CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Fragmenting Clumps and Forming Clusters: High-Resolution Views of Massive Star Birth

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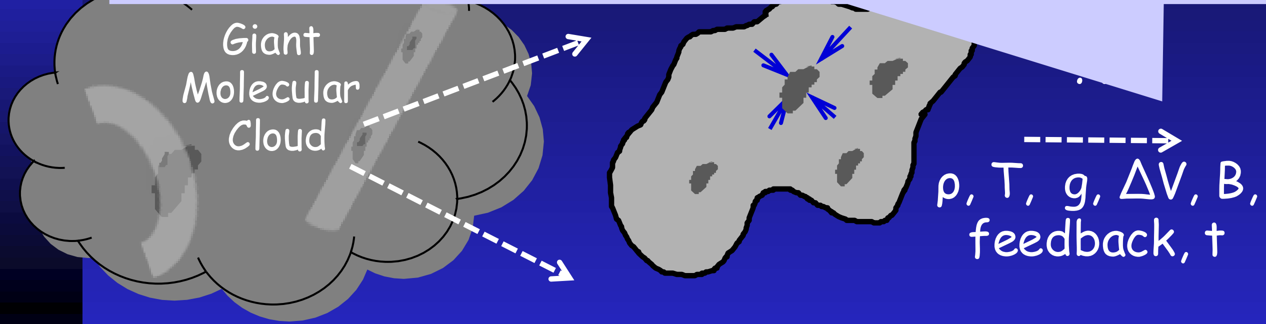
Harvard-Heidelberg Star Formation Series: 2014 -

Massive Star (Cluster) Formation

- How do massive clumps fragment into cores?
- Which processes affect fragmentation (thermal, turbulent, magnetic fields)?
- How do cores gain mass?
- What is relation between core mass function & stellar IMF?

