Initial Mass Function:
Universal...or Not?

ESO Cosmic Duologue 3 - Interview

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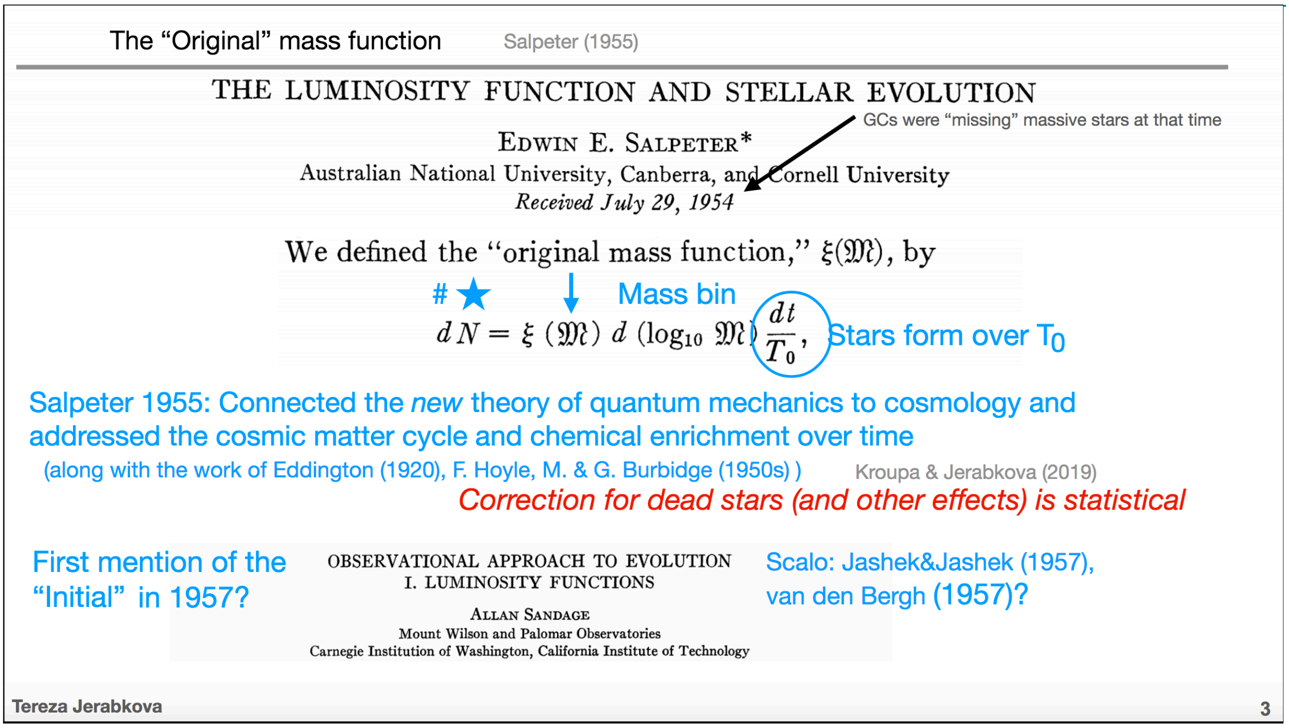
On Monday 25 May, 2020, the third ESO Cosmic Duologue took place. It consisted in a discussion between *Tereza Jerabkova* (IAC/GTC, La Palma, Spain; Bonn University, Germany) and *Andrew Hopkins* (AAO Macquarie - Macquarie University, Australia) and chaired by *Giacomo Beccari* (ESO), about the universality of the Initial Mass Function. Further information on this event, including a copy of the slides, the link to the video of the duologue, as well as to some background material, is available at https://www.eso.org/sci/meetings/2020/Cosmic-Duologues/duologue3.html.

As a follow-up to this successful event, we have asked our two speakers to answer in more details some of the questions raised during the event. This is provided below, where the answers are identified by the initials of the speaker.

1. What is this discussion being driven by? That we see a similar Initial Mass function (IMF) in most places with some divergences and trying to explain that (through either physics of selection effects)? Or that some physics defines that we should/should not see a universal IMF and seeing if we observe that in the Universe?

