ALMA constrains the stellar IMF of high-redshift dusty starburst galaxies

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The stellar initial mass function (IMF)

- Stellar initial mass function (IMF): probability distribution function which describes the relative numbers of stars that form in different mass ranges during a single star formation episode.
- Highly relevant to studies of star and galaxy formation and evolution, and **chemical evolution**.

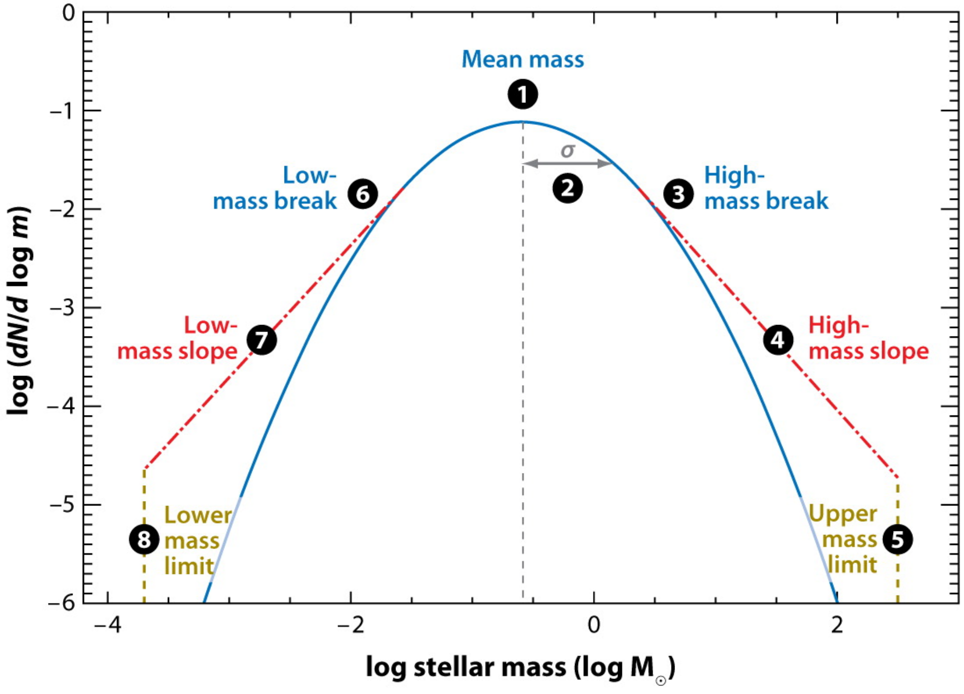

Figure from Bastian, Covey, Meyer (2010, ARA&A, 48, 339)

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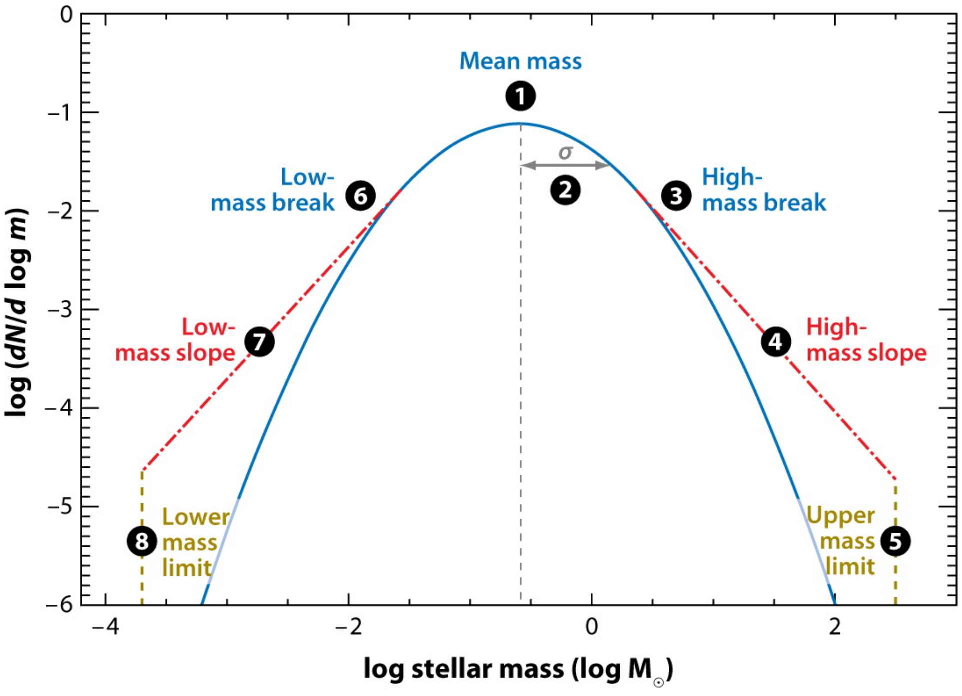
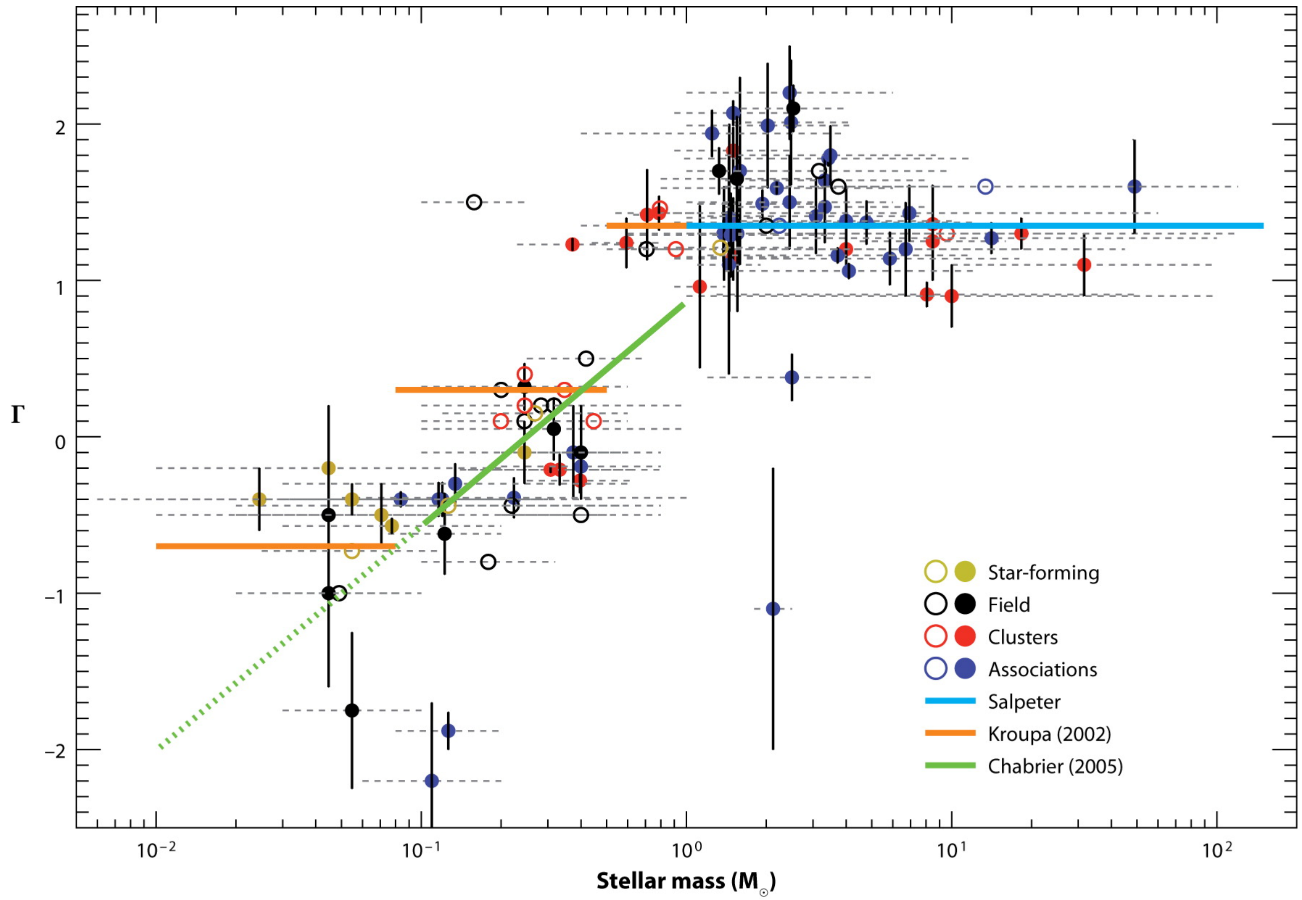


