Supermassive Primordial Black Holes from a Catalyzed Dark Phase Transition for Little Red Dots

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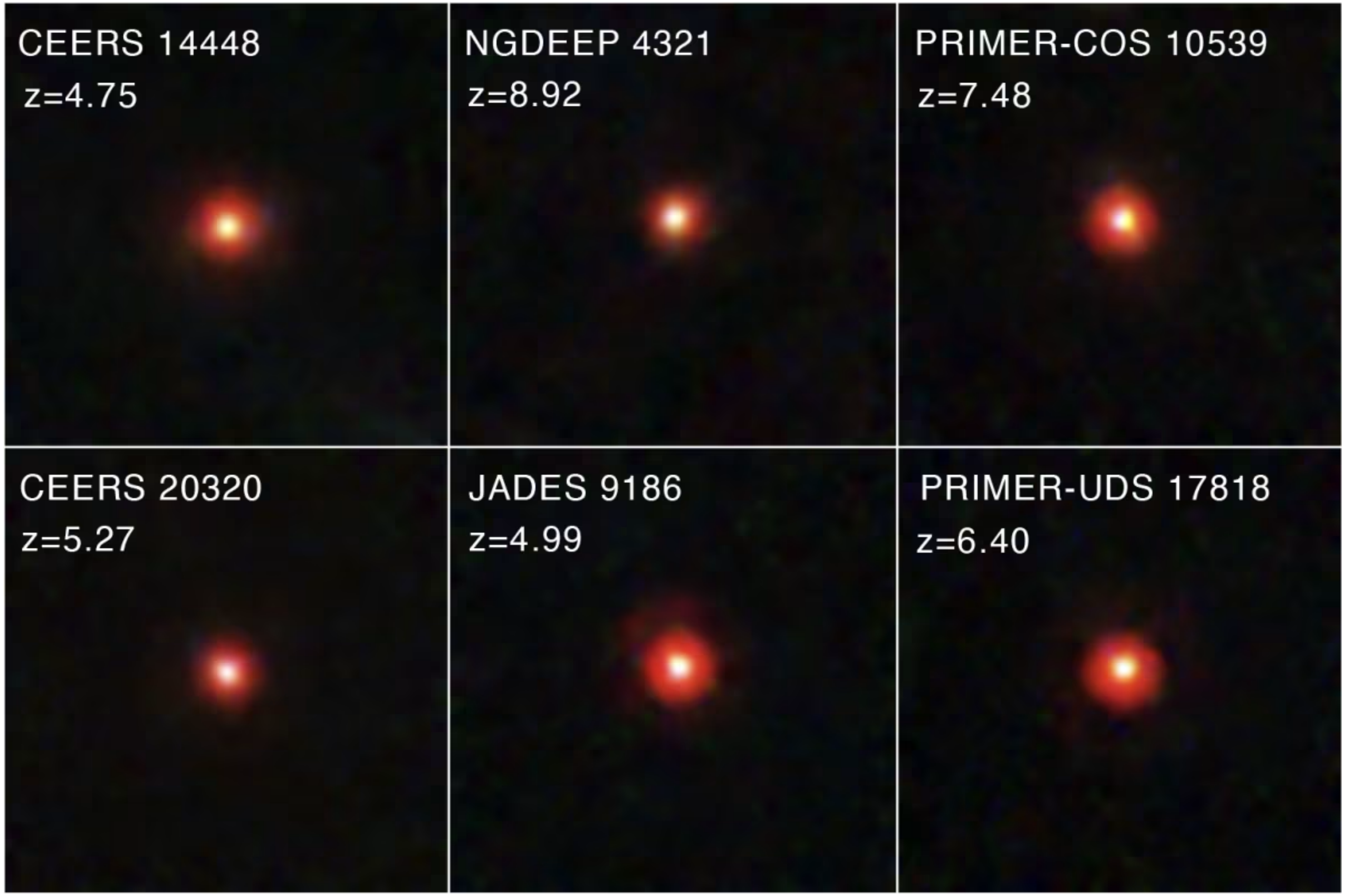
JWST and Little Red Dots

