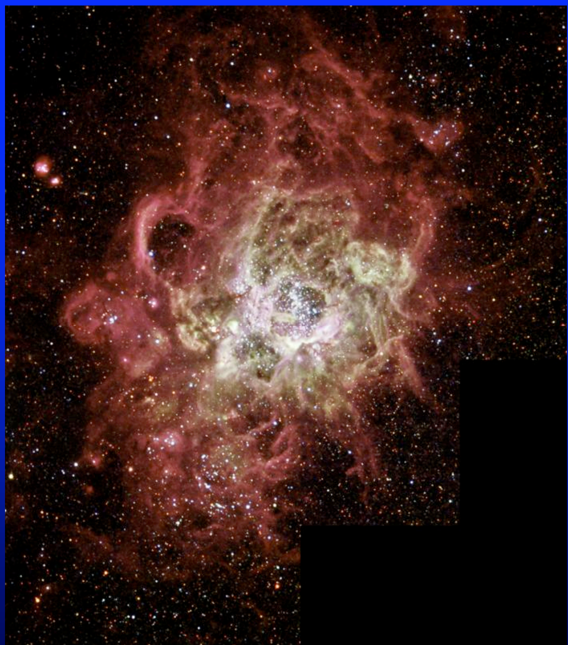
The University Of Sheffield.

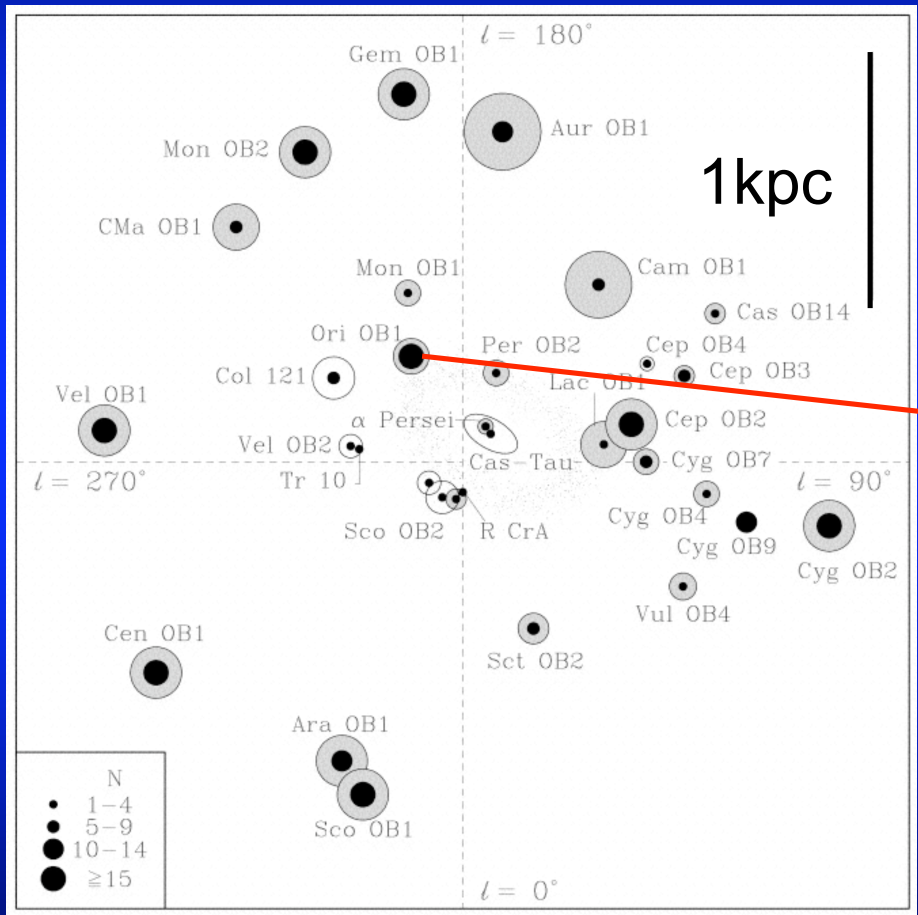
Environments of massive stars and the upper mass limit



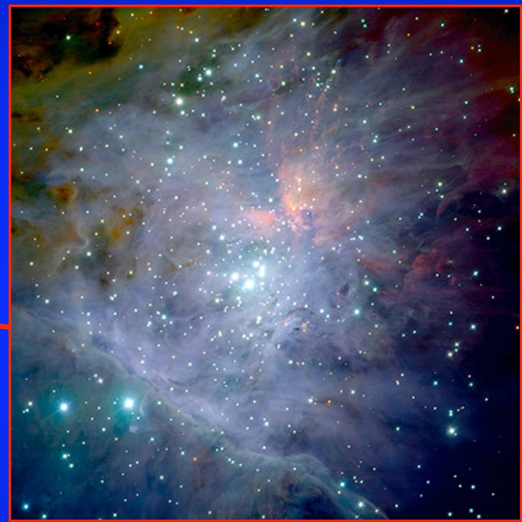
Paul Crowther

- Environment
  - HII regions: Signatures of massive stars
  - Massive stars & star clusters
  - Why so few SN in HII regions?
- Upper mass limit?

Distributed star formation: OB Associations

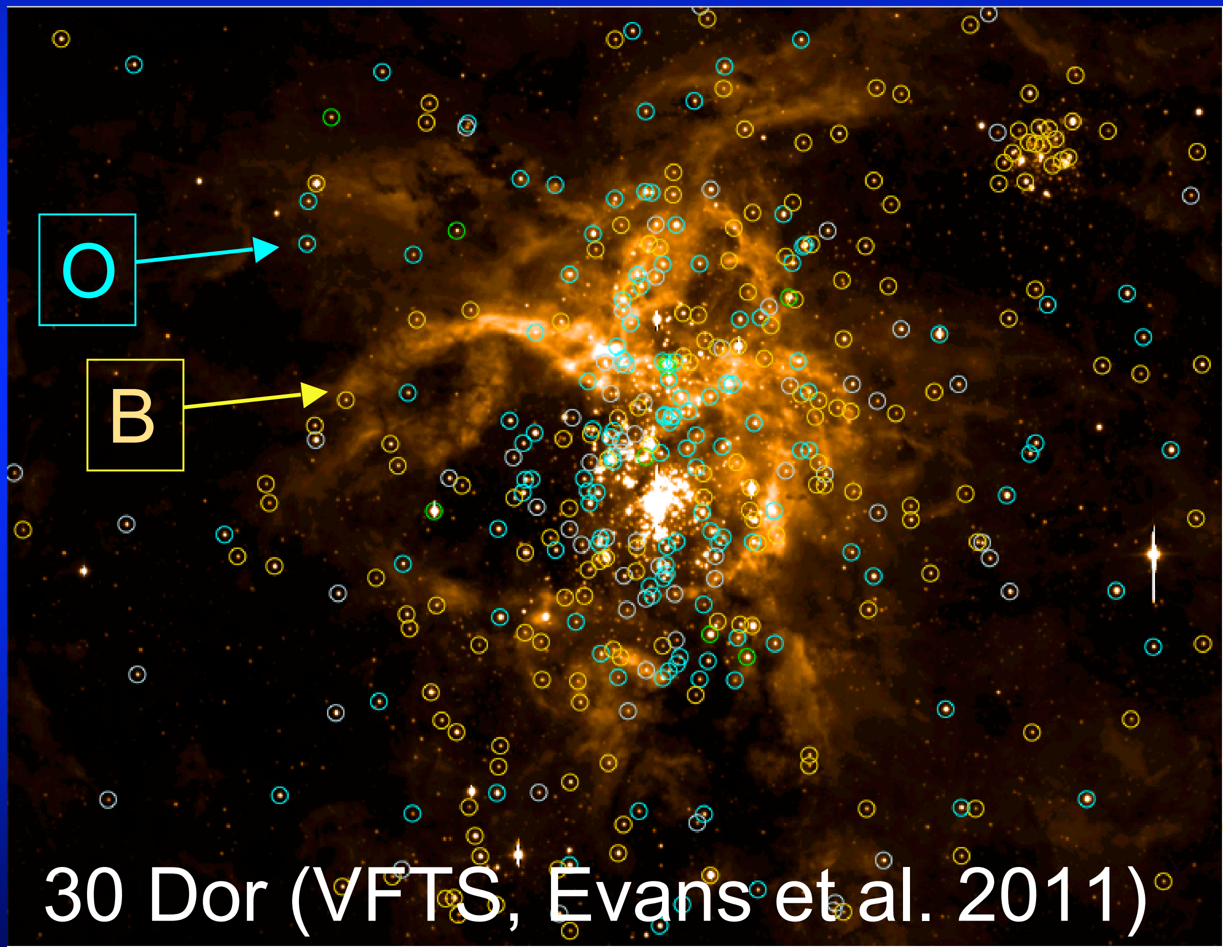


De Zeeuw et al. 1999



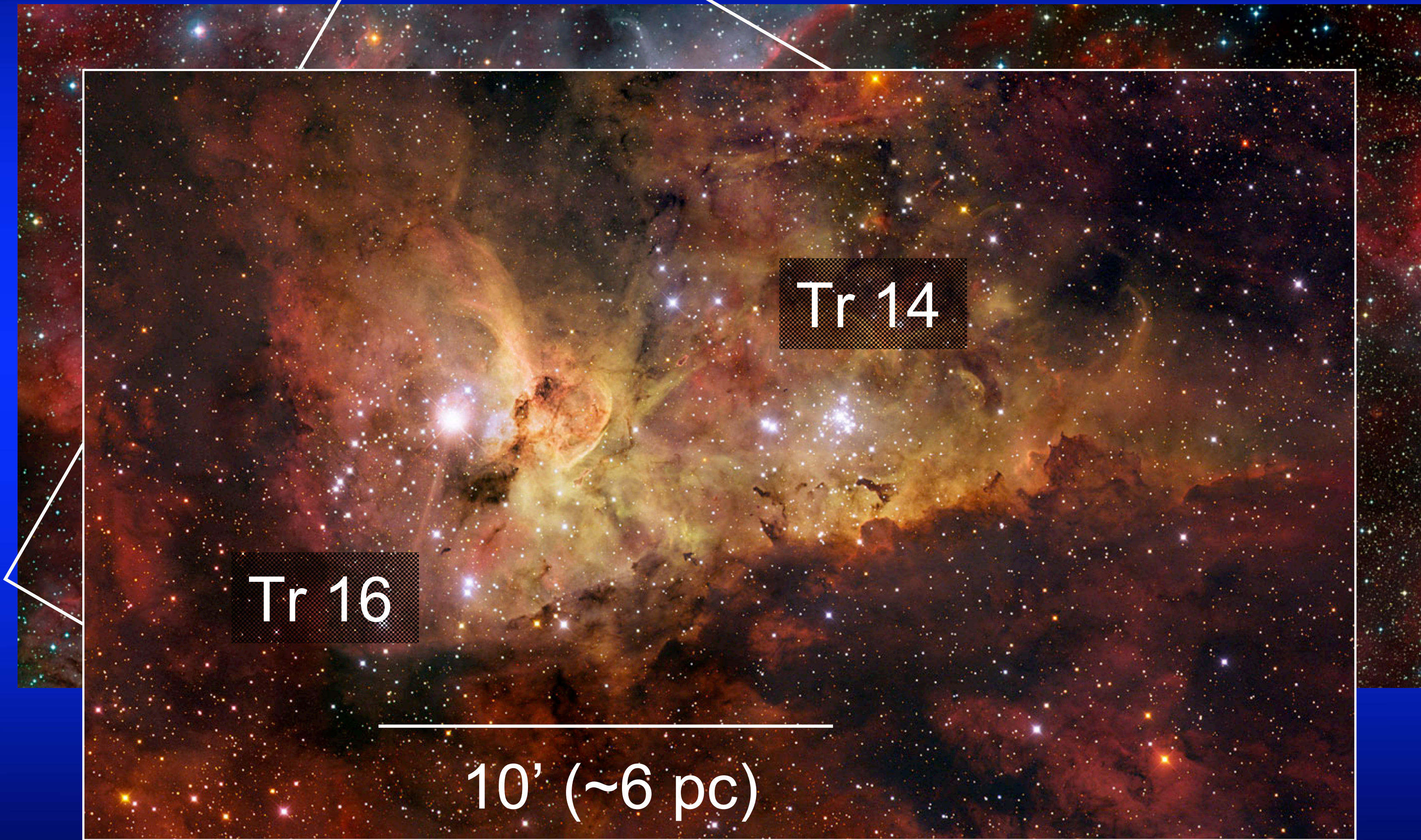
Orion Nebula Cluster (θ^1C Ori)

HII regions: Signatures of massive stars



5' (75 pc)

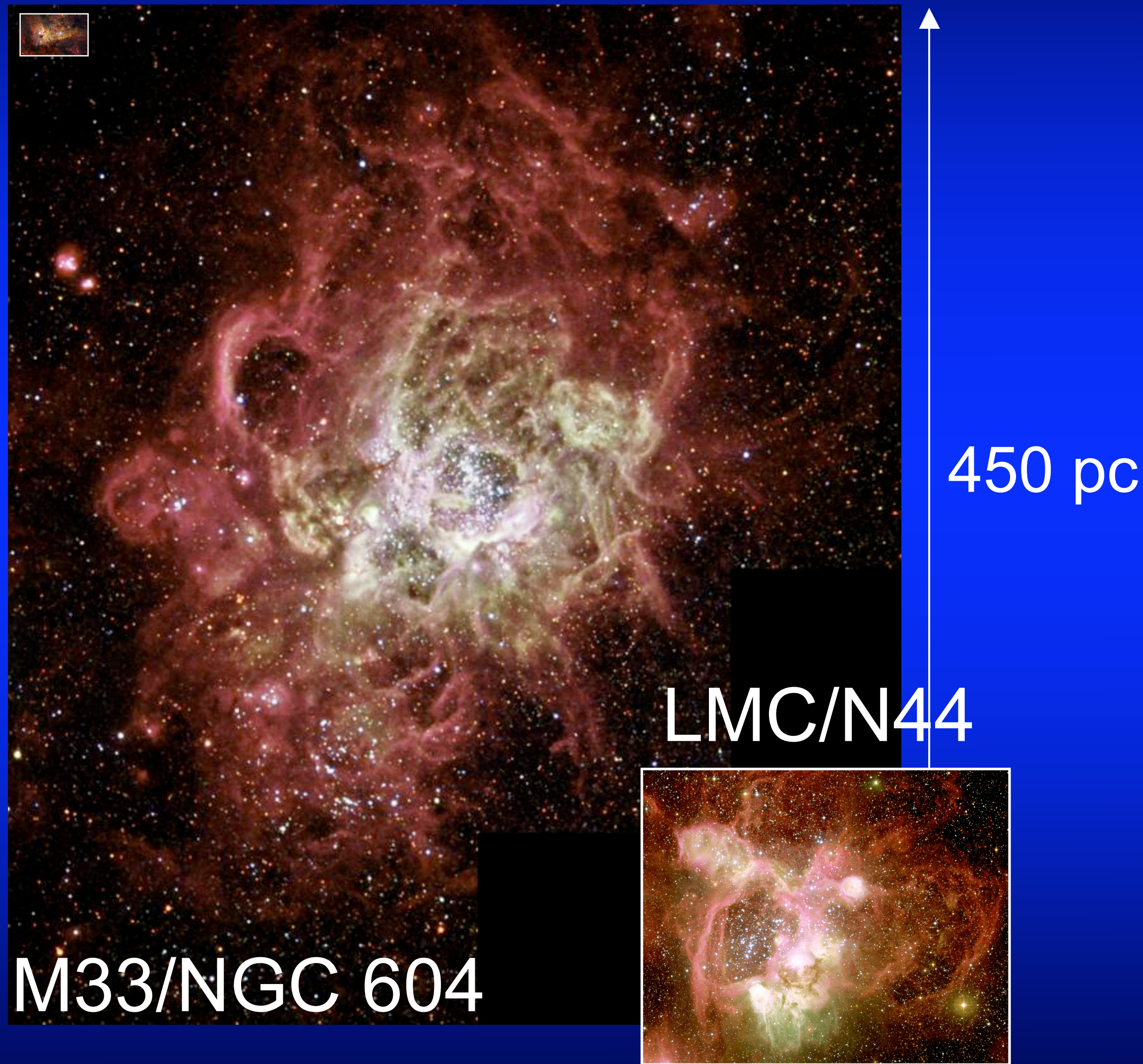
Milky Way Giant HII regions

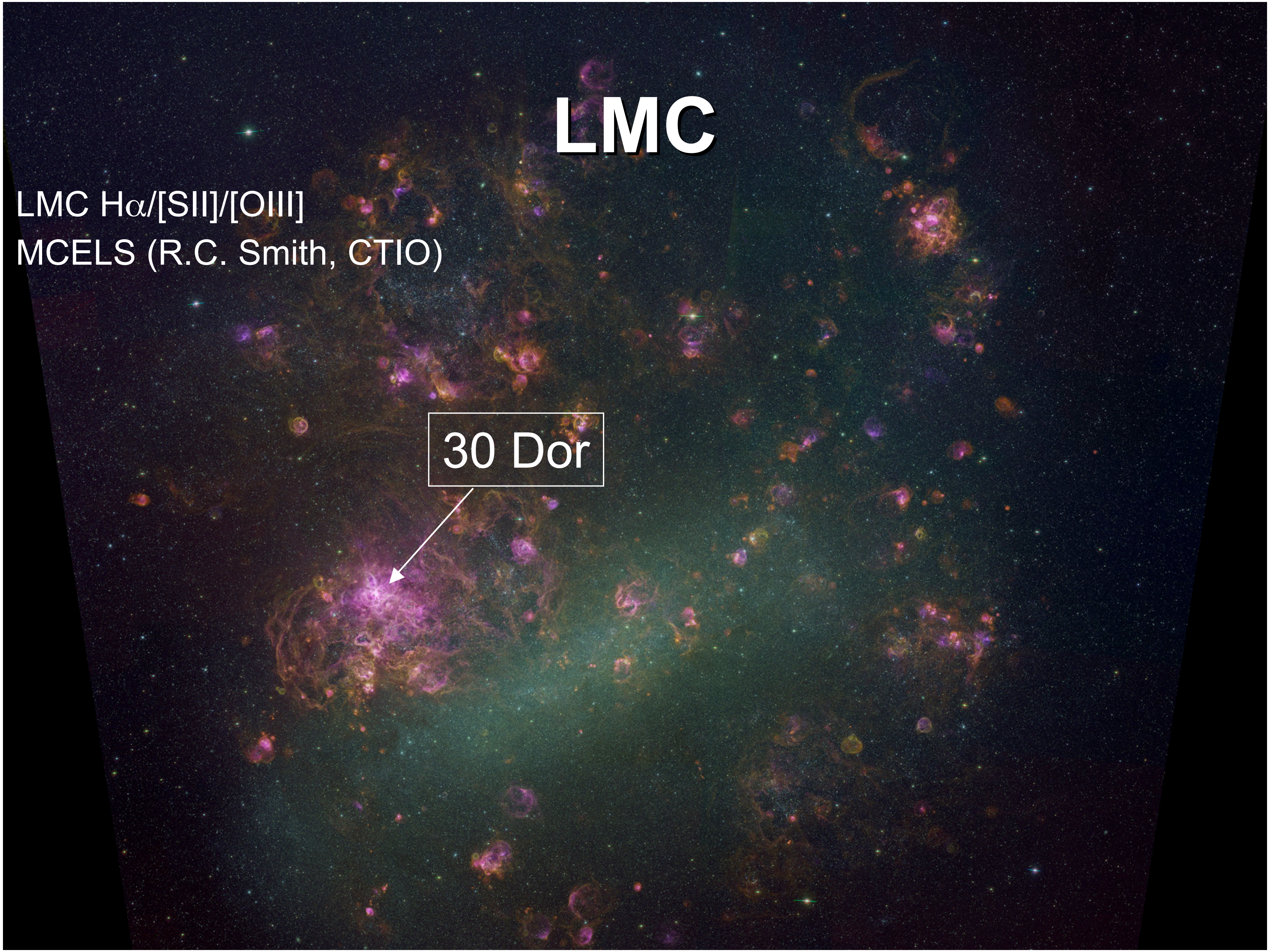


ESO 2.2m/WFI (BVR)

