A Massive Star Odyssey, from Main Sequence to Supernova
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The massive star Initial Mass Function

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Abstract. We review our current knowledge on the IMF in nearby environments, massive star forming regions, super star clusters, starbursts and alike objects from studies of integrated light, and discuss the various techniques used to constrain the IMF. In most cases, including UV-optical studies of stellar features and optical-IR analysis of nebular emission, the data is found to be compatible with a 'universal' Salpeter-like IMF with a high upper mass cut-off over a large metallicity range. In contrast, near-IR observations of nuclear starbursts and LIRG show indications of a lower $M_{\rm up}$ and/or a steeper IMF slope, for which no alternate explanation has yet been found. Also, dynamical mass measurements of seven super star clusters provide so far no simple picture of the IMF. Finally, we present recent results of a direct stellar probe of the upper end of the IMF in metal-rich H II regions, showing no deficiency of massive stars at high metallicity, and determining a lower limit of $M_{\rm up} \gtrsim 60$ - $90\,{\rm M}_\odot$.

1. Introduction

The stellar initial mass function (IMF) describes the relative distribution of stars with different masses after their formation. This basic quantity determines the relative radiative, chemical and mechanical 'production' of stars of different masses/types. It is is therefore of fundamental importance for a variety of issues in astrophysics, such as the understanding of stellar populations and the star formation history of the Universe, studies of the chemical evolution of galaxies, the interactions between stars and the interstellar medium etc.

The most fundamental question concerning the IMF is of course that of its physical origin, which remains largely unknown today. This issue, including *e.g.*, competing theories tracing the IMF back to fragmentation properties, negative feedback, or competitive accretion, is beyond the scope of the present review. Other questions include the existence of lower and upper mass limits of the IMF (*e.g.*, does an upper mass limit $M_{\rm up}$ exist? If so, is it 'intrinsic' — *e.g.*, due to fragmentation properties — due to stellar self-limitation, or both?), and the possible dependence of the IMF on 'environmental' conditions (*e.g.*, metallicity, gas pressure, stellar density, background radiation, *etc.*). Several of these questions are addressed in Gilmore & Howell (1998).

The more 'empirical' approach taken here is mainly to review our current knowledge on the IMF, its functional behaviour (single/multiple power law, or other), constraints on the upper and lower mass limits, and also techniques used to derive these quantities. Although observations of resolved stellar populations are briefly discussed (Section 2), the main focus of the review is on the massive star IMF in unresolved stellar populations, including especially massive star forming regions of various scales, *i.e.*, from giant H II regions to full blown starburst galaxies. Another recent review on the IMF in starbursts is found in Leitherer (1998).

The following notation will be used subsequently. The IMF χ is defined by $dN = \chi(m)dm$, which gives the number of stars with initial mass in the interval $[m, m + dm]$. Generally the IMF is described by a powerlaw $\chi = A\, m^{-\alpha}$, where the Salpeter (1955) slope is given by $\alpha = 2.35$. Other frequently used exponents are related to α by $\Gamma = -x = 1 + \gamma = 1 - \alpha$.

2. The IMF in the local Universe – resolved populations

Let us briefly recall what is known about the IMF from studies of resolved stellar systems in the local Universe.

Star counts in Galactic and Magellanic Cloud (MC) clusters/associations reveal an IMF with a slope close to Salpeter ($\alpha = 2.3 \pm 0.3$) above $\sim 1\,\mathrm{M}_\odot$ and two turn-overs below, as summarised in the detailed review of Kroupa (2002). Using a correction for binaries according to Sagar & Richtler (1991), Kroupa (2002) lists $\alpha = 2.7 \pm 0.3$. However, the reliability of this correction method for the massive star IMF, especially for masses $\gtrsim 10\,\mathrm{M}_\odot$, is not established. According to Kroupa (2002), no statistically significant variation of the slope is found, except seemingly for the Arches cluster analysed by Figer *et al.* (1999, *cf.* Figer, these Proceedings).

Recent studies of starburst like objects (*e.g.*, the giant H II regions R 136 in 30 Dor, NGC 3603) have shown that low mass stars with masses down to ~ 0.1 - $0.6\,\mathrm{M}_\odot$ are also formed in such environments (*e.g.*, Brandl *et al.* 1999; Sirianni *et al.* 2000). So far, no change of the lower mass cut-off compared to more quiescent star forming regions has thus been found.

