Unveiling the star formation mechanism with HWO

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

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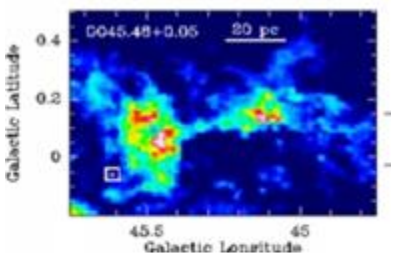
HABITABLE WORLDS OBSERVATORY

SHAPING THE ITALIAN CONTRIBUTION TO

SF: Interplay between gravity, turbulence, magnetic fields and feedback

GMCs
$10 \leq R \leq 150$ pc
$\Sigma \sim 0.0004$-0.06
(g/cm^2)



The star formation process starts in dense, cold molecular clouds.

The biggest are called giant molecular **clouds** (GMCs)

Total mass of molecular clouds in the Milky Way: **M ~ 2 x 10^9 M$_\odot$**

Typical free-fall time **$\tau_{ff} \sim 10^7$ yr**

Average. SFR ~ 200 M$_\odot$/yr

Observed SFR ~ 2 M$_\odot$/yr !!!

Gravity. Turbulence. Feedback?

Debated from 50+ years!!!
(Zuckerman & Palmer 1974)

Turbulence. Feedback?

SF: Interplay between gravity, turbulence, magnetic fields and feedback

GMCs
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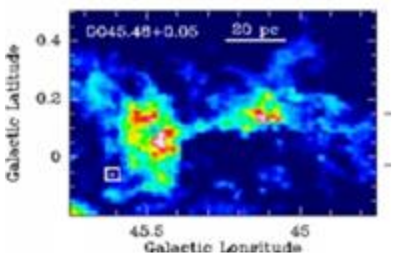
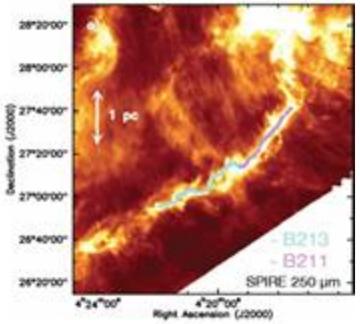
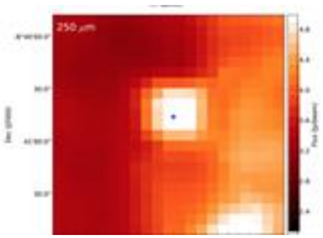


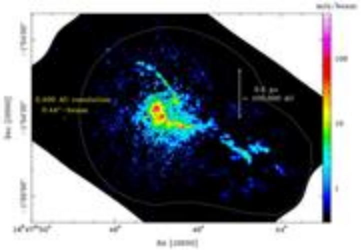
Galactic filaments
$1 \leq R \leq 100$ pc
$\Sigma \sim 0.0005$-0.5 (g/cm^2)



Clumps
$0.2 \leq R \leq 1$ pc
$\Sigma \sim 0.1$-5 (g/cm^2)



Fragments
R ~1000-2000 AU
$\Sigma \sim 1$-20 (g/cm^2)

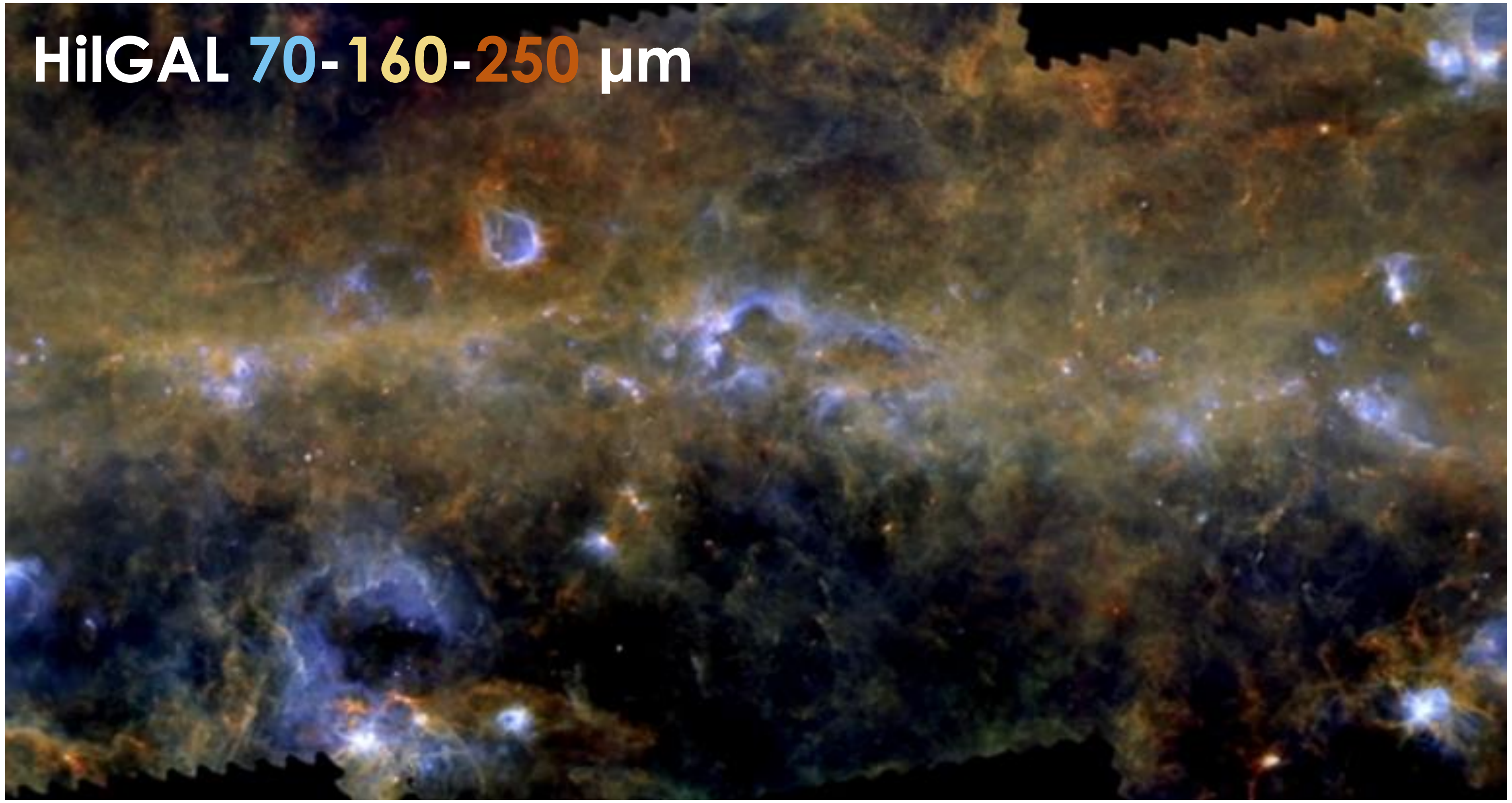


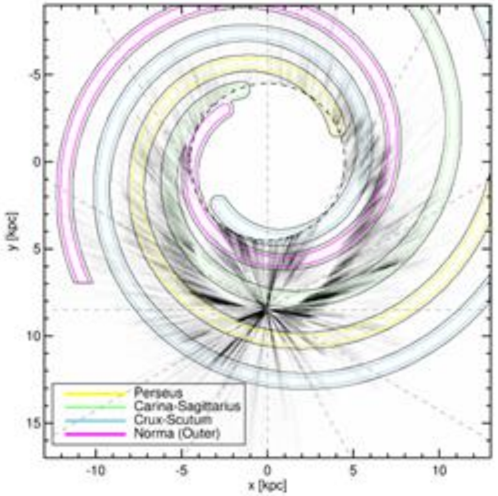
Gravity. Turbulence. Feedback?

