Dark Radiation Isocurvature from Cosmological Phase Transitions

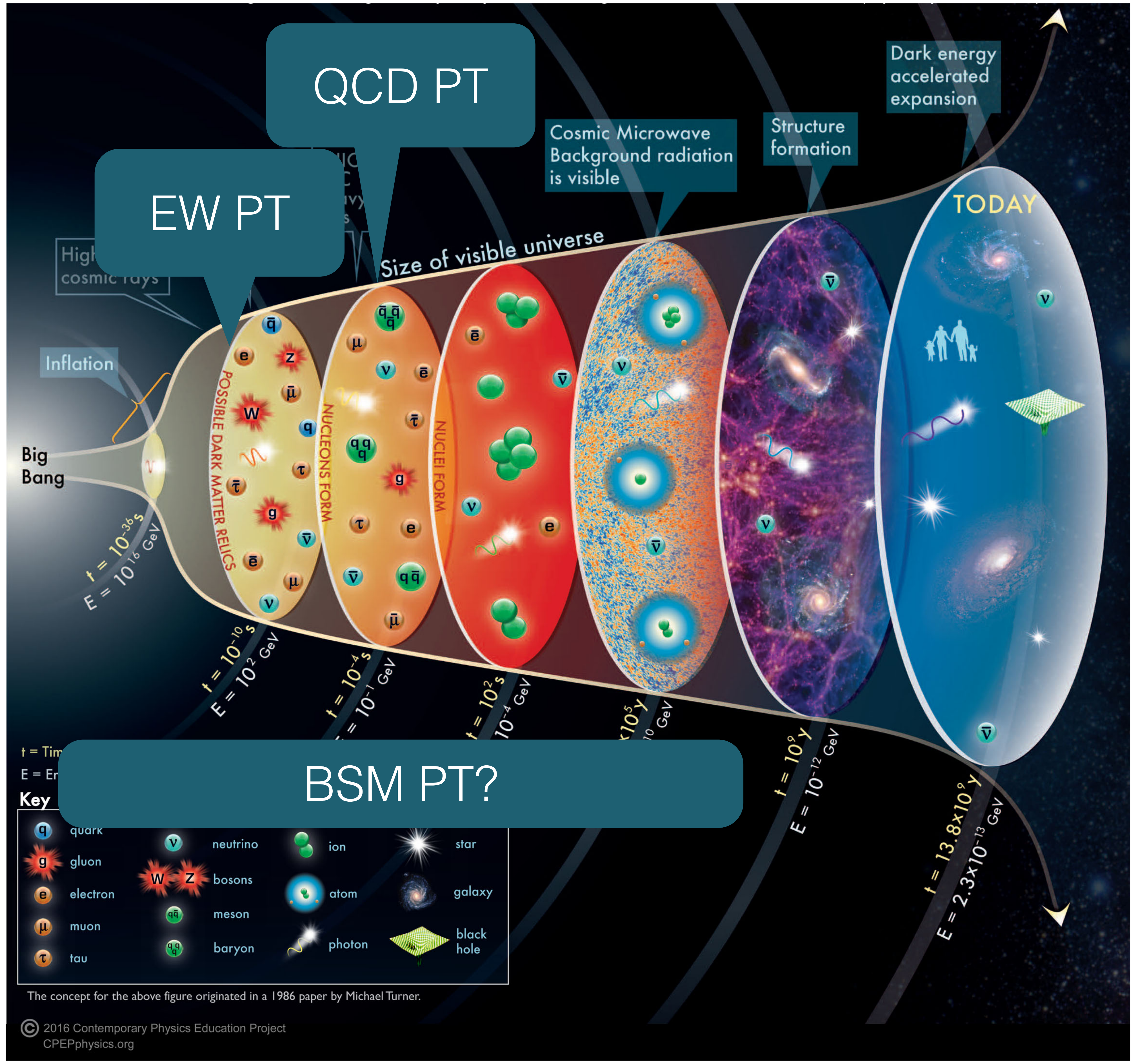
Peizhi Du
Rutgers University

CETUP Workshop 2024
Lead, South Dakota
June 17, 2024

in collaboration with Matthew Buckley, Nicolas Fernandez, Mitchell Weikert

(arXiv: 2402.13309)

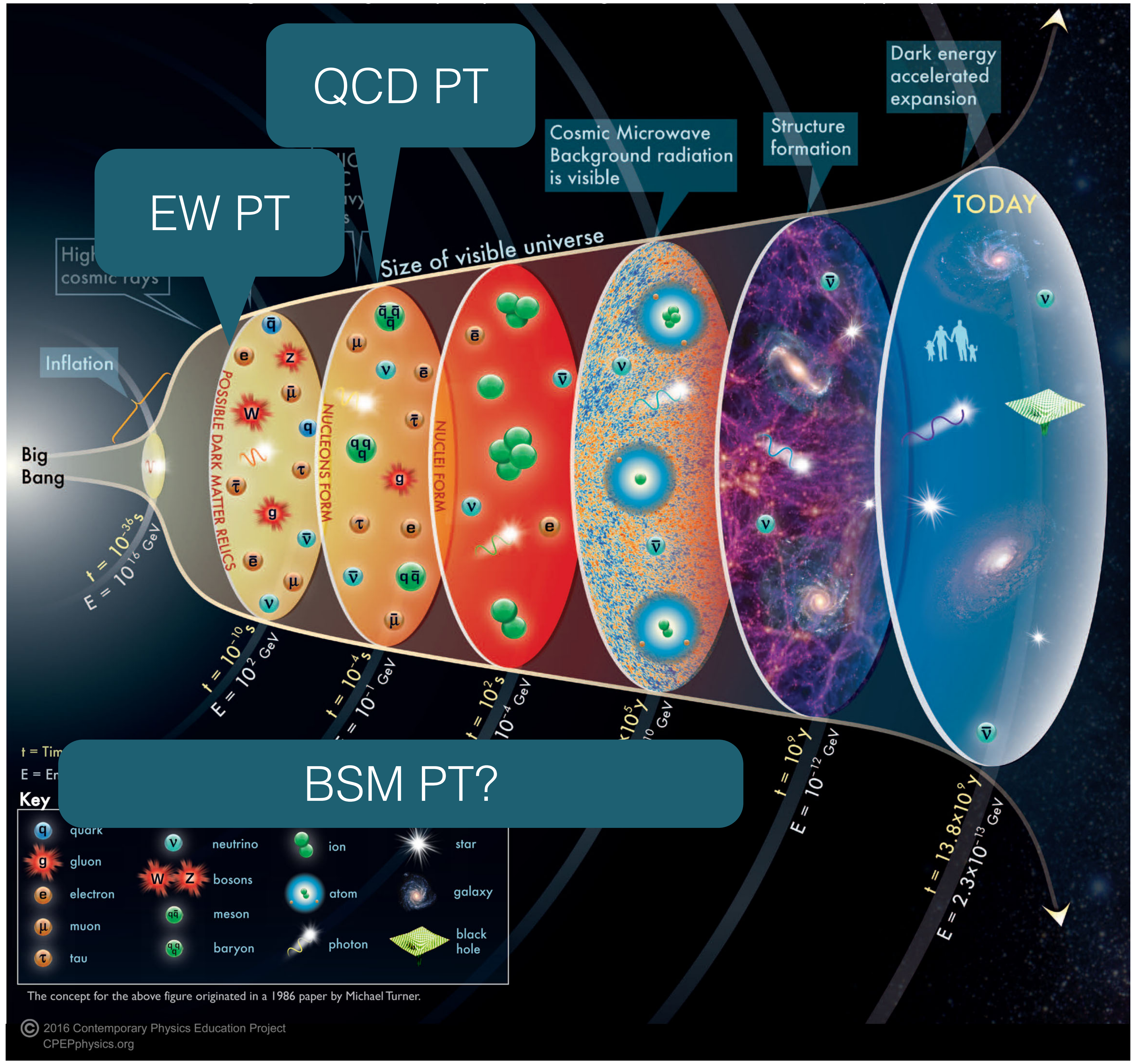
Cosmological Phase Transitons

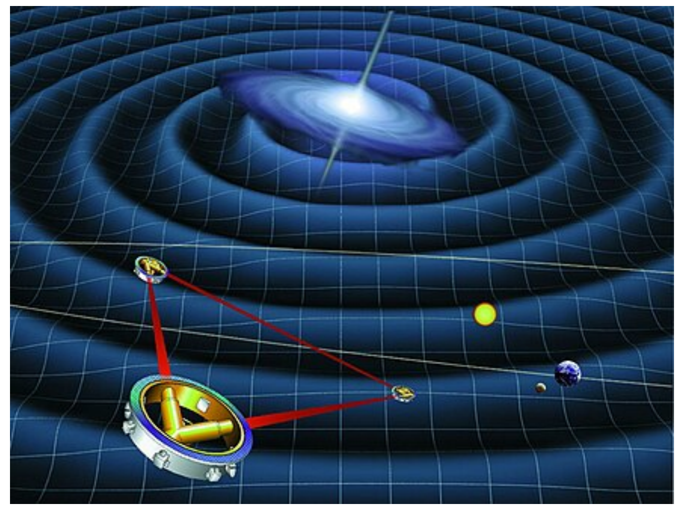


Rich new physics:

