MARYLAND CENTER FOR FUNDAMENTAL PHYSICS

Extra-dimensional Particle Production at the Cosmological Collider

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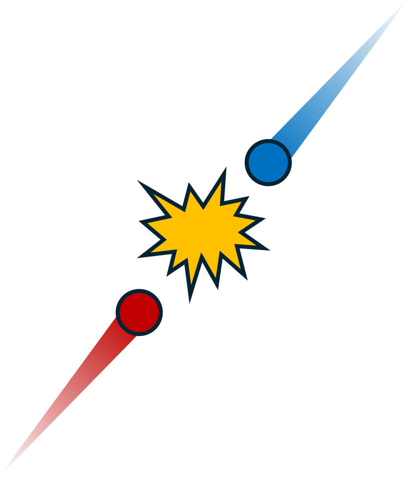
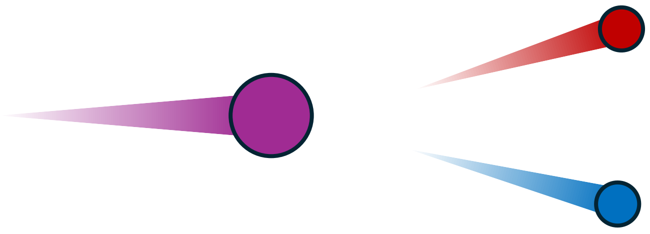
Based on arXiv:2606.XXXXX, in collaboration with Raman Sundrum (advisor)

Cosmological collider physics

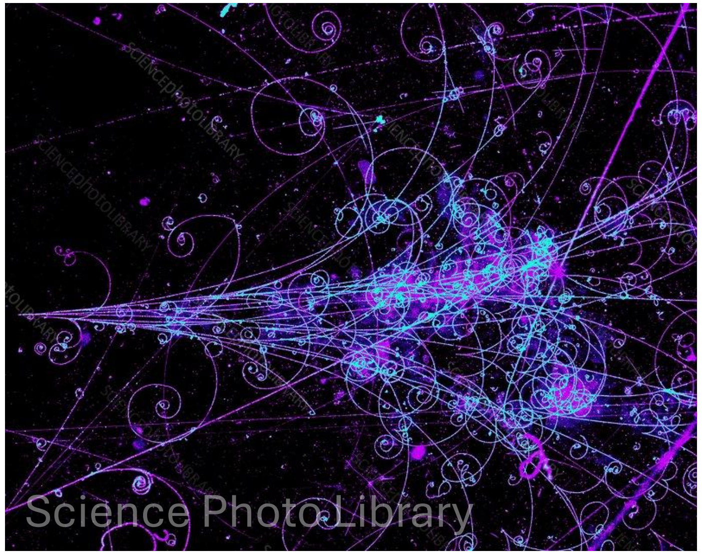
- Idea: use the rapid expansion of the universe during the **inflation** to probe physics at very high energy scales.
- Terrestrial collider:



