Minimal Warm Inflation with a heavy QCD axion

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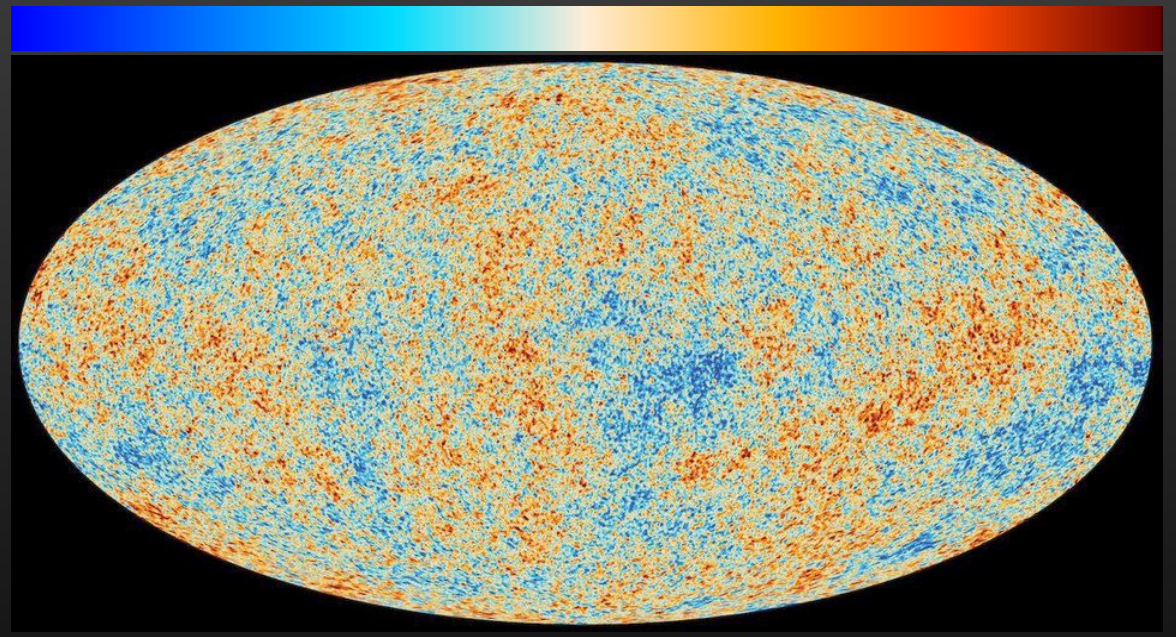
Based on: arXiv:2402.13535 (Berghaus, Forslund, Guevarra)

JCAP03(2020)034 (Berghaus, Graham, Kaplan)

Why Inflation?

- Universe is isotropic
- Universe is flat

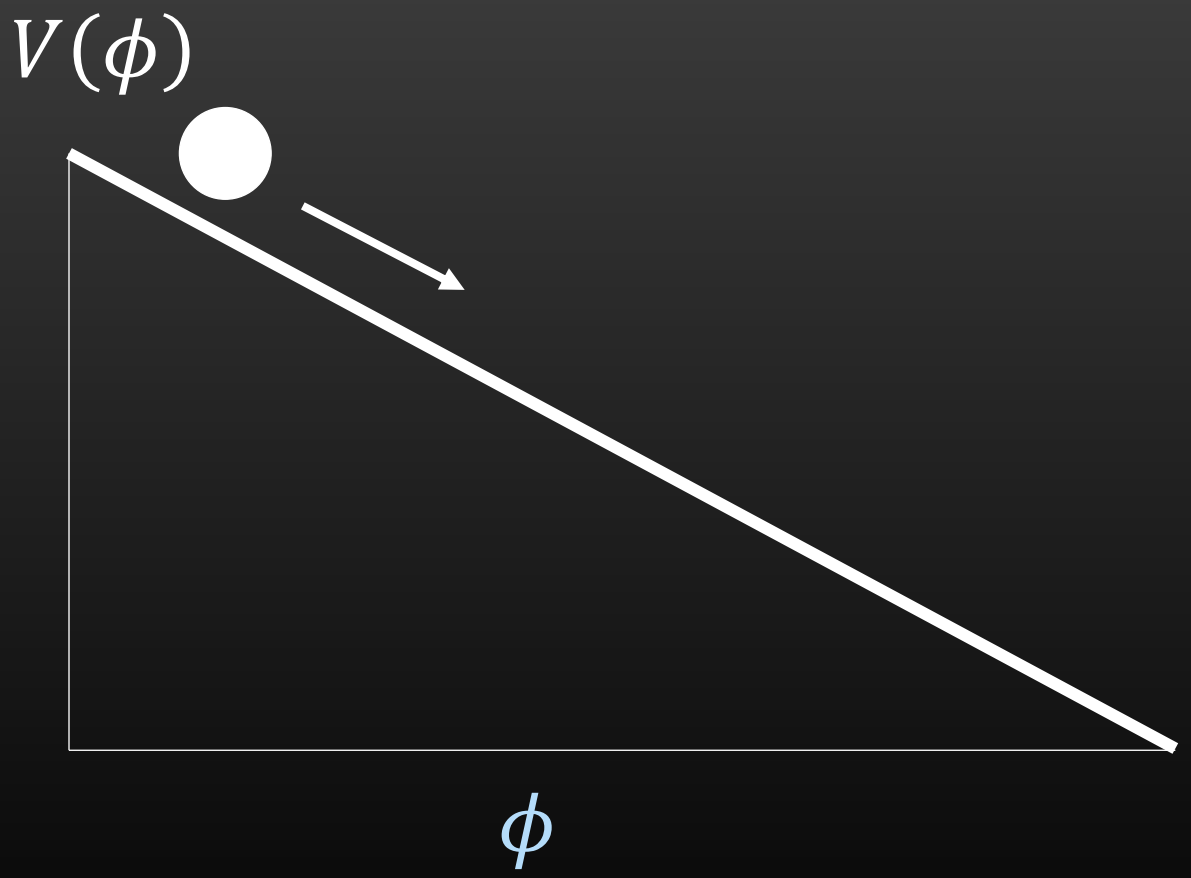
$$\frac{\delta T}{T} \approx 10^{-4.5}$$



Planck 2018

Period of accelerated expansion ($\approx$ 60 e-folds) can explain both

Slow-roll Inflation



- Slow-rolling scalar field has negative pressure

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Hubble friction

$\delta\phi \sim H$ (quantum fluctuations)