baryogenesis, dark matter, EW hierarchy problem…

Cosmological Phase Transitons

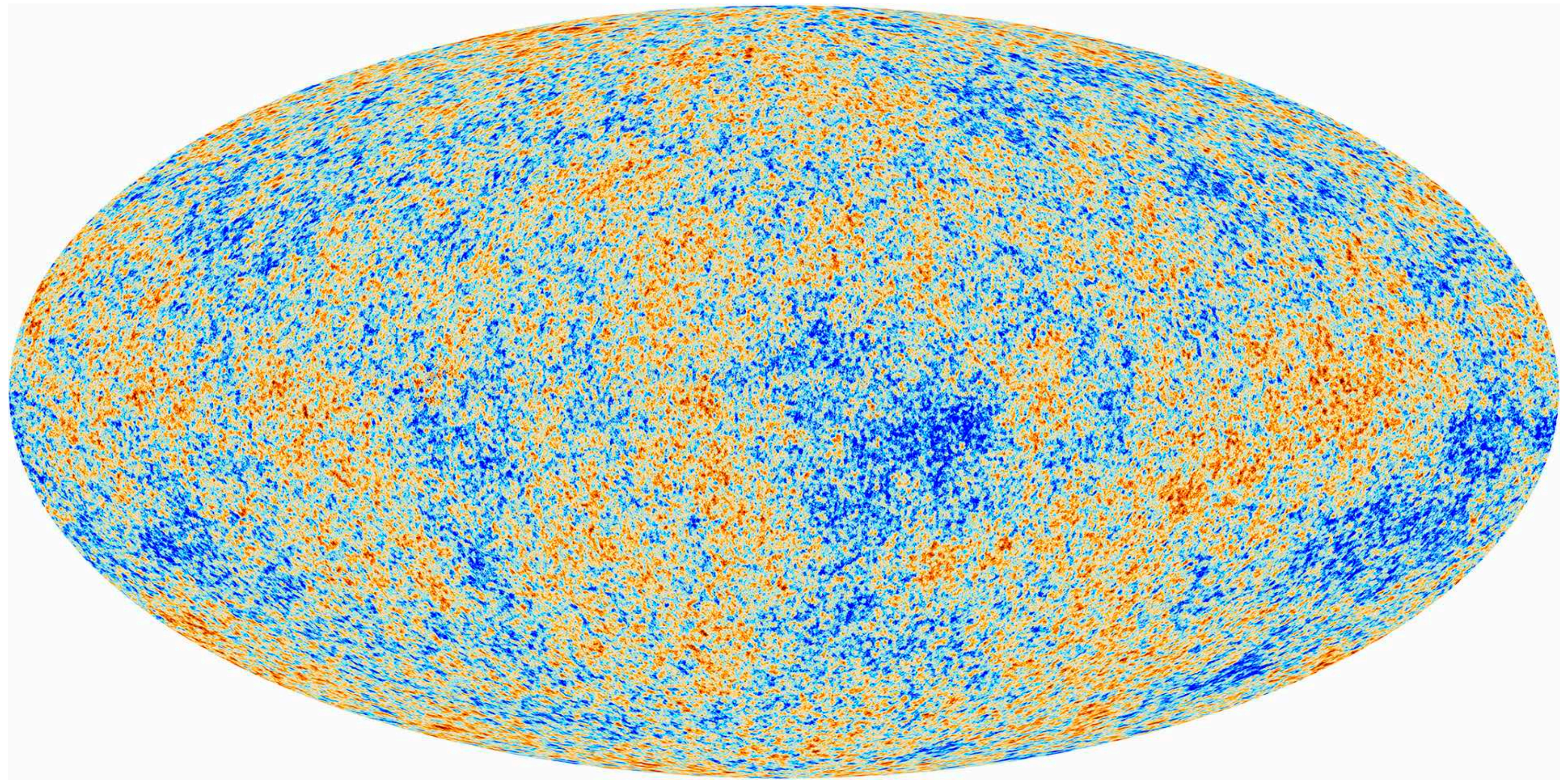




PTA

LIGO

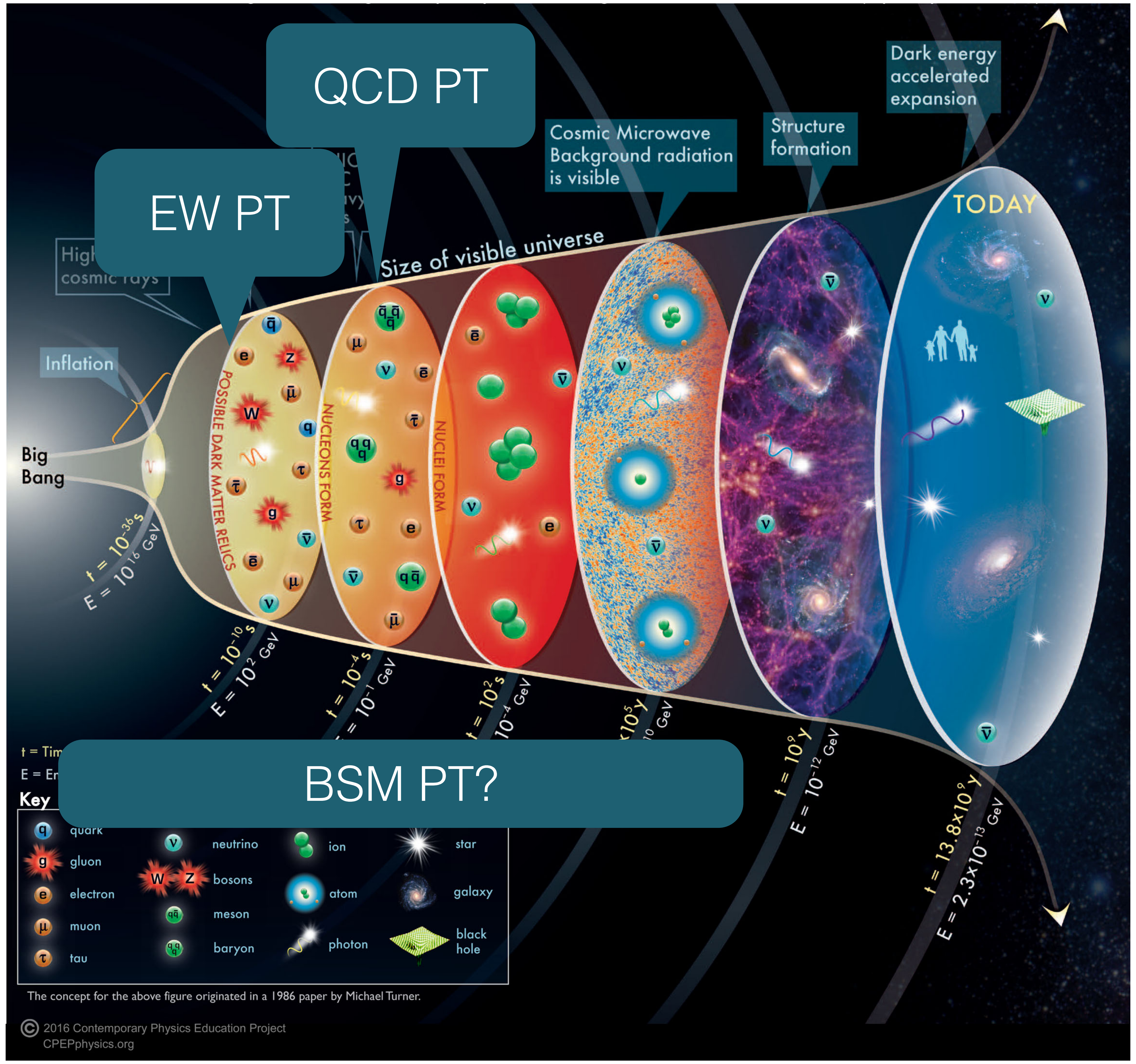
LISA



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

Exciting experimental probes:
GWs and CMB

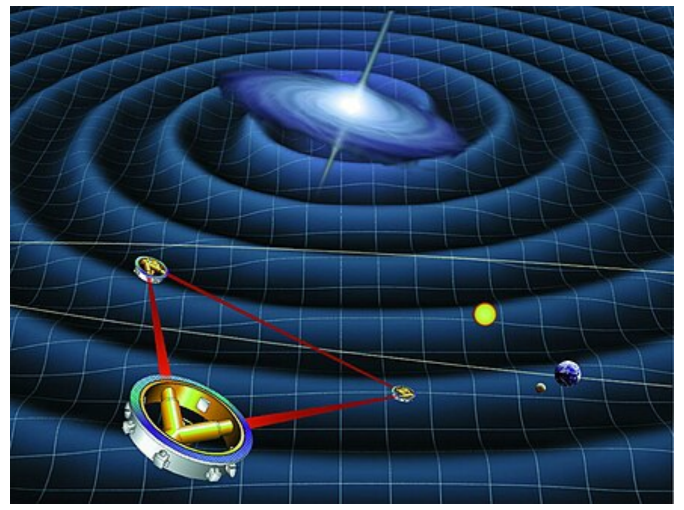
Cosmological Phase Transitons



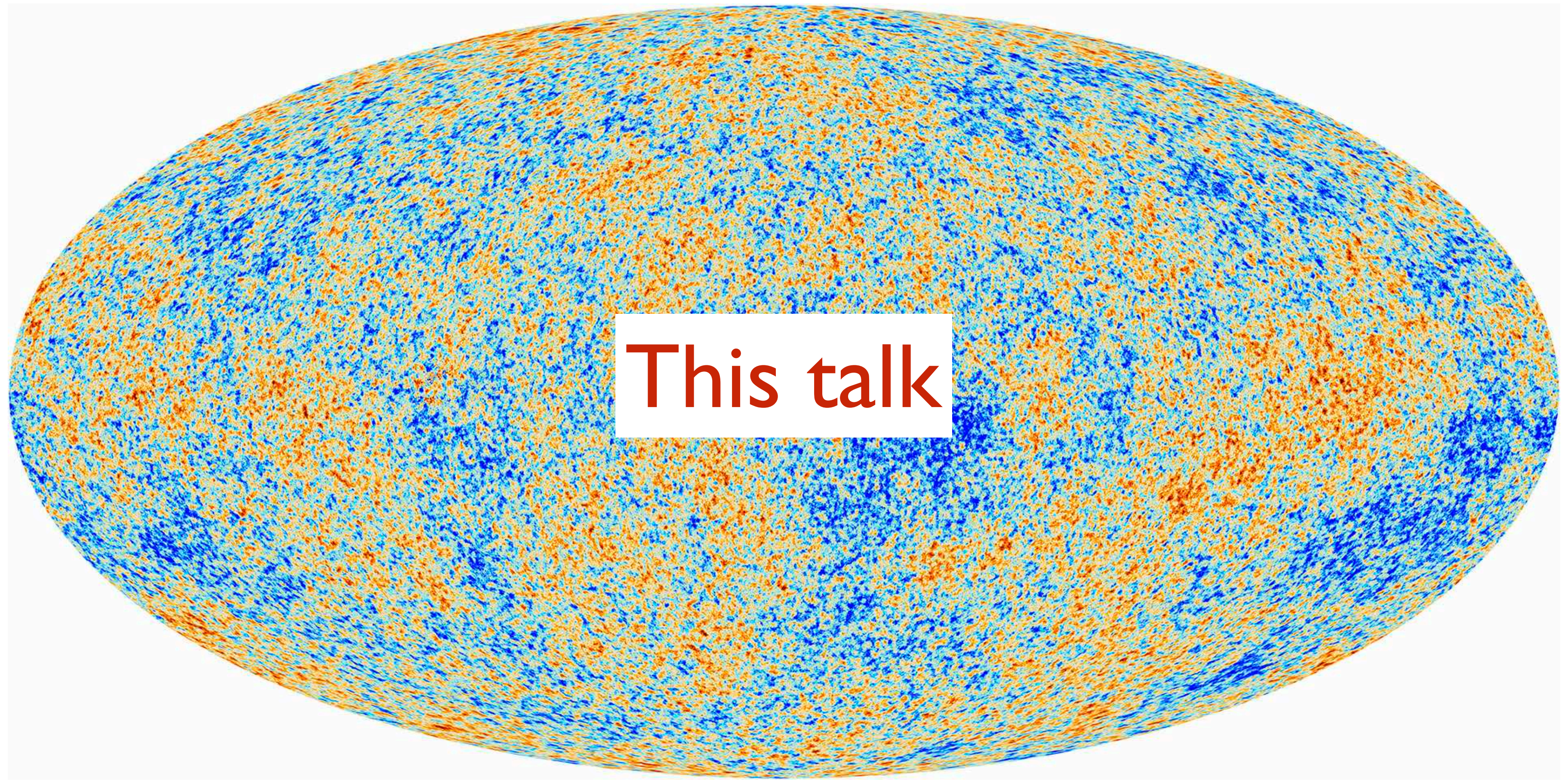
NANOGrav

PTA

LIGO



LISA



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

Exciting experimental probes:
GWs and CMB

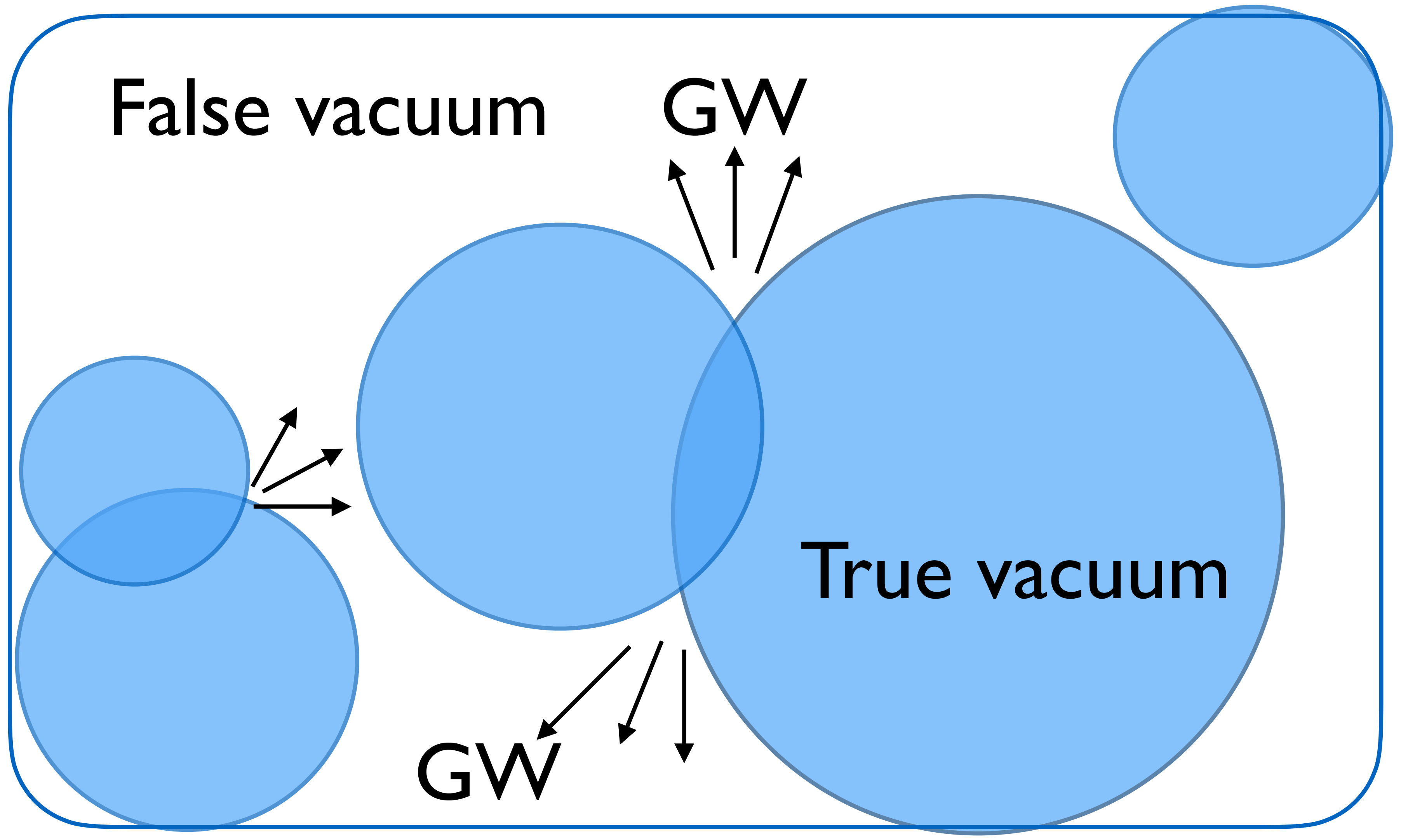
Outline of the talk

- 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

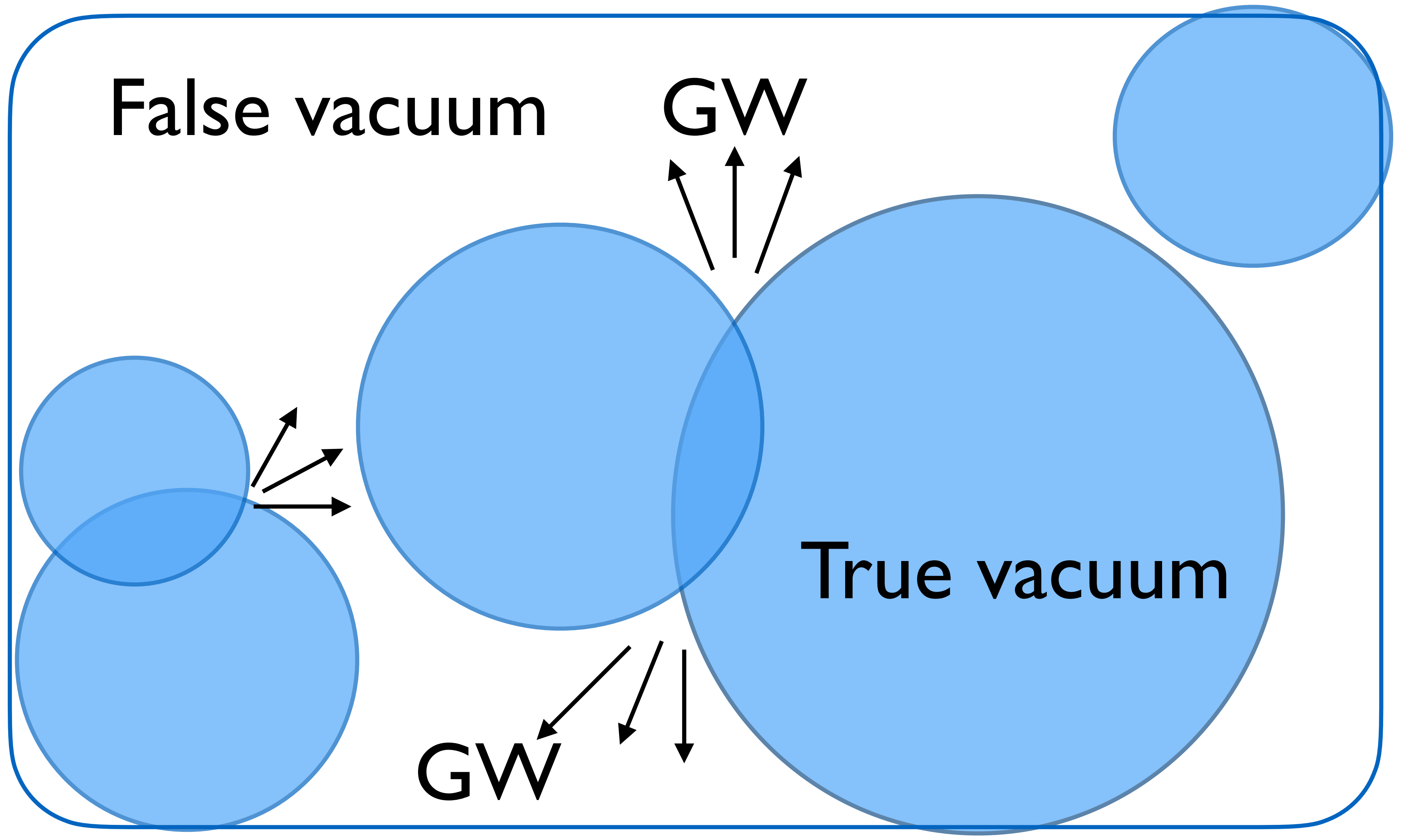
Signals from PT



- Gravitational waves

  bubble collisions, sound waves, turbulence…

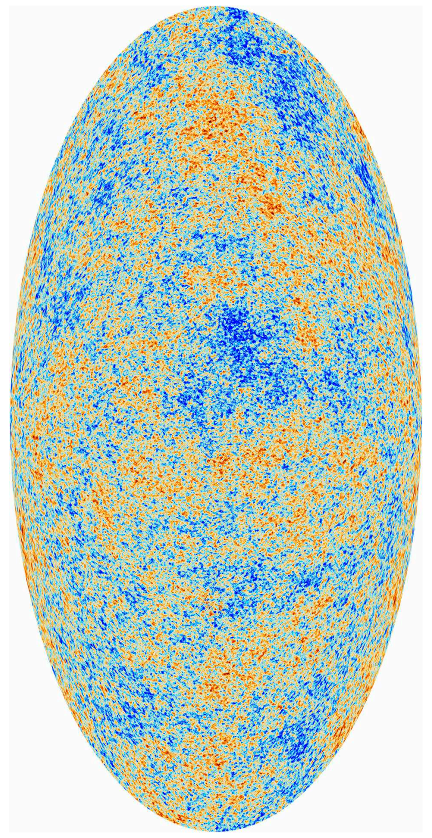
Signals from PT



- Gravitational waves

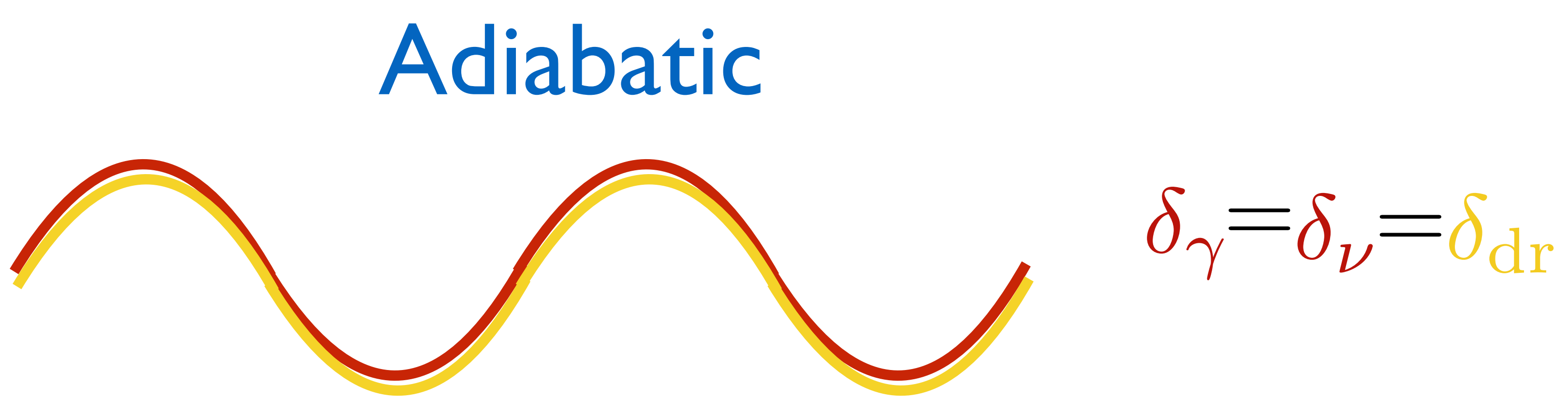
  bubble collisions, sound waves, turbulence…

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

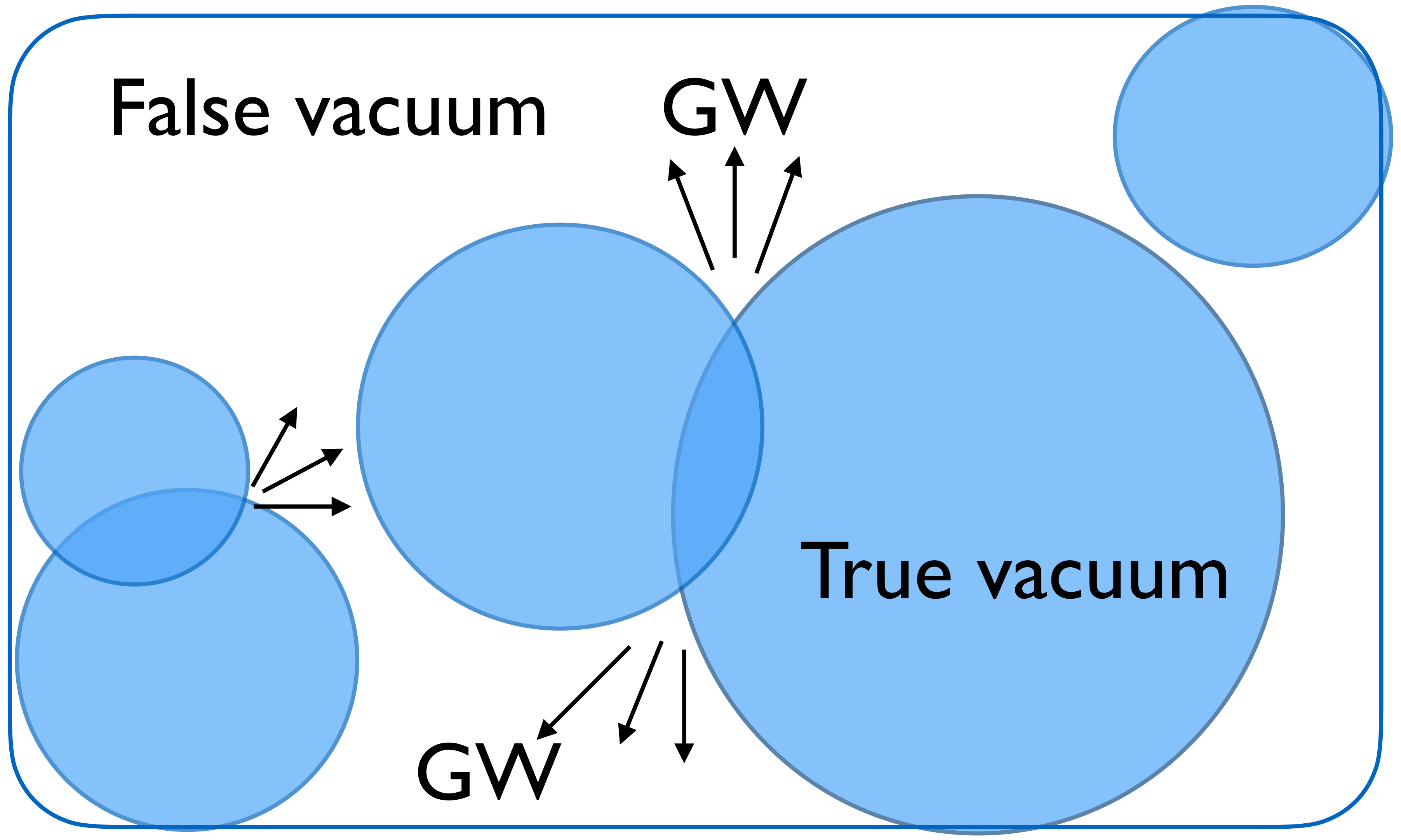


$\Delta N_{\rm eff} < 0.3$ (Adiabatic initial conditions)

Planck, 2018



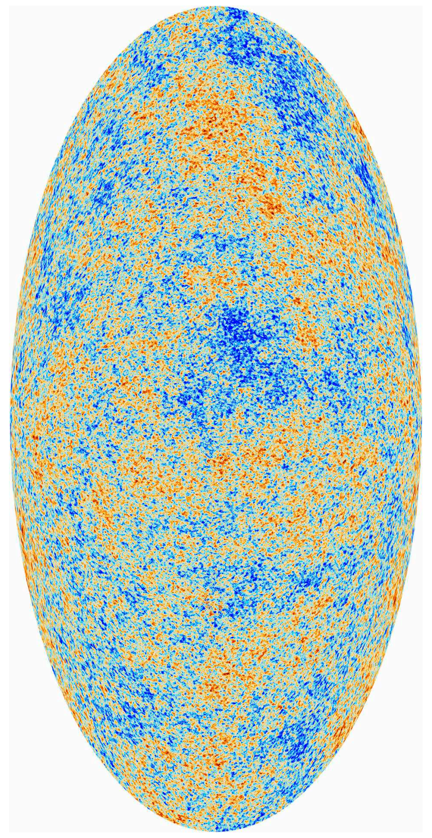
Signals from PT



- 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)

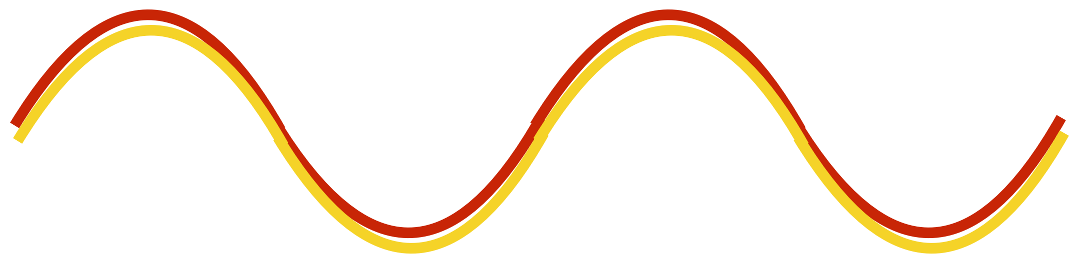
  Planck, 2018

- DR Isocurvature

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

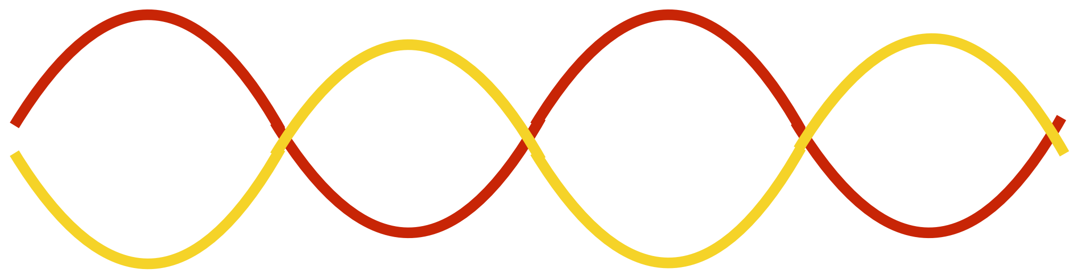
  Buckley,PD,Fernandez,Weikert, 2024

Adiabatic



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

Isocurvature



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

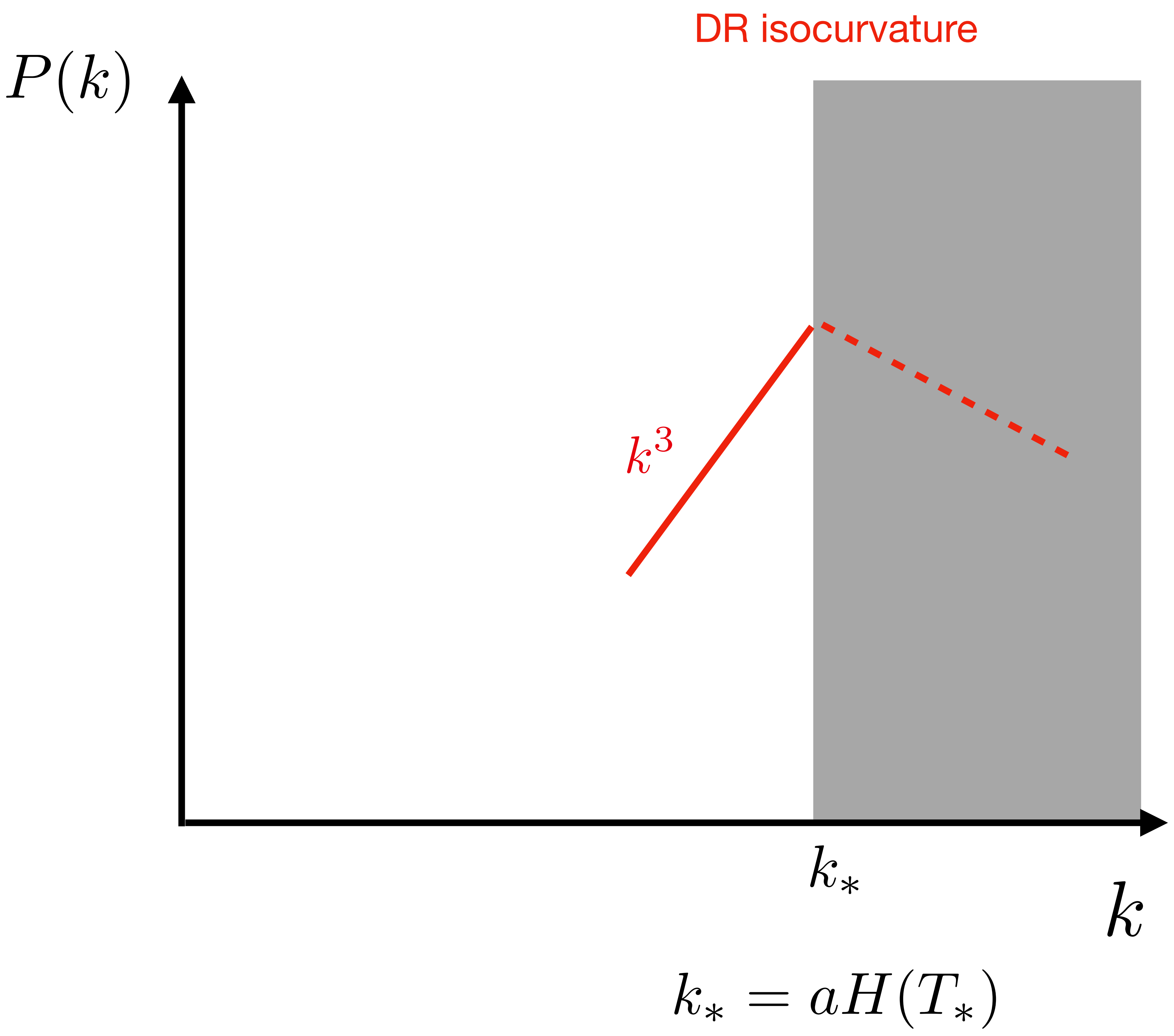
Bucher, Moodley, Turok, 2000
Ghosh, Kumar, Tsai, 2021

DR isocurvature from PT

- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

DR isocurvature from PT



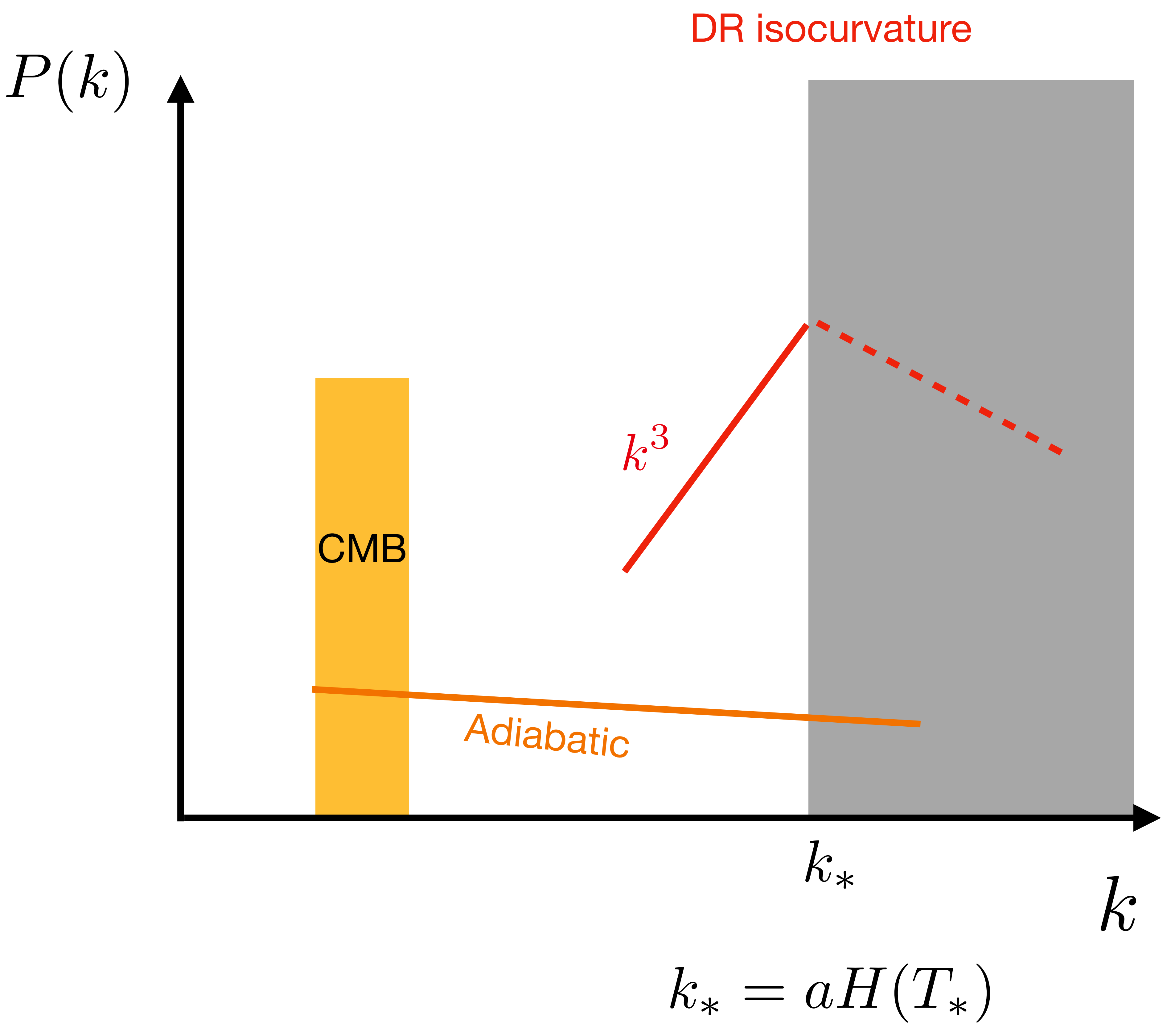
- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

