Probing flavor violation and baryogenesis via primordial gravitational waves

Based on JHEP 07 (2024) 228

With Prof. Seyda Ipek, Dr. Anish Ghoshal

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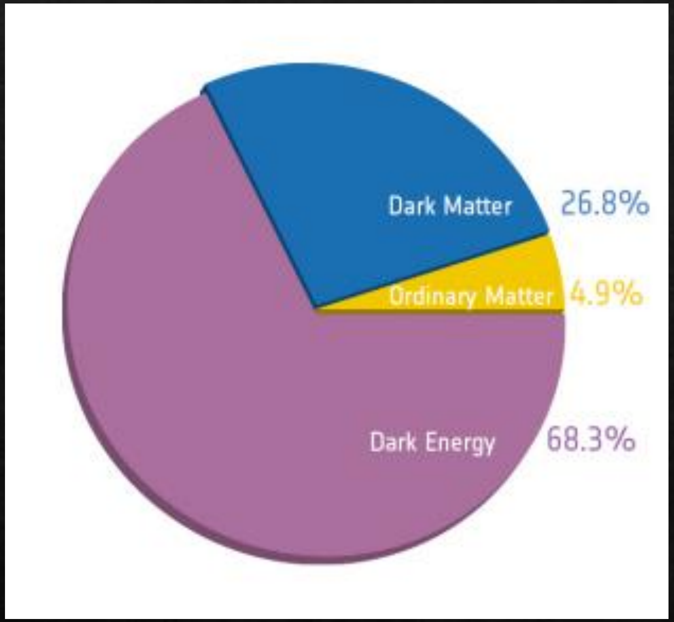
Limitations of the Standard Model

Dark matter

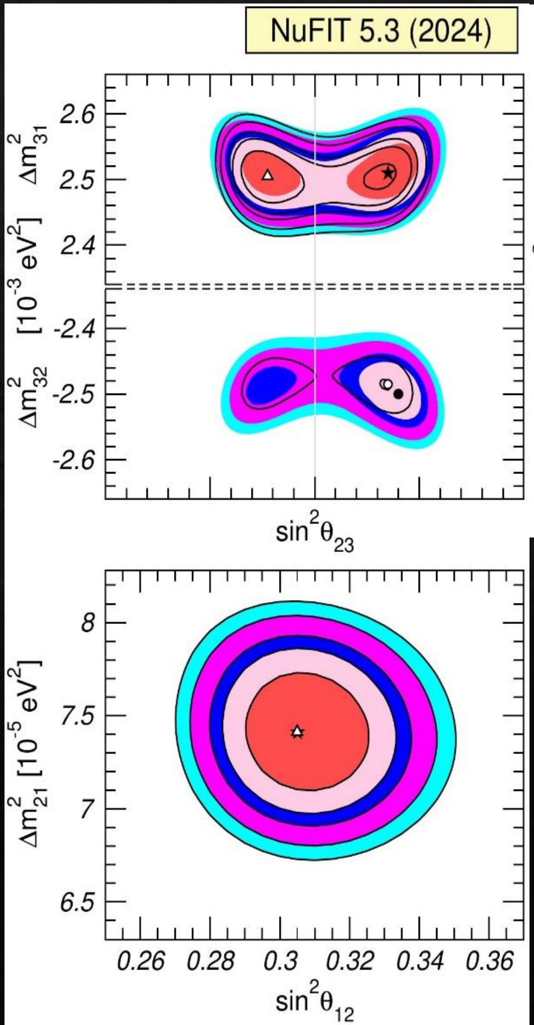


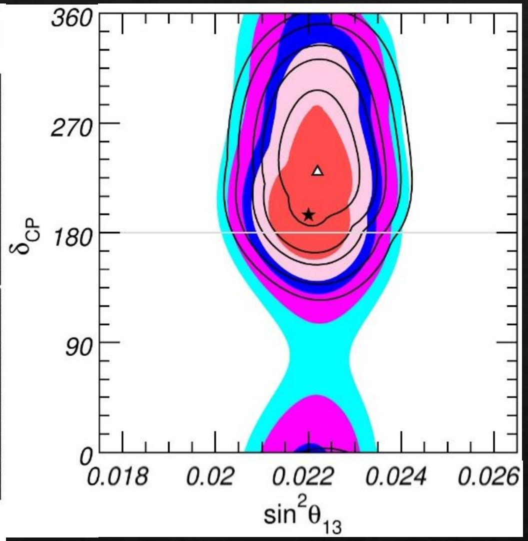
Credit: ESA Science & Technology - Planck's new cosmic recipe

