Particle Production in the Early Universe

Minimal Warm Inflation with a heavy QCD axion

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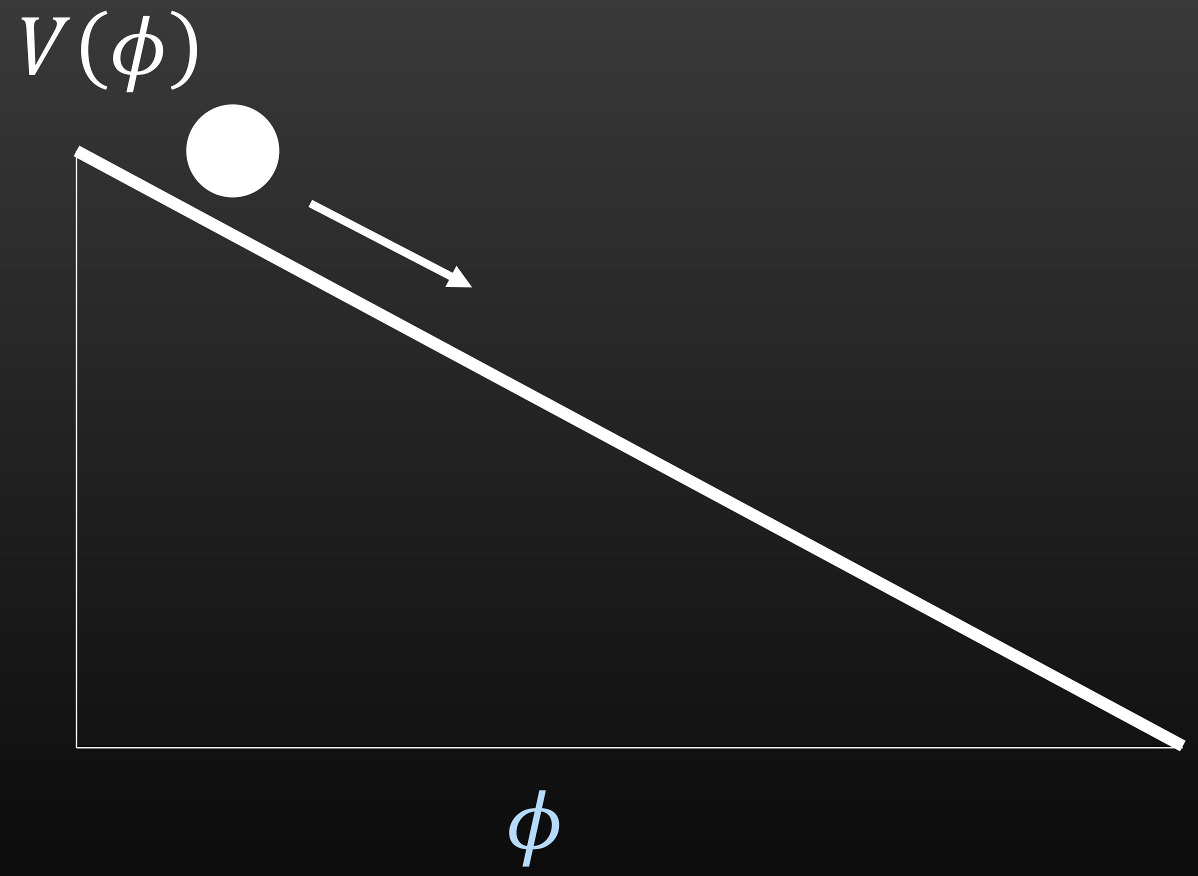
Based on: arXiv:2402.13535 (Berghaus, Forslund, Guevarra)
JCAP03(2020)034 (Berghaus, Graham, Kaplan)

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

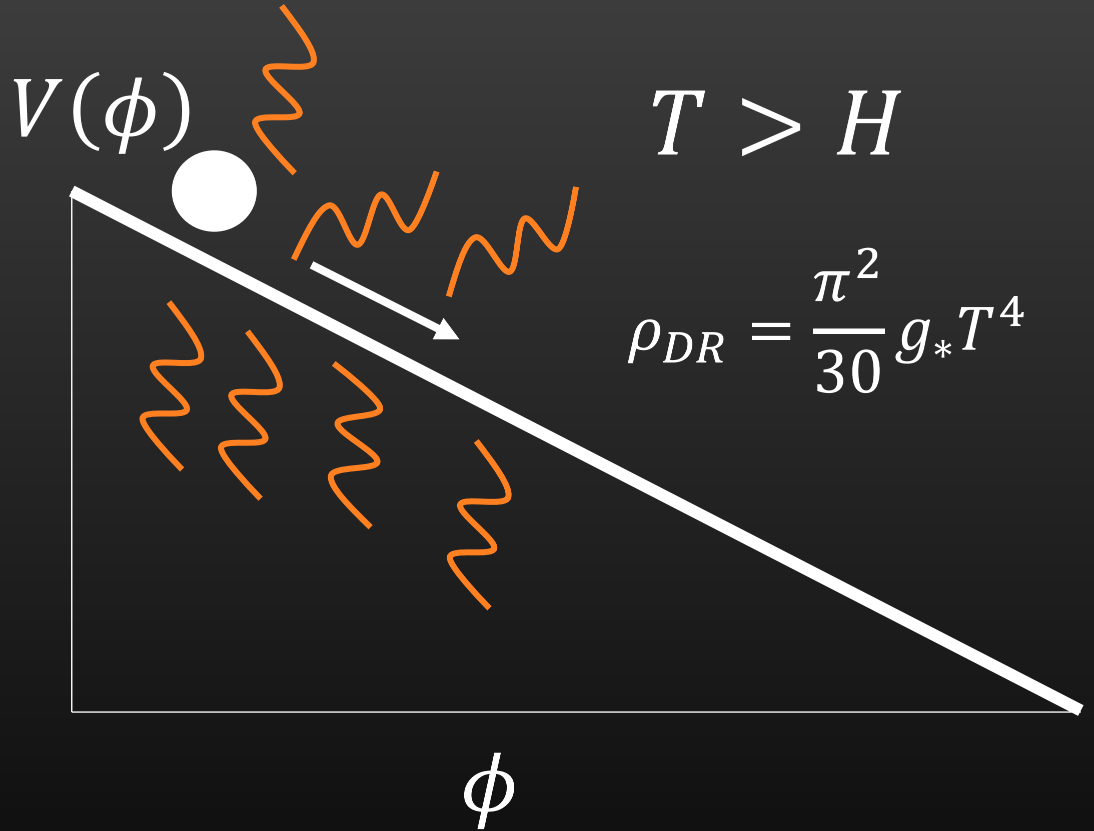
- Inflaton field fluctuations $\delta\phi$ source anisotropies
- Predicts an almost scale invariant CMB power spectrum:
- $$\Delta_R^2(k) = \underbrace{A_s}_{\sim 10^{-9}} \left(\frac{k}{k_*}\right)^{n_s - 1} \quad n_s - 1 \approx -0.035$$
- $r = 16\varepsilon_V < 0.1$

