Composite Hybrid Inflation

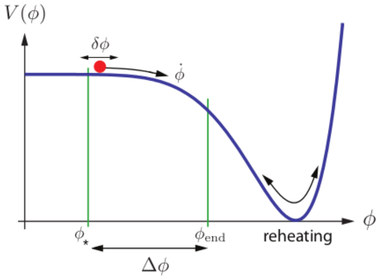
Collaboration between Giacomo Cacciapaglia (Paris), Dhong Yeon Cheong (Seoul), Aldo Deandrea (Lyon), Wanda Isnard (Lyon), Seong Chan Park (Seoul), Xinpeng Wang (Tokyo), Yang-li Zhang (Tokyo)

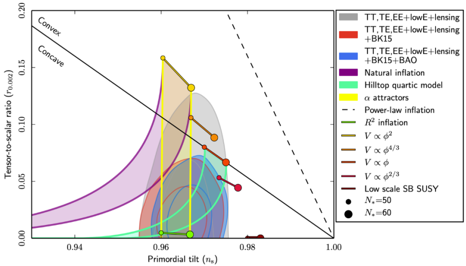
Based on arXiv:2307.01852 (JCAP 10 (2023) 063) +1 in preparation

Motivations

- Inflation proposes a simple explanation to CMB observations (Flatness and Horizon problem)
- Scalar fields ϕ dominated by their potential $V(\phi)$ are good candidates to have an accelerated expansion
- Precision tests from Planck [Planck, 1807.06277] $\to$ many models are ruled out
- Constraints on cosmological observables:

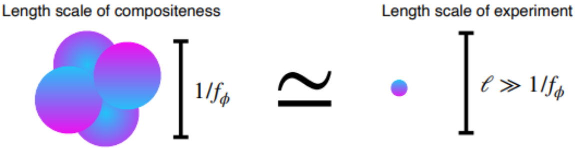
$$n_s = 0.9668 \pm 0.0037, \qquad r < 0.036, \qquad \mathcal{P}_{\mathcal{R}}(k^*) \simeq 2.9 \times 10^{-10}, \qquad \mathcal{N} \simeq 50 \sim 60$$





Motivations

- No consensus on the microscopic origin of the inflaton: pNGB? Higgs?
- SM is not complete: use BSM theories to find candidates for the inflaton?
- Compositeness: no fundamental scalars, bound states of fundamental fermions
  → Small field inflation from light pNGBs
  → Natural flat direction
  → Protects inflaton potential



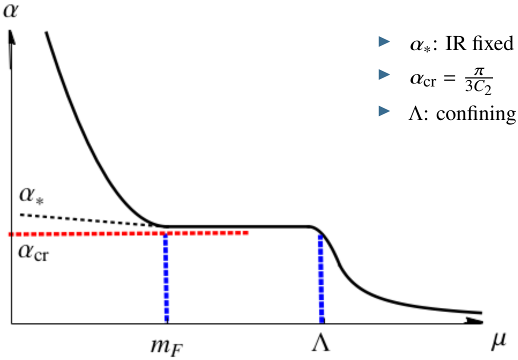
Content

I. The model

- SU(N_c) gauge theory, N_f Dirac fermions (Fundamental)

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}_j \left(i\not{D} - m_0 \right) \psi_j$$

- Such theory can exhibit a walking regime (scale invariance):

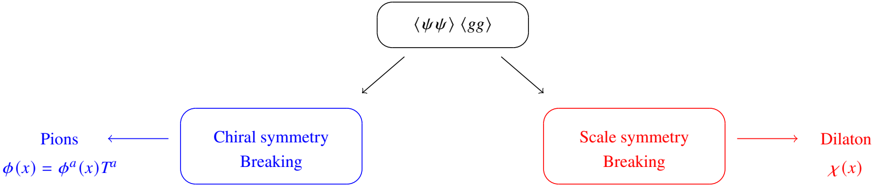


- α_*: IR fixed point
- $\alpha_{cr} = \frac{\pi}{3C_2}$
- Λ: confining scale

[Matsuzaki,Yamawaki 05']

I. The model

- In the IR, $\mu \leq m_F$, a fermion and/or a gluon condensate $\langle\psi\psi\rangle$ ($\langle gg\rangle$) can form.



