High-Mass Star Formation

— *The Herschel View: Status & Future Prospects* —

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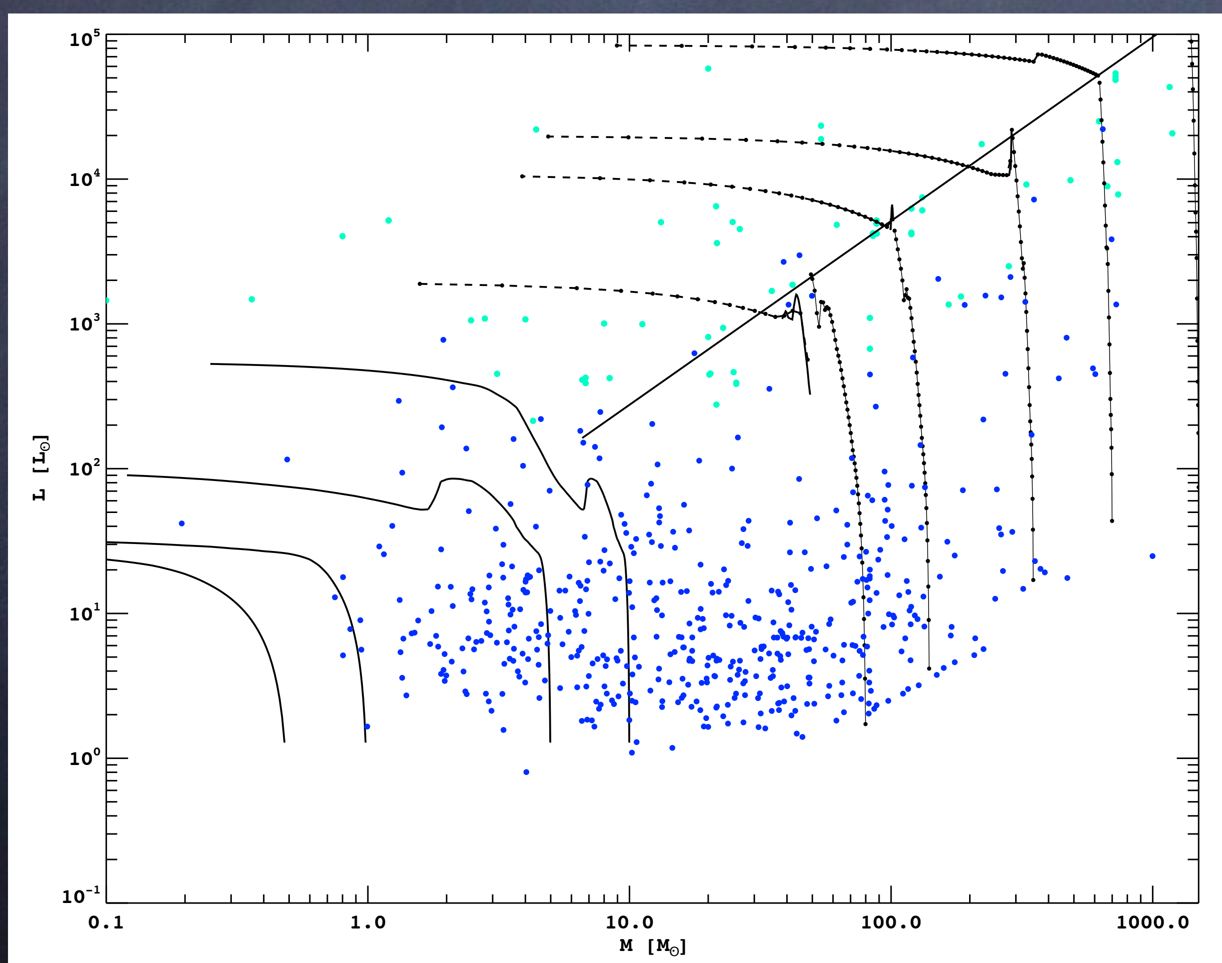
& the HOBYS, Hi-Gal & GCC Consortia

OVERVIEW

Mass	Designation	Sp. type
8–16 $M_\odot$	Early B-type massive stars	B3V to B0V
16–32 $M_\odot$	Late O-type massive stars	O9V to O6V
32–64 $M_\odot$	Early O-type massive stars	O5V to O2V[a]
64–128 $M_\odot$	O/WR-type massive stars	WNL-H[b]

Zinnecker et al 2007



$L_\odot$

$M_\odot$

- ISM dynamics/ chemistry
- Structure formation & evolution (from planets to galaxy scales)

OVERVIEW

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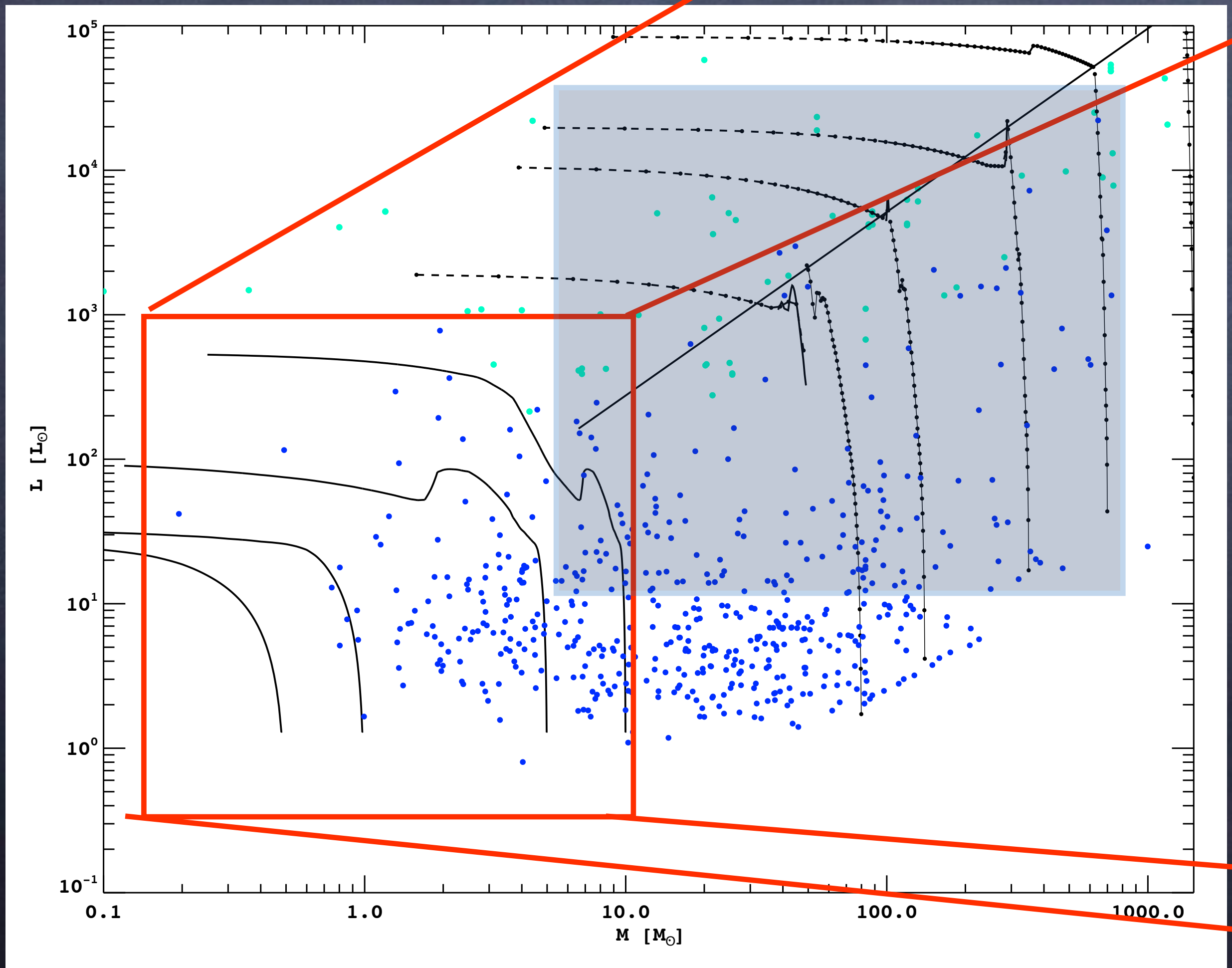
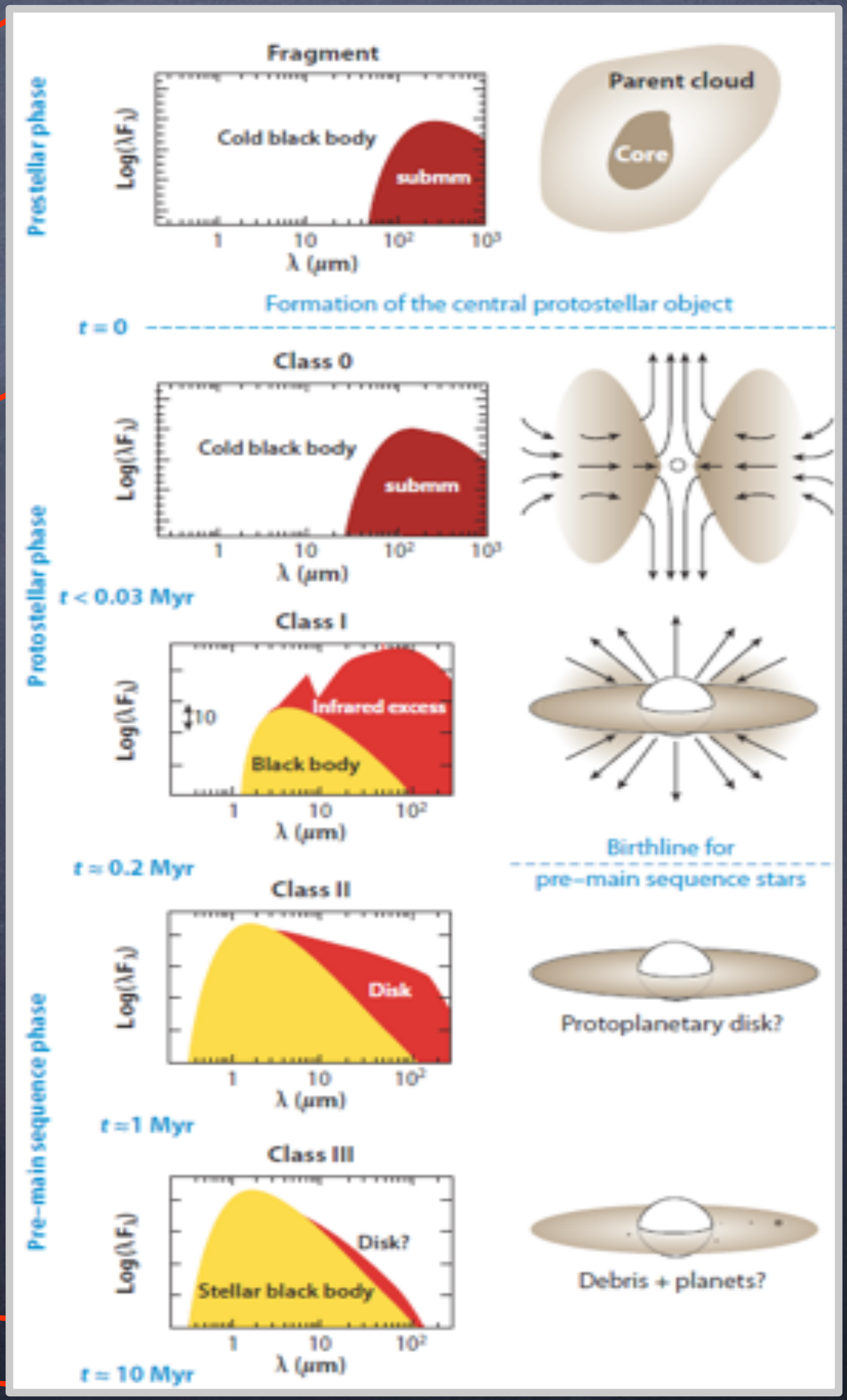