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

- Superhorizon modes scale as k^3

DR isocurvature from PT



- PT generates density fluctuations in DR

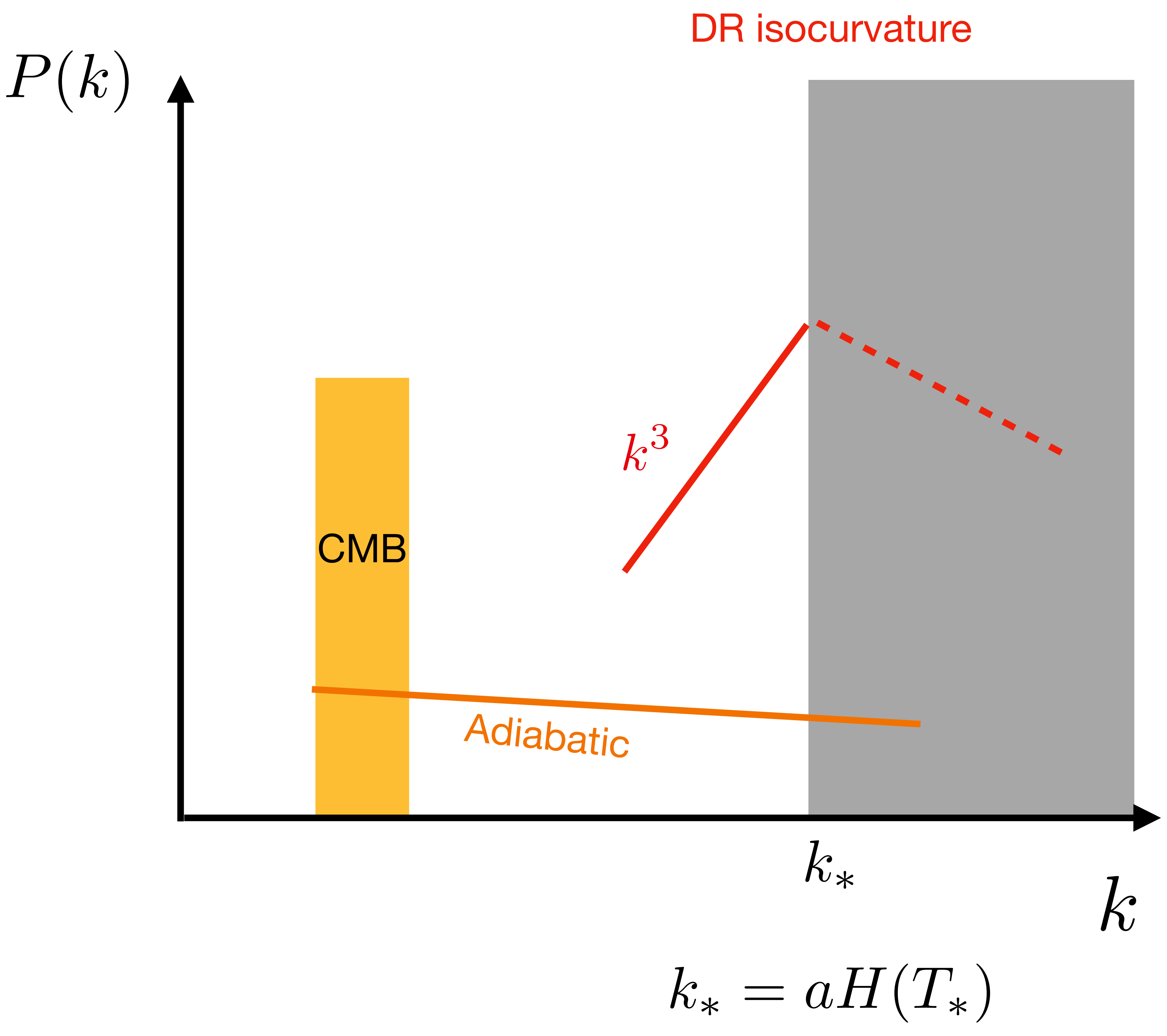
  $\Rightarrow$ DR from PT generically has isocurvature

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

- Superhorizon modes scale as k^3

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

DR isocurvature from PT



- PT generates density fluctuations in DR

  $\Rightarrow$ DR from PT generically has isocurvature

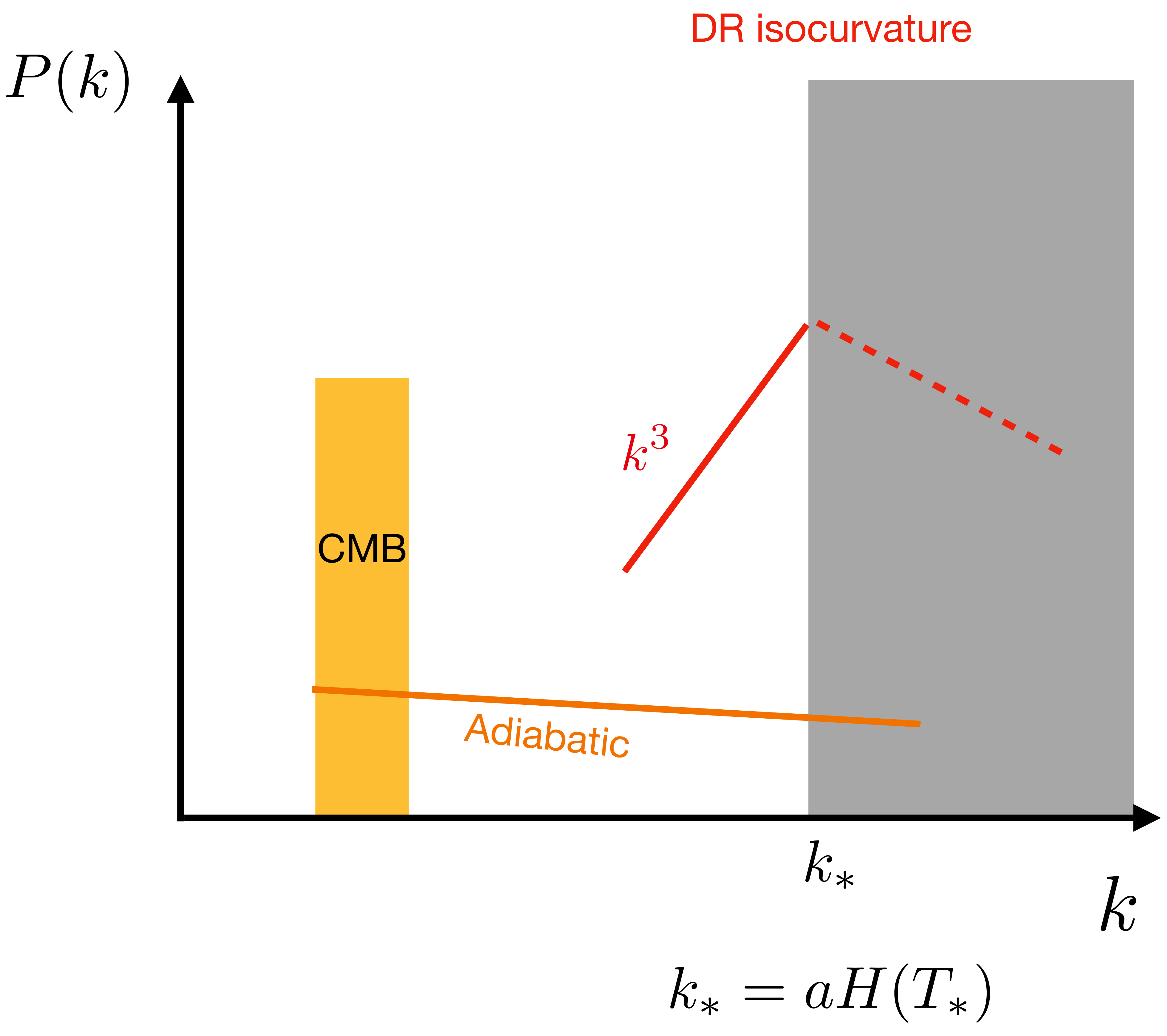
- Comoving horizon at PT sets the scale $k_* = aH(T_*)$

- Superhorizon modes scale as k^3

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

- 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 $k_* = aH(T_*)$

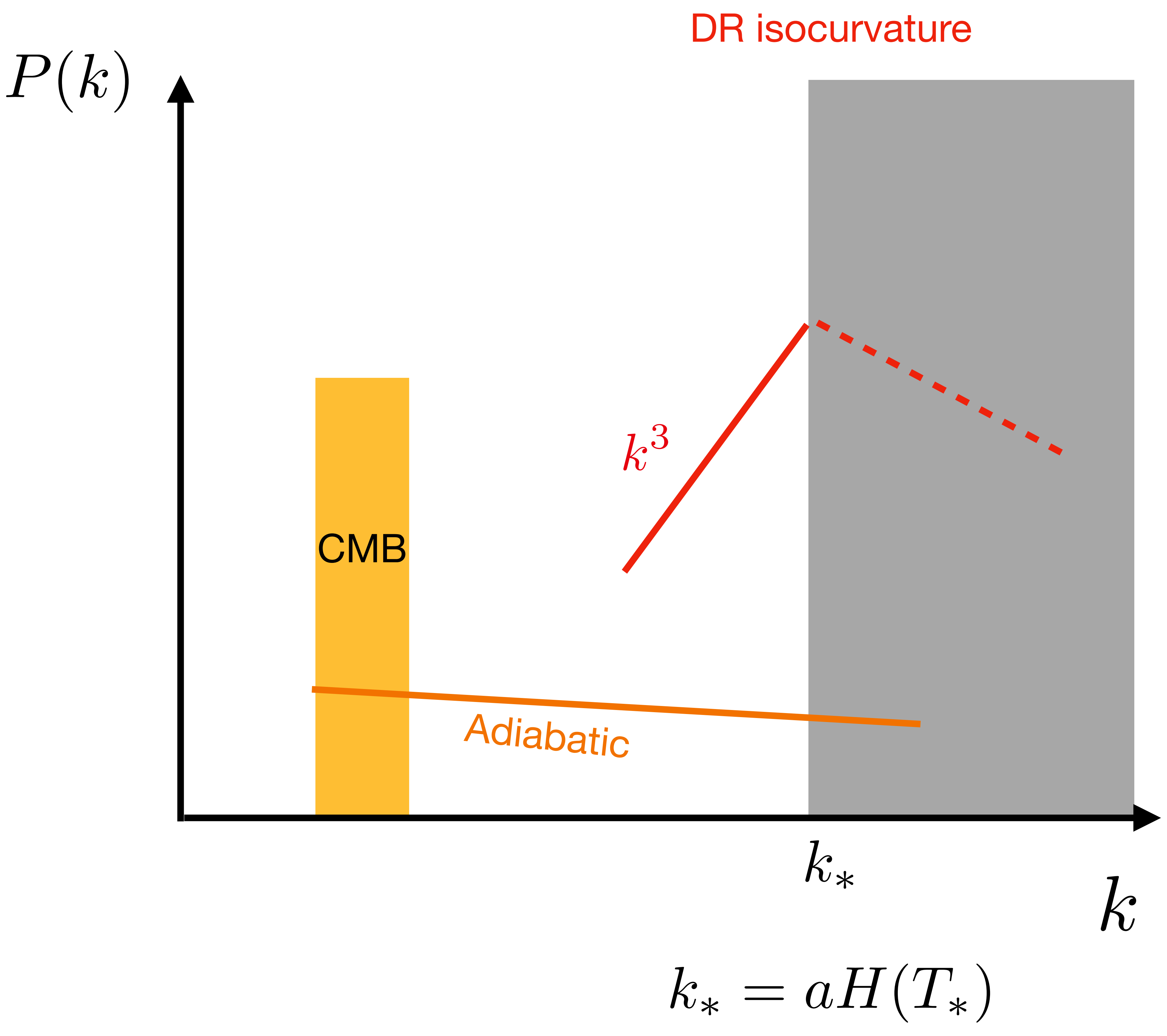
- Superhorizon modes scale as k^3

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

- How to get isocurvature signals in CMB?

  Low scale PT — Freese, Winkler, 2023; Elor, Jinno, Kumar, McGehee, Tsai, 2023

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 $T_* \gg T_{\rm CMB}$

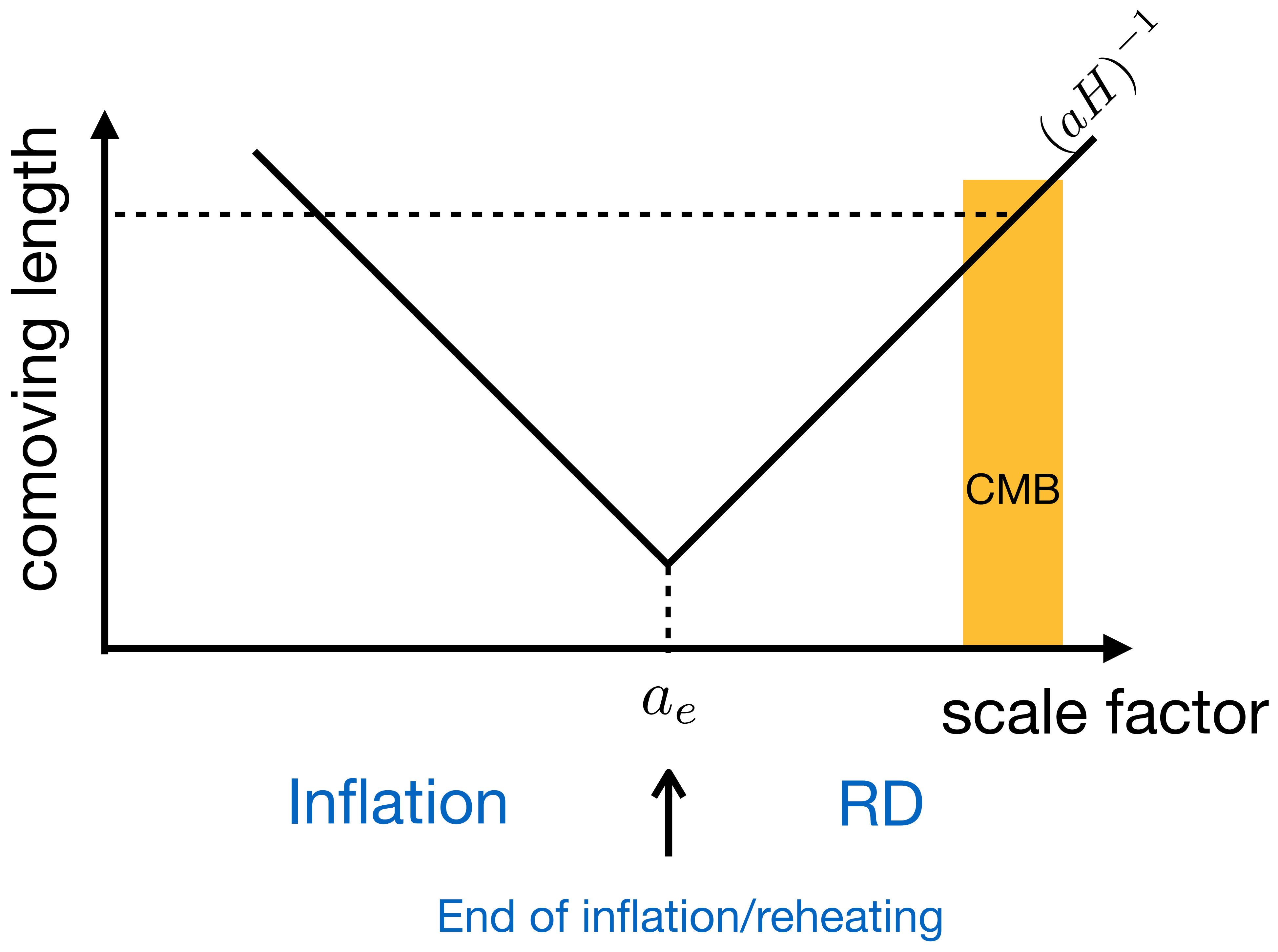
- How to get isocurvature signals in CMB?

  Low scale PT — Freese, Winkler, 2023; Elor,Jinno,Kumar,McGehee,Tsai, 2023

  Slow PT during inflation!

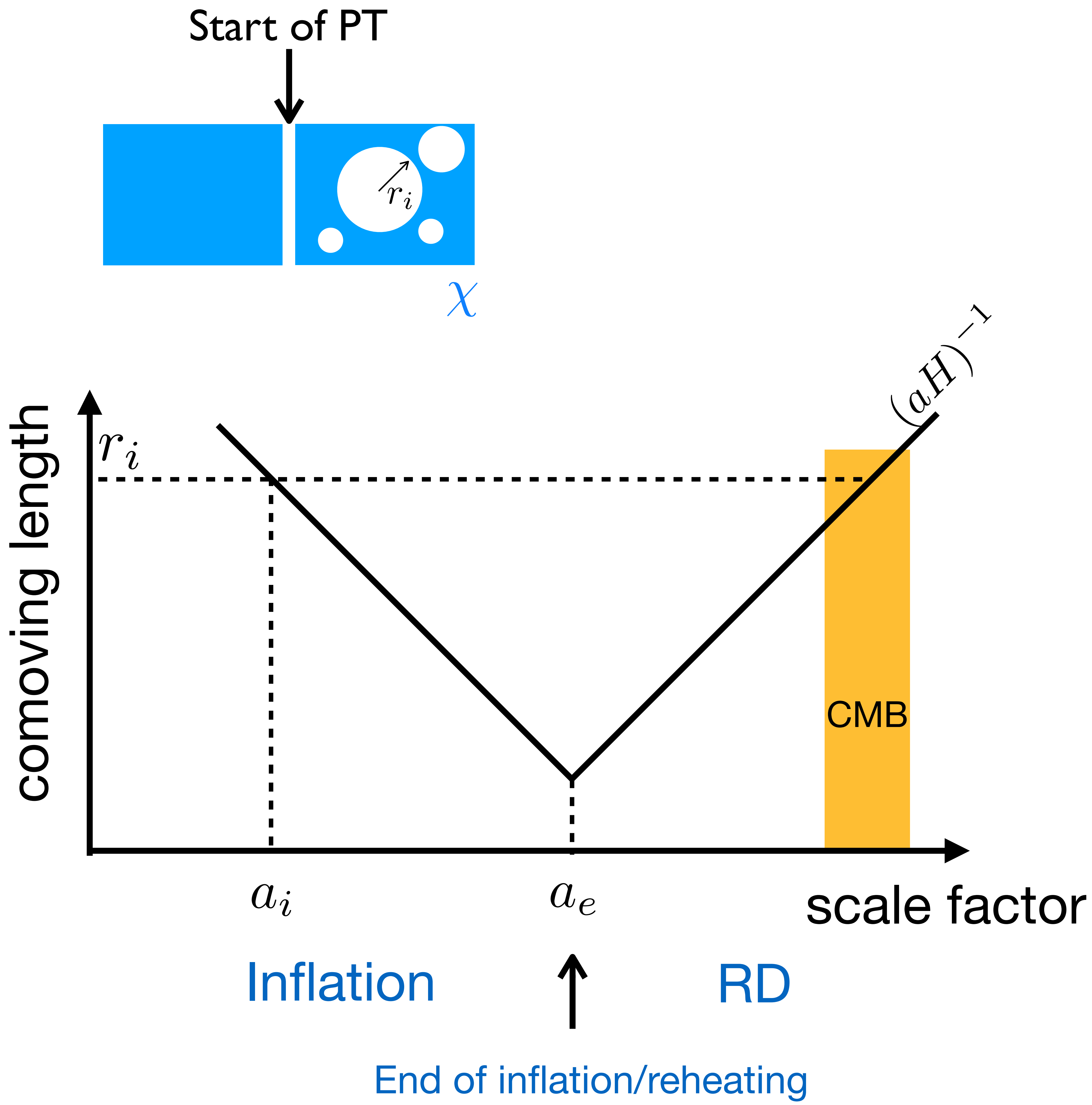
  Buckley,PD,Fernandez,Weikert, 2024

Slow PT during inflation



- Comoving horizon can be large during inflation

Slow PT during inflation



- Comoving horizon can be large during inflation

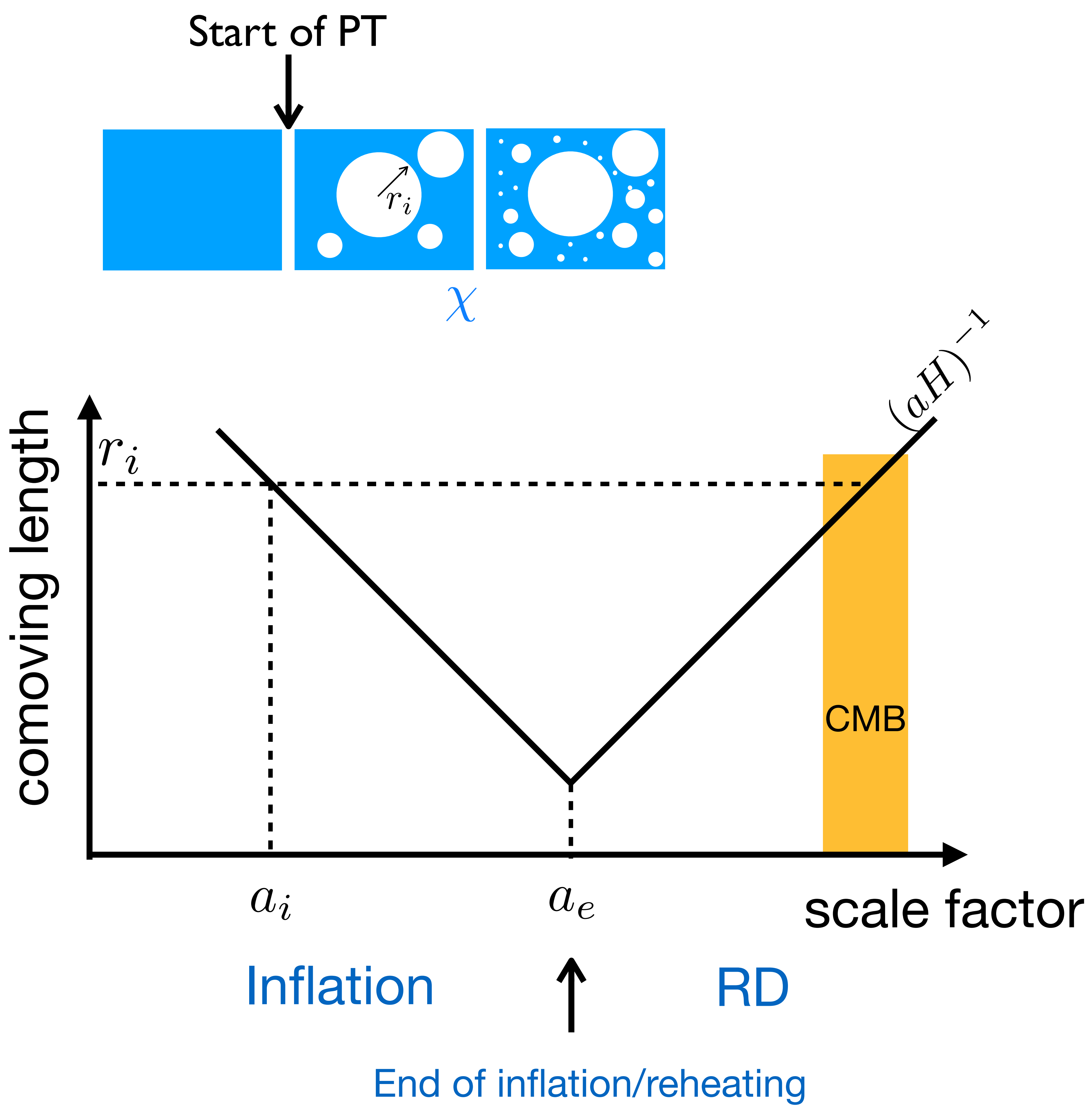
- PT during inflation can generate large bubbles

