భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

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PPC 2024

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WIMPy Leptogenesis in Non-Standard Cosmology

based on : **JCAP 03 (2023) 049 in collaboration with Debasish Borah (IITG)**

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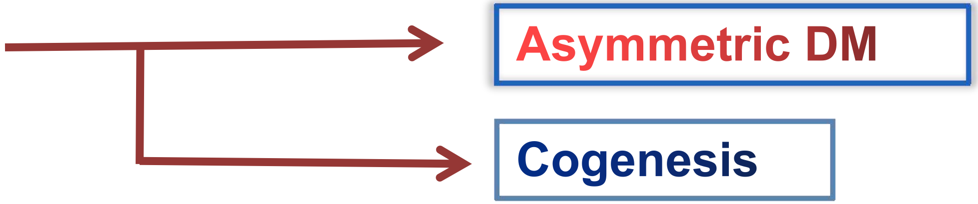
WIMPy Leptogenesis

- The abundance of baryons and dark matter (DM) in the Universe is very similar

$$\boxed{\Omega_{\rm DM} \approx 5\,\Omega_{\rm Baryon}}$$

Planck 2018

- **Mechanism for dynamic origin**



Asymmetric DM

Cogenesis

- **WIMPy leptogenesis:** Lepton asymmetry is generated from the **annihilation /co-annhilation** of WIMPs.

- **Model:** The minimal Scotogenic model is extended by extended by a Z_2 even triplet scalar Δ **Dasgupta et al 2020 (Phys.Rev.D 102 (2020) 5).**

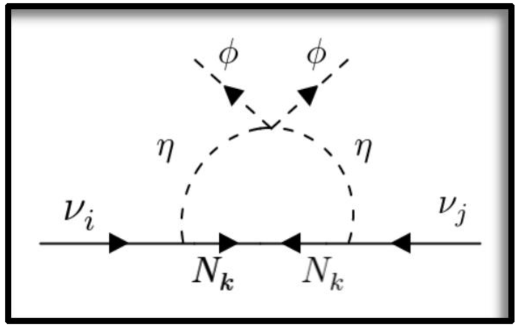
$$-\mathcal{L} \supset Y^N_{i\alpha}\overline{\ell_\alpha}\tilde{\eta}N_i + Y^{\Delta}_{\alpha\beta}\overline{\ell^c_\alpha}\Delta\ell_\beta + \text{h.c.},$$

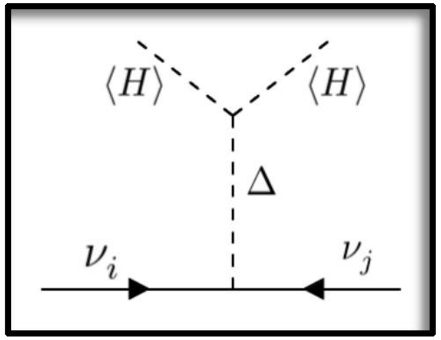
$$V \subset \mu_{\eta\Delta}\eta^\dagger\Delta\tilde{\eta} + \lambda''_{H\eta}(H^\dagger\eta)^2$$

- The inert scalar is a **WIMP**.

Neutrino Mass

Neutrino Mass





$$m_\nu = \left(Y^N\right)^T \Lambda^{-1} Y^N + Y^\Delta v_\Delta$$

Casas Ibarra- Parametrisation

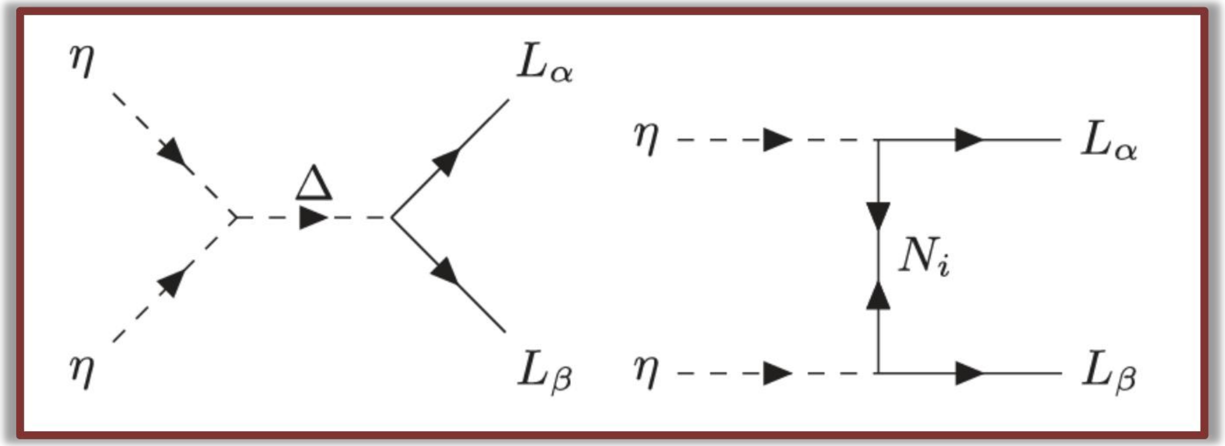
Casas and Ibarra 2001 (Nucl.Phys.B618 171-204)

$$Y^N_{i\alpha} = F_I^{1/2}\left(\Lambda^{-1/2}\mathcal{O}\hat{m}_\nu{}^{1/2}U^\dagger_{\rm PMNS}\right),$$
$$Y^\Delta_{\alpha\beta} = F_{II} v_\Delta^{-1}(U^*_{\rm PMNS}\hat{m}_\nu U^\dagger_{\rm PMNS}),$$

Effective RHN mass scale

$$\Lambda_{ii} = \frac{M_i}{16\pi^2}\left[\frac{m^2_{\eta R}}{M_i^2 - m^2_{\eta R}}\ln\left(\frac{M_i^2}{m^2_{\eta R}}\right) - \frac{m^2_{\eta I}}{M_i^2 - m^2_{\eta I}}\ln\left(\frac{M_i^2}{m^2_{\eta I}}\right)\right].$$

Asymmetry Production



$$\mathcal{M} = (\mathcal{C}_1\mathcal{M}_1 + \mathcal{C}_2\mathcal{M}_2)\mathcal{W},$$

$$\begin{aligned}\delta &\equiv |\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2 \\ &= -4\mathrm{Im}[\mathcal{C}_1\mathcal{C}_2^*]\mathrm{Im}[\mathcal{M}_1\mathcal{M}_2^*]|\mathcal{W}|^2,\end{aligned}$$