Figure from Bastian, Covey, Meyer (2010, ARA&A, 48, 339)

- 'Direct' method (star counts): IMF inferred from measured present-day mass function (PDMF) and adopted star formation history (SFH) (beware of binary stars…)
- Integrated properties: H_α+UV; M_{dyn}/L and $M_\star/L$; absorption line indices (Mg, Na, Ti, Ca…)

… all limited to optical, UV, NIR wavelengths!

Is the stellar IMF universal?



Bastian N, et al. 2010.
Annu. Rev. Astron. Astrophys. 48:339–89

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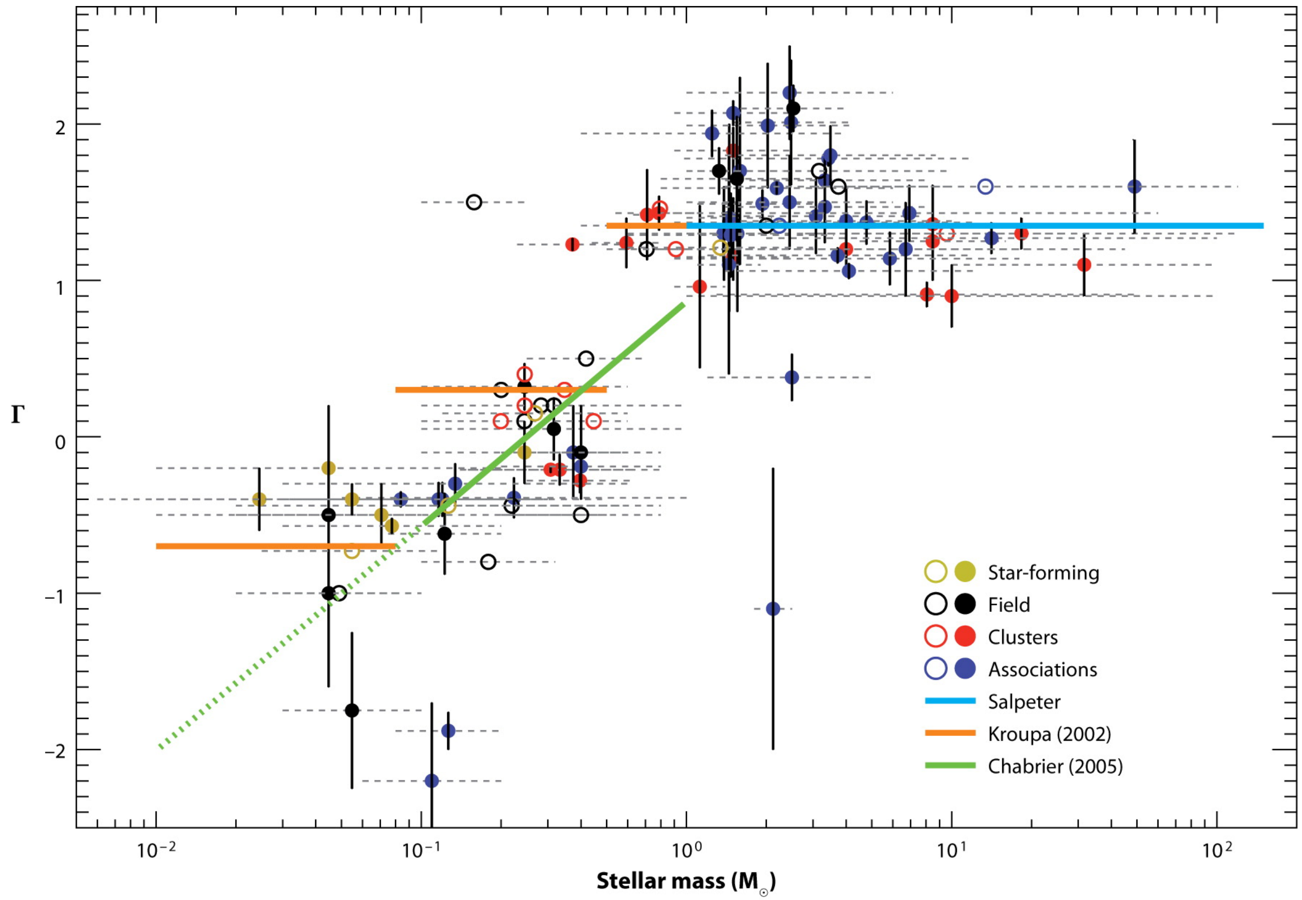

