Constraining galaxy scaling relations with empirical distribution function modelling

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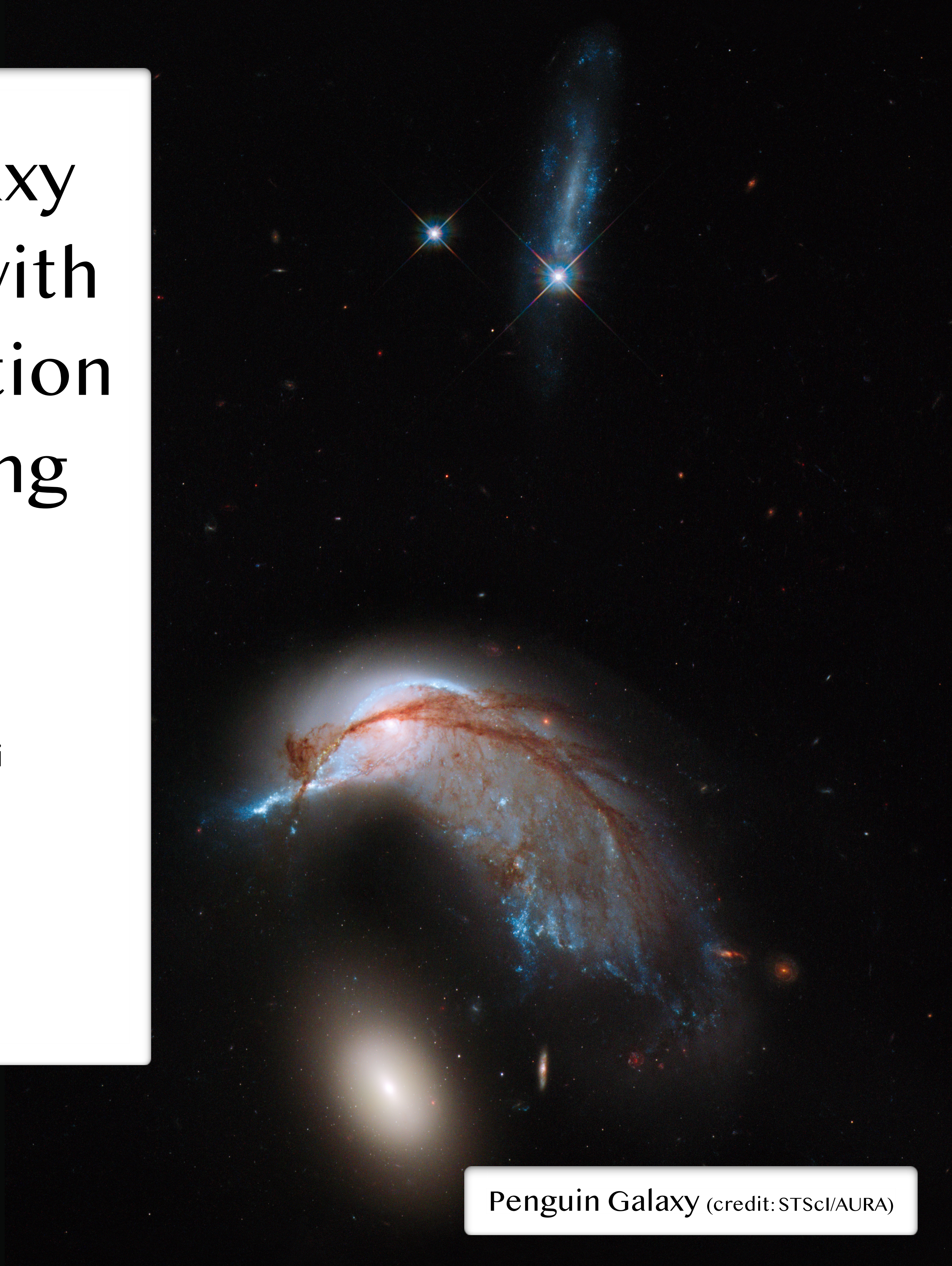


Penguin Galaxy (credit: STScI/AURA)

Outline

- Introduction:
  - The ingredients: galaxy scaling relations & distribution functions
  - Empirical modelling of distribution fcts.: example applications

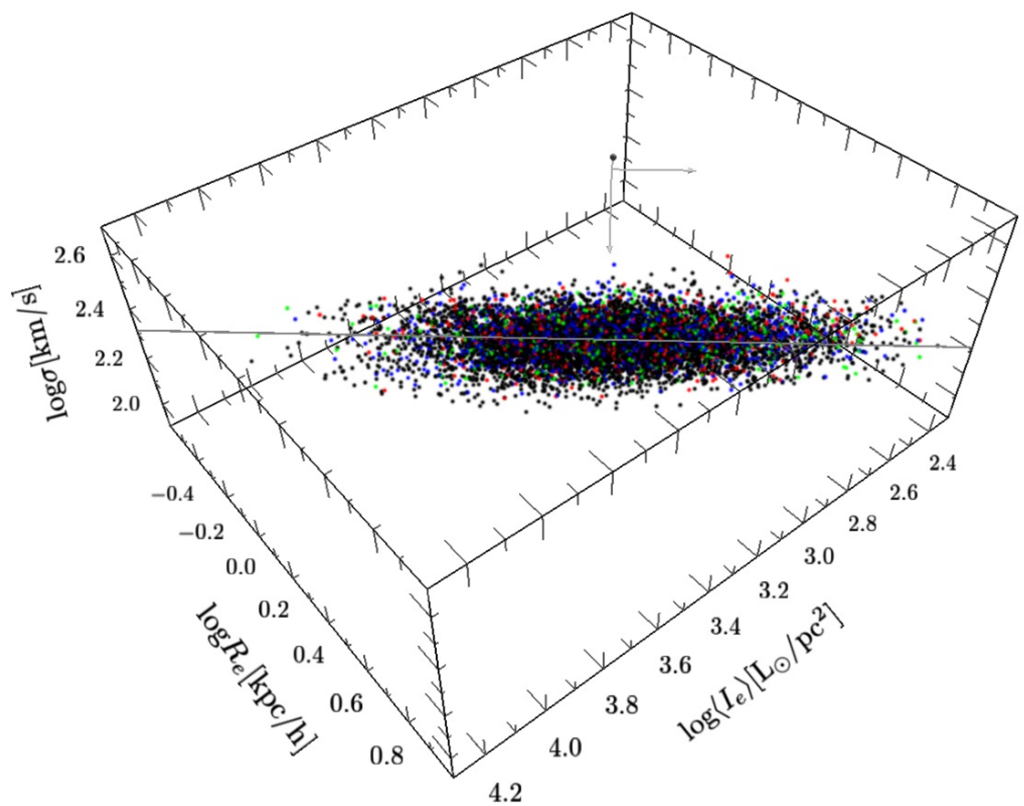
- Part 1: A new approach to measuring the redshift evolution of the radio GHz continuum - star-formation rate calibration

- Part 2: Inferring the dependence of the CO-to-H2 conversion factor on gas-phase chemical enrichment in low-redshift galaxies

GALAXY SCALING RELATIONS

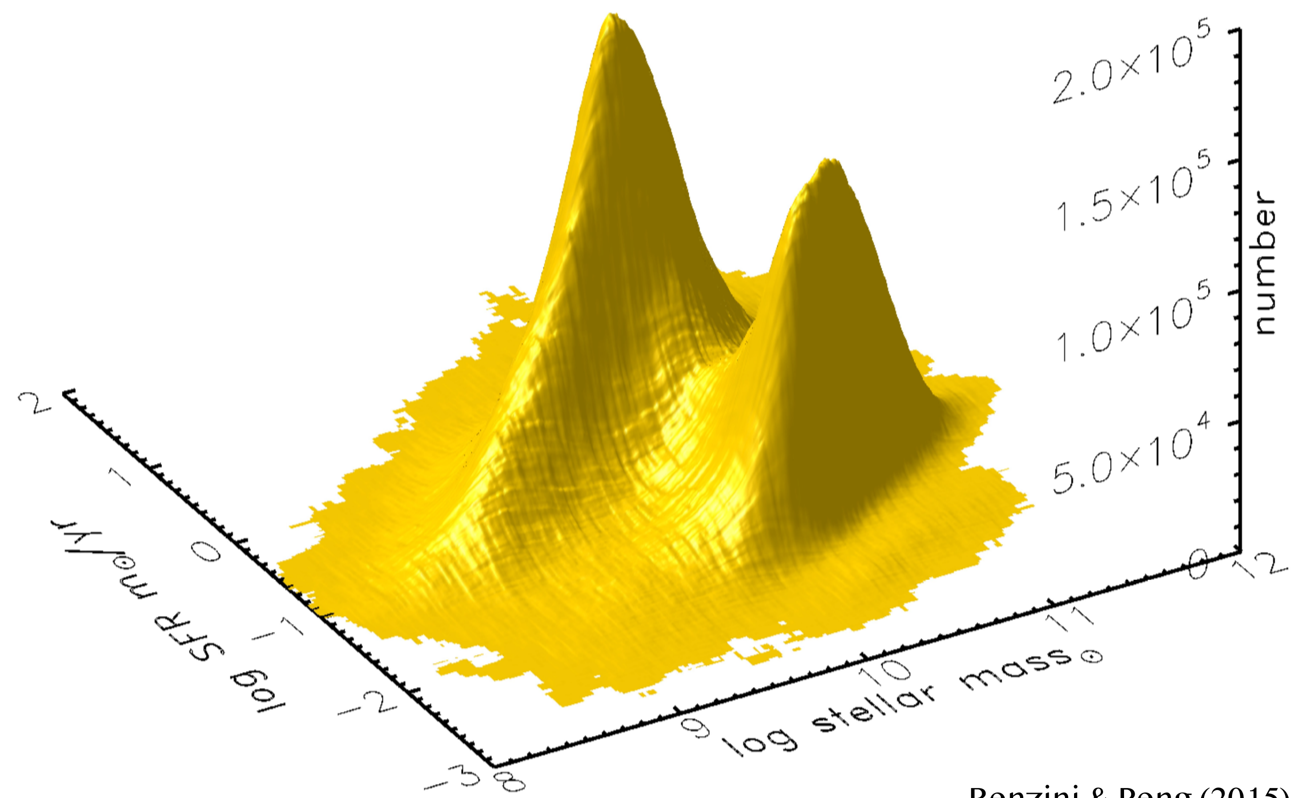
The (not always straightforward) imprint of formation processes

Fundamental plane of elliptical galaxies:



Magoulas et al. (2012)

Main sequence of star-forming galaxies:



