Cosmological Constraints on Late and Super-late Phase Transitions

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Shaping the Universe 01/27/25

Based on:

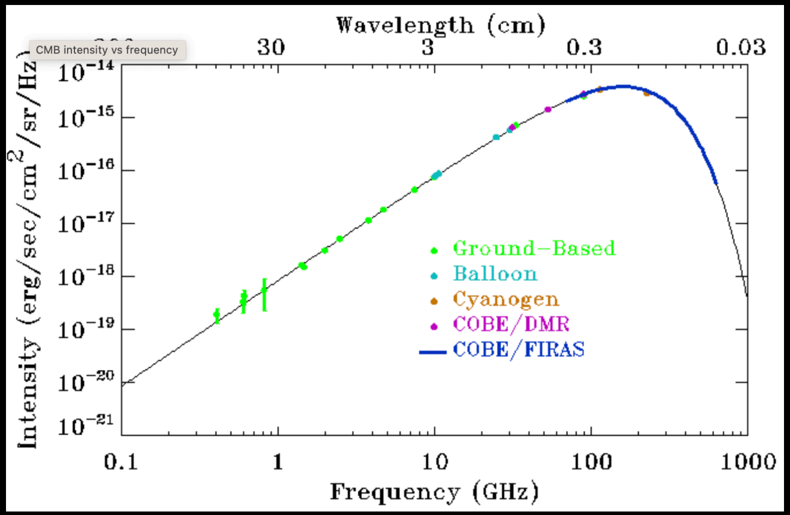
(Scalar perturbation) Gilly Elor, Ryusuke Jinno, Soubhik Kumar, Robert McGehee, YT [2311.16222]

(CC-dominant era) Seth Koren, YT, Runquing Wang [2509.07076]

(CMB B-mode) Kylar Green, Aurora Ireland, Gordan Krnjaic, YT [2410.23348]

Early Universe is like a hot & dense soup

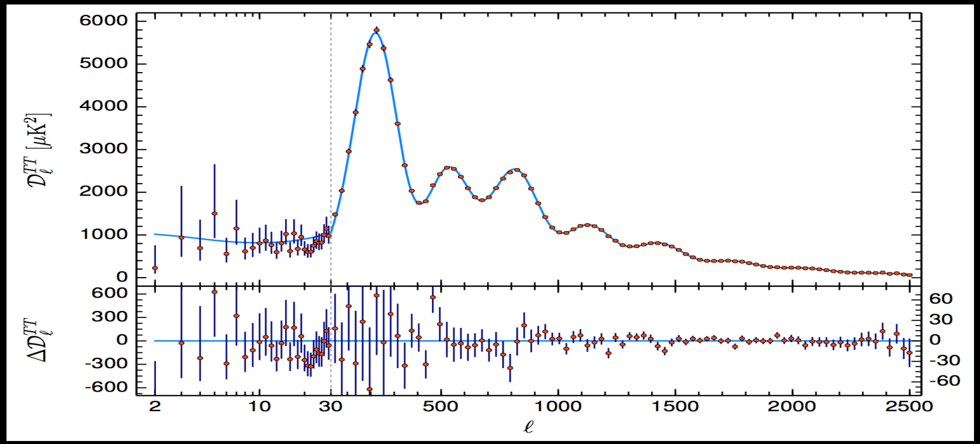
CMB energy spectrum



very close to blackbody spectrum

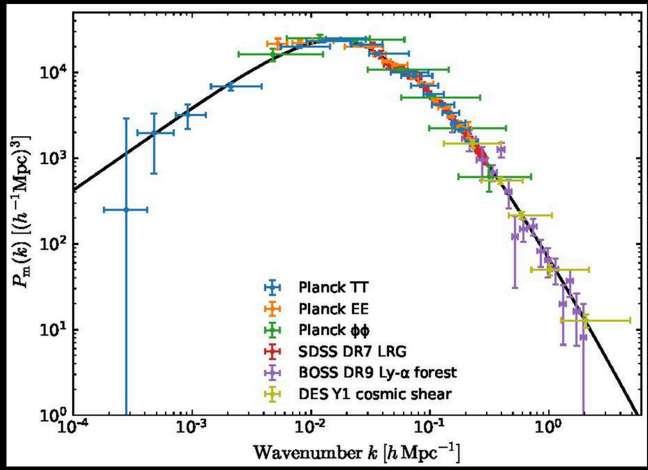
CMB anisotropy

of the last scattering surface



Large Scale Structure

clumpiness of the DM distribution



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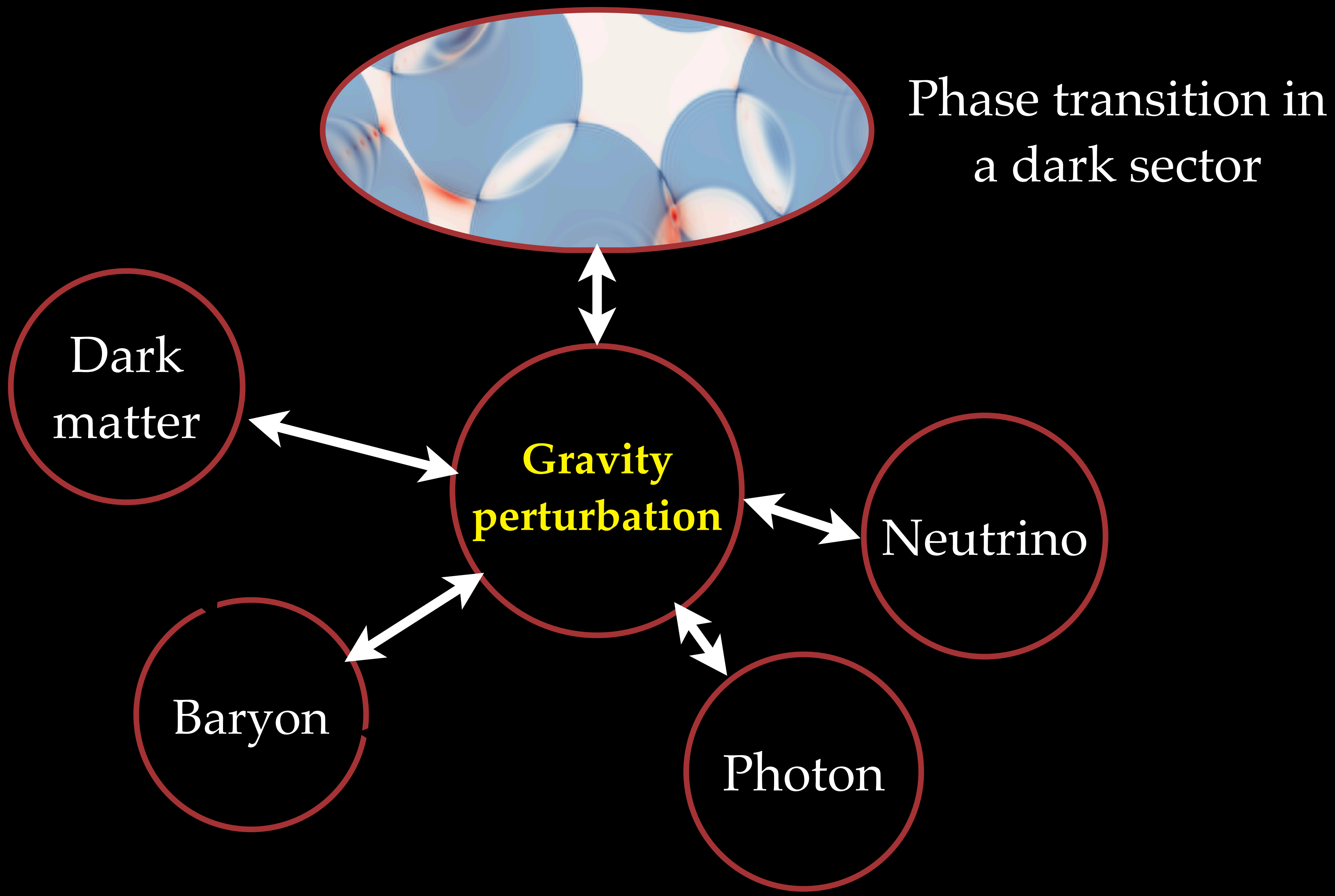
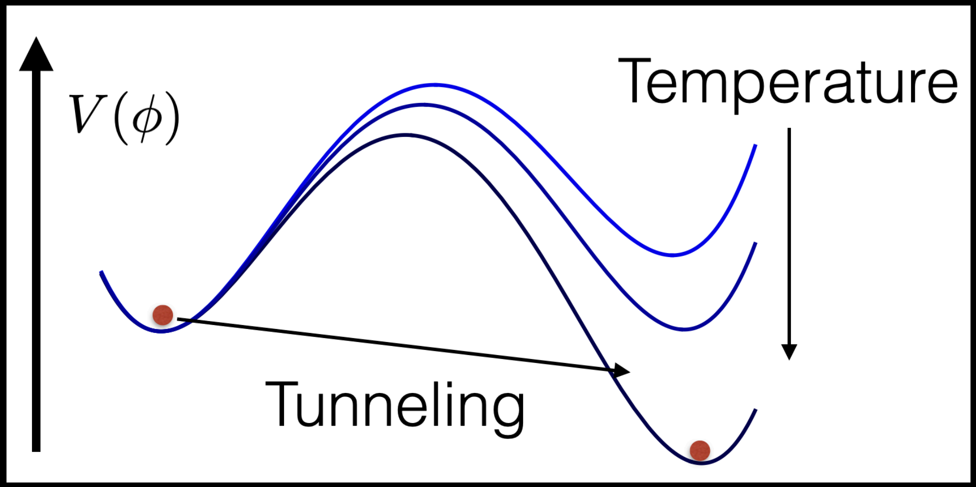
Let's consider first-order PT in a dark sector that leaves purely gravitational imprints on cosmo signals



Phase transition parameters



$$\Gamma \approx \Gamma_0 e^{\beta t}$$

Transition probability / volume & time

PT temperature $T_{\rm PT} \Rightarrow H^{-1}_{\rm PT}$, $\tau_{\rm PT}, z_{\rm PT}, T_{\rm PT}$

(comoving time, redshift, SM temperature at PT)

Average bubble size $\approx (8\pi)^{1/3} v_w \beta^{-1}$ $\beta / H_{\rm PT}$

(Parametrize the PT duration)

Fraction of the latent heat (assuming goes into dark radiation) compared to total energy density, $f_{\rm DR} = \rho_{\rm DR} / (\rho_{\rm DR} + \rho_{\rm SM})$

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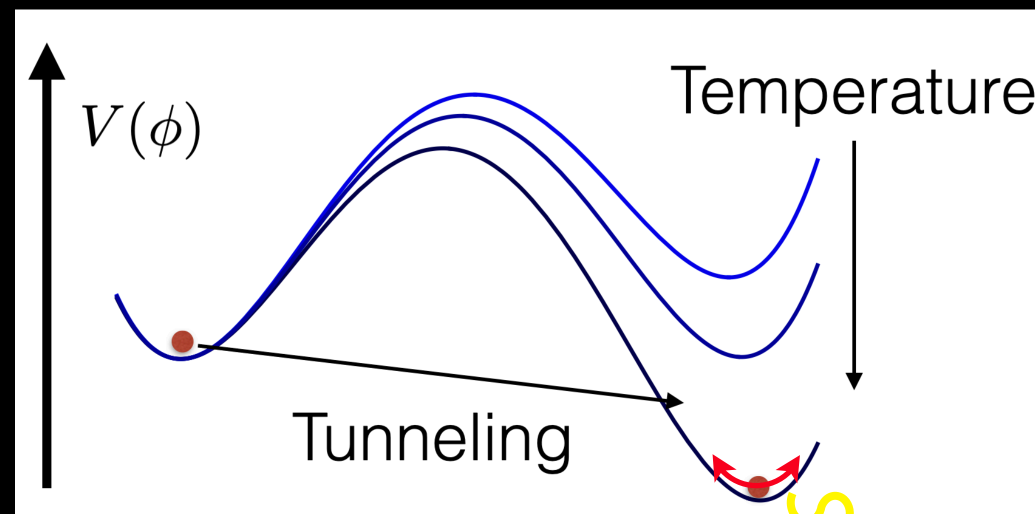
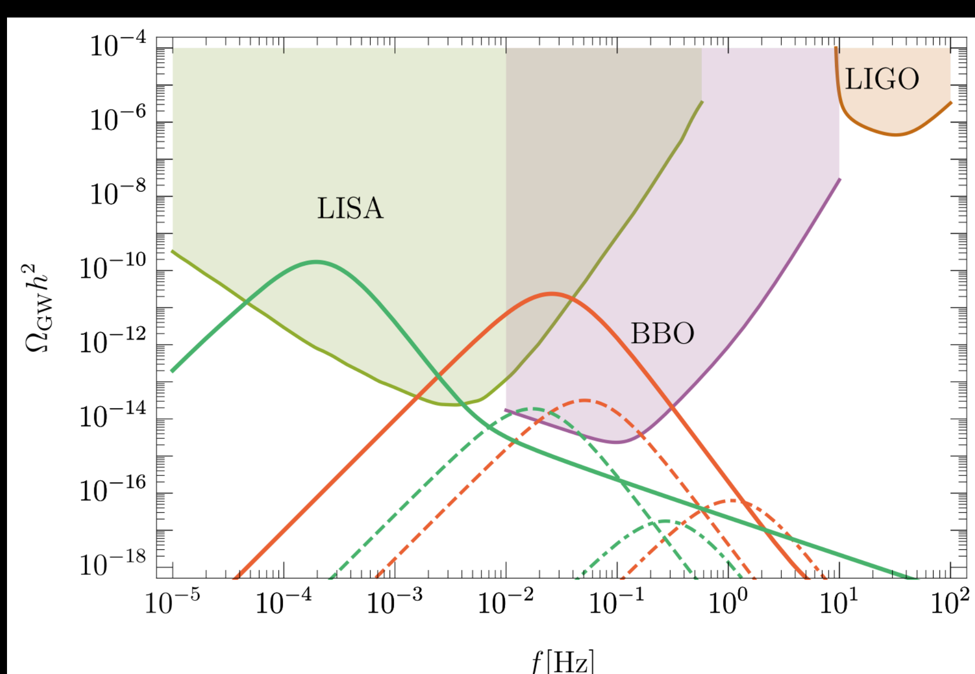
FOPT produces tensor perturbations that sources gravitational waves



