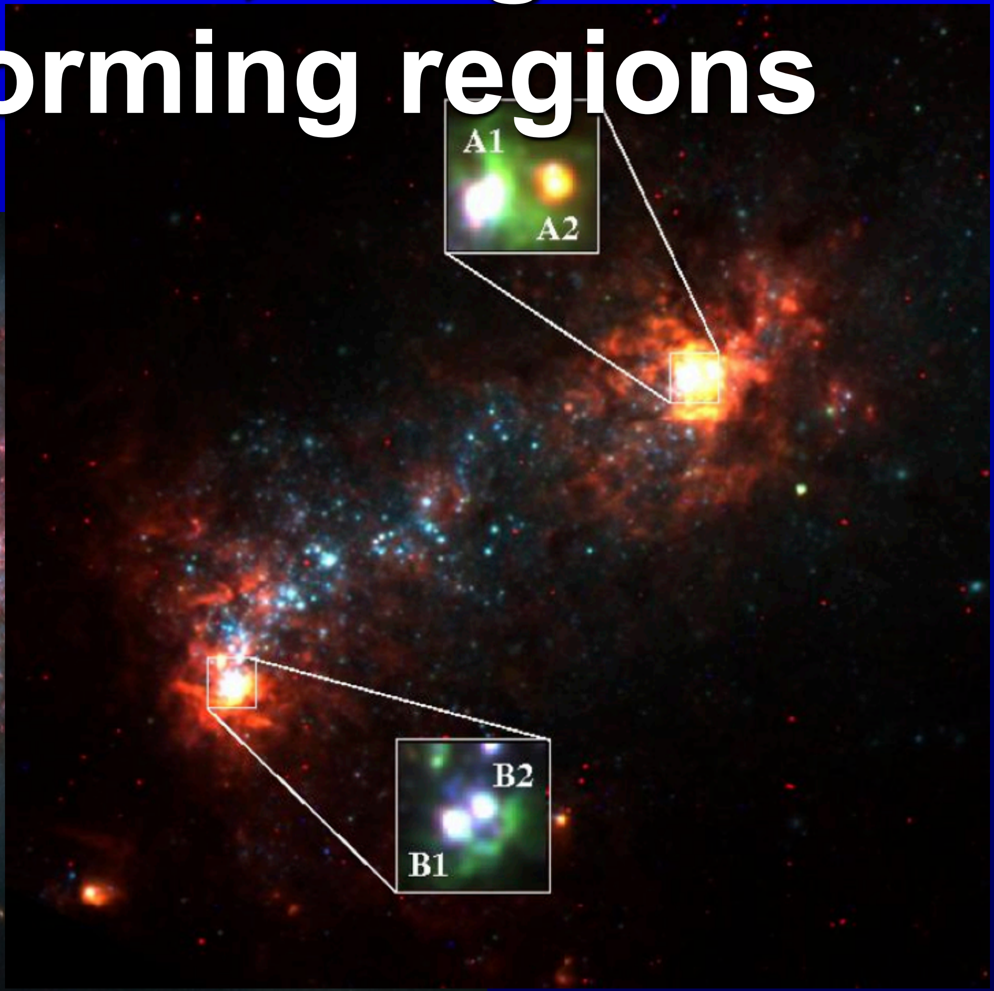
Massive stars, SNe, long-GRBs & their star-forming regions



Paul Crowther (Sheffield)

Massive star zoo

- Main sequence: early B dwarf (8-15 M_{sun}), O dwarf (>15-20 M_{sun}), H-rich WN (>100 M_{sun}?)
- Post main-sequence: OBA supergiants, red supergiants, yellow supergiants/hypergiants, Wolf-Rayet stars, Luminous Blue Variables
- Responsible for all ccSNe, (short+long) GRBs, X-ray binaries etc. & s.f. diagnostics (far-UV continuum, H-alpha, far-IR dust)

- Star clusters, IMF & massive star production in galaxies
- Massive stars & HII regions
- Association of ccSNe (& GRBs) with star forming regions of galaxies?
- Massive close binaries
- Magnetars

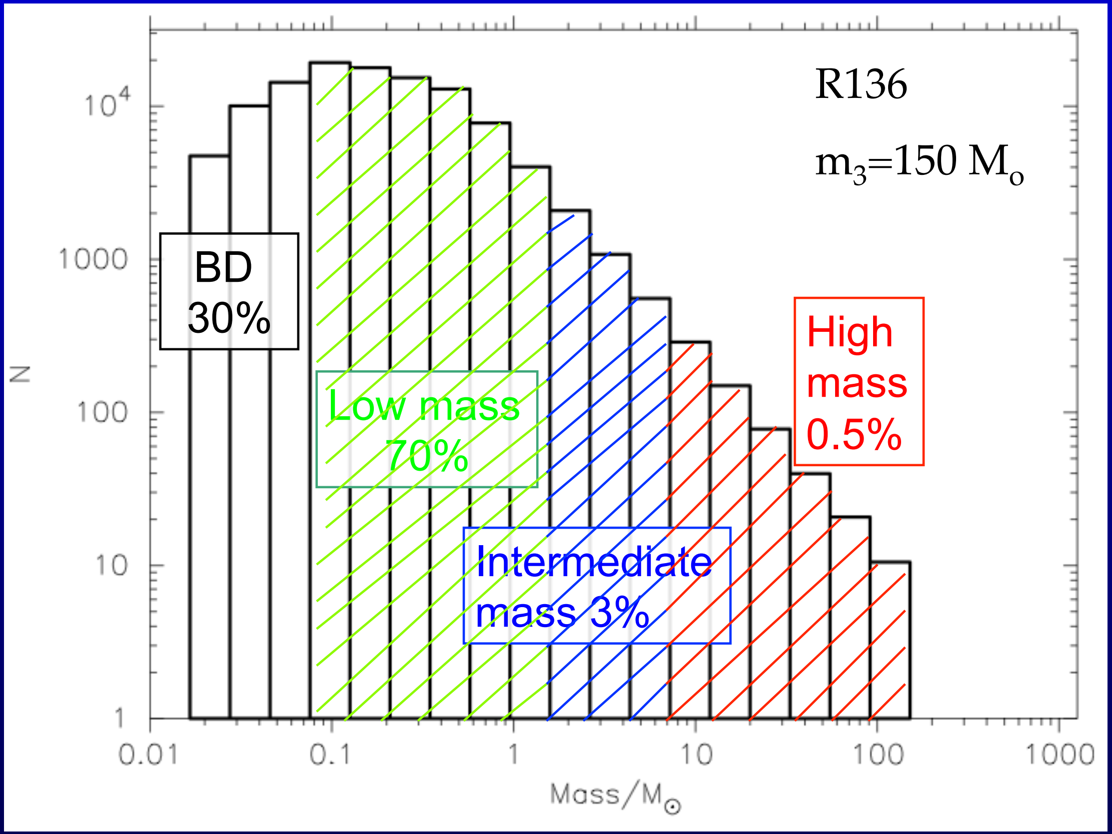
Star Formation in Clusters?

Most stars in local (Milky Way) s.f. regions form within a clustered environment (40-90%). Only a low fraction form within relatively dense environments (>200 YSOs/pc^2 Bressert+ 2010).

Cluster mass function follows power law $N(M) = CM^{-2}$ so the same total mass of stars form in clusters between 10 -100 M_{sun} as in 10^3 - 10^4 M_{sun} clusters

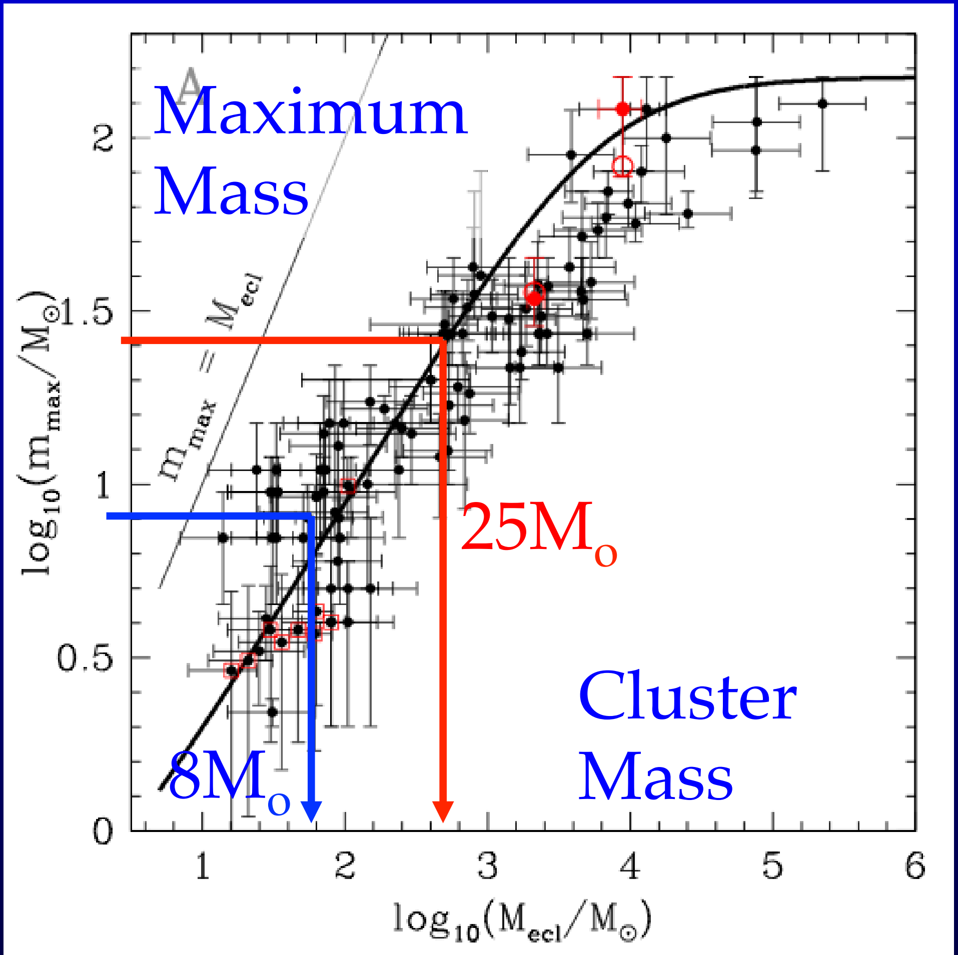
The cluster upper mass limit is truncated in galaxies with low s.f. intensities (Gieles 2009; Cook+ 2012)

Initial Mass Function?



IMF for massive stars follows Salpeter slope, so they are rare by number (<1%), although more significant by mass in young clusters (tens of %)

Maximum stellar mass?



Maximum stellar mass in scales with cluster mass

$M_{max} \sim 1.2\ M_{cl}^{.45}$

(Larson 2003) i.e.

8 M_{sun} above M_{cl} ~70 M_{sun}

25 M_{sun} above M_{cl} 500 M_{sun}

Weidner et al. (2010)

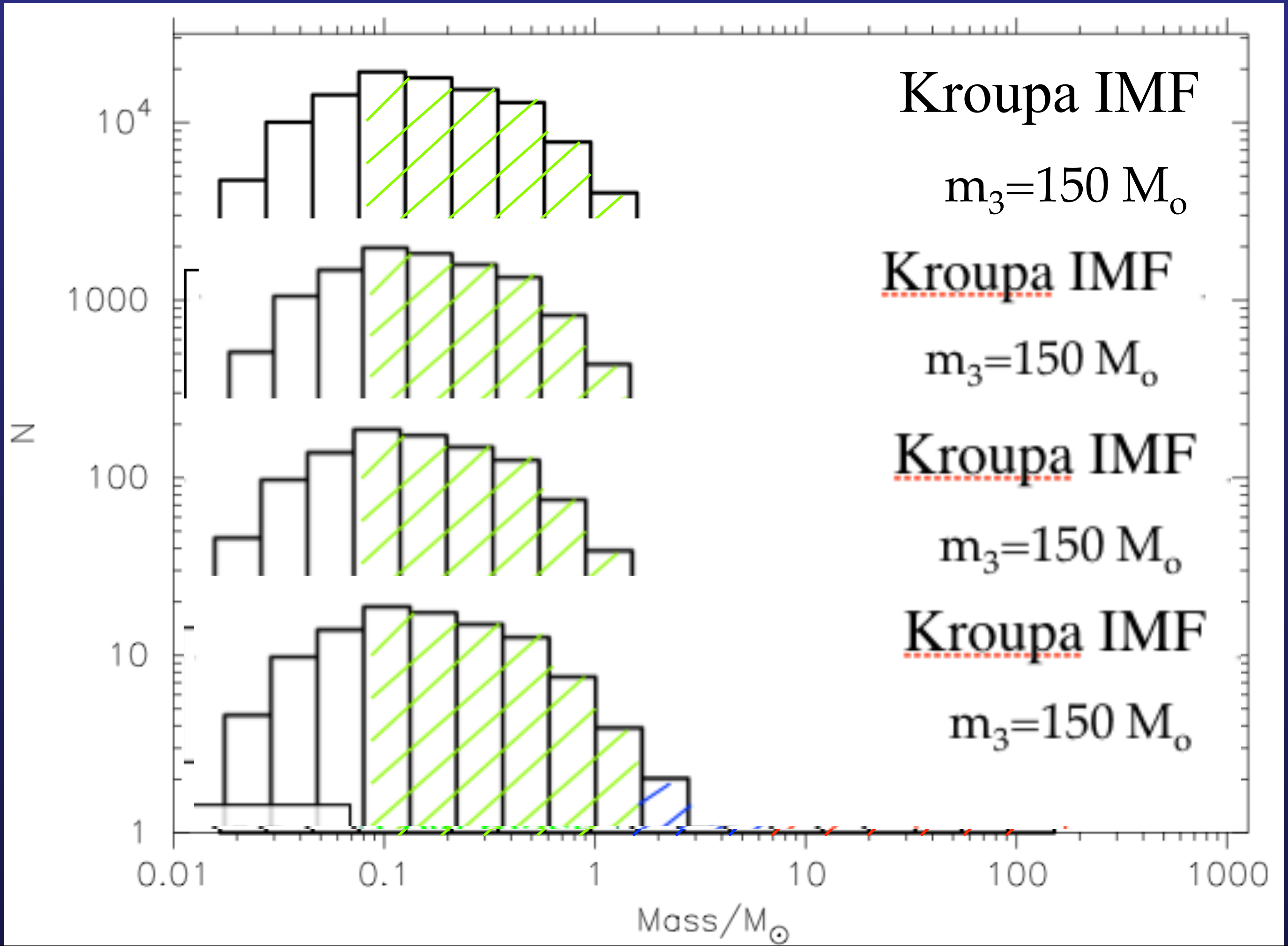
Massive Stars & the IMF

$M_{cluster}$
5×10^4 M_{sun}

$M_{cluster}$
5×10^3 M_{sun}

$M_{cluster}$
5×10^2 M_{sun}

$M_{cluster}$
5×10^1 M_{sun}



Star forming regions

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

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

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

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Massive stars & HII regions

Kennicutt (1998):
Stars with $M>10\ M_{sun}$ & $\tau<20$ Myr contribute significantly to the integrated ionizing flux (so emission lines provide a nearly instantaneous measure of the SFR)

