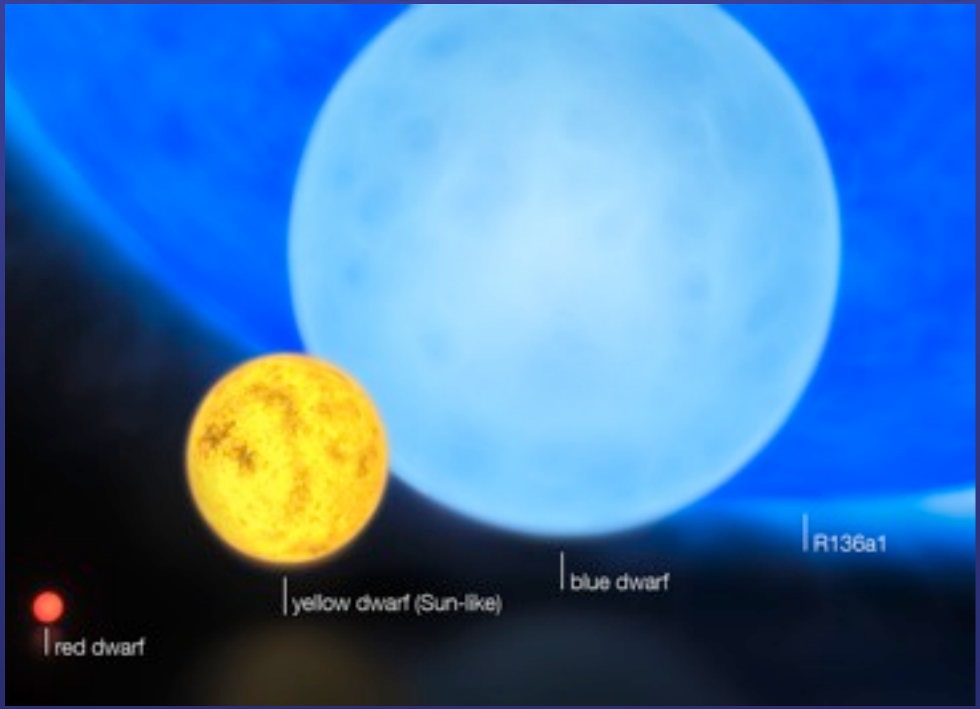
Very Massive Stars in the Local Universe



Paul Crowther (Sheffield)

Simon Goodwin (Sheffield), Raphael Hirschi (Keele), Hasan Kassim (Malaya), Richard Parker (ETH Zurich), Olivier Schnurr (AIP), Liza Yusof (Malaya), VLT FLAMES Tarantula Survey consortium

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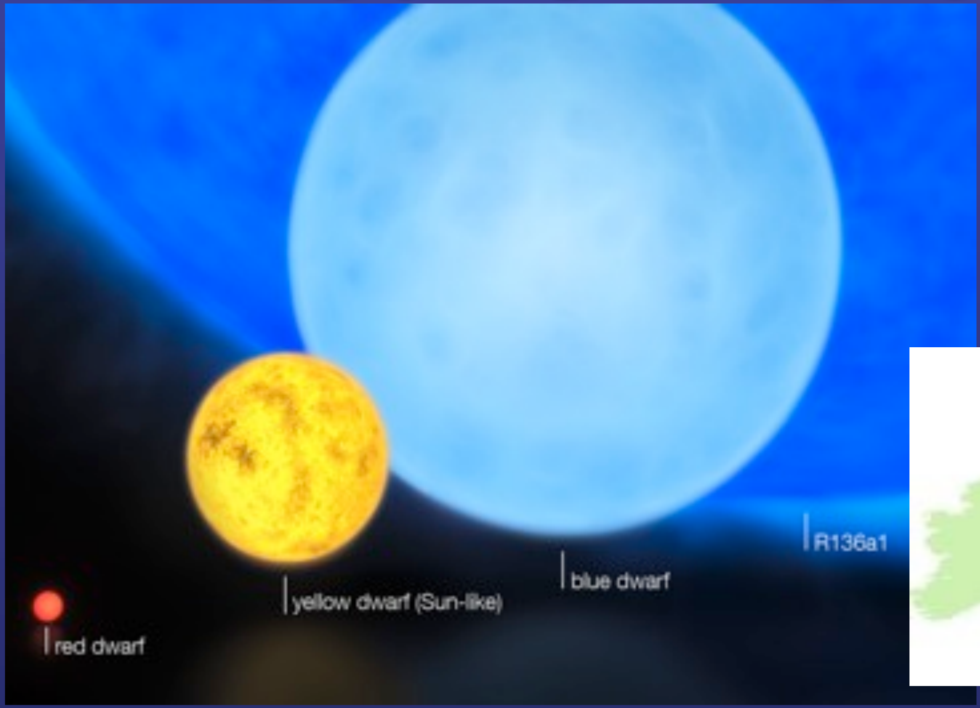

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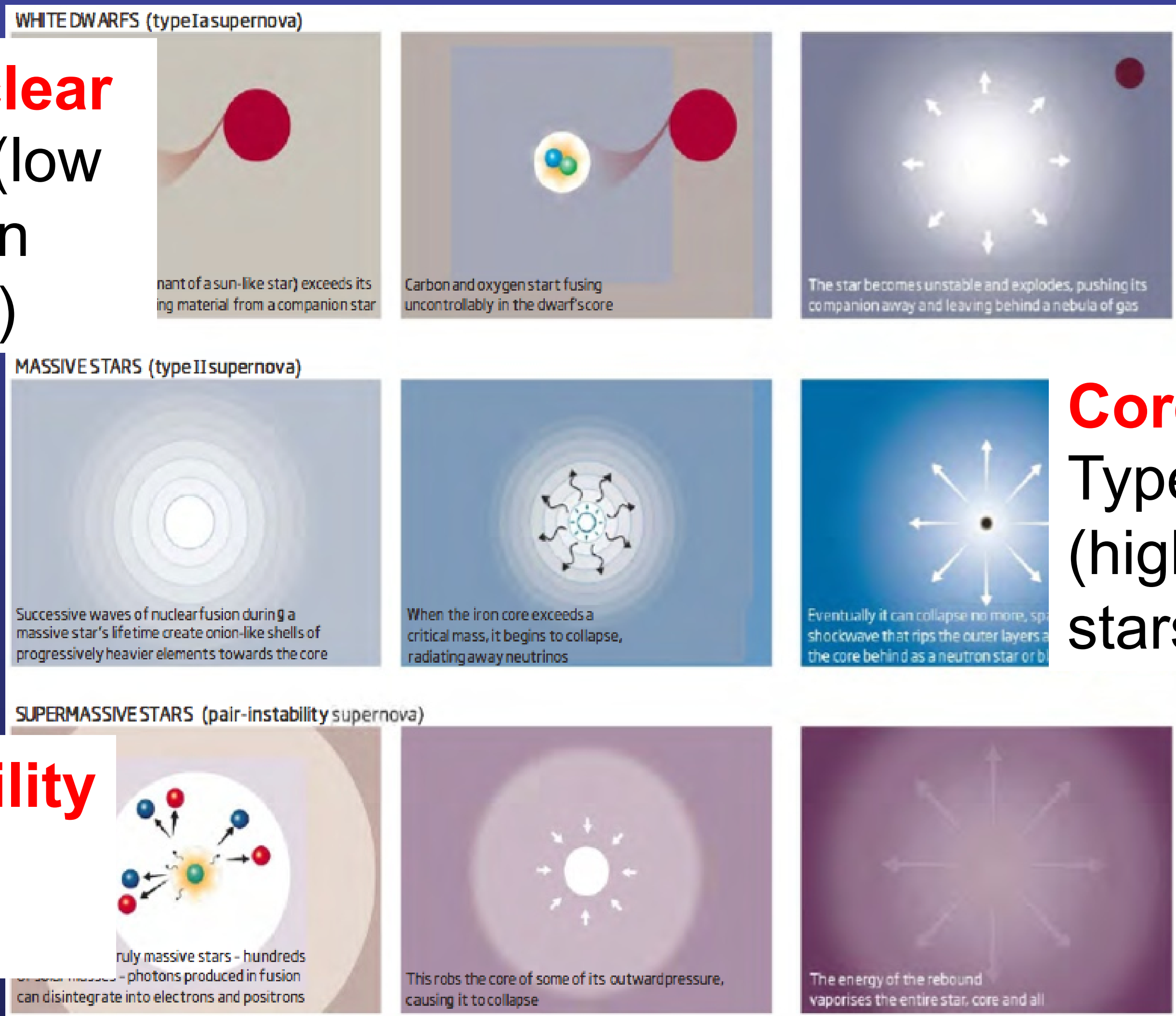
Nomenclature*

Mass Range (M_{sun})		Name
10 -	100	Massive stars
100 -	1,000	Very massive stars
1,000 -	10,000	Extremely massive stars
10,000 -	100,000	Ultra massive stars
100,000 -	250,000	Hyper massive stars

*"Borrowed" from Alex Heger, following metal-poor star nomenclature (Beers & Christlieb 2005)

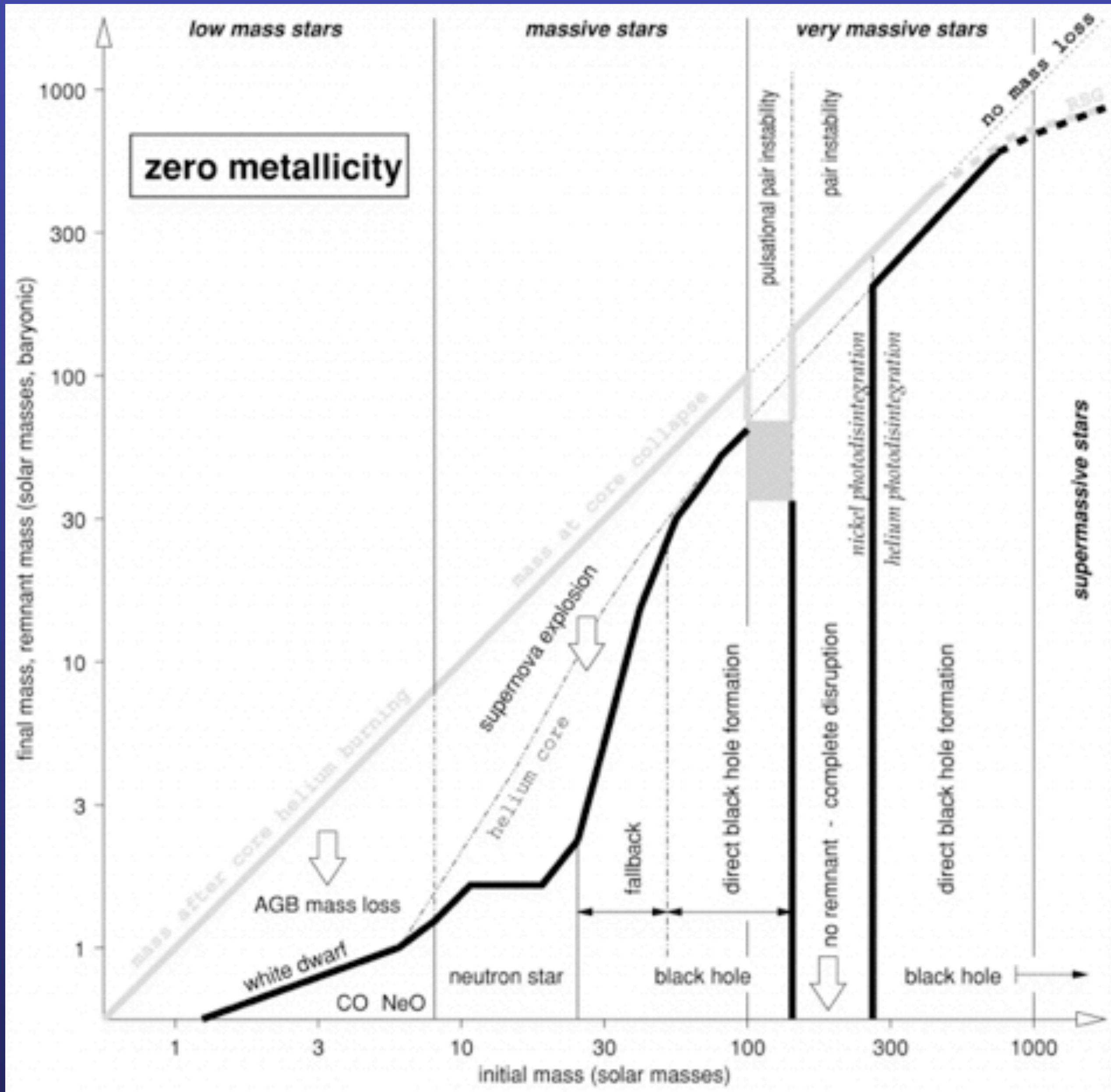
Motivation I

Thermonuclear
Type Ia SN (low mass stars in close binary)

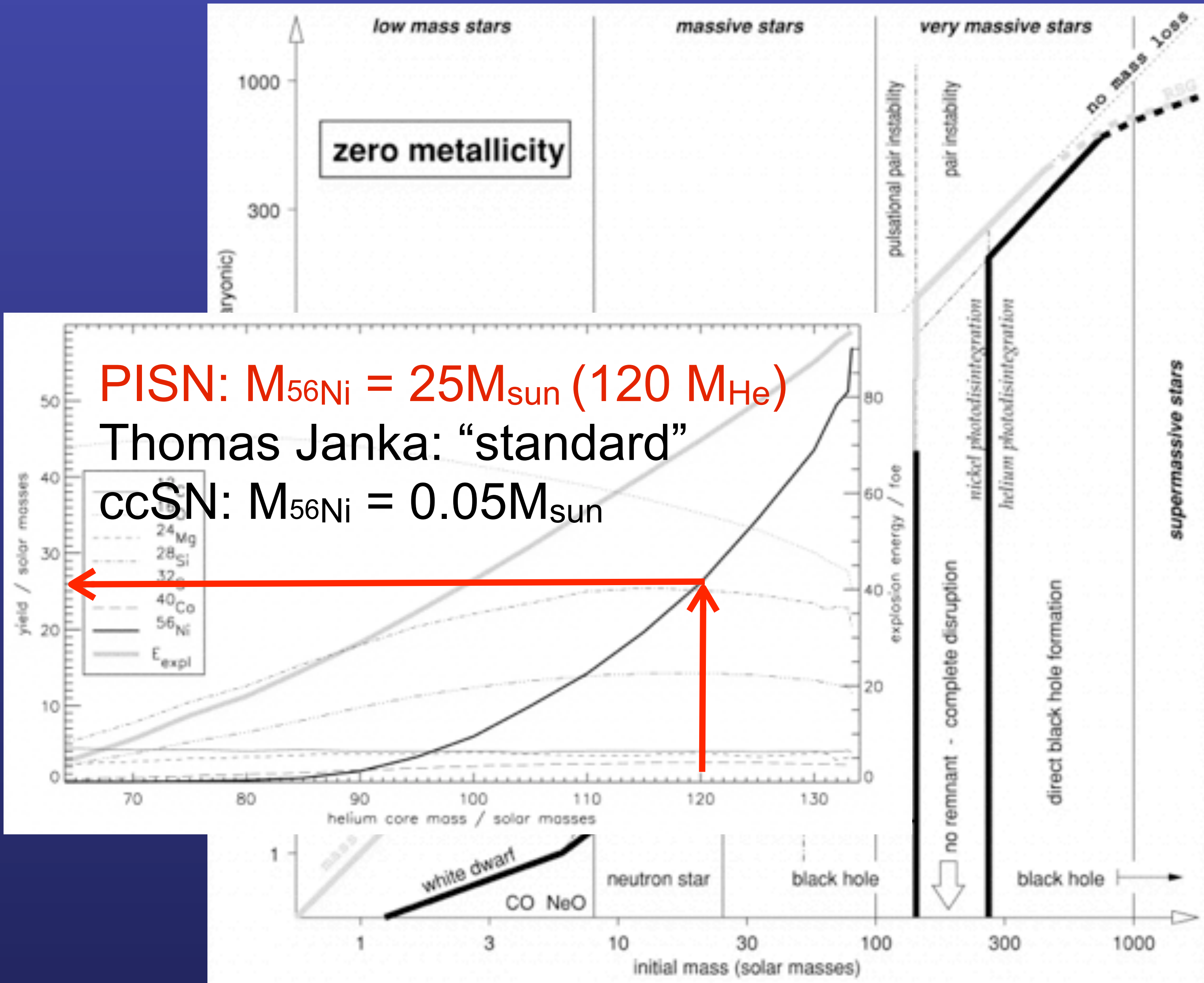


Core-collapse
Type II or Ib/c (high mass stars)

Pair-instability
(Very high mass)



Woosley & Heger (2002) 4

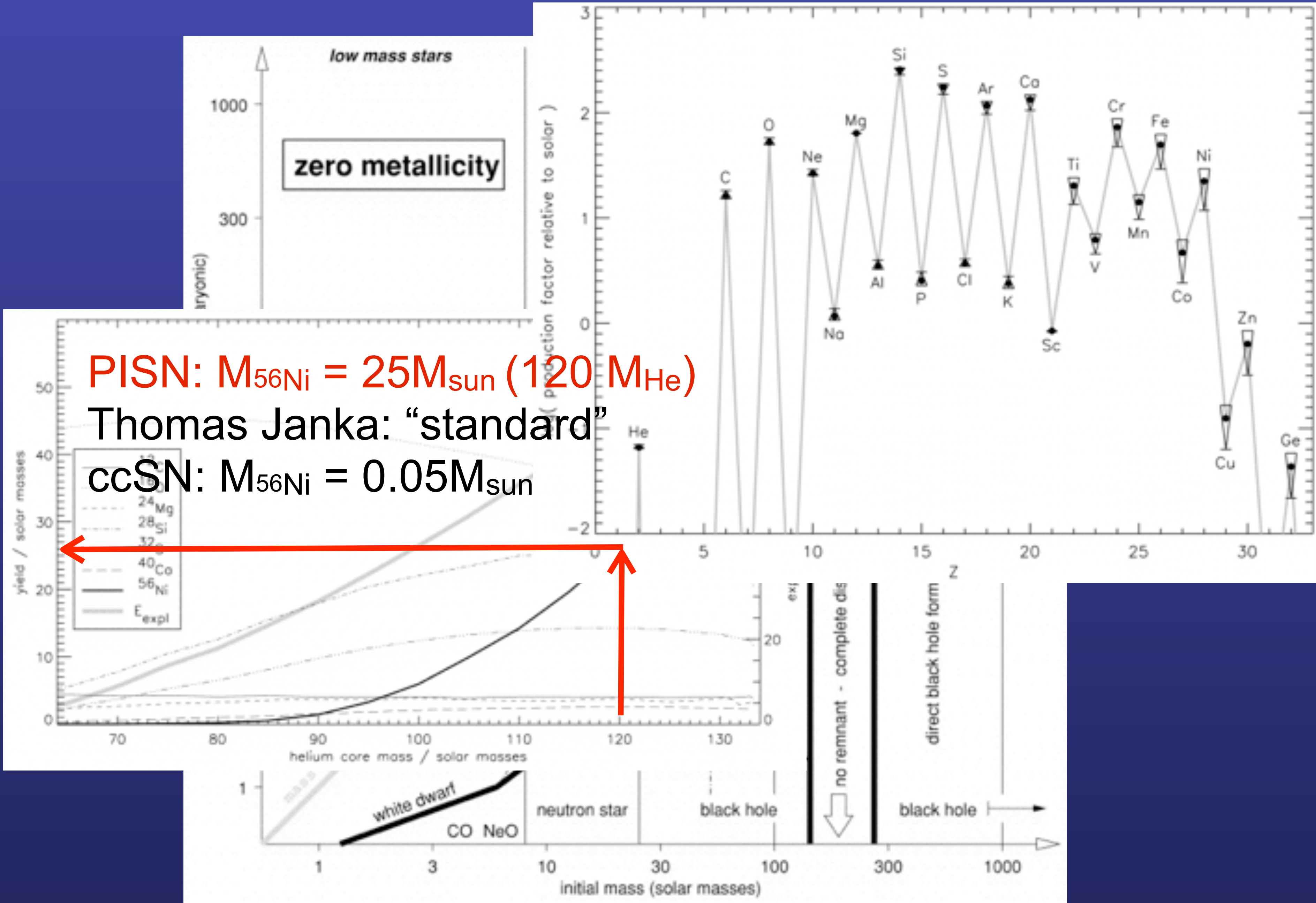


Woosley & Heger (2002)

PISN: $M_{56Ni} = 25M_{sun}$ (120 M_{He})

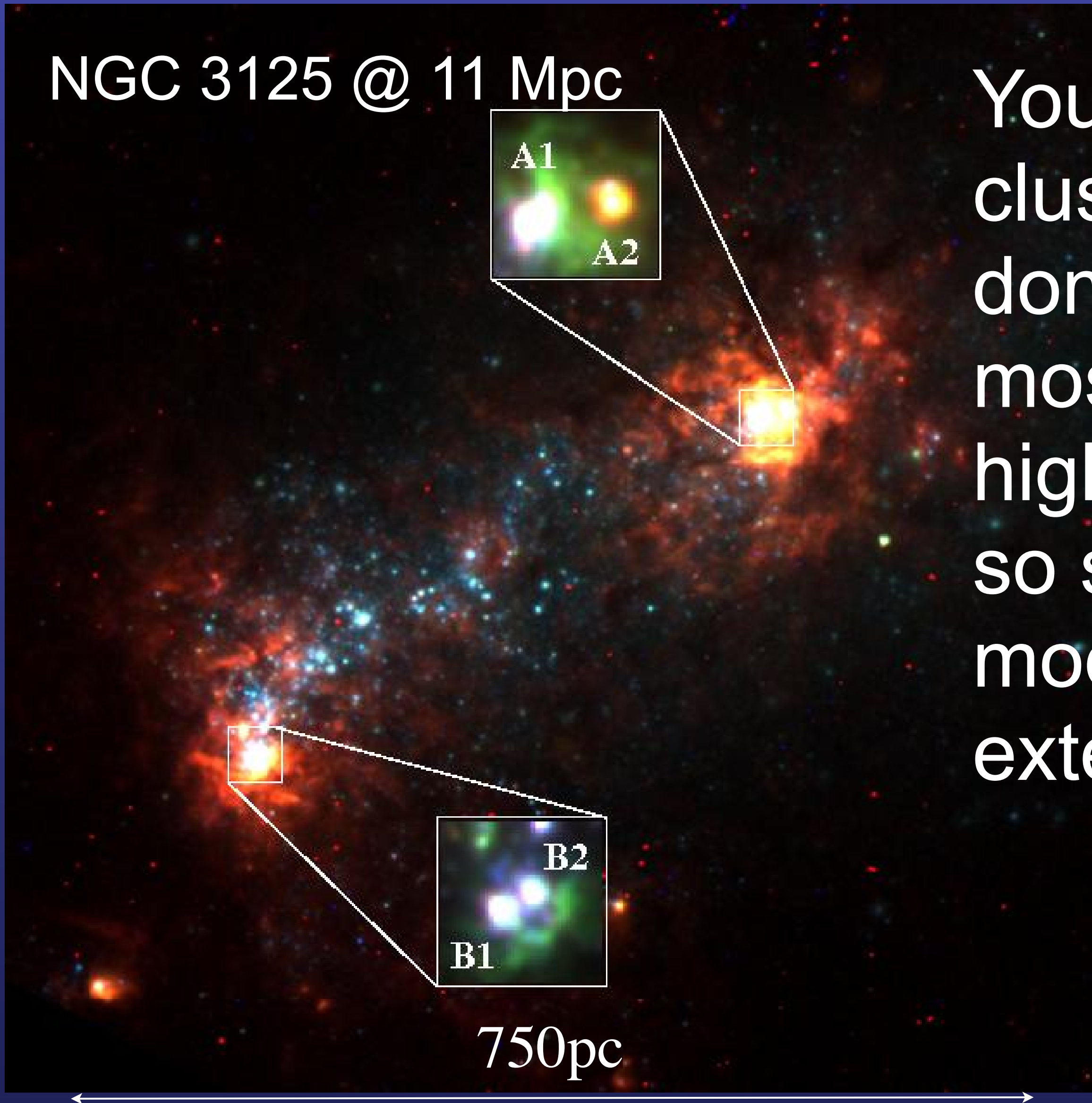
Thomas Janka: “standard”

ccSN: $M_{56Ni} = 0.05M_{sun}$



Woosley & Heger (2002)

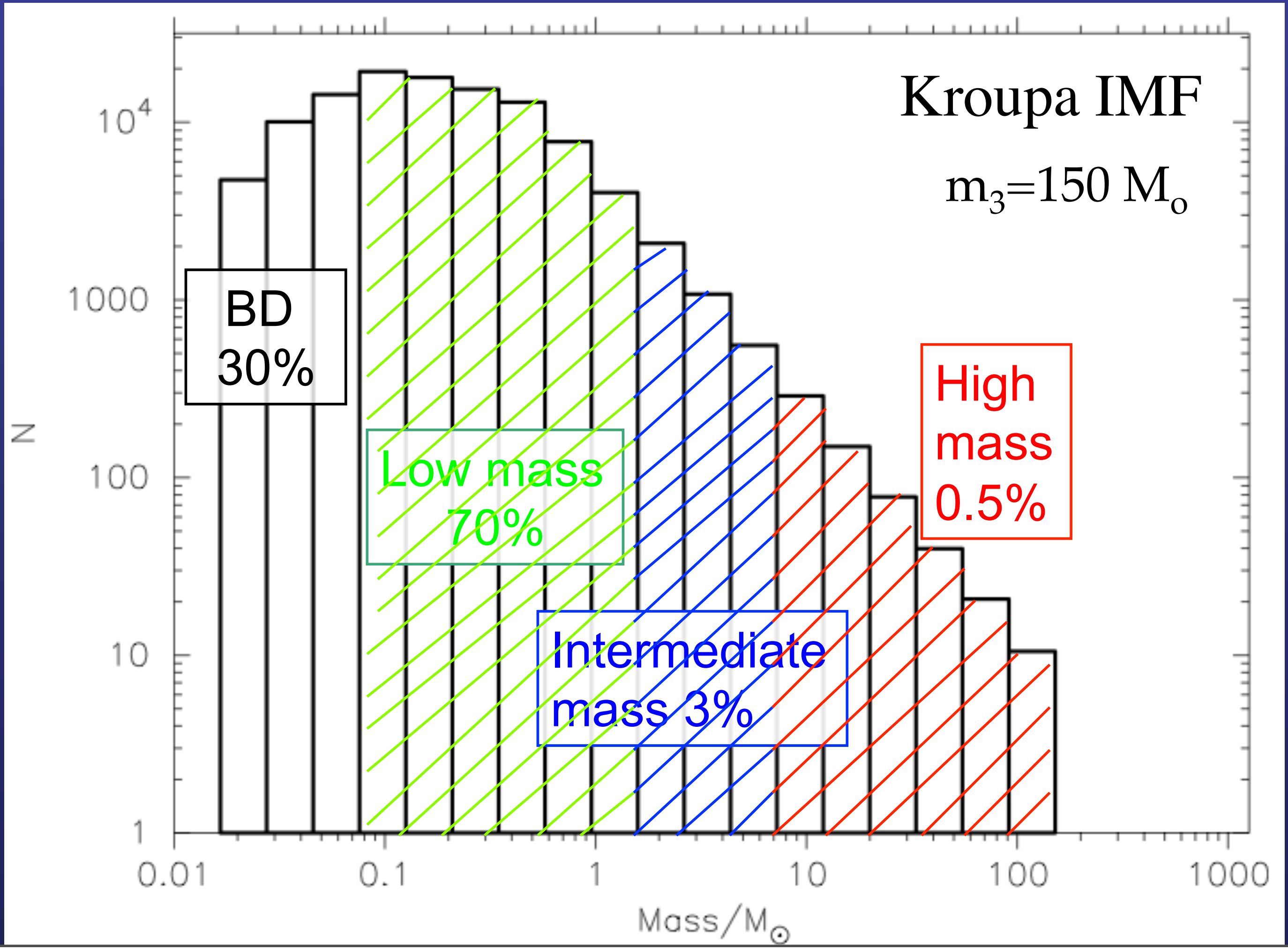
Motivation II



Young starburst clusters are dominated by the most luminous (= highest mass) stars, so spectral synthesis models need to extend up to M_{up}

Massive Stars & the IMF

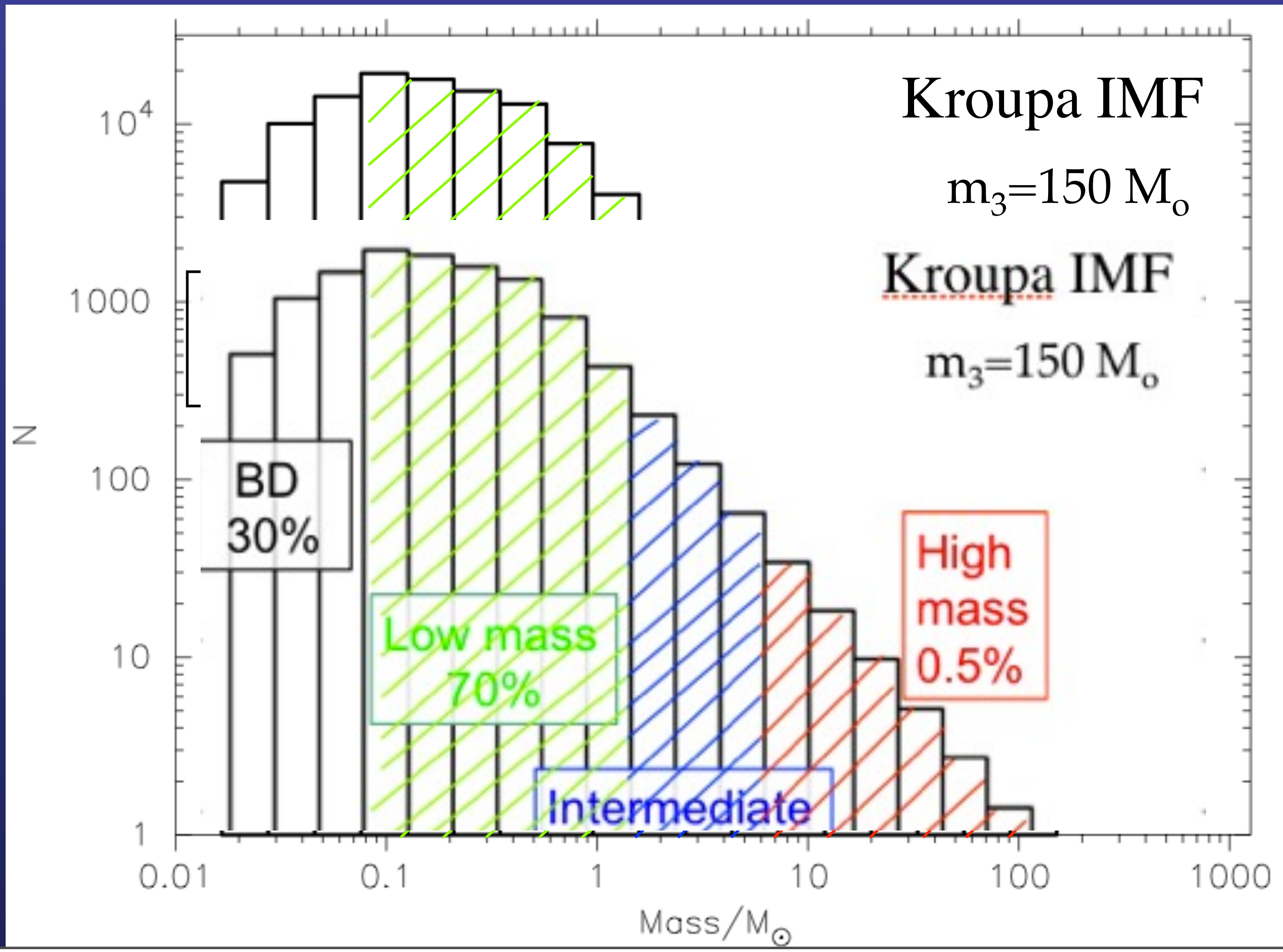
$M_{cluster}$
$5x10^4$ M_{sun}



Massive Stars & the IMF

$M_{cluster}$
$5x10^4$ M_{sun}

$M_{cluster}$
$5x10^3$ M_{sun}

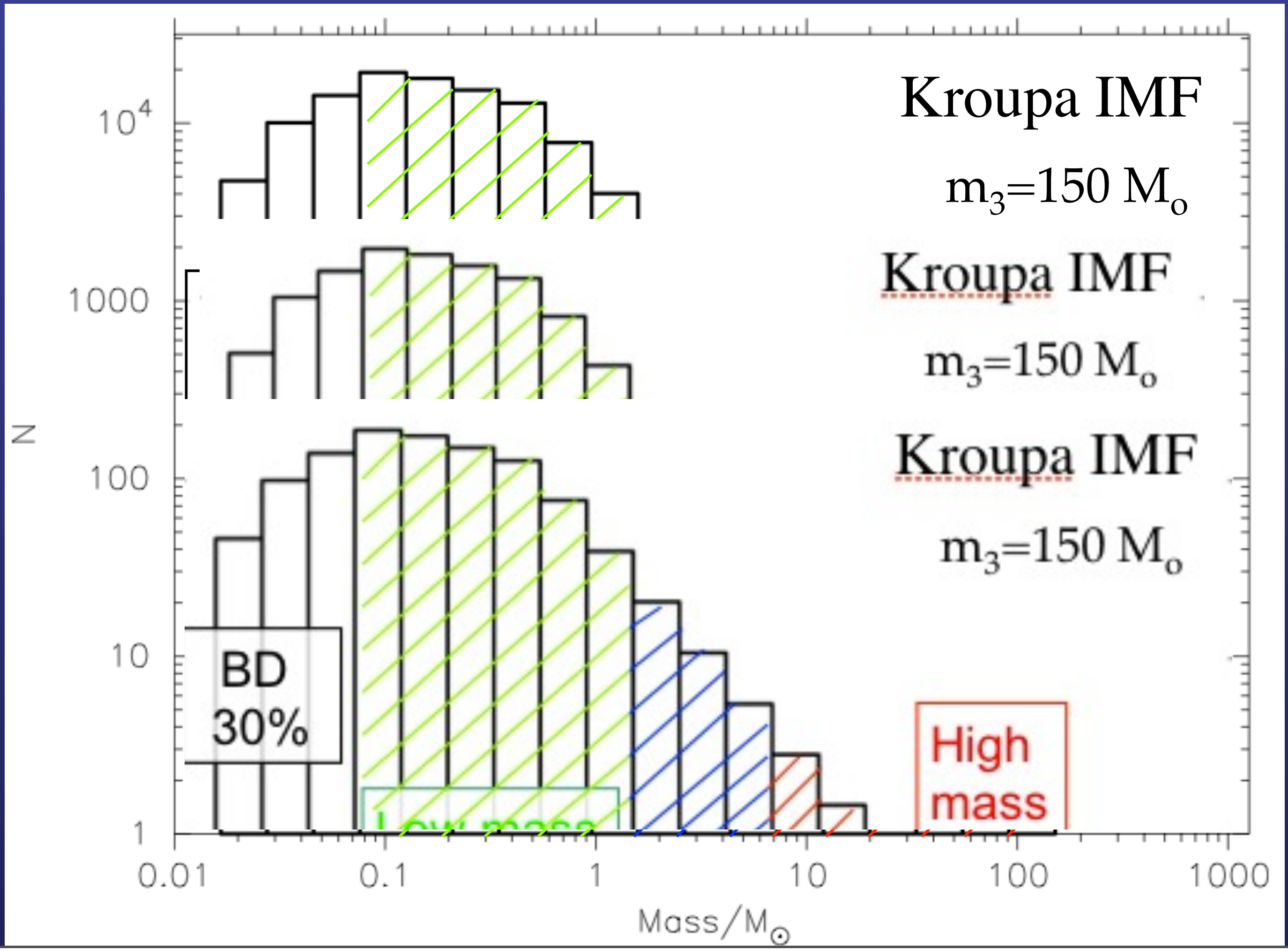


Massive Stars & the IMF

$M_{cluster}$ $5x10^4$ M_{sun}

$M_{cluster}$ $5x10^3$ M_{sun}

$M_{cluster}$ $5x10^2$ M_{sun}



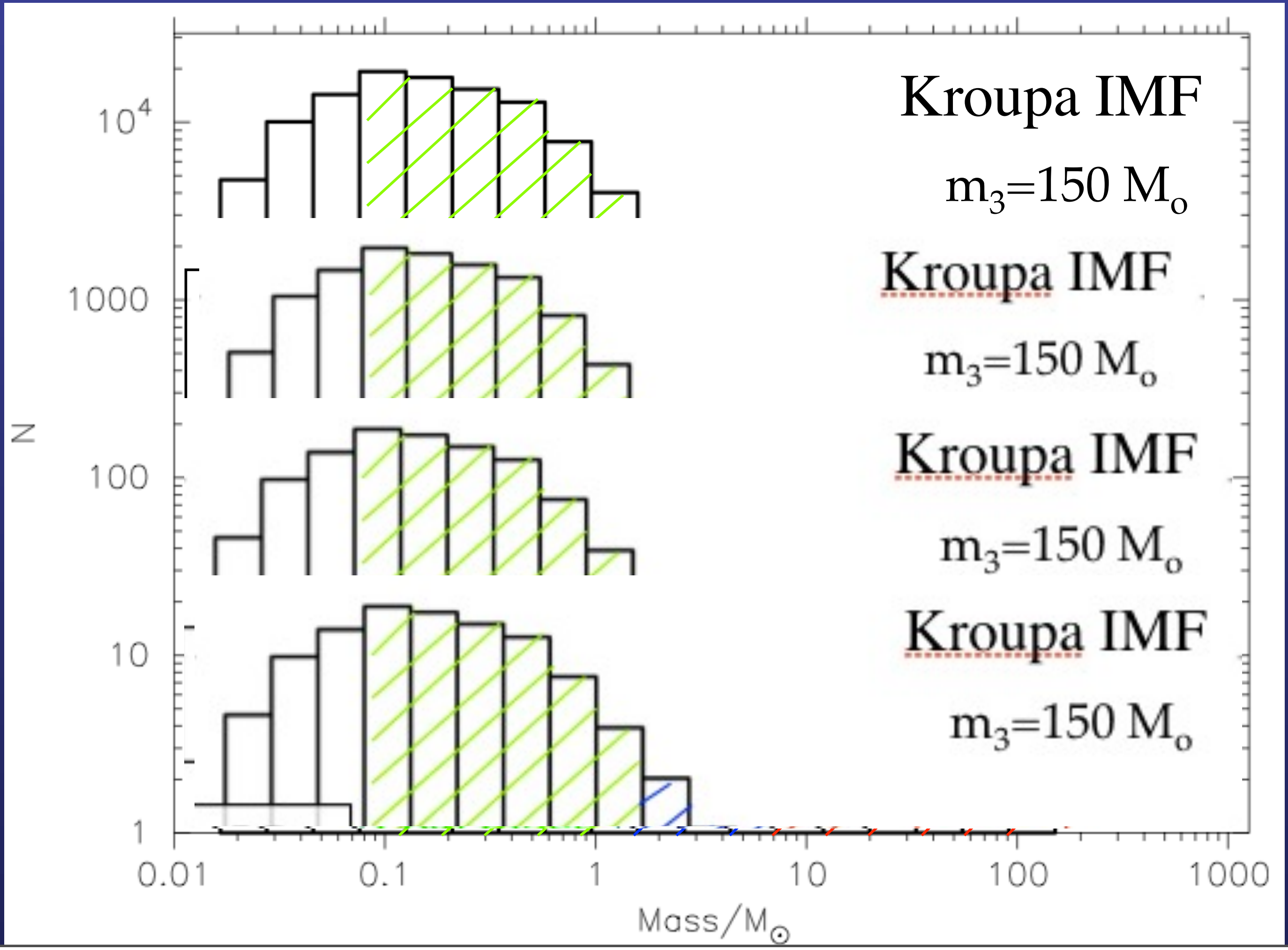
Massive Stars & the IMF

M cluster
5×10^4 Msun

M cluster
5×10^3 Msun

M cluster
5×10^2 Msun

M cluster
5×10^1 Msun



Massive Stars & the IMF

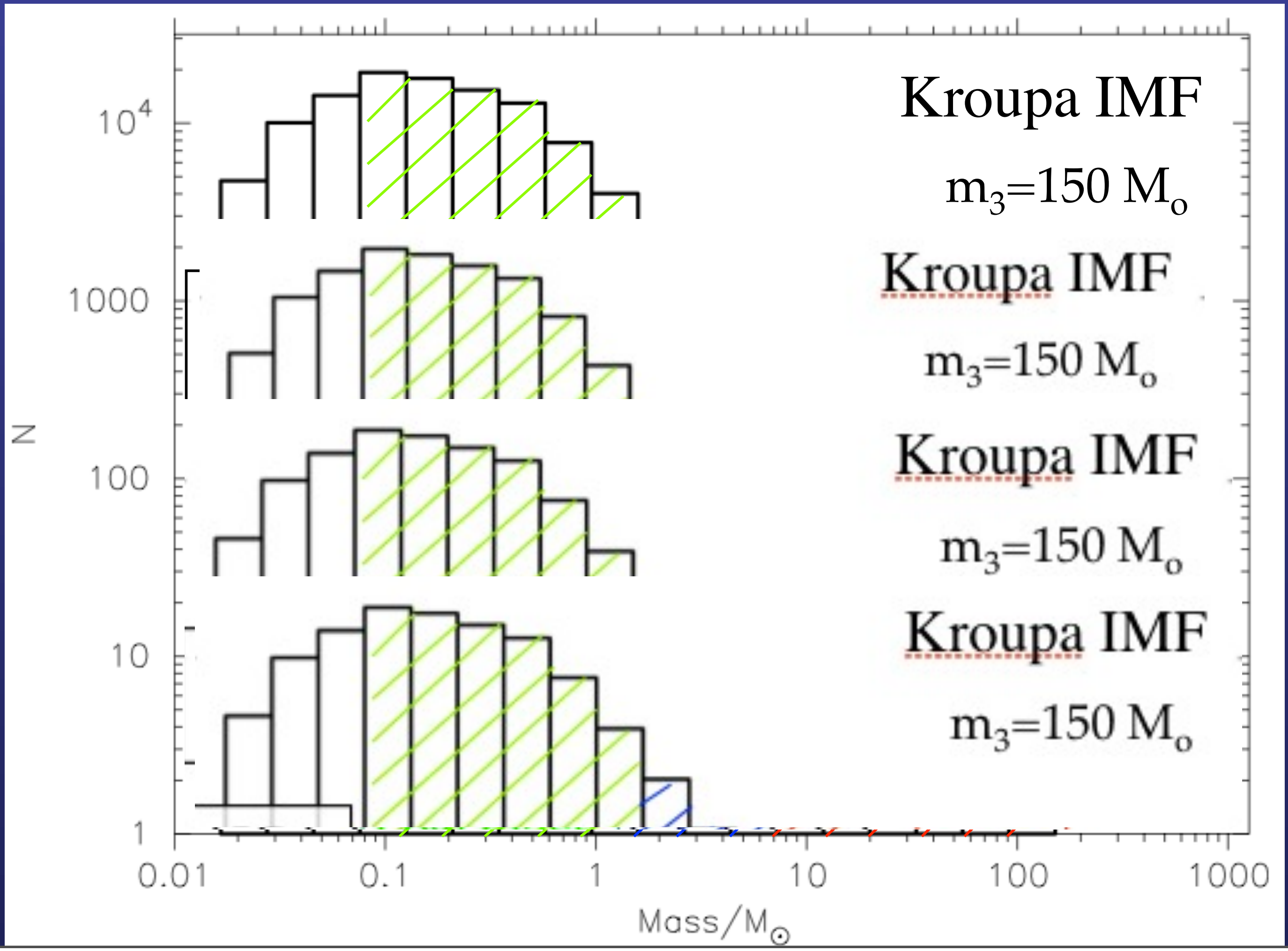
Amanda Karakas: “Stars more massive than 4 M_{sun} are rare”

$M_{cluster}$
$5x10^4$ M_{sun}

$M_{cluster}$
$5x10^3$ M_{sun}

$M_{cluster}$
$5x10^2$ M_{sun}

$M_{cluster}$
$5x10^1$ M_{sun}



Where (not) to look for very massive stars?

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- Orion Nebula? No
  2000 M_{sun} so IMF only sampled up to ~30 M_{sun}

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Westerlund 1? No
10^5 M_{sun} but too old at 4-5 Myr for v. massive stars

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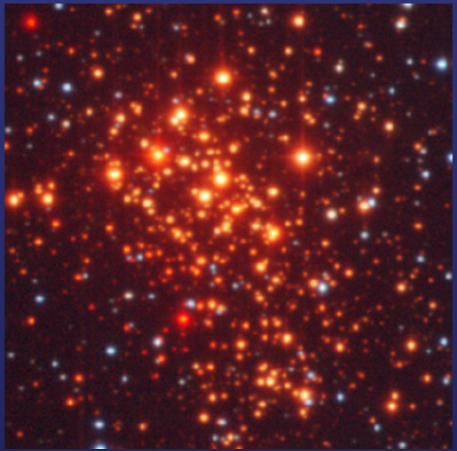

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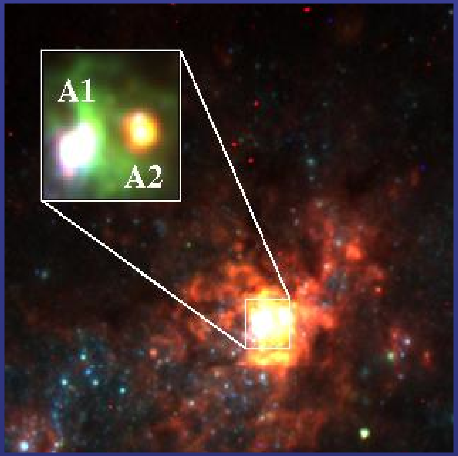

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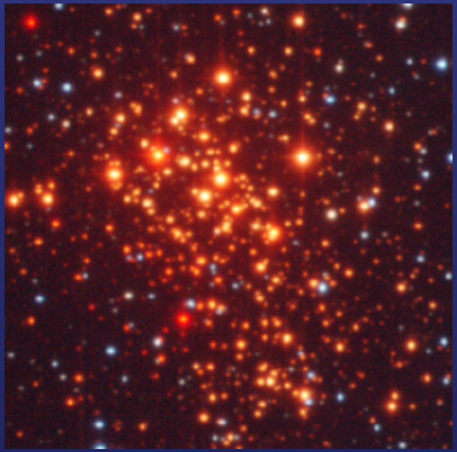
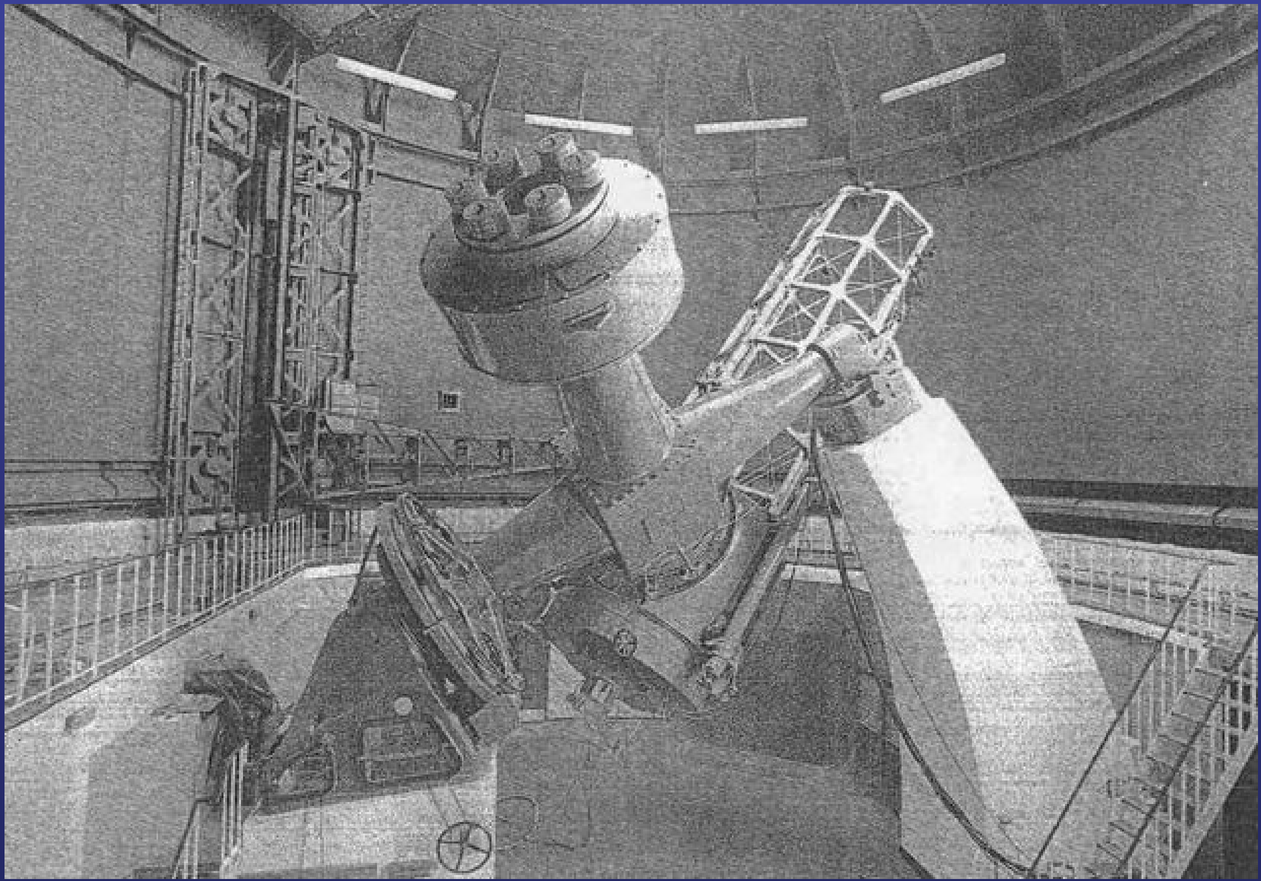


NGC3125-A1? No
10^5 M_{sun}, potentially young, but spatially unresolved

- **Part I: Why should we be cautious about `supermassive' stars?**
- Part II: Why should we question the conventional ~150 M_{sun} mass limit?
- Part III: So....what is the mass limit?
- Part IV: Astrophysical implications of very massive stars?
- Part V: Quantitative properties of massive stars in starburst regions


Large Magellanic Cloud
30 Doradus

Brightest stars in Magellanic Clouds (Feast+ 1960)



- Survey from Radcliffe telescope in S.Africa
- R1-50 (SMC)
- R51-158 (LMC)

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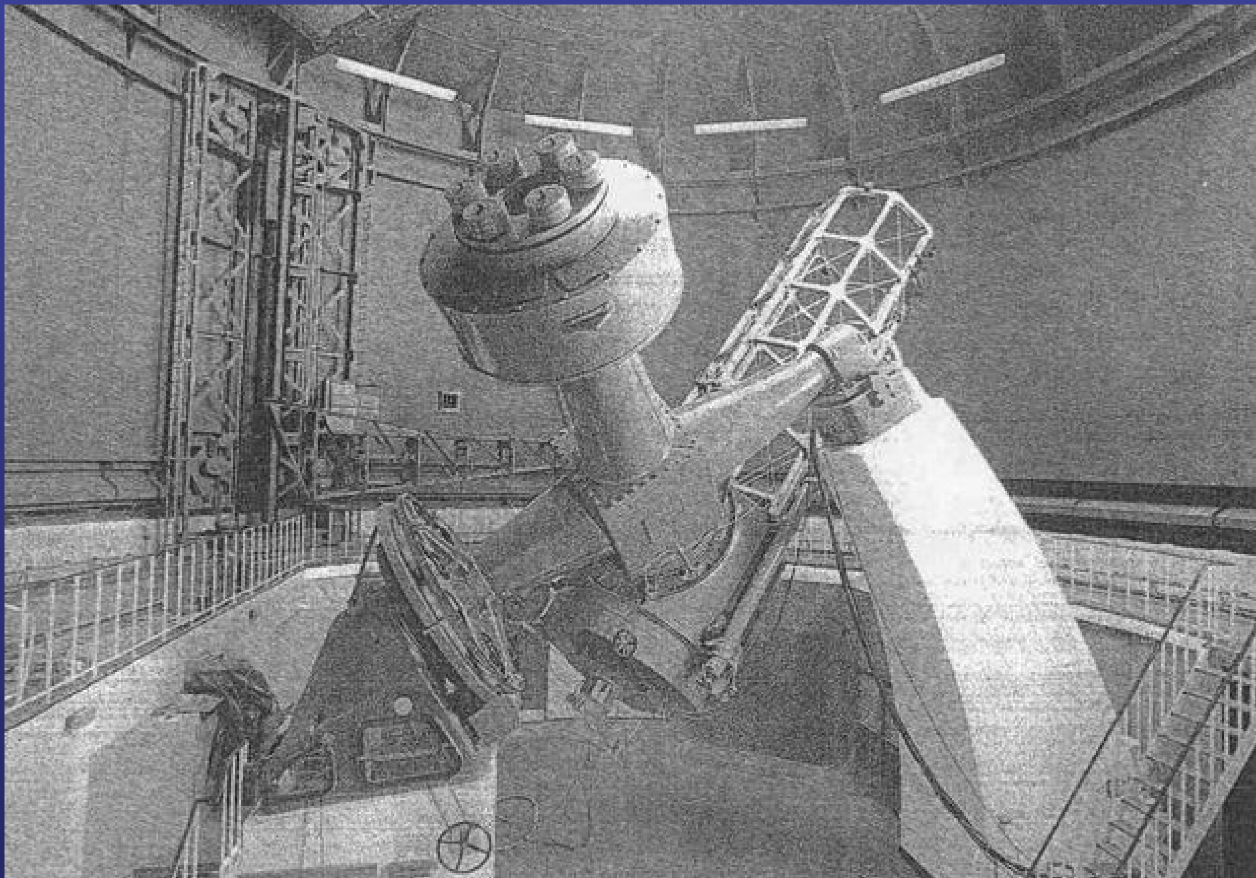

R71 poster Mehner et al.