Challenges

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

Warm Inflation

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



$T > H$

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

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

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

$\delta\phi \sim \sqrt{H\,T}$ (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 $L_{\text{int}} = -\phi\, J_{\text{int}}$

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

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

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

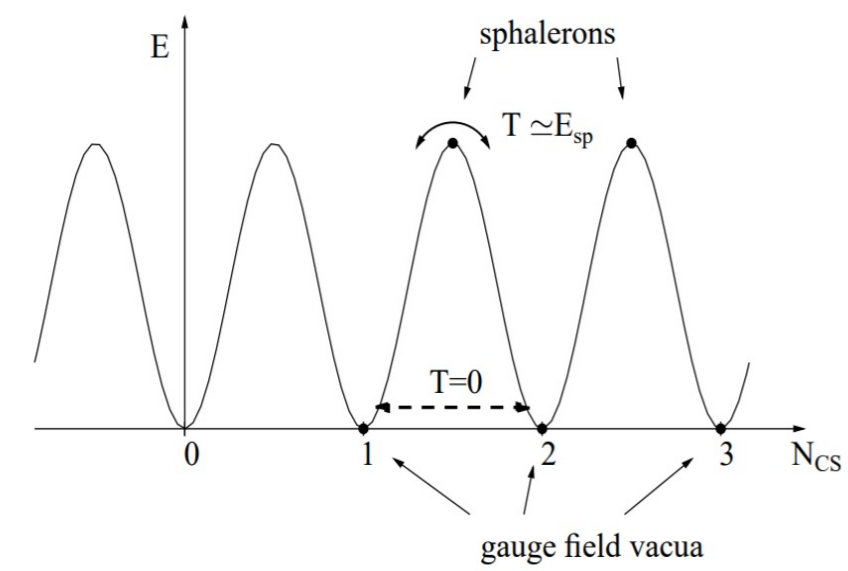
Minimal Warm Inflation

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

- Couple axion to non-Abelian gauge group $L_{\text{int}} = -\phi \frac{\alpha}{16\pi f}\tilde{G}G$

$T > H$

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



enhanced by sphalerons

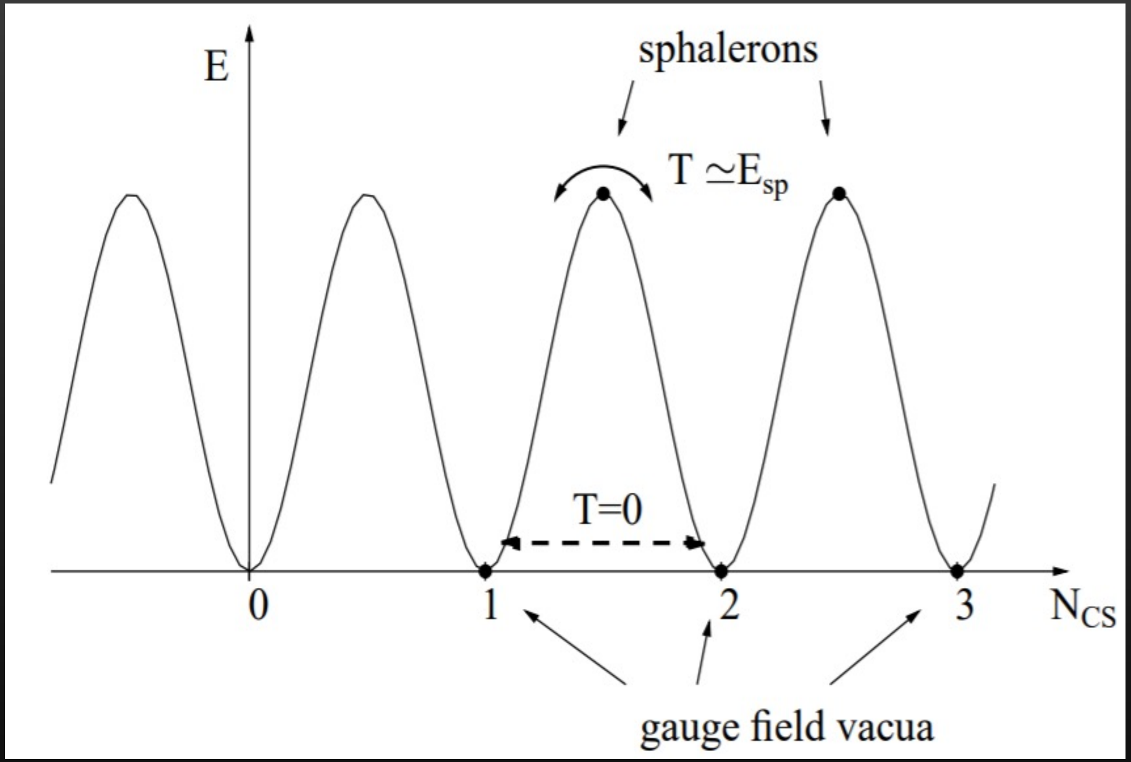
$$\left\langle \frac{\alpha}{16\pi f}\tilde{G}G \right\rangle(\phi) \approx m_{th}^2\phi + \Upsilon\dot{\phi} + O(\ddot{\phi})$$

Not allowed by symmetry

Sphaleron Heating

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

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



Herranen, arXiv:0906.3136

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

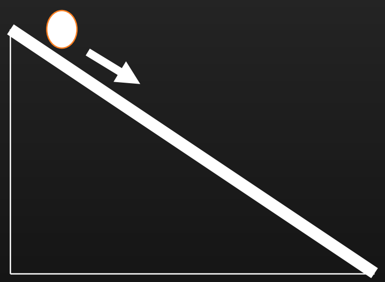
$$L_{\mathrm{int}} = -\phi\frac{\alpha}{16\pi f}\tilde{G}G \approx \dot{\phi}K^0$$

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

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 $\mathrm{r} \approx 16\varepsilon_V$



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

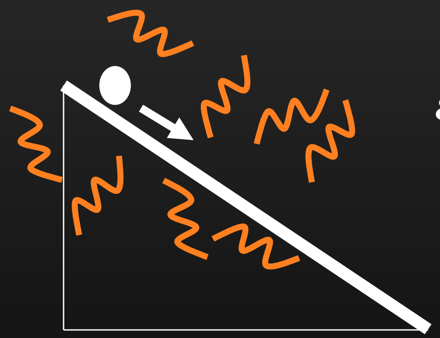
$$\eta_V = M_{Pl}^2 \frac{V''}{V} \ll 1$$

