Temporally resolving early galaxies: pinning down the internal workings of galaxies with star-formation variability

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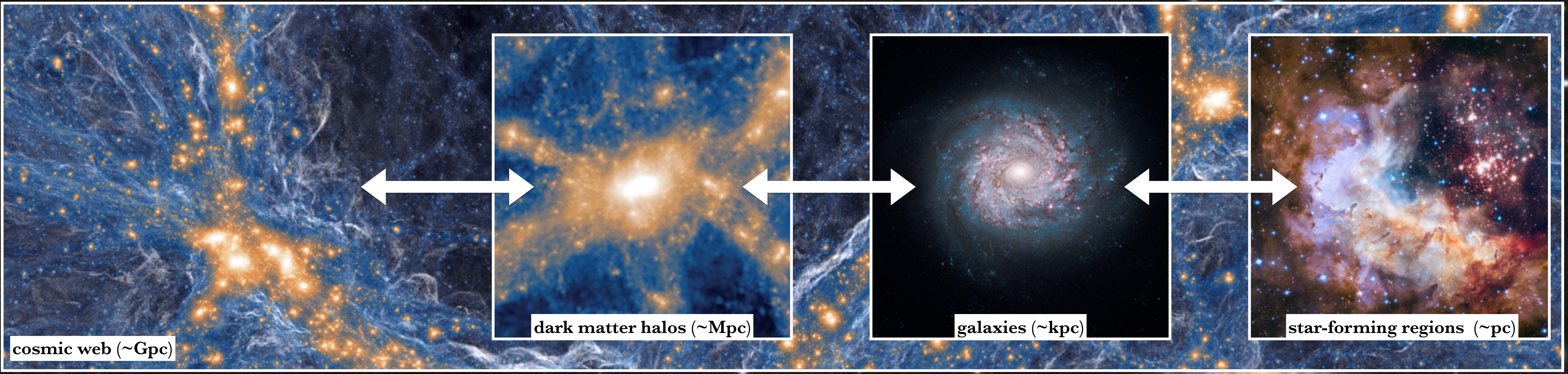
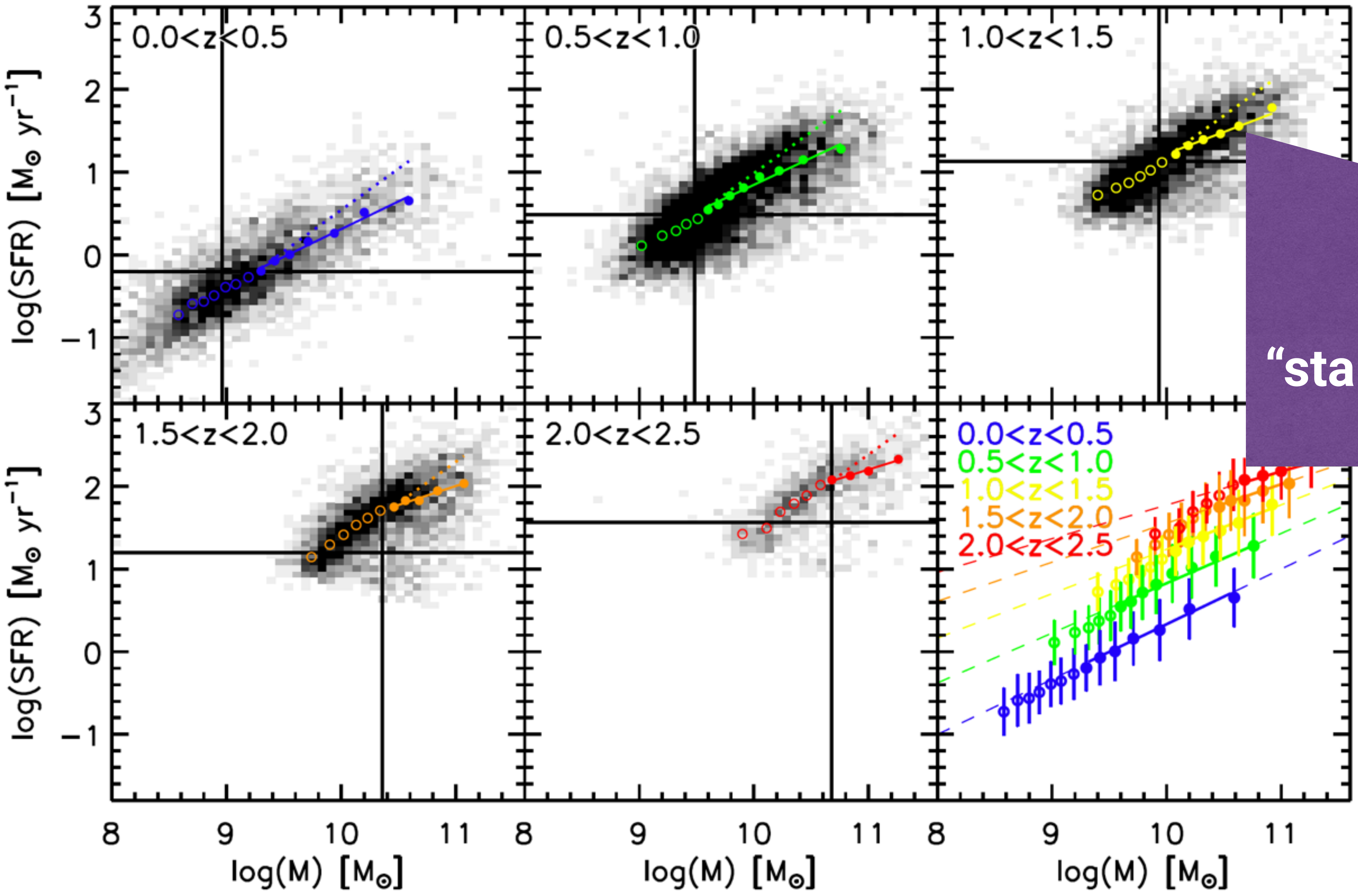
HARVARD & SMITHSONIAN

Which physical processes are regulating star formation in galaxies?