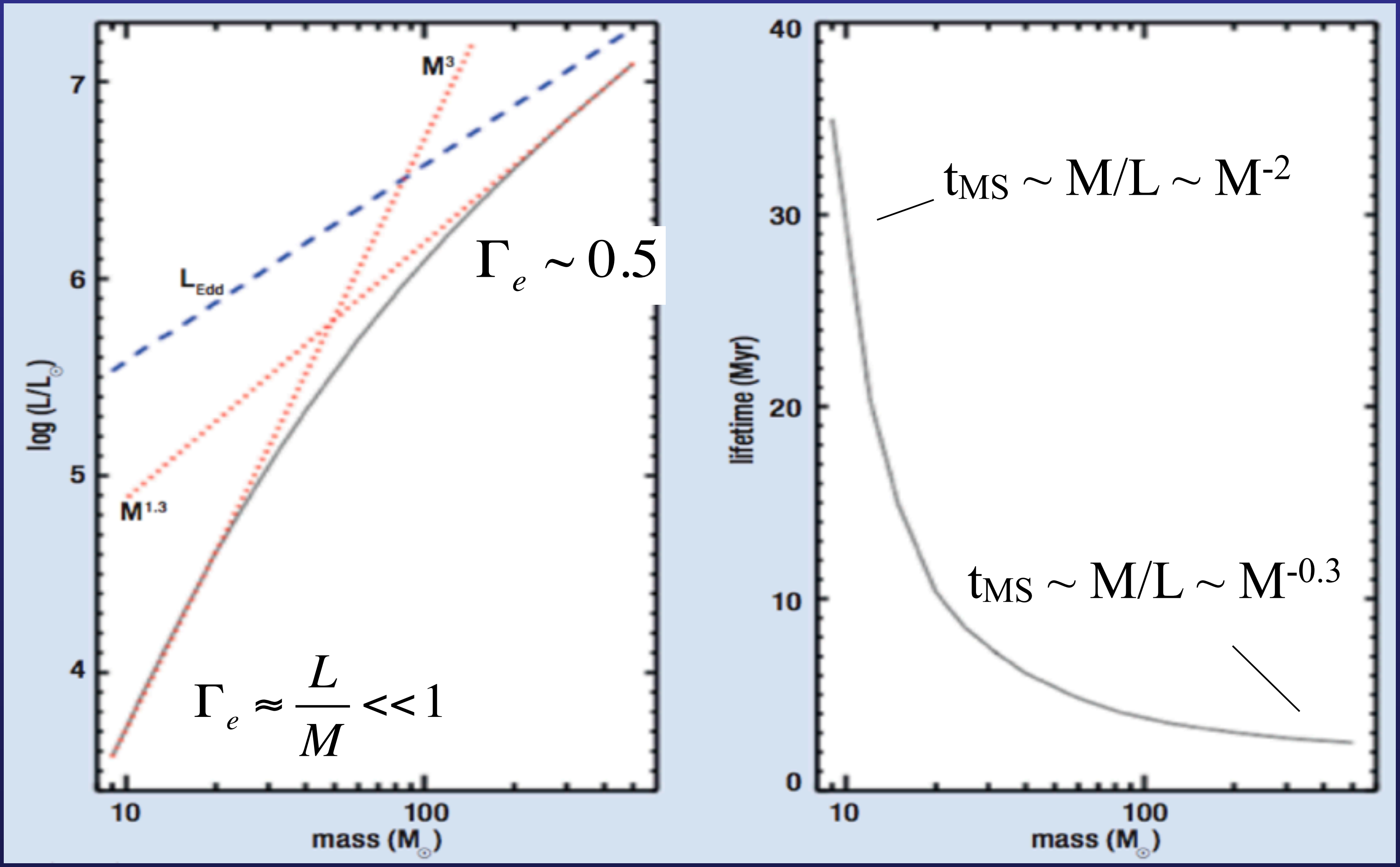
M74
B/V/Hα
(VLT)

Not all stars are born equal

Spectral Type	Mass M_o	τ_{MS} Myr	$L(H\alpha)$ 10^{37} $ergs^{-1}$
O3V	75	4	7
O7V	36	6	1
B0V	19	10	0.03
B2V	9	35	0.0003

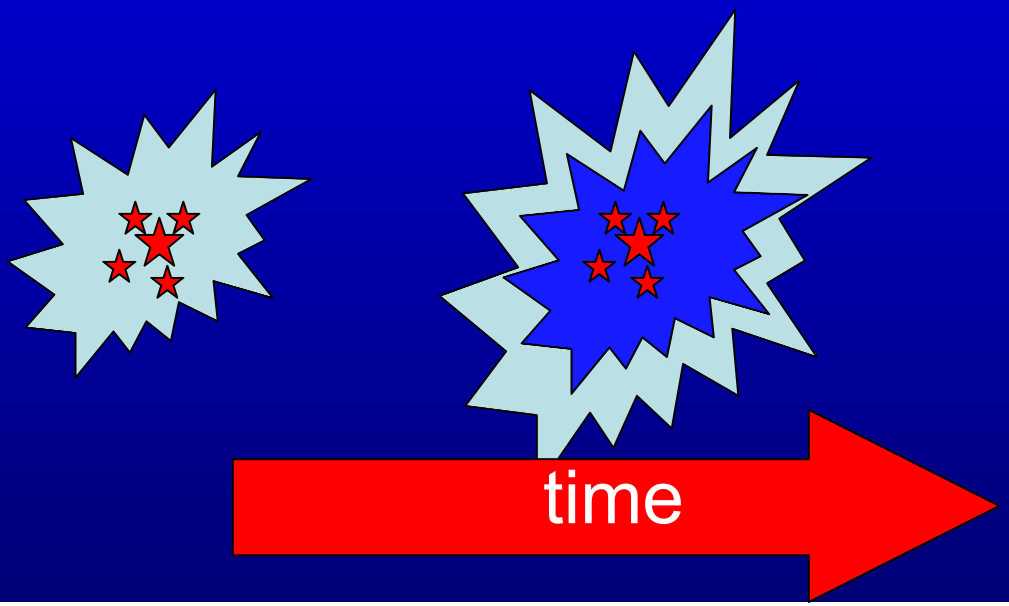
HII regions detectable in external galaxies are powered by hot, luminous O-type stars (<10Myr, >20 M_{sun}), not their more numerous B-type cousins

Lifetimes of massive stars?



Crowther (Astronomy & Geophys, IAU-GA Beijing 2012)

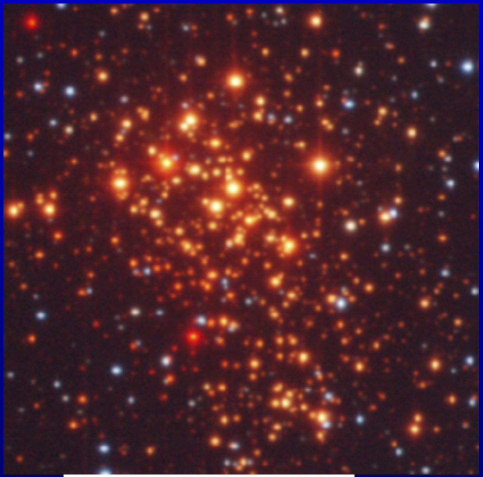
Gas rapidly lost from isolated, compact clusters



Gas is removed from isolated HII regions on a much shorter timescale than the lifetime of O-type stars (<10Myr) via radiative/mechanical feedback.

Walborn (2009)

HII timescale < O star lifetime



<1Myr → ~1.5Myr → ~3Myr → ~5Myr

HII region (<1Myr)

HII region (~1.5Myr)

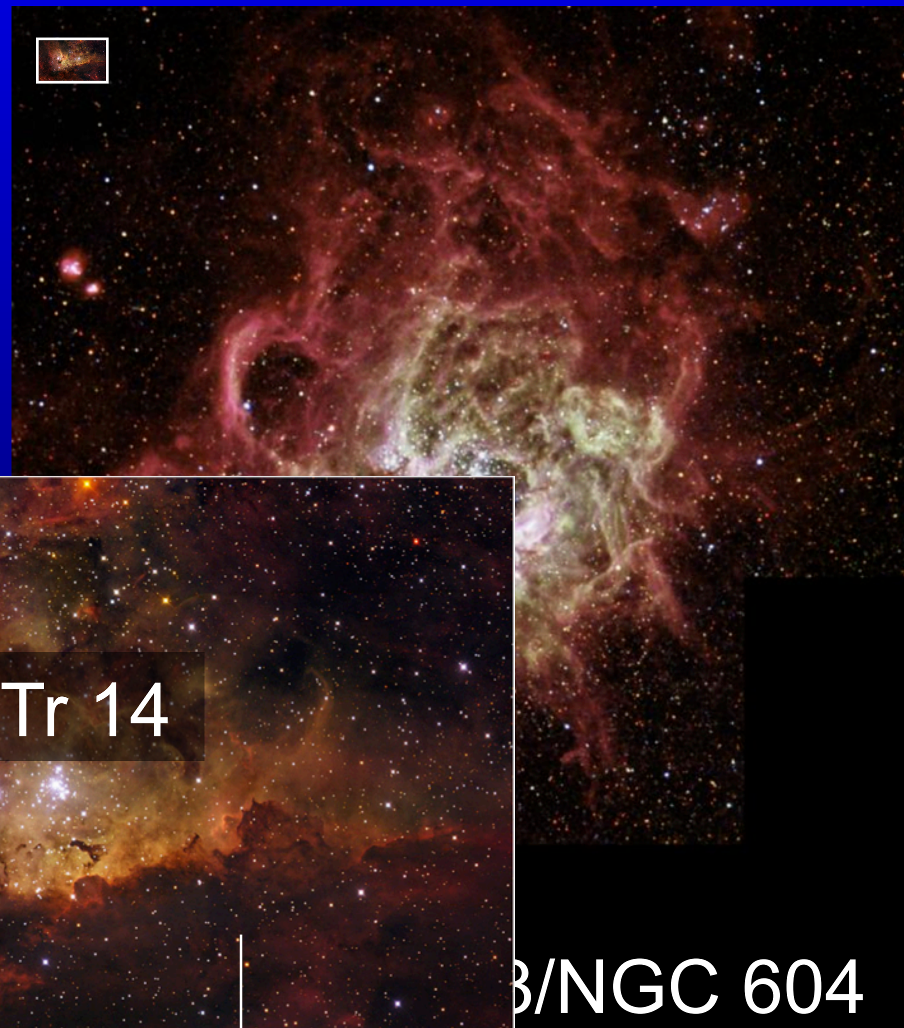
Not all HII regions are born equal either..

Region	HII region type	Diameter pc	L(Hα) 10^{37} erg/s
ONC	Classical	5	1
Rosette	Classical	50:	9
Carina	Giant	300:	150
NGC 604	Giant	400	450

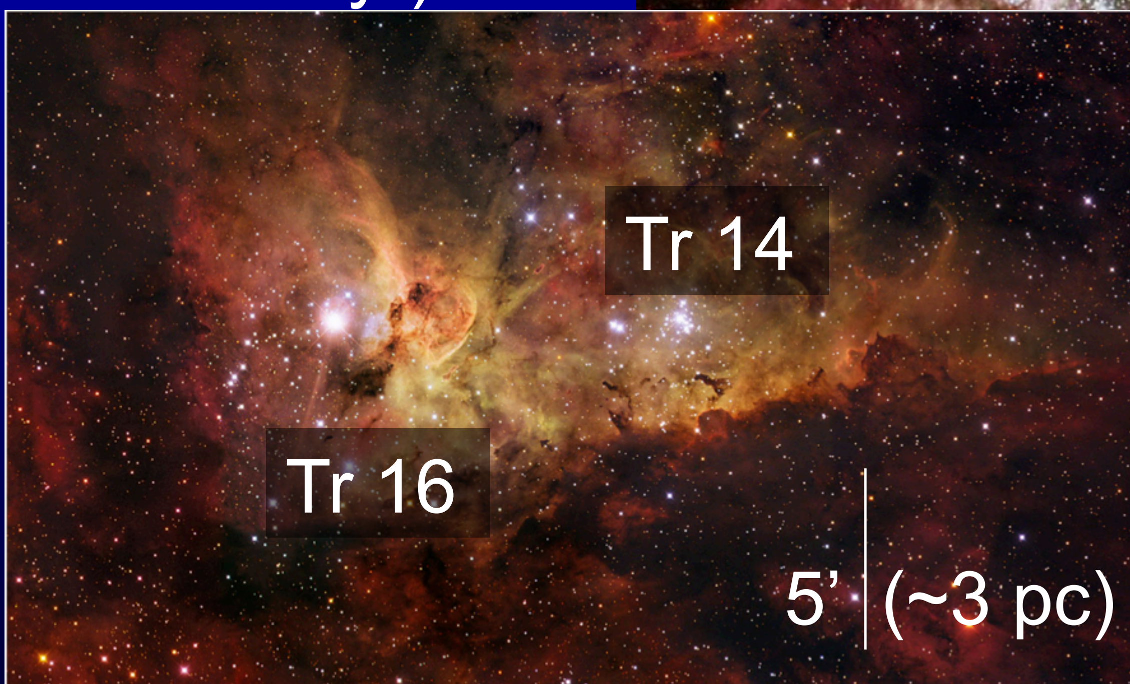
Classical HII regions typically powered by compact (single-aged) star clusters; (Super)giant HII regions are powered by multiple generations (~20±10 Myr).

