SMBH Growth in Massive Galaxies at Cosmic Dawn

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Advisor

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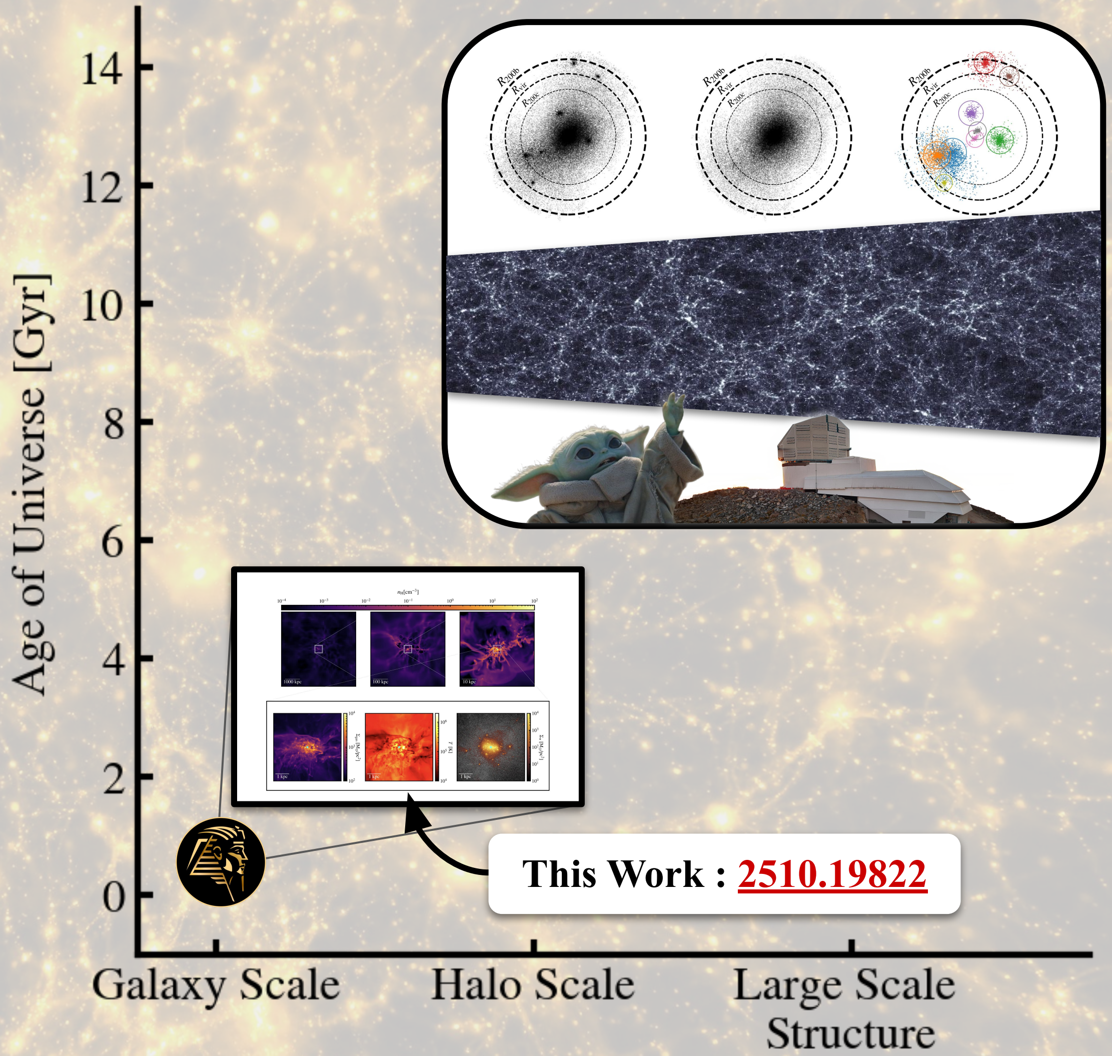
I'm developing the next generation of tools for simulating **halo scale observables on-the-fly**. I aim to study **baryonic feedback** across a large range of scales and epochs.

the Hertz FOUNDATION



What has JWST seen so far?

- Plethora of Massive Cosmic Dawn Galaxies (MDGs) with

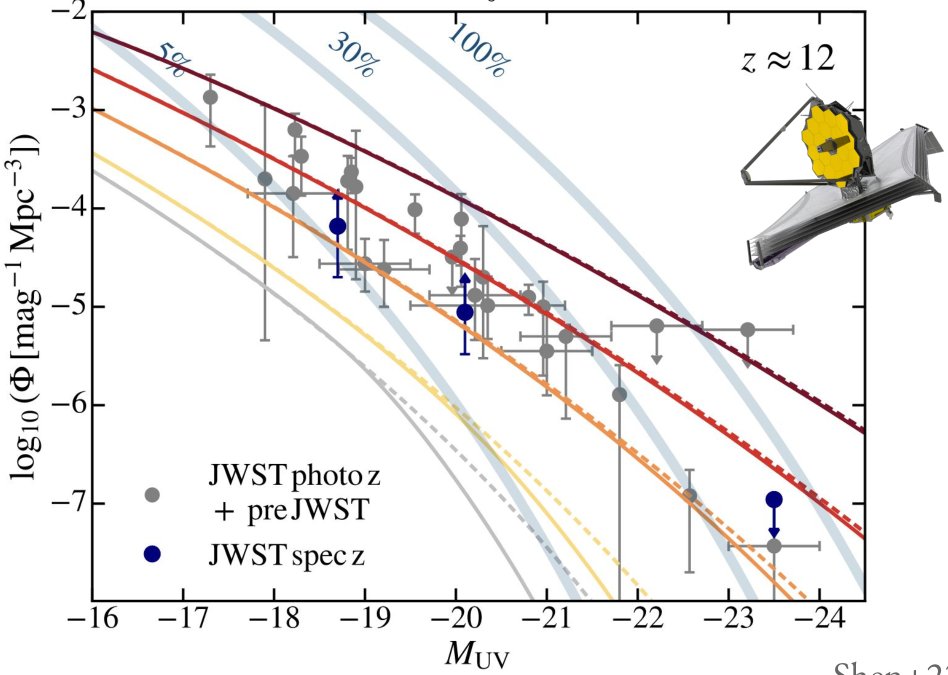
$$M_\star \gtrsim 10^8\ \mathrm{M}_\odot \qquad \dot{M}_\star \gtrsim 1\ \mathrm{M}_\odot/\mathrm{yr}$$

