The Conditions for the Creation of Massive Stars and their Distribution

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& the HOBYS, Hi-Gal Consortia

OVERVIEW

- Herschel studies of high mass star formation
- Our studies of far-IR/sub-mm clumps in W3
- Key observational ingredients and triggering
- Relationship to distribution of Massive Stars in the Galaxy
- Wrap-up

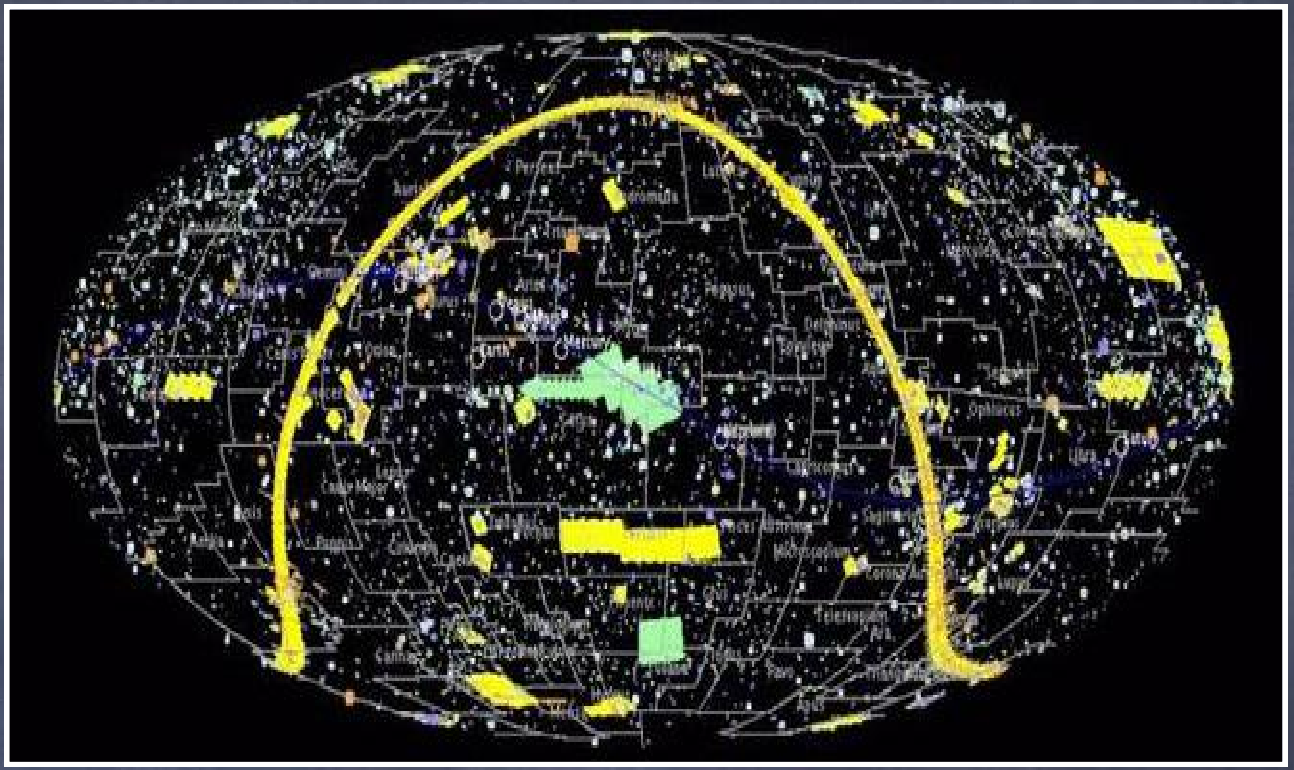
OVERVIEW

Herschel datasets point toward a scenario in which the onset of high-mass star formation (HMSF) is associated with locations where mass inf bw and <u>accumulation of material</u> are particularly enhanced relative
to the low-mass star formation case

- Convergence of f bws (e.g., Nguyen Luong+ 11; Hennemann+ 12)
- Association with supershells (e.g., Rygl+ 14)
- Intersection of f laments (e.g., Schneider+ 12)
- Stellar feedback (e.g., Minier+ 13; Russeil+ 13; Rivera-Ingraham+ 13; 15; 17)

EVOLUTION

- **MC Environment (>1pc scale)**, e.g., Rivera-Ingraham+ 15
- **Clumps (0.5-1pc scale) + Filaments** (e.g., Rivera-Ingraham+ 15; 16)
- **MDCs (0.1pc scale):** (Rivera-Ingraham+ 17a, subm)
  - Complete catalogue
  - Evolutionary classification
  - Characterization (stellar content, physical properties)
- **Statistical Studies** (Rivera-Ingraha. 17b, in prep)
  - Comparisons of HMSF regions in different parts of the galaxy



- **Herschel imaging survey of OB Young Stellar objects -** (HOBYS; PI. F. Motte). *In depth region analysis*
- **the Herschel infrared Galactic Plane Survey -** (Hi-GAL; PI. S. Molinari) *Statistical analysis of fields*

CURRENT STUDIES

- Used Herschel/PACS and SPIRE data maps – 70, 160, 250, 350 and 500 Ι m. Typically areas few degrees2.
- **For large-scale/more diffuse structures:**
  - Determine offset to pipeline product based on Planck/IRAS large-scale information.
  - Remove background/foreground ISM components using HI and CO (see Tige+ 17).
  - Use point-to-point information at 4 wavelengths to fit greybody (∩=2) dust model.
  - Map resolutions of 36”.
- **For clumps and cores:**
- **Temperature and column density/Av maps at 18” resolution used for core extraction (HOBYS standard)**
- Extraction of fluxes using *getSources* routine (Men’shchikov+ 12).
- Greybody dust model fit for **temperatures and mass determinations** (including well-known distances).

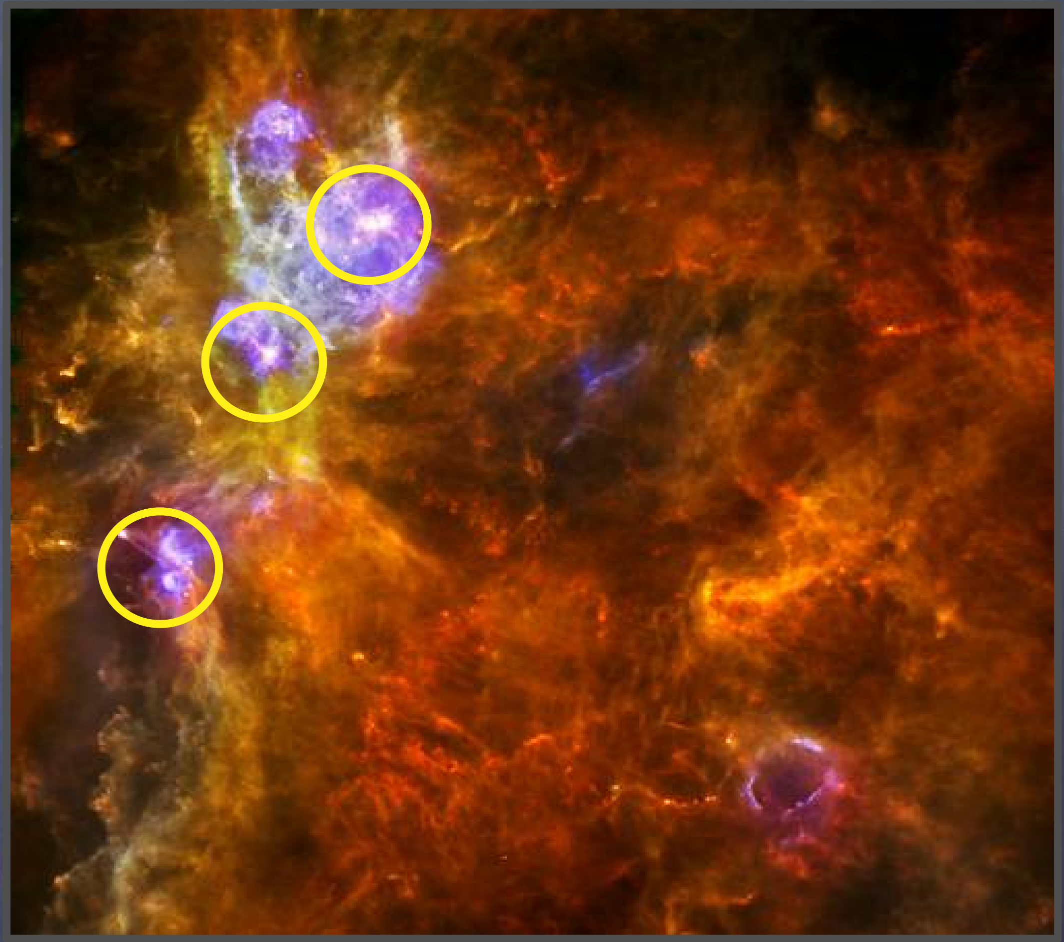
CURRENT STUDIES

- We have produced a global catalog of cores of W3 (Rivera-Ingraham+ 17)

- HMSF shown previously to be within 3 main clumps (W3 east, west and W3 (OH) – Rivera-Ingraham+ 13)

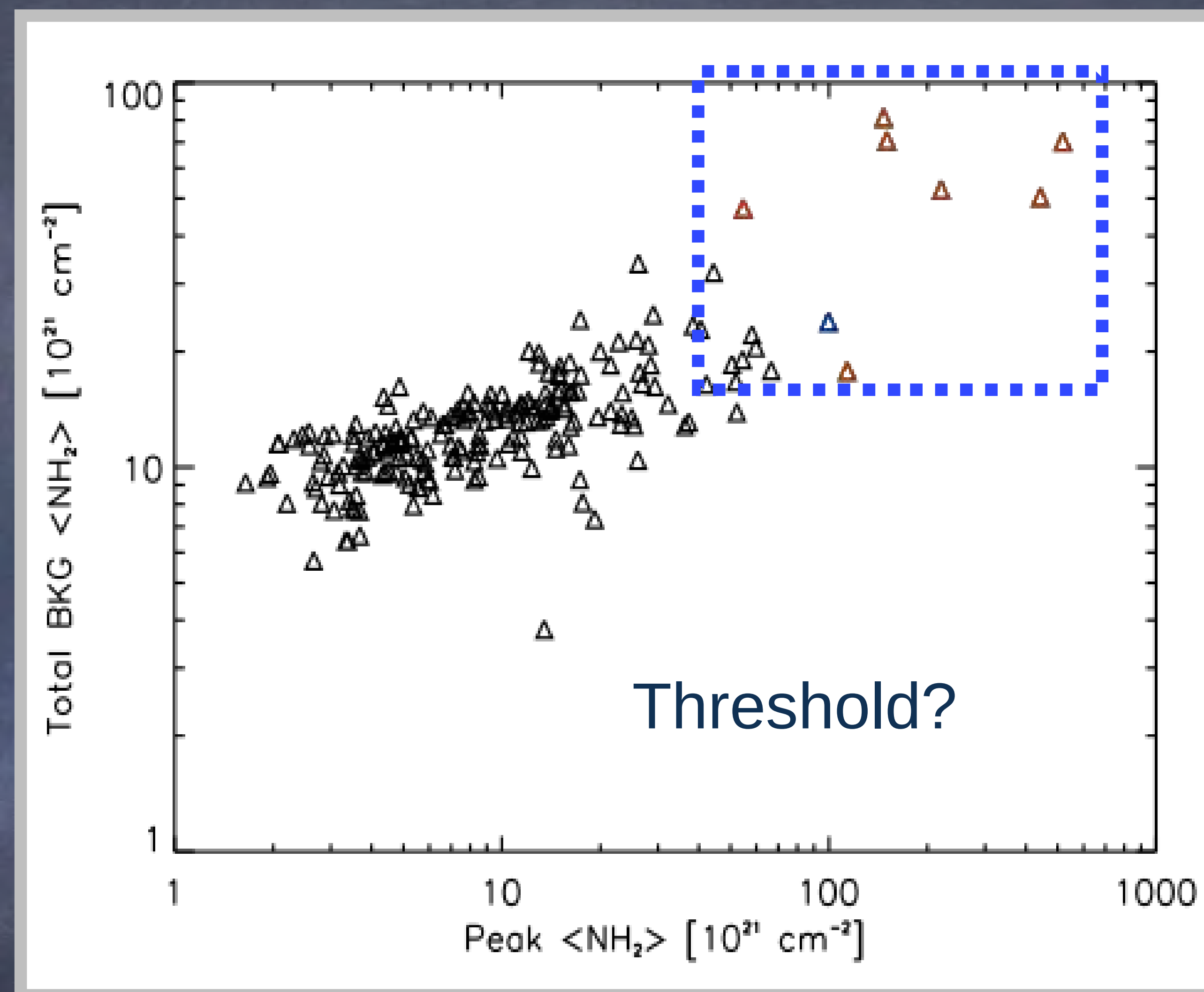
<NH2peak >= 1.7x1023cm-2,
<NH2-env >=4.6x1022cm-2,
<Mass >= 365M⊙

