NEOGAL

# Modelling SFR-M* and M*-Z relations to be observed at high-redshift with JWST

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# Motivation

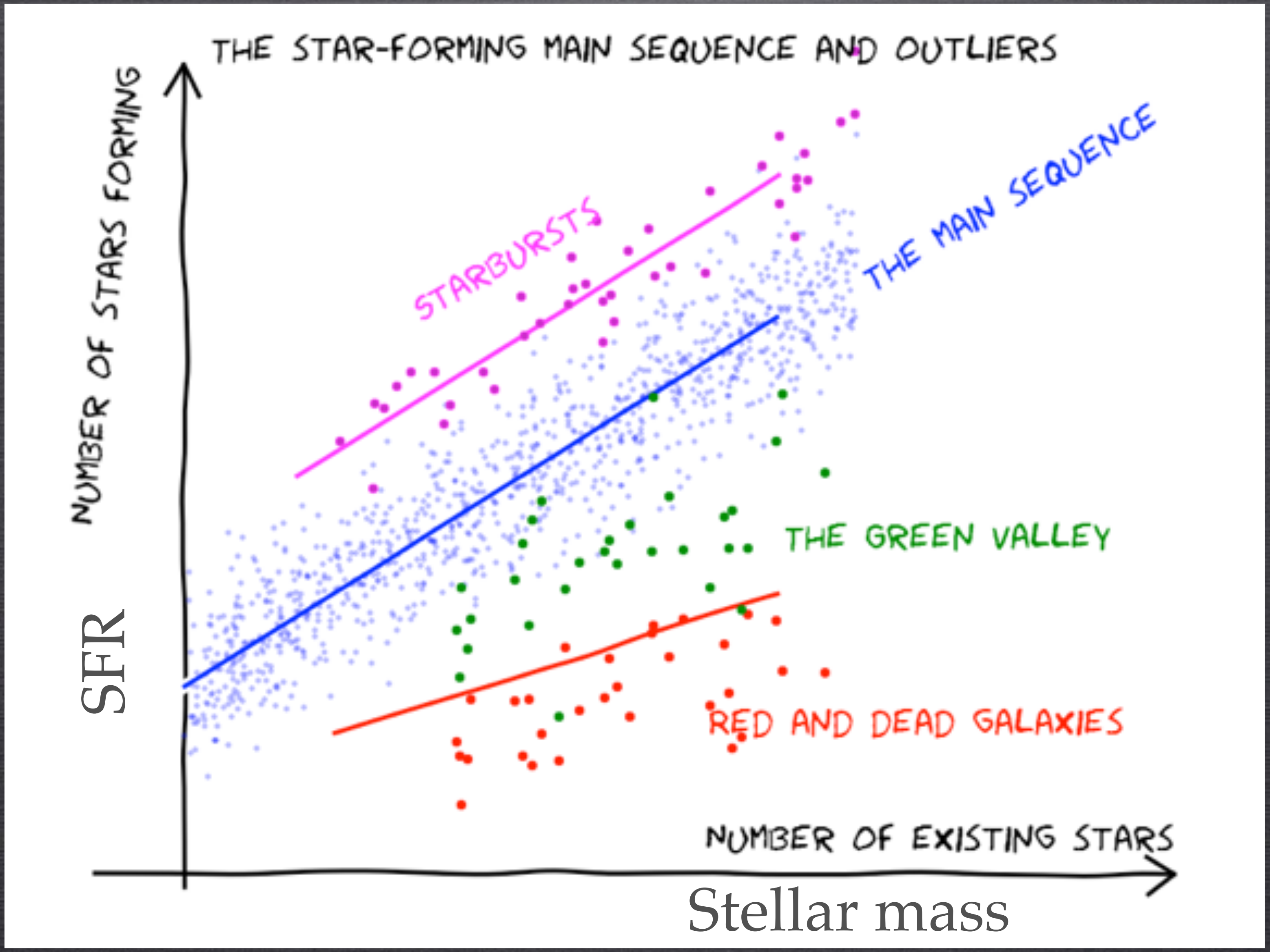


Image credit: Harry Ferguson
http://candels-collaboration.blogspot.fr/2013/02/star-formation-in-mountains.html

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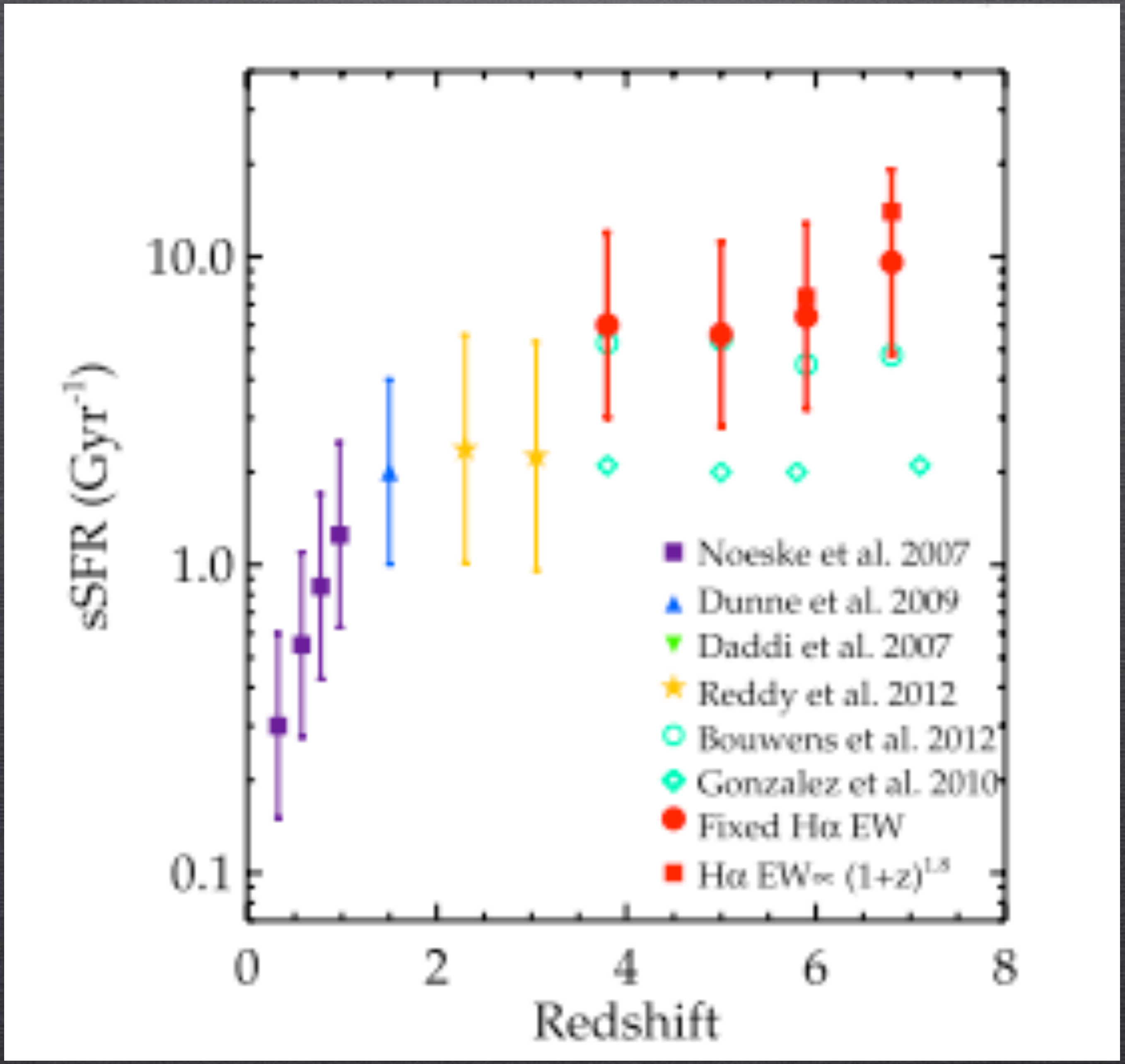


Stark+ 2013

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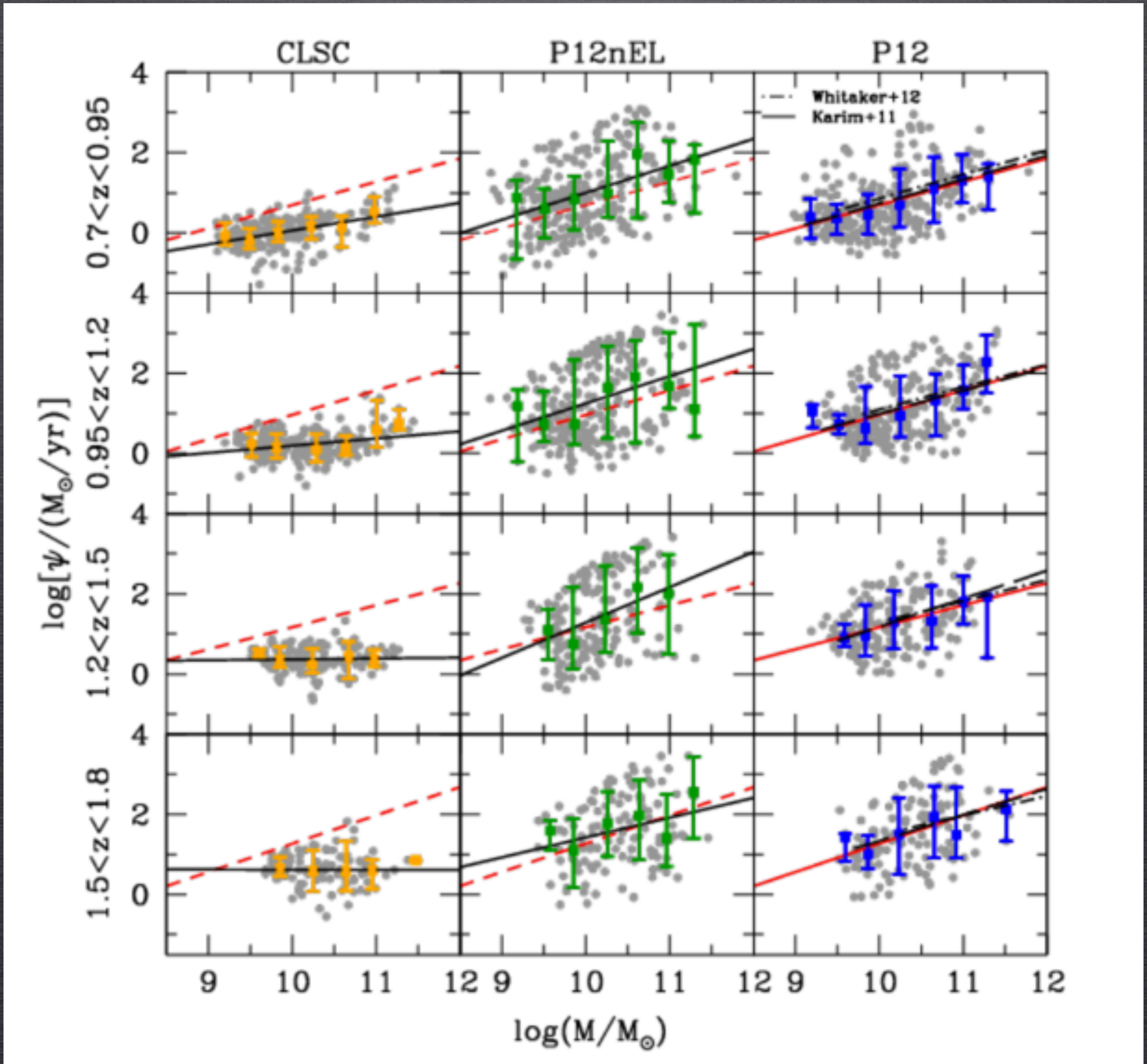
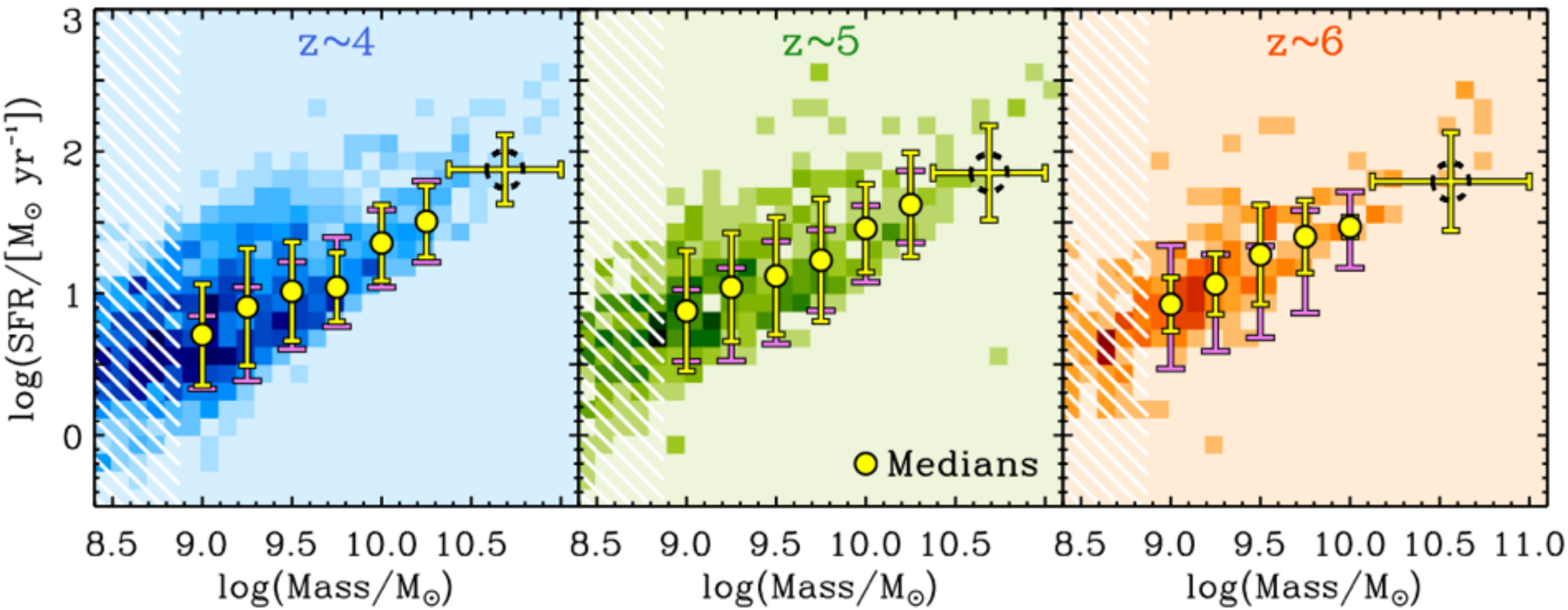