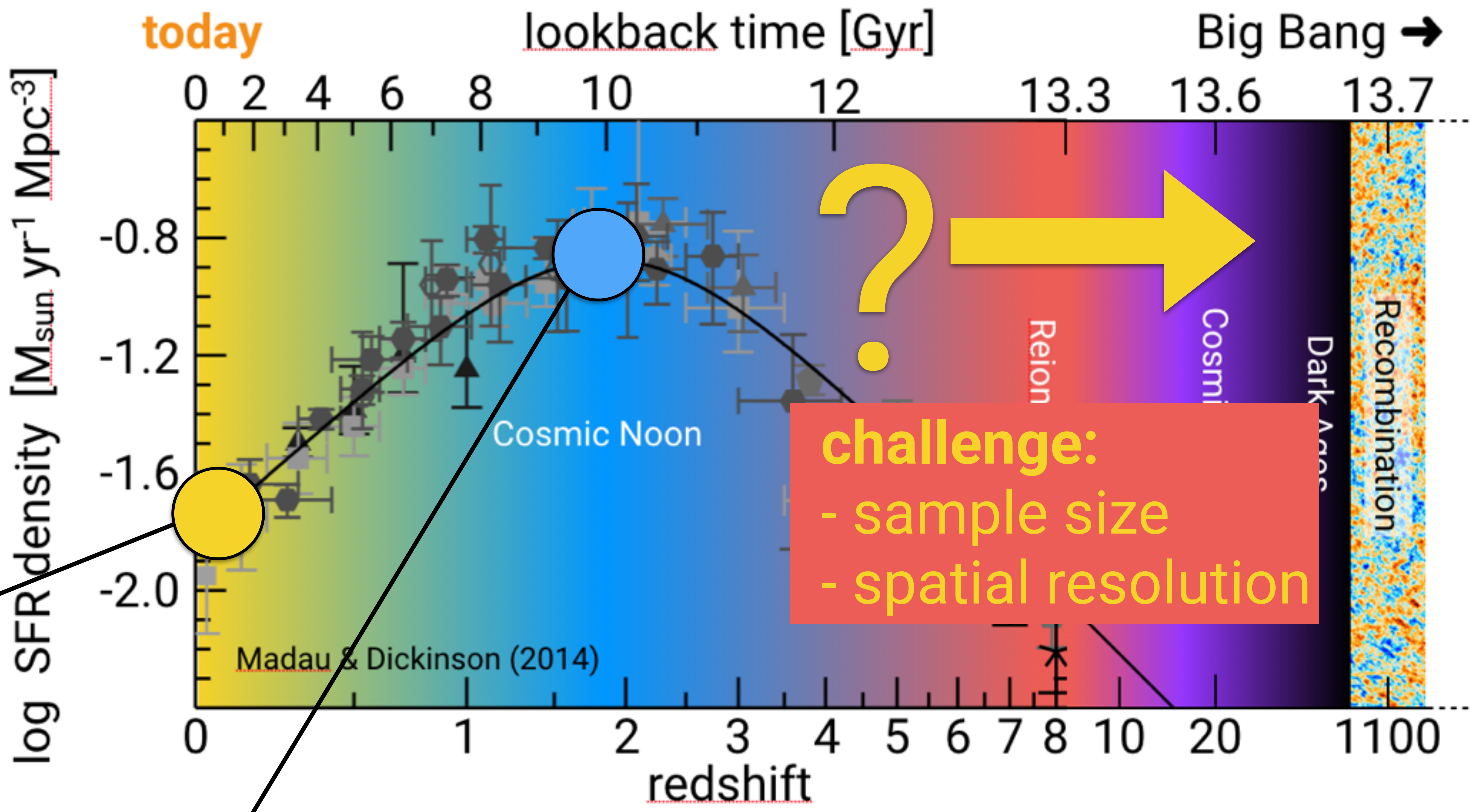
Star formation on global scales



"star-forming main sequence"
$\sigma_{MS} \approx$ 0.2-0.4 dex

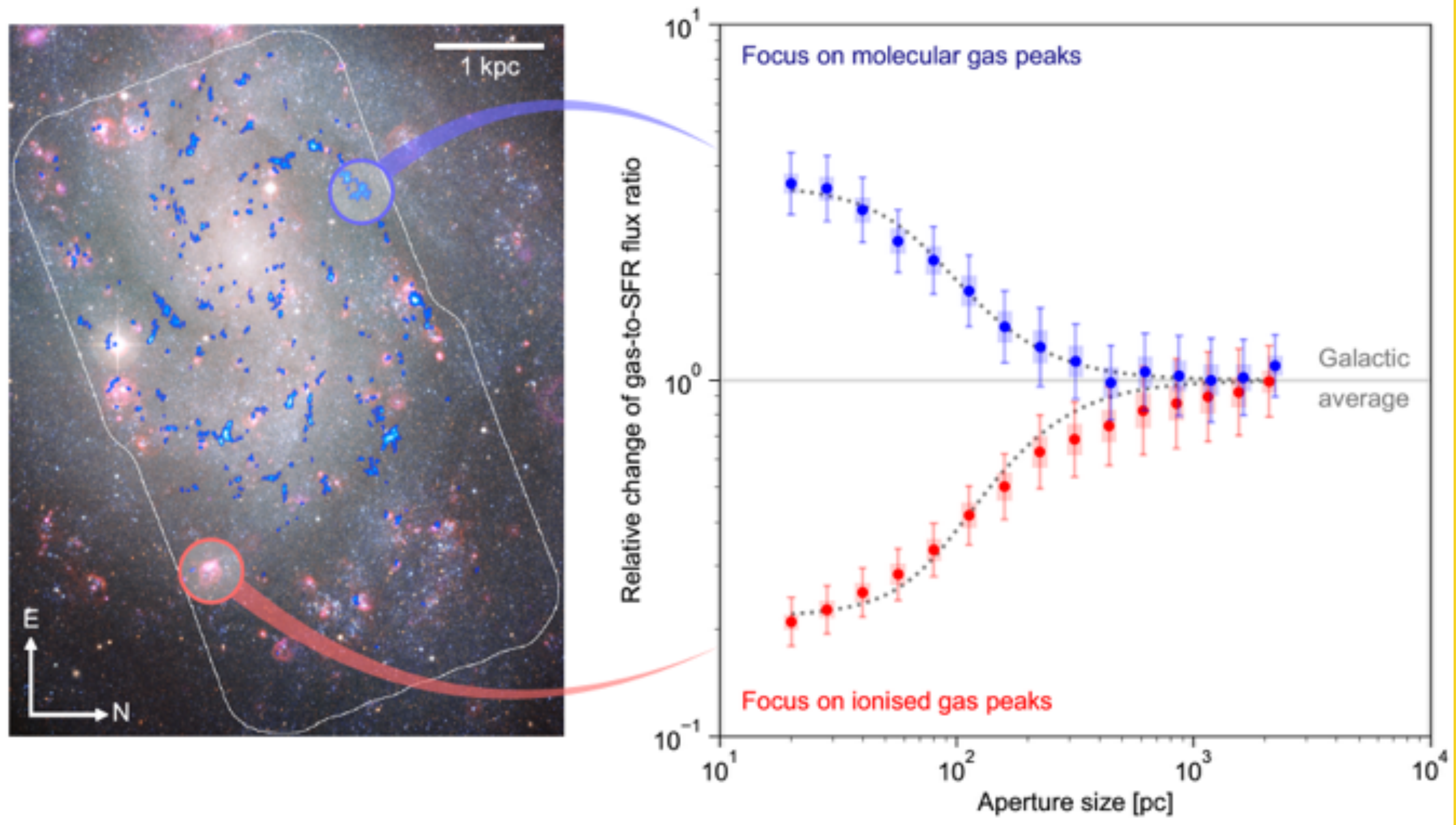
Whitaker + 2012,2014;
see also Brinchmann+ 04; Noeske+ 07ab; Daddi+ 07; Elbaz+07; Speagle+14; Schreiber+ 15; Panella+ 15; …

Spatially resolving galaxies



challenge:
- sample size
- spatial resolution

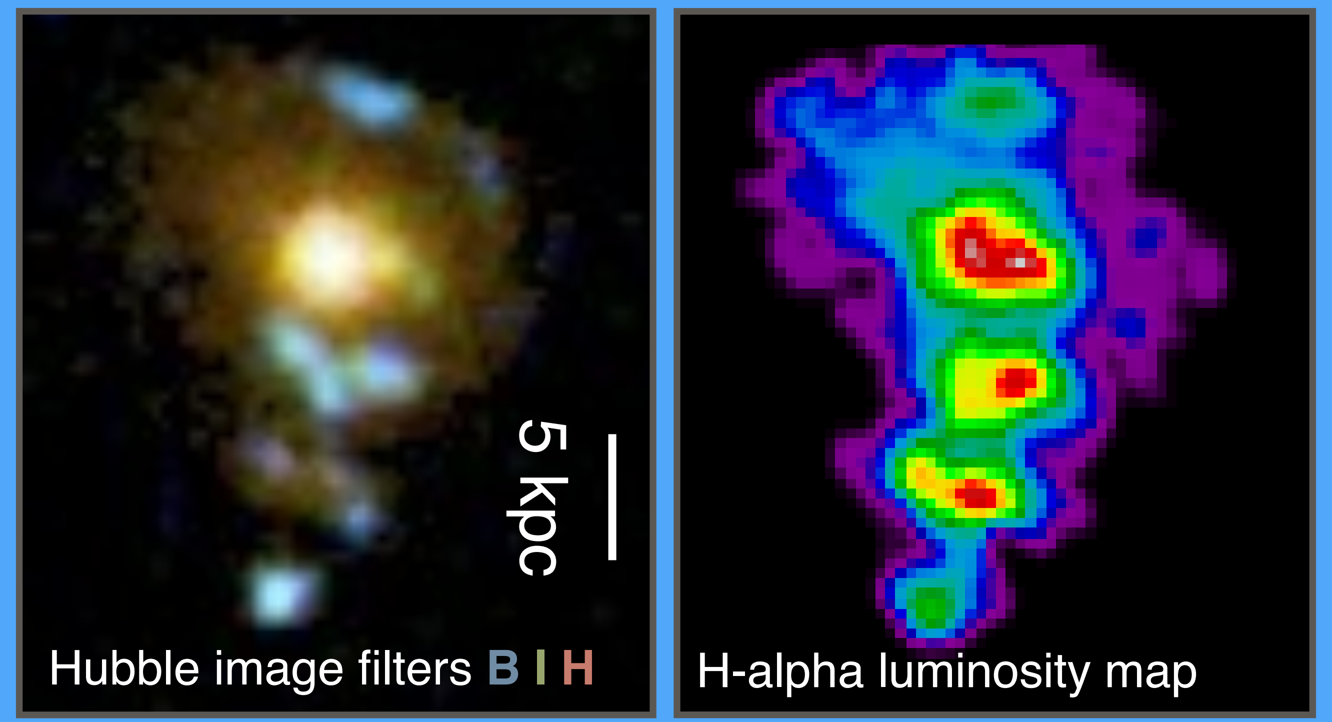
today's (z=0) galaxies:
galaxies can be resolved to the molecular cloud level with HST, VLT & ALMA



Inefficient star formation due to short-lived molecular clouds and rapid feedback (Kruijssen+ 2019)

