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Particle creation dynamics during inflation and reheating

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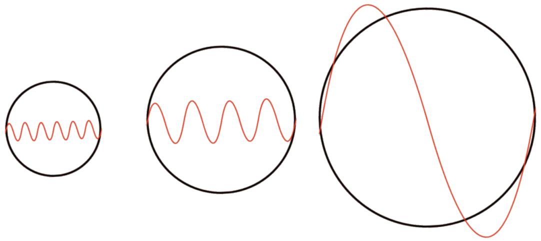
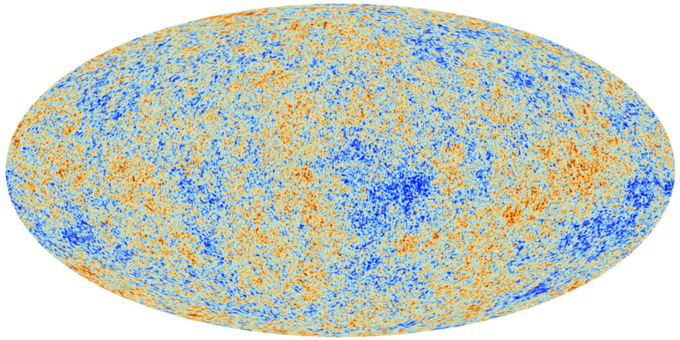
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Introduction: inflation – circa 2024





$$\mathcal{P}_\mathcal{R} = \frac{H_*^4}{4\pi^2\dot{\phi}_*^2}\left(\frac{k}{aH}\right)^{n_s-1}$$

$$\mathcal{P}_\mathcal{T} = \frac{2H_*^2}{\pi^2}\left(\frac{k}{aH}\right)^{n_t}$$

$$r \equiv \frac{\mathcal{P}_\mathcal{T}(k=k_*)}{\mathcal{P}_\mathcal{R}(k=k_*)}$$

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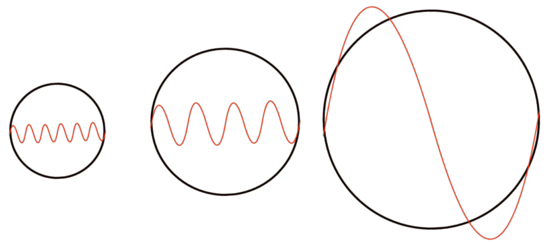

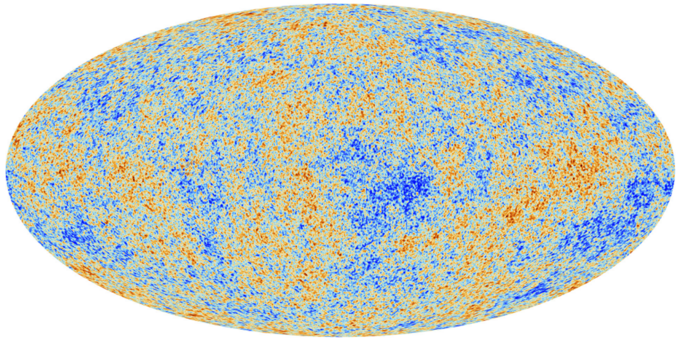

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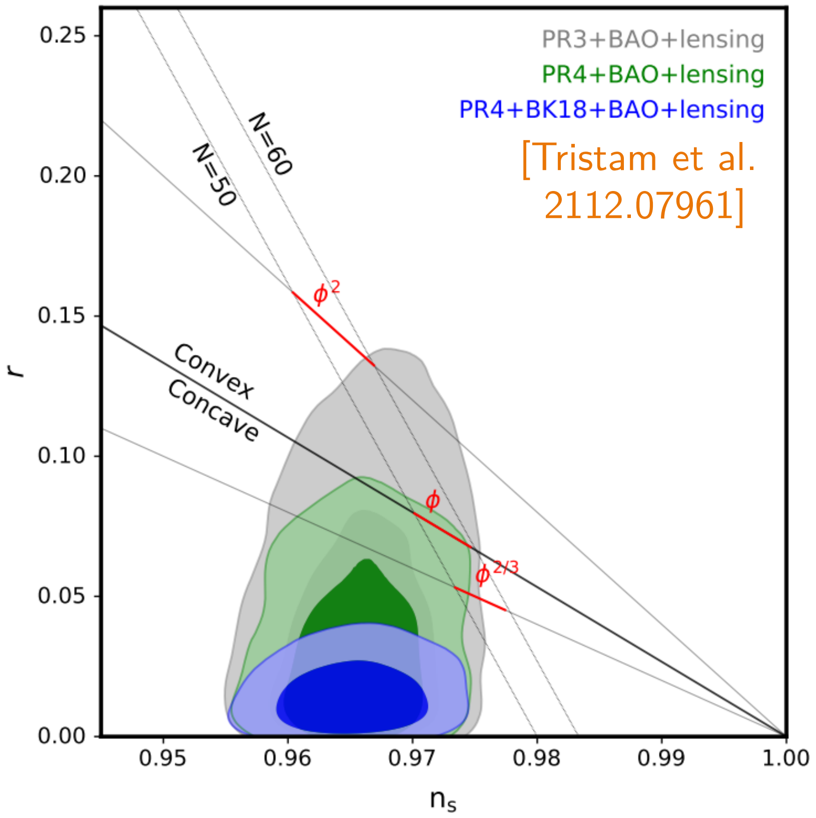

$$A_s(k_\star) \simeq 2.1 \times 10^{-9}$$
$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

[Planck '18]

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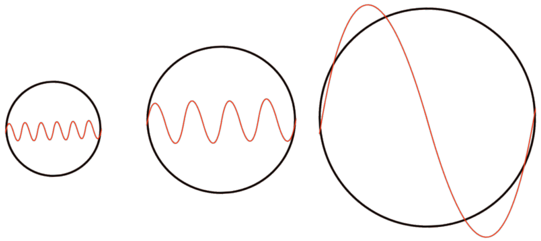
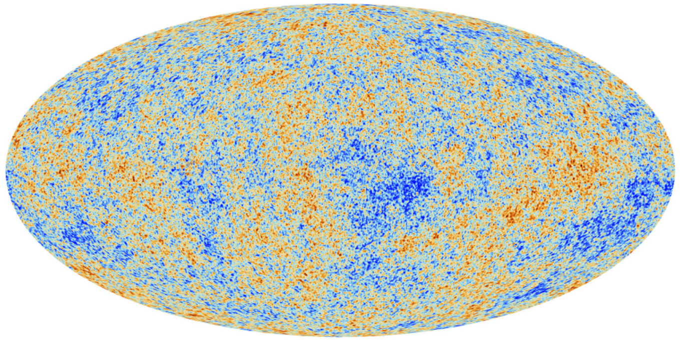


$\Rightarrow$



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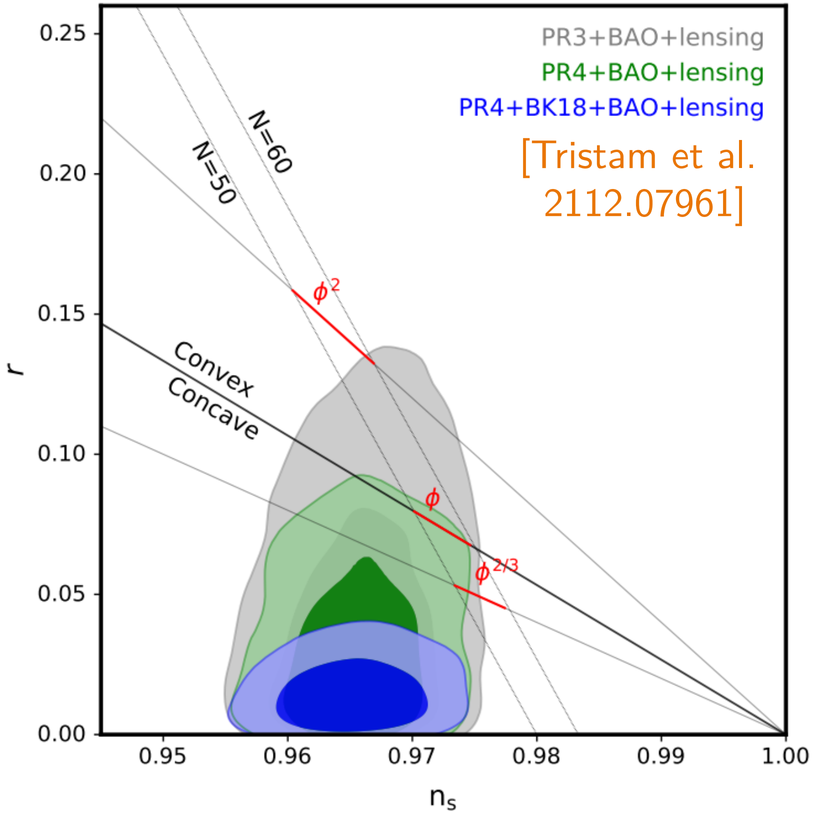