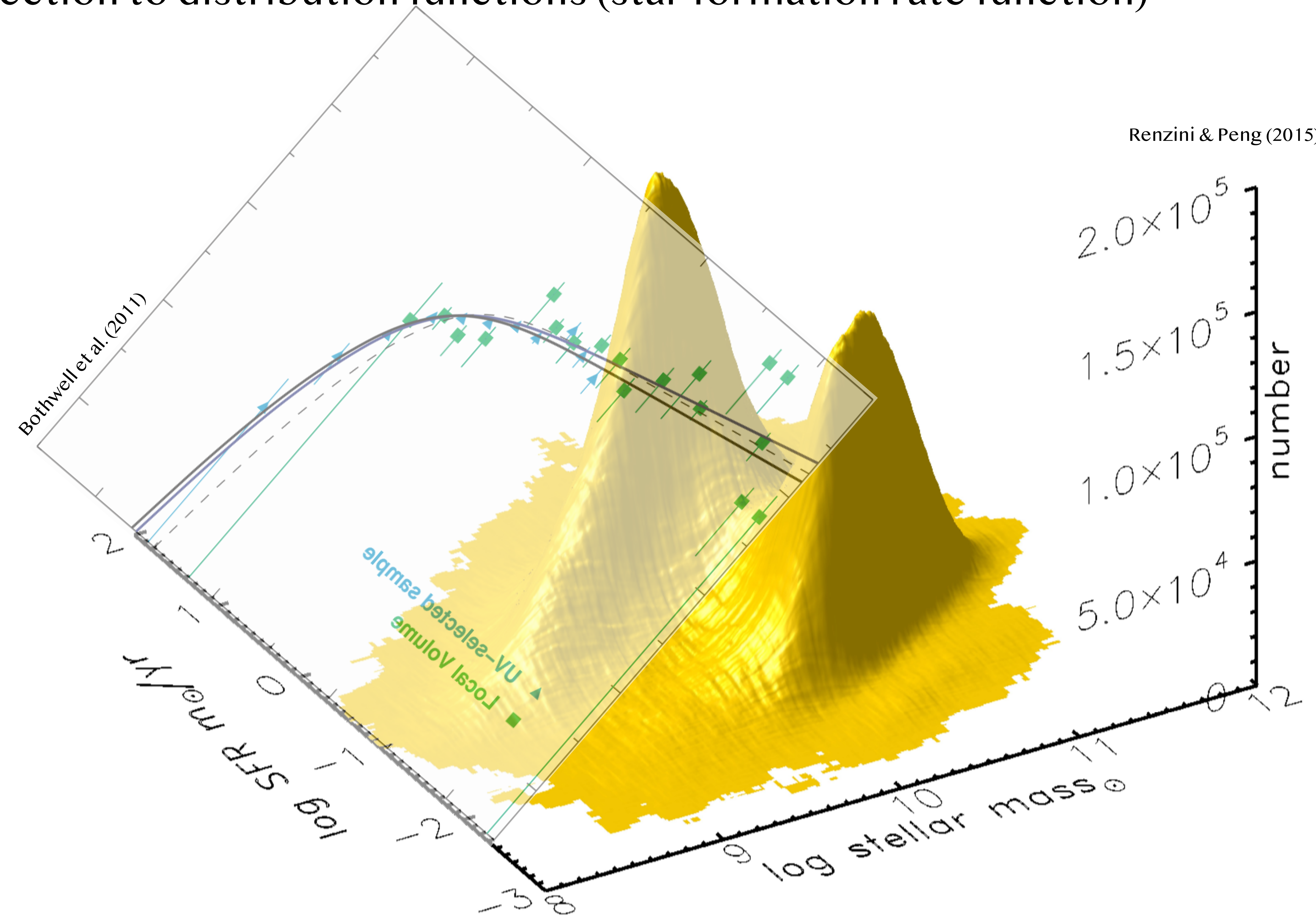
Renzini & Peng (2015)

(Not quite) formation as virialised systems.

Larger objects grow faster, by accreting more gaseous “fuel”.

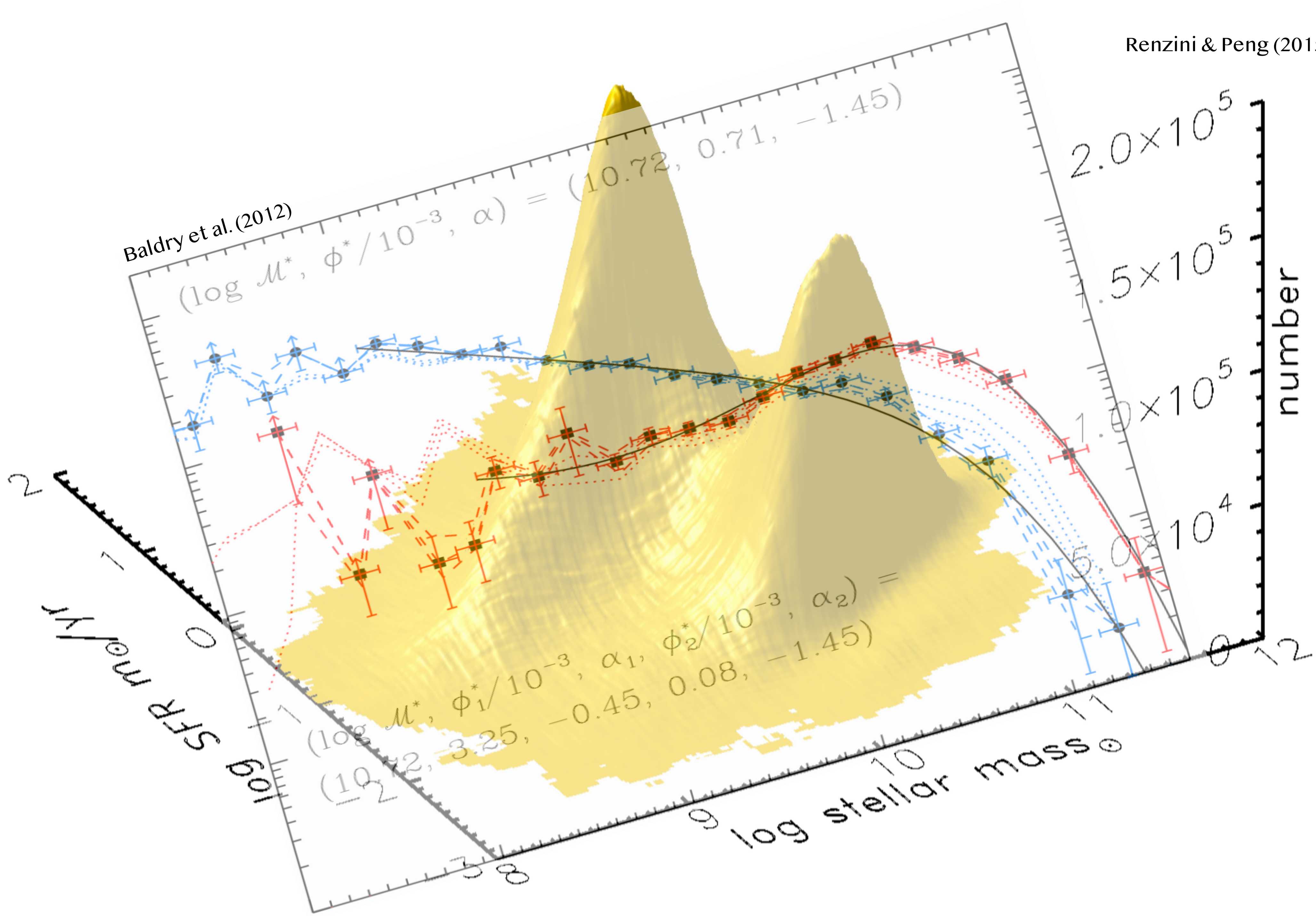
SFR-M$_\star$ SPACE

Projection to distribution functions (star-formation rate function)



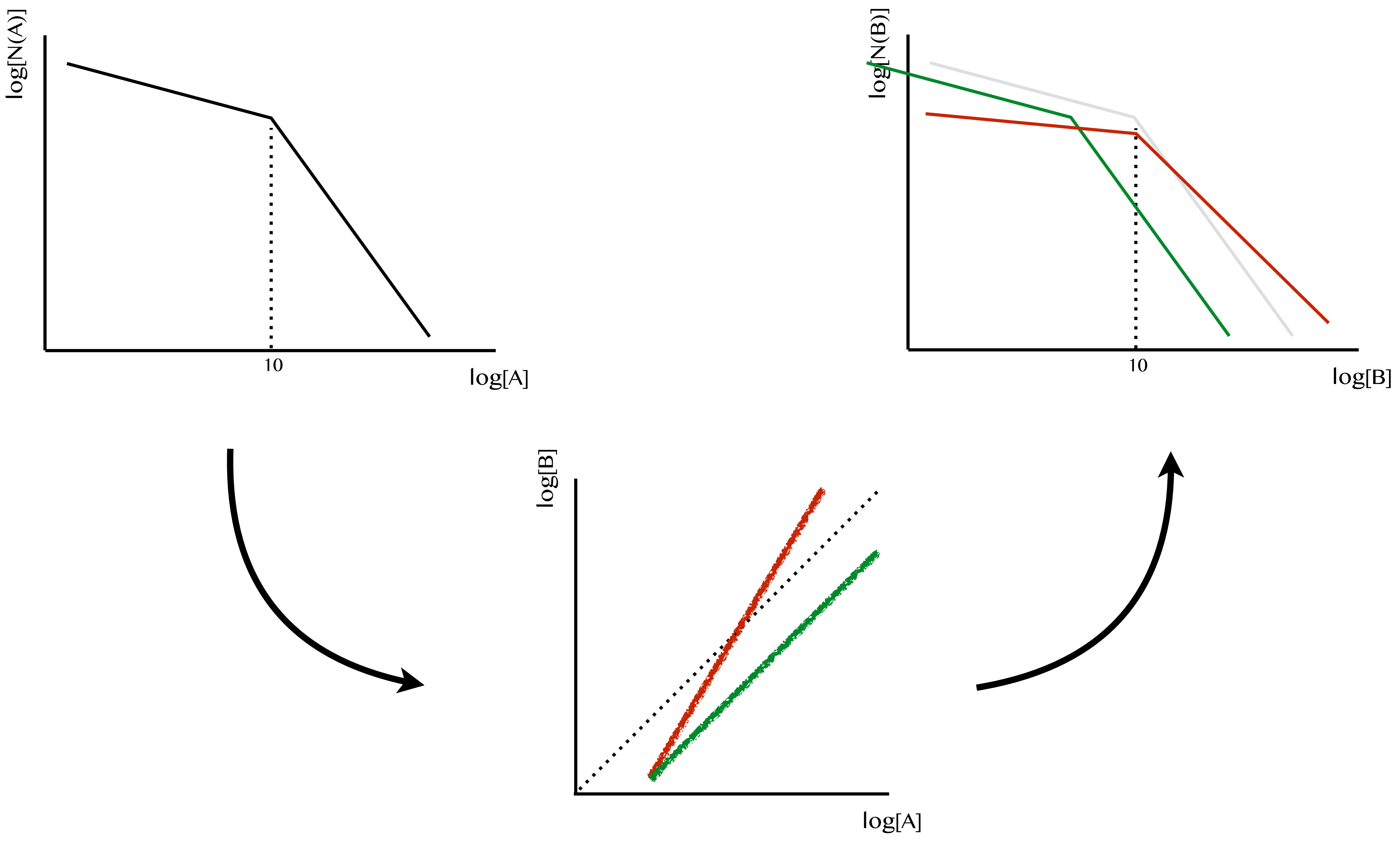
SFR-M$_\star$ SPACE

Projection to distribution functions (stellar mass function)