- Pion potential $\longrightarrow$ Chiral Lagrangian
- Dilaton potential $\longrightarrow$ couplings via scaling dimension + scale anomaly

I. The model

- Expansion of the Chiral Lagrangian with $M_P = 1$, $U(x) = \exp\left(\frac{i\phi}{f_\phi}\right)$:

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset \frac{1}{2}R - \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{f_\phi^2}{2}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] - \frac{\lambda_\chi}{4}\chi^4\left(\log\frac{\chi}{f_\chi} - A\right)$$
$$+ \frac{\lambda_\chi \delta_1 f_\chi^4}{2}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U + U^\dagger\right] + \frac{\lambda_\chi \delta_2 f_\chi^4}{4}\left(\frac{\chi}{f_\chi}\right)^{2\left(3-\gamma_{4f}\right)} \mathrm{Tr}\left[\left(U - U^\dagger\right)^2\right]$$
$$+ \frac{\lambda_\chi \delta_3 f_\chi^4}{2i}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U - U^\dagger\right] - V_0.$$

[Cacciapaglia, Pica, Sannino 20']

- f_ϕ/f_χ: decay constant of ϕ/χ
- γ_m/γ_{4f}: mass/4 fermi anomalous dimensions
- $\lambda_\chi/\delta_1/\delta_2/\delta_3$: dimensionless parameters

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Pion Mass

$$+\frac{\lambda_\chi\delta_1 f_\chi^4}{2}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m}\mathrm{Tr}\left[U+U^\dagger\right] + \frac{\lambda_\chi\delta_2 f_\chi^4}{4}\left(\frac{\chi}{f_\chi}\right)^{2\left(3-\gamma_{4f}\right)}\mathrm{Tr}\left[\left(U-U^\dagger\right)^2\right]$$

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4 Fermi

- f_ϕ/f_χ: decay constant of ϕ/χ
- γ_m/γ_{4f}: mass/4 fermi anomalous dimensions
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4 Fermi

$\mathbb{Z}_2$ Breaking

- f_ϕ/f_χ: decay constant of ϕ/χ
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Pion Mass $\quad + \frac{\lambda_\chi \delta_1 f_\chi^4}{2}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U + U^\dagger\right] + \frac{\lambda_\chi \delta_2 f_\chi^4}{4}\left(\frac{\chi}{f_\chi}\right)^{2\left(3-\gamma_{4f}\right)} \mathrm{Tr}\left[\left(U - U^\dagger\right)^2\right]$

$\mathbb{Z}_2$ Breaking $\quad + \frac{\lambda_\chi \delta_3 f_\chi^4}{2i}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U - U^\dagger\right] - V_0.$ — 4 Fermi

- Lattice data suggests: $0 < \gamma_m \leq 1$ and $0 < \gamma_{4f} \leq 1$
- Composite theory: $\max(\delta_1, \delta_2, \delta_3) \lesssim \frac{1}{\lambda_\chi}\left(\frac{f_\phi}{f_\chi}\right)^4$ [Leung,Love,Bardeen 89'] [LatKMI Collaboration 14', 17']
- De Sitter: $V_0 > 0$

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$$+\frac{\lambda_\chi \delta_3 f_\chi^4}{2i}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U - U^\dagger\right] - V_0.$$

4 Fermi

- Contributions from scalar mesons.... $\rightarrow$ $1 \le \gamma_m, \gamma_{4f} \le 2$
- Composite theory: $\max(\delta_1, \delta_2, \delta_3) \lesssim \frac{1}{\lambda_\chi}\left(\frac{f_\phi}{f_\chi}\right)^4$ [Leung,Love,Bardeen 89'] [LatKMI Collaboration 14', 17']
- De Sitter: $V_0 > 0$

I. The model

- Inflationary potential:

$$V(\phi,\chi) = -\lambda_\chi \delta_1 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \cos\frac{\phi}{f_\phi} - \lambda_\chi \delta_2 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{2\left(3-\gamma_{4f}\right)} \sin^2\frac{\phi}{f_\phi}$$
$$-\lambda_\chi \delta_3 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \sin\frac{\phi}{f_\phi} + \frac{\lambda_\chi}{4}\chi^4\left(\log\frac{\chi}{f_\chi} - A\right) + V_0$$