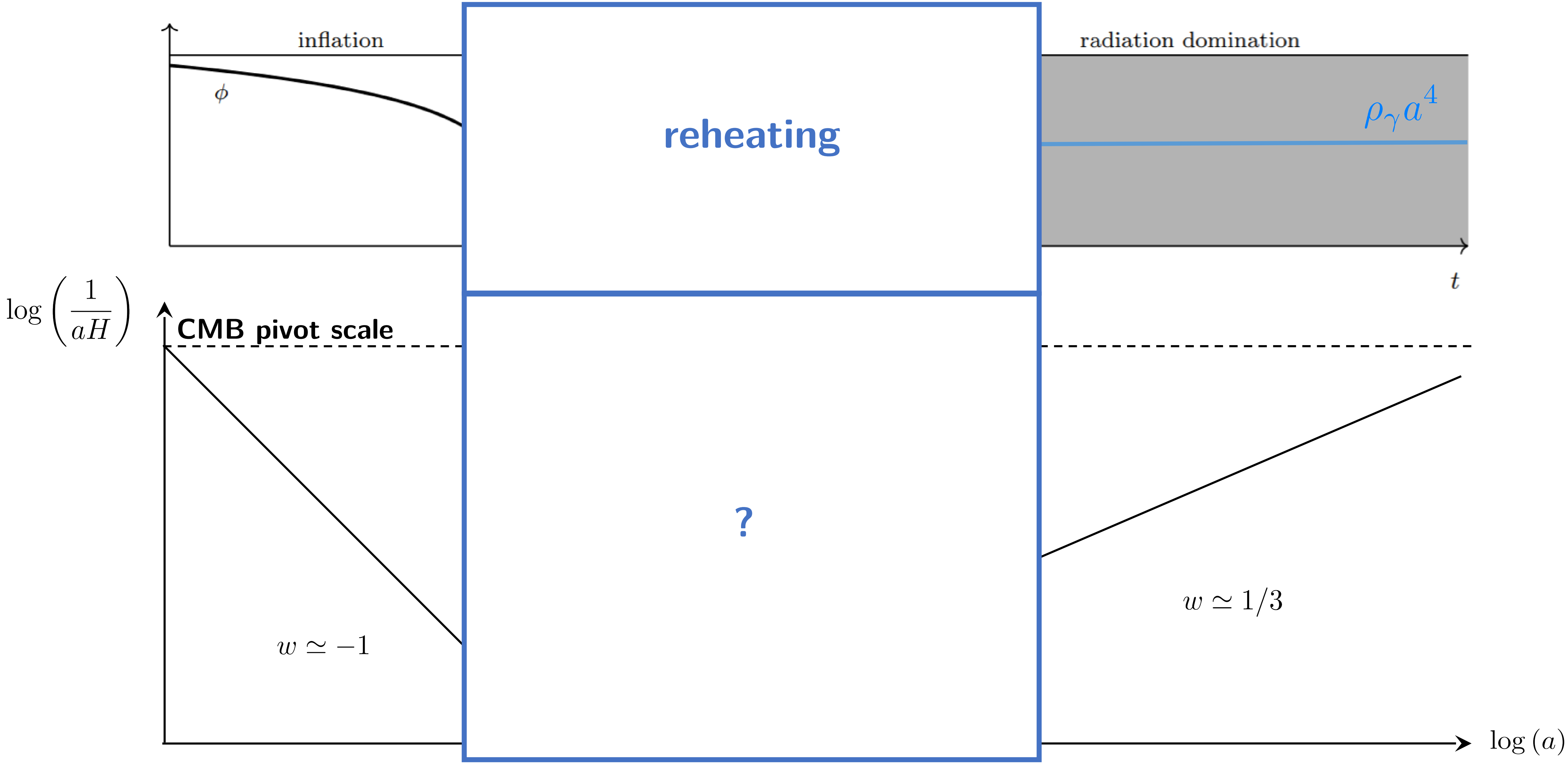
$$A_s(k_\star) \simeq 2.1 \times 10^{-9}$$
$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$ [Planck '18]

Slow-roll is a remarkable solution

- attractor solution
- predicts $n_s < 1$
- **adiabatic perturbations** frozen on super-horizon scales
- Non-gaussianities suppressed $f_{\rm NL} \sim n_s - 1$ [Maldacena '03]

$\rightarrow$ weak (self)interactions

Introduction



Outline

1. Particle production during inflation
2. Particle production during reheating

This talk is biased

1. Particle production during inflation

1.1 Production of a thermal bath during inflation

Warm inflation

- Production of relativistic particles: **allows for smooth transition to reheating**
- Any initially produced amount of particle dilutes **exponentially** $e^{-3\times 50} \simeq 10^{-66}$
  $\rightarrow$ **Production has to be sustained**
- Sizable interactions among particles induce thermalization $\rho_r = \frac{\pi^2}{30} g_\star T^4$ $T \gg H$

A broad literature:

[A. Berera & L. Z. Fang - arXiv:astro-ph/9501024]

[M. Bastero-Gil, A. Berera - arXiv:0902.0521]

[A. Berera, I. G. Moss & R. O. Ramos - arXiv:0808.1855]

[M. Bastero-Gil, A. Berera, R. O. Ramos & J. G. Rosa - arXiv:1604.08838]

[V. Kamali, M. Motaharfar & R. O. Ramos - arXiv:2302.02827] $\longrightarrow$ recent review

+ many more!

Warm inflation

- Production of relativistic particles: **allows for smooth transition to reheating**

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- Interaction between inflaton and thermal plasma can manifest as a **local dissipation rate** $\Gamma(\phi, T)$

$$\nabla_\mu T^{\mu\nu}_{(\phi)} = Q^\nu\,, \qquad \ddot{\phi} + (3H + \Gamma)\dot{\phi} + V_\phi = 0,$$

$$\nabla_\mu T^{\mu\nu}_{(r)} = -Q^\nu \qquad \dot{\rho}_r + 4H\rho_r = \Gamma\dot{\phi}^2,$$

$$\rho_r^{1/4} > H$$

$$\rho_r \ll \rho_\phi$$

radiation **subdominant**

- Initial conditions irrelevant: **warm inflation attractor solution** $\Gamma\dot{\phi}^2 \simeq 4H\rho_r$

- Fluctuation-dissipation $Q_\mu = -\Gamma\, u^\nu \nabla_\nu \phi\, \nabla_\mu \phi + \sqrt{\dfrac{2\Gamma T}{a^3}} \xi_t \nabla_\mu \phi$ ξ_t : white noise $\rightarrow$ perturbed level

Warm inflation

- At first order in perturbation theory:

$$\delta\ddot{\phi} + \dots = \sqrt{\frac{2\Gamma T}{a^3}}\,\xi_t,$$

$$\delta\dot{\rho}_r + \dots = -\sqrt{\frac{2\Gamma T}{a^3}}\,\dot{\phi}\,\xi_t,$$

$\longrightarrow$ **stochastic source**

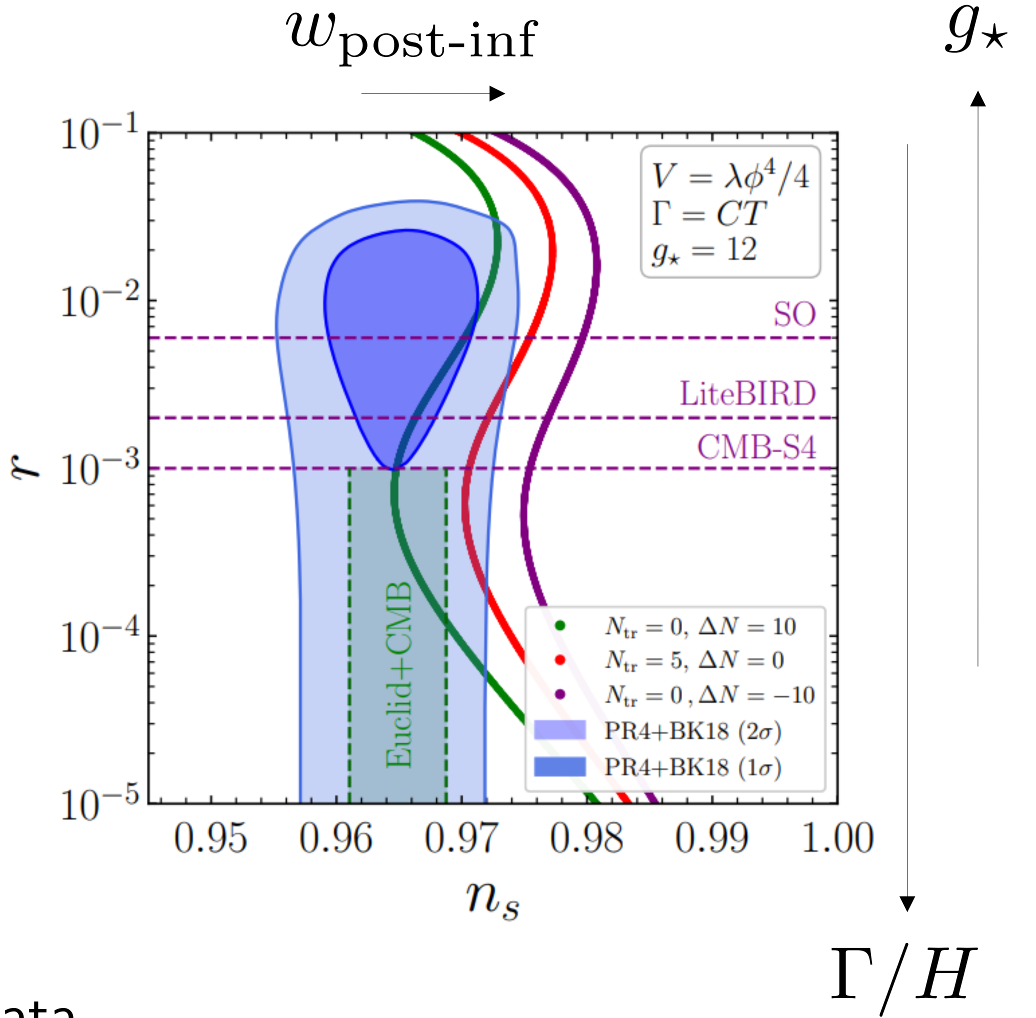
- Estimate power spectrum for **curvature perturbations:**

$\rightarrow$ Solve (**stochastic**) equations with frequentist approach: **requires $O(10^4)$ realizations for reasonable accuracy**

$\rightarrow$ Use Fokker-Planck approach to derive **deterministic** equation **for 2-point correlation function** $\langle|\mathcal{R}|^2\rangle$

[G. Ballesteros, M. A. G. Garcia, A. Perez Rodriguez, **MP** & J. Rey - arXiv:2208.14978]

[M. Bastero-Gil, A. Berera, R. O. Ramos & J. G. Rosa - arXiv:1604.08838]



- At **large dissipation**, insensitive to **initial conditions**
- Can **reconcile monomial inflation models** with CMB data

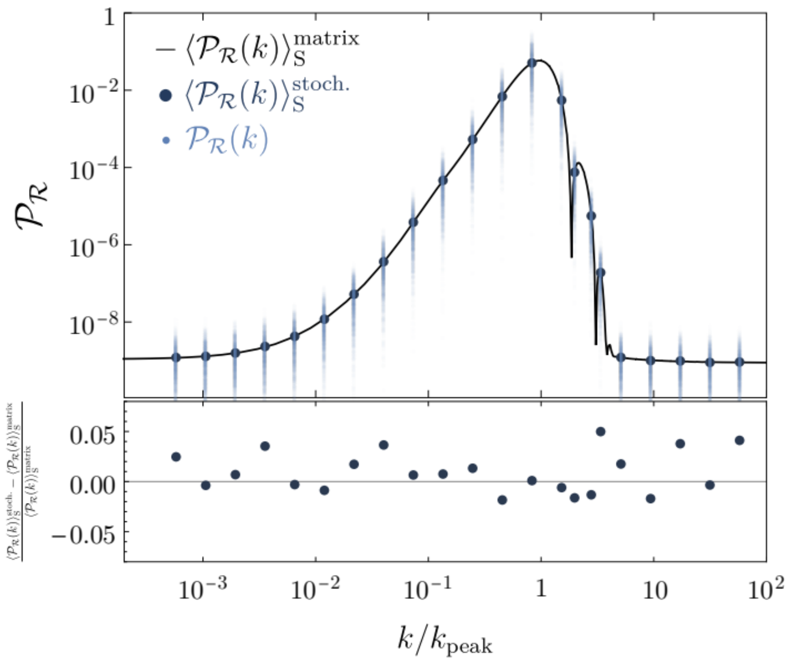
[G. Ballesteros, A. Perez Rodriguez & **MP** - arXiv:2304.05978]

