Right-handed Neutrino Dark Matter Relic Density in Non-Standard Cosmologies

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CAPES

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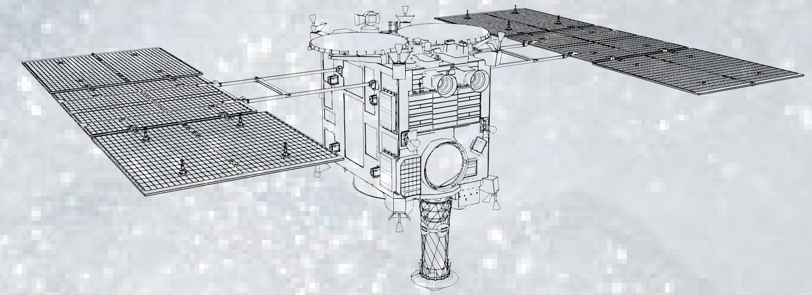
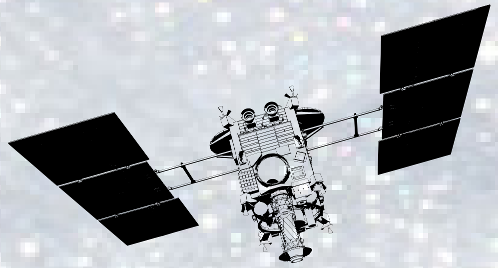
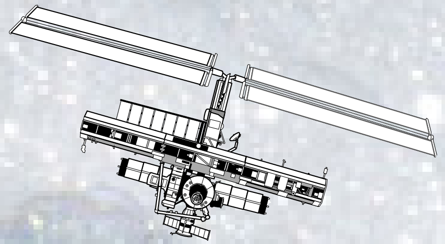
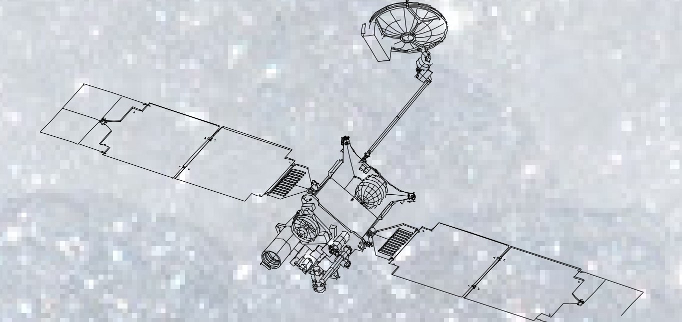
Outline







- INTRODUCTION
- NON-STANDARD COSMOLOGICAL HISTORIES
- RESULTS
- CONCLUSIONS



Hubble rate versus Annihilation Rate

Cosmology

Faster Than Usual Early Expansion

Quintessence

Early Radiation-dominated freeze-out

Early Matter-dominated freeze-out

Particle Properties

Type-I 2HDM

Fermions interact only with the second doublet.

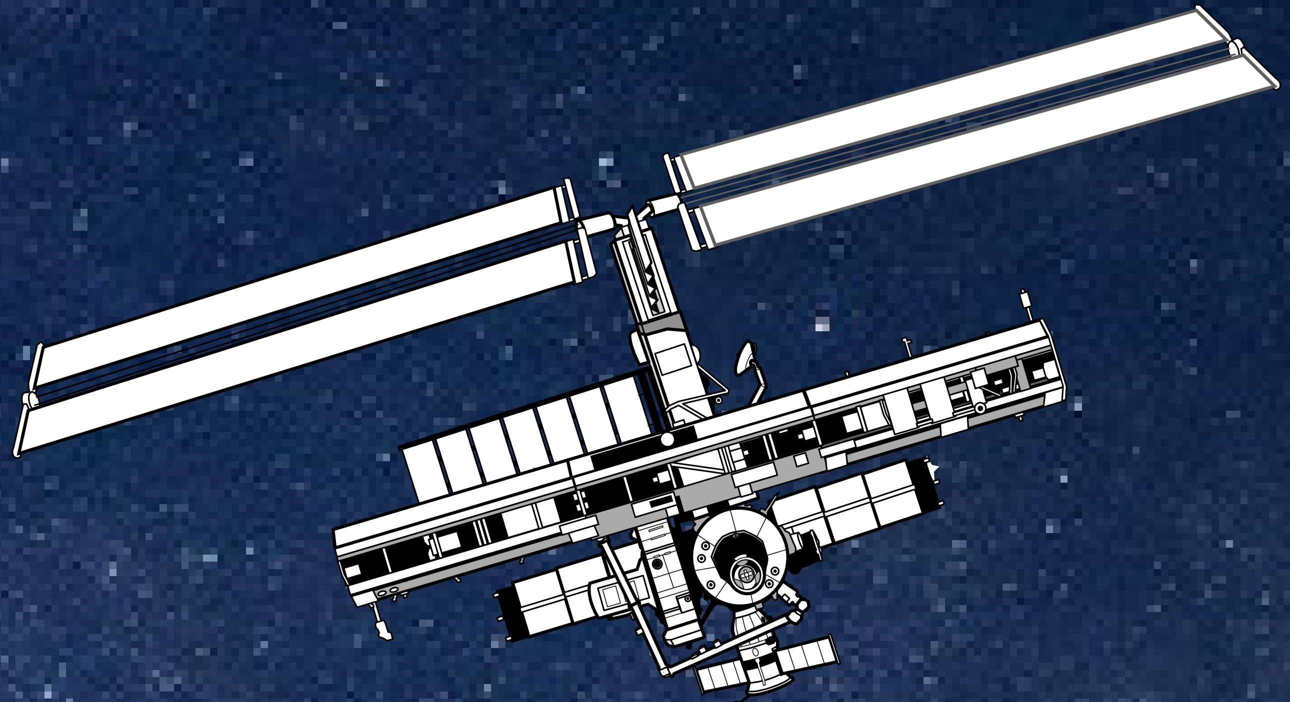
+ B-L symmetry

+ 2RHν + 1RHN

+ Scalar singlet

The scalar singlet spontaneously breaks the B-L symmetry.

