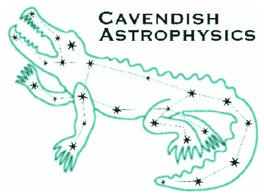
Constraining the stochasticity of star formation

Harry Bevins, Sandro Tacchella, Charlotte Simmonds



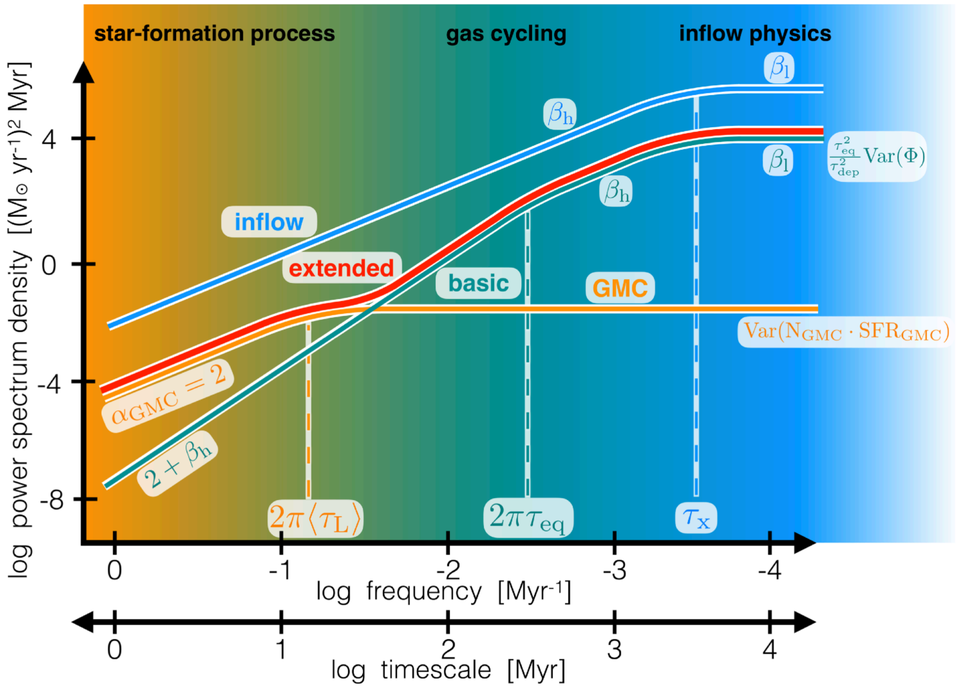
Main Sequence Galaxies

- MS galaxies lie on a relatively tight correlation between star formation rate and stellar mass $\mathrm{SFR} \propto M_*^{\alpha}$
- Normalisation of relationship and α vary with redshift
- Star formation driven by the same physical processes in these galaxies

CANDLES - Star formation in the Mountains

MS Power Spectral Density

- Expect formation to happen on common time scales in these galaxies
- Can define a Power Spectral Density function for star formation
- PSD tells you have strong any variations in star formation rate are on different time scales
- Strong PSD on small time scales means lots of rapid variations in star formation rate



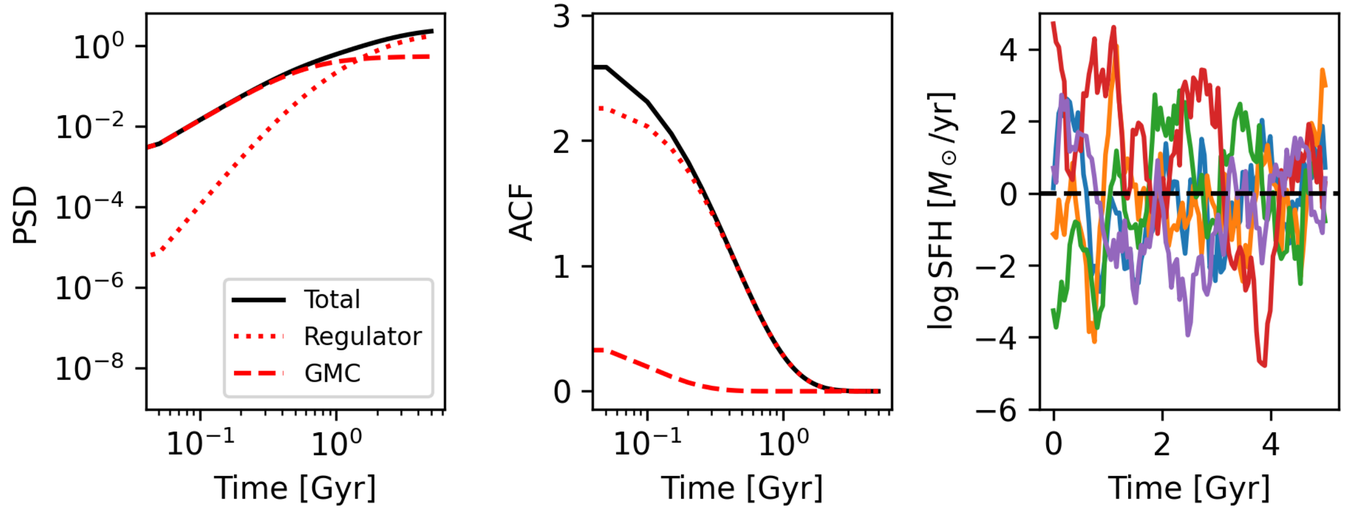
Tacchella et al 2020

MS Power Spectral Density

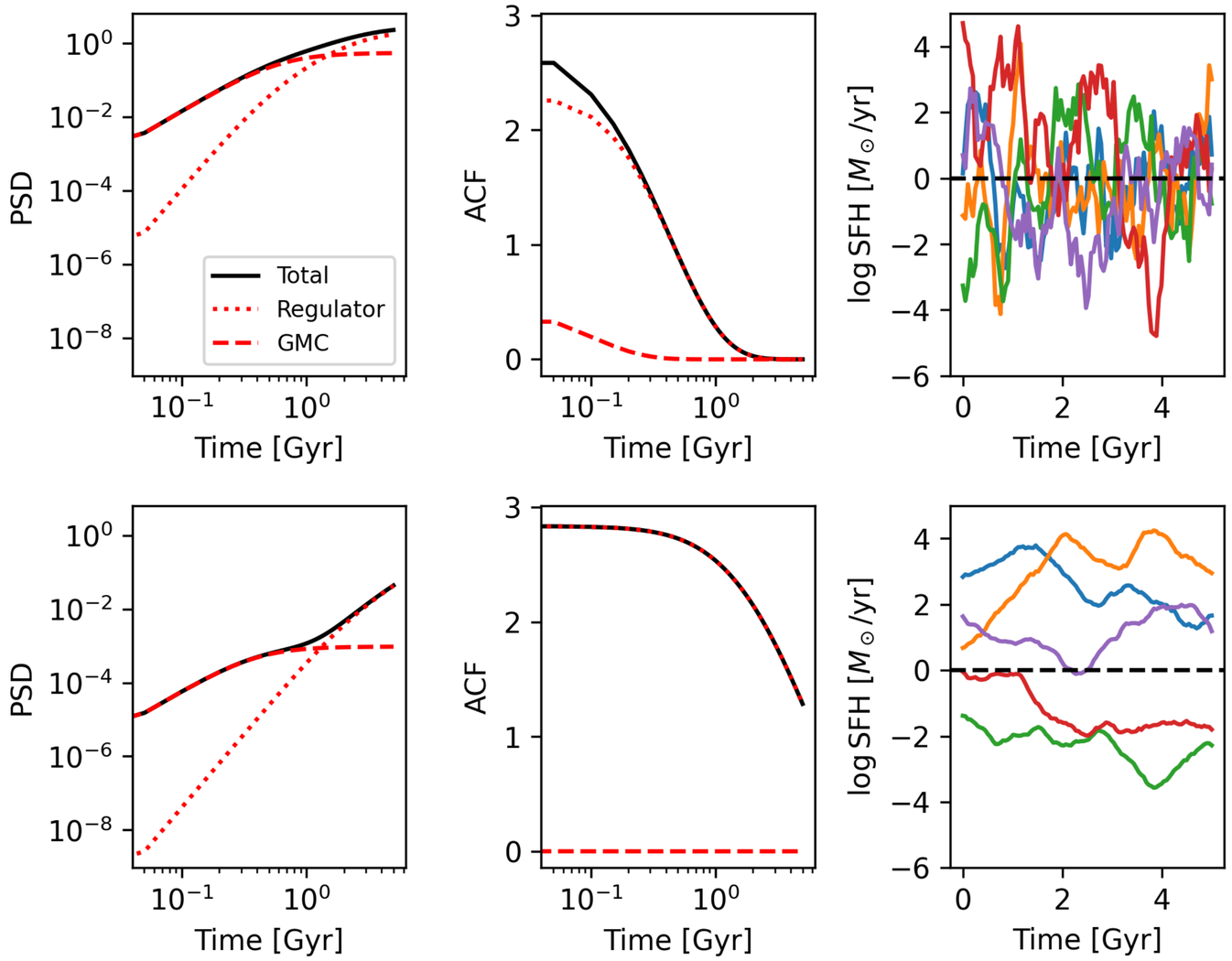
- Fourier transform PSD to get an Auto Correlation Function $C(\tau)$
- Define a Gaussian Process