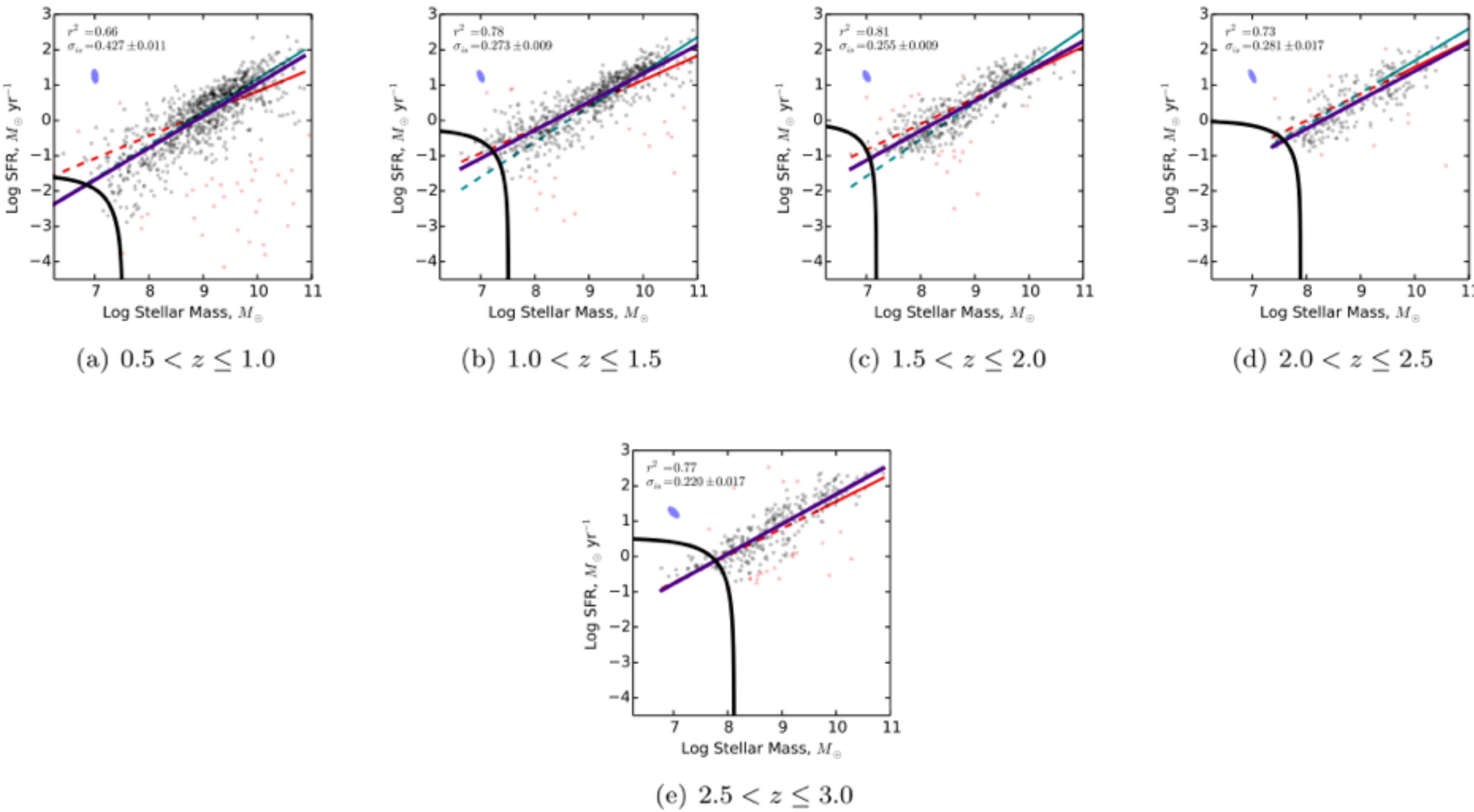

Pacifici+ 2014

# Previous work




Salmon+ 2015

# Previous work

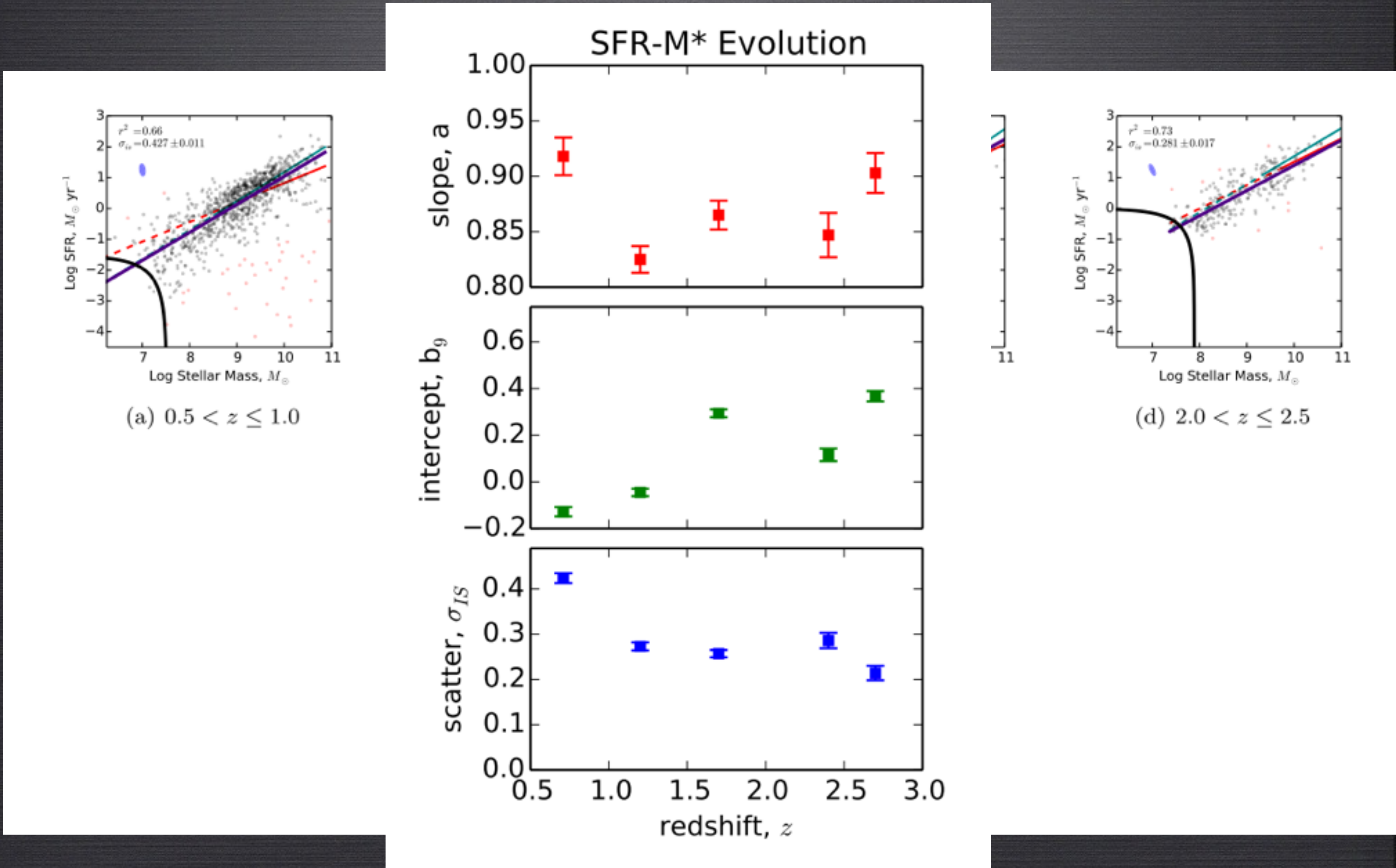



(a) $0.5 < z \leq 1.0$ (b) $1.0 < z \leq 1.5$ (c) $1.5 < z \leq 2.0$ (d) $2.0 < z \leq 2.5$