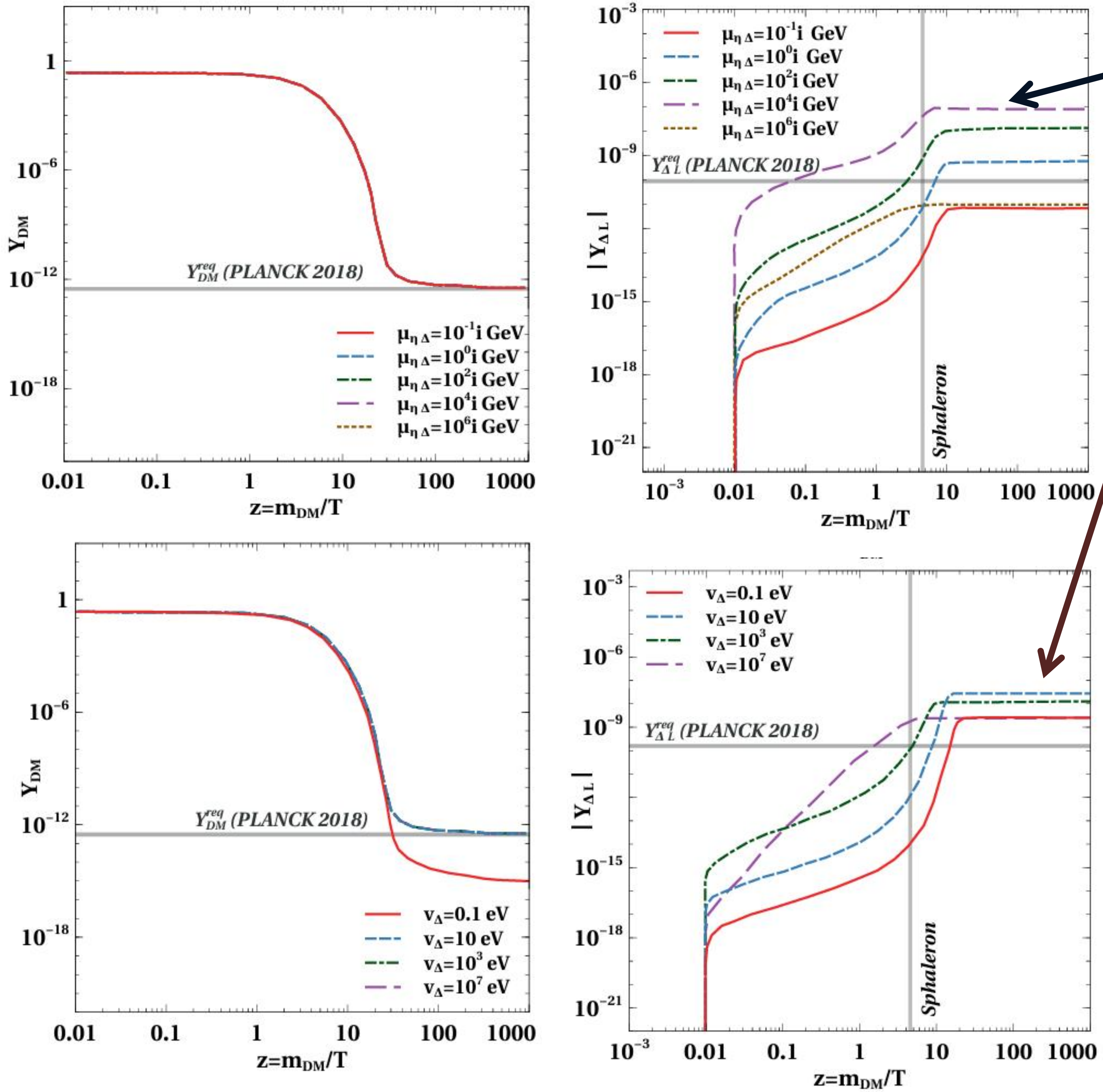
Asymmetry parameter at amplitude level

Boltzmann Equations

$$\begin{aligned}\frac{dY_\eta}{dz} &= -\frac{s}{\mathbf{H}(z)z}\left[\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\right)\langle\sigma v\rangle_{\eta\eta\longrightarrow \mathrm{SM\,SM}}\right], \\ \frac{dY_{\Delta L}}{dz} &= \frac{s}{\mathbf{H}(z)z}\left[\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\right)\boxed{\langle\sigma v\rangle^{\delta}_{\eta\eta\longrightarrow\ell\ell}}\right] - 2Y_{\Delta L}Y_l^{\rm eq}r_\eta^2\langle\sigma v\rangle_{\eta\eta\longrightarrow\ell\ell} \\ &\quad -2Y_{\Delta L}Y_\eta^{\rm eq}\langle\sigma v\rangle_{\eta\bar{\ell}\longrightarrow\eta\ell},\end{aligned}$$

Thermally averaged asymmetry parameter arising from DM annihilation

$$\langle\sigma v\rangle^{\delta}_{\eta\eta\longrightarrow ll} \approx \frac{16\pi}{m_\eta^4}\frac{1}{\tilde{\mu}^2_{\eta\Delta}\sum_{\alpha,\beta}|Y^{\Delta}_{\alpha\beta}|^2}\Gamma_{\Delta\longrightarrow\eta\eta}\Gamma_{\Delta\longrightarrow ll}\sum_i\left[\mu_{\eta\Delta}(Y^N Y^{\Delta^*}(Y^N)^T)\right] \frac{f[m_\Delta, m_\eta, M_i]r_{N_i}}{\sqrt{m_\Delta^2 - 4m_\eta^2}}\frac{zK_1(r_\Delta z)}{K_2^2(z)}$$

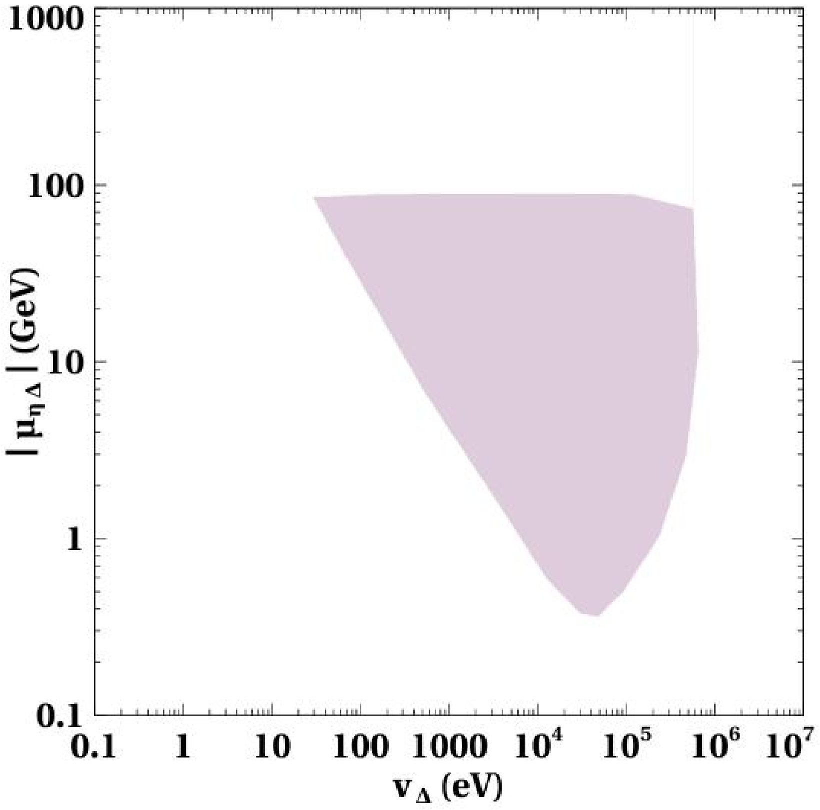


Two way behaviour with $\mu_{\eta\Delta}$ and v_Δ

$$m_{\eta_R} = m_{\rm DM} = 600 \text{ GeV}$$

$$m_{\Delta^\pm} = m_{\Delta^{\pm\pm}} = m_{\Delta^0} = 1.2 \text{ TeV}$$

$\lambda''_{H\eta} = 1 \times 10^{-5}$, $M_1 = 6$ TeV, and $M_{j+1}/M_j = 1.1$.