Matter-antimatter asymmetry

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 10^{-10}$$

Neutrino mass



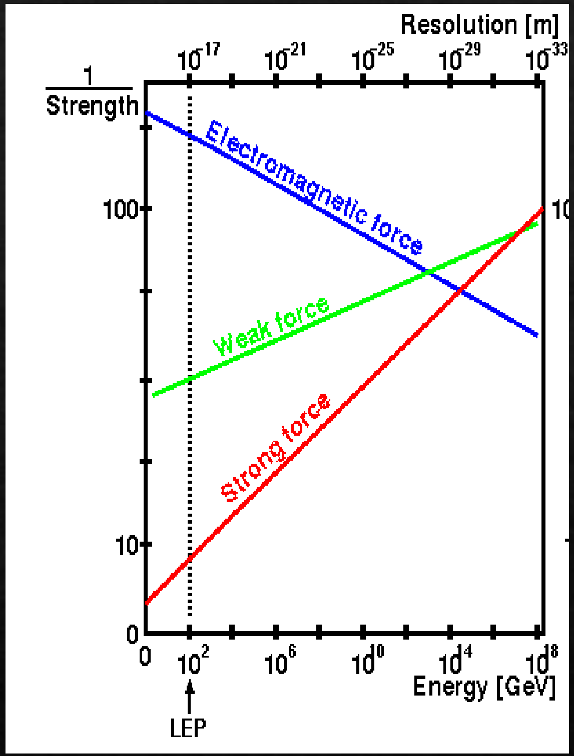


Fermion mass hierarchy

$$m_e \ll m_\mu \ll m_\tau$$

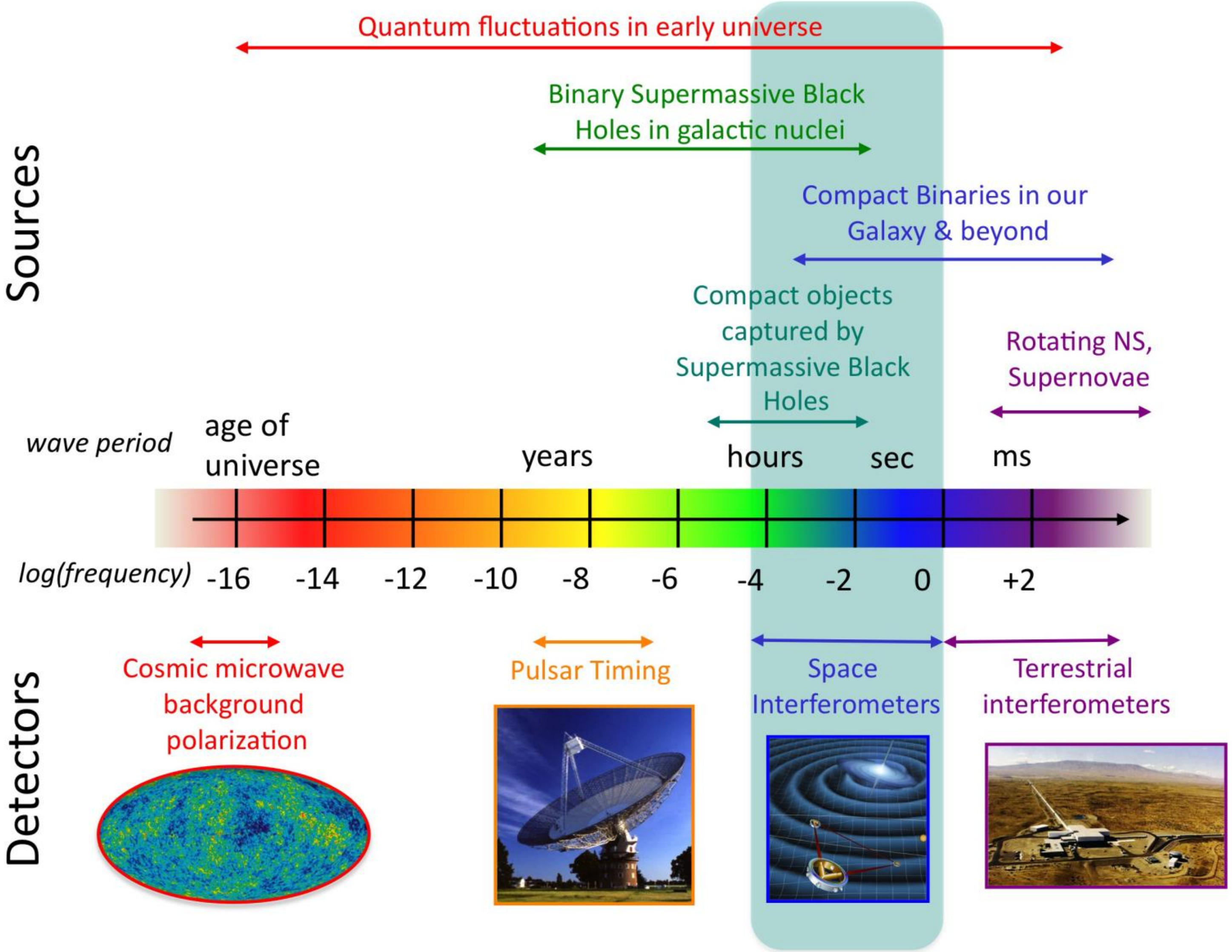
$$m_{u,d} \ll m_{c,s} \ll m_{t,b}$$

Gauge unification



Credit: physics.stackexchange.com/questions/254369/supersymmetry-and-grand-unification

The Gravitational Wave Spectrum

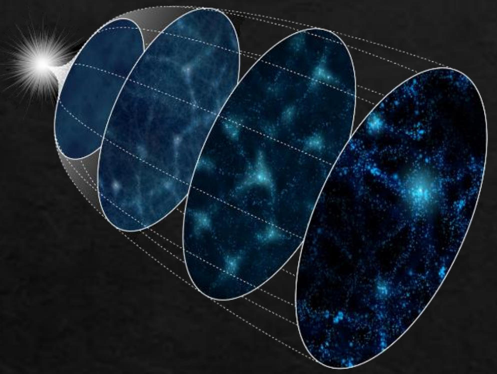


Credit: NASA

Sources of early gravitational waves

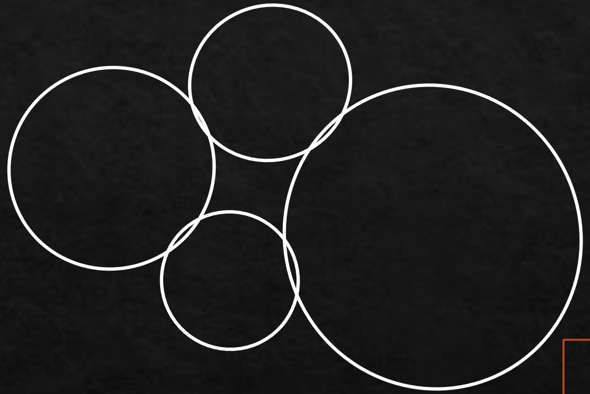
NANOGrav “New Physics” ApJL 2023

Inflation

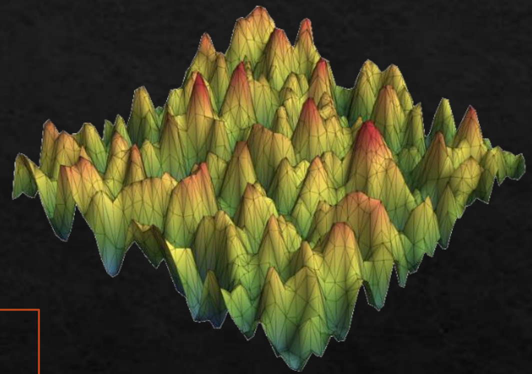


Credit: Institute of Statistical Mathematics (ISN).

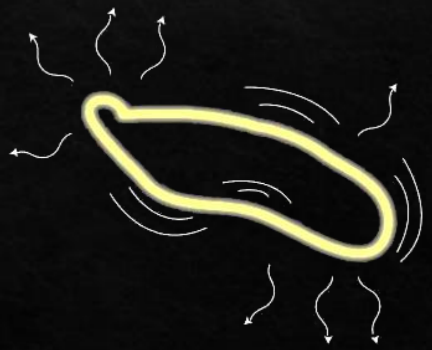
First-order phase transition



Scalar-induced gravitational waves



Cosmic strings



Credit: space.com

Domain walls

Sources of early gravitational waves

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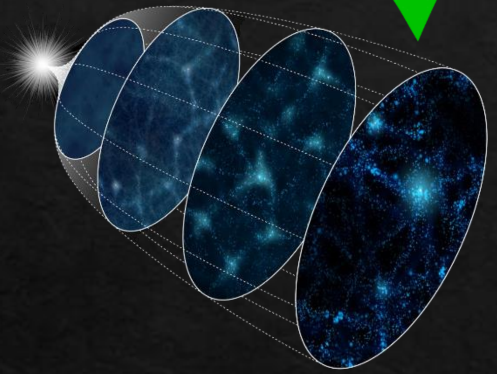
Inflation



Credit: Institute of Statistical Mathematics (ISN).