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

- Slow PT: remain incomplete during inflation

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

Slow PT during inflation



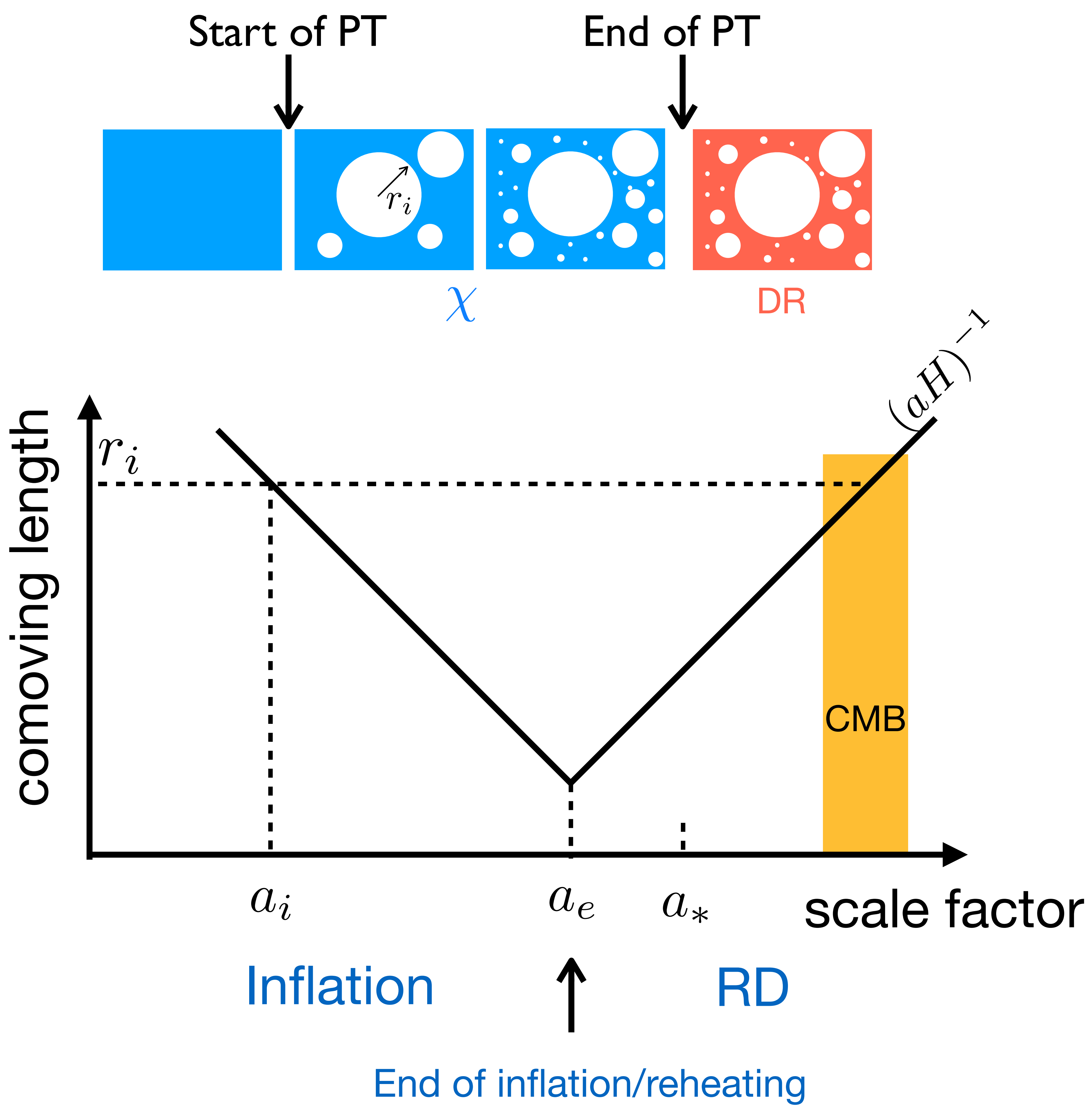
- Comoving horizon can be large during inflation
- PT during inflation can generate large bubbles

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

- Slow PT: remain incomplete during inflation

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

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

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

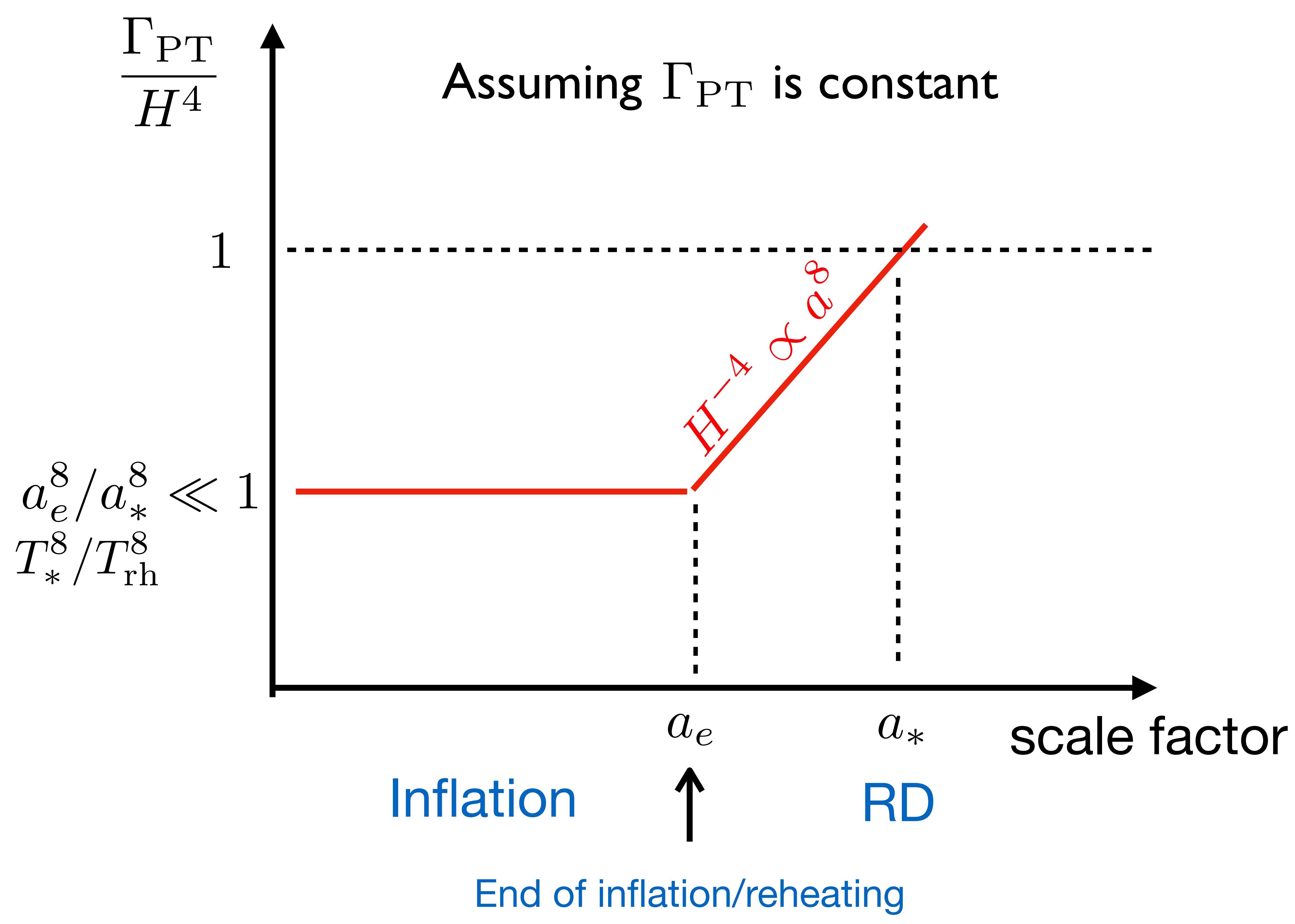
- PT will complete after inflation at $T_* < T_{\rm rh}$

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

- Vacuum energy of PT converts to DR generating isocurvature

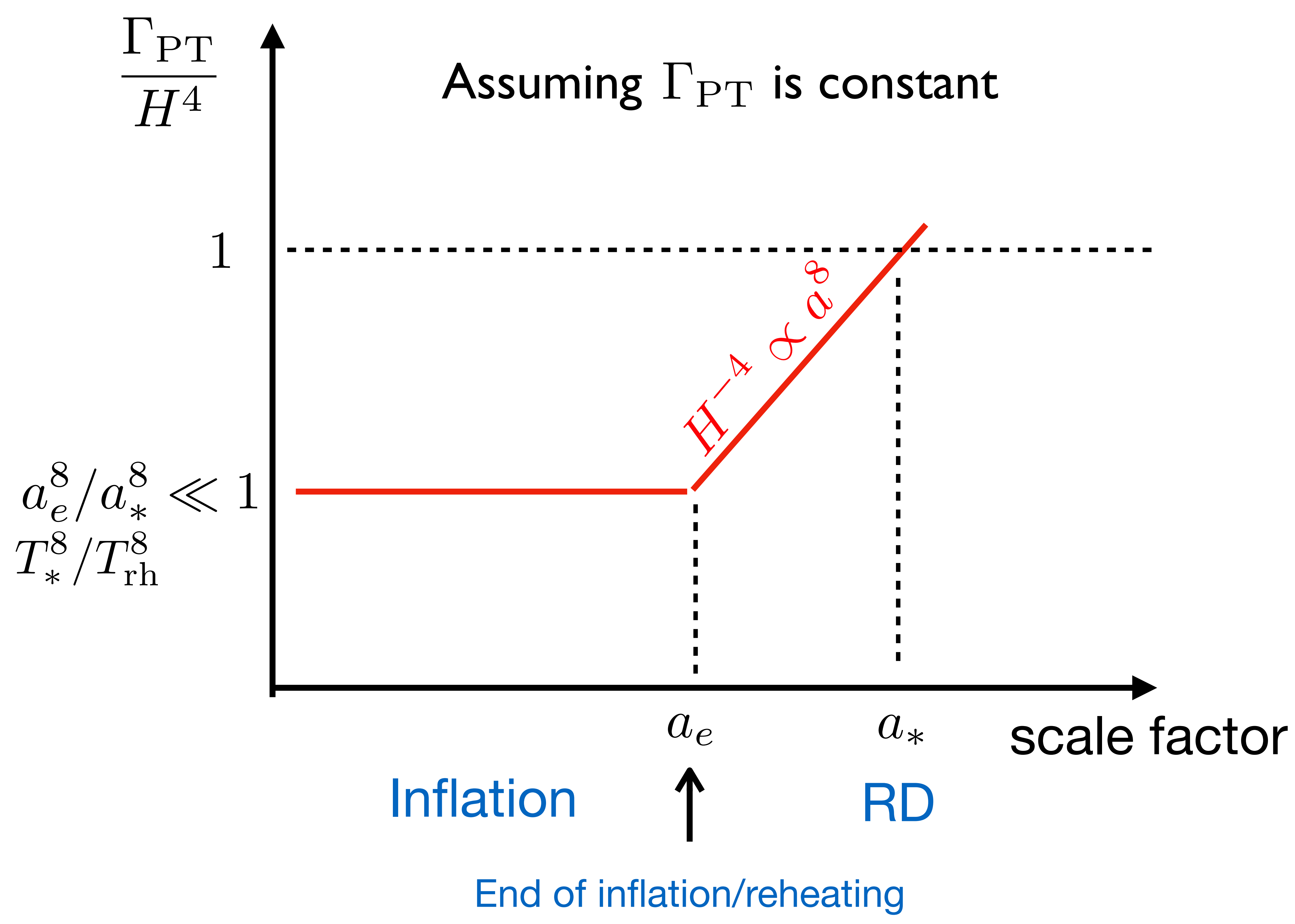
Models for slow PT during inflation

Generic feature for non-thermal PT
completes after inflation



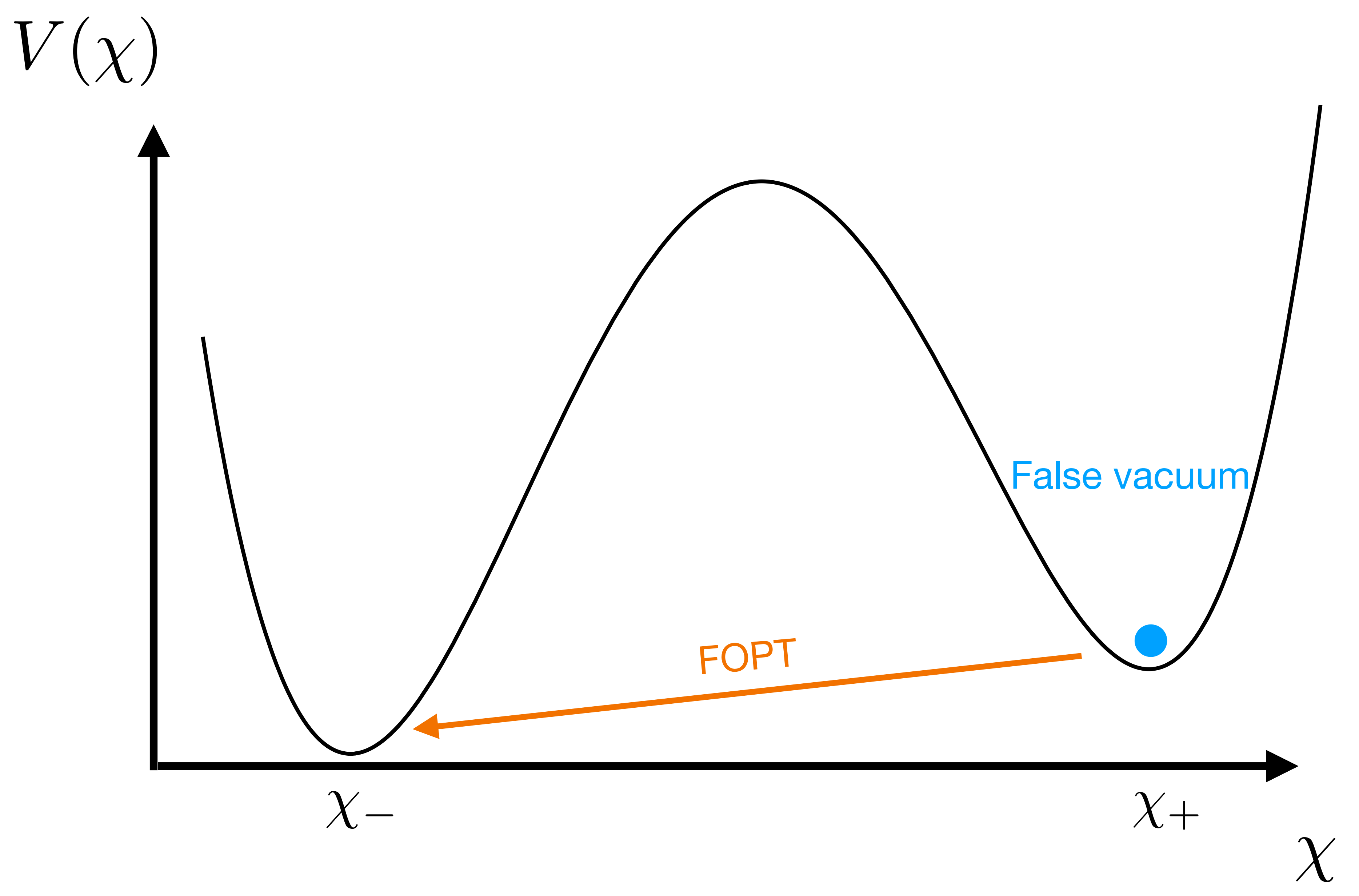
Models for slow PT during inflation

Generic feature for non-thermal PT completes after inflation



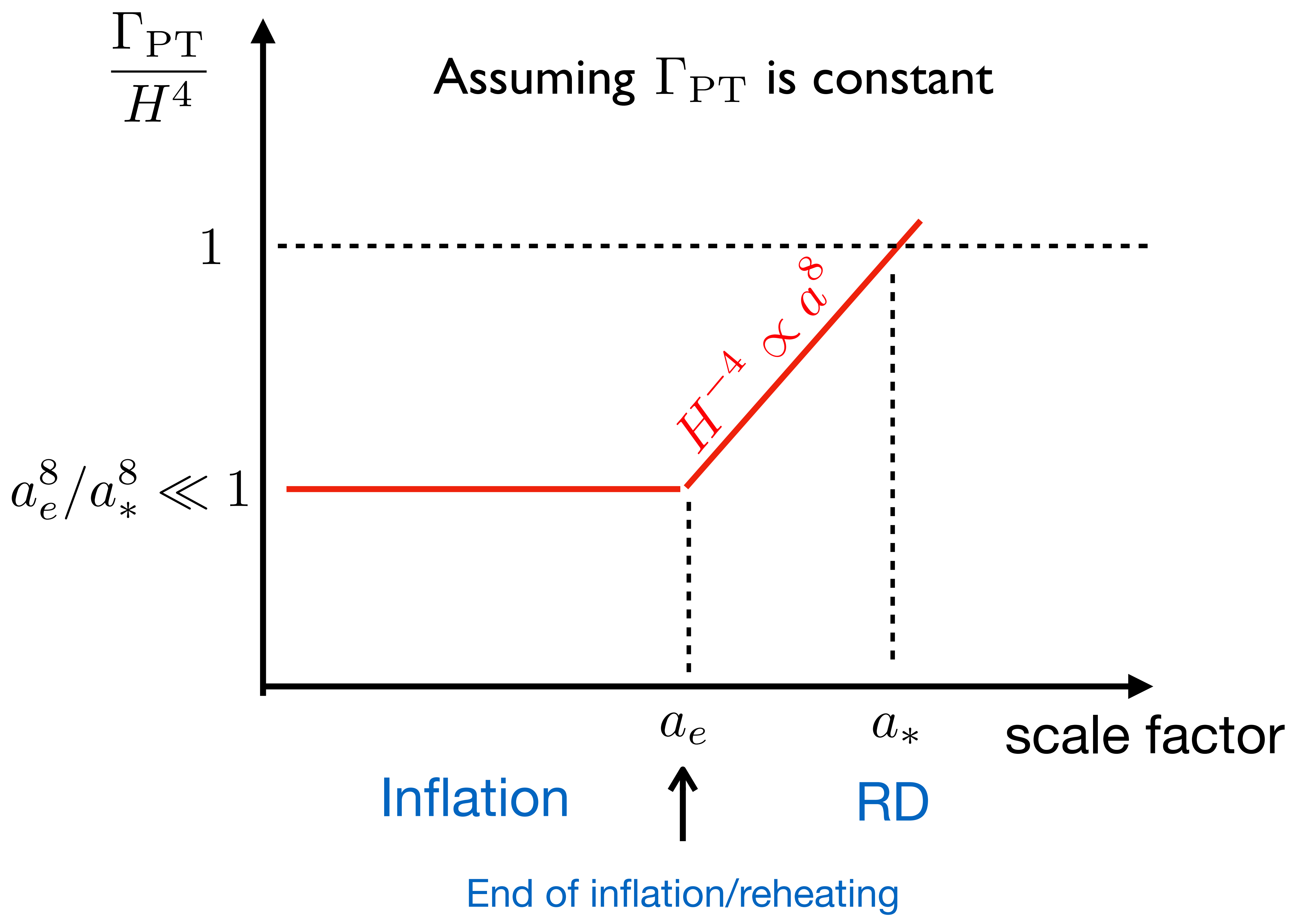
Simple(st) model is sufficient

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



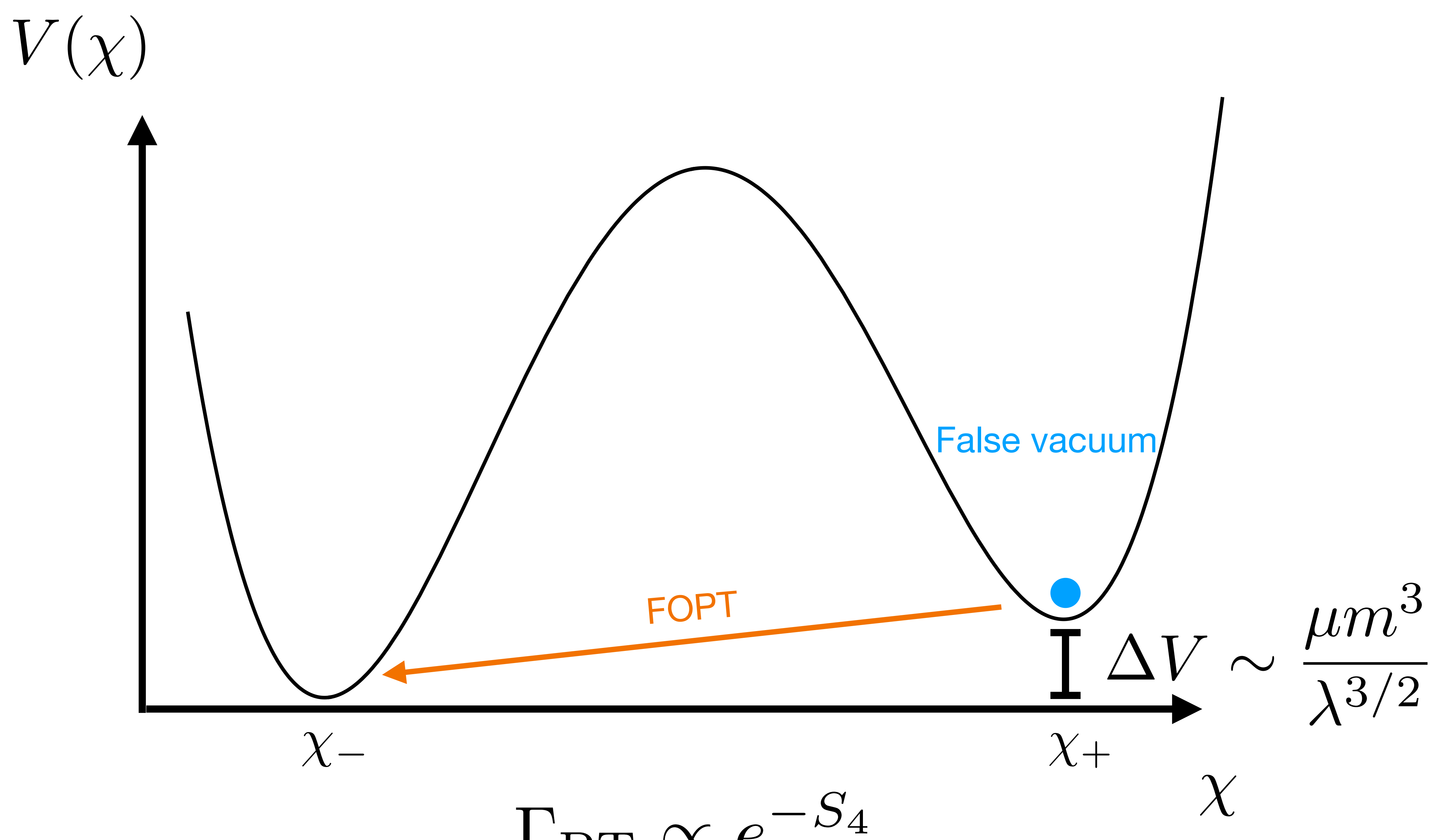
Models for slow PT during inflation

Generic feature for non-thermal PT completes after 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 $\Gamma_{\rm PT}$

What about the start of PT?

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

What about the start of PT?

Adding a trigger by coupling to inflaton

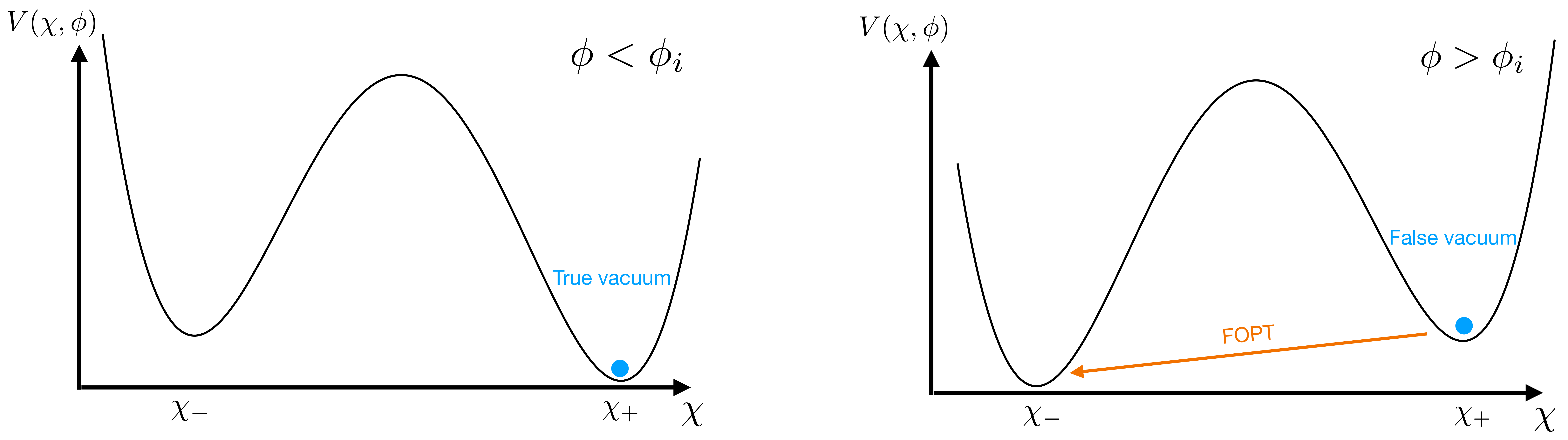
$$V(\chi,\phi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu(\phi)}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

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

What about the start of PT?