- Compact, red sources at high redshift
- Evidence for accreting massive BHs

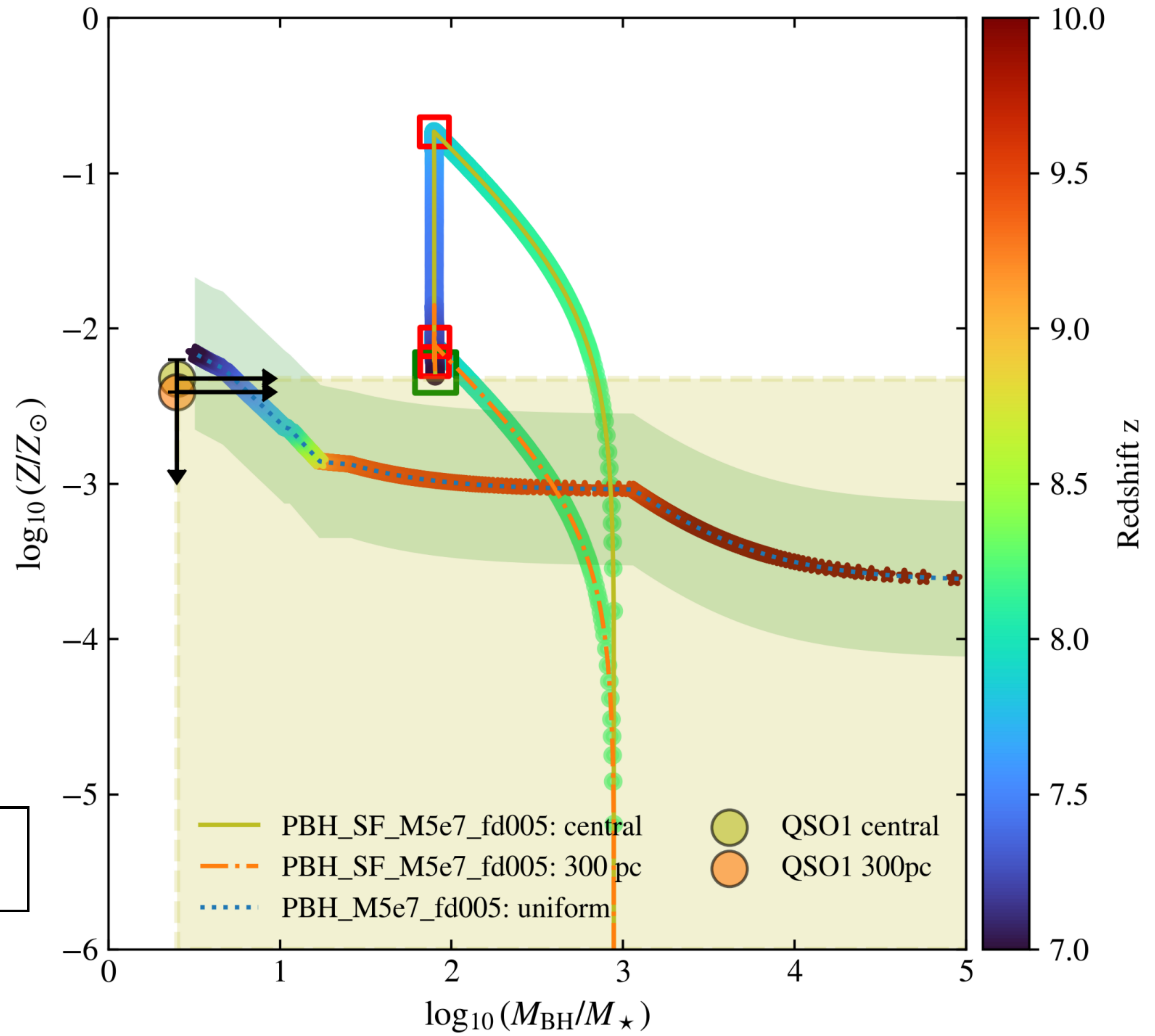


JWST reveals unexpectedly massive black holes

- Compact, red sources at high redshift
- Evidence for accreting massive BHs
- Extreme BH-to-stellar mass ratios
- Low metallicity environments

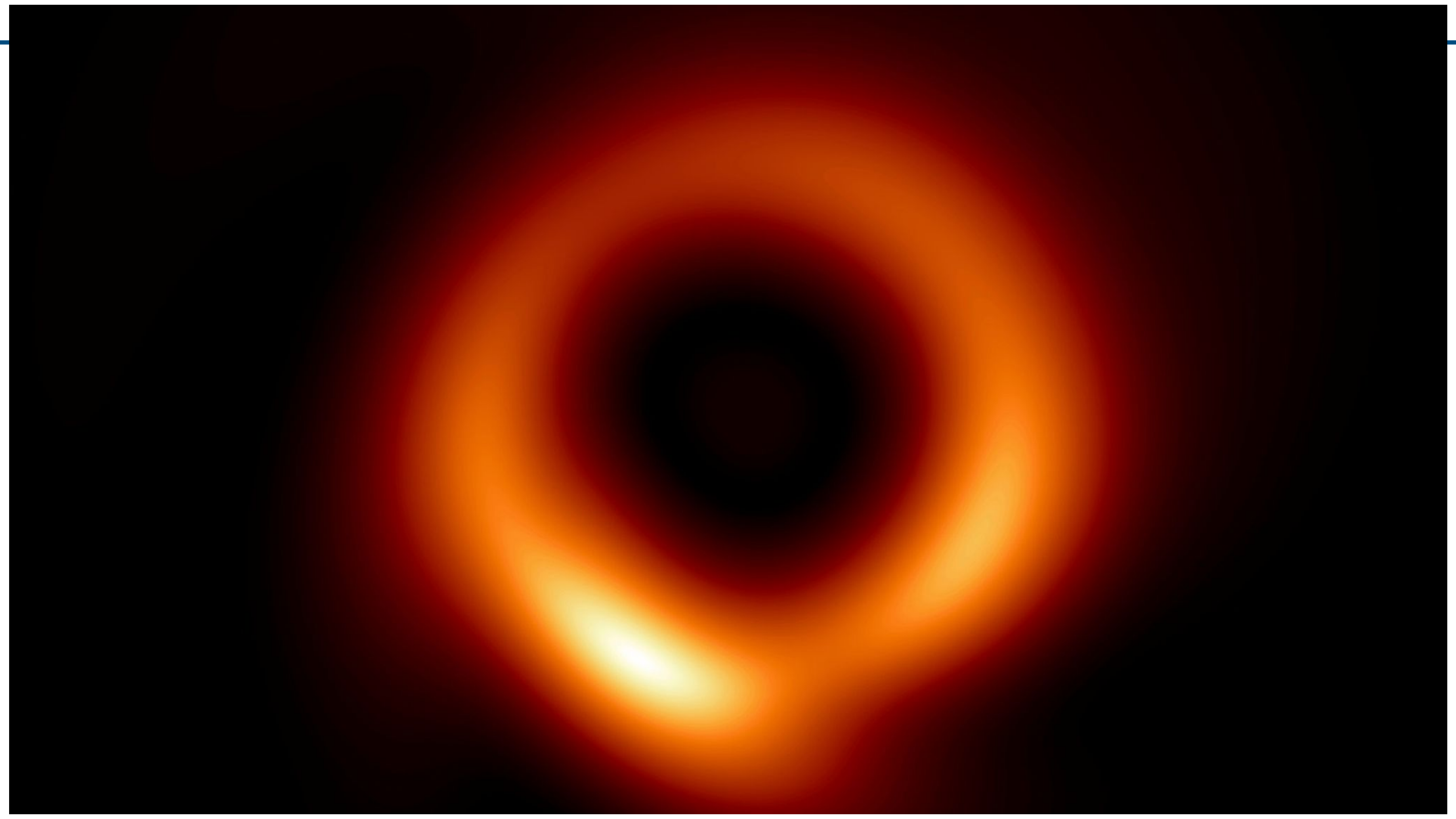
$$M_{\rm BH} \sim 10^7 M_\odot \qquad (z \sim 7)$$

A challenge for early SMBH formation



Zhang, Liu, Bromm, Kuhnel, 2512.14066 ApJL

The Supermassive Blackhole seed problem



- **Light seeds**

$$M_{\text{seed}} \sim 10 - 100\, M_\odot$$

  - Pop III stellar remnants
  - Long growth history required
  - Sustained rapid accretion

$$10 - 100\, M_\odot \xrightarrow[\text{limited cosmic time}]{\text{accretion}} 10^{7-9}\, M_\odot$$

- **Heavy seeds**

$$M_{\text{seed}} \gg 10^2\, M_\odot$$

  - Less growth required
  - Easier to reach early SMBHs

Can the seed itself already be supermassive?

