Stellar Populations in Massive Star-Forming Regions

Elena Sabbi

TOSCA 2024

Young Massive Clusters

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- Feedback from YMC deposits energy, momentum, and new metals in the ISM

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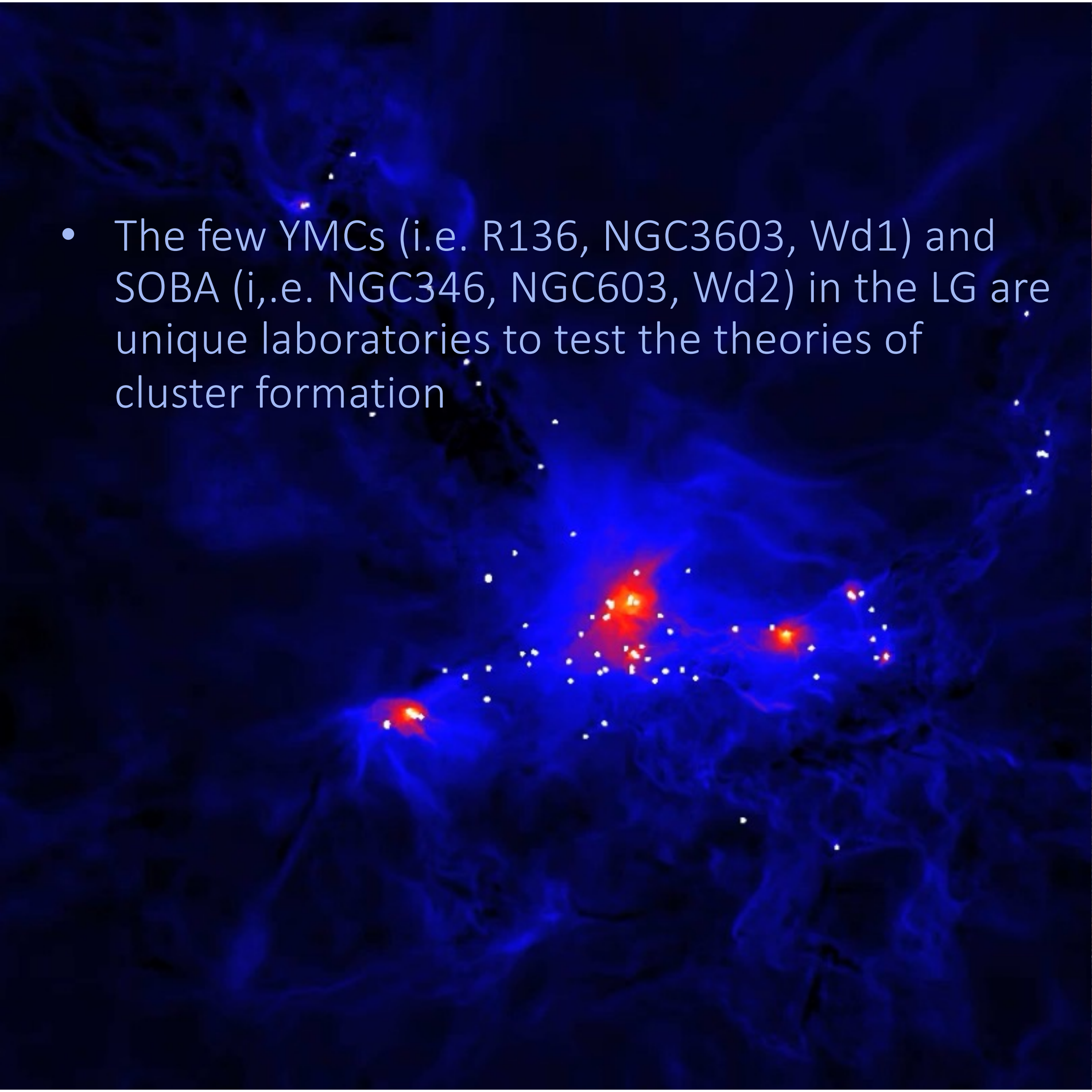
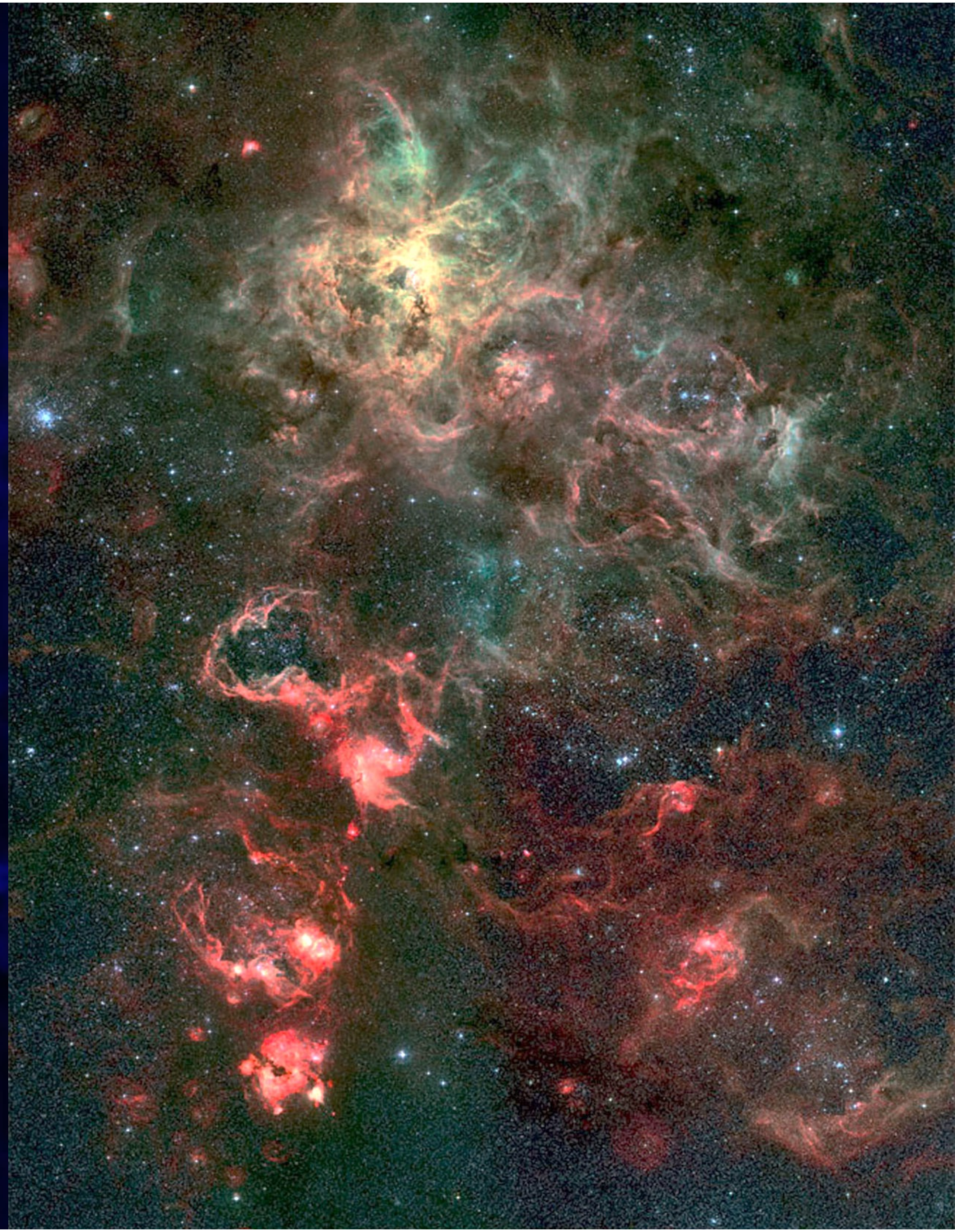
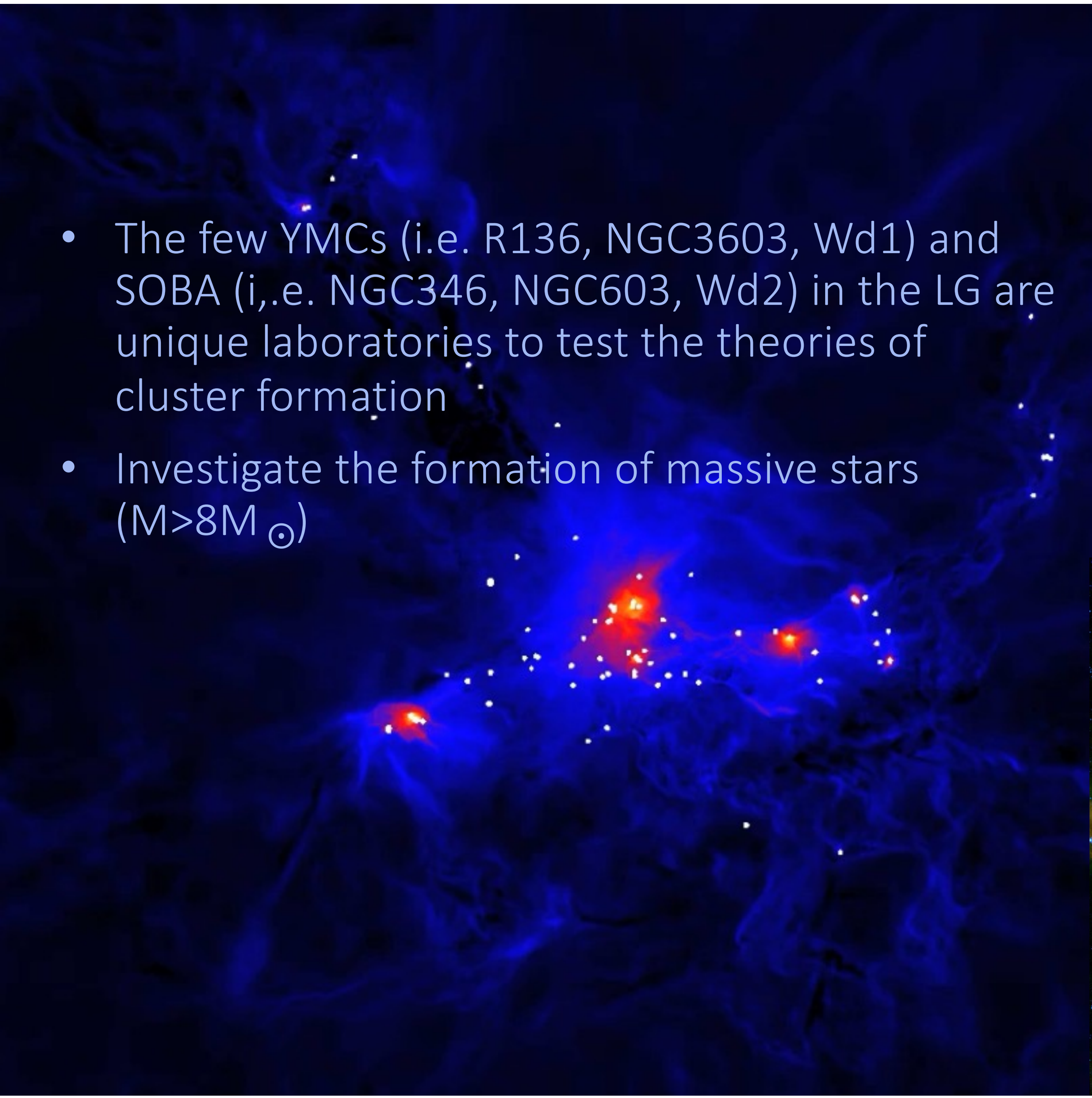
- Feedback from YMC deposits energy, momentum, and new metals in the ISM
  - It regulates galaxy growth, and is one of the Universe reionization sources
- YMCs are very bright -> Can be observed at high distance
  - Offer a glimpse of the earliest generations of stars



- The few YMCs (i.e. R136, NGC3603, Wd1) and SOBA (i,.e. NGC346, NGC603, Wd2) in the LG are unique laboratories to test the theories of cluster formation





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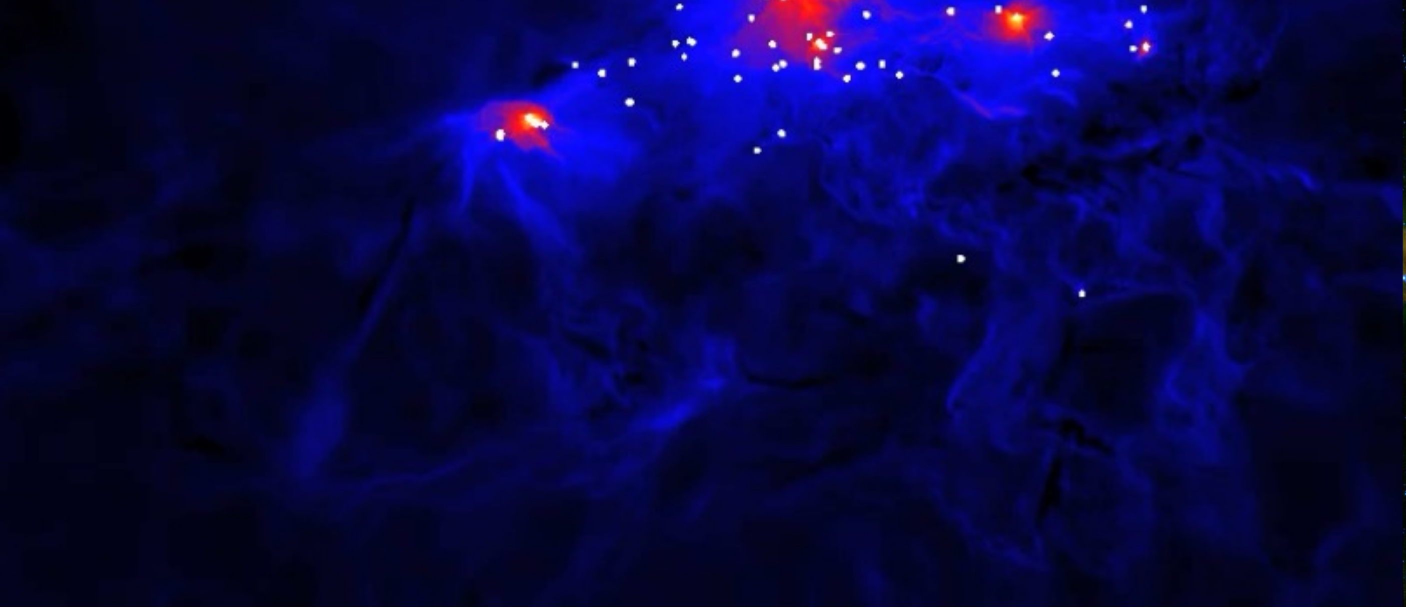
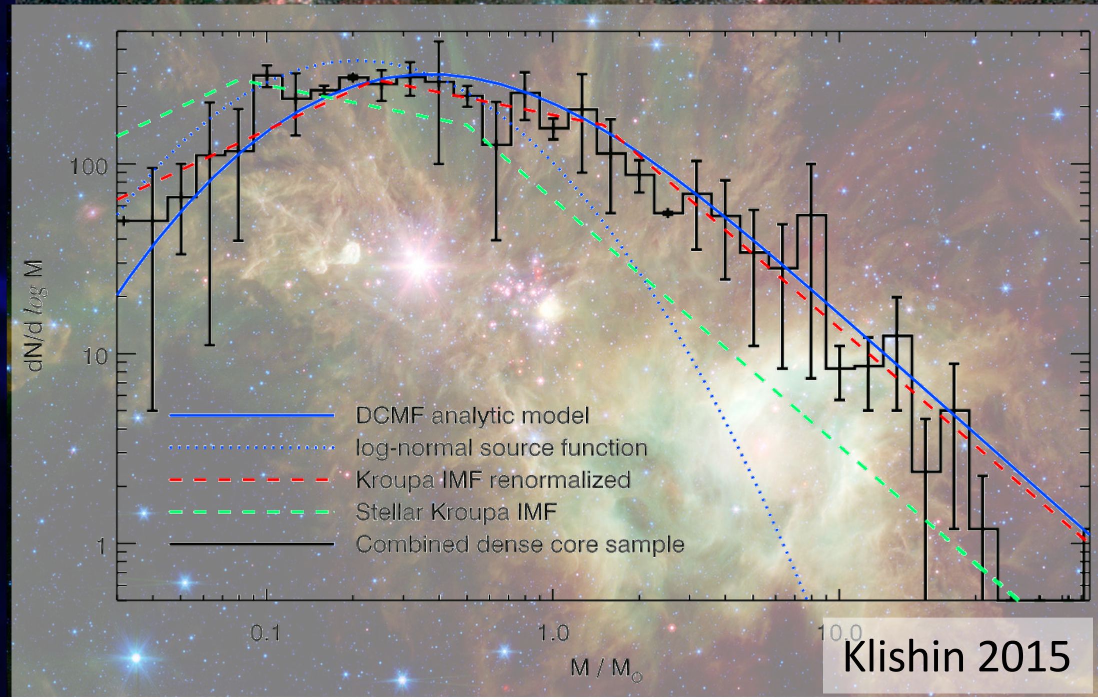
- Investigate the formation of massive stars ($M>8M_{\odot}$)
- Probe the universality of the stellar IMF





