Probing flavor violation and baryogenesis via primordial gravitational waves

Based on arXiv: 2405.03241

With Prof. Seyda Ipek, Dr. Anish Ghoshal

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DPF-PHENO 2024
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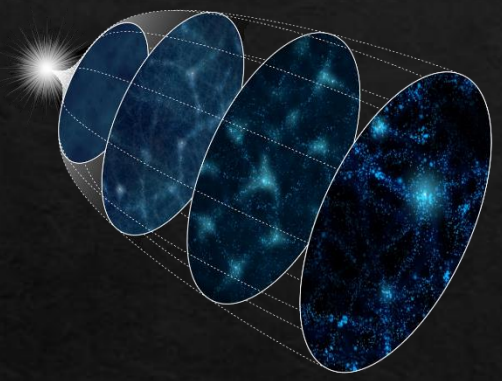
Sources of early gravitational waves

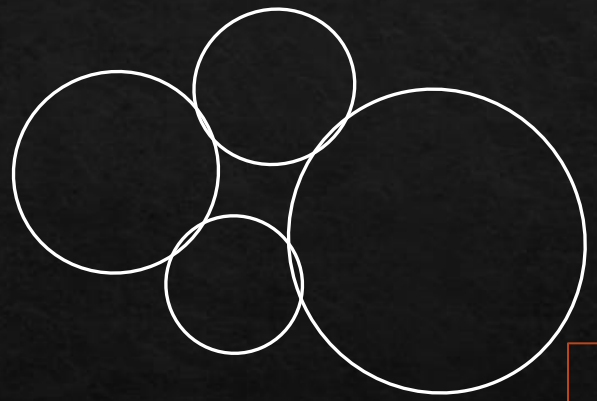
NANOGrav “New Physics” ApJL 2023

Inflation

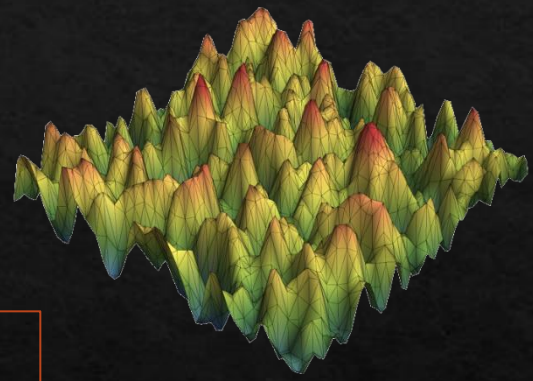


Credit: Institute of Statistical Mathematics (ISM).

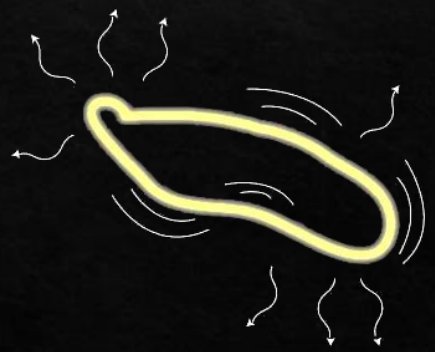
First-order phase transition



Scalar-induced gravitational waves



Cosmic strings



Credit: space.com

Domain walls

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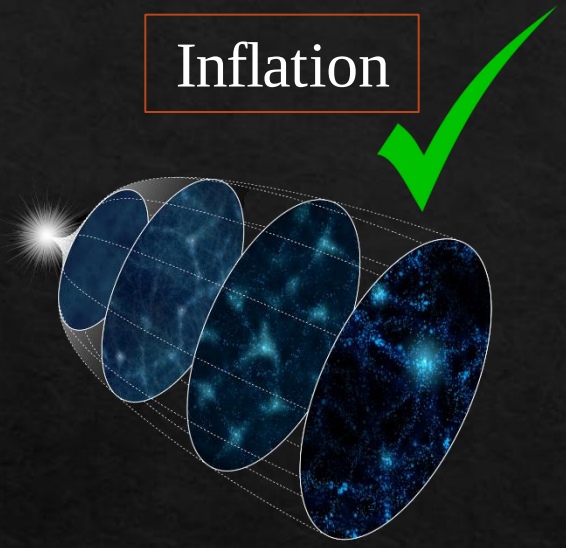

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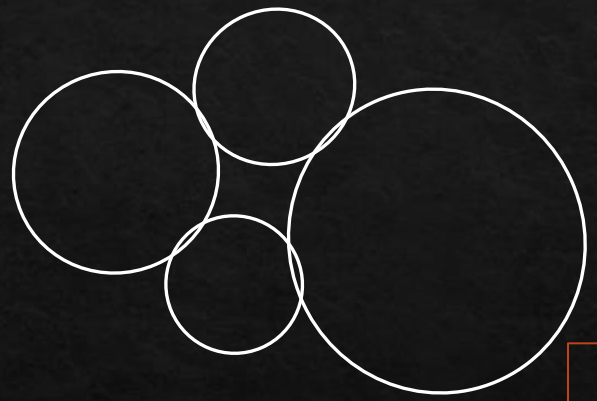

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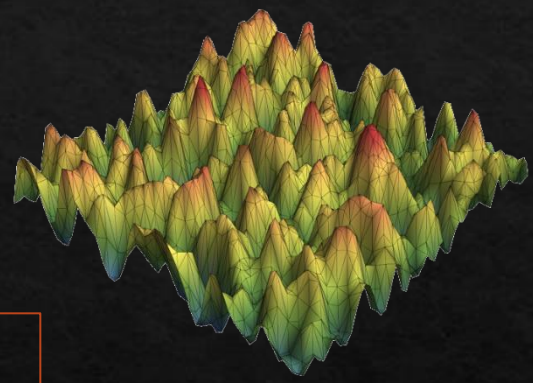

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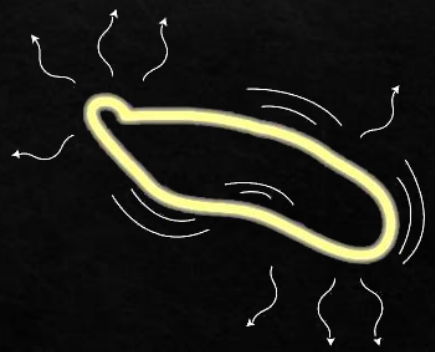

