The earliest stages of star and stellar clusters formation: turbulence and fragmentation

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Riunione Macroarea 2 15-16 Giugno, Bologna

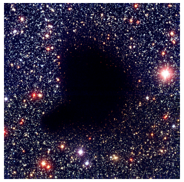
Outline

- The environment of (massive) star formation: clouds and clumps
- Massive clouds, clumps and cores: turbulent or self-gravity dominated regions? (A. Traficante)
- Fragmentation of high-mass dense clumps and the role of magnetic fields (F. Fontani)
- The CMF as a tool to investigate fragmentation and star formation (L. Olmi)
- Final remarks

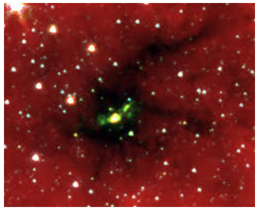
The environment of (massive) star formation

(Massive) star formation begins in cold, dense molecular clouds. Regions with an extension of few pc up to ~150 pc (giant molecular clouds, GMCs)

Isolated small clouds (Bok globules) and densest regions of GMCs are seen as dark cloud in the optical-NIR due to the absorption of the background light



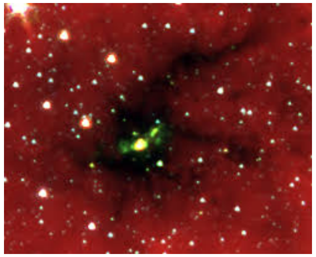
Barnard 68, Bok globule in Ophiuchus seen by VLT

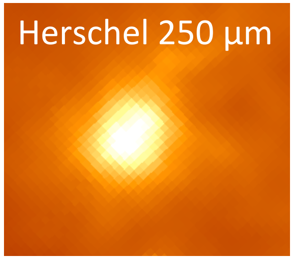


SDC335 seen by Spitzer at 8-24 µm (Peretto et al. 2013)

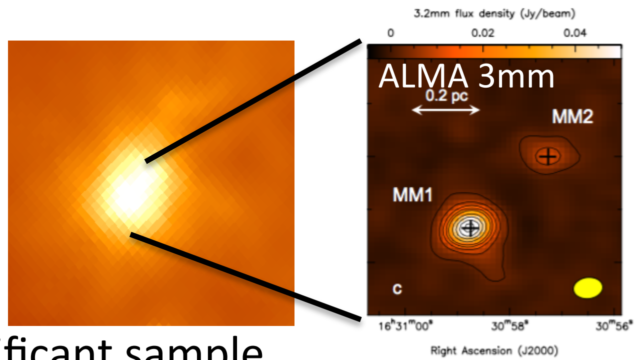
The densest part of the large clouds can be seen in absorption up to the mid-infrared. They are called infrared dark clouds (IRDCs)

Embedded in these clouds the *Herschel* far-infrared mission of the Galactic Plane Hi-GAL (Molinari et al. 2010) observed thousands of clumps: dense fragments of ~0.5-1 pc





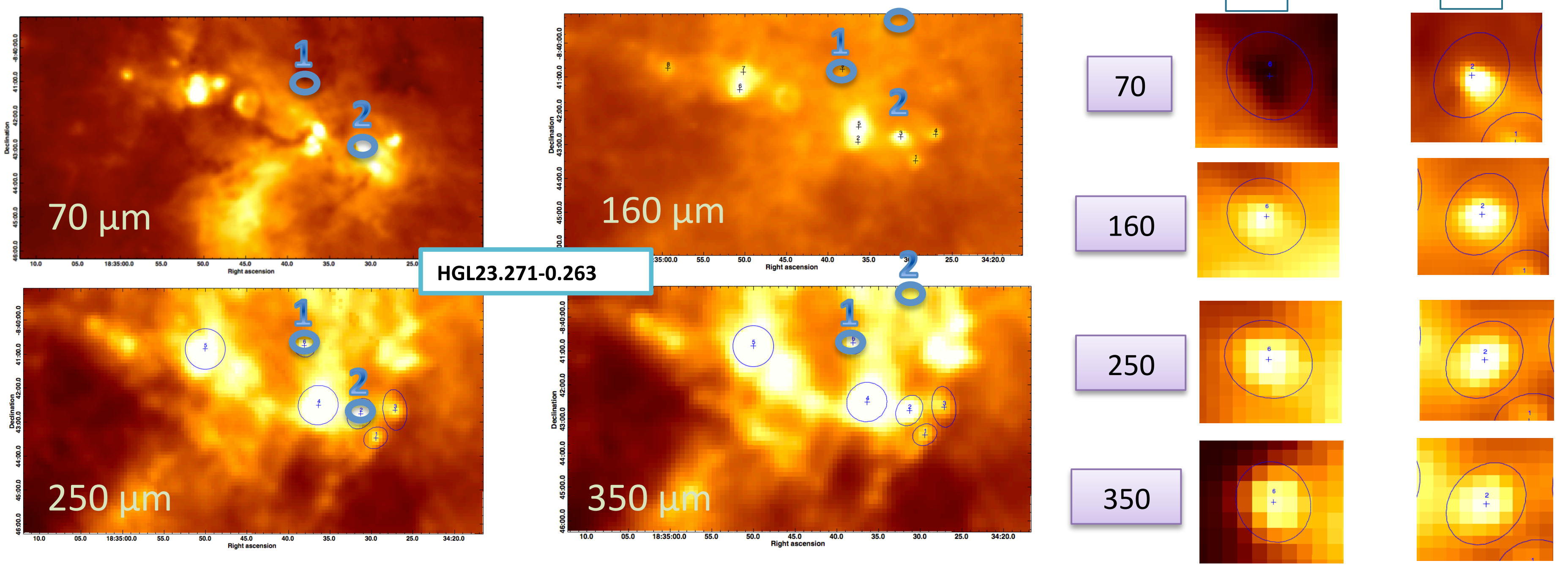
High-resolution radio follow-ups of these clumps revealed (and will reveal) the embedded cores (~0.1 pc), the precursors of (massive) stars.



We have now with Hi-GAL a statistically significant sample of (massive) clumps in the Galactic Plane

Survey of deeply embedded clumps

We produce a first large catalogue of (massive) clumps seen by Hi-GAL and embedded in ~3000 IRDCs (Peretto & Fuller 2009), ~1500 clumps (Traficante et al. 2015a, 2015b)



This sample is a great complement at the clouds data to investigate some fundamental open questions in massive star formation, e.g.: **star formation is highly inefficient and collapse requires several free-fall times (Federrath et al. 2016).** ***Evidence of local, slow collapse?***

Turbulent or self-gravity dominated regions ?