Fast Expanding Universe (FEU)

- The Universe is dominated by a scalar field that contributes to the energy density of the Universe **Profumo et al 2017** **(JCAP05 012)**

$$\rho_\phi \propto a^{-(4+n)}$$

$$n = 3\omega_\phi - 1$$

$$T_r \gtrsim (15.4)^{1/n}\ \mathrm{MeV}$$

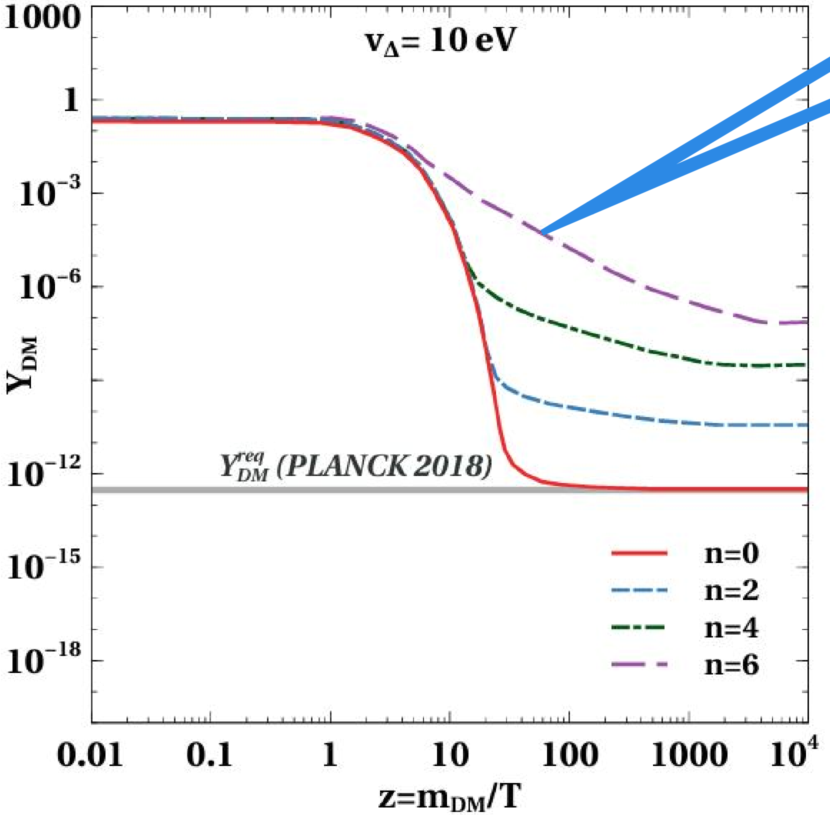
- Hubble expansion rate modifies

$$\mathbf{H}(T) \simeq \frac{\pi g_*^{1/2}(T) T^2}{3\sqrt{10} M_{\rm Pl}} \left[1 + \left(\frac{g_*(T)}{g_*(T_{\rm r})} \right)^{(1+n)/3} \left(\frac{T}{T_{\rm r}} \right)^n \right]^{1/2} .$$

- The set of Boltzmann equations

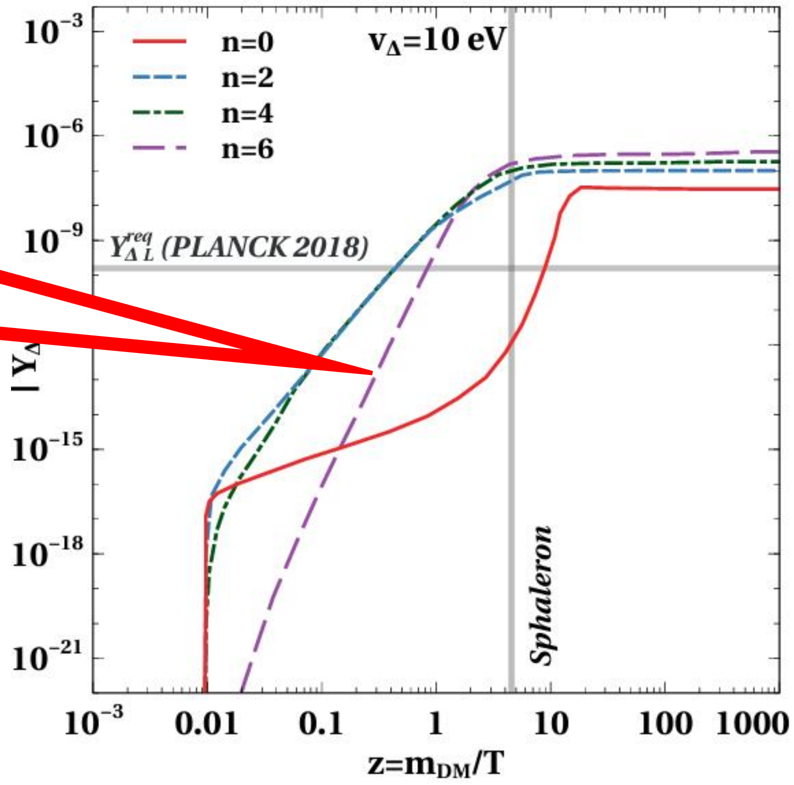
$$\begin{aligned}
\frac{dY_\eta}{dz} &= -\frac{s(z=1)}{z^{2-n/2} z_r^{n/2} \mathbf{H}_{\rm rad}(z=1)} \langle \sigma v \rangle_{\eta\eta \longrightarrow \mathrm{SM\,SM}} \left[Y_\eta^2 - (Y_\eta^{\rm eq})^2 \right] \\
\frac{dY_{\Delta L}}{dz} &= \frac{s(z=1)}{z^{2-n/2} z_r^{n/2} \mathbf{H}_{\rm rad}(z=1)} \langle \sigma v \rangle^\delta_{\eta\eta \longrightarrow \ell\ell} \left[Y_\eta^2 - (Y_\eta^{\rm eq})^2 \right] \\
&\quad - \frac{s(z=1)}{z^{2-n/2} z_r^{n/2} \mathbf{H}_{\rm rad}(z=1)} Y_{\Delta L} Y_l^{\rm eq} r_\eta^2 \langle \sigma v \rangle_{\eta\eta \longrightarrow \ell\ell} \\
&\quad - \frac{s(z=1)}{z^{2-n/2} z_r^{n/2} \mathbf{H}_{\rm rad}(z=1)} Y_{\Delta L} Y_\eta^{\rm eq} \langle \sigma v \rangle_{\eta\bar{\ell} \longrightarrow \eta\ell} .
\end{aligned}$$