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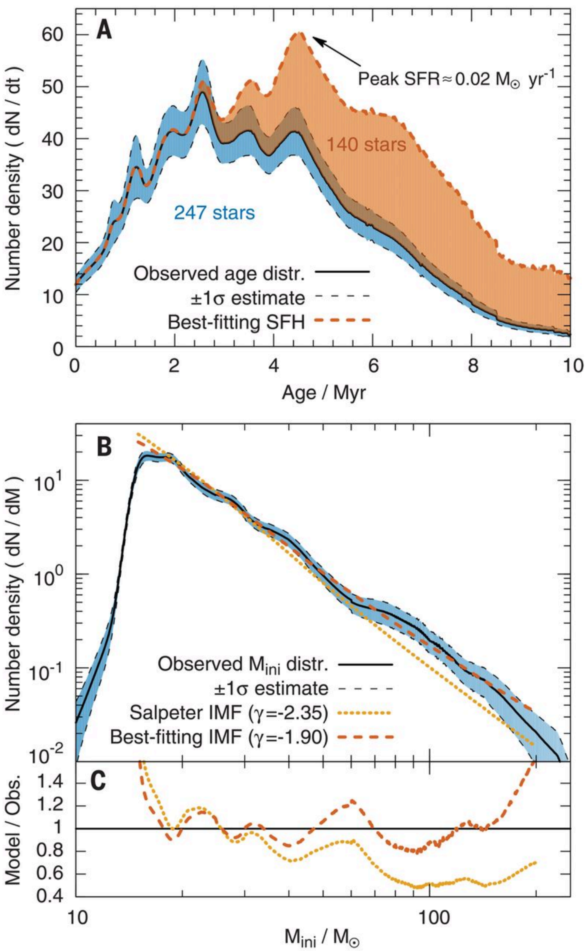
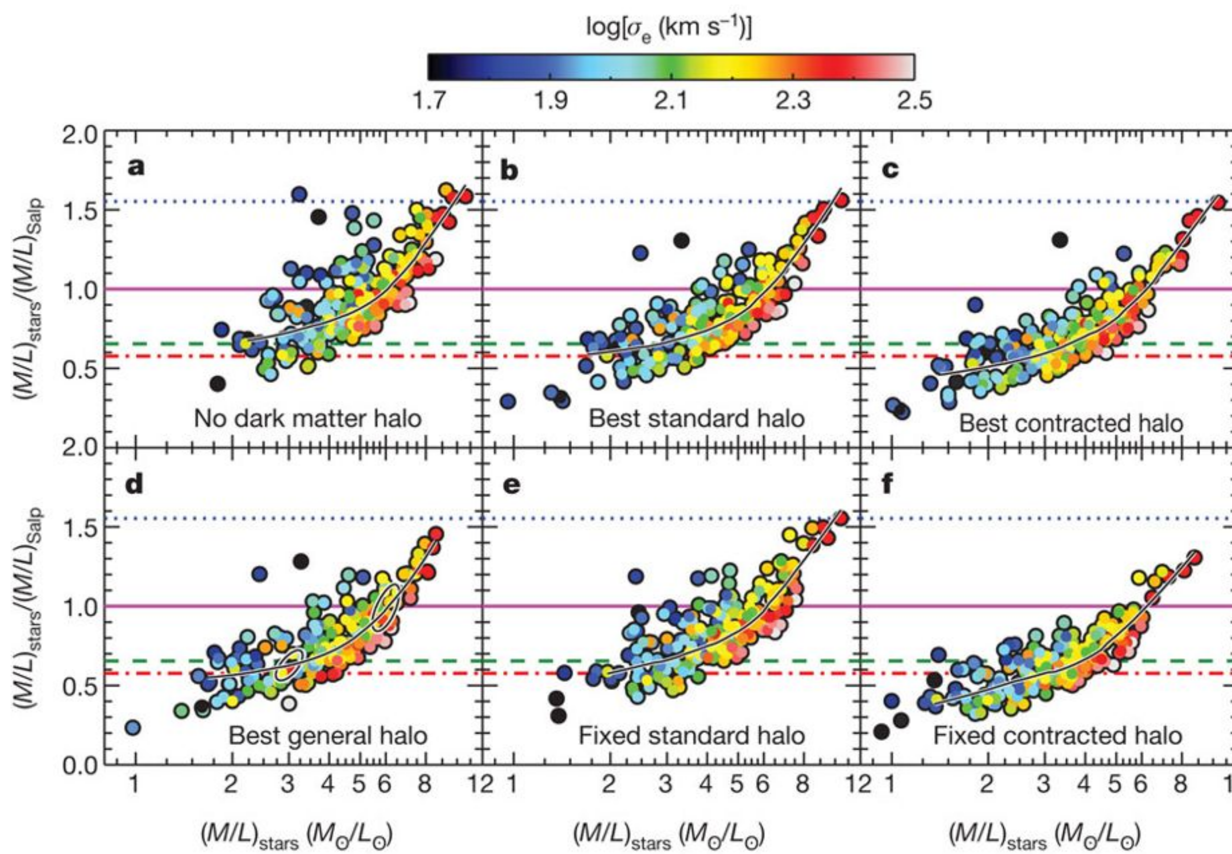
... locally, YES!

Is the stellar IMF universal?

- But **top-heavy** IMF in 30 Doradus… **(Schneider et al. 2018, Science, 359, 69)**
- … and large variations among early-type galaxies! **(Cappellari et al. 2012, Nature, 484, 485)**

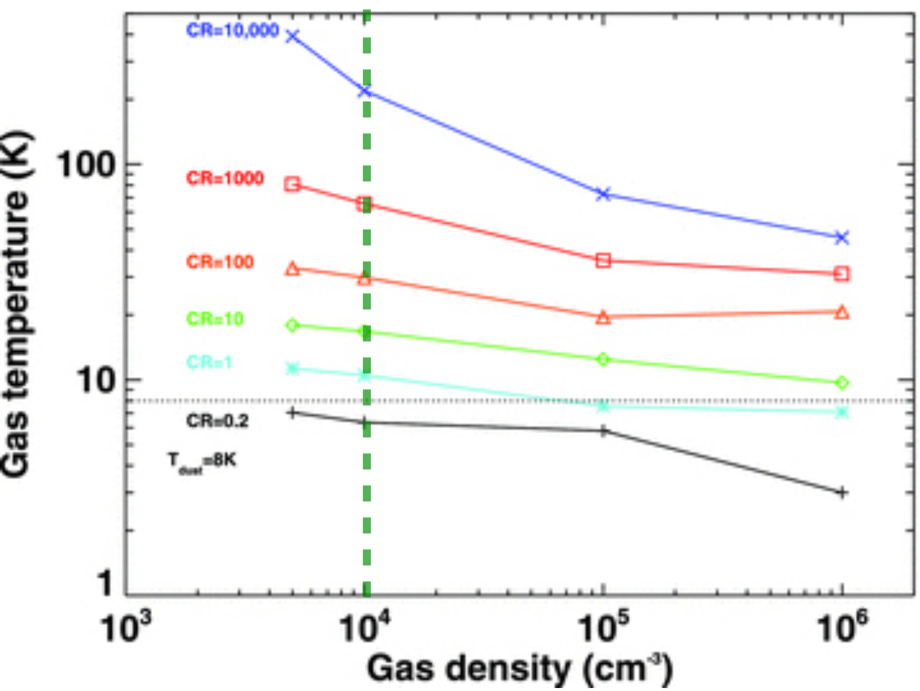


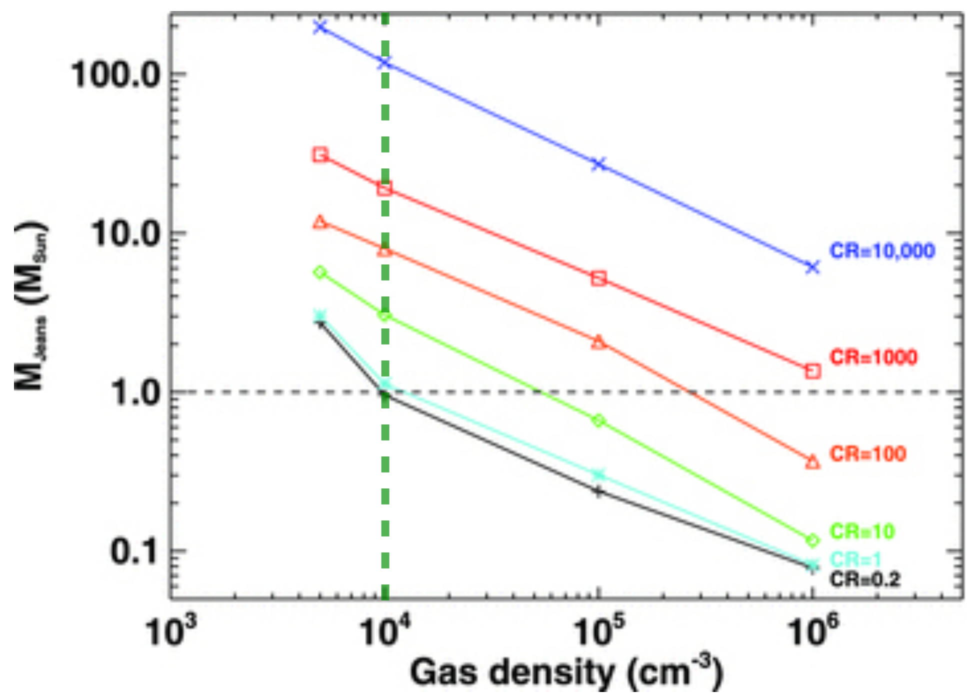


Is the stellar IMF universal?

