Title: Effects of primordial black holes on early star formation.

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Abstract: Primordial black holes (PBHs) have long been considered a promising candidate or an important component of dark matter (DM). Recent gravitational wave (GW) observations of binary black hole (BH) mergers have triggered renewed interest in PBHs in the stellar-mass (~ 10 - 100 Msun) and supermassive regimes (~ 10^7 - 10^11 Msun). Although only a small fraction (? 1%) of dark matter in the form of PBHs is required to explain observations, these PBHs may play important roles in early structure/star formation. We use cosmological zoom-in simulations and semi-analytical models to explore the possible impact of stellar-mass PBHs on first star formation, taking into account two effects of PBHs: acceleration of structure formation and gas heating by BH accretion feedback. We find that the standard picture of first star formation is not changed by stellar-mass PBHs (allowed by existing observational constraints), and their global impact on the cosmic star formation history is likely minor. However, PBHs do alter the properties of the first star-forming halos and can potentially trigger the formation of direct-collapse BHs in atomic cooling halos. On the other hand, supermassive PBHs may play more important roles as seeds of massive structures that can explain the apparent overabundance of massive galaxies in recent JWST observations. Our tentative models and results call for future studies with improved modeling of the interactions between PBHs, particle DM, and baryons to better understand the effects of PBHs on early structure/star formation and their imprints in high-redshift observations.

EFFECTS OF PRIMORDIAL BLACK HOLES ON EARLY STAR FORMATION

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Outline

Background

First star formation with stellar-mass PBHs

- Cosmological simulation
- Semi-analytical model
- Future work

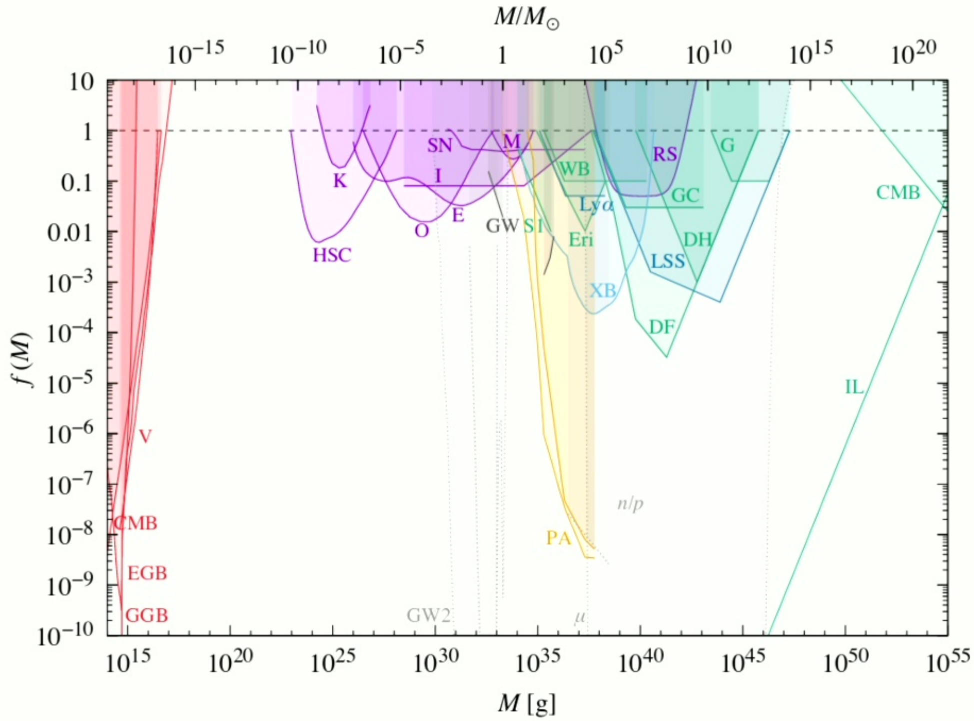
Massive galaxies seeded by supermassive PBHs

First stars: Population III (Pop III)

- Molecular coolants: $\mathrm{H_2}$ and HD ($Z \lesssim 10^{-6} - 10^{-3.5}\ \mathrm{Z_\odot}$)
- Formation sites: $M_\mathrm{h} \sim 10^{5-8}\ \mathrm{M_\odot}$ at $z \sim 10 - 40$
  - **Rees–Ostriker–Silk criterion ($t_\mathrm{cool} \lesssim t_\mathrm{ff}$) for $\mathrm{H_2}$ cooling:** $M_\mathrm{h} \gtrsim 1.54 \times 10^5\ M_\odot \left(\frac{1+z}{31}\right)^{-2.074}$ (Trenti & Stiavelli, 2009)
  - **Streaming motion (SM):** $M_\mathrm{h} \gtrsim 10^6\ \mathrm{M_\odot}$ (Schauer et al., 2021)
  - **Lyman-Werner (LW) feedback ($z \lesssim 15$):** $M_\mathrm{h} \gtrsim 3 \times 10^6\ \mathrm{M_\odot}$
- Typical star-forming cores/clumps:
  Jeans mass $M_J \sim \frac{3c_s^3}{G^{3/2}\rho^{1/2}} \sim 3000\ M_\odot \left(\frac{T}{200\ \mathrm{K}}\right)^{3/2} \left(\frac{n}{10^3\ \mathrm{cm^{-3}}}\right)^{-1/2}$
- More massive than metal-enriched (Pop I/II) stars:
  Broad, top-heavy initial mass function ($dN/dm_\star \propto m_\star^{-1}$)
- Unique stellar evolution: more compact, likely fast-rotating, little mass loss from line-driven stellar winds
- Progenitors of supermassive (10^4 to a few $10^5\ \mathrm{M_\odot}$) BH seeds
  (e.g., Visbal et al., 2014; Wise et al., 2019; Reinoso et al., 2023)

Primordial black holes (PBHs)

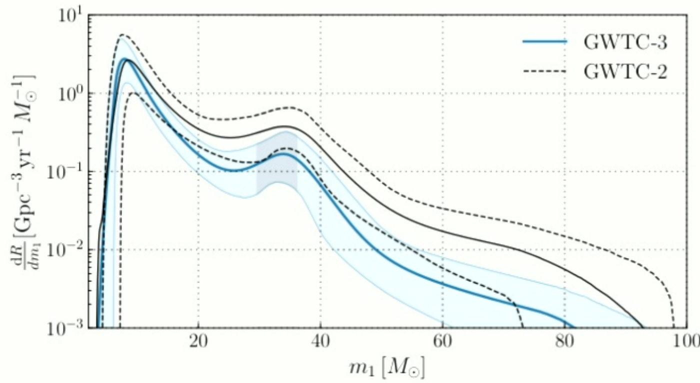
- Diverse formation mechanisms (collapse of inhomogenities of diverse origins at different epochs) $\rightarrow$ vast parameter space of PBH models
- Implications for a broad range of astrophysical phenomena $\rightarrow$ various constraints/evidence subject to uncertainties (Carr et al., 2021, 2023)



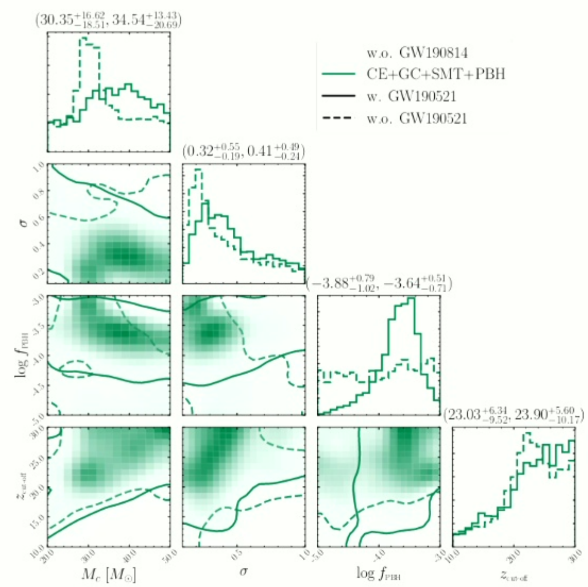
(Carr et al., 2021)

Stellar-mass PBHs hinted by GW observations

Recent gravitational wave (GW) observations of binary black hole mergers can be (partially $\sim 20\%$) explained by stellar-mass PBHs making up a small fraction $f_{\rm PBH} \sim 10^{-4} - 0.001$ of dark matter with $m_{\rm PBH} \sim 30\ {\rm M}_\odot$ (De Luca et al., 2021; Franciolini et al., 2022).



(Abbott et al., 2023)



(Franciolini et al., 2022)

Effects of PBHs[1] on early star formation

- **Cosmic structure formation** (gravitational, Carr & Silk, 2018)
  - 'Seed' effect ($f_{\rm PBH} \ll 1$)
    $M_{\rm B} \sim m_{\rm PBH} a/a_{\rm eq}$: mass bound to an isolated PBH (Mack et al., 2007)
  - 'Poisson' effect (discreteness noise)
    $\Delta^2_{\rm Poisson}(k) = (k/k_\star)^3$: variance of primordial Poisson (isocurvature) perturbations (per $\ln k$)
    $k_\star = (2\pi^2 \bar{n}_{\rm PBH})^{1/3}$: critical scale of order the mean separation between PBHs, $\bar{n}_{\rm PBH}$: cosmic average number density of PBHs
- **BH accretion feedback** ('non-gravitational')
  - Radiative feedback
    - Heating of gas by absorption of ionizing photons
    - Dissociation of $\mathrm{H_2}$ by LW photons
    - Ionization and heating by X-rays
  - Mechanical feedback
    jets, disk winds, shocks...

[1] We only consider PBHs with negligible Hawking radiation ($m_{\rm PBH} \gtrsim 10^{15}$ g).