$L_\odot$

$M_\odot$

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)

EVOLUTION

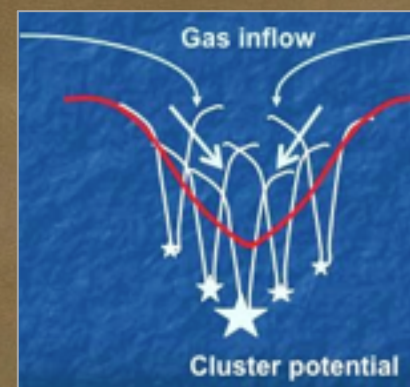
Competitive Accretion (Bonnell et al. 1997) "The rich get richer model", 'location, location, location'

Pre-existing (low-mass) overdensities

Bondi-Hoyle Accretion, determined by gas dynamics

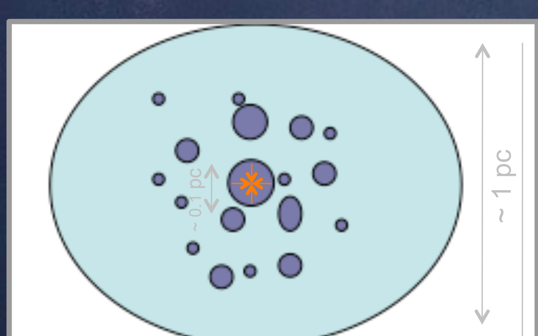
HMS form first or simultaneously, mass segregation

No HMS cores



I. Bonnell

Turbulent Core Model (McKee & Tan 2003)



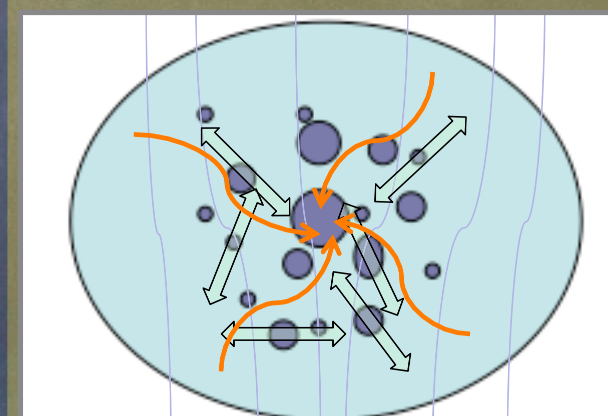
Credit: Zhi- Yun

No competition - already assigned mass

Pre-existing HM cores - characteristic scale

Turbulence support

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

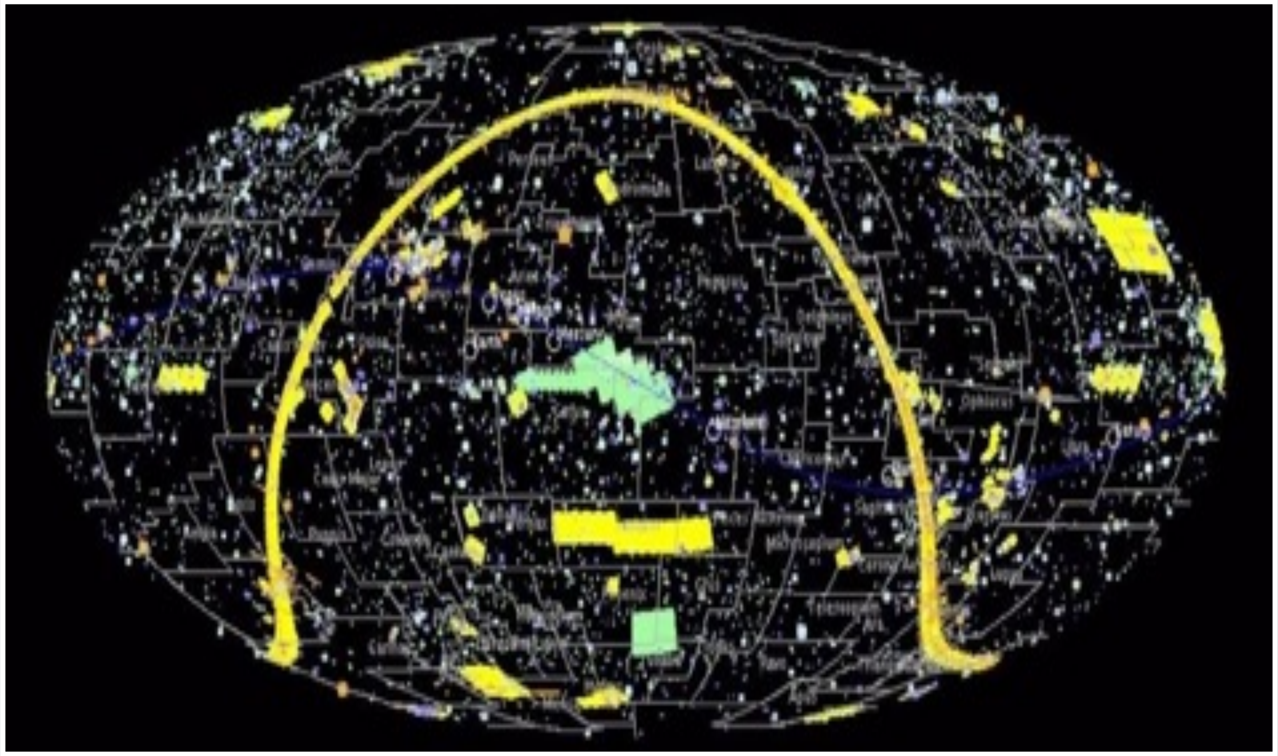
Filamentary inflows from large scale reservoirs

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

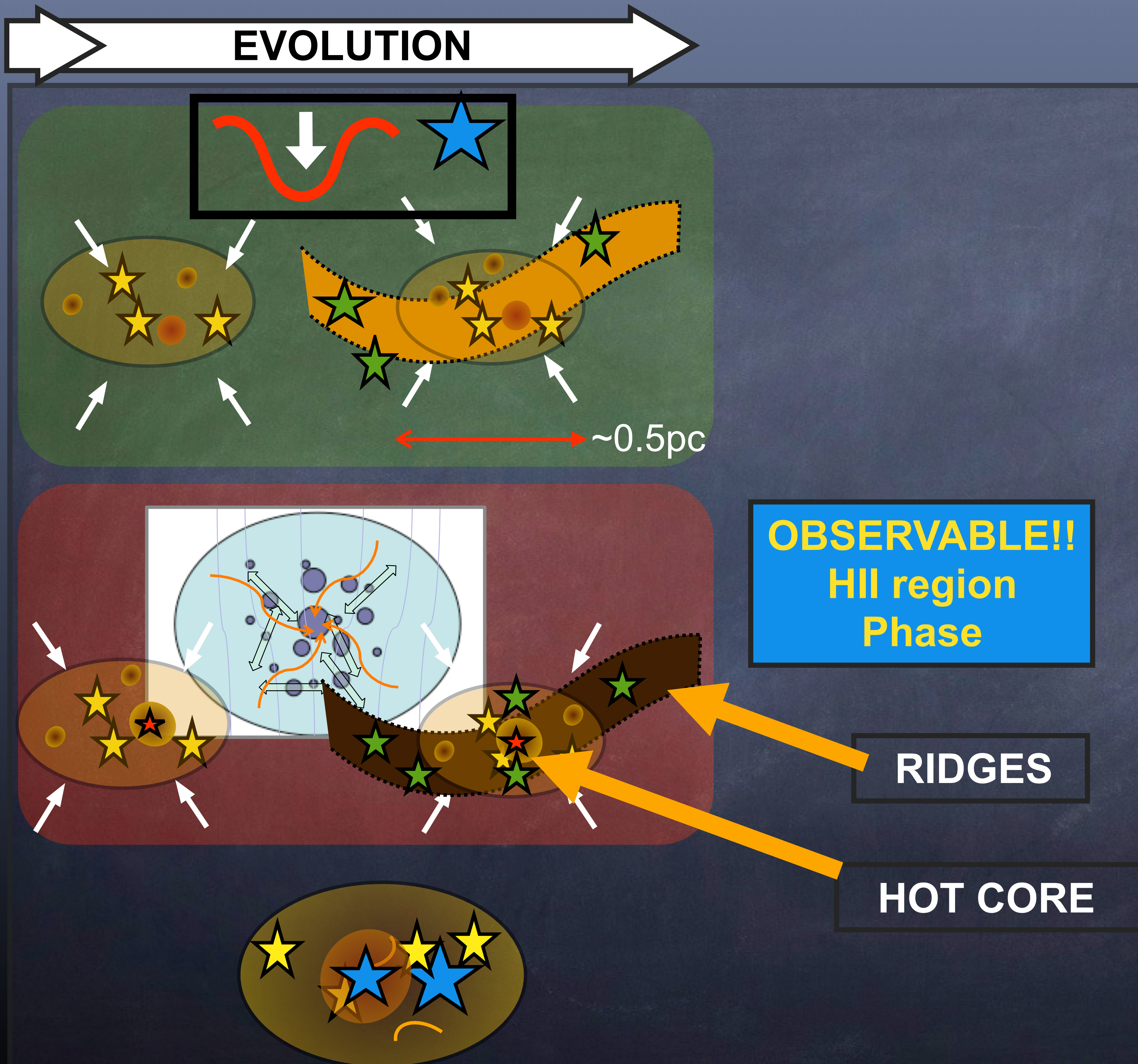
Turbulence important

EVOLUTION

- **MC Environment (>1pc scale)** (e.g., Rivera-Ingraham et al. 2015)
- **Clumps (0.5-1pc scale) + Filaments** (e.g., Rivera-Ingraham et al. 2015; 2016)
- **MDCs (0.1pc scale):** (Rivera-Ingraham et al. 2017, submm)
  - Complete catalogue
  - Evolutionary classification
  - Characterization (stellar content, physical properties)
- **Statistical Studies** (Rivera-Ingraham et al. 2017b, in prep)

