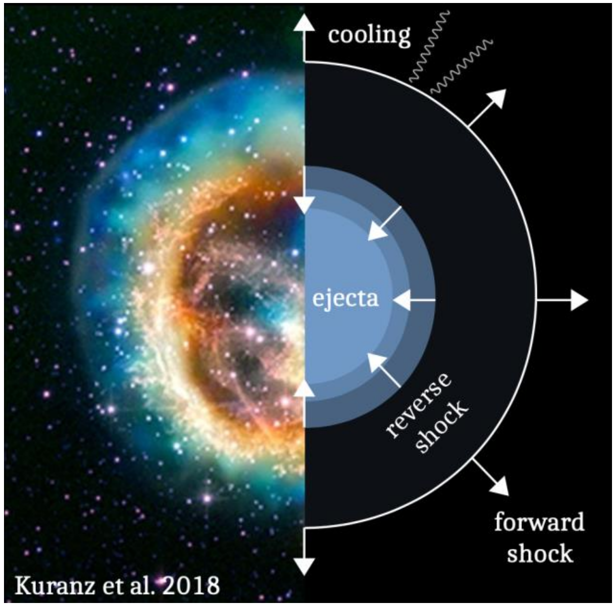
Supernova Remnants

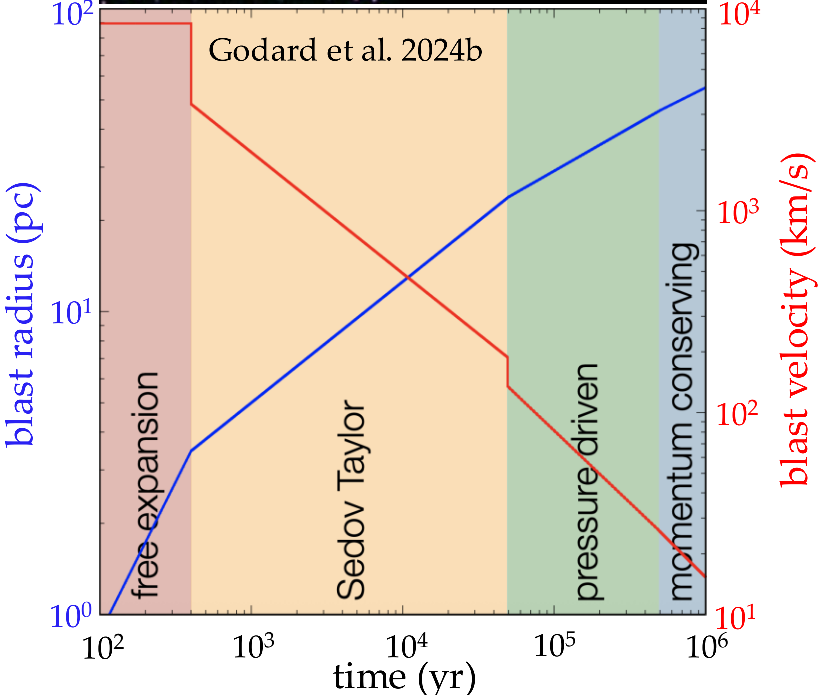
- SN explosion types at Chandrasekhar mass
stellar self gravitational attraction
> electron degeneracy pressure
  - **Ia** = thermonuclear white dwarf binary
  - **II, Ib, Ic** = core-collapse massive star

- The 4 **VERY** theoretical stages of SNRs:

phase	**Shock** velocity (km/s)	Emission of **photons**	Acceleration of **CRs**
free expansion	10^4	yes	YES
Sedov-Taylor	10^4 – few 10^2	yes	YES
Pressure-driven	few 10^2 – few 10	YES	no
Momentum-conserving	< few 10	YES	no

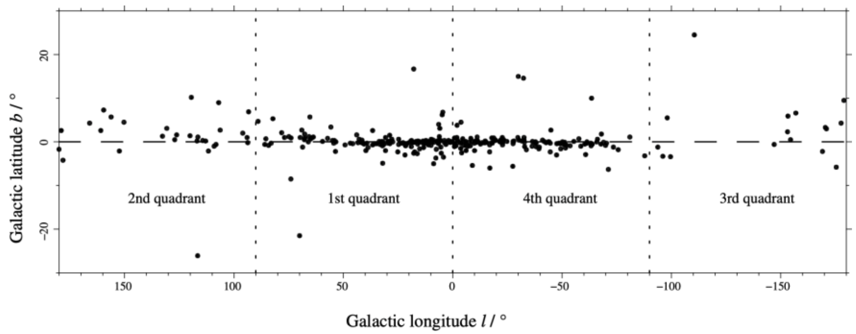
- Until the fade away time:
Feedbacks: shocks, photons, CRs production



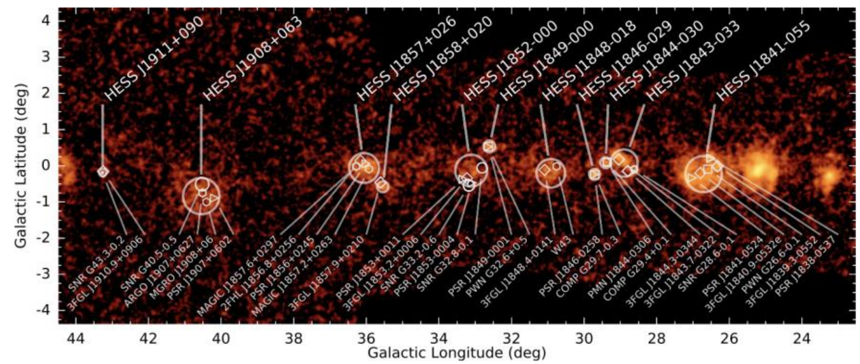


Because they are there

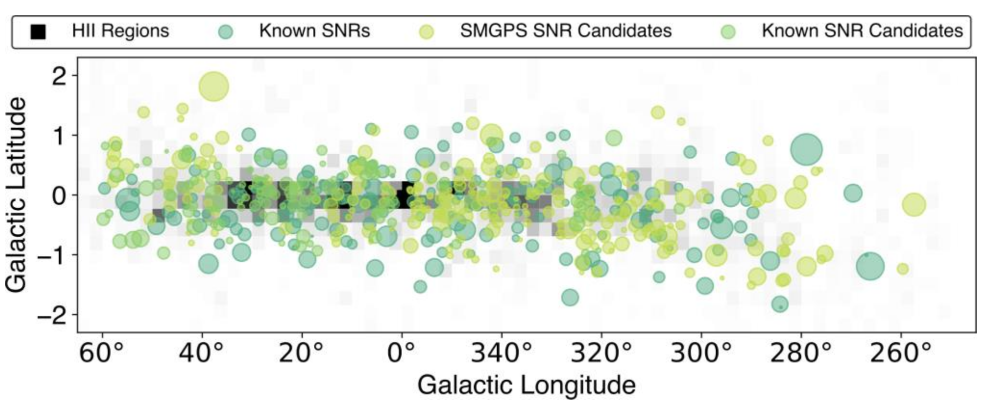
- The Green catalog: Green et al. 2025:
  - mostly from radio
  - **310** Galactic SNRs (+21, -5 w.r.t. 2019)

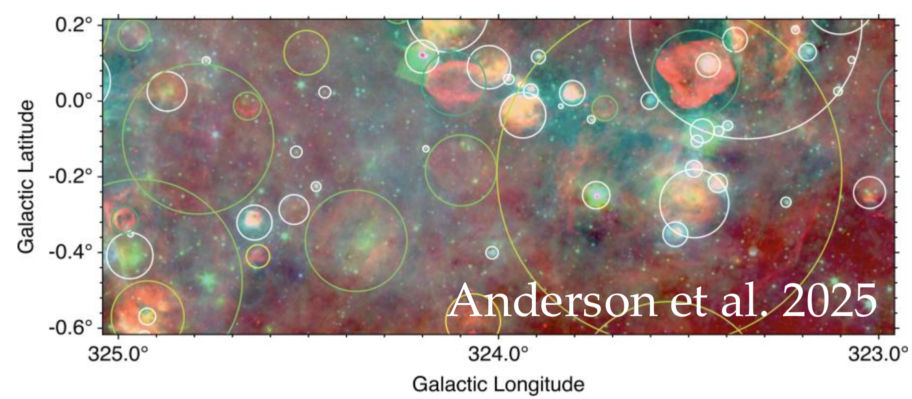


- The SNRcat: Ferrand & Safi-Harb 2012:
  - from X-ray and γ-ray
  - **383** Galactic SNRs



- Low frequency Radio observations:
  - MeerKAT: continuum without MIR
  - **+237** new Galactic SNR candidates





- How many more with the SKA ?

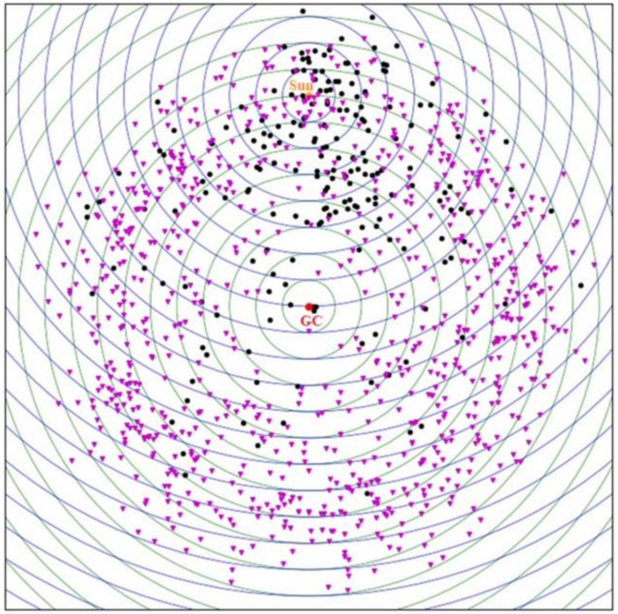
Because they are there

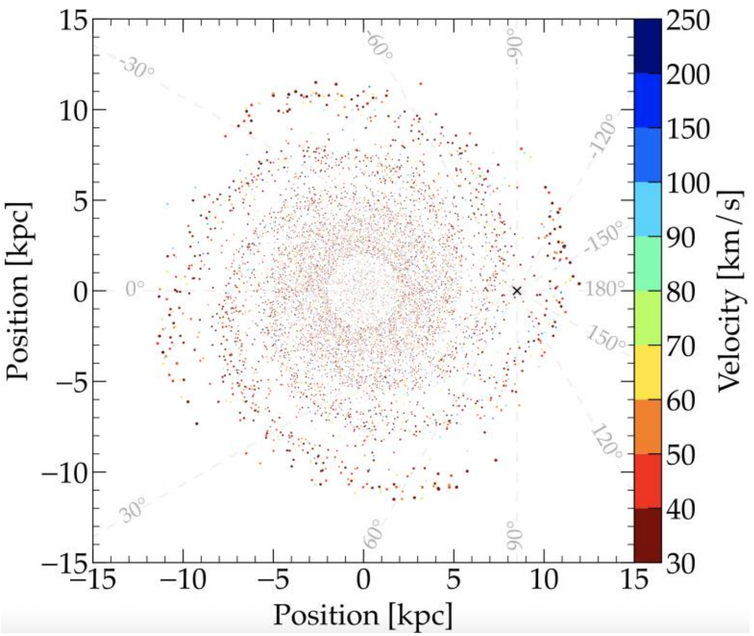
- Li et al. 1991: 1000 predicted (155 then observed)