EMPIRICAL DISTRIBUTION FCT. MODELLING

A tool for astrophysical constraints and predictions



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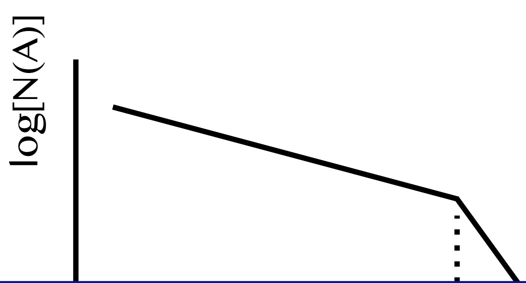
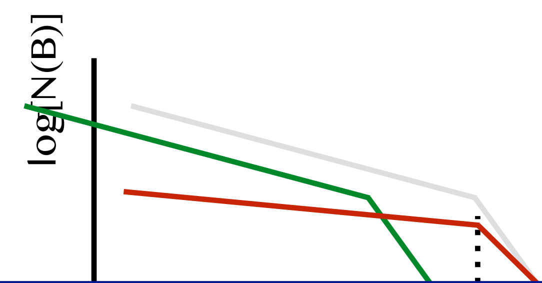
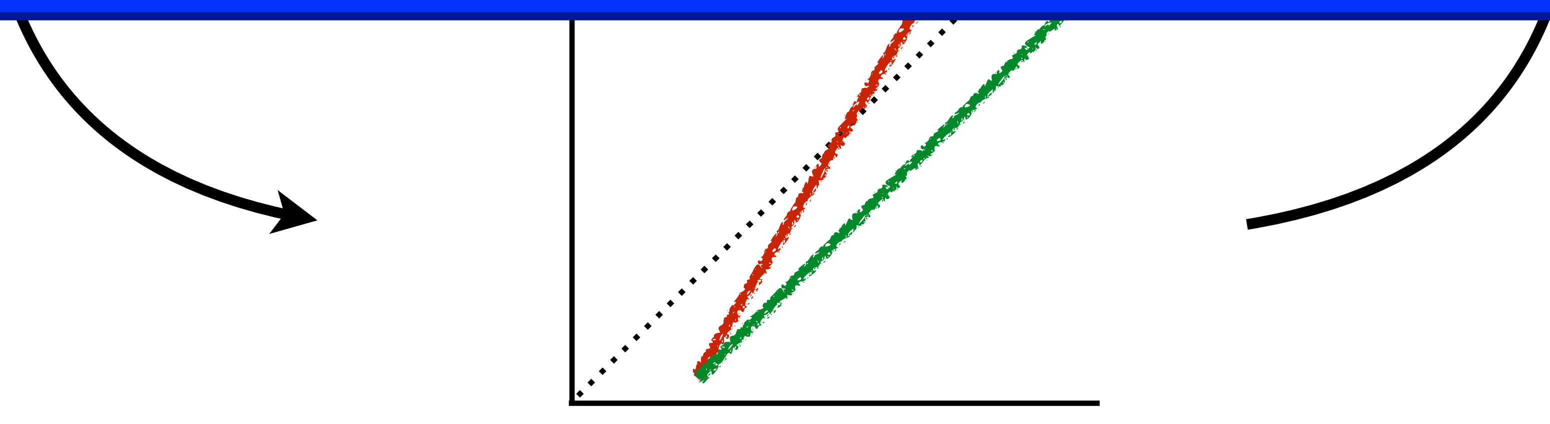




- Need to make sure to consider the same populations!
- Need to take into account (intrinsic!) scatter of scaling relations!
- Can convolve multiple scaling relations.

Our starting point: the galaxy stellar mass function.

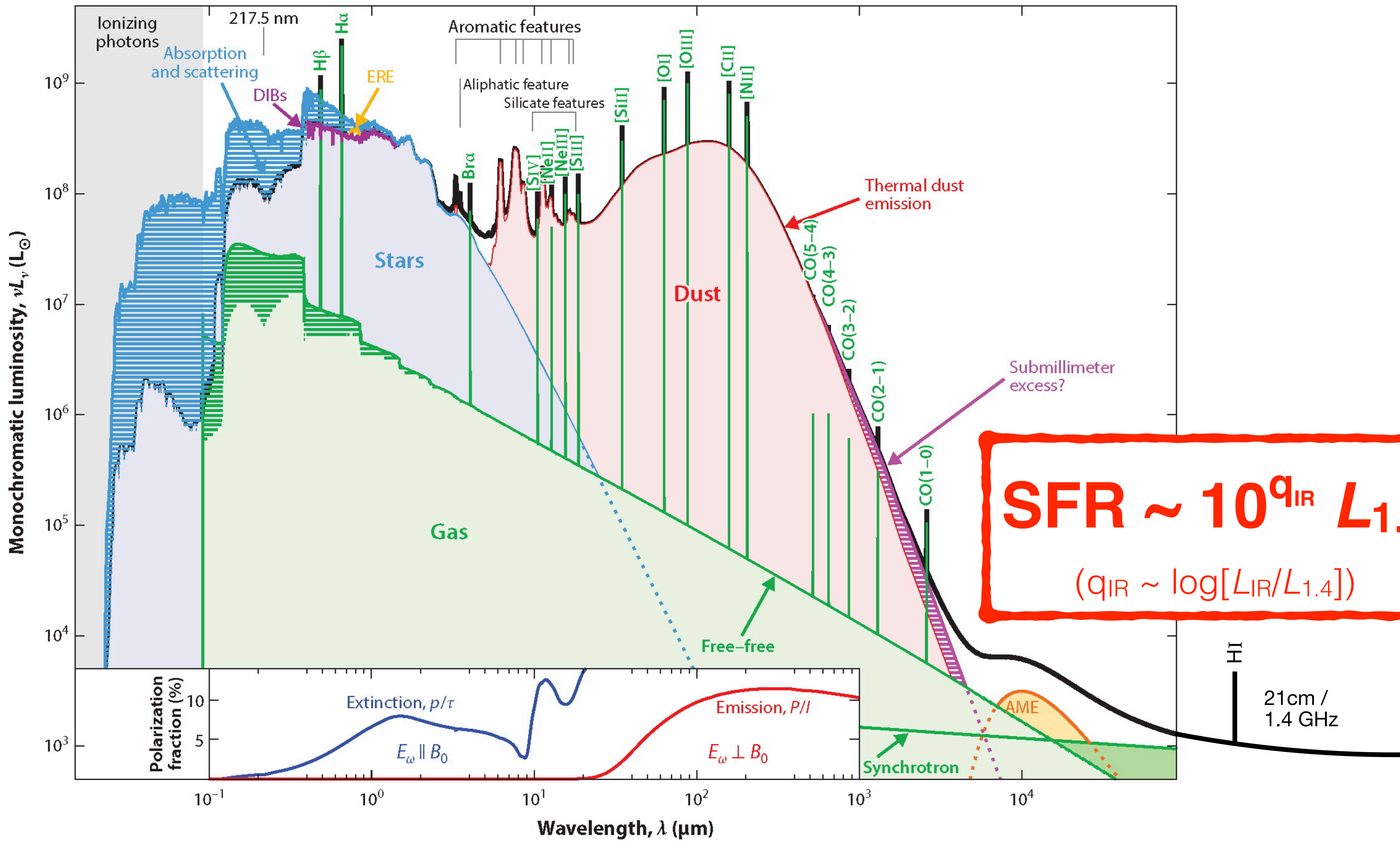


Summary

1. Empirical modelling of galaxy distribution functions provides (i) constraints on galaxy scaling relations, and (ii) a predictive framework for, e.g., survey design/optimisation.
2. Part 1: Through empirical modelling of the GHz luminosity function of star-forming galaxies we can test the consistency of different evolutionary recipes for the radio-SFR calibration. A calibration that varies only with redshift, and has no higher-order dependencies, seems to be disfavoured.
3. Part 2: Empirical modelling of the z~0 CO luminosity function suggests mild variations of the CO-to-H_2 conversion factor (α_{CO}) among Milky-Way-like galaxies, with a rapid increase for metal-poor galaxies (cf. the Wolfire model for α_{CO}).

PART 1: RADIO STAR-FORMATION RATES

How does the calibration of GHz continuum emission as an SFR tracer evolve?



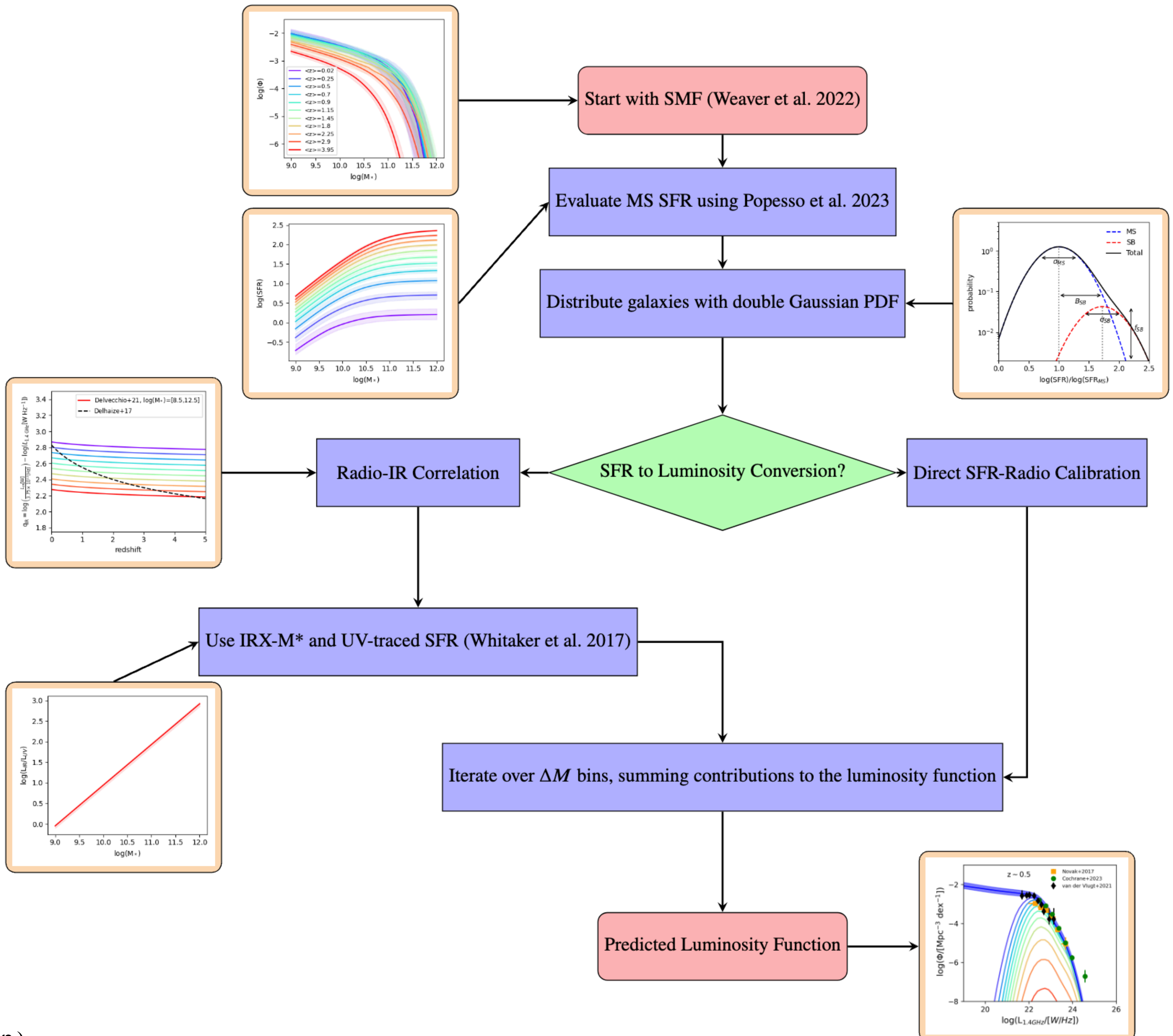
SFR ~ $10^{q_{IR}}$ $L_{1.4}$

(q_{IR} ~ log[$L_{IR}/L_{1.4}$])