The other two neutrinos generate the active neutrino masses via Type I Seesaw Mechanism.



Non-standard Cosmologies

Faster Than Usal Early Expansion

Density energy $\rho_\phi(t) \propto a(t)^{-(4+n)}, \quad n > 0$

The Hubble rate

$$H(T) \approx \frac{\pi}{3}\sqrt{\frac{g_\star}{10}}\frac{T^2}{M_{Pl}}\left(\frac{T}{T_r}\right)^{n/2}$$

The "Faster" Boltzmann Equation

$$\frac{dY_N}{dx} = -\frac{A\,\langle\sigma v\rangle}{x^{2-n/2}\,(x^n + x_r^n)^{1/2}}(Y_N^2 - Y_N^{eq\,2})$$

where

$$A = \frac{2\sqrt{2}\,\pi}{3\sqrt{5}}\,g_\star^{1/2}\,M_{Pl}\,m_N$$

Approximate analytical solutions

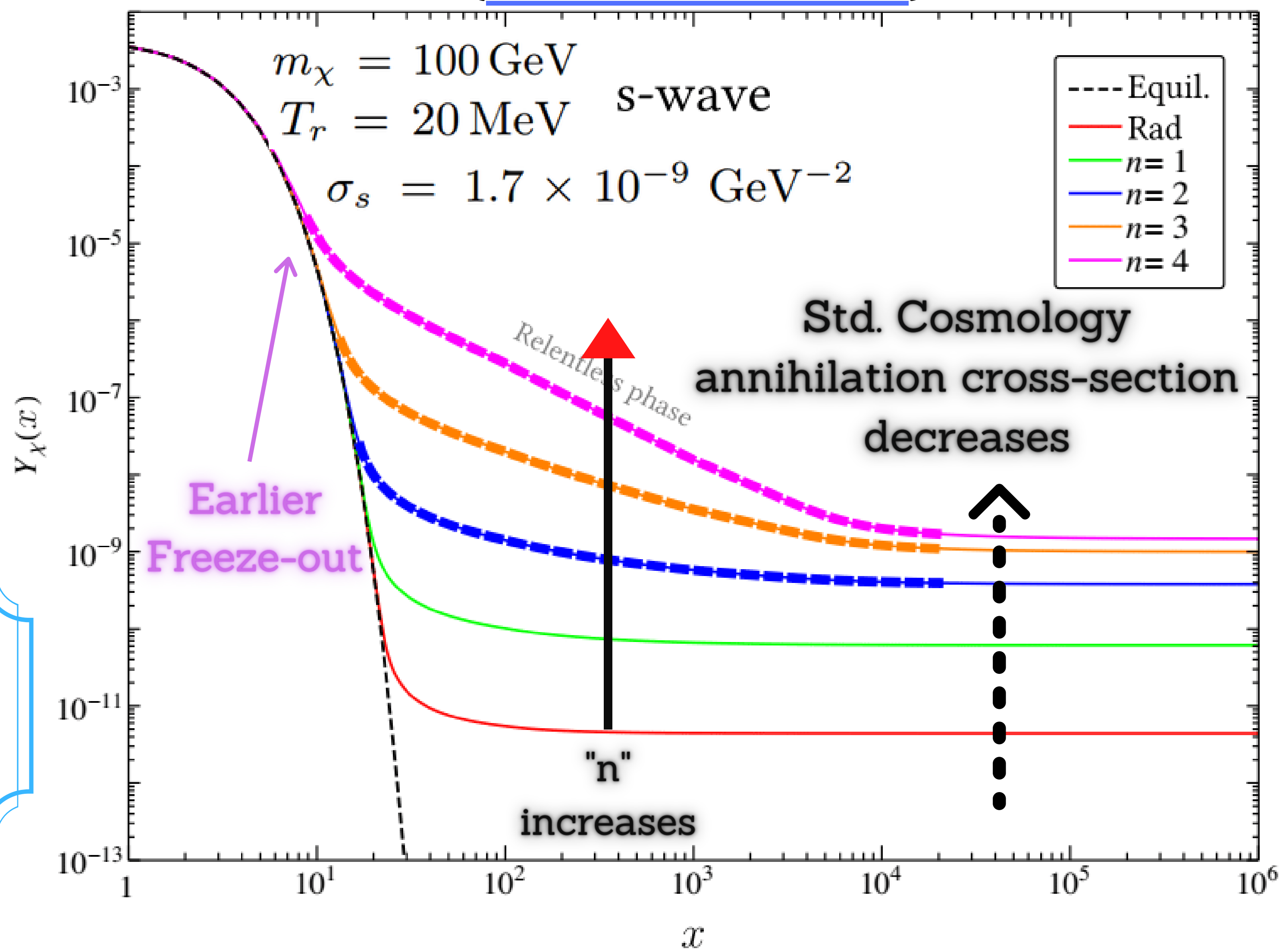
$$Y_N(x) \simeq \frac{x_r}{m_N\,M_{Pl}\langle\sigma v\rangle}\left[\frac{2}{x_f} + \log\left(\frac{x}{x_f}\right)\right]^{-1}, \quad n = 2$$

$$Y_N(x) \simeq \frac{x_r^{n/2}}{2\,m_N\,M_{Pl}\langle\sigma v\rangle}\left[x_f^{n/2-2} + \frac{x^{n/2-1}}{n-1}\right]^{-1}, \quad n > 2.$$

- Apply to the region between $x_f \lesssim x \lesssim x_r$.
- s-wave annihilation cross-section.

$$\boxed{\begin{aligned}\Omega_N h^2 &= \frac{s_0}{\rho_0}\,h^2\,m_N\,Y_N(x\to\infty)\\ &\simeq 2.82\times 10^8\,m_N\,Y_N(x\to\infty)\end{aligned}}$$

D'Eramo et al. (ArXiv: 1703.04793)



The Cosmological Parameters

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

Jacinto Neto @ PhenoBR 2021

Early Matter-dominated

The Boltzmann Equations

$$\frac{d\rho_\phi}{dt} = -3\,H\rho_\phi - \Gamma_\phi\,\rho_\phi,$$
$$\frac{ds}{dt} = -3\,H\,s + \frac{\Gamma_\phi\,\rho_\phi}{T} + 2\,\frac{E}{T}\,\langle\sigma v\rangle(n_N^2 - n_N^{2\,eq}),$$
$$\frac{dn_N}{dt} = -3\,H\,n_N - \langle\sigma v\rangle(n_N^2 - n_N^{2\,eq}),$$

$$\omega_\phi = 0$$

Unstable
scalar field

The scalar field decays only into SM radiation. Hence, injecting entropy into SM bath and diluting DM.