- Ranasinghe & Leahy 2022
  - 1 SN every 40 yrs, τ = 60 kyrs => 1500 expected
  - 3500 to 5600 Galactic SNRs
  - Confusion and lack of sensitivity in radio

- Adams et al. 2013:
  - $4.6^{+7.4}_{-2.7}$ Galactic SN/century
  - (Galactic SFR $3.6^{+8.3}_{-3.0}$ $M_{\odot}$/yr)

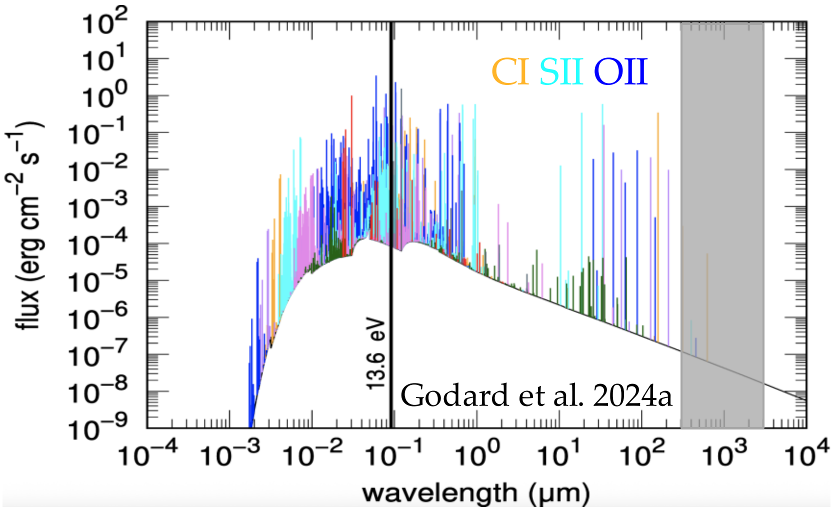
- Vigoureux et al., in prep. : ~10 000
  - ~4 Galactic SN/century
  - theoretical model, no interaction (yet)
  - H_2 surface density variation with R_{gal}
  - 4 arms



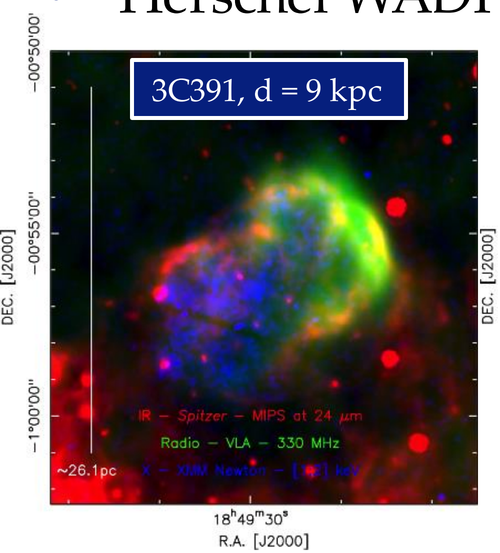


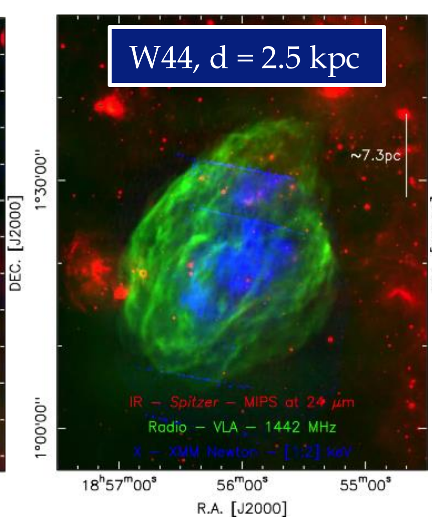
A science case for AtLAST ?

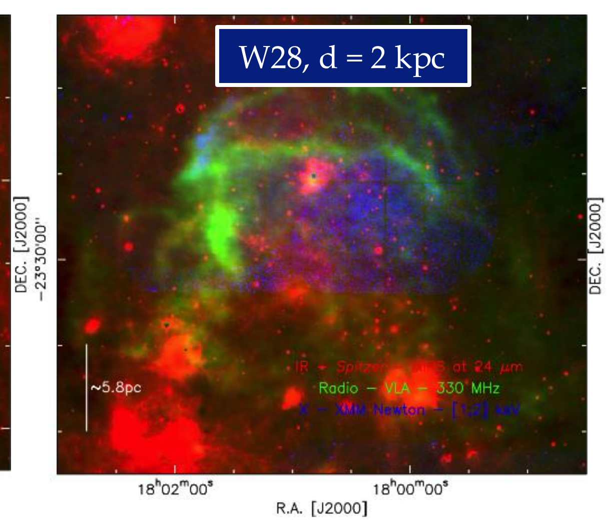
- Marginal for youngest, fastest SNRs:
  - $n_H = 1.0\ cm^{-3}$, $v_s = 200$ km/s
  - 4 lines in AtLAST bands
    - CI $E_{up} = 23.6$ & 62.5 K, $\upsilon = 492$ & 810 GHz
    - OII $E_{up} = 38605$ K, $\upsilon = 600$ GHz ?
    - SII $E_{up} = 21417$ K, $\upsilon = 953$ GHz ?

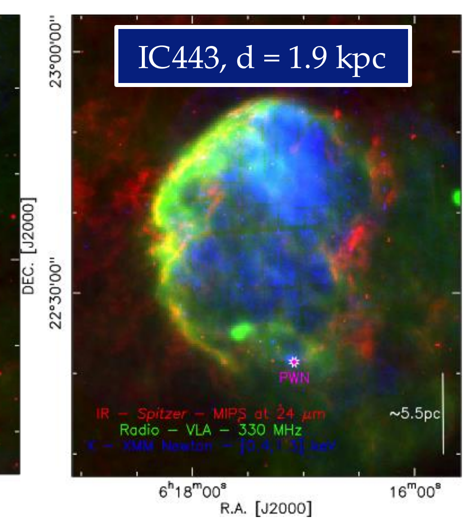


- A safe bet: SNRs interacting with their environment:
  - APEX program CO lines (+byproducts)
  - Herschel WADI KP









A science case for AtLAST.

- **Over long times (> 10 kyr) and large scales (> 10 pc), evolved SNRs:**

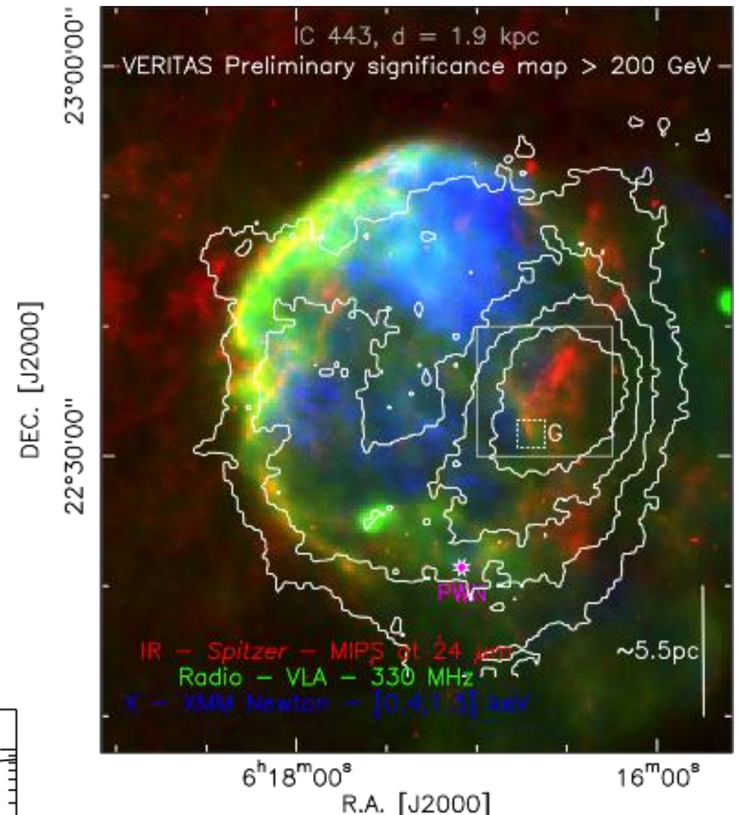
  - inject shock waves, photons, CRs in the ISM

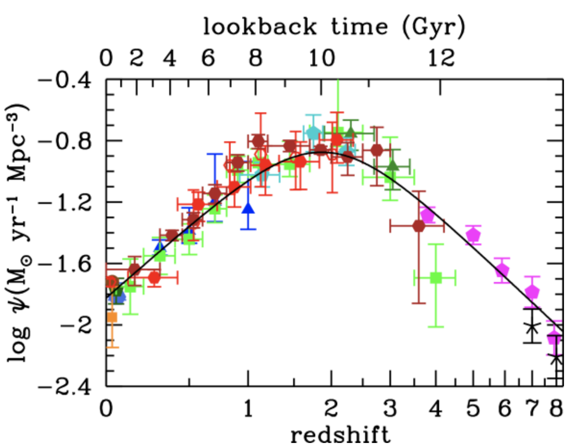
→ **Can we quantify the energetic and chemical impacts of SNRs on the ISM ?**

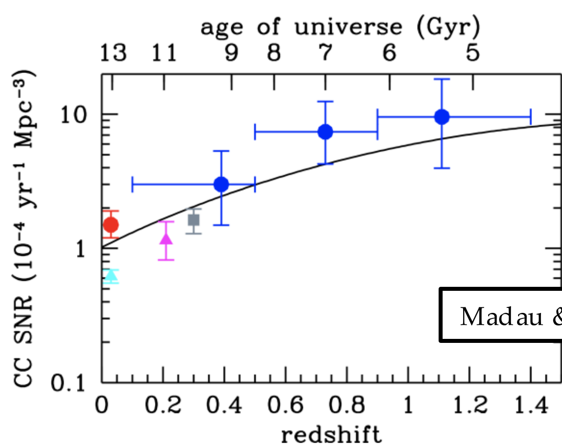
  - coexist with star formation episodes