Giant HII regions

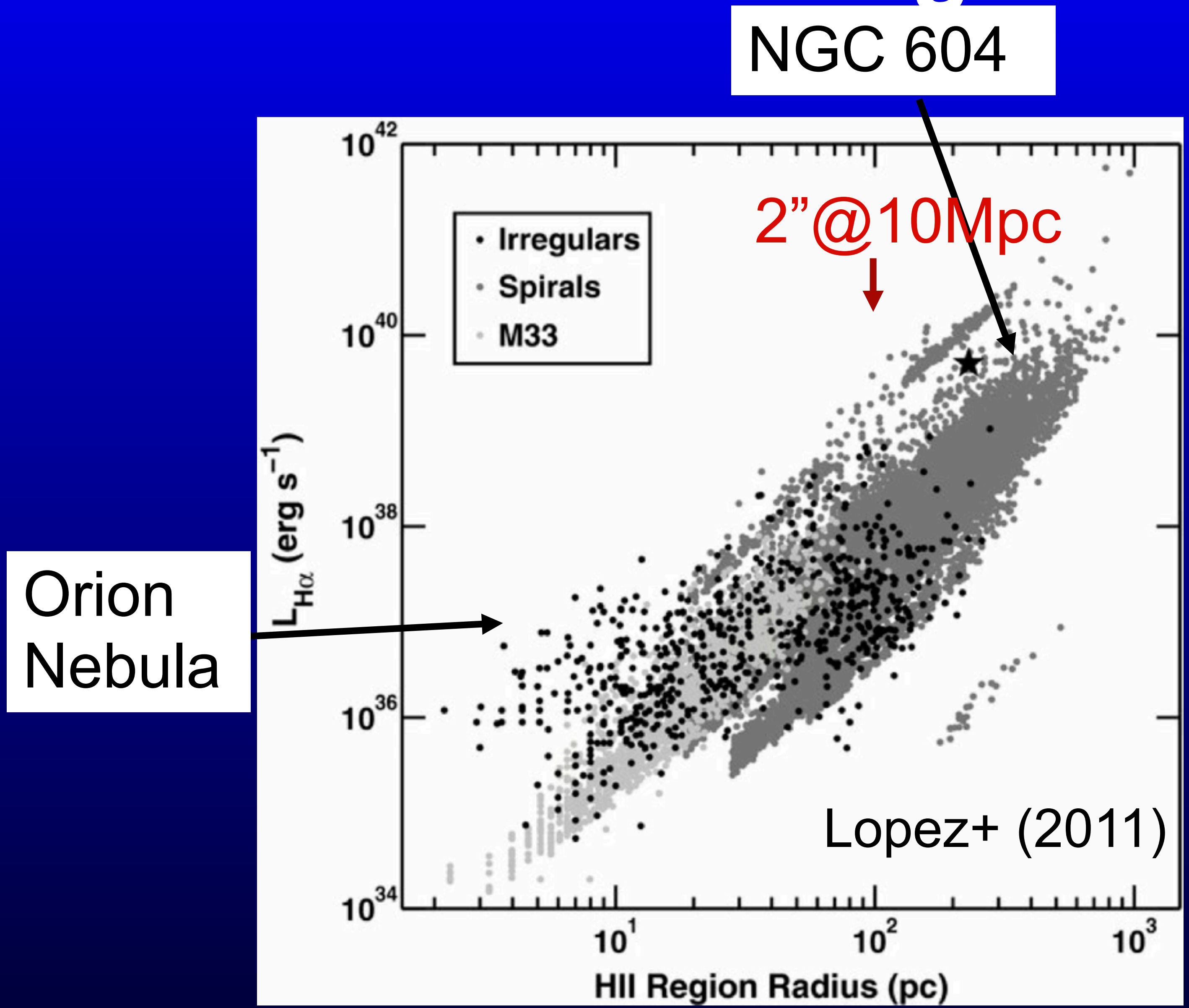
Large star forming regions host multiple, stellar pops (separated by ~few Myr).



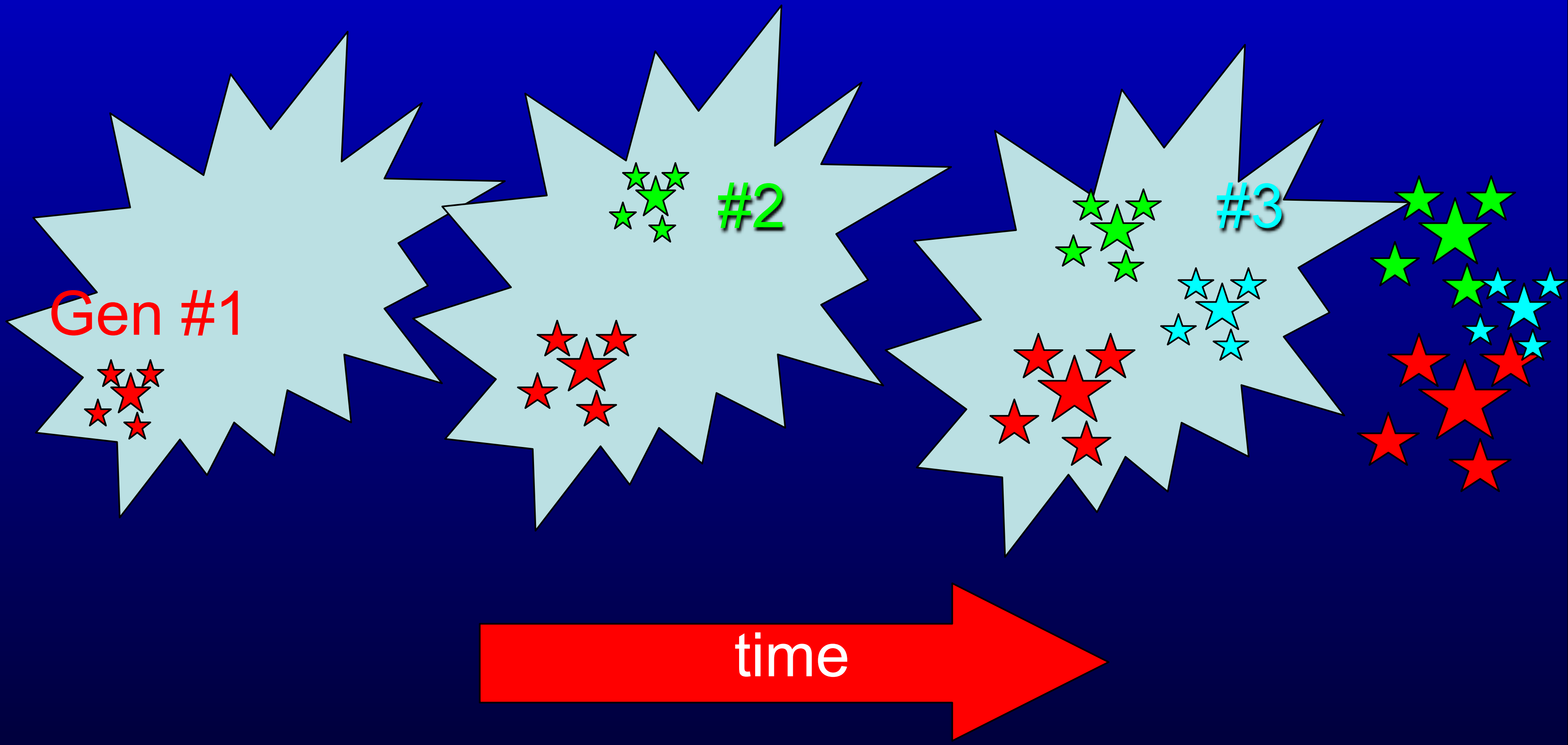
450 pc

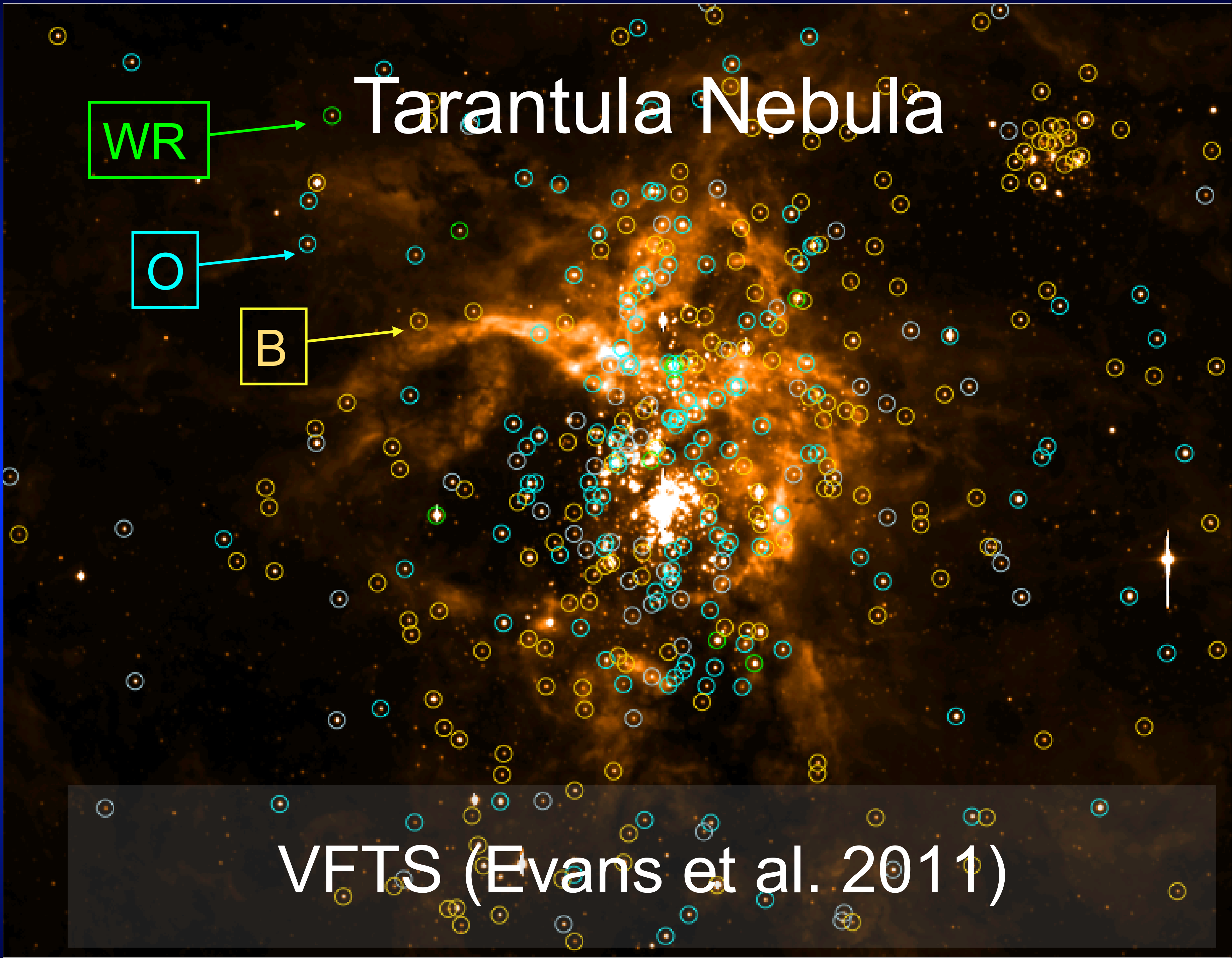


Size of HII regions



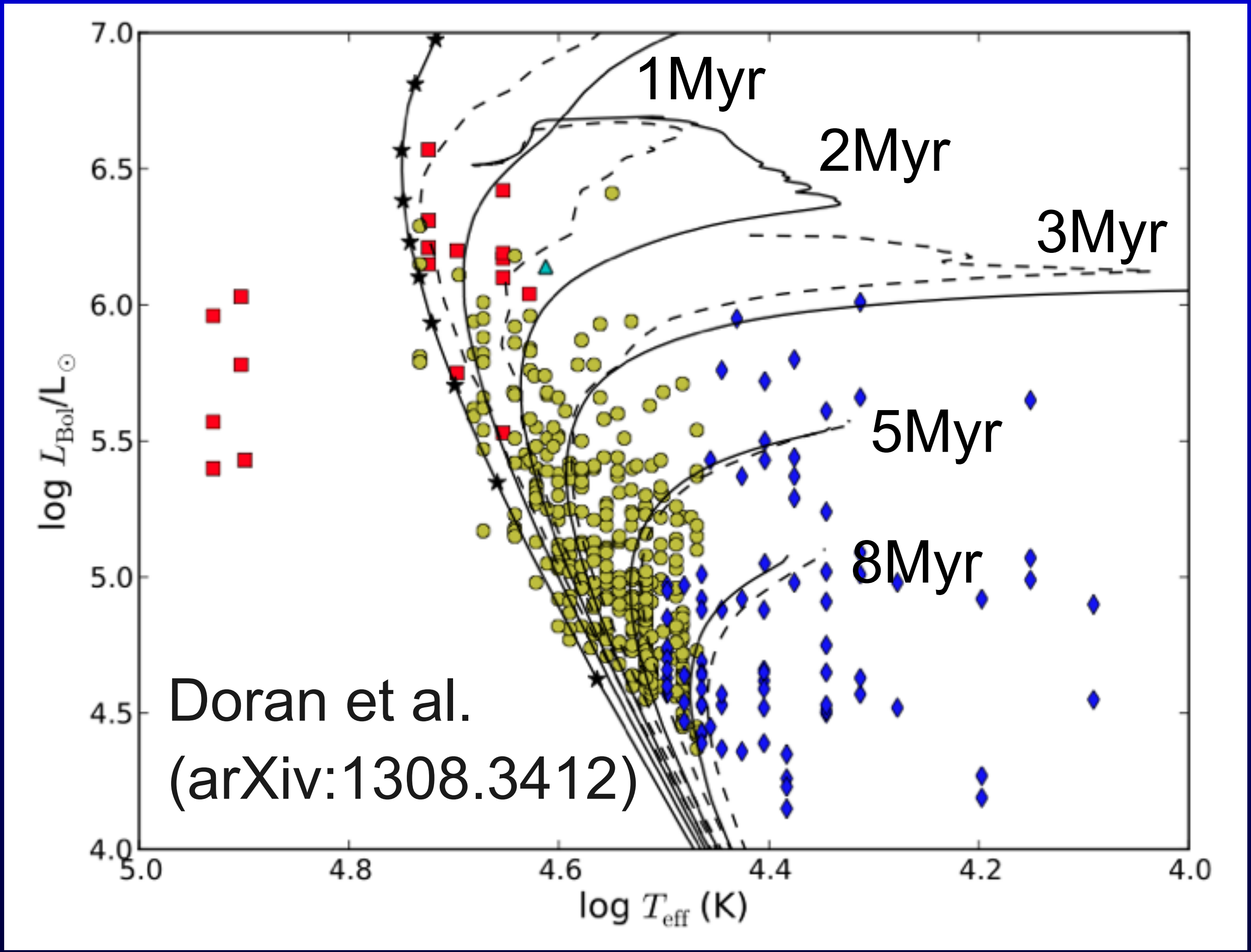
Multiple stellar pops in Giant HII regions (⇒messy)