Turbulence. Feedback?

Clumps and filaments physical properties

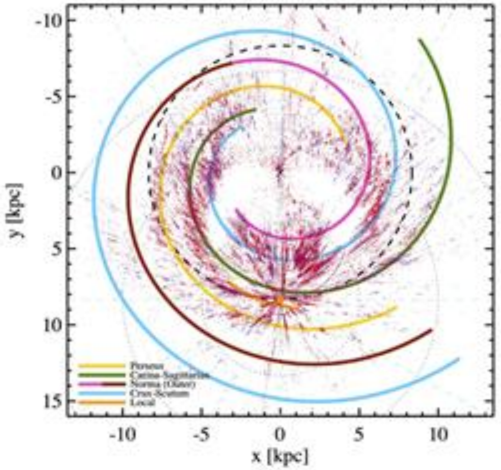
Hi-GAL: the (~900h) Herschel survey of the Galactic Plane in the FIR (70-160-250-350-500 μm, Molinari+10)





~30000 Hi-GAL filaments

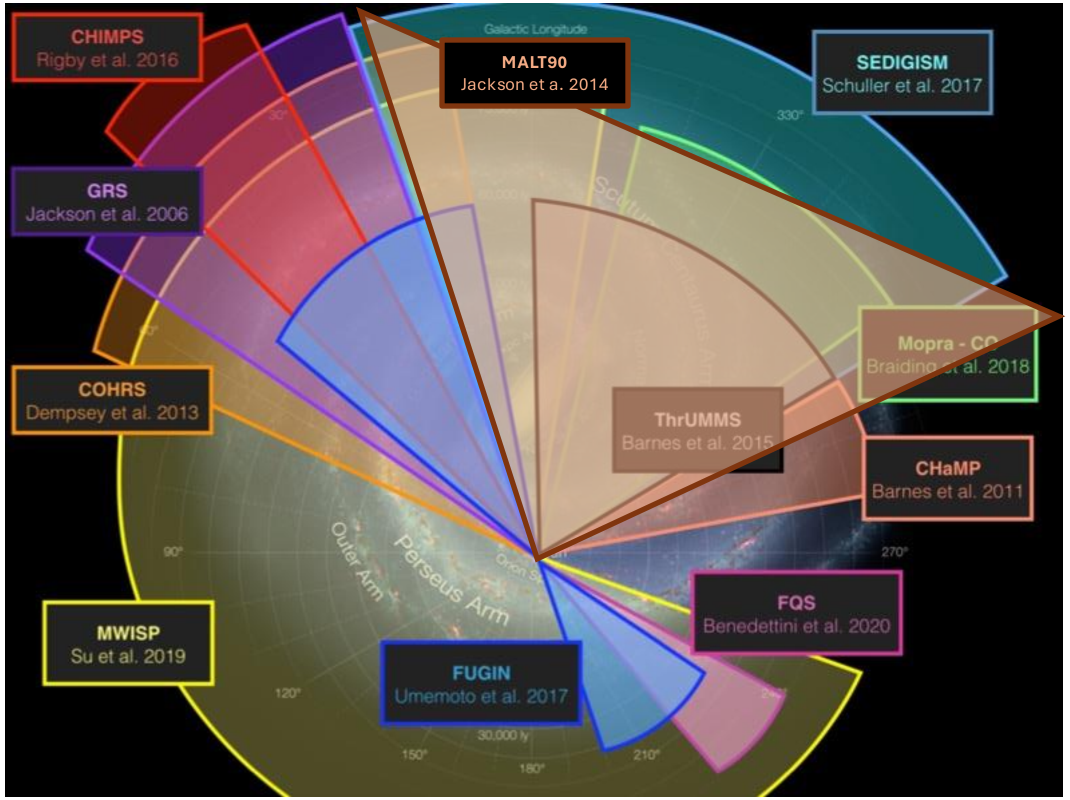
Schisano+20



~200000 Hi-GAL clumps

Elia+21

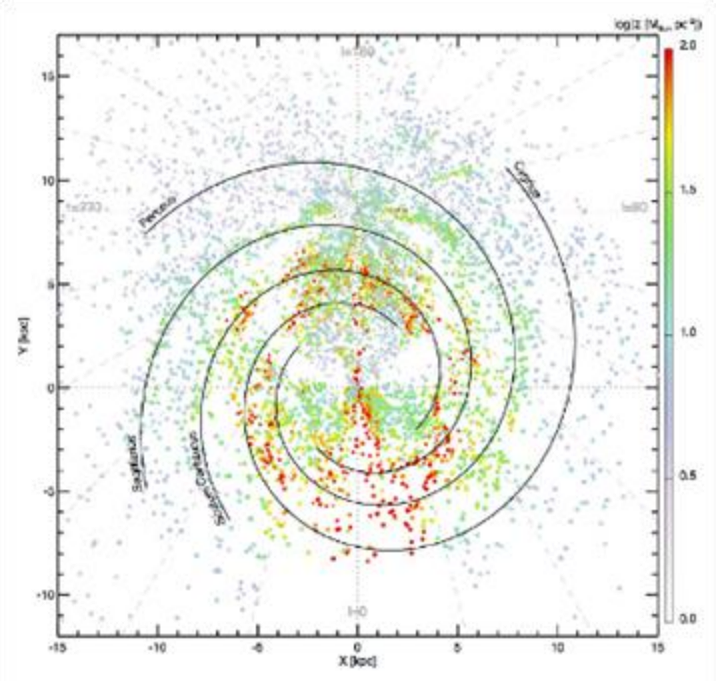
Clouds, filaments and clumps dynamics – CO/N_2H^+ (1-0) surveys