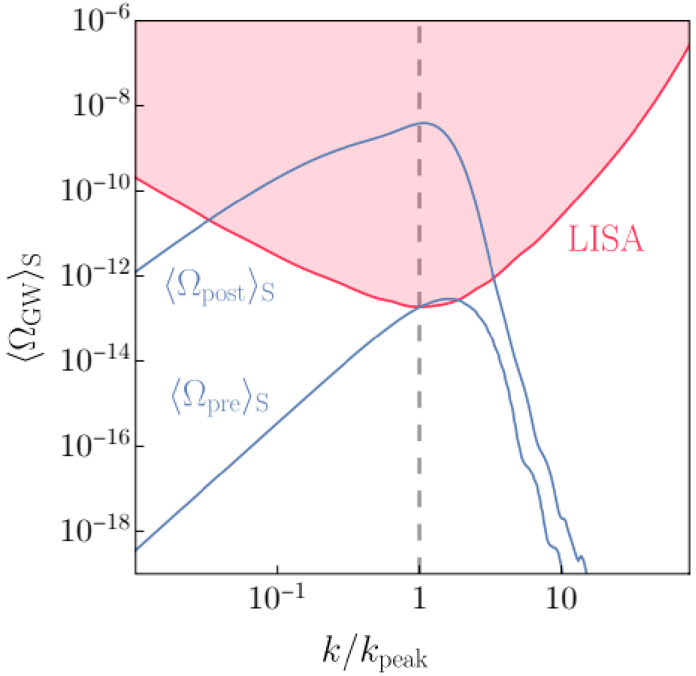
Dynamics of warm inflation: consequences for dark matter

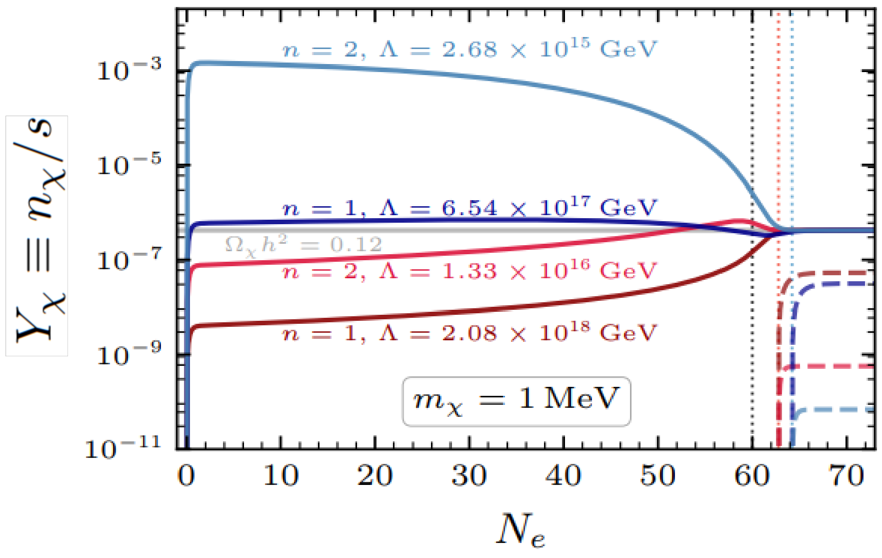
- **Transient** dissipative effects during warm inflation:
  - source large curvature perturbations
    $\rightarrow$ **PBH formation**: account for the DM
  - generate GW signal **observable** by LISA

[G. Ballesteros, M. A. G. Garcia, A. Perez Rodriguez, **MP** & J. Rey - arXiv:2208.14978]

[M. Bastero-Gil, M. S. Diaz-Blanco - arXiv:2105.08045]







- Dark matter production via UV freeze-in from non-renormalizable couplings to thermal bath

$$\dot{n}_\chi + 3Hn_\chi = T^{2n+4}/\Lambda^{2n}$$

[K. Freese, G. Montefalcone, B. Shams Es Haghi - arXiv:2401.17371]

$\rightarrow$ Isocurvature perturbations?

1. Particle production during inflation

1.1 Production of a thermal bath during inflation

1.2 Inflationary background as source for particle production

A (scalar) spectator field during inflation

Consider:

non-minimal coupling

ϕ-coupling

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(M_P^2 - \xi\chi^2)R + \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}\sigma\phi^2\chi^2\right]$$

Equation of motion $$\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} - \frac{\nabla^2}{a^2} + 3H\frac{\mathrm{d}}{\mathrm{d}t} + m_\chi^2 + \sigma\phi^2 - \xi R\right)\chi = 0$$

- **Quantize** the (rescaled) field $X(\tau, \boldsymbol{x}) \equiv a\chi = \int \frac{\mathrm{d}^3\boldsymbol{p}}{(2\pi)^{3/2}} e^{-i\boldsymbol{p}\cdot\boldsymbol{x}}\left[X_p(\tau)\hat{a}_{\boldsymbol{p}} + X_p^*(\tau)\hat{a}^\dagger_{-\boldsymbol{p}}\right]$

- **Harmonic oscillator** with **time-dependent** frequency $X_p'' + \omega_p^2 X_p = 0$

$$\omega_p^2(t) = p^2 + a^2(t)\hat{m}_{\mathrm{eff}}^2(t) \qquad \hat{m}_{\mathrm{eff}}^2 = m_\chi^2 + \sigma\phi^2 + \frac{1}{6}(1-6\xi)R$$

Gravity!

$$' \equiv \frac{\mathrm{d}}{\mathrm{d}\tau} \qquad \mathrm{d}t = a\,\mathrm{d}\tau$$

$\xi = 1/6$: **Conformal** coupling

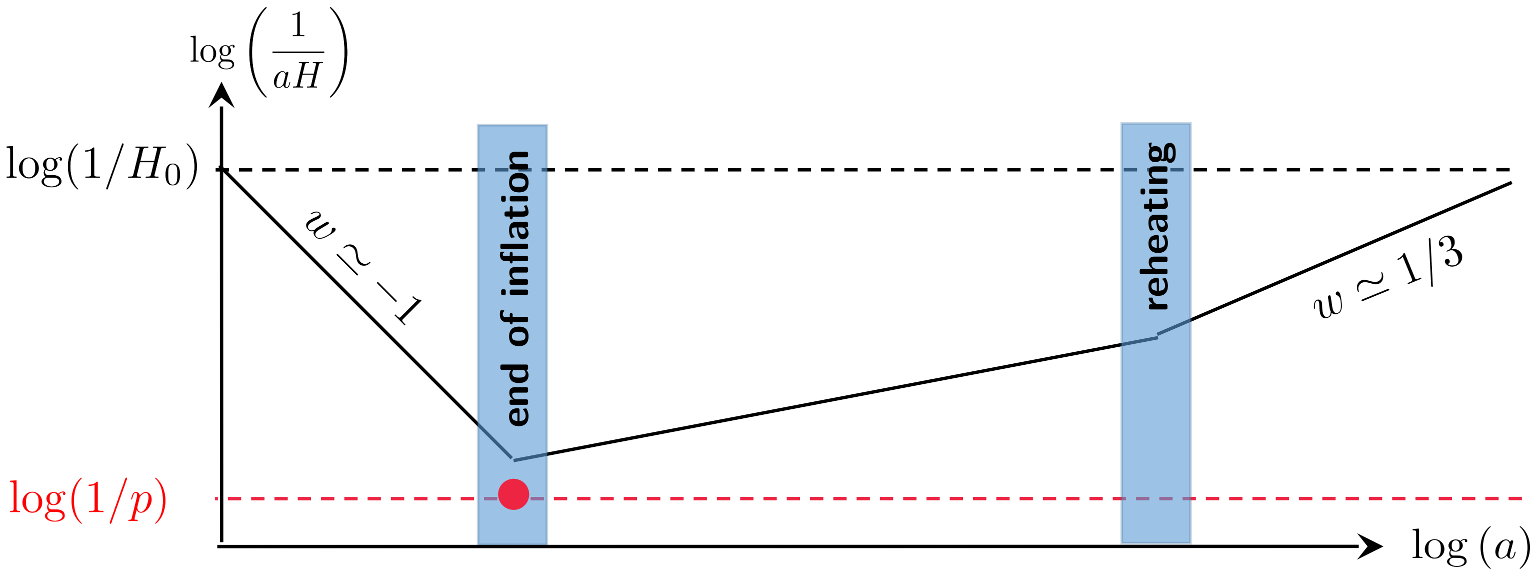
[L. Kofman, A. Linde, A. Starobinsky - arXiv:9704452 – arXiv:9405187]

A (scalar) spectator field during inflation

- **Initial conditions: Bunch-Davies** vacuum $X_p(\tau_0) = \frac{1}{\sqrt{2\omega_p}}$ $X'_p(\tau_0) = -\frac{i\omega_p}{\sqrt{2\omega_p}}$

- **Light scalar fields unstable during inflation!** $\omega_p^2 = p^2 + 2(aH)^2\left[\frac{m_\chi^2}{2H^2} + \frac{\sigma\phi^2}{2H^2} + 6\xi - 1\right]$

- **For** small physical scales: **modes** always **inside** horizon $p/(aH) \gg 1$ $\omega_p^2 > 0$ ● $\tau_0 = \tau_{\mathrm{end}}$