Creation

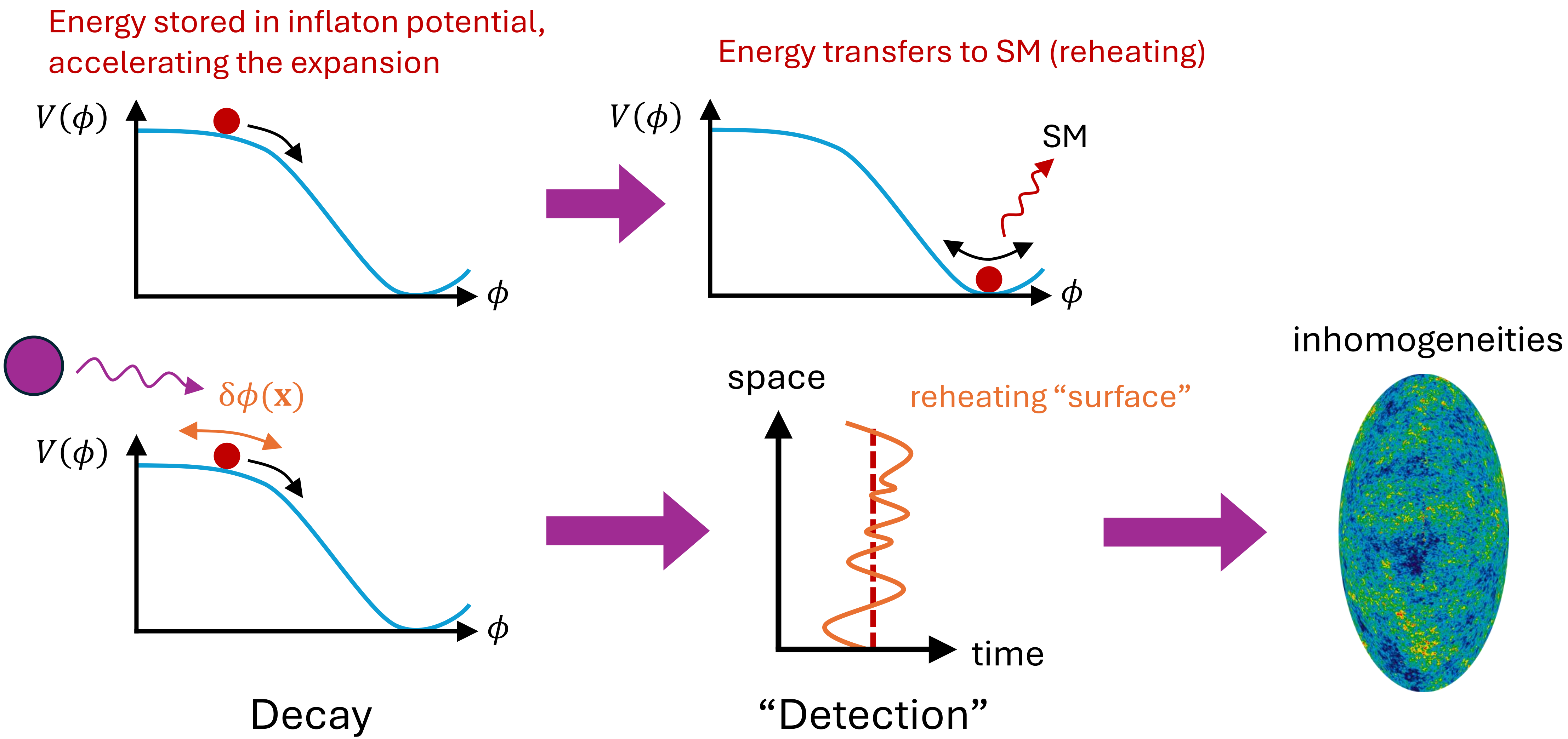


Decay



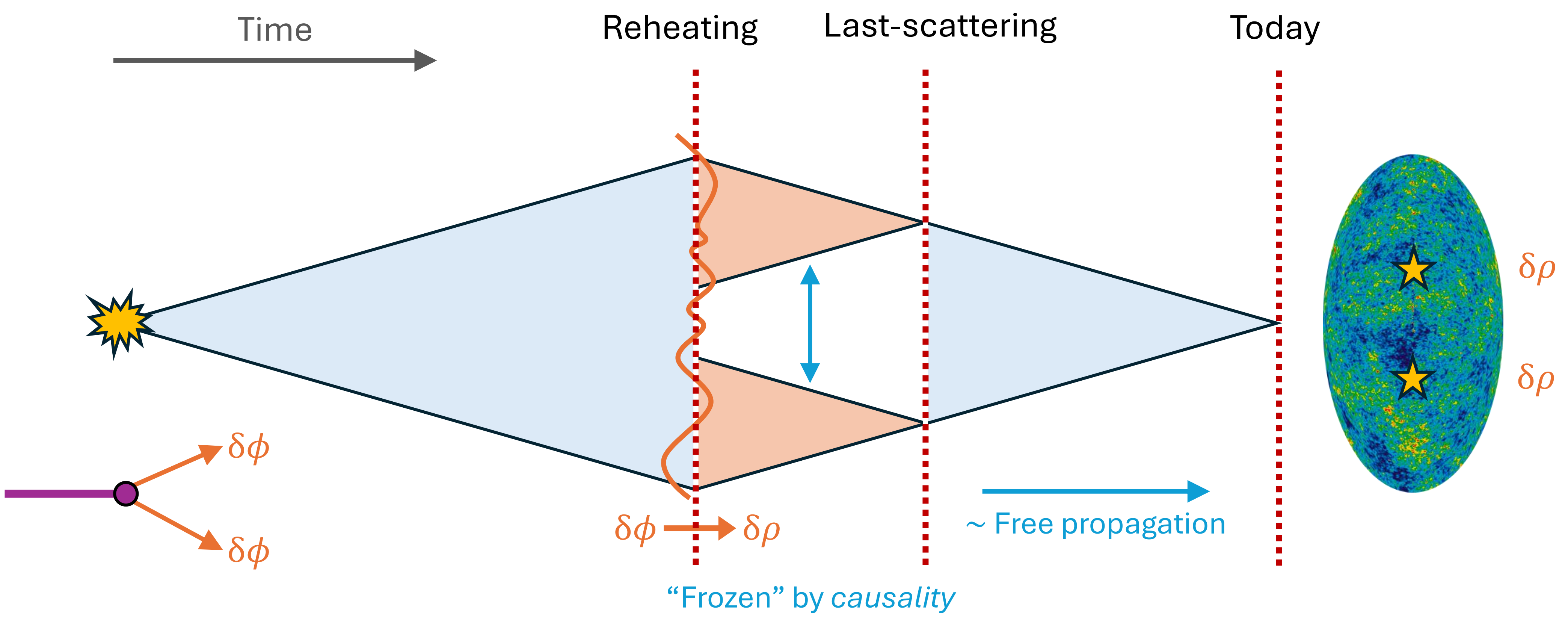
Detection

Inflation as the cosmological collider



Preservation of the signal

Signals on sufficiently large length scale can survive billions of years due to *causality*.



Particle creation during the inflation

- Time-dependence → Energy non-conservation → particle production.
- Spacetime expansion can create particles with $m \lesssim H$ [1].
- The rolling inflaton background can also creates particles through the **chemical potential mechanism** [2, 3].

$$H < 6 \times 10^{13}\ \mathrm{GeV},$$

$$(\dot{\phi})^{1/2} \approx 60H < 4 \times 10^{15}\ \mathrm{GeV}\ [4]$$

[1] X. Chen, Y. Wang, 0911.3380; N. Arkani-Hamed, J. Maldacena, 1503.08043; H. Lee et al., 1607.03735; X. Chen, Y. Wang, Z. Xianyu, 1612.08122; …
[2] N. Barnaby et al., 1102:4333; P. Adshead et al., 1803.04501; X. Chen et al., 1805.02656; L. Wang, Z. Xianyu, 1910.12876;
[3] A. Bodas, S. Kumar, R. Sundrum, 2010.04727; A. Bodas, E. Broadberry, R. Sundrum, 2409.07524; …
[4] **Planck** Collaboration, Y. Akrami et al., 1807.06211.