AH: This is a fundamental question. In his 1998 review, Kennicutt said "*Accurate knowledge of the form and mass limits of the stellar initial mass function, and its variation in different star formation environments, is critical to virtually every aspect of star formation, stellar populations, and galaxy evolution*". And: "*Testing the universality of this initial mass function remains as our primary challenge for the coming decade*". This remains a driver even more than two decades later. In the intervening time, numerous lines of evidence for variations in the IMF have been published, often with conflicting implications about the form of such variations. This is the motivation for the current discussion. The field has predominantly been observationally, rather than theoretically, led, with the theory and simulations often aiming to explain the similarities or differences in the observational data.

TJ: It was widely expected that the IMF varies with environment, from the theoretical perspective (e.g. Adams & Fatuzzo 1996) and being discussed as such in all the major reviews (e.g. Scalo 1986, Kroupa et al. 2013). Quite surprising results (as mentioned also by Salpeter in 2005 in the conference book "The Initial Mass Function 50 Years Later") came from the large survey of the LMC/SMC star clusters and star-forming regions by Massey et al. (1995). The authors found no systematic variations of the star-cluster's IMF with environment (LMC/SMC have significantly



lower metallicity than the MW) and while the uncertainty on individual measurements reaches 0.5-0.7dex, there seems to be a reasonably defined mean value and no trend. One challenge that we have is to understand why the IMF in star-clusters in the MW/LMC/SMC is that similar.

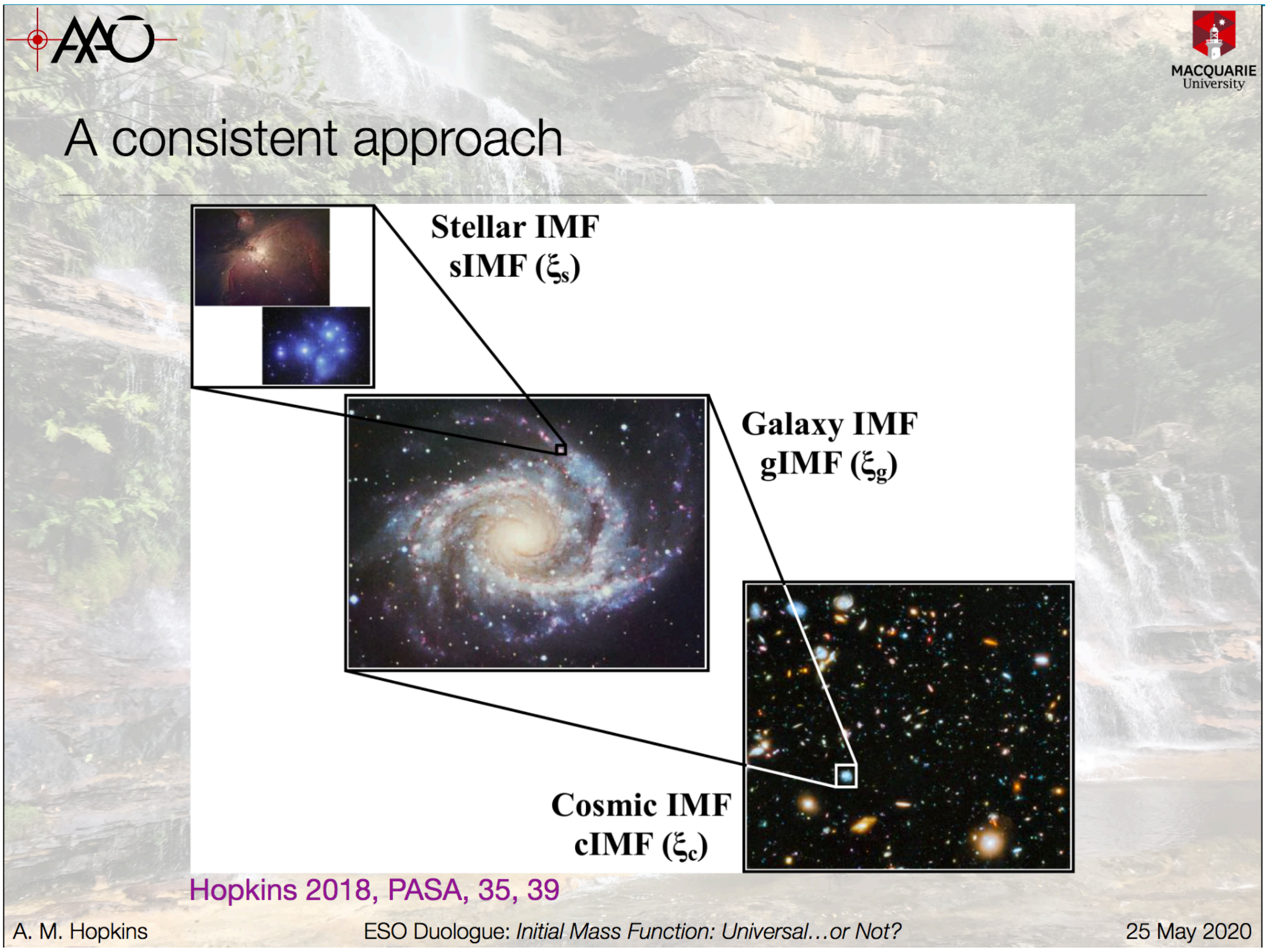
But on the other hand, we have a growing body of evidence on how the IMF varies significantly in more extreme environments (Galactic center, center of early type galaxies, massive star-burst clusters and galaxies). A very successful formulation, as derived from observed systems (ultra-compact dwarf galaxies and globular clusters) is that by Marks et al. (2012). Combined with integrating over a whole galaxy this formulation is, remarkably, consistent with the extragalactic constraints on the IMF variation by Lee et al. (2009) and Gunawardhana et al. (2011).

