The Unintended Consequences of Stochastic Sub-Resolution Modeling in Galaxy Formation

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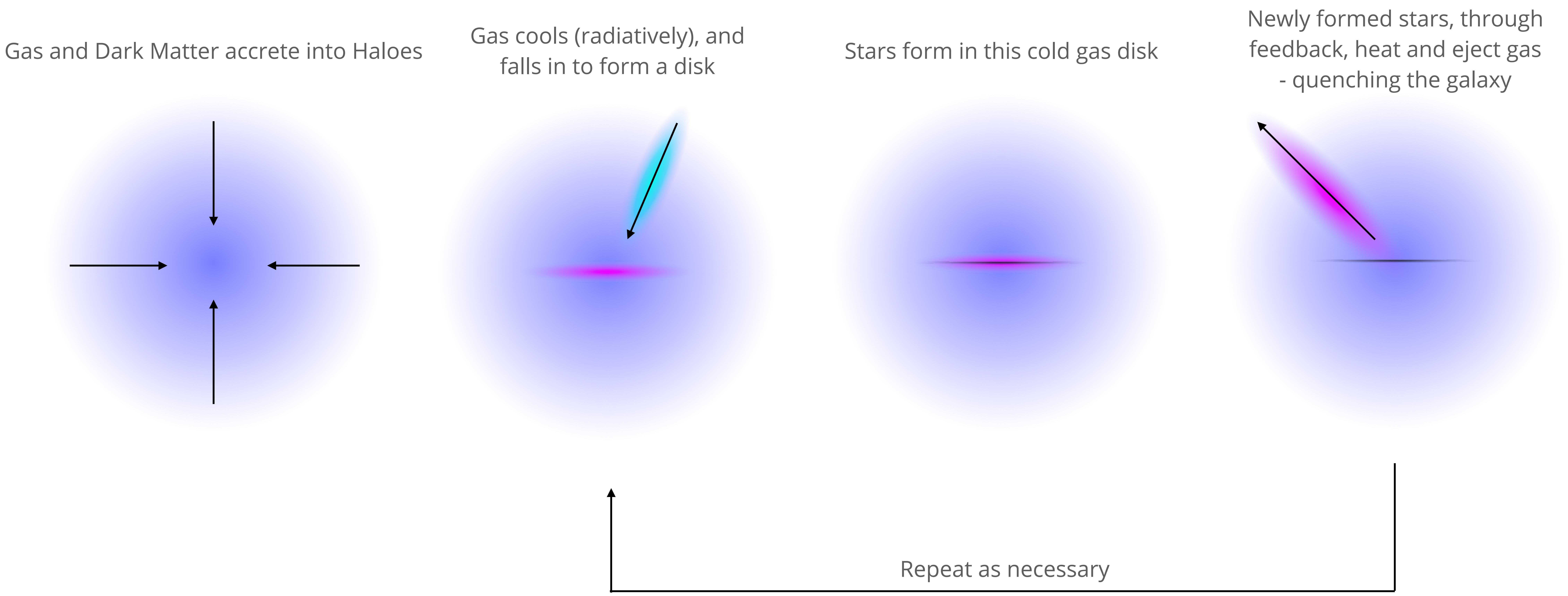
Gas temperature