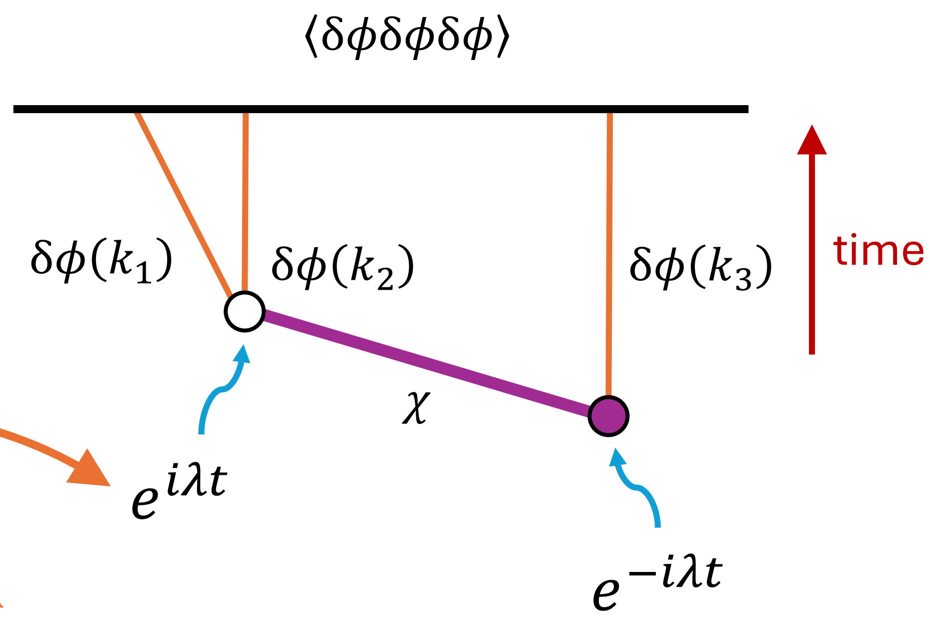
“Chemical potential”

- The scalar chemical potential model [5]:

$$\mathcal{L} = |\nabla\chi|^2 - m^2|\chi|^2 + \alpha\chi e^{i\phi/\Lambda} + \bar{\alpha}\bar{\chi}e^{-i\phi/\Lambda}$$

$\phi_{\rm bkg} \simeq \dot{\phi}t$

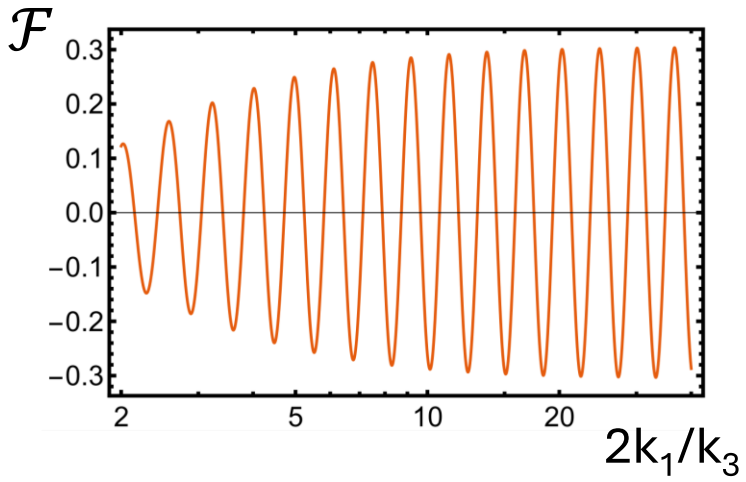
$\lambda = \dot{\phi}/\Lambda$



- Signal in *non-Gaussianity* (3pt function):

$$\mathcal{F} \sim \frac{\langle\delta\rho_{\mathbf{k}_1}\delta\rho_{\mathbf{k}_2}\delta\rho_{\mathbf{k}_3}\rangle'}{\langle\delta\rho_{\mathbf{k}_1}\delta\rho_{-\mathbf{k}_1}\rangle'\langle\delta\rho_{\mathbf{k}_3}\delta\rho_{-\mathbf{k}_3}\rangle'} \sim \sqrt{\frac{H^2}{\lambda m}}\left|\frac{\alpha}{H^2\Lambda}\right|^2\left(\frac{k_1}{k_3}\right)^{-\frac{3}{2}-\frac{i(\lambda-m)}{H}}$$

$\delta\rho \propto \delta\phi$

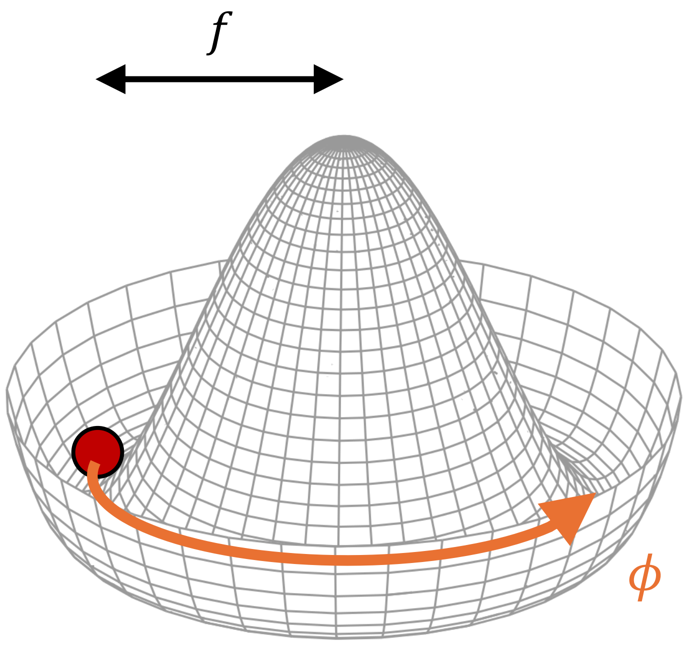


Everything looks great! But...

[5] A. Bodas, E. Broadberry, R. Sundrum, 2409.07524.