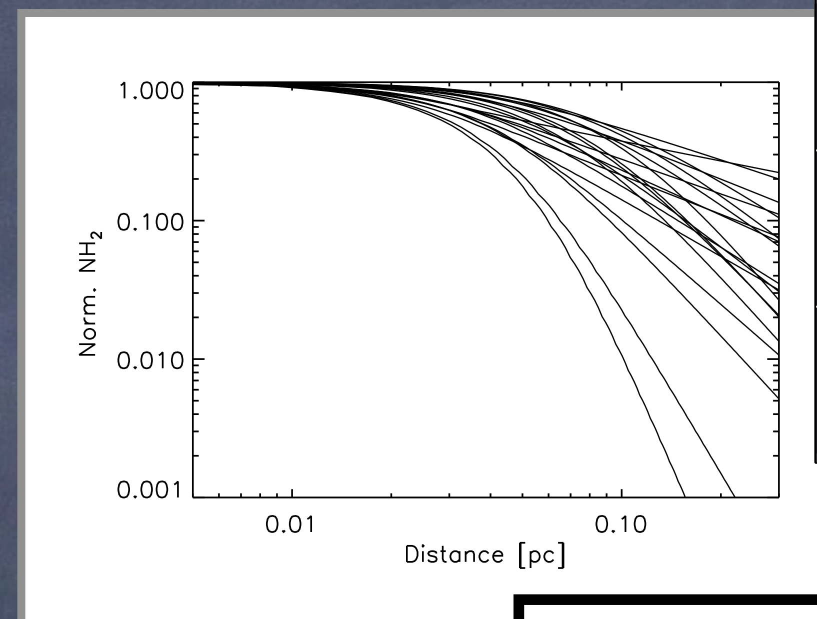


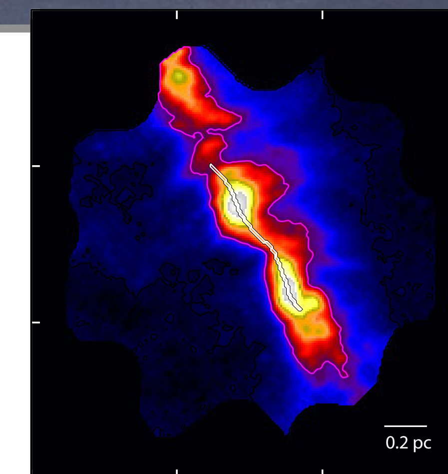
- **Herschel imaging survey of OB Young Stellar objects -** (HOBYS; PI. F. Motte)
- **the Herschel infrared Galactic Plane Survey -** (Hi-GAL; PI. S. Molinari)
- **Galactic Cold Cores -** (GCC; PI. M. Juvela)



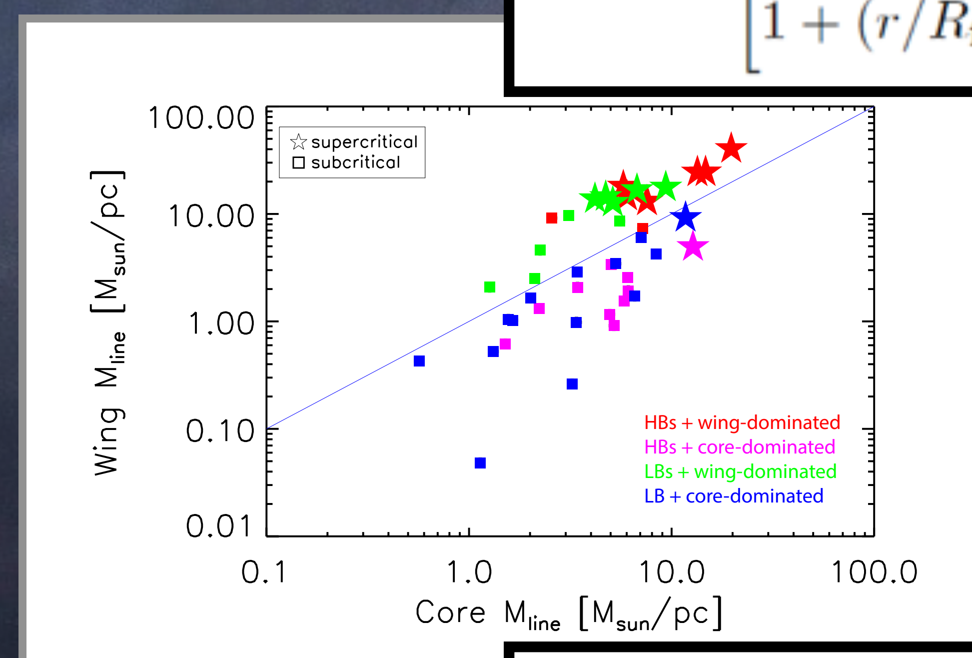
- Compact radio emission: HC, UC HII regions
- Masers
- Rich complex chemistry

EVOLUTION → Filaments (Environ)





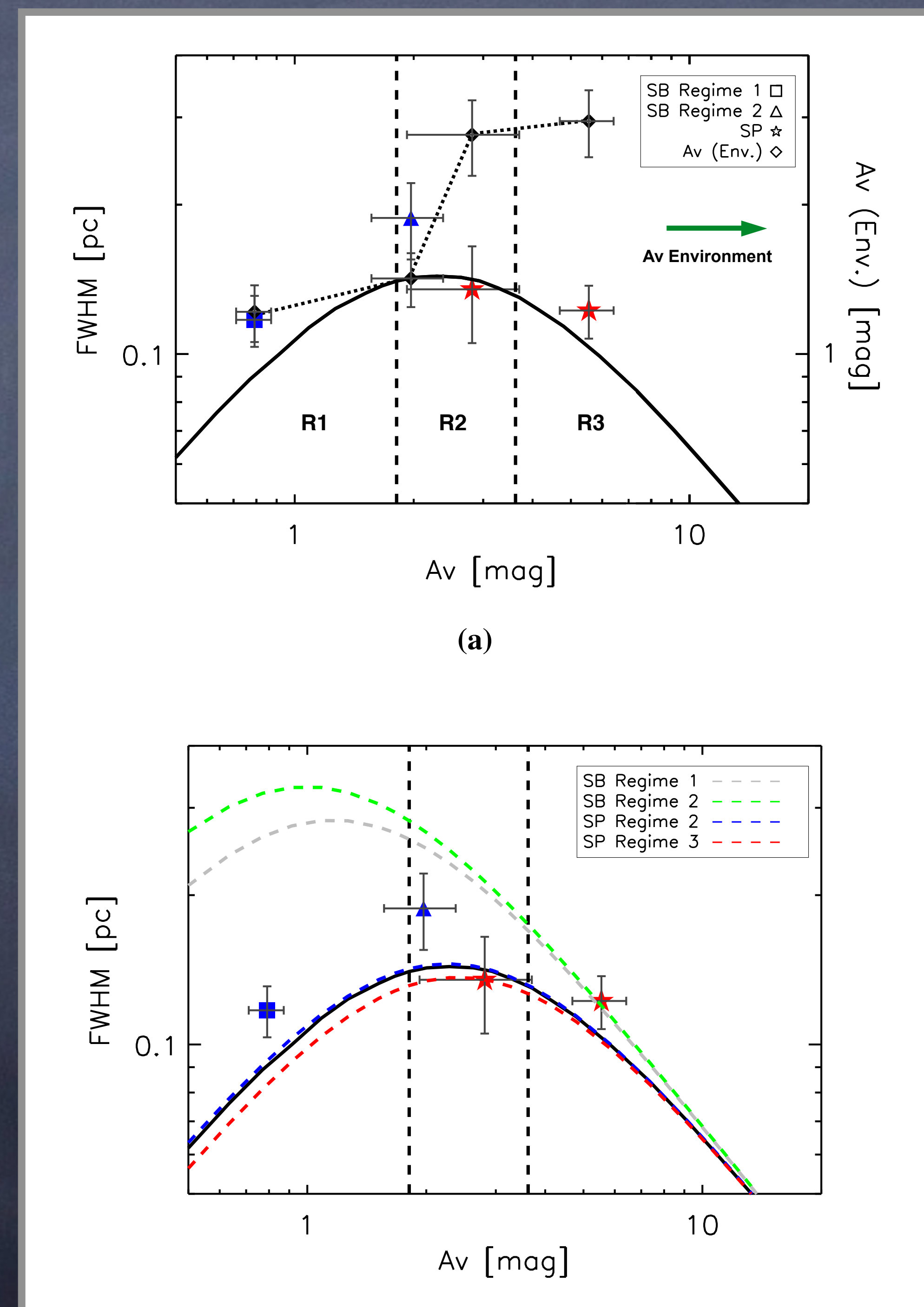
$$\rho_p(r) = \frac{\rho_c}{\left[1 + (r/R_{\rm flat})^2\right]^{p/2}}$$



$$M_{\rm line,crit} = 2\, c_s^2/G$$

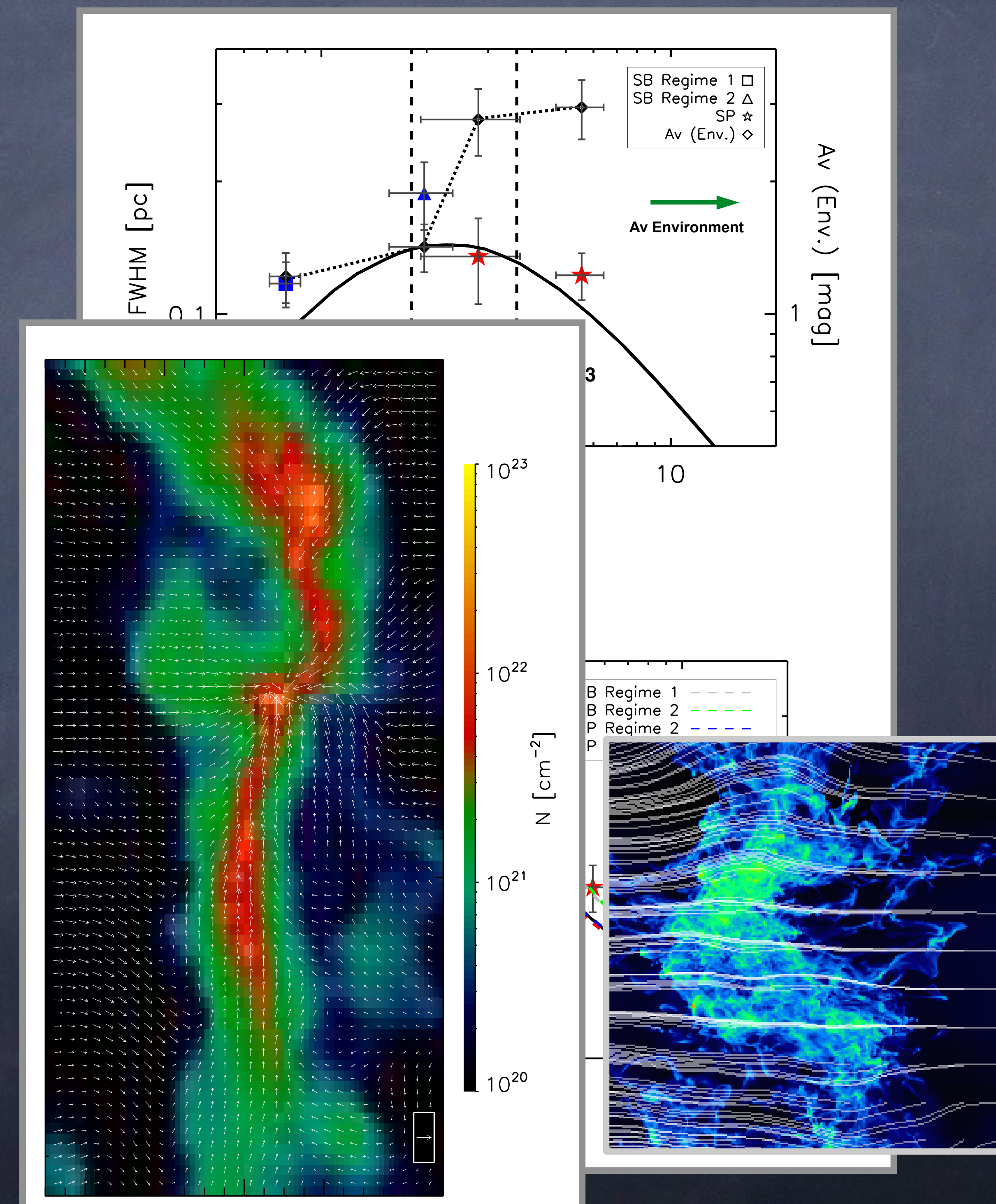
EVOLUTION

Filaments (Environ)