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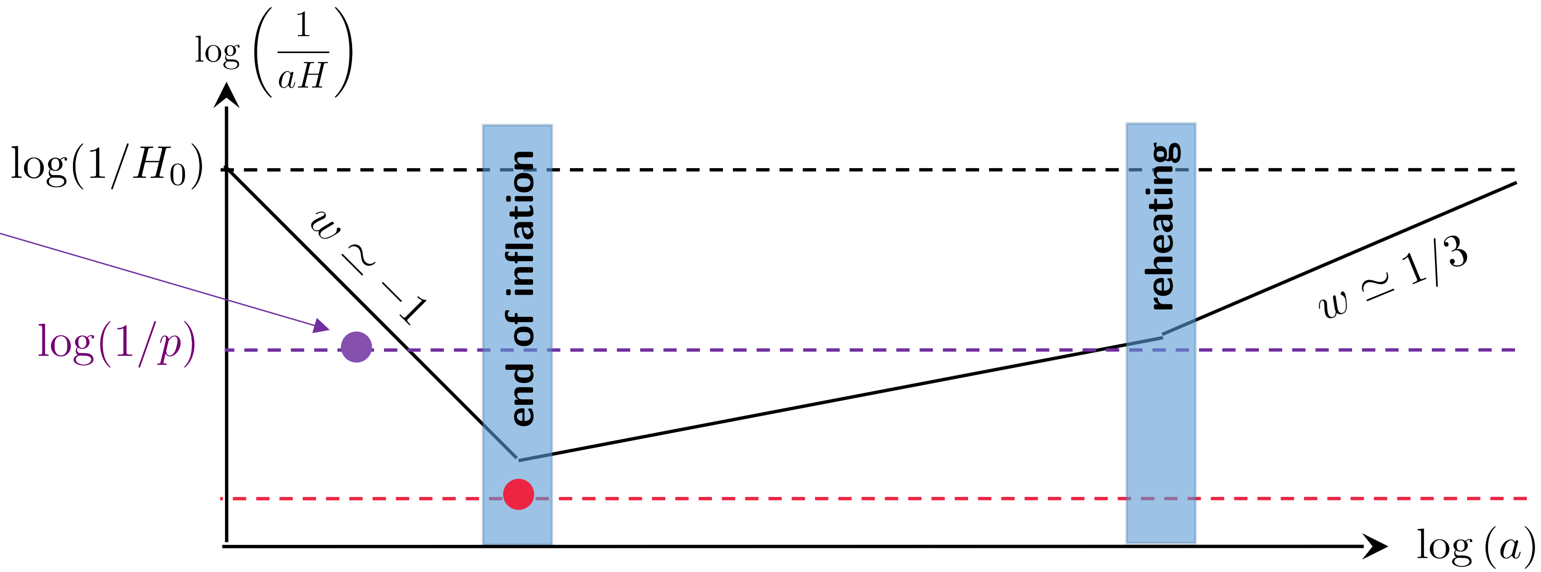
- **For** small physical scales: **modes** always **inside** horizon $p/(aH) \gg 1$ $\quad \omega_p^2 > 0 \quad$ ● $\tau_0 = \tau_{\rm end}$

- **For** $m_\chi^2 < 2H^2, \sigma/\lambda \ll 1, \xi < 1/6$ superhorizon **modes** experience $\omega_p^2(t_{\rm end}) < 0$

  ● $\tau_0 < \tau_{\rm end}$

  $$p^2 \gg a(\tau_0)^2 H(\tau_0)^2$$

  ➡ **Particle production!**



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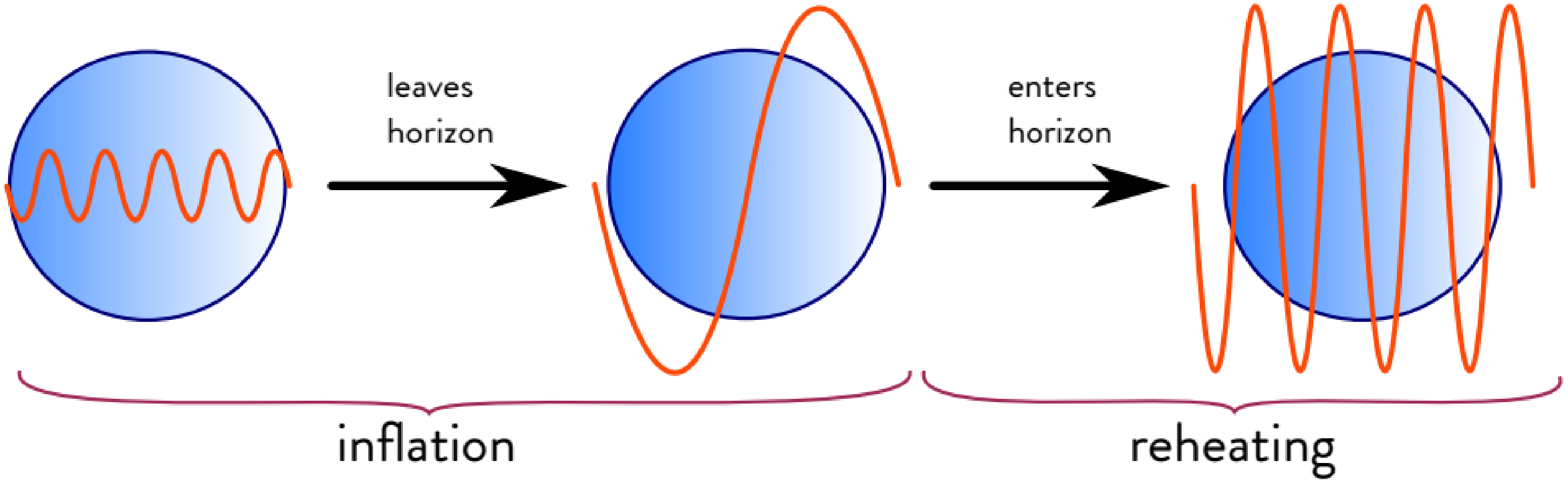


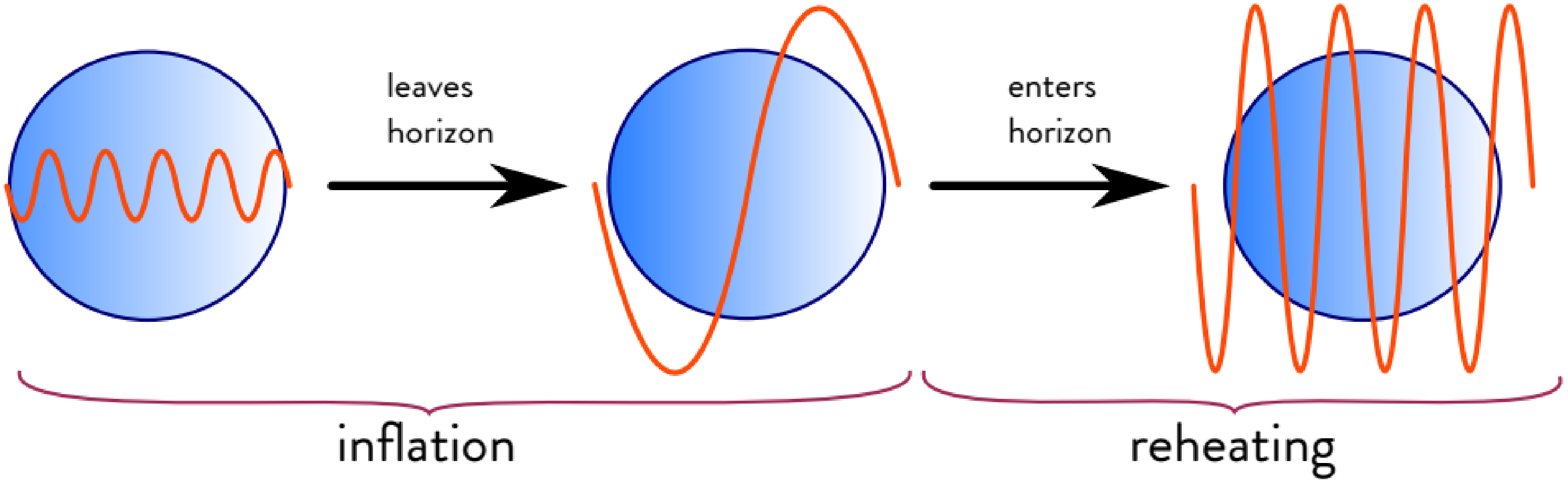
$\langle \chi \rangle = 0$ $\quad\xrightarrow[\text{“Random walk”}]{}\quad$ $\langle \chi \rangle = 0$ $\quad\longrightarrow\quad$ $|\beta_p|^2 = \frac{1}{2\omega_p} |\omega_p X_p - i X'_p|^2$

$\langle \chi^2 \rangle = 0$ $\qquad\qquad\qquad$ $\langle \chi^2 \rangle \neq 0$

Bogolubov coefficient

In curved space one must rely on **correlation functions**!

A (scalar) spectator field during inflation



$$\langle \chi \rangle = 0 \qquad \langle \chi^2 \rangle = 0$$

$\xrightarrow{}$ "Random walk"

$$\langle \chi \rangle = 0 \qquad \langle \chi^2 \rangle \neq 0$$

$$\longrightarrow \quad |\beta_p|^2 = \frac{1}{2\omega_p} |\omega_p X_p - i X_p'|^2$$

Bogolubov coefficient

➡ Match **particle interpretation** only at **later times**

Phase space distribution

$$f_\chi(p) = |\beta_p|^2$$

Comoving number density

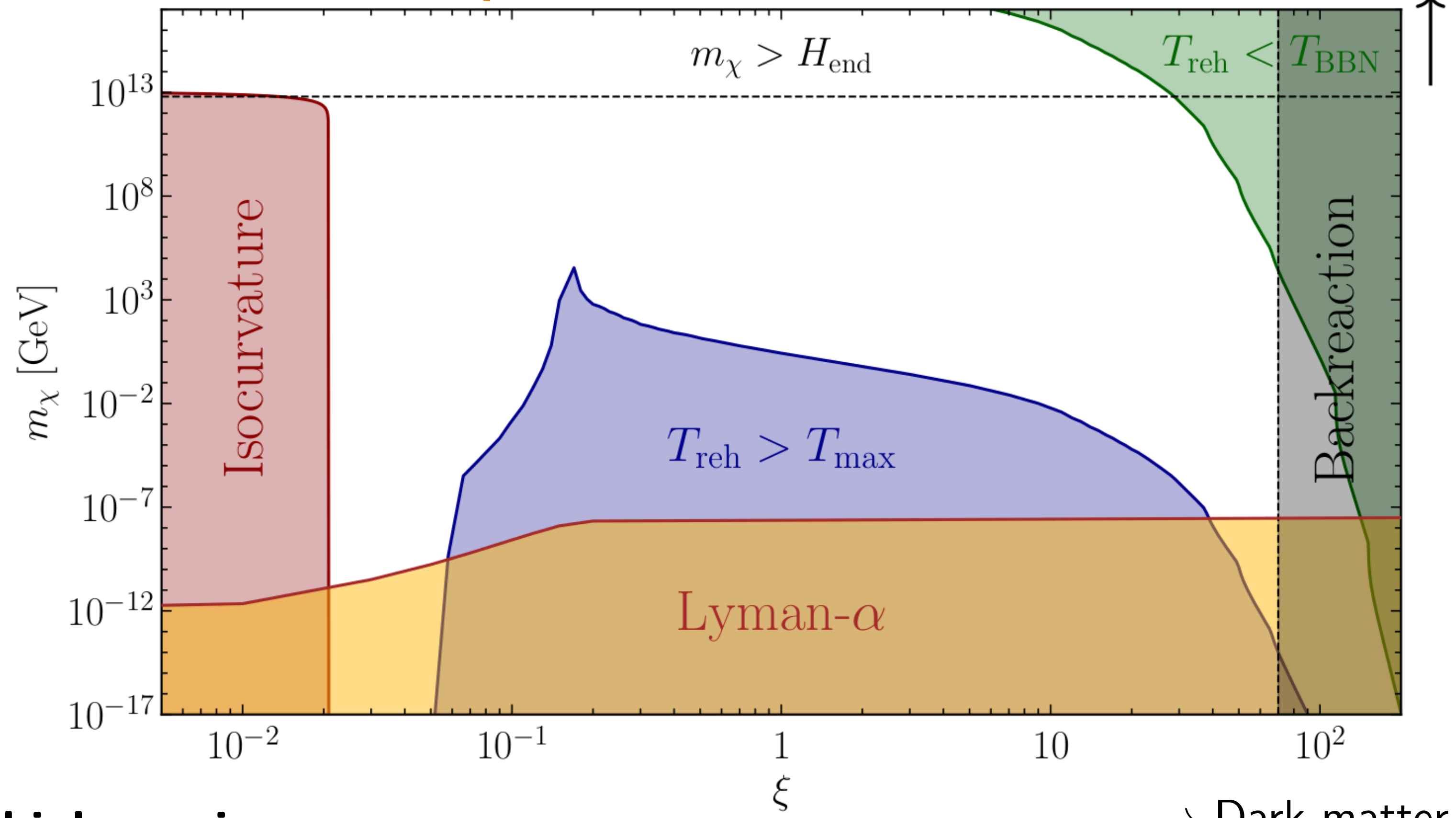
$$a^3 n_\chi = \int \mathrm{d}\log p \, \frac{p^3}{2\pi^2} |\beta_p|^2$$