Galliano F, et al. 2018.
Annu. Rev. Astron. Astrophys. 56:673–713

PREDICTING RADIO LUMINOSITY FCT. EVOLUTION

Ingredients

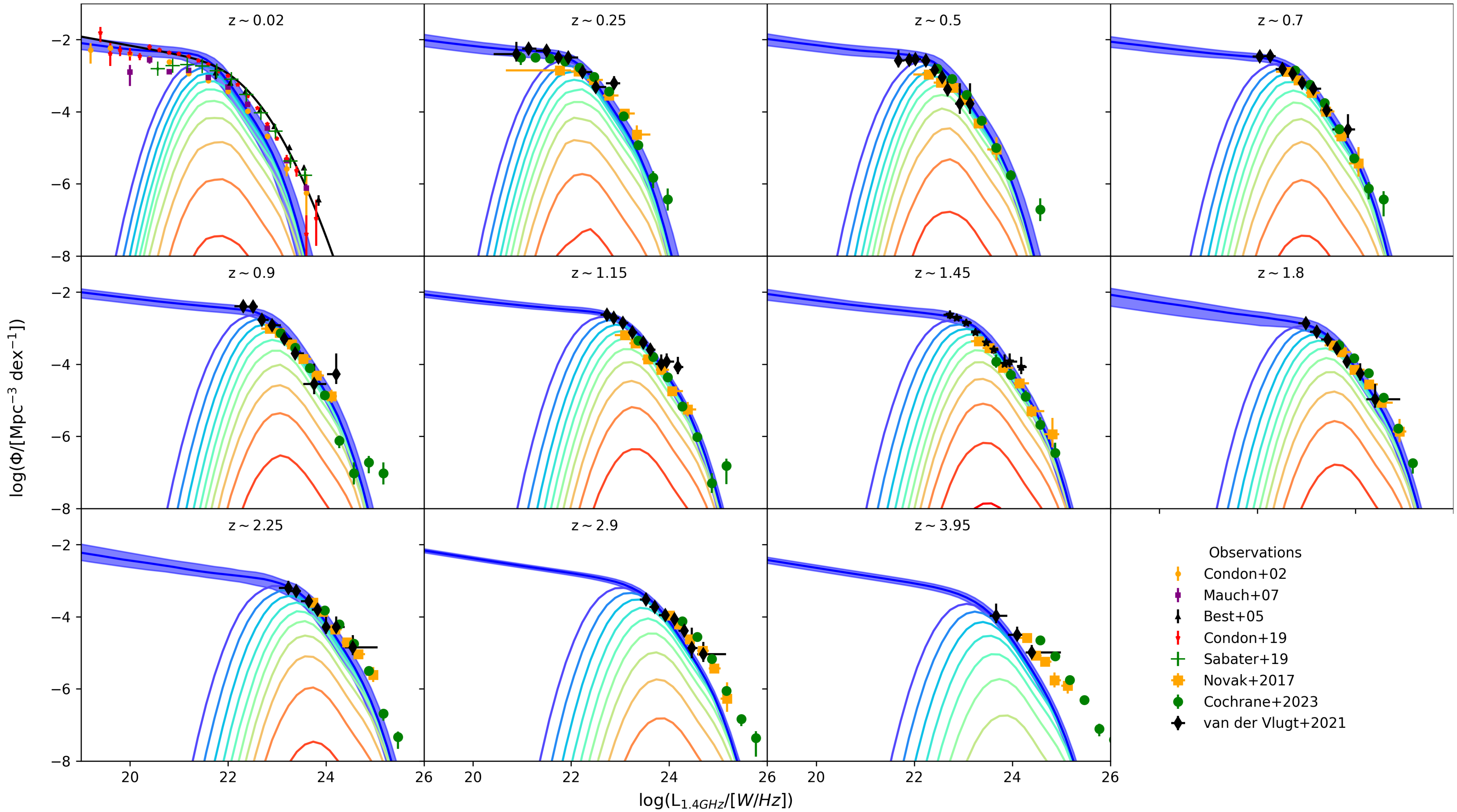


Leslie & Sargent (in prep.)

PREDICTING RADIO LUMINOSITY FCT. EVOLUTION

Comparison with data

Leslie & Sargent (in prep.)

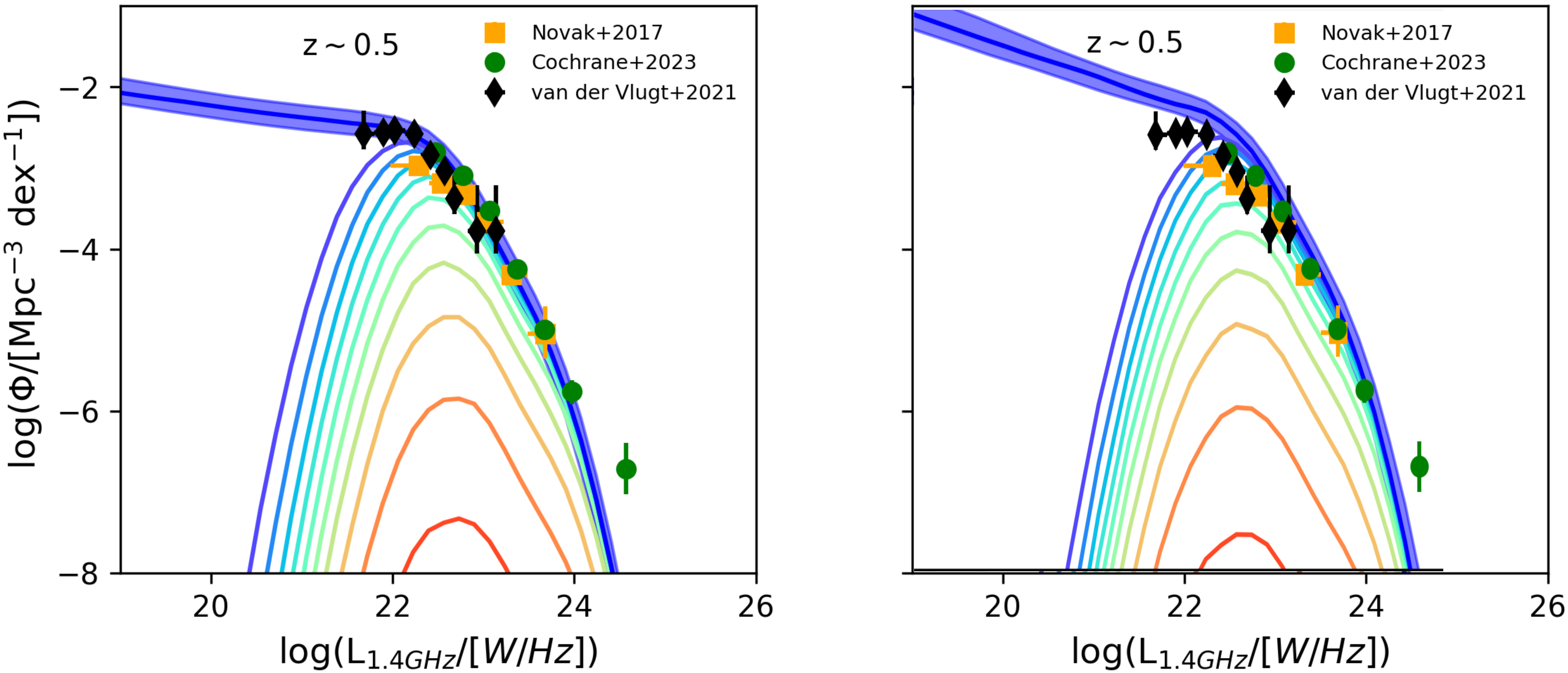


This is not a fit! Reassuring consistency observed between observed 1.4 GHz LFs for star-forming galaxies, and the expectations from empirical modelling.

(Note: this uses the stellar-mass-dependent qIR coefficient from Delvecchio et al. 2021. See also recent modelling work by Schober, Sargent et al. 2023.)

PREDICTING RADIO LUMINOSITY FCT. EVOLUTION

Comparing different radio-SFR calibration recipes and their evolution

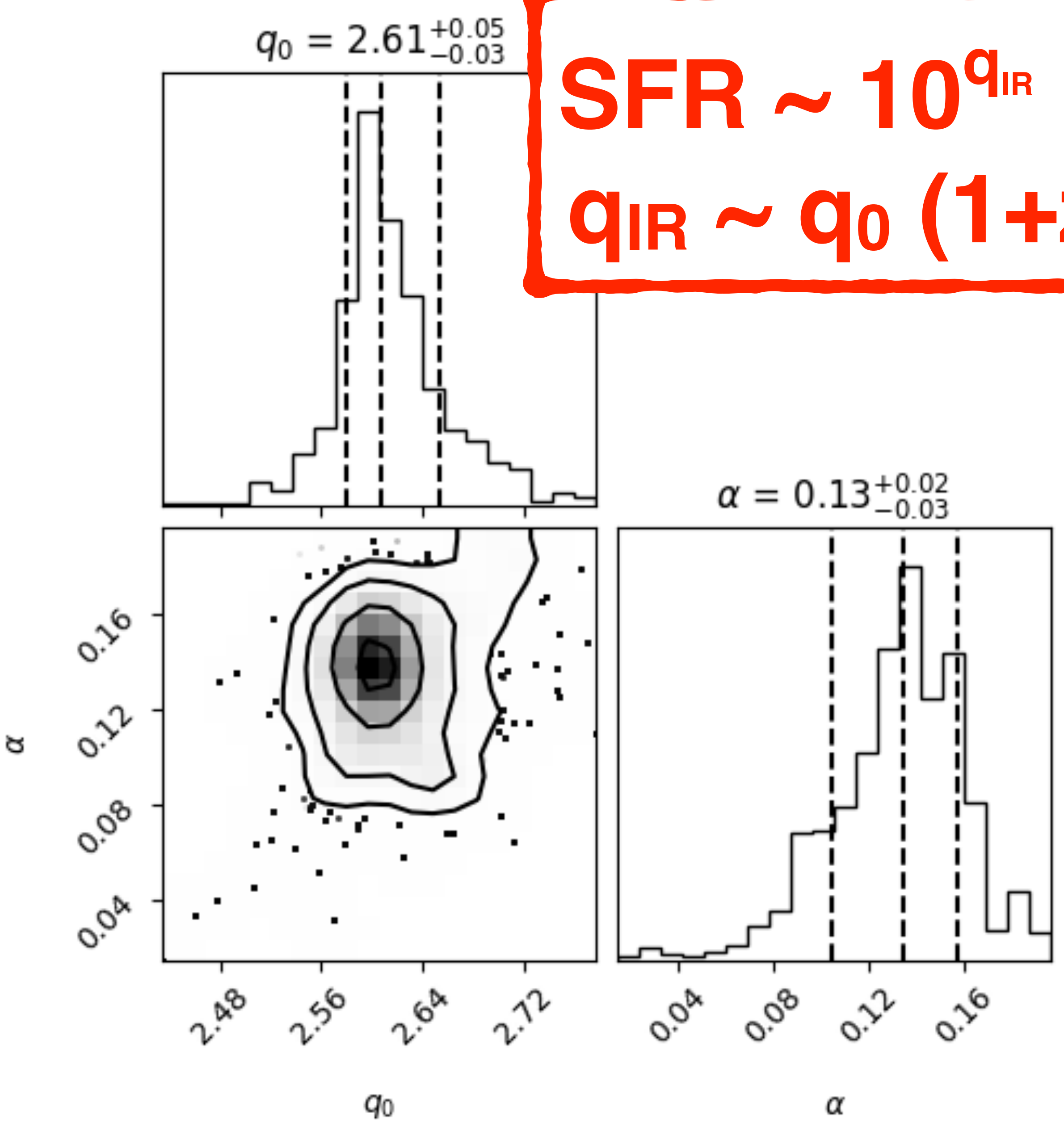


Leslie & Sargent (in prep.)

