Hi-GAL

The Milky Way as a Star Formation Engine

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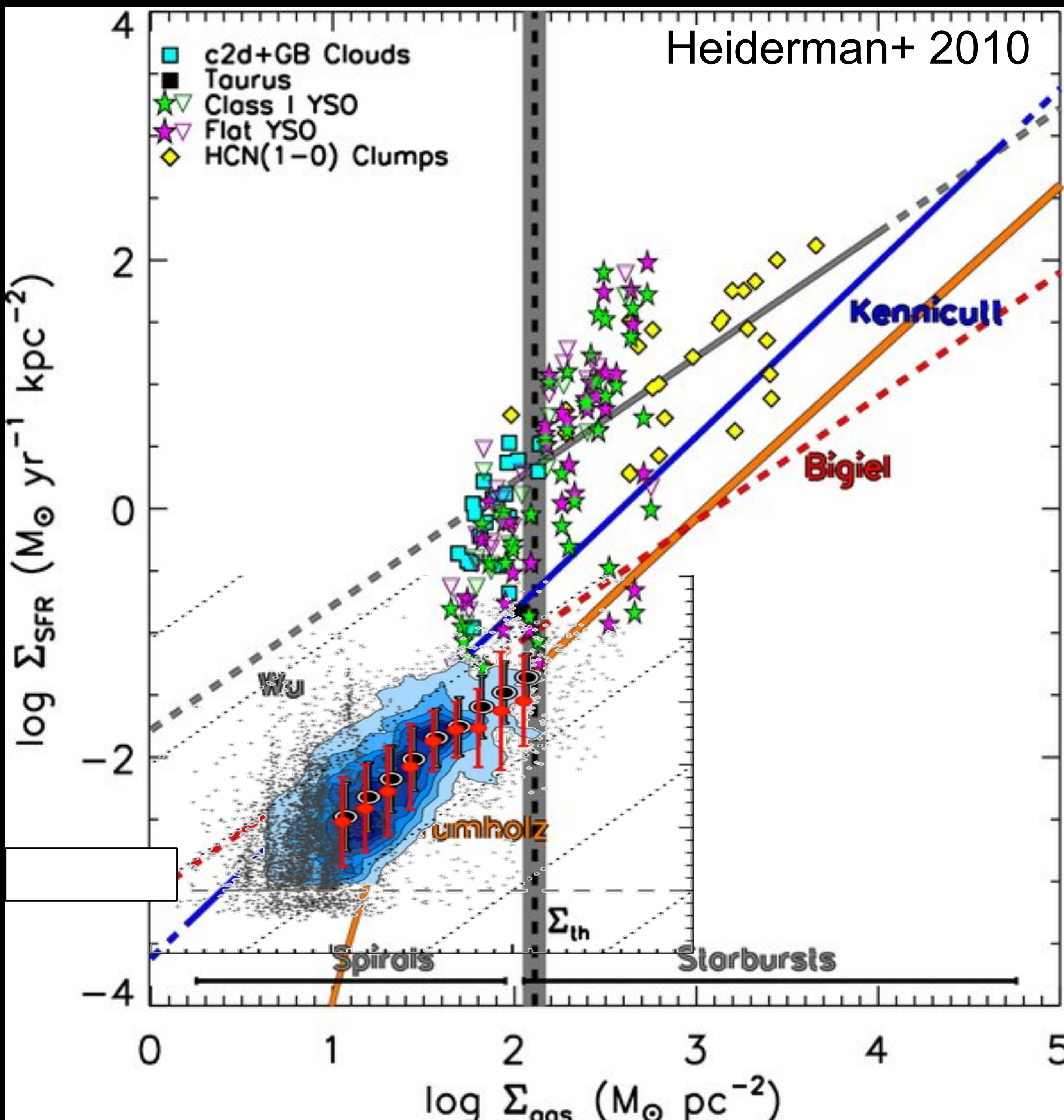
on behalf of the Hi-GAL & VIALACTEA Teams

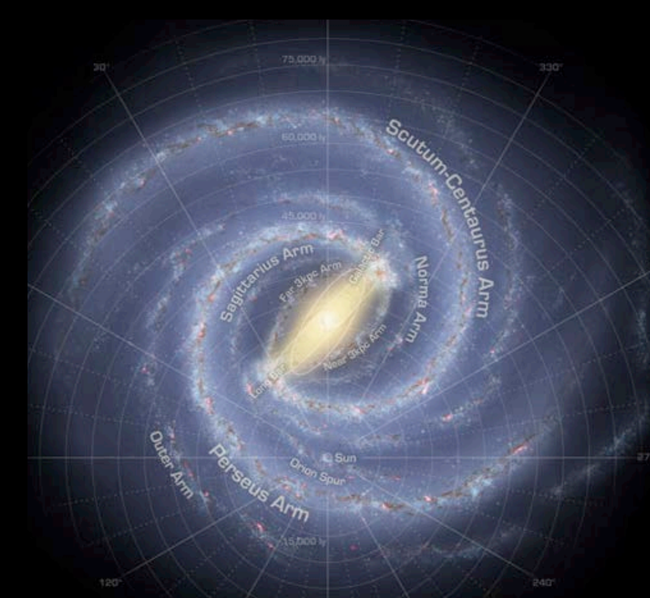
Herschel 10 Years: Science & Celebration, May 13-14 2019

Basic Rationale for star-formation-driven large Galactic Surveys



Aim: Identify the critical parameters that govern the formation and evolution of dense cluster-forming clumps within the diversity of environmental conditions:

- Spontaneous/triggered SF ?
- 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

SurveysSurveysSurveysSurveysSurveysSurveys...

Table 1: List of most representative surveys covering the Galactic Plane

Surveys facilities	λ or lines	Surveys notes
		Ground-based
Columbia/CfA	CO, ^{13}CO	9 - 25′ resolution (*Dame et al.*, 2001)
DRAO/ATCA/VLA	HI-21 cm OH/Hα-RRL/1-2GHz cont. 5GHz cont.	IGPS: unbiased HI-21cm $255° \leq l \leq 357°$ and $18° \leq l \leq 147°$ (*McClure-Griffiths et al.*, 2001; *Gibson et al.*, 2000; *Stil et al.*, 2006) + THOR: unbiased HI-21cm/OH/Hα-RRLs/1-2GHz cont. $15° \leq l \leq 67°$ (Beuther et al. in prep.)+ CORNISH: 5GHz continuum $10° \leq l \leq 65°$ (*Hoare et al.*, 2012)
FCRAO 14 m	CO, ^{13}CO	55″ resolution. Galactic Ring Survey (*Jackson et al.*, 2006) + Outer Galaxy Survey (*Heyer et al.*, 1998)
Mopra 22 m	CO, ^{13}CO, N_2H^+, (NH_3 + H_2O) maser, HCO^+/$H^{13}CO^+$ + others	HOPS: (*Walsh et al.*, 2011; *Purcell et al.*, 2012), MALT90: ~ 2000 clumps $20° \geq l \geq -60°$ (*Foster et al.*, 2013), Southern GPS CO: unbiased $305° \leq l \leq 345°$ (*Burton et al.*, 2013), ThrUMMS: unbiased $300° \leq l \leq 358°$ (*Barnes et al.*, 2013), CMZ: (*Jones et al.*, 2012, 2013)
Parkes	CH_3OH maser	Methanol MultiBeam Survey (*Green et al.*, 2009)
NANTEN/ NANTEN2	CO, ^{13}CO, $C^{18}O$	NGPS: unbiased, $200° \leq l \leq 60°$ (*Mizuno and Fukui*, 2004) + NASCO: unbiased in progress, $160° \leq l \leq 80°$
CSO 10 m	1.3 mm continuum	Bolocam Galactic Plane Survey (BGPS), 33″ (*Aguirre et al.*, 2011)
APEX 12 m	870 μm continuum	ATLASGAL, $60° \geq l \geq -80°$ (*Schuller et al.*, 2009)
		Space-borne
IRAS	12, 25, 60 and 100 μm cont.	3-5′, 96% of the sky
MSX	8.3, 12.1, 14.7, 21.3 μm cont.	Full Galactic Plane (*Price et al.*, 2001)
WISE	3.4, 4.6, 11, 22 μm continuum	All-sky (*Wright et al.*, 2010)
Akari	65, 90, 140, 160 μm continuum	All-sky (*Ishihara et al.*, 2010)
Spitzer	3.6, 4.5, 6, 8, 24 μm continuum	GLIMPSE+GLIMPSE360: Full Galactic Plane (*Benjamin et al.*, 2003), (*Benjamin and GLIMPSE360 Team*, 2013) + MIPSGAL, $63° \geq l \geq -62°$ (*Carey et al.*, 2009)
Planck	350, 550, 850, 1382, 2098, 3000, 4285, 6820, 10^4 μm cont.	All-sky, resolution $\geq 5'$ (*Planck Collaboration et al.*, 2013a)
Herschel	70, 160, 250, 350, 500 μm cont.	Hi-GAL: Full Galactic Plane (*Molinari et al.*, 2010a)

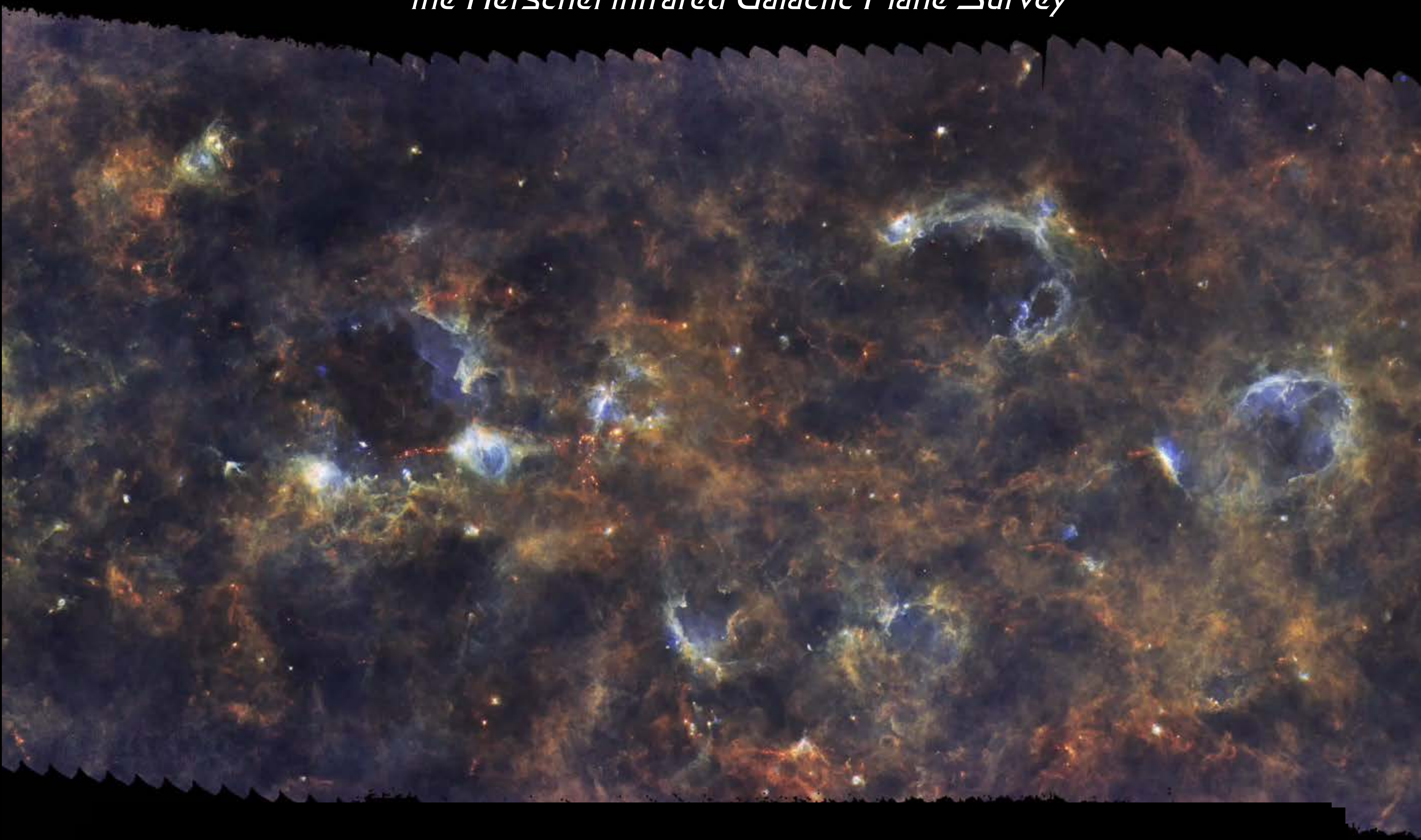
Molinari+ 2014, PP VI

Molinari et al. 2016

Hi-GAL

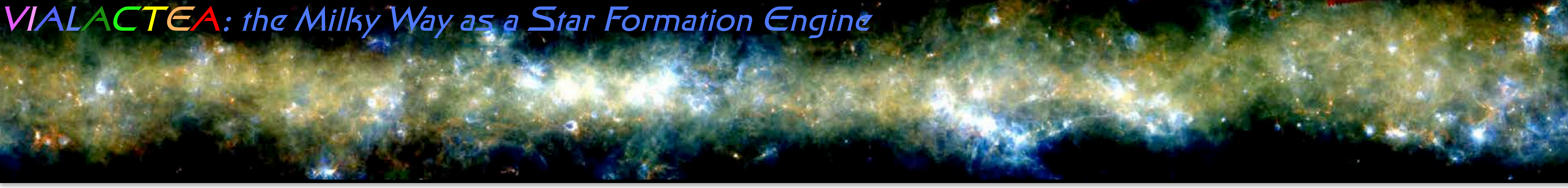
the Herschel infrared Galactic Plane Survey