Giant molecular clouds (GMCs) ^{12}CO data

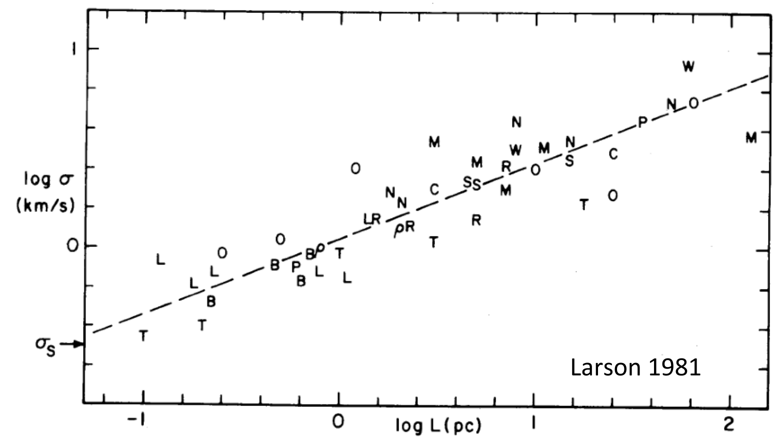
$$\sigma \propto R^{\Gamma}$$

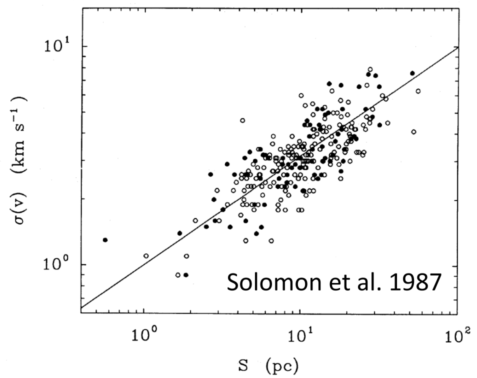
$$\Gamma \cong 0.38$$ Larson 1981

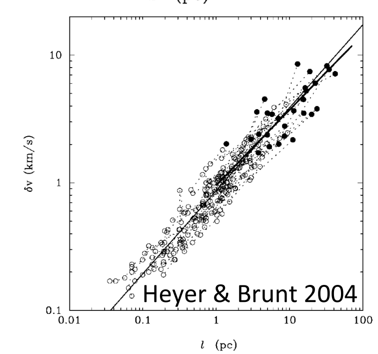
$$\Gamma \cong 0.5$$ Solomon et al. 1987
Heyer & Brunt 2004

Kolmogorov-Burger turbulence

- **Universality of cloud structures**
- **Turbulent dominated regions**
- **Turbulence slow down star formation and prevent global collapse (e.g. McKee & Tan 2003)**







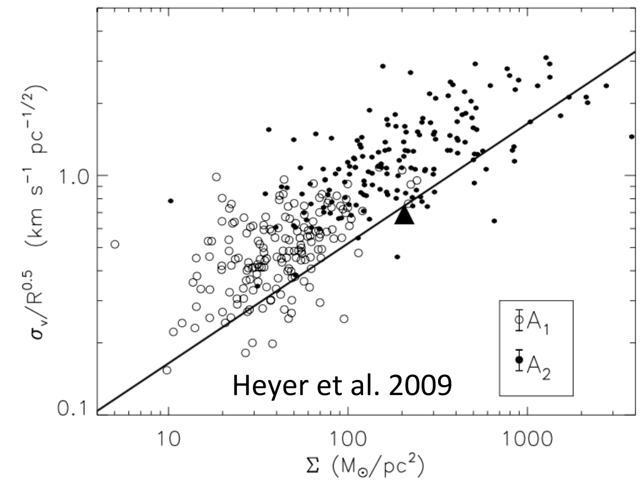
Turbulent or self-gravity dominated regions ?

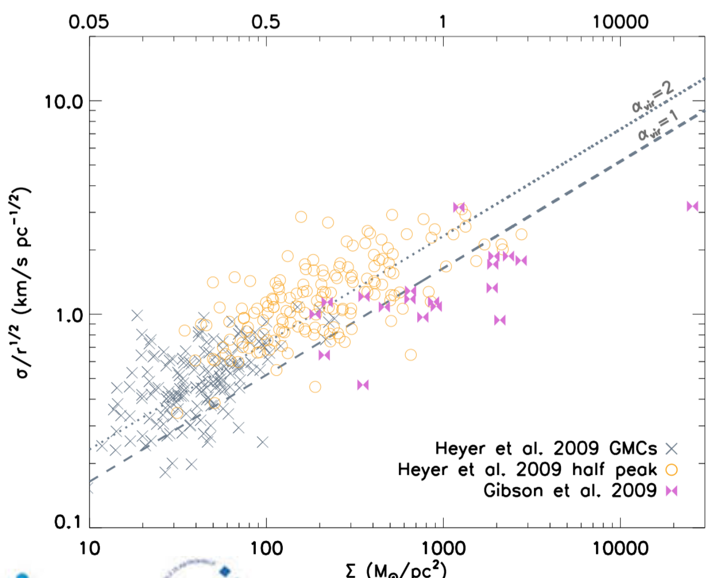
Revised GMCs results: **Heyer et al. 2009** using ^{13}CO data from the GRS Jackson et al. 2006

- higher angular resolution
- optically "thin" tracer

Range of clouds spanning different column densities

$$\frac{\sigma}{R^{1/2}} \neq \mathrm{const.} \;\Rightarrow\; \frac{\sigma}{R^{1/2}} \propto \Sigma$$





Ballesteros-Paredes et al. 2011

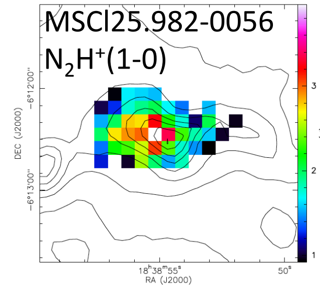
GMCs and massive clumps ~follow the Heyer relation

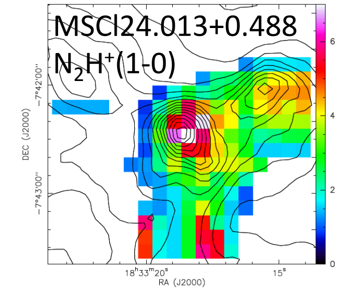
Supersonic motion in gravity dominated regions ➔ **Evidence of hierarchical and chaotic gravitational collapse.**

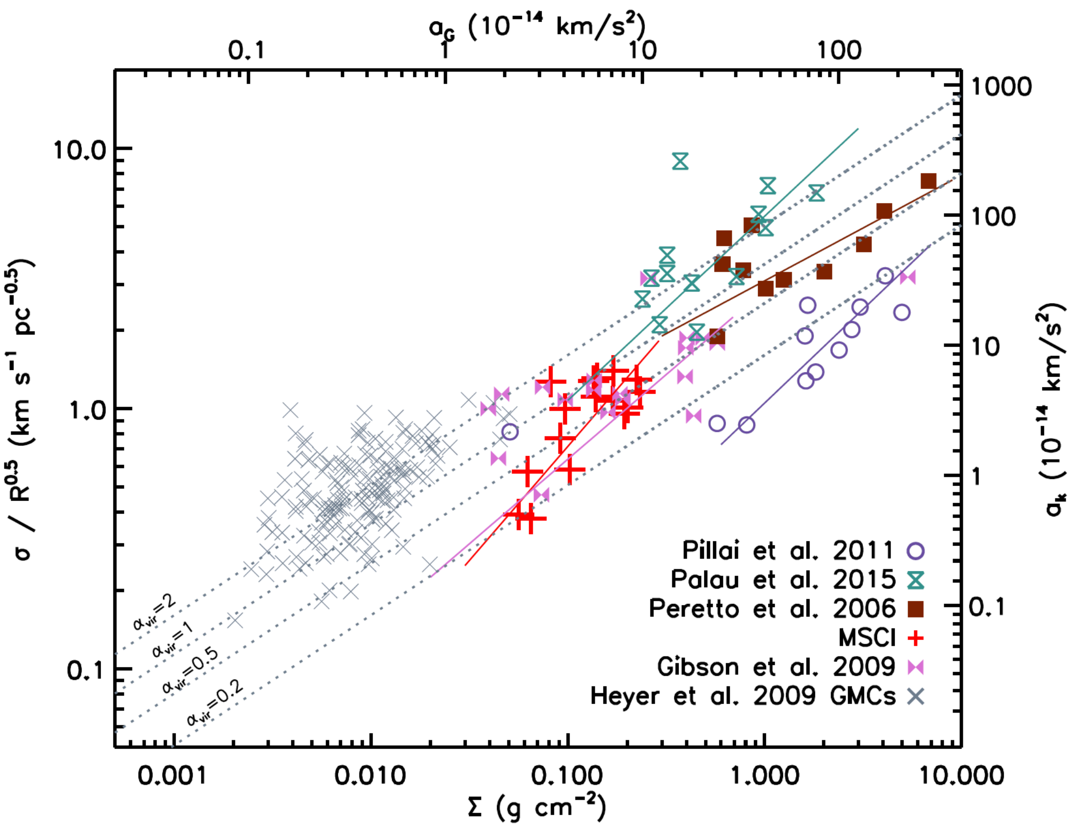
Turbulence is driven by gravity and regions are in fast, global collapse. Star formation slowed down by stellar feedback