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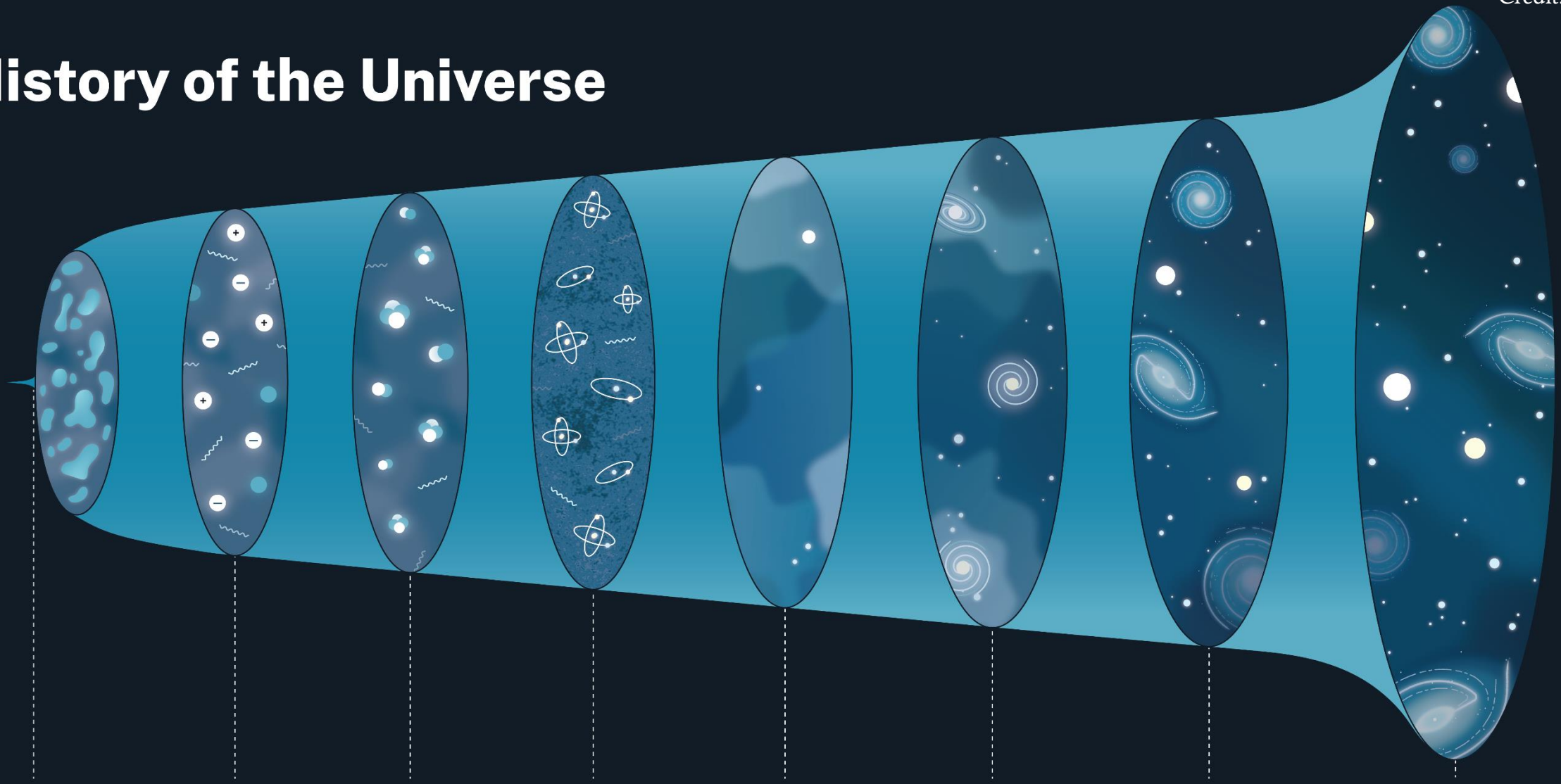
Domain walls

Thermal History of the Universe with Inflationary Gravitational Waves

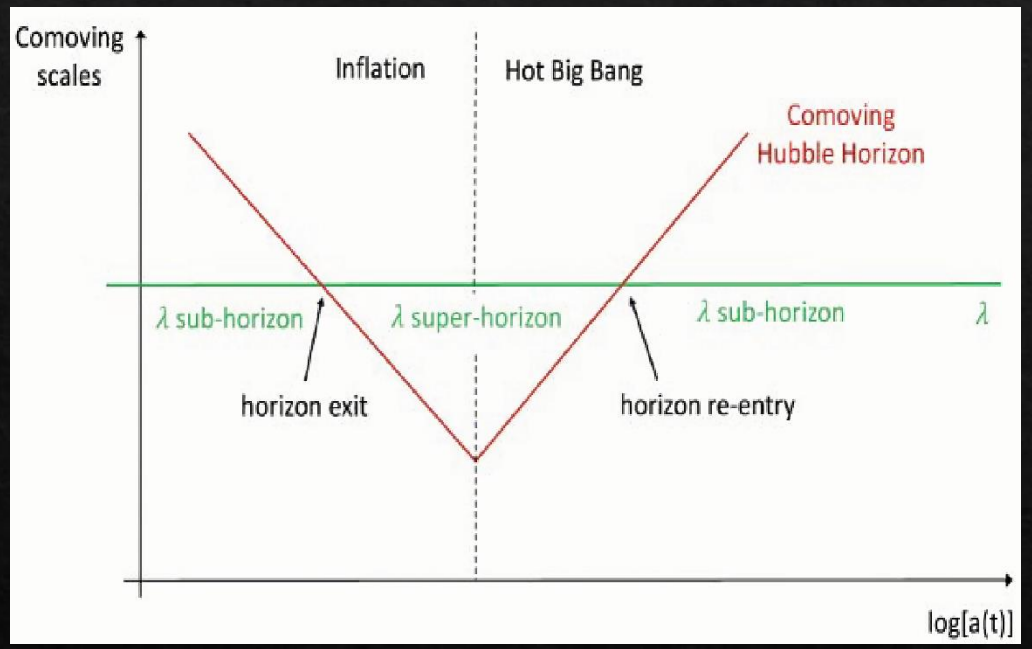
Credit: NASA.

History of the Universe



10^{-32} seconds	1 microsecond	3 minutes	380,000 years	200 million years	400 million years	10 billion years	13.8 billion years
Inflation	**First Particles**	**First Nuclei**	**First Light**	**First Stars**	**Galaxies & Dark Matter**	**Dark Energy**	**Today**
Initial expansion	Neutrons, protons, and electrons form	Helium and hydrogen form	The first atoms form	Gas and dust condense into stars	Galaxies form in dark matter cradles	Expansion accelerates	Humans observe the universe

Horizon re-entry of different scales after inflation



Credit: CERN.