Supermassive primordial black holes as seeds

- **Primordial heavy seed**

$$M_{PBH} \sim 10^7 - 10^9 M_\odot$$

  - Formed before galaxies
  - SMBH seed scale
  - Minimal growth

PBH → early SMBH

- **A concrete target**

$$M_{\mathrm{seed}} \sim 5 \times 10^7\, M_\odot$$

- Abell 2744--QSO1
  - Reproduces a BH-dominated high-z system
  - Extreme $M_{\mathrm{BH}}/M_\star$ ratio
  - Low metallicity

Can an early-Universe phase transition produce $10^{7-9} M_\odot$ PBHs?

PBHs from a first-order phase transition

- **Rare false-vacuum domains**
- First-order phase transition

$\downarrow$

Most regions $\longrightarrow$ true vacuum

$\downarrow$

Rare regions $\longrightarrow$ false vacuum survival

- **False-vacuum energy does not redshift**
- **Large FVDs become increasingly overdense**

SMBH is formed by overdense FVD

- **But there is a fast–slow tension**
- Cosmology requires fast phase transition
  - Vacuum energy →dark radiation
  - Avoid excessive $\Delta N_{\rm eff}$

V.S.

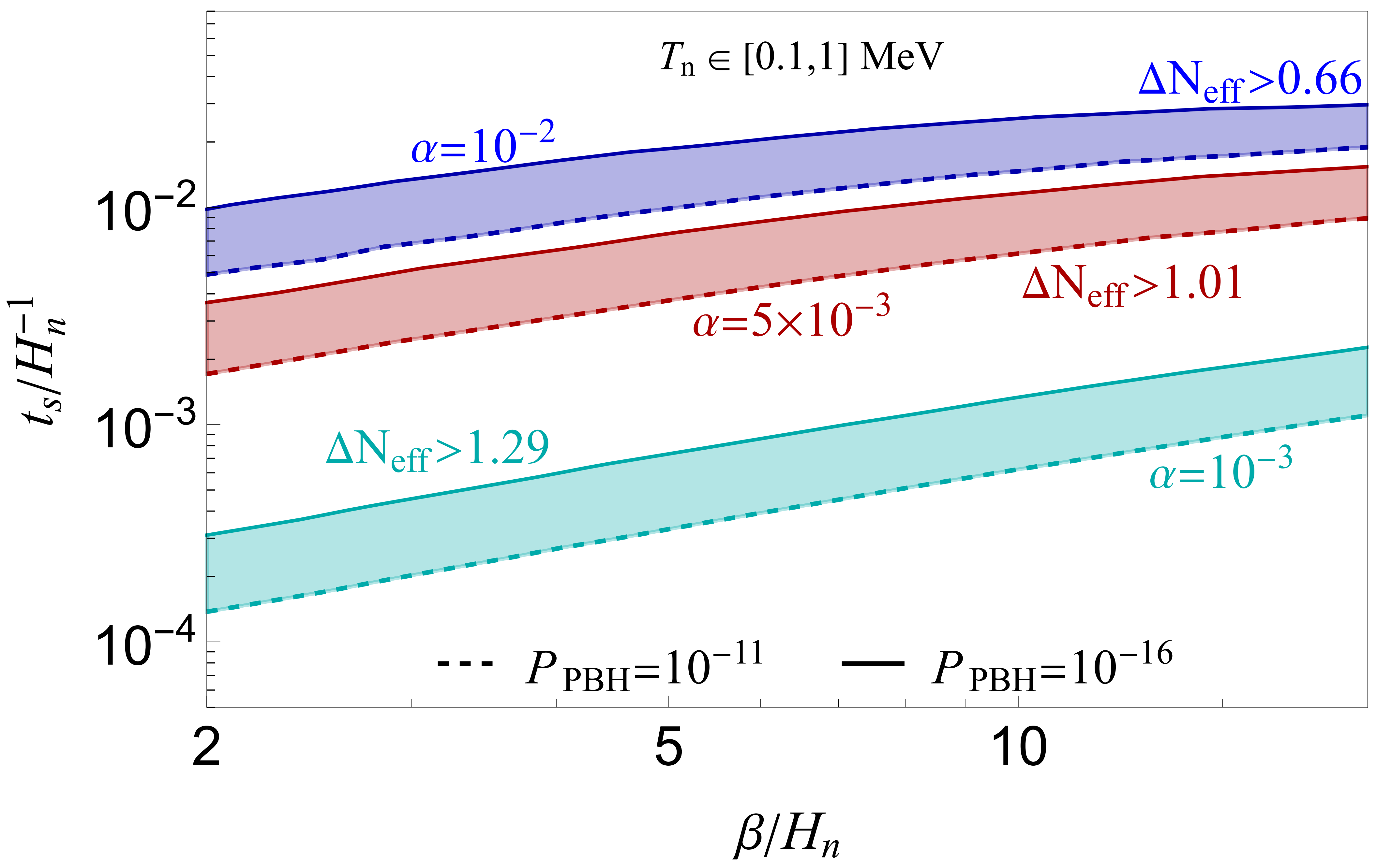
- PBH formation requires Long-lived FVDs
  - Rare regions must avoid bubble nucleation
  - Survive sufficiently large

Fast global completion V.S. rare long-lived domains

Conventional stochastic FOPT does not work

- **Even allowing a nontrivial nucleation history**

$$\text{Nucleationrate}: \Gamma(t) = H_n^4 e^{\beta(t-t_n)\left(1-\frac{t-t_n}{2t_s}\right)}$$