WIMPy Leptogenesis in a FEU



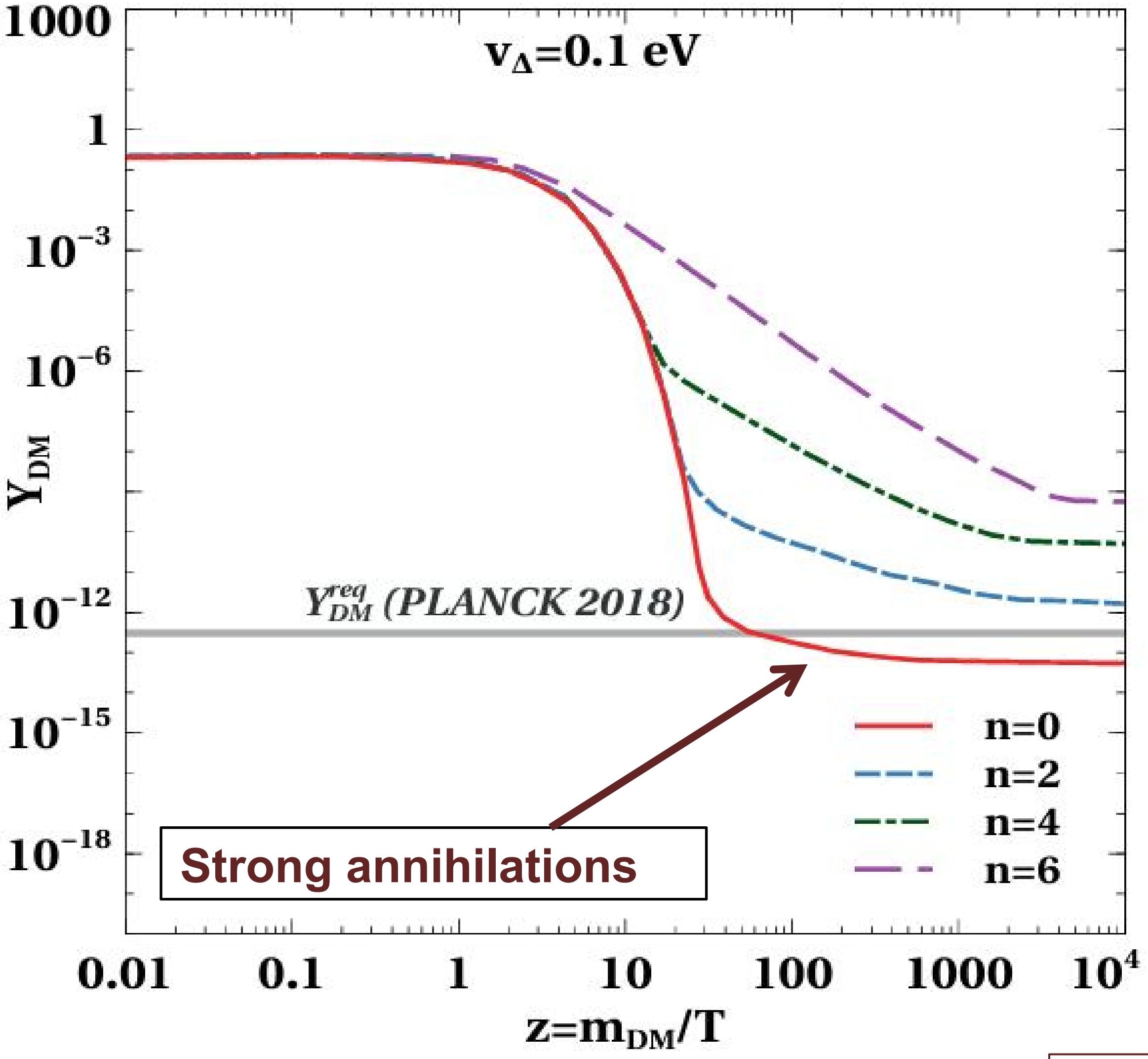
Relentless DM freeze-out

Reduction in Washouts, Departure from equilibrium

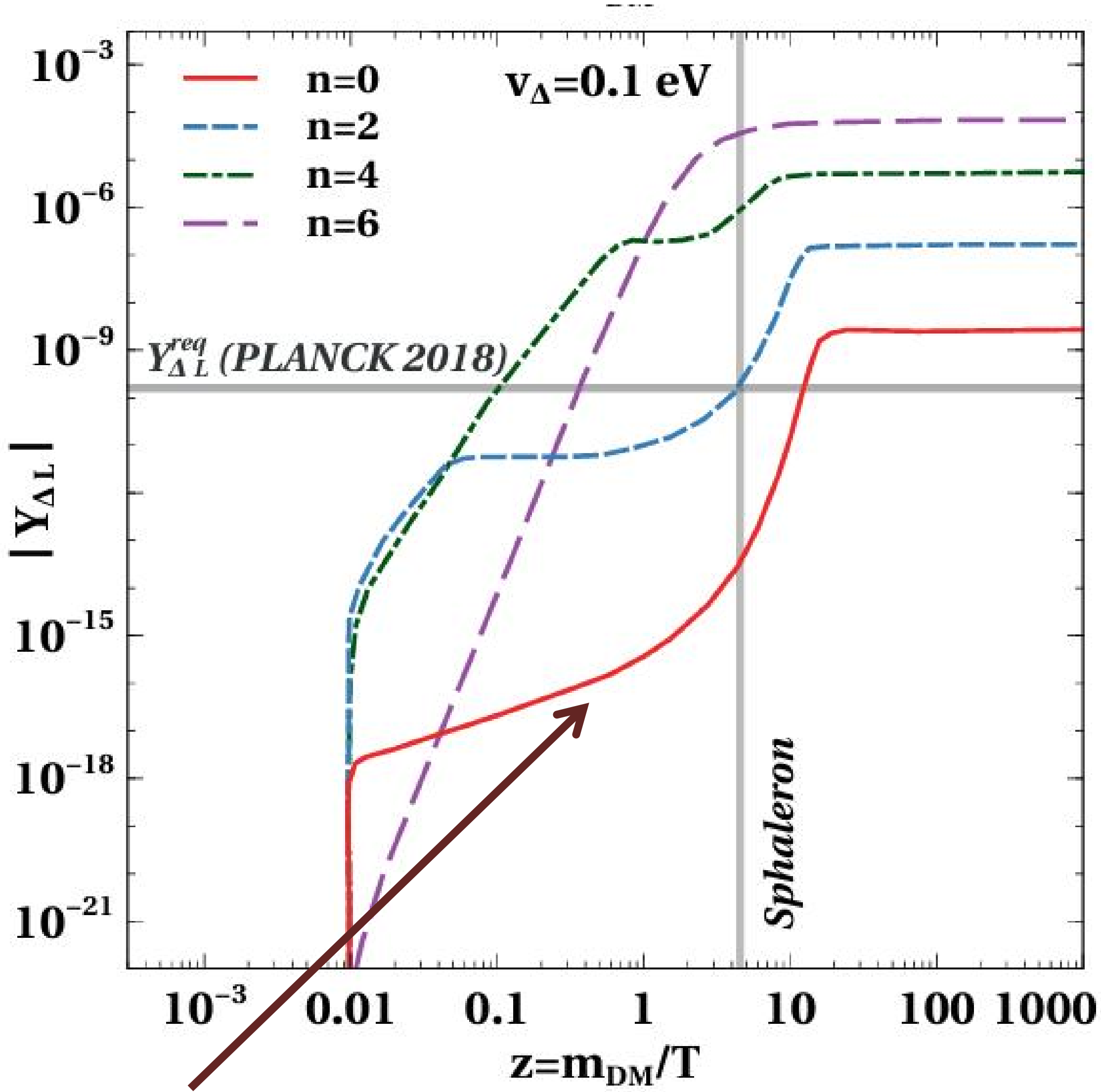


$$m_{\eta R} = 600\ \text{GeV}\quad m_{\Delta^\pm} = m_{\Delta^{\pm\pm}} = m_{\Delta^0} = 1.2\ \text{TeV}\quad M_1 = 6\ \text{TeV},\ M_{j+1}/M_j = 1.1$$

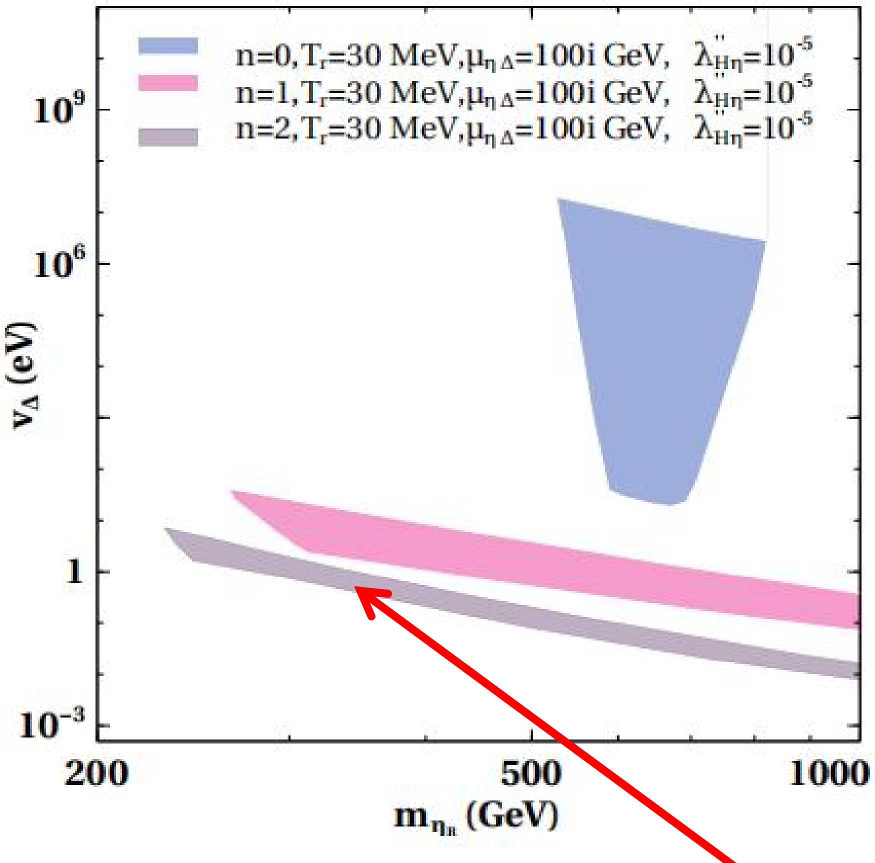
$$\mu_{\eta\Delta} = 10i\ \text{GeV},\ \lambda''_{H\eta} = 1\times 10^{-5}\ \text{and}\ v_\Delta = 10\ \text{eV}$$

