Dark Matter in Non-Standard Cosmology

1st October 2019 - MOCa 2019

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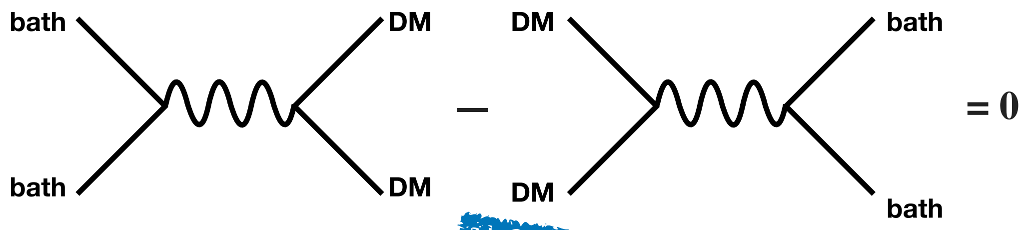
Outline

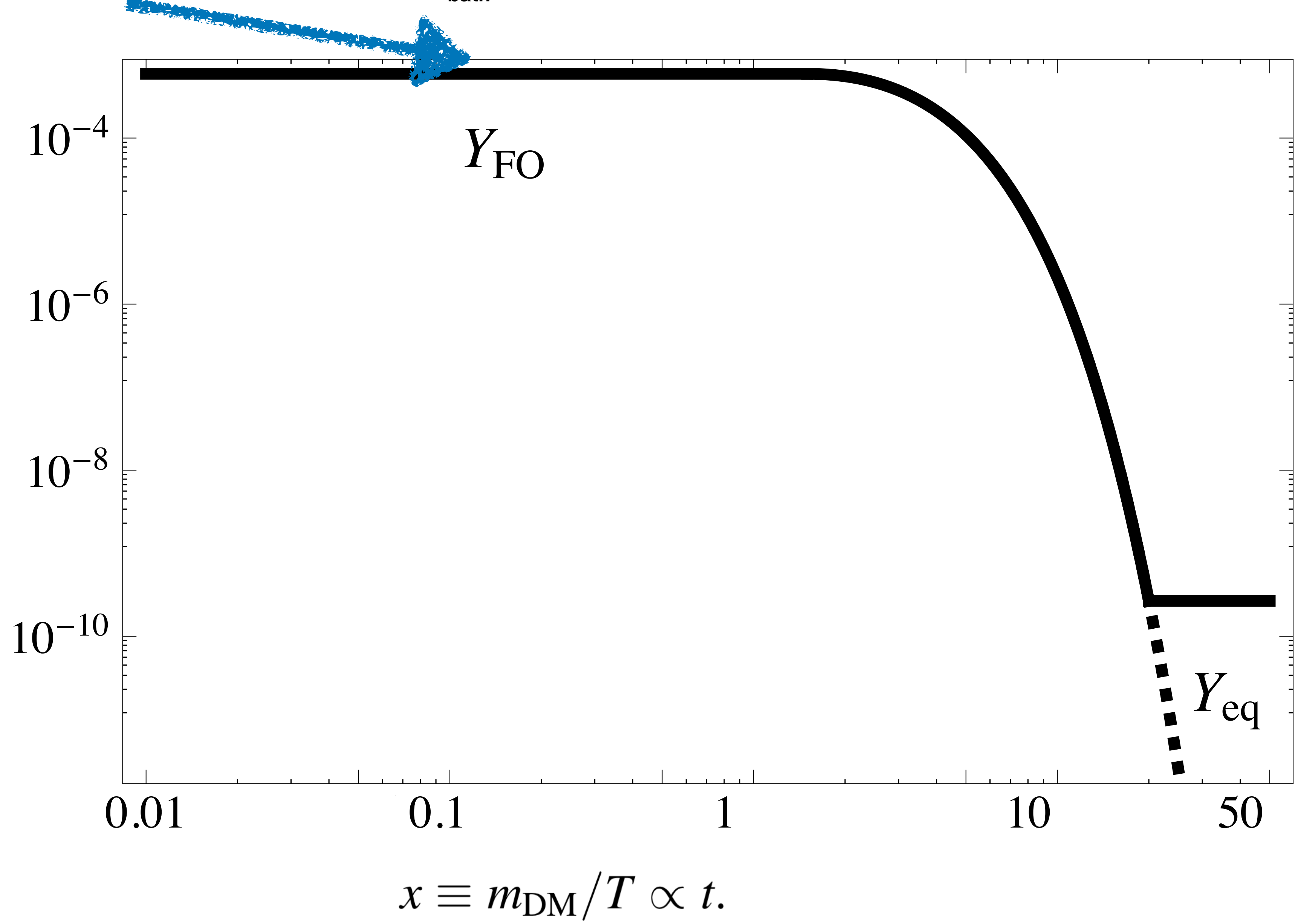
1. Thermal dark matter
2. Diluting dark matter
3. Freeze-out during matter domination
4. UV Freeze-in & non-standard cosmology

I. Thermal Dark Matter

Dark Matter Freeze-out



$$Y_{\rm DM} = \frac{n_{\rm DM}}{s}$$



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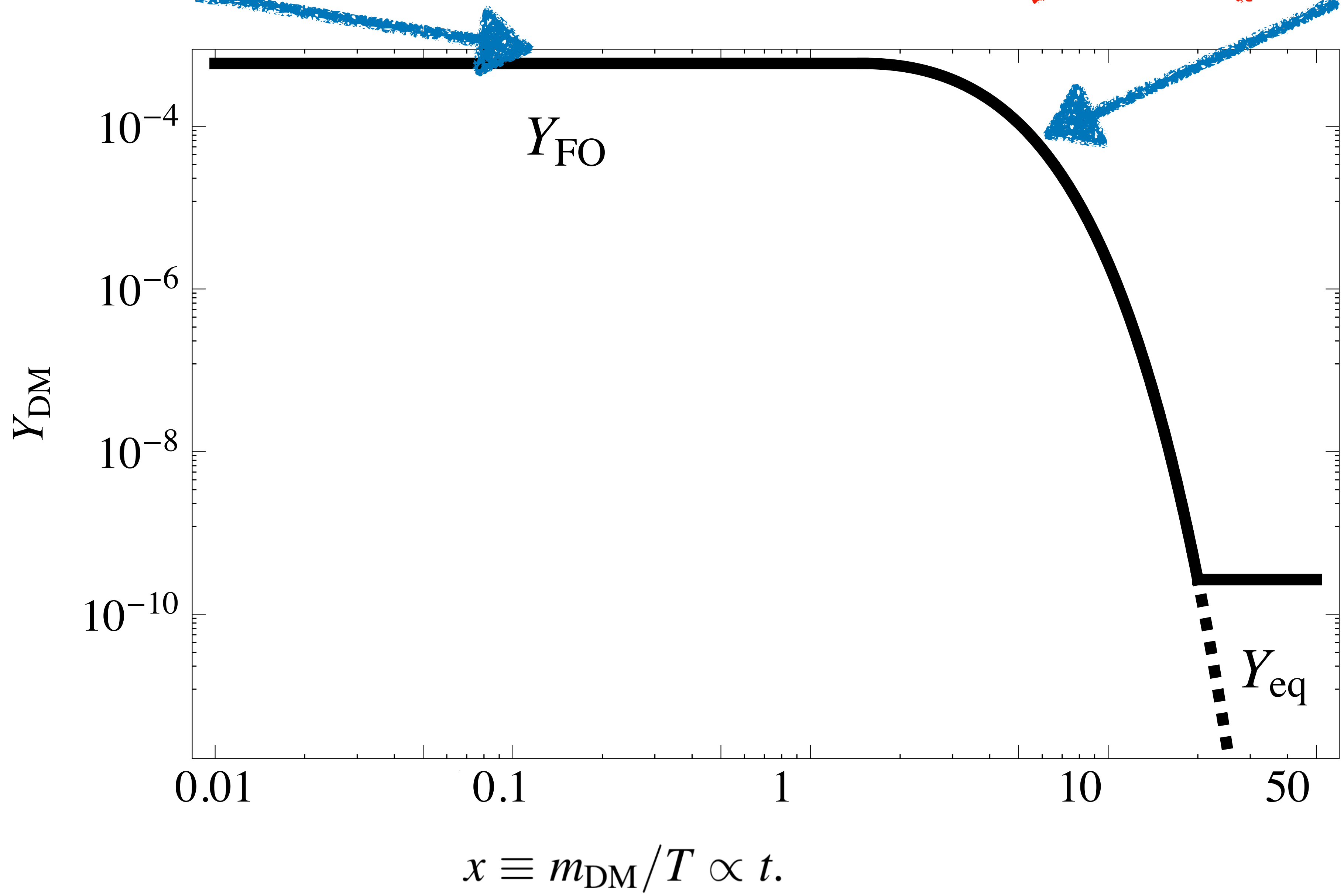

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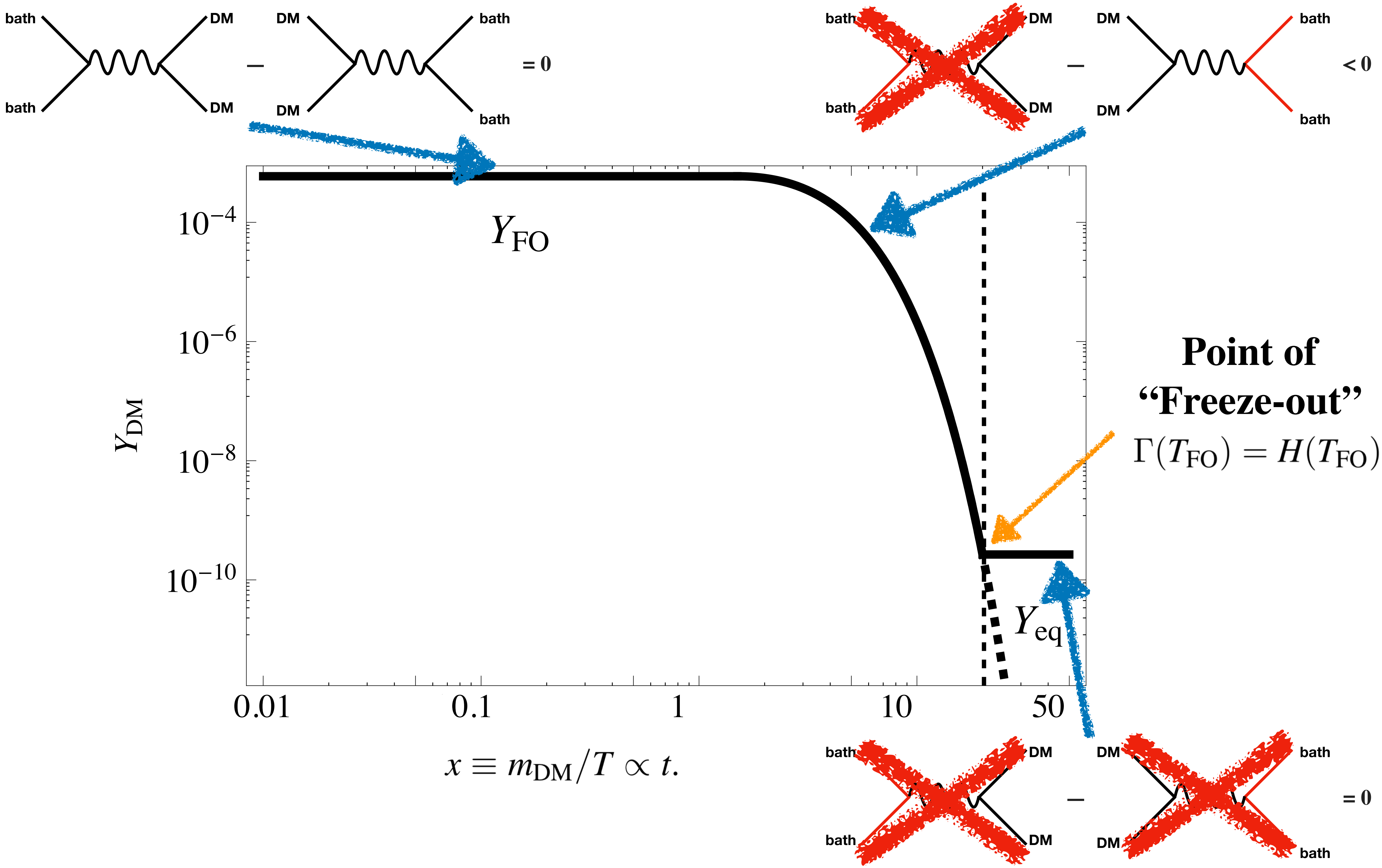
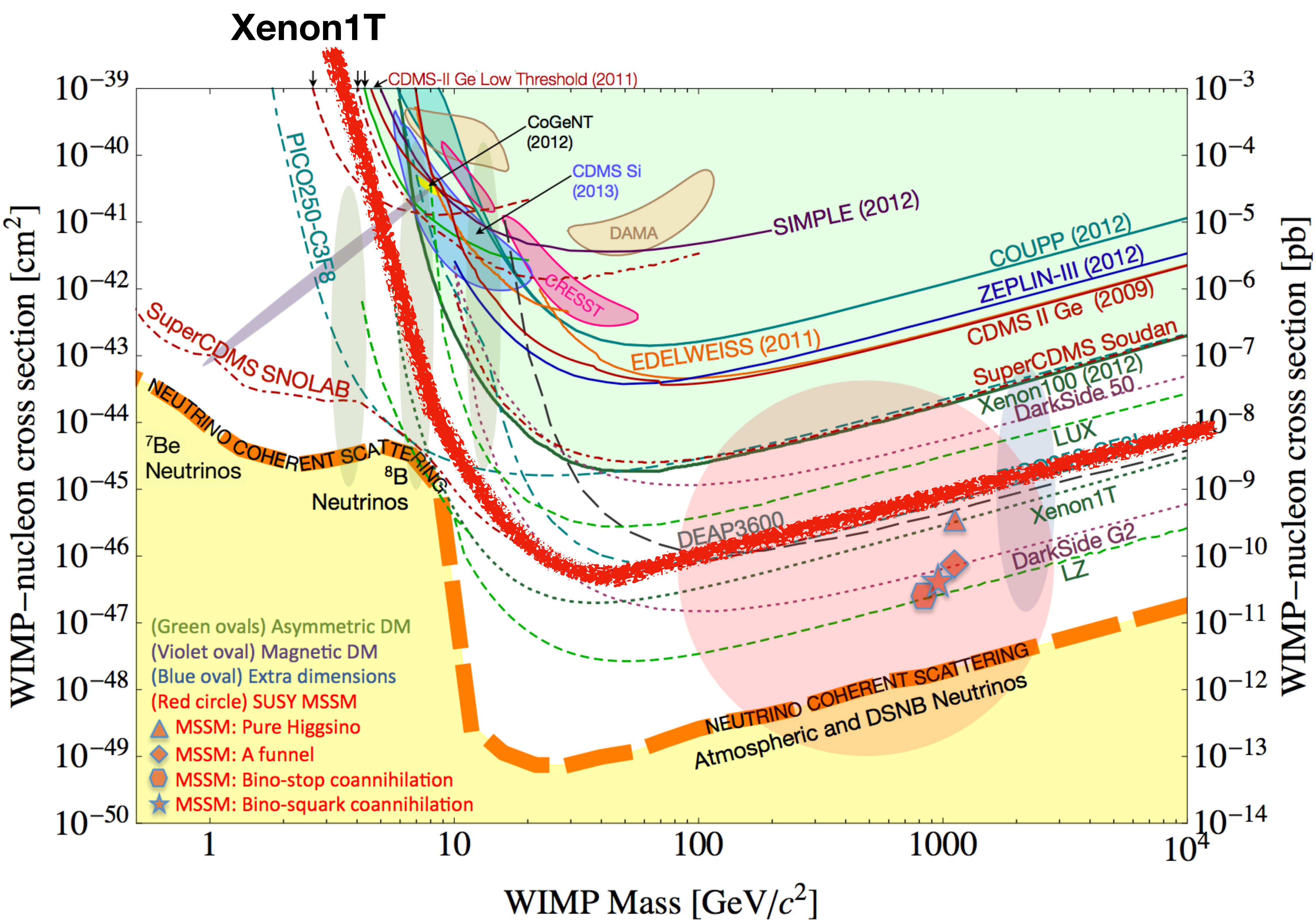
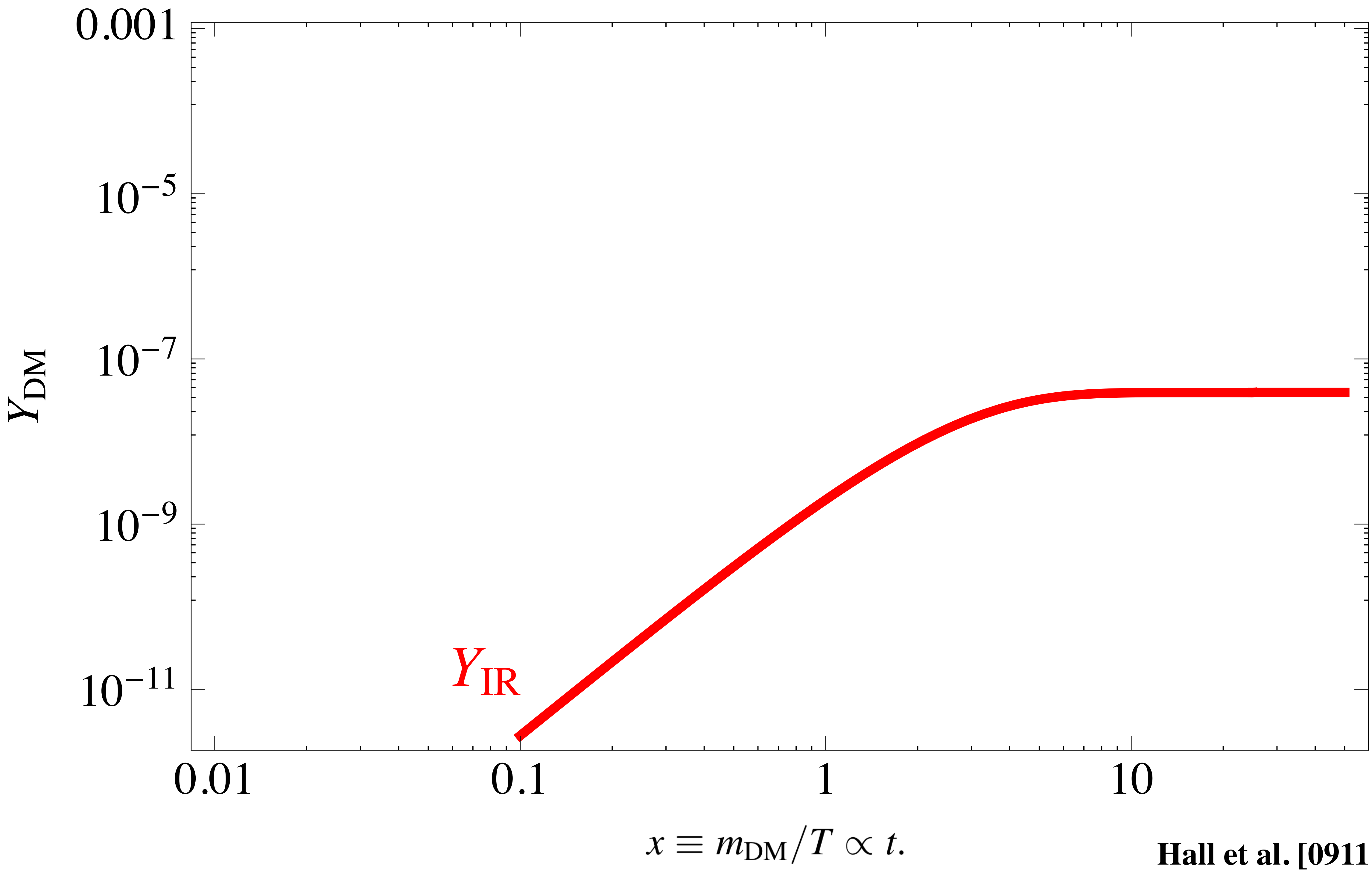