Galaxy Formation: A Schematic



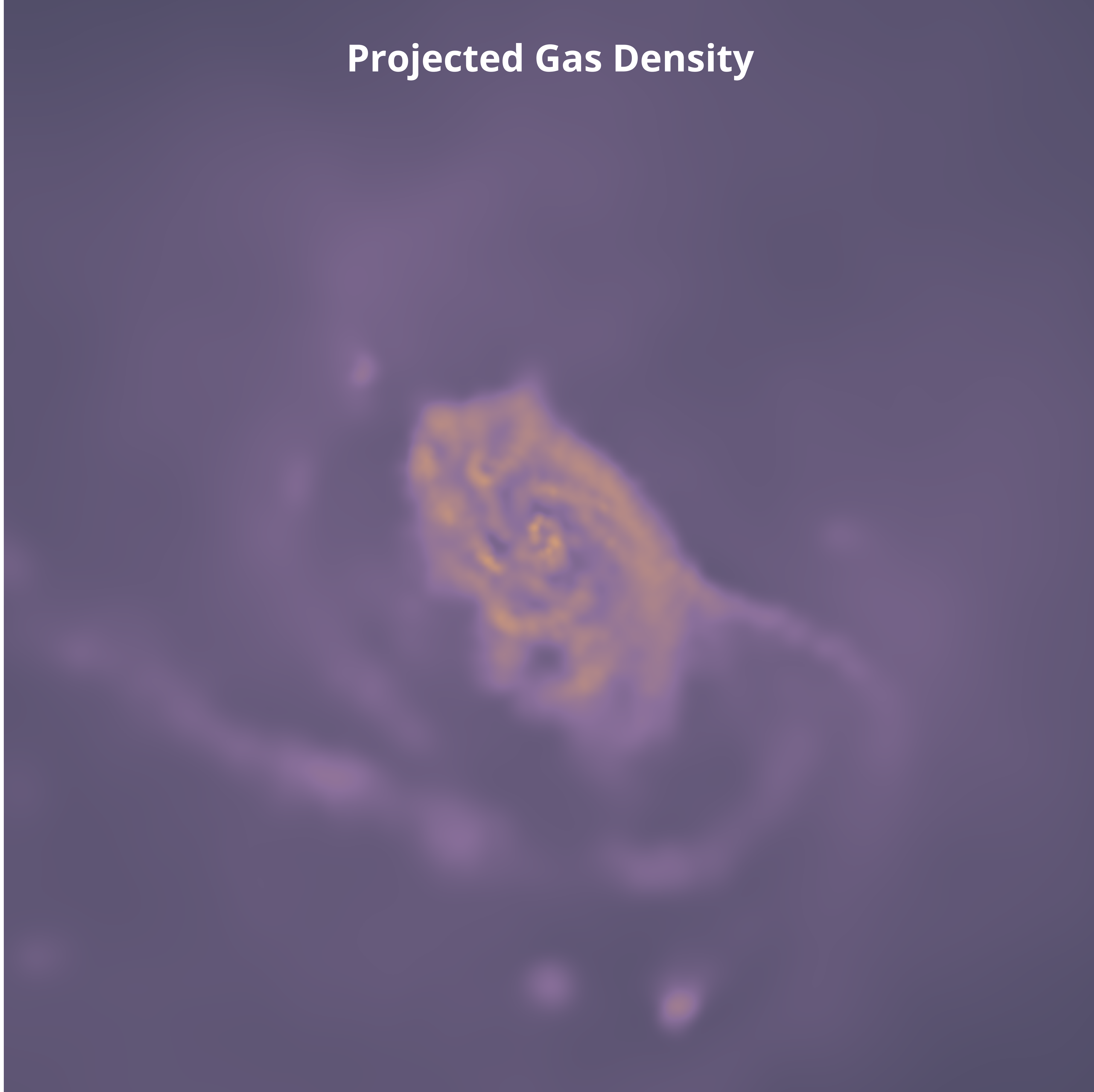
See Somerville & Dave (2015) for an excellent review, with Vogelsberger (2020) and Tumlinson et al. (2017)

Modeling Star Formation

Making stars is easy! I can write down a basic **Schmidt law**:

$$\dot{\rho}_* = \frac{\rho_g}{t_{\mathrm{ff}}}$$

With t_{ff} the free-fall time of a self-gravitating gas cloud.



Modeling Star Formation

The mass of stars that the gas forms can then be written by removing the volume dependence:

$$\dot{m}_* = \frac{m_g}{t_{\mathrm{ff}}} \approx 2 m_g \sqrt{G\rho}$$

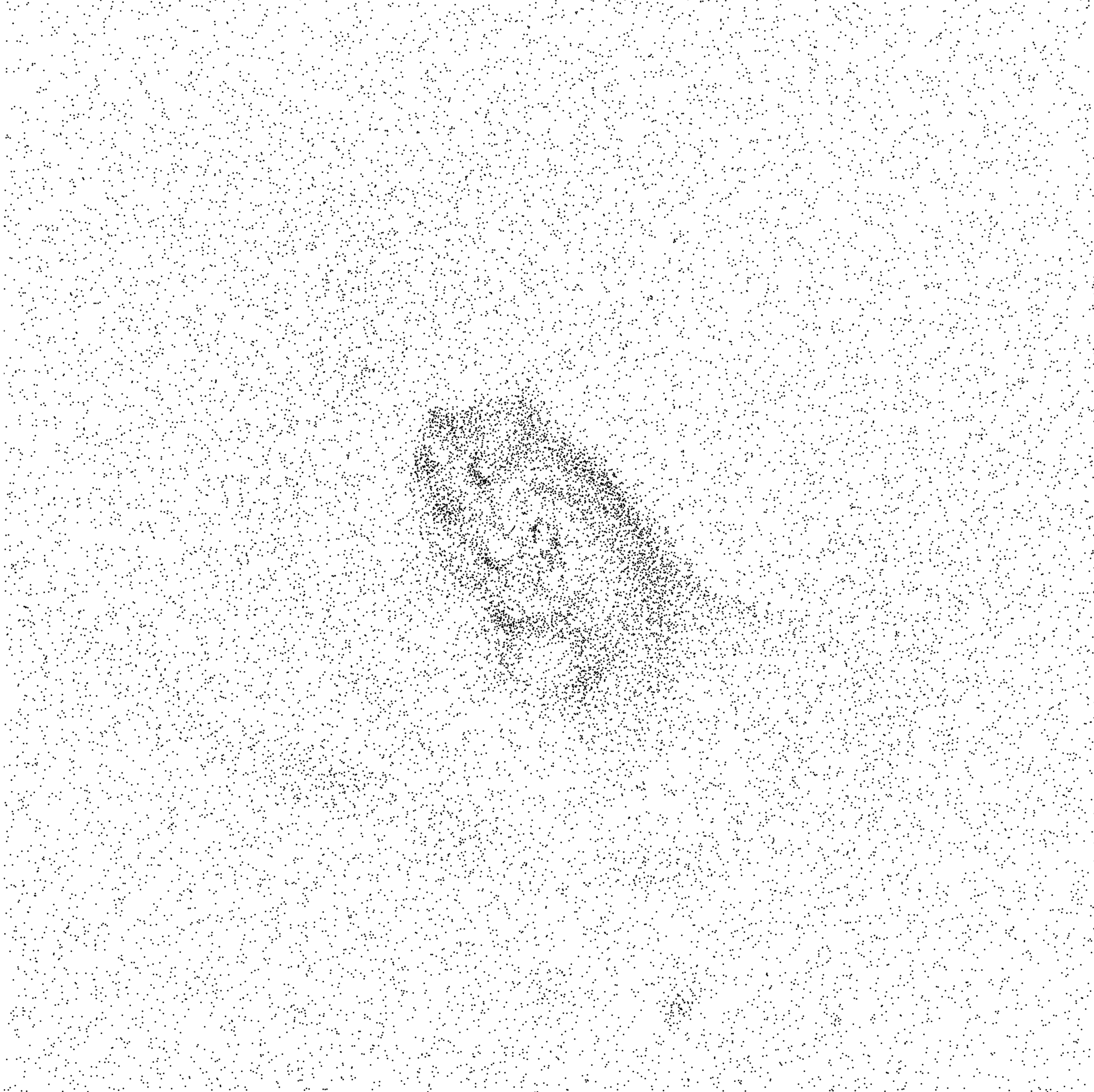
See also: Schaye & Dalla Vecchia (2009)

Modeling Star Formation

We have discrete particles, on discrete time-steps. So, we introduce the concept of a **stochastic sub-grid model**:

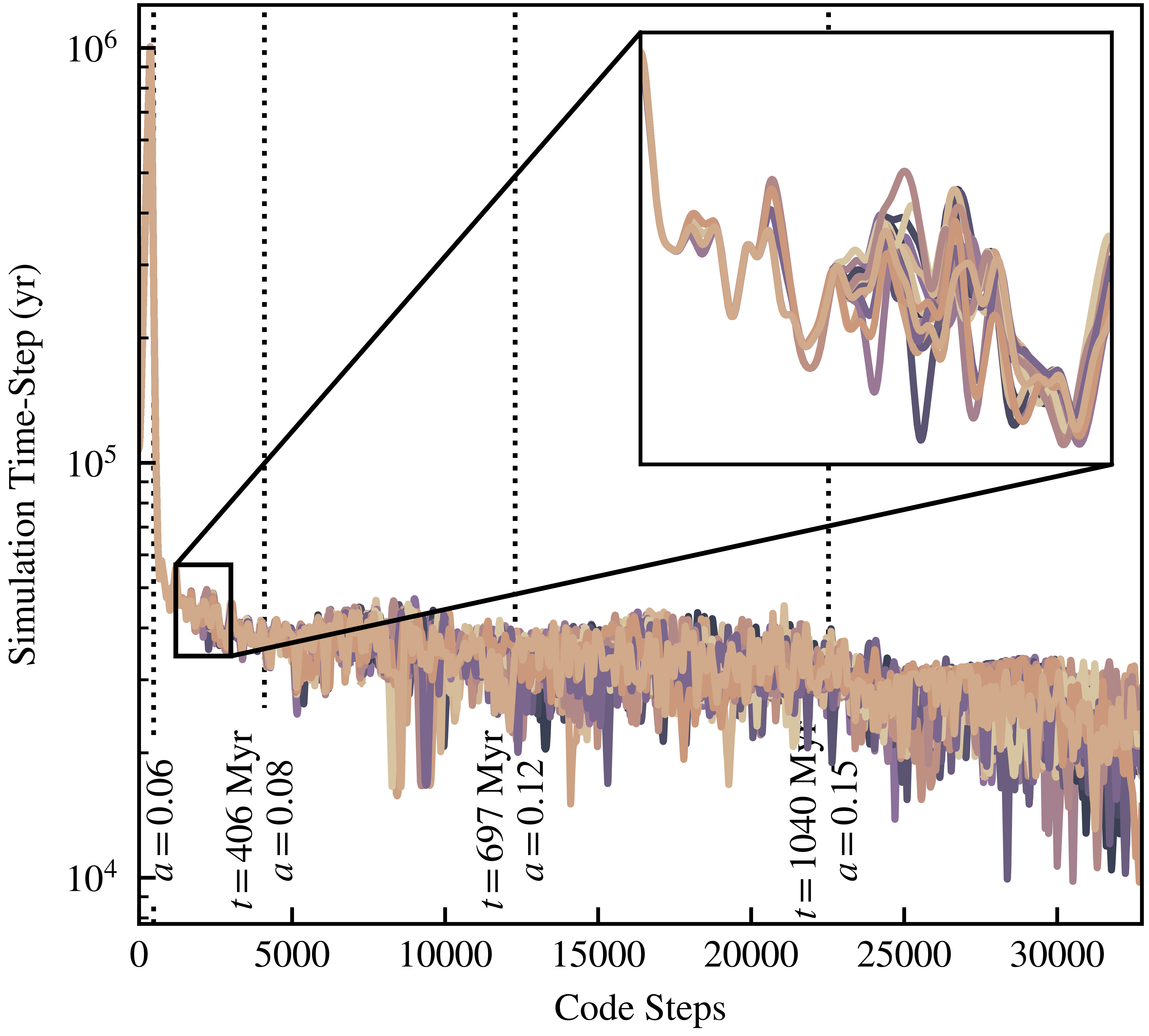
$$P_*(\Delta t) = \frac{\dot{m}_*}{m_g}\Delta t = \frac{\Delta t}{t_{\mathrm{ff}}} \approx \frac{\sqrt{G\rho}}{2}\Delta t$$

Note: EAGLE actually uses a pressure law for star formation, but that's more complicated and would distract from the point about probabilities.