$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad H^2 \approx \frac{V}{3M_{pl}^2}$$

$$\eta_V = M_{Pl}^2 \frac{V''}{V} \ll 1$$

Slow-roll Inflation

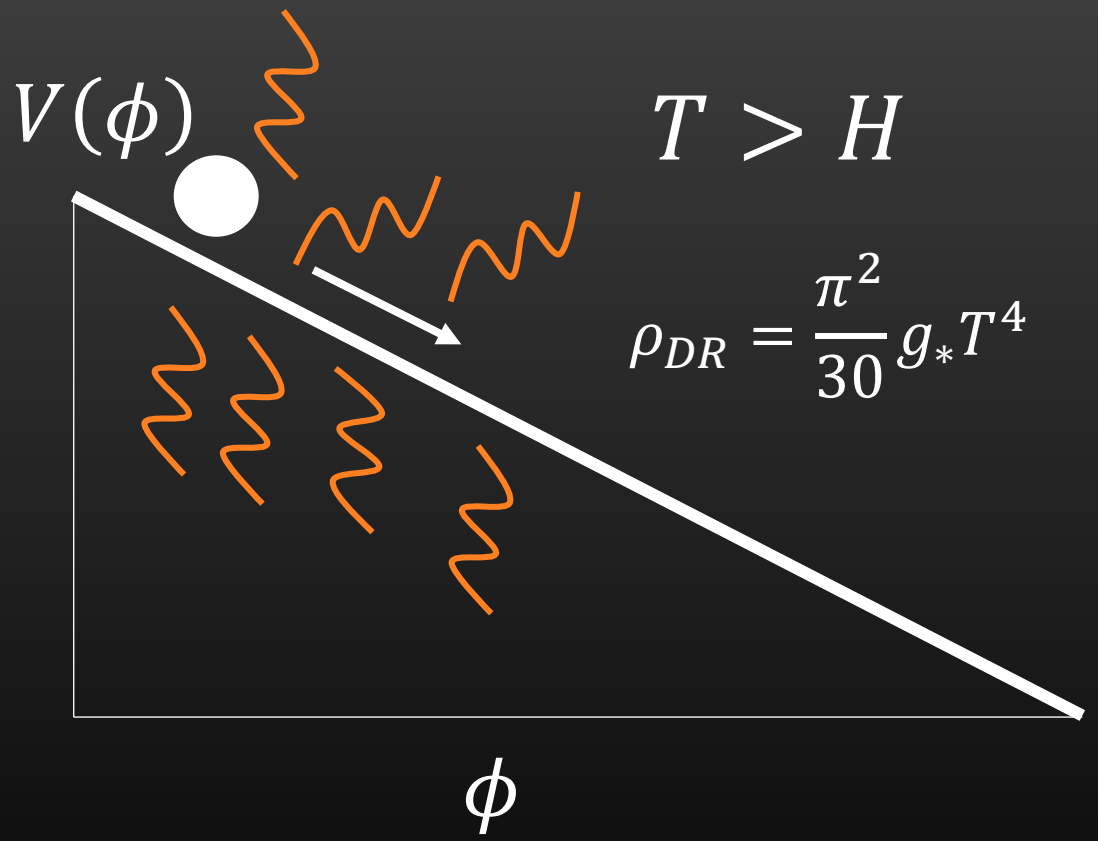
- Inflaton field fluctuations $\delta\phi$ source anisotropies
- Predicts an almost scale invariant CMB power spectrum:
- $$\Delta_R^2(k) = \underbrace{A_s}_{\sim 10^{-9}} \left(\frac{k}{k_*}\right)^{\overbrace{n_s - 1}^{\approx -0.035}}$$
- $r = 16\varepsilon_V < 0.1$

Challenges

- Simplest models overpredict r
- $\Delta\phi \geq M_{pl}$
- Models undistinguishable

Warm Inflation

Phys.Rev.Lett.75:3218-3221,1995 Berera, 1995



$$T > H$$

$$\rho_{DR} = \frac{\pi^2}{30} g_* T^4$$

$$3(\Upsilon)\dot{\phi} + V' \approx 0$$

$$4H\rho_{DR} \approx \Upsilon \dot{\phi}^2$$

$\delta\phi \sim \sqrt{H\,T}$ (classical) } suppresses r

$$\varepsilon_V = \frac{M_{Pl}^2}{2}\frac{3H}{\Upsilon}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta_V = M_{Pl}^2 \frac{3H}{\Upsilon}\frac{V''}{V} \ll 1$$

} reduces $\Delta\phi$

- larger non-gaussianities $f_{NL}^{warm} \sim 50$
- Unique bispectral shape

  Bastero-Gil, Berera, Moss, Ramos JCAP12(2014)008

  Mirbabayi, Gruzinov JCAP02(2023)012

Microphysics of Warm Inflation

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple scalar fields to light degrees of freedom $L_{\rm int} = -\phi\, J_{\rm int}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\langle J_{int} \rangle_{\rm non-eq}(\phi)$$

$$\langle J_{int} \rangle_{\rm non-eq}(\phi) \approx m_{th}^2 \phi + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

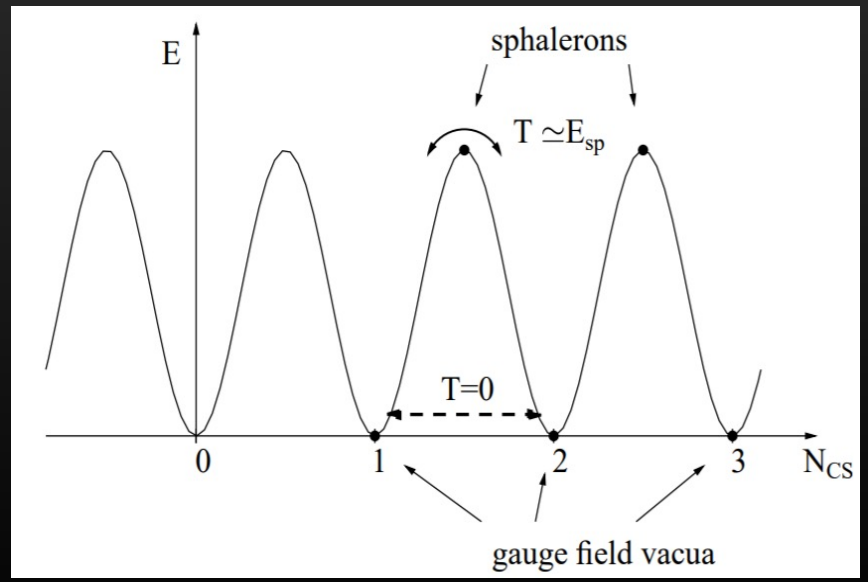
Usually $m_{th}^2 \phi \gg \Upsilon \dot{\phi}$, unless symmetry or other reason suppresses m_{th}^2