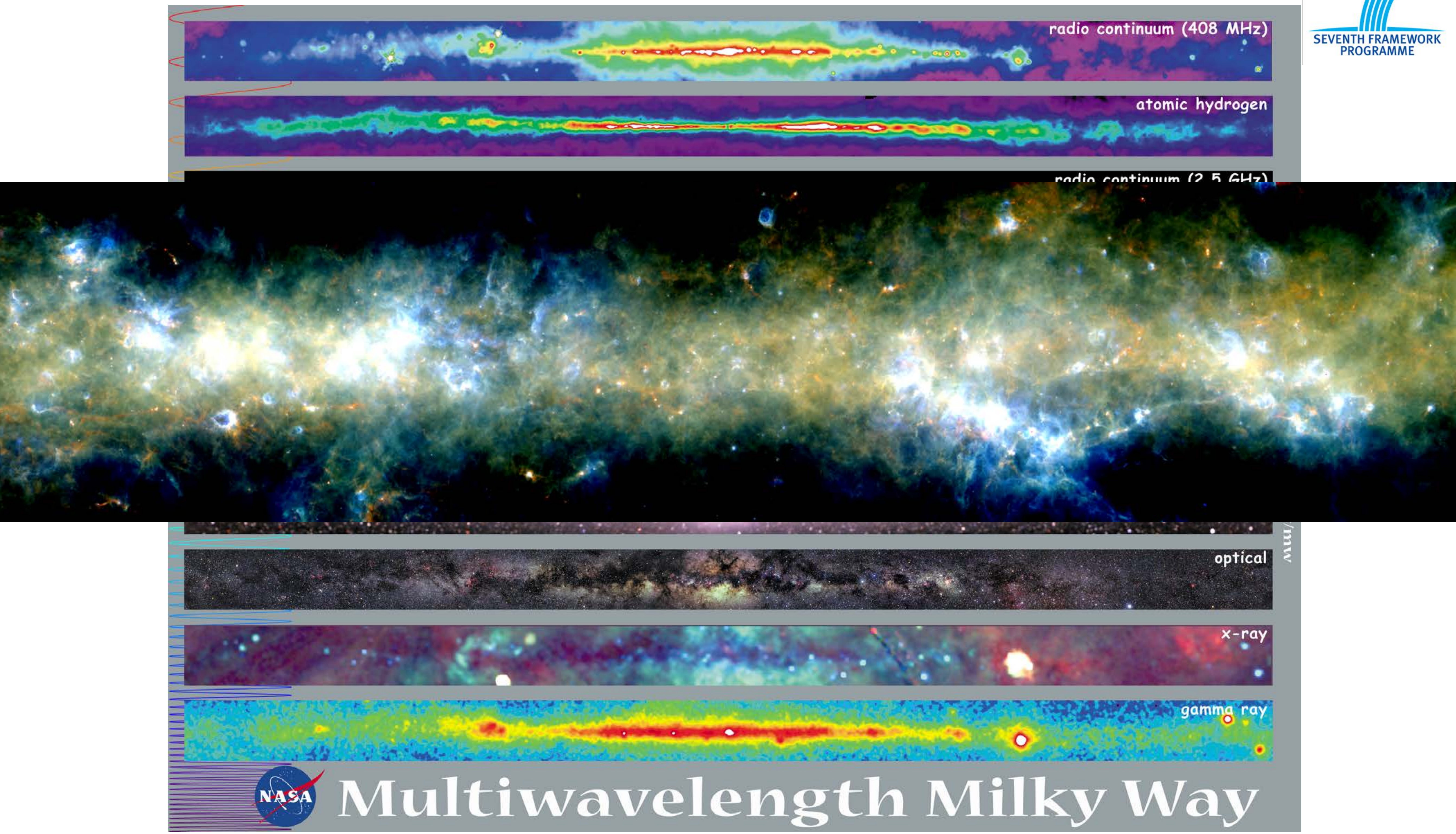
70-160-250μm composite



from cold starless clumps to hot HII Regions

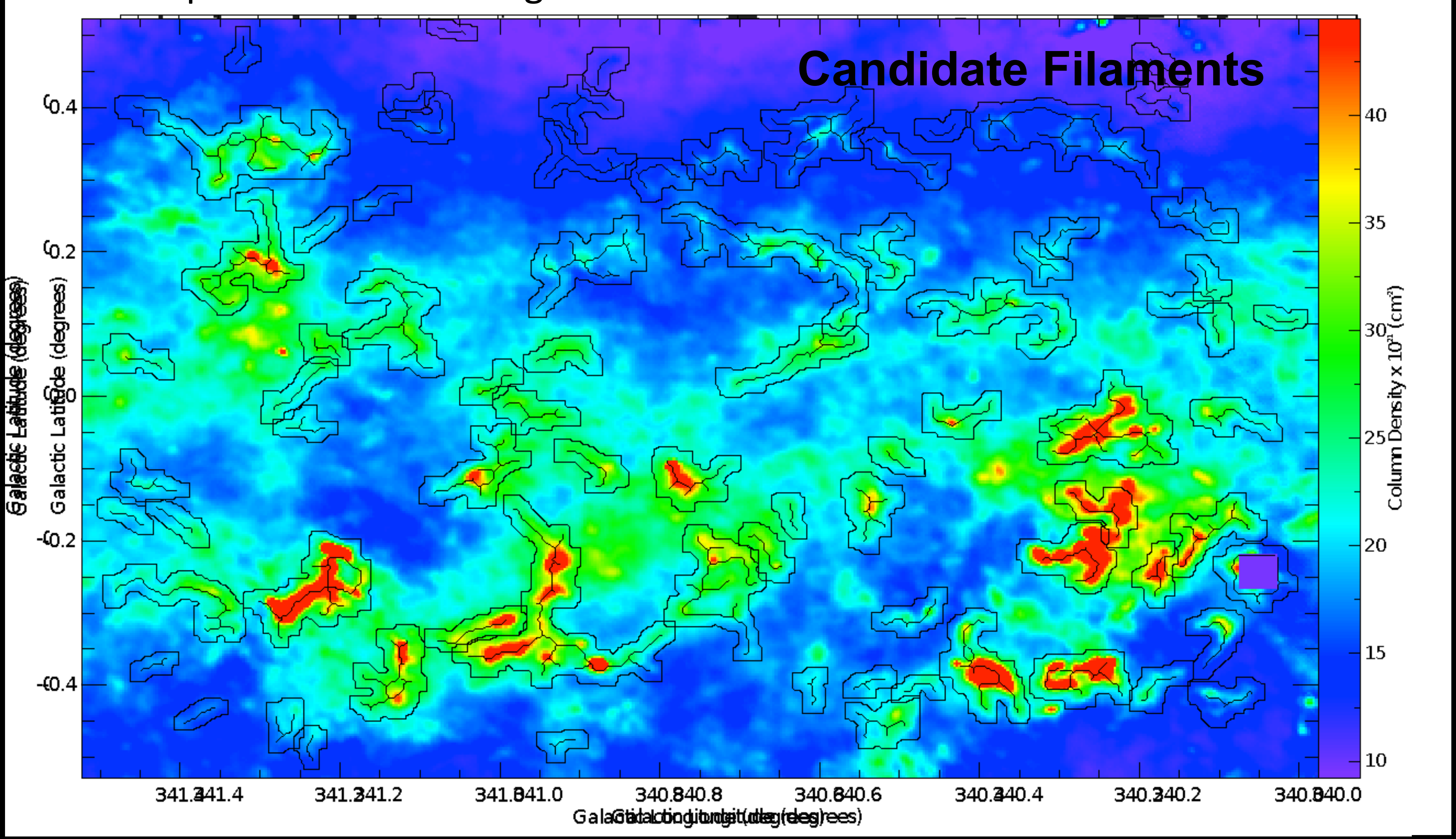
VIALACTEA: the Milky Way as a Star Formation Engine





The filamentary Milky Way

Example for a 1.5° x 1° region



Schisano et al. 2014

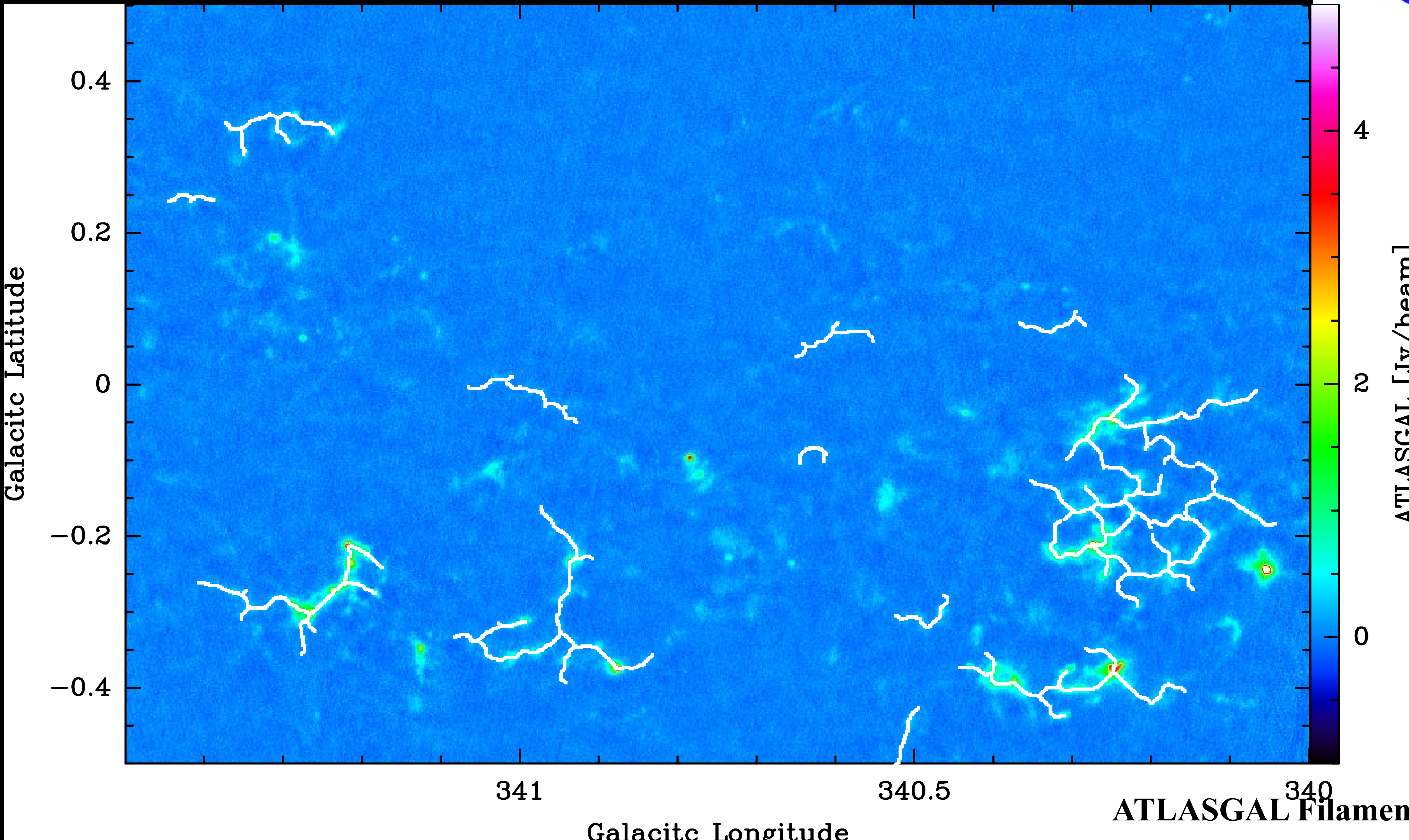
KEY SHAPE PARAMETERS:

-) elongated
-) extended
-) contrasted

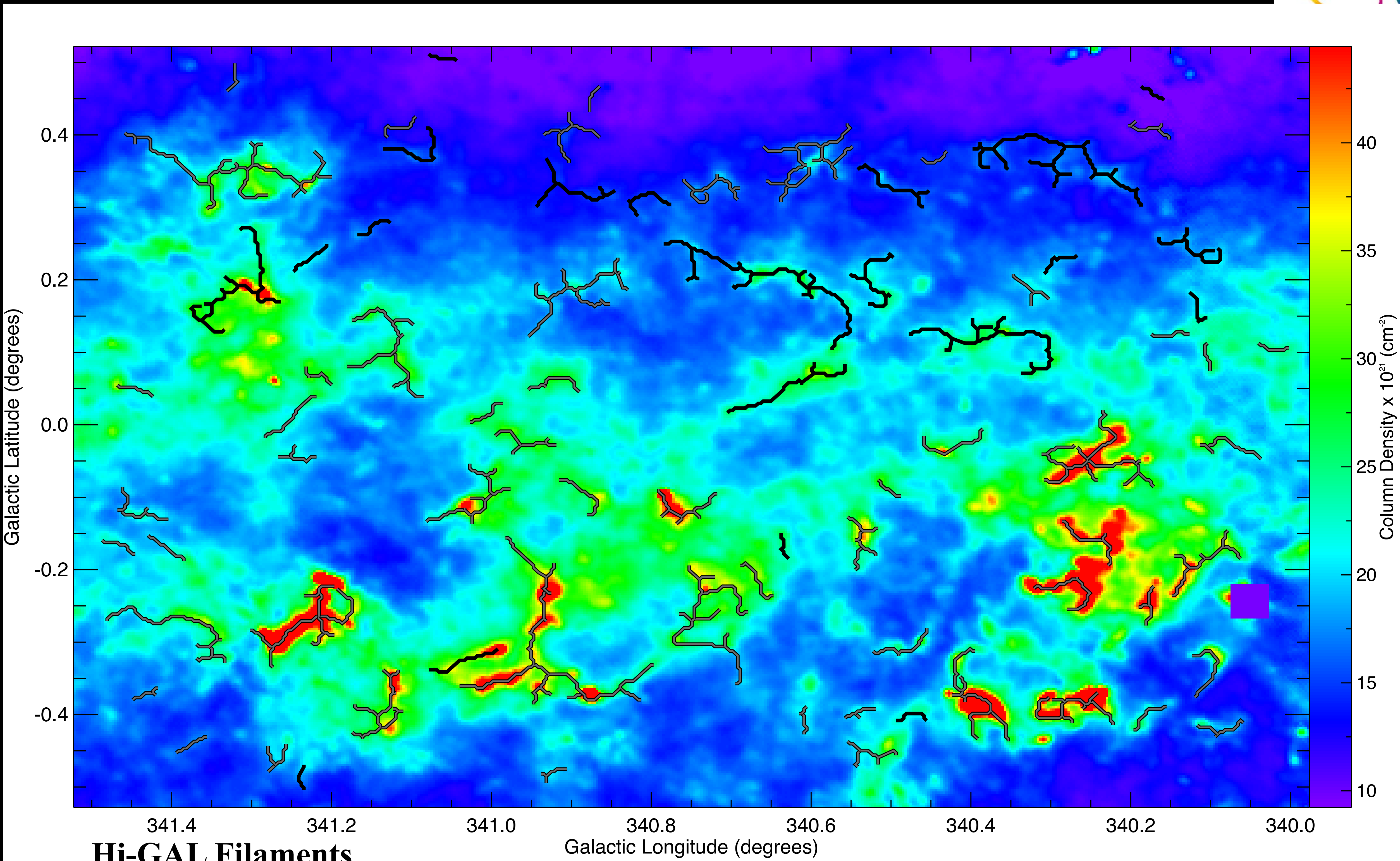
Tool applied to the entire dataset of Hi-GAL data building up an extensive catalogue of candidate filaments

The catalogue contains both **single isolated linear filaments** and large complex networks: a total of **32245** **candidates** in the Galactic Plane (Schisano+, subm.)

