Quasars & Little Red Dots from Black Hole Seeds formed by "*X-Fermion*" Dark Matter

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PART I. SETTING THE STAGE

COSMIC PUZZLES

Quasars

Extraordinarily luminous beacons powered by supermassive black holes (SMBHs), observed when the Universe was less than a billion years old.

Little Red Dots (LRDs)

New enigmatic, compact, infrared-bright sources discovered by JWST at high redshifts, challenging existing formation paradigms.

Aim

Explores "X-Fermion" dark matter as a unified origin for SMBHs in quasars and LRDs.

Cosmic and Scientific Timeline

- 1939: Oppenheimer–Snyder model proposed for gravitational collapse into black holes.
- 1945–1950s: Gamow, Fermi, and Turkevich propose hot Big Bang model and primordial nucleosynthesis theory.
- 1963: Discovery of quasar 3C 273 by M. Schmidt (z = 0.158)
  Roy Kerr discovers the exact solution for rotating black holes.
- 1964: Salpeter proposes accretion onto a $10^6\,M\odot$ object as power source for quasars.
- 1965: Penzias and Wilson detect the cosmic microwave background (CMB), confirming hot Big Bang theory.
- 1967–1971: Ruffini and Wheeler propose energy extraction from Kerr black holes; term “black hole” introduced.
- 1970: Zel’dovich suggests gravitational collapse of massive cores (10^6–$10^7\,M\odot$) as quasar engines.
- 2011–2018: GRAVITY collaboration and S-star motion analysis suggest presence of a dense fermionic core in the Galactic center.
- 2015: Ruffini et al. propose the RAR model: self-gravitating fermionic dark matter halo with degenerate core.
- 2020: Becerra-Vergara et al. show S-cluster stars consistent with fermionic model in Sagittarius A*.
- 2023–2025: Observations of Little Red Dots (LRDs) suggest SMBH seeds form before galaxies.

AGN & QUASAR FUNDAMENTALS

Central Engine: Supermassive Black Hole

Active Galactic Nuclei (AGN): Compact, luminous centers of galaxies powered by accreting supermassive black holes (SMBHs) (10^6–10^{10} M⊙).

Quasars: The most luminous AGN (bolometric luminosities ~10^{46}–10^{48} erg/s), visible to great distances.

Key Features:

- Broad emission lines (e.g., Hβ, C IV),
- Continuum emission across UV–X-ray,
- Often radio-loud jets or strong infrared from dust.

High-z Quasars: Over 200 known at z > 6, including few at z ≳ 7 with $M_{BH} \gtrsim 10^9$ M⊙.



Black Hole Mass

Reverberation mapping estimates the mass of a supermassive black hole by measuring the time delay between changes in the accretion disk's continuum emission and the response in the broad emission lines,

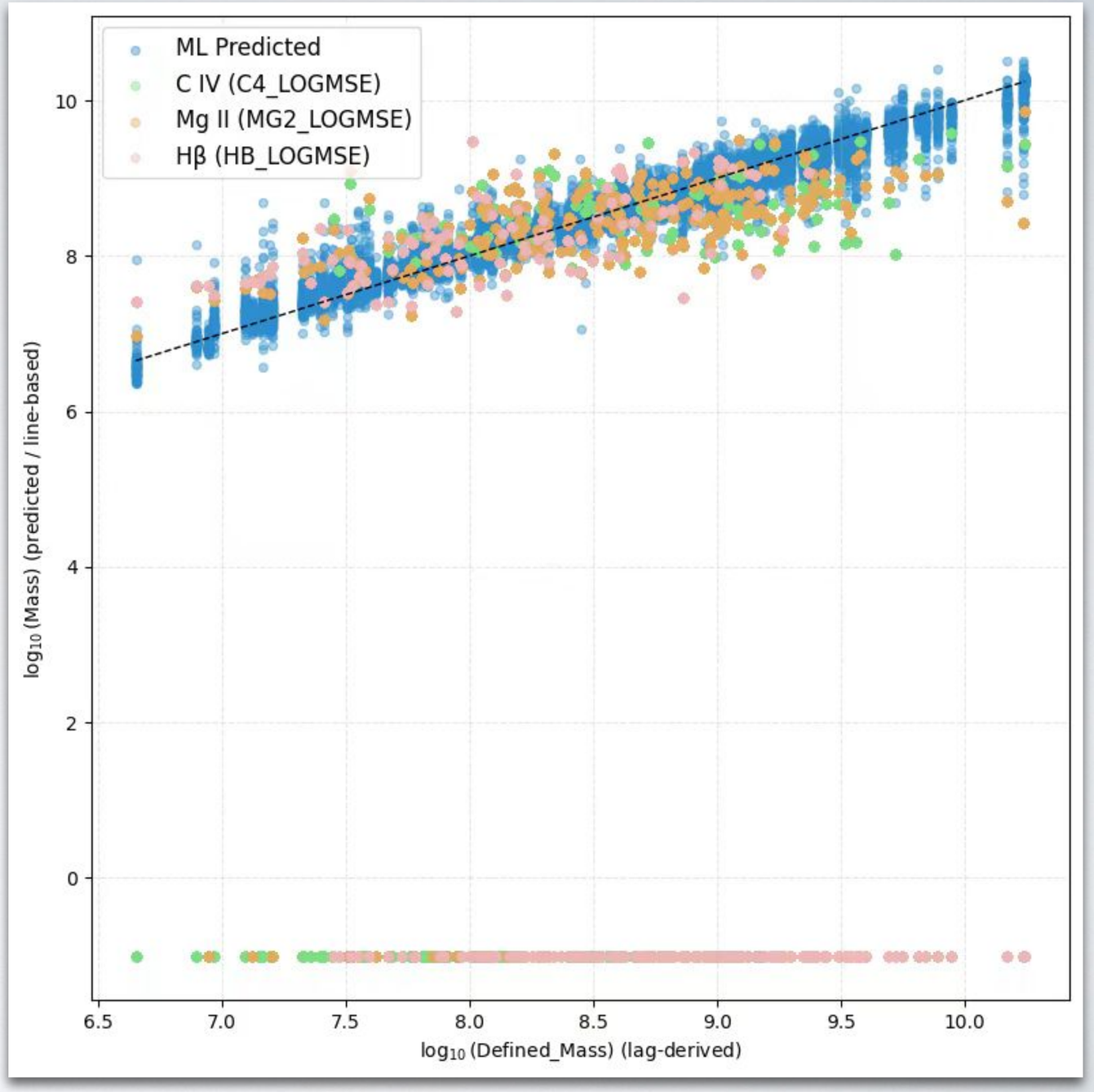
The response decay gives the size of the broad-line region (BLR) as $R = c \cdot \tau$.

The velocity of the gas in the BLR is obtained from the width of these broad emission lines.

Assuming the BLR gas is in virial equilibrium around the black hole, the black hole mass is then calculated by

$$M_{\mathrm{BH}} = f \cdot (c\tau\ \Delta V^2)/G$$

where $\Delta V$is the emission line width, G is the gravitational constant, and f is a factor that accounts for the geometry of the BLR.



THE HIGH-Z QUASAR GROWTH CHALLENGE

How did such massive BHs form so early?

Standard Stellar Remnant Seeds: Pop III star BHs (~10^2–10^3 M⊙) need to grow by ≳ 10^6 times by z ~ 7.

Eddington-Limited Accretion: Mass-doubling time $t_{\rm Edd} \approx 4 \times 10^7 yr$ (10% efficiency).

Time Available: Universe age at z ~ 7 is ≈ 0.8 Gyr → ≤ 20 e-foldings

Growth Required: From 10^2 to 10^9 M⊙ needs ~ 16 e-foldings (possible if continuous Eddington)

Complications: Realistic accretion is intermittent; feedback/ radiative effects can halt growth.

