If dark matter is fuzzy, the first stars form in massive pancakes

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TIFR Mumbai SOTU seminar: 13th December 2022

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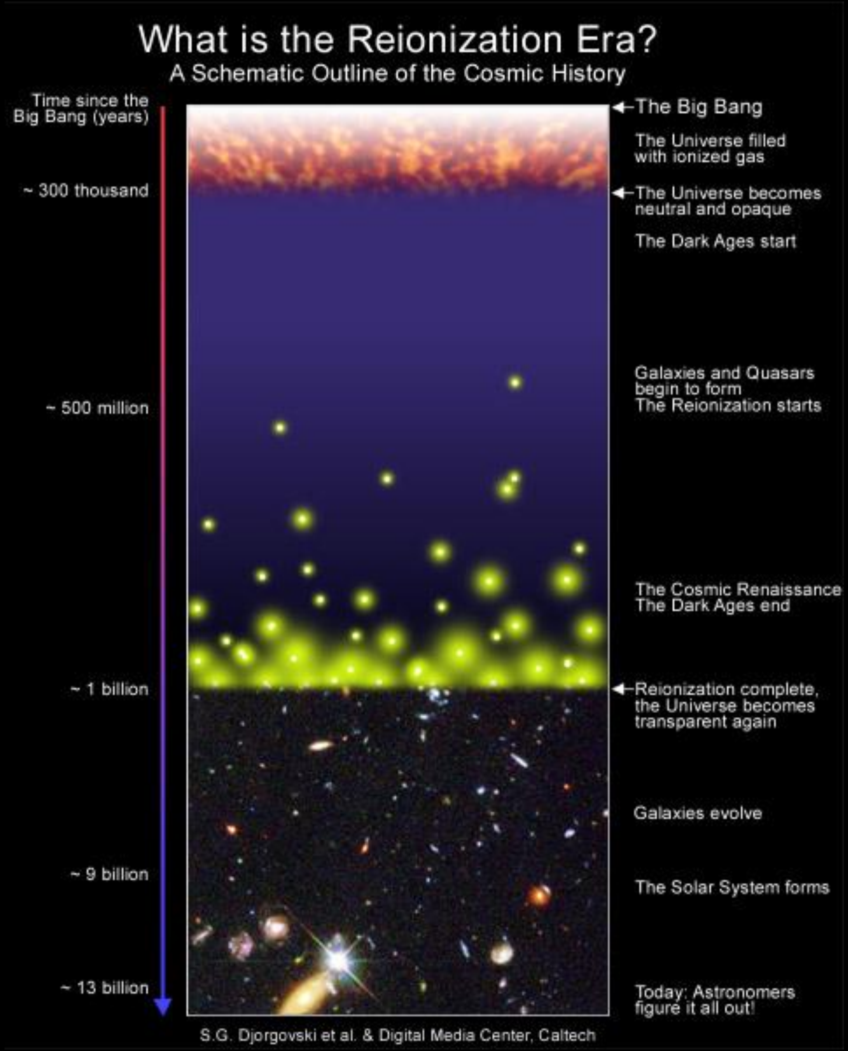


S.G. Djorgovski et al. & Digital Media Center, Caltech

What are the first stars?

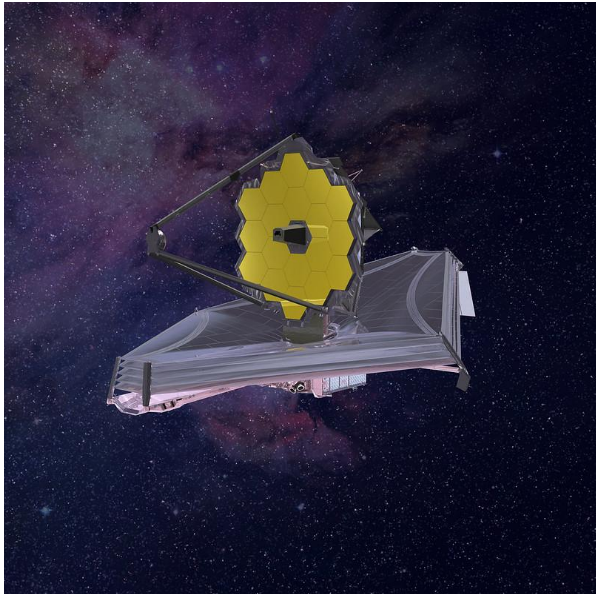
Why first stars?

- Metal enrichment
- Reionization
- Early galaxy formation
- Nature of dark matter

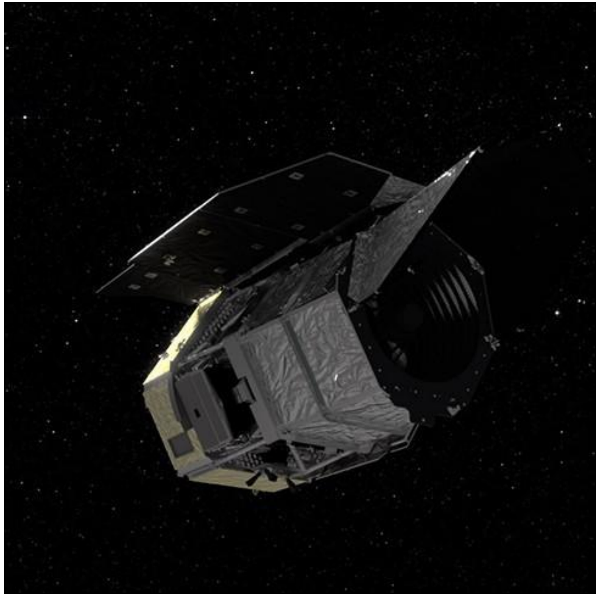
Important questions about Pop III stars

- When and where do they form?
- How late can Pop III stars form?
- What is the initial mass function (IMF) of Pop III stars?
- How does transition from Pop III to Pop II star formation take place?
- What are some of the predicted observational signatures of Pop III stars?

Signatures of first stars: JWST, Roman



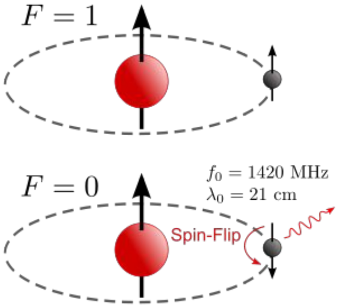
James Webb Space Telescope
Already detected many high-z massive galaxies

