Roads for Right-handed Neutrino Dark Matter: Fast Expansion, Standard Freeze-out, and Early Matter Domination

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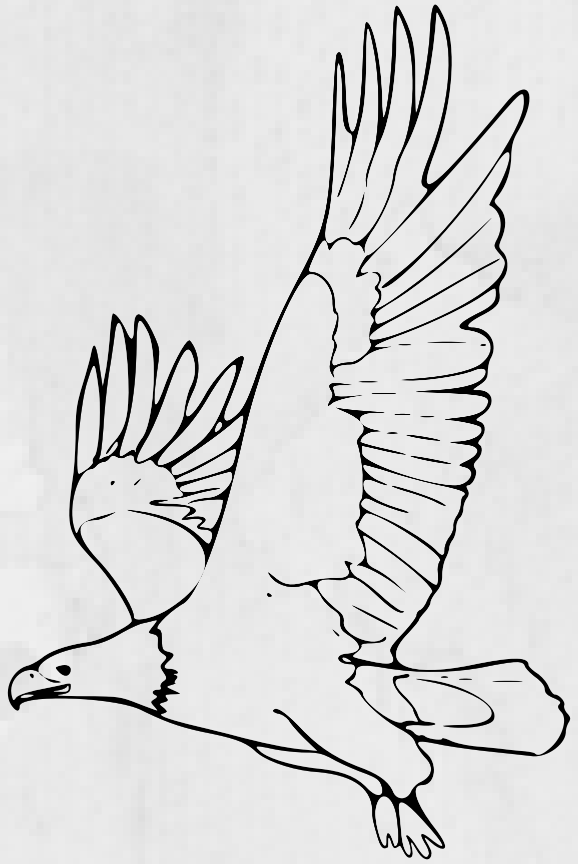
Outline

- BIRD'S EYE VIEW OF THE WORK
- NON-STANDARD COSMOLOGICAL HISTORIES
- RESULTS
- CONCLUSIONS



Bird's Eye View of the Work

Hubble rate versus Annihilation Rate

Faster Than Usual Early Expansion

Quintessence

Cosmology

Early Matter-dominated freeze-out

Early Radiation-dominated freeze-out

Fermions interact only with the second doublet.

Type-I 2HDM

+ B-L symmetry

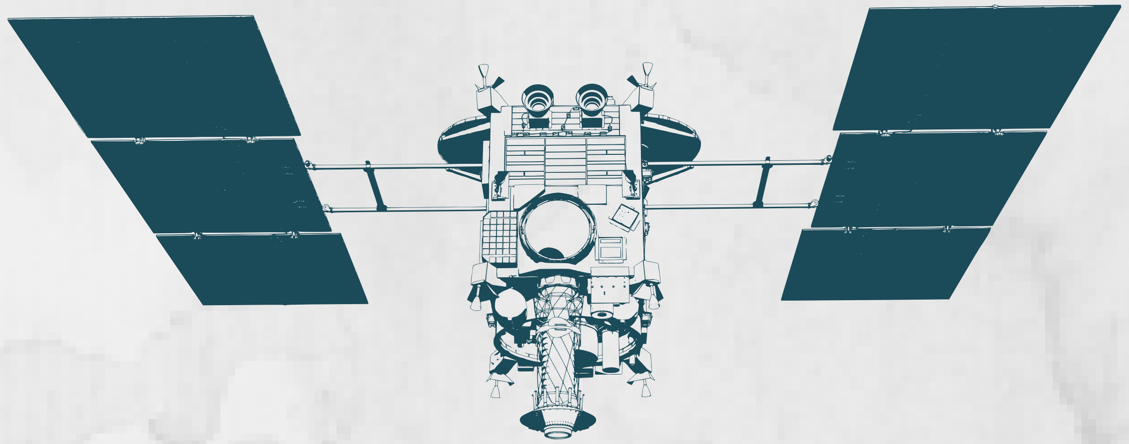
+ 2RHν + 1RHN

+ Scalar singlet

Particle Properties

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

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

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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

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

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Approximate analytical solutions

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

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

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

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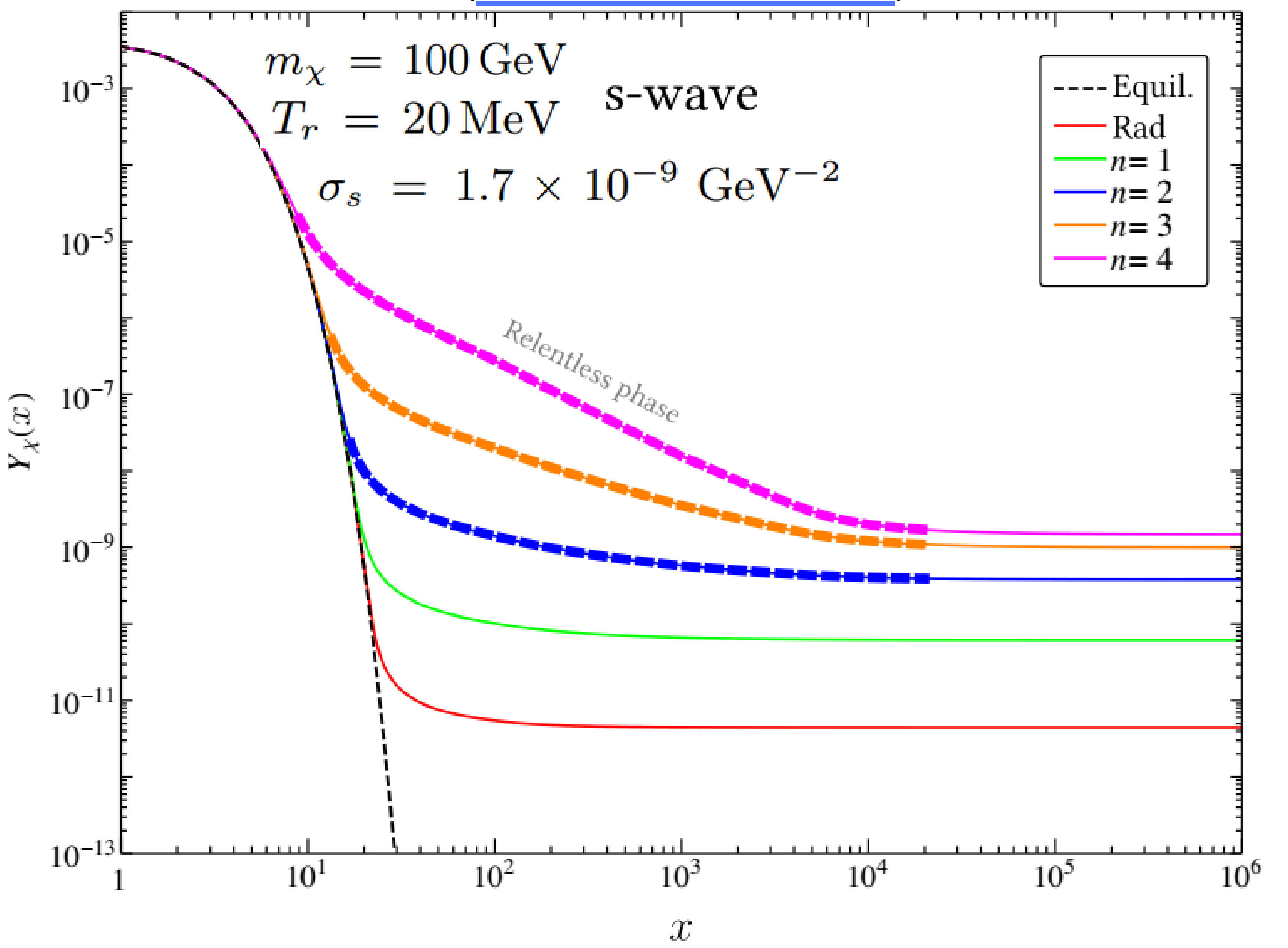
D'Eramo et al. (ArXiv: 1703.04793)



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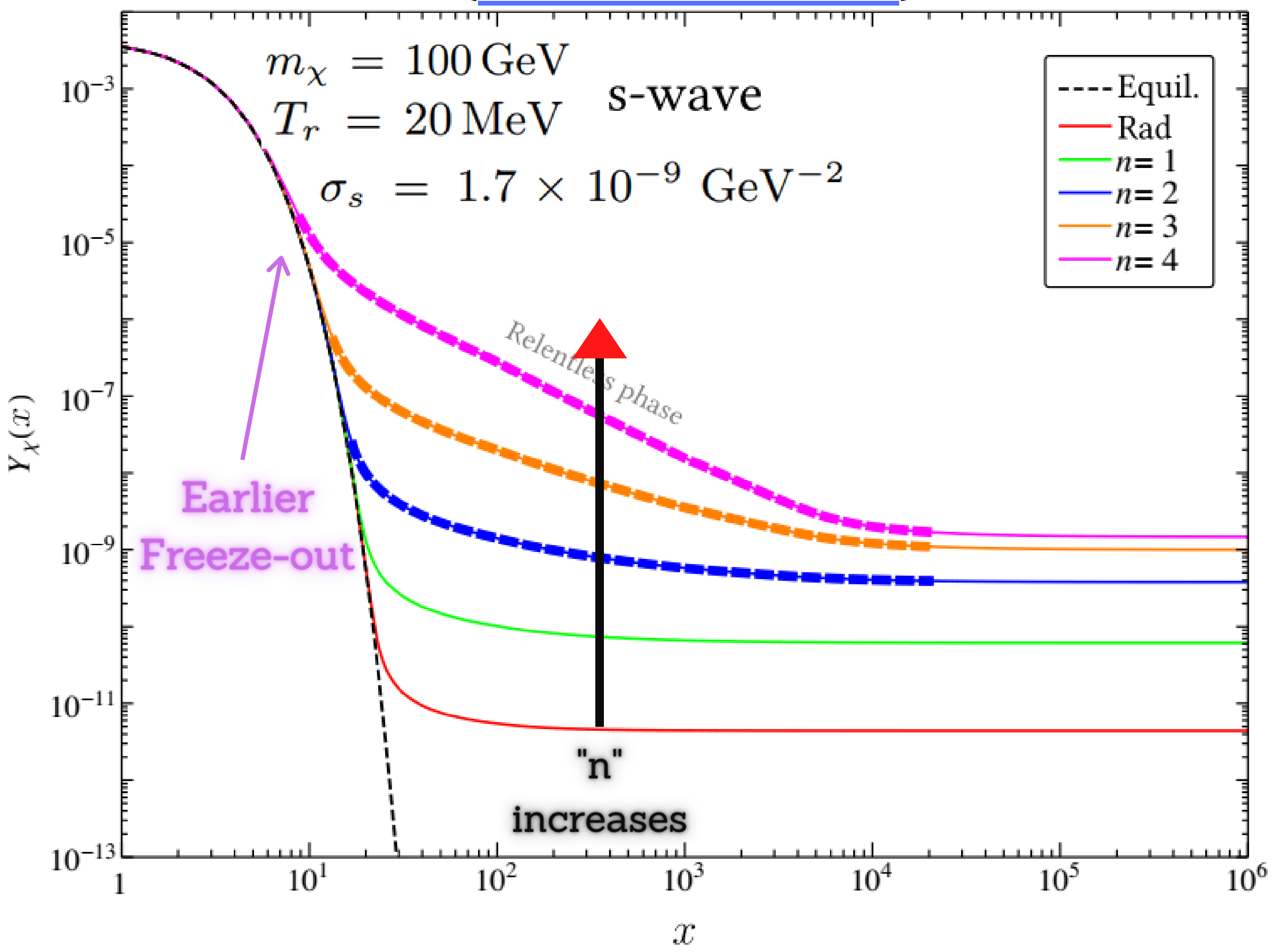