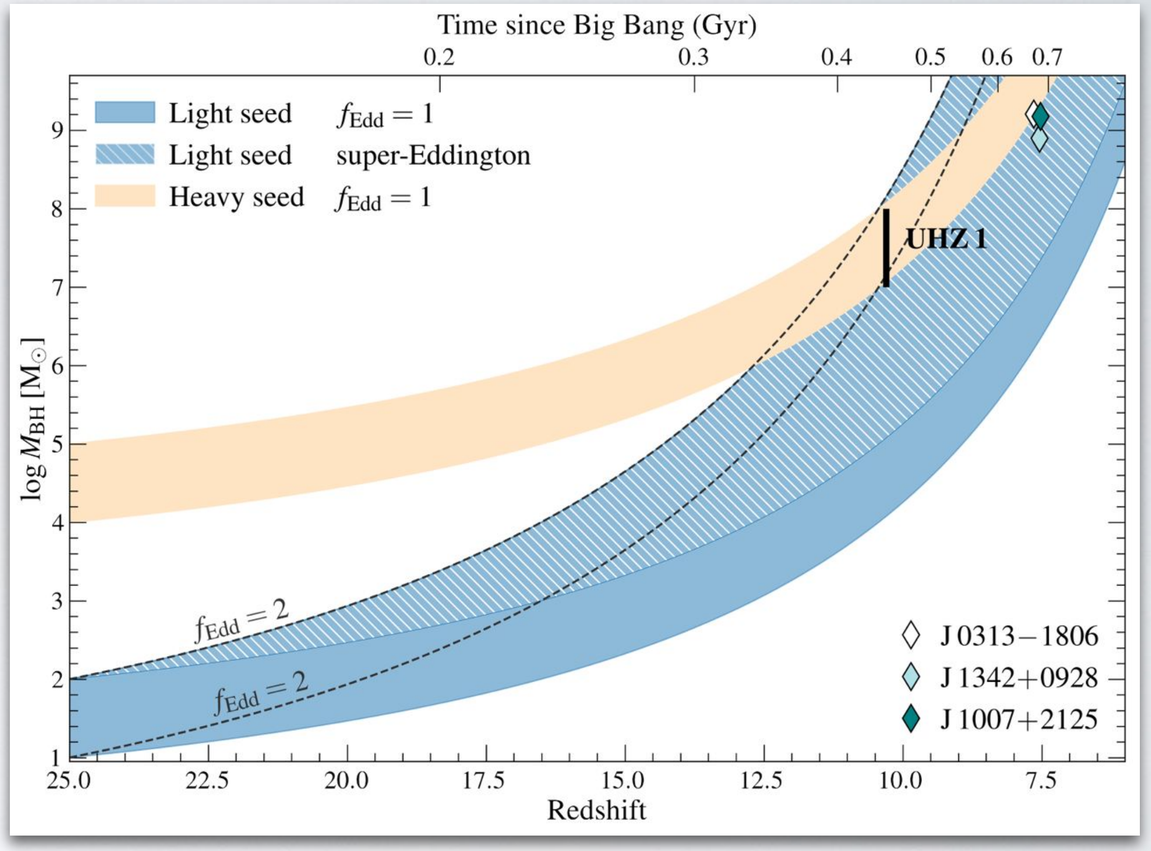


Figure from Bogdan et al., 2024

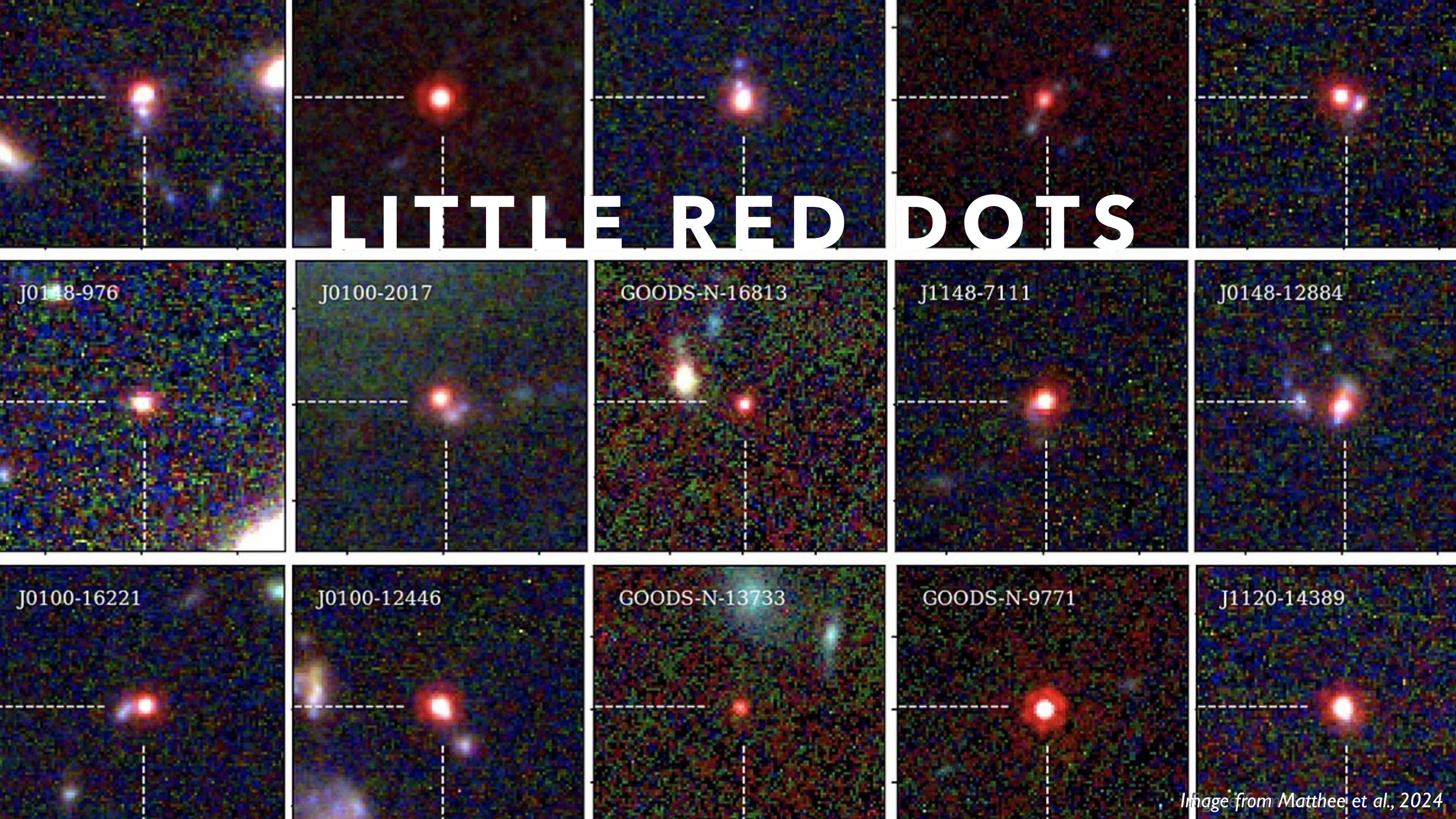


Image from Matthee et al., 2024

LITTLE RED DOTS (LRDS) – JWST'S SURPRISE

Small Red Galaxy at High Redshift

Discovery: JWST NIRCam surveys (COSMOS-Web, JADES, FRESCO) found numerous compact, red sources at z ≈ 2–12, dubbed Little Red Dots (LRDs).

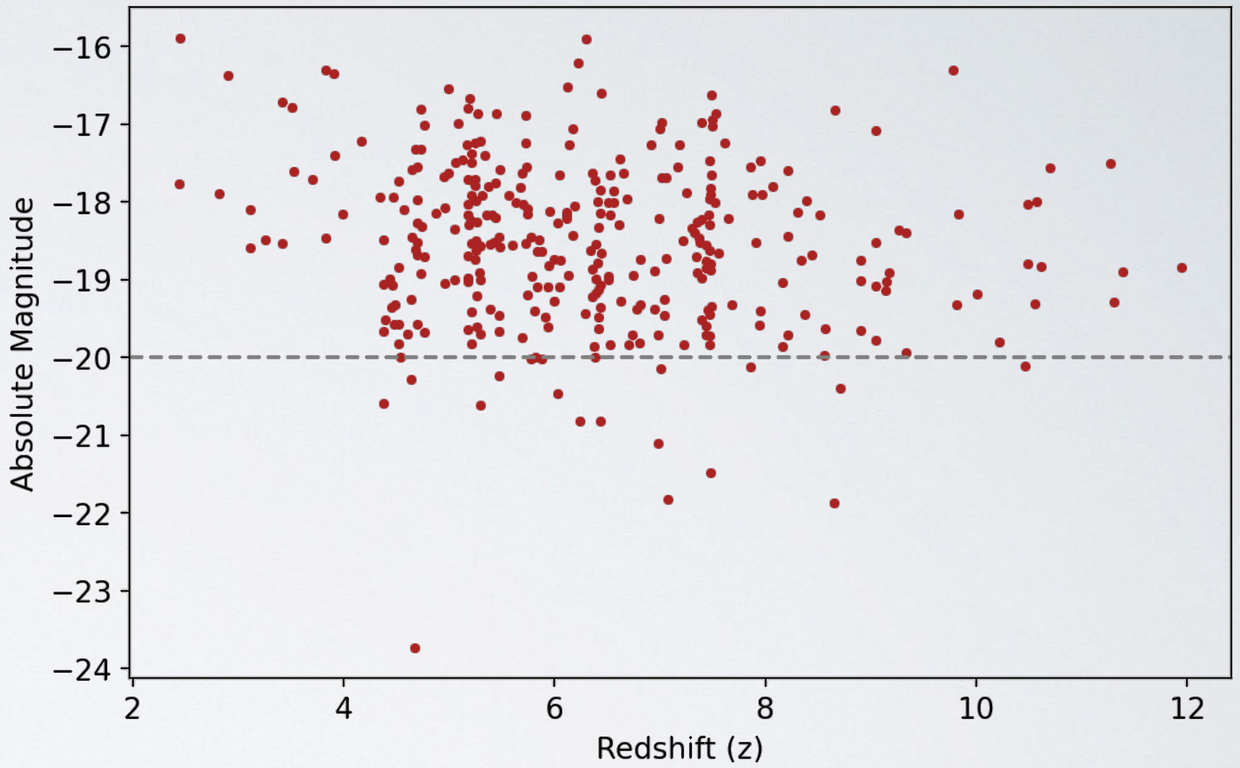
Appearance: Point-like in near-IR (sizes~100 pc), very red (rest-IR dominated), and numerous.

Spectroscopic AGN Signatures:

- Broad H α / H β lines (FWHM ~ 3000 km/s) → $M_{BH} \sim 10^6$–10^7 $M_\odot$
- No X-ray emission detected.

Host Galaxies:

- Stellar mass upper limits ~10^7–10^8 $M_\odot$
- No clear disk; some show faint clumps (merger/fragmentation).



Key Puzzle: BH-to-stellar mass ratios ~10% (local ratio < 1%) – how can BHs be so overmassive? And of ~10% of all galaxies, why so numerous at early universe?

Figure Credit: JWST Surveys, Kokorev et al. 2024

UNIFYING CHALLENGE: QUASARS & LRDS

High-z Quasars

Rare, extremely luminous, $M_{BH} \sim 10^{9}$–10^{10} $M\odot$ at $z < 10$.

LRDs

Numerous, faint red, with $M_{BH} \sim 10^{6}$–10^{7} $M\odot$ at $z \approx 4$–12.

Common Questions

How do BH seeds form and grow so rapidly?
What sets BH/host mass ratios?
Can a single formation channel explain both?

Objective

Propose a single, DM-based mechanism that seeds BHs in early halos, explaining both extremes.

PART 2: A NEW CANDIDATE
X-FERMION DARK MATTER

Evidence for DM
Rotation curves, gravitational lensing, cosmic microwave background (CMB), large-scale structure.

CDM (Cold DM)
Heavy particles ($\gtrsim$ GeV), negligible primordial velocity → small-scale structure forms early, cuspy halos (NFW).

WDM (Warm DM)
Thermal relics (~ keV-scale), significant early velocity → suppresses formation of halos below ~ 10^8 $M_\odot$ (free-streaming cutoff).

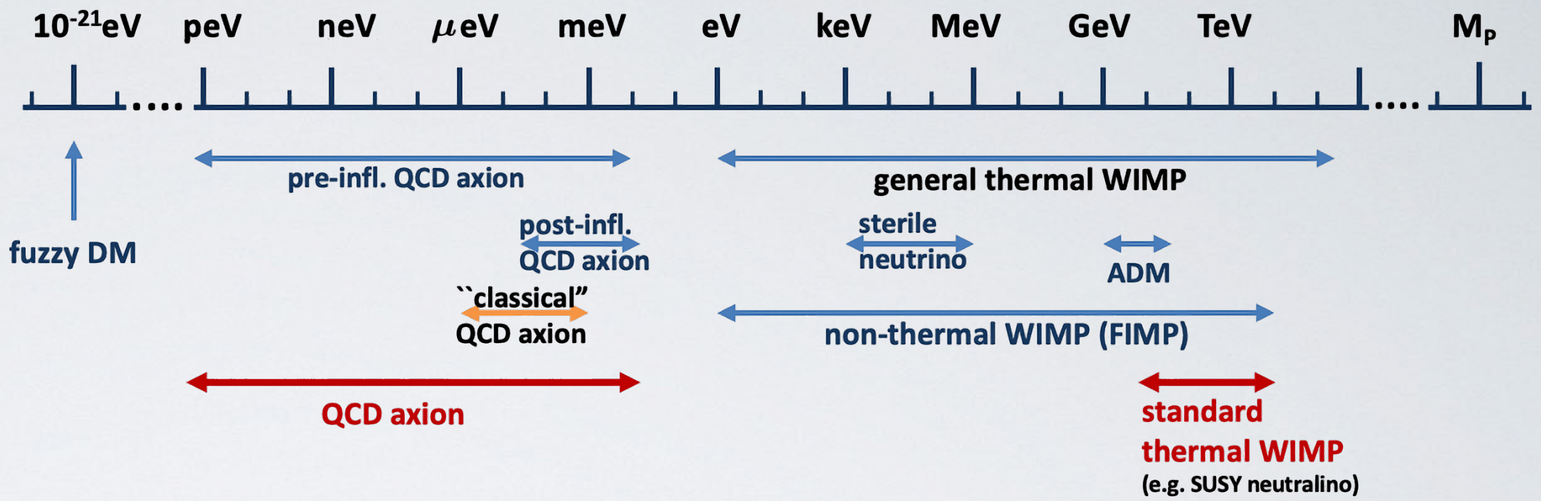
Fermionic DM
DM made of spin-½ particles (e.g. sterile neutrinos, other exotic fermions). At high densities, quantum degeneracy pressure creates finite-density cores.