Determination of $M_{\rm up}$ from stellar counts requires sufficient statistics. The minimum required stellar mass $M_{\rm tot}$ of a cluster in order to contain at least one star with mass $M_{\rm max}$ is given by $M_{\rm tot} \simeq (2\text{-}3) \times 10^3\, (M_{\rm max}/100\,\mathrm{M}_\odot)^{1.3}\,\mathrm{M}_\odot$. The range indicated here is valid for a slope $\alpha = 2.3$ and $\mathrm{M_{low}} = 1\,\mathrm{M}_\odot$ or for the Kroupa (2002) IMF and $\mathrm{M_{low}} = 0.01\,\mathrm{M}_\odot$. *E.g.*, in clusters with $M_{\rm tot} \simeq 10^4\,\mathrm{M}_\odot$ one expects thus one star of $\sim 250\,\mathrm{M}_\odot$. Therefore a determination of the upper mass limit above $\sim 100\,\mathrm{M}_\odot$ is indeed not possible for most Galactic and MC clusters/associations (Massey 1998). However, in the few most massive clusters (*e.g.*, Arches, R 136, Cyg OB2), provided they are also very young, this should in principle be possible. At the present stage, we simply note that stars with masses of the order of $\sim 100\,\mathrm{M}_\odot$ exist (*cf.* Special Session: Moffat & Puls, these Proceedings). Local studies have also found no dependence of the IMF on metallicity (Massey *et al.* 1995; Massey 1998).

3. The IMF measured in super star clusters

The determination of dynamical masses of super star clusters (SSC), based on velocity dispersion and cluster size measurements, has been pioneered by Ho & Filippenko (1996a,b). So far such mass determinations have been achieved for seven SSCs (Ho & Fillipenko 1996a,b; Smith & Gallagher 2001; Mengel *et al.* 2002; Gilbert & Graham 2001). Together with an age determination, the comparison of their mass/light ratio to predictions from evolutionary synthesis models can be used to constrain the IMF. This technique provides likely the most direct/best available constraints on the IMF among the studies dealing with integrated light measurements.

The current studies suggest diverse results (*viz.* Mengel *et al.* 2002): four SSCs tend to show L/M ratios compatible with IMF slopes close to Salpeter, two SSCs lying in the interaction region of the Antennae galaxies indicate a steeper IMF ($\alpha \simeq 3$), and one SSC (M 82-F) shows a flatter IMF, implying a dissolution over $\lesssim 2$ Gyr (Smith & Gallagher 2001). No simple picture emerges from this small sample. Given the importance of such combined dynamical and integrated light studies, it is likely that much larger samples will be studied in the near future.

4. UV, optical, and IR studies of starbursts

4.1. Starbursts and high-z galaxies in the UV

Numerous studies have analysed the rest-frame UV spectra of starbursts from nearby objects to high redshift. Among the stellar features detected (*cf.* review by Schaerer 2000), the strongest ones (UV wind lines of Si IVλ1400, C IVλ1550, N Vλ1240 and lines in the *FUSE* domain) can be used to constrain the parameters of the integrated population, such as age, SF history, and IMF, by means of evolutionary synthesis techniques. The most up-to-date model suited to such analysis is STARBURST99 (Leitherer *et al.* 1999; de Mello *et al.* 2000). is that all the objects contain young populations ($\lesssim$ 10 - 20 Myr) characterised by continuous star formation or instantaneous bursts — the distinction being often difficult to draw — which are populated with a rather normal Salpeter-like IMF with stars up to $M_{\rm up} \approx 60 - 100\,{\rm M}_\odot$. In a recent study, Tremonti *et al.* (2001) examine the stellar populations in the field of NGC 5253 and find a possible indication for a steeper IMF, although other explanations (*e.g.*, dissolution of clusters) are possible.

The similarity of the spectra of many high redshift galaxies (*e.g.*, Lyman break galaxies) with local starbursts is well recognised and offers many exciting possibilities. For example, from the beautiful spectrum of the lensed $z \simeq 2.7$ galaxy MS 1512-cB58 of Pettini *et al.* (2000), these authors and de Mello *et al.* (2000) derive a constant star formation, and IMF slope between Salpeter and ~ 2.8. A spectral analysis of the lensed galaxy S 2 by Le Borgne *et al.* (2002) also finds compatibility with a Salpeter IMF, although time-dependent dust obscuration (*cf.* Leitherer *et al.* 2002) may need to be invoked. Analysis from overall spectral energy distrubutions do not provide strong constraints on the IMF (Papovich *et al.* 2001).