- Survey from Radcliffe telescope in S.Africa
- R1-50 (SMC)
- R51-158 (LMC)

R136a: Supermassive star?

Central Object of the 30 Doradus Nebula, a Supermassive Star

Joseph P. Cassinelli, John S. Mathis and Blair D. Savage

Science, New Series, Vol. 212, No. 4502 (Jun. 26, 1981), pp. 1497-1501
(article consists of 5 pages)
Published by: American Association for the Advancement of Science
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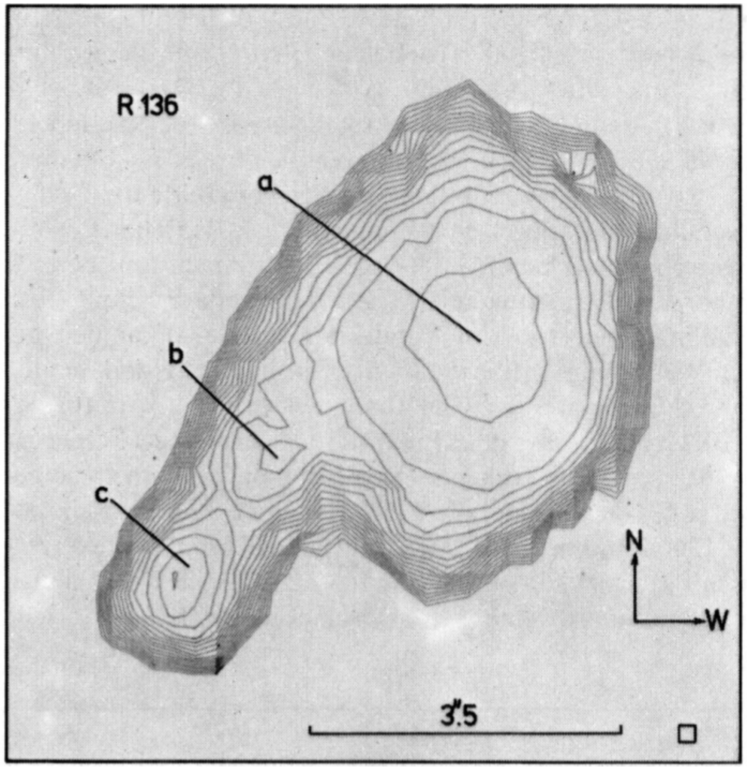

Abstract

R136 (HD 38268) is the central object of the 30 Doradus Nebula, a giant region
Observations of R136 at low and high spectral resolution with the International
massive stellar wind. An outflow speed of 3500 kilometers per second and a ter ne
spectra. The bulk of the observed ultraviolet radiation must come from R136a, te
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for the massive stellar wind.

ESO 3.6m: Feitzinger et al. (1980)

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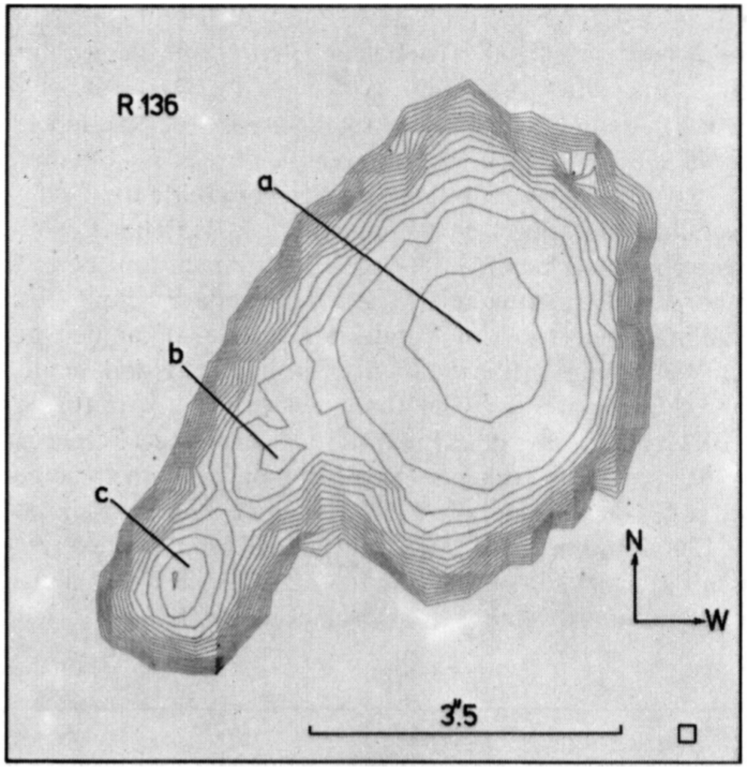

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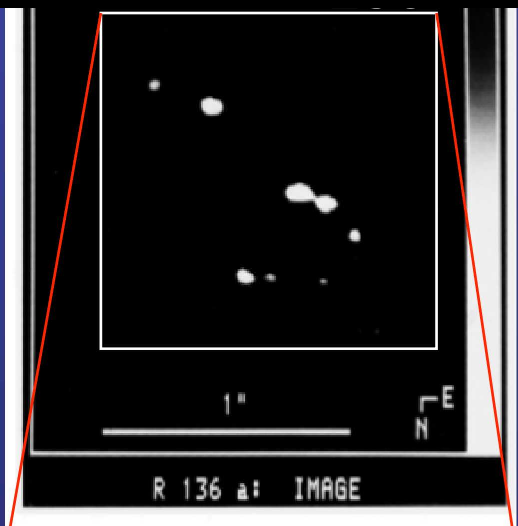
R136a: Dense star cluster

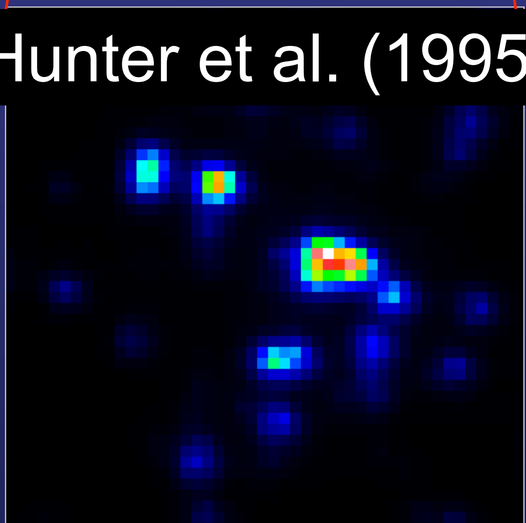
Weigelt & Baier (1985)

R136a: Dense star cluster

Weigelt & Baier (1985)

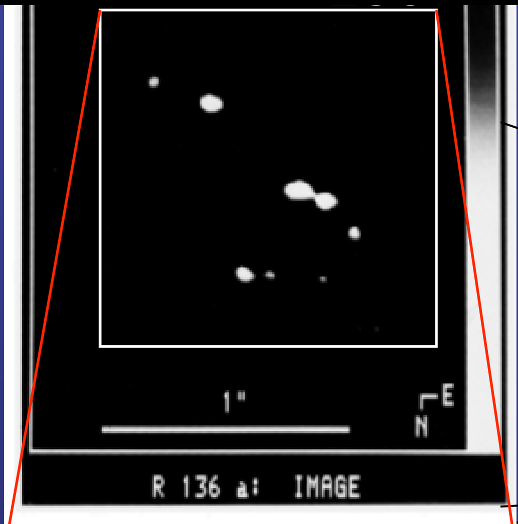


Hunter et al. (1995)



R136a: Dense star cluster

Weigelt & Baier (1985)



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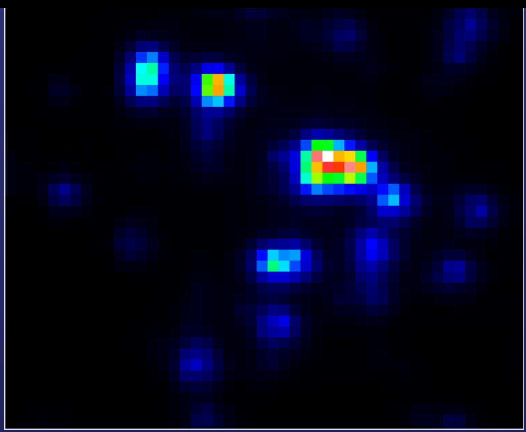
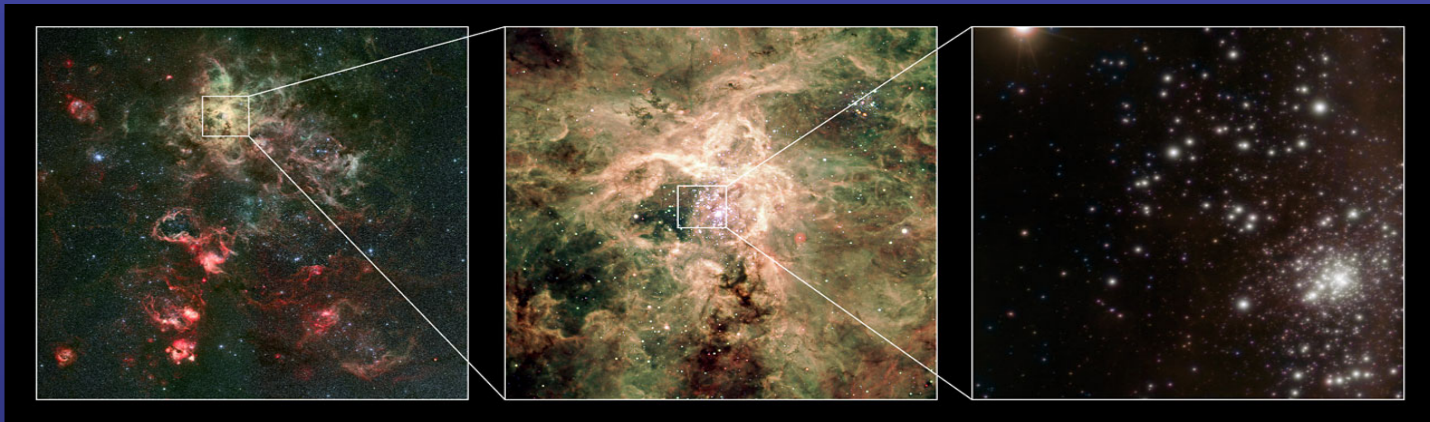


De Marchi et al. (2011)

Spectroscopy of R136 stars

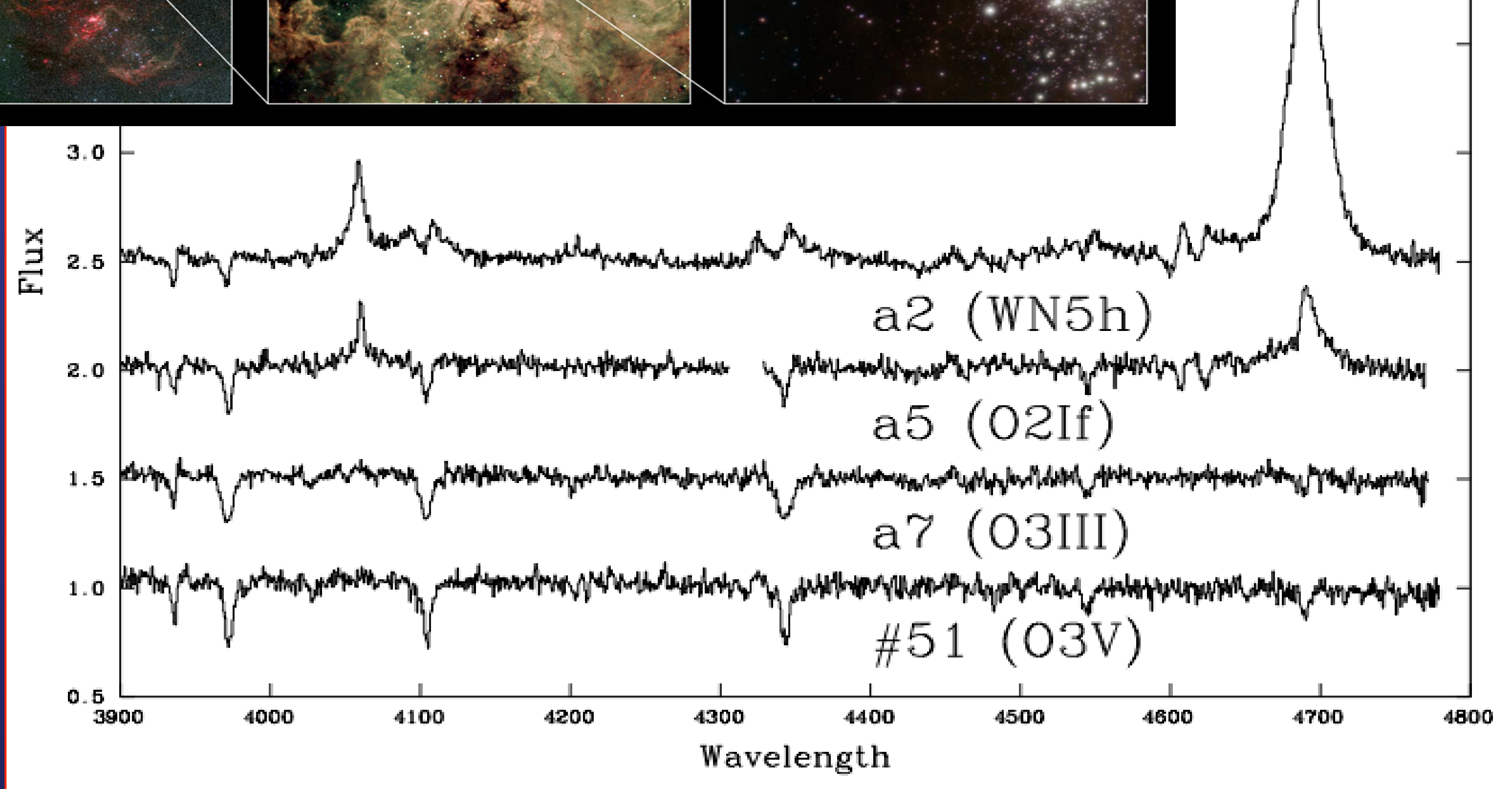


$M_V=-8$

$M_V=-6.4$

$M_V=-5.7$

$M_V=-5$



Temperatures for hot stars

PROBLEMS WITH CONTINUUM MEASURES
OF HOT STARS ...
(with apologies to H.J.G.L.M.L.)

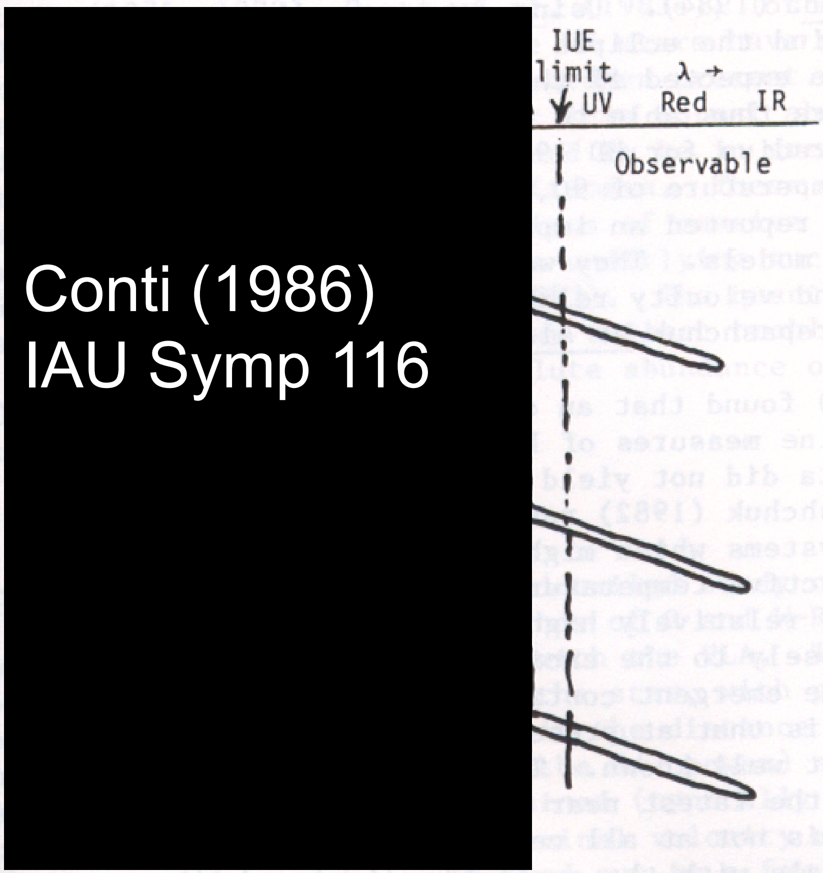


Fig. 2. Cartoon showing difficulty in discerning the nature of the "beast" existing below λ912 Å, the Lyman limit, if one only has the "tail" of the distribution to observe in the UV, optical, and IR wavelengths.

Temperatures for hot stars

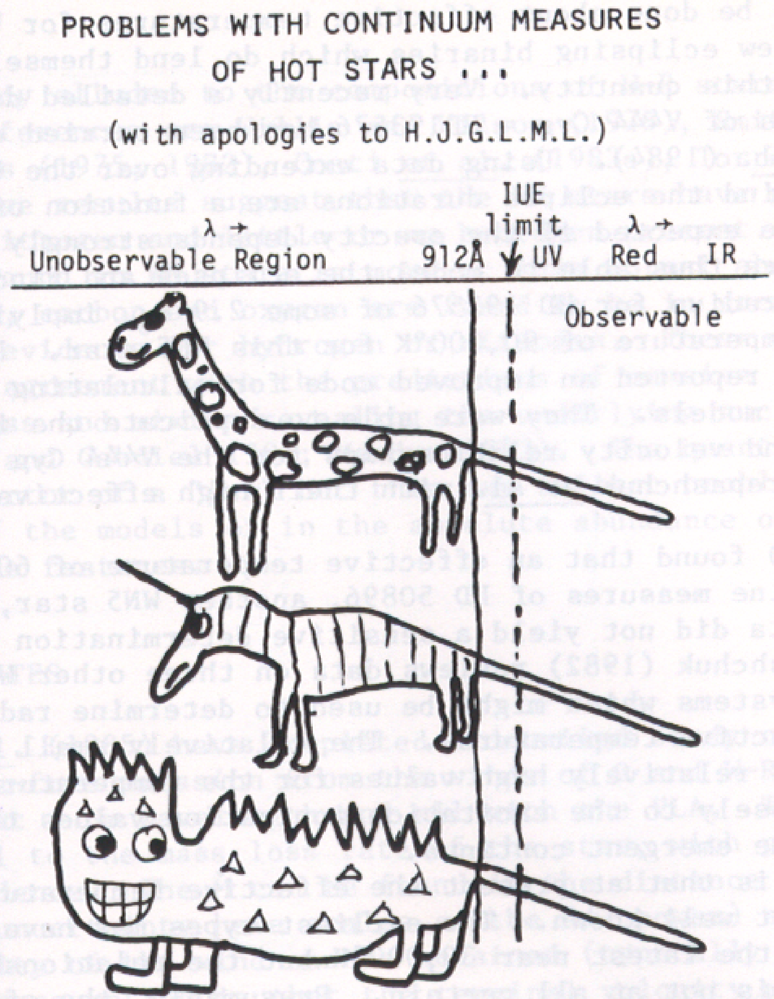
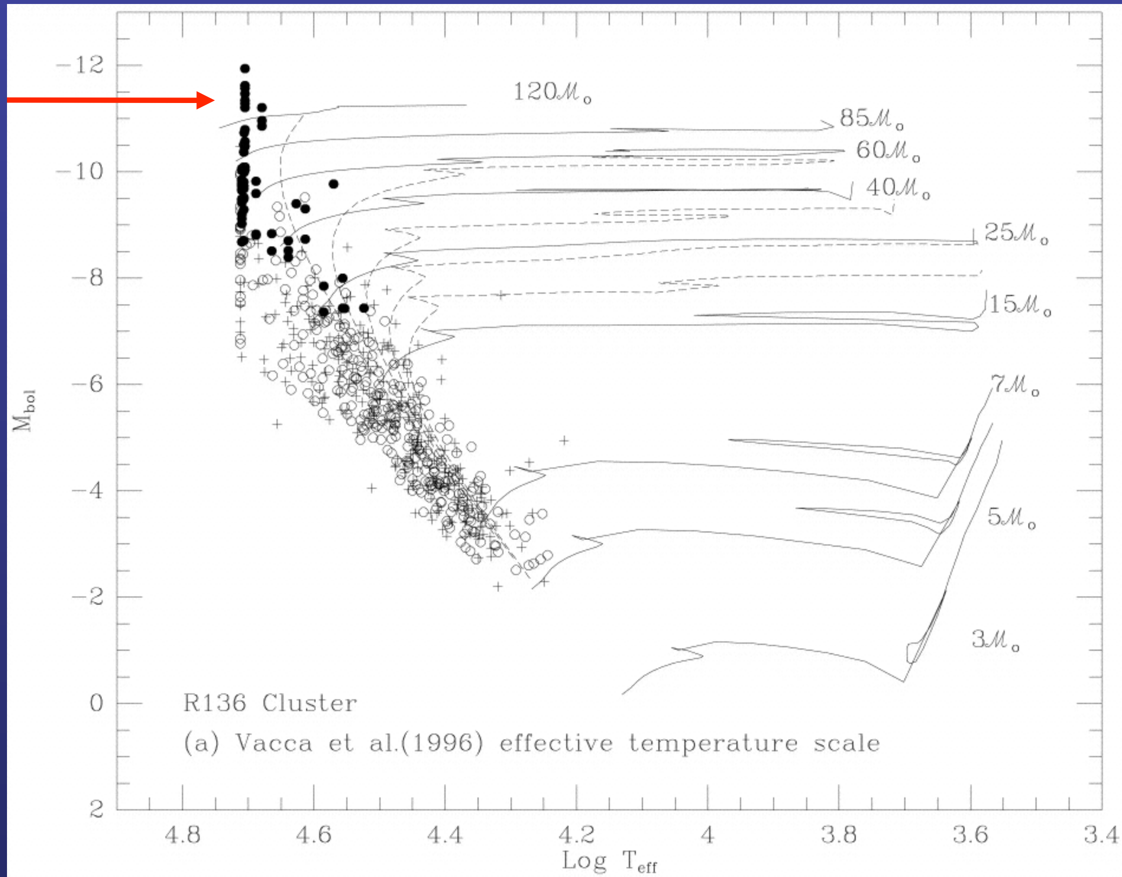


Fig. 2. Cartoon showing difficulty in discerning the nature of the "beast" existing below λ912 Å, the Lyman limit, if one only has the "tail" of the distribution to observe in the UV, optical, and IR wavelengths.

R136a

M_{init}~100-150 M_o for brightest stars within R136 based on:

- Sp-Type Teff calibration for early O stars;
- HST/WFPC2 photometry (Hunter+ 1995)



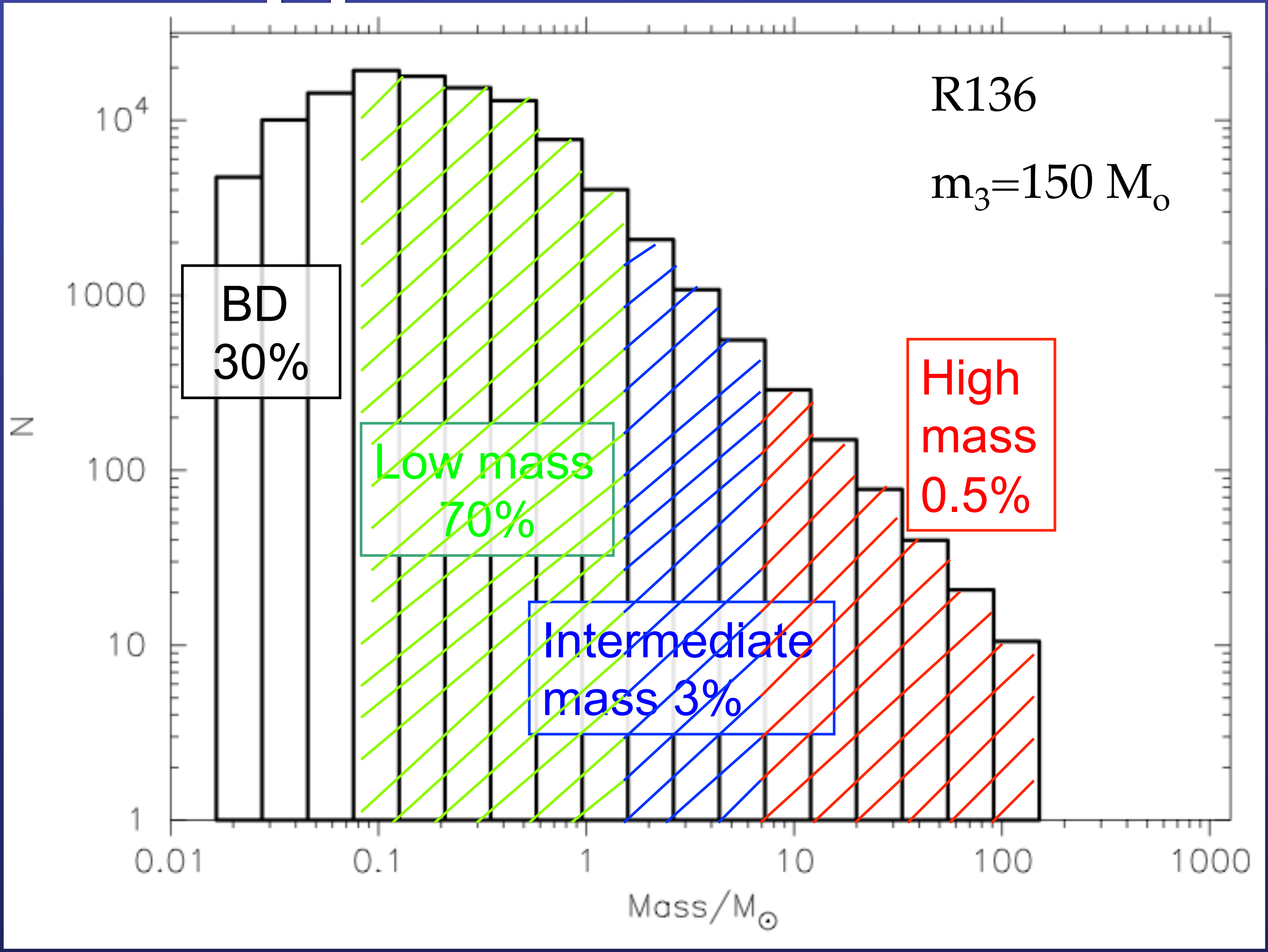
Massey & Hunter (1998)

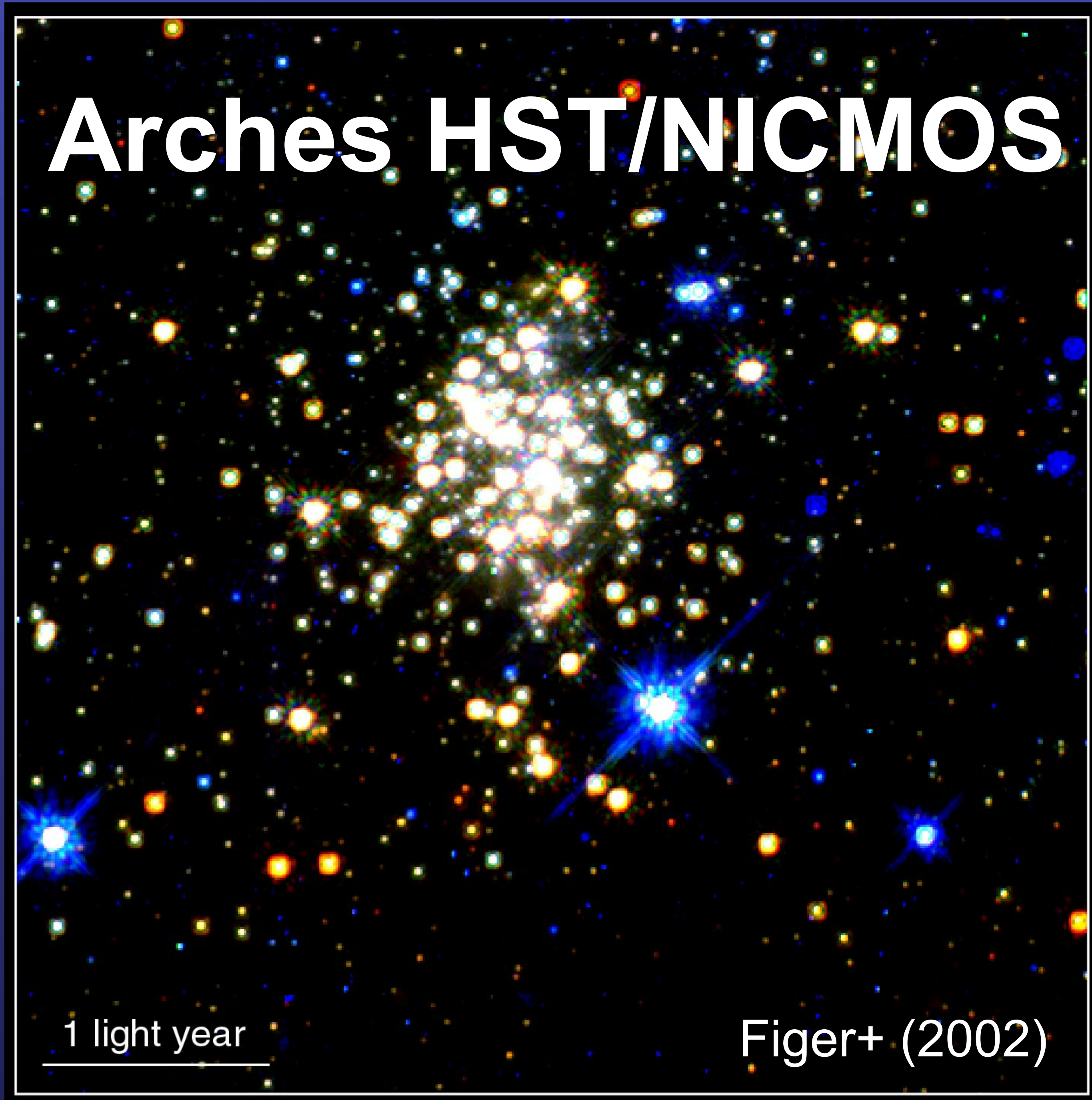
Upper mass limit?

``The very concept of an `upper mass cut-off' has to be considered carefully; at what mass does the IMF predict one star?''

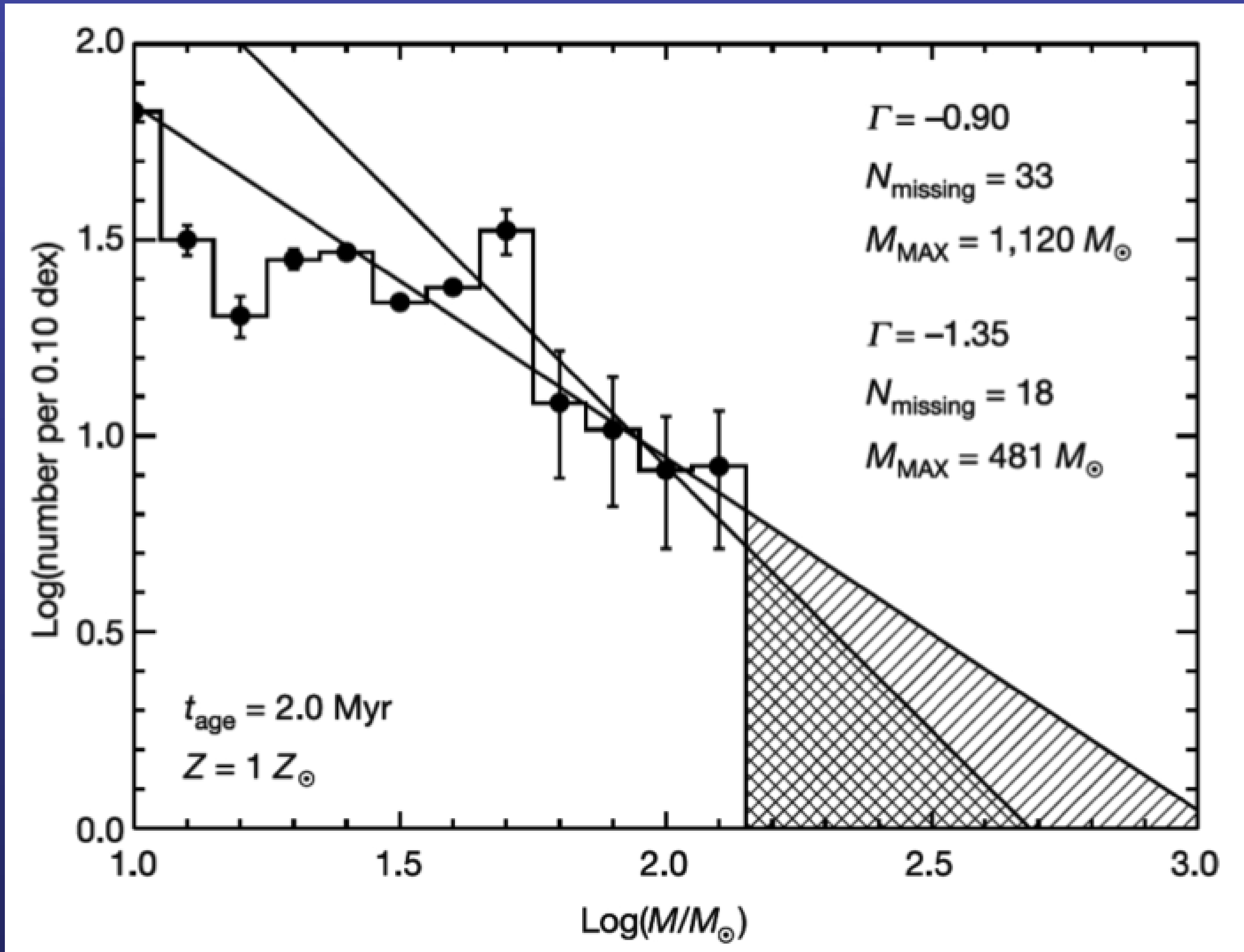
Massey & Hunter (1998)

Upper mass limit?




Arches HST/NICMOS
1 light year
Figer+ (2002)

M_{up}~150 M_{sun}?



Figer (2005)

Statistical Support for M_{up}~150 M_{sun}

M_{up} ~ 140 M_{sun} (R136; Weidner & Kroupa 2004)
M_{up} ~ 120-200 M_{sun} (R136; Oey & Clarke 2005)
M_{up} ~ 140-160 M_{sun} (R136; Koen 2006)

Statistical Support for M_{up}~150 M_{sun}

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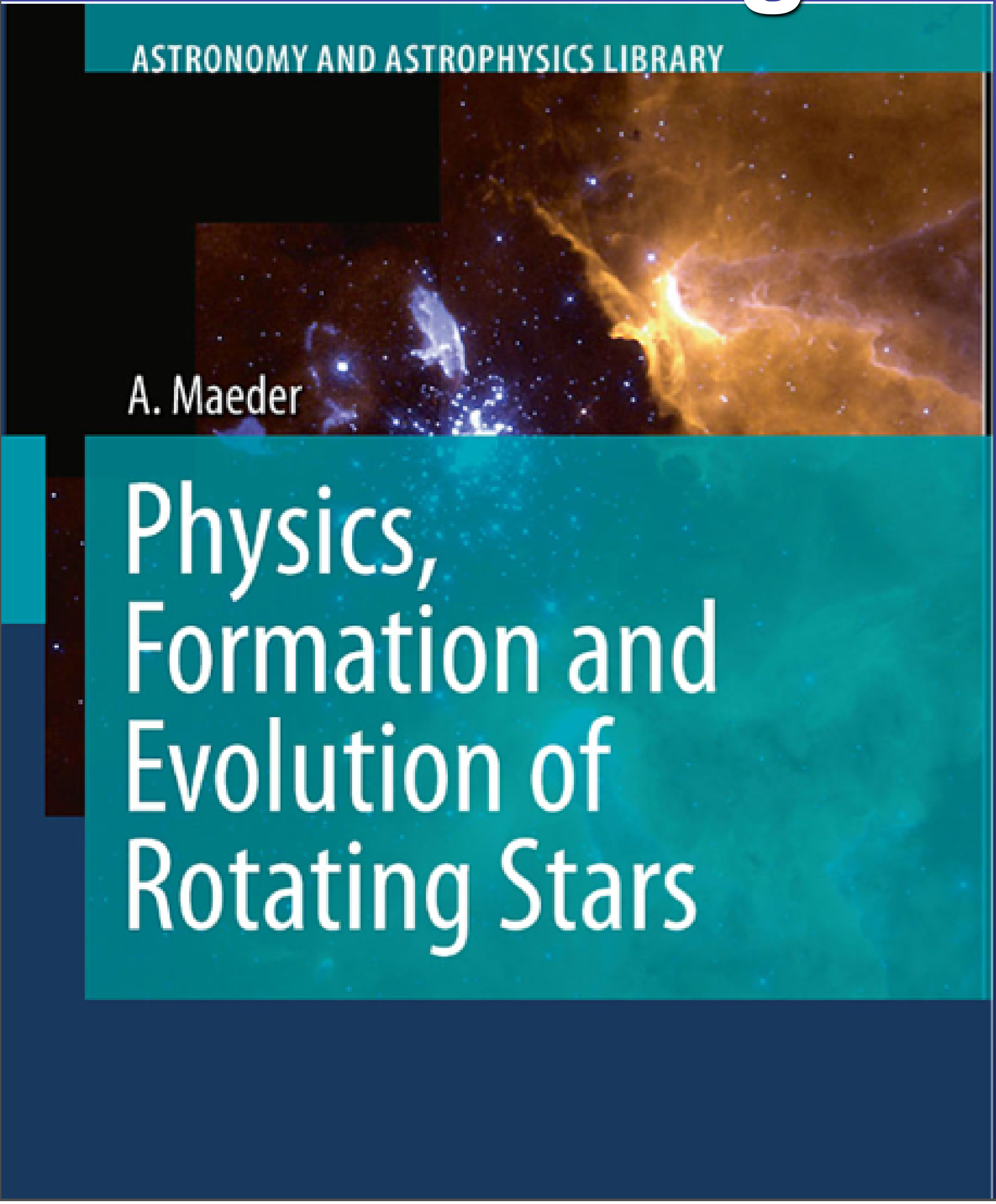
M_{up} ~ 120-200 M_{sun} (R136; Oey & Clarke 2005)
M_{up} ~ 140-160 M_{sun} (R136; Koen 2006)

Oey & Clarke (2005) statistically established M_{up} << 500 M_{sun} *if*, & only if, the most massive stars in R136 indeed have <150 Msun.

Eddington Limit I



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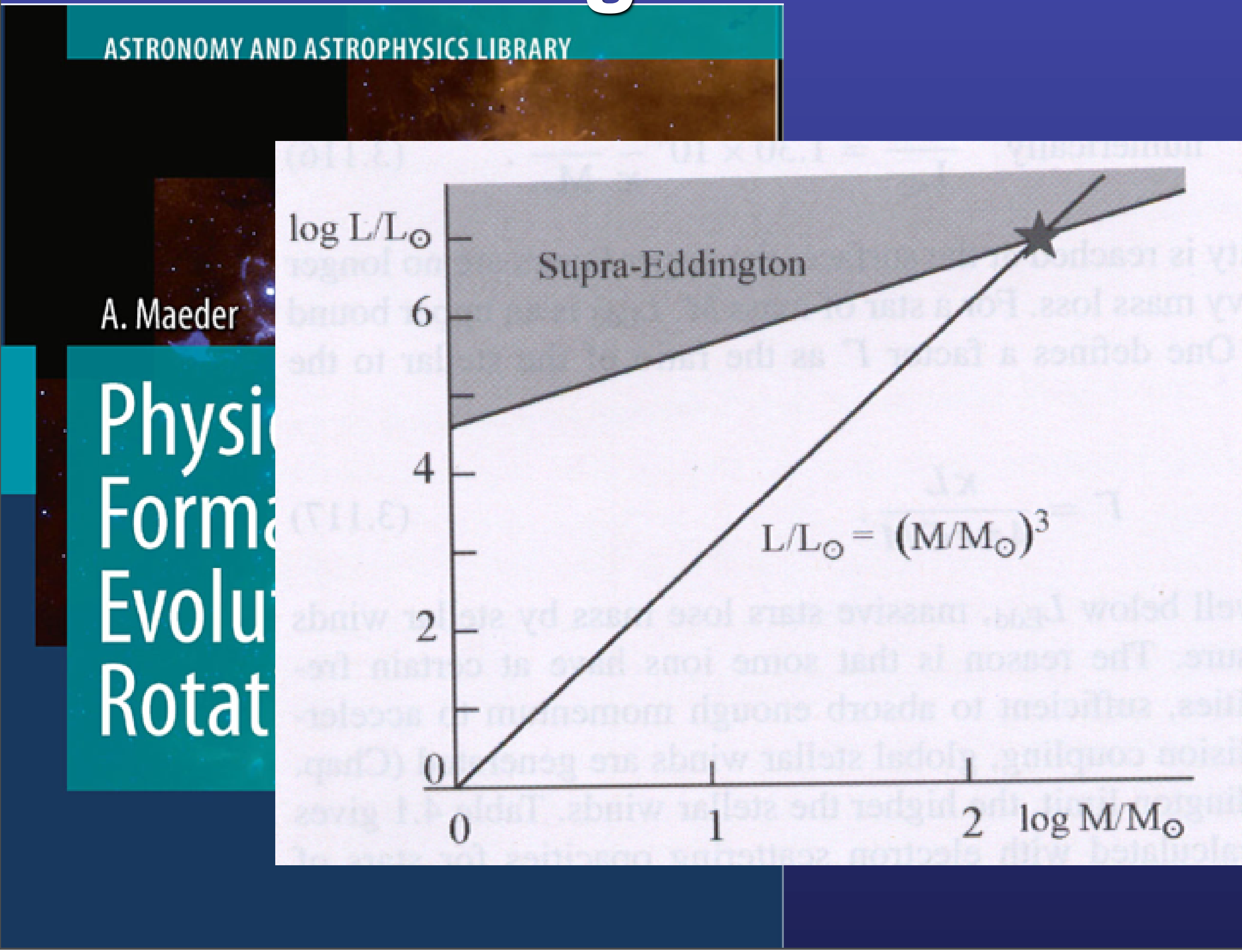
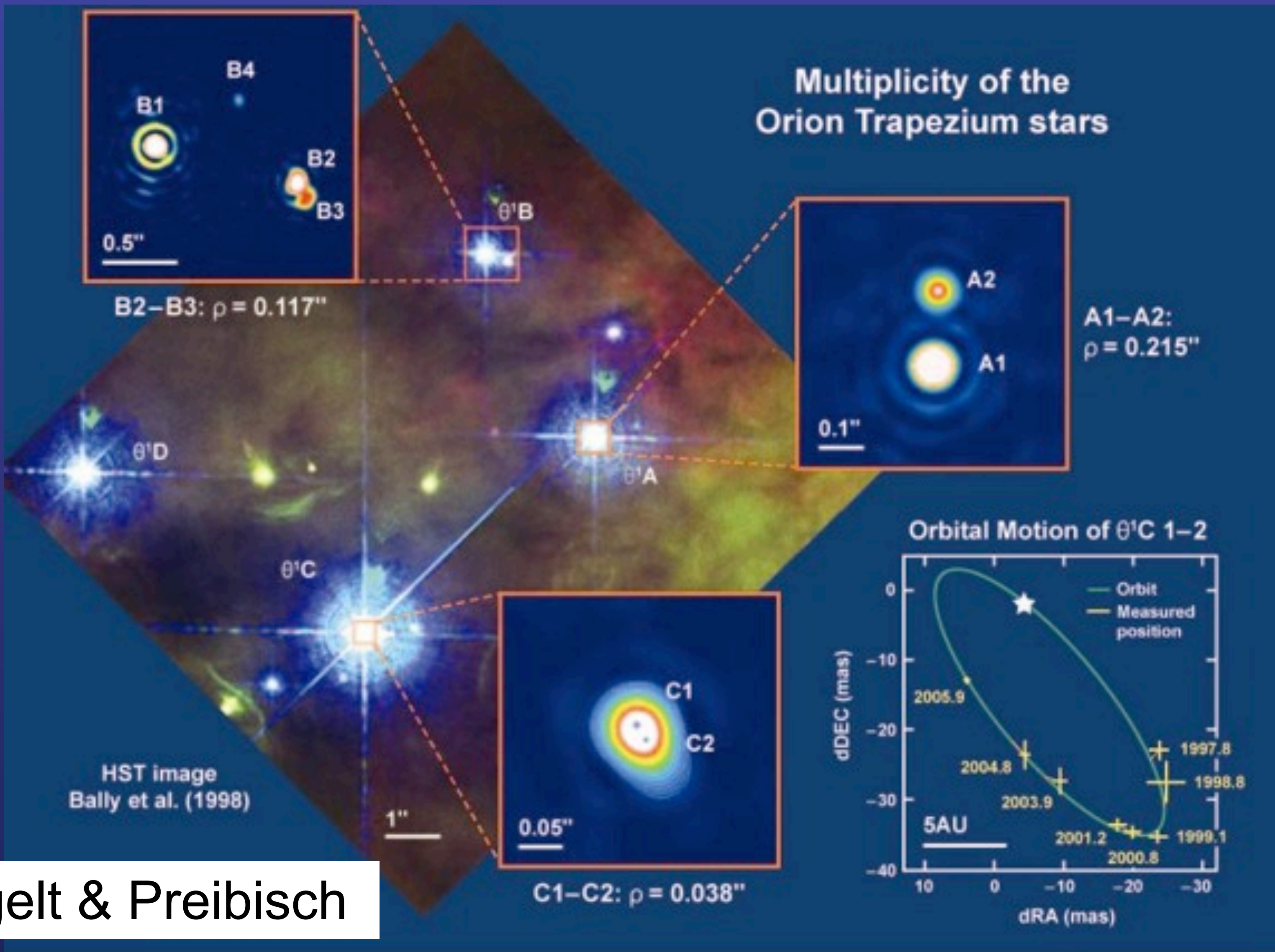


Massive stars prefer company



Weigelt & Preibisch

O-type binary statistics?