FIRST STAR FORMATION WITH STELLAR-MASS PBHS

Cosmological hydrodynamic simulations

- Simulation setup (Liu et al., 2022)
  - Parent box: $L \sim 200\ \mathrm{kpc}$, $m_{\mathrm{DM\ (gas)}} \sim 140\ (26)\ \mathrm{M_\odot}$, $z_{\mathrm{ini}} = 300$
  - Zoom-in regions
    - Case A: $M_{\mathrm{h}} \sim 3.7 \times 10^5\ \mathrm{M_\odot}$, $z \sim 28$, $\sigma_8 = 2.0$
    - Case B: $M_{\mathrm{h}} \sim 6.1 \times 10^5\ \mathrm{M_\odot}$, $z \sim 20$, $\sigma_8 = 1.6$
    - Resolution: $m_{\mathrm{DM\ (gas)}} \sim 2\ (0.4)\ \mathrm{M_\odot}$
  - PBH parameters: $m_{\mathrm{PBH}} = 33\ \mathrm{M_\odot}$, $f_{\mathrm{PBH}} \sim 10^{-4} - 0.1$ (fiducial model: $f_{\mathrm{PBH}} = 0.001$)
- Initial conditions deep in the matter-dominated epoch ($a_{\mathrm{ini}} \sim 10^{-3} - 0.01 \gg a_{\mathrm{eq}}$)
  - Linear perturbation theory
  - Initial distributions of PBHs
  - Perturbations of PBHs on particle dark matter (PDM)
- Sub-grid models for BH accretion and feedback
  - Bondi accretion
  - Thermal feedback

Linear perturbation theory[2]

- Primordial perturbations:
  $\delta_{\rm PDM}(a \to 0) \equiv \delta^0_{\rm PDM} = \delta^0_{\rm ad}$, $\delta_{\rm PBH}(a \to 0) \equiv \delta^0_{\rm PBH} = \delta^0_{\rm ad} + \delta^0_{\rm iso}$
  (Adiabatic and isocurvature)
- Constant difference field: $\delta_-(a) \equiv \delta_{\rm PBH}(a) - \delta_{\rm PDM}(a) = \delta^0_- = \delta^0_{\rm iso}$
  (assuming negligible velocities between PBHs and PDM)
- Evolution in the linear regime (Inman & Ali-Haïmoud, 2019)

$$\begin{aligned}
\delta_{\rm DM}(a) &\equiv (1 - f_{\rm PBH})\delta_{\rm PDM}(a) + f_{\rm PBH}\delta_{\rm PBH}(a) \\
&= T_{\rm ad}(a)\delta^0_{\rm ad} + f_{\rm PBH}T_{\rm iso}(a)\delta^0_{\rm iso} \\
\delta_{\rm PDM}(a) &= \delta_{\rm DM}(a) - f_{\rm PBH}\delta^0_{\rm iso} \\
&= T_{\rm ad}(a)\delta^0_{\rm ad} + [T_{\rm iso}(a) - 1]f_{\rm PBH}\delta^0_{\rm iso} \\
\delta_{\rm PBH}(a) &= \delta_{\rm PDM}(a) + \delta^0_{\rm iso} \\
&= T_{\rm ad}(a)\delta^0_{\rm ad} + \{1 + [T_{\rm iso}(a) - 1]\,f_{\rm PBH}\}\delta^0_{\rm iso}
\end{aligned}$$

[2] Linear perturbation theory is only strictly valid at large scales where we can treat PBHs as a quasi-homogeneous ideal pressure-less fluid like PDM.

Initial distributions of PBHs

Starting point: initial condition (IC) for ΛCDM where the standard adiabatic perturbations ($T_{\rm ad}(a)\delta^0_{\rm ad}$) are captured in the density and velocity fields of PDM

- Derive the overdensity field of PDM on a Cartesian grid where each cell contains about one PBH in on average.
  (The cell size corresponds to the scale below which the PBH discreteness noise is important.)
- Given the overdensity δ_i of each cell i, draw the number of PBHs in it, N_i, from a Poisson distribution with parameter $(\delta_j + 1) f_{\rm PBH} M_{\rm cell}/m_{\rm PBH}$, where $M_{\rm cell}$ is the average mass of DM per cell. If $N_i > 0$, place N_i PBHs randomly in cell i.
- Assign a velocity to each PBH as the velocity of its nearest-neighbor PDM particle. Reduce the mass of each PDM particle by a fraction of $f_{\rm PBH}$ for mass conservation.

Perturbations by PBHs ($[T_{\rm iso}(a)-1]f_{\rm PBH}\delta^0_{\rm iso}$)

- Zel'dovich approximation: $\vec{x}_j = \vec{x}_j + \vec{\psi}(\vec{x}_j)$, $\vec{v}_j = \vec{v}_j + \Delta\vec{v}(\vec{x}_j)$

$$\vec{\psi}(\vec{x}) = -\frac{2D_{\rm PBH}(a_{\rm ini})}{3\Omega_m H_0^2}\nabla\phi_{\rm iso}(\vec{x})\ ,\quad \Delta\vec{v}(\vec{x}) = \frac{a_{\rm ini}\dot{D}_{\rm PBH}(a_{\rm ini})}{D_{\rm PBH}(a_{\rm ini})}\vec{\psi}(\vec{x})$$

$$\nabla\phi_{\rm iso}(\vec{x}) = 4\pi G m_{\rm PBH}\sum_i \frac{\vec{x}-\vec{x}_i}{|\vec{x}-\vec{x}_i|^3}$$

- Growth factor (extrapolation):
  $D_{\rm PBH}(a_{\rm ini}) = T_{\rm iso}(a_{\rm ini}) - 1 = D_+(a_{\rm ini}) - 1 \sim a_{\rm ini}/a_{\rm eq}$, given $a_{\rm eq} \ll a_{\rm ini} \ll 1$
  ($D_{\rm PBH} \sim a_{\rm ini}/a_{\rm rec}$ for gas particles)
- Treatment of non-linear perturbations close to PBHs ('seed' effect)
  - $|\vec{\psi}| \gtrsim r$ for $r \lesssim d_{\rm nl} = [D_{\rm PBH}(a_{\rm ini})/\bar{n}_{\rm PBH}]^{1/3}$
  - Tentative solution: $\vec{\psi} = \min\left(1, d_{\rm PDM}/|\vec{\psi}|\right)\vec{\psi}$ to ensure linearity at the initial resolution scale, which suppresses the 'seed' effect at early stages
- Scale/range of PBH-induced perturbations
  - Strong perturbations (SP): all PBHs in the zoom-in region
  - **Fiducial perturbations: at most the 64 nearest PBH particles within $2d_{\rm PBH}$**
  - Weak perturbations (WP): only the nearest PBH
  - No perturbation (NP)

$d_{\rm PDM\ (PBH)}$: average separation between PDM particles (PBHs)

PBH accretion and heating

- Bondi accretion

$$\dot{m}_{\rm acc} = \frac{4\pi (G m_{\rm BH})^2 \rho_{\rm gas}}{\tilde{v}^3} \,, \quad \tilde{v} \sim \sqrt{v_{\rm rel}^2 + c_s^2}$$

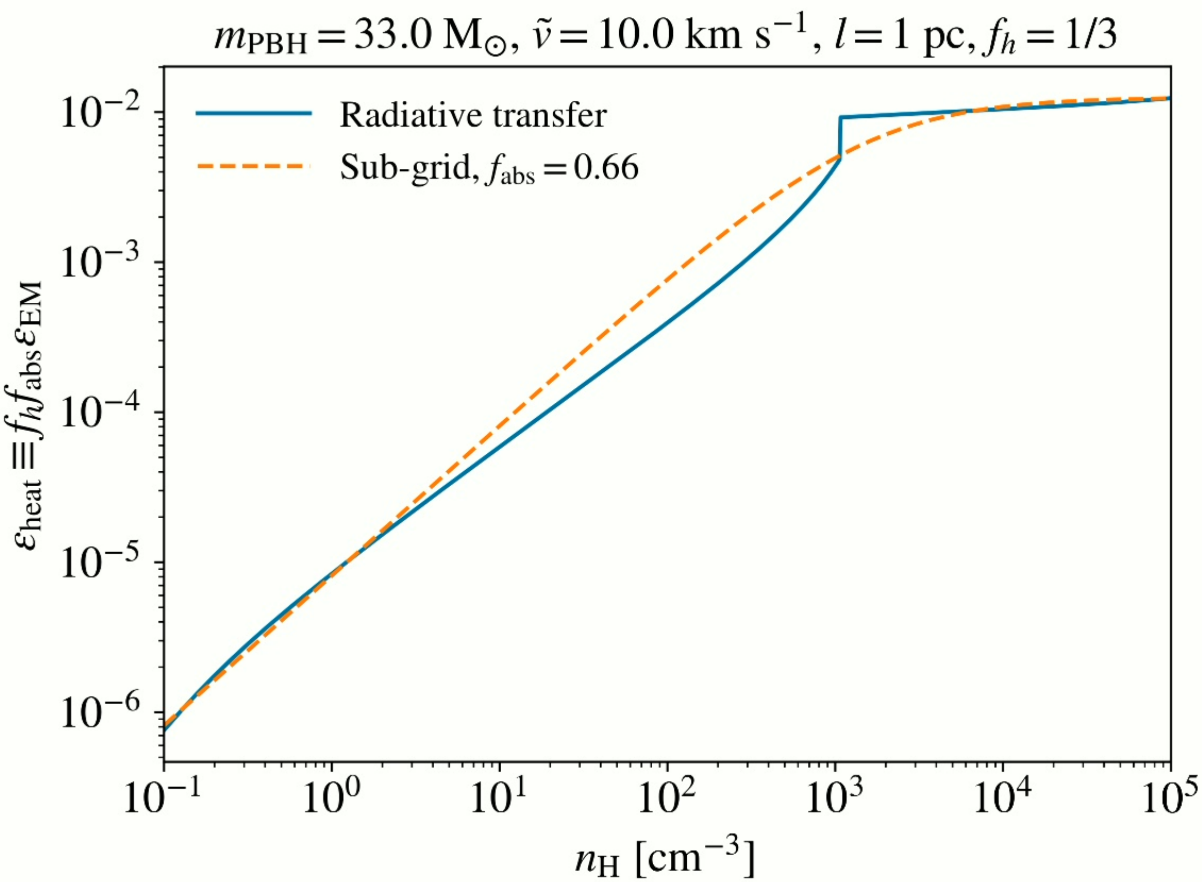
- Heating rate

$$P_{\rm heat} = \epsilon_r \epsilon_{\rm EM} \dot{m}_{\rm acc} c^2 \,, \quad \epsilon_{\rm EM} = \frac{\epsilon_0 A \eta}{1 + A\eta} \,, \quad \eta \equiv \frac{\dot{m}_{\rm acc}}{\dot{m}_{\rm Edd}}$$

$$\dot{m}_{\rm Edd} \simeq 2.7 \times 10^{-6}\ {\rm M_\odot\ yr^{-1}} \left(\frac{m_{\rm BH}}{100\ {\rm M_\odot}} \right) \left(\frac{\epsilon_0}{0.1} \right)^{-1}$$