Rivera-Ingraham+ 17



W3 region with Herschel – Rivera-Ingraham+ 15

EVOLUTION

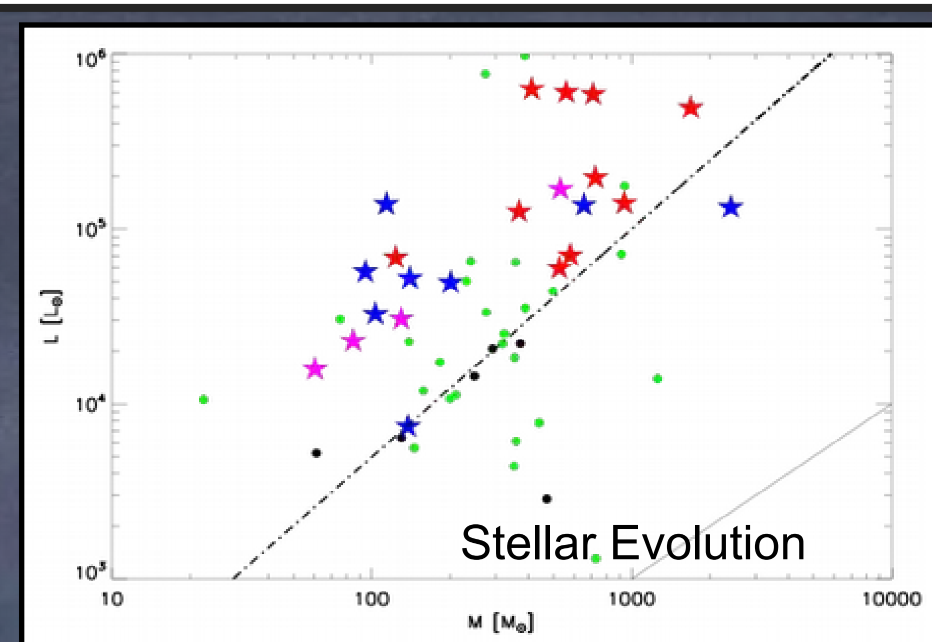


High peak col density and background col density

Hi-gal studies of the outer galaxy (d < 3kpc).

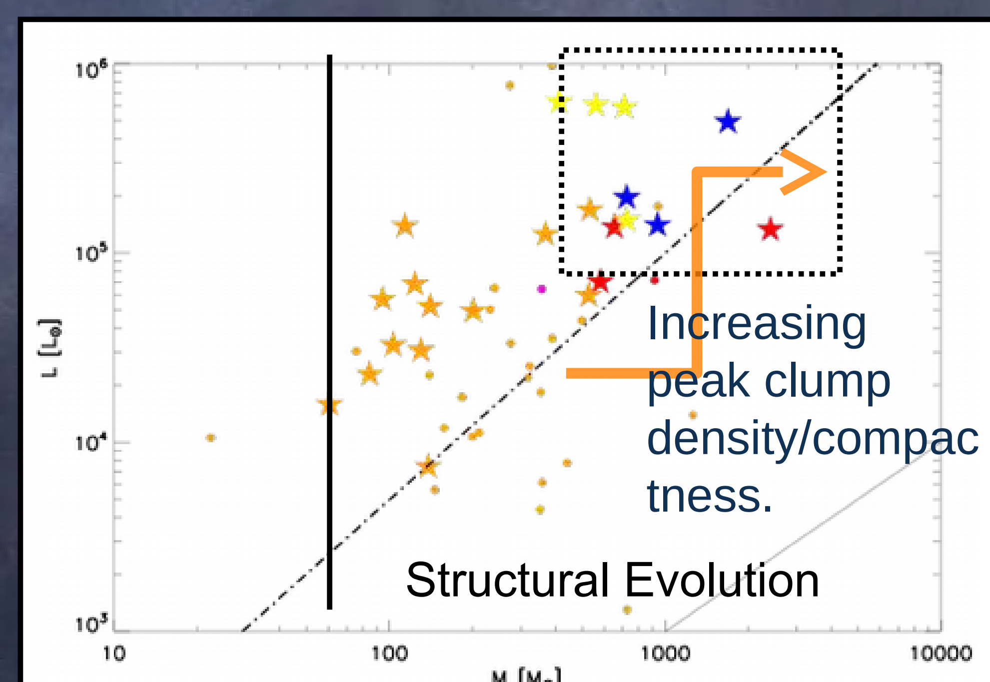
Evolution of Clump Environments

EVOLUTION

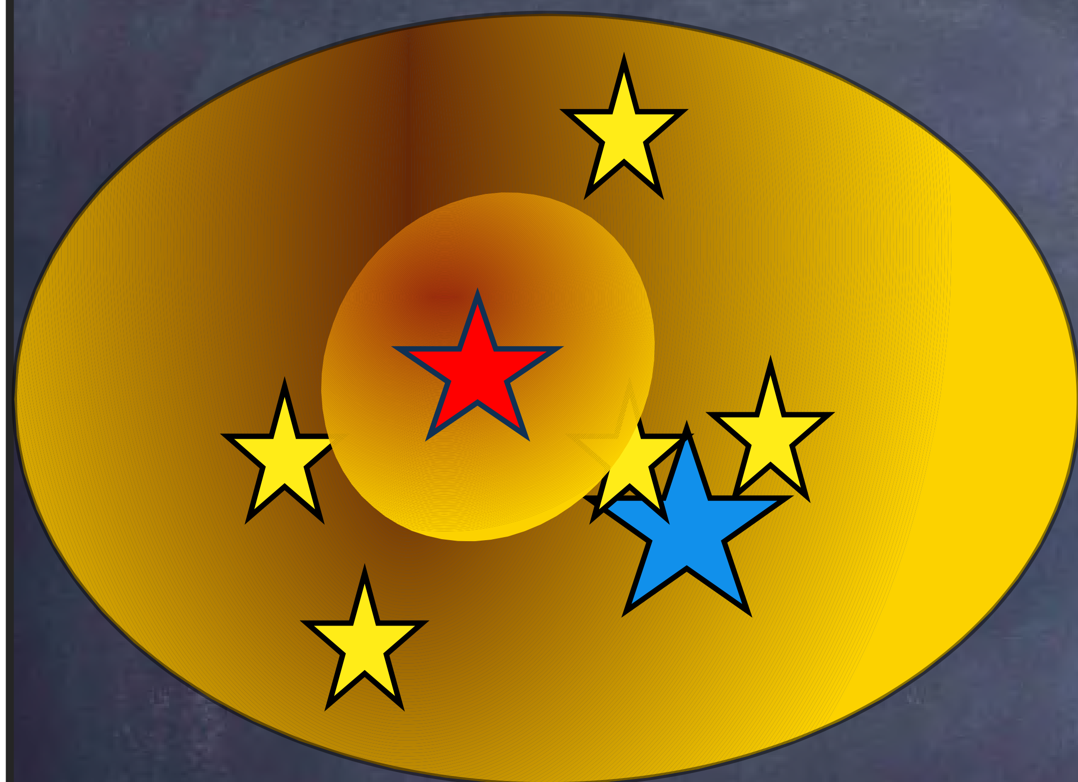


★ Strong HMSF features
★★ Weak HMSF features
• No HMSF

Hi-gal studies of the outer galaxy (d < 3kpc).



EVOLUTION



High central NH2.

- Deep gravitational well (core mass) [CONTAINMENT]

Environment mass → a signif icant, long-lasting supply of material

- Continuous assembly with large gas supply [MASS ACCRETION, GROWTH]
- Replenishment
- Counteracts feedback/disruption
- Provides conf inement needed w/ minimal disruption (e.g. Dale & Bonnell 11)

P α <NH2-env>2

α Δenv3/4

(McKee &Tan 03)

EVOLUTION

Parameter	All	Active [IR-bright]	Inactive [IR-quiet+starless+UCS]	Inactive [IR-quiet]	Inactive [Starless]
Number	442	3	30	10	6
Mass [$M_\odot$]	25 ± 3	324 ± 251	126 ± 9	118 ± 16	107 ± 10
<T [K]>	16.4 ± 0.3	34.7 ± 5.2	14.1 ± 1.2	11.7 ± 0.9	12.7 ± 3.2
L_{FIR} [$L_\odot$]	268 ± 106	24721 ± 6879	666 ± 226	80 ± 53	828 ± 821
				± 0.030	0.238 ± 0.052
				± 0.02	0.18 ± 0.02
				± 0.7	0.7 ± 0.2
				± 0.7	1.4 ± 0.7
				± 0.4	1.3 ± 0.5
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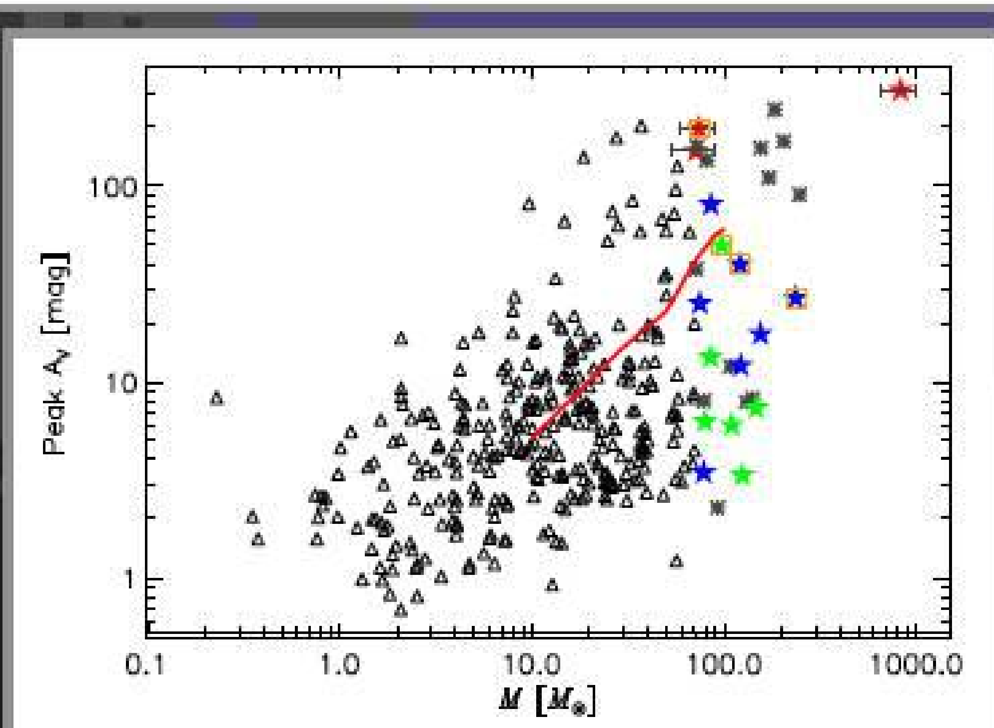