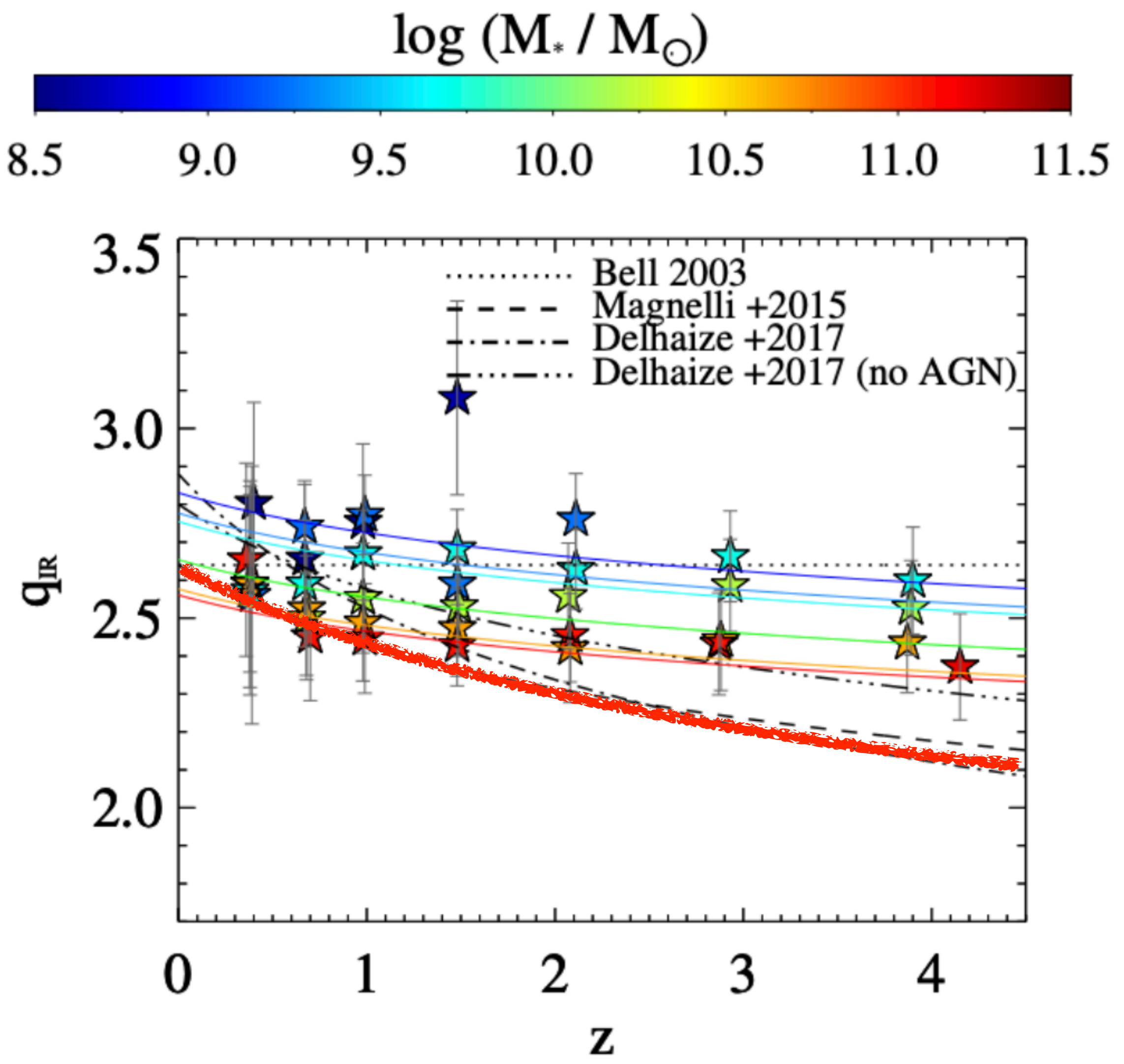
PREDICTING RADIO LUMINOSITY FCT. EVOLUTION

Comparing different radio-SFR calibration recipes and their evolution

$$\mathrm{SFR} \sim 10^{q_{IR}} L_{1.4}$$
$$q_{IR} \sim q_0 \, (1+z)^{-\alpha}$$



Leslie & Sargent (in prep.)



Delvecchio et al. (2021)

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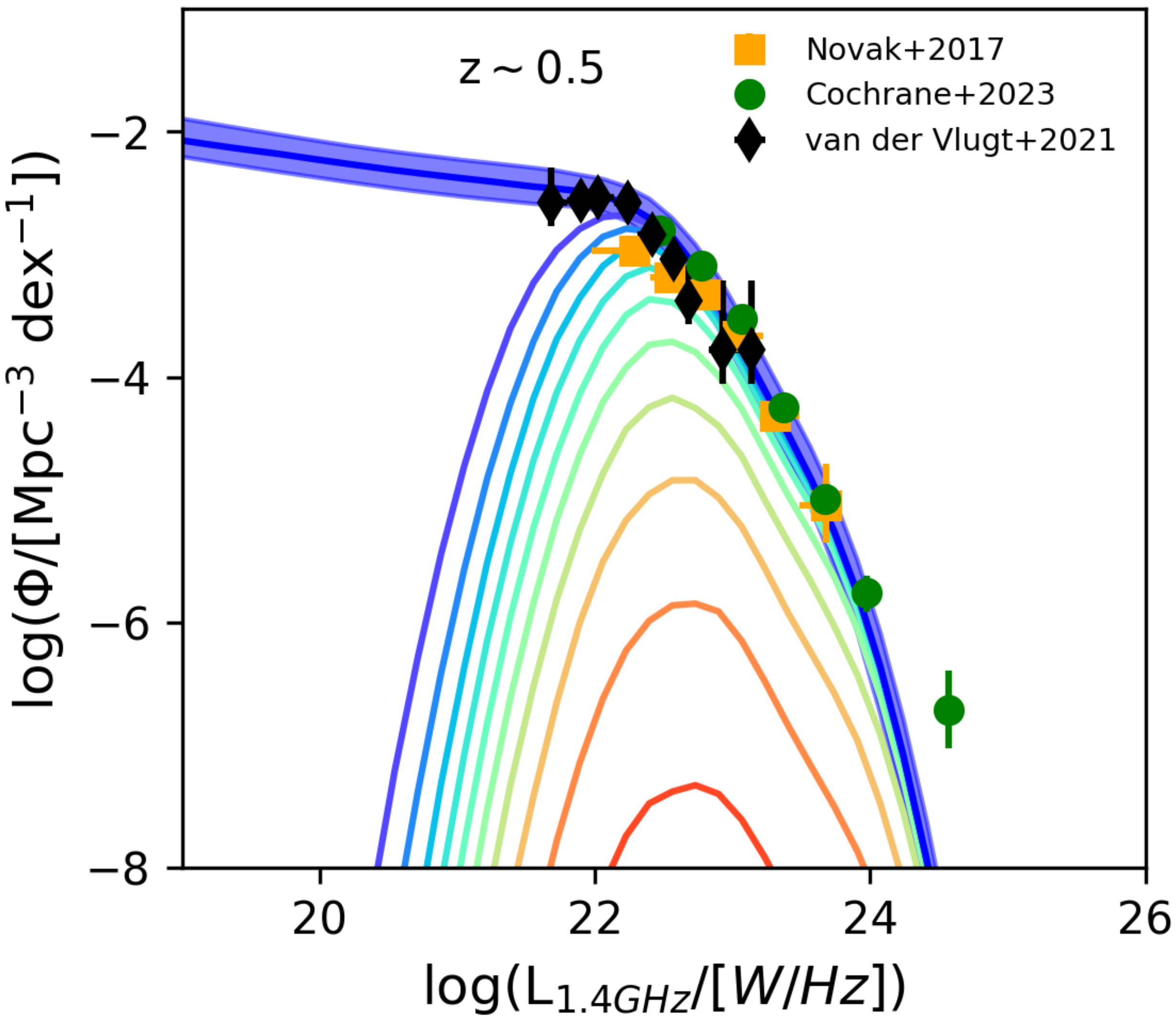
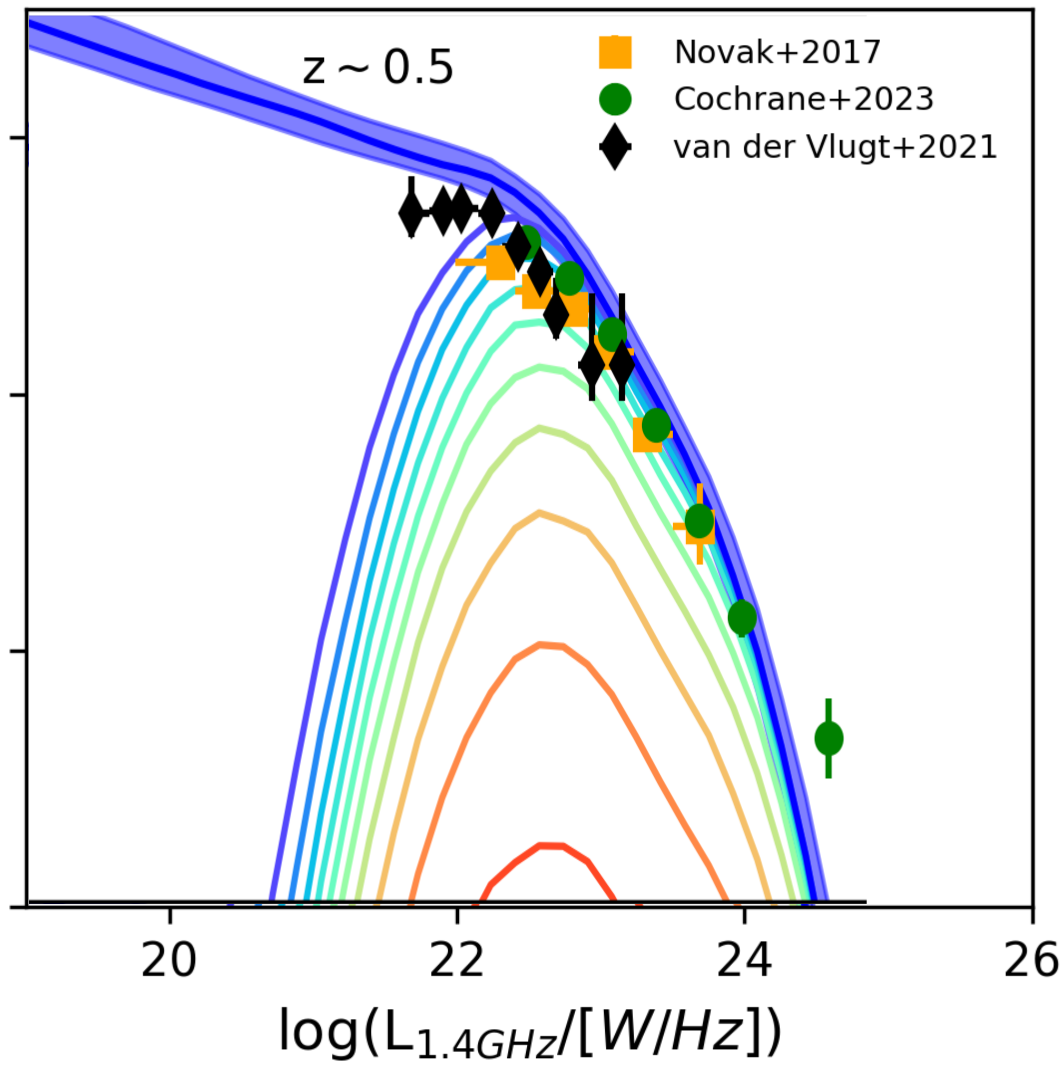
Comparing different radio-SFR calibration recipes and their evolution