Turbulent or self-gravity dominated regions ?

A follow-up of 18 massive starless clumps with IRAM 30m data provided a first sample of relatively quiet regions (Traficante et al. 2016)







GMC

× ^{13}CO data from GRS survey

Massive clumps

CS survey of massive IRDCs

N_2H+ survey of massive starless clumps

Massive cores

N_2H+ survey of pre- and proto-stellar cores in NGC2264

NH_3 survey of protoclusters

NH_2D survey of pre-protocluster in G29.9 and G35.2

Present and future radio observations

There is a good indication that the surface density (e.g. the gravity) guides the observed turbulence. **But we need a statistically significant sample of clumps-cores follow-ups** to look at: velocity gradients, infall motions; supersonic motions; fragmentation…

The topic is well recognized as primary importance in the community and several proposals have been already accepted:

PI A. Traficante

CoIs: S. Molinari (INAF-IAPS)
N. Peretto (Univ. of Cardiff)
N. Billot (IRAM)
Y. Shirley (Univ. of Arizona)
G. Fuller (Univ. of Manchester)
R. Smith (Univ. of Manchester)
R. Paladini (Caltech)
…

IRAM 30m project 034-14	high-mass clumps kinematics
IRAM 30m project 133-15	intermediate-mass clumps kinematics
IRAM 30m project 029-16	high-mass starless deuteration
VLA project 15b-213	fragmentation/gas temperature in a massive cloud
ALMA project 2015.1.00959	fragmentation and kinematics (PI: Y. Shirley. A. Traficante leads the kinematics)

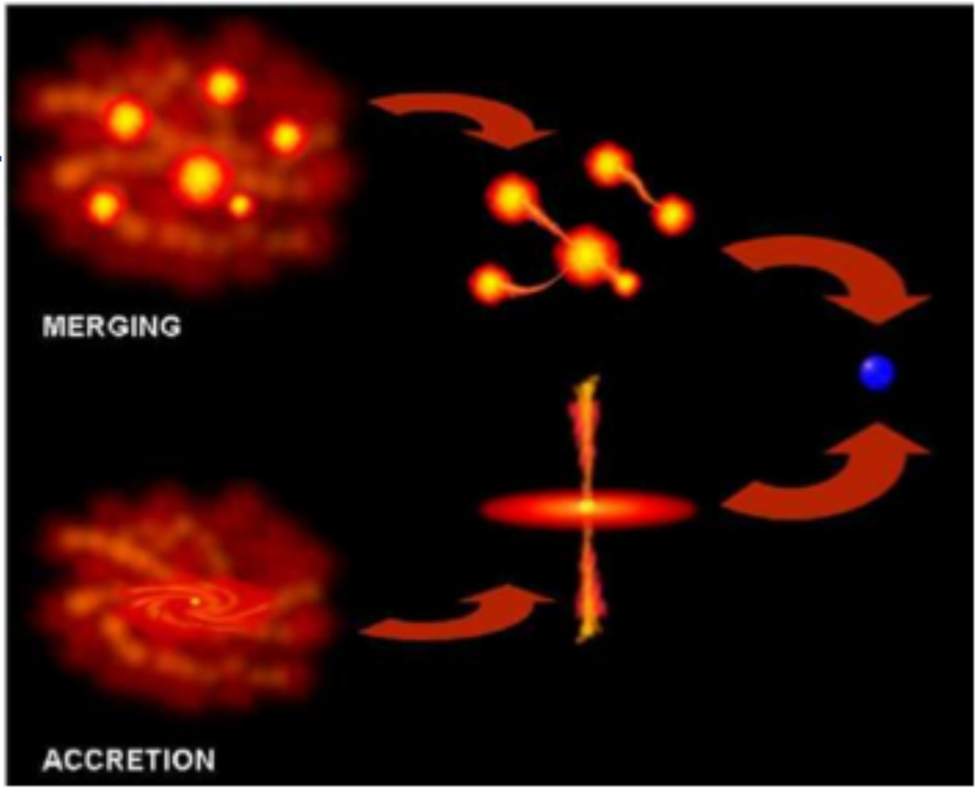
Fragmentation of high-mass dense clumps

FRANCESCO FONTANI
INAF-Osservatorio Astrofisico di Arcetri

Maite Beltràn	***INAF-OAA***	Benoit Commerçon	ENS Lyon (F)
Riccardo Cesaroni	***INAF-OAA***	Patrick Hennebelle	ENS Paris (F)
Alvaro Sanchez-Monge	U Cologne (D)	Paola Caselli	MPE (D)
Andrea Giannetti	MPIfR (D)	Steven Longmore	U Liverpool (UK)
Leonardo Testi	***ESO & INAF-OAA***	Jonathan Tan	U Florida (US)
Malcolm Walmsley	***INAF-OAA***	Richard Dodson	ICRAR (AUS)
Jan Brand	INAF-IRA	Maria Rioja	ICRAR (AUS)

From clouds to cores

Massive stars (and clusters) form
From the collapse of dense and
compact cores
($n \sim 10^5$ cm^{-3}, D~0.1 pc)
....HOW???