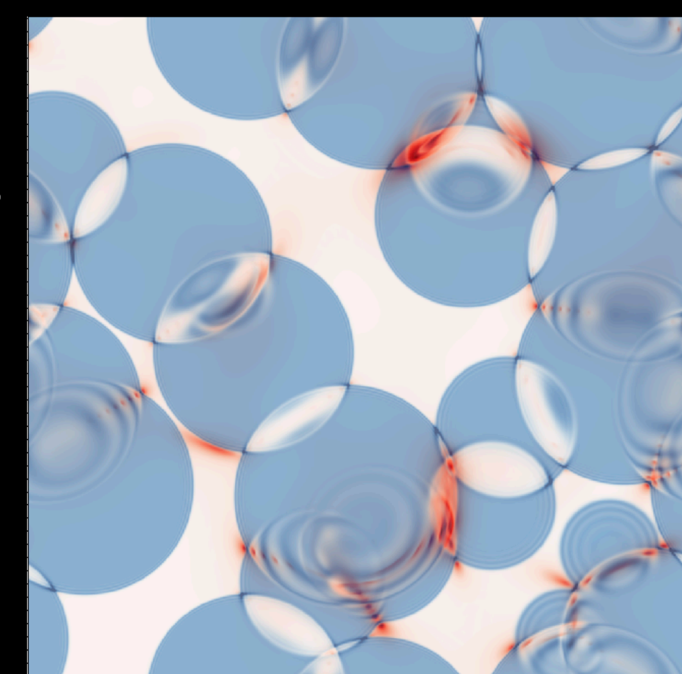
release energy



large tensor perturbations

produce

gravitational wave



Beniwal et al. 1702.06124

Cutting, Hindmarsh, Weir (2018)

FOPT also produces energy density (scalar) perturbations

How to quantify the scalar mode fluctuations?

Scalar Perturbations

from a first-order phase transition

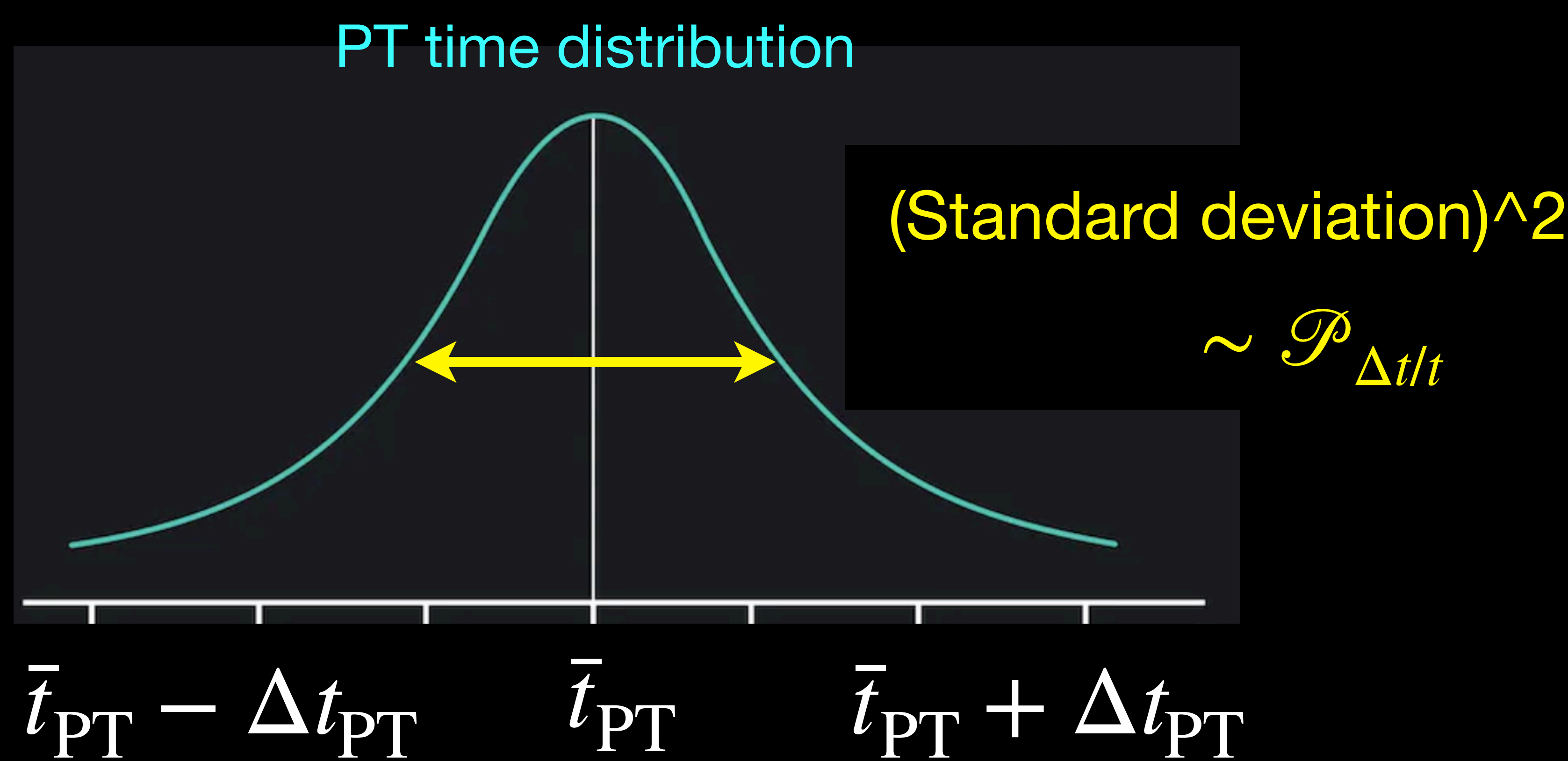
Start from the fluctuation of phase transition "time"

$$t_{\mathrm{PT}}(x) = \bar{t}_{\mathrm{PT}} + \Delta t_{\mathrm{PT}}(x)$$

$$\mathscr{P}_{\Delta t/t}(k) = \langle \Delta t_{\mathrm{PT}} \Delta t_{\mathrm{PT}} \rangle_k$$

$k \sim$ inverse of length separation

Two point function of the "PT time-fluctuation". This is like the square of standard deviation in time

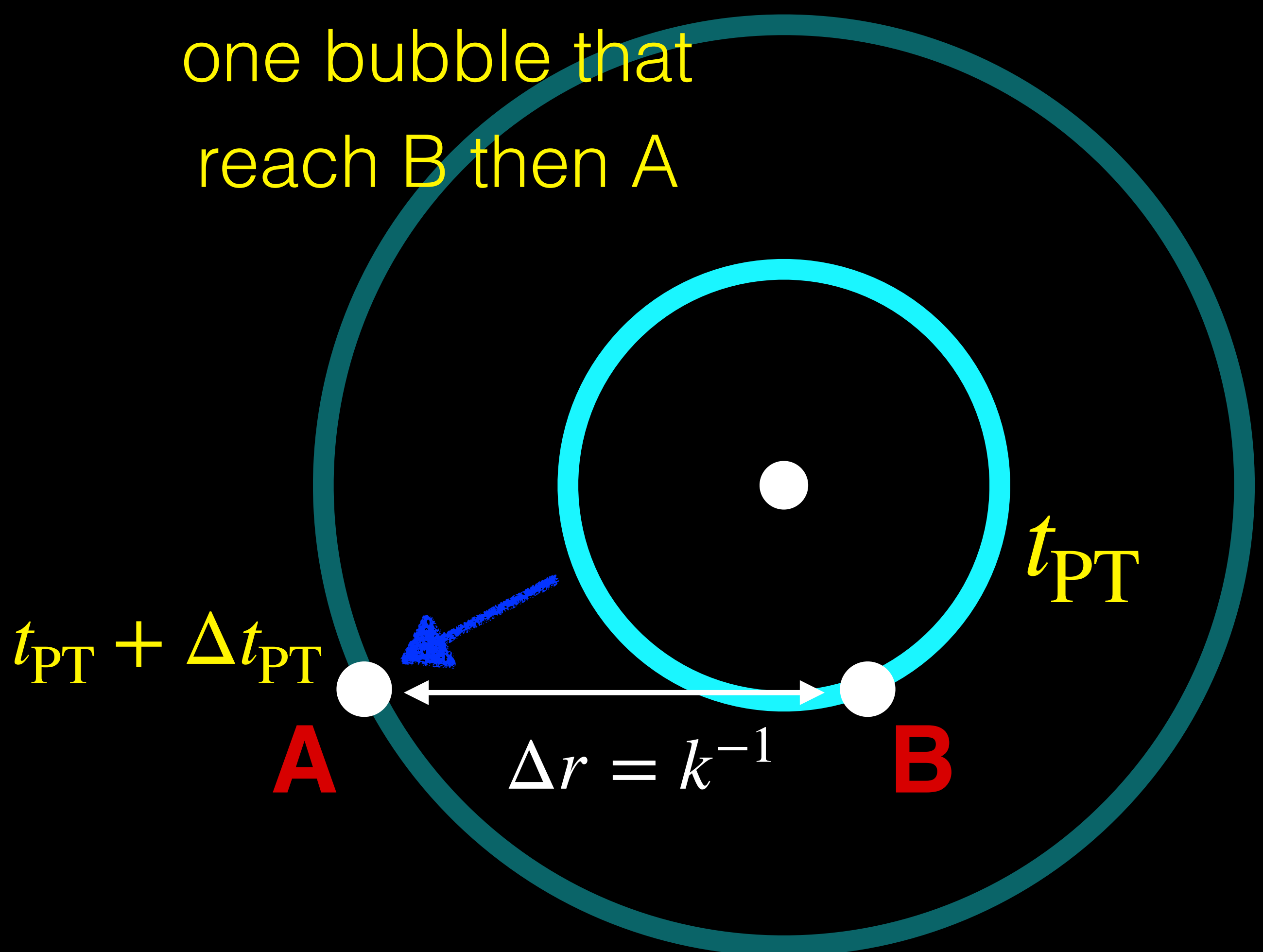


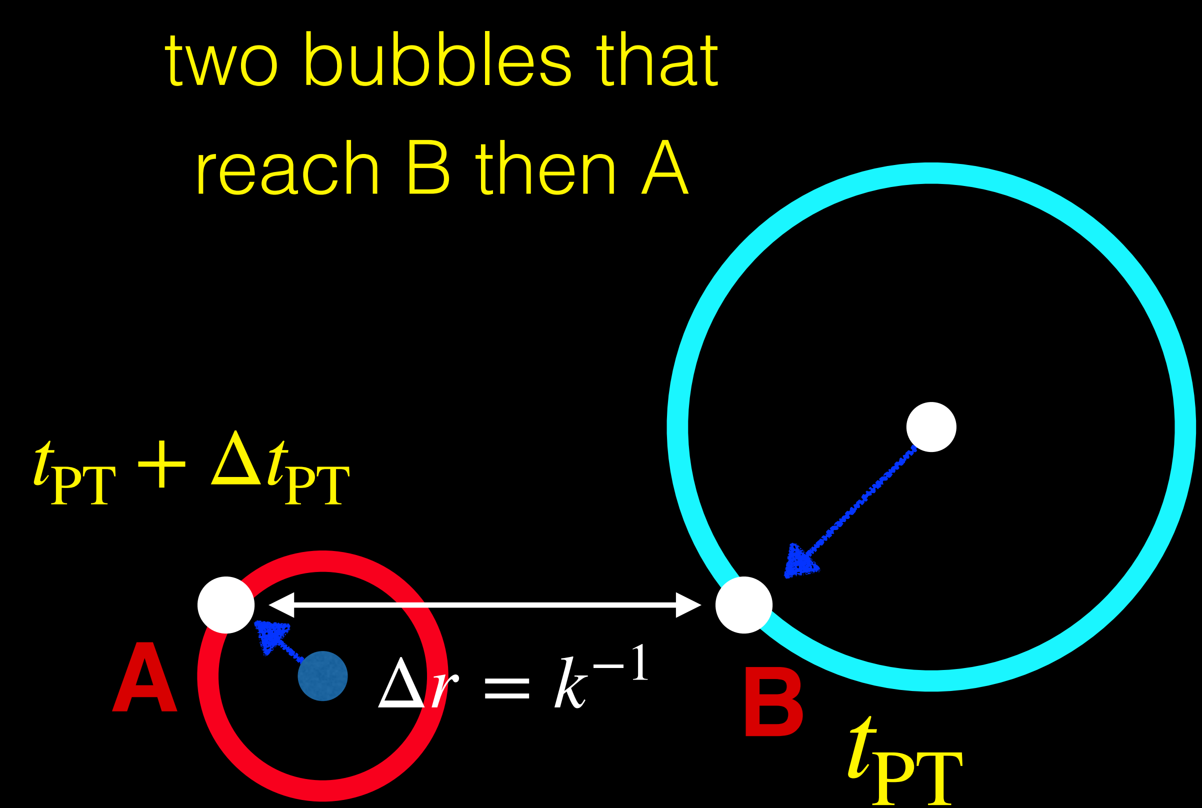
Start from the fluctuation of phase transition "time"