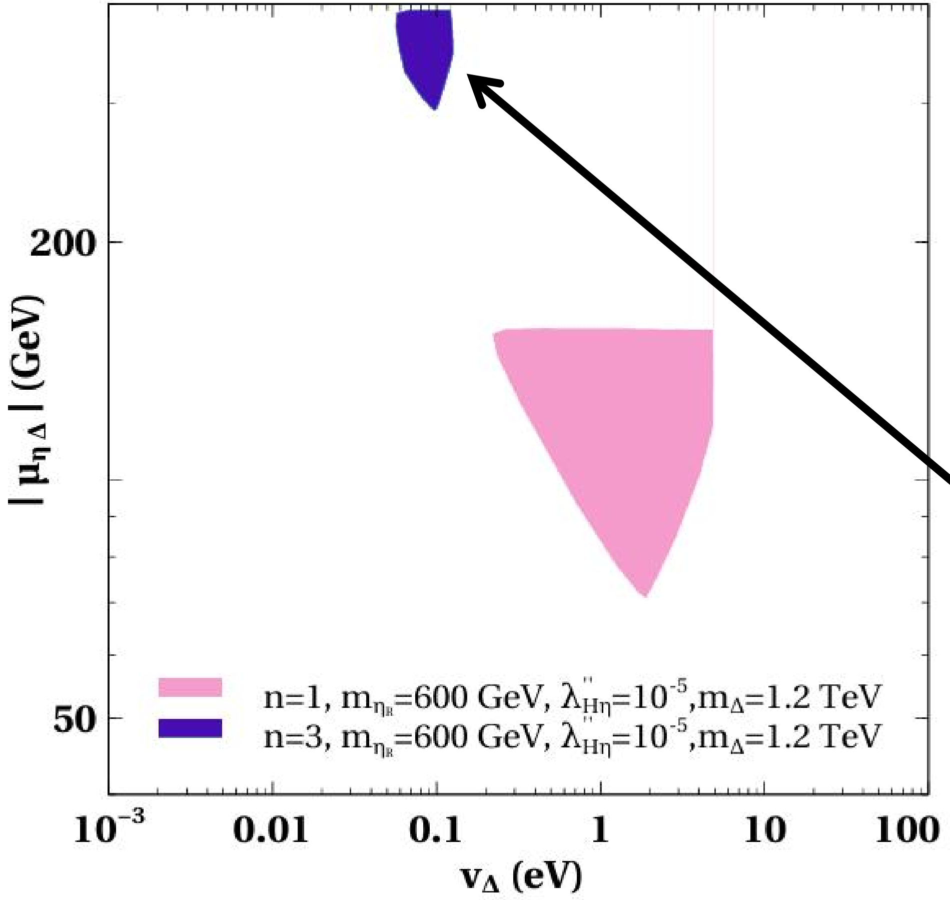


Strong annihilations



Strong Washouts





Faster expansion allows stronger annihilation

The mass of DM can be lower compared standard radiation domination (Desert region of IDM is accessible)

Early Matter Dominated Universe (EMD)

☐ In EMD scenario, a matter field is assumed to dominate the energy density of the pre BBN universe for a certain duration **Arias et al 2020** (PRD.105.023502).