Random Re-Simulations

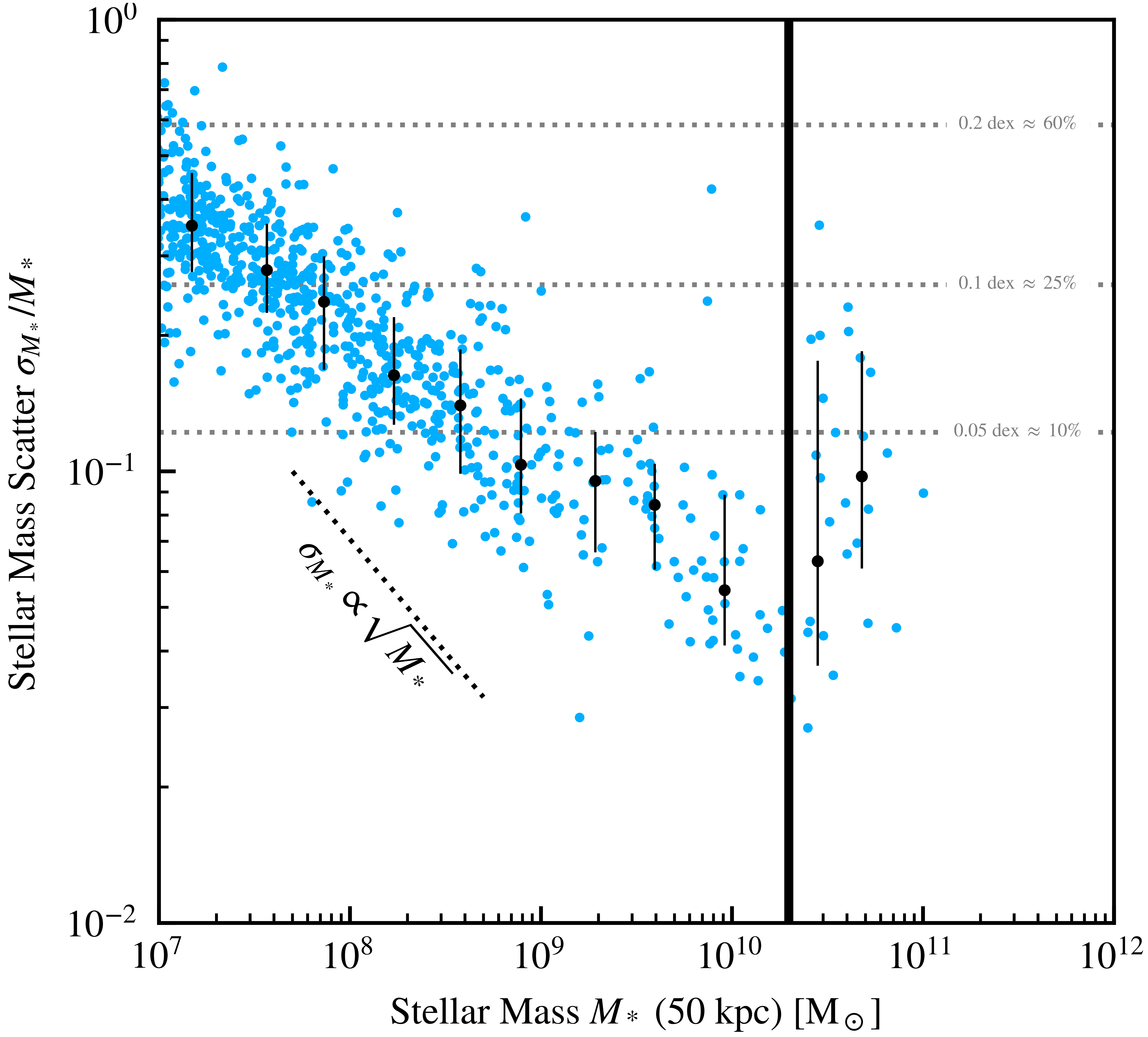
- Using a **non-reproducible** code (employs task-based parallelism), we **re-simulate** the **same volume** 16 times.
- Time-steps **diverge** between re-simulations after the **first stochastic event** (the birth of the first star).