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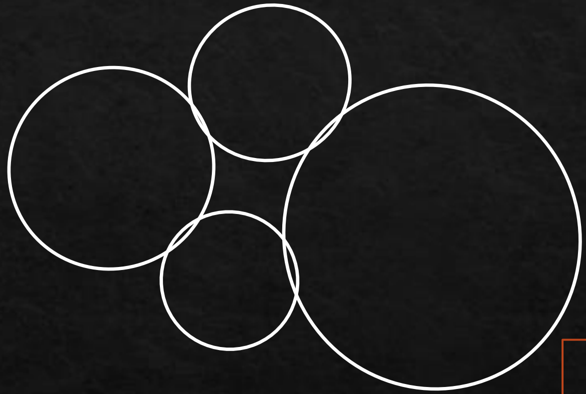

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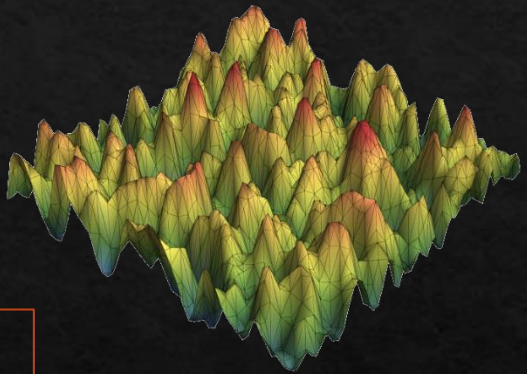

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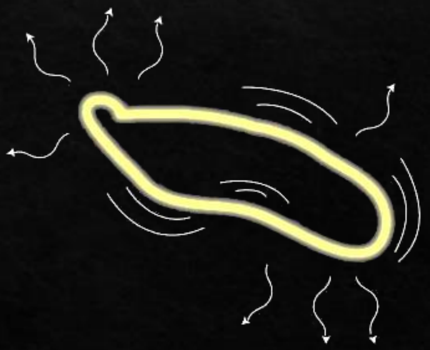
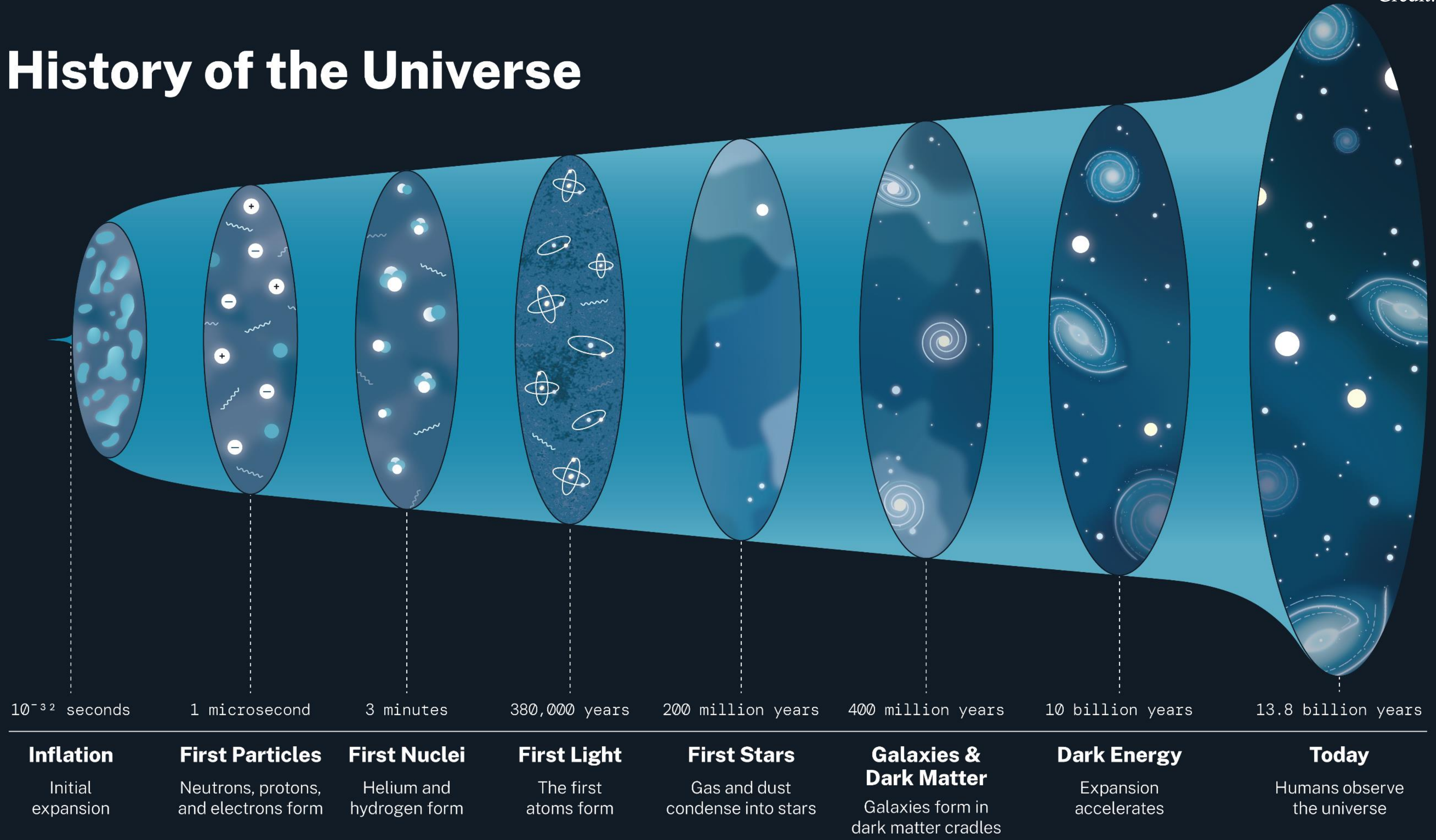


Credit: space.com

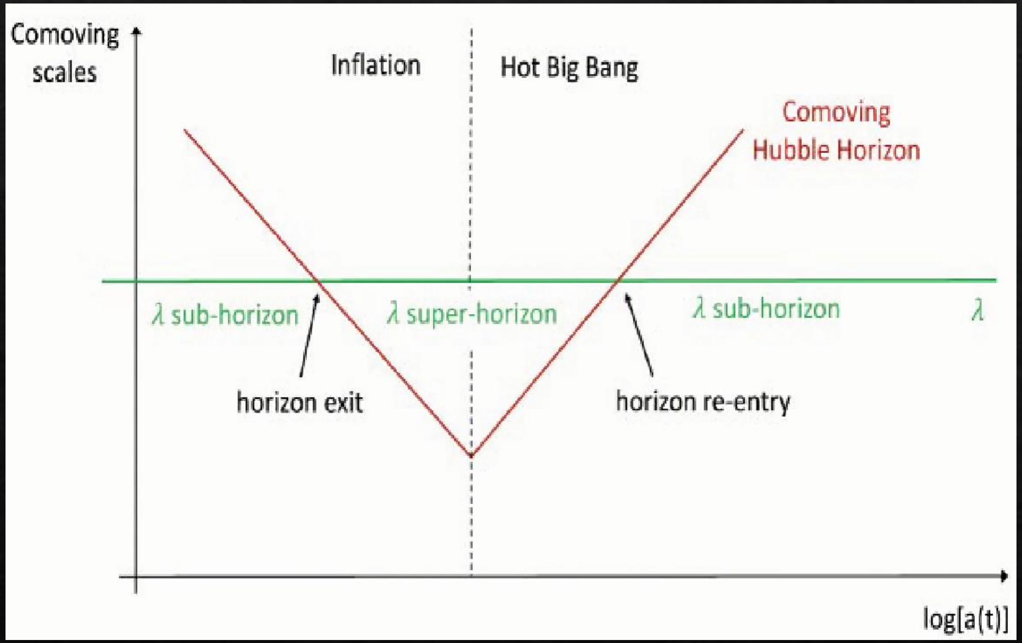
Domain walls

Thermal History of the Universe with Inflationary Gravitational Waves


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
Initial expansion
First Particles
Neutrons, protons, and electrons form
First Nuclei
Helium and hydrogen form
First Light
The first atoms form
First Stars
Gas and dust condense into stars
Galaxies & Dark Matter
Galaxies form in dark matter cradles
Dark Energy
Expansion accelerates
Today
Humans observe the universe