$$\log \mathrm{SFR}(t) \sim \mathcal{N}(\log \mathrm{SFR}(t) \,|\, \log \mathrm{SFR}_{\mathrm{base}}(t), \mathrm{C}(\tau))$$

- Using a modified version of the implementation in Iyer et al. 2022 [2208.05938] (https://github.com/kartheikiyer/GP-SFH)



Simulating Main Sequence Galaxies



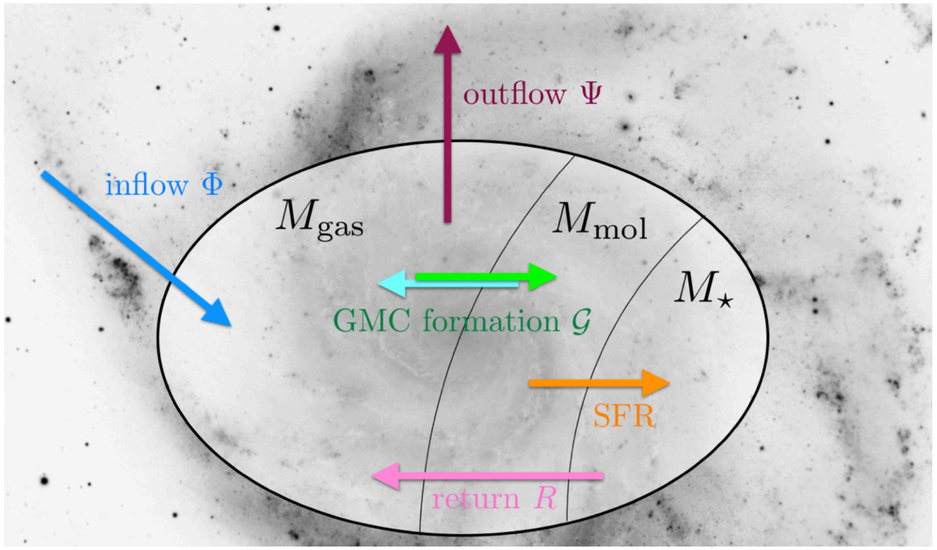
Choice of PSD?

- Extended Regulator Model
  - Captures quasi-equilibrium between gas inflow and cycling and includes formation of Giant Molecular Clouds [Tacchella et al 2020]

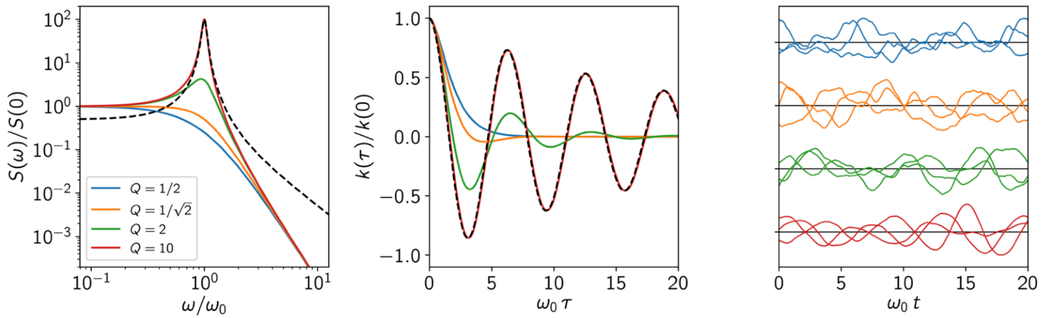
$$\sigma_{\rm reg}, \tau_{\rm in}, \tau_{\rm eq}, \sigma_{\rm dyn}, \tau_{\rm dyn}$$

- Simple Harmonic Oscilator
  - Oscillatory SFH with preferential scale [Foreman-Mackey et al. 2017]

$$S_0, \tau_0, Q$$



Tacchella et al. 2020



Foreman-Mackey et al. 2017

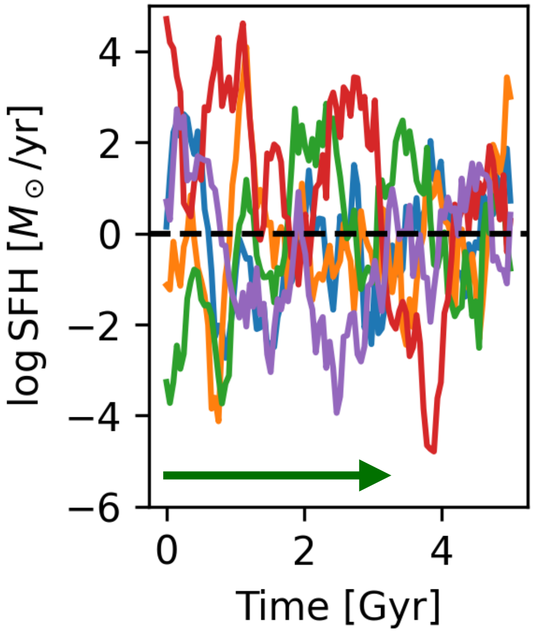
Main Sequence Scatter

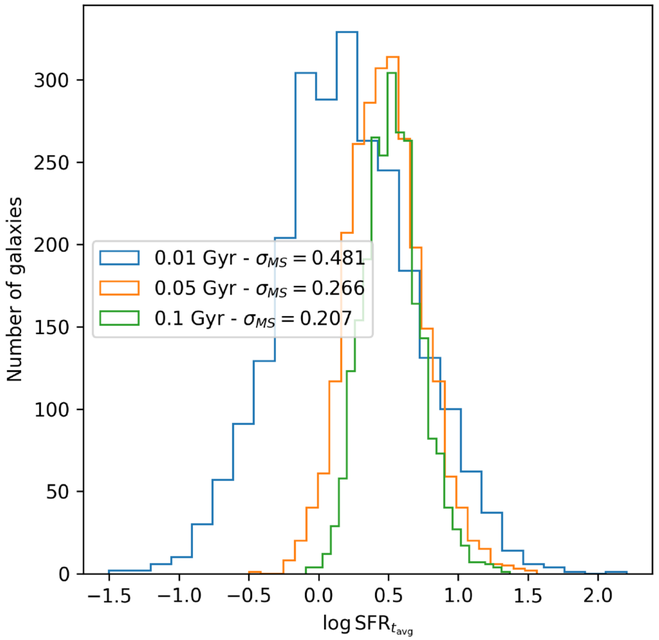
- We can probe the PSD parameters with SFH generated from our GP