Early Radiation-dominated Freeze-out $T_{eq} \ll T_f$

The Hubble rate

$$H_R(x) \simeq \frac{\pi}{3}\sqrt{\frac{g_\star}{10}}\frac{m_N^2}{M_{Pl}}x^{-2}$$

$\Longrightarrow$

The Boltzmann Equation is the standard one

$$\frac{dY_N}{dx} = -\frac{s\,\langle\sigma v\rangle}{H_R\,x}(Y_N^2 - Y_N^{eq\,2})$$

$\Longrightarrow$

Approx. Solution

$$Y_N^{std}$$

Early Matter-dominated

The energy conservation and the definition of κ provide the dilution factor

$$D \equiv \frac{s(T_2)}{s(T_1)} = \left(\frac{T_2}{T_1}\right)^3 = \kappa \frac{m_N}{T_{end}}$$

The Cosmological Parameters

$$\kappa = \left.\frac{\rho_\phi}{\rho_R}\right|_{T=m_N} \qquad T_{end} \equiv \left[\frac{90\, M_{Pl}^2}{\pi^2 g_\star(T_{end})}\right]^{1/4} \Gamma_\phi^{1/2}$$

$$T_{end} \gtrsim 4\,\mathrm{MeV}$$

The approximate standard solution

taking into account the entropy dilution

$$Y_N = \frac{Y_N^{std}}{D} \qquad \Omega_N h^2 = \frac{\Omega_N^{std} h^2}{D}$$

Early Matter-dominated Freeze-out

$$T_c \ll T_f \ll T_{eq}$$

The Hubble rate

$$H \simeq H_\star \left(\frac{g_\star(T)}{g_\star(T_\star)}\right)^{3/8} \left(\frac{T}{T_\star}\right)^{3/2} \left[(1-r) + r\left(\frac{T}{T_\star}\right)\right]^{1/2}$$

The $r \in [0,1]$ parameter

$$r \equiv \left.\frac{\rho_R + \rho_N}{\rho_\phi + \rho_R + \rho_N}\right|_{T=T_\star} = \left[1 + \frac{g_\phi(T_\star)}{g_\star(T_\star) + g_N}\left(\frac{m_\phi}{T_\star}\right)^4\right]^{-1}$$

$r \ll 1$

$r \simeq 1$

Early Matter-dominated

Early Matter-dominated Freeze-out $T_c \ll T_f \ll T_{eq}$

The approximate solution for BEQ

$$r \ll 1 \longrightarrow \quad Y_N^{MD} = \frac{3}{2}\sqrt{\frac{45}{\pi}}\frac{\sqrt{g_\star}}{g_{\star s}}\frac{x_f^{3/2}}{m_N\, M_{Pl}\,\langle\sigma v\rangle\, x_\star^{1/2}}$$

$$\boxed{Y_N = \zeta\, Y_N^{MD} \quad \Longrightarrow \quad \Omega_N h^2 = \zeta\, \Omega_N^{MD} h^2}$$

The "inverse" dilution factor

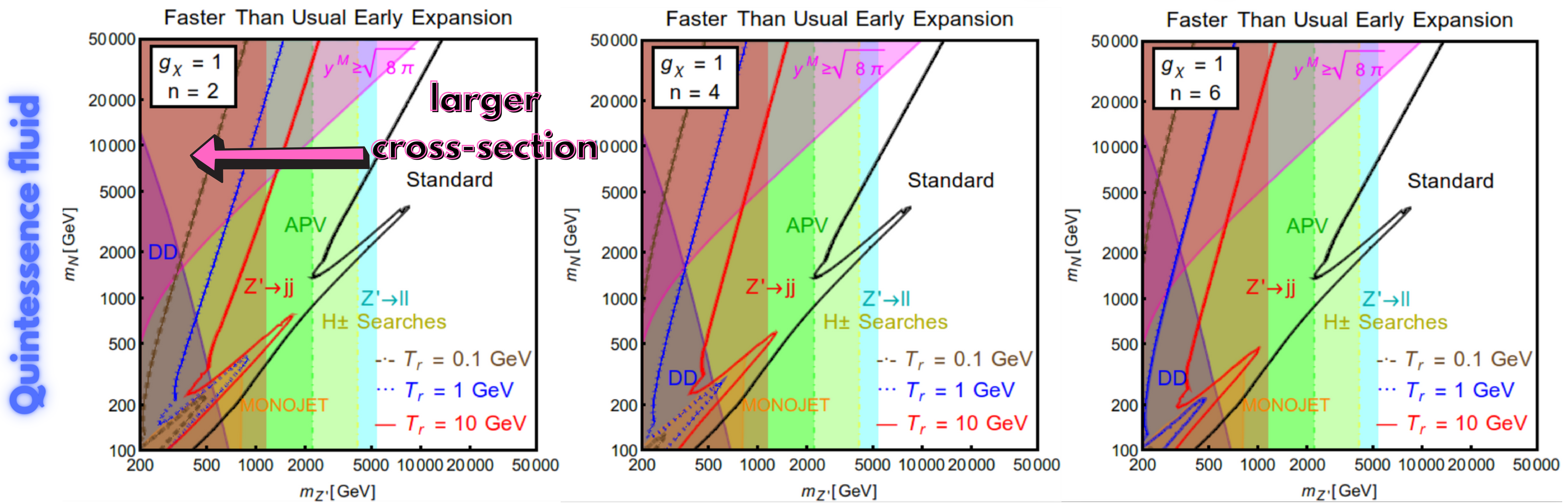
$$\zeta = \frac{s(T_1)}{s(T_2)} \simeq (1-r)^{-1}\,\frac{g_\star(T_c)}{g_\star(T_\star)}\,\frac{T_{end}}{T_\star}$$

The Cosmological Parameters

ζ , $T_\star$


Results

Faster Than Usal Early Expansion



The contours move toward smaller Z' masses to suppress the enhancement on the DM relic density.