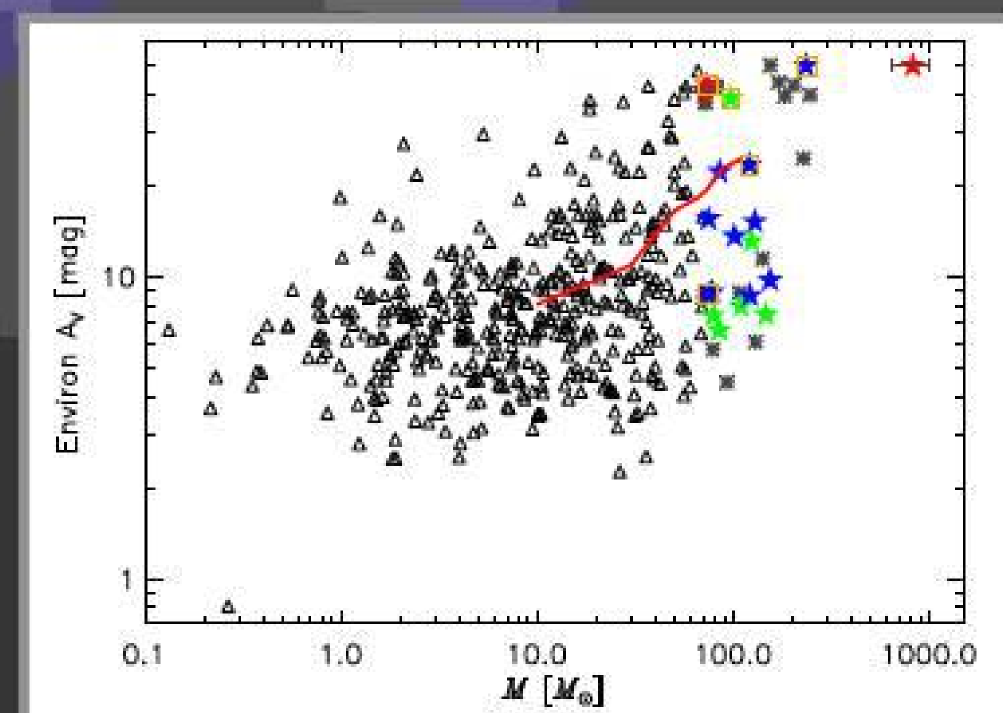

HOBYS W3 study, Rivera-Ingraham+ 17

MDCs extracted from W3 region

EVOLUTION

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Number	442	3	30	10	6
M		251		118 ± 16	107 ± 10
<		5.2			
L		6879		80 ± 53	828 ± 821
				± 0.030	0.238 ± 0.052
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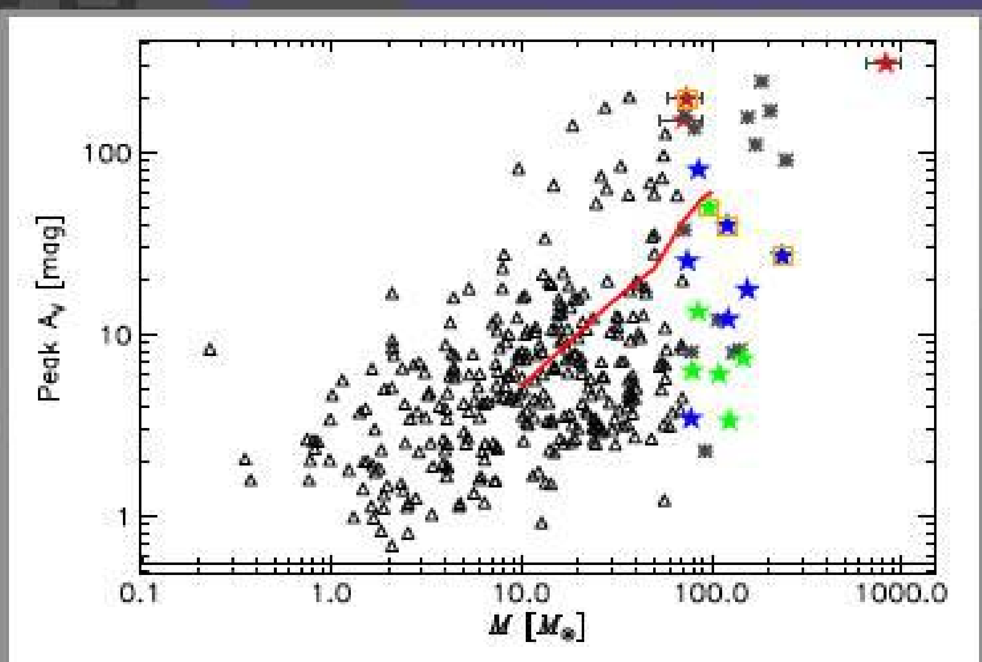
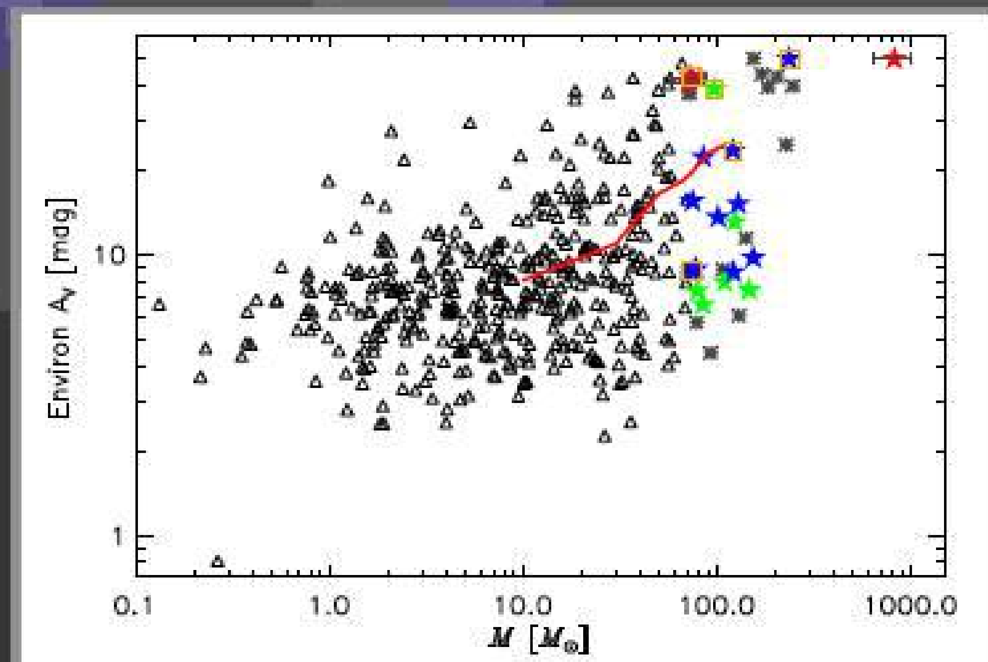
HMSF (radio, methanol masers)
LMIR>B3 star
Lsubmm/Lbol<1%
[70 μm]

LMIR<B3 star
Lsubmm/Lbol<1%
[70 μm]

No 70 μm above noise level





HOBYS W3 study, Rivera-Ingraham+ 17

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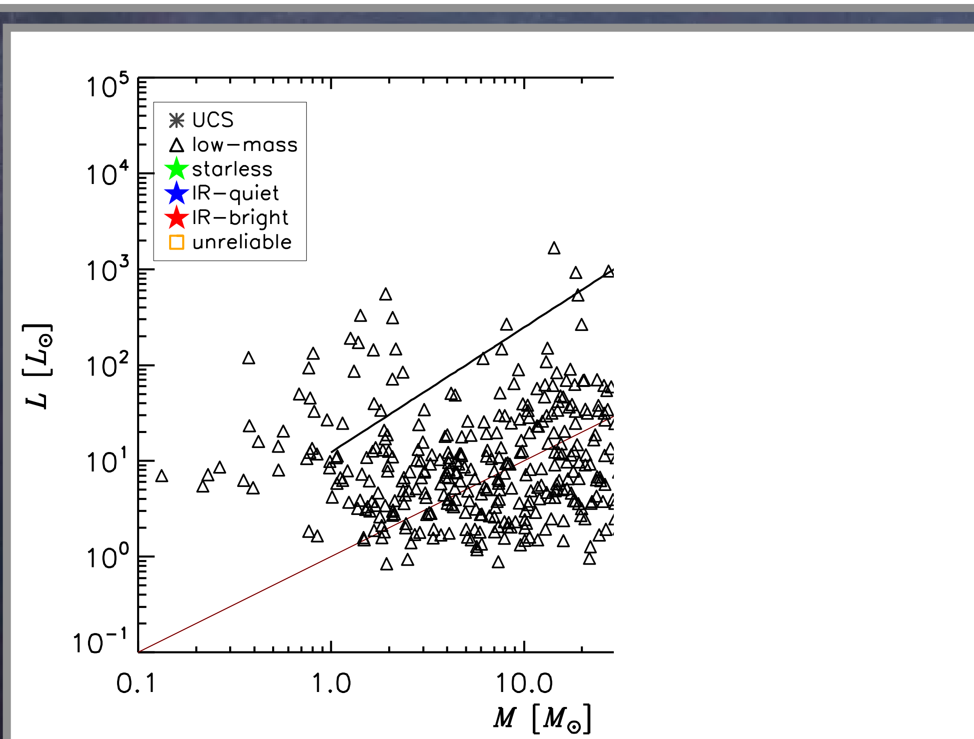

- NH2(peak) [bright/quiet] ~11
- FWHM [quiet/bright] ~2
- n [bright/quiet] ~7
- NH2(env) [bright/quiet] ~2.5

“Vertical” evolution, e.g. Molinari+ 08

MDCs "diagonal" core evolution

EVOLUTION

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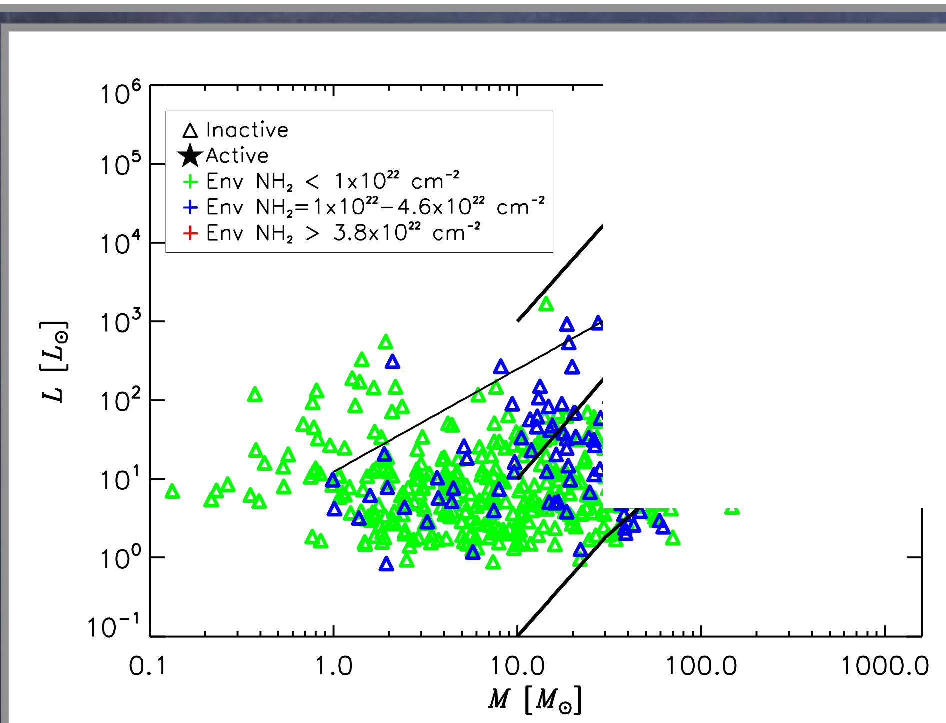
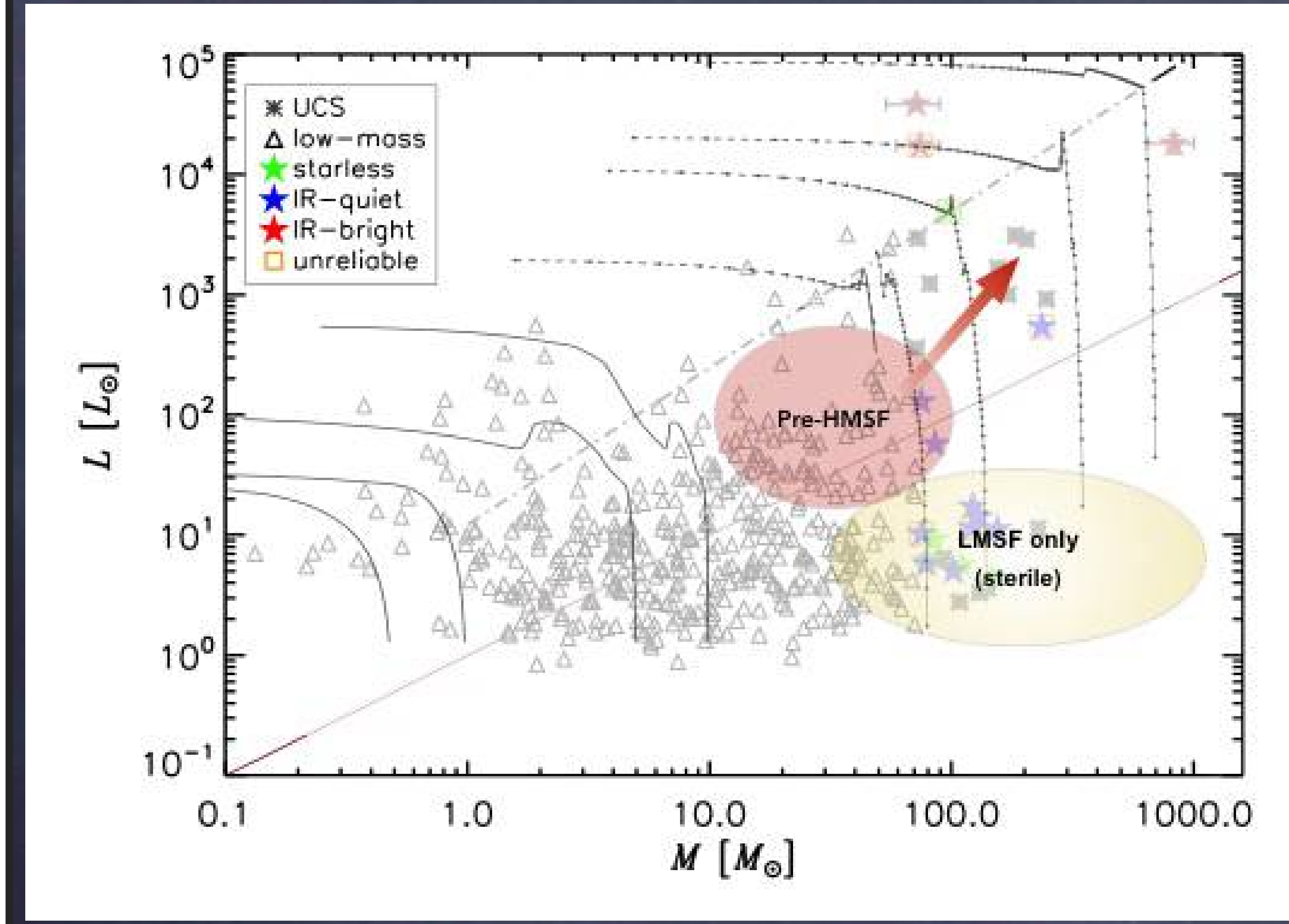