Any theory of star formation has to account for both of these observed aspects. Thus, the discussion is definitely driven by the observations, by the observed small variations in nearby star-forming regions and also by the observed significant variations of the IMF in more extreme environments.

2. Do we understand the theory behind cluster evolution and its environmental variations? Or is it an issue of uncovering the evolution history from observational tracers, i.e. using present day observations to infer IMF? I guess both, but which is the more dominant open question?

TJ: Yes, indeed, it is both aspects. For the individual star-clusters the formation and evolution are quite well understood. The environmental variations still carry more open questions, while being subject to strong constraints in order to reproduce present-day observations, given the cluster's initial conditions. However, in this case it is more difficult to infer the IMF from the observations – the dynamical processes and the unresolved binary stars can be only corrected for statistically (Kroupa et al. 1995, Banerjee & Kroupa 2012). For the composite IMFs in a field, I would say the effect of the environment plays a larger role, also because the environment changed significantly with time and now we observe a mixture of these different stellar populations.

AH: At the moment the discussion is being led by observations, but as yet with methods that haven't been demonstrated to be self-consistent, leading to apparently conflicting conclusions regarding the shape or evolution of the IMF. In principle, the observations can give us information about the shape and evolution of the IMF in different environments, but inconsistent methods and



conclusions are frustrating that approach. Theoretical considerations haven't yet established a definitive set of expectations either, and presently both theory and observation are to some degree bootstrapping each other to help us make small steps forward.

3. Do passive galaxies possibly have a star forming history?

AH: Yes, all galaxies have a star forming history. For high-mass ellipticals, discussed in the presentation as passive systems, their star formation histories are typically rapid in the early universe. They form the bulk of their stars in just a few Gyr, before having their star formation quenched, through mechanisms like AGN or supernova feedback. Subsequently they may grow further in mass through merging, but with minimal, if any, ongoing star formation. This means that the IMF being inferred for these systems using the dwarf/giant ratio method, for example, is the IMF of the population of stars when it formed many Gyr ago.

