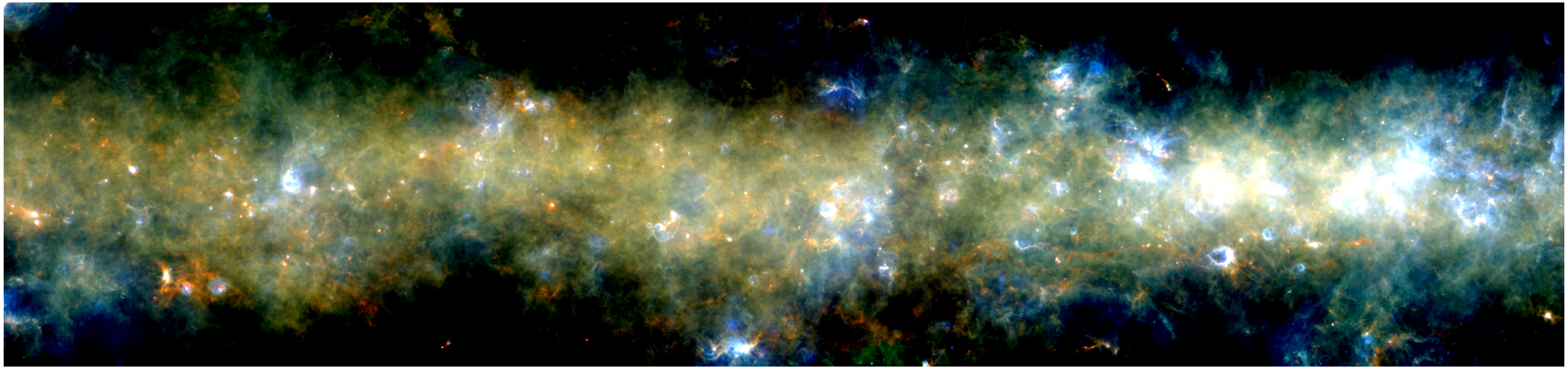
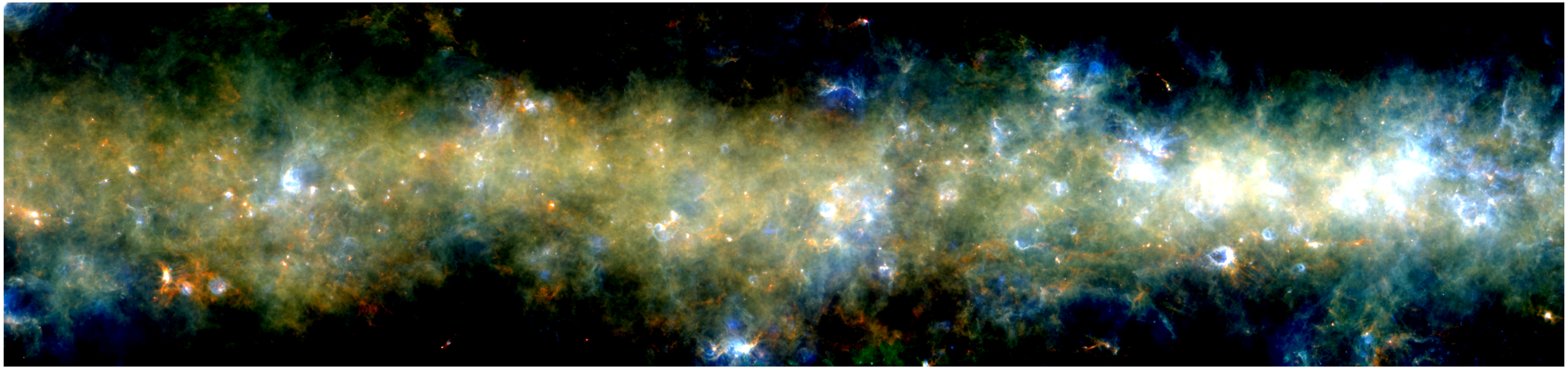


Galactic Massive Star Formation and the need of High Spatial Resolution

in the Herschel era

S. Molinari – INAF/IAPS, Rome

Thanks to Herschel and the latest GP Surveys



Toward a Predictive Global Model of Galactic Star Formation

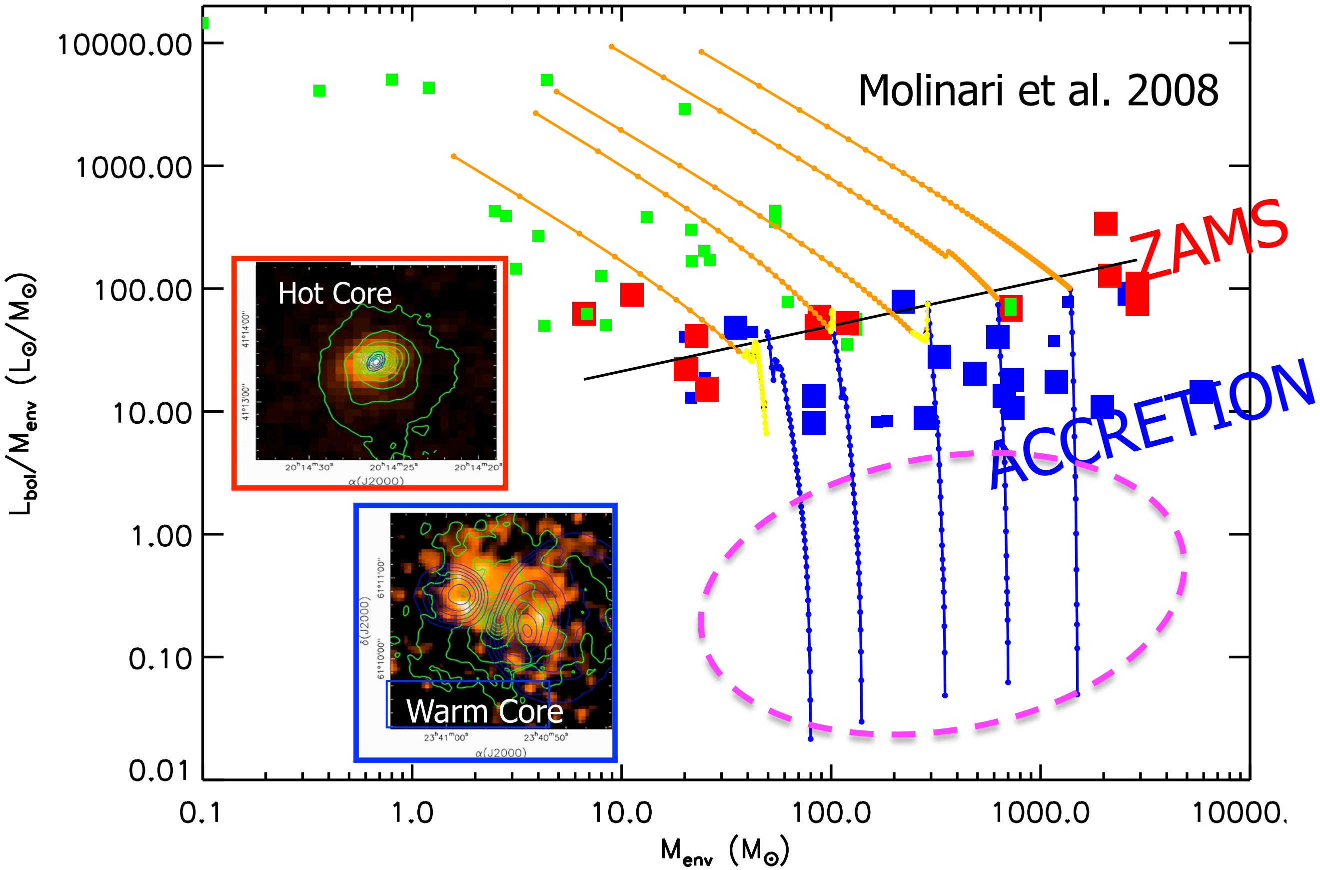
- The High-Mass Star Formation Timeline
- Measure the star formation rate and history Galaxy-wide
- Cold dust in the Galactic Plane and the Formation of Molecular Clouds
- Understanding star formation laws and the nature of thresholds as a function of ISM properties across a full range of galactocentric radii metallicity and environmental conditions
- Determining the relative importance of global *vs* local, spontaneous *vs* triggering, agents that give rise to star formation.
- Build bottom-up recipes and prescriptions useful for Xgal science

From massive pre-stellar clumps to HII regions

In a pre-Herschel SED analysis of sample of 42 intermediate and high-mass star forming region from the sample of Molinari et al. (1996), we suggested a Class 0-I-II sequence analogous to the low-mass regime: Warm Cores to Hot Cores to HII-driving objects

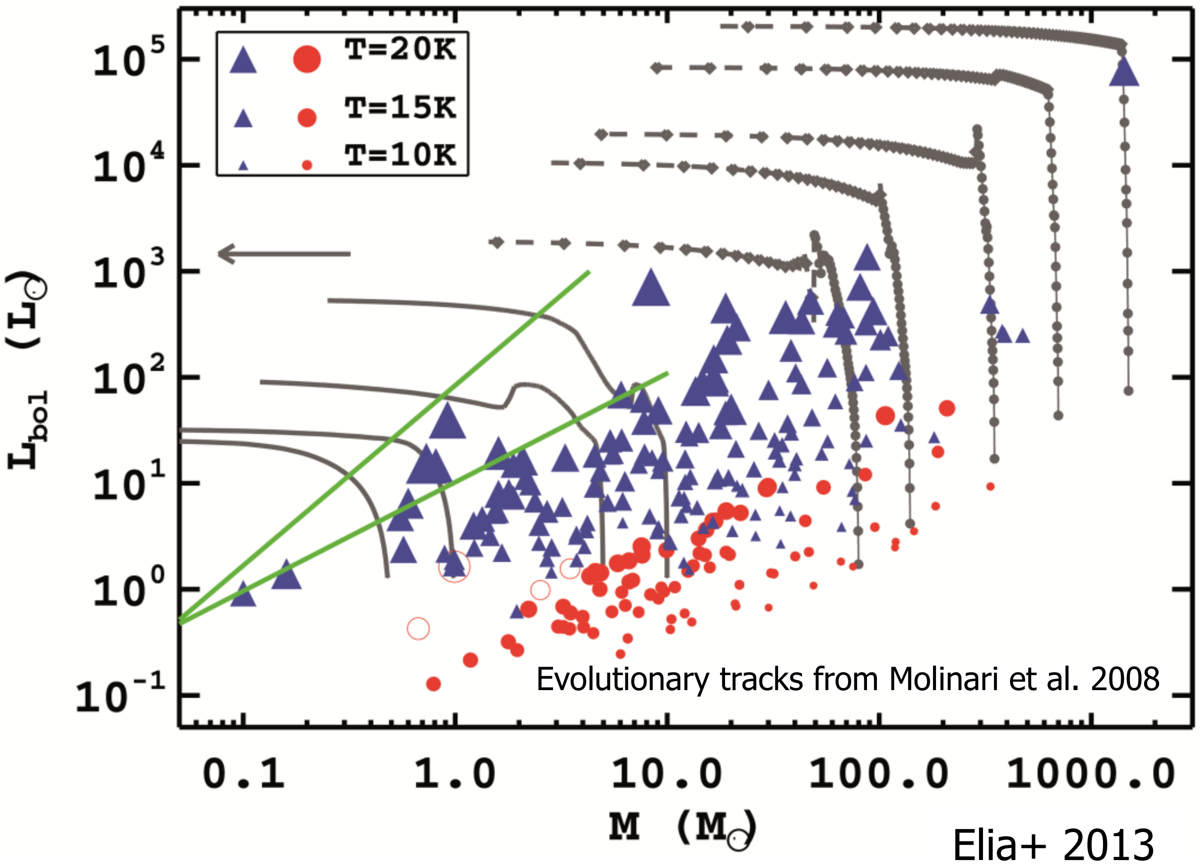
- Warm Cores SED sources are under-luminous with respect to UCHII/HotCores of similar envelope mass

- Concurring indications suggesting that the dominant source in the Warm Core objects is not yet on the ZAMS



Clumps evolutionary stage

- **Pre-stellar Sources (no 70μm counterpart)**
- **Proto-stellar Sources (with 70μm counterpart)**



Elia+ 2013

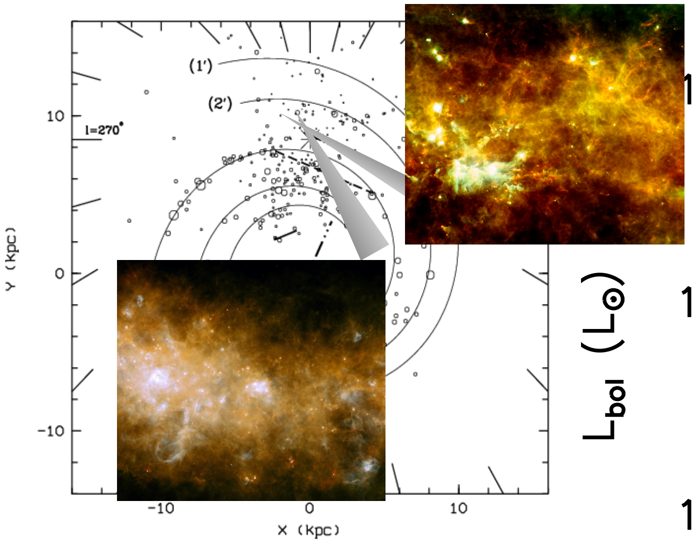
- A separation between **pre-stellar** and **proto-stellar** sources is quite clear in terms of L/M. The appearance and intensity of the 70μm (and shortward), clearly makes the difference.