Comparison Hi-GAL/ATLASGAL filaments



Comparison Hi-GAL/ATLASGAL filaments



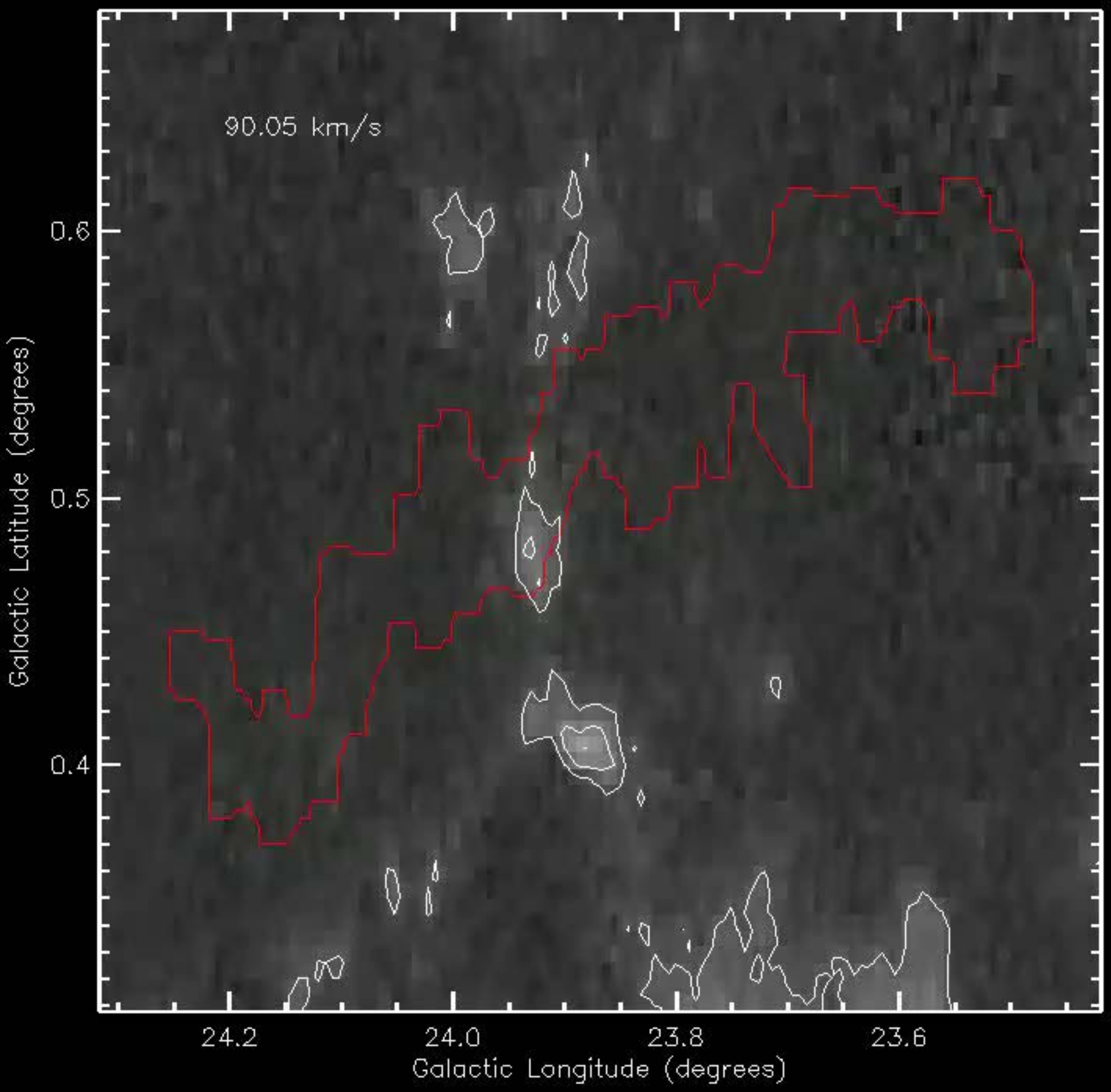
Velocity Coherence of 2D filaments

Exploring molecular line data looking for coherence in velocity space.

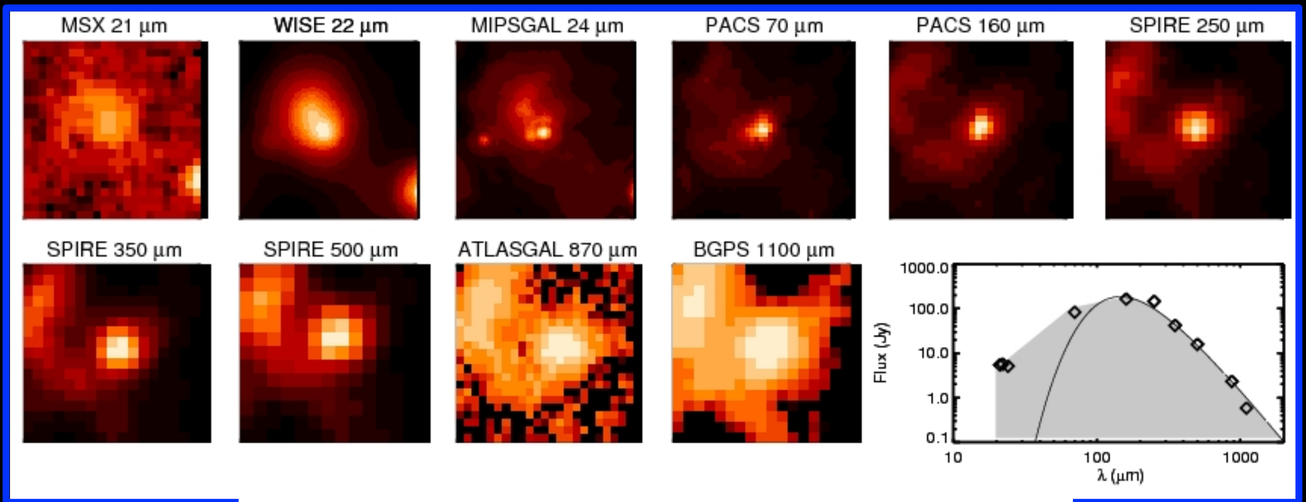
Looking for overlap between filament mask and contours of molecular line emission.

- On GRS data ~2300 features with ^{13}CO emission and velocity coherence $\Delta v < 4$ km/s
- Expanding by two orders of magnitude the sample already identified visually (few~10) (Ragan et al 2014, Wang et al 2015, Zucker et al. 2015).
- Analysis extended to other surveys: SEDIGISM, MOPRA, EXFC, OGS, FQS.

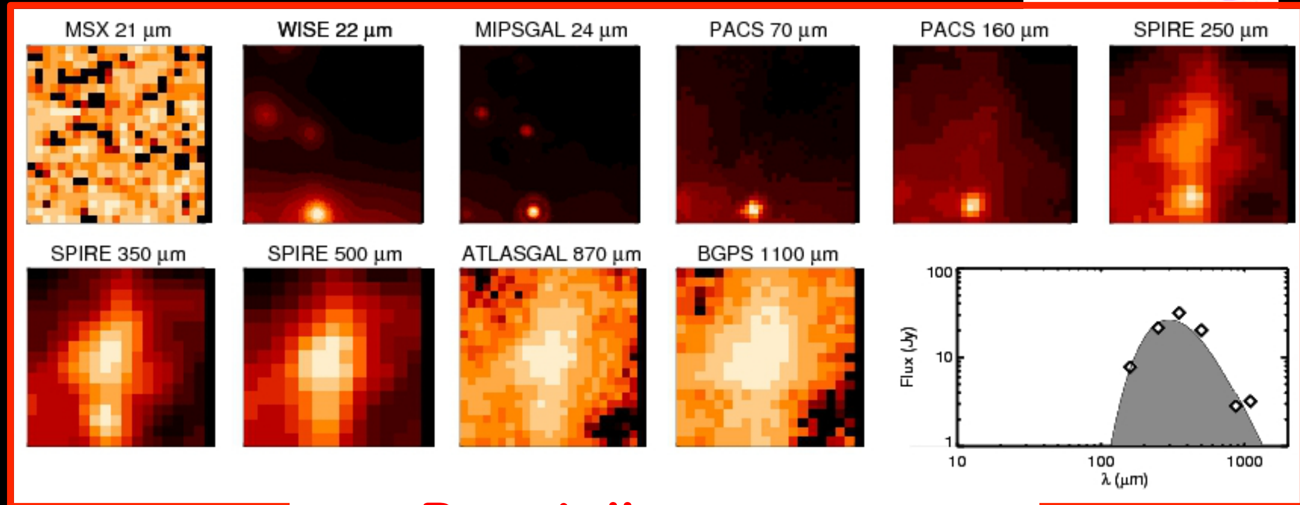
Schisano et al. 2019, in prep.



Compact sources on the Galactic Plane

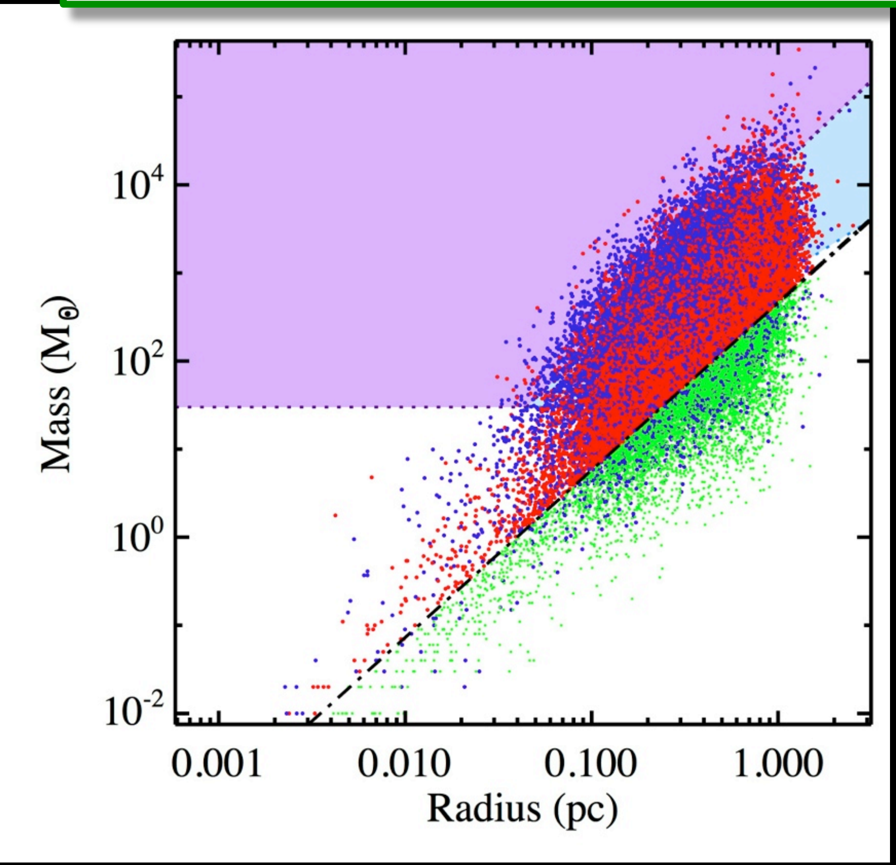


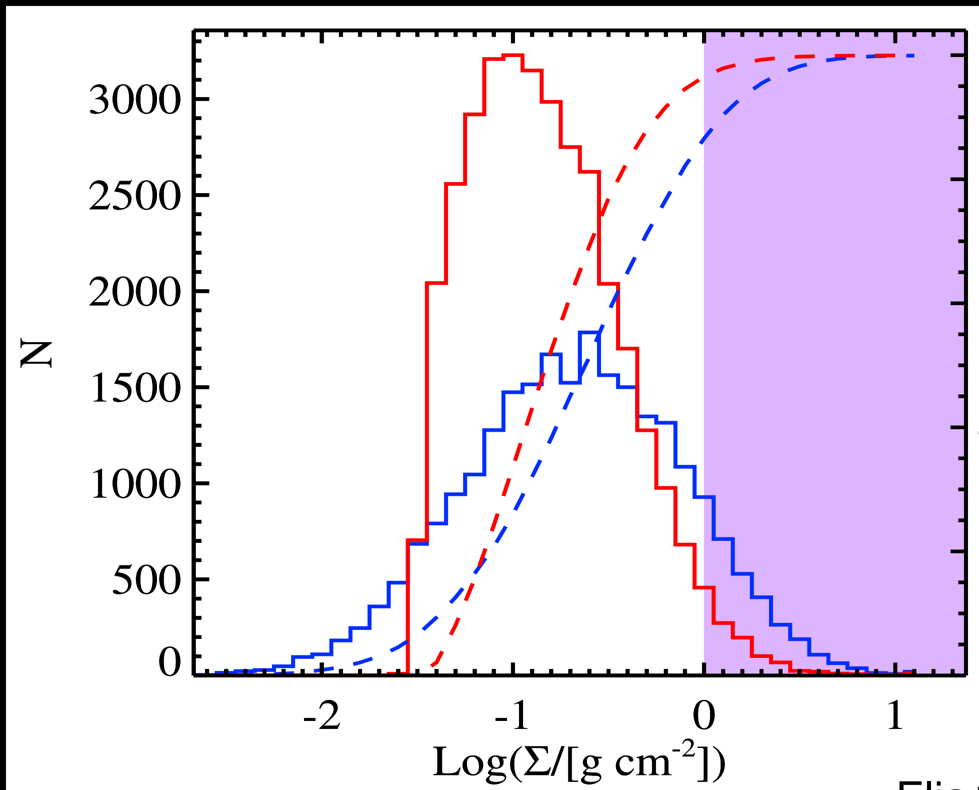
Proto-stellar sources



Pre-stellar sources

Nearly 150,000 compact clumps revealed (Elia+ 2017, 2019 in prep.)
Each source in Far-IR/submm single-dish surveys is a dense clump potentially hosting a protocluster in the making





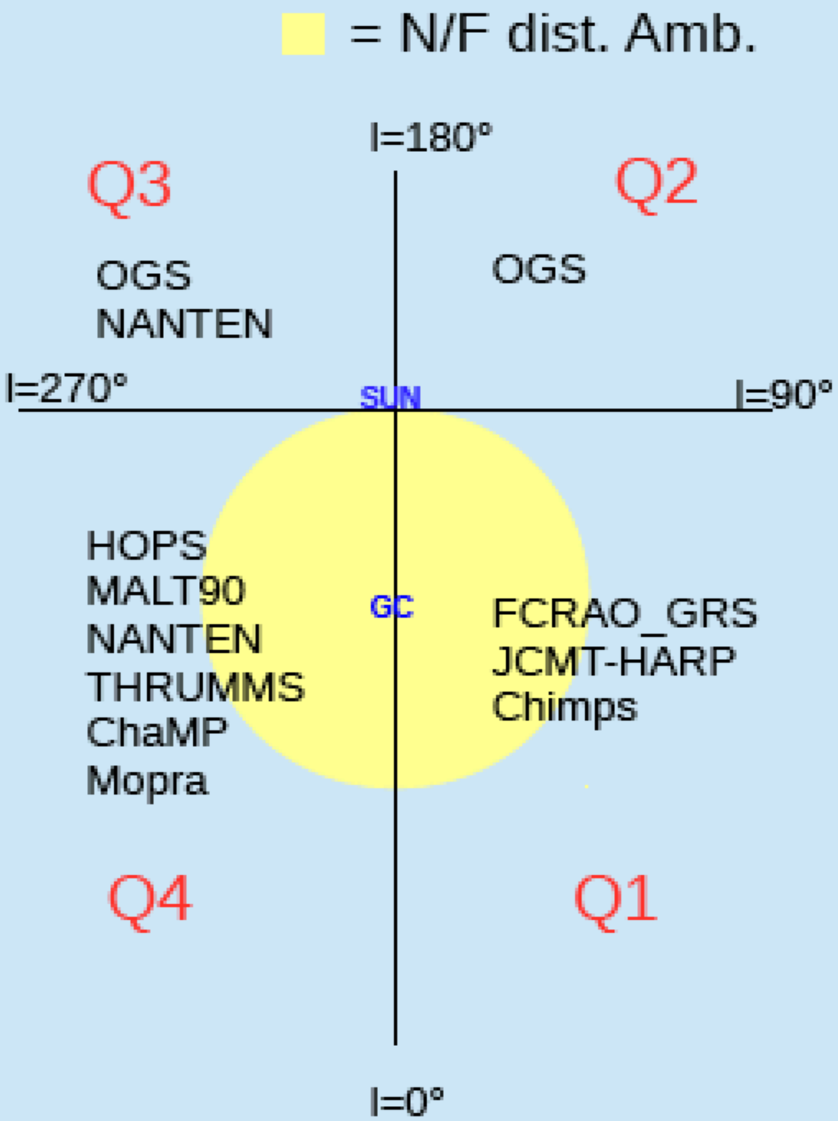
Elia+ 2017

Distance determination to Hi-GAL sources

Kinematical analysis of radio spectroscopic surveys

The VIALACTEA knowlegde database :