→ **Can we characterize star formation in SNRs environment, if any ?**

- **AtLAST sweet spot: FoV**



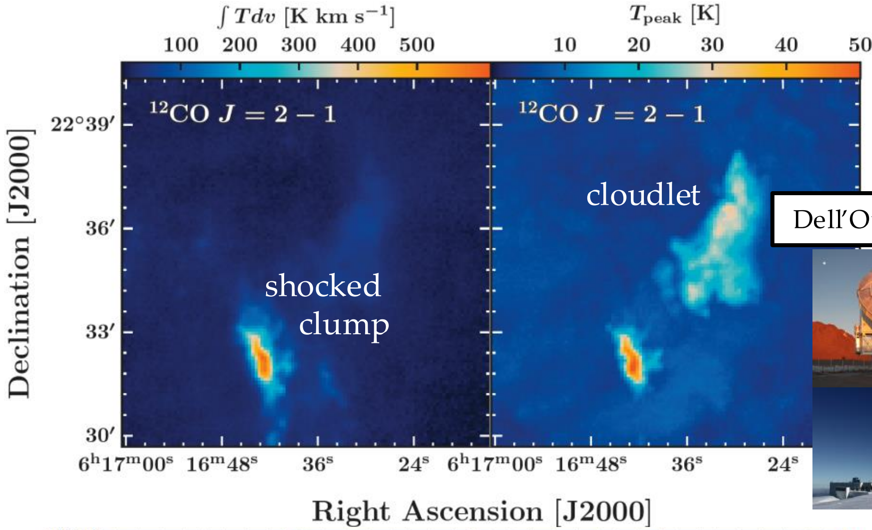




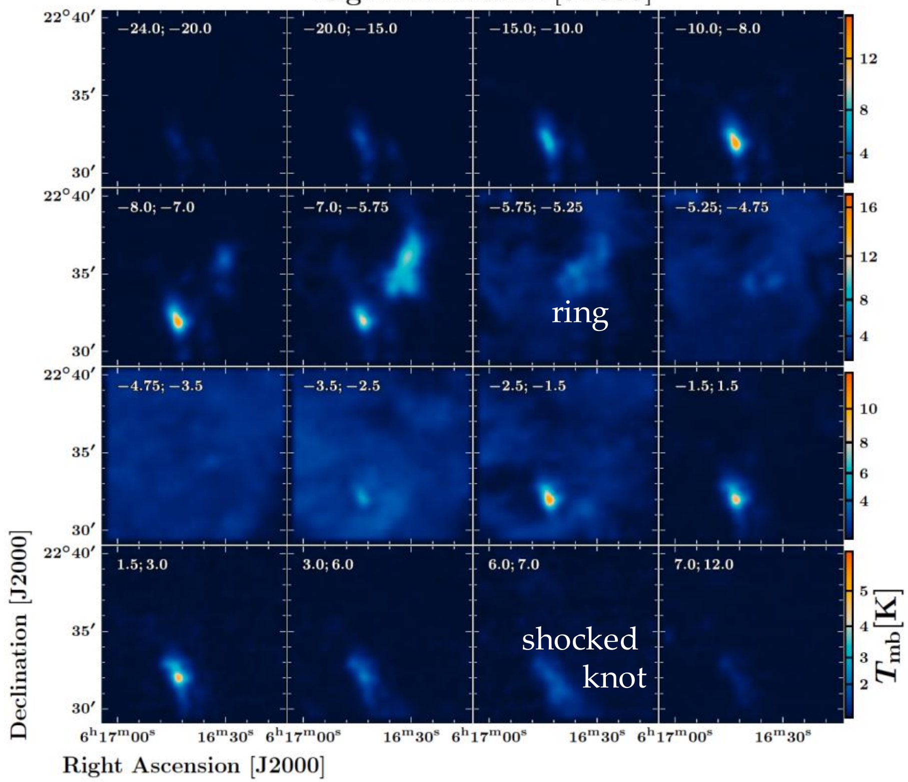
Madau & Dickinson 2014

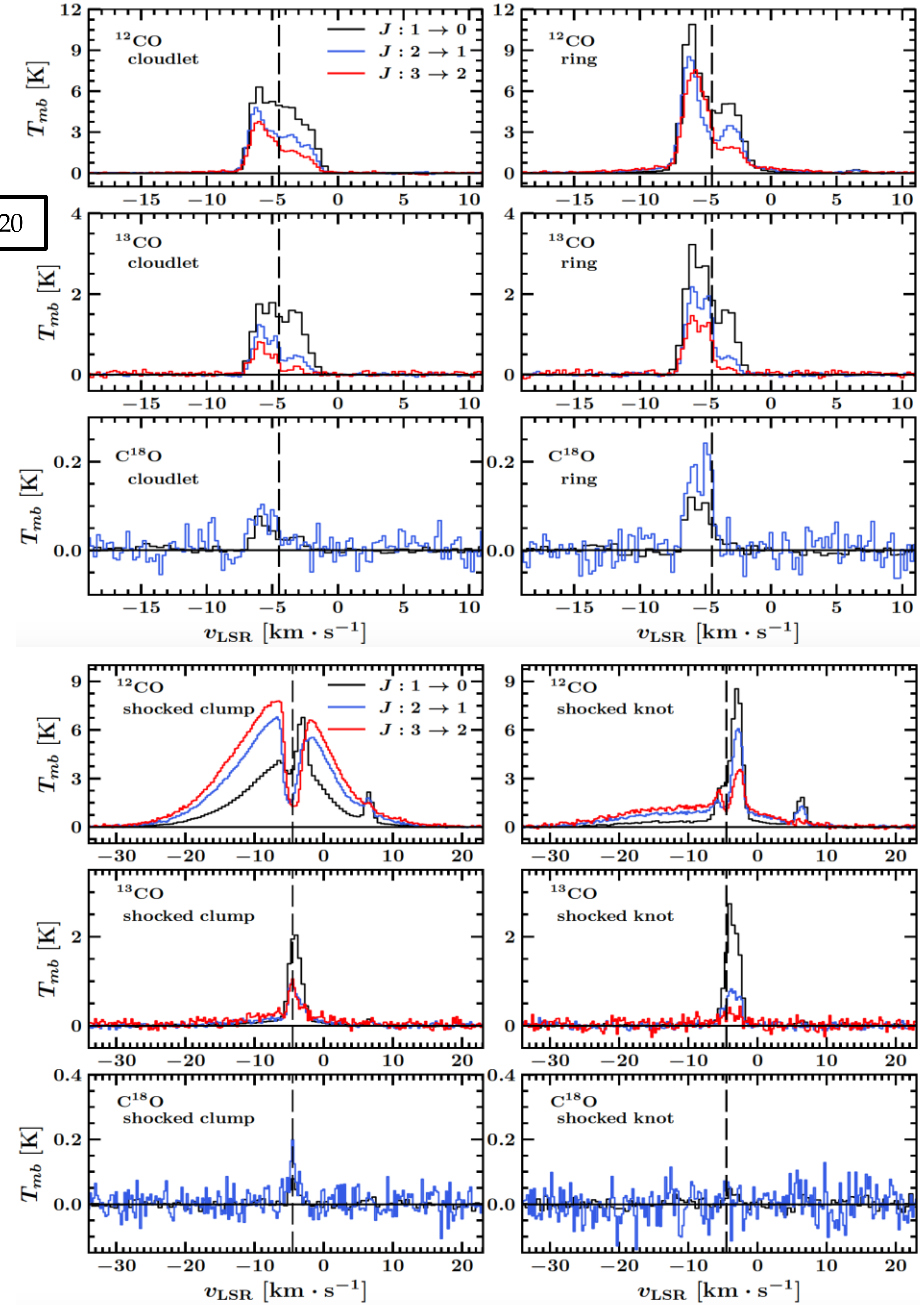
CO lines & dust continuum
velocities, densities, masses, temperatures, radiation fields

Measuring physical parameters from CO



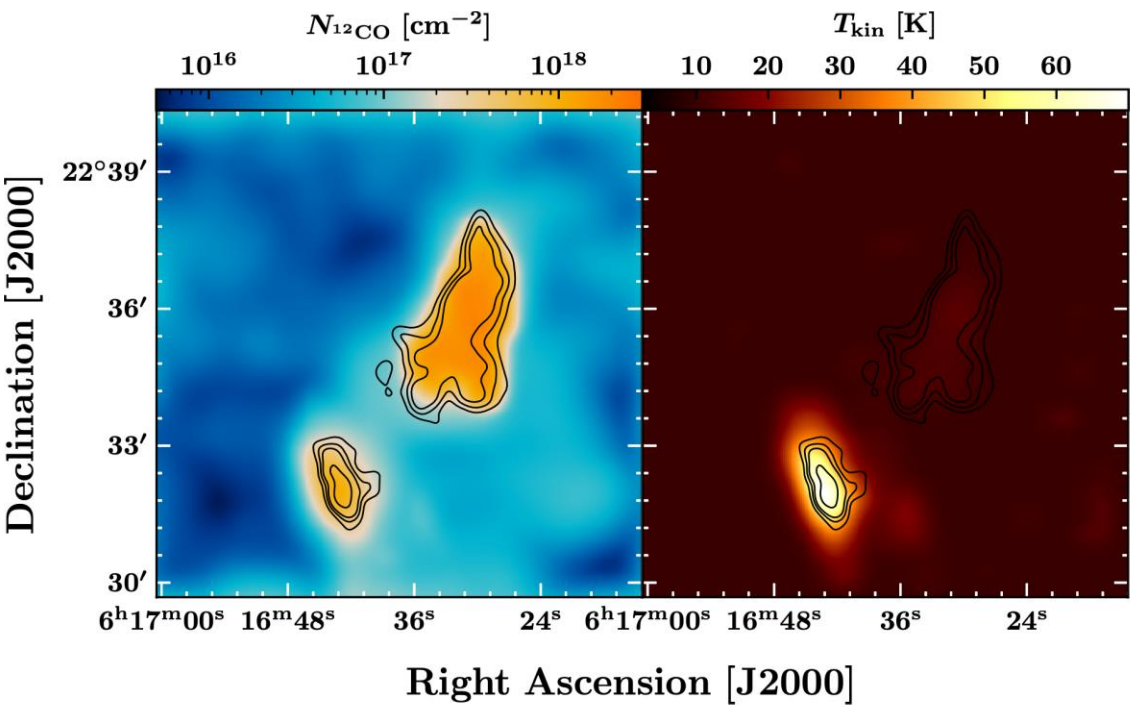
Dell'Ova et al. 2020

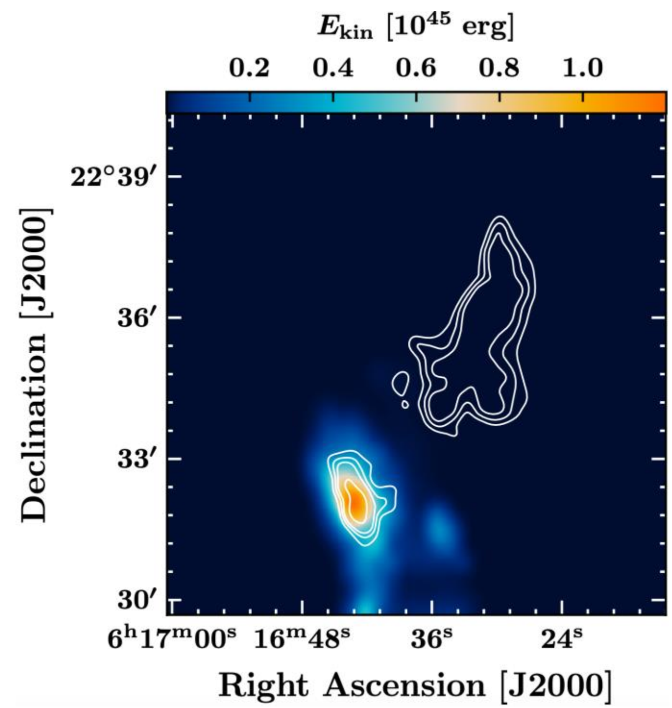




Measuring physical parameters from CO

- Assumptions:
  - Excitation diagram approach (maps, isotopologues)
  - LVG approach