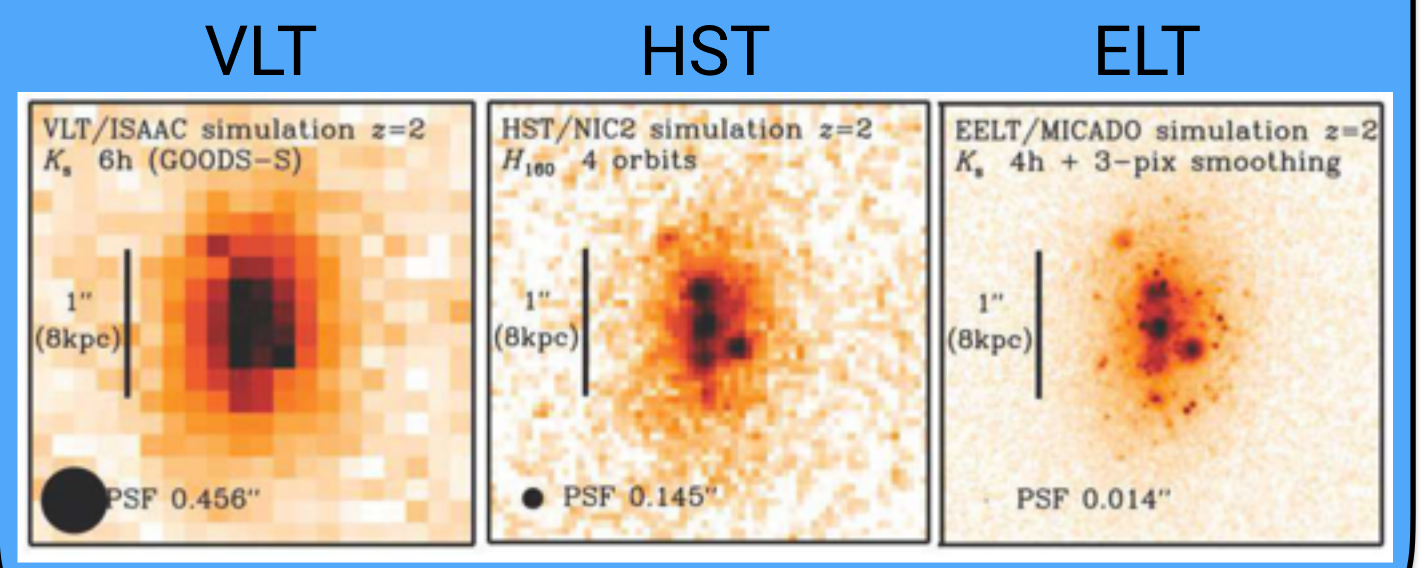
+ lensing
(e.g., Johnson+ 2017, Cava+ 2018, Vanzella+ 2019)

Cosmic Noon (z~1-3) galaxies:
AO on 10m telescopes + HST + ALMA with resolution of ~1 kpc



e.g., Genzel+ 2006, Förster Schreiber+ 2009, Law+ 2012, Tacchella+ 2015

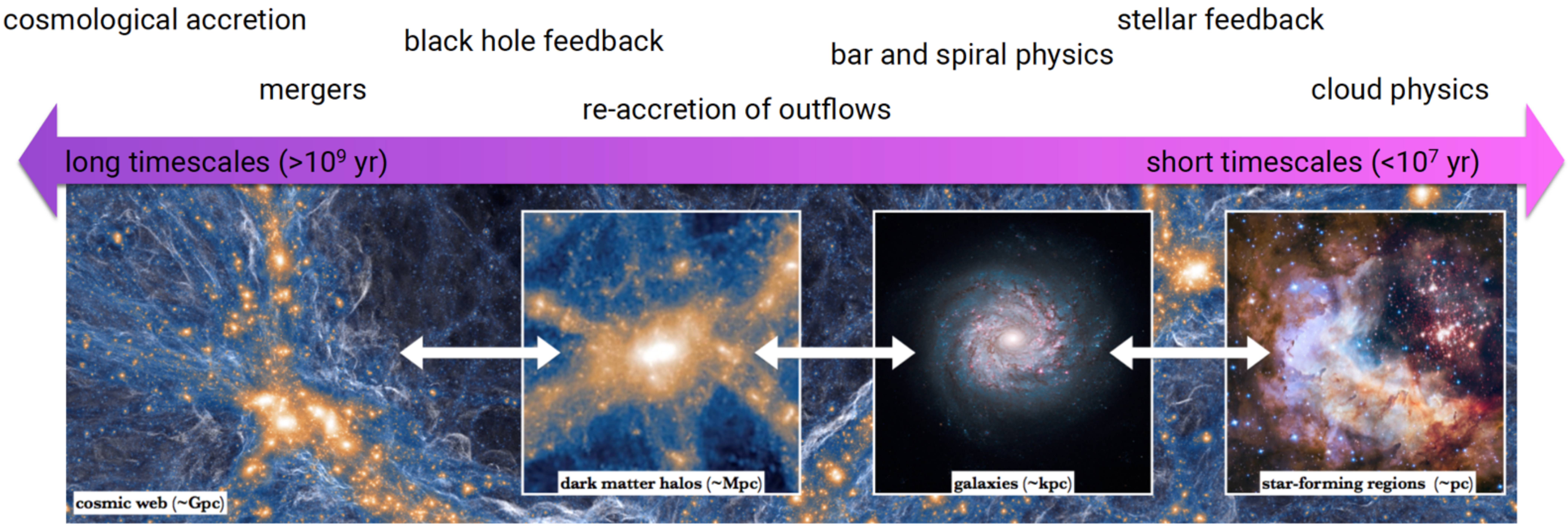
Future: ELT / GMT / TMT
resolve z~2 galaxies at a resolution of 100 pc, similar to today's local galaxies

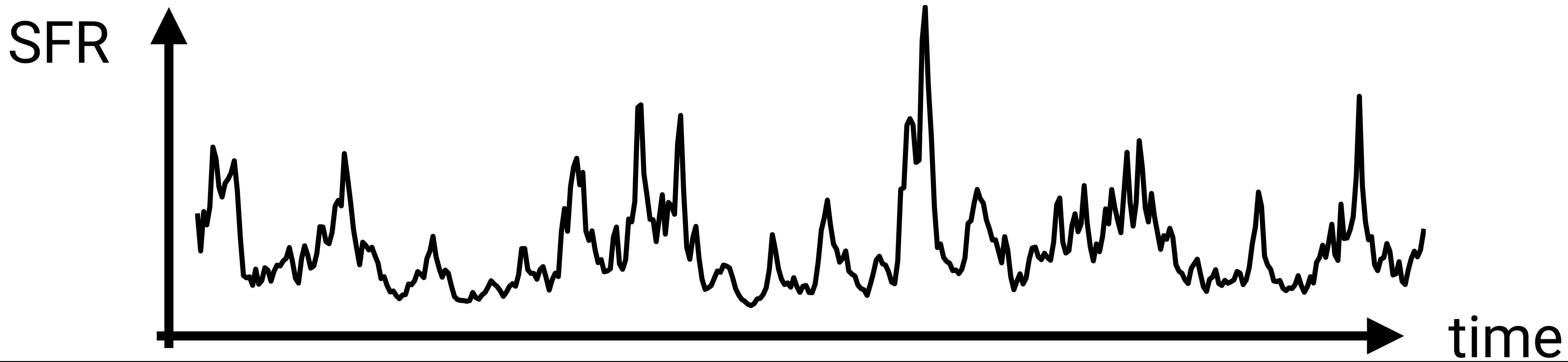


Davies+ 2016

Variability of star formation

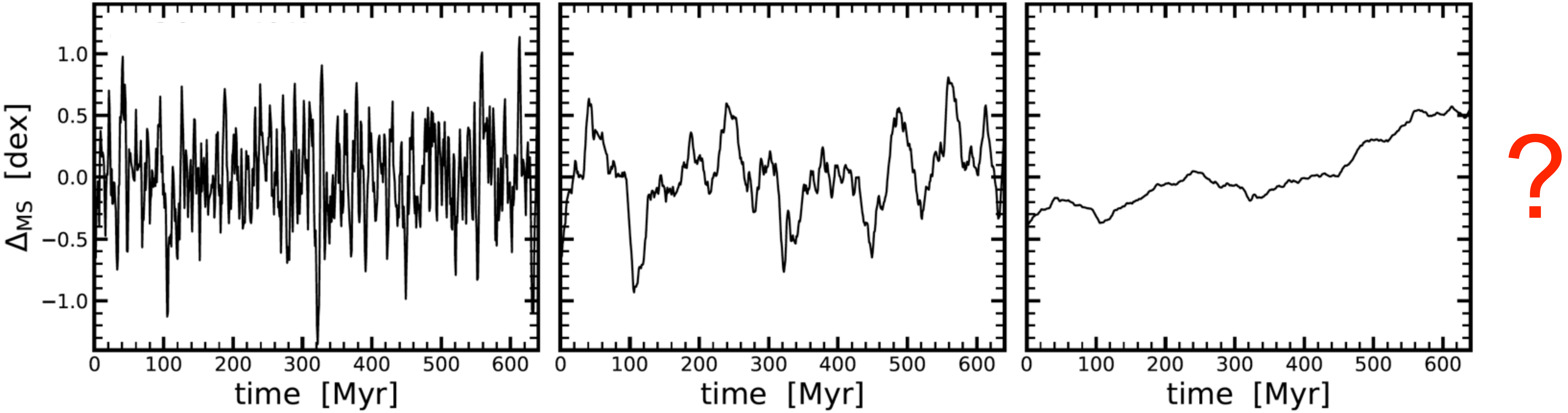
Star formation is regulated on multiple spatial and temporal scales!