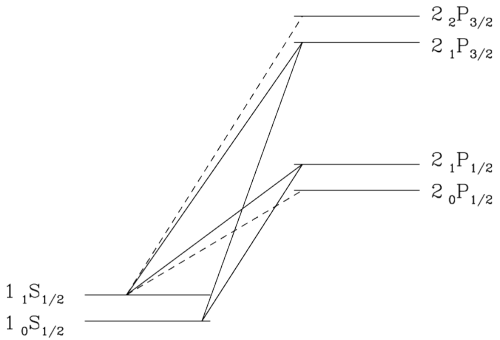


Roman Space Telescope (WFIRST)
Launching in 2025

Signatures of first stars: HI 21-cm signal

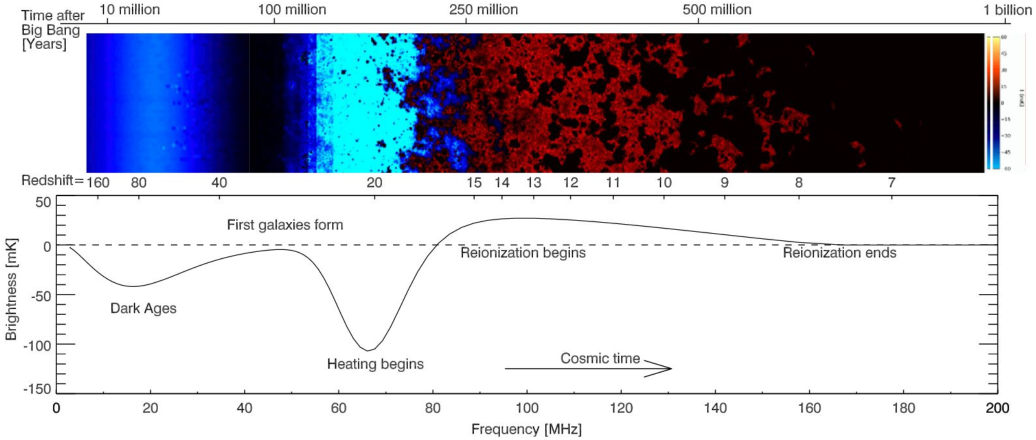
Hyperfine transition





Wouthuysen-Field effect

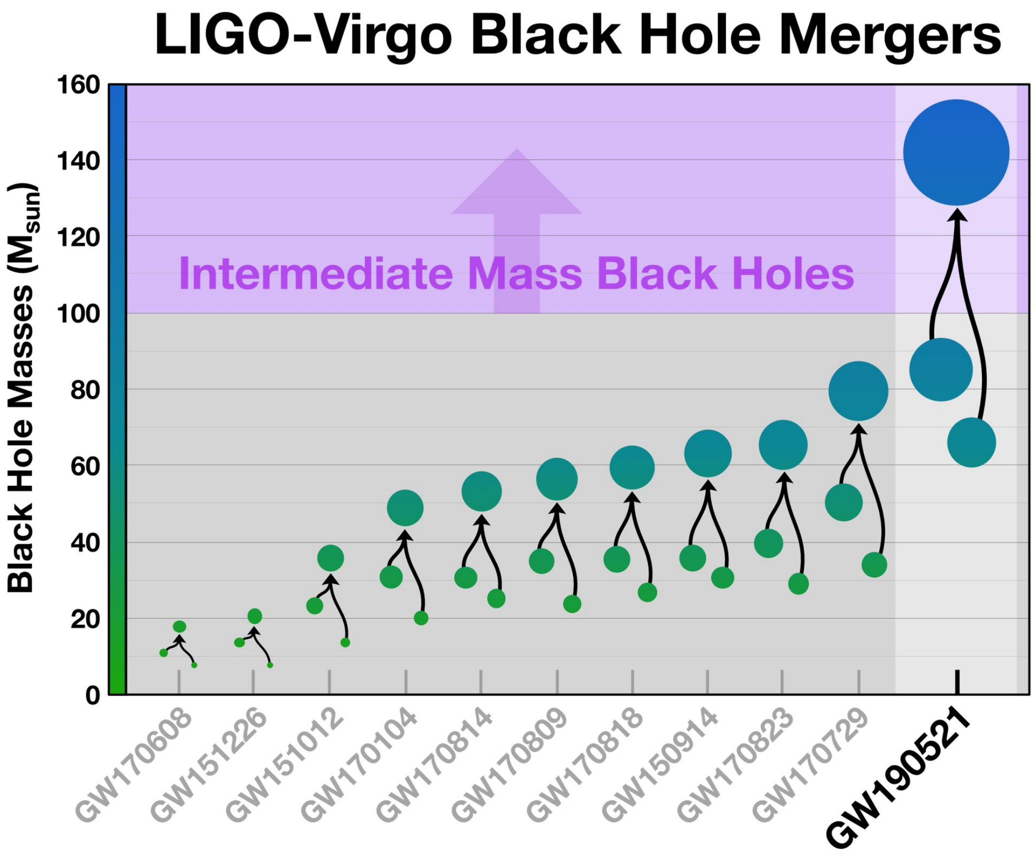
Couples 21-cm spin temperature to the gas kinetic temperature through Lyman-α.



See EDGES results

Images: Wiki, Pritchard & Furlanetto 2005, Pritchard & Loeb 2012

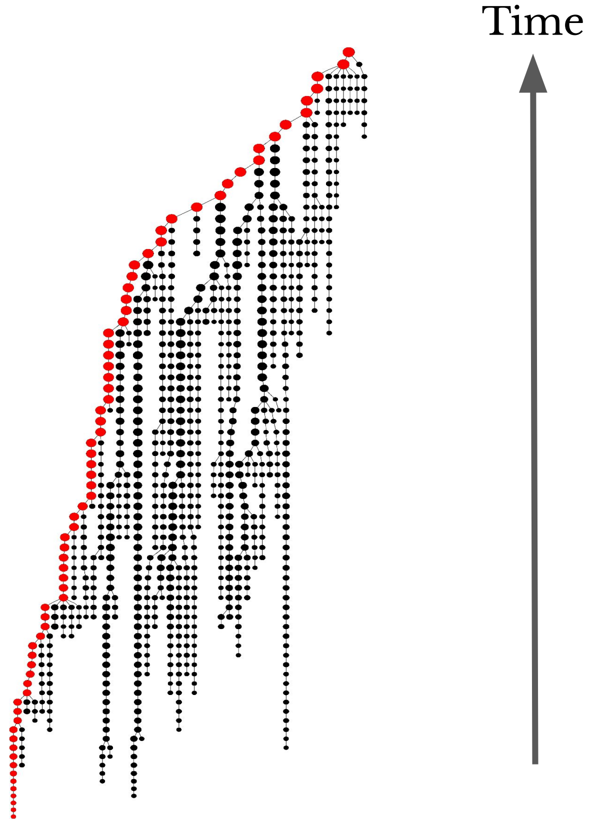
Signatures of first stars: Gravitational waves



Black hole mergers in the "missing gap" are proposed to be from the remnants of the first stars.

(Safarzadeh & Haiman, 2020; Kinugawa+ 2020; Liu & Bromm, 2020)

Hierarchical structure formation

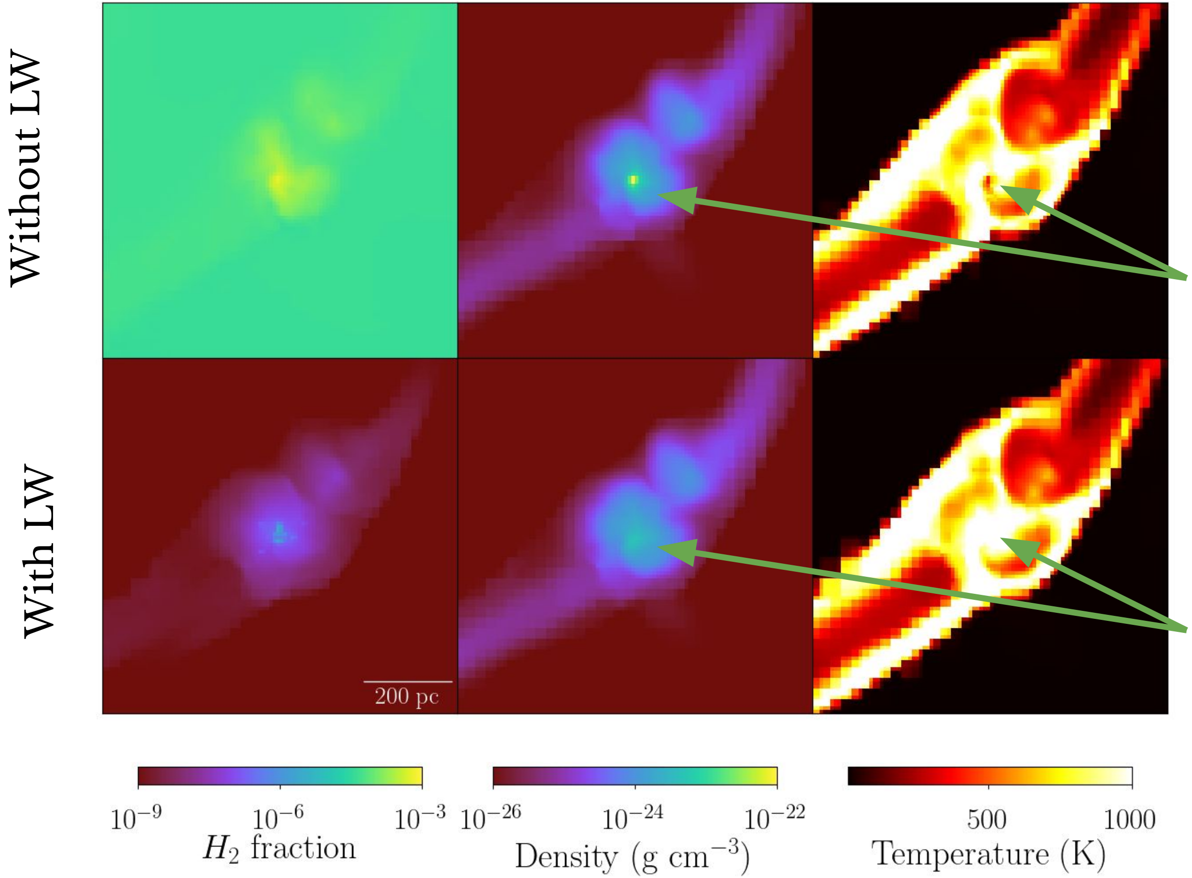


- Dark matter halos merge and accrete with time.
- The virial mass and temperature increase.
- Condition for star formation