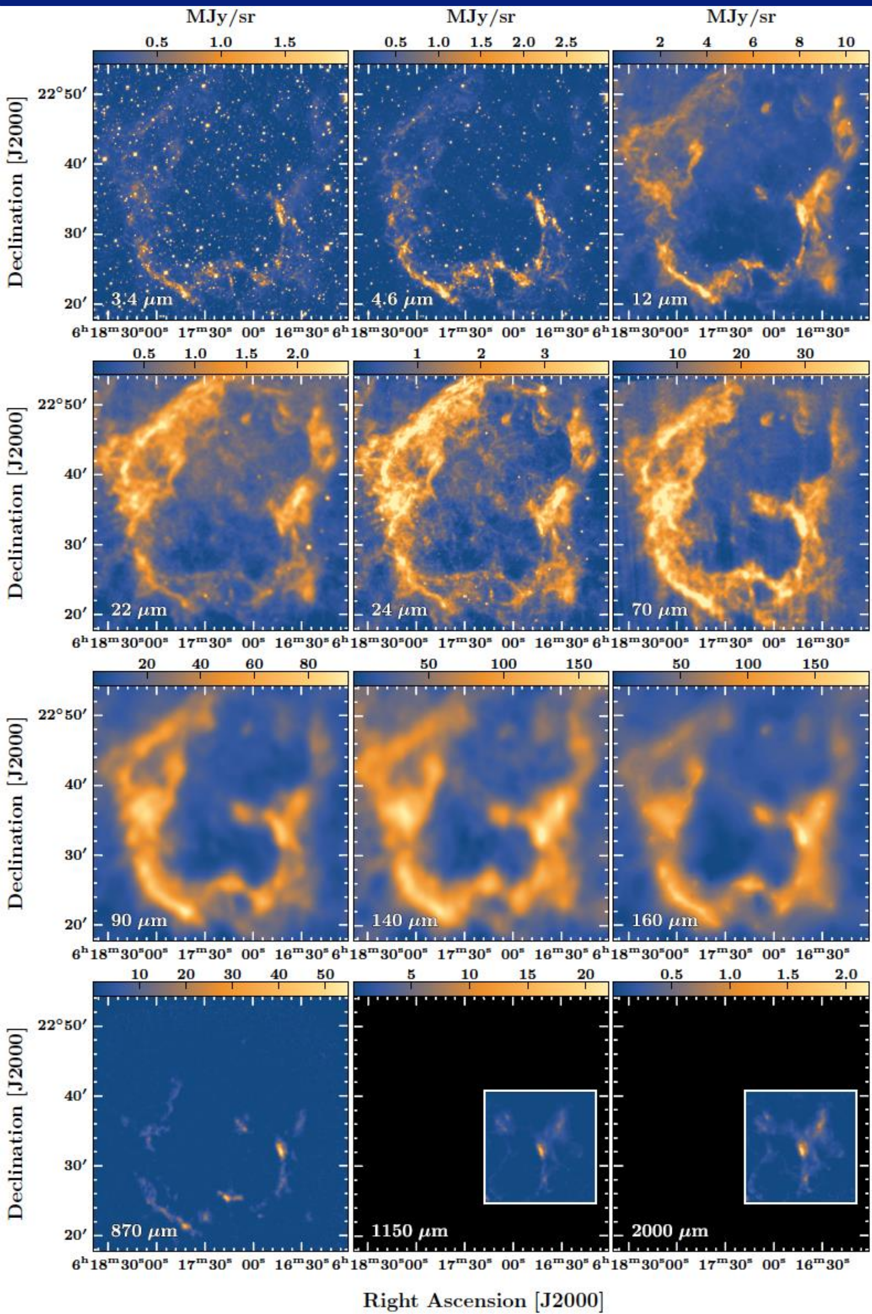


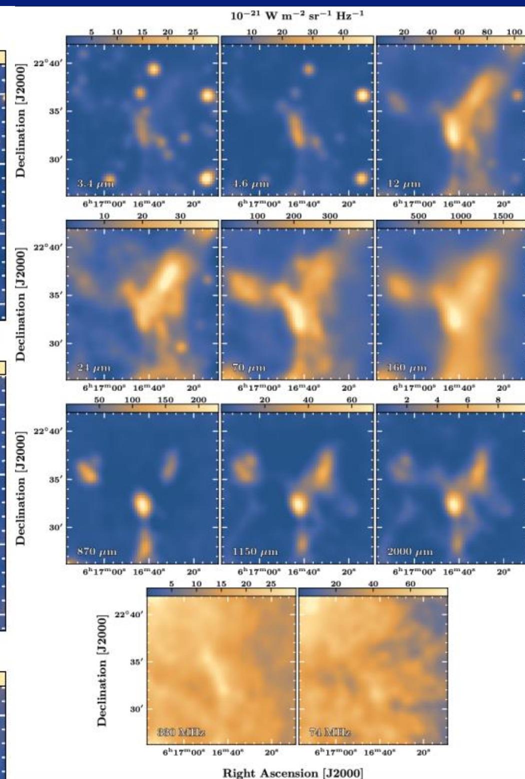
- Results:
  - dense structure identification
  - mass & density estimates
  - chemical & energetic impacts

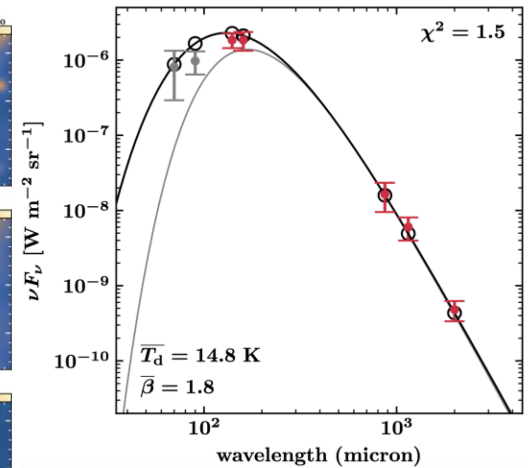
region	$\overline{N_{CO}}$[10^{17}cm^{-2}]	Mass ($M_\odot$)	$\overline{T_{kin}}$[K]
cloudlet (A)	$2.9^{+1.8}_{-1}$	180^{+190}_{-80}	10^{+1}_{-4}
ring-like structure (B)	$4.8^{+3.8}_{-1.9}$	160^{+190}_{-70}	12^{+2}_{-4}
shocked clump (C)	2.8^{+2}_{-1}	80^{+90}_{-40}	24^{+13}_{-11}
shocked knot (D)	$1.6^{+2.2}_{-1.1}$	15^{+30}_{-10}	16^{+7}_{-9}
ambient cloud	$0.8^{+1}_{-0.6}$	300^{+600}_{-200}	9^{+2}_{-4}
IC443G (extended)	$1.4^{+1.1}_{-0.6}$	700^{+900}_{-300}	10^{+2}_{-1}

Dell'Ova et al. 2020

Measuring physical parameters from the dust





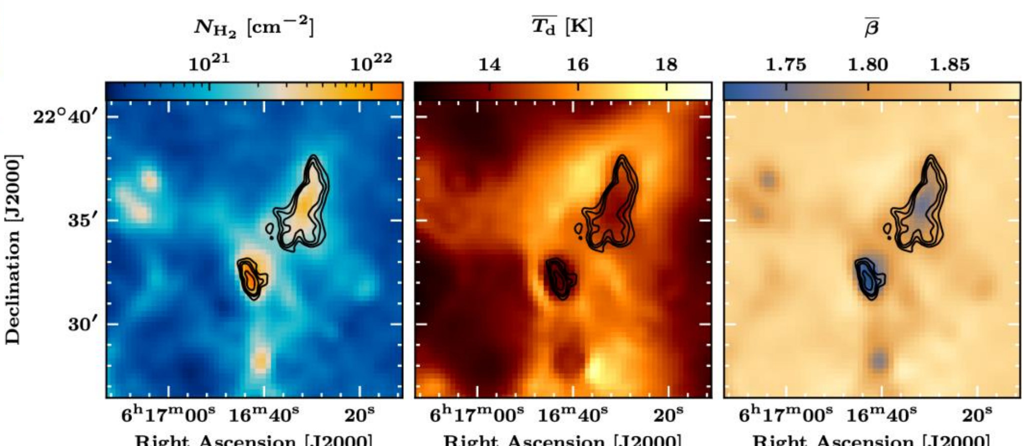


Dell'Ova et al. 2021

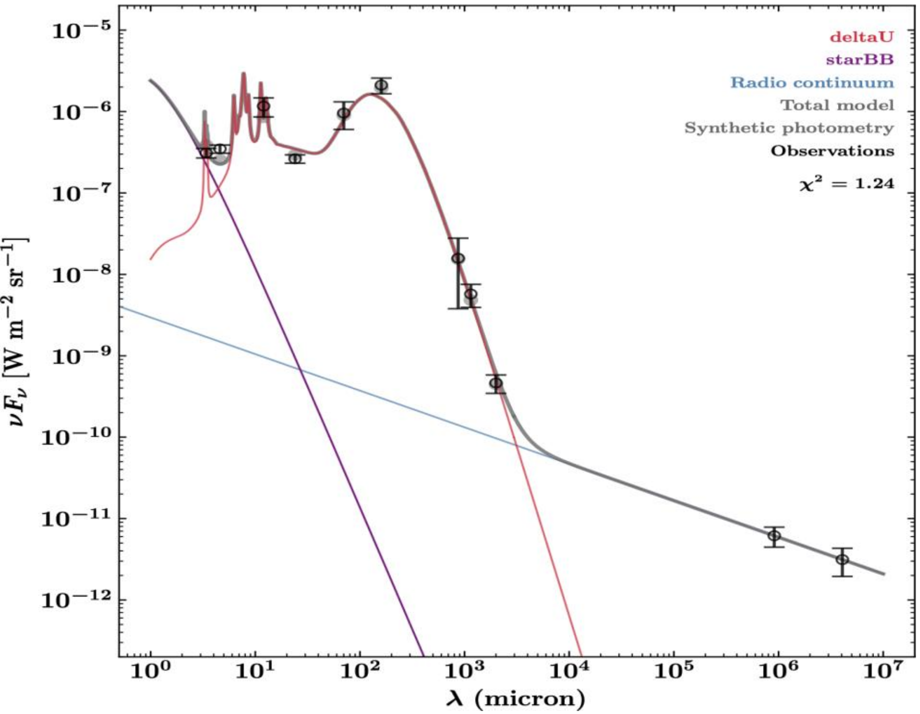
- PPMAP

(Marsh et al. 2015):