4.2. Optical studies of H II galaxies and alike objects

The optical spectra of massive star forming regions show both nebular and stellar lines and provide thus indirect (nebular) and direct (stellar) information on their stellar content, and thus information on the IMF. The former case is discussed in Section 5.

Among the stellar features detected in the optical (for a review see Schaerer 2000) are the Wolf-Rayet features (broad emission lines of He II λ4686, C IV λ5808, C III λ5696, possibly also N III λ4512, Si III λ4565) which are observed in objects covering a large range of metallicity ($1/50 \lesssim Z/\mathrm{Z}_\odot \lesssim 2$). Catalogues of these 'WR galaxies' have been compiled by Conti (1991) and Schaerer *et al.* (1999b). Studies on WR galaxies (mostly BCD, Irr, spirals) are summarised in the reviews of Schaerer (1999ab).

Including the detections of spectral signatures from both WN and WC stars in a fair number of objects covering a large metallicity range, the following overall conclusions emerge from the studies of Schaerer *et al.* (1999a) and Guseva *et al.* (2000). Except possibly at the lowest metallicities a good agreement is found between the observations and the evolutionary synthesis models of Schaerer & Vacca (1998). From this comparison one finds clear indications for short bursts ($\Delta t \leq 2$ - 4 Myr) in objects with subsolar metallicity, an IMF compatible with Salpeter, and a large upper mass cut-off of the IMF, in agreement with several earlier studies (Mas-Hesse & Kunth 1999; Schaerer 1996). In addition, the observed WC/WN star ratios provide new constraints for mass loss and mixing scenarios in stellar evolution models (Schaerer *et al.* 1999a), which should soon be confronted with predictions from rotation stellar models (*cf.* Maeder, Meynet, these Proceedings). New results on the IMF metal-rich starbursts have recently been obtained. They are summarised in Section 6.

4.3. Near-IR studies

Observations at longer wavelengths are of great interest, as massive star formation occurs frequently in regions hidden behind significant amounts of dust at UV-optical wavelengths.

Pioneering work on prototypical nearby starburst galaxies such as M 82 (distance 3.3 Mpc, where $1''$ corresponds to 15 pc) has been undertaken by Rieke *et al.* (1980, 1993), who measured a dynamical mass, the K-band and IR luminosities, L_K and L_{IR}, and the number of ionising photons of the nuclear region ($\sim 30''$). From the relatively low M/L_K, and the large 2 μm and UV flux, they concluded from synthesis modeling that an IMF favouring stars in the mass range $3 - 6 \lesssim \mathrm{M}/\mathrm{M}_\odot \lesssim 10$ over lower masses was required. Other indirect indications for such a so-called 'top-heavy' IMF have *e.g.*, been found for M 82 by Doane & Matthews (1993).

Subsequent observations at high spatial resolution have been obtained by several groups. *E.g.*, Satyapal *et al.* (1995, 1997) have obtained $1''$ resolution Fabry-Perot observations of Paschen-α, Brackett-γ, and CO bandheads, showing a strong spatial variation of extinction (with A_V varying from ~ 2 - 12) and on average a smaller extinction than determined from the large aperture in the Rieke *et al.* studies. From their analysis they conclude that there is no need for an IMF differing from the Salpeter IMF.

K-band integral field spectroscopic observations of a $16'' \times 10''$ region of M 82 has been obtained by Förster Schreiber (2000) and Förster Schreiber *et al.* (2001). A complex spatial structure including clusters of different ages and varying spatial extinction (whose derived amount is dust geometry dependent) is found. These studies illustrate the potential difficulty of obtaining robust conclusions from large aperture observations and the use of 'global models'.

4.4. The IMF in nuclear starbursts and LIRG

CO absorption features, H recombination line fluxes, and near-IR photometry have been used to study the stellar populations in luminous IR galaxies (LIRGs, defined by $L > 10^{11}\,L_\odot$). Generally theses objects show a relatively weak recombination line spectrum and soft spectra, and red supergiant features indicative of star formation over $\sim 10^{7-8}$ yr (Goldader *et al.* 1997). As the apertures sample rather large regions, it is thought that the overall activity can reasonably be represented by constant star formation.