CDM VS. X-FERMION

Introducing Fermionic DM (FDM)

Cold Dark Matter (CDM): Prevailing paradigm; particles were non-relativistic during structure formation.

CDM model: Successful in explaining large-scale structure (cosmic web).



CDM Challenges on Small Scales:

- **Cusp-Core Problem:** CDM predicts "cuspy" (sharply peaked) central densities in halos; observations suggest flatter "cores" in some galaxies.
- **Missing Satellites Problem:** CDM predicts far more small subhalos (hosting dwarf satellites) than observed around galaxies like Milky Way.

Fermionic Dark Matter (FDM): Alternative class of candidates.

- DM particles are fermions (obey Pauli Exclusion Principle).
- Crucial in high-density regions (halo centers).
- Pauli Exclusion Principle effective "degeneracy pressure."
- Counteracts gravitational collapse, can form a degenerate core, preventing infinite density cusps.

"X-FERMION" HALO

Theoretical Framework for X-Fermion Halo Structure

- **Treats self-gravitating fermions within General Relativity** (essential for compact cores, BH collapse).
- **Built from first principles**:
  - Fermion particles in thermodynamic equilibrium, obey Fermi-Dirac statistics.
  - Structure from Tolman-Oppenheimer-Volkoff (TOV) equations (hydrostatic equilibrium for relativistic fluid).
  - Equation of State (EOS) from fermion microphysics, incorporating:
    - Relativistic nature of particles at early universe then decelerates to newtonian.
    - Finite temperature effects.
    - Fermi-Dirac distribution distribution with escape effects:

$$f_c(\epsilon \leq \epsilon_c) = \frac{1 - e^{(\epsilon - \epsilon_c)/(k_B T)}}{e^{(\epsilon - \mu)/(k_B T)} + 1}$$

$$f_c(\epsilon > \epsilon_c) = 0.$$

"X-FERMION" HALO

A Dense Core and a Dilute Halo

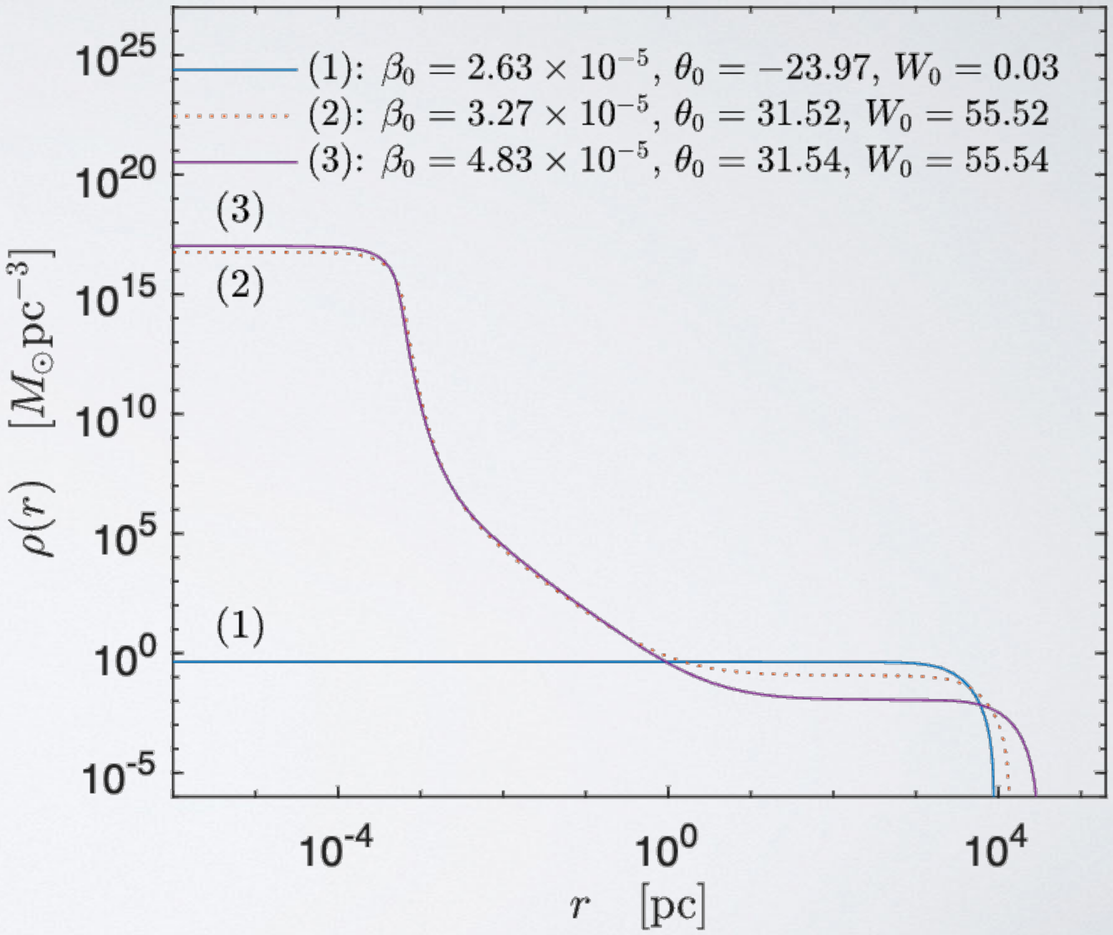
The Dense Core:

- Center of halo, high particle density.
- Fermion degeneracy pressure counteracts gravity, supporting a dense, compact core.
- Core density/radius sensitive to X-Fermion mass.
- General relativistic effects often appreciable.

The Dilute Halo:

- Surrounds dense core, extended, lower-density.
- Fermions less degenerate; halo primarily supported by thermal pressure/velocity dispersion.
- Explains flat rotation curves of galaxies.
- Density profile transitions from core plateau to power-law decline.

Unified description from galactic centers to peripheries in a single framework.



Stability of Halos: The Katz Criterion & Caloric Curves

Not all equilibrium configurations are stable over cosmological timescales. ⇒ **Thermodynamic stability check**

Katz criterion for stability

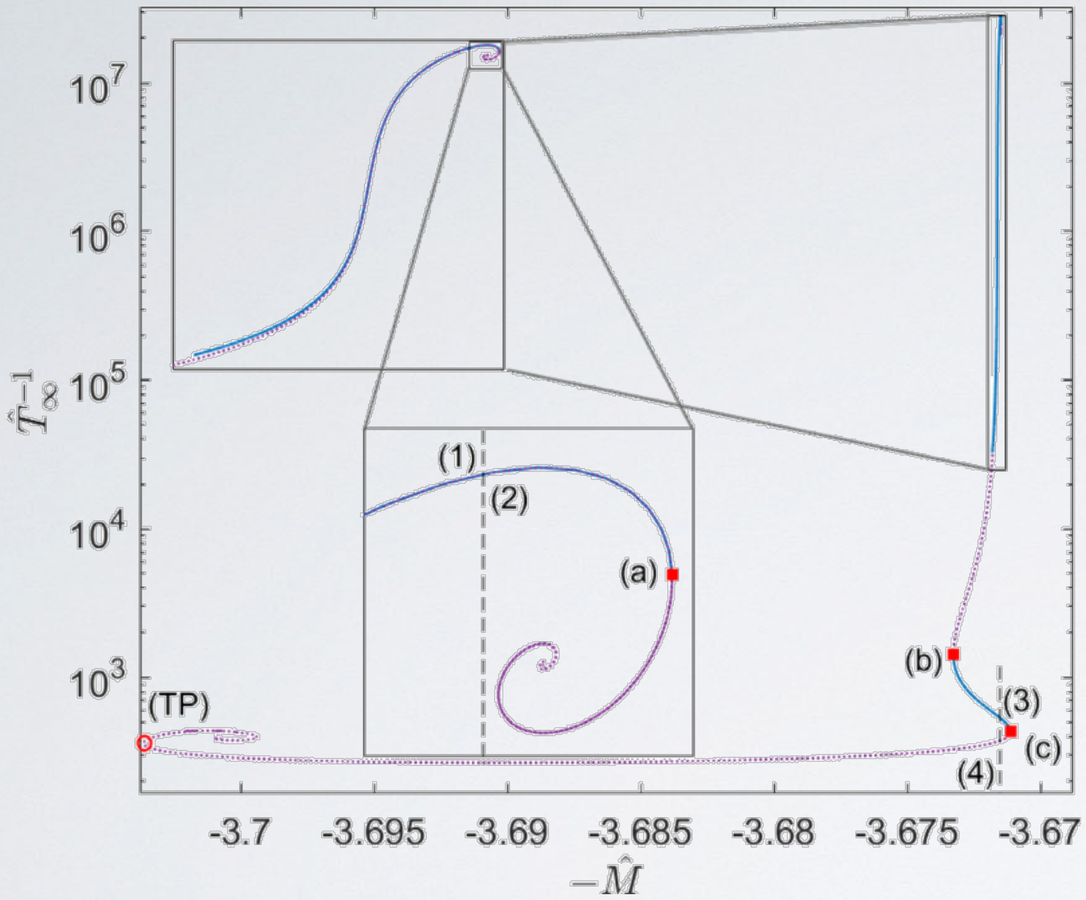
- Caloric curve: Plots e.g., inverse temperature ($1/T_\infty$) vs. total energy ($-\hat{M}$).
- Relates stability changes to topology of "*caloric curves.*"
- Shape (spirals, turning points) indicates transitions between stable/unstable states. Stable = entropy maxima.

For a given M_{vir} and m_X, caloric curves show

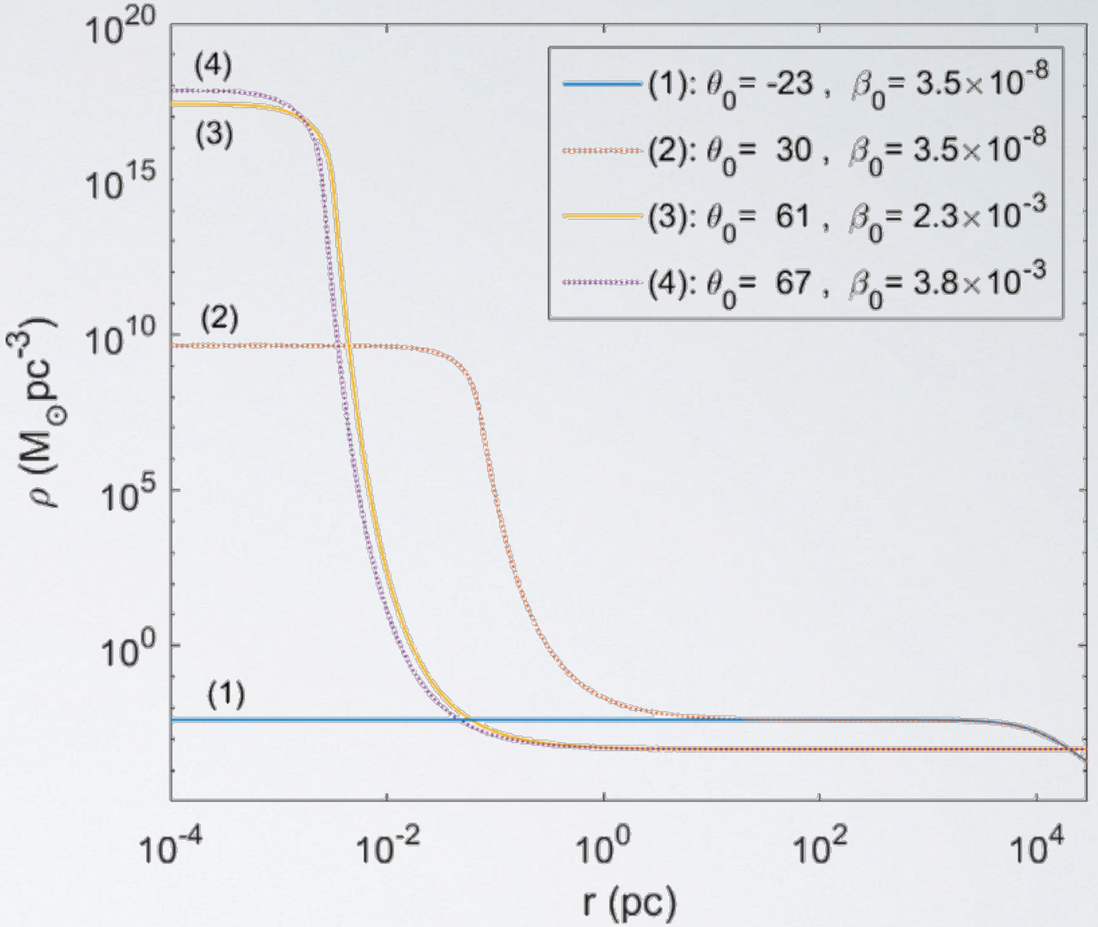
- *Stable Configurations*: Dense core + dilute halo; long-lived.
- *Unstable Configurations*: Core mass exceeds critical threshold ⇒ gravitational collapse to black hole seed.