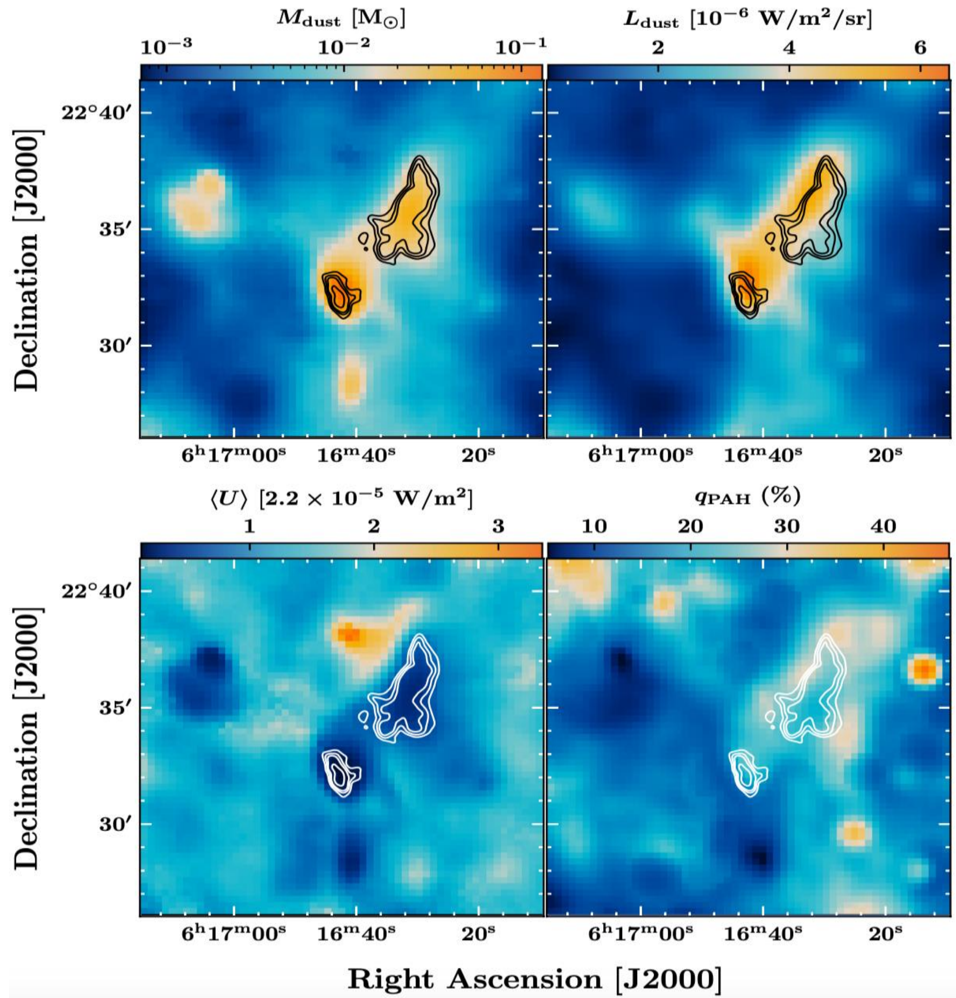
- dense structure
- mass & density
- temperature & beta

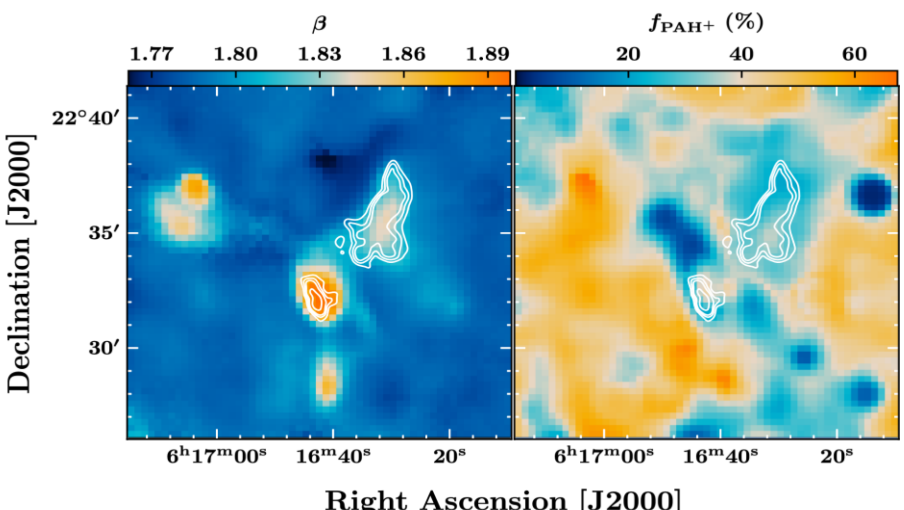


Measuring physical parameters from the dust



- HerBIE Results (Galliano et al. 2018):
  - dense structure identification
  - mass & density estimates
  - chemical impacts
  - IR to UV Radiation field estimate



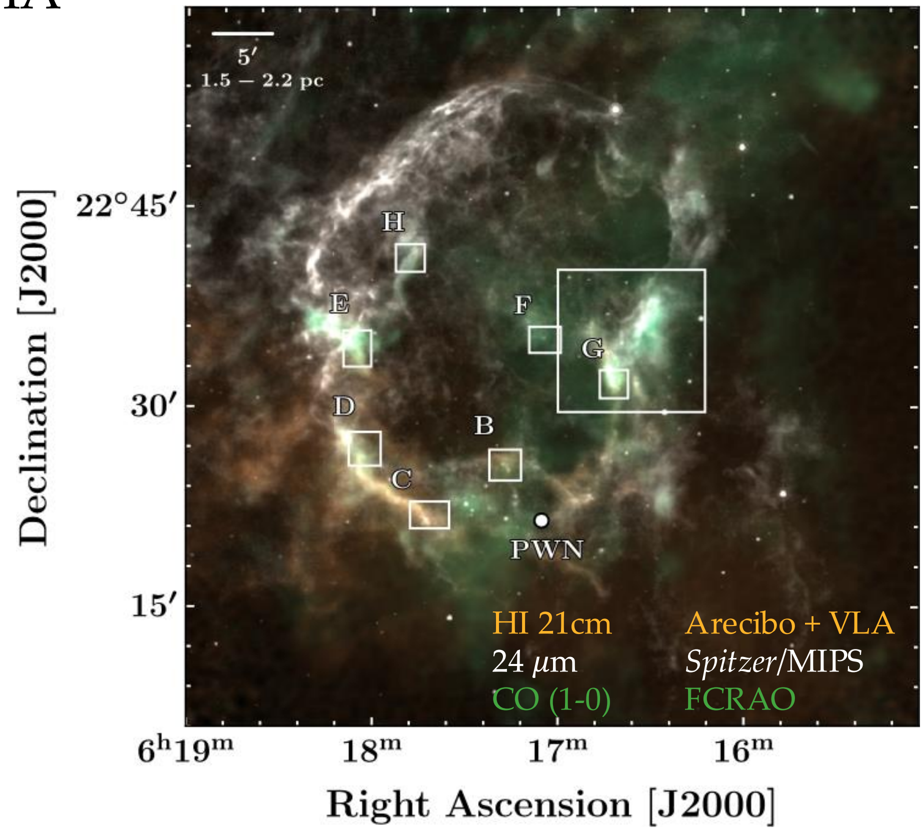


Synergies

- Lines, on much smaller fields:
  - H_2 from *Spitzer* and JWST (e.g., Dell'Ova et al. 2024)
  - CO from *Herschel*, ALMA, NOEMA

- Dust emission (SEDs building):
  - All other IR telescopes

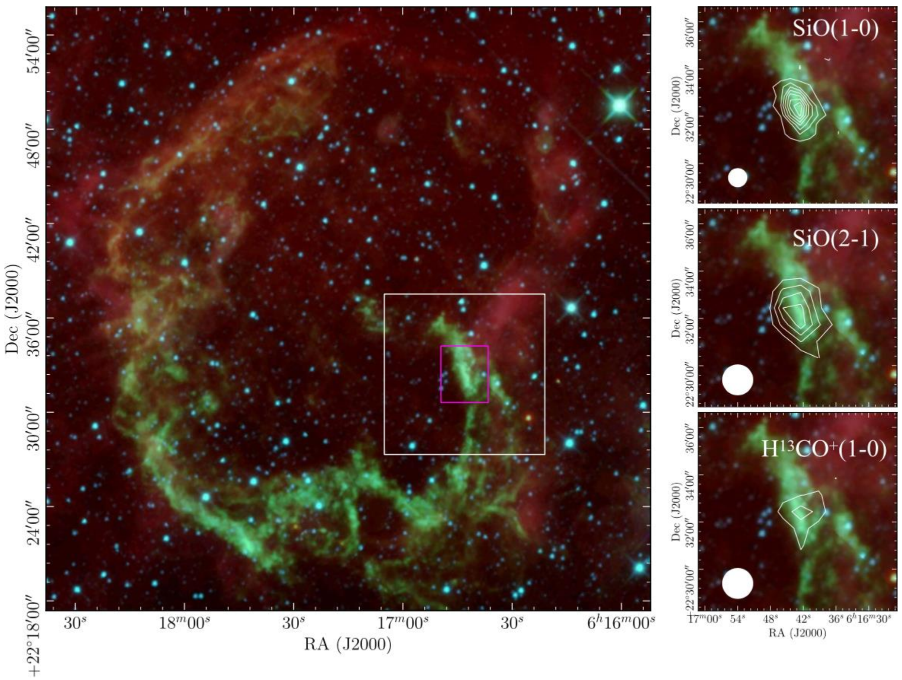
- Low frequency Radio observations:
  - SKA pathfinders and precursors
  - contributions to SEDs:
    - synchrotron (polarized)
    - free-free (unpolarized)

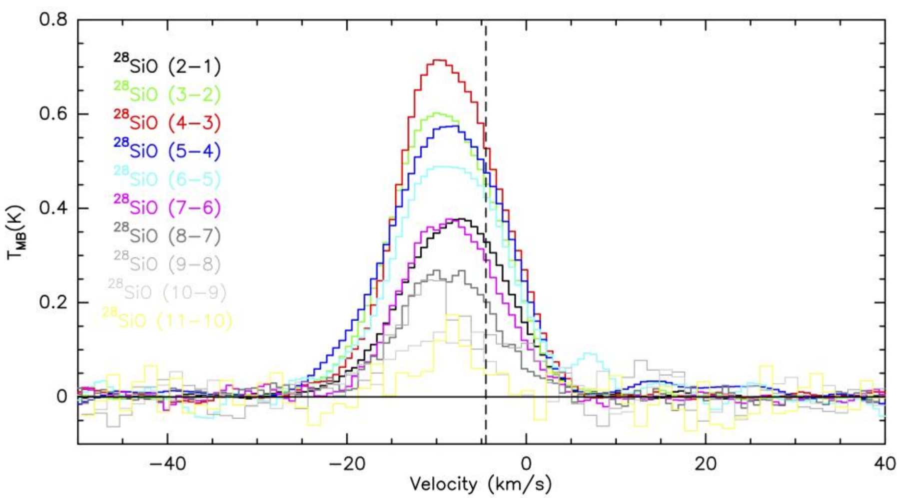


- AtLAST's unprecedented, adequate specifications:
  - Field of View & Angular resolution
  - Spectral coverage (CO J_{up} = 1, 2, 3, 4, 6, 7, 8 + cold dust)

Feedbacks
Shocks, photons, cosmic rays

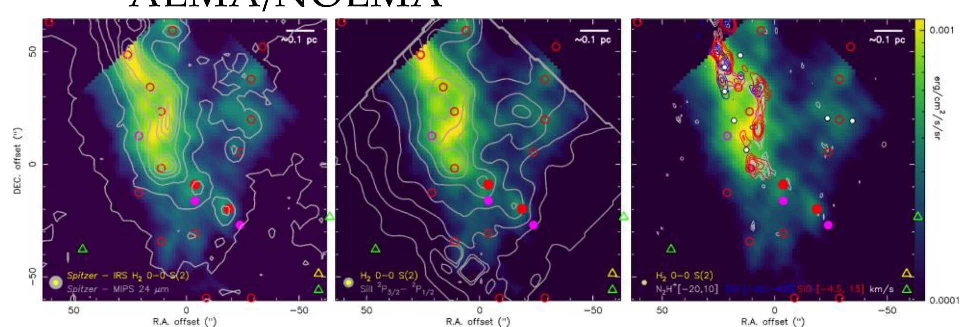
Shocks: SiO lines (and shock models)