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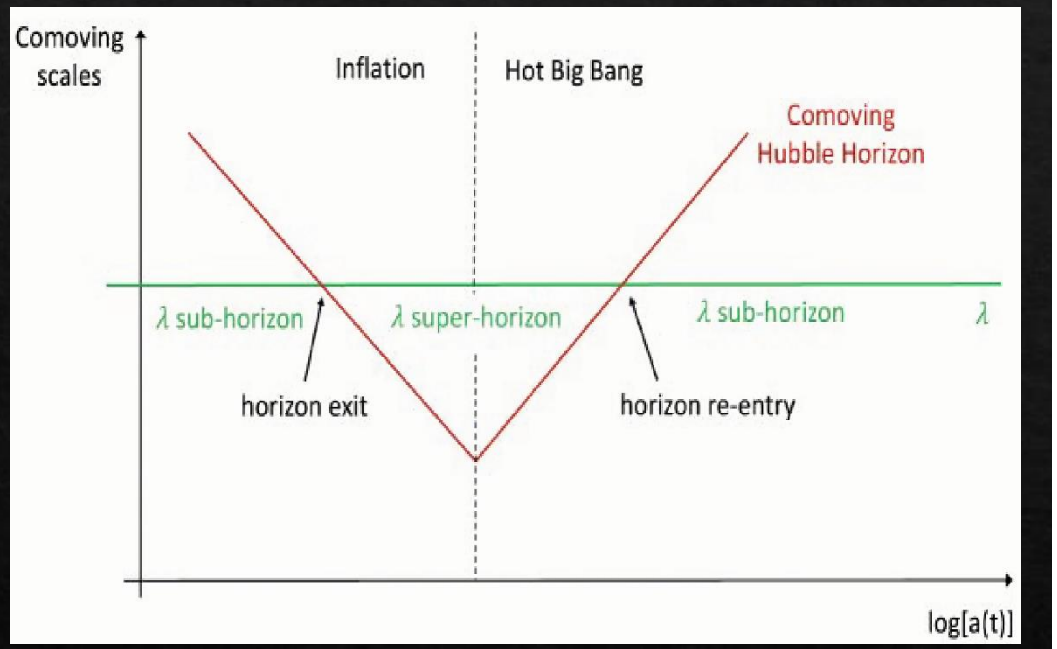

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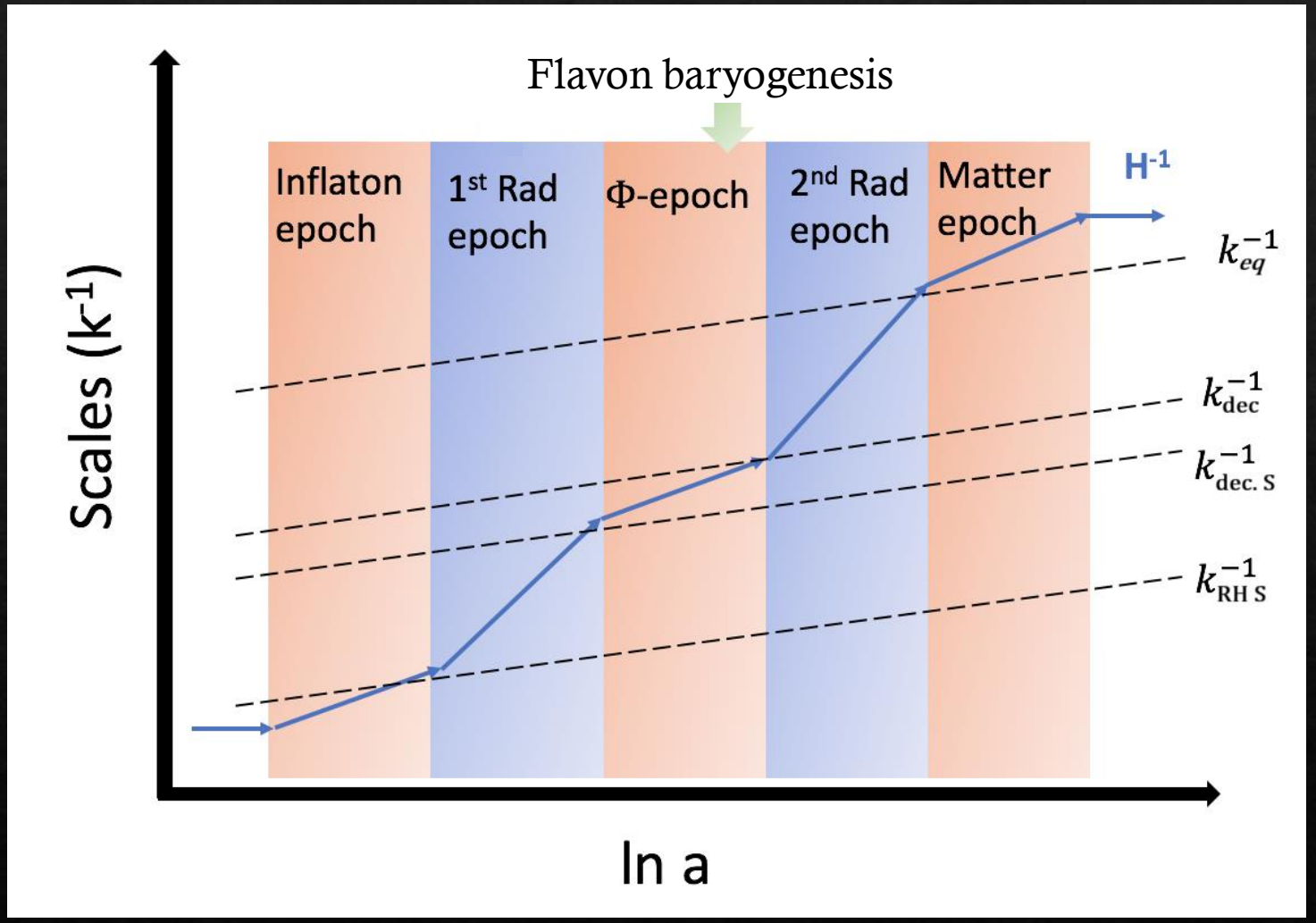

S. Dutta et. al., JHEP (2022).

GW spectra from inflation

$$\Omega_{GW}(k) = \frac{1}{12}\left(\frac{k}{a_0 H_0}\right)^2 T_T^2(k) P_T^{\text{prim.}}(k)$$

$$P_T^{\text{prim.}}(k) = A_T(k_*)\left(\frac{k}{k_*}\right)^{n_T}$$

$$T_{\text{in}} = 5.8 \times 10^6\,\text{GeV}\left(\frac{106.75}{g_*(T_{\text{in}})}\right)^{1/6}\left(\frac{k}{10^4\,\text{Mpc}^{-1}}\right)$$

$$A_T(k_*) = 2.0989 \times 10^{-9}\, r$$

$$T_T^2(k) = \Omega_m^2\left(\frac{g_*(T_{\text{in}})}{g_*^0}\right)\left(\frac{g_{*S}^0}{g_{*S}(T_{\text{in}})}\right)^{4/3}\left(\frac{3j_1(z_k)}{z_k}\right)^2 F(k)$$

Kuroyanagi et al JCAP 2014

Berbig et al JHEP 2023

$$F(k)_{\text{standard}} = T_1^2\left(\frac{k}{k_{\text{eq.}}}\right) T_2^2\left(\frac{k}{k_{\text{RH}}}\right)$$

$$F(k)_{\text{IMD}} = T_1^2\left(\frac{k}{k_{\text{eq.}}}\right) T_2^2\left(\frac{k}{k_{\text{dec.}}}\right) T_3^2\left(\frac{k}{k_{\text{dec. S}}}\right) T_2^2\left(\frac{k}{k_{\text{RH S}}}\right)$$