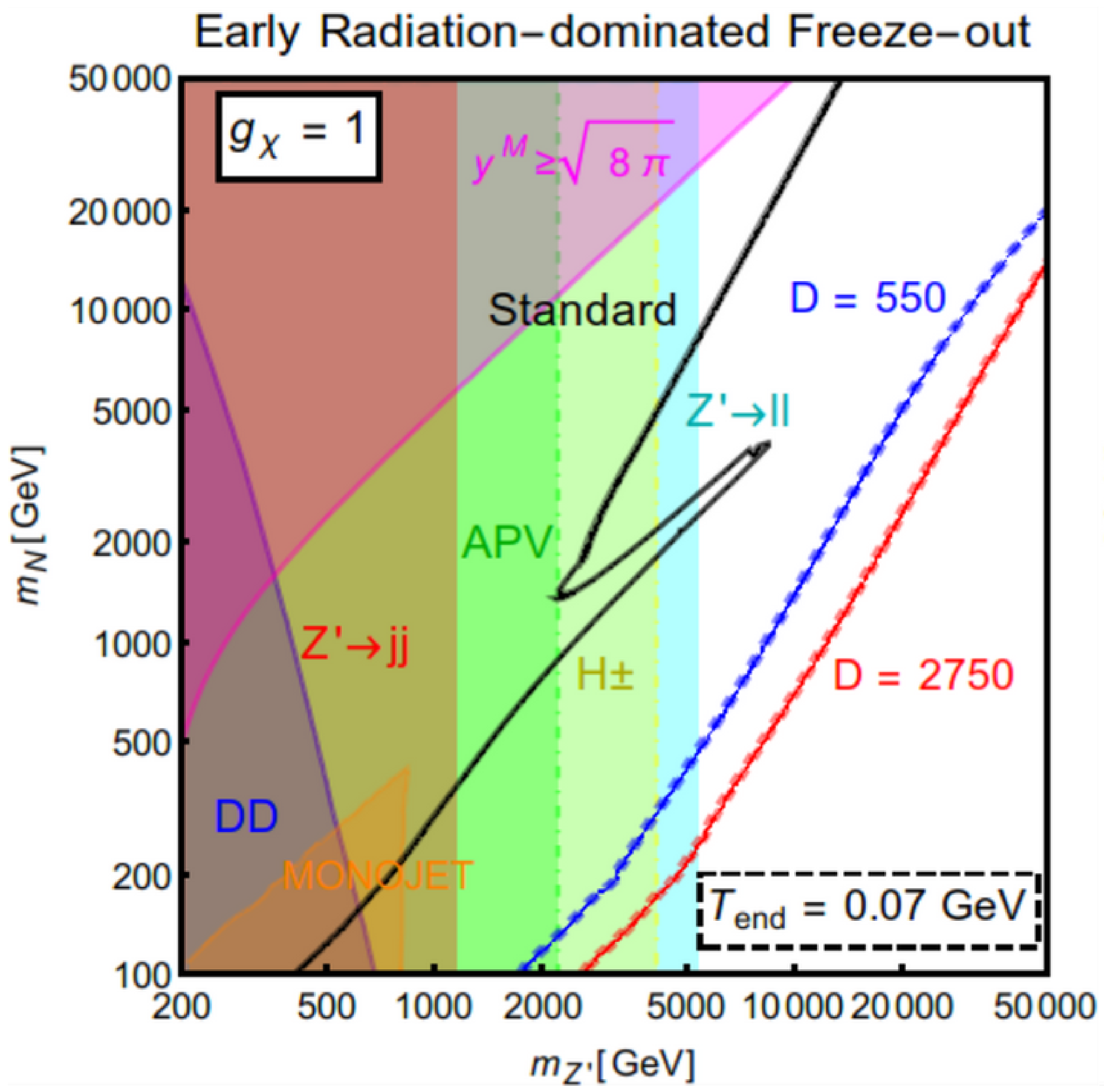
On the other hand,

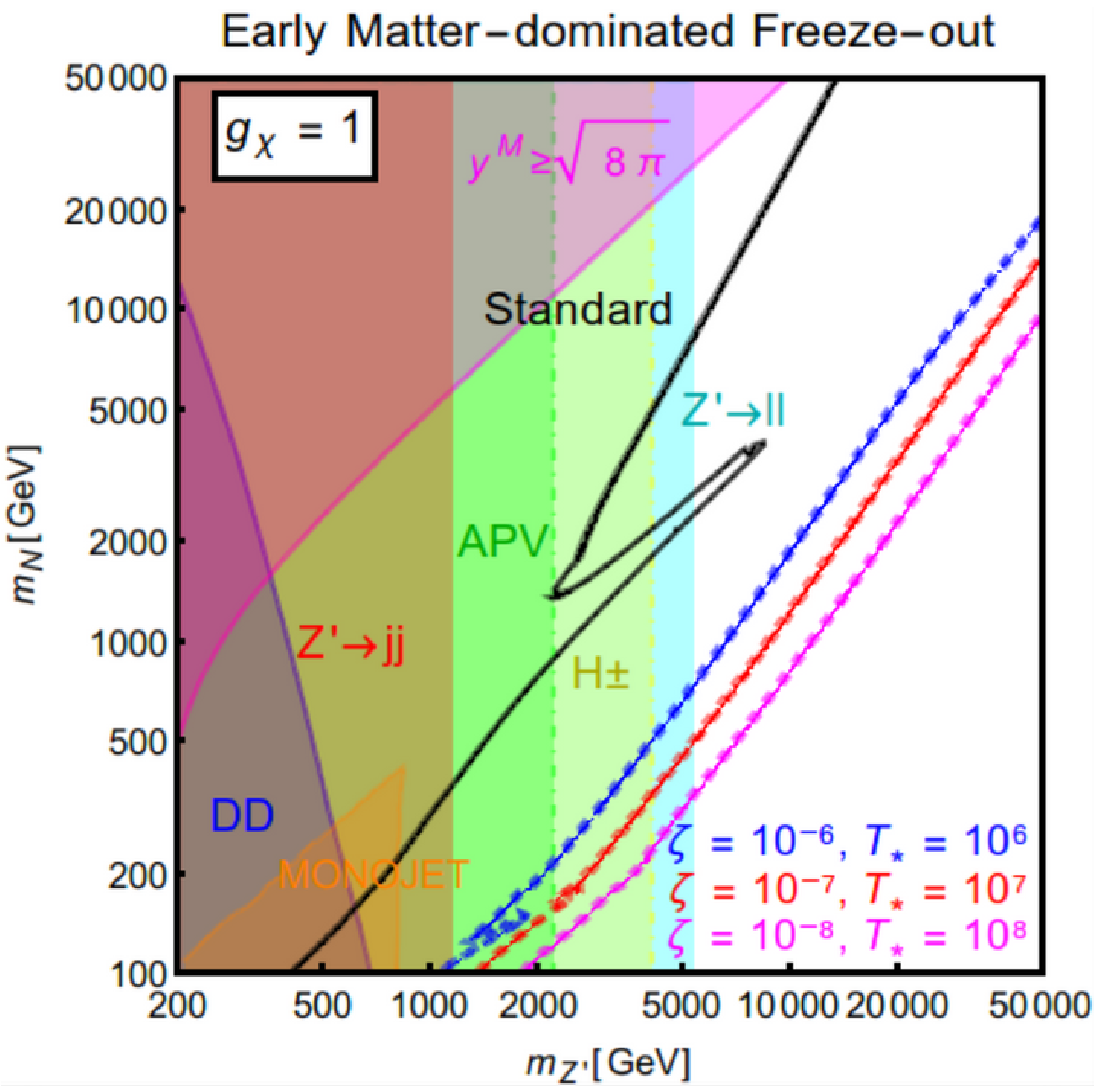
The heavier the DM mass, the larger the Z' mass

⇄

LONGER RELENTLESS PHASE