(e) $2.5 < z \leq 3.0$

Kurczynski+ 2016

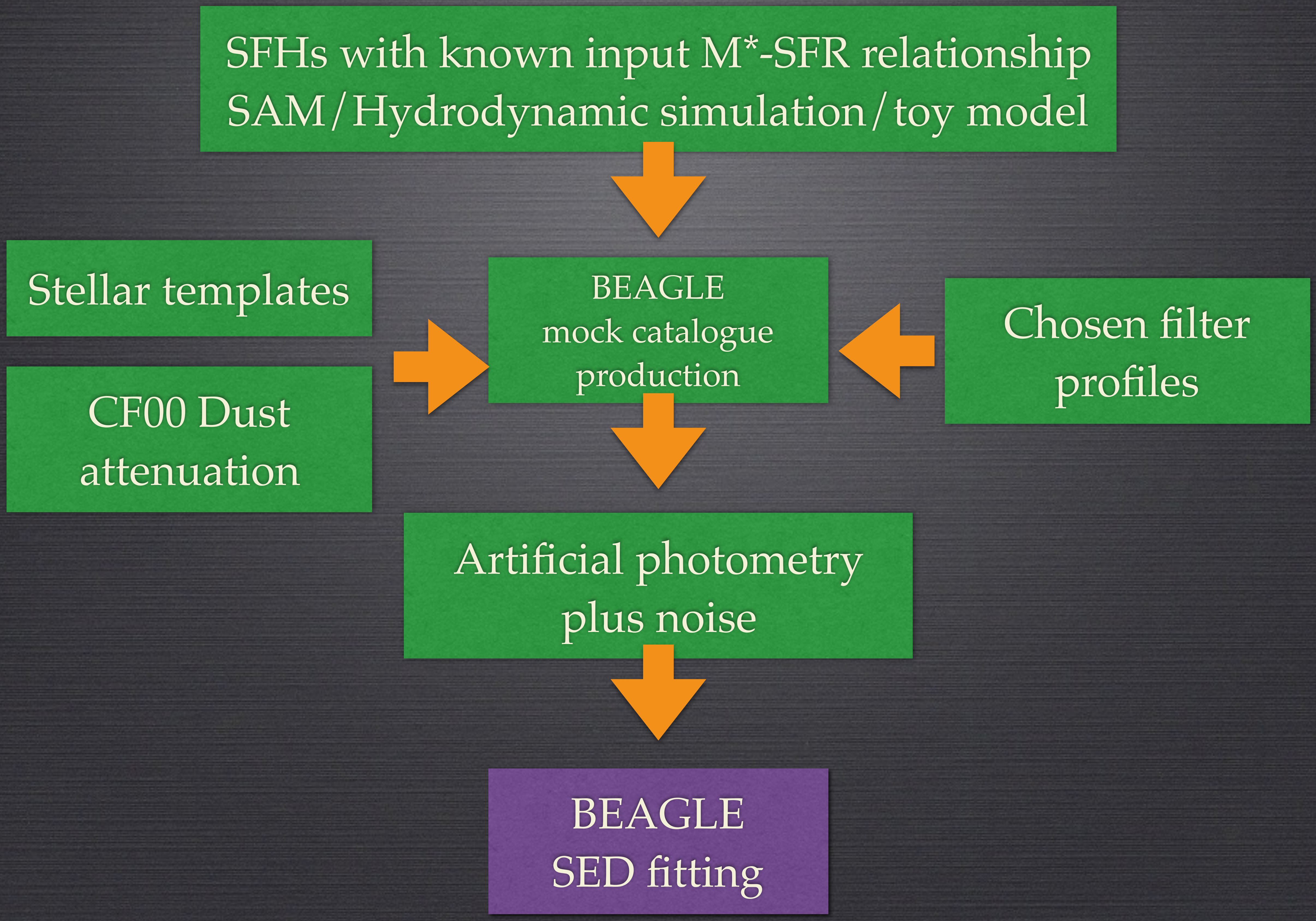
# Previous work




Kurczynski+ 2016

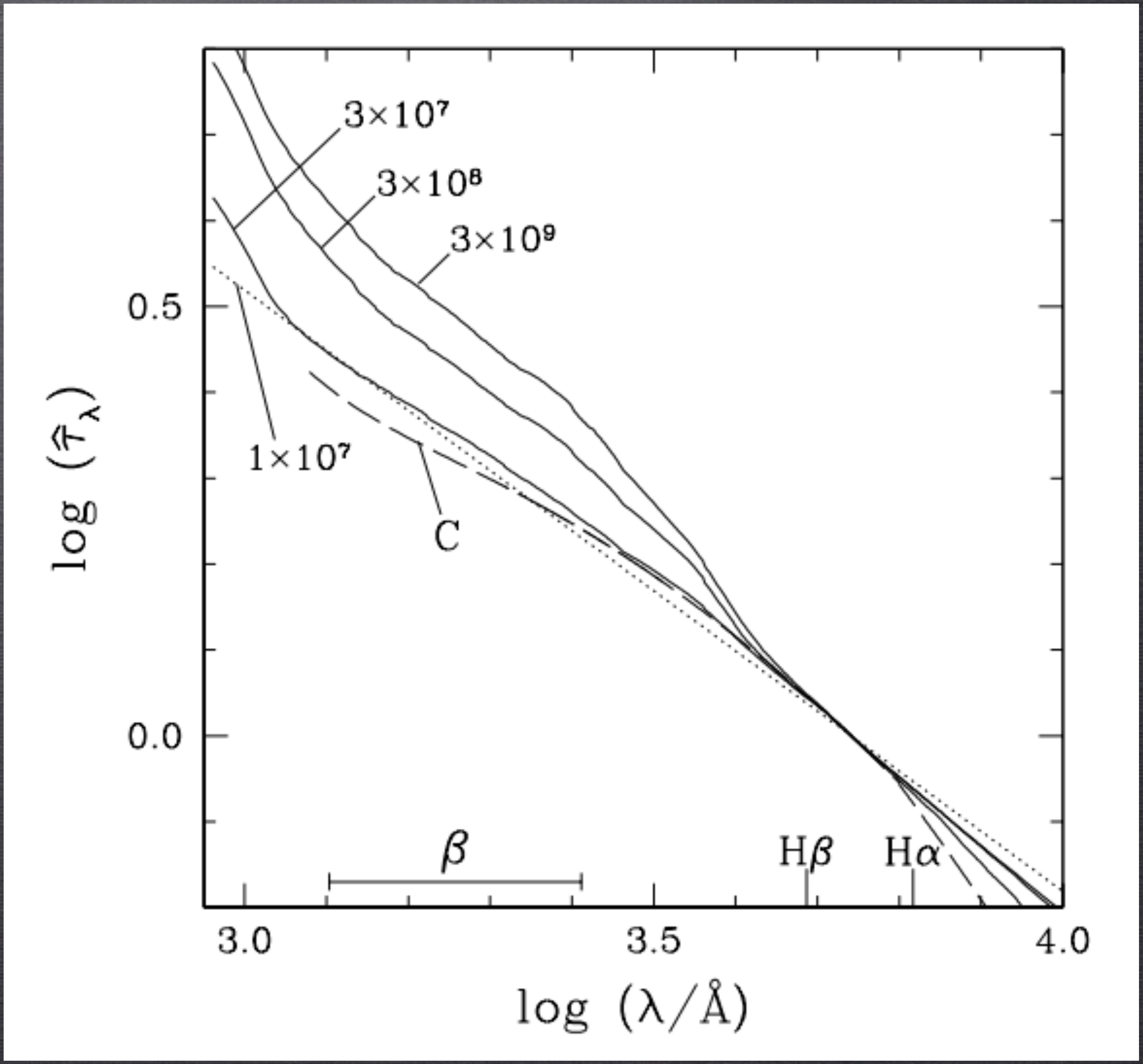
# Question

**How well can recover the intrinsic scatter from simulated, self-consistent star formation and chemical enrichment histories?**


SFHs with known input M*-SFR relationship
SAM/Hydrodynamic simulation/toy model
Stellar templates
CF00 Dust attenuation
BEAGLE
mock catalogue production
Chosen filter profiles
Artificial photometry plus noise
BEAGLE
SED fitting