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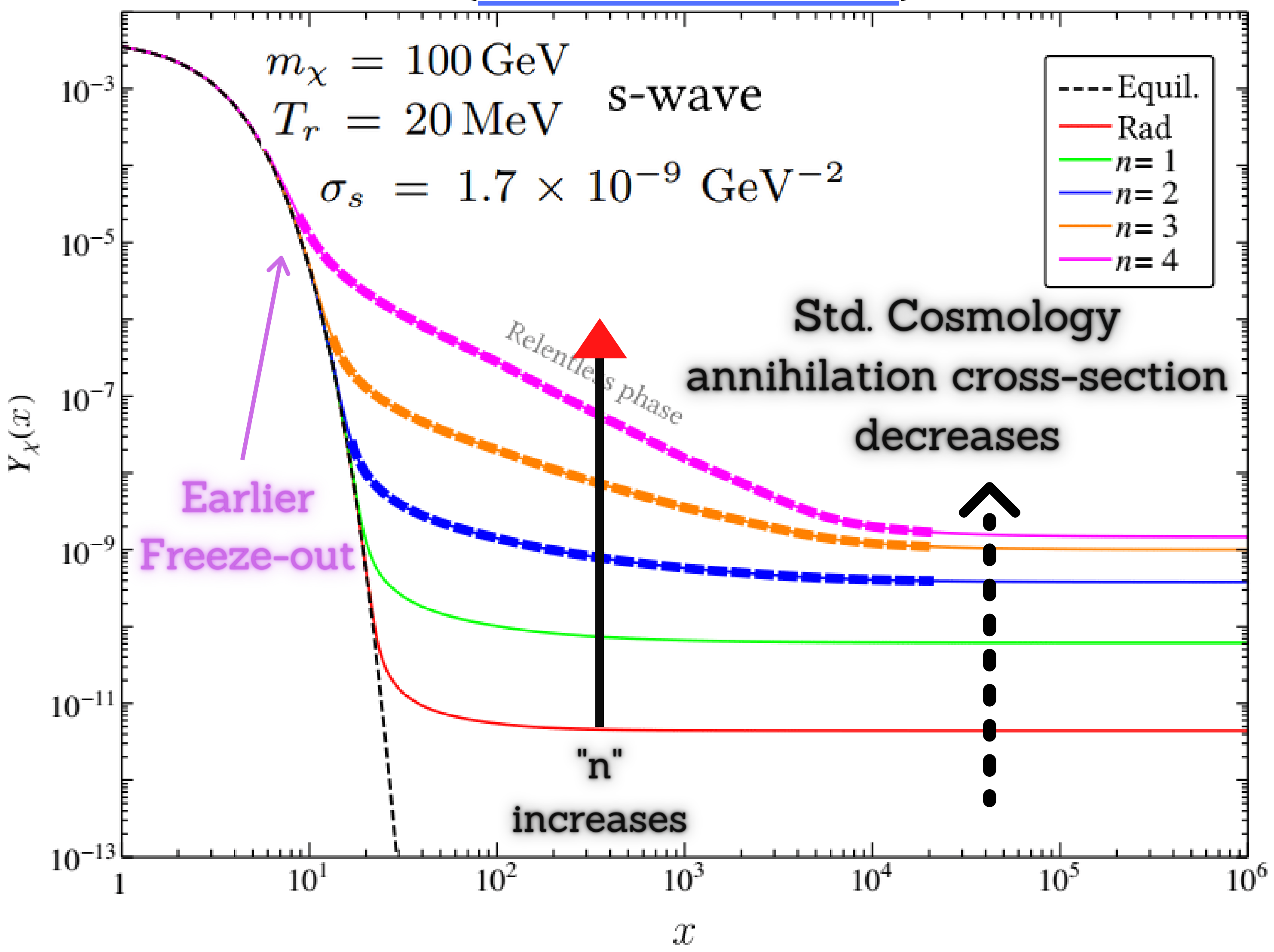

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$$\Omega_N h^2 = \frac{s_0}{\rho_0}\, h^2\, m_N\, Y_N(x\to\infty)$$
$$\simeq 2.82\times 10^8\, m_N\, Y_N(x\to\infty)$$

The Cosmological Parameters

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

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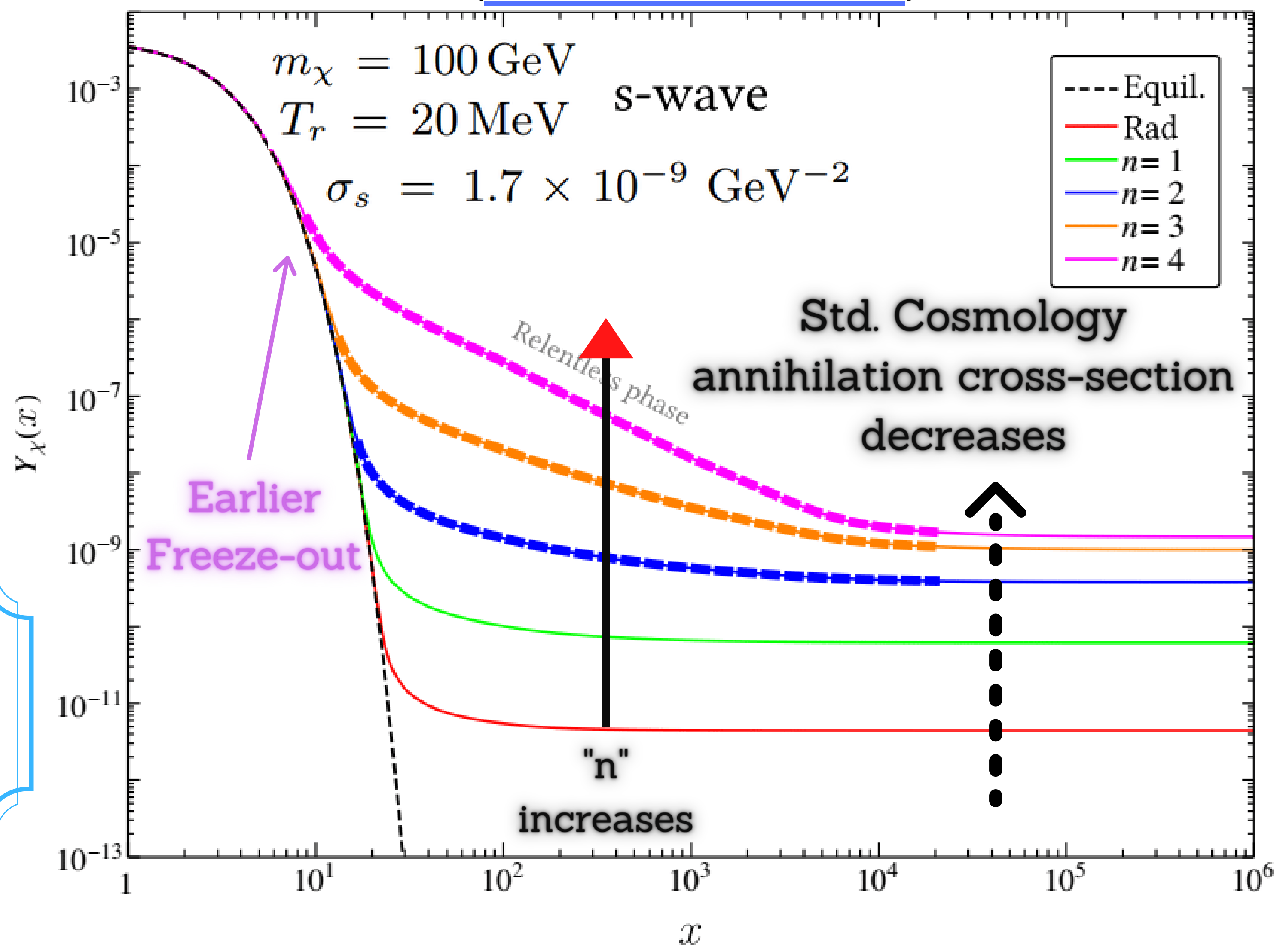

Early Matter-dominated

The Boltzmann Equations

$$\frac{d\rho_\phi}{dt} = -3\,H\rho_\phi - \Gamma_\phi\,\rho_\phi,$$
$$\frac{ds}{dt} = -3\,H\,s + \frac{\Gamma_\phi\,\rho_\phi}{T} + 2\,\frac{E}{T}\,\langle\sigma v\rangle(n_N^2 - n_N^{2\,eq}),$$
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$$\omega_\phi = 0$$