From EFT perspective…

$e^{i\phi/\Lambda}$ vs. $1 + \frac{i\phi}{\Lambda} - \frac{\phi^2}{2\Lambda^2} + \cdots$



- High-scale inflation requires [6]

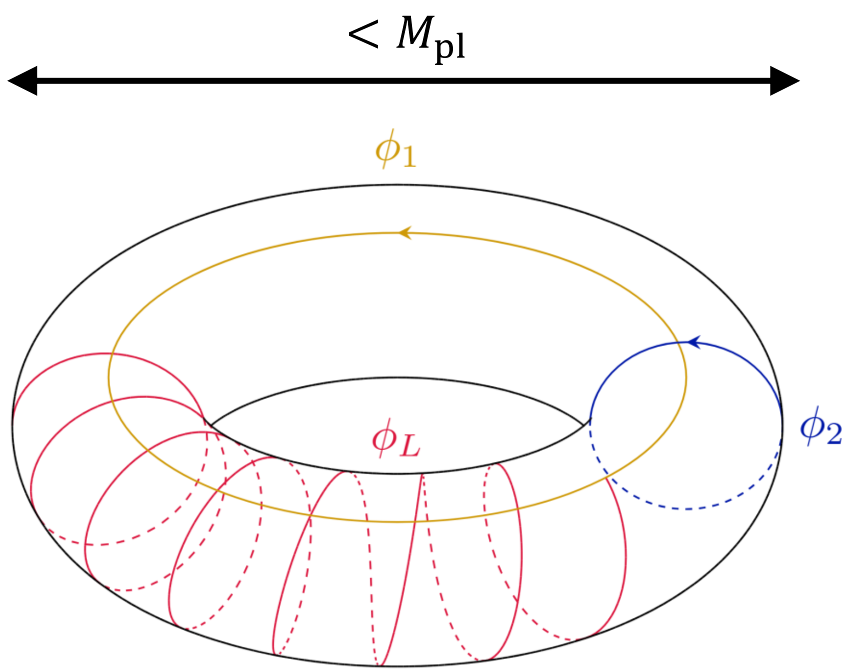
$$\Delta\phi \gtrsim N_e\sqrt{2\epsilon_H}M_{\rm pl} \gtrsim M_{\rm pl} \gg \Lambda.$$

✗ EFT expansion in ϕ/Λ.

- Tentatively: ϕ is a PNGB, $\Sigma \sim f e^{i\phi/f}$ [7].
  - $\Sigma^Q\chi \to \chi e^{iQ\phi/f}$, $\Lambda_{\rm chem} = f/Q$.
- $\Delta\phi \gtrsim M_{\rm pl}$ then requires $f \gtrsim M_{\rm pl}$ **(trans-Planckian problem)**.

[6] Lyth bound: D. H. Lyth, hep-ph/9606387.
[7] K. Freese et al., 10.1103/PhysRevLett.65.3233; F. Adams et al., hep-ph/9207245.

Solution: aligned-axion mechanism [8]



Bi-axion benchmark:

$N = 200, \qquad f_1 = f_2 = 2000H \approx 0.05 M_{\rm pl},$

$Q = 15, \qquad \lambda = Q\dot{\phi}_2/f_2 \approx 27H.$

- With multiple PNGBs, $f \gtrsim M_{\rm pl}$ can be realized on a higher-dimensional field space by "winding":

$$f_{\rm eff} \approx N f_2, \qquad f_2 < M_{\rm pl}, \qquad N \gg 1.$$

- $e^{iQ\phi_2/f_2} = e^{i\phi_L/\Lambda}, \Lambda = \frac{f_2}{Q} = \frac{f_{\rm eff}}{NQ}.$
- $N, Q = \mathcal{O}(1)$ is possible with more PNGBs [9].

Still one problem remains...

[8] J. E. Kim, H. P. Nilles, M. Peloso, hep-ph/0409138; ...
[9] K. Choi, H. Kim, S. Yun, 1404.6209.

Inflation from extra-dimensional gauge fields

- The winding trajectory must be enforced by a special scalar potential.
- Analogous to the QCD axion, scalar potential is UV-sensitive **("quality problem")**.
- Solution: PNGBs are the fifth components of 5D U(1) gauge fields

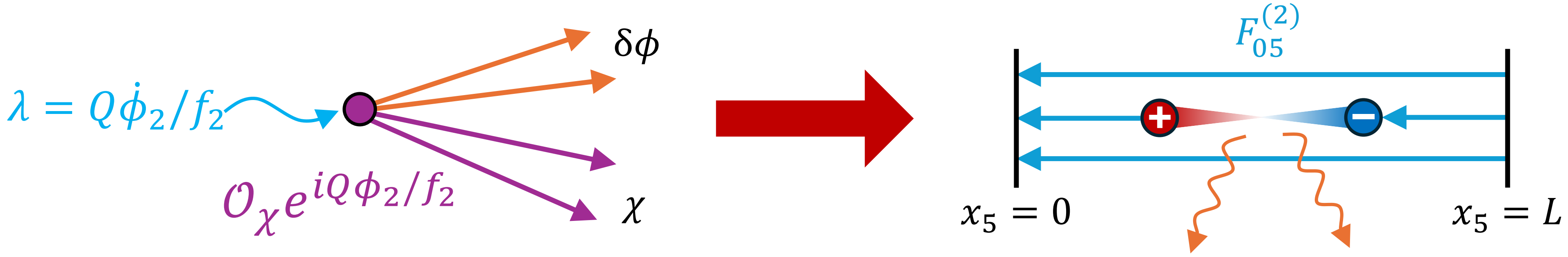
$$\phi(x) = \frac{1}{\sqrt{L}} \int_0^L A_5(x, x_5) \mathrm{d}x_5 \xrightarrow{\text{gauge fix}} \sqrt{L} A_5(x), \qquad f = \frac{1}{g_5 \sqrt{L}}.$$

- $V(\phi)$ can only arise non-locally (in 5D) through the *Hosotani mechanism* [10].
- The "quality" is then protected by 5D locality.