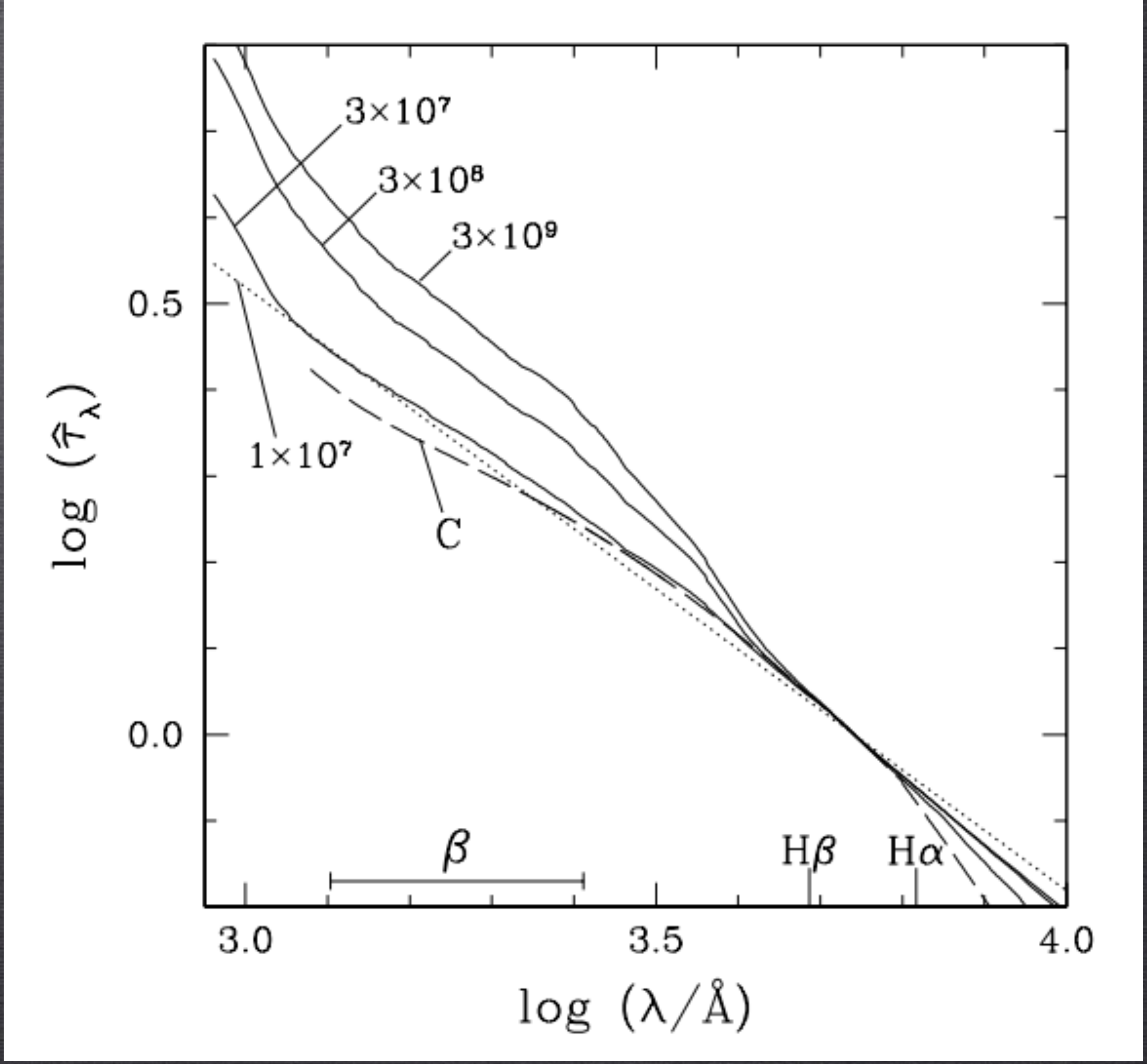
CF00 Dust attenuation

# CF00 Dust attenuation



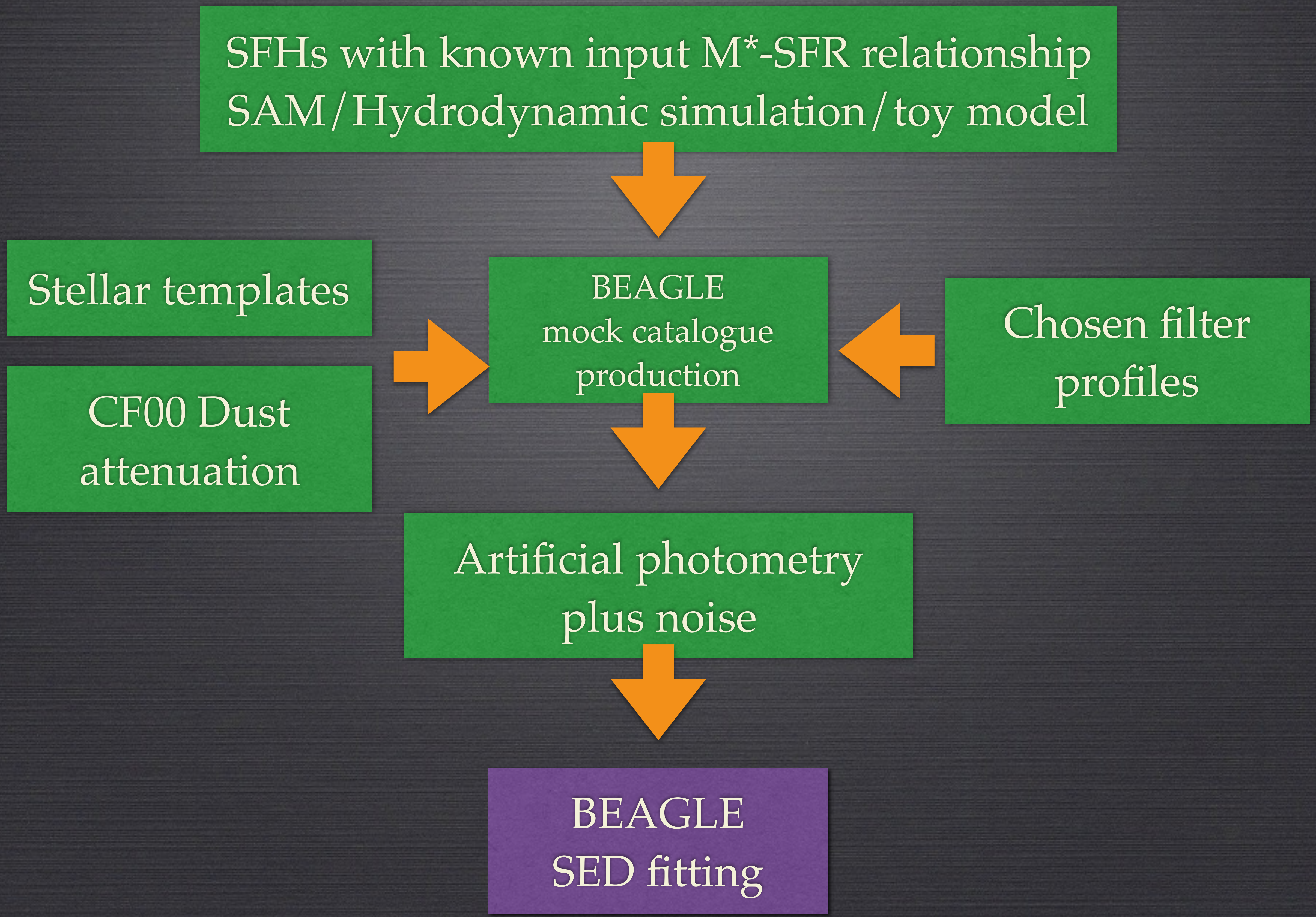

Charlot & Fall 2000

# CF00 Dust attenuation




See Brett Salmon's poster

Charlot & Fall 2000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BEAGLE
mock catalogue
production

BEAGLE
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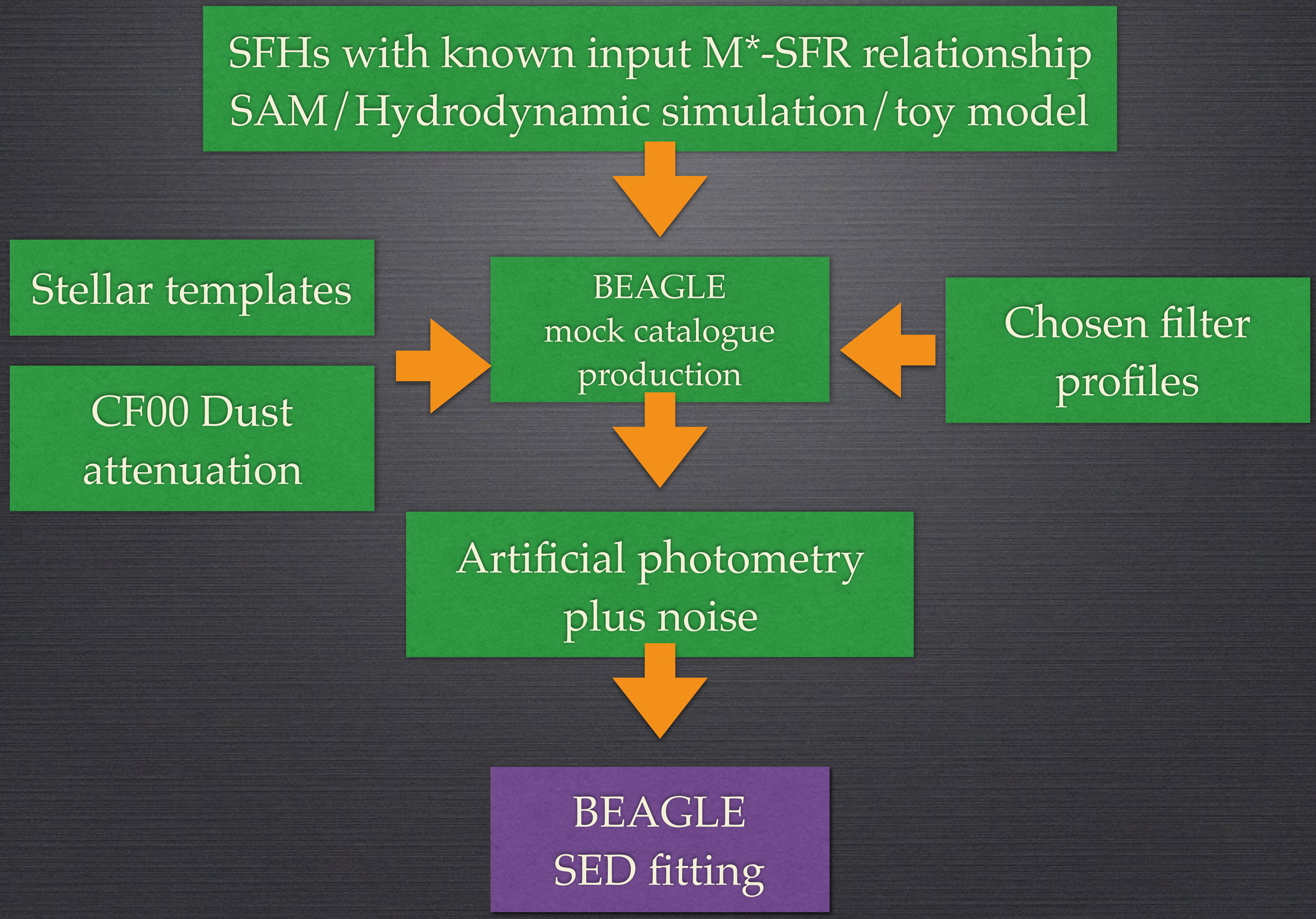
production

- **Includes self-consistent nebular emission based on wide grid of CLOUDY models - see Julia Gutkin’s poster!**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BEAGLE

SED fitting

BEAGLE
SED fitting

**At this stage we get to test impact of different fitting parameters on derivation of individual object physical parameters, as well as the M*-SFR relation as a whole.**

**Fitting parameters include:**

- **Sampling of SED (different filter sets)**
- **Depth of the data**
- **Dust prescriptions**
- **SFH prescriptions**

# MEASURING THE M*-SFR RELATION

## NOTATION

For galaxy $i$:

- $\mathrm{SFR}_i$ is $\log_{10}(\mathrm{SFR}/M_\odot \mathrm{yr}^{-1})$
- $\mathrm{M}_i$ is $\log_{10}(\mathrm{M}_\star/\mathrm{M}_\odot)$
- $\mathbf{\Theta}_i$ are the remaining parameters (e.g., metallicity, $z$)
- $\mathbf{y}_i$ are "observed" photometry, with known errors $\mathbf{\Sigma}_i$
- $\mu_i = \mathbf{G}(\mathrm{SFR}_i, \mathrm{M}_i, \mathbf{\Theta}_i)$ is predicted photometry from forward-model $\mathbf{G}$

# measuring the M*-SFR relation

## Multilevel model

*First Level*:

$$\mathbf{y}_i \mid \mathrm{SFR}_i, \mathrm{M}_i, \mathbf{\Theta}_i \sim N(\mu_i, \mathbf{\Sigma}_i)$$

*Second Level*:

$$\mathrm{SFR}_i | \mathrm{M}_i \sim \beta_0 + \beta_1 \mathrm{M}_i + N(0, \sigma)$$

$$\mathrm{M}_i \sim \mathrm{Uniform}(a, b)$$

# MEASURING THE M*-SFR RELATION

## POSTERIOR DISTRIBUTION

$$
\begin{aligned}
&P(\mathbf{SFR}, \mathbf{M}, \boldsymbol{\Theta}, \sigma, \beta_0, \beta_1 \mid \mathbf{Y}, \boldsymbol{\Sigma}) \\
&\qquad \propto P(\sigma) P(\beta_0, \beta_1) \prod_{i=1}^{\mathrm{N}} P(\mathbf{y}_i \mid \mathrm{SFR}_i, \mathrm{M}_i, \boldsymbol{\Theta}_i, \boldsymbol{\Sigma}_i) \\
&\qquad\qquad \times \prod_{i=1}^{\mathrm{N}} P(\mathrm{SFR}_i \mid \mathrm{M}_i, \beta_0, \beta_1, \sigma) P(\mathrm{M}_i) P(\boldsymbol{\Theta}_i),
\end{aligned}
$$

where $\mathbf{SFR} = (\mathrm{SFR}_1, \ldots, \mathrm{SFR}_N), \mathbf{M} = (\mathrm{M}_1, \ldots, \mathrm{M}_N)$, $\boldsymbol{\Theta} = (\boldsymbol{\Theta}_1, \ldots, \boldsymbol{\Theta}_N), \mathbf{Y} = (\mathbf{y}_1, \ldots, \mathbf{y}_N)$, $\boldsymbol{\Sigma} = (\boldsymbol{\Sigma}_1, \ldots, \boldsymbol{\Sigma}_N)$, and $N$ is the number of galaxies.

# measuring the M*-SFR relation

## Posterior Distribution

$$P(\mathbf{SFR}, \mathbf{M}, \mathbf{\Theta}, \sigma, \beta_0, \beta_1 \mid \mathbf{Y}, \mathbf{\Sigma})$$

Likelihood Function

$$\propto P(\sigma)P(\beta_0, \beta_1) \boxed{\prod_{i=1}^{\mathrm{N}} P(\mathbf{y}_i \mid \mathrm{SFR}_i, \mathrm{M}_i, \mathbf{\Theta}_i, \mathbf{\Sigma}_i)}$$

$$\times \prod_{i=1}^{\mathrm{N}} P(\mathrm{SFR}_i \mid \mathrm{M}_i, \beta_0, \beta_1, \sigma) P(\mathrm{M}_i) P(\mathbf{\Theta}_i),$$

where $\mathbf{SFR} = (\mathrm{SFR}_1, \ldots, \mathrm{SFR}_N), \mathbf{M} = (\mathrm{M}_1, \ldots, \mathrm{M}_N)$, $\mathbf{\Theta} = (\mathbf{\Theta}_1, \ldots, \mathbf{\Theta}_N), \mathbf{Y} = (\mathbf{y}_1, \ldots, \mathbf{y}_N)$, $\mathbf{\Sigma} = (\mathbf{\Sigma}_1, \ldots, \mathbf{\Sigma}_N)$, and $N$ is the number of galaxies.

