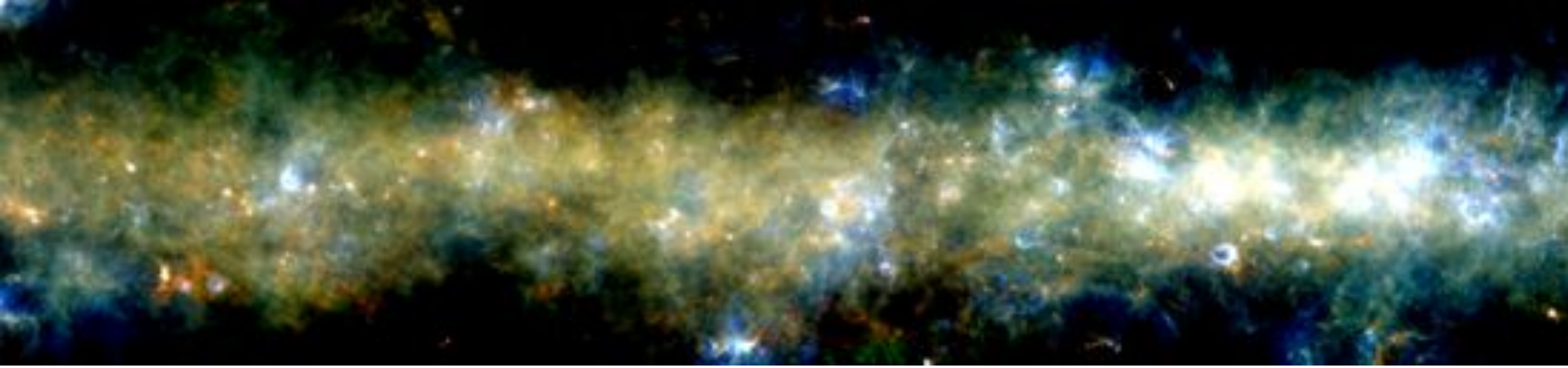


Global star formation in the Milky Way from the VIALACTEA Project

S. Molinari – INAF/IAPS, Rome

IAPS, Arcetri, Catania, Univ. Salento, Napoli, Trieste

D. Elia, A.M. Di Giorgio, M. Pestalozzi, E. Schisano, M. Merello M. Veneziani, A. Traficante, L. Testi, Cesaroni R., G. Umana, F. Strafella, M. Brescia, M. Molinaro & Hi-GAL/VIALACTEA Team

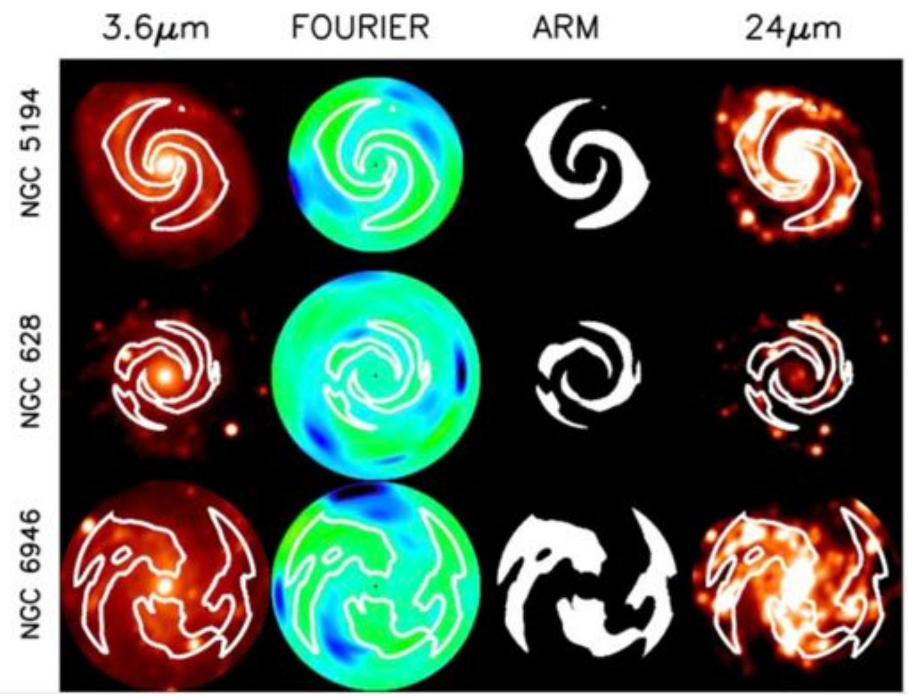
Key-questions in Galactic astronomy

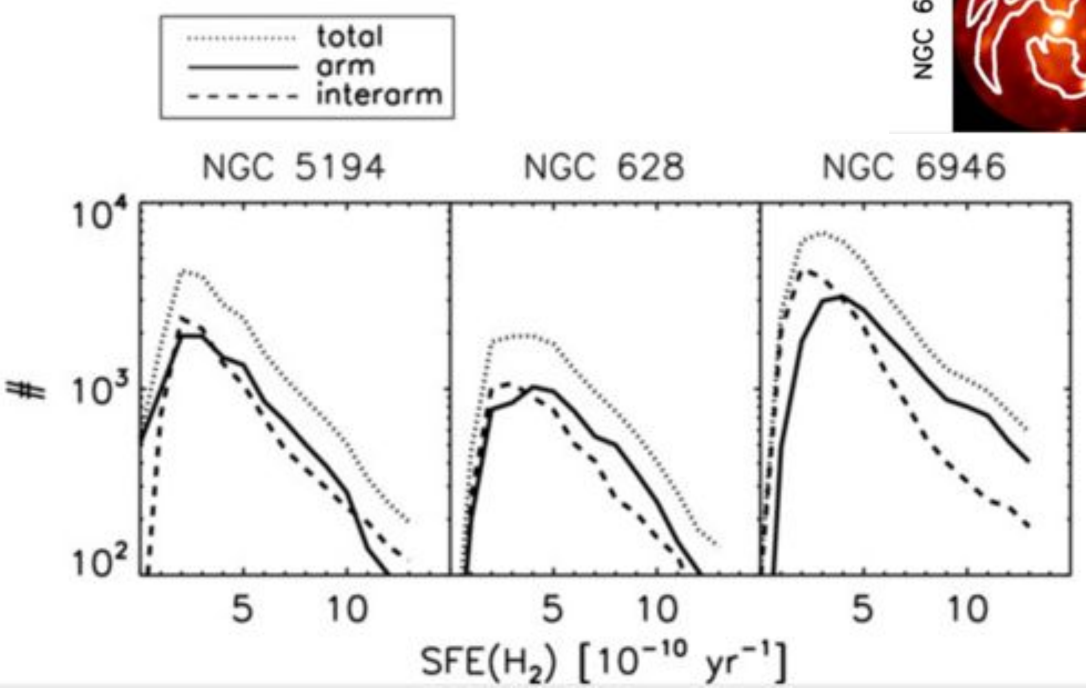
- What are the agents determining the star formation rate and history in a normal Galaxy like the Milky Way ?
- What are the ingredients determining star formation laws as a function of ISM properties across a full range of galactocentric radii, metallicity and environmental conditions ?
- What determines the relative importance of global *vs* local, spontaneous *vs* triggering, agents that give rise to star formation. What is the role of spiral arms ?
- Build bottom-up recipes and prescriptions useful for Xgal science

Setting the Milky Way in the extra-galactic context

the 1kpc-scale global view

- Use Spitzer+GALEX+Hα to map SFR, and THINGS to get the gas
- Remarkable arm/interarm contrast in SFR and Σ_{gas}



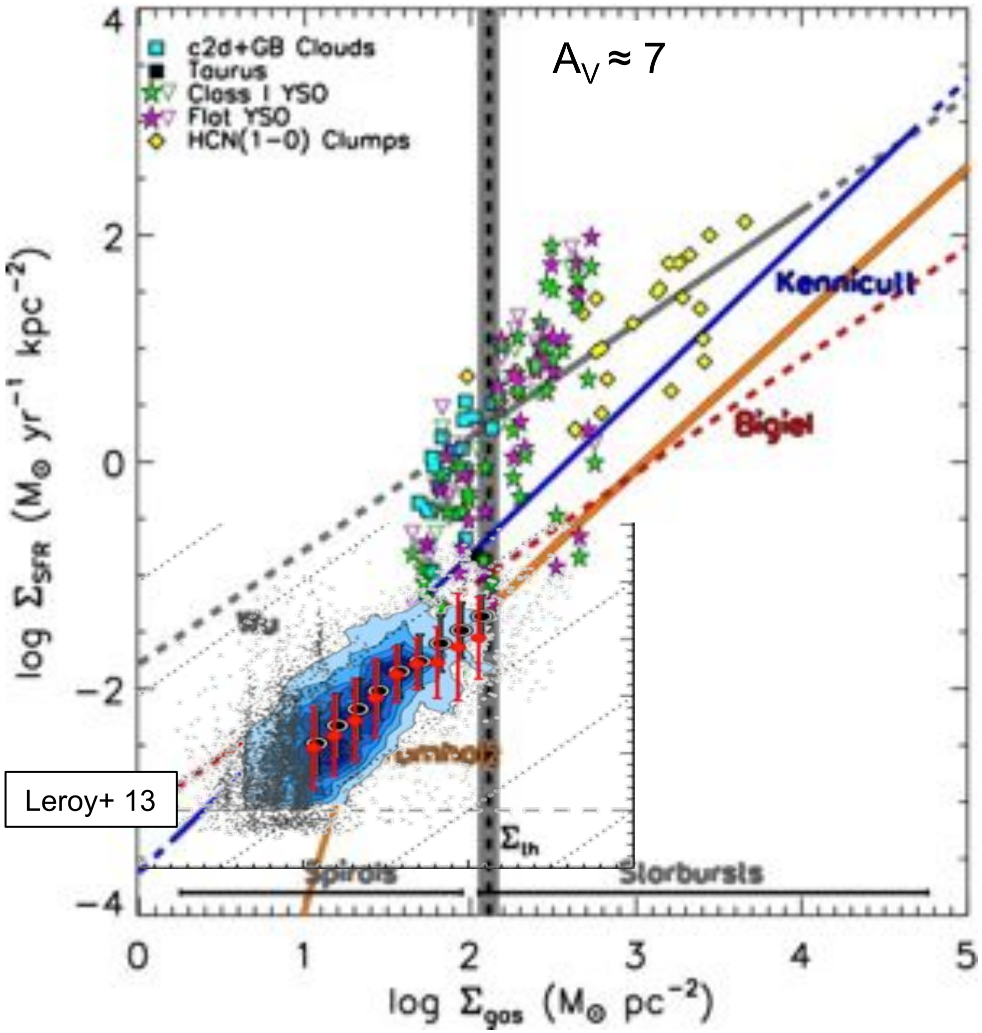


Foyle+ 10

….but remarkably uniform arm/inter-arm SFE

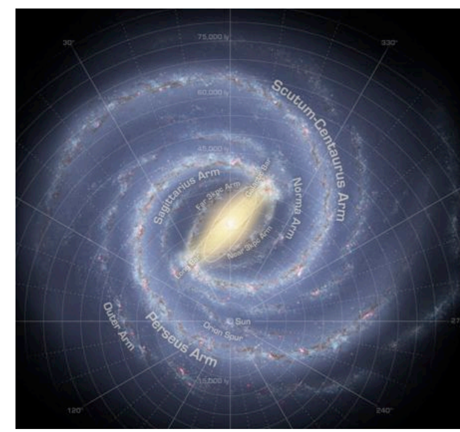
Setting the Milky Way in the extra-galactic context

Heiderman+ 2010



Identify the critical parameters that make star formation different:

- Spontaneous/triggered
- Star Formation on/off Filaments ?
- Depending on the position in the Galaxy
- w.r.t. Spiral Arms
- etc.



understand if & how the mix of the ingredients conspire to determine a global Star Formation law