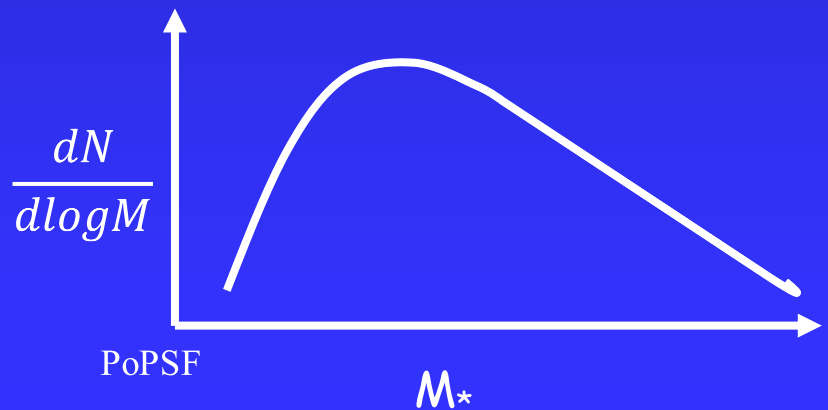


Young stellar cluster

10^2 pc
M ~ 10^5 Msun

pc-scale clump
10^3 – 10^4 Msun

10^2-10^3 stars with a range of stellar masses centrally peaked

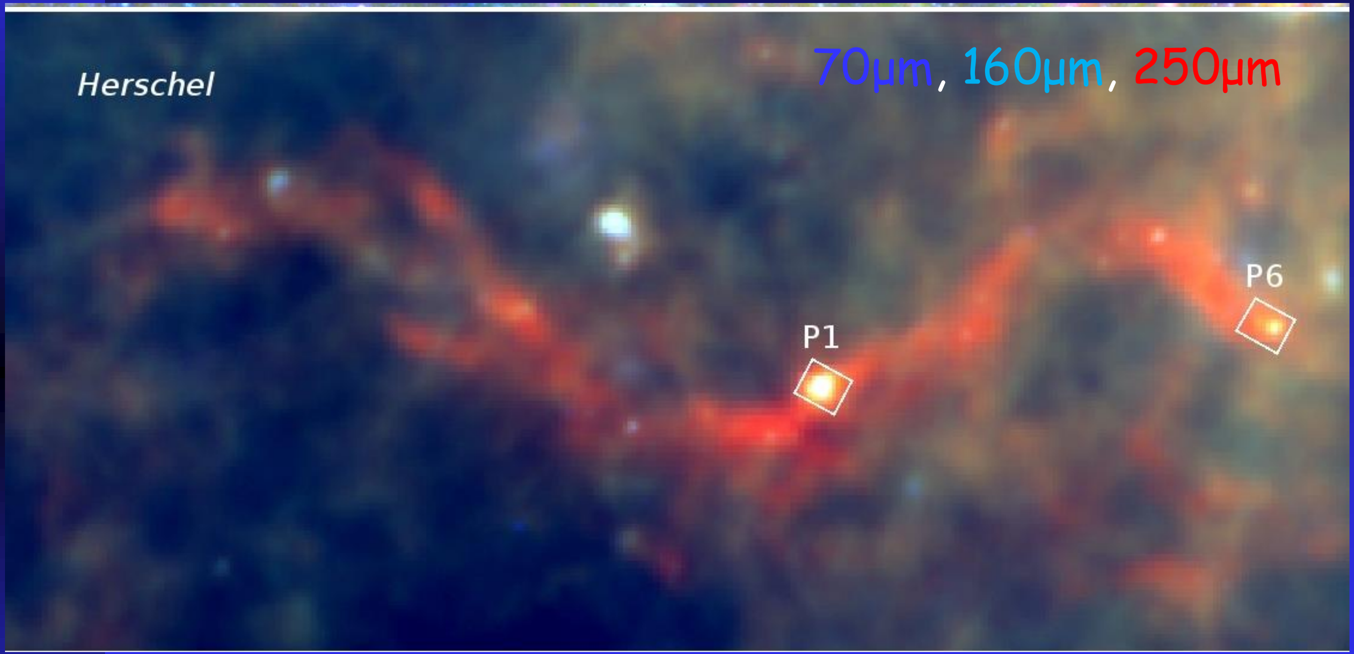


See Beuther, Kuiper, Tafalla 2025 for a review

Cradles of Massive SF: IRDCs

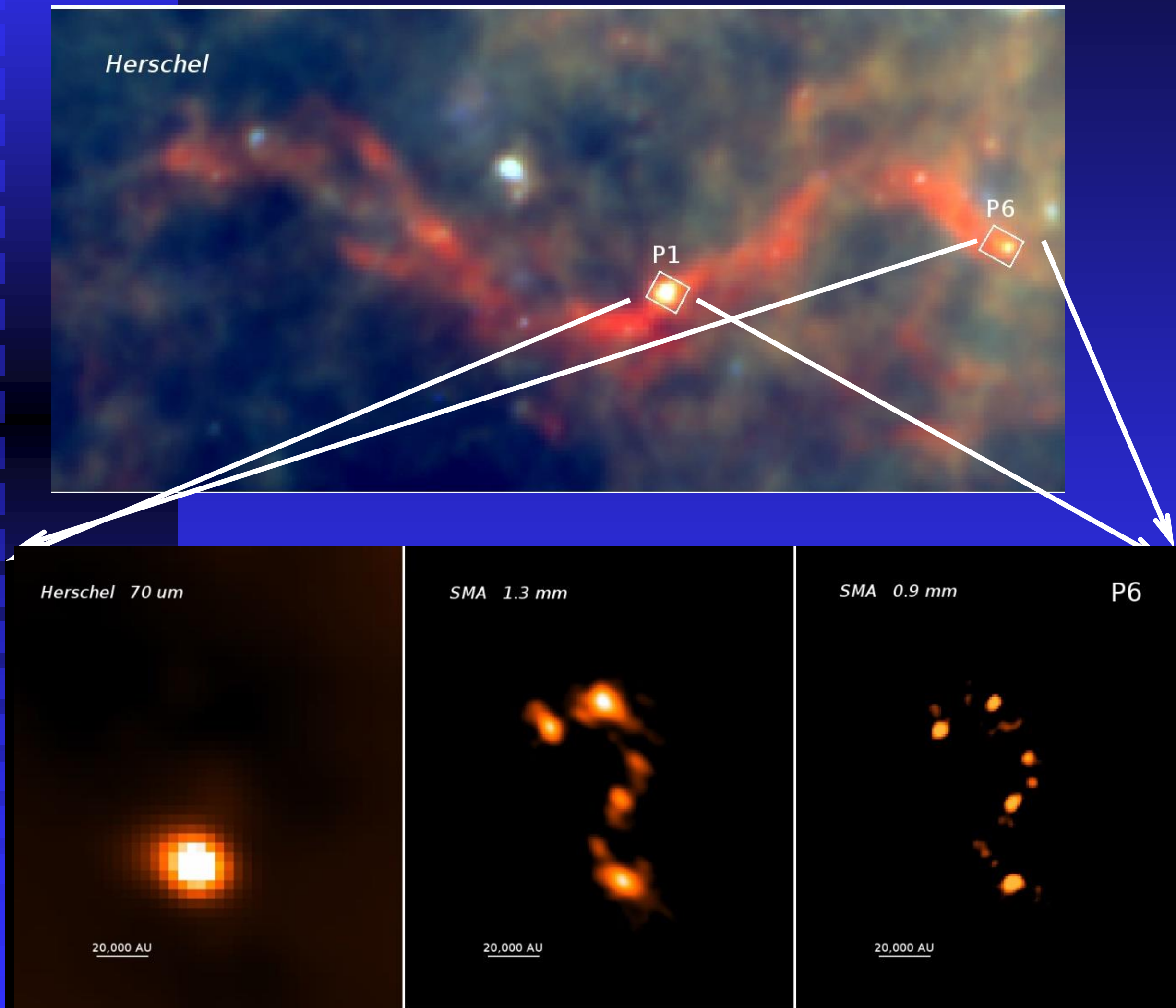
Dark from 8 to 70μm
Size = 28pc
T = 11-20 K