Minimal Warm Inflation

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple axion to non-Abelian gauge group $L_{\rm int} = -\phi \frac{\alpha}{16\pi f}\tilde{G}G$ $\quad T > H$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\left\langle \frac{\alpha}{16\pi f}\tilde{G}G \right\rangle(\phi)$$

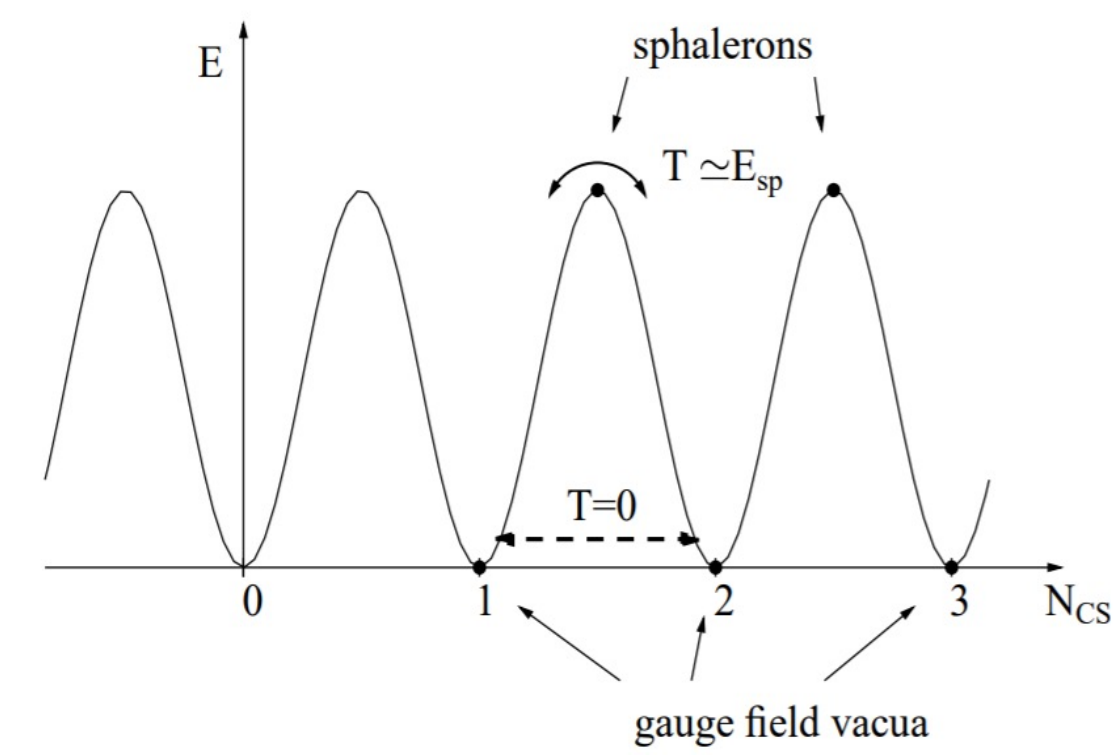


enhanced by sphalerons

$$\left\langle \frac{\alpha}{16\pi f}\tilde{G}G \right\rangle(\phi) \approx \cancel{m_{\rm tp}^2\phi} + \Upsilon\dot{\phi} + O(\ddot{\phi})$$

Not allowed by symmetry

Sphaleron Heating



Herranen, arXiv:0906.3136

$$N_{CS}(t) \equiv \int_0^t dt \int dx^3 \, \mathrm{Tr}\tilde{G}G$$

$$\partial_u K^u = \frac{\alpha}{16\pi f}\tilde{G}G$$

Nonzero $\langle\dot{\phi}\rangle$ biases sphaleron transitions

$$L_{\mathrm{int}} = -\phi\frac{\alpha}{16\pi f}\tilde{G}G \approx \dot{\phi}K^0$$

Real time sphaleron processes change topology and efficiently source particles: $\Upsilon \approx \alpha^5 N^5 \frac{T^3}{f^2}$

Hybrid Warm Inflation

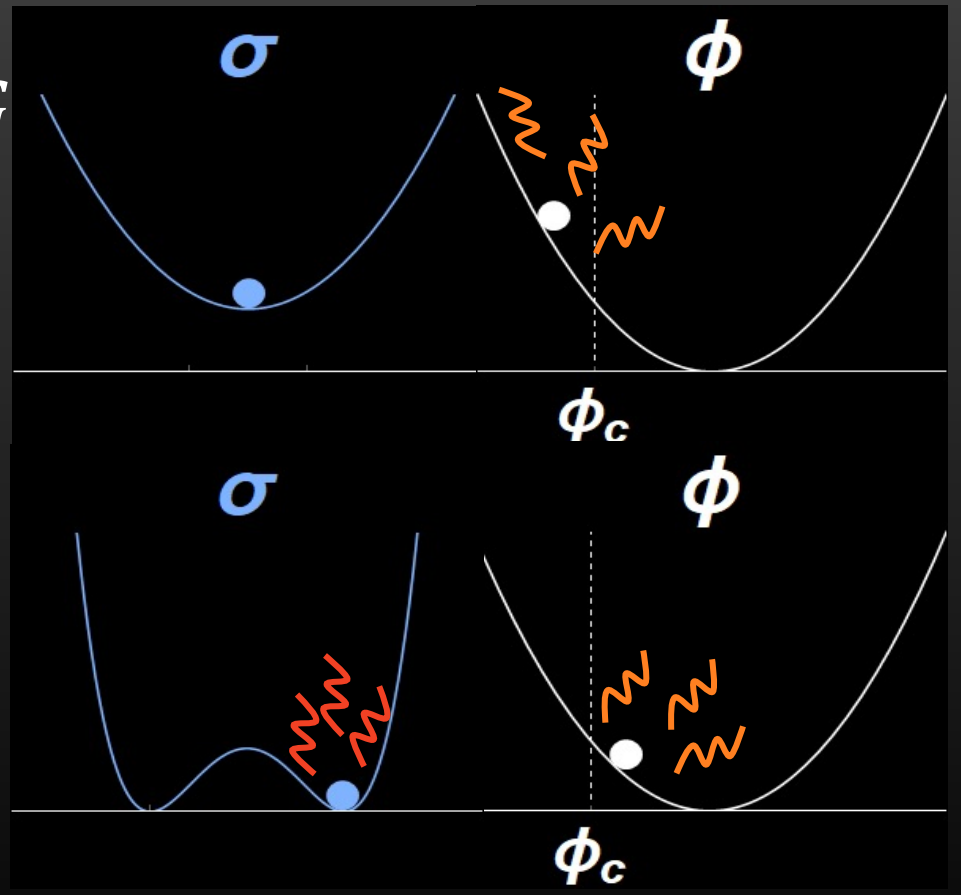
$$V = {M_\sigma}^4 + \frac{1}{2}{m_\phi}^2\phi^2; L_{int} = \frac{\alpha}{16\pi f}\frac{\phi}{f}\tilde{G}G$$