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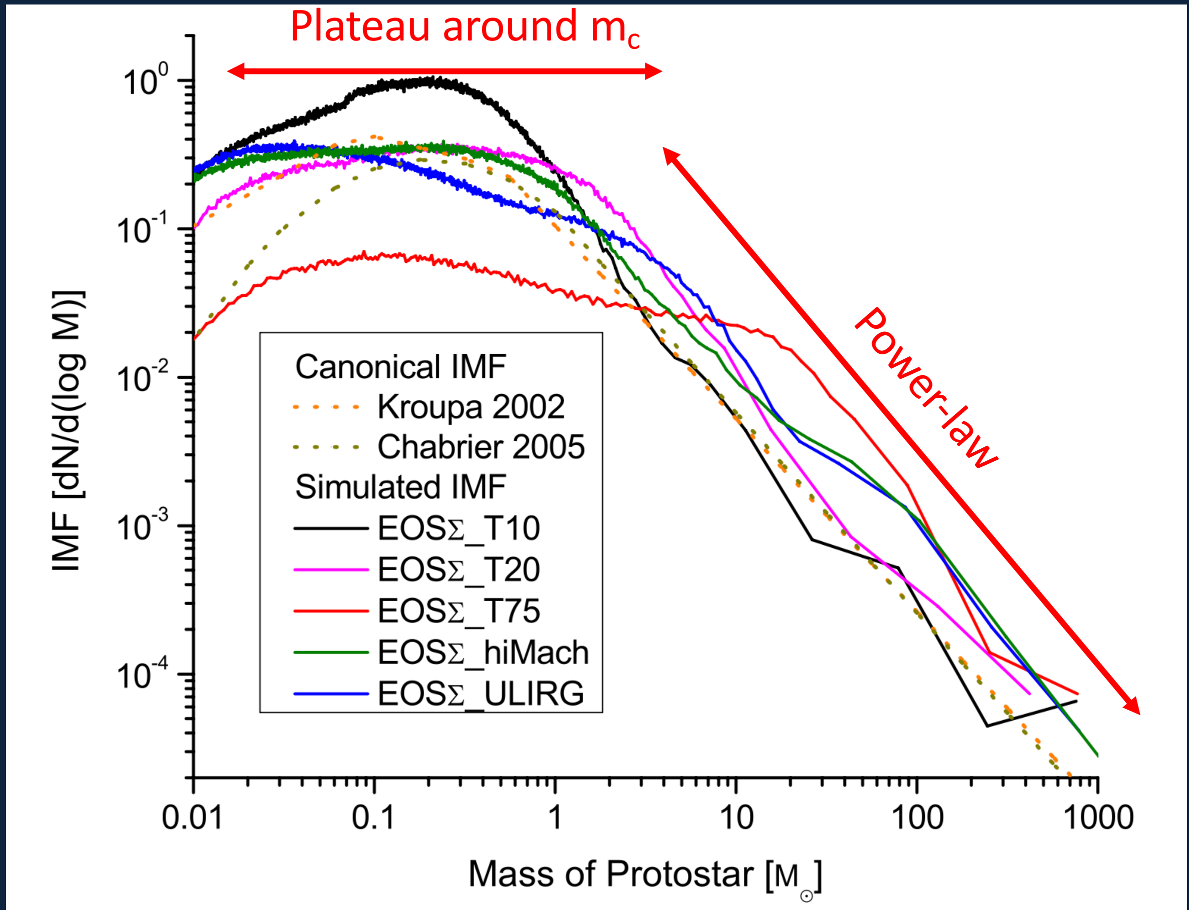
- Investigate the formation of massive stars ($M>8M_{\odot}$)
- Probe the universality of the stellar IMF
- Characterize the impact of UV radiation on circumstellar and protoplanetary disks

The IMF in Local Group Young Star Clusters



The IMF is key to correctly interpret, at all z, the history of stellar populations, element abundances, estimate the number of stellar transients (SNae, GRBs, GWs)

The ability to predict the shape of the IMF remains a major challenge for theories of SF

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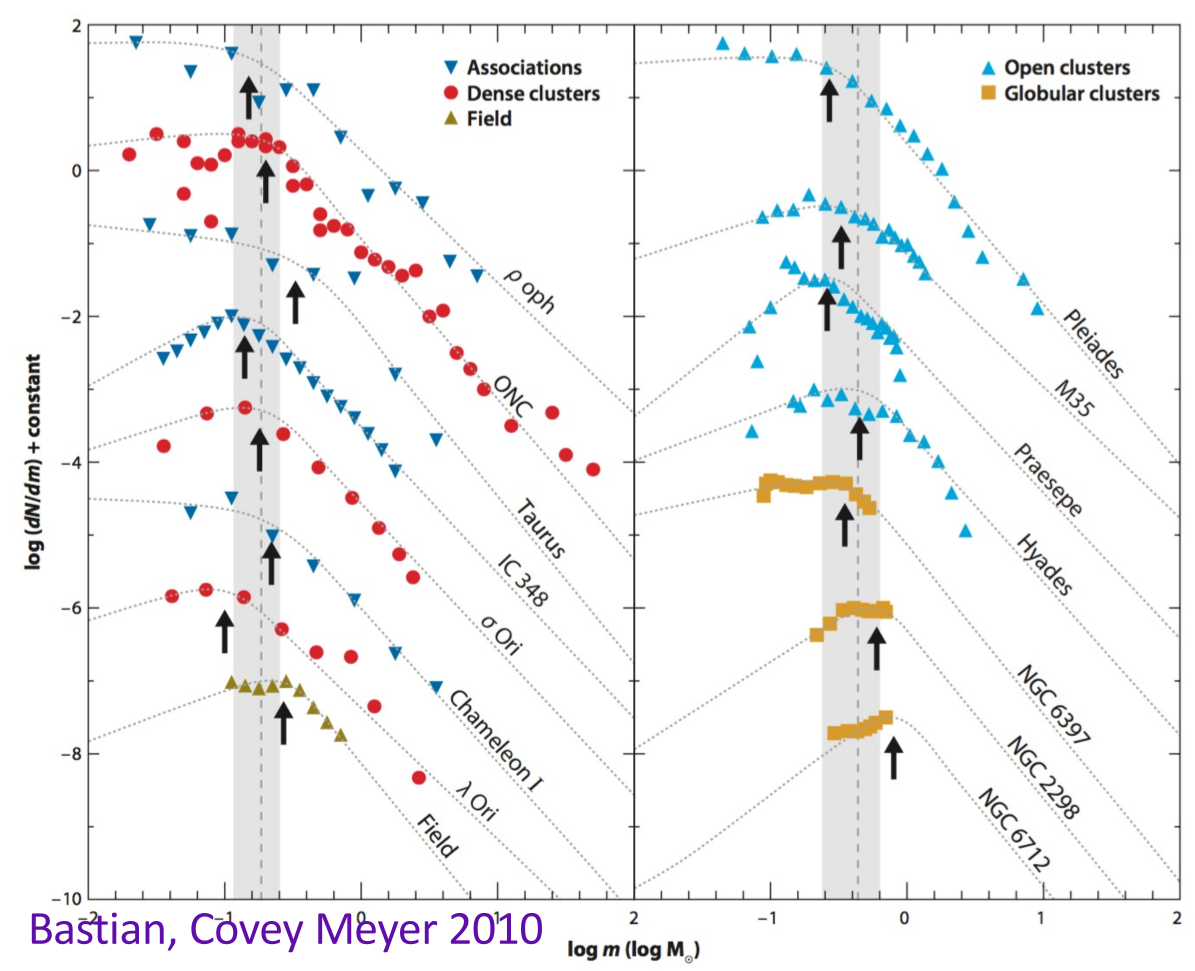

Bastian, Covey Meyer 2010

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Above 0.2-03 M $_{\odot}$ the IMF is remarkably uniform
(Bastian+2010, Offner+2014)

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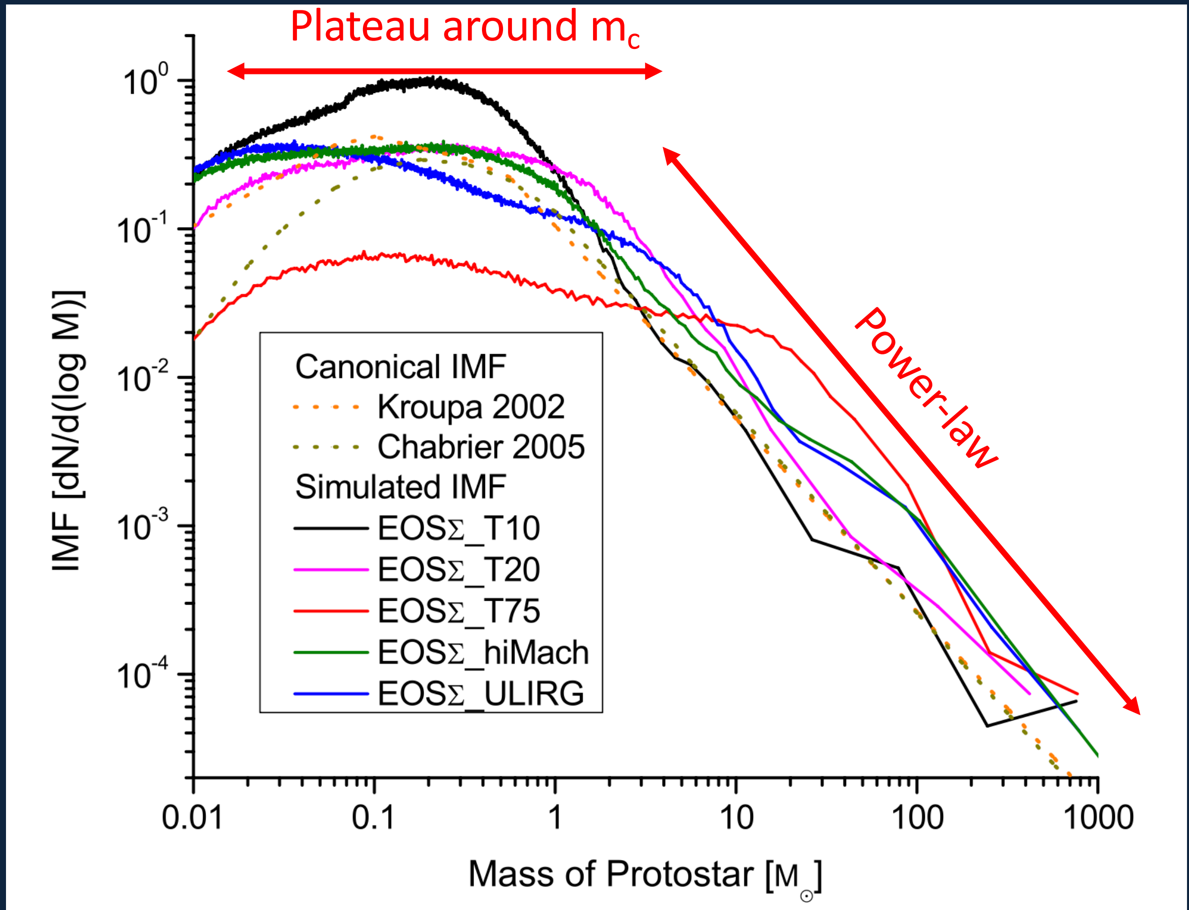