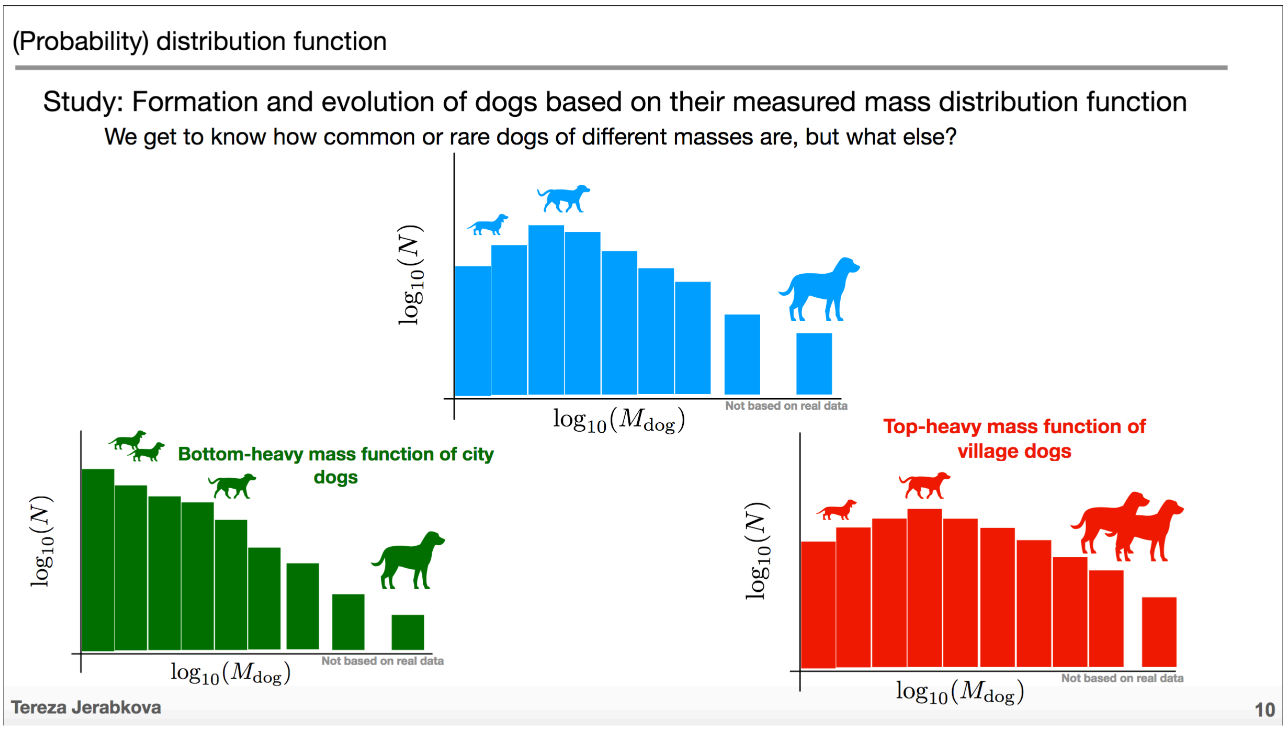
TJ: The current star-formation in passive galaxies has been recently studied in the ultraviolet by Salvador-Rusiñol et al. (2020). The authors found that the recent star-formation contributes around 0.5% of the total stellar mass. This fraction is lower for the most massive galaxies and increases towards the smaller masses. This further confirms that the most massive systems formed the fastest and lower-mass systems have more extended star-formation histories, being known as time-formation downsizing.

4. What is your sentiment about the fact that the kinematics (e.g., from *Atlas3d*) versus the weak absorption line (dwarf/giant) method applied to early-type galaxies give similar trends but not consistent values?

TJ: The weak absorption line method uses the information from the observable light to infer information on the contribution from stars with different stellar mass. The main parameters are the stellar libraries that are used to interpret the strength of the absorption lines – we have theoretical libraries or empirical libraries (e.g. EMILES). When using different libraries, there likely will be differences in the estimated IMF slope. To use the stellar kinematics in order to constraint the stellar IMF one needs to consider the presence of unseen matter (stellar remnants, non-baryonic component/different gravity), its spatial distribution, the full shape of the galaxy, possible orbit alignments and stellar libraries.

The additional/different assumptions required by each method are thus likely the cause for the differences in the inferred IMF, while the fact that the trend in how the slope changes is found to be similar is very promising.