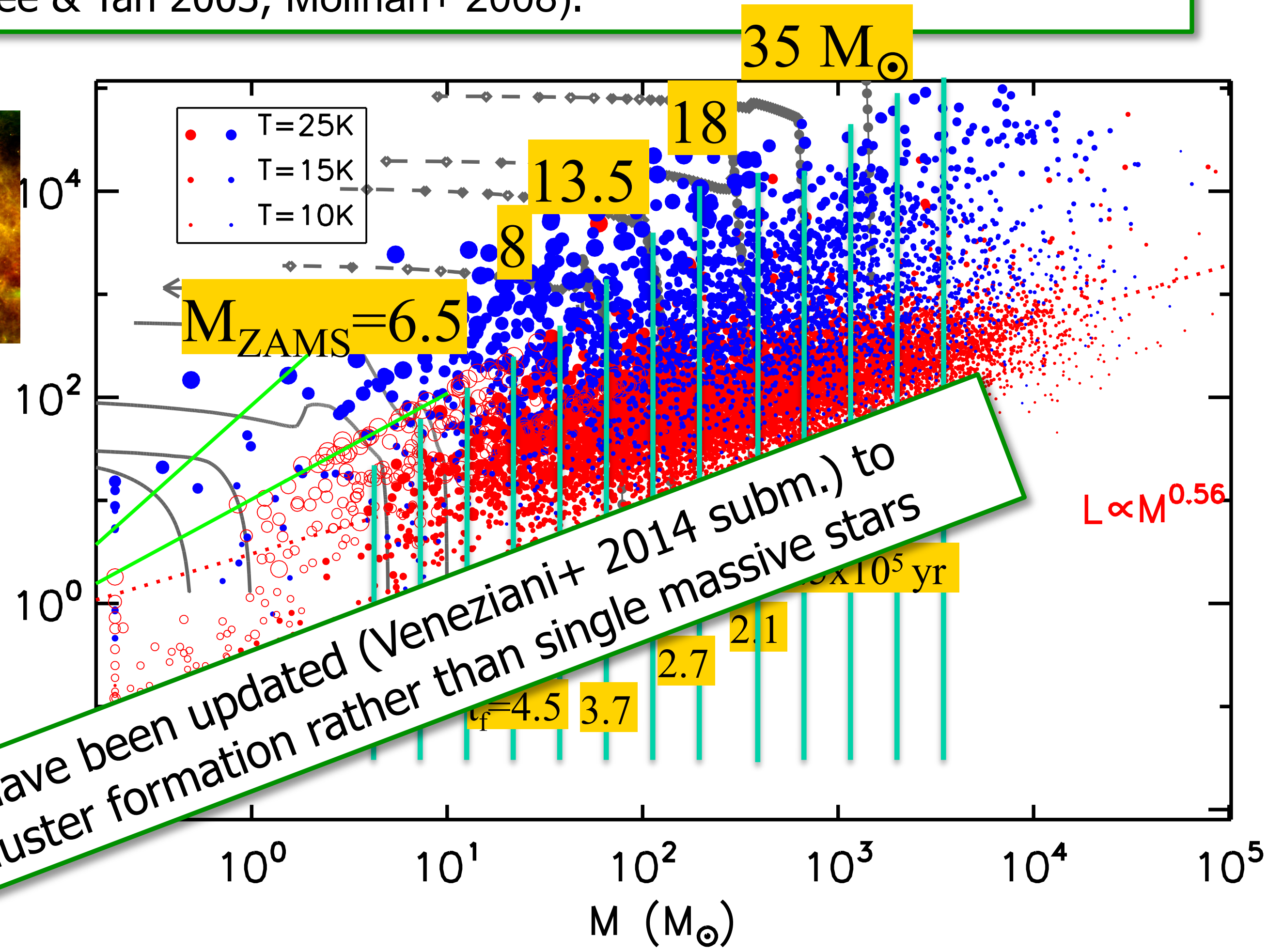
- Within each class, there is a clear trend of L/M with Temperature (estimated using only λ≥160μm)

Star Formation drives up the energy budget in the clump, raising its global temperature and luminosity. This can be ideally followed in the [L,M] diagram

Star Formation Rate from YSO counts

A first attempt in deriving the SFR in the two Hi-GAL SDP fields l=30° and l=59° (*Veneziani et al. 2013*), comparing YSO statistics for PROTOSTELLAR Clumps in the L *vs* M plot against evolutionary predictions (McKee & Tan 2003, Molinari+ 2008).





Prescriptions have been updated (Veneziani+ 2014 subm.) to account for cluster formation rather than single massive stars

Each bin i is associated to:

- final ZAMS mass $M_{ZAMS}(i)$
- formation time $t_f(i)$

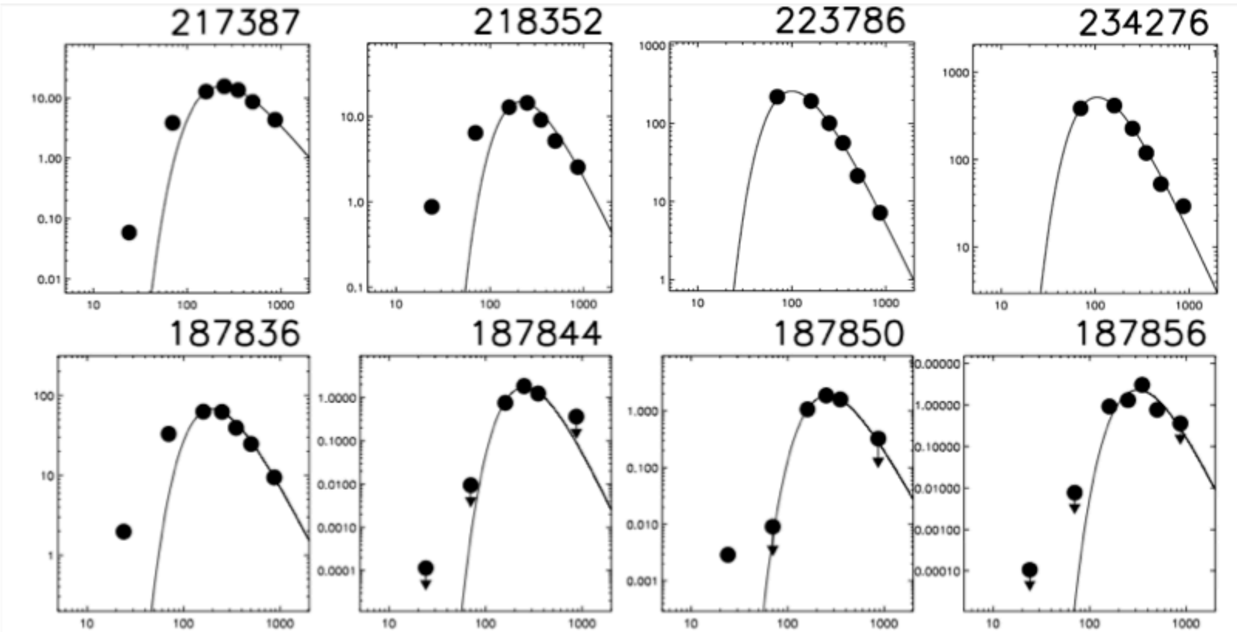
$$SFR = \sum_{i=1}^{N_{Mzams}} \sum_{j=1}^{N_{Sources}} n_M(i,j) M_{ZAMS}(i)/t_f(i)$$

l=30° → 0.067 M☉/yr
l=59° → 0.011 M☉/yr

Hi-GAL is statistics: Huge output…

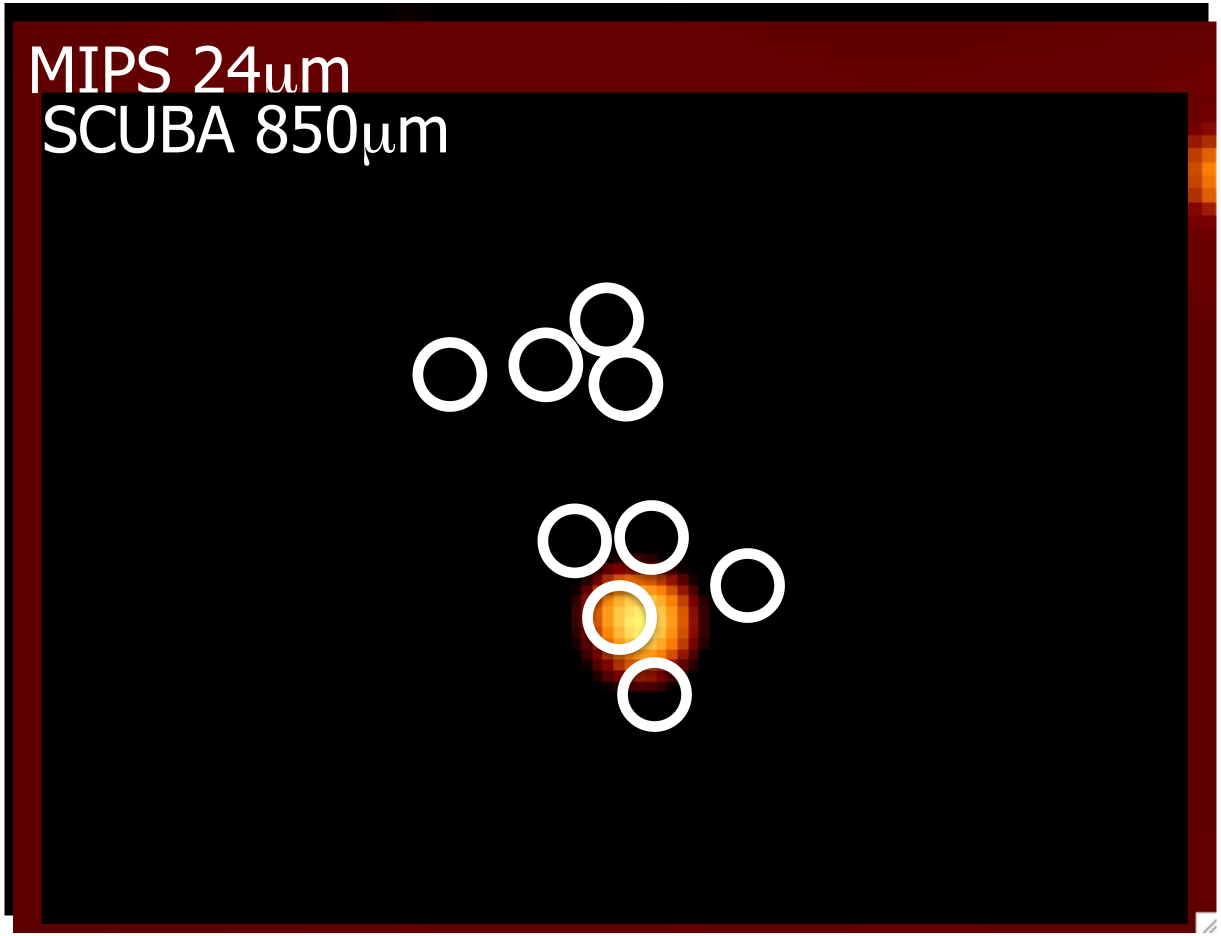
Using CuTEx package (Molinari+ 10) we attempted a first quick extraction from the entire inner Galaxy survey, resulting in a preliminar bandmerged catalogue of

428.000 entries.