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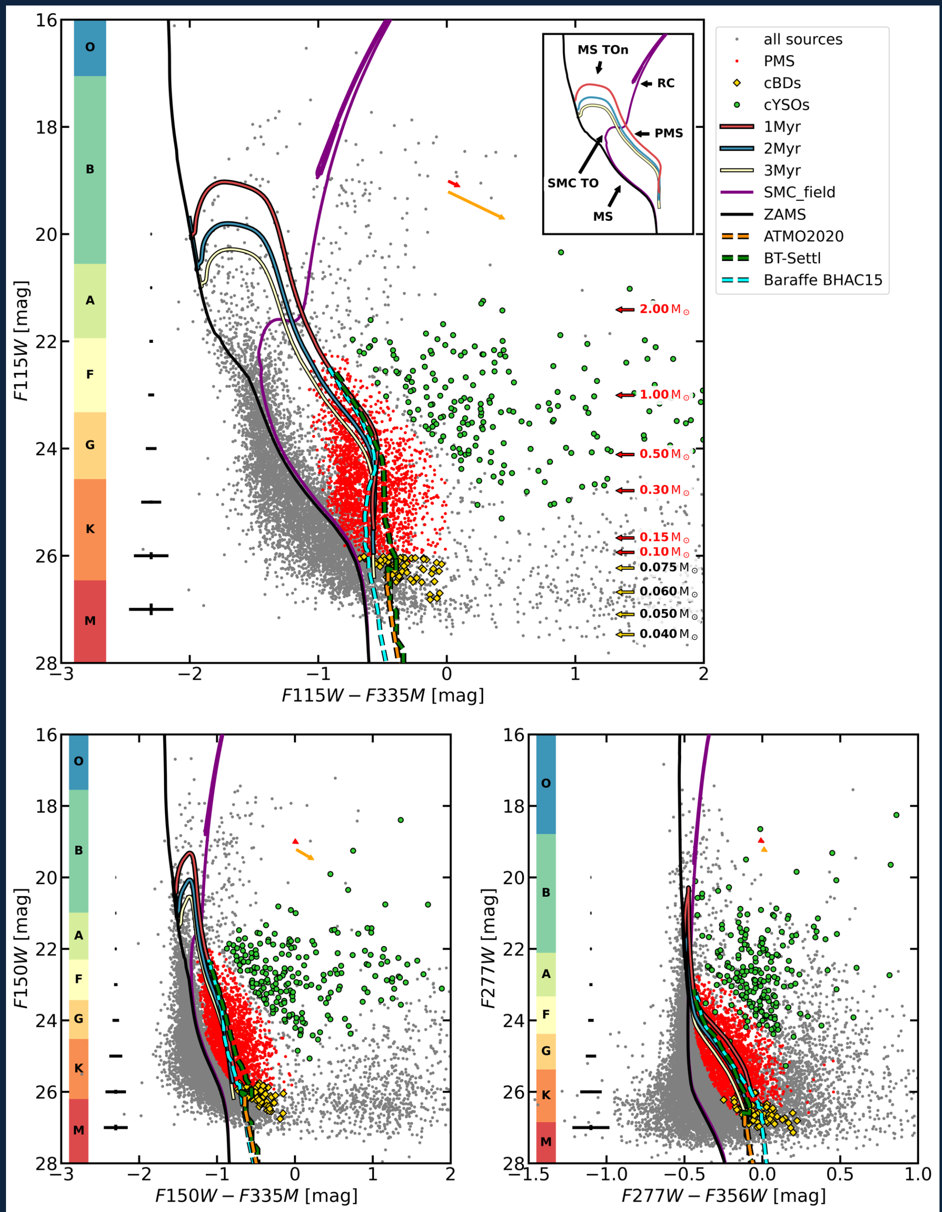
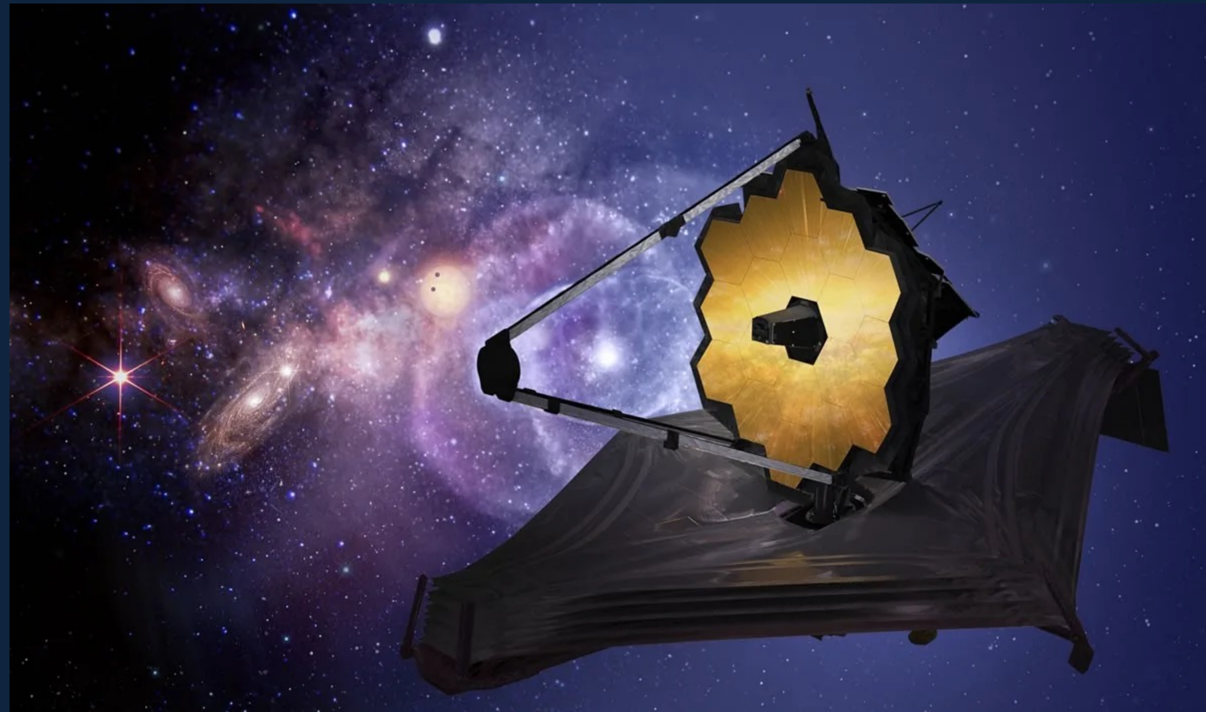
Above 0.2-03 $M_\odot$ the IMF is remarkably uniform (Bastian+2010, Offner+2014)

The origin of m_c is poorly understood:

- Bottom light IMF at low Z (Geha+2013, Gennaro+2018)?
- Bottom heavy IMF in early type galaxies (van Dokkum & Conroy 2010, Sonnenfeld+2015, Posacki+2015, Smith+2020)?



Zeidler+2024



JWST: Renewed interest in the IMF lower end

- Study BDs in the MW YMCs:
  Wd1 GO 1950 PI Guarcello;
  Arches & Quintuplet clusters GO 2045 PI Hosek;
  Sh2-284 GO 2317 PI Cheng;
  Wd2 GO 3523 PI Guarcello
- NIRCam detection of BDs in NGC 602 (Zeidler+2024)

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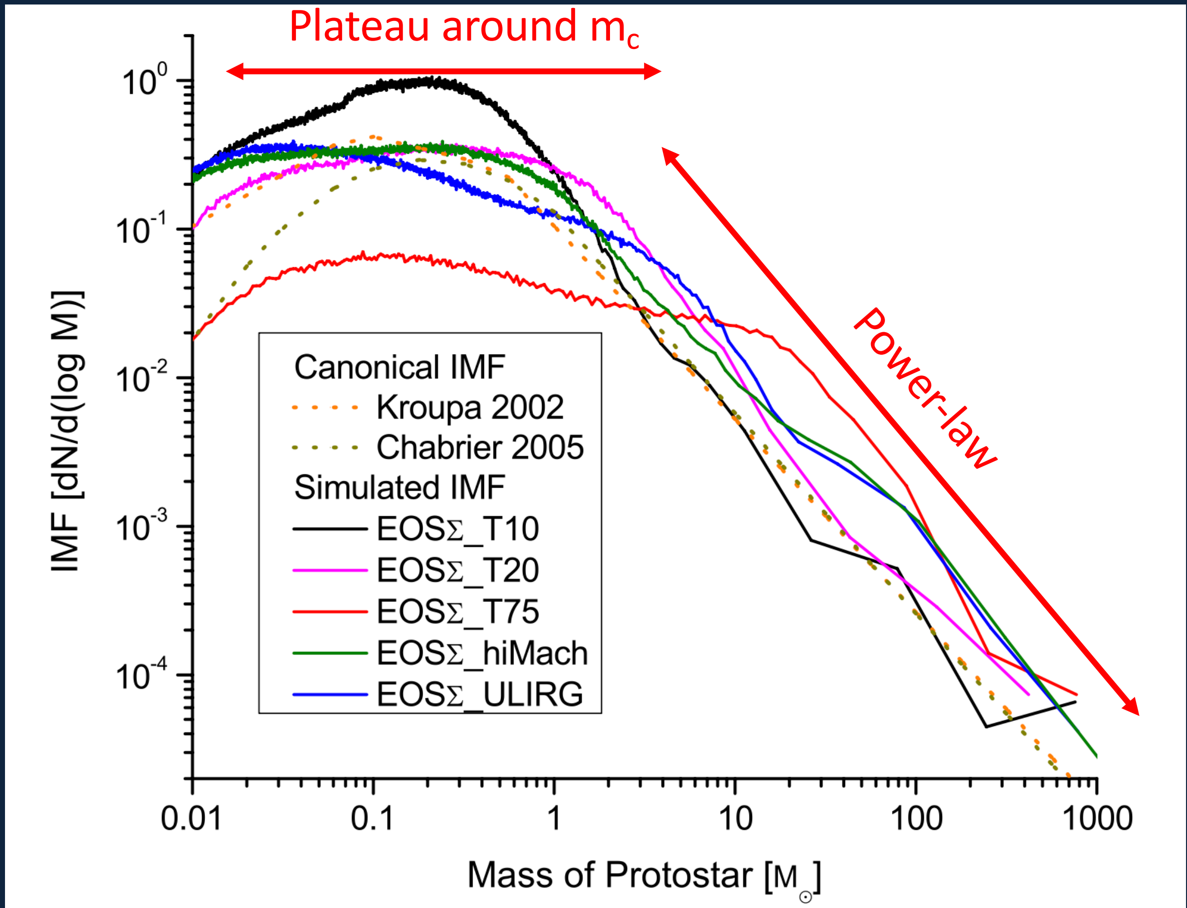

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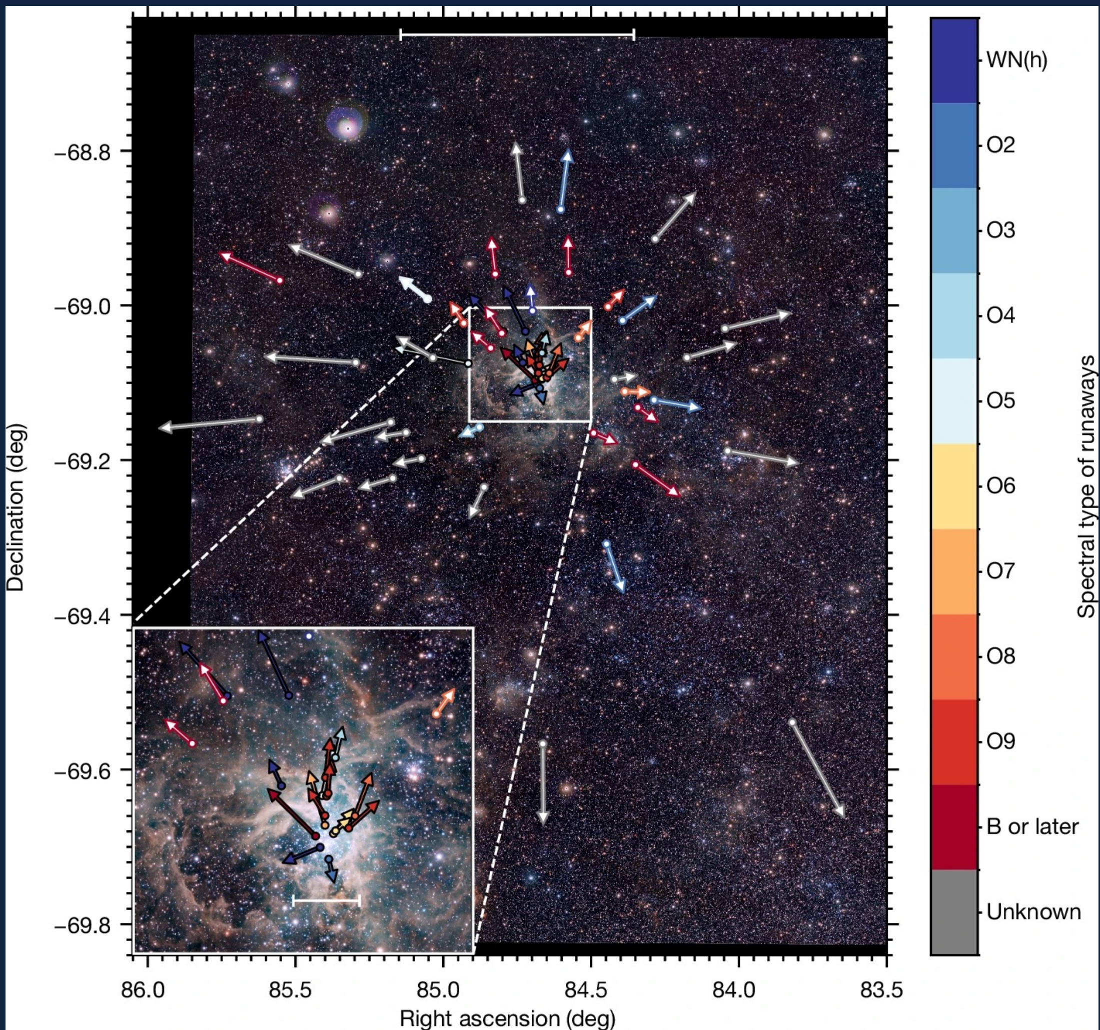
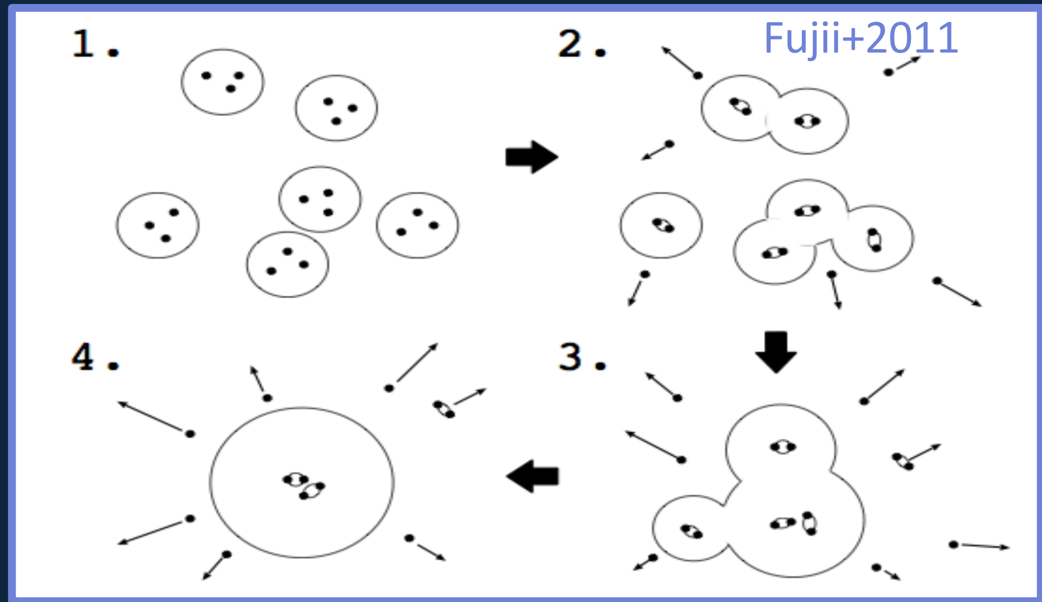
- Top heavy IMF in starburst?
  - MW YMC (Lu+2013, Hosek+2019) + 30 Dor (Cignoni+2015, Schneider+2018), NGC346 (Sabbi+2008)
  - CMF top-heavy in starburst environments (Pouteau+2022)?