Extragalactic Giant HII regions

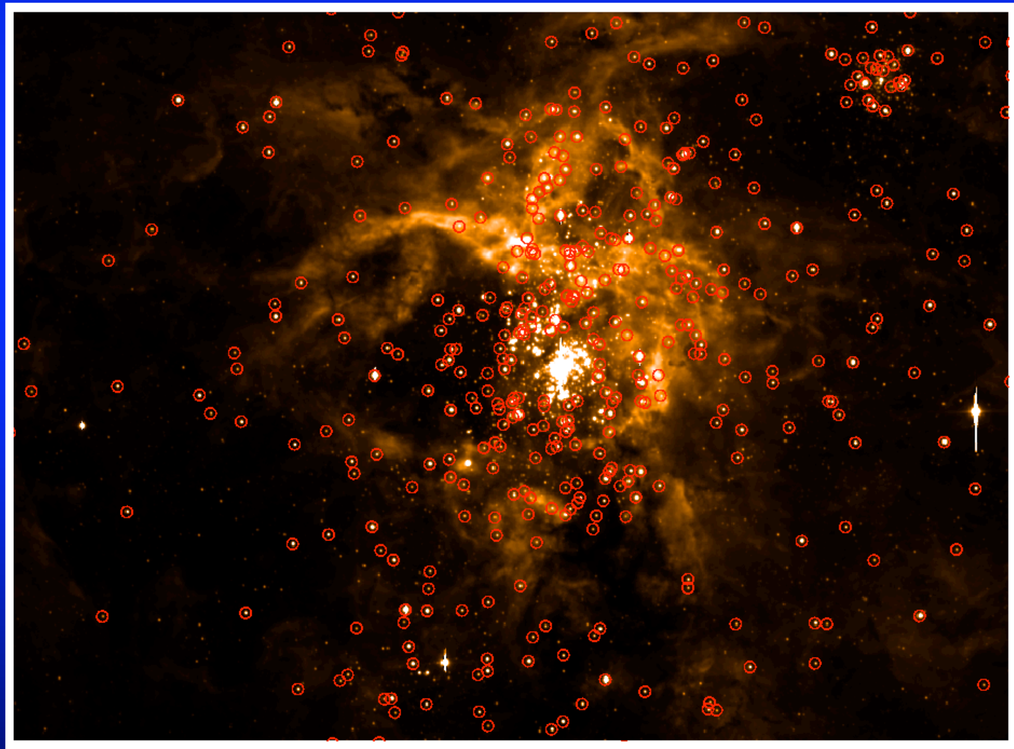
Large s.f. regions host multiple discrete stellar populations (separated by several Myr).




LMC
LMC Hα/[SII]/[OIII]
MCELS (R.C. Smith, CTIO)
30 Dor

Anatomy of a giant HII region: 30 Doradus

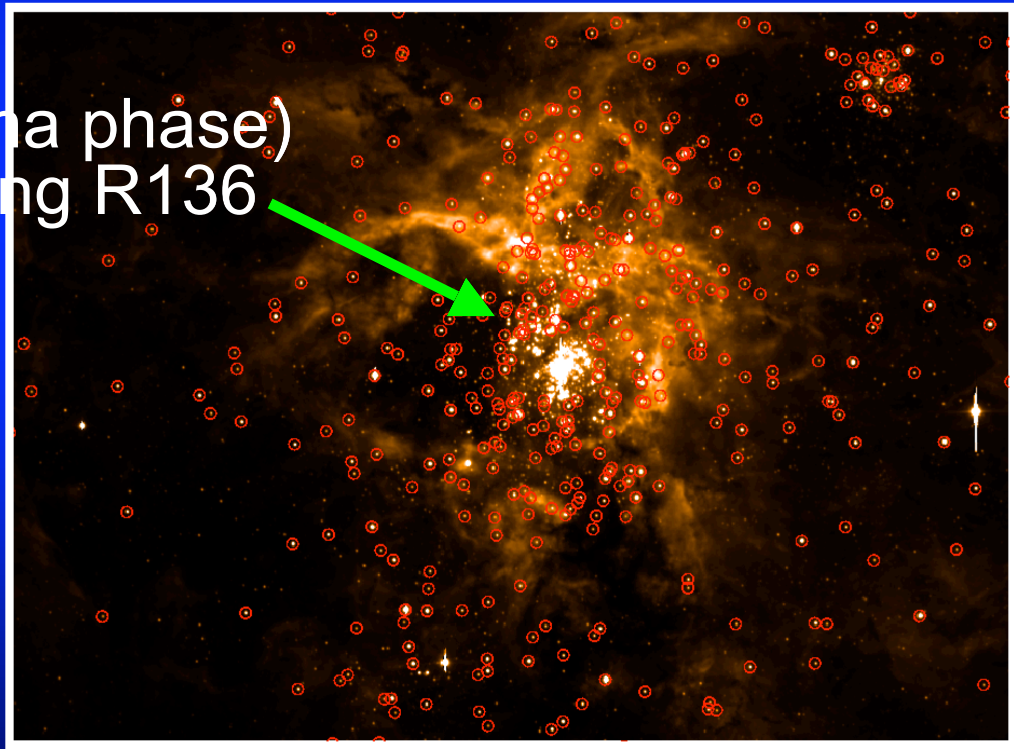
1) Young (Orion phase) embedded O stars to the N & W of R136



7' = 0.1 kpc

Anatomy of a giant HII region: 30 Doradus

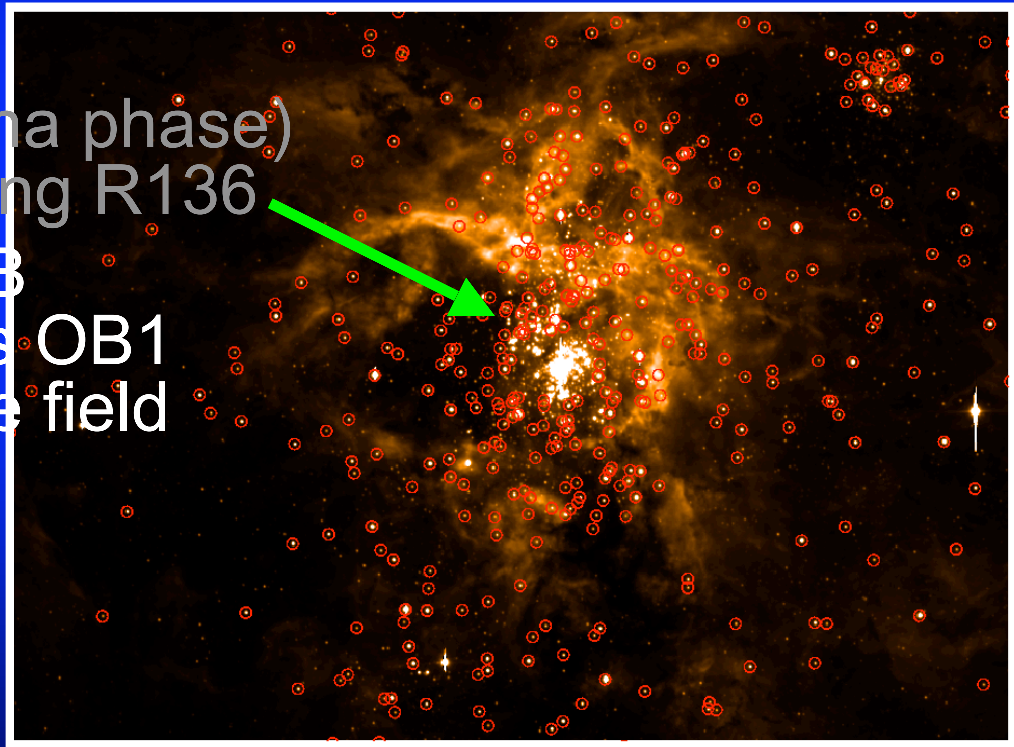
1) Young (Orion phase) embedded O stars to the N & W of R136
2) Central early-O (Carina phase) concentration, including R136



7’ = 0.1 kpc

Anatomy of a giant HII region: 30 Doradus

1) Young (Orion phase) embedded O stars to the N & W of R136
2) Central early-O (Carina phase) concentration, including R136
3) Older late-O & early-B supergiants (Scorpius OB1 phase) throughout the field



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Anatomy of a giant HII region: 30 Doradus

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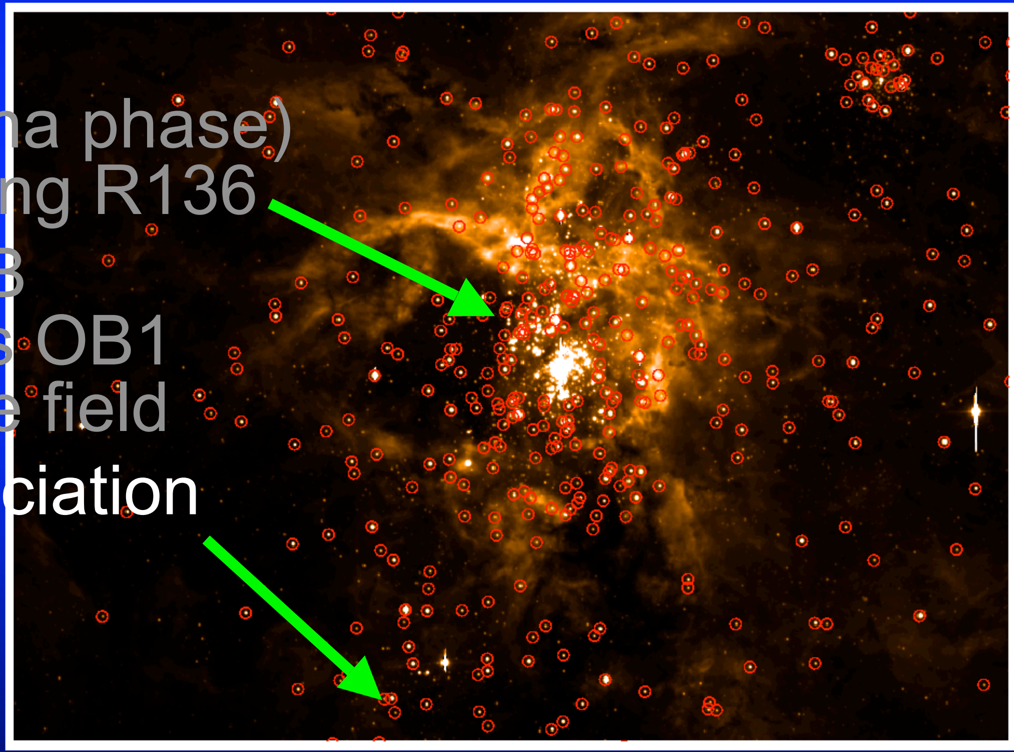
4) Sco OB1-phase association around R143



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Anatomy of a giant HII region: 30 Doradus

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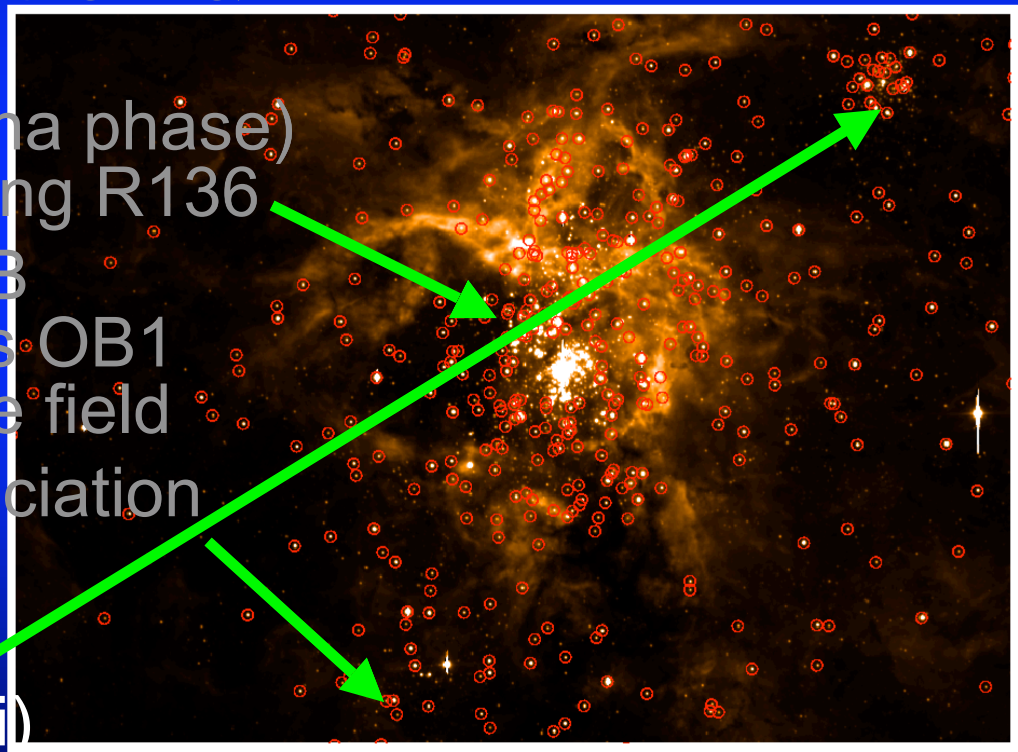
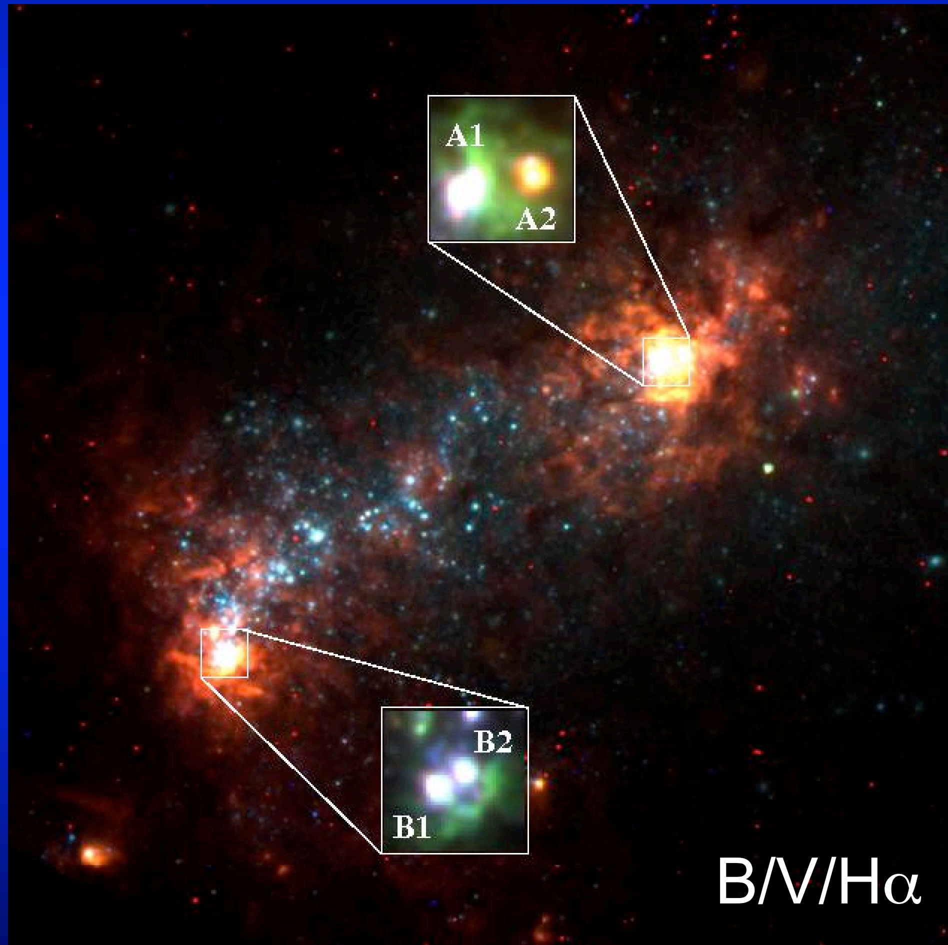
2) Central early-O (Carina phase) concentration, including R136
3) Older late-O & early-B supergiants (Scorpius OB1 phase) throughout the field
4) Sco OB1-phase association around R143
5) Older cluster 3’ NW of R136 (h & χ Persei)



7’ = 0.1 kpc

Starburst galaxies: NGC 3125

Young massive clusters in dwarf starburst galaxies (e.g. NGC 3125 @11Mpc, Hadfield & Crowther 2006)



20″ (1kpc)

- Environment
  - HII regions: Signatures of massive stars
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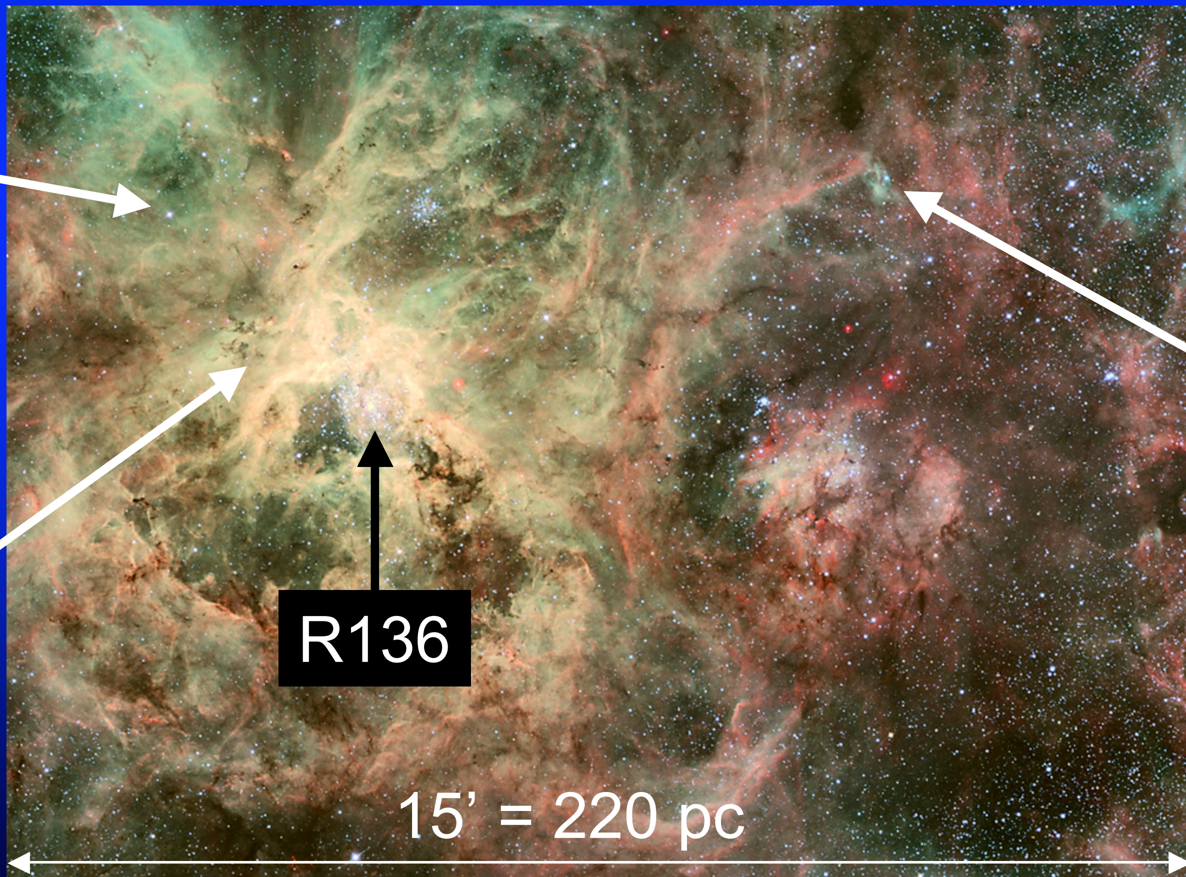
Massive stars & star clusters

- O stars (>20 M_{sun})
  - Formed in clusters*, short-lived, though could be ejected (by dynamical interactions or recoil following companion SN explosion).
- Early B stars (8-20 M_{sun})
  - If formed in low mass cluster, sufficiently long-lived that cluster may dissolve into field population.