"X-FERMION" HALO

Stability of Halos: The Katz Criterion & Caloric Curves



Equilibrium solutions along the caloric curve. The states within the continuous blue branches are stable (i.e., either local or global entropy maxima), while the violet branches—between (a) and (b) and after (c)—are unstable (i.e., either minimum or saddle point of entropy)



Density profiles corresponding to the equilibrium states of the caloric curve. Only the profiles (1) (resembling a pseudo-isothermal sphere) and the core-halo one (3) are stable, while profiles (2) and (4) are thermodynamically unstable.

Figures from Argüelles et al., 2020

"X-FERMION" CORE COLLAPSE

A New Path to SMBH Seeds

- **Fermion DM model predicts dense core at halo center** (fermion degeneracy pressure).
- **Provides direct channel for SMBH seed formation**: For massive enough halos, core can exceed critical mass ($M_{crit} \sim M_{x-fermion}^{-2}$) and collapse to BH. For $m_X \sim 50 - 300$ keV $\Rightarrow M_{seed} \sim 10^6 - 10^8 M_\odot$.

Advantages over Conventional Baryonic Seeding:

1. Heavier Seeds: $10^6 M_\odot$ vs. Pop III ($\sim 10^2 M_\odot$) or DCBH ($\sim 10^4 - 10^5 M_\odot$). Reduces subsequent growth needed.
2. Early Formation: As soon as first massive DM halos virialize and cores collapse.
3. Independence from Baryonic Physics: Primarily a DM phenomenon, less reliant on rare baryonic conditions.

Compelling solution to "time crunch" for high-z quasars.

SMBH SEED FORMATION MECHANISMS

Comparison

Feature	Pop III Stars	DCBH	PBHs	X-Fermion Core Collapse
Typical Seed Mass ($M_\odot$)	$\sim 10^2$	$\sim 10^4 - 10^5$	Wide range, speculative	$10^6 - 10^8$
Formation Redshift (z)	$> 15 - 30$	$> 10 - 20$	Very early Universe	> 10 (early DM halo virialization)
Key Requirements	Metal-free stars, SN	Pristine gas, LW background.	Early density fluctuations	Pauli exclusion, instability
Pros	Natural from first stars	More massive seeds	Forms early	Very massive seeds, direct DM channel
Cons	Seeds too small	Conditions rare?	No direct evidence	Specific DM

PART 3: PERTURBATION ASPECT

300 KEV X-FERMION

Focus on upper limit of X-Fermions mass $m_X \approx 300$ keV.

$$m_X \approx 300 \text{ keV} \Rightarrow \text{seed mass } \sim 10^5 - 10^6 M_\odot \,.$$

Significantly more massive than Pop III remnants ($\sim 10^2 M_\odot$).

Comparable/larger than DCBH seeds ($\sim 10^4 - 10^5 M_\odot$).

FREE-STREAMING LENGTH AND CUTOFF MASS

300 KeV X-Fermion

Velocity dispersion $v(z)$: relativistic at $z > z_{NR}$, non-relativistic at $z \leq z_{NR}$.

$$z_{NR} \approx 5.17 \times 10^8.$$

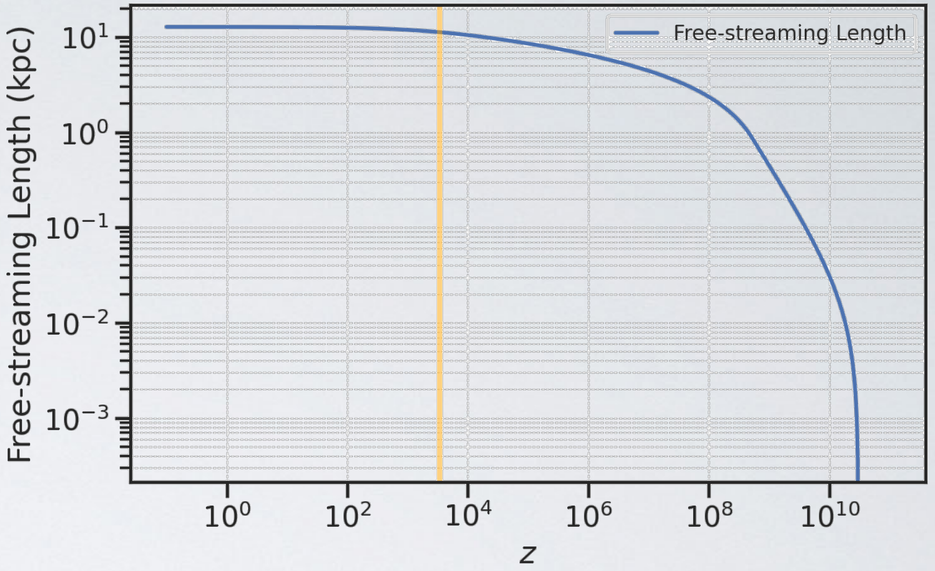
Free-Streaming Length (λ_{FS}): Characteristic comoving distance particle travels due to thermal motion before becoming bound. Structure formation suppressed on scales $< \lambda_{FS}$. For 300 keV X-Fermion:

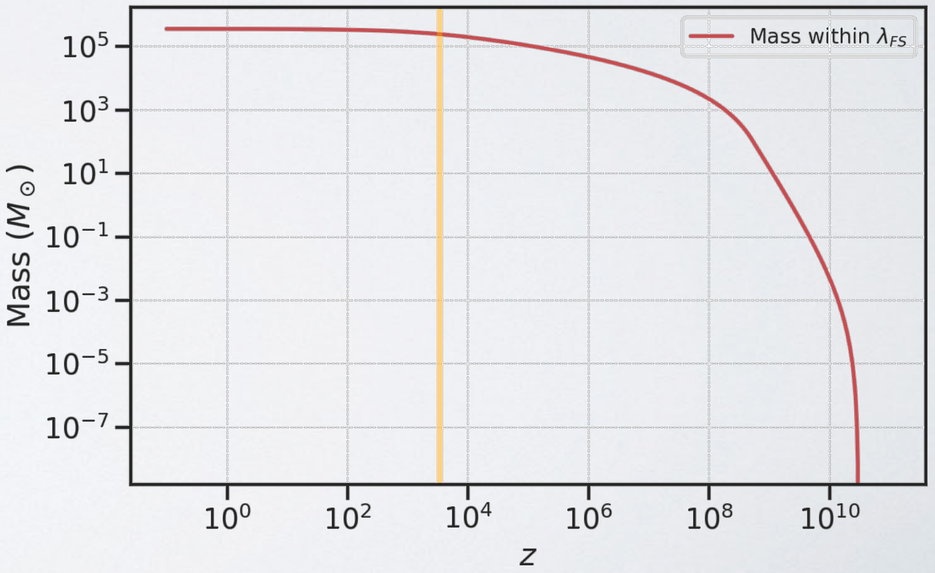
$$\lambda_{FS} \approx 12 \text{ kpc}.$$

Cutoff Mass Scale (M_{FS}): Halos below this mass are suppressed.

$$M_{FS} \approx 2.2 \times 10^5 M_\odot.$$

- Small enough not to erase galaxy-scale halo formation ($M > 10^6 M_\odot$).
- Large enough to potentially reduce small subhalos.





IMPACT ON GALAXY FORMATION

The Matter Power Spectrum

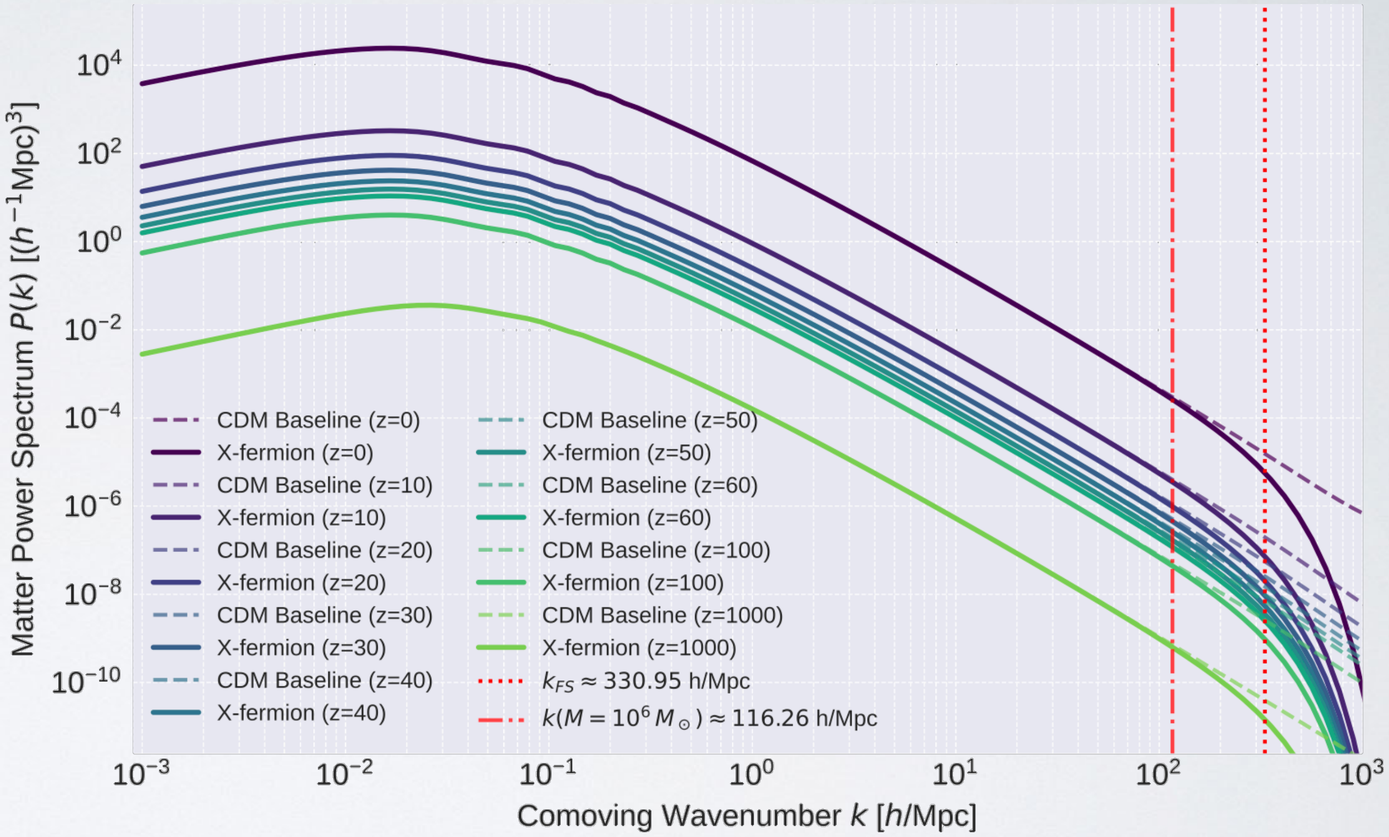
Impact on matter power spectrum:

$$P_{XF}(k, z) = P_{CAMB}(k, z) \times \exp[-(k/k_{FS})^2].$$

- Large scales (small k): $P_{XF} \approx P_{CDM}$ (retains CDM success for large structures).
- Small scales (large k, $k > k_{FS}$): P_{XF} drops sharply relative to CDM (suppression of sub-dwarf galaxies & smaller structures).