Credits: D. Colombo & J. Urquhart

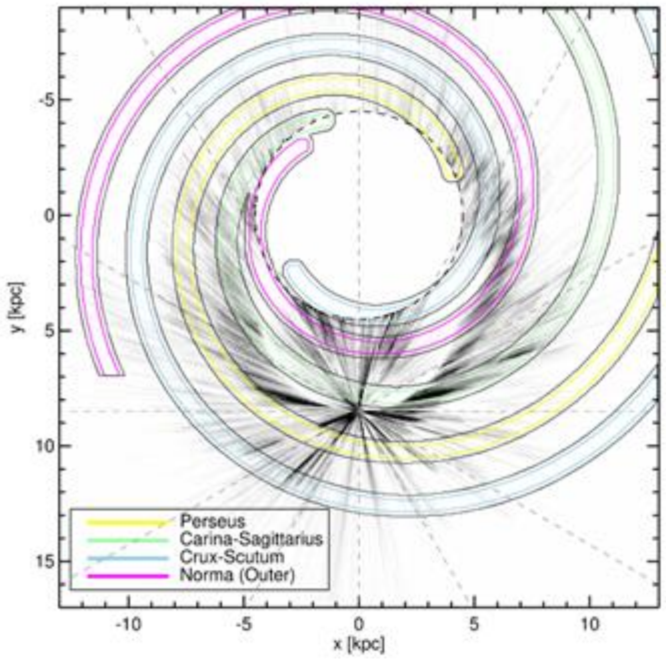
Survey	Transition	Coverage
GRS	^{13}CO (1-0)	15º < l < 55º
ThrUMMS	^{12}CO (1-0) ^{13}CO (1-0) $C^{18}O$ (1-0)	-60º < l < 0º
FUGIN	^{12}CO (1-0) ^{13}CO (1-0) $C^{18}O$ (1-0)	10º < l < 50º
SEDIGISM	^{13}CO (2-1) $C^{18}O$ (2-1)	-60º < l < 18º
COHRS	^{12}CO (3-2)	10º < l < 55º
CHIMPS	^{13}CO (3-2) $C^{18}O$ (3-2)	28º < l < 46º
CHIMPS2	^{12}CO (3-2) ^{13}CO (3-2) $C^{18}O$ (3-2)	-5º < l < 28º
MALT90	N_2H^+ (1-0)	-60º < l < 20º (2012 clumps)

Clouds, filaments and clumps in the Galaxy



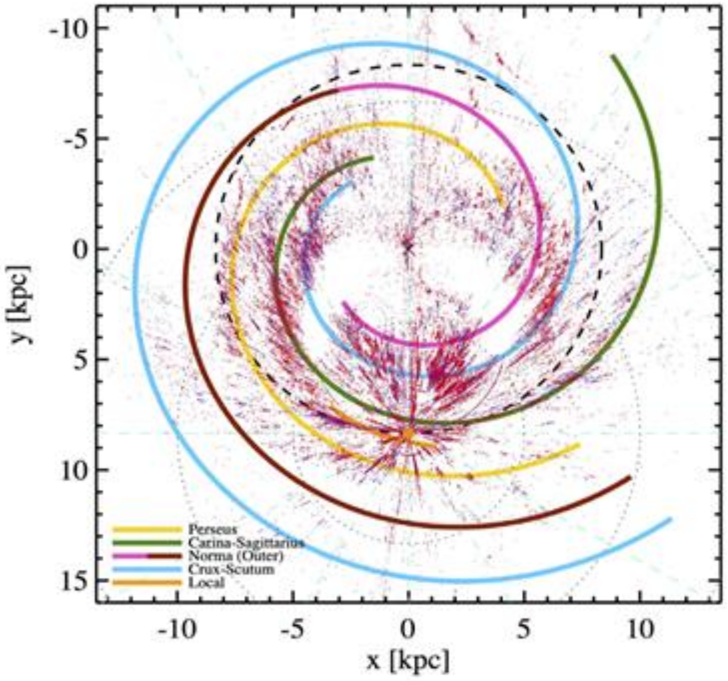
~8100 GMCs ^{12}CO (1-0)

Miville-Deschenes+17



~30000 Hi-GAL filaments

Schisano+20

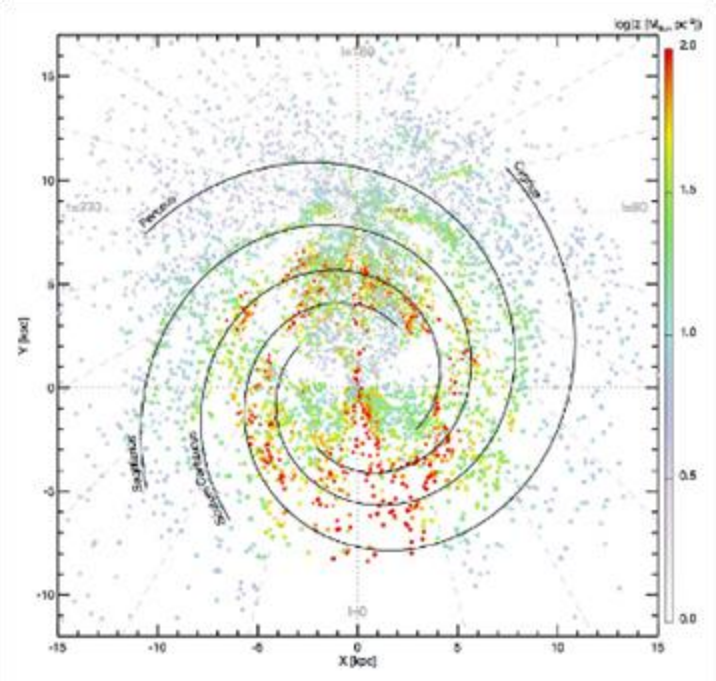


~150000 Hi-GAL clumps

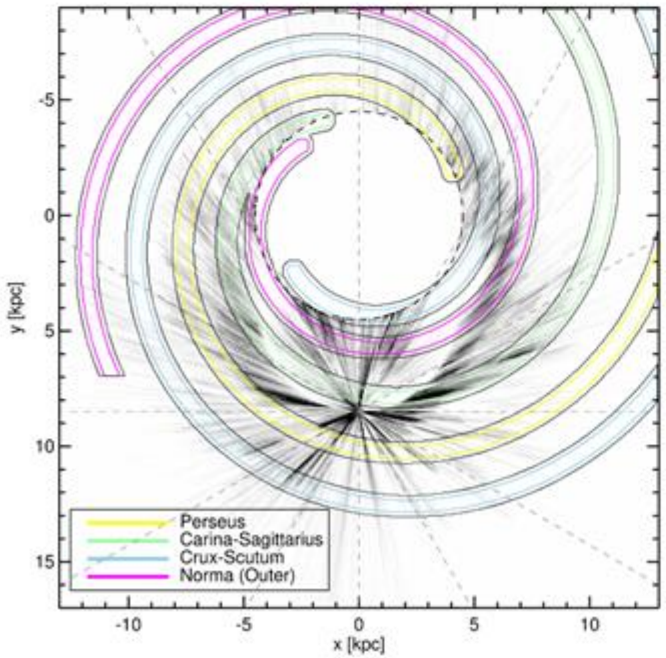
Elia+21

Galactic Plane surveys allow us to investigate the interplay beetwen gravity and turbulence across the different Galactic environments…