$$t_{cool} < t_{Hubble}$$

- Cooling with H_2.
- $M_{crit} \sim 10^5\text{-}10^6\ M_\odot$

Effect of Lyman-Werner radiation



Star-forming region with cold-dense gas

No star-formation

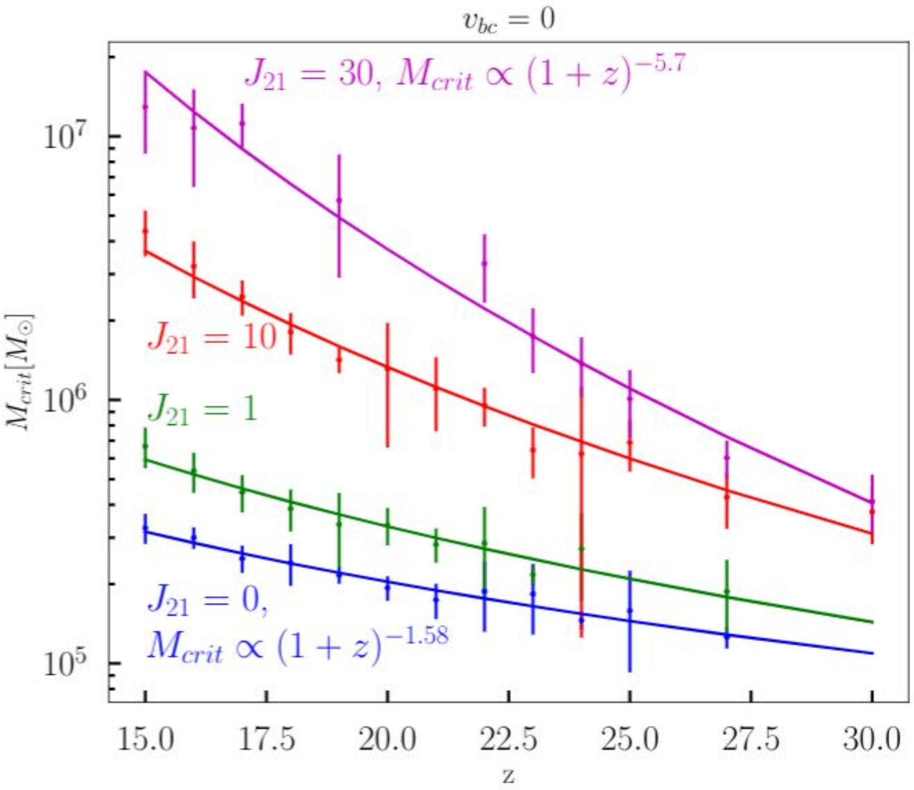
LW photons: 11.2-13.6 eV

Emitted by stars

Dissociate H_2

Increase M_{crit}

Dependence on LW radiation



- For J_{LW}=0, consistent with a fixed virial temperature.
- M_{crit} increases with LW flux.
- Steeper z-dependence with high LW flux.
- Self-shielding of H_2 is important.

Kulkarni+ 2021 ApJ

Effect of baryon-dark matter streaming velocity

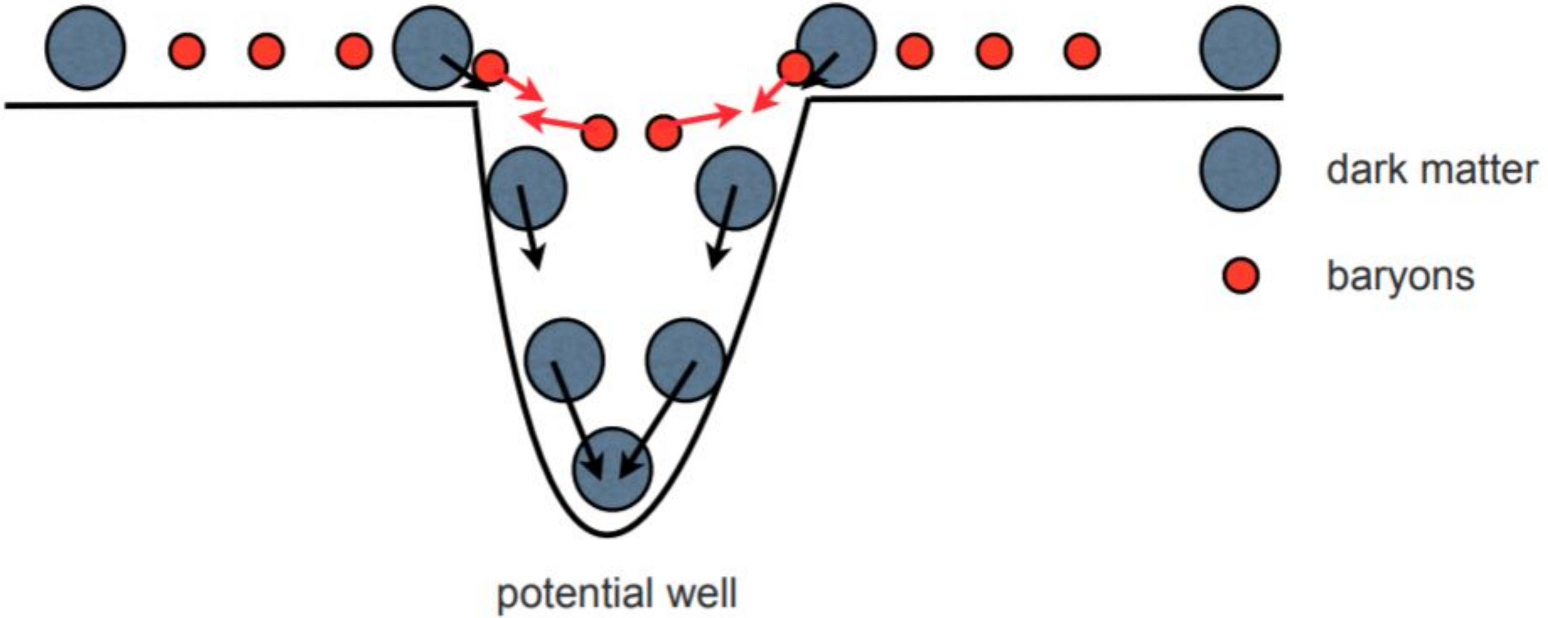
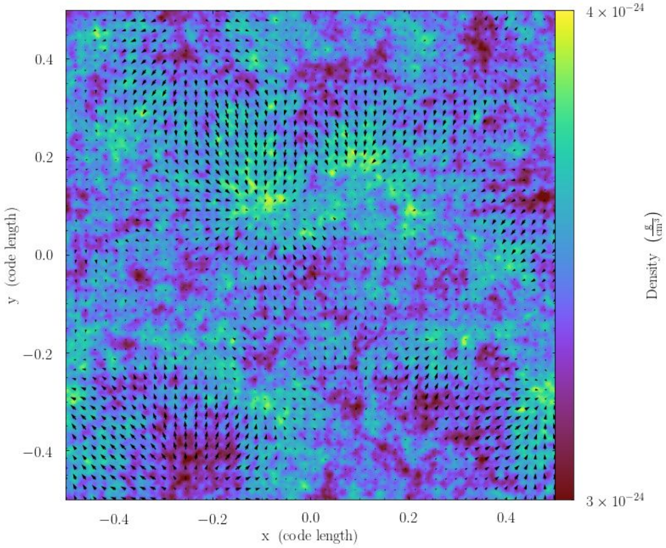
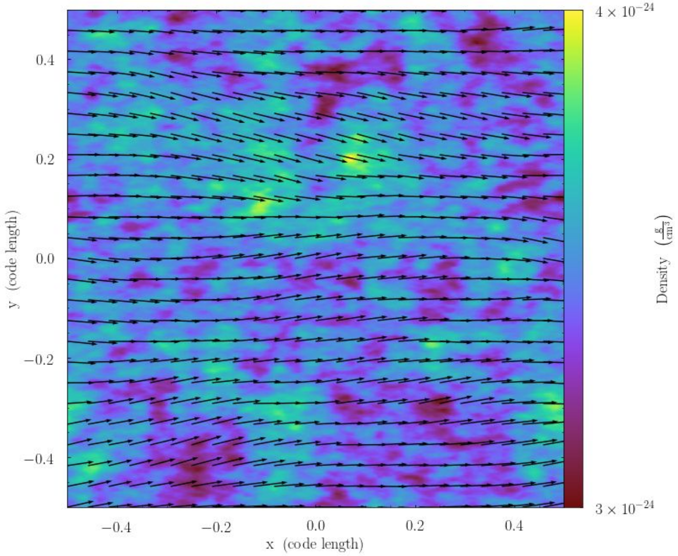