- CHaMP (HCO+ 1-0)
- HOPS (H2O 6-1-6_5-2-3 , NH3 1-1_1-1, NH3 2-2_2-2)
- FCRAO_GRS (13CO 1-0)
- MALT90 (HCO+ 1-0, HCN 1-0, N2H+ 1-0, HNC 1-0)
- THRUMMS (12CO 1-0, 13CO 1-0, C18O 1-0)
- NANTEN (12CO 1-0)
- OGS (12CO 1-0, 13CO 1-0)
- JCMT-HARP (12CO 3-2)
- Mopra CO survey (12CO 1-0, 13CO 1-0)
- CHIMPS (13CO 3-2, C18O 3-2)
- VGPS (HI 21cm)
- CGPS (HI 21cm)



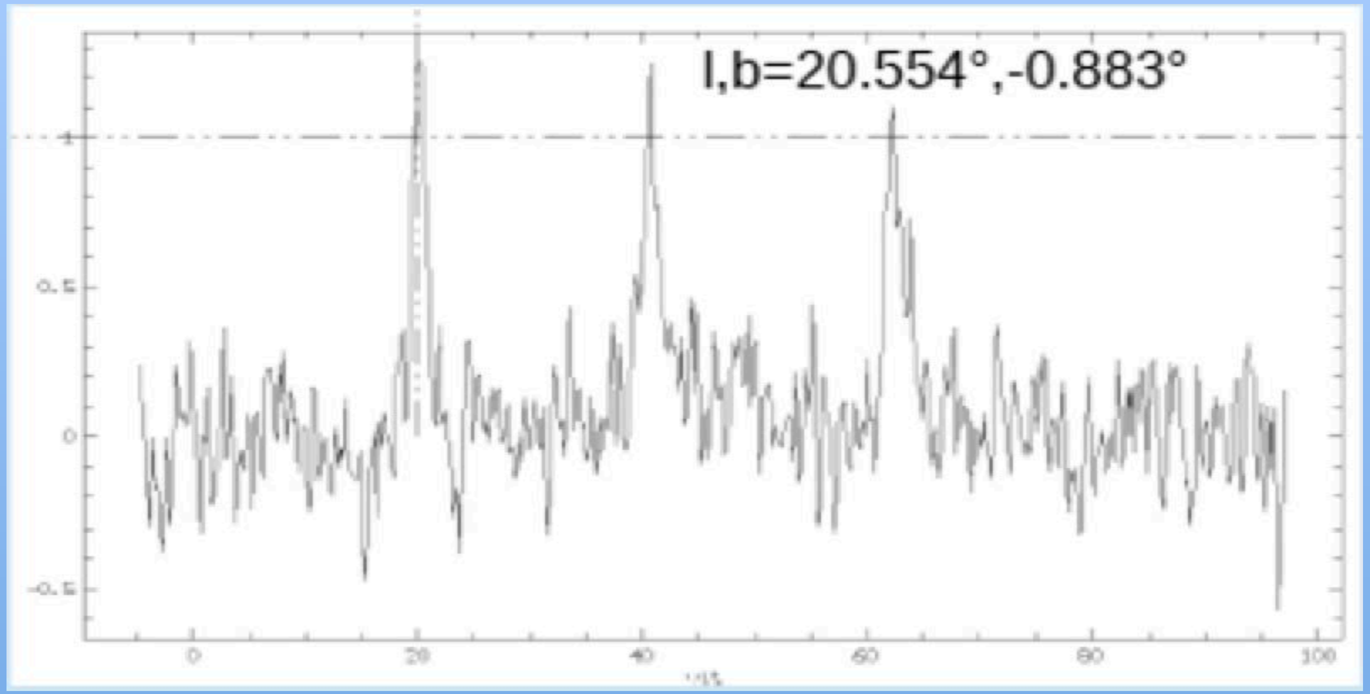
The general automatic process :

- Sub-cube extraction => around a source
- Profile fitting => velocities
- Morphological analysis => adopted velocity
- Distance hierarchical analysis

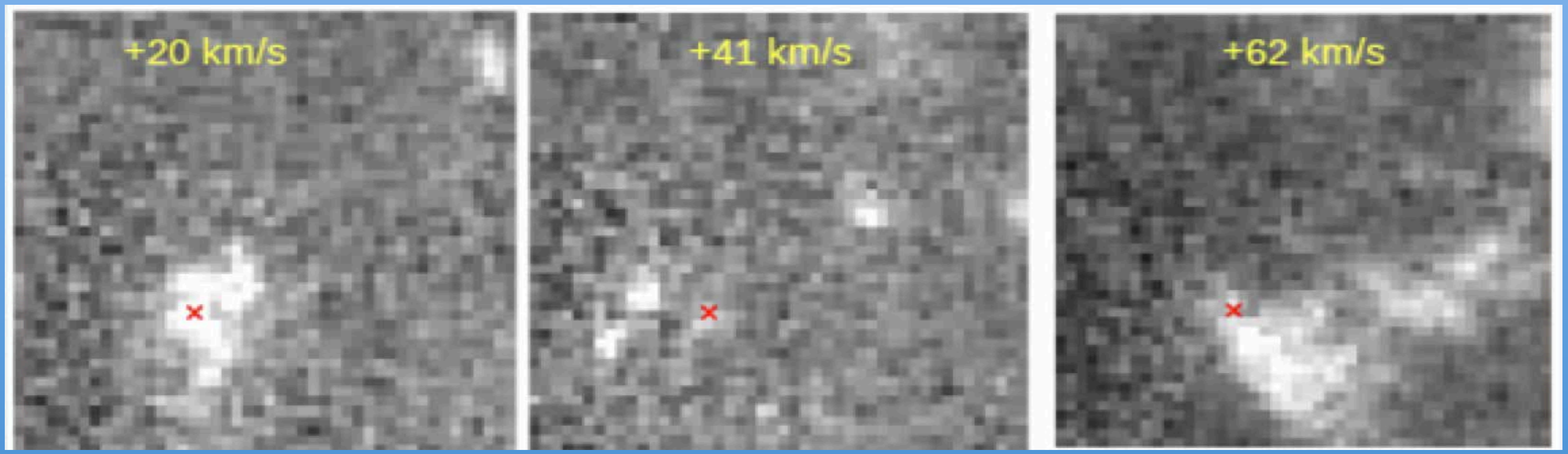
Russeil+ 2010, Zavagno+, in prep.

Distance determination to Hi-GAL sources

Automated morphological analysis of line-of-sight components



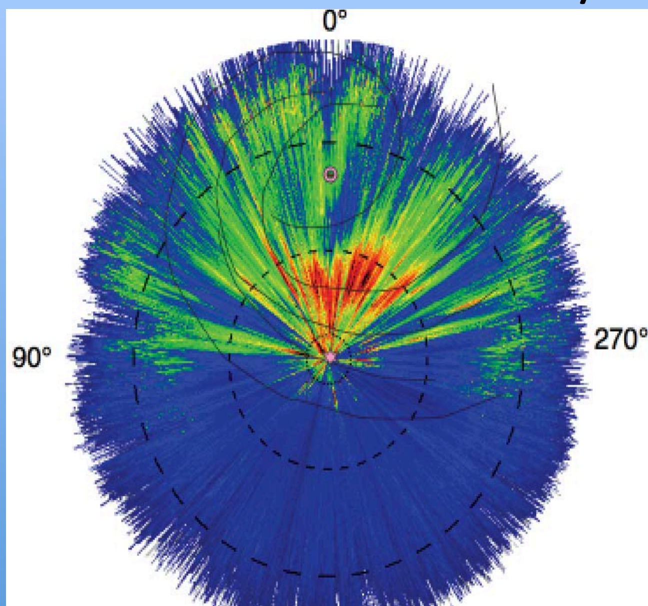
Assign scores based on morphology matching to Hi-GAL clumps



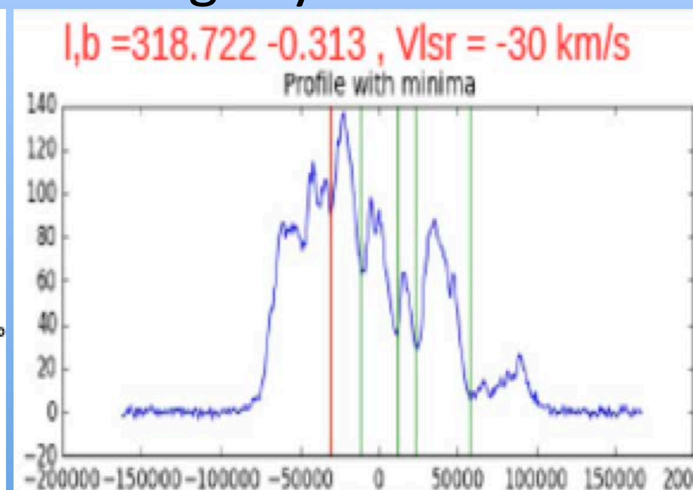
Russeil+ 2010, Zavagno+, in prep.

Distance determination to Hi-GAL sources

Near/Far ambiguity solution



Study of 3D dust extinction
(Marshall+ in prep.)



HISA method: matching HI-21cm profile dips with VLSR of CO emission associated to Hi-GAL clumps

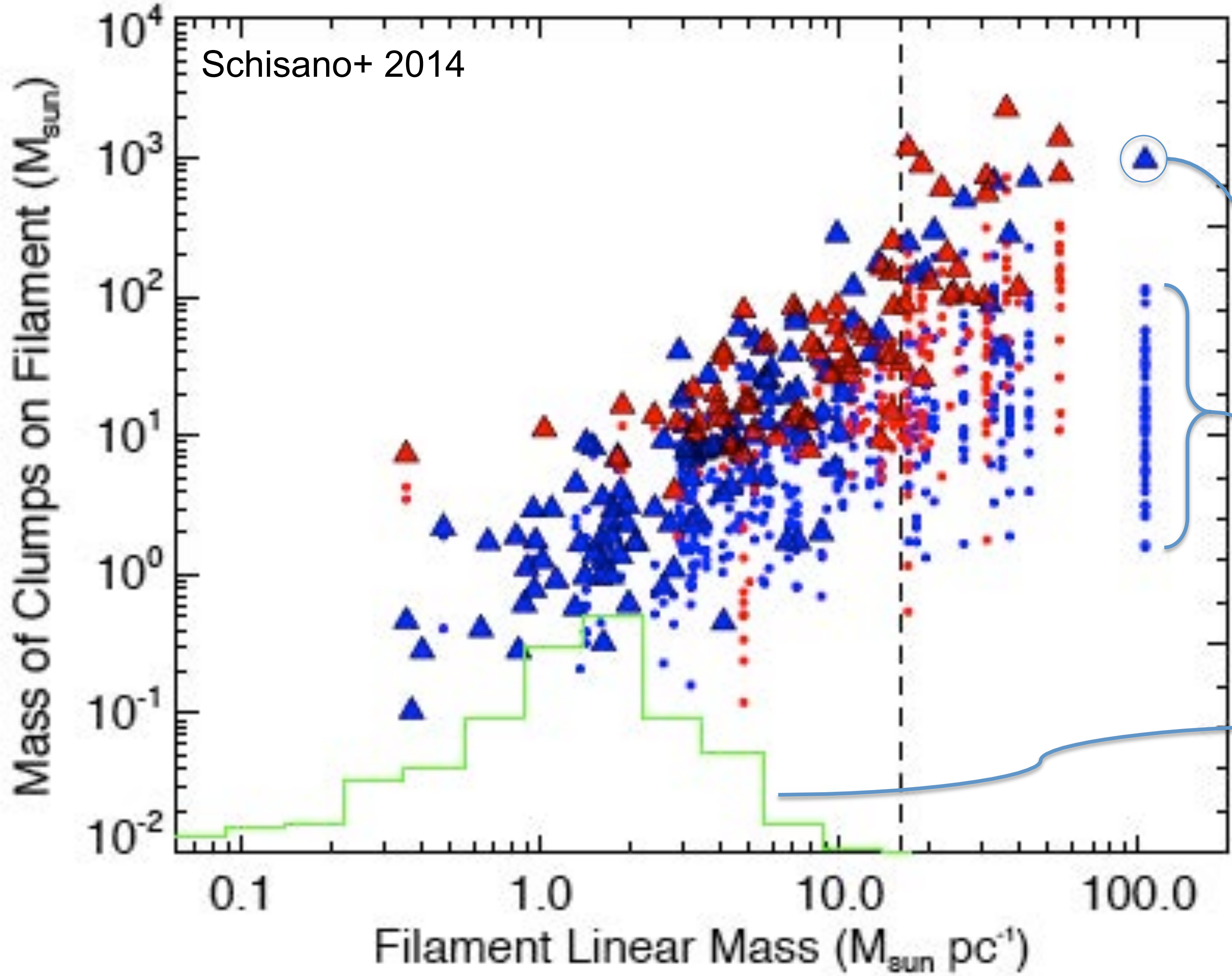
Hierarchical Decision tree

Method	Description
22	Tangent dist.
20	No dist. ambiguity
0	Maser parallaxe distance (Dist. err adopted 10 %)
1	d* grouping (Dist. err adopted 20 %)
2	dkin from extinction (d_ext err. adopted 30 %)
3	dkin from KDA sol. litterature
4	dkin grouping
5	dkin from KDA sol. IRDC/DC
6	« Daugther cloud » dist/KDA sol. assignment Q4 only
7	KDA sol. from HI profile
8	dkin - Solomon method (dist. to the plane)

Flow of decision

	Nb sources	Sources with Vel. (dist.)	0	1	2	3	4	5	6	7	8	No Amb	Tang	No sol.
Q1	57990	68 %	<0.5%	<2%	44%	<1%	<1%	<1%	--	--	<1%	15 %	2%	5%
Q2	15380	71 %	<0.1%	10%	--	--	--	--	--	--	--	« 60 % »	--	--
Q3	12409	69 %	<0.1%	11 %	--	--	--	--	--	--	--	« 57 % »	--	--
Q4	64438	88 %	<0.1%	2%	44%	<1%	<1%	3%	7%	--	5%	12%	8%	7%

Zavagno+, in prep.