Unstable scalar field

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

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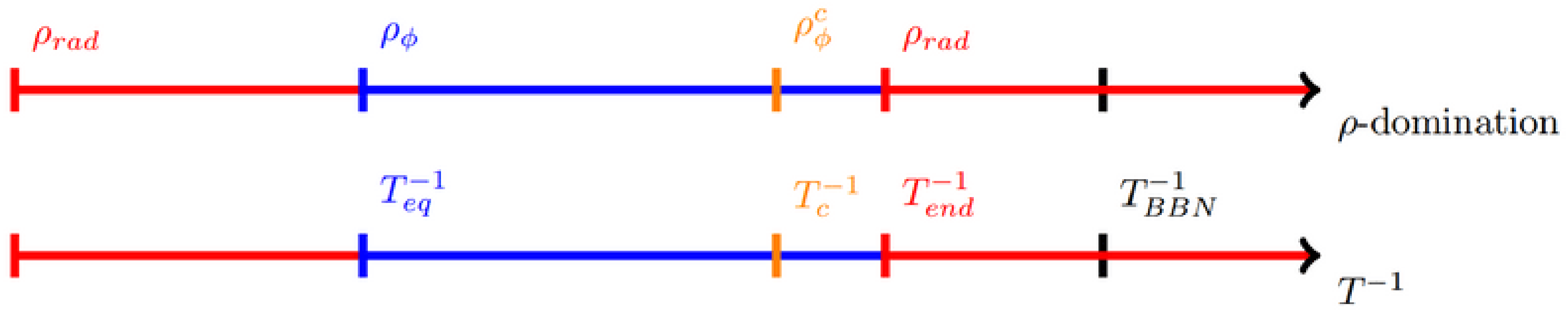

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Early Radiation-dominated Freeze-out $T_{eq} \ll T_f$

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Approx. Solution

$$Y_N^{std}$$

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

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

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The Cosmological Parameters

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

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

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The approximate standard solution

taking into account the entropy dilution

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

Early Matter-dominated

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

The Hubble rate

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

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

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

- $r \ll 1$
- $r \simeq 1$

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The approximate solution for BEQ

$r \ll 1 \longrightarrow$

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

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The "inverse" dilution factor

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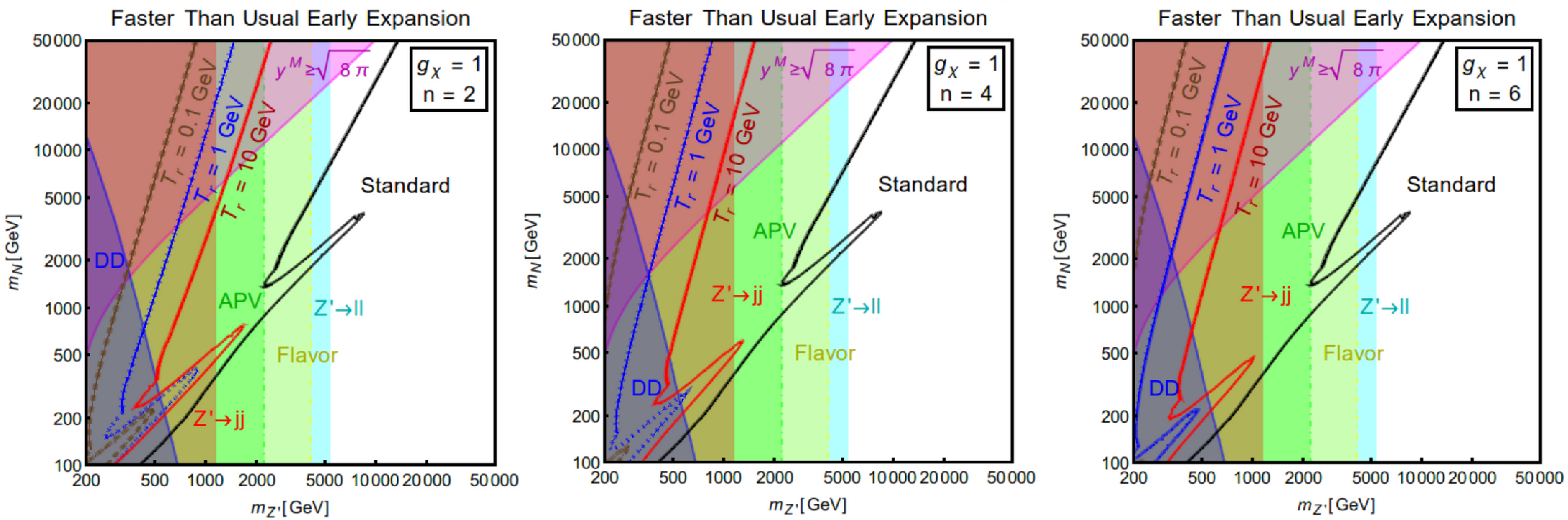
$$Y_N = \zeta\, Y_N^{MD} \quad \Rightarrow \quad \Omega_N h^2 = \zeta\, \Omega_N^{MD} h^2$$

The Cosmological Parameters

$\zeta\,,\, T_\star$

Results

Faster Than Usual Early Expansion



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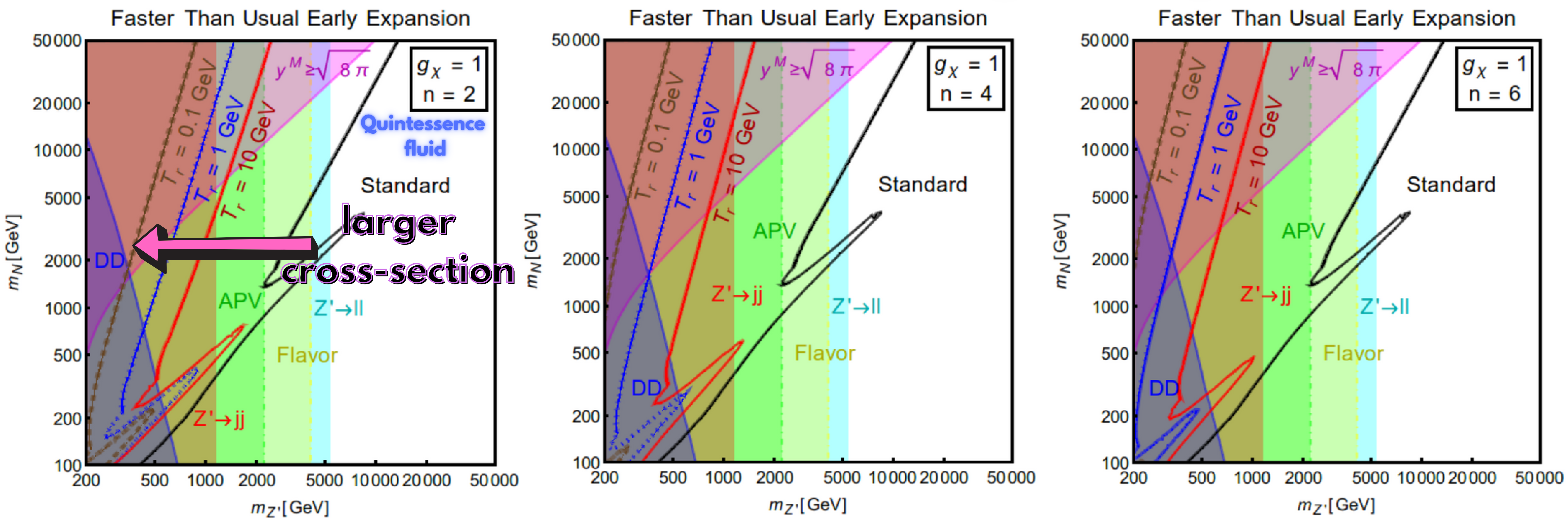

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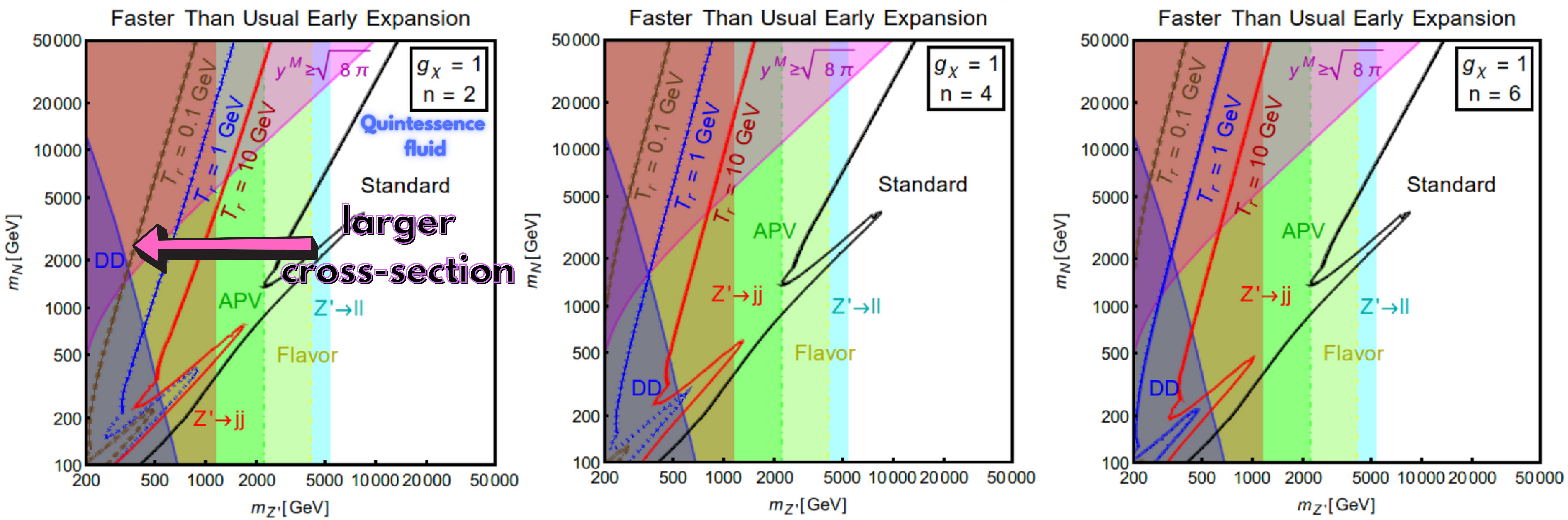

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The contours move toward smaller Z' masses to suppress the enhancement on the DM relic density.