$$\mathrm{SFR}_{t_{\mathrm{avg}}} = \frac{1}{t_{\mathrm{avg}}} \int_{t_{\mathrm{avg}}}^{t_0} \mathrm{SFR}(t')dt'$$

- Calculate for each galaxy and produce a distribution

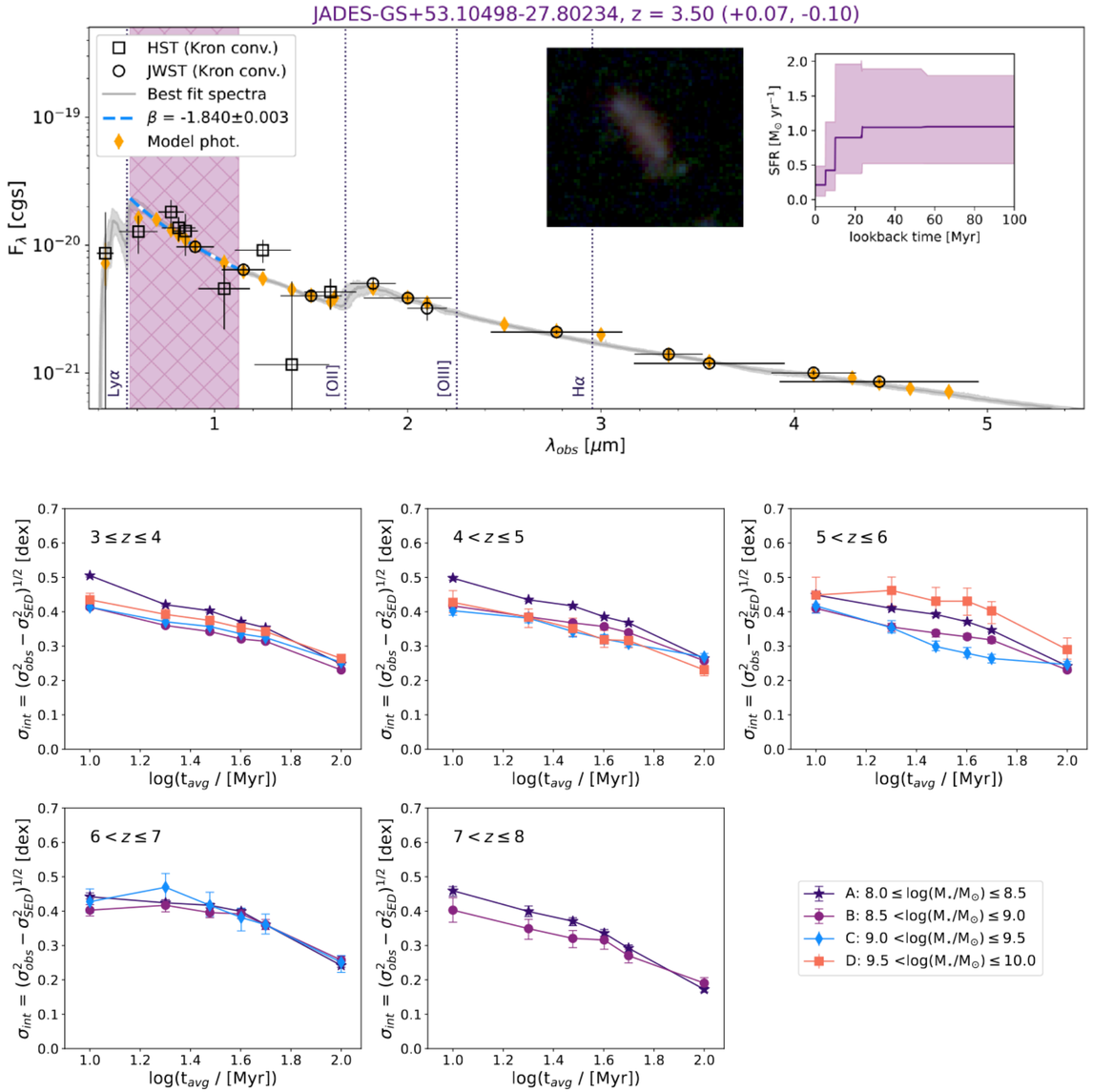
- Scatter around the mean $\mathrm{SFR}_{t_{\mathrm{avg}}}$ denoted $\sigma_{MS}(t_{\mathrm{avg}})$





