Connecting the Extremes: A Story of Supermassive Black Holes and Ultralight Dark Matter

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Supermassive Black Holes

- **Quasar**: extremely luminous active galactic nucleus, believed to be powered by a supermassive black hole, mass ranging from millions to tens of billions times the mass of the Sun

- observations of high-redshift quasars ($4 < z < 5$, and $z \gtrsim 7$) with $M \approx 10^9 \mathrm{M}_\odot$ which formed within the **first billion years after the Big Bang**

$\Rightarrow$ **How did the first SMBHs grow so large so fast?**

Formation of SMBH

- very efficient processes and special conditions are required to be maintained over several orders of magnitude of mass growth for the formation of these SMBHs in the early Universe [Inayoshi, Visbal, Haiman '19] $\rightarrow$ **feasible?**

$\rightarrow$ open question of origin of SMBHs at high redshifts

pSMBH: Idea [Davoudiasl, Denton, Gehrlein '21]

- don't want to rely on very efficient accretion and other special astronomical requirements $\rightarrow$ assume that the pSMBHs were **formed near the puzzlingly large masses of 10^9M$_\odot$**
- first order phase transition in early Universe, before the matter-radiation equality era $\rightarrow$ catalyst for the formation of **primordial SMBHs**

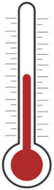
pSMBH: Idea [Davoudiasl, Denton, Gehrlein '21]

- onset of FOPT $\rightarrow$ suppression of the pressure response of the plasma $\rightarrow$ more likely that a horizon scale over-density would collapse and form a black hole

"A BLACK HOLE, IT'S WHAT I'VE ALWAYS WANTED"

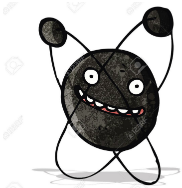
- pSMBH of mass $M \sim 10^9 \mathrm{M}_\odot$:
  size $R \sim M/M_{Pl}^2 \sim 10^{19}\ \mathrm{eV}^{-1} \rightarrow$ sets Hubble scale $H \sim T^2/M_{Pl}$
  T the temperature corresponding to the pSMBH formation

$$\Rightarrow \mathbf{T} \lesssim \mathbf{10}\ \mathrm{keV}$$



Ultralight Dark Matter

- Ultralight bosons with mass around 10^{-20} eV provide a possible DM candidate $\rightarrow$ can explain certain features of cosmic matter distribution that pose a challenge to the weakly interacting cold DM paradigm (cusp-core problem)
- testable in variety of ways



Ultralight Dark Matter

- natural candidate: **axion** from broken $U(1)_{PQ}$, mass is protected by a shift symmetry $\rightarrow$ can be quite light
- String theory: typically provide the requisite ingredients for such axions to arise, decay constants $f_a \sim \bar{M}_P \approx 2 \times 10^{18}$ GeV

$$m_a \sim \frac{\mu_a^2}{f_a} \sim 10^{-20}\ \text{eV} \left(\frac{\mu_a}{\text{keV}}\right)^2 \left(\frac{10^{17}\ \text{GeV}}{f_a}\right)$$

- small mass scale $\mu_a \sim$ **keV** : may arise due to **dynamics at low scales** in analogy with the QCD axion

Ultralight Dark Matter-pSMBH [Davoudiasl, Denton, Gehrlein '21]

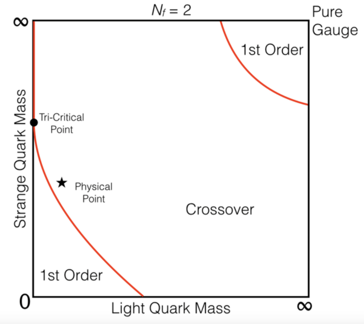
- introduce dark symmetry which can undergo FOPT at $T \sim$ keV to form pSMBH $\leftrightarrow$ generate mass scale for DM axion

$\rightarrow$ **connection between ultralight DM and SMBH**

bridging phenomena with very different mass scales

Specific Model example [Davoudiasl, Denton, Gehrlein '21]

- **dark $SU(3)_d$ gauge symmetry** with one generation of heavy, vector-like dark quarks Ψ, charged under $SU(3)_d$ and SM singlets
- $\Psi_{L,R}$ have mass $m_\Psi \sim f_a \gg \mu_a \rightarrow$ regime similar to "pure QCD" (quenched limit) $\rightarrow$ can undergo a first-order confinement phase transition