Hi-Gal

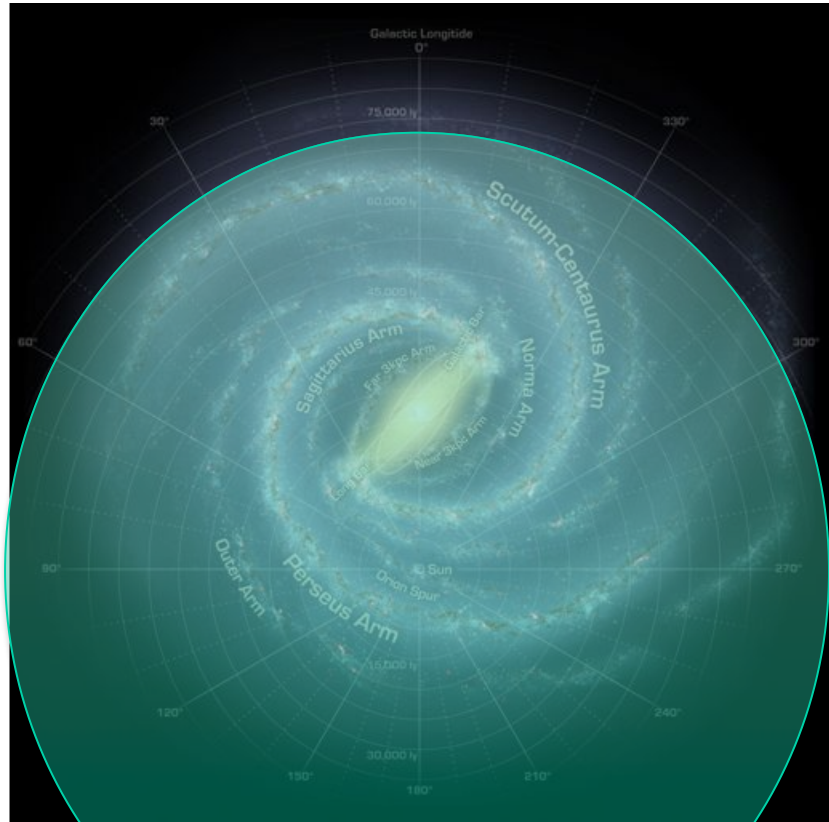
The Herschel infrared Galactic Plane Survey

The entire Plane has been observed. Images access (with registered astrometry and absolute flux calibration) and compact source catalogues for longitudes between 65° and 290° have been recently released

Simultaneous 5-bands (*70-160-250-350-500μm*) continuum mapping of 720 sq. deg. of the Galactic Plane (|*b*|≤1°)

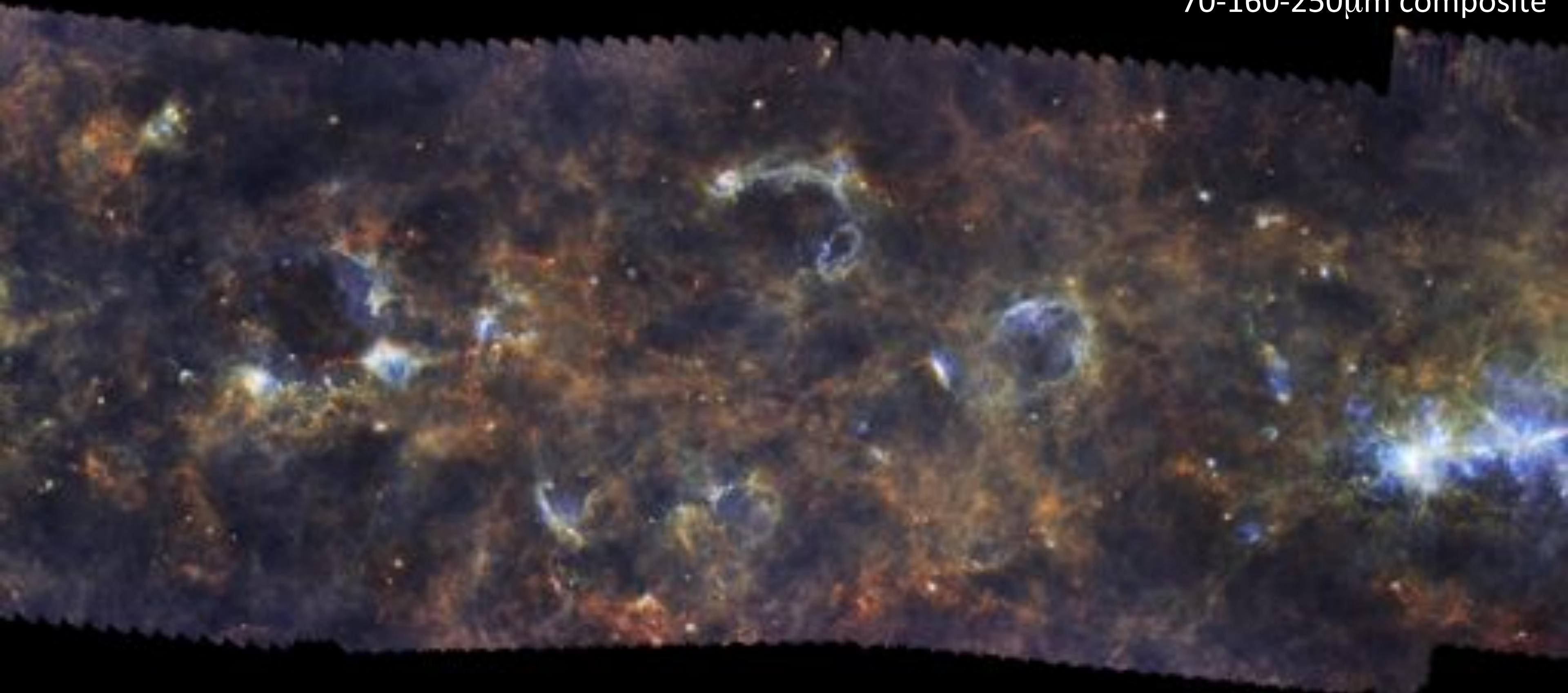
With almost 900 hours observing time is the largest OPEN TIME Herschel KP

Galaxy-wide Census, Luminosity, Mass and SED of dust structures at all scales from massive YSOs to Spiral Arms



Hi-GAL

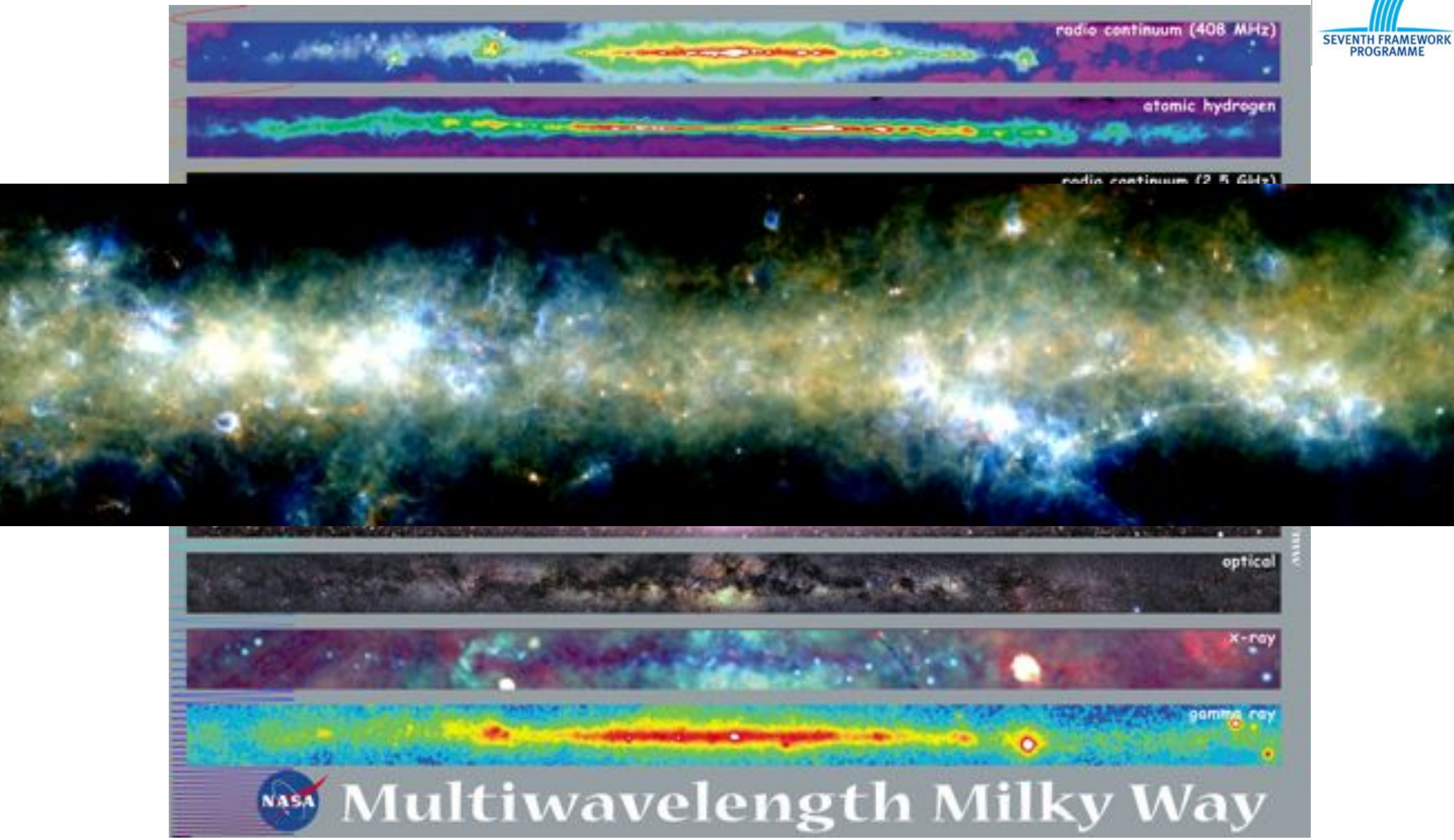
the Herschel infrared Galactic Plane Survey



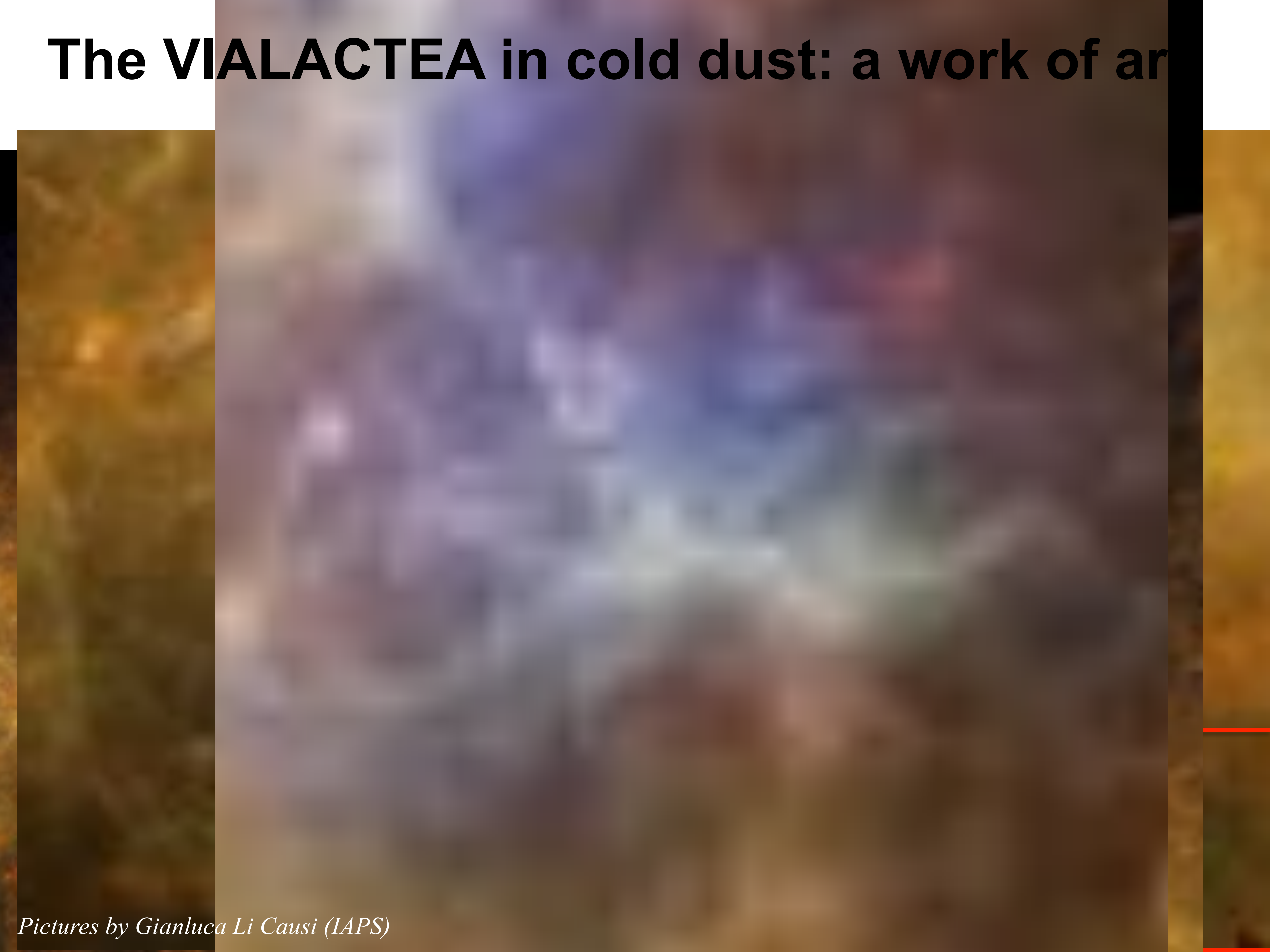
from cold starless clumps to hot HII Regions