Image: U of Oslo, AST4320 notes

Effect of baryon-dark matter streaming velocity



Without streaming



With streaming

Introduced at z~1100.

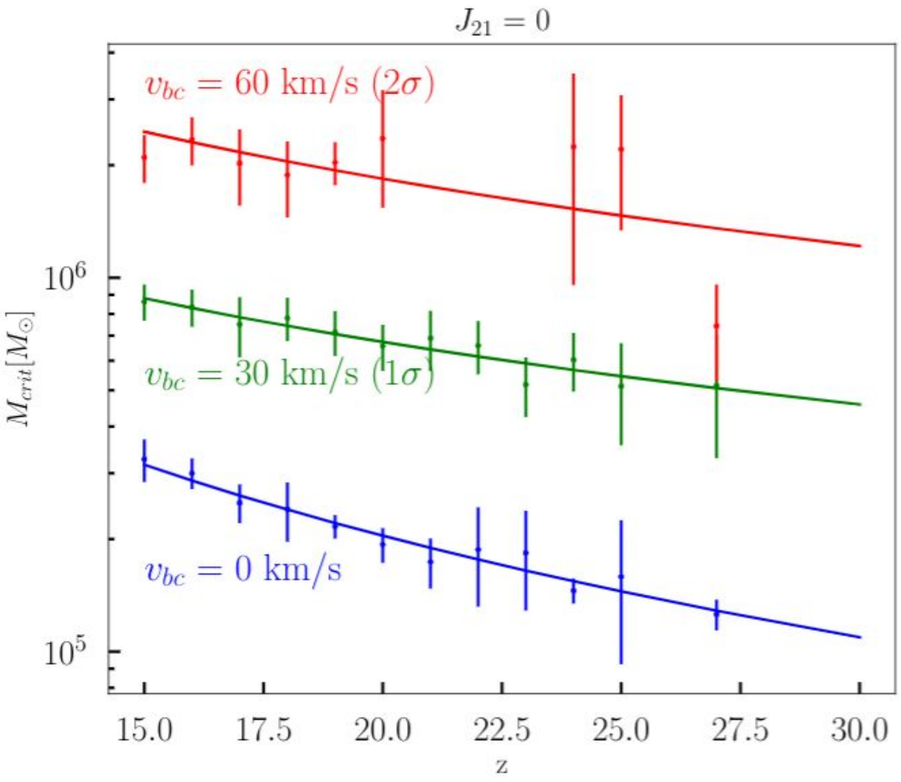
Coherent over 3-10 Mpc.

Maxwell distribution with RMS ~ 30 km/s.

$V \propto (1+z)$

ICs using CICASS

Dependence on streaming velocity

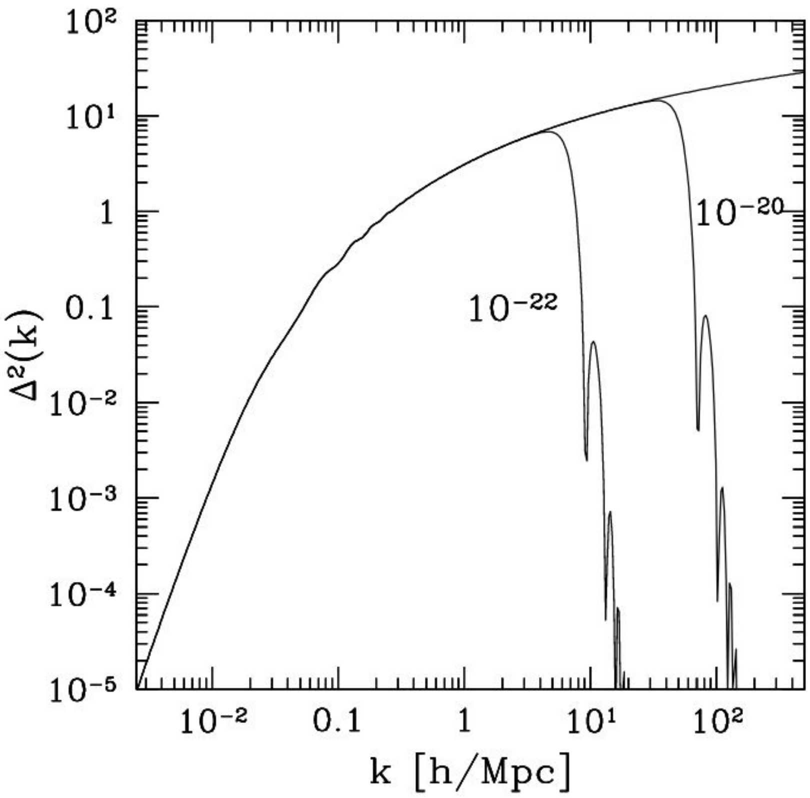


- M_{crit} is higher in the high streaming velocity environment.
- z-dependence becomes less steep in presence of streaming velocity.
- Expected as $v_{bc} \propto (1+z)$.

Kulkarni+ 2021 ApJ

Fuzzy dark matter

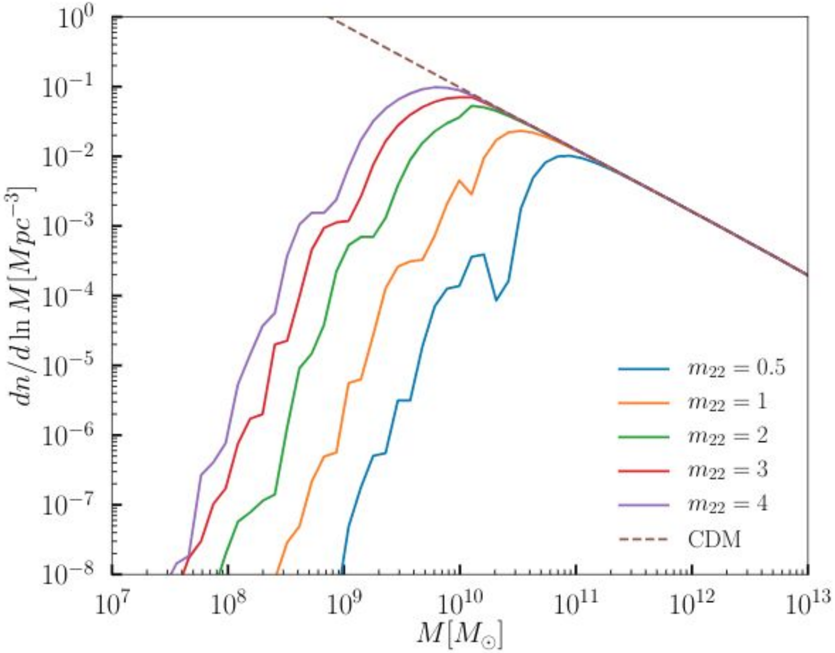
- Proposed to alleviate apparent small-scale problems of ΛCDM:
  - Missing satellites (?)
  - Cusp-core problem
  - Dynamical friction
- Made up of ultralight axions (m ~ 10^{-22} eV).
- De Broglie wavelength ~ kpc
- Cutoff in matter power spectrum at small scales.