Henning et al. 2010



G11.11: (Sub)mm continuum

Wang, Zhang et al. 2014

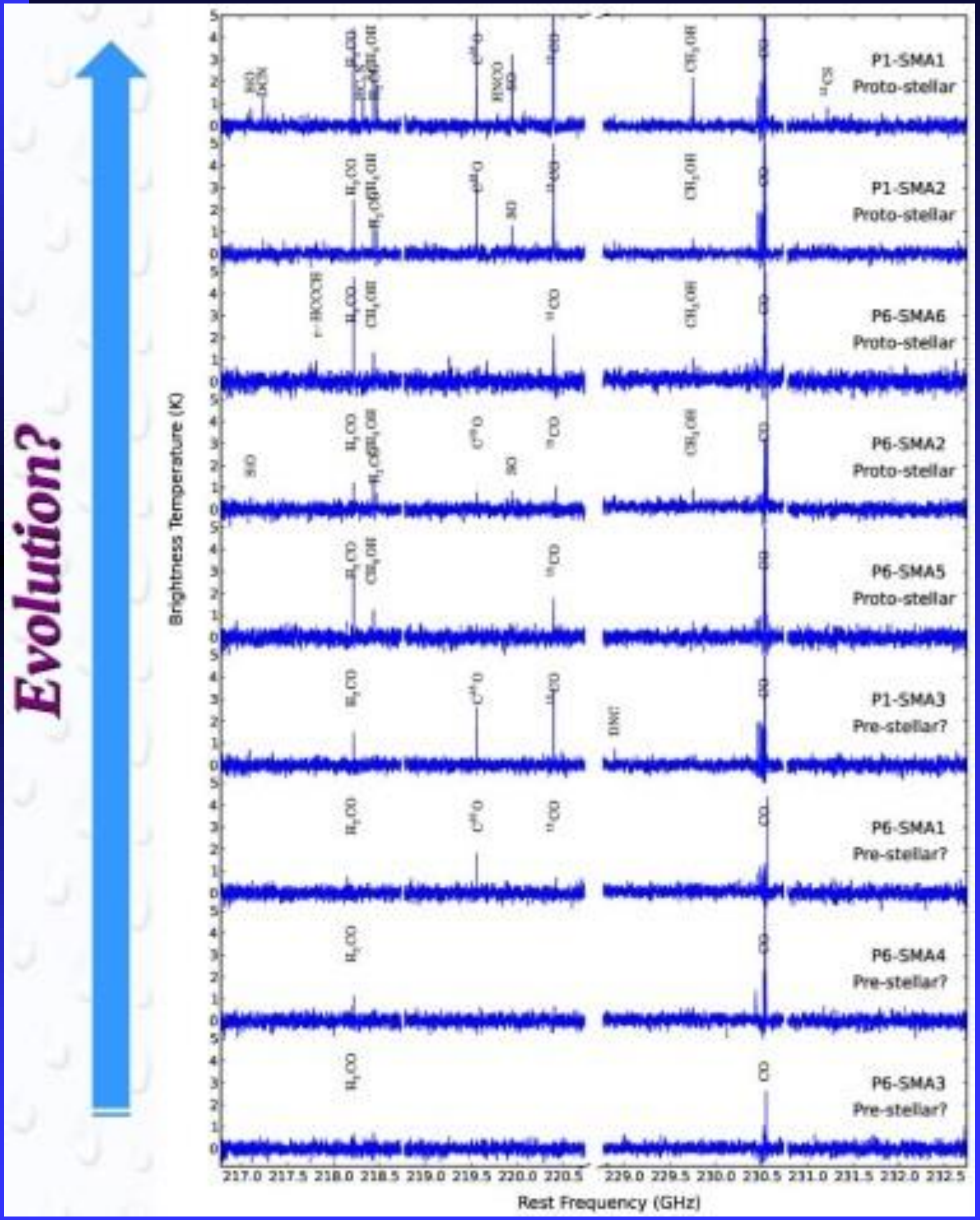


P1:
M(clump) ~ 10^3 Msun
L = 1300 Lsun
SMA detects 6 cores
5-23 Msun

P6:
M(clump) ~ 10^3 Msun
L = 140 Lsun
SMA detects 17 cores
3-28 Msun

T = 11-20 K
V = 1.5 kms^{-1}
M_{Jeans}(thermal) = 1 Msun
M_{vir} < M(cores)

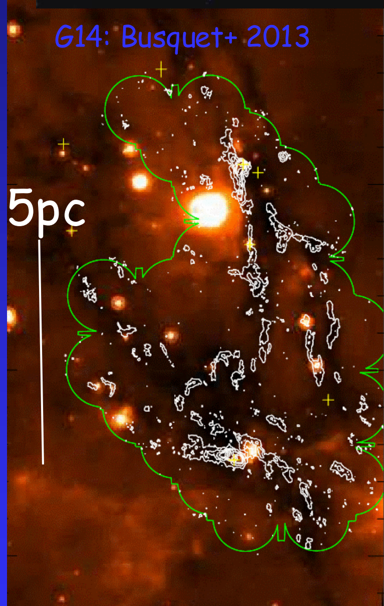
Chemical Evolution



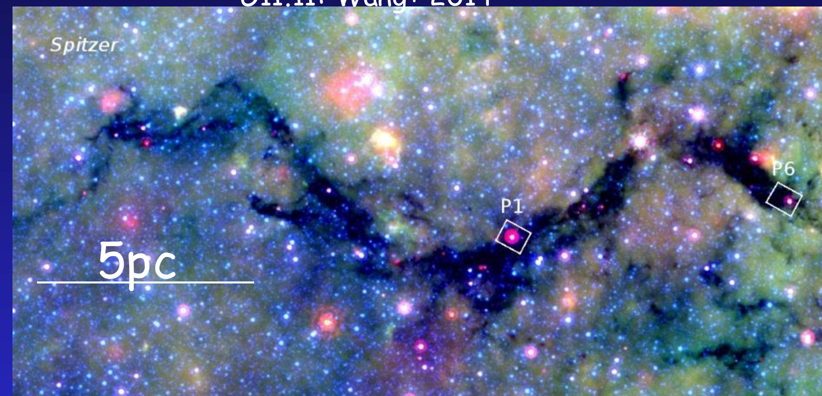
Several cores with no line emission other than CO → prestellar ??

Stellar heating evaporates complex organic molecules CH3OH, CH3CN, which then continue to evolve in gas phase reaction