EVOLUTION → Filaments (Environ)

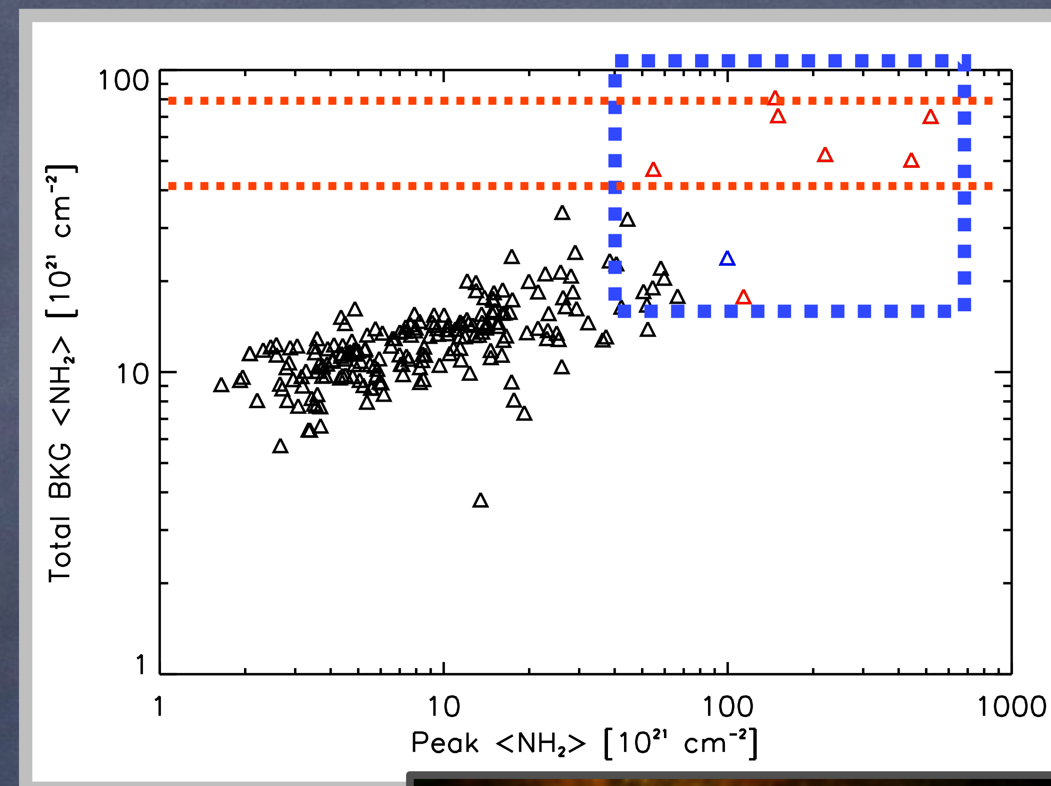
Gómez et al. 2014

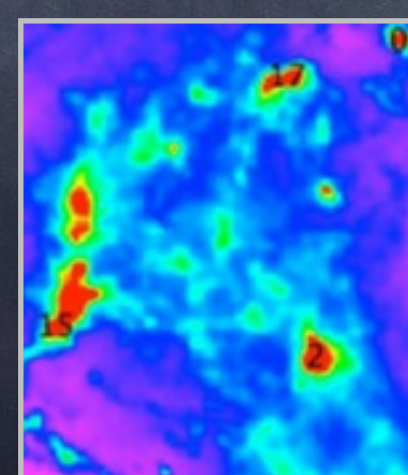


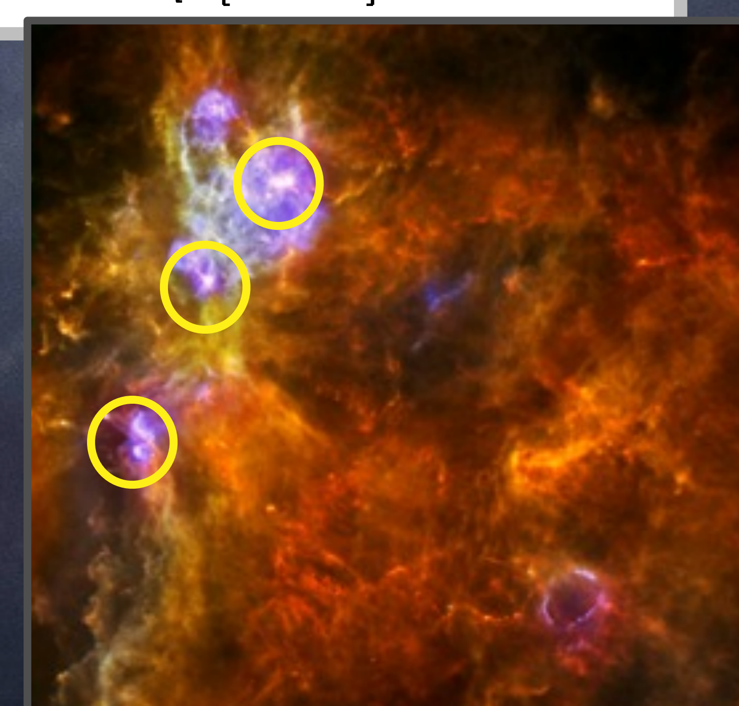
Fogerty et al. 2016

EVOLUTION

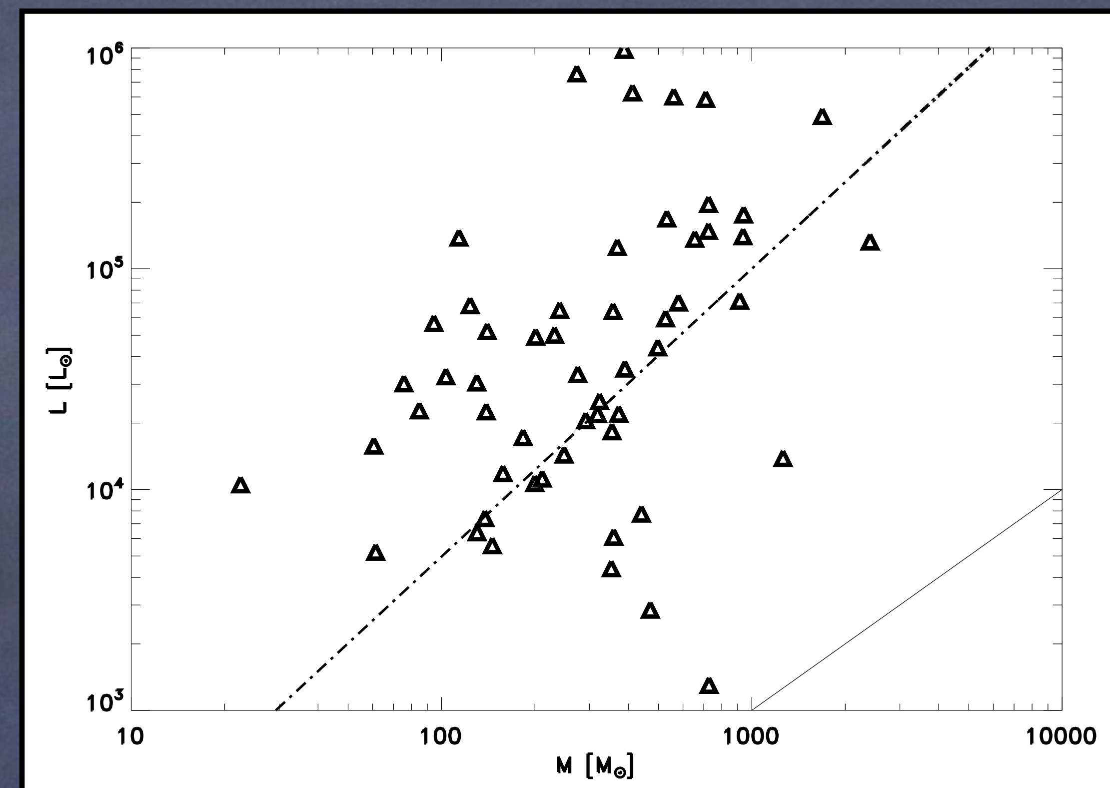
Clump (Environ)