- So massive that they are inconsistent with expectations

- Inferred UV Luminosity Function (UVLF) suggests ~10-30% of baryons must be converted into stars

- Typical Star Formation Efficiency (SFE) in the local universe is $\lesssim 5\%$

$$\dot{M}_\star = \epsilon_\star f_\mathrm{b} \dot{M}_\mathrm{acc}$$



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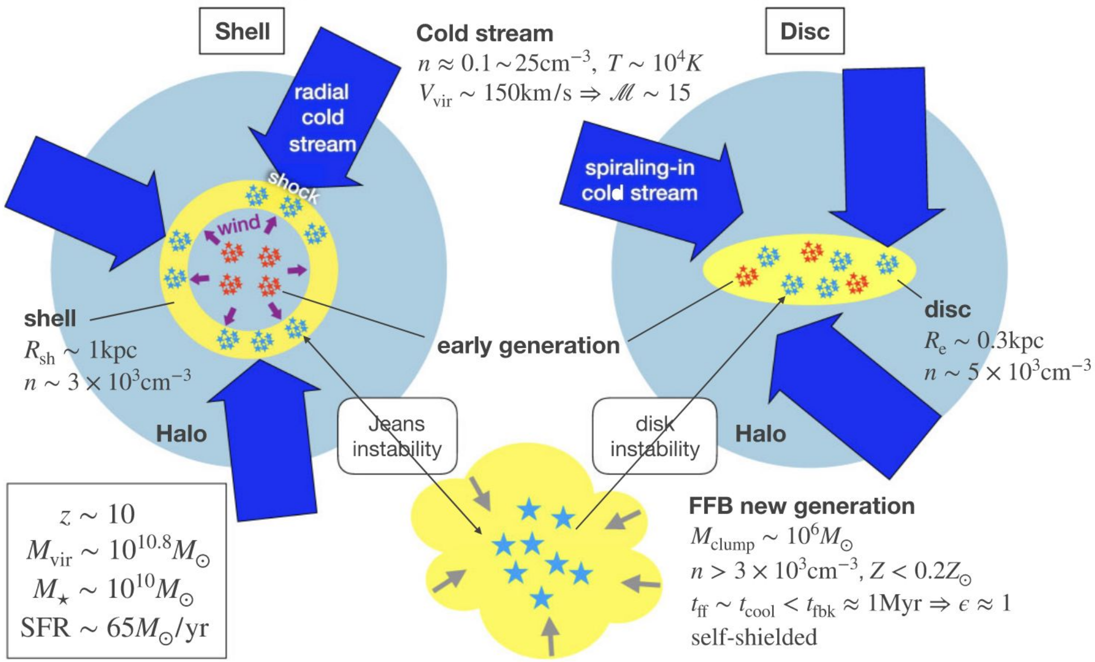
What if Star Formation was Intrinsically Efficient?



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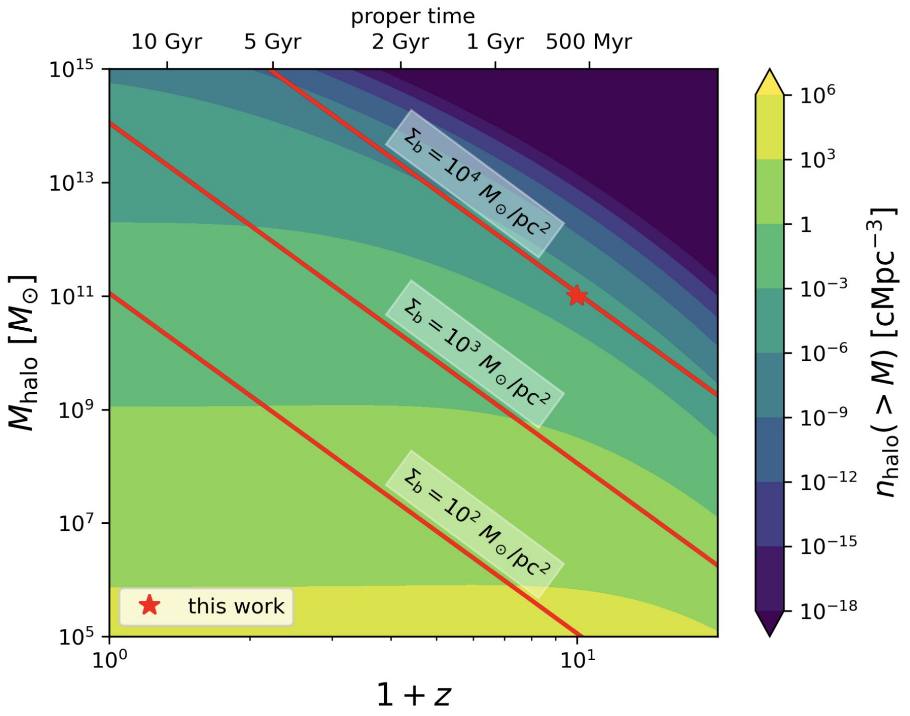
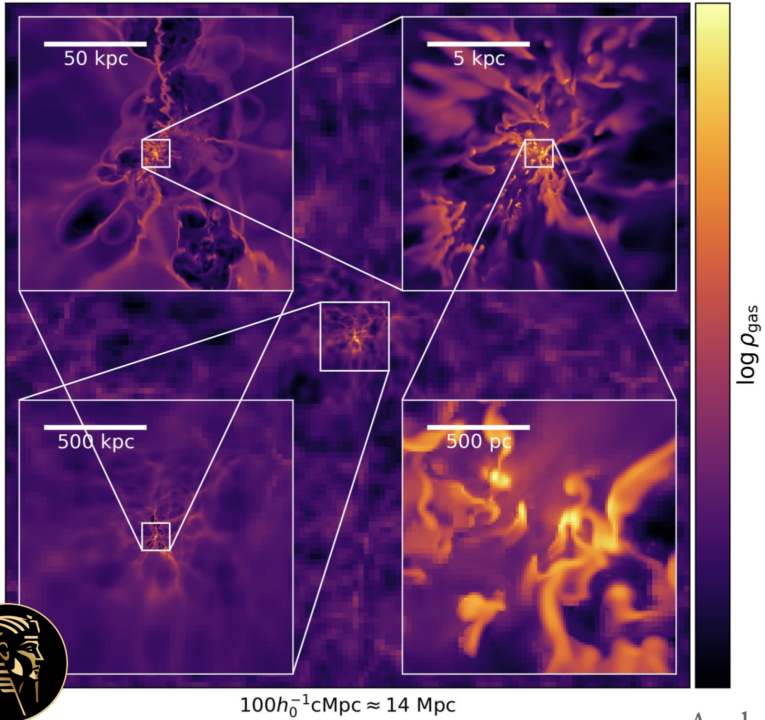