- 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 $\mathrm{r} \approx 0$



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

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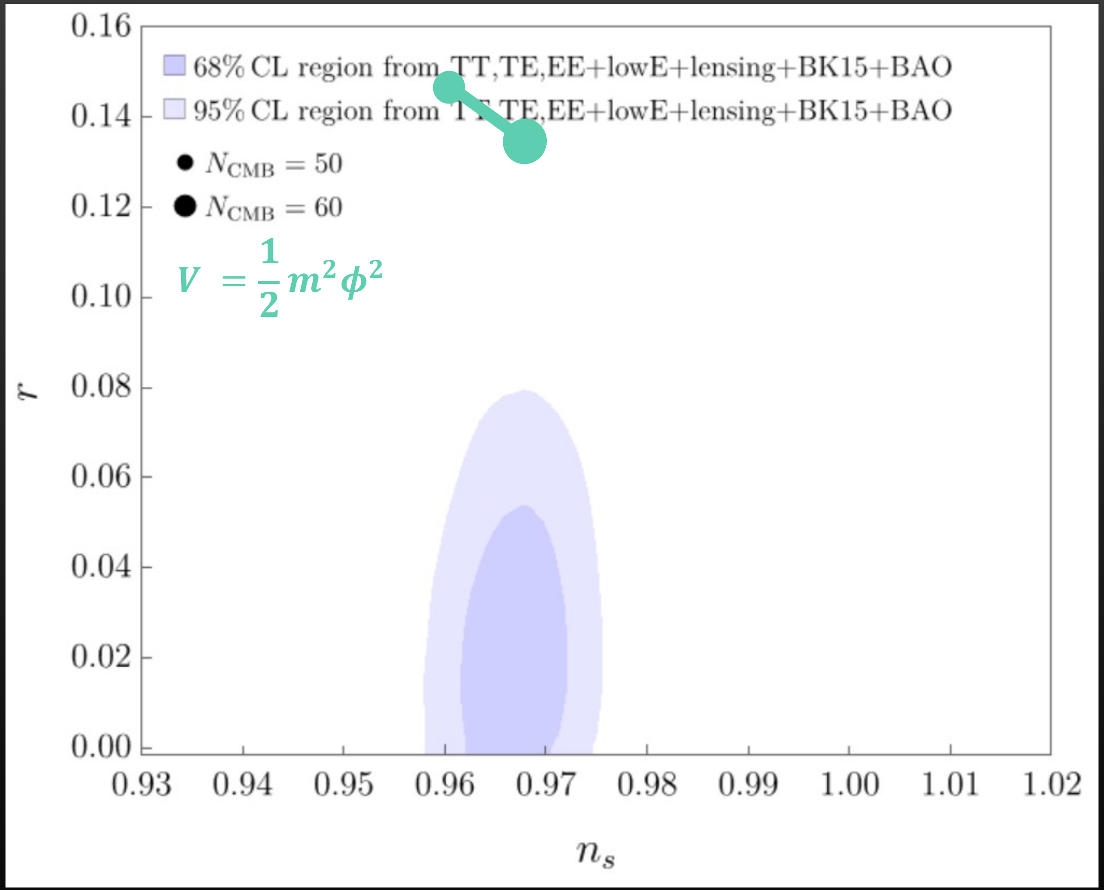
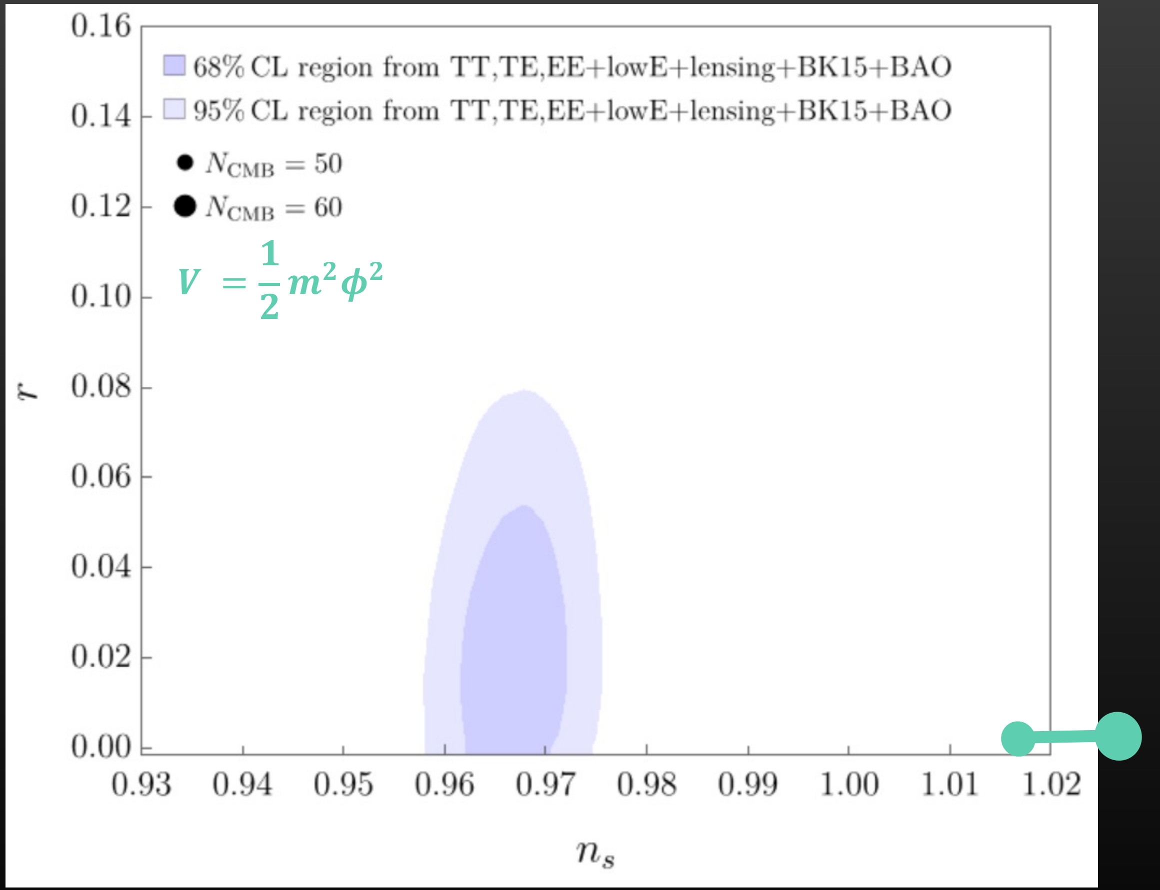
Bastero-Gil, Berera, Moss, Ramos JCAP12(2014)008