  - $\epsilon_{\rm EM}$: radiation efficiency with transition from thin disk to ADAF, $A = 100$ (Negri & Volonteri, 2017), $\epsilon_0 = 0.057$ (for non-spinning BHs)
  - $\epsilon_r = f_{\rm abs} f_h$=0.22: thermal coupling coefficient, $f_h = 1/3$: fraction of energy deposited as heat (Takhistov et al., 2022), $f_{\rm acc} = 0.66$ (calibrated to radiative transfer results)

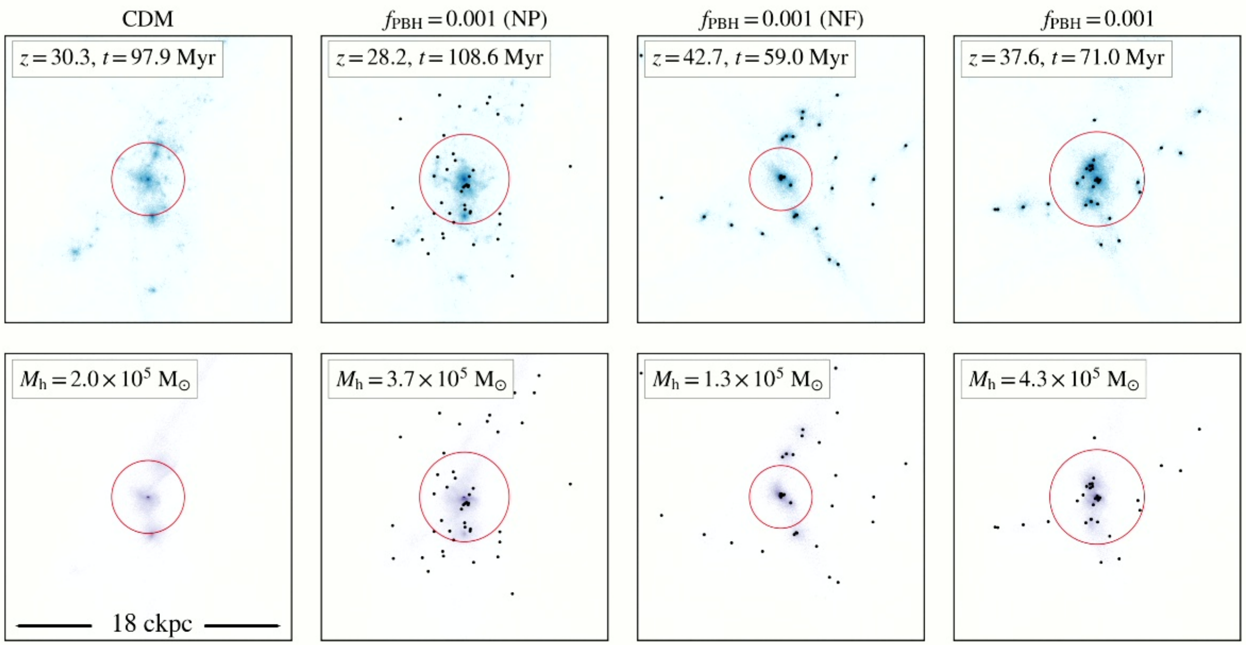
Coupling coefficient calibration



Positive VS negative effects (timing and site)

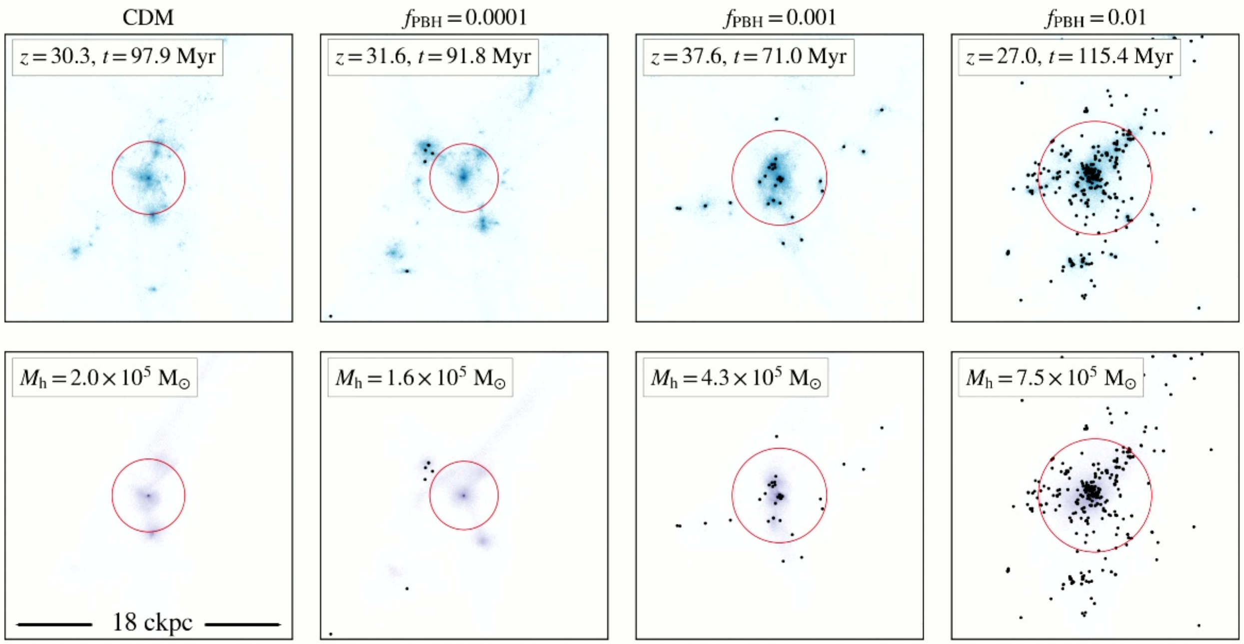
Onset of first star formation (FSF): $n_{\mathrm{H,max}} > 10^5\ \mathrm{cm}^{-3}$

Fiducial model ($f_{\mathrm{PBH}} = 0.001$) in Case A ($\sigma_8 = 2$): FSF is slightly delayed in NP (no perturbation), but significantly accelerated in NF (no feedback) and with combined perturbations and heating.



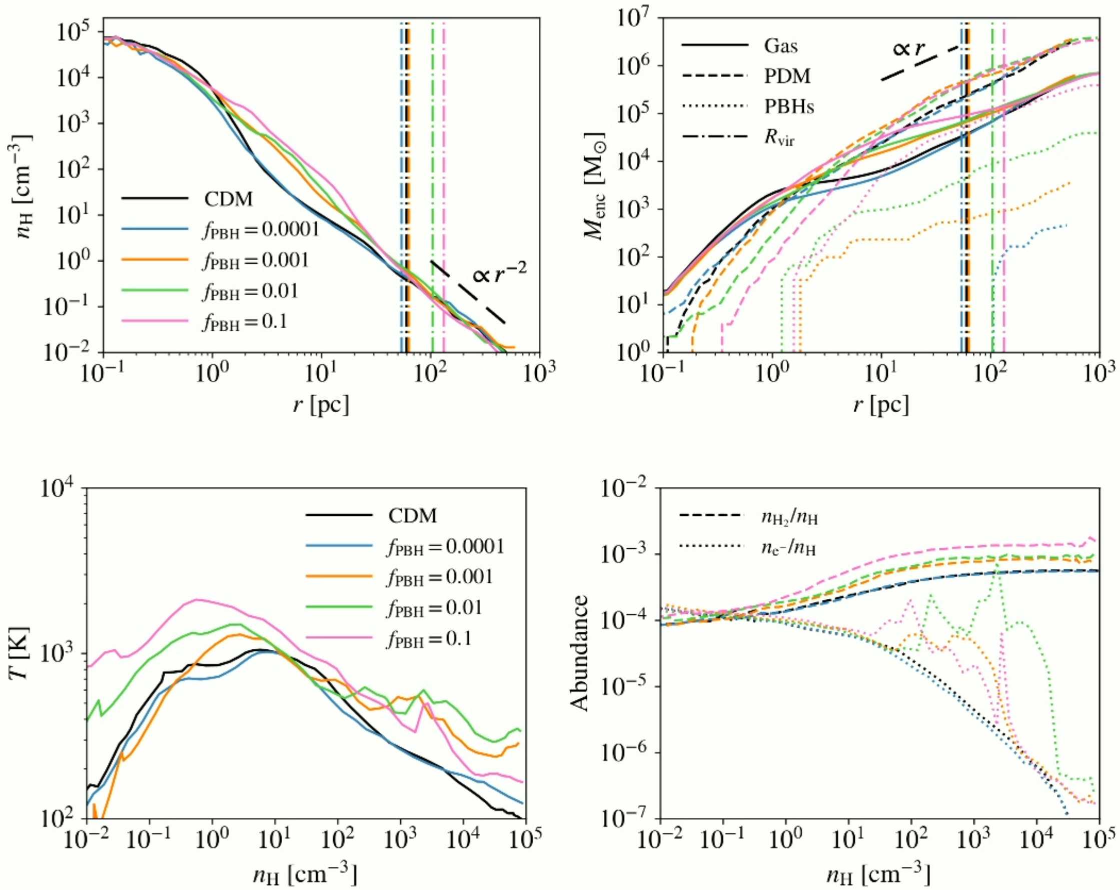
Dependence on f_{PBH} (timing and site)

FSF is accelerated for $f_{\mathrm{PBH}} \leq 0.001$, but delayed for $f_{\mathrm{PBH}} \geq 0.01$.
FSF is shifted to more massive halos by PBHs except for $f_{\mathrm{PBH}} = 10^{-4}$.