Andalman+25

Simulating a Massive Cosmic Dawn Galaxy (MDG)

- **Resolution**: $\Delta x = 10$ pc, $V = (100\ h^{-1}\ \mathrm{cMpc})^3$
- **Halo**: $10^{11}\ M_{sun}$ by $z \sim 9$
- **Star Formation**
  - Multi-Freefall Model w/ Subgrid Turbulence (no fixed SFE)
- **Stellar Feedback**
  - Photoionization Feedback (Thermal Energy Injection)
  - Type II SNe Feedback (Momentum and/or Energy Injection)



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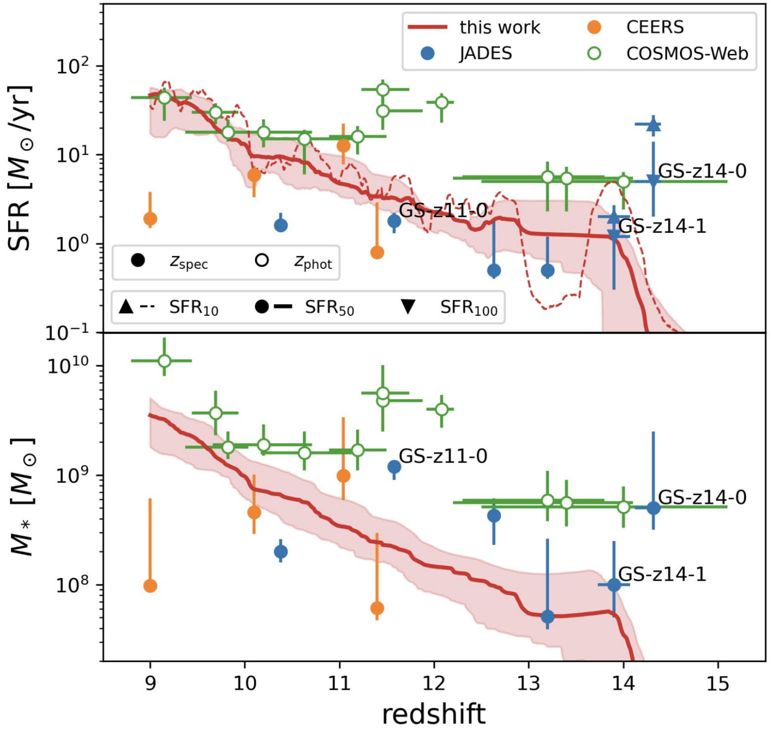
Simulating a Massive Cosmic Dawn Galaxy (MDG)



Andalman+25

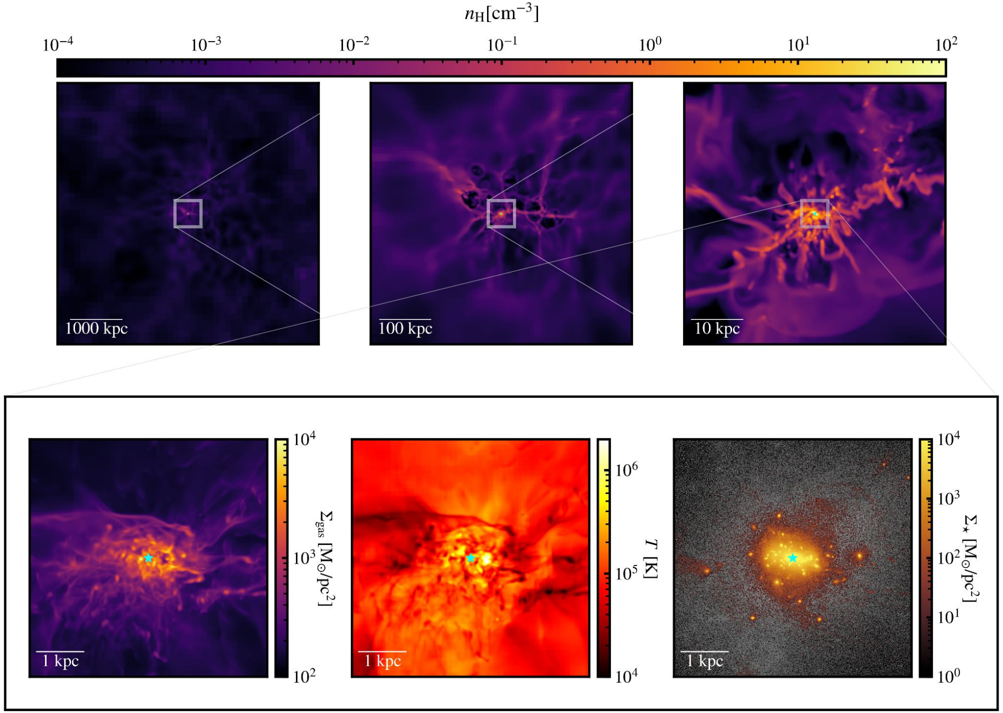
Simulating SMBHs in MDGs

- **Formation**: On-the-fly clump finder `PHEW` requires clump of 10^5 M_{sun} in gas and stars and 10^8 M_{sun} in dark matter
- **Accretion**: boosted Bondi-Hoyle-Lyttleton subgrid model with (super-)Eddington limit

$$\dot{M}_{\mathrm{BH}} = \min\left[\dot{M}_{\mathrm{bondi}}, \lambda_{\mathrm{edd.}}\dot{M}_{\mathrm{edd.}}\right]$$