Early Matter-dominated





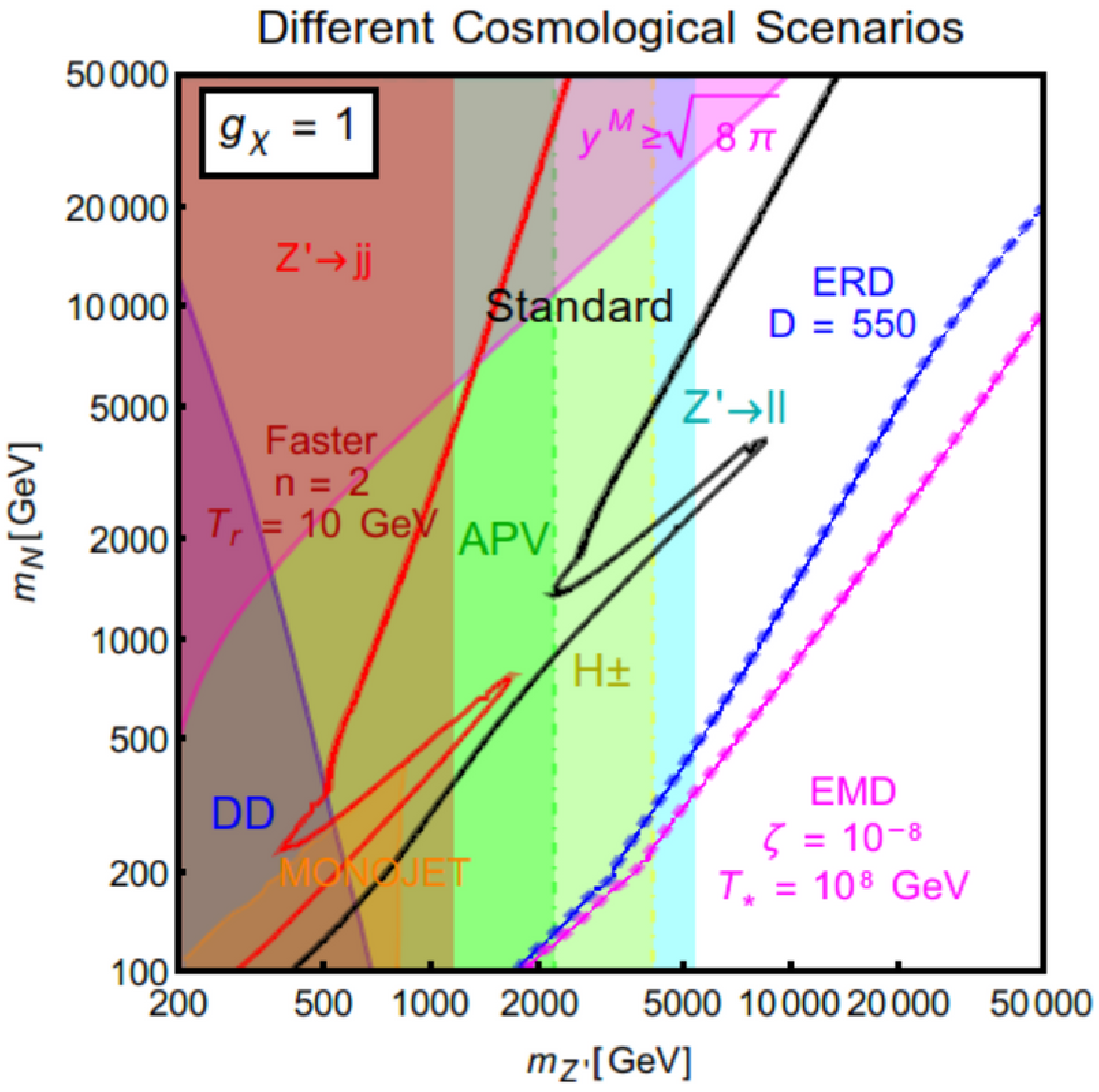
The larger the entropy after the decay of the scalar field, the smaller the cross-sections and the lighter the DM mass required.