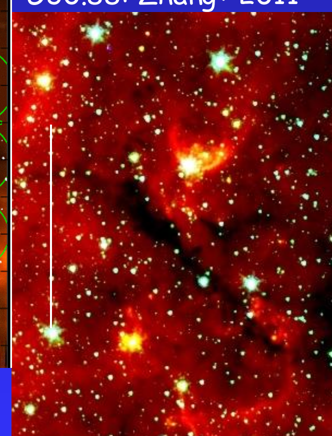
Recent High-Res Imaging of IRDCs



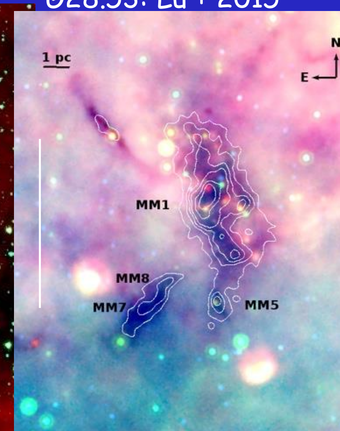
G11.11: Wang+ 2014



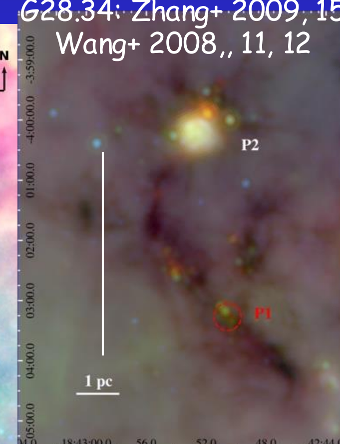
G30.88: Zhang+ 2011



G28.53: Lu + 2015

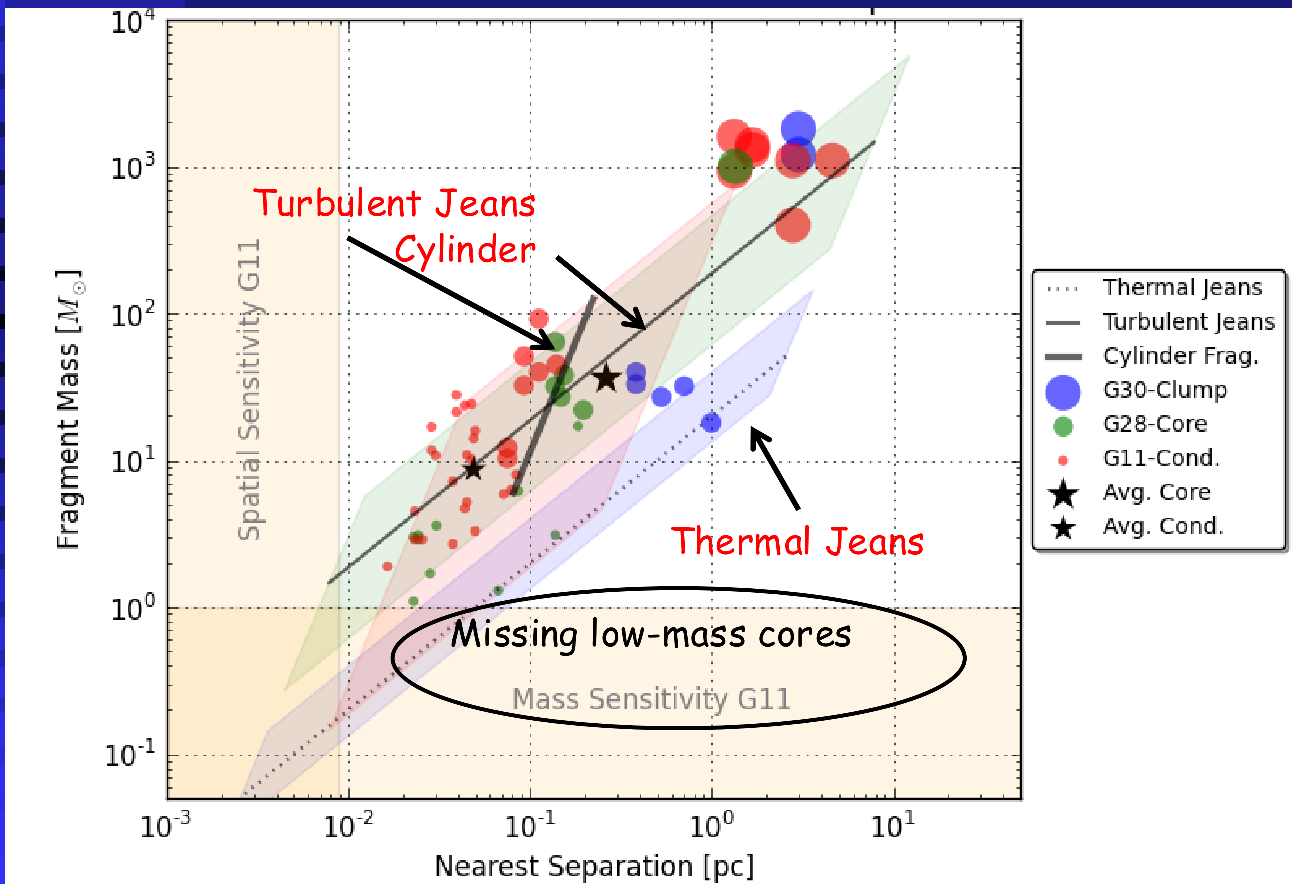


G28.34: Zhang+ 2009, 15
Wang+ 2008,, 11, 12



Hierarchical Fragmentation

Comparison with Jeans fragmentation:
Thermal fragmentation does not explain massive cores
Additional support from turbulence and/or magnetic fields



$$M/L = \left(\frac{2\delta_v}{G}\right)$$

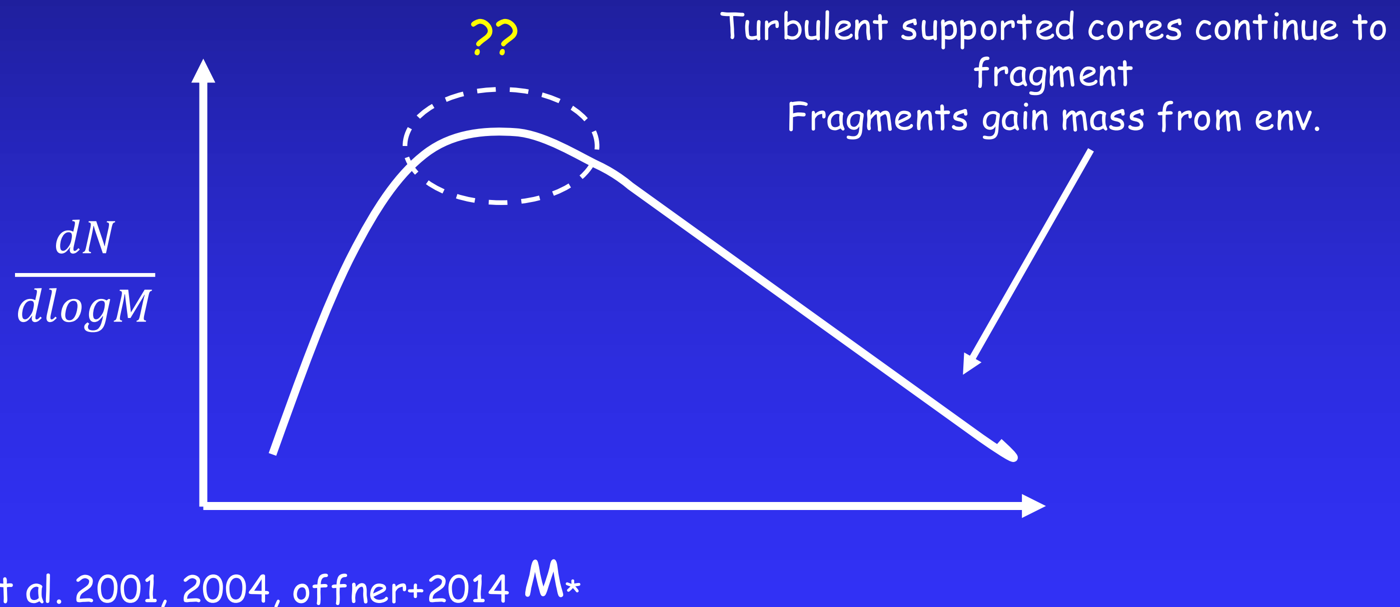
$$\lambda_{\max} = \begin{cases} 0.15\,\mathrm{pc}\left(\frac{c_s}{0.21\,\mathrm{km\,s^{-1}}}\right)\left(\frac{n}{3\times10^5\,\mathrm{cm^{-3}}}\right) \\ \text{for thermal support,} \\ 0.13\,\mathrm{pc}\left(\frac{\sigma}{0.72\,\mathrm{km\,s^{-1}}}\right)\left(\frac{n}{5\times10^6\,\mathrm{cm^{-3}}}\right) \\ \text{for turbulent support.} \end{cases}$$