- NH2(peak) [bright/quiet] ~18.5
- FWHM [quiet/bright] ~1.5
- n [bright/quiet] ~9.5
- NH2(env) [bright/quiet] ~4

[also see Tige+ 17]

HOBYS W3 study, Rivera-Ingraham+ 17

EVOLUTION



- **IR bright MDCs**: In W3 estimate lifetime ~ 105 yrs, for 100M⊙ accumulation : 10-3M⊙/yr
  (in agreement with mass accretion rate based on core environment)

- **Starless/IR-quiet**: shorter lifetime or non-existent HMSF

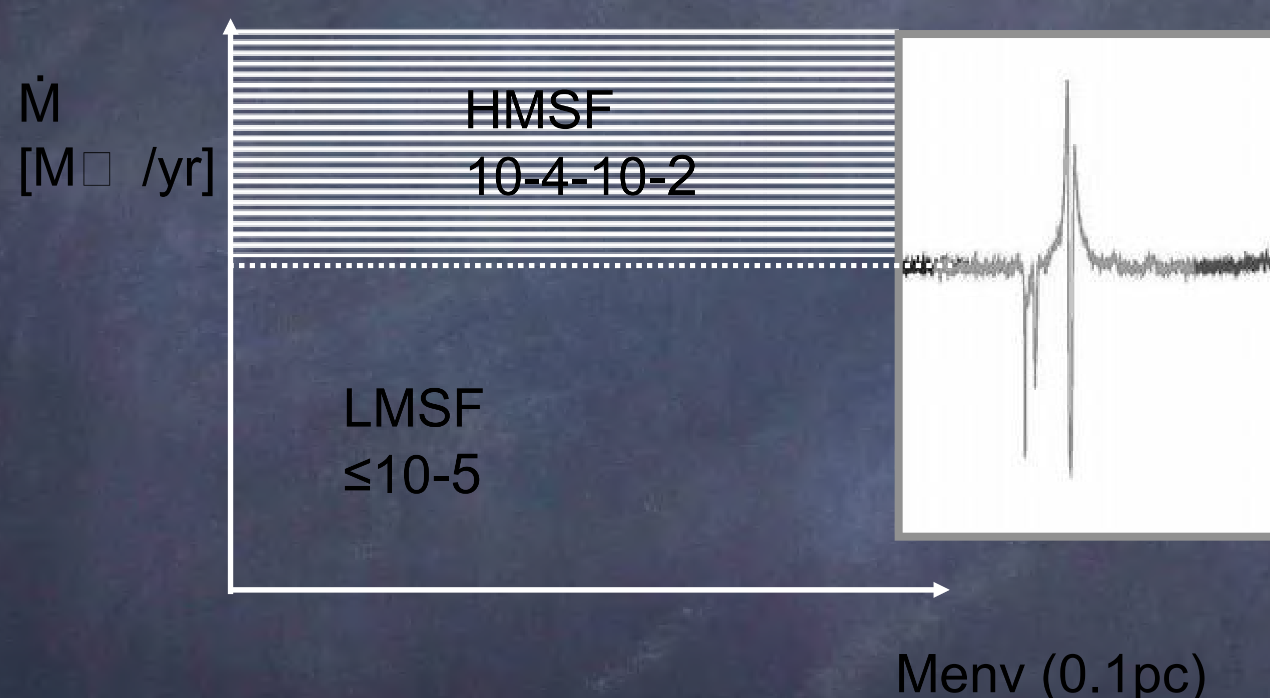
Supports…..

Large Scale Grav. collapse model + Evolution with core mass growth

A SWITCH FOR HMSF [?]

*EXCLUSIVE **combination** of conditions for 0.1 pc active cores with HMSF:*
<NH2> ~ 2x1023 cm-2 <NH2-env> ~ 5x1022 cm-
<M> ~ 600 MNº

*Max. efficiency and high mass convergent inflow in localised region: high **Ṁ***



Ṁ-threshold
or Ṁ-criterium

- **NH2** > Deep potential well + minimal disruption (e.g., Dale+ 05)
- **Env/M** > High inflow rate + lots of material + confinement (counteraction of stellar feedback)

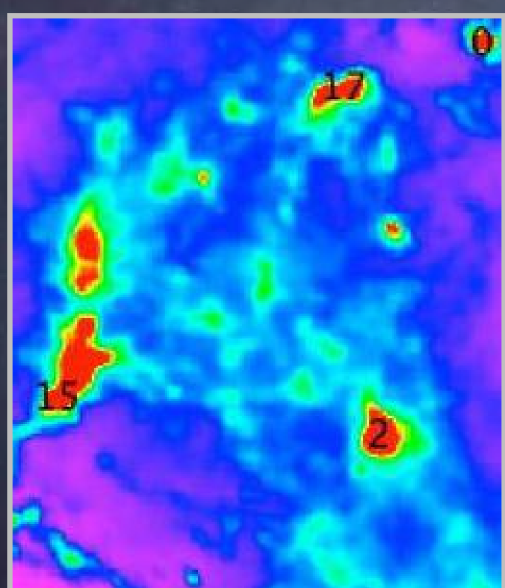
IN PROGRESS!

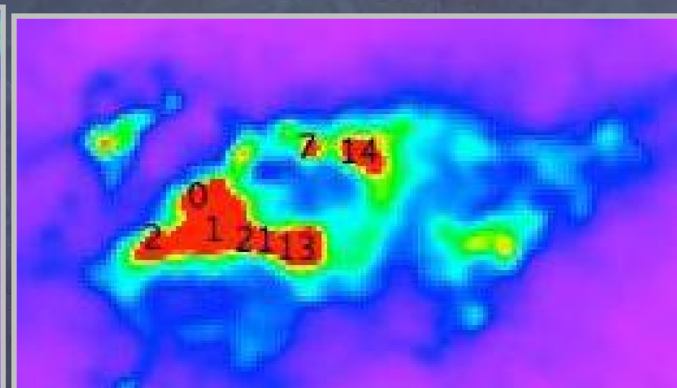
BIMODALITY IN HMSF

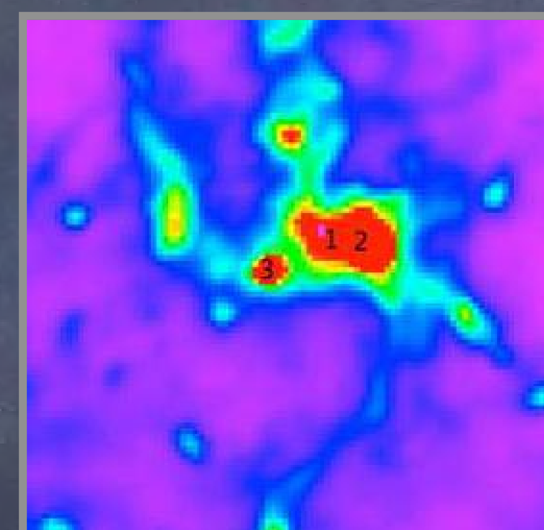
If $\dot{M}$ criterium is the key , then…

Gravity (Large Scale Collapse)
Easiest way, most common

Externally Driven SF Mode
(direct triggering)



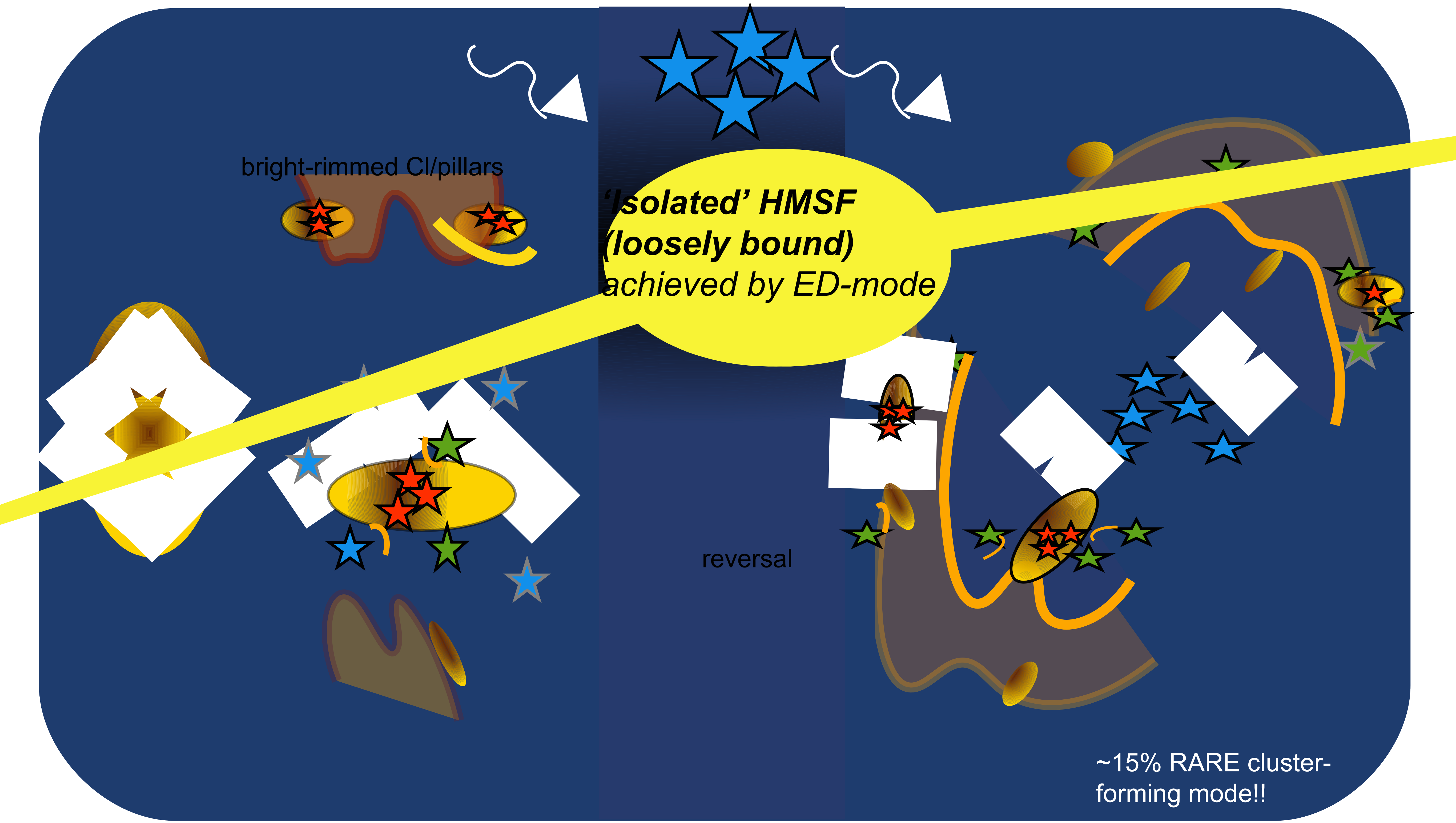




- Most common
- (extended) LMSF coeval with HMSF (youngest)
- Age distribution, primordial mass segregation

e.g., CCF Model
(Rivera-Ingraham+ 13)