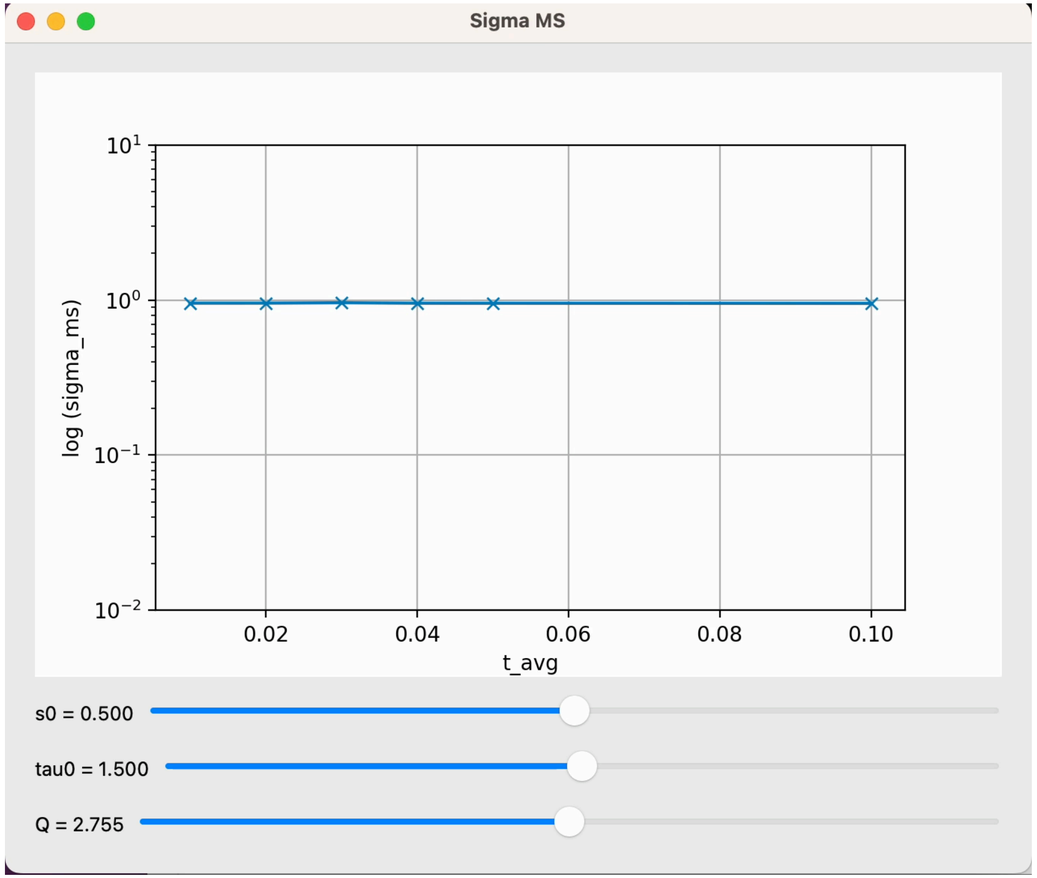
NIRCam Observations

- Simmonds et al. in prep and Simmonds et al 2024 [2409.01286]
- Fit photometric catalogue ($\sim 50{,}000$ galaxies) with FSPS and piecewise SFR
- Divide catalogue into mass and redshift bins
- Integrate over SFR on a range of different timescales
- Intrinsic scatter $\sigma_{MS}^{\mathrm{int}} = \sqrt{\sigma_{MS}^{\mathrm{obs}\ 2} - \sigma_{\mathrm{SED}}^{2}}$

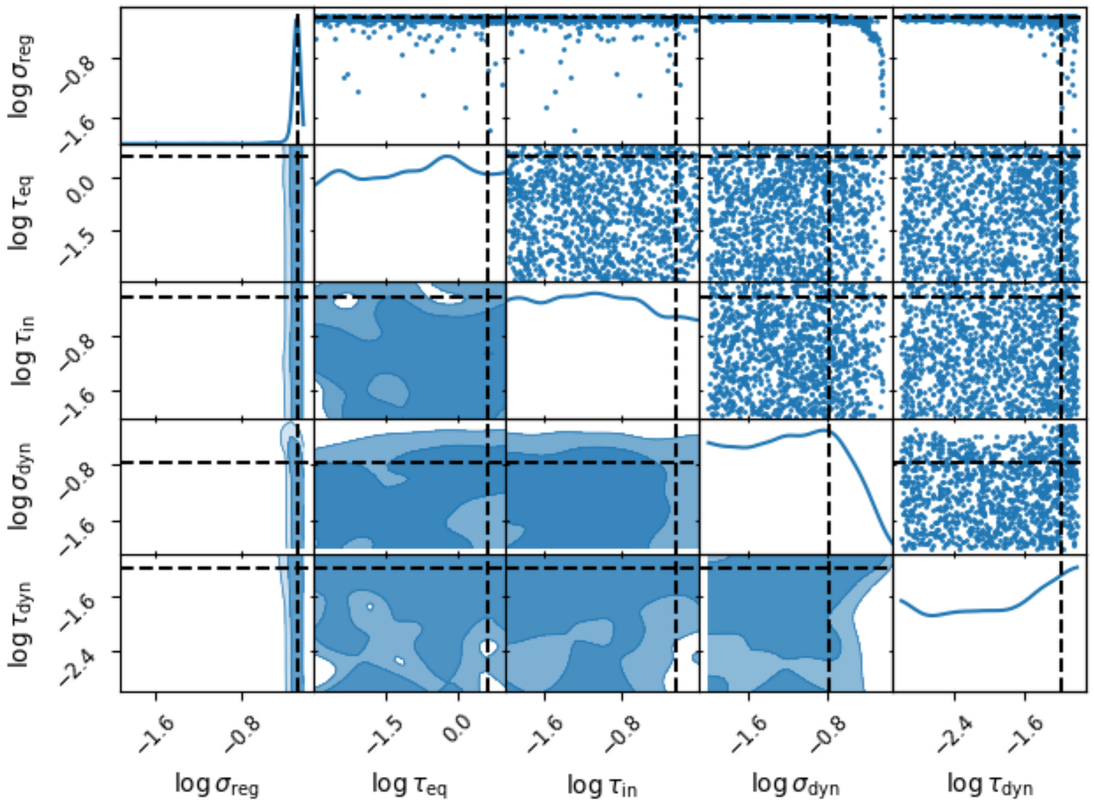


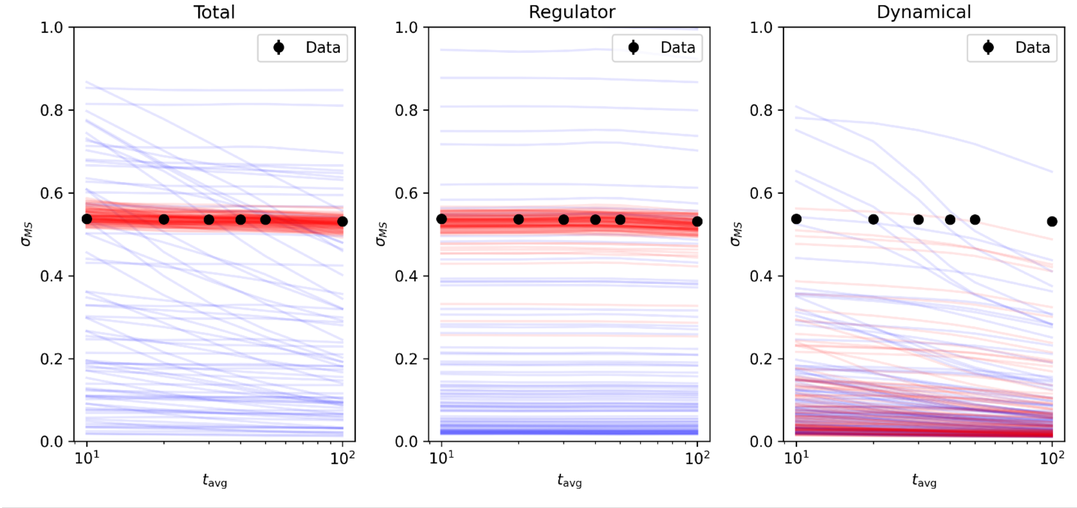
Likelihood Based Inference and Emulation

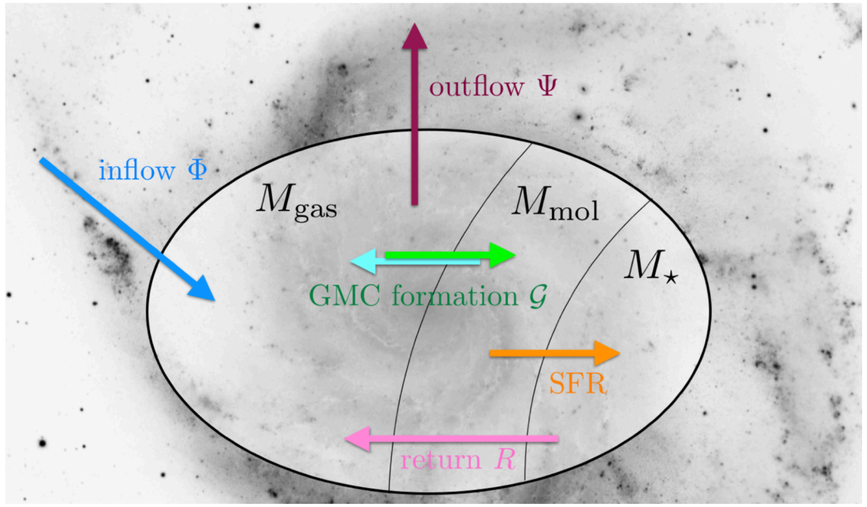
- Our goal is to infer $P(\theta_{\rm PSD} \,|\, \sigma_{MS}, M)$ but our simulation pipeline can be quite costly
- Generate 10,000 PSD samples and for each 2500 SFHs
- From these estimate $\sigma_{MS}(\theta_{PSD}, t_{\rm avg})$ and train a neural network emulator for inference
- Assume a gaussian likelihood, use estimated error from bootstrapping and a term for emulator error