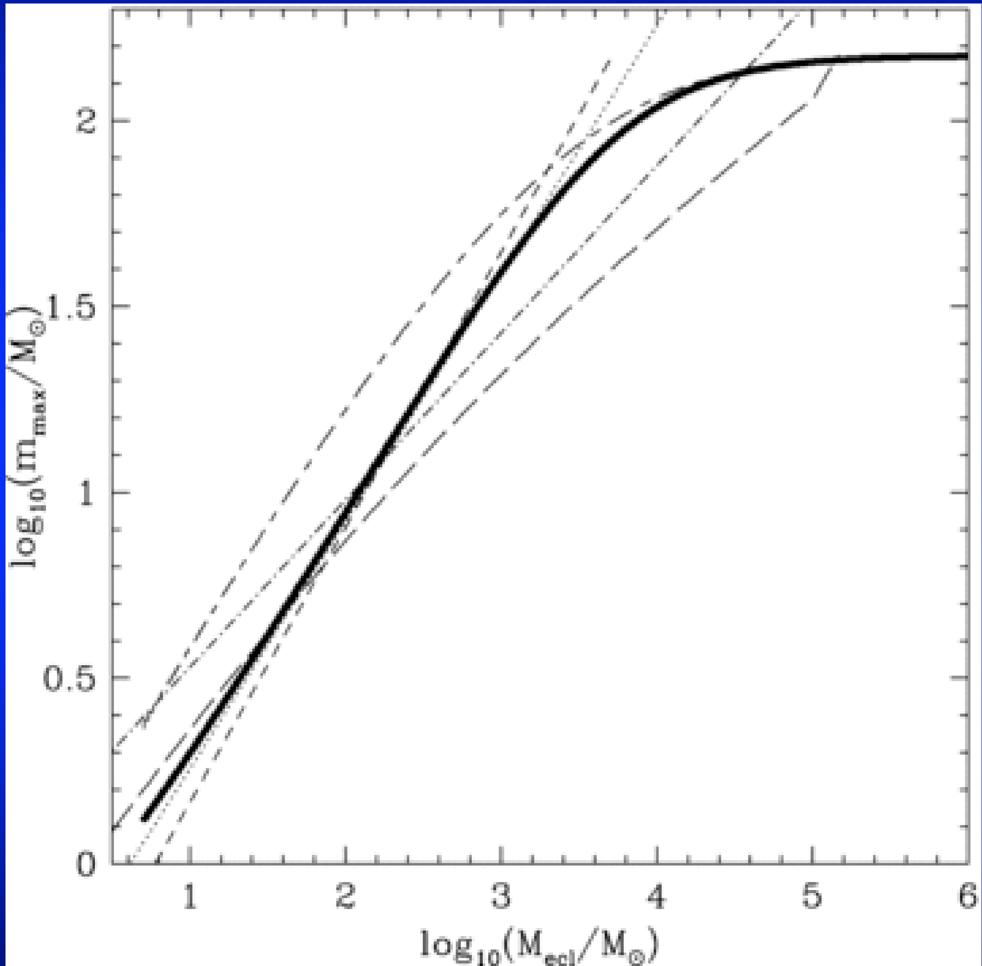
*(mostly). A few % of O stars appear to have formed "outside a clustered environment" (de Wit et al. 2005)

Massive stars in `isolation'?

Several very massive stars in 30 Dor are located far away from the central cluster R136, incl. VFTS 16 (Evans et al. 2010) VFTS 682 (Bestenlehner et al. 2011). Formed in situ or dynamically ejected (`runaways')?



Cluster mass-max stellar mass



Cluster Mass ~10^2 M_o to host at least one massive star (>8M_o)

Cluster mass ~10^3 M_o to host at least one O star (>25 M_o)

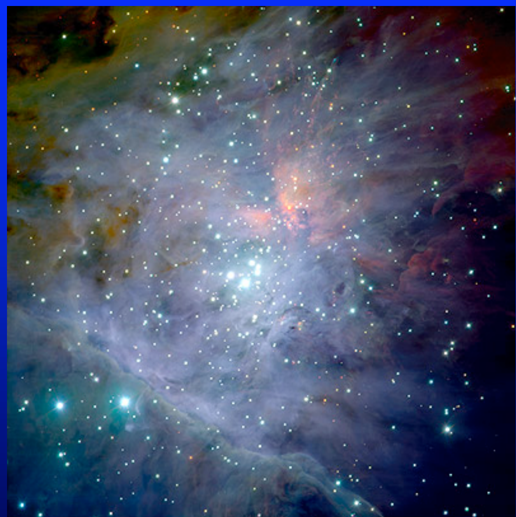
Cluster mass ~10^4 M_o to host one 100+ M_o star (>100 massive stars in total)

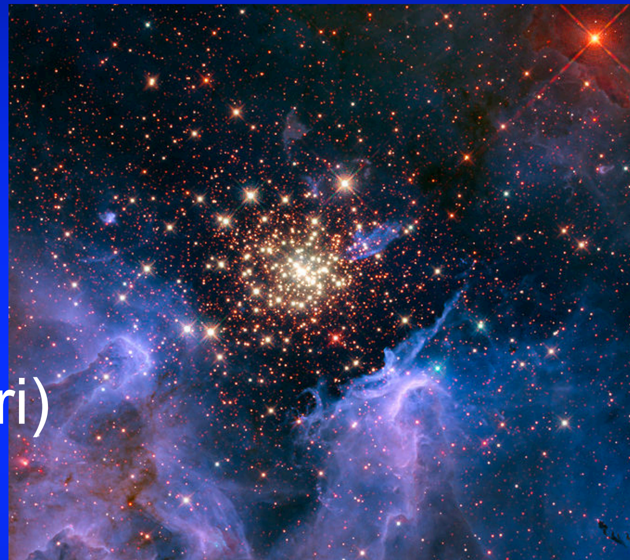
Weidner et al. (2010)

Young star clusters

ρ Oph (10^2 M_o)
M_{max}~8 M_o (ρ Oph)

ONC ($2x10^3$ M_o)
M_{max}~35 M_o (θ^1C Ori)





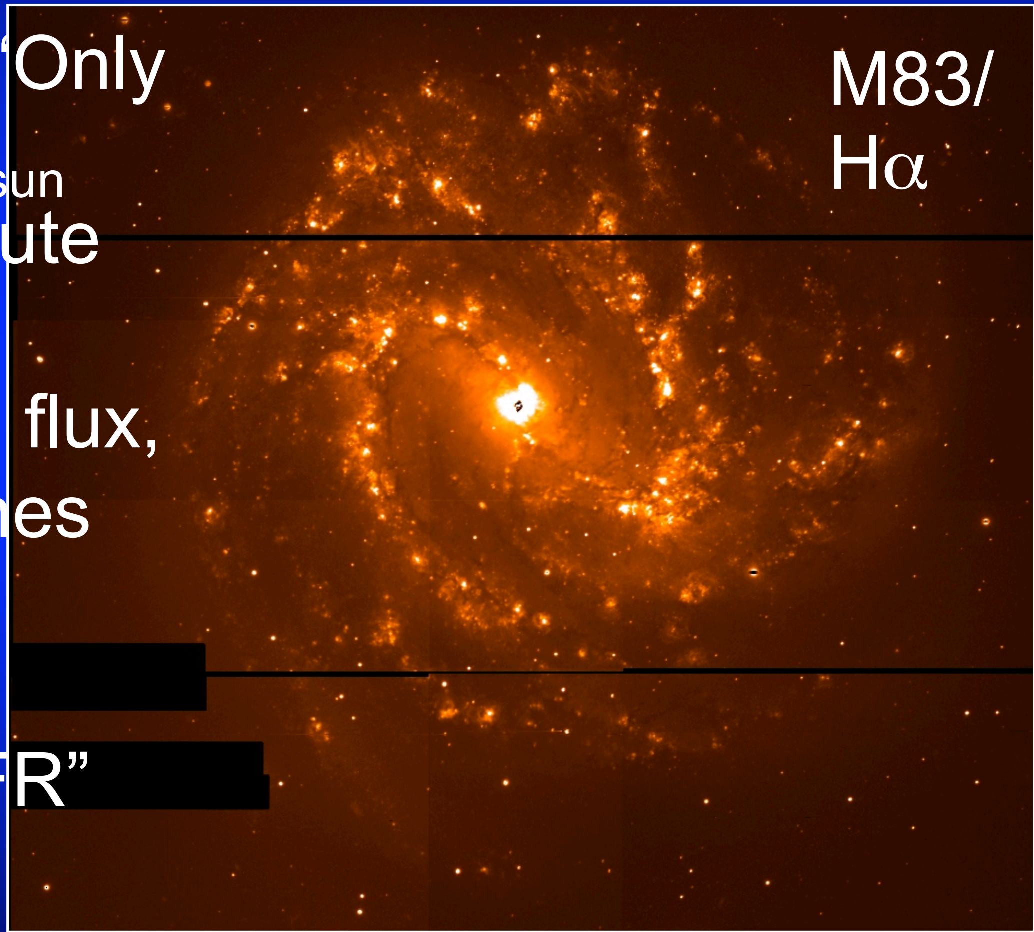
NGC 3603 (10^4 M_o)
M_{max}~170 M_o (3603-B)

Rare in small ponds, but common in big ones..

Tokyo fish market (earlier today)

HII regions ⇔ SFR

Kennicutt (1998): “Only stars with $M>10M_{sun}$ (τ<20 Myr) contribute significantly to the integrated ionizing flux, so the emission lines provide a <u>nearly</u> instantaneous measure of the SFR”

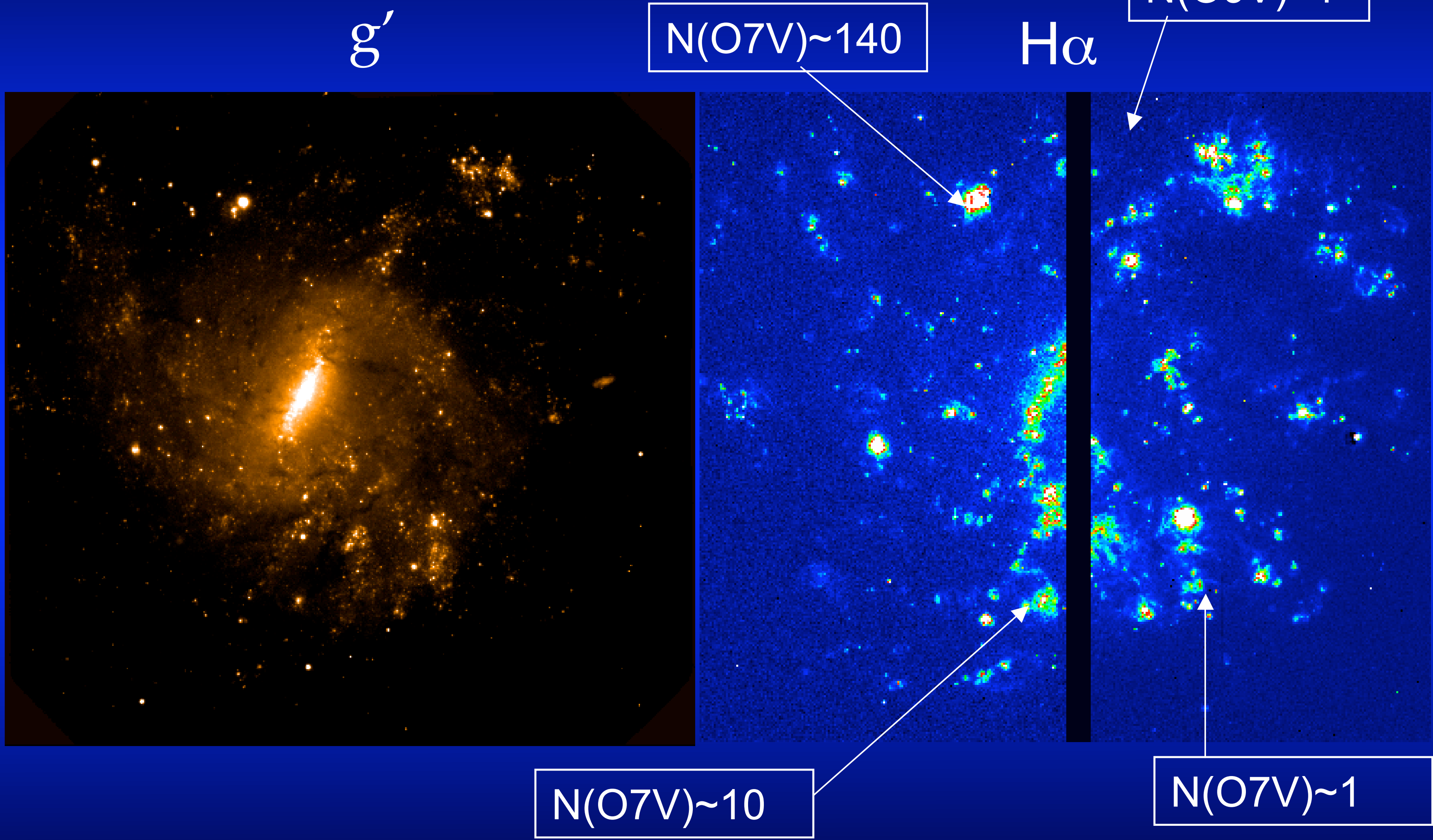


OB stars & HII regions

Spectral Type	Mass M_o	T_{eff} K	N_{LyC} 10^{49} s^{-1}
O3V	75	45,000	5
O5V	51	41,000	1.6
O7V	36	37,000	0.7
O9V	25	33,000	0.13
B0V	19	30,000	0.025
B1V	14	26,000	0.002
B2V	9	21,000	0.0002

1 x N_{LyC}(O3V, 75 M_o) = 25,000 x N_{LyC}(B2V, 9 M_o)

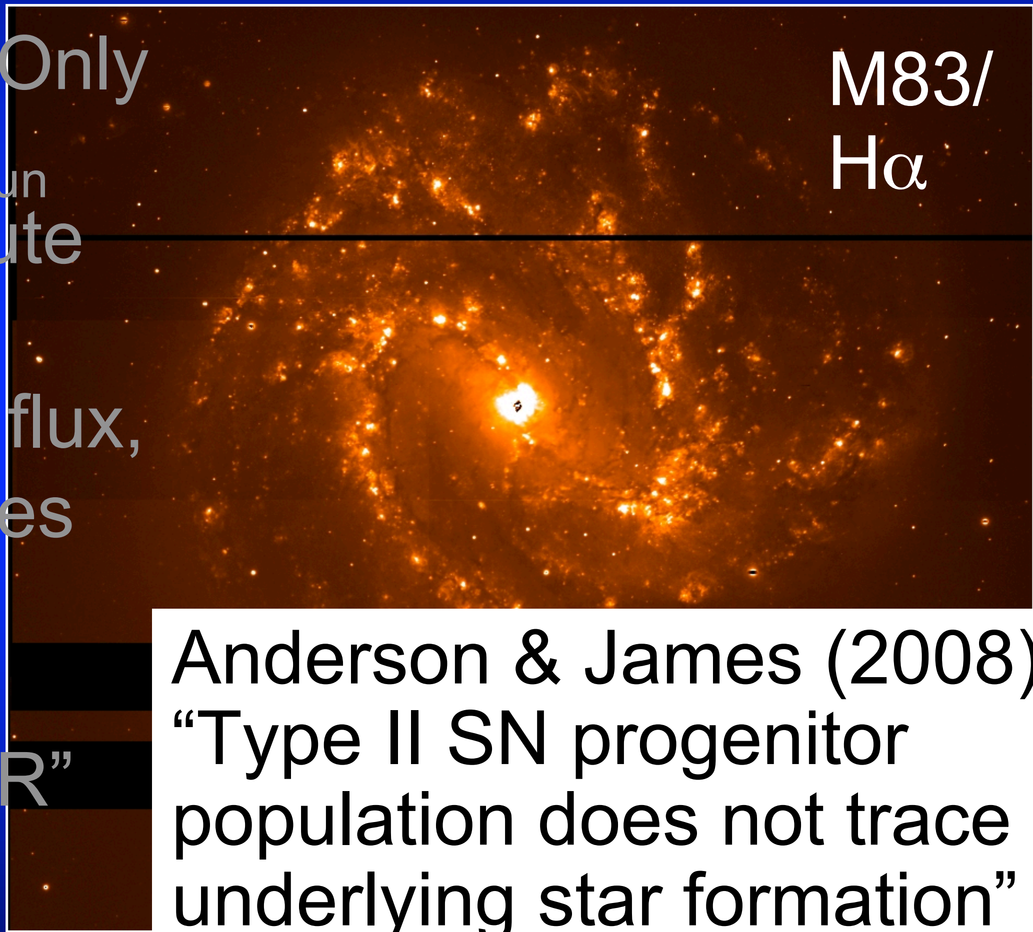
NGC 5068



Bibby & Crowther (MNRAS 2012)

Type II ccSNe ⇔ SFR?