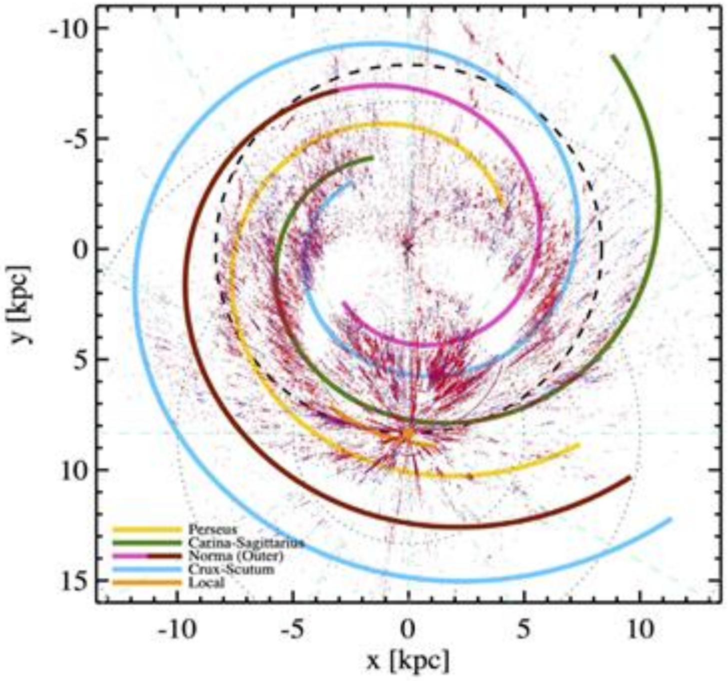
Clouds, filaments and clumps in the Galaxy



~8100 GMCs ^{12}CO (1-0)
Miville-Deschenes+17



~30000 Hi-GAL filaments
Schisano+20



~150000 Hi-GAL clumps
Elia+21

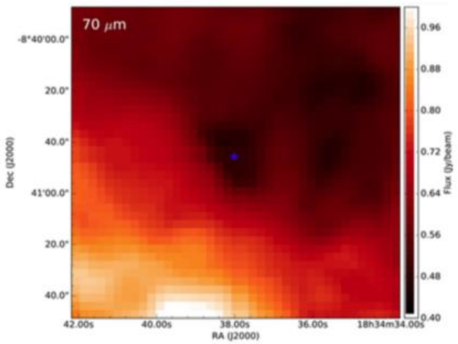
Galactic Plane surveys allow us to investigate the interplay beetwen gravity
turbulence across the different Galactic environm

...but...what about feedback?

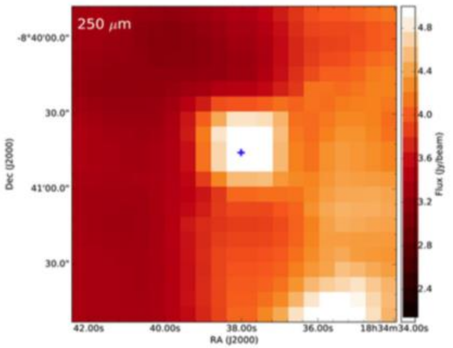
Star-forming clumps: where small scales feedbacks originate

SDC23271-0263

Hi-GAL 70 µm



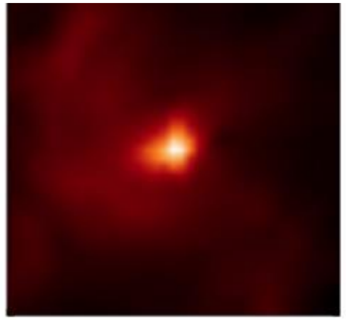
Hi-GAL 250 µm



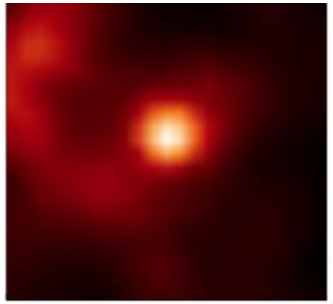
starless/pre-stellar
(70 µm-quiet)