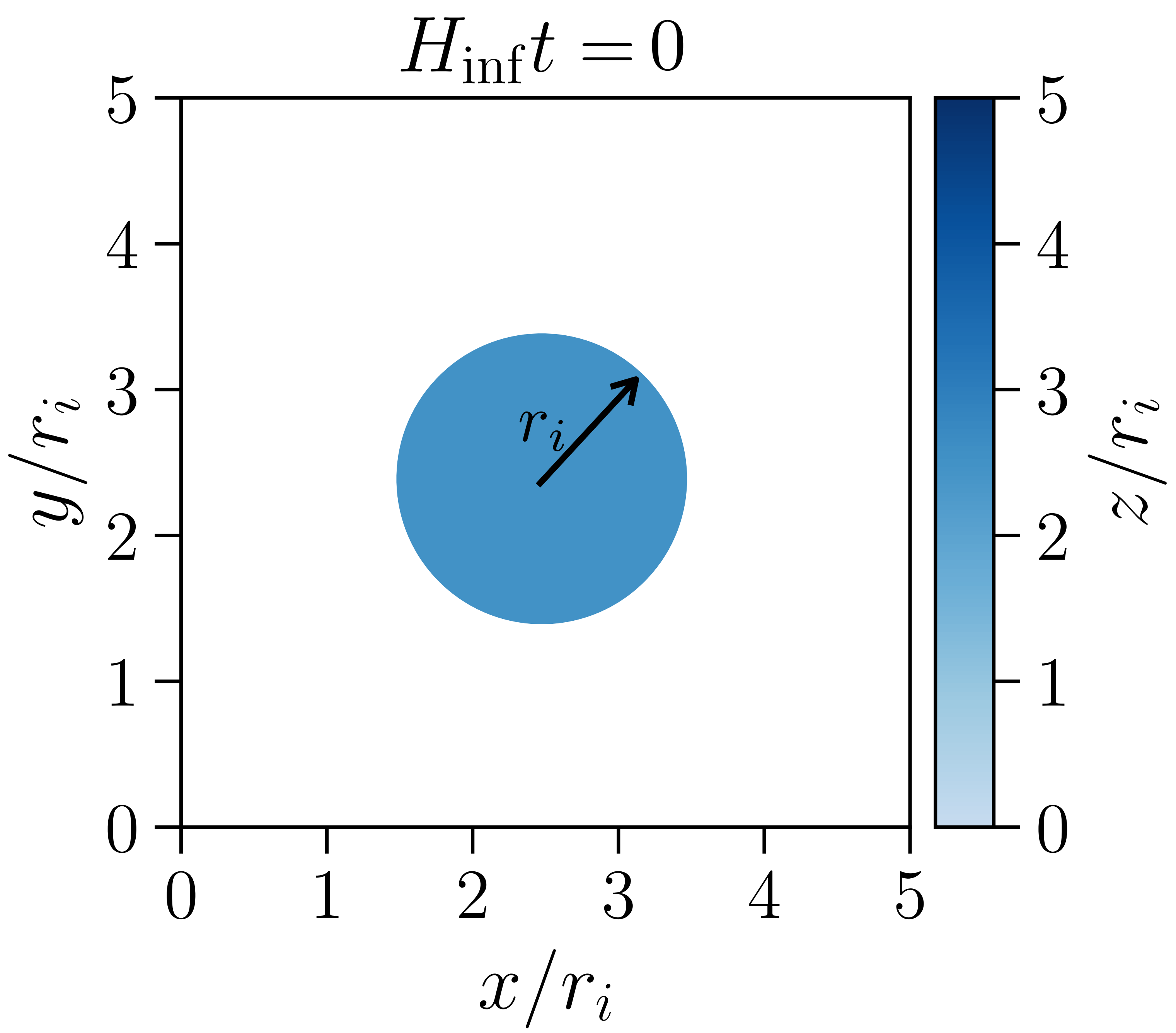
Adding a trigger by coupling to inflaton

$$V(\chi, \phi) = -\frac{1}{2}m^2\chi^2 + \frac{\mu(\phi)}{3}\chi^3 + \frac{\lambda}{4}\chi^4 \qquad \mu(\phi) = \mu \tanh\left(\frac{\phi - \phi_i}{\Delta\phi}\right)$$



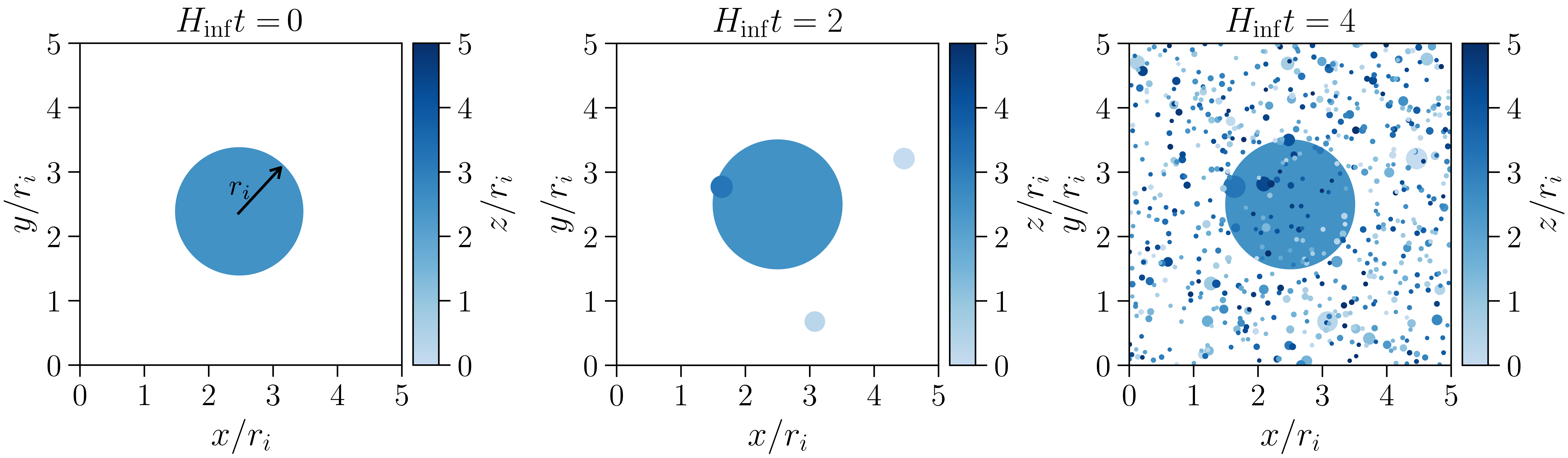
PT starts at a_i when $\phi = \phi_i$

Evolution of bubbles during inflation



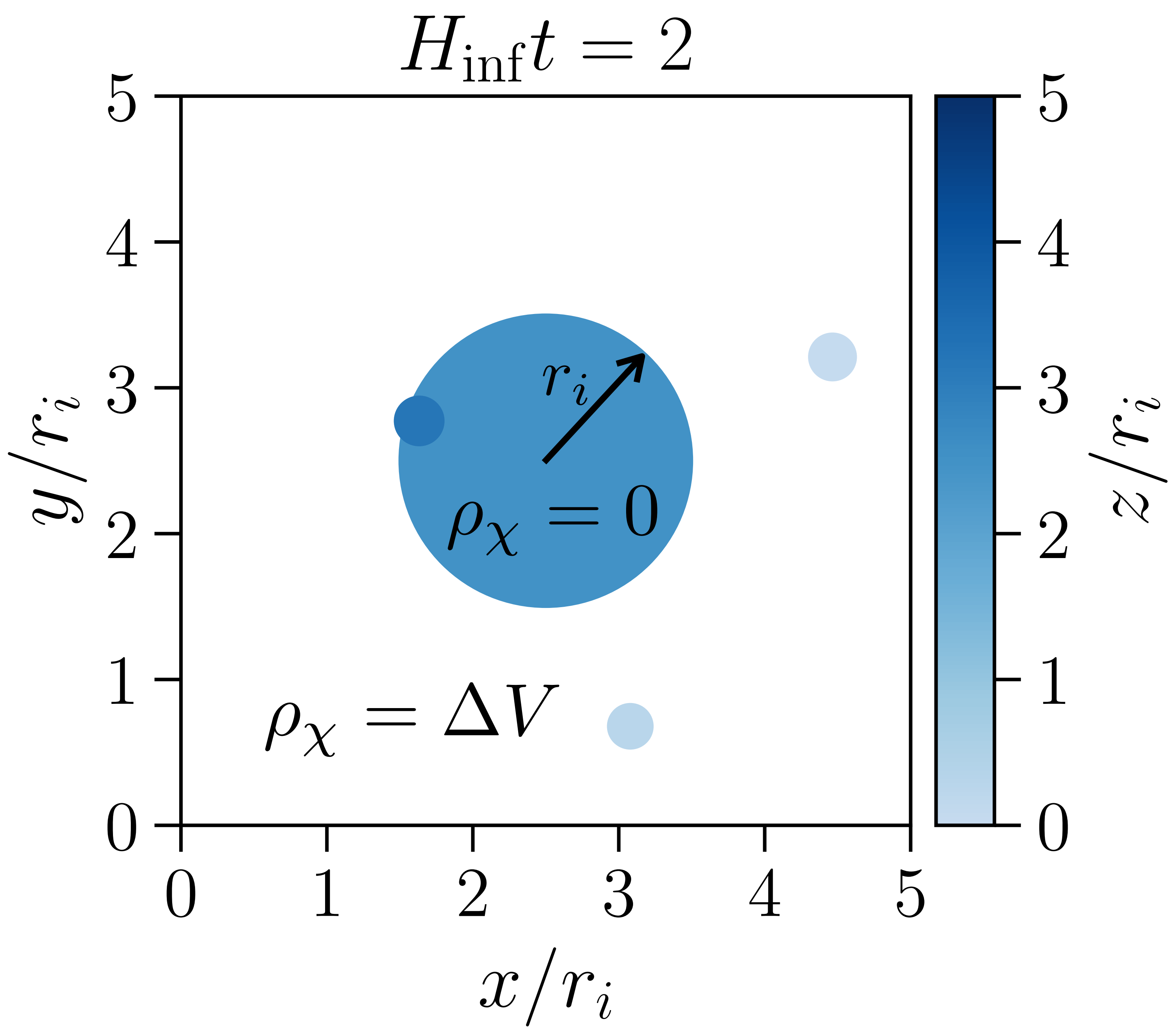
- Bubble sizes ⇔ horizon at nucleation $\quad r(t) = (a(t) H_{\rm inf})^{-1}$

Evolution of bubbles during inflation



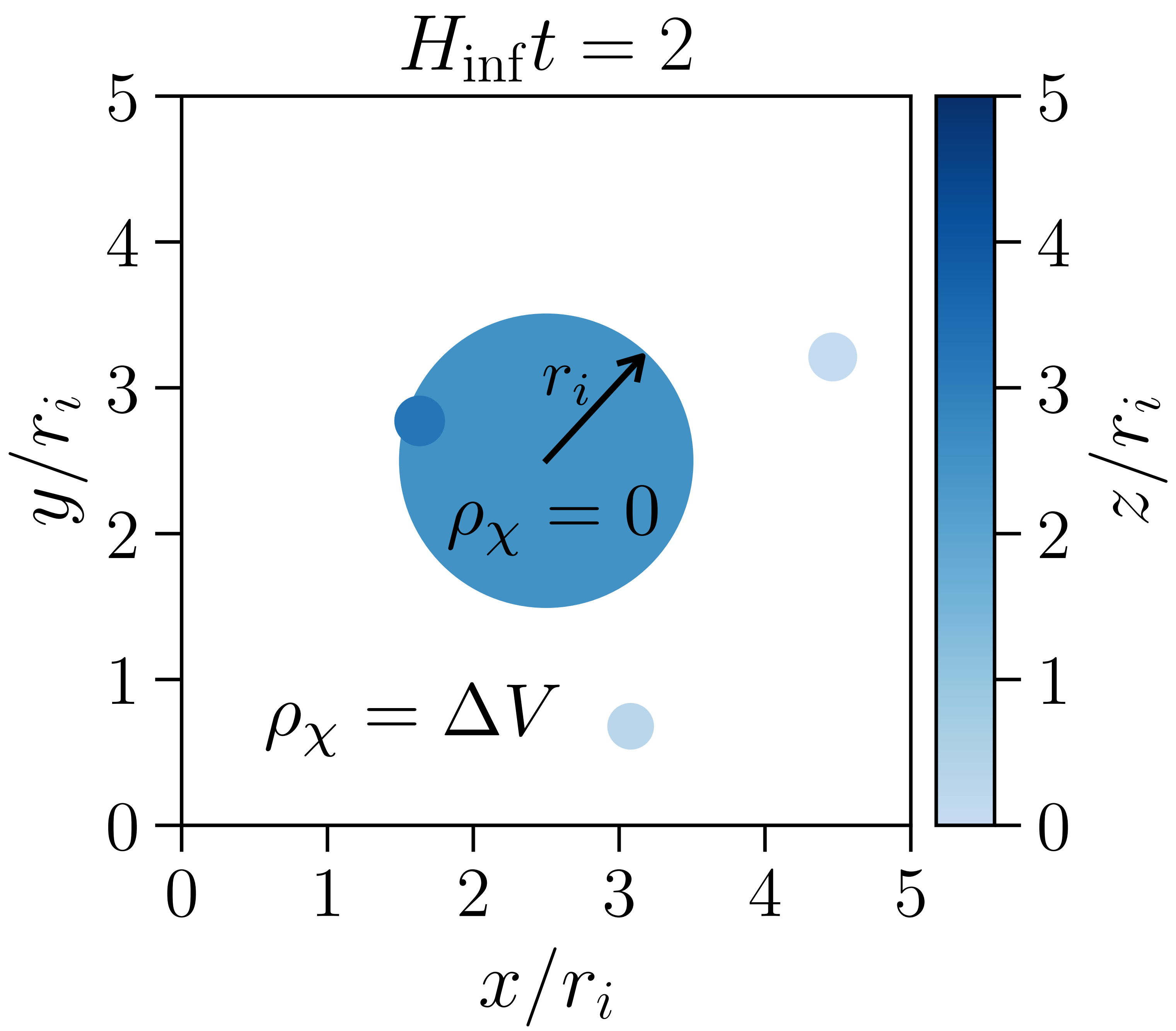
- Bubble sizes ⇔ horizon at nucleation $r(t) = (a(t)H_{\inf})^{-1}$
- Bubbles won't collide during inflation, PT remain incomplete
- True vacuum only occupies small fraction of space $\propto \Gamma_{\rm PT}/H_{\inf}^4 \ll 1$