Courtesy of L. Carbonaro

MAIN THEORIES:

1. MERGING:
   Fragmentation of a massive clump into many low-mass seeds which keep accreting from unbound gas, and/or merge through collisions
   (e.g. Bonnell et al. 1998, 2001, Bonnell & Bate 2005, Wang et al. 2010)

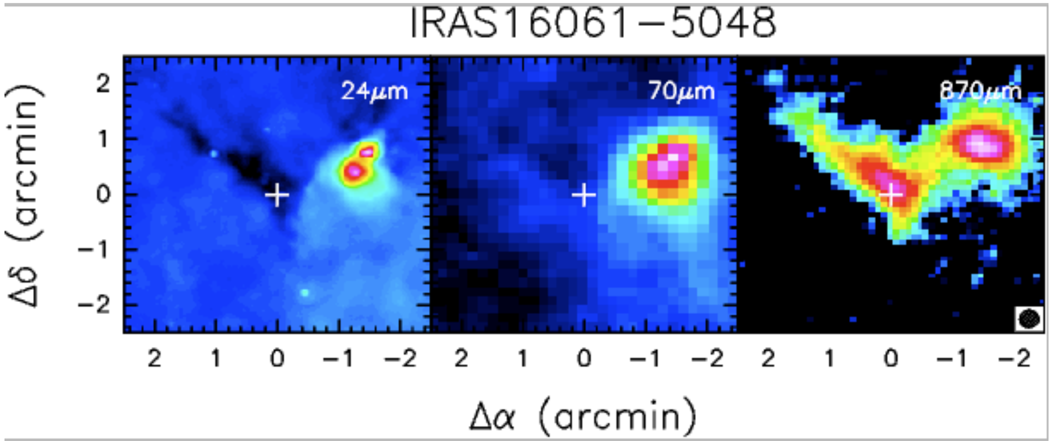
2. ACCRETION:
   Fragmentation of a massive clump inhibited, and non-spherical collapse into a single high-mass star or close binary system
   (e.g. Wolfire & Cassinelli 1978, McLaughlin & Pudritz 1996, Yorke & Sonnhalter 2002, Tan & McKee 2003)

Fragmentation of the parent clump crucial

Targets selection

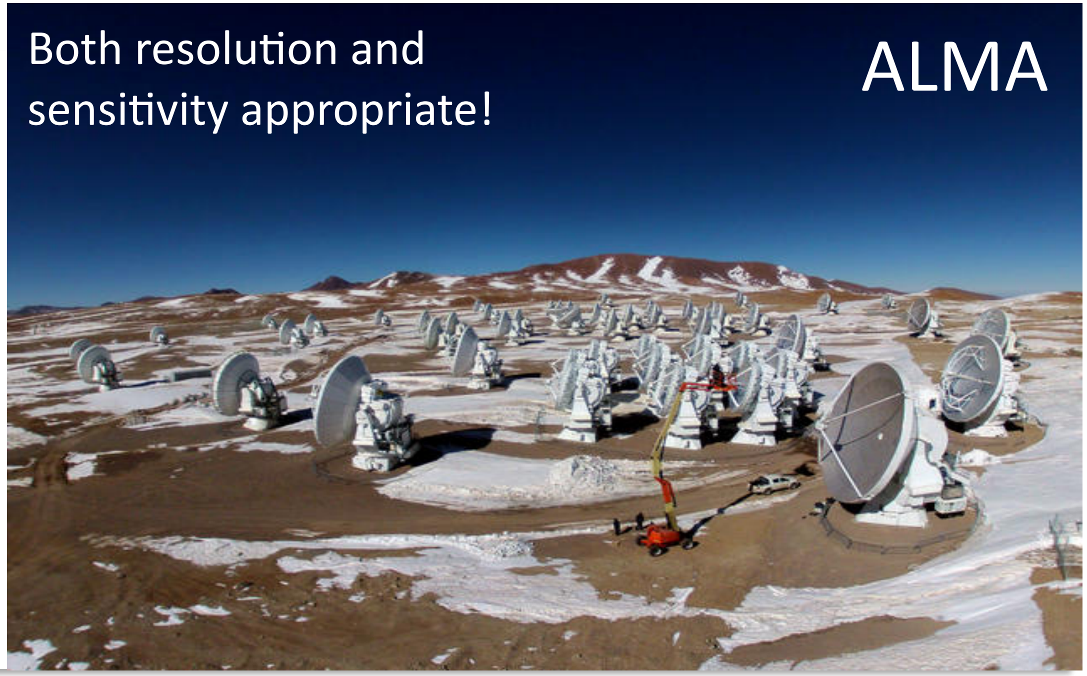
Initial sample: 95 (sub-)***millimeter continuum*** clumps, ***IR-dark***

(Fontani+2005; Beltrán+2006; Fontani+2012; Sánchez-Monge+2013; Giannetti+2014)



Selection criteria:

1. Potential massive SF clumps
2. Cold and chemically young
3. Not blended
4. Dense



What we expected to see….

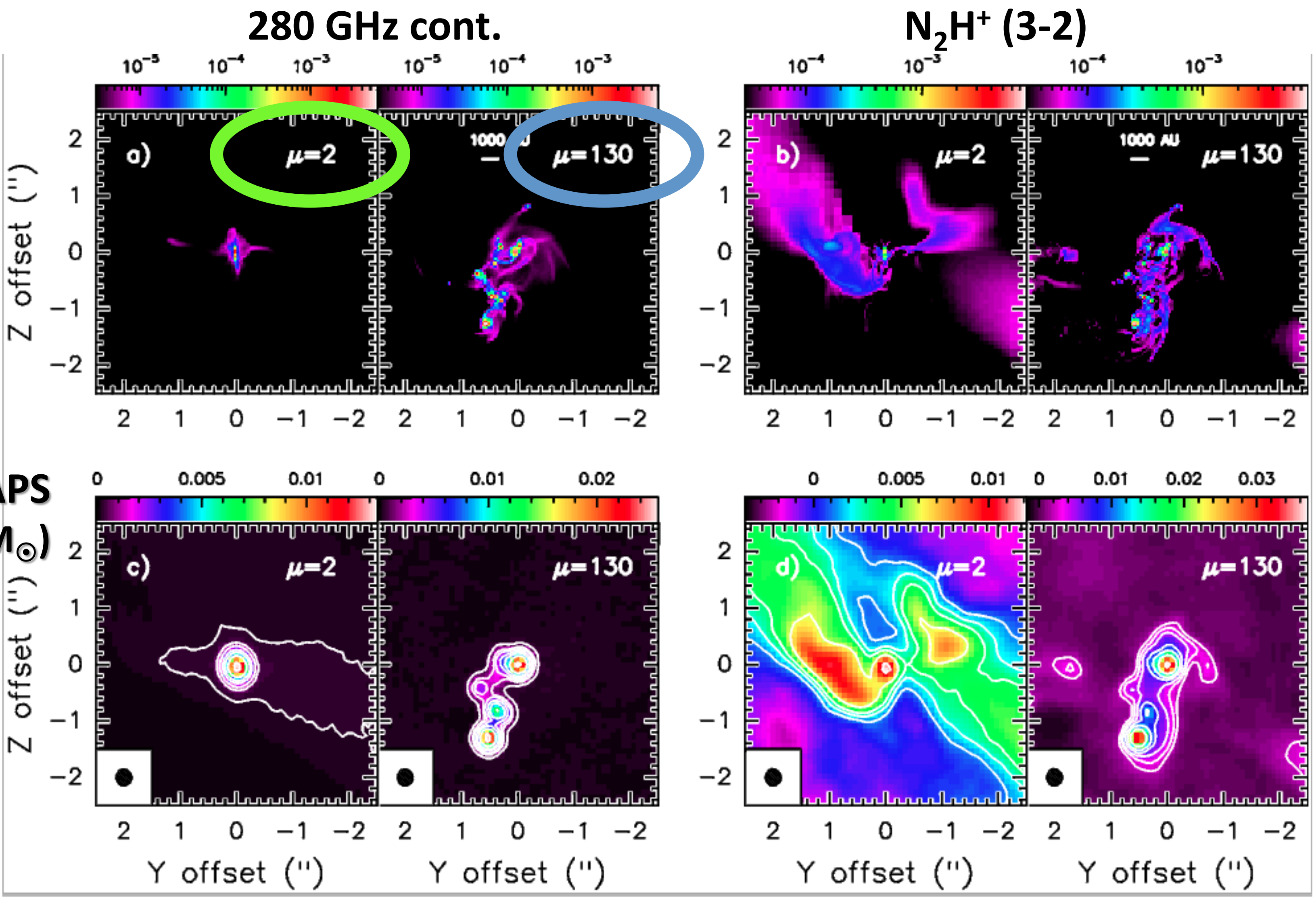
$\mu = (M/\Phi)/(M/\Phi)_{crit}$

μ = 2 , dominant magnetic support

μ = 130, faint magnetic support

MODEL
(Hennebelle+11, Commerçon+12)