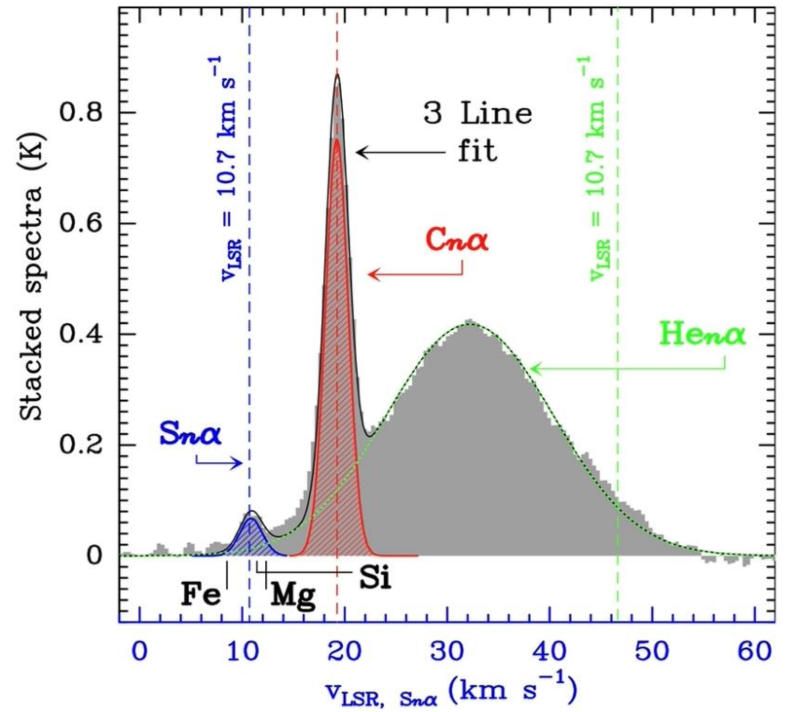
- **Cosentino et al. 2022:**
  - 12m ARO maps
  - ^{28}SiO (1-0) & (2-1)
- **Unpublished I30m/APEX data:**
  - Spectral survey, 2 positions
  - ~15 hours/line
  - ^{28}SiO, ^{29}SiO, ^{30}SiO

  (2-1) to (11-10), I30m & APEX
- **Necessary synergies:**
  - Complement with Si/SiII
    - Si $^3P_1$-$^3P_0$ & $^3P_2$-$^3P_1$ (129.7 & 68.5 μm), *Herschel*-PACS
    - Si$^+$ $^2P_{3/2}$-$^2P_{1/2}$ (34.82 μm), *Spitzer*-IRS
  - CO & H_2, Chemical surveys (IC443: van Dishoeck et al. 1993 & W28: Mazumdar et al. 2022)
  - ALMA/NOEMA

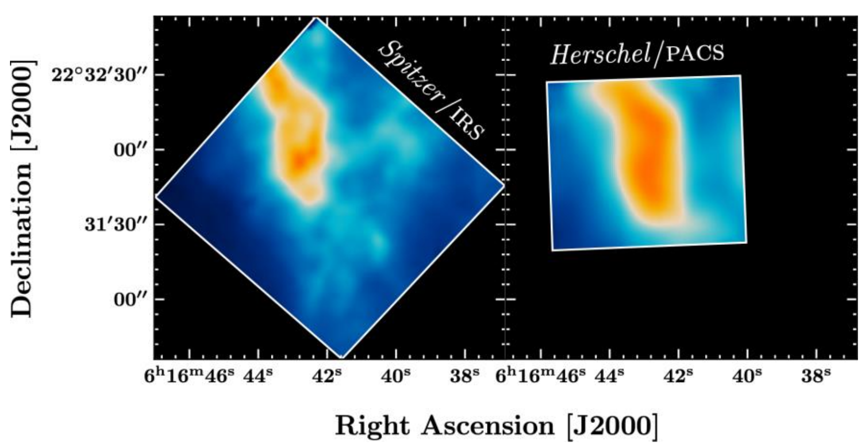


Photons: CI, C_2H (and PDR or irradiated shock models), RRLs

- Disentangle shocks from PDR-like effects
  - CI (Joblin et al. 2018)
    - $^3P_1 - {}^3P_0$, E_{up} = 23.6 K, ν = 492 GHz
    - $^3P_2 - {}^3P_1$, E_{up} = 62.5 K, ν = 810 GHz
  - specific diagnostics: C_2H & C chains
    - Teyssier et al. 2004 PDRs,
    - Beuther et al. 2008 massive SFRs
  - Radio Recombination Lines (RRLs):
    - H, C+He+S
    - Orion Bar: Cuadrado et al. 2019, Goicoechea et al. 2021, Pabst et al. 2024)



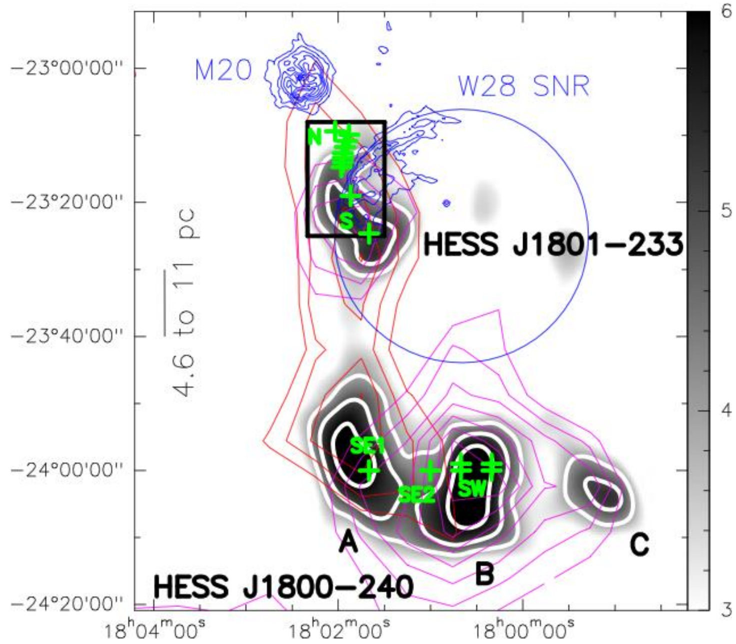
- Important synergies (Joblin et al. 2018):
  - CO & H_2, and chemical surveys
  - dust continuum
  - OI and C^+ observations (*Herschel*)

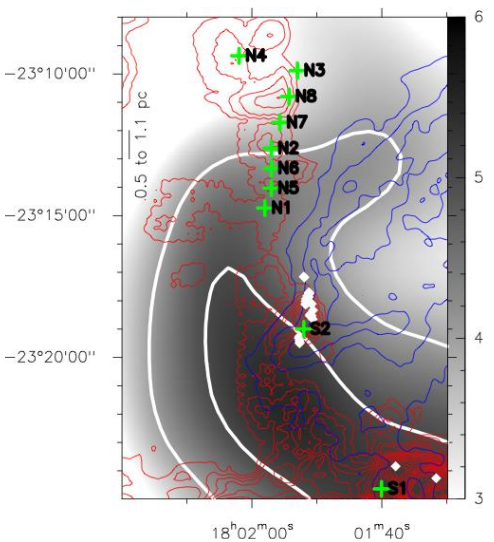


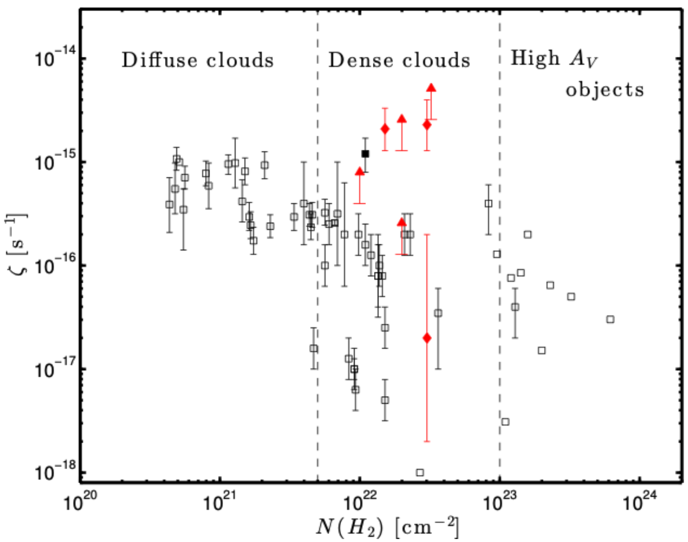
Cosmic rays: cosmic ray ionization rate measurements

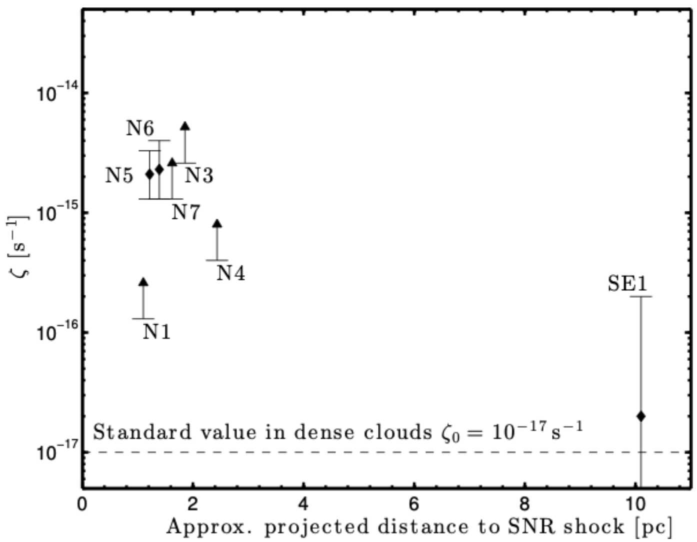
- ζ measurements, Vaupré et al. 2014:
  - in W28 ambient clouds
  - chemical modelling of
    - $H^{13}CO^+$ (1-0), DCO^+ (2-1)
    - ^{13}CO, $C^{17}O$, $C^{18}O$ (1-0) & (2-1)