Tarantula Nebula
WR
O
B
VFTS (Evans et al. 2011)

Tarantula Nebula Census

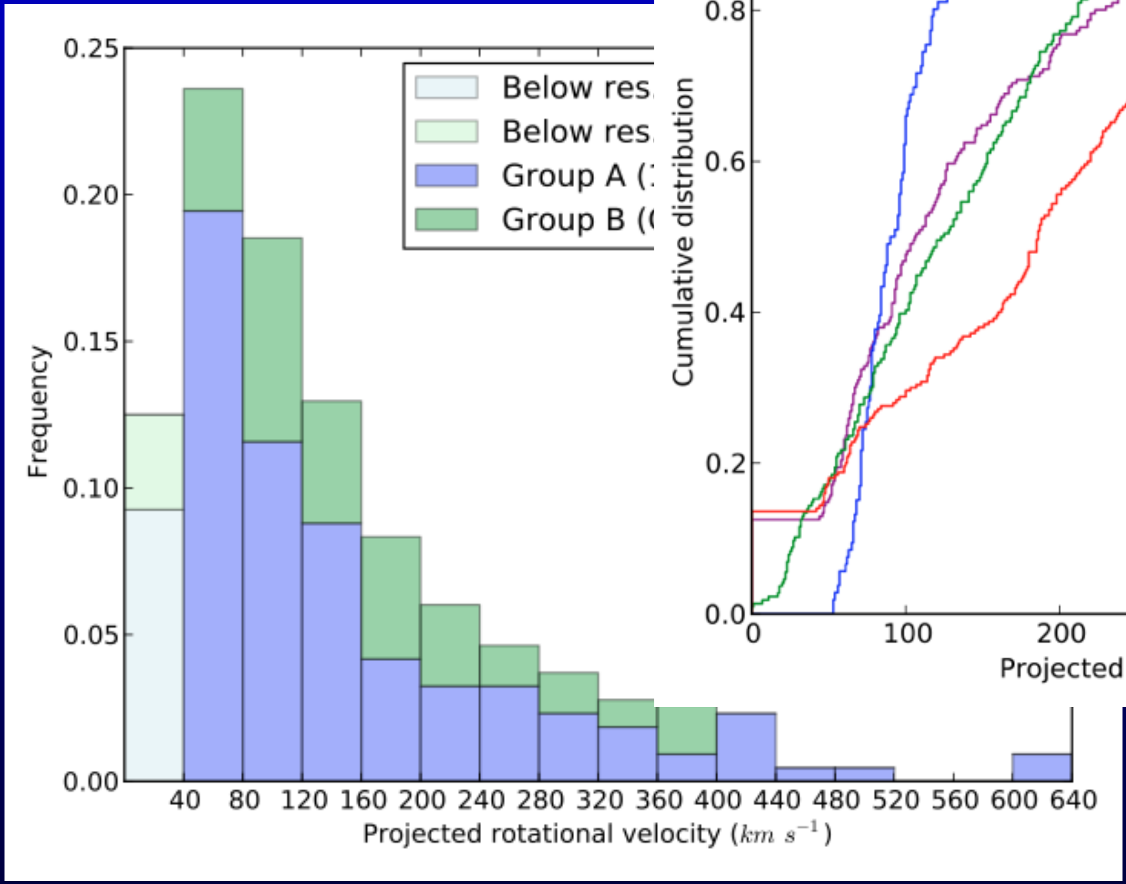


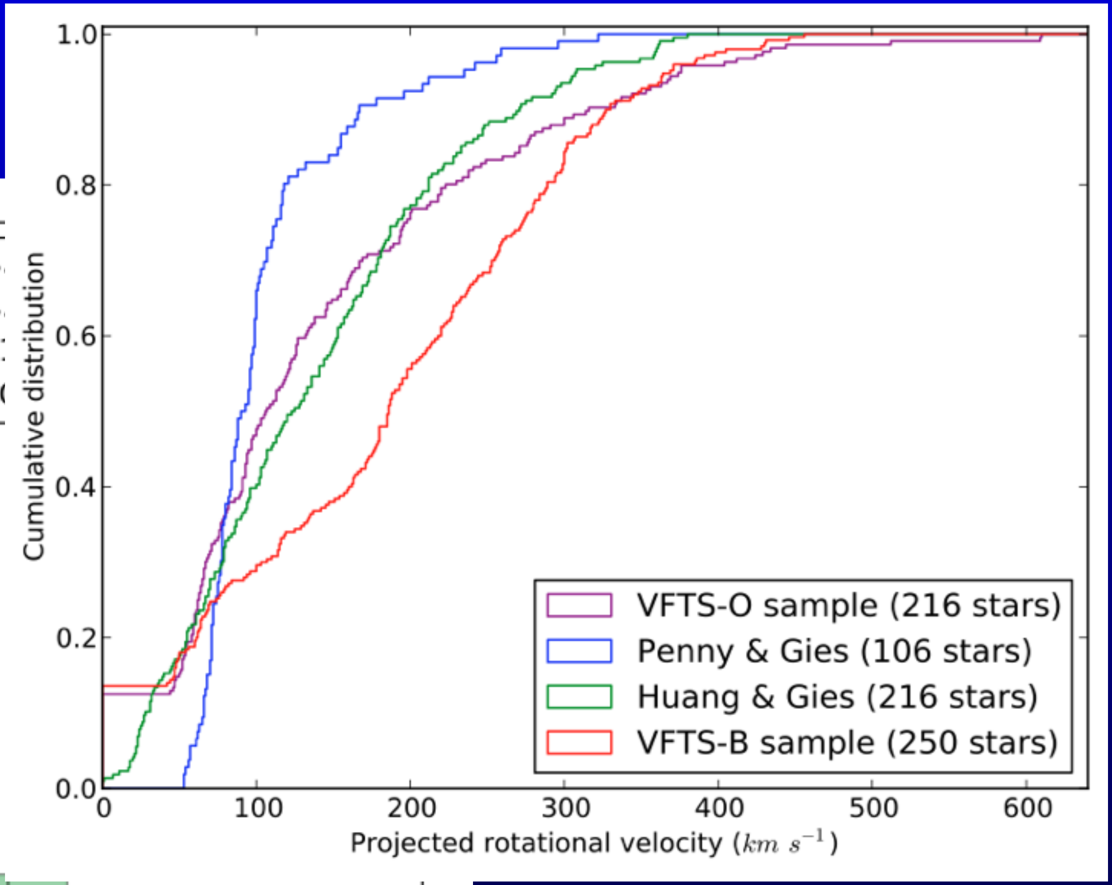
- Wide spread in OB/WR star ages in Tarantula Nebula.
- Analysis of integrated nebula implies ~3.5 Myr (Doran+ 2013)

Star formation diagnostics?

Doran+ 2013	SFR/Msun/yr (Salpeter)	SFR/Msun/yr (Kroupa)
Far UV continuum	0.10	0.07
Halpha (gas) A corrected	0.07	0.05
Halpha + Mid IR (dust). No A	0.05	0.035
Census	0.10	0.07

Aside for GRB pundits: Rotational velocities of O stars





Ramirez+ 2013

Environment?

M(30 Dor)~2.10^5 M$_{sun}$ **M(NGC346)~10^5 M$_{sun}$**

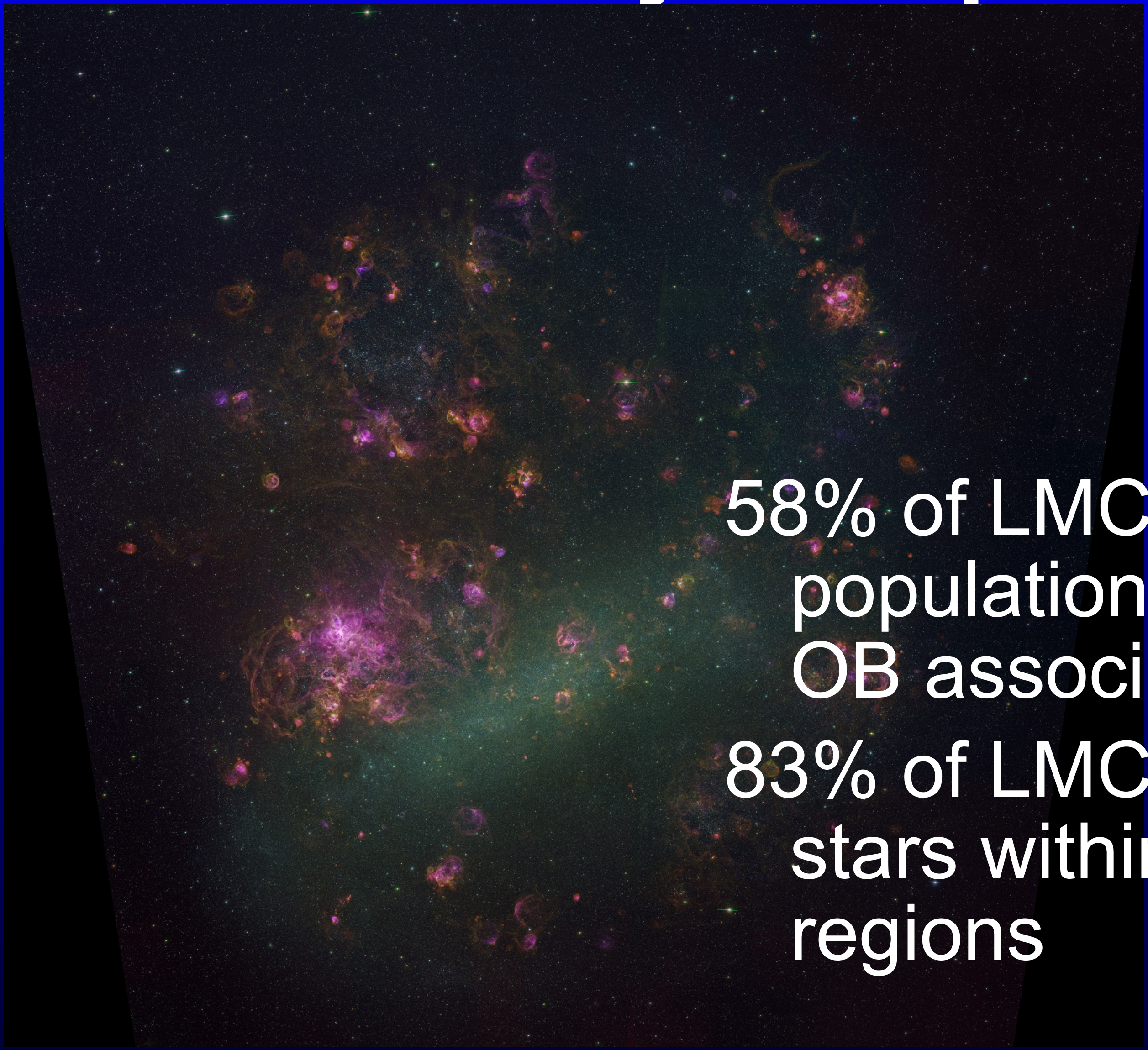
M$_{up}$~300 M$_{sun}$

(Crowther+ 2010)

M$_{up}$~70 M$_{sun}$

(Mokiem+ 2006)