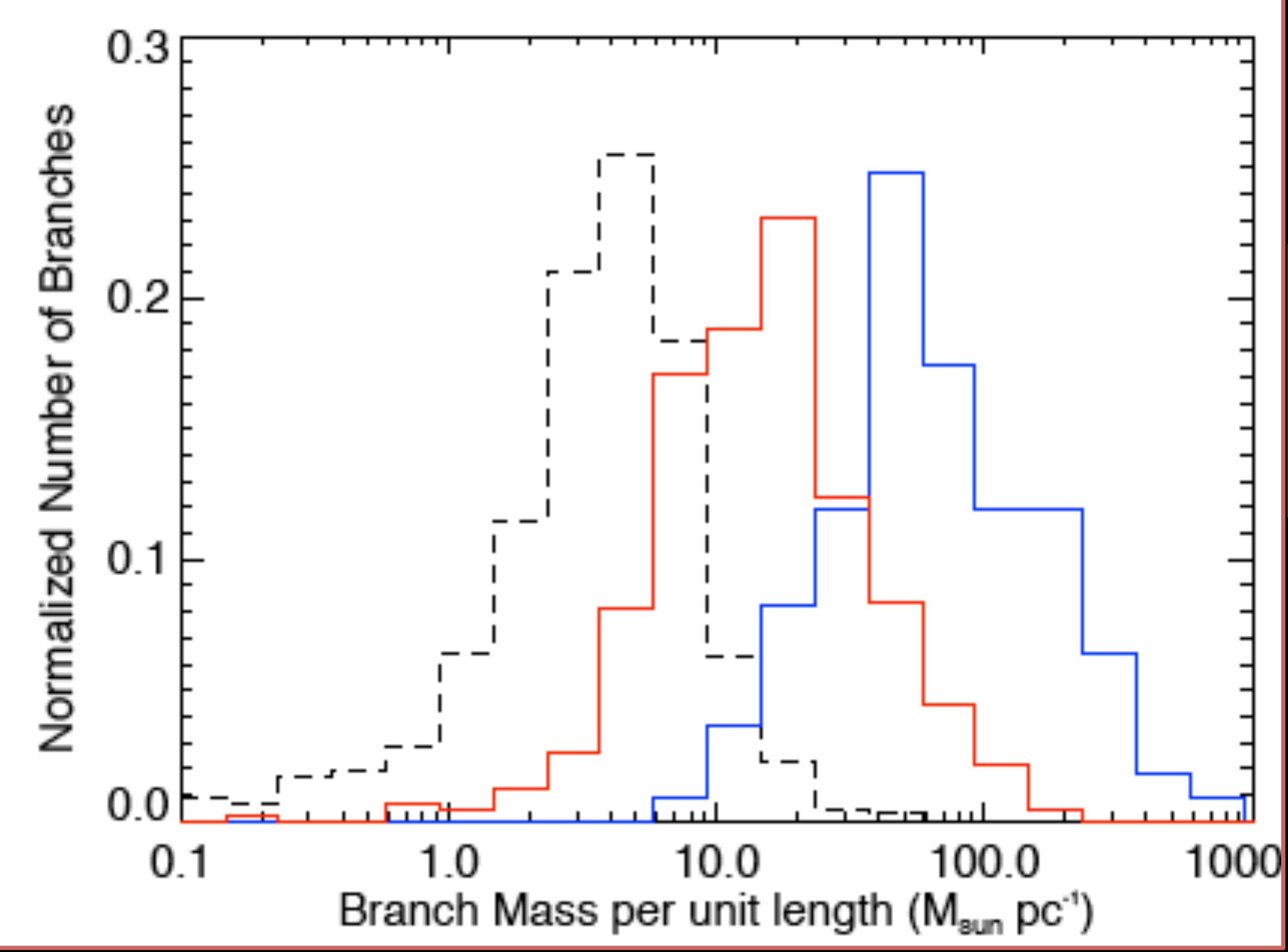


Total mass of clumps on each filament

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 ?



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**

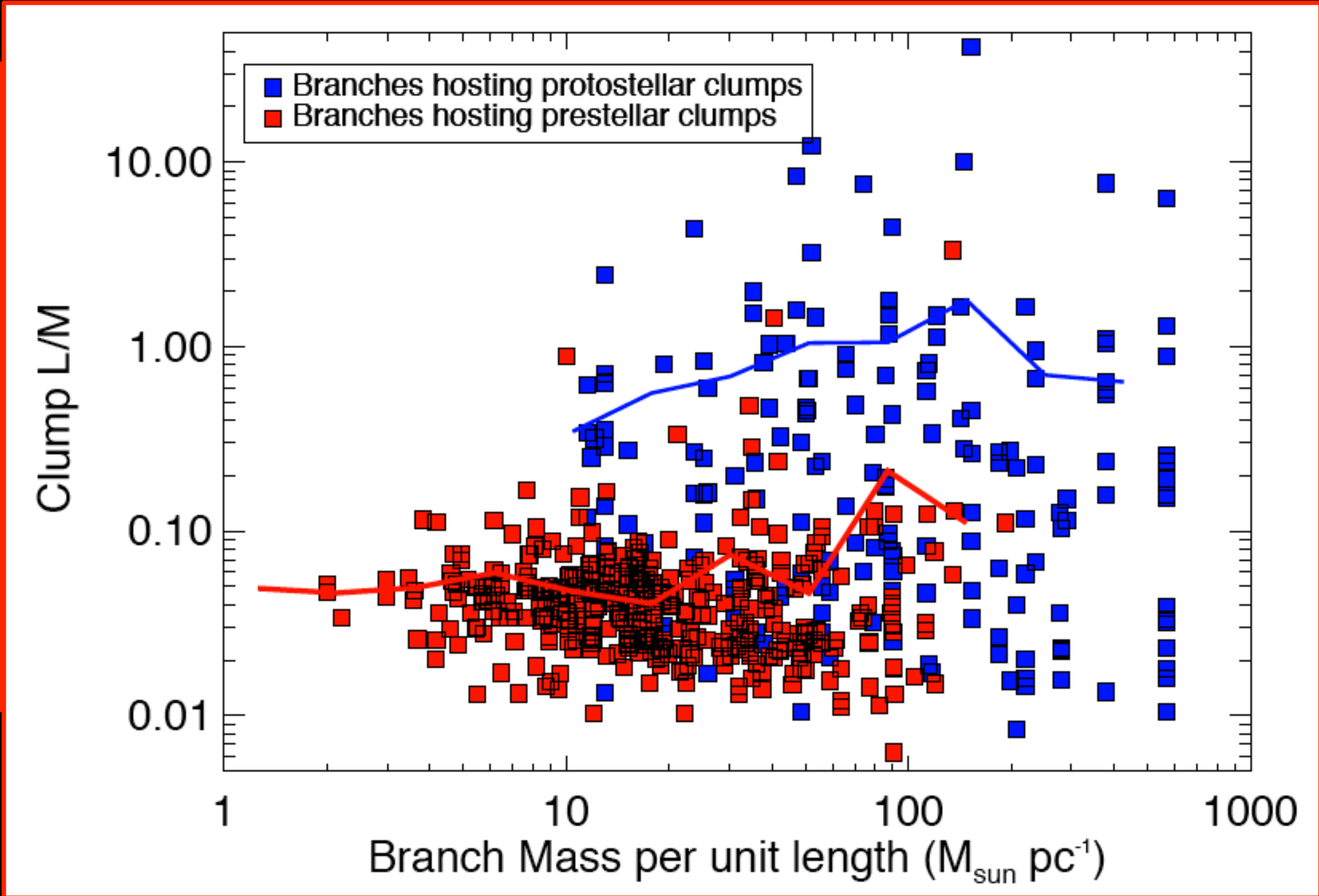
Red: filament branches with PREstellar Clumps

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+ 2014

Star Formation Rates from Protostellar Clumps counts

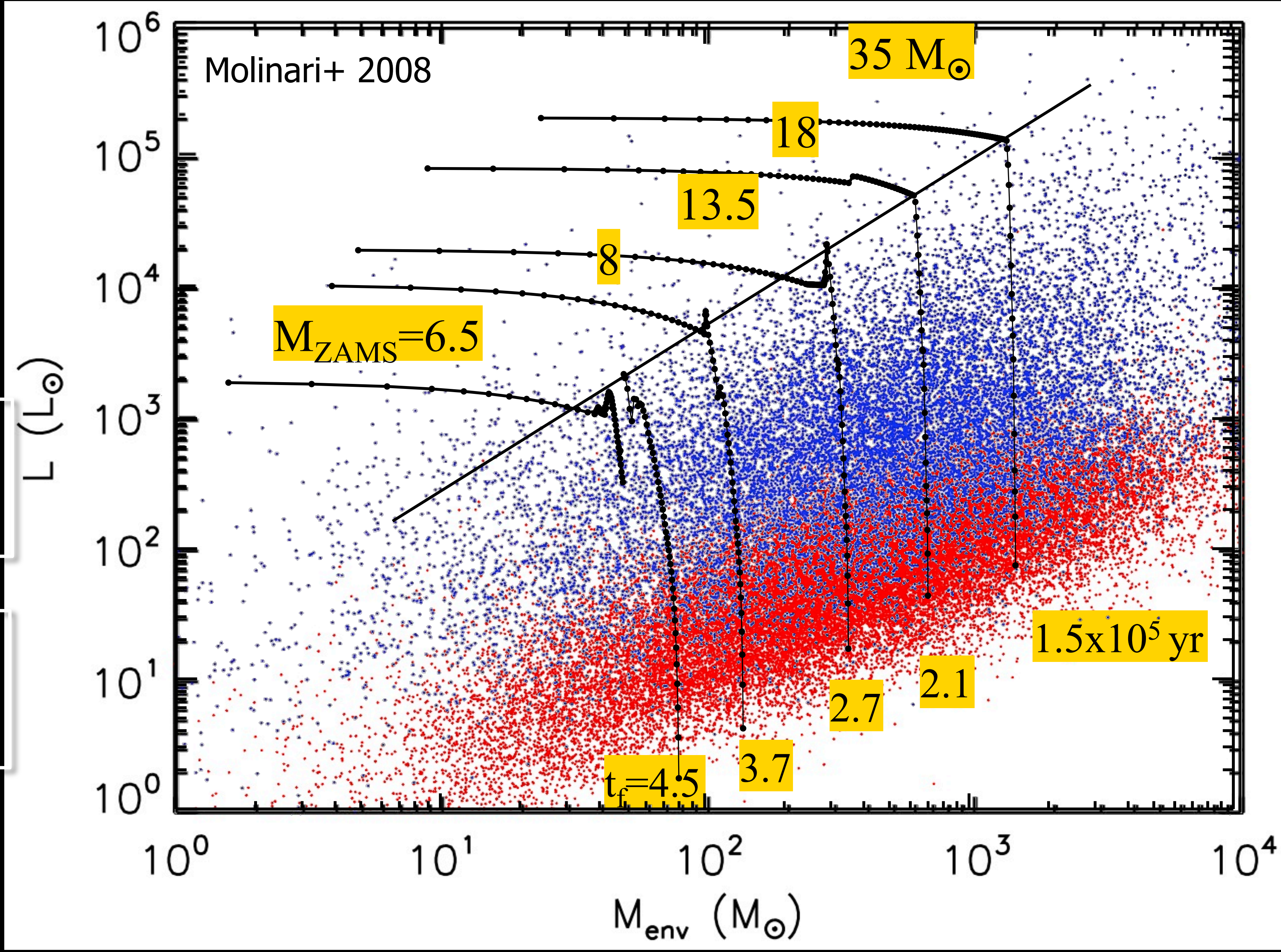
Each clump is associated to:

- final ZAMS masses M_{ZAMSi}
- formation times τ_i

$$SFR_C = \sum_i M_{i,ZAMS} / \tau_i$$

Prescriptions account for cluster formation with MC rather than single massive stars

Method calibrated against YSO-counts SFR from Gould Belt regions (Baldeschi+ 2017a,b)



SFR_C [$M_\odot yr^{-1}$] ~ 5.6 10^{-7} x $M_C^{0.736}$

Veneziani+ 2017

Star Formation Rates from Protostellar Clumps counts

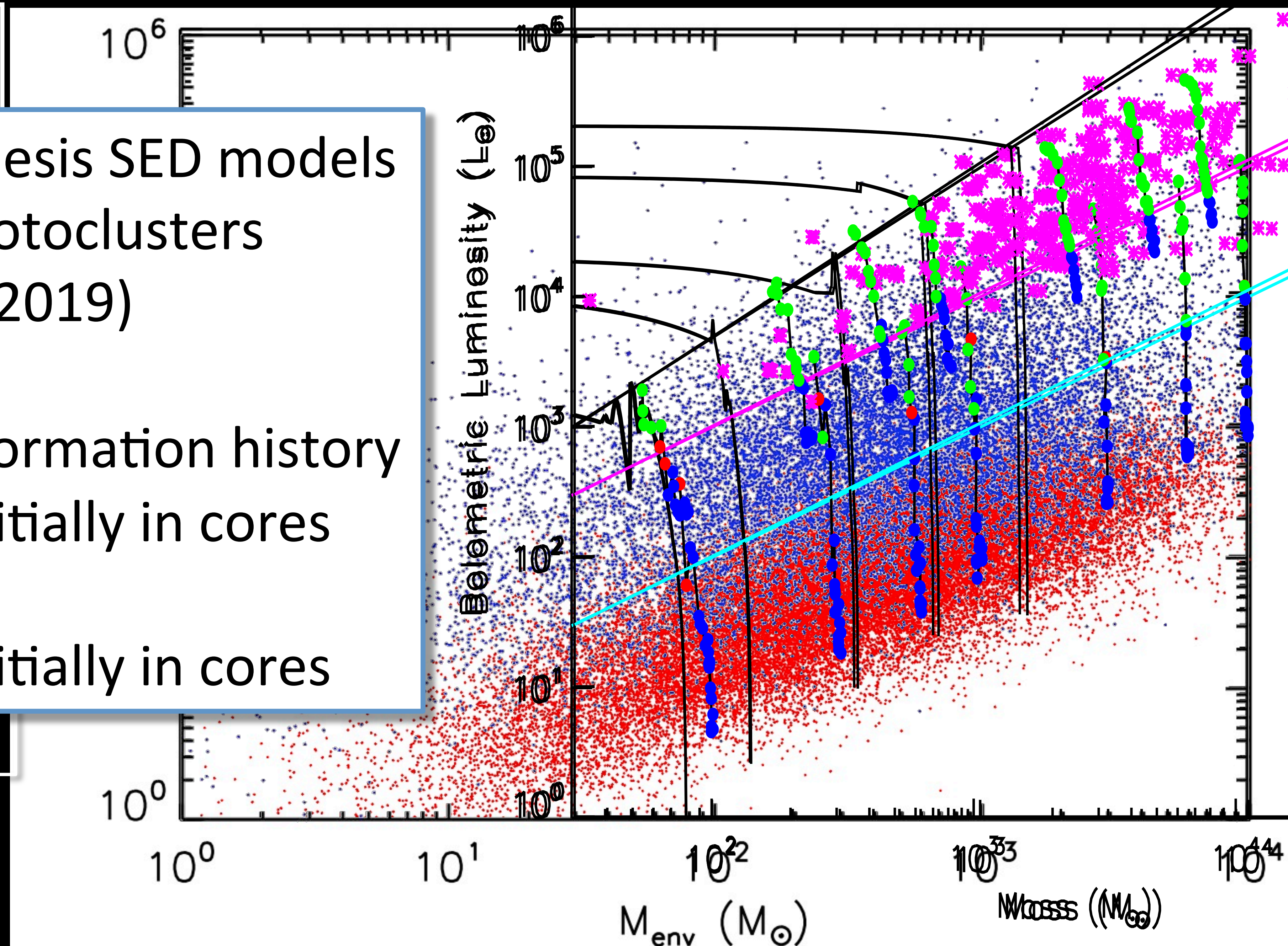
Each clump is associated to:
• final ZAMS masses M_{ZAMSi}

regions (Baldeschi+ 2017a,b)

New population synthesis SED models of embedded protoclusters (Molinari+ 2019)