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Prior Distribution

$$\times \boxed{\prod_{i=1}^{\mathrm{N}} P(\mathrm{SFR}_i \mid \mathrm{M}_i, \beta_0, \beta_1, \sigma) P(\mathrm{M}_i) P(\mathbf{\Theta}_i)},$$

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# Measuring the M*-SFR relation

## Posterior Distribution

$$P(\mathbf{SFR}, \mathbf{M}, \mathbf{\Theta}, \sigma, \beta_0, \beta_1 \mid \mathbf{Y}, \mathbf{\Sigma})$$

Hyperprior — Likelihood Function

$$\propto \underbrace{P(\sigma)P(\beta_0, \beta_1)}_{\text{Hyperprior}} \underbrace{\prod_{i=1}^{N} P(\mathbf{y}_i \mid \mathrm{SFR}_i, \mathrm{M}_i, \mathbf{\Theta}_i, \mathbf{\Sigma}_i)}_{\text{Likelihood Function}}$$

Prior Distribution

$$\times \underbrace{\prod_{i=1}^{N} P(\mathrm{SFR}_i \mid \mathrm{M}_i, \beta_0, \beta_1, \sigma) P(\mathrm{M}_i) P(\mathbf{\Theta}_i)}_{\text{Prior Distribution}},$$

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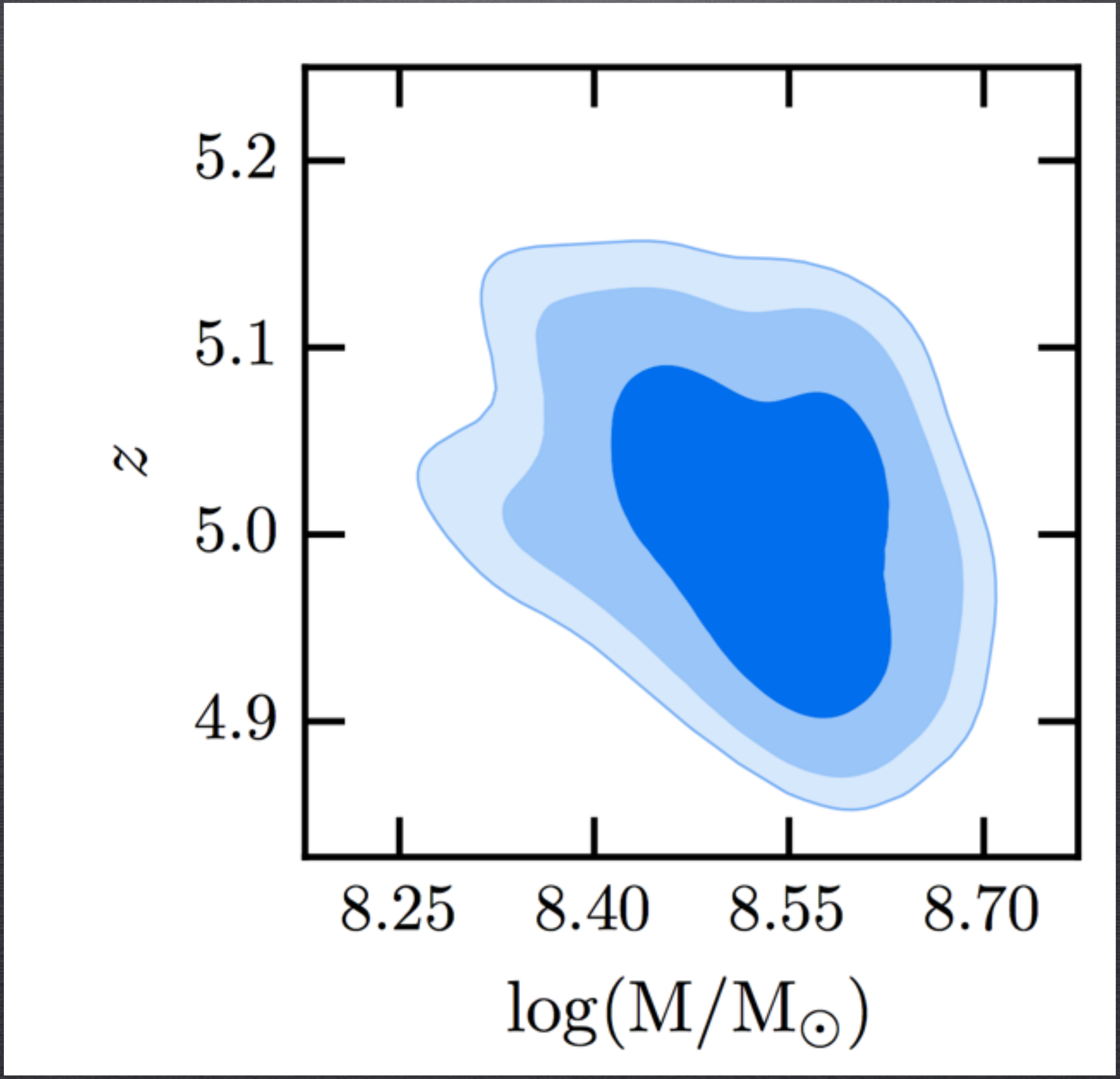
# MEASURING THE M*-SFR RELATION



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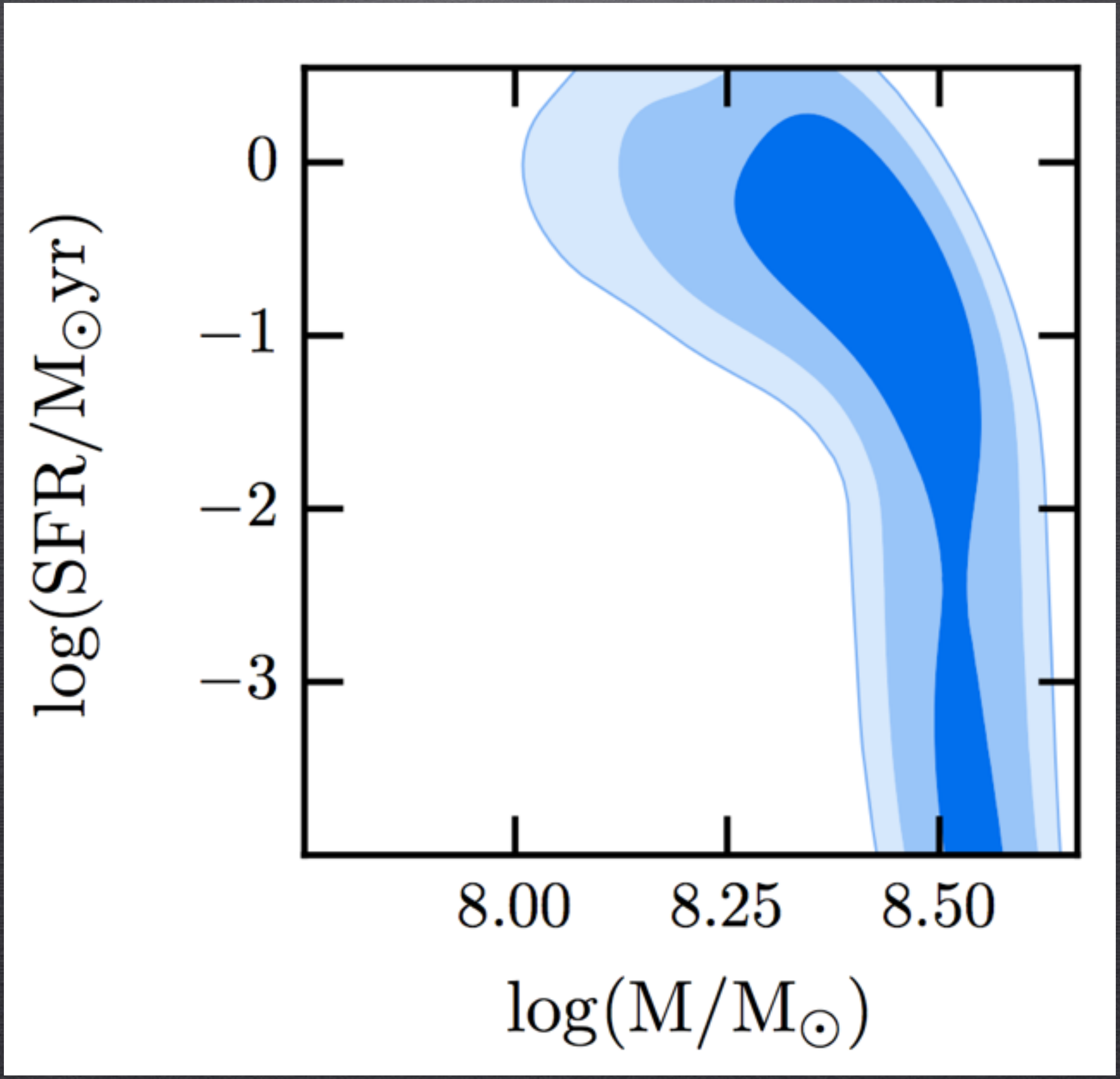

# measuring the M*-SFR relation

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# Test scenario

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**Input:**

**Constant SFHs drawn from M*-SFR relation with known parameters (intercept, slope and scatter).**

- No Dust
- Single metallicity
- Single Redshift
- Including nebular emission
- CANDELS Deep depths/filters + IRAC CH1 + CH2