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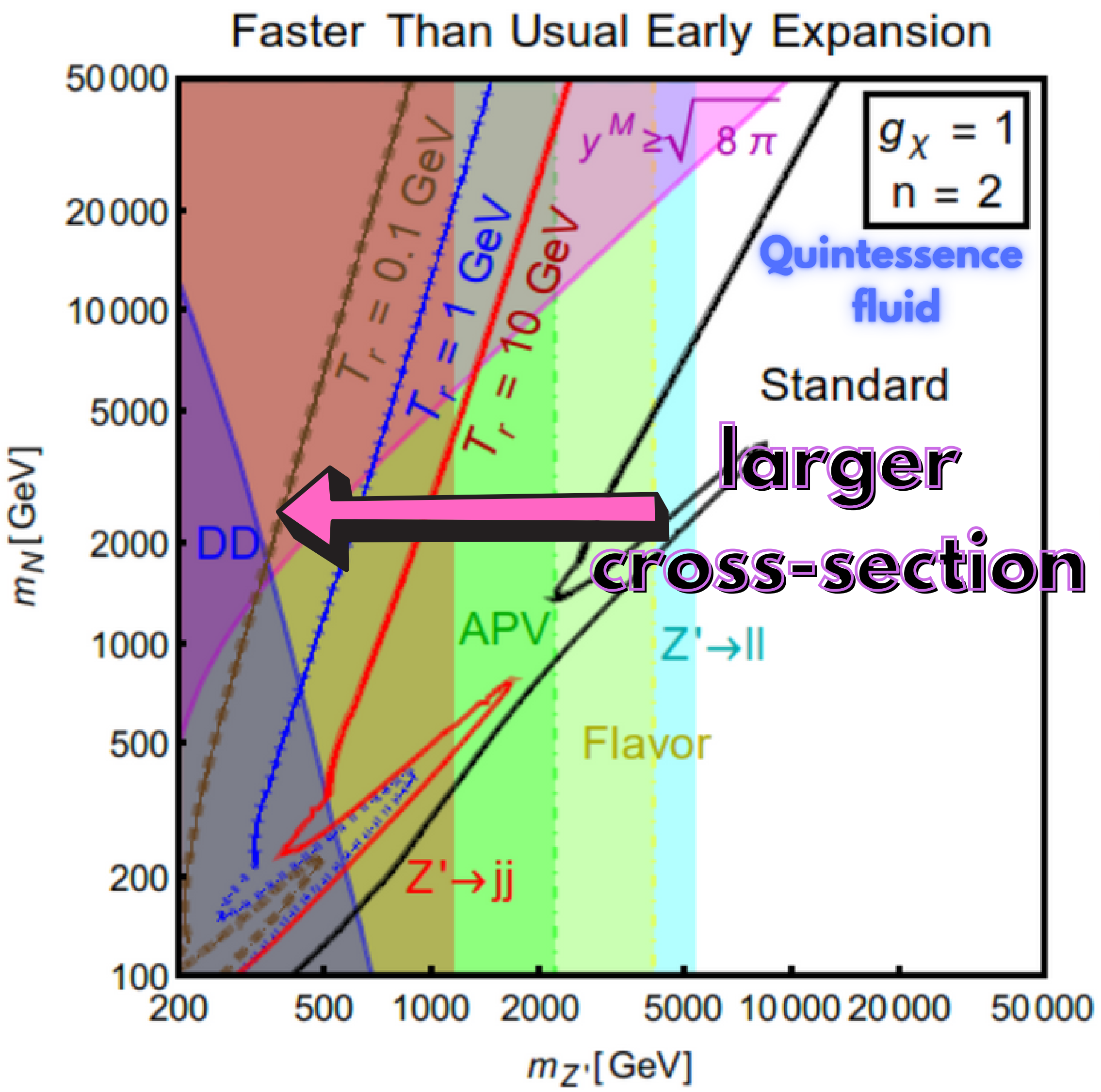