OB Runaways around YMCs

Stoop+2024



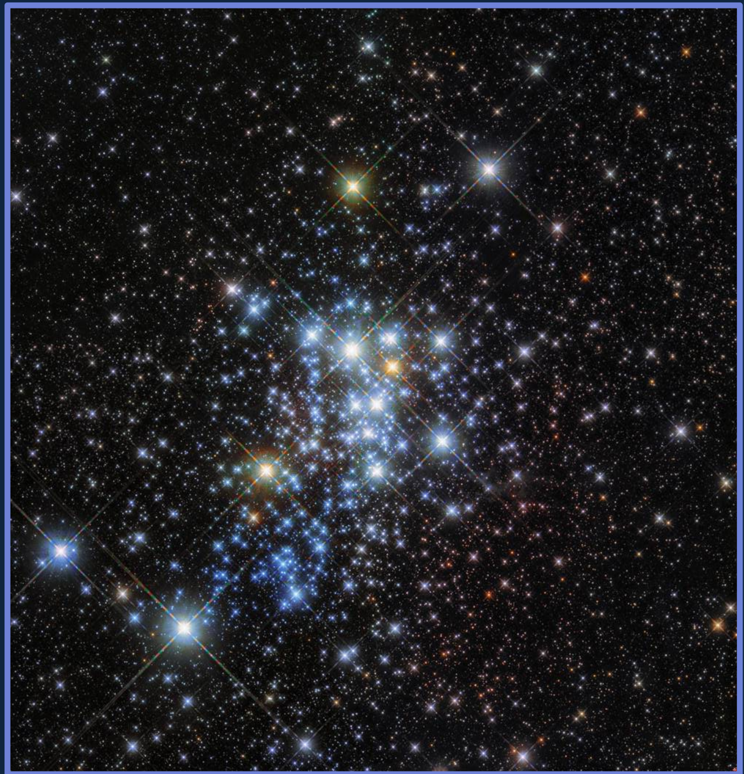
- Several YSCs are surrounded by an excess of (runaway and walkaway)OB stars (i.e. NGC3603 - Kalari+2019; M16 – Stopp+2023; R136 – Sana+2022, Stoop+2024)
- Origin:
  - Binary-Supernova Scenario (Blaauw 1961)
  - Dynamical Ejection Scenario (Poveda+1967, Hoogerwerf+2000; Fujii & Portegies Zwart 2011)

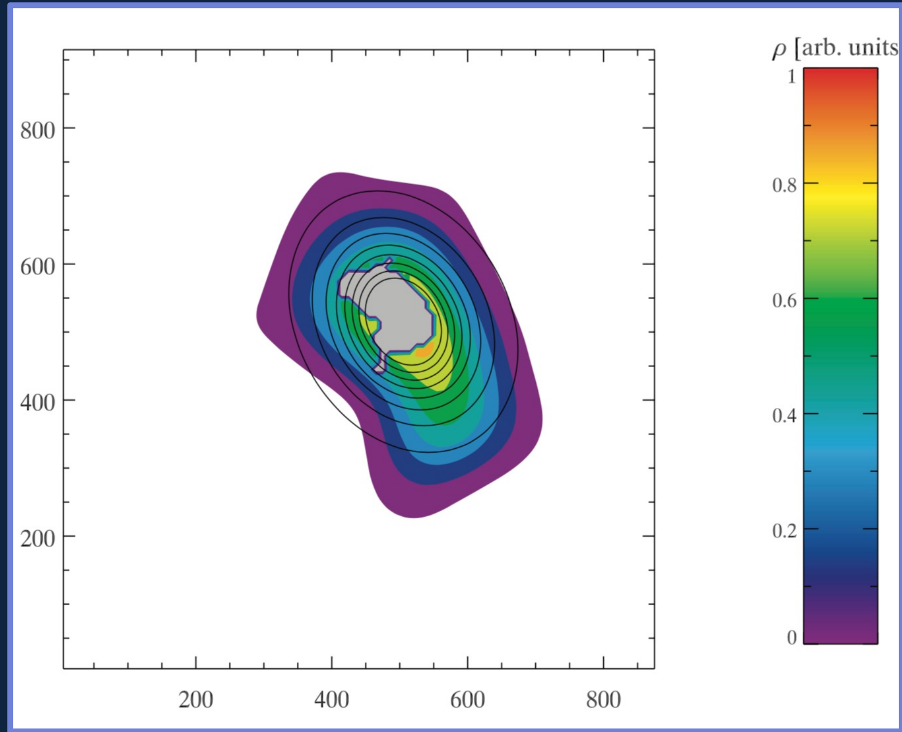


Star Cluster Formation Process

Model	Predicted Observables			
Monolithic Collapse	Single episode of SF	Expansion	Velocity dispersion does not depend on mass	e.g. Adams 2000, Kroupa+ 2001, Baumgardt+ 2007, Pfalzner+ 2013
Gravoturbulent Collapse	Multiple episodes of SF	Subclusters follow parallel paths	Velocity dispersion increases with mass	Lee+ 2016, Mapelli 2017, Ballone+2020
Hierarchical Collapse	Sequential SF	Subclusters points towards common center of mass	Velocity dispersion does not depend on mass	Klessen+ 1998, Bate+ 2003, Girichidis+ 2011, Vázquez-Semadeni+ 2017, 2019

Indirect Evidence of Clump Mergers





Westerlund 1: Elongation and spatial variations in the MF as possible indication of a merger between 2 sub-clusters.

(Gennaro et al. 2011)

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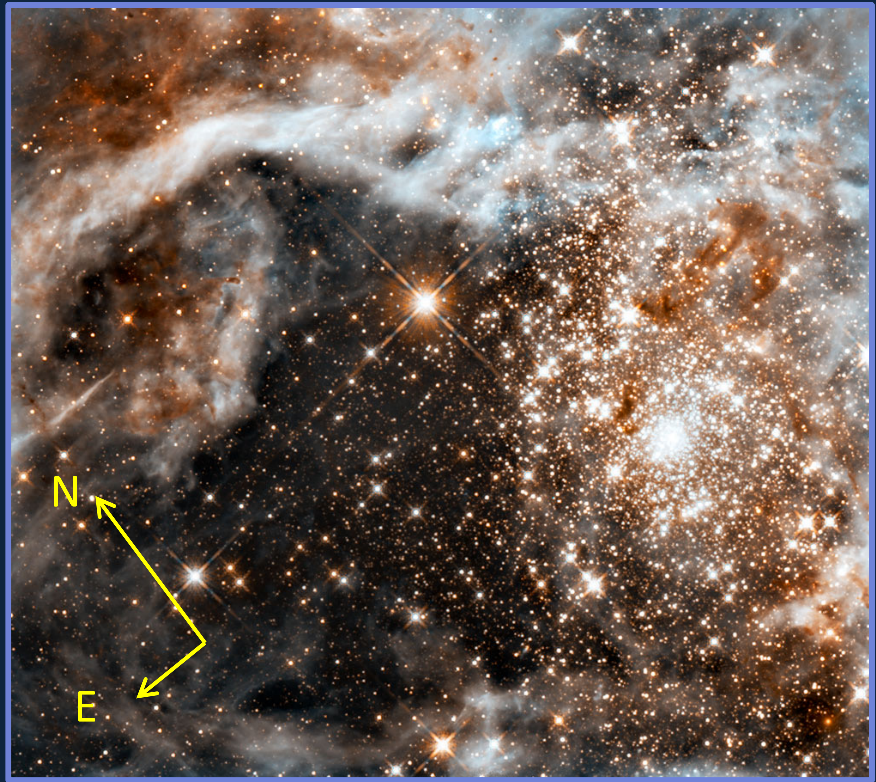

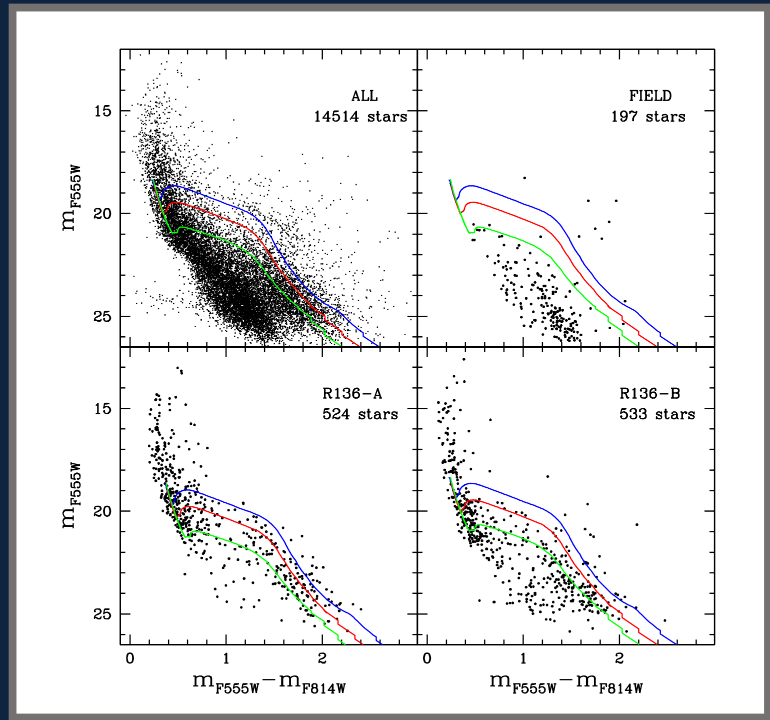

R136 & NE-clump: Two spatially- and age-distinct stellar populations in R136

(Sabbi et al. 2012)

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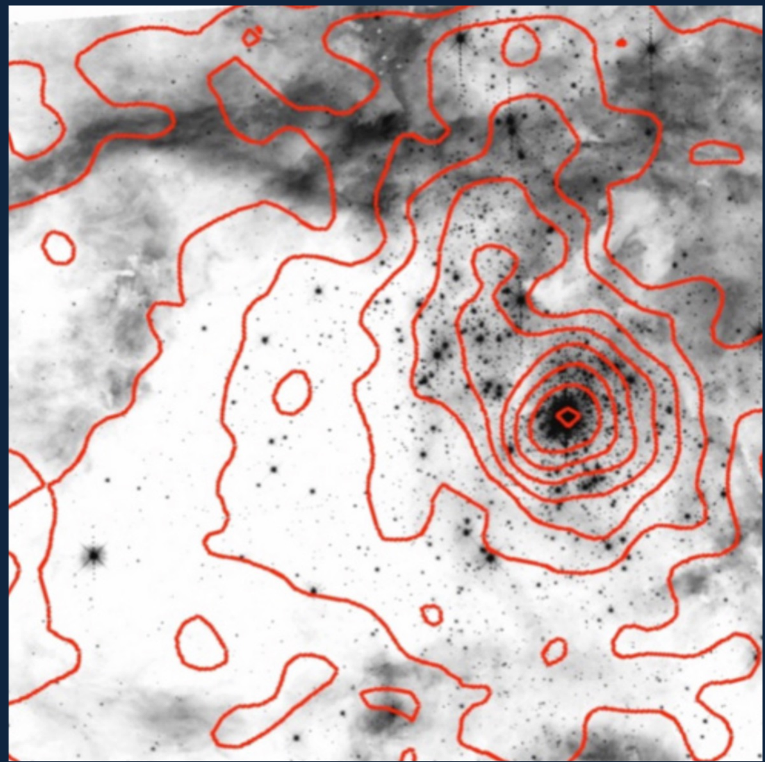
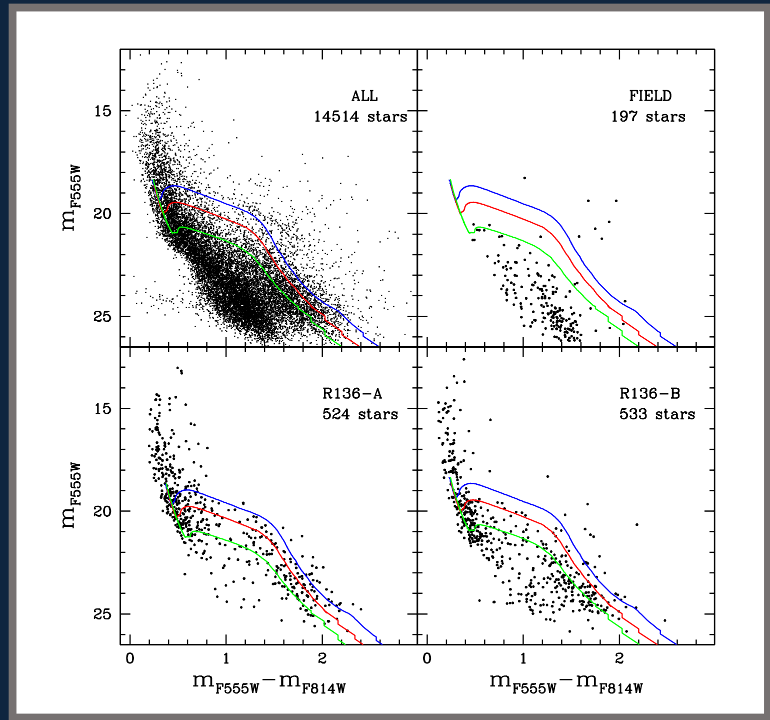
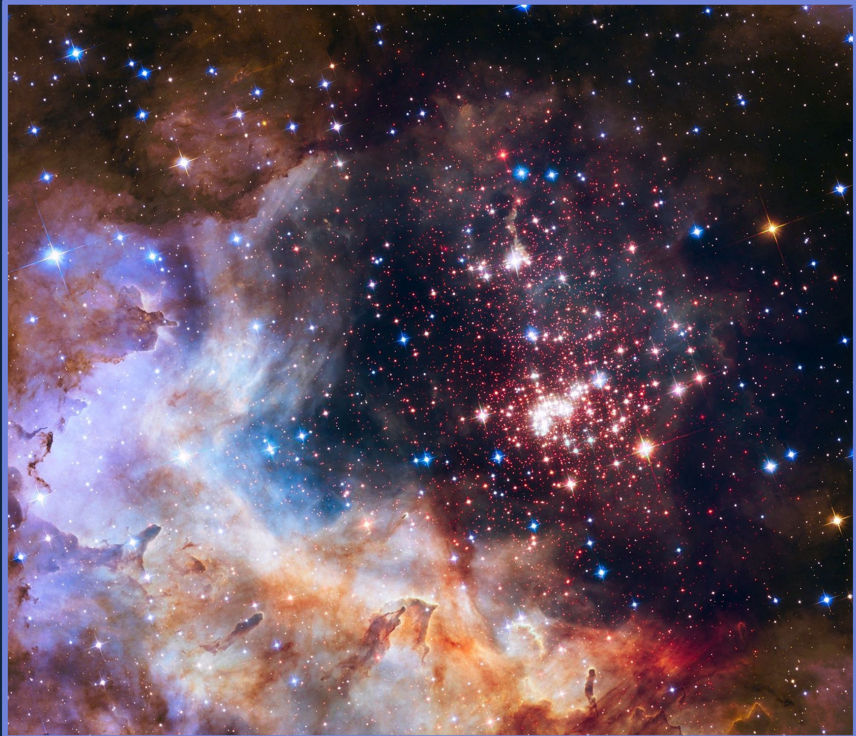
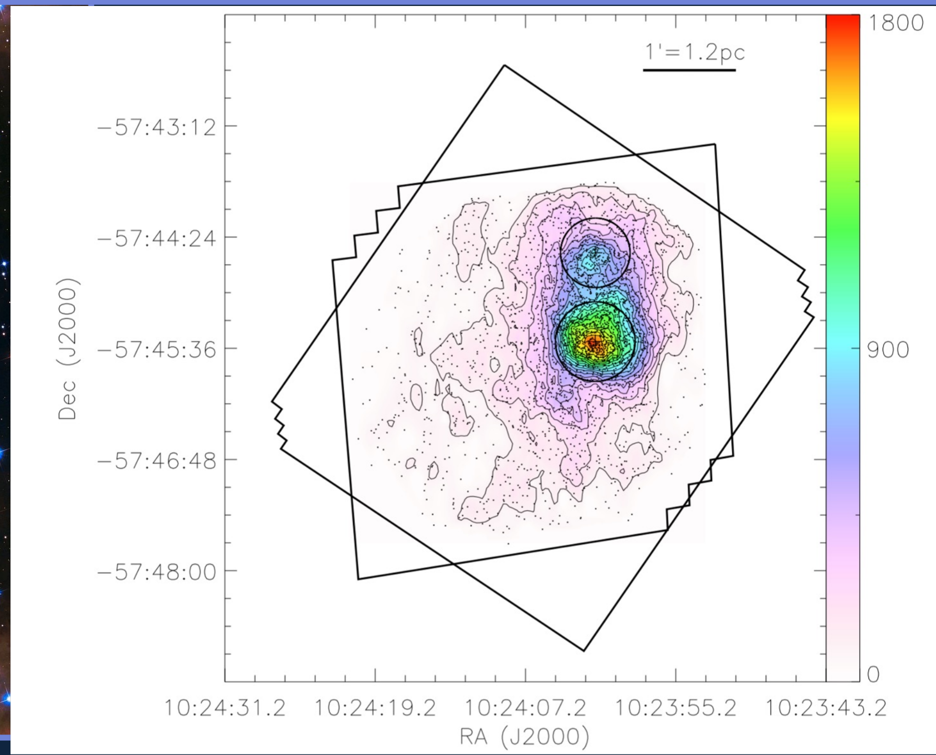




R136 & NE-clump: Two spatially- and age-distinct stellar populations in R136 *(Sabbi et al. 2012)*
The two clumps have different kinematics (Stoop+2024)