See Chandrasekhar & Fermi 1953;
Larson 1985; Nagasawa 1987

Wang+ 2011, 2012, 2014, Zhang+ 2009, 2011
See also Pillai et al. 2011

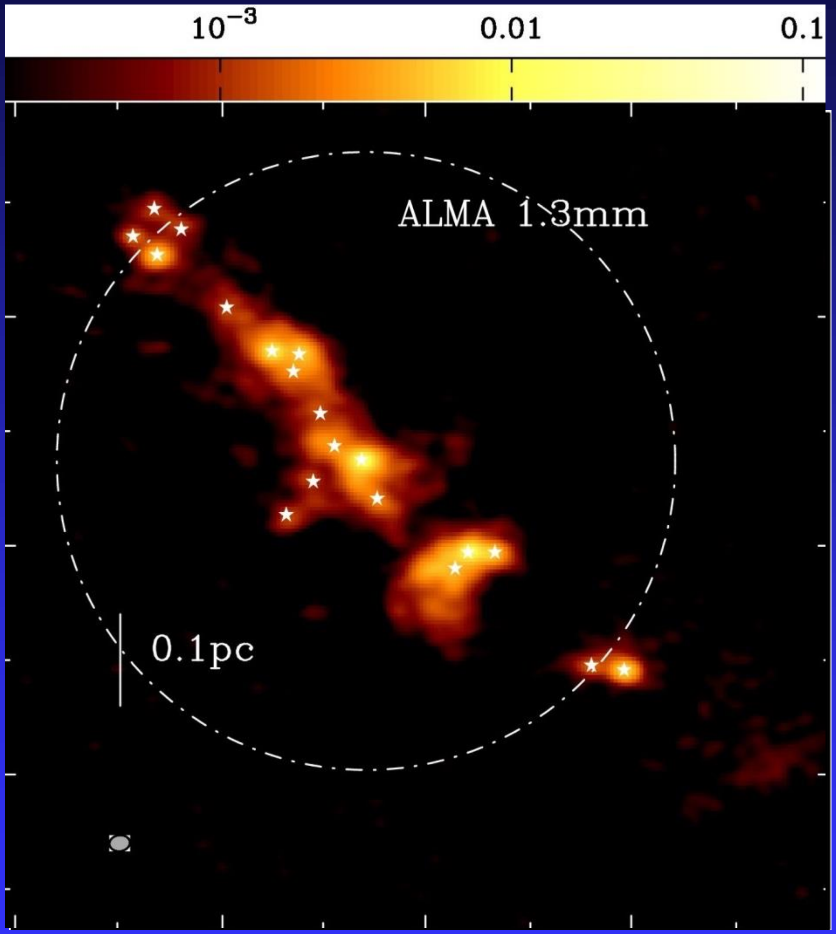
Origin of low-mass cores/stars

- Jeans mass = 1 Msun for typical T and n in massive clumps → Is the peak of stellar IMF related to the global Jeans mass ?



Larson 2005; Bonnell et al. 2001, 2004, offner+2014

IRDC G28.34: ALMA Observations



SMA → ALMA X30 sensitivity
38 cores

observations reached a 3σ mass sensitivity of 0.2 Msun, far below the global Jeans mass of 2 Msun.