Variability of star formation

Caplar & Tacchella (2019)
Tacchella, Forbes & Caplar (2020)
Matthee & Schaye (2019)
Abramson+ (2015)



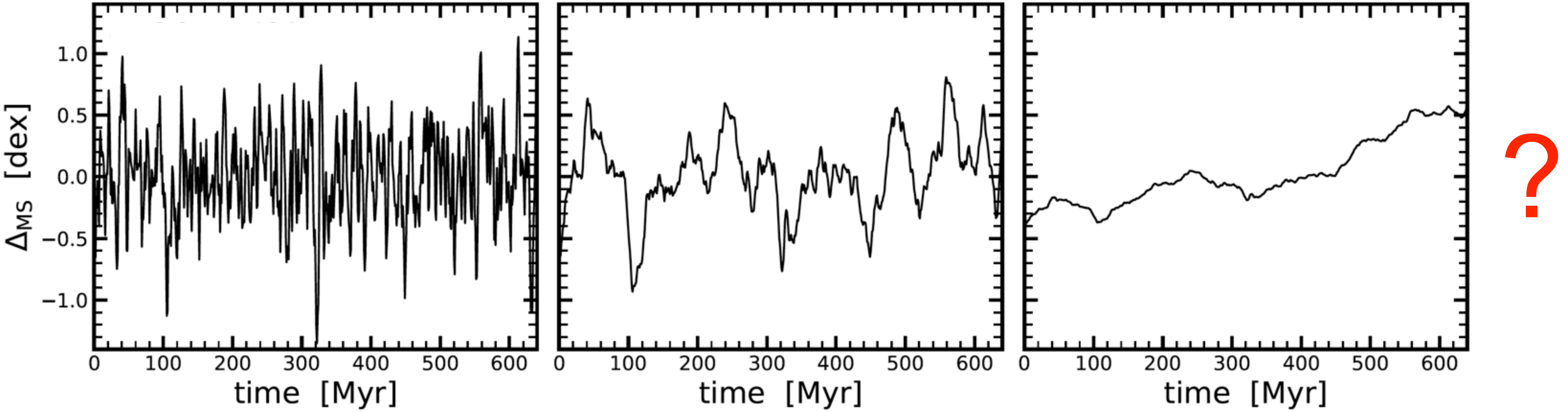
How do galaxies evolve about the star-forming main sequence?

Is σ_{MS} set by oscillation on short ($< t_H$) or long ($\approx t_H$) timescales?

- important for the physics of star formation
- important for the the interpretation of scaling relations

Variability of star formation

Caplar & Tacchella (2019)
Tacchella, Forbes & Caplar (2020)



Caplar & Tacchella (2019): idea from AGN light curve modeling
➜ look at the **power spectrum density** of the star-formation history!

$$\frac{d\mathrm{SFR}(t)}{dt} + \frac{1}{\tau_{\mathrm{eq}}} \cdot \mathrm{SFR}(t) = \tilde{\Phi}(t)$$

regulator model (e.g., Lilly+ 2013)

inflow rate is described as a stochastic processes (with a certain PSD)
➜ stochastic differential equation

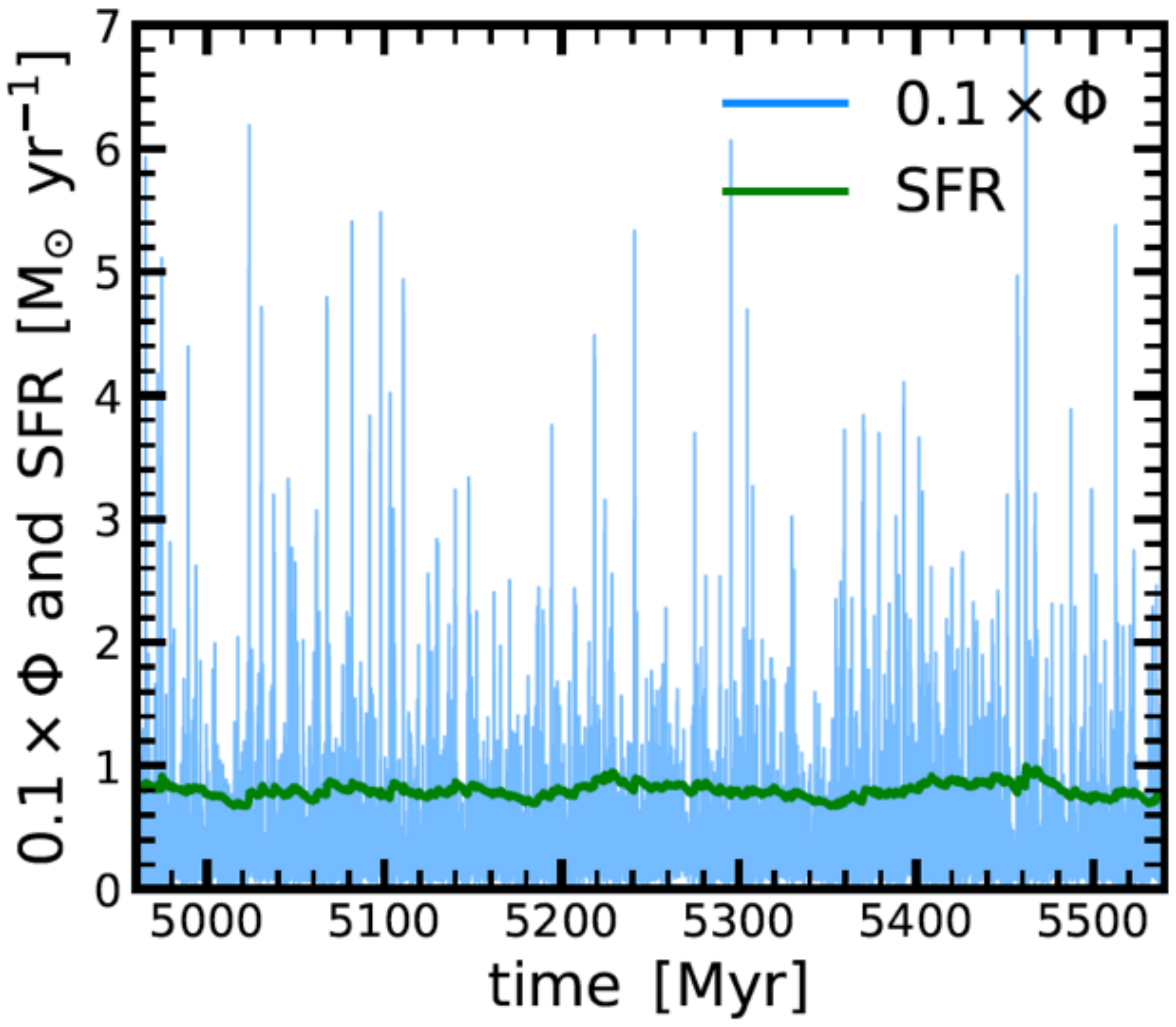
Regulator model: power spectral density

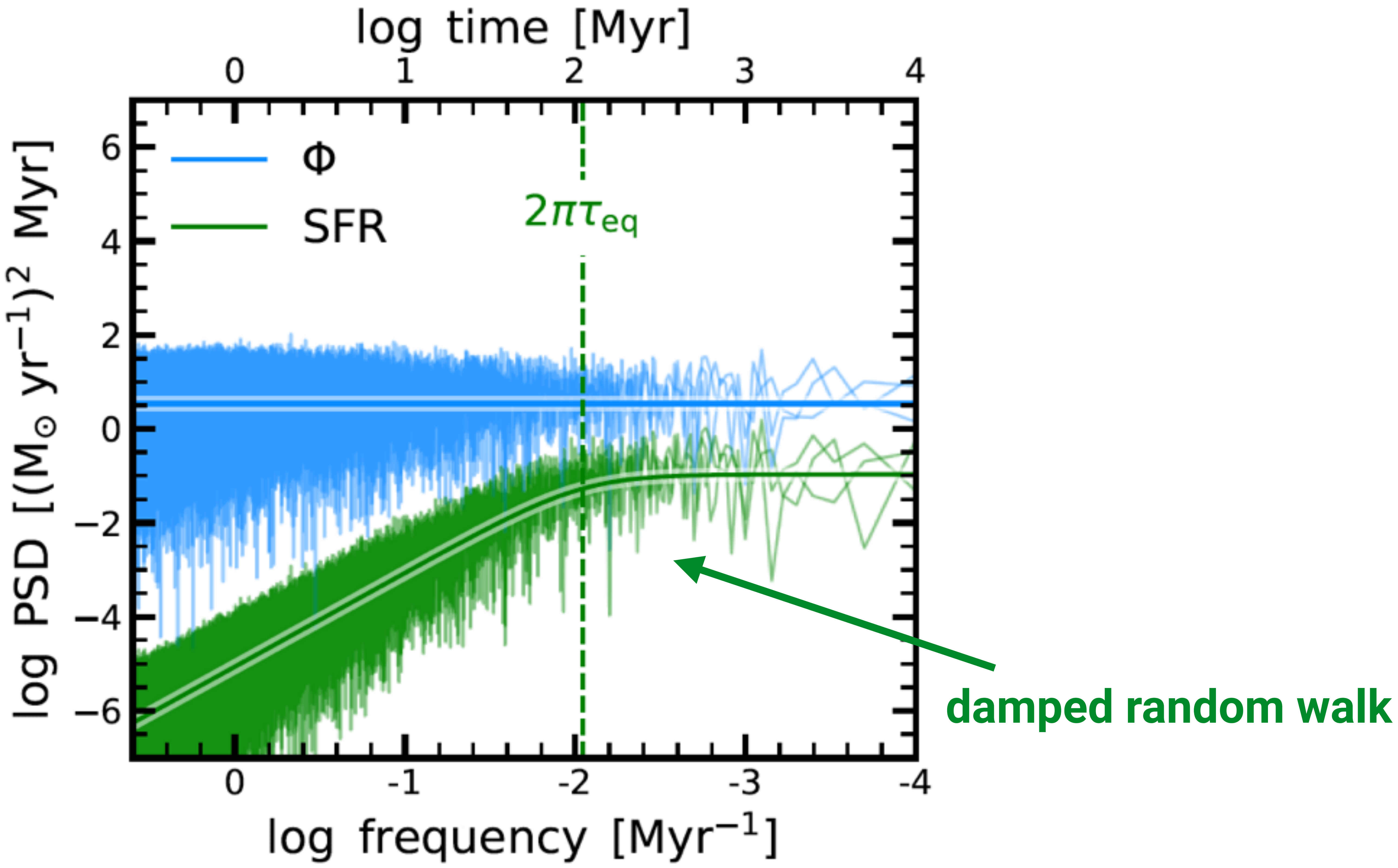
Tacchella, Forbes & Caplar (2020)

$$\frac{d\mathrm{SFR}(t)}{dt} + \frac{1}{\tau_{\mathrm{eq}}} \cdot \mathrm{SFR}(t) = \tilde{\Phi}(t)$$