- Results:
  - relatively high values
  - above 10^{-17} s^{-1}



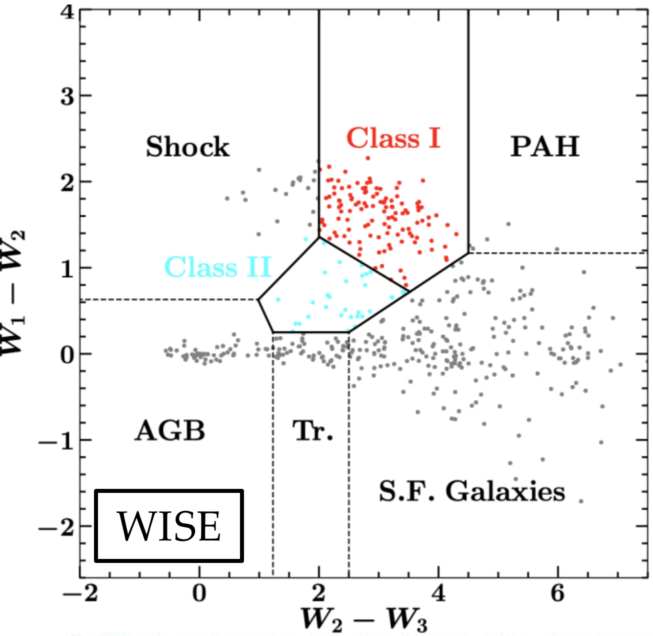


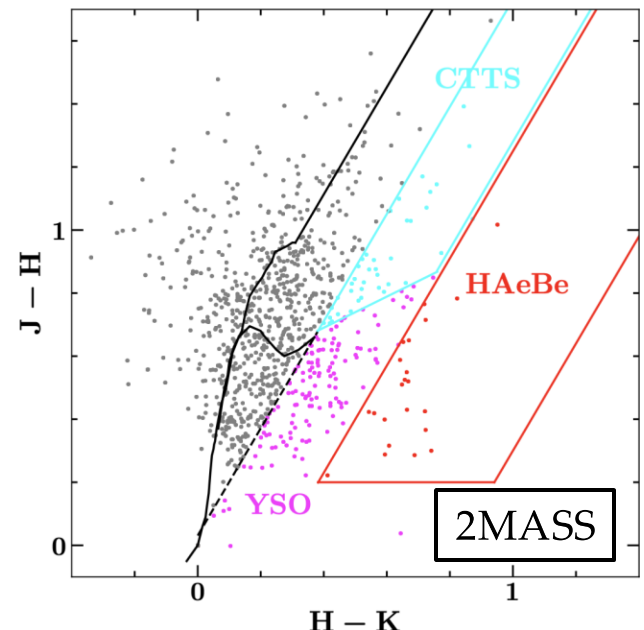




Star formation

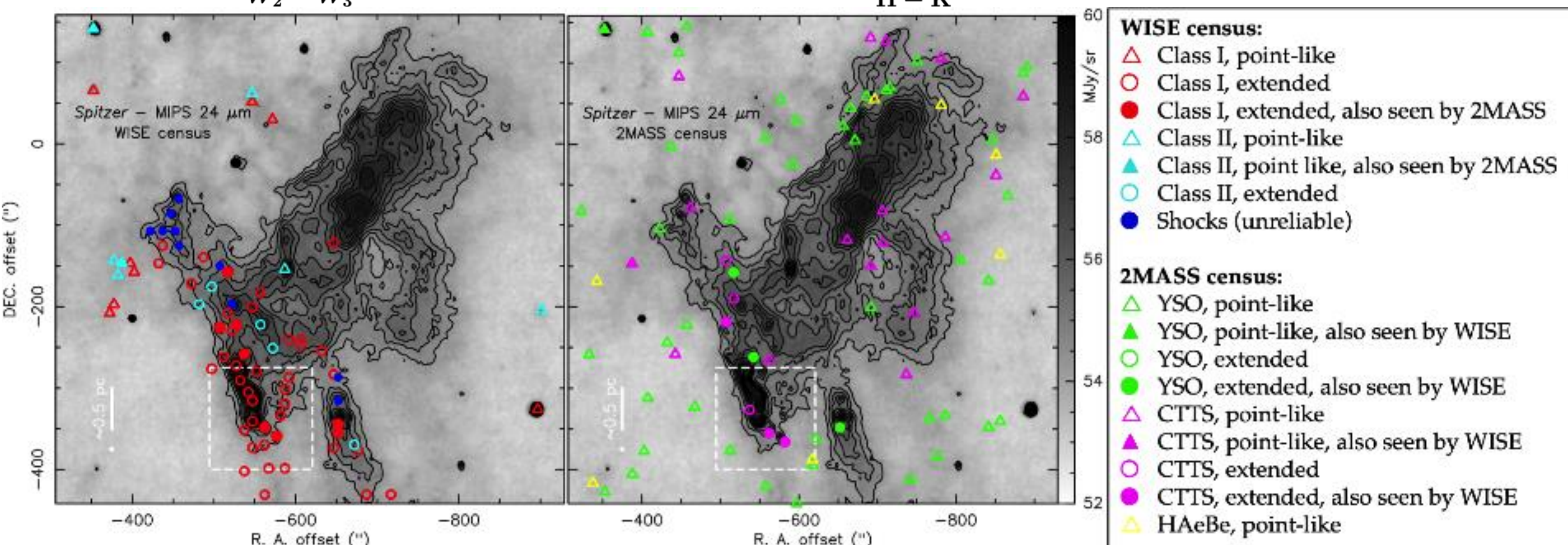
IR point source detections in IC443G-extended





Band	λ (μm)	$\Delta\lambda$ (μm)	*FWHM*(″)
WISE W_1	3.35	0.66	6.1
WISE W_2	4.60	1.04	6.4
WISE W_3	11.56	5.51	6.5
WISE W_4	22.09	4.10	12.0
2MASS *J*	1.235	0.162	2.5
2MASS *H*	1.662	0.251	2.5
2MASS *K*	2.159	0.262	2.5

Dell'Ova et al. 2020



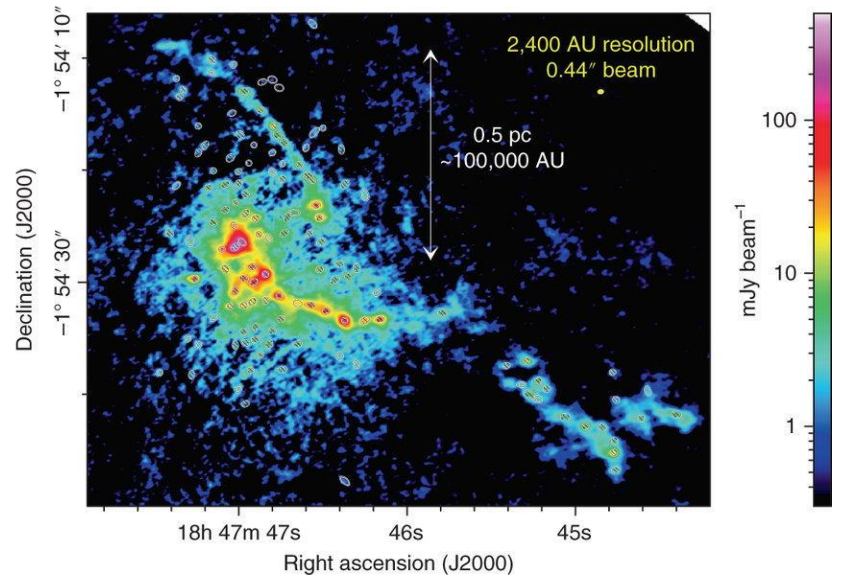
What needs to be done : local CMF studies

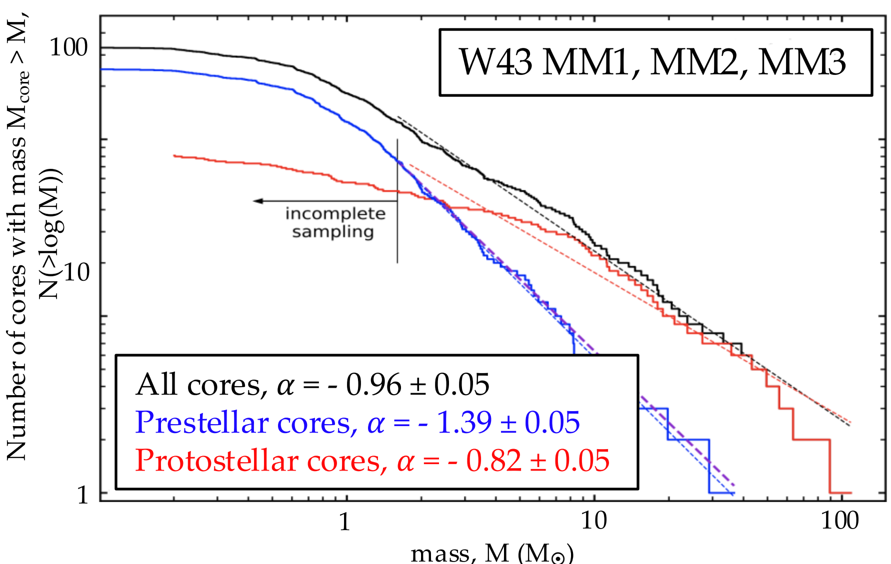
- ALMA-IMF LP (PI F. Motte et al.; Motte et al. 2022, Ginsburg et al. 2022):
  - 1 mm & 3 mm continuum : core extraction, CMF building

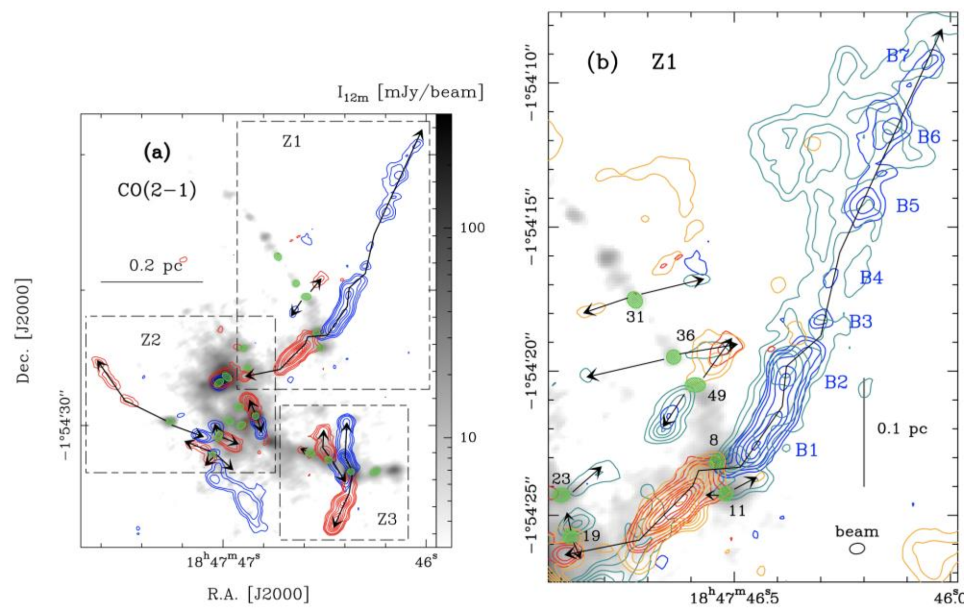
Motte et al. 2018, Pouteau et al. 2022, 2023, Armante et al., 2024, Louvet et al. 2024