Credits: Gianluca Li Causi (INAF-IAPS)

Molinari et al. 2016


radio continuum (408 MHz)
atomic hydrogen
optical
x-ray
gamma ray
NASA
Multiwavelength Milky Way

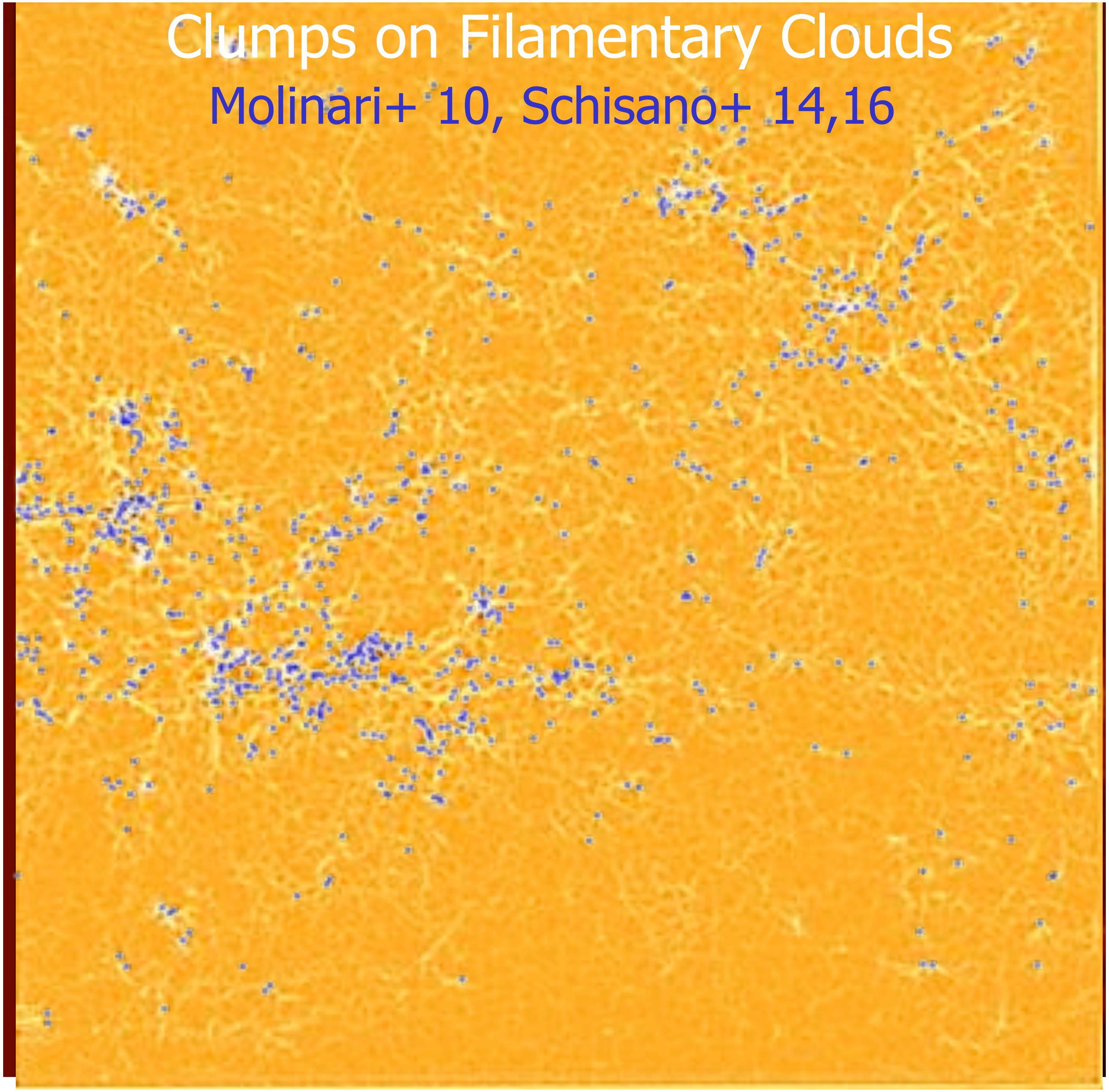
The VIALACTEA in cold dust: a work of ar



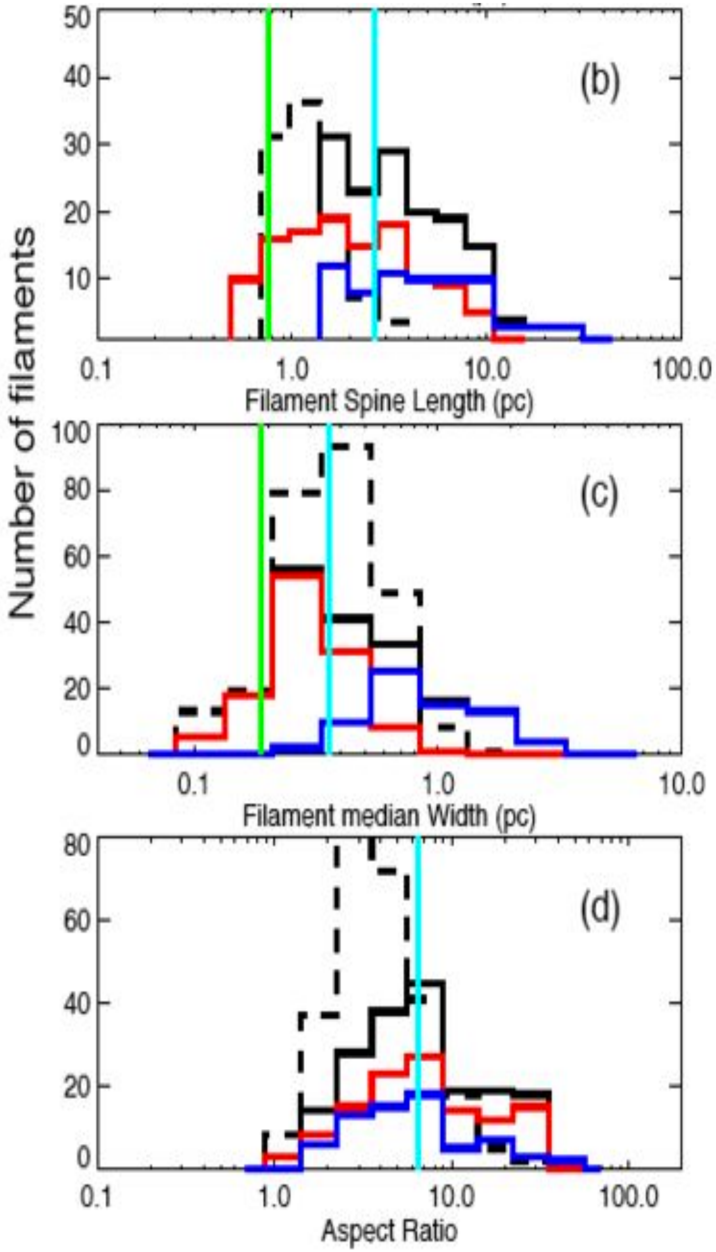
Pictures by Gianluca Li Causi (IAPS)