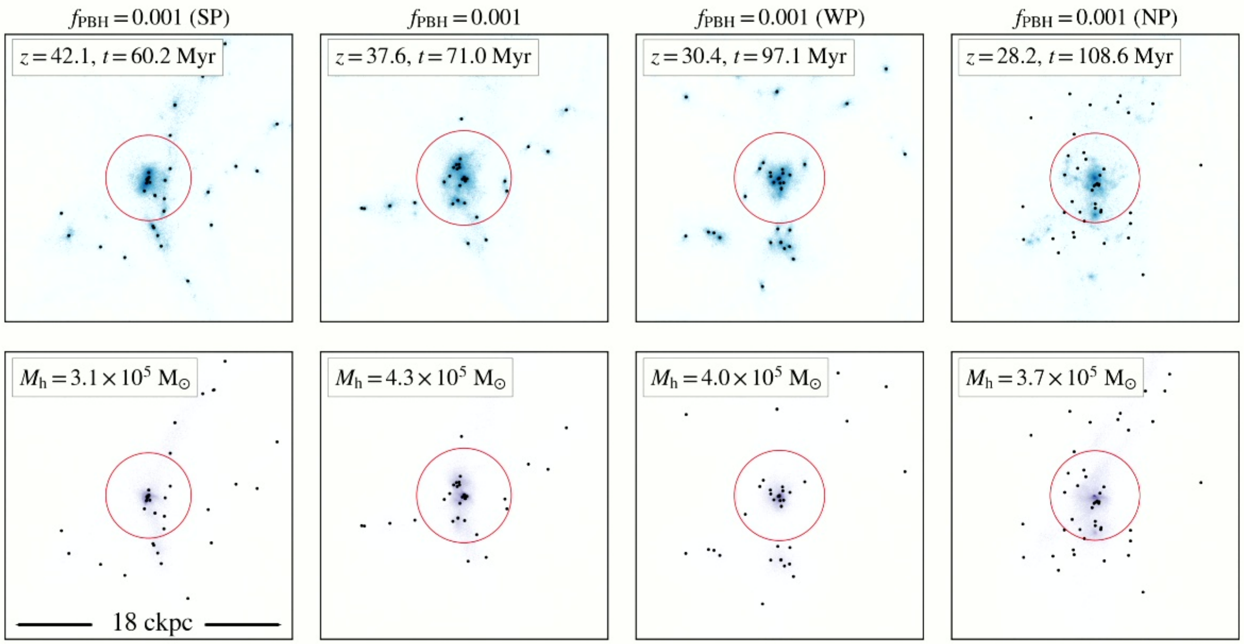
$f_{\mathrm{PBH}} = 0.1$: $z = 22.5$, $t = 150$ Myr, $M_{\mathrm{h}} = 9.2 \times 10^5\ \mathrm{M}_{\odot}$

Dependence on f_{PBH} (internal structure)



Dependence on IC (timing and site)

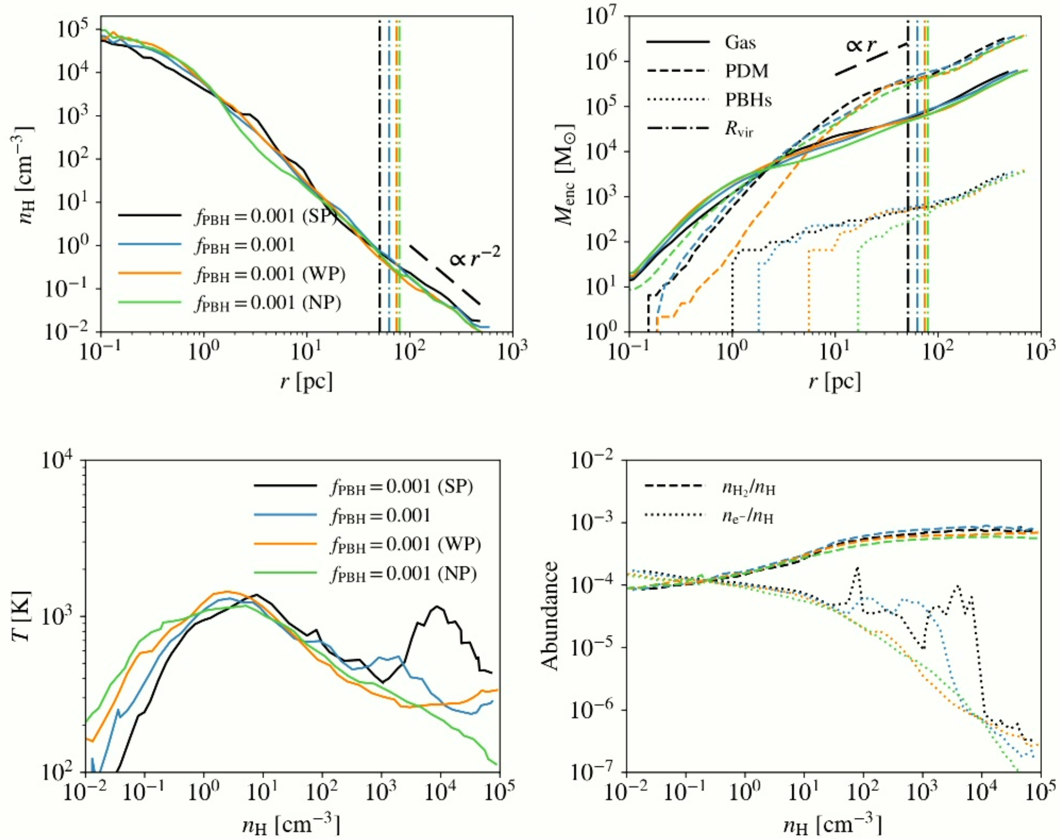
FSF happens earlier when stronger perturbations from PBHs are considered at larger scales (from right to left).



CDM: $z = 30.3$, $t = 97.9$ Myr, $M_h = 2 \times 10^5$ M$_\odot$

Dependence on IC (internal structure)

The WP model better captures the substructures around individual PBHs. $\rightarrow$
The concentration of PDM at FSF is significantly reduced.



Key findings from simulations

- **The typical condition for Pop III star formation is fullfilled in all simulation** with similar gas density profiles within $r \lesssim 1$ pc, independent of $f_{\rm PBH}$: At the moment with $n_{\rm H,max} > 10^5 \rm\ cm^{-3}$, a dense ($n_{\rm H} \gtrsim 10^4 \rm\ cm^{-3}$) cold ($T \lesssim 10^3$ K) gas clump of $\sim 10^3 \rm\ M_\odot$ has formed by run-away collapse in the central parsec. $\rightarrow$
The 'standard' picture of Pop III star formation is not changed by PBHs.
- **PBHs tend to slow down cloud collapse and reduce the central density of PDM.** The effect is stronger with higher $f_{\rm PBH}$, caused by the accretion and dynamical heating from PBHs and the PDM substructures around them.
- **At the onset of FSF, PBHs are at least 1 pc away from the gas density peak (except for NF): survivorship bias.** The dynamical friction timescale for a PBH to sink into the center is a few Myr, larger than the free-fall timescale $t_{\rm ff} \sim 0.5$ Myr of the star-forming clump, but comparable to the typical lifetimes of Pop III stars and relaxation timescales of Pop III star clusters. $\rightarrow$
PBHs are not expected to interact with Pop III star-forming disks directly. However, PBHs may still affect Pop III stellar evolution and the dynamics of Pop III star clusters.

Semi-analytical model

Halo mass function from the Press-Schecheter (PS) formalism[3]

- $\delta_{\rm DM}(a) = T_{\rm ad}(a)\delta^0_{\rm ad} + f_{\rm PBH} T_{\rm iso}(a)\delta^0_{\rm iso} \rightarrow$
  linear power spectrum *without any correlation between the adiabatic and isocurvature modes*:

$$P_{\rm DM}(k,a) = T^2_{\rm ad}(a)P^0_{\rm ad}(k) + f^2_{\rm PBH} T^2_{\rm iso}(a) P^0_{\rm iso}(k)$$
$$P^0_{\rm iso}(k) \equiv 2\pi^2 \Delta^2_{\rm Poisson}(k)/k^3 = \bar{n}^{-1}_{\rm PBH}\ , \quad k > k_{\rm eq}$$

- A (heuristic) correlation term can be introduced to better reproduce the halo mass functions in simulations:

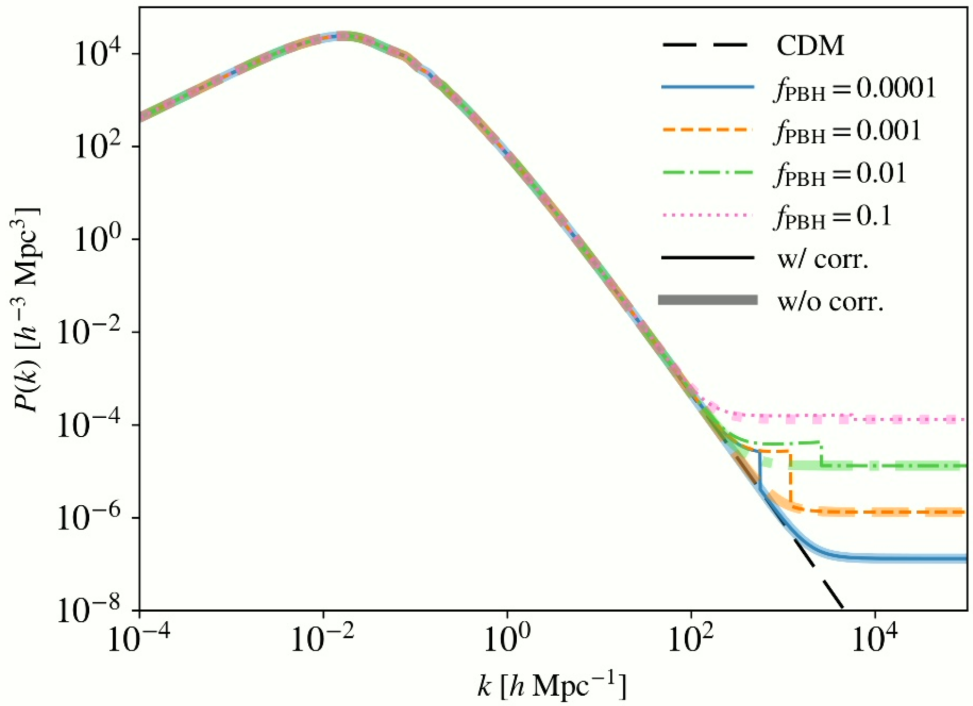
$$P_{\rm DM}(k,a) = T^2_{\rm ad}(a)P^0_{\rm ad}(k) + f^2_{\rm PBH} T^2_{\rm iso}(a) P^0_{\rm iso}(k) + P_{\rm corr}(k,a)$$
$$P_{\rm corr}(k,a) = f_{\rm PBH} T_{\rm iso}(a) \Delta^2_{\rm Poisson}(k) T^2_{\rm ad}(a) P^0_{\rm ad}(k), \quad k_{\rm eq} < k < 3k_\star$$