[10] N.S. Manton, 10.1016/0550-3213(79)90192-5; Y. Hosotani, 10.1016/0370-2693(83)90170-3.

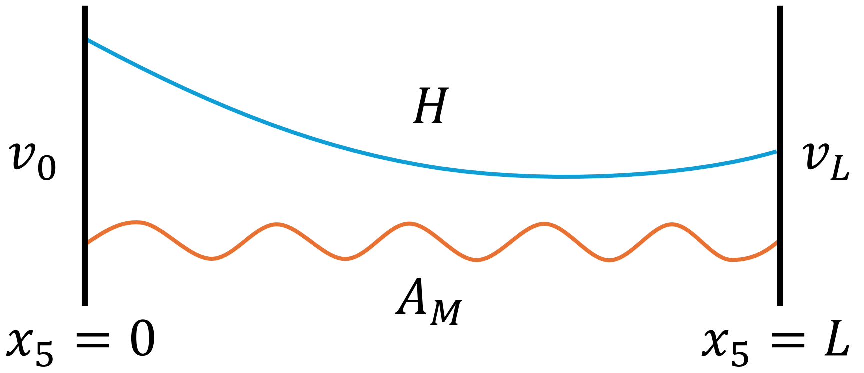
Back to “chemical potential”…

- Remarkably, we find that the *same* mechanisms also give rise to chemical potentials in the following way:
- Rolling inflaton background $\dot{\phi}_2 = \sqrt{L} F_{05}^{(2)}$ (5D electric field).
- Particles can be created analogous to the *Schwinger pair production* [11].
- We find 5D models reducing to known 4D chemical potential models & *new* models where the KK excitations can be detected (focus of this talk).



[11] Circular fifth dimension: K. Furuuchi, 1512.04684; Y. Yamada, 2403.13451.

Warmup

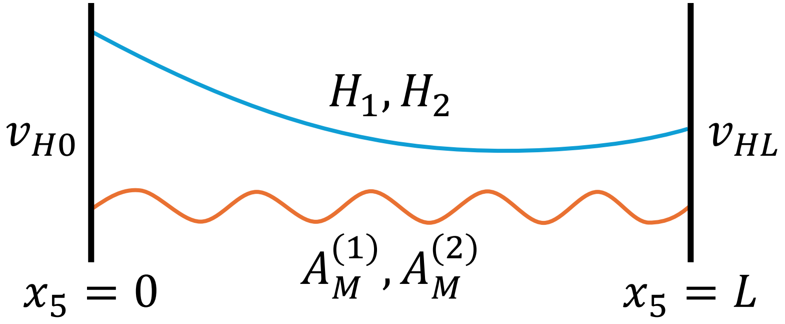


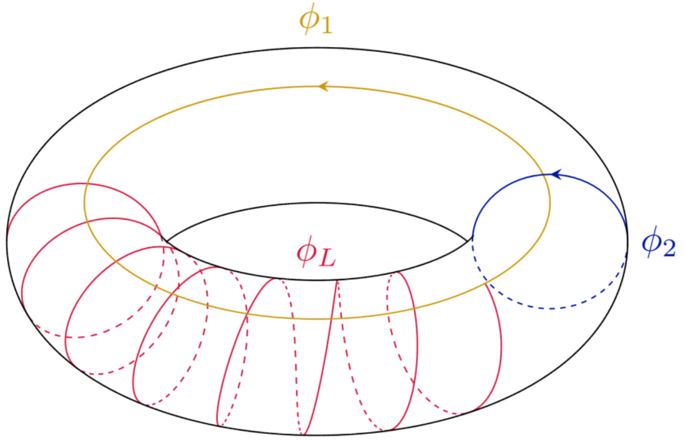
- Spacetime: 4D inflation (de Sitter) × interval of length L $(HL \ll 1)$
- U(1) gauge field A_M with Dirichlet boundary conditions $A_\mu(0) = A_\mu(L) = 0$, so that A_5 survives as a light scalar in 4D EFT.
- Charged particle H with boundary conditions $H(0) = v_0, H(L) = v_L$.

$$V_{\text{eff}} \sim -\frac{1}{L} \bar{H}(L) \underbrace{e^{iq_5 A_5 L}}_{\text{Gauge invariance (Wilson line)}} H(0) \cdot \underbrace{e^{-m_H L}}_{\text{Yukawa suppression } (H \text{ propagator})} + \text{c.c.} = -\frac{|v_0 \bar{v}_L|}{L} e^{-m_H L} \cos\frac{\phi}{f}$$

Generating the inflaton potential

	H_1	H_2
$\mathbf{U(1)_1}$	1	N
$\mathbf{U(1)_2}$	0	-1



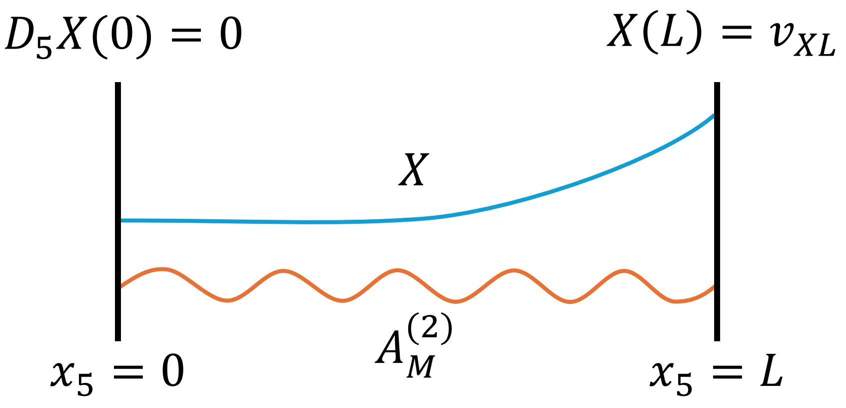


$$V_{\mathrm{eff}} = -V_1 \cos\frac{\phi_1}{f_1} - V_2 \cos\left(\frac{N\phi_1}{f_1} - \frac{\phi_2}{f_2}\right) + \cdots$$

- Integrating out the heavy mode enforces $\frac{N\phi_1}{f_1} - \frac{\phi_2}{f_2} = 0$.
- The light mode has effective potential: $V_{\mathrm{eff}}(\phi_L) = V_1\left(1 - \cos\frac{\phi_2}{Nf_2}\right)$.