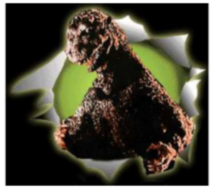
Energy density

$$\rho_\chi \simeq \frac{m_\chi^2}{2} \langle \chi^2 \rangle$$

Gravitational production of dark matter

[M. A. G. Garcia, **MP** & S.Verner, arXiv:2305.14446]





WIMPZILLAS

[E.W. Kolb, D.J.H. Chung, A. Riotto]

- **Generalization to higher spins**

Spin ½: if $m_\chi \to 0$: **conformally** coupled to gravity $\leftrightarrow$ scalar $\xi=1/6$

Spin 1: Transverse: $\leftrightarrow$ **conformally** coupled scalar $\xi=1/6$

Longitudinal: $\leftrightarrow$ **minimally** coupled scalar $\xi=0$ if $m_\chi \to 0$

Spin 3/2, 2: [E. W. Kolb & A. Long arXiv:2312.09042]

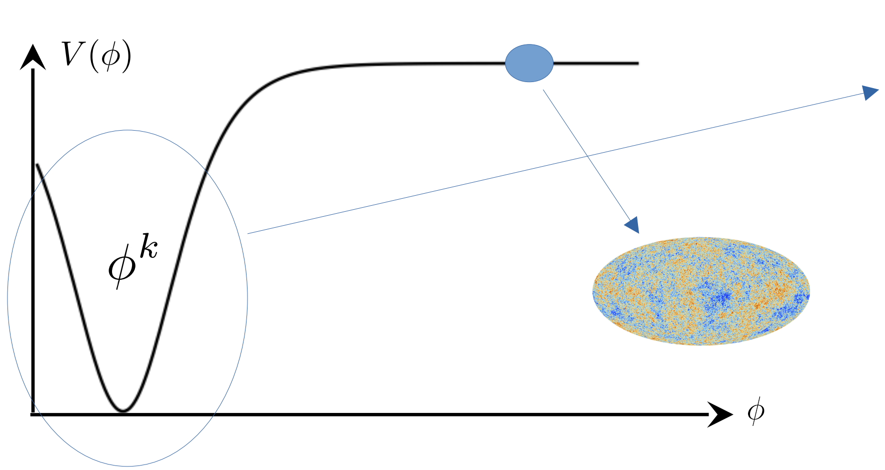
$\rightarrow$ Dark matter **can** be produced **gravitationally**

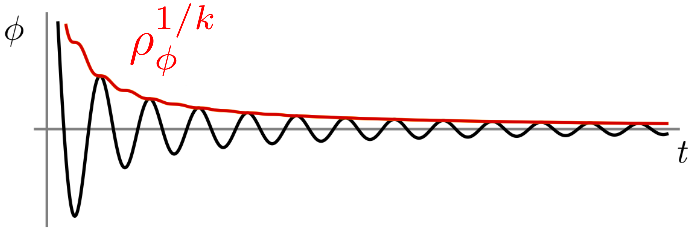
$\rightarrow$ Non-minimal coupling to gravity **mimics** direct coupling to the inflation

$$\xi \leftrightarrow \sigma/\lambda$$

2. Particle production during reheating

Reheating: transition to radiation domination





$$\langle \dot{\phi}^2 \rangle \simeq \langle \phi V'(\phi) \rangle$$

$$\rho_\phi \equiv \frac{1}{2}\langle \dot{\phi}^2 \rangle + \langle V(\phi) \rangle \simeq \left(\frac{k+2}{2}\right)\langle V(\phi) \rangle$$

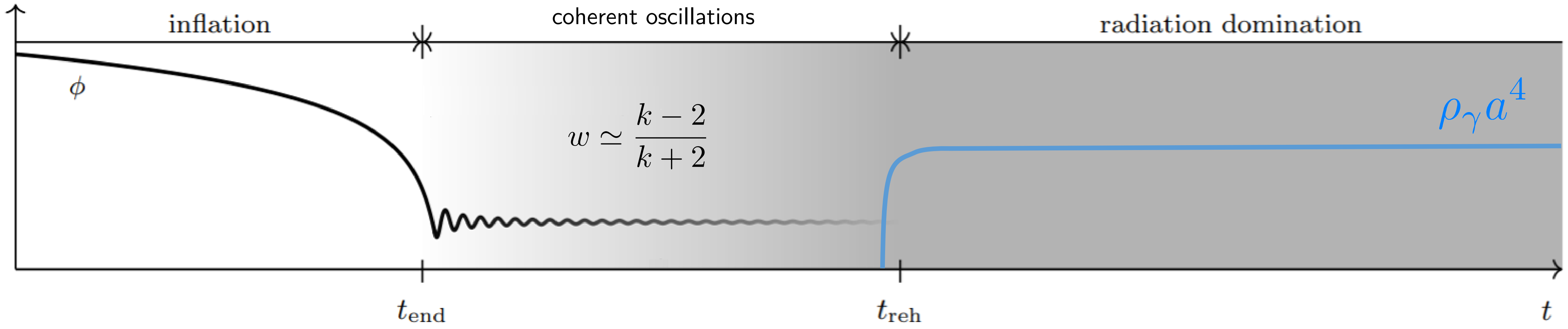
$$P_\phi \equiv \frac{1}{2}\langle \dot{\phi}^2 \rangle - \langle V(\phi) \rangle \simeq \left(\frac{k-2}{2}\right)\langle V(\phi) \rangle$$

$$w = \frac{k-2}{k+2}$$

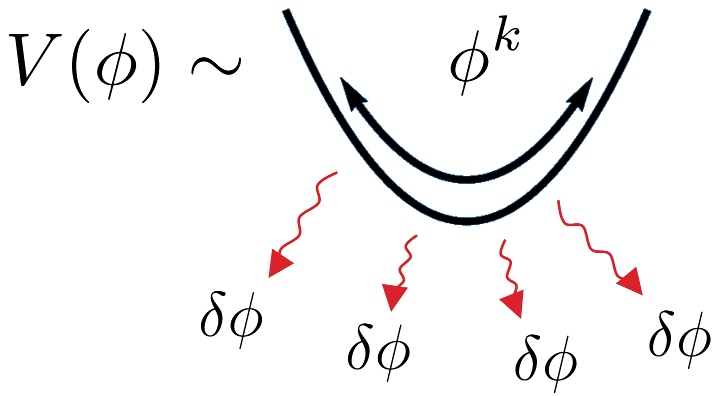
Coupling to radiation required to achieve reheating

$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = -\Gamma_\phi \rho_\phi (1+w_\phi)$$

$$\dot{\rho}_\gamma + 4H\rho_\gamma = \Gamma_\phi \rho_\phi (1+w_\phi)$$



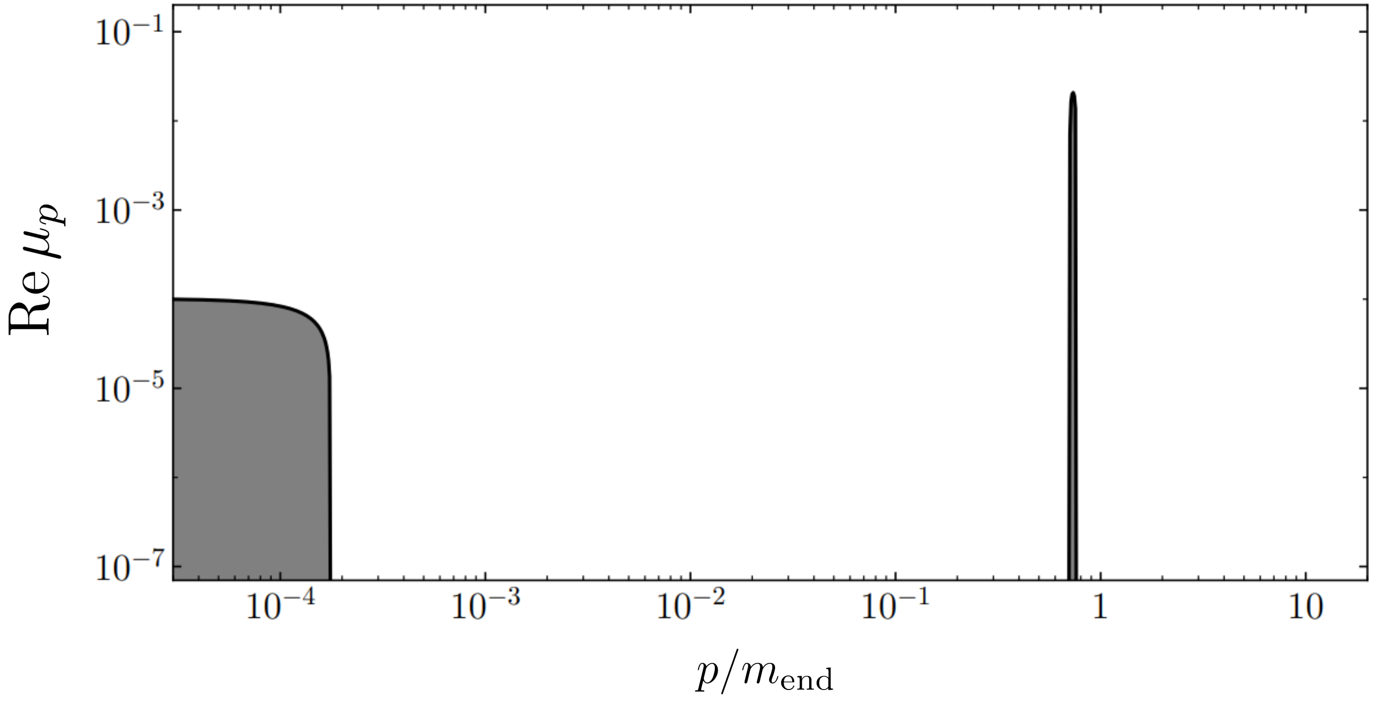
Resonances post-inflation



- Considering $k = 4$ and dimensionless time $z \equiv m_{\rm end}(\tau - \tau_{\rm end})$ with $m_{\rm end}^2 \equiv V_{\phi\phi}(\phi_{\rm end})$ the EOM for **inflaton fluctuations** is

$$\frac{\mathrm{d}^2 X_p}{\mathrm{d}z^2} + \left[\left(\frac{p}{m_{\rm end}}\right)^2 + \mathrm{sn}^2\left(\frac{z}{\sqrt{6}}, -1\right)\right] X_k = 0$$