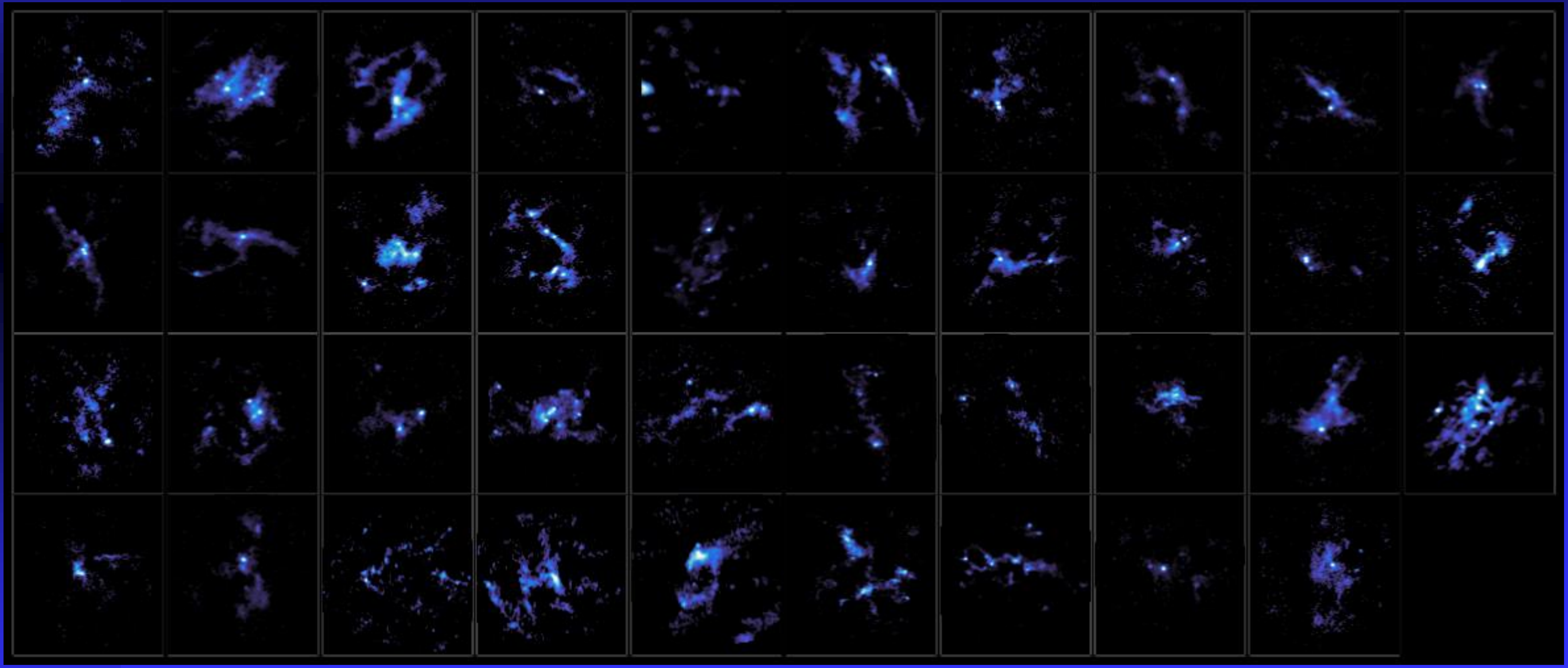
Zhang et al. 2009, 2015

See also Liu+ 2015; Cyganowski+ 2016; Henshaw+ 2016

ASHES: ALMA Survey of 70μm dark High-mass clumps in Early Stages

10-pointing mosaics per source with the 12-m array + ACA + TP at 224 GHz

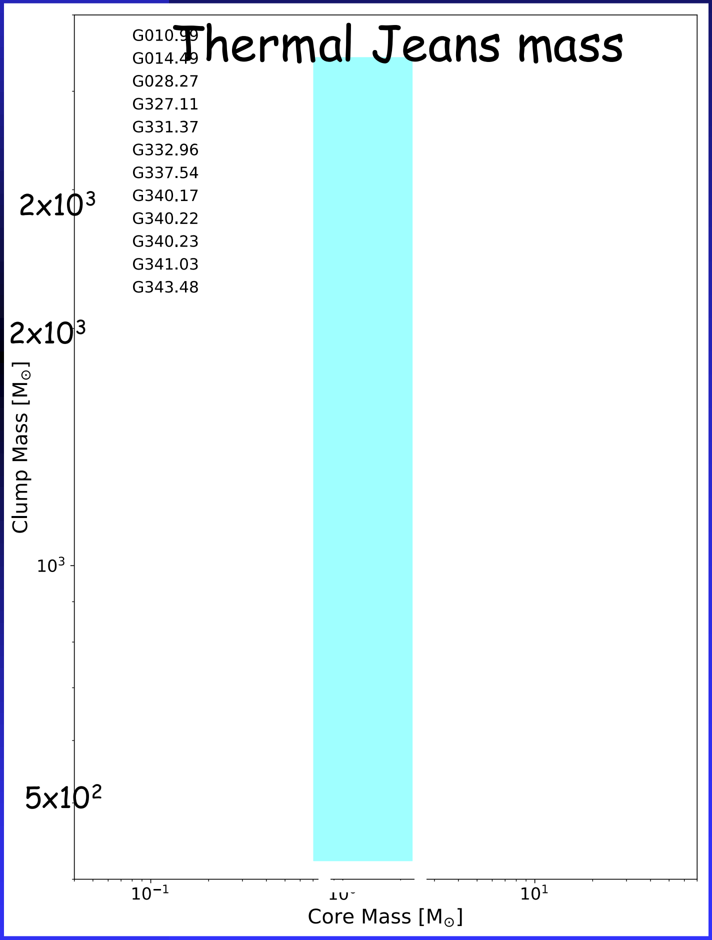
1.4mm continuum for 39 clumps



Sanhueza+ 2019; Morii et al. 2023

Core masses during fragmentation

ASHES: Sanhueza+ 2019 (12 massive clumps)



296 cores with masses from 0.12 to 30Msun
Mass spread x100
Mean mass ~ thermal Jeans mass

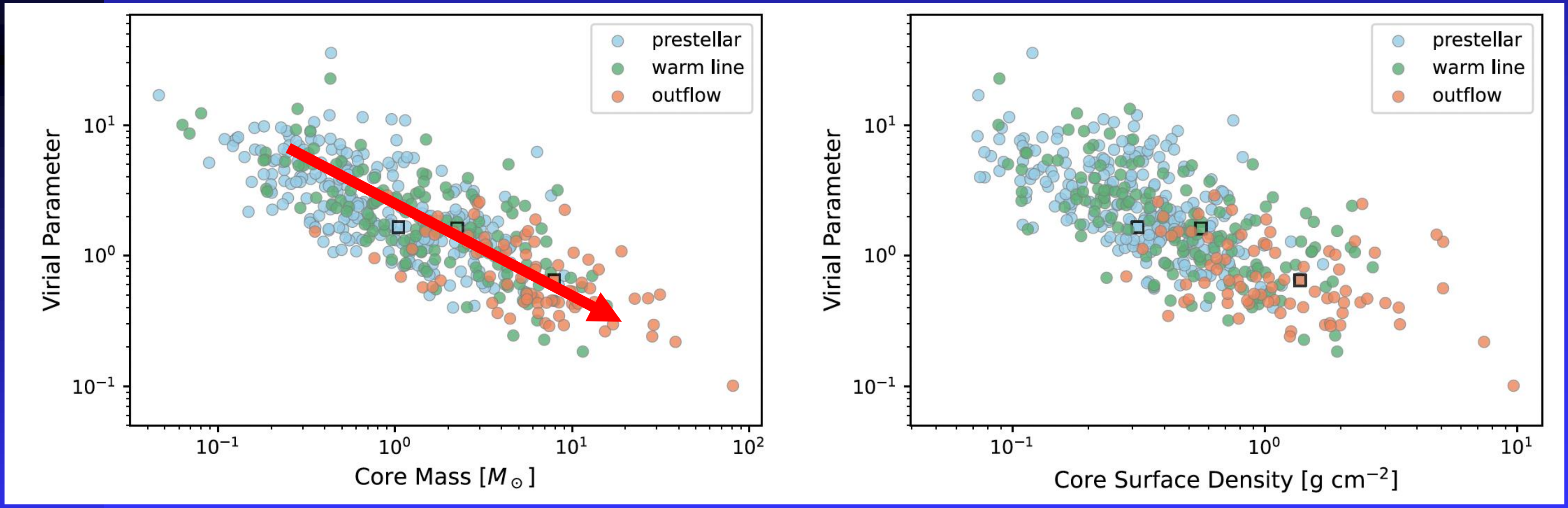
Observational parameters:

- Angular resolution ~1.2” (6,000 AU at 5 kpc)
- ~4 GHz bandwidth for cont. emission, σ~0.08-0.1 mJy (4σ of 0.4 M$_\odot$ at 5 kpc)

See also Svoboda et al. 2019
Morii et al. 2023 (39 clumps, 839 embedded cores with masses 0.05 to 81 M$_\odot$)

Core mass growth?