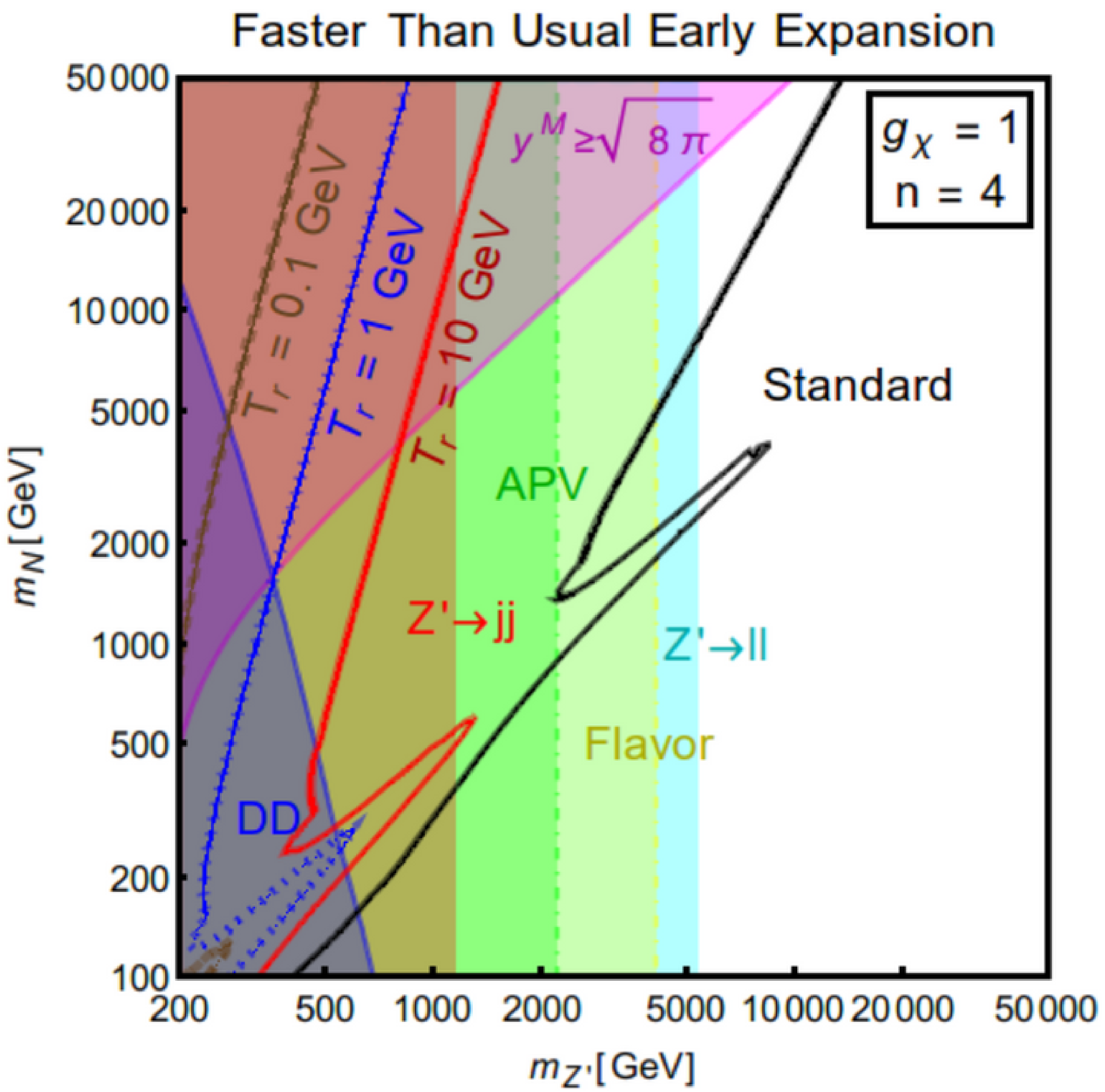

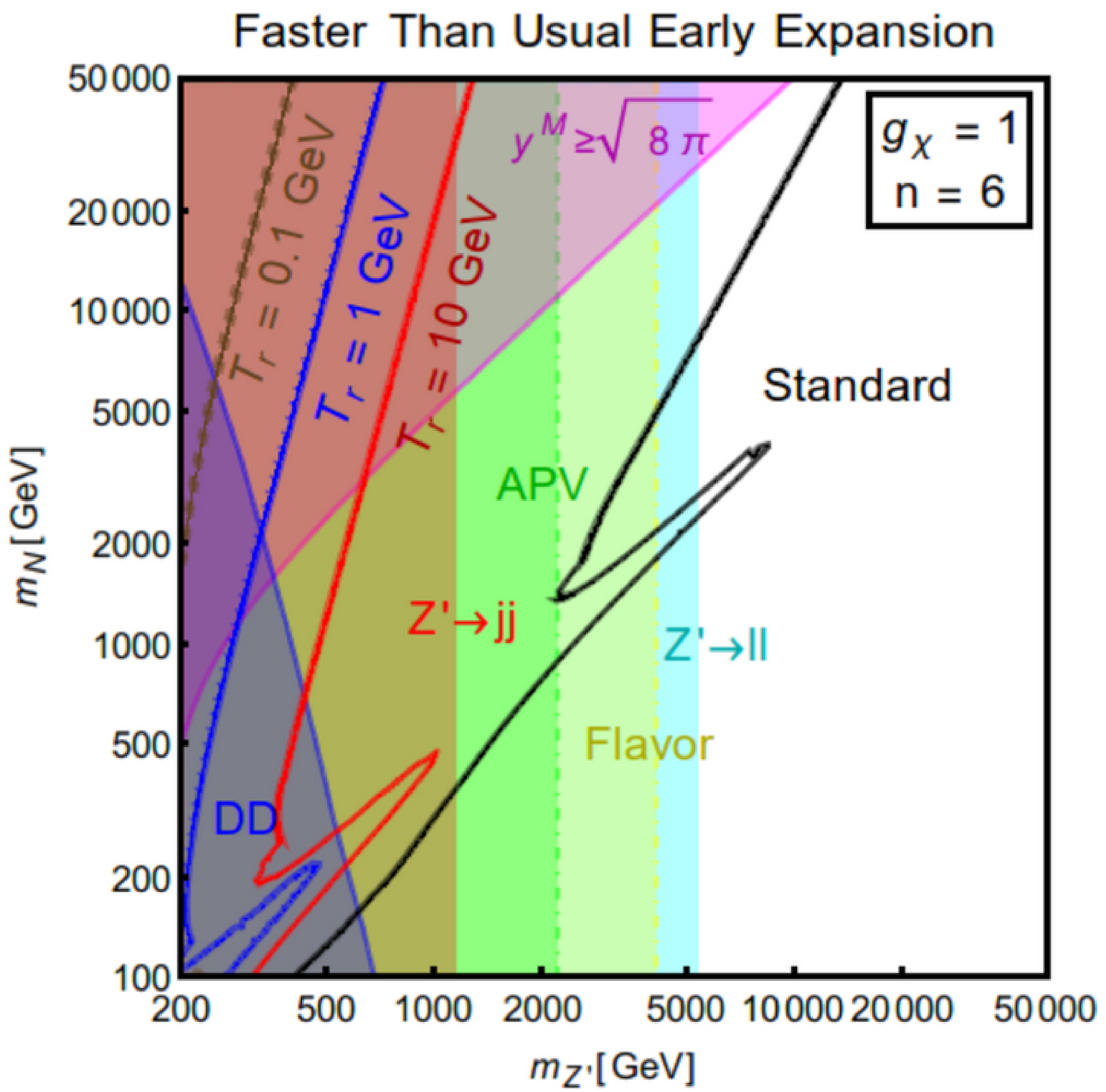

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On the other hand,

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

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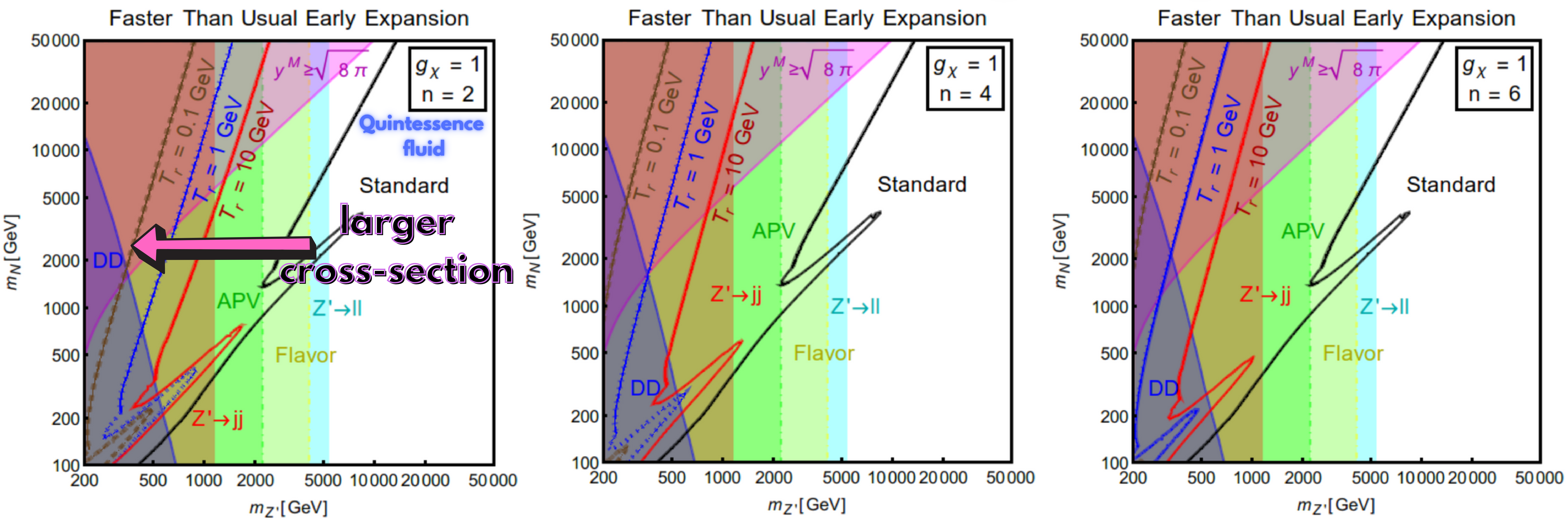

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The heavier the DM mass, the larger the Z' mass ⇄ LONGER RELENTLESS PHASE

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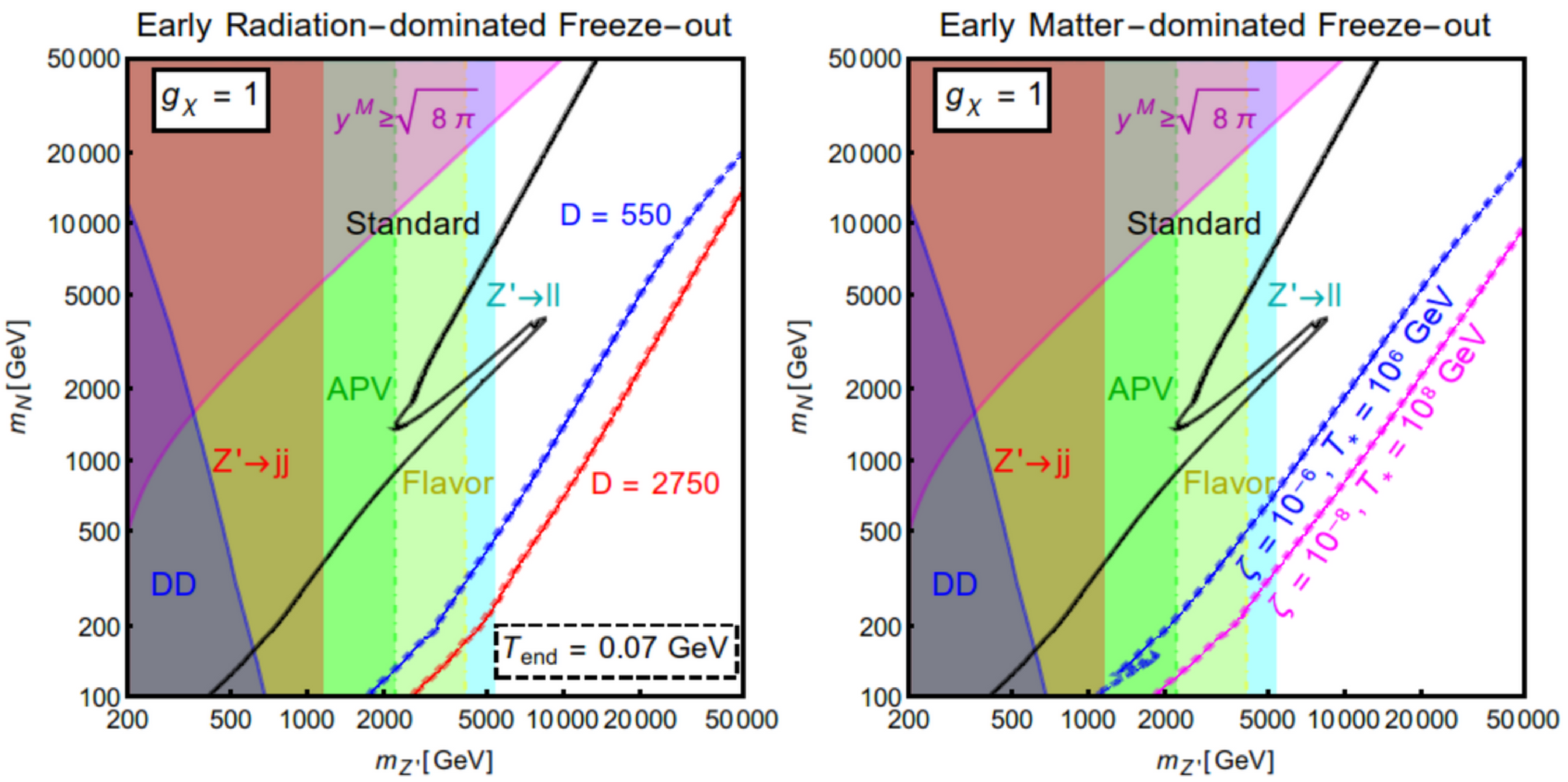

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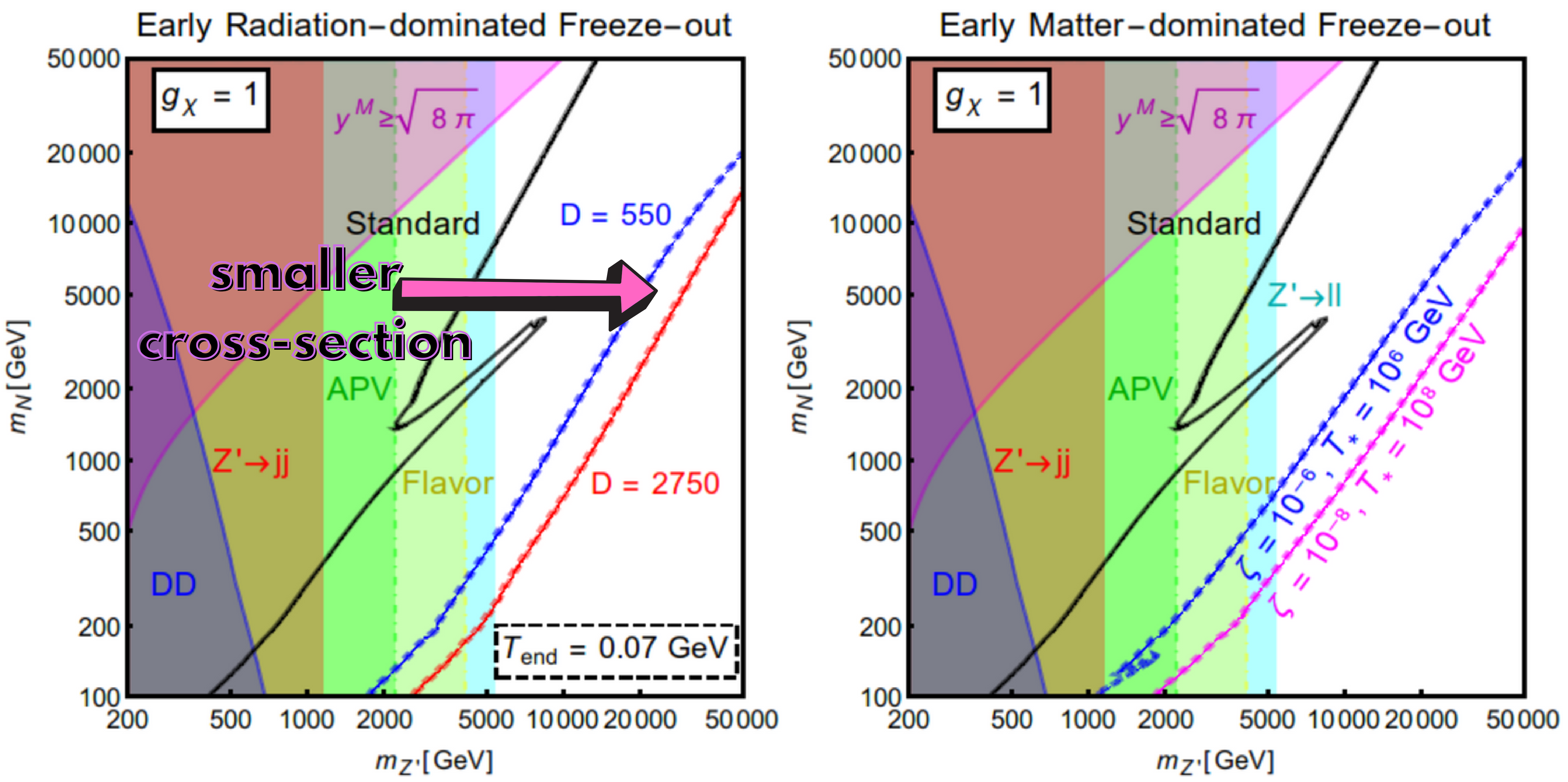