  - CO & SiO lines : outflow detection

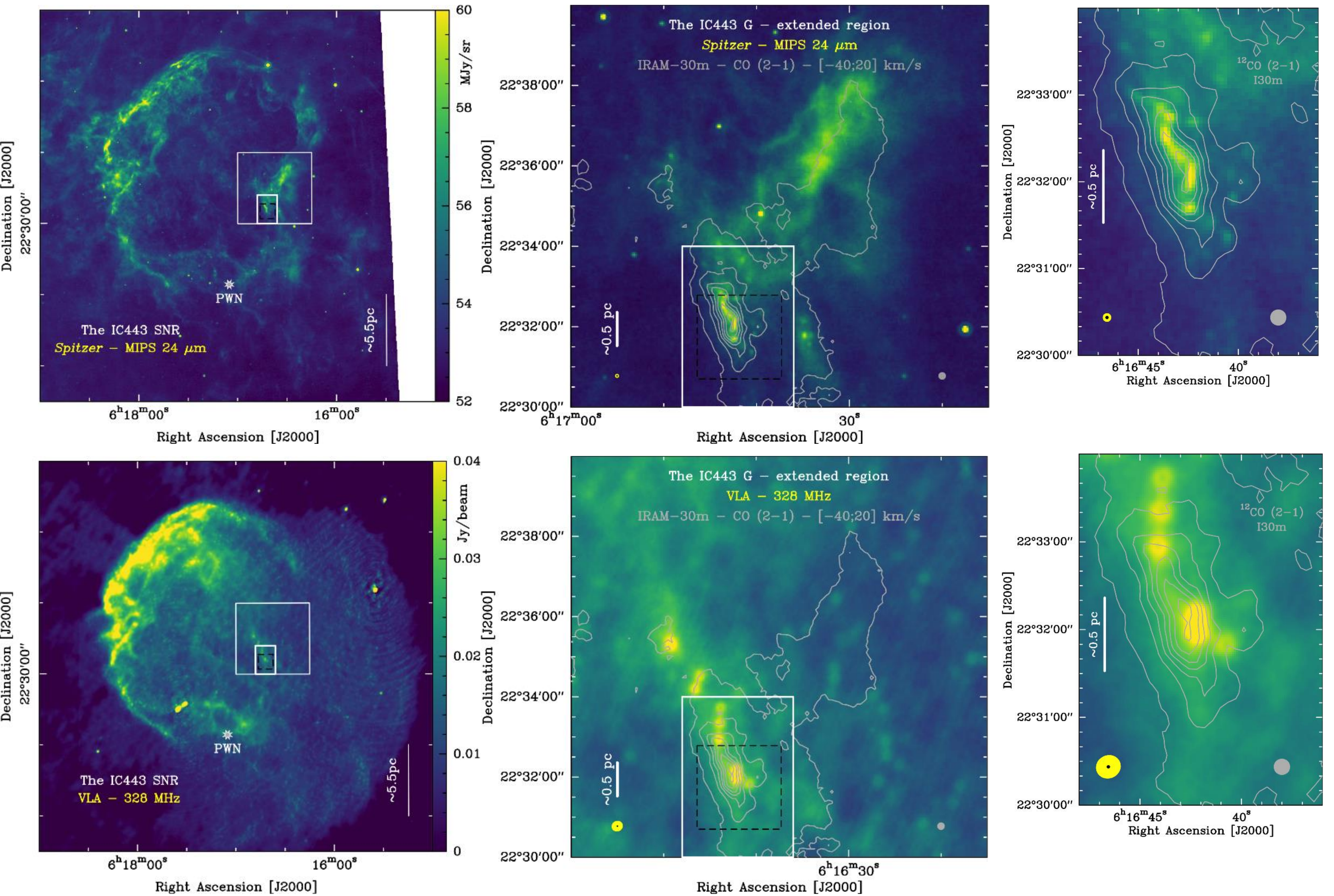
Nony et al. 2020, 2023, Armante et al. 2024, Towner et al. 2024, Valeille-Manet et al. 2024







One last ISM puzzle: synchrotron bubbles or compact HII regions ?



Perspective: towards Cosmic Rays science

A summary

- Based on the CO lines and dust emission, we can:
  - identify dense medium components
  - estimate their mass, density
  - measure the IR-to-mm local radiation field
  - characterize some aspects of the UV field (starlight, PAH^+/PAH)
  - characterize some dust properties

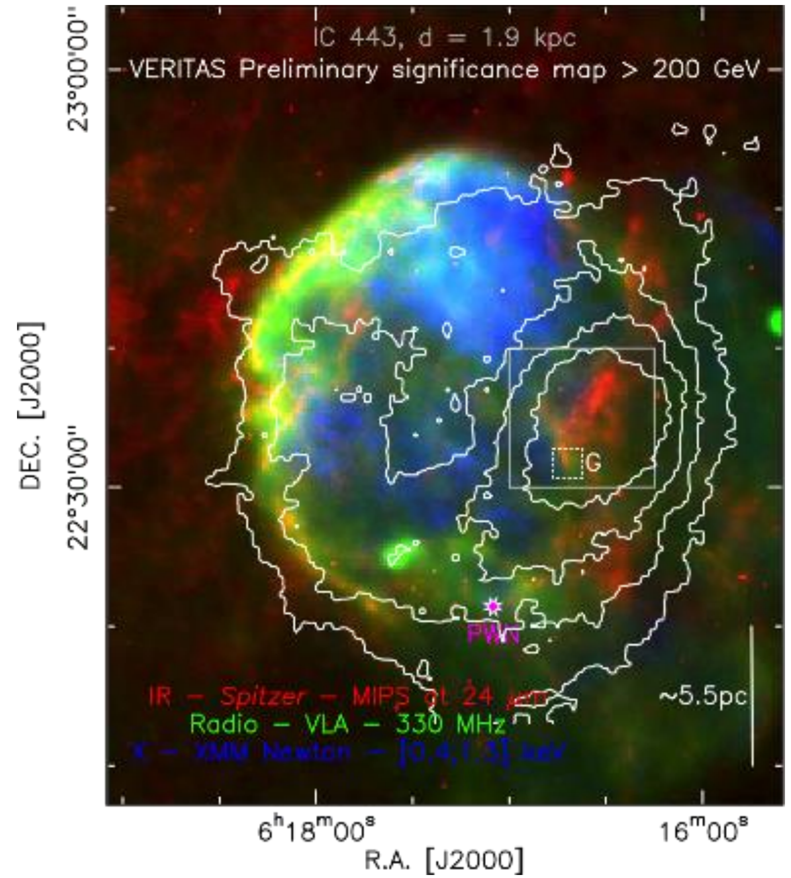
- Based on observations of selected species, we can:
  - quantify the contribution of shocks and photons to the energy injection
  - measure local cosmic ray ionization rates

- Based on our star formation studies, we can:
  - identify potential pre- and proto-stellar cores, build their CMF
  - start to investigate the potential outflows
  - identify radio bubbles (synchrotron bubbles or compact HII regions)

- All this on huge regions of the sky at high angular & spectral resolutions

A selective summary

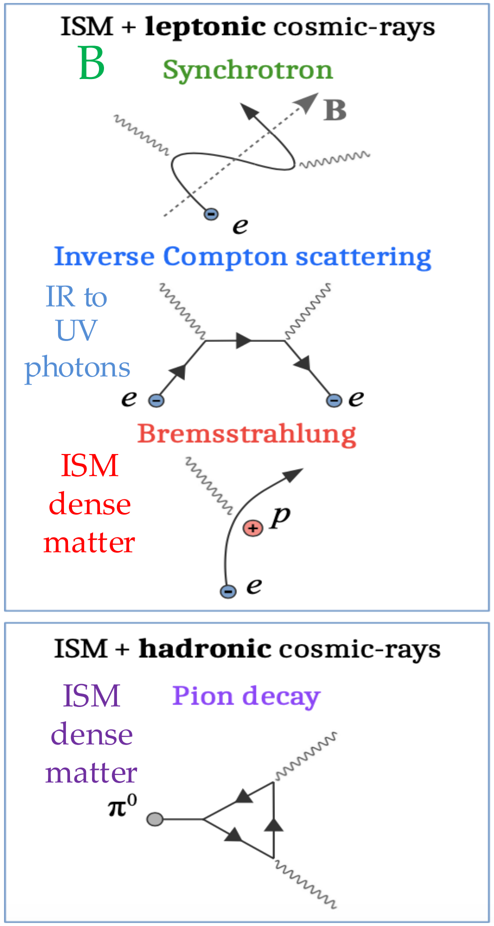
- Based on the CO lines and dust emission, we can:
  - identify dense medium components
  - estimate their mass, density
  - measure the IR-to-mm local radiation field
  - characterize some aspects of the UV field

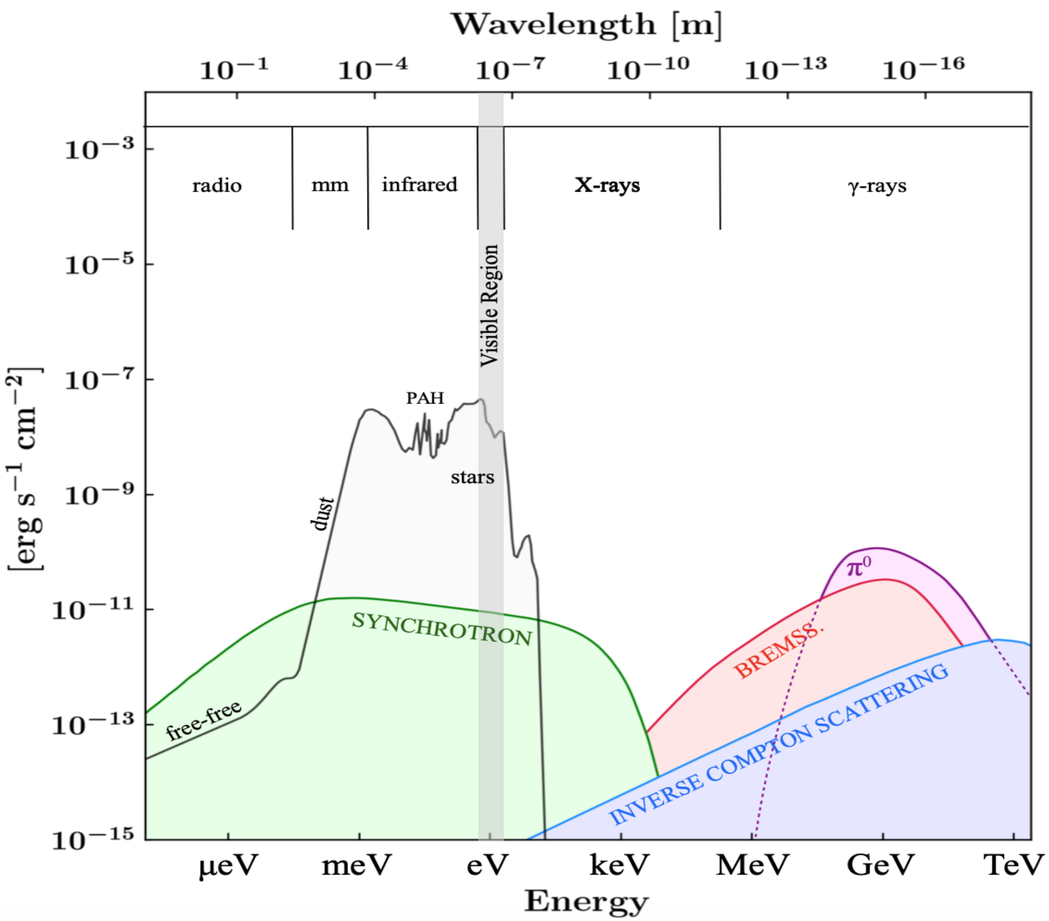


- Based on our star formation studies, we can:
  - start to investigate the potential outflows
  - identify radio bubbles

- The huge FoV means we can participate to the interpretation of the white contours: γ-ray emission, typically obtained at ~0.2º resolution (upcoming CTA a few arcmin)

Cosmic rays characterization in evolved SNRs





Thanks for your attention !