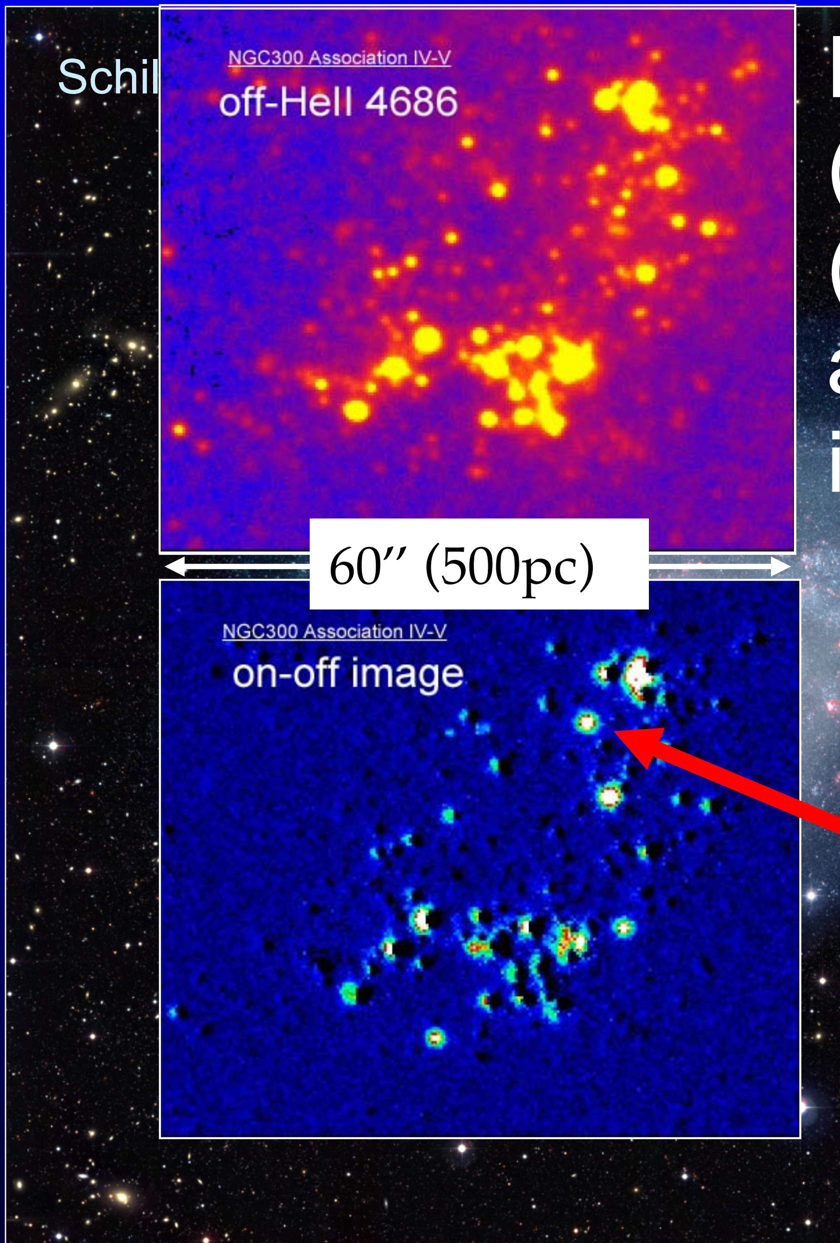
Wolf-Rayet Populations

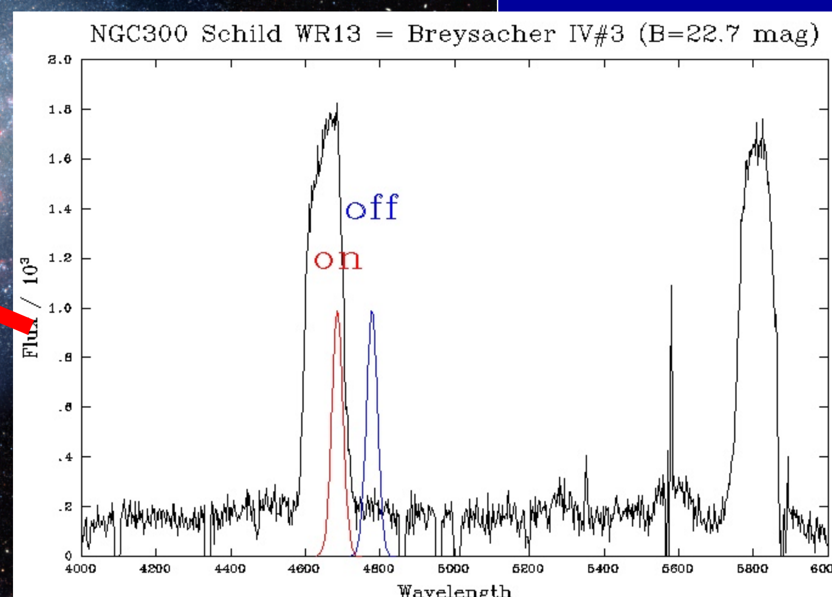


- 58% of LMC Wolf-Rayet population lie within OB associations
- 83% of LMC Wolf-Rayet stars within HII regions

How to find WR stars?

Narrow-band HeII (λ4684) & off-HeII (λ4751) imaging surveys allow WR stars to be identified in galaxies.





- Star clusters, IMF & massive star production in galaxies
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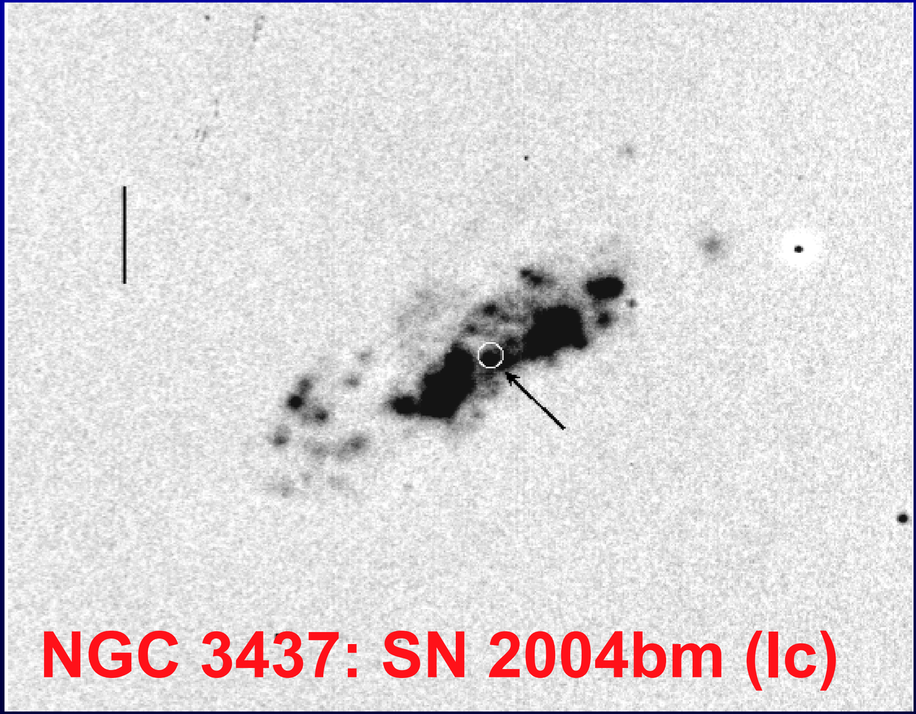
*also see Patrick Kelly’s talk on Thursday

Anderson & James (2008)

Type II SN progenitor population does not trace the underlying star formation. Our results are consistent with a significant fraction of Type II SNe arising from progenitor stars of <10 M_{o}..

Type Ib SNe show a higher degree of association with HII regions, while the Type Ic population accurately traces the Hα emission.



NGC 3437: SN 2004bm (Ic)

Anderson+ (2012)

SN type	N_{SNe}	<d> Mpc	Mean NCR*
II	163.5	32	0.25 ± 0.02
Ib	39.5	40	0.32 ± 0.04
Ic	52	42	0.47 ± 0.04

SNII ⇒ SNIb ⇒ SNIc

Progenitor mass →

NCR: Normalised Cumulative Rank pixel fn (0/1 = faintest/brightest Hα pix)

Crowther (2013)

Local (<15 Mpc) ccSNe, excluding SN imposters, SN with uncertain positions, high inclination hosts

SN type	N_{SNe}	<d> Mpc	N_{HII}/N_{SNe}
II	29	8.7	38 ± 11%
Ib/c	10	9.9	70 ± 26%

Differences between II/Ib/Ic?

- 38 ± 11% of type-II associated with HII regions. Why? Mostly IIP, whose (8-15+ M_{sun}) progenitors outlive (~20Myr) duty cycle of giant HII regions.
- 70 ± 26% of type Ib/c associated with HII regions. Why? Higher progenitor masses (>15 M_{sun}), consistent with a mix of close binary & single star scenarios (Bissaldi+ 2007; Smith+ 2011)

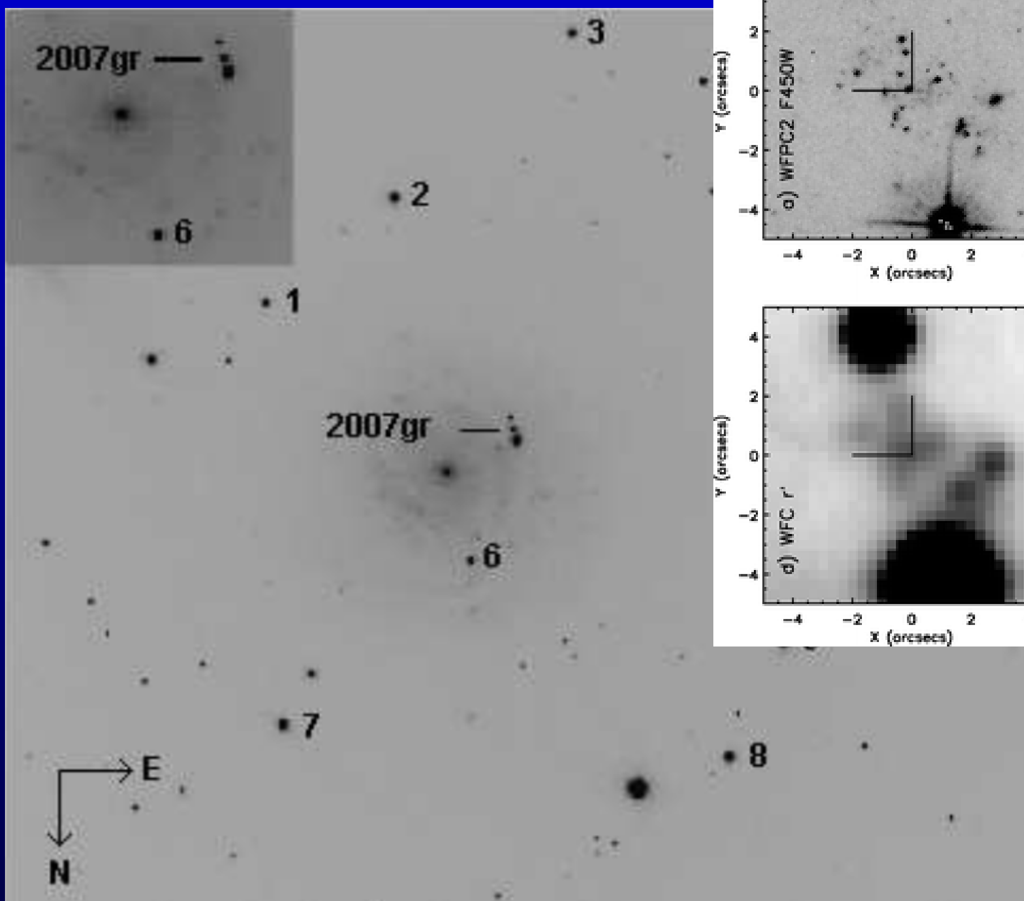
Several recent studies incl. larger statistics (albeit higher galaxy distances): Kuncarayakti et al. (2013), Kangas et al. (2013)

Smartt+ (2009)

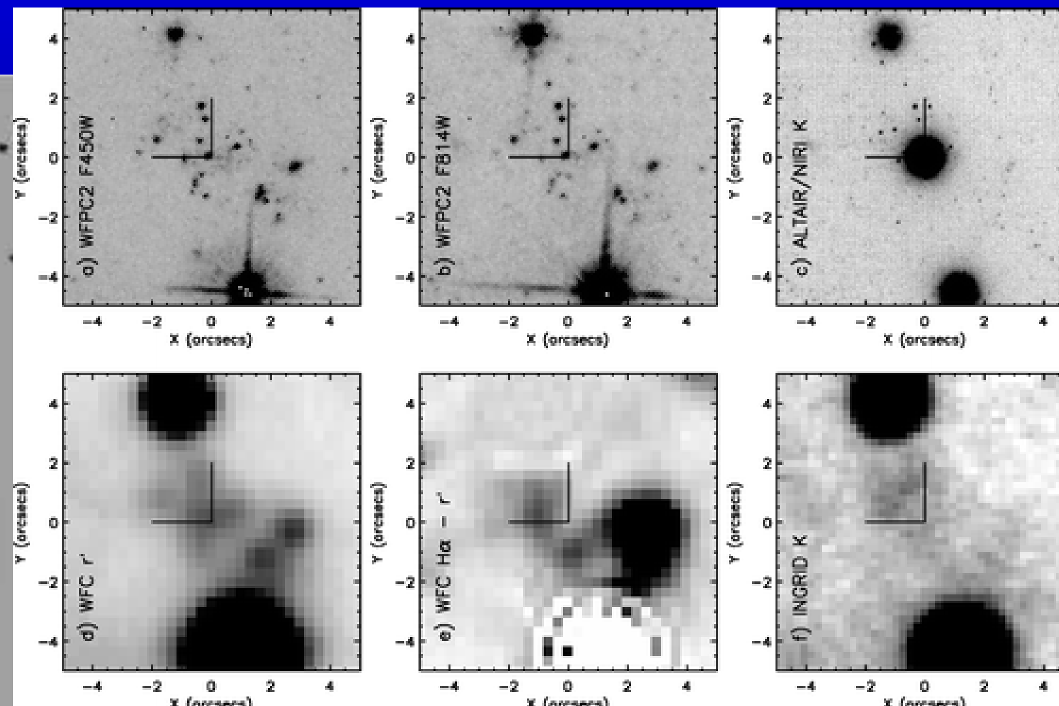
From subset of ccSNe (<2000km/s) with HST/high resolution ground-based imaging..

- 0 of 20 Type II's (<d> = 13 Mpc, mostly II-P) in bright HII regions (although many in loose associations). SN 2004am+SN 2004dj within compact clusters.
- 1 of 9 Type Ib/c's (<d> = 19 Mpc) lie in a large star-forming complex (SN 2007gr), although no HII emission at compact cluster position.