$\Delta^2_{\rm Poisson}(k) = (k/k_\star)^3$, $k_\star = (2\pi^2 \bar{n}_{\rm PBH})^{1/3}$, $k_{\rm eq} \sim 0.01\,{\rm Mpc}^{-1}$: horizon scale at matter-radiation equity

[3] Caution: The Press-Schechter formalism assumes that density fluctuations are Gaussian. However, in the presence of PBHs, the density field is non-Gaussian, especially at small scales dominated by isocurvature perturbations from the Poisson distributed PBHs!

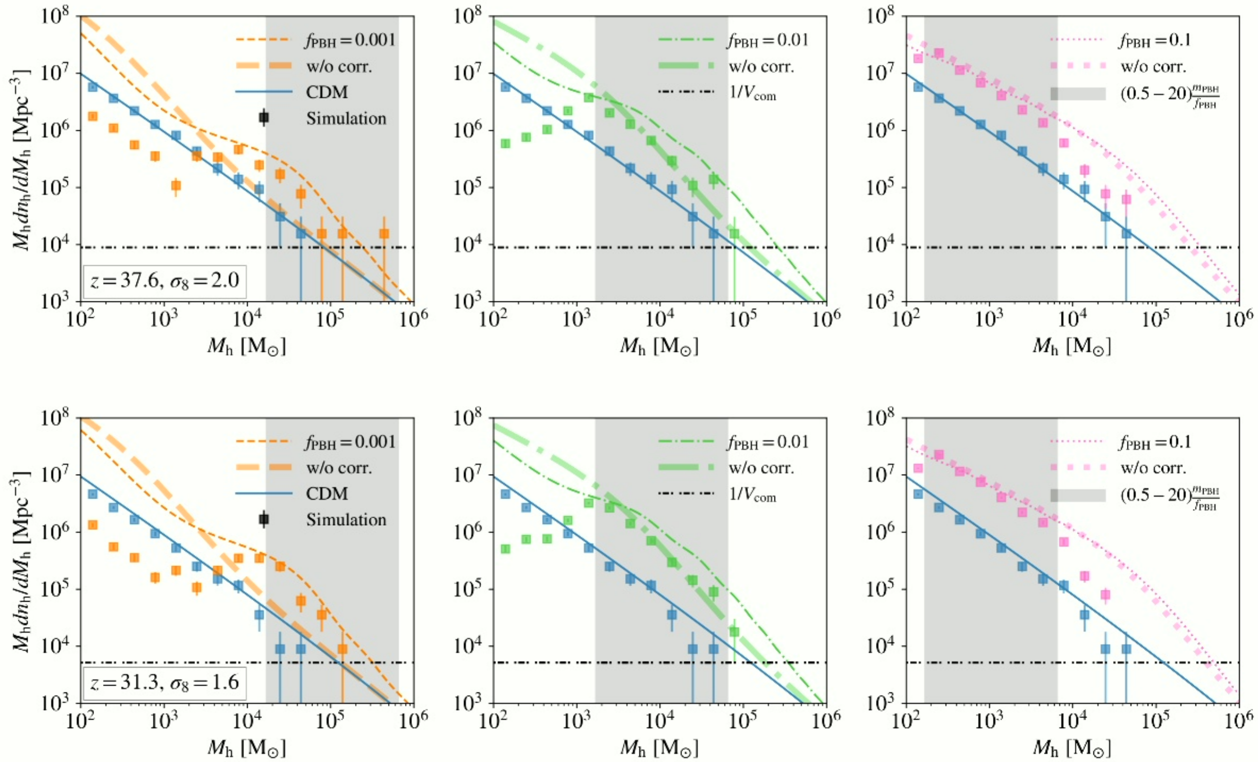
Linear power spectrum

The correlation term is most important in the intermediate case with $f_{\mathrm{PBH}} \sim 0.001$.



PS formalism vs simulations (1)

Overproduction of small halos with $M_{\rm h} \lesssim 0.5 m_{\rm PBH}/f_{\rm PBH} \rightarrow$
The tidal fields from PBH-induced halos suppress the formation of small-scale (PBH-less) structures.



Halo mass threshold $M_{\rm mol}$ for star formation

Rees–Ostriker–Silk criterion (for $\rm H_2$ cooling): $t_{\rm cool} \lesssim t_{\rm ff}$

- Timescales

$$t_{\rm cool} = \frac{(3/2)k_B T_{\rm vir}}{\Lambda(T_{\rm vir}, n_{\rm H}) x_{\rm H_2} - \Gamma_{\rm PBH}}\,, \quad t_{\rm ff} = \sqrt{\frac{3\pi}{32 G \rho_{\rm gas}}}$$

- Cooling & heating rates (Trenti & Stiavelli, 2009)

$$\Lambda(T_{\rm vir}, n_{\rm H}) \simeq 10^{-31.6}\ {\rm erg\ s^{-1}} \left(\frac{T}{100\ {\rm K}}\right)^{3.4} \left(\frac{n_{\rm H}}{10^{-4}\ {\rm cm^{-3}}}\right)$$

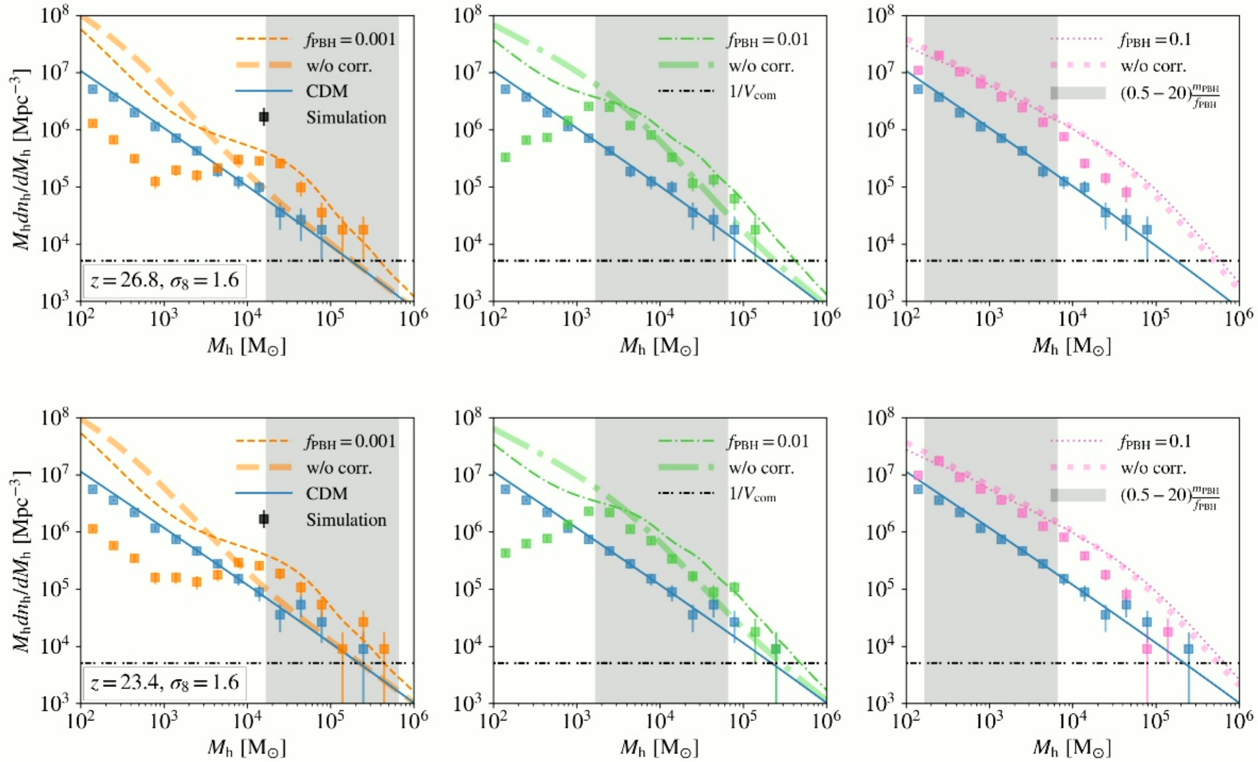
$$x_{\rm H2} \simeq 3.5 \times 10^{-4} \left(\frac{T_{\rm vir}}{1000\ {\rm K}}\right)^{1.52} \times \max[1, 3(f_{\rm PBH}/0.1)^{0.15}]$$

$$\Gamma_{\rm PBH} = \frac{f_{\rm PBH}\mu m_{\rm H}(\Omega_m - \Omega_b)}{m_{\rm PBH}\Omega_b} P_{\rm heat}(m_{\rm PBH}, \rho_{\rm gas}, \tilde{v}), \quad \mu = 1.22$$