GW spectra from inflation

Kuroyanagi et al JCAP 2014

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$$k_{\text{eq.}} = 7.1 \times 10^{-2}\,\text{Mpc}^{-1} \cdot \Omega_m h^2$$

$$k_{\text{dec.}} = 1.7 \times 10^{14}\,\text{Mpc}^{-1} \left(\frac{g_{*S}(T_{\text{dec.}})}{g^0_{*S}}\right)^{1/6} \left(\frac{T_{\text{dec.}}}{10^7\,\text{GeV}}\right)$$

$$k_{\text{RH}} = 1.7 \times 10^{14}\,\text{Mpc}^{-1} \left(\frac{g_{*S}(T_{\text{RH}})}{g^0_{*S}}\right)^{1/6} \left(\frac{T_{\text{RH}}}{10^7\,\text{GeV}}\right)$$

$$k_{\text{dec. S}} = k_{\text{dec.}} \Delta^{2/3}$$

$$k_{\text{RH S}} = k_{\text{RH}} \Delta^{-1/3}$$

$$T_1^2(x) = 1 + 1.57x + 3.42x^2$$

$$T_2^2(x) = \left(1 - 0.22x^{3/2} + 0.65x^2\right)^{-1}$$

$$T_3^2(x) = 1 + 0.59x + 0.65x^2$$

$$\Delta = \frac{s\,a^3|_{\text{after}}}{s\,a^3|_{\text{befroe}}}$$

Dilution factor from entropy injection

Flavon baryogenesis

Flavon baryogenesis

$$\mathcal{L} \supset \left(\frac{v_S + S}{\Lambda_{\rm FV}}\right)^{n_i} \bar{e}^i_R \phi^* \ell^i_L + \text{h.c.}$$

Chen et al PRD 2019

$$S \to \bar{\ell}_L + e_R + \phi\,, \quad S^* \to \bar{e}_R + \ell_L + \phi^*$$

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RD: Right-handed electrons come into equilibrium at $T \sim 10^5$ GeV

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Sphalerons act only on the left-handed asymmetry at $T \sim 160$ GeV

Flavon baryogenesis

Boltzmann equations:

$$\frac{d\rho_S}{dt} + 3H\rho_S = -\Gamma_S \rho_S \,,$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_S \rho_S \,,$$

$$\frac{d\Delta_{e_R}}{dt} = -3H\Delta_{e_R} - \Gamma_{LR}\Delta_{e_R} + B_e \Gamma_S \Delta_S$$

$$\Gamma_S \simeq 2.3 \times 10^{-17}\,\mathrm{GeV} \left(\frac{m_S}{\mathrm{TeV}}\right)^3 \left(\frac{10^{10}\,\mathrm{GeV}}{\Lambda_{\mathrm{FV}}}\right)^2 \,,$$

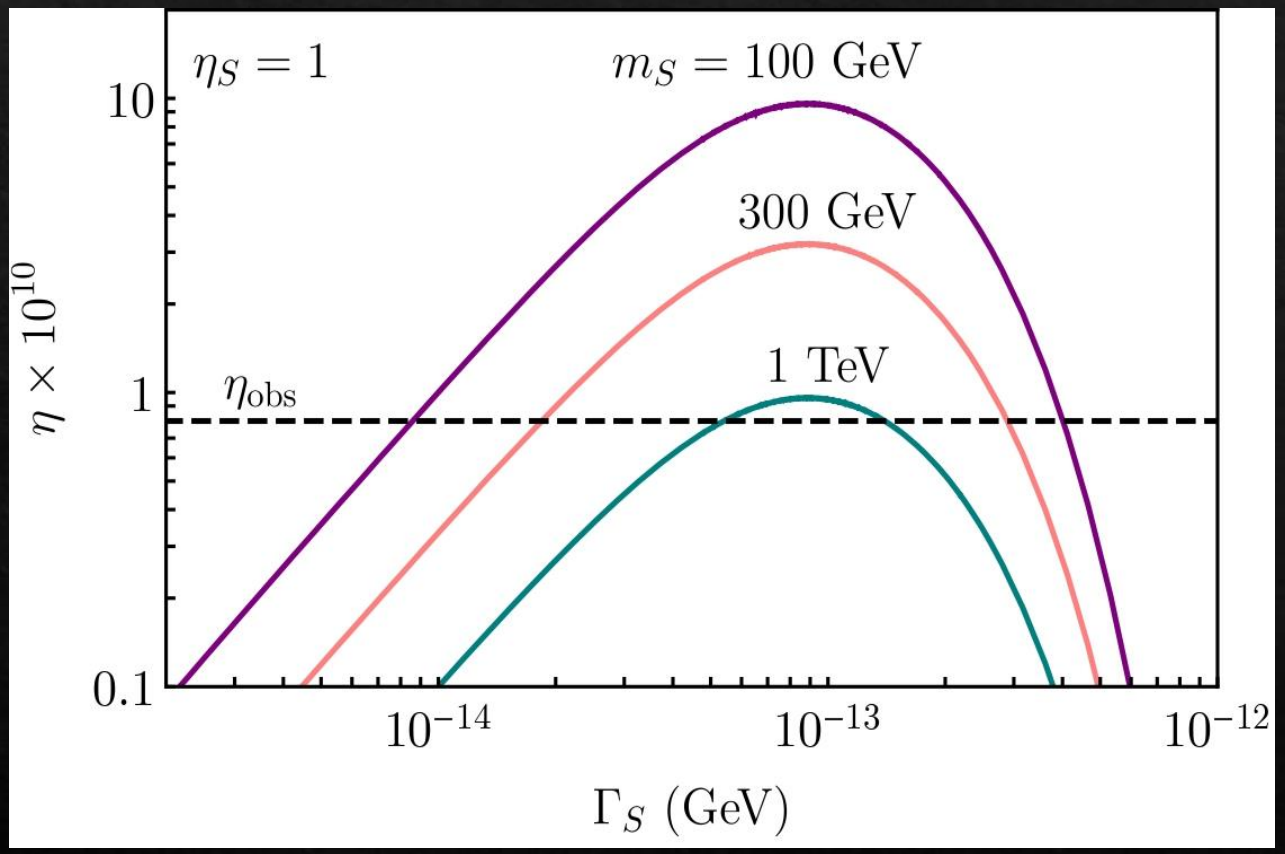
$$H^2 = \frac{8\pi}{3M_{\mathrm{Pl}}^2}(\rho_S + \rho_R) \,,$$