$5x10^5$ years flat Star Formation history
10% clump mass initially in cores

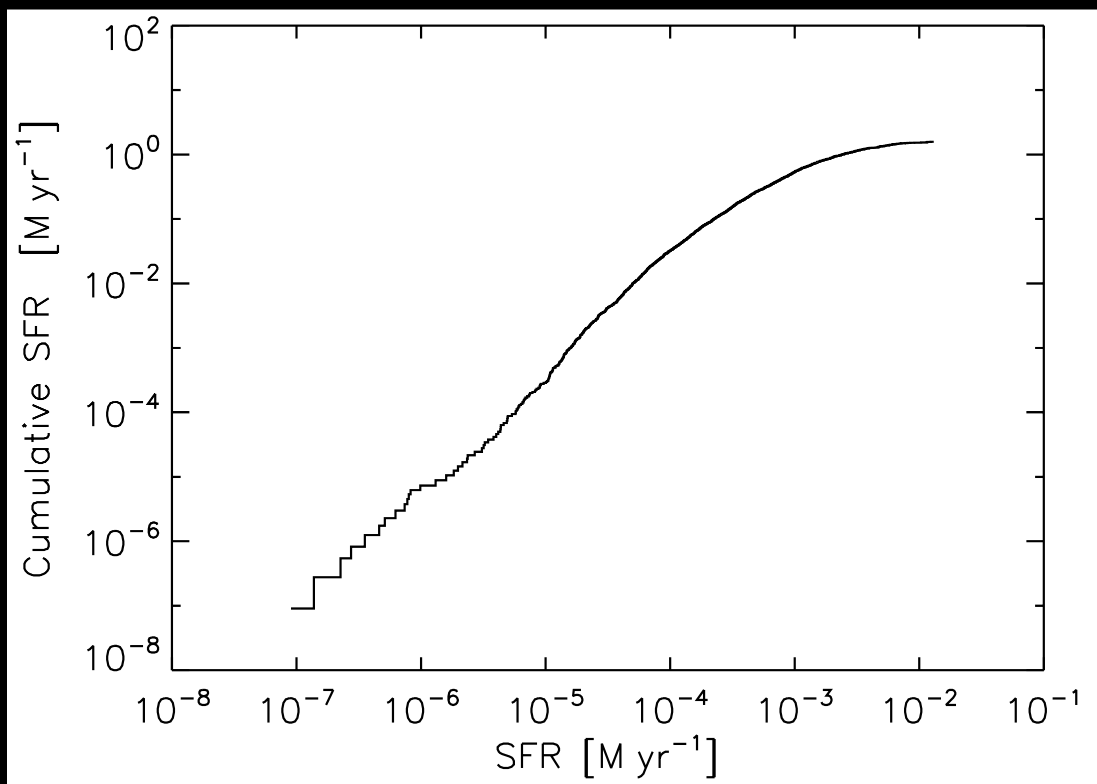
30% clump mass initially in cores



Veneziani+ 2017

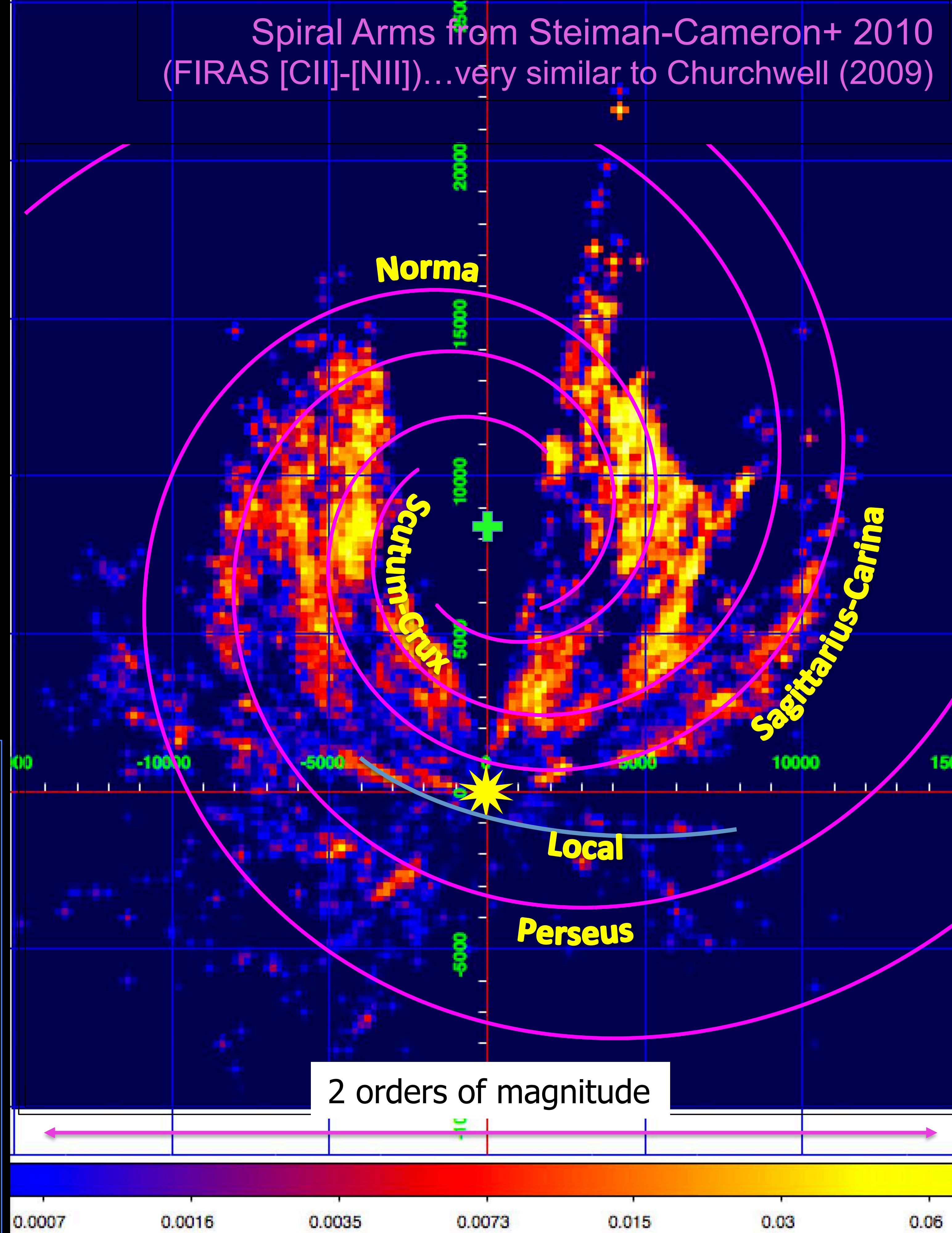
$SFR_C\ [M_\odot yr^{-1}] \sim 5.6\ 10^{-7} \times M_C^{0.736}$

The Milky Way Map of the Star Formation Rate

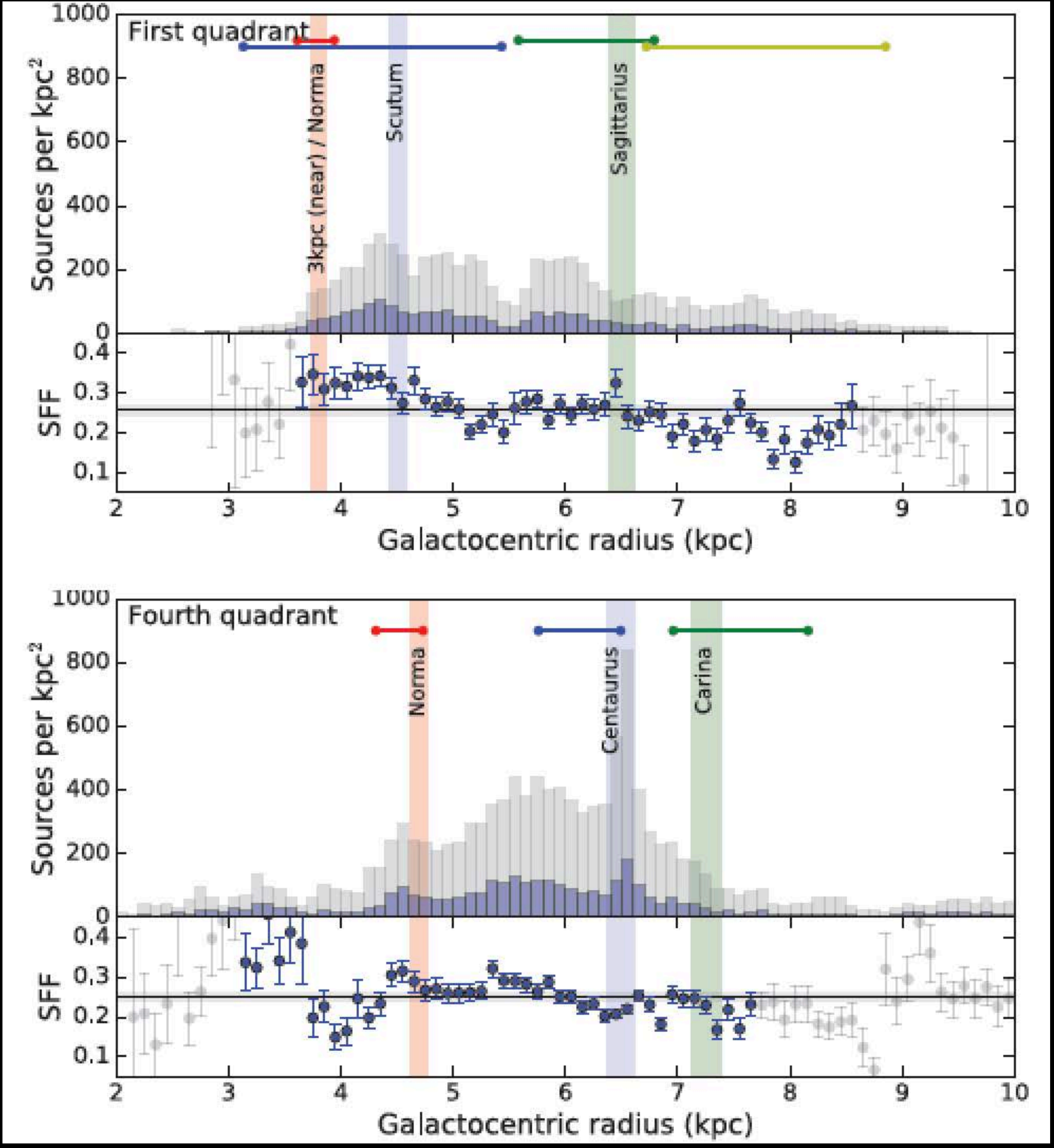


- Cumulative distribution yields an integrated SFR ≈ 1.6 $M_{\odot} yr^{-1}$
- 20% of the cells are contributing 65% of the total SFR
- The +15°≥ *l* ≥ -10° adds ≈ 0.57 $M_{\odot} yr^{-1}$ assuming all clumps at D=8400pc

Elia+ in prep.



The role of Spiral Arms: triggers or collectors ?



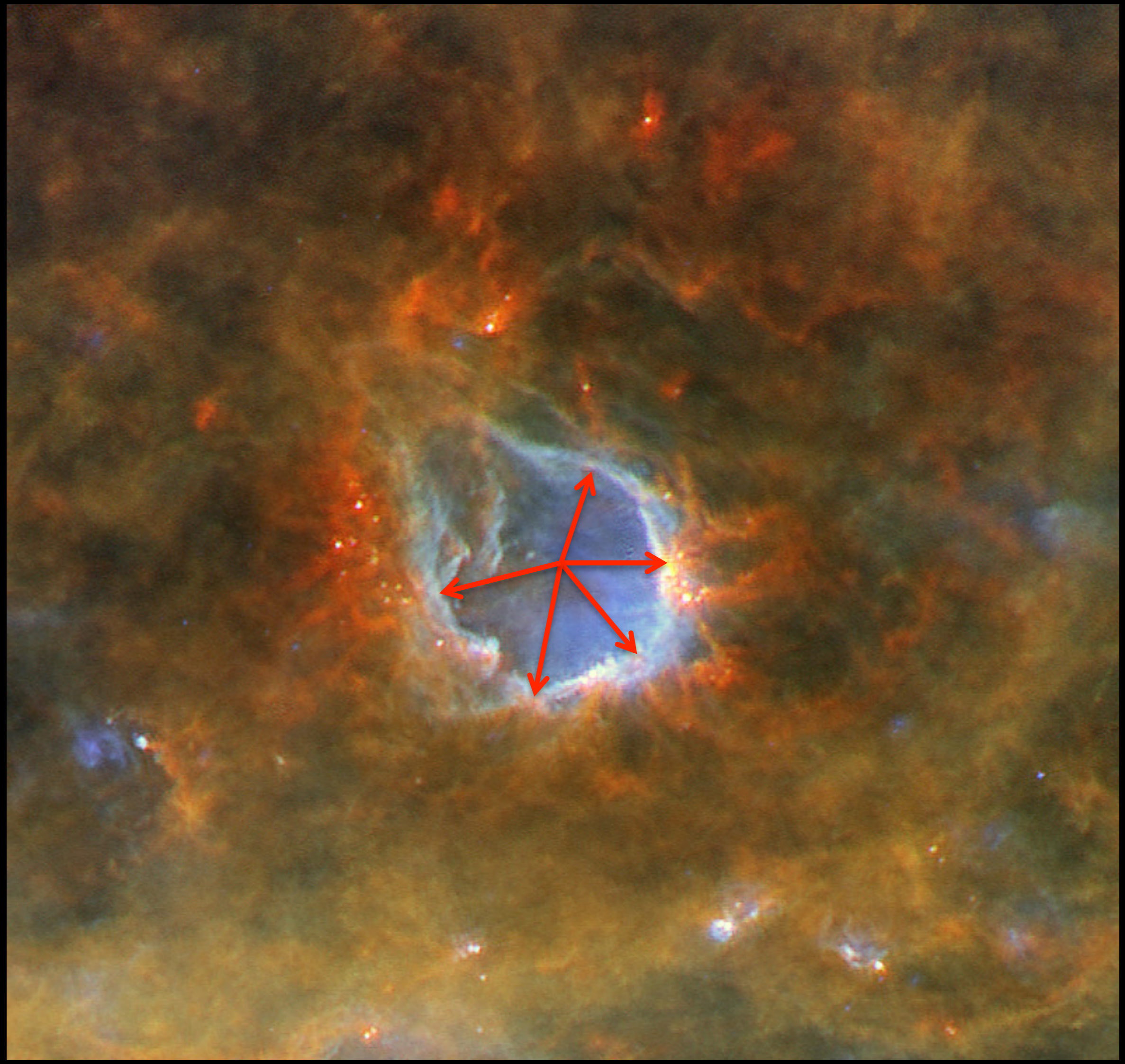
Protostellar clumps

All clumps

- Star formation efficiency and fraction are not enhanced in spiral arms → arms are collectors, rather than triggers
- Slow decreasing trend in star formation efficiency as a function of Galactocentric radius