Consequences for Galaxy Formation:

- Predicts fewer small DM halos vs. CDM (helps "missing satellites").
- Smoother potential wells ⇒ may alleviate "cusp-core problem."



IMPACT ON GALAXY FORMATION

Halo Number Density

Mass Variance $\sigma^2(M,z)$: Quantifies density fluctuations on mass scale M:

$$\sigma^2(M,z) = \frac{1}{2\pi^2}\int_0^\infty k^2 P_{XF}(k,z)\,|\,W(kR)\,|^2\,dk$$

where $W(kR)$ is the top-Hat window function.

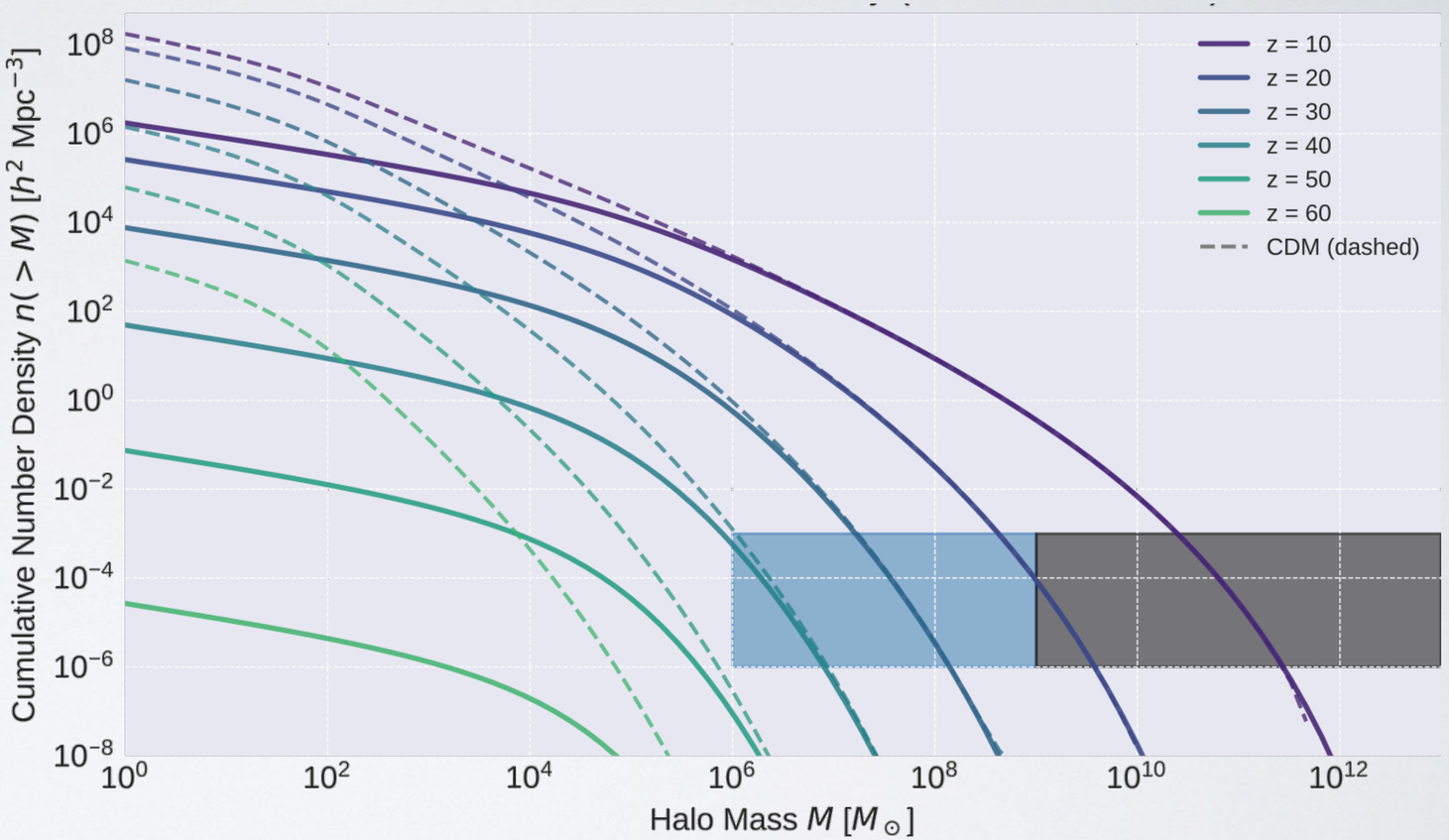
The differential number density per mass interval:

$$\frac{dn}{dM}(M,z) = \frac{\rho_{m0}}{M^2} f_{\mathrm{ST}}(\sigma)\left|\frac{d\ln\sigma}{d\ln M}\right|$$

with $f_{\mathrm{ST}}(\sigma)$ is the multiplicity function.

Cumulative Number Density: Halos with mass $> M$ at redshift z:

$$n(>M,z) = \int_M^\infty \frac{dn}{dM'}(M',z)\,dM'$$



PART 4: GROWING QUASARS
FROM ~300 KEV X-FERMION COLLAPSE

Considering the density changes caused by cosmic expansion, a model incorporating the competition between Eddington-limited accretion and Bondi accretion is used to estimate the initial mass and environmental density of high-redshift quasars.

SMBH Growth Primarily by Accretion of Baryonic Matter

Two Principal Regimes

1. Eddington-limited Accretion:

Radiation pressure from accreting matter balances inward gravity. Eddington Luminosity:

$$L_{Edd} = \frac{4\pi G M_{BH} c m_p}{\sigma_T}.$$

Eddington Accretion Rate:

$$\dot{M}_{Edd} = L_{Edd}/(\eta c^2)$$

Efficiency $\eta \sim 0.1$. Often sets upper limit on BH growth.

2. Bondi-Hoyle-Lyttleton Accretion:

Gravitational capture of gas from a relatively uniform medium. Bondi Rate:

$$\dot{M}_B = \frac{4\pi (G M_{BH})^2 \rho_b}{c_s^3}$$

depends on BH mass M_{BH}, gas density ρ_b sound speed c_s. Accretion is supply-limited.

Actual accretion rate

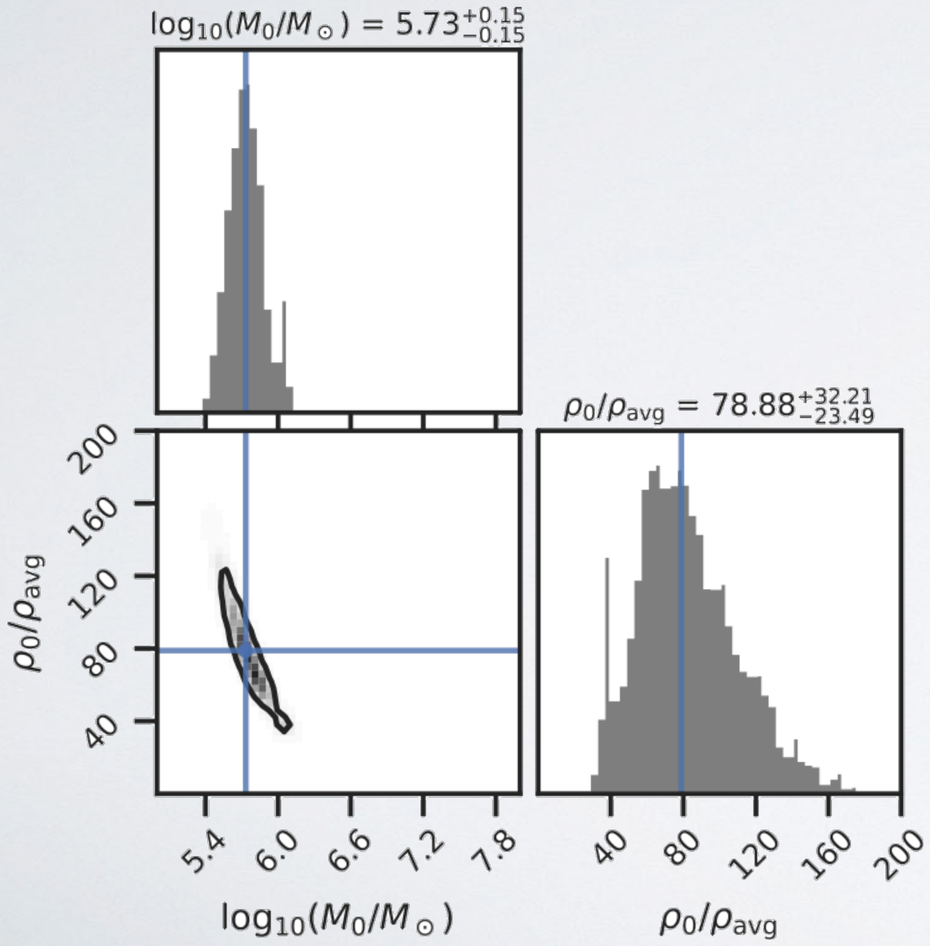
$$\dot{M} \approx \min(\dot{M}_{Edd}, \dot{M}_B)$$

Early Universe: High $\rho_b(z) \propto (1+z)^3 \Rightarrow$ potentially $\dot{M}_B \gg \dot{M}_{Edd}$ (Eddington-limited).
Later, $\dot{M}_B$ may drop below $\dot{M}_{Edd}$ (Bondi-limited).

FITTING QUASAR OBSERVATIONS

Method

Given an observed quasar's mass $M_{BH,\mathrm{obs}}$ and bolometric luminosity $L_{\mathrm{bol,\,obs}}$ at redshift z_{obs}, infer the initial seed mass M_0 and environmental overdensity factor $f_\rho = \rho_0/\rho_{\mathrm{avg}}$ at initial redshift z_0.