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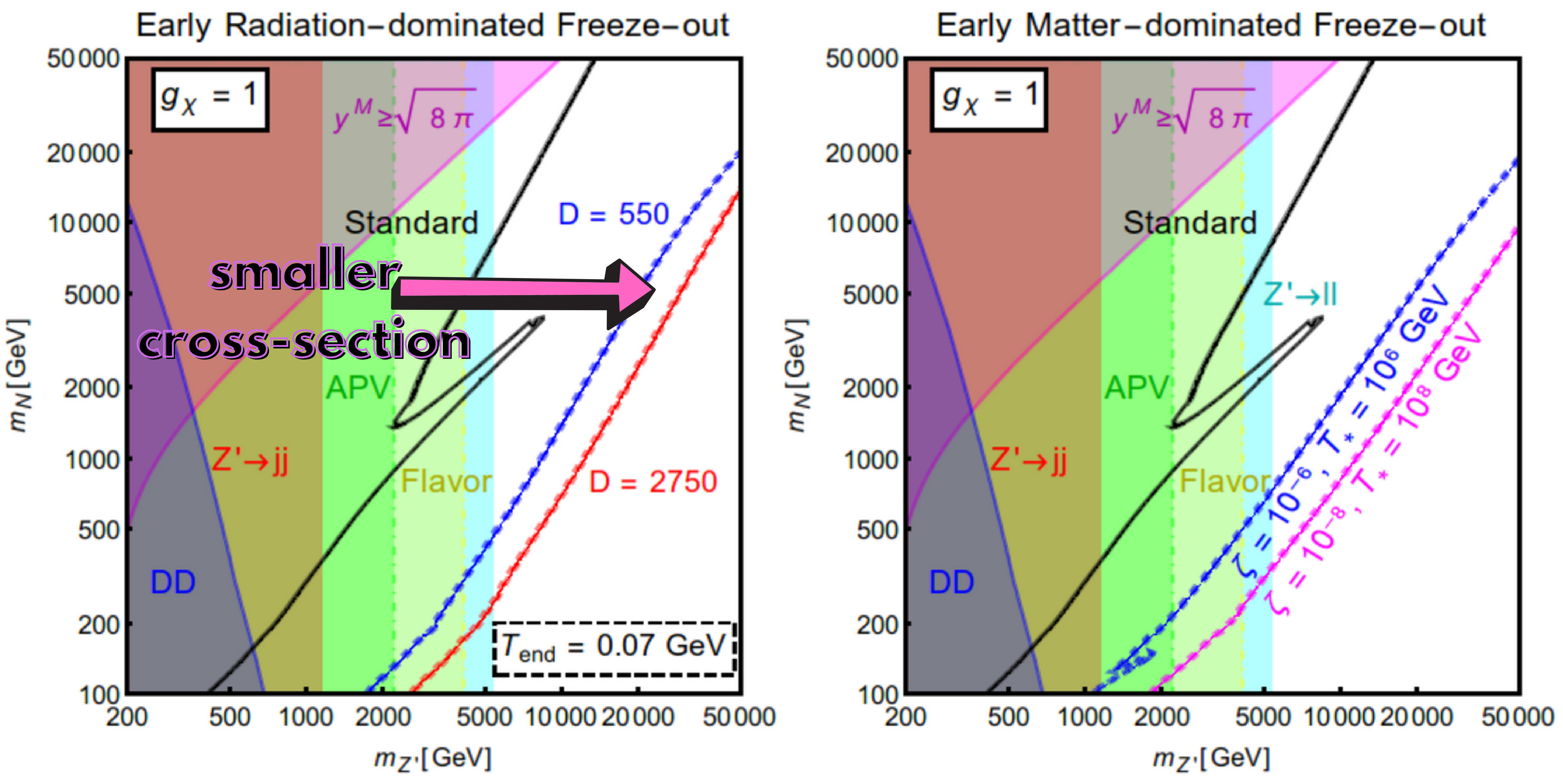

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The entropy after the decay must be larger for matter-dominated freeze-out.

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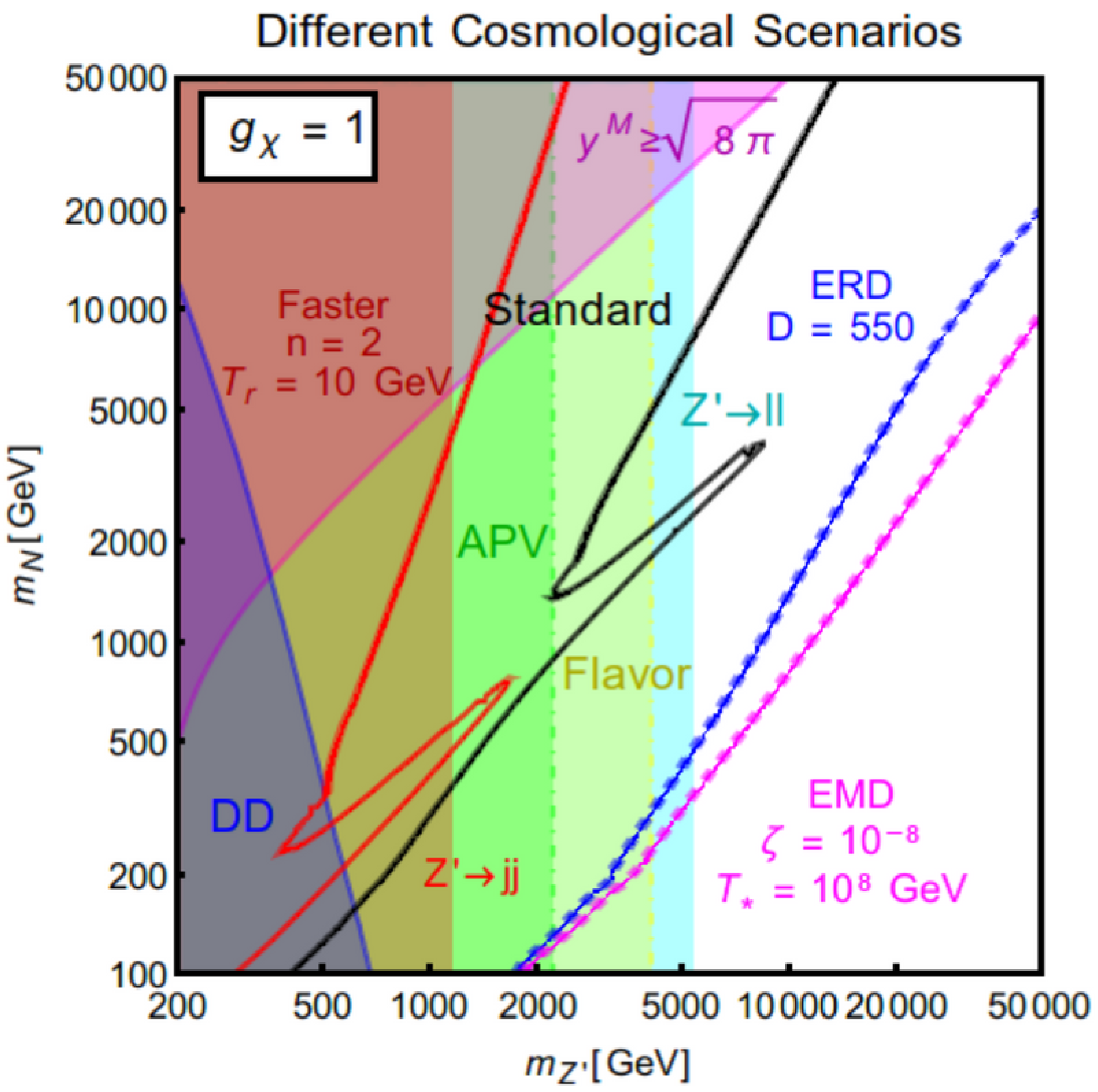
The Relentless phase x Entropy injection