Jacobi elliptic function

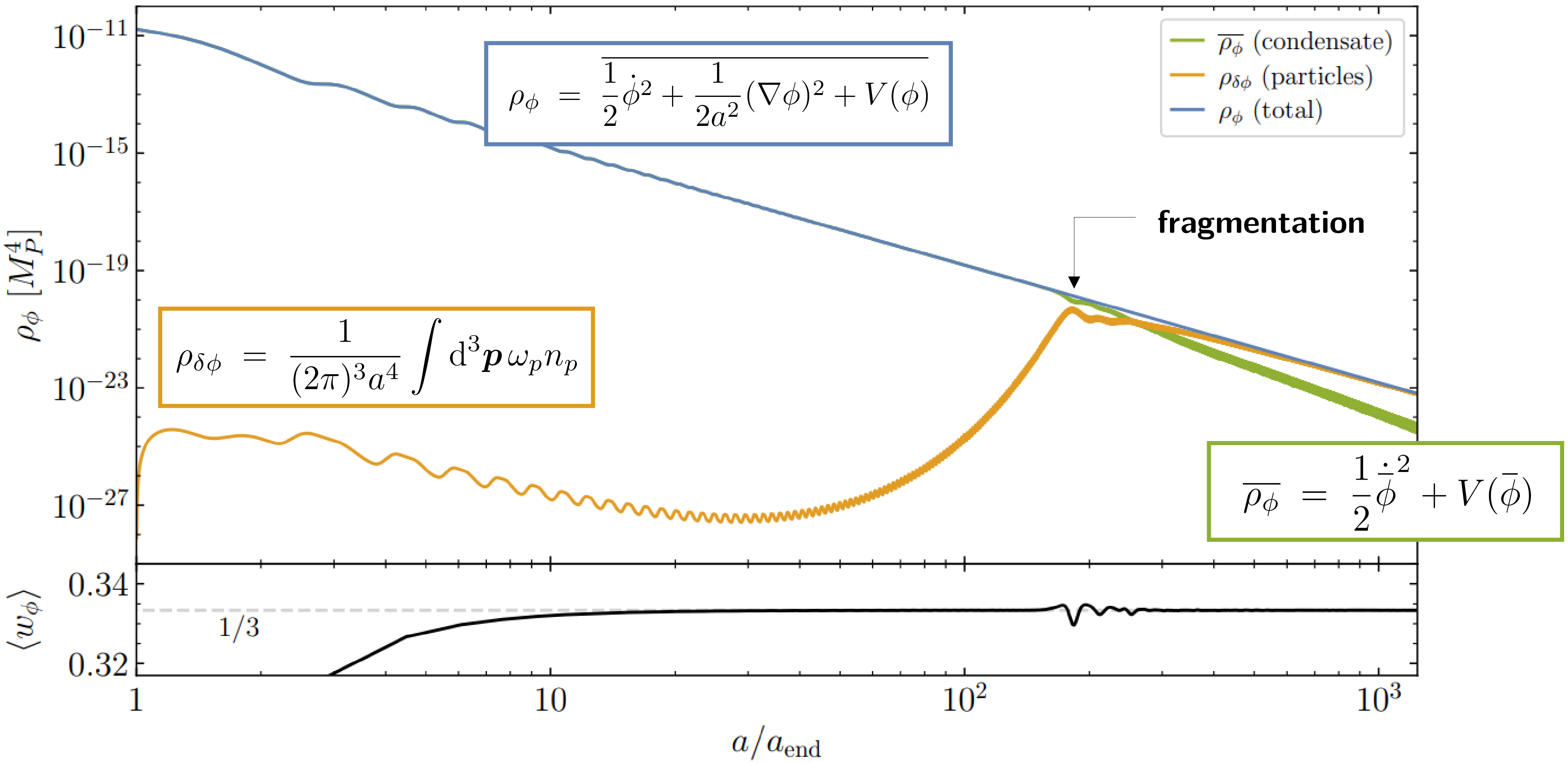


- Solutions given in terms of **Floquet index** $X_p(\tau) = e^{\mu_p \tau} g_1(\tau) + e^{-\mu_p \tau} g_2(\tau)$

- Floquet chart is **time-dependent** for **non-quartic** potentials $k \neq 4$

- Parametric resonances affect all **scalar quantities ("preheating")**

Self-fragmentation of the inflaton condensate $k = 4$



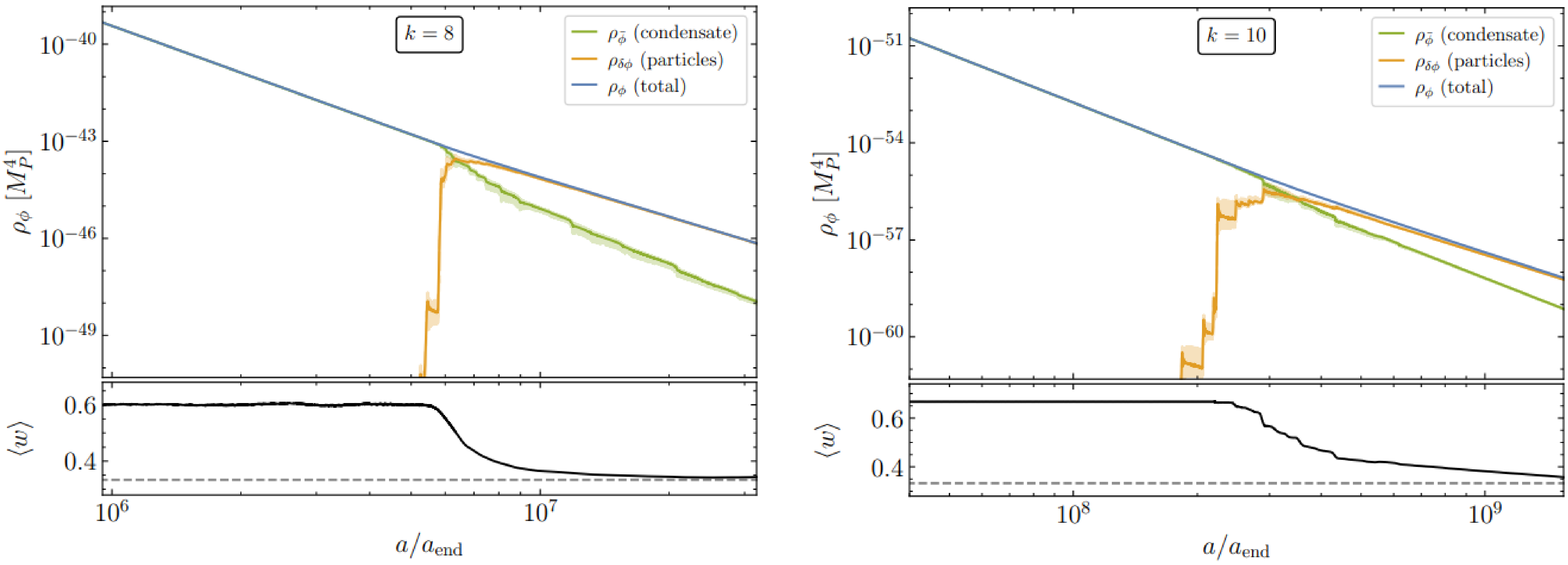
- **Lattice simulations with $\mathcal{C}$osmo$\mathcal{L}$attice**

[D G. Figueroa, A. Florio, F. Torrenti, W. Valkenburg, arXiv:2102.01031]

$$V(\phi) \;=\; \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k$$

Self-fragmentation of the inflaton condensate

[M. A. G. Garcia, M. Gross, Y. Mambrini, K. Olive, **MP** & J-H Yoon, JCAP 12 (2023) 028]



- Fragmentation occurs later for **larger *k***
- **The condensate subsists!** ➡ **generic for any *k***

$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k$$

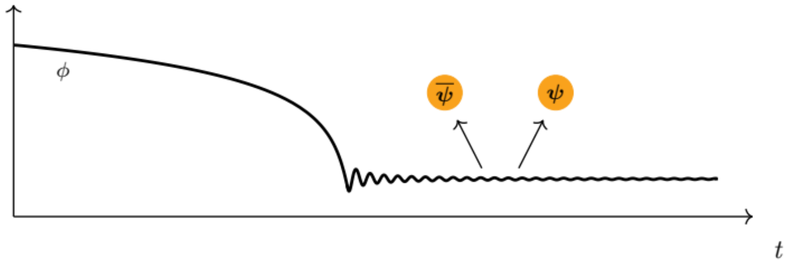
Reheating and inflaton fragmentation

production rate

Consider **coupling to fermions** $\mathcal{L} \supset -y\phi\bar{\psi}\psi$

$$\dot{\rho}_\psi + 4H\rho_\psi = \underbrace{R_\phi + R_{\delta\phi}}_{\text{production rate}}$$
$$\dot{\rho}_\phi + 3H(1+w_\phi)\rho_\phi = -(R_\phi + R_{\delta\phi})$$