SN 2007gr (Ic)

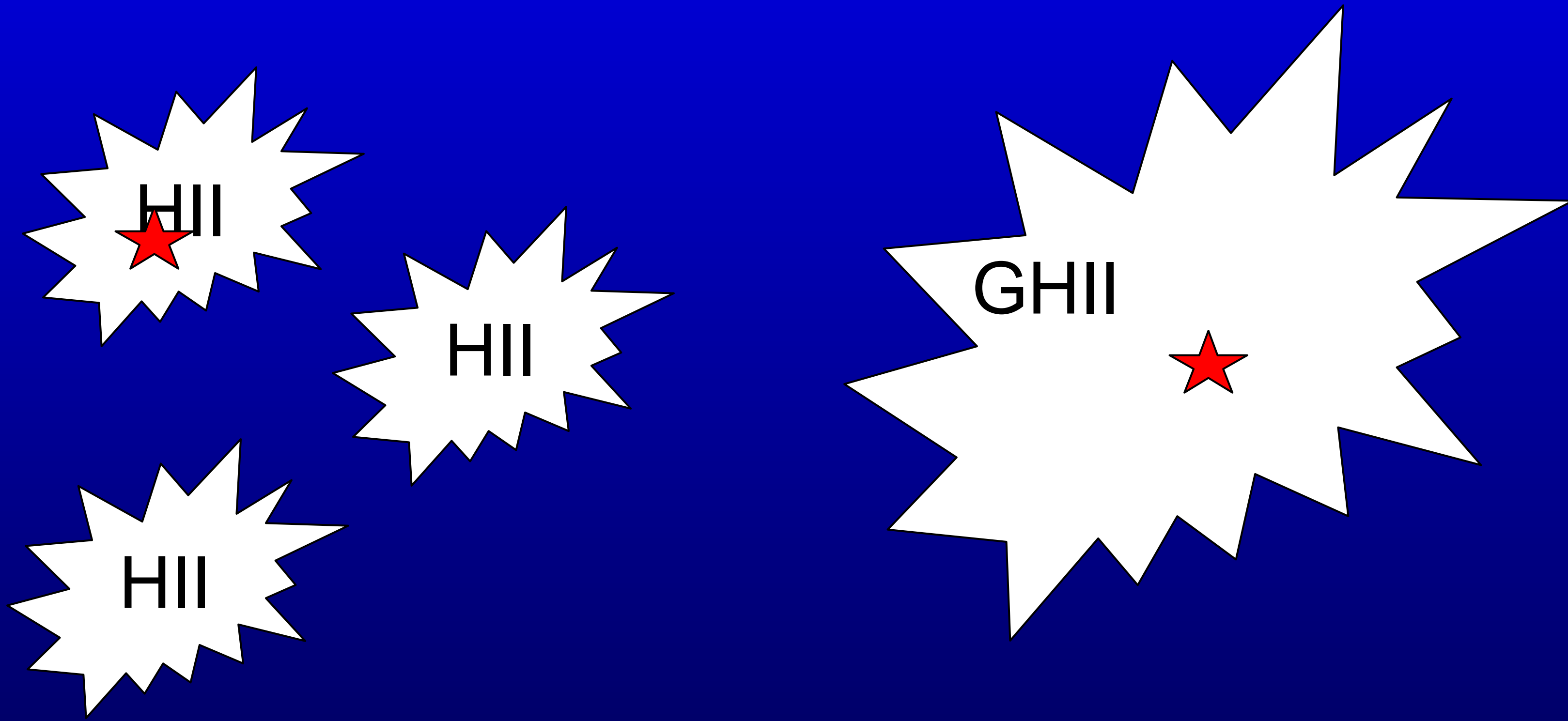


NGC 1068: Hunter et al. (2009)



Crockett et al. (2008)

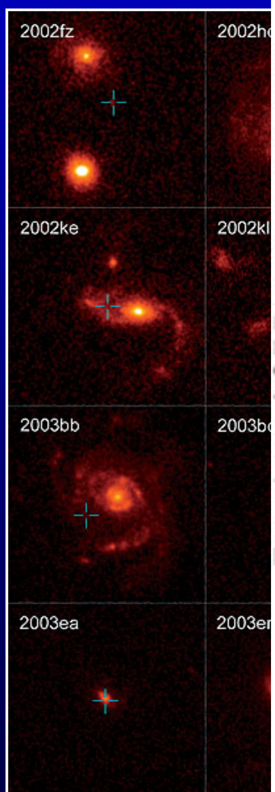
Resolution, Resolution, Resolution

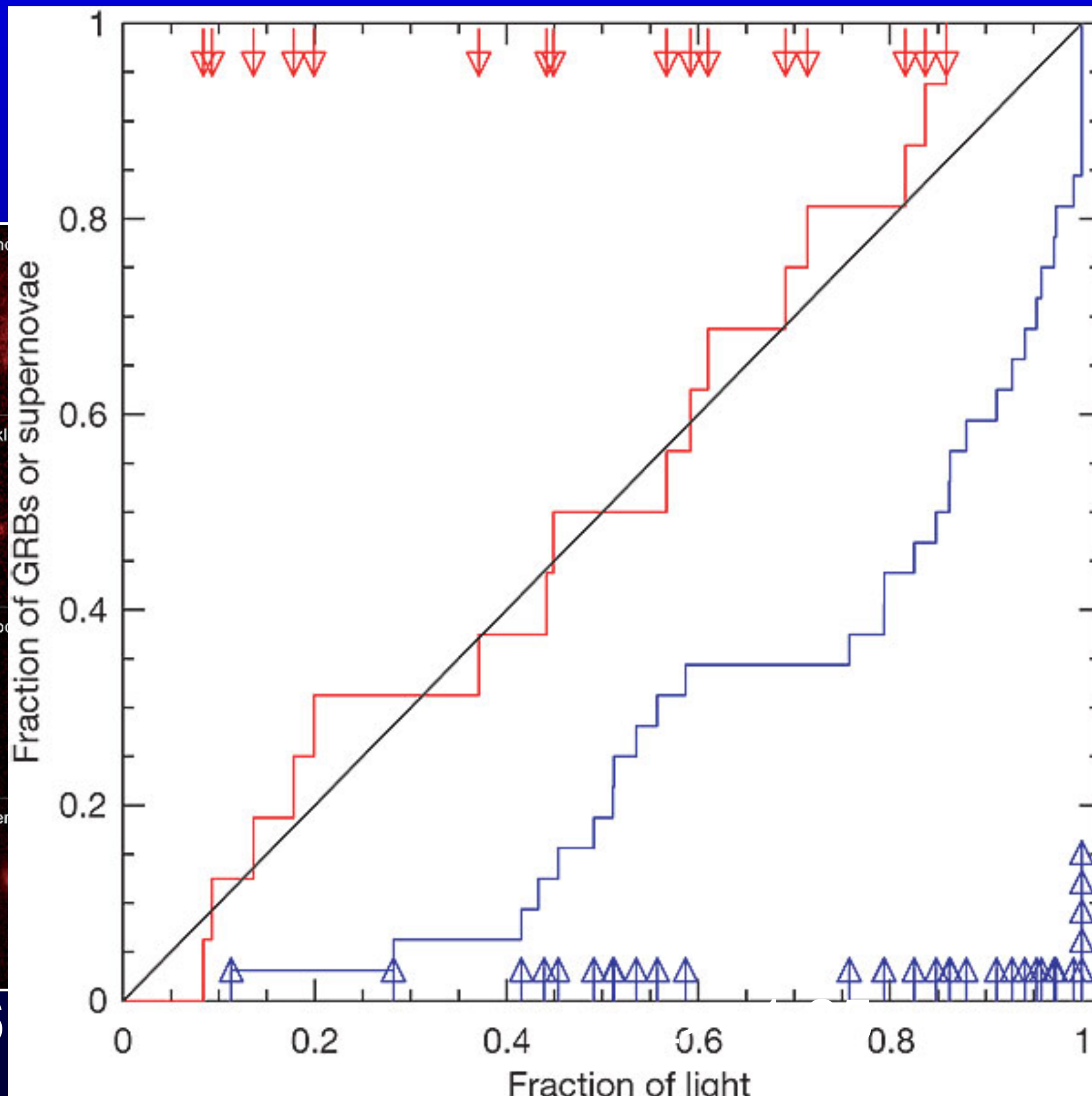


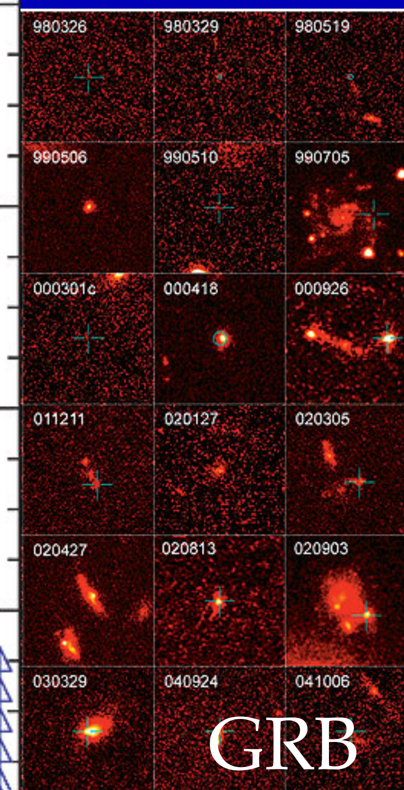
SN in compact HII region $\Rightarrow$ v.high mass progenitor (duty cycle ~4 Myr)

SN in giant HII region $\Rightarrow$ wide range of progenitor masses ($\Delta\tau$~20 Myr)

Long-GRBs inhabit brighter regions of their host galaxy than ccSNe (Fruchter+ 2006)

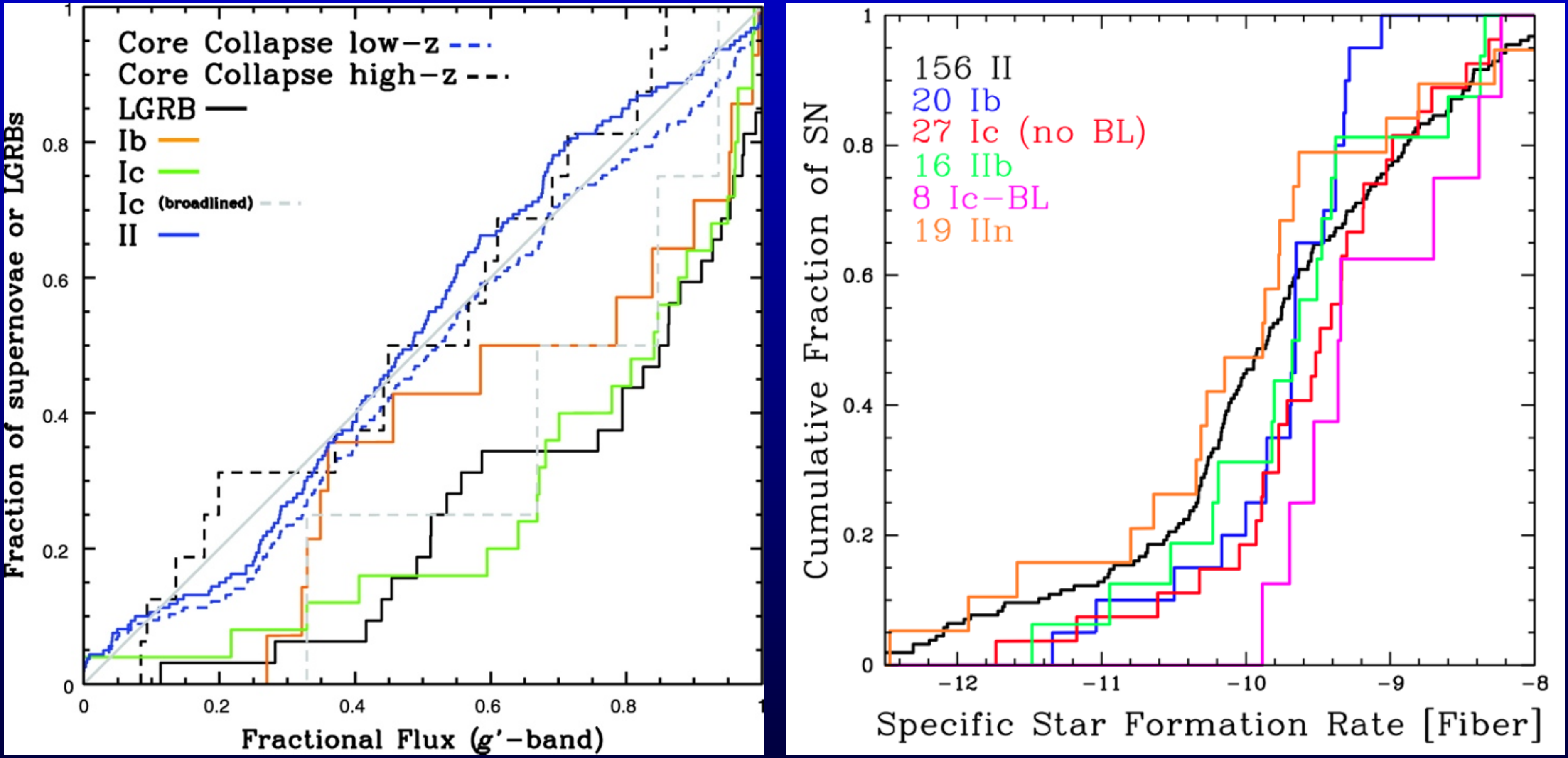




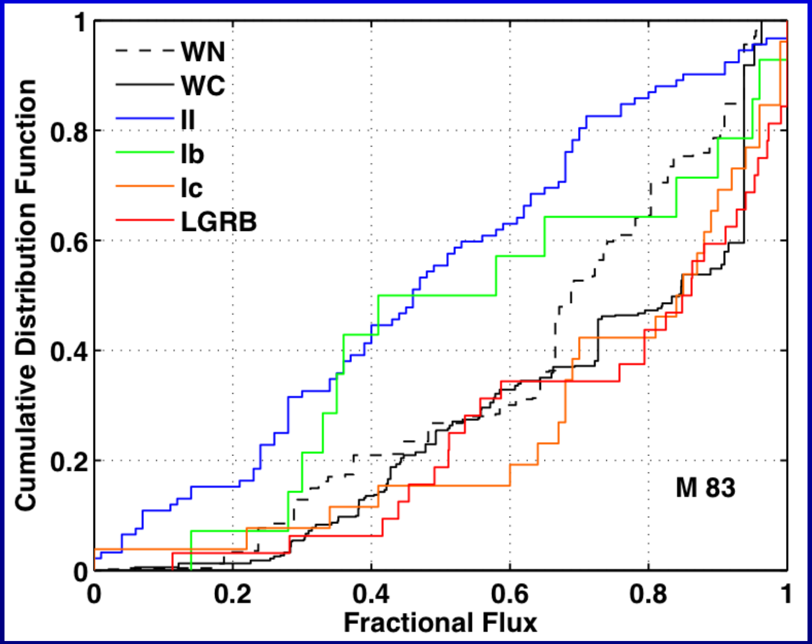


<z>=0.6

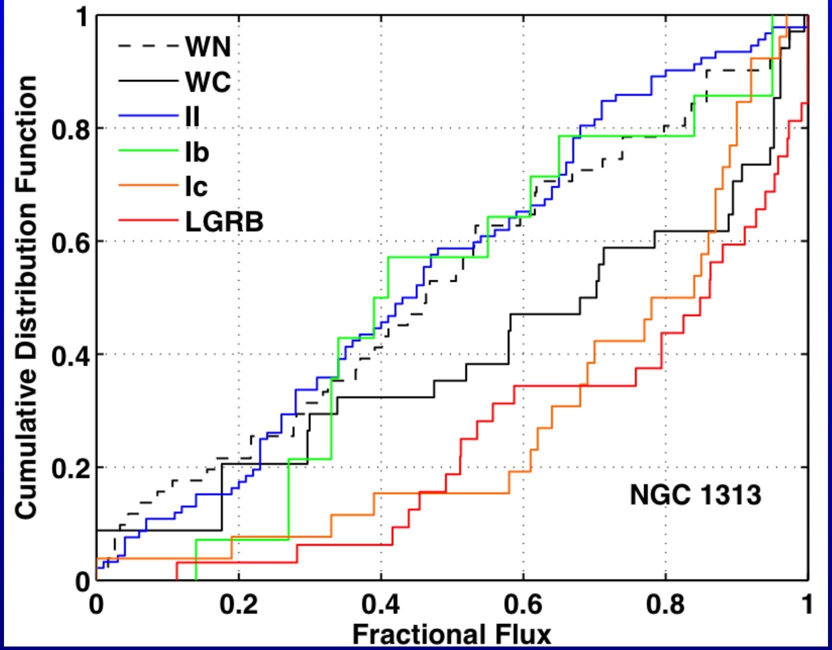
Ic SNe (+broad-lined) prefer the brightest regions of their host (Kelly+ 2008) & galaxies with the highest specific star formation rates (Kelly & Kirshner 2012)