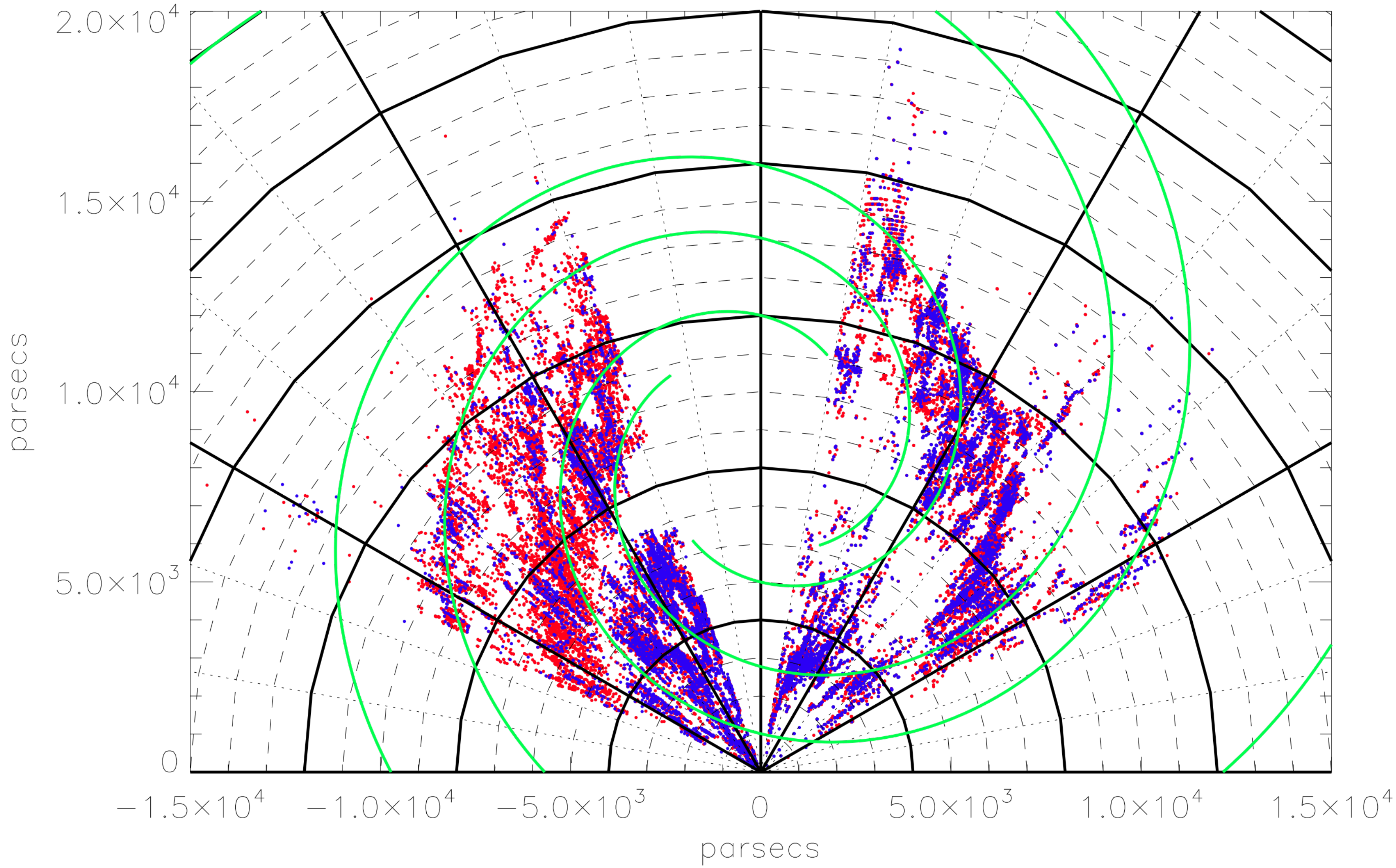
The catalogue contains:
peak and integrated fluxes, sizes at the different wavelengths.
For sources with counterparts in at least three bands (more than 90000 at the moment in the inner Galaxy) we augment SED coverage with on-target counterpart extraction from ATLASGAL and MIPSGAL24, with estimates of distances, T, L, M and size, for **about 60000** of them…
preliminar is a key word ;)

The continuum ZOO in Intermediate Mass SFRs

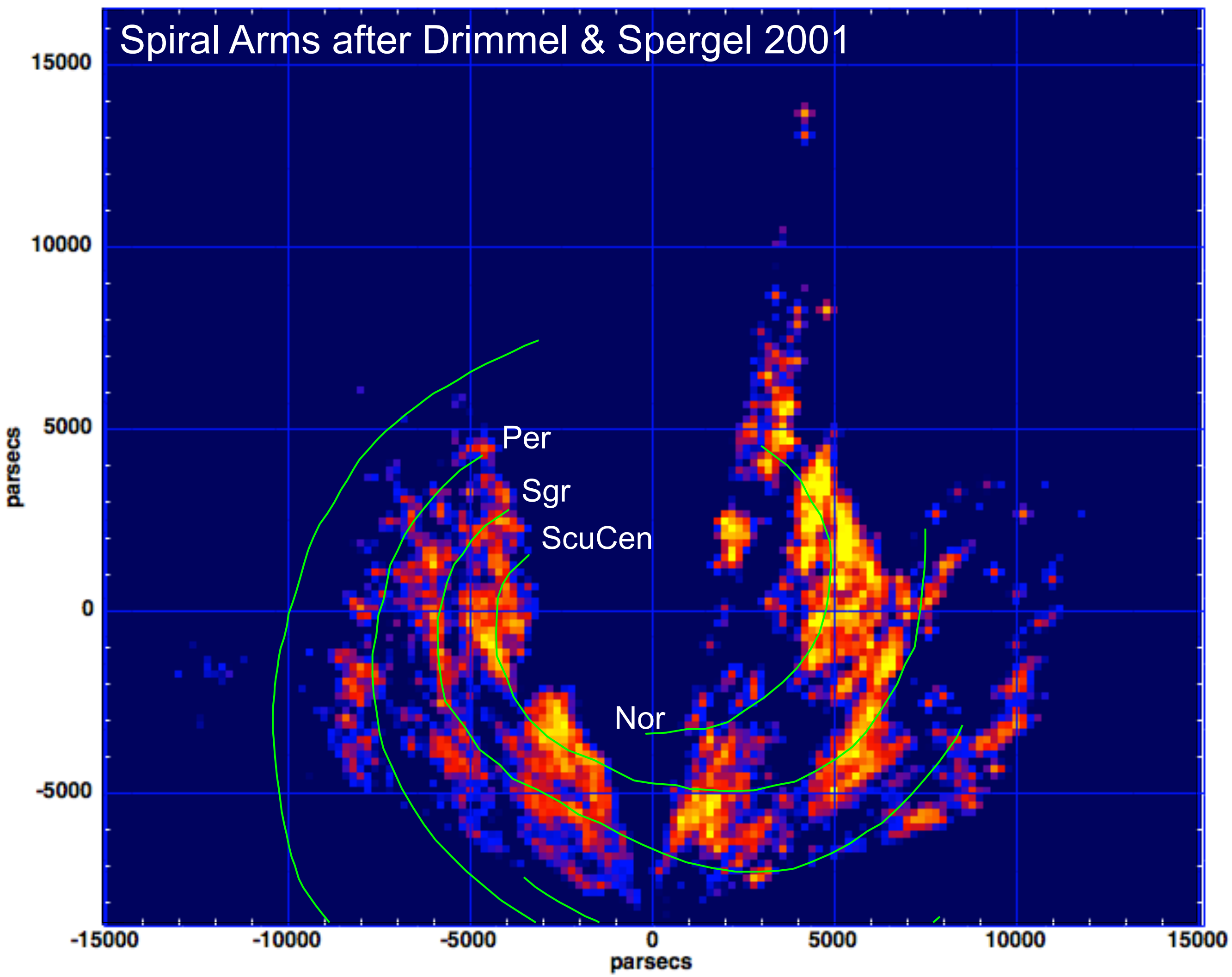


- Intermediate and High-Mass SFRs are systems where YSOs with very different SEDs coexist.
- Is the SED shape an age indicator ? Degeneracies control need good λ coverage
- Herschel is doing much especially in nailing down L_{bol} and M_{env}
- ....however, the $\lambda<70\mu m$ range is the critical one to constrain the SED models

Hi-GAL is statistics: Huge output…

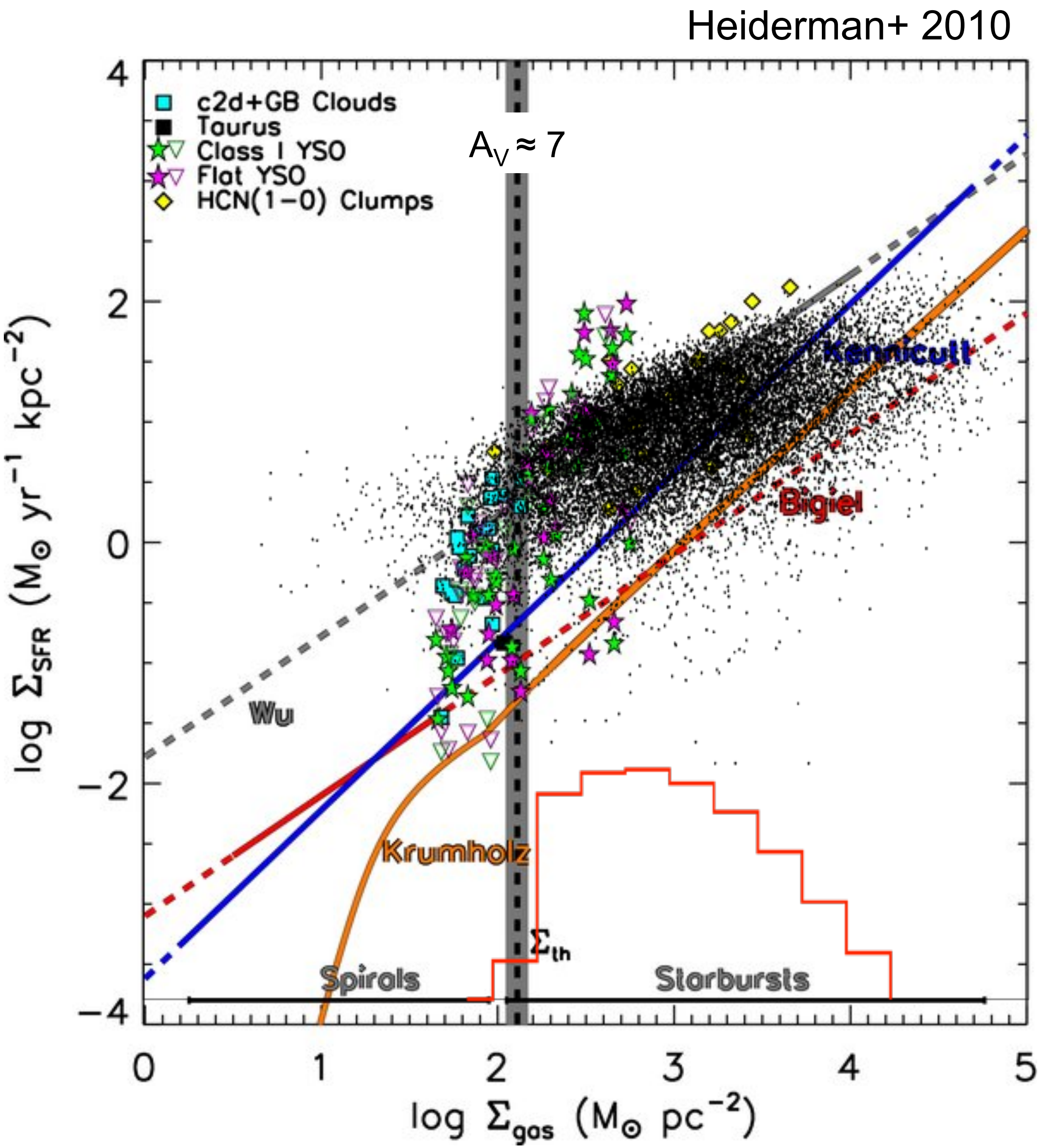


For the first time it IS possible to obtain a spatially resolved map of the Star Formation Rate and Efficiency in the Milky Way