Density perturbations from bubbles



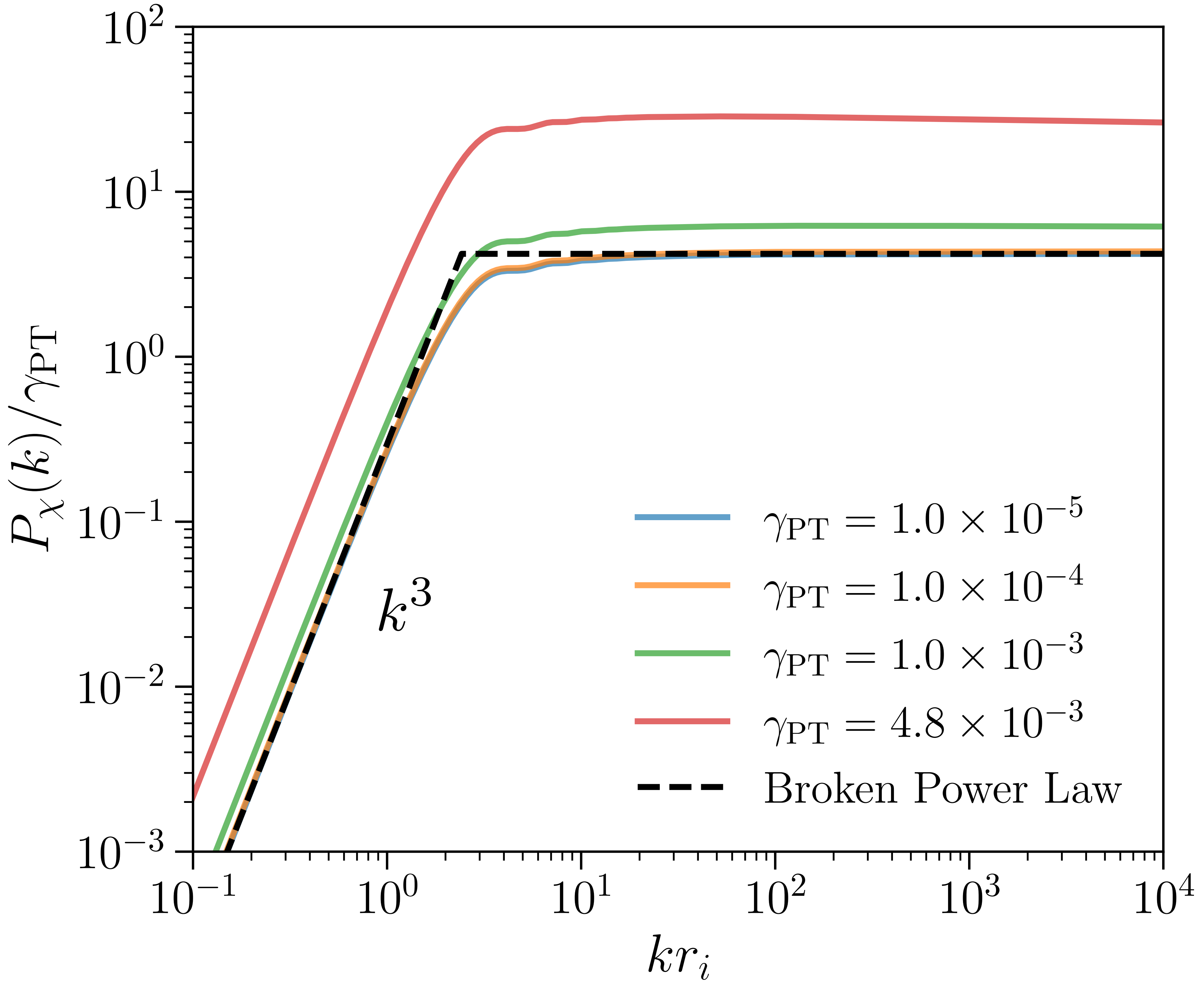
Biggest bubble has radius r_i

Density perturbations from bubbles



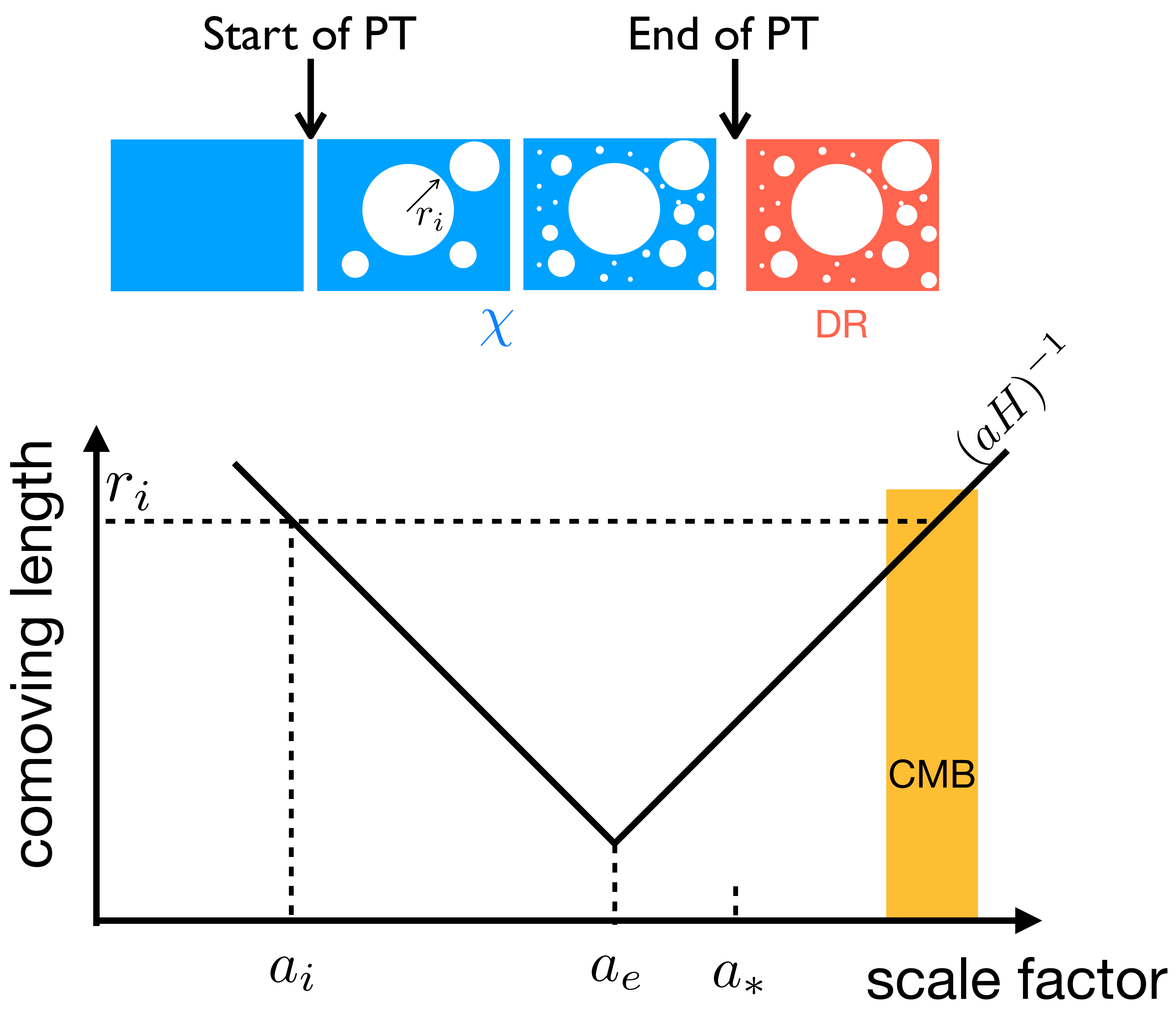
Biggest bubble has radius r_i

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



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

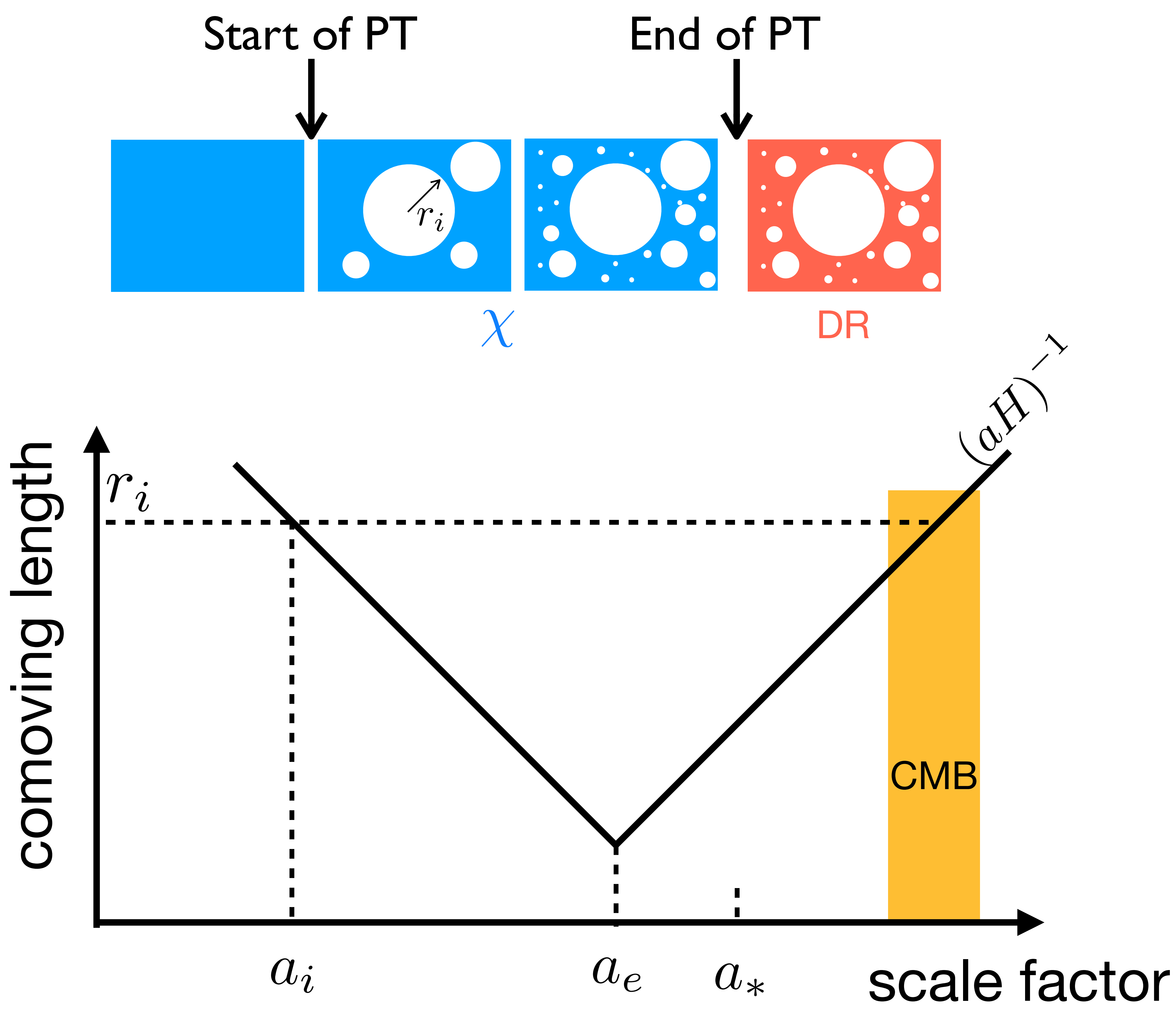
DR isocurvature from PT



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

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

DR isocurvature from PT



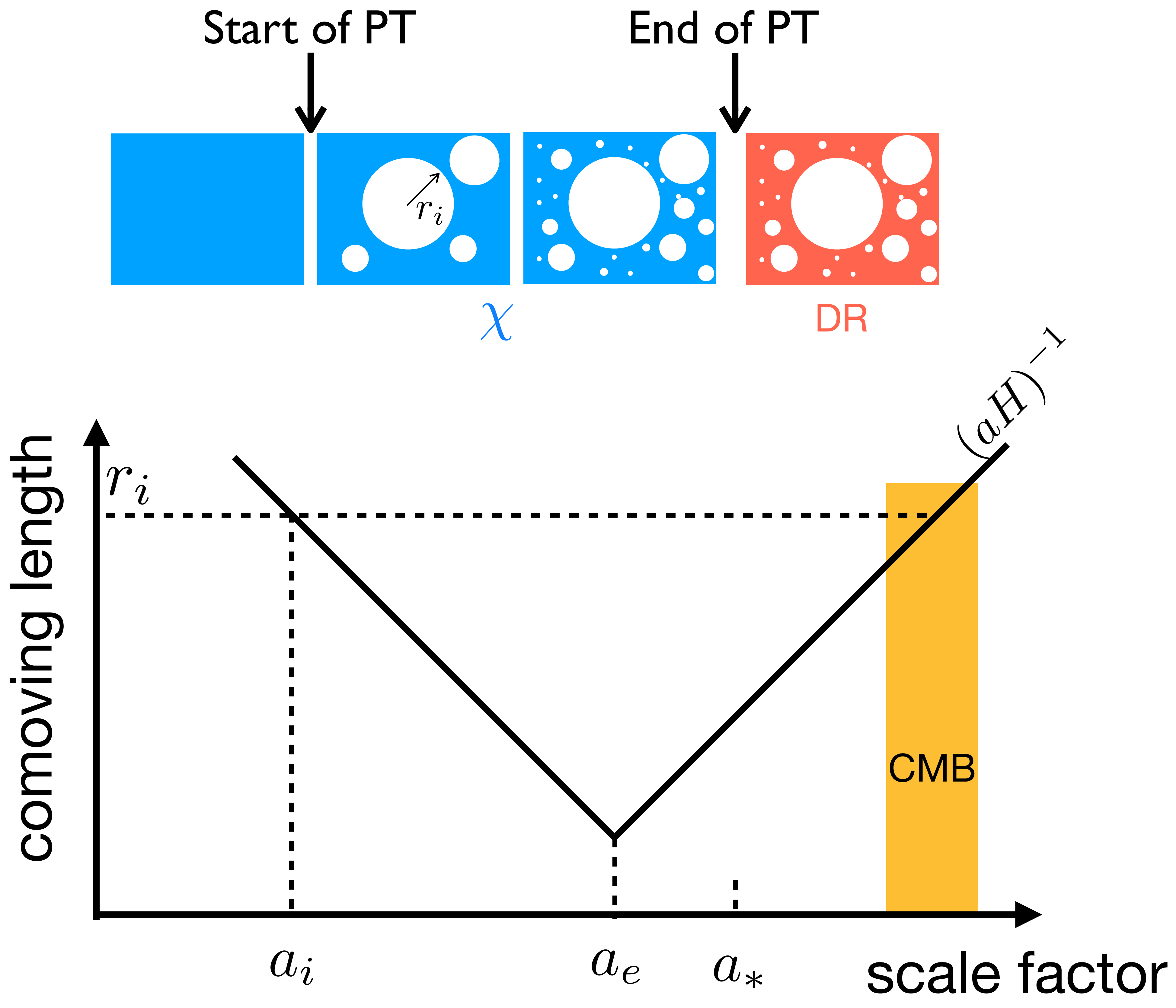
- When PT competes at a_* , $\rho_\chi \to \rho_{\rm dr}$

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

- 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

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

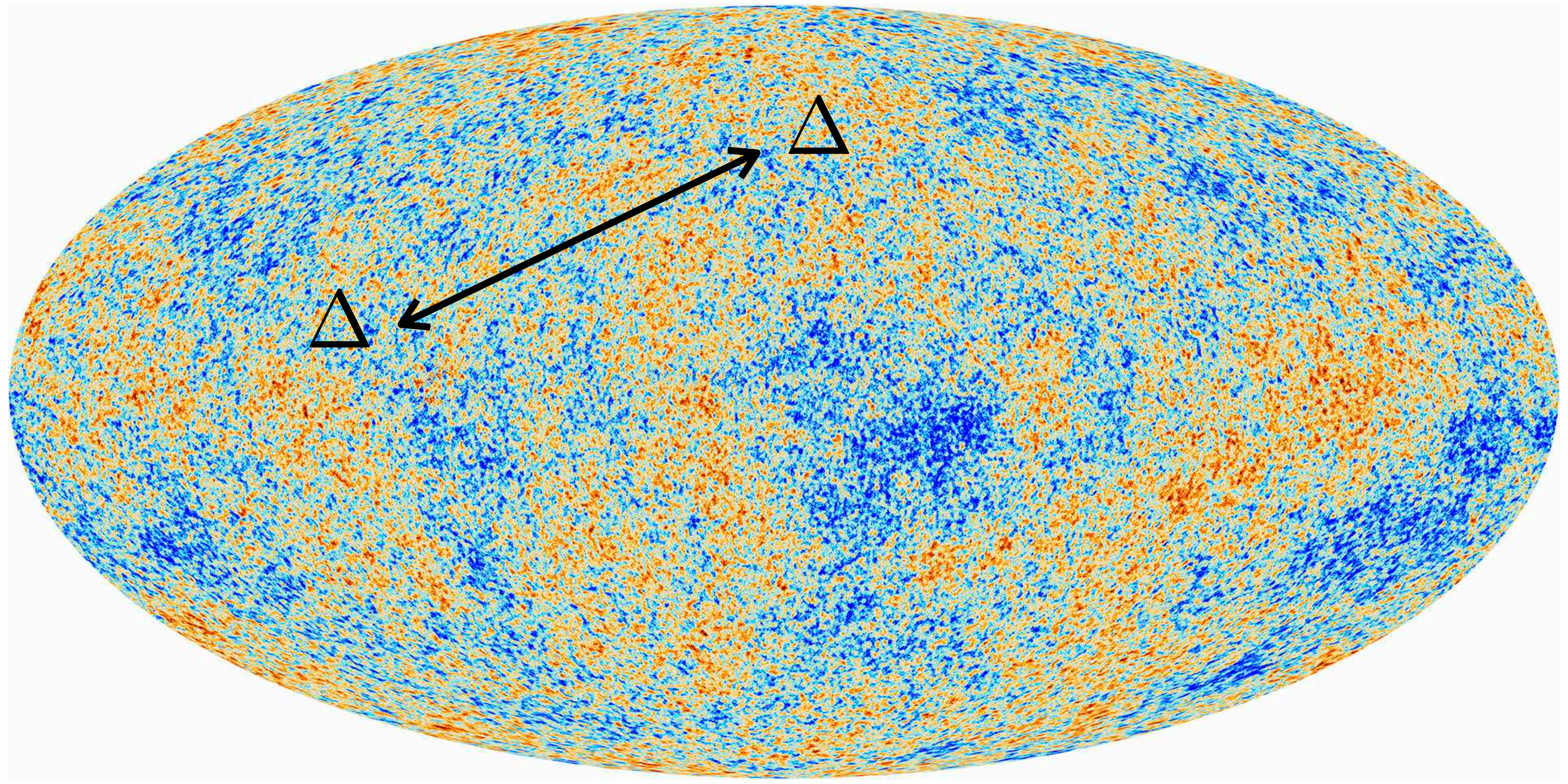
- Isocurvature power spectrum

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

DR inherits large scale isocurvature perturbations from χ field

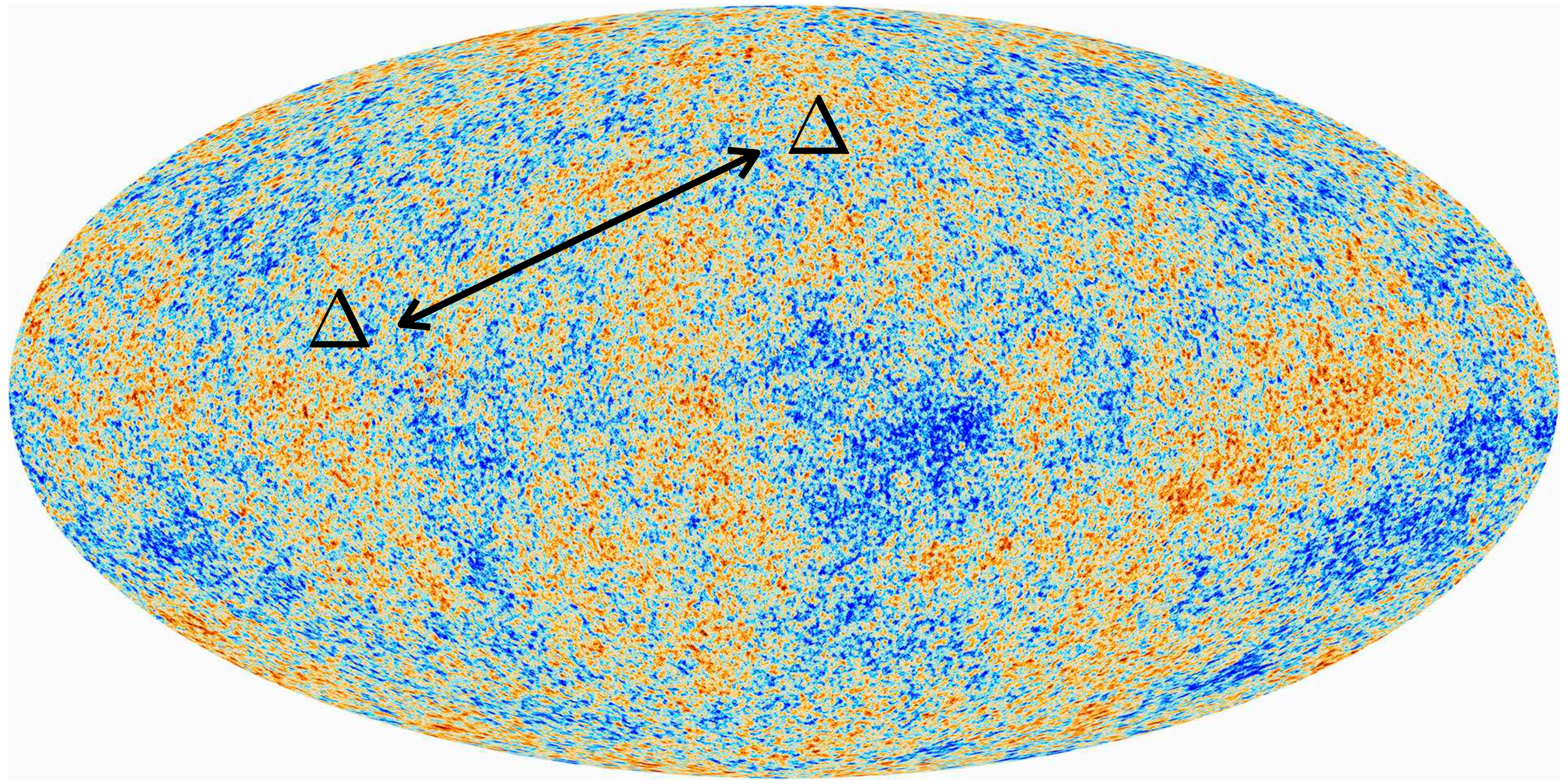
DR isocurvature in CMB

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



DR isocurvature in CMB

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



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

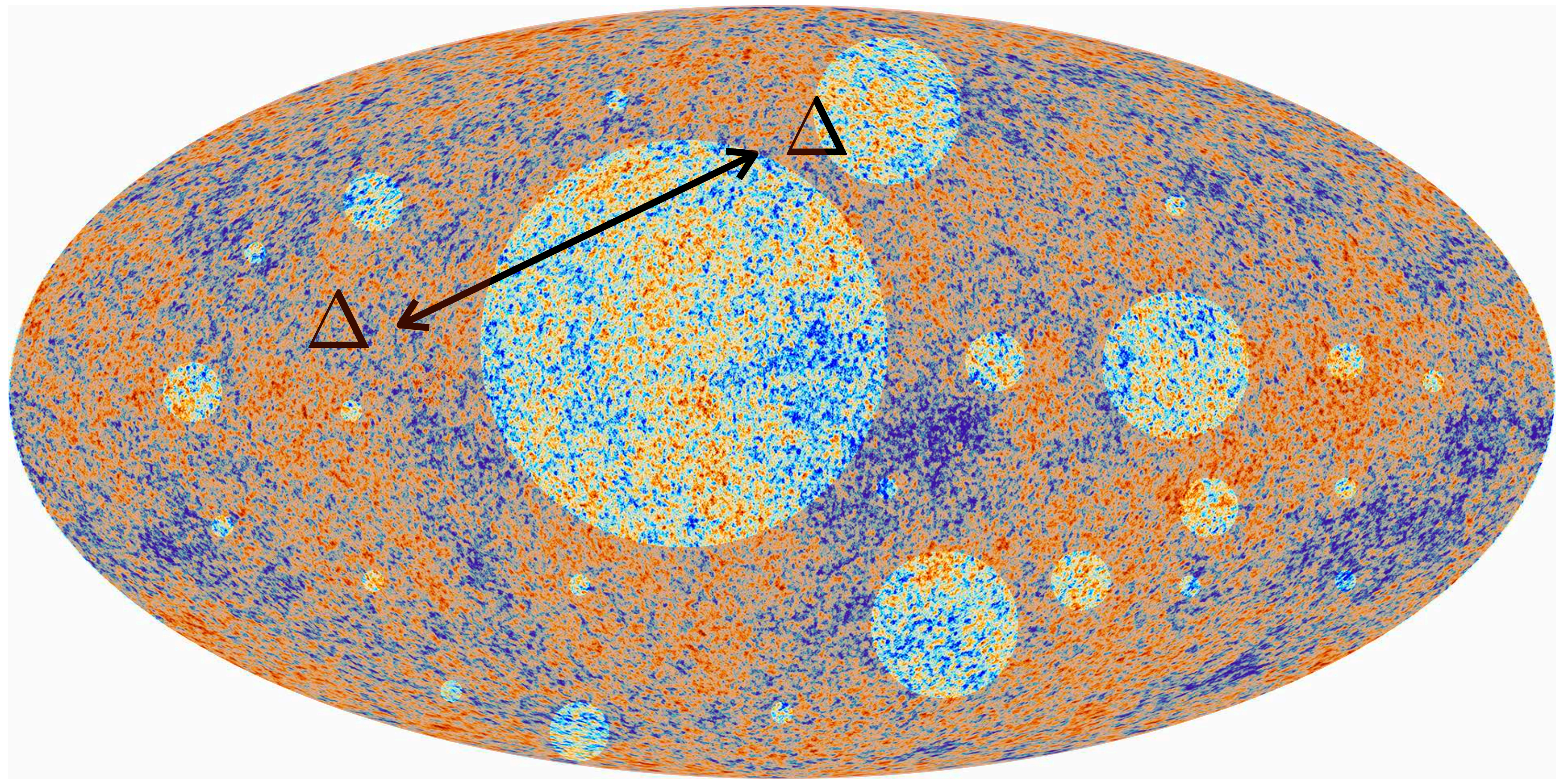
$$C_\ell^{TT} = 4\pi \int d(\ln k) P_{\rm ad}(k) |\Delta_\ell^{\rm ad}(k)|^2$$

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

Standard ΛCDM

DR isocurvature in CMB

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



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

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

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

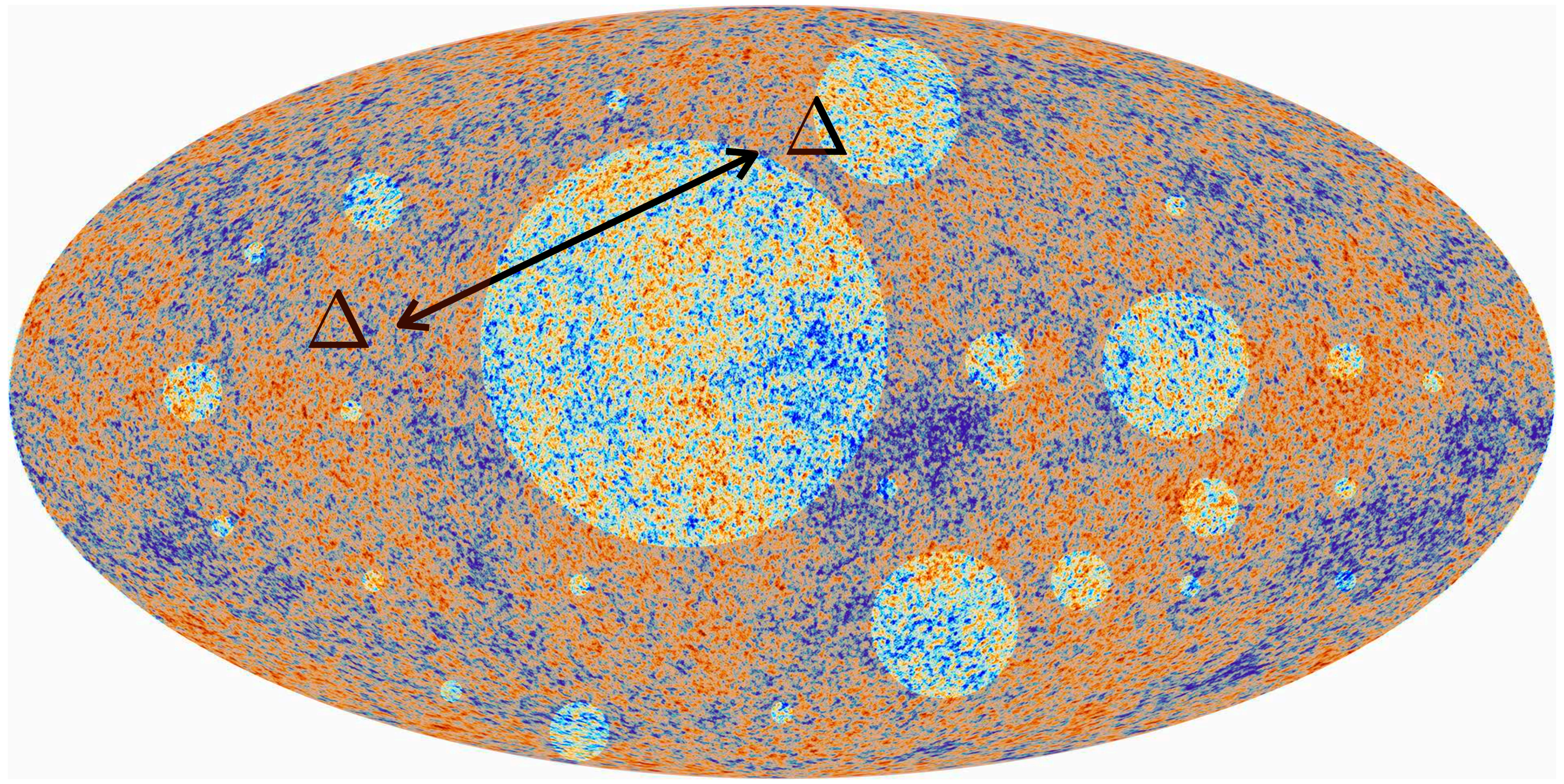
Standard ΛCDM

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

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

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

- Mapping to PT parameters

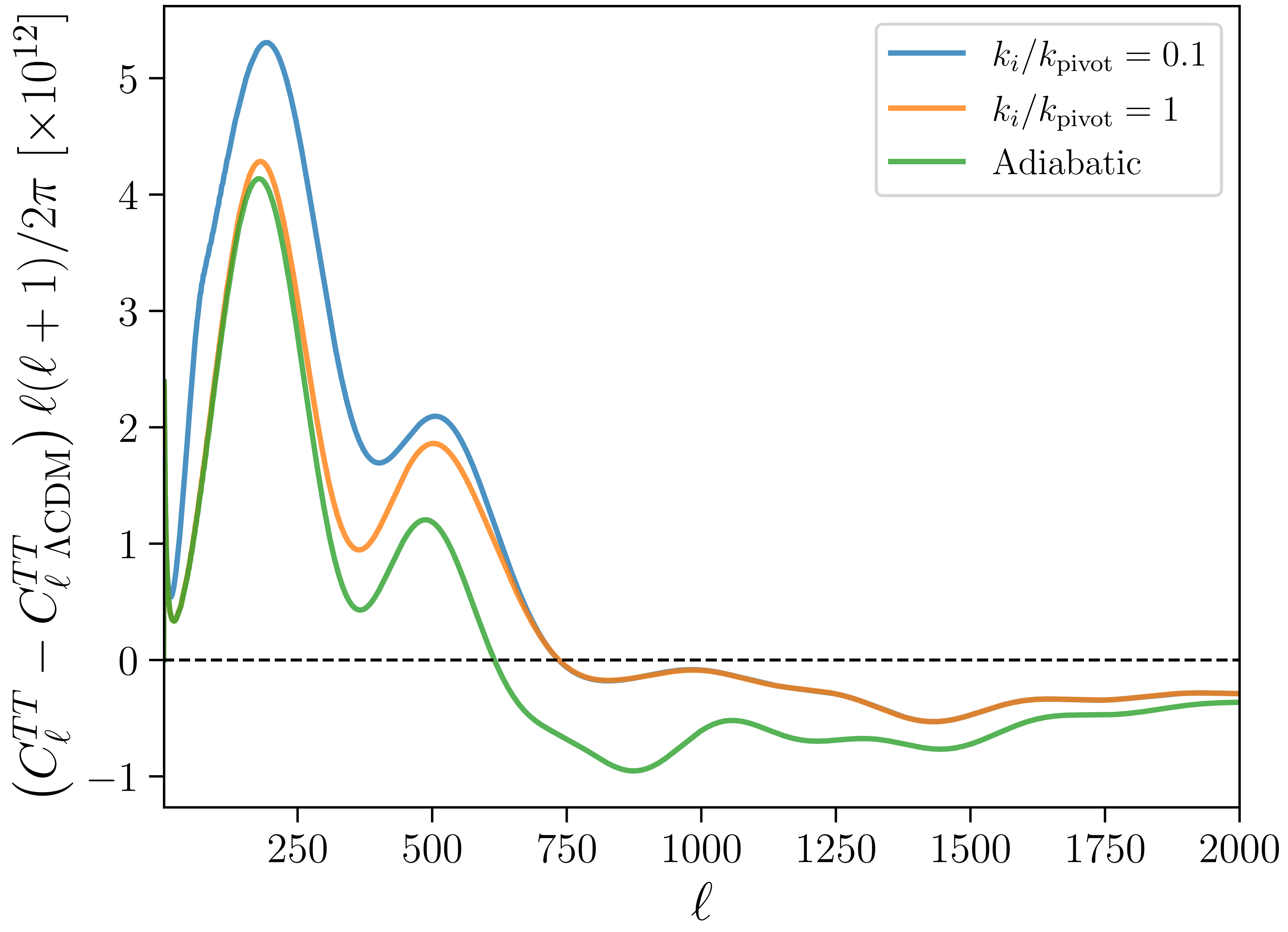
$$f_{\rm iso}^2 A_s \sim \gamma_{\rm PT} = (T_*^8/T_{\rm rh}^8)$$