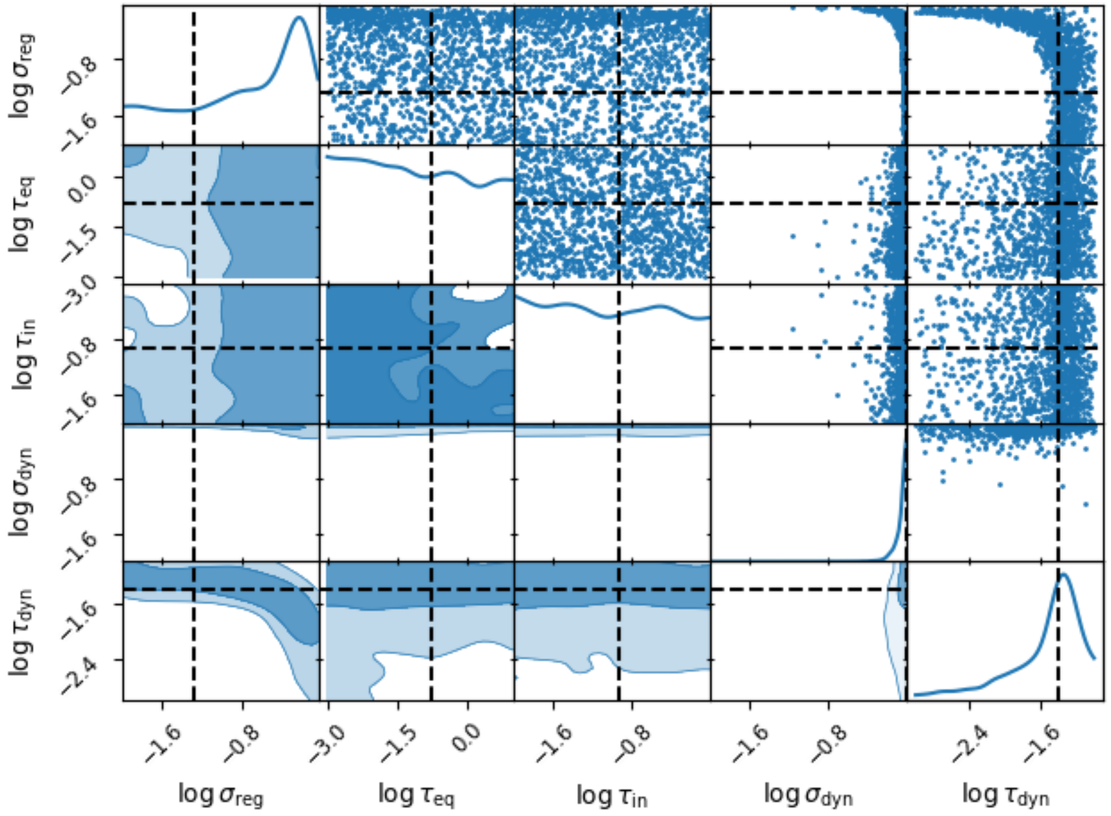
Toy Example - Regulator Dominated

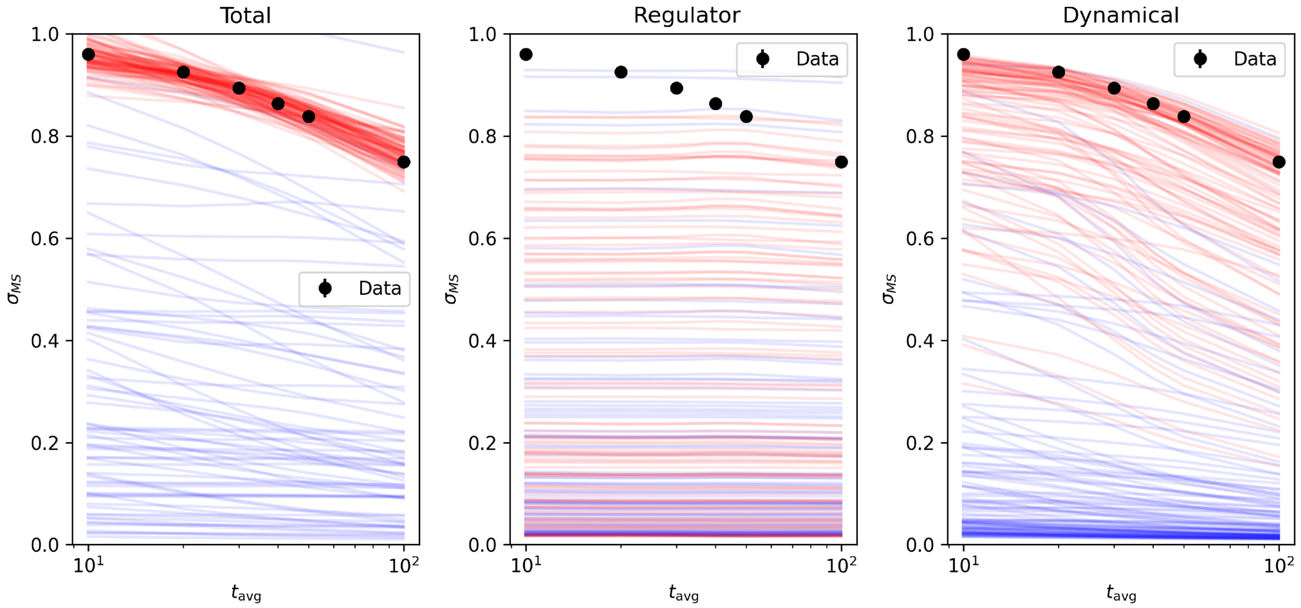