Using a standard Salpeter IMF, evolutionary synthesis models have difficulties in reproducing simultaneously the low Brγ equivalent width and the CO strength; fitting the latter implies an overproduction of ionising photons. This result is interpreted as a possible reduction of the upper mass cut-off of the IMF (values of $30 \leq M_{\rm up} < 100\,M_\odot$) and/or a steeper IMF slope (Goldader *et al.* 1997). Similar observational trends and results are obtained for nuclear starbursts by Coziol *et al.* (2001). If true, it is not clear what causes this deviation of the IMF from the otherwise seemingly 'universal' Salpeter IMF. Is this related to a higher metallicity (*cf.* however Section 6), which could be expected in such evolved regions of galaxies, or possibly related to a high ISM pressure due to interactions in LIRGs?

Potential problems affecting the analysis include underlying populations which dilute/reduce $W(\rm Br\gamma)$ (there are good indications for this, *cf.* Coziol *et al.* 2001), absorption of ionising photons by dust (however, absorption of more than 50 % would be needed to reproduce the observed $L_{\rm Br\gamma}/L_{\rm IR}$), and mixed stellar populations or discontinuous SF. However, to date no alternative solution to the above near-IR analysis of LIRG and nuclear starbursts is known.

We note also that contradictory results were obtained from a detailed optical study of the massive star content of six metal-rich nuclear starbursts (Schaerer *et al.* 2000).

5. Stellar populations and the IMF from nebular studies

For many years optical studies have been used to reconstruct the stellar content of giant H II regions, H II galaxies or alike objects from their emission line spectra, including recombination lines and forbidden metallic transitions (*e.g.*, reviews by Stasińska 1996; García-Vargas 1996).

The development of extended grids of combined starburst and photo-ionization models at various metallicities has allowed to reproduce the main observed emission line trends and the observed increase of the electron temperature with decreasing metallicity. Concerning the IMF, such comparisons have in particular shown a compatibility of the Salpeter IMF for metallicities down to $\sim 1/50\,Z_\odot$ (the metallicity of I Zw 18), and a presence of massive stars with $M_{\rm up} \gtrsim 80\,M_\odot$ (García-Vargas *et al.* 1995; Stasinska & Leitherer 1996).

Other advances *e.g.*, in the understanding of nebular diagnostics, the origin of the emission line sequences, and the presence of underlying populations have been made by such extensive studies; also some interesting unsolved questions remain (*cf.* Stasińska *et al.* 2001; Moy *et al.* 2001; Kewley *et al.* 2001; Stasińska & Izotov 2003).

5.1. *ISO* observations

Interesting advances have been made with the advent of mid-IR spectroscopic observations of starbursts and LIRGs observed with *ISO*-SWS/LWS in the 4-

200 μm range and apertures typically between 14 - 30″. This wavelength range is in particular rich in atomic fine structure lines originating in ionised gas.

A case study of M 82 using *ISO*-LWS (40 - 200 μm) spectra was undertaken Colbert *et al.* (1999), who find that the observed emission line spectrum of M 82 is compatible with an instantaneous burst at ages $\sim$3 - 5 Myr, a Salpeter IMF, and a high upper mass cut-off. However, as already pointed out earlier (Schaerer 2000), the shorter wavelength (SWS) data is clearly incompatible with the Colbert *et al.* model predicting too hard a spectrum; their photo-ionisation model is underconstrained.

A different approach was adopted by Förster-Schreiber (1998) and Thornley *et al.* (2000), who aim at an interpretation of the observed relatively low excitation as traced by the [Ne III]15.5/[Ne II]12.8 μm line ratio. In their model the ensemble of clusters/H II regions and the gas clouds in M 82 are described by a single 'effective' ionisation parameter, whose value is adopted as typical for a sample of 27 starbursts in the starburst and photo-ionisation models of Thornley *et al.* (2000). From their modeling they conclude that the observations are compatible with a high upper mass cut-off ($M_{\rm up} \simeq 50 - 100\,{\rm M}_\odot$). However, to reproduce the relatively low average [Ne III]/[Ne II] ratio, short timescales of SF (attributed to possible negative feedback) are required. This result could also be affected by several uncertainties. *E.g.*, how reliable/appropriate is the use of a single mean ionisation parameter for such a diversity of objects? Also, metallicity variations, which — as shown by Martín-Hernández *et al.* (2002) — are known to affect the Neon line ratio, are not taken into account. Finally, it is well possible that physically unrelated regions, all included in the large *ISO* aperture, contribute to the emission of Ne^{2+} and Ne^{+}. Future high spatial resolution observations (ground-based and with *SIRTF*) should help to establish the reliability of mid-IR diagnostics and allow many interesting applications.

