The Possibility of Observing Primordial Black Holes with Hydrogen Subordinate Lines

Viktor K. Dubrovich[1] Yury N. Eroshenko[2] Stanislav I. Shirokov[1]

[1]Special Astrophysical Observatory, Russian Academy of Sciences

[2]Institute for Nuclear Research, Russian Academy of Sciences

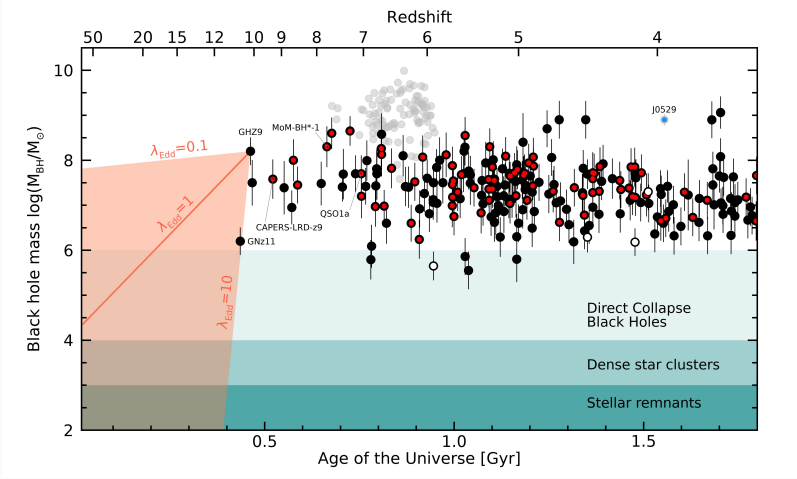
Supermassive Black Holes at High Redshifts

- Quasars at redshifts $z > 7$
- SMBHs in galaxies at $z \sim 10$ (JWST)
- "Little red dots", which probably contain SMBHs
- SMBH's seeds could explain the early formation of galaxies *(Guo, Khlopov, Liu, Wu, Wu, Zhu 2023)*

Hypothesis

These early black holes or their seeds may be primordial black holes (PBHs)

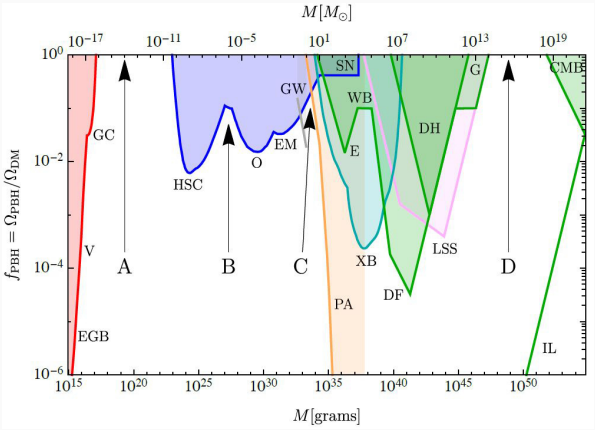
Black hole mass as a function of age of the Universe



(Übler, arXiv:2610.18263)

Supermassive Primordial Black Holes

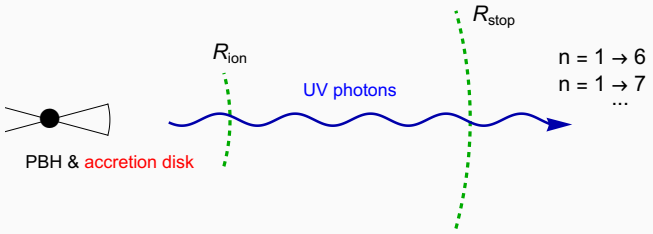
- Constraints on CMB μ-distortions in the model of adiabatic perturbation collapses
- There are no μ distortions in the domain wall collapse model *(Rubin, Khlopov, Sakharov 2000)*
- Dynamical constraints: $f_{\rm PBH} \leq 10^{-5}$ for $M_{\rm PBH} \sim 10^8 M_\odot$



(Carr, Kuhnel, arXiv:2110.02821)

Physical Mechanism

- Accreting PBH emits UV
- UV radiation excites H atoms
- CMB de-excites them



Key idea

Radiation from a PBH populates high-n levels of hydrogen, creating a Fraunhofer-like absorption spectrum in the CMB: $n = 5 \to 6$, $n = 6 \to 7$, etc.

$$L_\nu = \frac{dL}{d\nu} = \frac{L}{\nu_{max}} e^{-\nu/\nu_{max}}$$

where $\nu_{\max} = E_{max}/h$, $E_{max} \sim 1$ keV – 1 Mev *(Carr, 1981)*

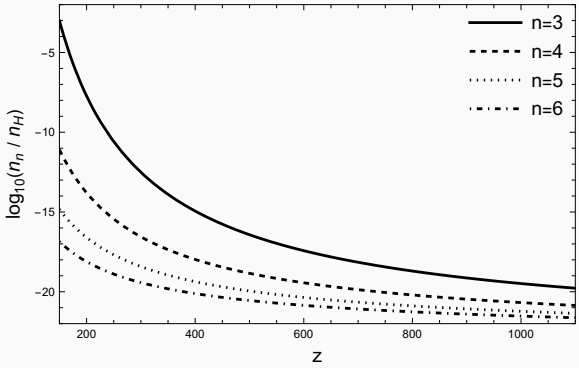
Population of excited levels

The relative population of level n is given by

$$\frac{n_n}{n_H} \simeq 10^{-11} \left(\frac{L}{10^{44}\,\mathrm{erg\,s^{-1}}}\right) \left(\frac{n}{4}\right)^2 \left(\frac{r}{50\,\mathrm{kpc}}\right)^{-2} \left(\frac{J(h\tilde{\nu}_n/kT)}{1.24\times10^{-12}}\right)^{-1} \left(\frac{E_{\mathrm{max}}}{100\,\mathrm{keV}}\right)^{-1},$$

