Dark Radiation Isocurvature from Cosmological Phase Transitions

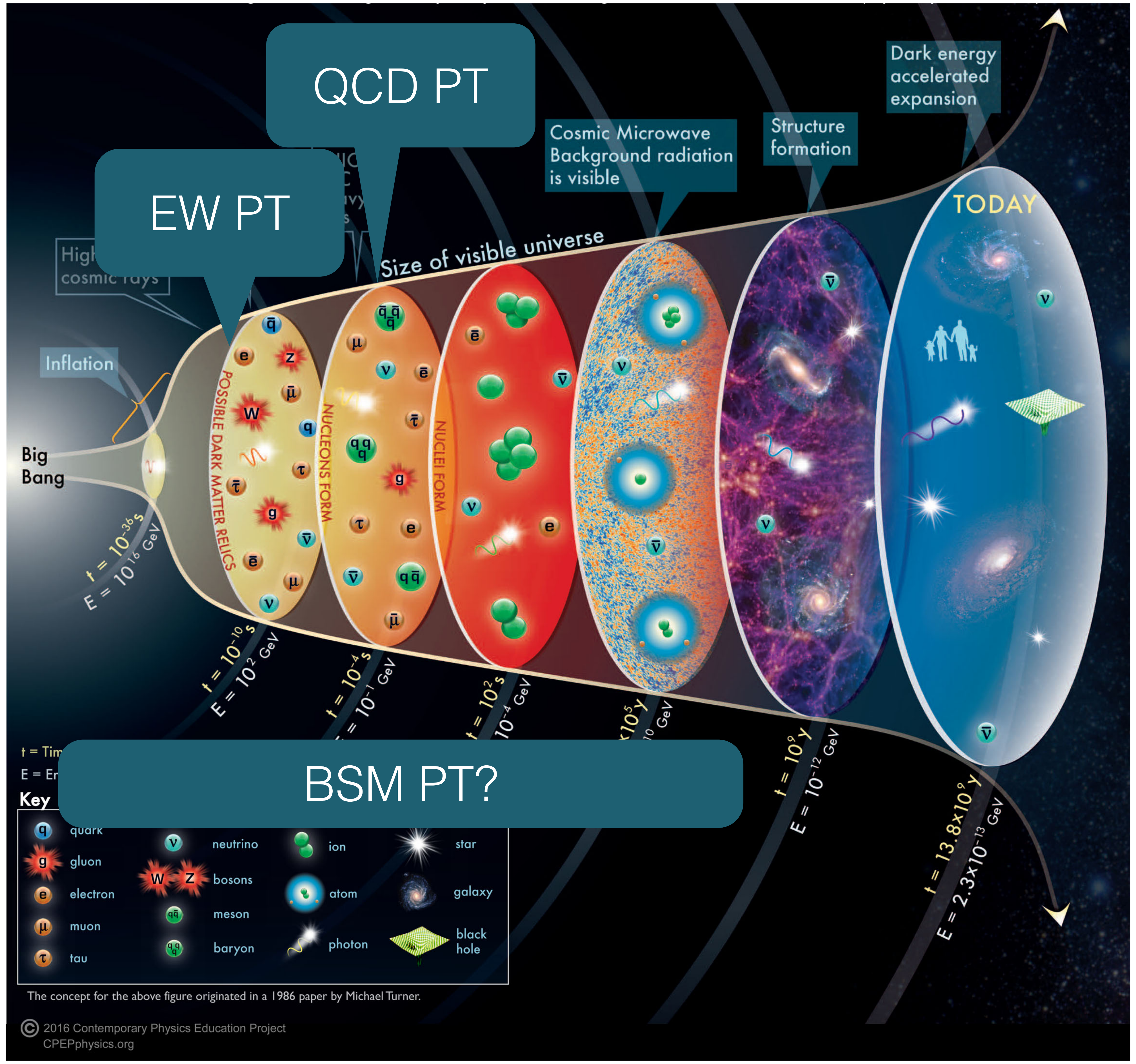
Peizhi Du
University of Science and Technology of China

The 2025 Beijing Particle Physics and Cosmology Symposium
September 28, 2025

in collaboration with Matthew Buckley, Nicolas Fernandez, Mitchell Weikert

(JCAP 07 (2024) 031)

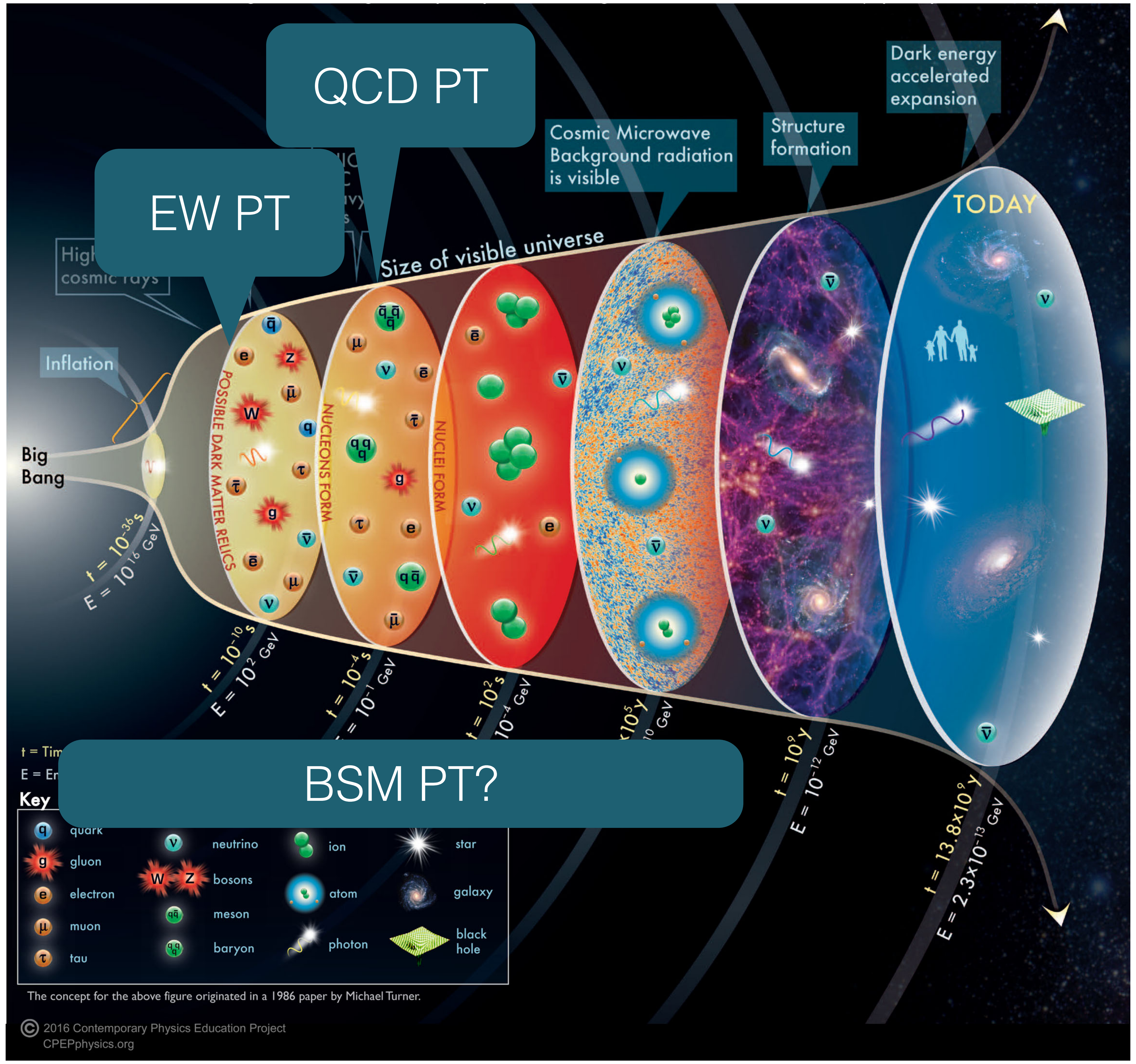
Cosmological Phase Transitons



Rich new physics:

baryogenesis, dark matter, EW hierarchy problem…

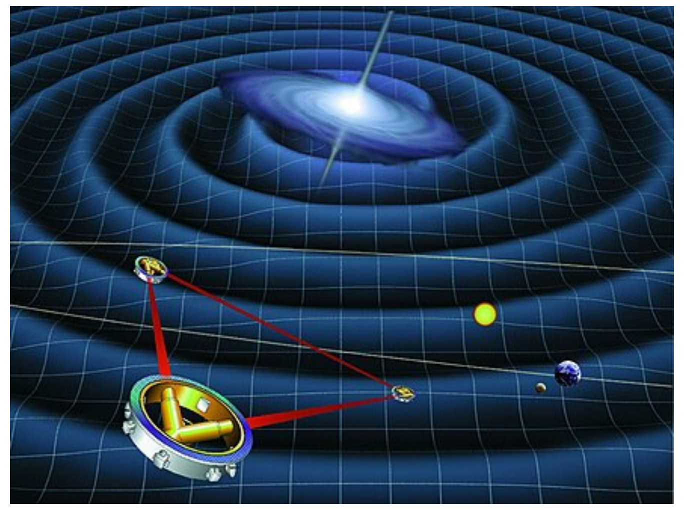
Cosmological Phase Transitons



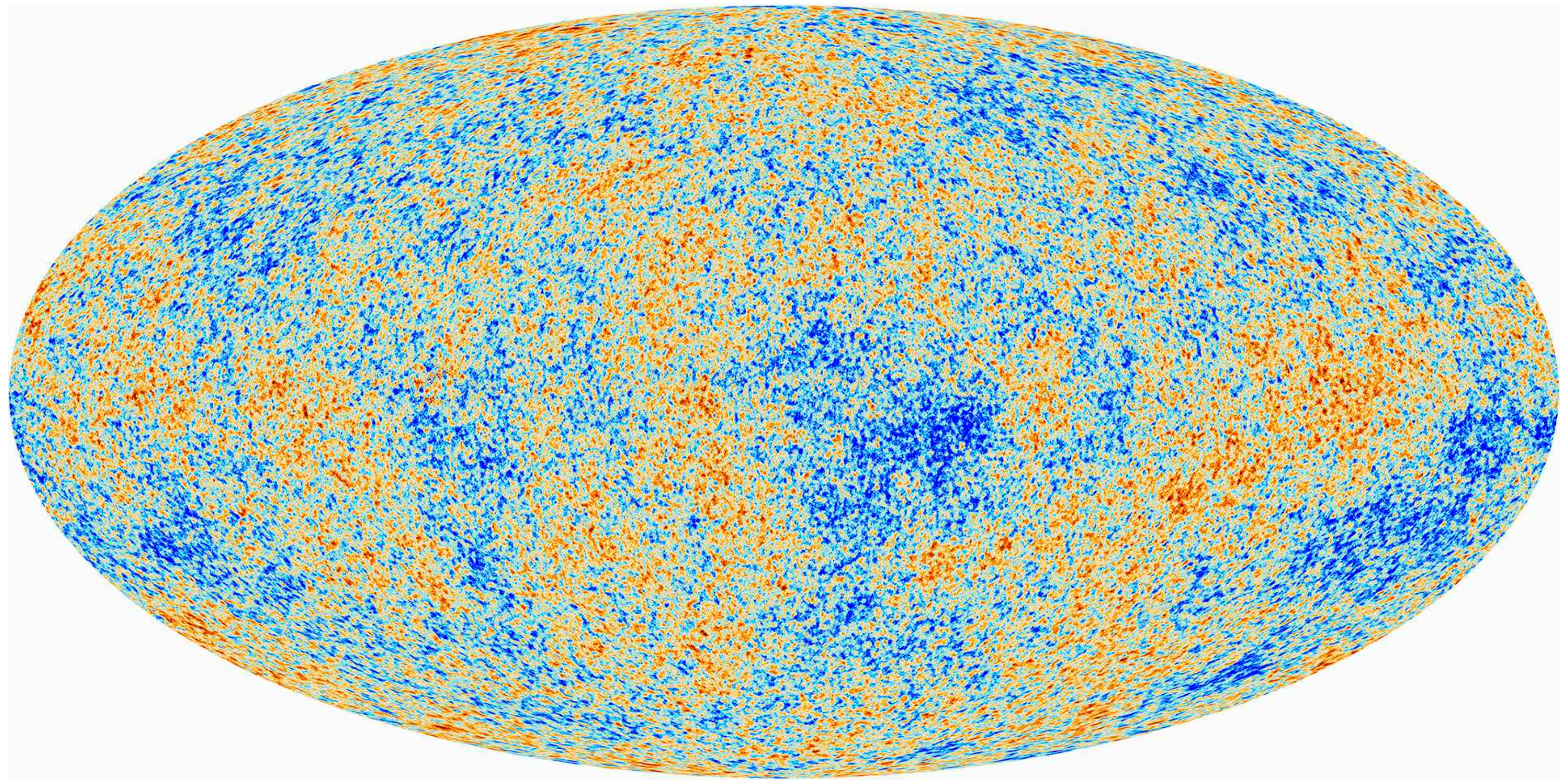
NANOGrav

PTA

LIGO



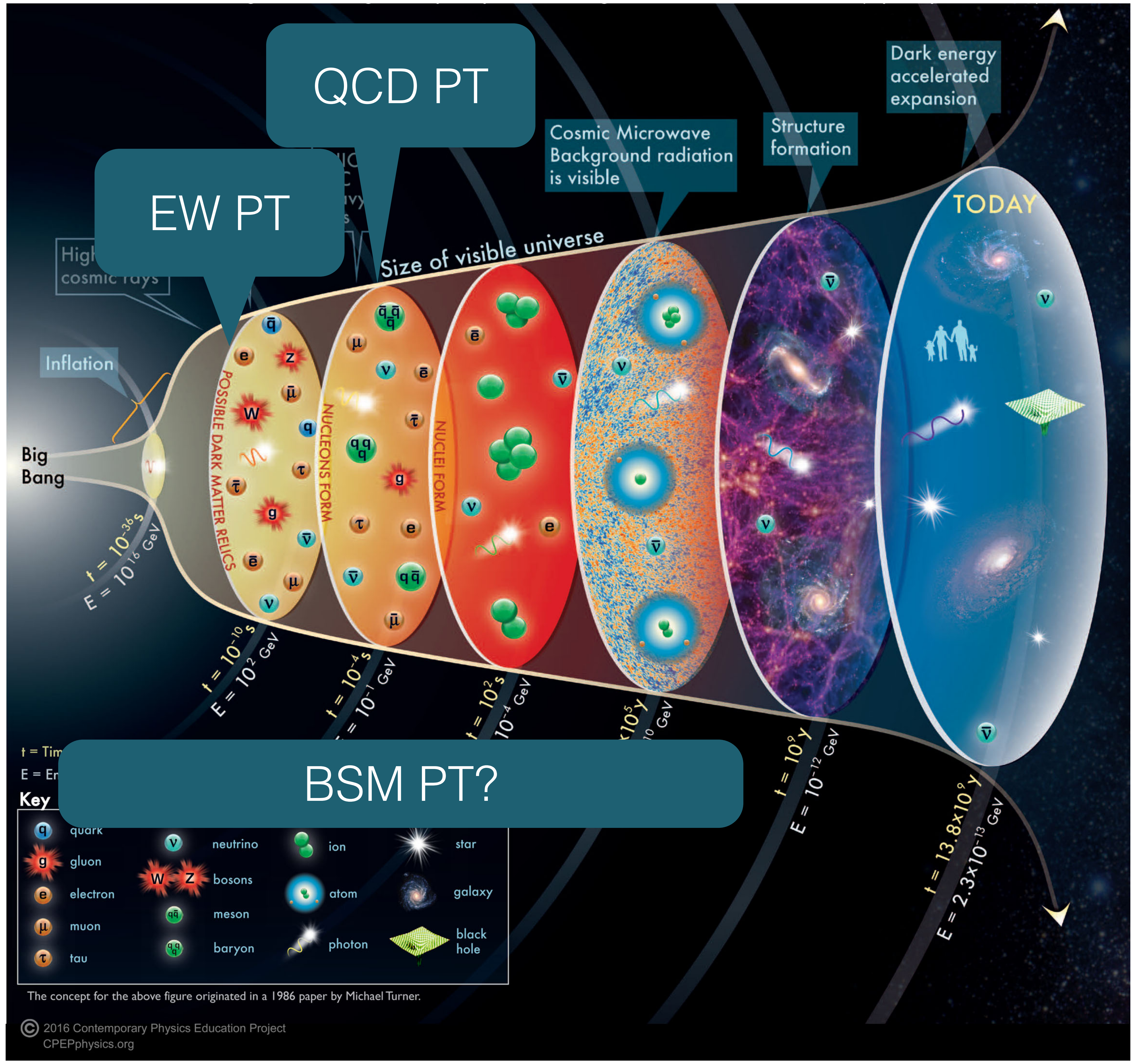
LISA



Rich new physics:
baryogenesis, dark matter, EW hierarchy problem…

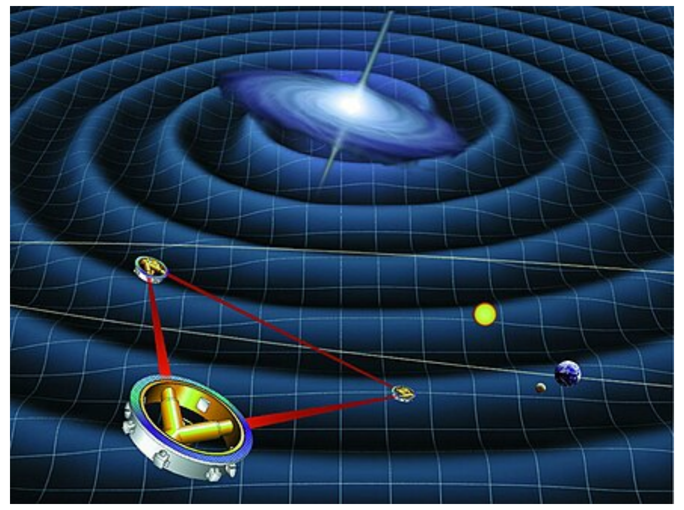
Exciting experimental probes:
GWs and CMB

Cosmological Phase Transitons

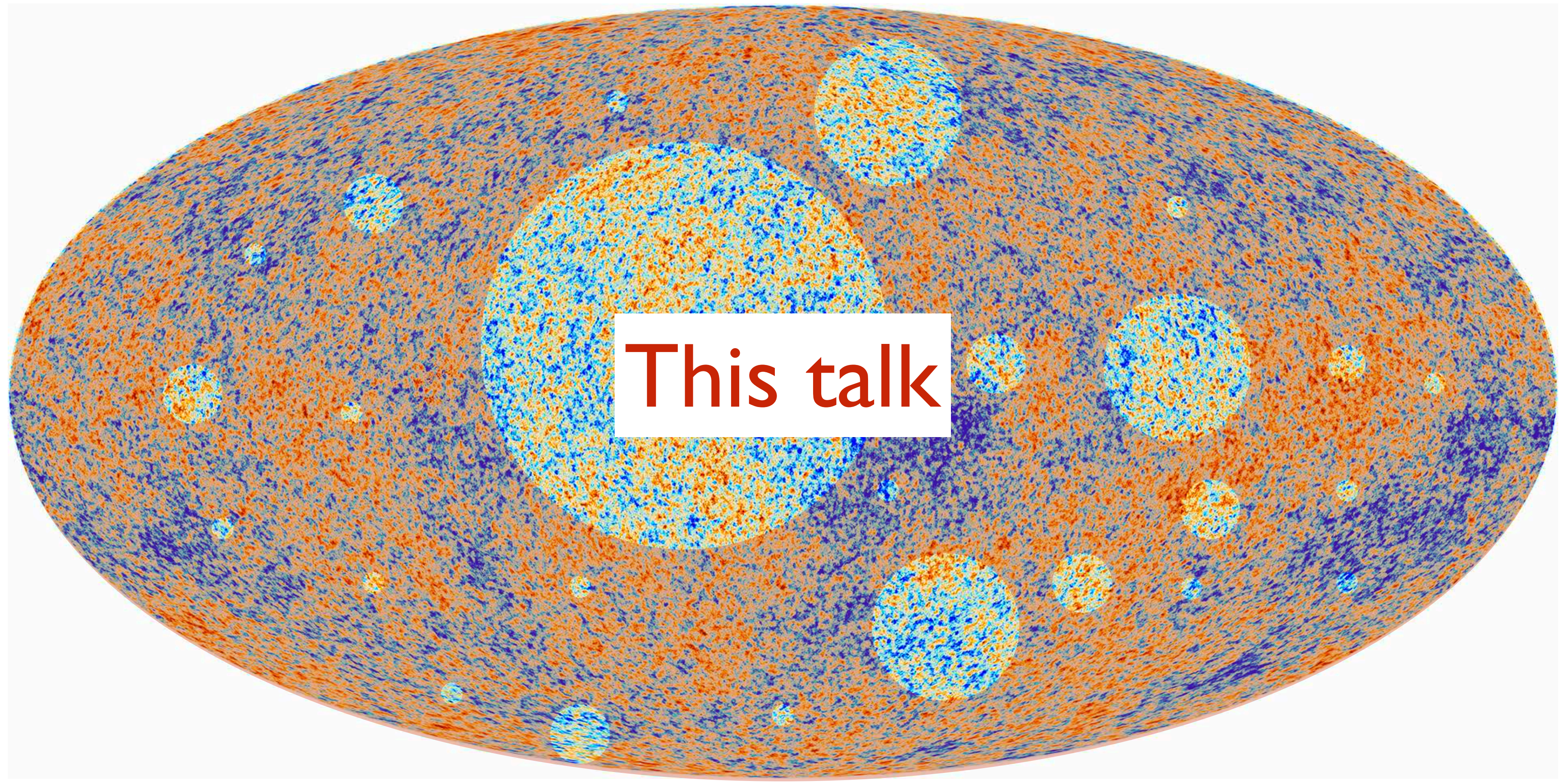


PTA

LIGO



LISA



Rich new physics:
baryogenesis, dark matter, EW hierarchy problem…

Exciting experimental probes:
GWs and CMB

Outline of the talk

- Signals from PT
- Slow PT during inflation and evolution of bubbles
- DR isocurvature from PT
- DR isocurvature in CMB