The entropy after the decay must be larger for matter-dominated freeze-out.

The Relentless phase x Entropy injection

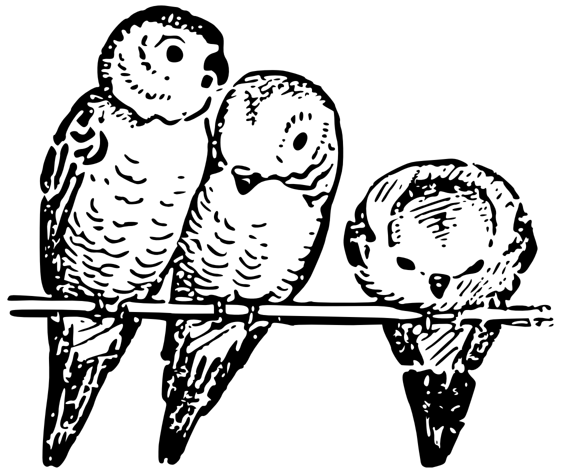
Freeze-out during larger expansion rates requires larger cross-sections.

Post-freeze-out in which the DM number density is suppressed by unstable matter field gives lower cross-sections.



Conclusions

Conclusions



- We explored the impact of different non-standard cosmologies on the right-handed neutrino in a 2HDM augemented by B-L gauge symmetry.
    1. Relentless freeze-out (faster than usual early expansion);
    2. Radiation-dominated freeze-out; and
    3. Matter-dominated freeze-out.
- For faster expanding, it is very bounded due to large cross-sections.

- For early radiation-dominated freeze-out, the model can be completely unconstrained for DM mass around $\simeq$ 200 GeV.
- For early matter-dominated freeze-out, a completely unconstrained DM mass arises from nearly 400 GeV up so.

Thank you!

Backup Slides

The Particle Physics Model

Particle Content

Type I 2HDM augmented by B-L gauge symmetry

STANDARD QUARK SECTOR

$$Q_{aL} = \begin{pmatrix} u_{aL} \\ d_{aL} \end{pmatrix} \sim (\mathbf{3}, \mathbf{2}, 1/6, 1/3),$$

$$u_{aR} \sim (\mathbf{3}, \mathbf{1}, 2/3, 1/3) \text{ and } d_{aR} \sim (\mathbf{3}, \mathbf{1}, -1/3, 1/3).$$

STANDARD LEPTONIC SECTOR + 3RHN

$$L_{aL} = \begin{pmatrix} e_{aL} \\ \nu_{aL} \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, -1/2, -1),$$

$$e_{aR} \sim (\mathbf{1}, \mathbf{1}, -1, -1) \text{ and } N_{aR} \sim (\mathbf{1}, \mathbf{1}, 0, -1),$$

GAUGE SECTOR

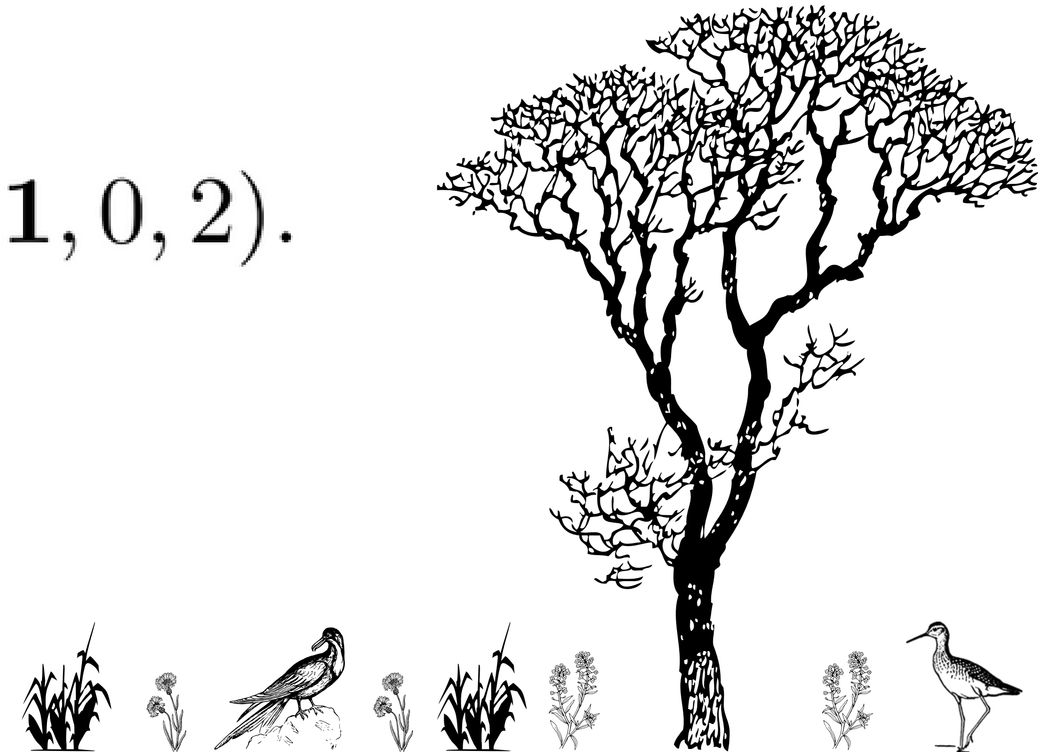
$$A,\ W^{\pm},\ Z,\ Z' \text{ and } g_i \text{ (gluons)}$$