Mirbabayi, Gruzinov JCAP02(2023)012

Cold Inflation vs. Warm Inflation : $V = \frac{1}{2}m^2\phi^2$

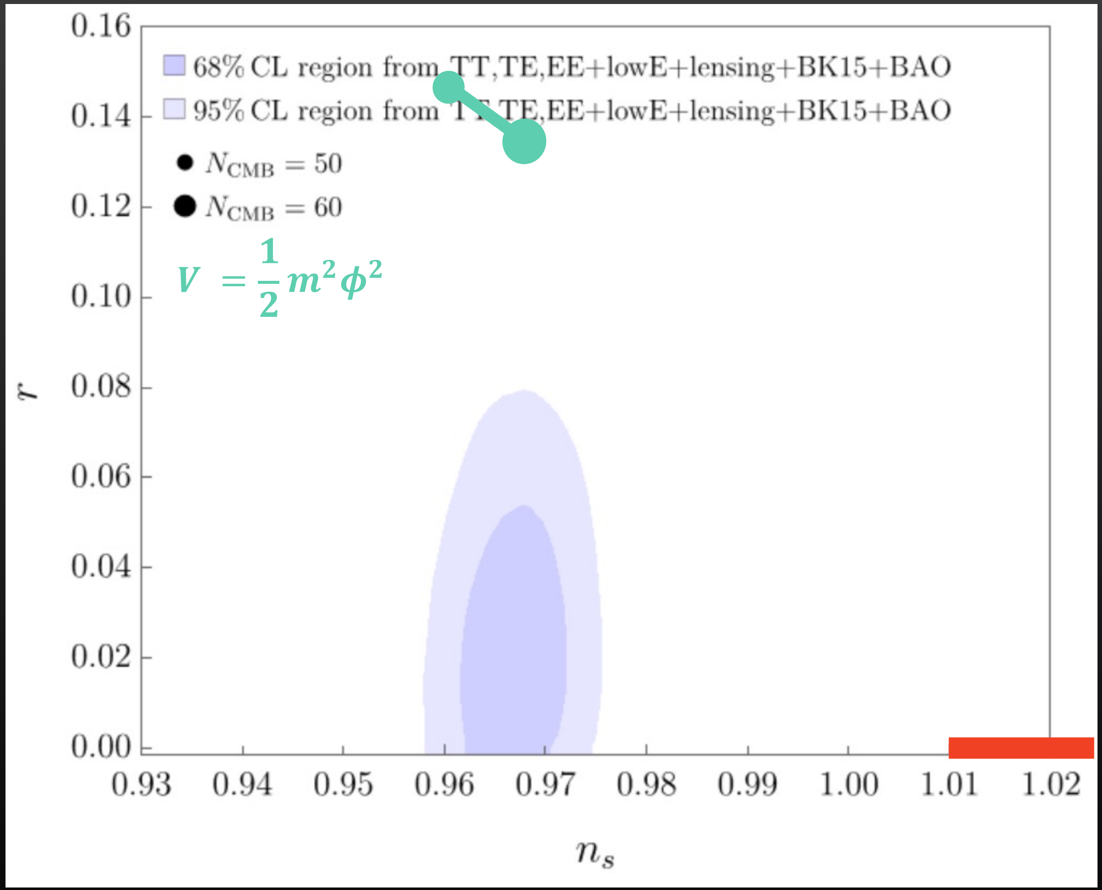


Cold

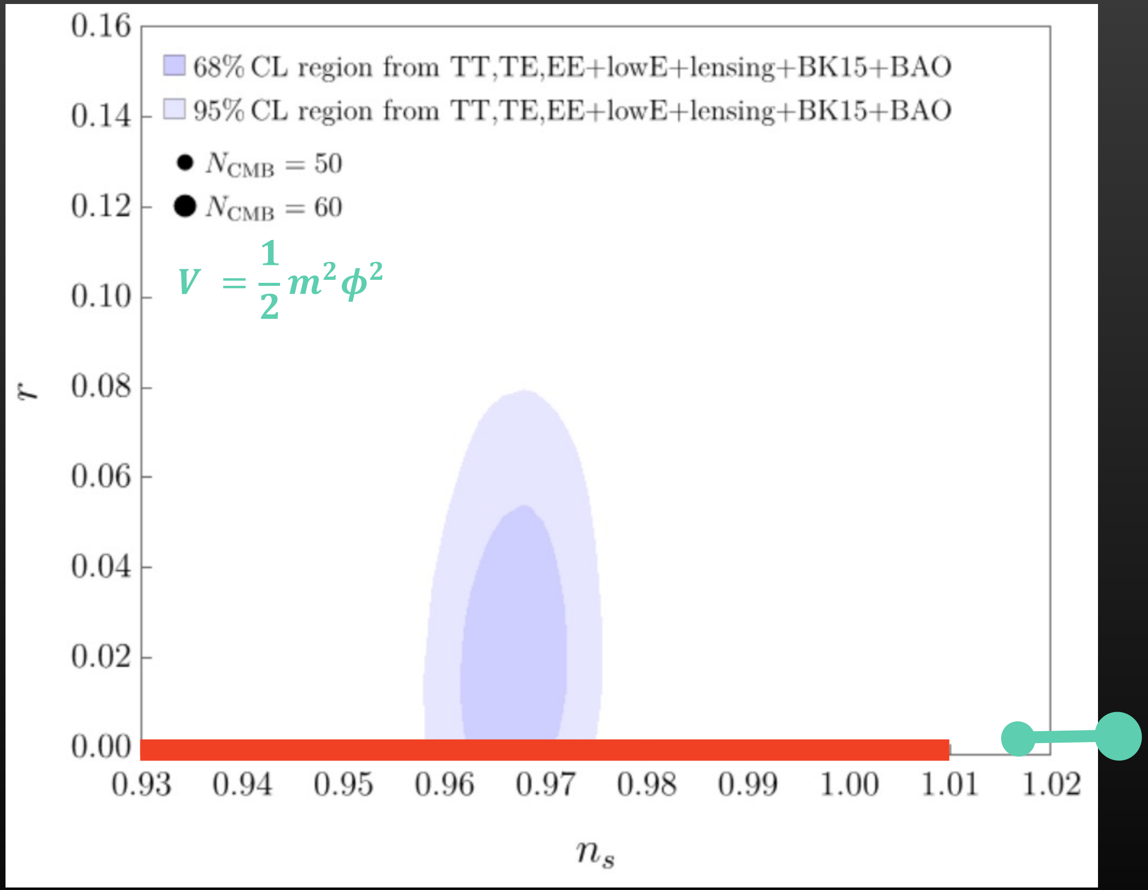


Warm

Cold Inflation vs. Warm Inflation : Hybrid



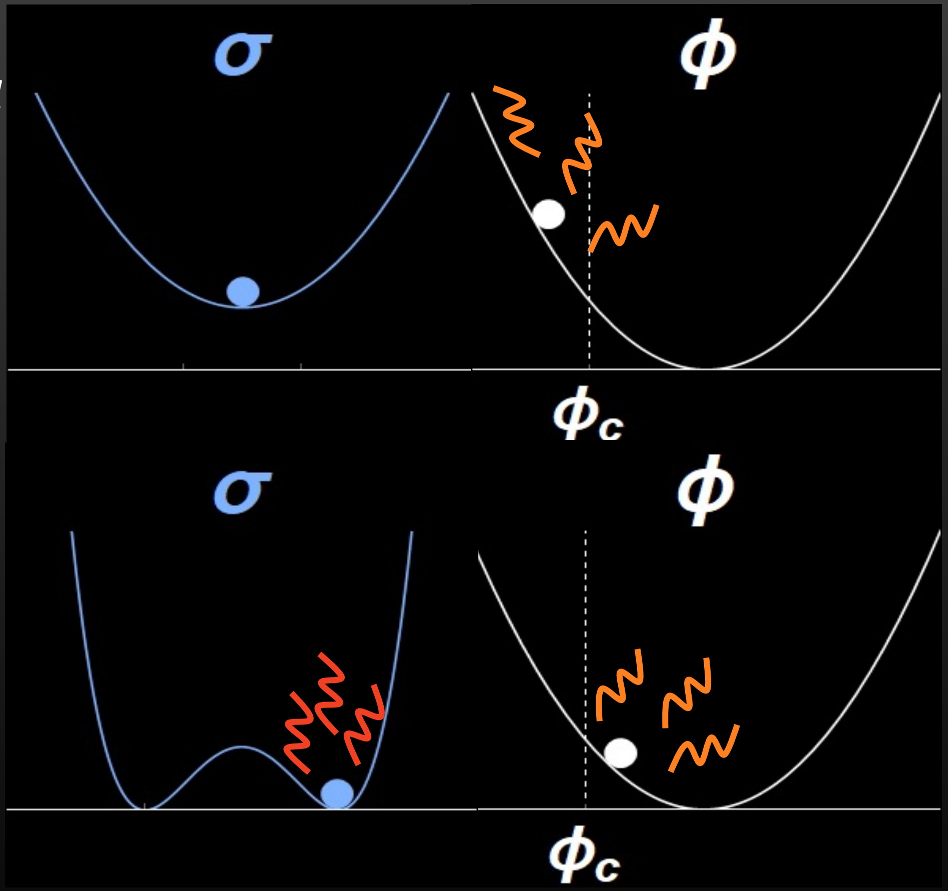
Cold



Warm

Hybrid Minimal Warm Inflation

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



σ drives inflation