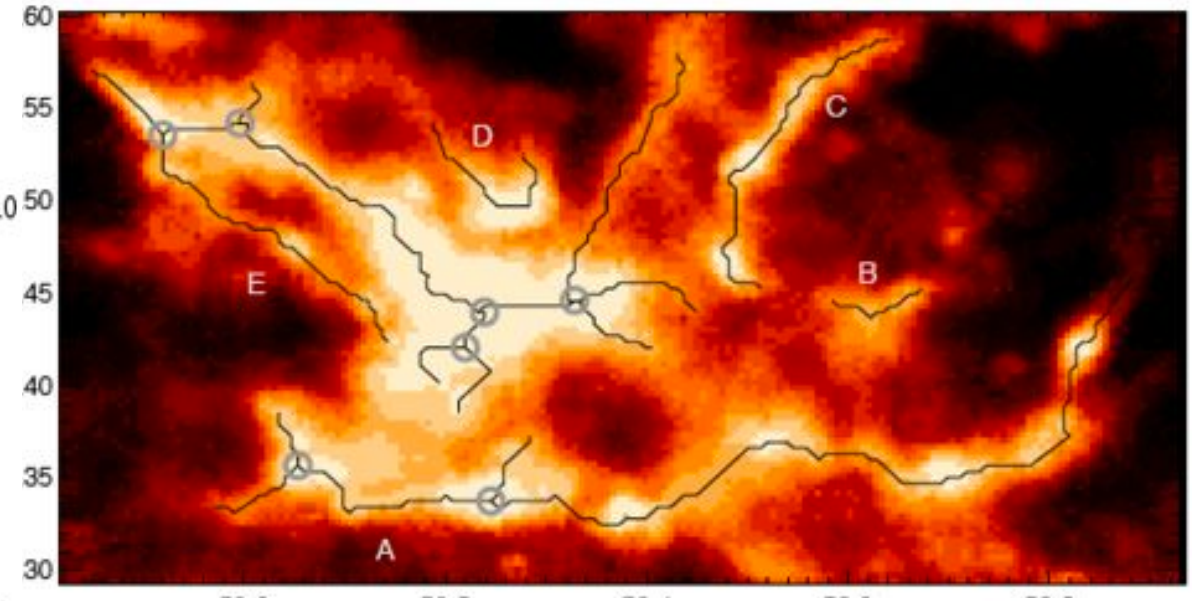
Clumps on Filamentary Clouds

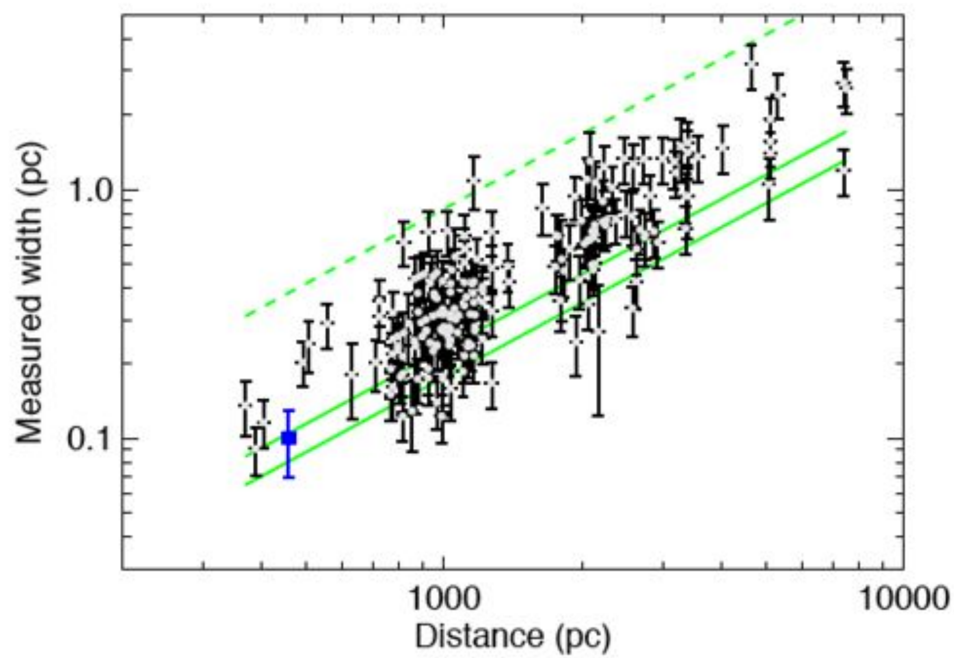
Molinari+ 10, Schisano+ 14,16



Filament Properties

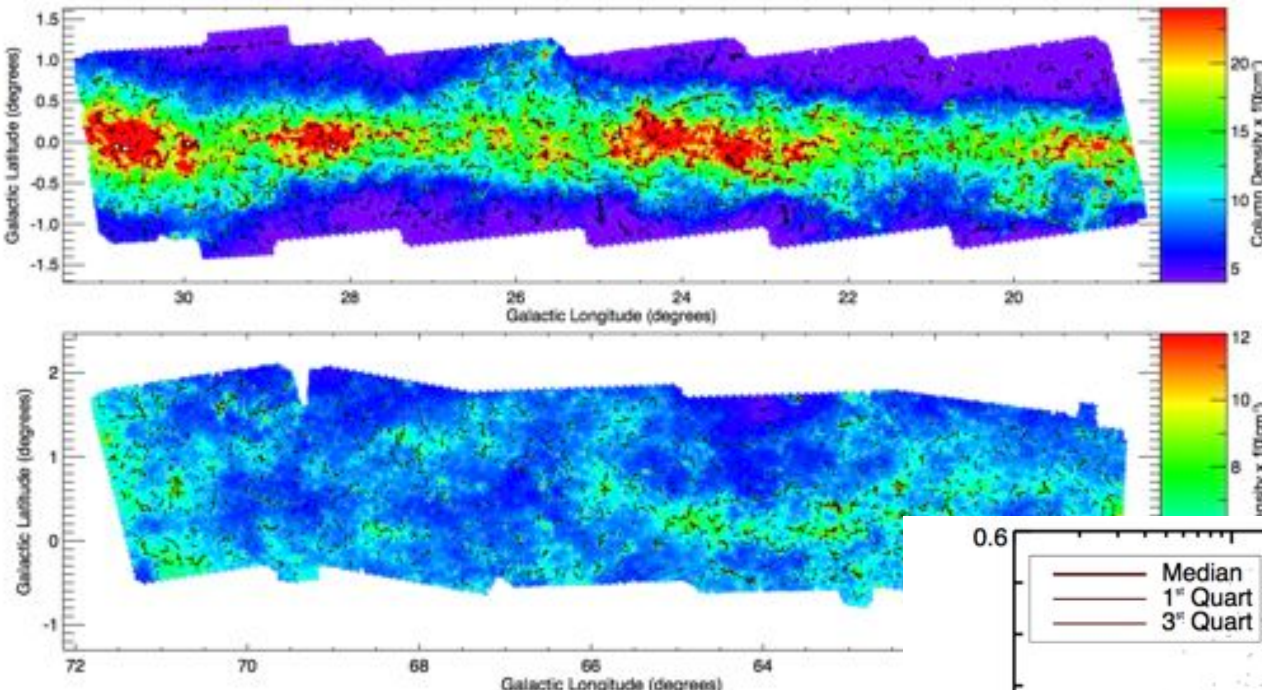




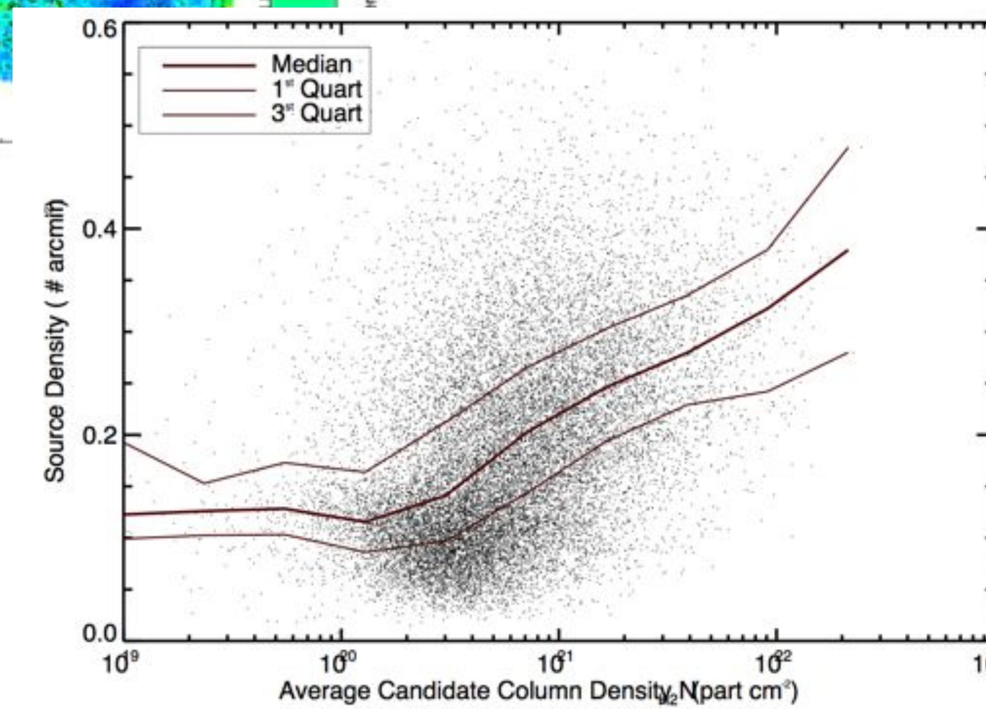


Schisano+ 14

A Filamentary Galaxy



- 30324 candidate dense filamentary structures in the entire Milky Way Plane
- 116000 sub-structures
- Nearly 60% of VIALACTEA sources are associated with filaments



- The density of star-forming clumps increases with the density of the hosting filament
- A threshold of filament density seems to exist for the onset of active star formation

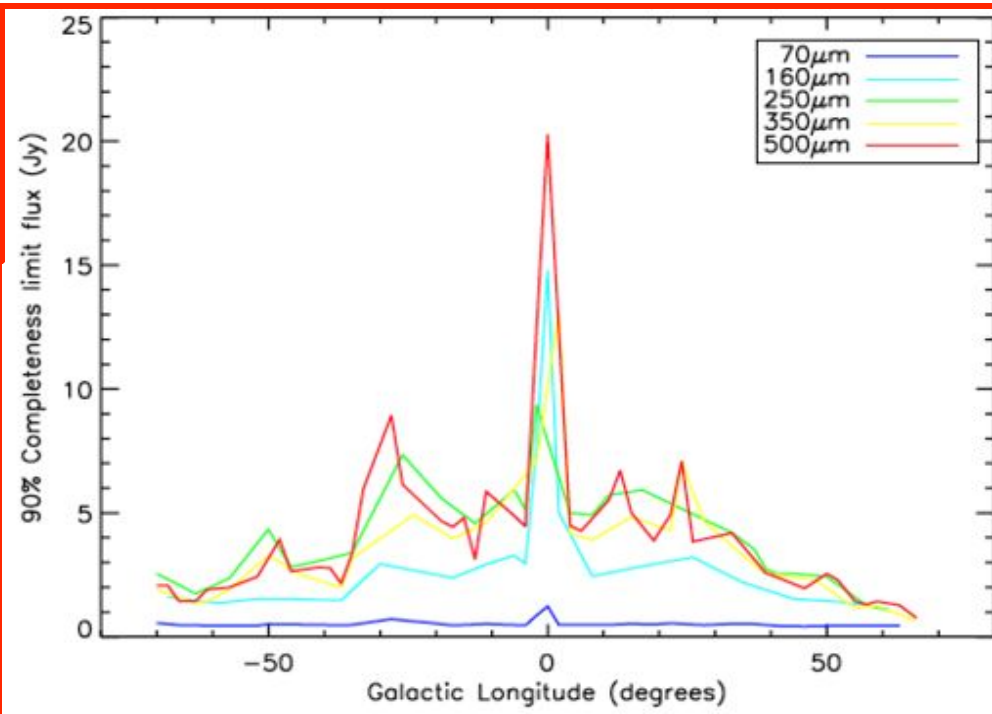
Schisano+ 2016

VIALACTEA is statistics

- First-generation Hi-GAL Photometric Catalogues created using CuTEx package (Molinari+11) for the inner Galaxy
- Naïve band-merging produces a catalogue of **519400** entries Clump catalogue down-selected filtering "nice" SEDs with at least three adjacent counterparts 160-500μm yields **99180** entries

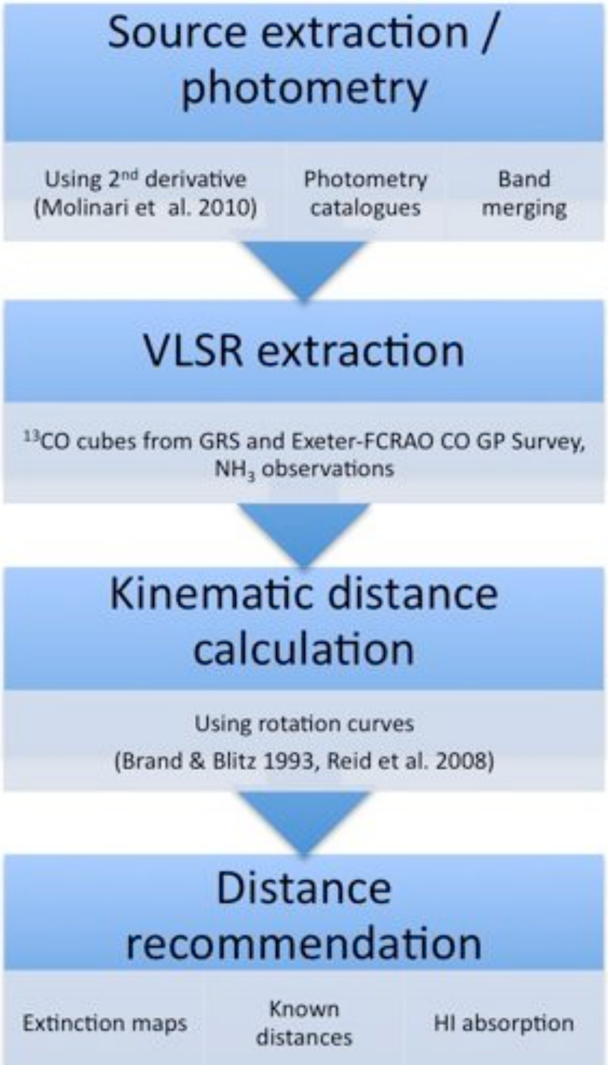
Band	$N_{sources}$
PACS-70μm	122 971
PACS-160μm	292 051
SPIRE-250μm	280 258
SPIRE-350μm	161 855
SPIRE-500μm	85 880

Estimating completeness limits is not for the faint-hearted !