Current Bounds



Freeze-in

Freeze-in assumes dark matter **initially has negligible abundance.**



Hall et al. [0911.1120]

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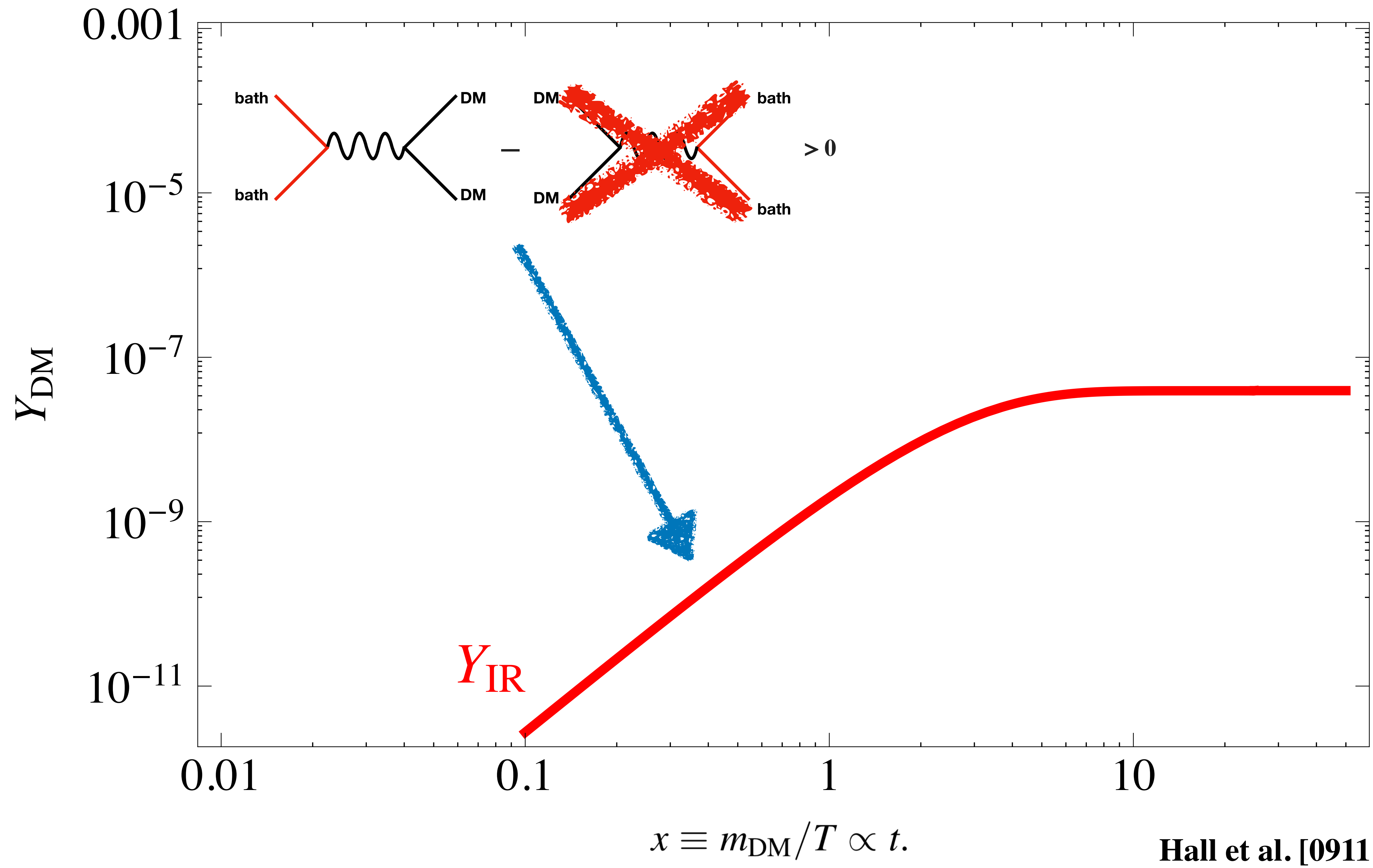

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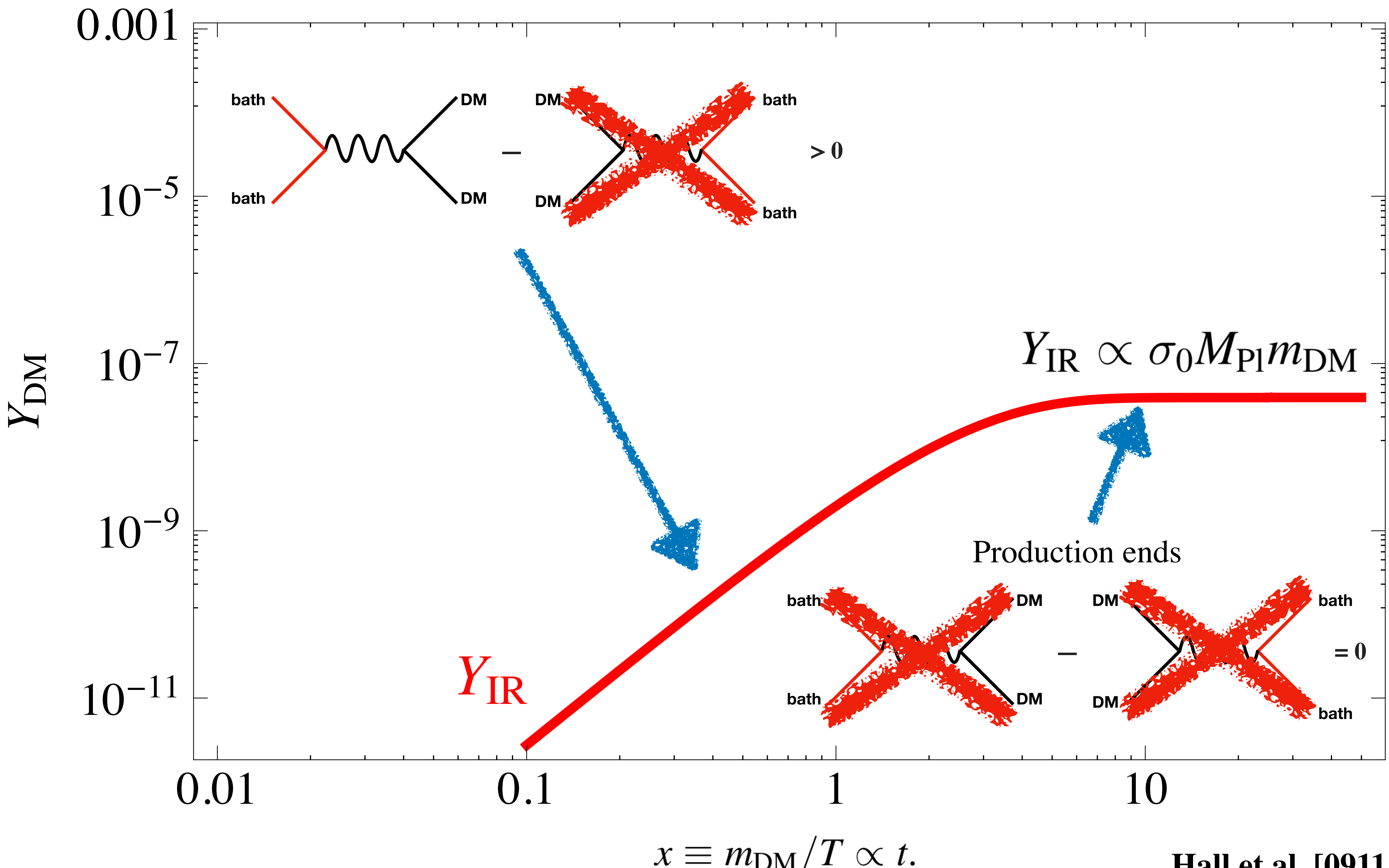

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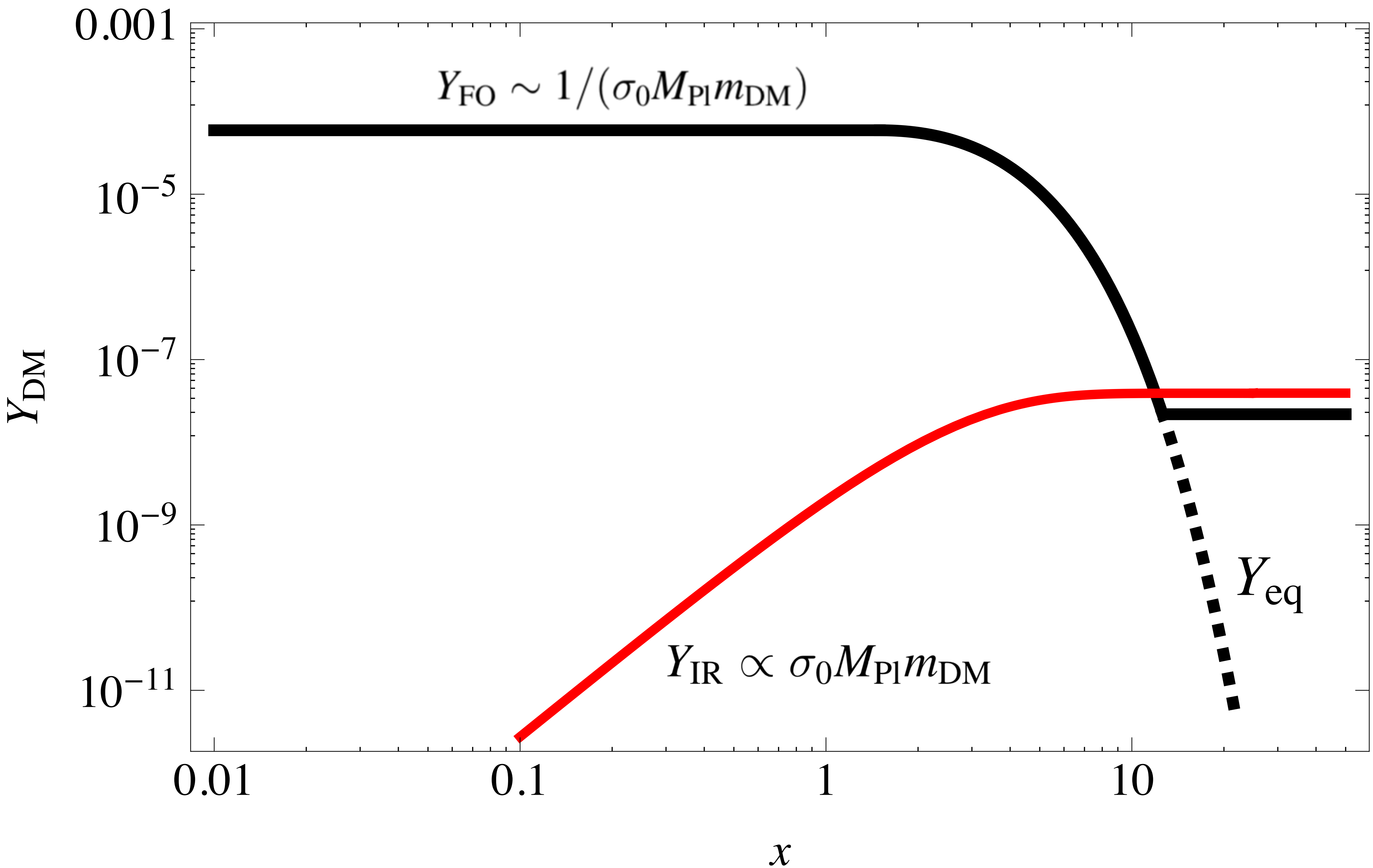
Freeze-in vs Freeze-out



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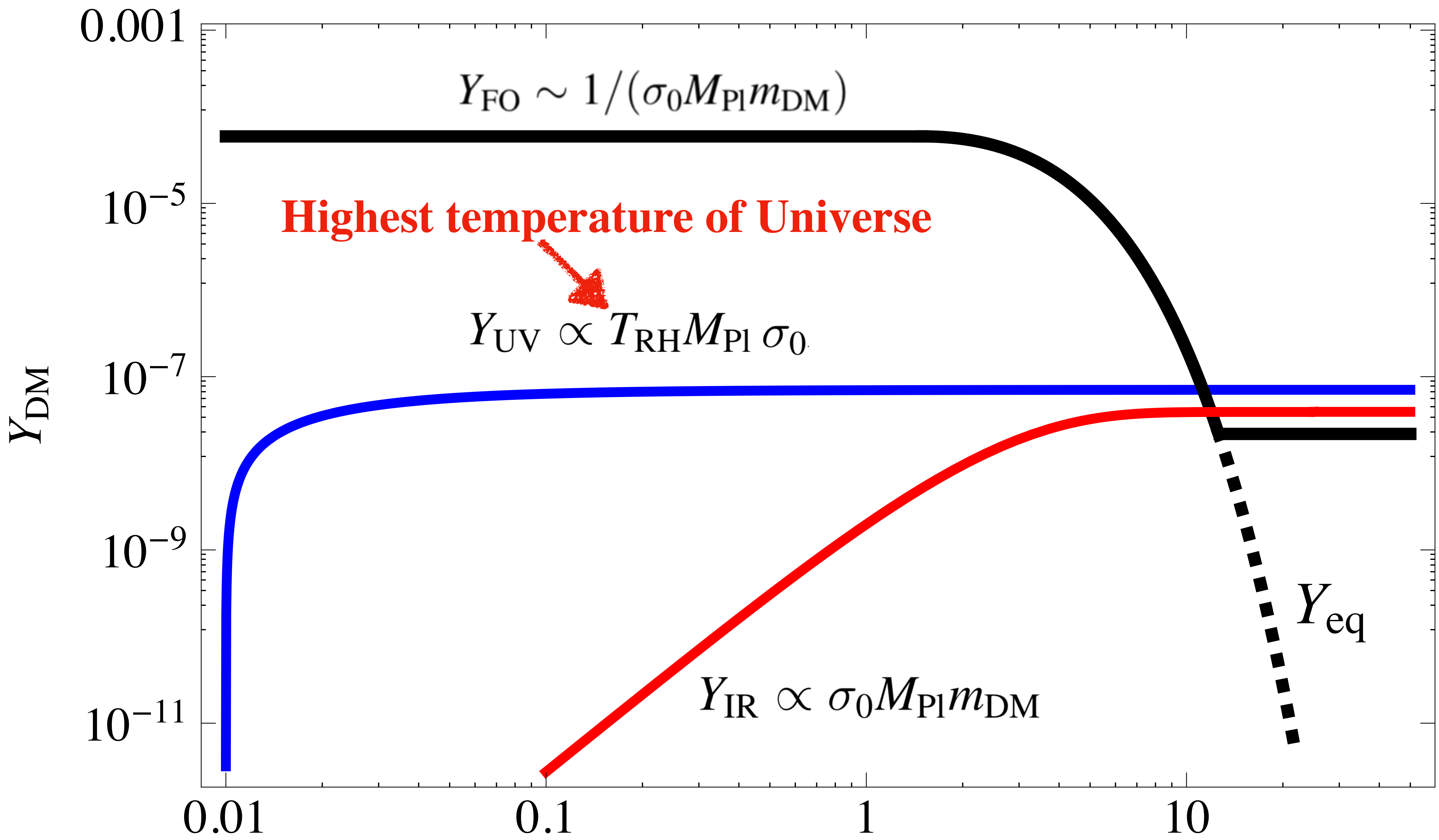
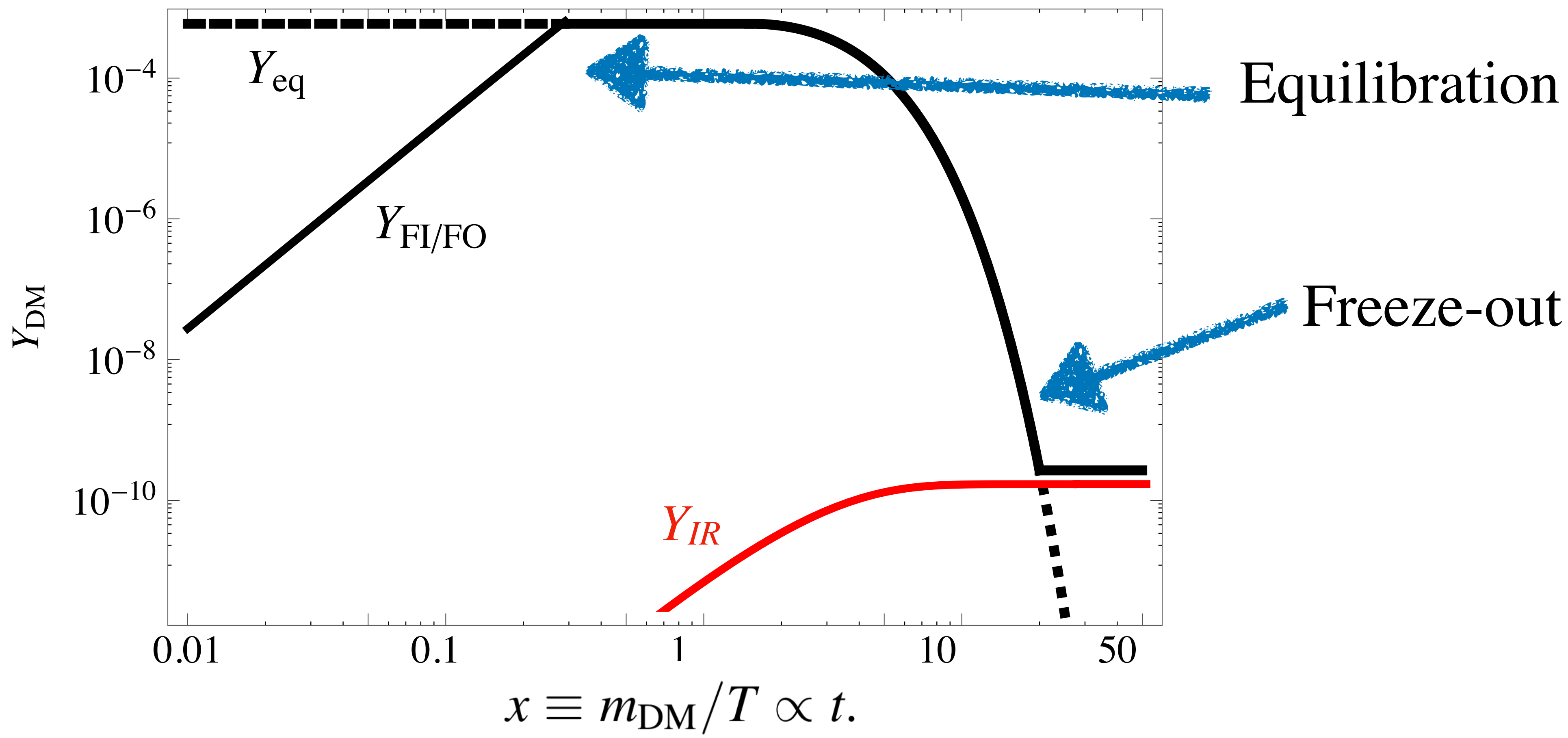


Parameter **depends very different** in all three cases.

Elahi, Kolda & JU JHEP 1503 (2015) 048

Equilibration and FIMPS

If energy exchange is too large, **risk dark matter equilibration** with thermal bath.