Kennicutt (1998): "Only stars with $M>10M_{sun}$ (τ<20 Myr) contribute significantly to the integrated ionizing flux, so the emission lines provide a nearly instantaneous measure of the SFR"



Anderson & James (2008): "Type II SN progenitor population does not trace underlying star formation"

- Environment
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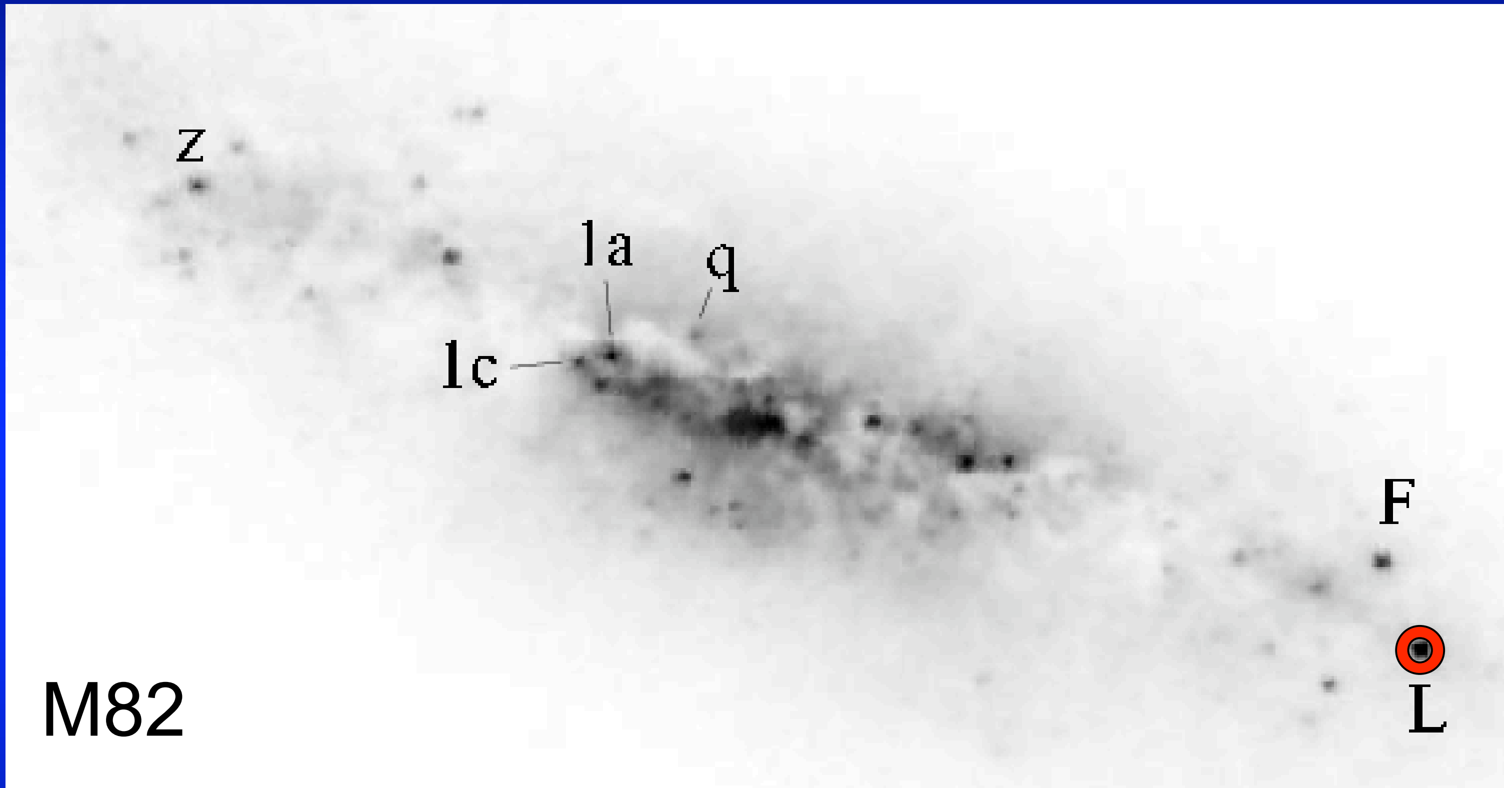
Statistics?

- Local (<2000km/s) ccSN sample with HST/ground-based imaging (1999-2008.5):
  - 0 of 20 Type II's (mostly II-P) in bright HII regions, (although many in loose associations). 2004am+2004dj in compact clusters

Smartt et al. (2009 & priv comm.)

SN 2004am (II-P)



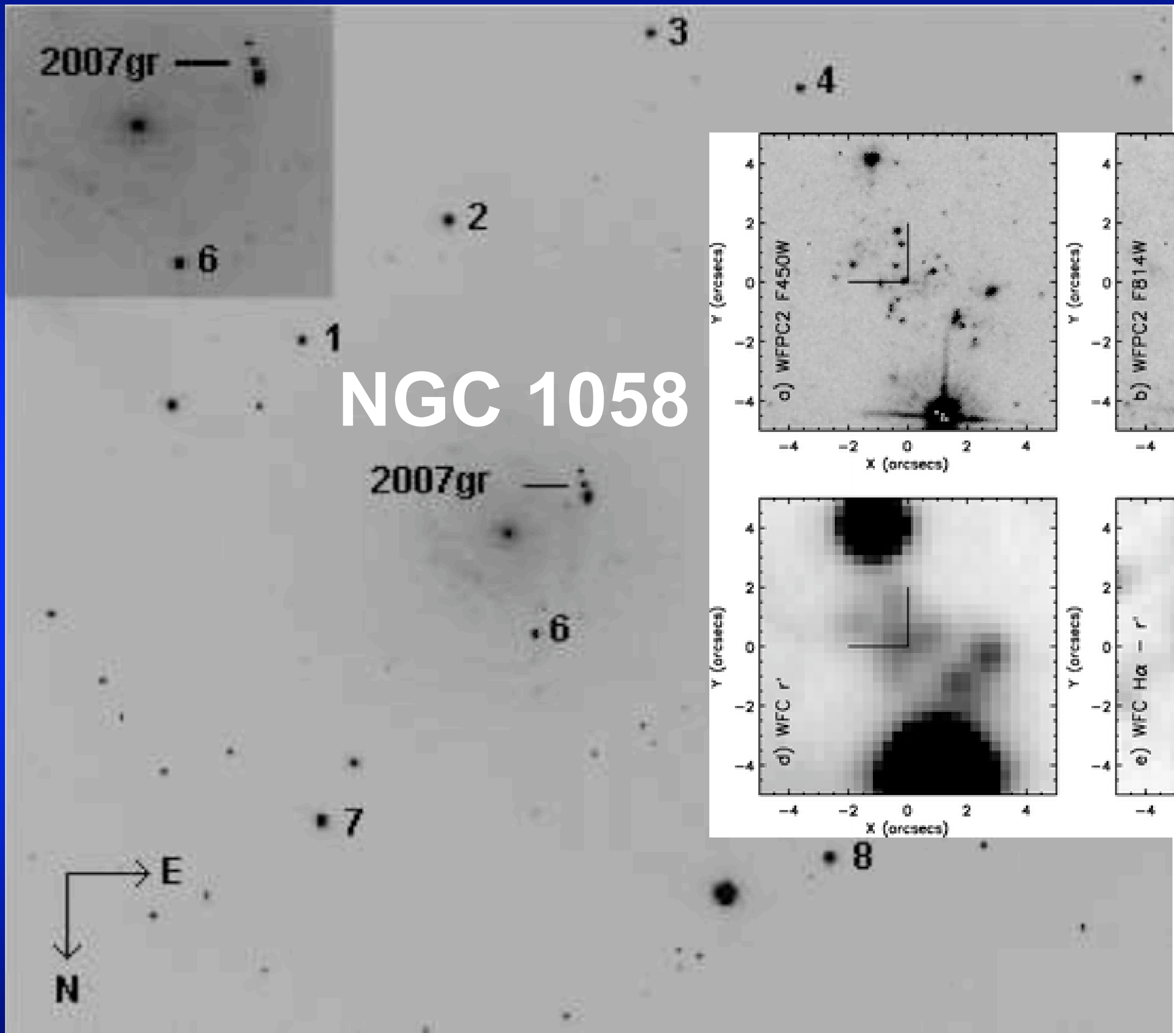
Spatially coincident with high mass, relatively young star cluster: M82-L (10-35 Myr, Lançon et al. 2008; $4 \times 10^6\ M_o$ McCrady et al. 2007)

Statistics?

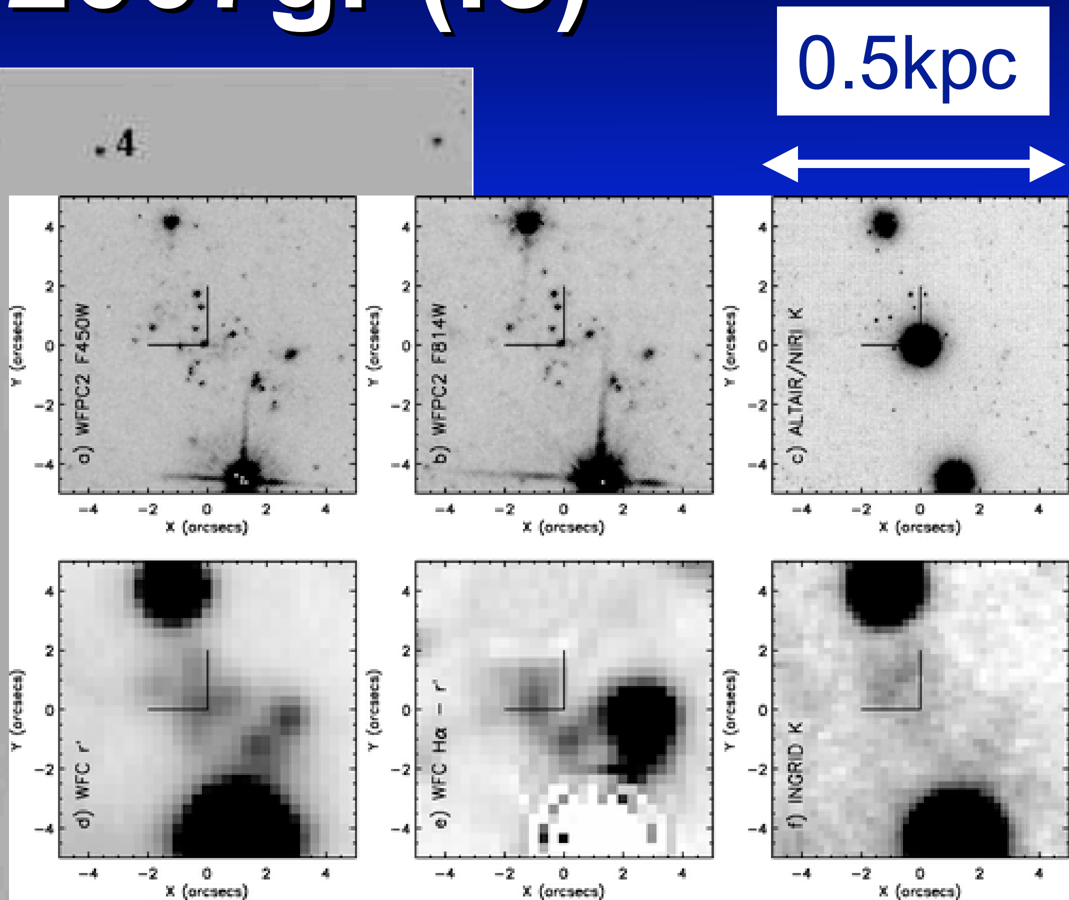
- Local (<2000km/s) ccSN sample with HST/ground-based imaging (1999-2008.5):
  - 0 of 20 Type II's (mostly II-P) in bright HII regions, (although many in loose associations). 2004am+2004dj in compact clusters
  - 1 of 10 Type Ib/c's in a large star-forming complex (SN 2007gr) although no HII emission at compact cluster position

Smartt et al. (2009 & priv comm.)

SN 2007gr (Ic)



Hunter et al. (2009)



Crockett et al. (2008)

Statistics?

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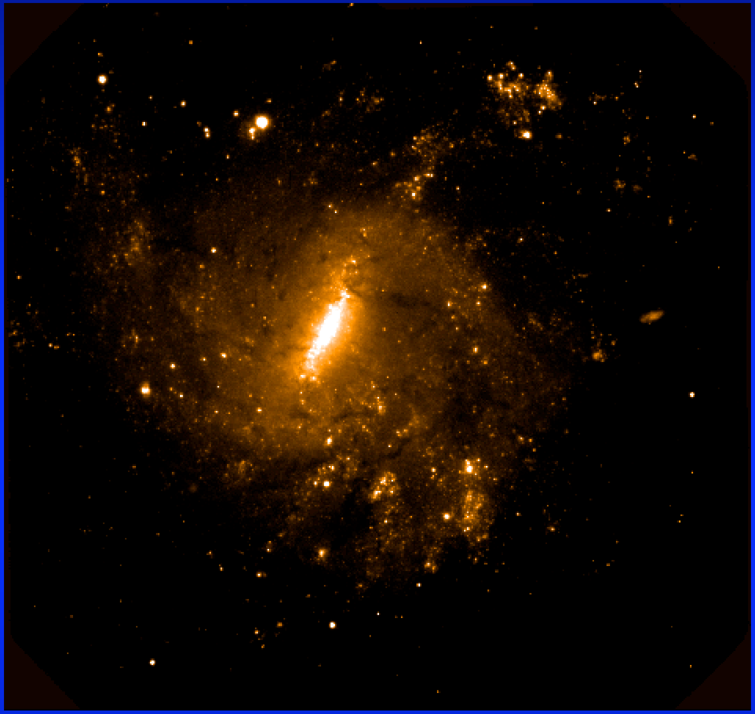
  - 1 of 10 Type Ib/c's in a large star-forming complex (SN 2007gr) although no HII emission at compact cluster position
- More extensive study (albeit at larger distances) by James & Anderson (2006) & Anderson & James (2008): Anderson talk

Smartt et al. (2009 & priv comm.)

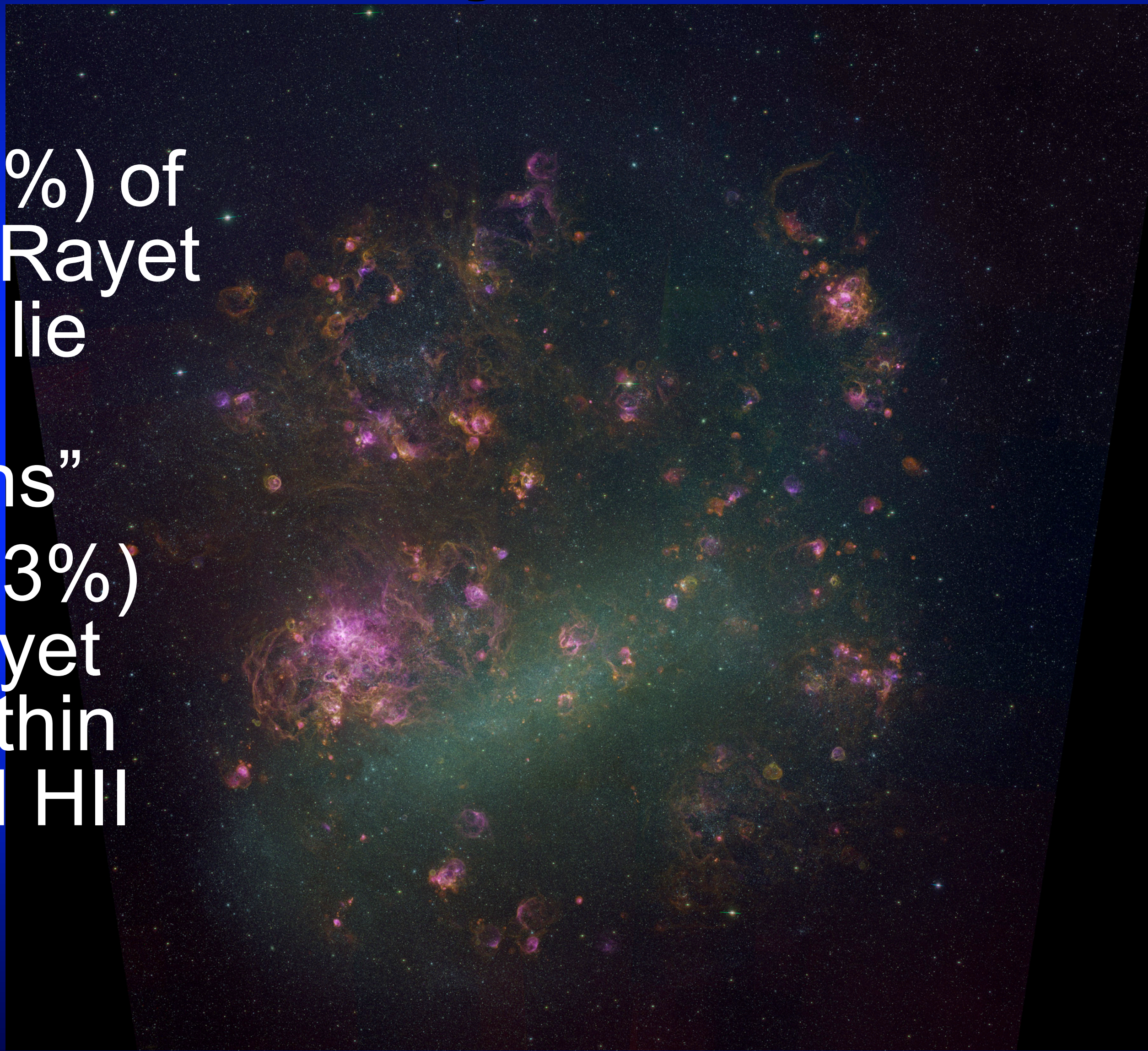
Wolf-Rayet stars ⇔ HII regions

1) VLT/Gemini survey of Wolf-Rayet (WR) population of nearby star-forming galaxies (talk: Joanne Bibby)
2) 160 WR candidate regions in NGC 5068 (~5 Mpc) from narrow-band images.
3) Moderate star formation rate (~0.6 M_{sun}/yr)

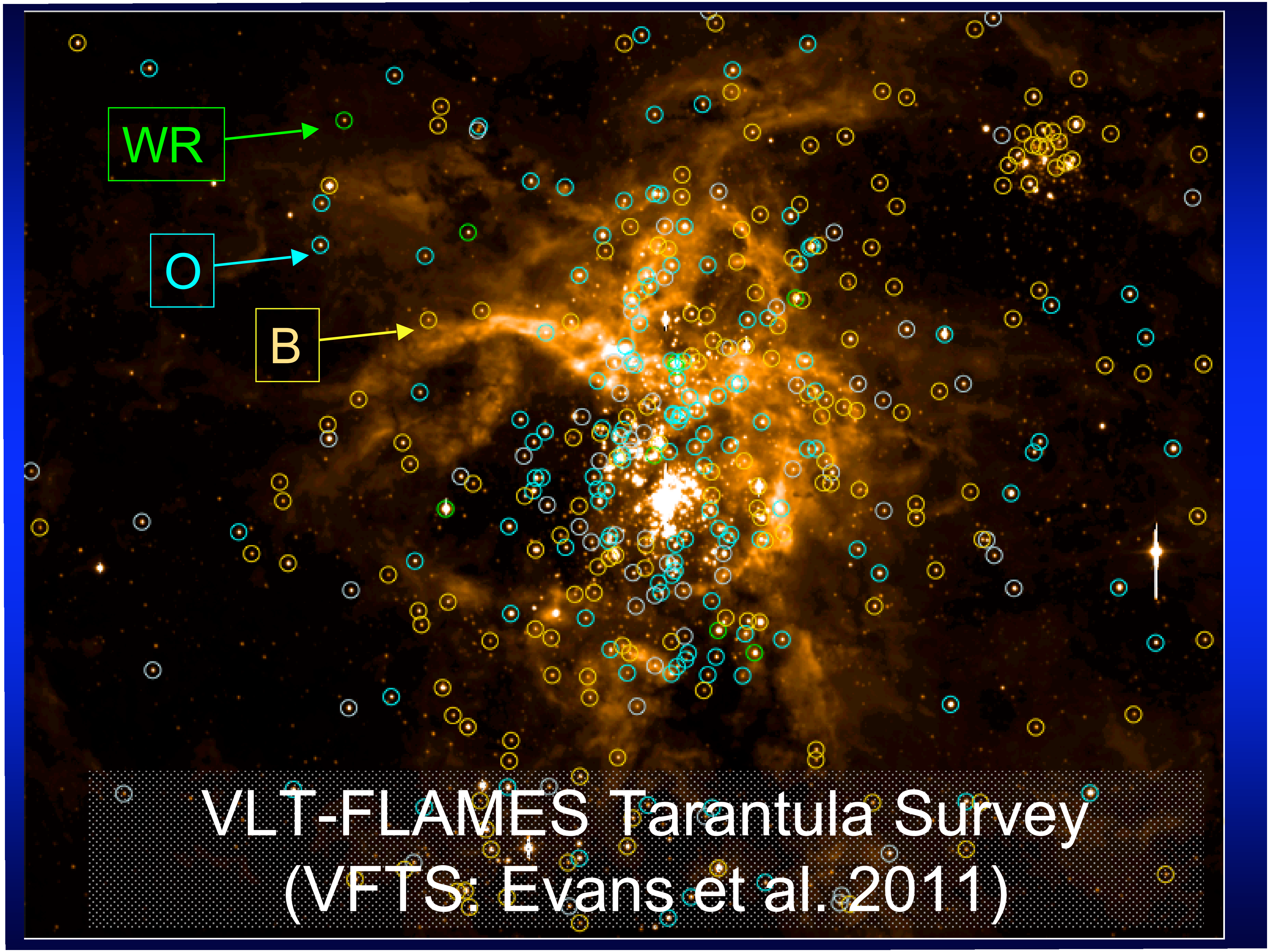


50% of Wolf-Rayet candidates are associated with either giant or bright HII regions, 25% with “faint” nebulosity & 25% without any nebular association.