σ drives inflation

ϕ rolls towards ϕ_c

σ reheats into Standard Model

ϕ sources radiation bath



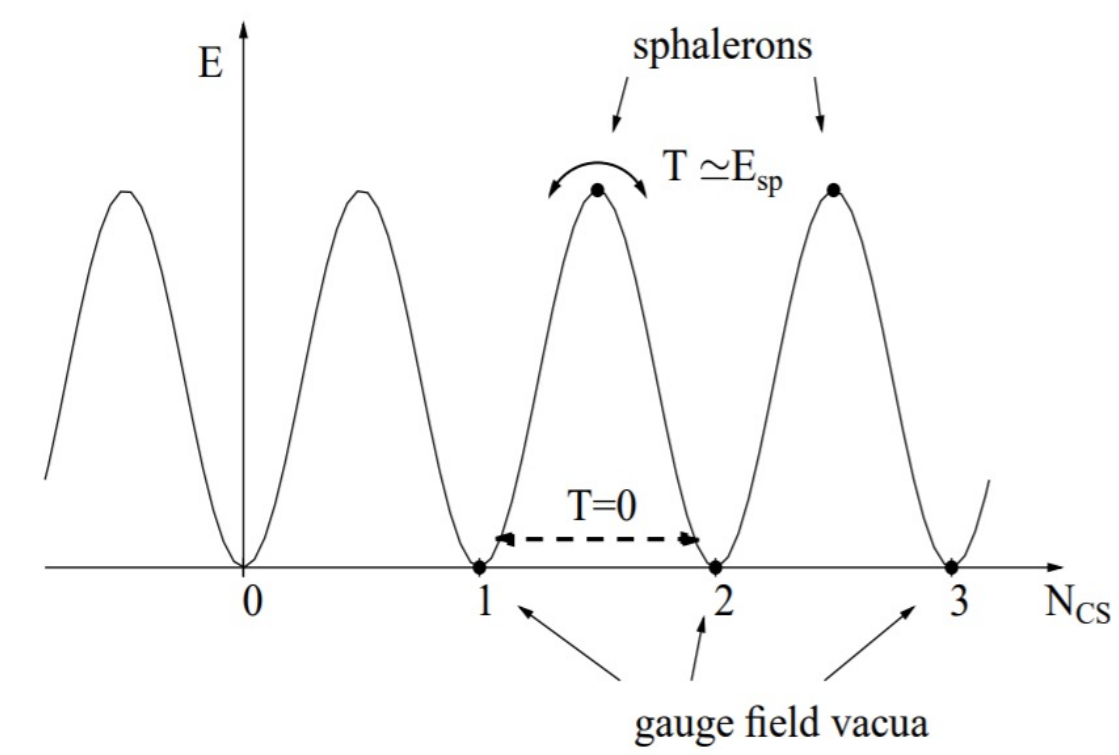
$$T_{RH} \gg T$$

Can we have warm inflation with SM QCD?

$$L_{\text{int}} = -\phi \frac{\alpha_s}{16\pi f} \tilde{G} G$$ SM strong force SU(3)

$$V_{\text{UV}} = \Lambda^4 \left(1 - \cos \frac{\phi}{f_\phi}\right)$$ heavy QCD axion