- **Feedback**: Isotropic thermal energy injection, "quasar mode"

$$L_{\mathrm{AGN}} = \epsilon_{\mathrm{r}}\epsilon_{\mathrm{c}}\dot{M}_{\mathrm{BH}}c^2$$



Suite of Numerical Experiments

Run Name	AGN Feedback	Seed Mass [$M_\odot$]	$\lambda_{edd.}$	Stellar Feedback
Fiducial_Andalman+25	N/A	N/A	N/A	Fiducial
super_edd_AGN	Yes	10^4	3	Fiducial
super_edd_no_AGN	No	10^4	3	Fiducial
no_edd_AGN	Yes	10^4	∞	Fiducial
no_edd_no_AGN	No	10^4	∞	Fiducial
edd_AGN	Yes	10^4	1	Fiducial
edd_no_AGN	No	10^4	1	Fiducial
high_seed_edd_AGN	Yes	10^5	1	Fiducial
high_seed_edd_no_AGN	No	10^5	1	Fiducial
low_stellar_edd_AGN	Yes	10^4	1	Low
low_stellar_edd_no_AGN	No	10^4	1	Low

SMBH Growth in the MDG Environment

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Impact on the Host Galaxy

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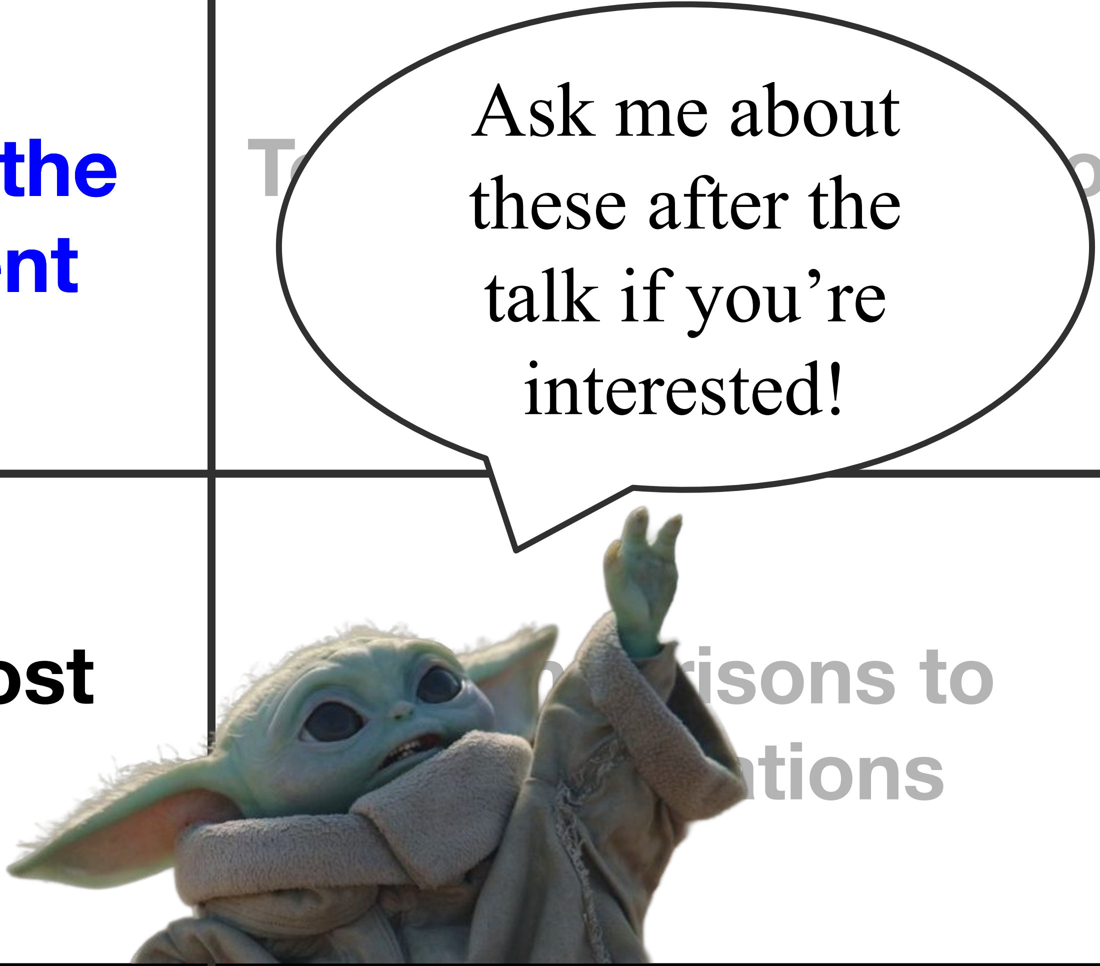
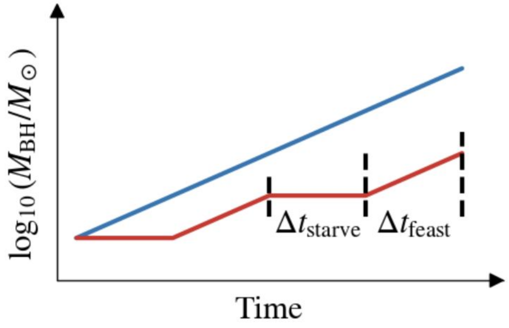
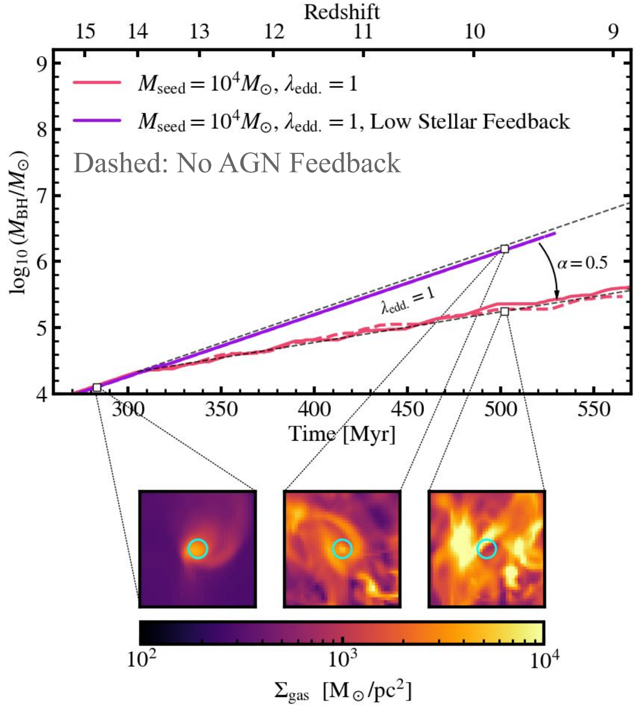