- Characteristic gas density and velocity
$\rho_{\rm gas} = m_{\rm H} n_{\rm H}/X = \Delta_{\rm gas}\bar{\rho}_{\rm gas}$, $\Delta_{\rm gas} = 1300$, $X = 0.76$, $\tilde{v} \sim \sqrt{GM_{\rm h}/R_{\rm vir}}$

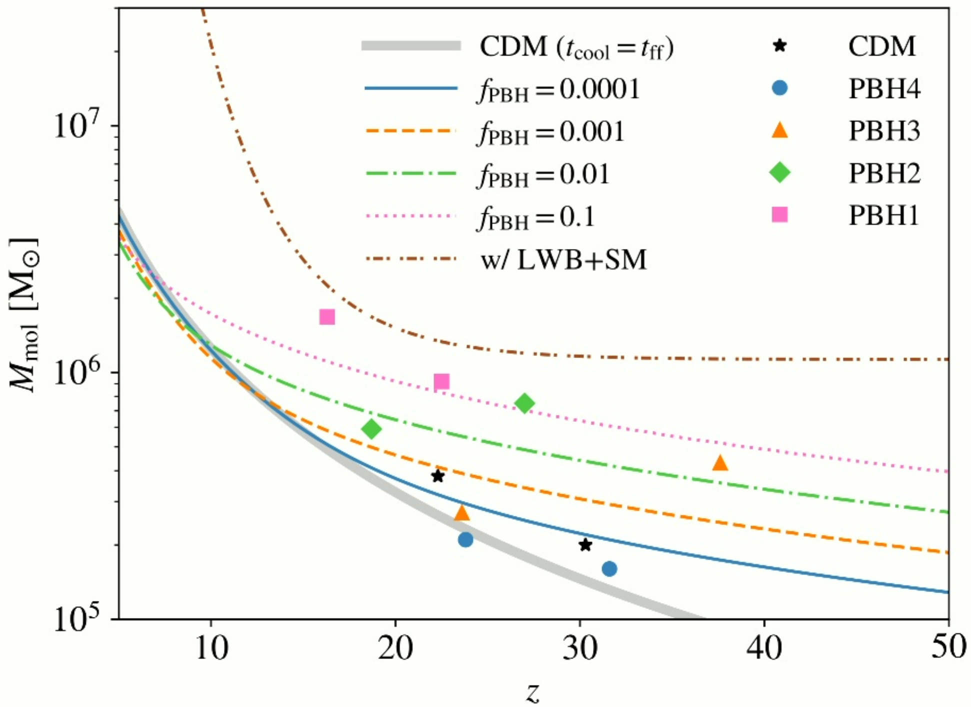
PS formalism VS simulations (2)

Overproduction of massive haloes with $M_{\rm h} \gtrsim 20 m_{\rm PBH}/f_{\rm PBH}$ for $f_{\rm PBH} \gtrsim 0.01 \rightarrow$ Tightly bound PBH-seeded (sub)structures delay the assembly of larger halos. The non-linear growth of large-scale fluctuations caused by PBHs is slower than expected from the linear theory extrapolation (Inman & Ali-Haïmoud, 2019).



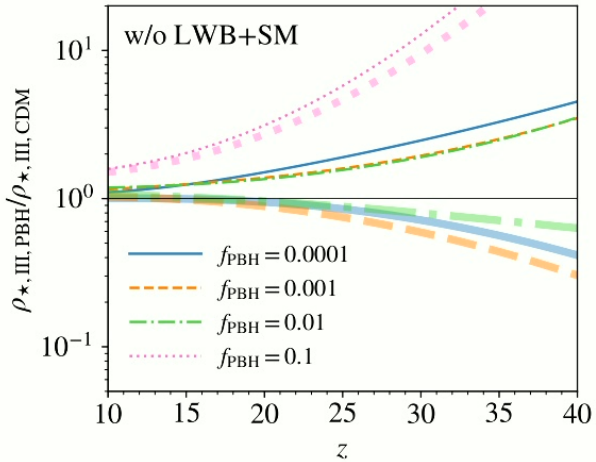
Analytical predictions VS simulations

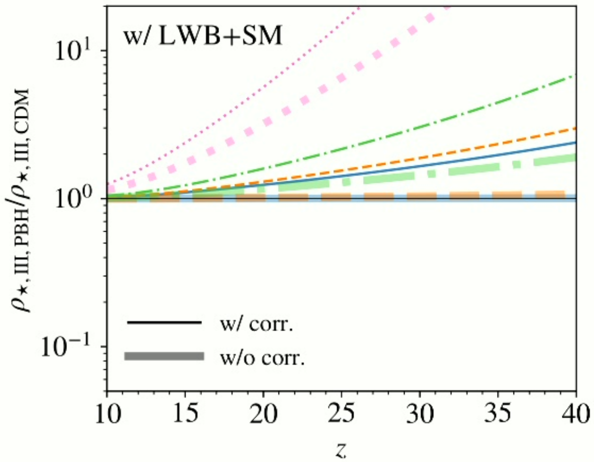
The effects of PBHs are overwhelmed by the environmental effects from Lyman-Werner background (LWB) and baryon-DM steaming motion (SM) in most regions of the Universe (Schauer et al., 2021).



Cosmic stellar mass density

$$\rho_{\star,\mathrm{III}} = \epsilon_{\star,\mathrm{III}} \frac{\Omega_b}{\Omega_m} \int_{M_{\mathrm{mol}}}^{10^8\ \mathrm{M}_\odot} \frac{dn_{\mathrm{h}}}{dM_{\mathrm{h}}} M_{\mathrm{h}} dM_{\mathrm{h}}\ , \quad \epsilon_{\star,\mathrm{III}} = const.$$





The variation is within a factor of ~ 3 at $z \lesssim 30$ for $f_{\mathrm{PBH}} \lesssim 0.01$ allowed by observational constraints[4].

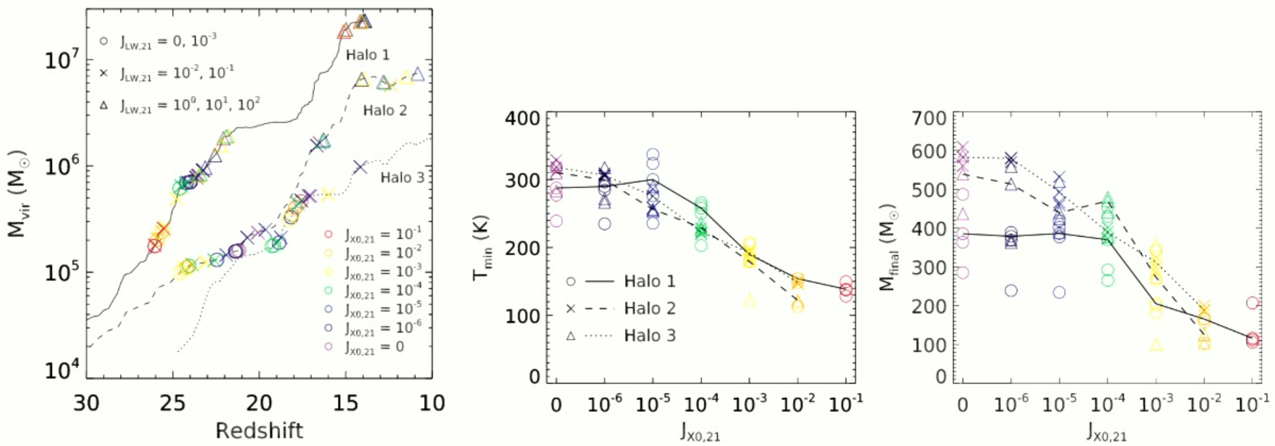
[4] The halo abundances are likely overestimated by the PS formalism for $f_{\mathrm{PBH}} \gtrsim 0.01$.

Tentative conclusions

- PBHs accelerate early structure formation but meanwhile increase the halo mass threshold for star formation with heating. Given these two competing effects, **the global impact of PBHs on Pop III star formation is minor for PBH models allowed by current observational constraints** ($f_{\rm PBH} \lesssim 0.01$). This is also true when typical environmental effects from LWB and SM are considered, in which case the heating effect of PBHs becomes unimportant.
- **The PS formalism cannot fully capture the non-linear dynamics and non-Gaussianity caused by PBHs in structure formation.** It is non-trivial to build an accurate analytical model for the halo mass functions in PBH cosmologies.

Future work: other forms of BH feedback

- LW radiation: dissociation of $\mathrm{H_2} \rightarrow$ increase of M_{mol}, formation of direct-collapse BHs (DCBHs)
- X-rays: enhancement of $\mathrm{H_2}$ formation $\rightarrow$ decrease of M_{mol} and star formation efficiency (with enhanced cooling and reduced accretion rates)

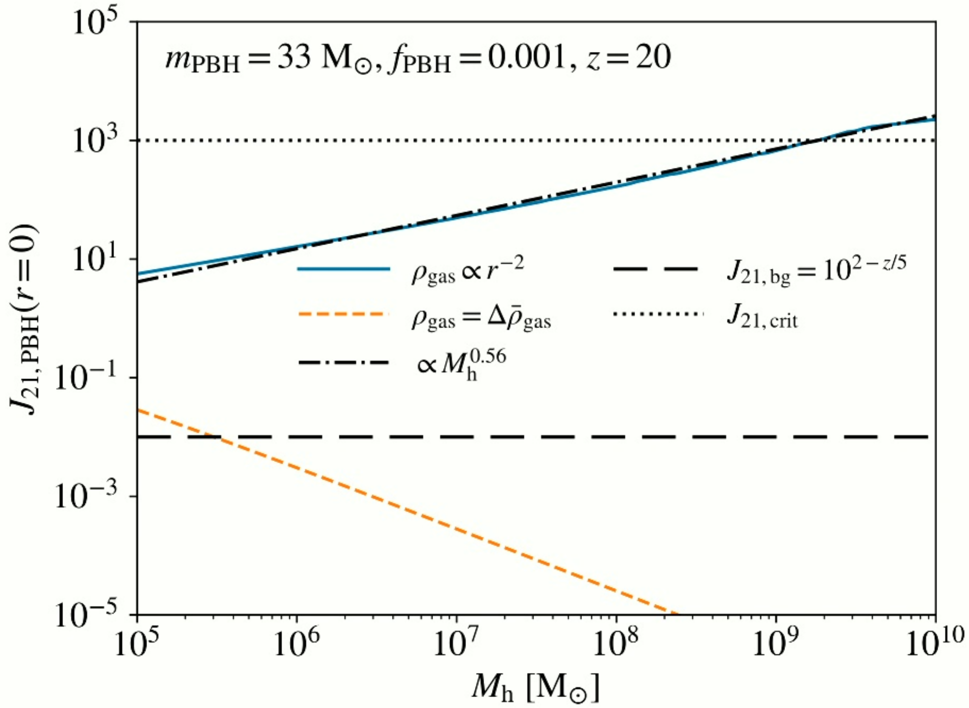


(Park et al., 2021)