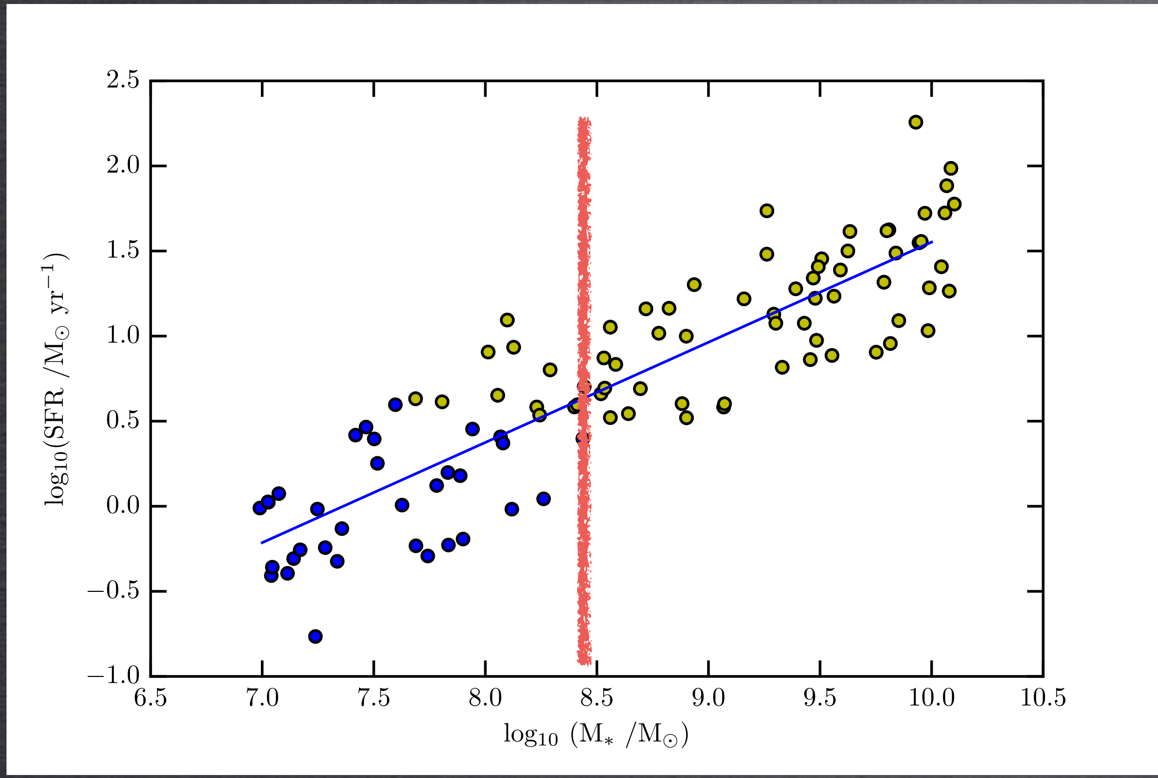
**SED Fitting:**

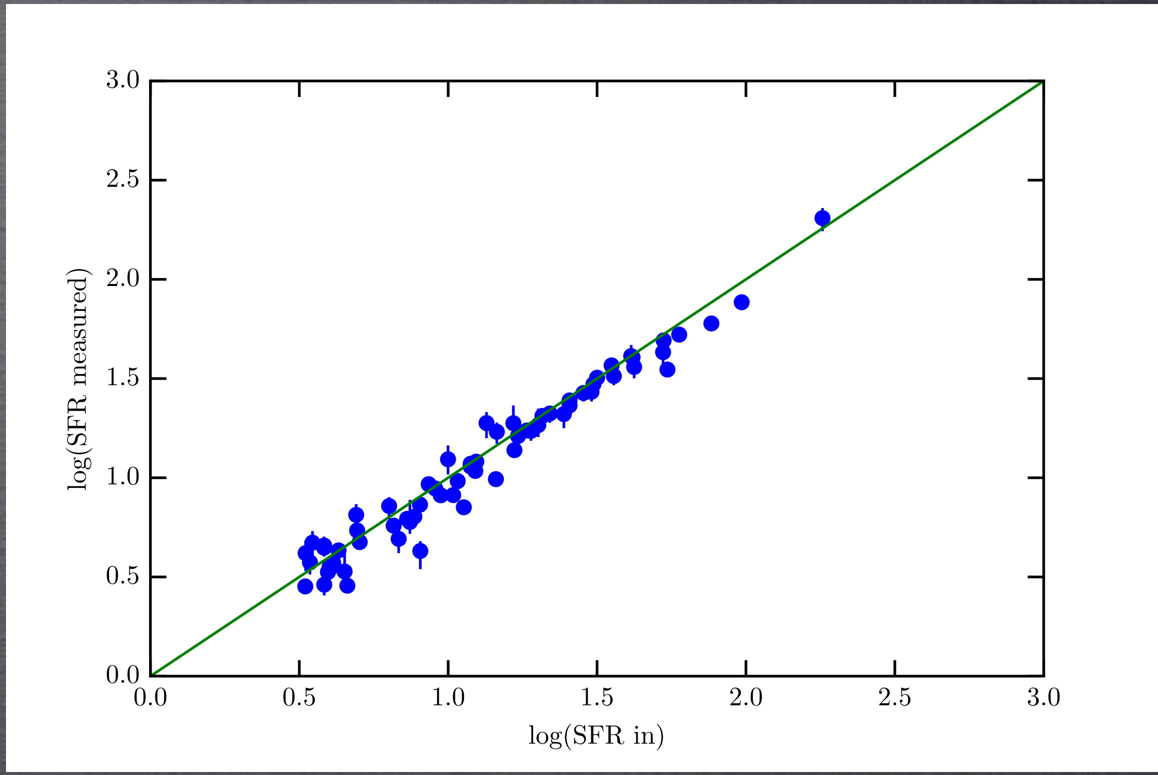
- Constant SFHs
- No Dust
- Redshift left free
- Metallicity left free

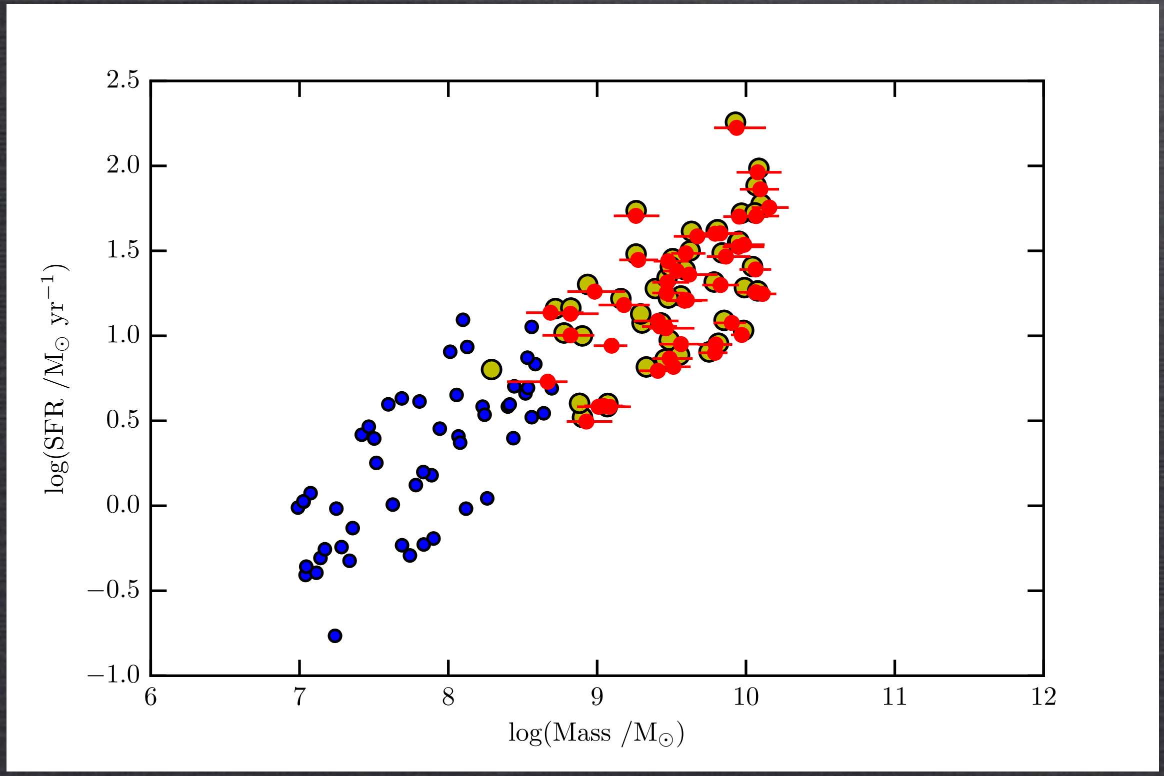
**Test:**

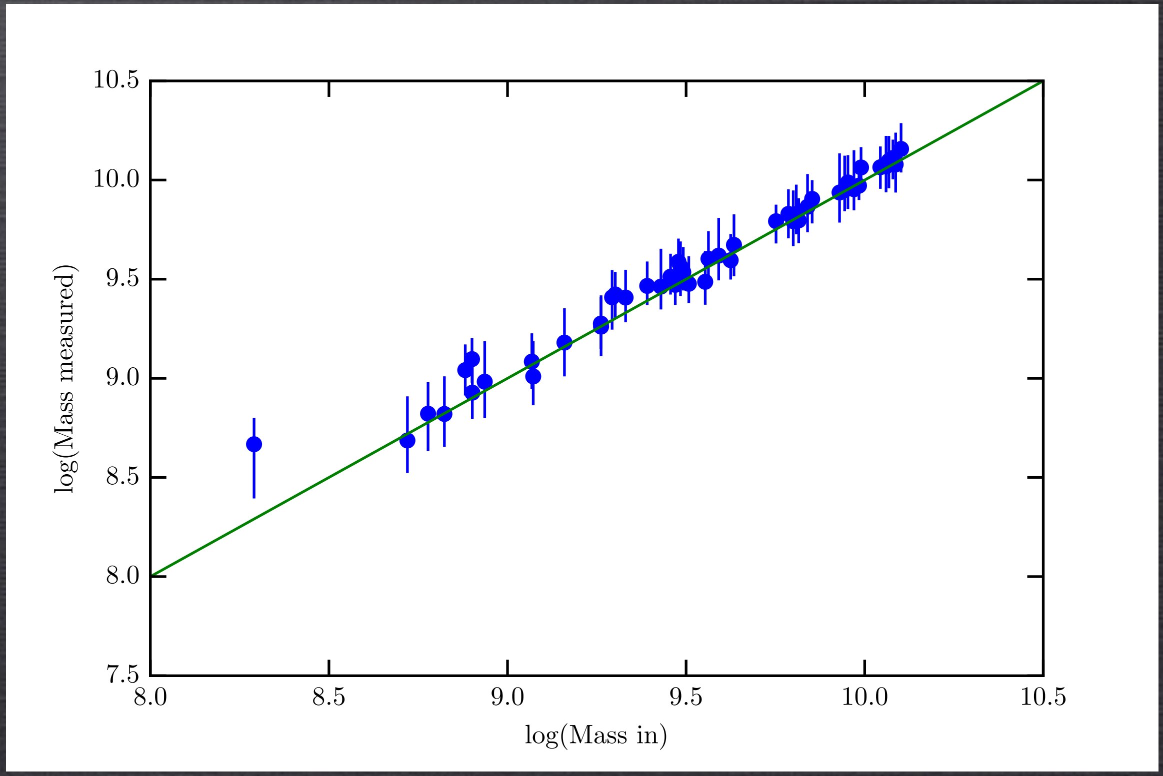
- Can we recover the input M*-SFR relation parameters?

# Test scenario



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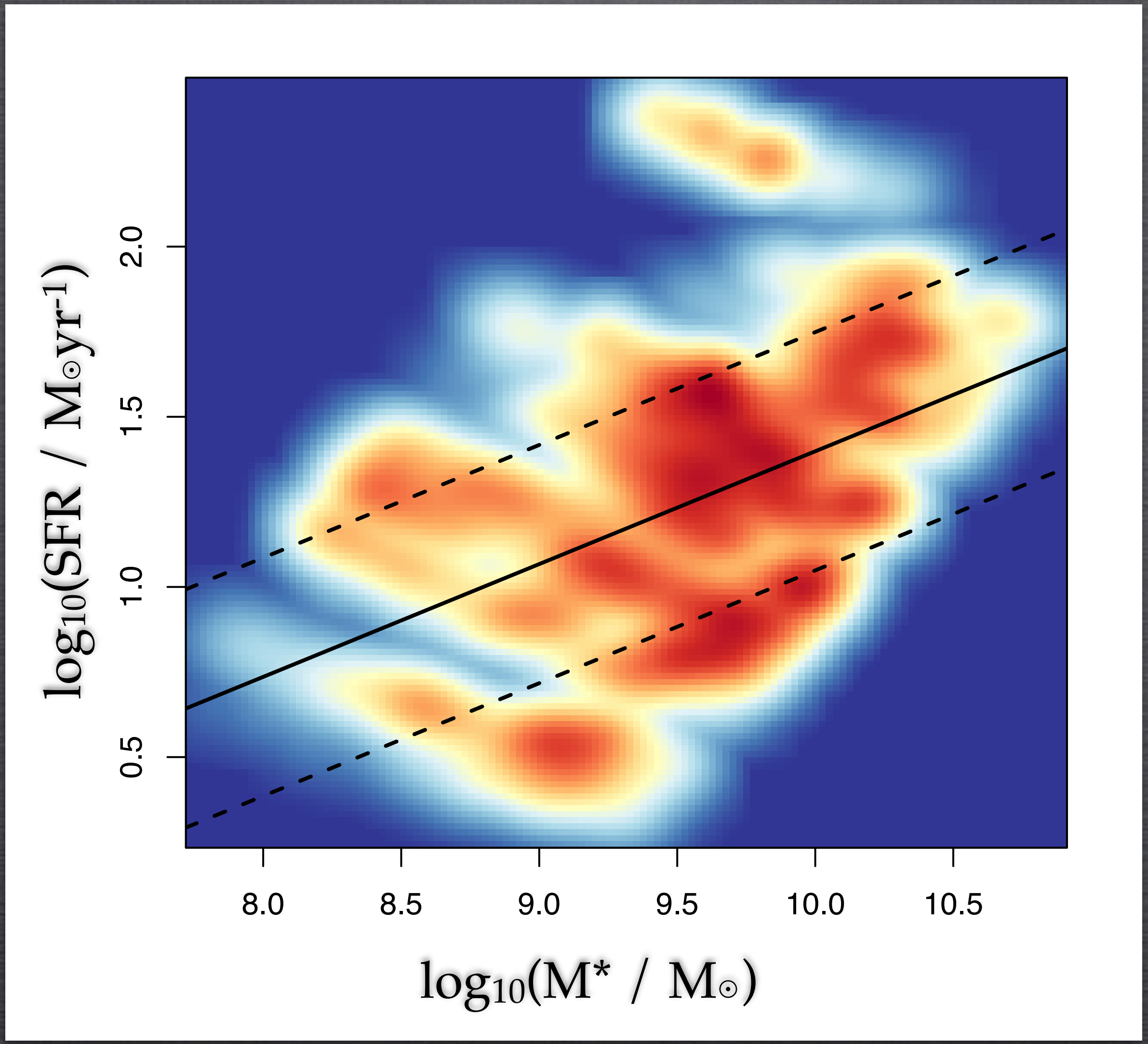