ϕ rolls towards ϕ_c

σ reheats into Standard Model

ϕ sources radiation bath

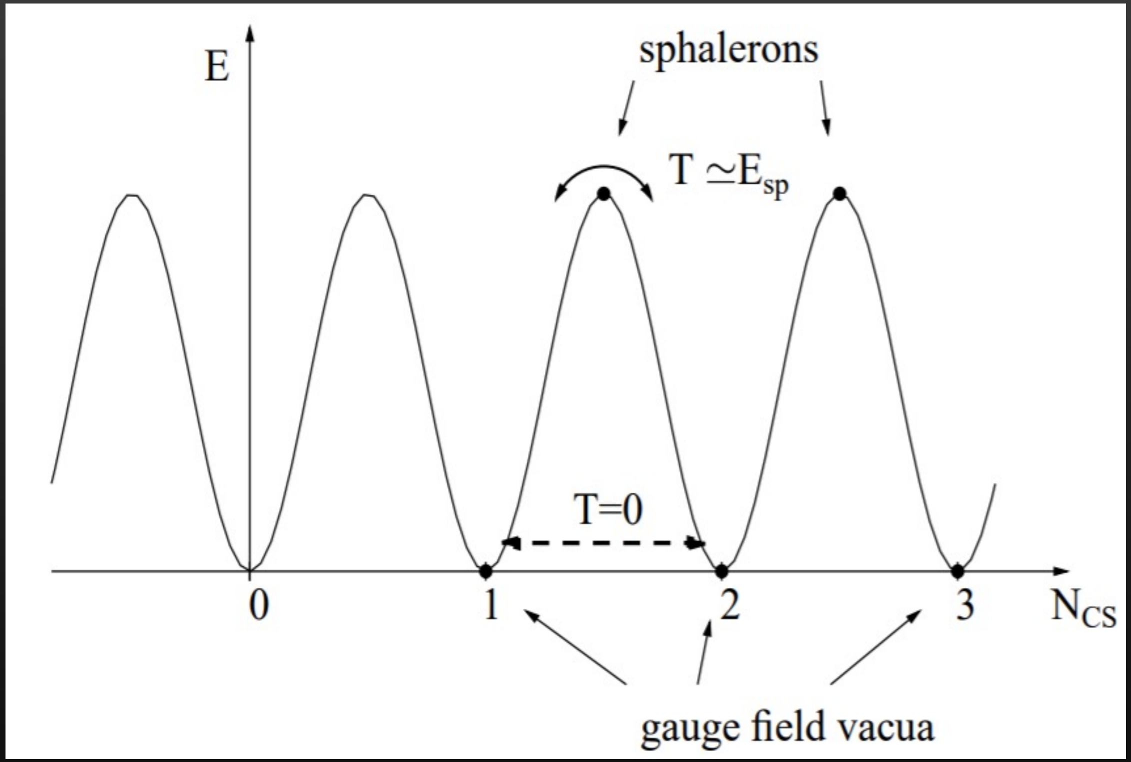
$$T_{RH} \gg T$$

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 light fermions

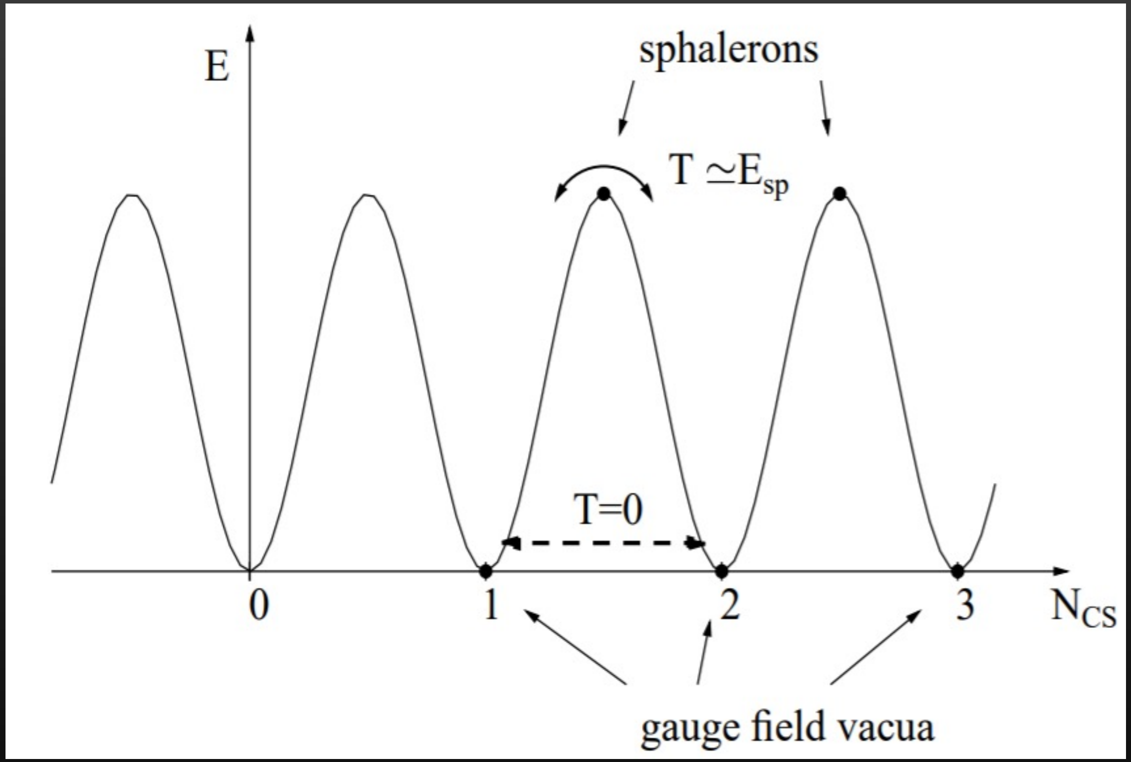


Herranen, arXiv:0906.3136

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

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

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