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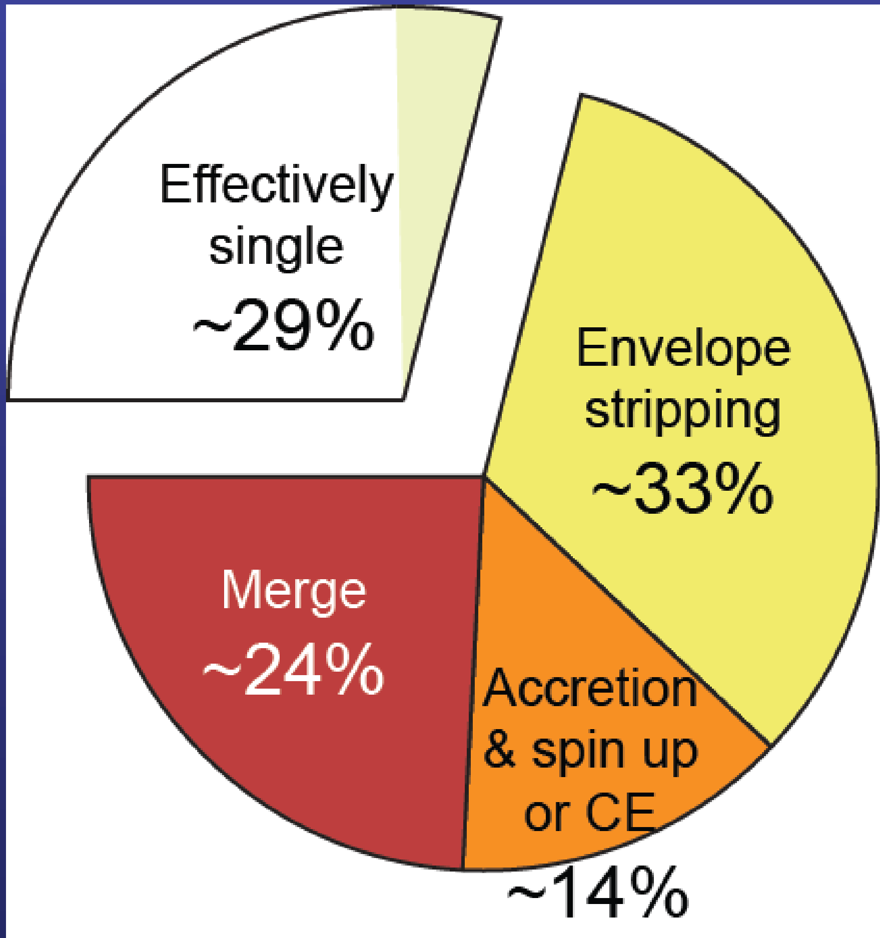
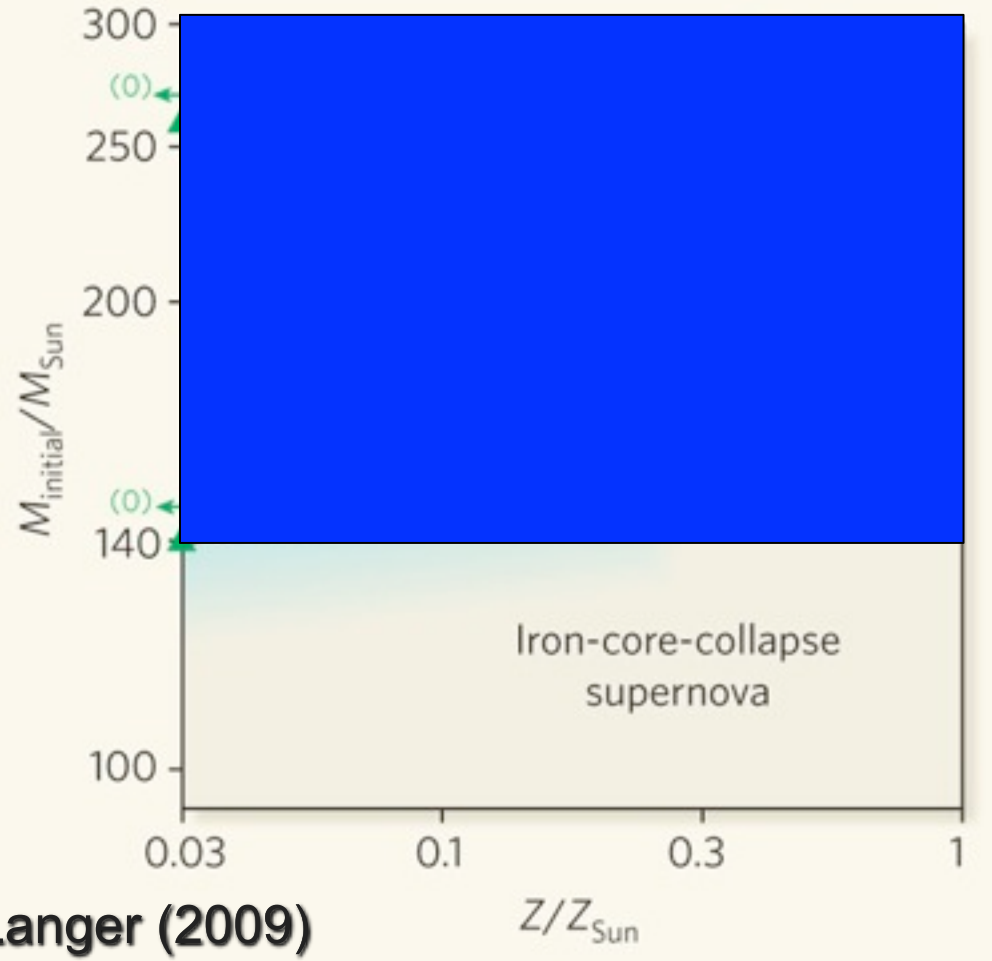


Sana+ (2012, Galactic clusters)

Solely ccSNe from massive stars in local Universe



Langer (2009)

$M_{up} \sim 150 M_{\odot}$

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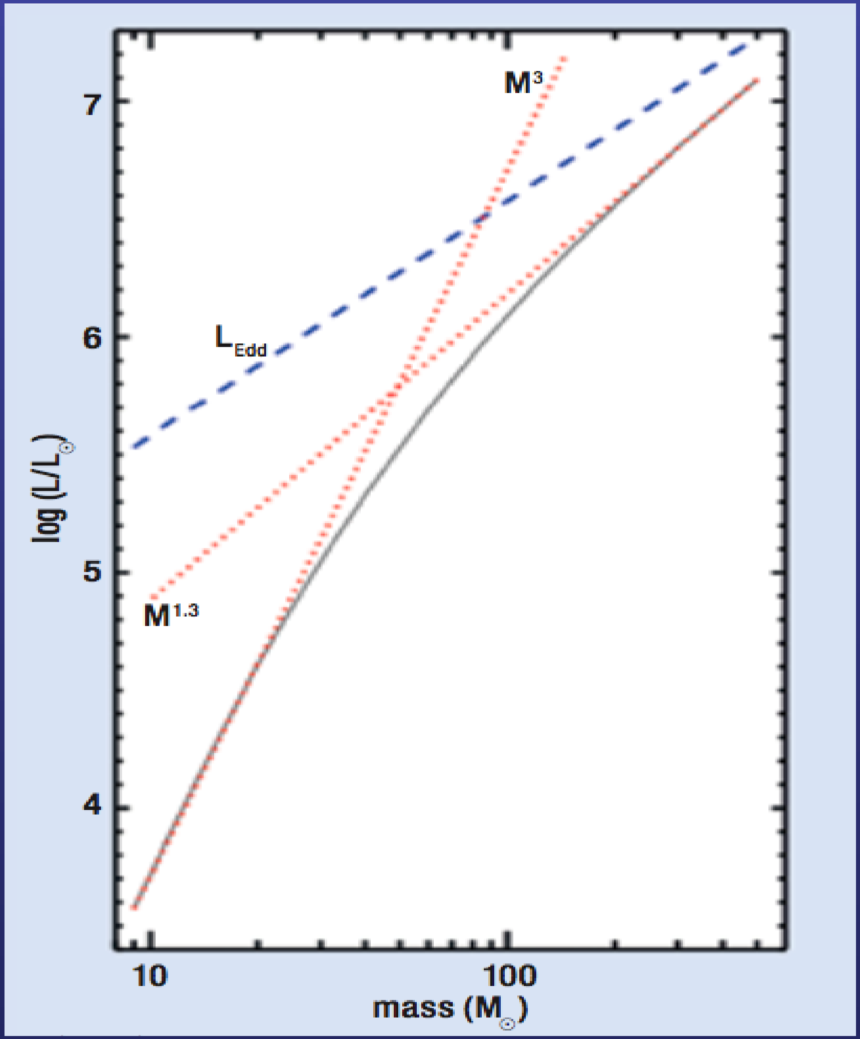
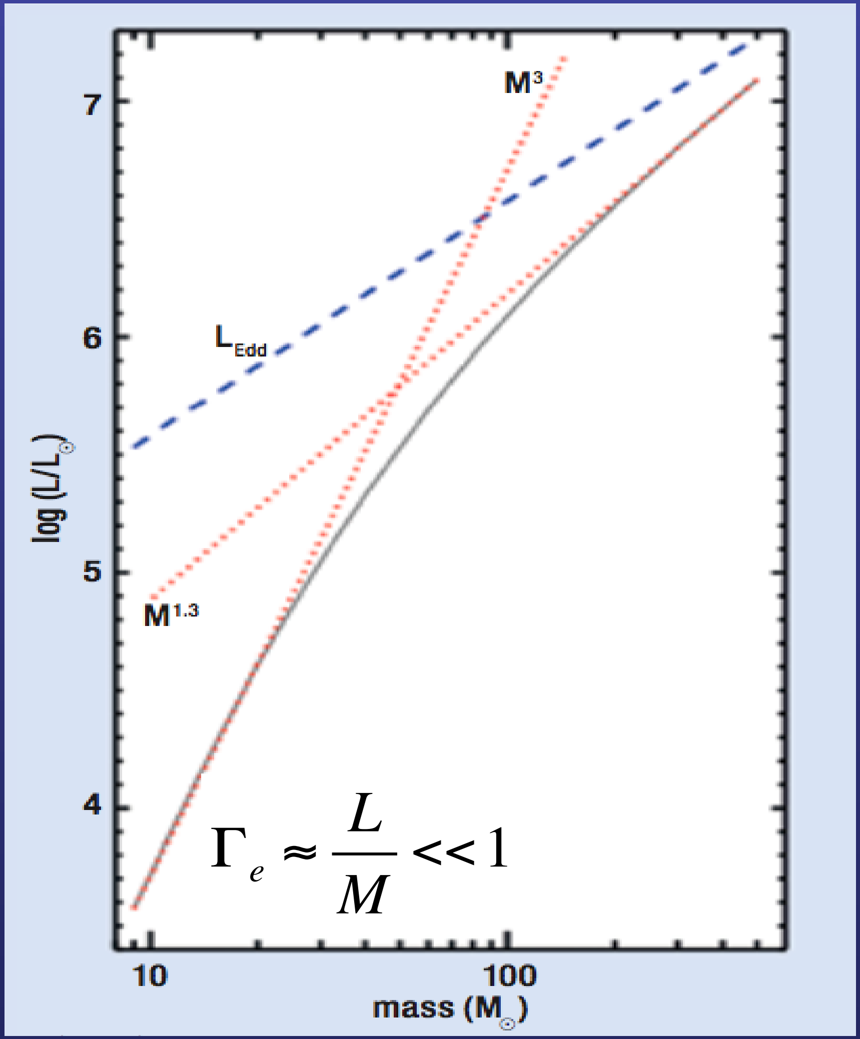
Eddington limit II



Crowther (IAU-GA, A&G)

Eddington limit II



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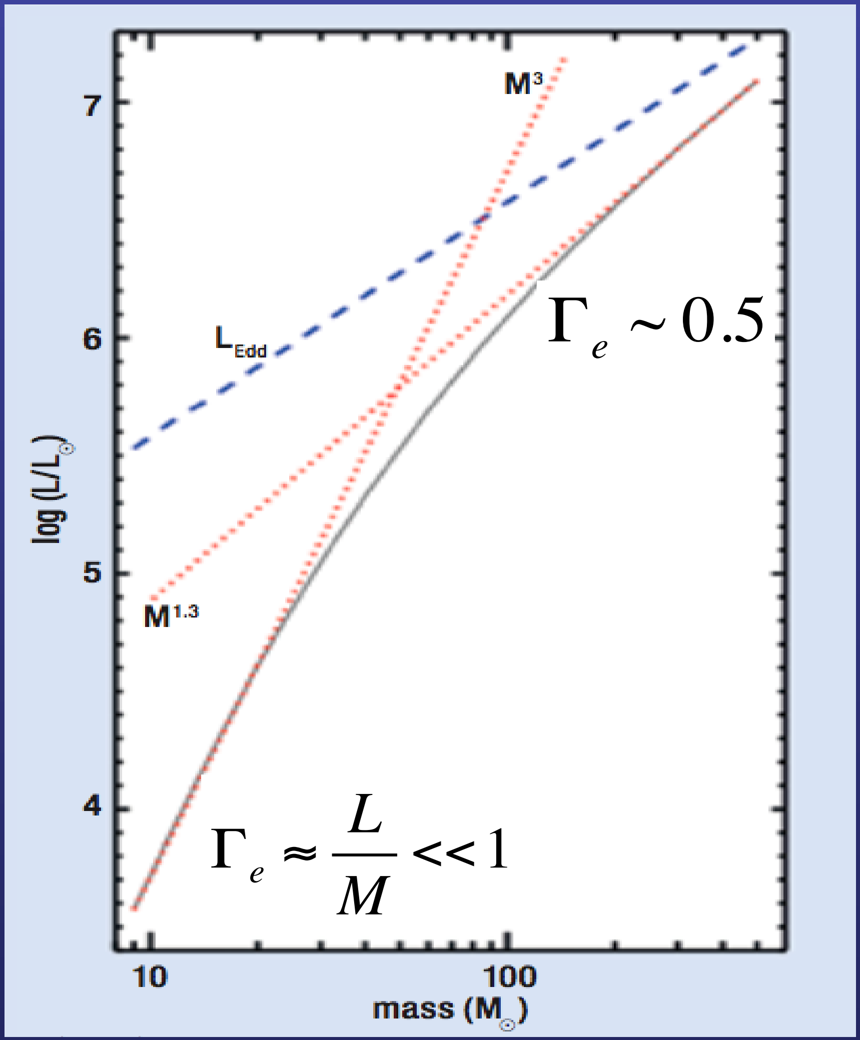

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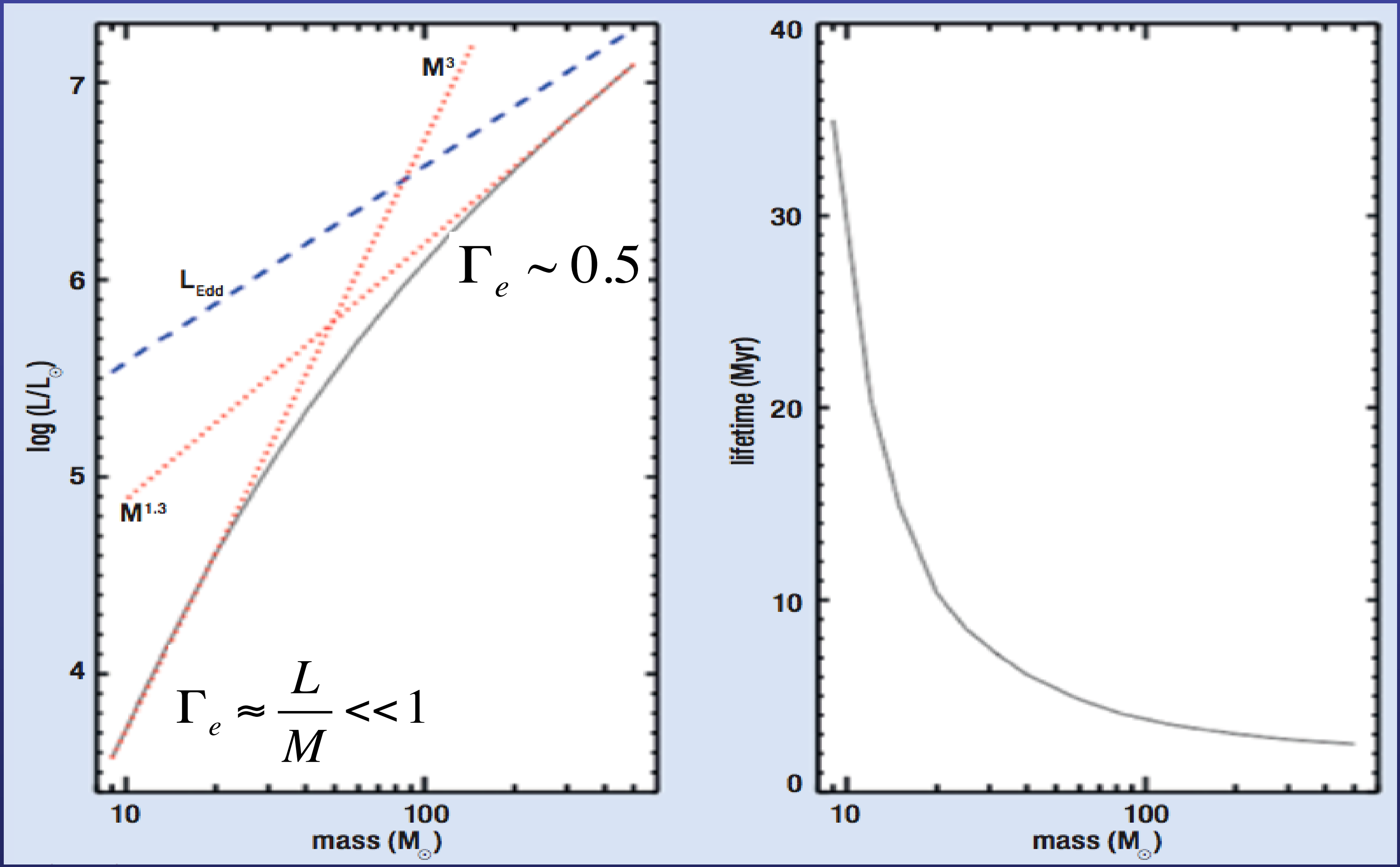

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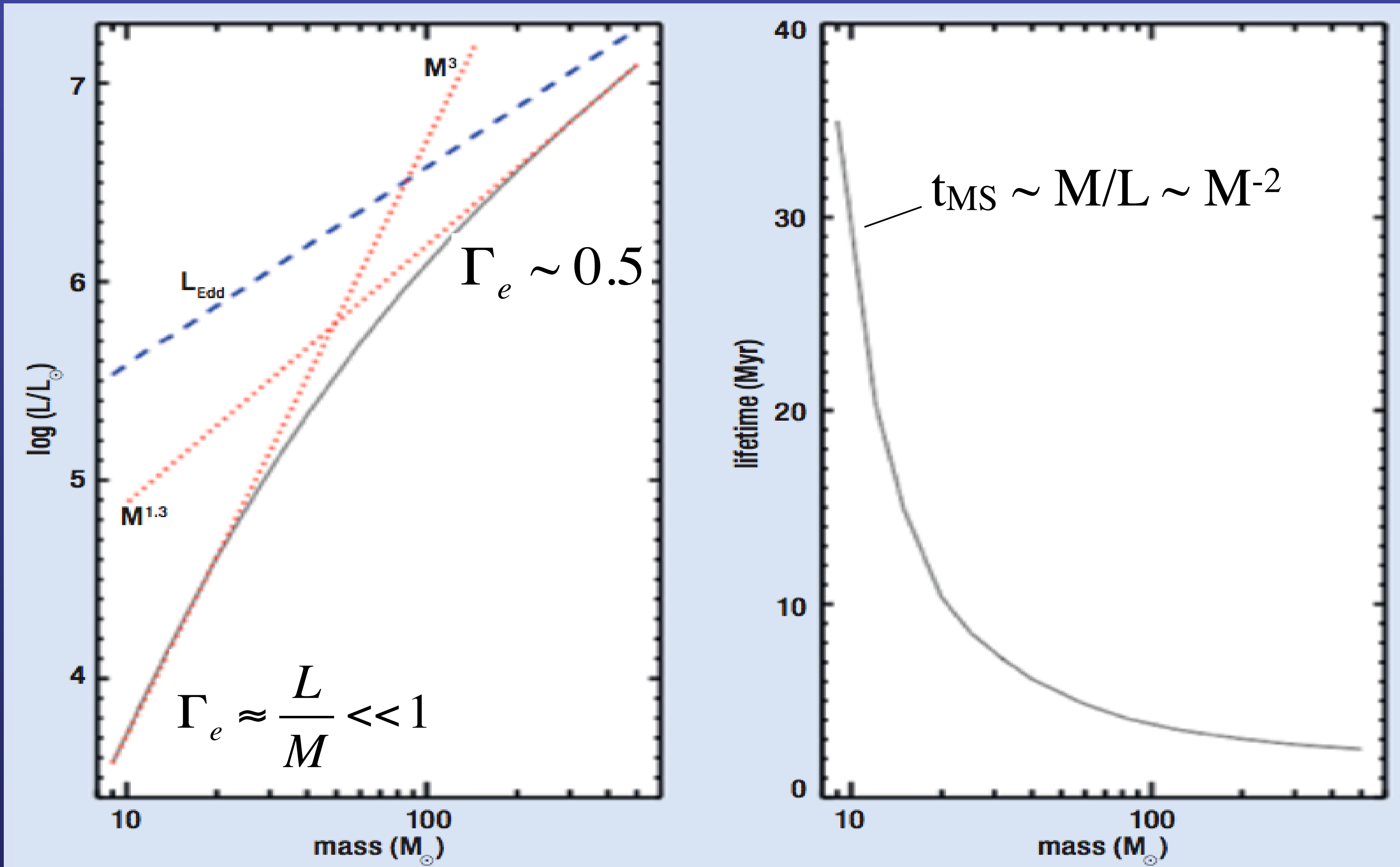
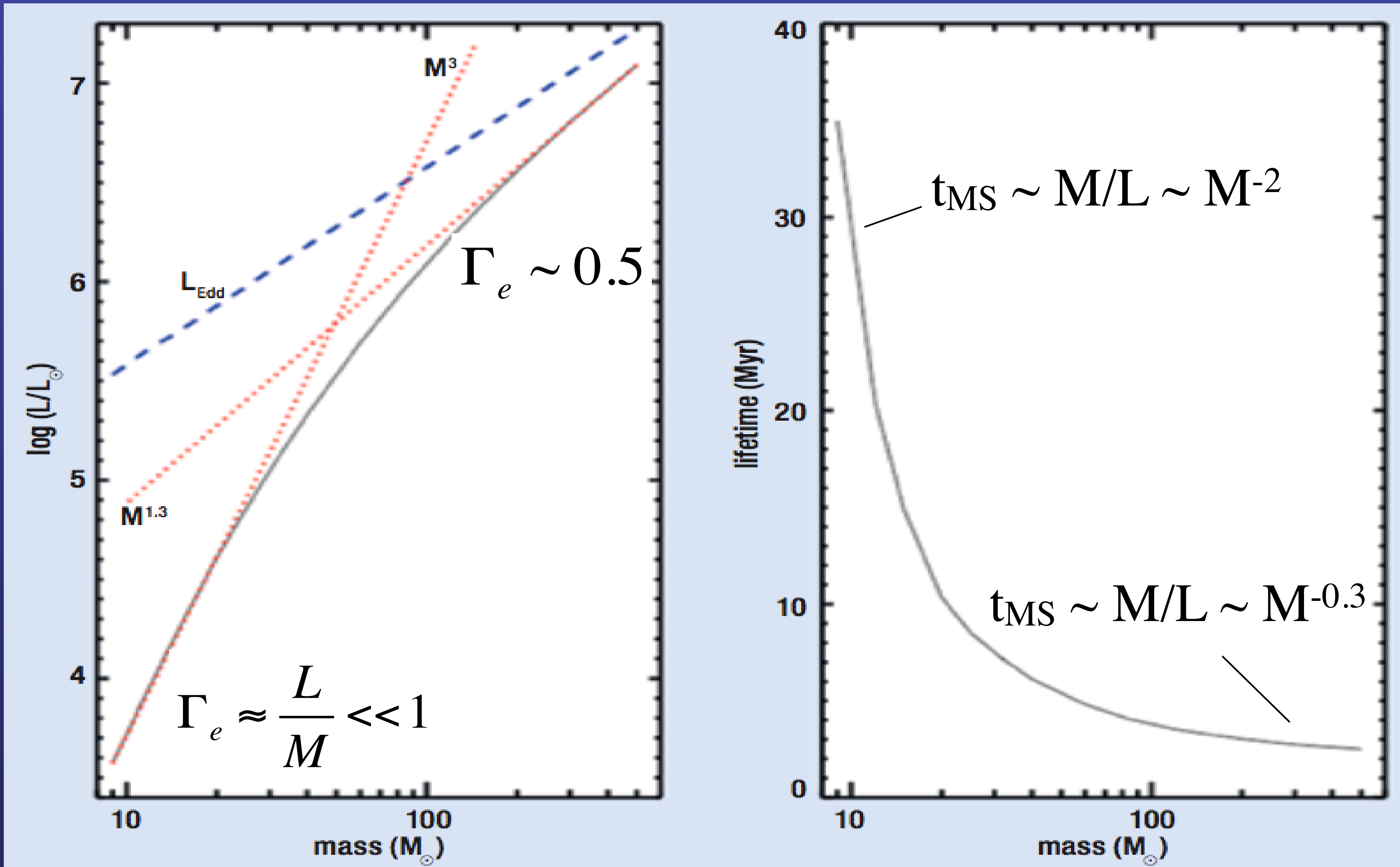


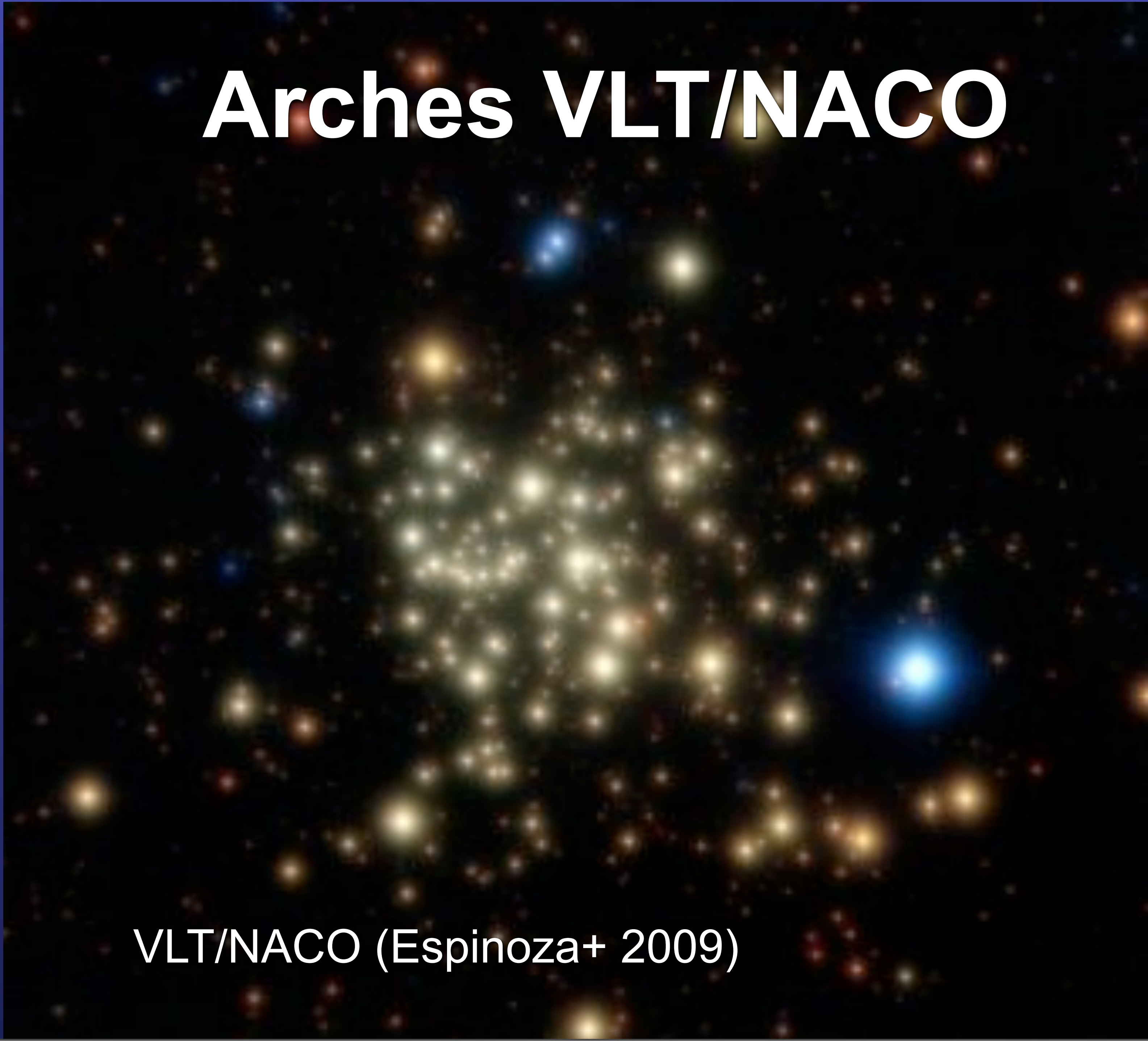
Crowther (IAU-GA, A&G)

Eddington limit II



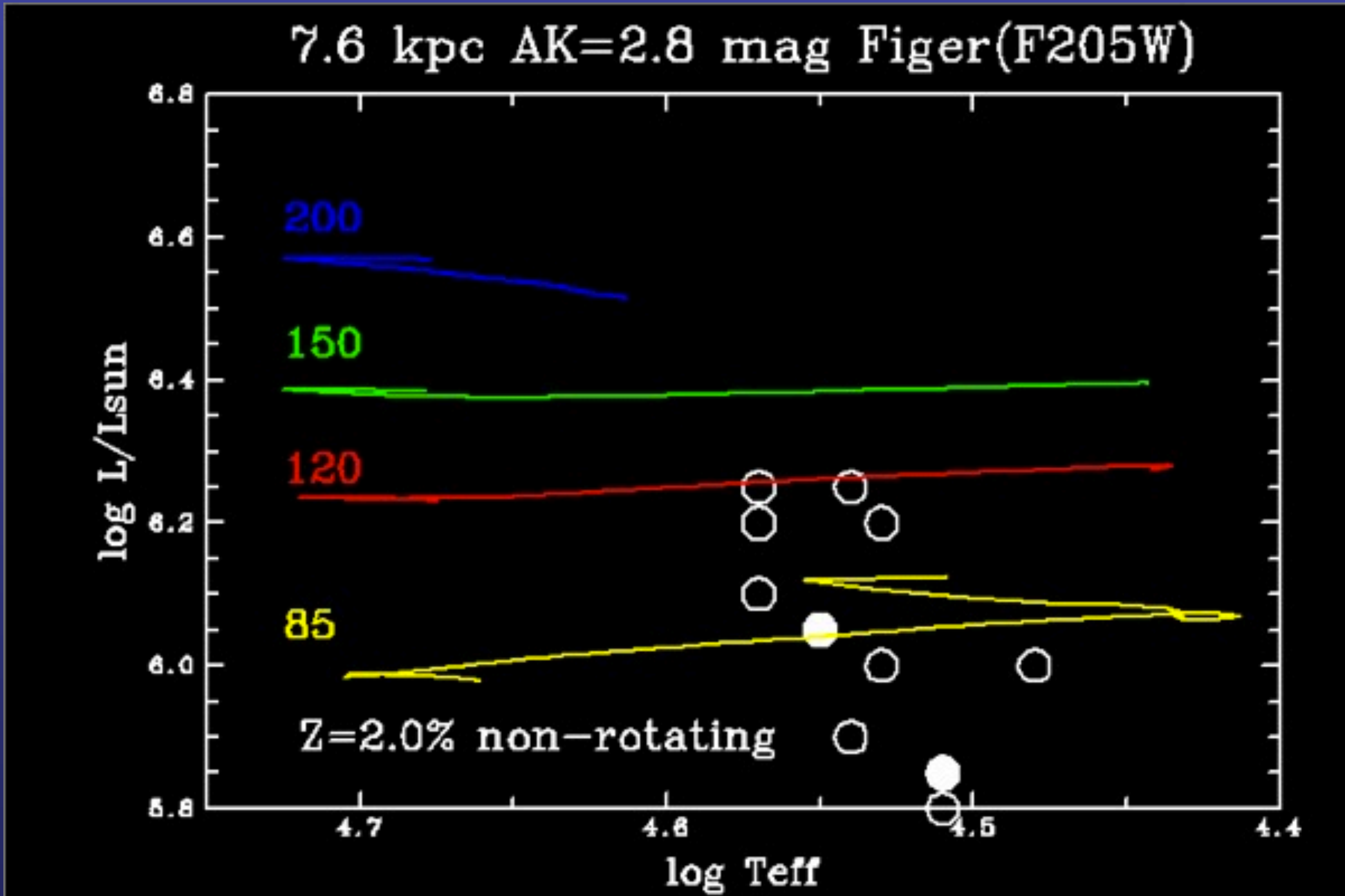
Crowther (IAU-GA, A&G)

Arches VLT/NACO

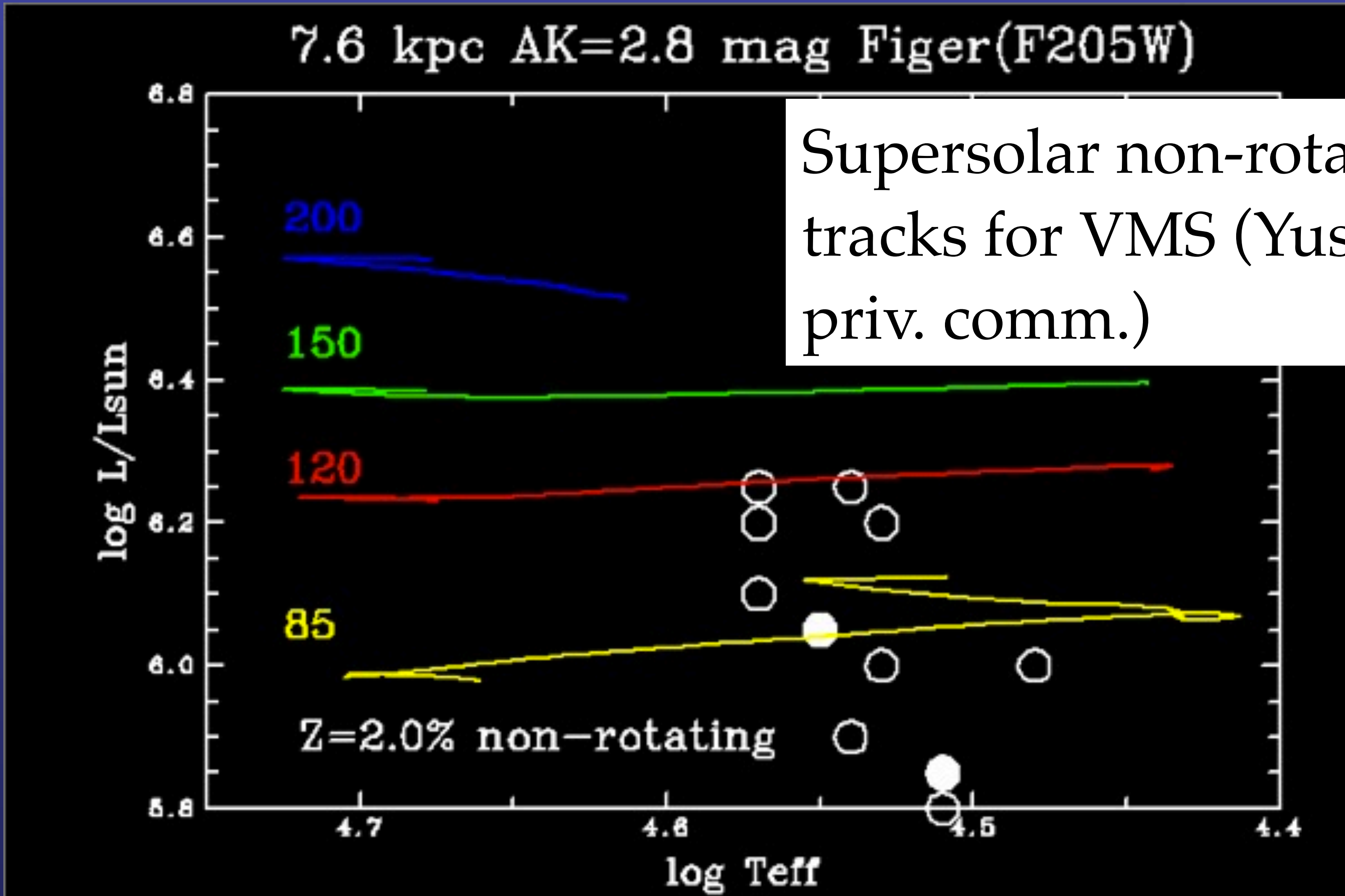


VLT/NACO (Espinoza+ 2009)

NICMOS photometry, low A_K

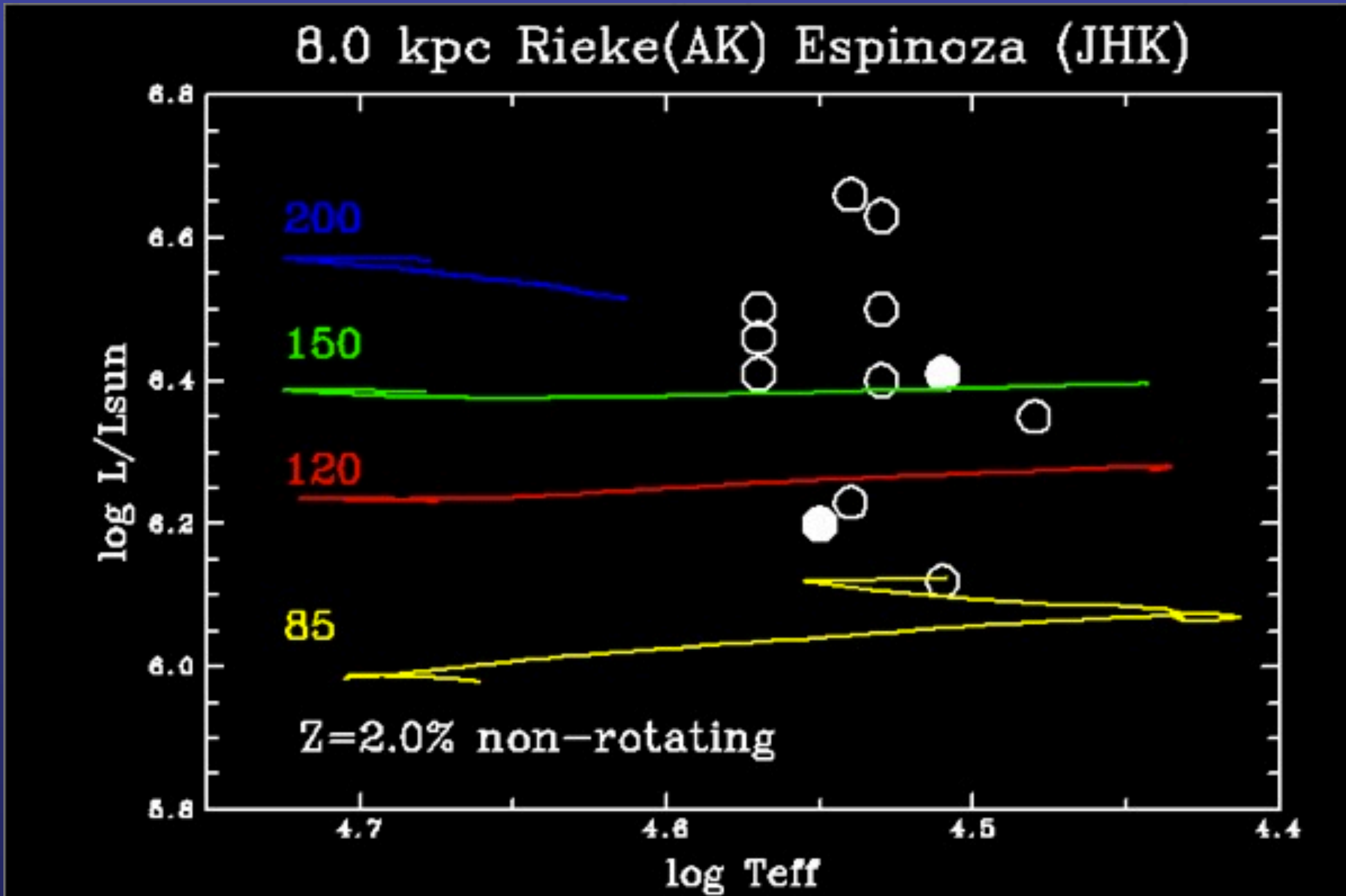


NICMOS photometry, low AK



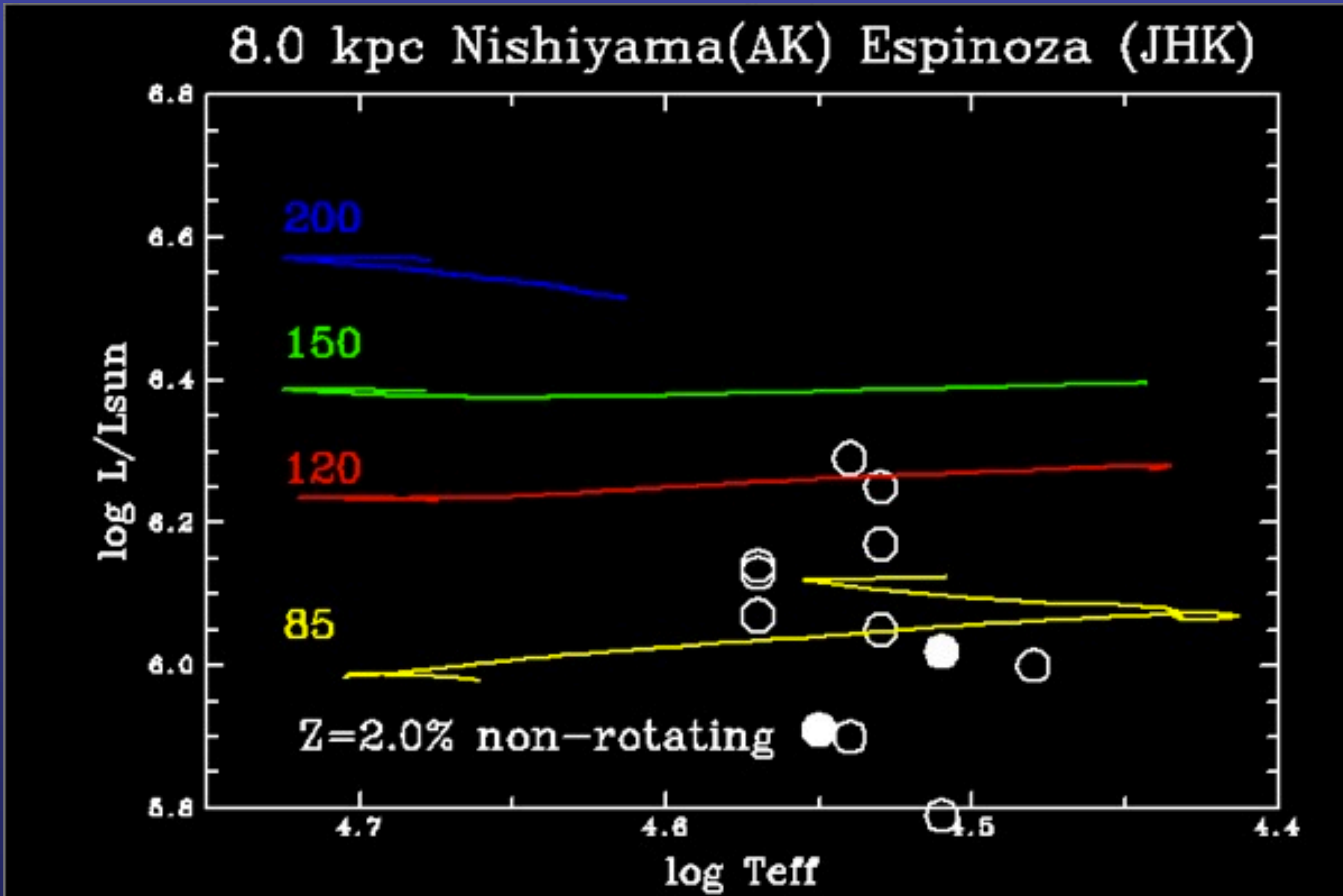
Supersolar non-rotating tracks for VMS (Yusof, priv. comm.)

NACO photometry, Rieke law



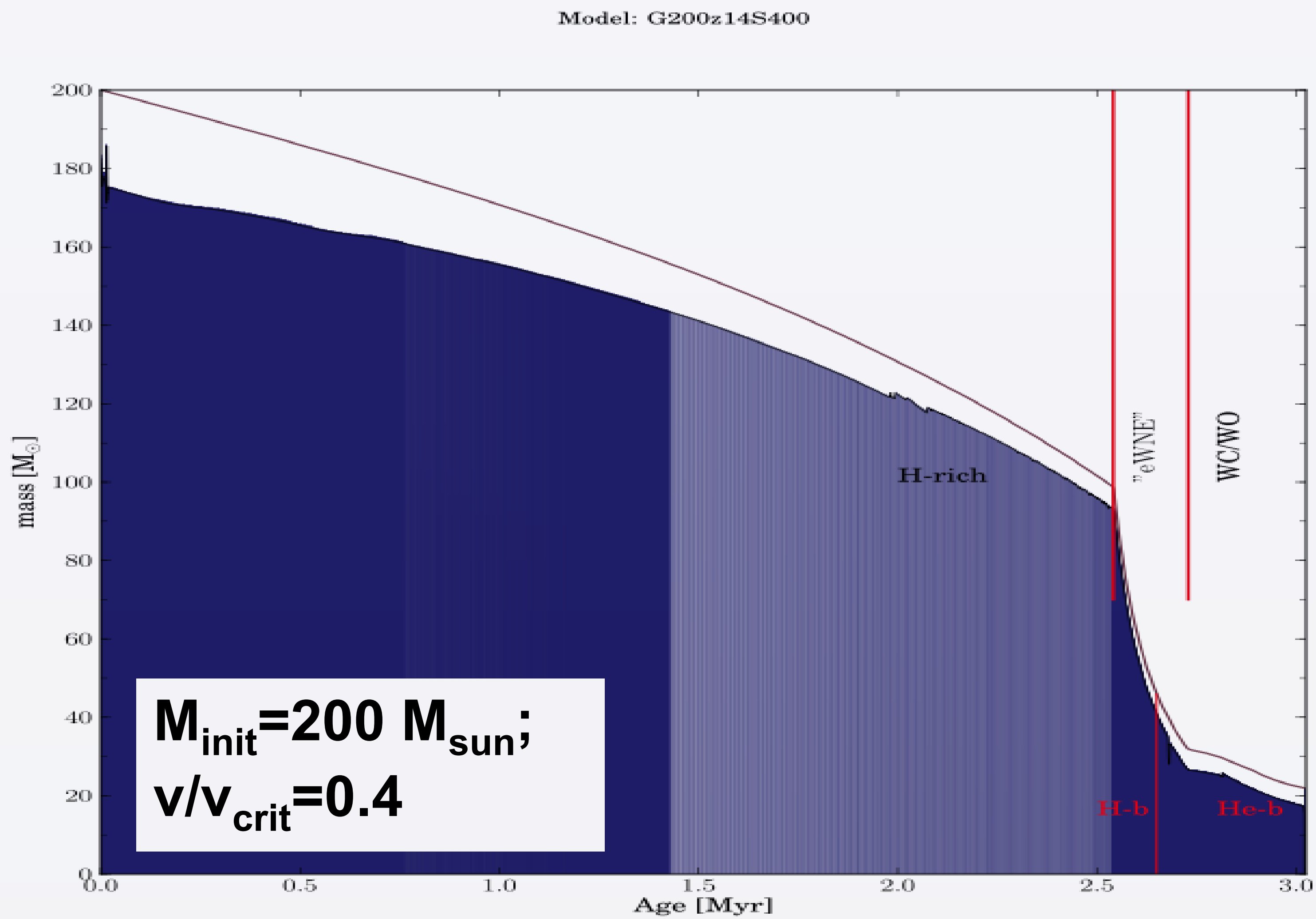
ting
sof,

NACO photometry, Nishiyama law



ting
sof,

Colossal convective cores



M_{init}=200 M_{sun};
v/v_{crit}=0.4

Arches: Rosetta stone for M_{up}?

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- M_{up} >200 M_{sun} (VLT/NACO + Rieke et al. near-IR extinction law), or..

Arches: Rosetta stone for M_{up}?

- M_{up} >200 M_{sun} (VLT/NACO + Rieke et al. near-IR extinction law), or..
- M_{up} <120 M_{sun} (VLT/NACO + Nishiyama et al. near-IR extinction law).

Arches: Rosetta stone for M_{up}?

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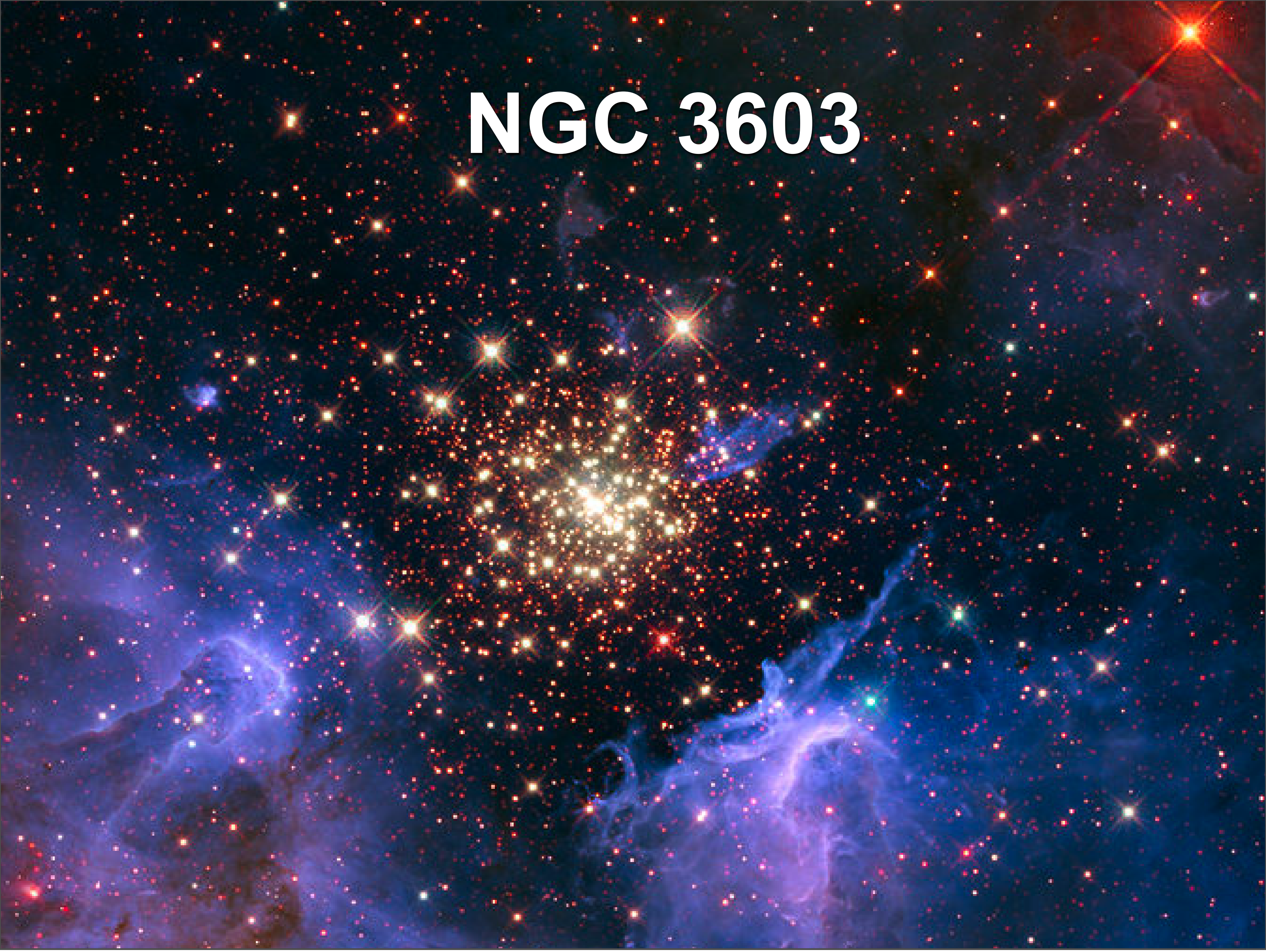
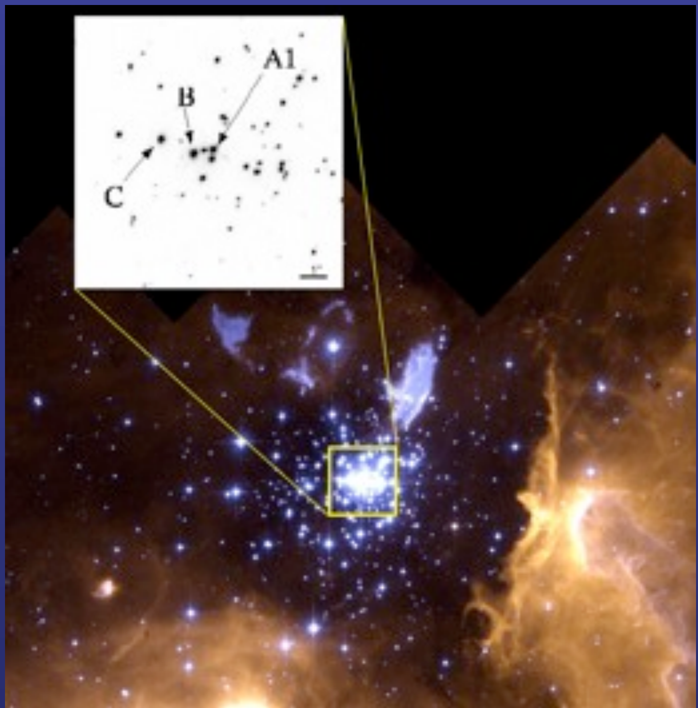
- Alternatively, Schneider et al. (submitted) propose τ = 3.5 Myr - if brightest stars are binary products (rejuvinated via mergers)


NGC 3603

Gold Standard: Eclipsing Binary NGC 3603-A1



M_{dyn}:116±31$M_{\odot}$ + 89±16$M_{\odot}$ for A1a+b in 4 day orbit (Schnurr+ 2008). NGC 3603-B has an identical subtype to A1, yet is 0.5 mag brighter ⇒ higher mass

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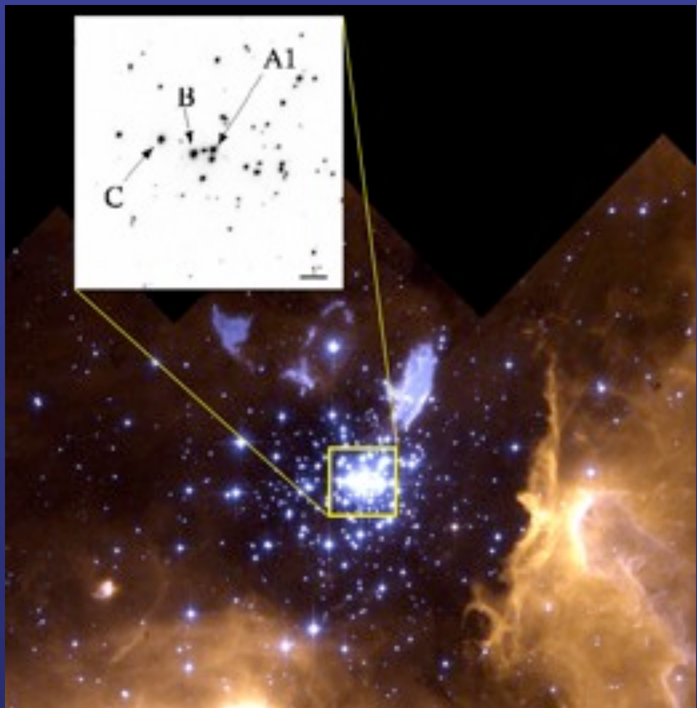

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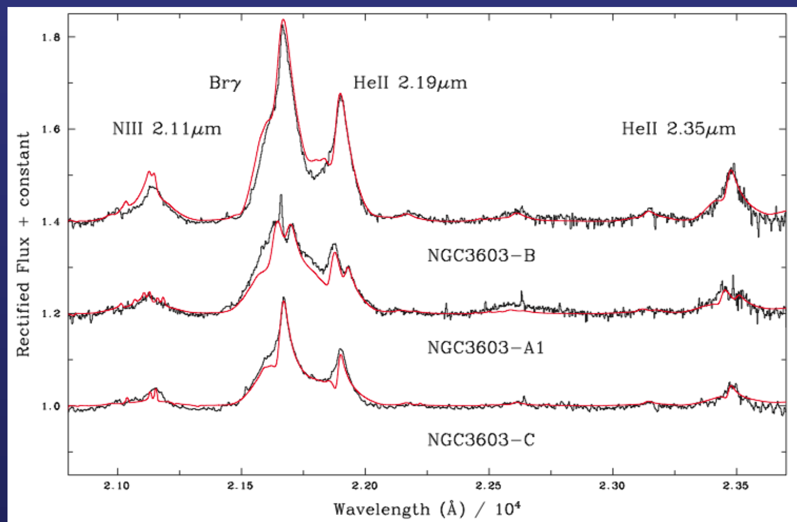
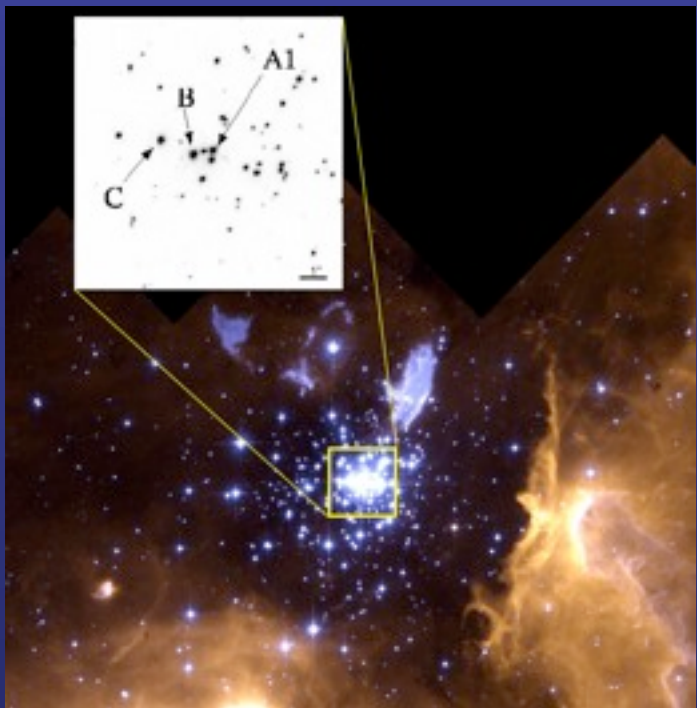


Gold Standard: Eclipsing Binary NGC 3603-A1

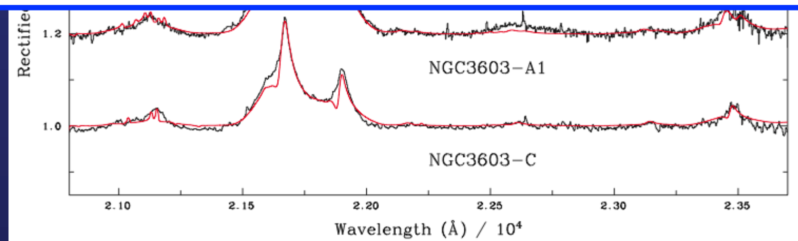


M_{dyn}:116±31$M_\odot$ + 89±16$M_\odot$ for

$M_{current}$:120 $M_\odot$ + 92 $M_\odot$ (M_{init}~100-150 $M_\odot$) for A1a+b from spect analysis & evol. models.