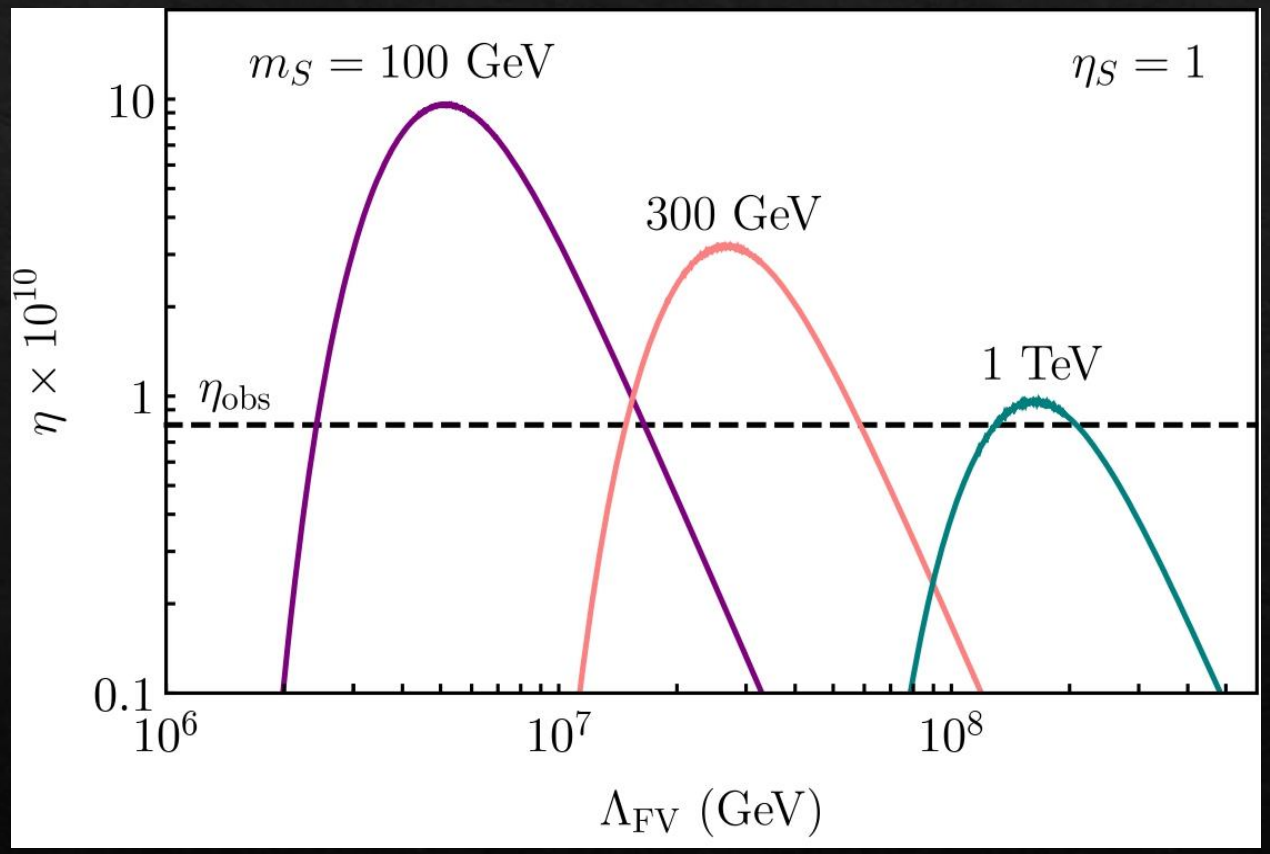
$$\Delta_S = \eta_S \frac{\rho_S}{m_S}$$

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{198}{481} \frac{\Delta_{e_R}(T = T_{\mathrm{EW}})}{s}$$