SMBH Growth in the MDG Environment

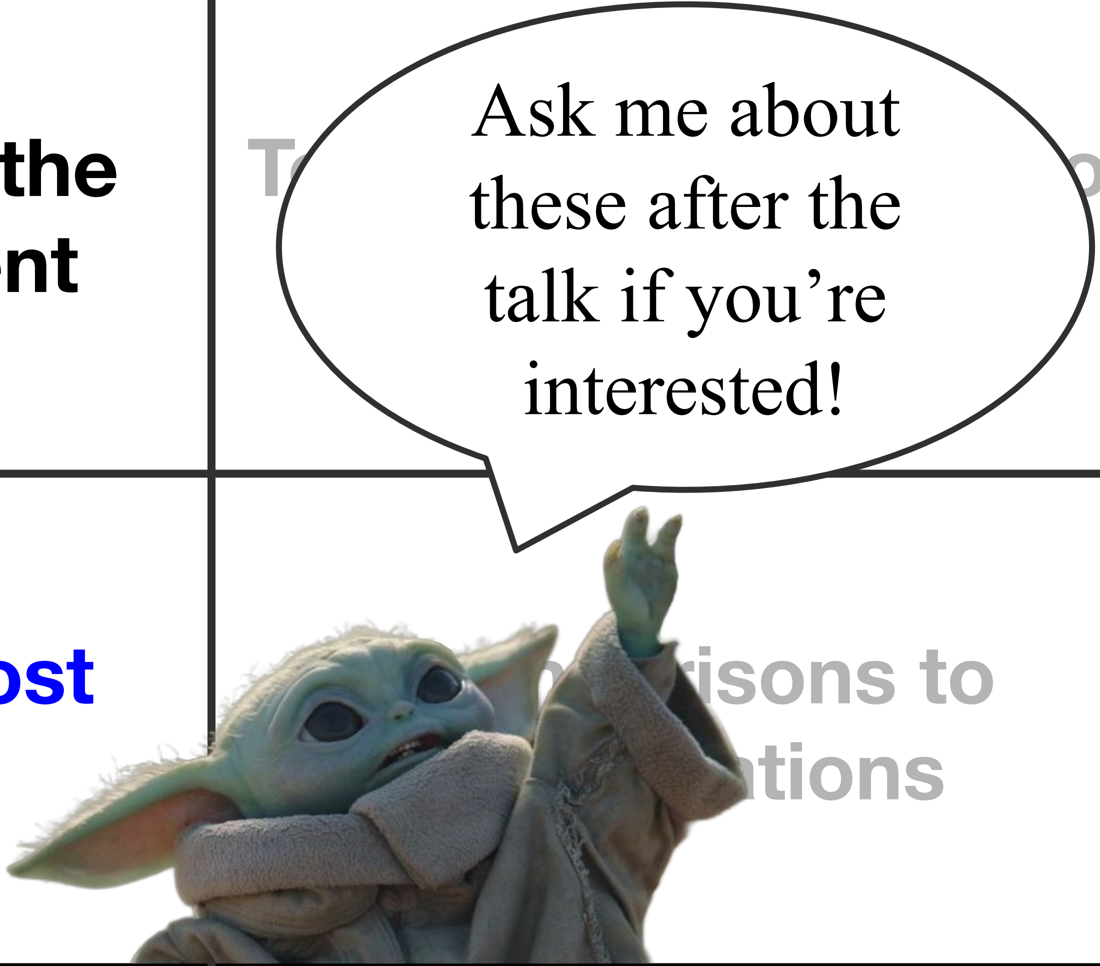
- Stellar feedback seeds a turbulent-multiphase interstellar medium (ISM) with cold-dense patches *($n \sim 10^3$ cm^{-3})* and hot-diffuse pockets *($n \sim 10$ cm^{-3})*
- The SMBH grows in bursts of maximal Eddington accretion as it plunges into cold-dense patches of the ISM (feast modes)



SMBH is starved ~50% of the time!