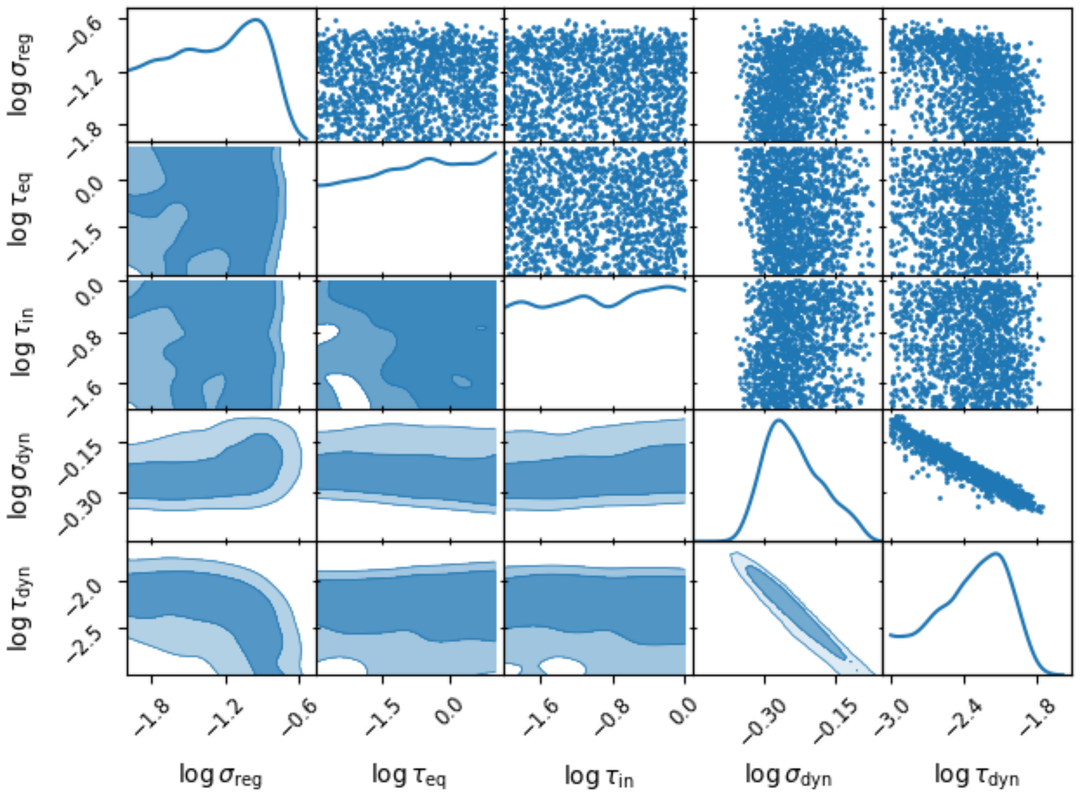


Toy Example - Dynamical Dominated

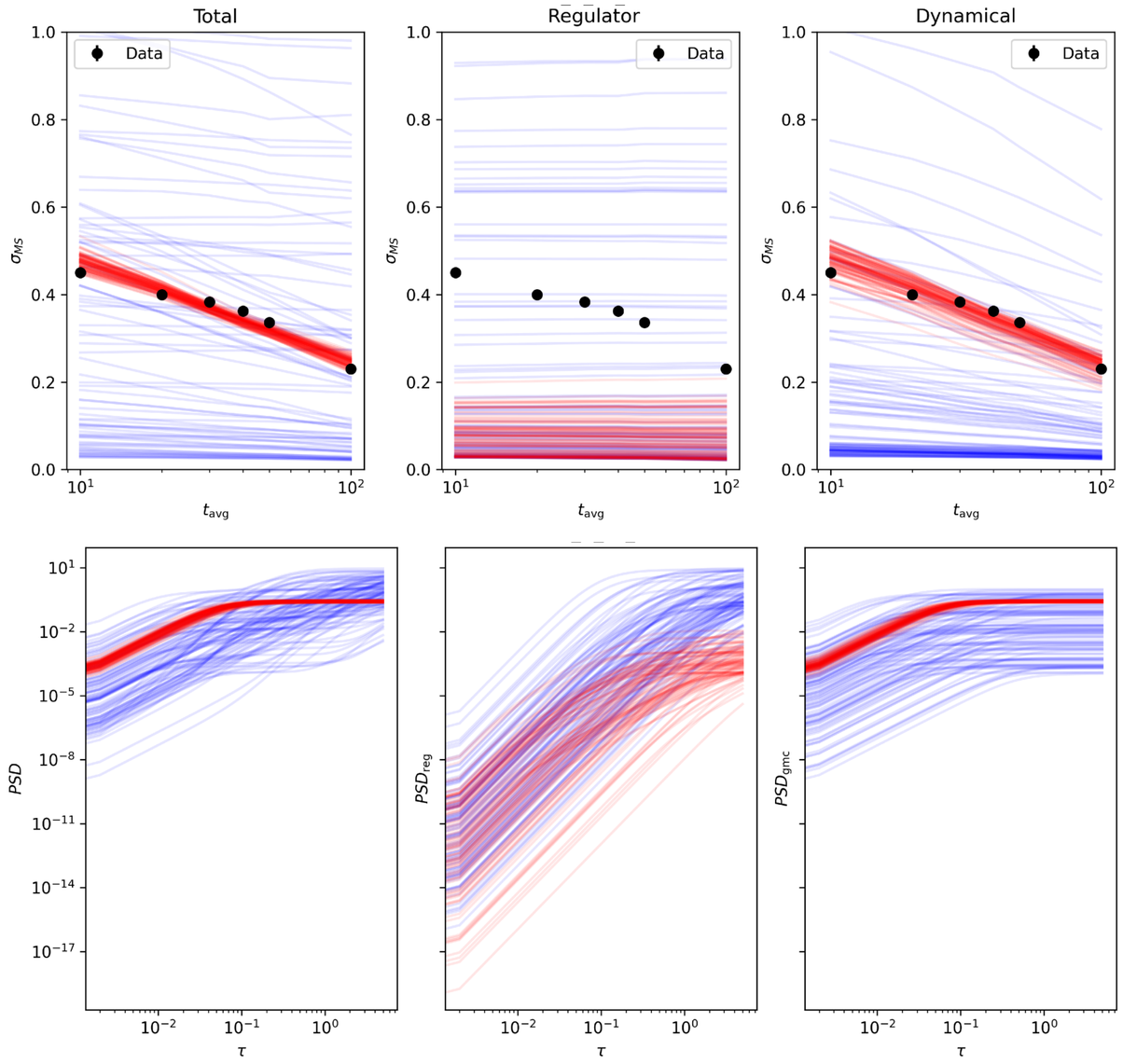