Hui ARA&A 2021

Fuzzy dark matter

- Made up of ultralight axions (m ~ 10^{-22} eV).
- Minimum halo mass ~ 10^8 - 10^9 $M_\odot$.
- First stars form in much more massive halos at lower redshift.
- Smoking gun signature for FDM?
- Accurate simulations needed to make observational predictions.



Kulkarni & Ostriker 2022 MNRAS

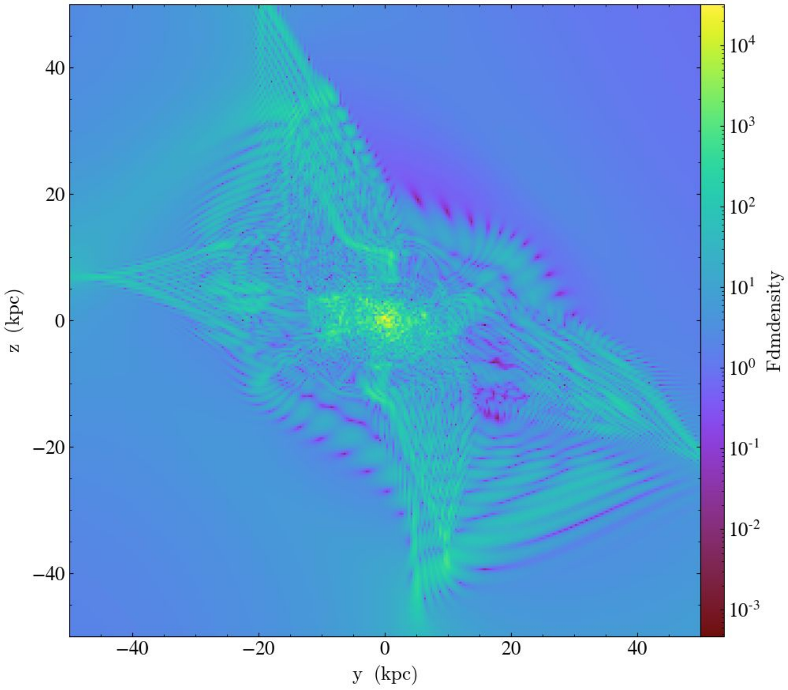
Numerical evolution of FDM

Schrödinger-Poisson equations

$$i\hbar\left(\partial_t\psi + \frac{3}{2}H\psi\right) = \left(-\frac{\hbar^2}{2m_a a^2}\nabla^2 + m_a\Phi\right)\psi,$$

$$\nabla^2\Phi = 4\pi G a^2(\rho - \bar{\rho}),$$

$$\psi \equiv \sqrt{\frac{\rho_{\rm FDM}}{m_a}}e^{i\theta}; \quad \rho_{\rm FDM} = m_a|\psi|^2.$$

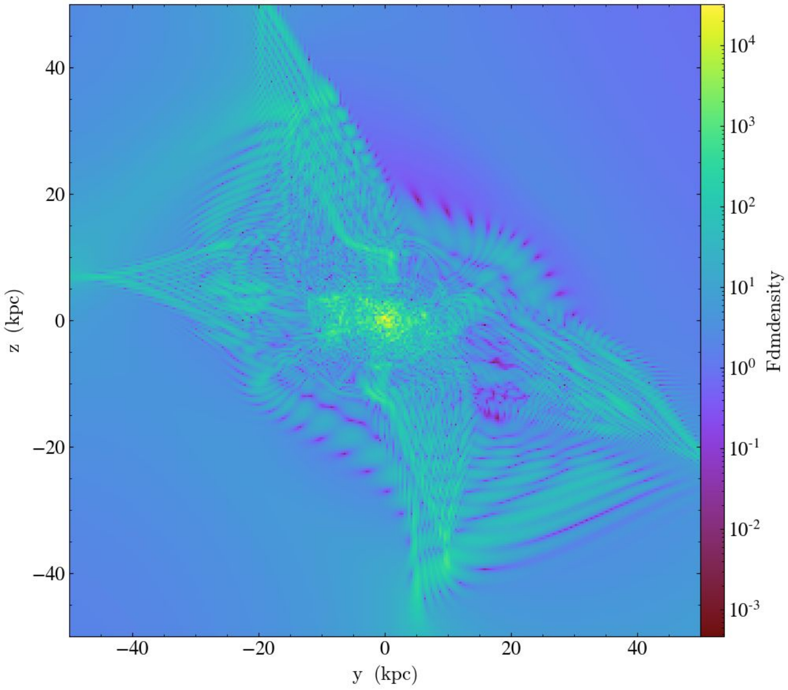


De Broglie wavelength needs to be resolved by the cell size.

Collapsed halo at z = 6 in DM only simulation.