➜

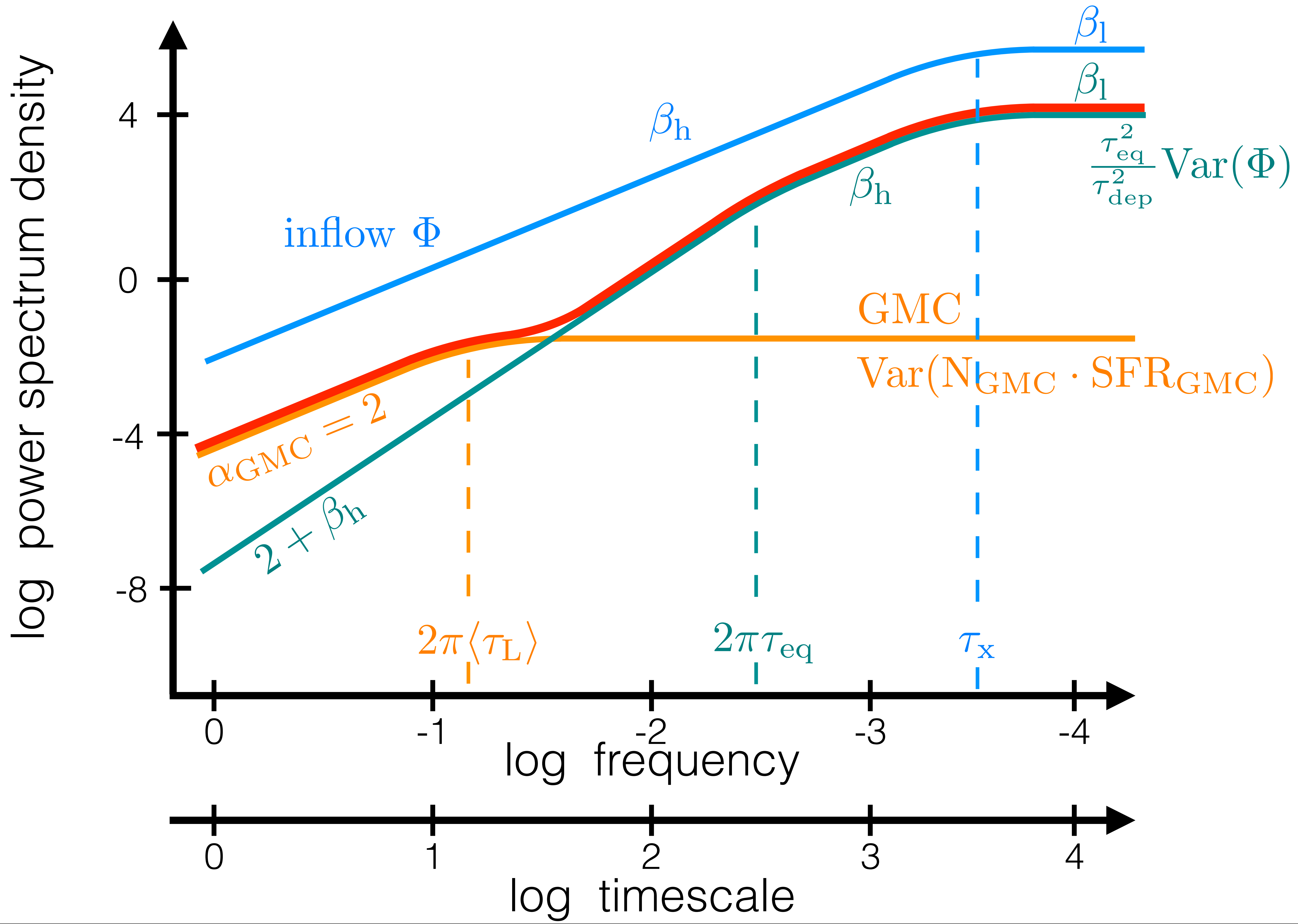
$$\mathrm{PSD}(f) = \frac{\sigma_{\mathrm{reg}}^2}{1 + (2\pi\tau_{\mathrm{eq}} f)^2}$$ with $\sigma_{\mathrm{reg}}^2 \propto \mathrm{Var}(\Phi)$





Tacchella, Forbes & Caplar (2020)

Power spectral density (PSD)



- full model ("extended regulator model)
  ➜ GMCs sustain star formation
  ➜ source of SF variability:
  - inflow rate
  - GMC sampling
- breaks correspond interesting timescale of the galaxy:
  - average lifetime of GMCs
  - equilibrium timescale ($\approx t_{dep}/\lambda$)
  - decorrelation timescale in accretion