- **Two competing requirements**
- **Enough PBHs for LRDs**
  - $10^{-16} \lesssim P_{PBH} \lesssim 10^{-11}$
  - Requires long-lived FVDs
  - Favored by a slower transition
- **But a slow transition enhances**

$$\frac{\rho_{DR}}{\rho_R} \to \text{large } N_{eff}$$

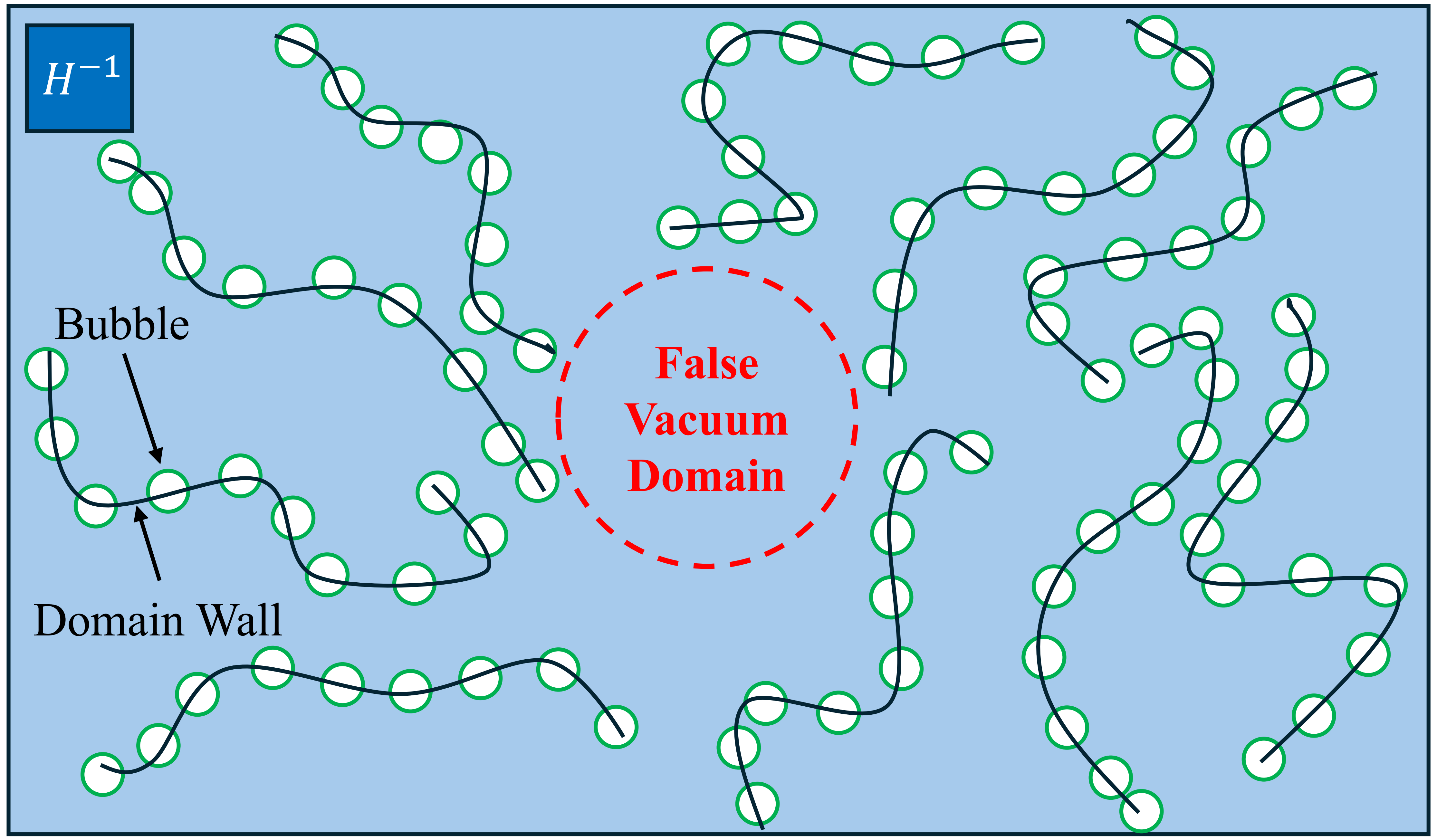
  - SM radiation keeps red-shifting
  - Vacuum energy is released later
  - ρ_{DR}/ρ_R becomes too large

LRD-sized PBH abundance $\Longrightarrow$ ΔN_{eff} tension

Changing the stochastic nucleation history does not remove it.

Our idea: domain-wall catalyzed phase transition

- **Domain walls as nucleation catalysts**



- **Typical regions**
  - Domain Wall passes through
  - Catalyzed bubble nucleation
  - Fast phase transition
- Most of the Univ. converts rapidly
- **Rare regions**
  - No DW penetration
  - No catalytic nucleation
  - Long-lived FVD $\Longrightarrow$ PBH
- Controlled by DW spatial statistics
- Rare large voids survive

Completion and survival are controlled by different physics

Why domain walls solve the fast–slow tension

- **Fast global completion**
  - DW-induced nucleation rate：

$$\Gamma_{\rm DW}(t) \simeq C_{\rm DW} n_{\rm DW}\, \delta(t - t_n)$$

- Bubbles per Hubble patch

$$N_{\rm bubble} = C_{\rm DW} n_{\rm DW} H_n^{-3} \gtrsim 1$$

  - Strong catalytic nucleation

    $C_{\rm DW} \gg 1$
  - $C_{\rm DW} = 1$ for point catalysts
  - Transition completes rapidly
  - Controlled by $C_{\rm DW}$

- **Rare FVD survival**

$$\langle n \rangle \simeq 2 n_{\rm DW} L^2 R_{\rm FVD}$$

  - $\langle n \rangle \propto R_{\rm FVD}$
  - $P^{\rm DW}_{\rm surv} \sim e^{-R_{\rm FVD}}$ v.s.