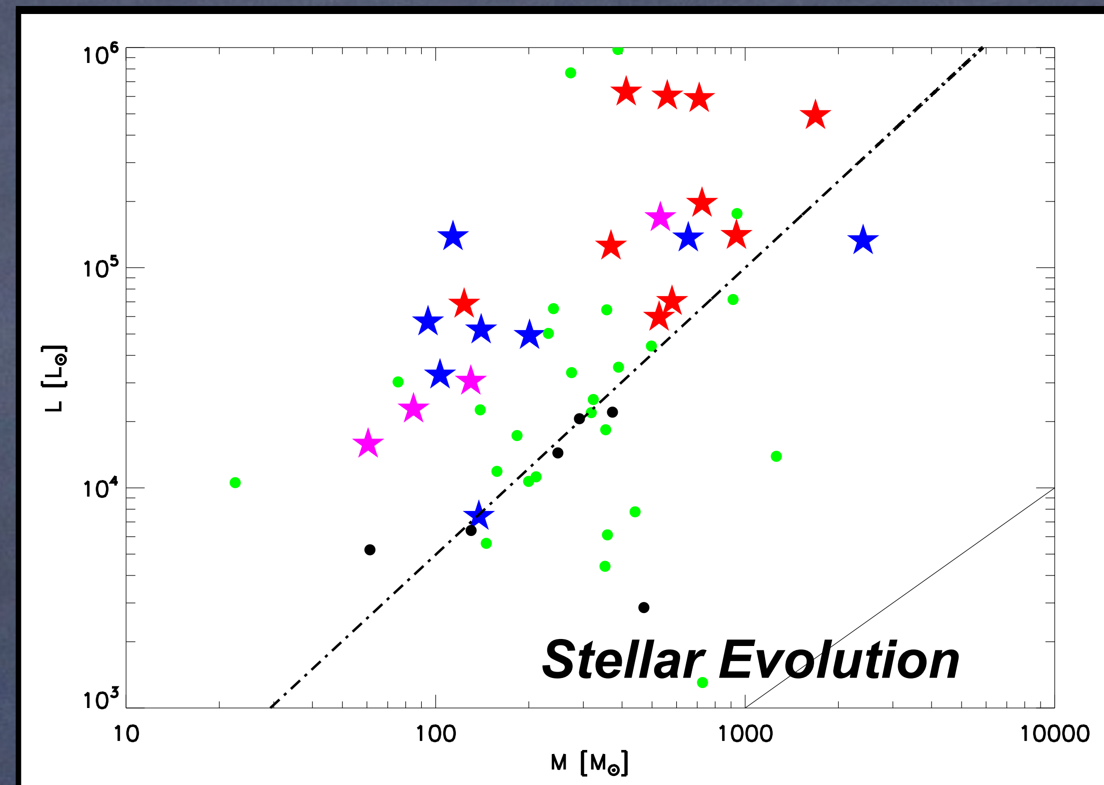




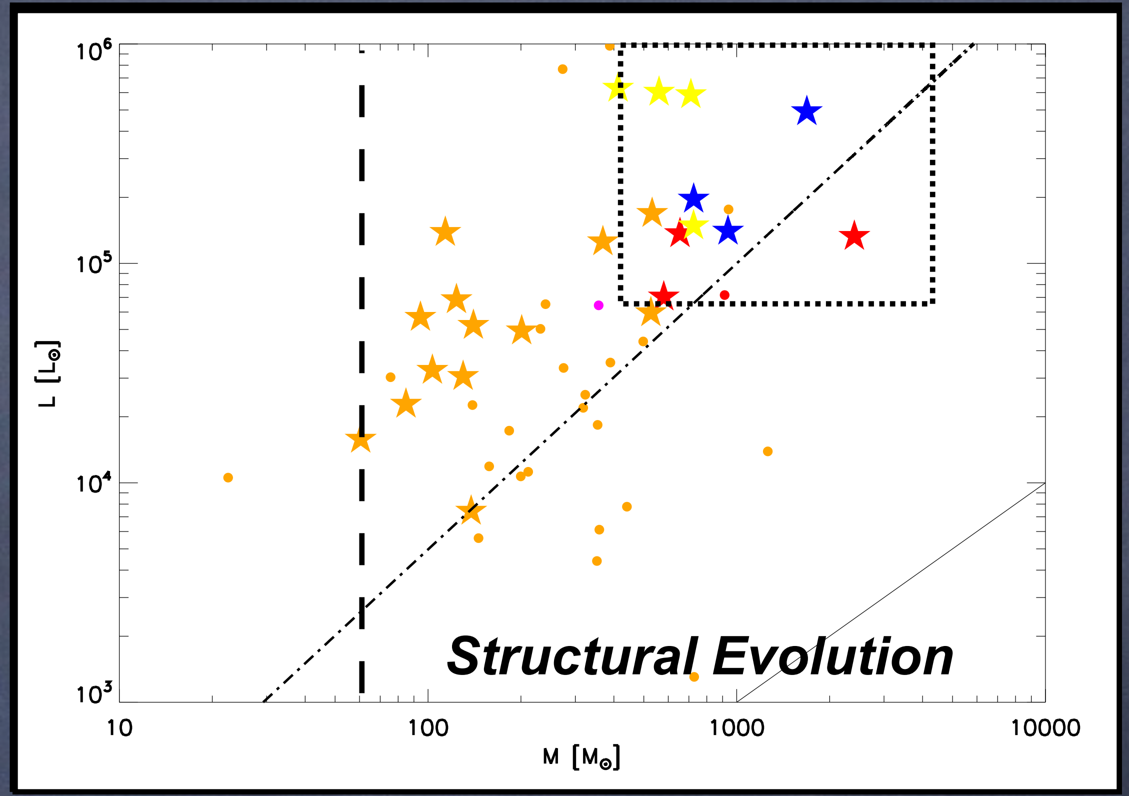
EVOLUTION Clump (Environ)



EVOLUTION **Clump (Environ)**



EVOLUTION Clump (Environ)

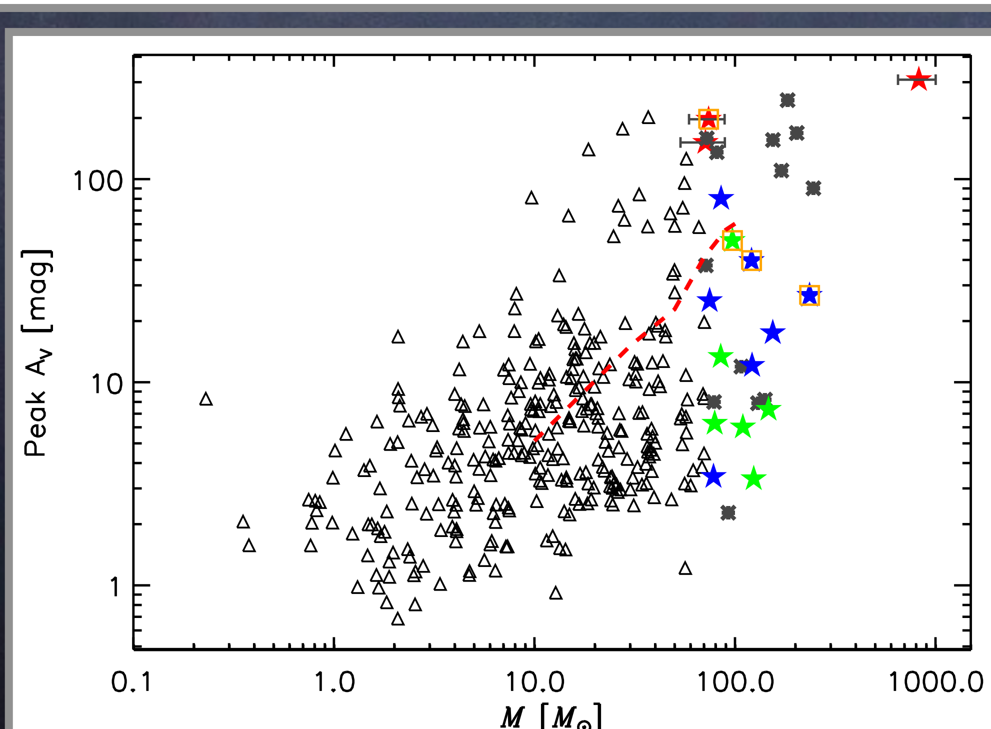


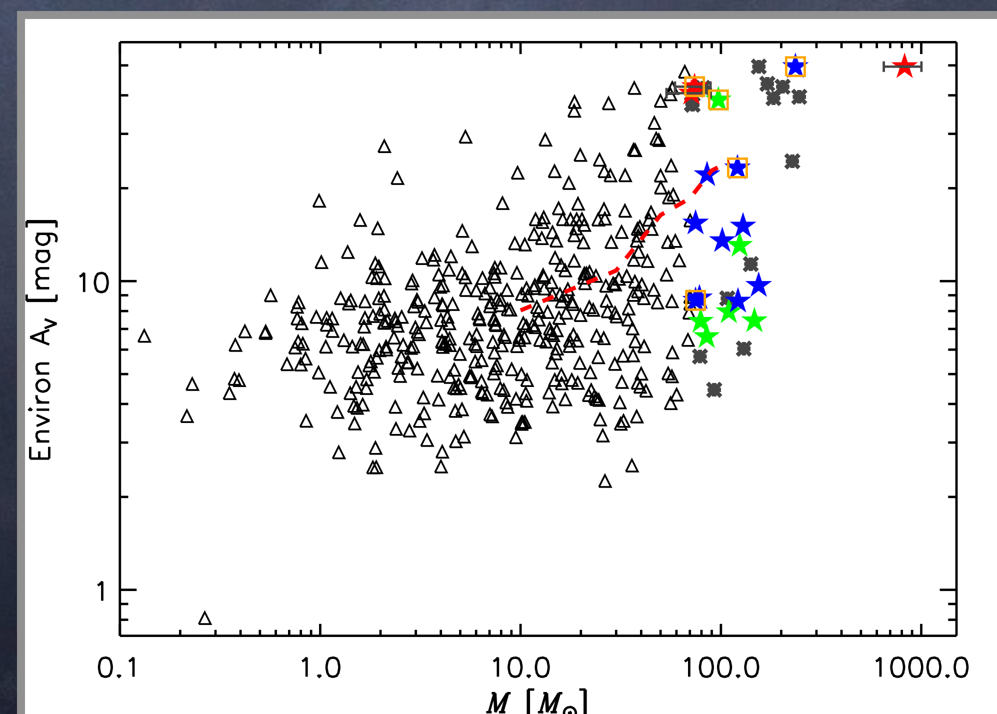
EVOLUTION

MDCs

EVOLUTION MDCs

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_{bol} [$L_\odot$]	268 ± 106	24721 ± 6879	666 ± 226	80 ± 53	828 ± 821
$L_{sub/bol}$	0.094 ± 0.004	0.004 ± 0.003	0.186 ± 0.026	0.190 ± 0.030	0.238 ± 0.052
FWHM[a] [pc]	~0.10	0.07 ± 0.02	0.15 ± 0.01	0.16 ± 0.02	0.18 ± 0.02
$< n_{H_2} >$ [10^5 cm^{-3}]	1.2 ± 0.1	15.3 ± 1.6	3.3 ± 0.7	2.2 ± 0.7	0.7 ± 0.2
$N_{H_2,p}$ [10^{22} cm^{-2}]	1.2 ± 0.2	20.6 ± 4.4	4.5 ± 1.1	1.9 ± 0.7	1.4 ± 0.7
$N_{H_2,env}$ [10^{22} cm^{-2}]	~1.0	4.2 ± 0.3	2.0 ± 0.3	1.6 ± 0.4	1.3 ± 0.5
X_{ISRF}	2.3 ± 0.2	13.1 ± 5.7	5.9 ± 1.5	2.2 ± 1.1	2.6 ± 1.9





EVOLUTION → **MDCs** →

Parameter	All	Active [IR-bright]	Inactive [IR-quiet+starless+UCS]	Inactive [IR-quiet]	Inactive [Starless]
Number	442	3	30	10	6
M	[illegible]	…251	[illegible]	118 ± 16	107 ± 10
[illegible]	[illegible]	…5.2	[illegible]	11.…	[illegible]
[illegible]	[illegible]	…6879	[illegible]	80…	[illegible]
[illegible]	[illegible]	…0.003	[illegible]	…190	[illegible]
FW…	[illegible]	…0.02	0.15 ± 0.01	0.16 ± 0.02	0.18 ± 0.02
$< n_{H_2} >$ [illegible]	[illegible]	…1.6	3.3 ± 0.7	2.2 ± 0.7	0.7 ± 0.2
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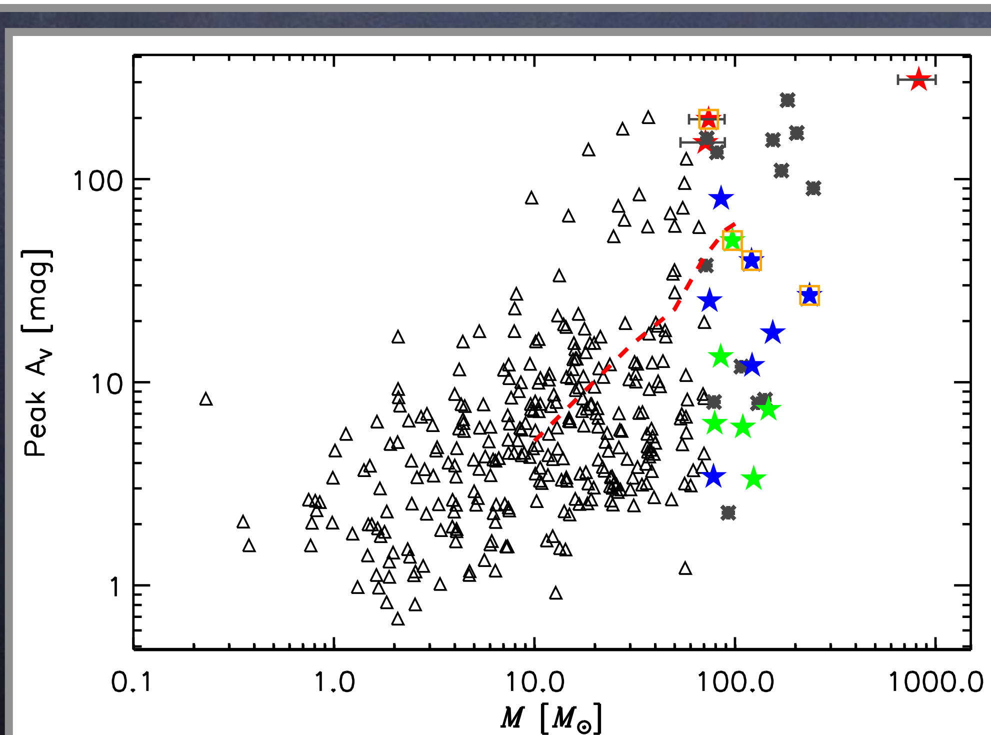
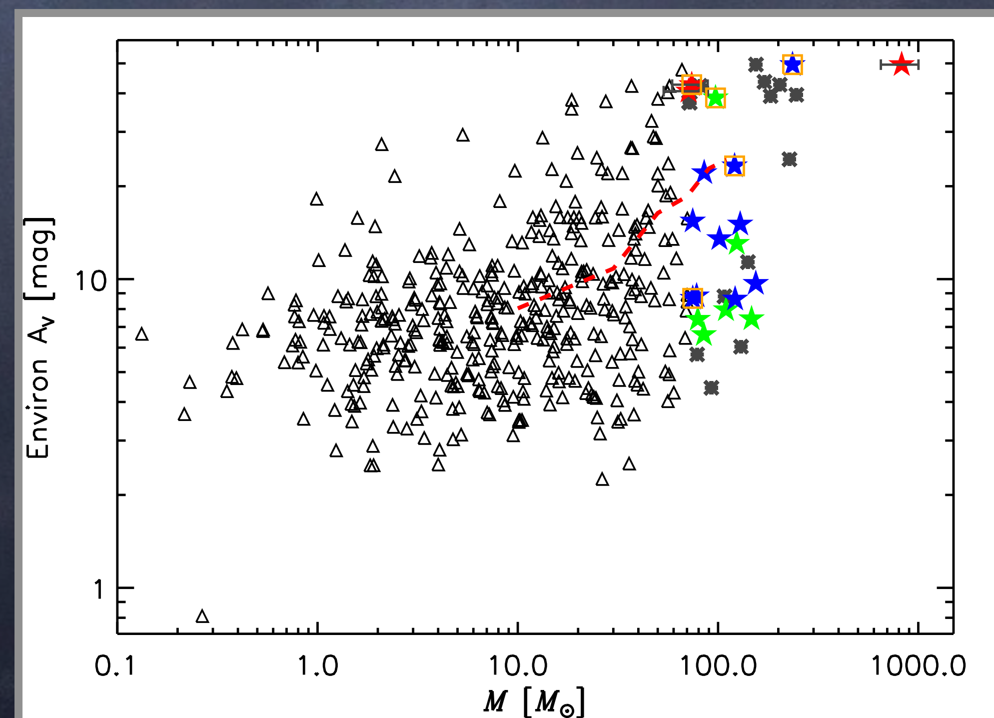
HMSF (radio, masers)
LMIR>B3
Lsub/Lbol<1%
[70 µm]