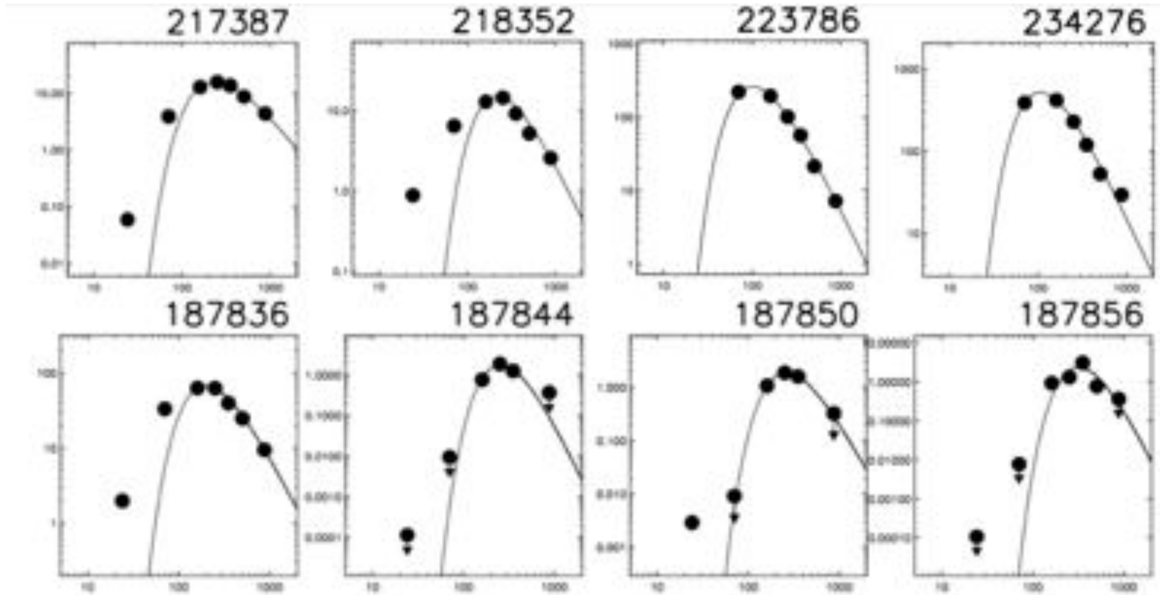


Molinari+ 2015, submitted

VIALACTEA is statistics



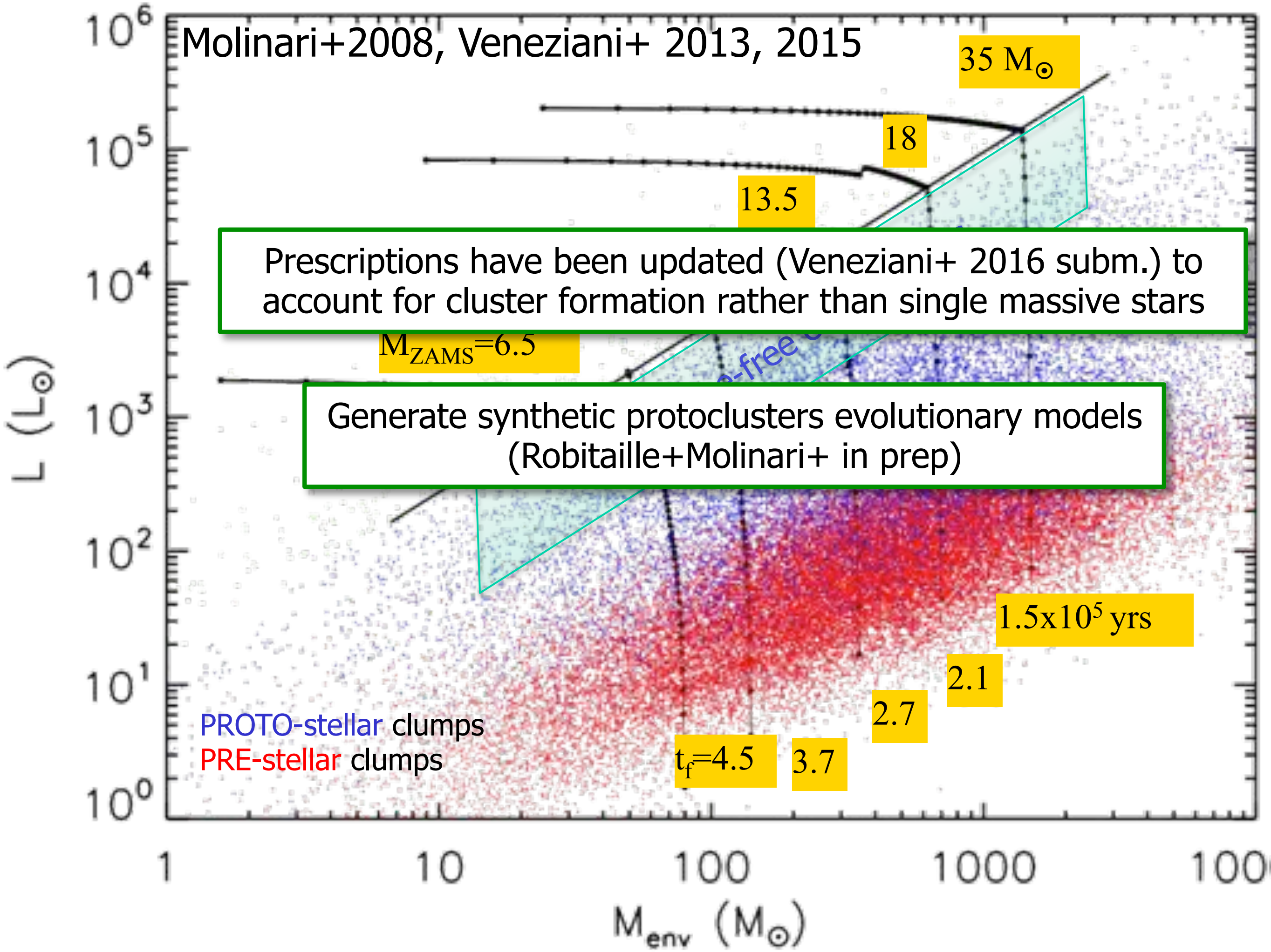
Russeil+ 2010



- For the 99180 inner Galaxy sources with counterparts in at least three bands, we augment SED coverage with ATLASGAL, BGPS, MIPSGAL, WISE, MSX
- A first set of distance estimates (with different levels of reliability) has been carried out excluding l<14° and l>350°, yielding T, L, M and size, for **56656** sources

Elia+ 2016,Merello+ 2016, in prep

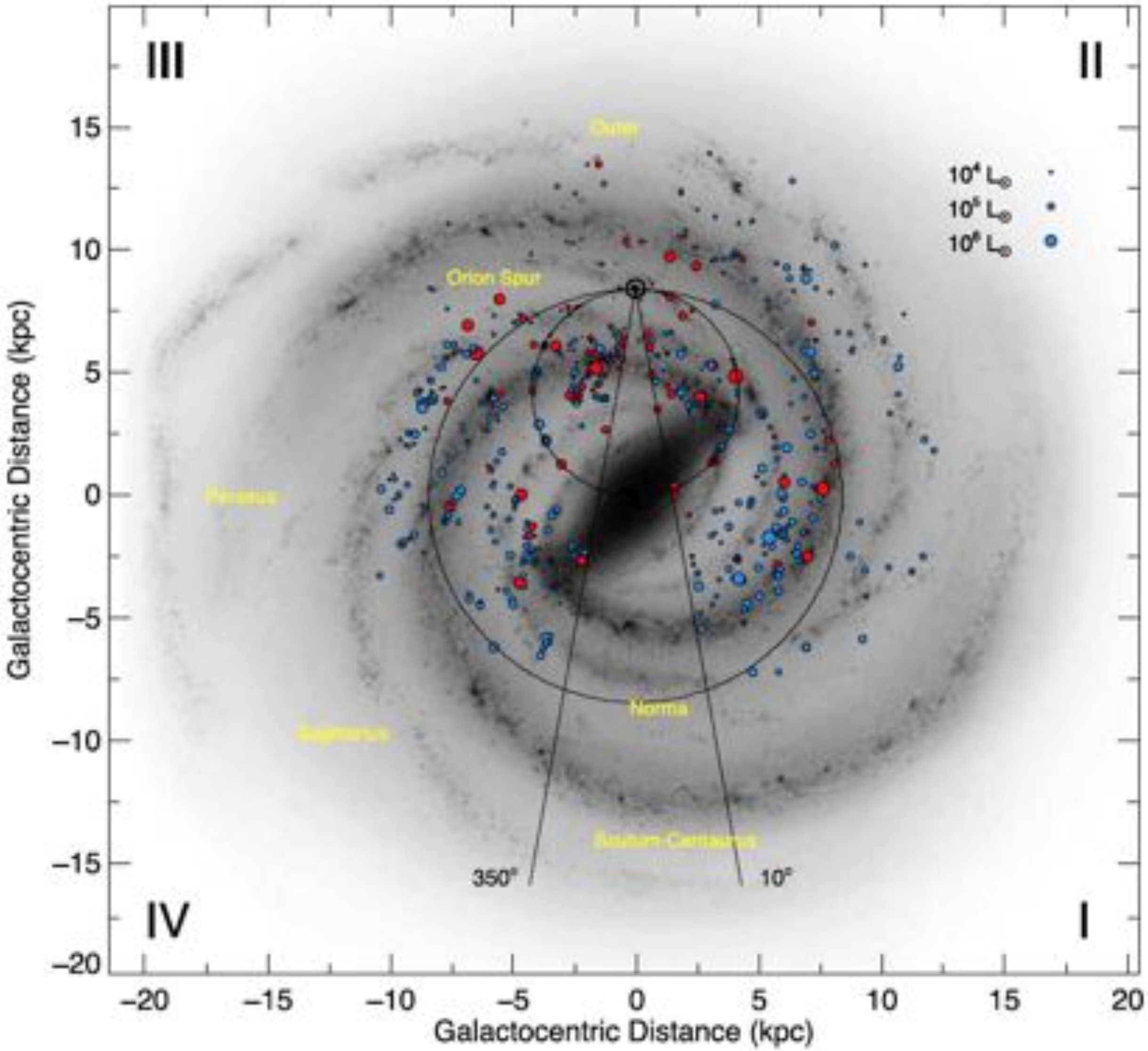
Evolutionary Toolkit



IR → radio photometric SED coverage IS essential to: *i)* derive L_{bol} and M_{clump}, *ii)* obtain an evolutionary probe, *iii)* estimate the **Star Formation Rate**

$$SFR = \sum_{i=1}^{N_{Mzams}} \sum_{j=1}^{N_{Sources}} n_M(i,j) M_{ZAMS}(i) / t_f(i)$$