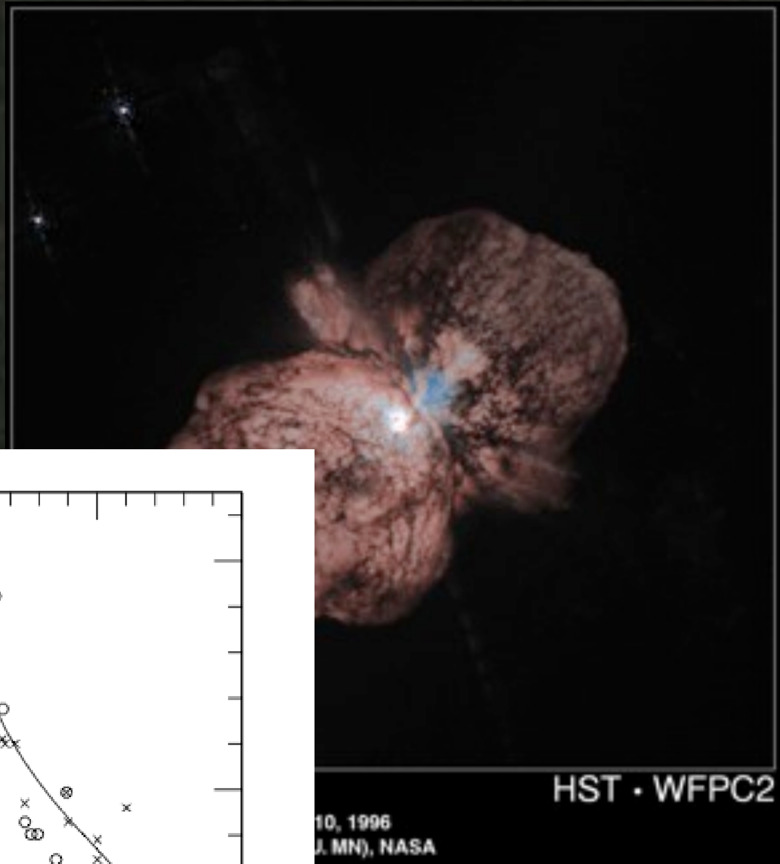
$M_{current}$~130 $M_\odot$ (M_{init}~170 $M_\odot$) for -B

s

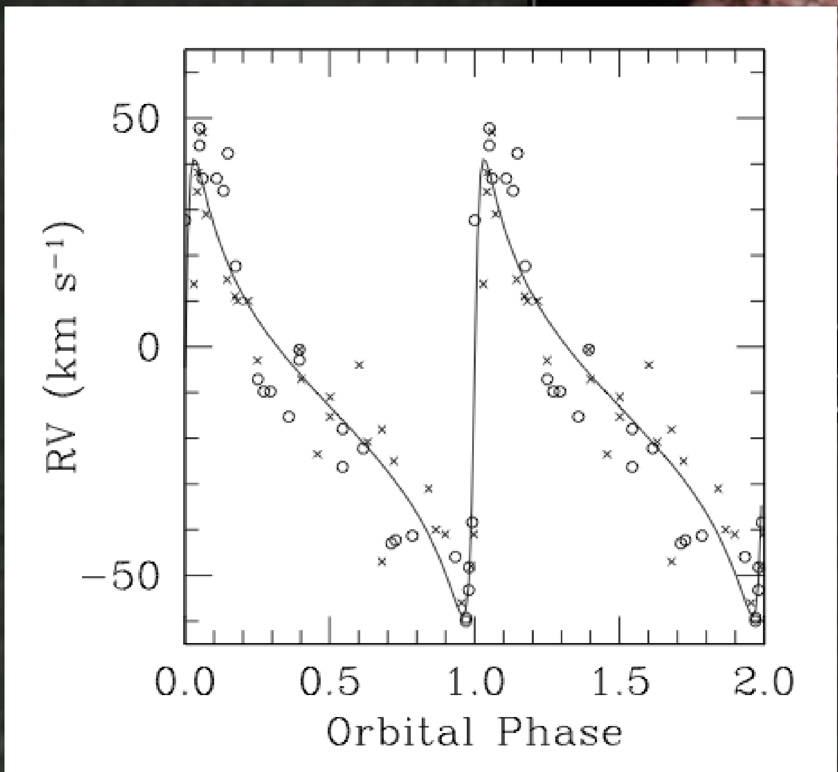


η Carinae

AAT



Giant Eruption in 19th Century, forming the Homunculus nebula. η Car now identified as 120+30? $M_\odot$ system (~5.5 yr period, Damineli 1996)



M_{init} ~200 M_{sun} for primary?

- Part I: Why should we be cautious about `supermassive' stars?
- Part II: Why should we question the proposed ~150 Msun upper mass limit?
- **Part III: So....what is the mass limit?**
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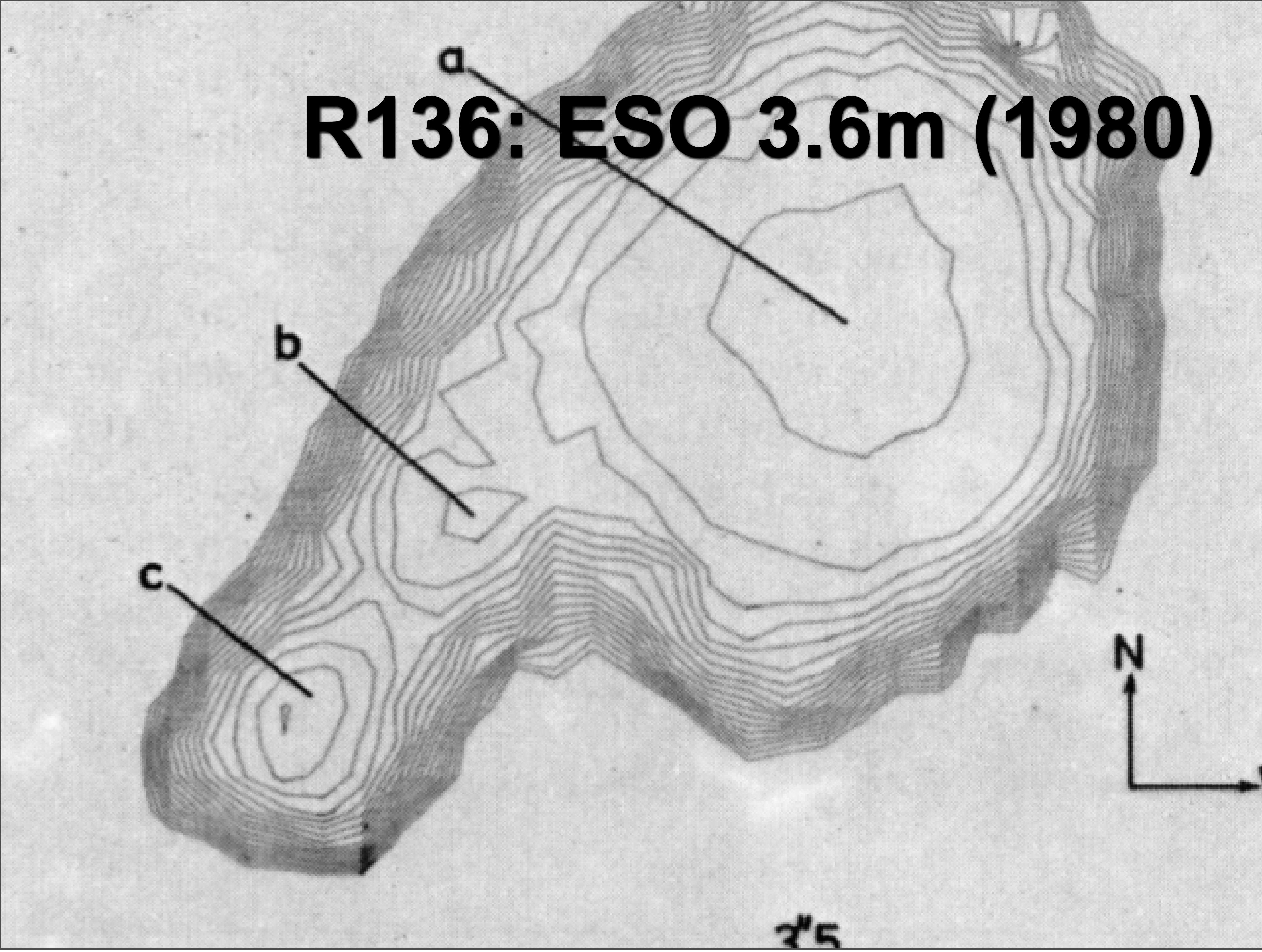
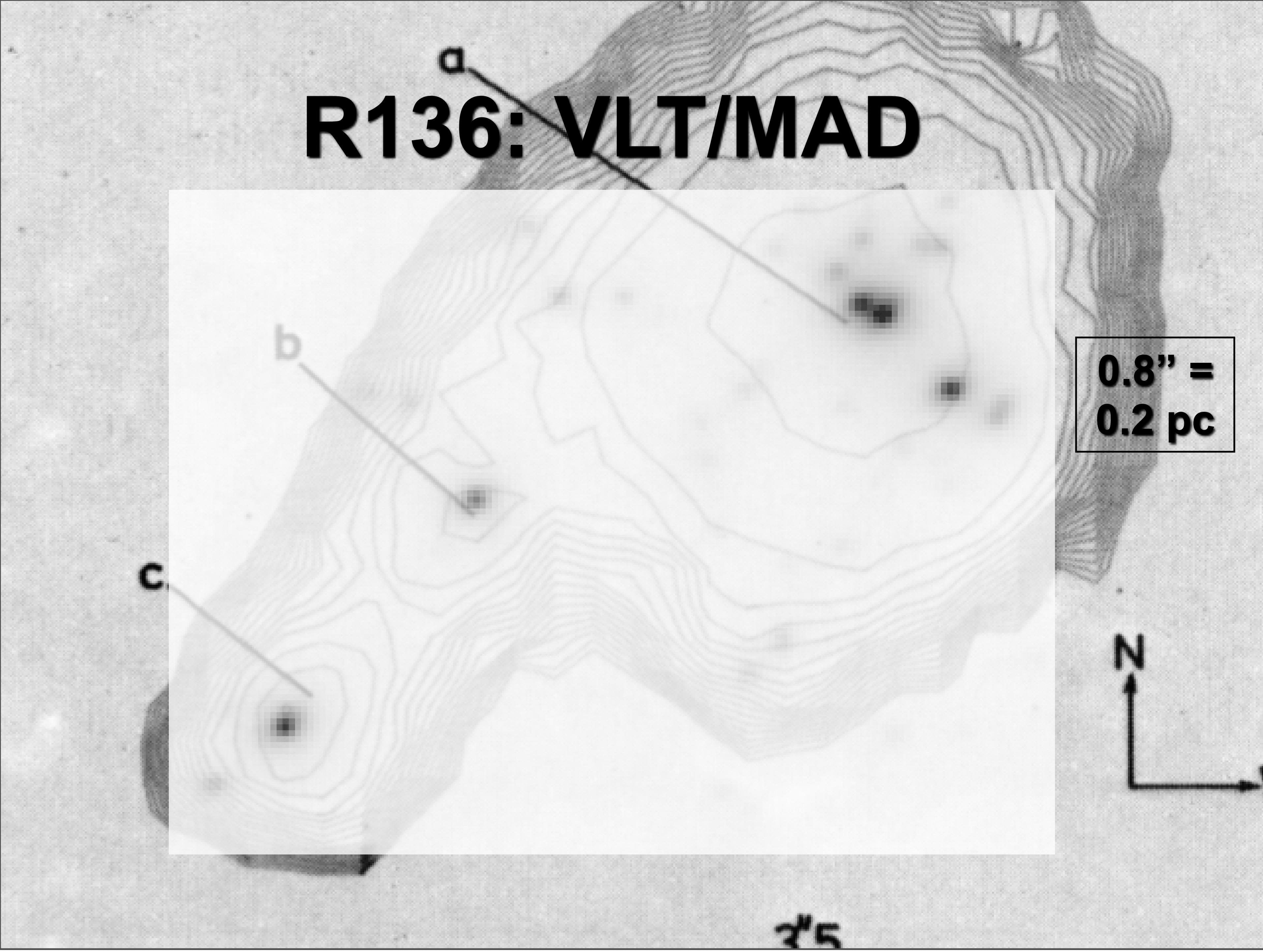
- Part V: Quantitative properties of massive stars in starburst regions

R136: ESO 3.6m (1980)



R136: VLT/MAD



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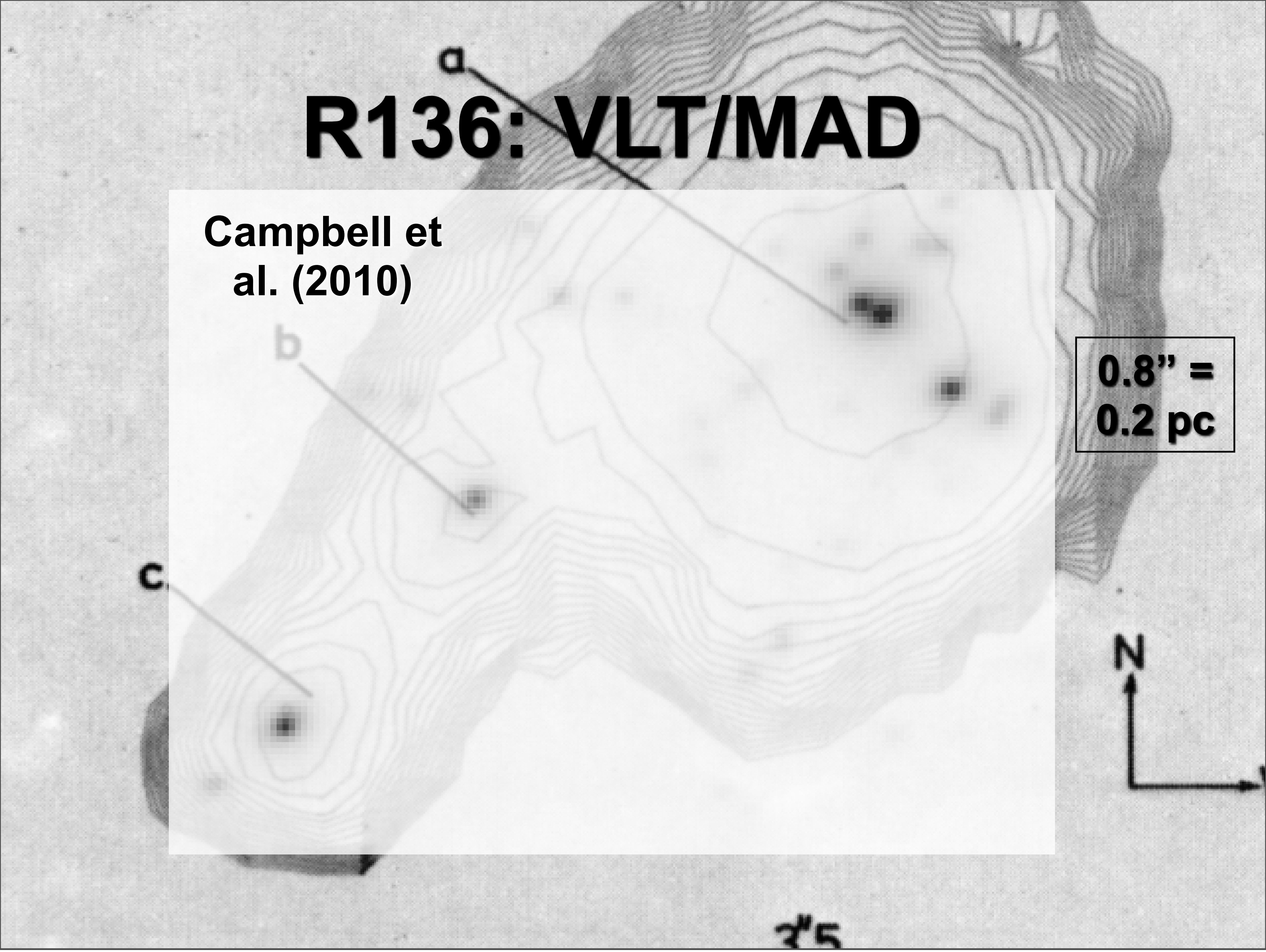
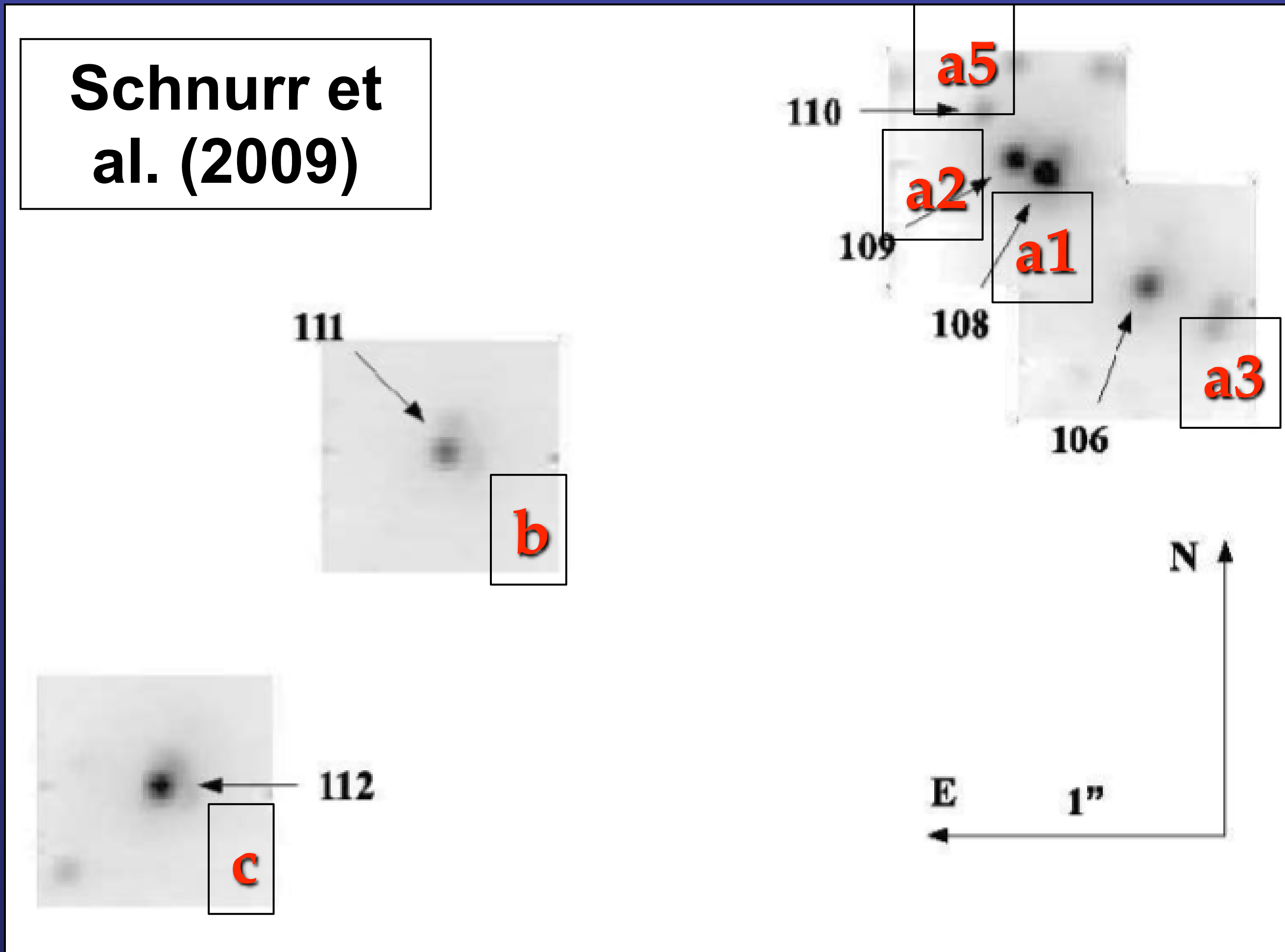
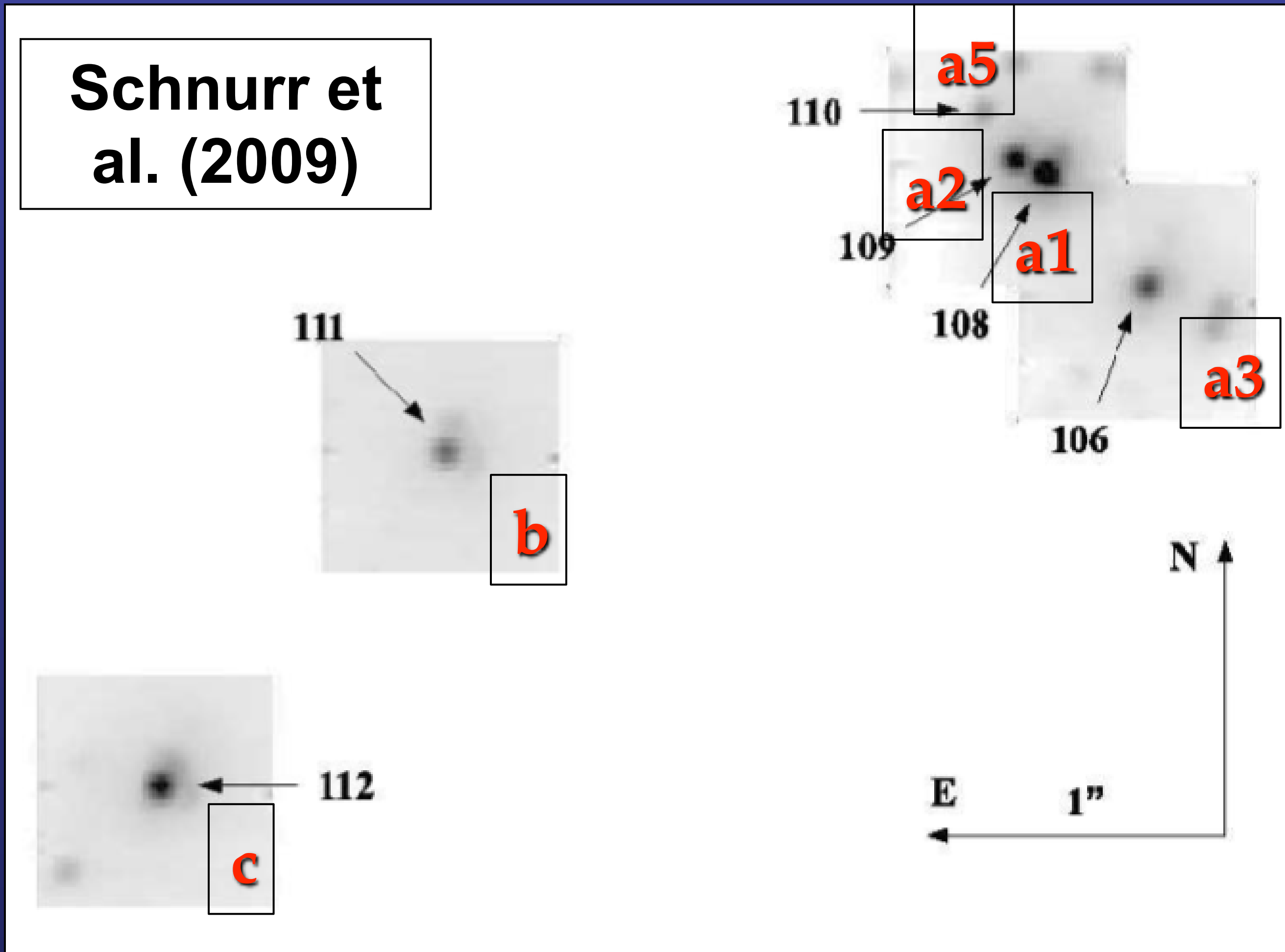


R136: VLT/SINFONI

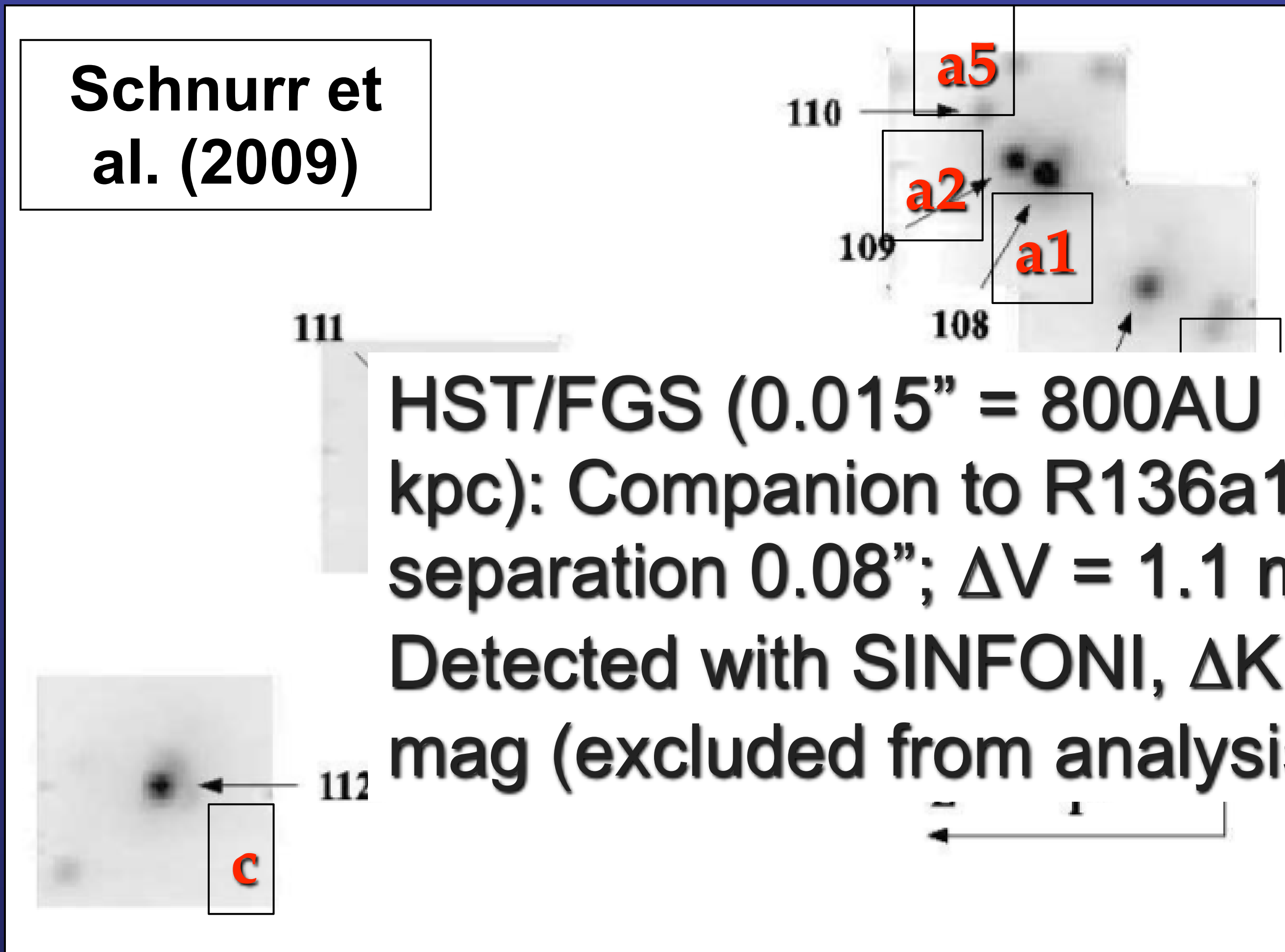


R136: VLT/SINFONI



0.8" = 0.2 pc

Crowding?

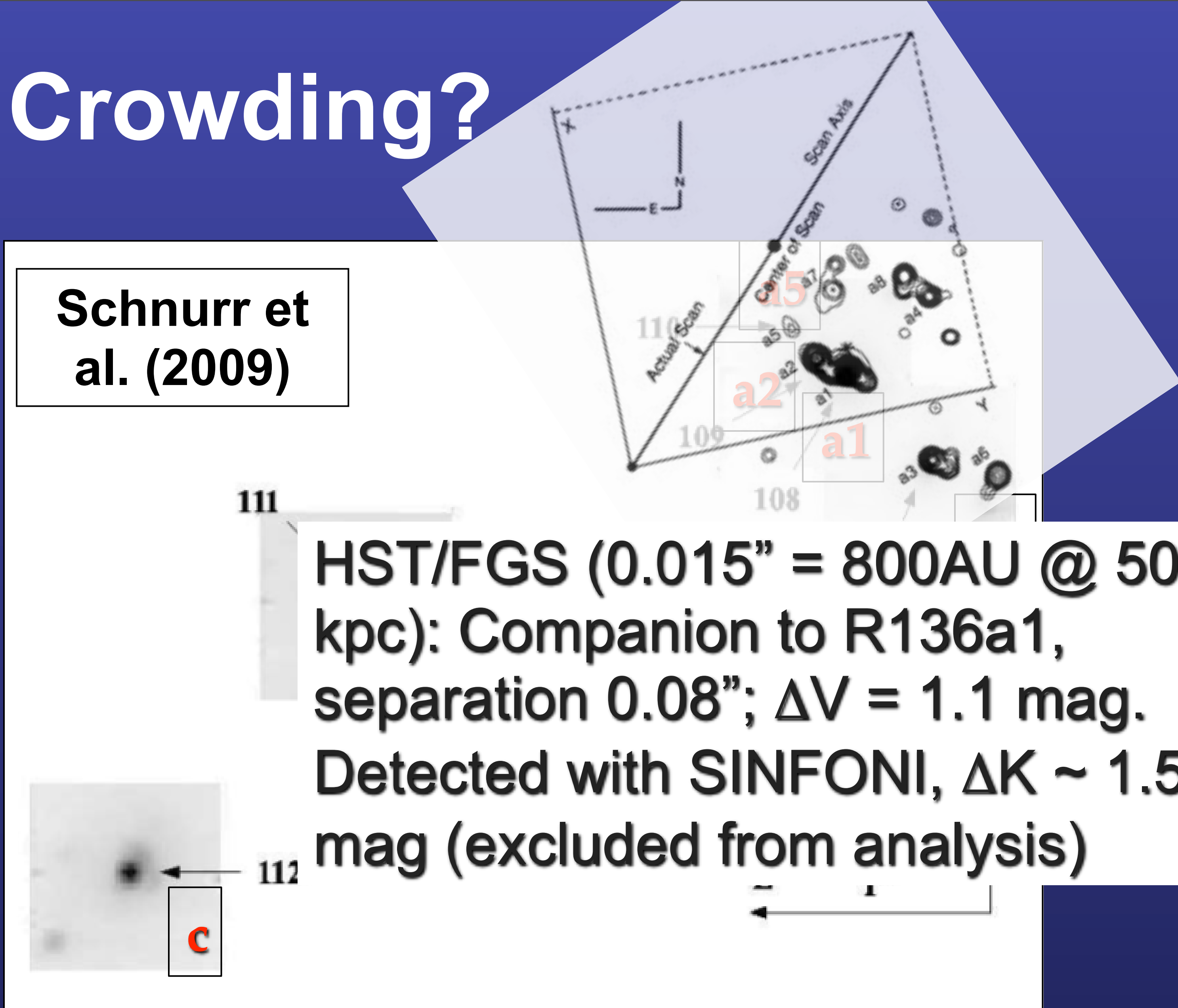


HST/FGS (0.015" = 800AU @ 50 kpc): Companion to R136a1, separation 0.08"; ΔV = 1.1 mag. Detected with SINFONI, ΔK ~ 1.5 mag (excluded from analysis)

Lattanzi et al. 1994

Crowding?

Schnurr et al. (2009)



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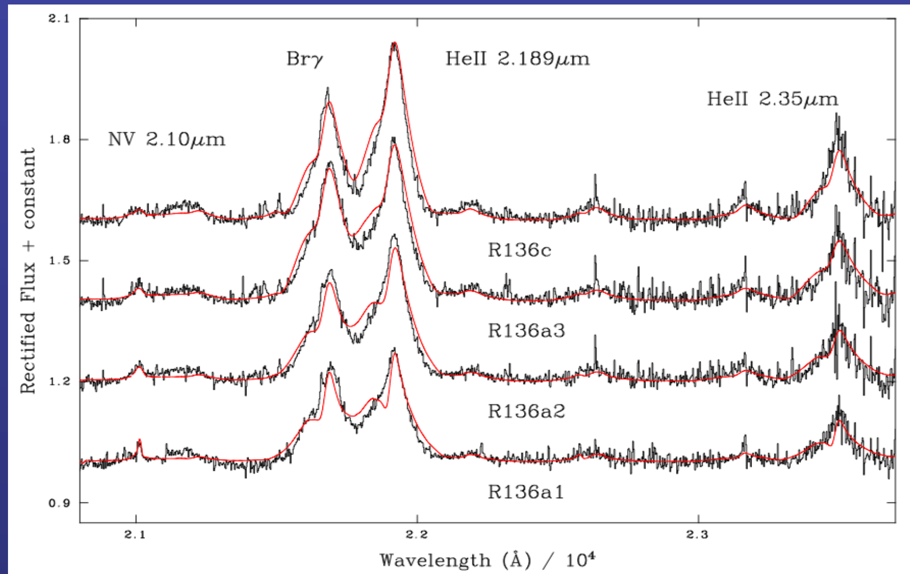
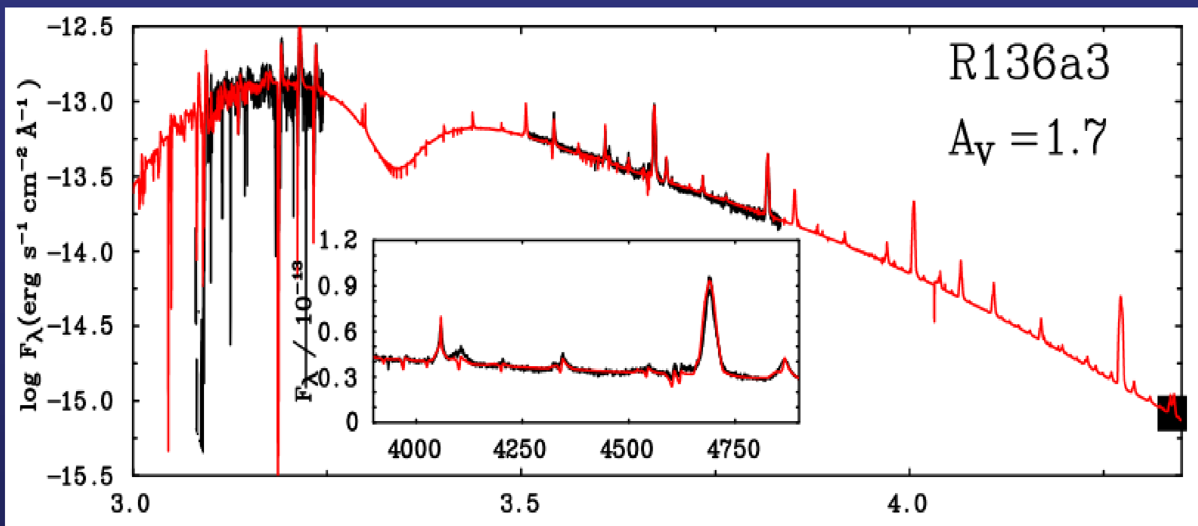
Lattanzi et al. 1994

Spectral analysis

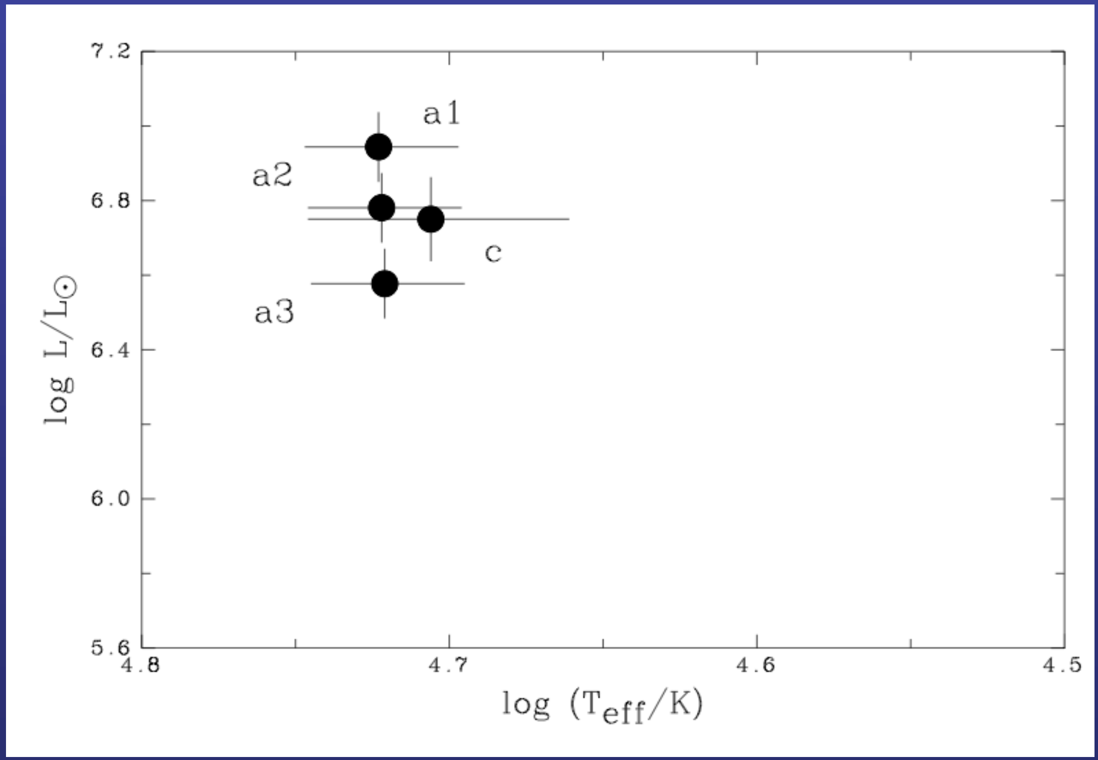
T_{eff}, log $L/L_{\odot}$, dM/dt, X_H for brightest R136 stars from analysis of VLT/ SINFONI



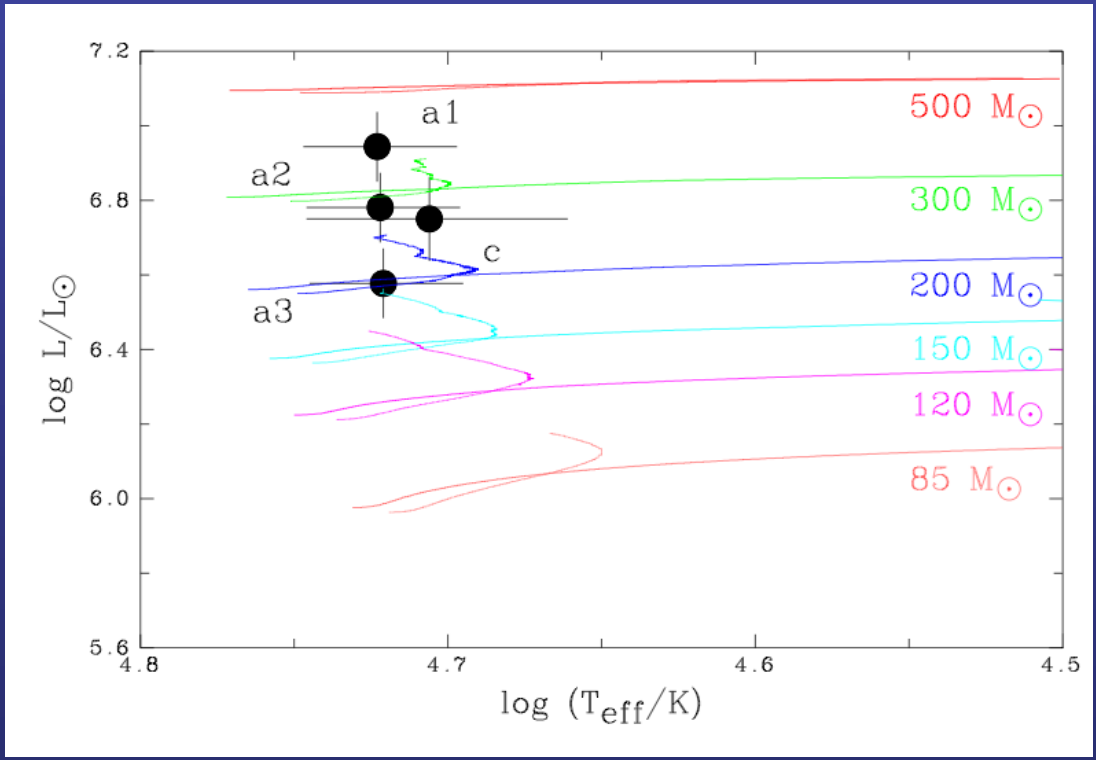


Schnurr+ (2009); Crowther+ (2010)

Current masses?

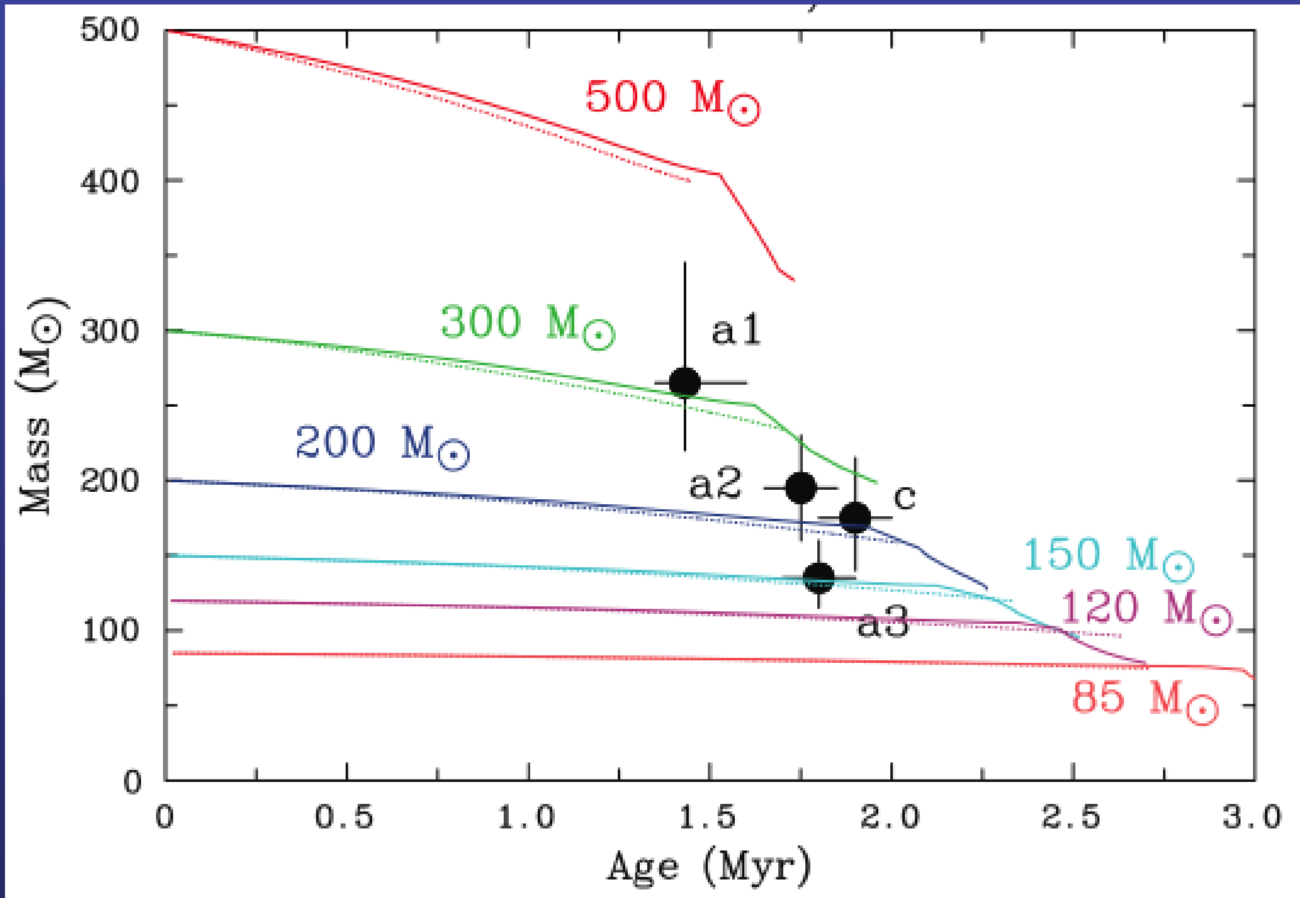


Current masses?



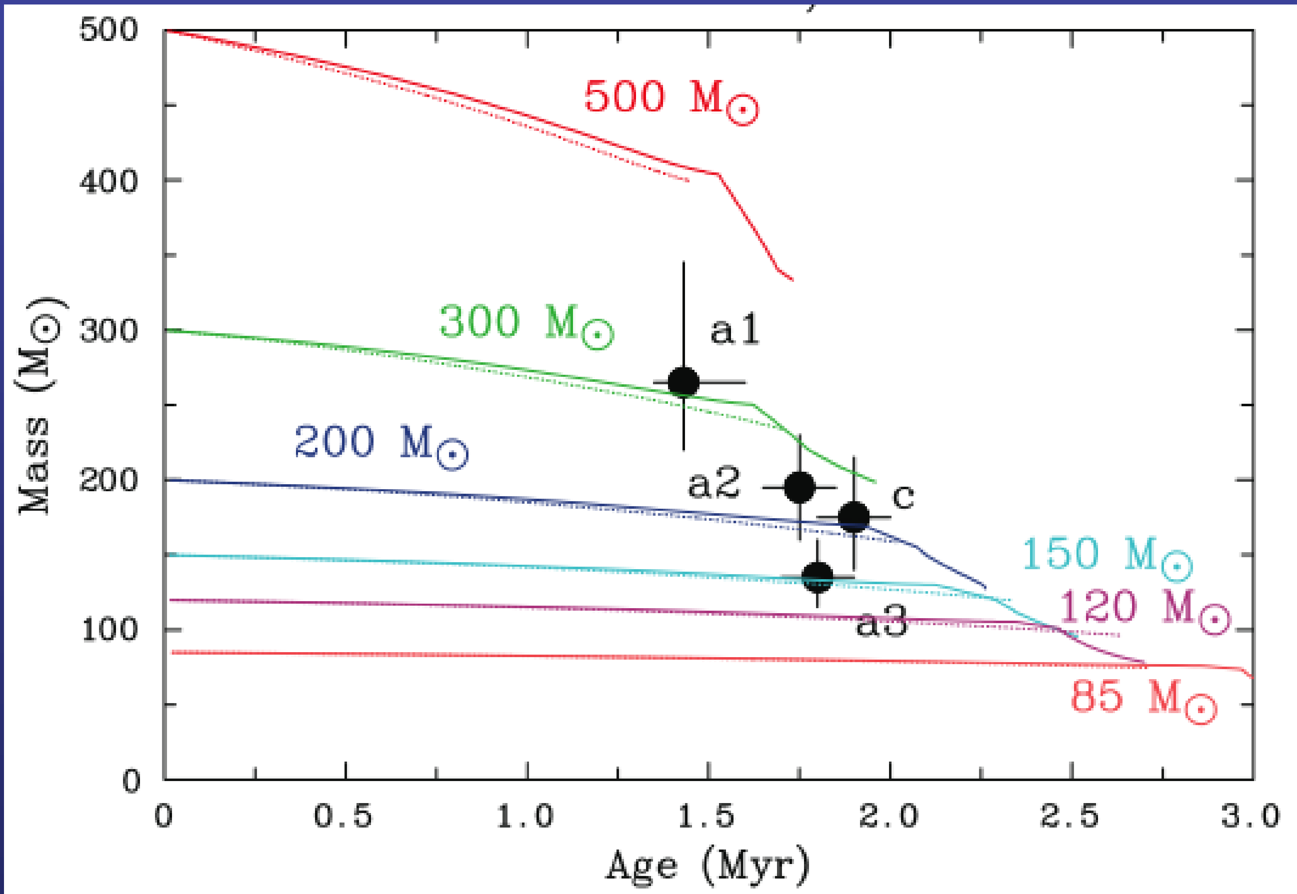
T_{eff}/kK~50-53kK & log ($L/L_{\odot}$)~6.6-6.9 + evol. models from Yusof, Hirschi+ (2013) ⇒ $M_{current}$ = 135 - 265 $M_{\odot}$, ages ~ 1.5 - 2Myr

Initial masses?