Indirect Evidence of Clump Mergers

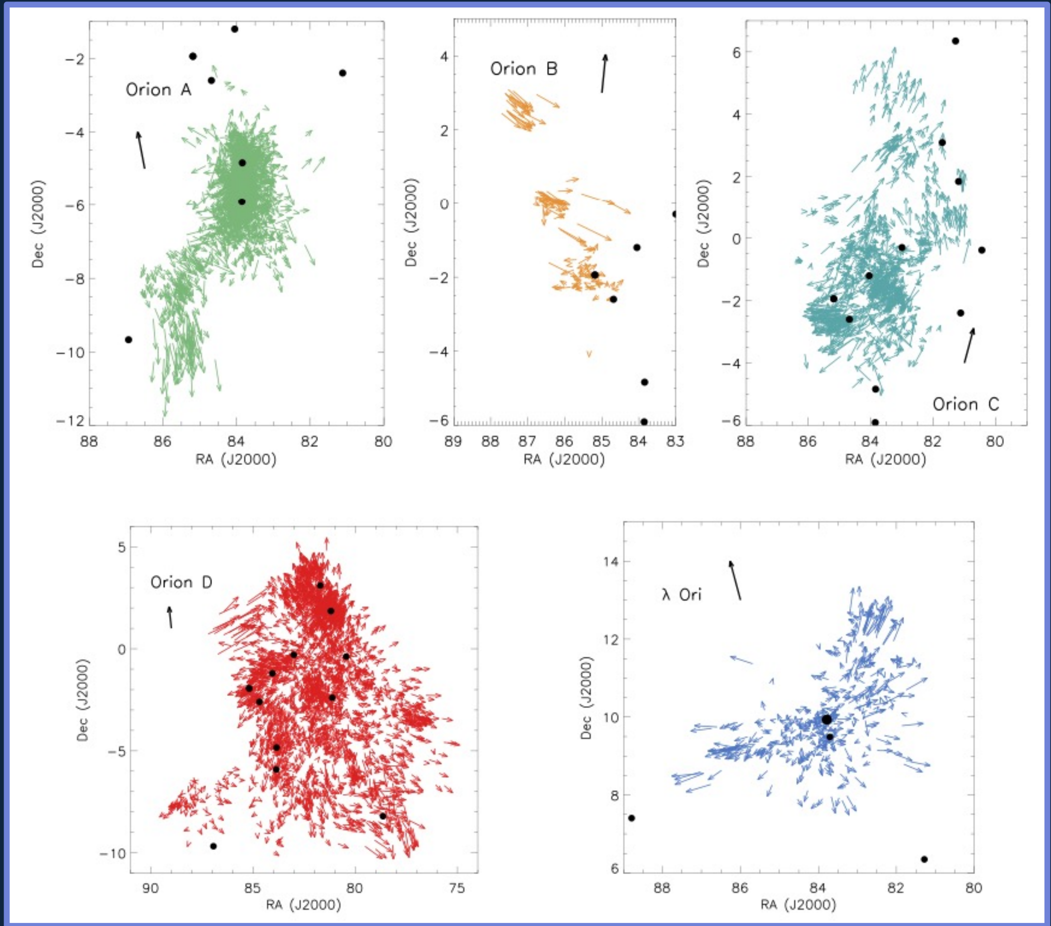




Westerlund 2: Two coeval but spatially-distinct clumps

(Zeidler, Sabbi et al. 2015)

Star Cluster Formation Process: Internal Kinematics



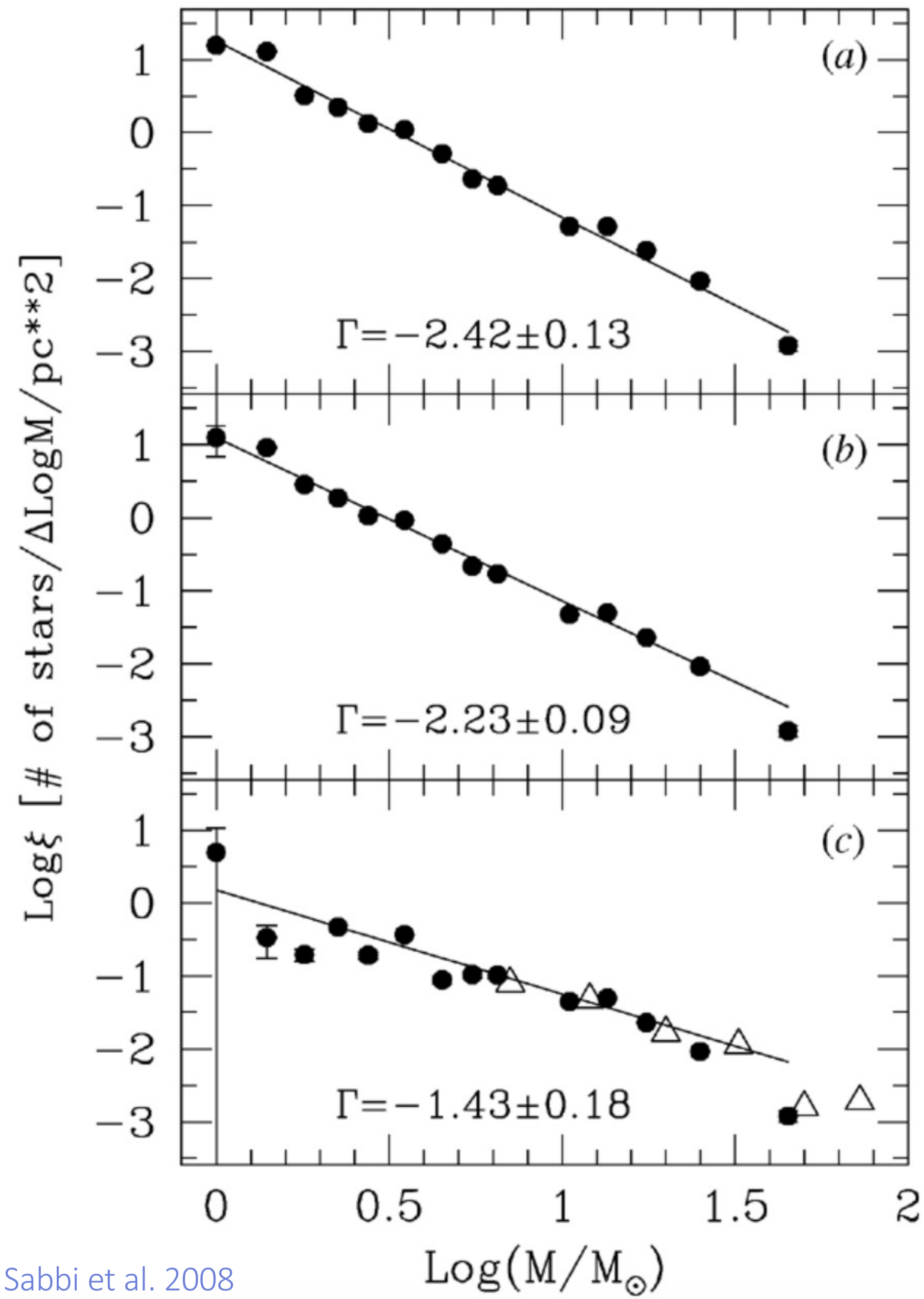
Kounkel et al. 2018

- Gaia has provided kinematic information for several MW star forming regions (Orion, Taurus, Serpens, ρOph, NGC6530, IC5070).
  - Relatively low SFR and stellar density
  - Only one metallicity

Großschedl et al. 2018; Kounkel et al. 2018; Getman et al. 2019; Luhman 2018; Galli et al. 2019; Cànovas et al. 2019; Herczeg et al. 2019; Kuhn et al. 2019, 2020).

NGC346

- Most massive SF region in the SMC



Sabbi et al. 2008

NGC346

- Most massive SF region in the SMC
- M>1 M☉ : Global MF consistent with Salpeter, but slope changes with distance from the center (Sabbi+2008)
- ~50 pc in diameter (SOBA) – t_c = 2e8 yr

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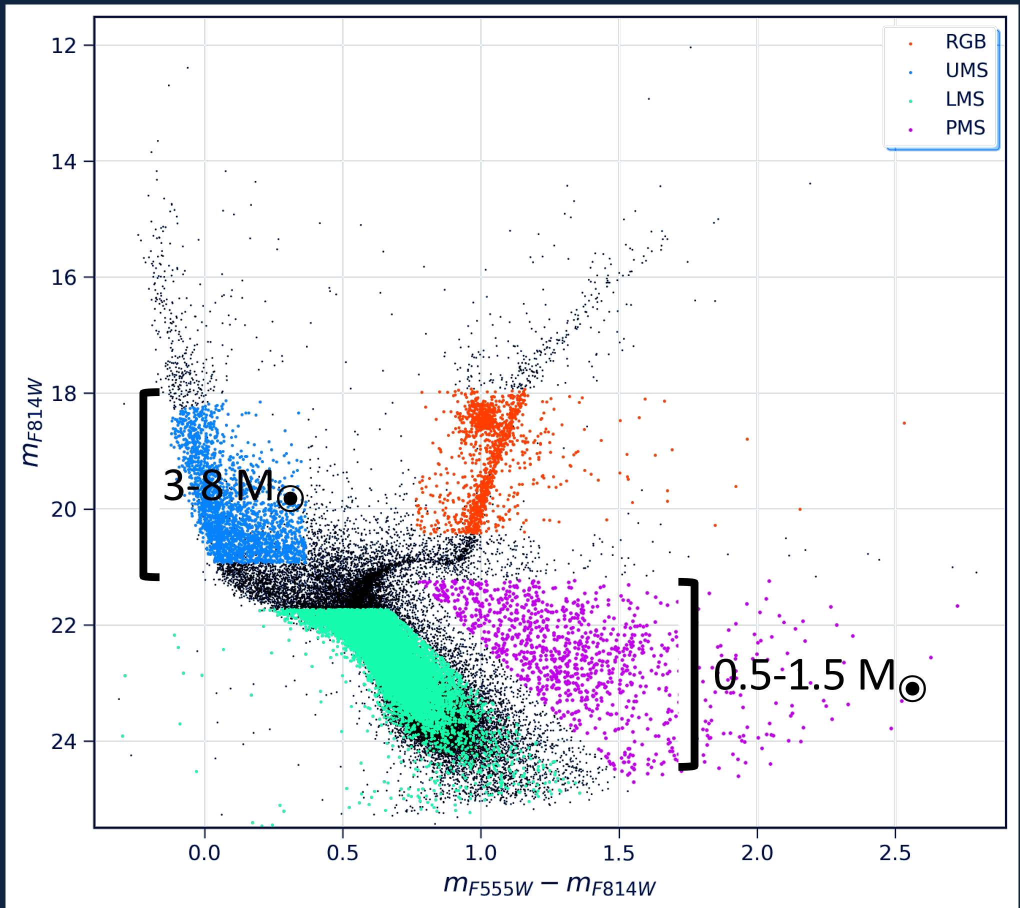
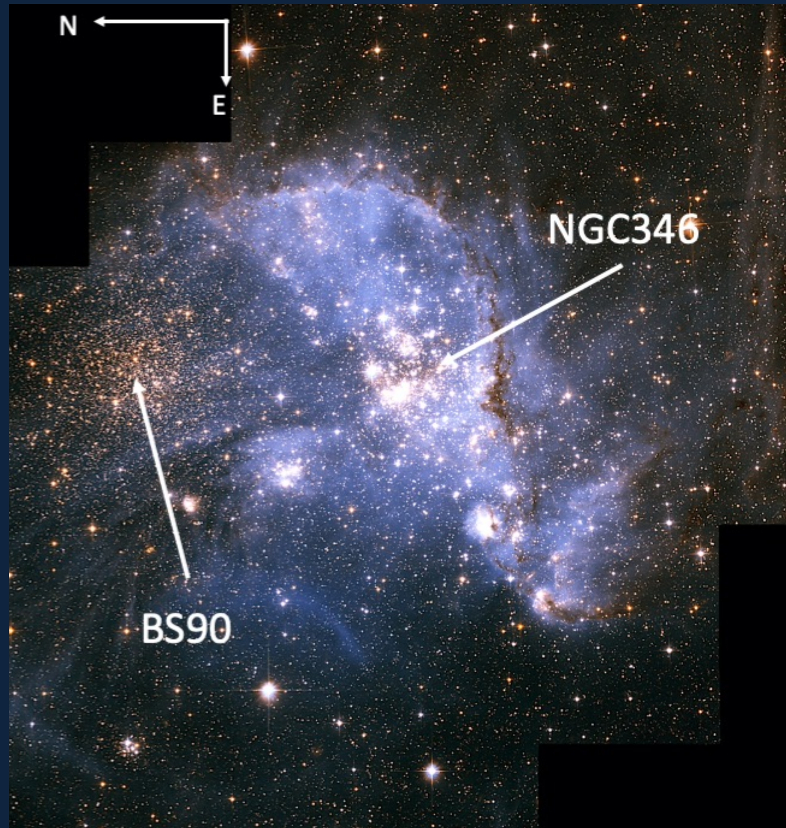
- M>1 $M_\odot$: Global MF consistent with Salpeter, but slope changes with distance from the center (Sabbi+2008)
- ~50 pc in diameter (SOBA) – t_c = 2e8 yr
- Age spread: <2 Myr in the center, ~5 Myr in the outskirt (Evans+2006, Sabbi+2007, Cignoni+2013, Dufton+2019)

What can cause synchronized SF over wide scale?