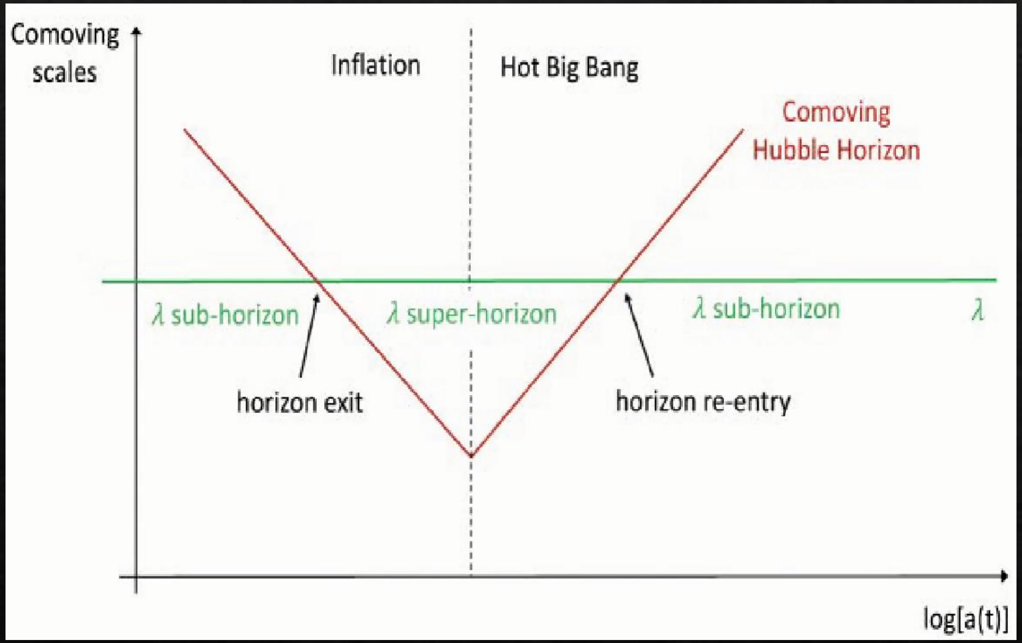
Credit: NASA.

Horizon re-entry of different scales after inflation



Credit: CERN.

Horizon re-entry of different scales after inflation



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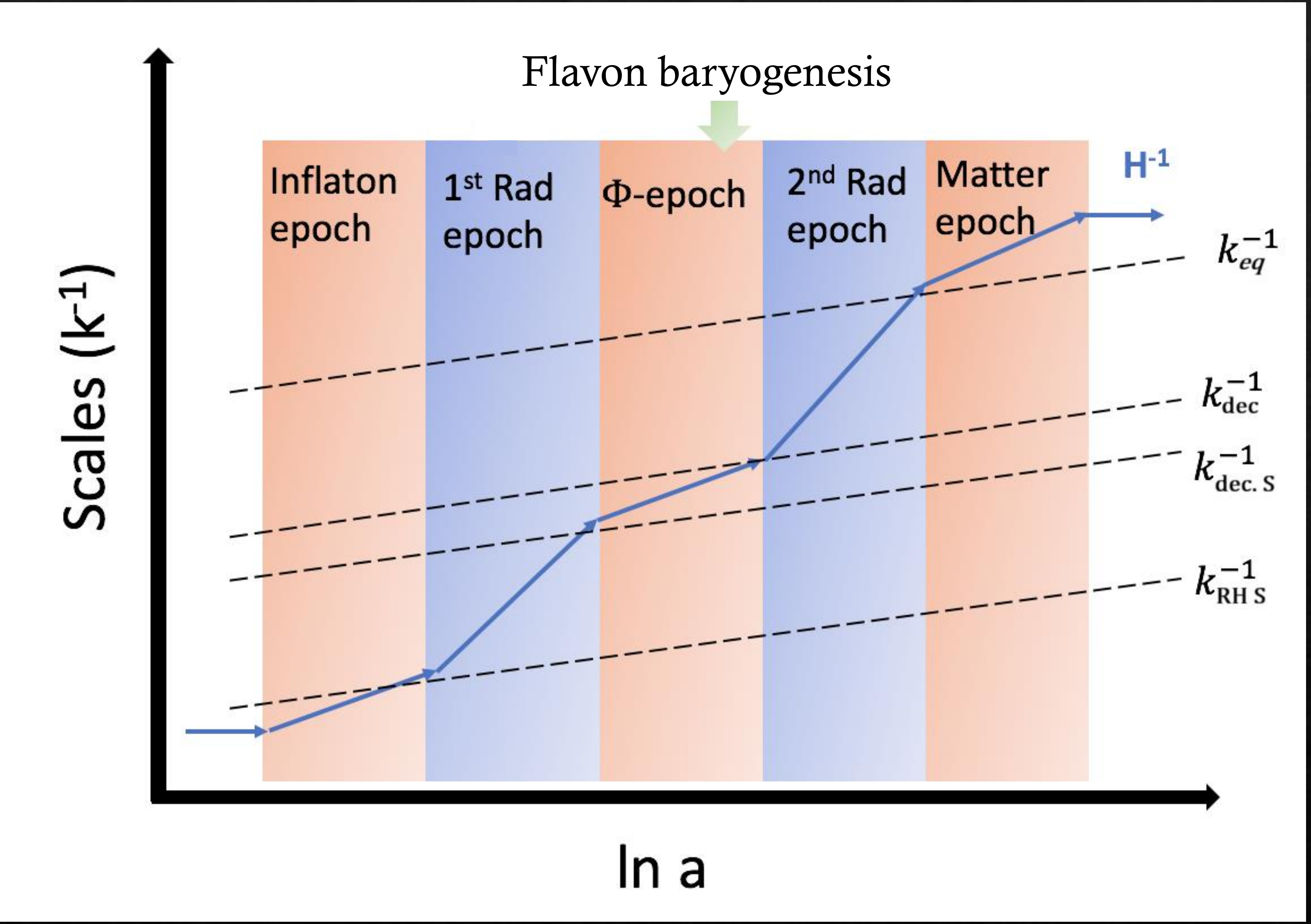