For MS phase evolutionary models of Yusof+ (2013) adopt dM/dt prescription from Vink+ (2001) ~ few x 10^{-5} $M_\odot$ /yr# ⇒ M_{init} = 165 - 320 M_{sun}

Initial masses?



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#Spectroscopic dM/dt ~ 5 x 10^{-5} $M_\odot$/yr

Monday, April 15, 2013

Upper Mass Limit

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

Philip Massey[1]

[1] *Lowell Observatory, 1400 W Mars Hill Road, Flagstaff, AZ 86001*

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.

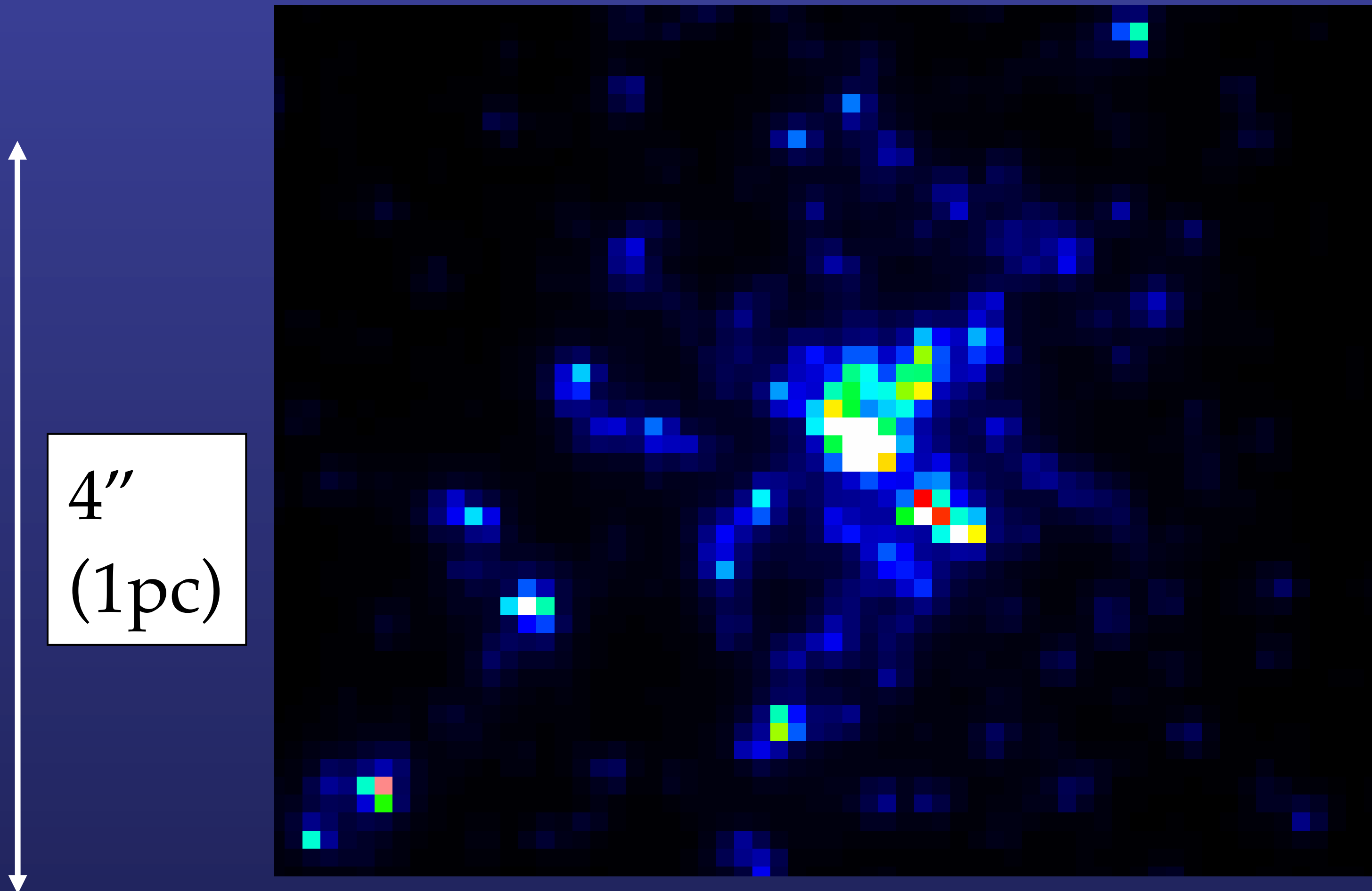
Jun 2010 Sedona workshop

Massey & Hunter redux

M_{init}~120-150 M_o for R136a1-3, according to Massey & Hunter (1998) from T_{eff}~51kK (adopted) using early O star calibration (Vacca+ 1996), yet Crowther+ (2010) obtained M_{init}~165-320 M_o for R136a1-3 from T_{eff}~53kK (derived).

Why such different mass estimates?

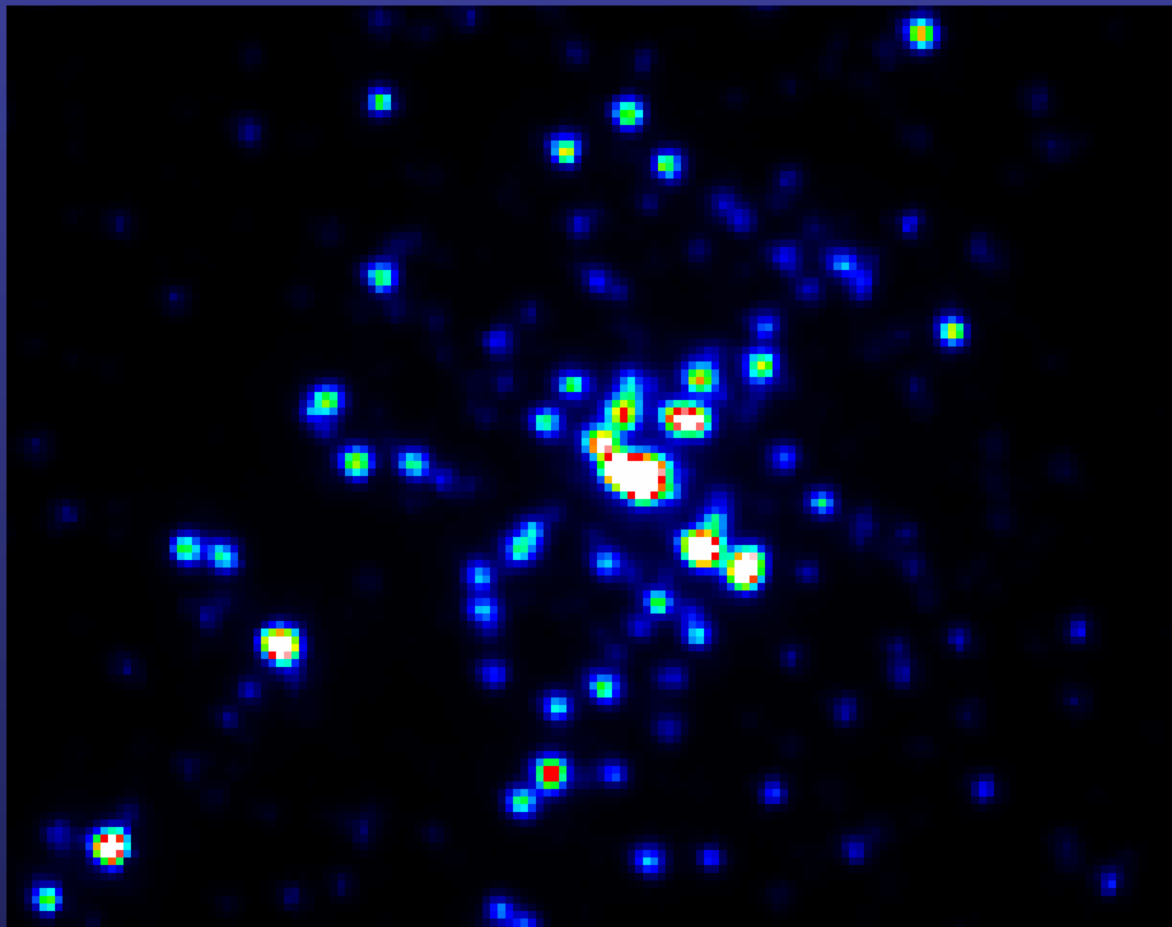
R136 (WFPC2)



m_{F555W} = 12.84 for R136a1 (WFPC2, Hunter+ 95)

R136 (WFC3)

4″
(1pc)



m_{F555W} =
12.84 for
R136a1
(WFPC2,
Hunter+ 95)

m_{F555W} =
12.28 for
R136a1
(WFC3,
De Marchi
+2011)

Massey & Hunter redux

R136a1	WFPC2/old	WFC3/new
m_{F555W}	12.82	12.28
E(B-V)	0.5	0.5
M_V	-7.3	-7.8
Log L/L_{sun}	6.65	6.87
M_{init}^*/M_{Sun}		

Massey & Hunter redux

R136a1	WFPC2/old	WFC3/new
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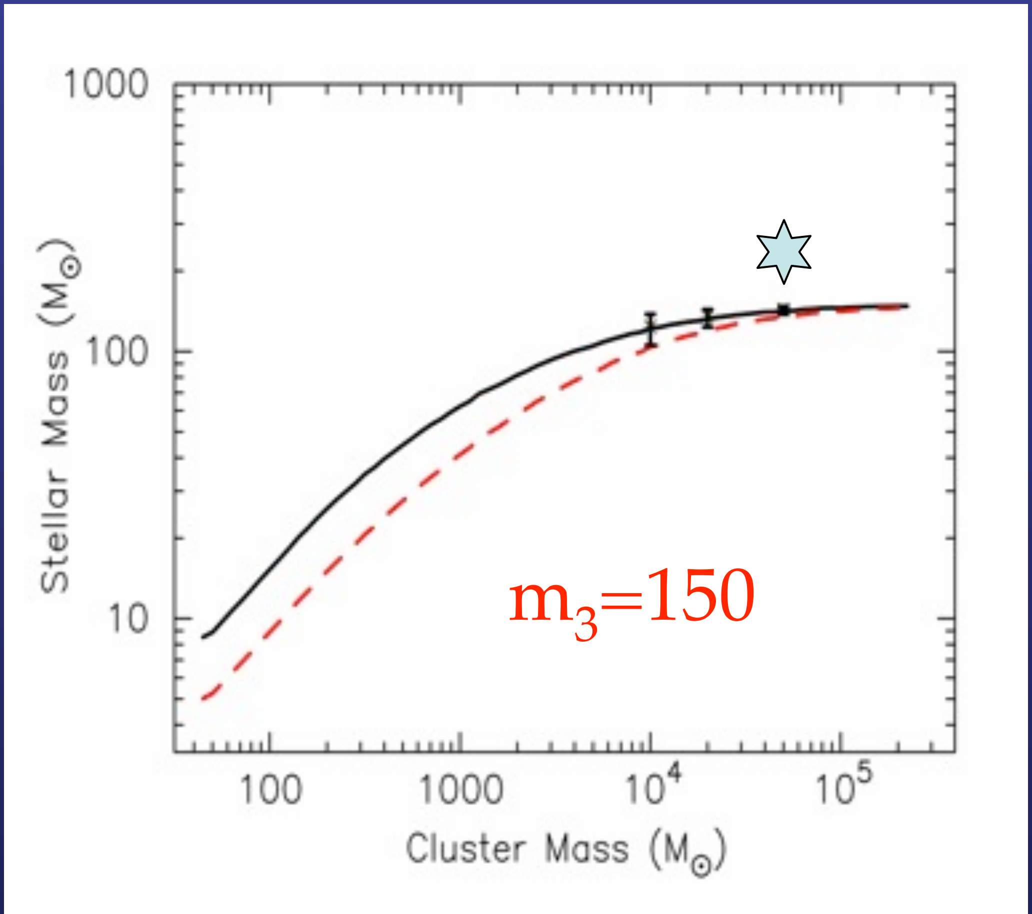
E(B-V)	0.5	0.5
M_V	-7.3	-7.8
Log L/L_{sun}	6.65	6.87
$M_{init,*}/M_{Sun}$	185:	285

*Contemporary Geneva models for LMC (Yusof+ 2013)

Is there an upper mass limit?

Monte Carlo simulations for clusters, using stellar distributions randomly sampled from (Kroupa) IMF with upper mass limits of m_3 = 150, 300 & 1000 $M_\odot$



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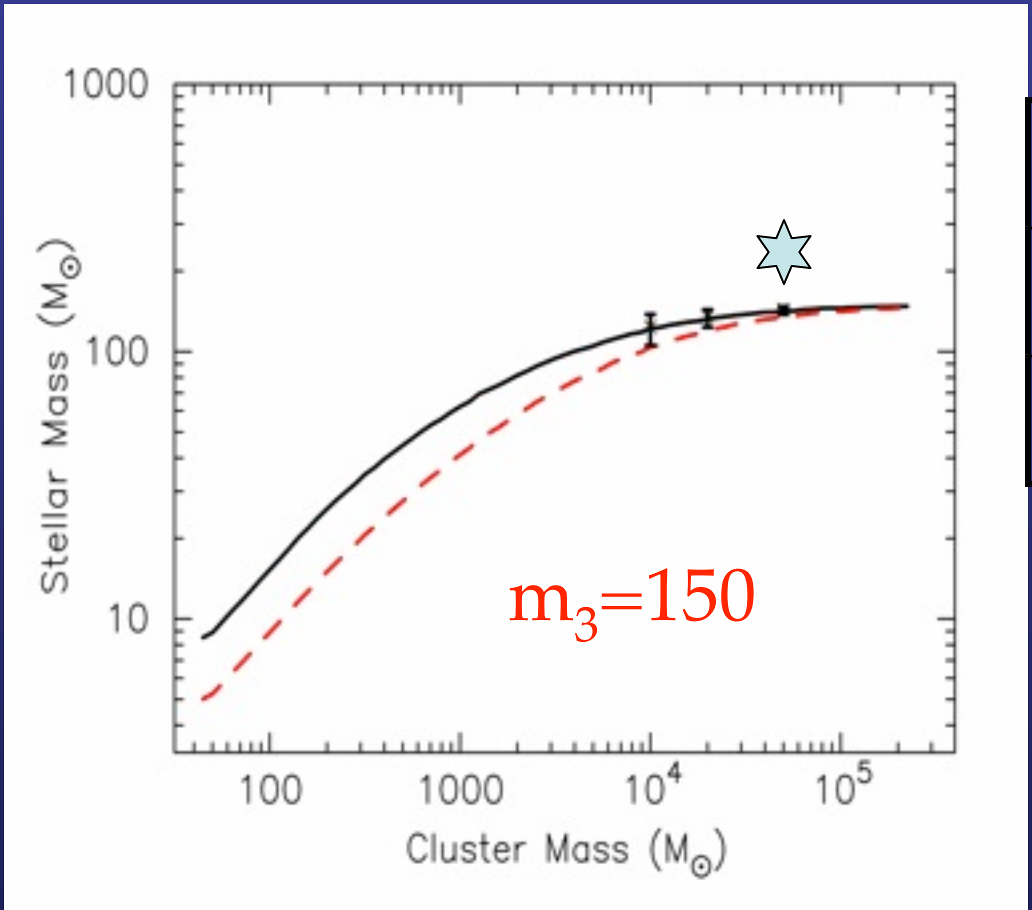

R136: $M_{avg,3}$~260 M_o	
m_3	$M_{avg,3}$
150	150

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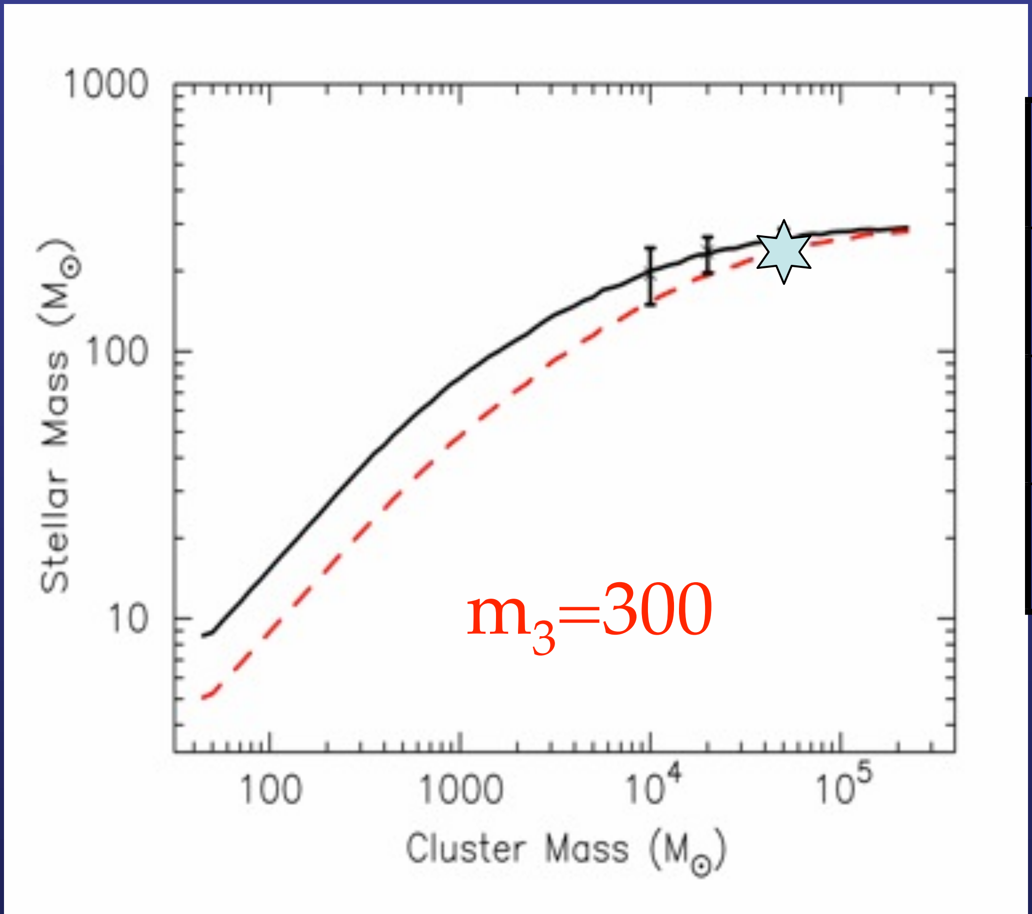

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m_3	$M_{avg,3}$
150	150
300	230

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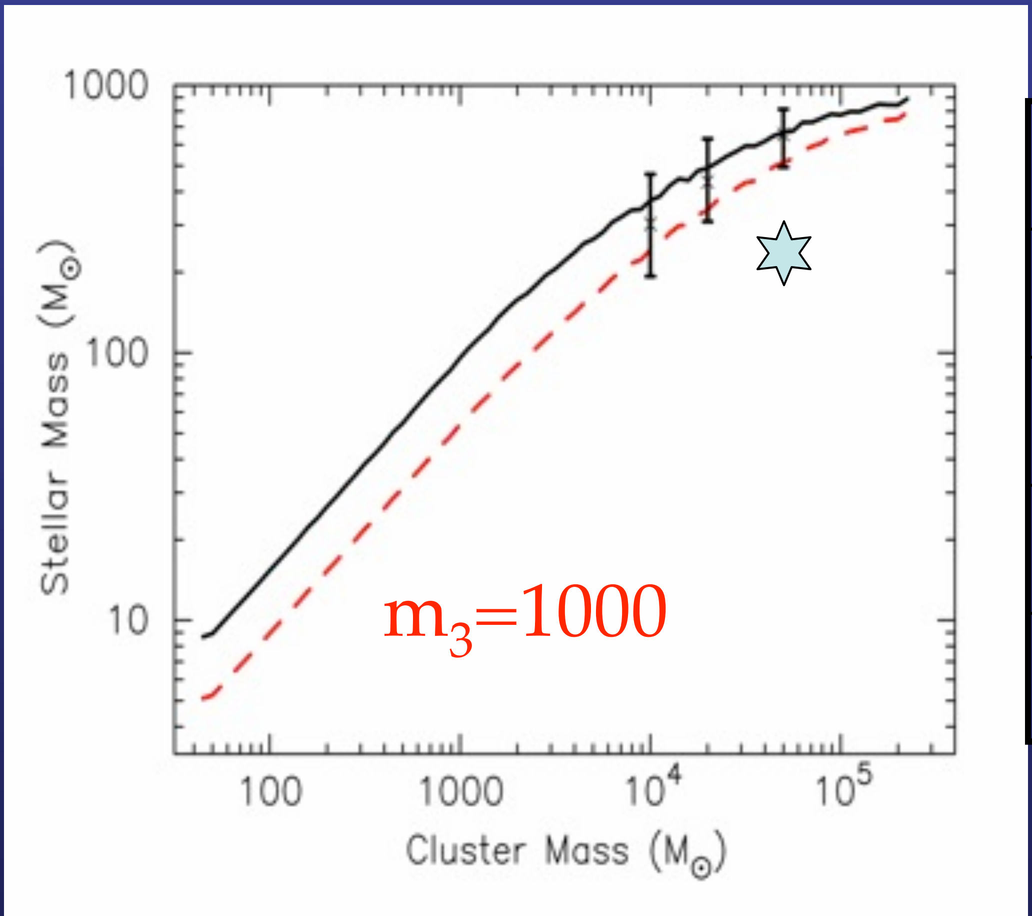
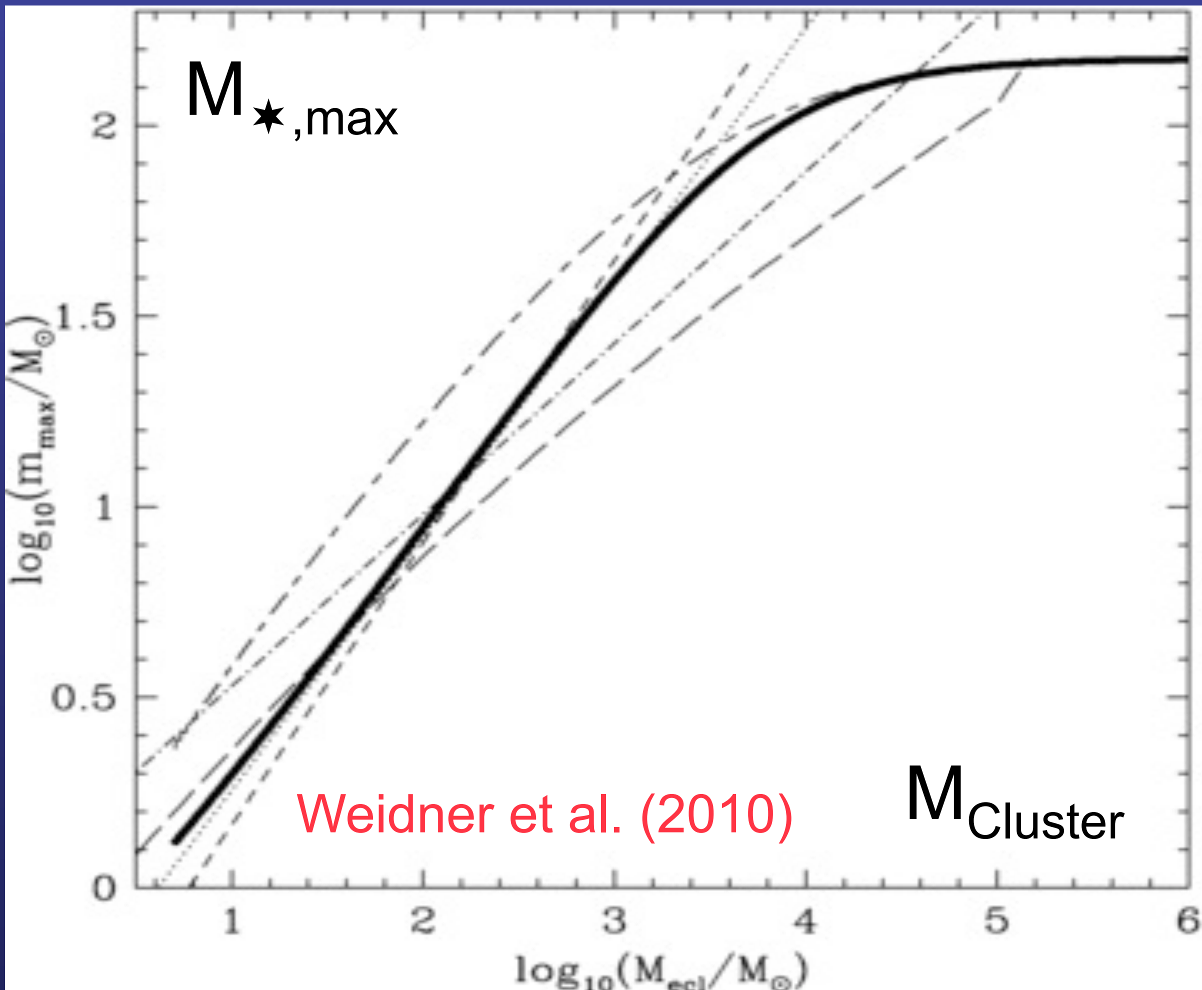


R136: $M_{avg,3}$~260 M_o	
m_{up}	$M_{avg,3}$
150	150
300	230
1000	500

$M_{cluster}$-$M_{star,max}$ relation



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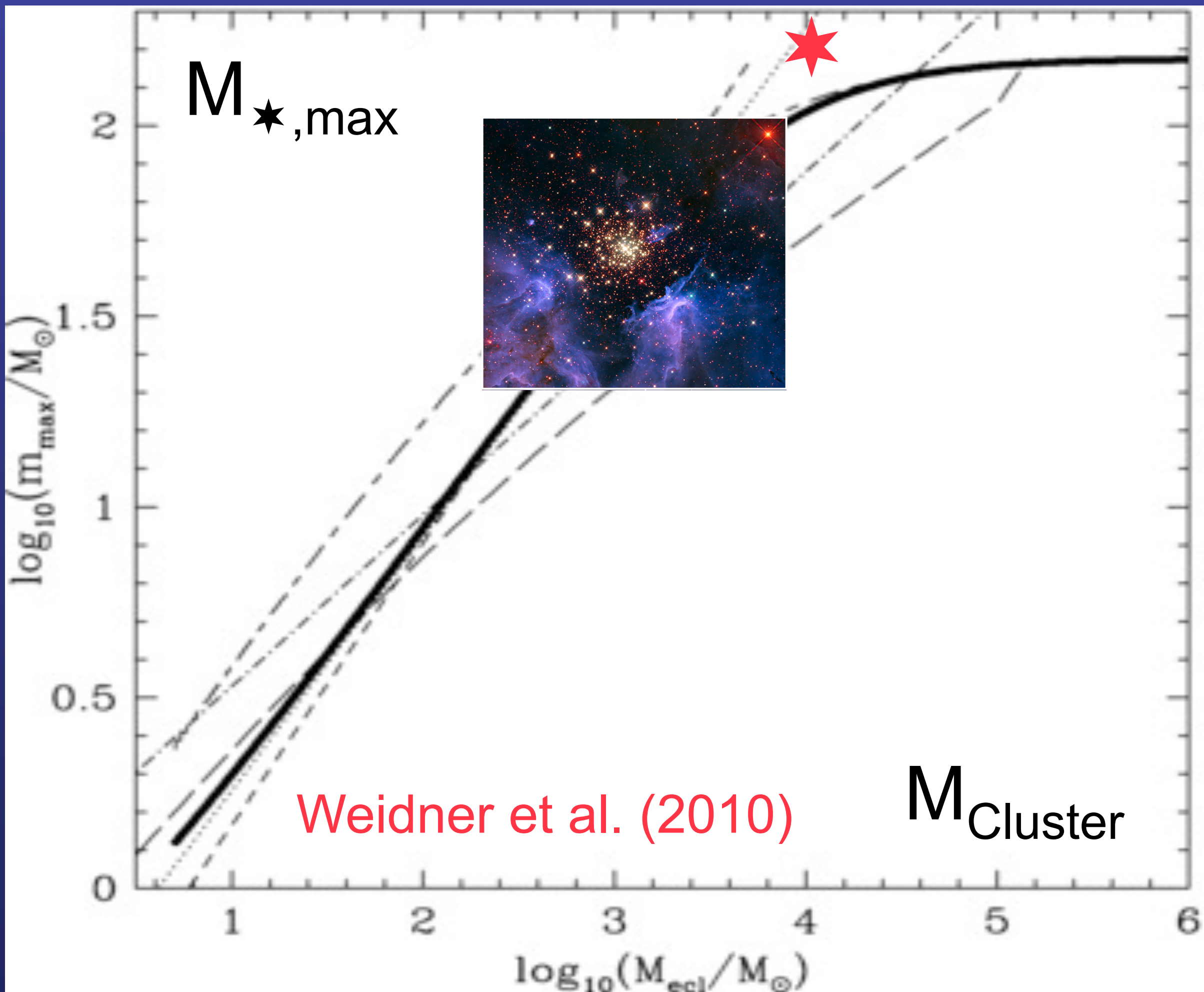

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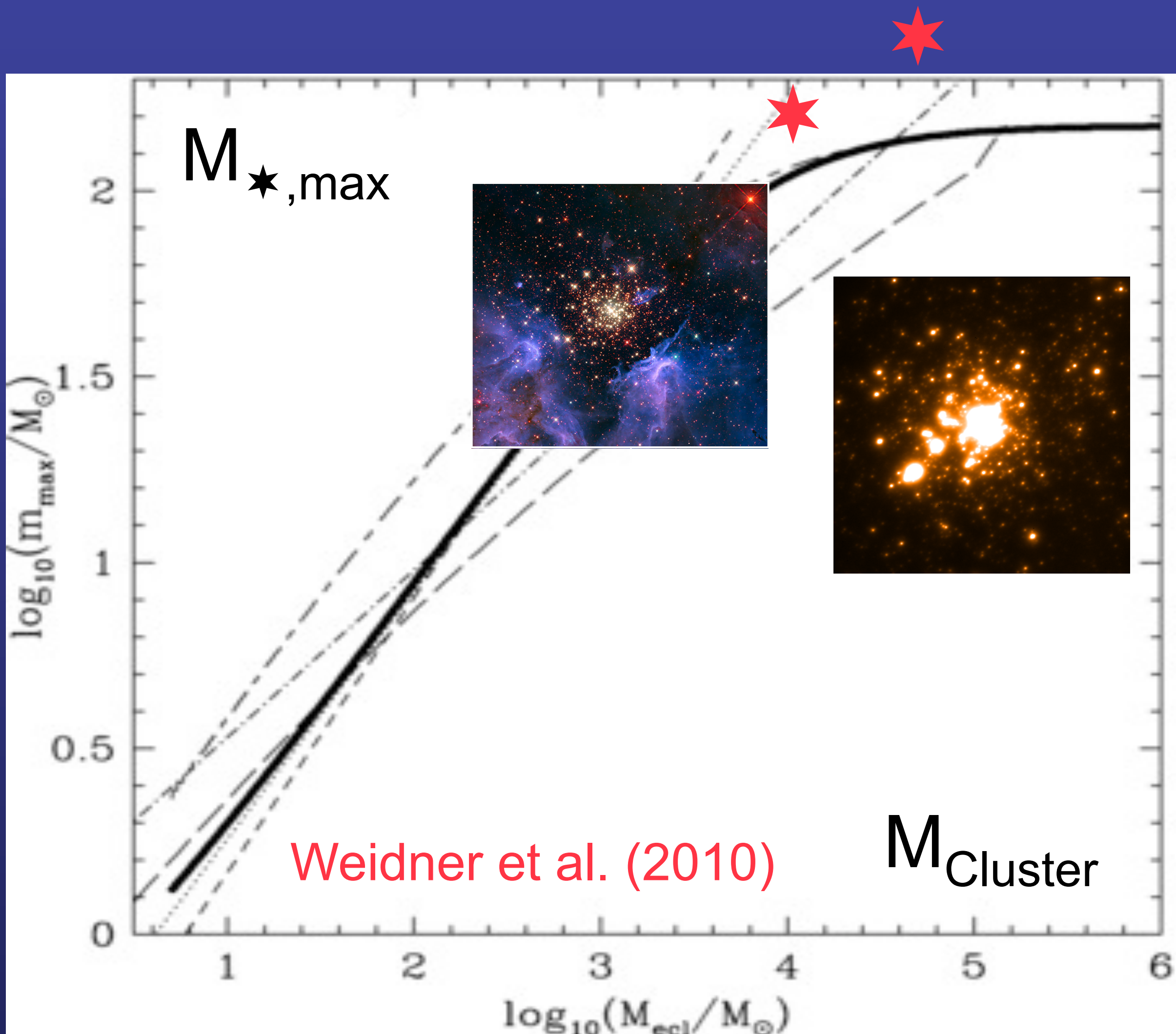

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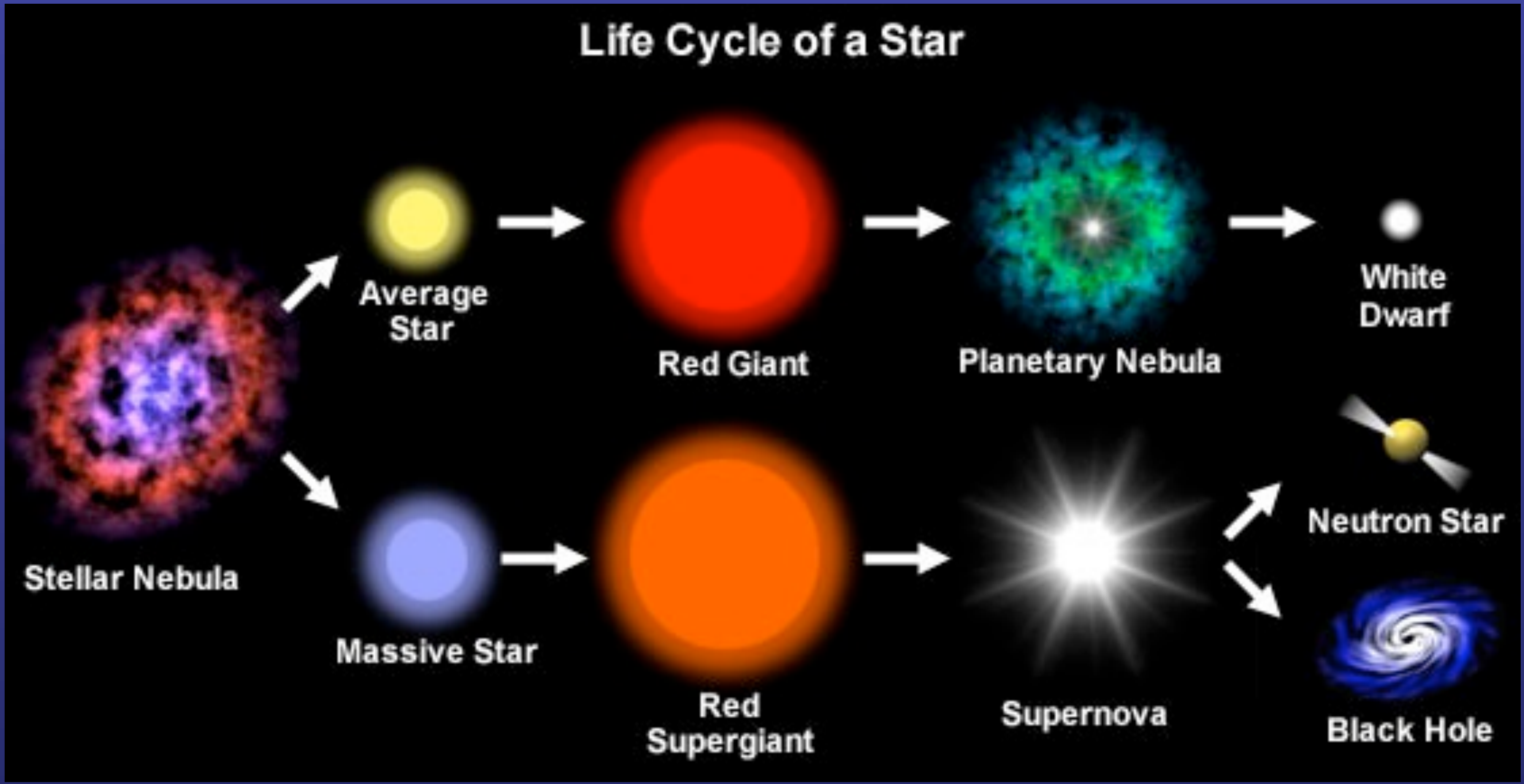
“Size matters”



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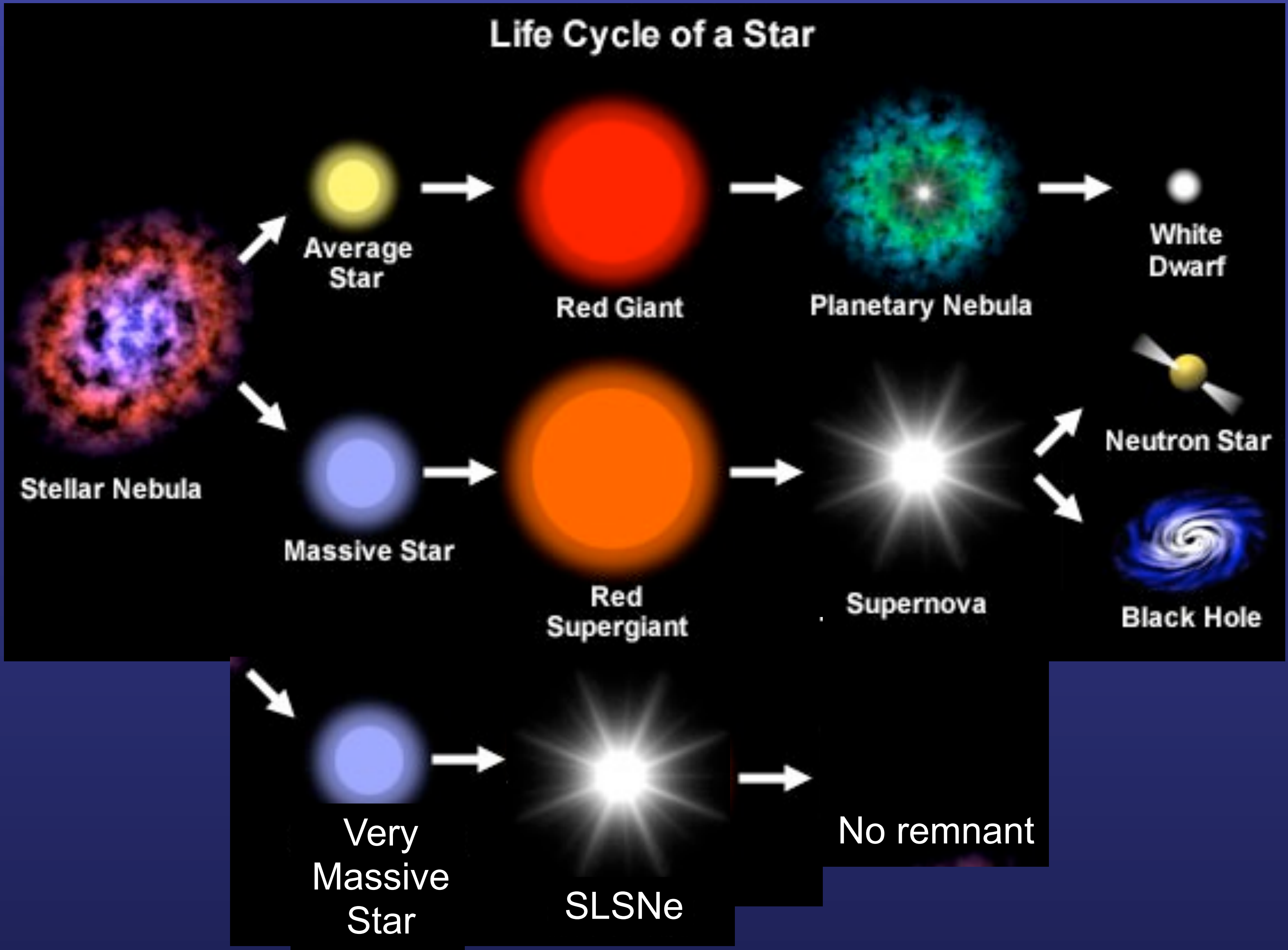
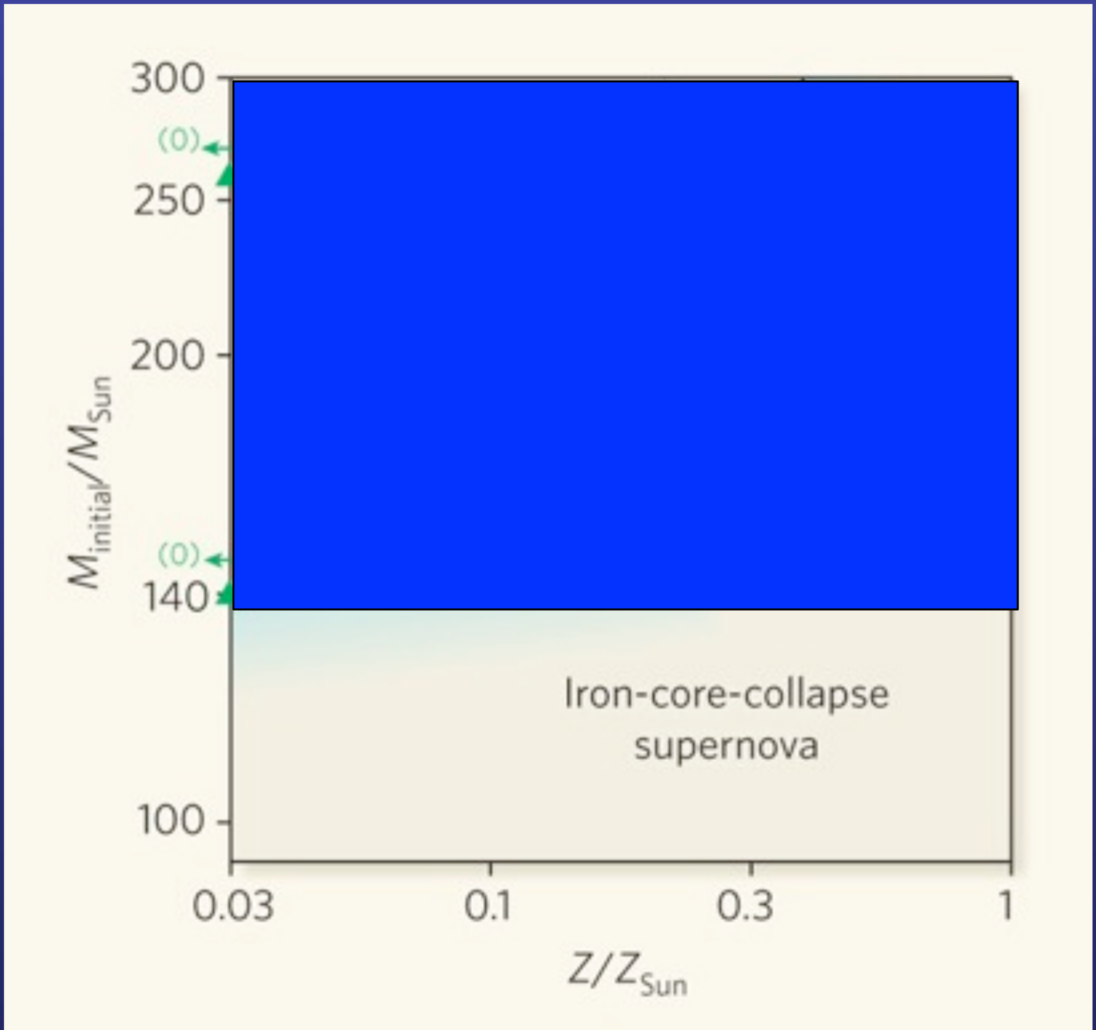


Pair Production SN?