MCMC fitting steps:

1. For a given (M_0, f_ρ), integrate $\dot{M} = \min(\dot{M}_{Edd}, \dot{M}_B)$ forward until z_{obs}.
2. Compute model predictions at z_{obs}:
3. $M_{BH,\mathrm{model}}(z_{\mathrm{obs}}), \quad L_{\mathrm{bol,\,model}}(z_{\mathrm{obs}})$.
4. Define a likelihood comparing $\{M_{BH,\mathrm{model}}, L_{\mathrm{bol,\,model}}\}$ to $\{M_{BH,\mathrm{obs}}, L_{\mathrm{bol,\,obs}}\}$, incorporating observational uncertainties.
5. Use MCMC to sample the posterior $P(M_0, f_\rho \mid M_{BH,\mathrm{obs}}, L_{\mathrm{bol,\,obs}})$.

FITTING QUASAR OBSERVATIONS

Case Study: J0313-1806 (z=7.64)

Observed:

$M_{BH} = (1.6 \pm 0.4) \times 10^9 M_{\odot}$,

$L_{bol} = (1.4 \pm 0.1) \times 10^{47}$ erg s^{-1}.

Universe age at $z = 7.642 \approx 670$ million years.

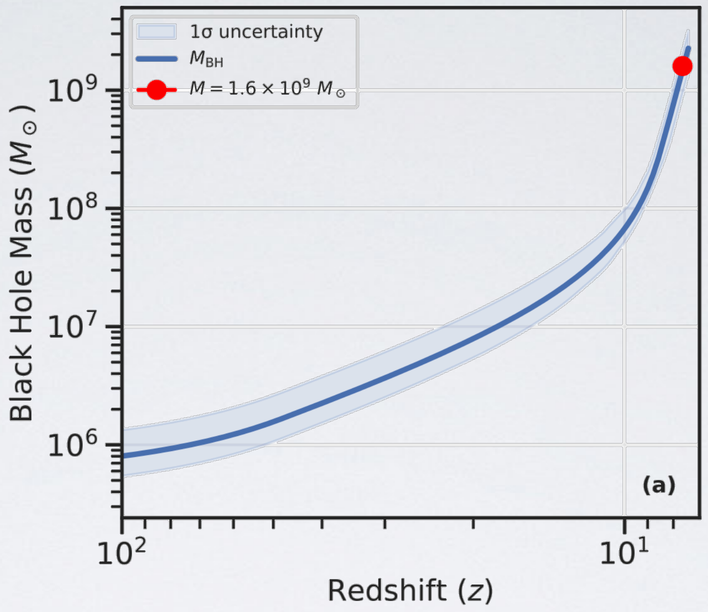
MCMC Reconstruction ($z = 20$):

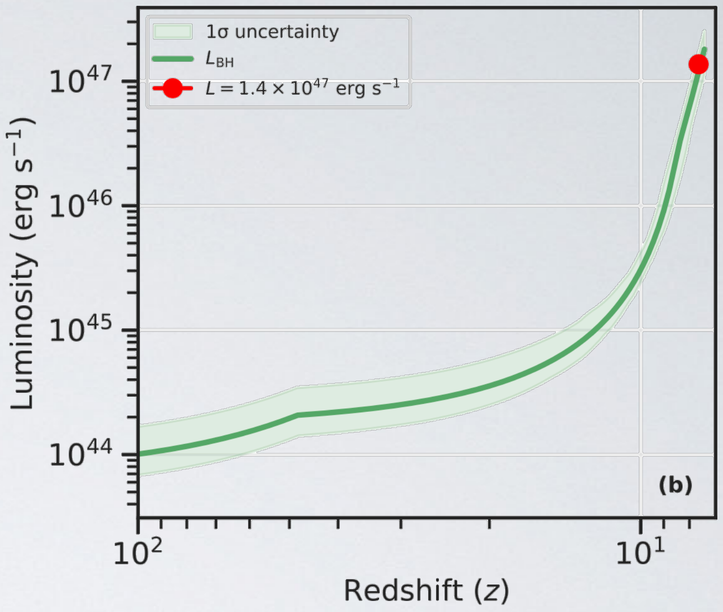
Inferred initial seed mass

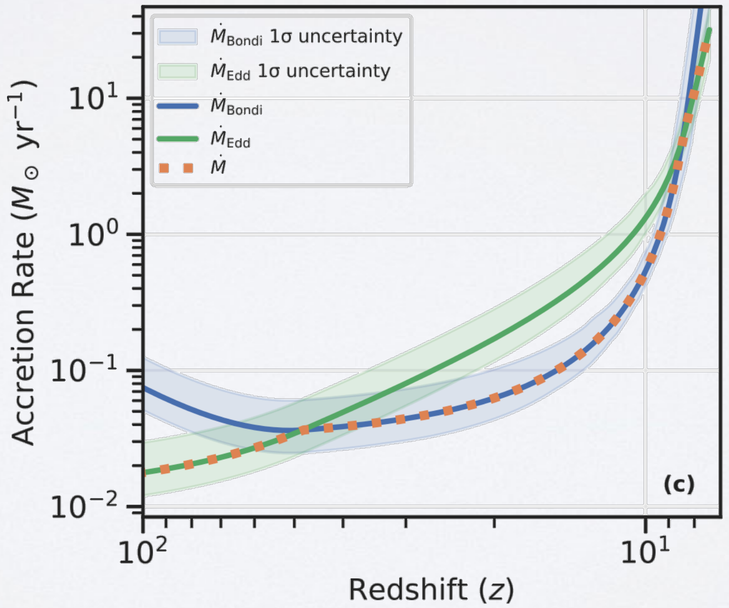
$M_0 \approx 7.5^{+5.6}_{-2.9} \times 10^6 M_{\odot}$.

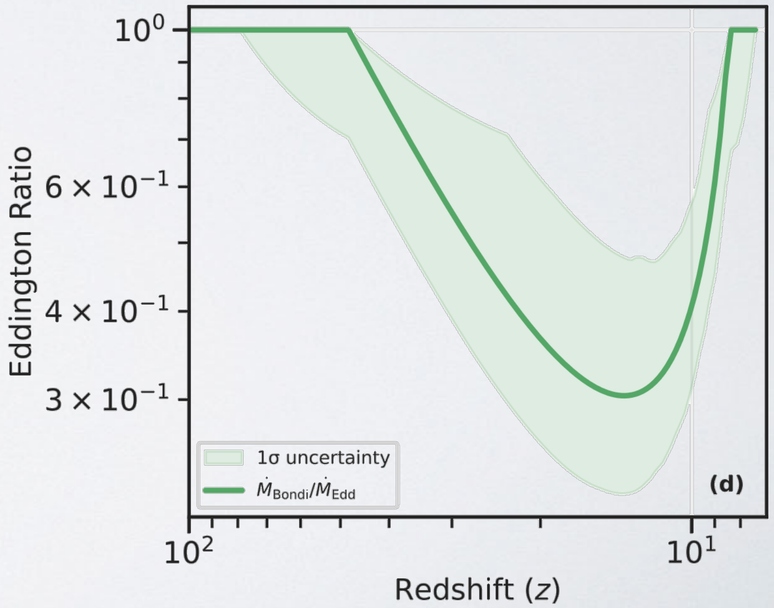
Required local density enhancement

$f_\rho \approx 77.1^{+47.6}_{-30.0}$ times cosmic mean.









FITTING QUASAR OBSERVATIONS

Case Study: J0100+2802 (z=6.30)

Observed:

$M_{BH} = (1.24 \pm 0.19) \times 10^{10} M_{\odot}$,

$L_{bol} = 1.62 \times 10^{48}$ erg s^{-1}.

Universe age at $z = 6.30 \approx 860$ million years.

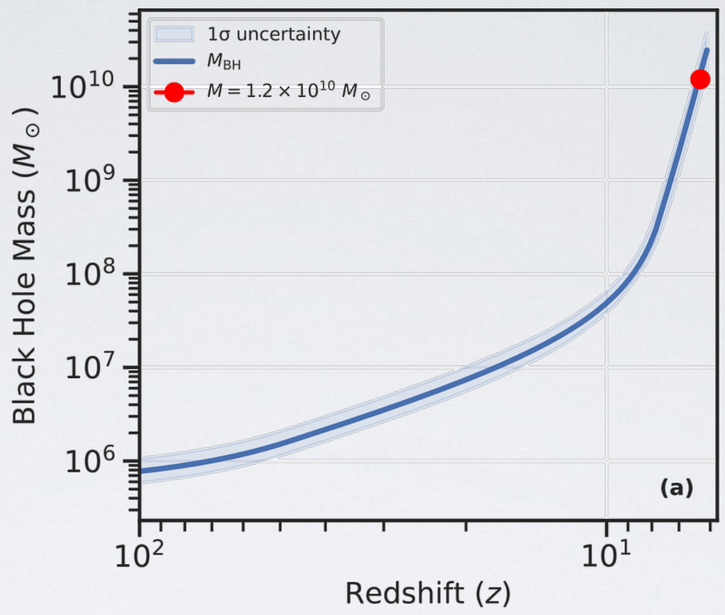
MCMC Reconstruction ($z = 20$):

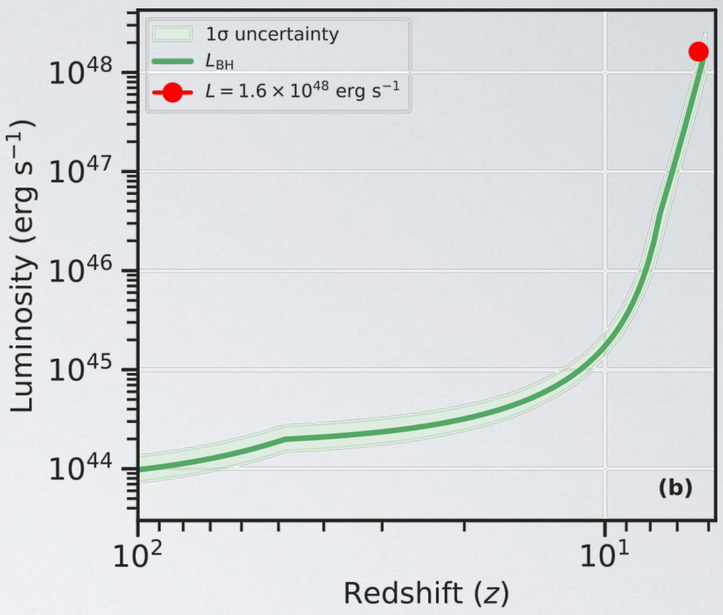
Inferred initial seed mass

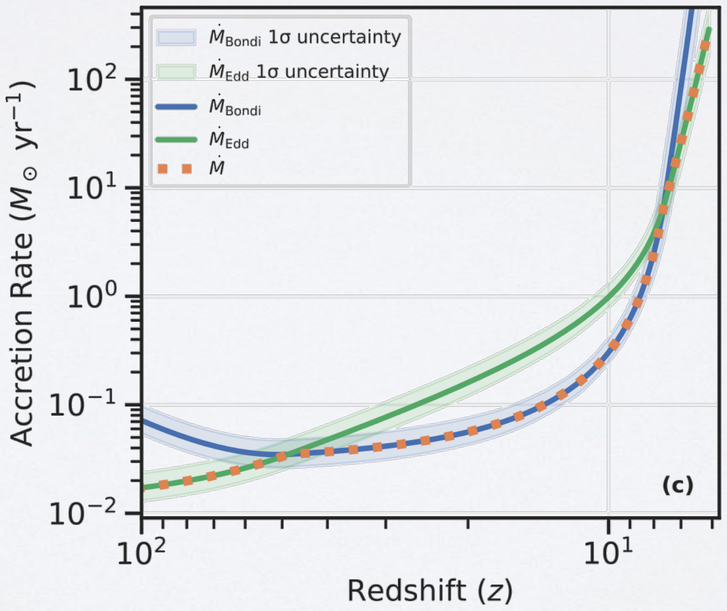
$M_0 \approx 6.9^{+3.1}_{-1.9} \times 10^6 M_{\odot}$.