- VEV requirements: $V(\phi_0,\chi_0)=0\,,\quad V_\chi(\phi_0,\chi_0)=0\quad$ and $\quad V_\phi(\phi_0,\chi_0)=0$

$$\chi_0 = f_\chi\,, \qquad \phi_0 = f_\phi \arccos\frac{\delta_1}{2\delta_2} \quad \text{for} \quad 0<\delta_1<2\delta_2$$

$$A = \frac{1}{4}\left(1 + 2\frac{\delta_1^2}{\delta_2}(\gamma_m - \gamma_{4f}) - 8\delta_2(3-\gamma_{4f}) + 2(3-\gamma_m)\delta_3\sqrt{4-\frac{\delta_1^2}{\delta_2^2}}\right)$$

$$V_0 = \frac{\lambda_\chi f_\chi^4}{16}\left(1 + 2\frac{\delta_1^2}{\delta_2}(2+\gamma_m - \gamma_{4f}) - 8\delta_2(1-\gamma_{4f}) - 2(1+\gamma_m)\delta_3\sqrt{4-\frac{\delta_1^2}{\delta_2^2}}\right)$$

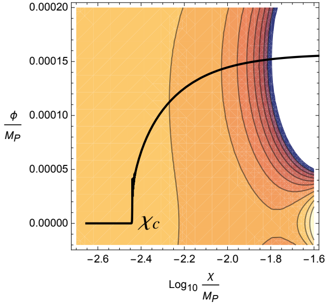
II. Inflationary Dynamics

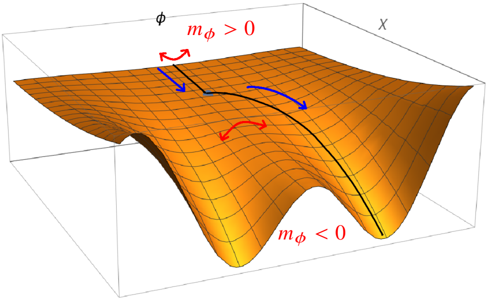
- Background evolution $\left(X' = \frac{dX}{d\mathcal{N}},\quad \epsilon : \text{slow roll parameter}\right)$:

$$\chi'' + (3-\epsilon)\chi' + (3-\epsilon)\frac{V_{,\chi}}{V} = \frac{\phi'^2\chi}{f_\chi^2}$$

$$\phi'' + (3-\epsilon)\phi' + \left(\frac{f_\chi}{\chi}\right)^2 (3-\epsilon)\frac{V_{,\phi}}{V} = -2\frac{\phi'\chi'}{\chi}$$

- Leads to a **Hybrid Inflation**, Pions are waterfall fields





II. Inflationary Dynamics

- Inflation can be divided in 3 Stages:

1. Effective dilaton slow roll inflation

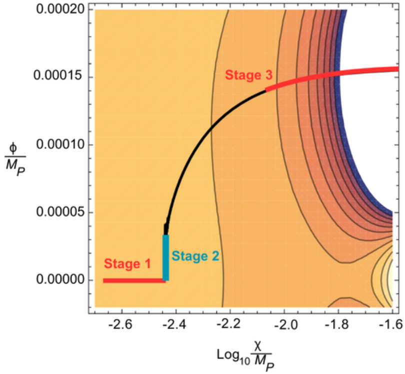
$$\chi^* \quad \rightarrow \quad \chi_c = \chi(m_\phi^2 = 0)$$
$$\phi \sim 0$$

2. Effective pion slow roll inflation, tachyonic instability

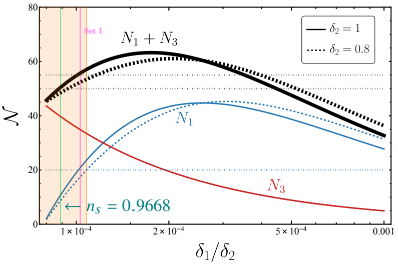
$$\chi_c$$
$$\phi_c \quad \rightarrow \quad \phi_{2f} = \frac{2\pi}{3} f_\phi$$

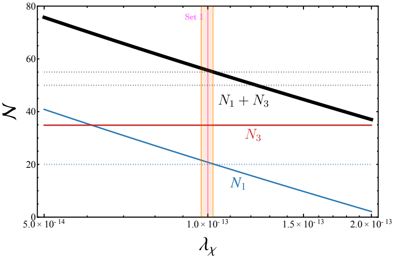
3. 2nd phase of effective dilaton slow roll inflation

$$\chi_c \quad \rightarrow \quad \chi_f \sim \chi_0 = f_\chi$$
$$\phi_0$$



- E-folding number for each stage of inflation: $\mathcal{N}_{tot}(\delta_1, \delta_2, \lambda_\chi, f_\chi) = \mathcal{N}_1 + \mathcal{N}_2 + \mathcal{N}_3 \sim \mathcal{N}_1 + \mathcal{N}_3$
- Slow-roll approximation: $\mathcal{N}_{tot} \simeq 61.6 - \frac{1}{12}\ln\left(\frac{45V_0}{\pi^2 g_s T_{reh}^4}\right) - \ln\left(\frac{V_0^{1/4}}{H^*}\right) \in [48, 55]$