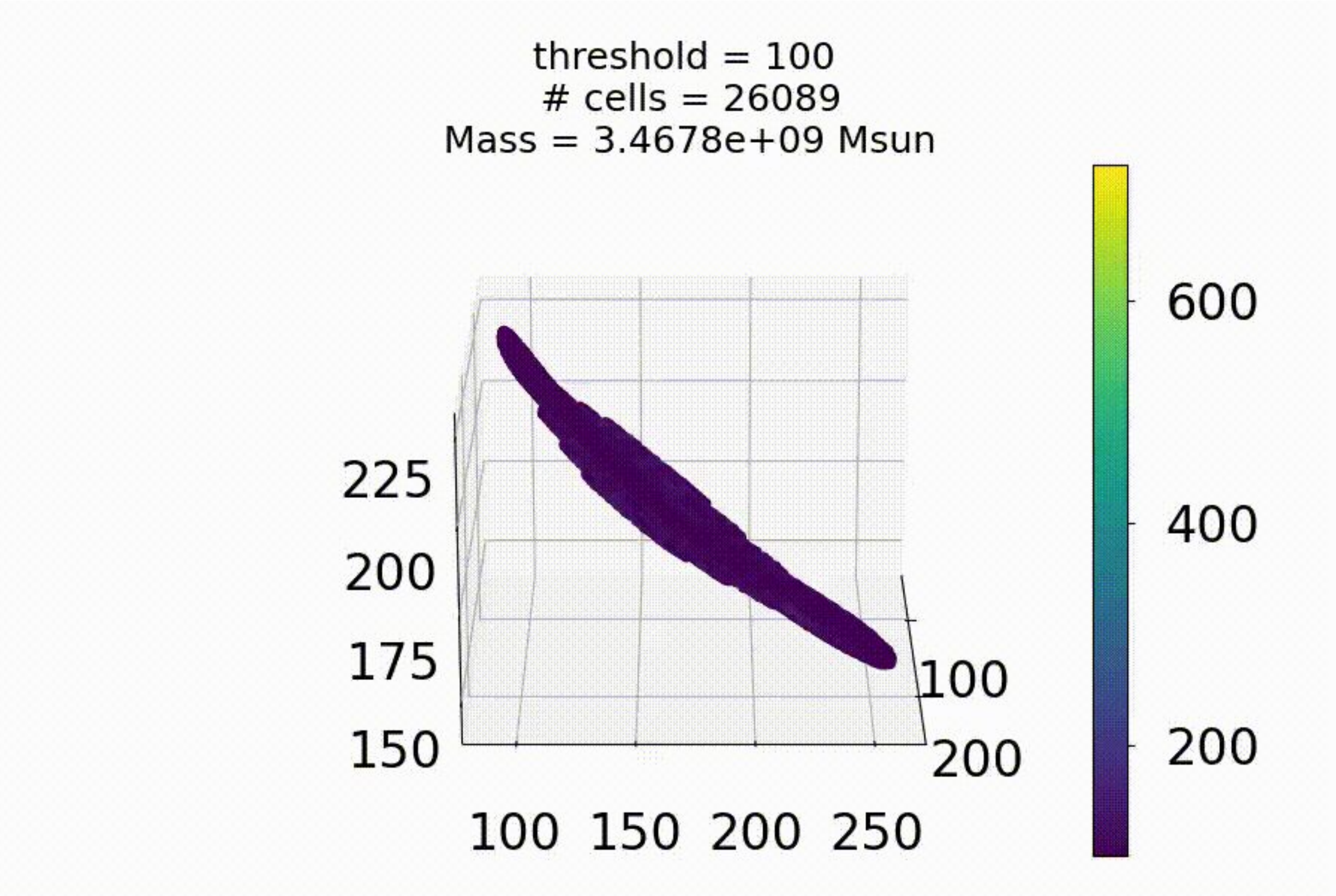
Numerical evolution of FDM

- Cosmological hydro simulations using the adaptive mesh refinement code Enzo.
- Box size 1.7 h^{-1} Mpc.
- Primordial non-equilibrium chemical network and cooling.
- 1024^3 root grid with 9 additional refinement levels.
- Follow protostellar collapse with highest resolution 0.4 pc (at z = 10).



Collapsed halo at z = 6 in DM only simulation.

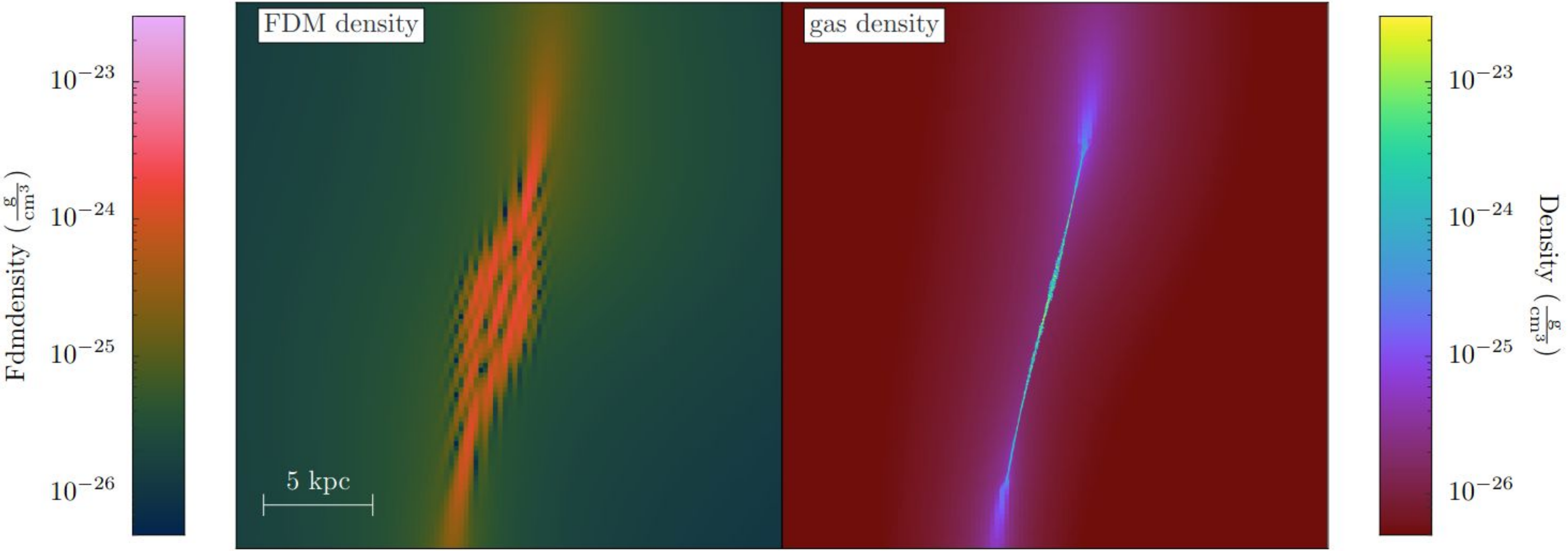
Geometry of the sheet (Zel’dovich pancake)

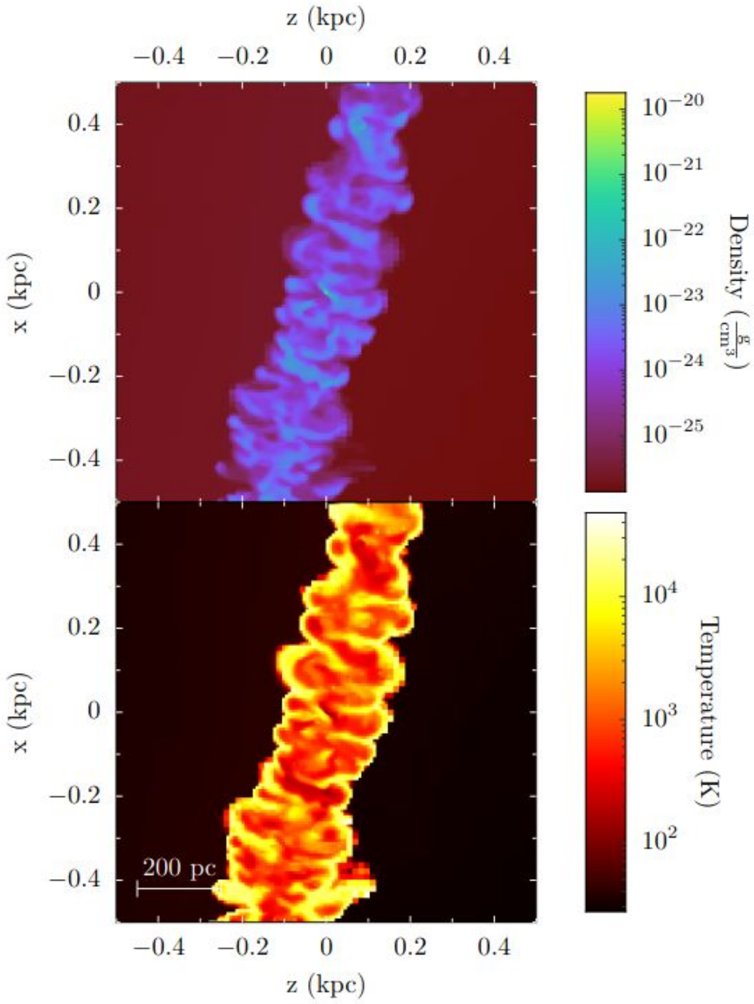


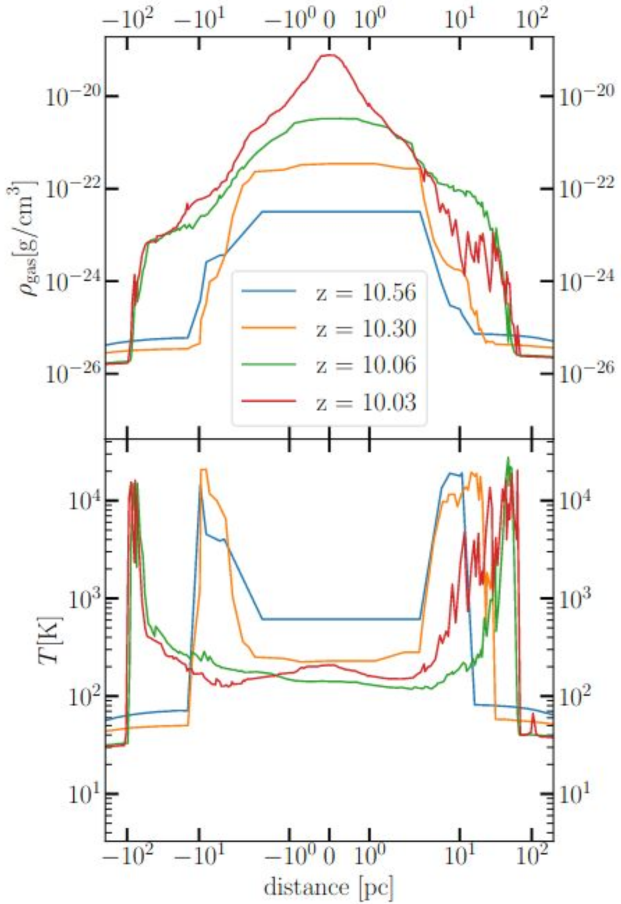
Region with dark matter overdensity > 100.