SCALAR SECTOR

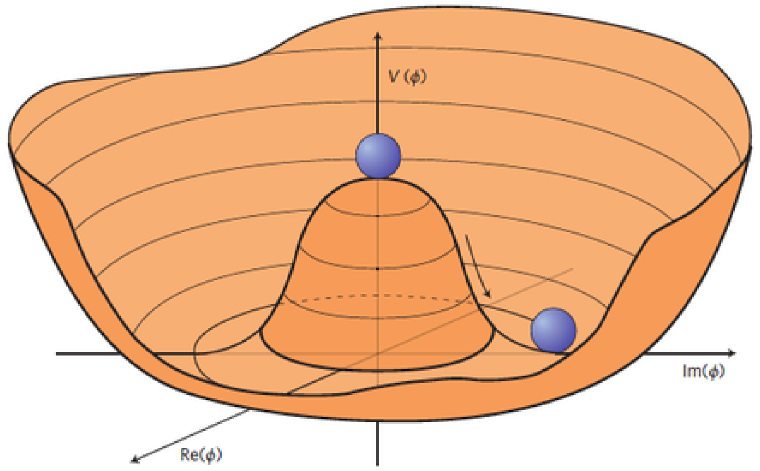
$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, 1/2, 2),$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, 1/2, 0),$$

$$\Phi_s \sim (\mathbf{1}, \mathbf{1}, 0, 2).$$



Yukawa Lagrangian



John Ellis et al. ([ArXiv: 1504.07217](https://arxiv.org/abs/1504.07217))

$$-\mathcal{L}_{Y_1} = y^d_{ab}\bar{Q}_a\Phi_2 d_{bR} + y^u_{ab}\bar{Q}_a\widetilde{\Phi}_2 u_{bR} + y^e_{ab}\bar{L}_a\Phi_2 e_{bR} + h.c.,$$

Fermions interact only with the second doublet.

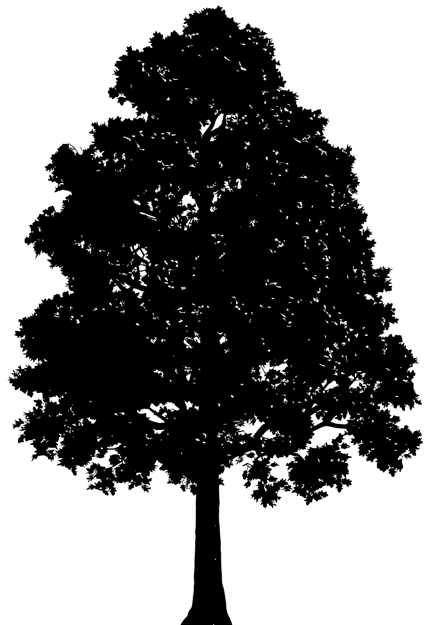
$$-\mathcal{L}_{Y_2} \supset y_{ab}\bar{L}_a\widetilde{\Phi}_2 N_{bR} + y^M_{ab}\overline{(N_{aR})^c}\Phi_s N_{bR} + h.c.\,,$$

The scalar singlet spontaneously breaks the B-L symmetry.

@ Dirac mass

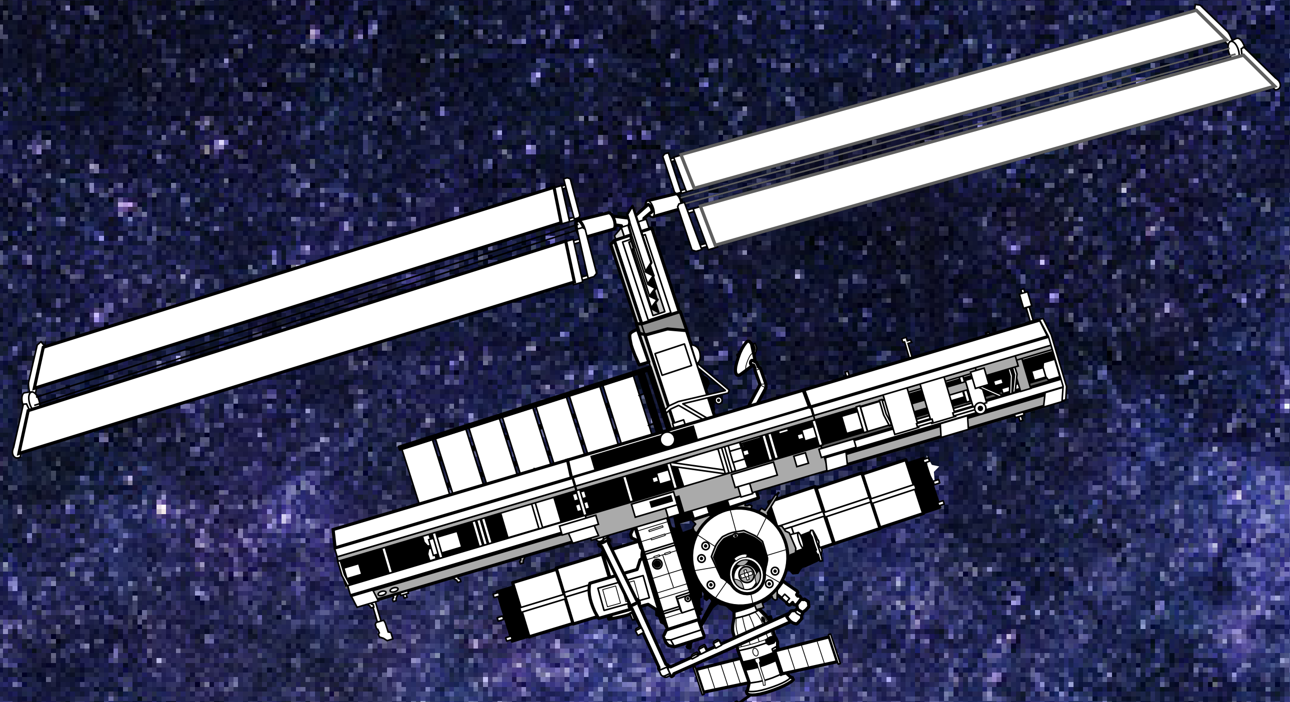
@ Majorana mass

The DM candidate is odd under a Z2 symmetry to ensure stability.