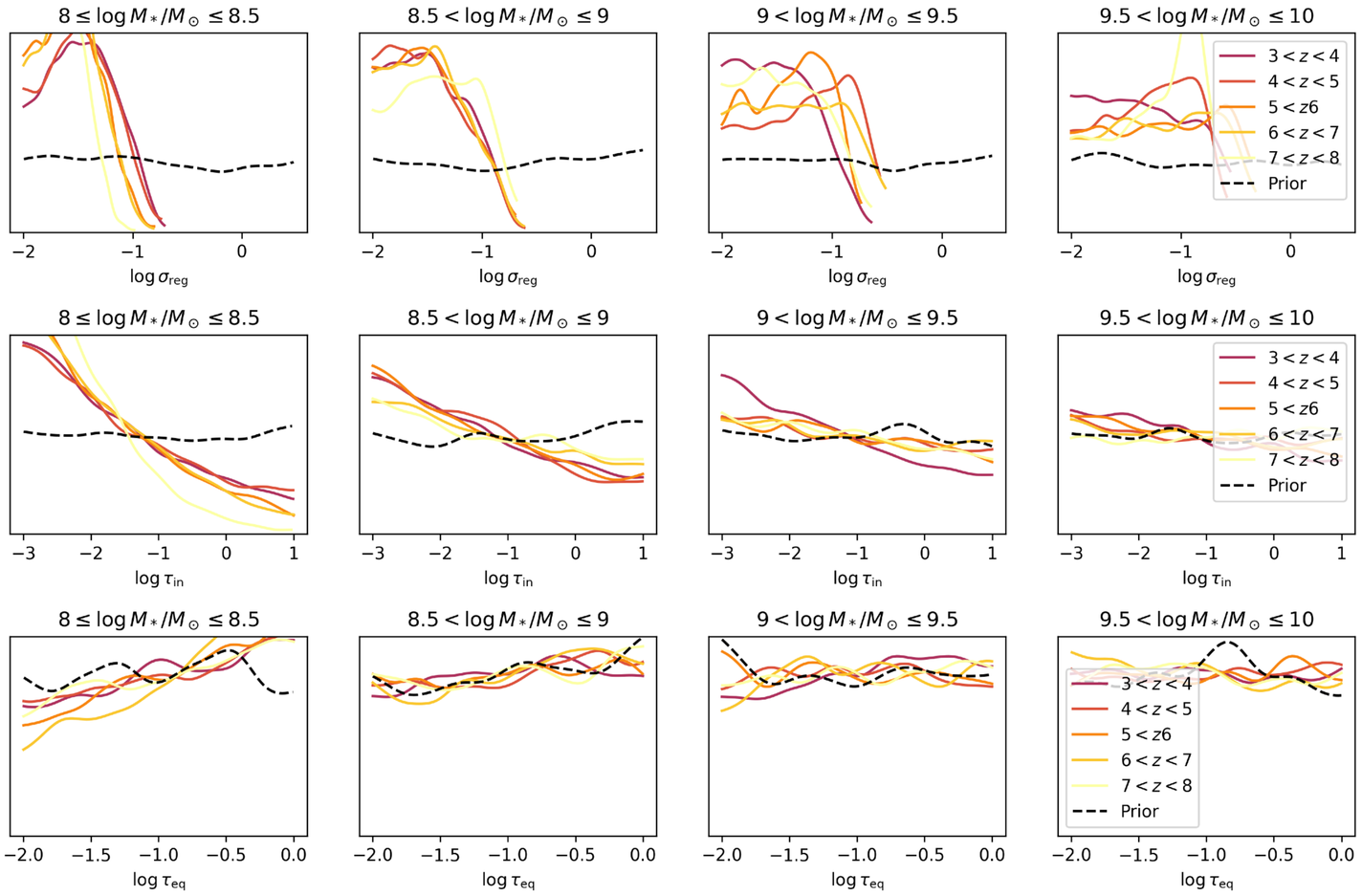
Real Data



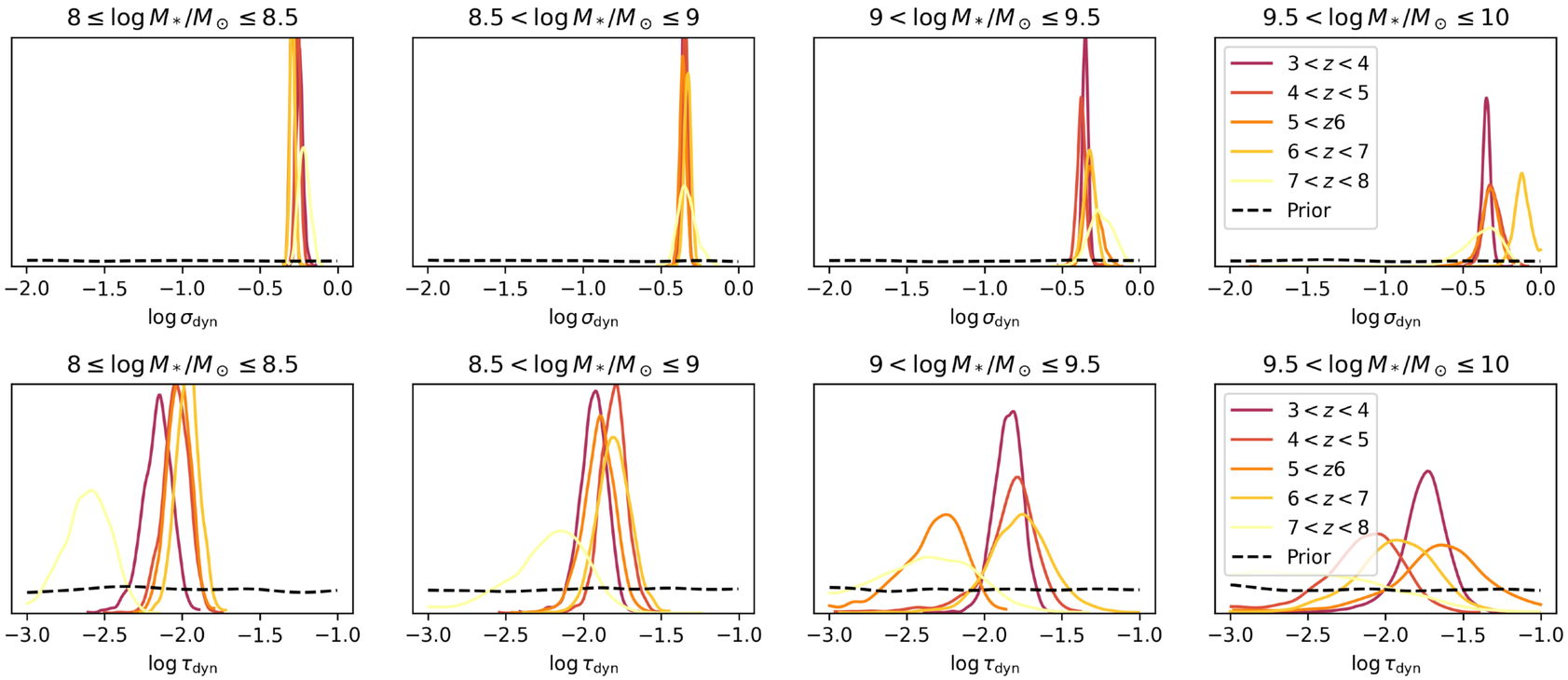
$$8 \leq \log M_*/M_\odot \leq 8.5$$
$$5 < z < 6$$