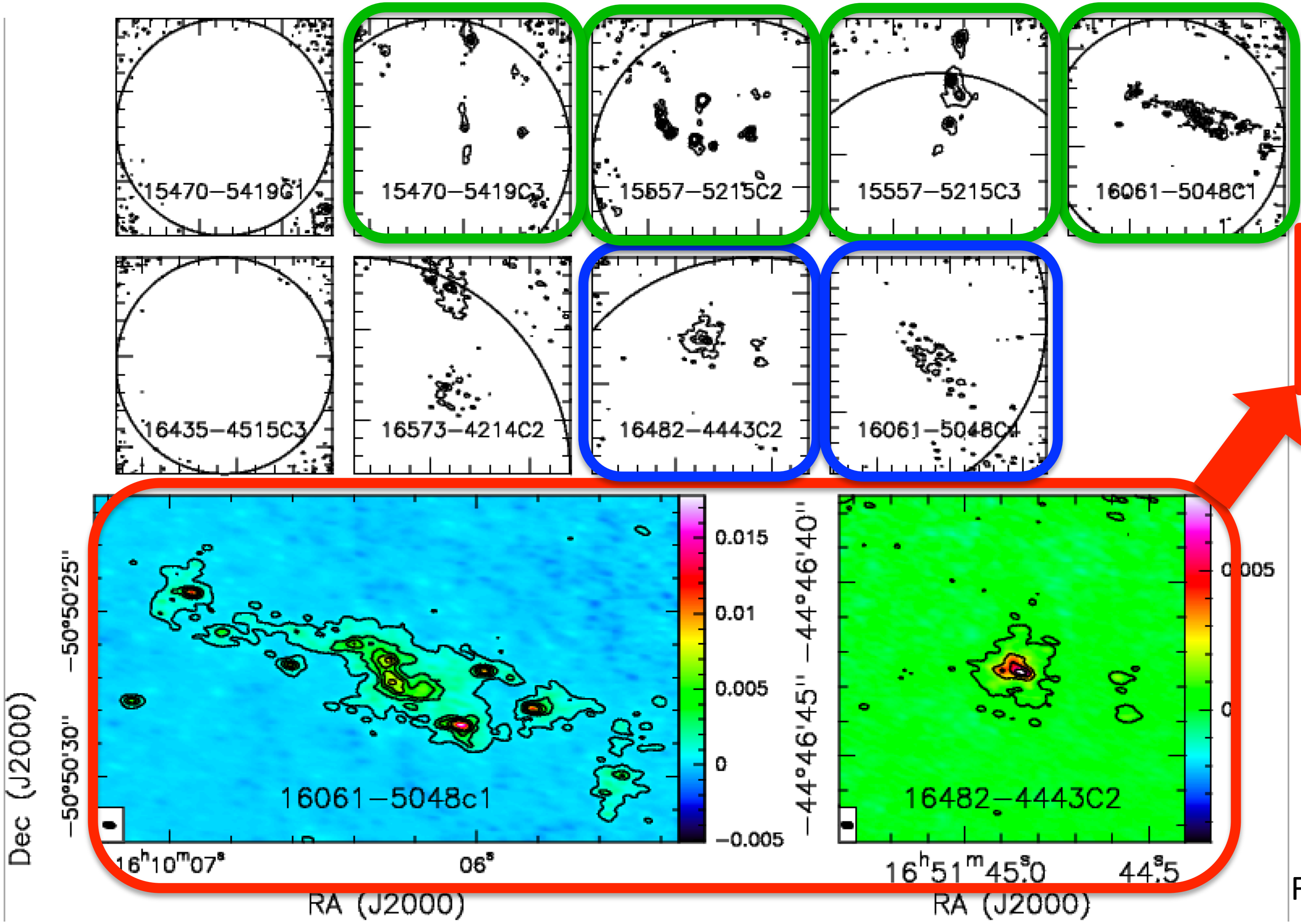
SYNTHETIC MAPS
(θ ~ 0.27'', 0.07 $M_{\odot}$)



...and what we see!

ALMA @ 278 GHz

(projects: 2012.1.00336.S ; 2015.1.00449.S PI: Fontani)



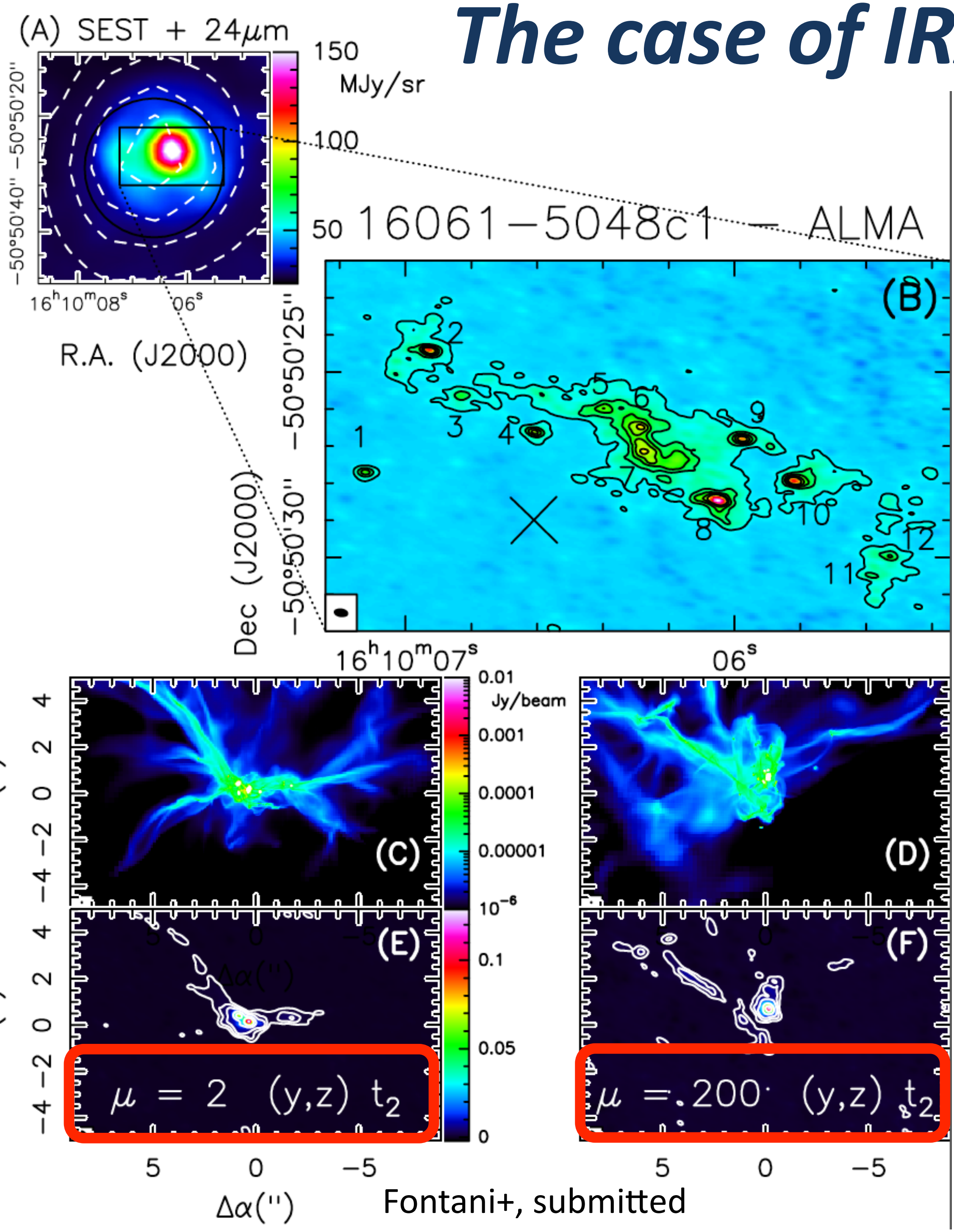
Resolution: θ~0.25"