$M_{up} > 150 M_{\odot}$

Langer (2009)

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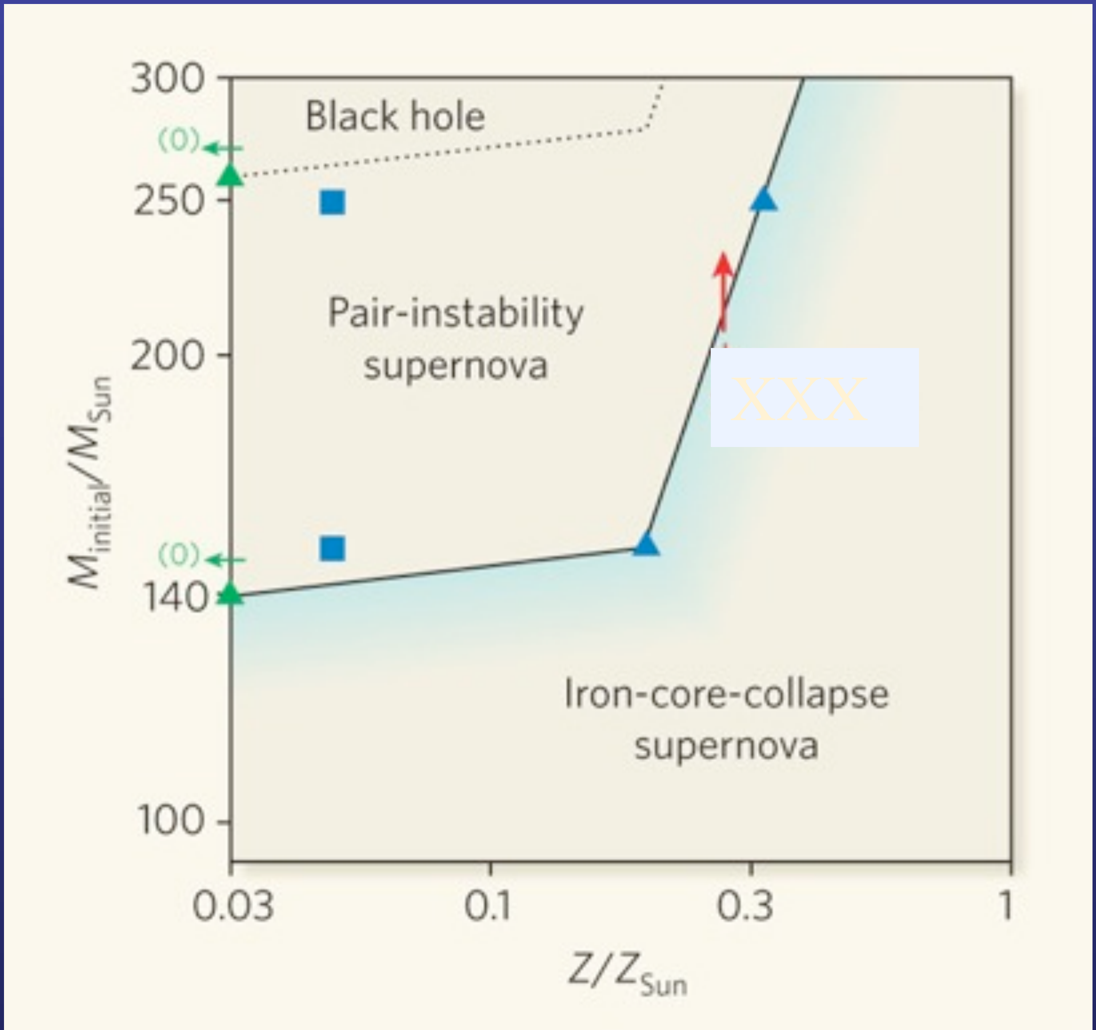

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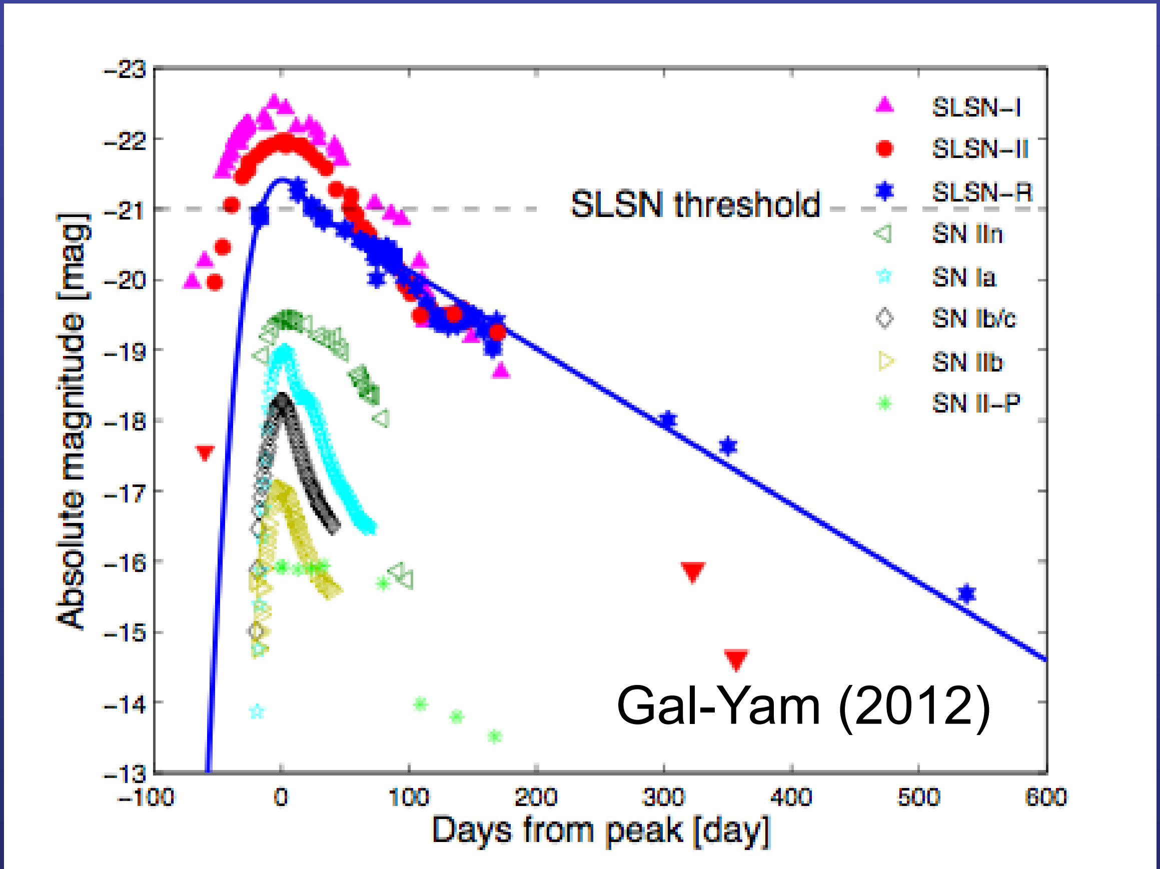
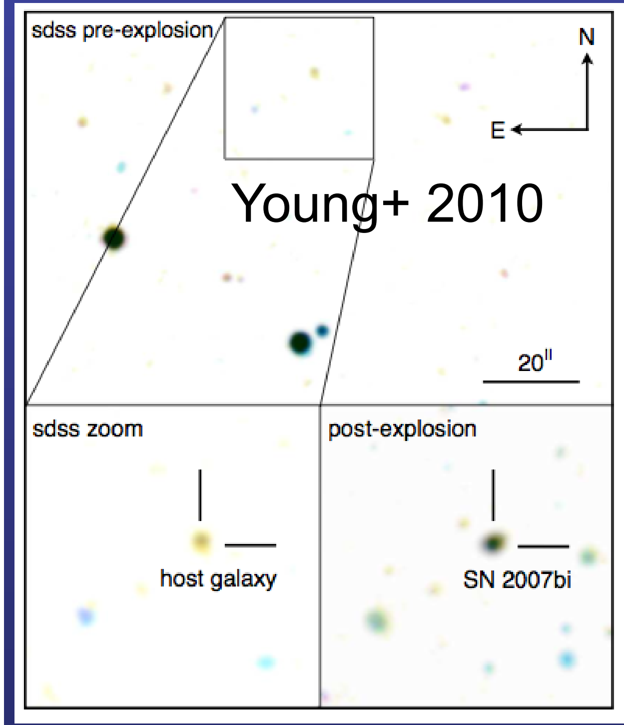
Langer (2009)

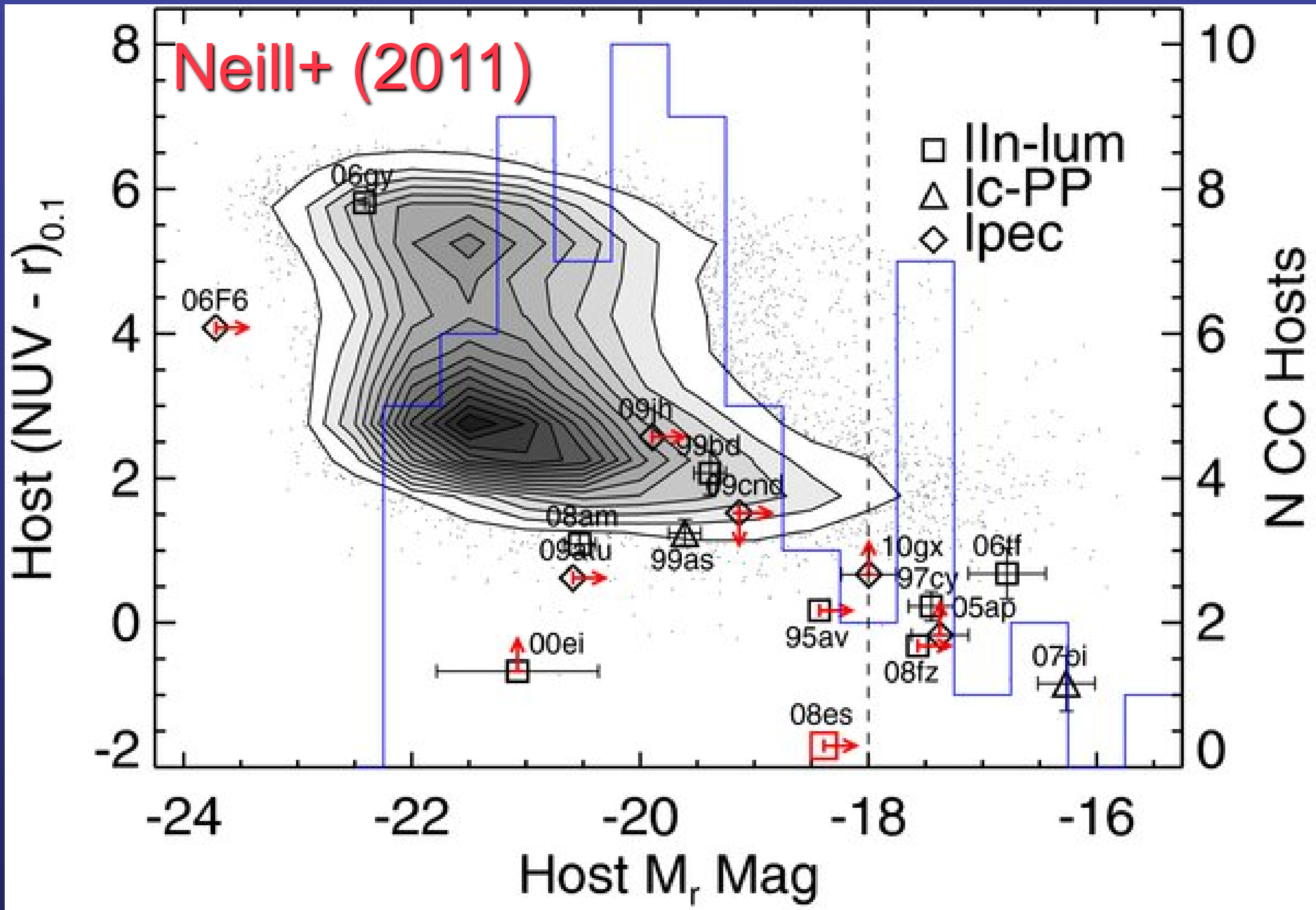
Super Luminous SNe





3 flavours of SLSNe (M_R<-21 mag) incl. SN 2007bi (Gal Yam+ 2009; Young+ 2010)

Extreme hosts for SLSNe



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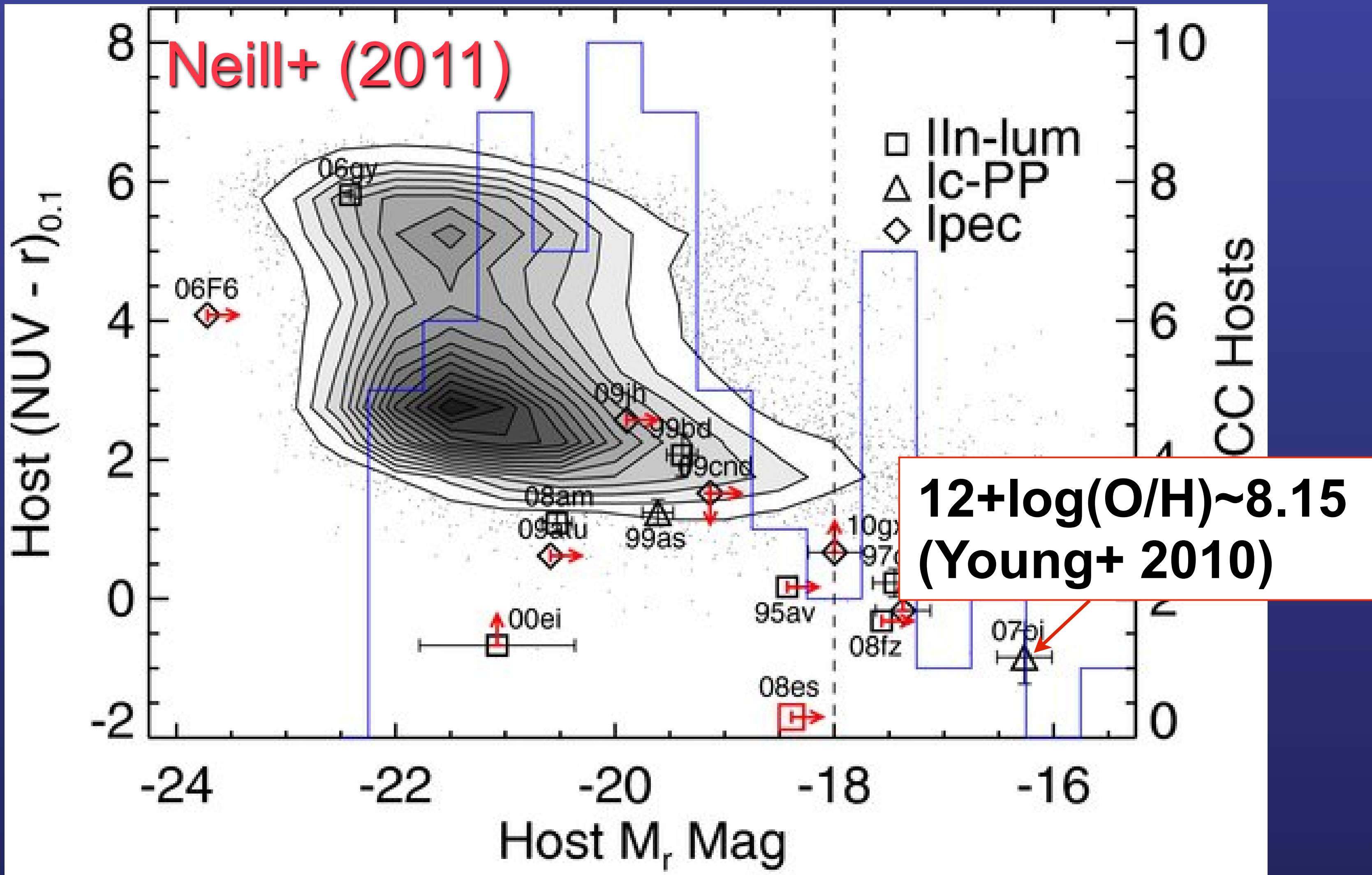
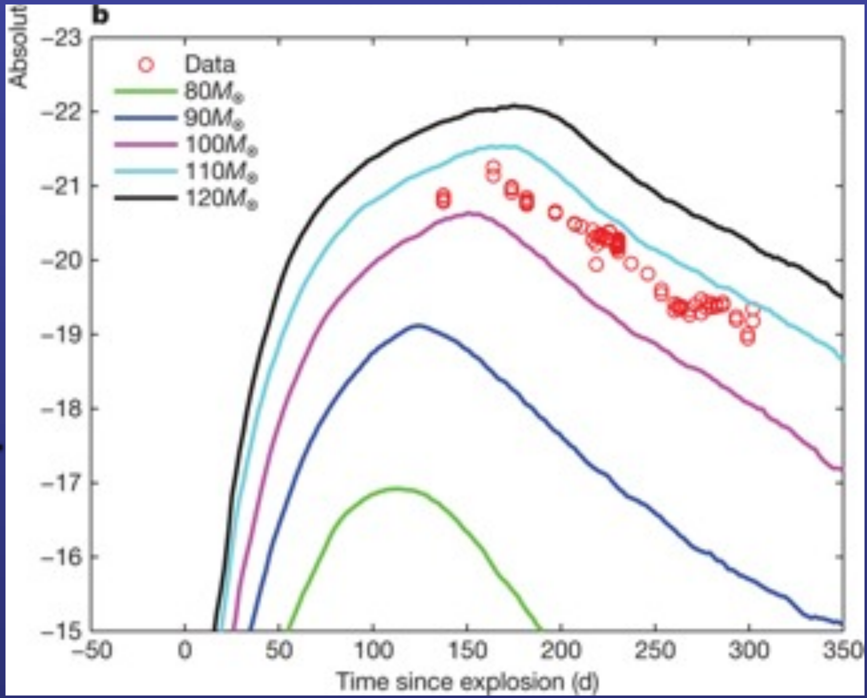


SN 2007bi

Several $M_\odot$ of ^{56}Ni required to reproduce light-curve of type Ic SN 2007bi ⇒ $M_{core} > 100\ M_\odot$ & $M_{init} \sim 200\ M_\odot$ [Gal-Yam+ 2009



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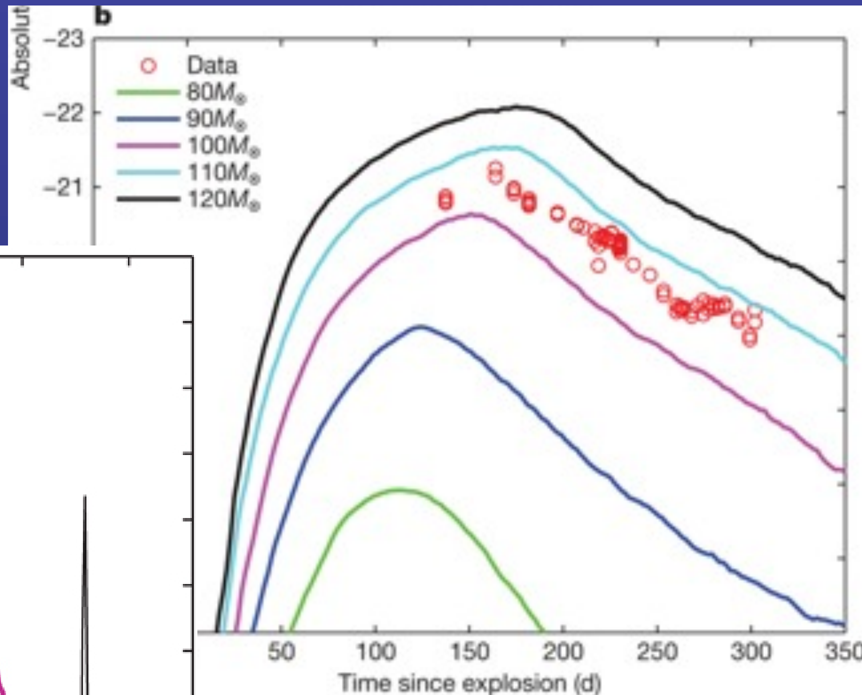
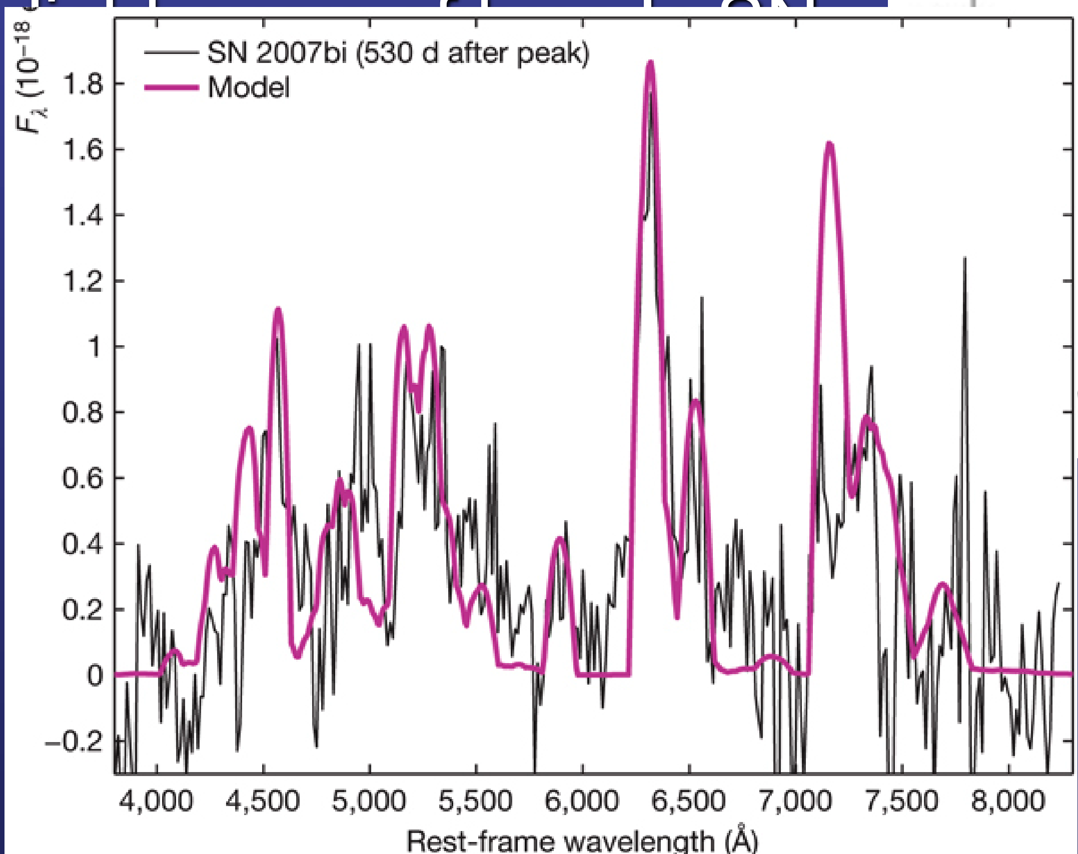
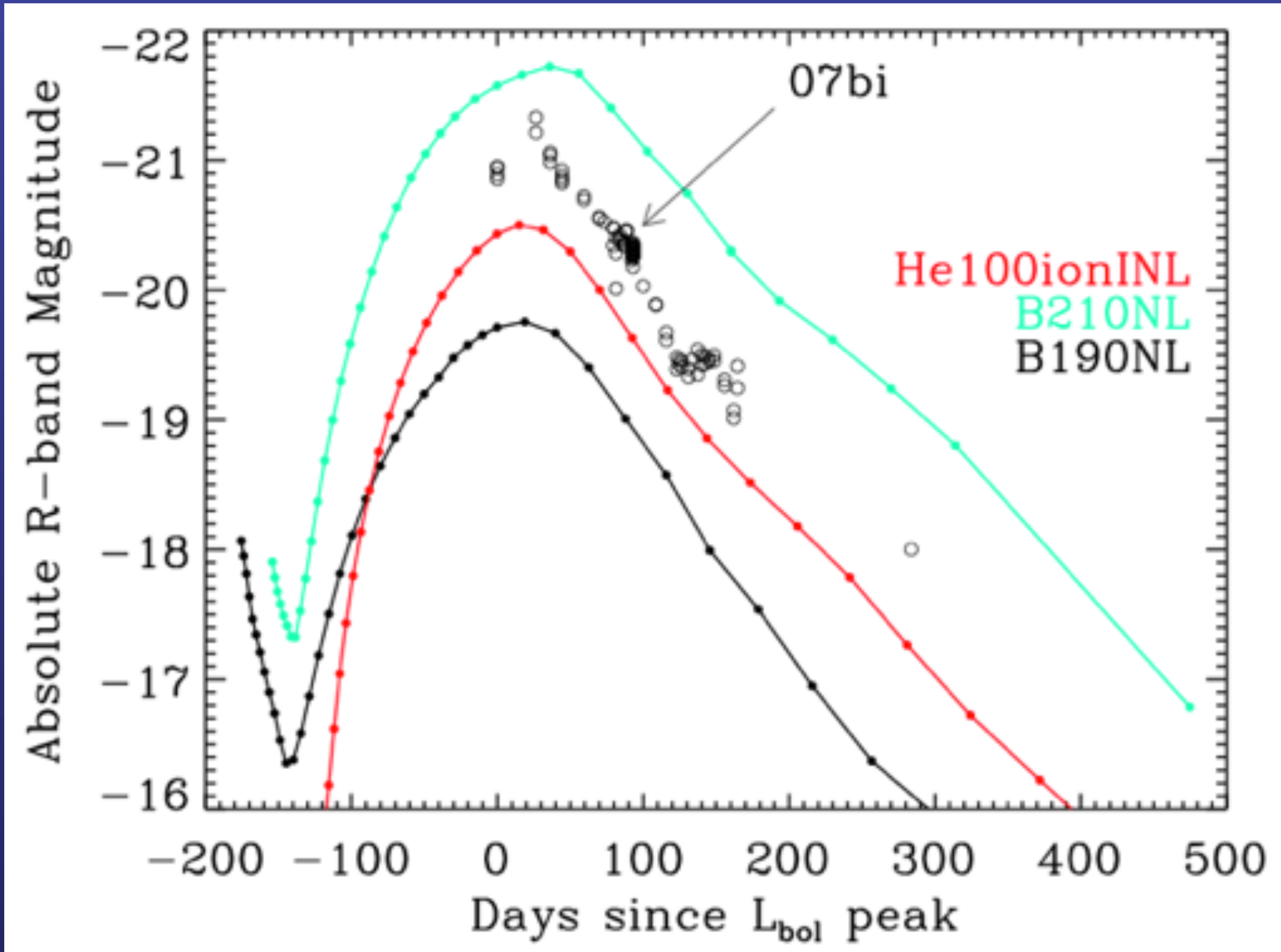




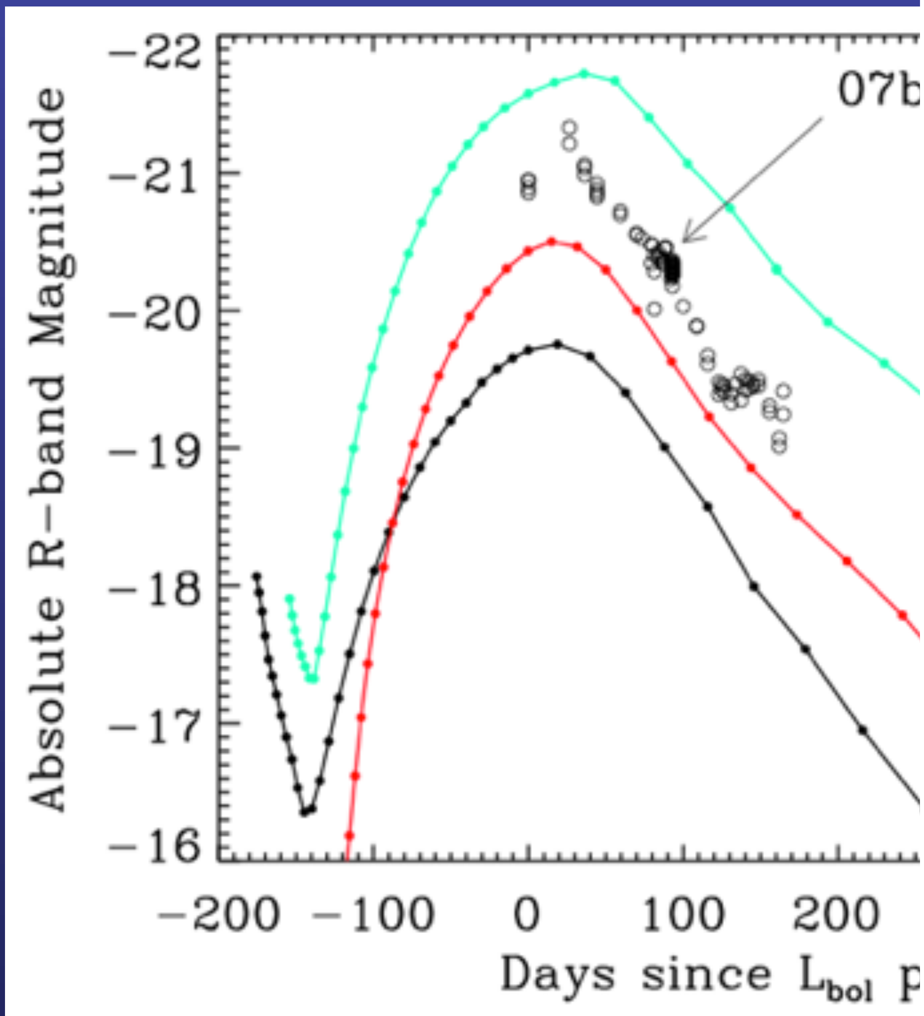
Nebular phase also consistent with $M_{Ni,init}$~5 $M_\odot$ (10x SN 1998bw)

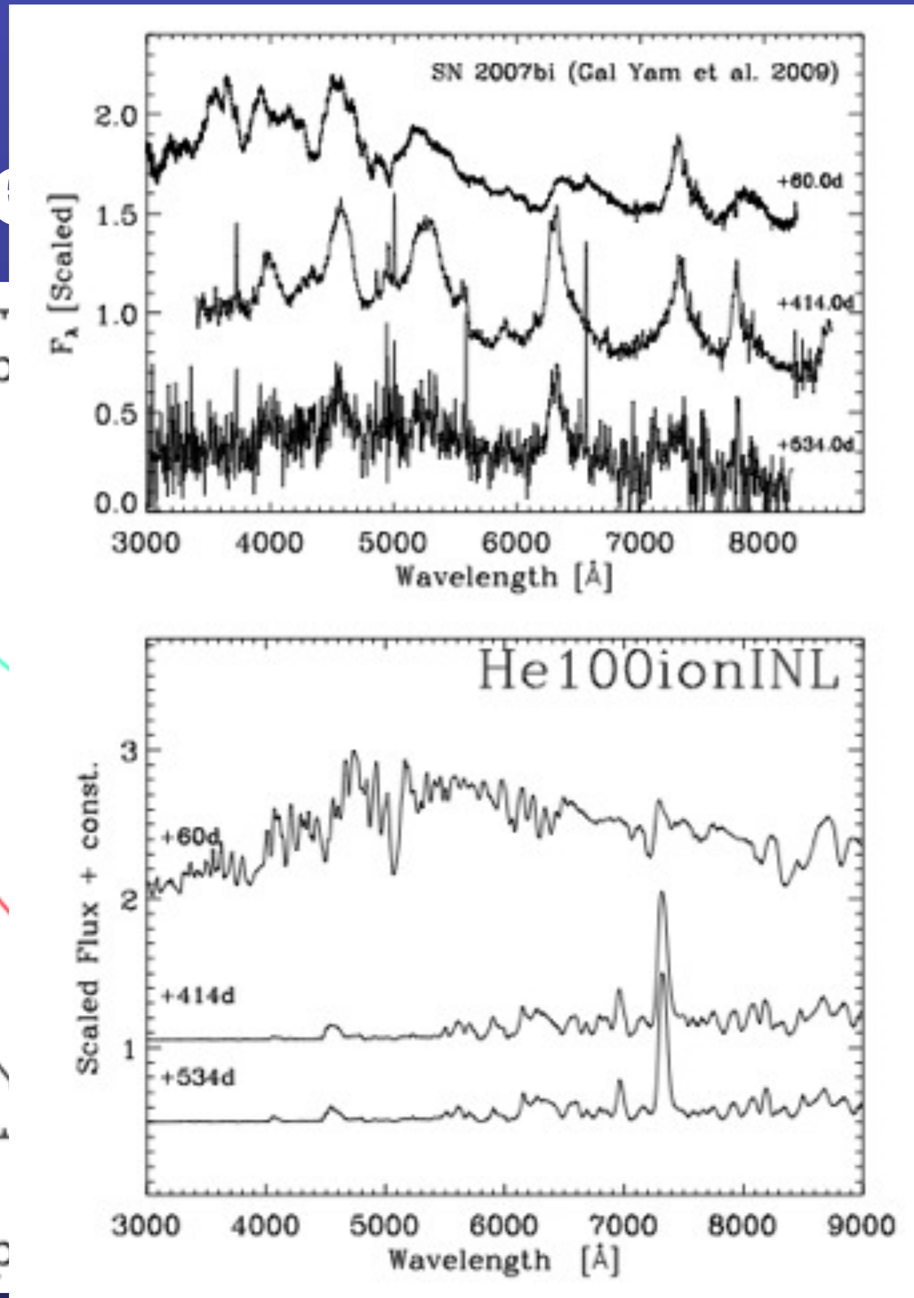
SN2007bi (alternate view)



Dessart, Hillier+ 2012; Dessart, Waldman+ 2013

SN2007bi (alte





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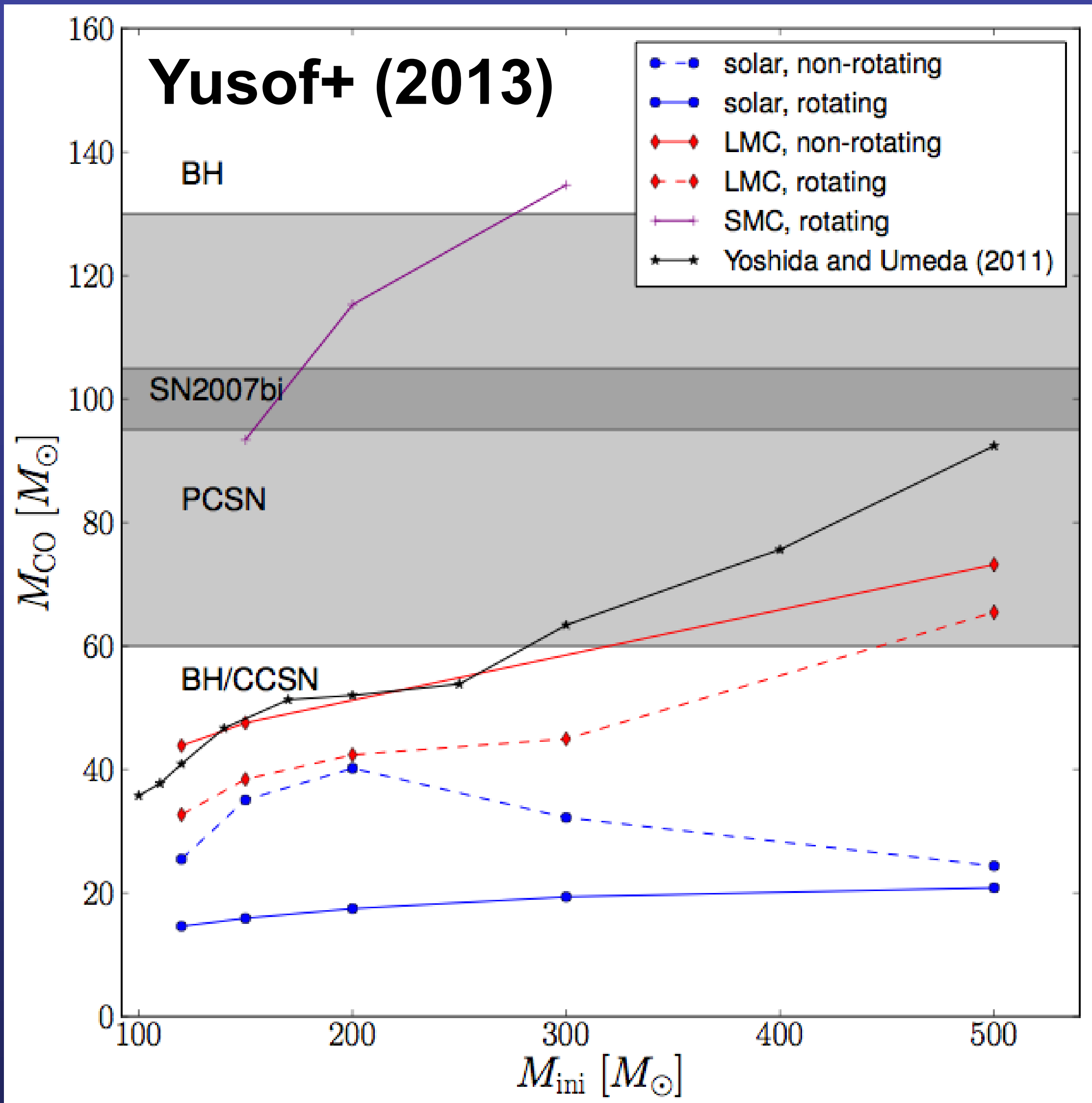
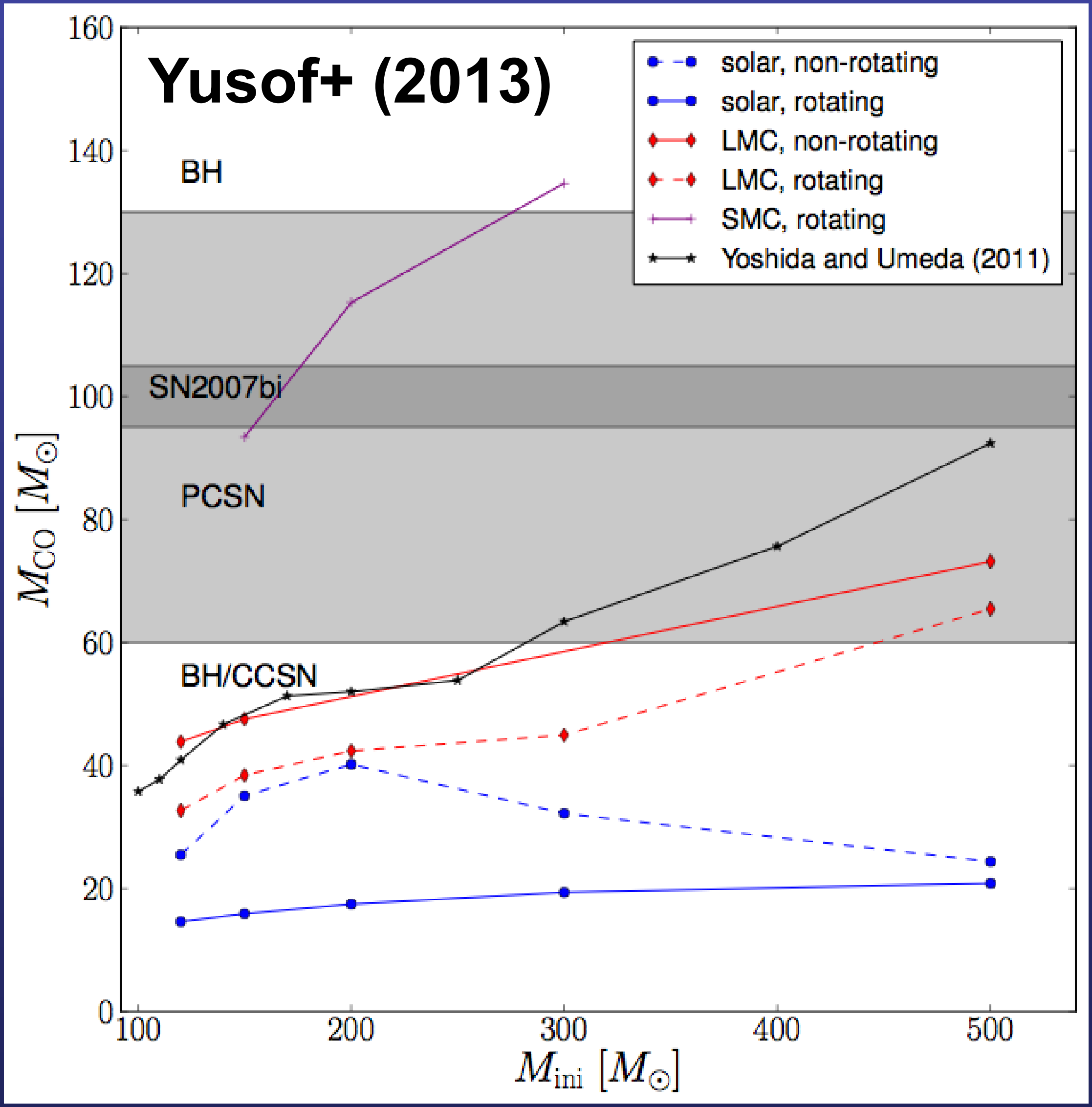
Death of VMS?

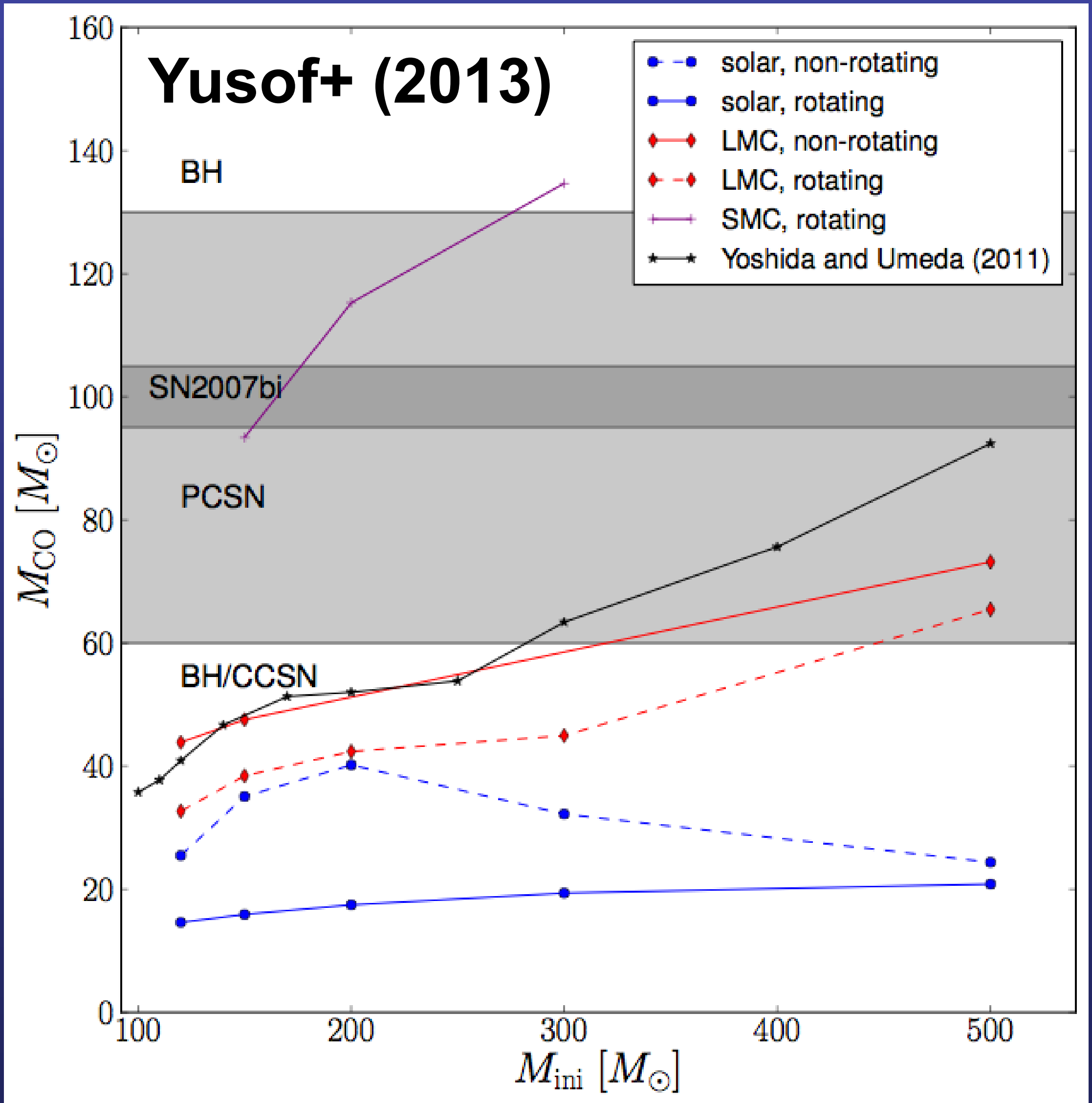

Yusof+ (2013)
solar, non-rotating
solar, rotating
LMC, non-rotating
LMC, rotating
SMC, rotating
Yoshida and Umeda (2011)
BH
SN2007bi
PCSN
BH/CCSN
M_{CO} $[M_\odot]$
M_{ini} $[M_\odot]$
0
20
40
60
80
100
120
140
160
100
200
300
400
500

Death of VMS?



If M_{up}~300 $M_\odot$ PISNe restricted to SMC-metallicity or lower*

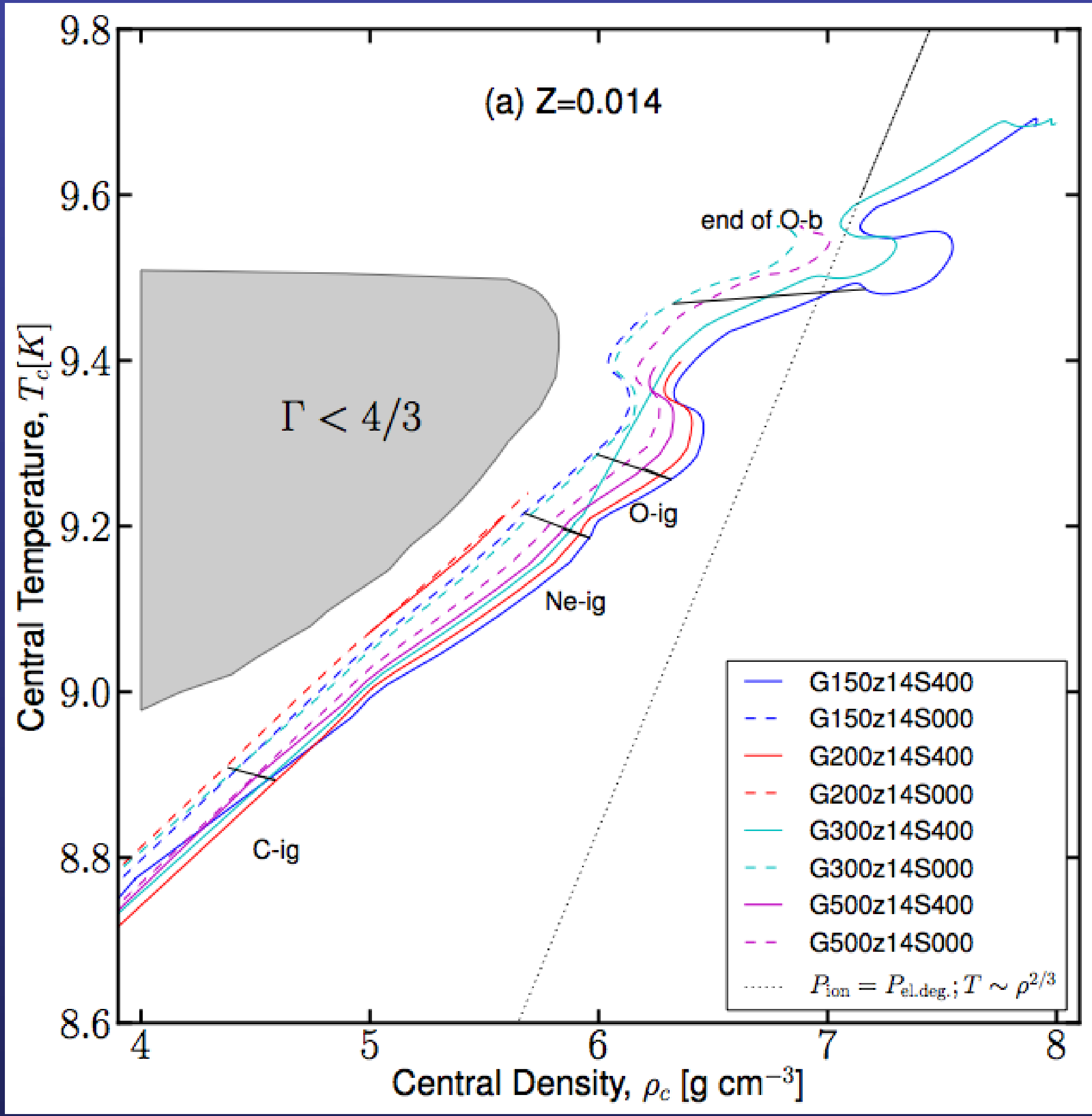
Death of VMS?



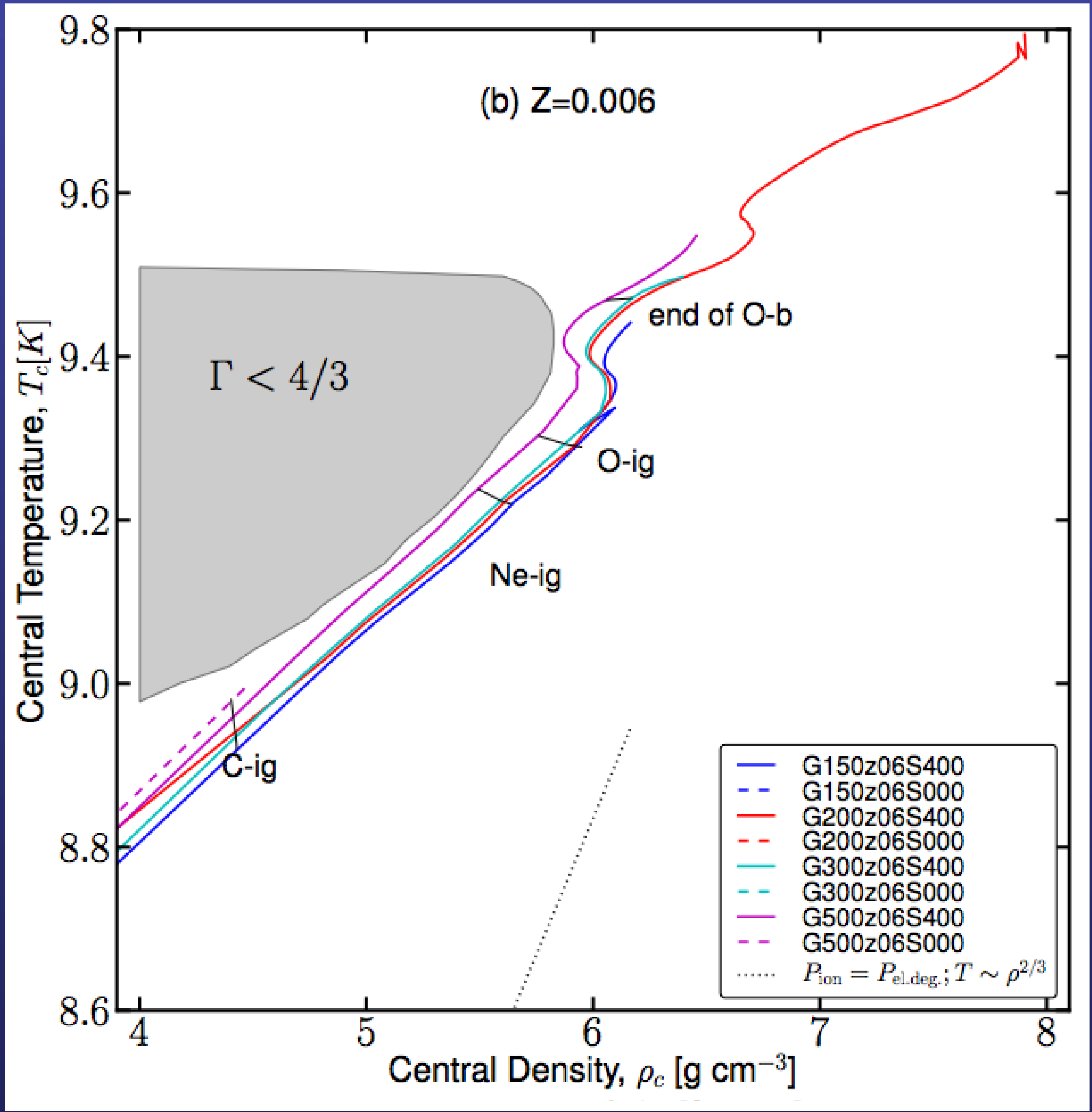
If M_{up}~300 $M_\odot$ PISNe restricted to SMC-metallicity or lower*

*Sensitive to post-main sequence mass-loss (Nugis & Lamers 2000); Gräfener & Hamann 2008)

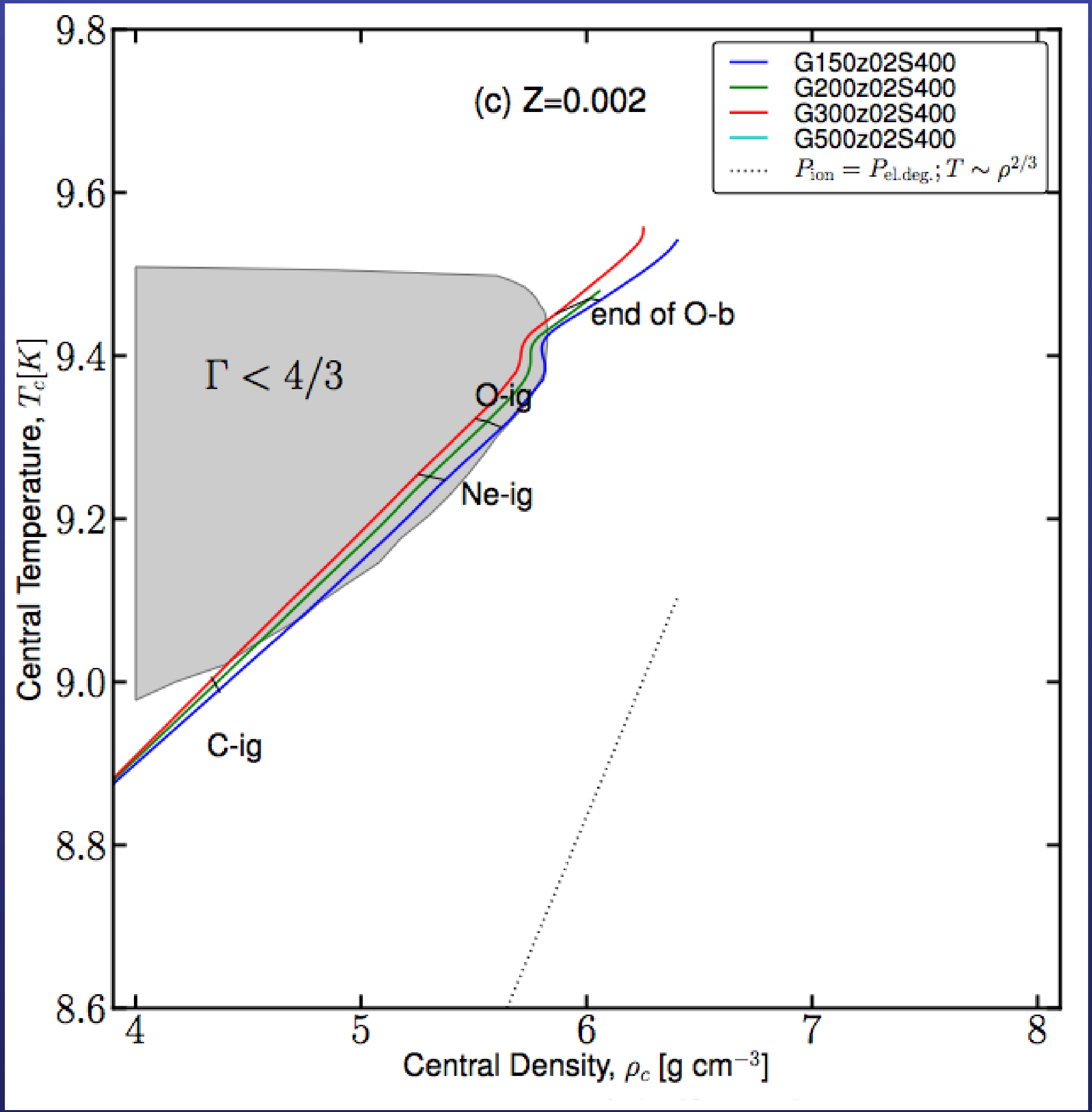
Solar Metallicity



LMC Metallicity



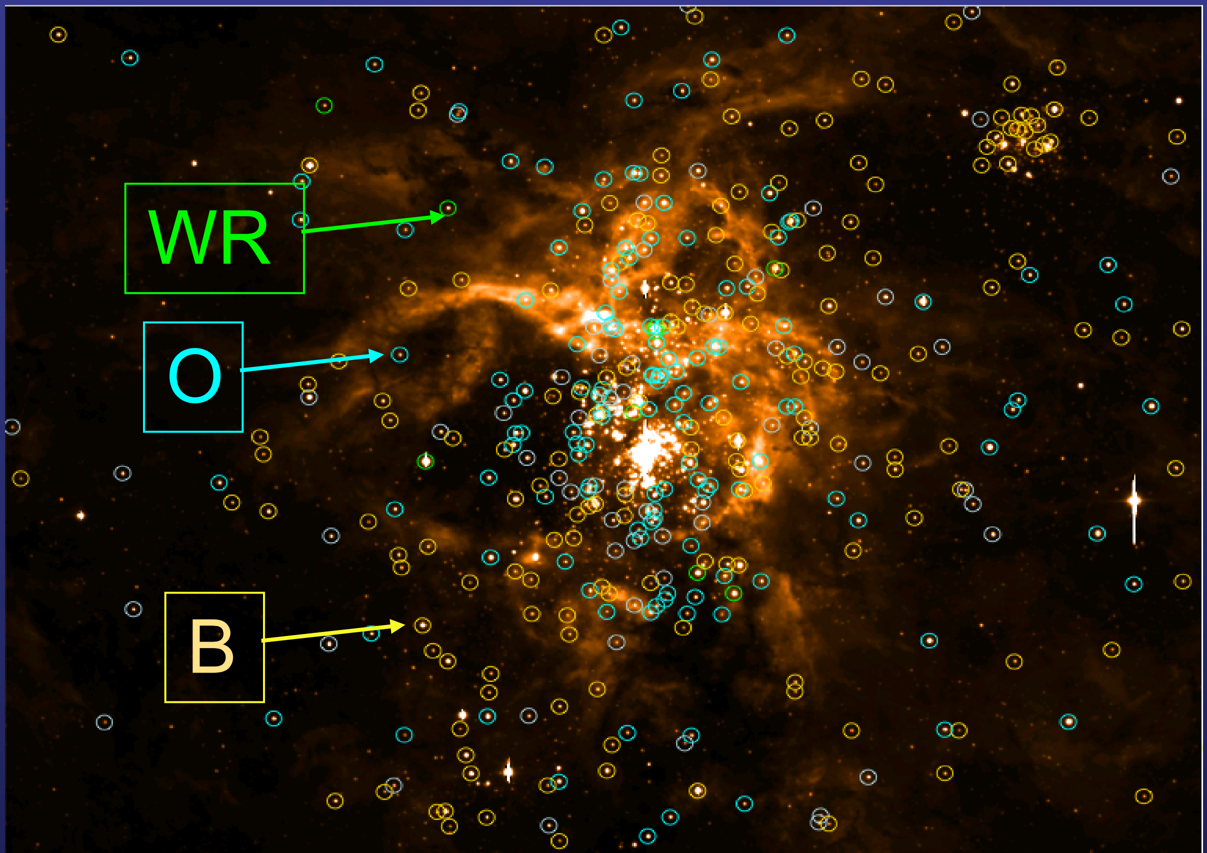
SMC Metallicity



- Part I: Why should we be cautious about `supermassive' stars?
- Part II: Why should we question the proposed ~150 Msun upper mass limit?
- Part III: So....what is the mass limit?
- Part IV: Astrophysical implications of very massive stars?
- **Part V: Quantitative properties of massive stars in starburst regions**

VLT FLAMES Tarantula Survey

- Multi-epoch spectroscopy of 800+ OB stars in 30 Doradus (Tarantula Nebula).