S. Dutta et. al., JHEP (2022).

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

Berbig et al JHEP 2023

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

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

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

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

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

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

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

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

$$\Delta = \frac{s\,a^3|_{\rm after}}{s\,a^3|_{\rm before}}$$

Dilution factor from entropy injection

Flavon baryogenesis

Froggatt-Neilsen Mechanism

Fermion mass hierarchy

Froggatt-Neilsen Mechanism

$U(1)_{\mathrm{FN}}$

Fermion mass hierarchy

Froggatt-Neilsen Mechanism

		$U(1)_{\mathrm{FN}}$
Flavon	S	-1
Fermion	ψ_i	Q_i

Fermion mass hierarchy

Froggatt-Neilsen Mechanism

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Fermion mass hierarchy

Effective operator: $$y_{ij}\psi_i\psi_j H \left(\frac{v_S+S}{\Lambda_{\mathrm{FV}}}\right)^{n_{ij}}$$

$$n_{ij} = Q_i + Q_j$$

$$y_{ij} \sim \mathcal{O}(1)$$

Froggatt-Neilsen Mechanism

Fermion mass hierarchy

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$$n_{ij} = Q_i + Q_j$$

$$y_{ij} \sim \mathcal{O}(1)$$

$$\epsilon = \frac{v_S}{\Lambda_{\mathrm{FV}}}$$

$$Y_{ij} = \begin{pmatrix} \epsilon^{n_{11}} & \epsilon^{n_{12}} & \epsilon^{n_{13}} \\ \epsilon^{n_{21}} & \epsilon^{n_{22}} & \epsilon^{n_{23}} \\ \epsilon^{n_{31}} & \epsilon^{n_{32}} & \epsilon^{n_{33}} \end{pmatrix}$$

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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Δ_{l_L} asymmetry is balanced by Δ_{e_R} asymmety (no LNV)

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$$\Gamma_{LR} \simeq 10^{-2} y_e^2 T \qquad y_e \simeq 2.9 \times 10^{-6}$$

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

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IFD: Right-handed electrons does not equilibriate till $T \sim 100$ GeV

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

Flavon baryogenesis

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Chen et al PRD 2019

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

We are agnostic of the exact model that creates the initial flavon asymmetry. We simply assume that far below $\Lambda_{\rm FV}$, the flavon potential preserves an approximate $U(1)_S$ symmetry that is broken explicitly by small S-number violating terms responsible for the initial asymmetry,

$$V_S = m^2|S|^2 + \begin{pmatrix} S\text{-number violating terms} \\ \text{suppressed by } \Lambda_{\rm FV} \end{pmatrix}$$

Flavon baryogenesis

Boltzmann equations:

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

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

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

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

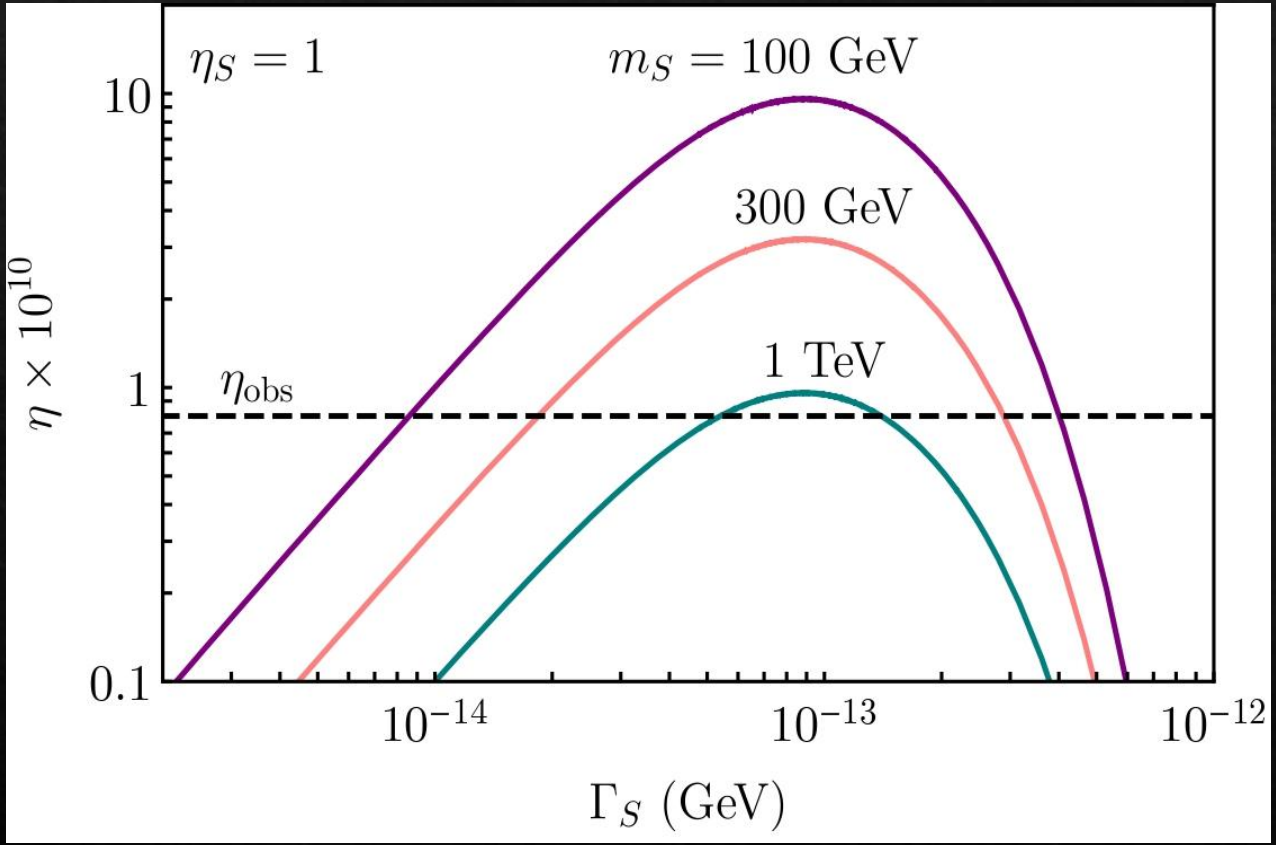
$$H^2 = \frac{8\pi}{3M_{\text{Pl}}^2}(\rho_S + \rho_R)\,,$$