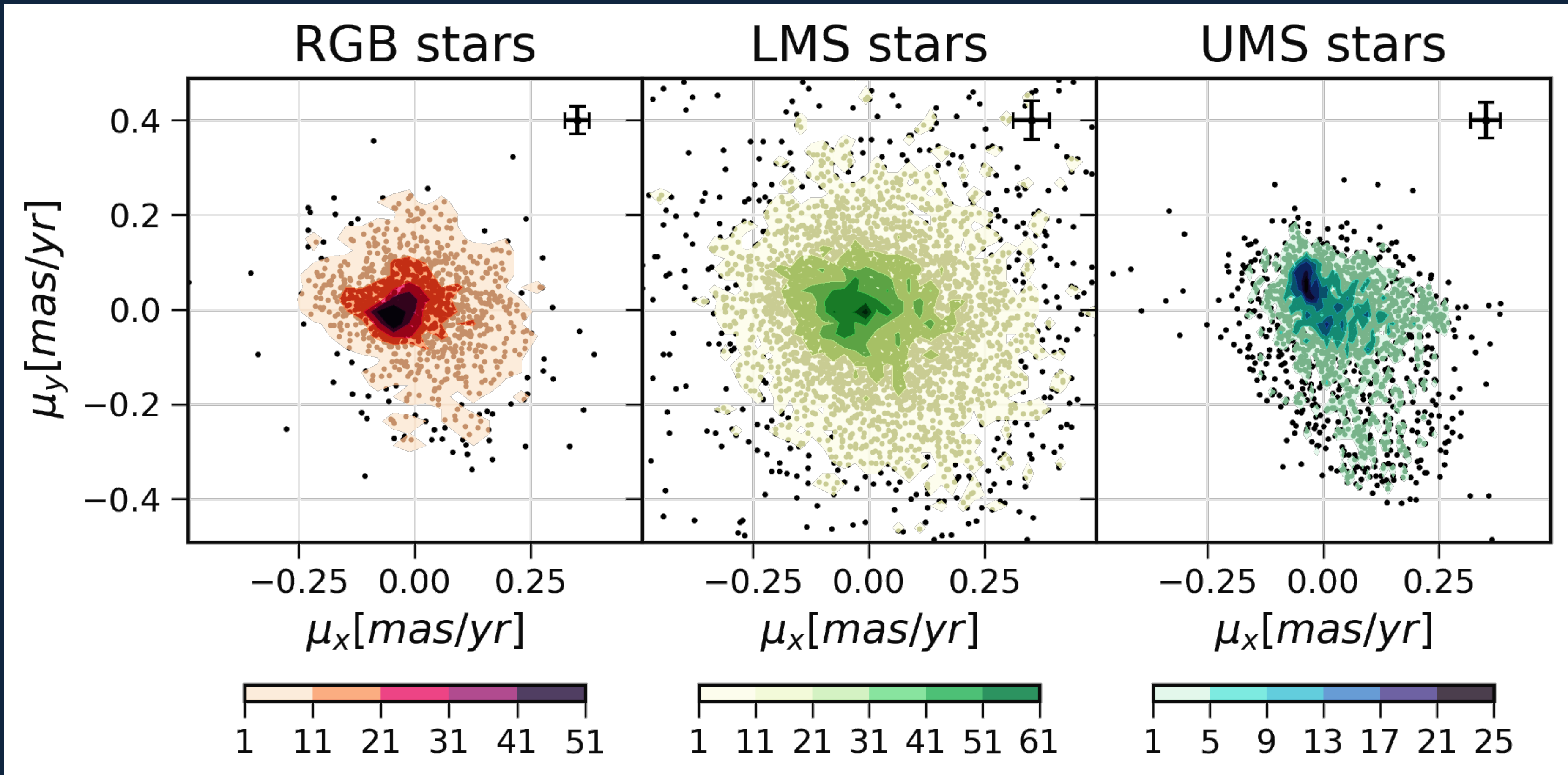
NGC346





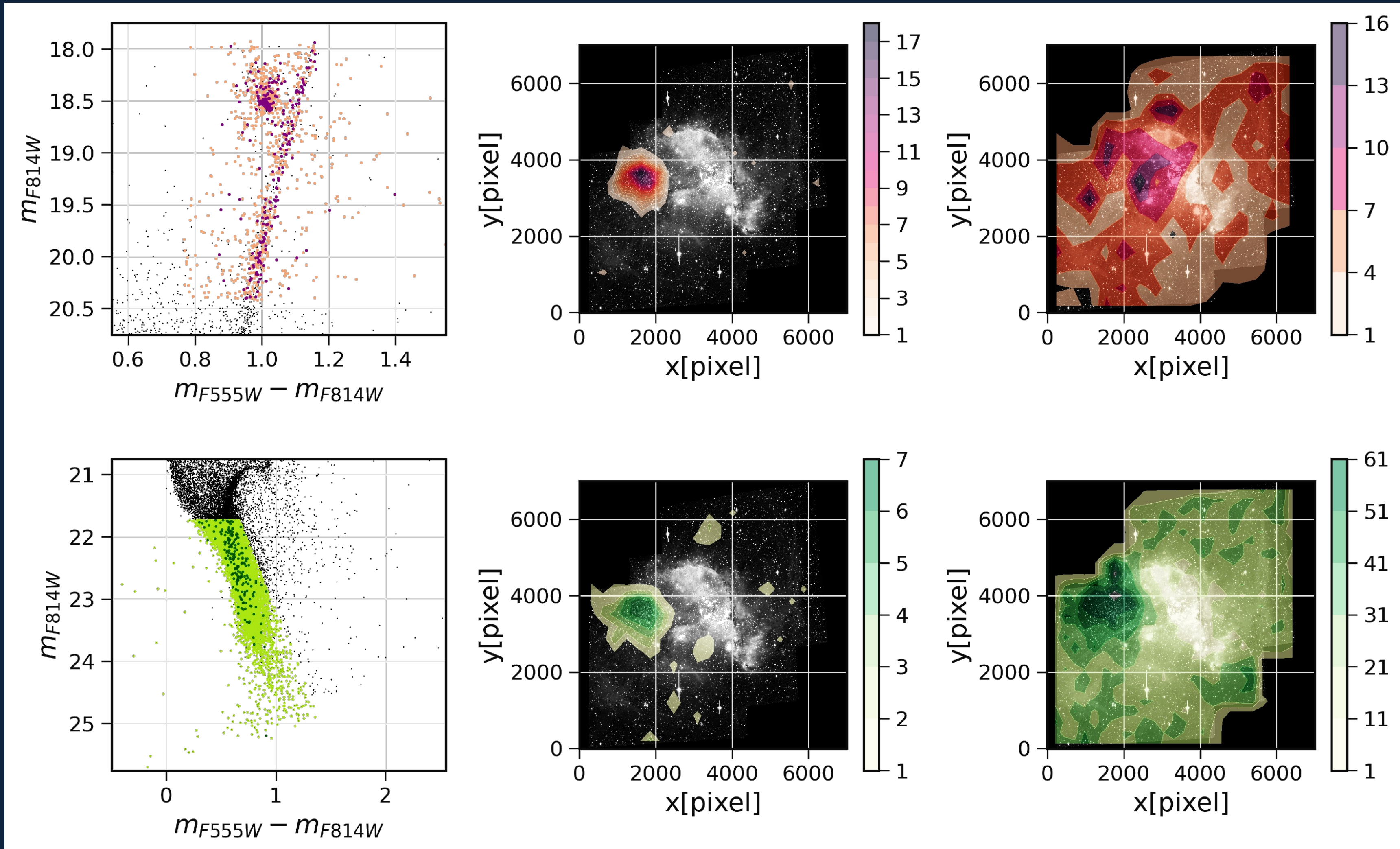
Sabbi+ 2022

PMs of NGC346 stellar populations



Sabbi+ 2022

Field and Old Cluster



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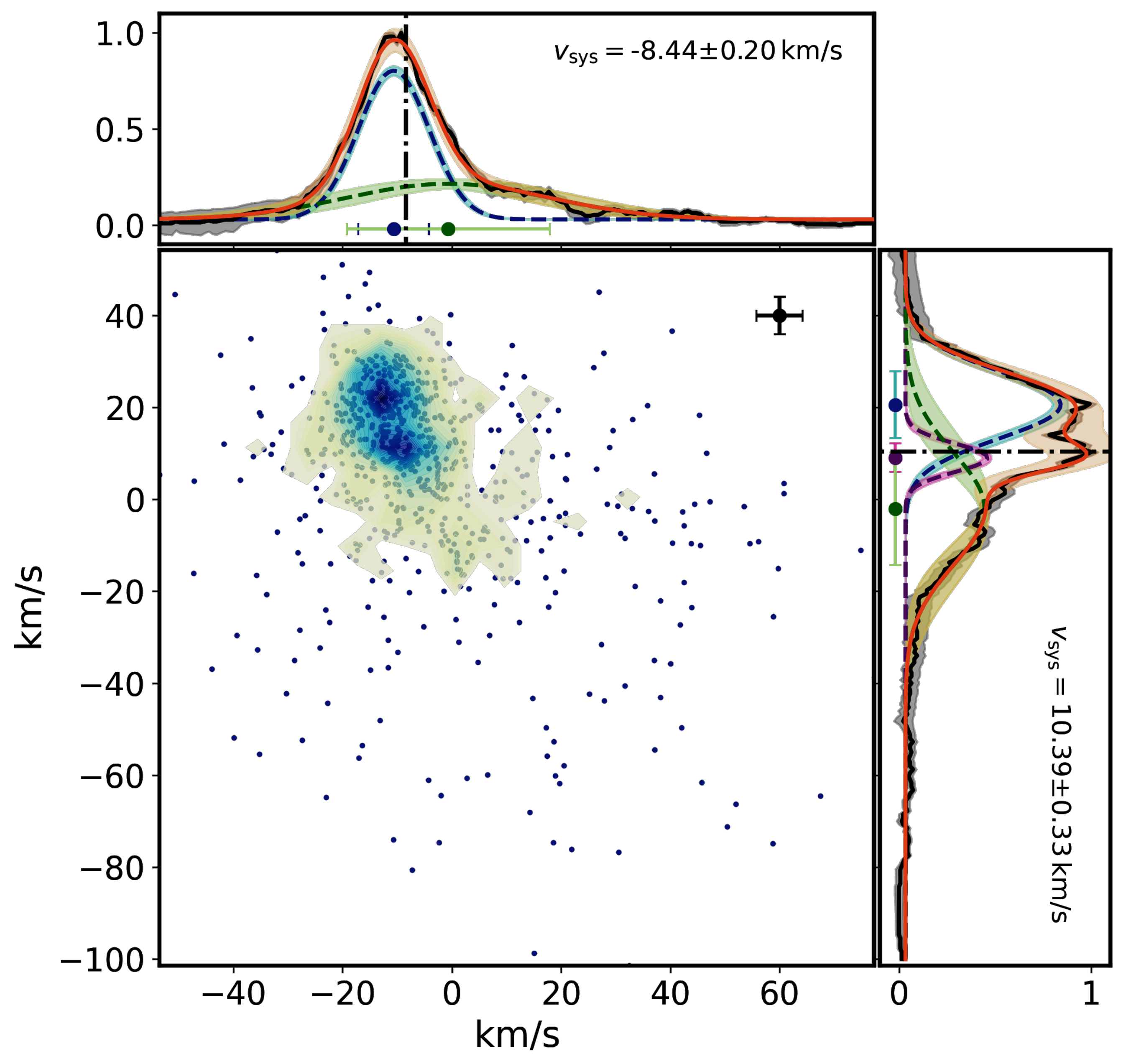