5.2. Metal-rich H II regions

Emission lines in low excitation H II regions have, *e.g.*, been used to study the properties of metal-rich regions in spiral galaxies. From their analysis of the emission line trends, the observed [O II]/[O III] ratio, and He I λ5876/Hβ Bresolin *et al.* (1999) found indications for a limitation of the upper mass cut-off of the IMF of $M_{\rm up} \lesssim 35\,{\rm M}_\odot$. However, such indirect diagnostics depend strongly on the adopted stellar tracks (*e.g.*, outdated tracks from 1991 in the above study) and model atmospheres (*cf.* Schaerer 2000, and the special session summarised by Schaerer, Crowther & Oey, these Proceedings). In fact, new sophisticated non-LTE line blanketed atmosphere models for O-type and WR stars predict a softening of the radiation field, as required to reconcile the photo-ionisation models and a higher value of $M_{\rm up}$ with the observations (Smith *et al.* 2002; these Proceedings). However, whether this can fully reproduce the observed line trends with a 'normal' IMF at high metallicities remains to be shown.

We now discuss a *direct* approach to constrain the IMF in metal-rich environments.

6. New light on the IMF in metal-rich environments

To probe the upper end of the IMF in metal-rich environments we have recently undertaken VLT-FORS1 observations of five relatively nearby galaxies targeting

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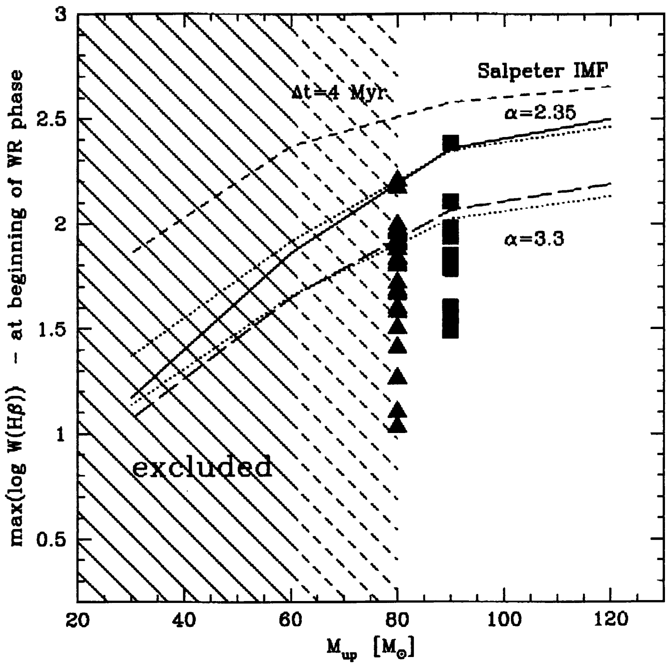

Figure 1. Maximum predicted Hβ equivalent width at the beginning of the WR phase as a function of $M_{\rm up}$ for solar metallicity ($Z = 0.02$) burst models with a Salpeter IMF (upper three curves) and a steeper IMF ($\alpha = 3.3$, lower two curves). The dotted curves show models for $Z = 0.04$. The short dashed line corresponds to an extended burst of duration $\Delta t = 4$ Myr (Salpeter IMF, $Z = 0.02$.) The observations are plotted at arbitrary $M_{\rm up}$. The observed maximum ($\log W(\mathrm{H}\beta) \simeq 2.2$ - 2.4) indicates $M_{\rm up} \simeq 80$ - $90\,\mathrm{M}_\odot$ for a Salpeter slope, and $\gtrsim 120\,\mathrm{M}_\odot$ for $\alpha = 3.3$, or somewhat lower values for extended bursts.

known metal-rich H II regions in their disks (Pindao *et al.* 2002). The nuclei were avoided due to the complex mix of their stellar populations.

Spectra of $\sim$ 90 H II regions were obtained yeileding a mean metallicity of $12 + \log(\mathrm{O/H}) \simeq 8.9 \pm 0.2$, *i.e.*, close to solar. As suspected, we found stellar signatures of WR (WN and WC) stars in a large number of regions, *i.e.*, 27 regions plus 15 candidate WR regions. Including previous studies (Castellanos 2001; Bresolin & Kennicutt 2002; Castellanos *et al.* 2002) our observations now nearly quadrupel the number of metal-rich H II regions where WR stars are known. The salient result concerning the IMF is the following (see Pindao *et al.* 2002 for details).