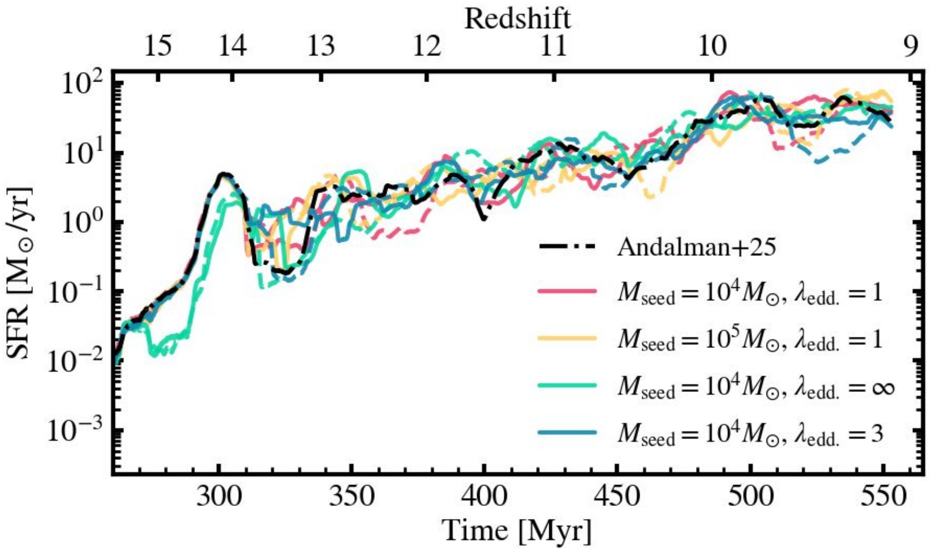
SMBH Growth in the MDG Environment



Impact on the Host Galaxy

How is the galaxy impacted by the SMBH

- We see no evidence of galaxy scale quenching!
- At Cosmic Dawn, halo growth is exponential and rapid (growth timescale comparable to the Salpeter timescale)
- Halo growth is so fast that any gas heated by AGN feedback is immediately smothered and replaced with cold-dense gas from cosmic filaments
- Constant supply of cold gas sustains the SFR in the disk of the galaxy



Conclusions

- Stellar feedback creates a turbulent-multiphase ISM which stochastically starves the SMBH ~ 50% of the time in the bursty epoch.

- We see no quenching from AGN feedback. This is due to the fact that halo growth is fast enough to replace any gas heated or accreted by the SMBH.

- The SMBH m... me massive enough,
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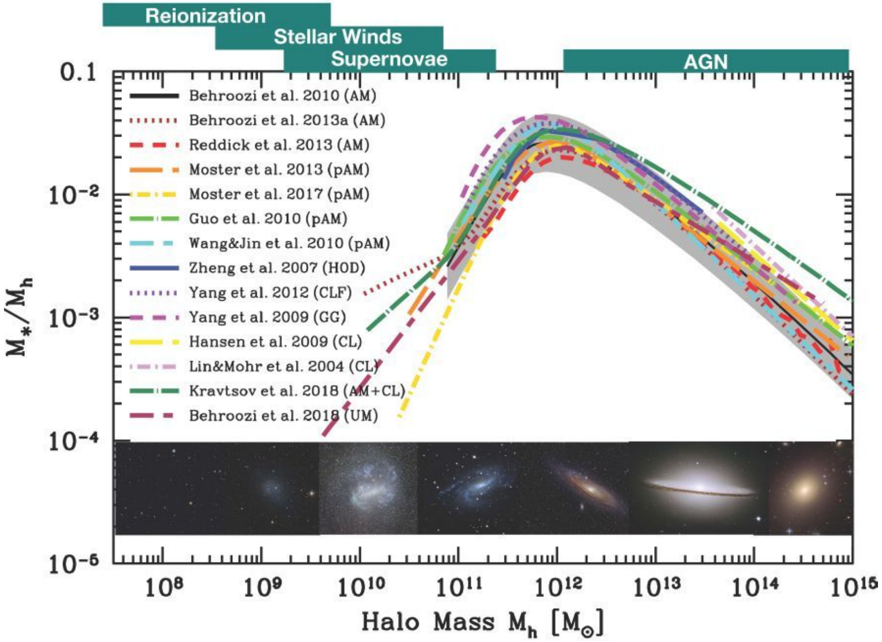
Extra Slides

Galaxy - SMBH Coevolution



- SMBHs are known to play a key role in suppressing star formation in massive galaxies
- MDGs evolve into the most massive galaxies
  - $M_{\rm halo} \gtrsim 10^{13}$ $M_\odot$ by $z = 0$
- We might expect AGN feedback to suppress SFR in MDGs at Cosmic Dawn