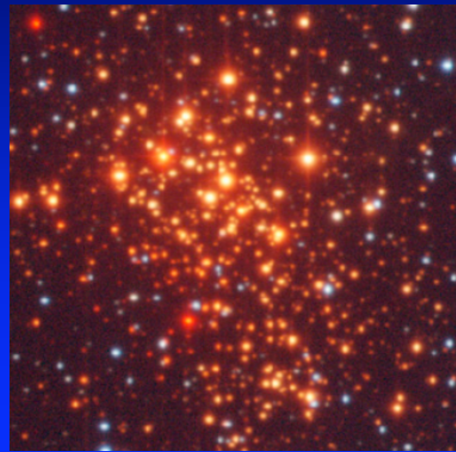
LMC: Wolf-Rayet stars



1) 78/134 (58%) of LMC Wolf-Rayet population lie within “OB associations”
2) 112/134 (83%) of Wolf-Rayet stars lie within catalogued HII regions


WR
O
B
VLT-FLAMES Tarantula Survey
(VFTS: Evans et al. 2011)

Star clusters: Ages

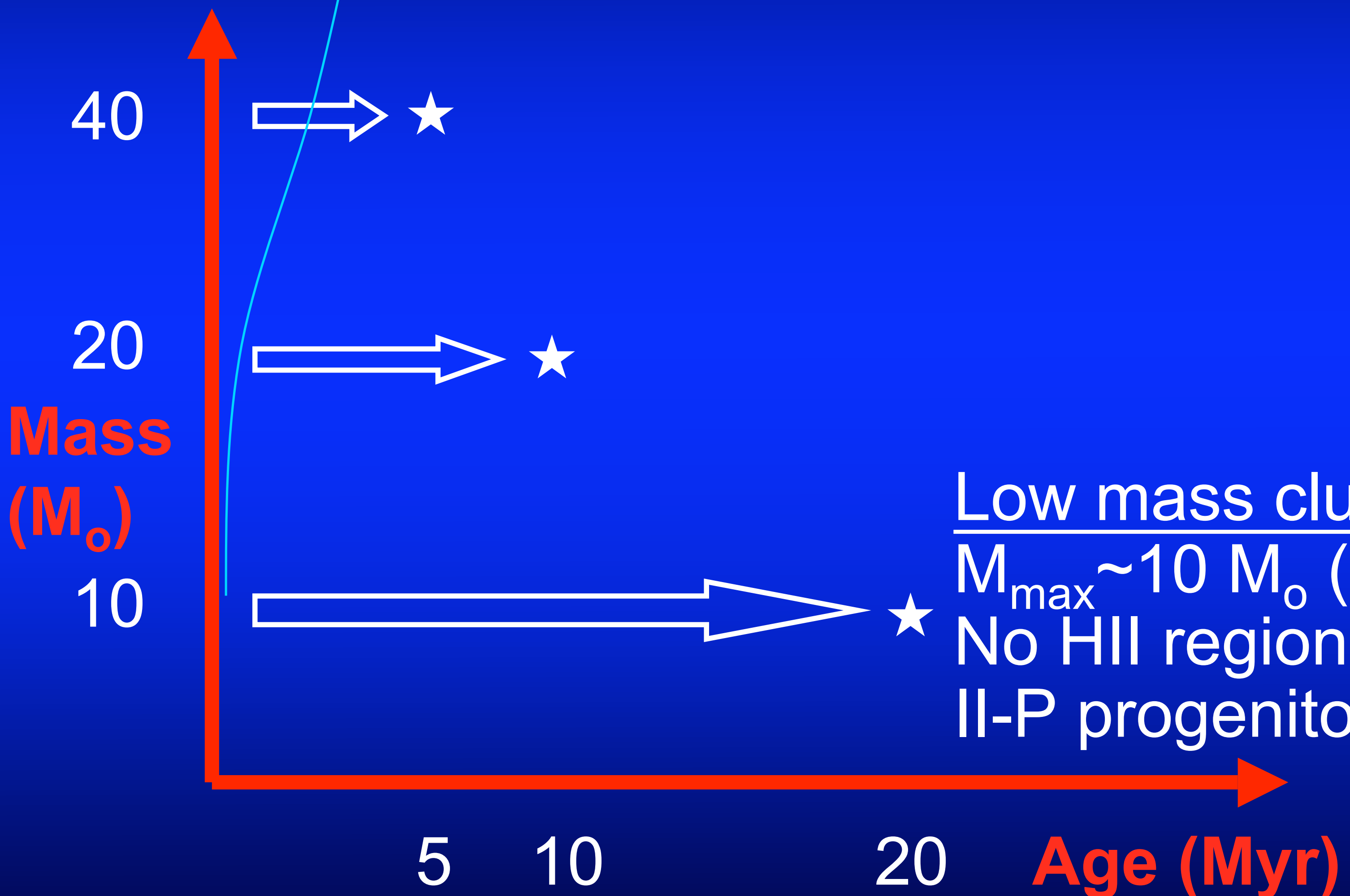


<1Myr → ~1.5Myr → ~3Myr → ~5Myr

Object	Visually Brightest Stars	MS Turnoff Spectrum	MS Turnoff Mass[$M_\odot$]	Age [yrs]	H II, Dust	Red Sg
Orion Nebula	ZAMS O, (IR)	(PMS)		$< 10^6$	Yes	No
Carina Nebula	O2, WNL	O3	100	$1–2 \times 10^6$	Yes	No
Scorpius OB1	OB Sg	O6	50	$3–4 \times 10^6$	No	No
Westerlund 1	AF Sg	O7–O8	35	$4–5 \times 10^6$	No	Yes
Perseus OB1	AF Sg	B0–B1	20	$7–9 \times 10^6$	No	Yes

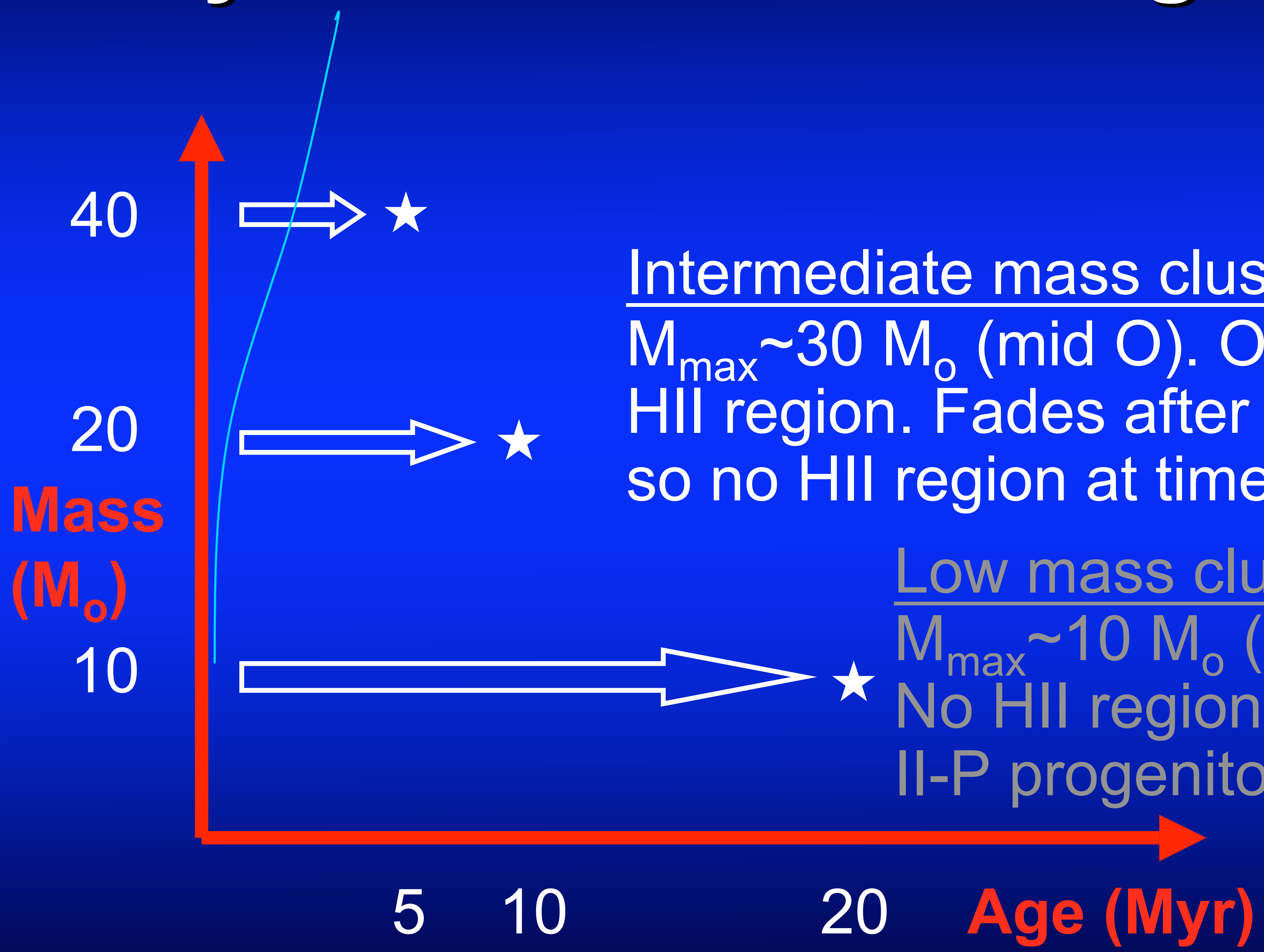
Walborn (2009)

Why so few SN in HII regions?



Low mass clusters with M_{max}~10 M_o (early B). No HII region from type II-P progenitor

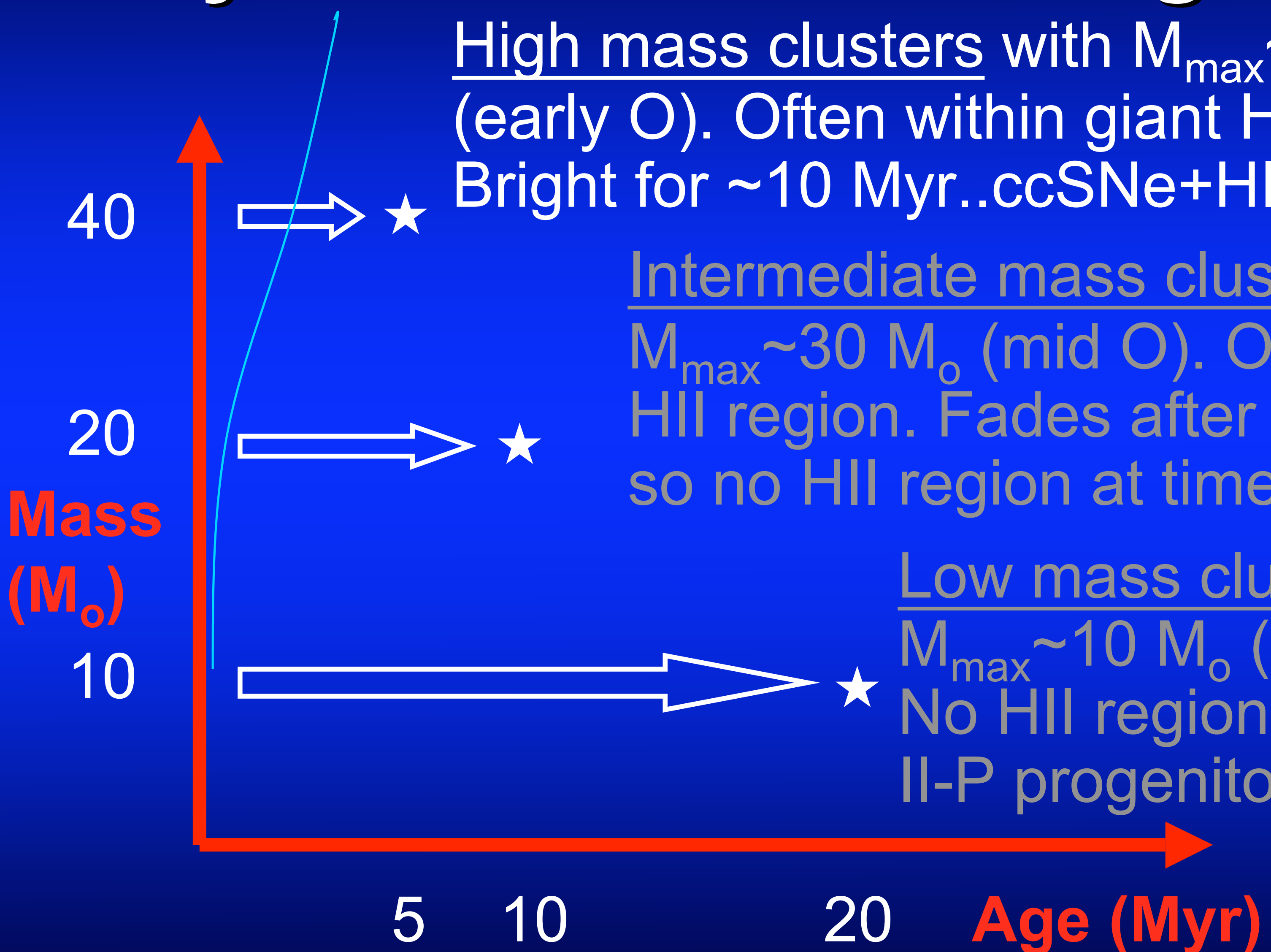
Why so few SN in HII regions?



Intermediate mass clusters with M_{max}~30 M_o (mid O). Orion-type HII region. Fades after few Myr.. so no HII region at time of ccSN

Low mass clusters with M_{max}~10 M_o (early B). No HII region from type II-P progenitor

Why so few SN in HII regions?



High mass clusters with M_{max}~100 M_o (early O). Often within giant HII region. Bright for ~10 Myr..ccSNe+HII region?

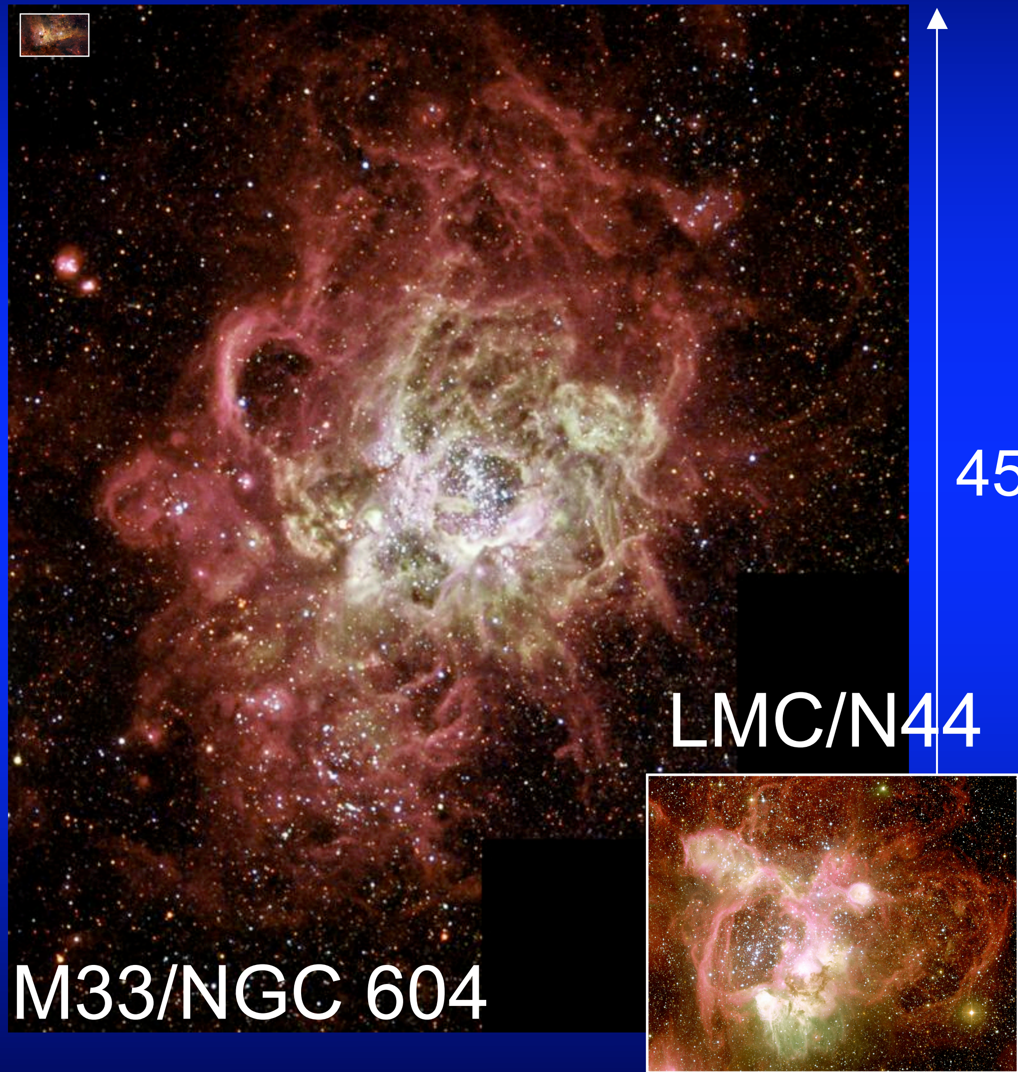
Intermediate mass clusters with M_{max}~30 M_o (mid O). Orion-type HII region. Fades after few Myr.. so no HII region at time of ccSN

Low mass clusters with M_{max}~10 M_o (early B). No HII region from type II-P progenitor

Giant HII regions

Large s.f. regions host multiple discrete stellar populations (separated by several Myr).