LMIR<B3
Lsub/Lbol<1%
[70 µm]

No 70 µm above noise level





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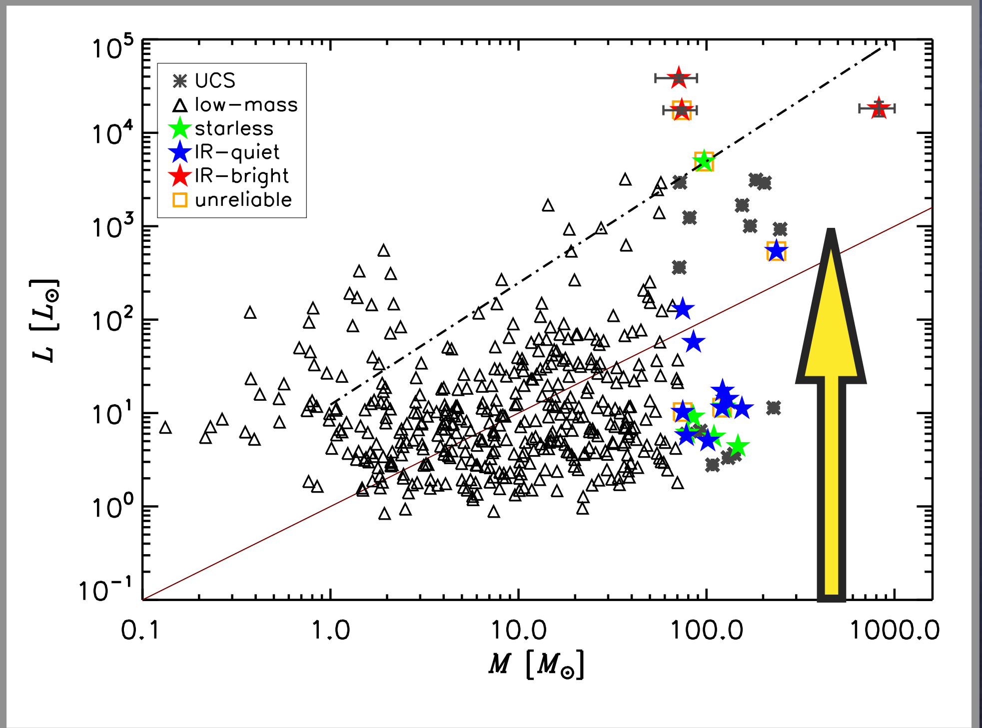

- ★ N_{H_2}(peak) [bright/quiet] ~11
- ★ FWHM [quiet/bright] ~2
- ★ n [bright/quiet] ~7
- ★ N_{H_2}(env) [bright/quiet] ~2.5

EVOLUTION → MDCs

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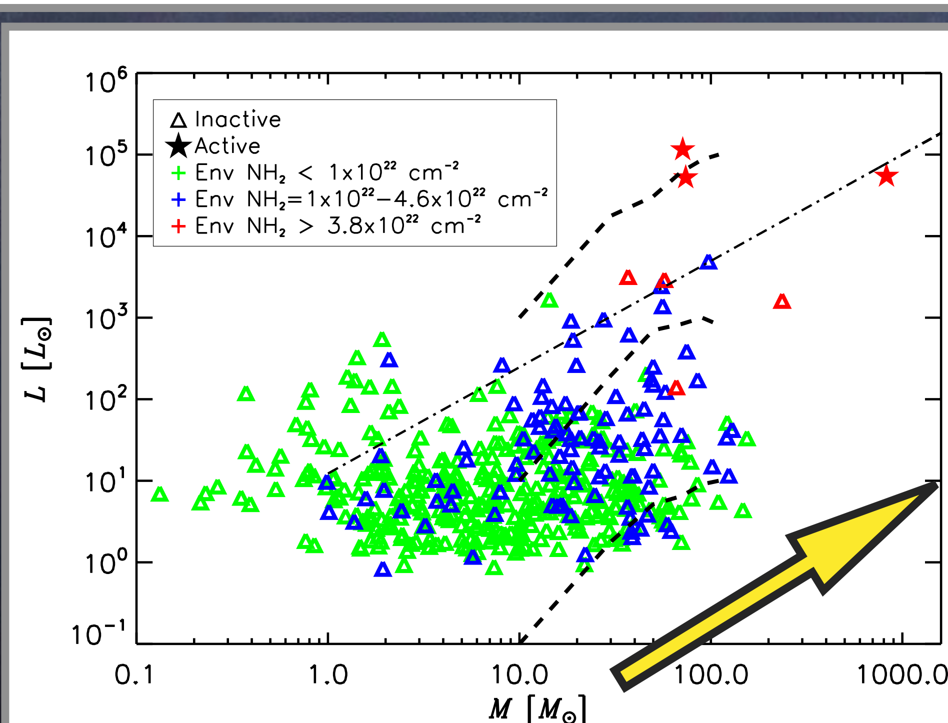
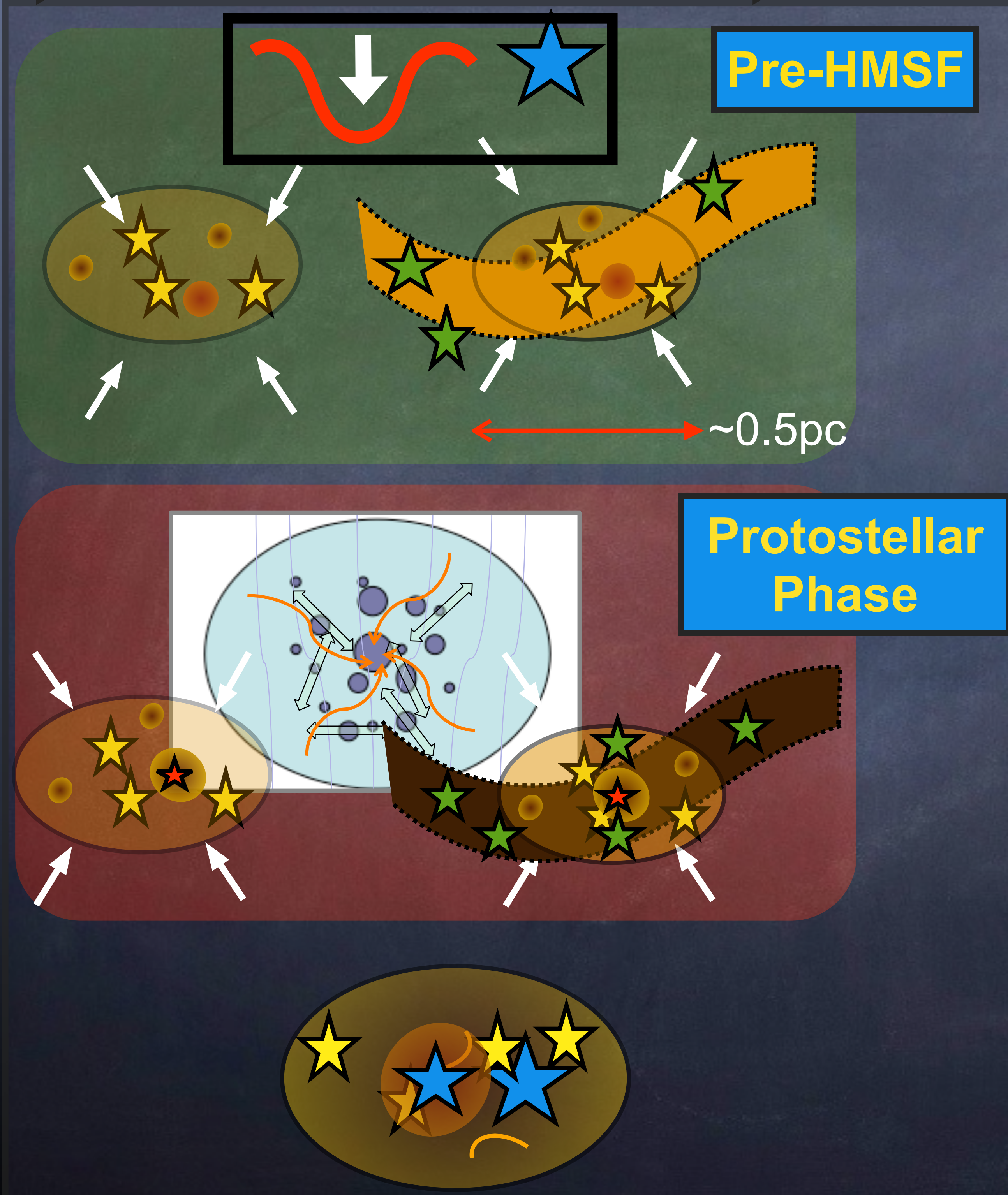
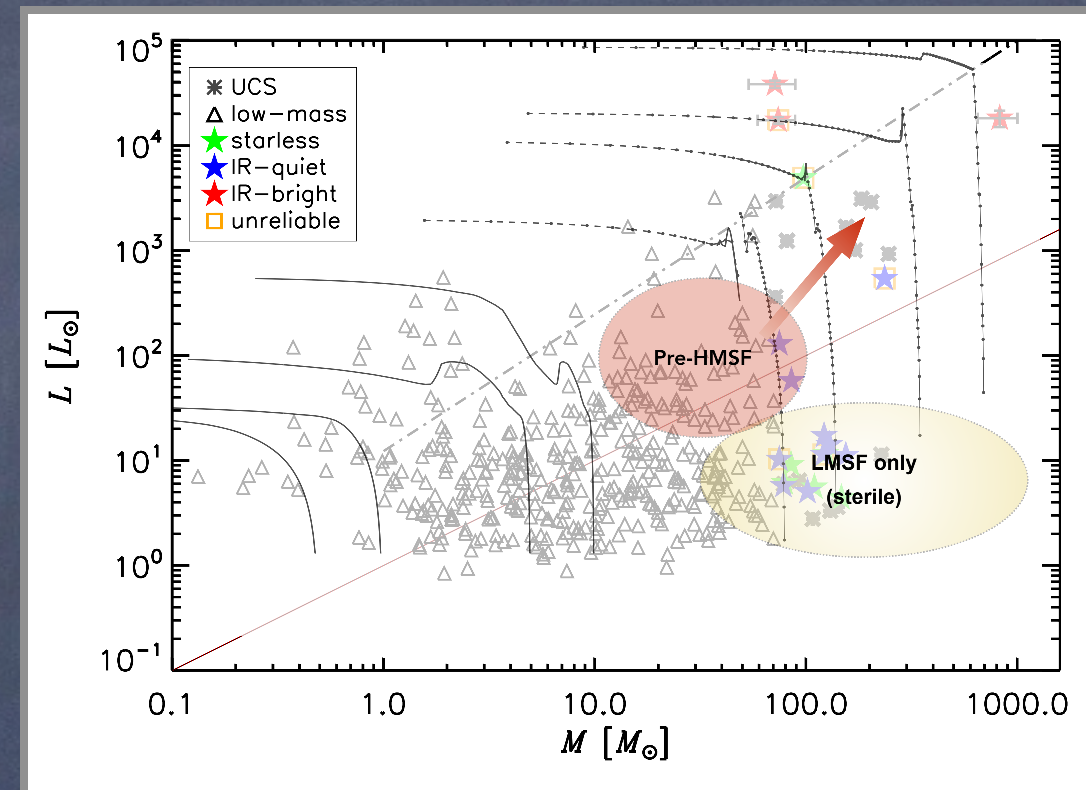