$$\eta_{\mathrm{obs}} = \frac{n_B - n_{\bar{B}}}{s} \simeq 8 \times 10^{-11}$$

Flavon baryogenesis





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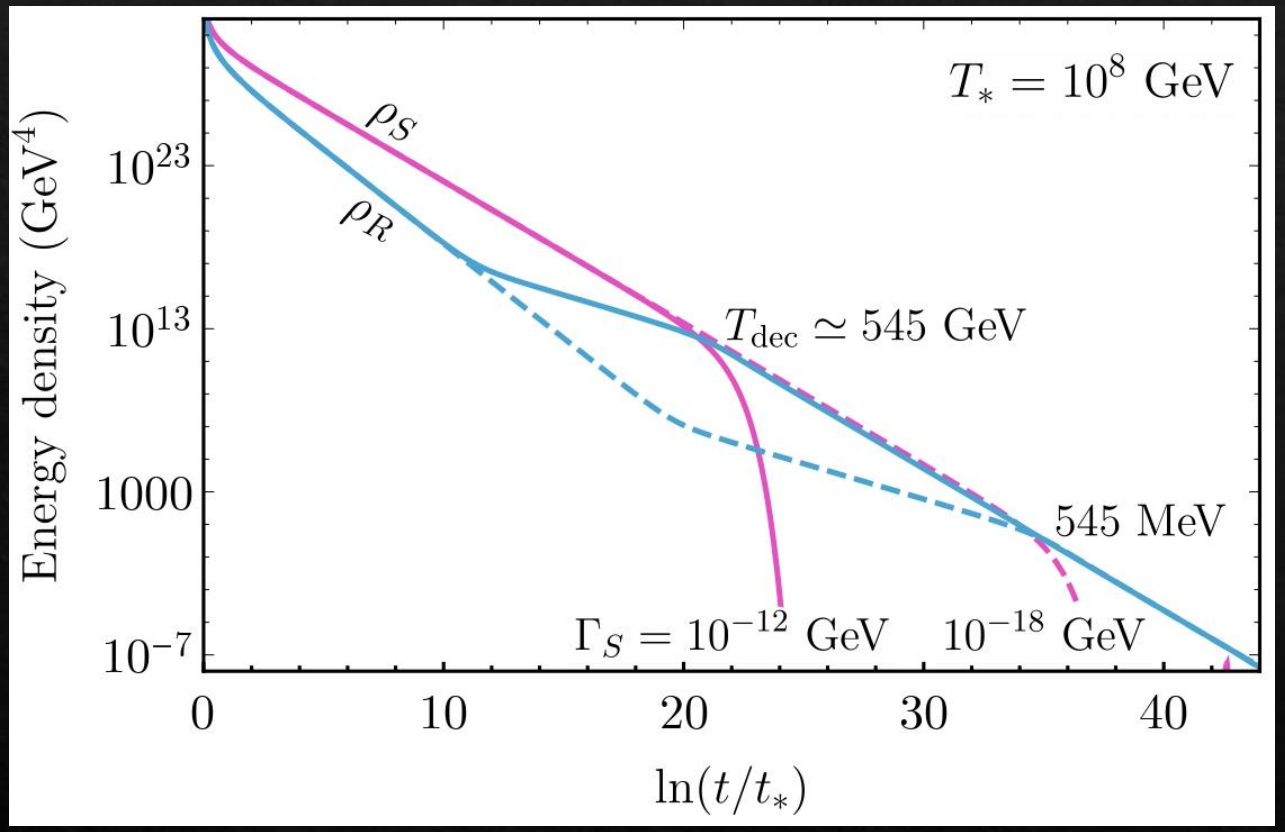
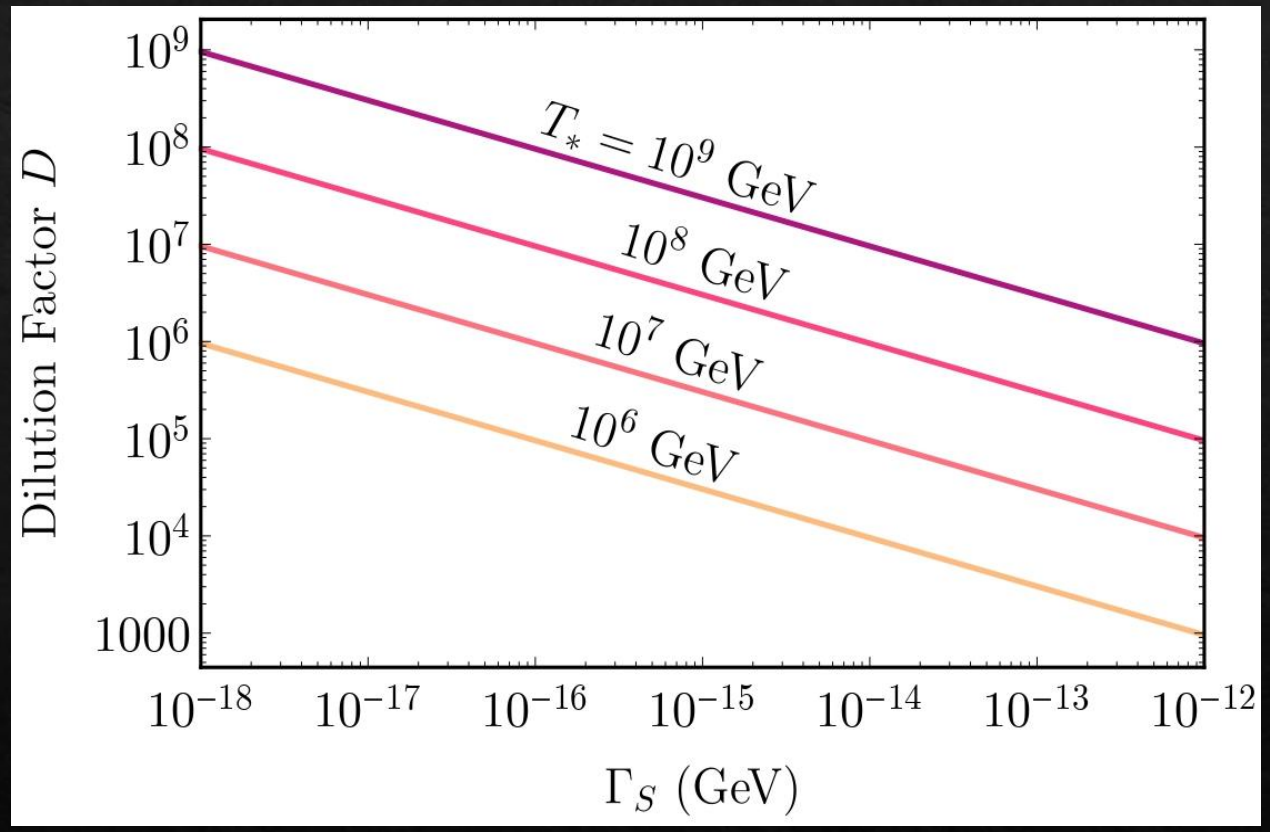




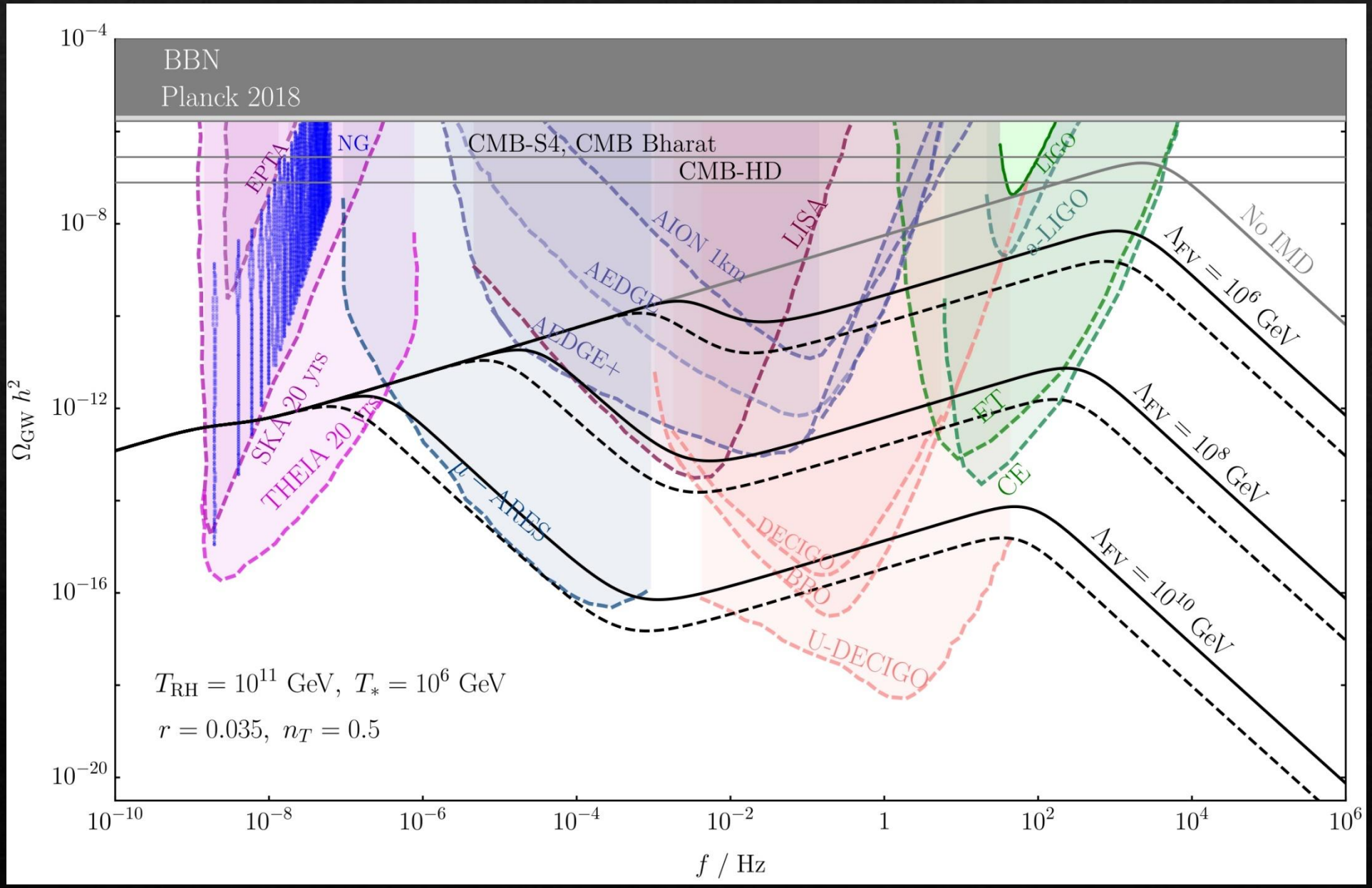
Flavon baryogenesis

$$T_{\rm dec} \simeq 1.8\ {\rm GeV} \sqrt{\frac{\Gamma_S}{10^{-17}\ {\rm GeV}}} \simeq 2.7\ {\rm GeV} \left(\frac{m_S}{\rm TeV}\right)^{3/2} \left(\frac{10^{10}{\rm GeV}}{\Lambda_{\rm FV}}\right)$$