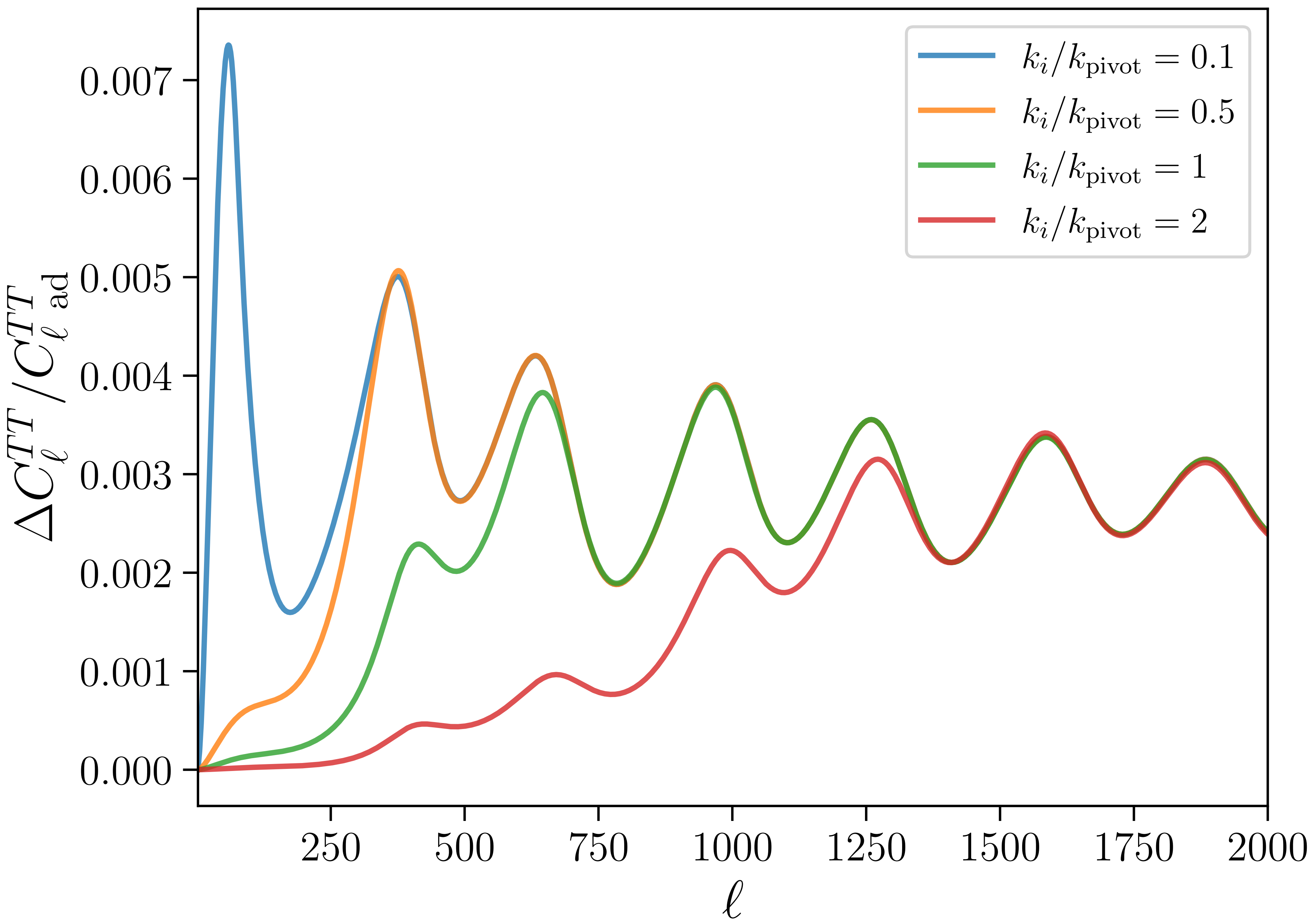
$$k_i \sim r_i^{-1}$$

DR isocurvature in CMB

Simulation from modified CLASS

$k_{\text{pivot}} = 0.05\,\text{Mpc}^{-1}$





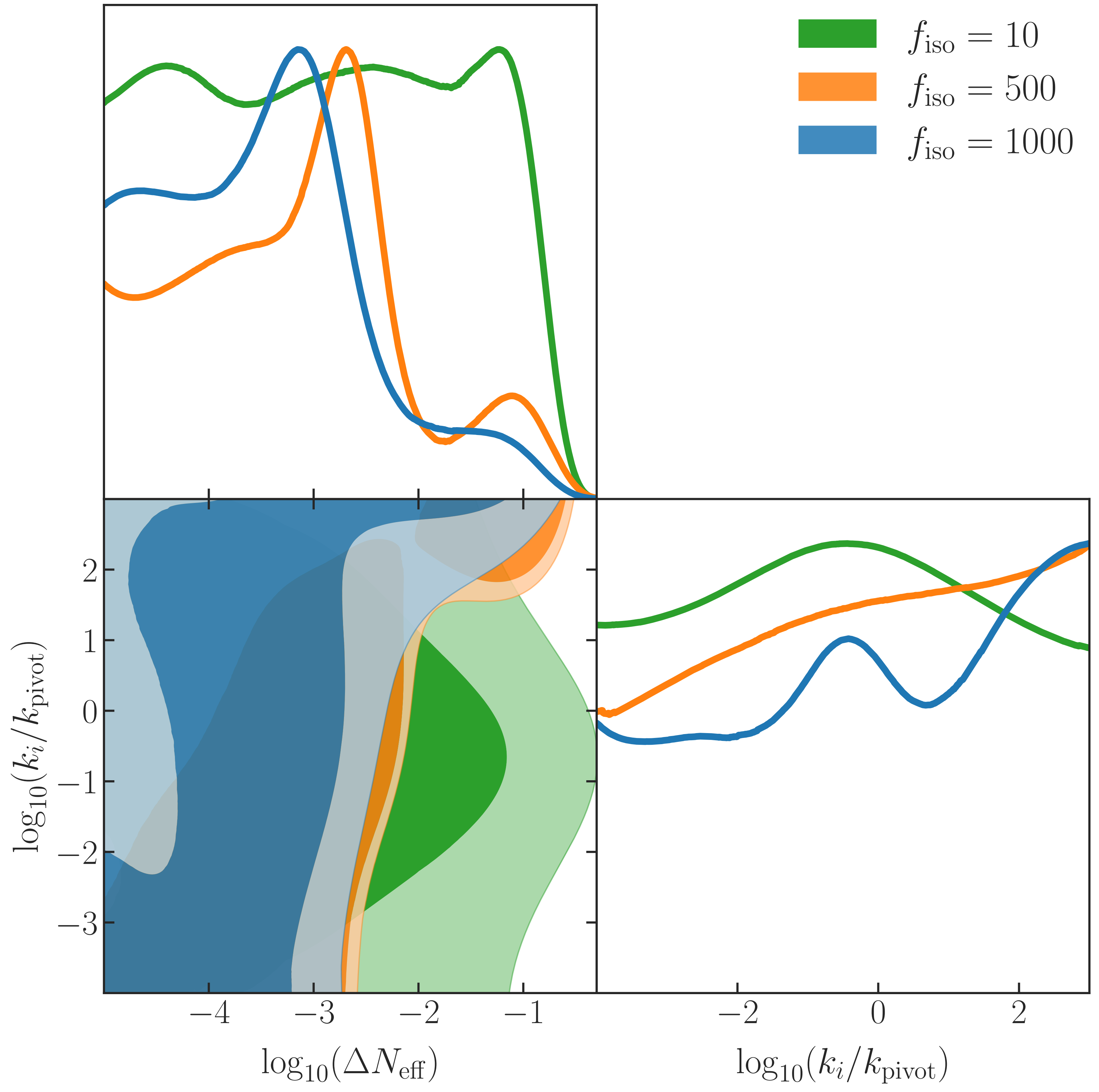
$$P_{\text{iso}}(k) = f_{\text{iso}}^2 A_s \begin{cases} (k/k_i)^3 & k \le k_i \\ 1 & k > k_i \end{cases}$$

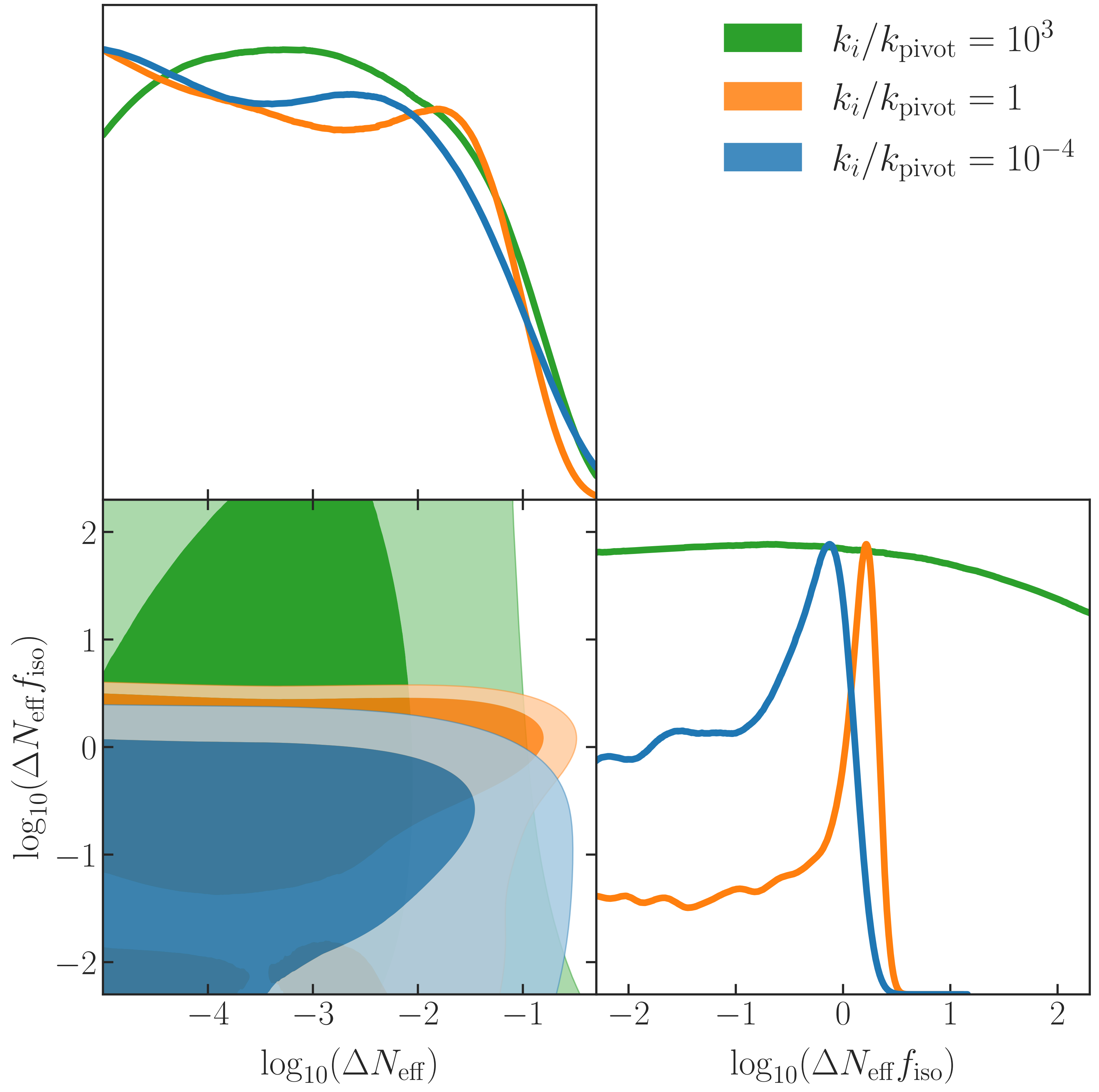
$$\Delta N_{\text{eff}} = 0.1 \quad f_{\text{iso}} = 10$$

DR isocurvature constraint

Constraints from Planck18+BAO

$k_{\rm pivot} = 0.05\,{\rm Mpc}^{-1}$





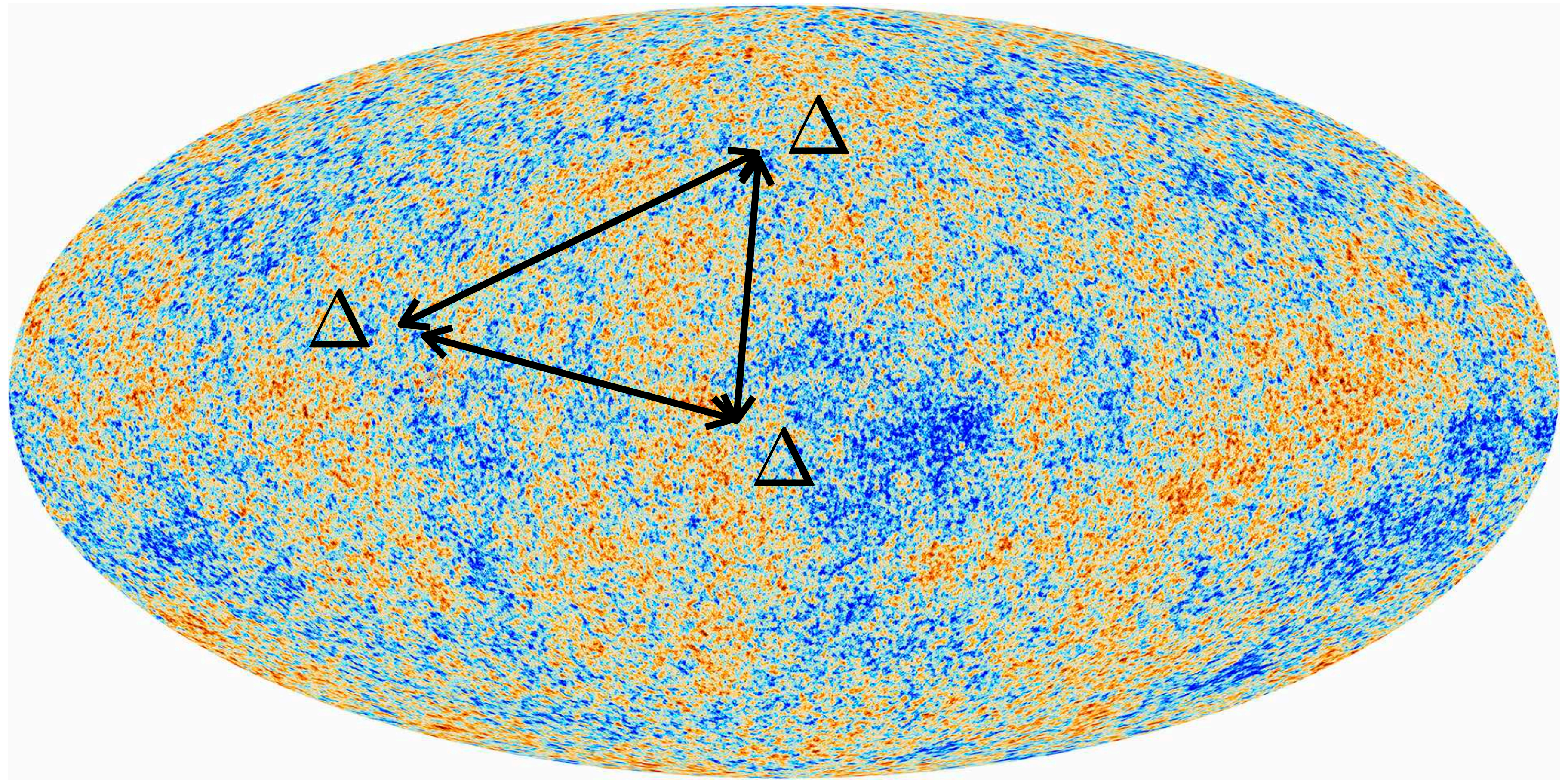
For $k_i \lesssim k_{\rm pivot}$ $\quad \Delta N_{\rm eff} f_{\rm iso} \lesssim O(1)$

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

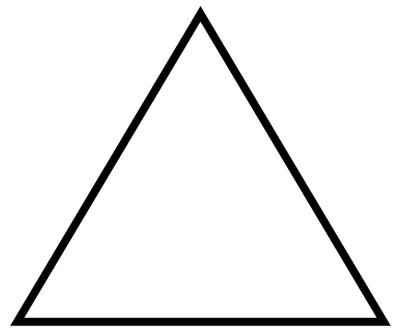
$$f_{\rm iso}^2 A_s \sim \gamma_{\rm PT} = (T_*^8/T_{\rm rh}^8)$$

Buckley,PD,Fernandez,Weikert, 2024

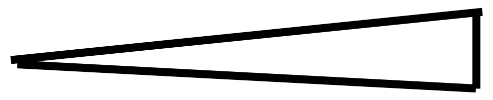
Non-Gaussianity from DR isocurvature



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

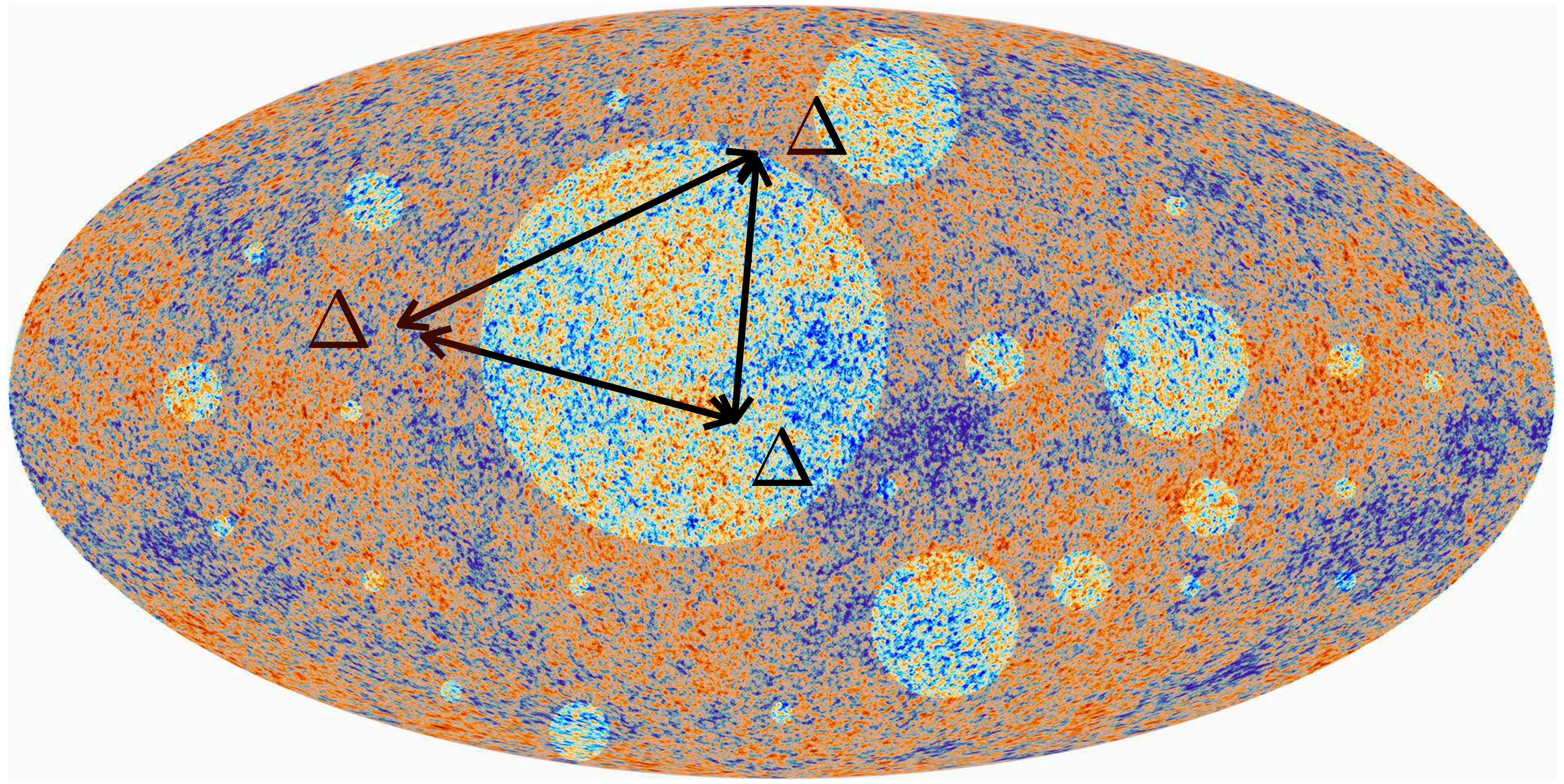


$k_1 \approx k_2 \approx k_3$
equilateral

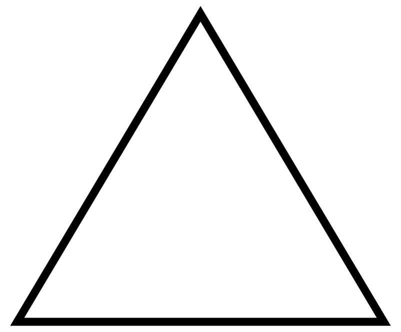


$k_1 \approx k_2 \gg k_3$
local (squeezed limit)