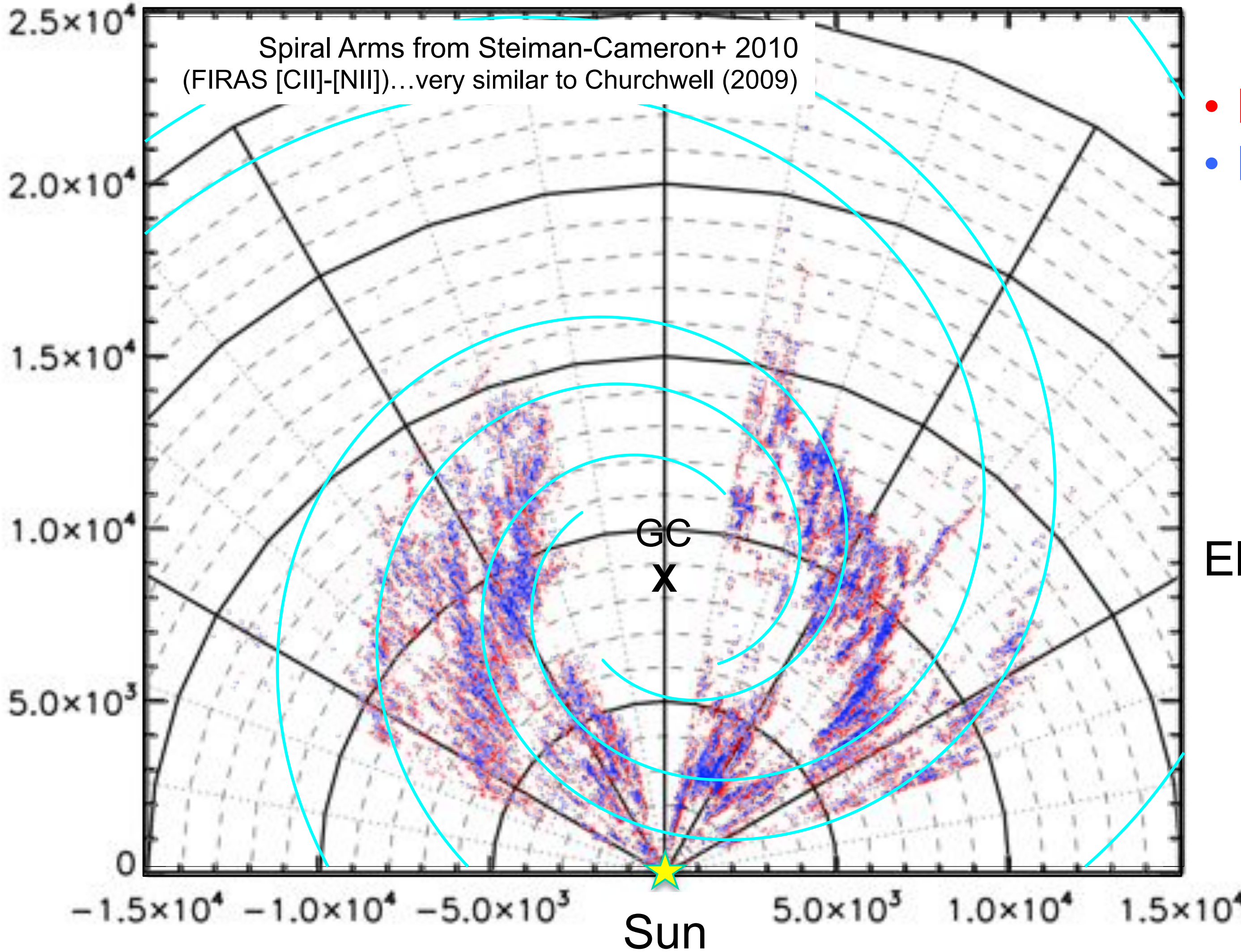
Global distribution of star formation



Urquhart+ 2014

Sources with $L>10^4\,L_\odot$ out of 1650 RMS objects with known distance

Global distribution of star formation from Hi-GAL

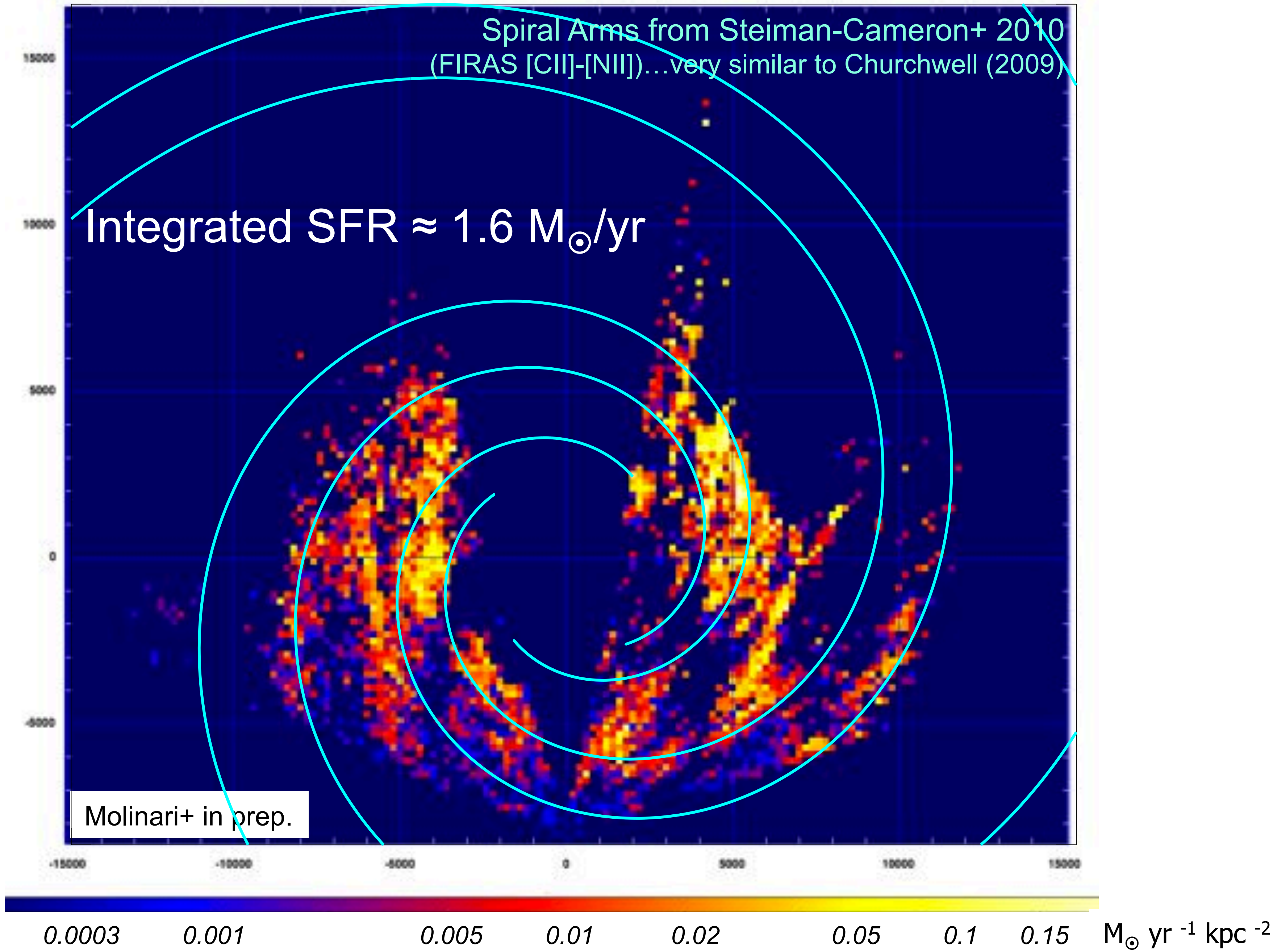


- Prestellar (no 70μm)
- Protostellar (70μm)

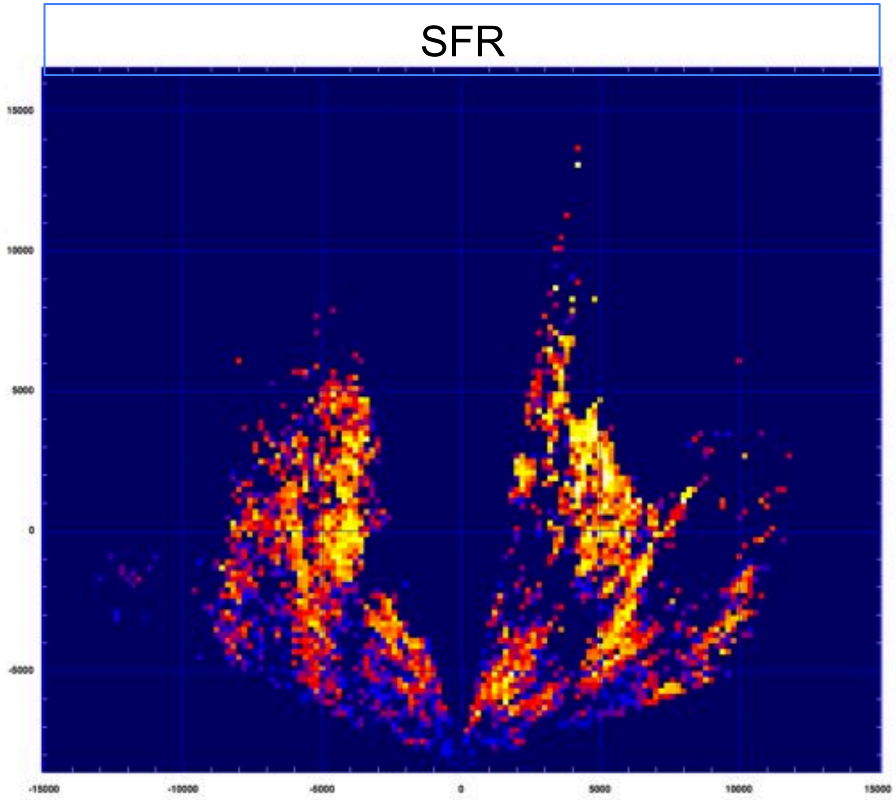
Elia+ 2016, in prep

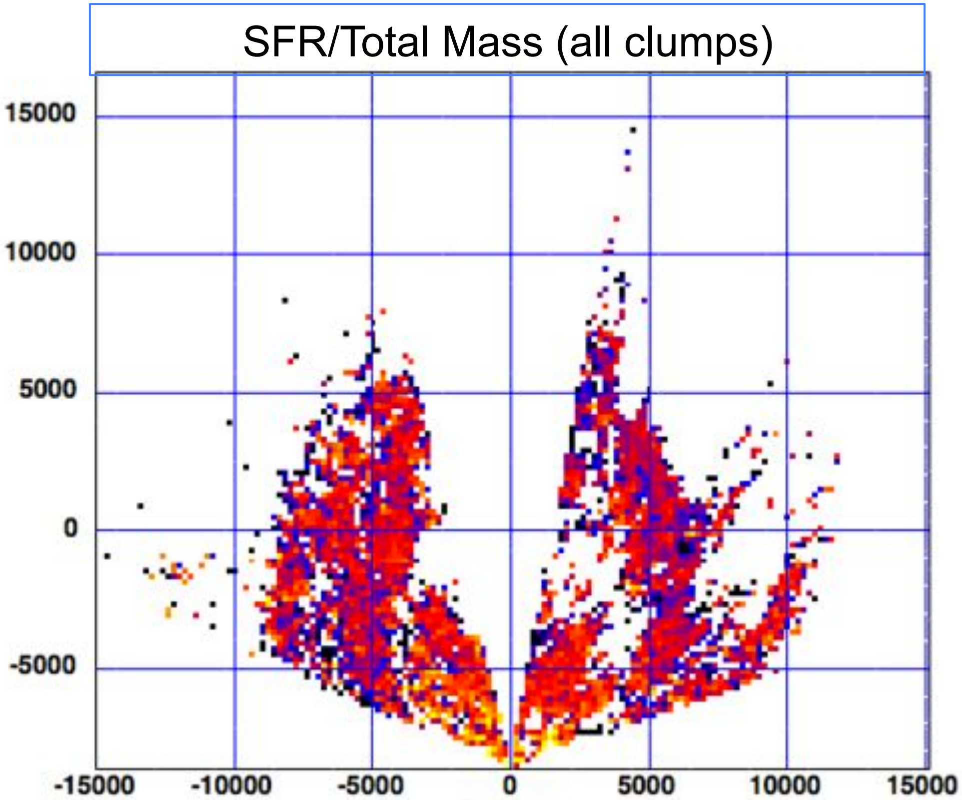
Caution when talking of arm and interarm: arm width ? Local motions ?

The Milky Way Map of the Star Formation Rate



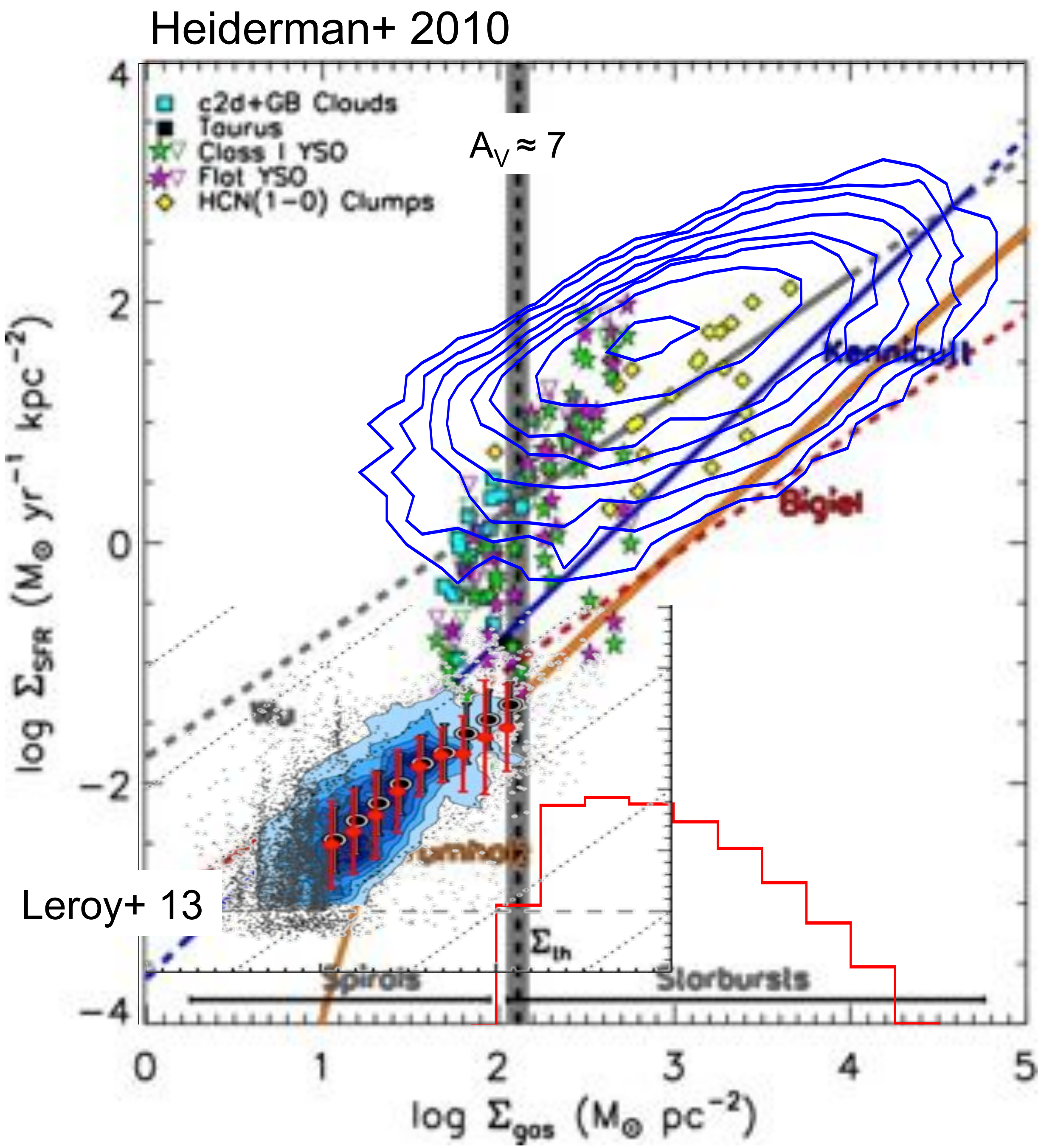
Star Formation Efficiency





SFR/Clump Mass map shows much less dynamical range than the SFR map, preliminary confirming the role of spiral arms as SF clump collectors, rather than SF triggers