$$D = \frac{s(T_{\rm after})a^3(T_{\rm after})}{s(T_{\rm before})a^3(T_{\rm before})} = \left(1 + 2.95 \left(\frac{2\pi^2 \left\langle g_*(T)\right\rangle}{45}\right)^{1/3} \frac{(\frac{\rho_S}{s}|_{\rm initial})^{4/3}}{(M_{\rm Pl}\,\Gamma_S)^{2/3}}\right)^{3/4}$$

$$\simeq 2 \times 10^6 \left(\frac{T_*}{10^6\ {\rm GeV}}\right) \left(\frac{\Lambda_{\rm FV}}{10^{10}\ {\rm GeV}}\right) \left(\frac{\rm TeV}{m_S}\right)^{3/2},$$

Probing Flavon baryogenesis



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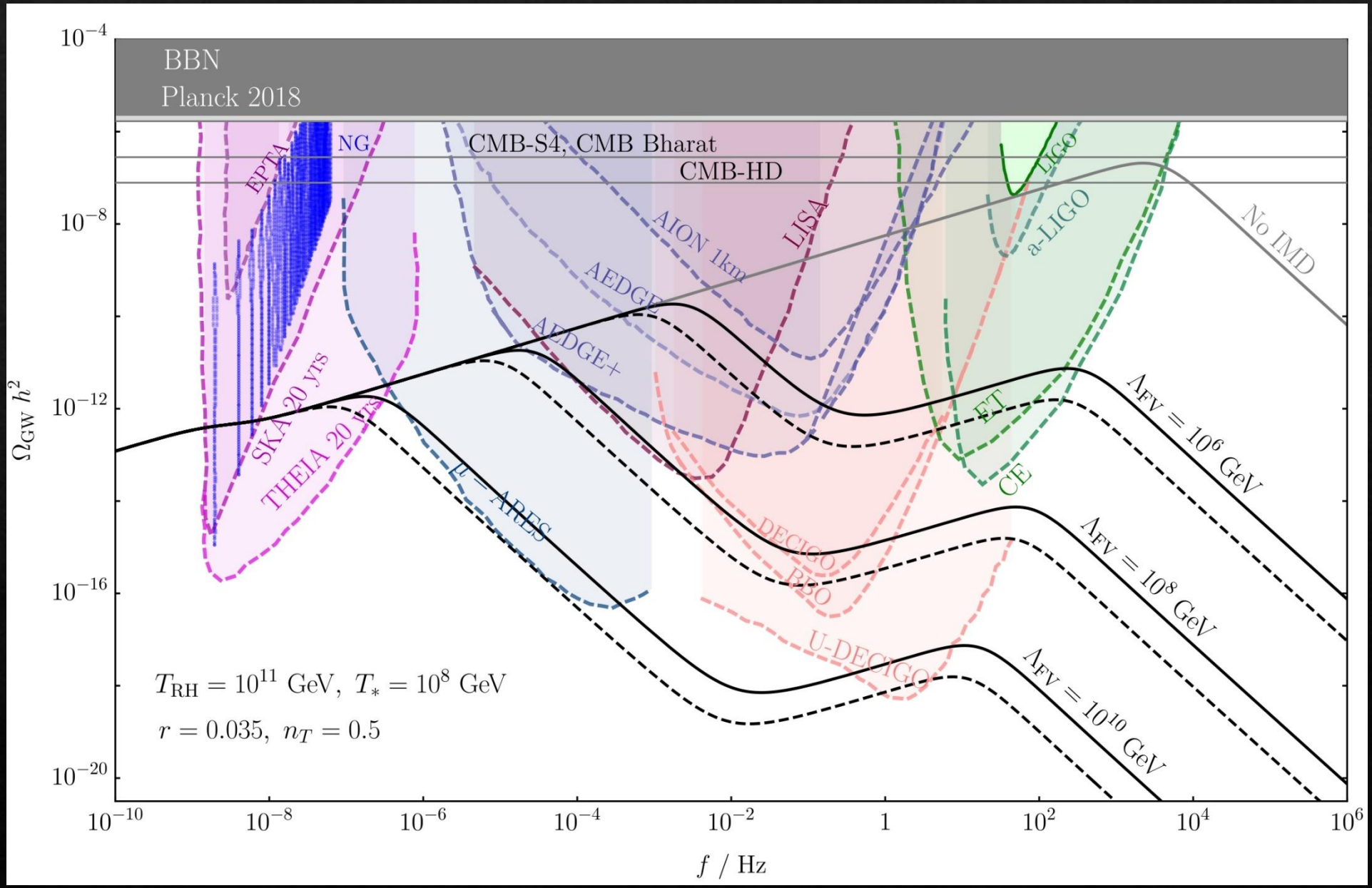
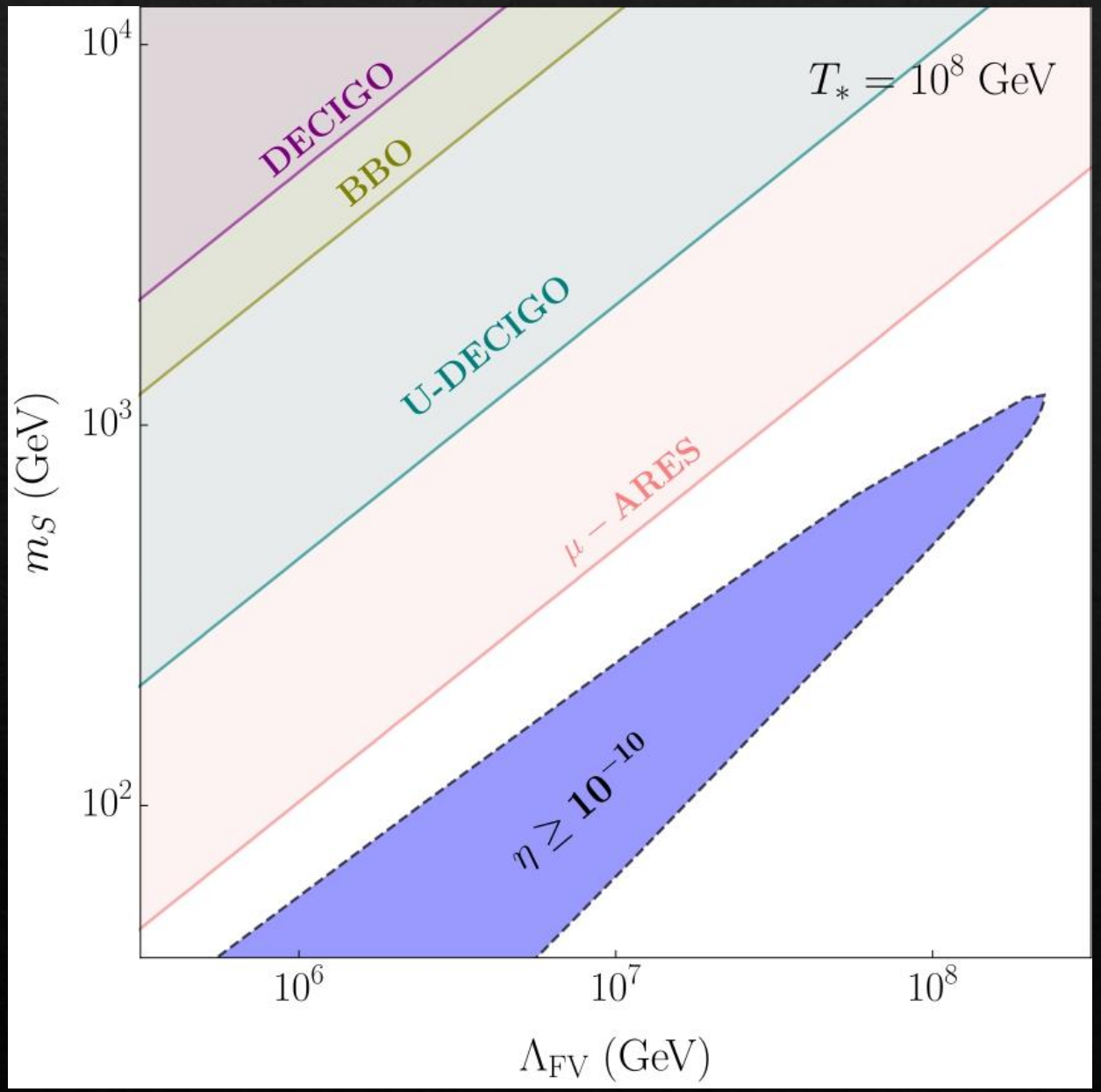