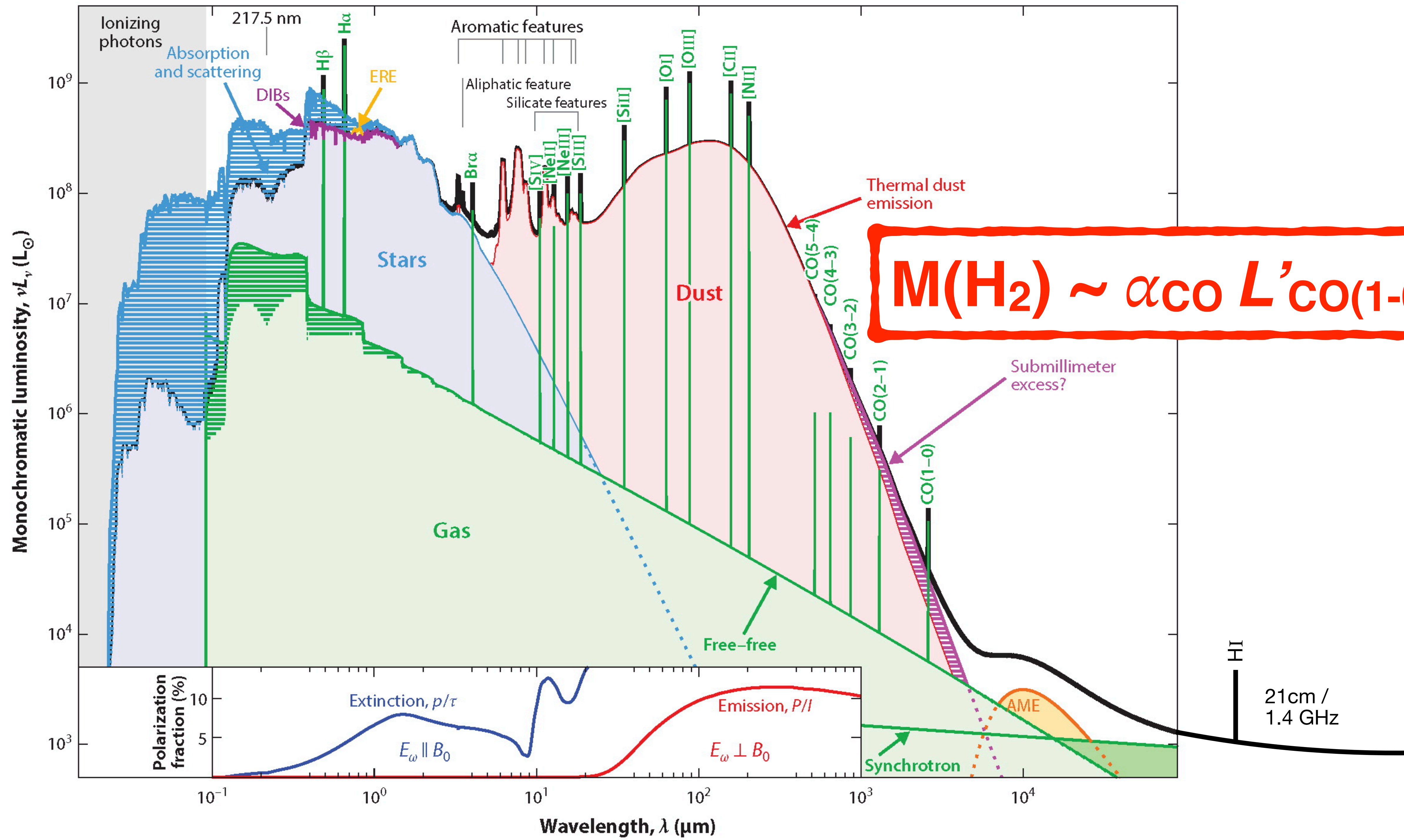




Leslie & Sargent (in prep.)

PART 2: MOLECULAR GAS MASS MEASUREMENTS

Inferring the full molecular gas reservoir from the emission of a tracer



$$M(H_2) \sim \alpha_{CO}\, L'_{CO(1\text{-}0)}$$

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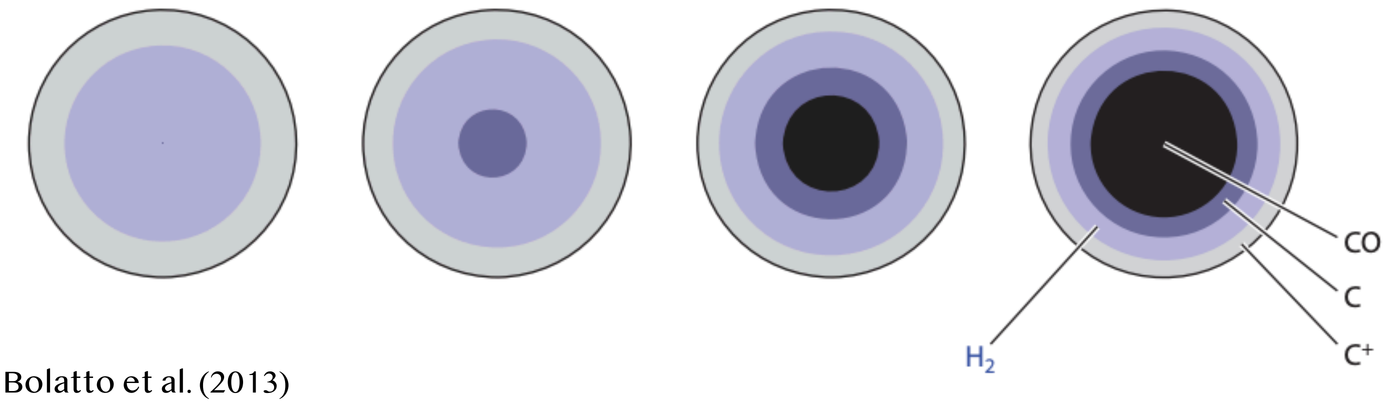
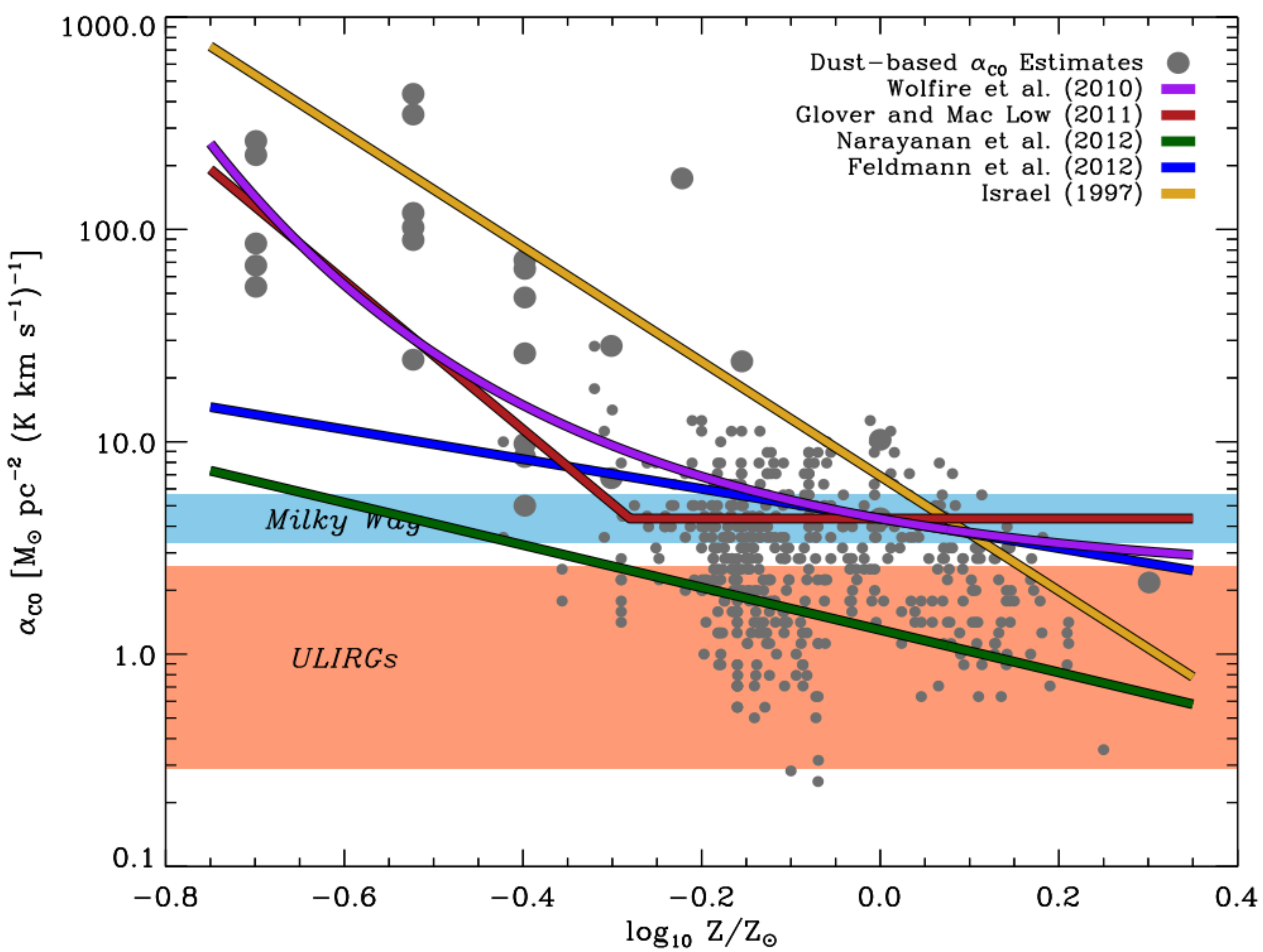
THE CO-TO-H_2 CONVERSION FACTOR

Strong variations with metal-enrichment of the interstellar gas



Bolatto et al. (2013)



$$M(H_2) \sim \alpha_{CO}\, L'_{CO(1\text{-}0)}$$

$$\alpha_{CO} \sim (Z/Z_\odot)^{-\beta}$$

In the absence of dust (and associated dust shielding) photodissociation of CO happens more readily. The tracer becomes hard to detect.