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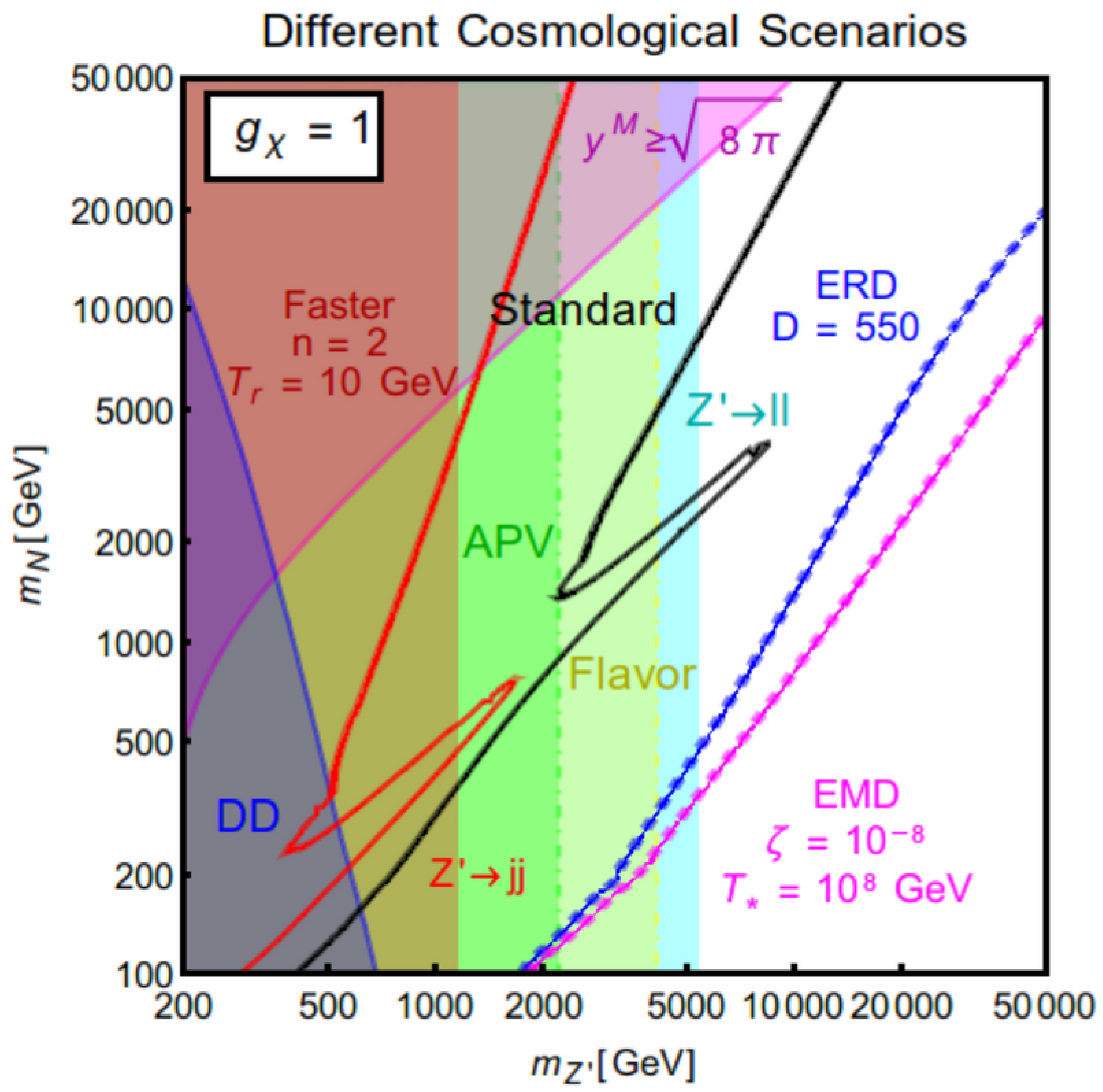
The Relentless phase x Entropy injection

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



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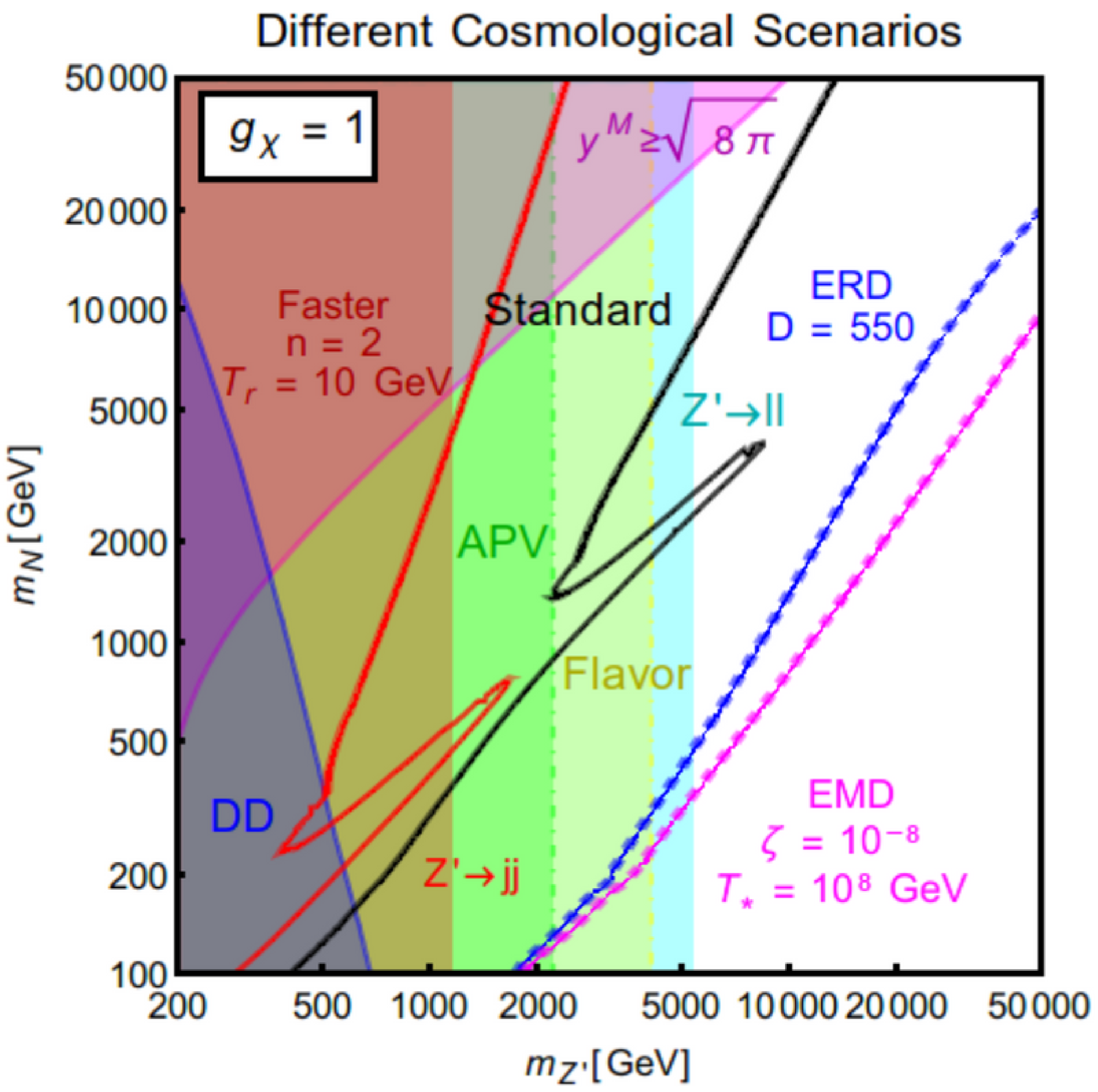
The Relentless phase x Entropy injection

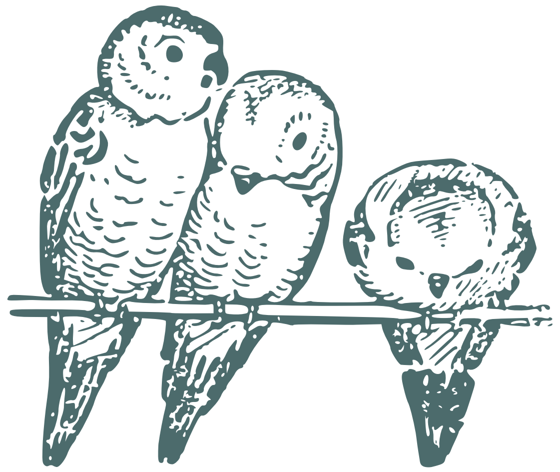
Freeze-out during larger expansion rates requires larger cross-sections.

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



Conclusions

Conclusions



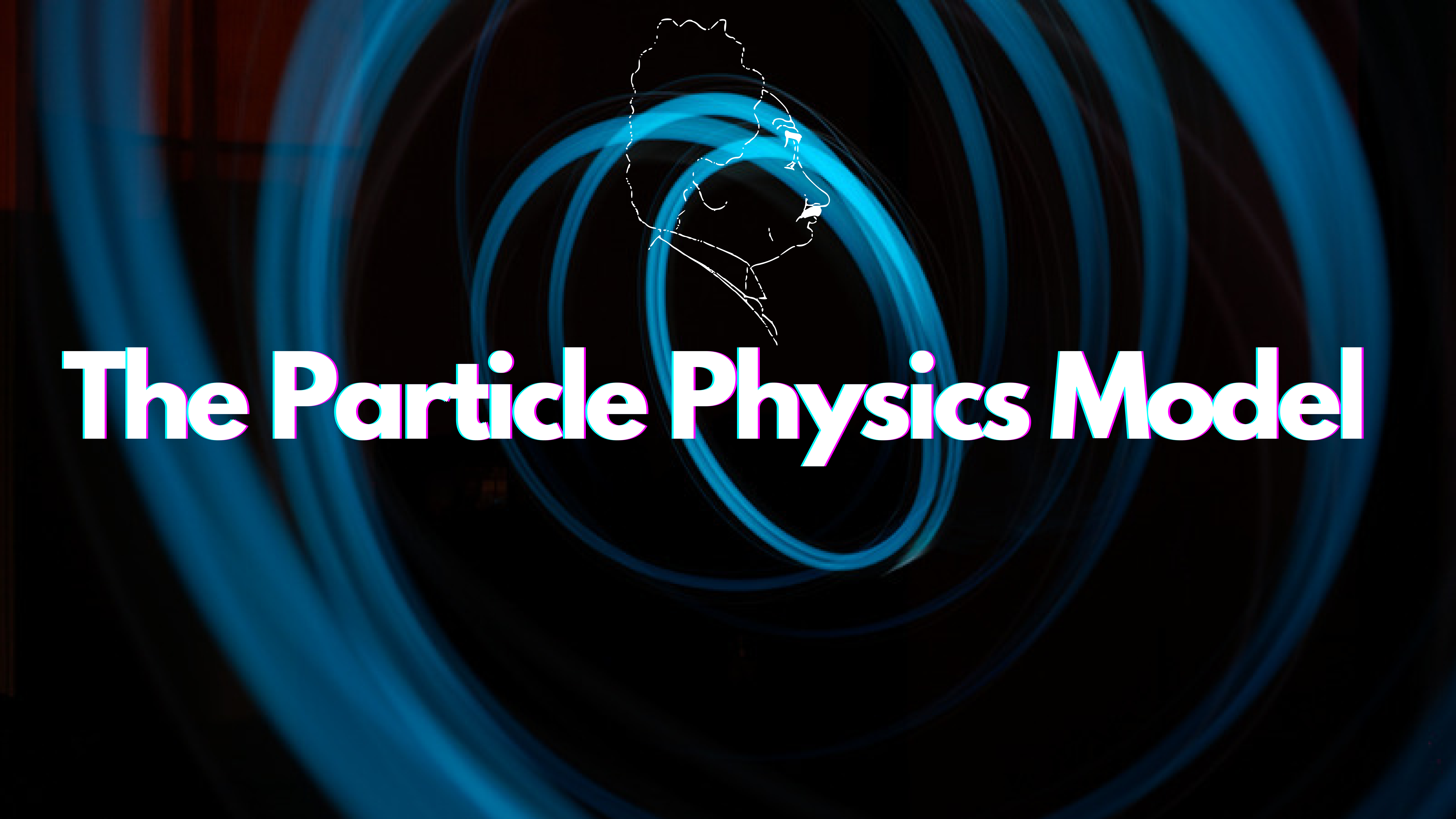
- We explored the impact of different non-standard cosmologies on the right-handed neutrino in a 2HDM augemented by B-L gauge symmetry.
    1. Relentless freeze-out (faster than usual early expansion);
    2. Radiation-dominated freeze-out; and
    3. Matter-dominated freeze-out.
- For faster expanding,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