$$\mathscr{P}_{\Delta t/t}(k) = \langle \Delta t_{\rm PT} \Delta t_{\rm PT} \rangle_k$$

$k \sim$ inverse of length separation

Calculate the correlation function by multiplying the $\Delta t_{\rm PT}$ square to the probability of a given bubble expansion setup





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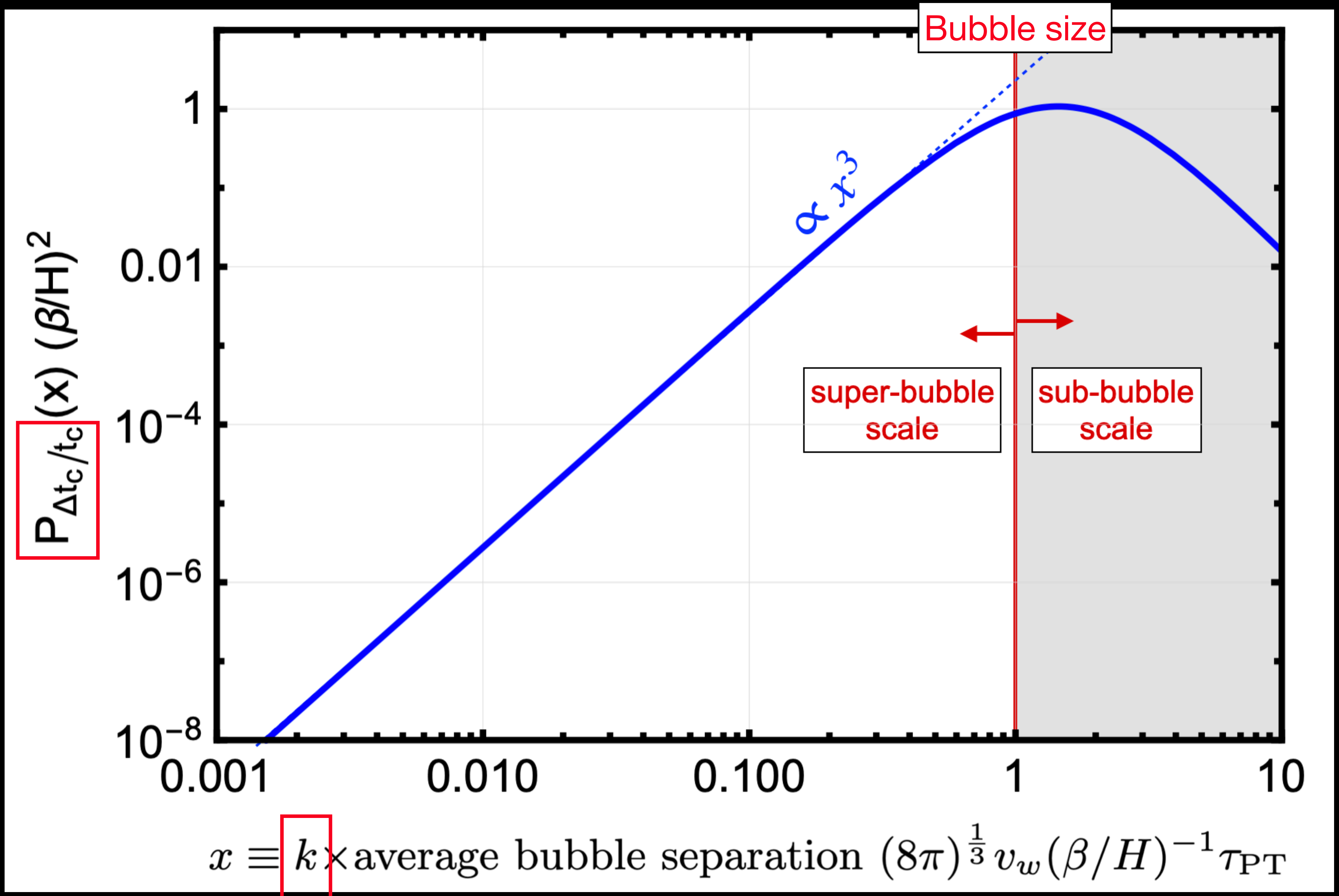
$\mathscr{P}_{\Delta t/t}(k) = \langle \Delta t_{\rm PT} \Delta t_{\rm PT} \rangle_k$ of PT time fluctuation, which is universal under specific parametrization



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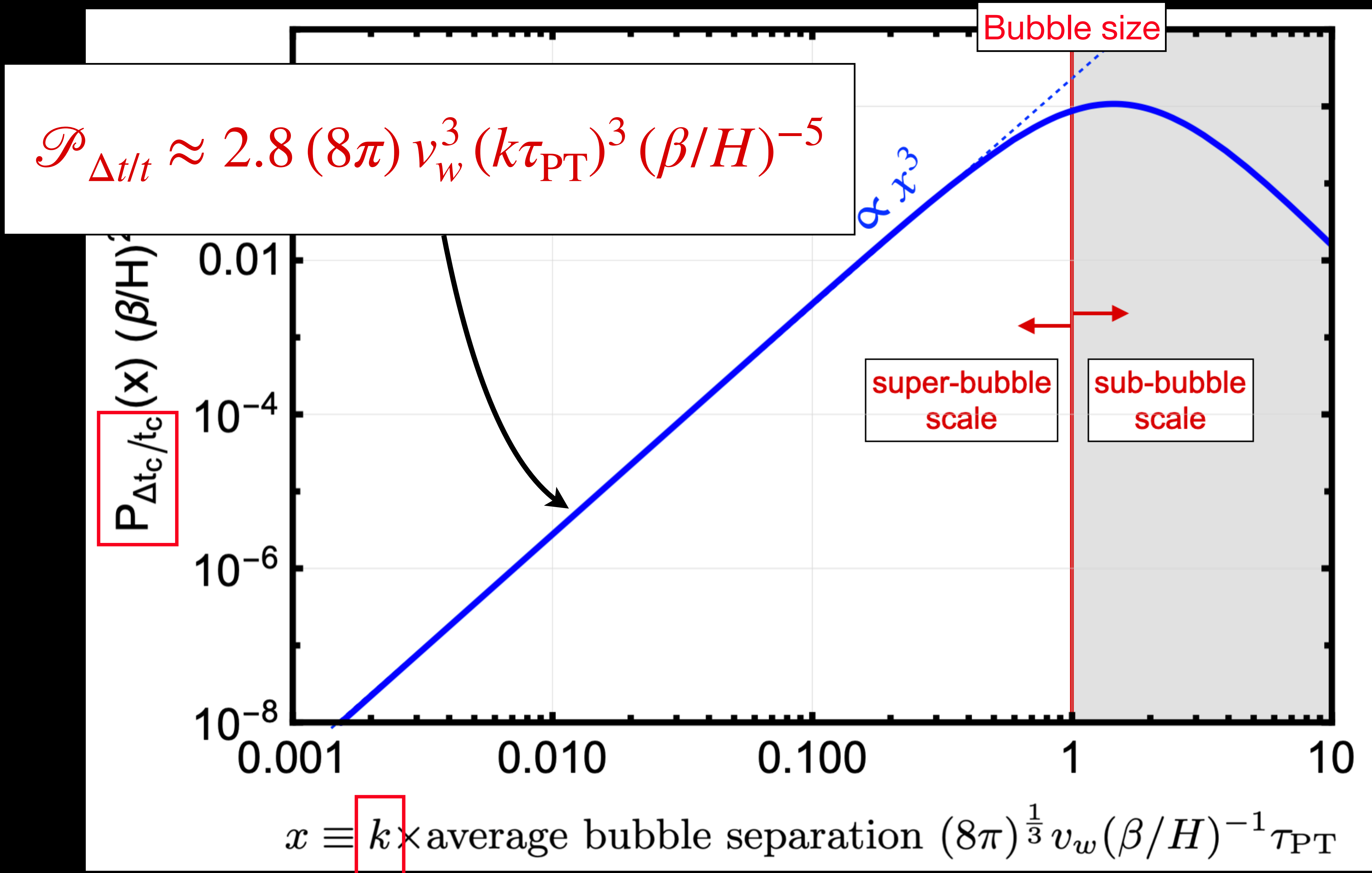
The power-law dependence can be explained by simple statistical fluctuation $\approx 1/\sqrt{N_{\rm bubbles}}$



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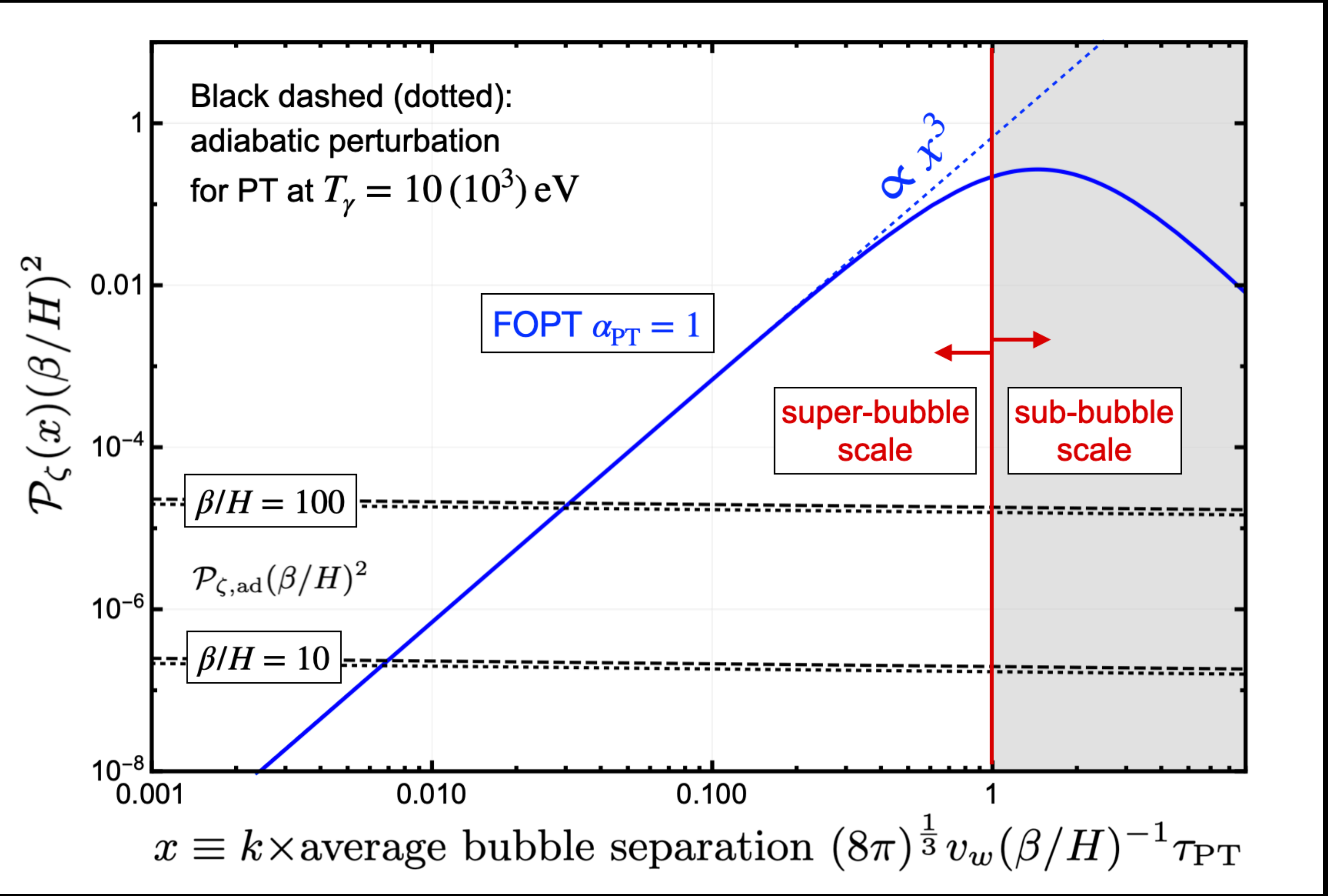
PT-time fluctuations + redshift differences between dark radiation and vacuum energy convert isocurvature into curvature perturbations

$$\mathscr{P}_{\zeta}(k) = f_{\rm DR}^2 \mathscr{P}_{\Delta t/t}(k) + \mathscr{P}_{\rm ad}(k)$$

$$\mathscr{P}_{\Delta t/t} \approx 3(8\pi)\, v_w^3\, (k\tau_{\rm PT})^3\, (\beta/H)^{-5}$$