☐ Important parameters $\boxed{k = \rho_\phi^{\text{in}} / \rho_{\text{rad}}^{\text{in}}}$ $\boxed{T_{\text{end}}}$

☐ Evolution equations

$$\frac{d\rho_\phi}{da} = -\frac{\Gamma_\phi \rho_\phi}{\mathbf{H} a} - \frac{3(1+\omega)\rho_\phi}{a}$$

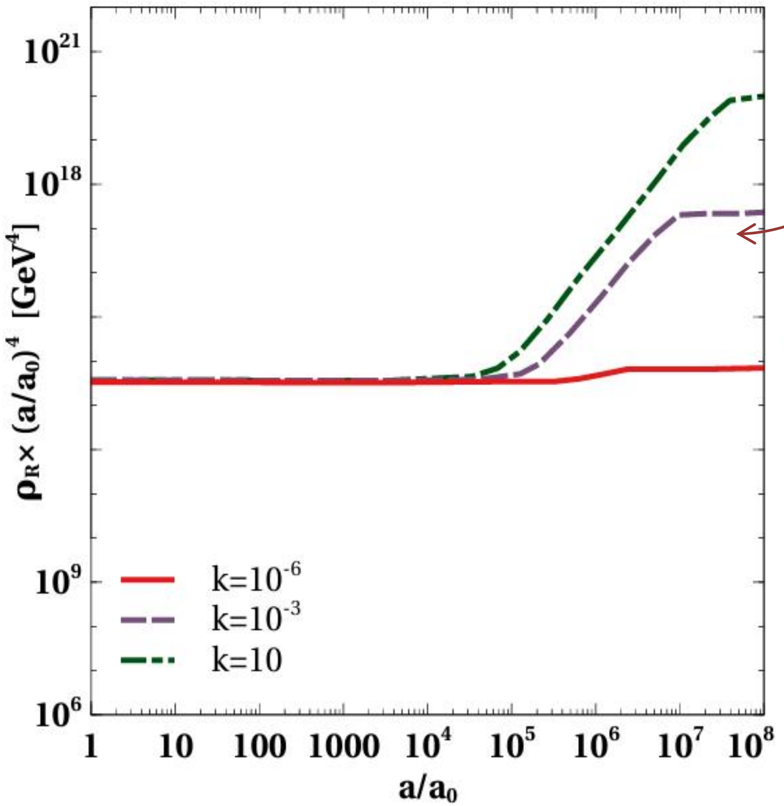
$$\frac{ds}{da} + \frac{3s}{a} = \frac{\Gamma_\phi \rho_\phi}{T \mathbf{H} a} + \frac{2E}{T \mathbf{H} a} \frac{\langle \sigma v \rangle_{\eta\eta \longrightarrow \text{SM SM}}}{a^6} \left[N_\eta^2 - (N_\eta^{\text{eq}})^2 \right]$$

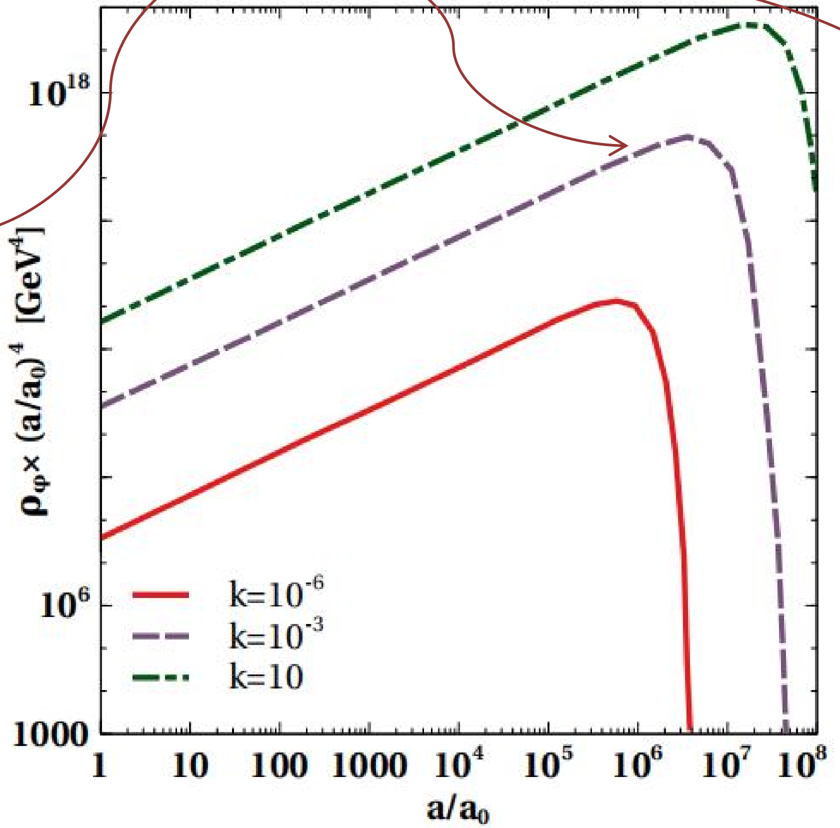
$$\frac{dT}{da} = \left(1 + \frac{T}{g_{*s}} \frac{dg_{*s}}{dT}\right)^{-1} \left[-\frac{T}{a} + \frac{\Gamma_\phi \rho_\phi}{3 \mathbf{H} s a} \left(1 - b \frac{E}{m_\phi}\right) + \frac{2}{3} \frac{E \langle \sigma v \rangle_{\eta\eta \longrightarrow \text{SM SM}}}{\mathbf{H} s a^7} \left[N_\eta^2 - (N_\eta^{\text{eq}})^2 \right] \right]$$