Sensitivity: ~0.07 $M_\odot$

Two "extreme" cases:
- 12 fragments
- 1 fragment

Fontani et al., in preparation

The case of IRAS 16061-5048C1



Fontani+, submitted

Despite many fragments, overall morphology more in line with ***strong magnetic support (μ=2)***!!

…but a higher statistics is mandatory!!!

Simulations run specifically for this clump:

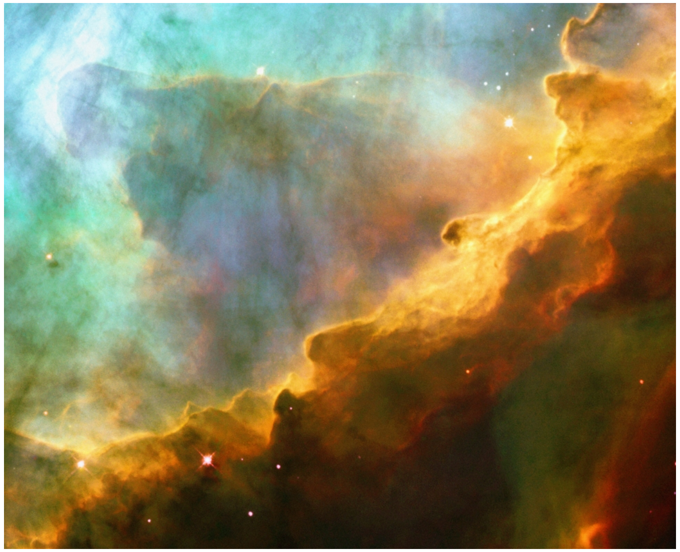
- M = 300 M_{sun}
- T_k = 20 K
- Mach number = 6.44

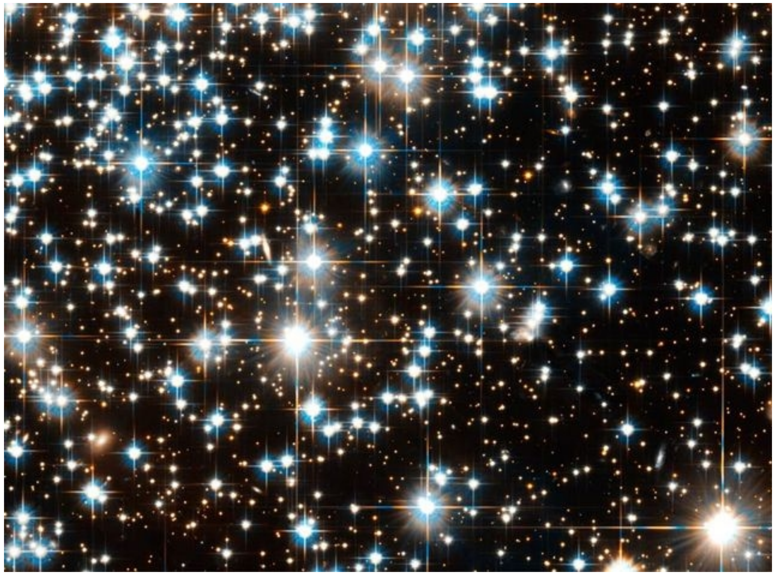
The CMF as a tool to investigate fragmentation and SF

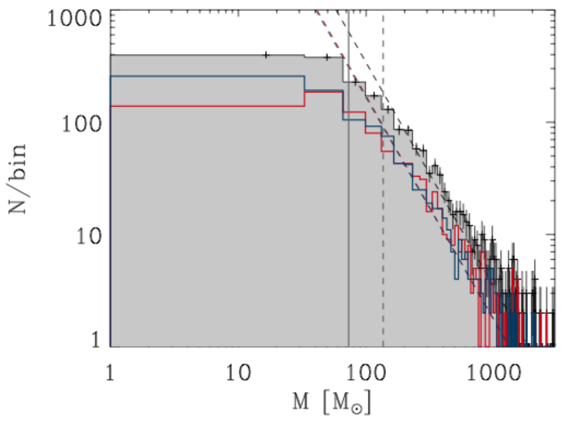
Luca Olmi, INAF-OAA

(INAF-OAA, INAF-IAPS, UPR)

CMF: Physical meaning

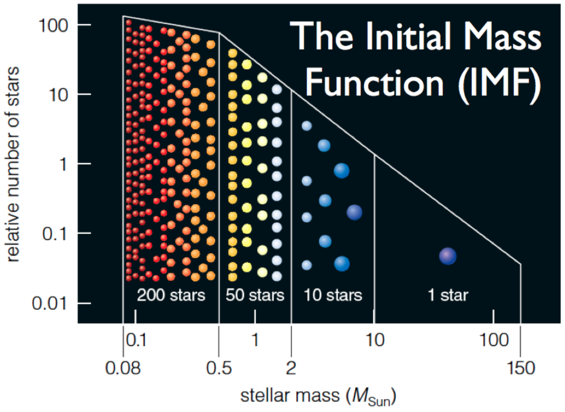






CMF

IMF scaled version of CMF?



Determining the parent distribution of CMF may help to understanding how dense molecular clumps/cores produce the full spectrum of stellar masses

CMF: Observational issues

Determining the parent distribution is complicated:
- Needs CMF over large (mass) dynamic range
- Most distributions look similar over limited range.