    $P^{\rm stochastic}_{\rm surv} \sim e^{-R^3_{\rm FVD}}$
- Survival set by DW statistics
- Large voids are less suppressed
- Rare long-lived FVDs remain possible

$C_{\rm DW} \longrightarrow$ global completion & $\mathrm{DW\ spatial\ statistics} \longrightarrow$ rare survival

From a surviving FVD to a supermassive PBH

- **A long-lived false-vacuum domain**

$$\rho_{\rm V} = \Delta V = \text{const.}$$

$$\rho_{\rm R} \propto a^{-4}$$

- Increasing density contrast
  - Radiation keeps diluting
  - Vacuum energy remains stored
  - Large FVDs become super-critical

- **Super-critical collapse criterion**
  - $t_{\rm V} = \dfrac{1}{2}\sqrt{\dfrac{3M_{\rm Pl}^2}{\rho_{\rm V}}}$
  - $t_{\rm hc} = \dfrac{H(t_{\rm in})R^2(t_{\rm in})}{2}$

$$t_{\rm hc} > t_{\rm V}$$

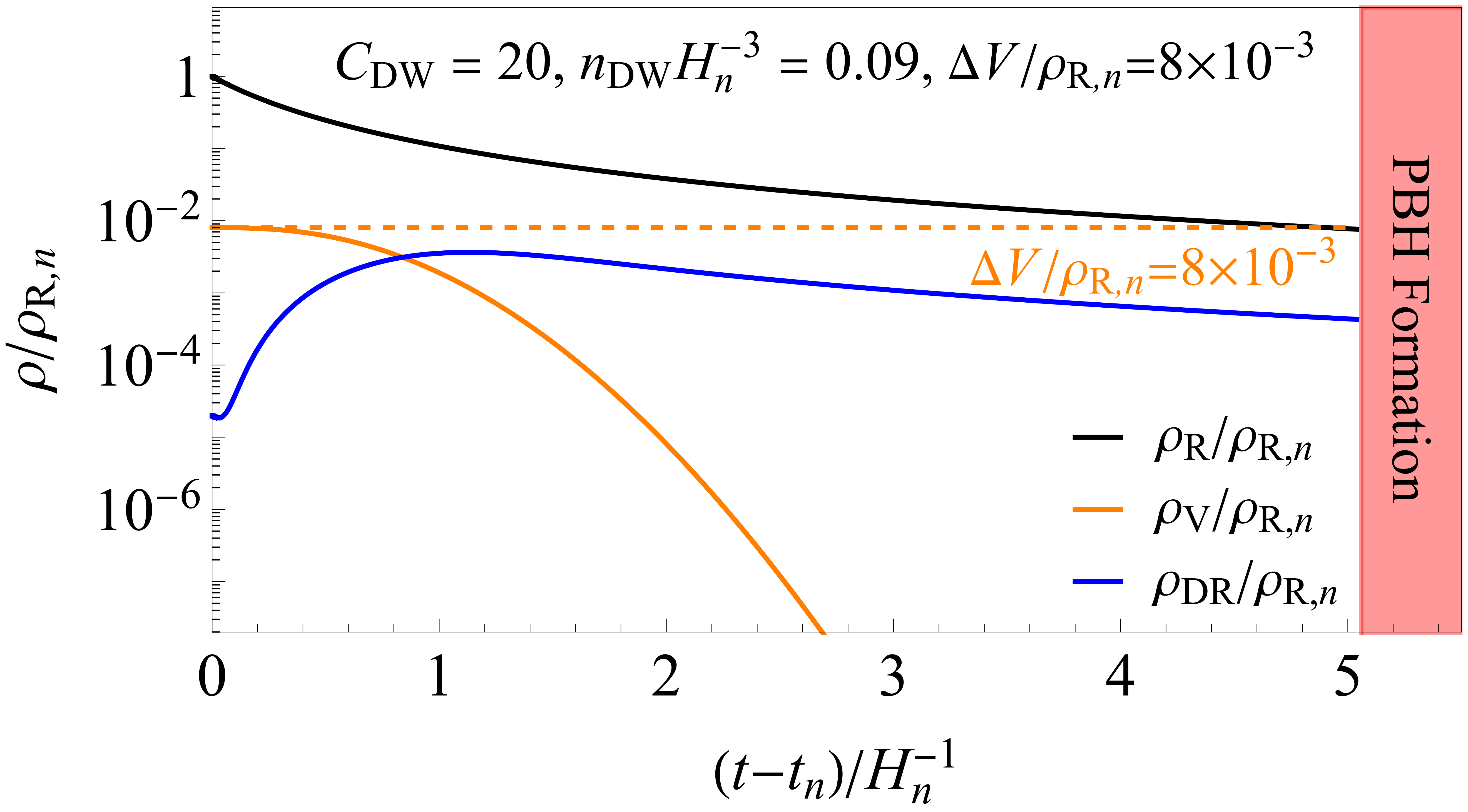
- Sufficiently large FVDs become super-critical

$$M_{\rm PBH} \simeq \frac{4\pi}{3}\rho_{\rm tot}(t_{\rm in})R_{\rm FVD}^3(t_{\rm in})$$

Rare surviving FVD $\longrightarrow$ $t_{\rm hc} > t_{\rm V}$ $\longrightarrow$ Supermassive PBH