Theoretical expectations: **COSMIC RAY (CR) + CMB HEATING ➦ TOP-HEAVY IMF**

(Papadopoulos 2010, ApJ, 720, 226; Papadopoulos et al. 2011, MNRAS, 414, 1705)



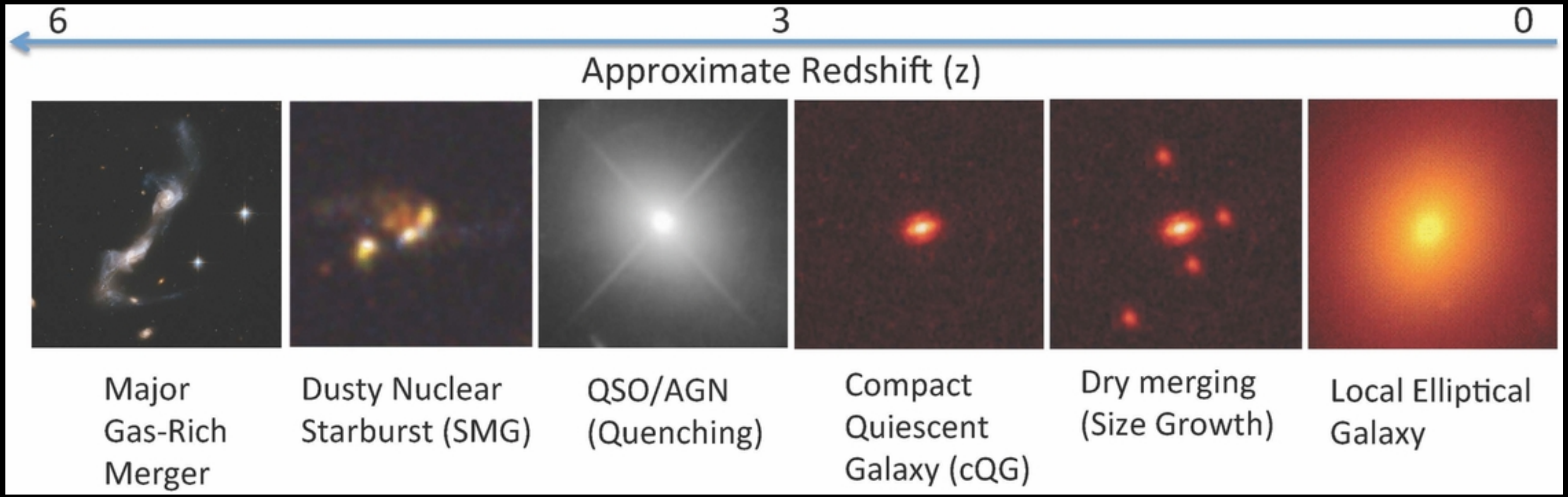


T_{CMB}(z=10) equivalent to T_{gas}(100xCR_{MW})

(Zhang et al. 2016, RSOS, 3, 160025)

Dusty starburst galaxies at high redshift

- Very high apparent star formation rates (SFR ~ 100–1000 $M_{\odot}$ yr^{-1})
- Expected to evolve into today's elliptical galaxies; most stars formed in (early) starburst(s)
- Severe dust obscuration (A_V > 100; **e.g. Simpson et al. 2017, ApJ, 844, L10**) prevents using UV/optical/IR!

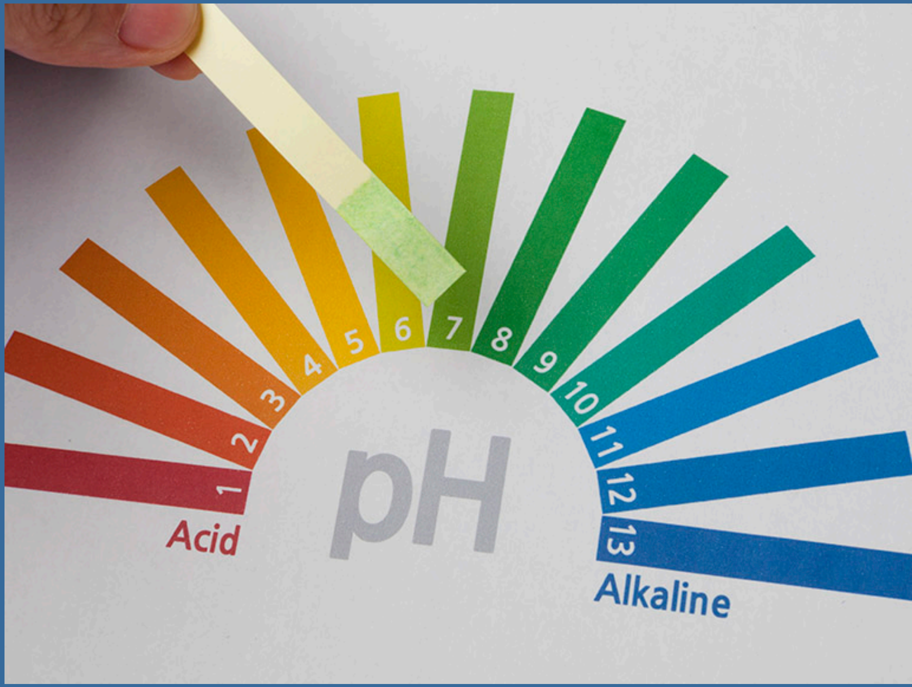


Schematic illustration of the formation and evolution sequence for massive early-type galaxies (Toft et al. 2014, ApJ, 782, 68)

The project:

Use C and O isotopes to probe the prevailing IMF in dust-enshrouded starburst galaxies @ high z

(Romano et al. 2017, MNRAS, 470, 401; Zhang, DR et al. 2018, Nature, 558, 260)



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- Observe CNO bearing molecules in the ISM at millimeter/submillimeter wavelengths
- These, in principle, provide the best *indirect* evidence for IMF variations