10

Cosmological Constraints

"Late": $T_{\rm SM} \sim$ eV to GeV

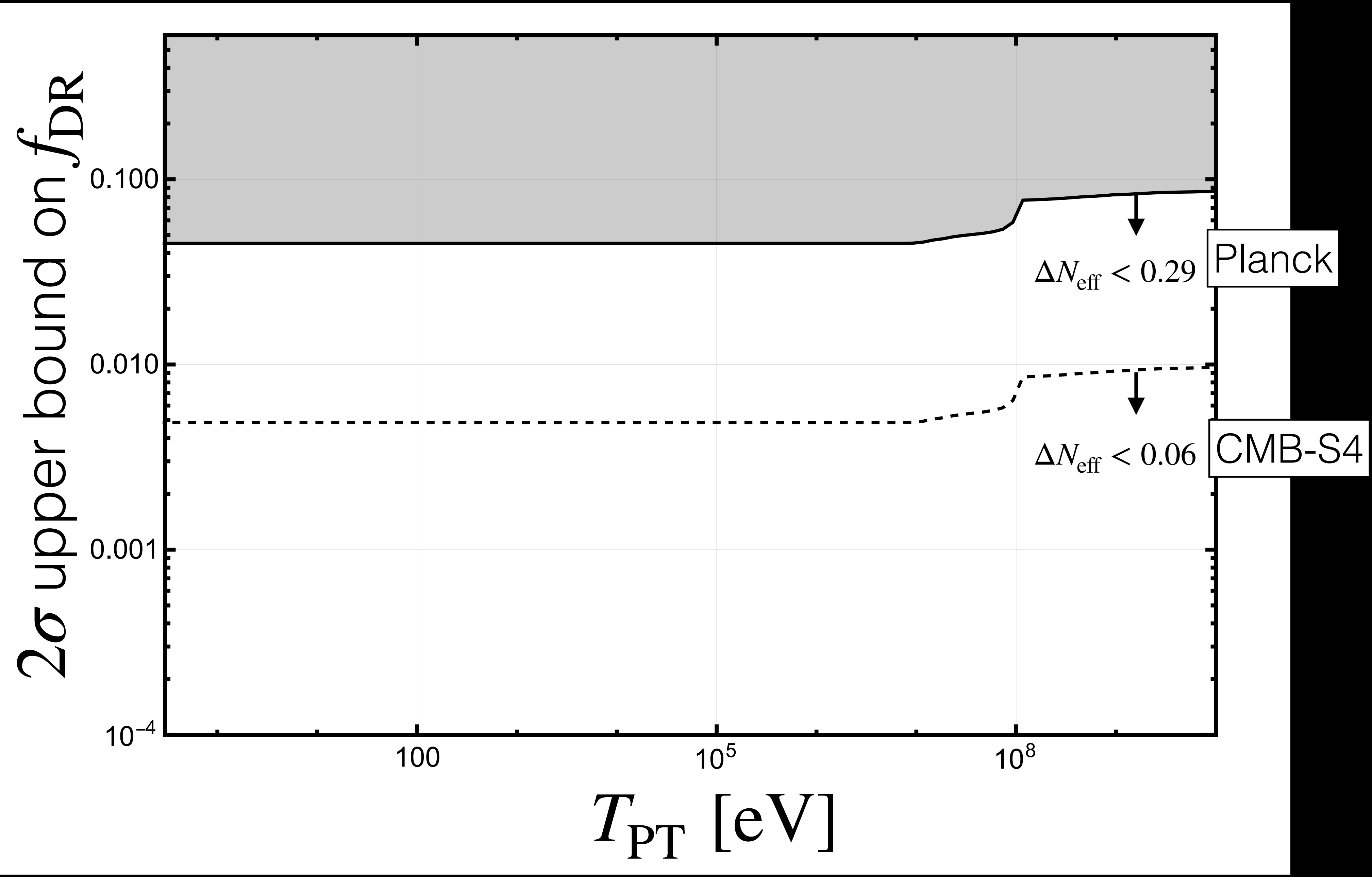
"Super-late": $z < 0.3$, dark energy domination

Let's start from "late"

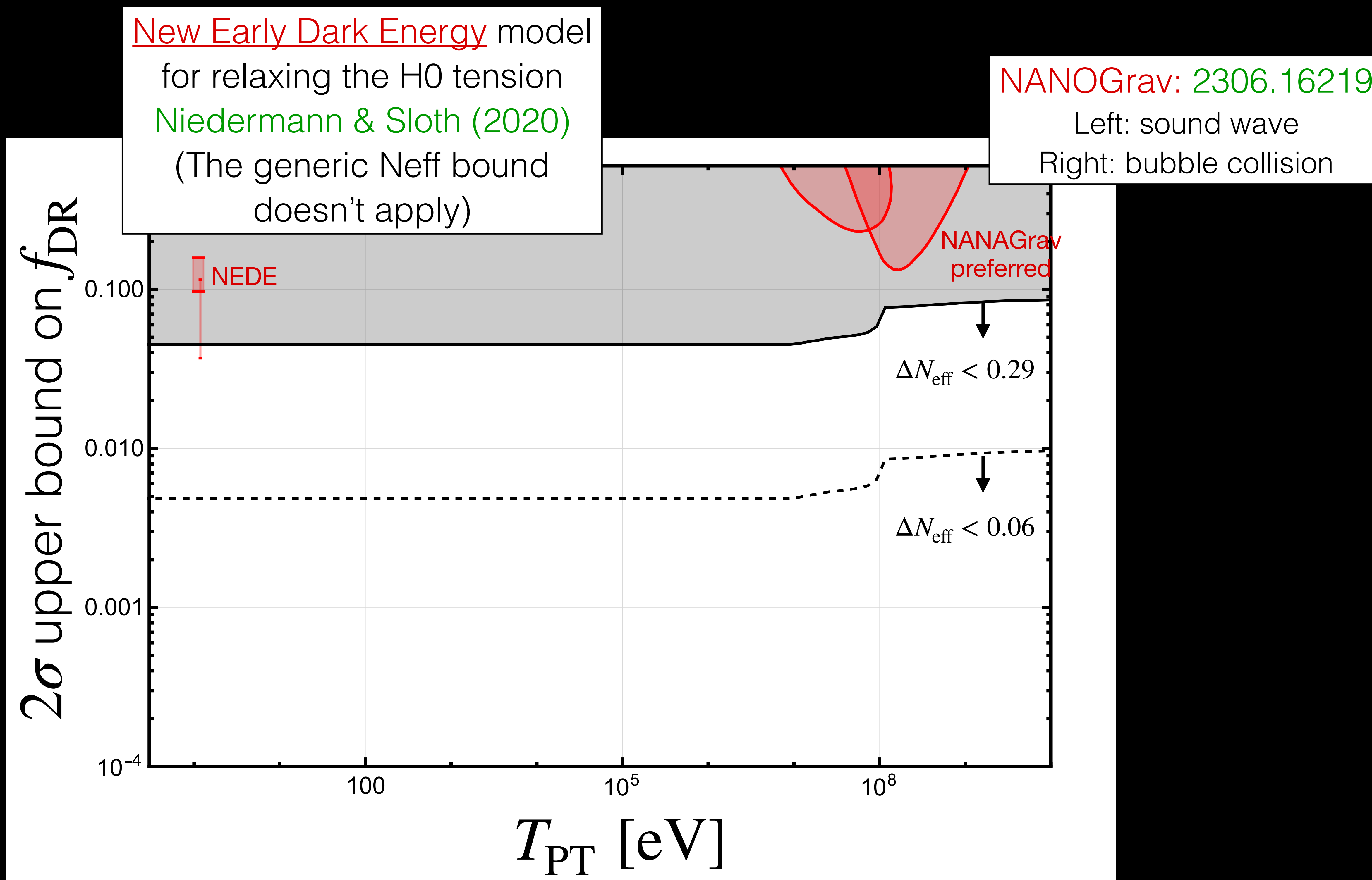
"Late": $T_{\rm SM} \sim$ eV to GeV

"Super-late": $z < 0.3$, dark energy domination

Explore $f_{\rm DR}$ bound/sensitivity with PT temperature between eV and GeV $f_{\rm DR} = \rho_{\rm DR}/(\rho_{\rm DR} + \rho_{\rm SM})$

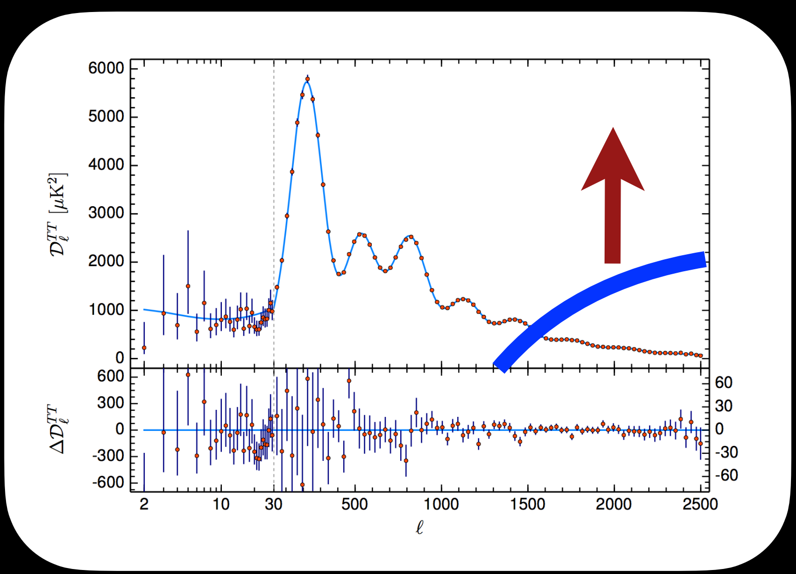


Some motivations of FOPT in the temperature window



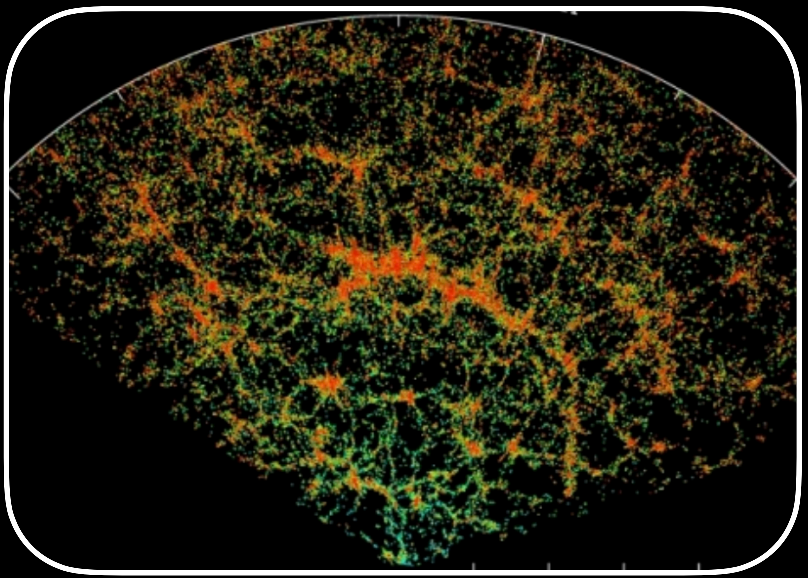
Phase transition curvature perturbation modifies various cosmological signals