The large sample of WR regions allows us to derive fairly model independent constraints on $M_{\rm up}$ from the maximum observed Hβ equivalent width of the WR regions. Independently of the exact tracks and metallicity, we derive *a lower limit for* $M_{\rm up}$ *of 60 - 90* $\mathrm{M}_\odot$ in the case of a Salpeter slope, and larger values for steeper IMF slopes. This constitutes a lower limit on $M_{\rm up}$ as all observational effects known to affect potentially the Hβ equivalent width (loss of photons in slit or leakage, dust inside H II regions, differential extinction, underlying population) can only reduce the observed $W(\mathrm{H}\beta)$. This result is also consistent with our previous analysis of six metal-rich nuclear starbursts with WR features indicating $M_{\rm up} \gtrsim 35-50\,\mathrm{M}_\odot$ (Schaerer *et al.* 2000). From these analysis we conclude that the most direct stellar probes show no deficiency of massive stars at high metallicity.

7. Summary and conclusions

In short, our current knowledge on the IMF in nearby environments, massive star forming regions, starbursts and alike objects reviewed above can be summarised as follows:
(*i*:) *Resolved stellar populations* show a general consensus with a Salpeter-like IMF for masses $M \gtrsim 1\,\mathrm{M}_\odot$ and the existence of stars with masses of $\sim 100\,\mathrm{M}_\odot$ or more. Given these strong indications one may consider that the burden of proof is now reversed for studies from integrated light!
(*ii*:) Analysis of *Super Star Clusters* including dynamical mass measurements yield ambiguous conclusions on the slope of the IMF. Few cases are, however, observed so far.
(*iii*:) *UV-optical studies of stellar populations in H II galaxies* and alike objects generally show IMFs compatible with Salpeter and a large upper mass cut-off $M_{\rm up}$.
(*iv*:) *Near-IR studies of nuclear starburst and LIRG* show indications of a lower $M_{\rm up}$ and/or a steeper IMF slope. No alternate explanation for the relatively weak recombination line spectrum and soft spectra has so far emerged.
(*v*:) *Nebular studies (optical to mid-IR) of H II galaxies and starbursts* show no variation of the IMF from $1/50 \leq Z/Z_\odot \lesssim 1$. Indications of a lower value of $M_{\rm up}$ at high metallicity from nebular lines are probably due to inadequacies in the adopted stellar evolution / atmosphere models.
(*vi*:) *Direct probes of WR stars in metal-rich H II regions* show no deficiency of massive stars at high metallicity. A lower limit on $M_{\rm up} \gtrsim 60-90\,\mathrm{M}_\odot$ has recently been derived from a such large sample.

In most cases a seemingly 'universal' IMF, with a powerlaw slope close to the Salpeter IMF is thus found. As for the physics of star formation, its origin remains largely unknown.

How universal is such a 'universal' IMF? Does this behaviour only break down at very low metallicities, such as encountered in the earliest phases of the Universe, and suggested by several investigations on the formation of Population III objects These, and other challenging questions are likely to remain unanswered for several more years.

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Discussion

LEITHERER: I doubt that lack of spatial resolution can fully explain the apparently peculiar IMF in some starburst galaxies. There are quite a few experiments in Local Group galaxies which use large apertures to measure the nebular emission lines, thereby simulating decreased spatial resolution. They generally found a normal IMF.

SCHAERER: In general I agree. However, concerning the mid-IR diagnostics, it is well possible that spatially the emission of [Ne III] and [Ne II] could be quite different (*e.g.*, from compact clusters *vs.* diffuse extended gas). Future observations should help to track this in more detail.

ZINNECKER: A word of caution on the dynamical masses of super star clusters and their IMF. First, the measured velocity dispersion may not measure the cluster mass, because these clusters may not yet be virialized. Second, tight massive binaries may mimick a higher velocity dispersion than that corresponding to the depth of the potential well (see, *e.g.*, Bosch *et al.* 2002 on the R 136 cluster).

SCHAERER: Some of these aspects are discussed in the original papers. I presume it is difficult to rule out or prove your arguments in a straight forward way.

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