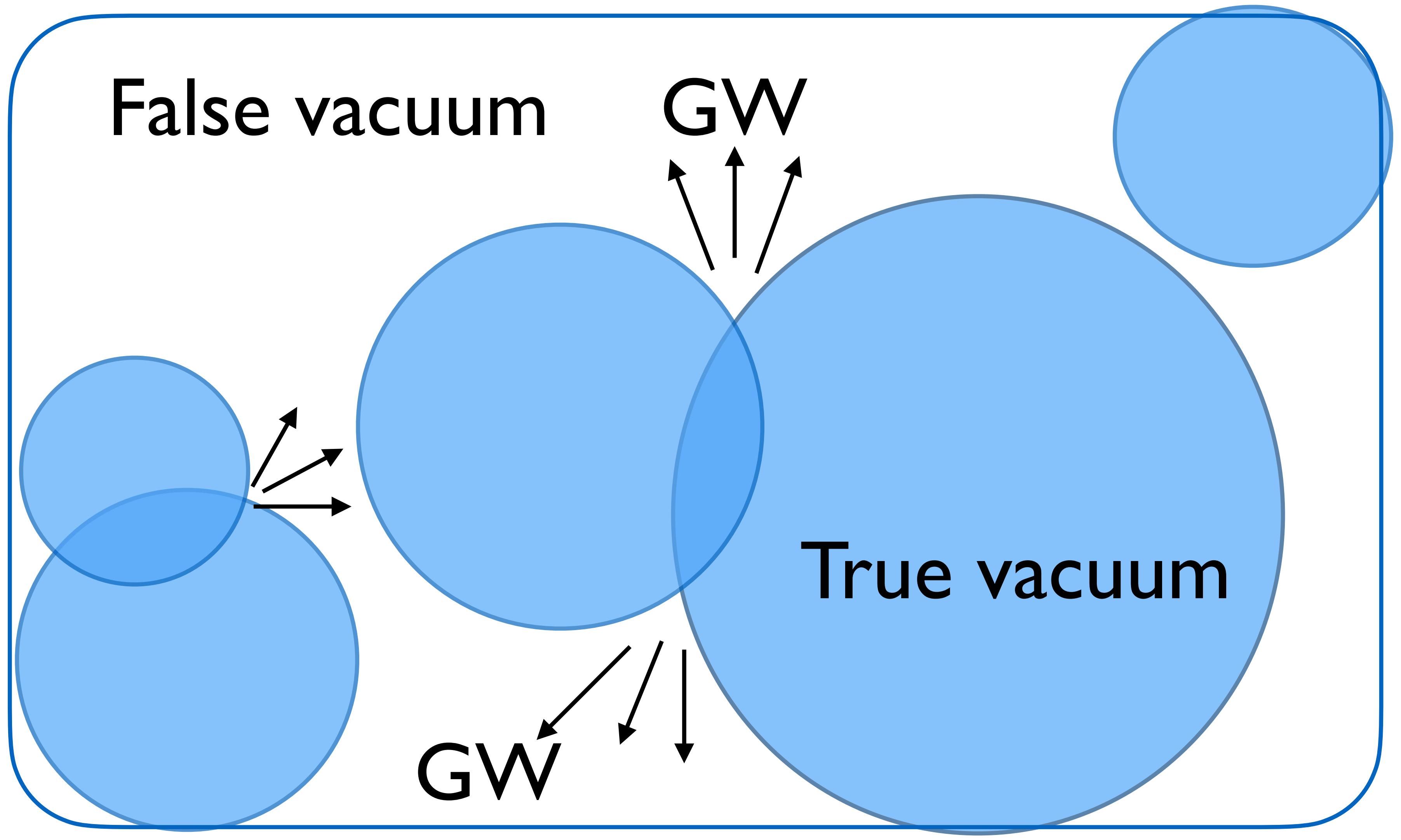
    Angular power spectrum

    Non-Gaussianity
- Future directions and conclusions

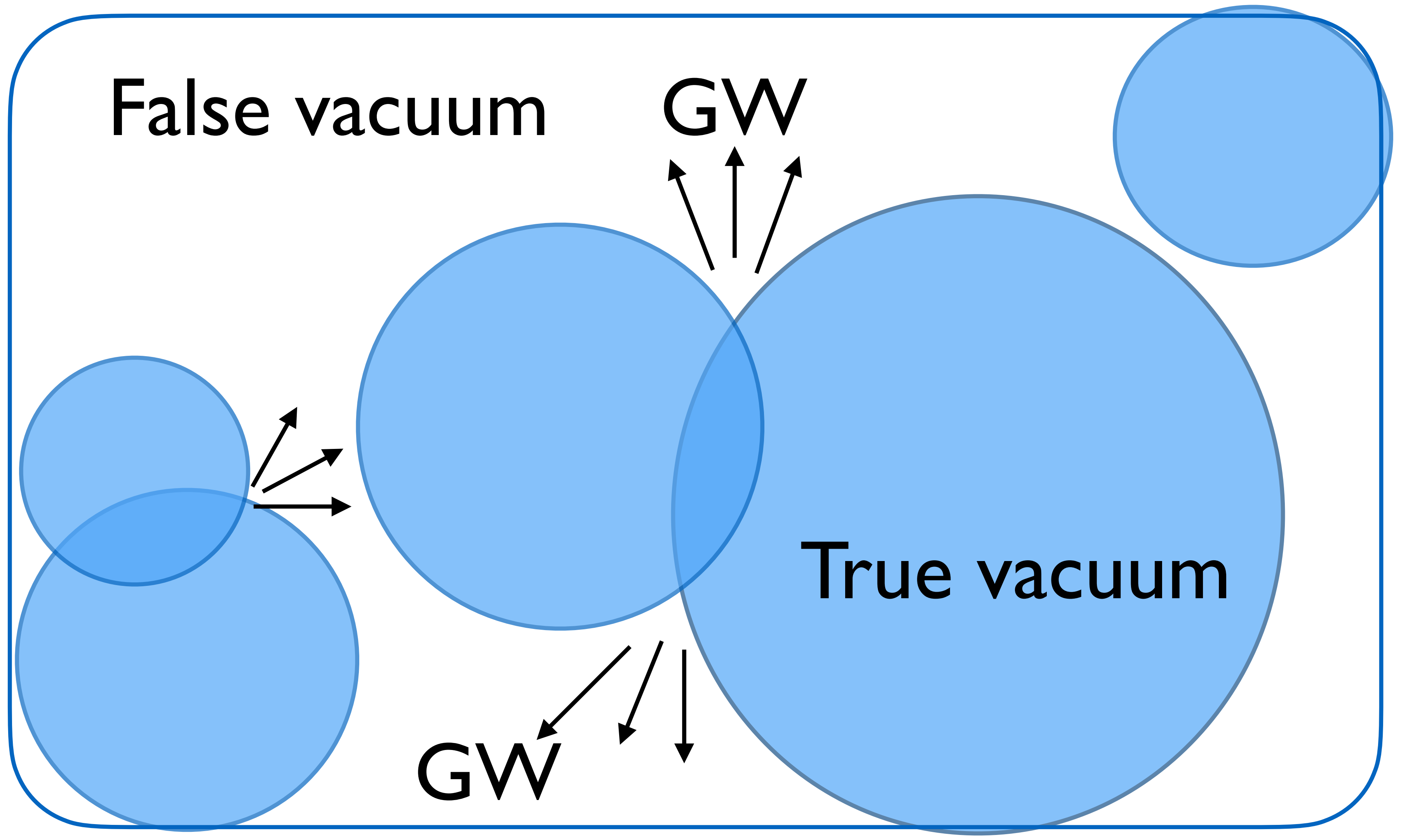
Signals from PT

- Gravitational waves

  bubble collisions, sound waves, turbulence…

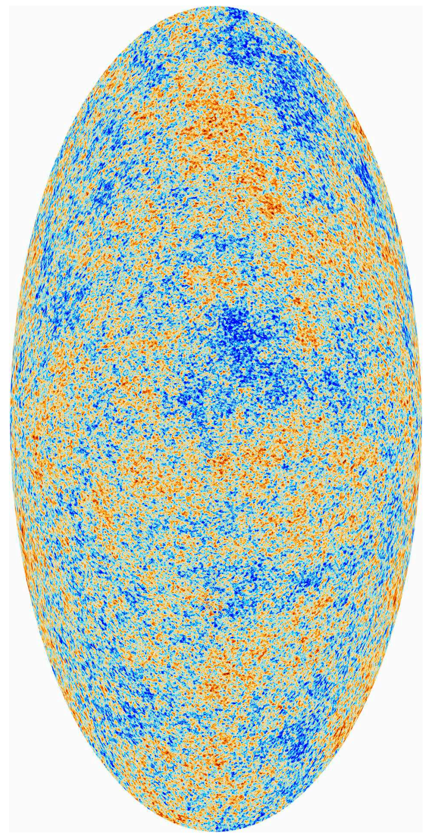


Signals from PT



- Gravitational waves

  bubble collisions, sound waves, turbulence…

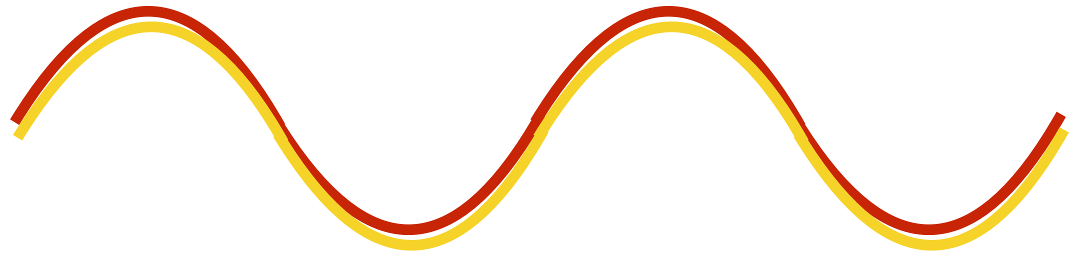


- DR energy density $\Delta N_{\rm eff} \equiv 3.044 \frac{\rho_{\rm dr}}{\rho_\nu}$

  $\Delta N_{\rm eff} < 0.3$ (Adiabatic initial conditions)

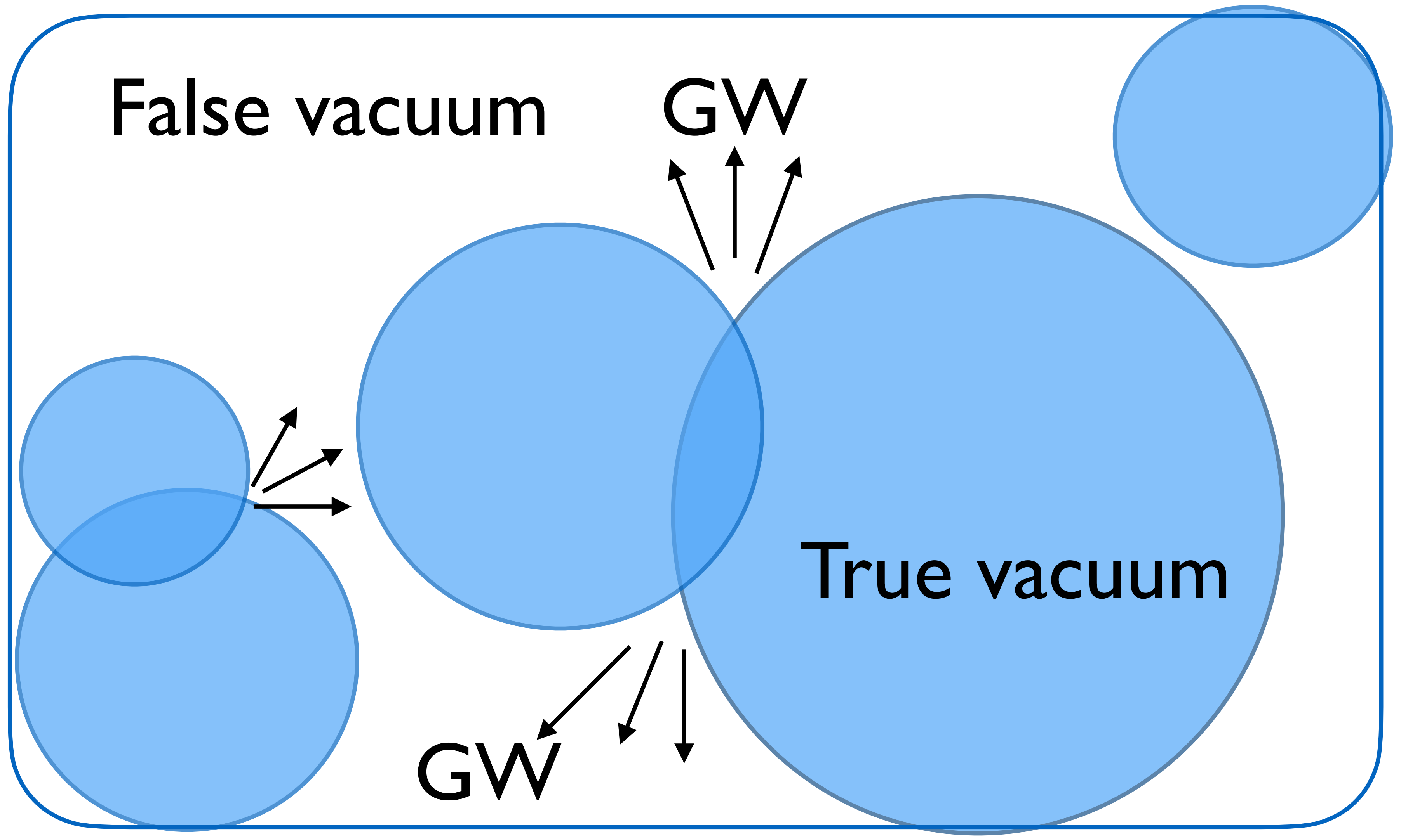
  Planck, 2018

Adiabatic



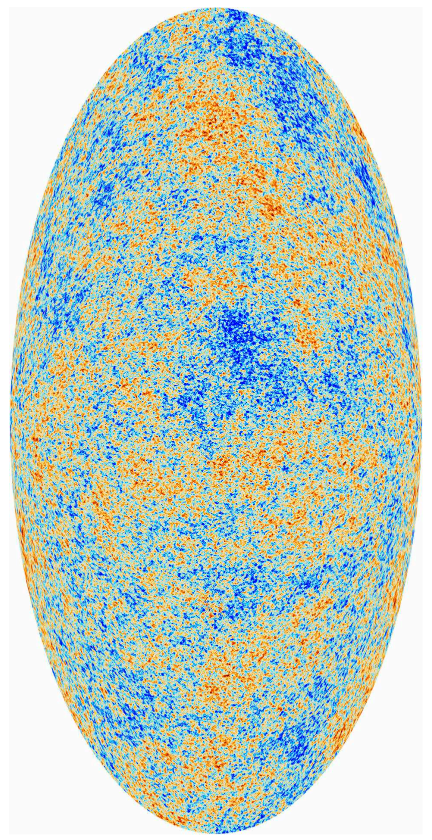
$\delta_\gamma = \delta_\nu = \delta_{\rm dr}$

Signals from PT



- Gravitational waves

  bubble collisions, sound waves, turbulence…



- DR energy density $\Delta N_{\mathrm{eff}} \equiv 3.044 \frac{\rho_{\mathrm{dr}}}{\rho_\nu}$

  $\Delta N_{\mathrm{eff}} < 0.3$ (Adiabatic initial conditions)

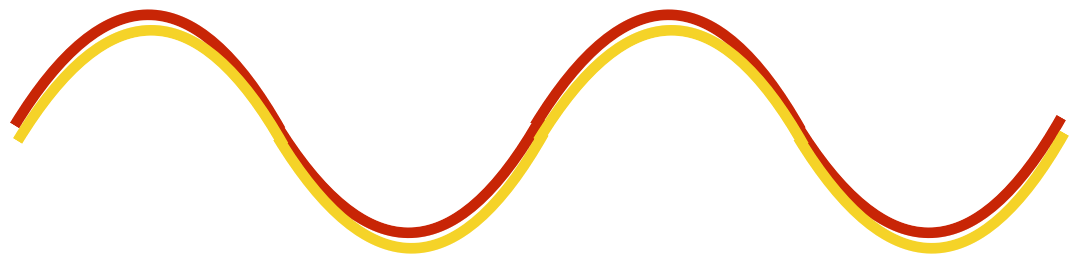
  Planck, 2018

- DR Isocurvature

  $\Delta N_{\mathrm{eff}} \lesssim 10^{-5} (T_*/T_{\mathrm{rh}})^{-4}$

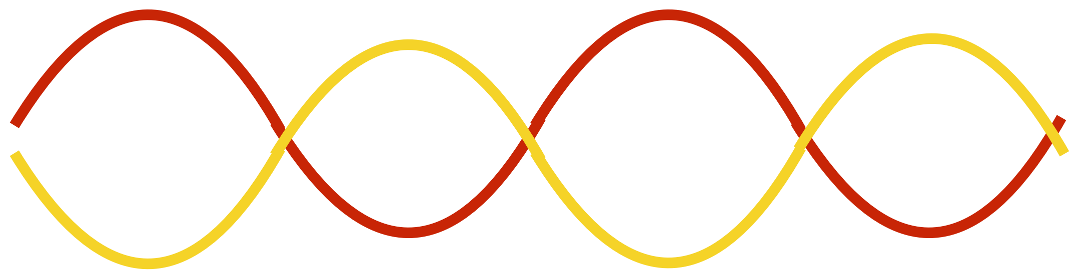
  Buckley,PD,Fernandez,Weikert,*JCAP*, 2024

Adiabatic



$\delta_\gamma = \delta_\nu = \delta_{\mathrm{dr}}$

Isocurvature



$\delta\rho_\gamma + \delta\rho_\nu + \delta\rho_{\mathrm{dr}} = 0$

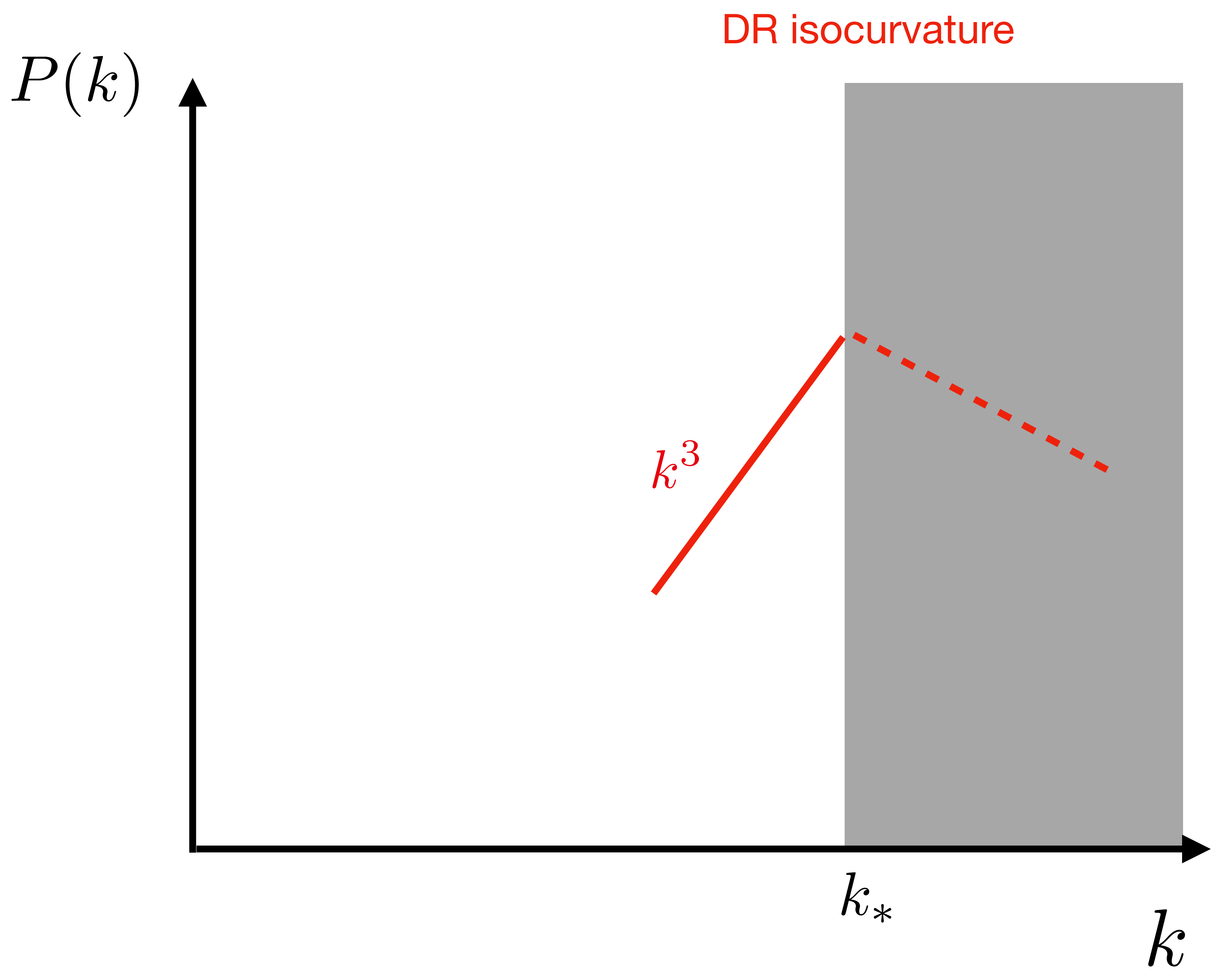
Bucher, Moodley, Turok, *PRD,* 2000
Ghosh, Kumar, Tsai, *JCAP,* 2022

DR isocurvature from PT

- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

DR isocurvature from PT



$k_* = aH(T_*)$

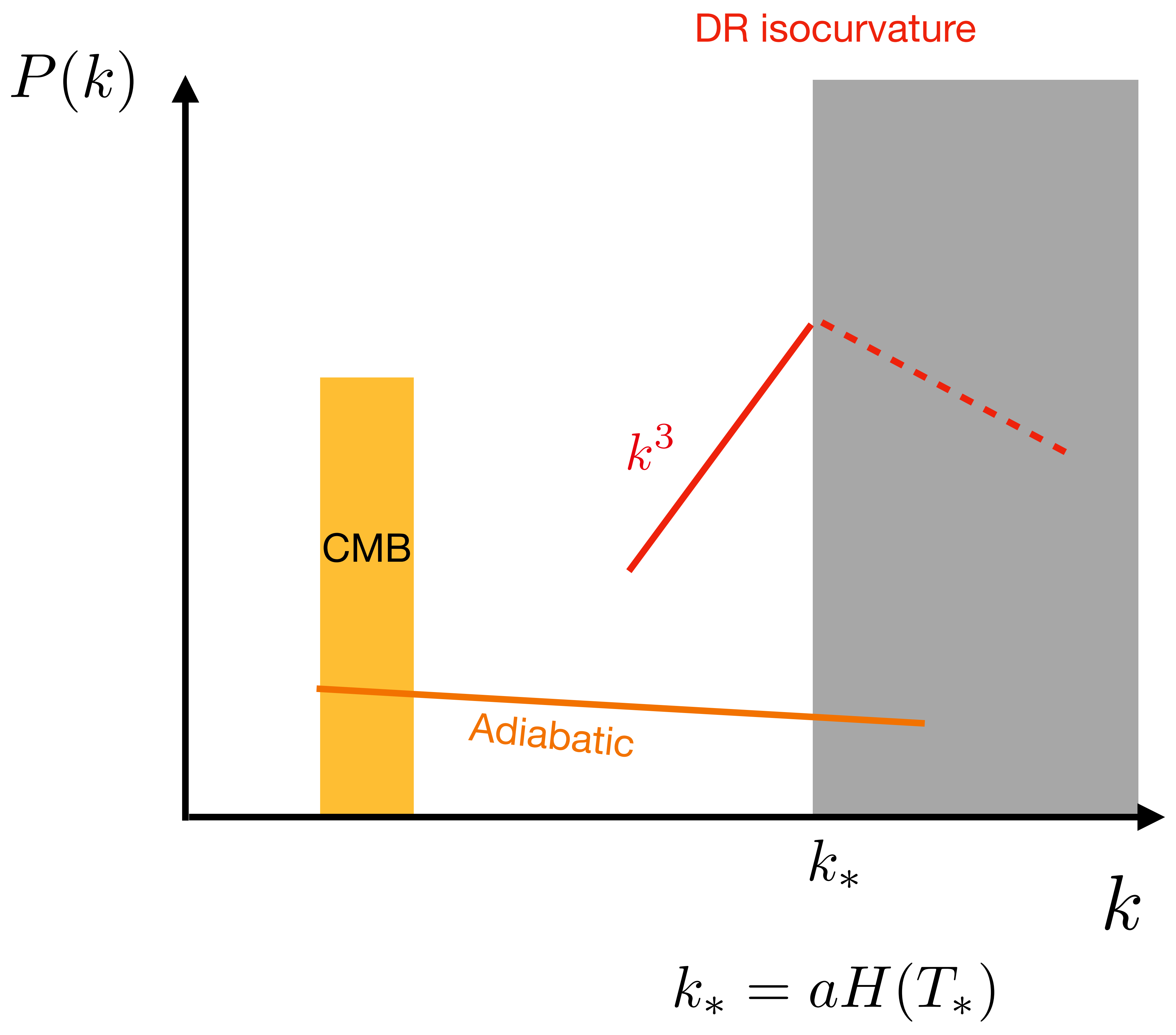
- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

- Superhorizon modes scale as k^3

DR isocurvature from PT



- PT generates density fluctuations in DR

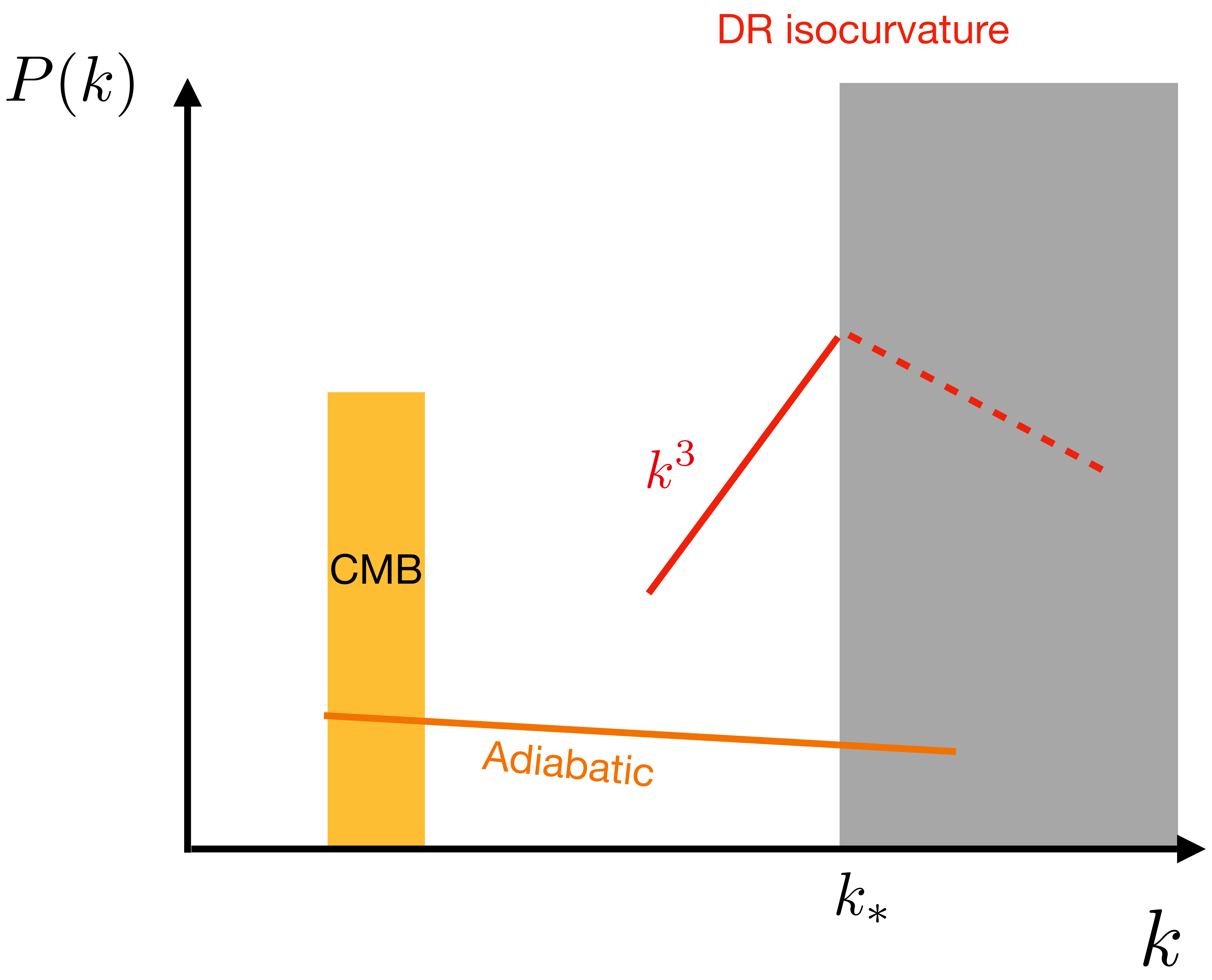
  $\Rightarrow$ DR from PT generically has isocurvature

- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

- Superhorizon modes scale as k^3

  $\Rightarrow$ Invisible to CMB if $T_* \gg T_{\rm CMB}$

DR isocurvature from PT



$k_* = aH(T_*)$

- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

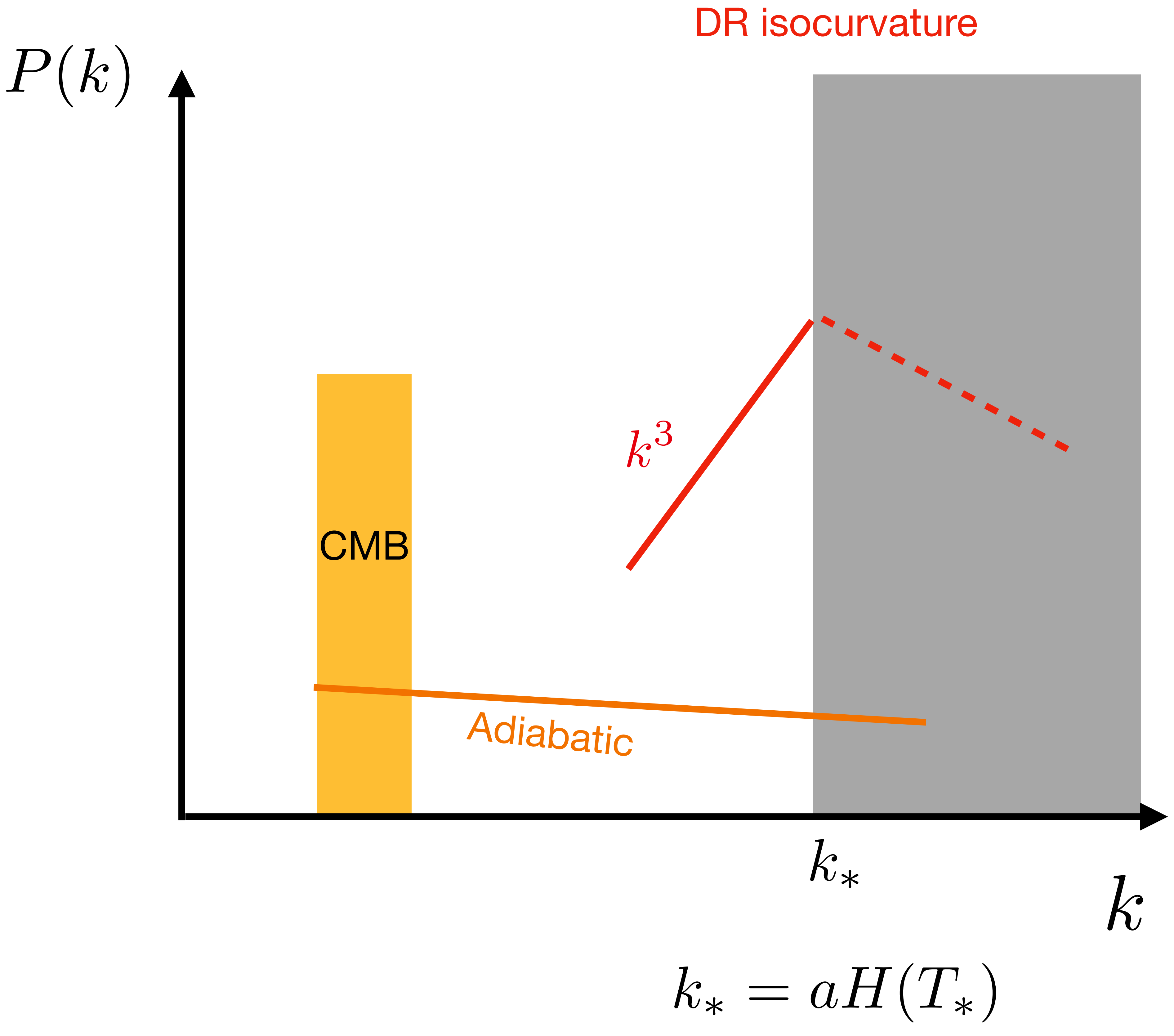
- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

- Superhorizon modes scale as k^3

  $\Rightarrow$ Invisible to CMB if $T_* \gg T_{\rm CMB}$

- How to get isocurvature signals in CMB?

DR isocurvature from PT



- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

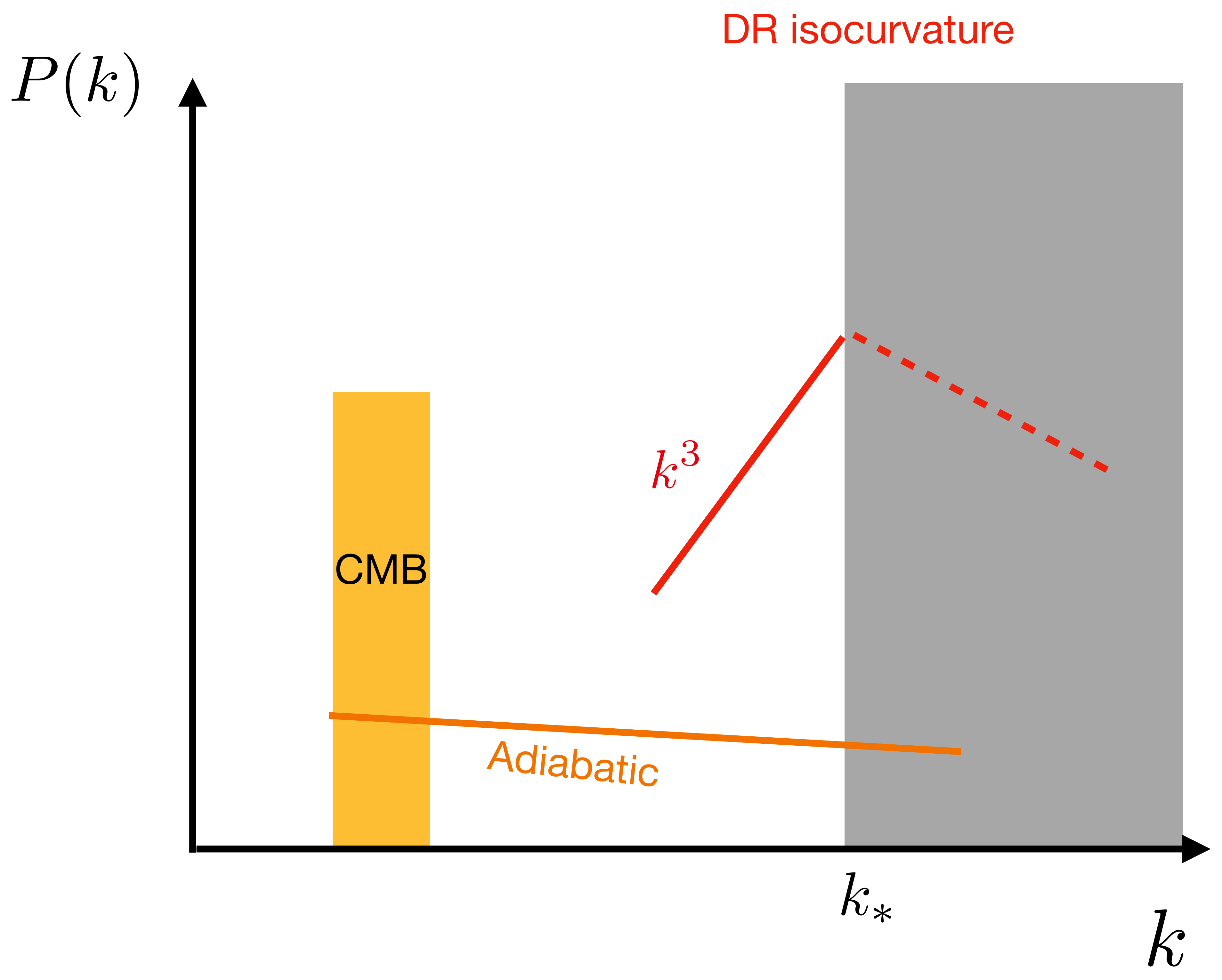
- Superhorizon modes scale as k^3

  $\Rightarrow$ Invisible to CMB if $T_* \gg T_{\mathrm{CMB}}$

- How to get isocurvature signals in CMB?

  Low scale PT — Freese, Winkler, *PRD*, 2023; Elor,Jinno,Kumar,McGehee,Tsai, *PRL*, 2024

DR isocurvature from PT



$k_* = aH(T_*)$

- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

- Superhorizon modes scale as k^3

  $\Rightarrow$ Invisible to CMB if $T_* \gg T_{\mathrm{CMB}}$

- How to get isocurvature signals in CMB?

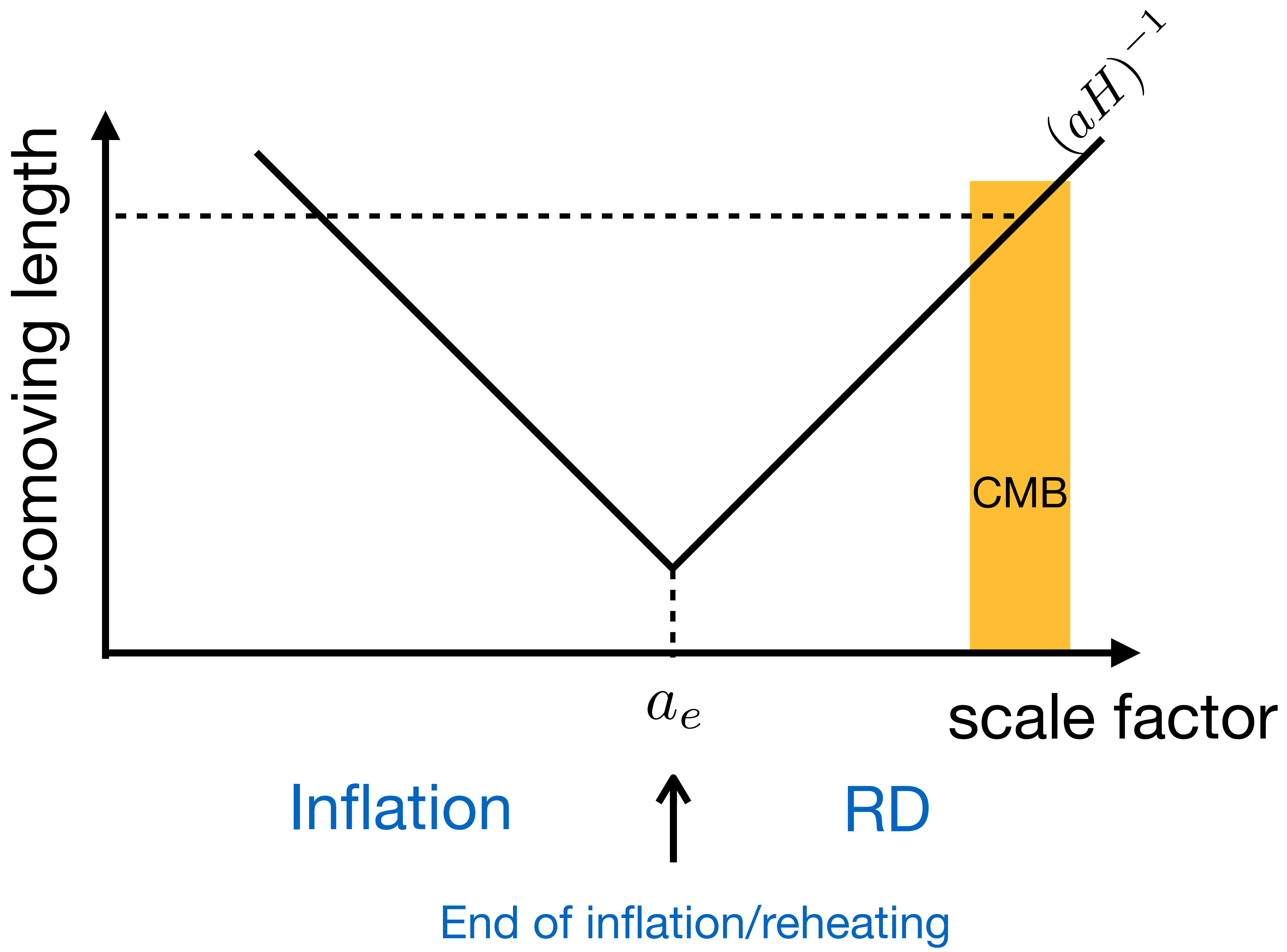
  Low scale PT — Freese, Winkler, *PRD*, 2023; Elor, Jinno, Kumar, McGehee, Tsai, *PRL*, 2024

  Slow PT during inflation!

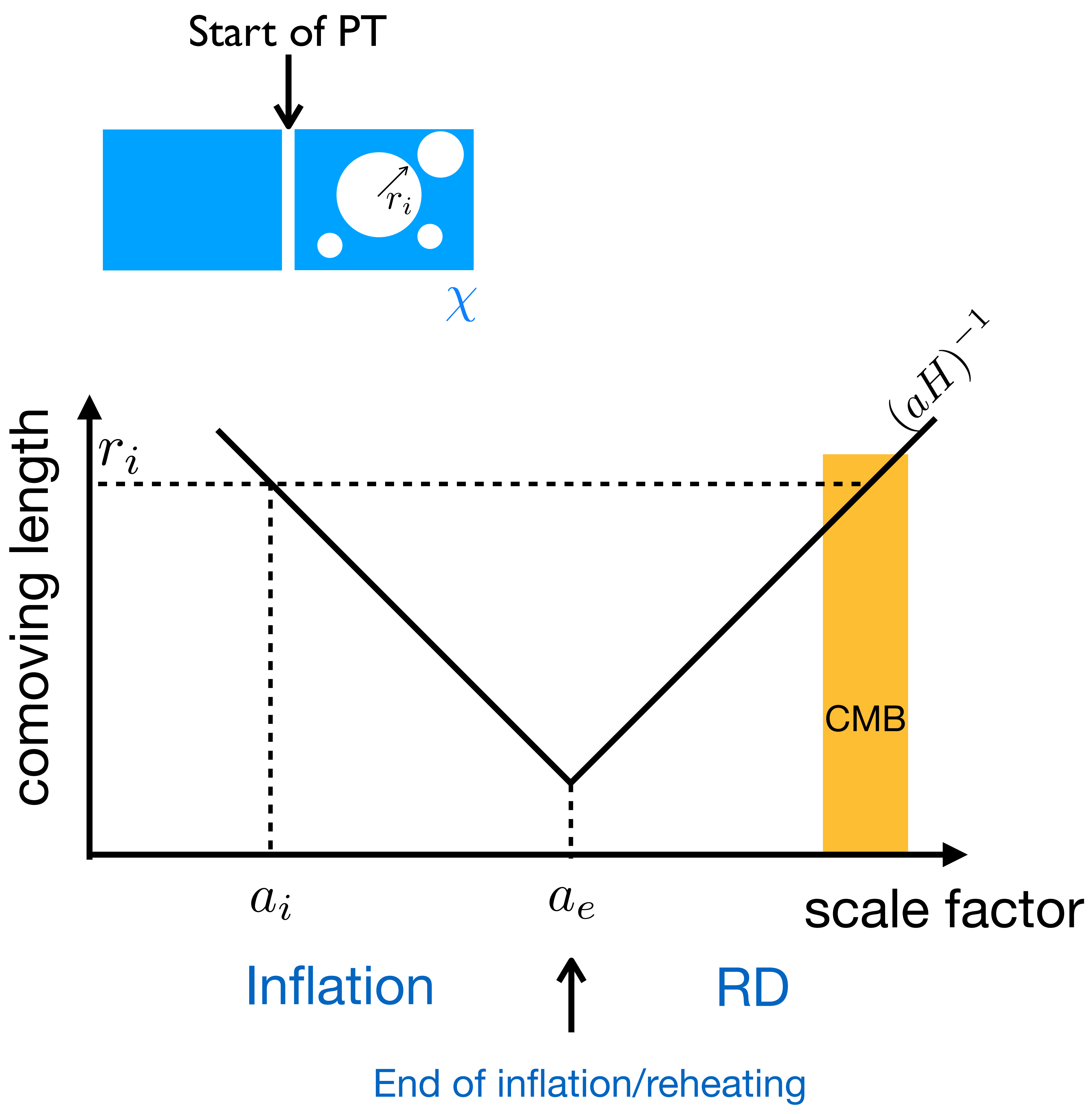
  Buckley, PD, Fernandez, Weikert, *JCAP*, 2024

Slow PT during inflation

- Comoving horizon can be large during inflation



Slow PT during inflation



- Comoving horizon can be large during inflation

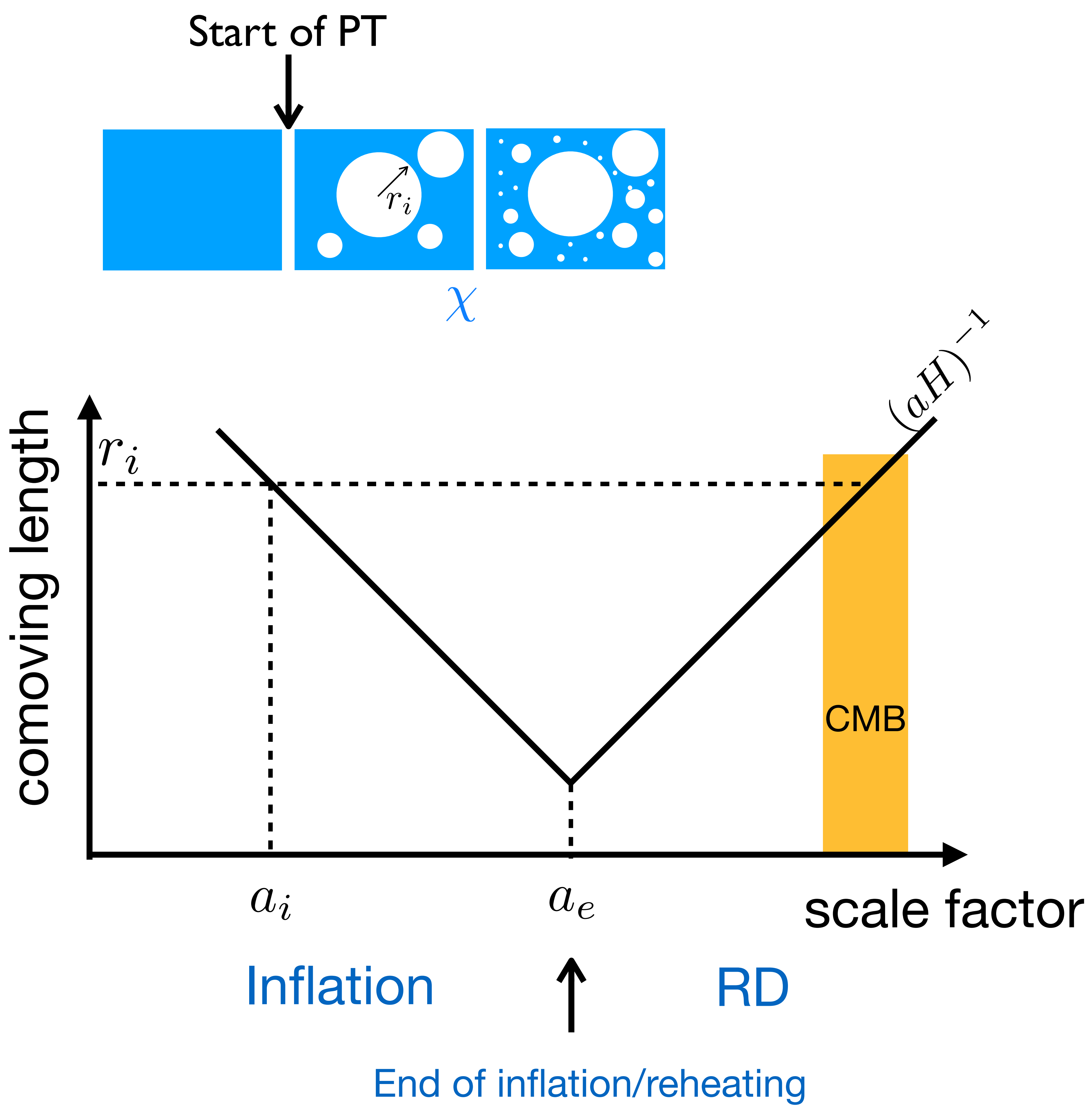
- PT during inflation can generate large bubbles

$$r(a) = (aH_{\text{inf}})^{-1}$$

- Slow PT: remain incomplete during inflation

$$\Gamma_{\text{PT}} \ll H_{\text{inf}}^4$$

Slow PT during inflation



- Comoving horizon can be large during inflation

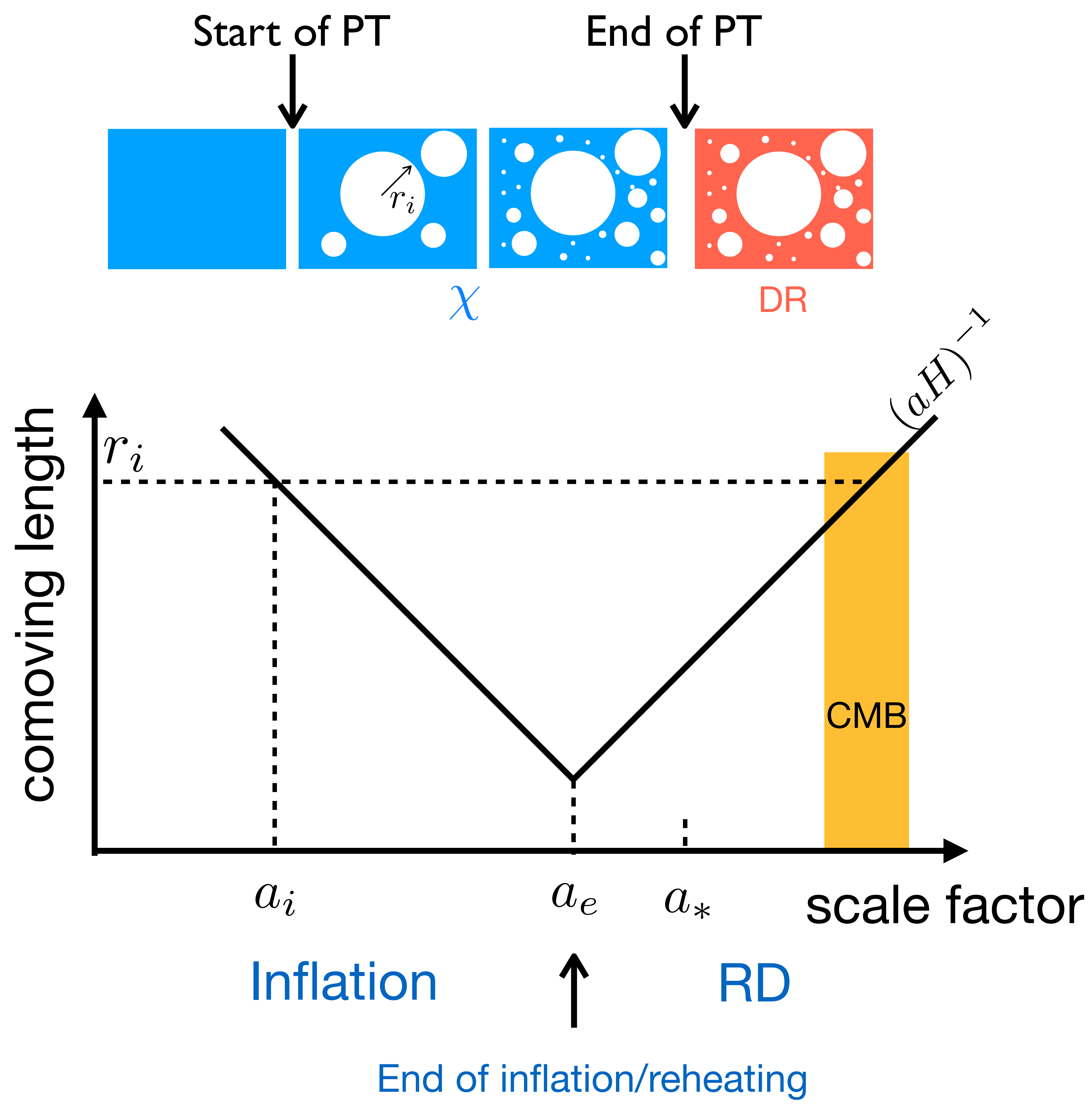
- PT during inflation can generate large bubbles