28

Lyman-Werner feedback from PBHs

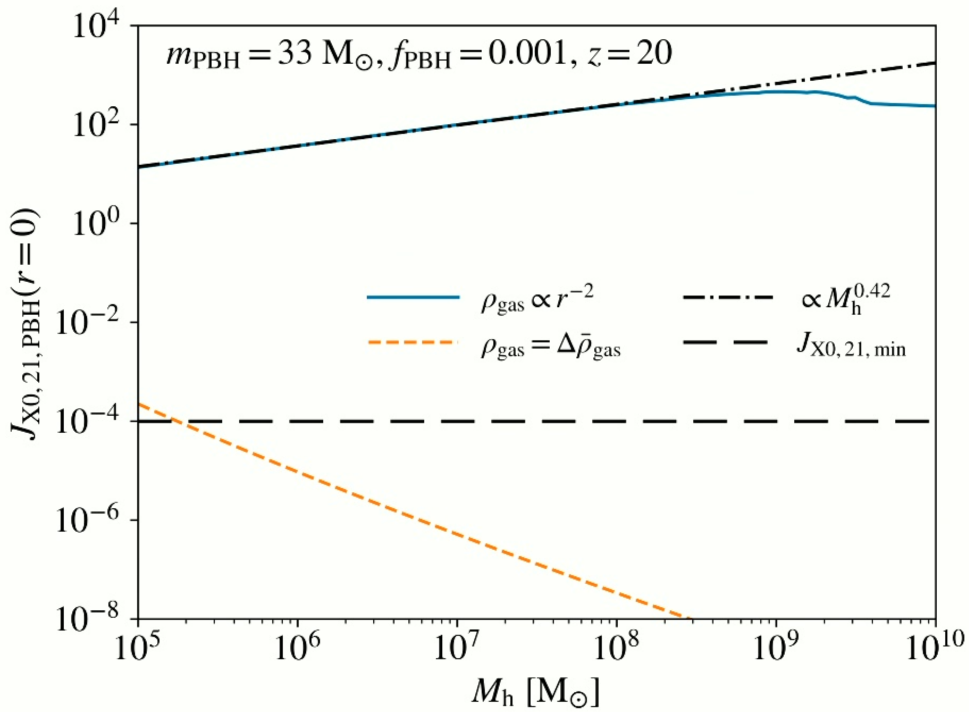
DCBH formation criterion with PBHs (in atomic cooling halos):
$M_\mathrm{h} \gtrsim 3.3 \times 10^7 \, (f_\mathrm{PBH}/0.01)^{-1.8} \, (m_\mathrm{PBH}/33 \ \mathrm{M}_\odot)^{-1.6} \ \mathrm{M}_\odot$



$J_{21,\mathrm{crit}} \sim 1000$: critical LWB intensity for DCBH formation (Sugimura et al., 2014), $J_{21,\mathrm{bg}}$: LWB intensity from stars (Greif & Bromm, 2006)

X-ray feedback from PBHs

The gas and PBH distributions matter a lot → We need radiative hydrodynamic simulations to figure out what's really going on!



$J_{\rm X0,21,min}$: minimum X-ray background intensity (at 0.2 keV) to significantly affect Pop III star formation (Park et al., 2021)

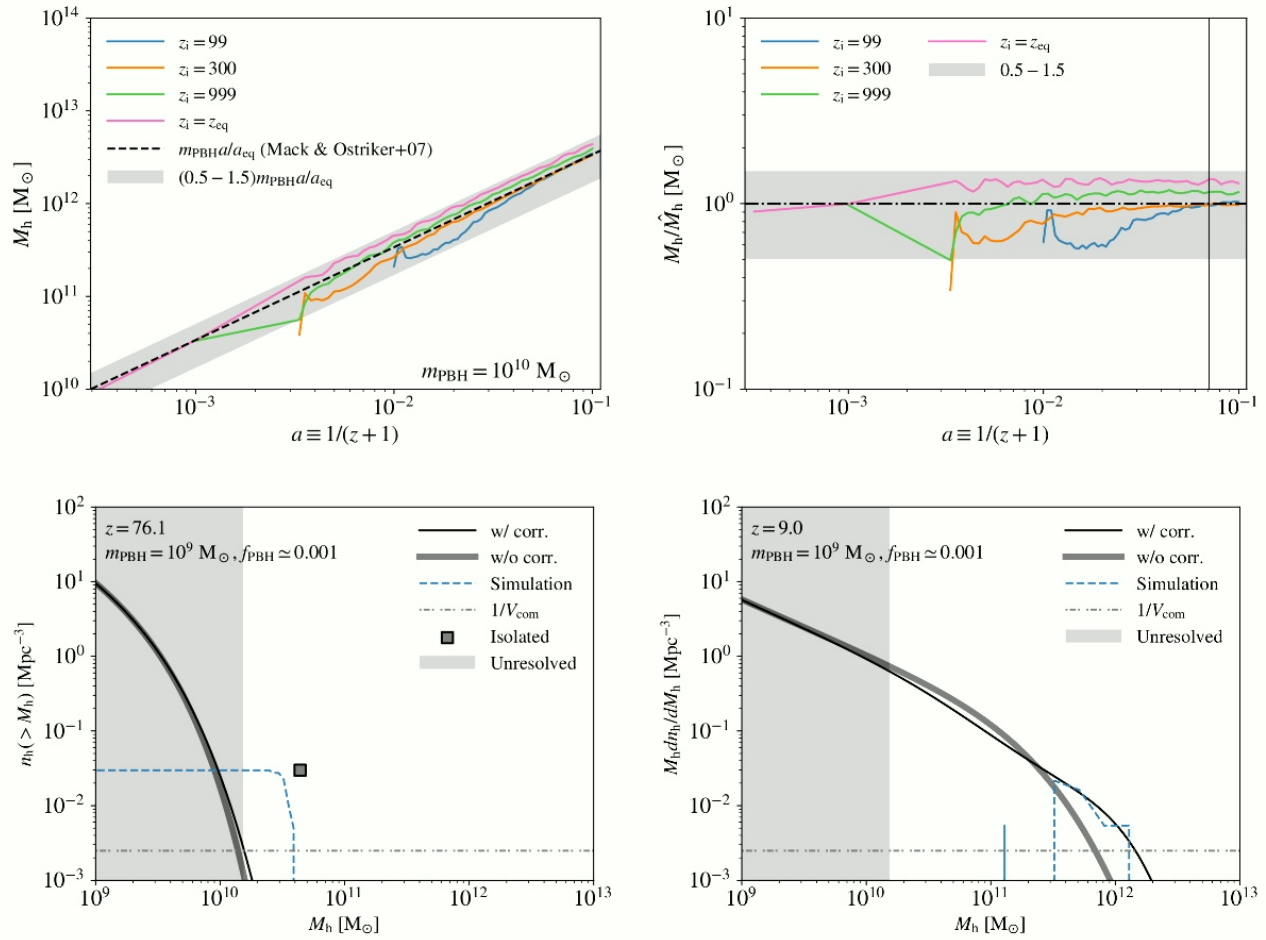
Improving the ICs of cosmological simulations

- Combining 'seed' and 'Poisson' effects (Liu & Bromm, 2023)
  - Apply a new truncation for the perturbation from the nearest PBH (at a distance of r):

$$\vec{\psi} = \min\left(1, f_{\rm shrink} r/|\vec{\psi}|\right) \vec{\psi}\ , \quad f_{\rm shrink} = 1 - \Delta_{\rm vir}^{-1/3} \approx 0.822$$

    This will create a uniform sphere of PDM with an overdensity of $\Delta_{\rm vir} = 18\pi^2 \sim 200$ and radius of $\sim d_{\rm nl}$ around each PBH, mimicking the non-linear structure seeded by it.
  - Apply the original resolution-dependent truncation for the displacement caused by the other PBHs.
- Growth factor of PBH perturbations
  A smaller growth factor $D_{\rm PBH} \sim 0.18 a_{\rm ini}/a_{\rm eq}$ is required to produce $M_{\rm B} \sim m_{\rm PBH} a/a_{\rm eq}$ in simulations of structure formation around a single PBH using GIZMO (Hopkins, 2015) and AREPO (Springel, 2010).