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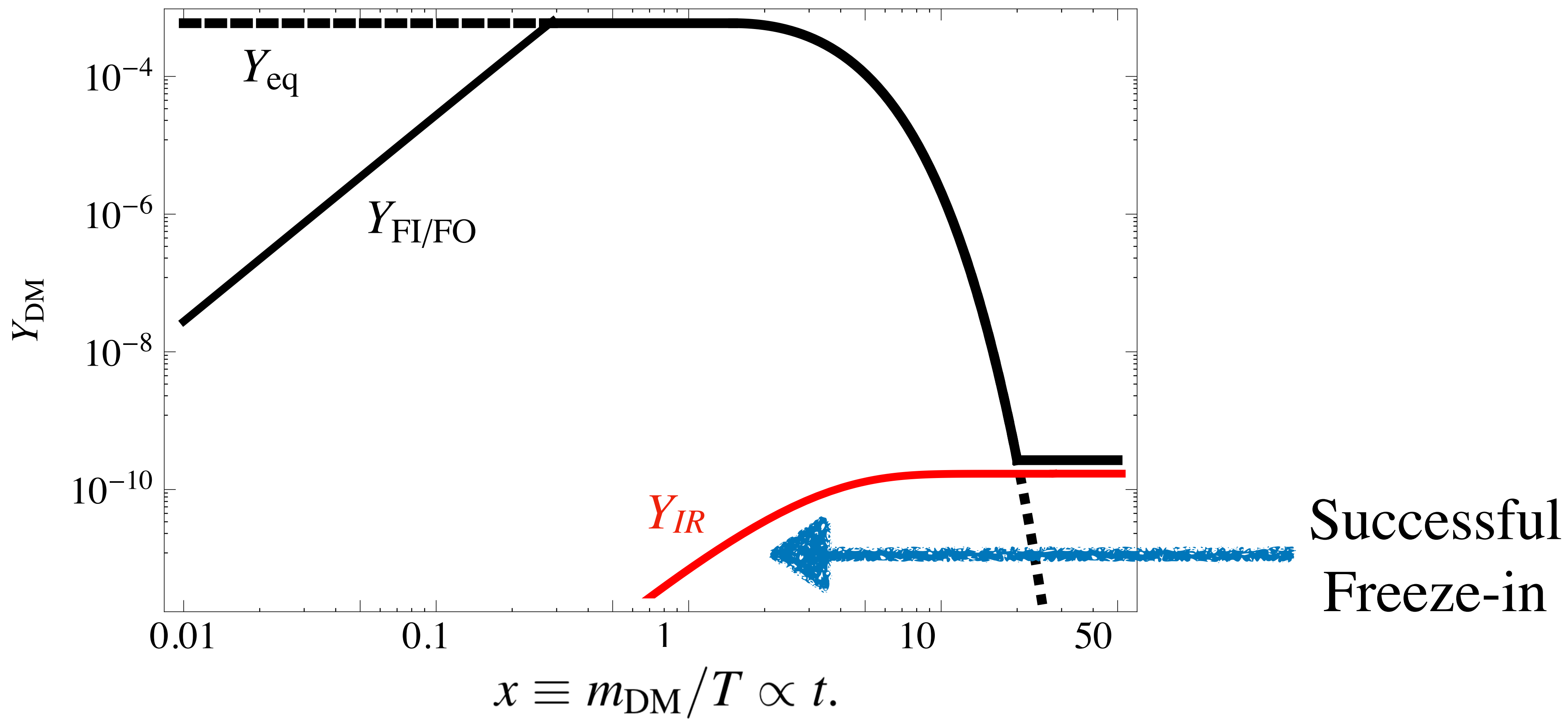


For IR Freeze-in with GeV DM this require couplings: $\lambda \lesssim 10^{-7}$

Avoiding equilibration requires very `feeble' couplings: **FIMP Dark Matter.**

Requires dedicated experiments for light dark matter or long lived states.

II. Diluting Dark Matter

Cosmological Impact

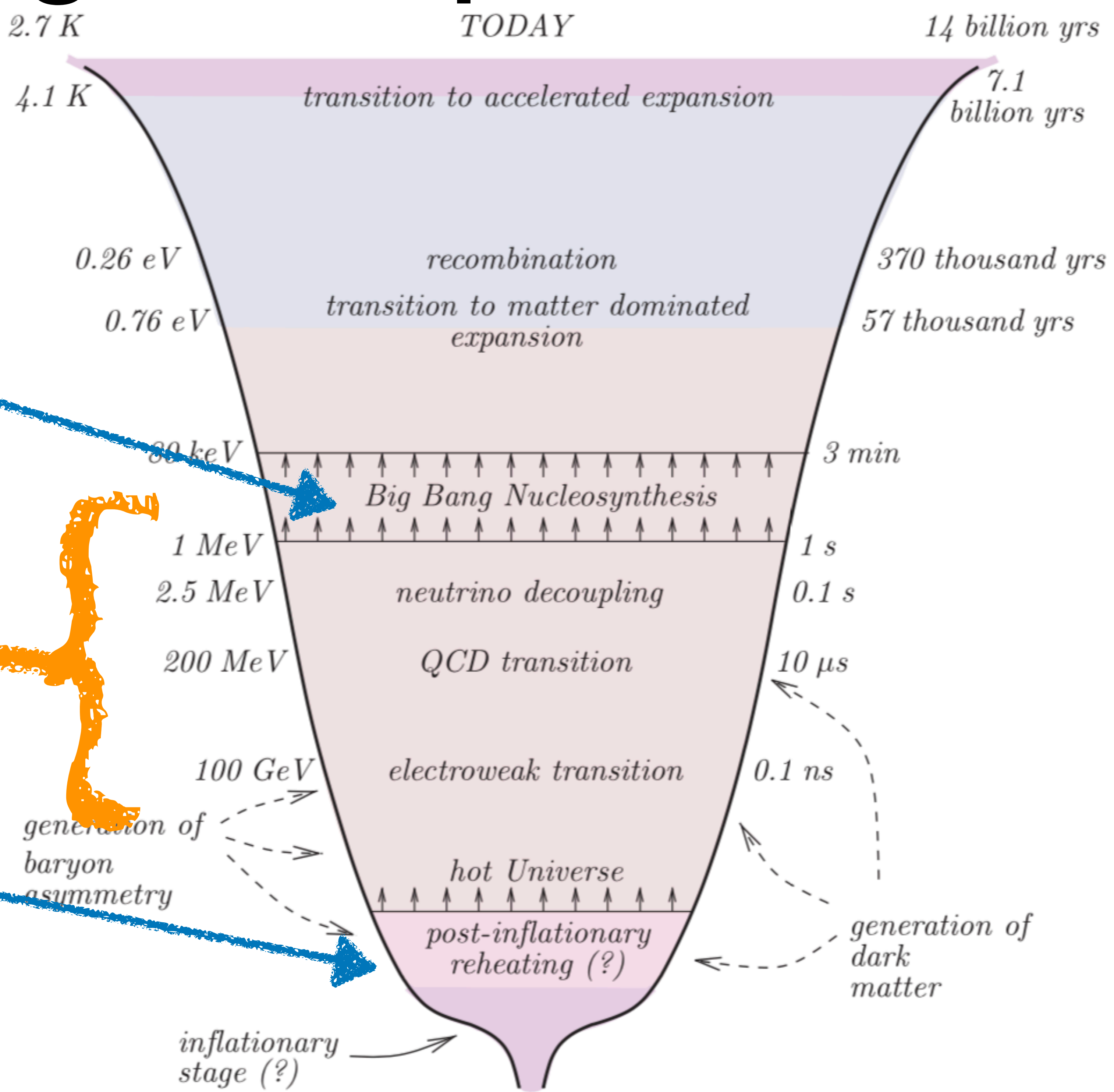
Earliest cosmological evidence

(know to be radiation dominated)

Non-Standard Model cosmological events?

End of Inflation

(start of radiation domination?)



Cosmological Impact

After dark matter is frozen out its number does not change from interactions.

$$\Omega_{\rm DM} \propto m_{\rm DM} Y_{\rm DM} \propto m_{\rm DM} \frac{n_{\rm DM}}{n_\gamma}$$

However, **decaying particles** can heat SM bath, & **dilute $Y_{\rm DM}$** since $n_\gamma \propto T^3$.

Gelmini and Gondolo [hep-ph/0602230]

⋮

Randall, Scholtz & JU [1509.08477]
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$$\Omega_{\rm DM} \propto \zeta m_{\rm DM} Y_{\rm FO}$$

Dilution factor ζ from temperature after decays $T_{\rm after}$ compared to without decays:

$$\zeta = \left(\frac{T_{\rm without}}{T_{\rm after}}\right)^3 \leq 1$$

Because of dilution, correct relic density for **weaker interactions with SM.**

Changes expectation for $m_{\rm DM}$ and σ_0 and **reduces tension with experiments**.

Dilution from a Decaying State

Add a state χ which becomes **matter-like** at $T_{\rm crit}$ — typically $T_{\rm crit}=m_\chi$

Friedman equation for gives **evolution of energy** for $H(T_{\rm crit}) > H > \Gamma_\chi$

$$H^2 \simeq \frac{\pi^2}{90}\frac{g_\star T_{\rm crit}^4}{M_{\rm Pl}^2}\left[R_\chi\left(\frac{1}{\Delta a}\right)^3 + R_{\rm rad}\left(\frac{1}{\Delta a}\right)^4\right] \quad \text{with} \quad R_i \equiv \rho_i/(\rho_\chi+\rho_{\rm rad})\big|_{\rm crit}$$

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The relative **energy density in χ grows** until it decays at:

$$\Delta a_\Gamma \equiv \frac{a(H=\Gamma_\chi)}{a(T_{\rm crit})} \simeq \left(\frac{\pi^2 g_\star T_{\rm crit}^4}{90 M_{\rm Pl}^2 \Gamma_\chi^2} R_\chi\right)^{1/3}$$

If **χ is long lived**, it may evolves to dominate the energy density of Universe.

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χ decay heats the bath, to $T_{\rm RH} \simeq \sqrt{M_{\rm Pl}\Gamma_\chi}$, any **frozen-out species diluted:**

$$\zeta = \left(\frac{T_{\rm without}}{T_{\rm after}}\right)^3 \simeq \left(\frac{R_{\rm rad}}{R_\chi}\Delta a_\Gamma^{-1}\right)^{3/4} \sim 10^{-10}\left(\frac{T_{\rm RH}}{10~{\rm MeV}}\right)\left(\frac{10^8~{\rm GeV}}{T_{\rm crit}}\right)$$

for $R_{\rm rad}/R_\chi \simeq 1,$

III. Freeze-out During Matter Domination

Changes to the Expansion Rate

Notable, expansion rate H depends critically on cosmology:

$$H \propto \begin{cases} T^2 & \text{During radiation domination} \\ T^4 & \text{During particle decays (heating)} \\ T^{3/2} & \text{During matter domination} \end{cases}$$

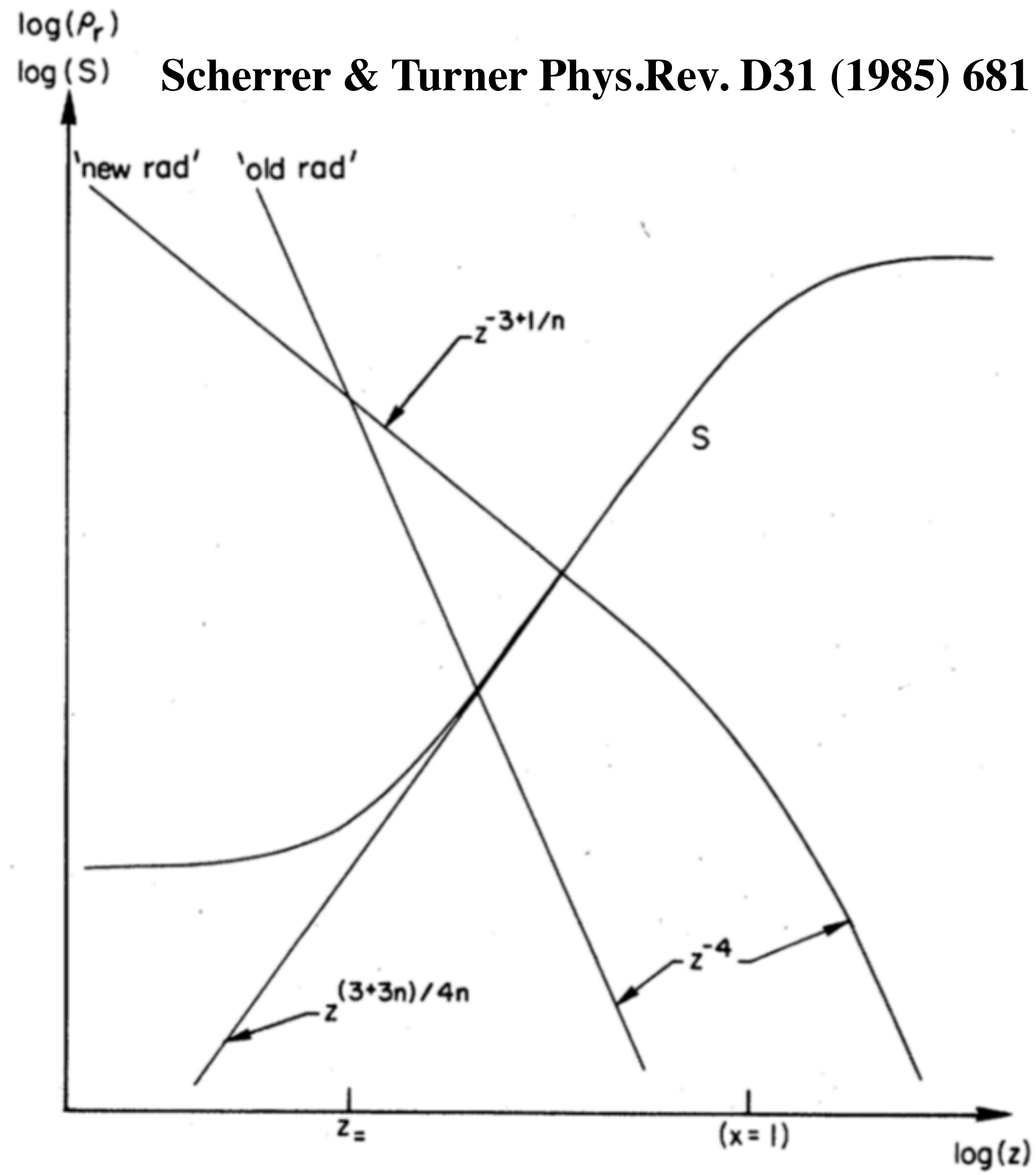
Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

Hamdan & JU [1710.03758]
Also (in passing): Kamionkowski & Turner PRD 42 (1990) 3310

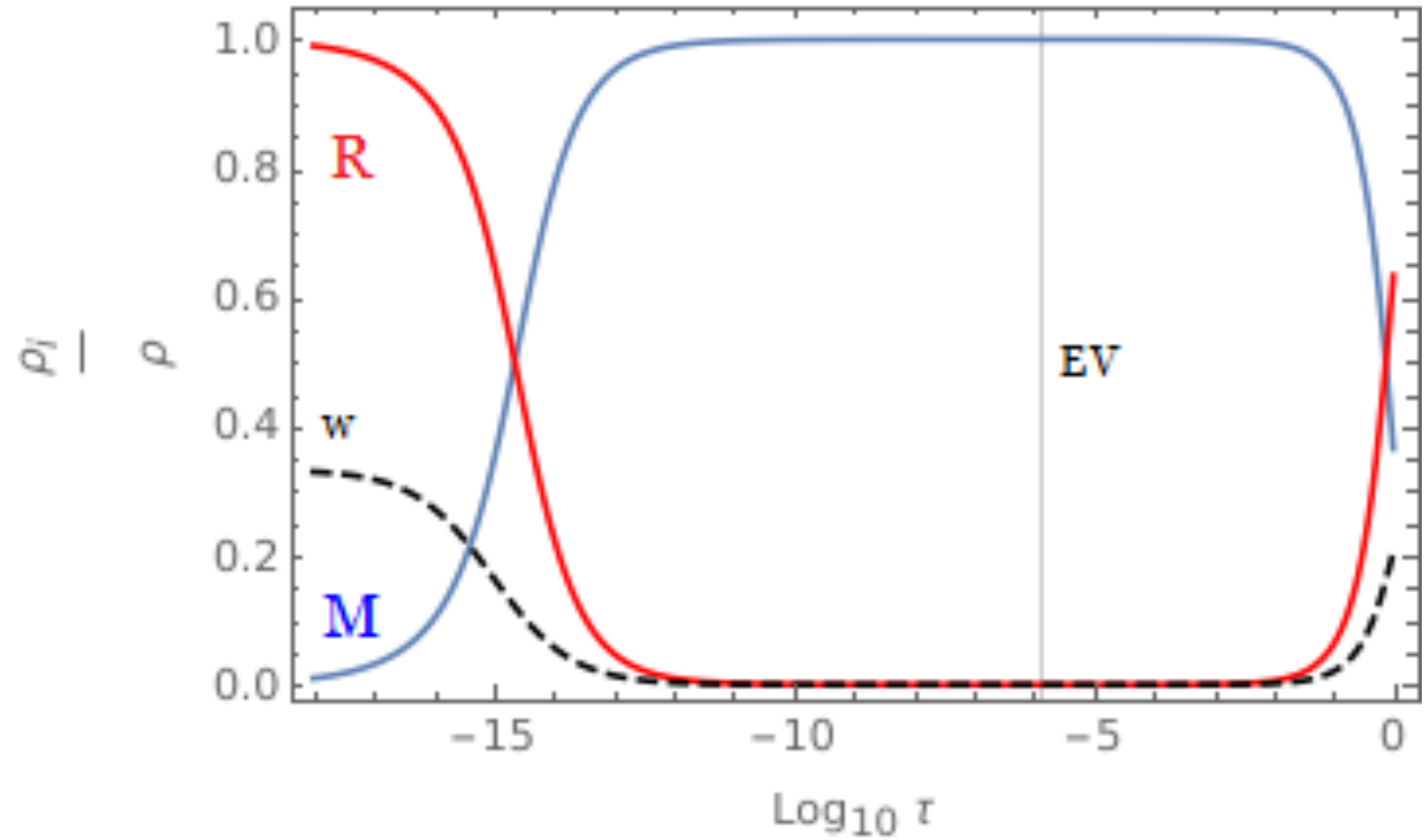
Recall $T_{\rm FO}$ is defined $\Gamma(T_{\rm FO}) = H(T_{\rm FO})$, changing H impacts final $Y_{\rm DM}$.