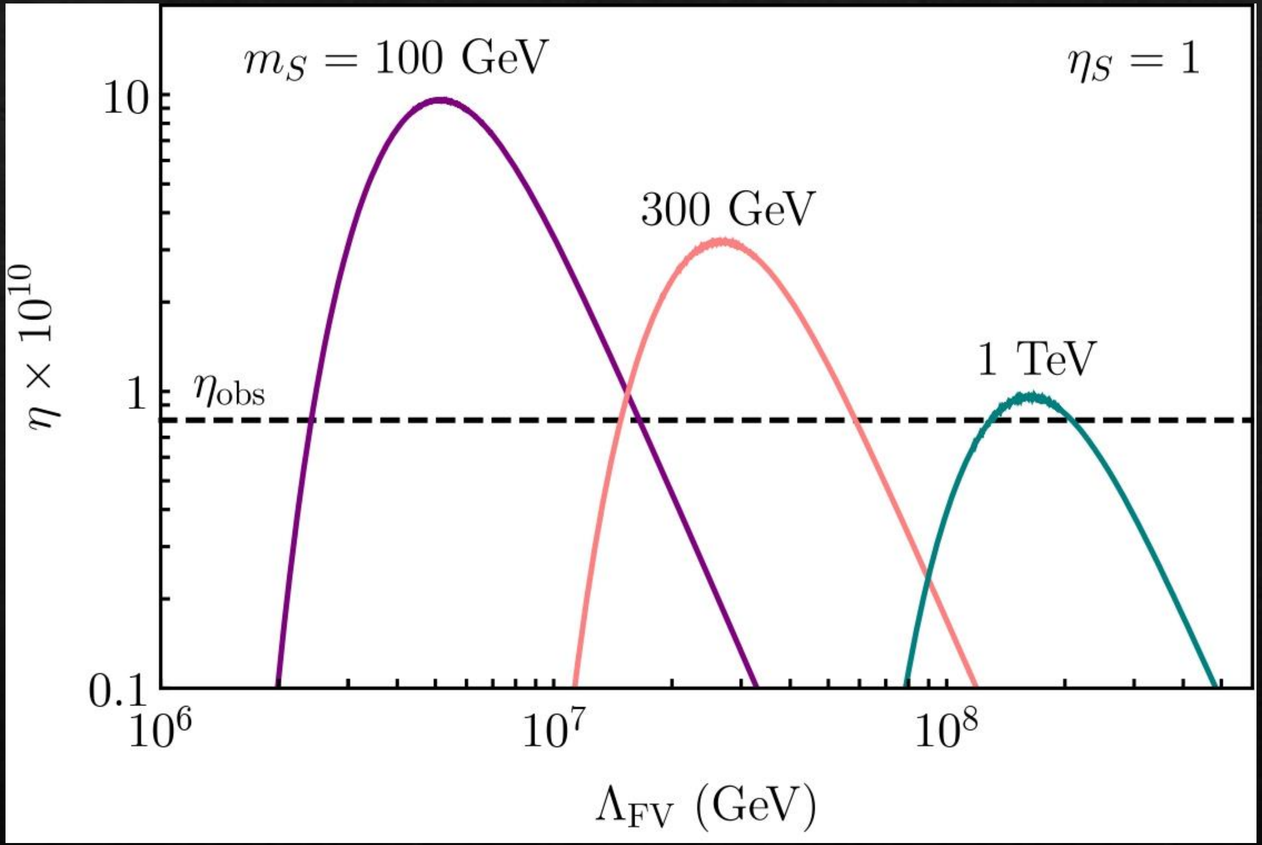
$$\Delta_S = \eta_S \frac{\rho_S}{m_S}$$

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

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

Flavon baryogenesis





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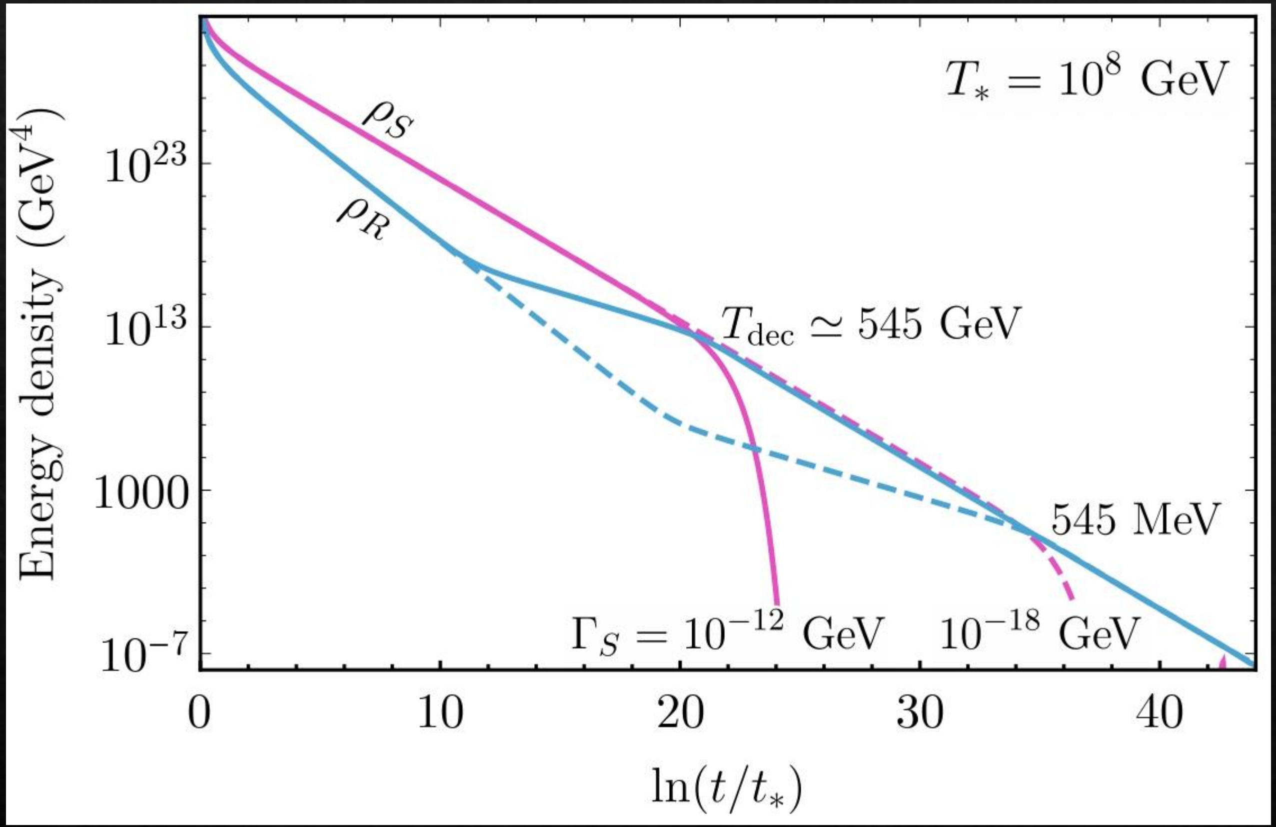
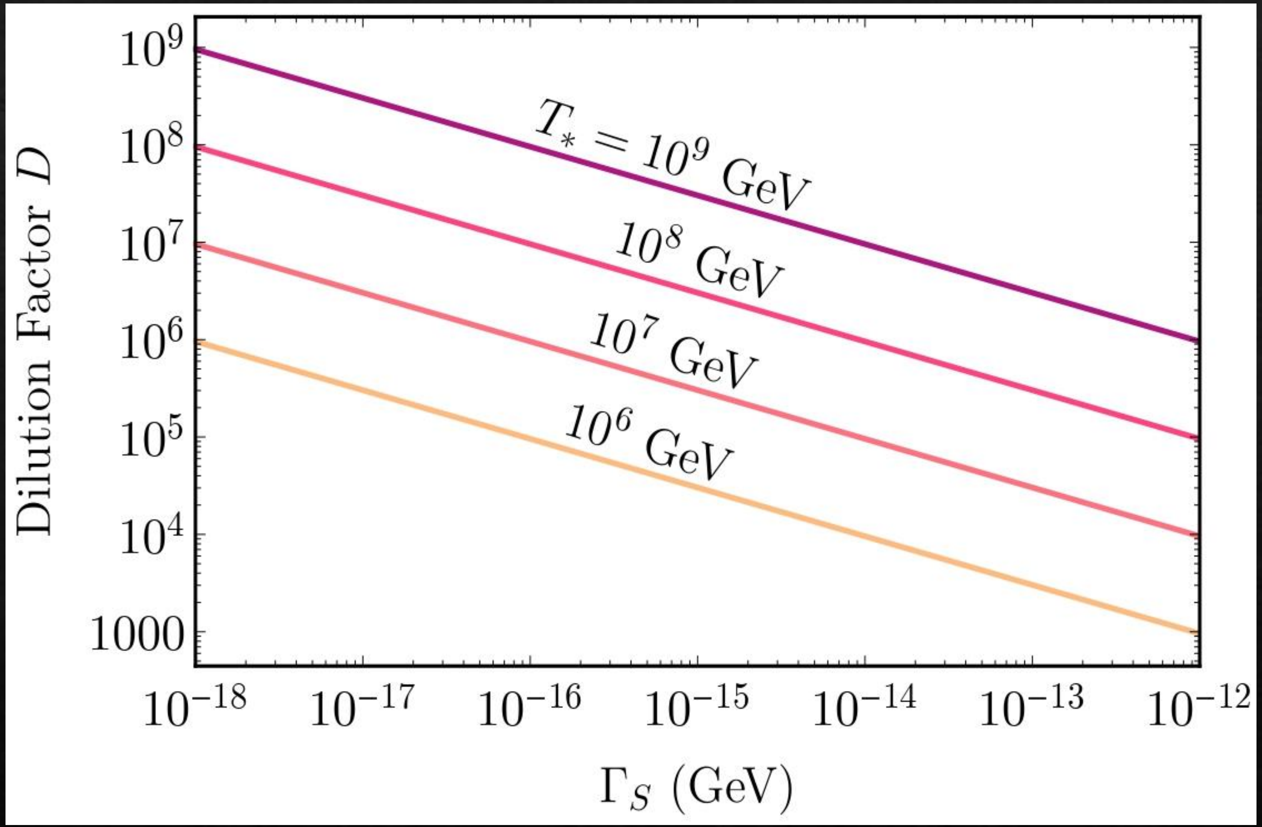