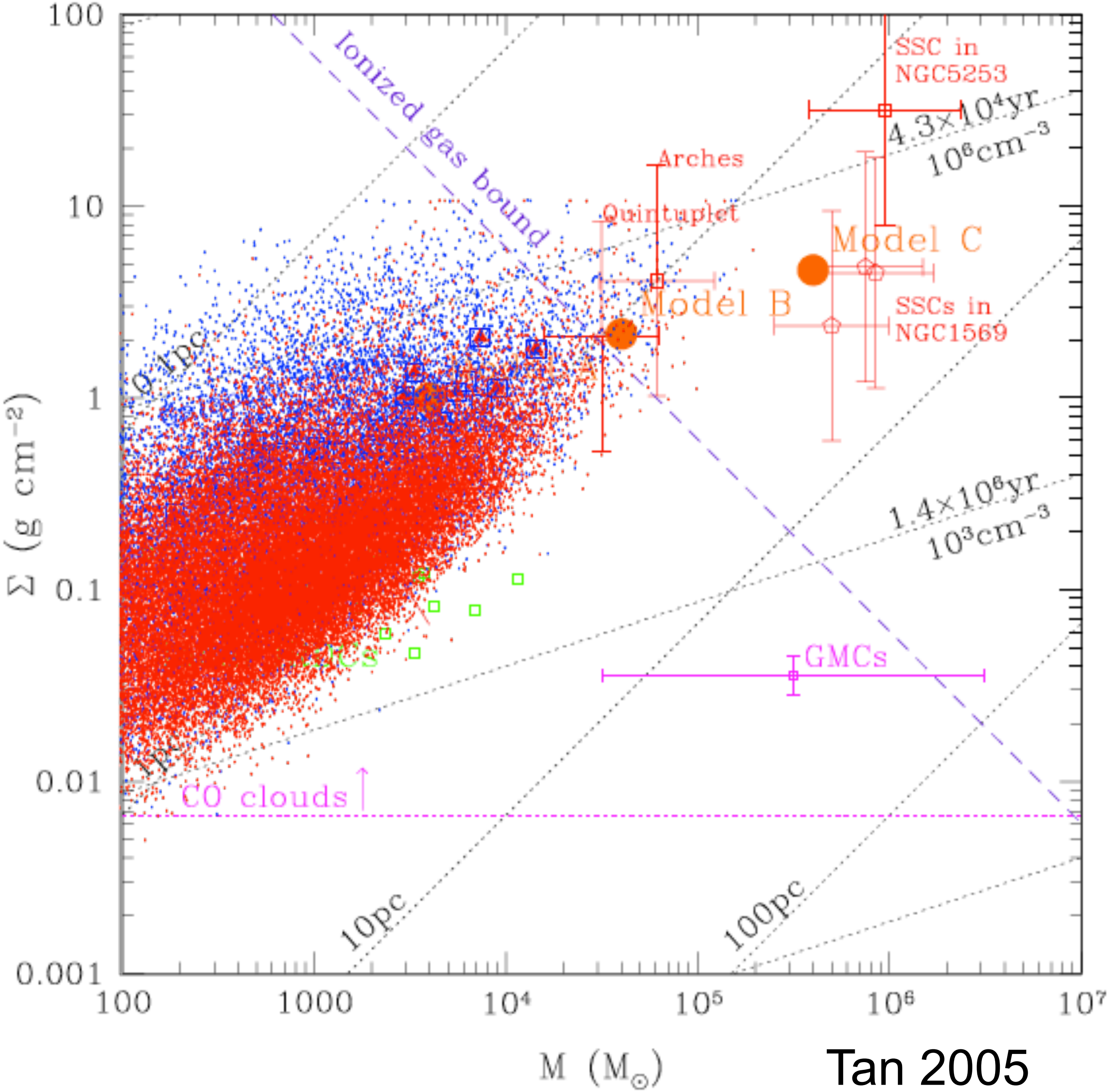


Integrated SFR ≈ 0.2 $M_{\odot}$/yr

Molinari+ in prep.



Heiderman+ 2010
c2d+GB Clouds
Taurus
Class I YSO
Flat YSO
HCN(1−0) Clumps
A_V ≈ 7
Kennicutt
Bigiel
Wu
Krumholz
Σ_th
Spirals
Starbursts
log Σ_SFR (M⊙ yr^−1 kpc^−2)
log Σ_gas (M⊙ pc^−2)
4
2
0
−2
−4
0
1
2
3
4
5



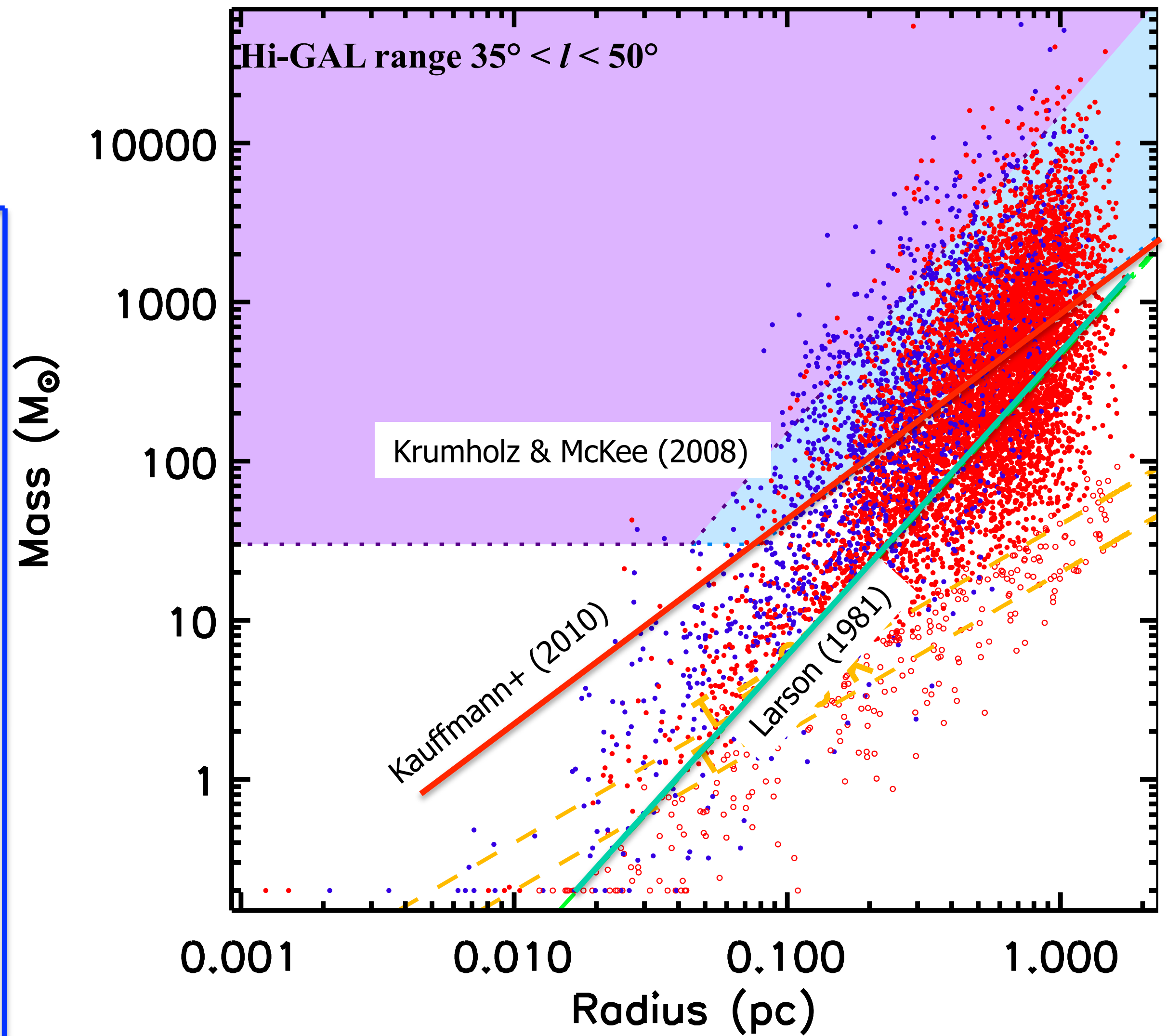
Ionized gas bound
SSC in
NGC5253
4.3×10⁴yr
10⁶cm⁻³
Arches
Quintuplet
Model C
Model B
SSCs in
NGC1569
1.4×10⁶yr
10³cm⁻³
GMCs
CO clouds
0.1pc
1pc
10pc
100pc
Σ (g cm⁻²)
M (M⊙)
100
10
1
0.1
0.01
0.001
100
1000
10⁴
10⁵
10⁶
10⁷

Tan 2005

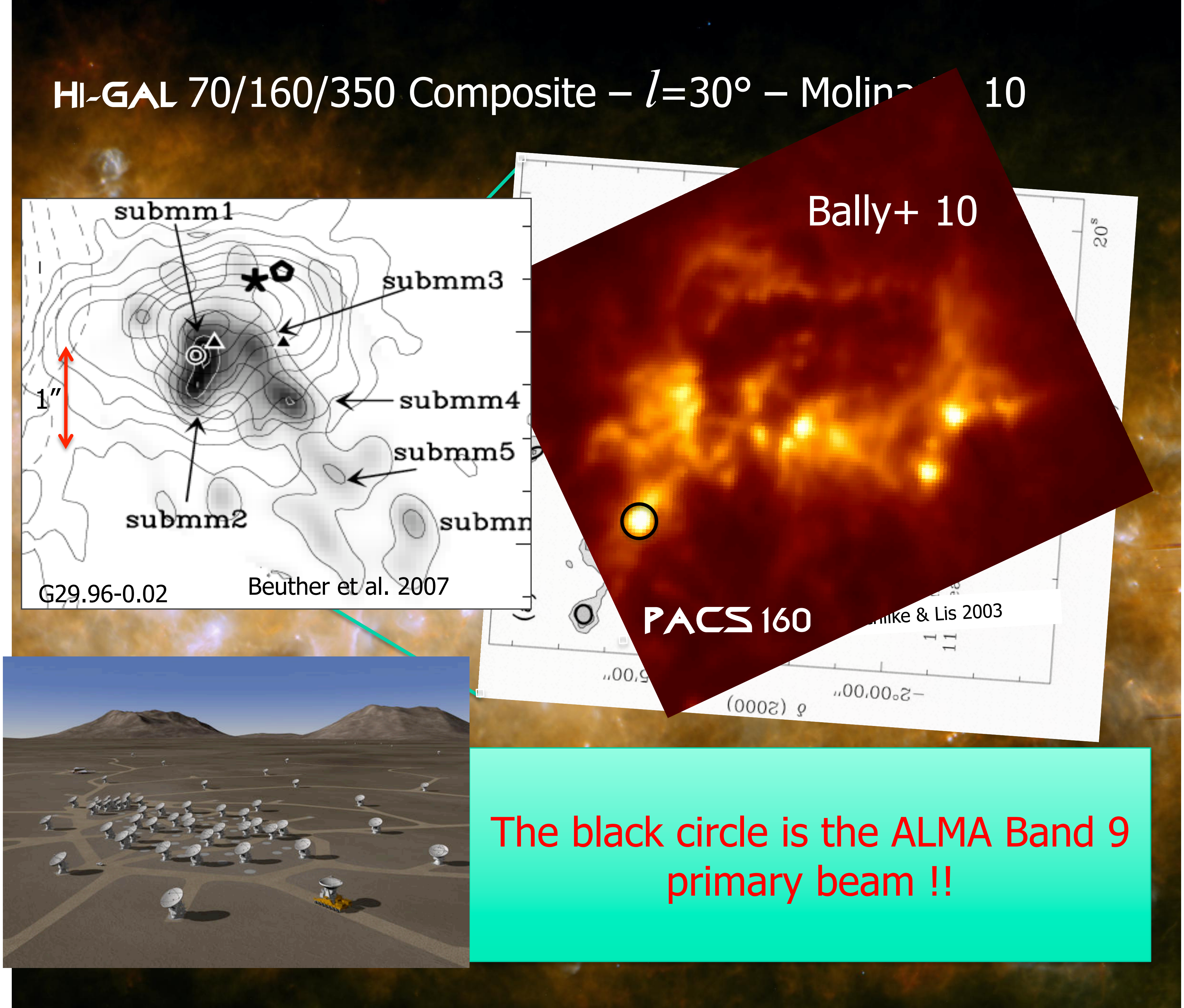
Nature of the compact Dense Clumps

* Hi-GAL sources with counterpart in at least 3 adjacent bands, and with known distance

- The majority of sources are gravitationally bound clumps according to Larson (1981).
- Herschel sensitivity is such that a solid multiband Far-IR detection in the Galactic Plane is likely a solid dense clump detection
- Less than half of the compact Clumps have densities high-enough to compare with known sites of intermediate and high-mass star formation (Kauffmann+ 2010).