Decays vs Matter Domination

Scherrer & Turner Phys.Rev. D31 (1985) 681



Hamdan, Thesis 2018 & Chanda-Hamdan-JU [1910.xxxxx]



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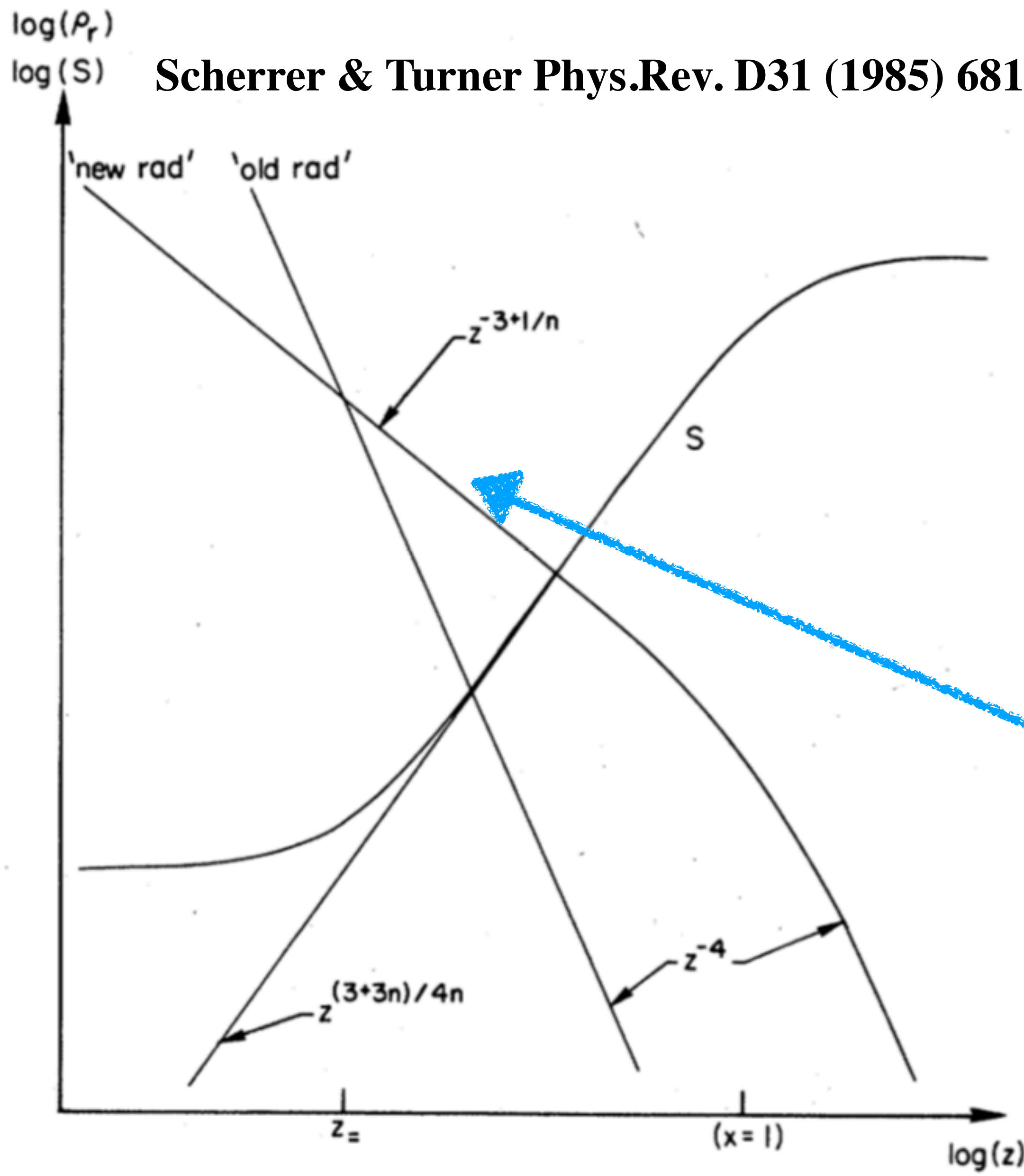

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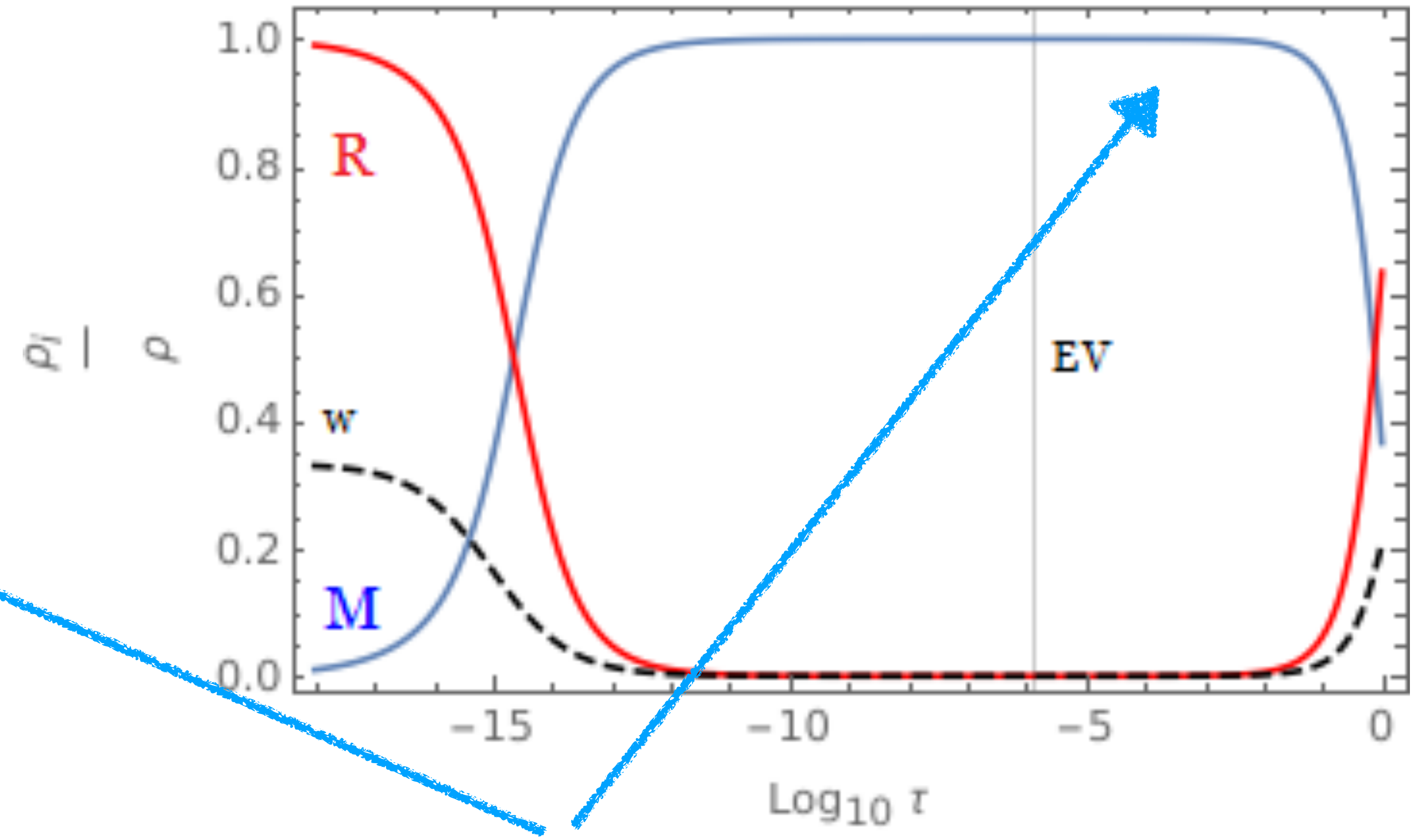

Decay Regime

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi \rho_\phi + \langle\sigma v\rangle 2\langle E_X\rangle \left[n_X^2 - (n_X^{eq})^2\right]$$

$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle \left[n_X^2 - (n_X^{eq})^2\right] \quad .$$

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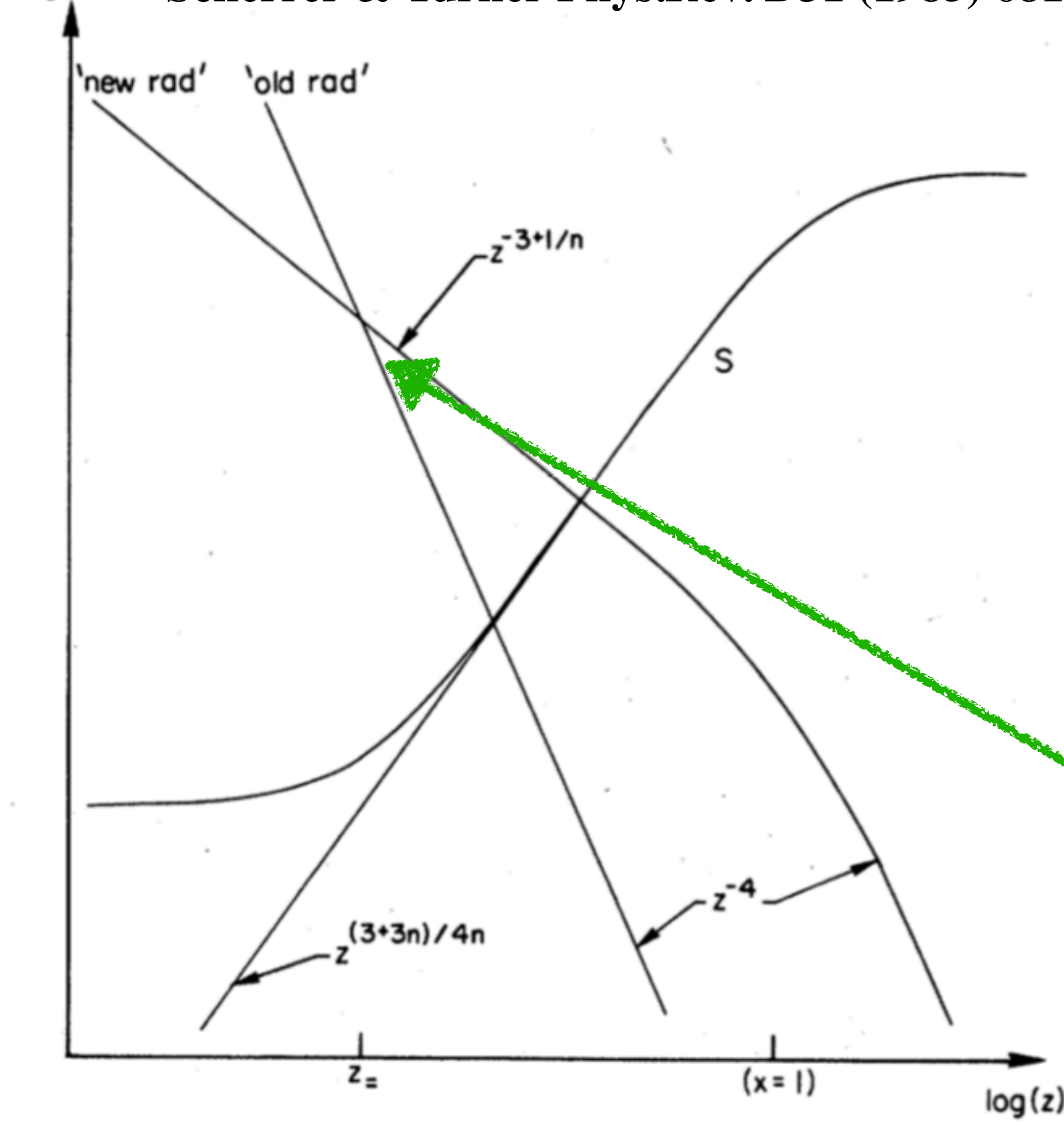

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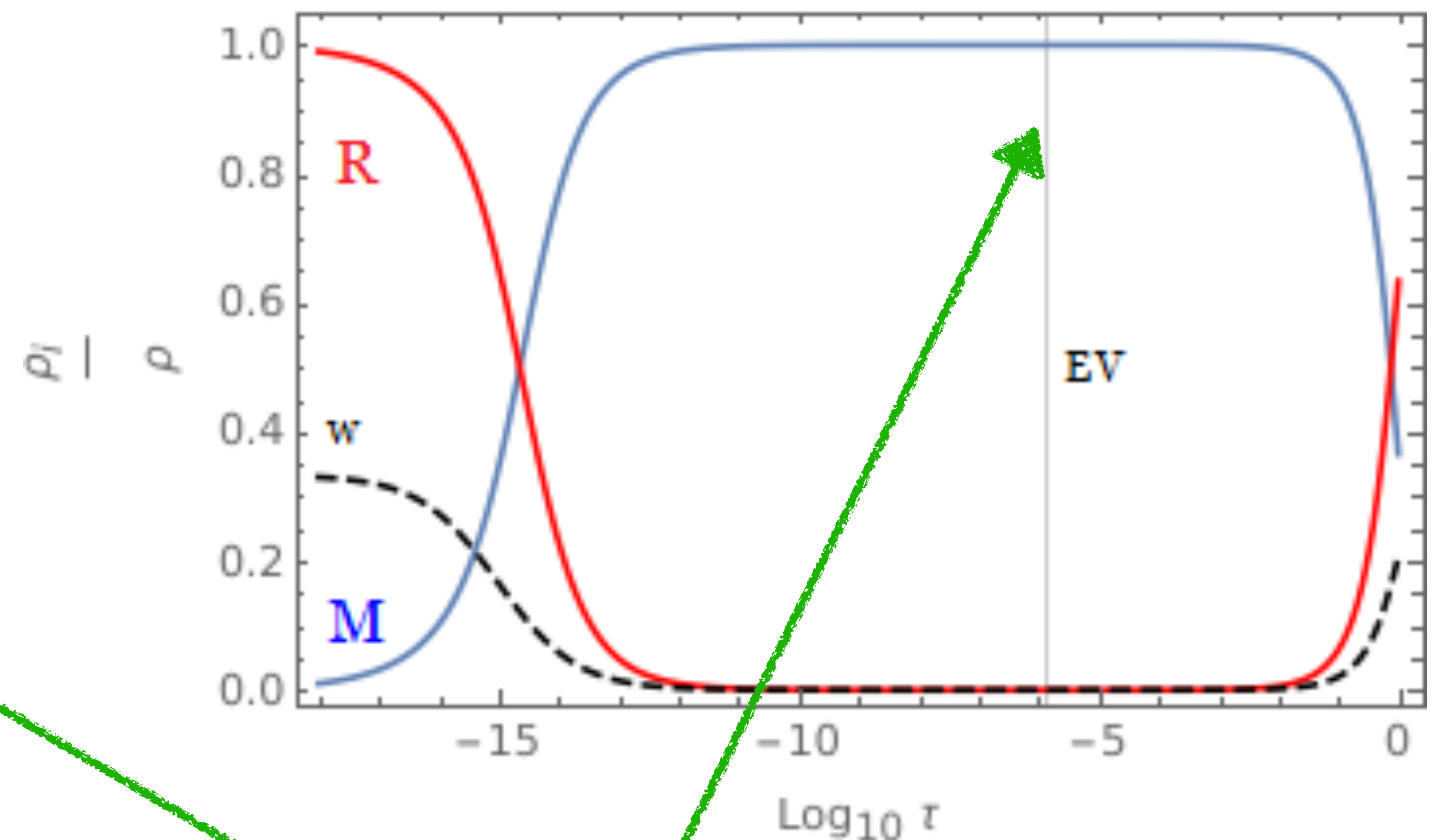

Point of non-negligible
entropy production in bath.

Decays vs Matter Domination

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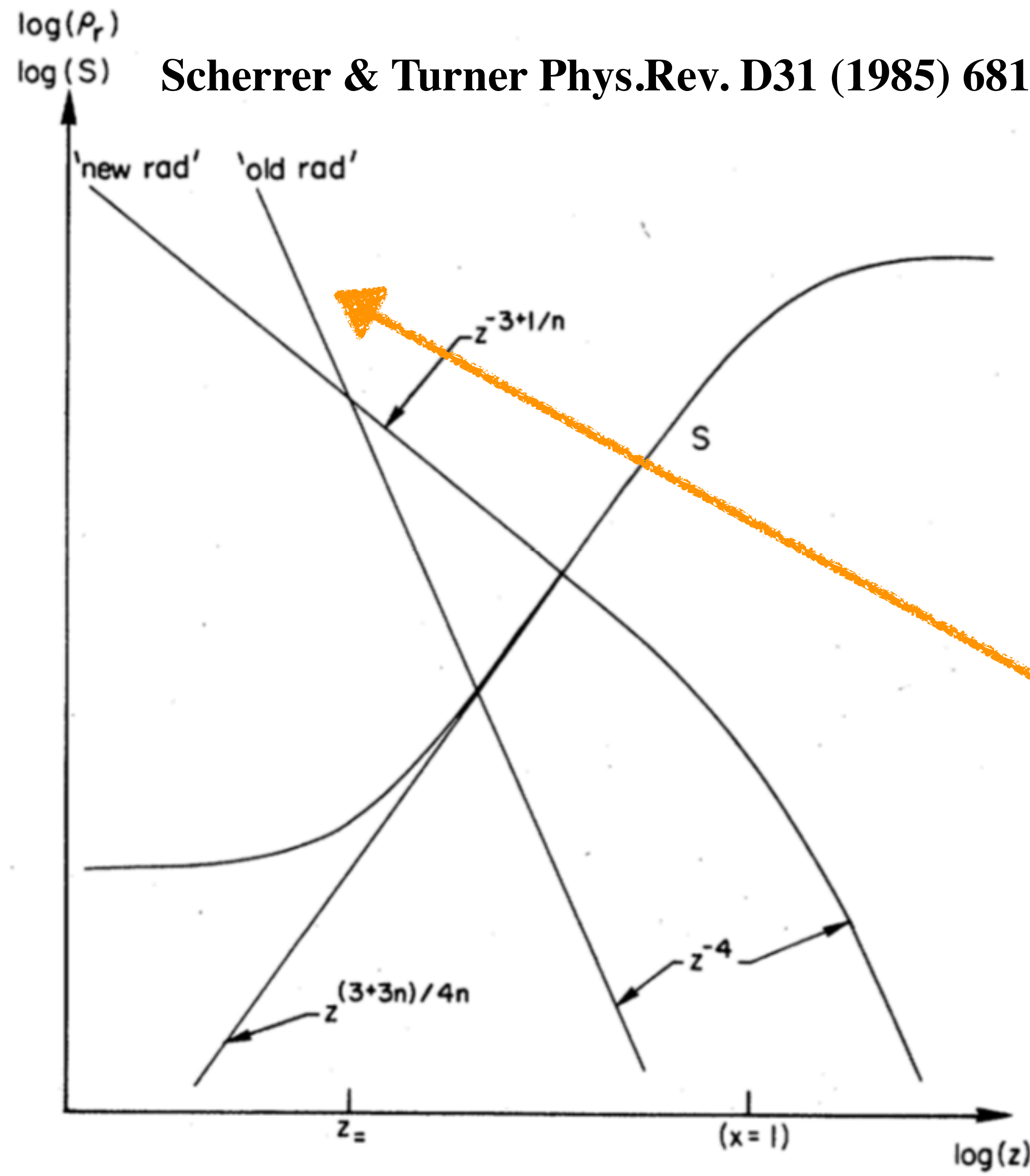

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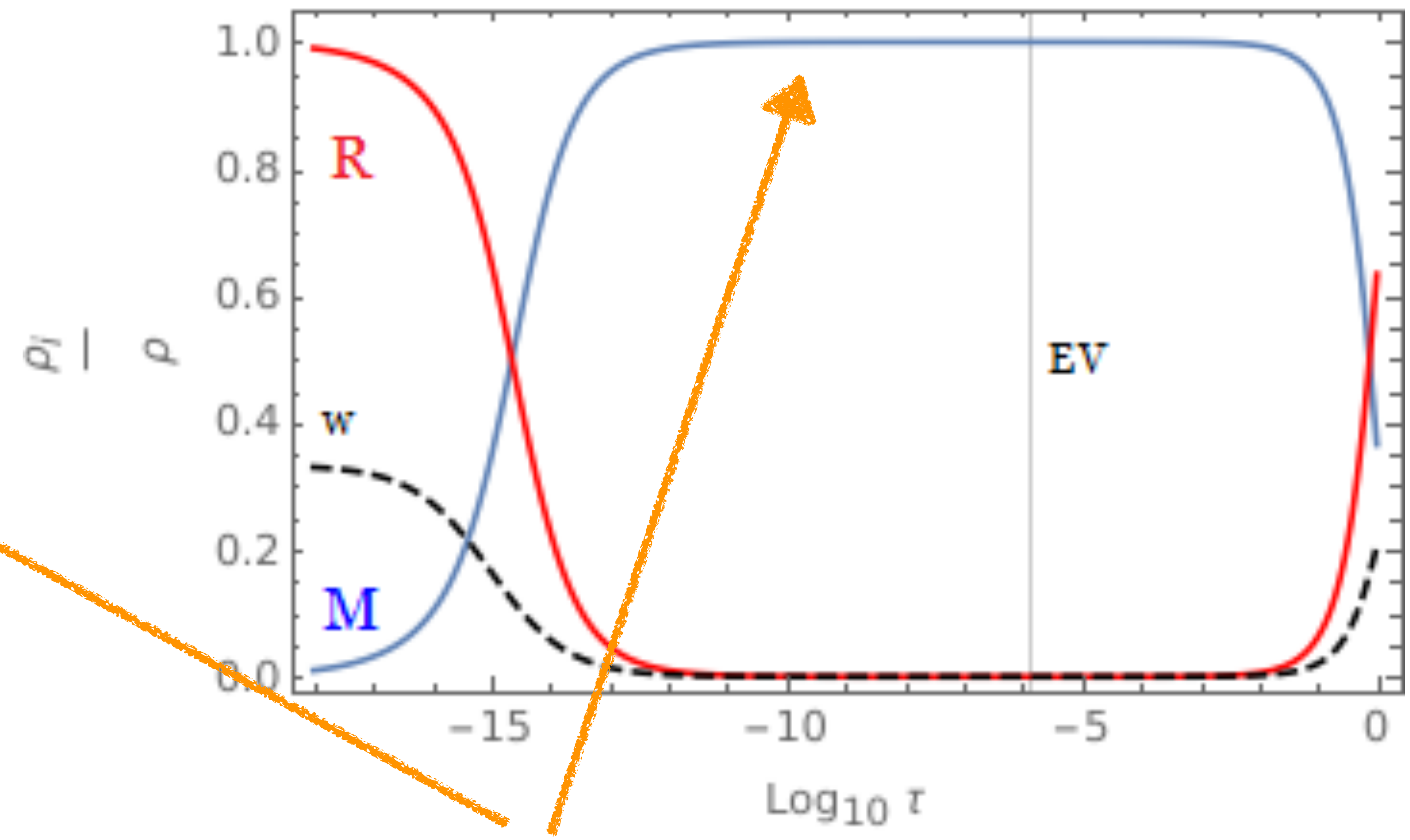

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Matter Dominated Freeze-out

One can **emulate** the standard Boltzmann treatment

$$\dot{n}_X + 3Hn_X = -\langle\sigma v\rangle[n_X^2 - (n_X^{\rm eq})^2]$$

but with different form for H

$$H \simeq H_\star \left(\frac{g_*(T)}{g_*(T_\star)}\right)^{3/8} \left(\frac{T}{T_\star}\right)^{3/2} \left[(1-r) + r\left(\frac{T}{T_\star}\right)\right]^{1/2} \text{ for } r = \begin{cases} 1 & \text{RD} \\ 0 & \text{MD} \end{cases}$$

Where $T_\star$ is temperature χ becomes matter-like and $H_\star \equiv H(T_\star)$

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Radiation dominated freeze-out

$$T_{\rm FO}^{\rm RD} \simeq \frac{m_{\rm DM}}{\ln\left[m_{\rm DM}M_{\rm Pl}\sigma_0\right]}$$

$$Y_{\rm FO}^{\rm RD} = 3\sqrt{\frac{5}{\pi}}\frac{\sqrt{g_\star}}{g_{\star S}}\frac{(n+1)x_F^{n+1}}{M_{\rm pl}m_{\rm DM}\sigma_0}$$

Scherrer and Turner, PRD 33 (1986) 1585

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Hamdan & JU [1710.03758]

Matter Dominated Freeze-out

$Y_{\rm DM}$ in matter dominated FO **different to radiation dominated** case.