$$r(a) = (aH_{\text{inf}})^{-1}$$

- Slow PT: remain incomplete during inflation

$$\Gamma_{\text{PT}} \ll H_{\text{inf}}^4$$

Slow PT during inflation



- Comoving horizon can be large during inflation
- PT during inflation can generate large bubbles

$$r(a) = (aH_{\rm inf})^{-1}$$

- Slow PT: remain incomplete during inflation

$$\Gamma_{\rm PT} \ll H_{\rm inf}^4$$

- PT will complete after inflation at $T_* < T_{\rm rh}$

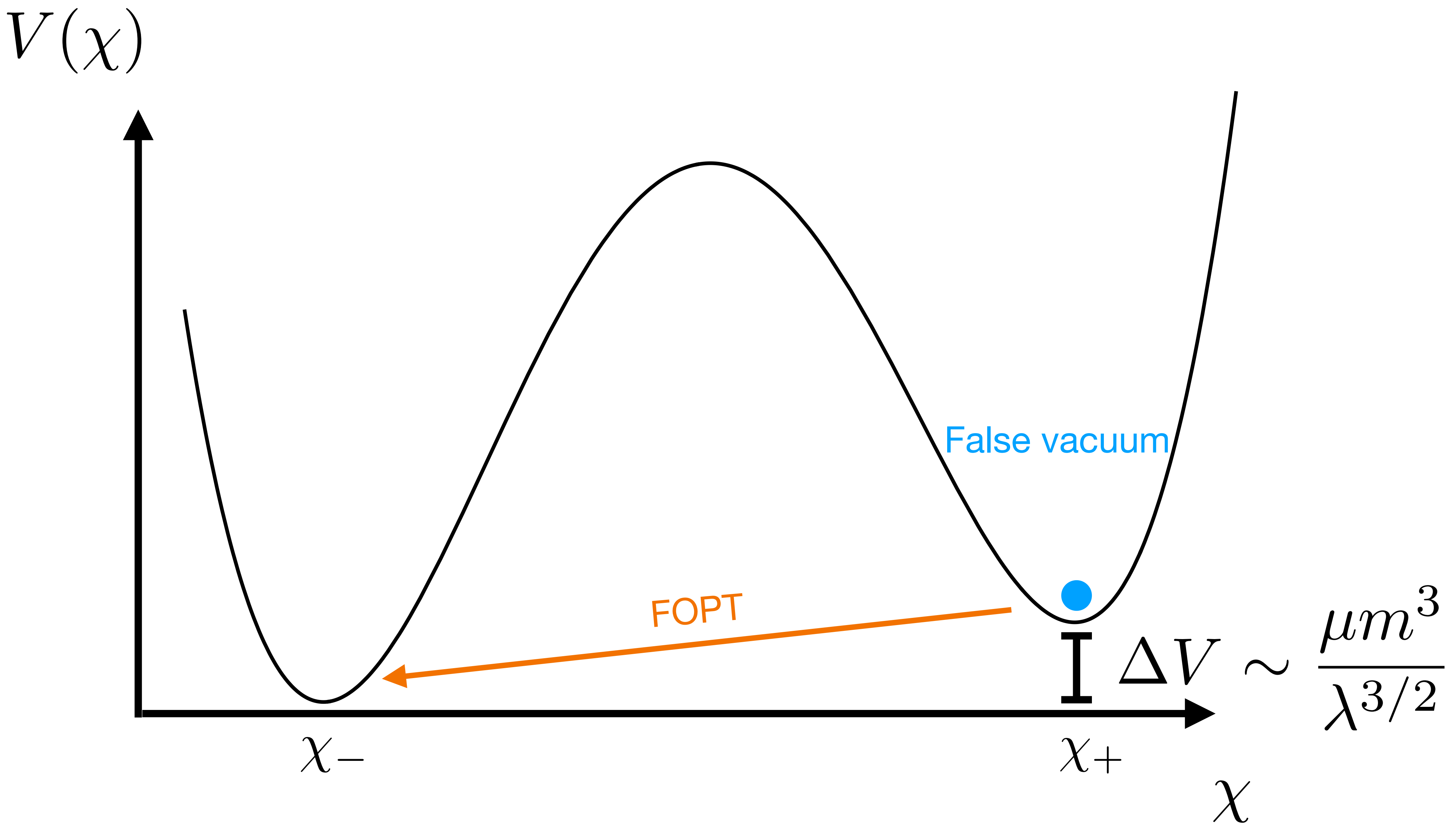
$$\Gamma_{\rm PT} = H(T_*)^4$$

- Vacuum energy of PT converts to DR generating isocurvature

Models for slow PT during inflation

Simple(st) model is sufficient

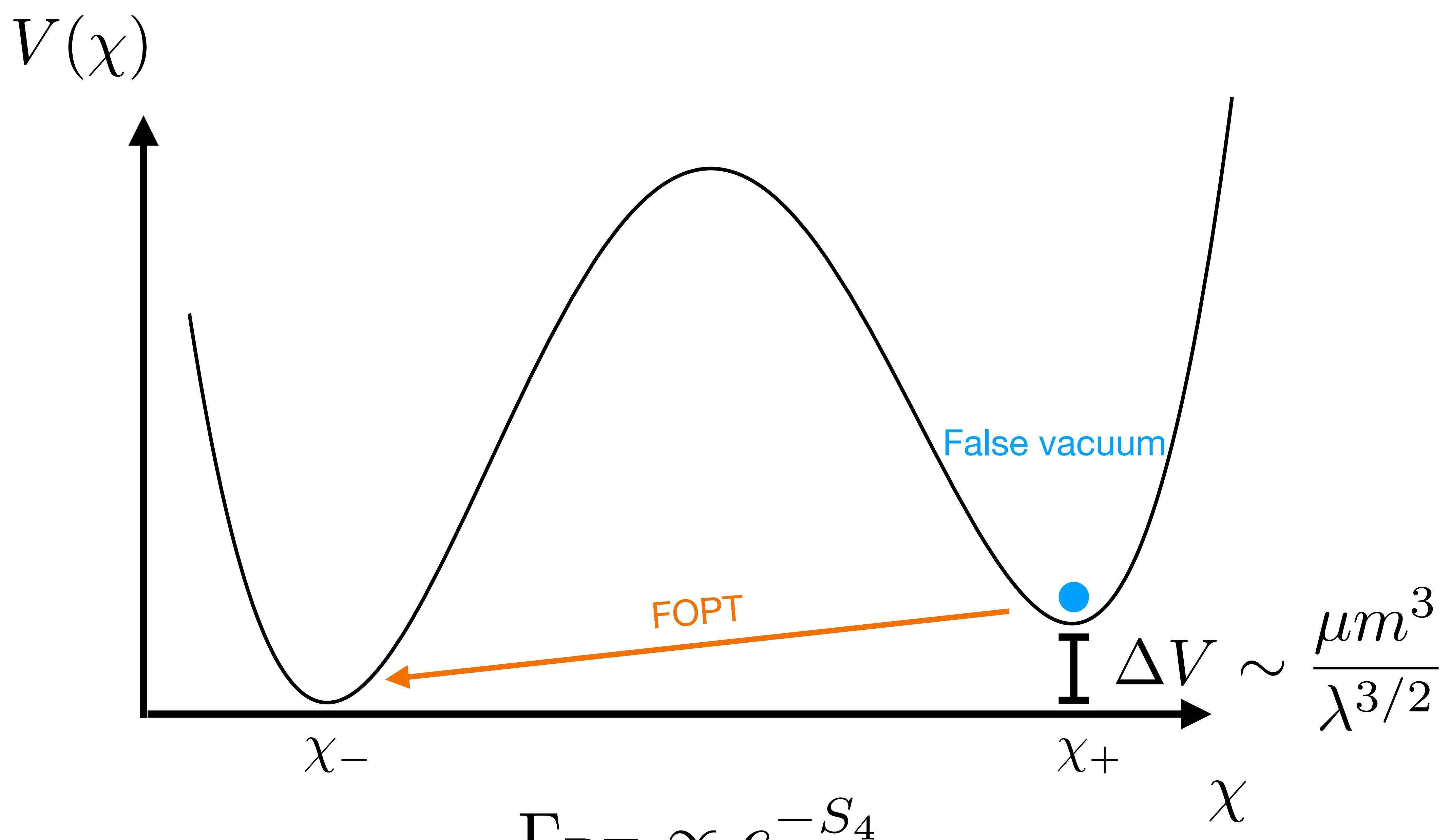
$$V(\chi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$



Models for slow PT during inflation

Simple(st) model is sufficient

$$V(\chi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$



$$\Gamma_{\rm PT} \propto e^{-S_4}$$

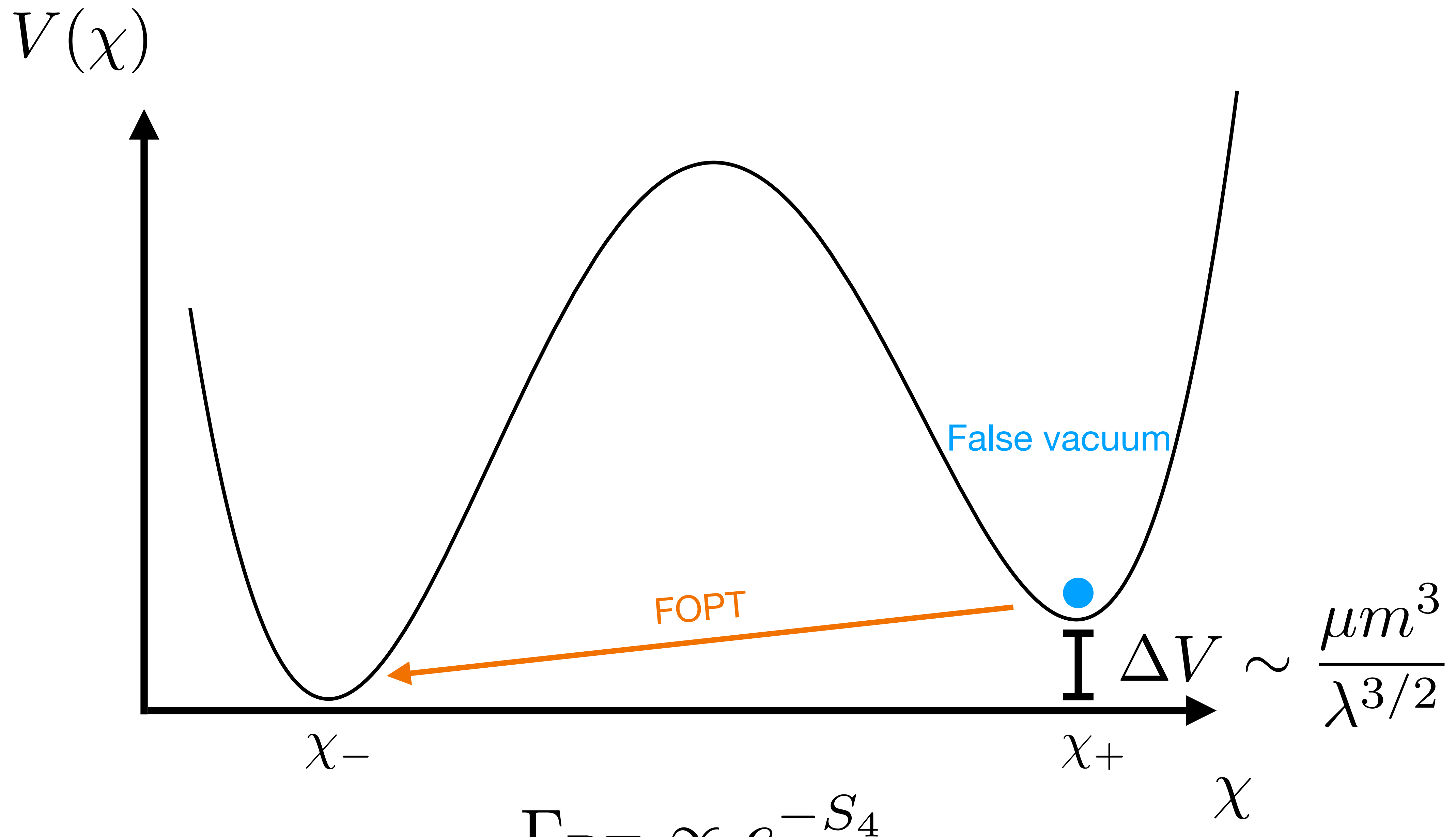
$$S_4 \sim \lambda^{1/2}\left(\frac{m}{\mu}\right)^3$$

Small μ leads to small $\Gamma_{\rm PT}$

Models for slow PT during inflation

Simple(st) model is sufficient

$$V(\chi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$



$$\Gamma_{\rm PT} \propto e^{-S_4}$$

$$S_4 \sim \lambda^{1/2}\left(\frac{m}{\mu}\right)^3$$

Small μ leads to small $\Gamma_{\rm PT}$

Adding a trigger by coupling to inflaton

$$V(\chi,\phi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu(\phi)}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

$$\mu(\phi) = \mu\,\tanh\left(\frac{\phi-\phi_i}{\Delta\phi}\right)$$

Models for slow PT during inflation

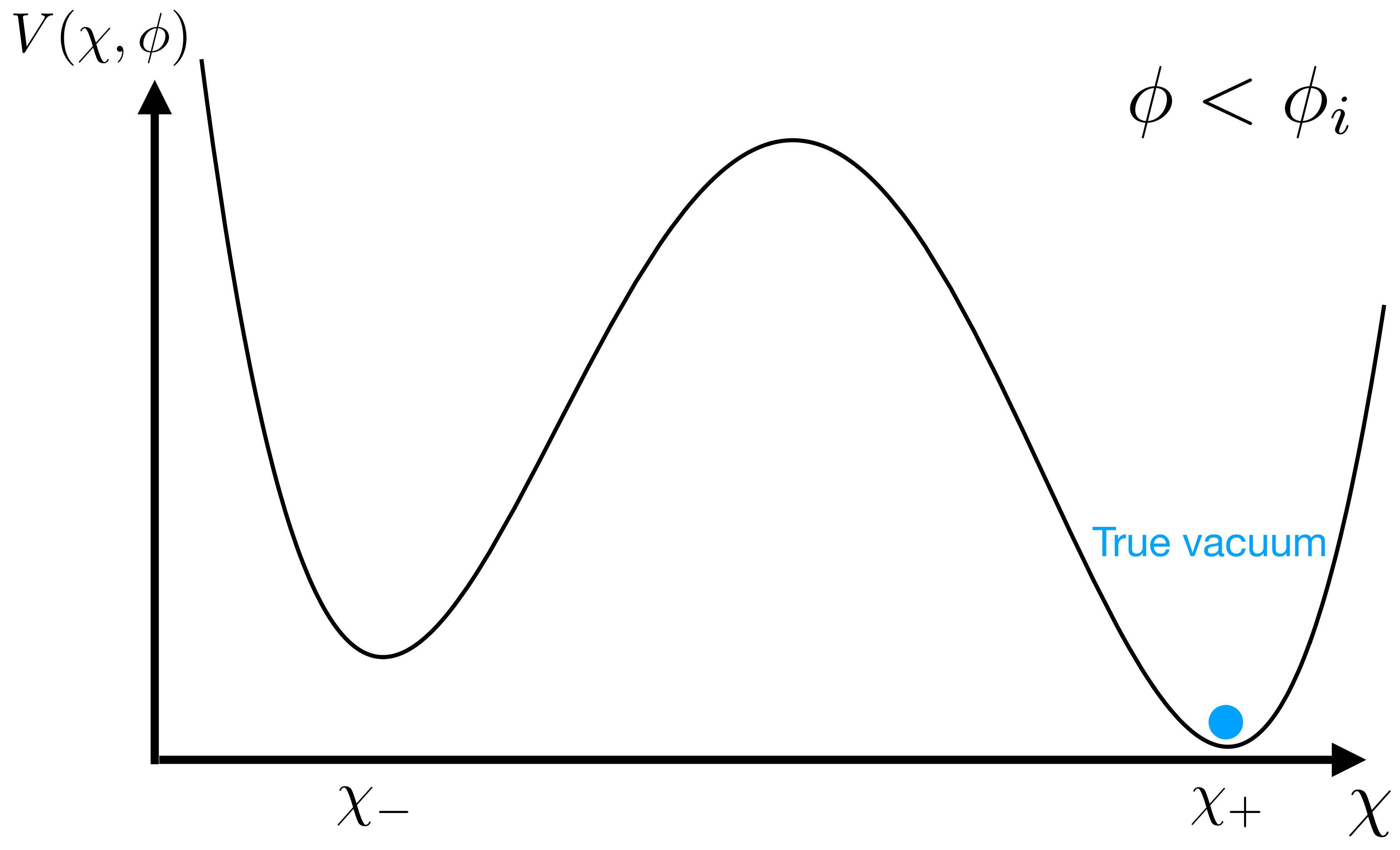
Simple(st) model is sufficient

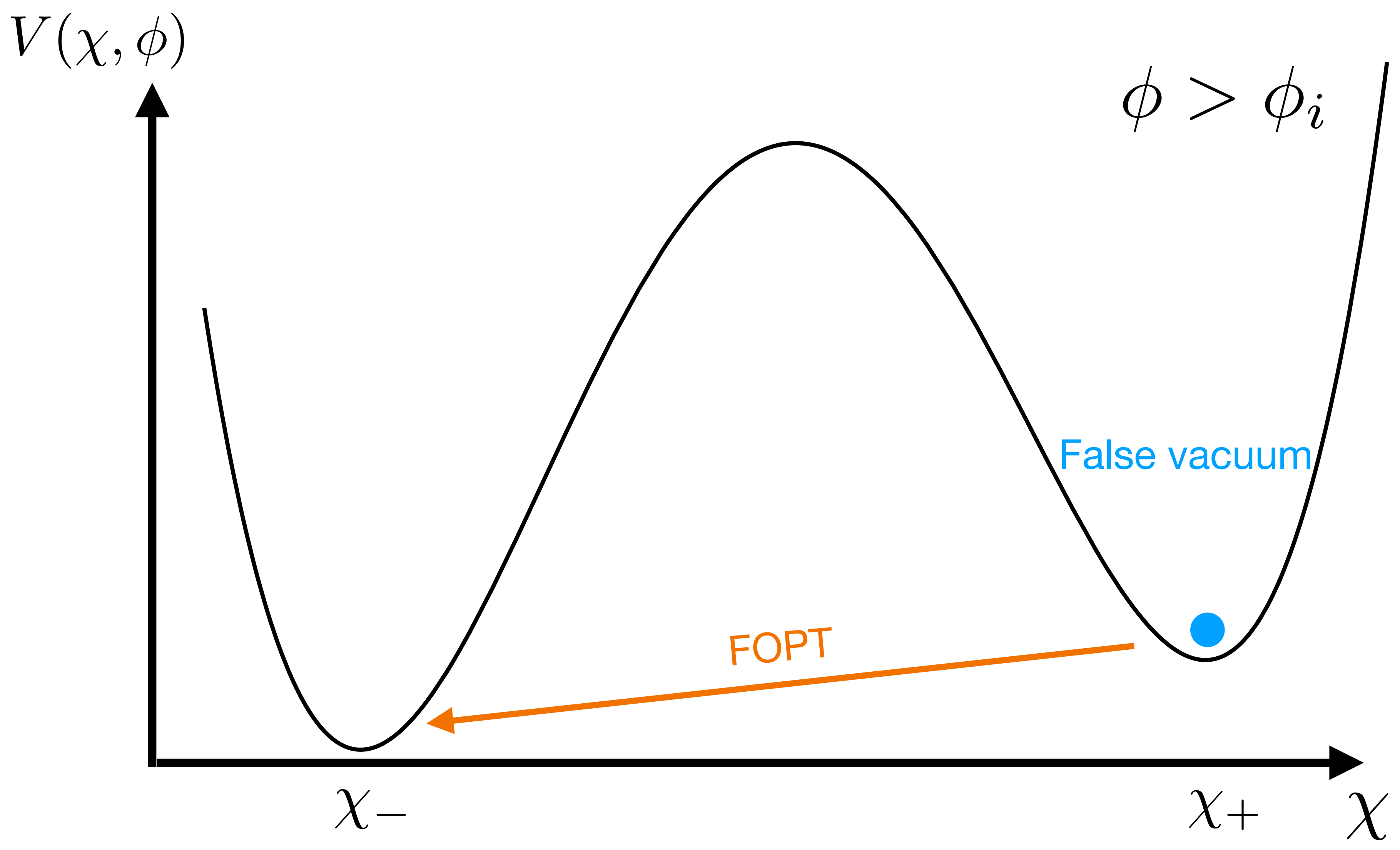
$$V(\chi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

Adding a trigger by coupling to inflaton

$$V(\chi,\phi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu(\phi)}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

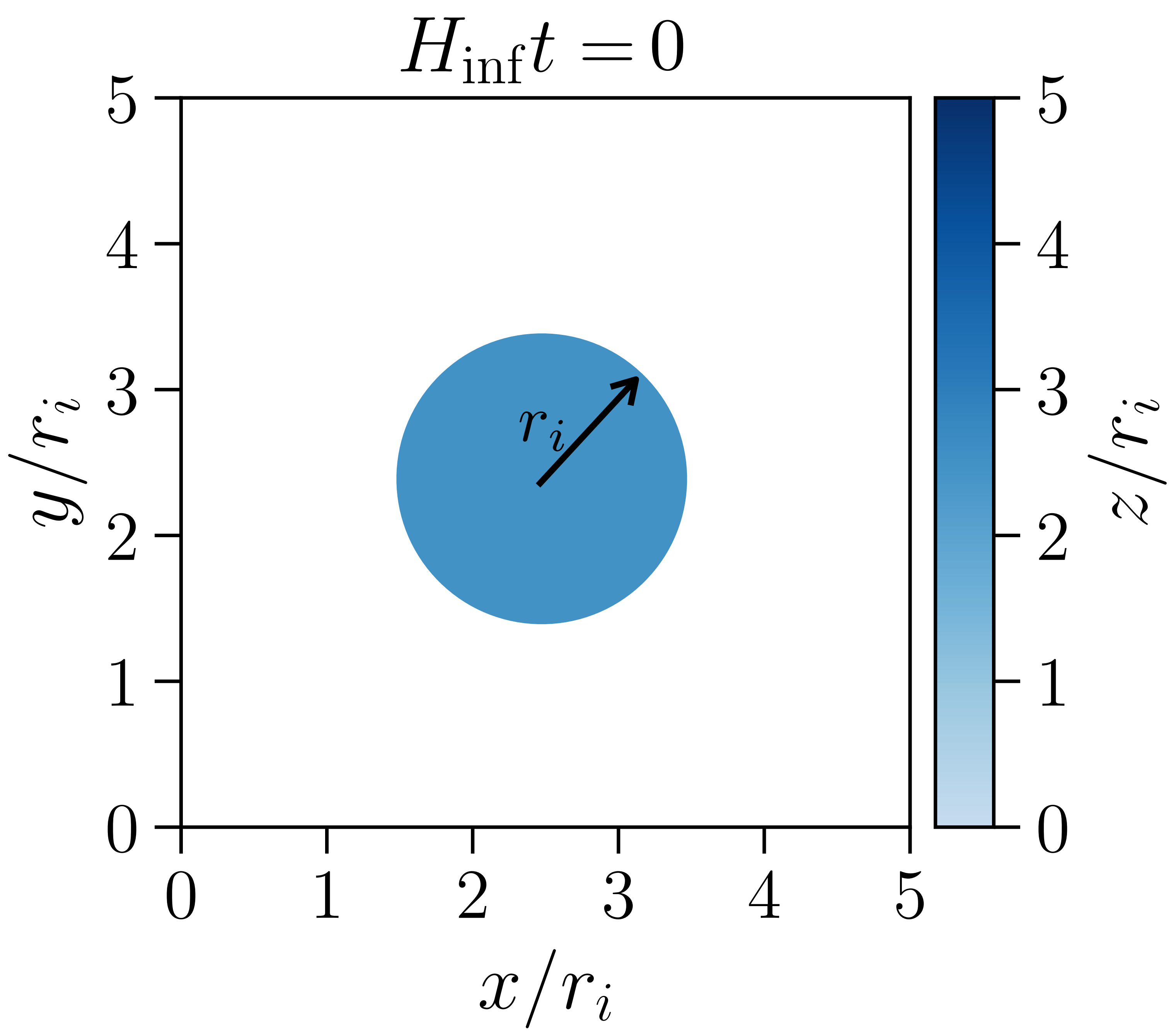
$$\mu(\phi) = \mu \tanh\left(\frac{\phi-\phi_i}{\Delta\phi}\right)$$