- NH$_2$(peak) [bright/quiet] ~18.5
- FWHM [quiet/bright] ~1.5
- n [bright/quiet] ~9.5
- NH$_2$(env) [bright/quiet] ~4

EVOLUTION MDCs





- **IR-Bright MDCs;** lifetime t~1.5x10^{5}yr, ~100Msun @ 10^{-3}Msun/yr
- **Starless/IR-quiet:** Shorter or non-existent

Large Scale Grav. collapse model

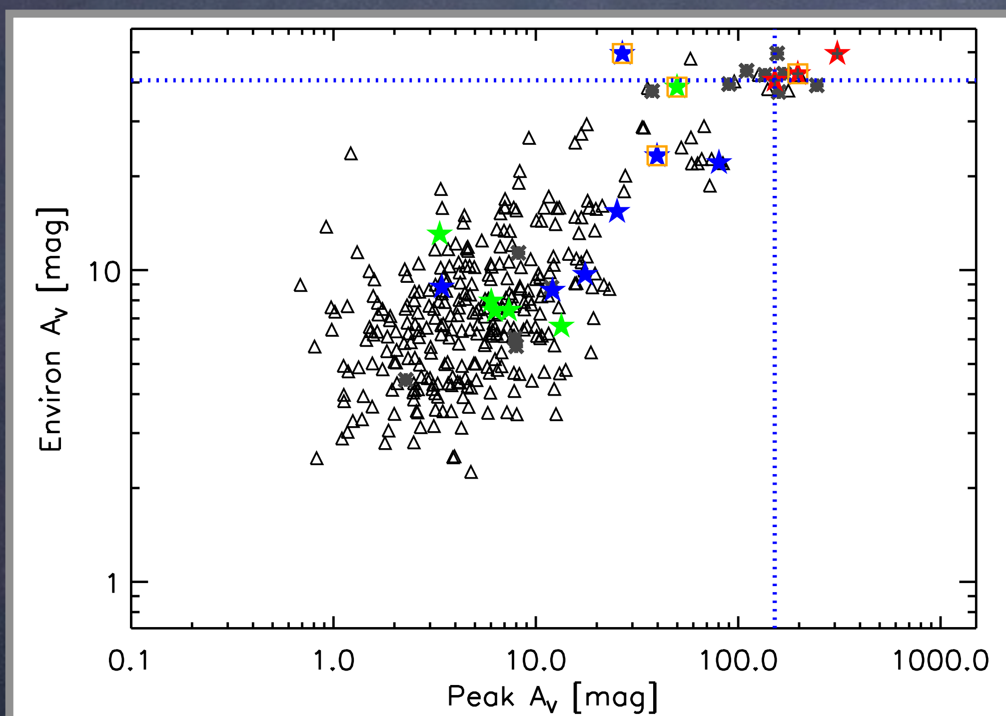
Evolution with core mass growth

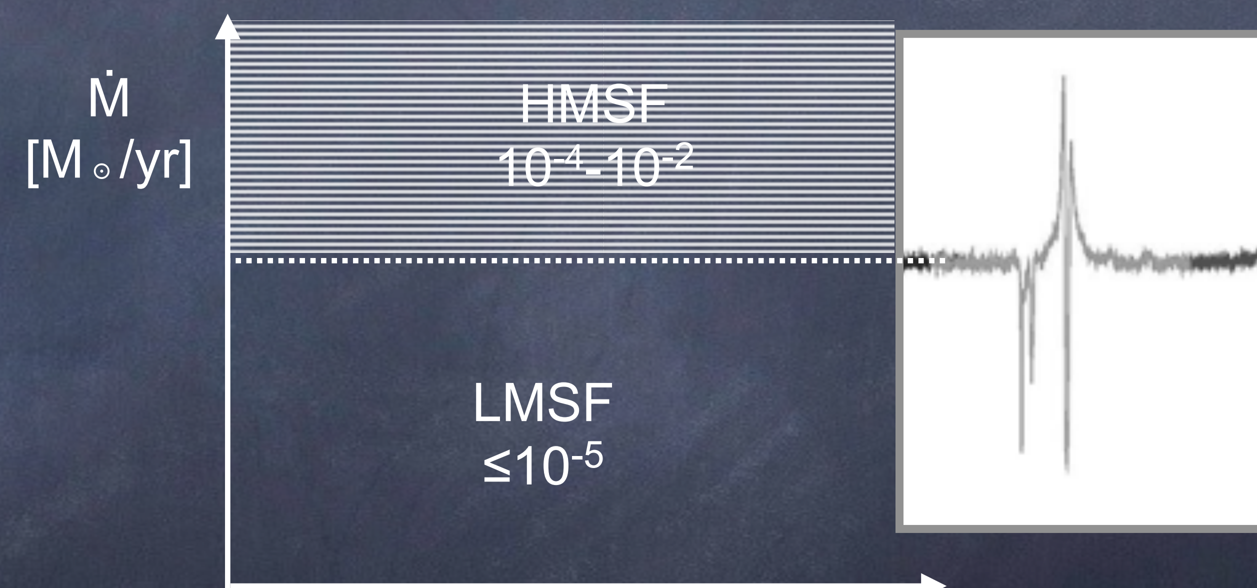
A SWITCH FOR HMSF [?]

*EXCLUSIVE **combination** of conditions for 0.1 pc cores with HMSF:*
$<N_{H_2}> \sim 2\times10^{23}\ cm^{-2}$ $<N_{H_2\text{-}env}> \sim 5\times10^{22}\ cm^{-2}$
$<M> \sim 600\ M_\odot$

*Max. efficiency and high mass convergent inflow in localised region: **$\dot{M}$***

e.g., Wolfire & Cassinelli 1987





Ṁ-threshold or Ṁ-criterium

M_{env} (0.1pc)

- **N_{H_2}** > Deep potential well + minimal disruption (e.g., Dale et al. 2005)
- **Env/M** > High inflow rate + lots of material + confinement (counteraction of stellar activity)

$$P \propto \pi G {<}N_{H_2-env}{>}^2$$

$$\dot{m} \propto \Sigma_{env}^{3/4}$$

e.g., Mckee & Tan 2003

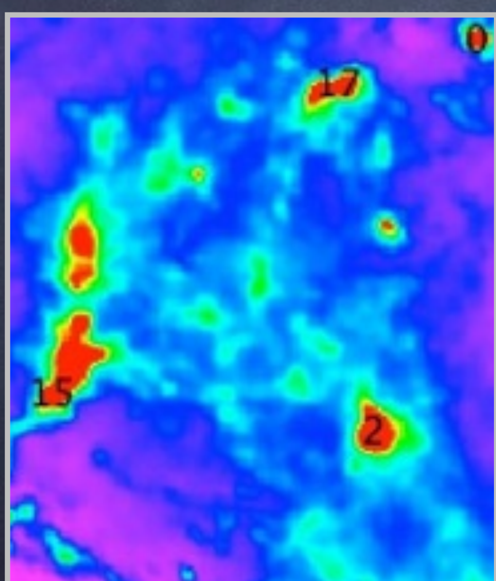
IN PROGRESS!

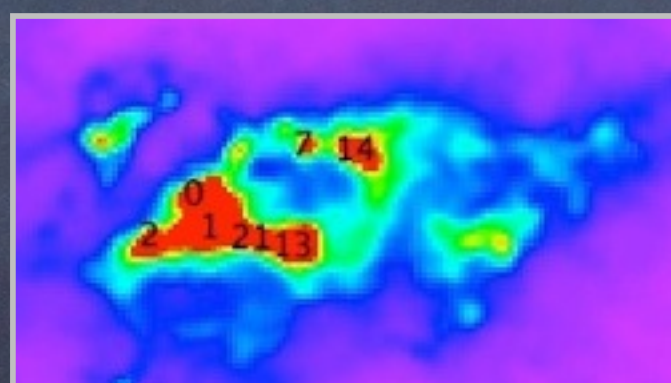
BIMODALITY IN HMSF

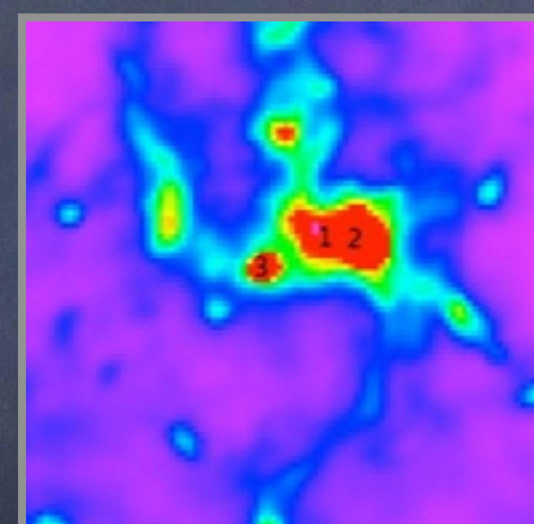
If Ṁ criterium is the key , then…

Gravity (Large Scale Collapse)
Easiest way, most common

Externally Driven SF Mode
(direct triggering)