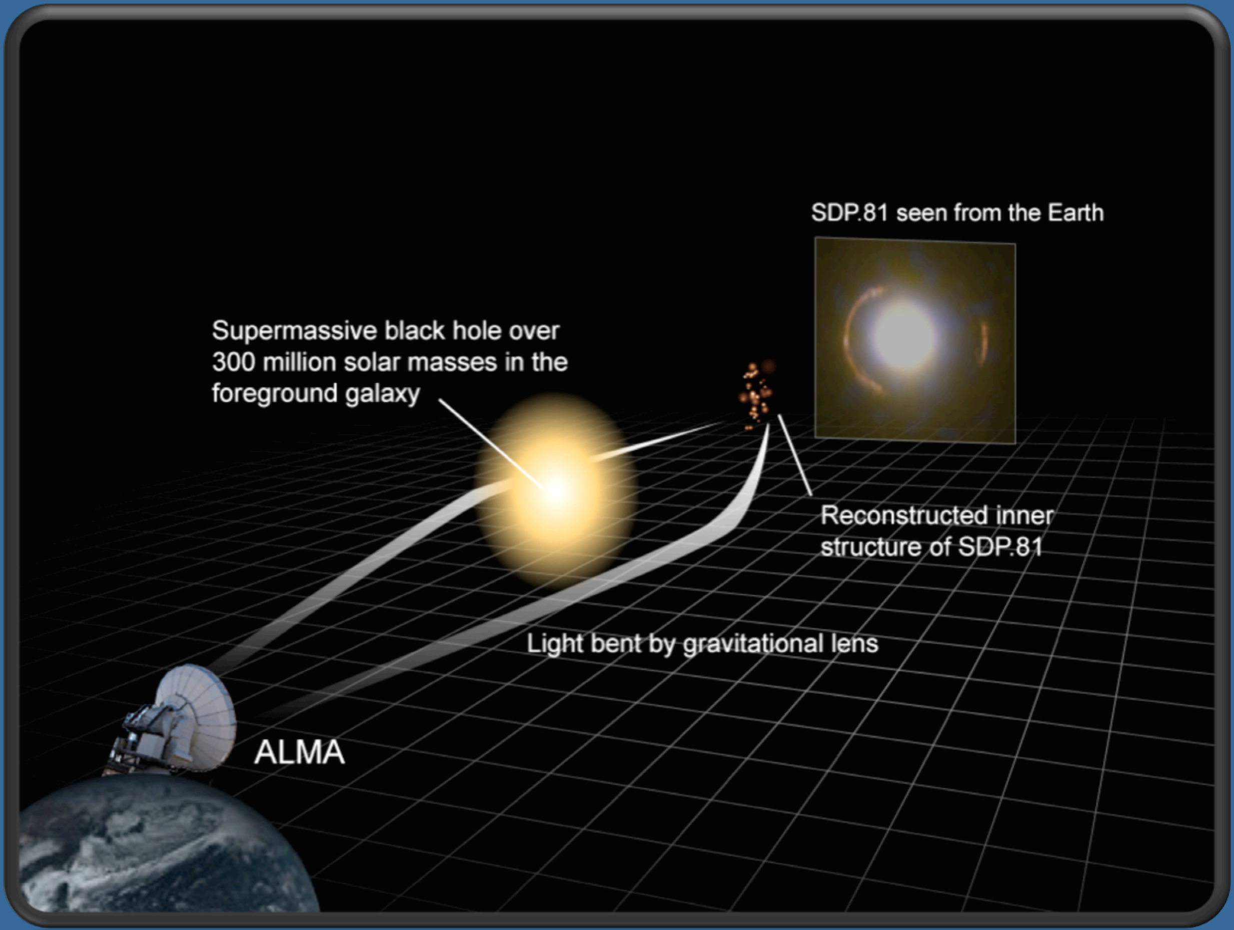
  (Henkel & Mauersberger 1993, A&A, 274, 730; Papadopoulos et al. 2014, ApJ, 788, 153)

- **Use $^{13}C/^{18}O$ as best diagnostic**

Our ALMA observations: a sample of four strongly lensed SMGs

Zhang, DR, et al. (2018, Nature, 558, 260)

- Strong CO emitters
- $z \sim 2–4$
- SFR ~ 800–2000 $M_{\odot}$ yr^{-1}
- $M_{\star} \sim 10^{11}$ $M_{\odot}$



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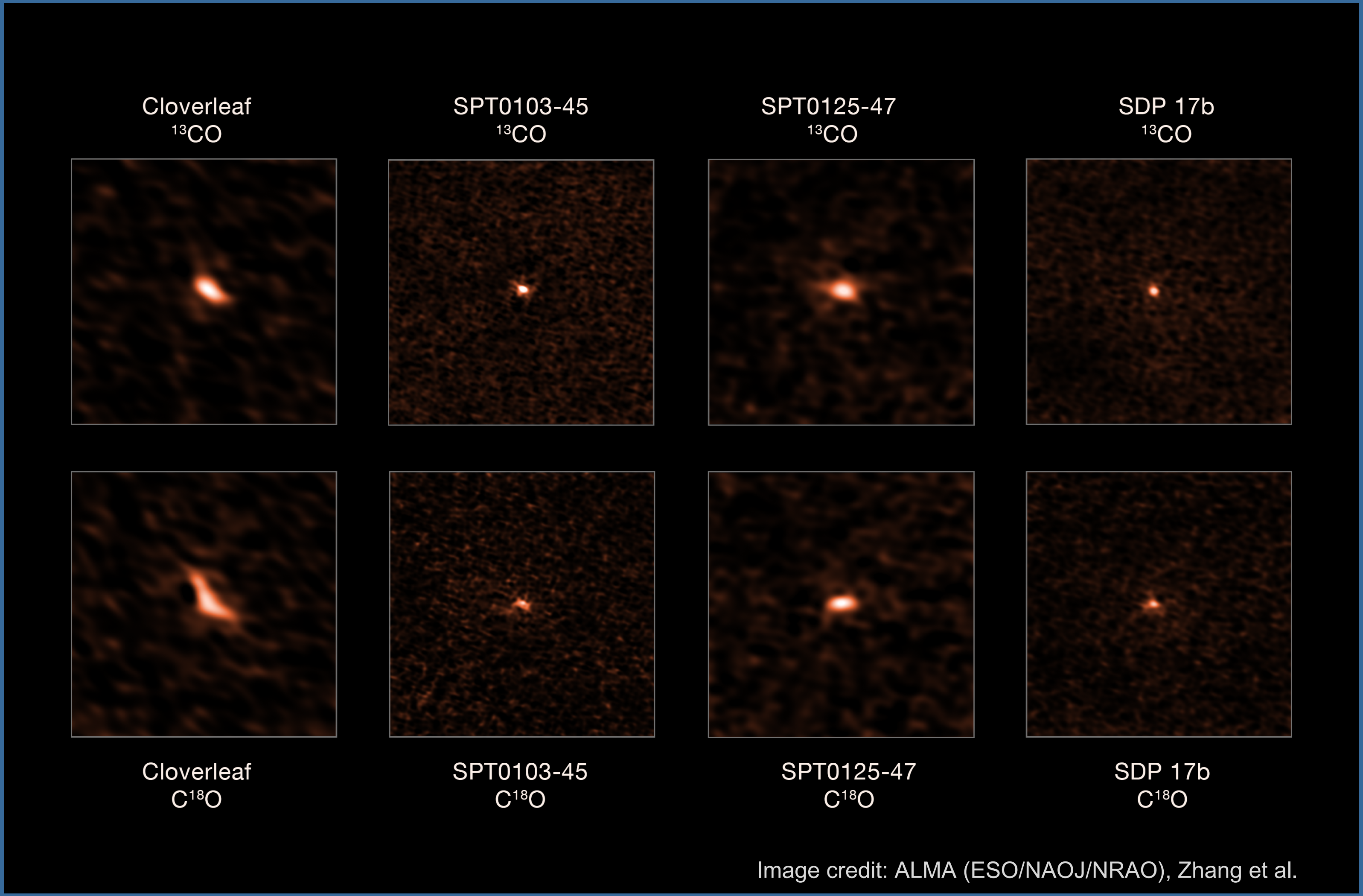