Hi-GAL #110522

Hi-GAL 70 µm

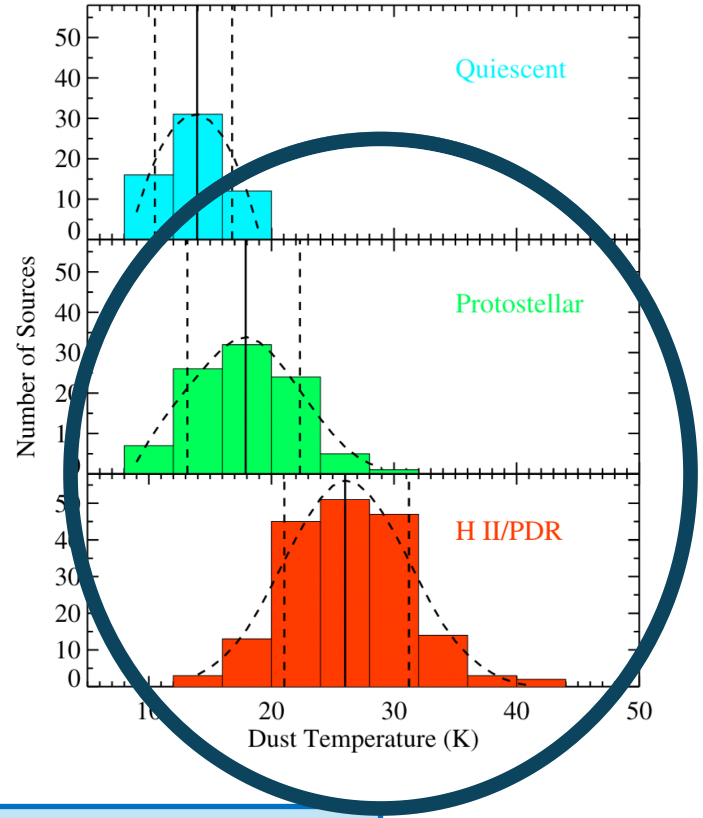


Hi-GAL 250 µm



protostellar

Hoq+13



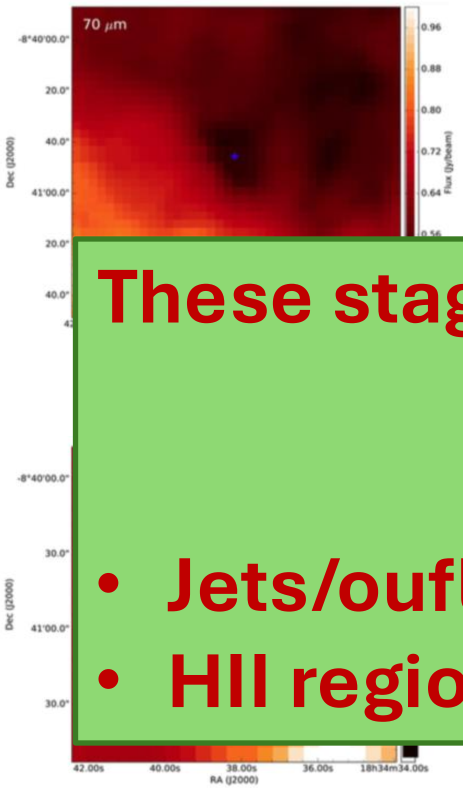
MIR dark
MIR/NIR bright
PDR/HII regions

Hoq+13
Urquhart+14
Svoboda+16
Traficante+18
Merello+19

Star-forming clumps: where small scales feedbacks originate

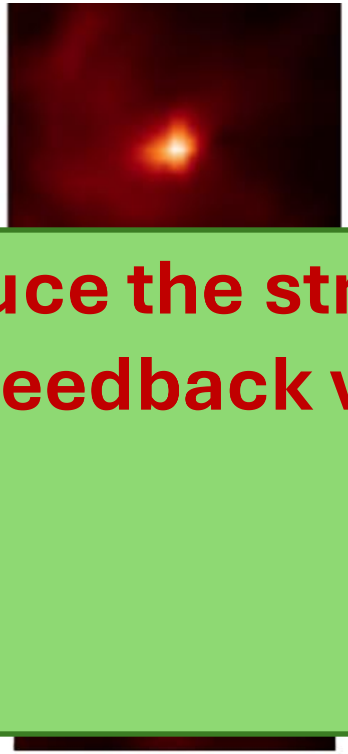
SDC23271-0263

Hi-GAL 70 µm

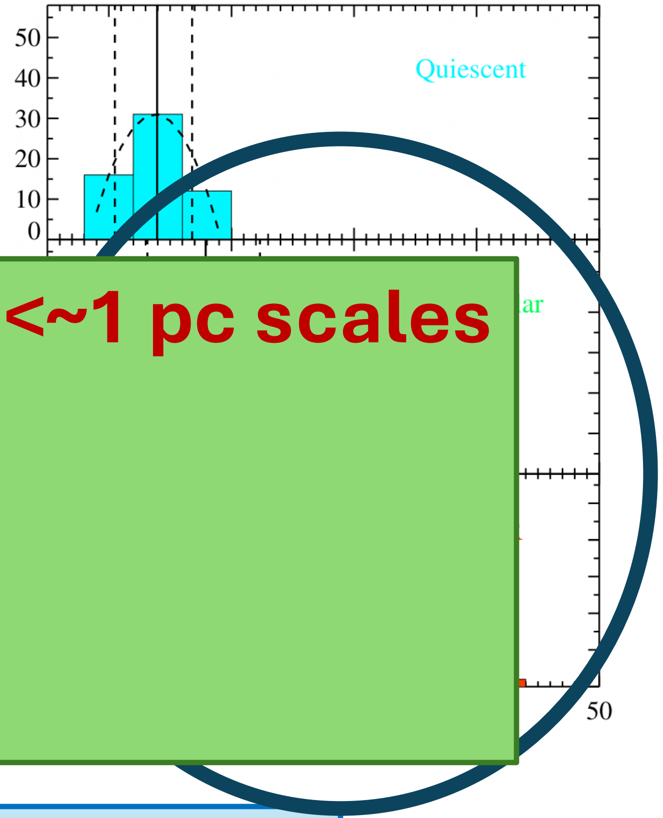


Hi-GAL #110522

Hi-GAL 70 µm



Hoq+13



These stages produce the strongest <~1 pc scales feedback via:

- **Jets/ouflows**
- **HII regions**

starless/pre-stellar
(70 µm-quiet)

protostellar

MIR dark
MIR/NIR bright
PDR/HII regions

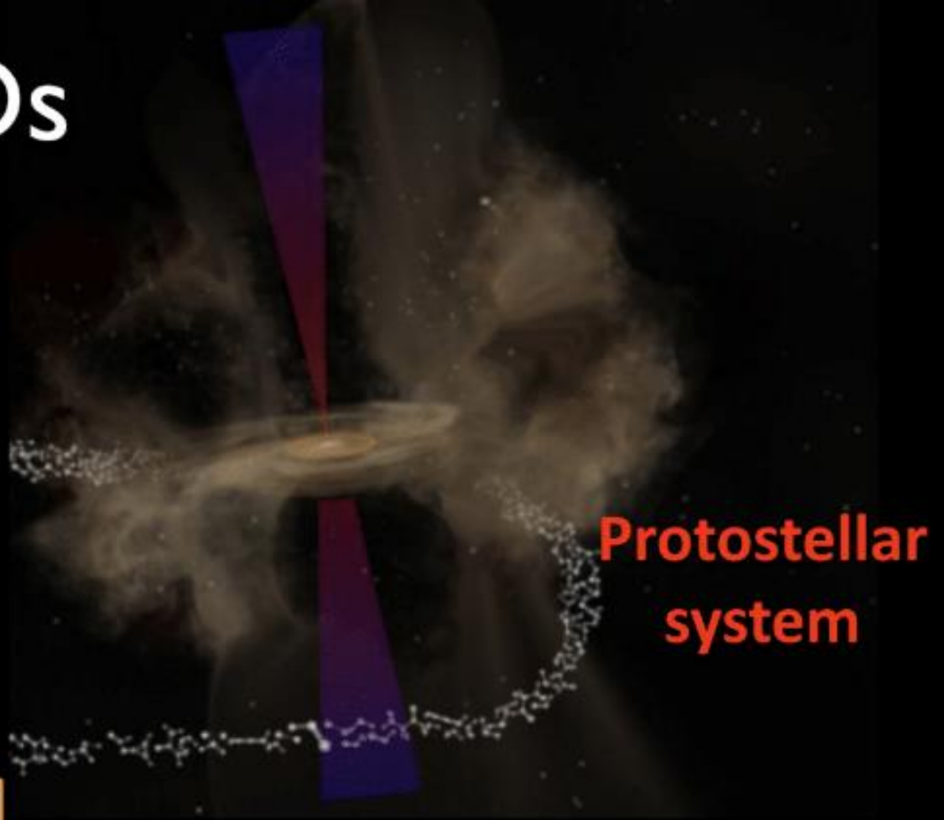
Hoq+13
Urquhart+14
Svoboda+16
Traficante+18
Merello+19