…On average AND preliminary AND with caveats…



Hints that SF Laws break down at sub-kpc scale

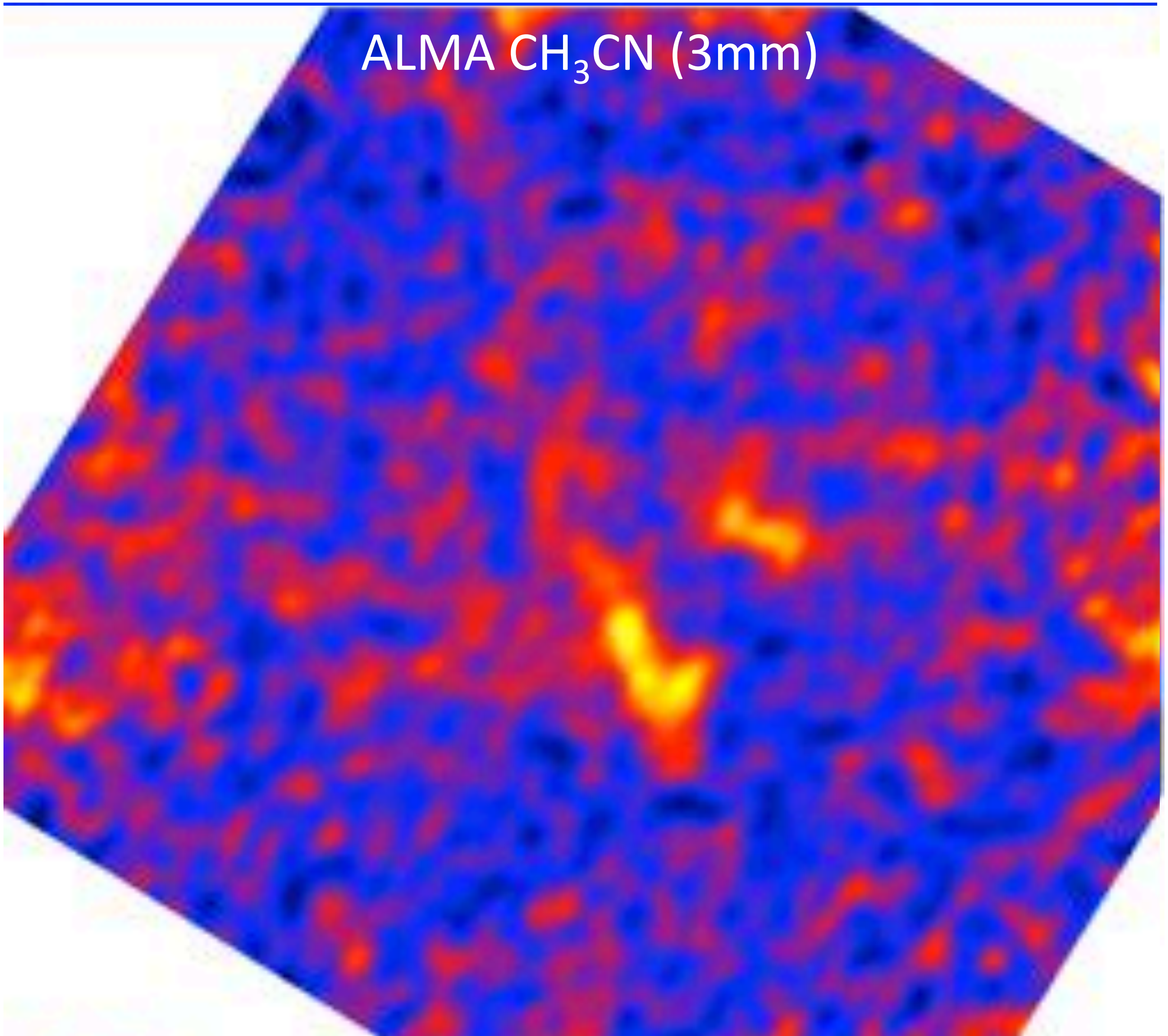
Identify the critical parameters that make star formation different:

- Spontaneous/triggered
- Filaments or not
- Depending on the position in the Galaxy
- w.r.t. spiral arms
- etc.

…and understand if & how the mix of the ingredients influences a global SF law

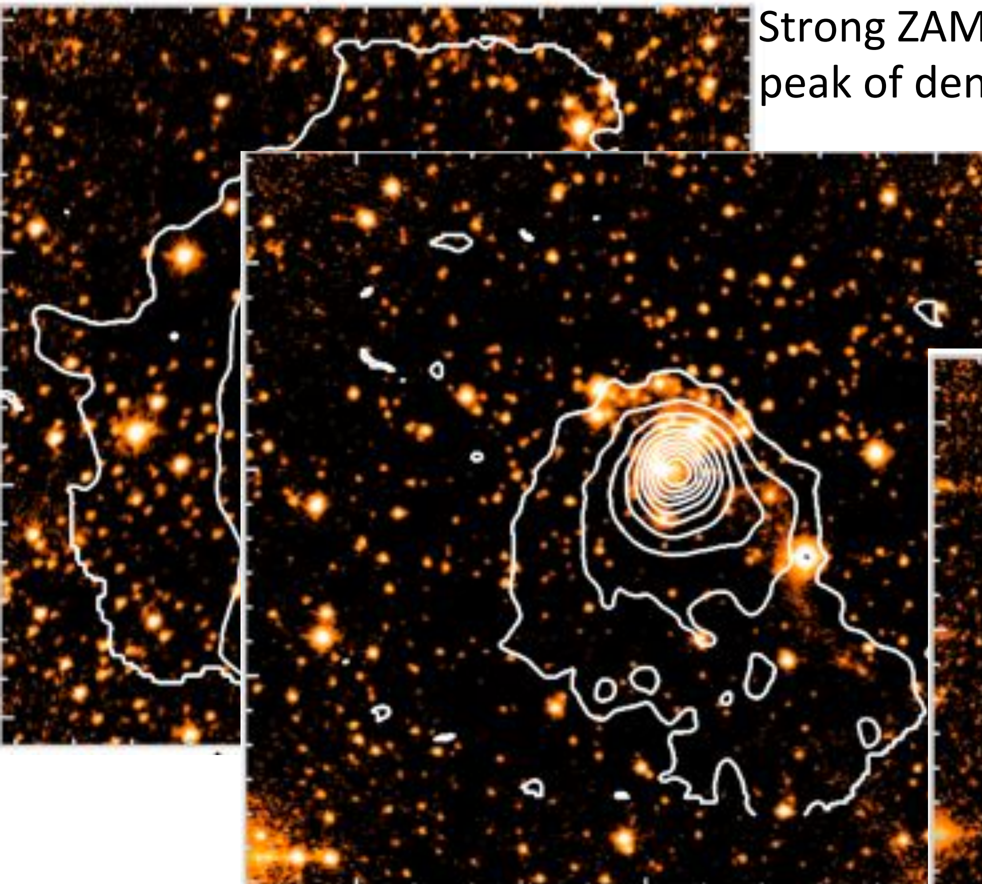
Contours represent the distribution of the nearly 16000 inner Galaxy protostellar clumps from Hi-GAL (Elia+ 2016 in prep)

Next level of complexity: fragmentation of clumps into cores and the pathways toward ZAMS stars



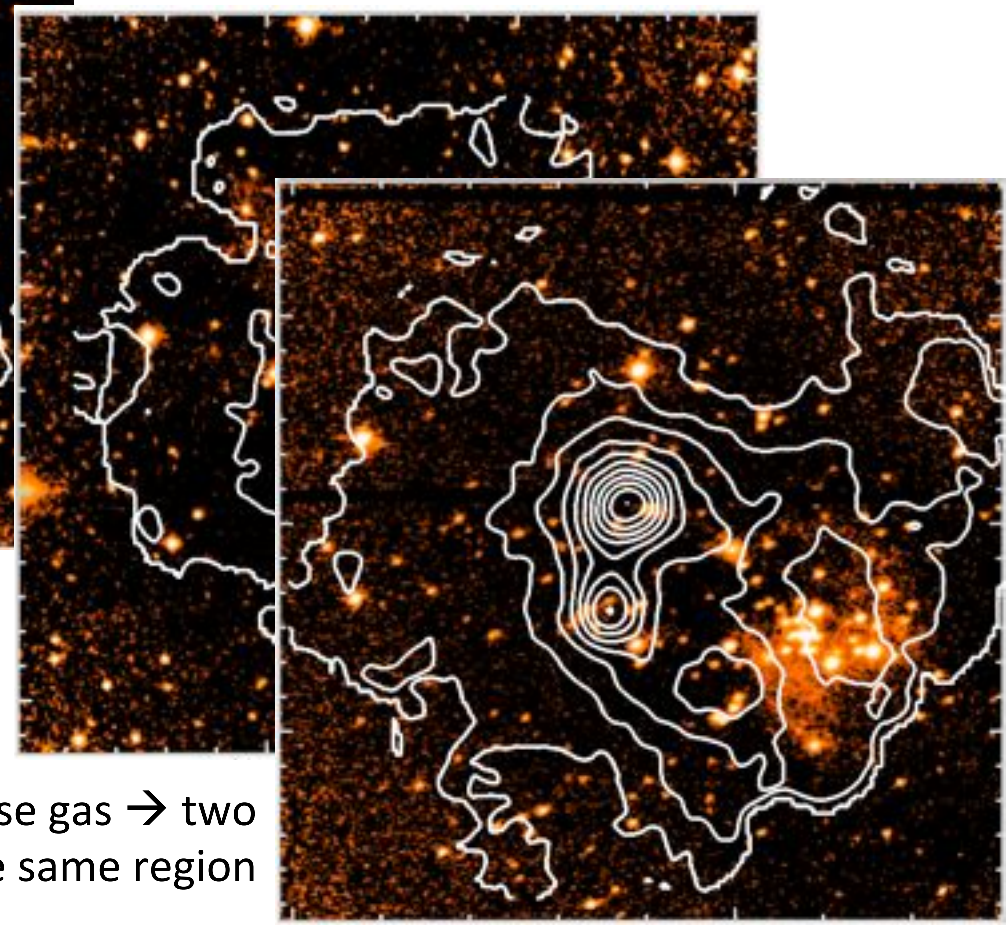
The Zoo of Dense Clumps and Young Clusters

(image: Ks – contours: cold dust)



Strong ZAMS source and YSO cluster coincident with the peak of dense gas → well evolved system

Rich YSO cluster coincident with the peak of dense gas → massive ZAMS likely not yet there