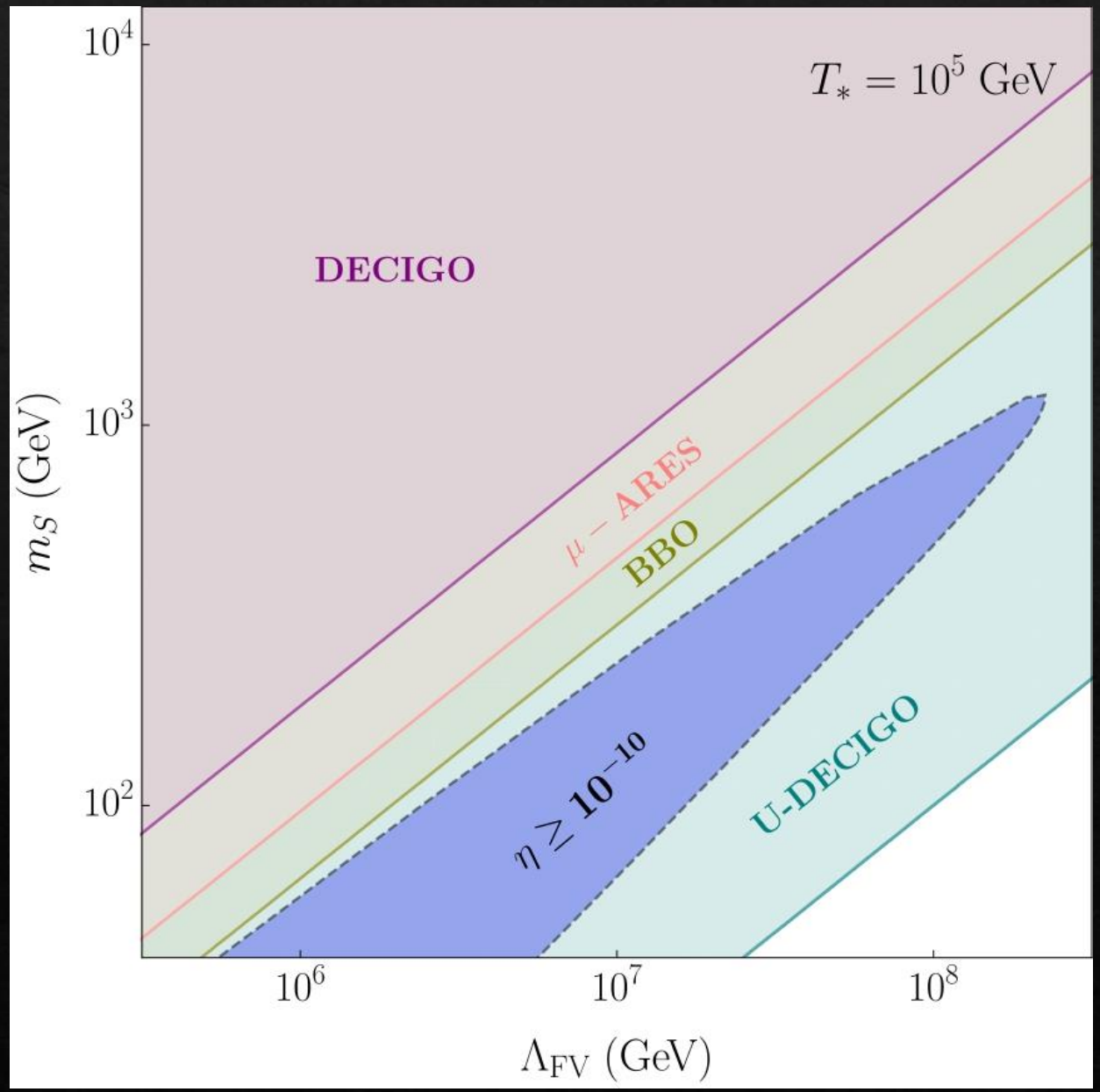
Probing Flavon baryogenesis

$$\Omega_{\rm exp}(f)h^2 = \frac{2\pi^2 f^2}{3H_0^2} h_{\rm GW}(f)^2 h^2$$

$$\mathrm{SNR} \equiv \sqrt{\tau \int_{f_{\rm min}}^{f_{\rm max}} \mathrm{d}f \left(\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm exp}(f)h^2} \right)^2}$$

Probing Flavon baryogenesis





Thank you !!