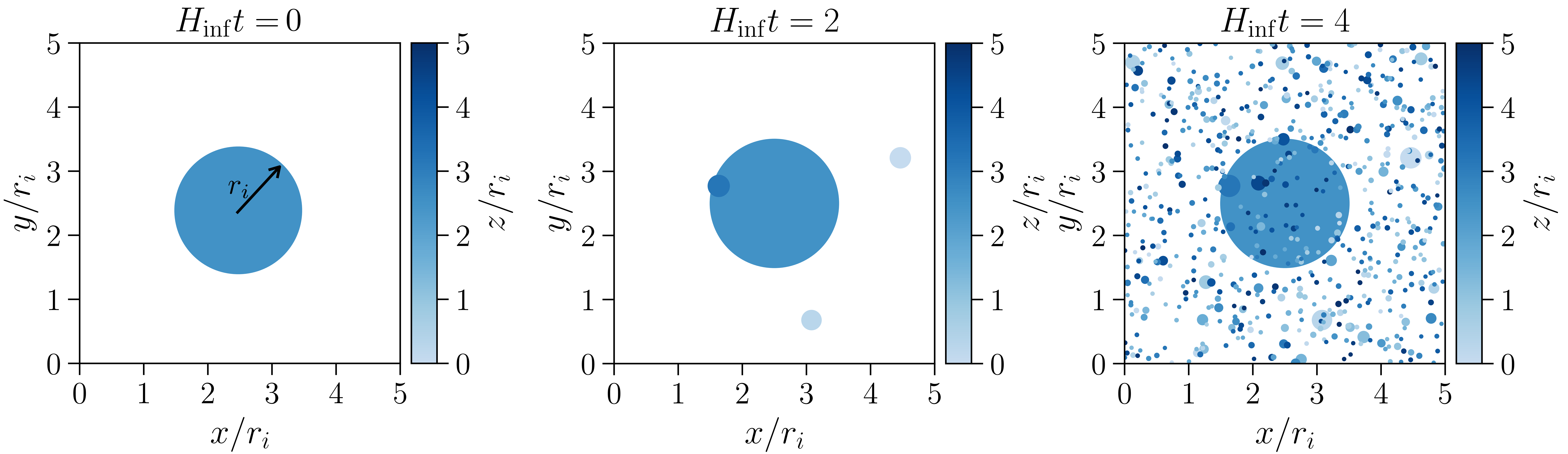
PT starts at a_i when $\phi = \phi_i$

Evolution of bubbles during inflation



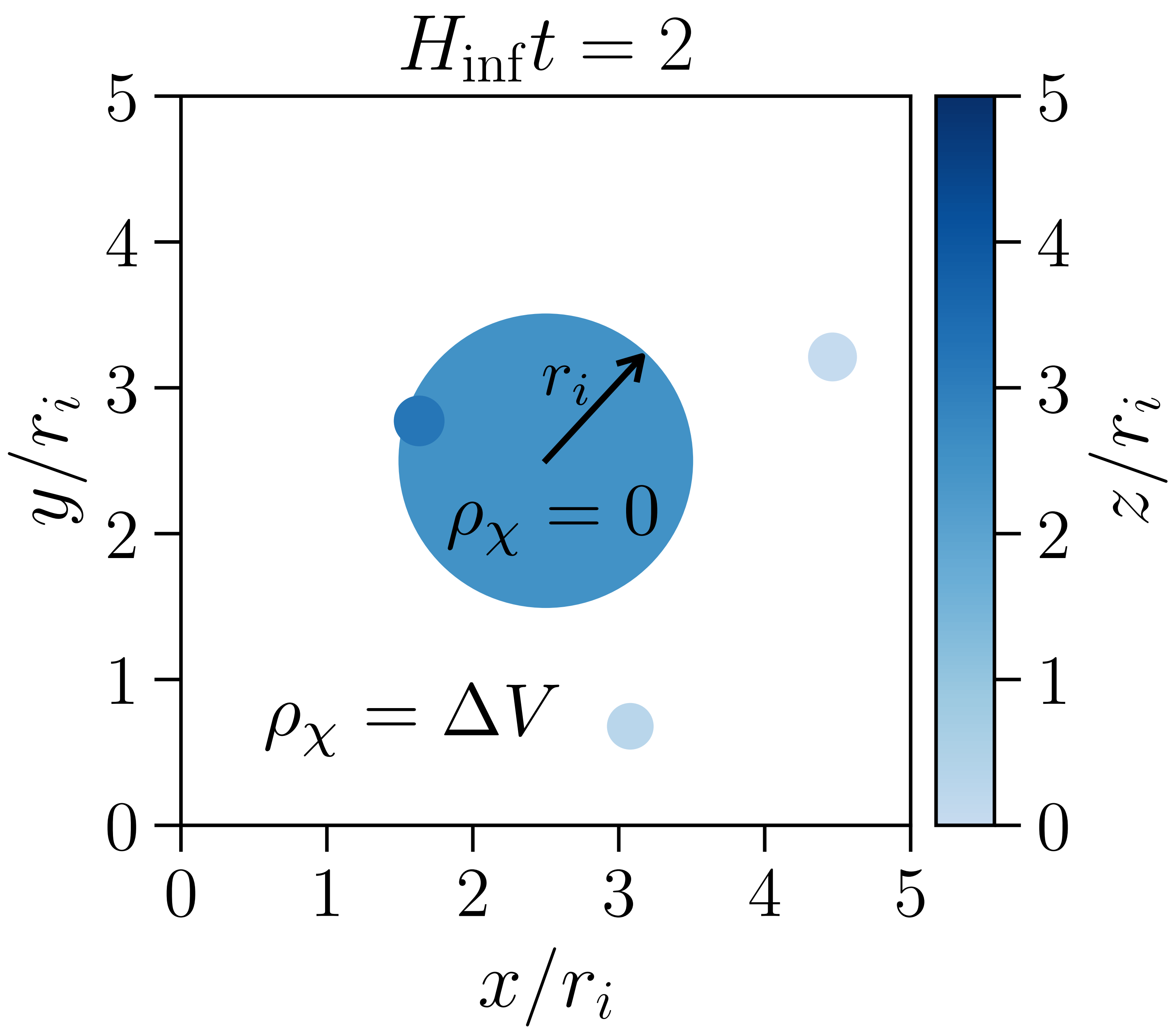
- Bubble sizes ⇔ horizon at nucleation $r(t) = (a(t)H_{\rm inf})^{-1}$

Evolution of bubbles during inflation



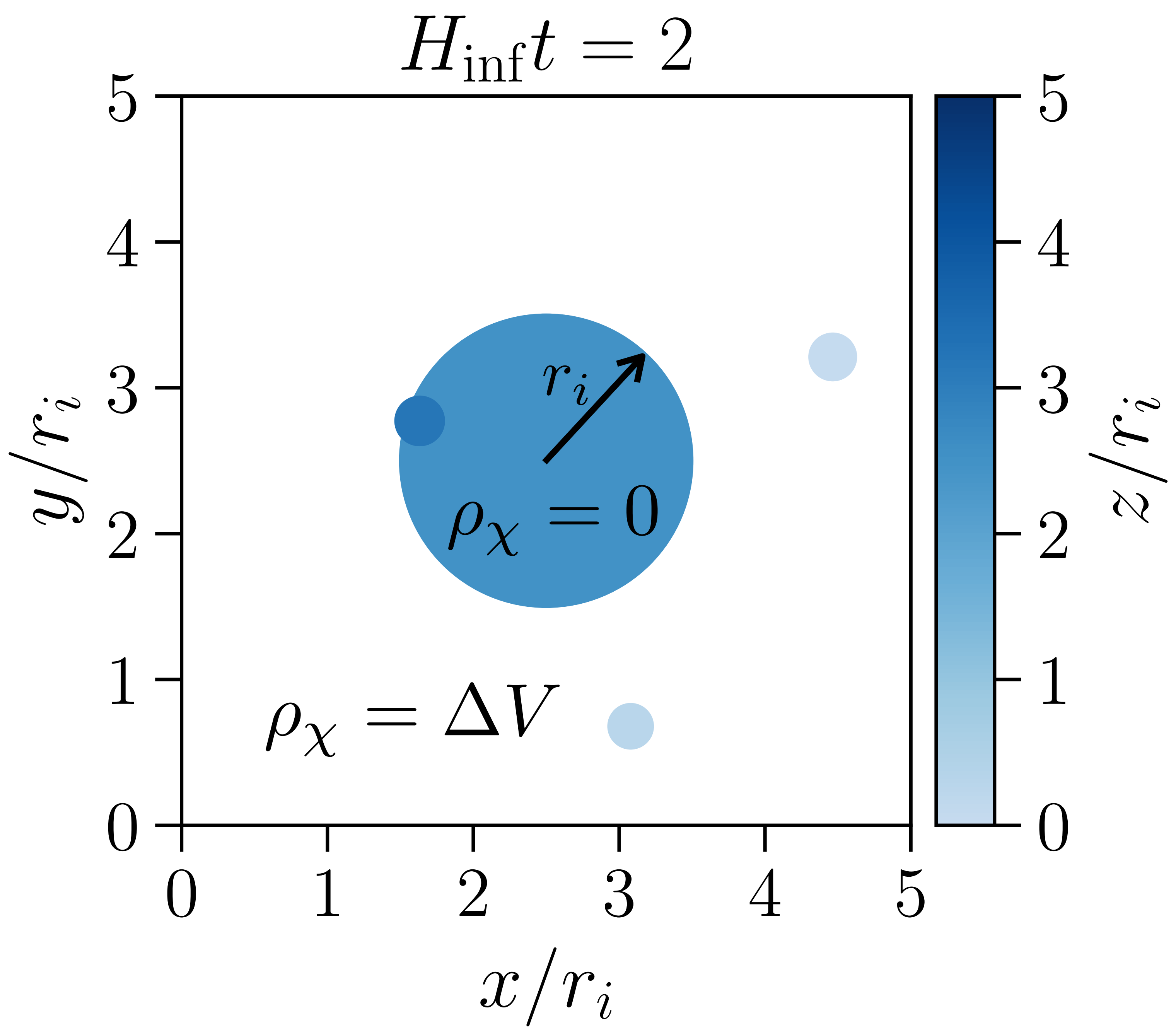
- Bubble sizes ⇔ horizon at nucleation $r(t) = (a(t)H_{\rm inf})^{-1}$
- Bubbles won't collide during inflation, PT remain incomplete
- True vacuum only occupies small fraction of space $\propto \Gamma_{\rm PT}/H_{\rm inf}^4 \ll 1$

Density perturbations from bubbles



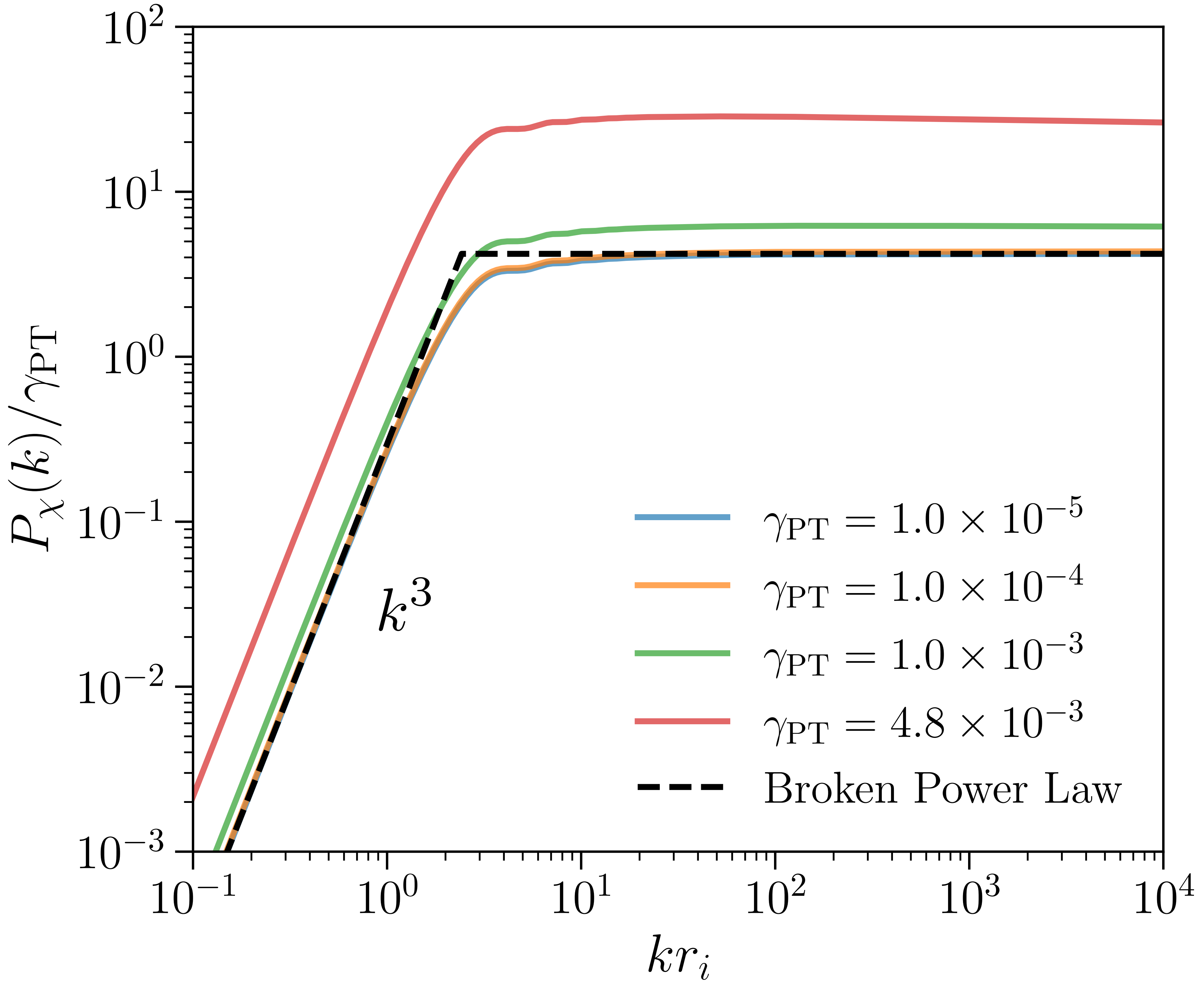
Biggest bubble has radius r_i

Density perturbations from bubbles



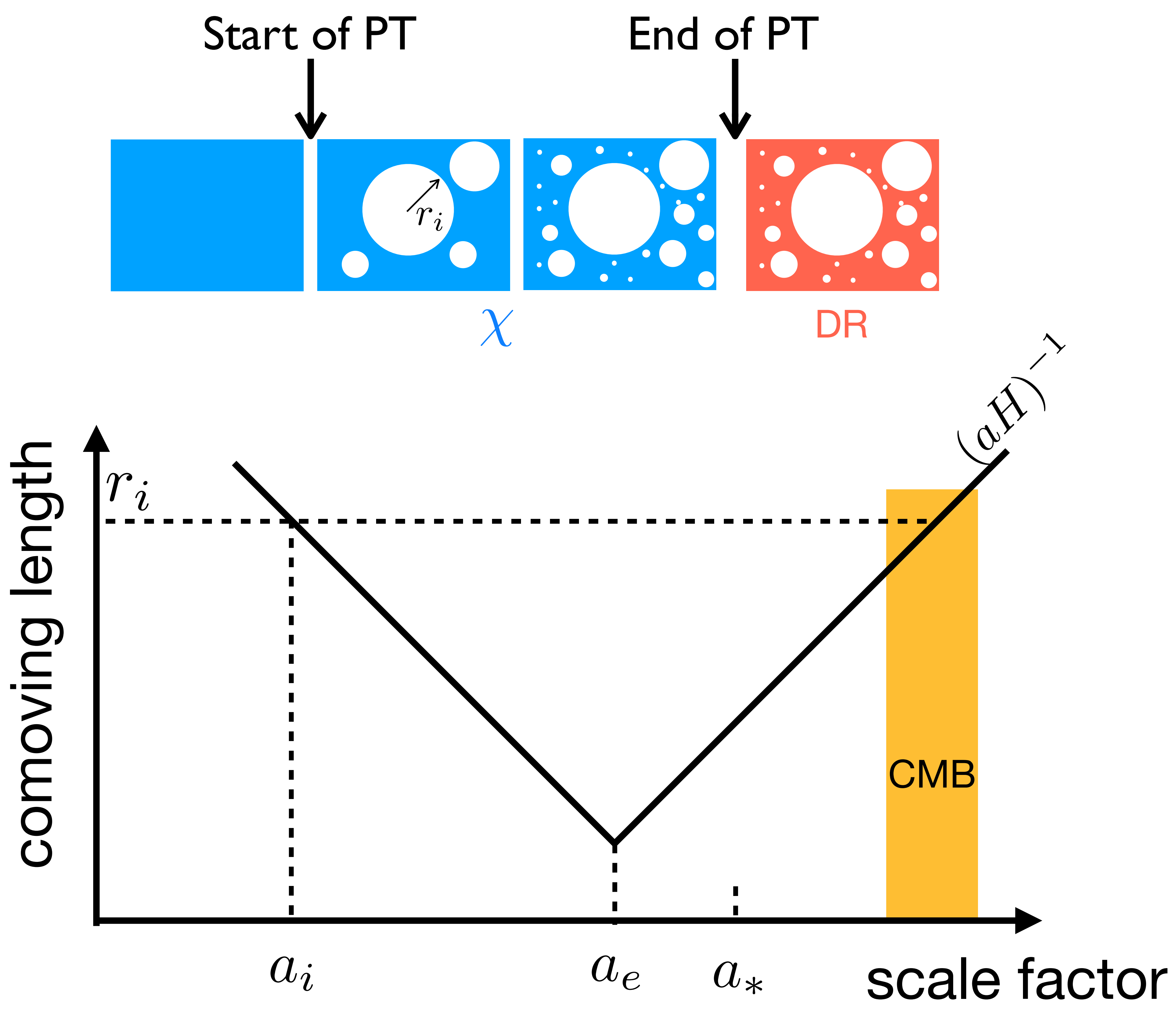
Biggest bubble has radius r_i

$$P_\chi(k) \sim \langle \delta_\chi(k)\delta_\chi(k)\rangle$$



$$\gamma_{\rm PT} \equiv \Gamma_{\rm PT}/H_{\rm inf}^4$$

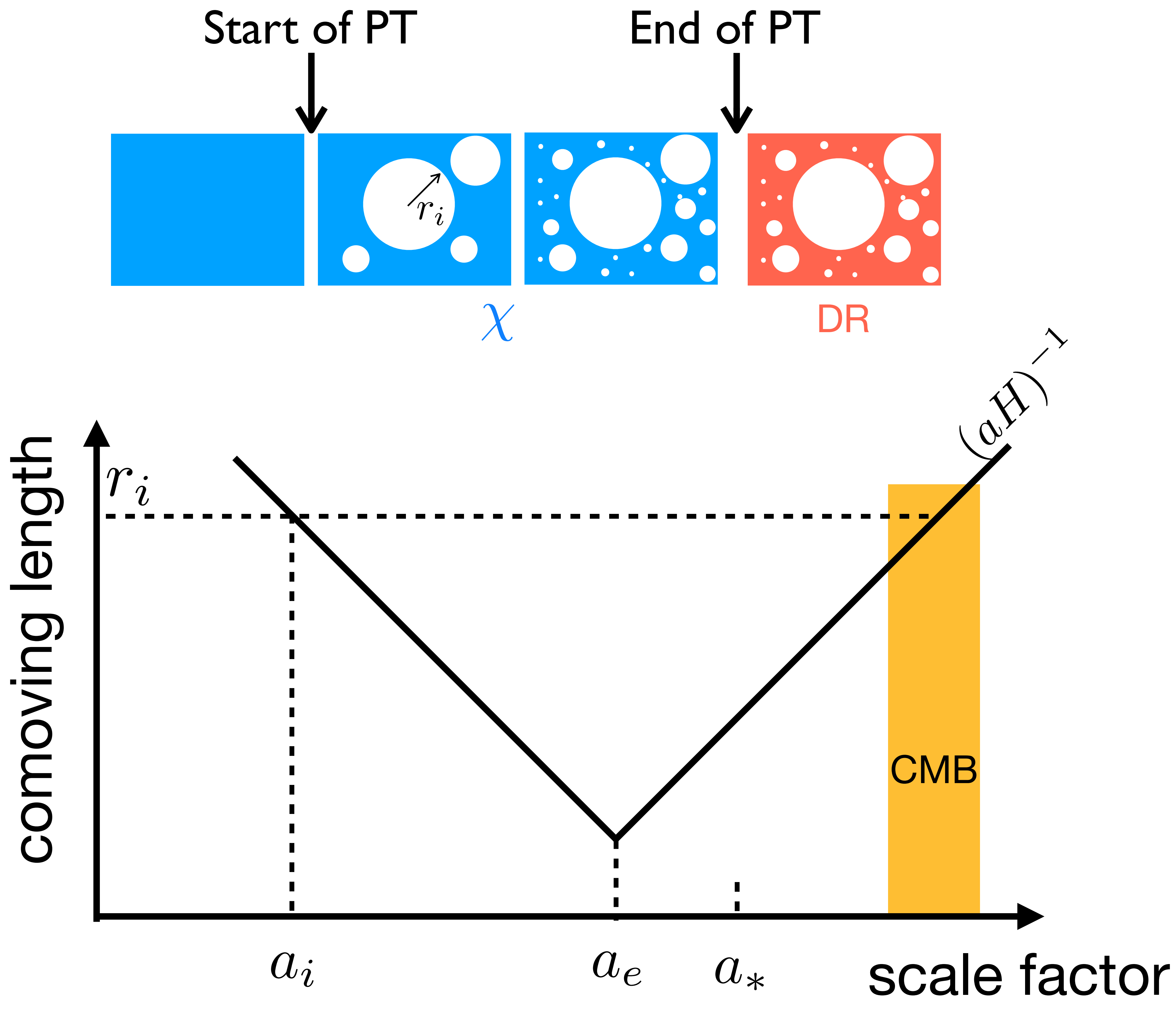
DR isocurvature from PT



- When PT competes at a_* , $\rho_\chi \to \rho_{\rm dr}$

$$\delta_{\rm dr} \approx \delta_\chi$$

DR isocurvature from PT



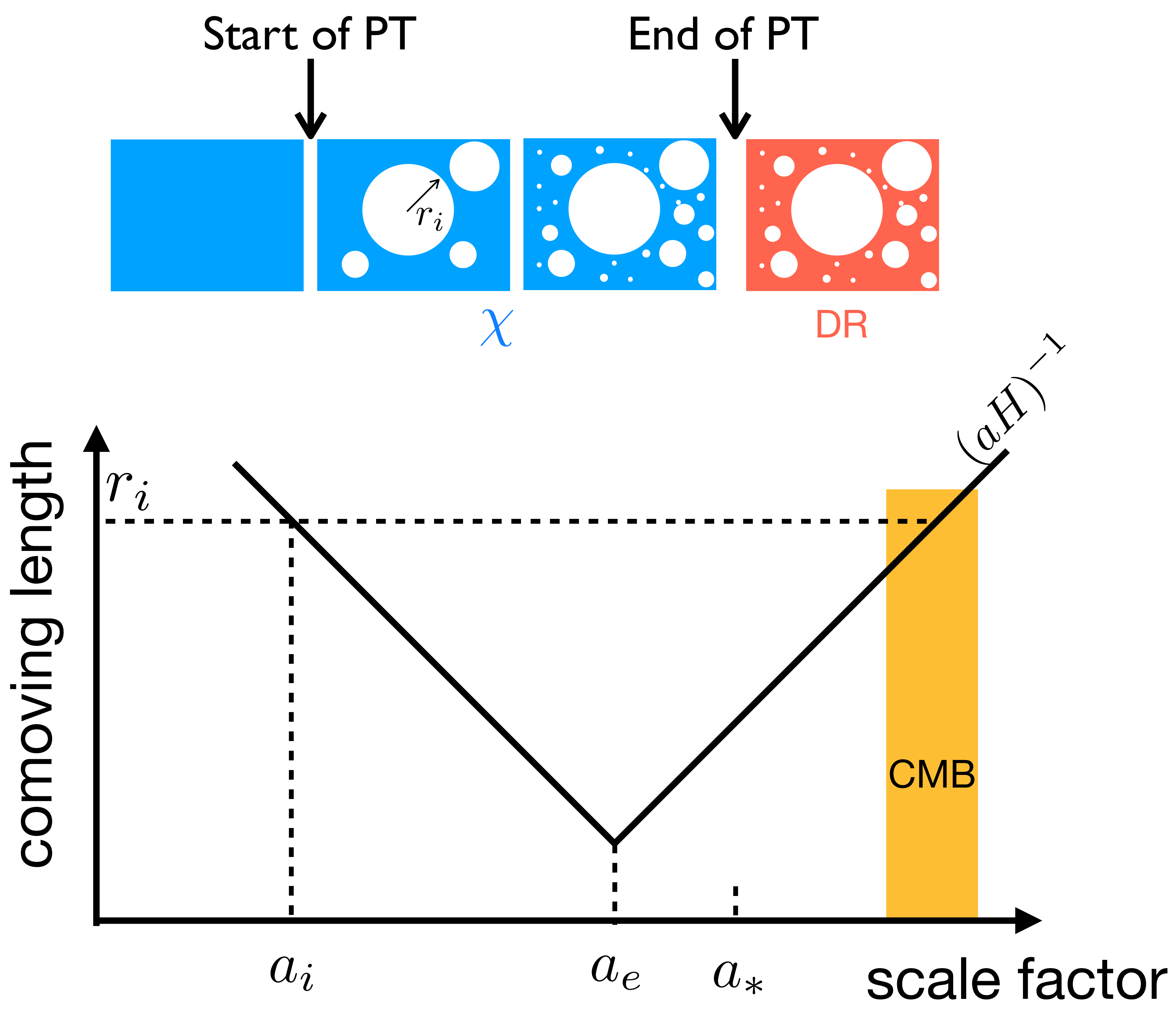
- When PT competes at a_* , $\rho_\chi \to \rho_{\rm dr}$