The Dark Side of the Slides

Backup


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

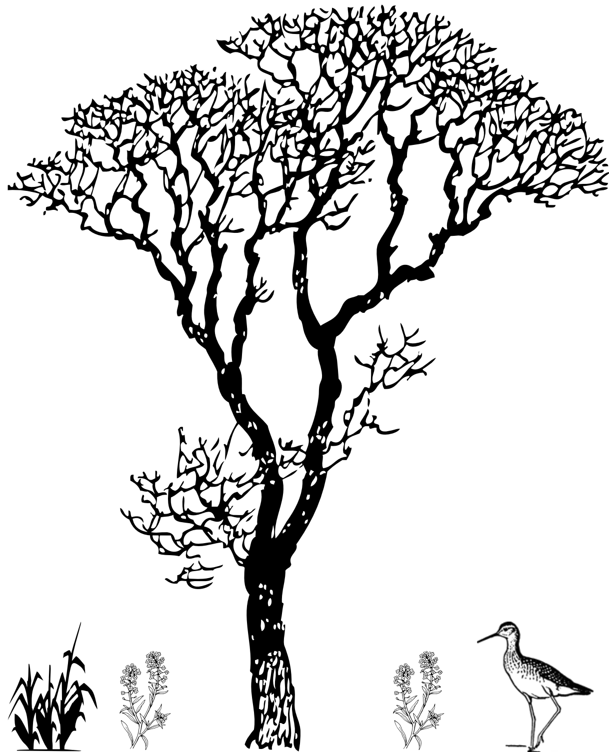
$$A,\ W^{\pm},\ Z,\ Z' \text{ and } g_i \text{ (gluons)}$$

SCALAR SECTOR

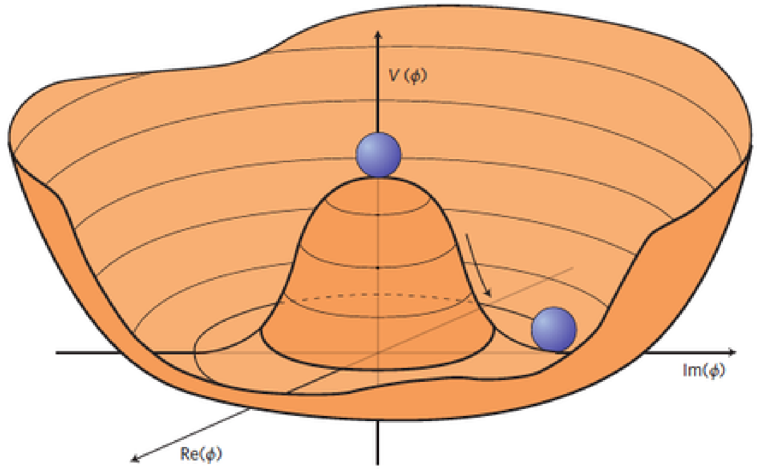
$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, 1/2, 2),$$

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

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



Yukawa Lagrangian



John Ellis et al. (ArXiv: 1504.07217)

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

Fermions interact only with the second doublet.

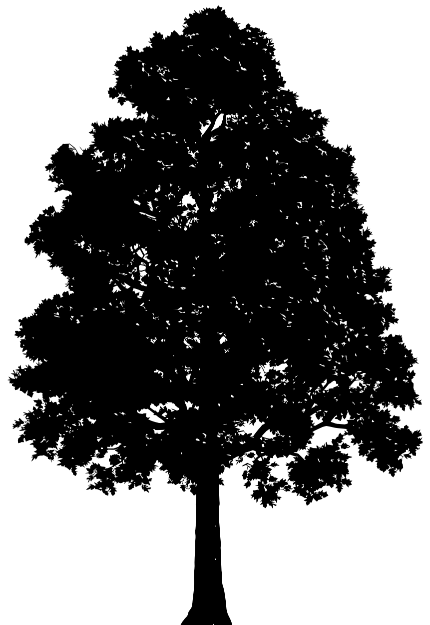
$$-\mathcal{L}_{Y_2} \supset y_{ab}\bar{L}_a\widetilde{\Phi}_2 N_{bR} + y^M_{ab}\overline{(N_{aR})^c}\Phi_s N_{bR} + h.c.\,,$$

@ Dirac mass

@ Majorana mass

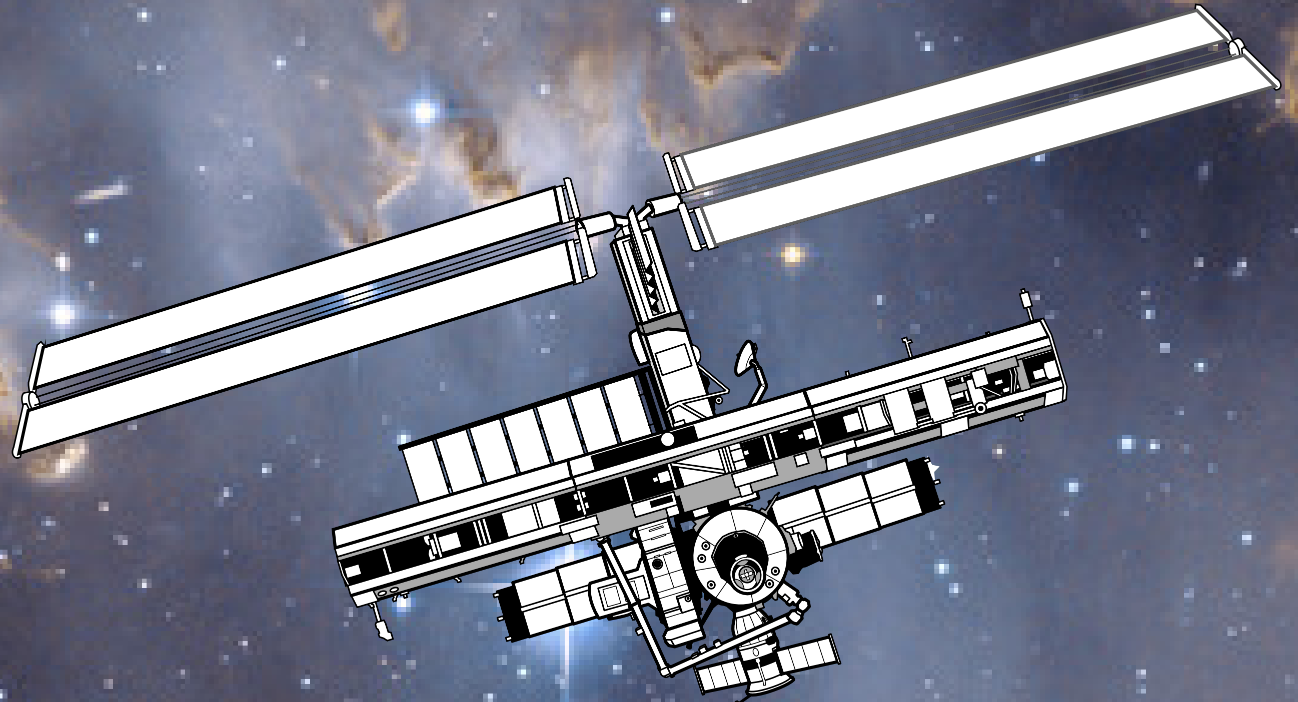
The scalar singlet spontaneously breaks the B-L symmetry.

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.

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



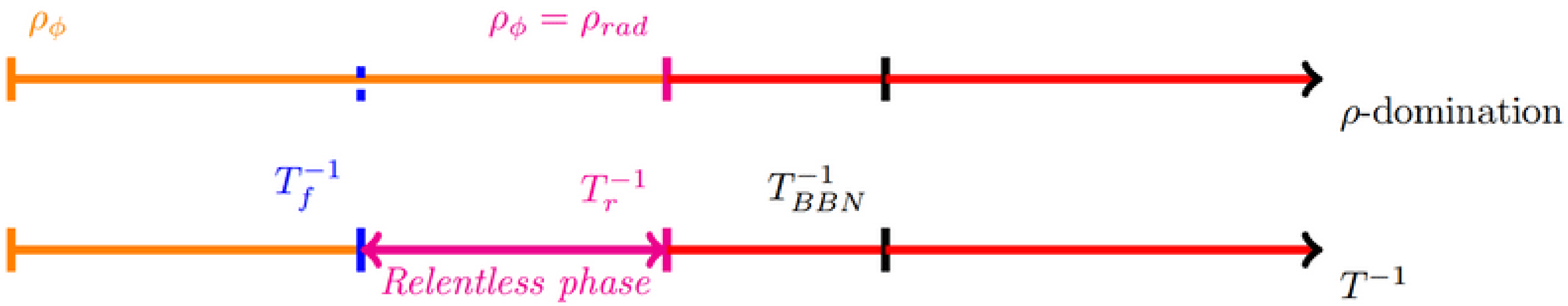
Non-standard Cosmologies

Faster Than Usal Early Expansion

Brief Thermal History

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

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



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

The Cosmological Parameters

$$(n,\, T_r)$$

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

Faster Than Usal Early Expansion

The Relentless Phase

For s-wave annihilation cross-section and $n \geq 2$.

$H \propto T^{2+n/2}$ and after freeze-out $\Gamma \propto T^3$, starting the relentles phase in which DM tries unsuccessfully get back to thermal equilibrium.

Just when T_r, the Hubble rate wins and the relentless phase takes over.