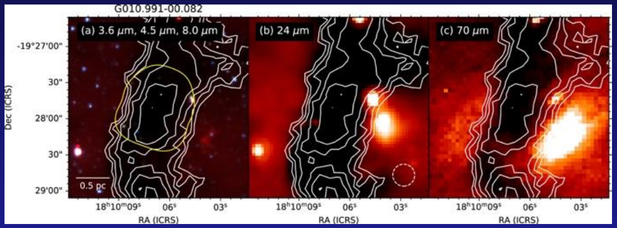
- Protostellar cores more massive than prestellar cores;
- Protostellar cores tend to have virial parameters < 1
- Cores increase mass as they evolve

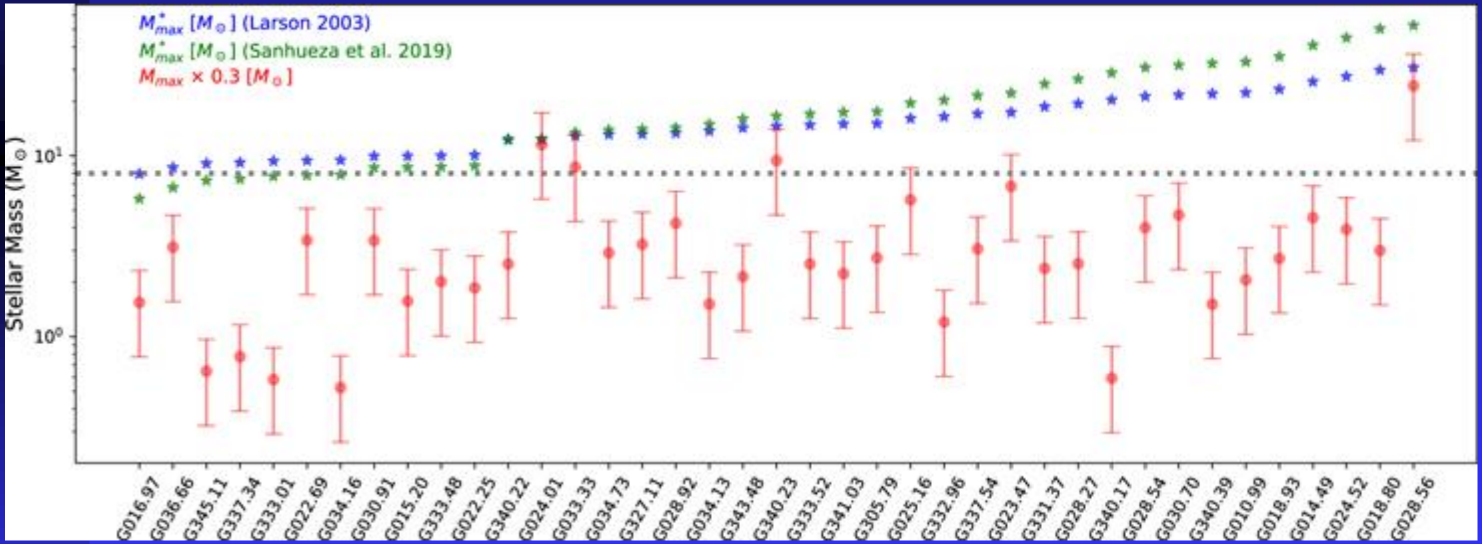


Sanhueza+ 2019; Morri+ 2023

Max. core mass in protoclusters

- Max. core mass in clumps << stellar mass expected → continuous core mass growth
- Massive (~10^2 Msun) starless cores are rare (implication to massive SF models)

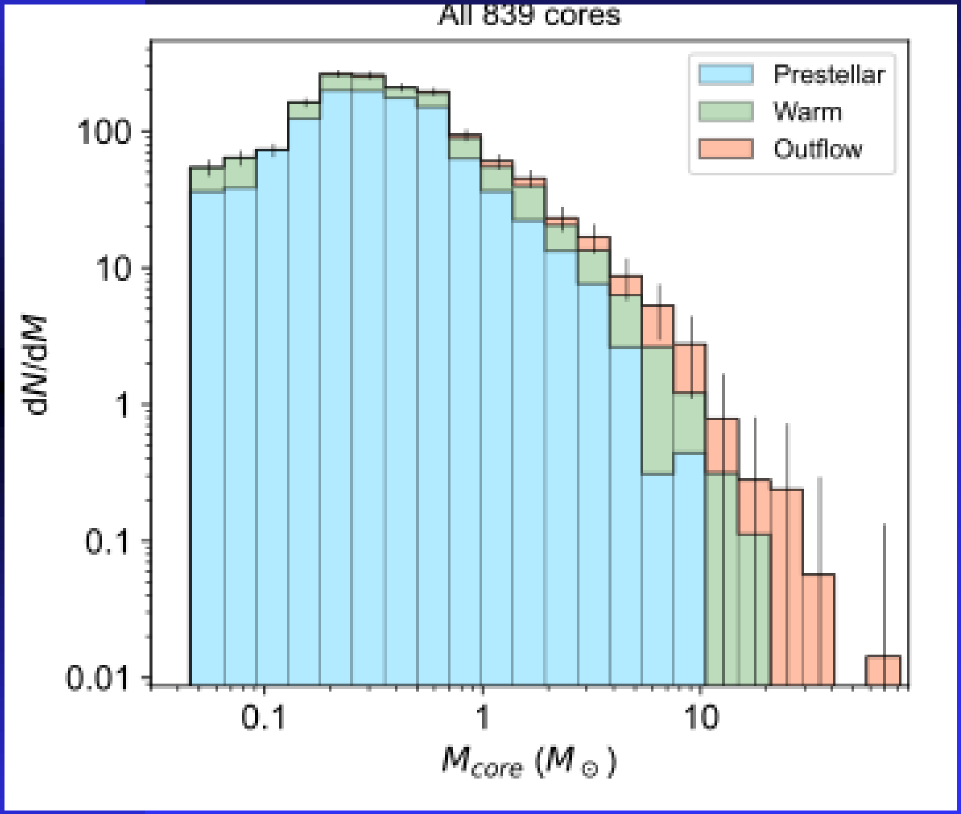




Morii+ 2023 (39 IRDC clumps)