Some SN will be associated with bright HII regions, (albeit not necessarily a solitary cluster).



SNe: Why rarely associated with HII regions?

- Don't expect most ccSNe to be associated with s.f. regions..
- Isolated star cluster:
  - HII region absent for 10M_o progenitor, faint for intermediate mass (25 M_o) progenitor
  - HII region *may* still be bright for a very massive (~100? M_o) progenitor..
- Large star forming complex:
  - Giant HII region bright for >10Myr (sequential s.f.), so 20-50+ M_o progenitors would appear to be "associated" with star-forming region..

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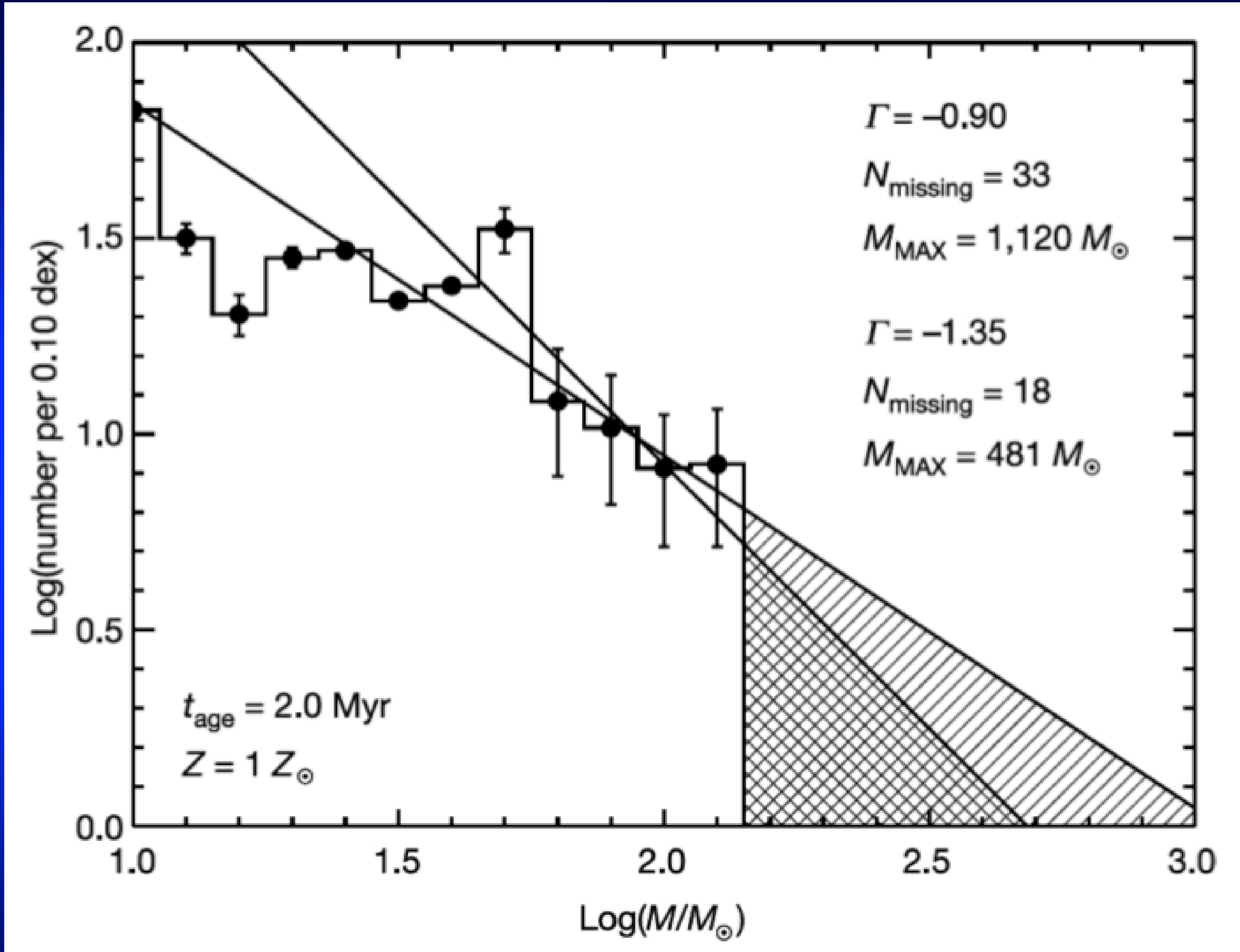
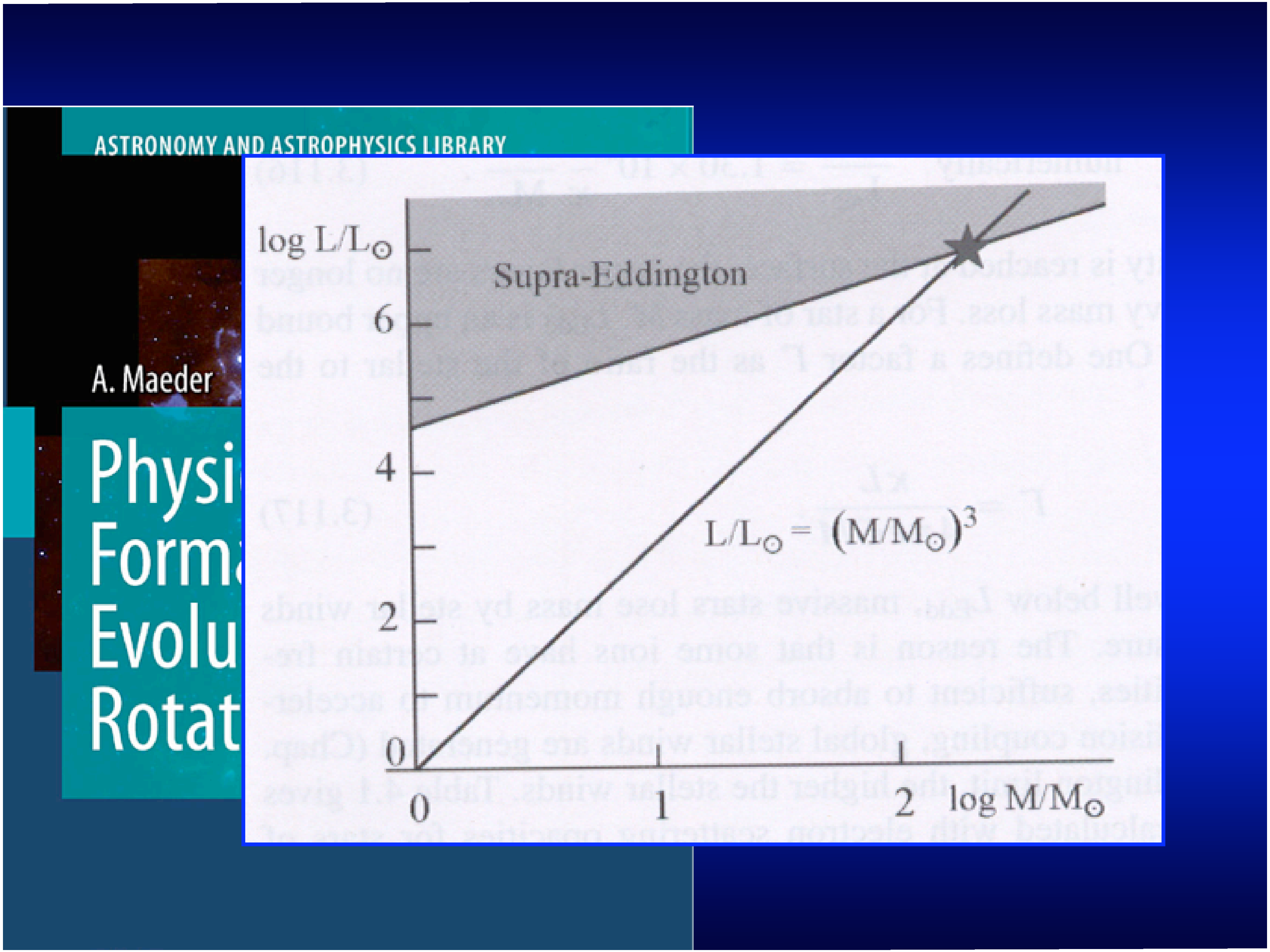
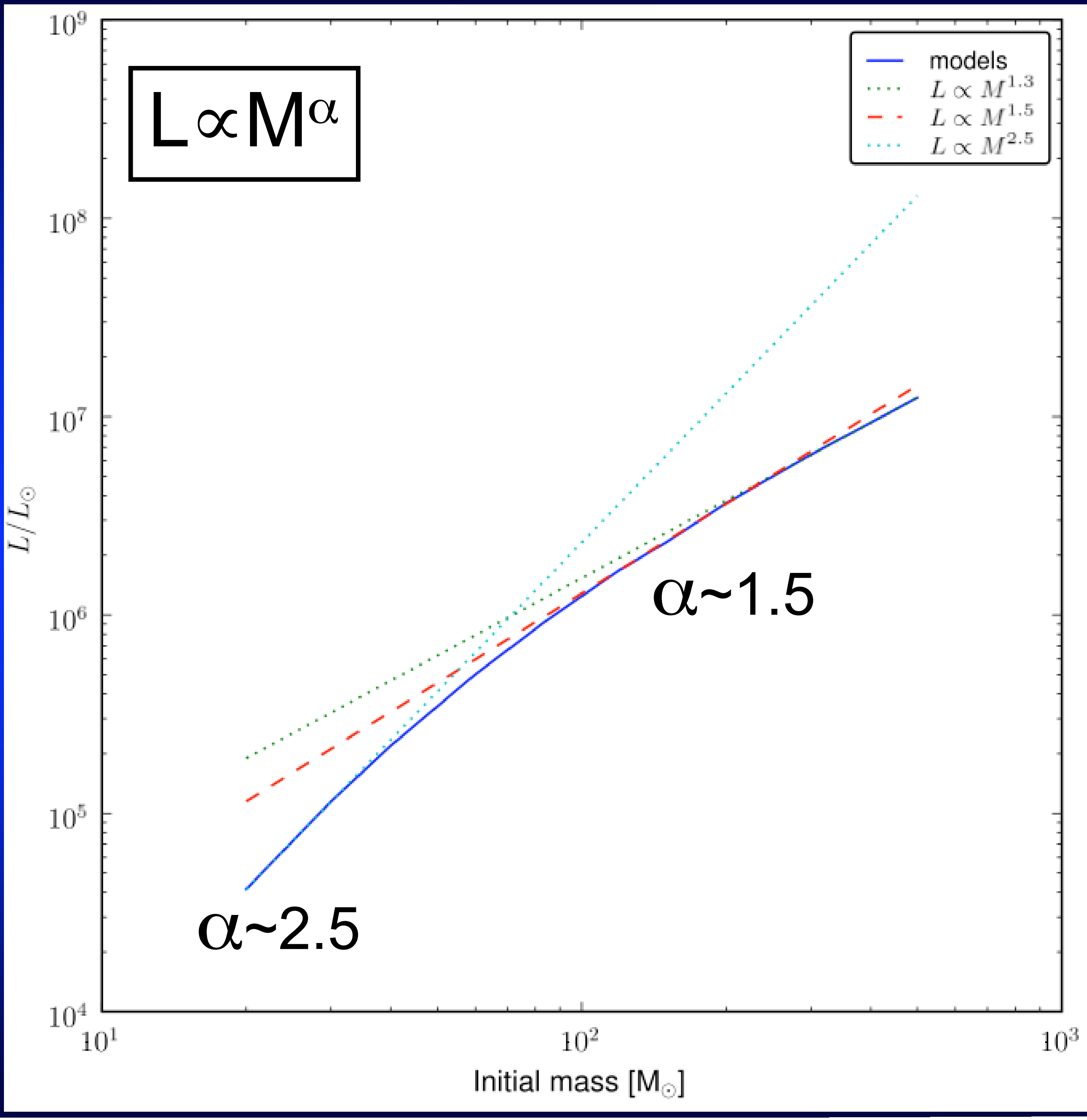


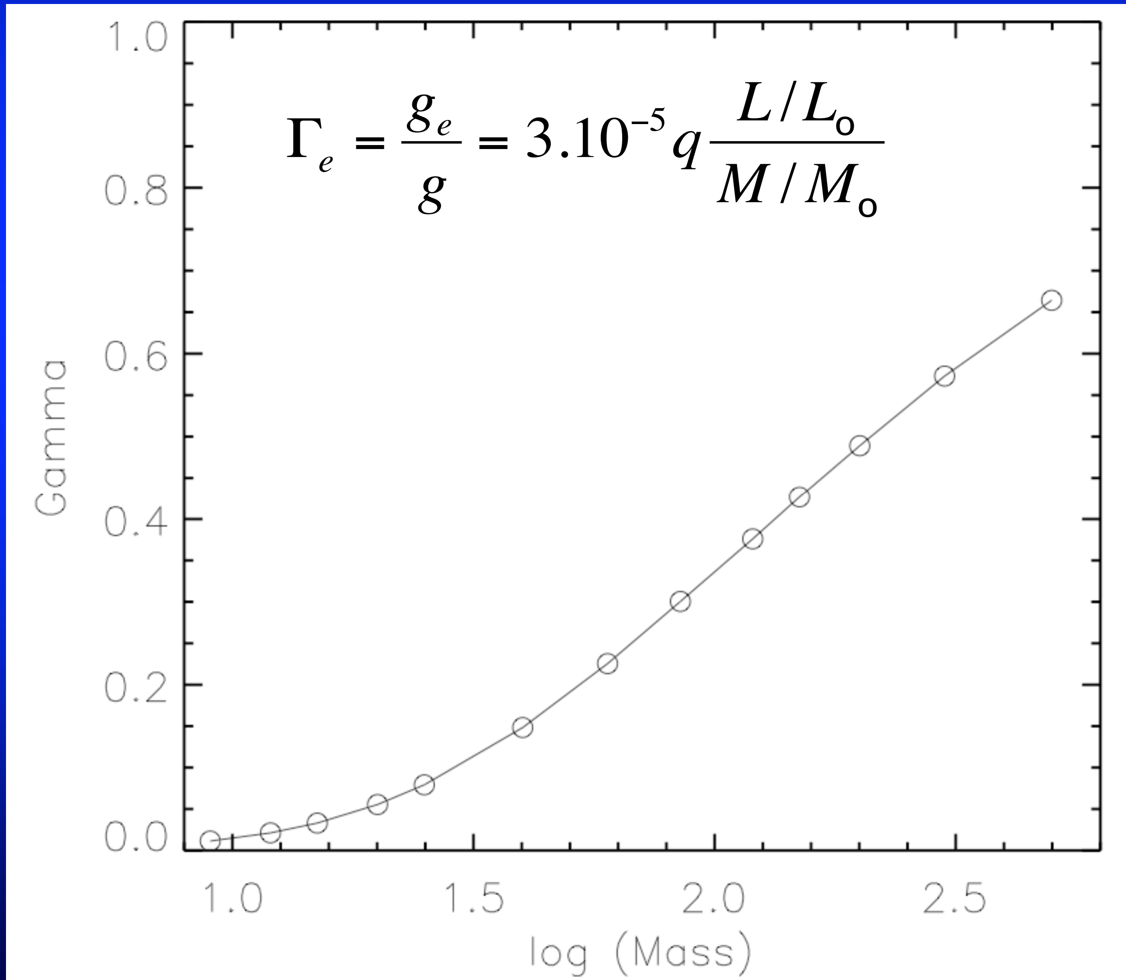
Figer (2005), Nature


ASTRONOMY AND ASTROPHYSICS LIBRARY
A. Maeder
log $L/L_\odot$
Supra-Eddington
$L/L_\odot = (M/M_\odot)^3$
0
2
4
6
0
1
2
log $M/M_\odot$



L∝M^α
models
L ∝ M^1.3
L ∝ M^1.5
L ∝ M^2.5
α~1.5
α~2.5
L/L⊙
Initial mass [M⊙]
10^4
10^5
10^6
10^7
10^8
10^9
10^1
10^2
10^3

Very massive stars don't exceed the Eddington Limit (at least not ZAMS ones)



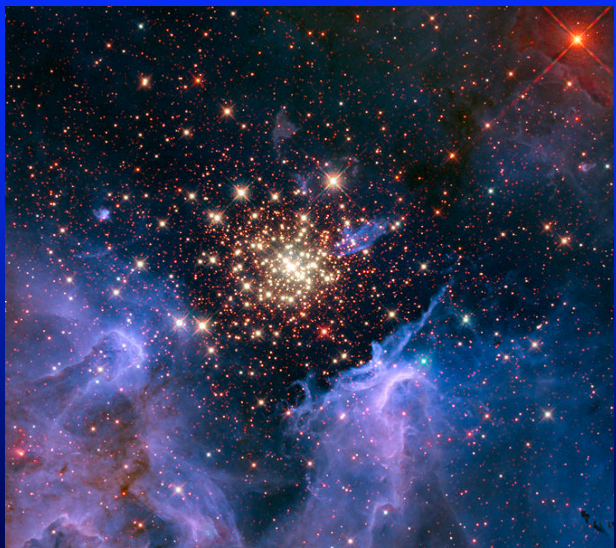
$$\Gamma_e = \frac{g_e}{g} = 3.10^{-5} q \frac{L/L_o}{M/M_o}$$

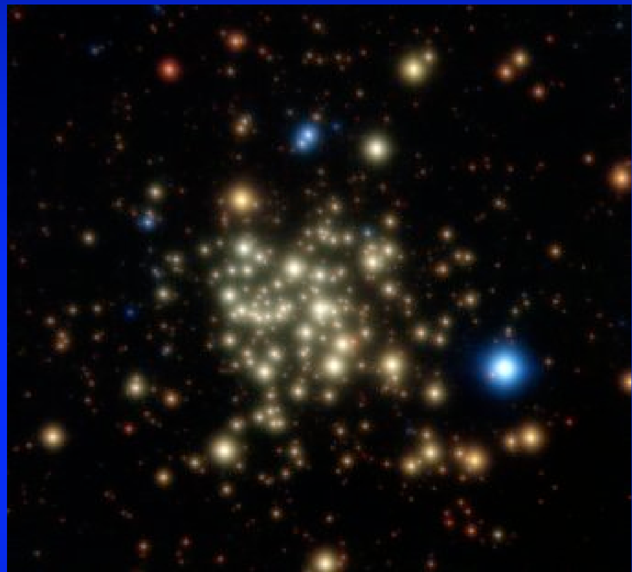
Eddington Limit (Γ_e=1)

Big game hunting: Where to look?