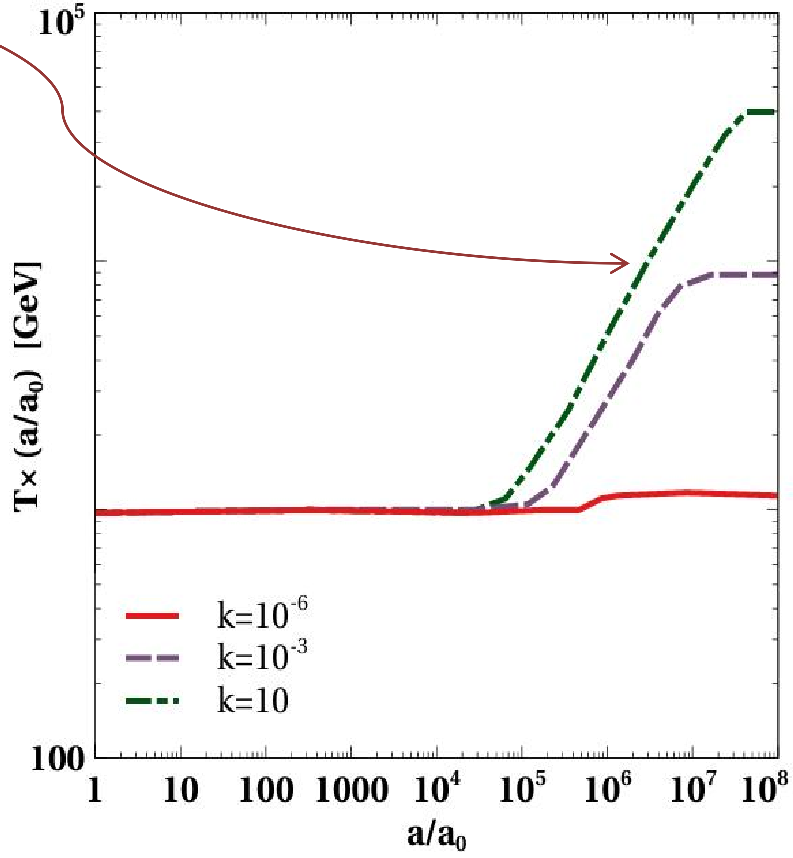
$$\mathbf{H}(a) = \sqrt{\frac{\rho_\phi(a) + \rho_{\text{rad}}(a)}{3 M_{\text{Pl}}^2}} \qquad \Gamma_\phi = \sqrt{\frac{\pi^2 g_*(T_{\text{end}})}{90 M_{\text{Pl}}^2}} T_{\text{end}}^2$$

Presence of the matter field increases the expansion rate.

When the matter field decays it injects entropy in the plasma.





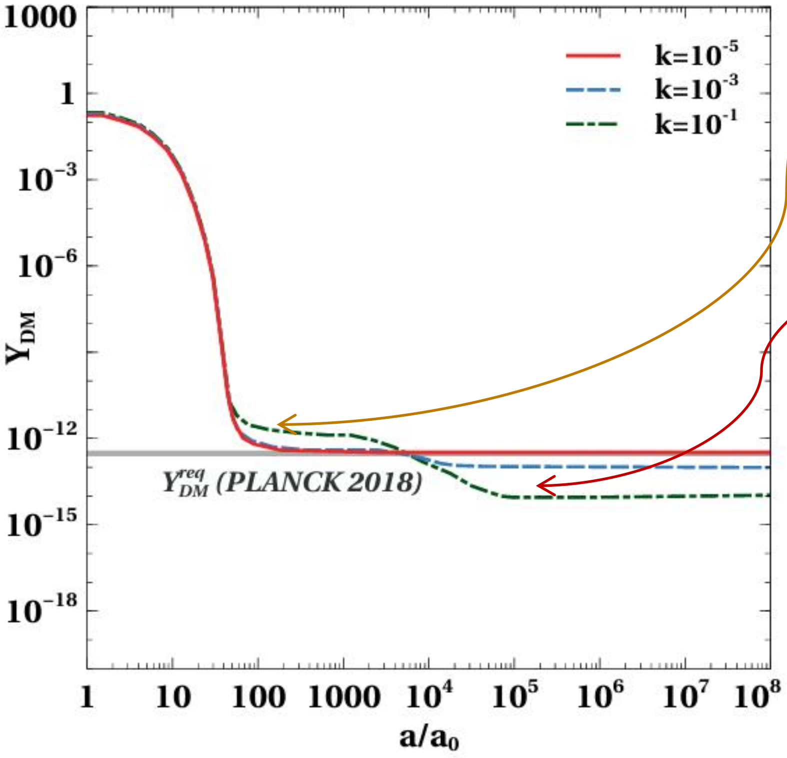


$$\frac{dN_\eta}{da} = -\frac{\langle\sigma v\rangle_{\eta\eta\longrightarrow \mathrm{SM\,SM}}}{\mathbf{H}a^4}\left[N_\eta^2 - (N_\eta^{\mathrm{eq}})^2\right]$$

$$\frac{dN_{\Delta L}}{da} = \frac{\langle\sigma v\rangle^{\delta}_{\eta\eta\longrightarrow ll}}{\mathbf{H}a^4}\left[N_\eta^2 - (N_\eta^{\mathrm{eq}})^2\right] - \frac{N_{\Delta L}}{\mathbf{H}a^4} N_l^{\mathrm{eq}} r_\eta^2 \langle\sigma v\rangle_{\eta\eta\longrightarrow ll} - \frac{N_{\Delta L}}{\mathbf{H}a^4} N_\eta^{\mathrm{eq}} \langle\sigma v\rangle_{\eta\bar{l}\longrightarrow \eta l}$$

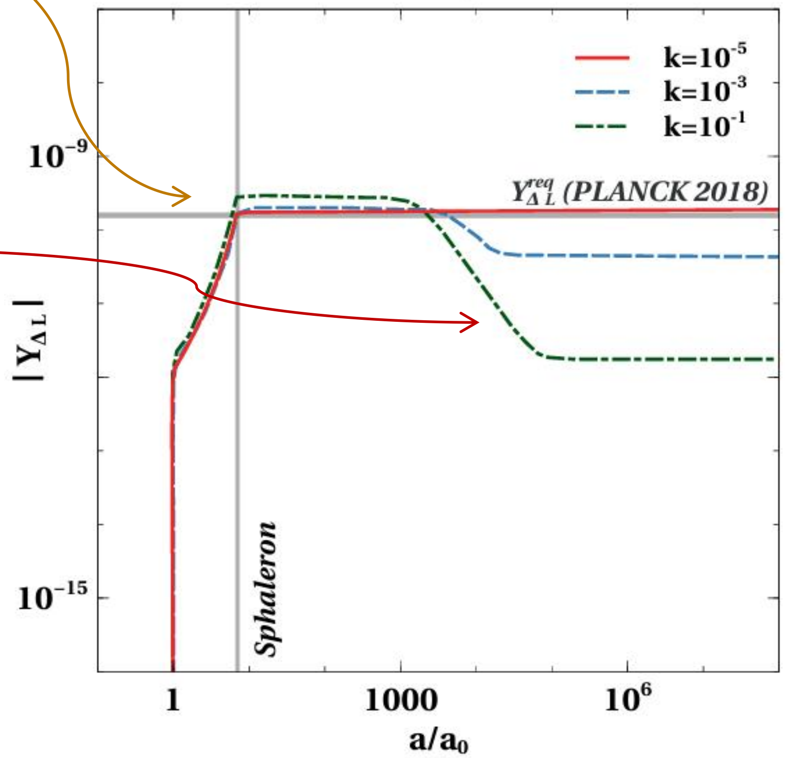
Early freeze out due to increase in expansion rate of the Universe.