Generating the chemical potential

	X
$\mathbf{U(1)_1}$	0
$\mathbf{U(1)_2}$	Q



- Naïvely:

$$\mathcal{L}_{\text{eff}} \sim \frac{1}{L}\bar{X}(L)e^{iQq_5A_5^{(2)}L}X(0)\cdot \underline{e^{-m_X L}} \propto \bar{v}_{XL}X(0)e^{iQ\phi_2/f_2}.$$

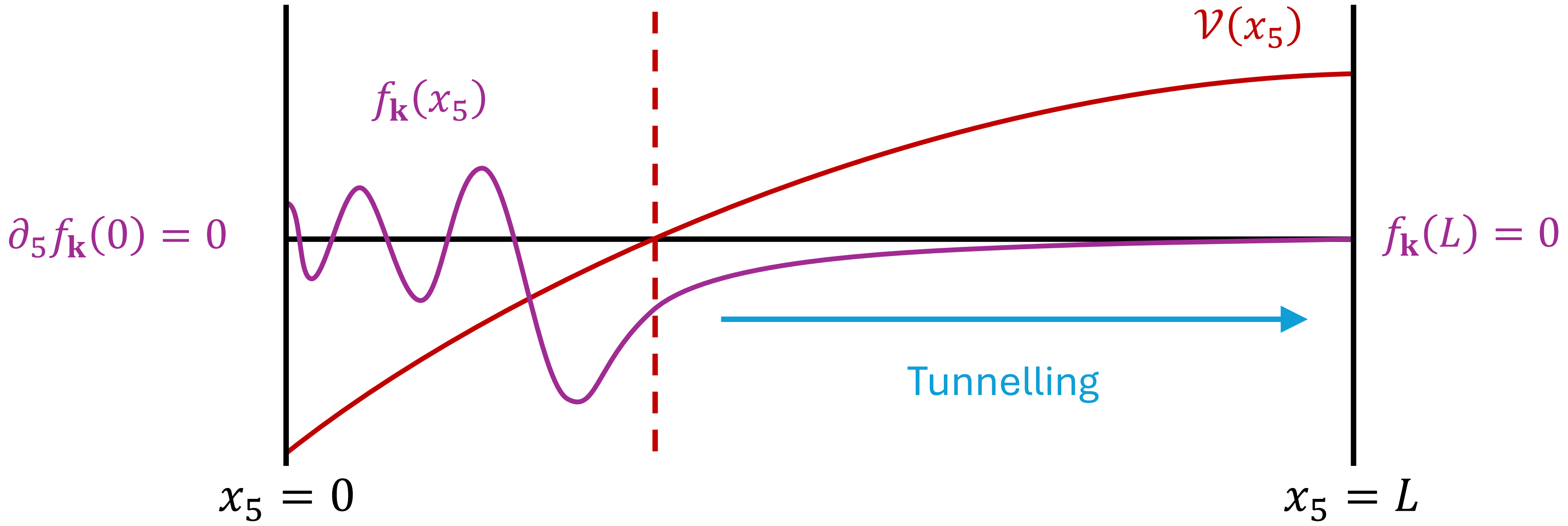
Similar to the scalar chemical potential model

- Need to consider the back-reaction from the 5D electric field to get the correct exponential factor.