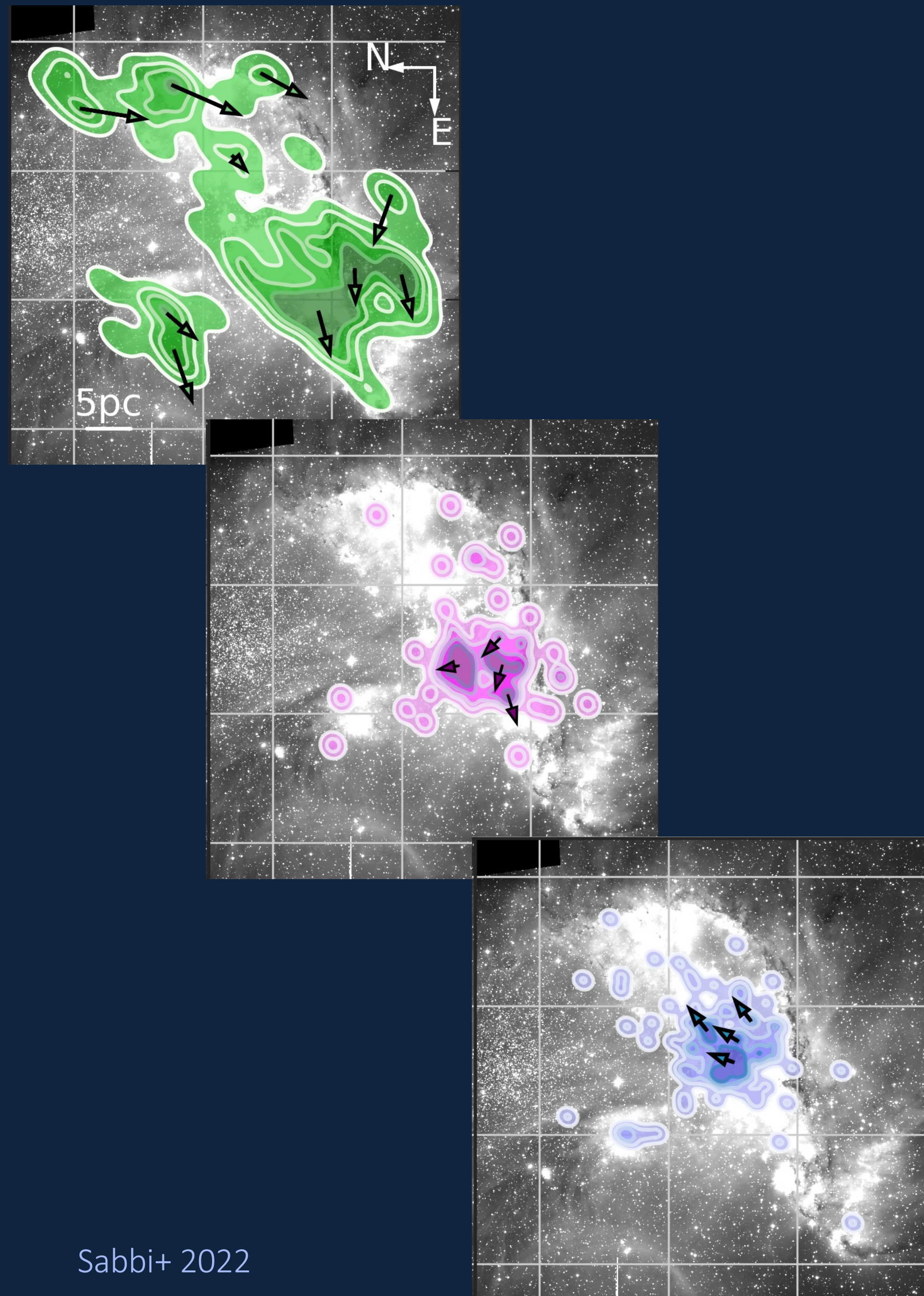

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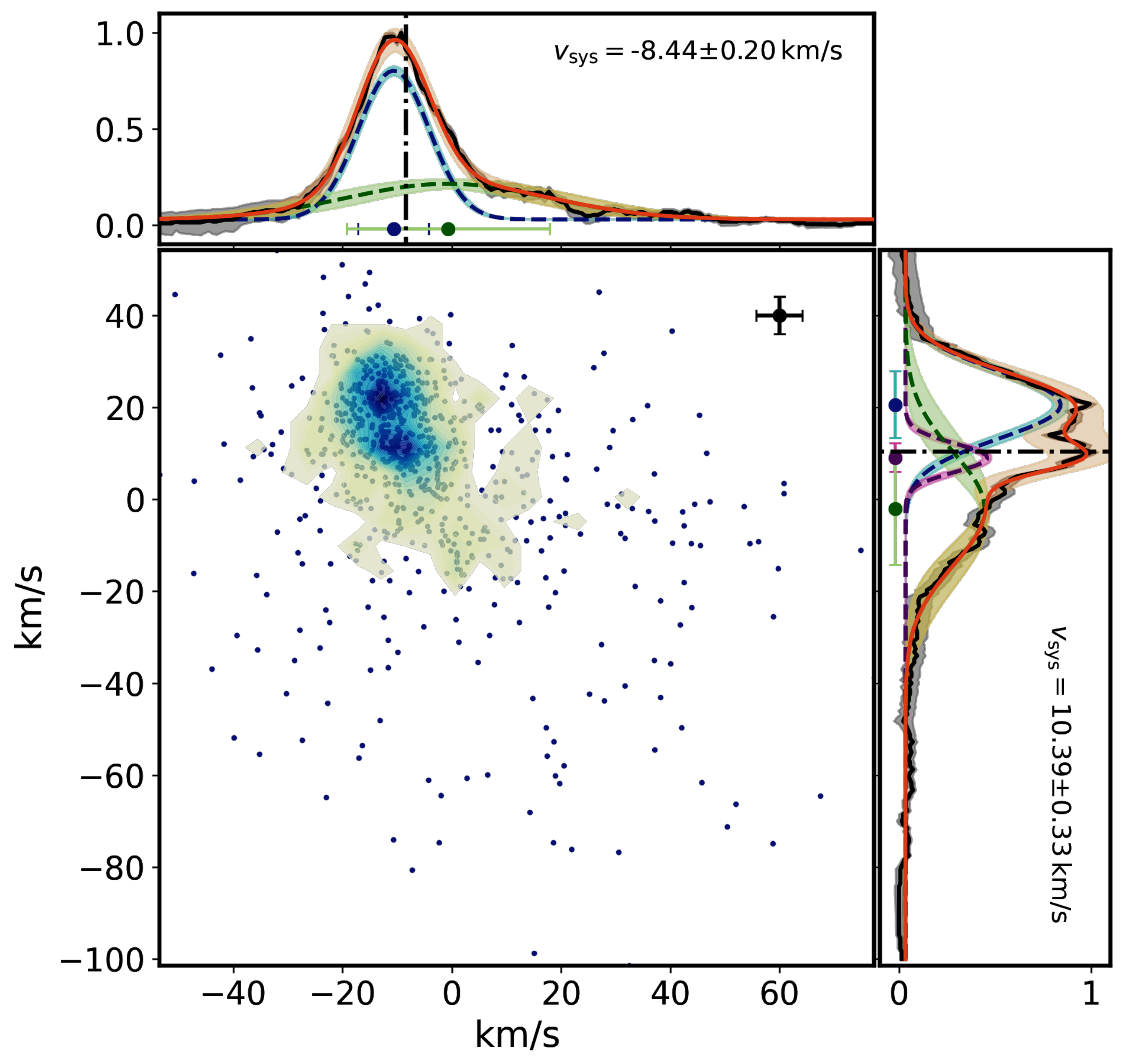
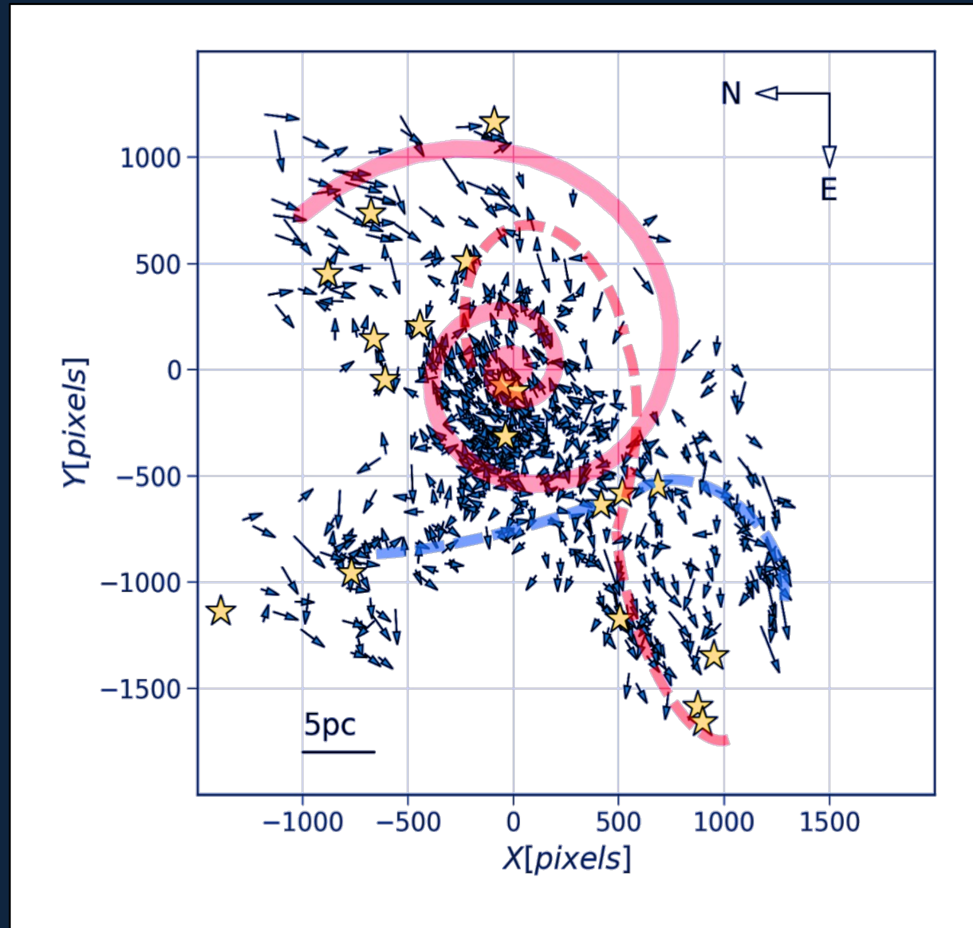
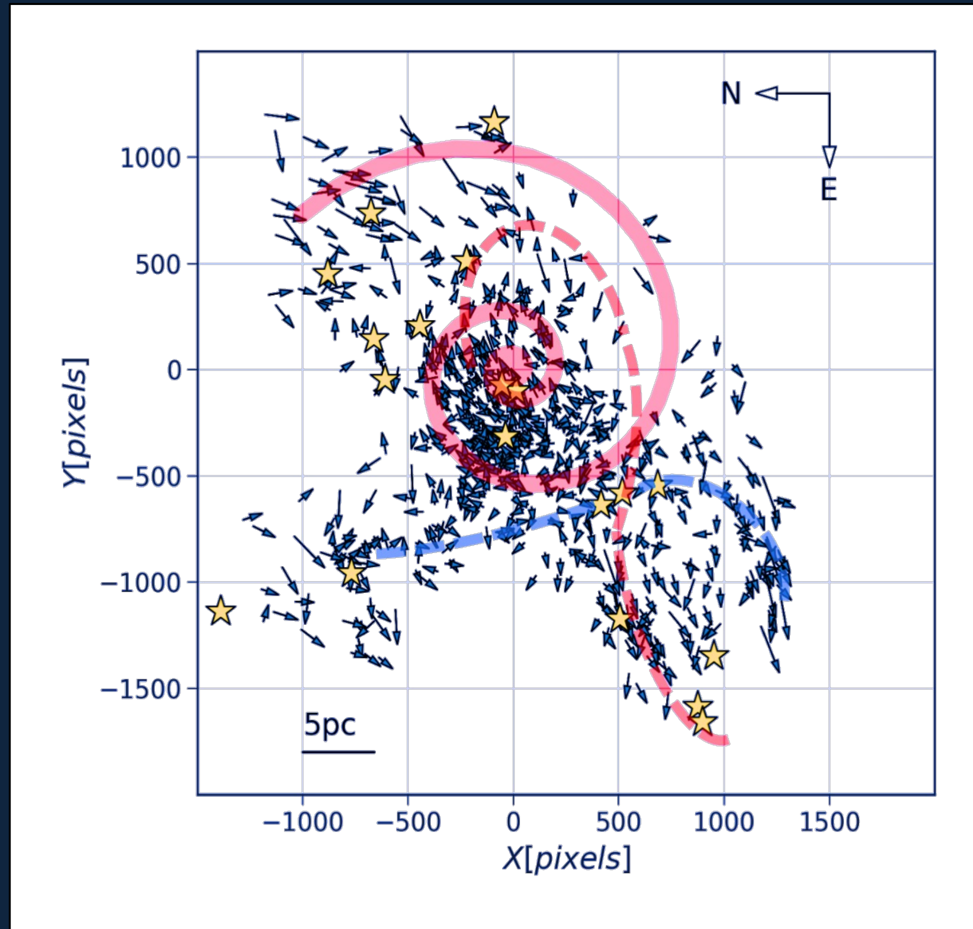


- Rotation in the center independently confirmed by RV study (Zeidler+2022)



Sabbi+ 2022

NGC346 kinematics, PDMF, Age distribution, YSO location consistent with gravoturbulent collapse



Sabbi+ 2022

Disk Life(time) in Highly Irradiated Environments

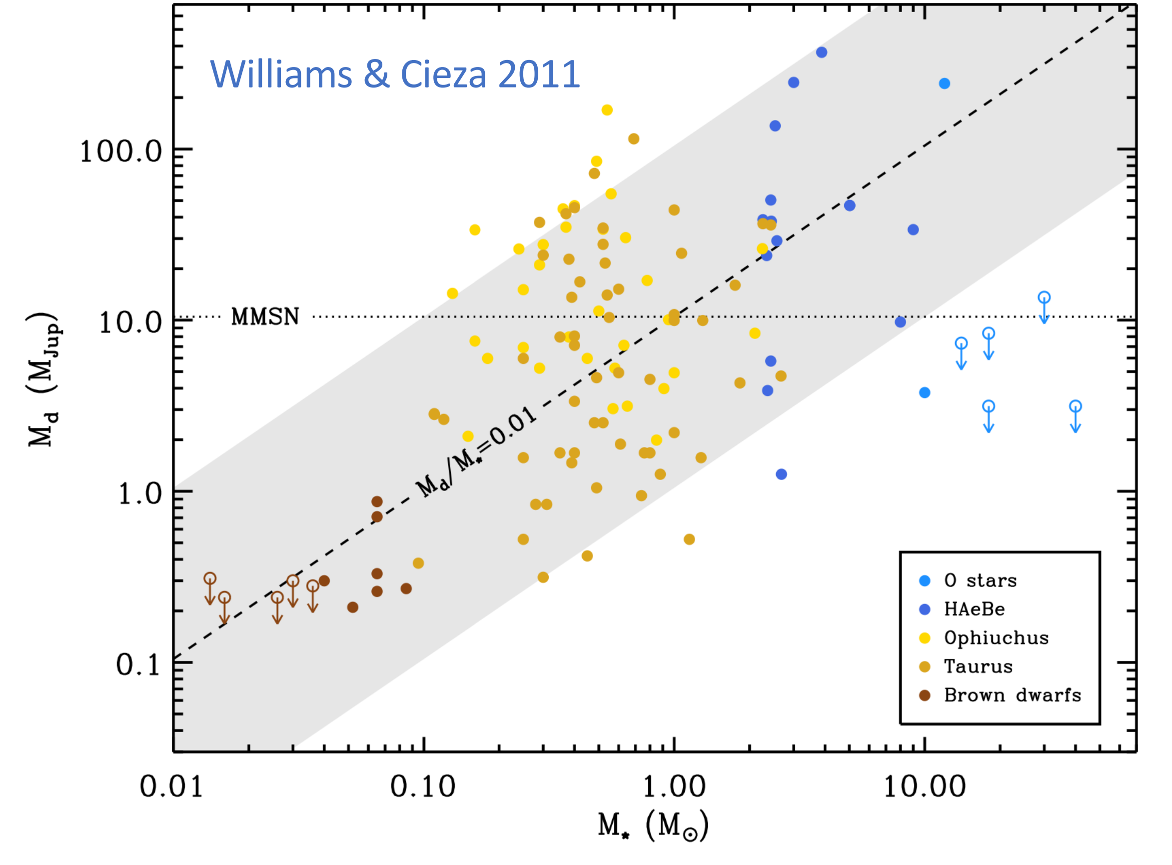
Disks are observed around a wide range of stars from very low-mass to intermediate mass Herbig Ae/Be stars.

Circumstellar disks form almost immediately after the molecular core collapses.

Disk masses don't increase with time during the Class 0 collapse phase implying a rapid transport onto the star.

The disk lifetime is a fundamental parameters on disk evolution and sets the limit on the time available for planet formation.

Submillimeter measurements of Class II YSO disks



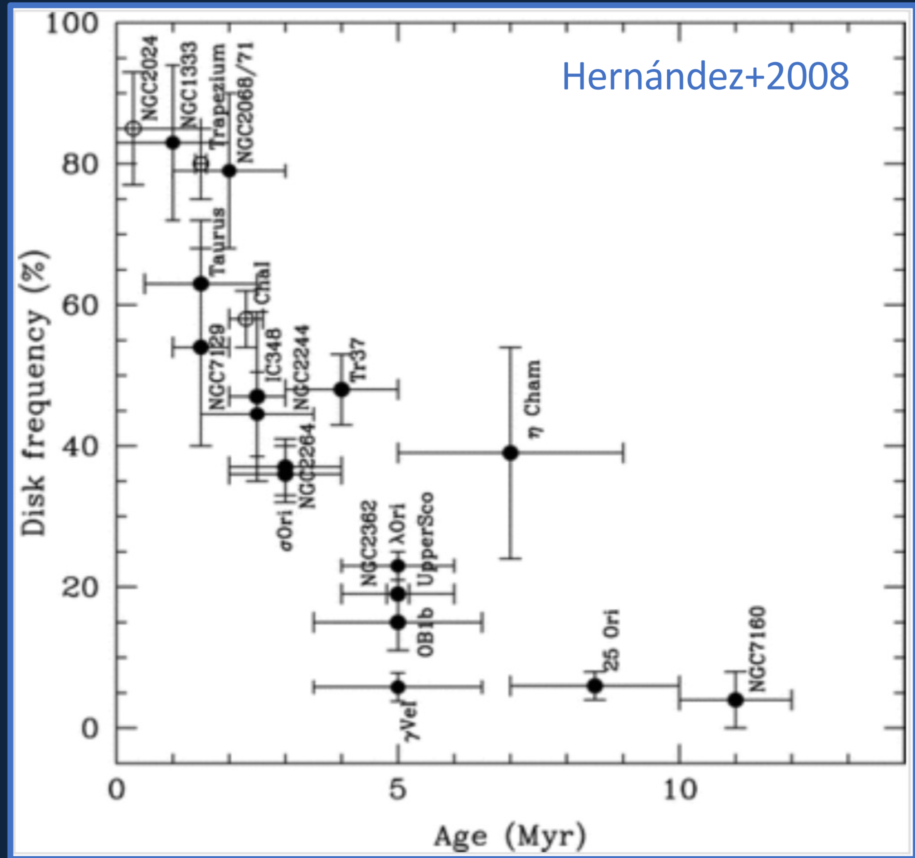
Disk masses tend to be lower around low mass stars

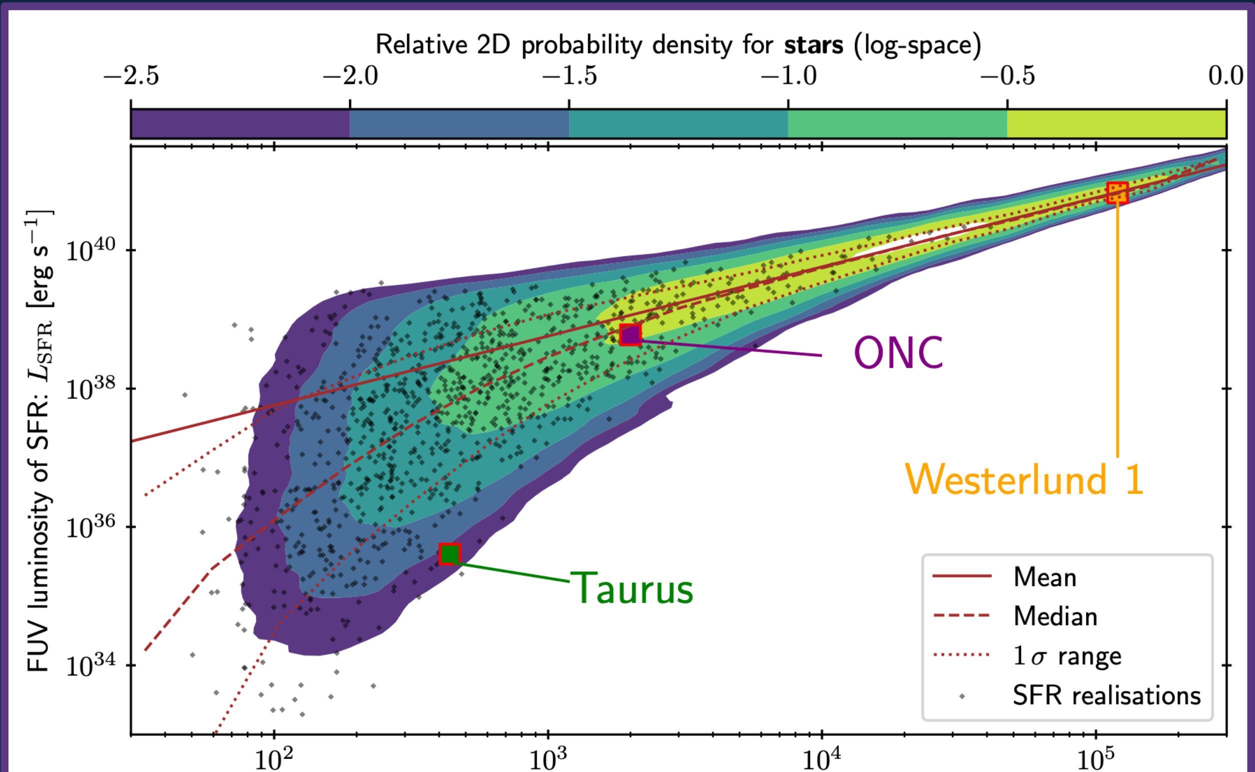
No submillimeter detection of a disk around optically visible O stars.