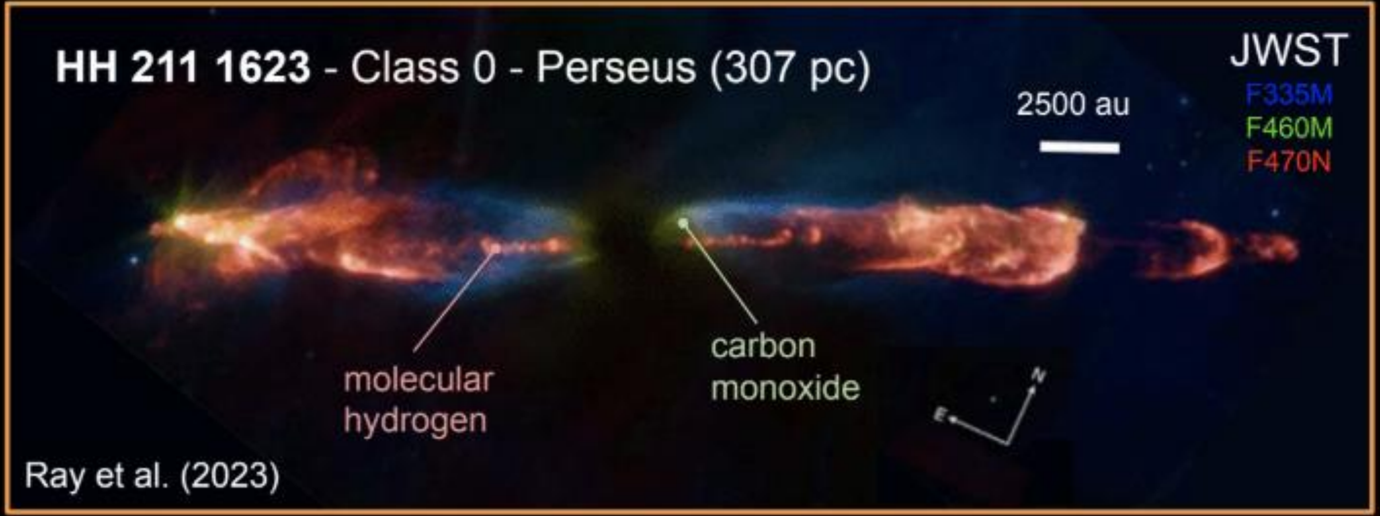
Jet and Outflows in YSOs

Ubiquitous in accreting YSOs of
all evolutionary phases

Optical jet
high velocity (~100 km s-1)
well-collimated structures

Molecular outflow
low velocity (~10 km s-1)
wide opening angle

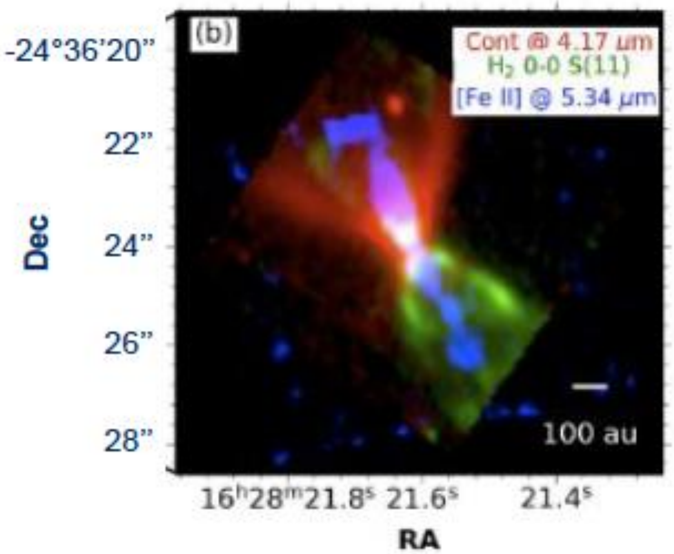


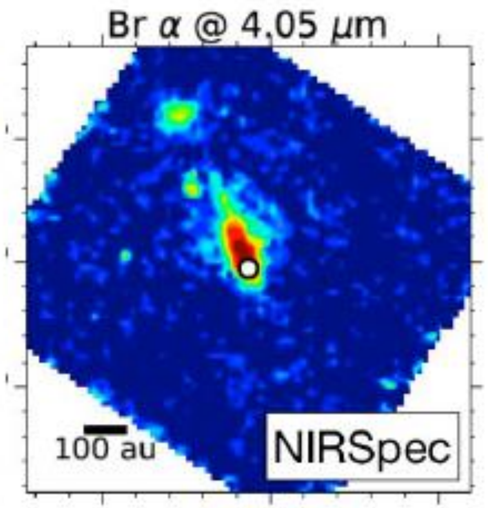


- **Remove angular momentum** from the disc→allow disc-protostar accretion
- Bring **chemically "*rich*" material into the envelope**
- **Outflow-envelope interaction**:
  shocks →grains sputtering/shattering
  envelope dispersion → final stellar mass
- **Dust recycling**

Slide credits: G. Sabatini

Ionised jet component (RRL)



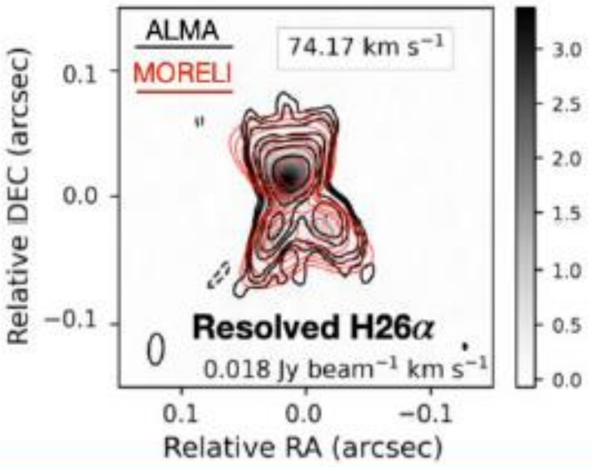


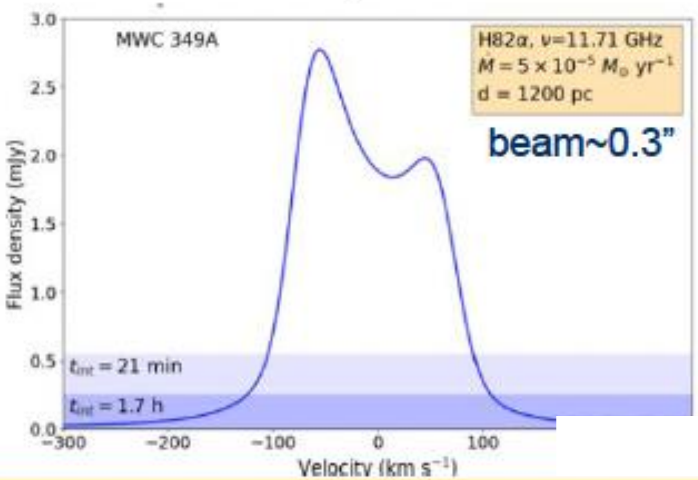
JWST revealed that even very low-mass and young sources can power an ionized jet

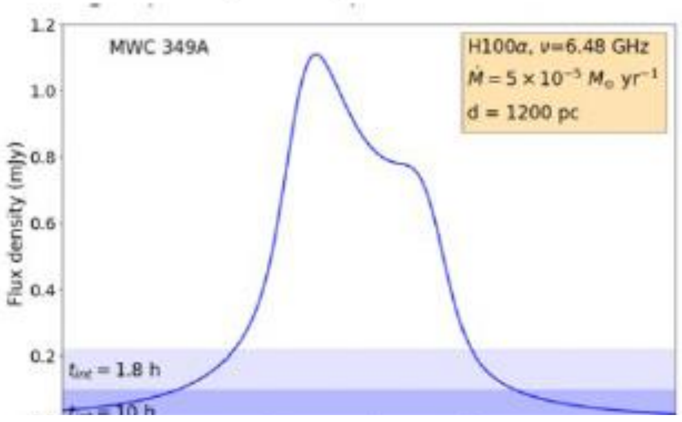
(e.g. Narang et al. 2023, van Dishoeck et al. 2025)

Slide credits: G. Sabatini

(Martínez-Henares et al. 2023, 2024)