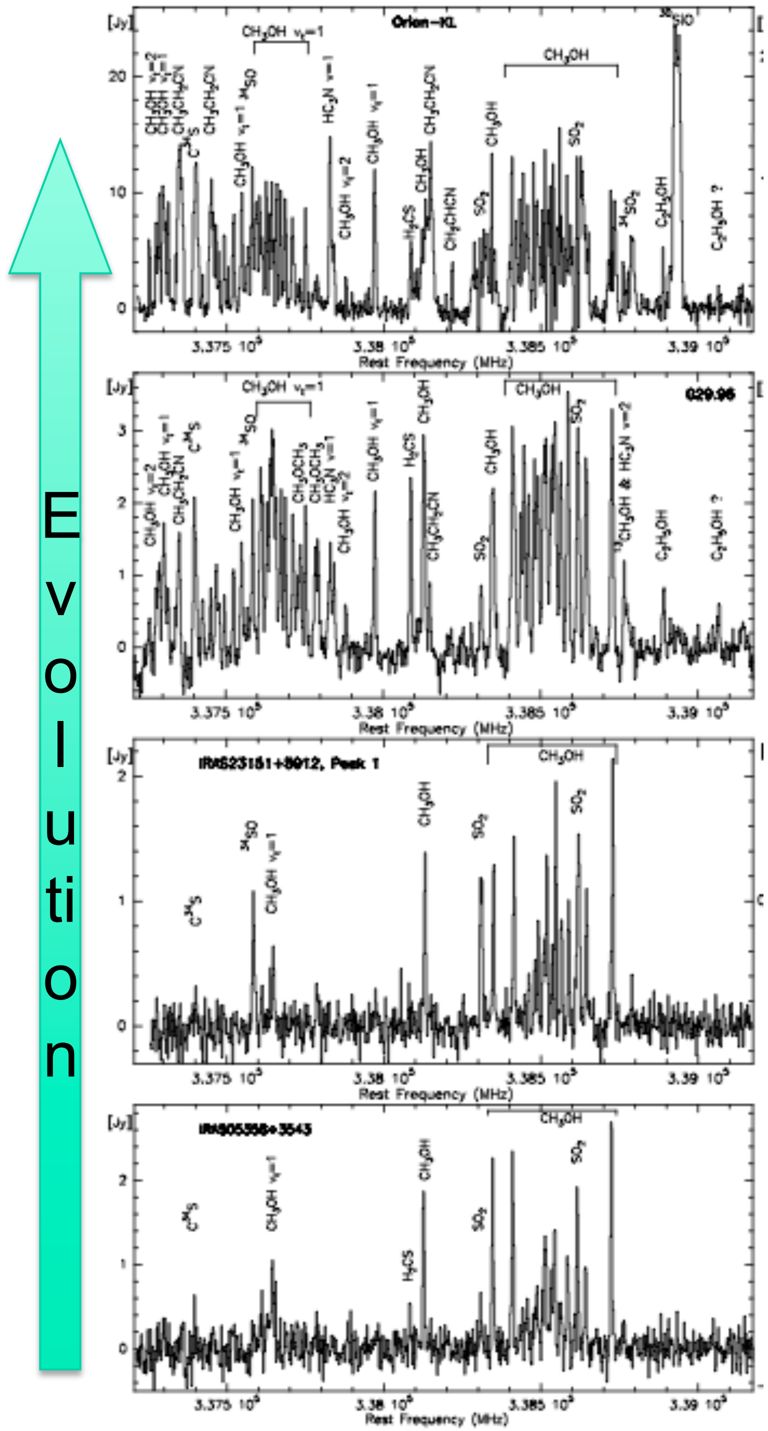


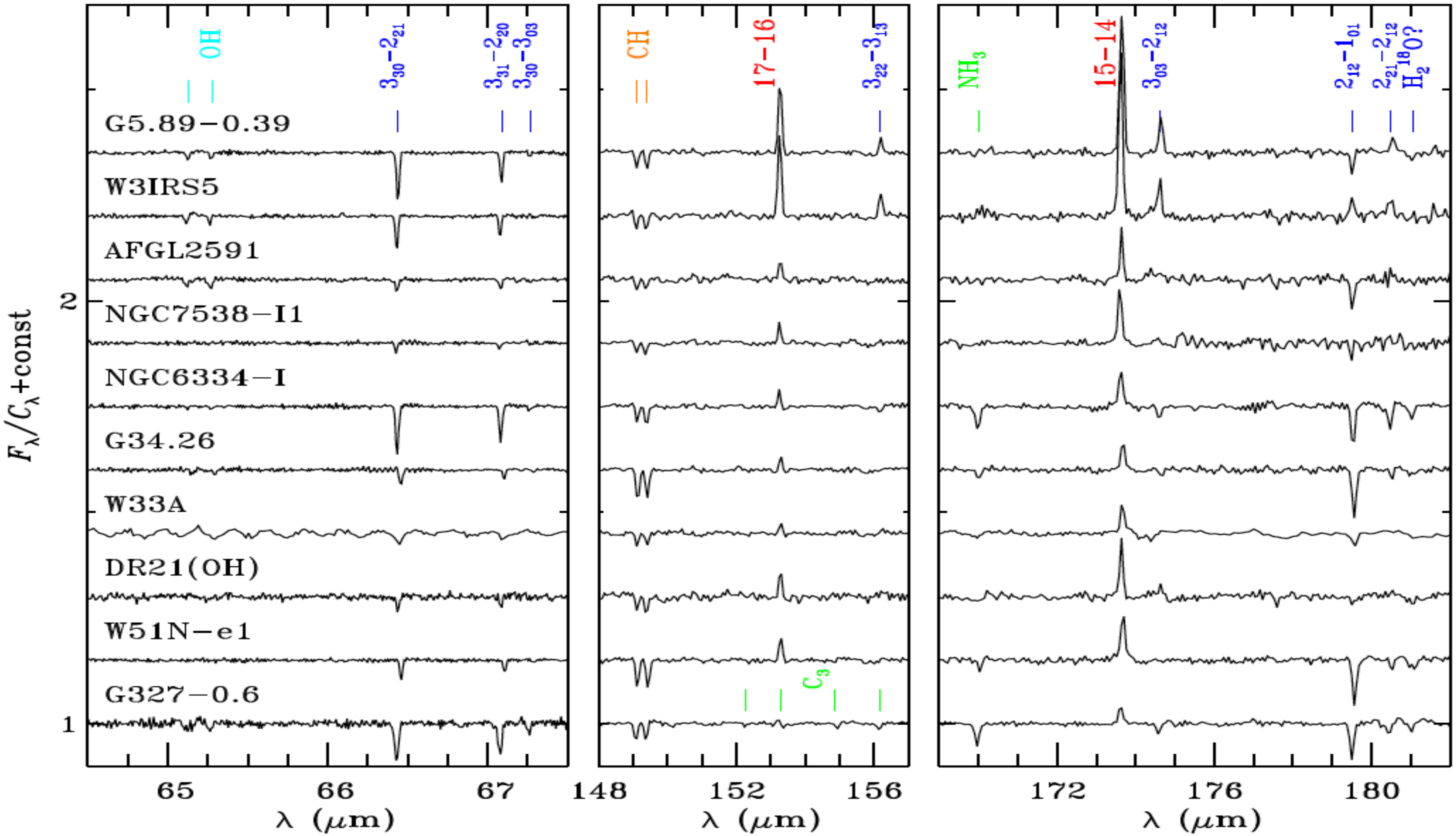
Pezzuto+, in prep.


Hi-GAL 70/160/350 Composite – l=30° – Molina 10
submm1
submm3
submm4
submm5
submm2
1″
G29.96-0.02
Beuther et al. 2007
Bally+ 10
PACS 160
ilke & Lis 2003
The black circle is the ALMA Band 9 primary beam !!

Chemistry fingerprints are the essential complement for a correct evolutionary assessment

…only available on a numerable set of sources





FIR Spectroscopy toward High-mass YSOs reveals also lines in absorption.

In CO (emission) between 40 and 80% of the CO line cooling comes from the quiescent envelope (Karska+ 2014)

Intermediate and Massive Star Formation is entering the Mega-SED era

• Bolometric luminosities are at the foundation of SFR estimates. Herschel mostly reveals clumps for d≥1kpc systems; a factor 10 jump in spatial resolution at the peak of SEDs (≤200μm) is needed. ALMA is a strong actor, but it is not ideal for large surveys and for dust temperature estimates.

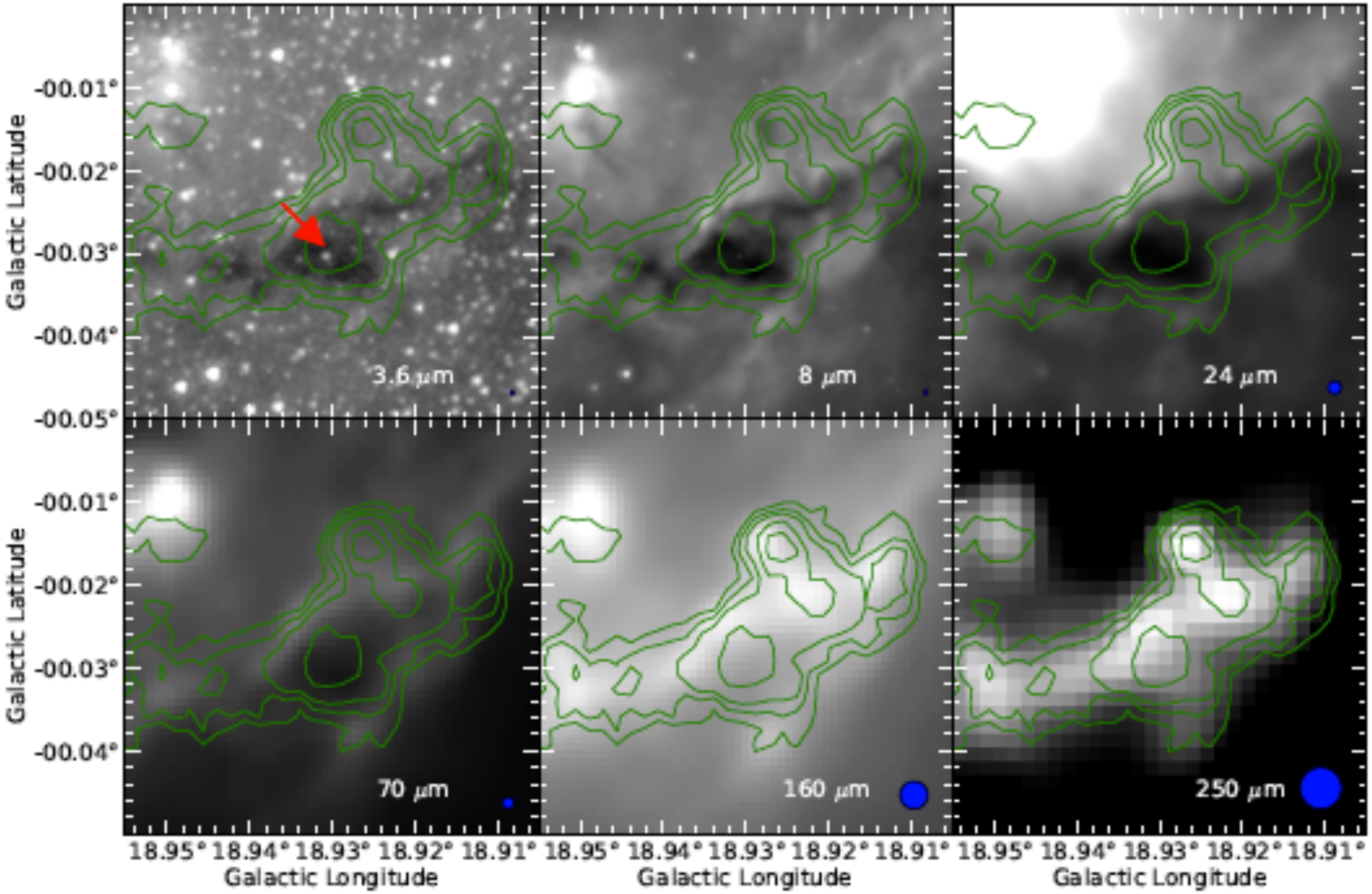
• Excellent imaging SED coverage at subarcsec resolution is needed between 20 and 100 μm to govern the SED diversity. SOFIA may likely do a lot, but not ideal for large surveys: SPICA.

• Chemical fingerprinting is the essential complement to the SED continuum characterization. Here ALMA and CCAT will be strong players.