Changes CMB fluctuations



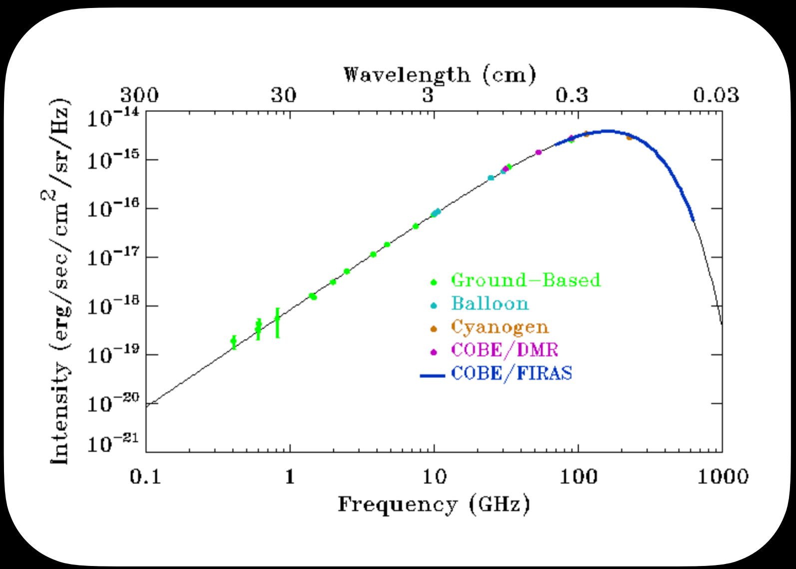
Enhance CMB power spectrum with a well-predicted spectral shape

Modifies structure formation



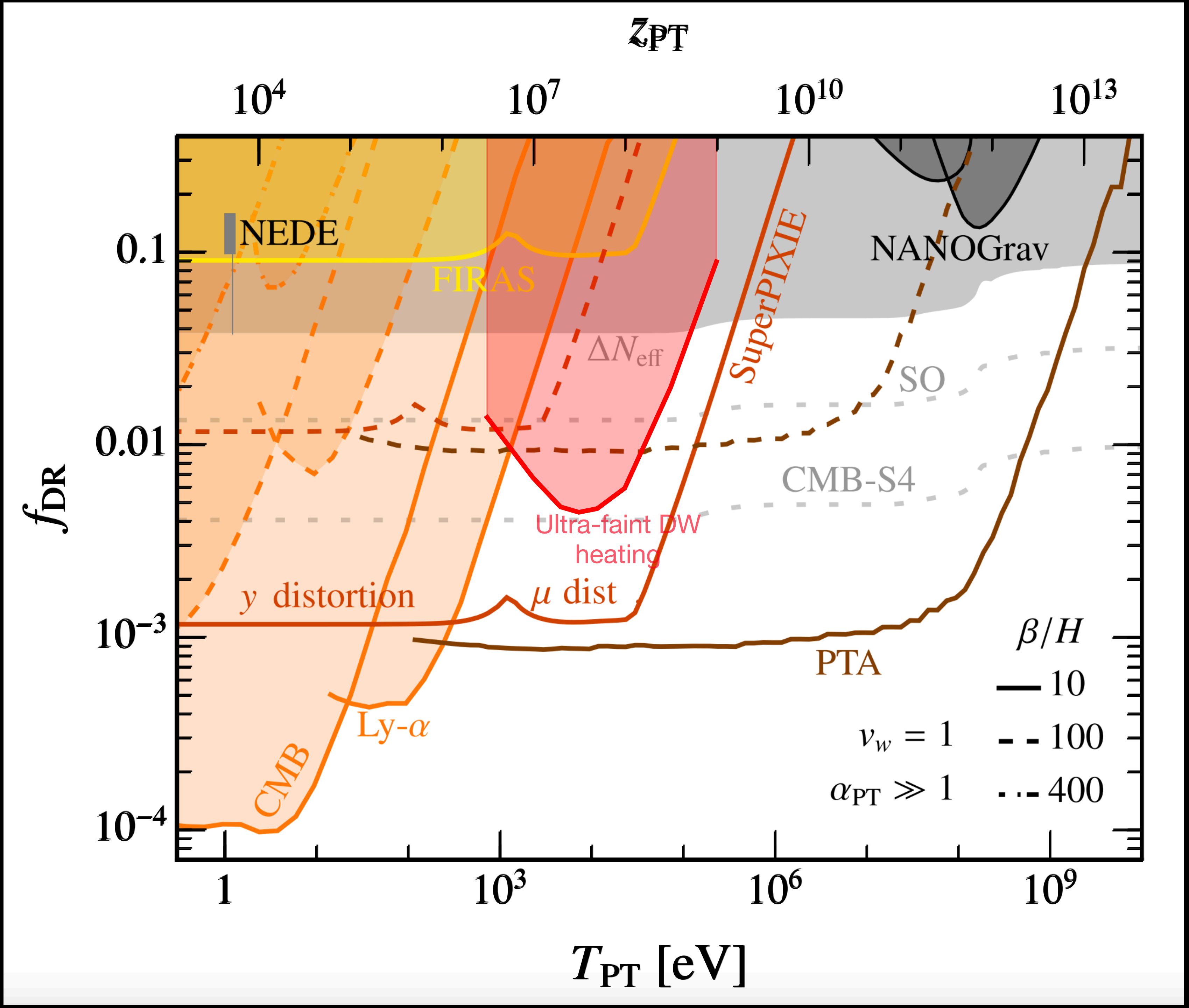
Enhance DM perturbations, produce more DM clumps

Distort CMB's blackbody spectrum



Temperature fluctuations disrupt photons' blackbody spectrum

Current (color-filled) and future sensitivity (2σ)



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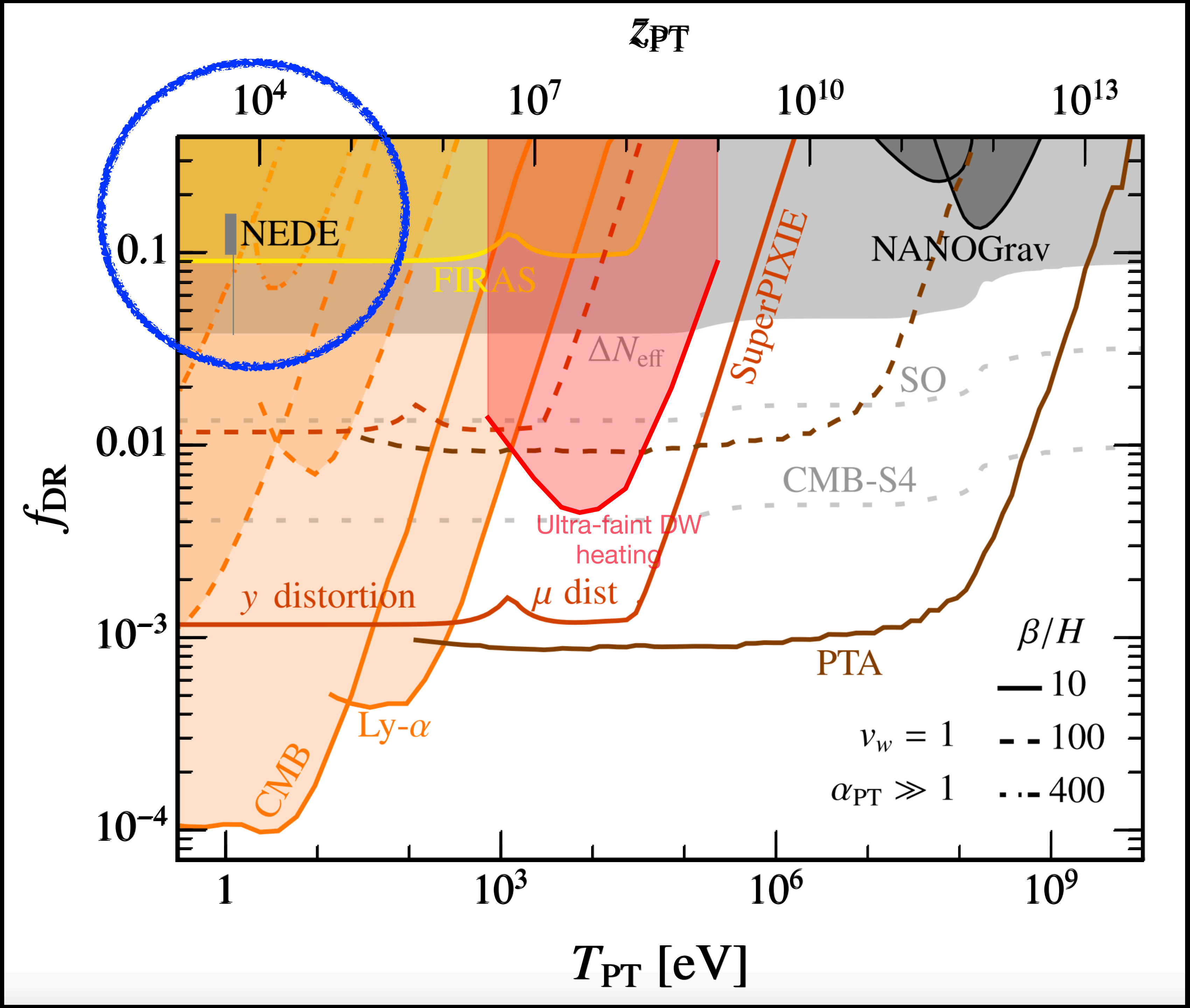
NEDE model needs to consider phase transition with $\beta/H > 400$

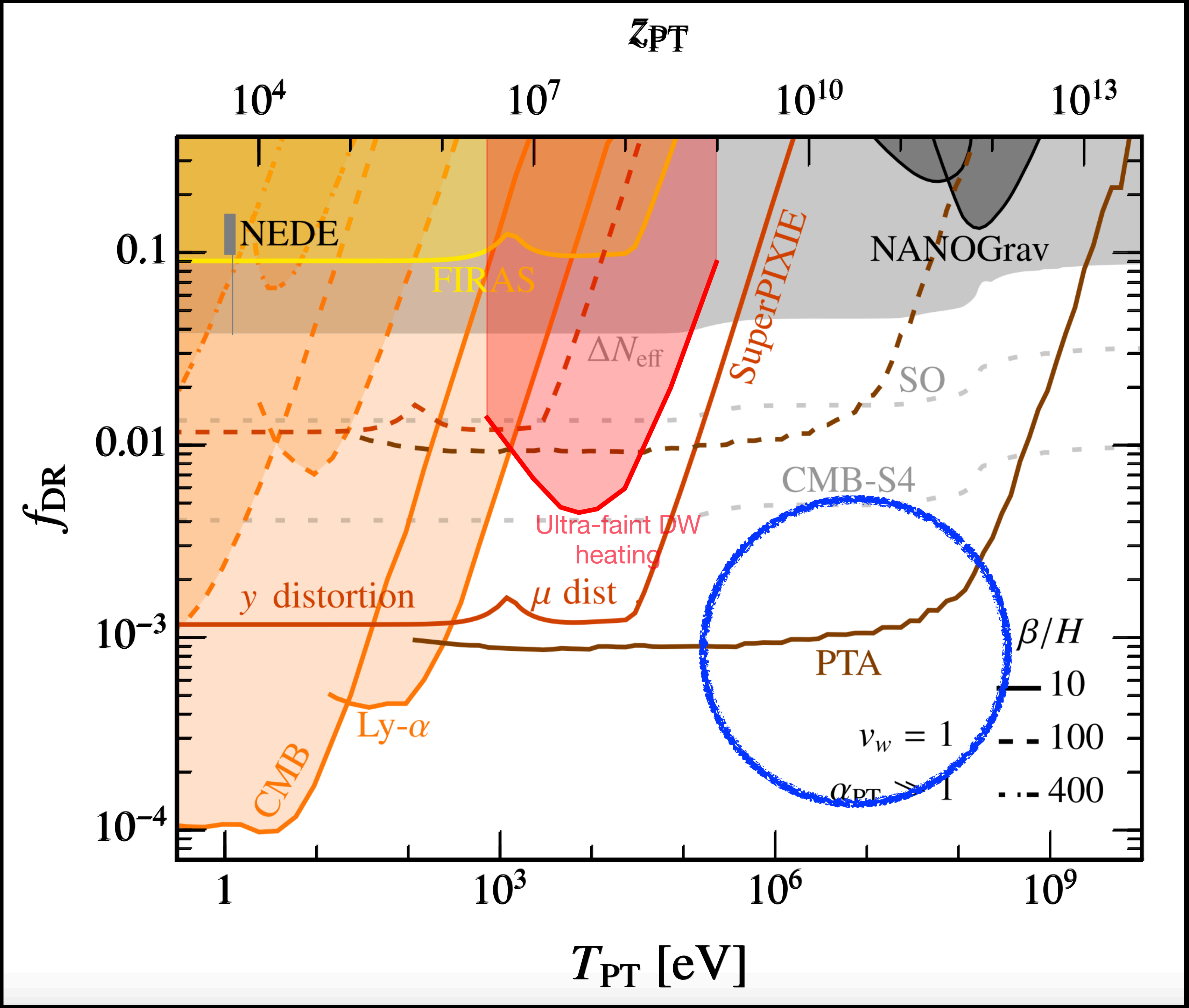
(Niedermann & Sloth (2020) does consider large β/H with a trigger field)