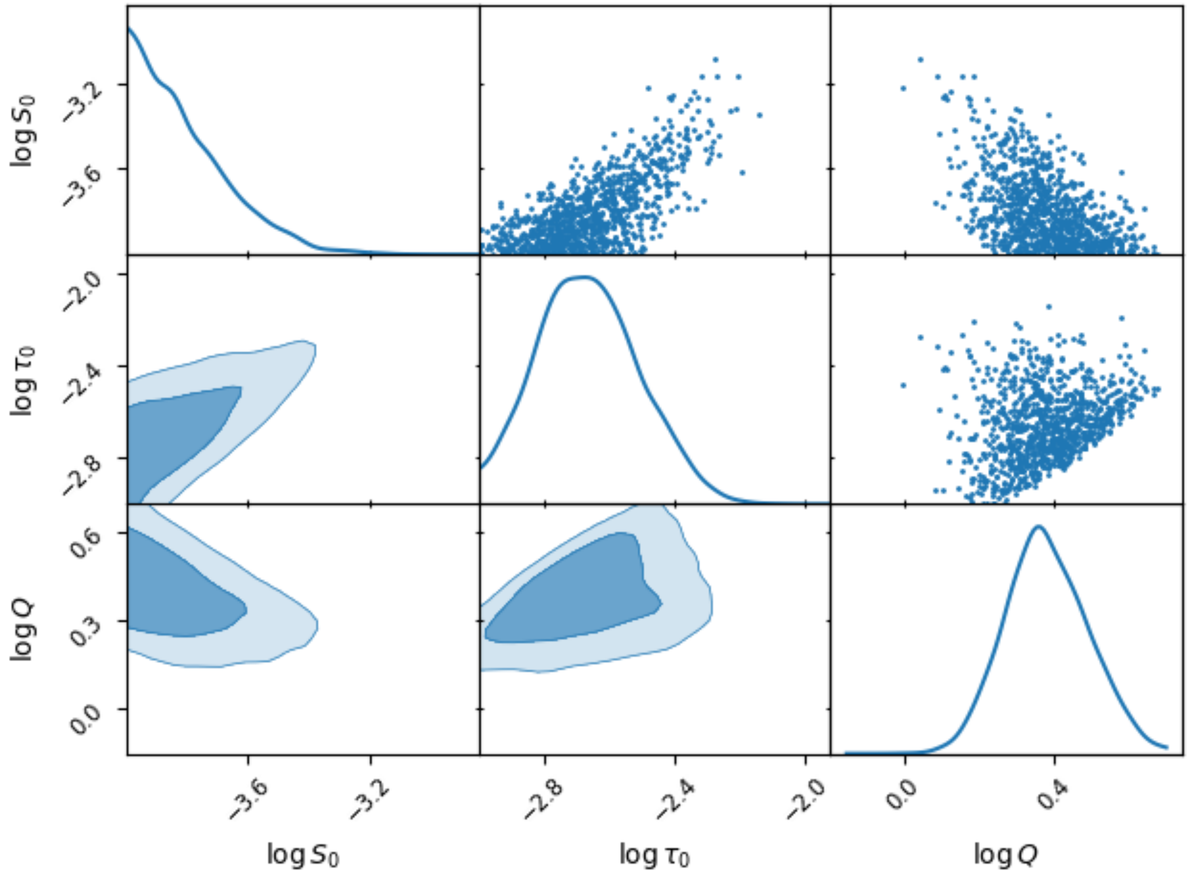
Real Data - Regulator Component



Real Data - Dynamical Component



Real Data - SHO



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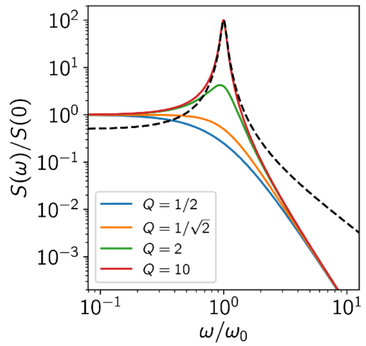

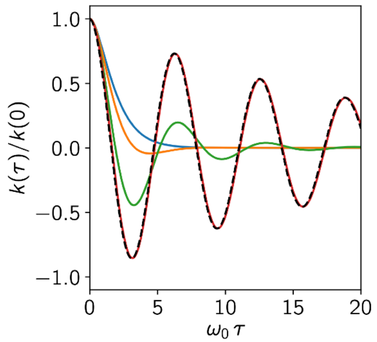

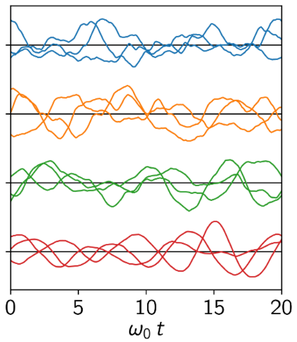

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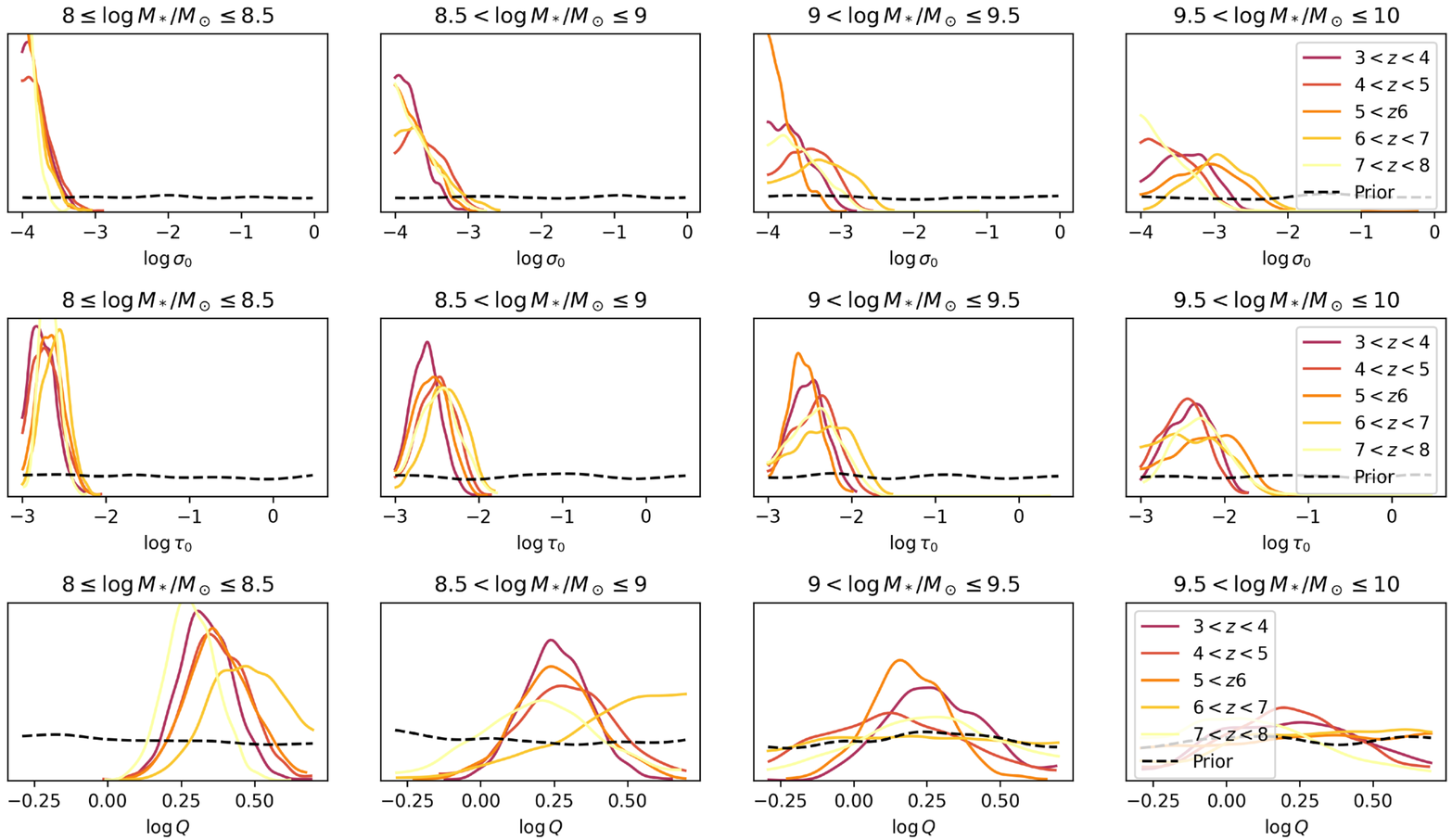

Conclusions

- We can constrain population level models for star formation rates as a function of mass and redshift
- Observations from JWST over average time scales of $t \leq 0.1$ Gyr prefer star formation driven by GMC formation
- Validate emulator accuracy against recent work in Bevins et al. 2025 (2503.13263)
- Write up and publish some of our results
- Extend the work to better account for SED fitting errors on each observed galaxy with NRE