Ragan+ 2016

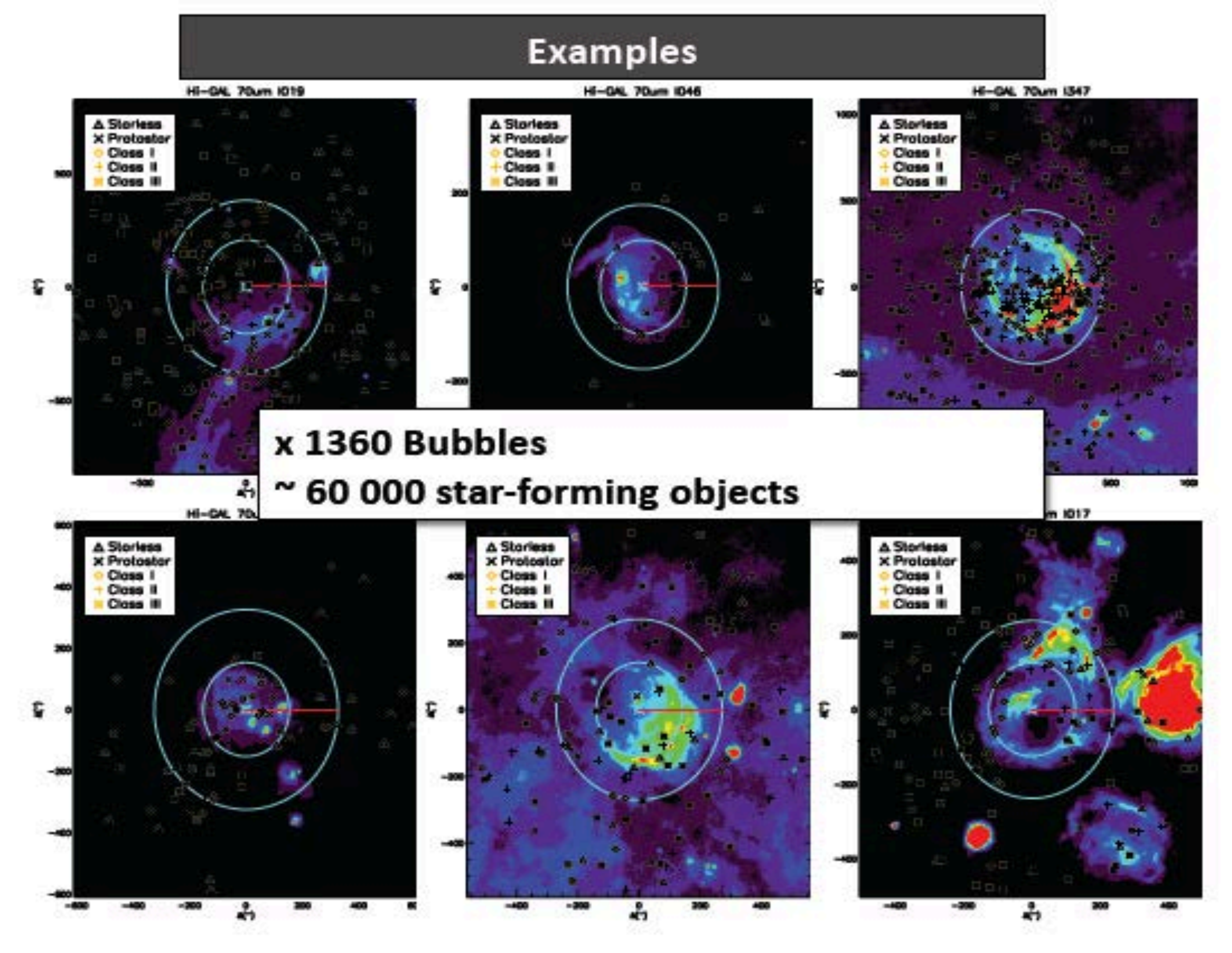
Bubbles and Triggered Star Formation



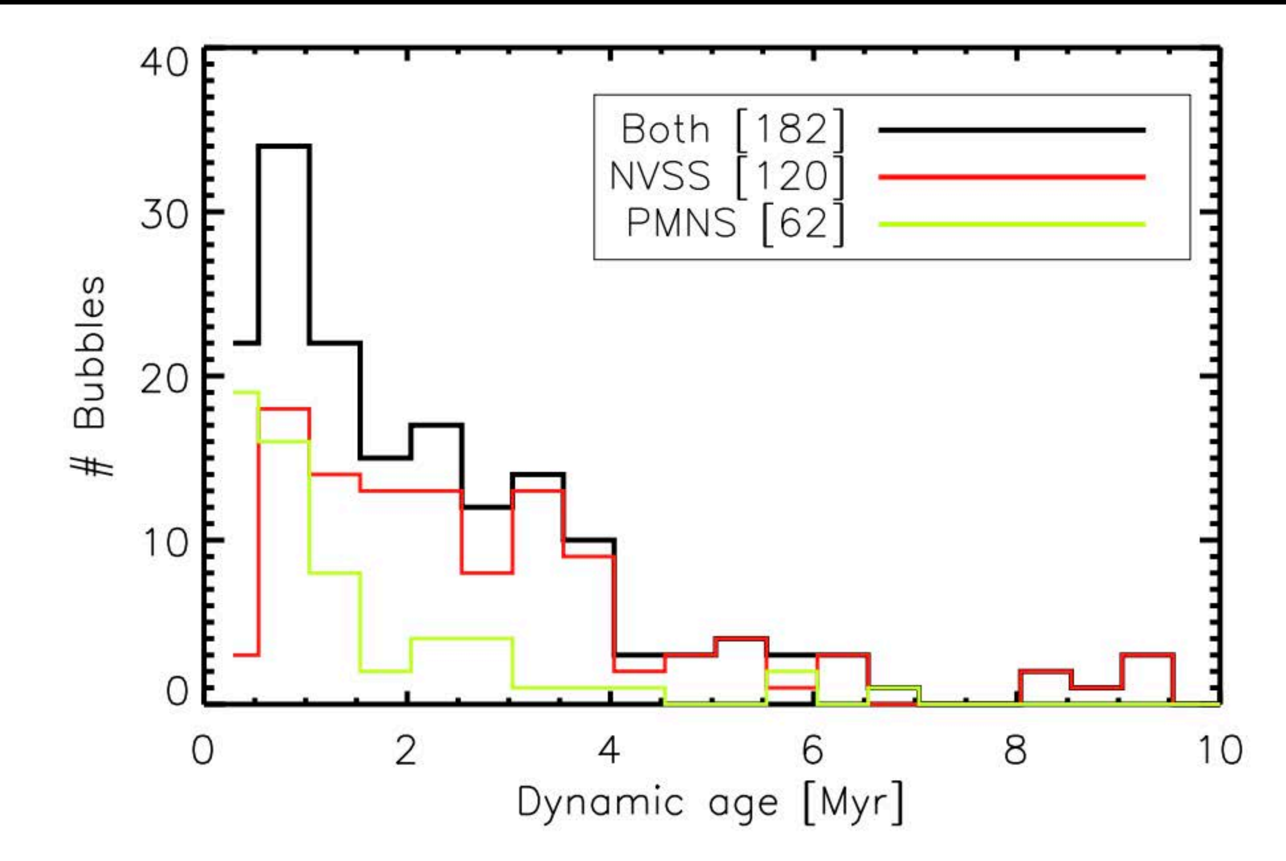
Palmeirim+ 2017

Statistics of sources in proximity of bubbles:

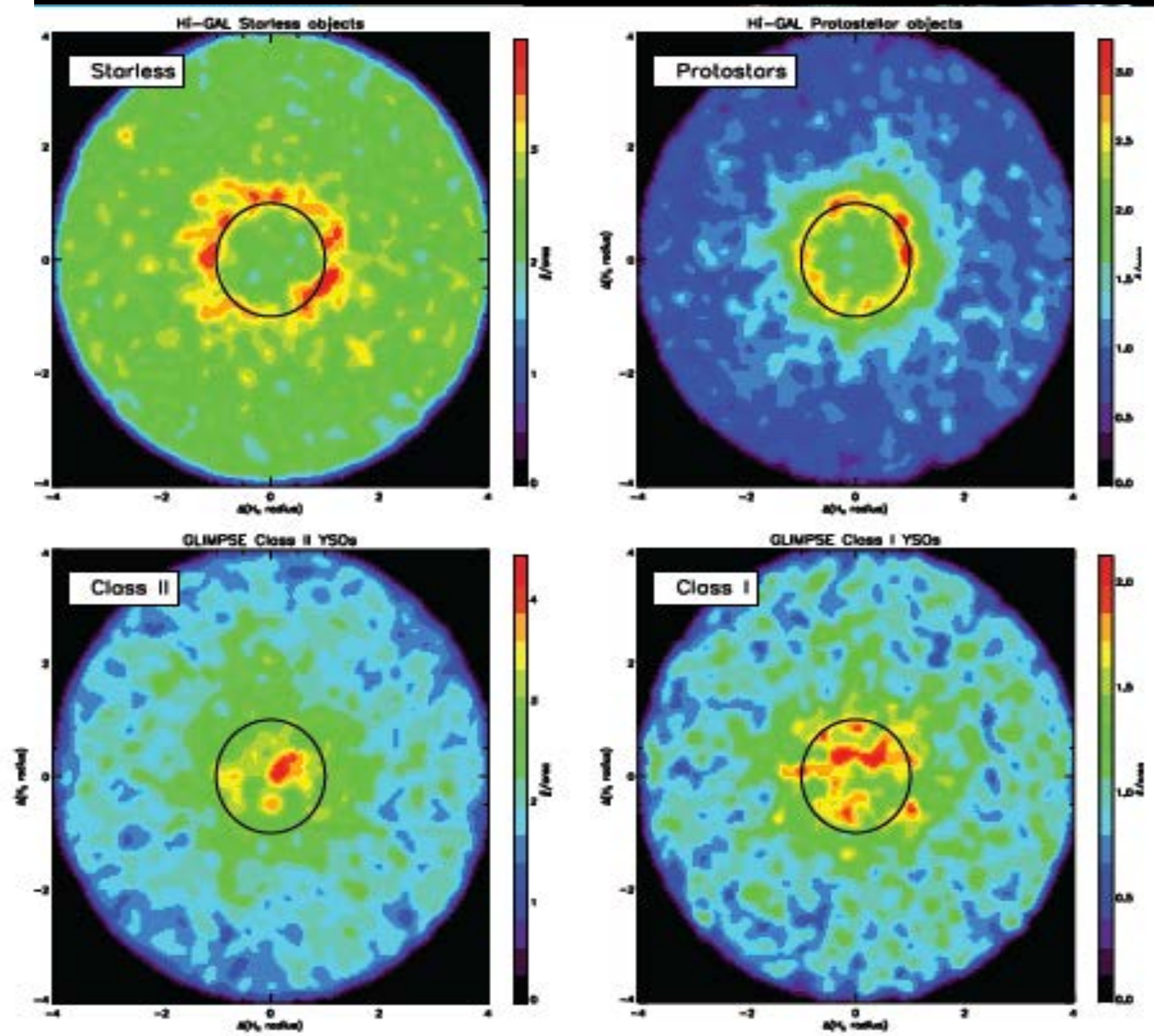
- Star-forming sources surface density enhanced by **80%**
- Clump formation efficiency enhanced by **50%**



Bubbles and Triggered Star Formation



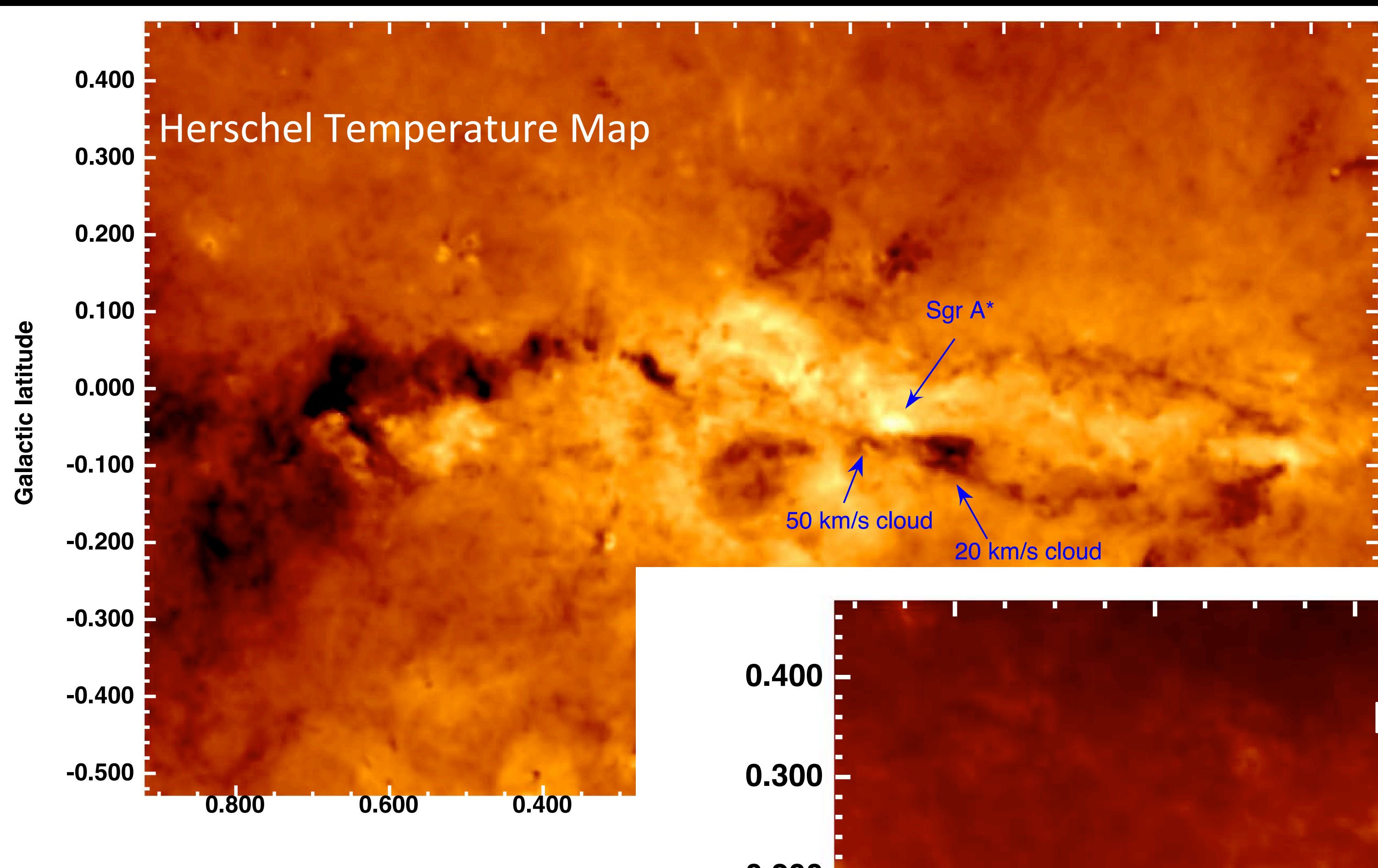
Evolutionary trends in source distribution