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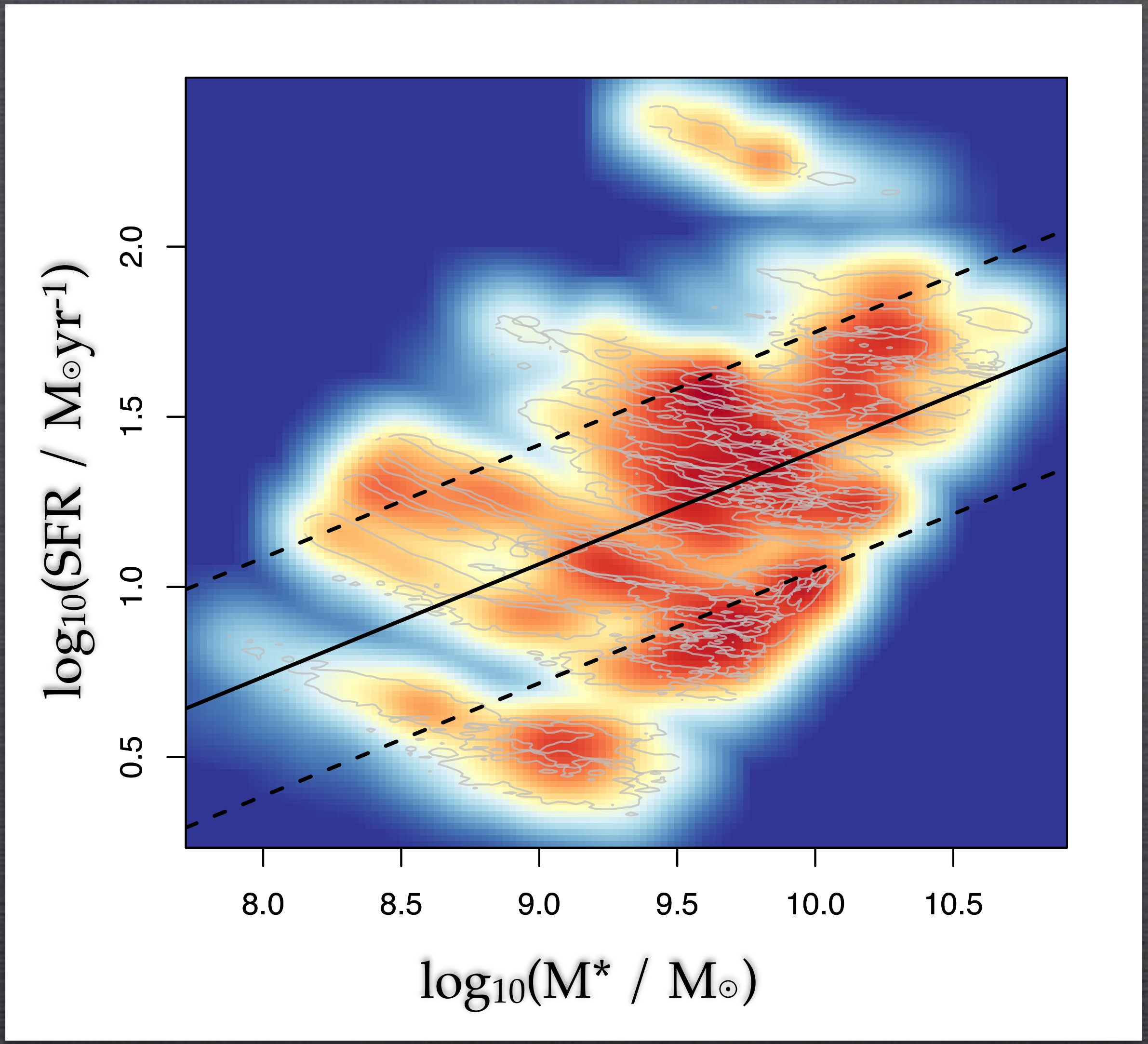

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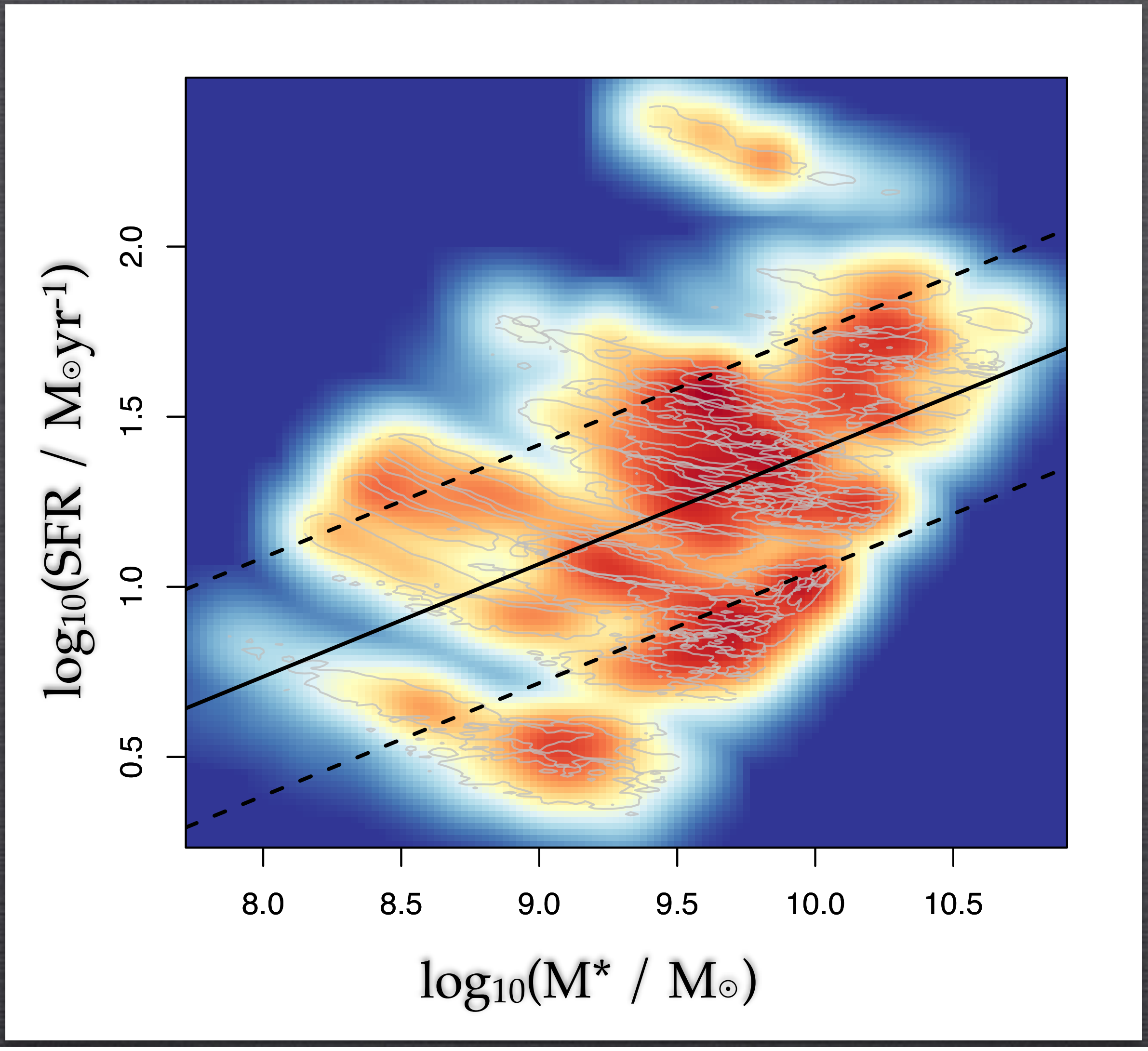