Condensate contribution

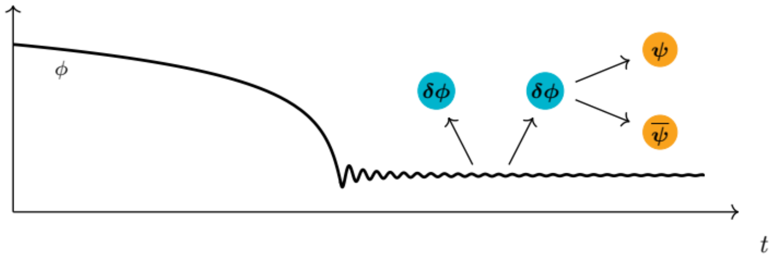


$$\Gamma_\phi = \frac{1}{8\pi(1+w_\phi)\rho_\phi}\sum_{n=1}^{\infty}\langle|\mathcal{M}_n|^2 E_n\beta_n\rangle \simeq \alpha^2\frac{y^2}{8\pi}m_\phi(t)$$

efficiency

$$R_\phi = \frac{4}{3}\Gamma_\phi\overline{\rho_\phi}$$

Quanta contribution



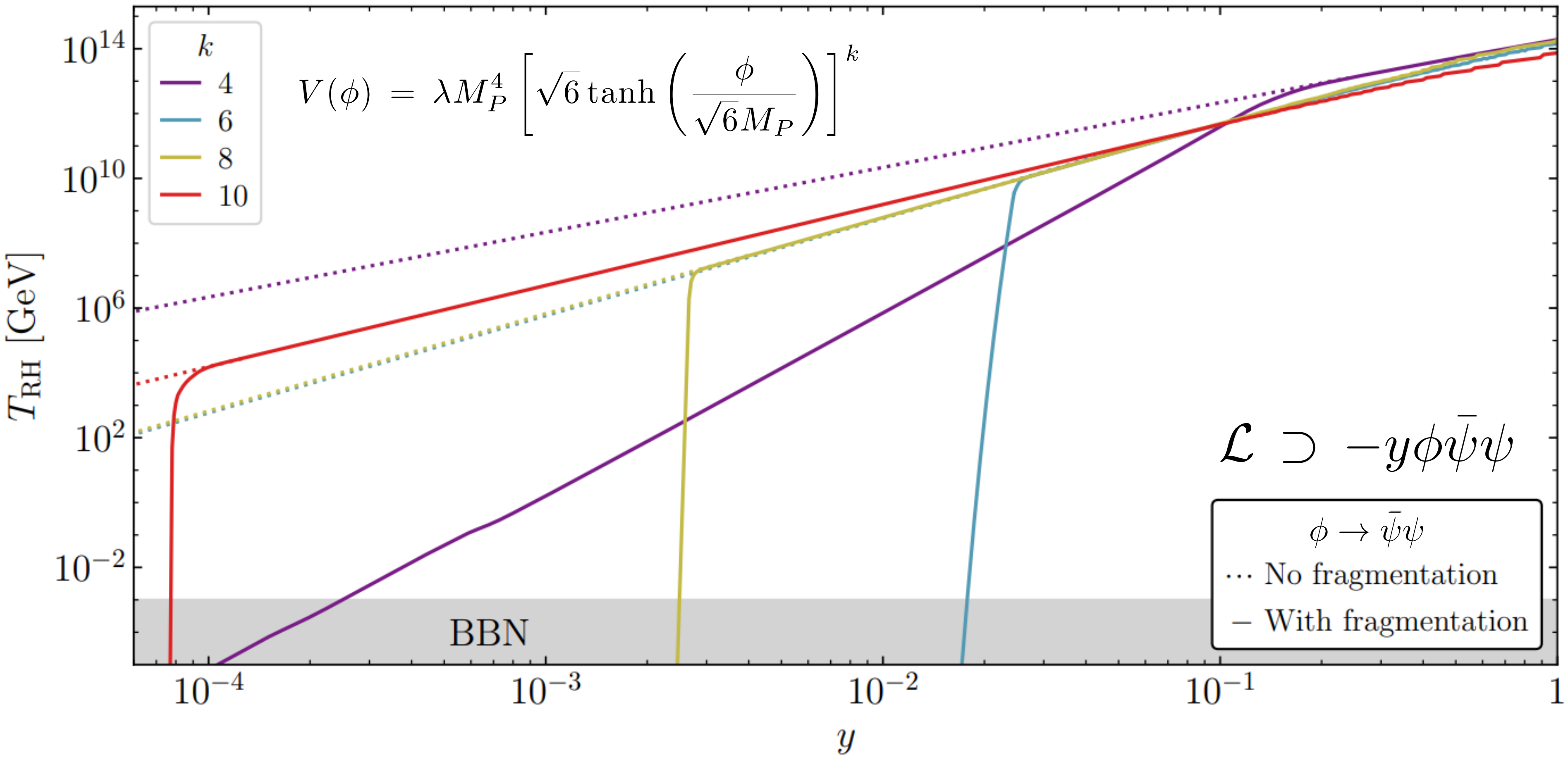
$$R_{\delta\phi}(t) = \Gamma_{\delta\phi}m_\phi n_{\delta\phi}$$

$$\Gamma_{\delta\phi} = \frac{|\mathcal{M}_{\delta\phi\to\bar{\psi}\psi}|^2}{16\pi m_\phi}\sqrt{1-\frac{4m_\psi^2}{m_\phi^2}} \simeq \frac{y^2}{8\pi}m_\phi(t)$$

- Estimate **number density** from the **lattice**
- **Mass term** induced by **leftover condensate:**
  ➡ **allow** quanta to decay!

[M. A. G. Garcia & **MP**, JCAP 11 (2023) 004]

Effect on reheating temperature



- **Large** (non-perturbative) **couplings** required: could backreact and cause early fragmentation?
- At large ***k***, **post-fragmentation** decays **extremely suppressed**

[M. A. G. Garcia, M. Gross, Y. Mambrini, K. Olive, **MP** & J-H Yoon, JCAP 12 (2023) 028]

Gravitational waves

- **Tensor** perturbations of the metric $\mathrm{d}s^2 = a(\tau)^2\Big[\mathrm{d}\tau^2 - \Big(\delta_{ij} + h_{ij}\Big)\,\mathrm{d}x^i\,\mathrm{d}x^j\Big]$
- Sourced by Tranceverse-Traceless (TT) scalar **inhomogeneities**

$$h''_{ij}(\boldsymbol{p},\tau) + 2\mathcal{H}h'_{ij}(\boldsymbol{p},\tau) + k^2 h_{ij}(\boldsymbol{p},\tau) = \frac{2}{M_P^2}\left[\int \frac{\mathrm{d}^3\boldsymbol{q}}{(2\pi)^{3/2}}\, q_i\, q_j\, \phi(\boldsymbol{q},\tau)\,\phi(\boldsymbol{p}-\boldsymbol{q},\tau)\right]^{\mathrm{TT}}$$

Gravitational waves

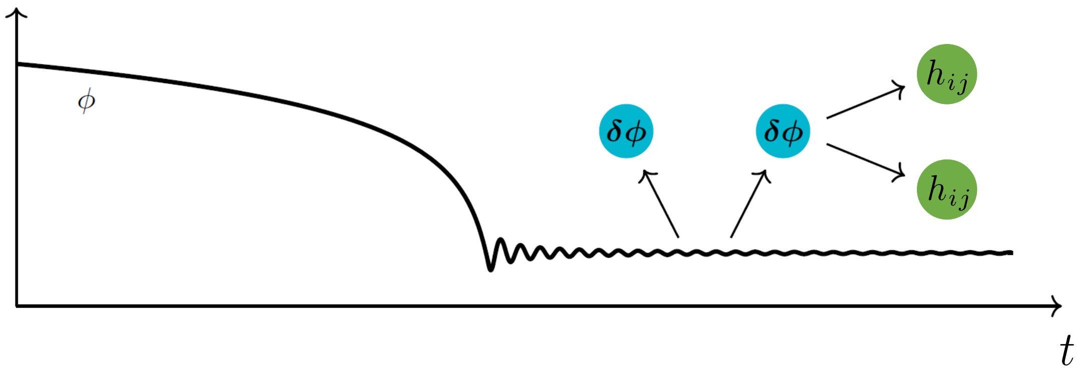
- **Tensor** perturbations of the metric $\mathrm{d}s^2 = a(\tau)^2\Big[\mathrm{d}\tau^2 - \Big(\delta_{ij} + h_{ij}\Big)\,\mathrm{d}x^i\,\mathrm{d}x^j\Big]$

- Sourced by Tranceverse-Traceless (TT) scalar **inhomogeneities**

$$h''_{ij}(\boldsymbol{p},\tau) + 2\mathcal{H}h'_{ij}(\boldsymbol{p},\tau) + k^2 h_{ij}(\boldsymbol{p},\tau) = \frac{2}{M_P^2}\left[\int \frac{\mathrm{d}^3\boldsymbol{q}}{(2\pi)^{3/2}}\, q_i\, q_j\, \phi(\boldsymbol{q},\tau)\,\phi(\boldsymbol{p}-\boldsymbol{q},\tau)\right]^{\mathrm{TT}}$$

- <u>Homogeneous solution:</u>
  - depends **only** on **expansion**
  - flat tensor power spectrum generated from **inflation enhanced** by **stiff equation-of-state era**

- <u>Inhomogeneous solution:</u>
  - depends on dynamics of the **inflaton** and **inhomogeneities**



Gravitational waves: quartic case $k = 4$

- **Tensor** perturbations of the metric $\quad \mathrm{d}s^2 = a(\tau)^2\Big[\mathrm{d}\tau^2 - \Big(\delta_{ij} + h_{ij}\Big)\,\mathrm{d}x^i\,\mathrm{d}x^j\Big]$

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- Use Boltzmann **approach** to predict spectrum of inflaton fluctuations $\quad \phi \to \delta\phi\,\delta\phi$

$$f_{\delta\phi}(|\boldsymbol{p}|,t) \simeq \frac{\pi}{c^2}\left(\frac{m_{\mathrm{end}}}{H_{\mathrm{end}}}\right)\left(\frac{a(t)}{a_{\mathrm{end}}} - 1\right)\sum_{n=1}^{\infty}\frac{|\hat{\mathcal{P}}_n|^2}{n^2\beta_n}\delta\left(\frac{|\boldsymbol{p}|}{m_{\mathrm{end}}} - \frac{1}{2}nc\beta_n\right)$$

$$\beta_n \equiv \sqrt{1 - \frac{4m_\phi^2}{n^2\omega_\phi^2}} = \sqrt{1 - \left(\frac{2}{nc}\right)^2}$$

$$c \equiv \sqrt{\frac{2\pi}{3}\frac{\Gamma(3/4)}{\Gamma(1/4)}}$$

series of peaks!

energy levels of inflaton potential

[M. A. G. Garcia & **MP**
JCAP 11 (2023) 004]

Gravitational waves: quartic case $k = 4$

- **Tensor** perturbations of the metric $\quad \mathrm{d}s^2 = a(\tau)^2\left[\mathrm{d}\tau^2 - \left(\delta_{ij} + h_{ij}\right)\mathrm{d}x^i\,\mathrm{d}x^j\right]$