Test results from DM only simulations

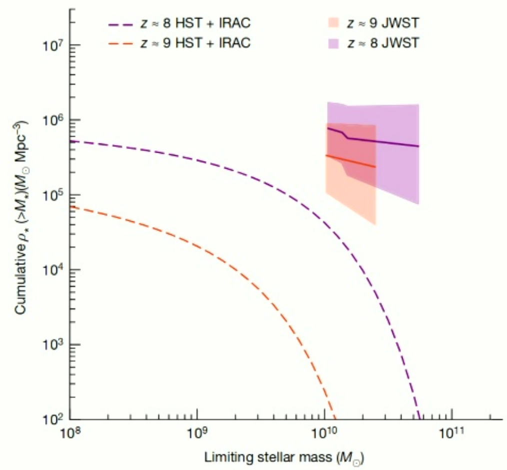


32

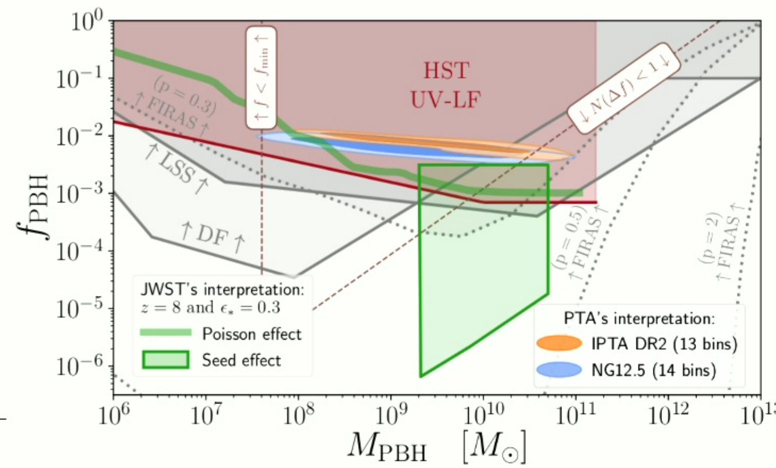
MASSIVE GALAXIES SEEDED BY SUPERMASSIVE PBHS

Evidence for supermassive PBHs

Recent JWST observations have discovered a population of unusually massive galaxy candidates at $z \gtrsim 8$. $\rightarrow$
Accelerated formation of massive structures by supermassive ($\gtrsim 10^9\ \mathrm{M}_\odot$) PBHs (Liu & Bromm, 2022)!?
The low-frequency stochastic GW background can be fully explained by PBH mergers with $m_{\mathrm{PBH}} \sim 10^8 - 10^{11}\ \mathrm{M}_\odot$ and $f_{\mathrm{PBH}} \sim 0.01$.



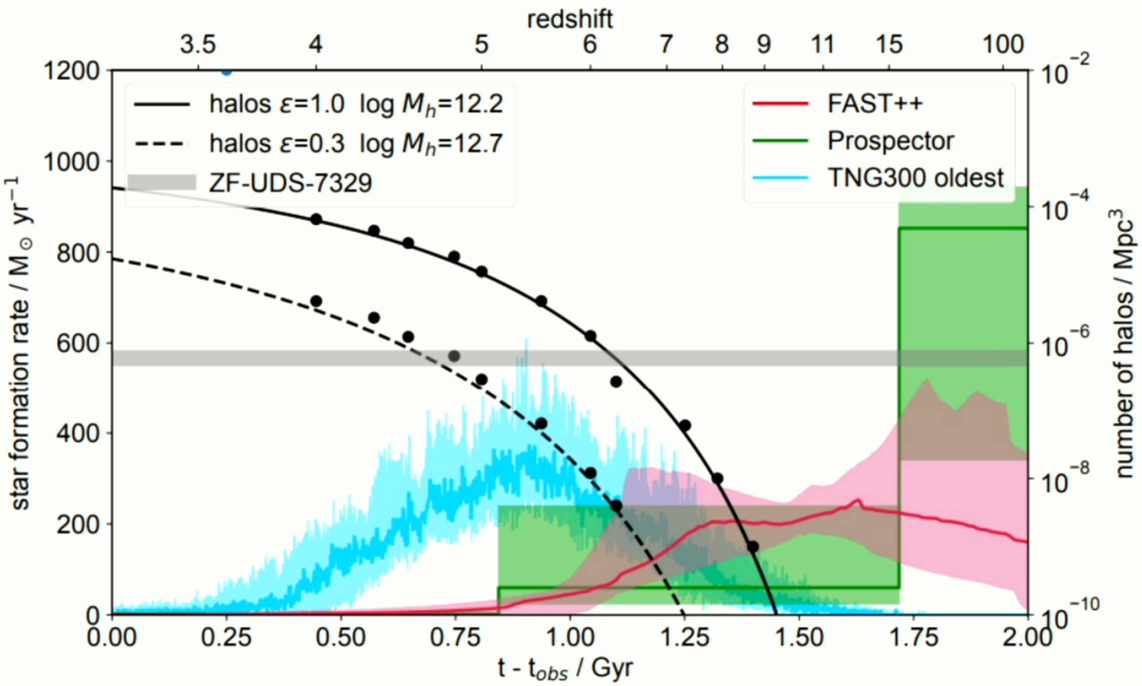
(Labbé et al., 2023)



(Gouttenoire et al., 2023)

A massive galaxy in tension with ΛCDM

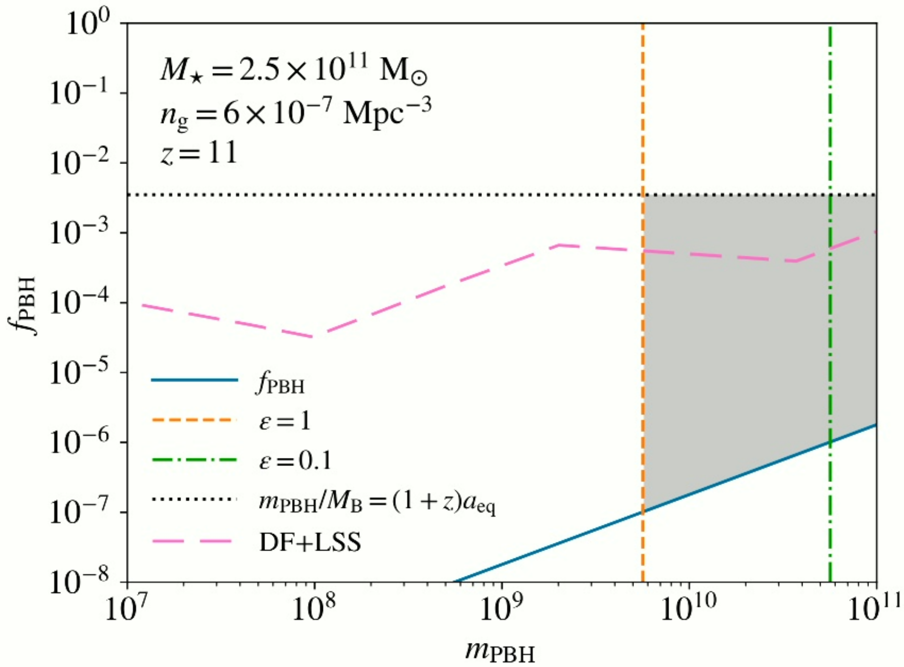
The observed spectrum of ZF-UDS-7329 is consistent with an old stellar population formed at $z \gtrsim 11$ with a total mass of $M_\star \sim 2.5 \times 10^{11}\ \mathrm{M}_\odot$, not expected to occur until $z \sim 6$ in ΛCDM!



(Glazebrook et al., 2023)

The PBH scenario

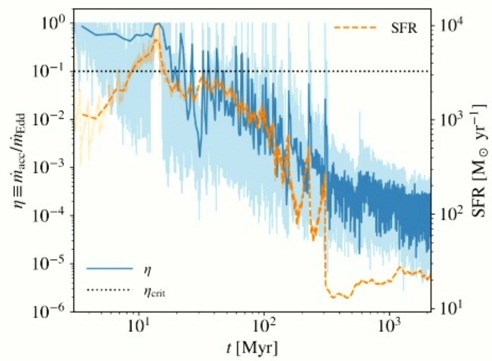
Number density requirement: $n_g < \bar{n}_{\rm PBH} \propto f_{\rm PBH}/m_{\rm PBH}$
Mass requirement: $M_\star = \epsilon(\Omega_b/\Omega_m)M_{\rm B} = \epsilon(\Omega_b/\Omega_m)m_{\rm PBH}/[(1+z)a_{\rm eq}]$
PBH parameters: $m_{\rm PBH} \gtrsim 5.6 \times 10^{10\ (9)}\ {\rm M}_\odot$, $f_{\rm PBH} \gtrsim 10^{-6\ (7)}$, given the **star formation efficiency** $\epsilon = 0.1\ (1)$.

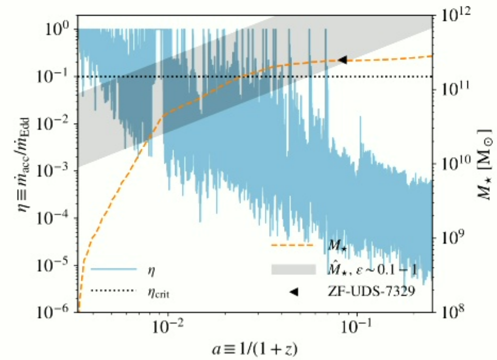


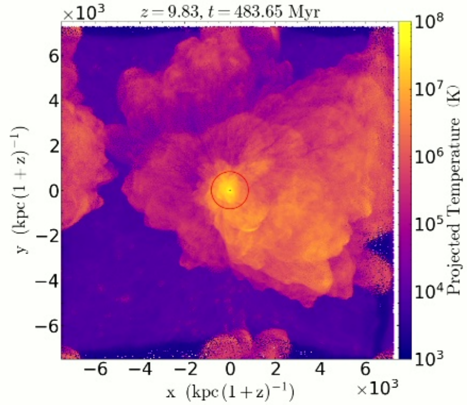
36

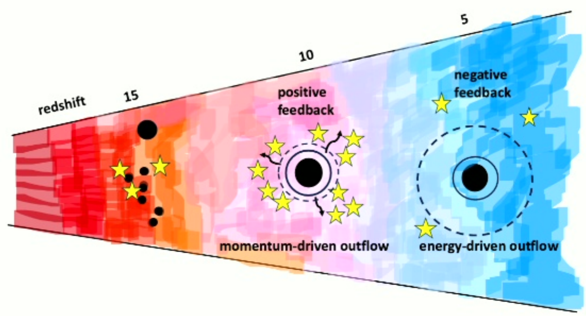
Idealized simulations

- A single PBH with $m_{\mathrm{PBH}} = 5 \times 10^{10}\ \mathrm{M}_\odot$ in a $L = 10\ h^{-1}\mathrm{Mpc}$ box
- AREPO with the IllustrisTNG sub-grid models (Pillepich et al., 2018)









(Silk et al., 2024)