Results & comparison with literature data

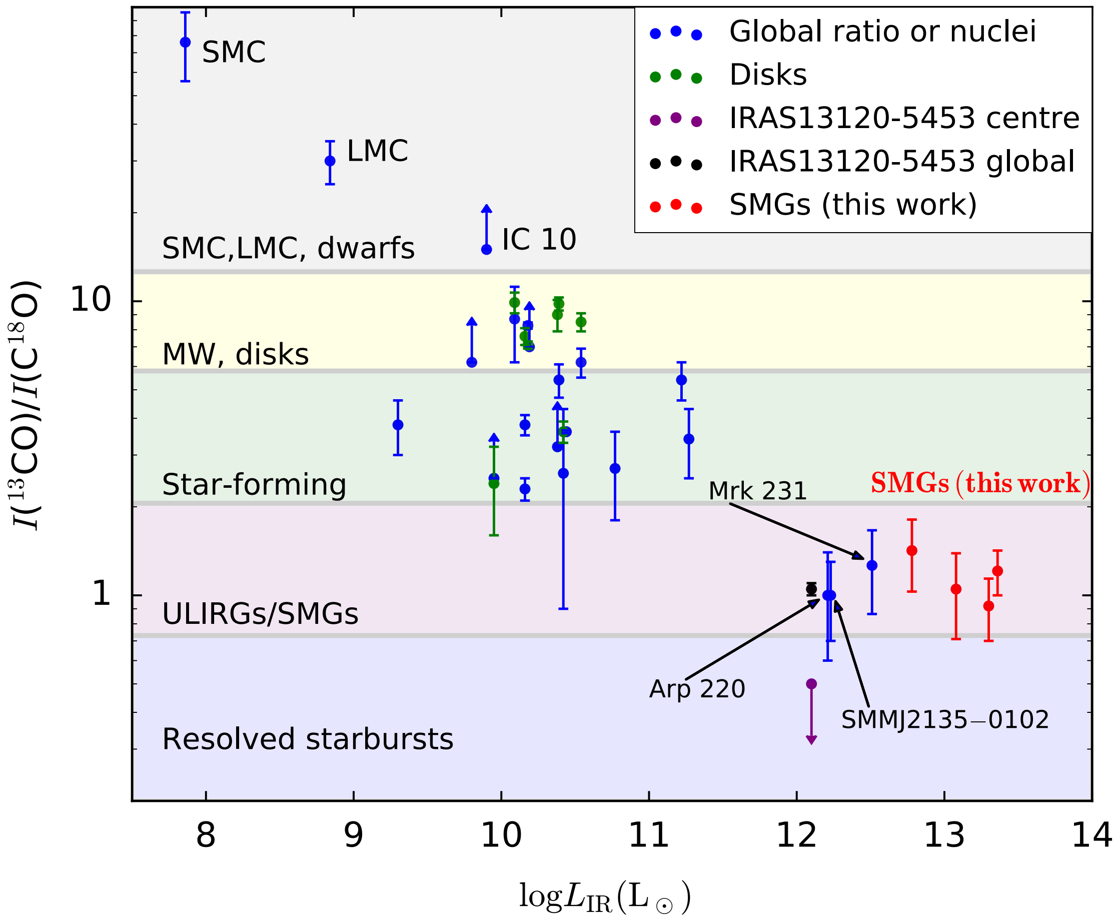


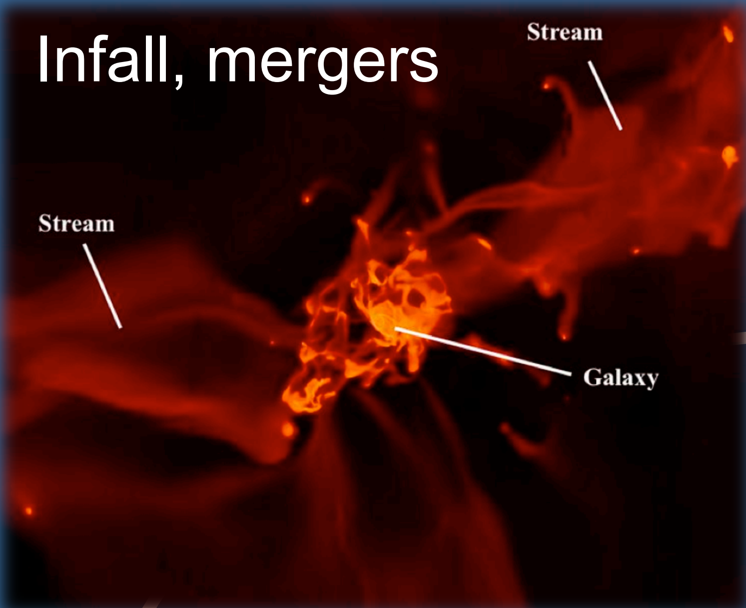
Figure from Zhang, DR, et al. (2018, Nature, 558, 260)

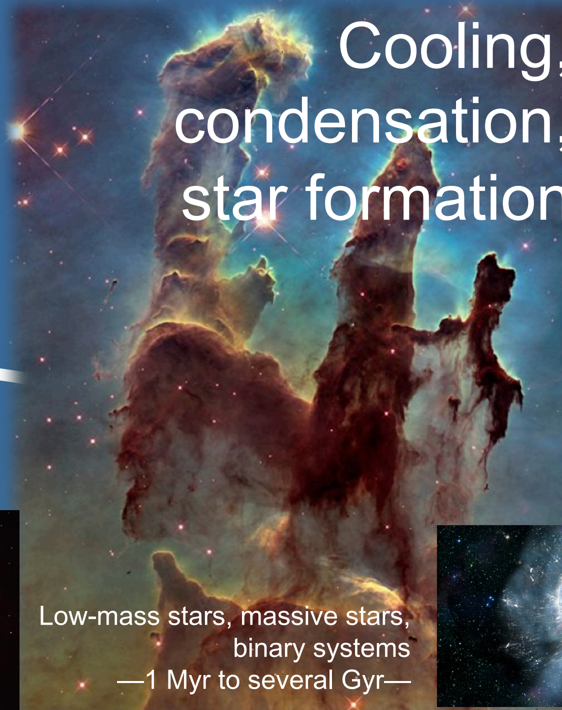
- All our galaxies have

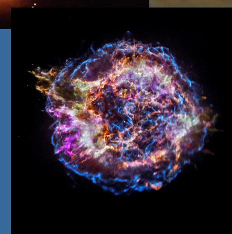
  $I(^{13}CO)/I(C^{18}O) \simeq {}^{13}C/{}^{18}O \sim 1$

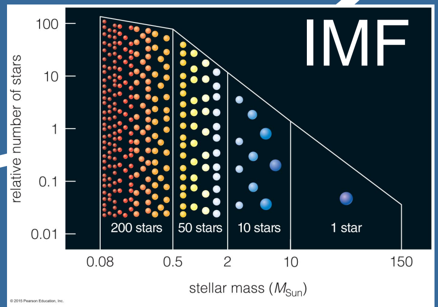
- Systematic trend of decreasing $^{13}C/^{18}O$ with L_{IR}

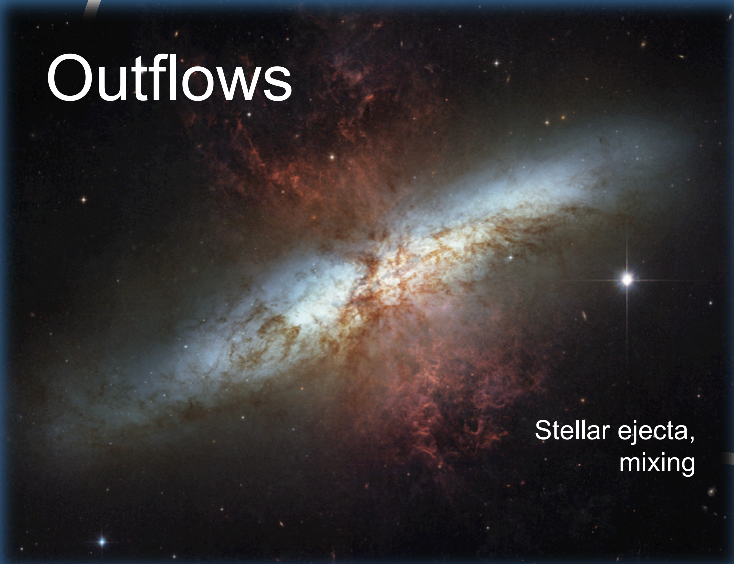
Interpretation: galactic chemical evolution models