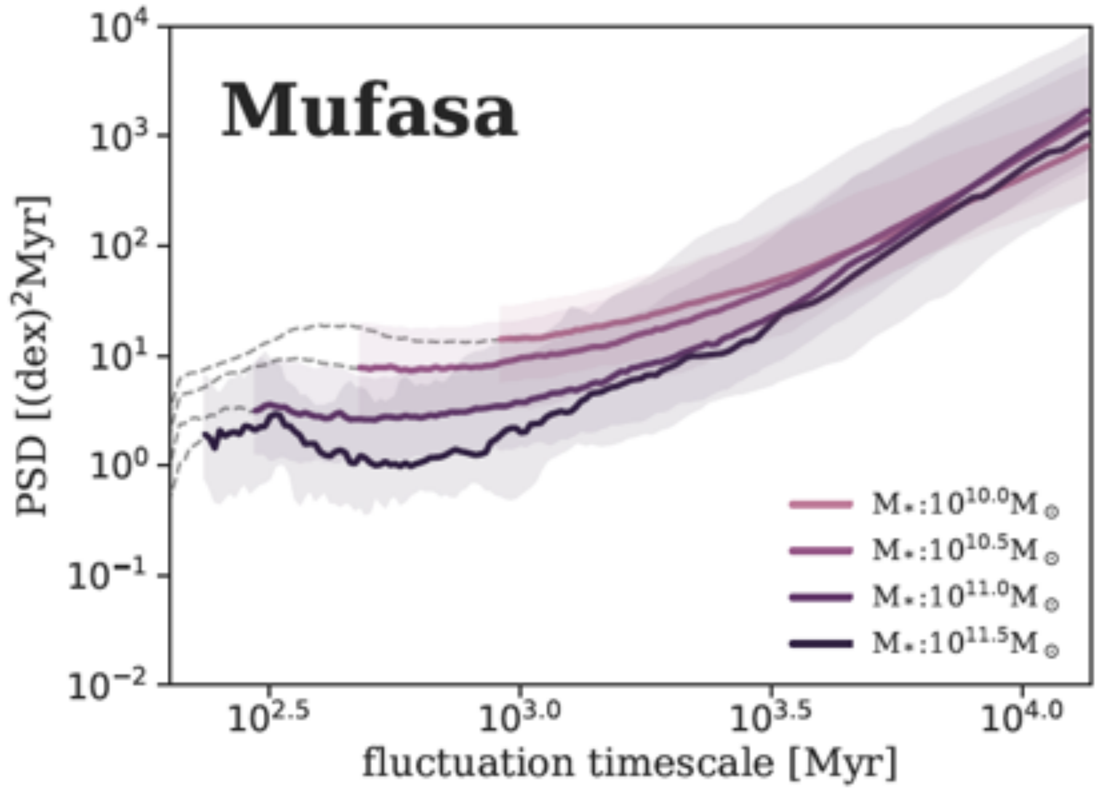
Landscape of numerical simulations

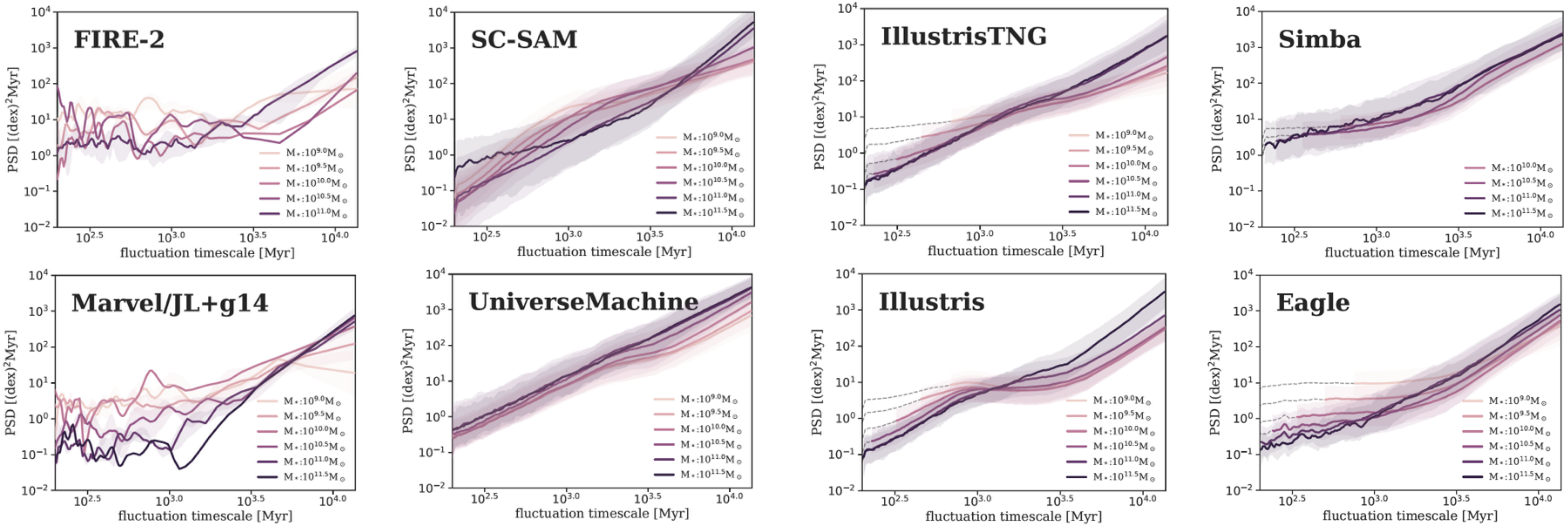
Nelson+ (2019)
Vogelsberger+ (2020)

PSD of different numerical models

Iyer, Tacchella+ (2020)

large diversity in PSD shape and normalization…
interesting parameter space!
Different implementation of feedback and star formation lead to different variability of star formation!

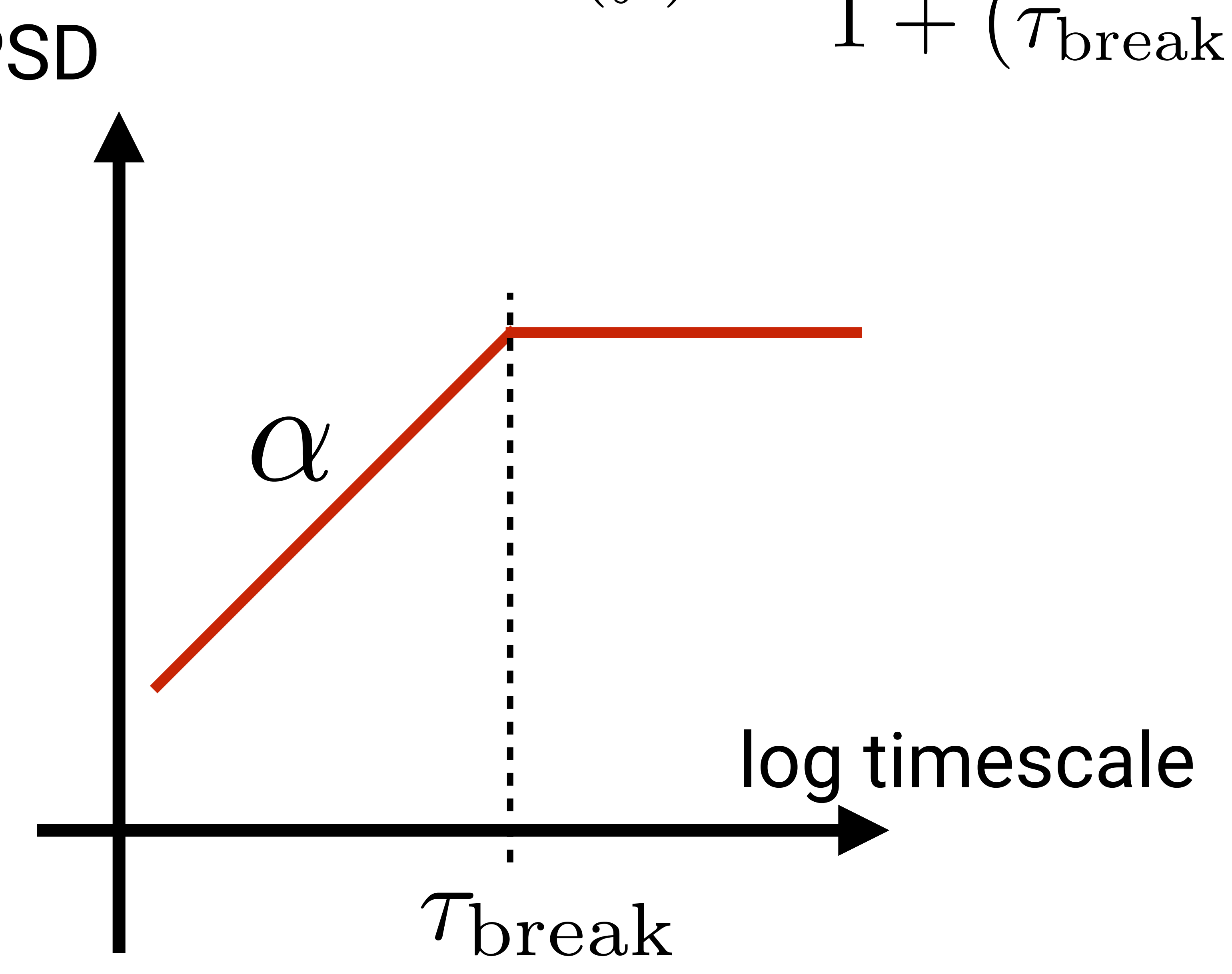


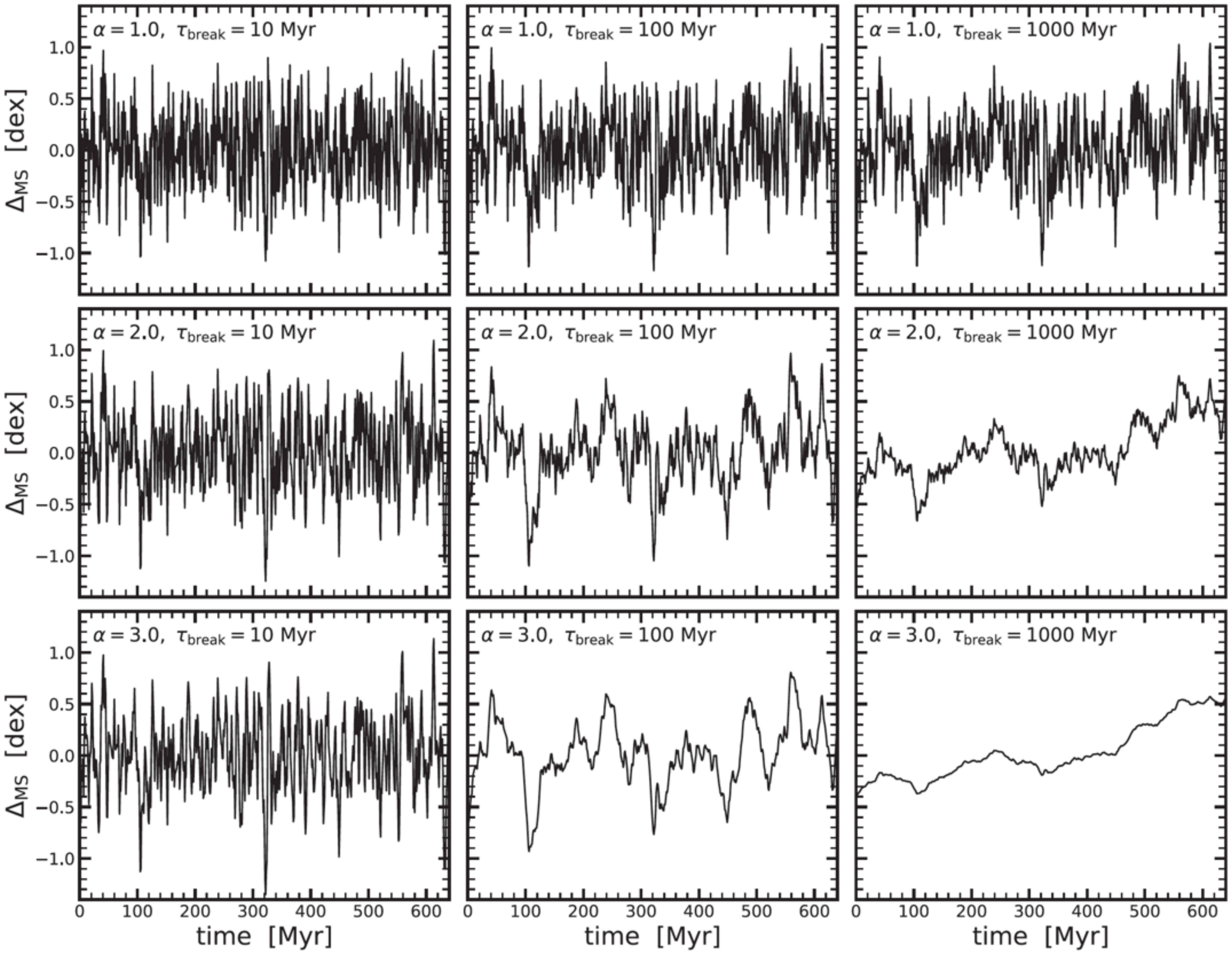


First attempt to constrain the PSD observationally

"No one trusts a model except the person who wrote it; everyone trusts an observation, except the person who made it." — Harlow Shapley