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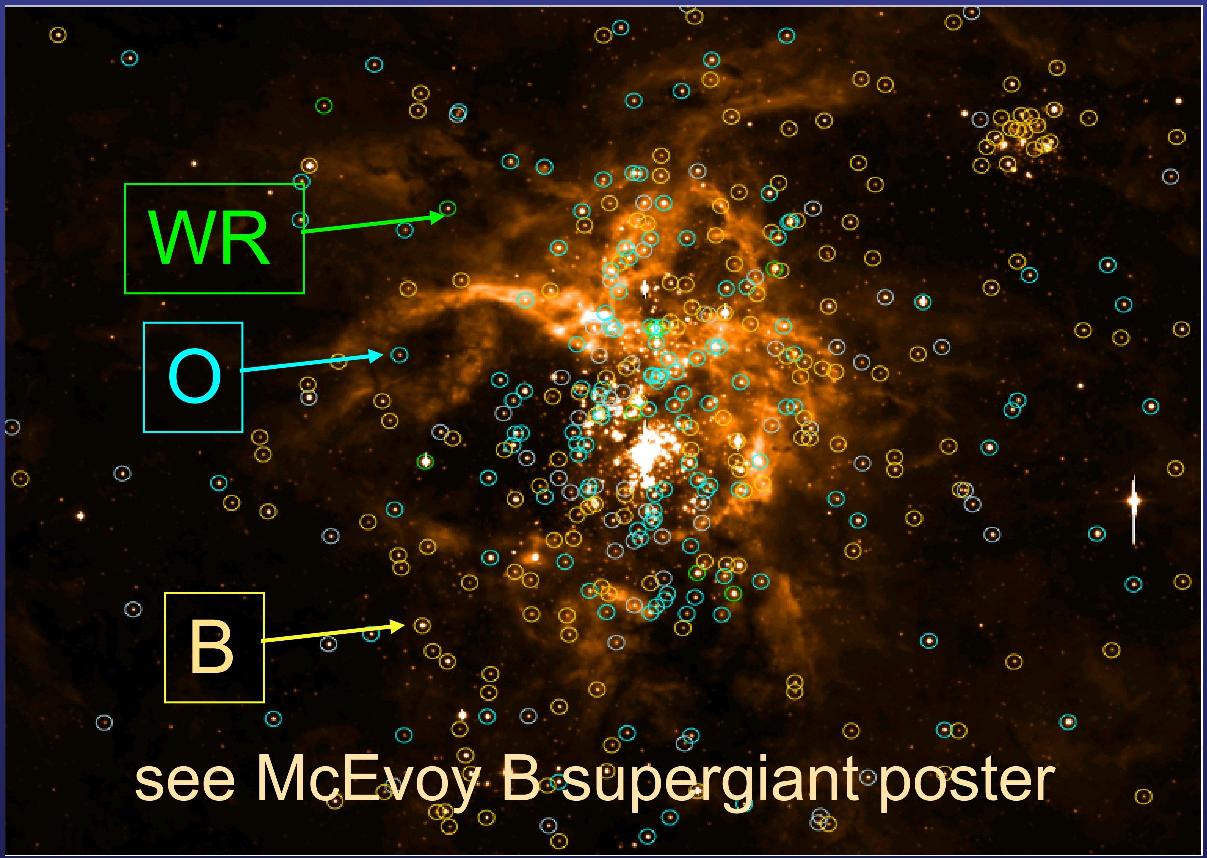
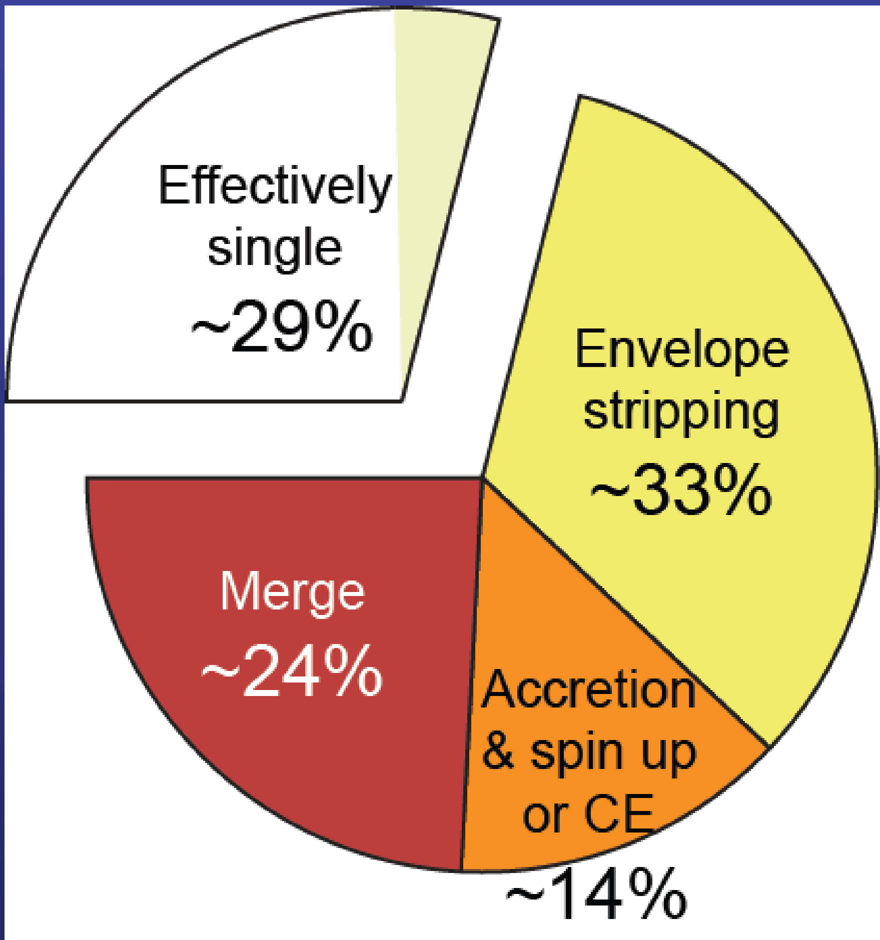


VLT FLAMES Tarantula Survey

- Multi-epoch spectroscopy of 800+ OB stars in 30 Doradus (Tarantula Nebula).
- Some key results:
  - 35% Binary fraction, from which inferred intrinsic fraction 51% (Sana+ 2013)
  - Fastest rotating O stars (~600 km/s; Dufton+ 2011, “OVnnn” Walborn+ in prep) & rotational distribution for OB-type stars (Dufton+ 2013; Ramirez+ in prep)
  - High mass `runaway’ (90 M_{sun}; Evans+ 2010) & ‘walkaway’ (150 M_{sun}: Bestenlehner+ 2011) from R136

VFTS binary statistics?



Sana+ (2012, Galactic clusters)

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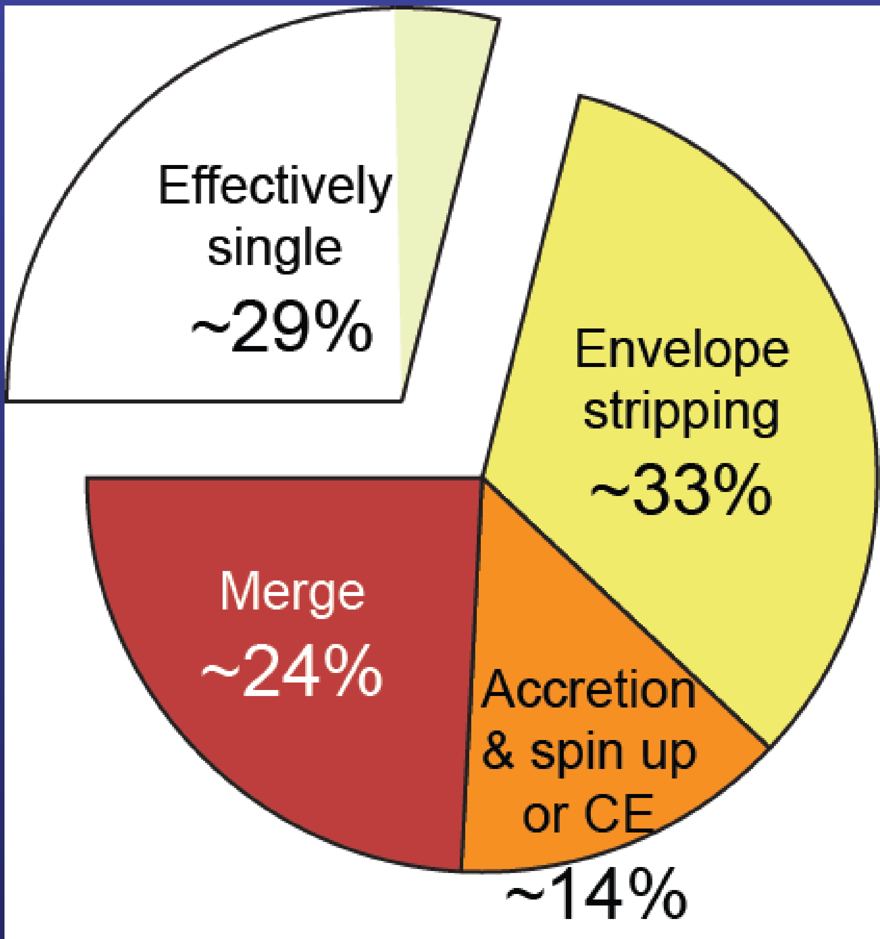
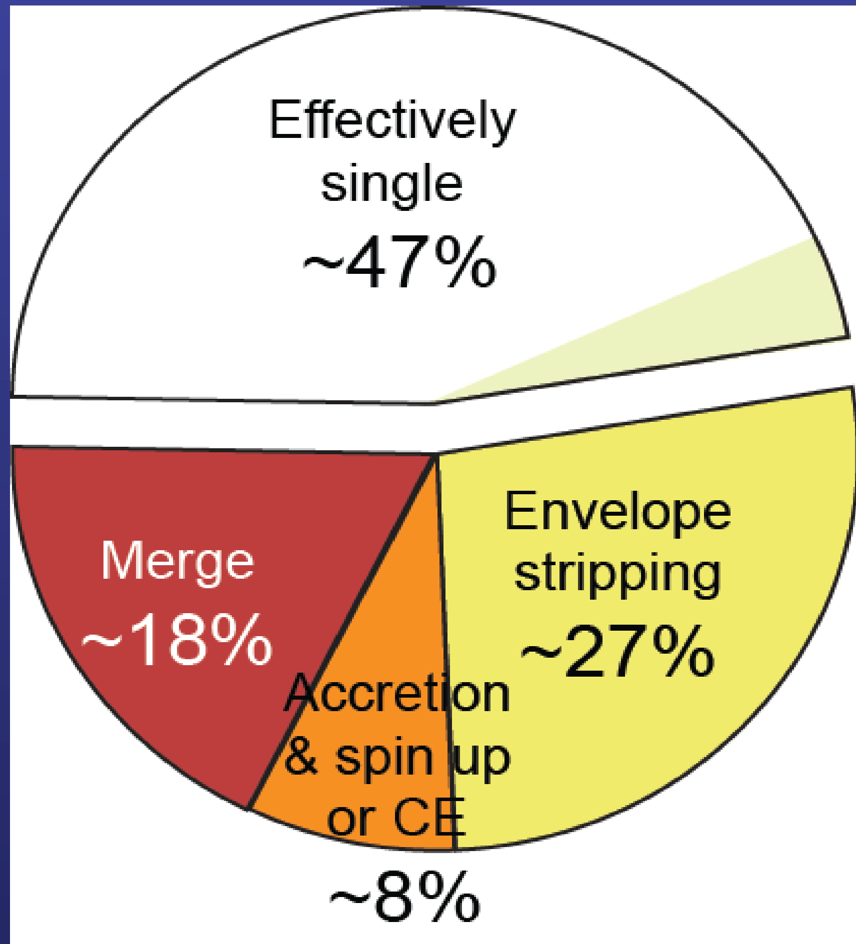
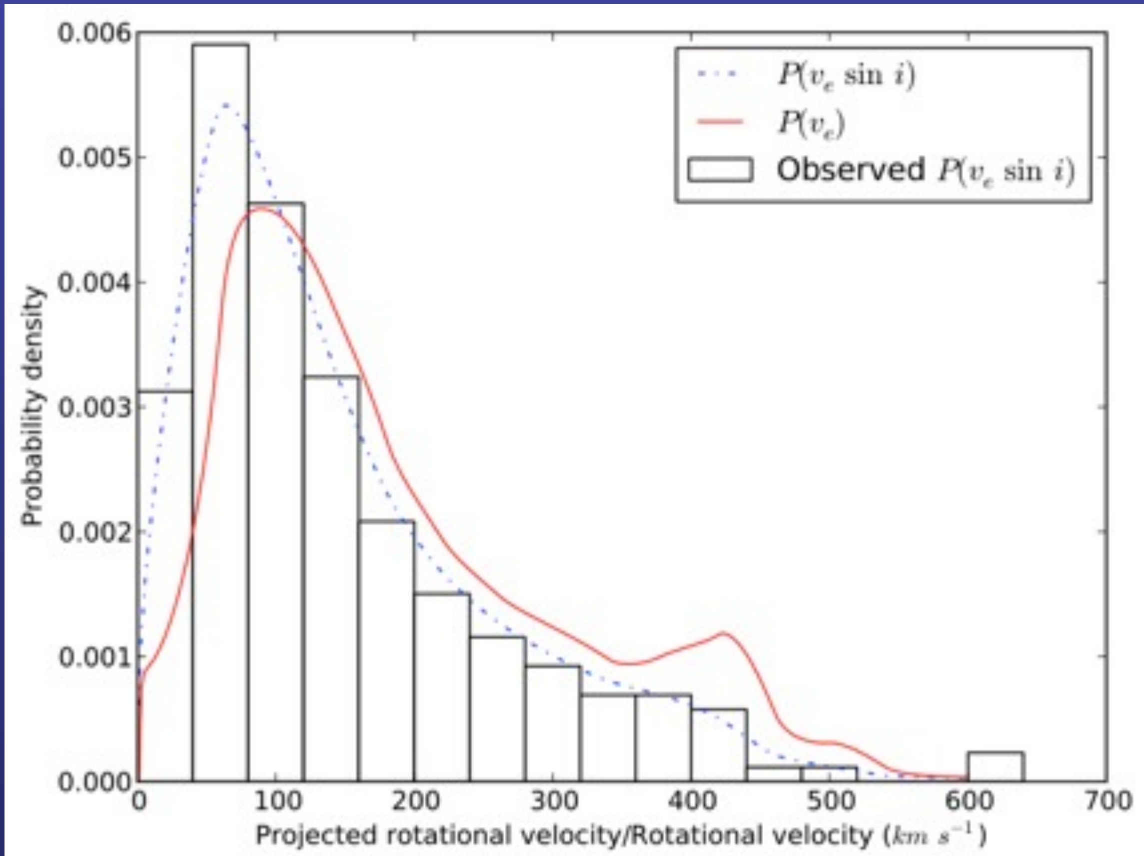




Sana+ (2012, Galactic clusters)   Sana+ (2013, VFTS:30 Dor)

VFTS OB-star velocity distribution



216 single O stars
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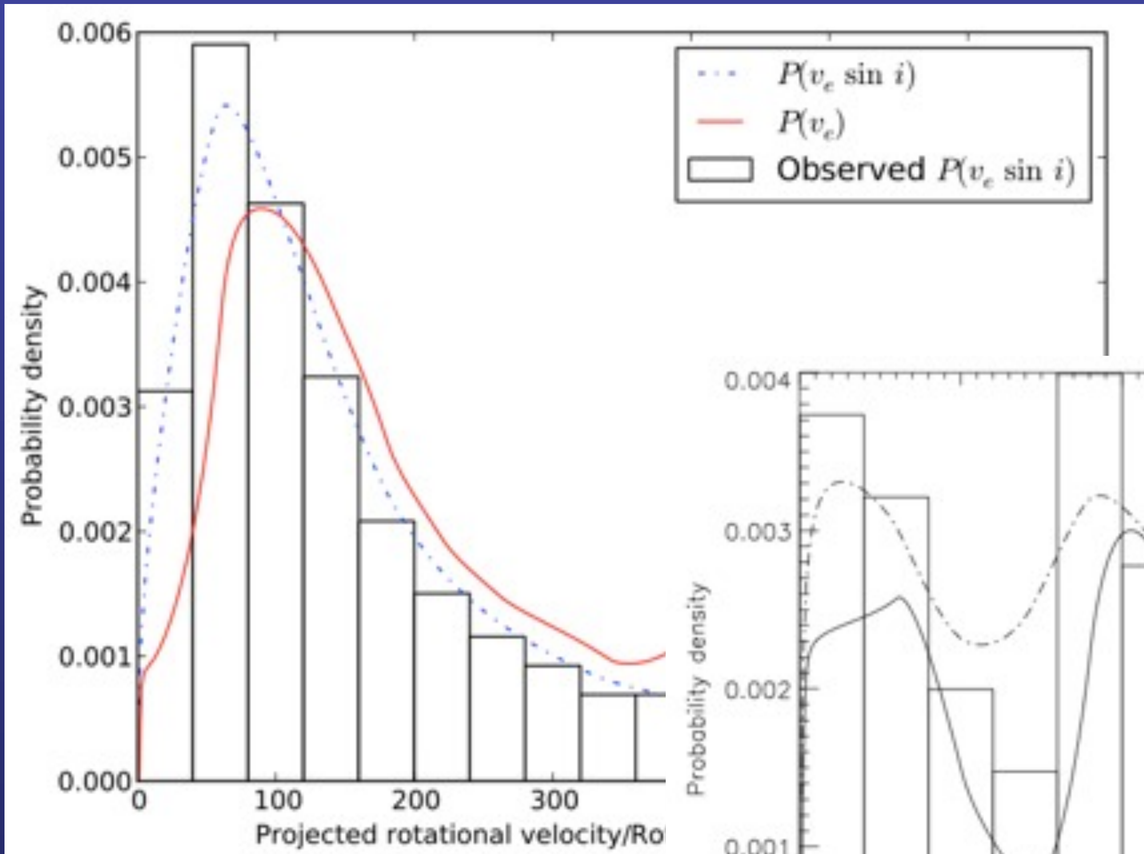
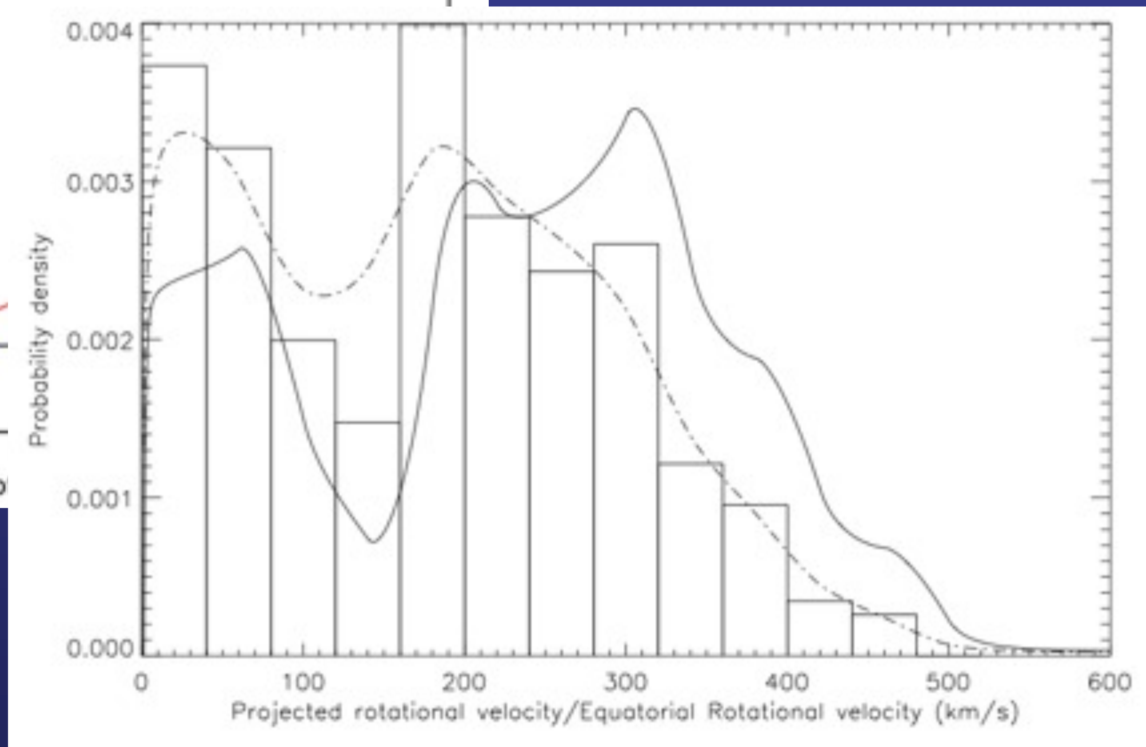


334 single, non-supergiant B stars (Dufton+ 2013)



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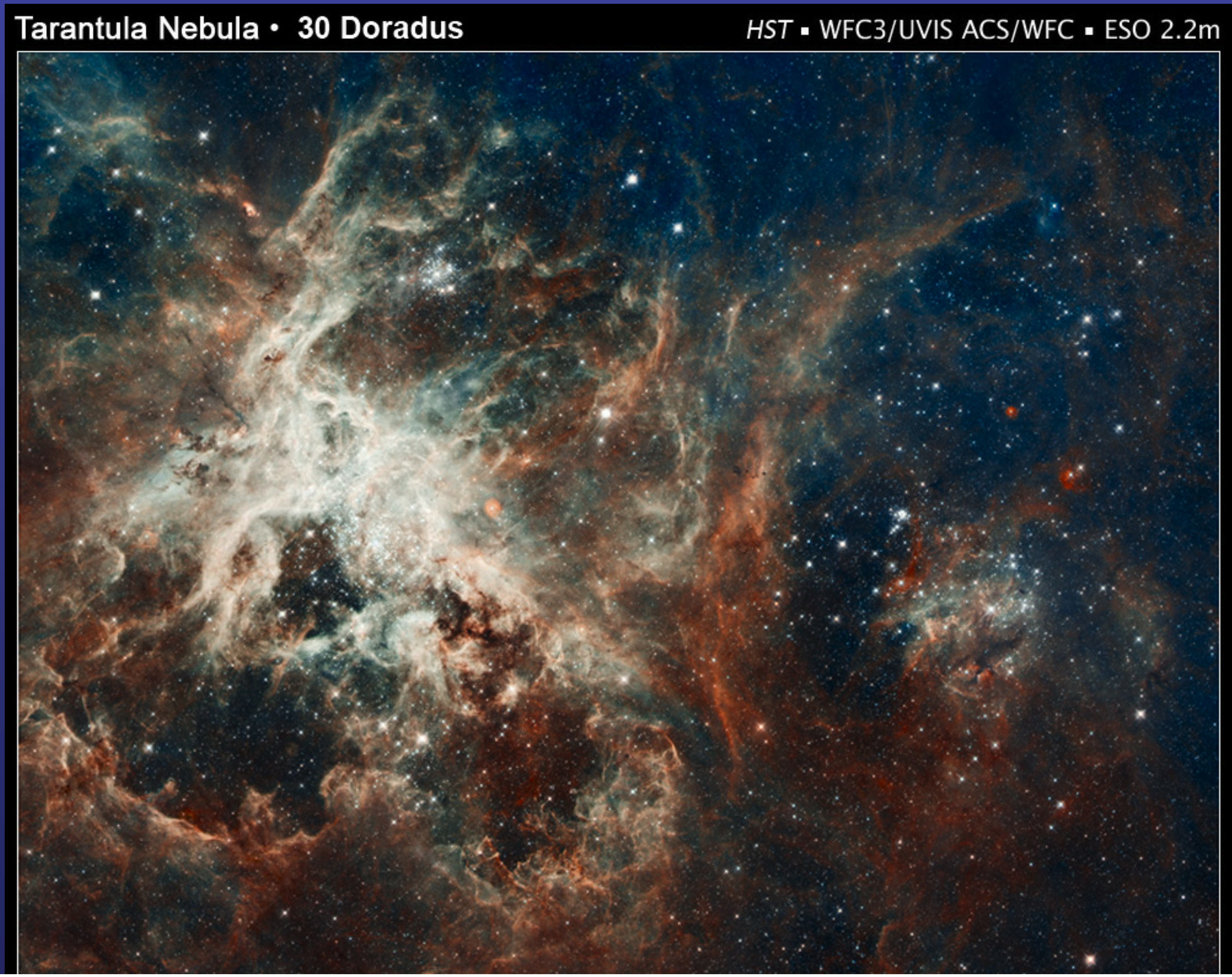
- VFTS 016 (O2III-If, 90 M_{sun}), offset from R136 by 120 pc [projected] is a likely runaway via dynamical ejection from proto-cluster (Evans+ 2010)

Runaways?



#016: Evans+ (2010); # 682: Bestenlehner+ (2011)

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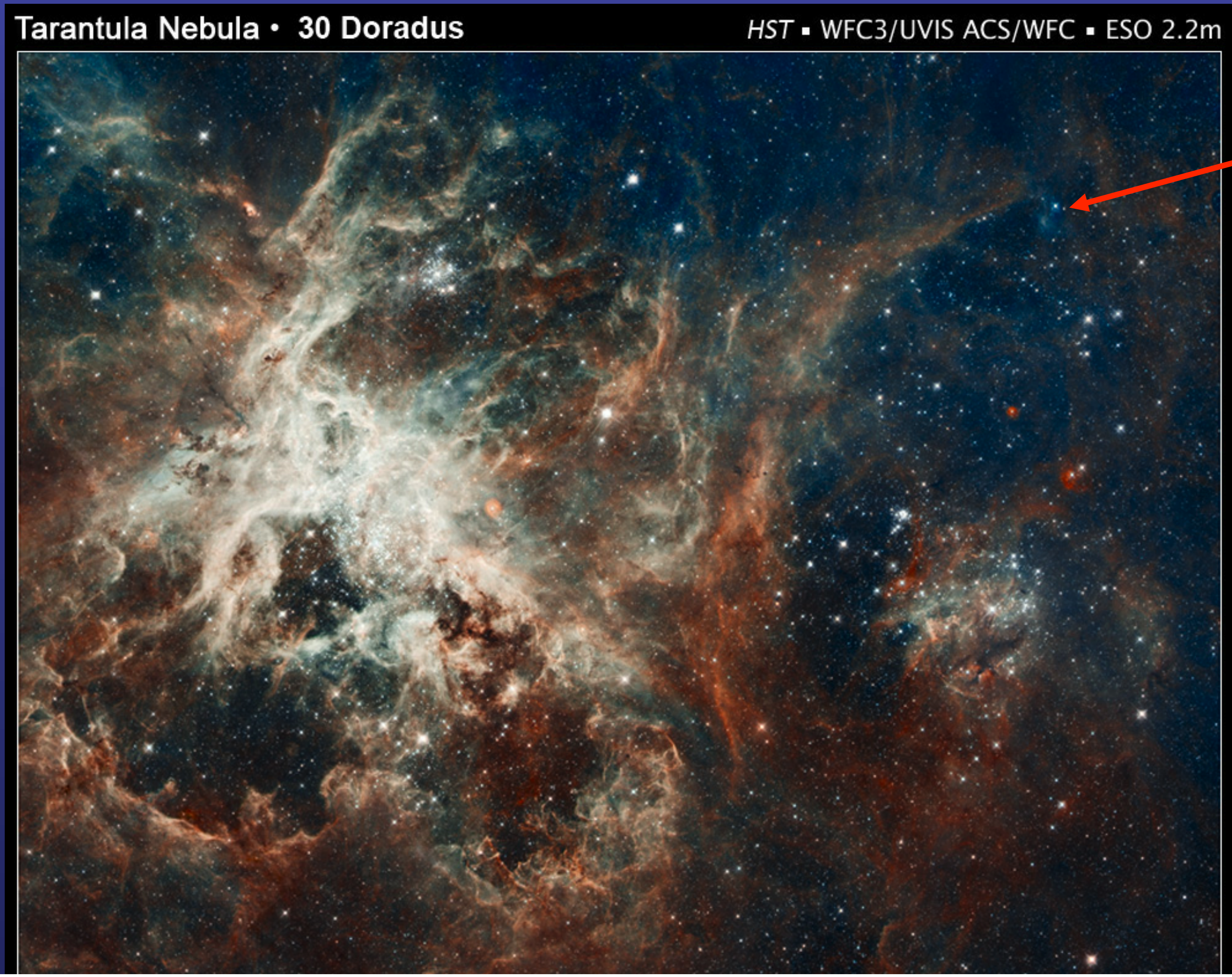

VFTS #016 ($90 M_{\odot}$)

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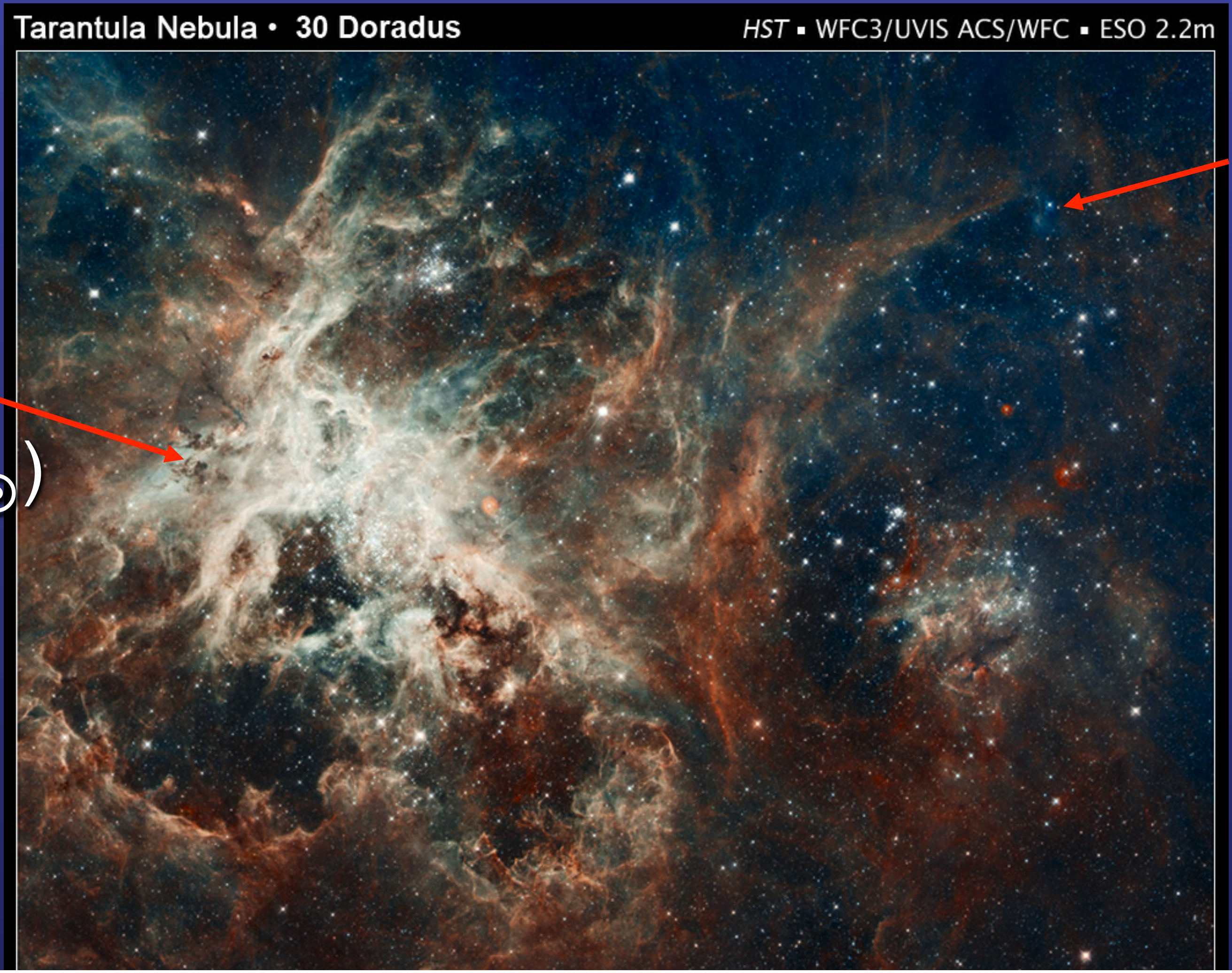
Runaways?

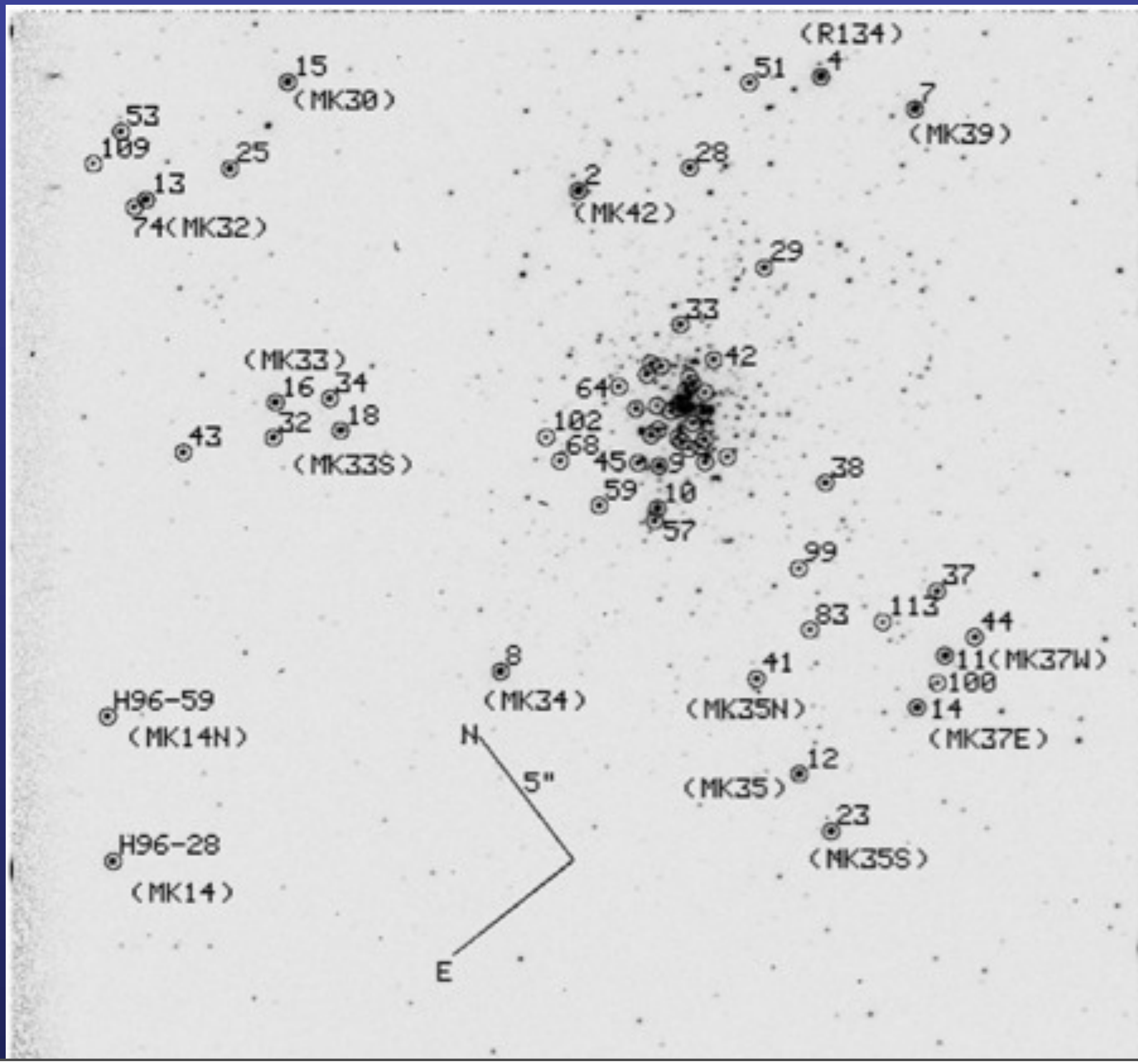


VFTS #682 (150$M_\odot$)

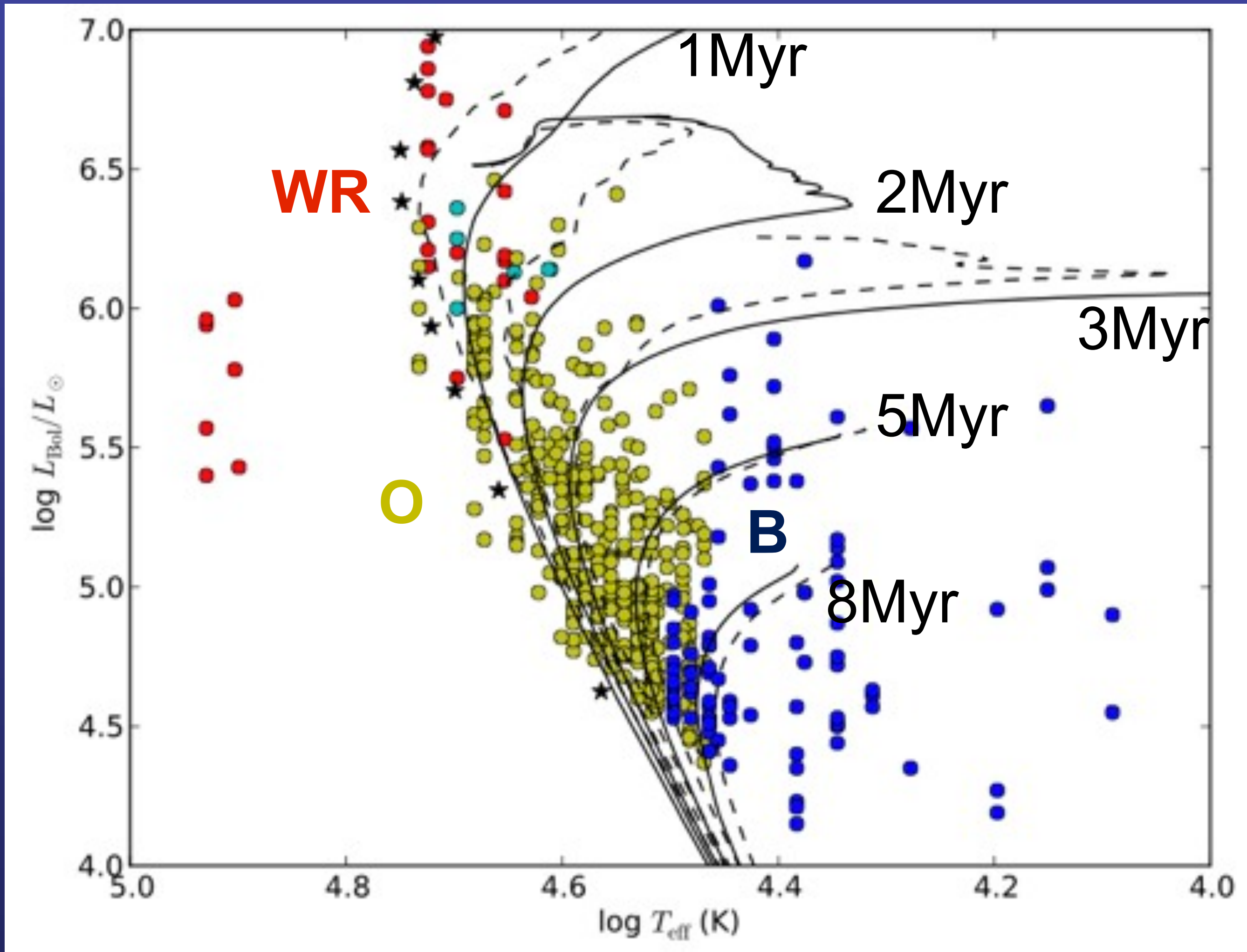
VFTS #016 (90$M_\odot$)

#016: Evans+ (2010); # 682: Bestenlehner+ (2011)

R136 region: Massey & Hunter



Massive stars in 30 Doradus



Doran, Crowther+ (2013)

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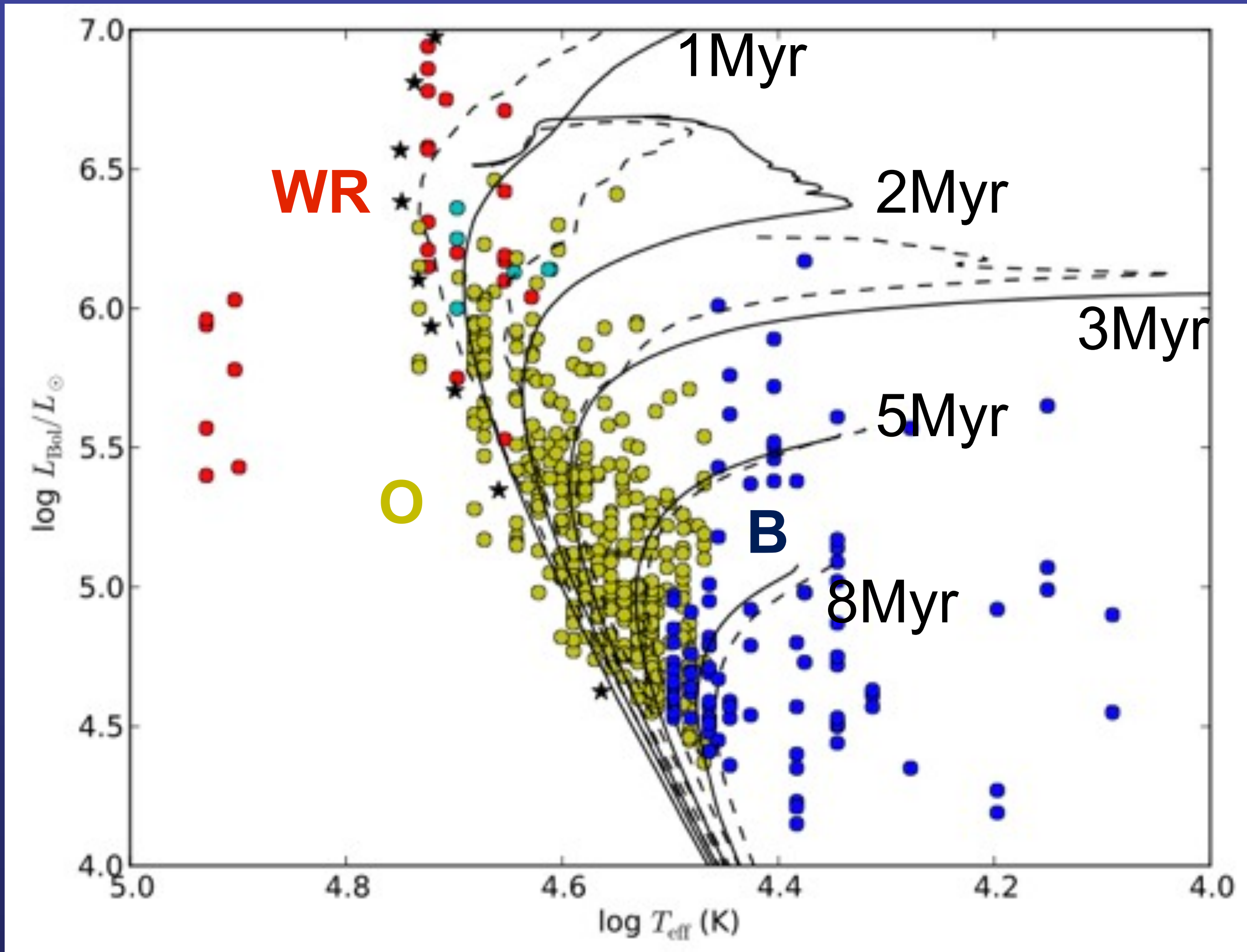
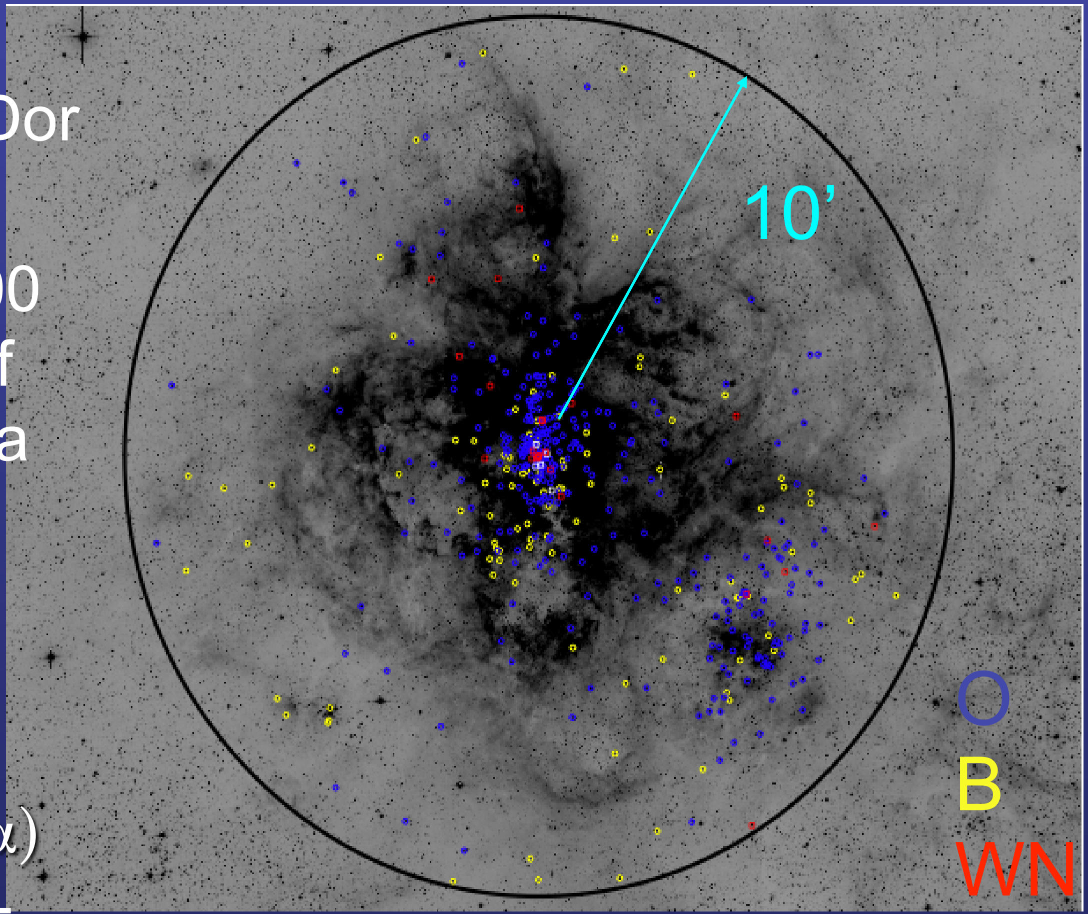


Age from $EW_{H-alpha}$ ~3.5Myr

Doran, Crowther+ (2013)

Stellar feedback

- R136a1 alone contributes 8% of 30 Dor ionizing output
- ~12 stars with M_{init}>100 M_{sun} contribute 30% of the total (remainder via 500+ O & luminous B stars)
- Direct census implies SFR=0.09 M_{sun}/yr vs 0.07 M_{sun}/yr from L(Hα)
- 40% of global wind KE from only 12 very massive stars.