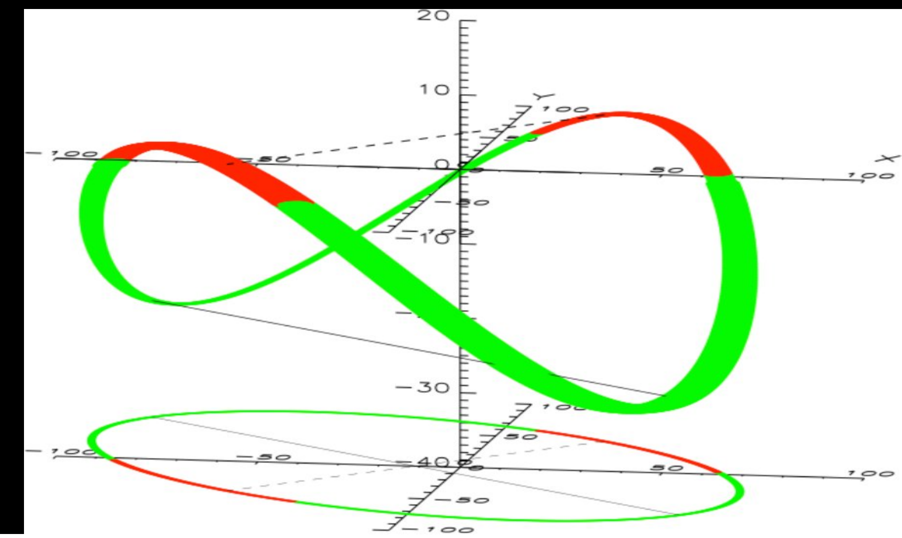


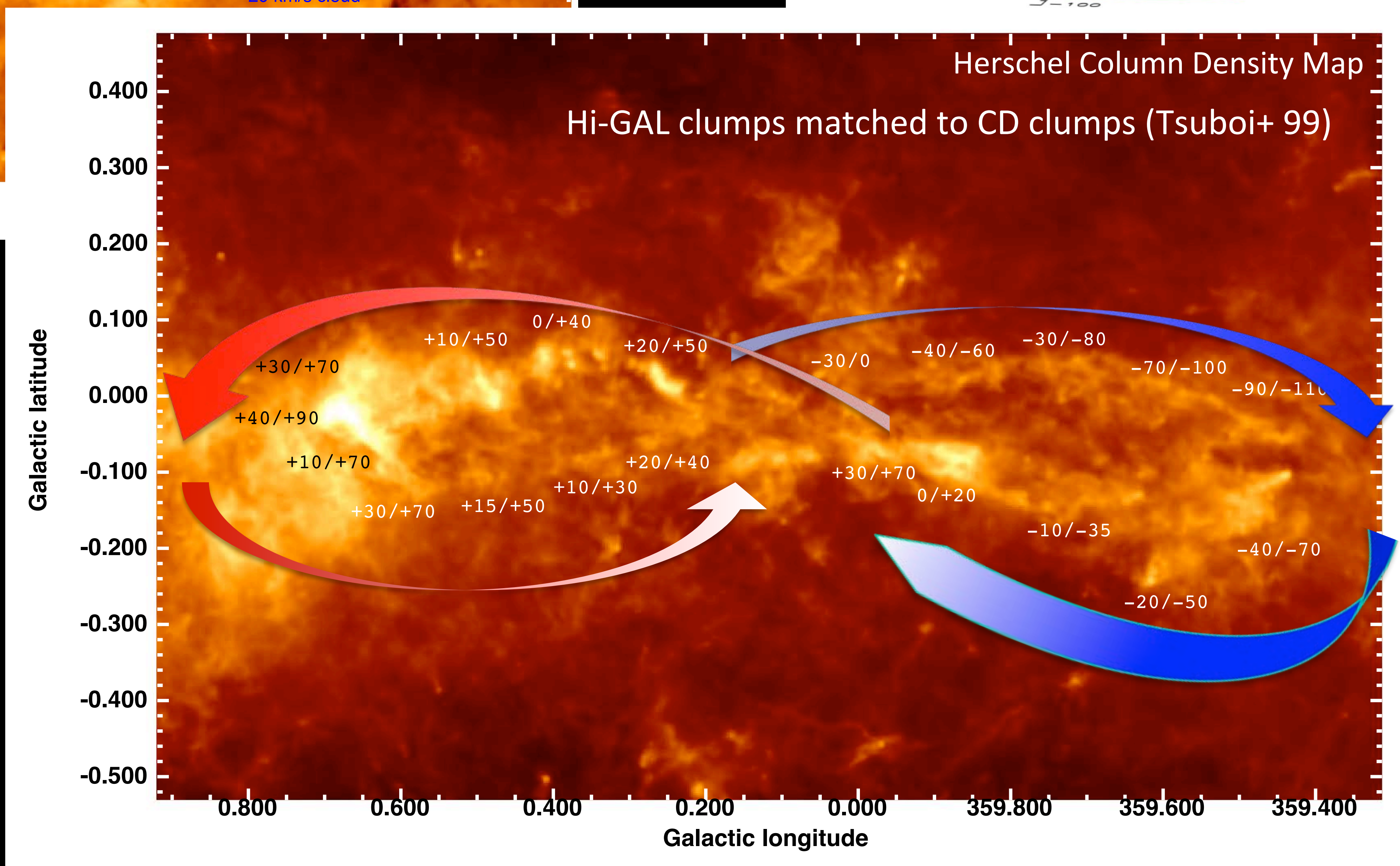
- Evidence of sequential star formation
- Bubble dynamical timescales agrees with SF clumps ages spreads

Palmeirim+ 2017

The Galactic Center

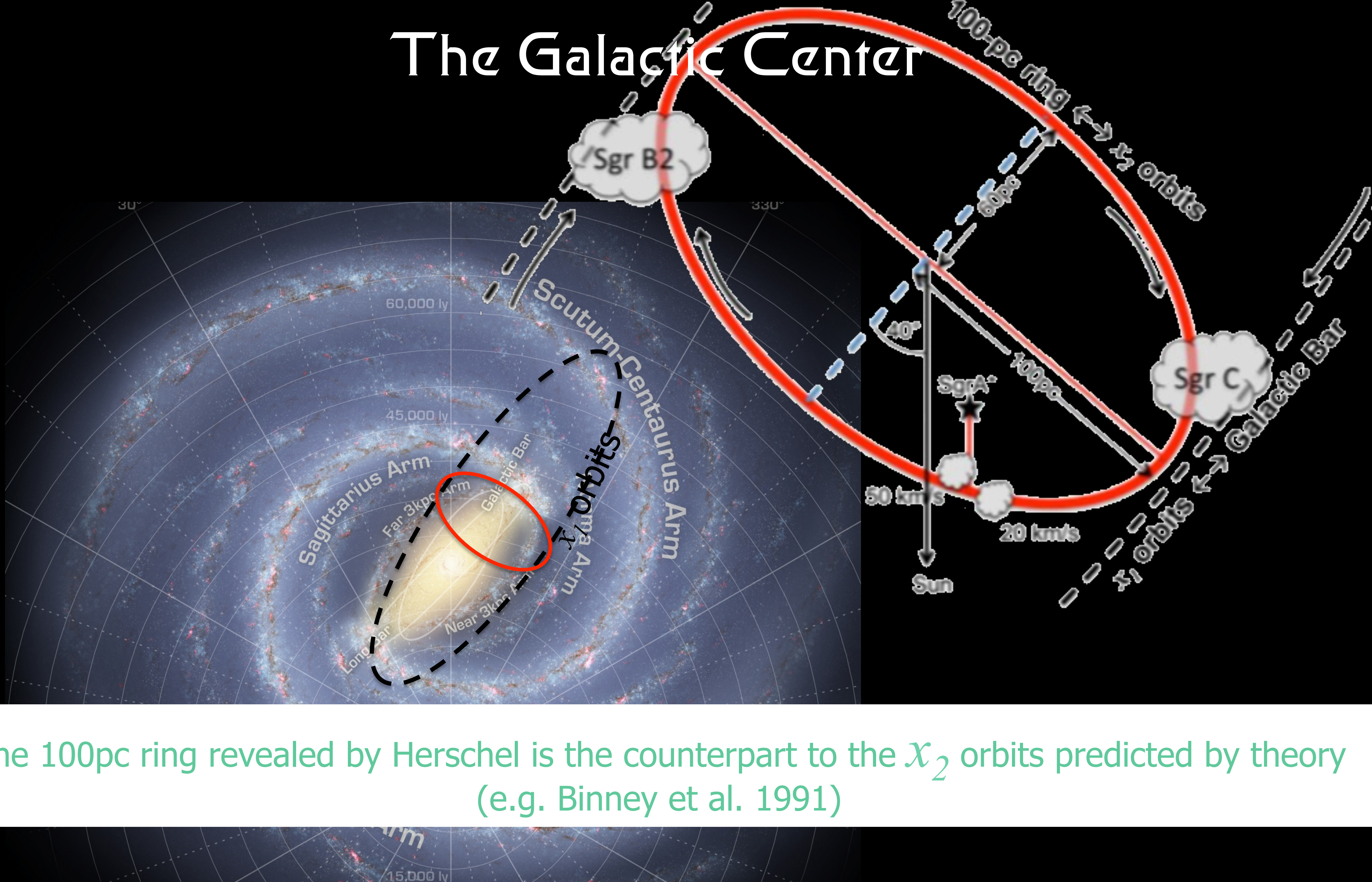






Molinari+ 2011

The Galactic Center

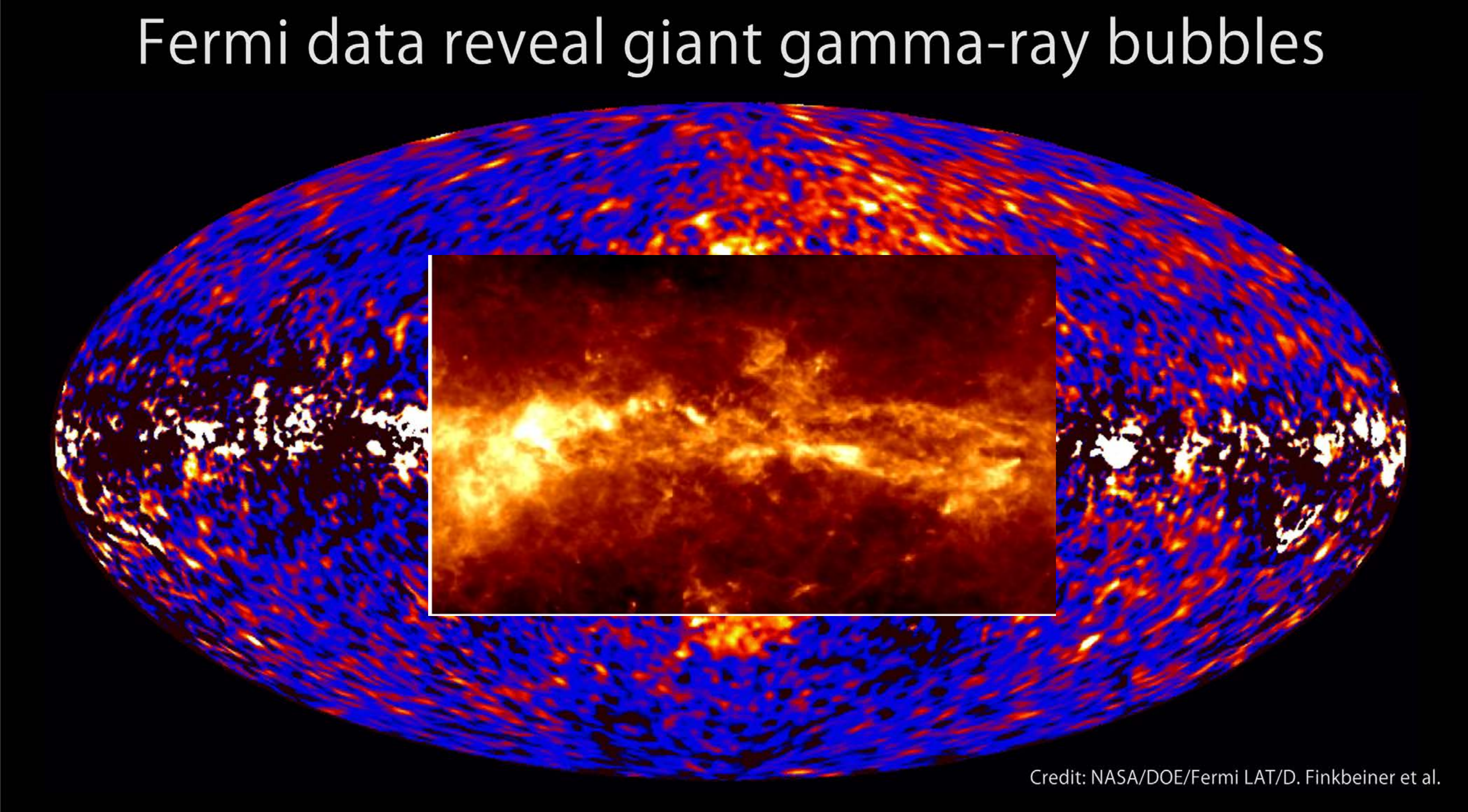


The 100pc ring revealed by Herschel is the counterpart to the x_2 orbits predicted by theory (e.g. Binney et al. 1991)

SgrB2 and SgrC are conveniently located at the converging points between the x_1 and x_2 *orbits*, where shock-focusing mechanism may favor the formation of massive clouds

The Galactic Center

A past AGN phase for the Milky Way ?



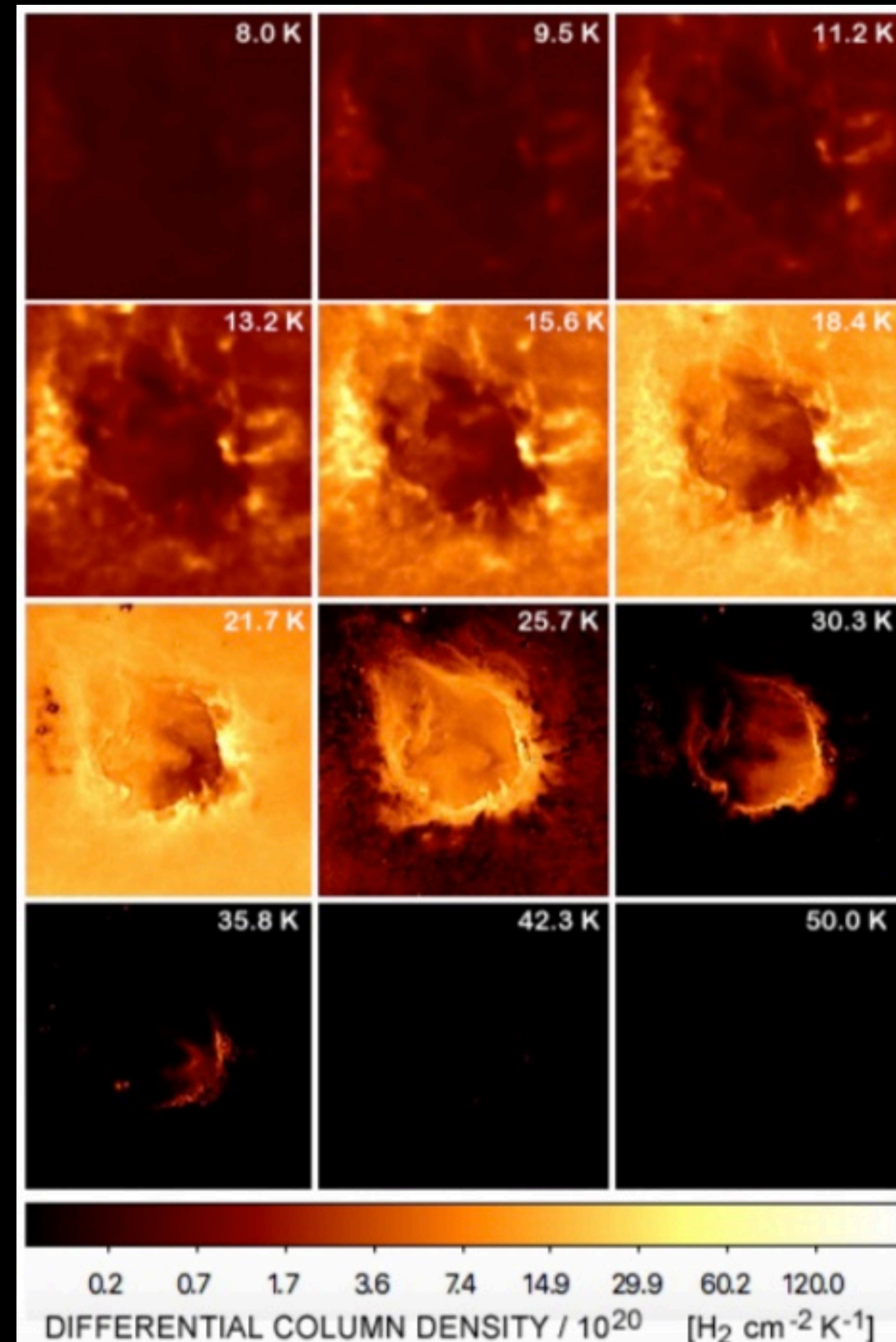
Could the 100-pc ring be the remnant of the large AGN dusty torus ?

PPMAP:
T-dependent Column Density
(Marsh+ 2017)

- Allow T (and optionally, β) to vary along line of sight
- Use all observed images at their *native* resolution
- Output is a 3D cube of differential column density (x,y,T) or a 4D hypercube (x,y,T, β)
- Bayesian procedure, based on *Point Process* concept

- Clumpy structure at low temperatures (cores, star formation)
- Spherical structure at high temperatures (PDR)

RCW 120



Hi-GAL is a vision come true