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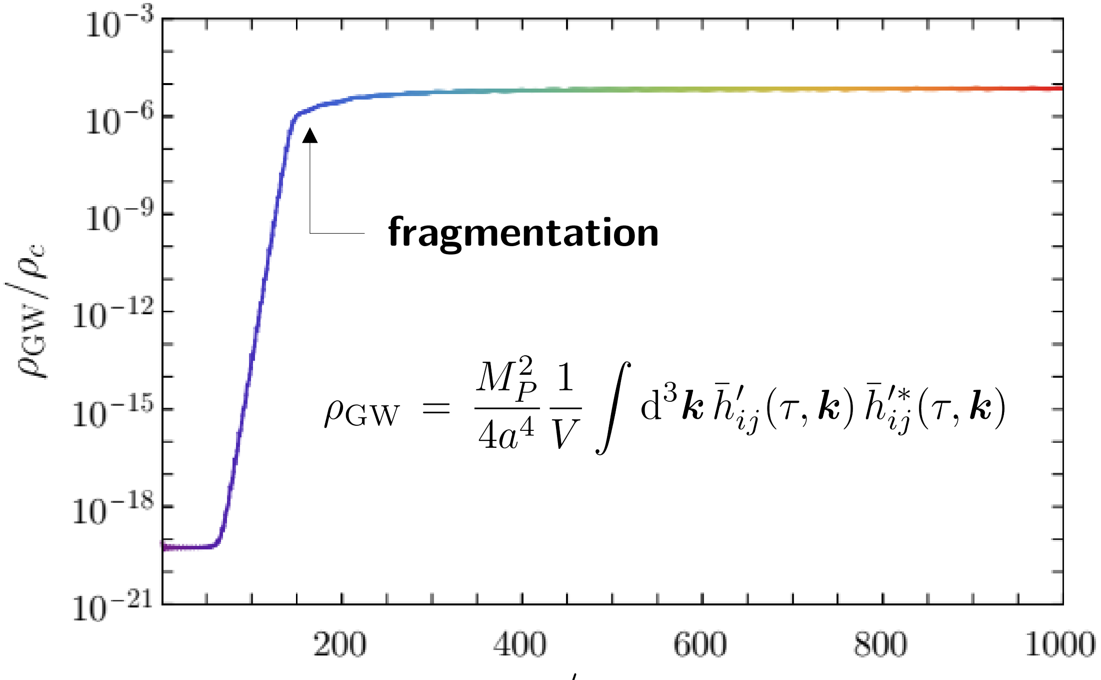
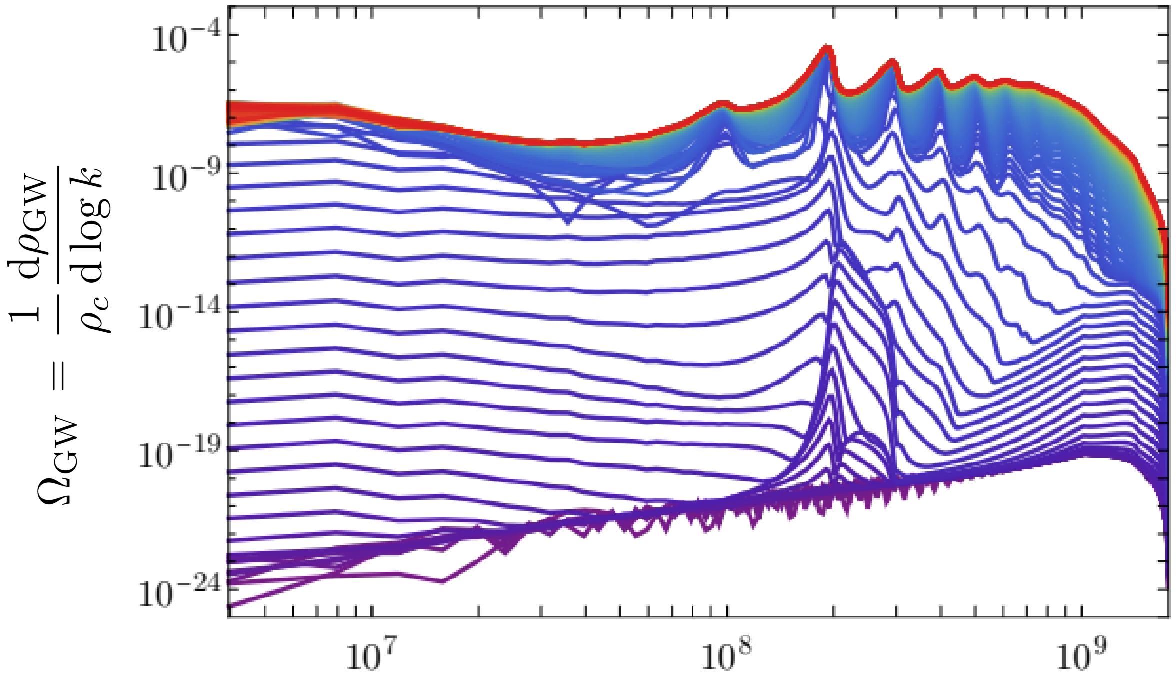


a/a_{end}

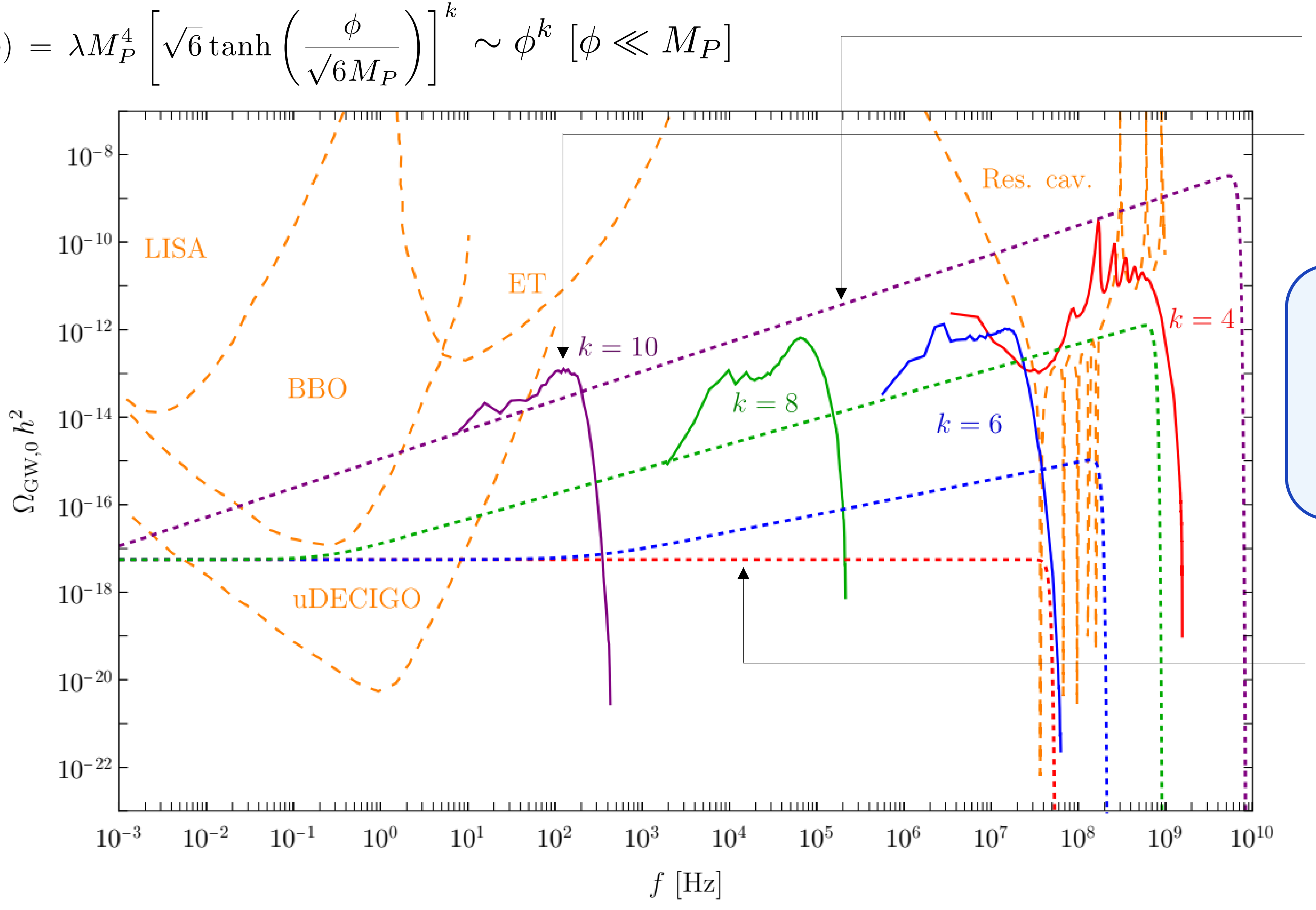


[M. A. G. Garcia & **MP** JCAP 11 (2023) 004]

f [Hz]

Gravitational waves from post-fragmentation reheating

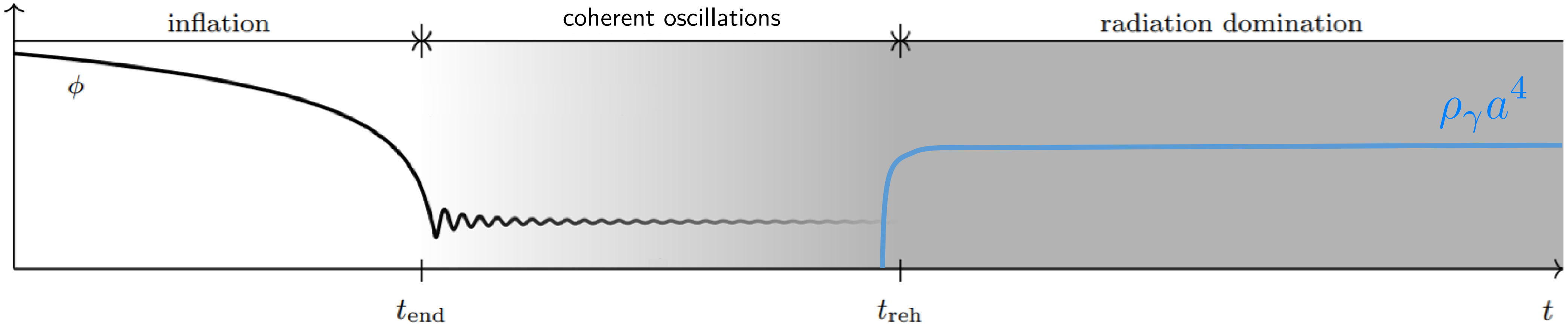
$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k \sim \phi^k \; [\phi \ll M_P]$$



Multi-wavelength GW detectors as probe of (post)inflation history

[M. A. G. Garcia & **MP** arXiv:2404.16932]

Take home message



- The **expanding universe** as a **source** for **particle production**
- (Post)inflation **dynamics** offers a **rich spectrum** of phenomenological implications
- **Inhomogeneities** might **reveal** (post-)inflationary history

Thank you for your attention