AH: A couple of thoughts here. First, there may be differences in the underlying samples of objects measured (range of velocity-dispersion, or mass, sampled) that contribute to the quantitative differences. Another is that the calibration of the Stellar population synthesis (SPS) tools that are used in inferring the IMF slope for the dwarf/giant method may not be perfect. Yet another is that the constraint from kinematics is on the mass-integrated IMF rather than the shape of the IMF specifically, so some trade-off between mass distributed at the low vs high mass end could contribute. It would be valuable to explore some self-consistency tests between the existing metrics for inferring IMF properties, so far lacking, to address the issues of quantitative discrepancies.



5. **Why would the star formation rates (SFR) estimated through low-frequency radio observations be under-estimated?**

AH: Radio observations have been used for some decades now as probes of SFR in galaxies, and as measures of the cosmic star formation history (SFH – e.g., Haarsma et al. 2000; Seymour et al. 2008). More recent results at high-z (z<5, Novak et al. 2017) suggest an *excess* in the SFH compared to the UV-selected estimates by Bouwens and others, shown in the compilation by Madau & Dickinson. If robust, this excess exacerbates the discrepancy between the SFH and the cosmic stellar mass density. This work has primarily been done with radio data at 1.4 GHz and higher frequencies. More recent work at low radio frequencies, such as with *LOFAR* and *MWA*, has not focused on the star forming galaxy population, due to issues of sensitivity, but the *SKA* will be able to explore this.

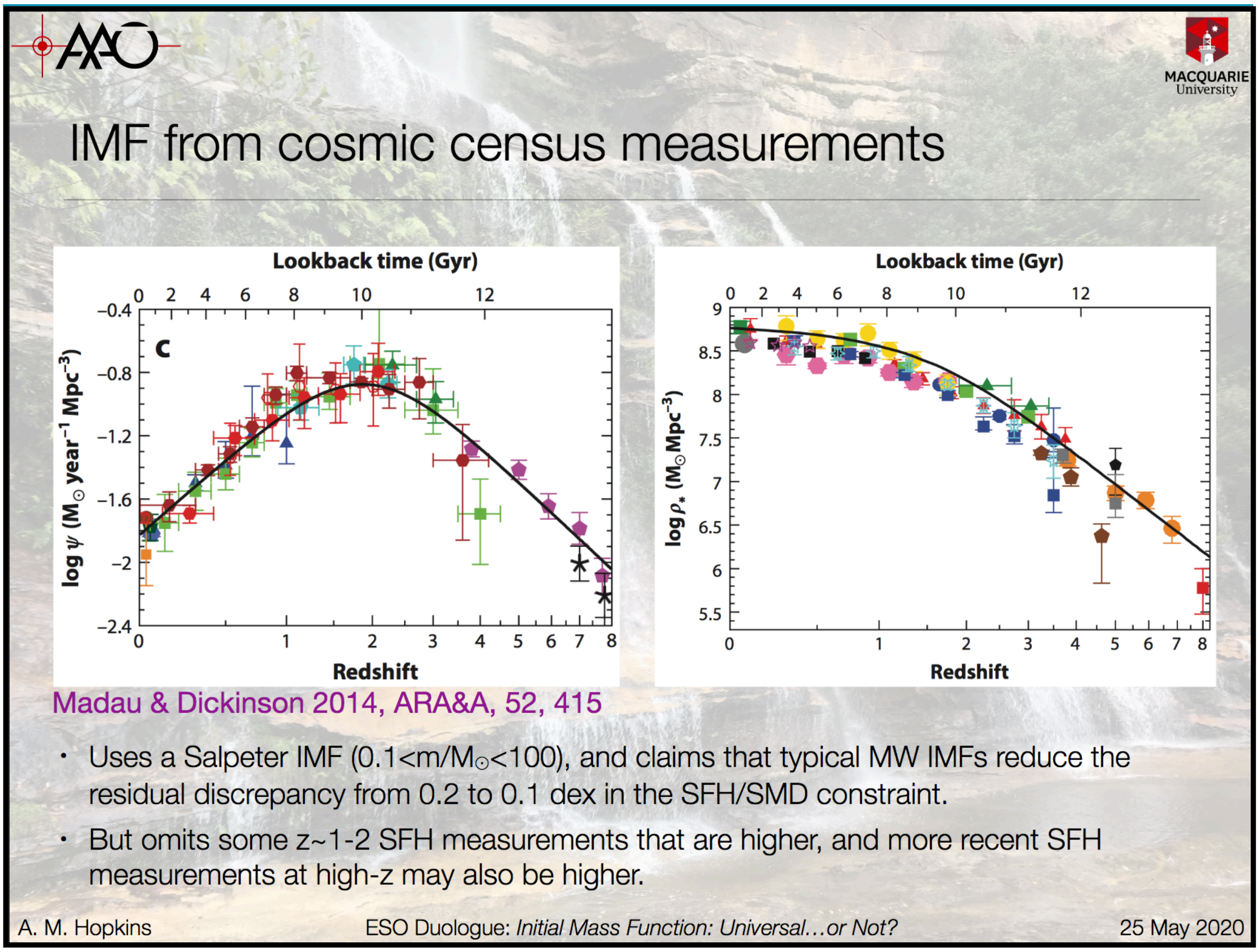
TJ: To wrap this question into a more general context, in order to estimate the SFR from observations we use different tracers of young stars (Hα, UV, mm/radio). Each of these tracers is sensitive only to a certain range of stellar masses, but the SFR is the rate of formation of all stars. Therefore, we need the stellar IMF to add in the stellar masses invisible for the used method and in addition to correct for more biases such as the presence of dust that obscures some stars or stellar binaries (mergers and interacting binaries can mimic young stars). If we know the IMF, dust content, stellar binary distribution, …, then any SFR tracer can be used to estimate the actual/physical SFR of a galaxy.