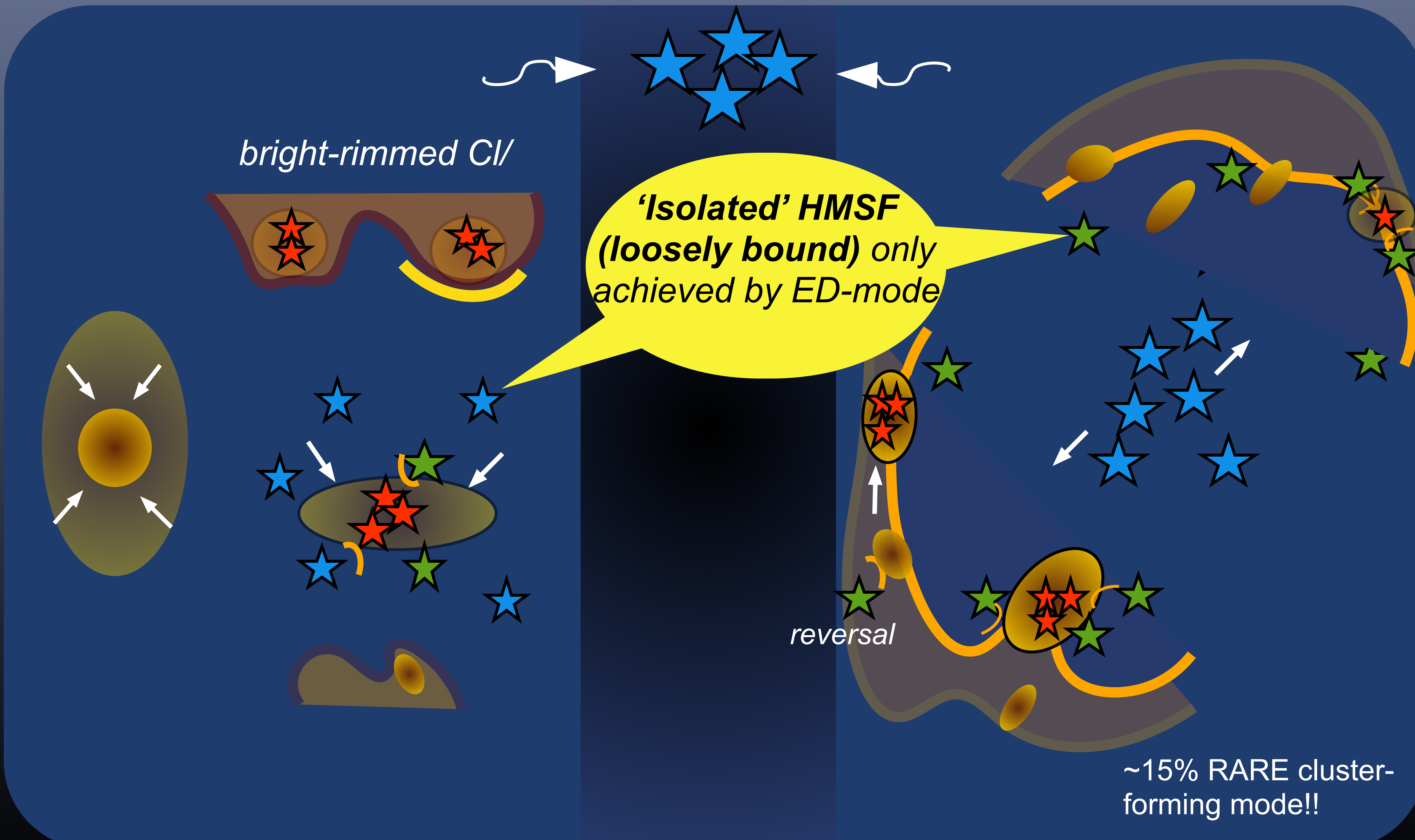




- Most common
- (extended) LMSF coeval with HMSF (youngest)
- Age distribution, primordial mass segregation

e.g., CCF Model

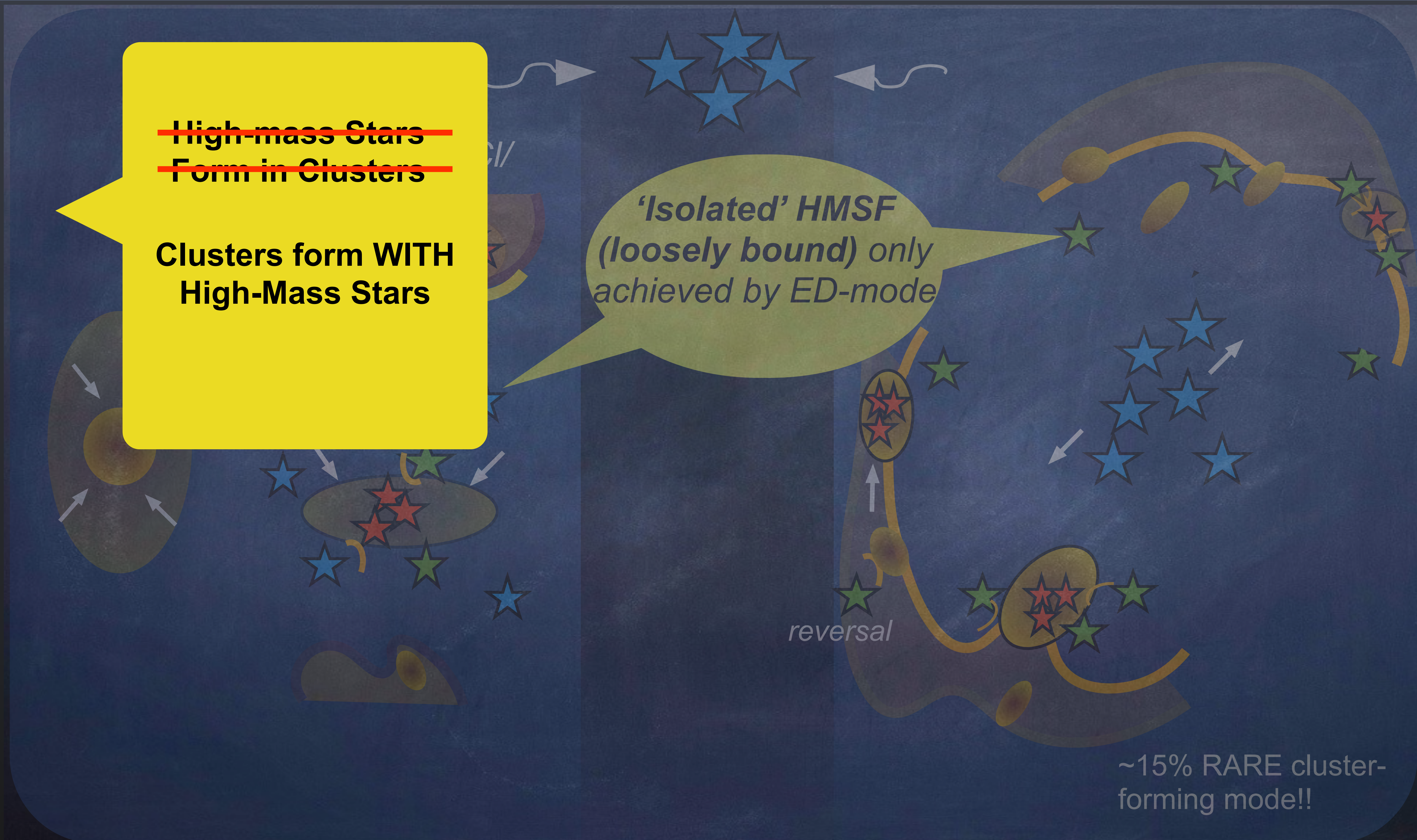
BIMODALITY IN HMSF



BIMODALITY IN HMSF

~~High-mass Stars~~
~~Form in Clusters~~

Clusters form WITH High-Mass Stars



SUMMARY & FUTURE PROSPECTS

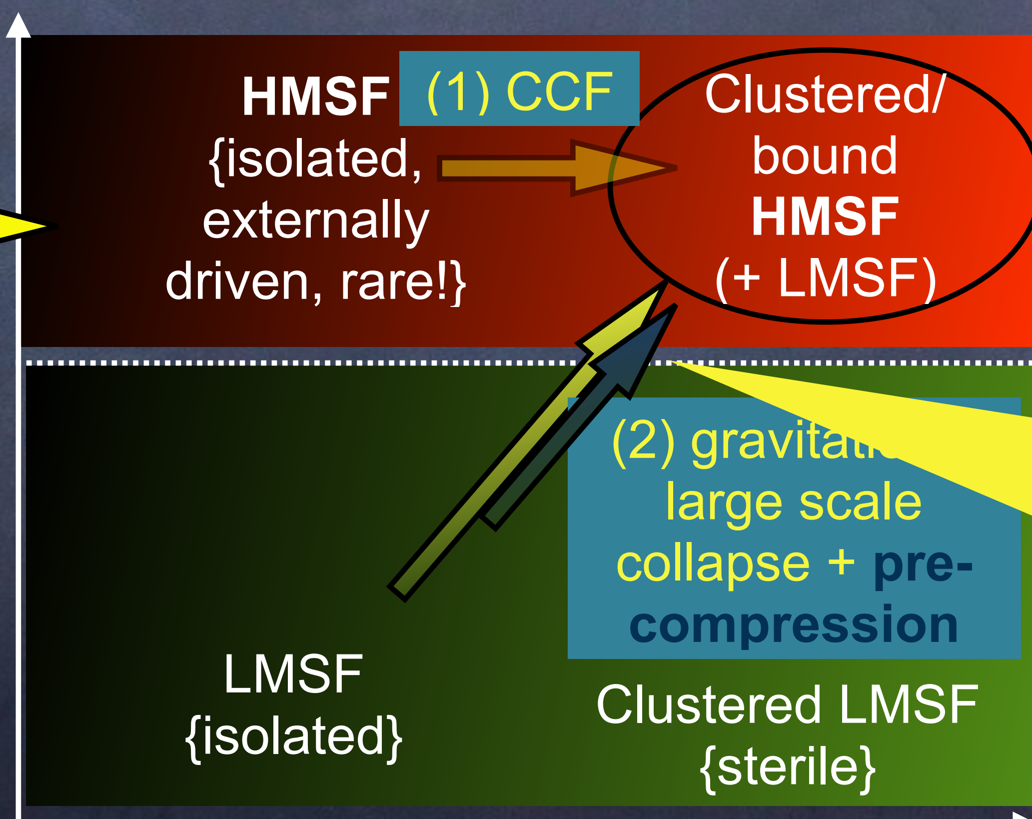
- Isolated HMSF, no/few companions, formed in peripheries of triggered regions
- > loose associations
- > subclusters neighbourhoods of associations, out-in progression

Evolutionary Model
F(t)

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

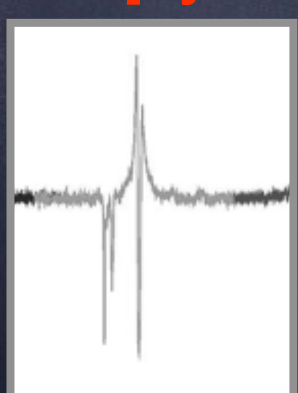
Triggering +external feedback

$\dot{M}$ [$M_\odot$/yr]



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

Threshold 10^{-4}
[Dynamics]



Convergent Localised High Inflow/collapse Rate
(10^{-4} - 10^{-2} M/yr ; e.g., Fuller et al. 2005; Herpin et al. 2012, etc.)

40 M_{env} [$M_\odot$] (0.1pc-scale)

[Single-Star Envelopes vs IMF: Seeds or cores? Interferometry: ALMA, PdBI…]

(1) Rivera-Ingraham et al. 2013; 2015 (2) Rivera-Ingraham et al. 2017a; 2017b