BIMODALITY IN HMSF



BIMODALITY IN HMSF

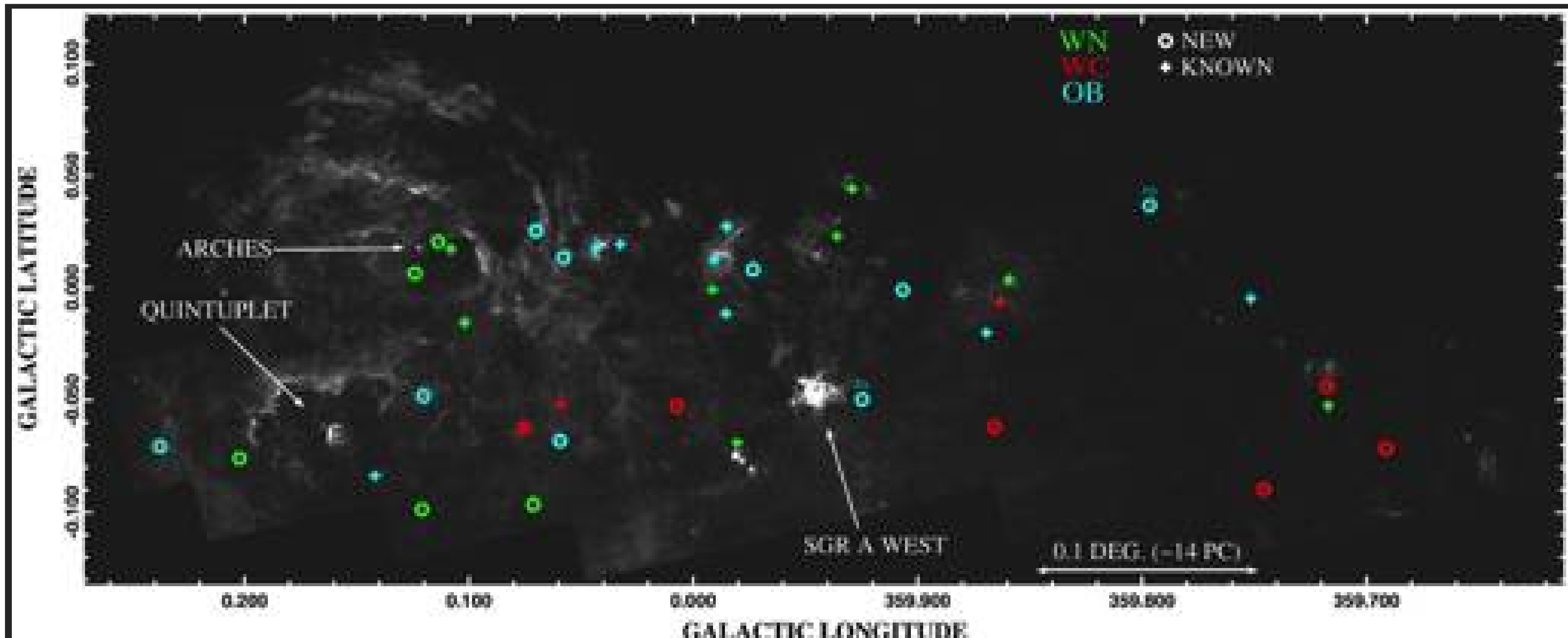
~~High-mass Stars Form in Clusters~~

Clusters form WITH High-Mass Stars

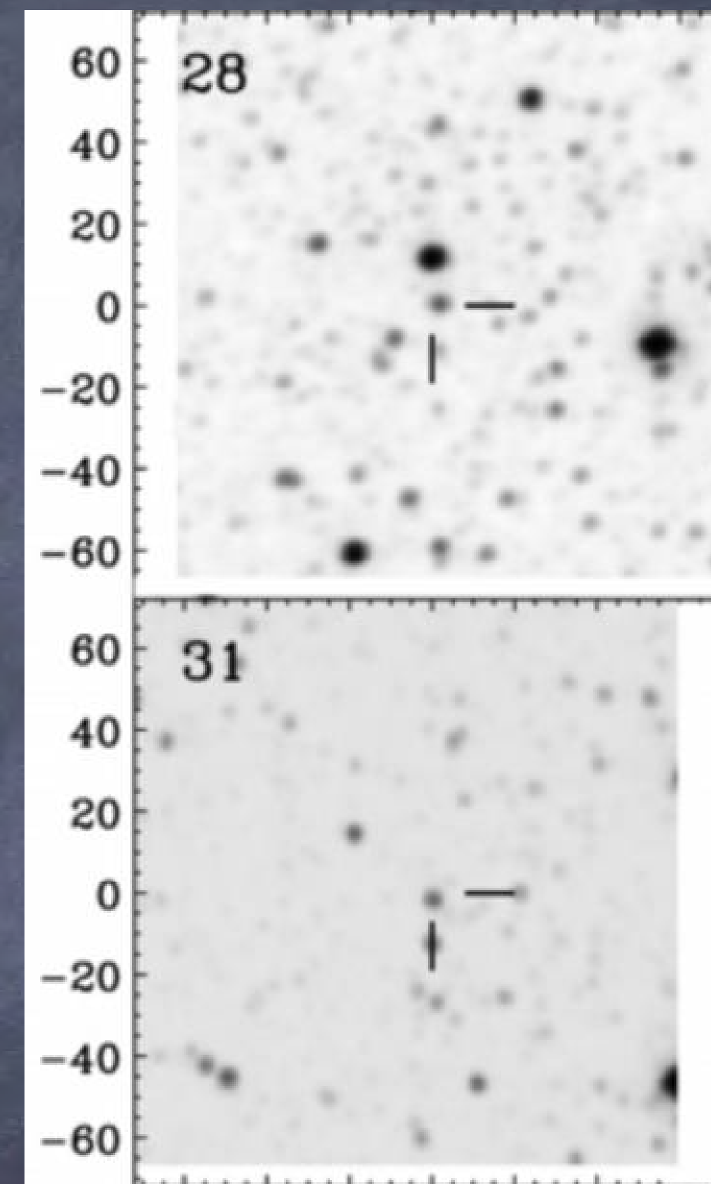
MASSIVE STAR DISTRIBUTION

- Considerable substructure based on X-ray emitting population
- No evidence for mass segregation.
- <u>No evidence massive stars are in regions of higher local density.</u>
- Cyg OB2 has always been a substructured, unbound association (Wright+ 14)
- No obvious expansion from PMs (Wright+ 16)

MASSIVE STAR DISTRIBUTION



O/WR stars towards Galactic Center (Mauerhan+ 11b)



Example 2MASS Ks band images of “new” WR stars (Mauerhan+ 11a)

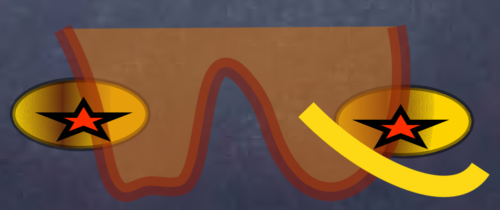
~70% of WR/LBV stars are NOT found within 4 stellar cluster radii (Rosslowe & Crowther 17). In loose OB assocns./in field.

Also note Marston+ 15; 16.

Massive star expulsion from young clusters.
Binaries in SNe?

Low mass clusters ~10^2-10^3 $M_\odot$.

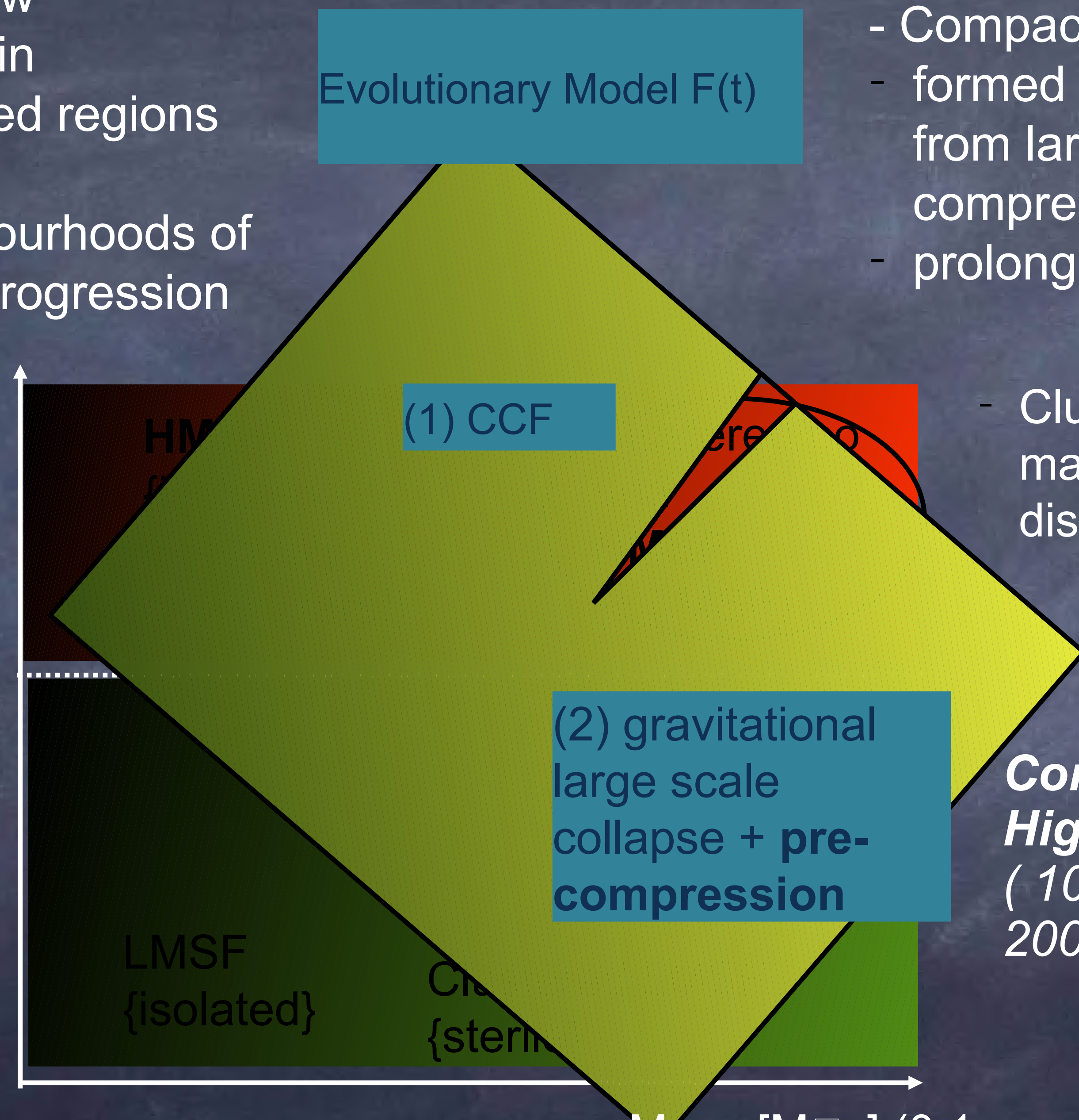
Distributed/more isolated – e.g. via triggered SF.