Future **Pulsar Timing Array** measurement of DM clumps

Lee, Mitridate, Trickle, Zurek (2012): may provide a cross check of the PTA GW from PT

Allali, Jungkind, Tsai, Yang (in progress)



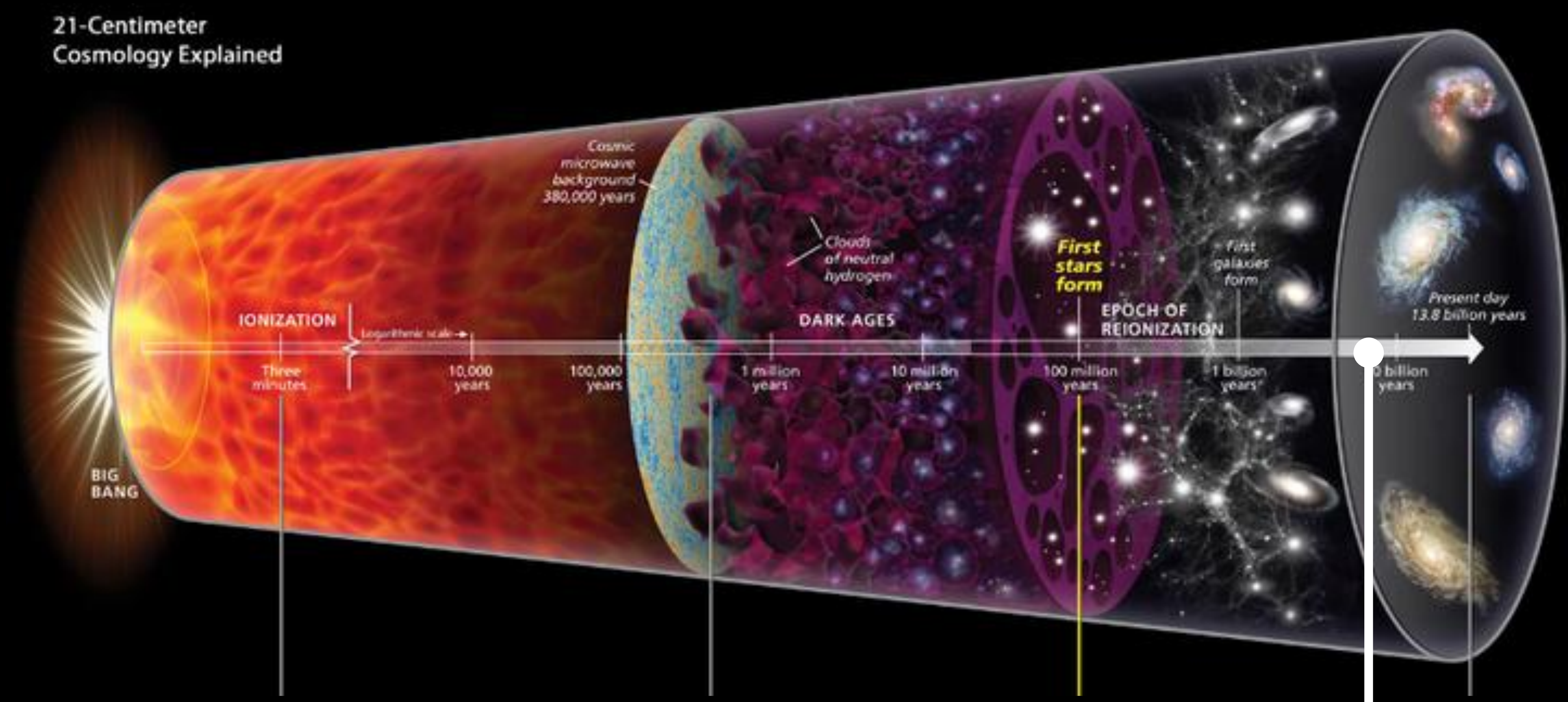
What about a "super-late" FOPT?

"Late": $T_{\rm SM} \sim$ eV to GeV

"Super-late": $z < 0.3$, dark energy domination

Seth Koren, YT, Runquing Wang (2509.07076)

When the Universe was dominated by vacuum energy (dark energy, DE), in the last few billion years, it is plausible that the field associated with the DE underwent a phase transition, tunneling to a lower energy vacuum



If FOPT happens at the DE-dominant era, how can we see it?

One thing this super late FOPT can do, is to modify the Hubble expansion

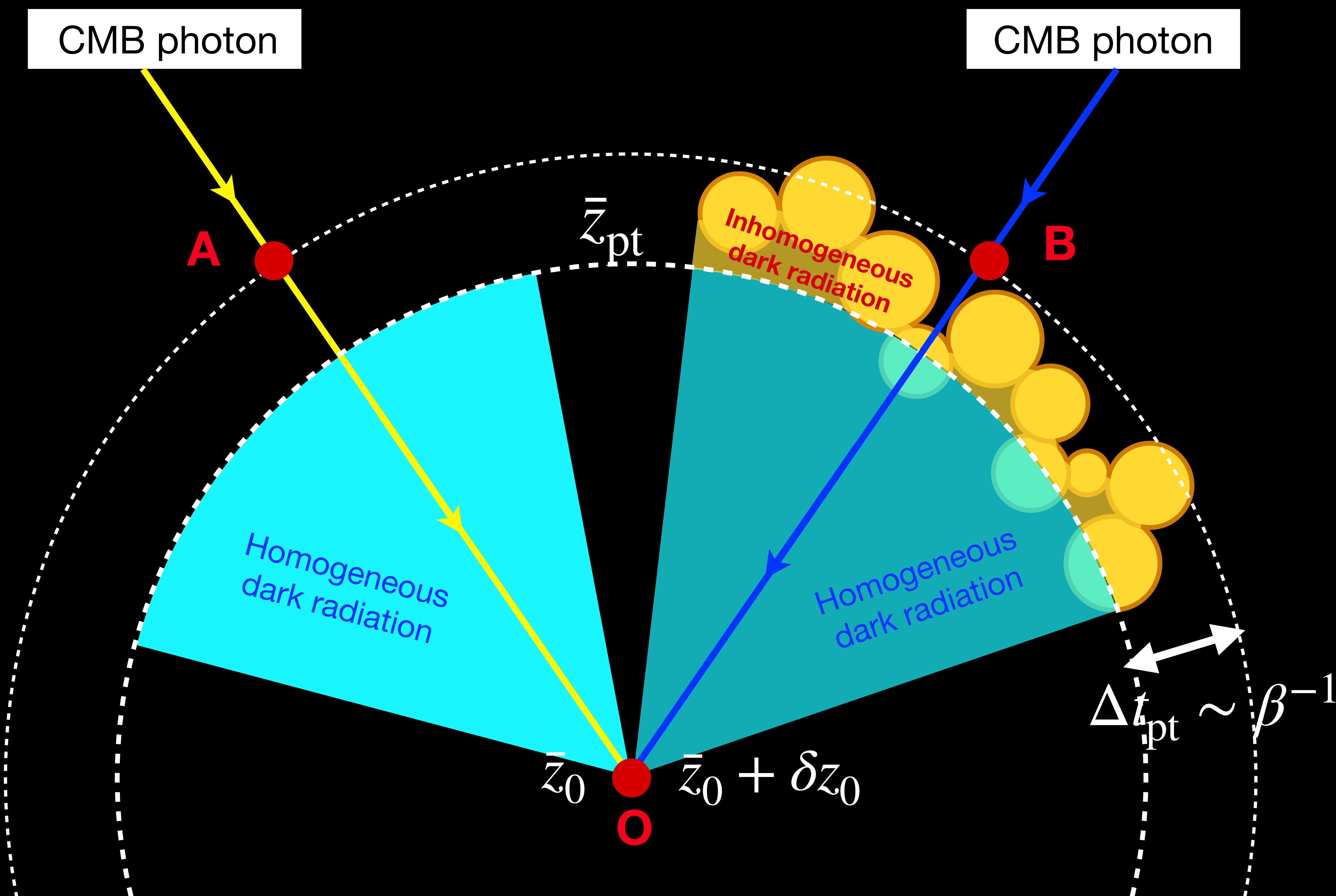
Assuming a fraction r of dark energy went into dark radiation

$$H_{\rm pt}(z, z_{\rm pt}, r) = H_0 \sqrt{\Omega_\Lambda(1-r) + r\,\Omega_\Lambda \left(\frac{1+z}{1+z_{\rm pt}}\right)^4 + \Omega_m(1+z)^3}$$

Hubble expansion slows down due to the redshift of dark radiation energy

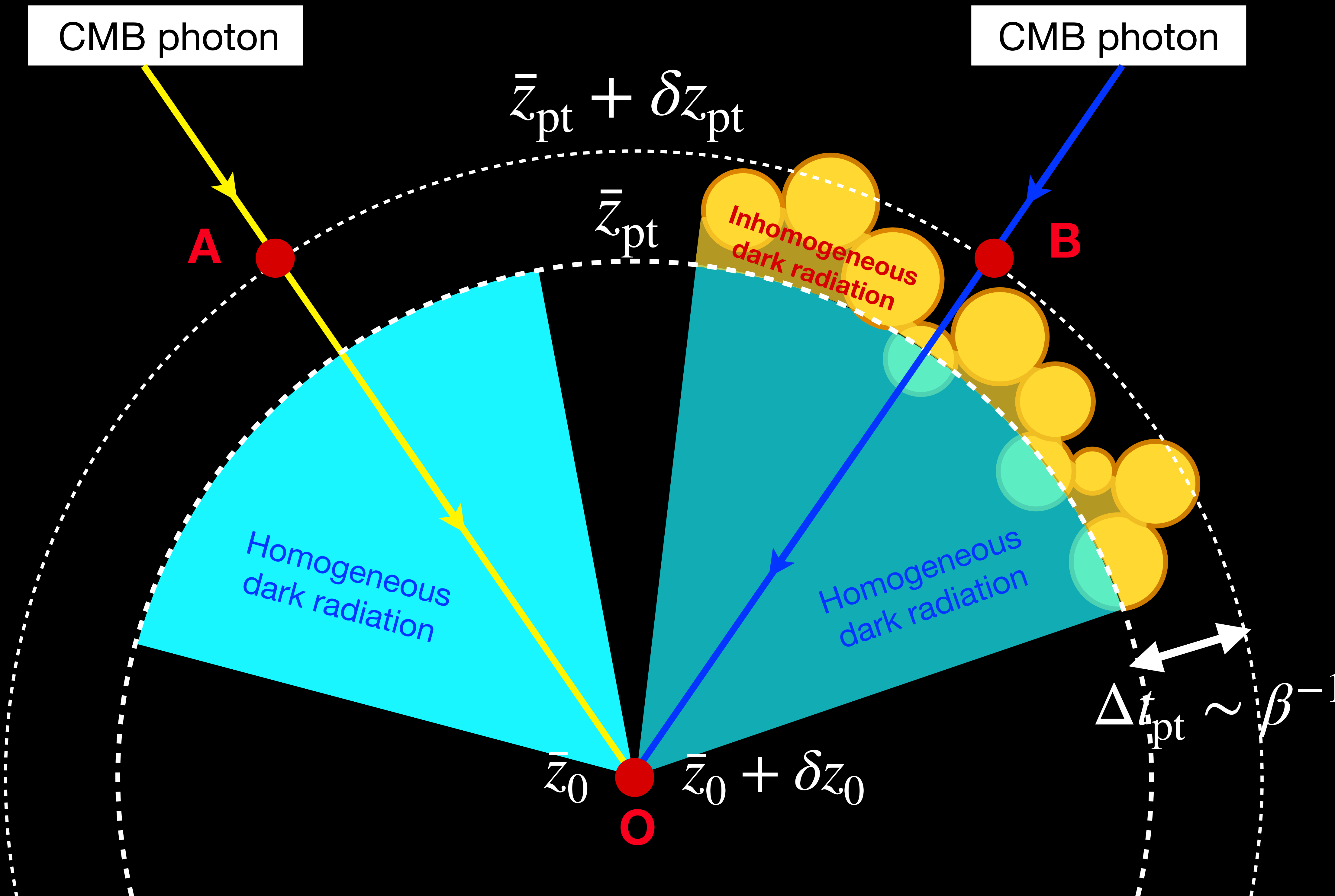
However, constraints on such late time Hubble expansion is quite weak, only sensitive to r more than about 65%

Use what we've learned: FOPT generate perturbations, cosmo observations are good at probing perturbations!