$\lambda_\chi = 1\times10^{-13}$

$\delta_1 = 1.03\times10^{-4}, \quad \delta_2 = 1$

$f_\chi = 0.5\, M_P$

III. Constrains on the parameter space

- Anomalous dimensions fixed by the underlying gauge theories
- Potential contains 7 free parameters:

$$(\delta_1,\ \delta_2,\ \delta_3,\ f_\chi,\ f_\phi,\ \lambda_\chi,\ \chi^*)$$

- δ_3 dictates the enhancement of the power spectrum for the curvature perturbations:

$$\mathcal{P}_{\mathcal{R}}^{\max} \approx \left(\frac{\partial \mathcal{N}_2}{\partial \phi}\right)^2\Bigg|_{\phi=\phi_c,\chi=\chi_c} \langle \delta\phi^2 \rangle \propto \delta_3^{-2}$$

$\rightarrow$ set δ_3 such as $\mathcal{P}_{\mathcal{R}}^{\max}$ allows PBH production, $\delta_3 \sim 10^{-12}$

- Pivot scale: $\mathcal{P}_{\mathcal{R}}(k^*) \simeq 2.9 \times 10^{-10} \quad \rightarrow \quad \chi^* = 2.6 \times 10^{-3}$

- De Sitter: $V_0 > 0$, Rapid Stage 2: $|m_\phi|^2_{\mathrm{St2}} \gg H^2$

  Composite consistency: $\max(\delta_1,\, \delta_2,\, \delta_3) \lesssim \frac{1}{\lambda_\chi}\left(\frac{f_\phi}{f_\chi}\right)^4$

  $\rightarrow \quad f_\chi = 0.5 M_P, \qquad f_\phi = 10^{-3} M_P, \qquad \delta_2 = 1$

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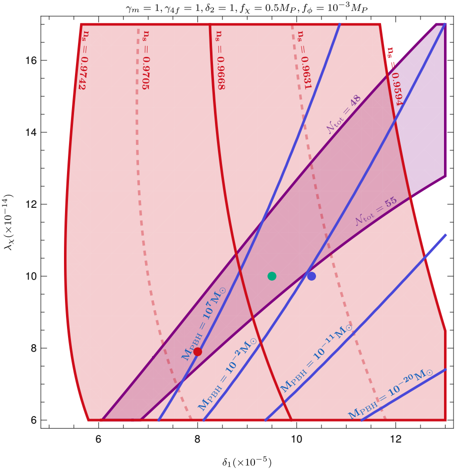
III. Constrains on the parameter space

- Parameter space satisfying Planck observations:

$$n_s = 0.9668 \pm 0.0037, \qquad r < 0.036, \qquad \mathcal{N}_{\rm tot} \in [48, 55]$$

$\gamma_m = 1$
$\gamma_{4f} = 1$



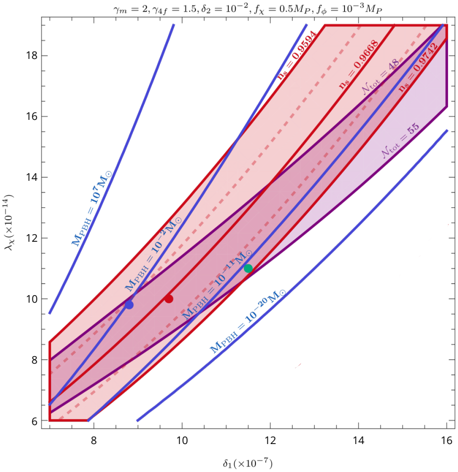
PBH as the whole of Dark Matter:
$M_{\rm PBH} \in [10^{-16}, 10^{-11}] M_\odot$
$\longrightarrow$ Asteroid mass range

[Montero-Camacho JCAP08(2019) 031]