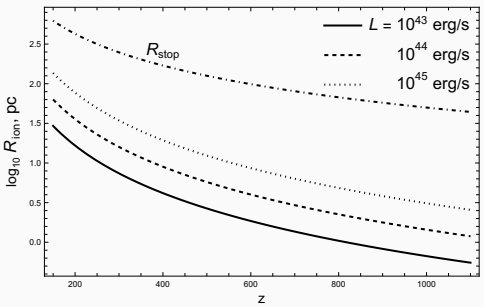
where $J(x) = \int_x^\infty \frac{dx}{x(e^x-1)}$.

- The population scales as r^{-2}
- Comparison with equilibrium: At $z = 150$, the Boltzmann population for $n = 4$ is $\sim 10^{-167}$; the source boosts it to $\sim 10^{-11}$ — a factor of $\sim 10^{156}$!

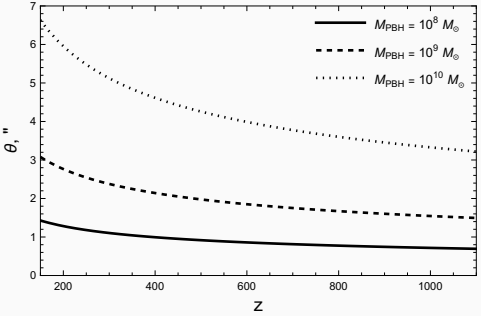


Ionization radius and angular size

$$R_{\rm stop}(z) = 0.12 \left(\frac{M_{\rm PBH}}{10^8 M_\odot}\right)^{1/3} \left(\frac{1+z}{501}\right)^{-4/3} \ \text{kpc}$$



Ionization radius



Angular size of the stop radius

Observation prospects

For a transition $5 \to 6$ at $z = 150$:

- Gas density $n_H(z) \simeq 2 \times 10^{-1}\,\mathrm{cm}^{-3}$.
- Enhanced region size $L \sim 50\,\mathrm{kpc}$.
- Column density of excited atoms $N_{\mathrm{col}} \simeq 3 \times 10^{11}\,\mathrm{cm}^{-2}$.
- Doppler width $\Delta\nu_D/\nu_0 \sim 10^{-5}$ (thermal).

Using the integrated cross section,

$$\tau \sim \frac{(\pi e^2/mc) f_{5\to6}}{\Delta\nu_D} N_{\mathrm{col}} \sim 3.$$

Consequence

Optical depth $\tau \sim 1$ is achievable; the line becomes observable.

Which lines to observe?

Transition	$\lambda_{\rm rest}$	$\lambda_{\rm obs}(z=300)$	$\lambda_{\rm obs}(z=1000)$
$5 \to 6$	$7.46\,\mu$m	$2.24\,$mm	$7.47\,$mm
$6 \to 7$	$12.36\,\mu$m	$3.72\,$mm	$12.37\,$mm

- At $z \sim 1000$, transitions fall into the centimetre band (accessible from ground).
- At $z \sim 300$, they lie in the millimetre range (ALMA, NOEMA, future space telescopes).
- Frequency separation $\Delta\nu/\nu \sim 0.3$ — easily resolved.

Sensitivity and detectability

Radiometer equation:

$$\sigma_T = \frac{T_{\rm sys}}{\sqrt{\Delta\nu\, t_{\rm int}}}.$$

For a 10% line at $\nu \sim 1\,\mathrm{GHz}$:

- Line depth: $\Delta T/T \simeq \tau\,(T_{\rm CMB} - T_{\rm gas})/T_{\rm CMB} \sim 10\%$
- Line width: Doppler broadening $\Delta\nu/\nu \sim 10^{-5}$ (thermal), turbulent broadening may increase to 10^{-3}
- $T_{\rm sys} \sim 100\,\mathrm{K}$ (SKA mid-band), bandwidth $\Delta\nu \sim 1\,\mathrm{MHz}$
- The absorption signal is expected to be clean and distinguishable
- To reach S/N=5, $t_{\rm int} \sim 2.5\,\mathrm{s}$ (after beam dilution factor ~ 36).

Advantage

The predicted signal is within reach of current and future radio telescopes (SKA, uGMRT, Spektr-M).

Conclusions

- We propose a new mechanism to detect massive compact objects (PBHs) in the Dark Ages via absorption in hydrogen subordinate lines.
- Radiation from the object boosts the population of high-n levels by ~ 10 orders of magnitude, making $\tau \sim 1$.
- Lines fall into the radio band (mm–cm), accessible from ground-based telescopes (SKA, uGMRT).
- Expected signatures: line depth $\sim 10\%$, width $\sim 10^{-4}$, angular size $\sim 10''$.
- The signal is clean (SZ and free–free are negligible) and could reveal the first compact objects in the Universe.

Future work: Full radiative transfer + realistic accretion disk models.

Thank you for your attention!