6. Can we get information on the slope of the IMF from star formation simulations (for a given environment?) or are there too many uncertainties? And if so, is it consistent with the observed slopes?

AH: Yes. Simulations test many different elements of star formation theory, and are challenged by the broad range of physics and scales involved. Broadly, simulations are valuable in identifying the effect on IMF shape that may be induced by various physical processes. And simulations have definitely been produced that predict the IMF slope. Indeed, most published IMF shapes have corresponding simulation work that attempts to explain why that shape has been found, within the scope of those particular simulations. For more details, see, e.g., work by Krumholz (2014, 2016) and by Offner (2014), and other references in section 7 of Hopkins (2018).

TJ: Possibly worth mentioning is that we have available quantitatively different types of simulations that can be broadly divided into two groups: 1) statistical accounting for the complex physical processes in order to reproduce bulk properties of stellar populations (and in this case also the slope of the IMF), here I would highlight the work of Zinnecker (1984), Adams & Fatuzzo (1996) and Essex et al. (2020); 2) (magneto-)hydrodynamical simulations parametrizing the complex processes and aiming to account for them in a more realistic/physical way such as exemplified by the papers of Mathew Bate (e.g. Bate, 2014) and Vazquez-Semadeni et al. (2019).

However, it is important to realize that the current hydrodynamical simulations are not able to form stars self-consistently, mainly because we do not have the computational capacity to do so and it is not expected to improve in the near future. Similar problems are present in order to account for binary stars and dynamical processes. Thus, as shown historically to be the case, astronomy is an empirically driven science and given the fact that the “dense” gas in which stars form has the properties of an excellent vacuum in a laboratory on Earth, this is not that surprising.



7. Coming at this from a (star formation) radio background, what is your opinion on using molecular line transition ratio observations in constraining IMF variation? I'm aware of 13CO/C18O, but in future possibly additional tracers to be used? Possible biases? A good tool to compare Galactic and (near-)extragalactic sources?

TJ: The use of molecular line transitions and more concretely the ALMA facility to estimate the IMF has been pioneered by Romano et al. (2017) and its capabilities has been demonstrated by Zhang et al. (2018). There are a number of assumptions and caveats, however, that have been addressed in detail in Romano et al. (2019, 2020).

AH: The more tracers we have the better! With such a complex and challenging field, the more observational constraints we can bring to bear, the more opportunity there will be to improve our understanding. There is a clear need to extend existing population synthesis tools beyond optical/IR to encapsulate information at such wavelengths in order that we can explore, self-consistently, the observational IMF metrics from such data.

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