DM Projected Density
Gas Temperature
HI Projected Density
1 Mpc
Gas Temperature

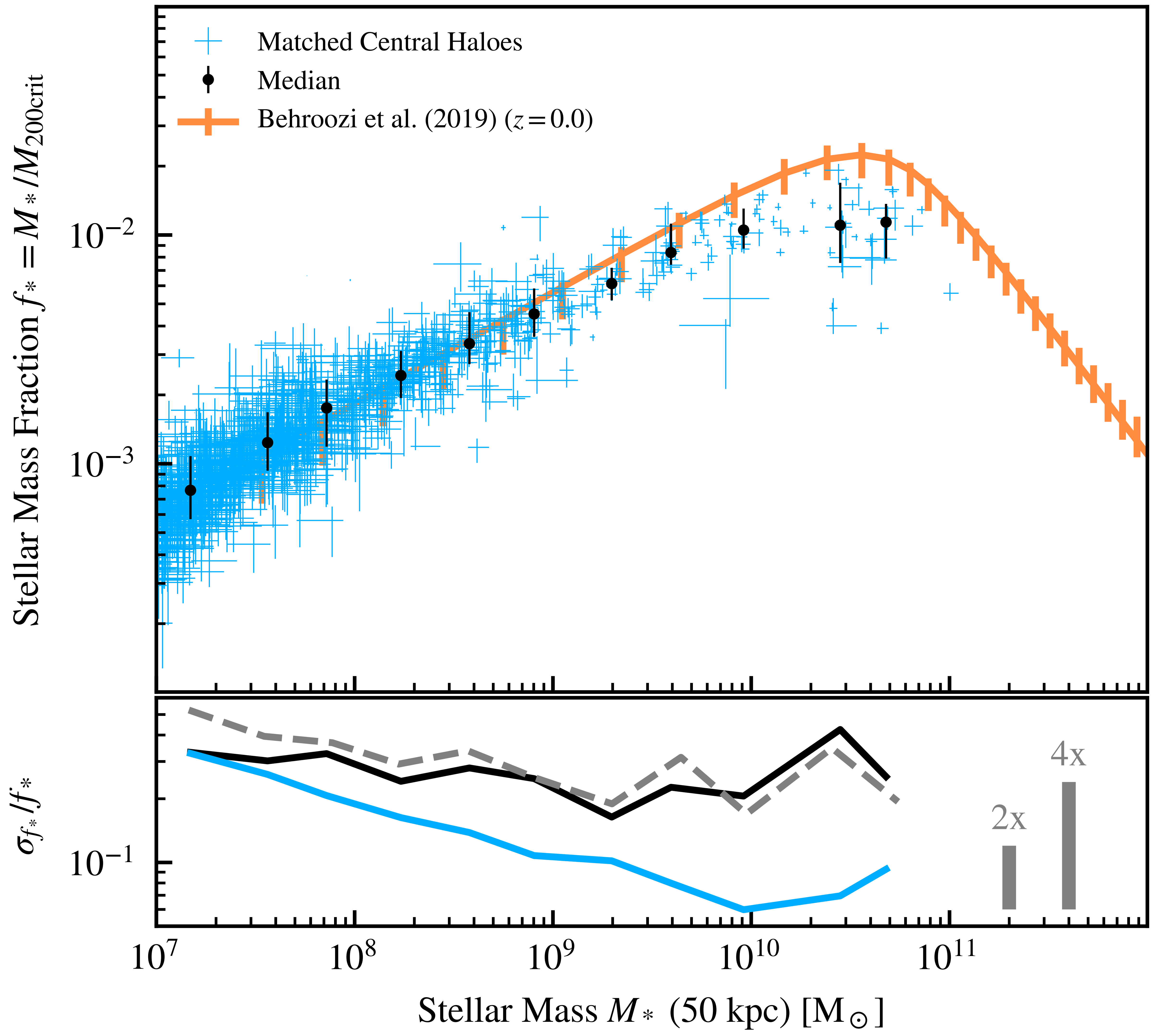
Galaxy Variability

- **Simple properties** of galaxies can easily **vary by over 10%** between re-simulations of the same objects!
- Stochasticity of **cumulative processes** typically follows a **Poisson** noise-like distribution, until **new sub-grid physics** kicks in!