Wechsler & Tinker 18

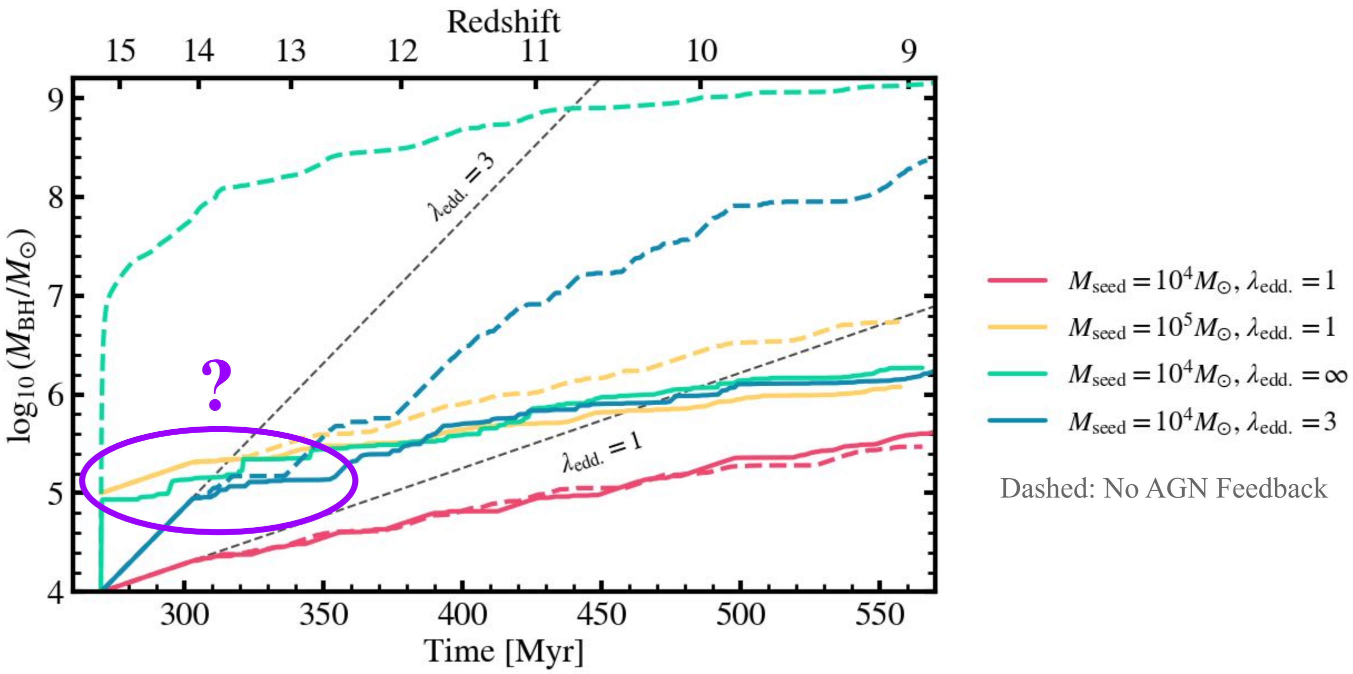
SMBH Growth in the MDG Environment

To Self-Regulate or Not to Self-Regulate

Impact on the Host Galaxy

Comparisons to Observations

To Self-Regulate or Not to Self-Regulate

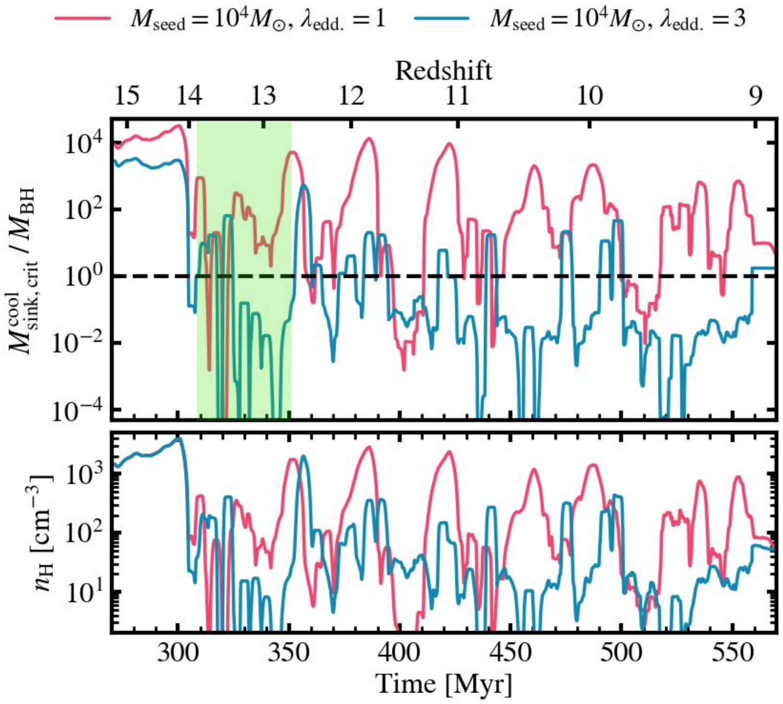


What's Going On?

$$\rho \frac{d\epsilon}{dt} = \underbrace{\frac{L_{\rm AGN}}{V_{\rm sink}}}_{\text{AGN Heating}} - \underbrace{n_{\rm H}^2 \Lambda(T, Z)}_{\text{Cooling}}$$

AGN Heating balances Cooling

$$M_{\rm sink,crit}^{\rm cool} \simeq \frac{2\times 10^4\ {\rm M_\odot}}{\lambda_{\rm edd.}} \left(\frac{n_{\rm H}}{10\ {\rm cm^{-3}}}\right)^2 \left(\frac{Z}{Z_\odot}\right) \left(\frac{r_{\rm sink}}{40\ {\rm pc}}\right)^3$$



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What's Going On?

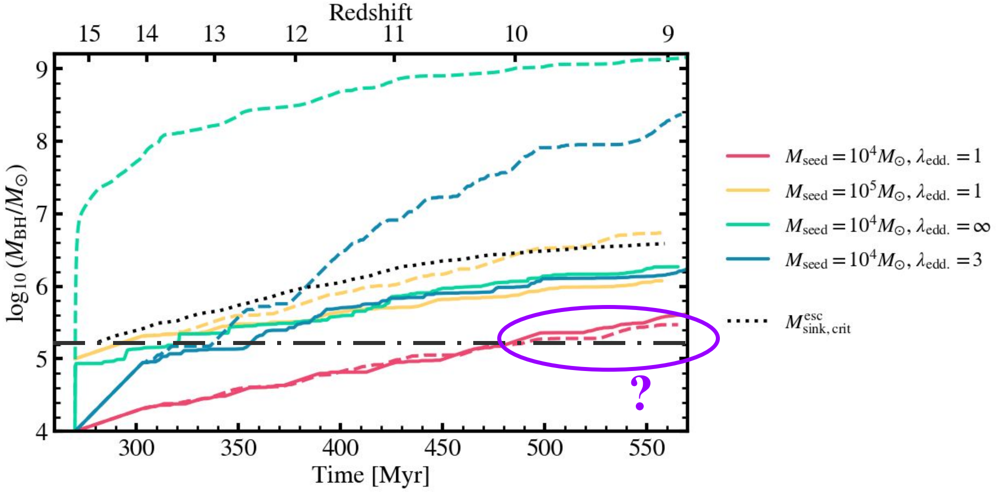
$$M_{\rm BH} \gtrsim M_{\rm sink,crit}^{\rm cool}$$

Runaway heating in the hot-diffuse ISM

$$\rho\frac{d\epsilon}{dt} = \underbrace{\frac{L_{\rm AGN}}{V_{\rm sink}}}_{\text{AGN Heating}} - \underbrace{n_{\rm H}^2\Lambda(T, Z)}_{\text{Cooling}}$$

Temperature increases rapidly with time. Capped by adiabatic expansion

$$M_{\rm sink,crit}^{\rm esc} \text{ when } c_{\rm s,max} \simeq v_{\rm esc}$$



Caveat: Both critical masses are resolution dependent quantities and can be tuned