Larger surviving domains $\Longrightarrow$ heavier PBHs

Benchmark evolution of the catalyzed transition



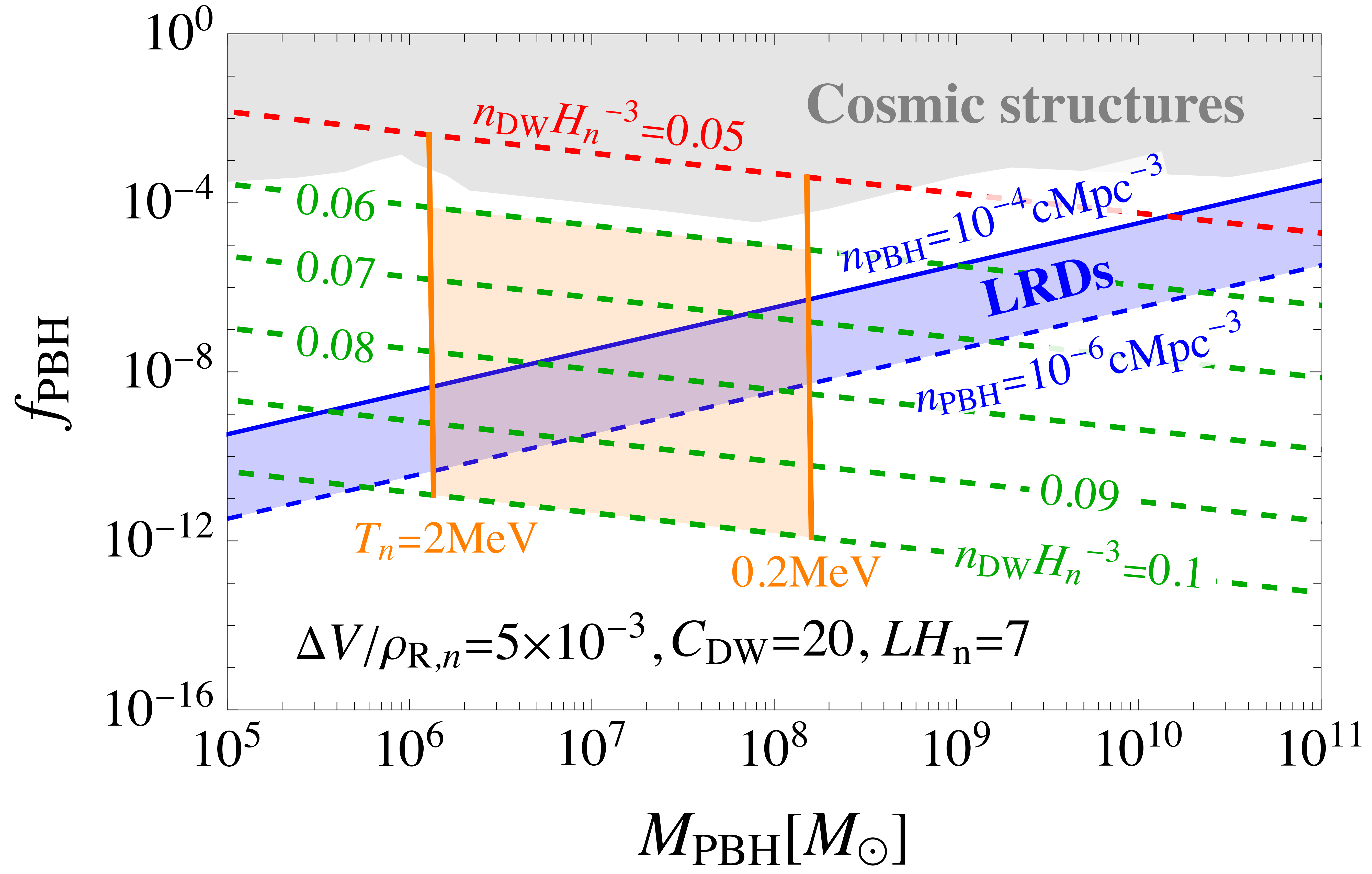
1. Rapid global transition $\rho_{\rm V} \longrightarrow \rho_{\rm DR}$
   - Completed within a few Hubble times
   - SM radiation remains dominant
2. Rare FVDs survive longer
   $\rho_{\rm V}^{\rm FVD} = \Delta V$
   - Vacuum energy remains trapped
   - Density contrast keeps growing
3. PBH formation $\Delta V \gtrsim \rho_{\rm R}(t_{\rm PBH})$

➡Super-critical PBH

Fast average evolution + long-lived rare FVDs

The behavior required for SMPBH formation is realized simultaneously

Supermassive PBHs for Little Red Dots



- PBH mass $T_n \longrightarrow M_{\rm PBH}$
  - Lower T_n → larger horizon scale
  - Heavier surviving FVDs
  - Nearly monochromatic mass
- PBH abundance $n_{\rm DW} \longrightarrow f_{\rm PBH}$
  - Controls rare FVD probability
  - Strong exponential sensitivity
  - Can match LRD abundance

The mechanism reaches the mass and abundance required by LRDs

$$M_{\rm PBH} \lesssim 10^{10}\, M_\odot$$

Cosmological constraints

- Phase-transition completion

$N_{\text{bubble}} = C_{\text{DW}} n_{\text{DW}} H_n^{-3} \gtrsim 1$

- Strong DW catalysis
- Rapid percolation
- Benchmark safely completes

- Dark radiation: ΔN_{eff}

$$\Delta N_{\text{eff}} \simeq 4.4 \frac{\rho_{\text{DR}}}{\rho_R}$$

- Current bound: $\Delta N_{\text{eff}} \lesssim 0.3$
  - Dark sector remains subdominant
  - Fast PT limits ρ_{DR}/ρ_R
  - Benchmark satisfies the bound