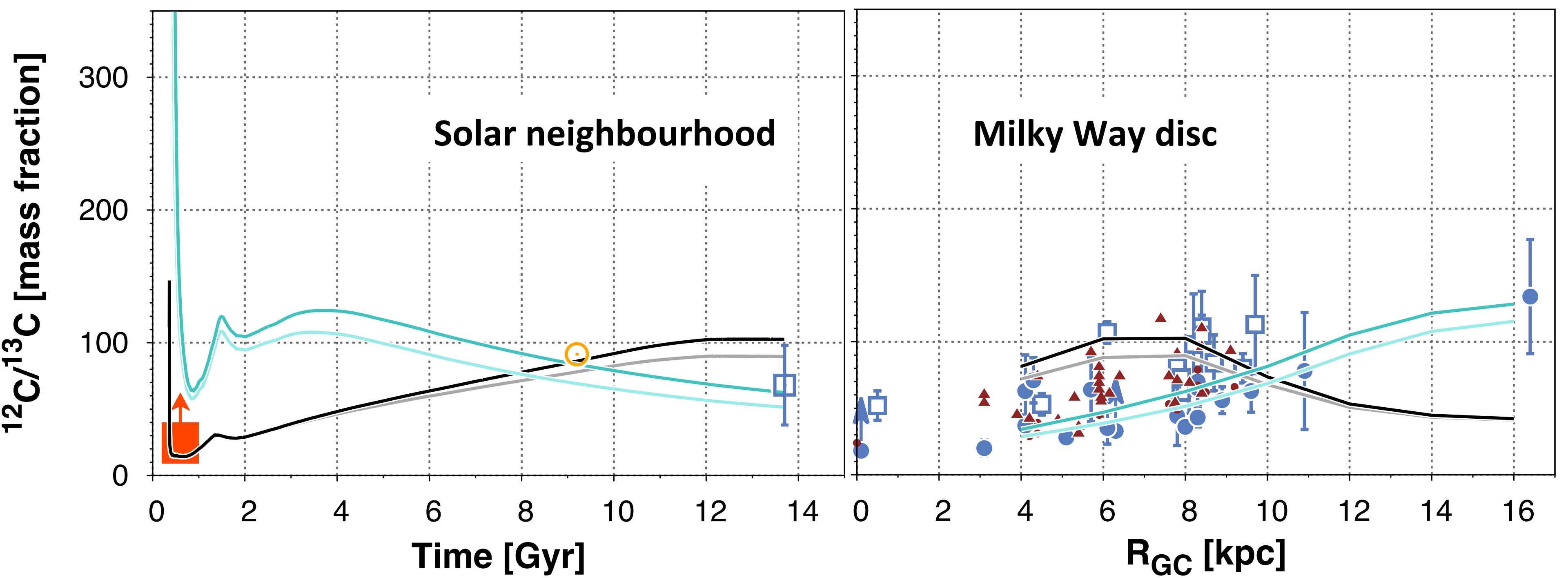






The Milky Way as a benchmark

Romano et al. (2017, MNRAS, 470, 401)



Halo stars

Solar system

Local ISM

Data from CO, H_2CO, CO_2 and CN

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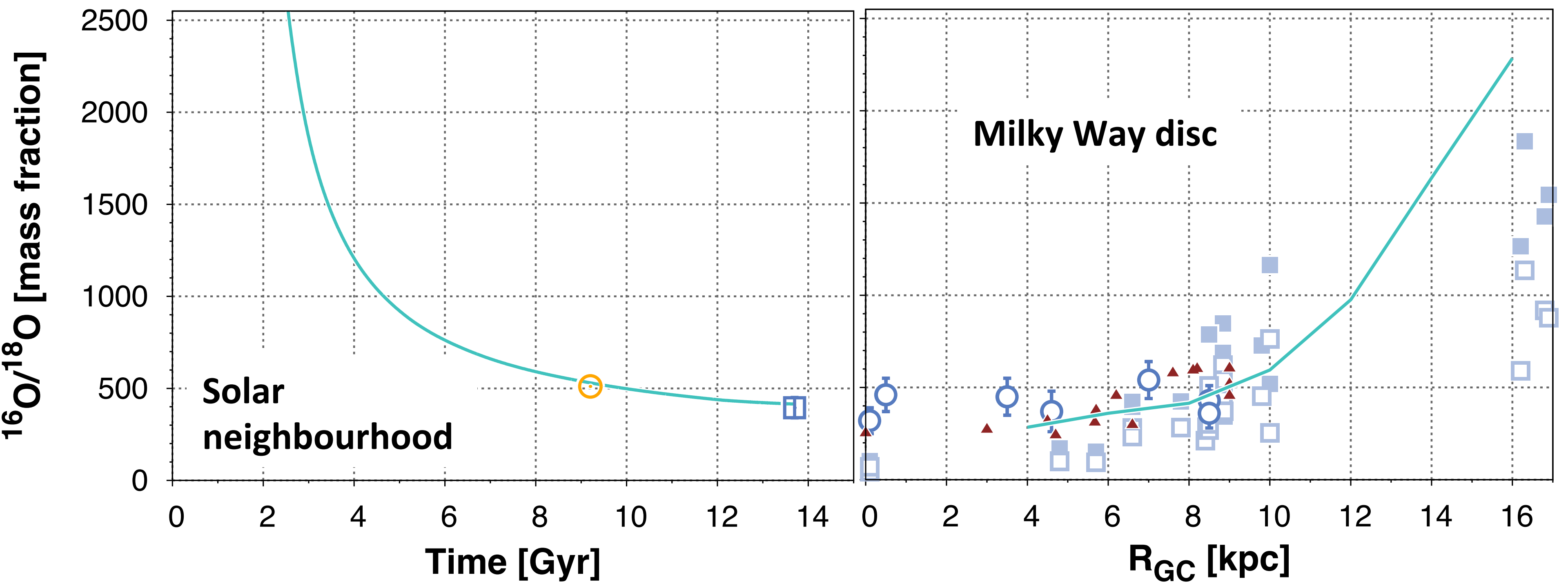
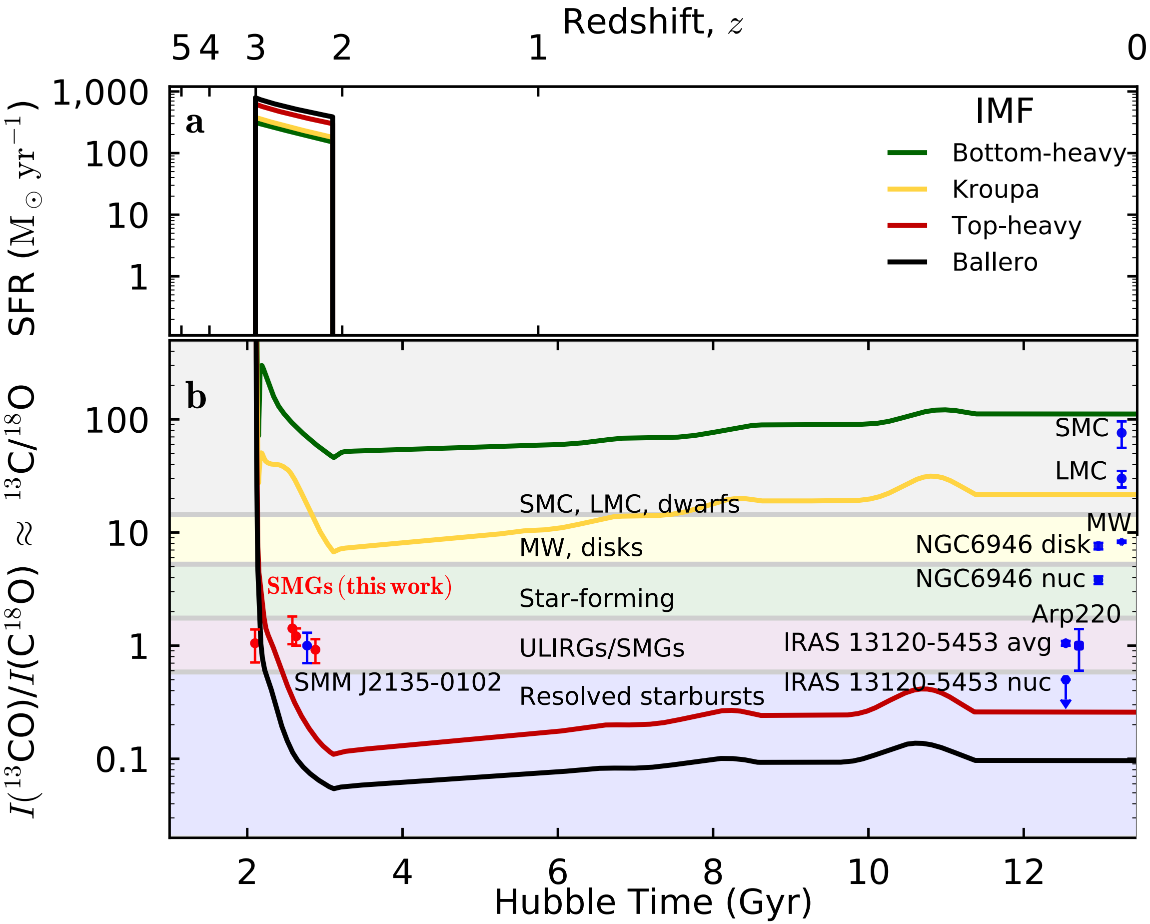