Radiation domination restored after freeze-out as **“matter” decays** to SM.

Required because **observations imply** radiation domination prior to current epoch.

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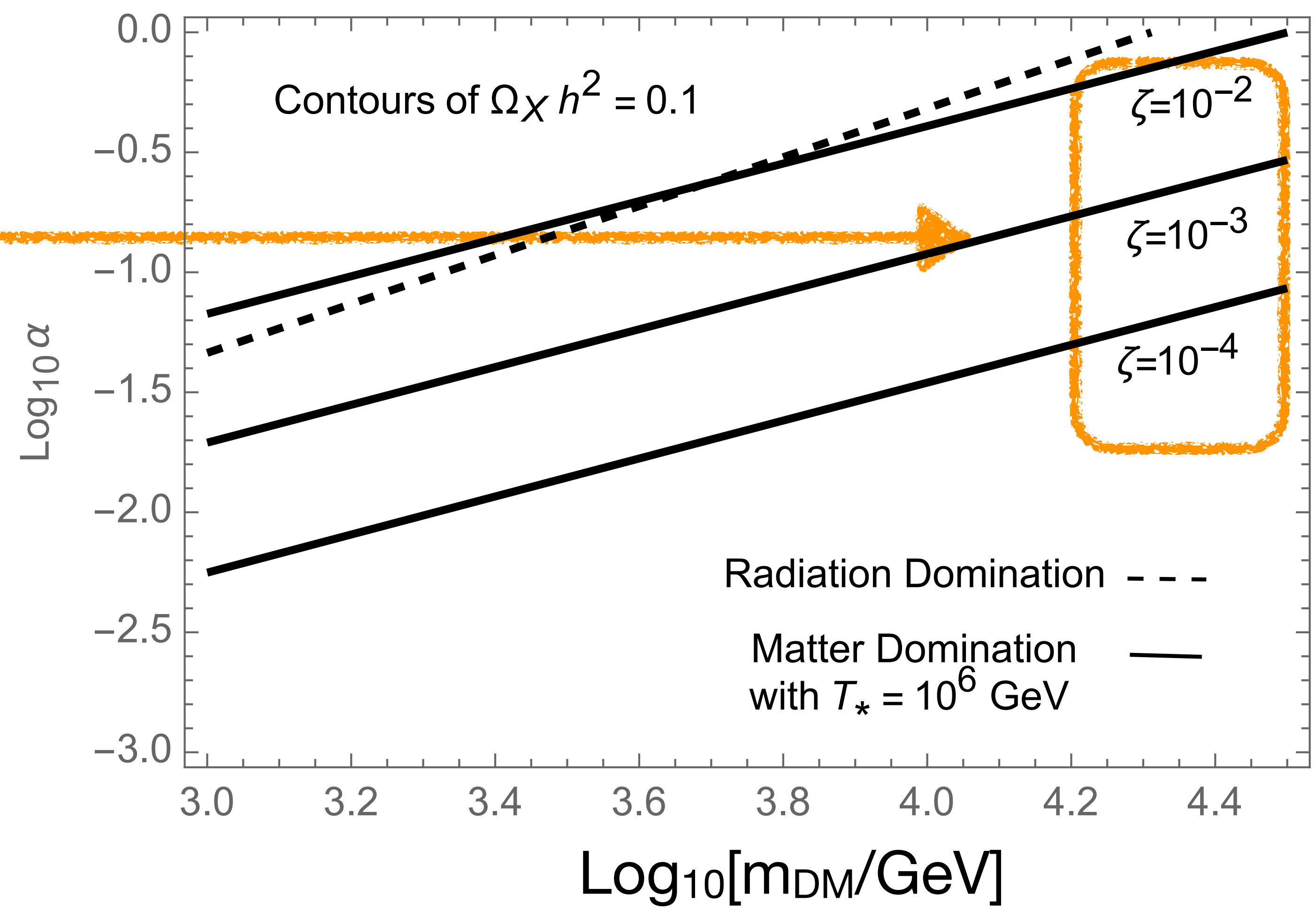

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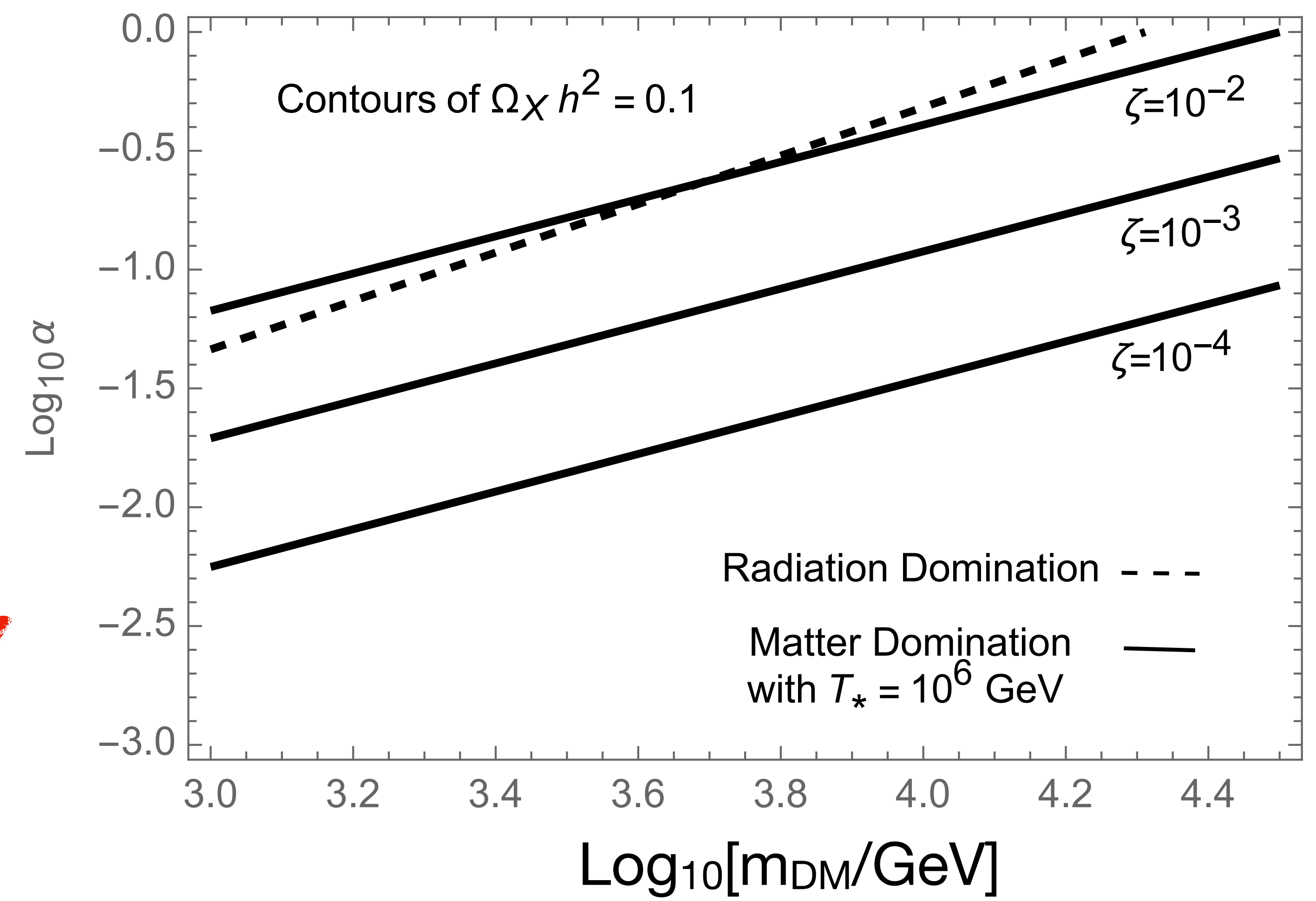
More dilution implies smaller couplings



Weakening search limits
compared to radiation dominated FO.

Hamdan & JU [1710.03758]

Matter Dominated Freeze-out

For DM freeze-out **during matter domination**,
whilst avoiding cosmological constraints:

a). Universe **matter dominated** during freeze-out

b). Decay of χ prior to **BBN**

c). Decay of χ after dark matter freeze-out

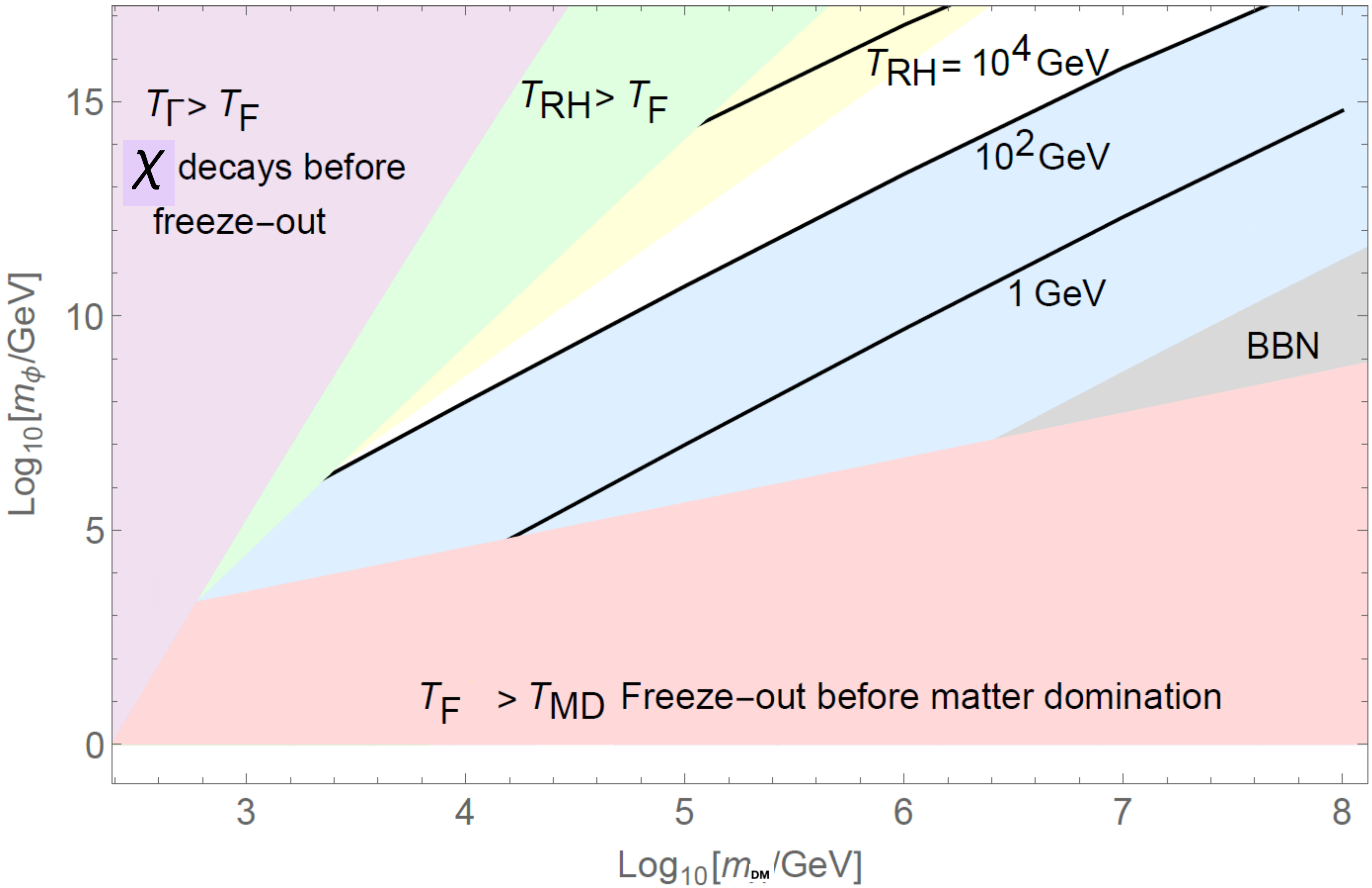
d). χ **decays negligible** during dark matter freeze-out

o.w./ similar to Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

e). Decays of χ prior to **EWPT** (optional - model dependent)

MDFO Parameter space

Putting this together, the parameter space for $\sigma \sim \frac{\alpha_{\rm DM}^2}{m_{\rm DM}}$, $\alpha = 0.1$ and $T_\star \simeq m_\chi$



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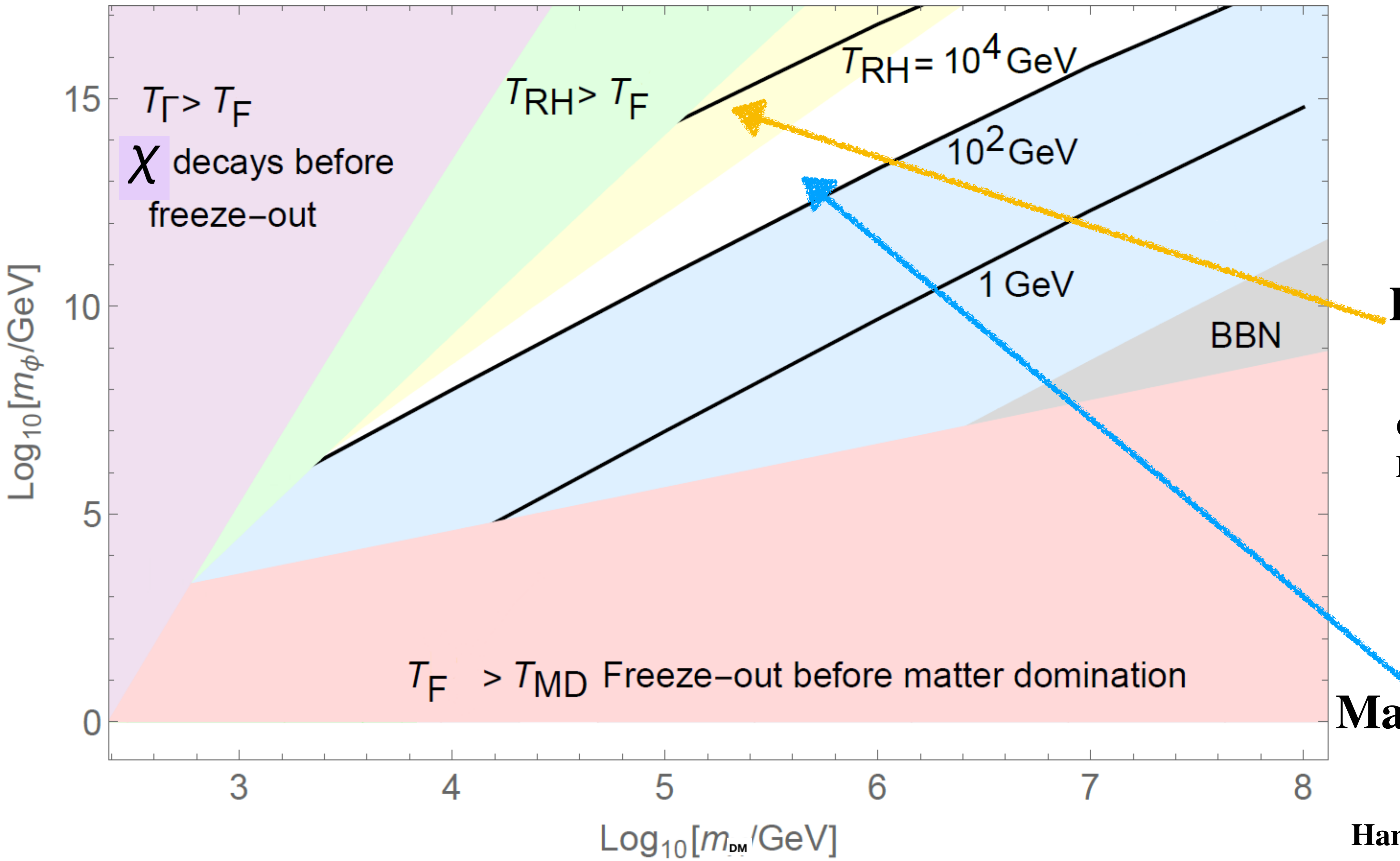