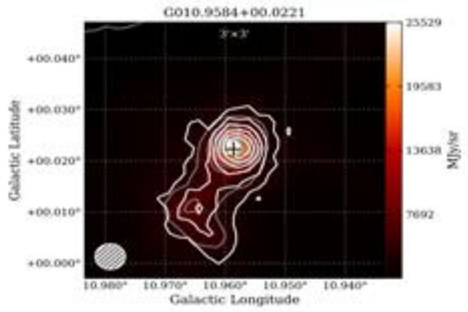




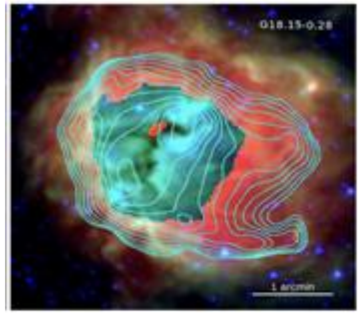
HII regions in the Galaxy

Hyper-compact (HCHII) → **Ultra-compact HII (UCHII)** → **HII regions**

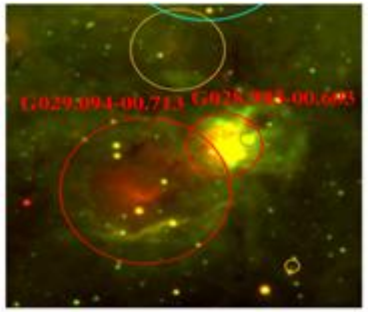
Hyper-compact (HCHII)	Ultra-compact HII (UCHII)	HII regions
Diameter $\lesssim 0.05$ pc	Diameter $\lesssim 0.1$ pc	Diameter $\gtrsim 1$ pc
$n_e \gtrsim 10^5$ cm^{-3}	$n_e \sim 10^4$ cm^{-3}	$n_e \sim 10^3$ cm^{-3}
$N_{Ly} \sim 10^{46}$ s^{-1}	$N_{Ly} \sim 10^{47}$ s^{-1}	$N_{Ly} \sim 10^{47-48}$ s^{-1}
33 (mostly serendipitously)	~600	~8000



HCHII @5 GHz from CORNISH (black cross). Map and white contours: Hi-GAL @250 µm (Yang+21)



RGB image (red = 24 µm, green = 8.0 µm, and blue = 4.5 µm) with contours of 3.6 cm emission from VLA of UCHII region (de la Fuente+20)

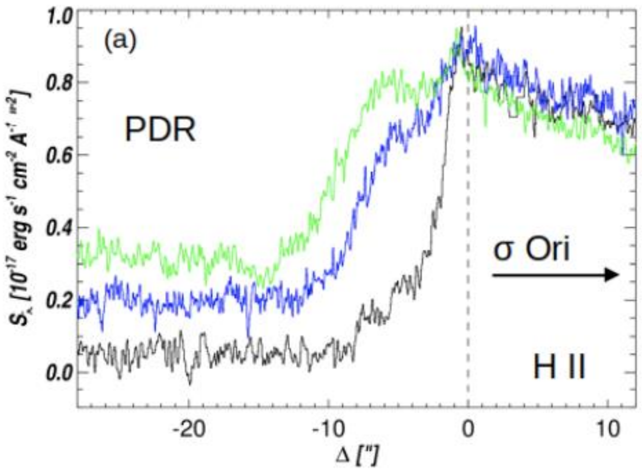


HII region in the l=29° identified with WISE @12 µm and @22 µm (Anderson+14)

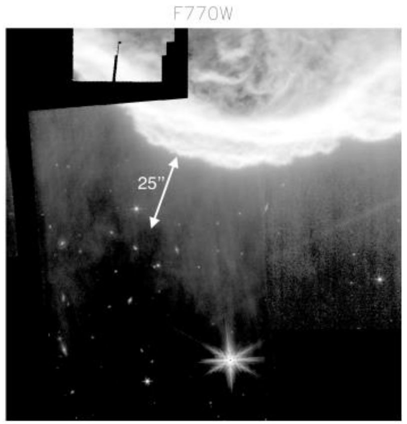
HII regions, PDRs and ionization fronts

Resolved PDR substructure (size ~400 AU) revealing:

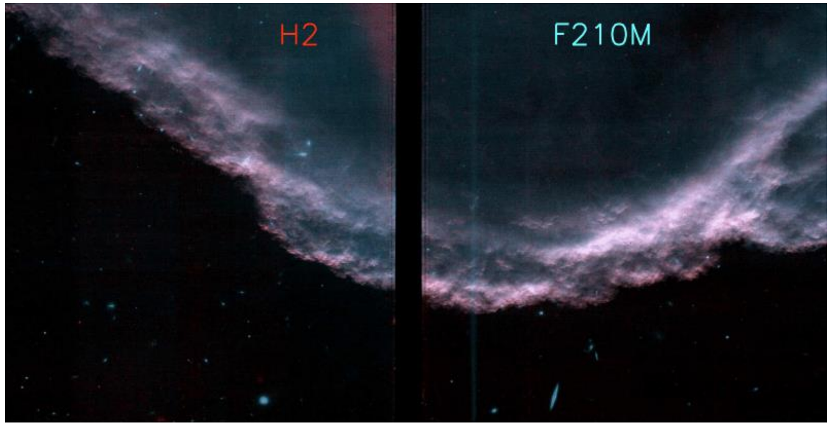
- Ionization and dissociation fronts **coincident** within **<100 AU**
- First direct detection of **photoevaporative dust flow** from a PDR edge.
- Strong **color gradients and dust attenuation** across the PDR traced from 0.7–25 µm.



H_α profile from HST (black), F187N (blue) and F405N (green) Abergel+24



Photoevaporative dust flow F770W JWST filter (Abergel+24)



The horsehead nebula @2.12µm (H_2 line, red) and with the F210M filter (blue) from JWST (Abergel+24)

The transformational science of HWO

Jets and Protostellar Outflows (imaging + IFU UV spectrograph)

- **Sub-arcsecond UV imaging** of **jet collimation**, shock knots, and bow fronts: 0.01" corresponds to a linear scale of 10 AU @1kpc. 500 AU@50 kpc, enough to **resolve jets in the LMC**!
- **Line diagnostics** (C IV, Si II, ...) to study **shock-heated and UV-illuminated gas**
- Capability to isolate **jet-launching zones** from surrounding envelope

Photoionization Feedback from HII regions (imaging + IFU UV spectrograph)

- **High-resolution UV imaging** to resolve ionization fronts and PDRs down to **10–50 AU** scales in nearby regions
- **UV spectroscopy** (e.g., C IV, Si IV, H_2 lines, ...) to probe **hot gas**, **PDRs**, and **photoevaporation flows**
- **Spectral resolution** (R ≈ 10,000–30,000) enables **velocity-resolved profiles** of expanding bubbles and interfaces