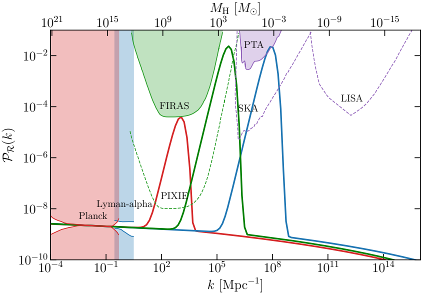
III. Constrains on the parameter space

- Other values of γ_m and γ_{4f} change the correlation between n_s and $M_{\rm PBH}$

$\gamma_m = 2$
$\gamma_{4f} = 1.5$



- δ_3 induces an enhancement of the curvature perturbation power spectrum $\mathcal{P}_\mathcal{R}$



$\gamma_m = 1$
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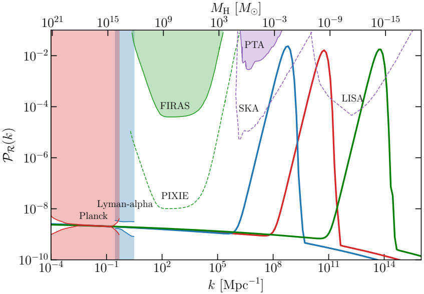

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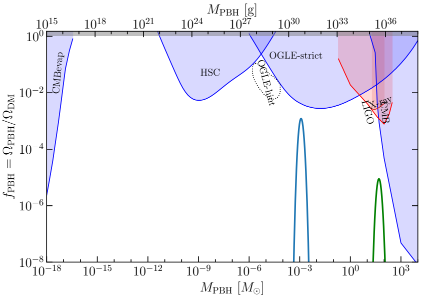
IV. PBH and GW signatures

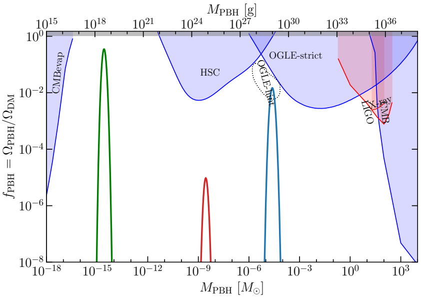
- Use Press-Schechter formalism to compute the corresponding PBH abundance and mass

$$f_{\rm PBH}(M_{\rm PBH}) \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \simeq \left(\frac{\beta(M)}{1.6\times10^{-9}}\right)\left(\frac{10.75}{g_*(T)}\right)^{1/4}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)\left(\frac{M_\odot}{M_{\rm PBH}}\right)^{1/2}$$

$$M_{\rm PBH} \simeq 4.64\times10^{15}\gamma\left(\frac{g_*}{106.75}\right)^{-\frac{1}{6}}\exp(-2\mathcal{N}_1)M_\odot$$



$\gamma_m = 1, \quad \gamma_{4f} = 1$



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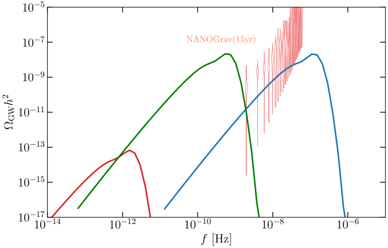
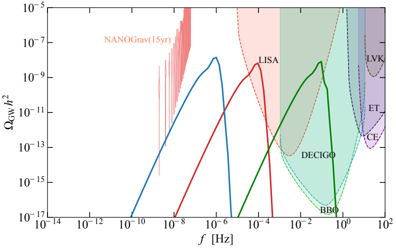
IV. PBH and GW signatures

- Stochastic GW background energy density

$$\Omega_{\mathrm{GW}}\left(\eta_0, k\right) = c_g \frac{\Omega_{r,0}}{6} \int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u \left(\frac{4v^2 - \left(1 + v^2 - u^2\right)^2}{4uv} \right)^2 \overline{\mathcal{I}^2(v,u)}\, \mathcal{P}_{\mathcal{R}}(kv)\, \mathcal{P}_{\mathcal{R}}(ku)$$



$\gamma_m = 1, \quad \gamma_{4f} = 1$



$\gamma_m = 2, \quad \gamma_{4f} = 1.5$

Conclusion

- Inflation requires a scalar particle to drive the accelerated expansion
  $\rightarrow$ Compositeness is a way to protect scalar potentials
  $\rightarrow$ Test whether the inflaton could be a composite particle
- Consider a general setup with a $SU(N)$ gauge theory with fundamental fermions
- Confinement leads to the breaking of global symmetries: presence of pions and a dilaton
- Pions and dilaton potential constrained by the composite theory, framework to test inflation
- Introducing a $\mathbb{Z}_2$ breaking term leads to $\mathcal{P}_{\mathcal{R}}$ enhancement
  $\rightarrow$ Production of PBH, DM candidate if we consider higher anomalous dimensions
  $\rightarrow$ Stochastic GW background, possible probes by Nanograv, LISA or Decigo depending on the anomalous dimension values