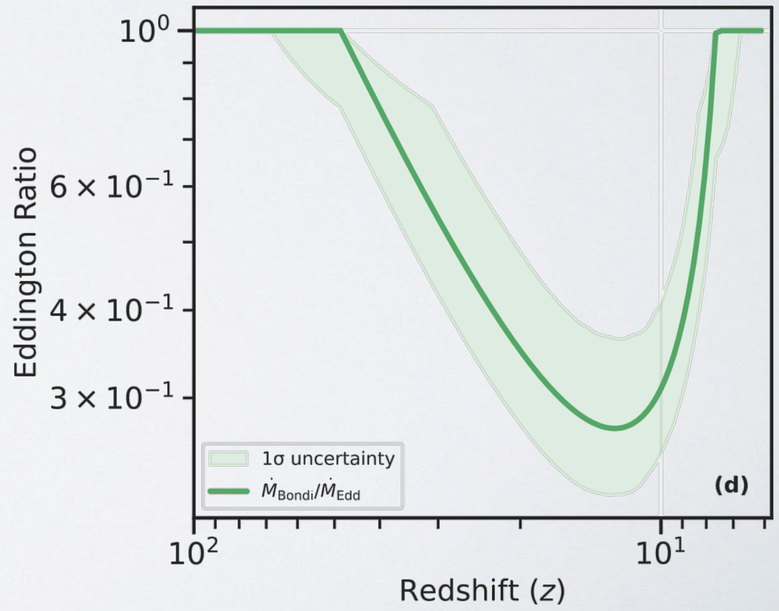
Required local density enhancement

$f_{\rho} \approx 78.9^{+32.2}_{-23.5}$ times cosmic mean.









PART 5: A UNIFIED PICTURE FOR QUASARS AND LRDS

WITH ~300 KEV X-FERMION

X-fermion model for quasars requires $M_0 \sim 10^6 M_\odot$ seeds in dense environments ($f_\rho \sim 10 - 200$).

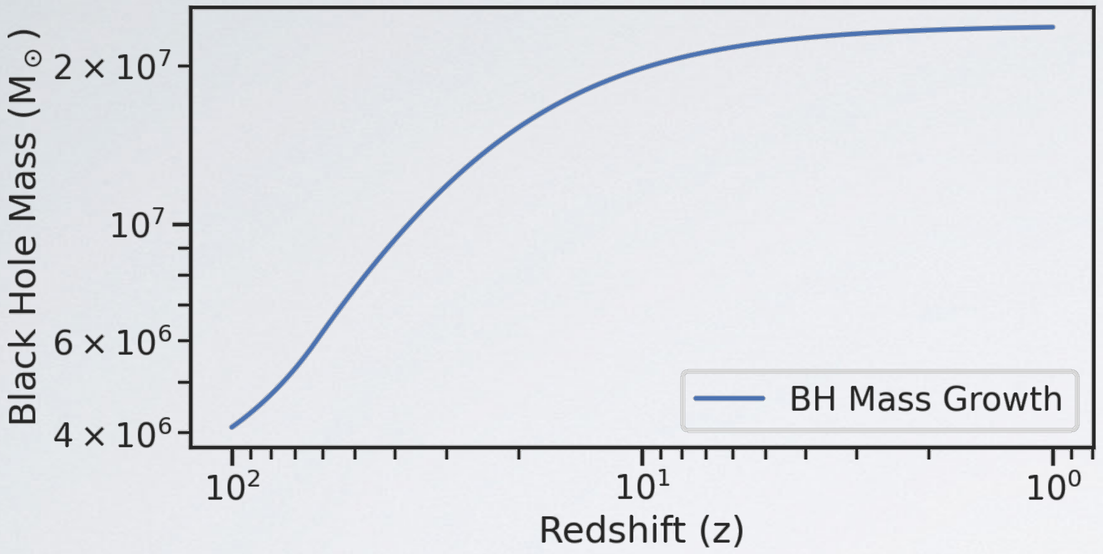
Question: What if these conditions are not met?

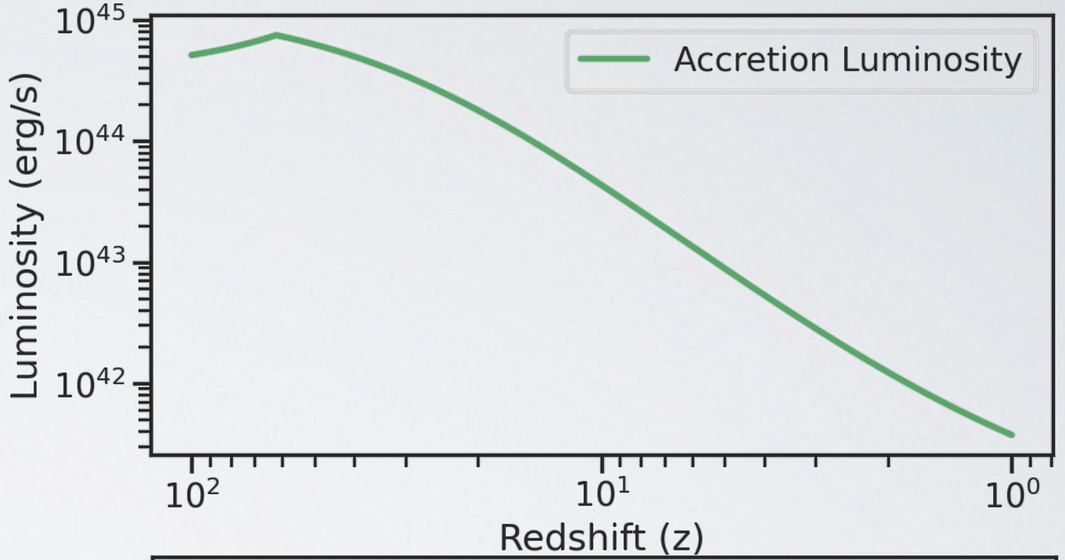
- X-fermion core collapse can produce a range of seed masses (depends on parent DM halo).
- Seeds form in various environments (differing f_ρ).

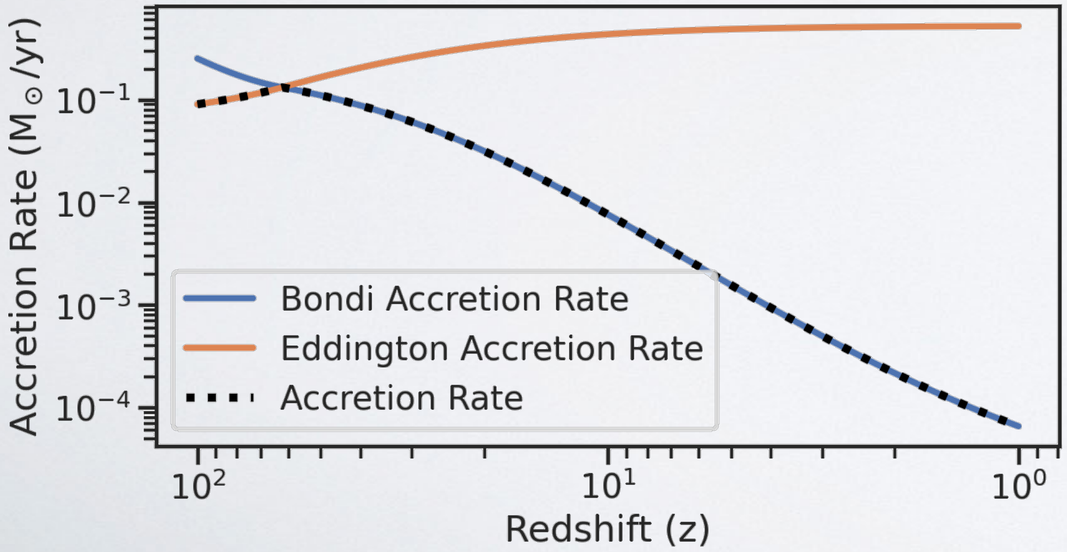
GROWING THE SEEDS

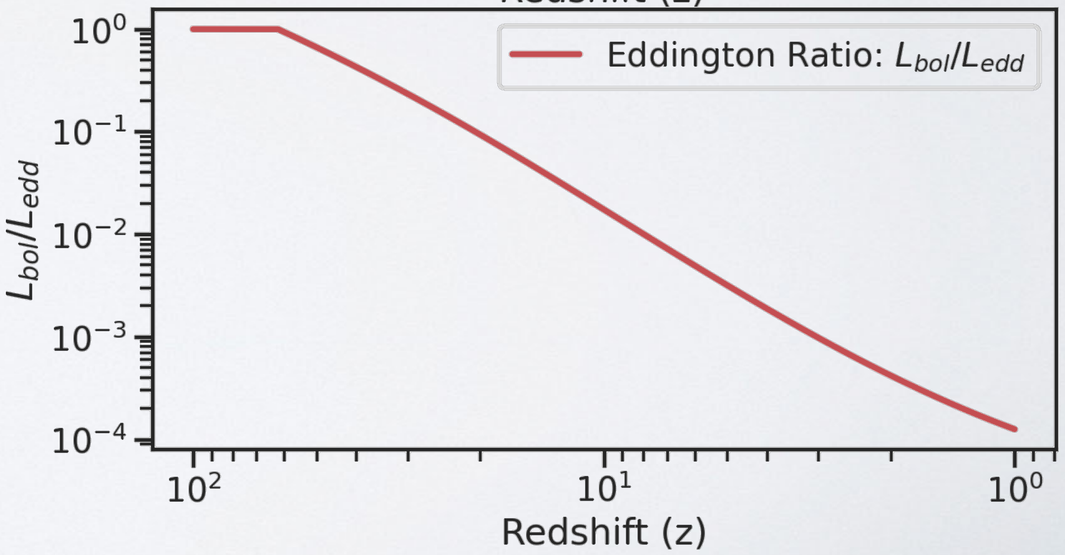
LRDs: Growth in Low-Density Environments or from Smaller Seeds

If X-fermion seed has smaller M_0 or lower f_ρ, growth history differs from quasar progenitor.









CONSISTENCY WITH LRD OBSERVATIONS

LRDs: Growth in Low-Density Environments or from Smaller Seeds

Lower Luminosity

Slower growth (lower M_0 or f_ρ) ⇒ less massive BHs, lower accretion rates ⇒ fainter.

No Strong X-ray and Radio Emission

Model predicts LRDs host smaller SMBHs with accrete at smaller Eddington accretion ratio λ_{Edd}. Consistent with multi-wavelength data, that lower accretion rates in LRDs naturally lead to weaker X-ray (corona) and radio (jet) emission.

Compact Appearance

Compact = Low density surroundings.