SUMMARY & FUTURE PROSPECTS

- Isolated HMSF, no/few companions, formed in peripheries of triggered regions
- > loose associations
- > subclusters neighbourhoods of associations, out-in progression

- Compact bound massive clusters
- formed @ center of potential wells from large scale collapse or active compression of dense region:
- prolonged SF

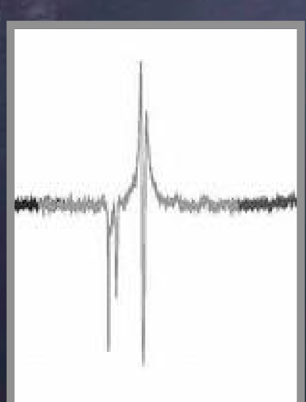


Triggering +external feedback

/yr]

Threshold 10-4

[Dynamics]



- Cluster Diversity: richness, age, mass/stellar dynamics and distribution **[JWST, Gaia]**

Convergent Localised High Inflow/collapse Rate

(10-4 - 10-2 M/yr ; e.g., Fuller et al. 2005; Herpin et al. 2012, etc.)

(1) Rivera-Ingraham+ 13; 15

(2) Rivera-Ingraham+ 17a; 17b

Backup slides

Essential Points

OVERVIEW

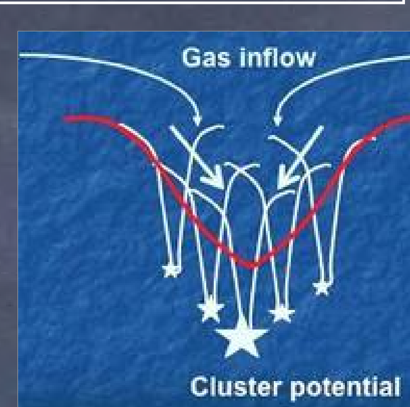
- Unique processes associated with conditions and onset of HMSF
- Environment conditions are important
- HMSF requires a column density threshold
- Potential   rather than M relation to HMSF
- Containment needed
- HMSF can take time – not necessarily f rst stars
- Clusters not essential to HMSF
- High mass stars distribution – changing perspective with less clustering.

Competitive Accretion (Bonnell et al. 1997, 2001)

"The rich get richer model", 'location, location, location'

Pre-existing (low-mass) overdensities

Bondi-Hoyle Accretion, determined by gas dynamics

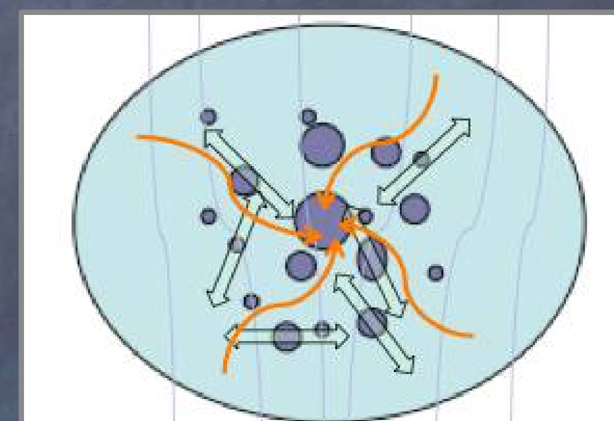


HMS form first or simultaneously, mass segregation

No HMS cores

Outflow Regulated Clump Fed Model

(Wang et al. 2010)

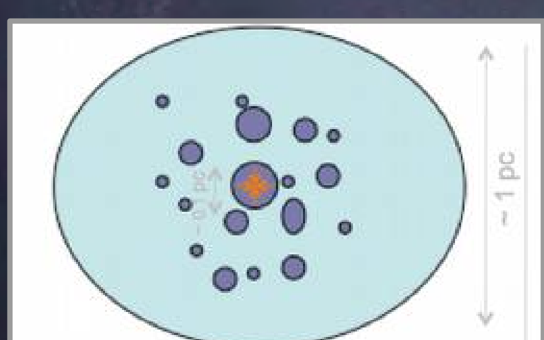


Credit: Zhi- Yun

No pre-assigned mass/core - fed from pre-exist. collapsing clump

Mass segregation

Turbulent Core Model (McKee & Tan 2003)



Credit: Zhi- Yun

No competition – mass already assigned to cores

Pre-existing HM cores - characteristic scale

Turbulent support

Filamentary inflows from large scale reservoirs

No pre-existing seeds but Grav potential important - location, location, location

Turbulence important

EVOLUTION

Cores within clumps

- Starless
- IR active
- IR quiet

OVERVIEW

THEORETICAL CHALLENGES

Evolution: Mechanism, pre-stellar cores?…

Physics: e.g., Radiation pressure

Preferential Cluster formation

Cluster primordial mass segregation and age distribution

Bimodality? Threshold?

OBSERVATIONAL CHALLENGES

Large Distances (kpc - Resolution)

Rare (Statistics)

Disruptive

Short lifetimes

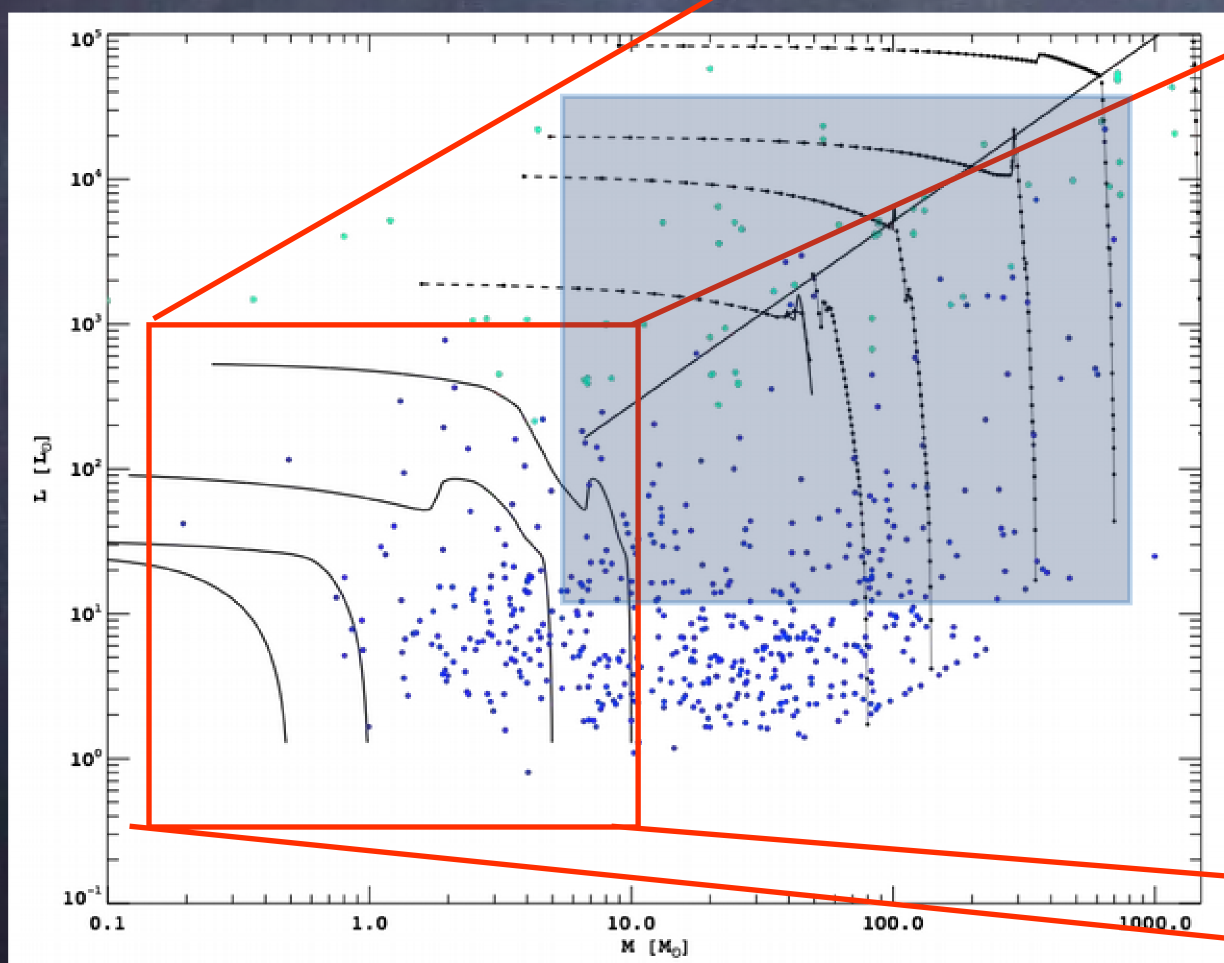
Highly-embedded (IR/submm)

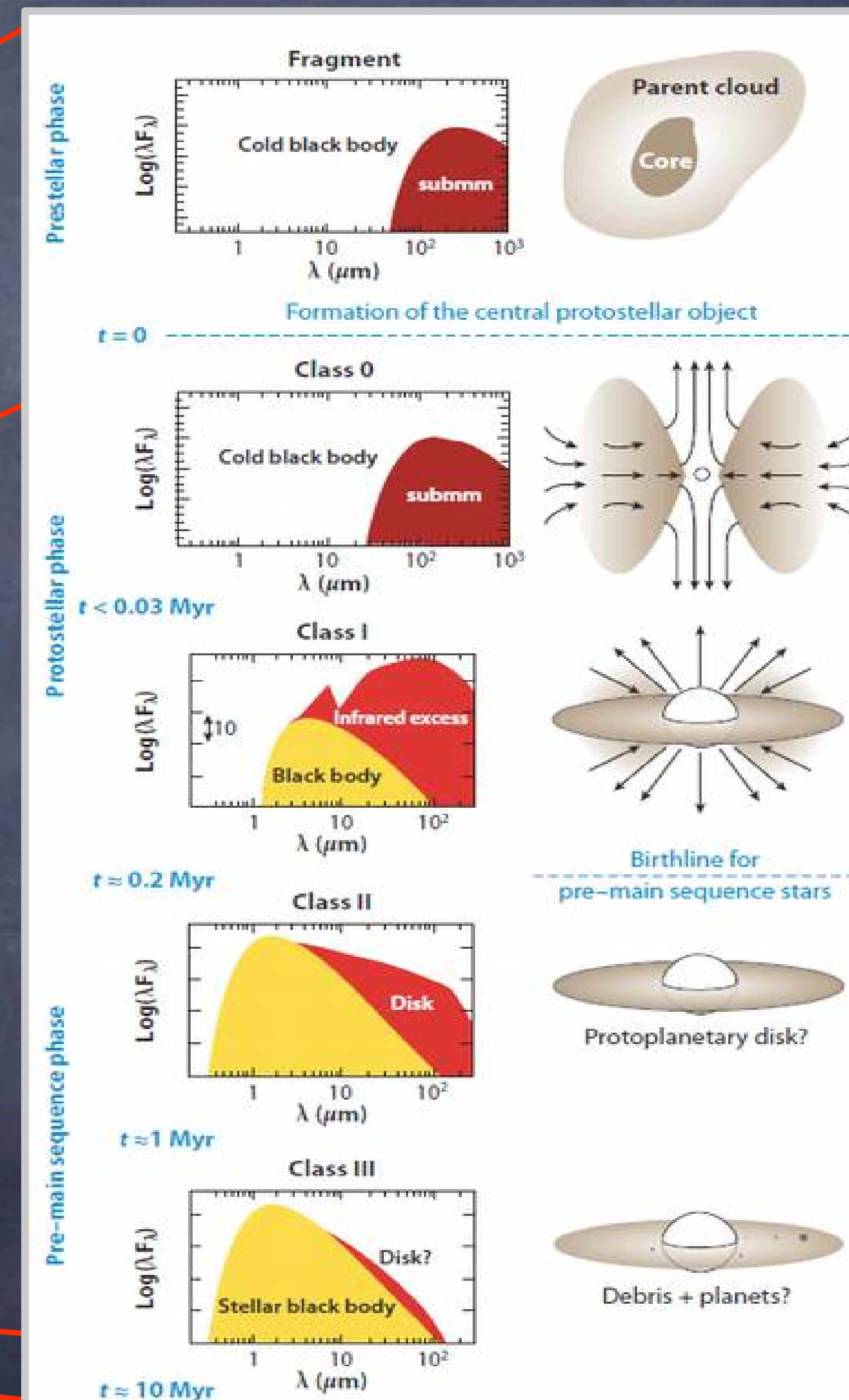
Highly Clustered (Resolution)