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

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

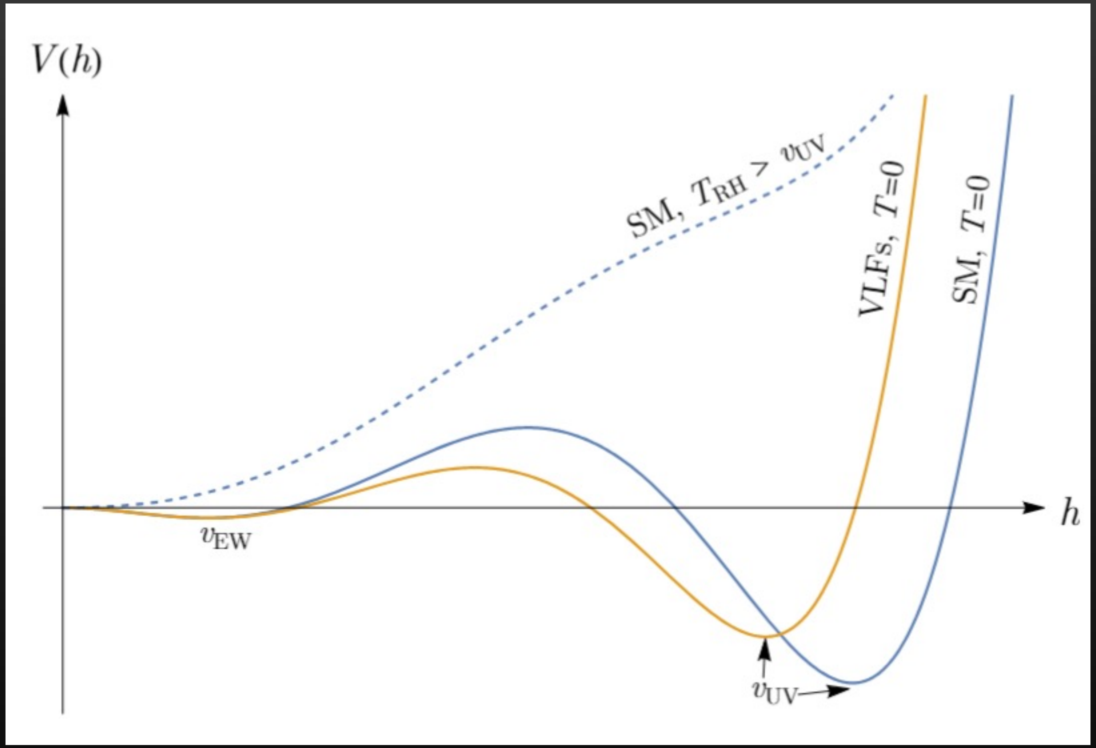
Solution: heavy SM quarks during warm inflation

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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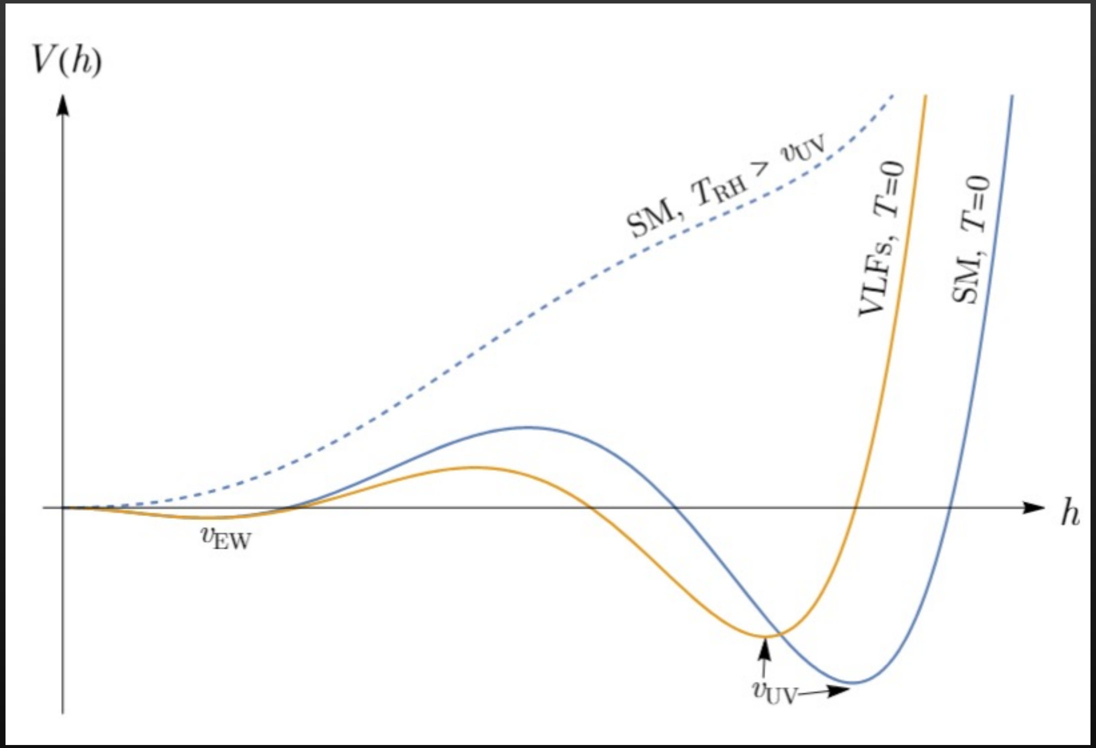
QCD quark masses are proportional to v_{UV}