Feedback in SF regions: MeerKAT and SKA

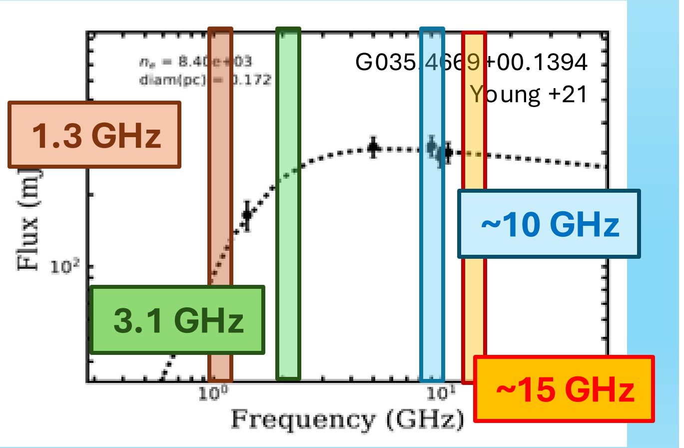
SKAO

- MeerKAT (and SKA) offer a unique opportunity to investigate **with μJy sensitivity and (sub)arcsec resolution the feedback mechanisms** in (massive) star formation. And the incoming **Band 5B will open a critical observational window**

- **Synergies with existing existing observatories** (e.g. ALMA, MeerKAT) **will provide a multi-faceted view** of the free-free emission from HII regions, synchrotron emission from radio jets and RRLs to trace the gas dynamics in Galactic star-forming complexes (see incoming SKA chapters by: A. Traficante; G. Sabatini; A. Karska; L. Podio, E. Bianchi).

MeerKAT + SKA radio surveys of the Galactic Plane (GP)

- **1.3 GHz** GP survey released (Goedhart+23)
- **3.1 GHz** GP survey from MPiA + pilot survey across 330°< l < -334° under analysis (in collaboration with SARAO).
- **10-15 GHz** GP survey proposed for **MeerKAT Band 5B (INAF/SARAO) and SKA** (PI INAF, A. Traficante)



SED from UCHII region (Yang+23)

HWO + SKA: synergies and complementarities

Feature	HWO (UV/Optical)	SKA Band S, L and 5b (~1-15 GHz)
Traces	Hot gas (10^4–10^6 K), ionized shocks, UV-illuminated gas (PDRs)	Cold ionized gas (10^2–10^4 K), synchrotron, hypercompact HII regions, thermal jets
Resolution	~0.01–0.05" (10–50 AU @ 1 kpc)	~0.05–0.1" (50–100 AU @ 1 kpc)
Diagnostics	high-resolution photometry, UV lines (C IV, Si IV, H_2), kinematics	Radio Continuum (free-free & synchrotron), spectral index
Environment	Jet bases, shocked layers, PDRs	Ionized jets, compact H II, outflows
Strengths	Velocity-resolved UV tracers, fine spatial structure	Dust penetration, thermal/non-thermal separation

Combined outcome:

- Quantify **total feedback energy budget**: thermal, mechanical, and non-thermal
- Reconstruct the **full temperature and density gradient** in feedback zones — from base to large-scale cavity
- Match jet velocities (UV) to spatial extents (radio) → derive **momentum injection rates**

The transformational science of HWO: from UV to IR

(in collaboration with R. Paladini, Caltech/IPAC, co-chair of the sub-WG "Star formation and ISM" in HWO

Investigate how the extinction curve varies—revealing how dust grains influence light across different wavelengths—in order to determine the physical properties of these grains, which are fundamental building blocks of planets and key players in galaxy evolution

Relevance To Astro2020:

Section F: "Report of the Panel on the Interstellar Medium and Star and Planet Formation"

F-Q1: How do star-forming structures arise from, and interact with, the diffuse ISM?
F-Q2b: What is the origin and prevalence of high-density structures in molecular clouds and what role do they play in star formation?
F-Q4b: What is the range of physical environments available for planet formation?

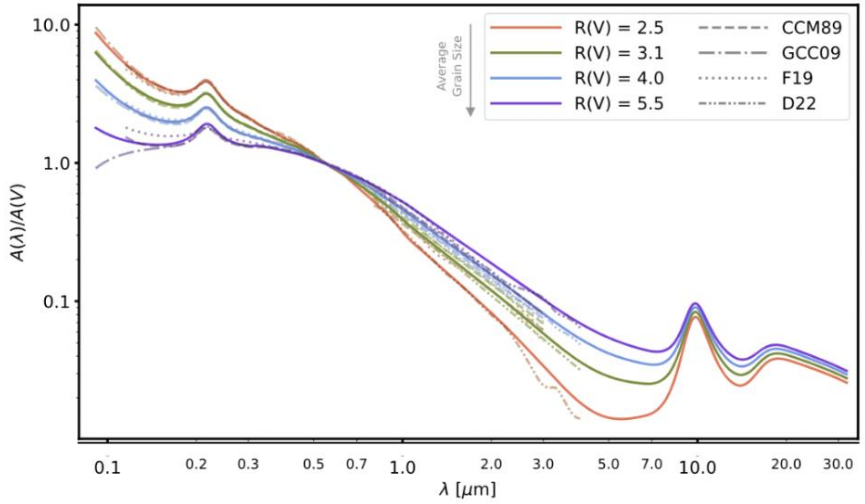
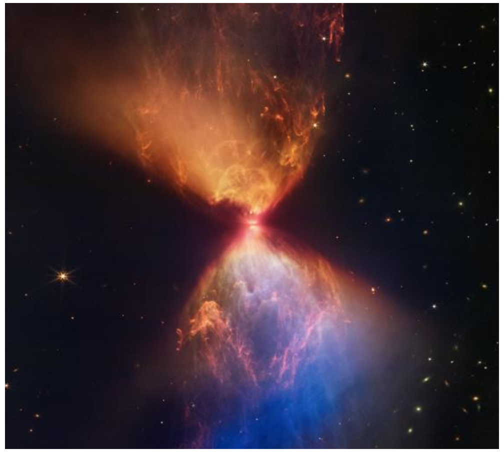


Figure 1. *Gordon et al. (2023)'s Galactic R(V) relationship evaluated for four representative R(V) values aand compared with literature R(V) relationships for the same R(V) values (Cardelli et al. 1989; Gordon et al. 2009; Fitzpatrick et al. 2019; Decleir et al. 2022).*

Acquire a large and diverse sample of UVOIR dust extinction curves—from the Milky Way to galaxies in the Local Group and Local Volume—spanning a broad range of environments, with the goal of developing a more comprehensive understanding of dust property variations and their implications for star and planet formation, as well as galaxy evolution

Conclusions: feedback mechanisms in SF regions with HWO

Jets and Protostellar Outflows from local clouds to nearby galaxies	• Trace **the launch, collimation, and propagation** of protostellar jets • Measure **jet-driven shocks** and their role in regulating accretion • Assess the **momentum and energy injection** into the surrounding cloud • Explore how jets influence **fragmentation and turbulence** in dense cores
HII regions photoionization Feedback from local clouds to nearby galaxies	• Study the evolution and structure of **H II regions and their surrounding PDRs** • Identify the role of **photoionization** in triggering or suppressing star formation • Quantify the **ionization fronts**, compression of clumps, and cloud dispersal • Investigate how **feedback** alters star formation efficiency and cluster morphology



L1527 seen by JWST

NGC 604 seen by HST