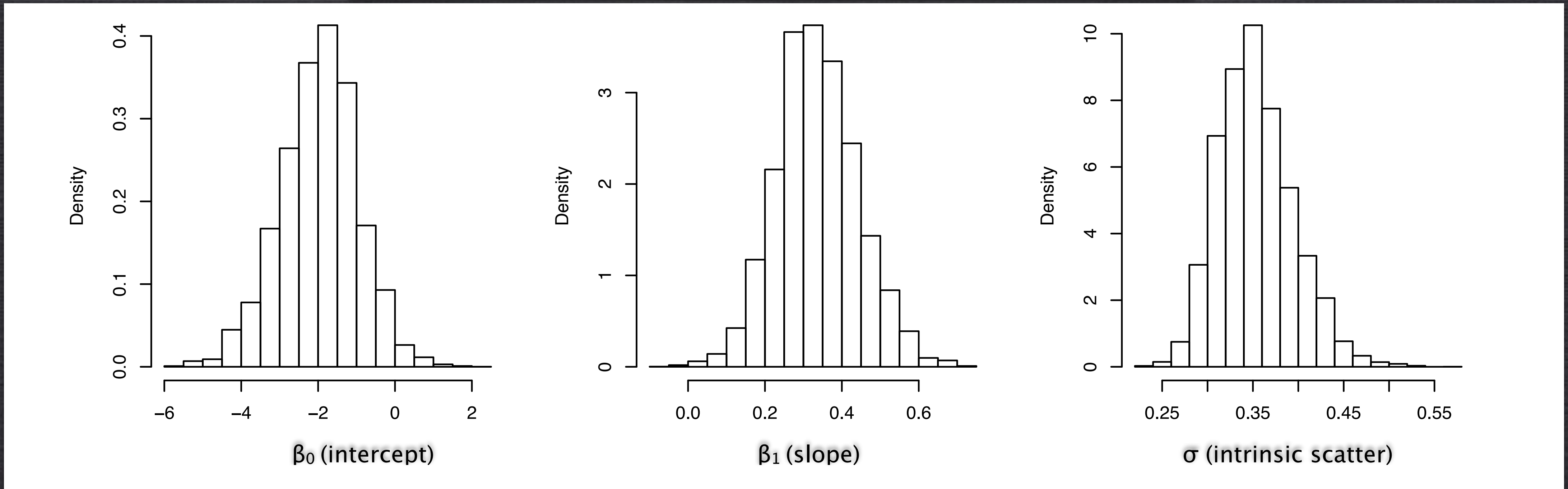

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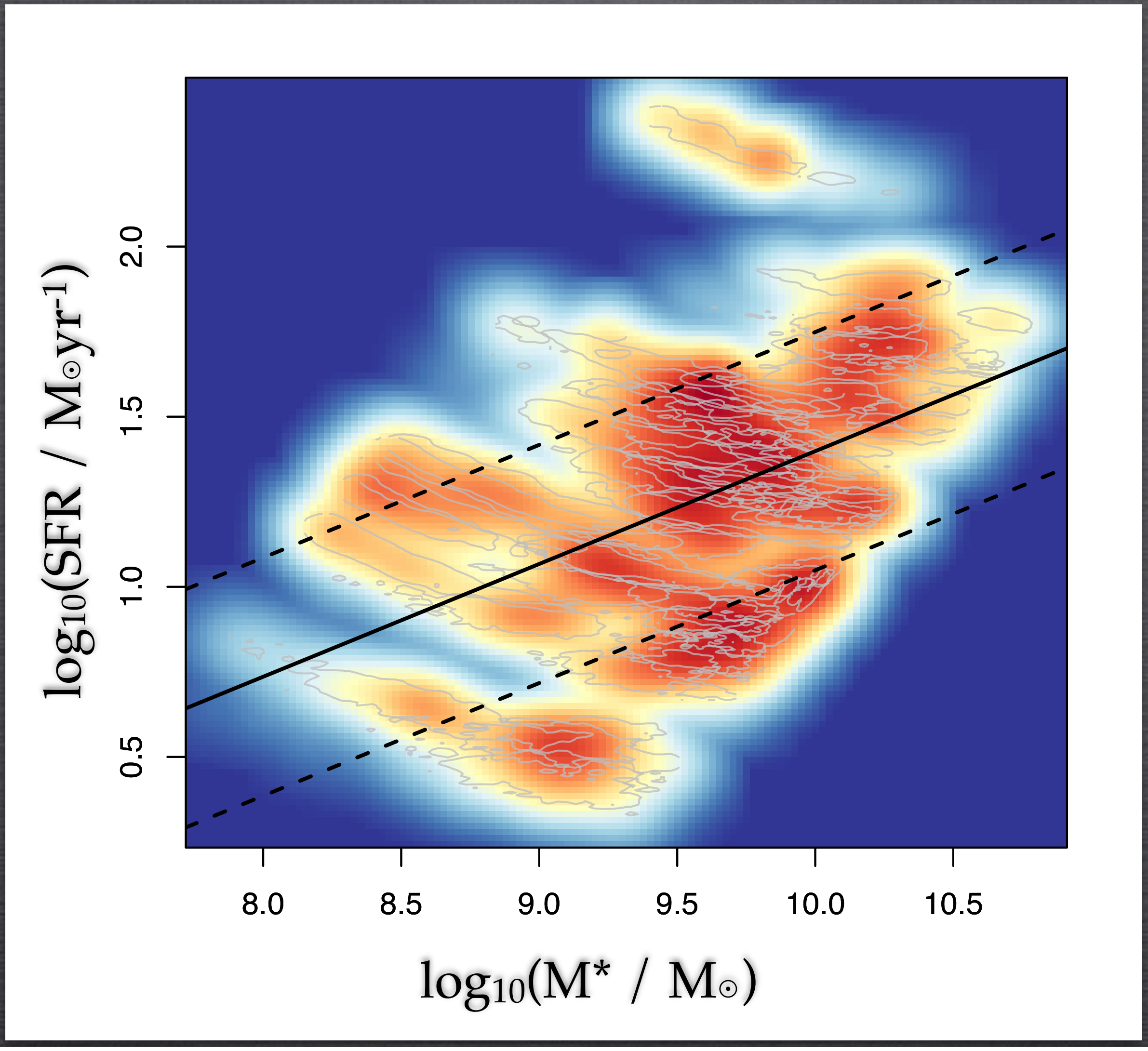


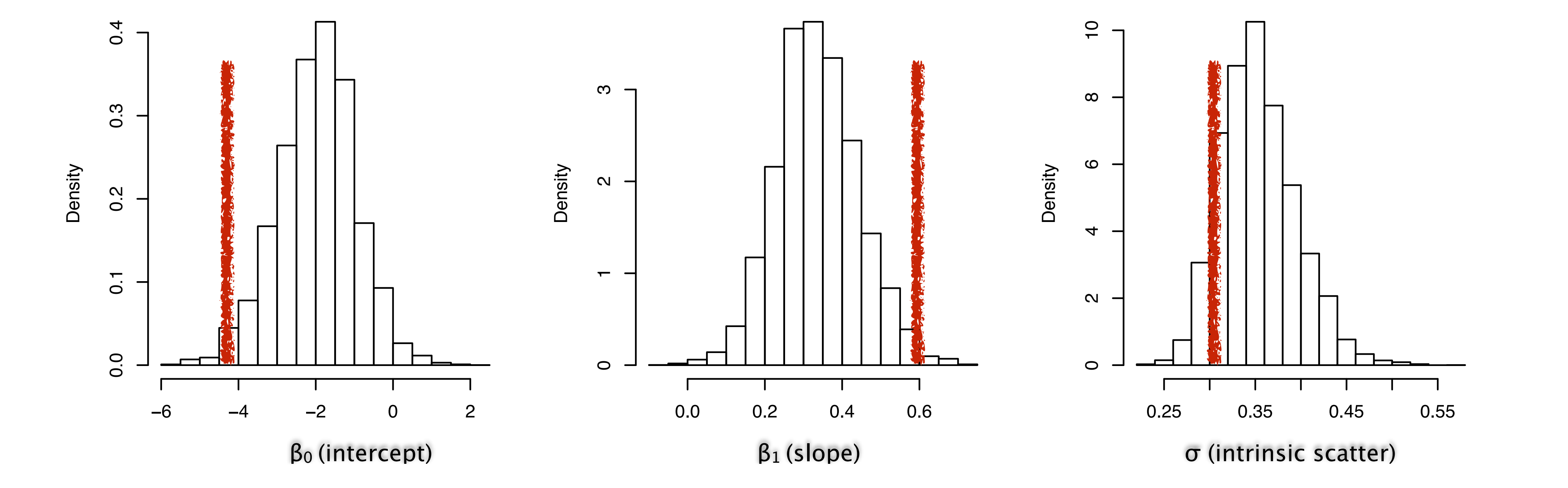

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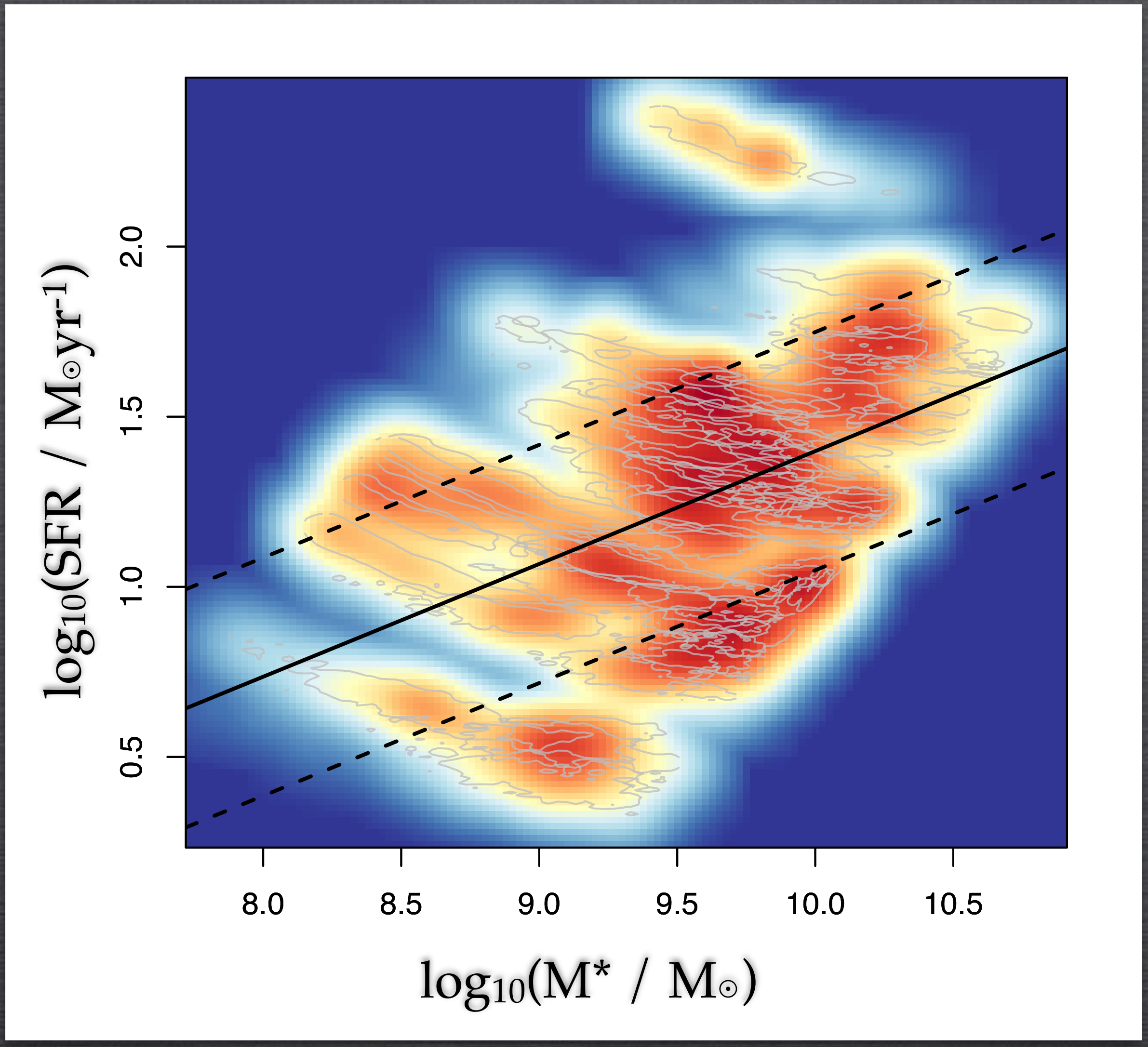


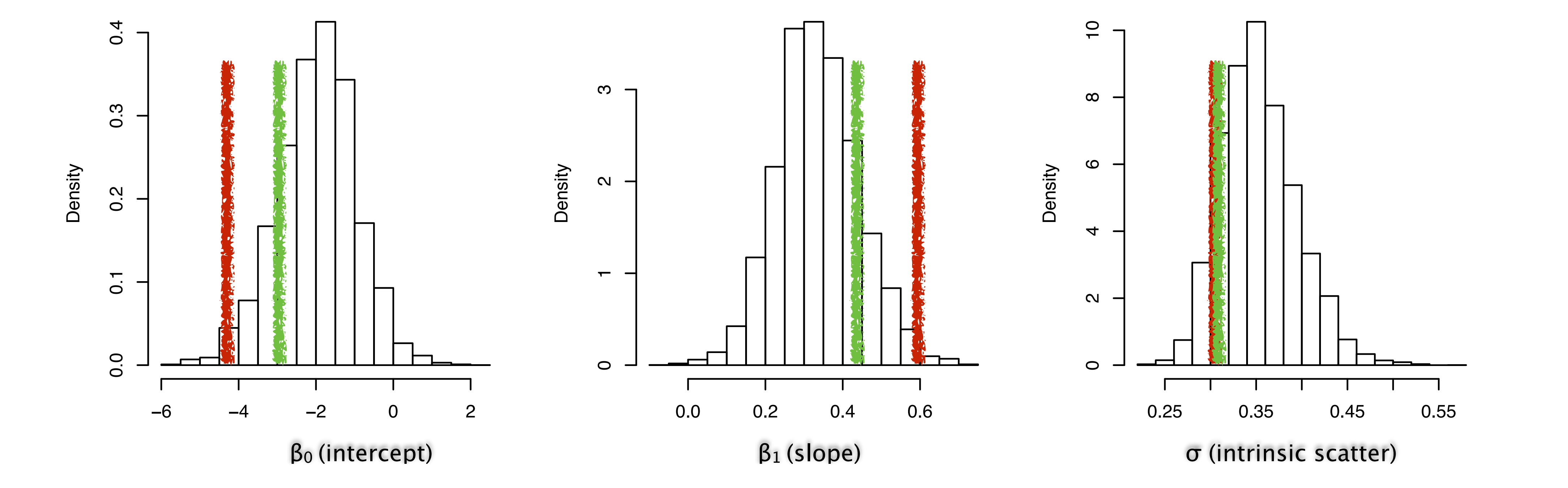

# Summary

BEAGLE allows us to both produce mock photometry with self-consistent SF and chemical enrichment histories and nebular emission as well as performing full Bayesian SED fitting (see Jacopo Chevallard's talk and Julia Gutkin's poster).

Our Bayesian Hierarchical modelling can recover and provide the full uncertainties in slope, intercept and intrinsic scatter of the M*-SFR relation.

- No assumption of shape of joint uncertainties in M*-SFR for individual objects.
- Allows us to assess and compare different selection and SED fitting strategies.

For more results - see my talk at the Malta "Signals from the Deep Past" conference