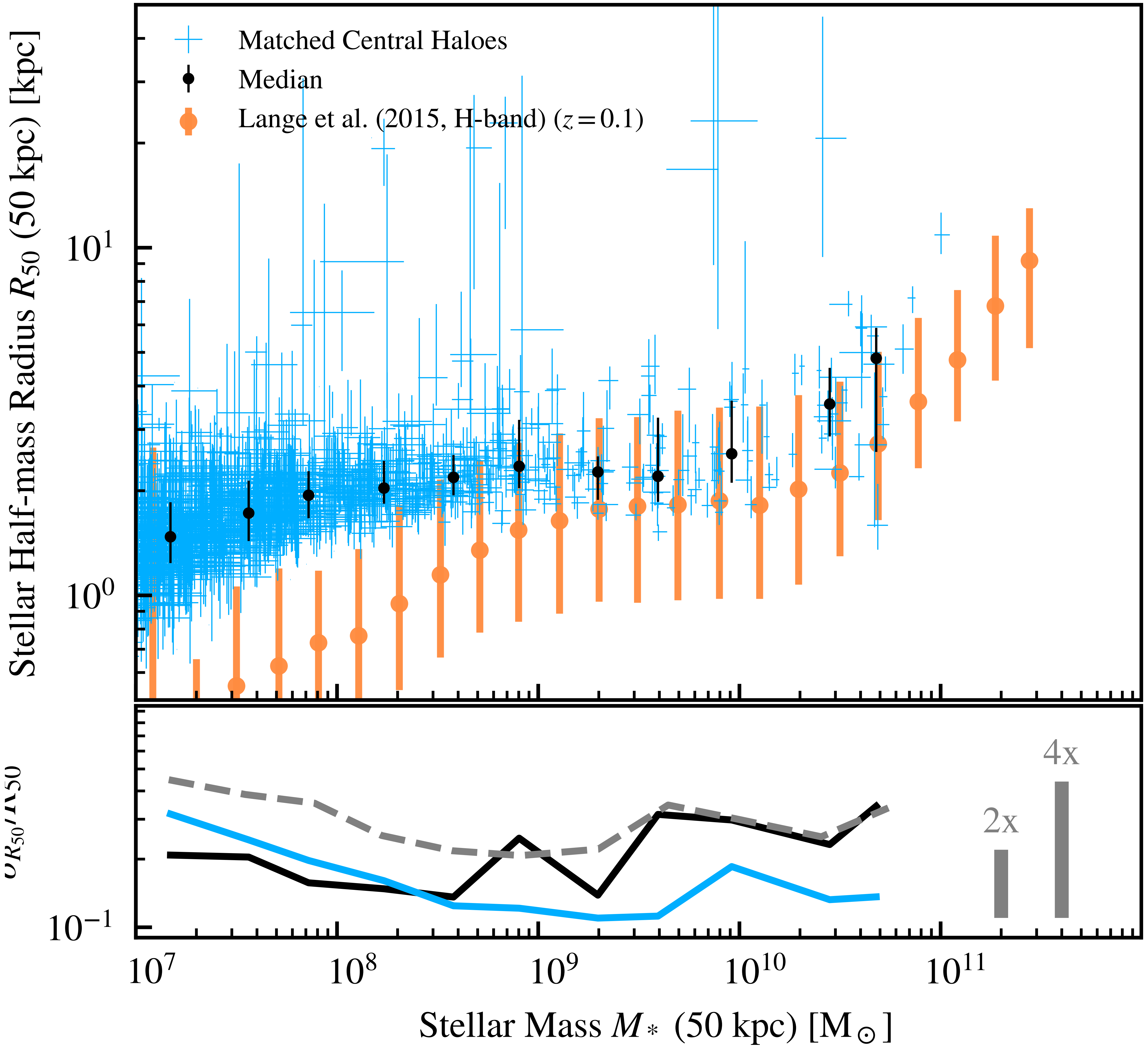
Impact on Scaling Relations

- **Key output** of galaxy formation simulations: **predictions** for the **shape** and **scatter** in **galaxy scaling relations**.
- At the **lowest masses** (with the highest Poisson error), **scatter** in the **scaling relation** is dominated by **random variability** between simulations.