Sphaleron heating with fermions

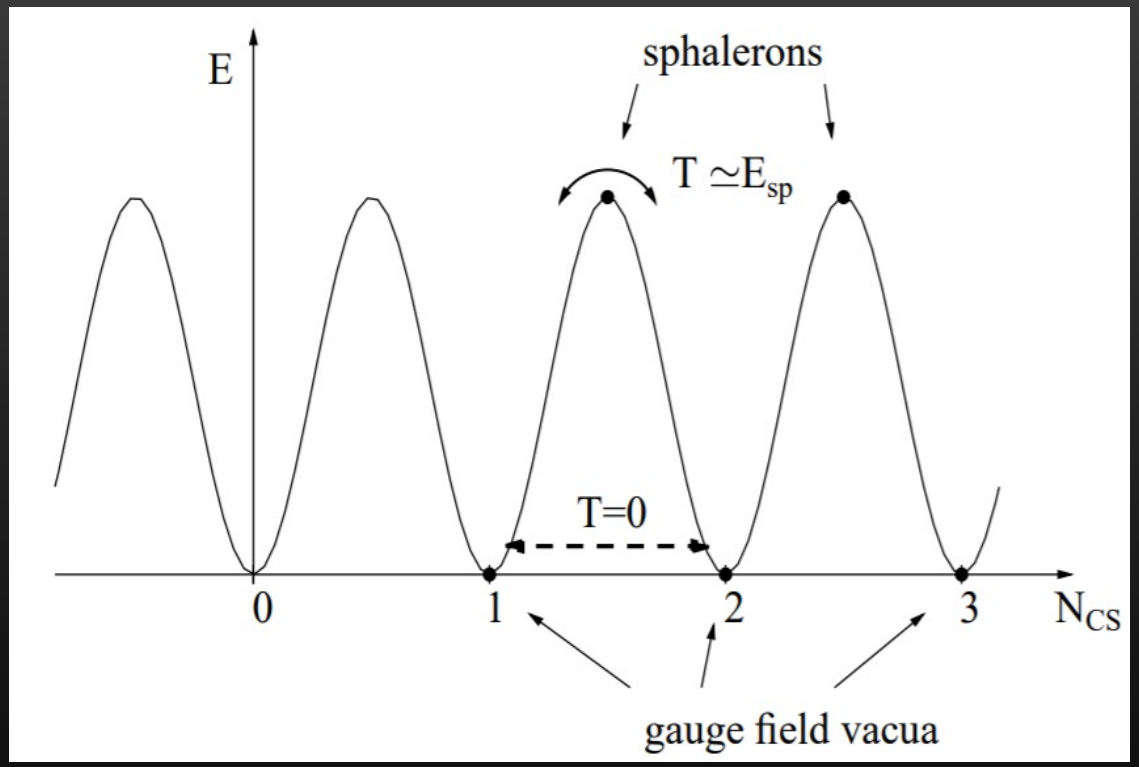


- Topology changes built up chiral charge
- Chiral chemical potential counteracts $\langle \dot{\phi} \rangle$

Herranen, arXiv:0906.3136

$$\Upsilon \approx \alpha^5 N^5 \frac{T^3}{f^2}$$

Sphaleron heating with light fermions



Herranen, arXiv:0906.3136

$$\Upsilon \approx \alpha^5 N^5 \frac{T^3}{f^2}$$

QCD sphaleron heating suppressed due to light quarks

$$\Upsilon_{eff} = \Upsilon \left(\frac{\Gamma_{chir}}{\Gamma_{chir} + 2f^2/T^2\,\Upsilon} \right)$$

$$\Upsilon_{eff} \sim \alpha\, N\, \frac{m^2}{f^2} T \text{ if } m \ll \alpha^2 N^2 T$$

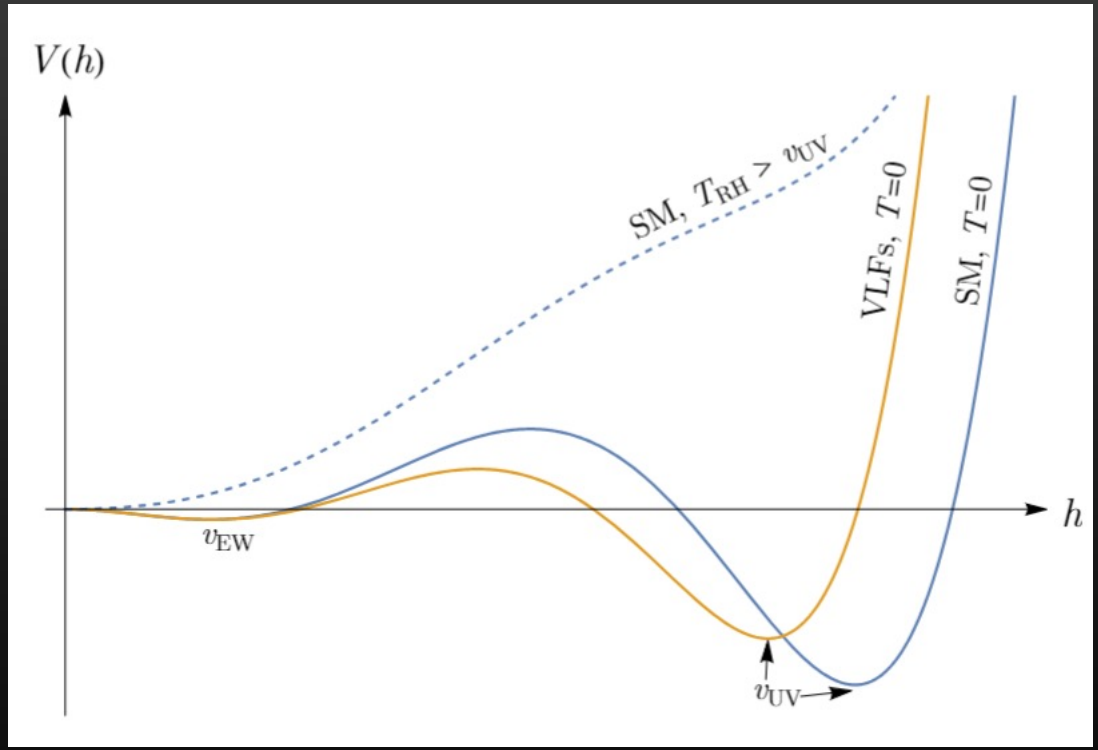
Solution: heavy SM quarks during warm inflation