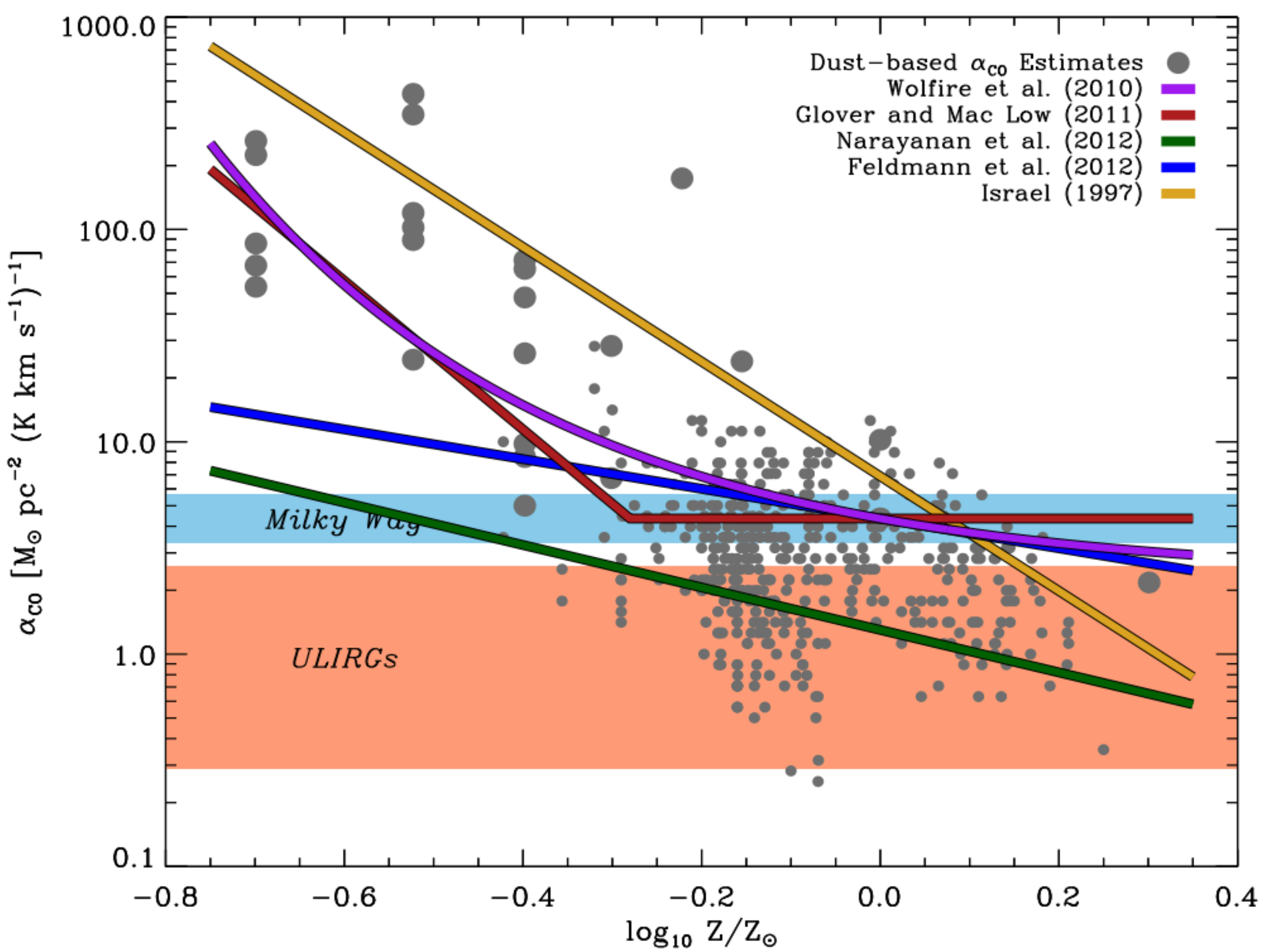
METALLICITY-DEPENDENCE OF α_{CO}

Constraints from z~0 CO luminosity function matching

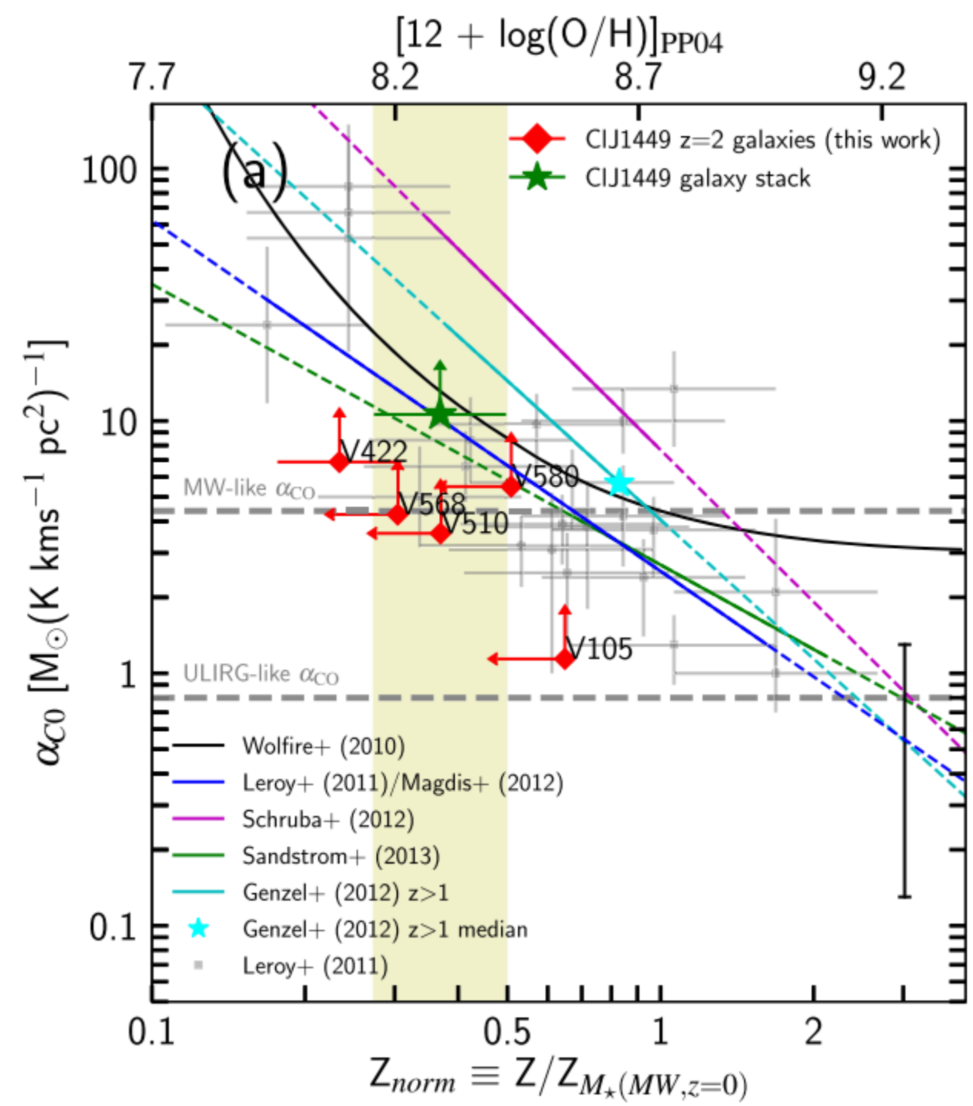
$$M(H_2) \sim \alpha_{CO} \, L'_{CO(1\text{-}0)}$$

$$\alpha_{CO} \sim (Z/Z_\odot)^{-\beta}$$

Understanding the aCO vs. Z relation is important in view of lower metal content in high-z galaxies… (e.g., here at z~2):



Bolatto et al. (2013)



Coogan, Sargent et al. (2019)

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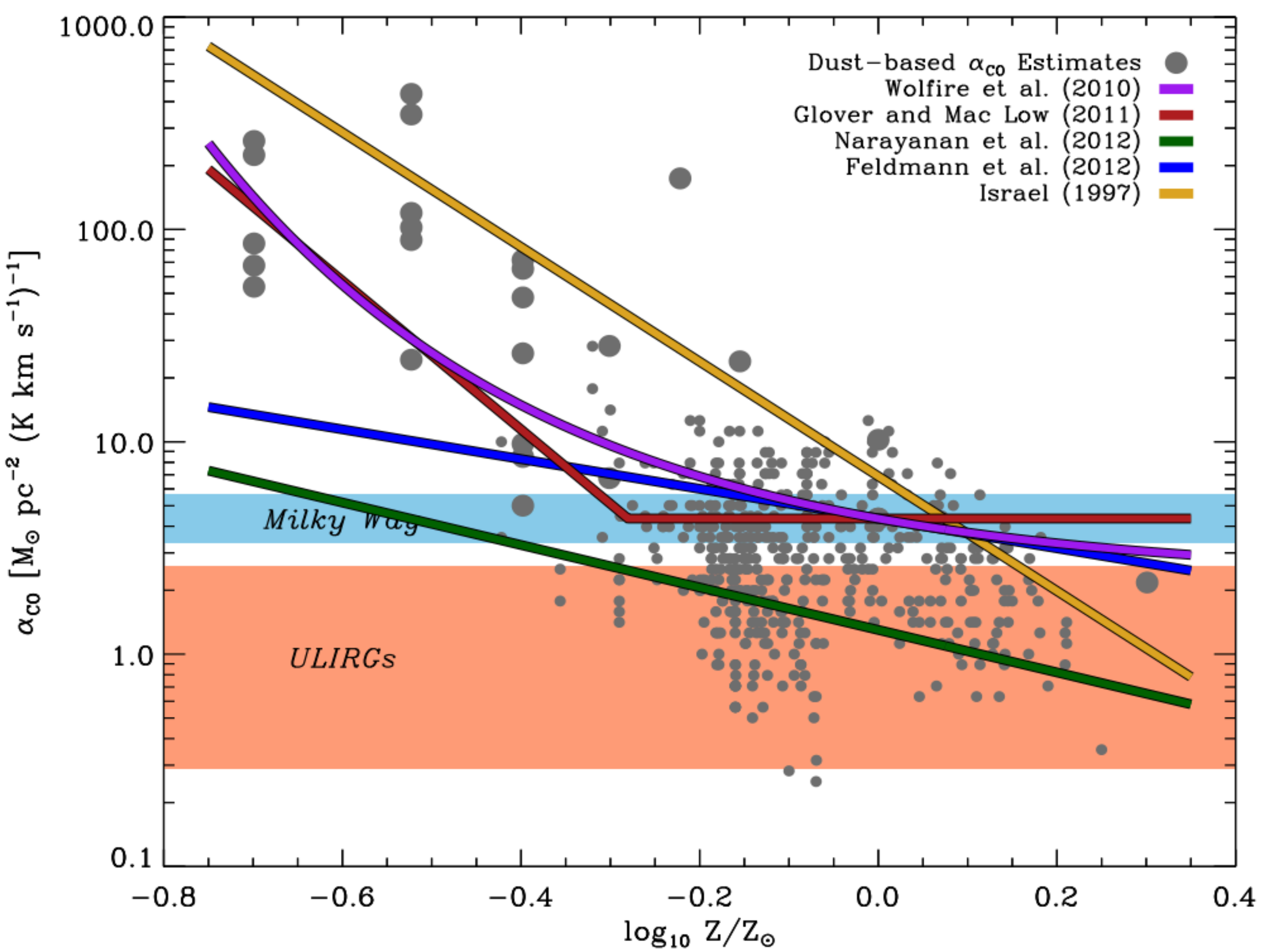
$$\alpha_{CO} \sim (Z/Z_{\odot})^{-\beta}$$