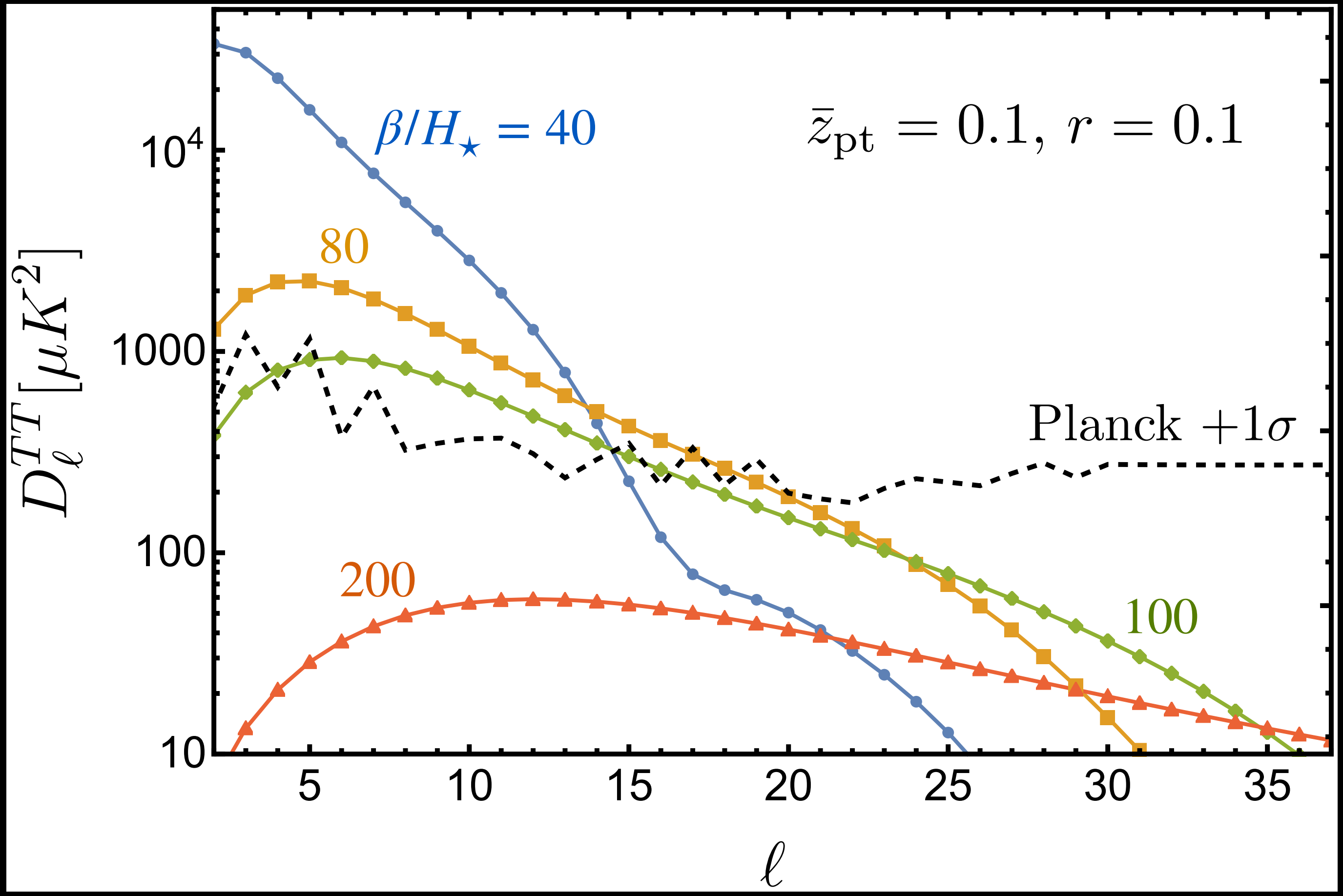
Comoving time (independent of cosmic expansion) remains

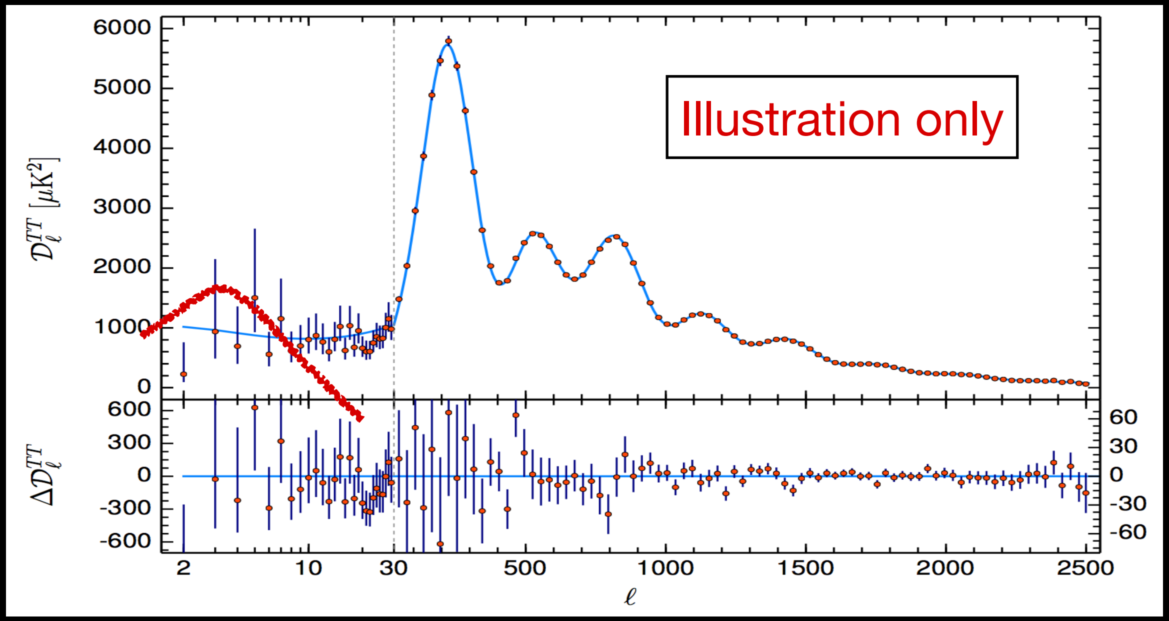
the same $\chi_{AO}\Big|_{0}^{\bar{z}_{\rm pt}+\delta z_{\rm pt}} = \chi_{BO}\Big|_{\delta z_0}^{\bar{z}_{\rm pt}+\delta z_{\rm pt}}$



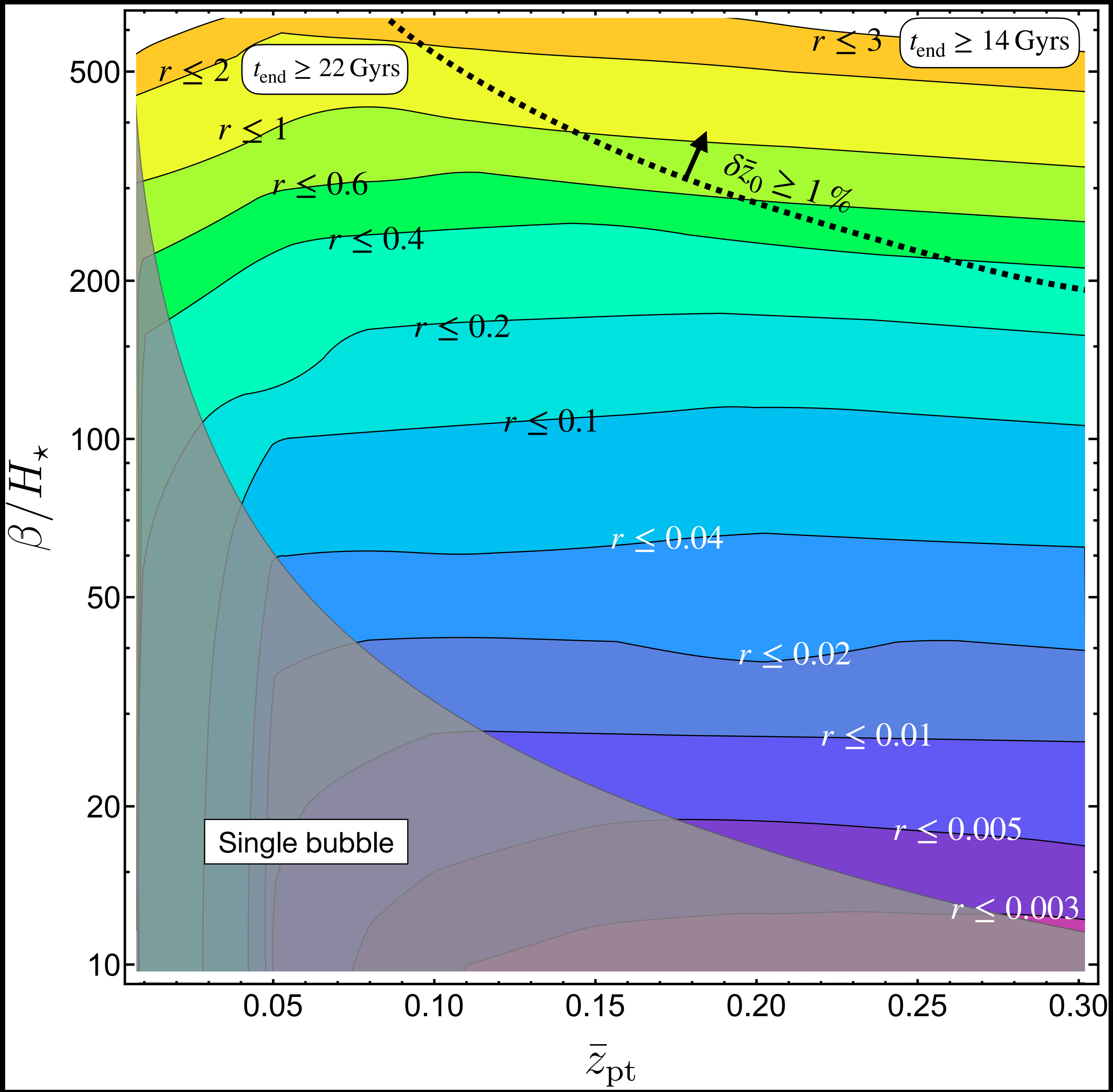
Once solving the fluctuations in the final photon redshift δz_0, we can compute the resulting contribution to the CMB power spectrum (similar to the Sachs-Wolfe effect)

Signals from FOPT





Existing upper bounds on the fraction of dark energy r that can go into dark radiation



$r > 1$ means the Universe would eventually transition into an anti–de Sitter phase and begin to contract. Our bounds indicate that this could only occur at least about 10 billion years from now

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About the tensor mode perturbations

$$d\ell^2 = a(t)^2\left[(1+\zeta)\,\delta_{ij} + h_{ij}\right] dx_i\, dx_j$$

background expansion

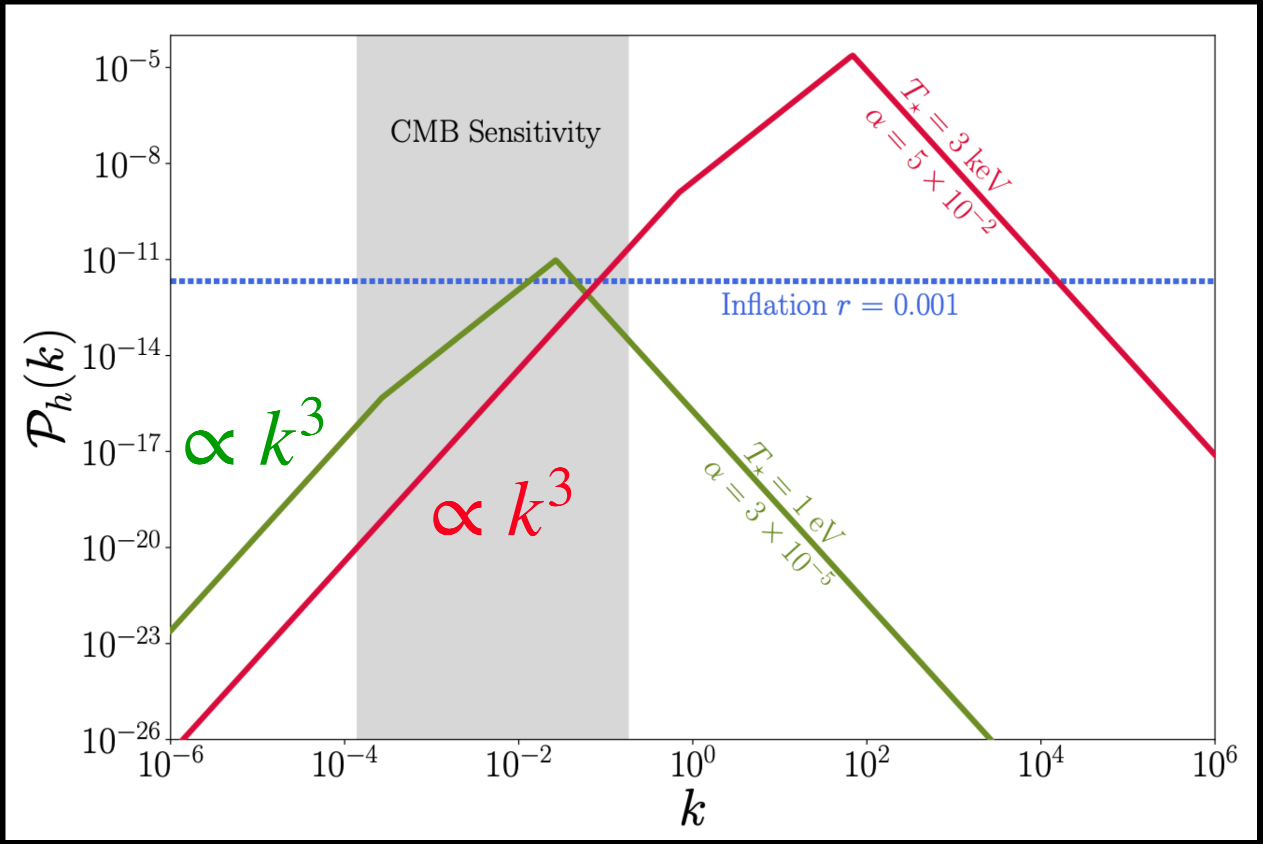
scalar perturbation

tensor perturbation

Kylar Green, Aurora Ireland, Gordan Krnjaic, YT (2410.23348)