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

MWI with a heavy QCD axion

Requires $T_{RH} \gg T$ for Higgs to relax to v_{EW}

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

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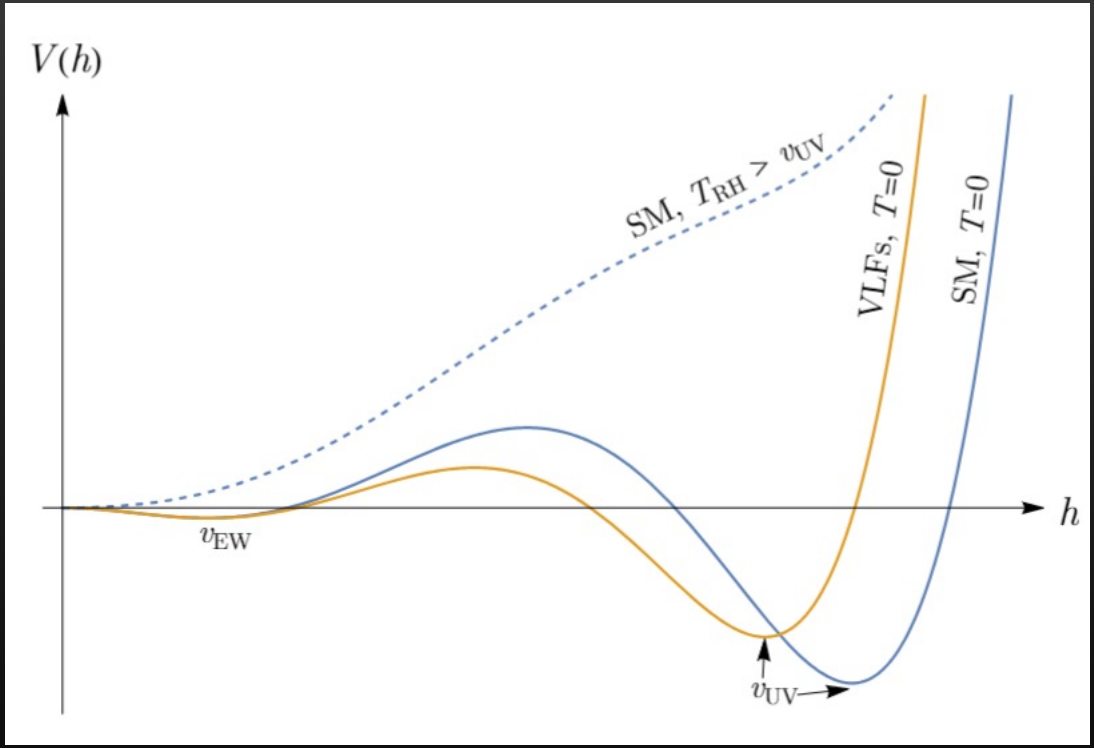

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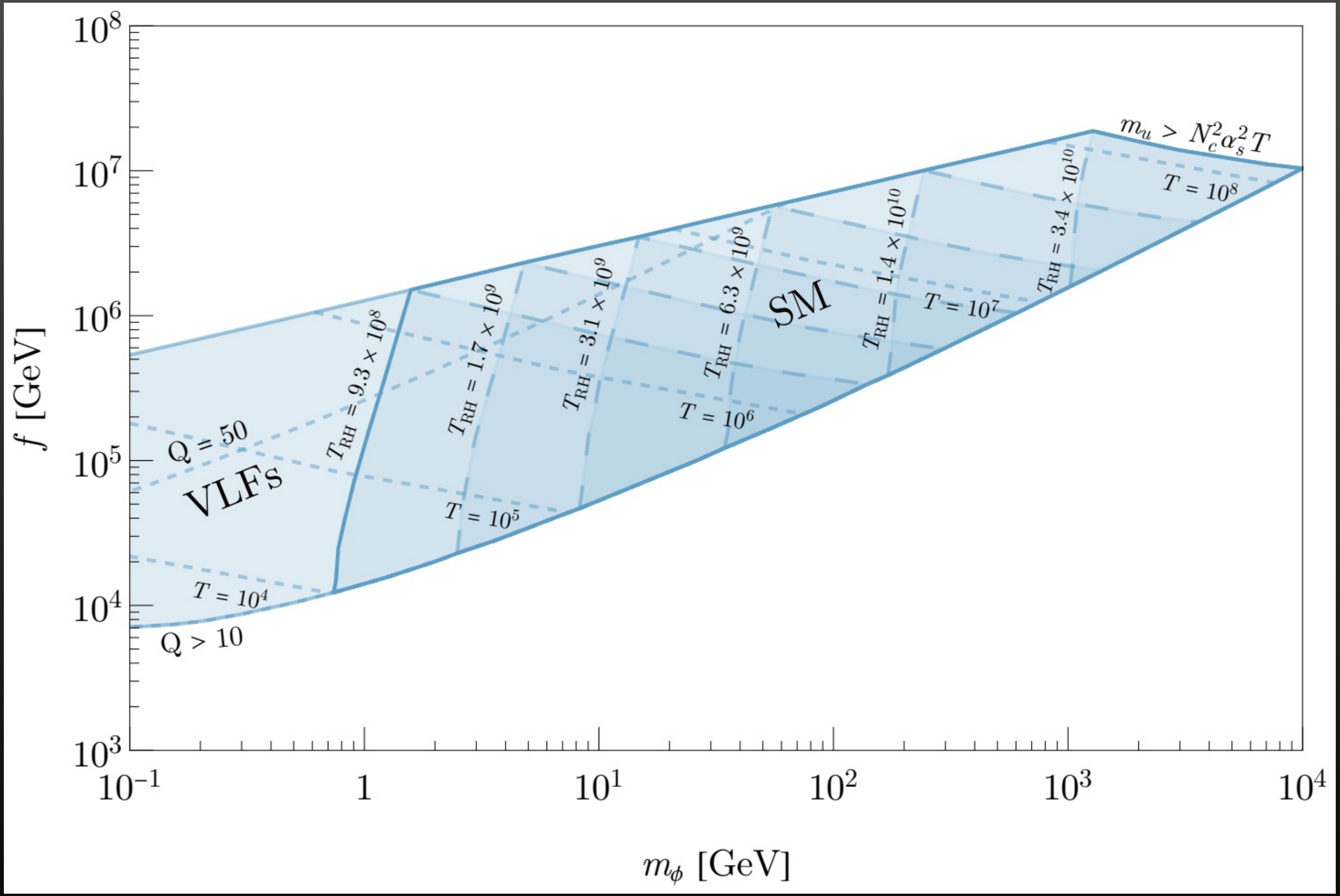
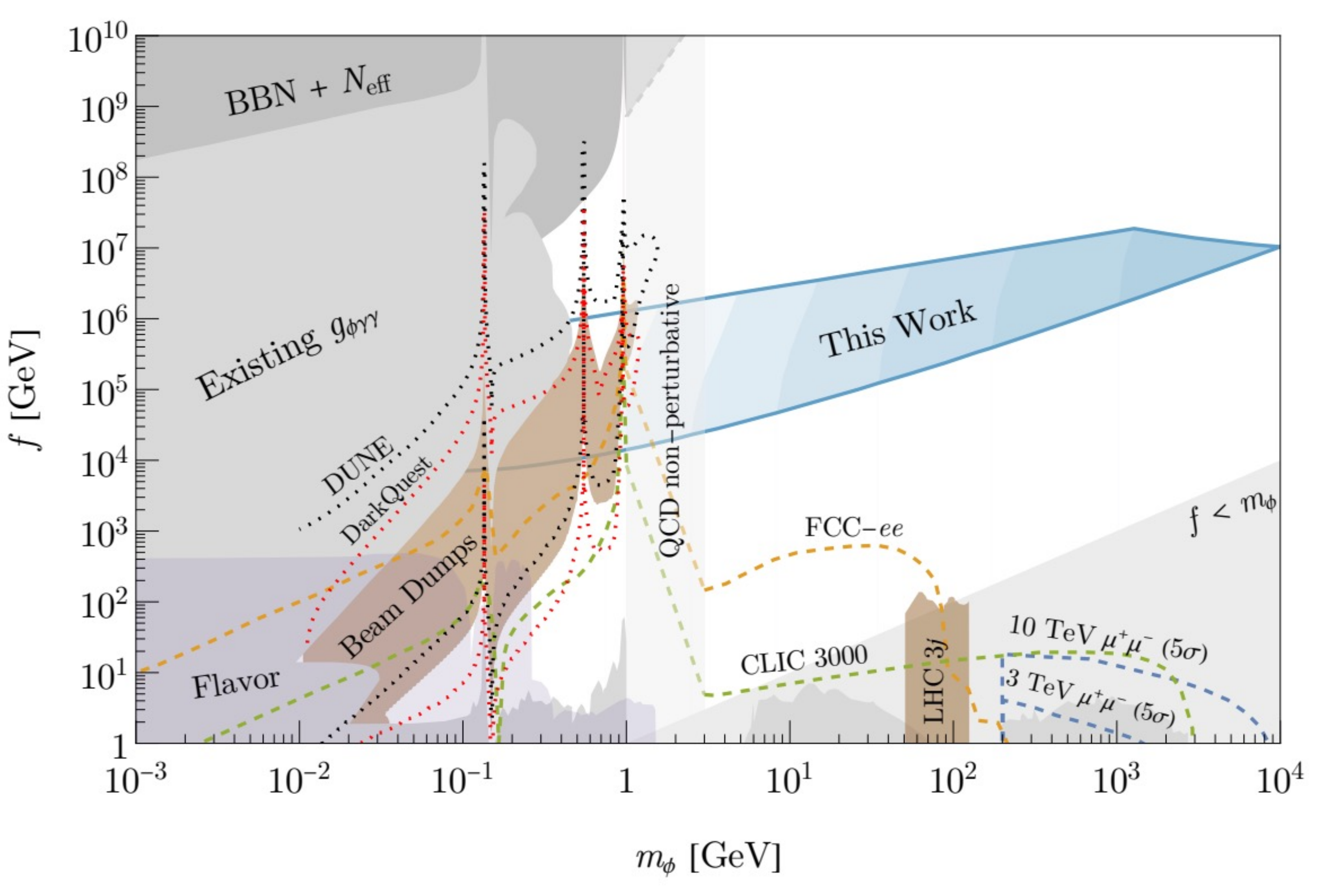