Decay Regime

$H \propto T^4$

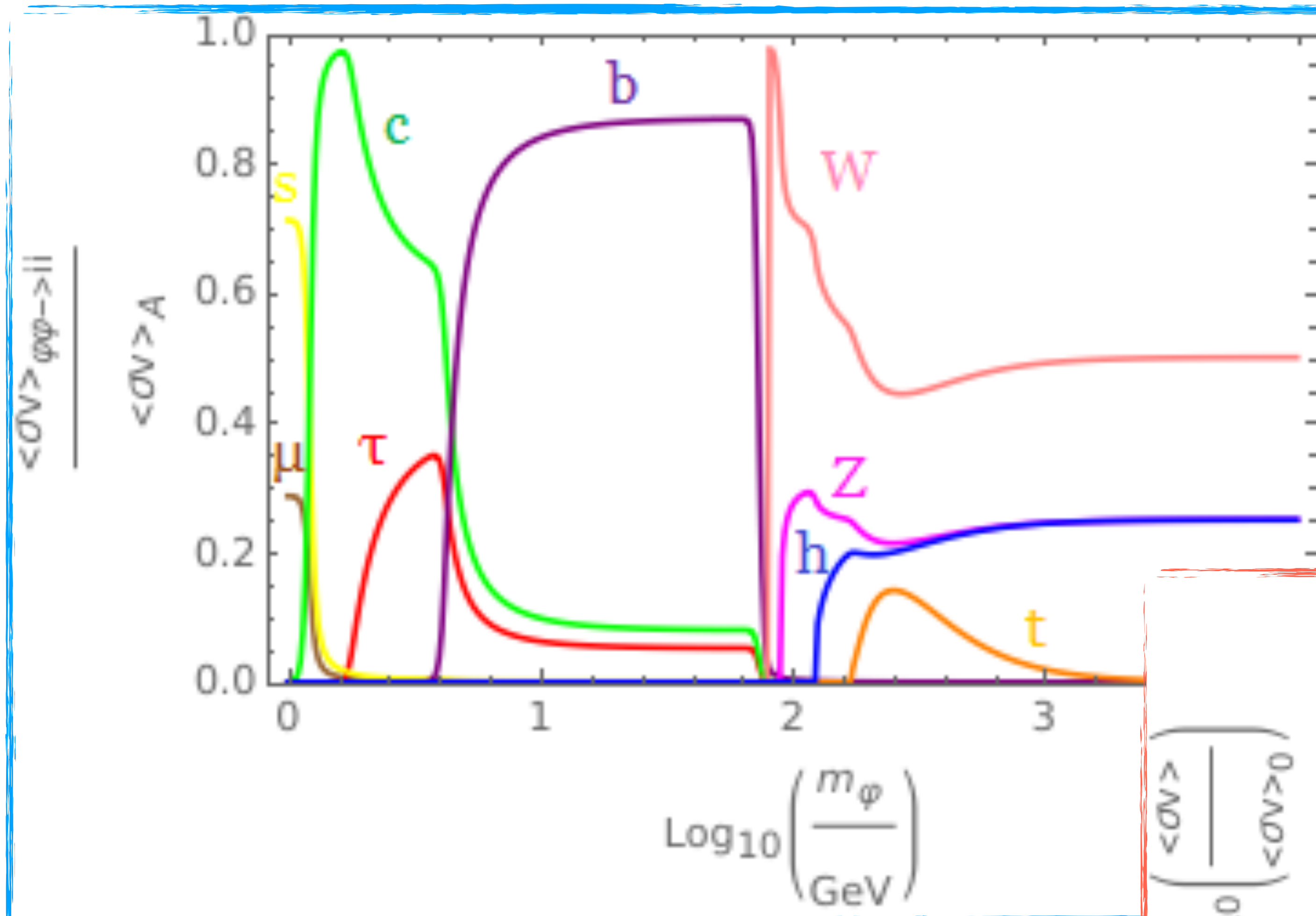
Giudice, Kolb, & Riotto, PRD 64 (2001) 023508

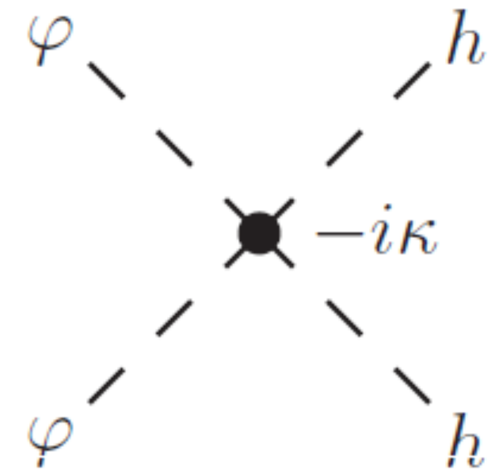
Matter Domination

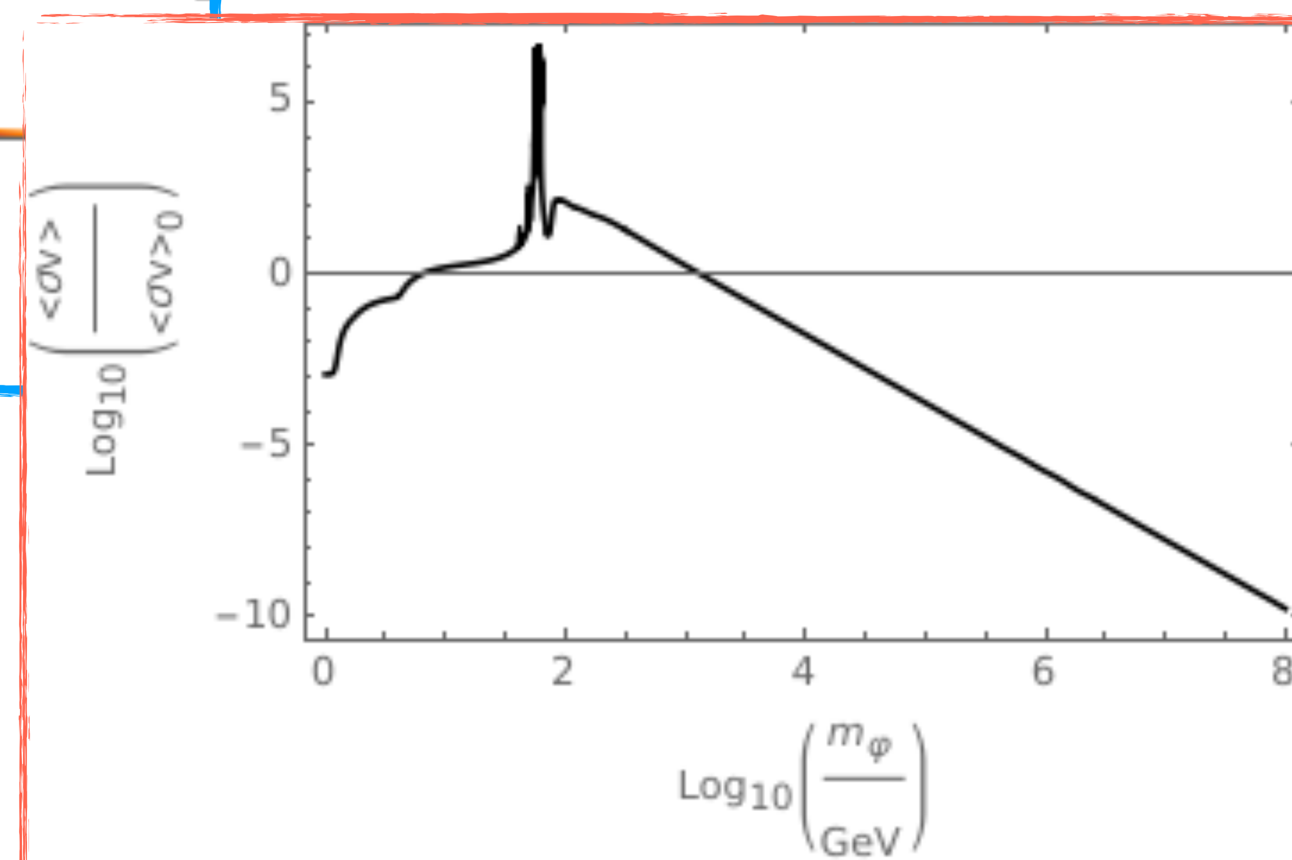
$H \propto T^{3/2}$

Hamdan & JU [1710.03758]

Example: Scalar Higgs Portal







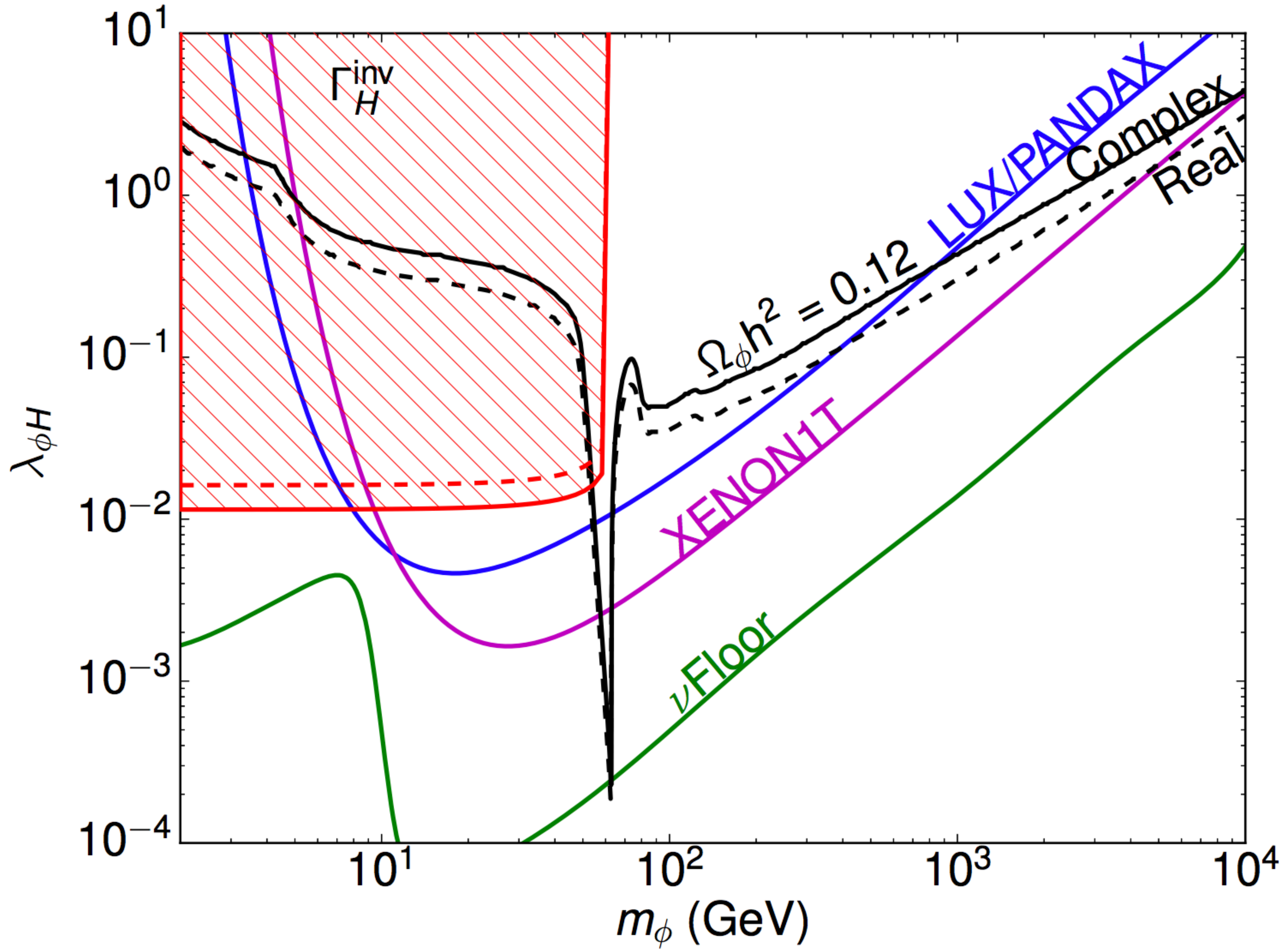
Annihilation cross section

units of thermal relic cross section.

$$\langle \sigma v \rangle_0 = 3 \times 10^{-26} \text{cm}^3/\text{s}$$

Classic Ref: Cline, Kainulainen, Scott, Weniger [1306.4710]

Example: Scalar Higgs Portal



Scalar Higgs Portal assuming **Standard Cosmology**…

Escudero-Berlin-Hooper-Lin [1609.09079]

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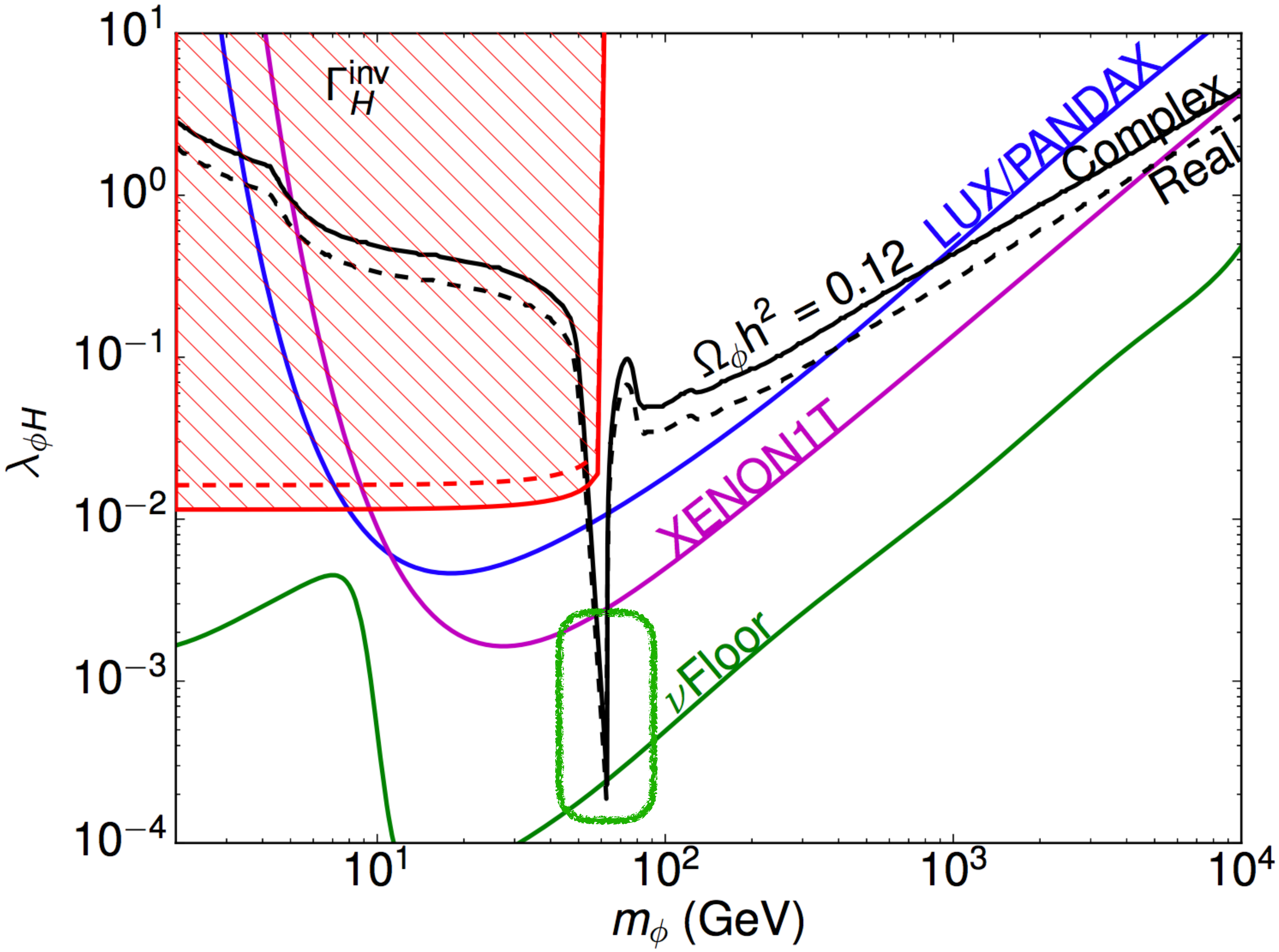


Scalar Higgs Portal assuming Standard Cosmology is **experimentally excluded** away from region of resonant annihilation via the Higgs.

Escudero-Berlin-Hooper-Lin [1609.09079]

MDFO via Higgs Portal

Again considering the case $\sigma_0 \sim \frac{\kappa^2}{m_\varphi^2}$ and $T_\star \simeq m_\chi$

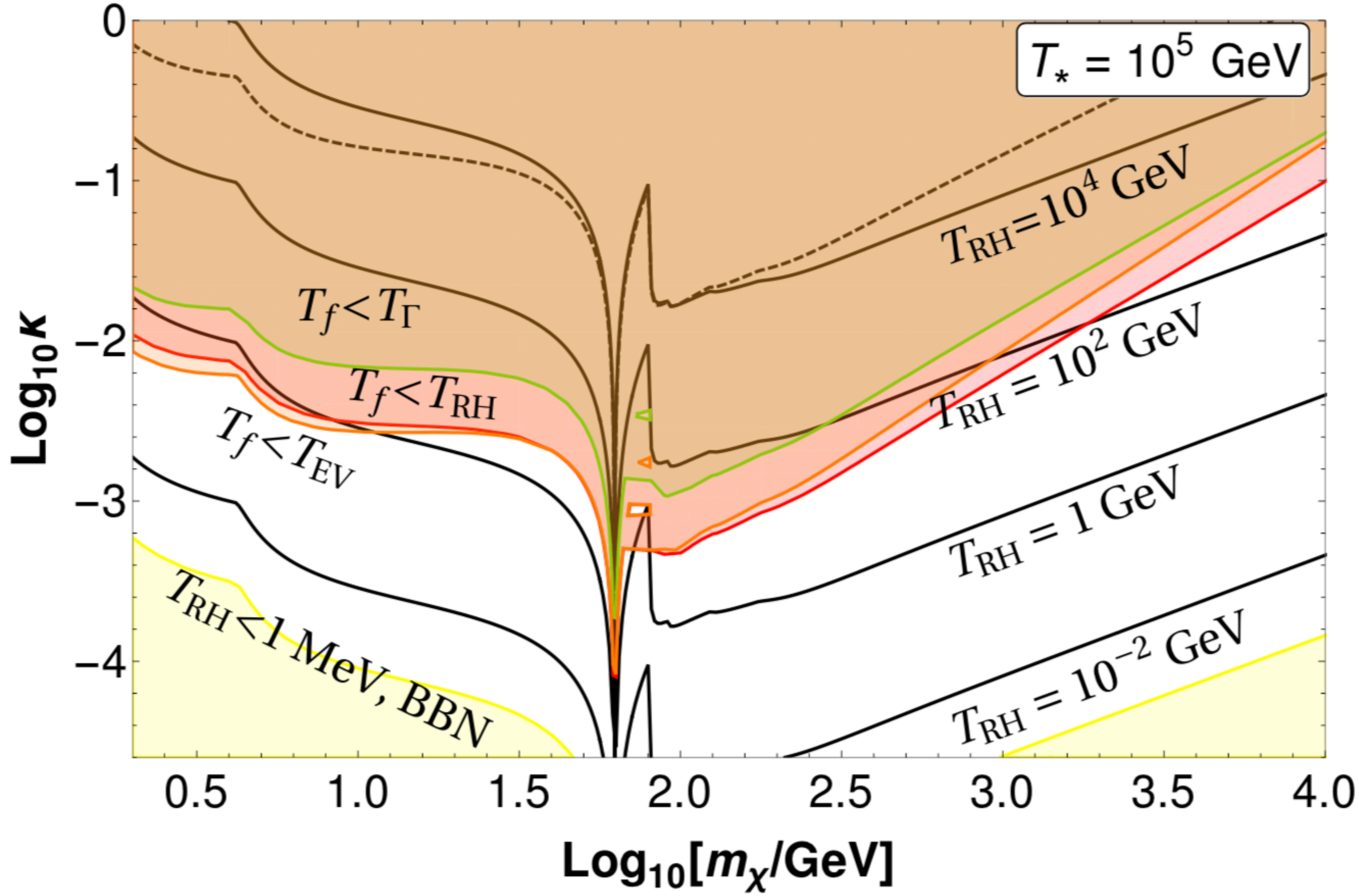
Cosmological requiremer

a). Matter dominated during freeze-out

b). χ decay prior to **BBN**

c). χ decay after FO

d). χ **decays negligible** during FO



Hamdan, Thesis 2018 & Chanda-Hamdan-JU [1910.xxxxx]

MDFO via Higgs Portal

Experimental limits:

cf. Escudero-Berlin-Hooper-Lin [1609.09079]