Units: comoving kpc/h

Gas collapses on a much thinner sheet





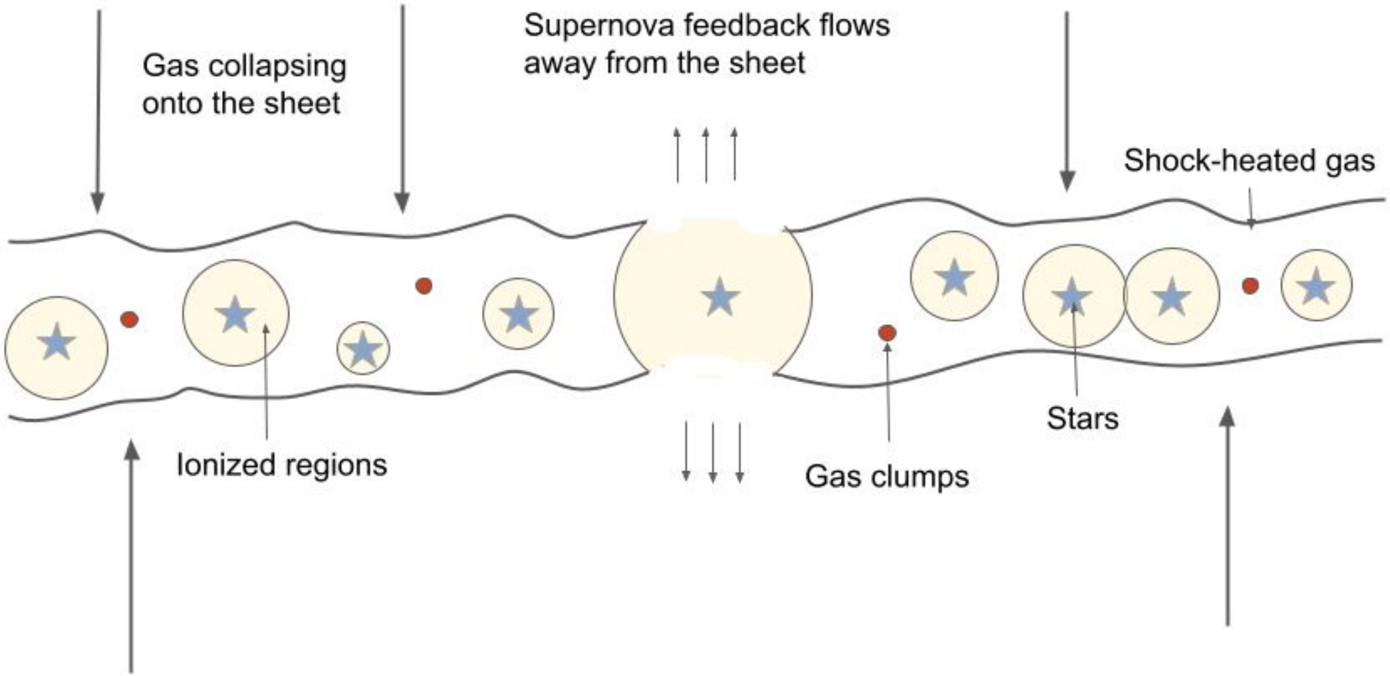


Sheet grows in thickness with time.

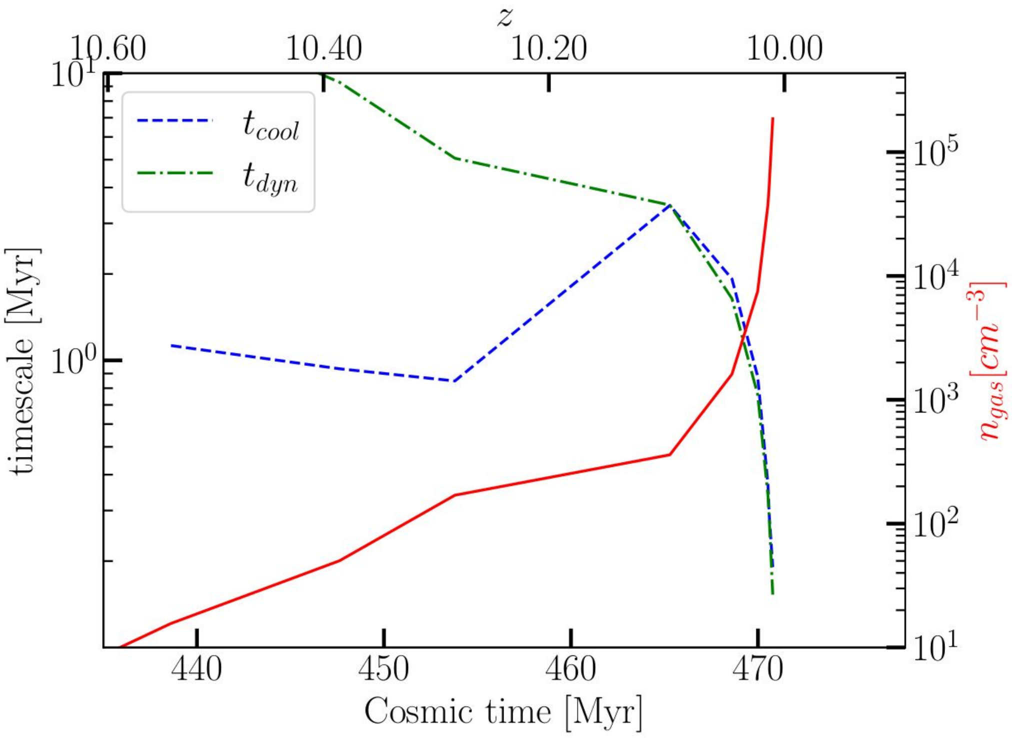
Gas can cool with H_2 transitions.