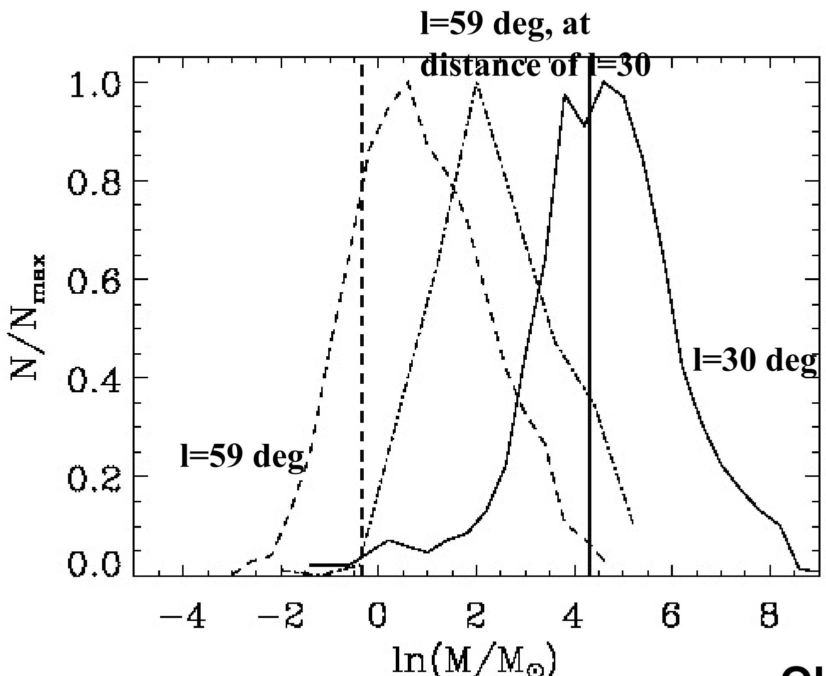
CMFs are usually measured over "large" regions of sky $\Rightarrow$ sum of many local cloud mass functions

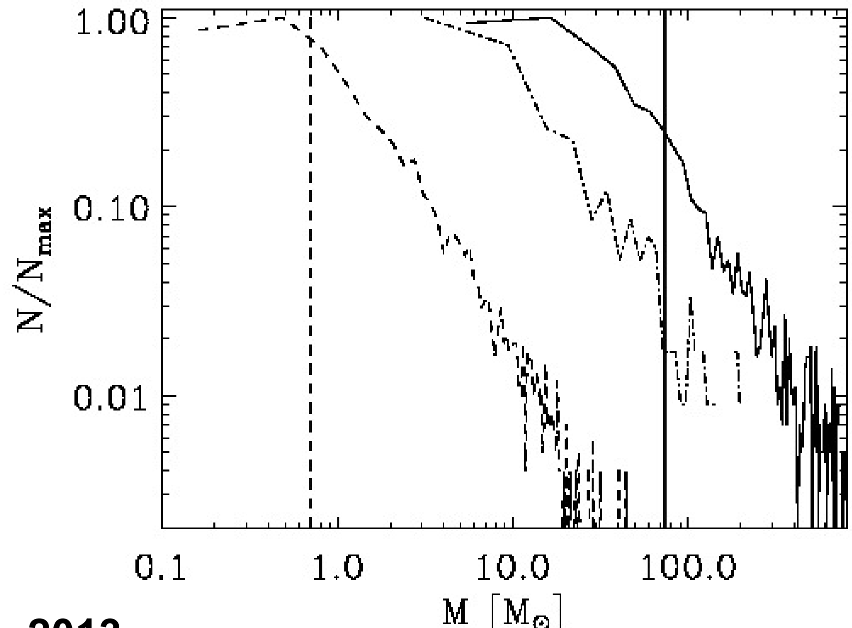
How does the CMF change at progressively higher angular resolution? Different physical processes at play?

$\Downarrow$

- ***Large samples (Hi-GAL)***
- ***Bayesian inference techniques***
- ***High-angular resolution***

CMF: Large angular scales





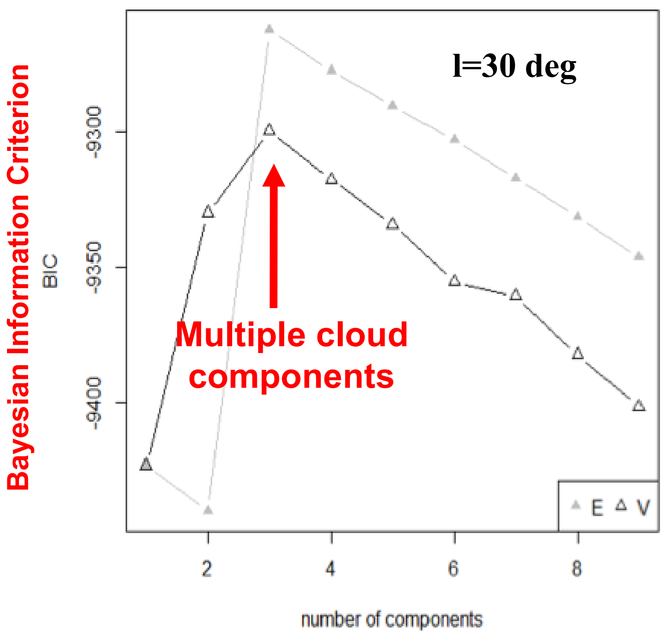
Olmi *et al.*, 2013

The CMFs of the two SDP fields (~4deg^2) have very similar shapes but different mass scales (distance effects not enough). Evidence that the overall process of SF in the two regions is very different (Olmi *et al.*, 2013, 2015).

BUT

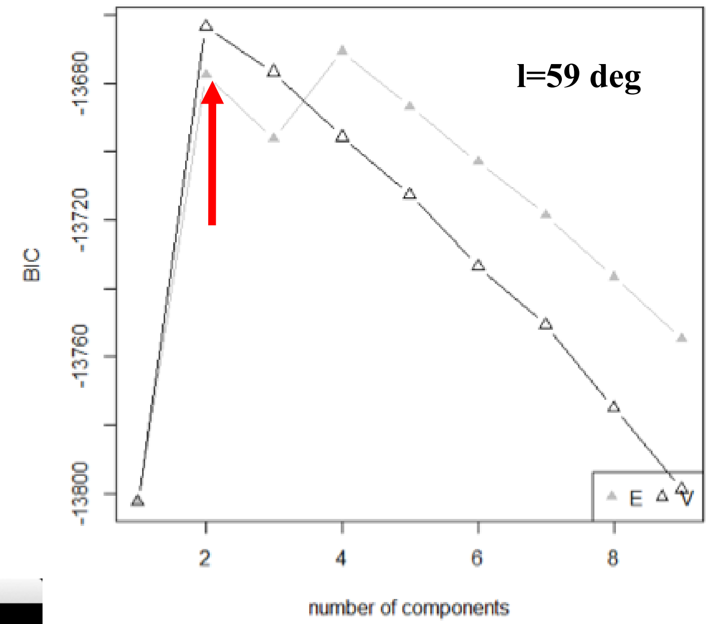
Clustering effects?