- CMB spectral distortion

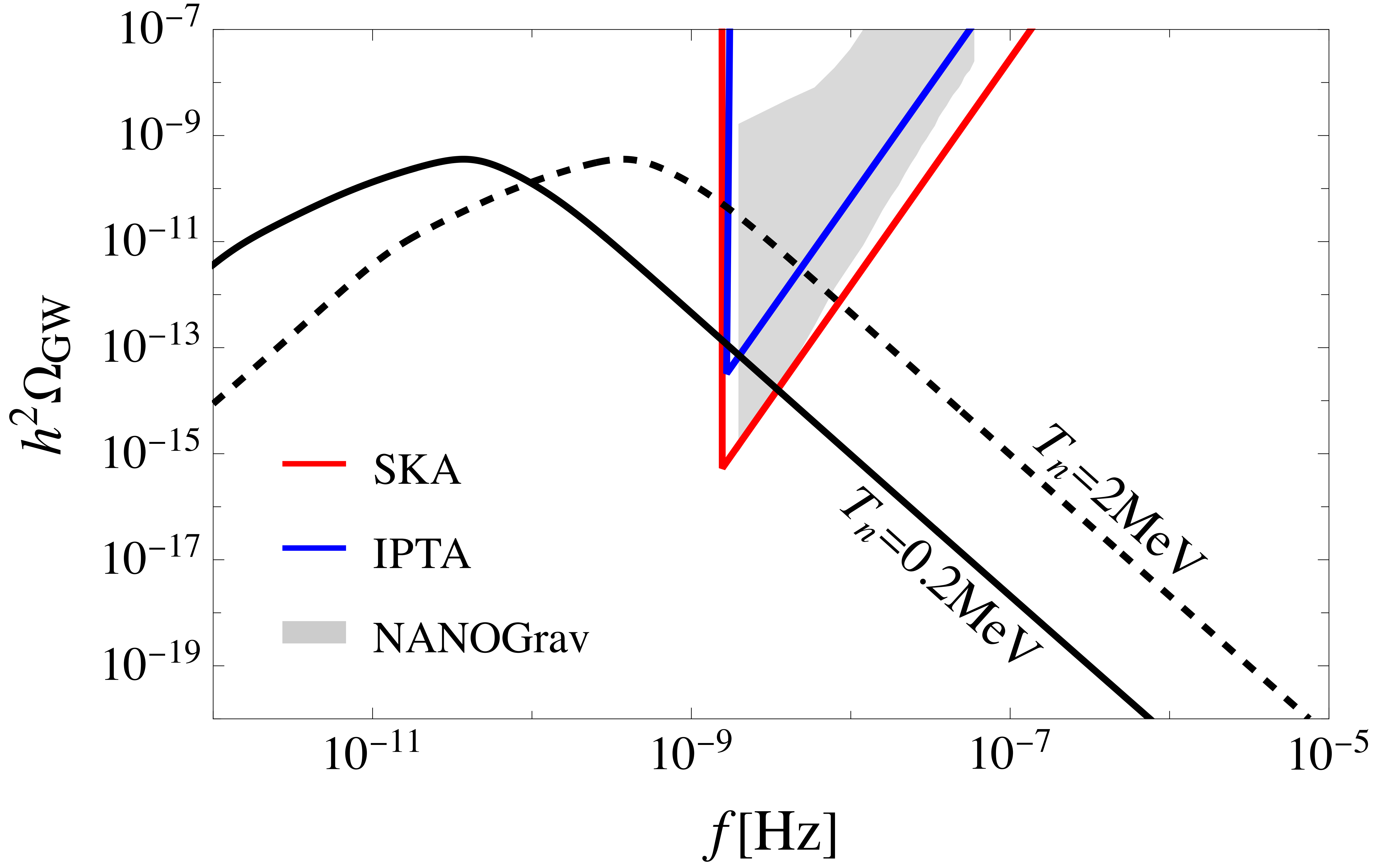
$\text{FOPT} \to \mathscr{P}_\zeta \to \mu$-distortion

  - FIRAS: $\mu < 4.7 \times 10^{-5}$
  - Finite bubble statistics induce $\mathscr{P}_\zeta$
  - Stronger for slower transitions
  - Rapid catalysis suppresses the effect

Strong DW catalysis → Rapid global PT

SMPBH formation without violating cosmological constraints

A correlated prediction: ultra-low-frequency gravitational waves



- The same phase transition

  Catalyzed FOPT → Bubble collisions

  → Stochastic GW background

- Ultra-low-frequency signal
  - $f_{\rm peak} \sim 10^{-2} - 10^{-1}$ nHz
  - Sub-MeV transition scale
  - Below conventional mHz–Hz searches
  - Near the low-frequency PTA frontier

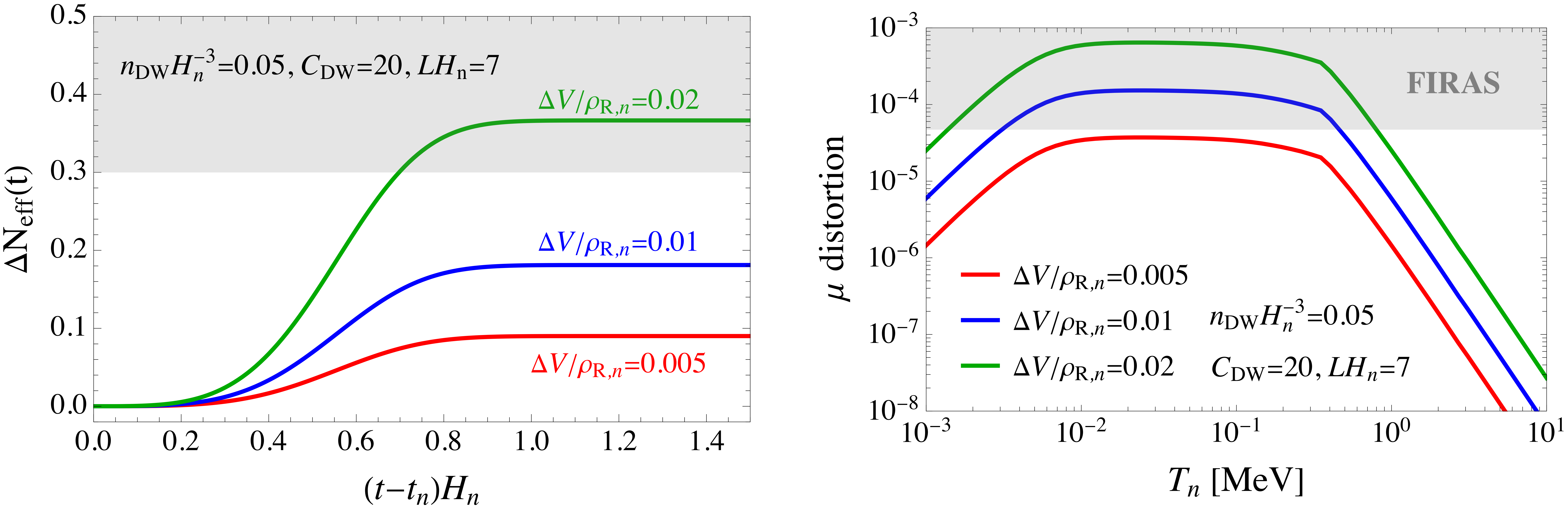
The LRD explanation predicts an independent cosmological signal