arxiv: 2402.13535

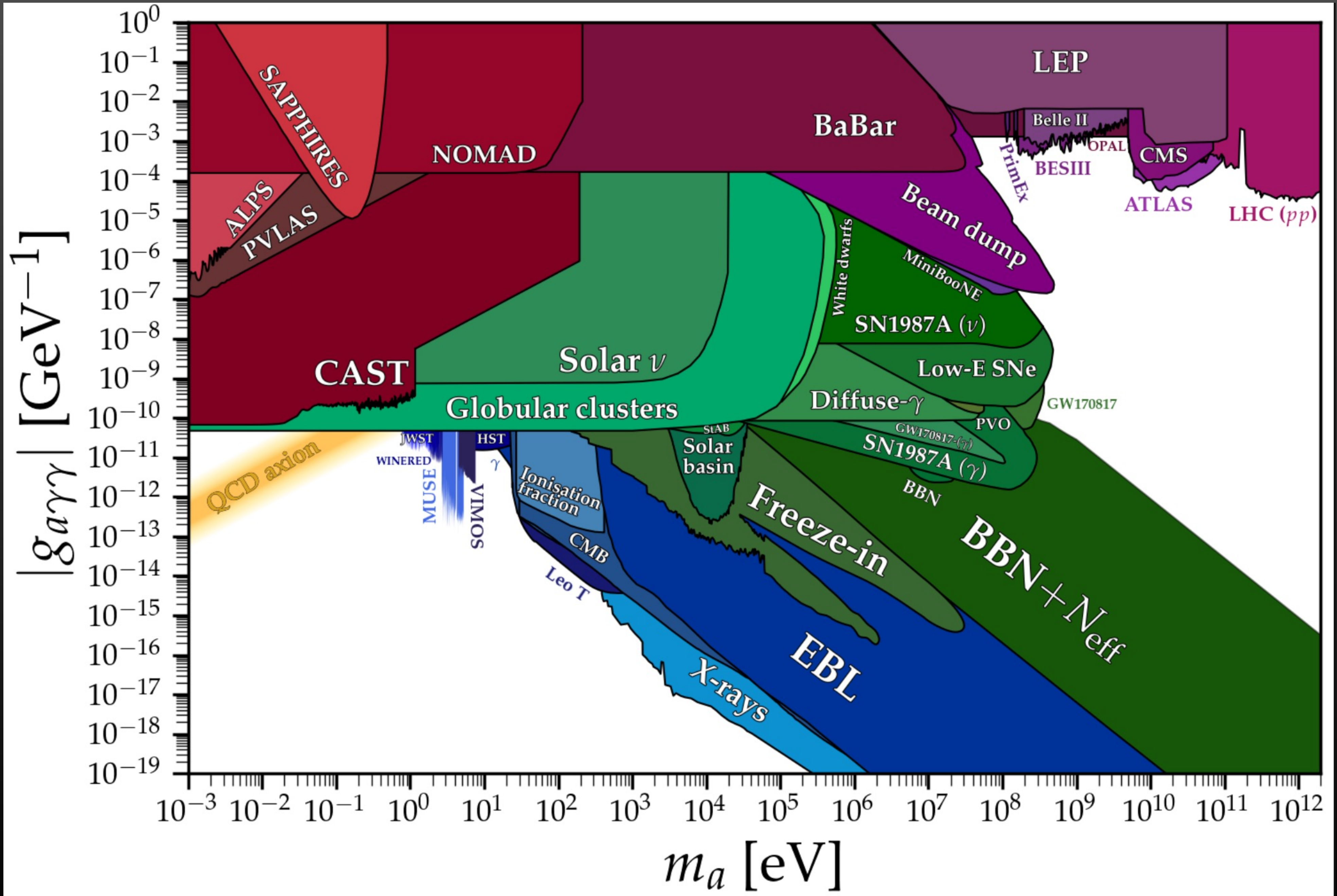


arxiv: 2402.13535

Conclusions & Outlook

- Warm inflation is interesting alternative to cold inflation
- Axion coupling to SU(N) is a *minimal* model for thermal particle production via sphaleron heating
- Proof of principle realization for warm inflation with SM particles

Thank You



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