10^4 M_o

NGC 3603



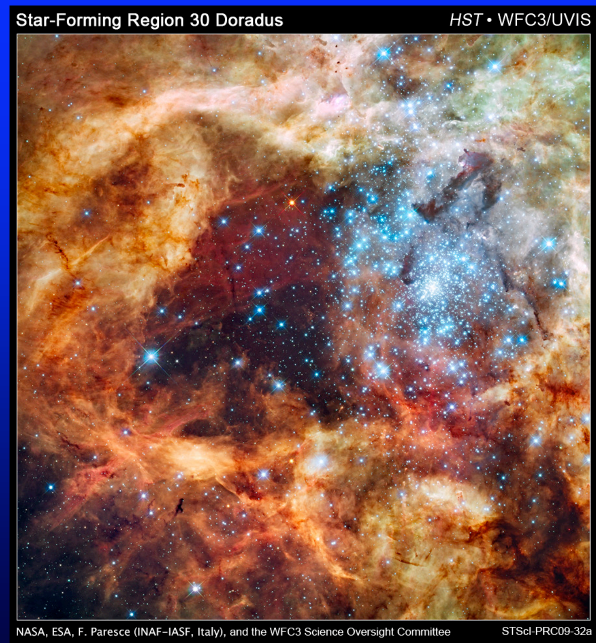


Arches (G.C)

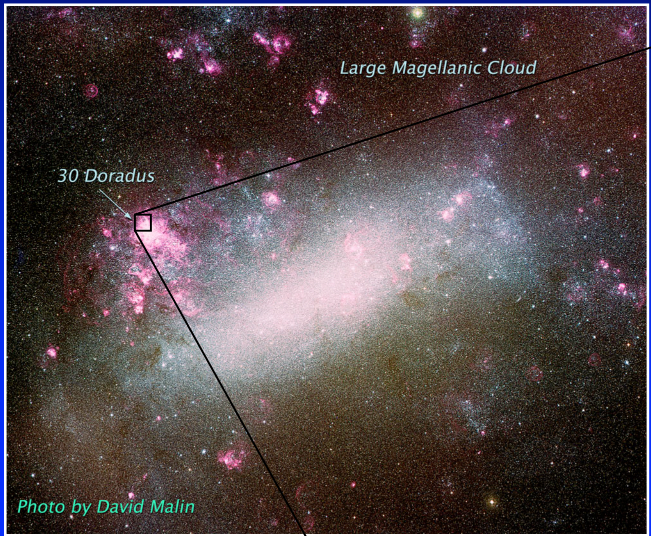
$2x10^4$ M_o

$5x10^4$ M_o

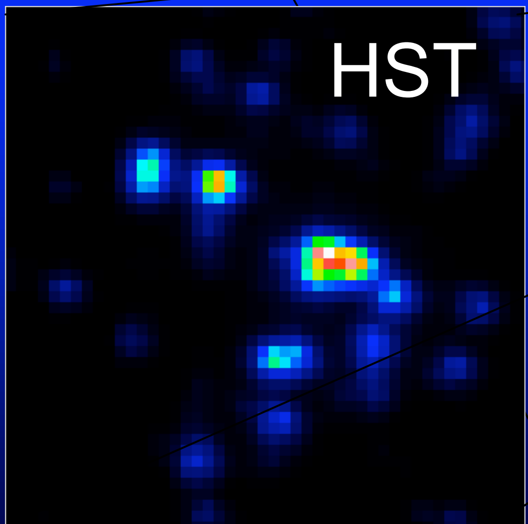
R136a (LMC)

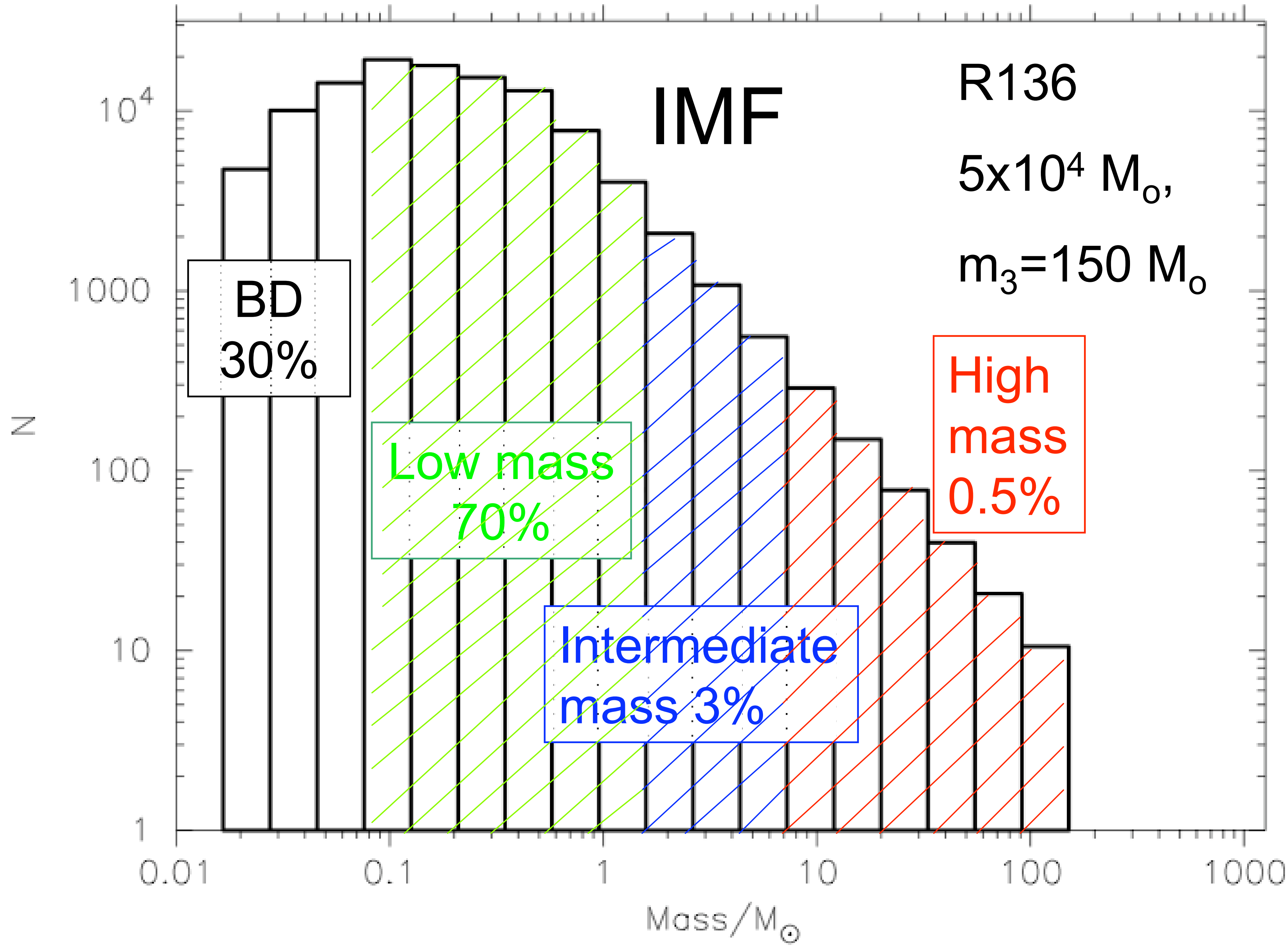


R136

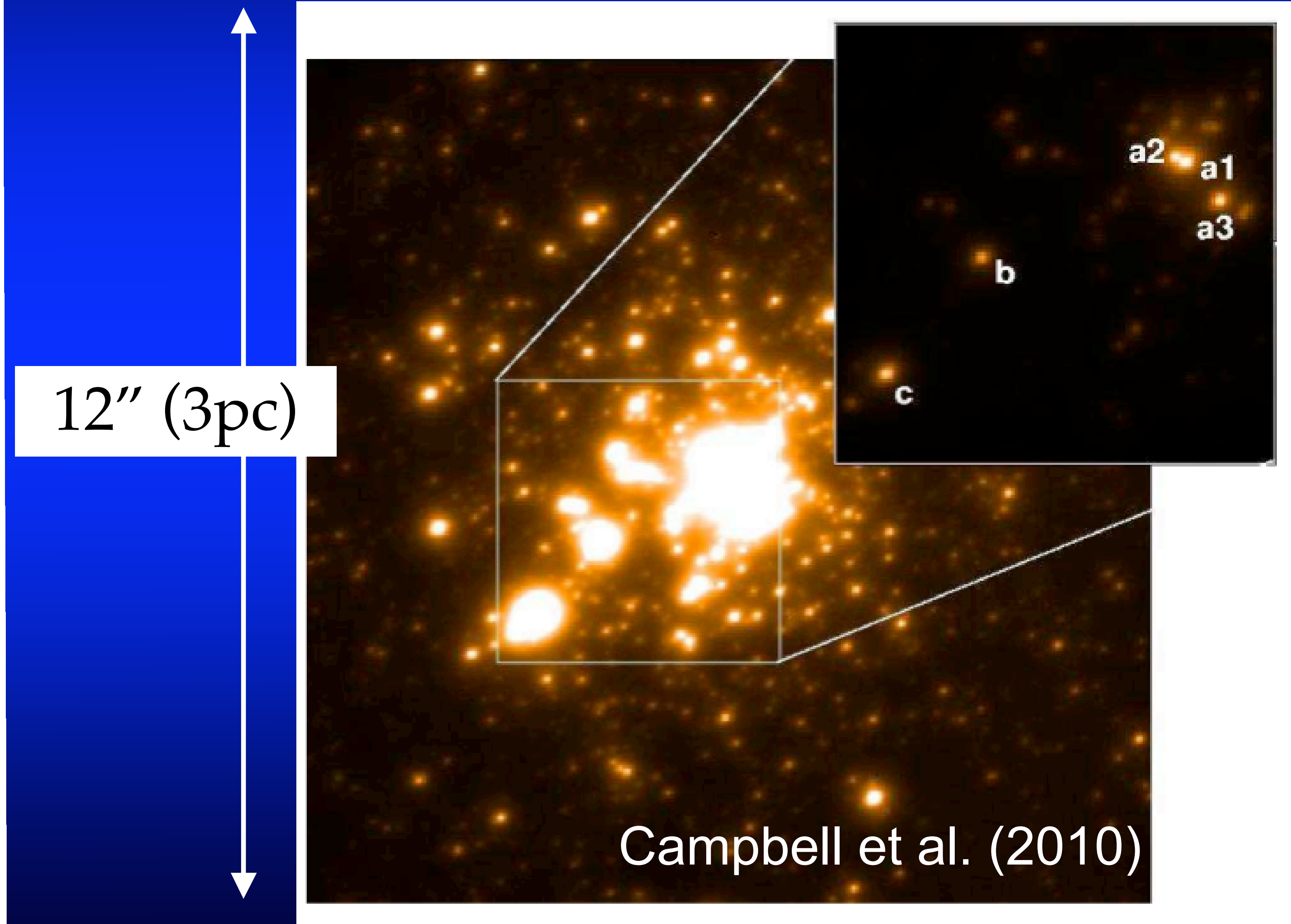

Large Magellanic Cloud
30 Doradus
Photo by David Malin


Star-Forming Region 30 Doradus
HST • WFC3/UVIS
NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee
STScI-PRC09-32a

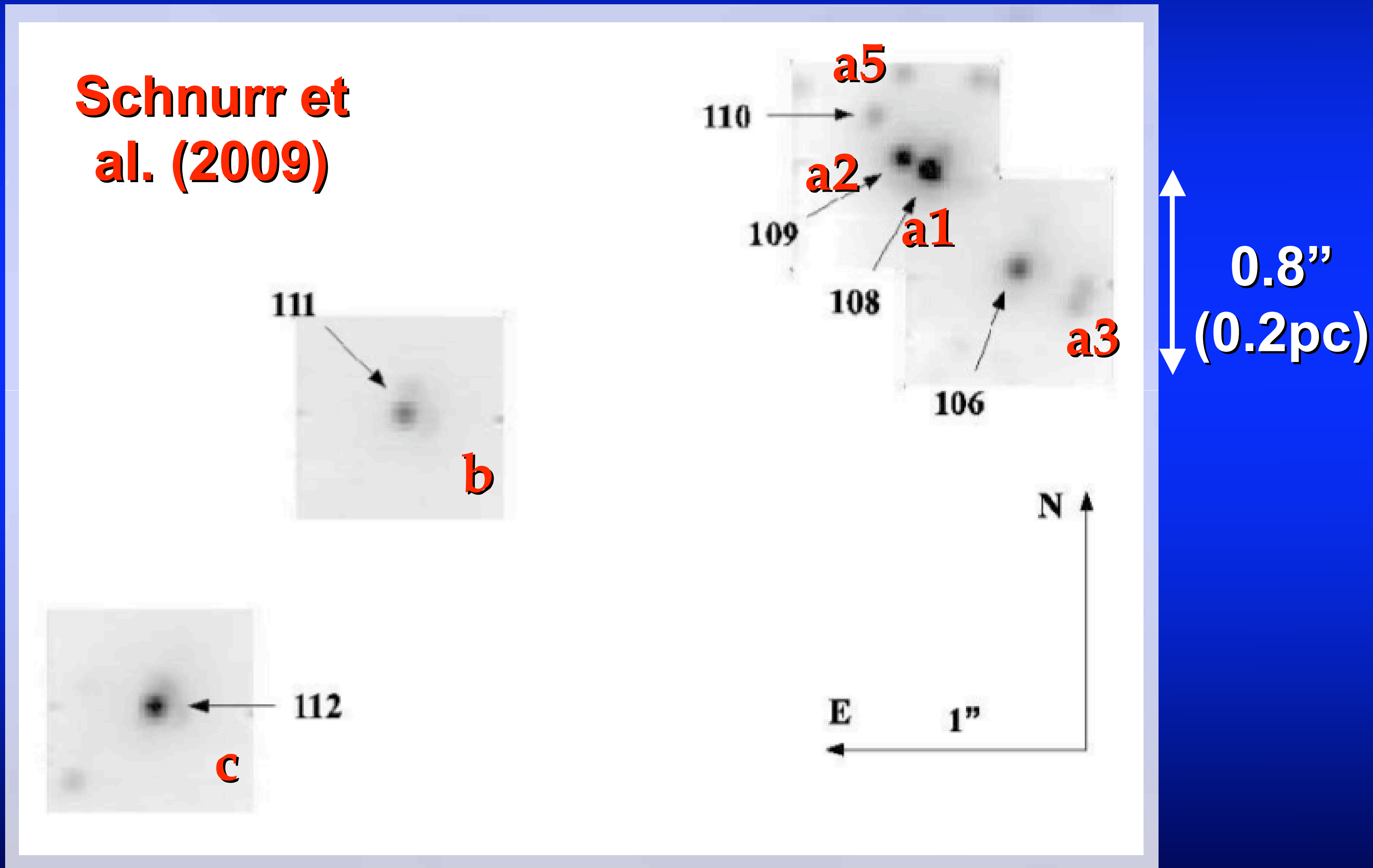

HST


IMF
R136
5x10^4 M_o,
m_3=150 M_o
BD
30%
Low mass
70%
Intermediate
mass 3%
High
mass
0.5%
N
10^4
1000
100
10
1
0.01
0.1
1
10
100
1000
Mass/M_⊙

R136: VLT/MAD imaging

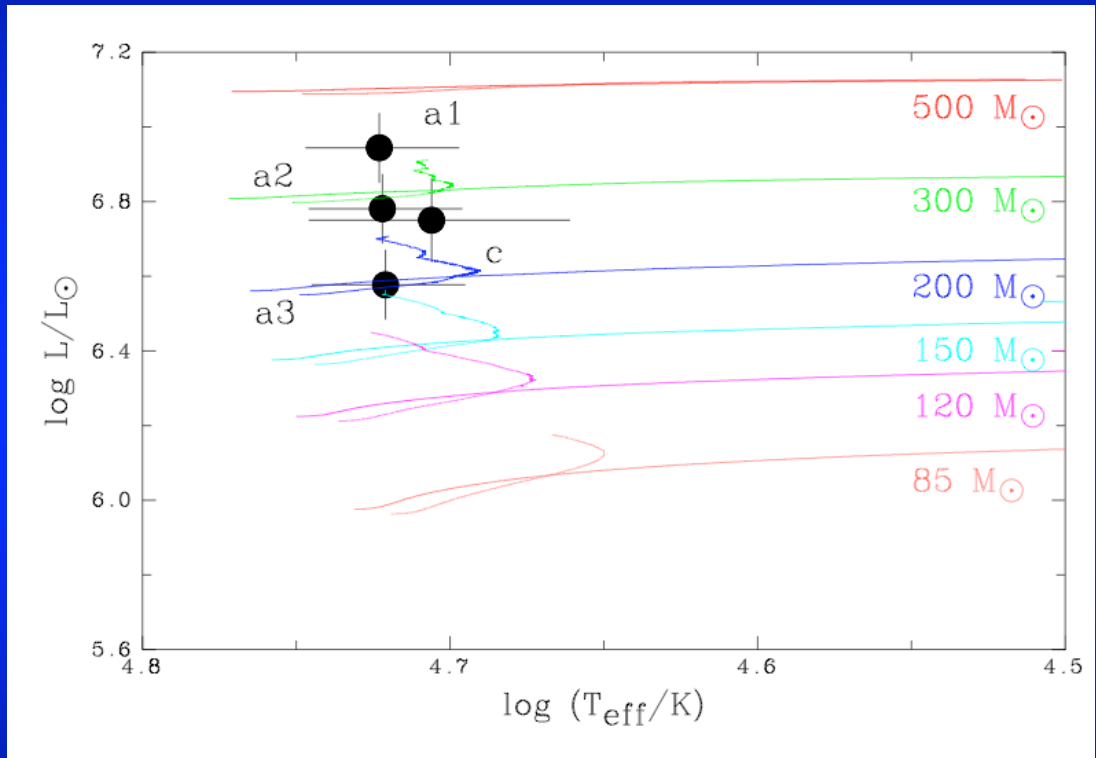


R136: VLT/SINFONI spectroscopy



R136a1: m_{Ks}=11.1 A_{Ks}=0.2 M_{Ks}=-7.6

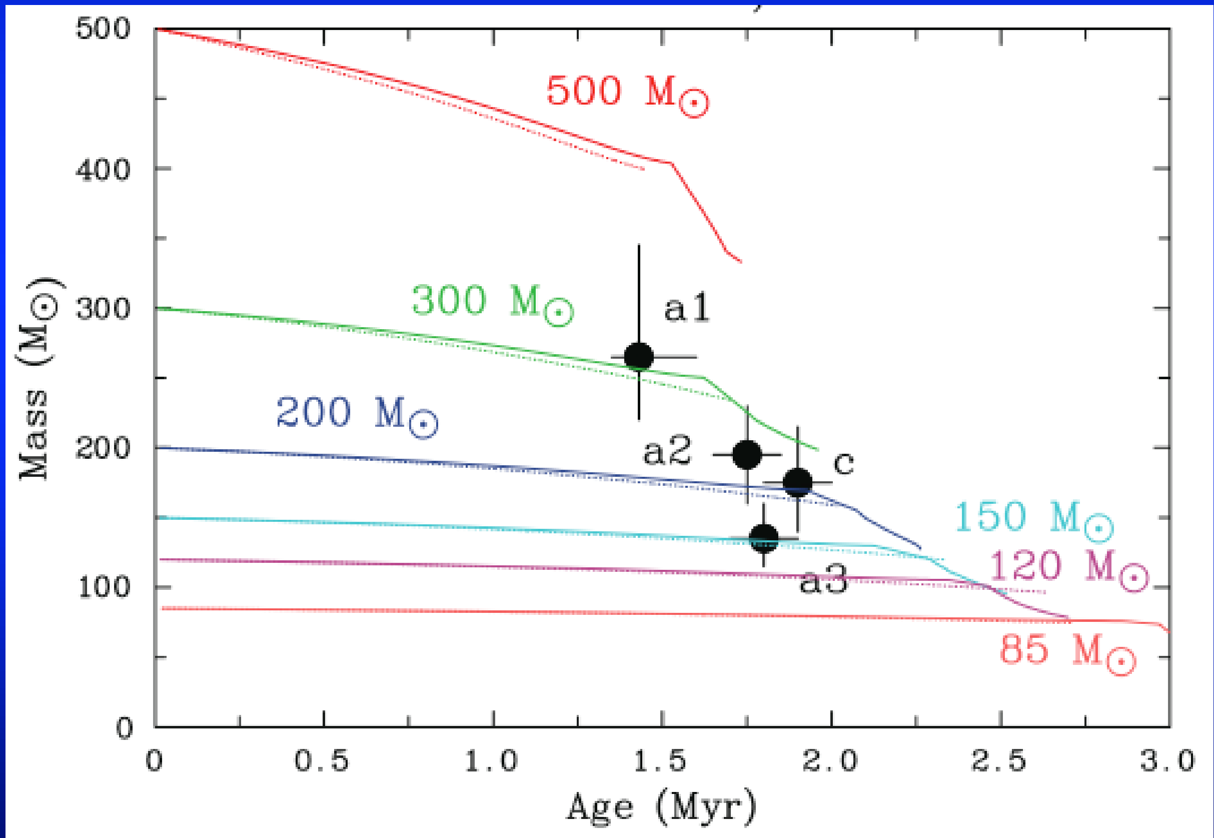
Masses of brightest R136 stars?