WR versus SN/long-GRB



Hadfield+ (2005)



Hadfield & Crowther (2007)

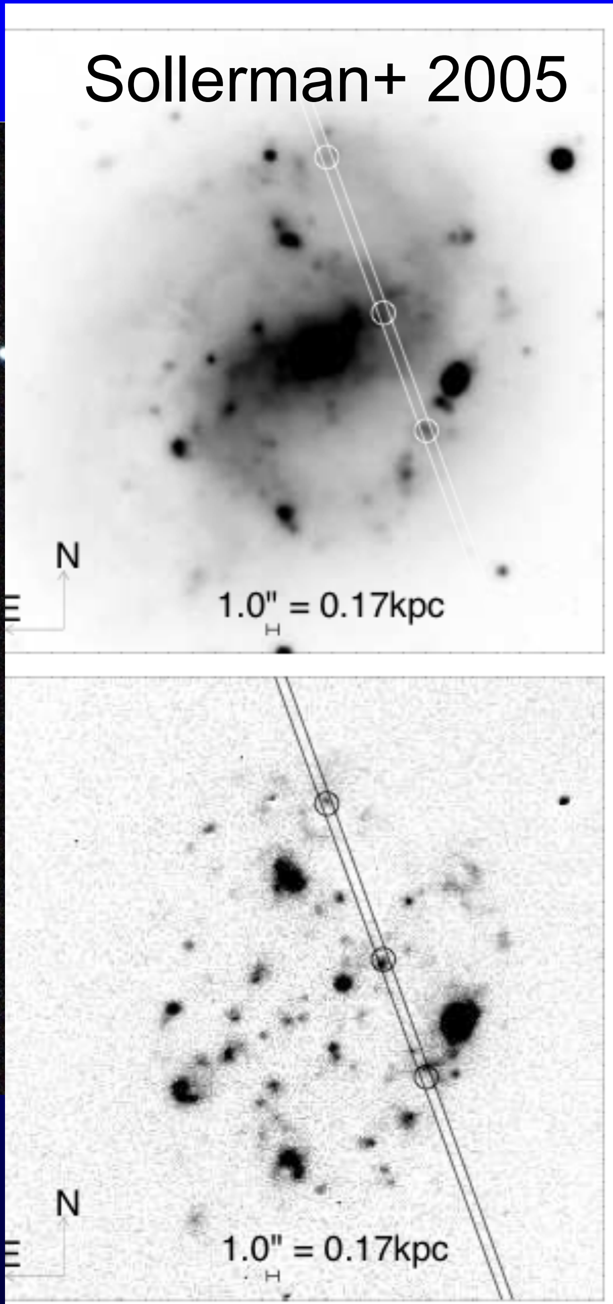
Leloudas+ (2010, 2011) compare locations of WR stars in nearby galaxies with Ib/c SNe & GRBs revealing a fair consistency between WC and Ic ccSNe (+ between WN & Ib ccSNe)

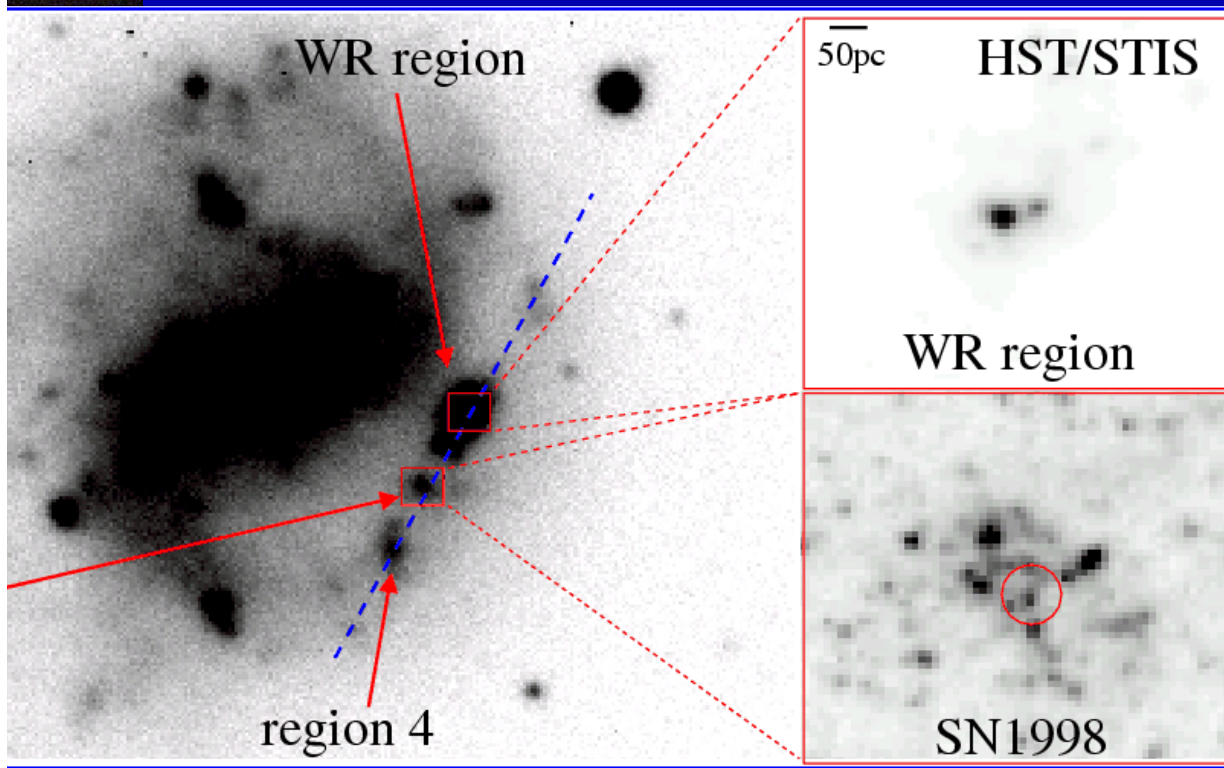
Implications of (broad-band) spatial location of ccSNe?

- Individual star clusters rapidly fade once the most massive stars die (1 mag from 5-10 Myr, 1 mag from 10-60 Myr)
- In reality, individual clusters are not resolved in ground-based images, so differences between II and Ib/c ccSNe likely relate to their different frequencies in large s.f. complexes
- Very high mass stars (50 M_{sun}+) are expected to be common in bright s.f. regions (eg Tarantula Nebula) suggesting some (broad-lined?) Ic arise from high mass stars

980425/SN1998bw

0.0085, low luminosity GRB) occurred
ndred pc from a giant HII region in
n which WR stars were detected
ha at SN/GRB position: Sollerman+ 2005)





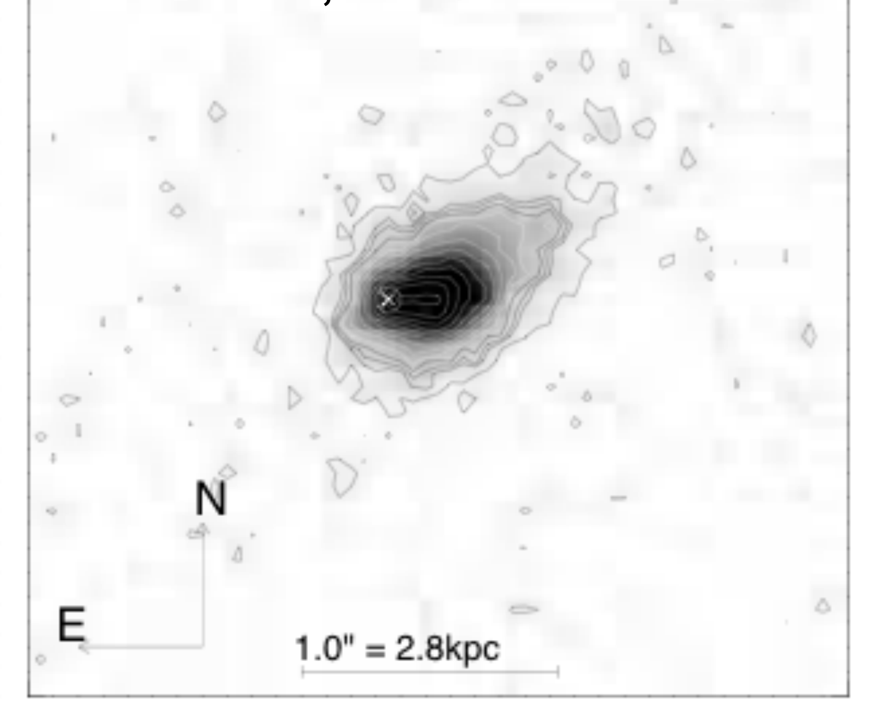
Aside: Massive Star runaways?

- 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}). Formed in low mass clusters, 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)

GRB 030329/SN 2003dh

- F606W, Sollerman+ 2005



Low z (~0.17) counterpart to cosmological GRB (Hjorth+ 2003). High specific star formation intensity (Gorosabel+ 2005)

Implications of (broad-band) spatial location of GRBs?

- Hosts of high-z GRBs (from Fruchter+ 2006) are typically metal-poor dwarfs.
- Broad-lined Ic SNe (coincident with long-GRBs at low metallicity) favour high star formation intensities (Kelly & Kirshner 2012) which will lead to disproportionately numerous massive star clusters (Billett+ 2002; Portegies Zwart+ 2010).
- The preference of broad-lined Ic SN and long-GRBs towards the brightest regions of their hosts suggests high mass (50?+ M_{sun}) progenitors since massive star clusters will host large numbers of such stars.

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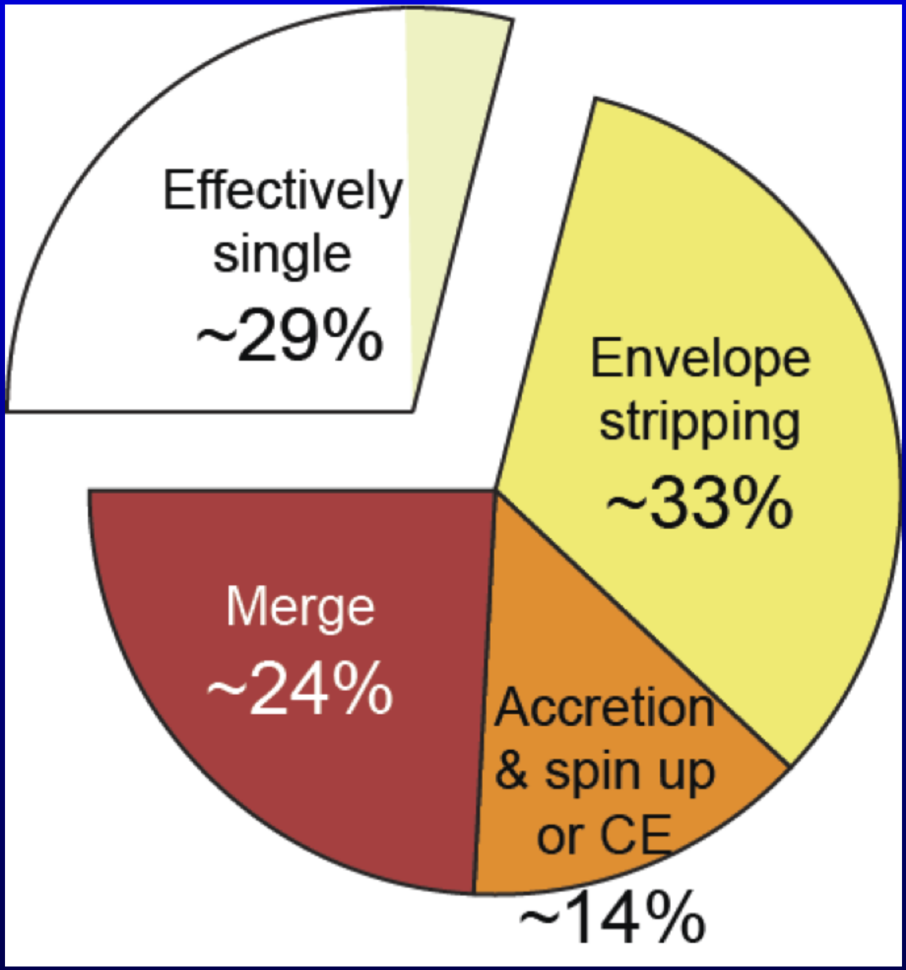
Preference for Ib/c ccSNe in inner regions of interacting galaxies?

Ib/c SNe are more centrally condensed in their host galaxies than type II, especially in disturbed/interacting systems (Habergham et al. 2010, 2012). Habergham et al. attribute this to a top heavy IMF (yet Ib and II ccSNe likely span a similar mass range).