Kulkarni+22, arXiv:2210.11515

Sheet geometry shields forming Pop III stars: limited self-regulation results in huge burst



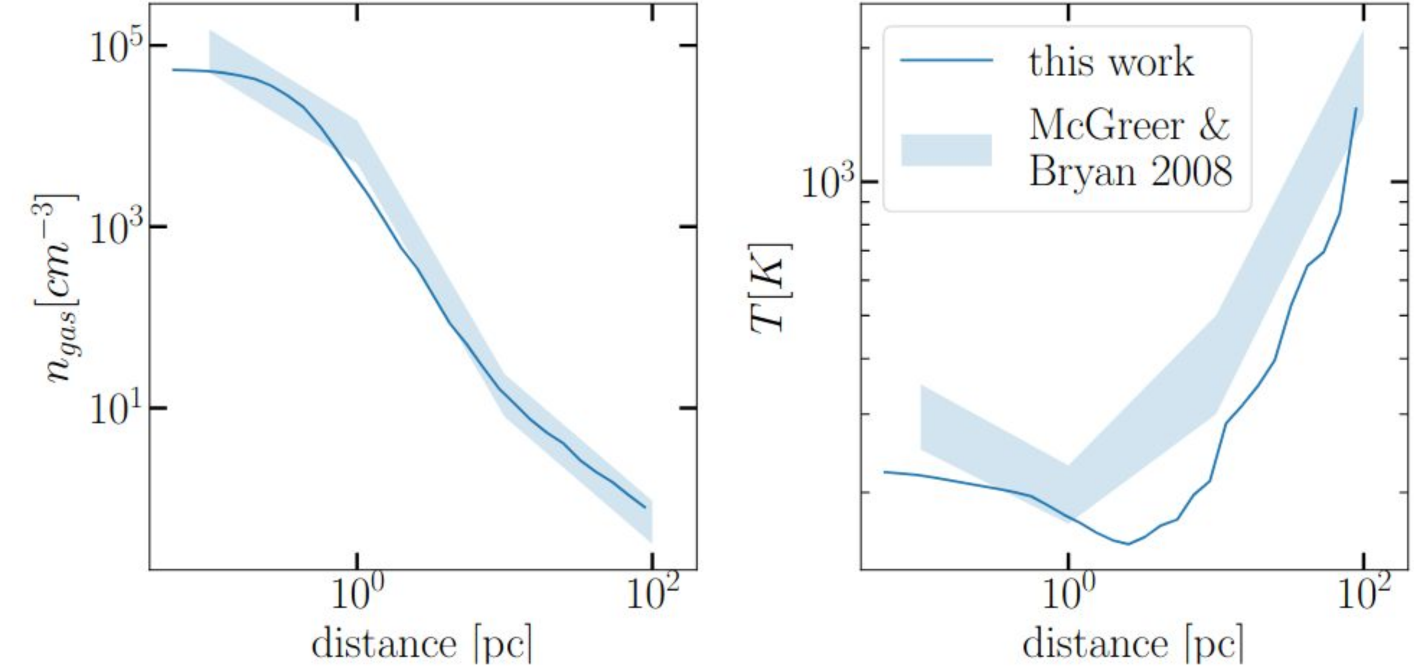
Protostellar collapse



Gas density increases as the cooling time and the dynamical rapidly decrease with time.

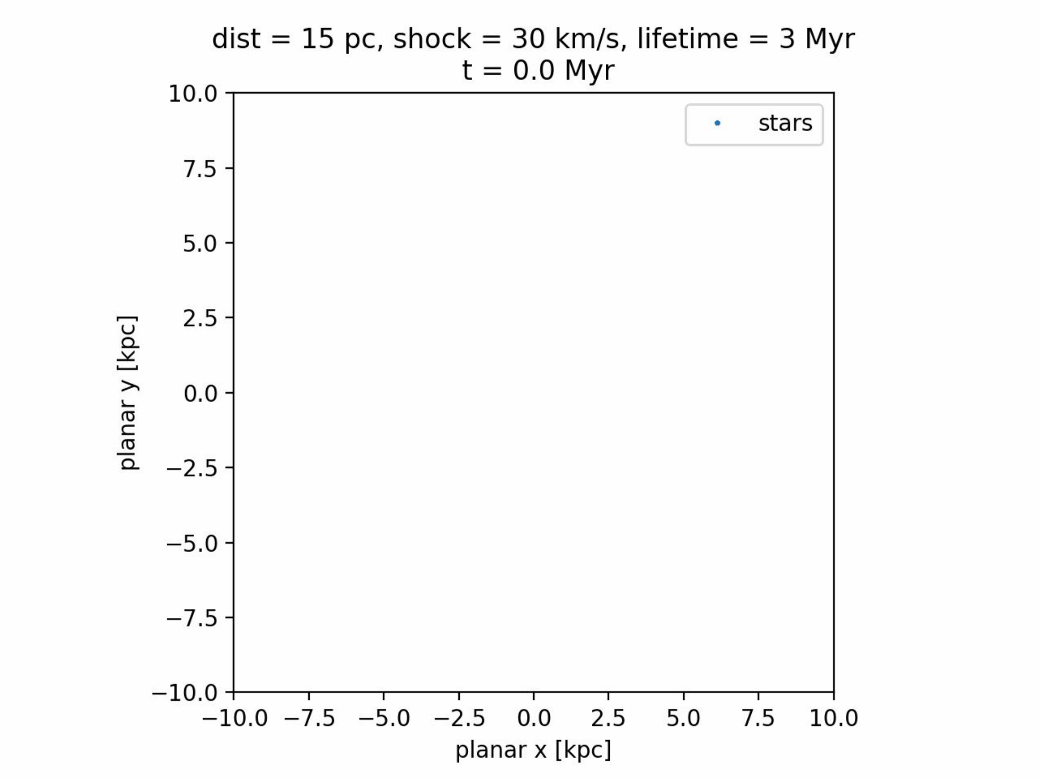
Kulkarni+22, arXiv:2210.11515

Clump profiles are similar to the profiles in ΛCDM minihalos



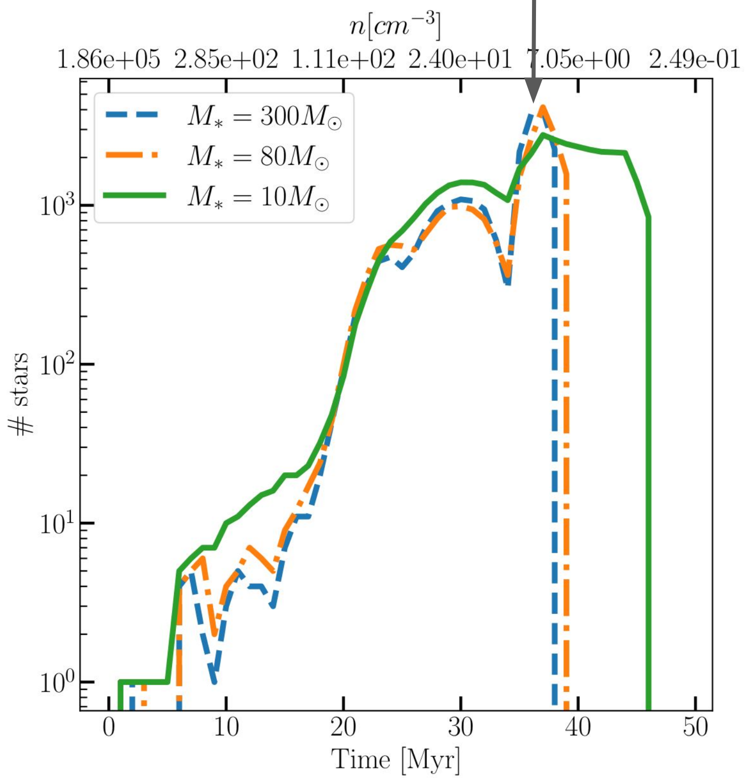
Kulkarni+22, arXiv:2210.11515

Clump evolution: a semi-analytic model



dist = 15 pc, shock = 30 km/s, lifetime = 3 Myr
t = 0.0 Myr

Pop III starburst



- Stars formed at gas density peaks.
- Star formation prevented in ionized bubbles.

Kulkarni+22, arXiv:2210.11515

Observational signatures

- Estimated stellar mass of $8\text{x}10^4$ $M_\odot$.
- Detectable with JWST at z ~ 6 with 100 hours exposure (Zackrisson+ 2011) or lower if strongly lensed.
- 2-3 galaxies per NIRCam field of view at z = 6.

Summary

- In FDM cosmology, first stars form in massive pancakes.
- The properties of the collapsing protostars are similar to CDM.
- Fragmentation of the sheet and minimal feedback effects result in the formation of massive Pop III galaxies.
- Estimated stellar mass of $8 \times 10^4\ M_\odot$. Detectable with JWST at z ~ 6 with 100 hours exposure. (Zackrisson+ 2011)
- 2-3 galaxies per NIRCam field of view at z = 6.
- Smoking gun signature for FDM potentially observable with the JWST.