Comparison of T_{eff}, $\log L/L_o$ with evolutionary models (Yusof, Hirschi et al. 2012).

Initial masses of R136 stars?

$M_{current}$ = 135-265 M_o, ages ~ 1.5-2 Myr

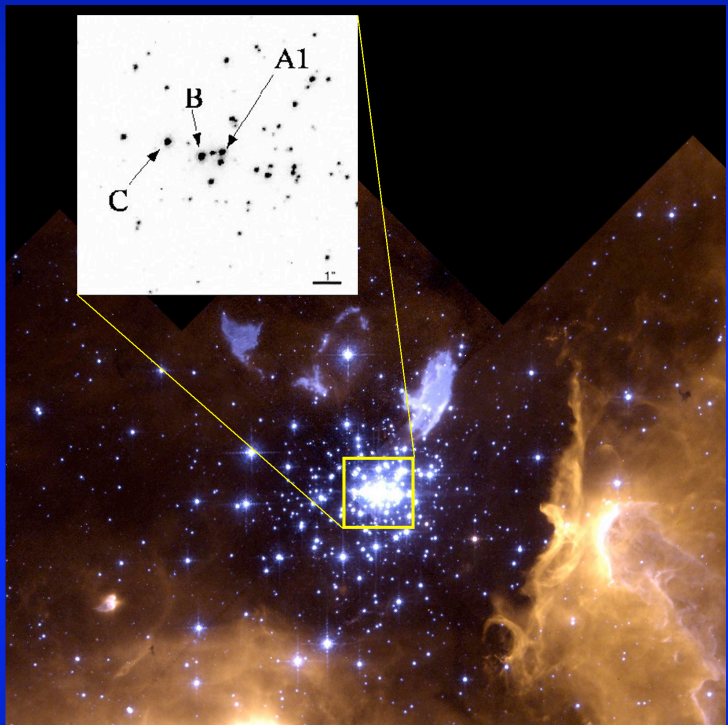


Evolutionary models adopt theoretical rates of mass loss (several x 10^{-5} M_{sun}/yr*)

M_{init}=165-320M_o

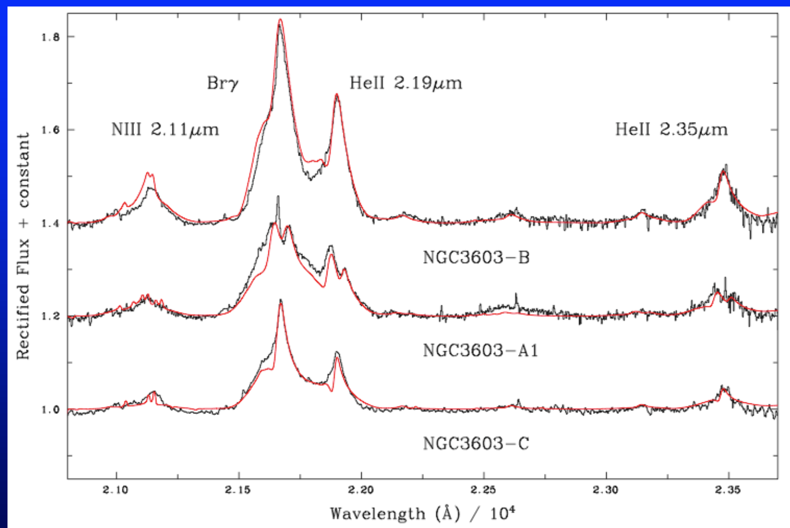
*Spectroscopic dM/dt ~ 5 x 10^{-5} M_{sun}/yr

Gold standard or sub-standard?



NGC 3603 hosts an eclipsing binary A1a+b for which dynamical masses have been derived M_{dyn}:116±31M_o + 89±16M_o (Schnurr et al. 2008)

Spectral analysis + evolutionary models $M_{current}$:120 M_o + 92 M_o



Surprising?

The Slope of the Upper End of the IMF and the Upper Mass Limit: An Observer's Perspective

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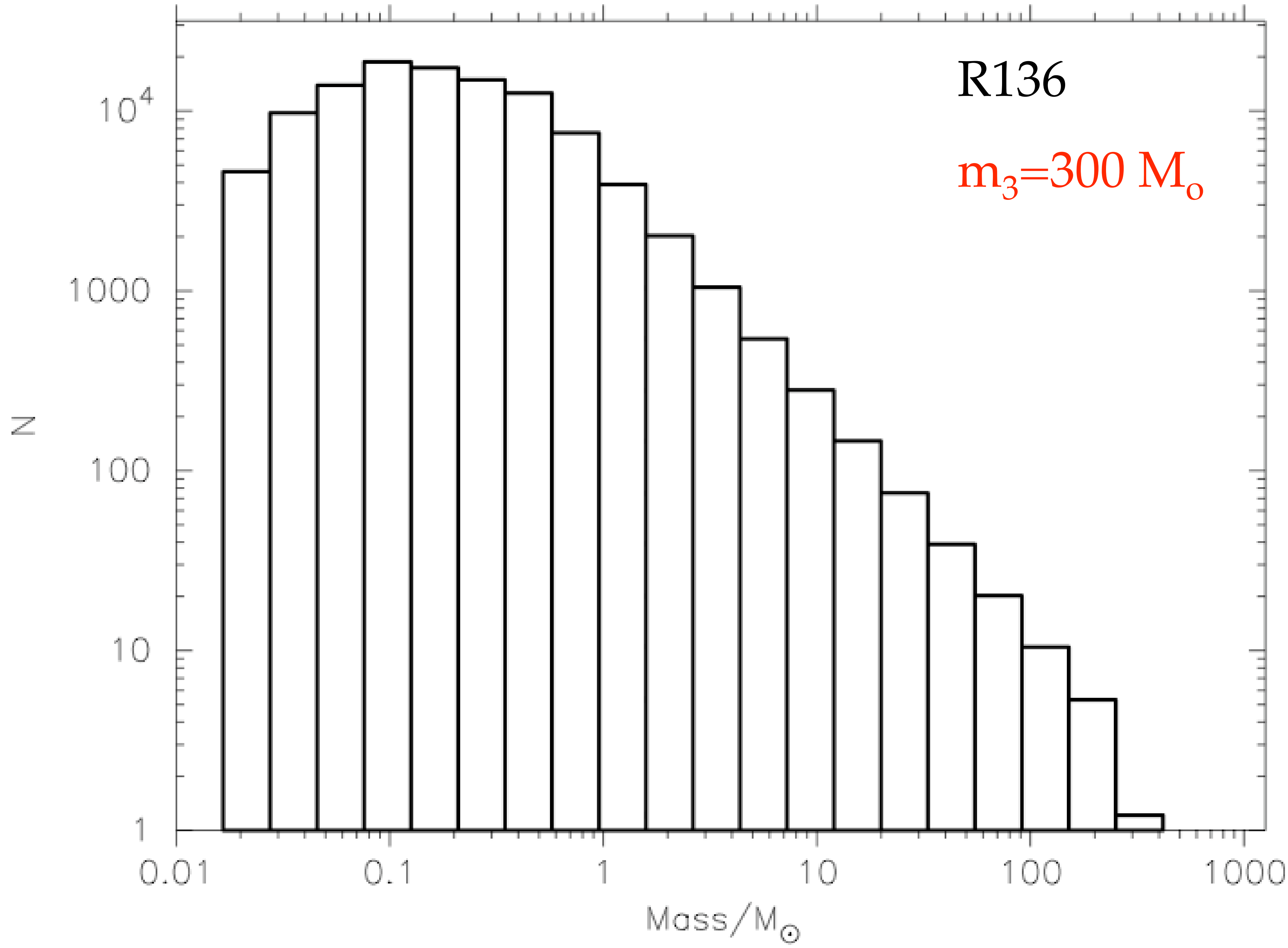
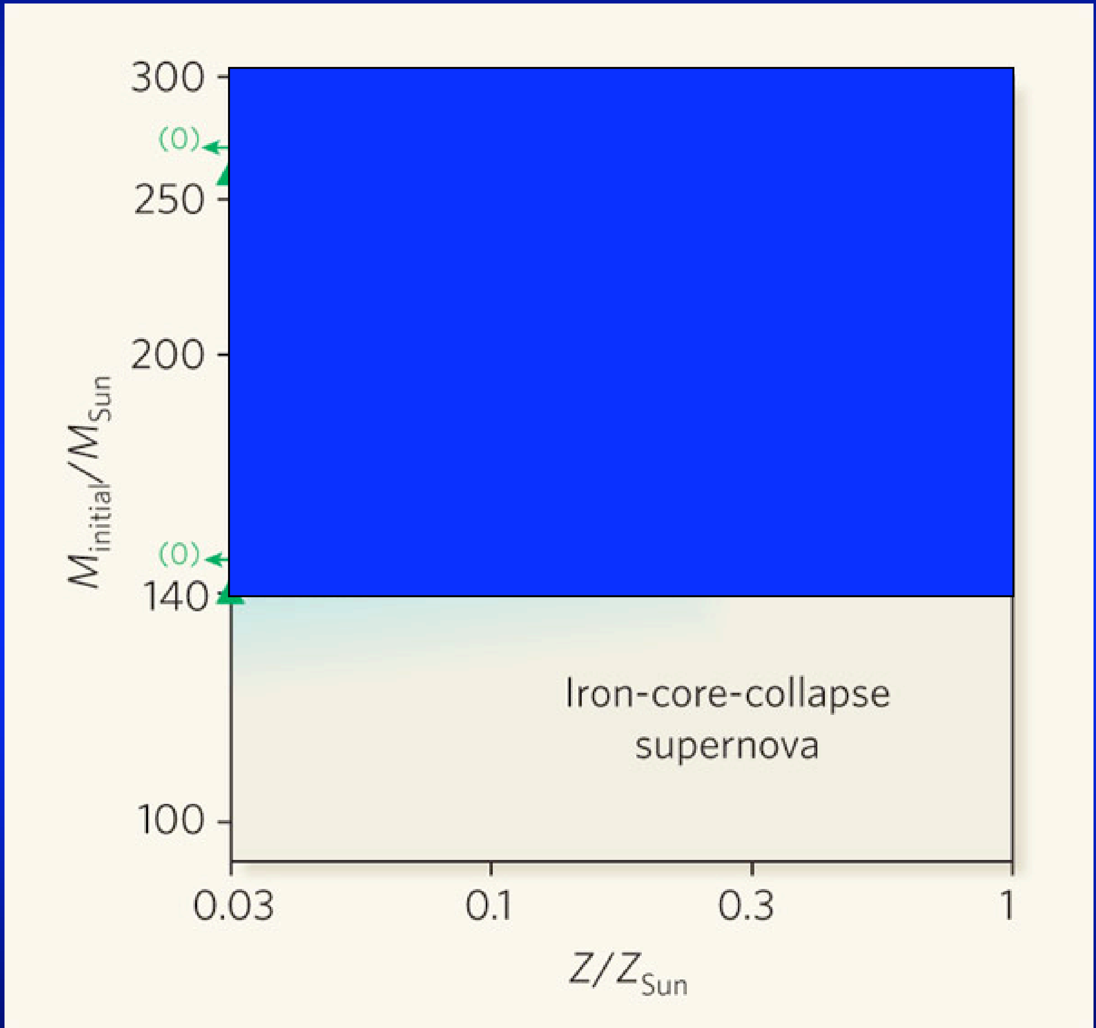
Abstract. There are various ways of measuring the slope of the upper end of the IMF. Arguably the most direct of these is to place stars on the H-R diagram and compare their positions with stellar evolutionary models. Even so, the masses one infers from this depend upon the exact methodology used. I briefly discuss some of the caveats and go through a brief error analysis. I conclude that the current data suggest that the IMF slopes are the same to within the errors. Similarly the determination of the upper mass "limit" is dependent upon how well one can determine the masses of the most massive stars within a cluster. The recent finding by Crowther et al. (2010) invalidates the claim that there is a $150 M_\odot$ upper limit to the IMF, but this is really not surprising given the weakness of the previous evidence.

Jun 2010 Sedona workshop


R136
m_3=300 M_o
N
10^4
1000
100
10
1
0.01
0.1
1
10
100
1000
Mass/$M_\odot$

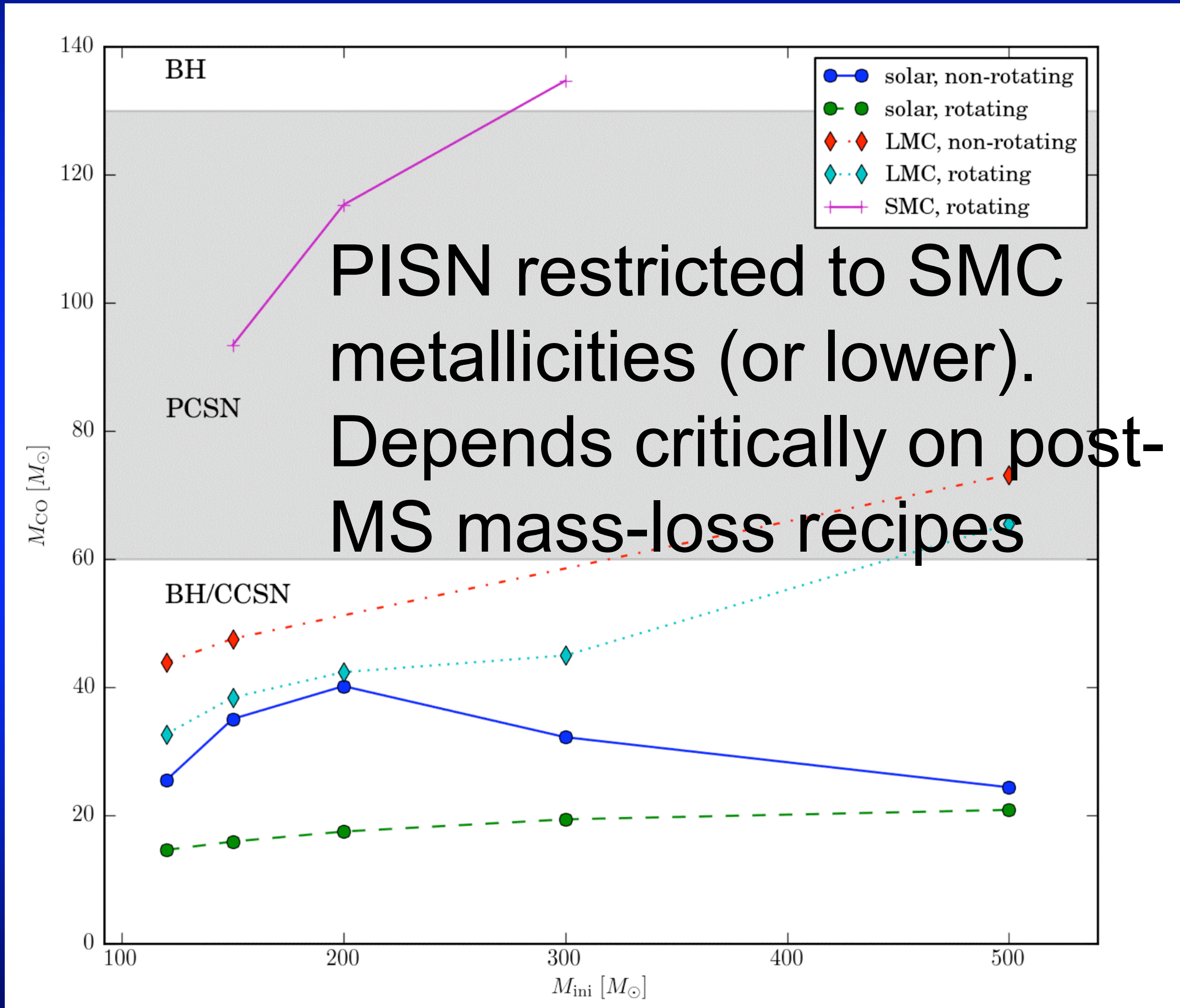
Local PISNe?



Langer (2009)

Upper limit m_{up}>150 M_o. required for the possibility of pair instability SNe (PISNe) in local universe.. (SN 2007bi?? Gal-Yam et al. 2009 & talk)

Death of Very Massive Stars



M_{CO}

$M_{initial}$

Details: Jorick Vink talk

Yusof, Hirschi et al. (in prep)

Very Massive Stars:

- Rare:
  - Limited to high mass (>10^4 M_o) young (<2 Myr) clusters. Only ~15 stars initially more massive than >150 M_o known in Milky Way & Mag Clouds.
- Location:
  - 'Isolated' clusters (e.g. Arches) or within a large star-forming complex (30 Doradus). Not all large s.f. complexes will host sufficiently massive clusters (e.g. NGC 604/M33).
- Fate: Very sensitive to mass-loss prescription:
  - for $Z > Z_{LMC}$: core-collapse SN?;
  - For $Z < Z_{SMC}$: pair-instability SN?