$$\delta_{\rm dr} \approx \delta_\chi$$

- Generating isocurvature

$$S_{{\rm dr},\gamma} = \delta_{\rm dr} - \delta_\gamma \neq 0$$

DR isocurvature from PT



- When PT competes at a_* , $\rho_\chi \to \rho_{\rm dr}$

$$\delta_{\rm dr} \approx \delta_\chi$$

- Generating isocurvature

$$S_{{\rm dr},\gamma} = \delta_{\rm dr} - \delta_\gamma \neq 0$$

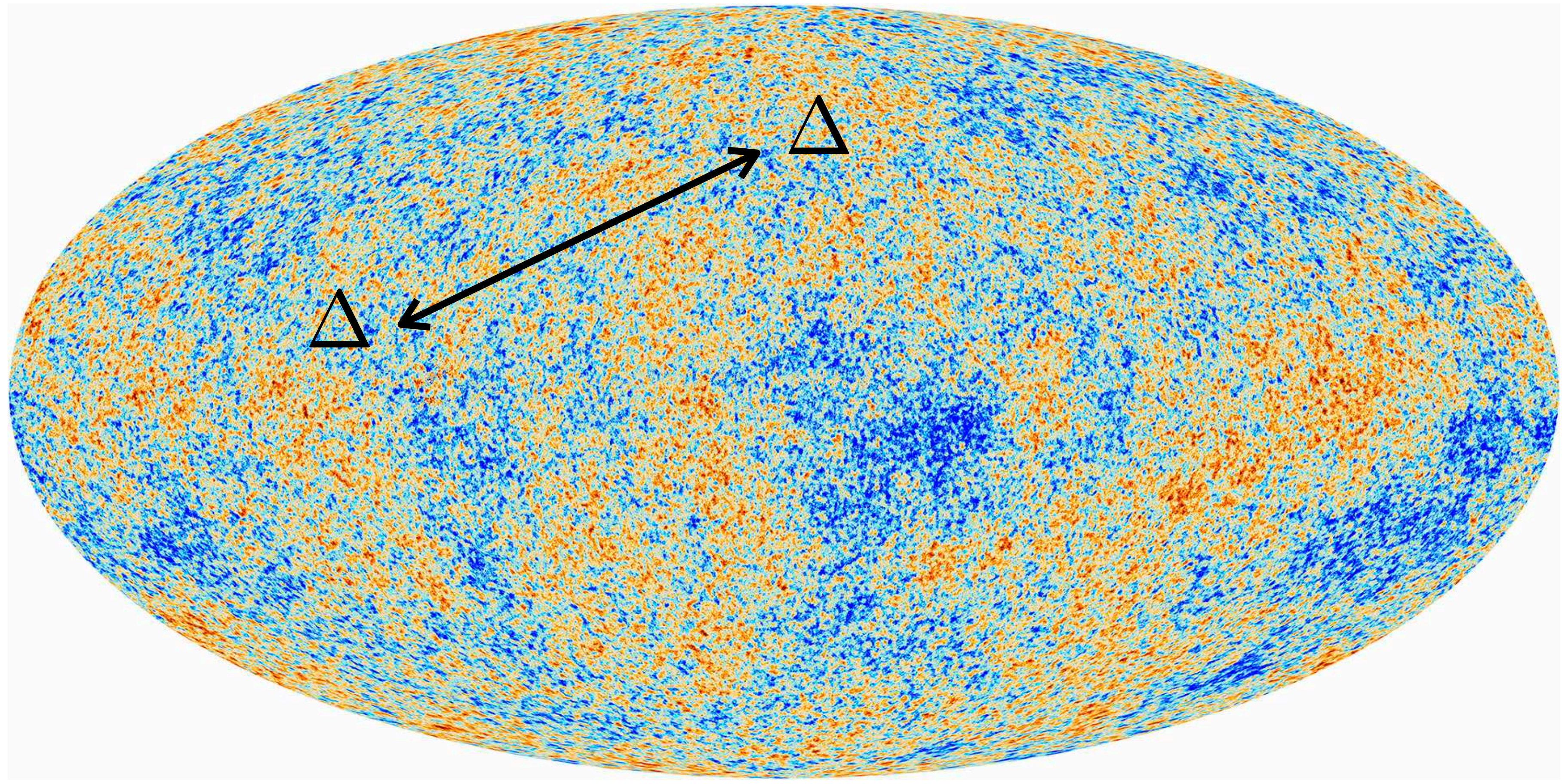
- Isocurvature power spectrum

$$P_{\rm iso} \sim \langle S_{{\rm dr},\gamma} S_{{\rm dr},\gamma} \rangle \sim P_\chi$$

DR inherits large scale isocurvature perturbations from χ field

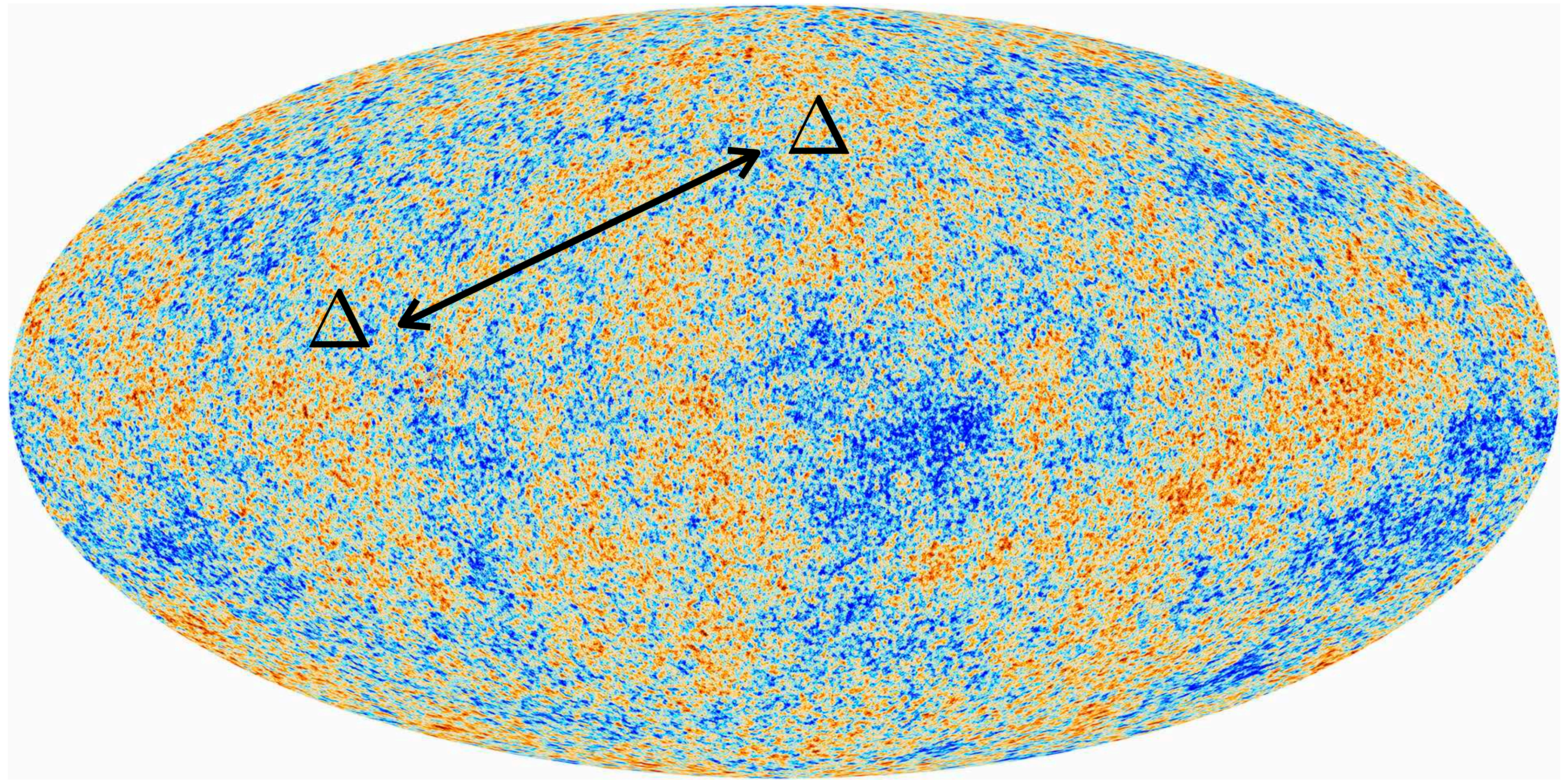
DR isocurvature in CMB

$$\Delta \equiv \Delta T/\bar{T}$$



DR isocurvature in CMB

$$\Delta \equiv \Delta T/\bar{T}$$



- $\langle \Delta\Delta \rangle$ gives angular power spectrum:

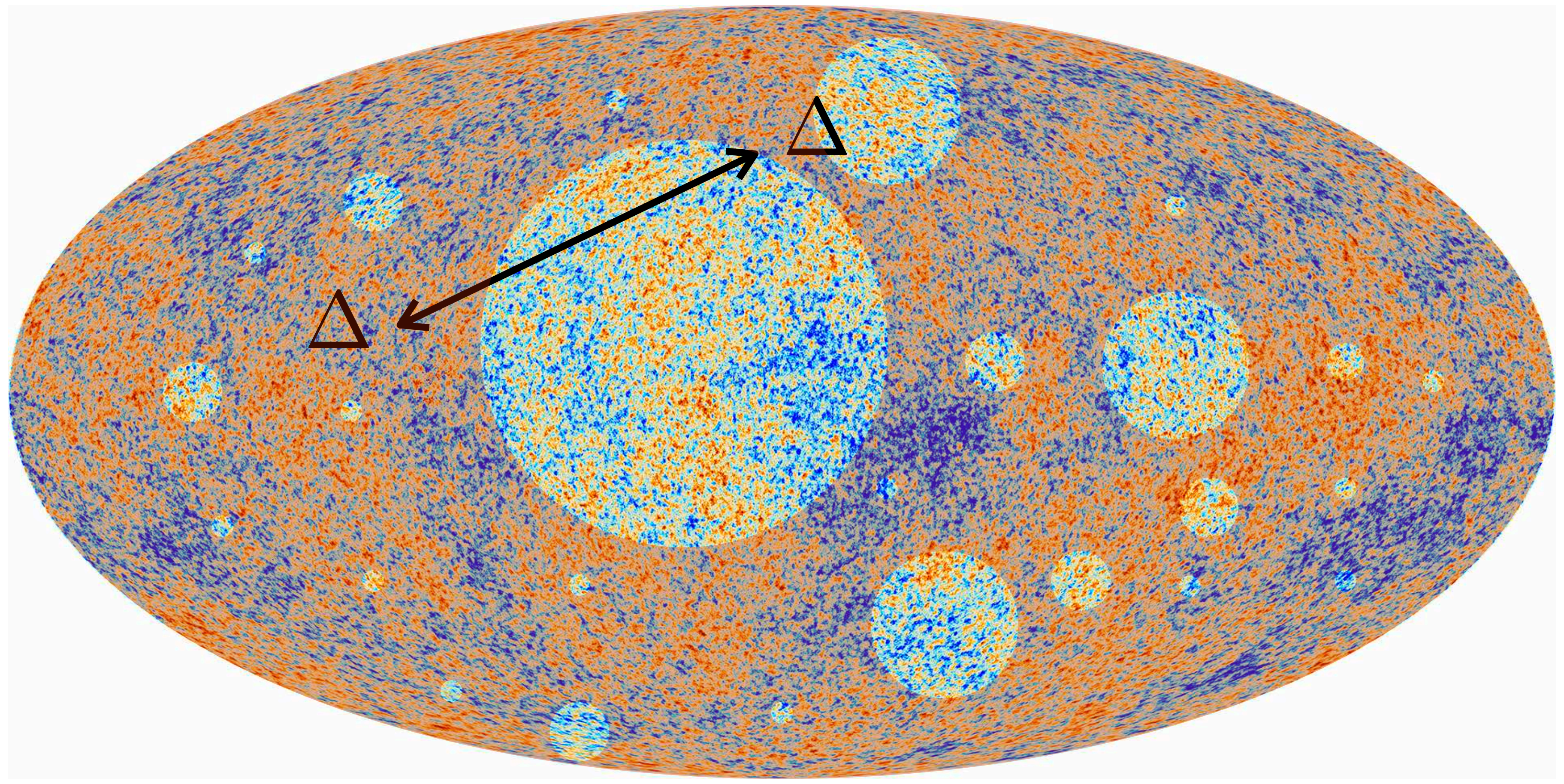
$$C_\ell^{TT} = 4\pi \int d(\ln k) P_{\rm ad}(k) |\Delta_\ell^{\rm ad}(k)|^2$$

$$P_{\rm ad}(k) = A_s \left(\frac{k}{k_{\rm pivot}}\right)^{n_s - 1}$$

Standard ΛCDM

DR isocurvature in CMB

$$\Delta \equiv \Delta T/\bar{T}$$



- $\langle \Delta\Delta \rangle$ gives angular power spectrum:

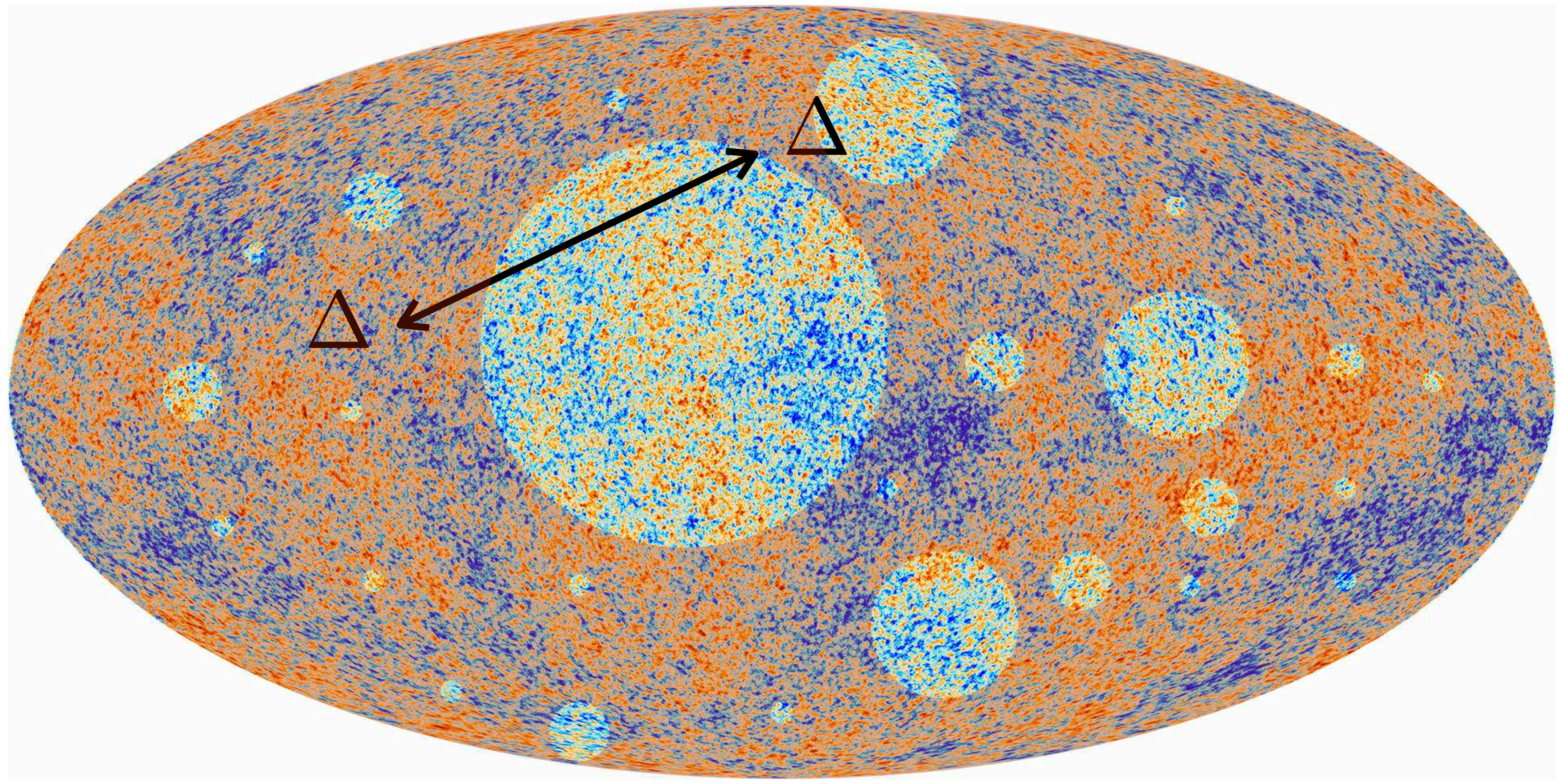
$$C_\ell^{TT} = 4\pi \int d(\ln k) \left(P_{\rm ad}(k) |\Delta_\ell^{\rm ad}(k)|^2 + P_{\rm iso}(k) |\Delta_\ell^{\rm iso}(k)|^2 \right)$$

$$P_{\rm ad}(k) = A_s \left(\frac{k}{k_{\rm pivot}} \right)^{n_s - 1}$$ Standard ΛCDM

$$P_{\rm iso}(k) = f_{\rm iso}^2 A_s \begin{cases} (k/k_i)^3 & k \leq k_i \\ 1 & k > k_i \end{cases}$$ DR iso from PT

DR isocurvature in CMB

$$\Delta \equiv \Delta T/\bar{T}$$



- $\langle \Delta\Delta \rangle$ gives angular power spectrum:

$$C_\ell^{TT} = 4\pi \int d(\ln k)\, \left(P_{\rm ad}(k)|\Delta_\ell^{\rm ad}(k)|^2 + P_{\rm iso}(k)|\Delta_\ell^{\rm iso}(k)|^2\right)$$

$$P_{\rm ad}(k) = A_s \left(\frac{k}{k_{\rm pivot}}\right)^{n_s-1}$$ Standard ΛCDM

$$P_{\rm iso}(k) = f_{\rm iso}^2 A_s \begin{cases} (k/k_i)^3 & k \leq k_i \\ 1 & k > k_i \end{cases}$$ DR iso from PT

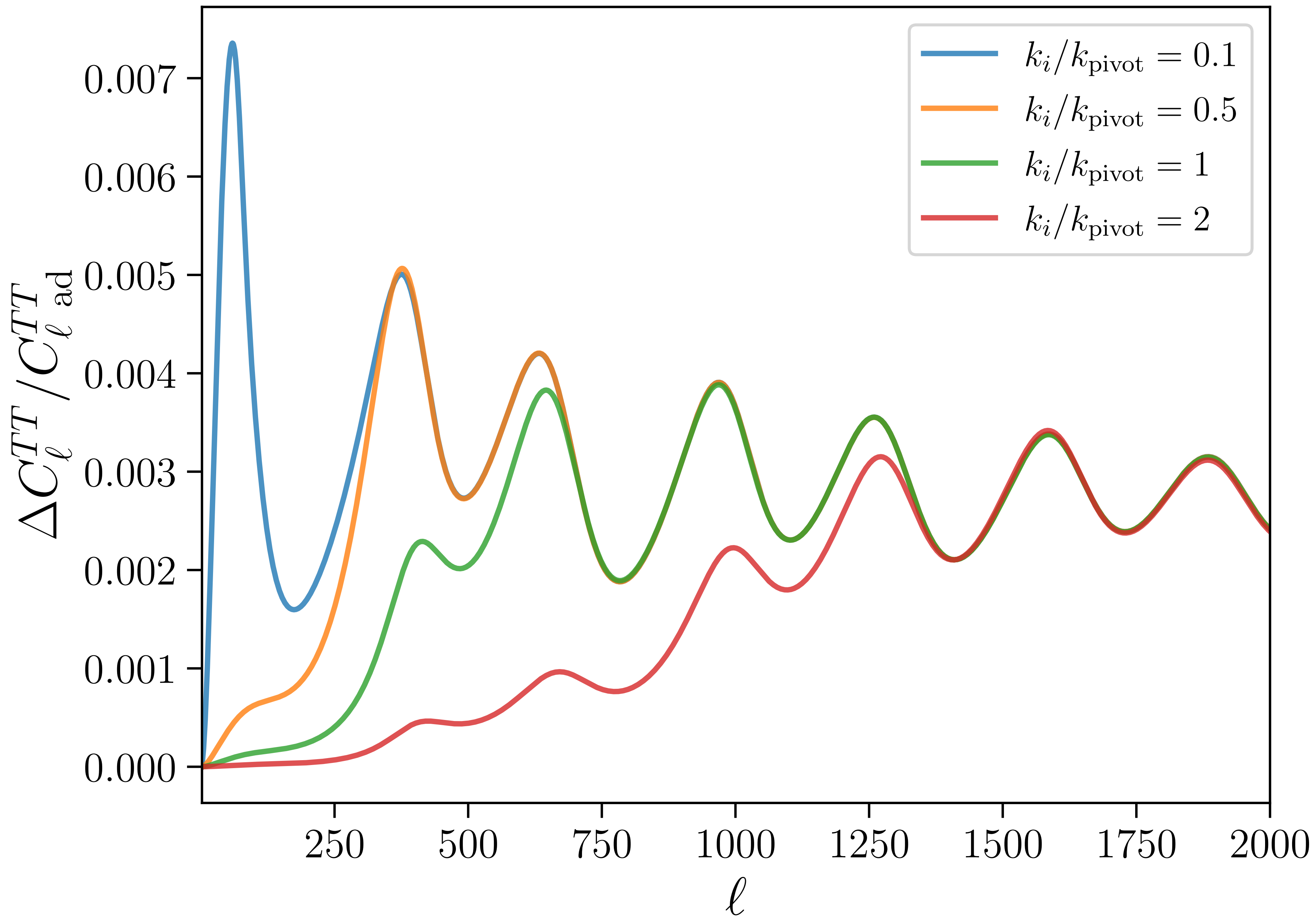
- Mapping to PT parameters

$$f_{\rm iso}^2 A_s \sim \gamma_{\rm PT} = (T_*^8/T_{\rm rh}^8)$$

$$k_i \sim r_i^{-1}$$

DR isocurvature in CMB

Simulation from modified CLASS

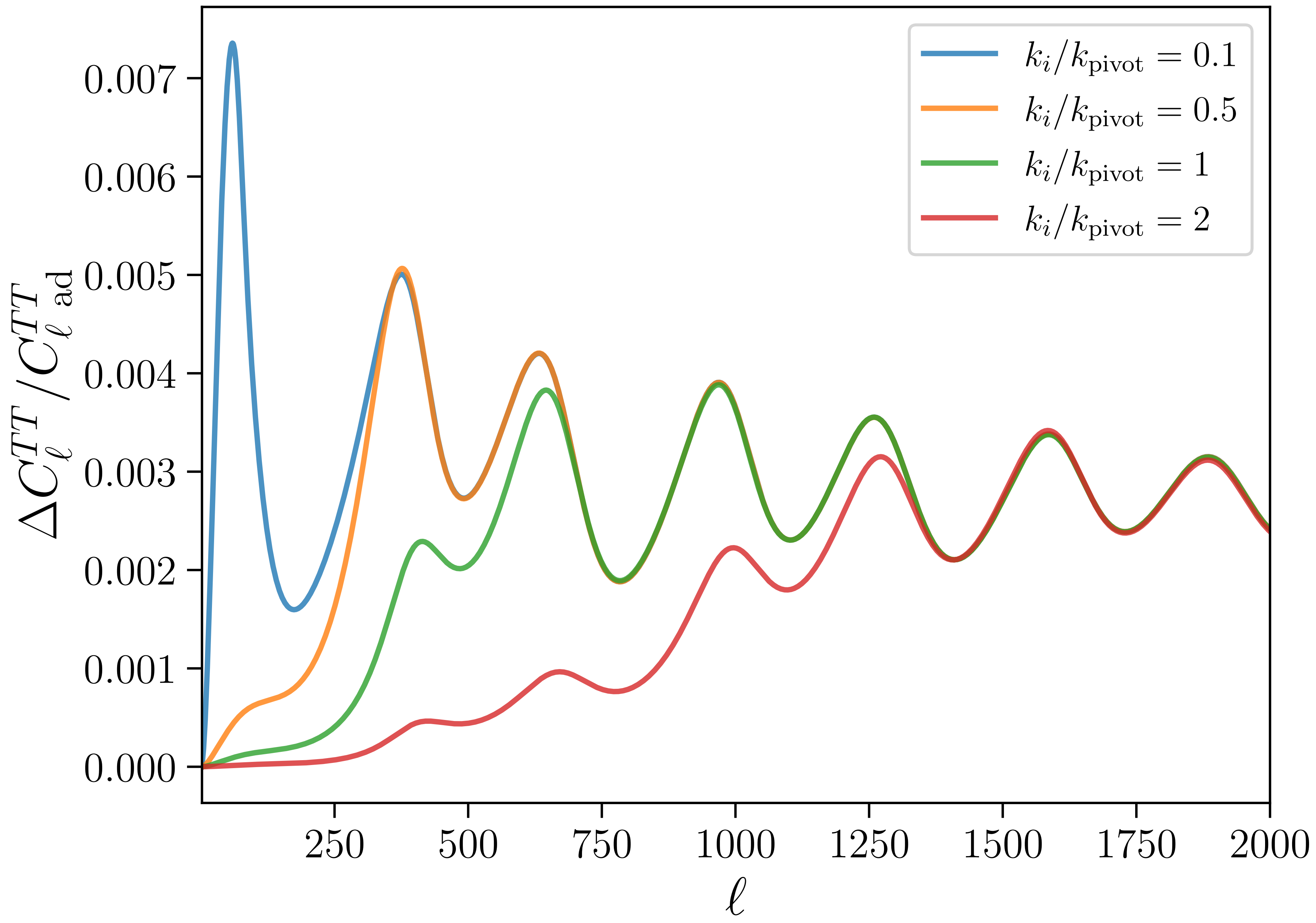


$$\Delta N_{\rm eff} = 0.1 \quad f_{\rm iso} = 10 \quad k_{\rm pivot} = 0.05\,{\rm Mpc}^{-1}$$

$$P_{\rm iso}(k) = f_{\rm iso}^2 A_s \begin{cases} (k/k_i)^3 & k \le k_i \\ 1 & k > k_i \end{cases}$$