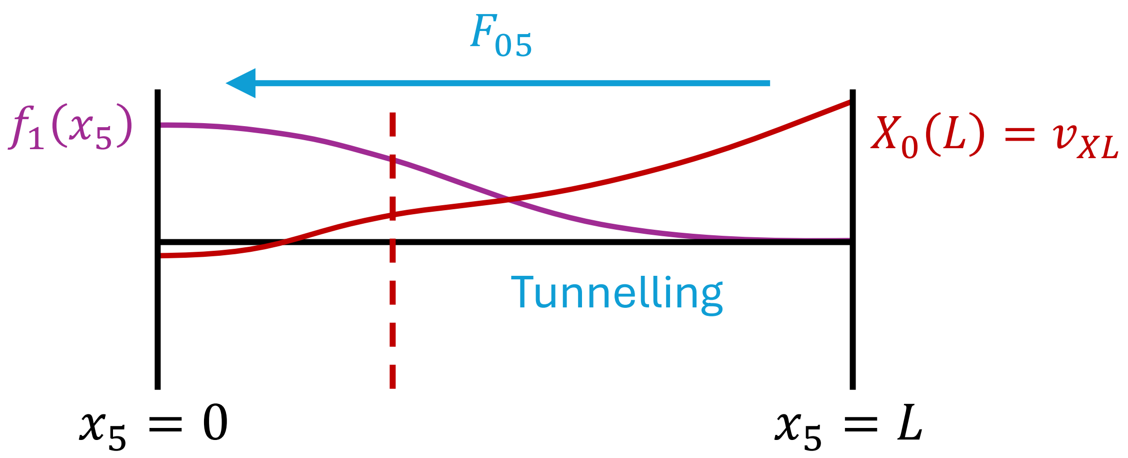
Estimating the signal size

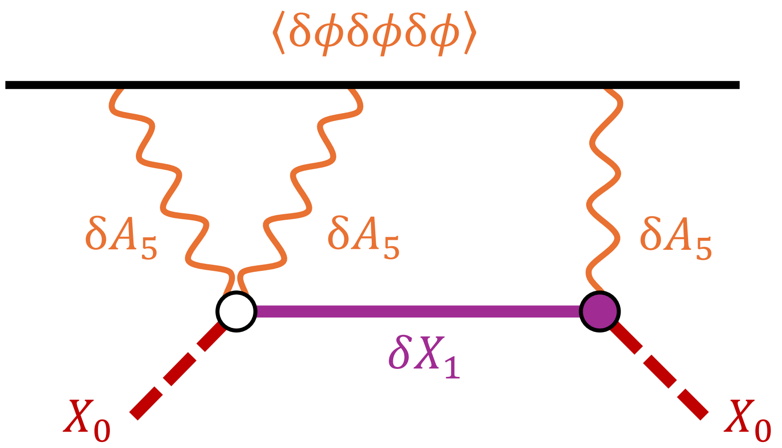
- KK expansion: $X(x, x_5) = X_0(x_5) + \sum_{n,\mathbf{k}} \delta X_{n\mathbf{k}} e^{-i\omega_n t + i\mathbf{k}\cdot\mathbf{x}} f_{n\mathbf{k}}(x_5)$ $\quad (X_0(L) = v_{XL})$
- The mode functions satisfy a “1D Schrödinger-like equation”:

$$\left[-\partial_5^2 + \mathcal{V}(x_5)\right] f_{\mathbf{k}}(x_5) = 0, \qquad \mathcal{V}(x_5) = -\left(\omega + \lambda \frac{L - x_5}{L}\right)^2 + \left(\mathbf{k}^2 + m_X^2\right).$$



Estimating the signal size





- The 4D effective vertices are proportional to

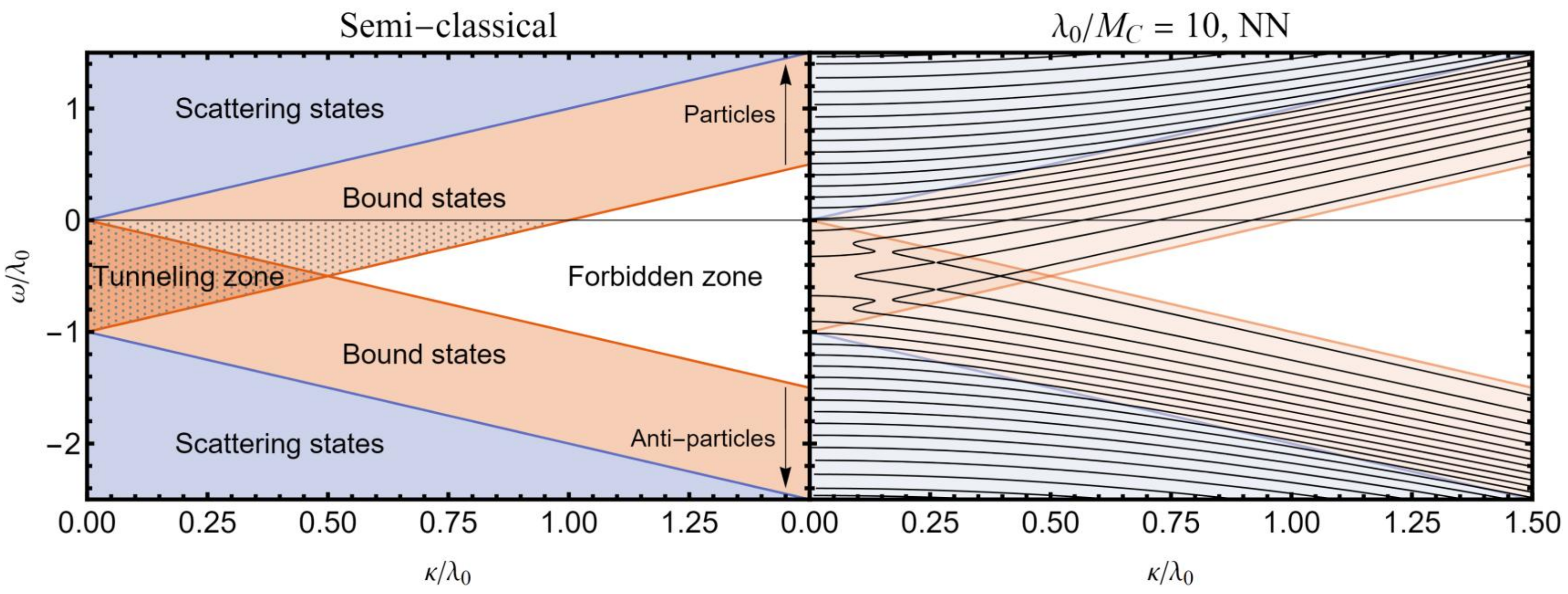
$$\int_0^L f_1(x_5)X_0(x_5)\mathrm{d}x_5 \sim \sqrt{L}v_L \boxed{\exp\left(-\frac{\pi m_X^2}{4Qq_5F_{05}}\right)} = \sqrt{L}v_L \boxed{\exp\left(-\frac{\pi m_X^2 L}{4\lambda}\right)}.$$