Summary

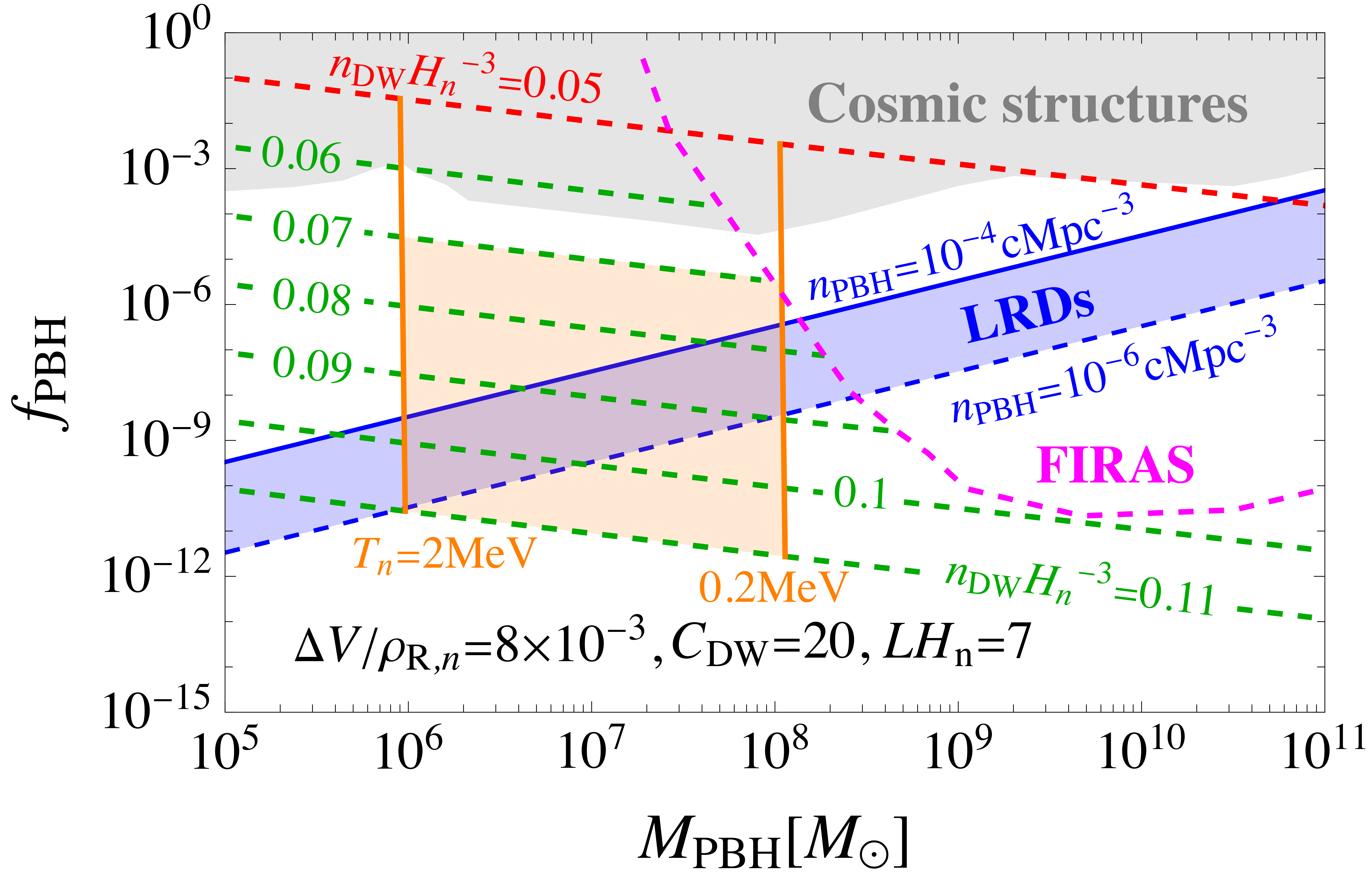
- **JWST motivation**
  - Little Red Dots - massive BHs at high z, heavy seeds motivated
- **Conventional FOPT problem**
  - FAST completion vs. Long-Lived False Vacuum Domains
  - Controlled by the same stochastic nucleation
- Our mechanism — Domain-wall catalysis
  - FAST globally + RARE survival locally
  - catalysis → completion, DW statistics → rare FVDs
- Phenomenology
  - $M_{\rm PBH} \sim 10^6 - 10^{10} M_\odot$, LRD-relevant abundance
  - Cosmologically viable, ultra-low-frequency GWs

Little Red Dots may probe a sub-MeV dark-sector phase transition

Backup


$n_{\rm DW}H_n^{-3}$=0.05, $C_{\rm DW}$=20, $LH_{\rm n}$=7
$\Delta V/\rho_{R,n}$=0.02
$\Delta V/\rho_{R,n}$=0.01
$\Delta V/\rho_{R,n}$=0.005
$\Delta N_{\rm eff}(t)$
$(t-t_n)H_n$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.2
1.4
FIRAS
μ distortion
T_n [MeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-2}
10^{-1}
10^{0}
10^{1}
$\Delta V/\rho_{R,n}$=0.005
$\Delta V/\rho_{R,n}$=0.01
$\Delta V/\rho_{R,n}$=0.02
$n_{\rm DW}H_n^{-3}$=0.05
$C_{\rm DW}$=20, LH_n=7

Backup



$n_{\rm DW}H_n^{-3}$=0.05
Cosmic structures
0.06
0.07
0.08
0.09
0.1
$n_{\rm DW}H_n^{-3}$=0.11
$n_{\rm PBH}=10^{-4}\,{\rm cMpc}^{-3}$
LRDs
$n_{\rm PBH}=10^{-6}\,{\rm cMpc}^{-3}$
FIRAS
T_n=2MeV
0.2MeV
$\Delta V/\rho_{R,n}=8\times10^{-3}, C_{\rm DW}=20, LH_n=7$
$f_{\rm PBH}$
$M_{\rm PBH}[M_\odot]$

Backup