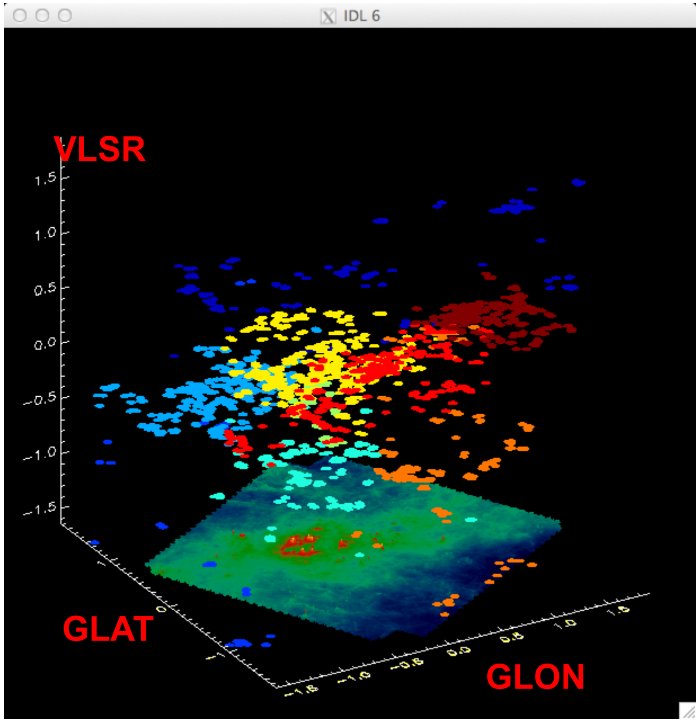
CMF: Clustering



L. M. Torres' MS Thesis

(*MCLUST* analysis)





Bayesian Inference

Bayesian inference can be used for estimating the model parameters

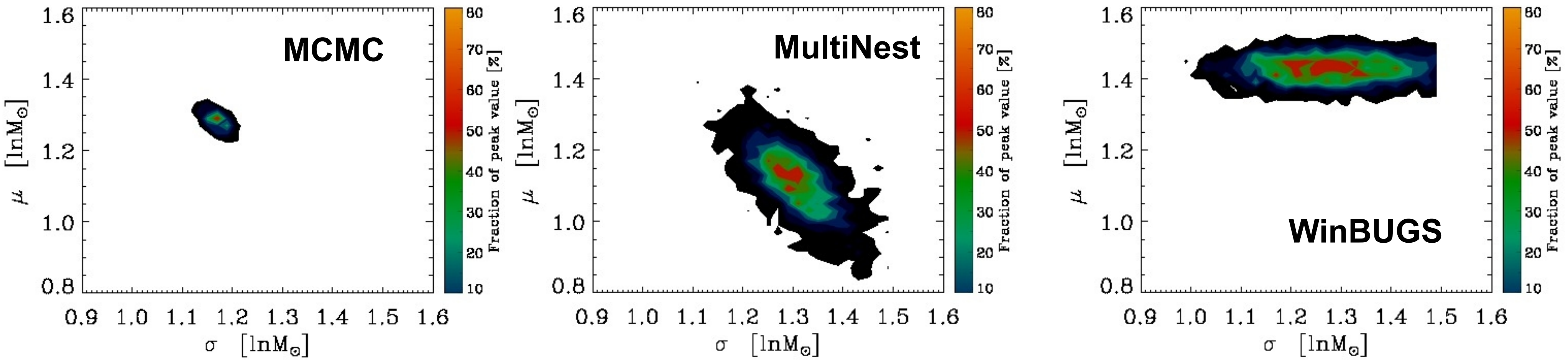
Bayes theorem also allows to calculate the ratio of the probabilities that two competing models have generated the data, given any prior information (model comparison)

- ***Setting Priors***
- ***Numerical computation***
- ***Model setting (e.g., Hennebelle & Chabrier)***

"Model selection for the mass distribution of a star-forming region in the Milky Way using the Expected Posterior Prior approach."

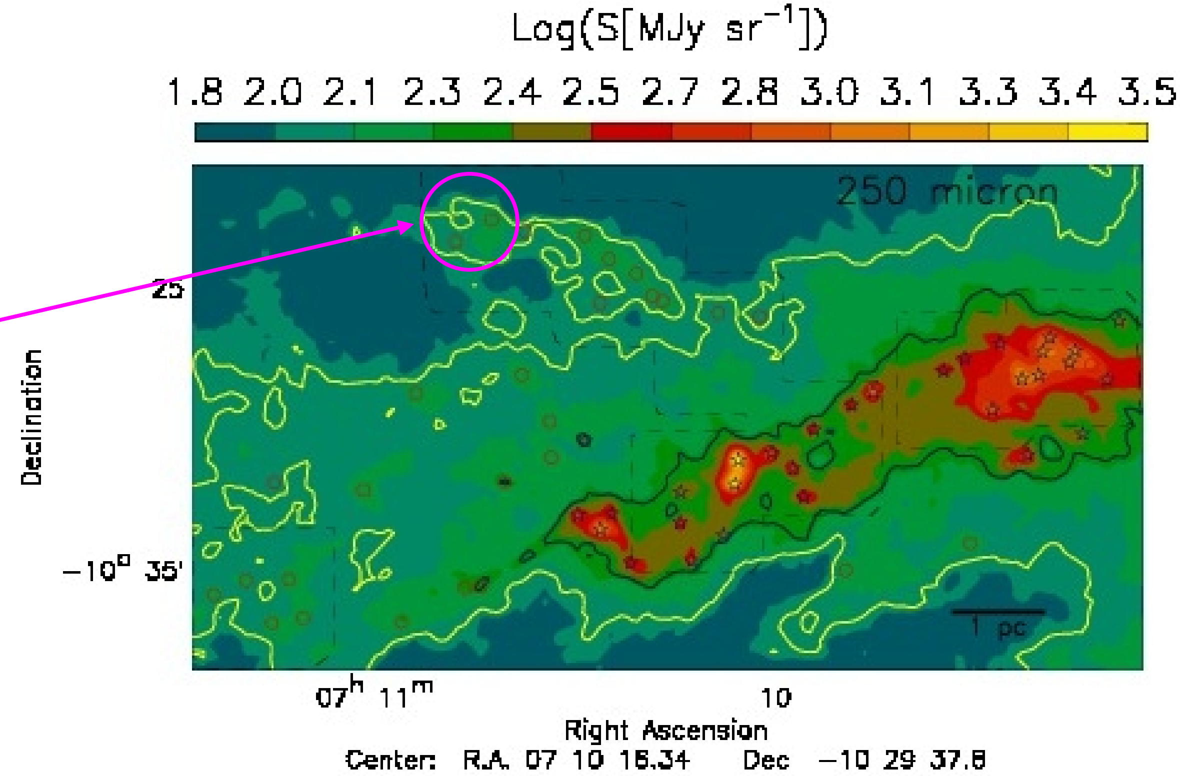
By

Richard A. Clare Morales



Olmi *et al.*, 2013, 2014

Higher Resolution (ALMA)



- **l=224deg region: low confusion ⇒ isolated and well-defined cloud**

- **Uniform (low) ambient temperature ⇒ coeval & recent SF process**
- **Segregation of starless and proto-stellar clumps (Elia et al. 2013, Olmi et al. 2016 subm.)**

ALMA+ACA continuum and spectral line mapping of clumps ⇒ FMF (Fragment Mass Function)

Overall conclusions

– Understanding the role of turbulence in HMSF requires statistically significant samples, and a thorough analysis of 1000s objects observed in the FIR/sub-mm.

– At small spatial scales, magnetic support in HMSF can be dominant even for a highly fragmented clump, but statistically significant samples are also required $\Rightarrow$ ALMA, NOEMA

– "Decoding" the CMF at low- and high-spatial resolution will help to identify the physical processes responsible for fragmentation at different spatial scales.