Core Mass Function in protostellar clusters

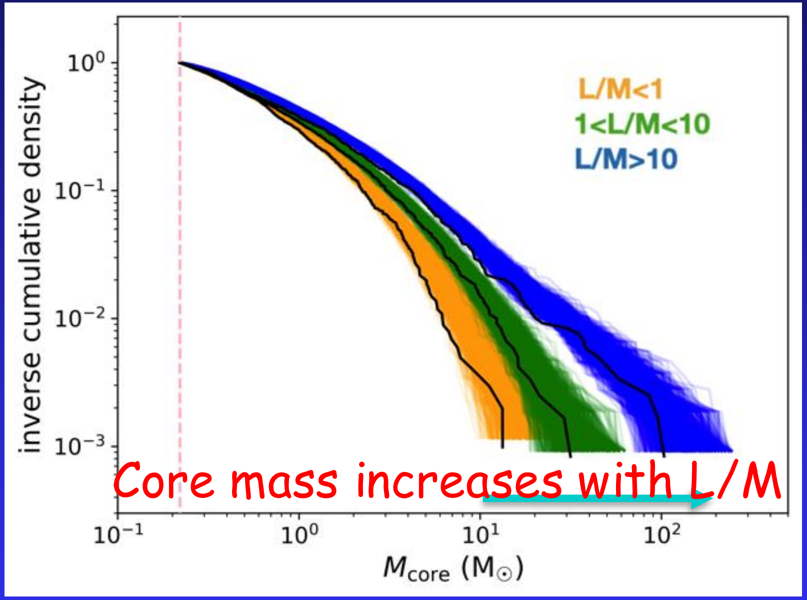
Morii et al. 2025



- CMF slope flattens from prestellar to protostellar cores → more massive cores among protostellar cores

Core mass function in protoclusters

- ALMAGAL surveyed 1017 massive clumps, Band 6, rms=0.1mJy, majority samples with d<7.5 kpc
- Compact continuum sources identified using CuTEx
- CMF grows in max mass for clumps at more evovled evolutionary stages characterized by luminosity/(clump mass) L/M, suggestive of a continuous core mass growth

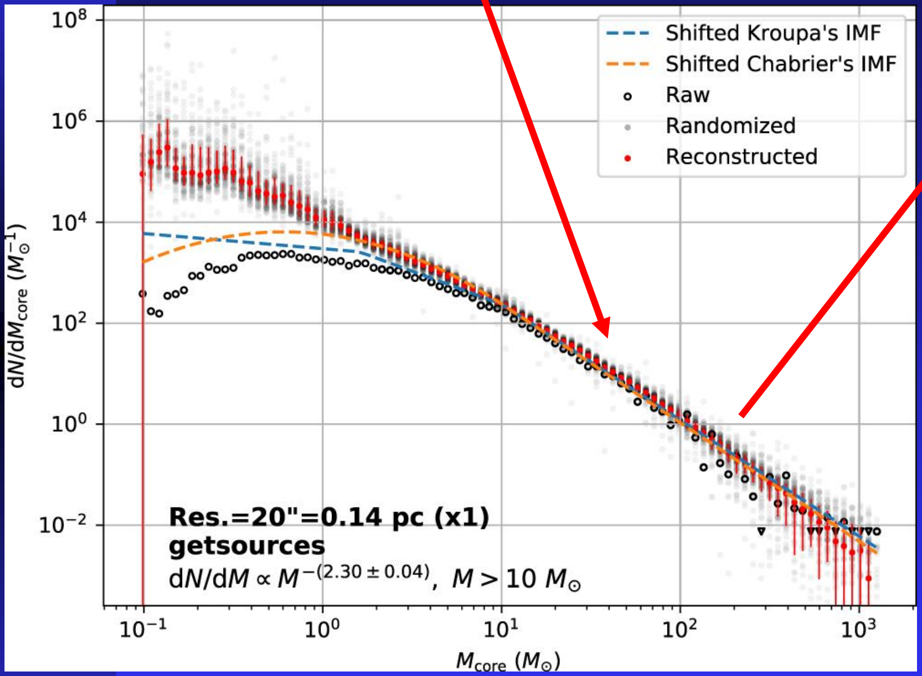


Coletta+ 2024. (1017 clumps)
Also ALMA_IMF, Pouteau+ 2023

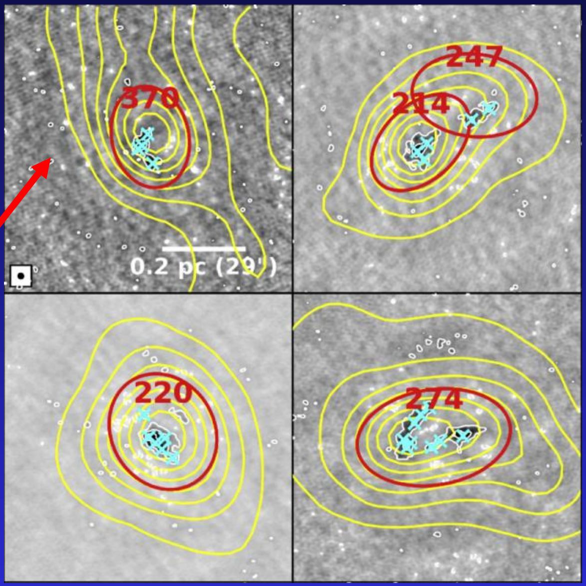
CMF & Stellar IMF: Case study of Cygnus-X GMC

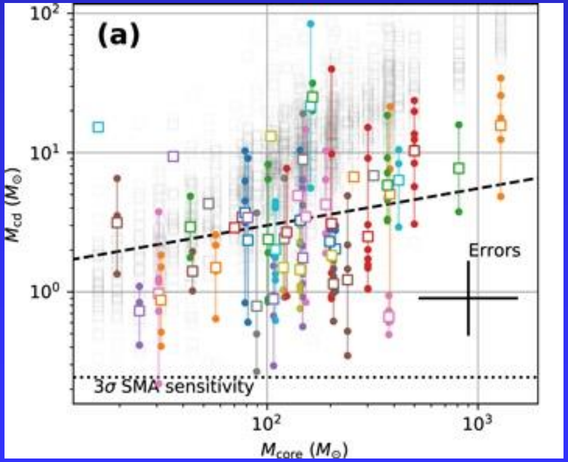
A Salpeter-slope CMF

But cores continue to fragment



Cores further fragment





Cao et al. 2019, 2021

Conclusions

- Massive cores in a protostellar cluster are x10 more massive than Jeans mass, pointing to additional support of turbulence and magnetic fields
- Cores often continue to fragment as they evolve
- Observed CMF is a snapshot and it continues to evolved
- Stellar IMF is not inherited from CMF despite similar shape

Many questions remain:

- Formation of binaries and multiples
- Effect of magnetic fields