• High sensitivity FIR-submm continuum & spectroscopy is needed to unlock access to the far side of the Galaxy

Rapid-fire & sensitive multiband continuum and spectroscopic snapshots for (tens of) thousands of clumps: Fast FIR-submm mapper (going below 200μm) – CCAT, MILLIMETRON, SPICA, TALC, …

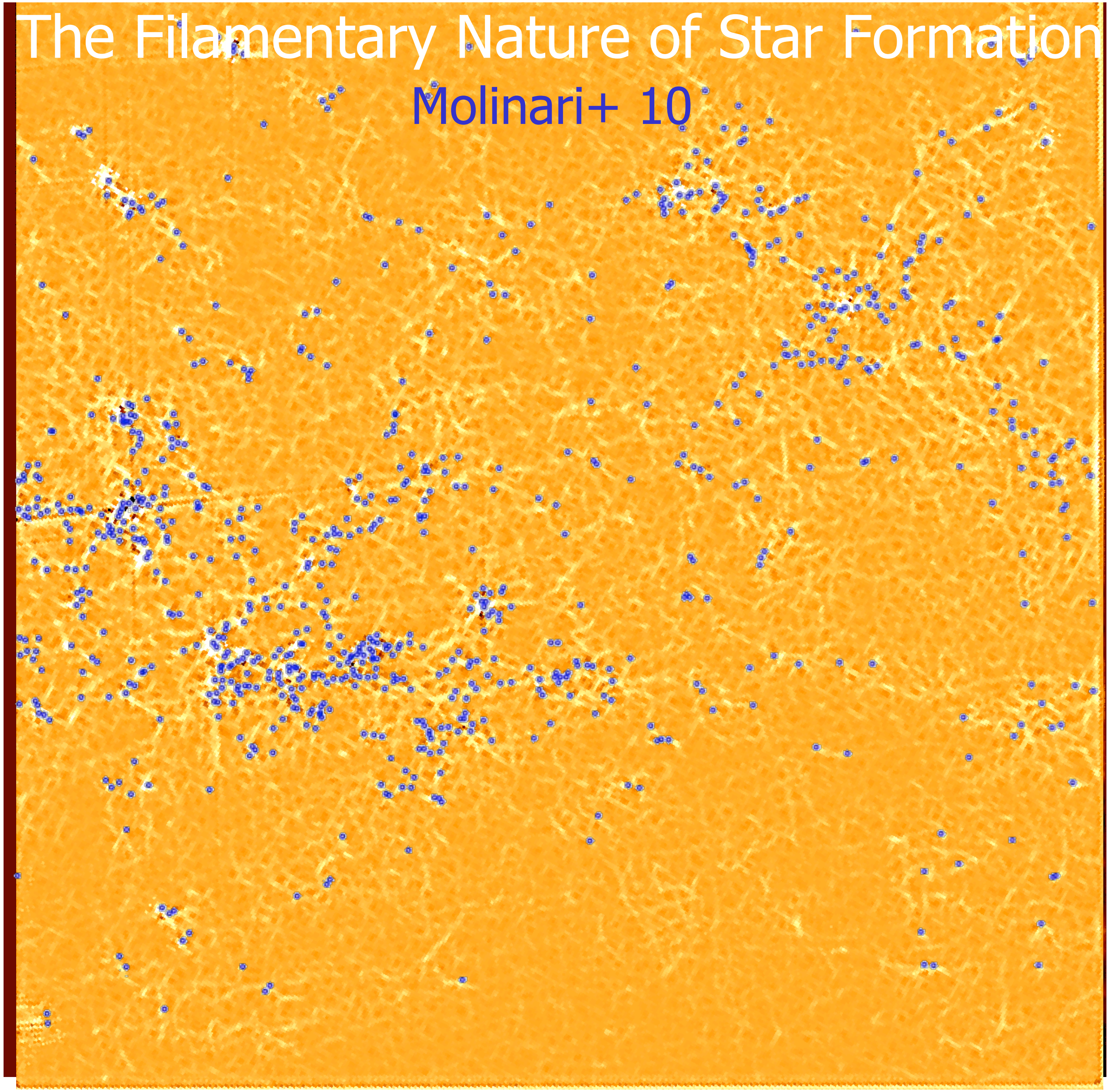
Filaments: from darkness to light

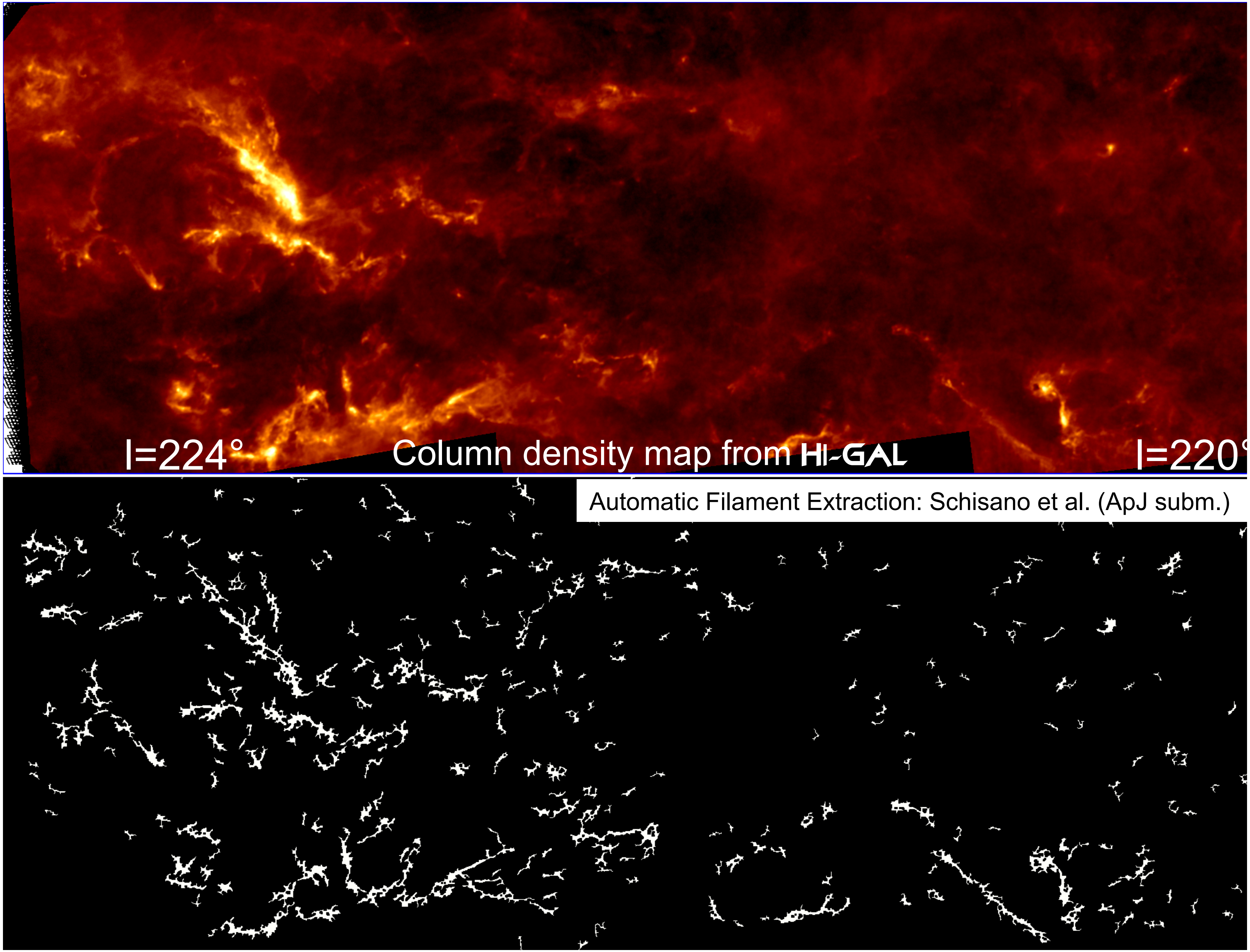


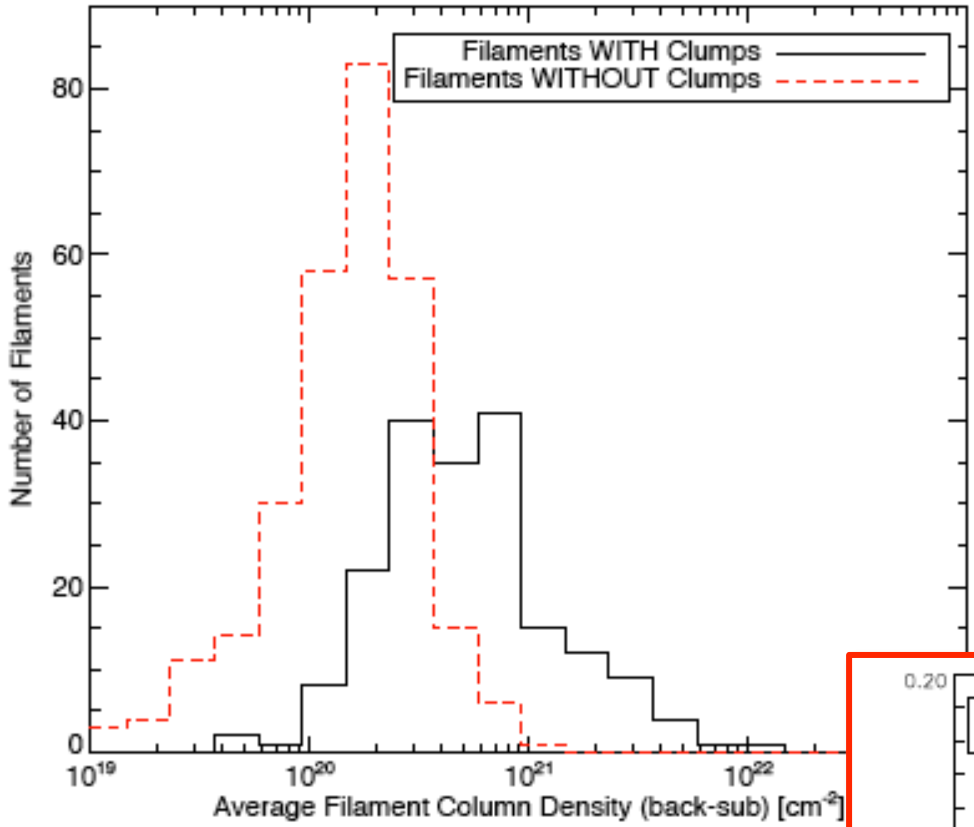
Tackenberg+ 2012

The Filamentary Nature of Star Formation

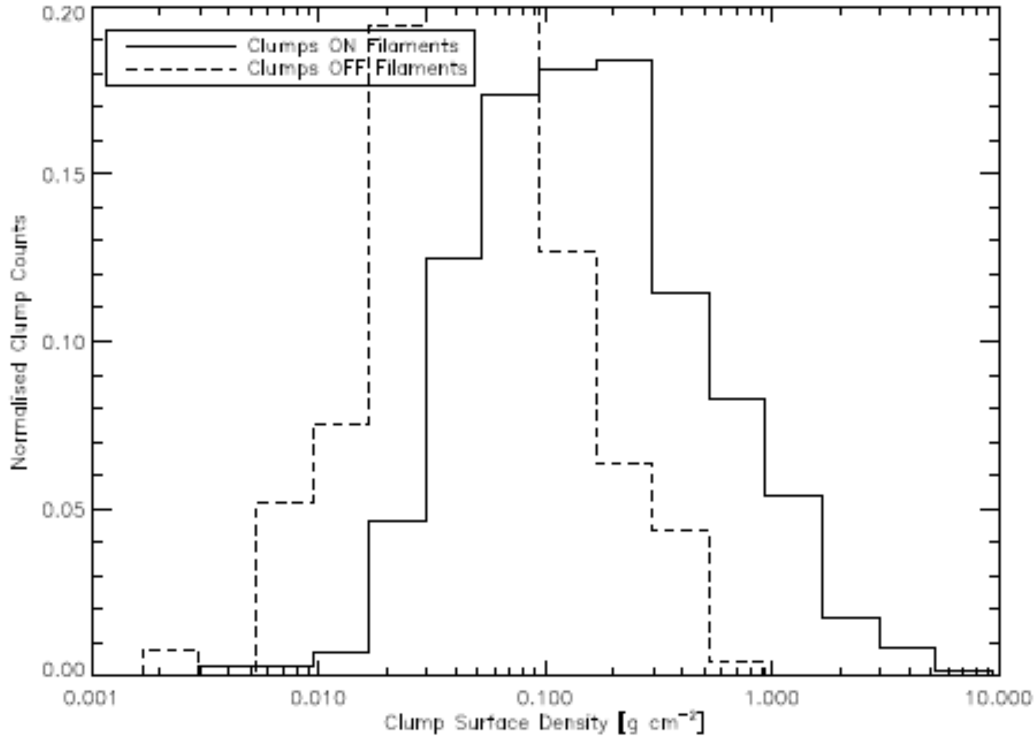
Molinari+ 10




l=224°
Column density map from HI-GAL
l=220°
Automatic Filament Extraction: Schisano et al. (ApJ subm.)