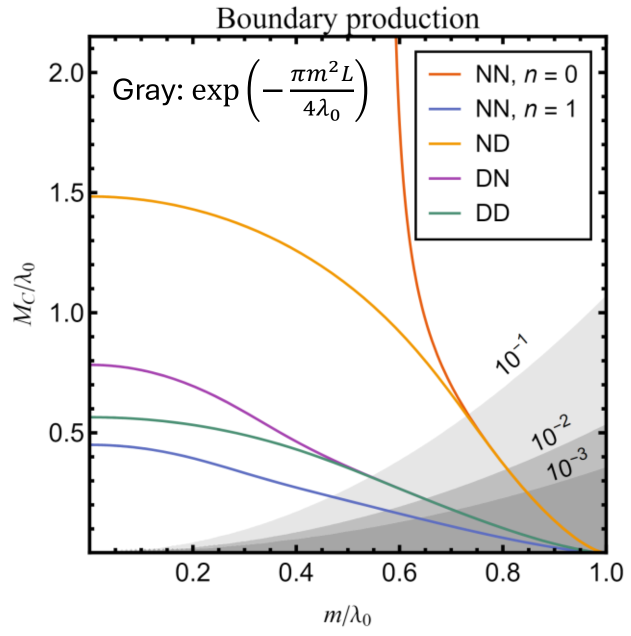
Schwinger mechanism
(Instead of naïve $e^{-m_X L}$)

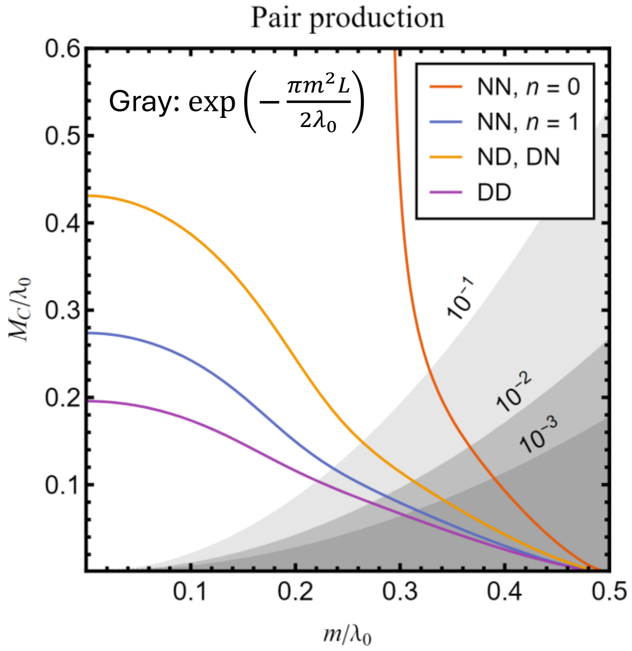
- The signal size ($\lambda \sim m_X \sim L^{-1}, v_{XL} \sim v_{H0} \sim v_{HL}$):

$$\mathcal{F} \sim \frac{1}{\epsilon_H}\left(\frac{m_X}{H}\right)^3 \exp\left(-\frac{\pi m_X^2 L}{2\lambda}\right) \sim 20\left(\frac{m_X}{H}\right)^3 \exp\left(-\frac{\pi m_X^2 L}{2\lambda}\right).$$

Spectrum and constraints







Boundary production: shaded region.
Pair production: tunneling zone.

Comparison with experiments

- When $\lambda \sim m_X \sim L^{-1} \sim 30H \lesssim 2 \times 10^{15}$ GeV and $m_X^2 L \lesssim \lambda$, we expect $\mathcal{F} \sim \mathcal{O}\left(1 - 10^5\right)$.
  - Current CMB constraint: $\mathcal{F} < \mathcal{O}(10 - 100)$ [12], Upcoming LSS experiments: $\mathcal{F} < \mathcal{O}(1 - ?)$ [13].
- Experimental search requires the full shape of the 3pt function $\mathcal{F}(k_1, k_2, k_3)$.
- In some special limits, the model reduces to the 4D scalar chemical potential model where the full 3pt function can be calculated analytically [5]

$$\mathcal{F}(k_1,k_2,k_3) = -\frac{20}{3}\frac{|\alpha|^2}{\Lambda^2}\frac{\lambda^2 e^{\pi\lambda}}{\left(\frac{3}{2}+i\lambda\right)^2+\mu^2}\cdot p^{-3}\mathbf{F}_{i\mu}^{\frac{1}{2}-i\lambda}(1)\left[\mathbf{F}_{i\mu}^{-\frac{3}{2}+i\lambda}(p)+\frac{p}{2}\mathbf{F}_{i\mu}^{-\frac{1}{2}+i\lambda}(p)+\frac{p^2}{16}\mathbf{F}_{i\mu}^{\frac{1}{2}+i\lambda}(p)\right].$$

$$p := \frac{2k_1}{k_3}, \qquad \mathbf{F}_{i\mu}^{\rho}(p) := \frac{\Gamma(\rho+i\mu)\Gamma(\rho-i\mu)}{\Gamma\left(\frac{1}{2}+\rho\right)}\,{}_2F_1\left(\begin{matrix}\rho+i\mu,\rho-i\mu\\ \frac{1}{2}+\rho\end{matrix};\frac{1-p}{2}\right)$$

- The full 3pt function of the 5D model is still unknown for general parameters.

[5] A. Bodas, E. Broadberry, R. Sundrum, 2409.07524.
[12] **Planck** Collaboration, 1905.05697; S. Kumar et al., 2604.07434.
[13] M. Alvarez et al., 1412.4671; **SPHEREx** Collaboration, 1412.4872; ...

Conclusion

- We showed that a robust theory of high-scale inflation with aligned extra-dimensional axions naturally leads to a chemical potential mechanism ~ 5D Schwinger mechanism.
- Simple models with KK excitations as targets can generate signals observable within upcoming LSS experiments.
- Related results of ours: loop chemical potential, 5D Chern-Simon theory → spin-1 helicity-dependent chemical potential, ...
- Future directions: full shape of the 3pt function, including warping (AdS/CFT), SUSY, multi-axion version, ...

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Thank you!