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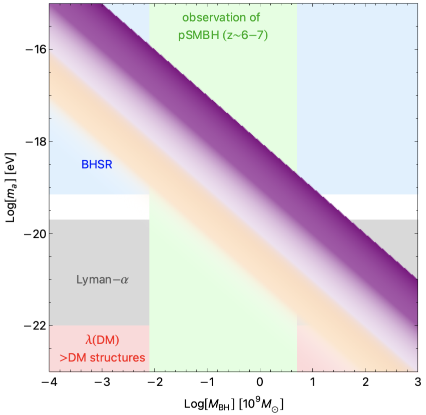
- PQ charges of $\Psi_{L,R}$ anomalous under PQ symmetry $\to$ coupling of the axion to the dark gluons $\mathcal{L} \supset (a/f_a) G_{d\,\mu\nu} \tilde{G}_d^{\mu\nu}$
- phenomenology of model example: contribution to N_{eff} (requires $T_d \lesssim 0.36\, T$ to be in agreement with observation), formation of glueballs

Relation between the axion mass and the SMBH mass

- with $R \sim 1/H$ and $\mu_a \sim T$

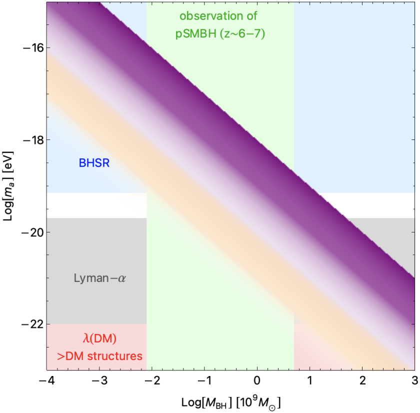
$$m_a = \varepsilon' \frac{M_{Pl}^3}{f_a M_{BH}} \, ,$$

- $f_a = 10^{17}$ GeV (purple) and $f_a = 10^{18}$ GeV (orange)
- color intensity represents a decrease in ε' from 1 to 0.01



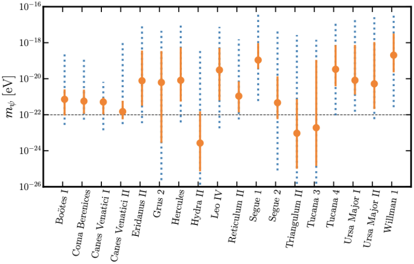
Constraints

- Lyman-α forest measurements [Rogers et al '20] disfavor ultralight bosons with masses $\lesssim 2 \times 10^{-20}$ eV
- spin down of SMBHs due to superradiance: disfavors ultralight bosons with masses $\gtrsim 7 \times 10^{-20}$ eV [Stott et al '18]
- size of smallest DM structures in the Universe: lowest bosonic DM mass of $\gtrsim 10^{-22}$ eV

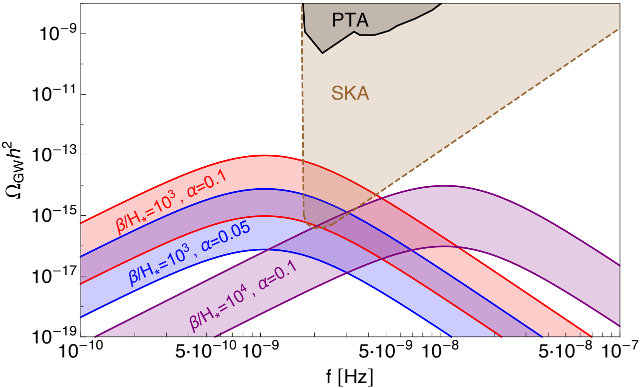


Constraints/Hints?

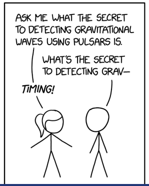
- baryonic feedback is expected to be negligible for ultra-faint dwarf (UFD) galaxies [Lazar et al '20] $\rightarrow$ robust (?) hint for a finite wavelength for DM from the UFDs from [Hayashi et al '21]
- examined 17 UFDs, found that they prefer DM masses in the $\sim 10^{-21} - 10^{-20}$ eV region with considerable uncertainties
- not yet at the level of discovery and the best fit point of the weighted average, 1.4×10^{-21} eV, is disfavored by Lyman-α measurements.



[Hayashi et al '21]



future pulsar timing arrays like SKA can probe parts of our parameter space!



Summary & Conclusions

- **novel** possible connection between the observations of $\sim 10^9 M_\odot$ **SMBHs** at redshifts $z \sim 6-7$ and **ultralight axion DM** of mass close to $\sim 10^{-20}$ eV
- dark sector confining **first order phase transition**, characterized by scales of 10 keV, that provides a catalyst for the primordial formation of $\sim 10^9$ SMBHs and endows the ultralight axion with mass, in a fashion similar to the QCD axion
- model **consistent** with a broad range of constraints
- **predictions**: expect $\Delta N_{eff} \sim 0.1$, gravitational waves in the pico to nano Hz regime, generated by the assumed phase transition, SMBH superradiance signatures

Thank you for your attention!