OVERVIEW

Mass	H-burning designation	Sp. type
8-16M⊙	Early B-type massive stars	B3V to B0V
16-32M⊙	Later O-type massive stars	O9V to O6V
32-64M⊙	Early O-type massive stars	O5V to O2V
64-128M⊙	O/WR type massive stars	Of?/WNL-H

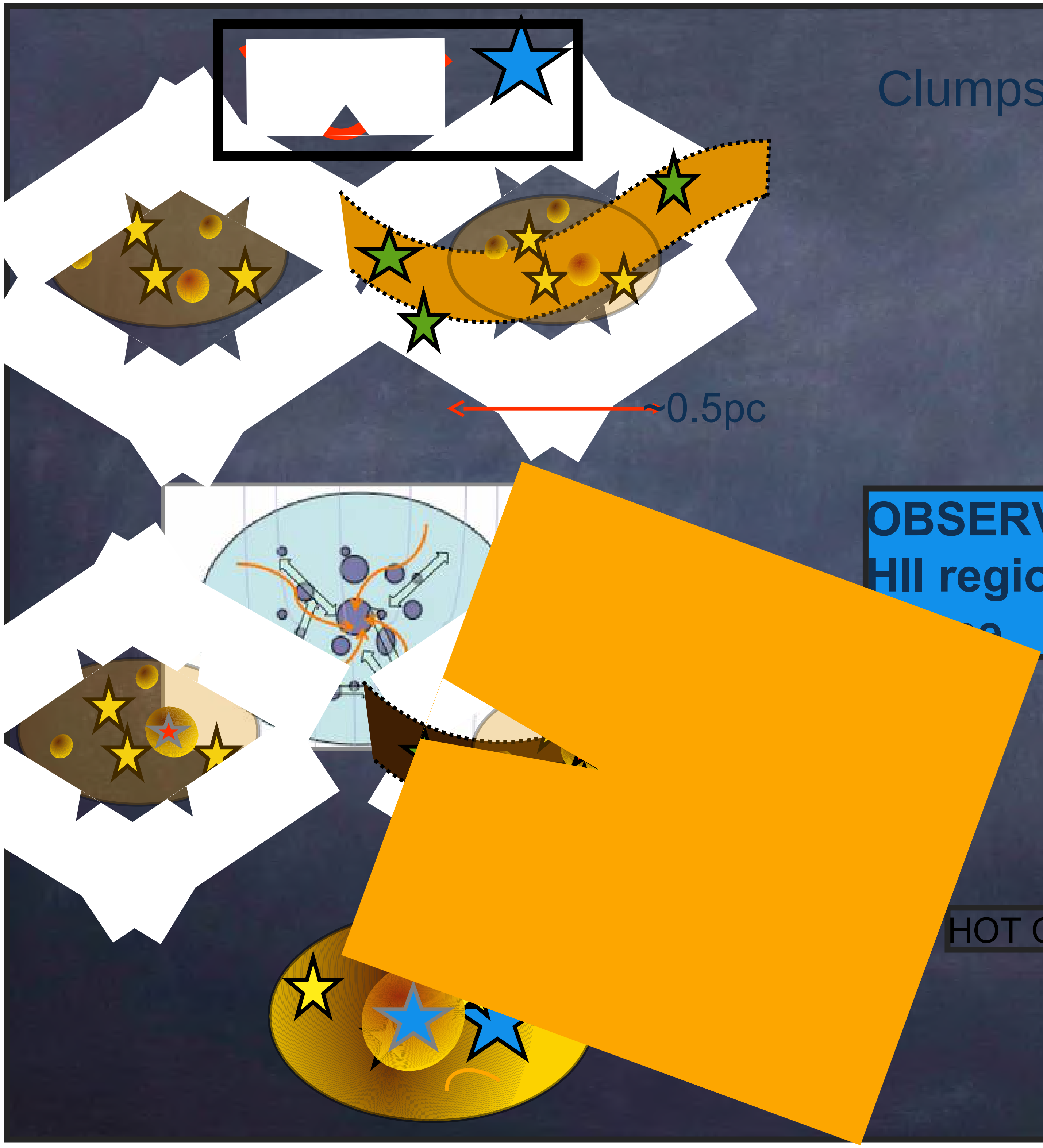
Zinnecker et al 2007





EVOLUTION

Clumps and Filaments



OBSERVABLE!!
HII region

HOT CORE

- Compact radio emission: HC, UC HII regions
- Masers
- Rich complex chemistry

EVOLUTION

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Lsubmm/Lbol<1%
[70 µm]

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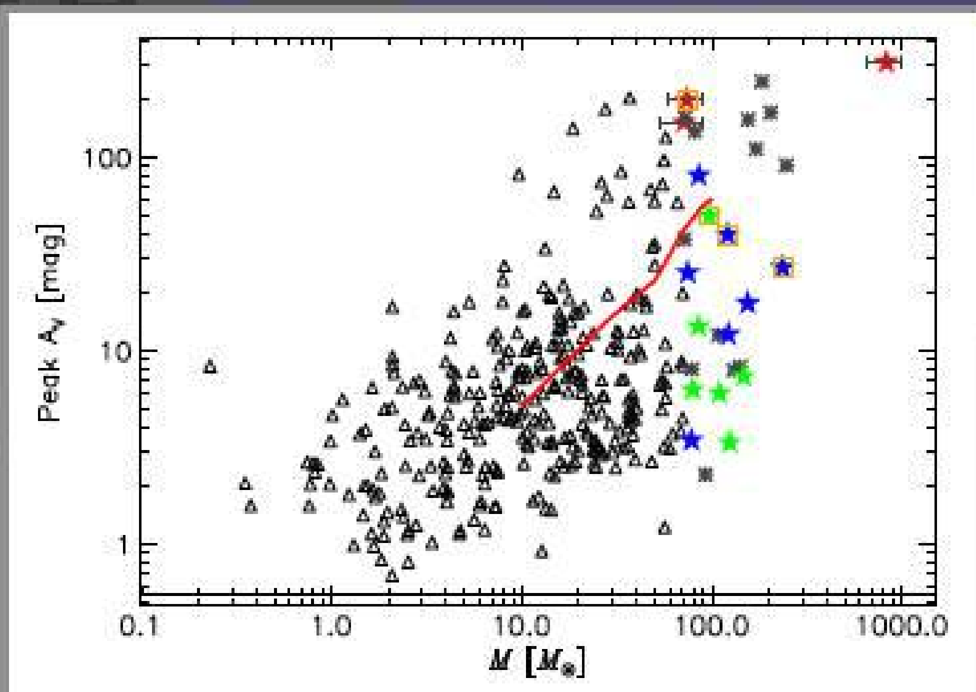
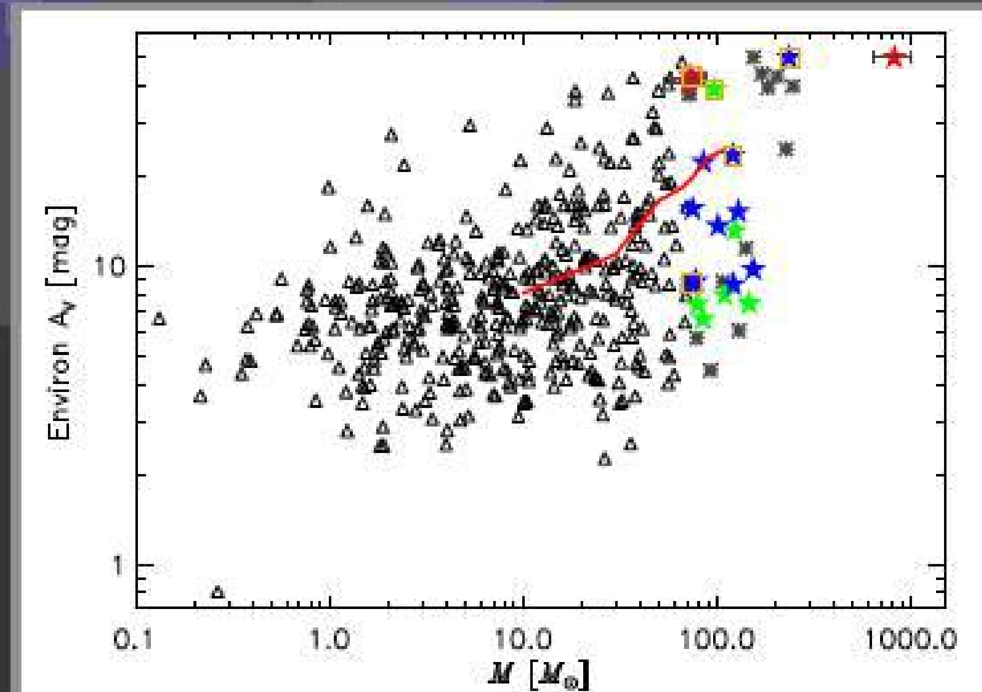
[70 µm]