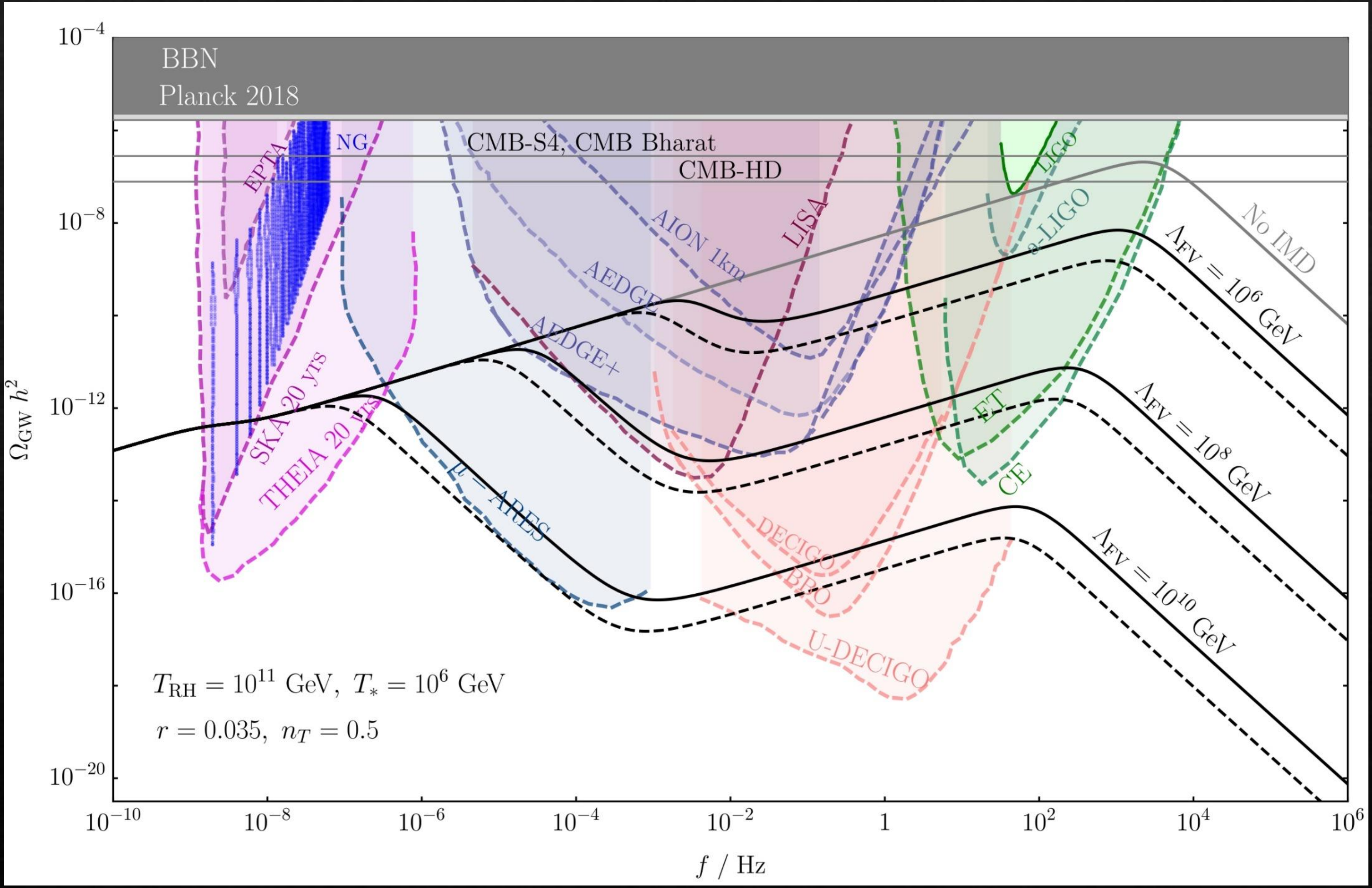
Flavon baryogenesis

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

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

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

Probing Flavon baryogenesis



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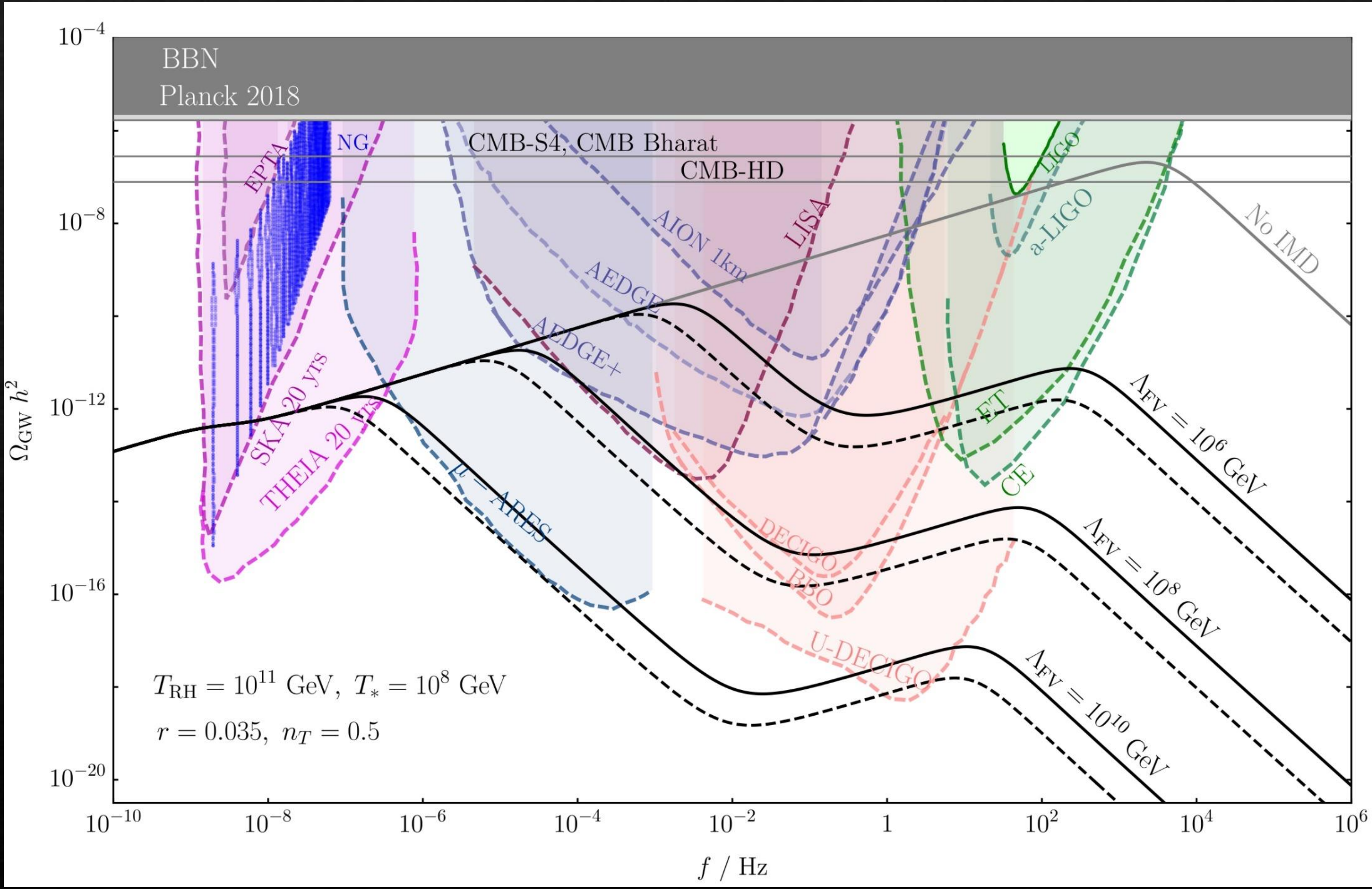
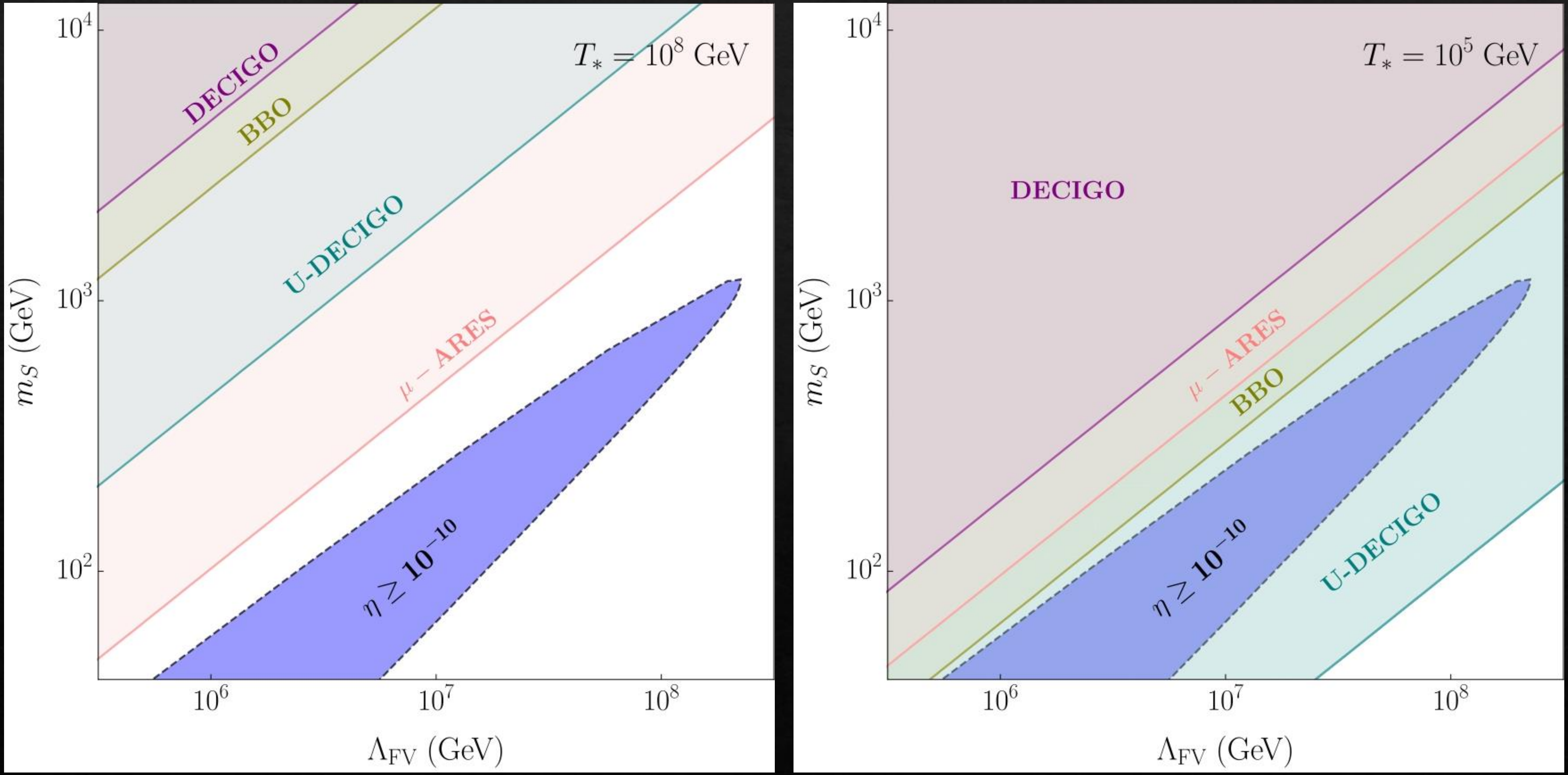


Probing Flavon baryogenesis

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

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

Probing Flavon baryogenesis



Conclusions

- ✓ We explore the connection between flavor violation, baryogenesis, and gravitational waves, focusing on how the dynamics of the flavon field, which explains the fermion mass hierarchy in the SM, could produce a detectable baryon asymmetry and imprint unique spectral features in primordial GWs.
- ✓ We analyze the suppression of primordial gravitational wave spectra due to flavon domination and decay, identifying model parameters for which both baryon asymmetry and GW signals are detectable by future GW detectors like U-DECIGO, BBO, LISA, ET and μ-ARES.
- ✓ As GW detector technology advances, the precision achieved could enable the high-energy physics and gravitational wave communities to test BSM mechanisms related to flavor physics, matter-antimatter asymmetry, and inflationary cosmology in unprecedented detail.

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Thank you !!