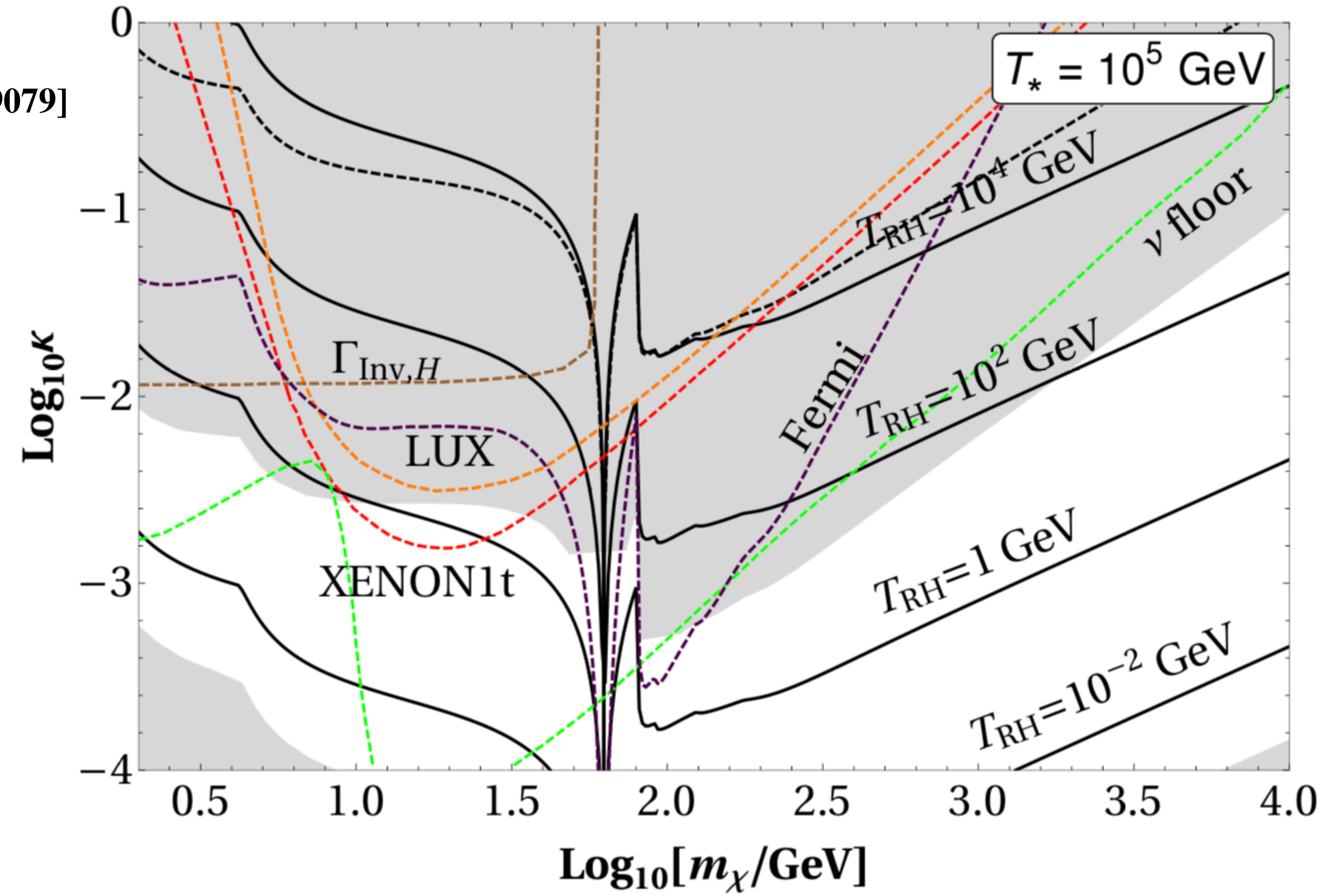
a). Fermi-LAT

b). Xenon1T

c). LUX/PandaX

d). Invisible Higgs decay

e). Neutrino Floor



In MDFO **Higgs Portal revived** as a viable model.

Hamdan, Thesis 2018 & Chanda-Hamdan-JU [1910.xxxxx]
See also: Bernal, Cosme & Tenkanen [1803.08064], Hardy [1804.06783]

IV. UV Freeze-in & Non-Standard Cosmology

Enhancements during UV Freeze-in

UV freeze-in: the production cross section of DM from thermal bath is:

$$\langle \sigma v \rangle \sim \frac{T^n}{\Lambda^{2+n}}$$

The **DM abundance** is expected to be

$$Y \sim \int_0^{T_{\rm RH}} \frac{M_{\rm Pl}\, T^n}{\Lambda^{n+2}} \sim \frac{M_{\rm Pl}\, T_{\rm RH}^{n+1}}{\Lambda^{n+2}} \, .$$

$T_{\rm RH}$ is reheat temperature assuming instantaneous decay of inflaton.

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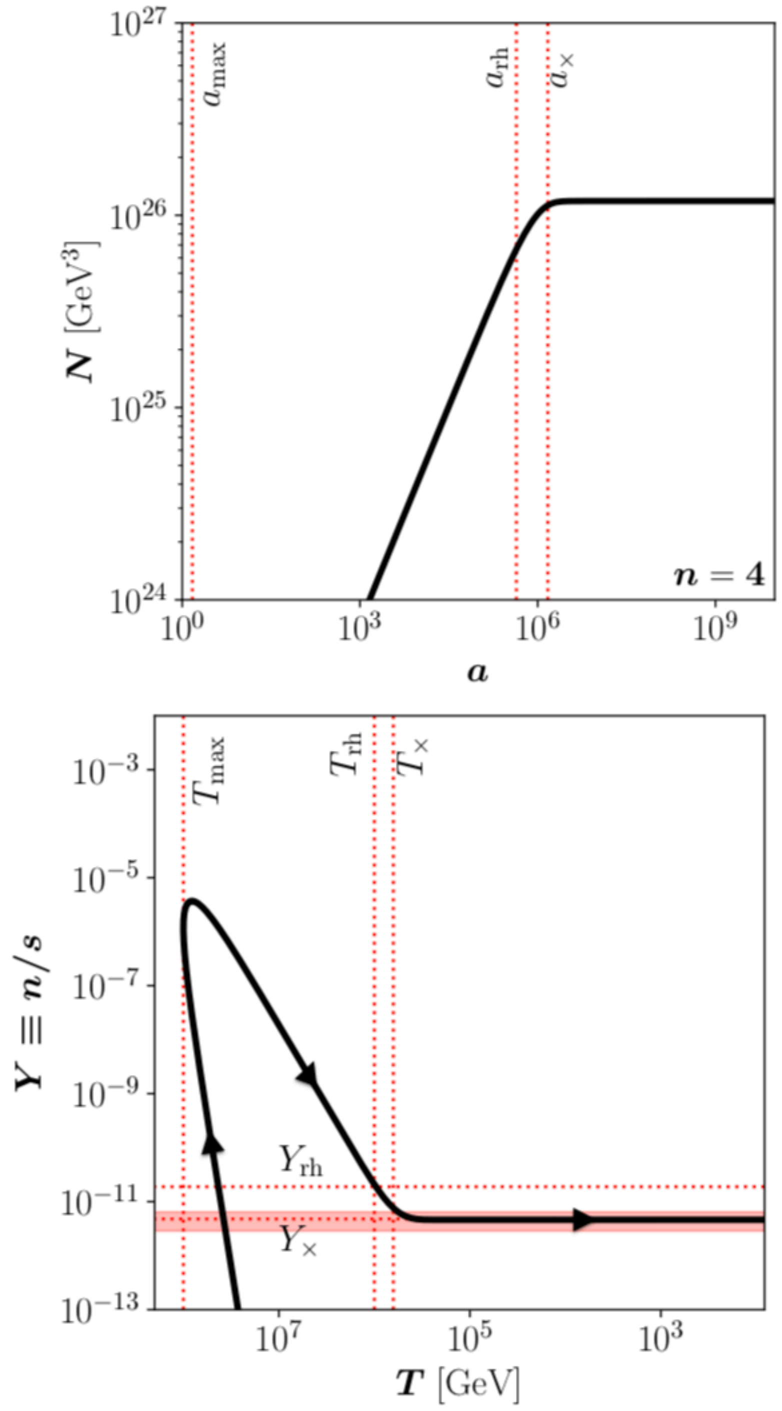
Assuming universe **initially matter dominated** before reheating then **for *n*>6** then DM abundance **enhanced** relative to sudden decay approx.

Garcia, Mambrini, Olive, Peloso, [1709.01549].

Changing operator dimension



Bernal, Elahi, Maldonado, & JU [1909.07992]

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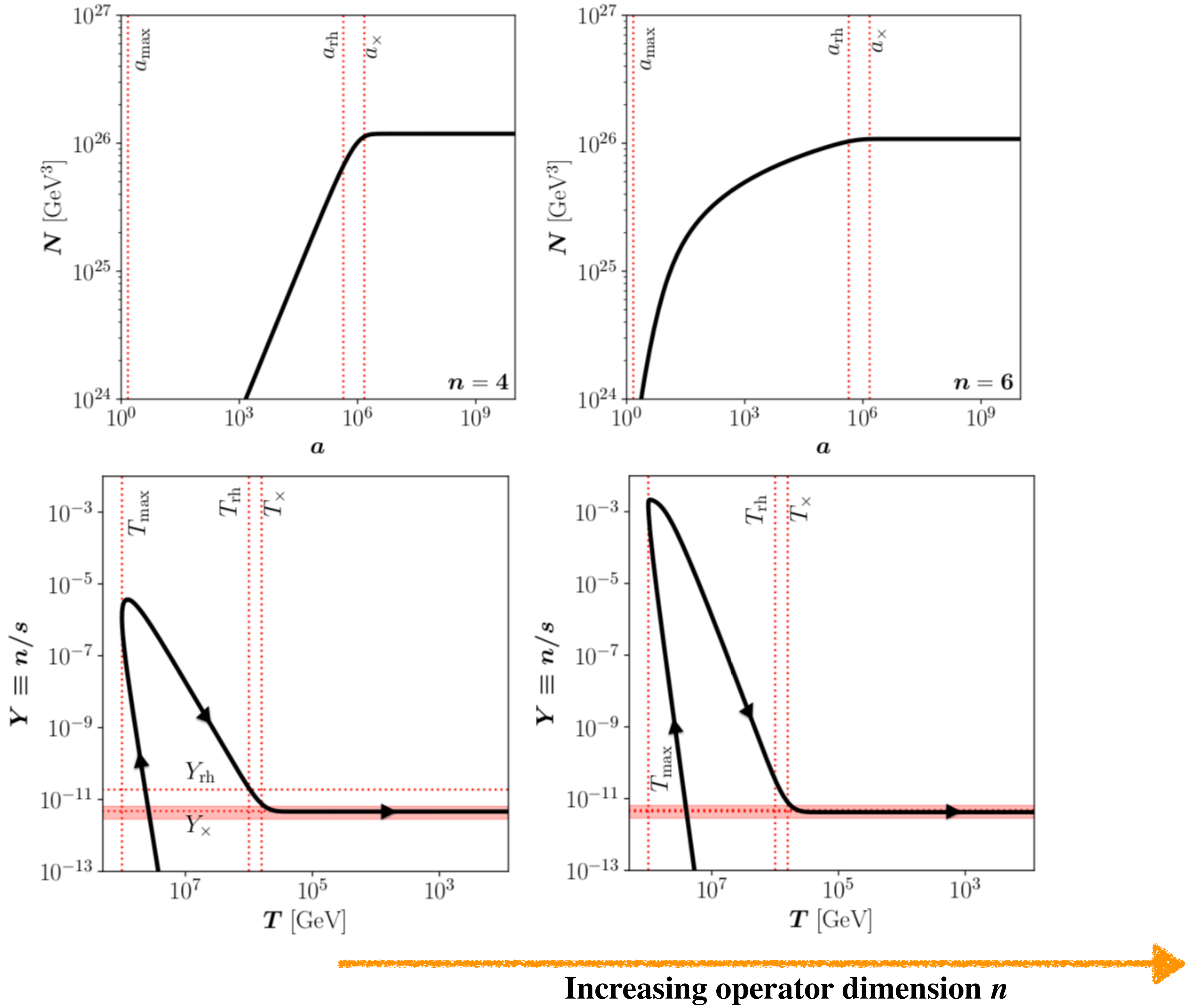

Bernal, Elahi, Maldonado, & JU [1909.07992]

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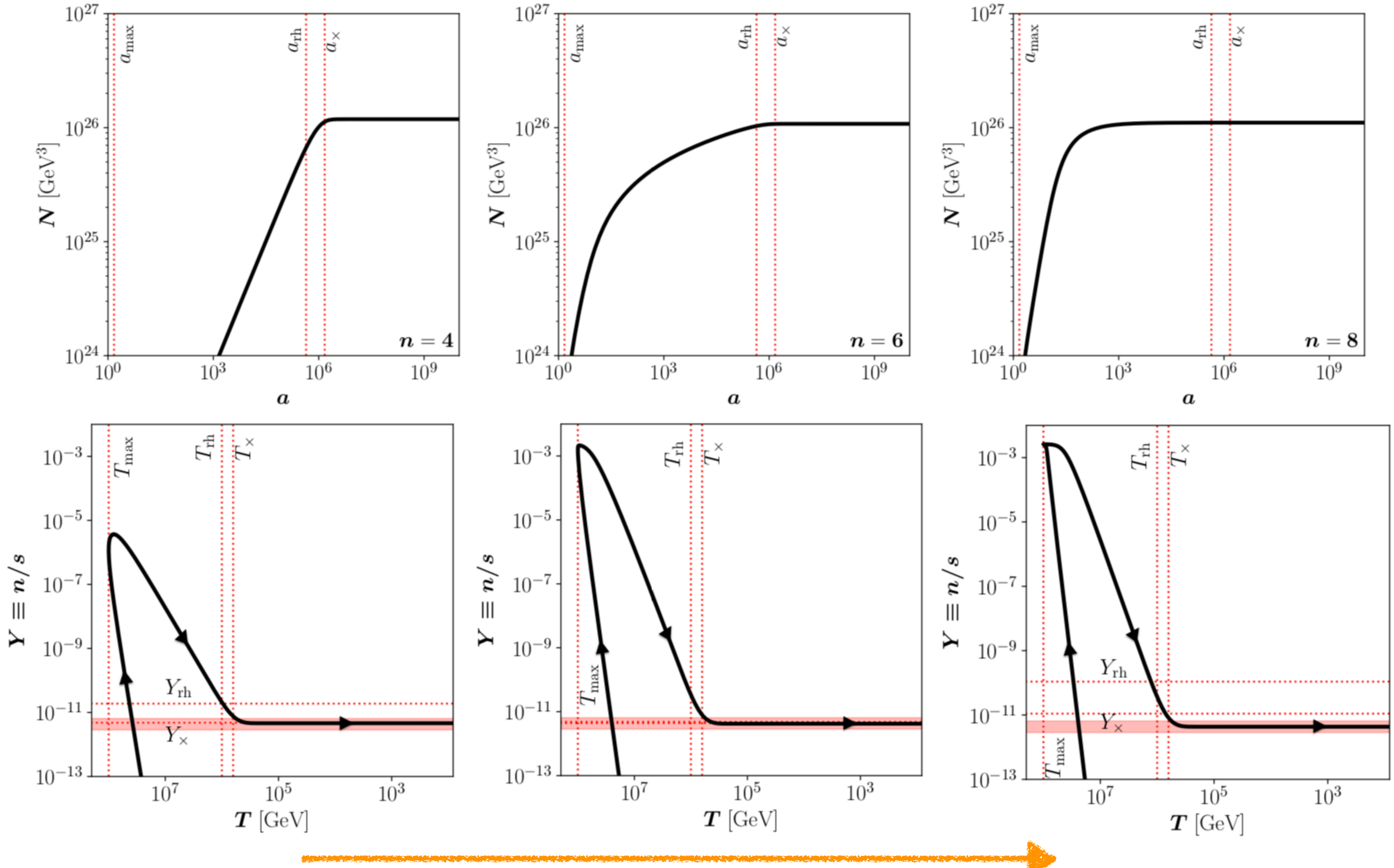

Increasing operator dimension *n*

Bernal, Elahi, Maldonado, & JU [1909.07992]

Transition from non-standard cosmology

If the early universe is dominated by field evolving as:

$$\rho_\phi(t) = \rho_\phi(t_I)a^{a+m}$$

The **equation of state** for ϕ is $\omega = \frac{p_\phi}{\rho_\phi} = \frac{m+1}{3}$

If the state ϕ is **decaying** to Standard Model radiation then the evolution follows

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi \qquad \frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_\phi\,\rho_\phi$$

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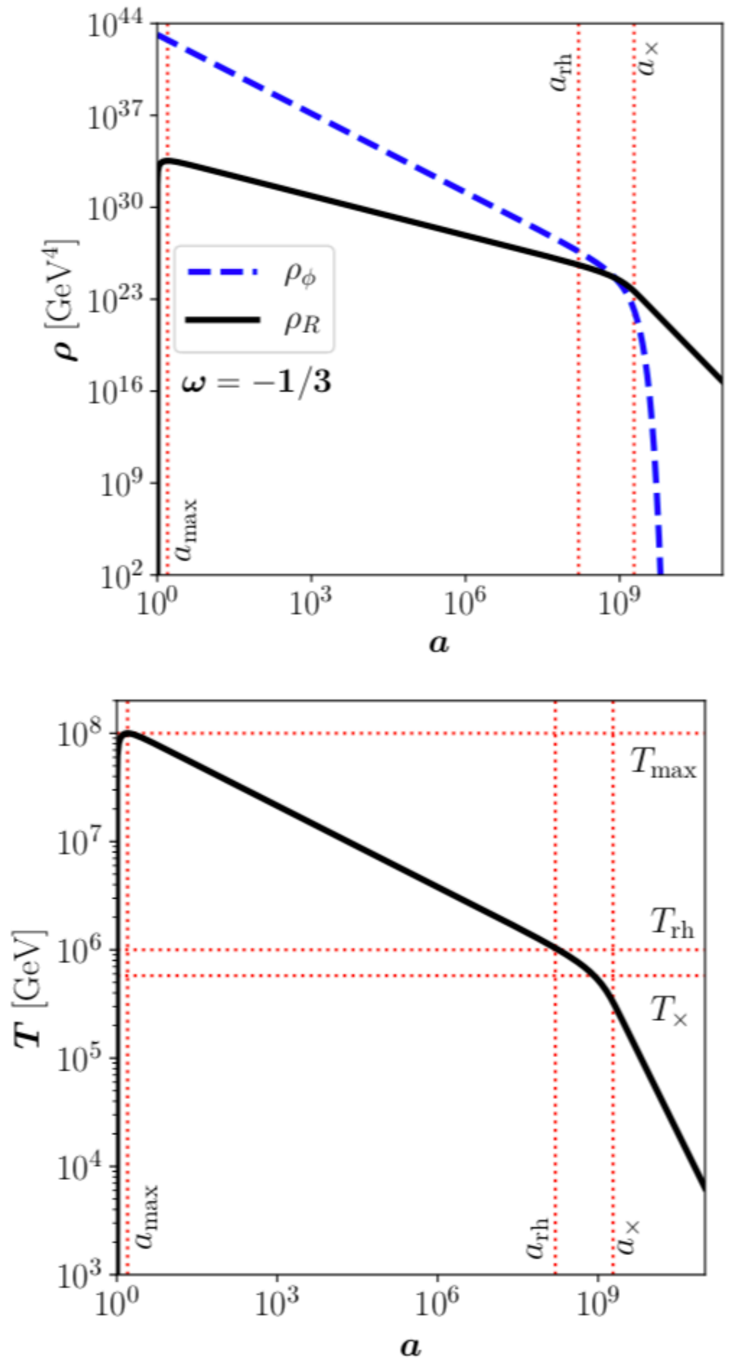
It follows the **energy densities evolve** as

$$\rho_\phi(a) = \rho_\phi(a_{\rm in}) \left[\frac{a_{\rm in}}{a}\right]^{3(1+\omega)} = 3\, M_{\rm Pl}^2\, H_{\rm in}^2\, \left[\frac{a_{\rm in}}{a}\right]^{3(1+\omega)}$$

$$\rho_R(a) = \frac{6}{5-3\omega} M_{\rm Pl}^2\, H_{\rm in}\, \Gamma_\phi\, \frac{a_{\rm in}^{\frac{3}{2}(1+\omega)}}{a^4} \left[a^{\frac{5-3\omega}{2}} - a_{\rm in}^{\frac{5-3\omega}{2}}\right]$$