MWI with a heavy QCD axion

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

The Standard Model quartic of the Higgs runs negative at high energies

Higher dimensional operator can stabilize a second UV Higgs vev



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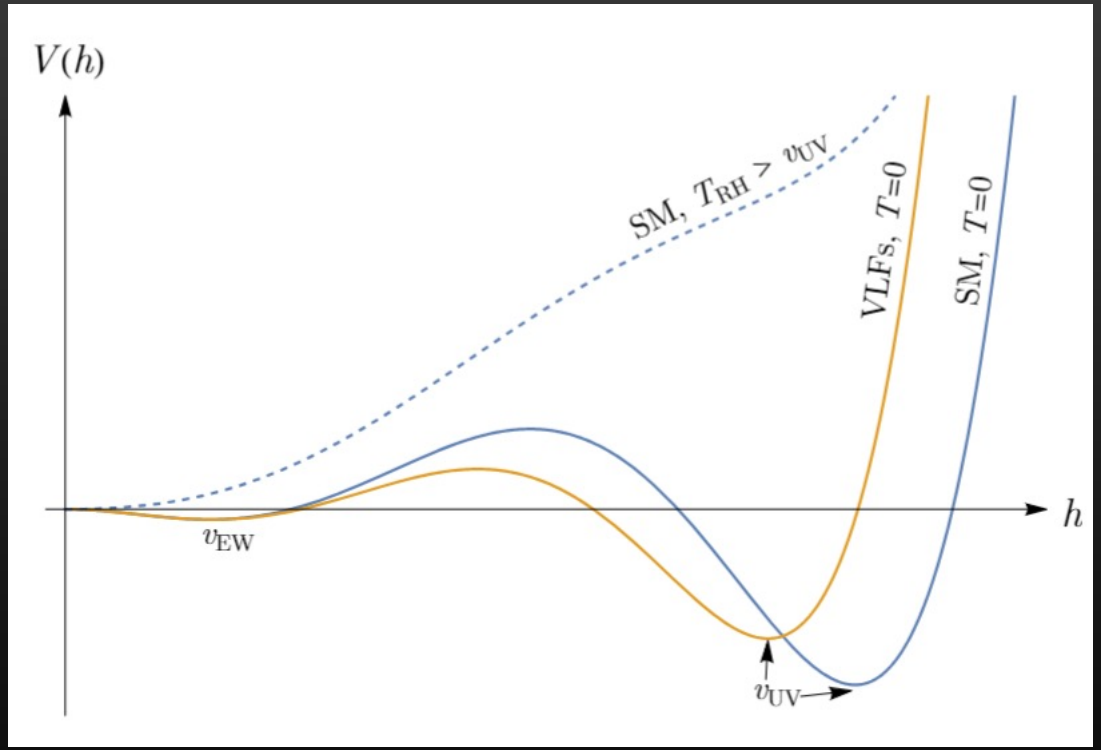
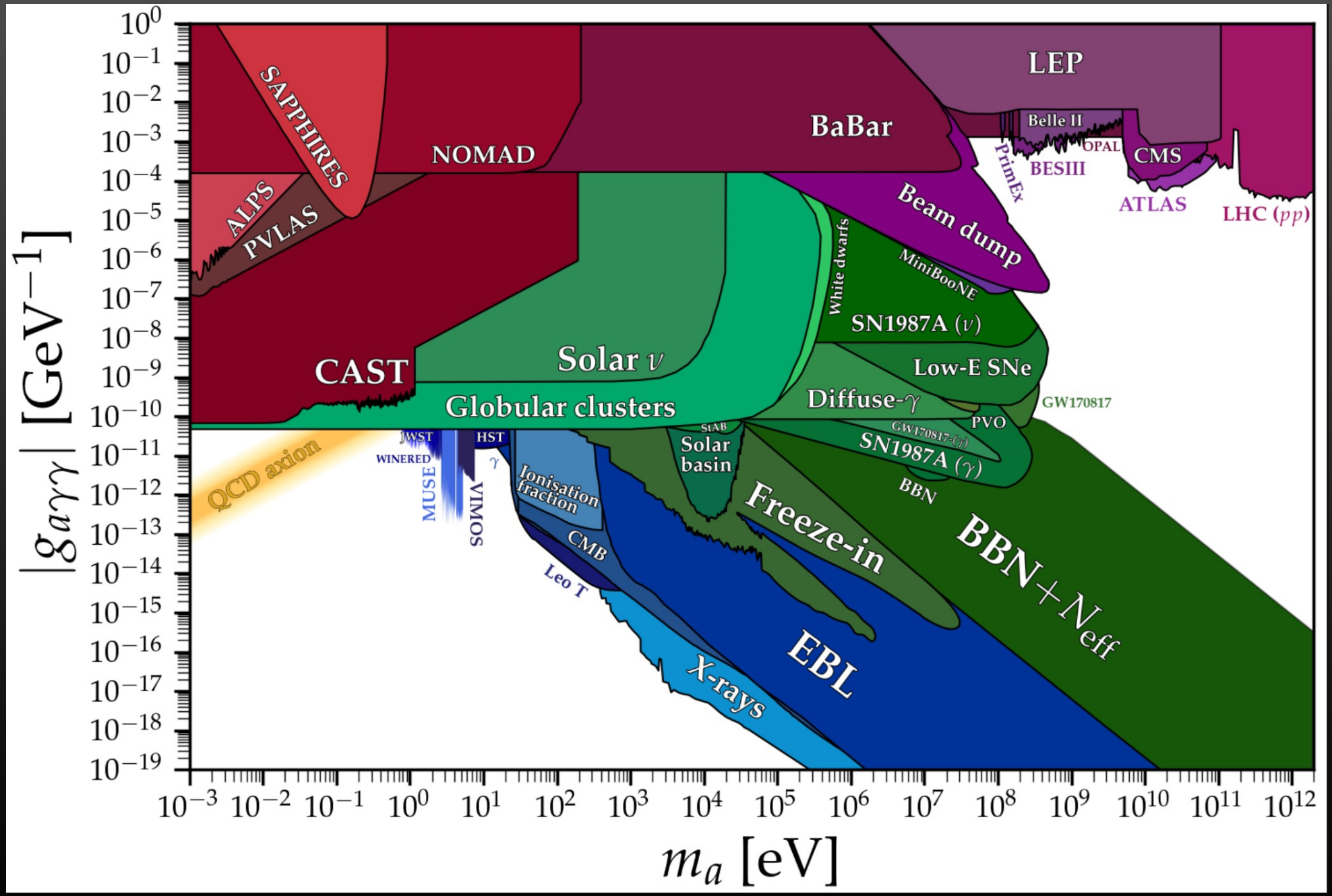
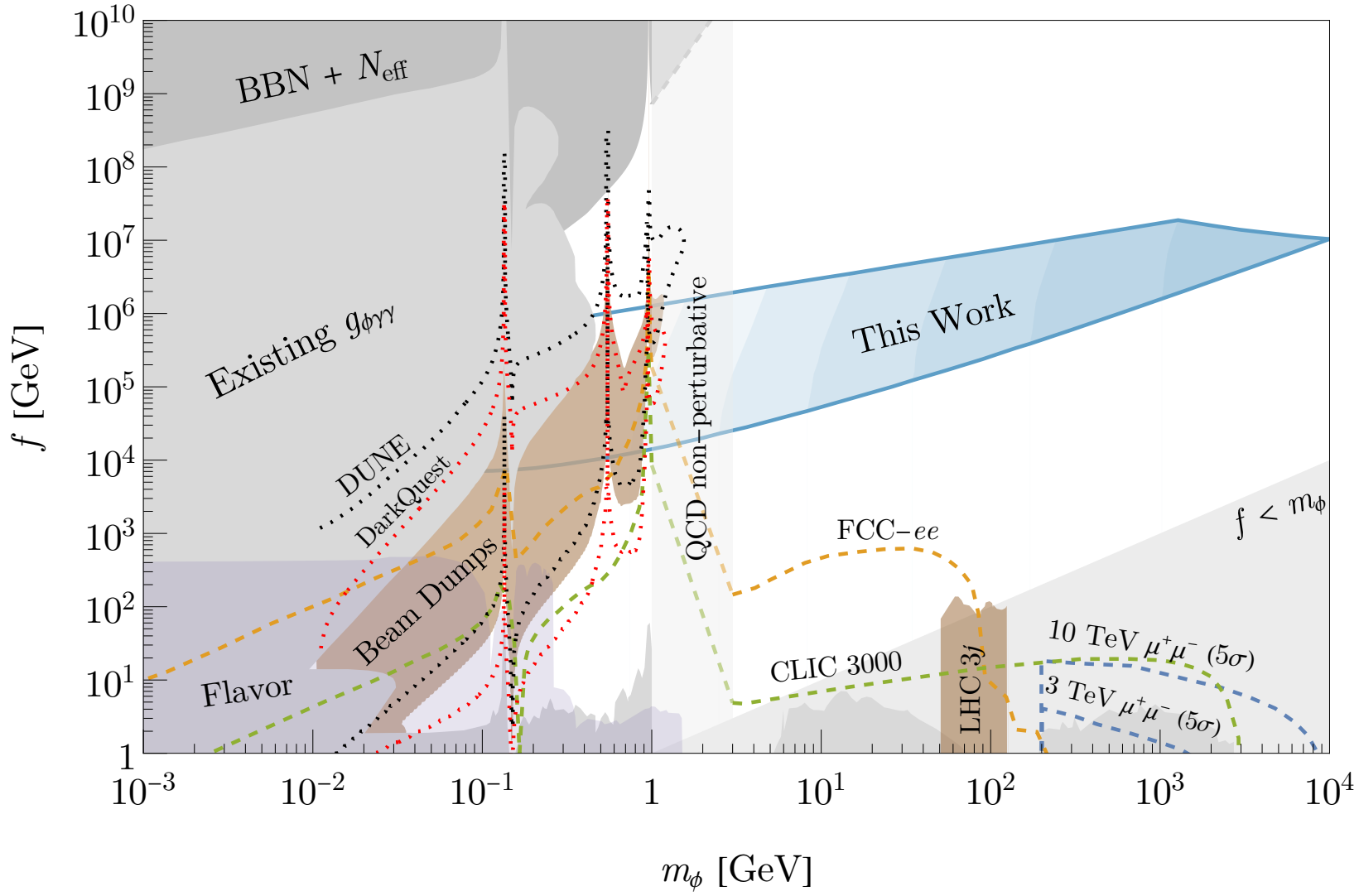
QCD quark masses are proportional to v_{UV}