A UNIFIED PICTURE

Parameter Space Exploration

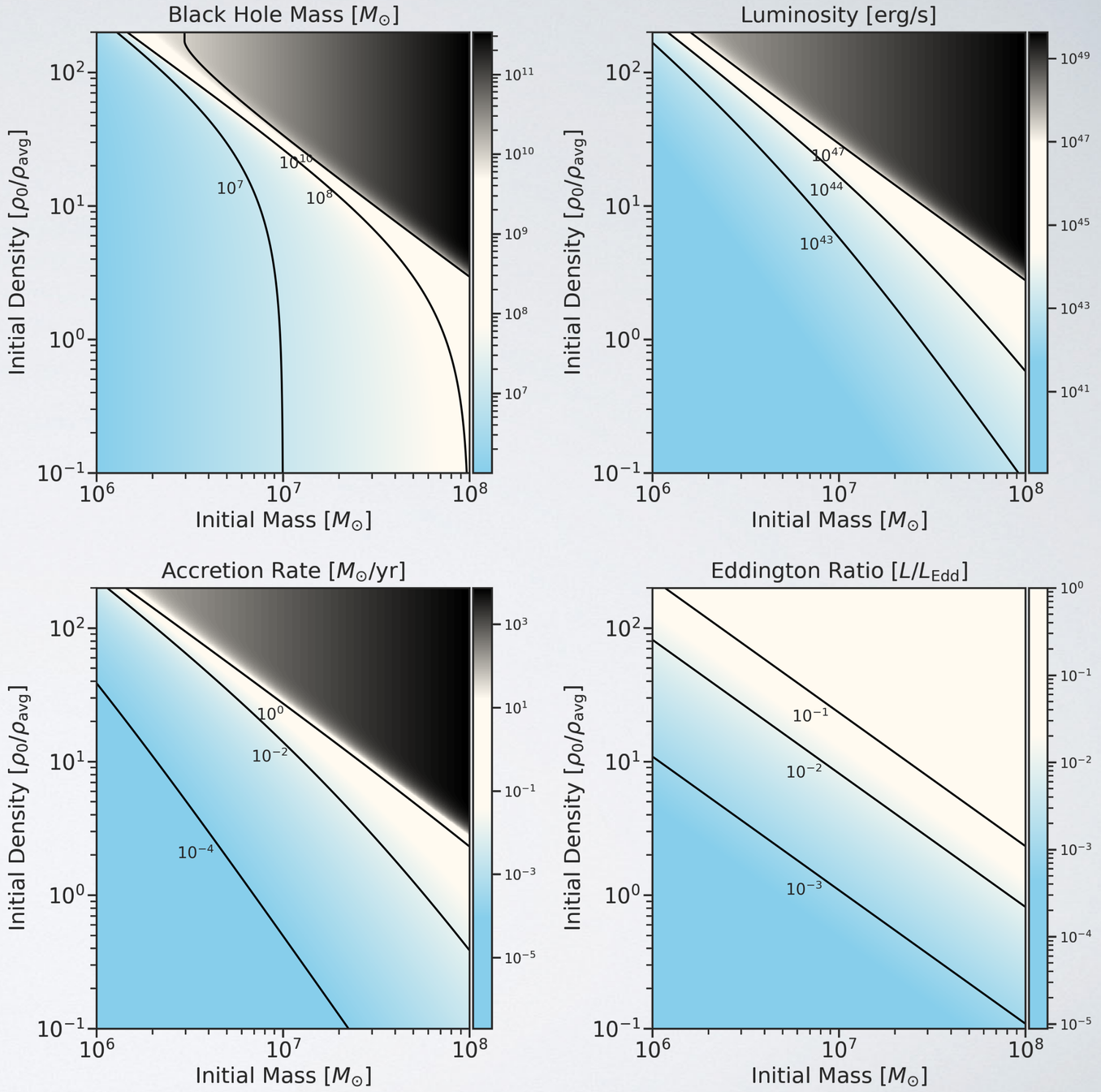
The final state of black holes after evolving from $z = 30$ to $z = 10$ as a function of initial seed mass and ambient density enhancement.

(a) Final black hole mass in $M_\odot$, showing that higher masses can be achieved with either more massive seeds or denser environments.

(b) Final bolometric luminosity, exhibiting similar parameter dependence as mass.

(c) Accretion rate at $z = 10$, showing higher rates for larger black holes in denser media.

(d) Eddington ratio ($L/L_{\rm Edd}$) at $z = 10$, with contours marking transitions between different accretion regimes.

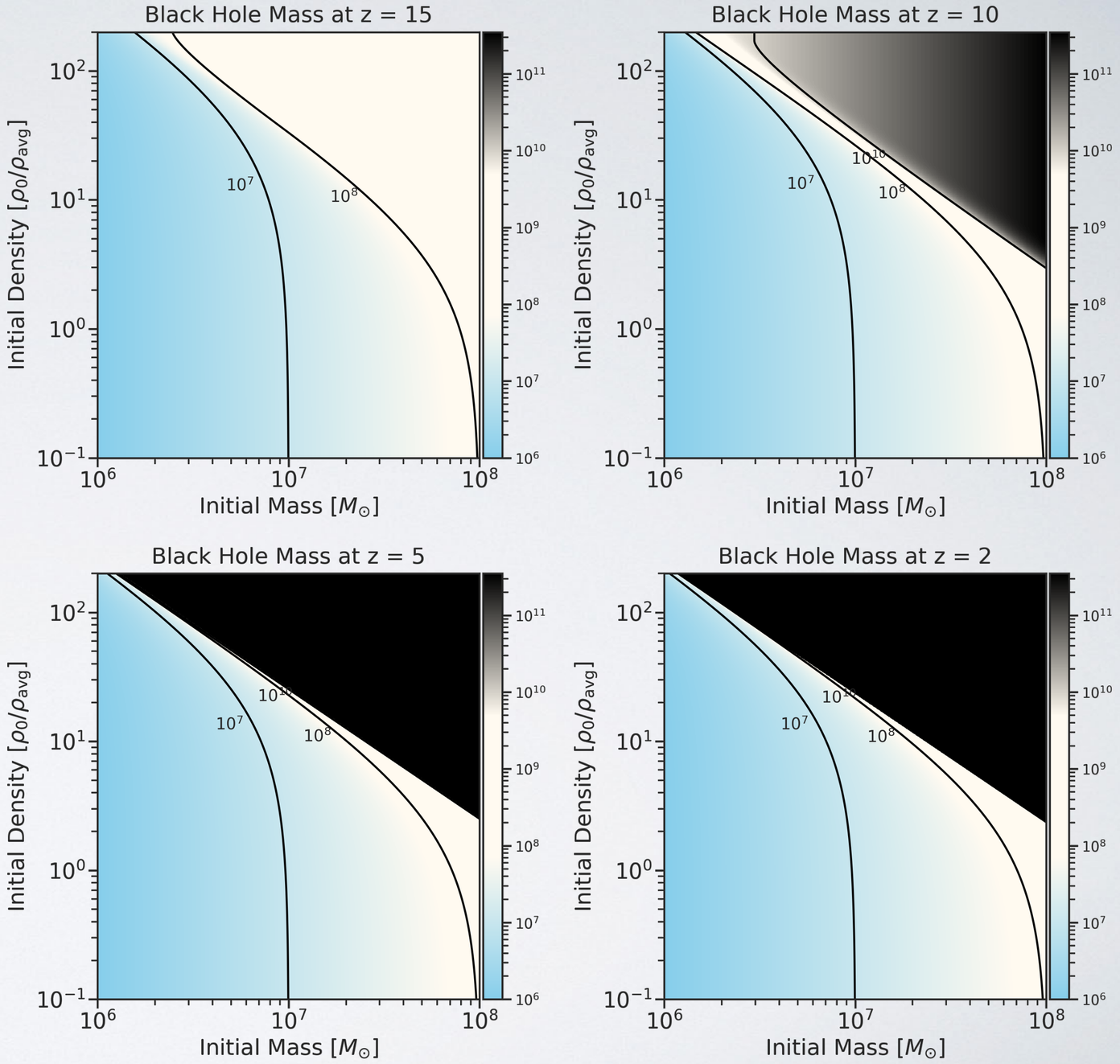


A UNIFIED PICTURE

Parameter Space Exploration

Black hole mass evolution from early to late cosmic epochs.

These panels show the final black hole mass (color scale) as a function of initial seed mass (10^6-$10^8 M_\odot$) and ambient density enhancement ($\rho_0/\rho_{\rm avg}$) from $z = 30$ to $z = 15$, 10, 5, and 2. Black contour lines mark masses of 10^7, 10^8, and $10^{10} M_\odot$.



A UNIFIED PICTURE

Parameter Space Exploration

Feature	Typical High-z Quasar	Typical LRD
Initial Seed Mass (M_0)	$\sim 10^7 M_\odot$ (massive DM halo core collapse)	Potentially $< 10^7 M_\odot$ (less massive halo) or similar M_0 in poor environment.
Environment Density (f_ρ)	High ($f_\rho \gtrsim 50$)	Lower ($f_\rho \lesssim 50$)
Dominant Accretion Phases	Initial Eddington, Transitional Bondi, Later Eddington	Brief initial Eddington? Primarily Bondi-dominated, decaying accretion rate.
Final M_{BH} (typical)	$10^8 - 10^{10} M_\odot$ by $z < 10$	Significantly lower, e.g., $10^5 - 10^8 M_\odot$ at similar z, stop growing at low z.
Luminosity	Very high ($L_{bol} > 10^{47}$ erg/s), near Eddington	Lower ($L_{bol} < 10^{46}$ erg/s), sub-Eddington
Key Observational Signature	Bright across EM spectrum, broad lines.	Compact, red, IR-bright, X-ray/radio faint, may show broad lines.

TIMELINE

$z \sim 20 - 30$

First DM halos of $10^6 - 10^7\, M_\odot$ collapse (but core mass < $M_{\rm crit}$, remain stable).

$z \sim 10 - 20$

Halos of $M \gtrsim 10^8\, M_\odot$collapse, DM core reaches $M_{\rm crit}$, BH seed of $\sim 10^6 - 10^8\, M_\odot$ forms.

$z < 20$

DM-seeded BHs begin accreting baryons; galaxy hosts assemble via mergers and star formation.

$z < 10$

Some seeds have grown to $> 10^8\, M_\odot \rightarrow$ bright quasars,

Seeds in smaller or/and low density halos remain $\sim 10^6 - 10^8\, M_\odot \rightarrow$ faint LRDs.

THANK YOU / TÄNAN

CONCLUSION

- **Natural Formation of Massive BH Seeds:** Collapse of dense fermionic DM cores (~ 300 keV X-Fermion) $\Rightarrow \sim 10^6 M_\odot$ seeds. Alleviates quasar growth timescale problem.
- **Explaining High-z Quasar Growth:** Massive seeds + physical accretion model (Eddington/ Bondi in overdensities) reconstructs growth of J0313-1806, J0100+2802 without super-Eddington accretion.
- **Plausible Origin for LRDs:** Same seeding, but in lower gas density environment, or smaller seeds $\Rightarrow$ less luminous, slower-growing BHs, matching LRD traits.
- **Cosmological Consistency:** ~ 300 keV X-Fermion suppresses structure $< 10^6 M_\odot$, retains large-scale CDM success, may solve small-scale CDM issues (e.g., missing satellites).

THANK YOU / TÄNAN