Solar system

Local ISM

Data from H_2CO, OH and CO

Modeling our ALMA galaxies…



- Only an **IMF biased** towards high-mass stars can reproduce a ratio $^{13}C/^{18}O \sim 1$ in our SMGs ! (Necessary to resolve the starburst regions…)

IMF Name	$\alpha 0$	$\alpha 1$	$\alpha 2$	$m0$ $M_\odot$	$m1$ $M_\odot$	$m2$ $M_\odot$	$m3$ $M_\odot$
Bottom heavy	−1.7	−1.7	−1.7	0.1	0.5	1.0	100
Kroupa	−0.3	−1.2	−1.7	0.1	0.5	1.0	100
Top heavy	−0.3	−1.1	−1.1	0.1	0.5	1.0	100
Ballero	−0.3	−0.95	−0.95	0.1	0.5	1.0	100

Figure from Zhang, DR, et al. (2018, Nature, 558, 260)

Modeling our ALMA galaxies...

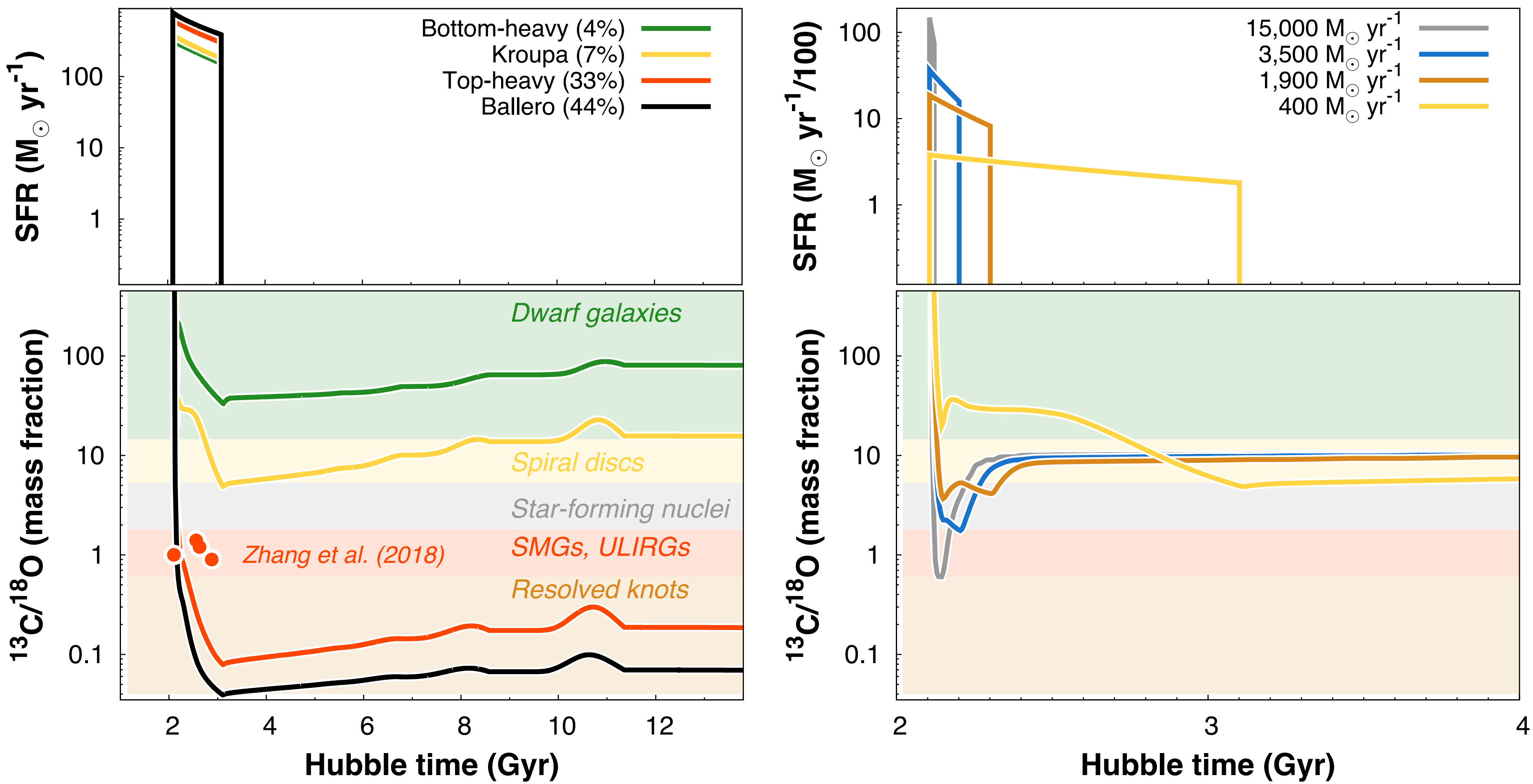


Figure from Romano et al. (2019, Springer Proceedings in Physics, Proc. of Intl. Conf. "Nuclei in the Cosmos XV", LNGS Assergi, Italy)

Conclusions

- ALMA measurements of $^{13}C/^{18}O$ ratios in the ISM of dusty starburst galaxies at high redshift are a new powerful tool to determine the shape of their stellar IMF

- $^{13}C/^{18}O \sim 1$ for our sample of galaxies points to an IMF biased towards massive stars in powerful starbursts


That's all Folks!

That's not all Folks!