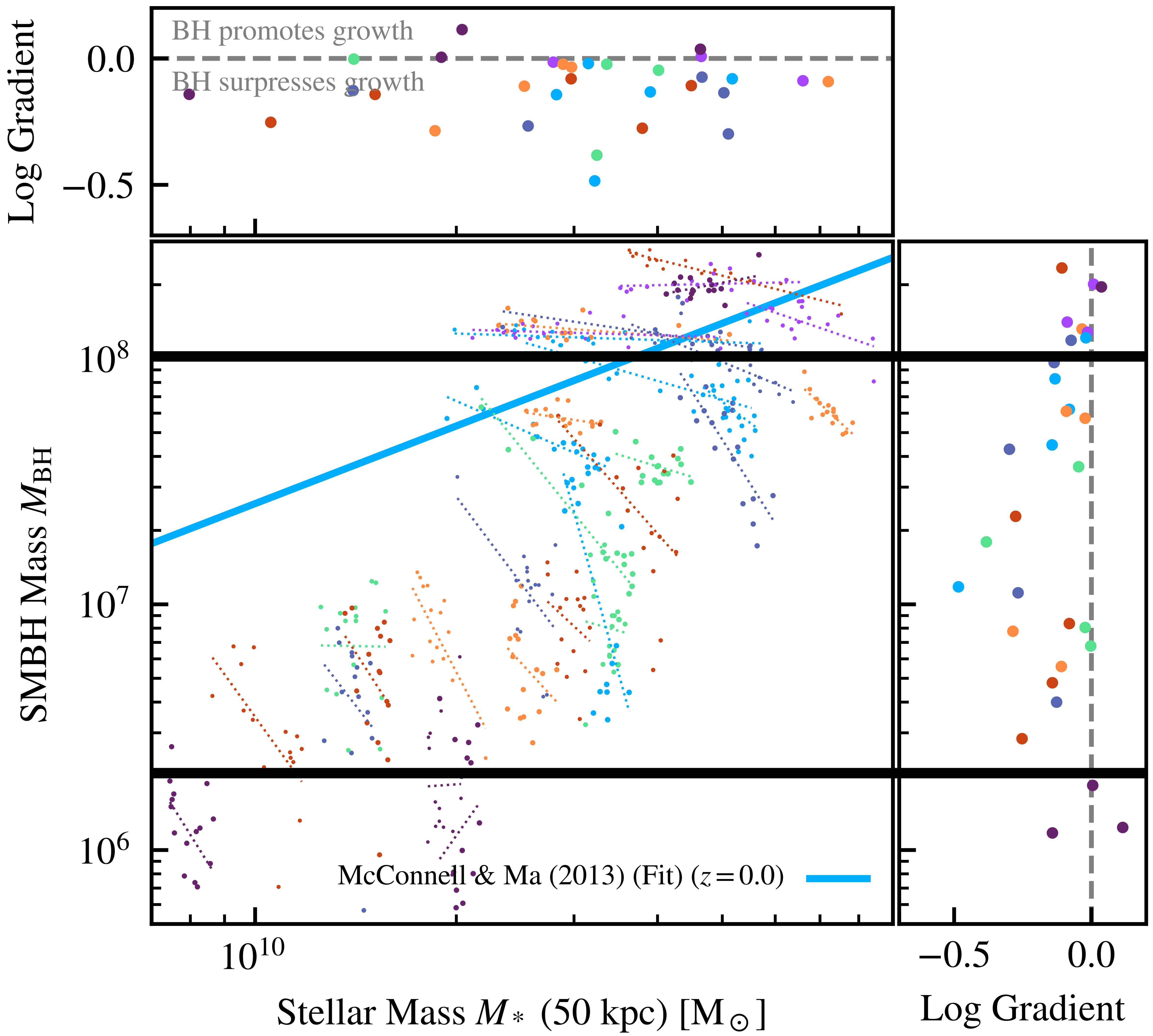
Impact on Scaling Relations

- **Sizes** of galaxies show even **higher** levels of variability, with **random scatter** a **significant component** in the scatter in this scaling relation even up to **high galaxy masses**.
- **Open question**: are the **extreme predictions** of the model **valid**, or should we always **take the median**?



Understanding Models Through Stochasticity

- **Small variations** in individual galaxy properties **correlate** with each other, for instance here the **black hole mass** and **galaxy stellar mass**.
- Here we can learn that **black holes** only significantly **back-react** on their galaxies **up to a mass of 10^8** solar masses, and **above** this just **grow with the galaxy**.



Conclusions

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- **Stochastic** sub-grid/sub-resolution models are **extremely convenient** in codes that **couple to gravity**.
- These models have a **significant impact** on the **chaotic nature** of their associated numerical simulations!
- By understanding **correlations within** this **chaos**, we can **better understand** the underlying **model**.