- Either very high photoevaporation rates destroy the disk by the time the O star is optically visible;
- or O stars form with a different mechanism (Zinnaecker & Yorke 2007).

Strong correlation between NIR excess (1 – 5 µm) and accretion (Hartigan, Edwards & Ghandour 1995) .

In nearby star-forming regions, 60-80% of stars younger than 1Myr show NIR excess. At 10Myr less than 10% of the stars have NIR excess.
Average inner disk lifetime ≃ 3Myr (Strom et al. 1989, Haisch+ 2001; Hernández+ 2008; Richert+ 2018).





Winter & Hawort 2022

At 140 pc from us, Taurus-Auriga is an excellent observing place to study the properties of disks – spatial resolution 140 AU/arcsec

Taurus' IMF is peculiar:

- peak at 0.8 $M_\odot$;
- A few stars with M>1M $_\odot$;
- not enough BDs;
- too many binaries.

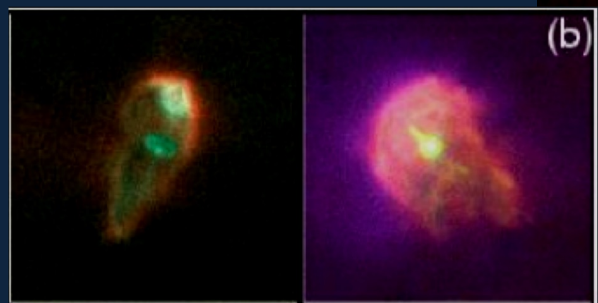
Field stars more closely resemble populations that formed in rich clusters than in Taurus (Goodwin+2004)

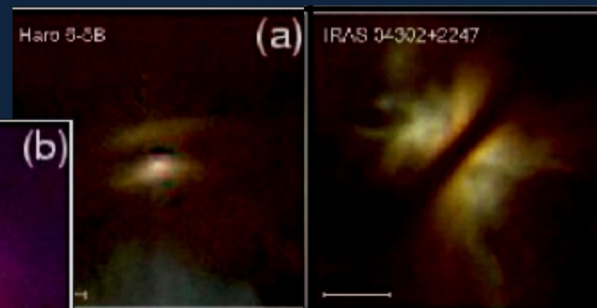
In the Solar Neighborhood 70-90% of the young stars formed in rich embedded clusters. ~75% of these are in with massive stars (M> 8 $M_\odot$, Lada & Lada 2003)

The analysis of meteorites indicates that The Sun formed near a massive star (Hester & Steven J. Desch)

FUV radiation from nearby stars photoevaporates gas from the surface of the disk, and pushes it back into a characteristic teardrop shape (e.g., Johnstone+1998)

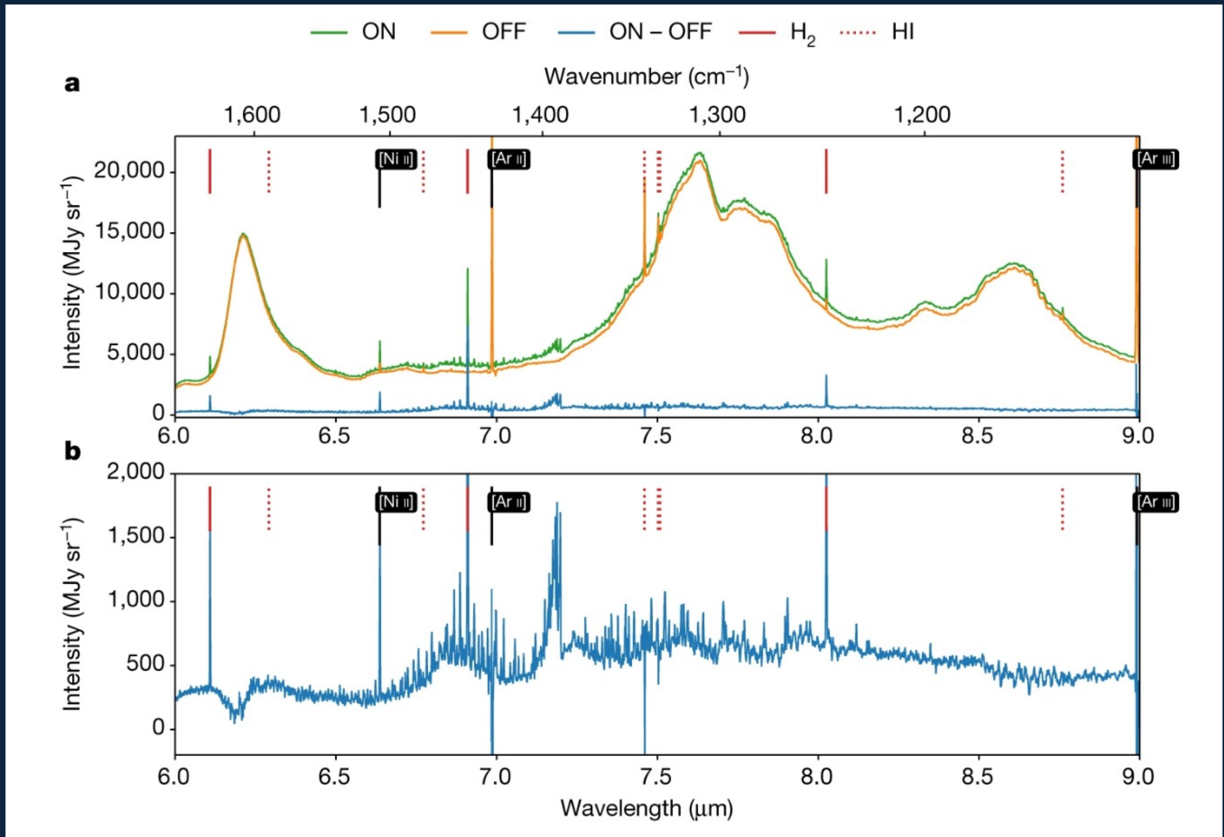
Bally+2000





Padgett+1999

Impact of External UV Radiation on Disks

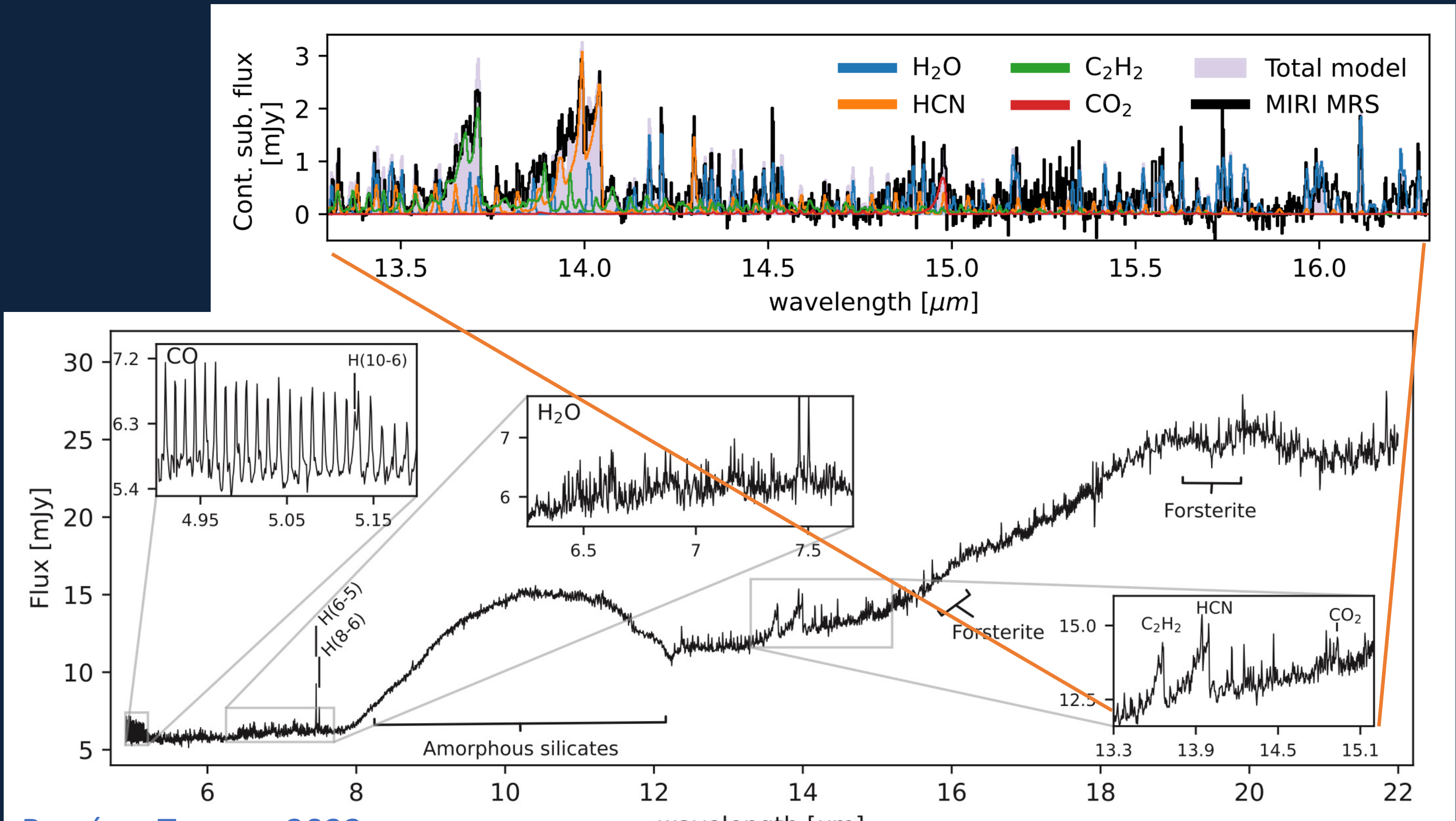


NIRCam + MIRI observations of the protoplanetary disk in Trapezium show that **FUV radiation dominates the chemistry of the inner disks**:

- The 7 µm band shows **ro-vibrational CH_3^+** caused by FUV radiation on the disk high-density gas.
- H_2O, HCN, CH_4, C_2H_2 are absent.

(Berné+2023)

Protoplanetary Disks in NGC6357

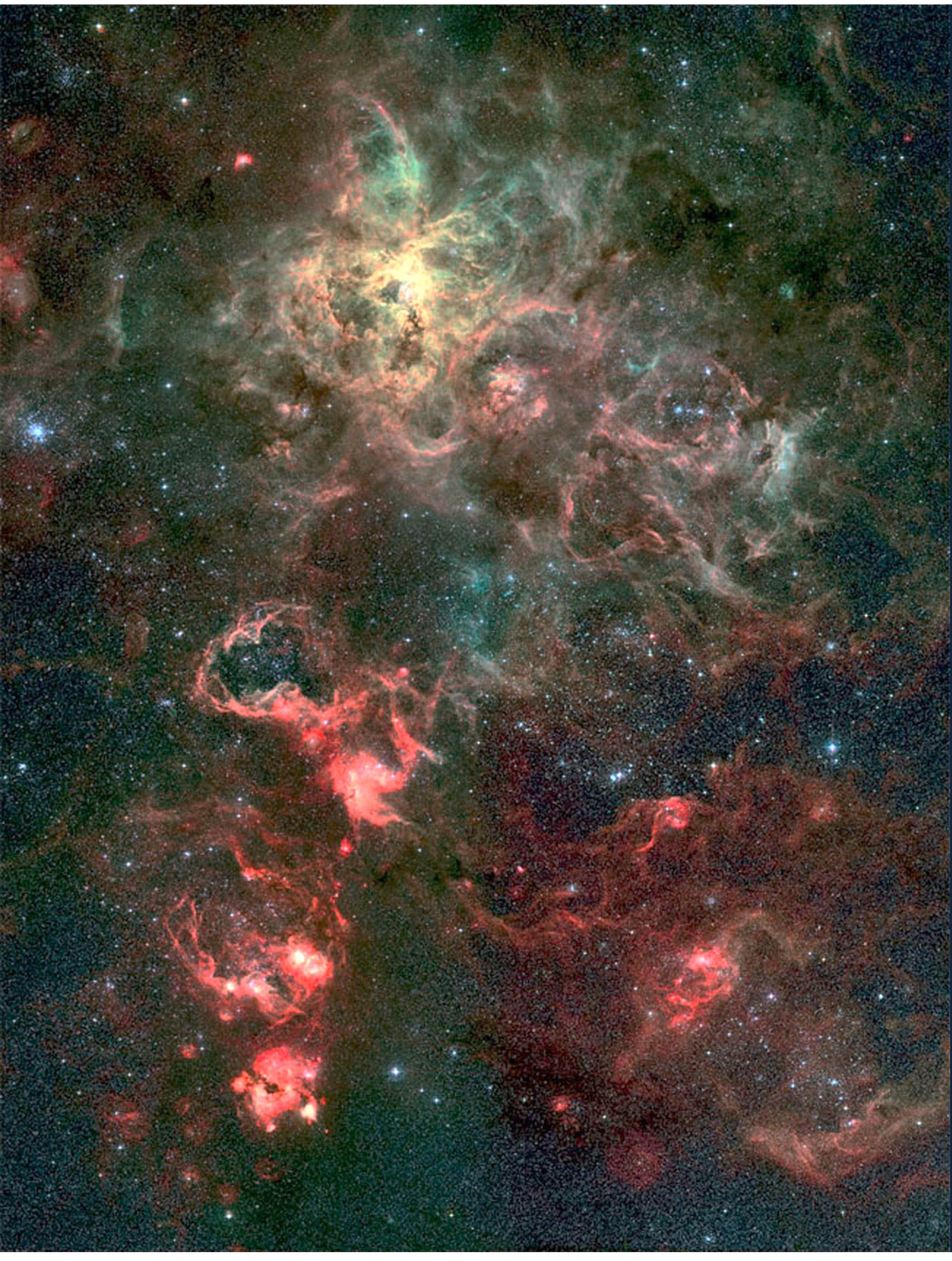


Ramírez-Tannus+2023

The protoplanetary disks in NGC 6357 **are not** affected by UV irradiation.
Spectrum remarkably similar to disks nearby star-forming regions, **with rich molecular inventory**.

Thermochemical models, (e.g Antonellini et al. 2015) predict MIR emission lines several order of magnitude stronger than observed – possibly truncated disk.

Different planetary system architectures?



Conclusions

- YMCs are laboratories to test theories of stars & clusters formation;
- Kinematic studies of YSCs in the LG can reveal the cluster assembly process;
- Hierarchical collapse seems to explain clusters structure & kinematics, + origin of OB runaways – important for SNae, GRBs and GWs
- Pre-SN feedback, FUV & x-ray irradiation can alter the geometry of future exo-planetary systems