DR isocurvature in CMB

Simulation from modified CLASS

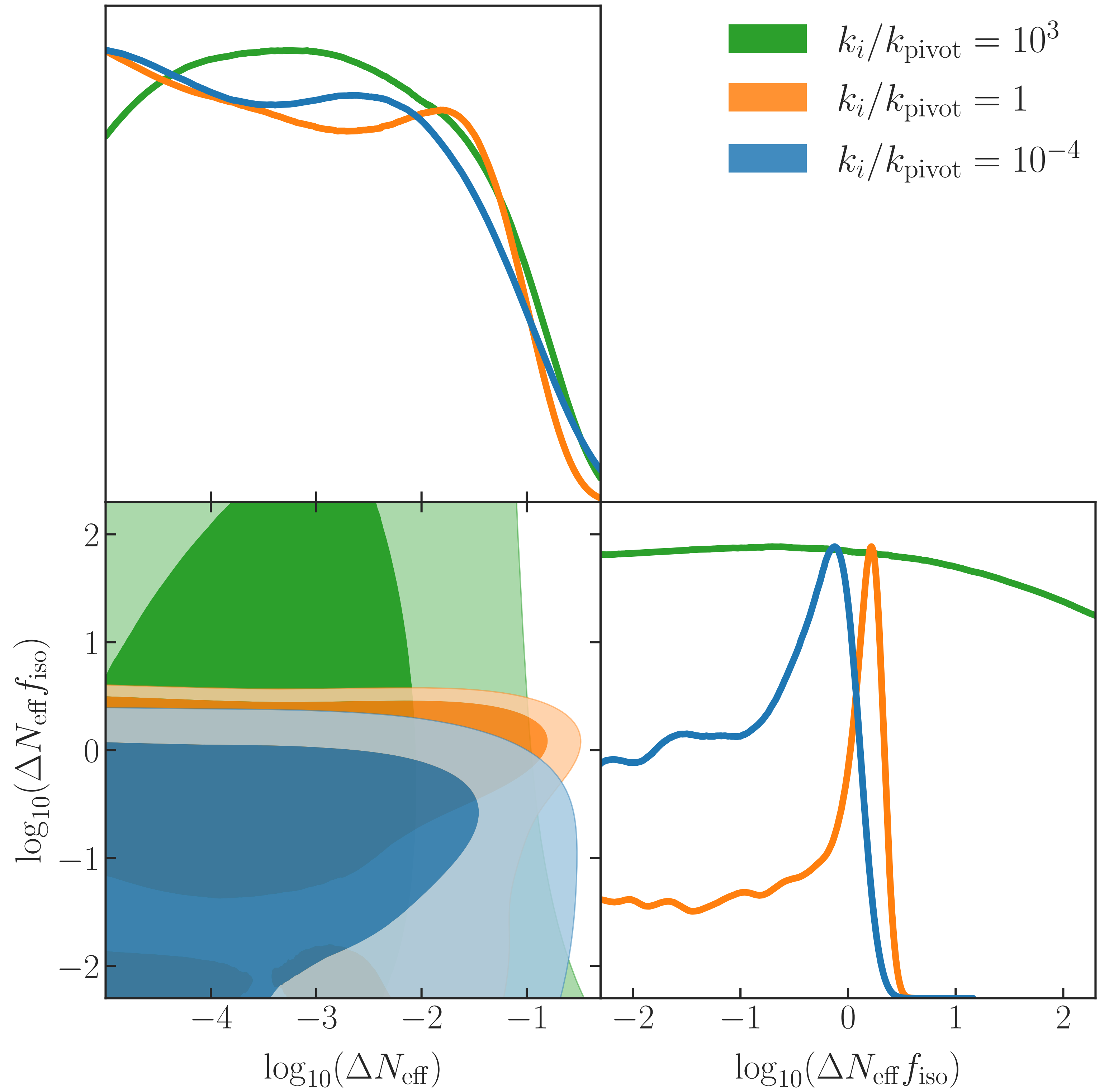


$$\Delta N_{\rm eff} = 0.1 \quad f_{\rm iso} = 10 \quad k_{\rm pivot} = 0.05\,{\rm Mpc}^{-1}$$

$$P_{\rm iso}(k) = f_{\rm iso}^2 A_s \begin{cases} (k/k_i)^3 & k \le k_i \\ 1 & k > k_i \end{cases}$$

$$f_{\rm iso}^2 A_s \sim \gamma_{\rm PT} = (T_*^8/T_{\rm rh}^8)$$

Constraints from Planck18+BAO

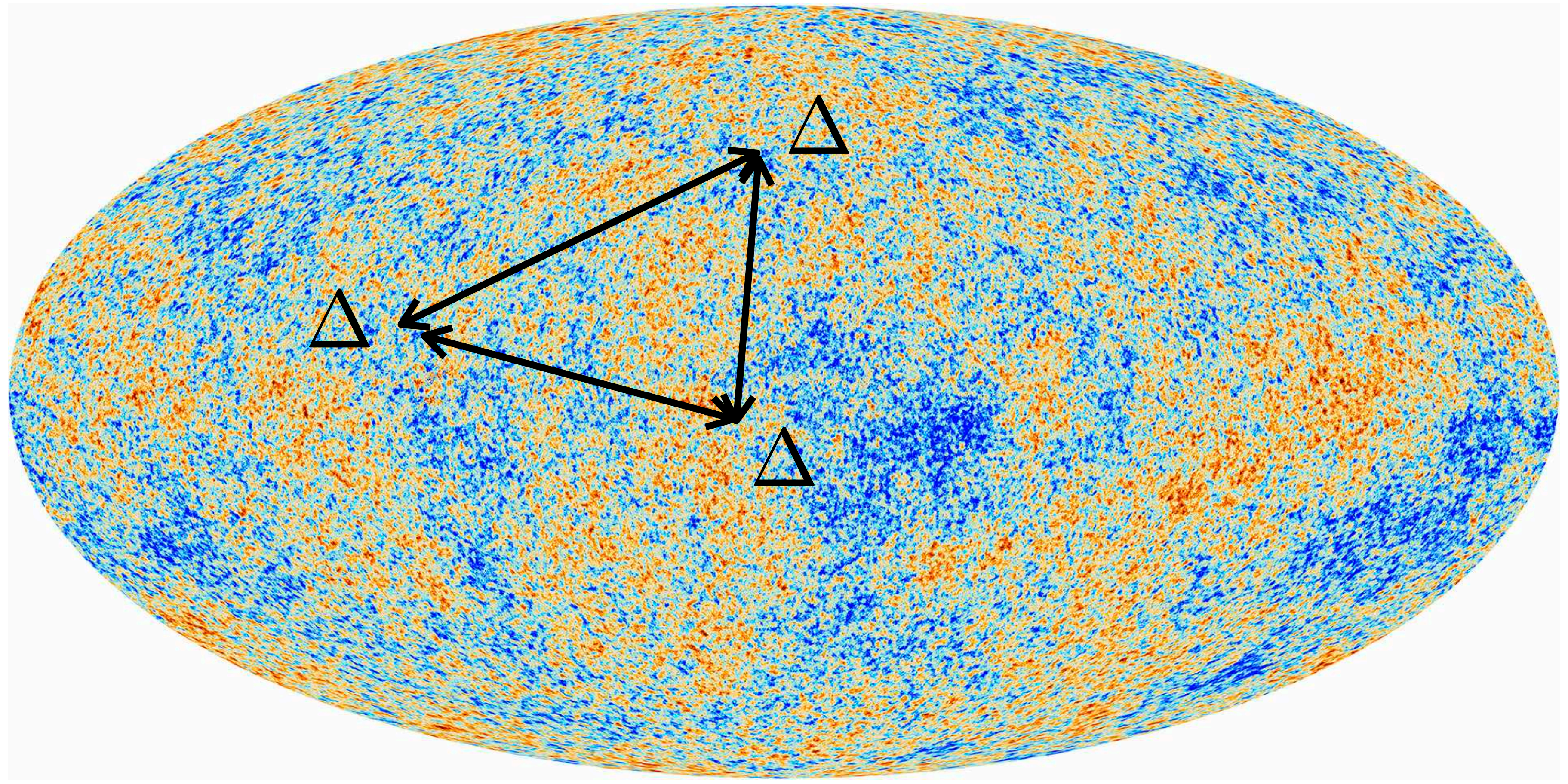


For $k_i \lesssim k_{\rm pivot}$ $\quad \Delta N_{\rm eff} f_{\rm iso} \lesssim O(1)$

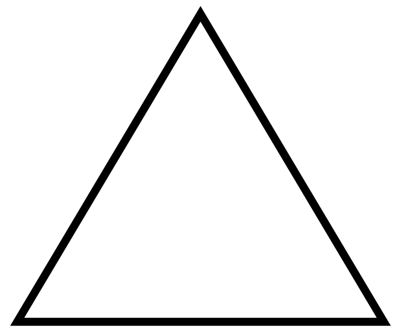
$$\Delta N_{\rm eff} \lesssim 10^{-5}(T_*/T_{\rm rh})^{-4}$$

Buckley, PD, Fernandez, Weikert, *JCAP*, 2024

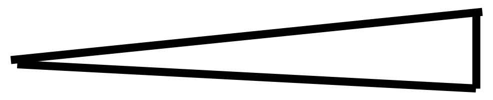
Non-Gaussianity from DR isocurvature



- $\langle \Delta\Delta\Delta \rangle$ encodes non-Gaussianity

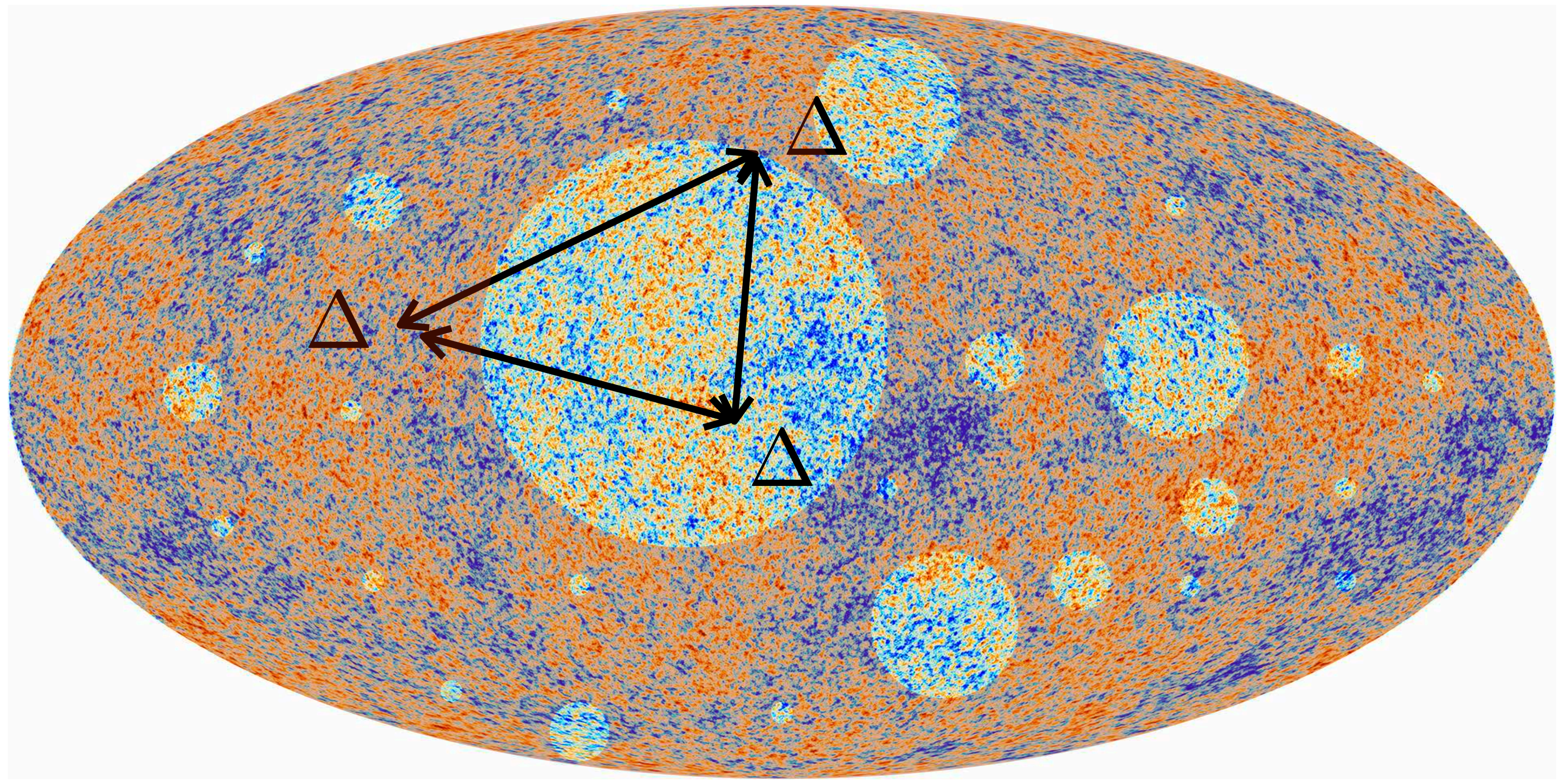


$k_1 \approx k_2 \approx k_3$
equilateral

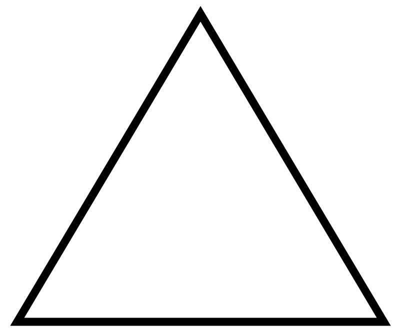


$k_1 \approx k_2 \gg k_3$
local (squeezed limit)

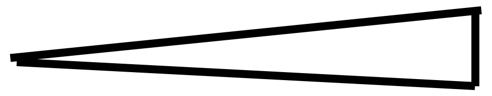
Non-Gaussianity from DR isocurvature



- $\langle \Delta\Delta\Delta \rangle$ encodes non-Gaussianity



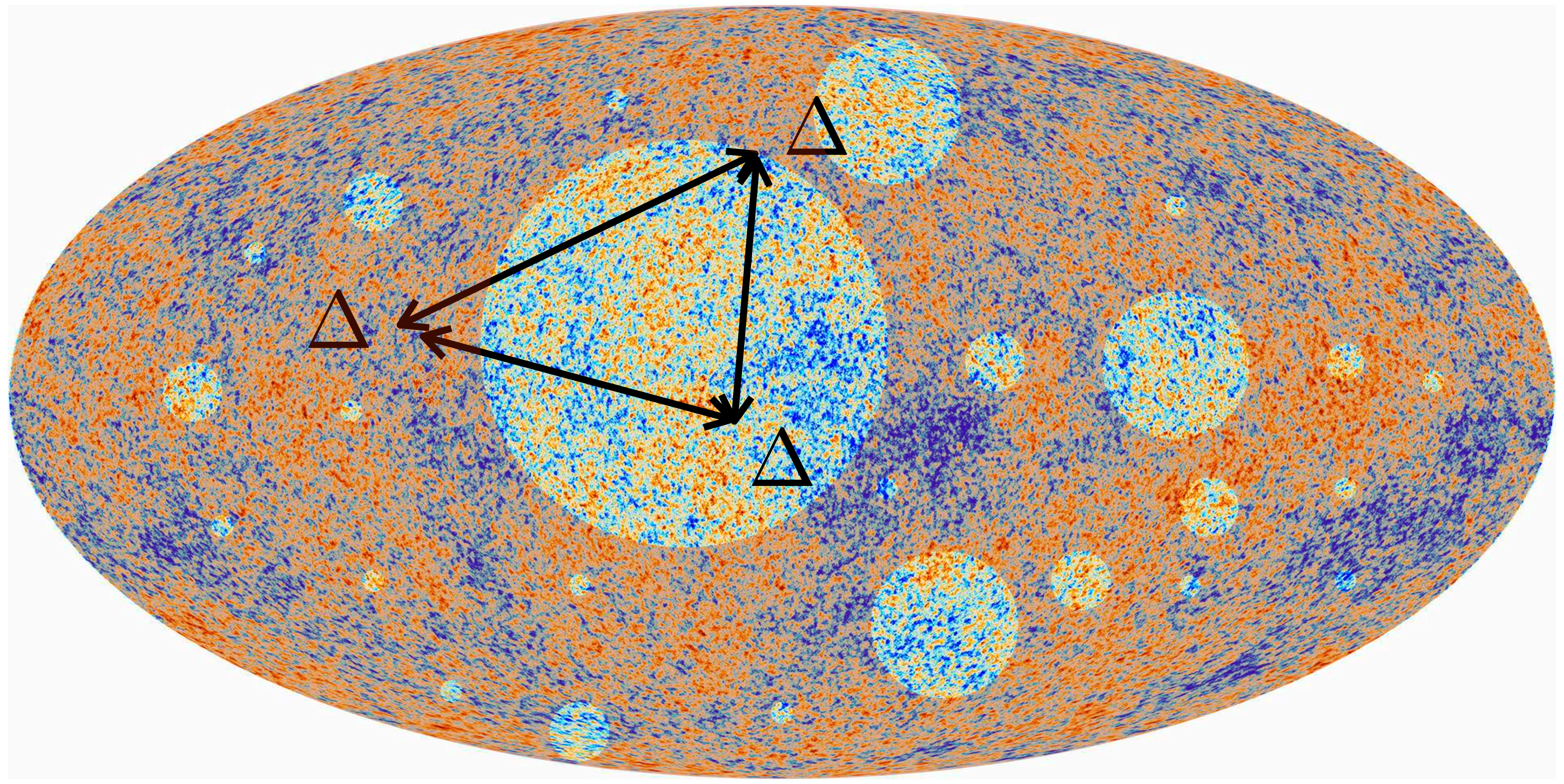
$k_1 \approx k_2 \approx k_3$
equilateral



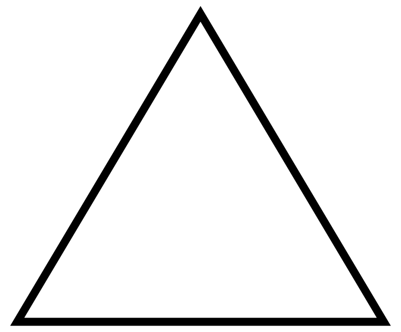
$k_1 \approx k_2 \gg k_3$
local (squeezed limit)

- DR isocurvature non-Gaussianity needs dedicated searches!

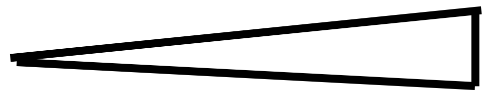
Non-Gaussianity from DR isocurvature



- $\langle \Delta\Delta\Delta \rangle$ encodes non-Gaussianity



$k_1 \approx k_2 \approx k_3$
equilateral



$k_1 \approx k_2 \gg k_3$
local (squeezed limit)

- DR isocurvature non-Gaussianity needs dedicated searches!

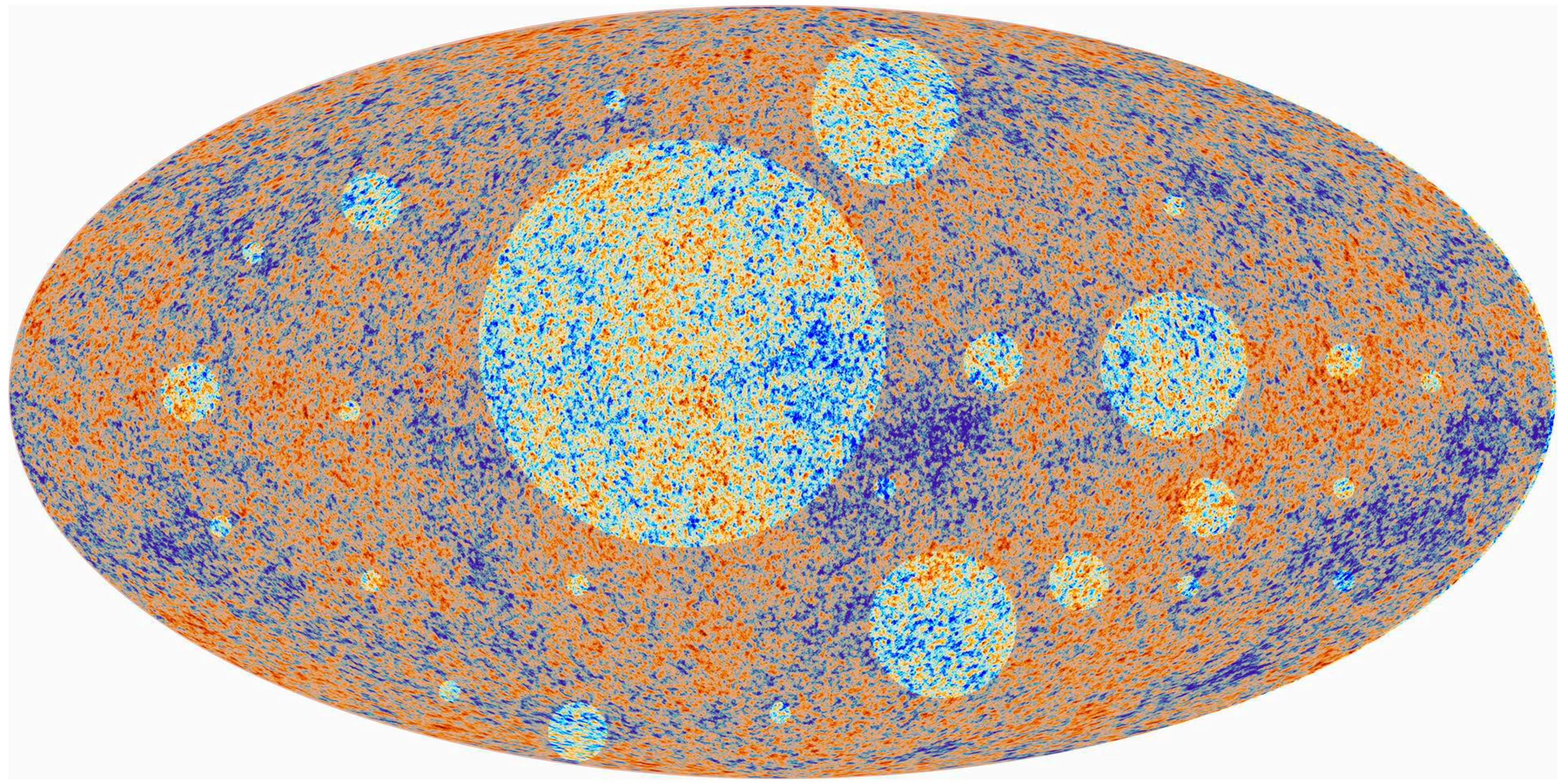
- Estimation based on neutrino iso NG with equil. config.