$T_{\mathrm{end}} < T_{\mathrm{Sph}}$



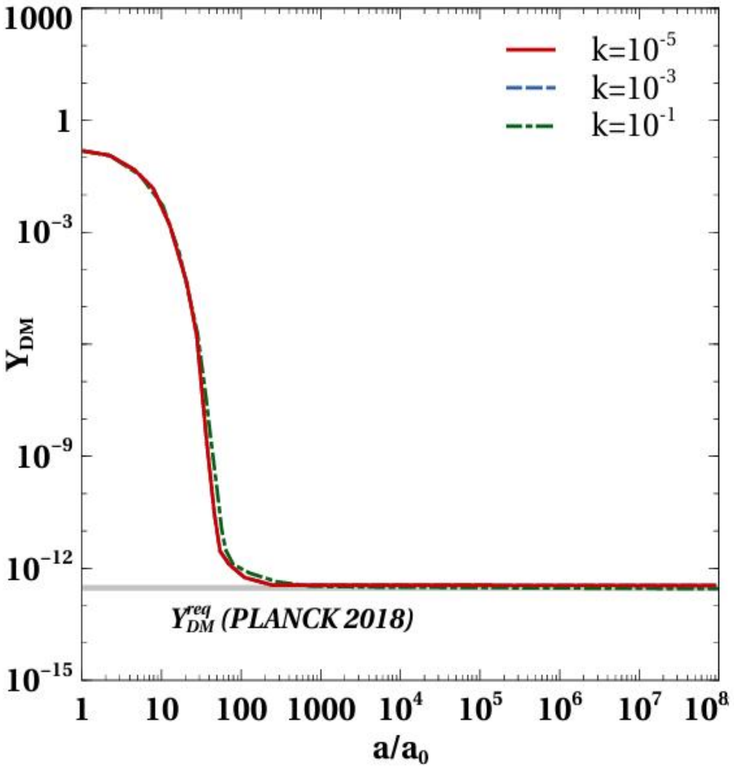
Entropy injection dilutes the DM abundance and Asymmetry.

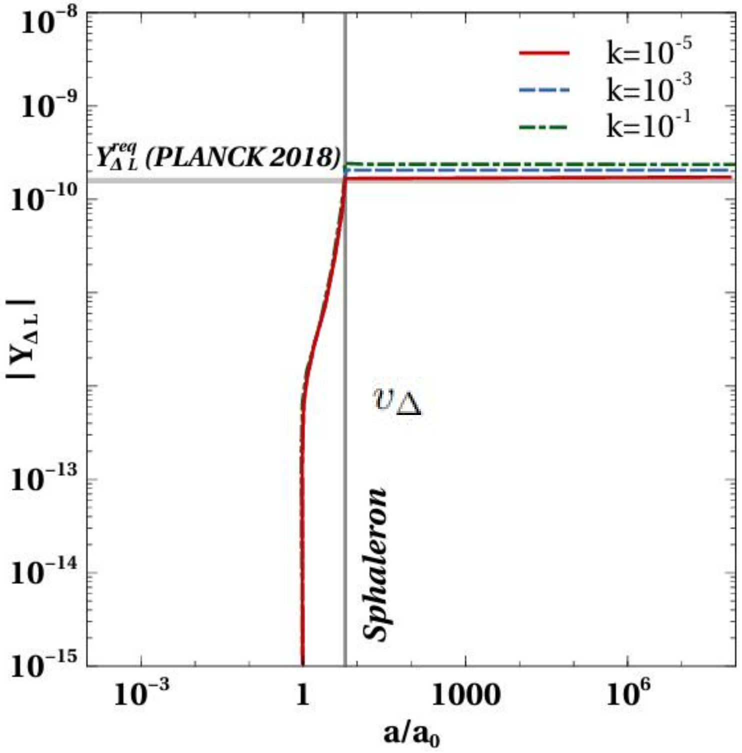
$T_{\mathrm{end}} = 200$ MeV

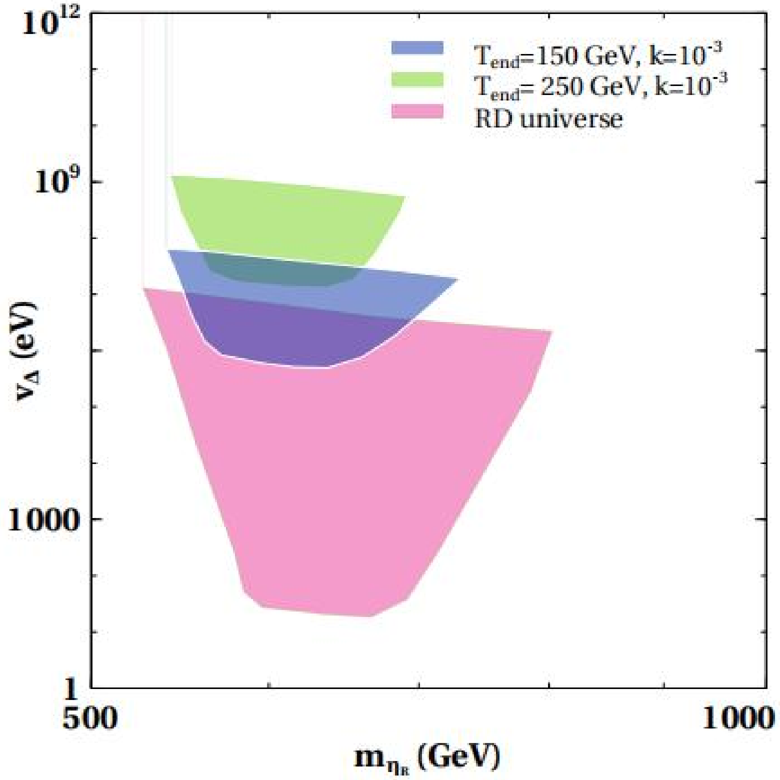


$T_{\rm end} > T_{\rm Sph}$ $T_{\rm end} = 250\ {\rm GeV}$

Minimal entropy dilution effect as temperature is high.
Increase in expansion rate increases the asymmetry.







Mass of DM remains same due to gauge annihilations, whereas v_Δ Increases from the requirement of observed asymmetry.

Conclusions

- We consider a low scale WIMPy leptogenesis model in modified cosmological backgrounds (**Fast Expansion**, **Early matter Domination**, **Scalar Tensor Gravity**). The viable parameter space changes.

- A **Fast Expanding Universe** makes the desert region of the inert doublet DM model accessible. This can open up interesting detection prospects of such lighter DM at both direct as well as indirect detection experiments together with colliders.

- Similar results are seen for the **Scalar Tensor Gravity** theory.

- An Early matter domination does not change the DM parameter space due to the entropy dilution.

- Such modified cosmological cosmological scenarios can also be probed due their impact on primordial gravitational wave (GW) spectrum **Wells et al 2018** **(JHEP01(2019)081)** and **Bernal et al 2019** **(PhysRevD.100.063502)**.

THANK YOU!