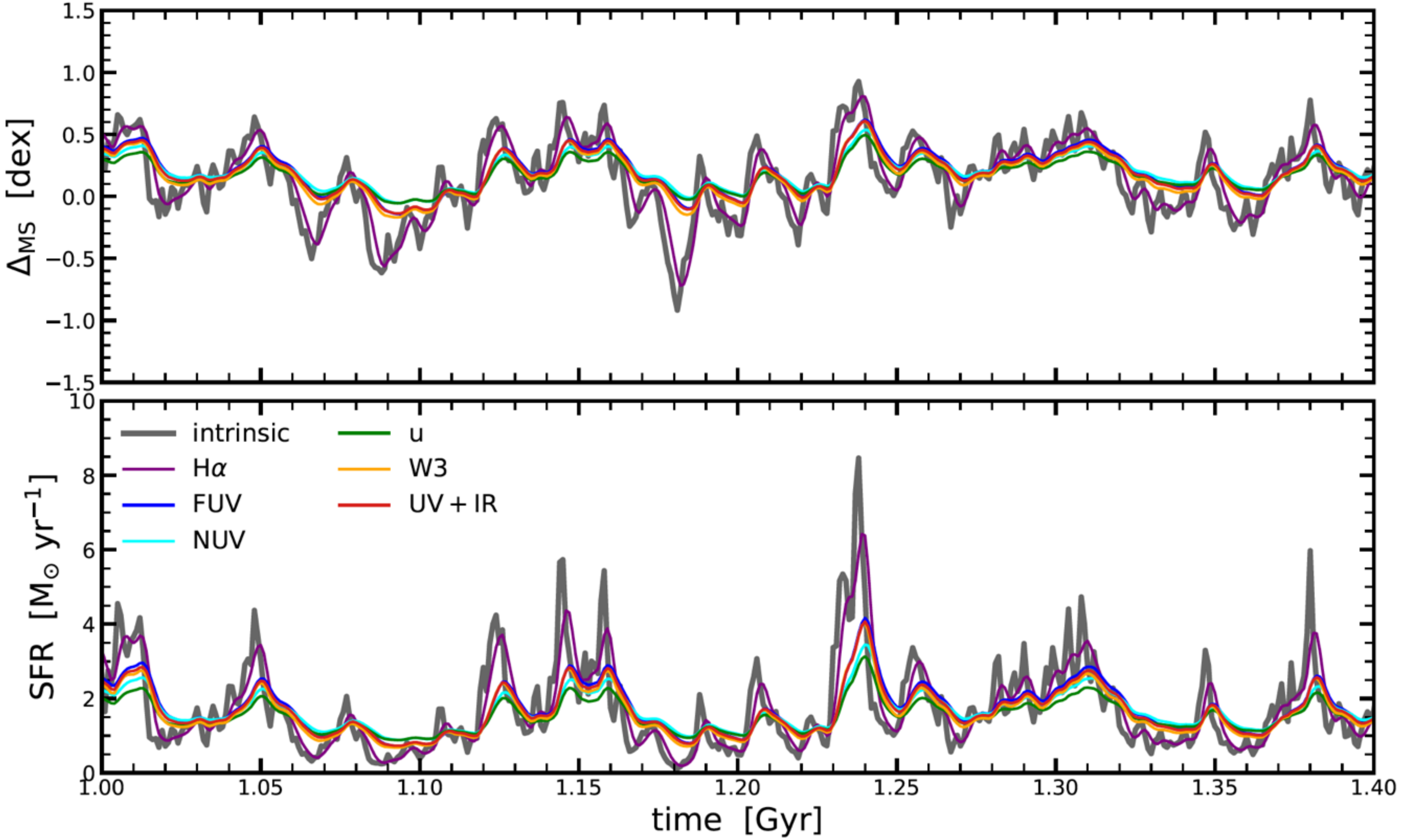
$$\mathrm{PSD}(f) = \frac{\sigma^2}{1 + (\tau_{\mathrm{break}} f)^{\alpha}}$$



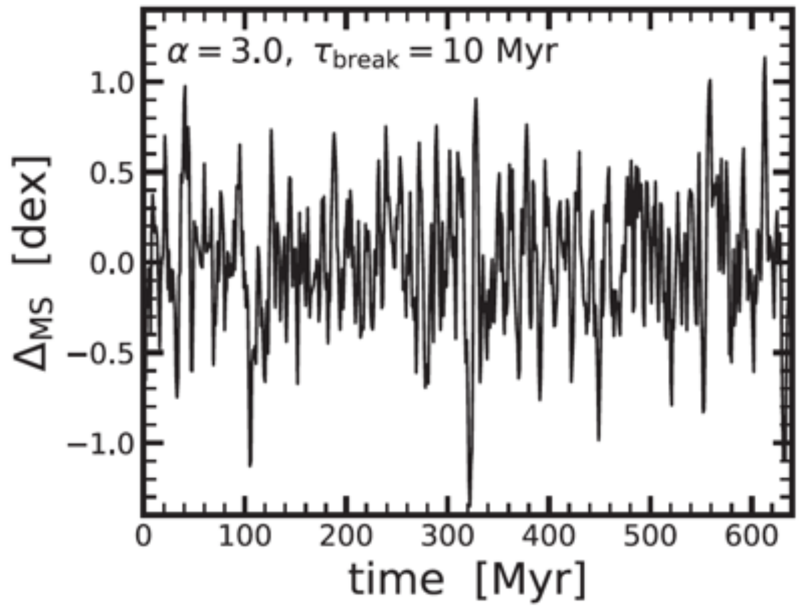


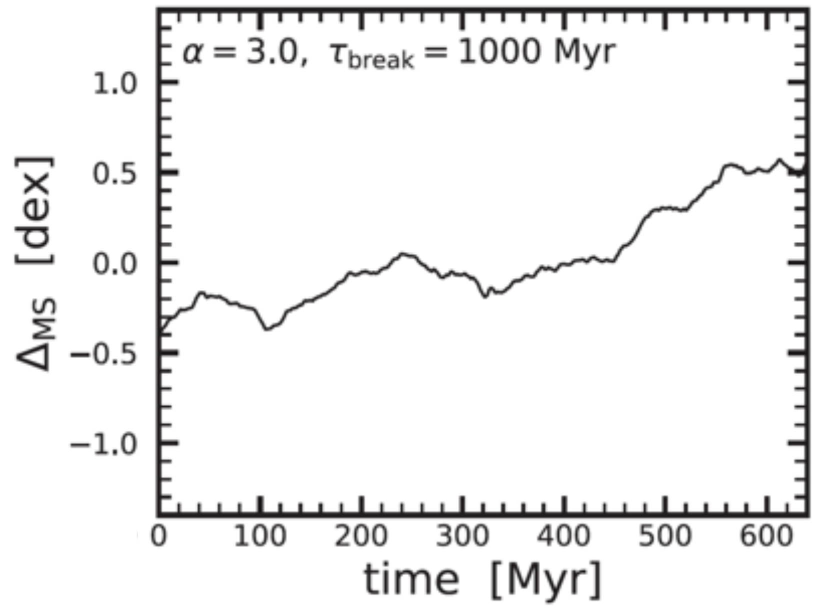
Caplar & Tacchella (2019)

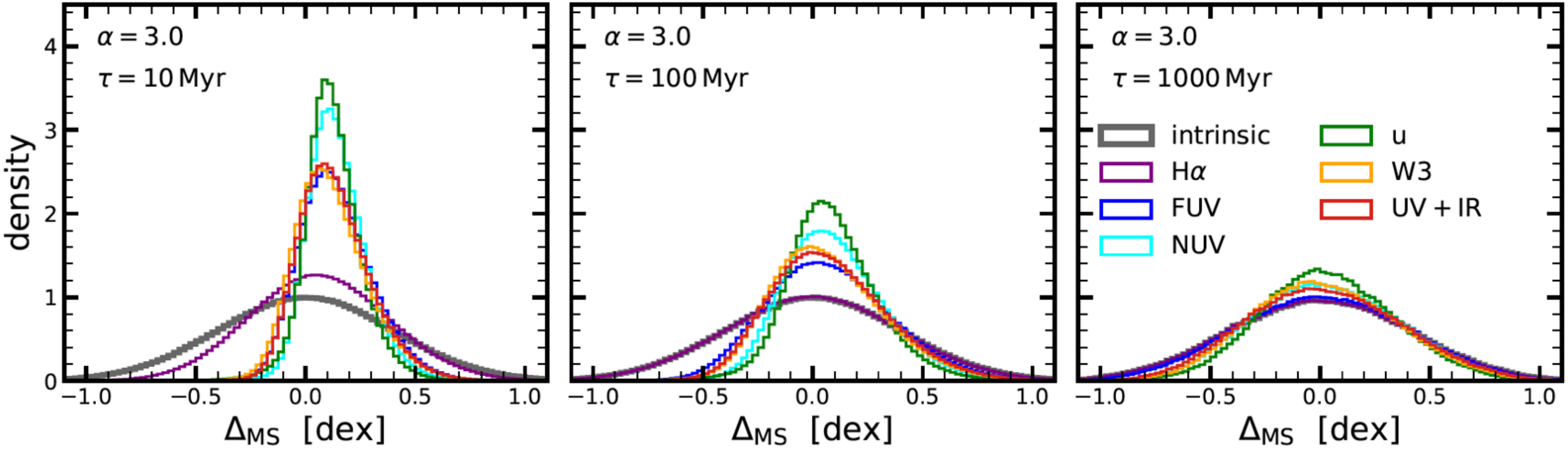
Modeling star-formation histories with a power spectrum