Similar method as scalar perturbation

gives tensor power spectrum e.g., Jinno & Takimoto (2016)



$$\mathscr{P}_h(k) \propto \langle \Pi_{ij}(k)\, \Pi^*_{ij}(k) \rangle$$

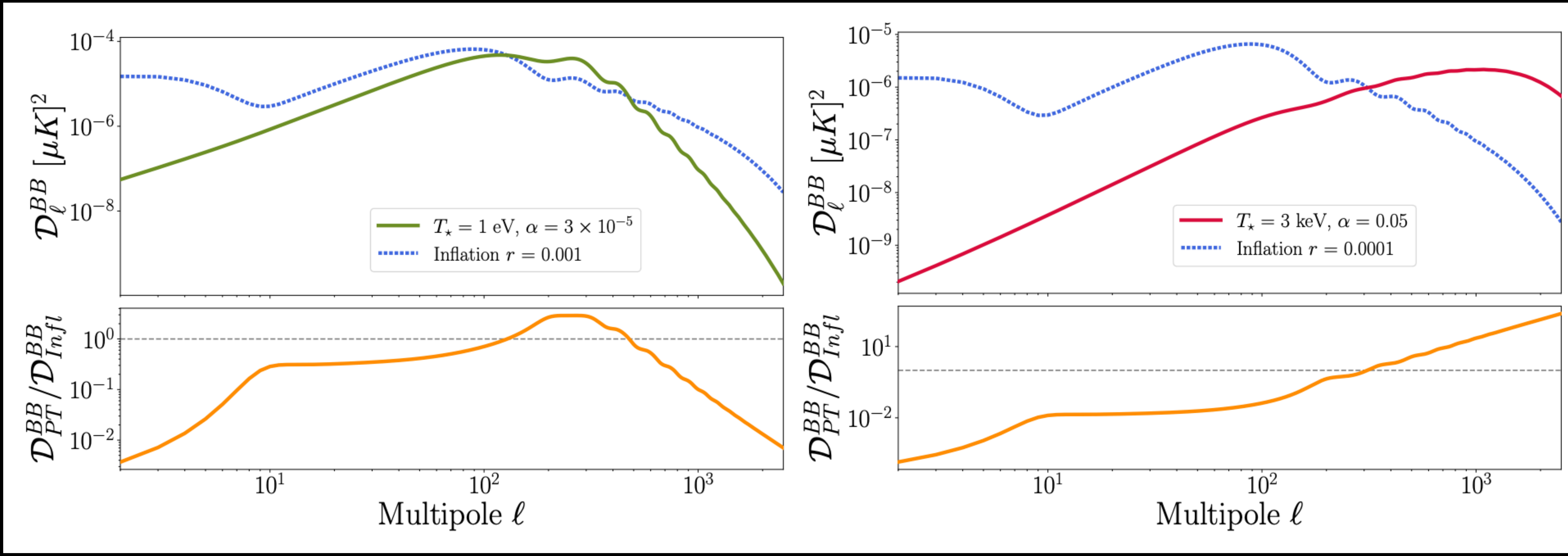
Green, Ireland, Krnjaic, **YT** (2024)

During PT $$h''_{ij} + 2\mathscr{H} h'_{ij} + k^2 h_{ij} = 8\pi G a^2 \Pi_{ij}$$

Right after PT $$h''_{ij} + 2\mathscr{H} h'_{ij} + k^2 h_{ij} = 0$$ *h* propagates after horizon entry

Tensor power spectrum generates CMB B-modes

$$C_\ell^{\rm BB} = 36\pi \int_0^\infty \frac{dk}{k} \mathscr{P}_h(k)\, F_\ell(k)^2$$

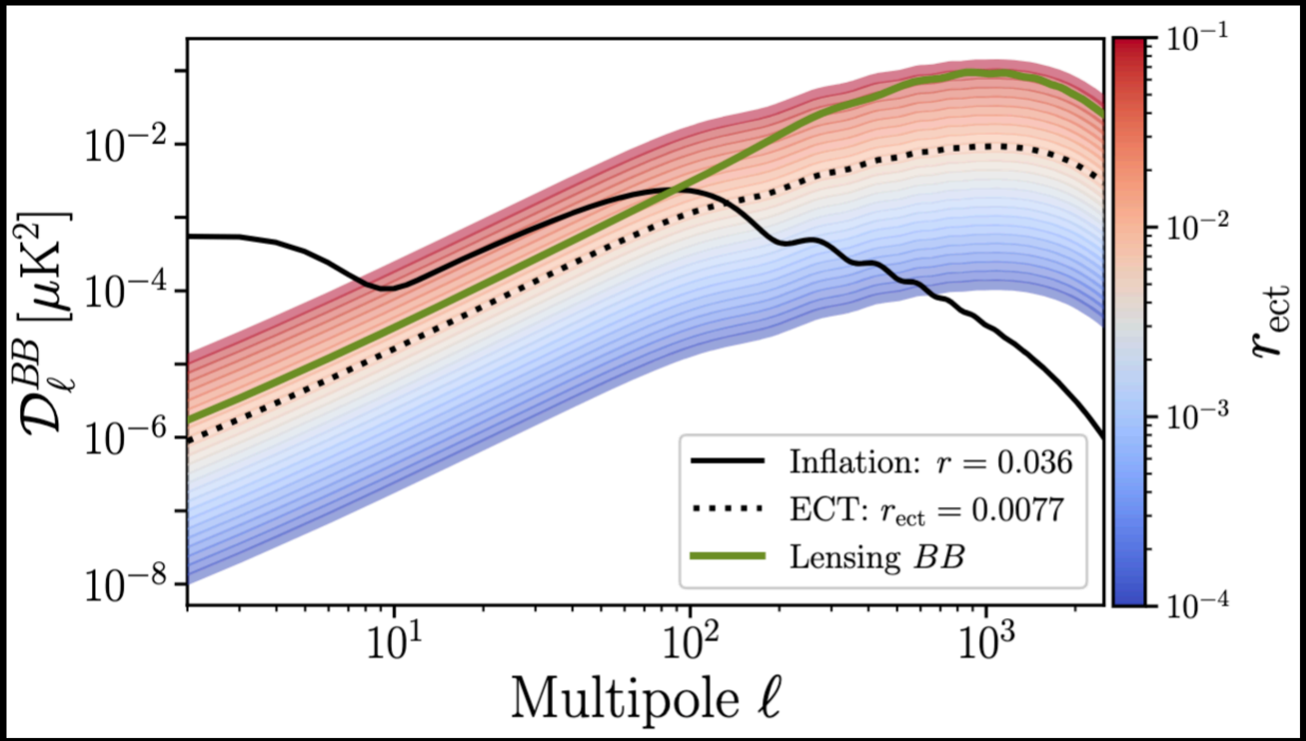


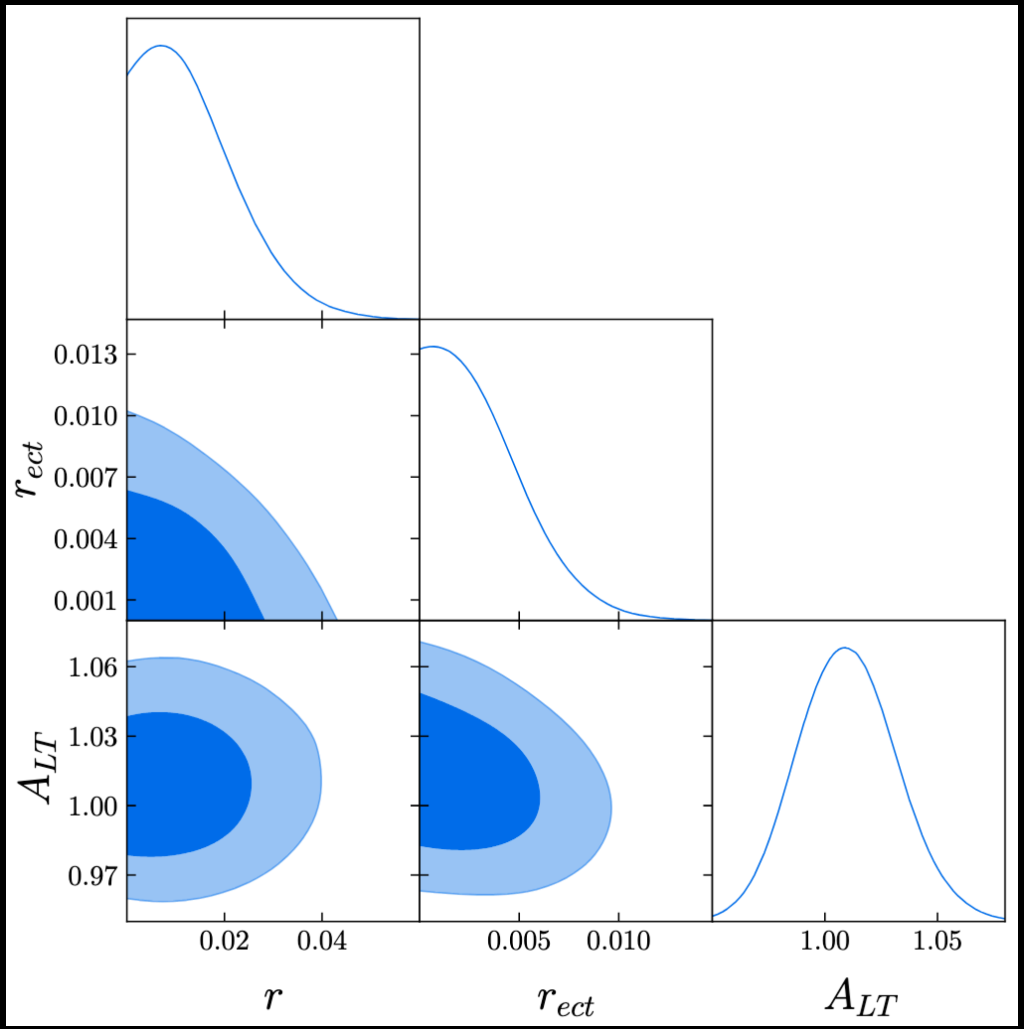
Can use a generic tensor power spectrum to parametrize any

Early Causal Tensor sources

(early sources turn on and off before the CMB-sensitive scale $z > 7 \times 10^4$)

$$\mathscr{P}_h(k) \equiv r_{\rm ect} A_s \left(\frac{k}{0.05\,\mathrm{Mpc}^{-1}} \right)^3$$





Can set an upper bound on $r_{\rm ect}$ with existing B-mode measurements (Zebrowski, Ireland, Reichardt, Greene, Krnjaic, YT, Bouchet to appear this week)

Summary

First order phase transition (FOPT) generates super-horizon scalar & tensor mode perturbations

Lead to much tighter constraints and future sensitivity to the phase transition signals, even if the FOPT solely exists in a dark sector

Future observation of FOPT is possible with both scalar and tensor-mode perturbations. (CMB anisotropy, Large Scale Structure, CMB energy spectrum)

There're many ways cosmology can probe new physics gravitationally. (Cosmic strings, domain walls, …) FOPT is only one example