Walking Regime

- Miranski scaling: $m_F \simeq 4\Lambda \exp\left(\frac{-\pi}{\sqrt{\frac{\alpha}{\alpha_{\rm cr}}-1}}\right)$

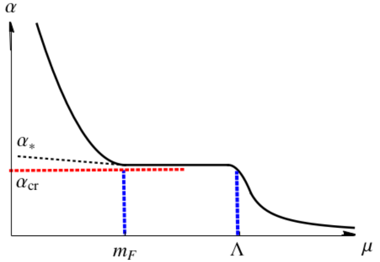
$$\Longrightarrow \beta(\alpha) = \frac{\partial\alpha}{\partial \ln\Lambda} = -\frac{2\alpha_{\rm cr}}{\pi}\left(\frac{\alpha}{\alpha_{\rm cr}} - 1\right)^{\frac{3}{2}}$$

- Solving this equation yields:

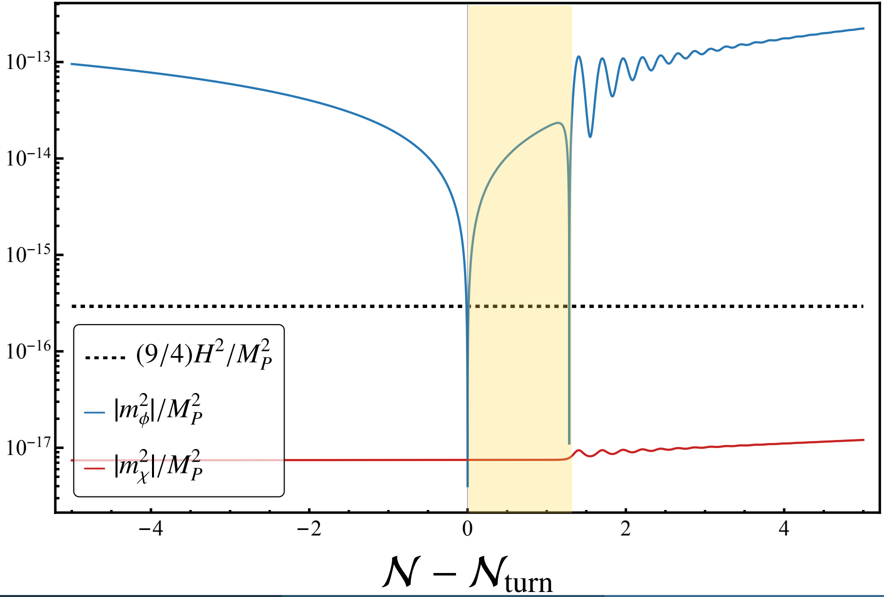
$$\alpha(\mu) = \alpha_{\rm cr}\left(1 + \frac{\pi^2}{\ln^2 \frac{\mu}{m_F}}\right)$$

$\Longrightarrow$ Walking regime for $\mu \gg m_F$

- Conclusion: Walking regime for $m_F \ll \mu \ll \Lambda$ where $\alpha \sim \alpha_* \sim \alpha_{\rm cr}$



Effective masses of the composite particles



Domain Walls decay

- $\mathbb{Z}_2$ breaking term: gap between vacua $\Delta V = V(\phi_0, \chi_0) - V(-\phi_0, \chi_0) = \lambda_\chi f_\chi^4 \delta_3 \sqrt{4 - \frac{\delta_1^2}{\delta_2^2}}$.
- Decay of Domain Walls, GW signatures
- Estimation of the peak of GW spectrum: [Ferreira 2204.04228]

$$f_p^0 \simeq 9.5 \times 10^7 \text{Hz} \left(\frac{g_*(T_\star)}{10.75}\right)^{-\frac{1}{12}} \left(\frac{\lambda_\chi}{10^{-13}}\right)^{1/4} \left(\frac{f_\chi}{0.5 M_P}\right)$$

$\rightarrow$ Too high for current GW detectors

Inclusion of latest ACT results