The other two neutrinos generate the active neutrino masses via Type I Seesaw Mechanism.

$$(\nu\; N)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$



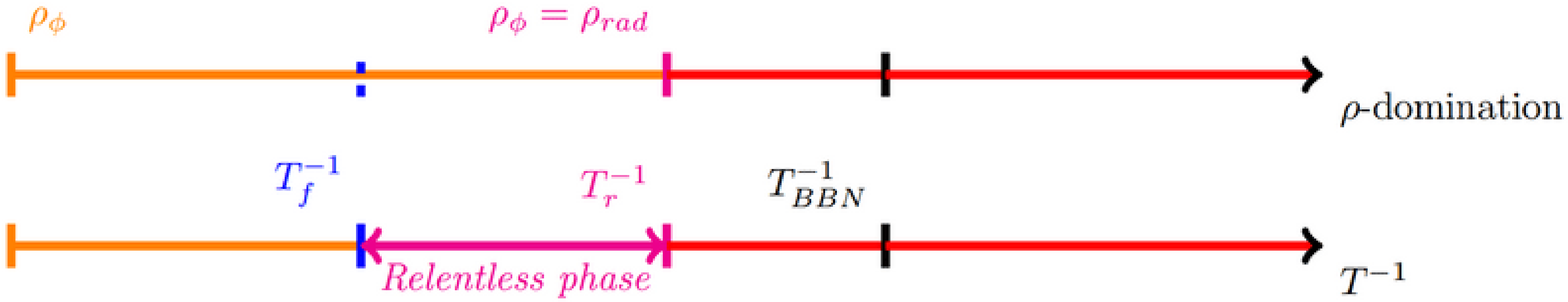
Non-standard Cosmologies

Faster Than Usal Early Expansion

Brief Thermal History

$$\rho_\phi(t) \propto a(t)^{-(4+n)}, \quad n > 0$$

$$\rho_\phi(T) = \rho_\phi(T_r)\left(\frac{g_{\star\,s}(T)}{g_{\star\,s}(T_r)}\right)^{(4+n)/3}\left(\frac{T}{T_r}\right)^{4+n}$$



$$\begin{aligned}\rho(T) &= \rho_R(T) + \rho_\phi(T) \\ &= \rho_R(T)\left[1 + \frac{g_\star(T_r)}{g_\star(T)}\left(\frac{g_{\star\,s}(T)}{g_{\star\,s}(T_r)}\right)^{(4+n)/3}\left(\frac{T}{T_r}\right)^n\right]\end{aligned}$$

The Cosmological Parameters

$$(n,\, T_r)$$

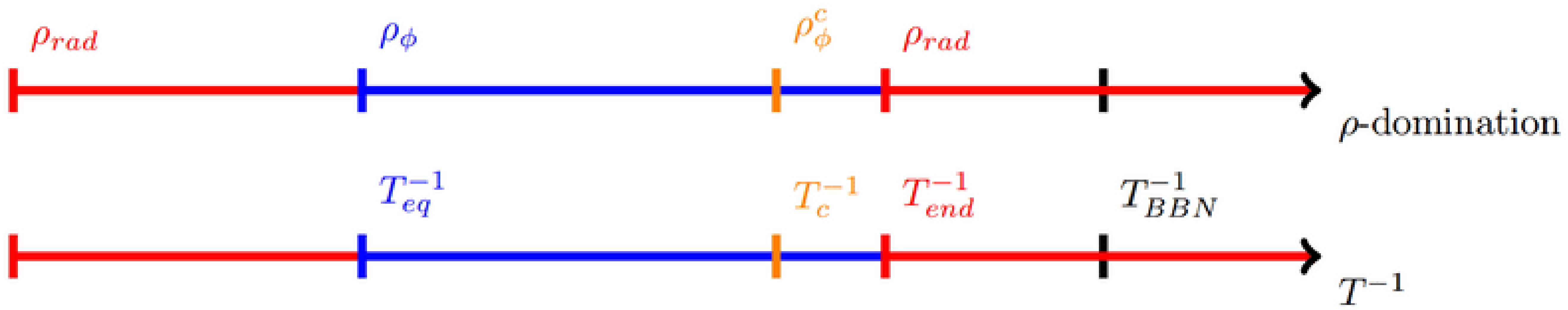
$$\boxed{T_r \gtrsim (15.4)^{1/n}\,\text{MeV}}$$

Early Matter-dominated

Brief Thermal History

$\omega_\phi = 0$

Unstable scalar field



The Boltzmann Equations

$$\frac{d\rho_\phi}{dt} = -3\,H\rho_\phi - \Gamma_\phi\,\rho_\phi,$$

$$\frac{ds}{dt} = -3\,H\,s + \frac{\Gamma_\phi\,\rho_\phi}{T} + 2\,\frac{E}{T}\langle\sigma v\rangle(n_N^2 - n_N^{2\,eq}),$$

$$\frac{dn_N}{dt} = -3\,H\,n_N - \langle\sigma v\rangle(n_N^2 - n_N^{2\,eq}),$$

The Cosmological Parameters

$$\kappa = \left.\frac{\rho_\phi}{\rho_R}\right|_{T=m_N}$$

$$T_{end} \equiv \left[\frac{90\,M_{Pl}^2}{\pi^2 g_\star(T_{end})}\right]^{1/4}\Gamma_\phi^{1/2}$$

$$T_{end} \gtrsim 4\,\mathrm{MeV}$$

The scalar field decays only into SM radiation. Hence, injecting entropy into SM bath and diluting DM.