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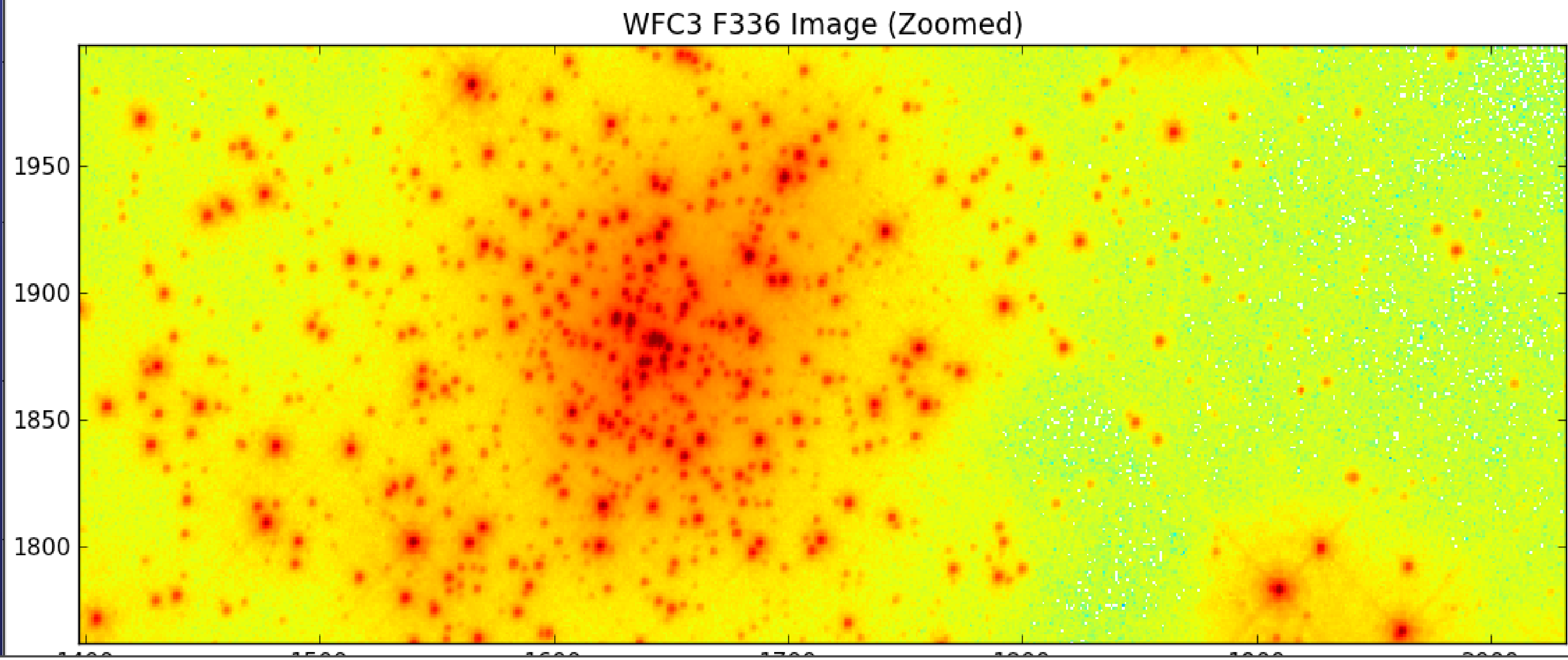
Next step: STIS spectroscopy

0.2” slits -> UV/blue/Hα sampling of central pc of R136



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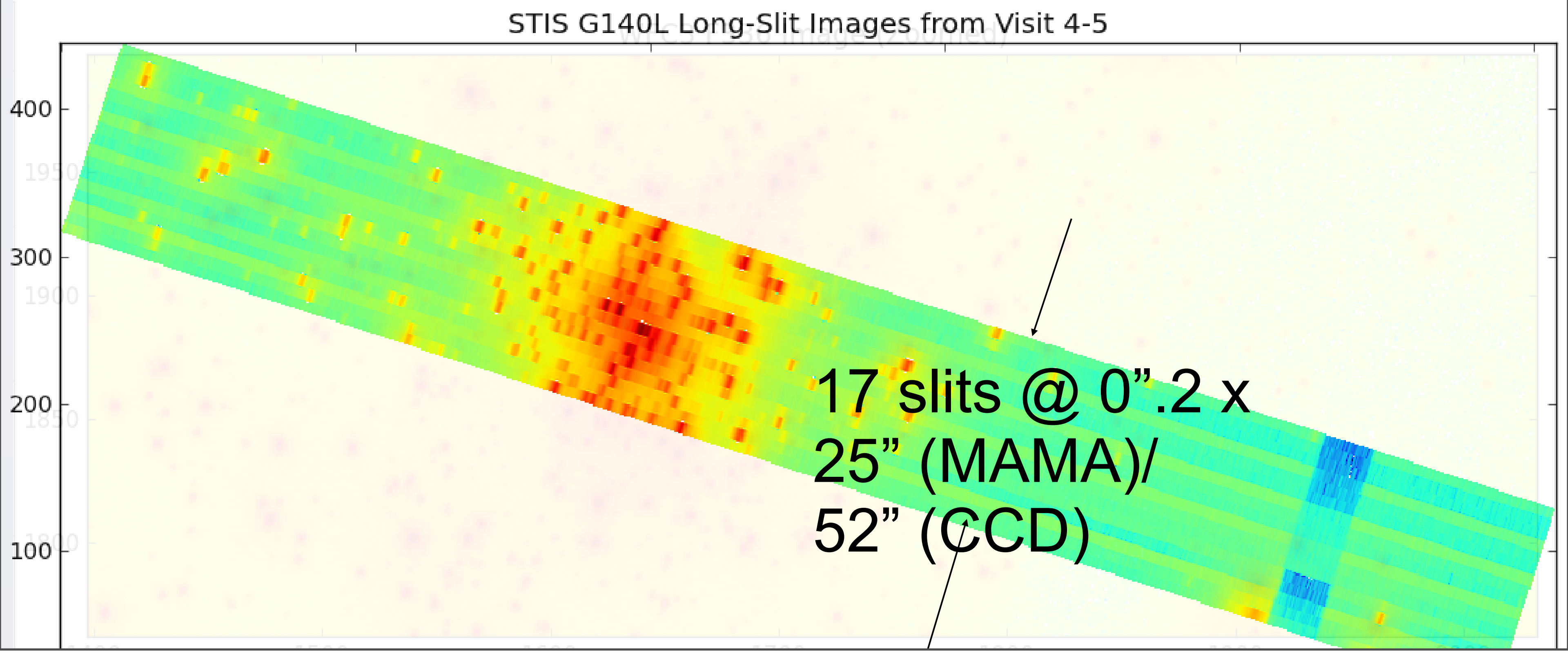
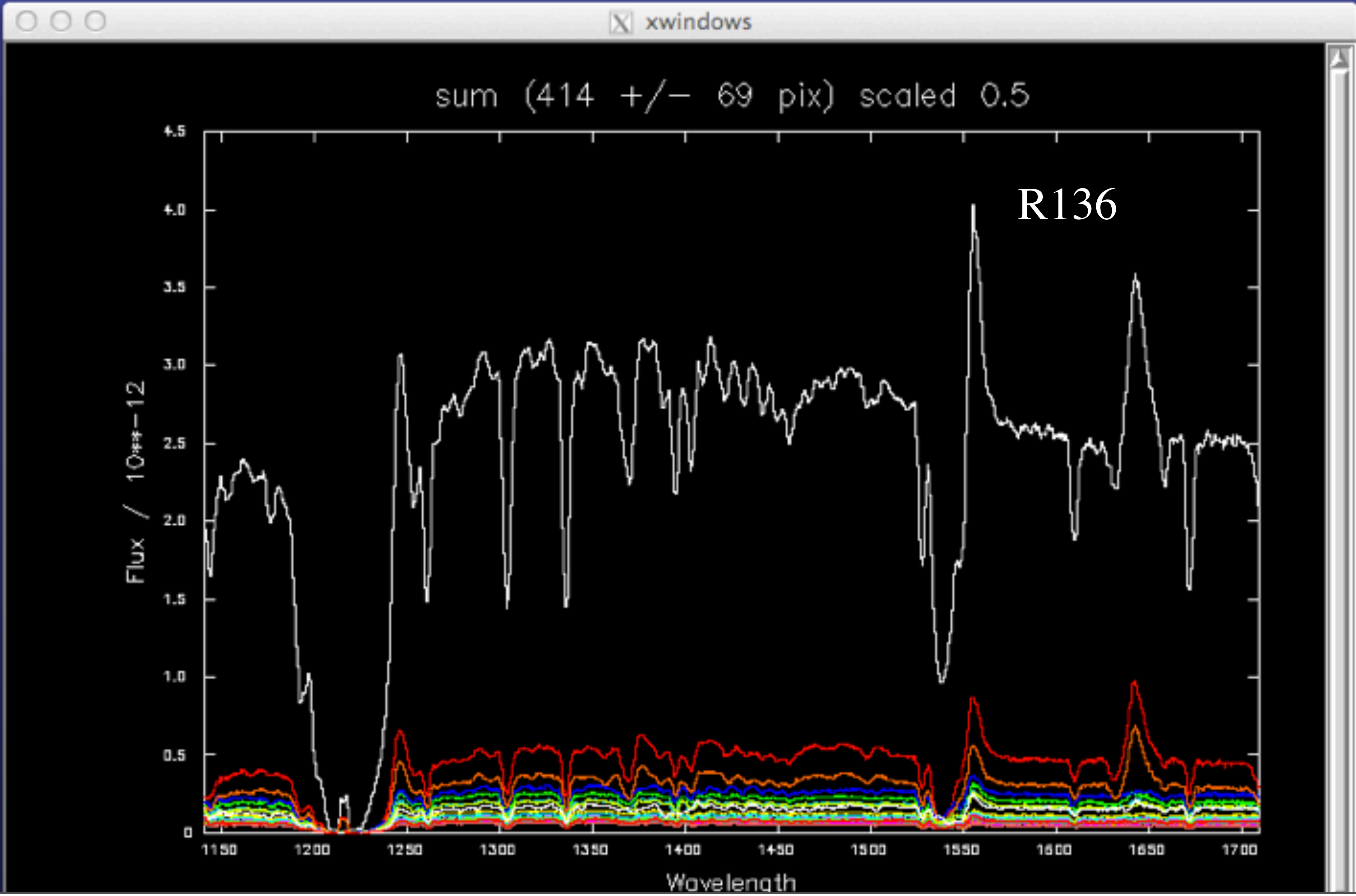


R136 integrated UV spectrum



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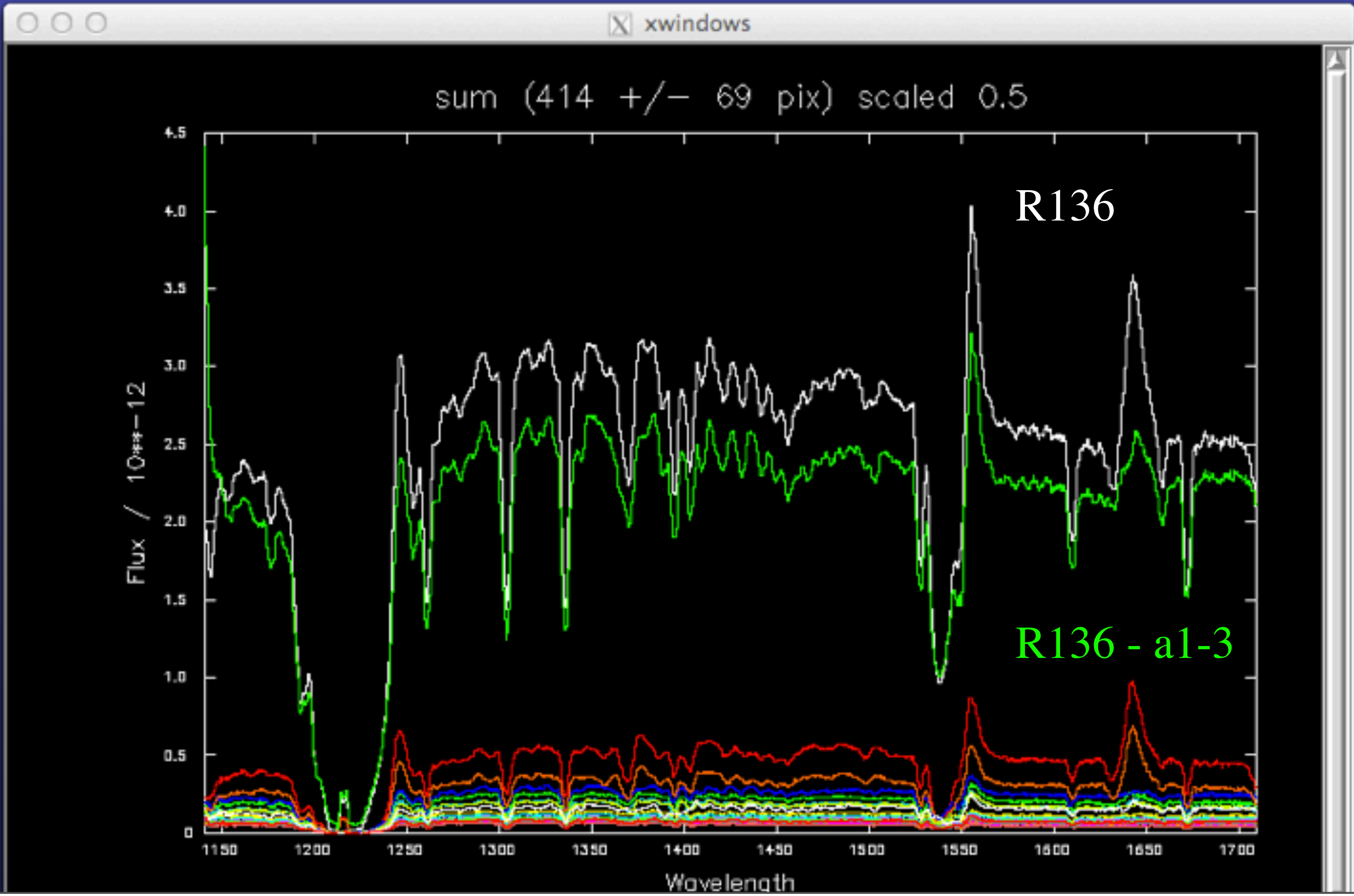
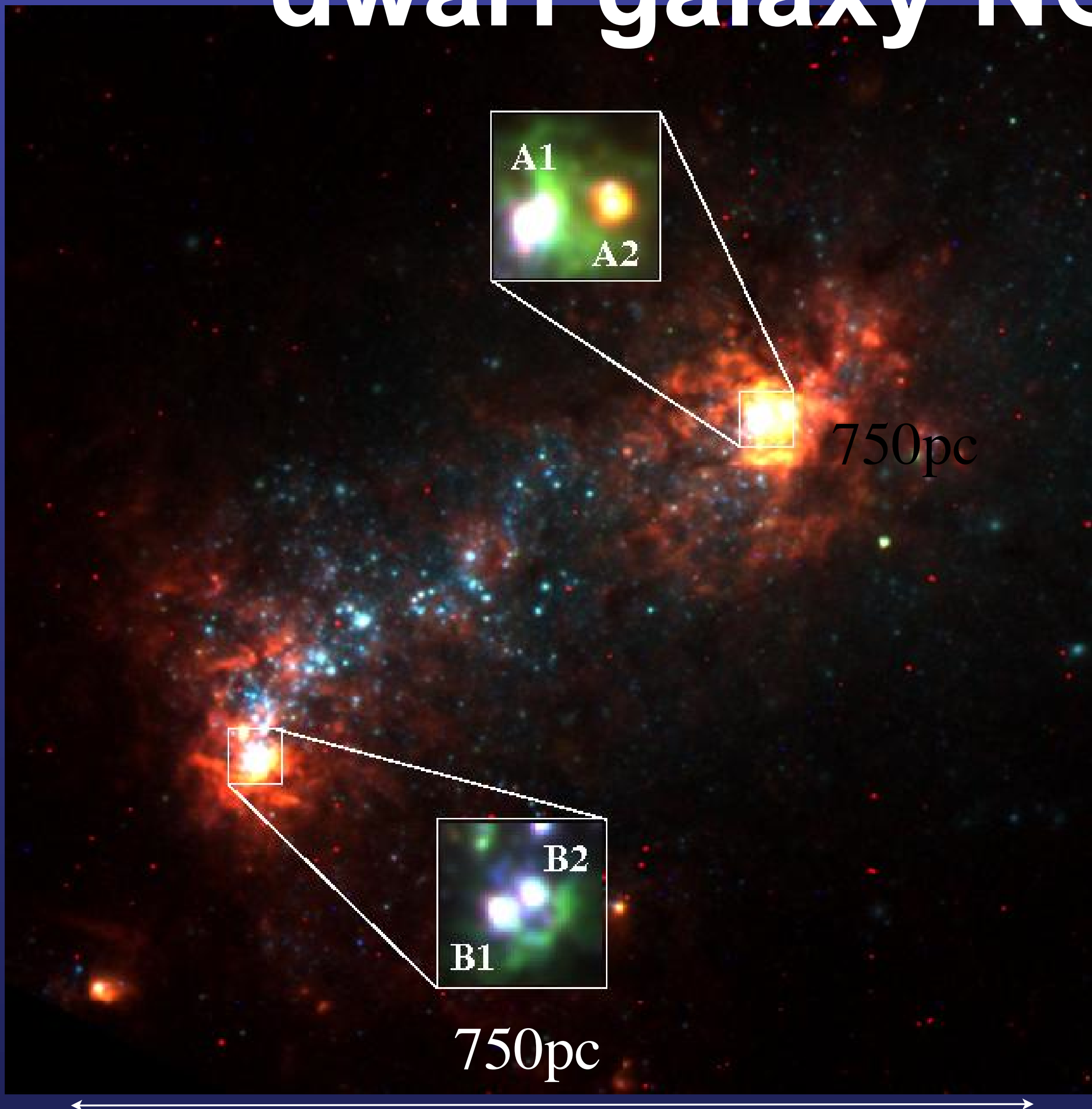


Monday, April 15, 2013

Cluster A1 in blue compact dwarf galaxy NGC 3125



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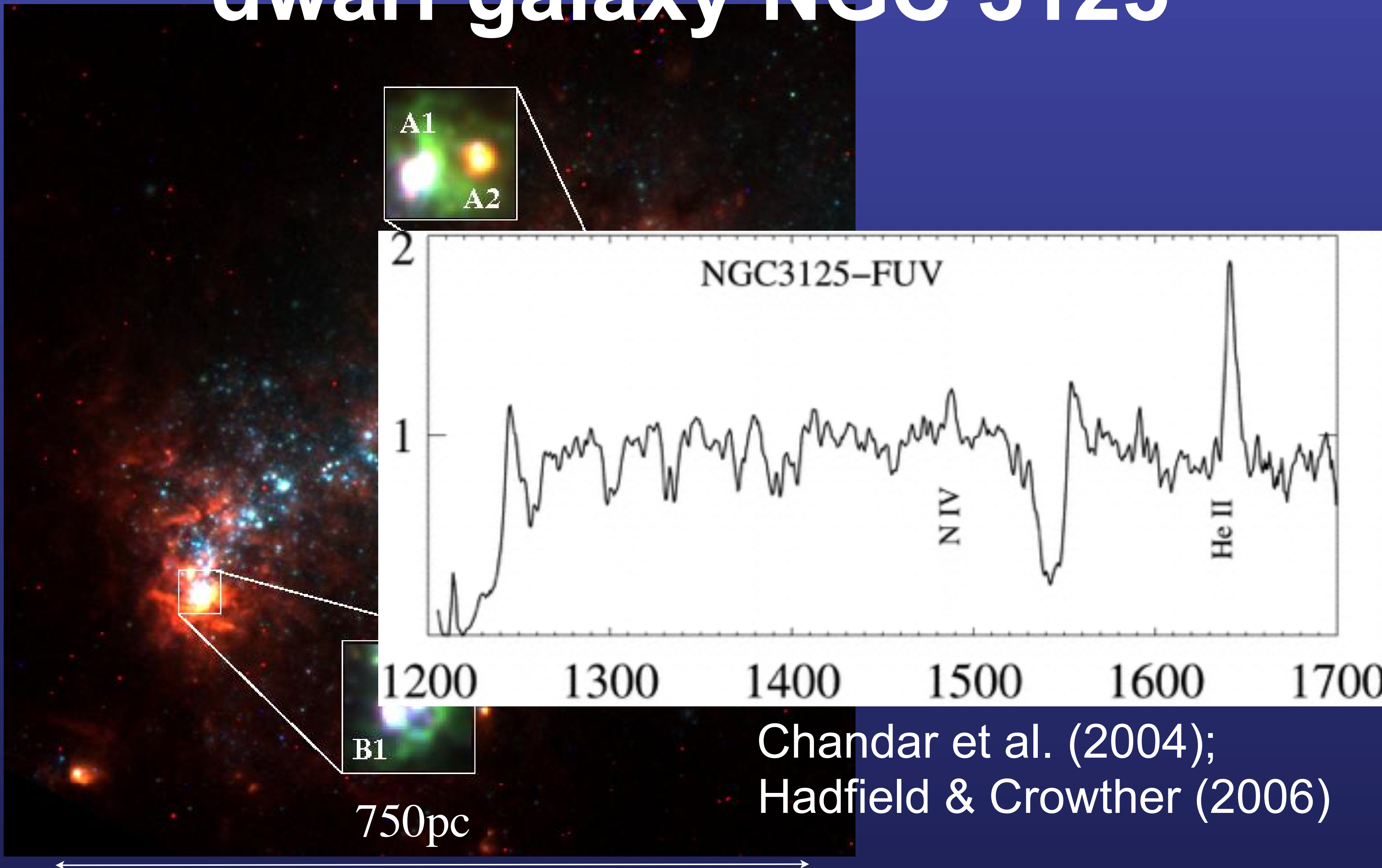

Chandar et al. (2004); Hadfield & Crowther (2006)

Summary

Mass Range (M_{sun})		Name
10 -	100	Massive stars
100 -	1,000	Very massive stars
1,000 -	10,000	Extremely massive stars
10,000 -	100,000	Ultra massive stars
100,000 -	250,000	Hyper massive stars

Summary

Mass Range (M_{sun})	Name
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100 - 300?	Very massive stars
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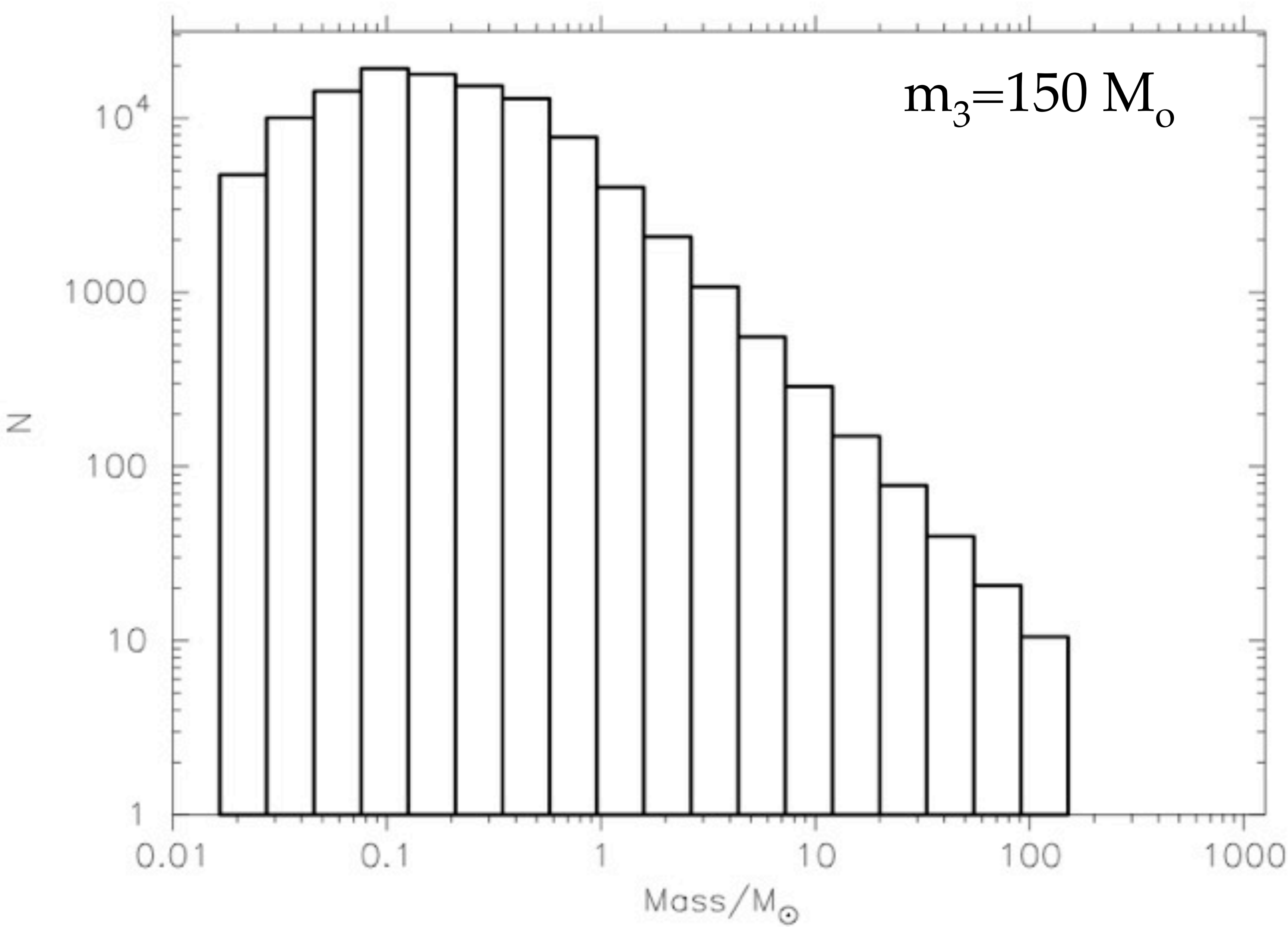
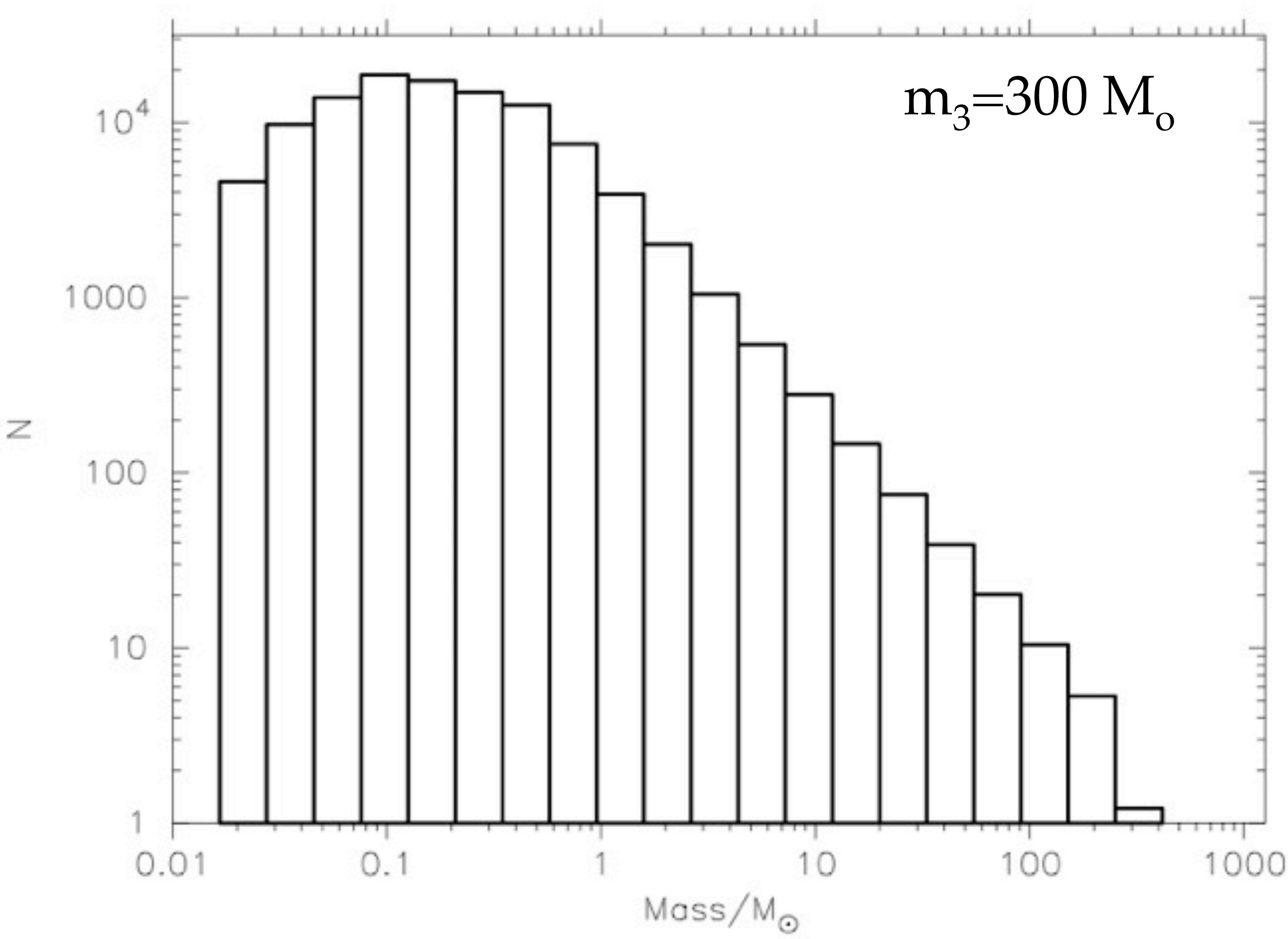


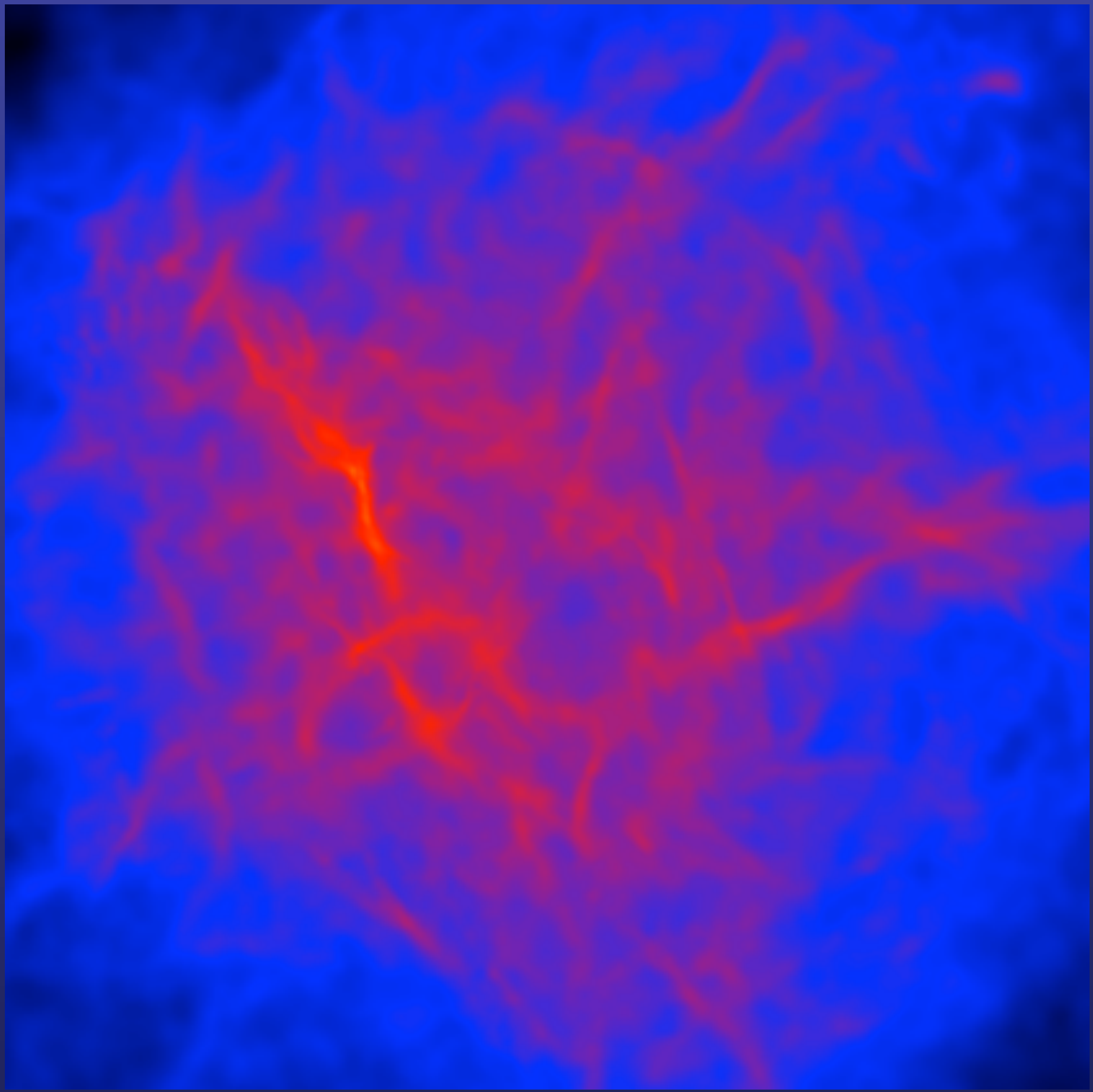
m3=150 Mo
10^4
1000
100
10
1
N
0.01
0.1
1
10
100
1000
Mass/M☉



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

Issues?
Formation; Multiplicity

Formation of R136a cluster?



Simulation courtesy of Ian Bonnell

Massive Star Formation?

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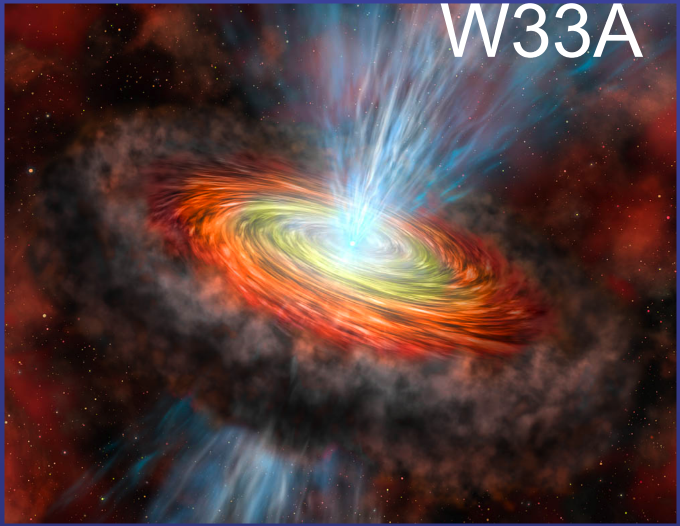
- **Core accretion** (Krumholz, McKee)
  - Mass of a massive star is set by the mass of the core in which it forms
- **Competitive accretion** (Bonnell, Zinnecker)
  - The most massive stars formed are those lying deepest in the gas potential, capable of accreting the most mass (primordial mass segregation)

Issues with VMS?

For either scenario, stability limits to accretion disks? (if so prevent VMS forming directly)

Stellar mergers of lower mass stars may be required, but this necessitates high proto-cluster densities ~10^8 $M_\odot$ pc^{-3} (Bonnell+ 1998)



Joshua Barnes

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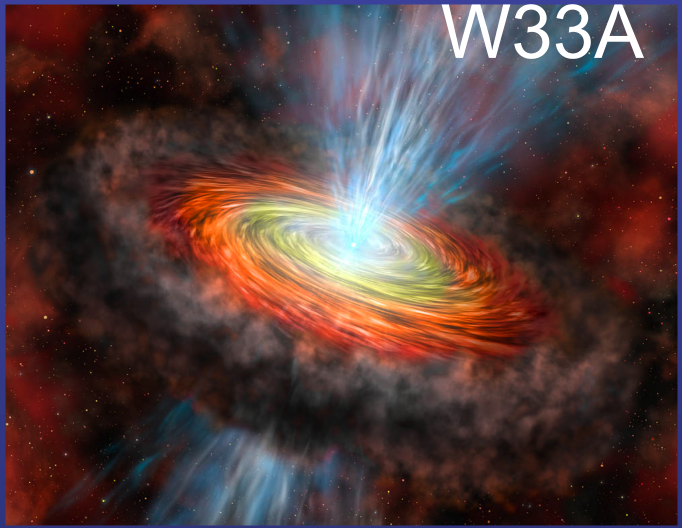
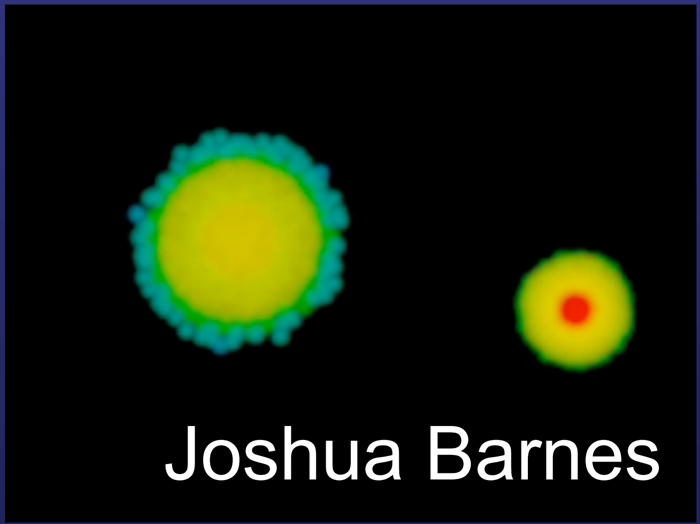
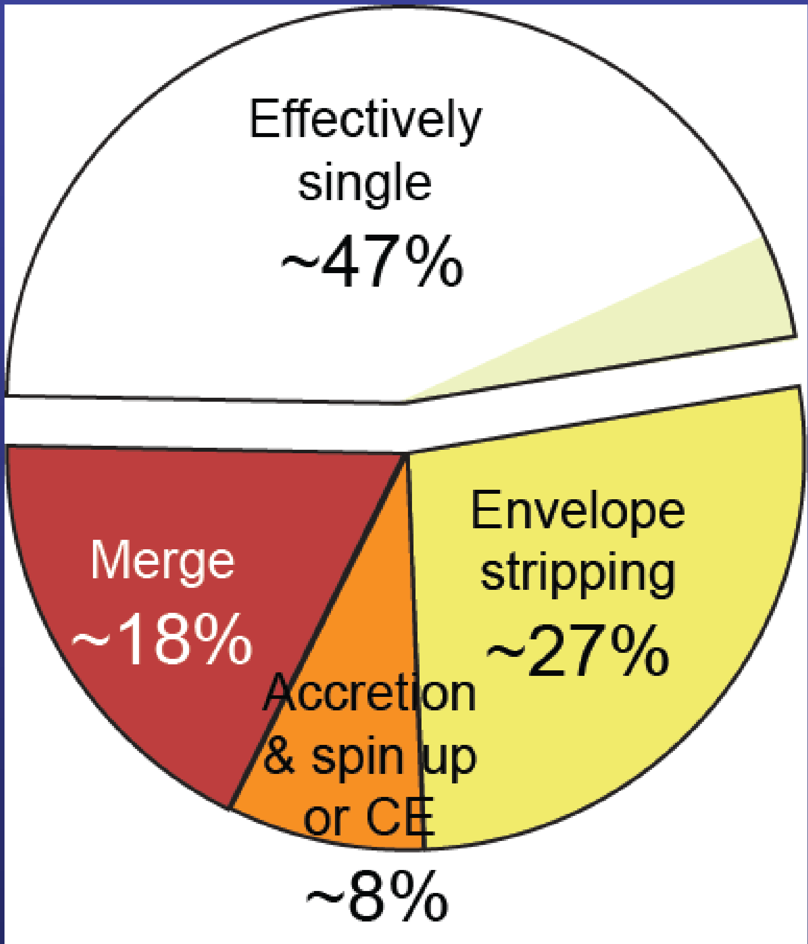




R136a1: merger remnant?



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Might R136a1, a2 etc. be post-merger systems (Banerjee+ 2012)?

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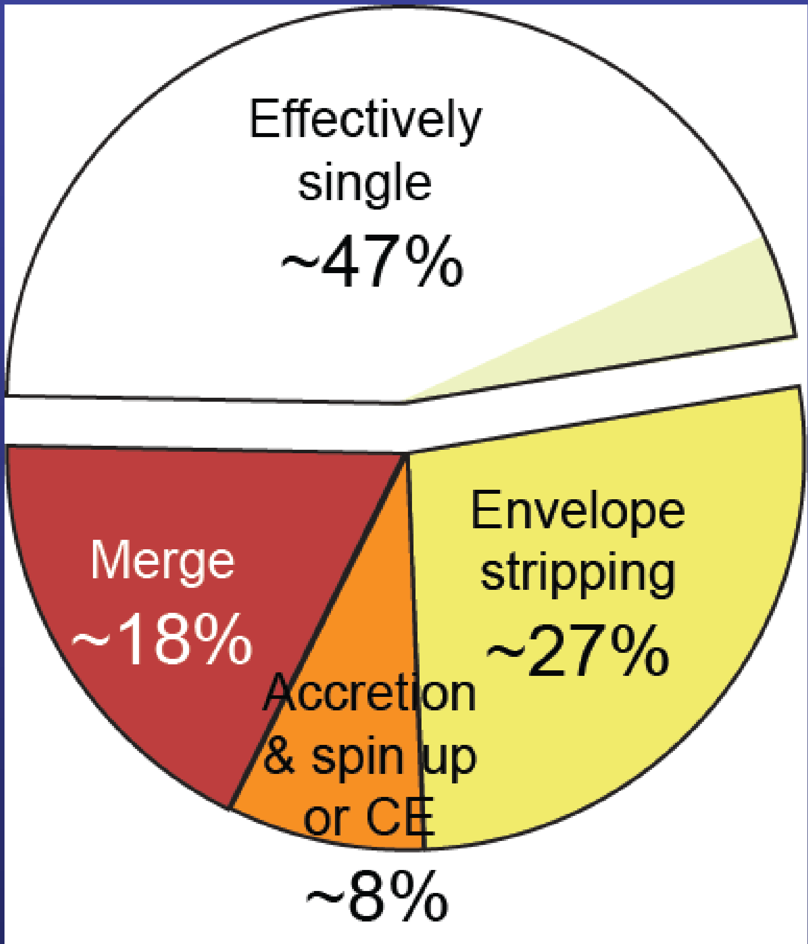

Sana+ (2012, LMC 30 Dor)

Might R136a1, a2 etc. be post-merger systems (Banerjee+ 2012)?

R136a stars are (mostly) rapid rotators, in favour of this scenario, but young cluster age (<2Myr) argues against it

Issues?
Formation; Multiplicity

R136a1 as a v.compact cluster?

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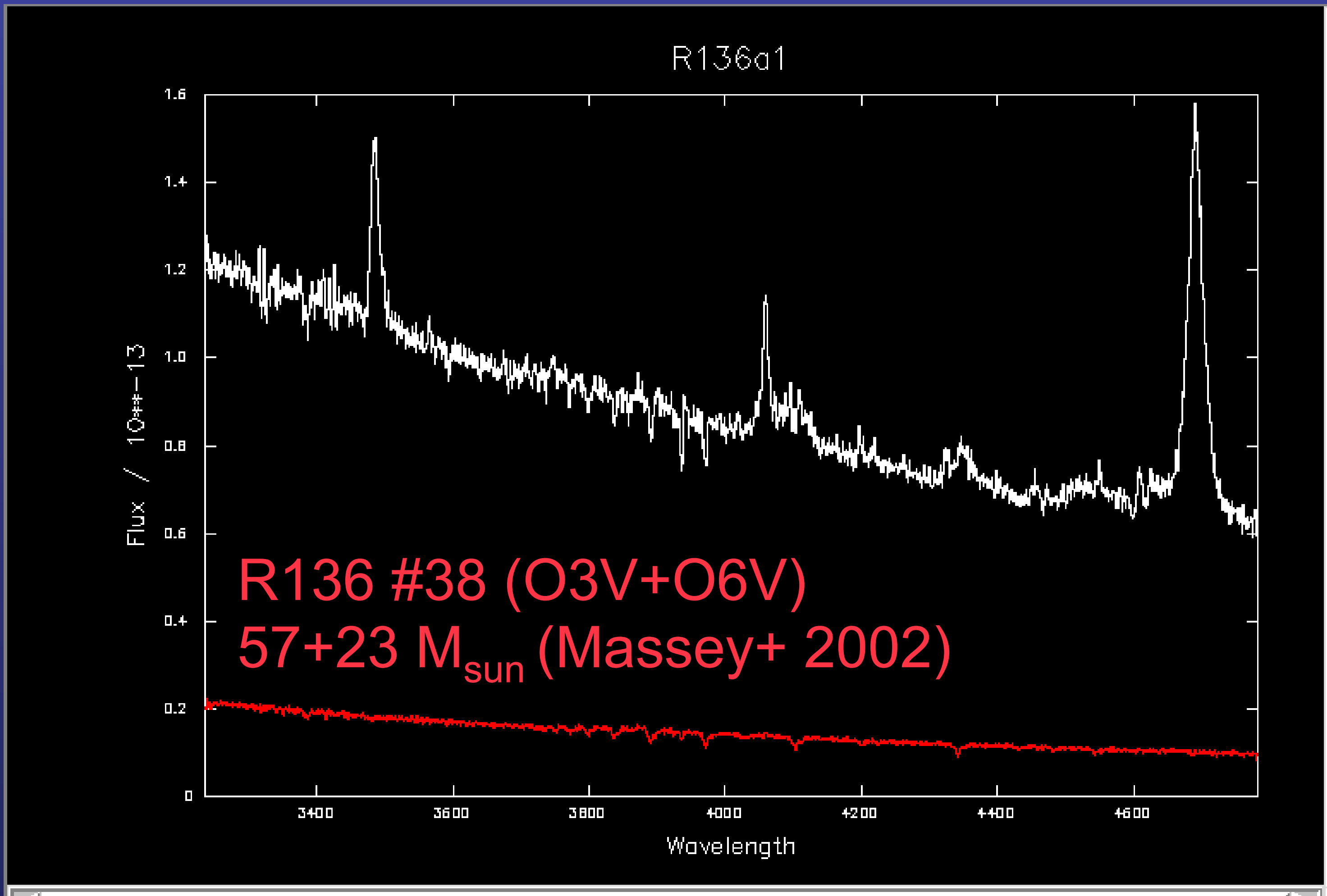

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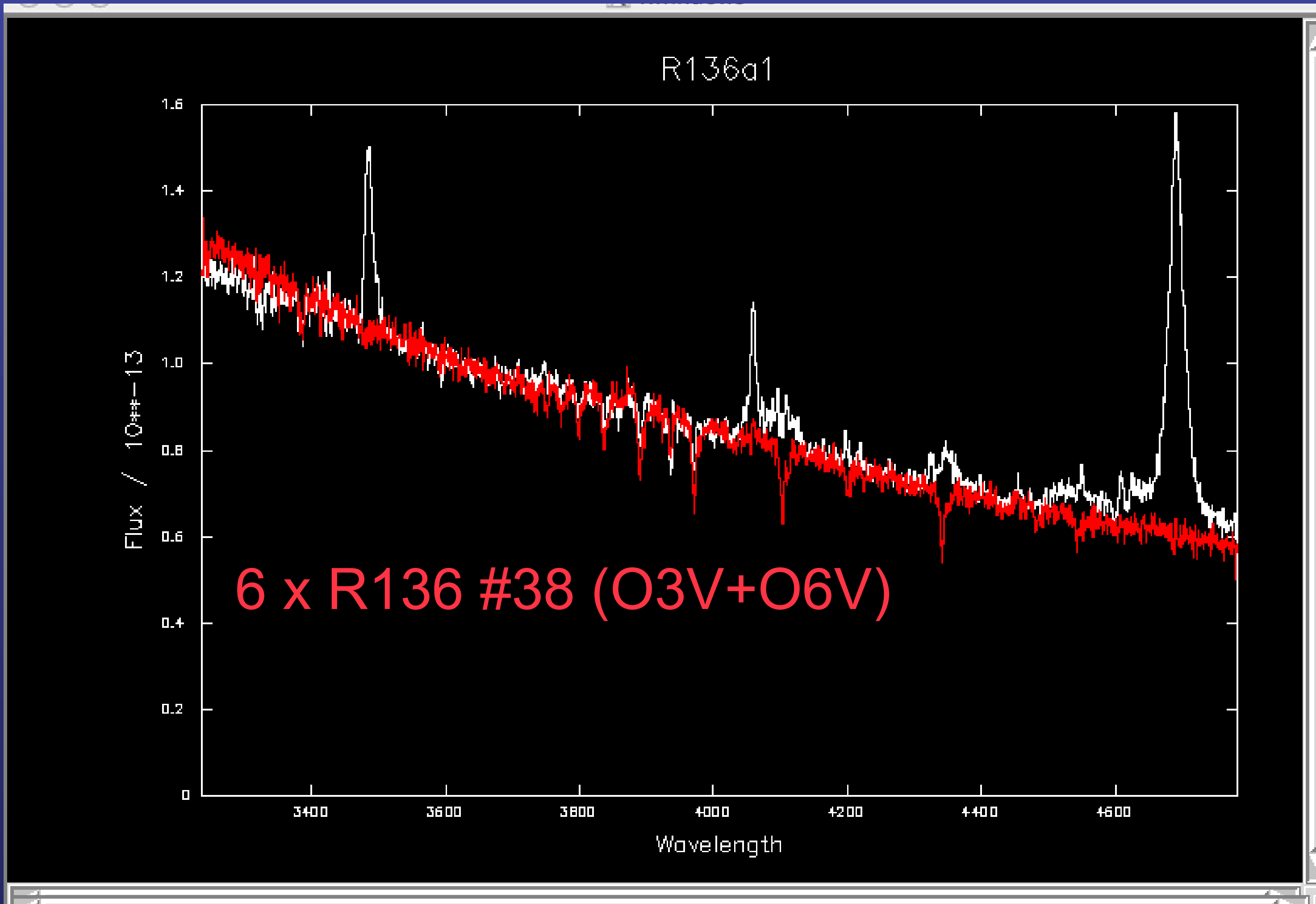

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q=0.5	$230 + 110\ M_{\odot}$	WN5h+O2If*
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For q<<1, the primary dominates its appearance so M_{up} ~ 150 M_{sun} is greatly exceeded <u>*unless*</u> q ~ 1 for R136a1 (& R136a2 & R136c)..

How to identify binaries?

- Short period - days to weeks - equal mass binaries excluded by VLT/SINFONI monitoring (Schnurr+ 2009)*

*Unless unfavourable orientation (for R136a1, a2, c)

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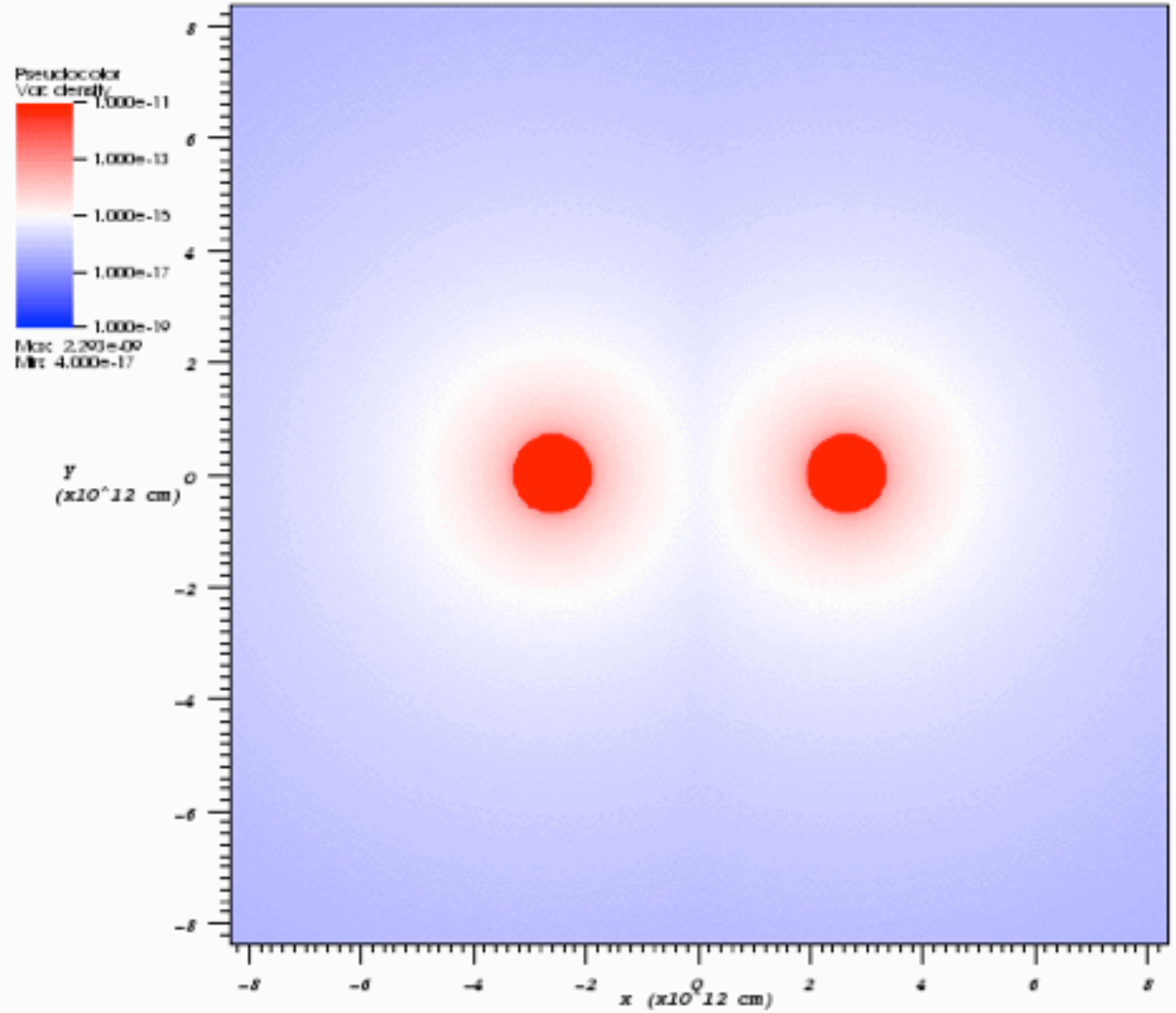

3D simulation by Julian Pittard

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- Long periods - months to years - equal mass binaries would easily have eluded spectroscopic detection. 
- The absence of strong, hard X-rays from R136a1,a2 argue against equal mass [strong winds] binaries... 

*Unless unfavourable orientation (for R136a1, a2, c)