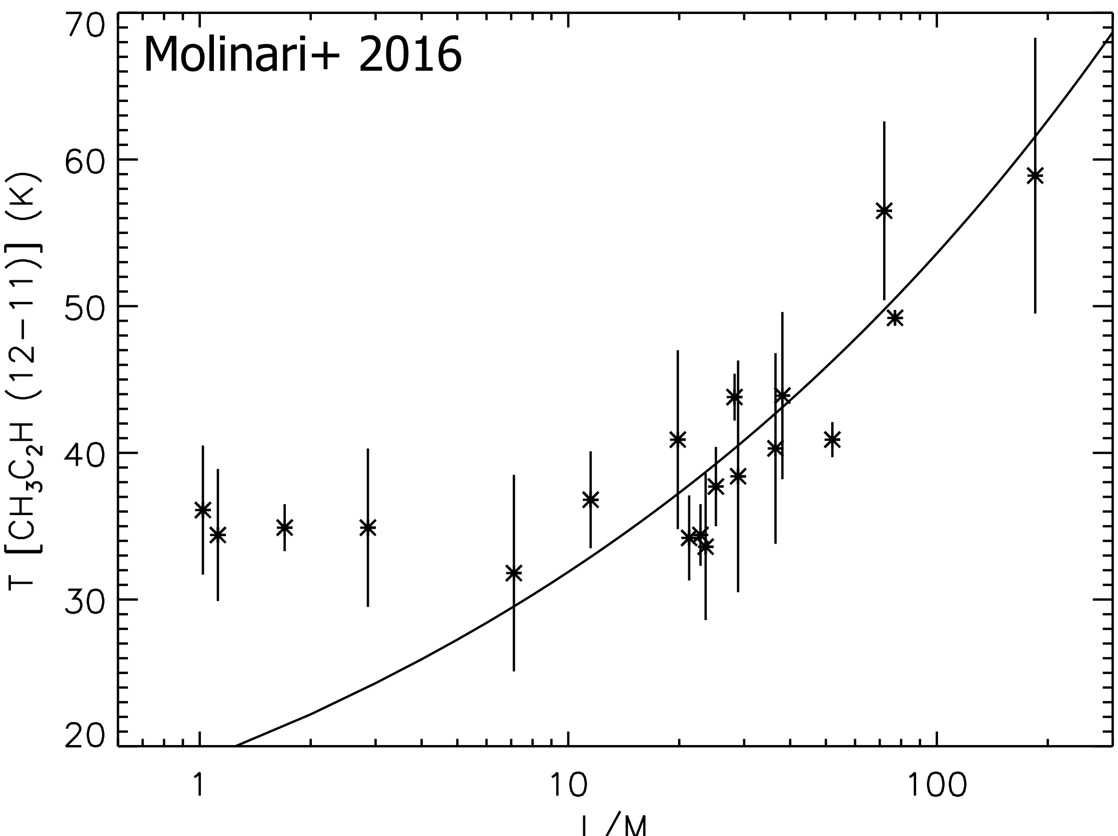


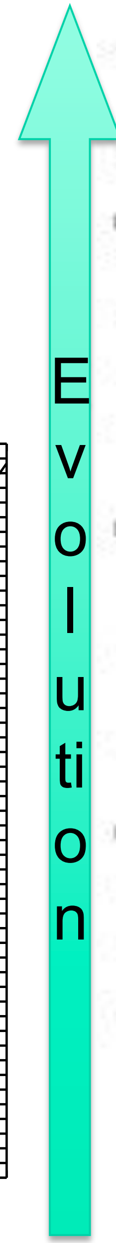
Rich YSO cluster AROUND the peak of dense gas → the seed of massive stars not yet there, but still part of the same Star Formation event

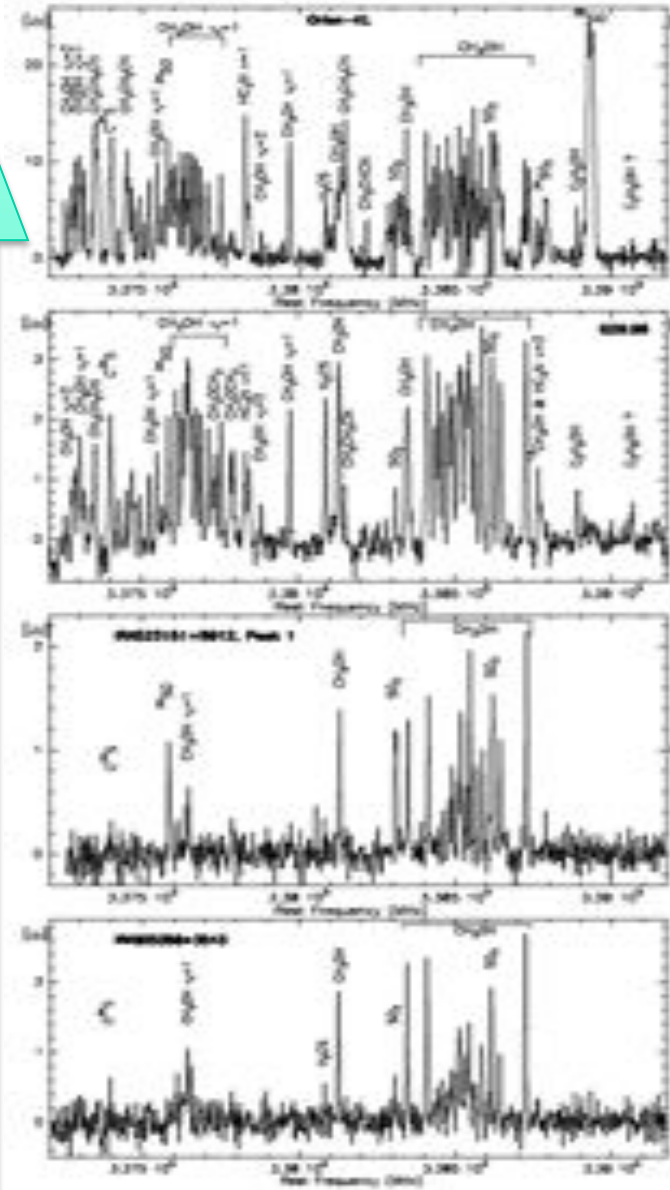
Rich YSO cluster OFFSET with the peak of dense gas → two distinct star formation events in the same region

Evolutionary Toolkit

Calibration of Far-IR/submm evolutionary diagnostics against molecular tracers.



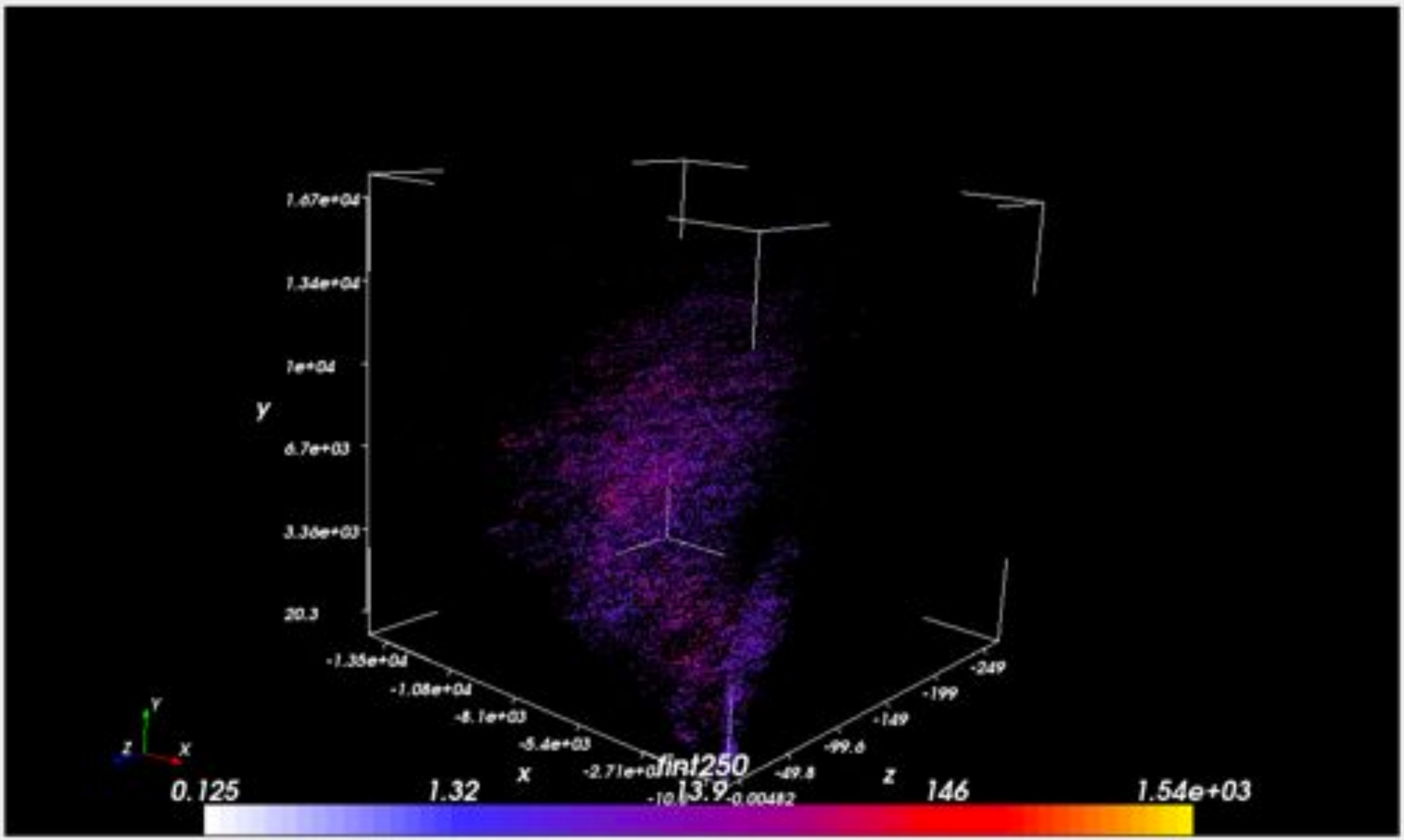




IR →radio chemical fingerprinting IS the essential complement for a correct evolutionary assessment

VIALACTEA Knowledge-base and Visualization

Visualization-driven access to the VIALACTEA KB: images, spectral cubes, source and filaments catalogues



A Strategic View: Observations & Facilities

Star-forming as well as potentially star-forming clumps must be resolved into individual components from the Infrared to the Radio in order for their SFR to be determined:

- **1 → 20μm** imaging for Protoclusters SF History, and high-resolution spectroscopy for internal protocluster dynamics: ***JWST**, **E-ELT**, **FLARE** (ESA-M5) for deep and large-scale surveys*
- **30 → 200μm** imaging to constrain SED and L_{bol} as evolutionary probes and SFR estimators, in a most critical and unexplored spectral range: *need **>**10-meter class space telescopes to provide at least a factor 10 jump in spatial resolution compared to HERSCHEL: → MILLIMETRON ? TALC ?*
- **200μm → 3mm** imaging and spectroscopy to study fragmentation evolution, constrain the upper-end of the IMF and to obtain the chemical fingerprinting (CO, HCO^+, CH_3CN, CH_3C_2H, NH_3, N_2H^+, ...): *>10/30-meter class radio-telescopes like **JCMT**, **IRAM**, **APEX**, (CCAT) for large-scale surveys, and of course **ALMA** (1000 clumps survey PI proposal in Cycle 4) and **NOEMA** for deep surveys.*
- **1cm → 21cm** high-sensitivity continuum (free-free) and spectroscopy (OH, RRL) to detect as the first signals of star-birth*: large surveys with **JVLA**, **MeerKAT**, **SKA***.

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A Strategic View: Observations & Facilities

ISM clouds and filamentary structures must be mapped throughout the Galactic Plane to constrain the formation mechanisms of dense clouds, how they evolve into dense filaments, and how they fragment and feed star-forming clumps (protoclusters).

- Sensitive large-scale (tens-of-degrees scale) spectroscopic mapping of low [v_s ,n_0] shock tracers: **[OI], low-J CO, SiO, [CII], [NII]**…, to see if **converging flows** shocks really exist + velocity-resolved atomic and HI→H_2 transitions tracers to evaluate the role and dissipation of turbulence and WNM pressure confinement: **HI, [CI], low-J CO, [NII]**, …: *>10-30-meter class JCMT, IRAM, APEX, CCAT telescopes are fast mappers with the required sensitivity for low-J CO, SiO.* ***[OI], [CII], [NII]*** *need a* ***space telescope in the Far-IR with heterodyne ($R=10^6$-10^7)*** *resolutions :* ***FIRSPEX*** *(ESA-M5), MILLIMETRON*
- High-spatial and spectral resolution filament (subdegree-scale) spectroscopic mapping to obtain detailed kinematic mapping (resolution <0.5 km/s) on a wide range of aspect-ratio filaments, reveal infall profiles across and/or along the filament and measure the dynamics of clumps along the filaments; use a variety of tracers like **N_2H^+, HCO^+, NH_3,…** : needs **IRAM**, **NOEMA**, **ALMA**, **JVLA**, **MeerKAT**, **SKA**.