$$\Delta N_{\rm eff}^3 f_{\rm iso}^2 \lesssim 2 \times 10^{-4}$$

Buckley,PD,Fernandez,Weikert, *JCAP,* 2024

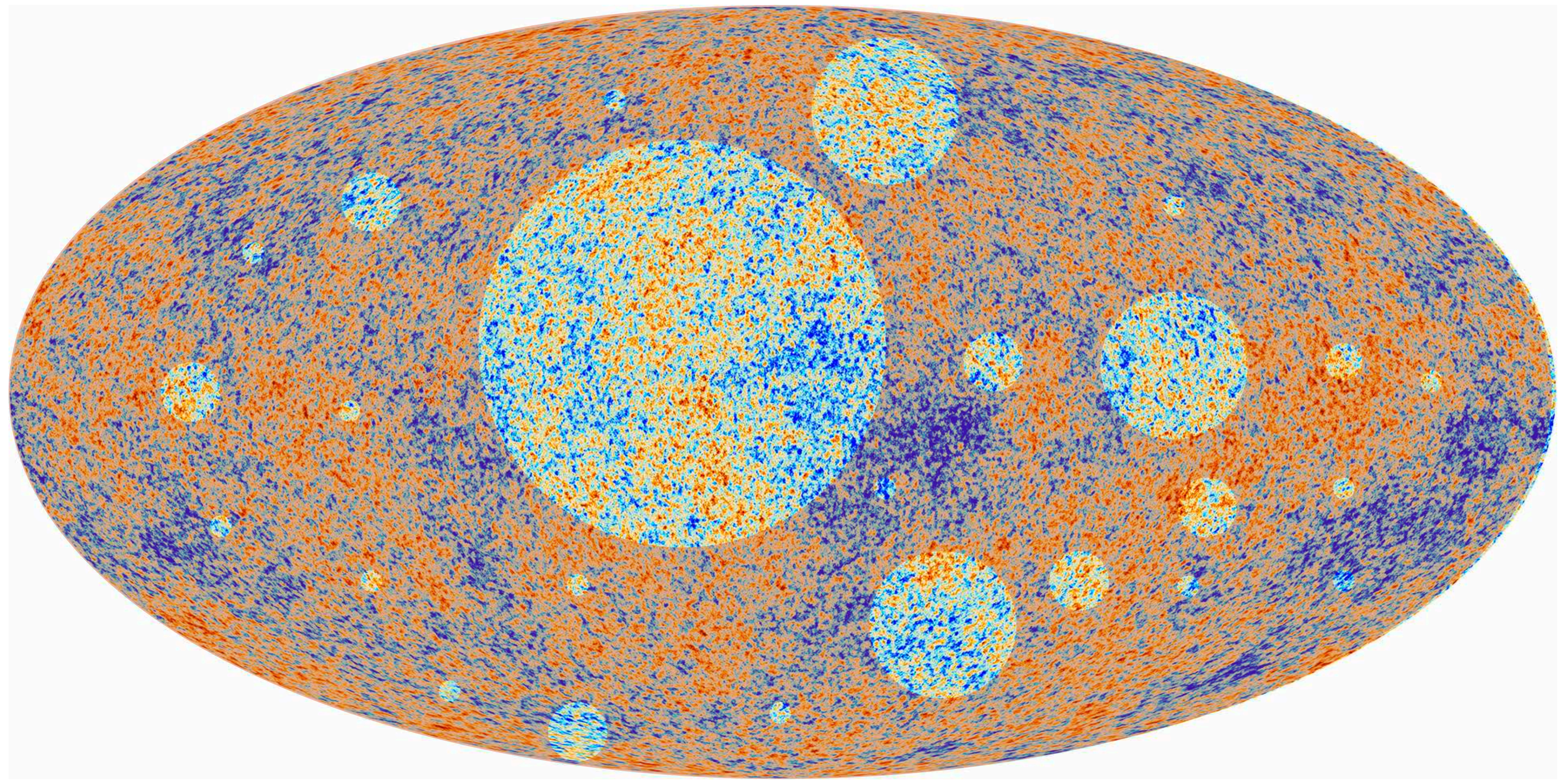
could be stronger than two-point functions $\Delta N_{\rm eff} f_{\rm iso} \lesssim O(1)$

Future directions

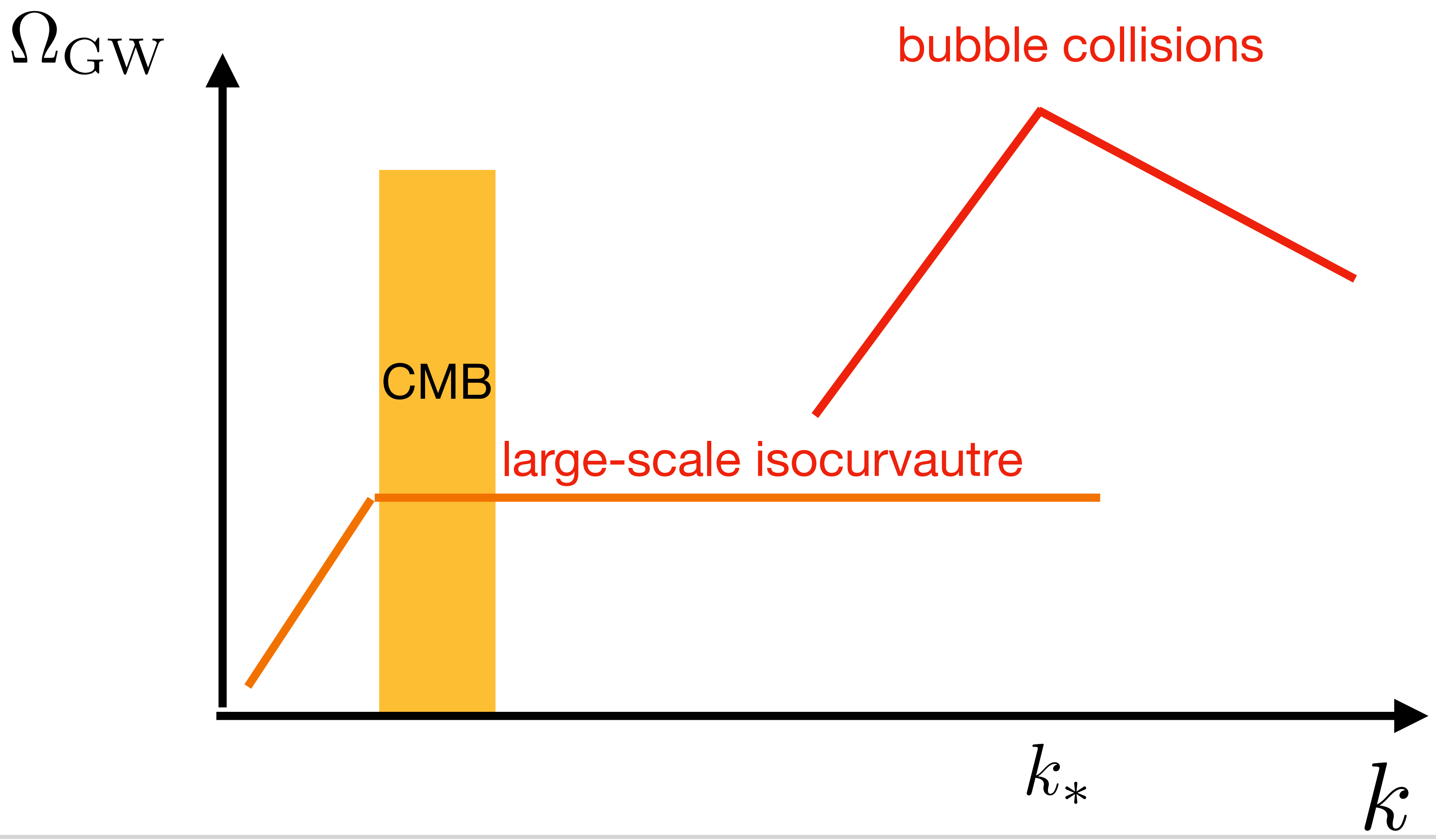


- Dedicated study for general form of non-Gaussianity

Future directions



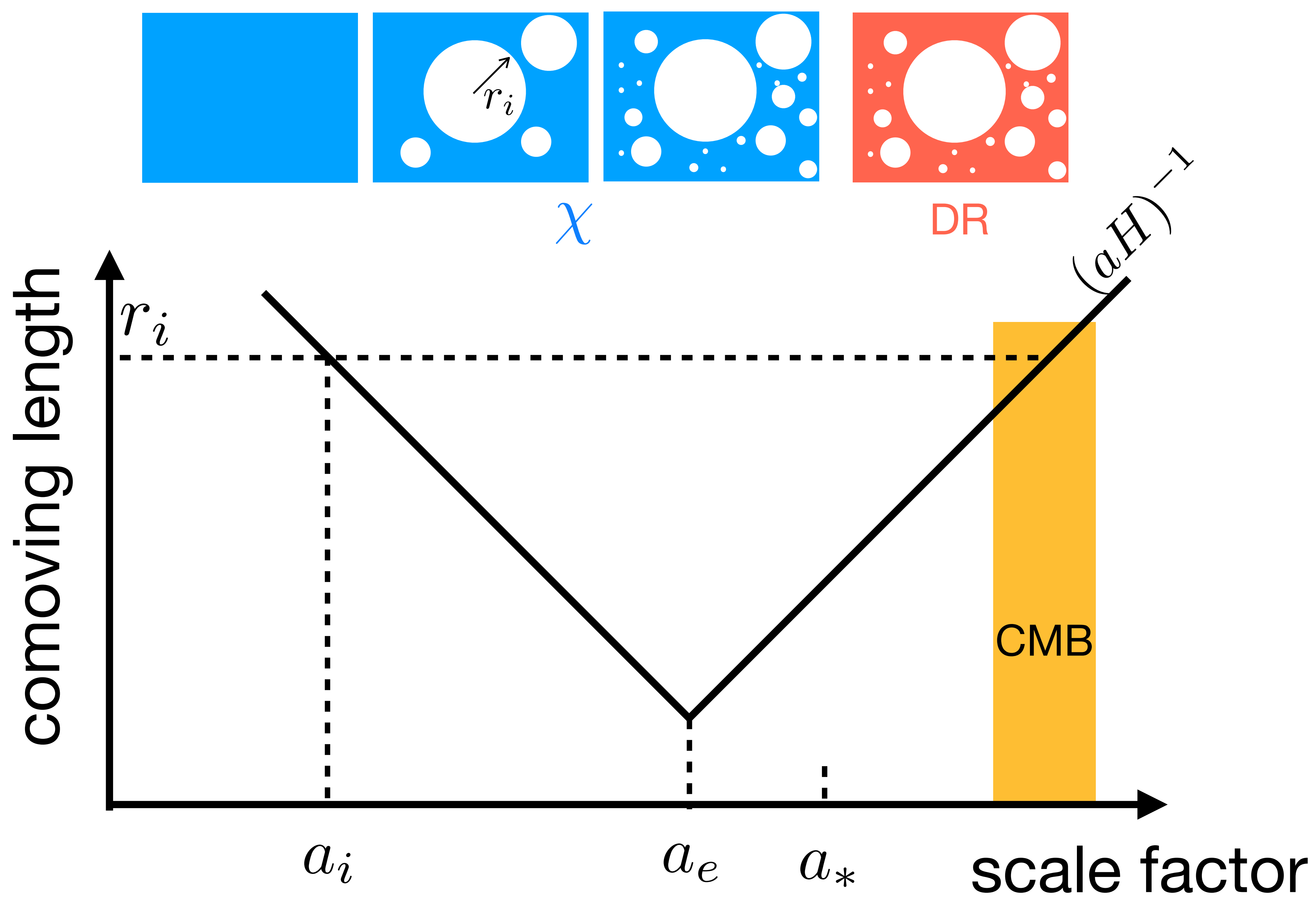
- Dedicated study for general form of non-Gaussianity

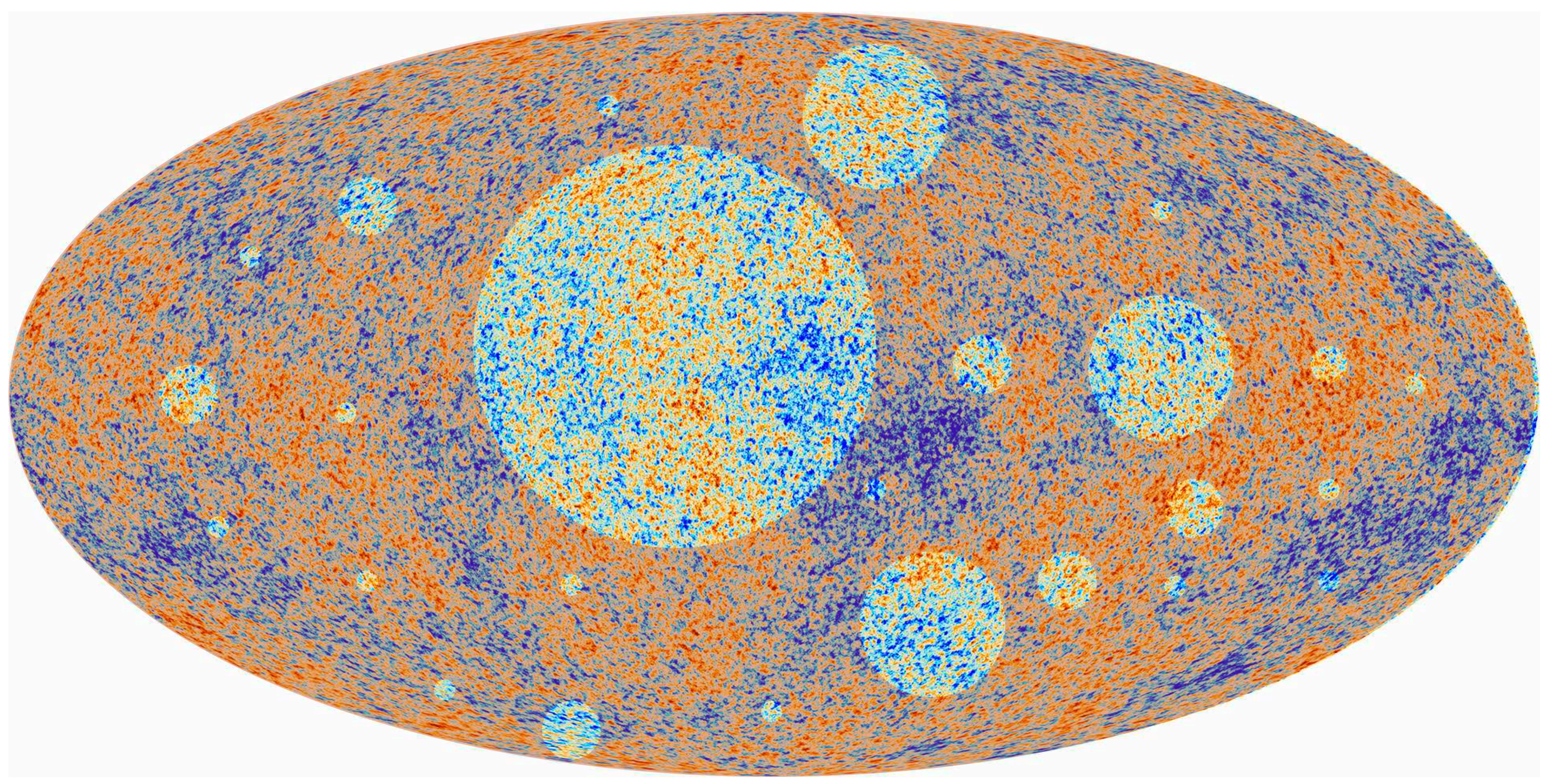


- GWs from PT could have large-scale isocurvature

Conclusions

- Slow PT during inflation can generate large scale DR isocurvature in CMB
- DR isocurvature can put stronger constraint on $\Delta N_{\rm eff}$
- DR isocurvature also generates non-Gaussianity in CMB, dedicated studies are needed

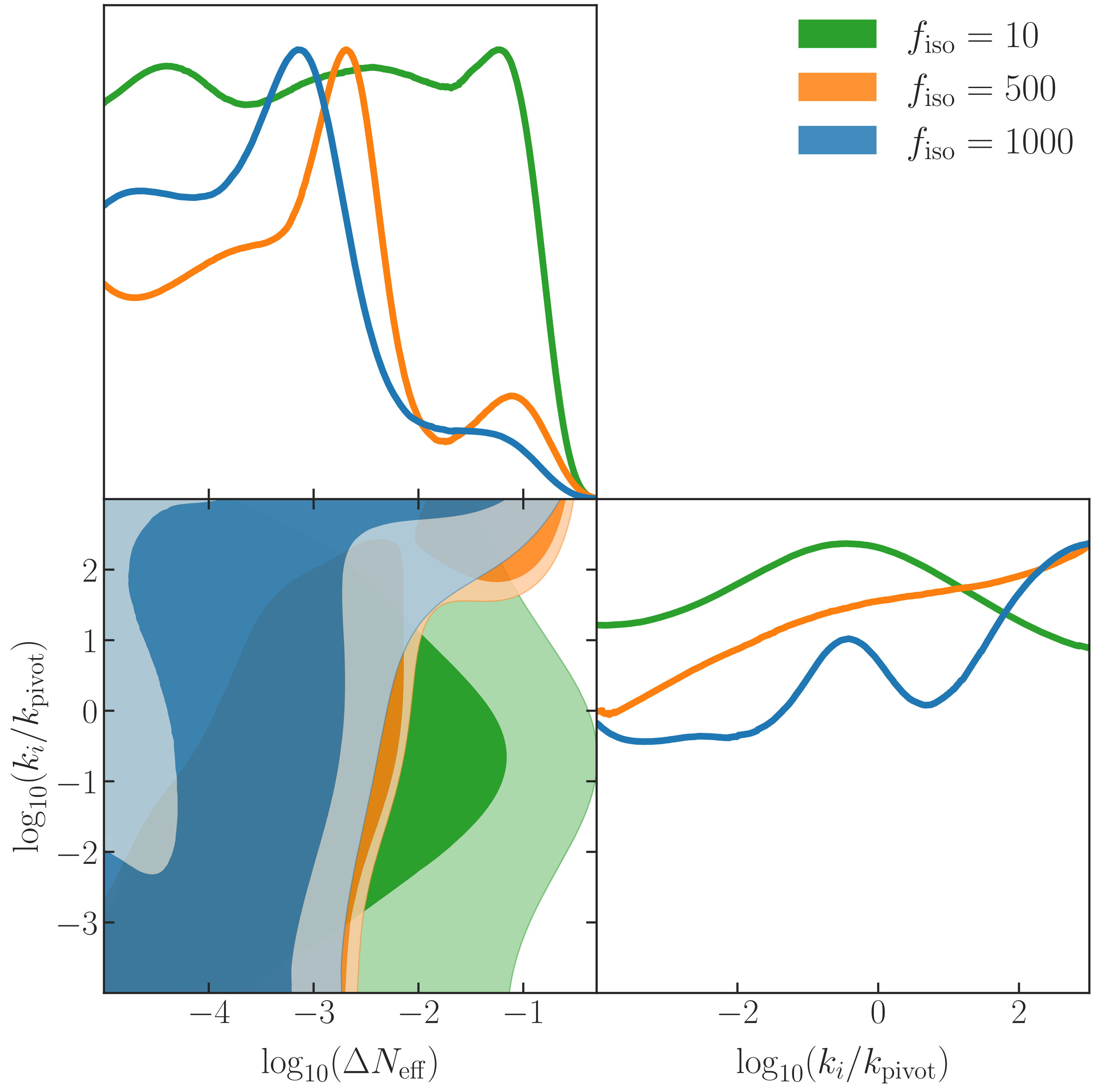


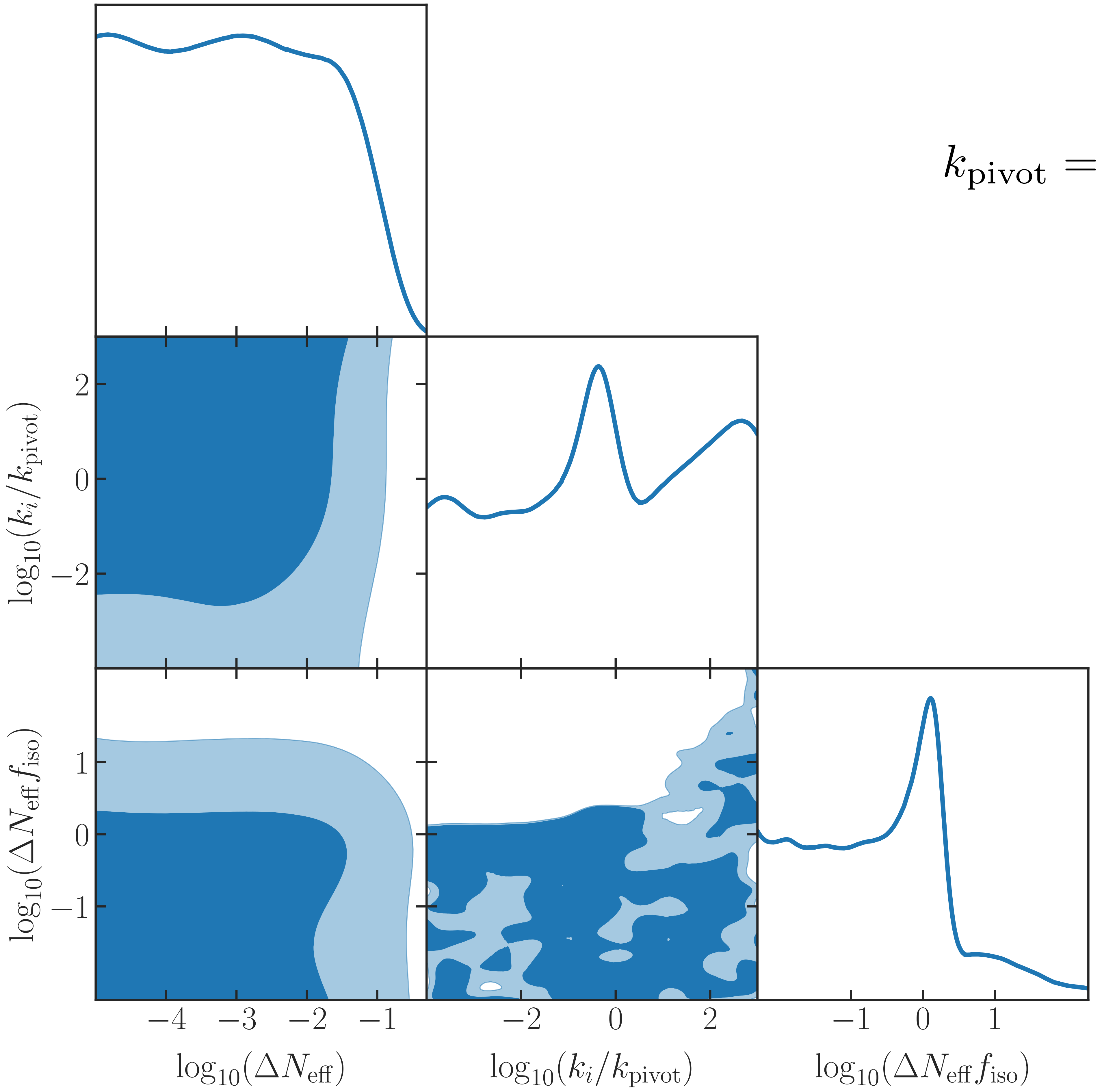


Thank you!

DR isocurvature constraint

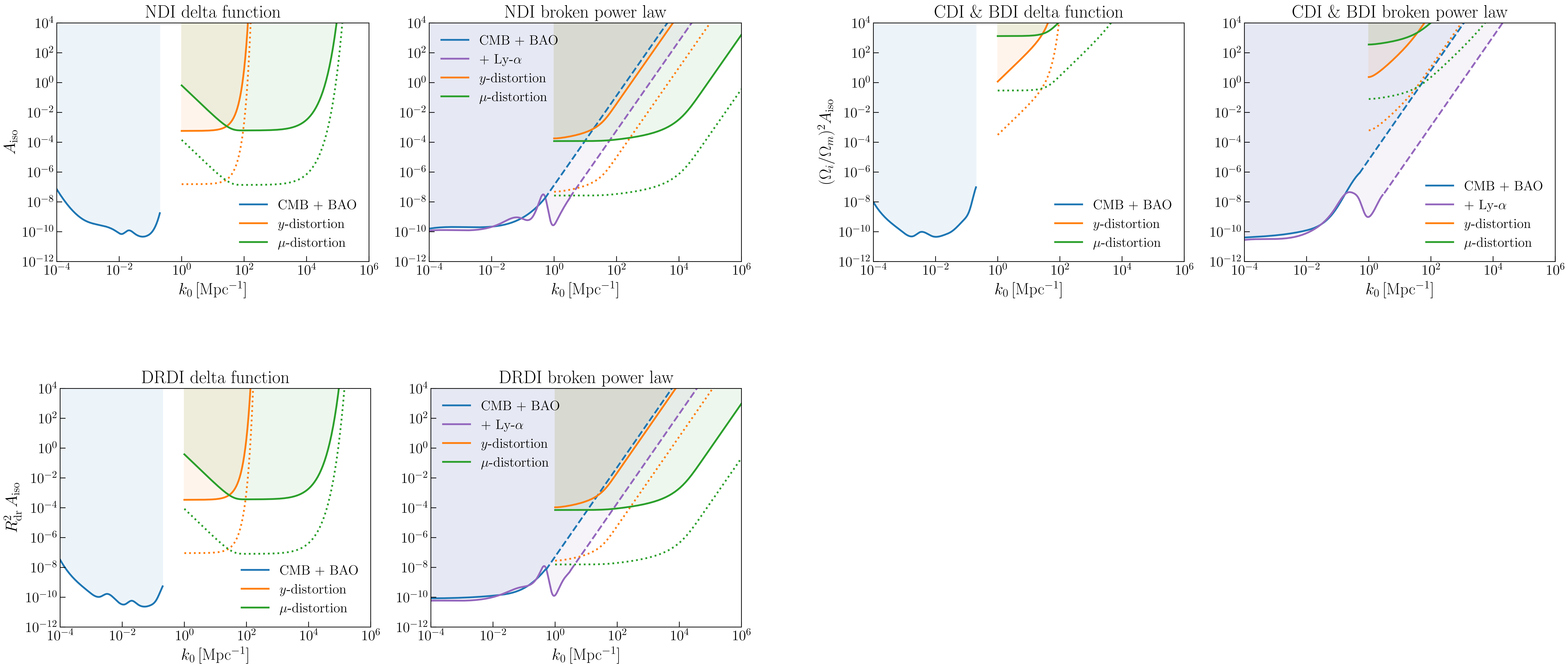
Constraints from Planck18+BAO





Buckley,PD,Fernandez,Weikert, 2024

General isocurvature constraints



Buckley,PD,Fernandez,Weikert, 2025