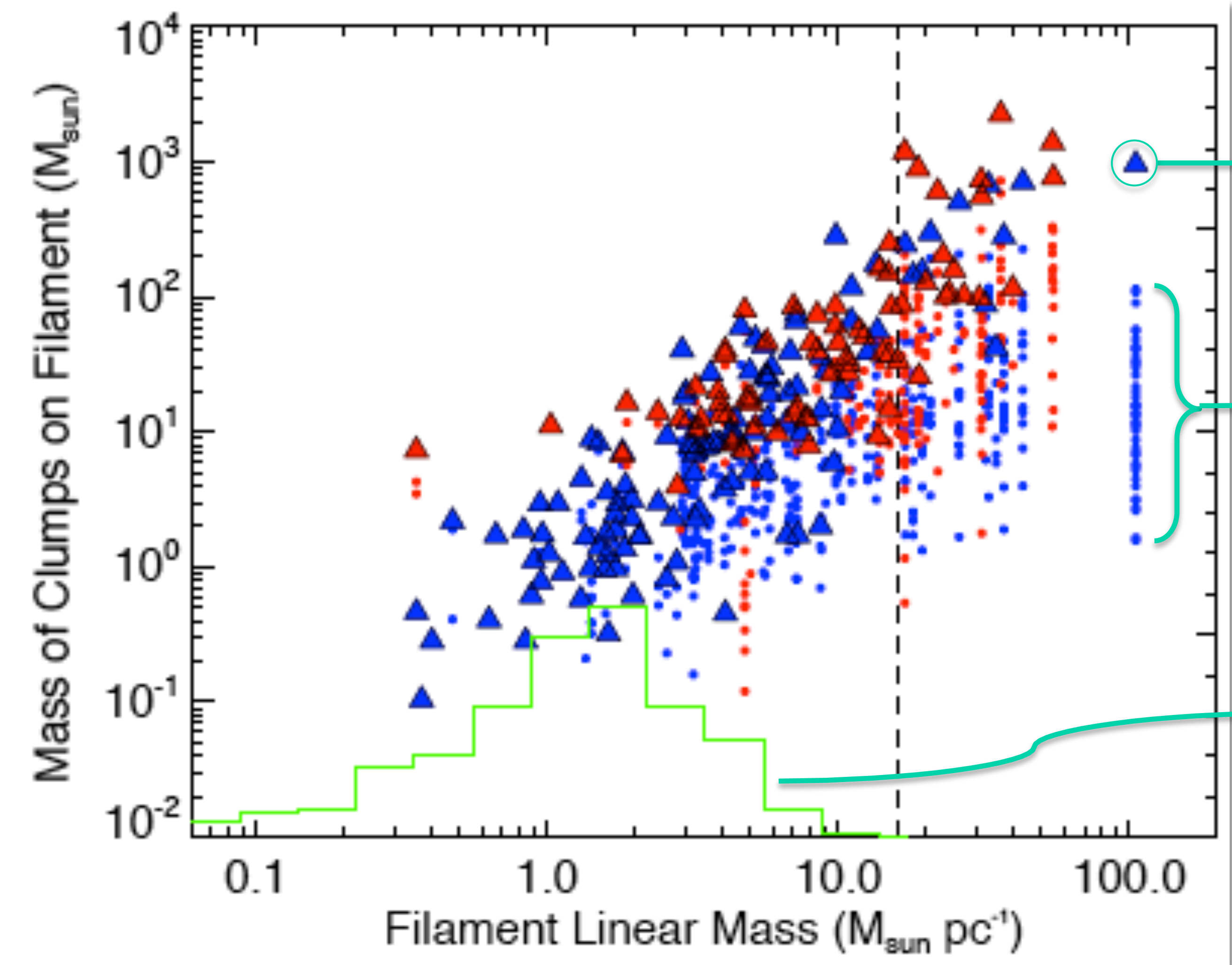


Filaments that host dense clumps are denser



Clumps located on filaments are denser

Schisano et al. 2013, ApJ subm. (B4-P73)



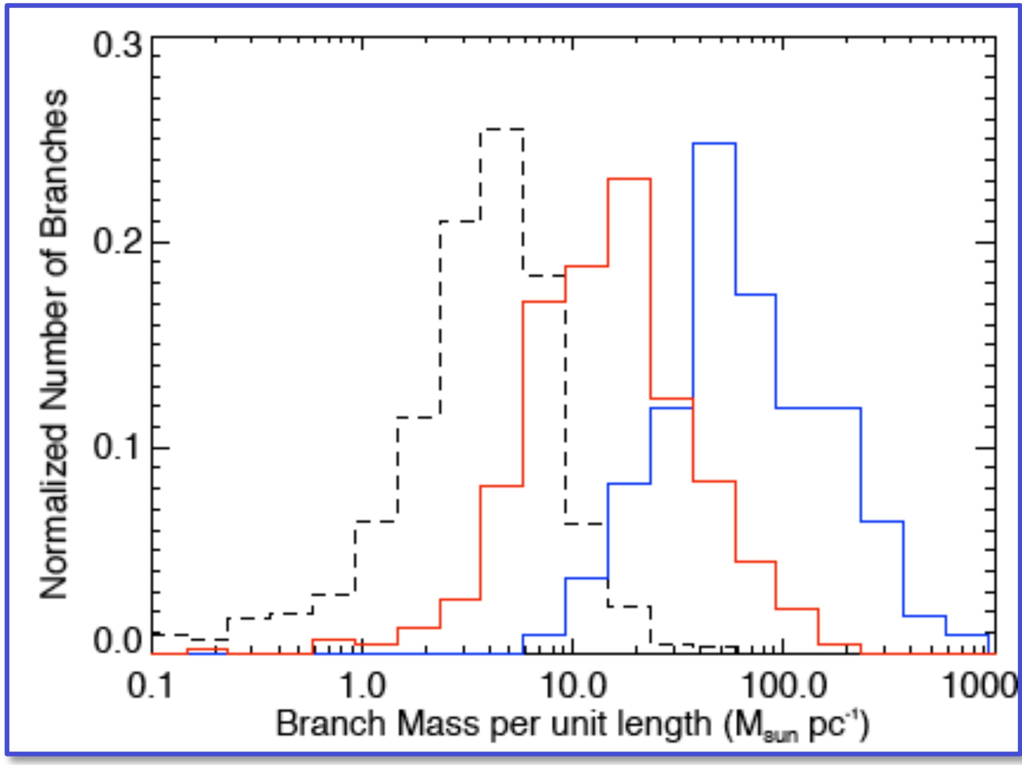
Total mass of clumps on each filament

Mass of individual clumps on filaments

Distribution of linear mass for filaments with NO clumps

Do more massive clumps form on more massive filaments ?
Or do filaments grow mass from the surrounding environments and channel more mass to the clumps ?
No clear evidence for thresholds

Schisano et al. 2014, ApJ subm.



Evolutionary effects are clearly visible as a function of the filaments linear masses

Blue: filament branches with PROTOstellar Clumps, **i.e. with a 70μm counterpart**

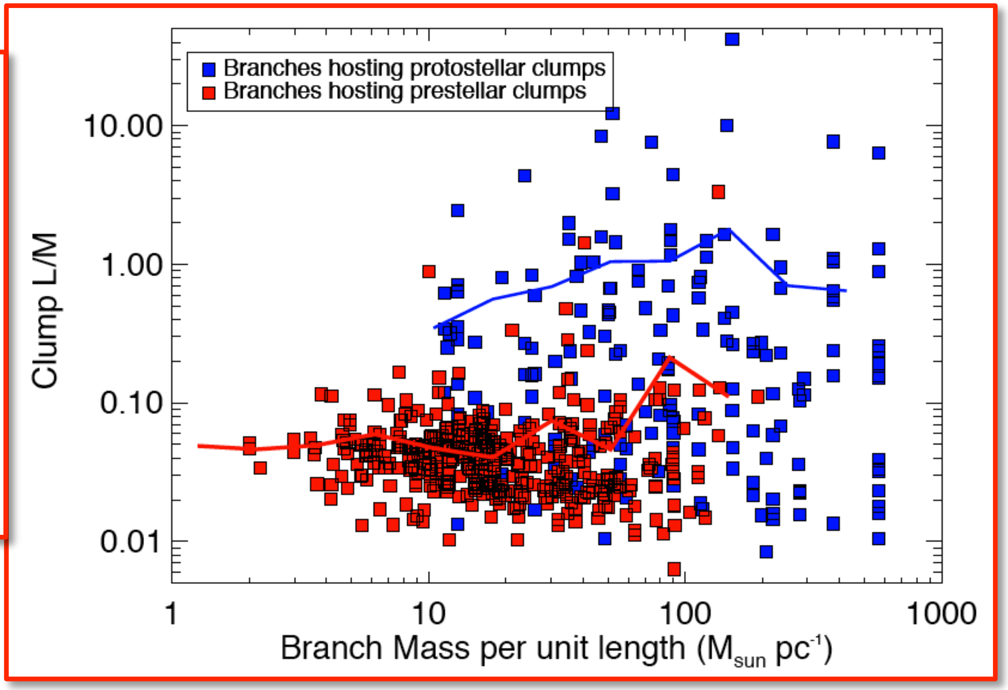
Red: filament branches with PREstellar Clumps

Black: filament branches with NO Clumps

1) Accretion rates ≈ 10^{-2}-10^{-3} $M_\odot$/pc/yr are needed to explain the differences in evolutionary terms (see also Kirk +13, Peretto+ 13)

or…

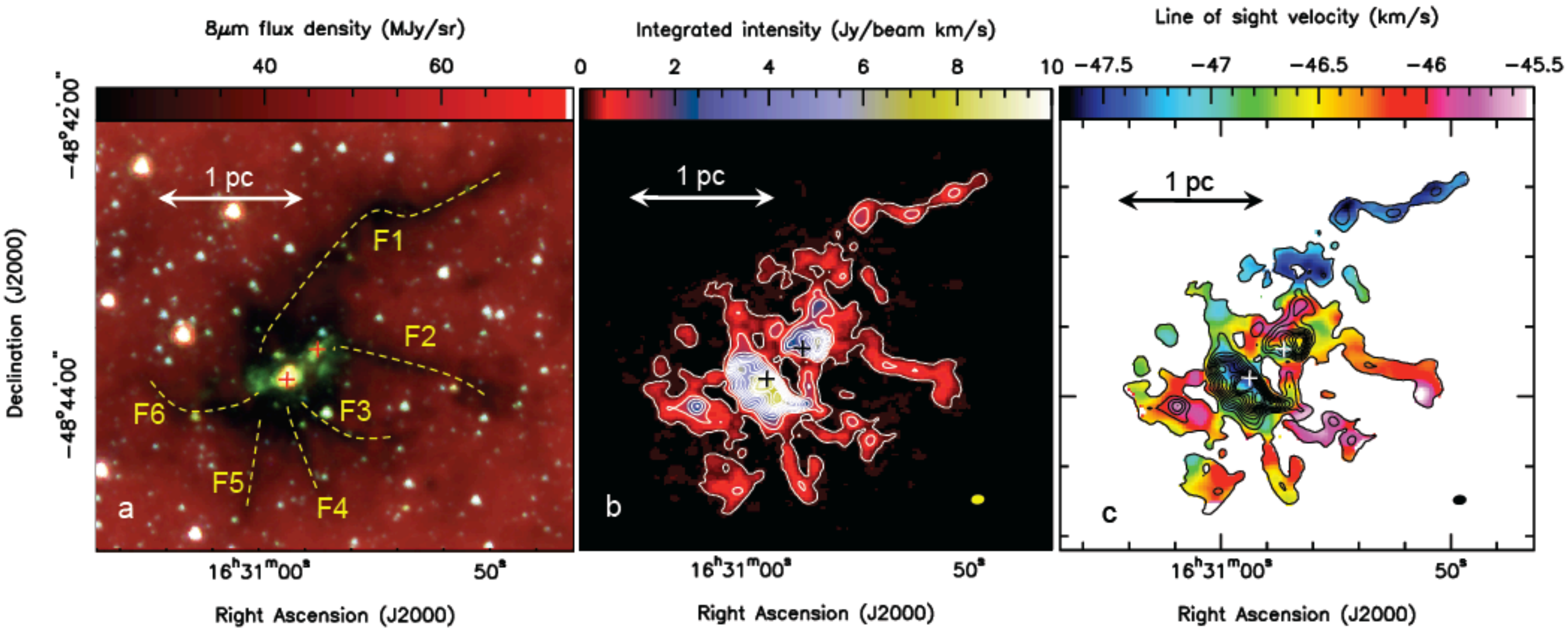
2) Differences in linear masses, clump masses and L/M are imprinted at the time of filament formation.