restores $\Upsilon_{eff} \to \Upsilon$ if $m \gg \alpha^2 N^2 T$


LEP
BaBar
Belle II
OPAL
PrimEx
BESIII
CMS
ATLAS
LHC (pp)
SAPPHIRES
NOMAD
ALPS
PVLAS
Beam dump
White dwarfs
MiniBooNE
SN1987A (ν)
Low-E SNe
CAST
Solar ν
Globular clusters
Diffuse-γ
GW170817
PVO
GW170817-(γ)
SN1987A (γ)
StAB
Solar basin
JWST
HST
WINERED
MUSE
VIMOS
γ
Ionisation fraction
QCD axion
CMB
Leo T
Freeze-in
BBN
BBN+$N_{\rm eff}$
EBL
X-rays
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]


BBN + $N_{\rm eff}$
Existing $g_{\phi\gamma\gamma}$
DUNE
DarkQuest
Beam Dumps
Flavor
QCD non-perturbative
This Work
FCC–ee
CLIC 3000
LHC 3j
10 TeV $\mu^+\mu^-$ (5σ)
3 TeV $\mu^+\mu^-$ (5σ)
$f < m_\phi$
f [GeV]
m_ϕ [GeV]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^{-3}
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4

Conclusions & Outlook

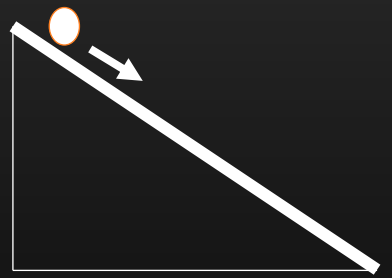
- Warm inflation is interesting alternative to cold inflation
- Axion coupling to SU(N) is a simple model for thermal particle production via sphaleron heating
- Proof of principle realization for warm inflation with SM particles
- Analysis of chirality violation in full SM sector exciting avenue forward

Thank You

Cold Inflation vs. Minimal Warm Inflation

$$H \ll \Upsilon \propto \alpha^5 \frac{T^3}{f^2}$$

- $\Delta_R^2(k) \propto \delta\phi^2 \propto H^2$
- Tensor to scalar ratio $r \approx 16\varepsilon_V$



$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

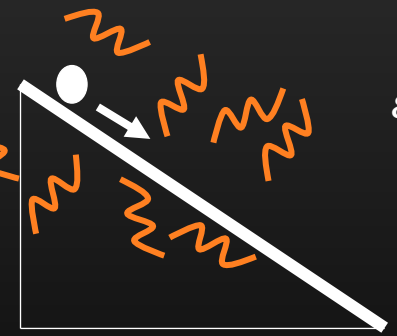
$$\eta_V = M_{Pl}^2 \frac{V''}{V} \ll 1$$

- Small non-gaussianities

- $\Delta_R^2(k) \propto \delta\phi^2 \propto H\,T\left(\frac{\Upsilon}{3H}\right)^{\frac{16}{2}}$

Bastero-Gil, Berera, Ramos *et al* JCAP07(2011)030

- Tensor to scalar ratio $r \approx 0$



$$\varepsilon_V = \frac{M_{Pl}^2}{2}\frac{3H}{\Upsilon}\left(\frac{V'}{V}\right)^2 \ll 1$$