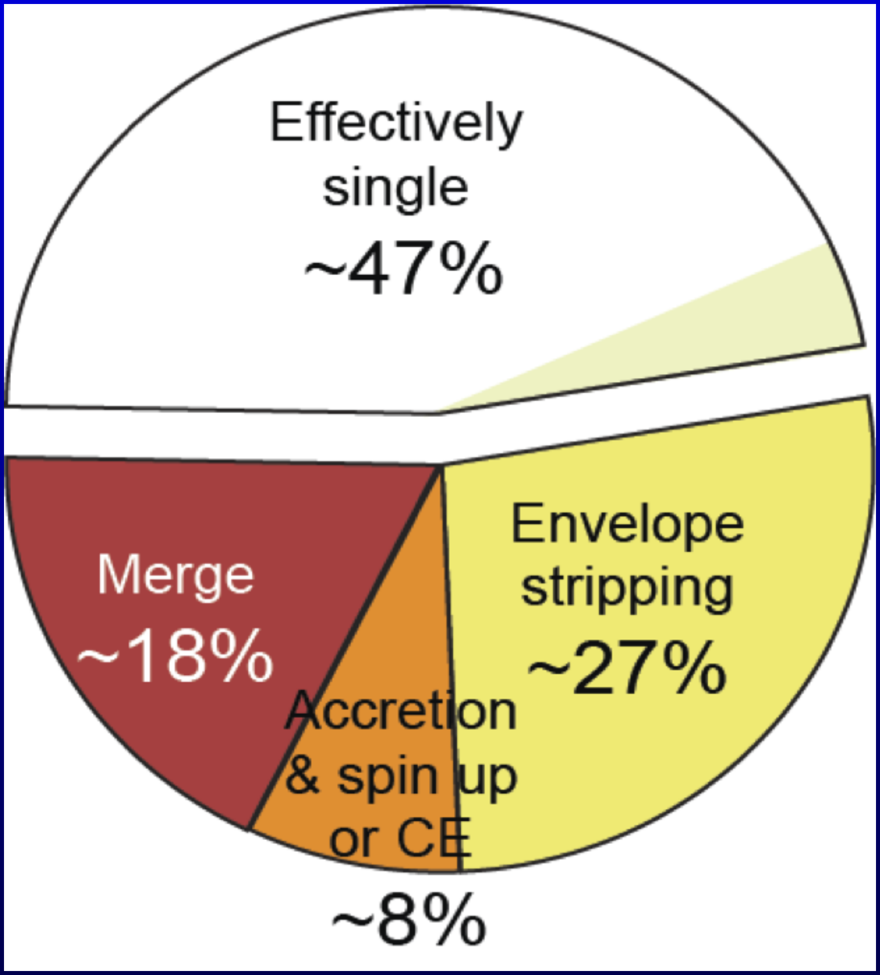
Alternatively, close binary evolution may play a dominant role. In quiescent s.f. galaxies compact massive star clusters are relatively rare (e.g. Milky Way), yet starbursts (e.g. M82) & interacting systems (e.g. Antennae) are teeming with such super star clusters.

NGC 4038-4039 • Antennae Galaxies

O star binary statistics?



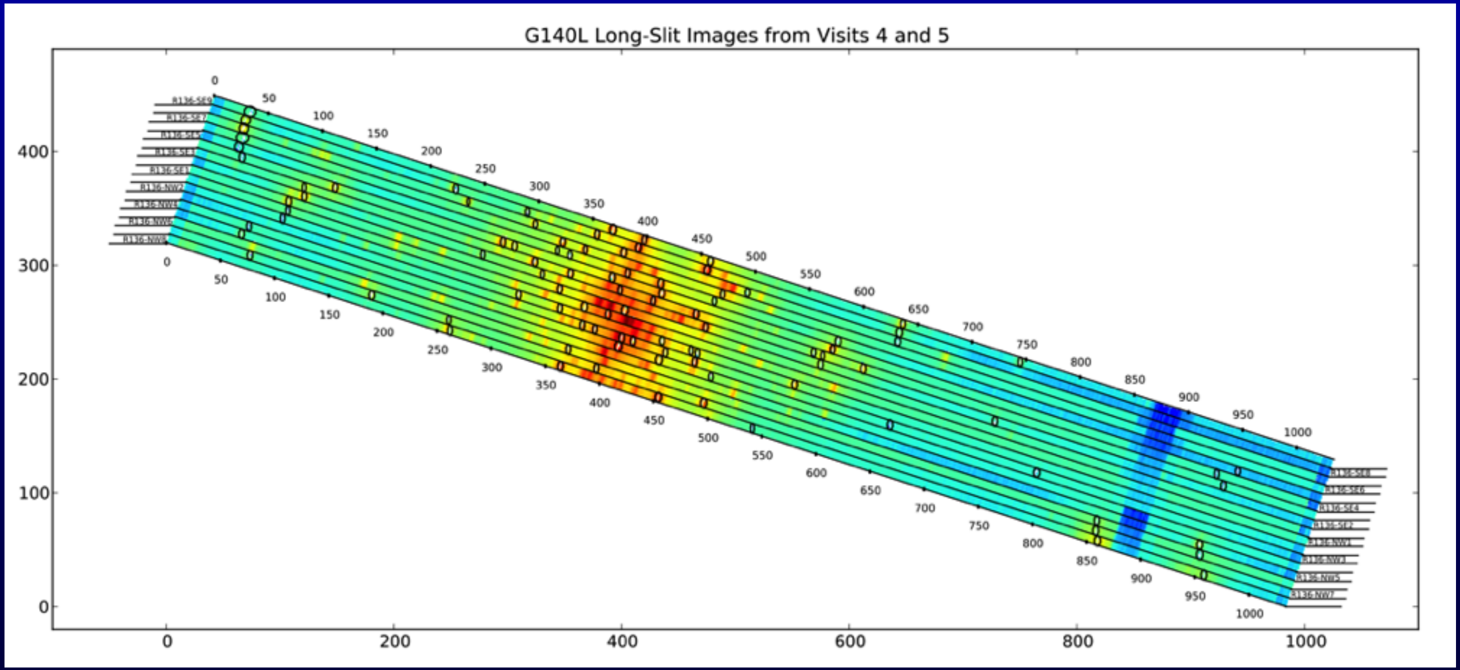
Sana+ (2012, Galactic clusters)



Sana+ (2013, VFTS:30 Dor)

Binaries in R136 star cluster?

Sana et al. assess binary fraction of OB associations & Tarantula (excluding R136). HST/STIS observations will set lower limit on R136 massive binary fraction (Apr 2012-2013)



Why close binaries?

Within dense stellar systems, 'soft' binaries soften (=widen further) via interactions with other stars but 'hard' binaries harden (=become closer) via Heggie-Hills law.

King et al. (2012) identify an excess of close (low mass) binaries in high density s.f. regions with respect to the lower density regions.

Massive close binaries in dense high mass clusters would favour the production of stripped (Ib/c) ccSNe in such environments via RLOF transfer of H-envelope from primary to secondary.

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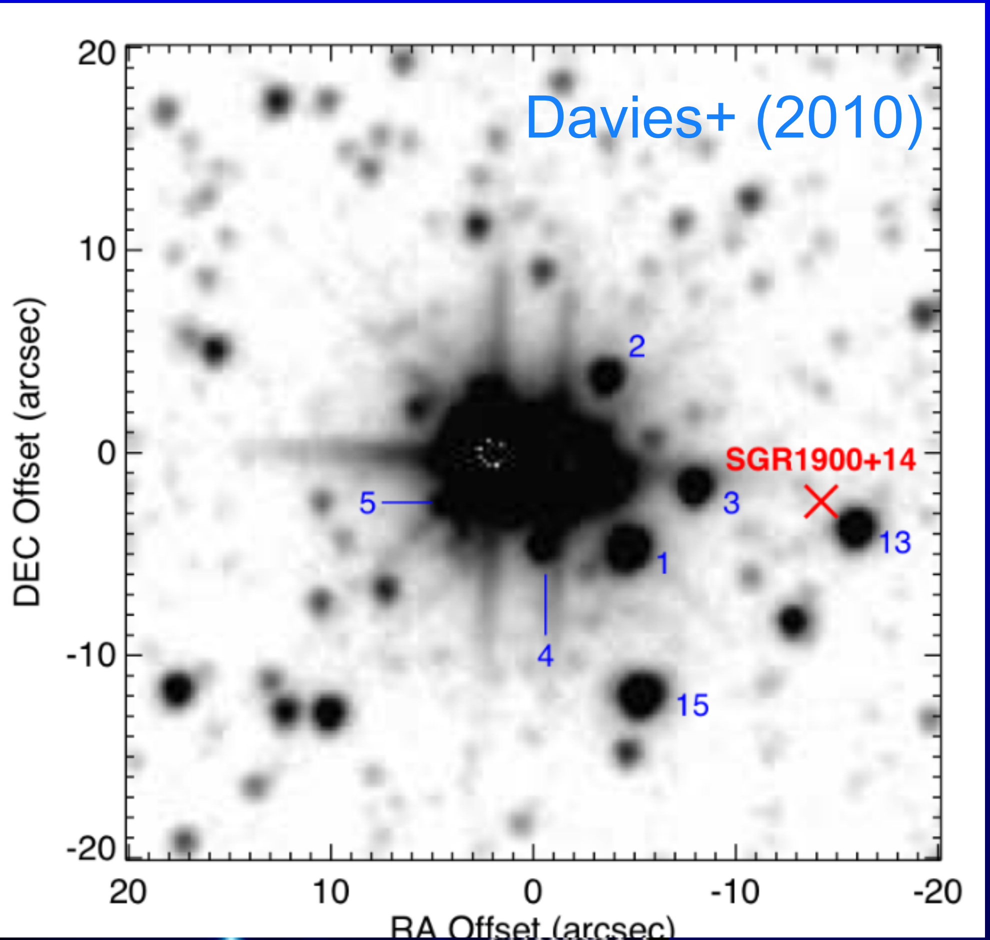
Magnetar progenitor masses?

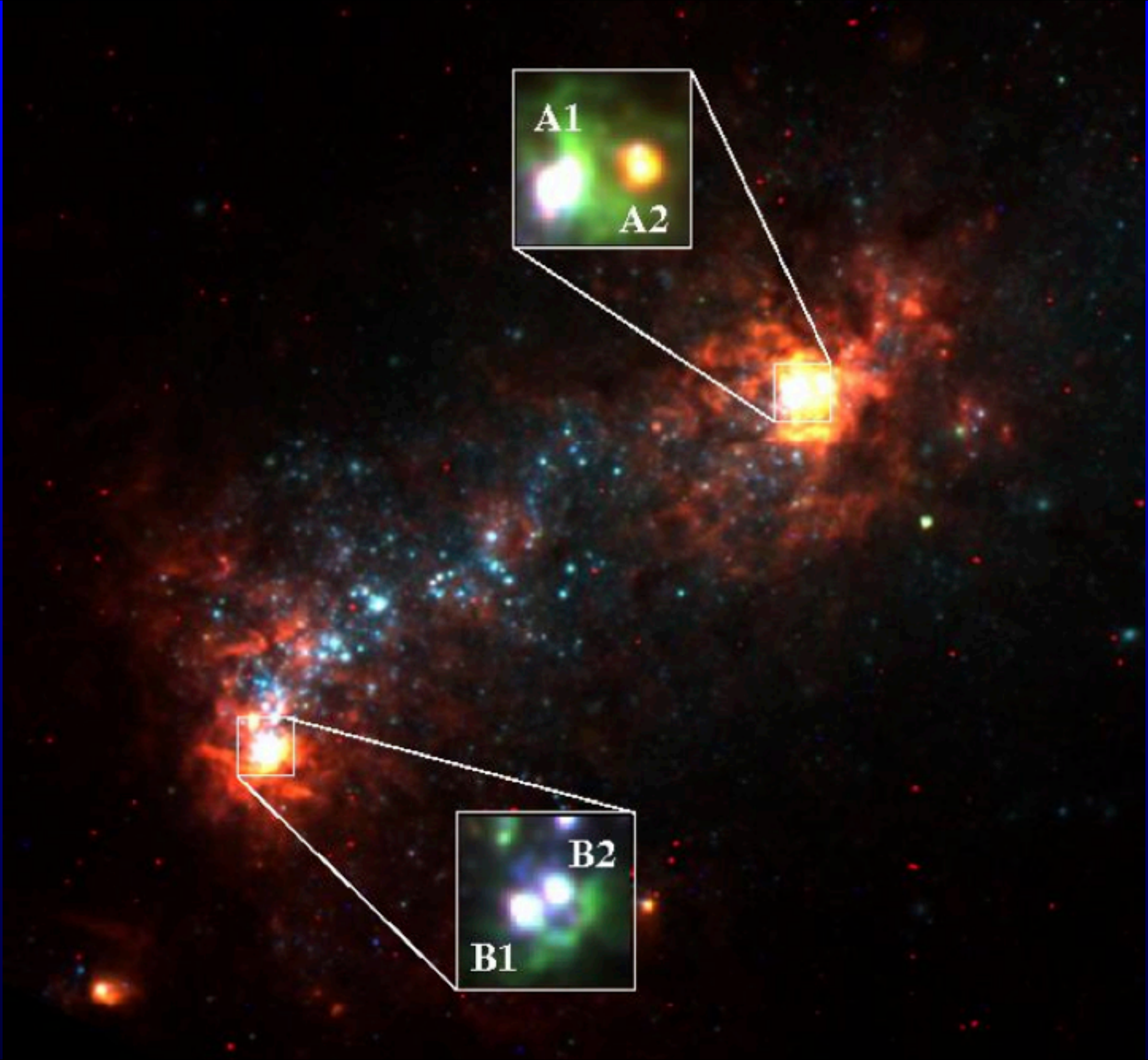
SGR / AXP	Cluster
1806-20	Cl 1806-20 ~8.7kpc
1E1647-455	Westerlund ~5kpc
1900+14	Cl 1900+14 ~12kpc
1E1841-045	RSG2/3? ~6kpc (Kes



Magnetars may be produced both by ~15 Msun (RSG?) and ~50 Msun (WR?) progenitors

Summary: SNe/GRB implications?

- Death of 10 M_{sun} star (II-P)
  - Not associated with classical HII region & unlikely to be associated with giant HII region (outlives gas rich phase). Unlikely to be associated with a bright region in host galaxy.
- Death of 25 M_{sun} star (IIb?)
  - Not associated with classical HII region but may be associated with giant HII region (long duty cycle). May be associated with a bright region in host galaxy.
- Death of 50 M_{sun} star (broad lined Ic/GRB?)
  - Unlikely to be associated with classical HII region (gas rich phase is short) but v.likely to be associated with giant HII region. Very likely to be associated with bright region of host galaxy


A1
A2
B2
B1

Metal-poor GRB? (Graham talk)

- Long GRBs prefer metal poor environments (e.g.Modjaz+ 2008), although Levesque+ (2010) identify several metal-rich hosts.
- Kelly+ (2013) note spatial coincidence of GRB130702A with a metal-poor satellite (S1) of bright red galaxy (S2)