Missing the Train of Self-Regulation

- If the SMBH fails to achieve self-regulation at Cosmic Dawn, it will be forced to wait until a later time ($z \sim 6$)
- Halo grows exponentially → exponential metal enrichment

$$\dot{Z} \propto \dot{M}_\star \propto \dot{M}_{\rm halo}$$

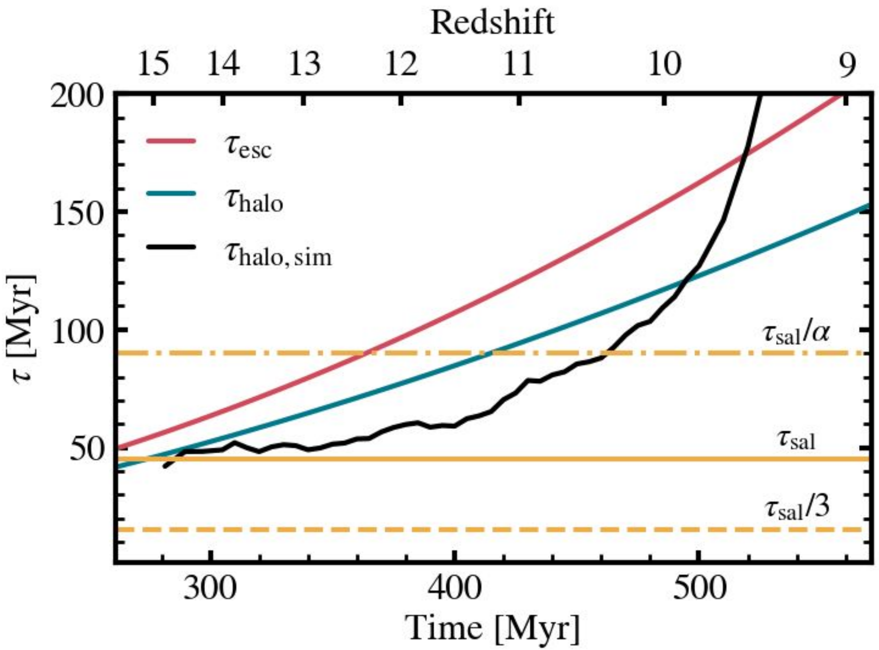
- Secular evolution of the critical cooling mass is dictated by the exponential growth of the halo

$$\left.\frac{\dot{M}^{\rm cool}_{\rm sink,crit}}{M^{\rm cool}_{\rm sink,crit}}\right|_{n_{\rm H}} = \frac{\dot{Z}}{Z} \approx \frac{1}{\tau_{\rm halo}}$$

$$\dot{M} = M/\tau \;\rightarrow\; M \propto e^{t/\tau}$$

Missing the Train of Self-Regulation

- If $\tau_{\rm halo} < \tau_{\rm sal.}/\alpha\lambda_{\rm edd.}$ then the SMBH is not capable of surpassing the critical cooling mass (due to metal enrichment)
- The self-regulated critical mass grows exponentially, but slower than the critical cooling mass due to cosmological expansion impacting halo size
- Then at later time $\rightarrow M_{\rm sink,crit}^{\rm cool} > M_{\rm sink,crit}^{\rm esc}$ meaning the SMBH that fails to self-regulate at Cosmic Dawn can end up more massive by $z \sim 6$



SMBH Growth in the MDG Environment

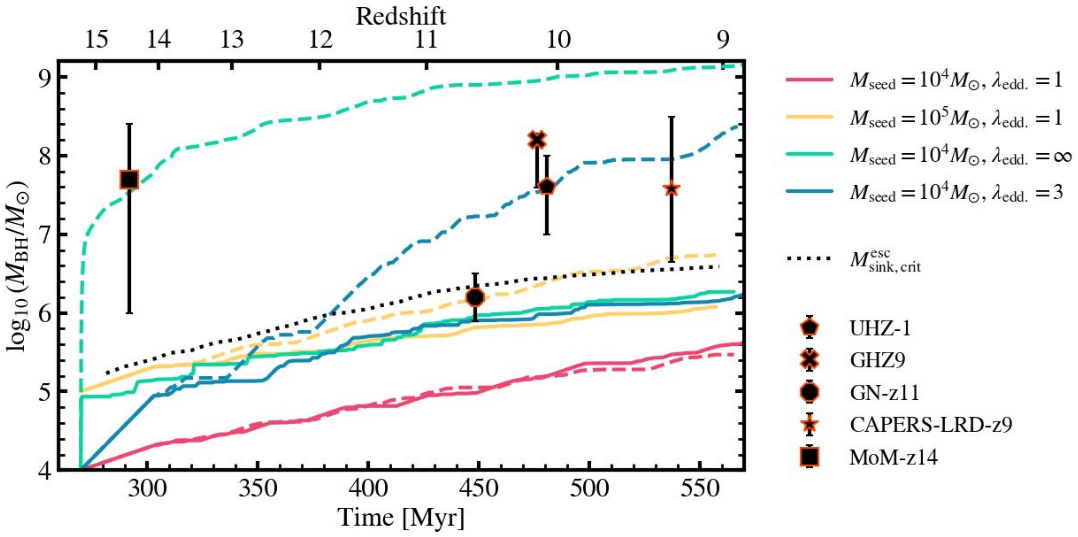
To Self-Regulate or Not to Self-Regulate

Impact on the Host Galaxy

Comparisons to Observations

Comparisons to SMBH Mass Estimates

- Best match to observations is the blue-dashed simulation: marginally super-Eddington with no AGN feedback
- At fixed resolution and radiative efficiency, $\epsilon_c \sim 0.15\%$ is required to have self-regulated SMBHs comparable to observations
    - $M^{\rm esc}_{\rm sink,crit} \propto \frac{r_{\rm sink}}{\sqrt{\epsilon_c \epsilon_r}}$



Comparisons in the M_{BH} - M_* Plane

- Best match to observations is the blue-dashed simulation: marginally super-Eddington with no AGN feedback
- Rapid rightward movement which slows around *z ~ 13-14.*
- Only super-Eddington growth with no AGN feedback is capable of upward movement into the overmassive *JWST* AGN population.
- Halo growth slows as simulations approach local relations