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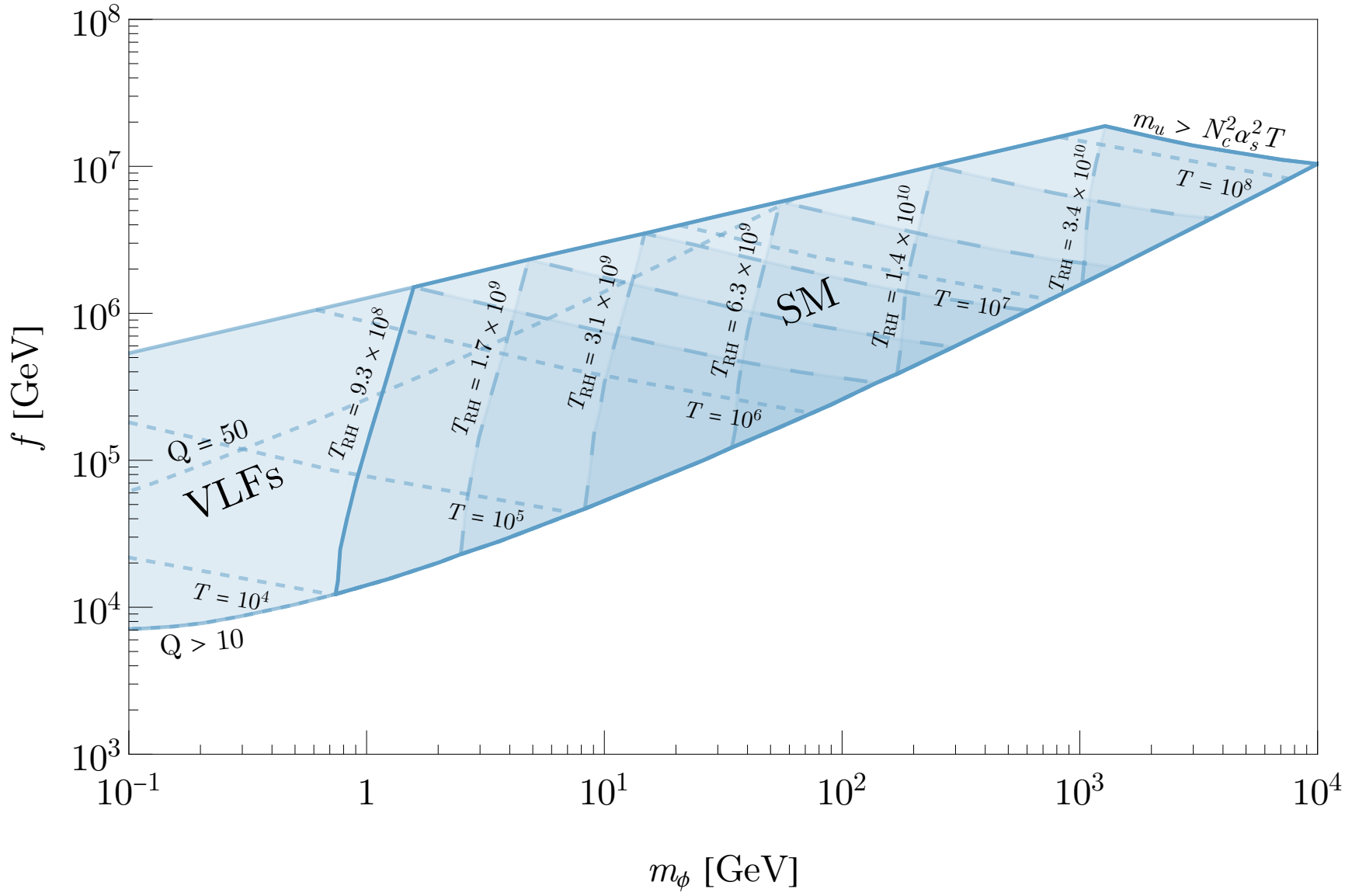
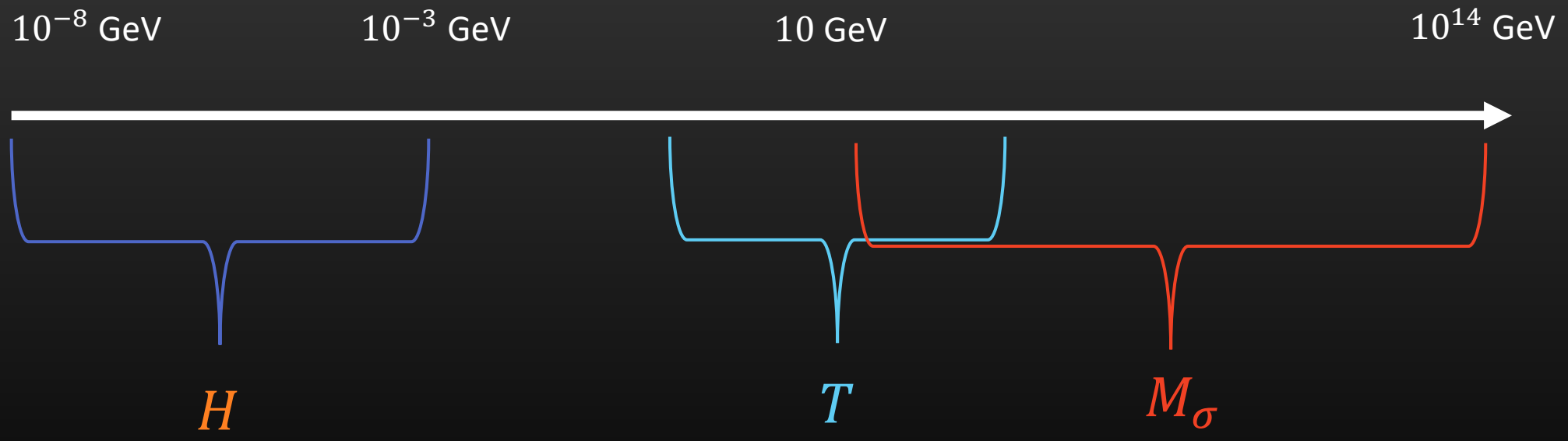

10^8
10^7
10^6
10^5
10^4
10^3
f [GeV]
10^{-1}
1
10^1
10^2
10^3
10^4
m_ϕ [GeV]
$m_u > N_c^2 \alpha_s^2 T$
$T = 10^8$
$T_{RH} = 3.4 \times 10^{10}$
$T = 10^7$
$T_{RH} = 1.4 \times 10^{10}$
$T_{RH} = 6.3 \times 10^9$
$T = 10^6$
$T_{RH} = 3.1 \times 10^9$
$T_{RH} = 1.7 \times 10^9$
$T = 10^5$
$T_{RH} = 9.3 \times 10^8$
$T = 10^4$
SM
VLFs
Q = 50
Q > 10

Reheating

Couple waterfall field to Standard Model: $\frac{\alpha_B}{16\pi f_B}\frac{\sigma}{}\tilde{B}B$