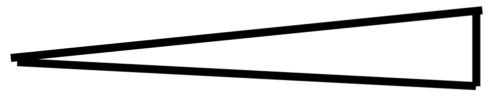
Non-Gaussianity from DR isocurvature



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



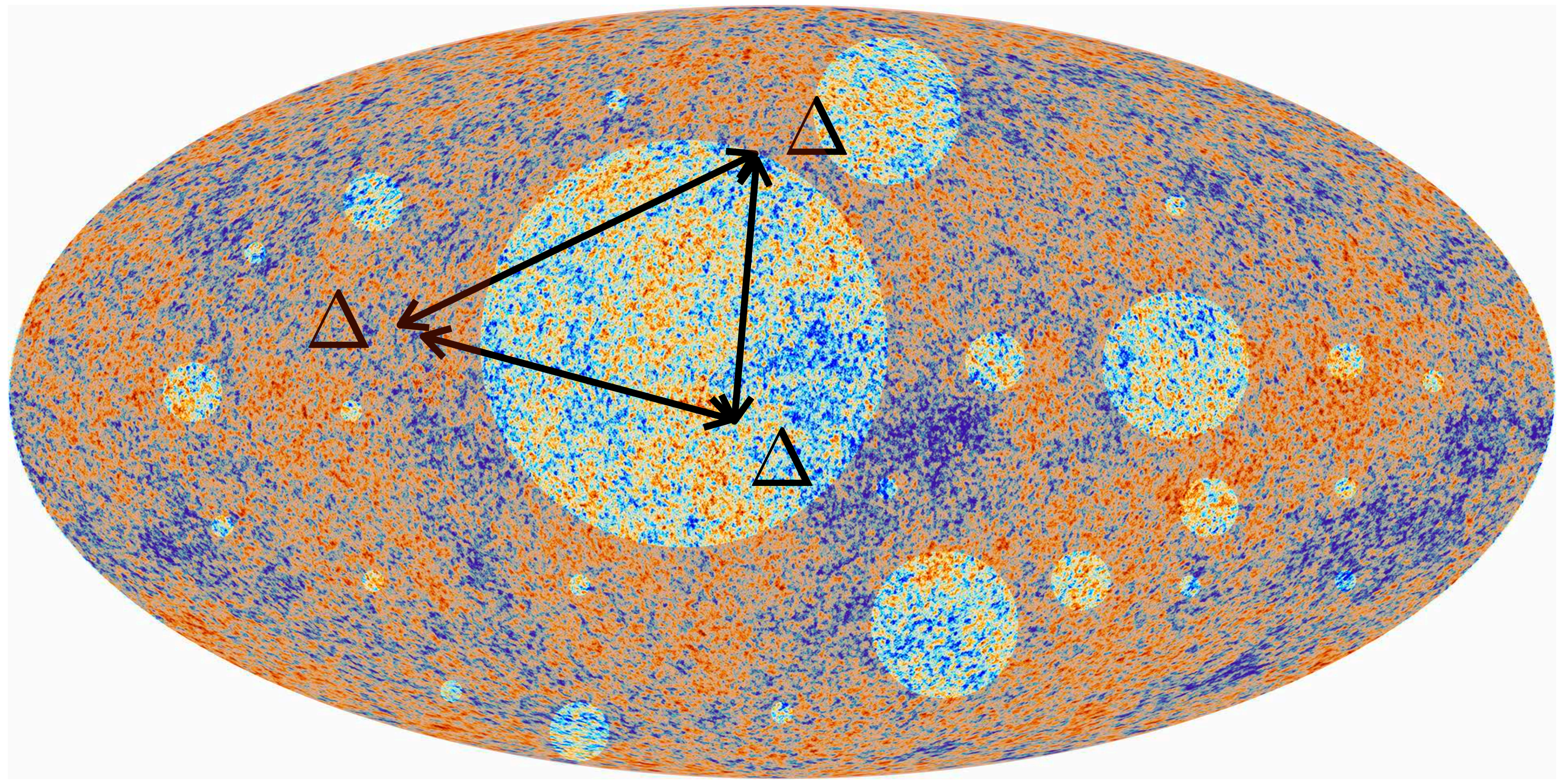
$k_1 \approx k_2 \approx k_3$
equilateral



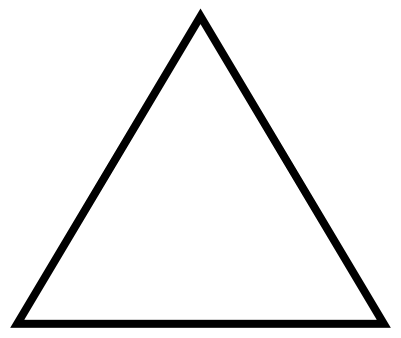
$k_1 \approx k_2 \gg k_3$
local (squeezed limit)

- DR isocurvature non-Gaussianity needs dedicated searches!

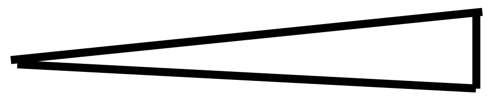
Non-Gaussianity from DR isocurvature



- $\langle \Delta\Delta\Delta \rangle$ 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!

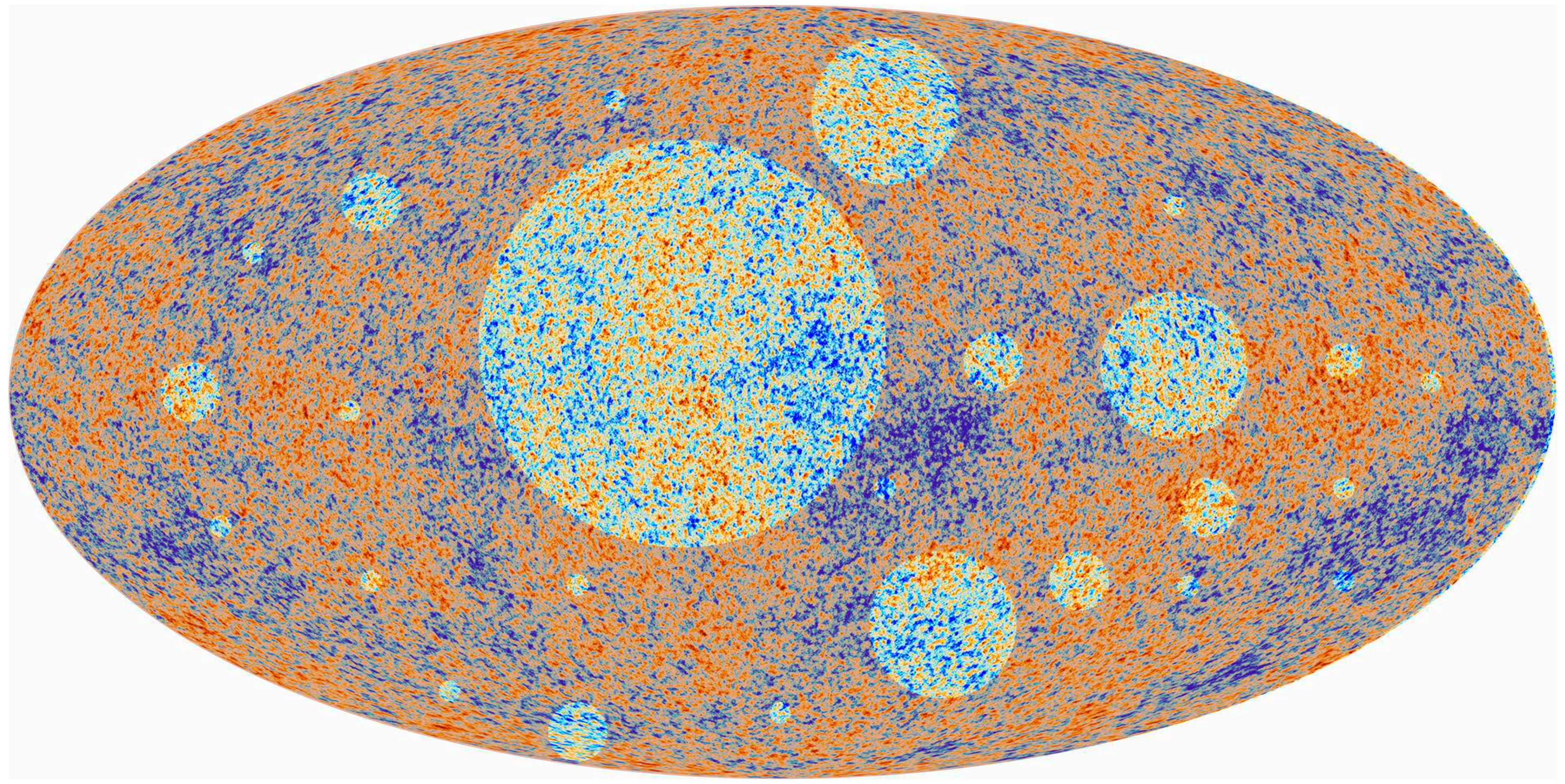
- Estimation based on neutrino iso NG with equil. config.

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

Buckley,PD,Fernandez,Weikert, 2024

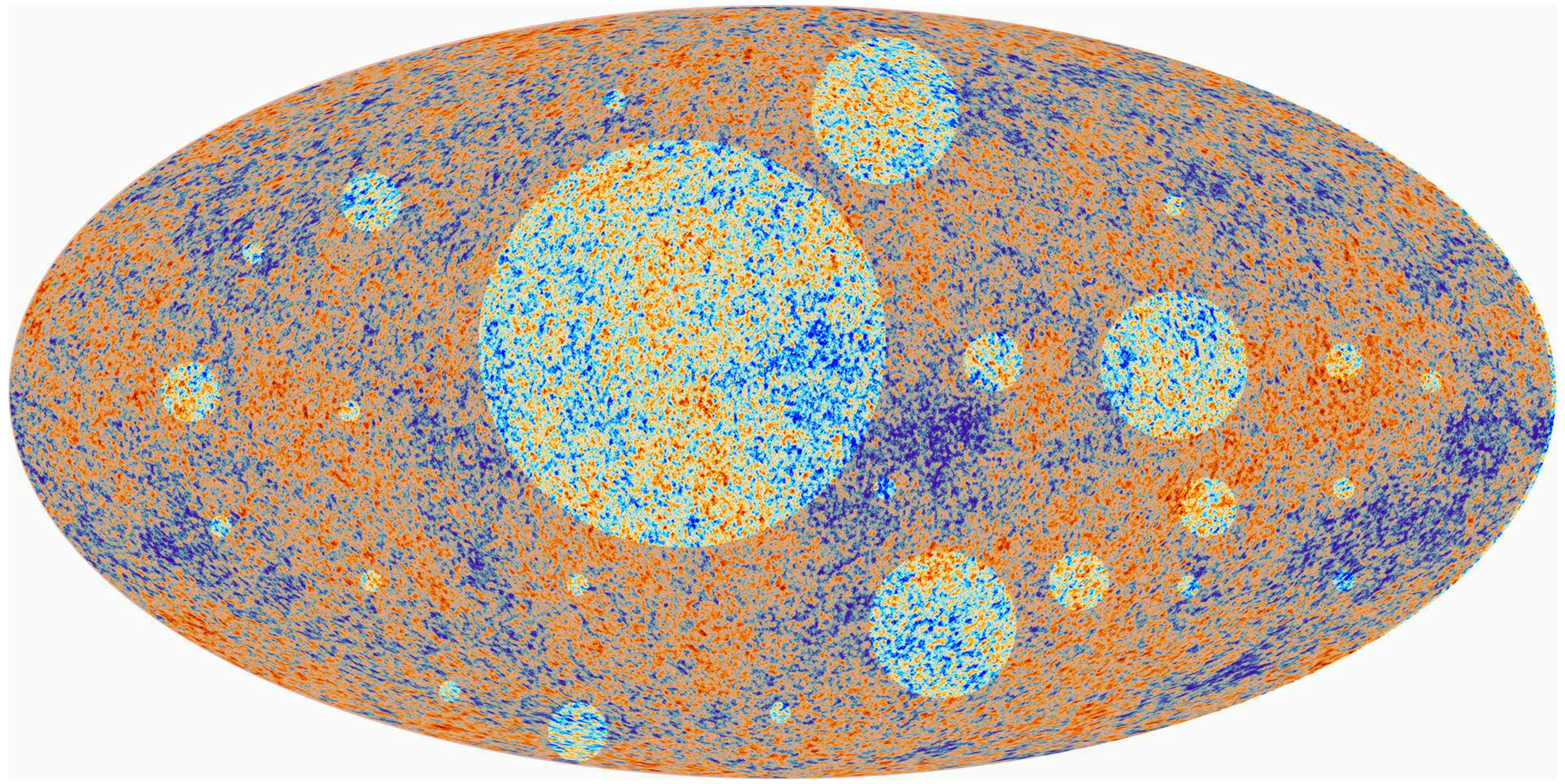
could be stronger than two-point functions $\Delta N_{\rm eff} f_{\rm iso} \lesssim O(1)$

Future directions

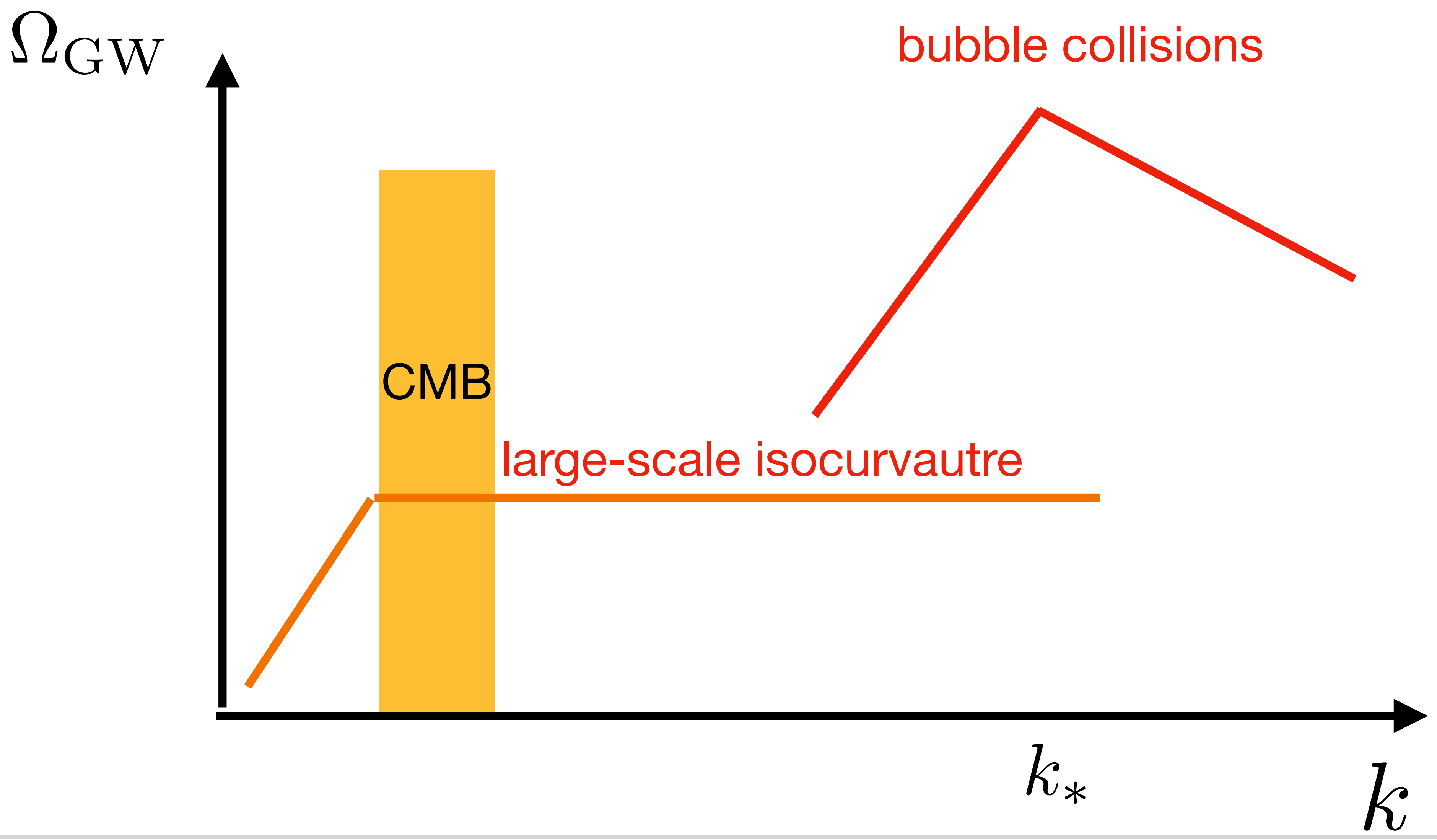


- Dedicated study for general form of non-Gaussianity

Future directions



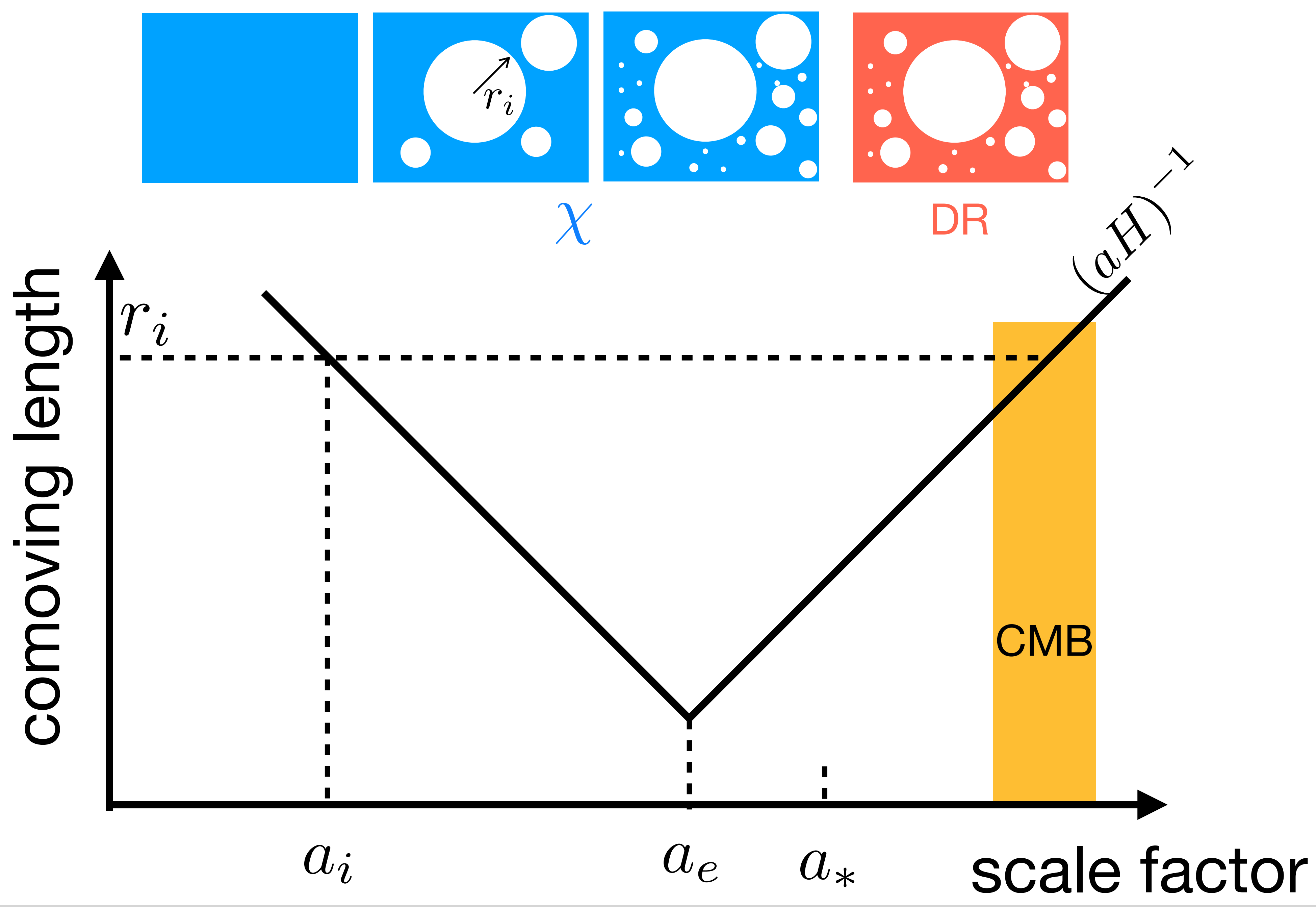
- Dedicated study for general form of non-Gaussianity

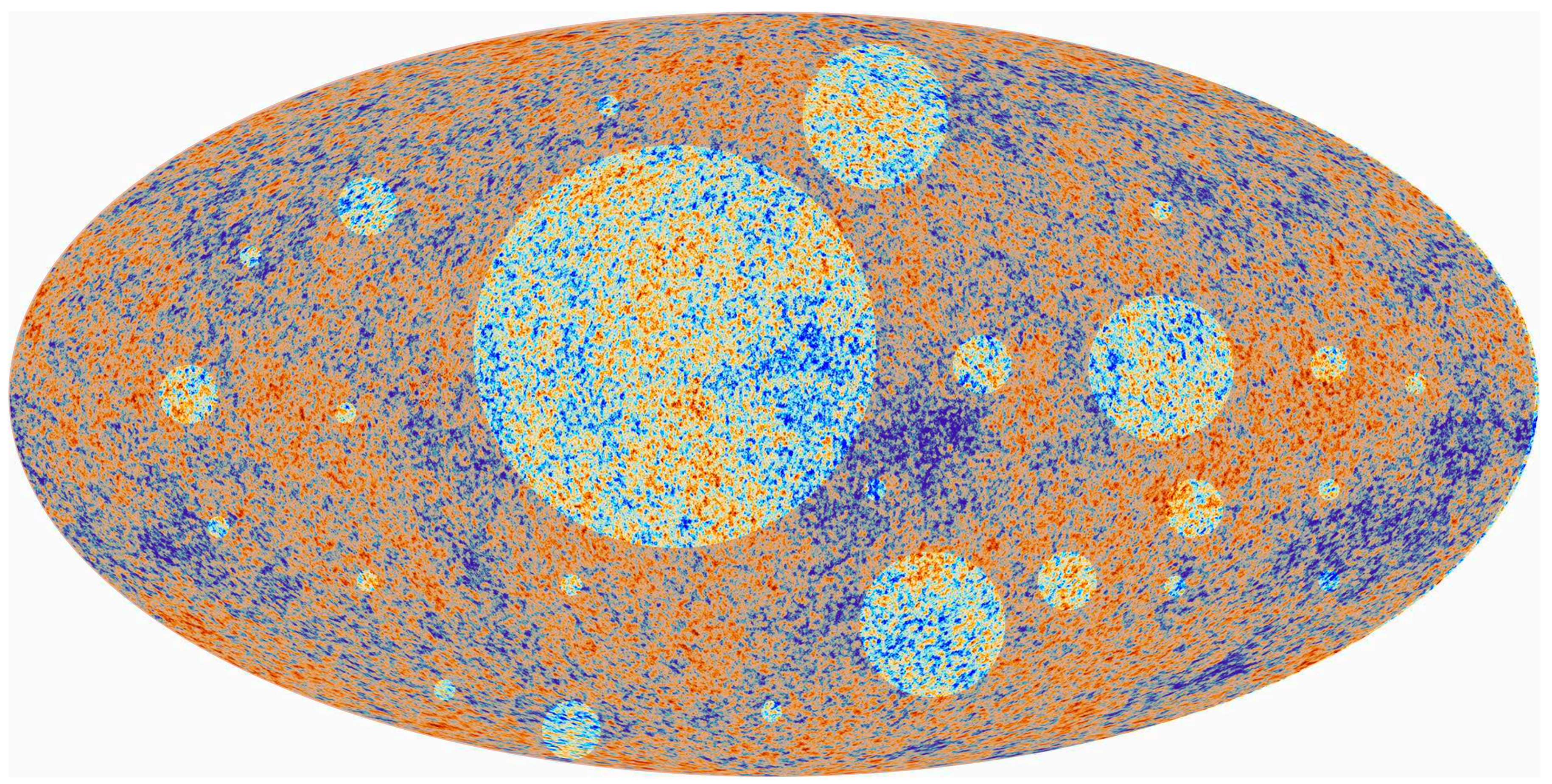


- GWs from PT could have large-scale isocurvature

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!