SFMS distribution seen by different SFR indicators



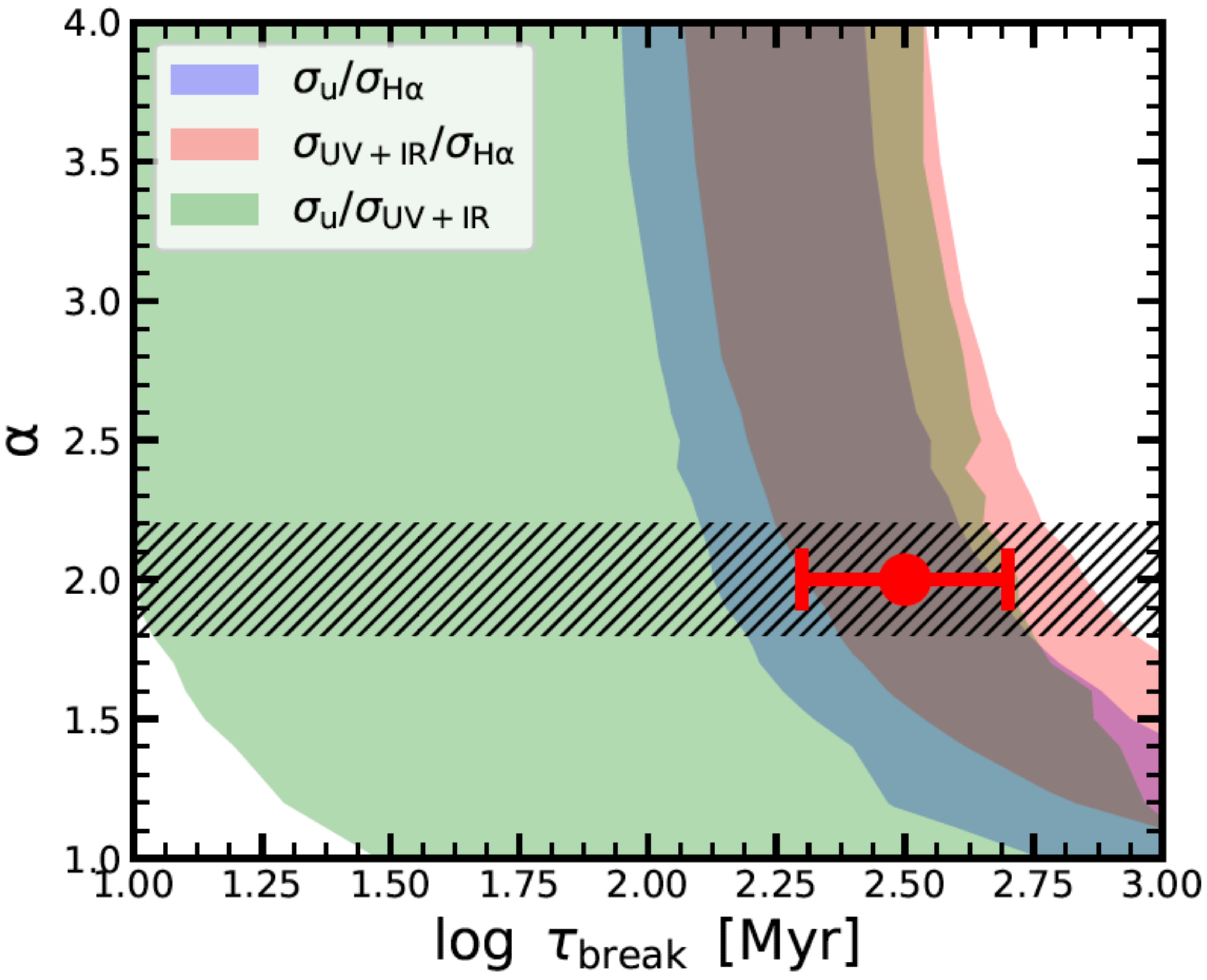




Caplar & Tacchella (2019)

Current constraints on the PSD

for MW-mass galaxies:

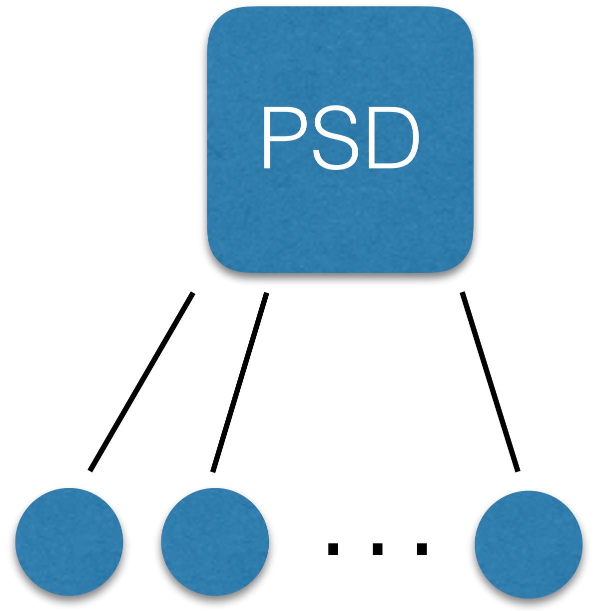


Observational data:

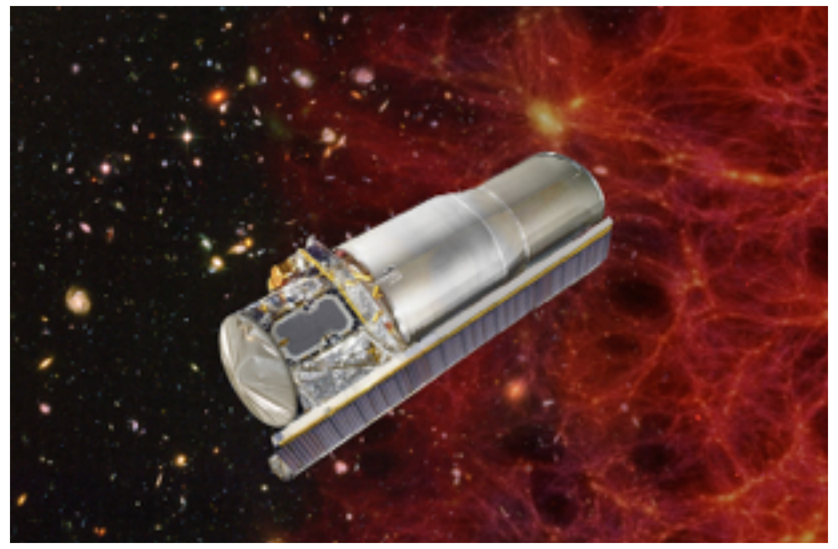
- GAMA survey; z<0.1; 9000 galaxies
- Davies et al. 2019 measured the MS scatter for different indicators:

$$\tau_{\rm break} = 320^{+190}_{-120}\ {\rm Myr}$$

- see also Wang & Lilly 2020: $\alpha = 1 - 2$
- more work ahead to measure PSD:
  - select galaxies with the same PSD (i.e. control for galaxy properties such as environment, stellar mass, etc.)
  - break degeneracy between IMF, Z, attenuation, etc.
    ➜ couple SED modelling with PSD measurement via Bayesian hierarchical model



Requirement:
large, homogeneous photometric datasets with coverage of emission lines



Conclusions

- Star formation involves a variety of processes acting from small/short to large/long timescales
  ➜ Power Spectrum Density (PSD) is a powerful way to quantify the star-formation variability and test different model of galaxy formation and evolution
- Breaks of the PSD correspond interesting timescales of galaxies:
  - average lifetime of GMCs
  - equilibrium timescale ($\approx t_{dep}/\lambda$)
  - decorrelation timescale in accretion

  ➜ resolve galaxies temporally to learn about the internal workings (Tacchella+ 20)
- Theoretical models (numerical, SAMs) make a wide range of predictions for the PSD (Iyer, Tacchella+ 20)
- Observations of z~0: star-formation histories decorrelate on ~300 Myr (Caplar & Tacchella 19)
- Current on-going work:
  - self-consistently predict H-alpha emission from simulations (how well does H-alpha trace the SFR?)
  - build an "SED-fitting" framework to break dust-Z-PSD degeneracy (first hierarchical mode, later beyond)
- much science ahead with ATLAS:
  - extend this approach beyond z>3 => measure PSD as a function of redshift
  - large number of galaxies are crucial (split galaxies in sub-groups with the same PSD, use ergodicity to constrain PSD)