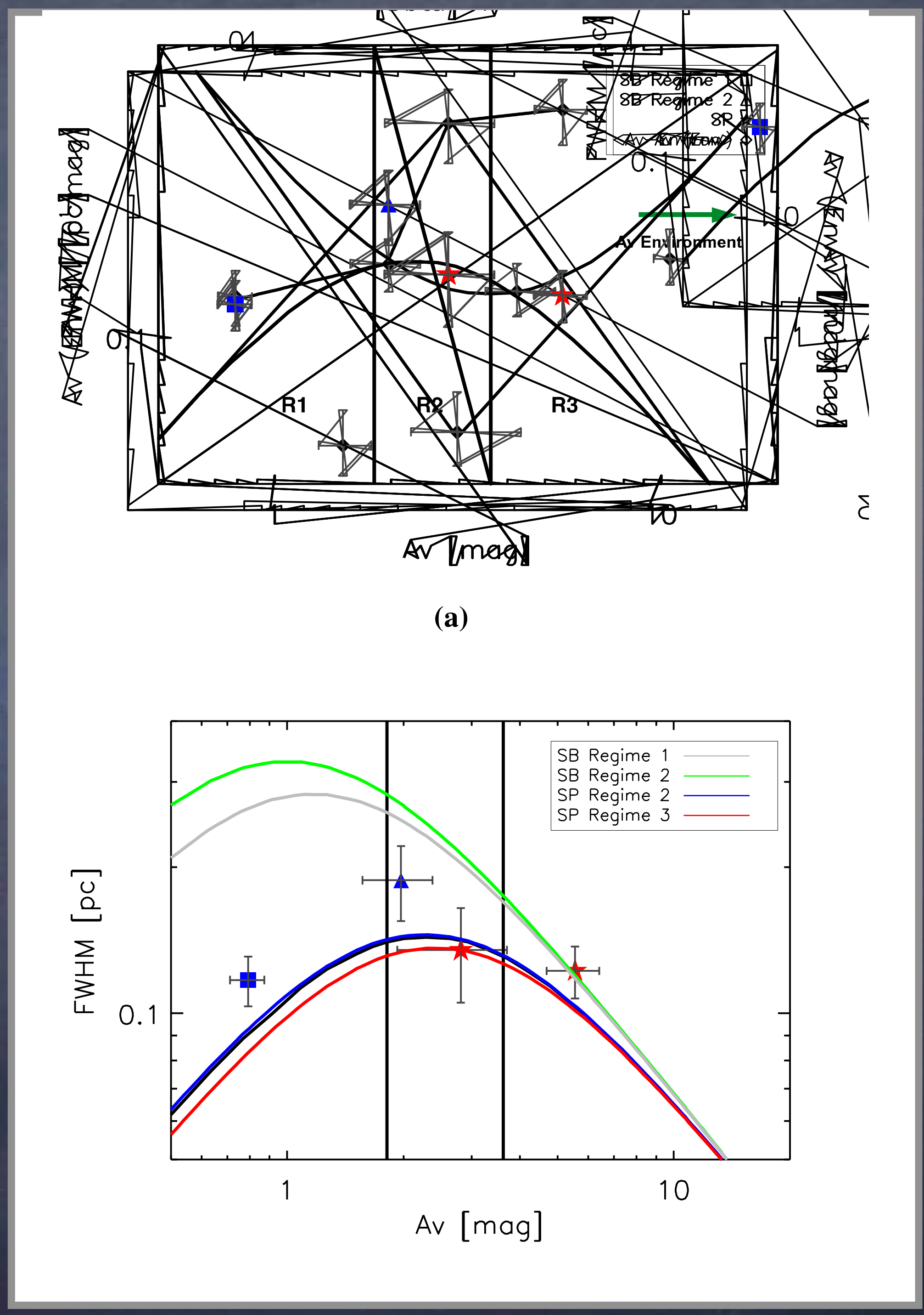
No 70 µm above noise level



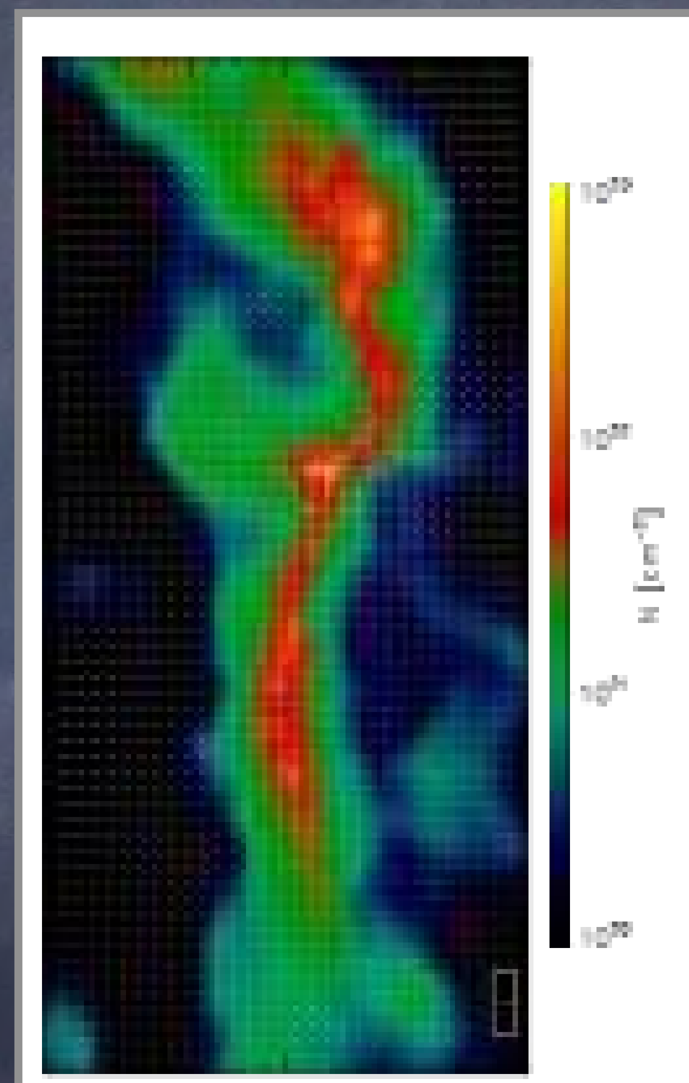


HOBYS W3 study, Rivera-Ingraham+ 17

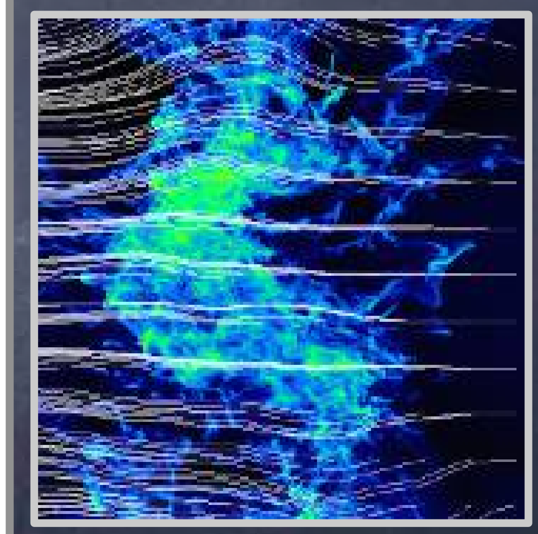
EVOLUTION


(a)
SB Regime 1
SB Regime 2
SP Regime 2
SP Regime 3
FWHM [pc]
0.1
1
10
Av [mag]

EVOLUTION



Gómez et al. 2014

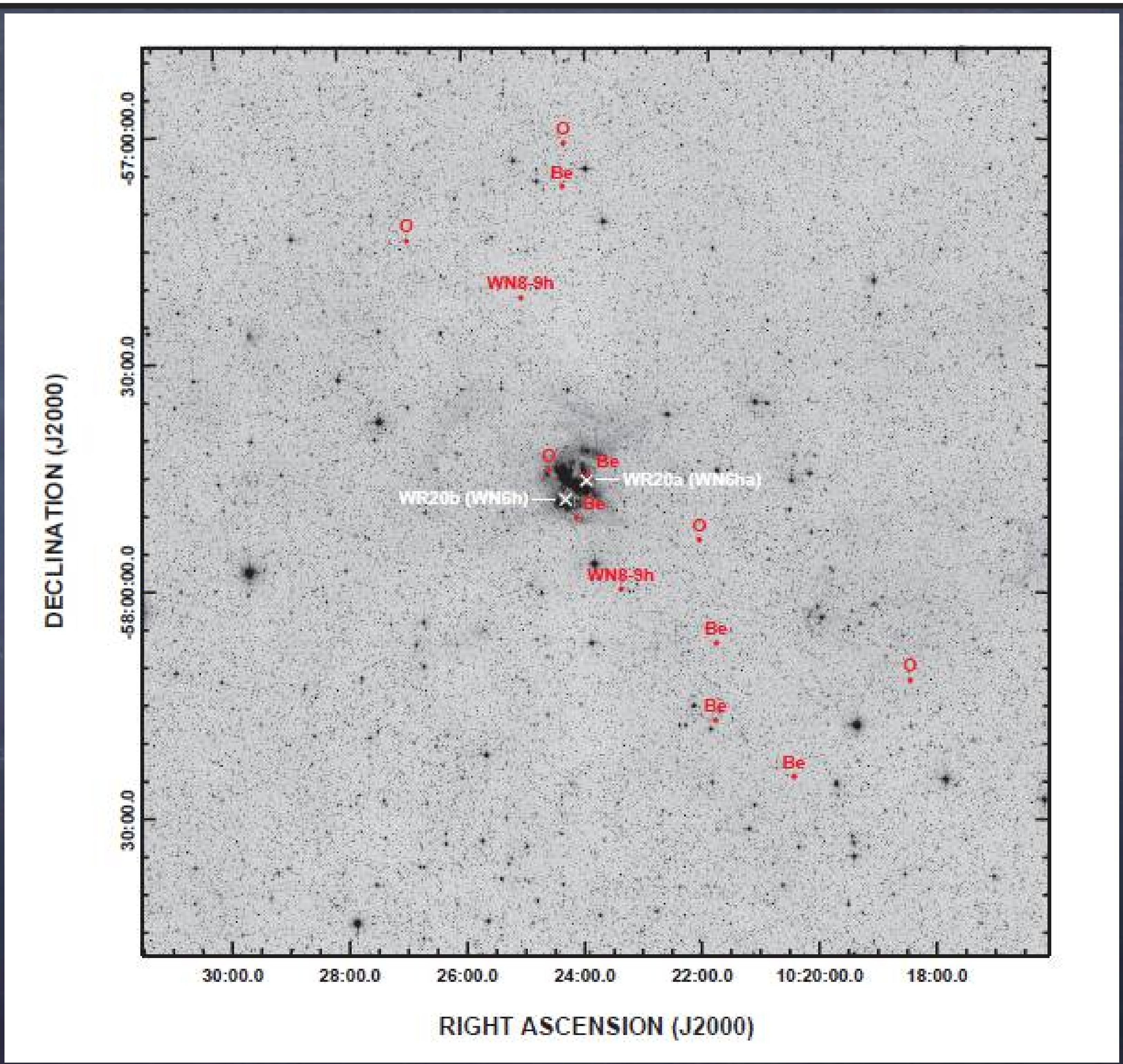


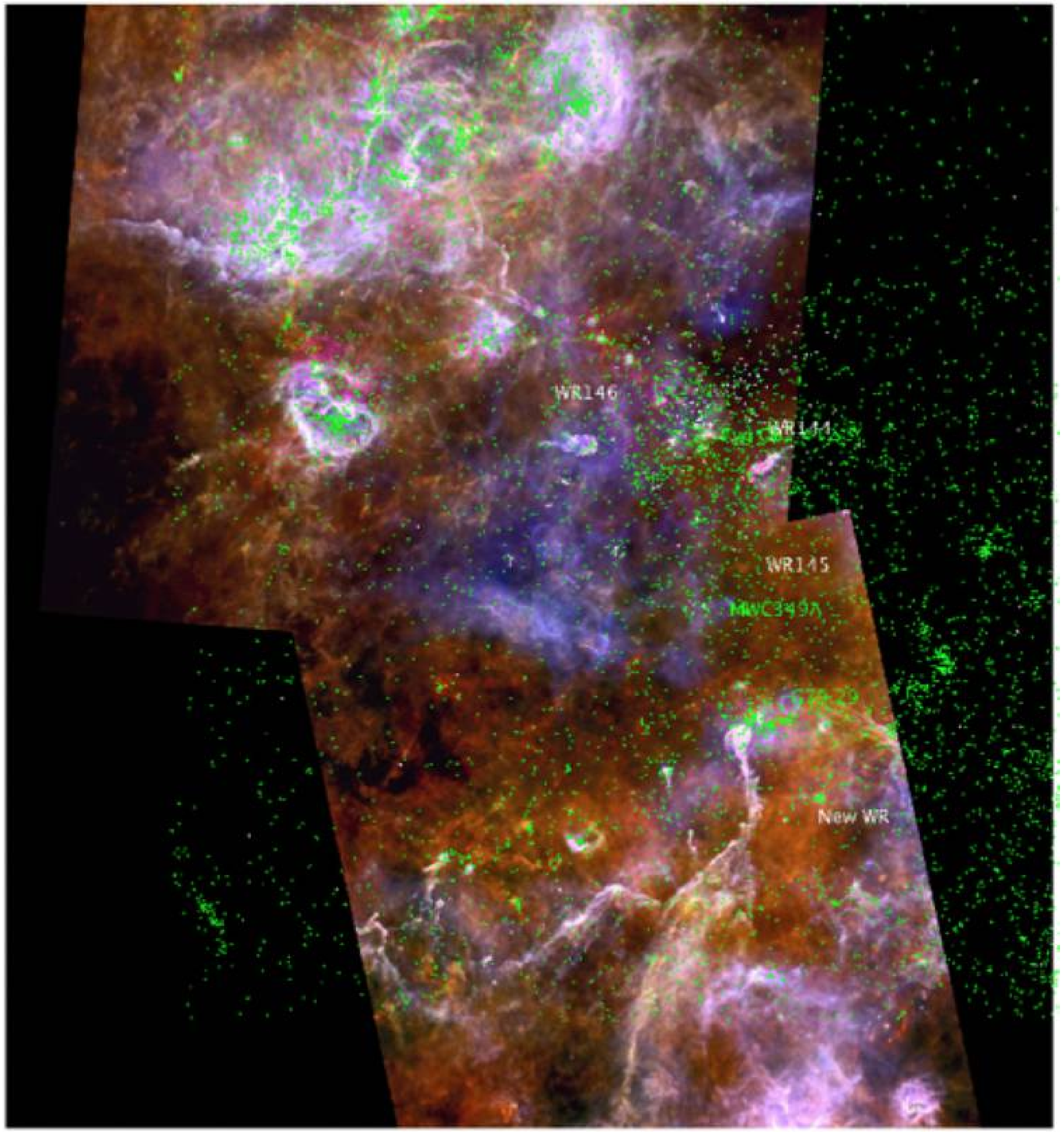
Fogerty et al. 2016

MASSIVE STAR DISTRIBUTION

New WRs (and O stars) on the ‘edge’ of RCW49 – scattered out from Westerlund 2 cluster?

Roman-Lopes+ 11a,11b




WR146
WR144
WR145
New WR