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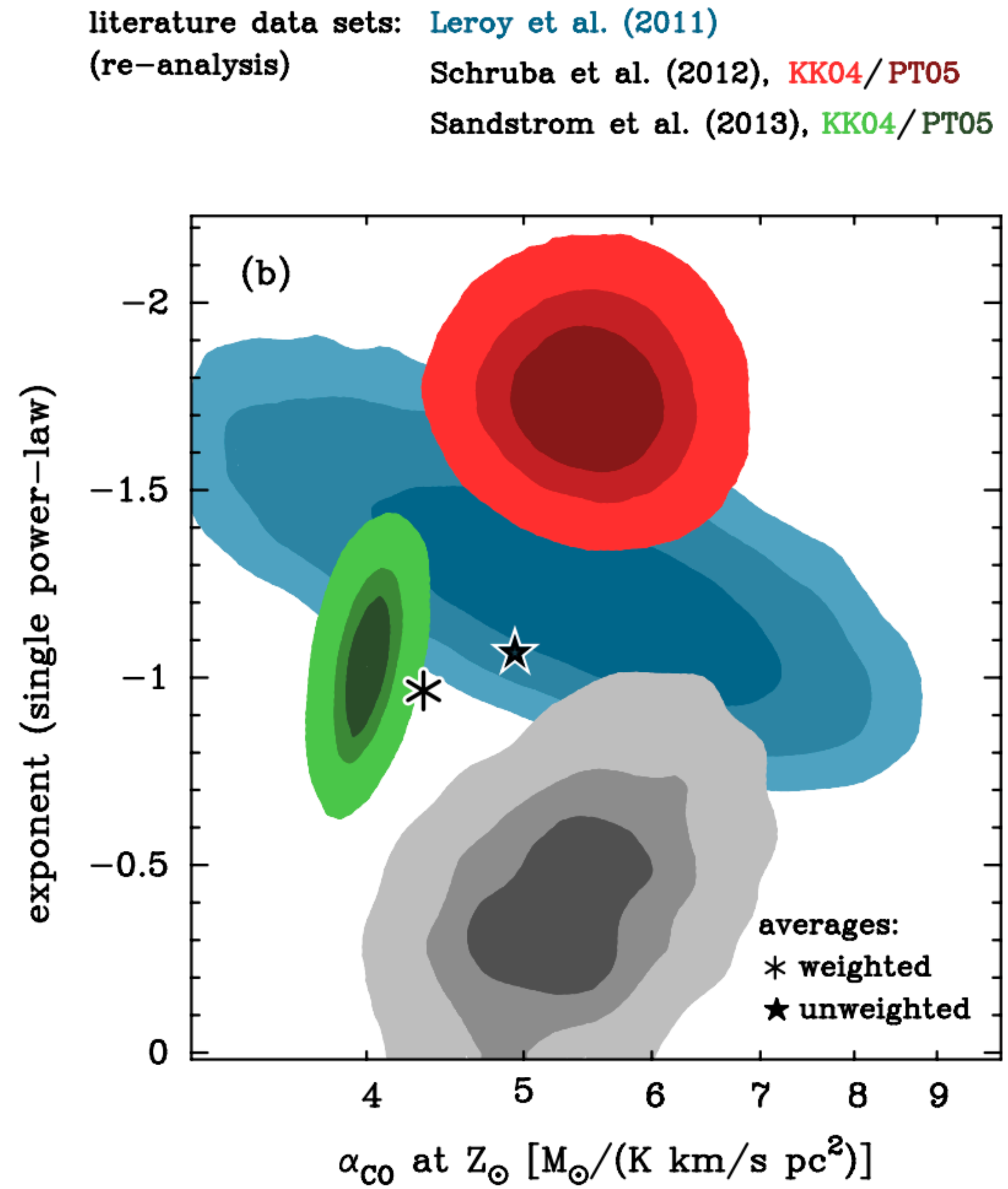

Sargent et al. (in prep.)

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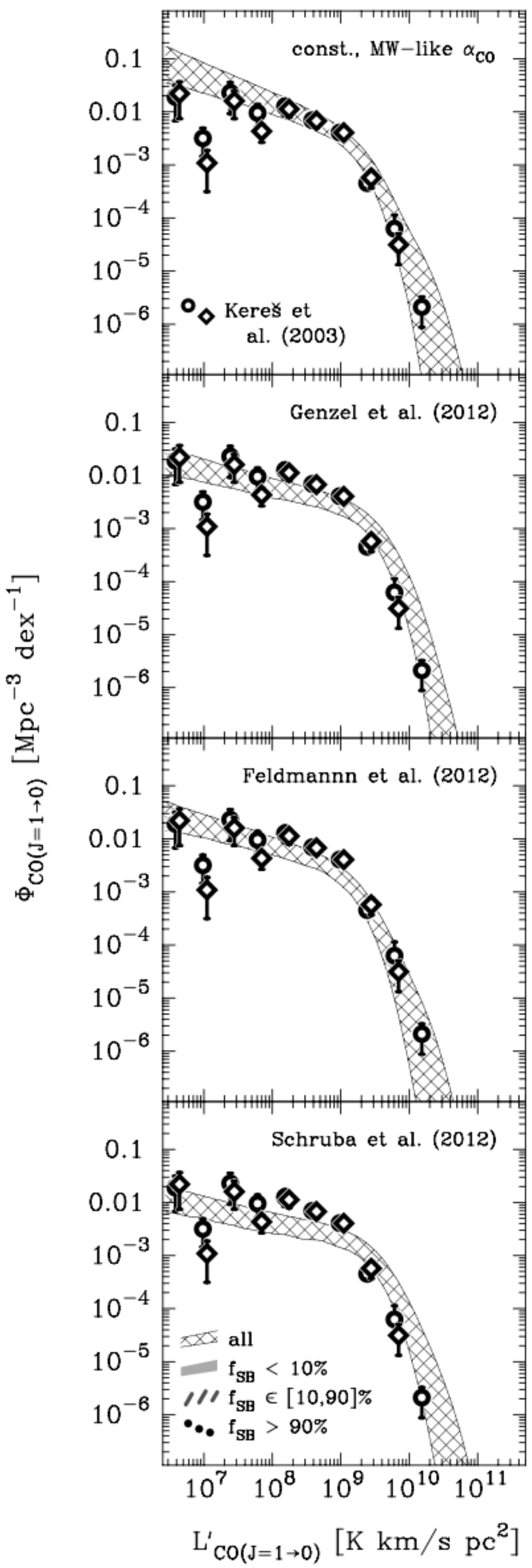

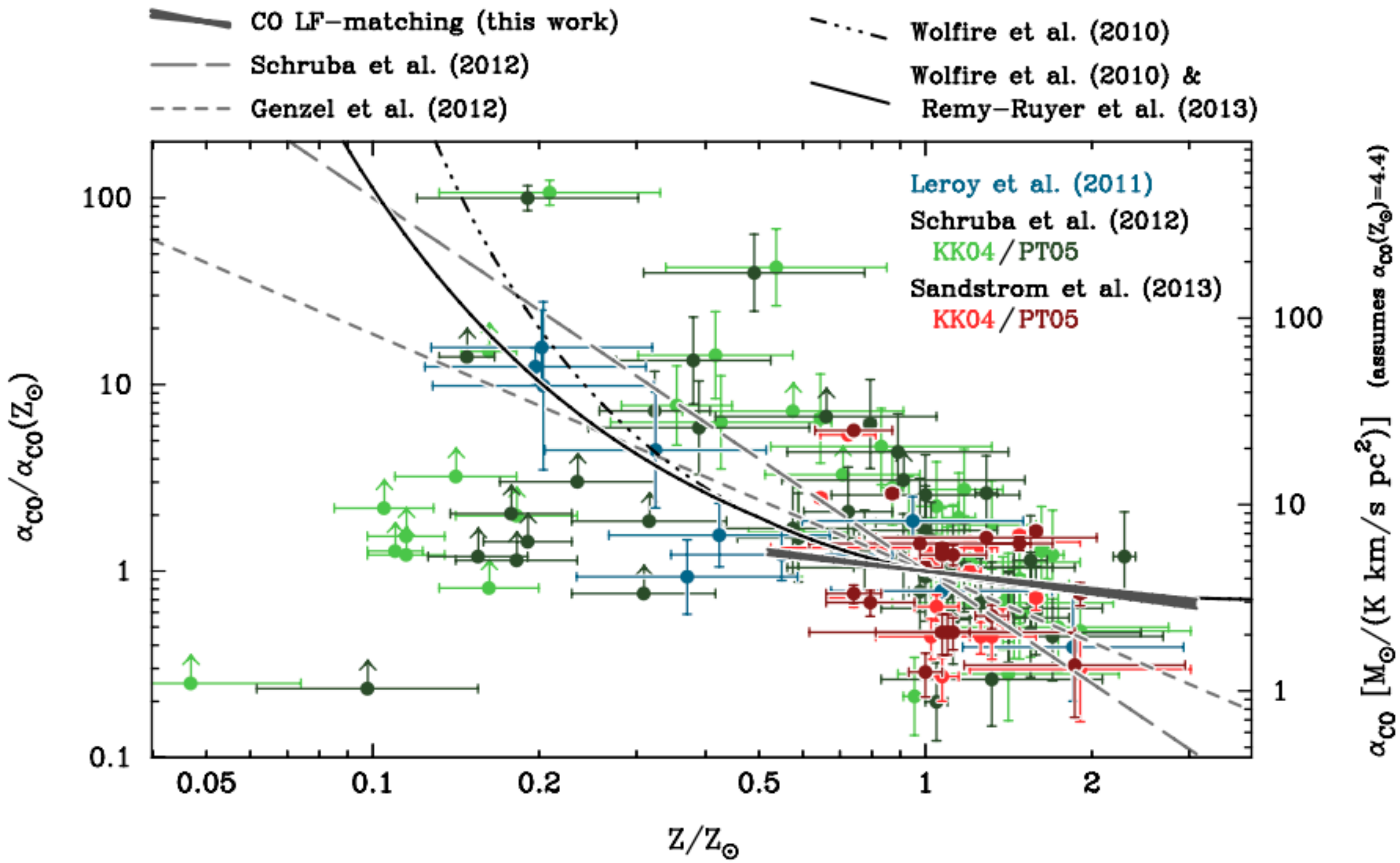

Sargent et al. (in prep.)

Consistent with Milky-Way like α_{CO} - and slow variations of α_{CO} - in the solar metallicity regime.

(Modelling ingredients used: Galaxy stellar mass function; SFR-M* distribution; Schmidt-Kennicutt relation; metallicity-dependent CO-to-H2 conversion factor; z~0 CO LF.)

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