Schisano et al. 2014, ApJ subm.)

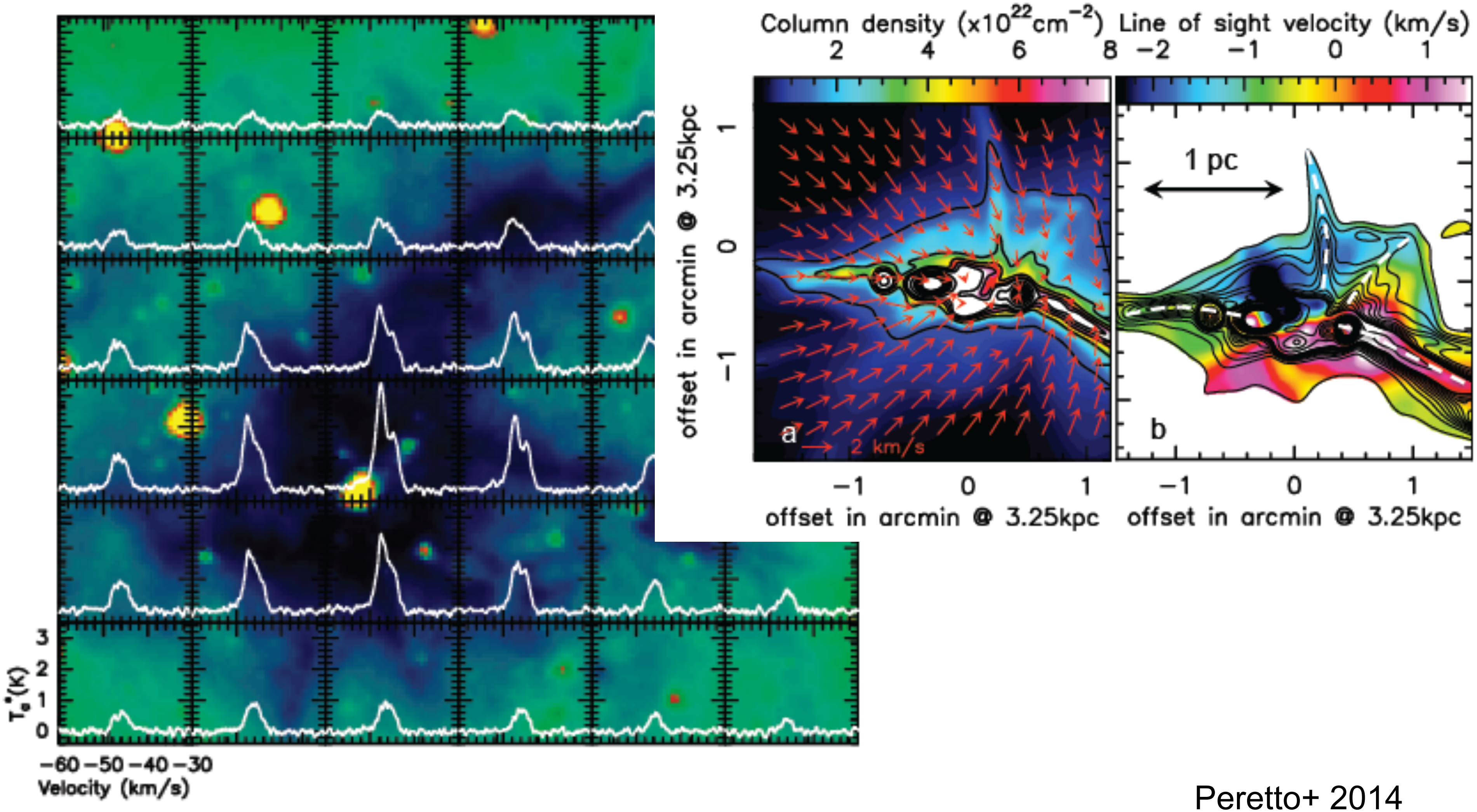
Filamentary IRDC SDC335

Peretto+ 2013



CH_3OH and N_2H^+ with ALMA (3mm band) reveal ordered motions along the filaments: filament accretion onto the central massive cores

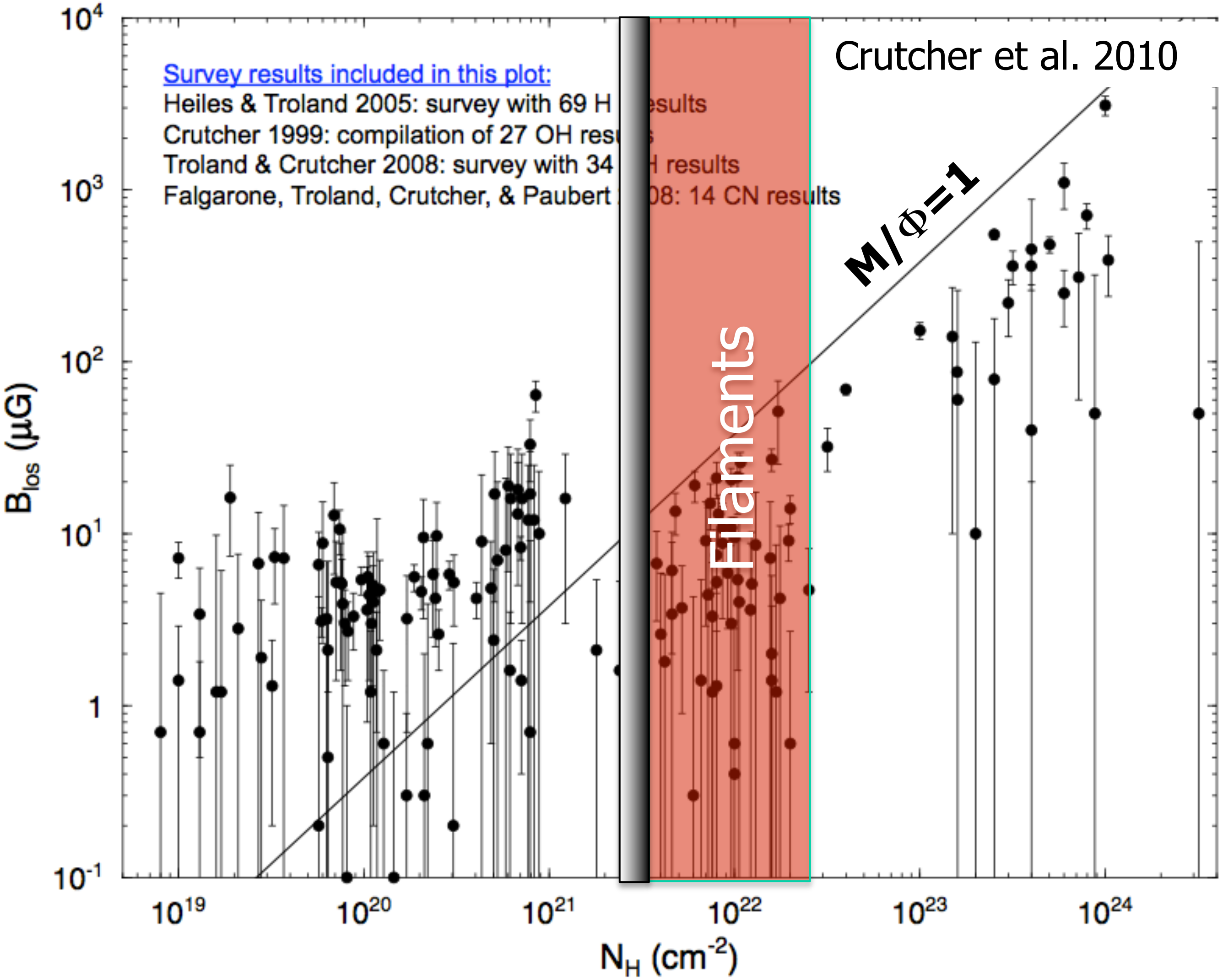
Filamentary IRDC SDC335

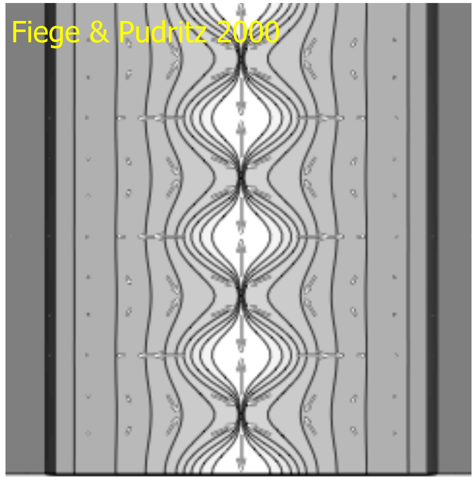


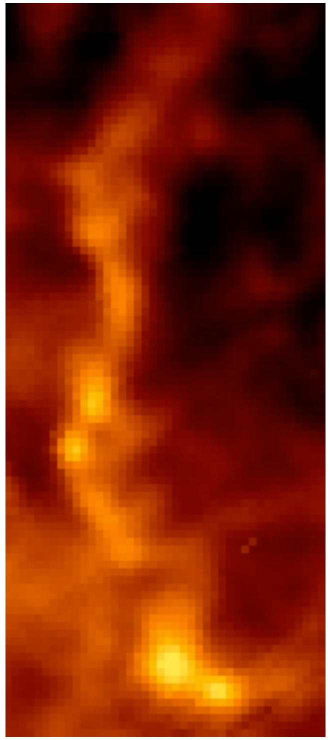
Peretto+ 2014

Single-dish millimeter spectroscopy (HCO+ 1-0) suggests global collapse: clump accretion onto the filaments.

Is B important in filament fragmentation ?







Filaments hosting compact sources span a N(H) range which is compatible with structures losing magnetic support and starting to collapse

Herschel is pushing Galactic Star Formation into the Mega-Cloud era

- How do filamentary molecular clouds form ?
  - Role of turbulence (?)
  - Is WNM pressure confinement important to keep clouds confined till thermal instability, and then gravitational instability, take over ?
  - Do we understand the HI→H_2 transition ? HISA, HINSA, $\tau_{HI \rightarrow H2}$
  - Do converging flows really exist ? are they relevant (i.e. is this the way molecular clouds form fast) ?
  - Role of magnetic field in channeling ISM onto the filaments.

- Sensitive large-scale spectroscopic mapping (around the filaments)
  - low [v_s ,n_0] shock tracers: low-J CO, H_2O, SiO, [SiII], [OI], [CII], [NII]…, to see if converging flows shocks really exist (e.g. Jimenez-Serra+ 2010 on G35.39, Schneider+ 10 on DR21): would be good for SPICA/SAFARI if we had the spectral resolution…
  - velocity-resolved atomic and HI→H_2 transitions tracers to evaluate the role of turbulence and WNM pressure confinement: [CI], low-J CO, [NII], …
- Sensitive large-scale continuum polarimetry mapping

Herschel is pushing Galactic Star Formation into the Mega-Cloud era

- How do filament fragmentation proceeds ?
  - Do clumps on filaments continue to accrete from the filament material ?
  - Do clumps on filaments move and merge (Inutsuka & Miyama 1997) ? many of the clumps on filaments show 24μm counterpart so it's unlikely that things go too fast ?
  - Role of magnetic field. Helicoidal B: do such things exist ?

- Detailed filament-scale spectroscopic mapping
  - detailed kinematic mapping on a wide range of aspect-ratio filaments to reveal infall profiles along the filament.
  - dynamics of clumps along the filaments
- Sensitive filament-scale continuum polarimetry mapping

Conclusions

Spatial resolution at 1” and below, both in continuum and spectroscopy in the FIR-submm is a must to achieve the next quantum leap in Galactic Star Formation

- ALMA is a tremendous competitor, and it will be there for quite some time
  - ALMA’s spectroscopic capabilities are ideally set to study the chemistry and dynamics of the innermost dense regions in massive star formation, avoiding optical depth problems.
  - It can resolve effectively the high-mass end of mass functions in massive clumps.
- However….
  - There is the need to observe thousands (several) of compact sources and filamentary structures: a fast high-resolution mapper is needed.
  - ALMA will not be able to constrain the dust temperature: a continuum facility below 250μm is needed.
  - FIR lines are main coolants contrary to submm lines: good to trace ISM shocks; important for outflows/jets ? For disks around massive stars a lot is being done with submm interferometry