Dark Matter and Non-Standard Cosmology



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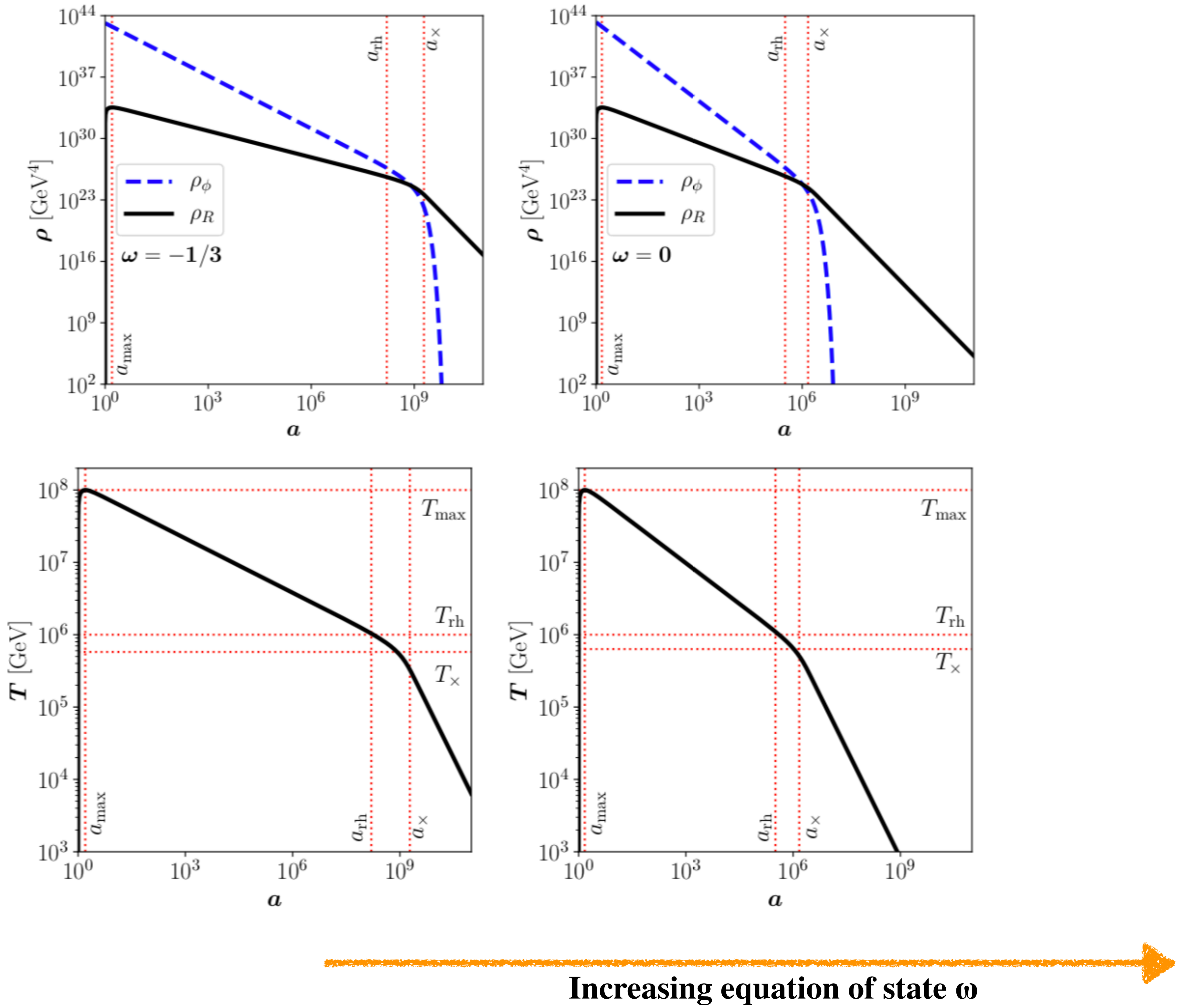

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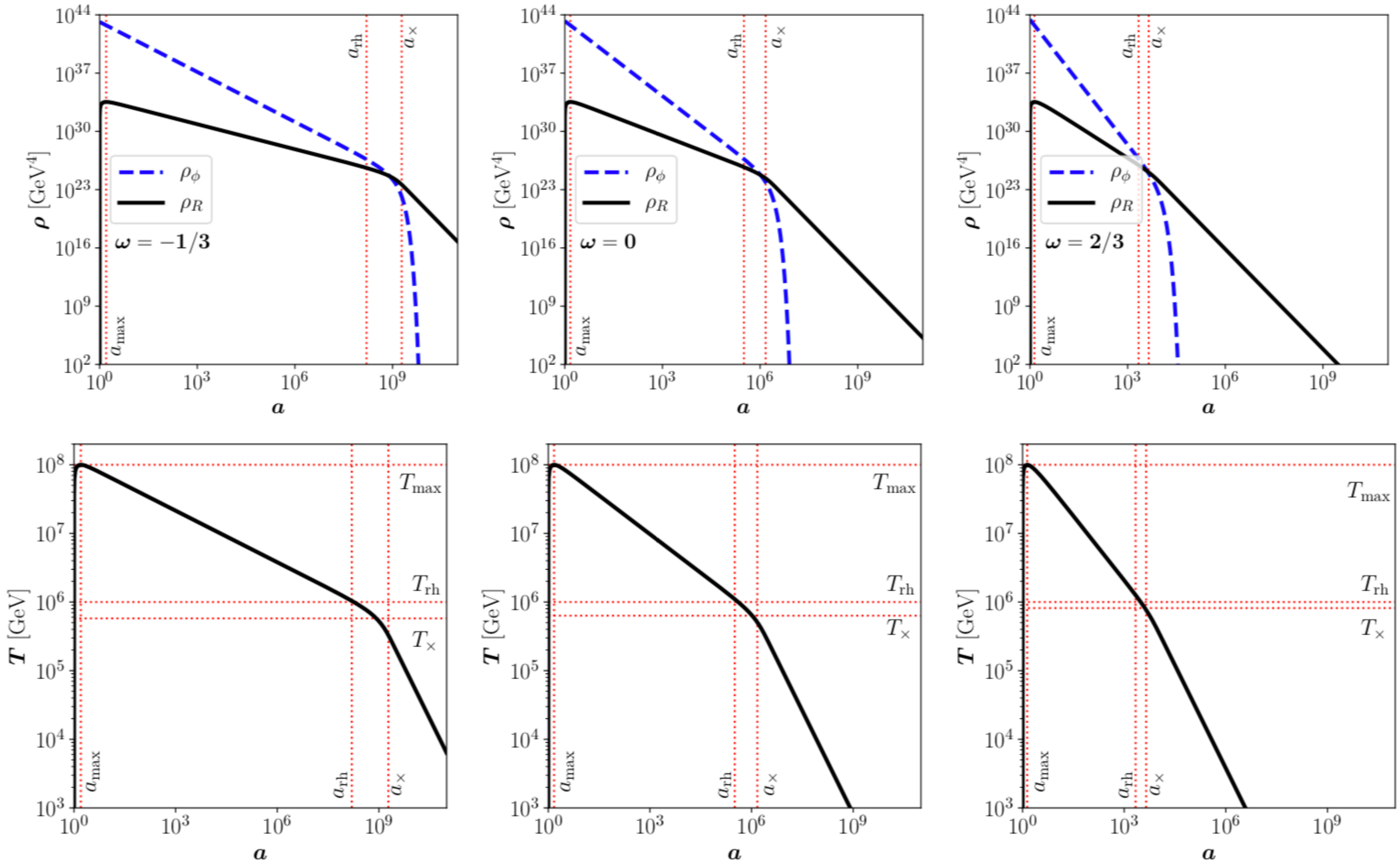


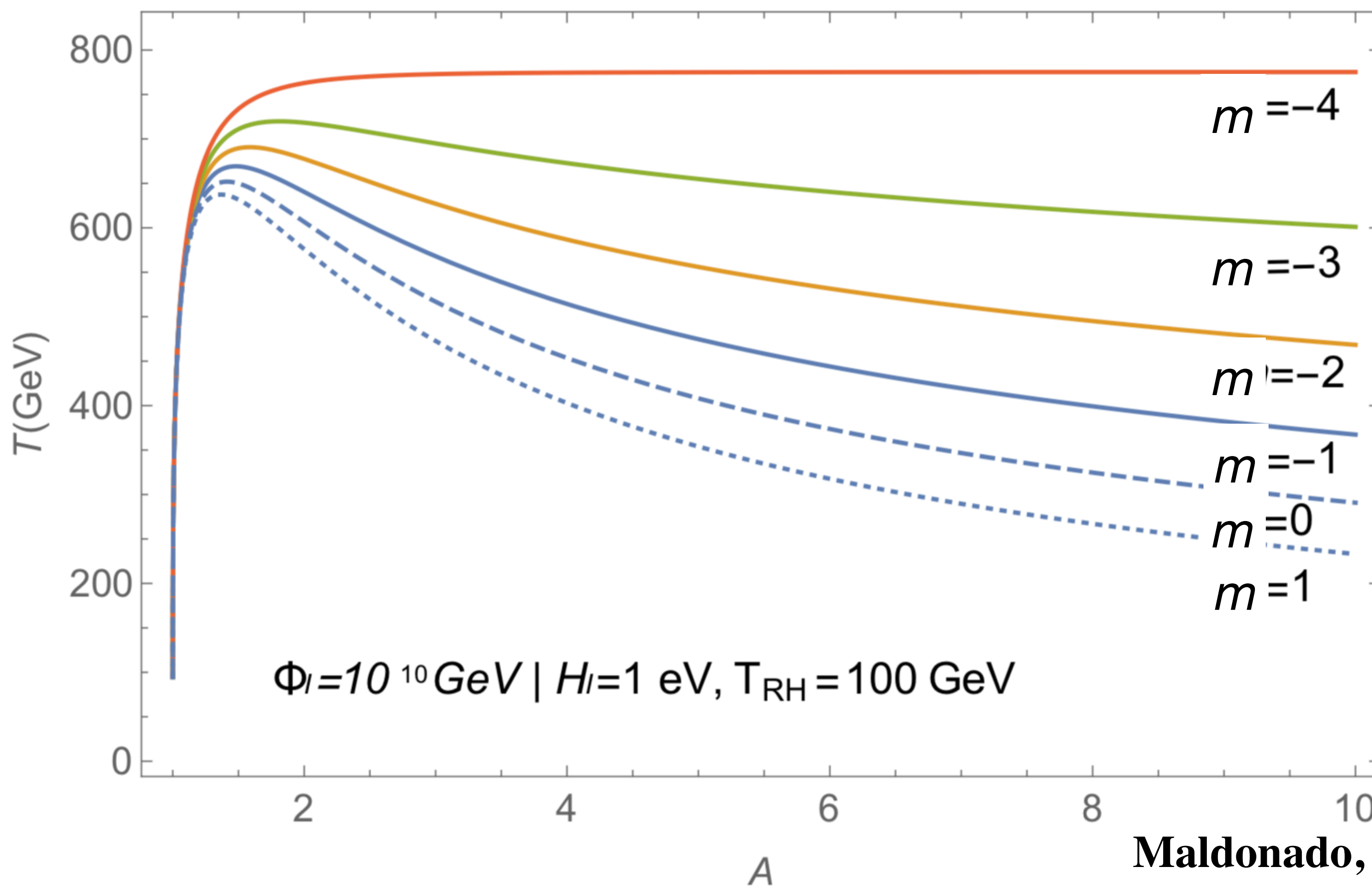
Increasing equation of state ω

Transition from non-standard cosmology

Given the **radiation** evolution: $\rho_R(a) = \frac{6}{5-3\omega} M_{\rm Pl}^2 H_{\rm in} \Gamma_\phi \frac{a_{\rm in}^{\frac{3}{2}(1+\omega)}}{a^4}\left[a^{\frac{5-3\omega}{2}} - a_{\rm in}^{\frac{5-3\omega}{2}}\right]$

The **temperature**, related via $\rho_R = \frac{\pi^2 g_*(T)}{30} T^4$, evolves according to

$$T = \left(\frac{45}{4\pi^3}\frac{g_*(T_{\rm RH})}{g_*^2(T)}\right)^{1/8} (H_I M_{\rm Pl} T_{\rm RH}^2)^{1/4} \left(\frac{A^{-(2+m/2)} - A^{-4}}{2-m/2}\right)^{-4} \quad \text{where} \quad A \equiv \frac{a}{a_I} = a T_{\rm RH}$$



Maldonado, & JU [1902.10746]

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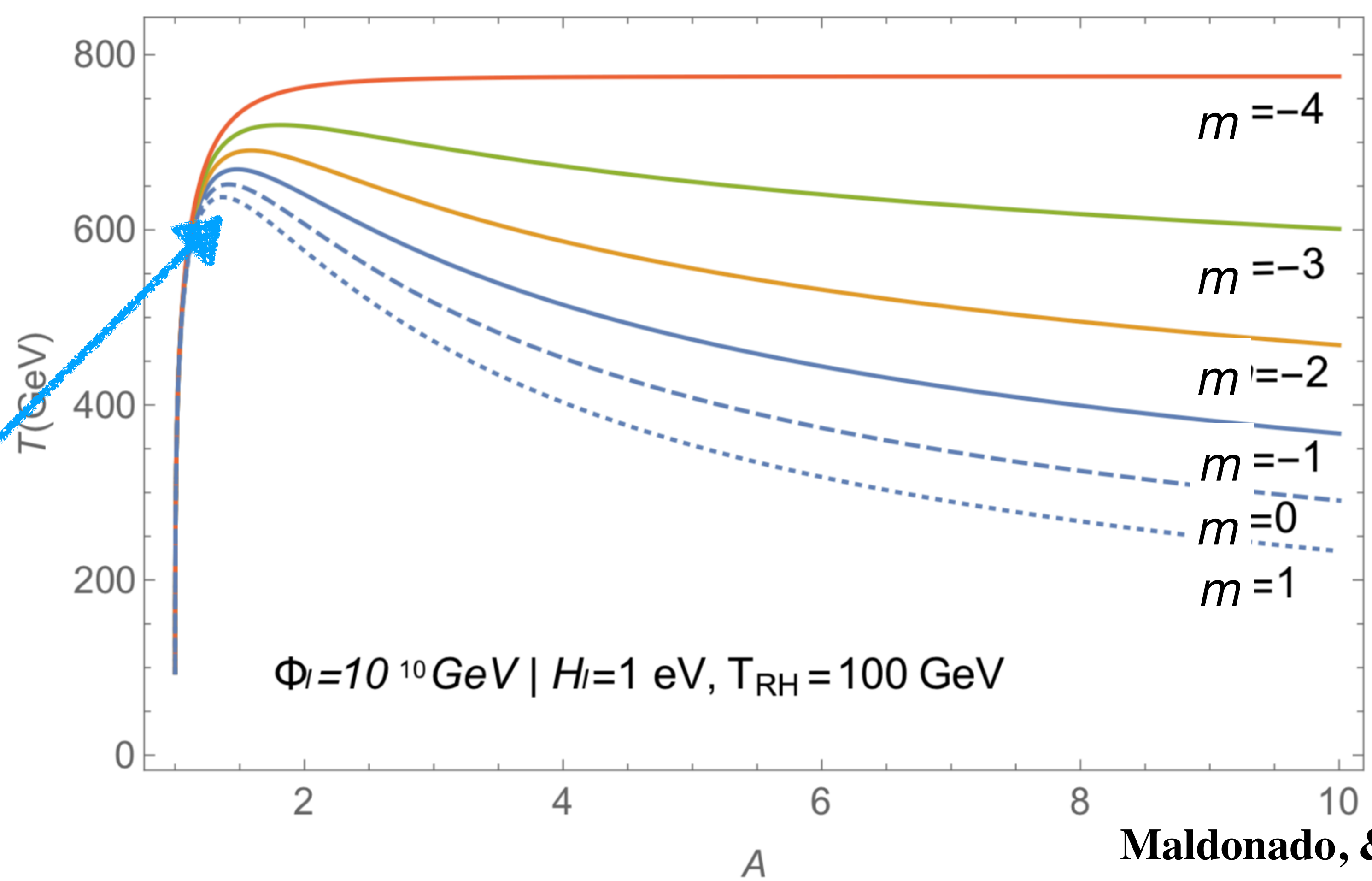

Define

$T_{\rm max} \geq T_{\rm RH}$

Maldonado, & JU [1902.10746]

Dark Matter and Non-Standard Cosmology

This change in cosmological evolution **impacts the dark matter**.

The comoving number density $N \equiv n \times a^3$ evolving according to

$$\frac{dN}{da} = -\frac{\langle \sigma v \rangle}{a^4\, H}\left(N^2 - N_{\rm eq}^2\right)$$

Implying at temperature T

$$N(T) = \frac{8\,\zeta(3)^2\, g^2}{3\pi^4\,(n-n_c)(1+\omega)}\left[\frac{a_\times^{3+\omega}}{a_{\rm in}^{1+\omega}}\right]^{\frac{3}{2}}\frac{T_\times^{4\frac{3+\omega}{1+\omega}}}{\Lambda^{n+2}\, H_{\rm in}}\left[T_{\rm max}^{n-n_c} - T^{n-n_c}\right]$$

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This can be **converted into a yield** $Y(T) = \dfrac{N(T)}{s(T)\, a^3}$

And integrating to the 'end' of ϕ decays give the **relic abundance** $(n \neq n_c)$

$$Y(T_\times) = \frac{180\,\zeta(3)^2\, g^2}{\pi^7\, g_{\star s}} \sqrt{\frac{10}{g_\star}} \frac{1}{(n-n_c)(1+\omega)} \frac{M_{\rm Pl}\, T_\times^{\frac{7-\omega}{1+\omega}}}{\Lambda^{n+2}} \left[T_{\rm max}^{n-n_c} - T_\times^{n-n_c}\right].$$

with $n_c \equiv 2 \times \left(\dfrac{3-\omega}{1+\omega}\right)$

Enhancements during UV Freeze-in

For a **fixed operator dimension *n*** (varying ω) the boost is

$$B \simeq \begin{cases} \frac{1}{3}\frac{7-\omega_c}{\omega_c-\omega} & \text{for } \omega < \omega_c\,, \\ \frac{8}{3}\frac{7-\omega}{(1+\omega)^2}\ln\frac{T_{\max}}{T_{\rm RH}} & \text{for } \omega = \omega_c\,, \\ \frac{1}{3}\frac{7-\omega_c}{\omega-\omega_c}\left[\frac{T_{\max}}{T_{\rm RH}}\right]^{\frac{8(\omega-\omega_c)}{(1+\omega)(1+\omega_c)}} & \text{for } \omega > \omega_c\,, \end{cases}$$

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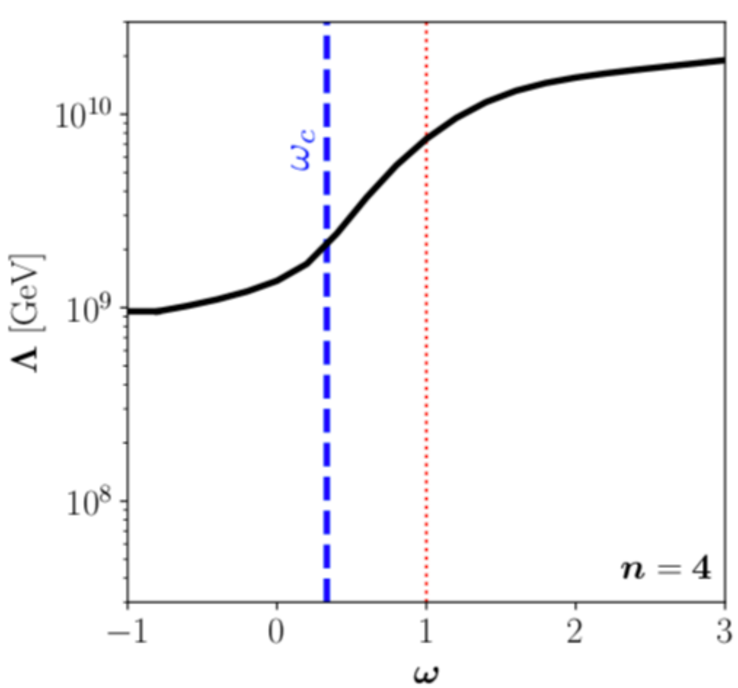

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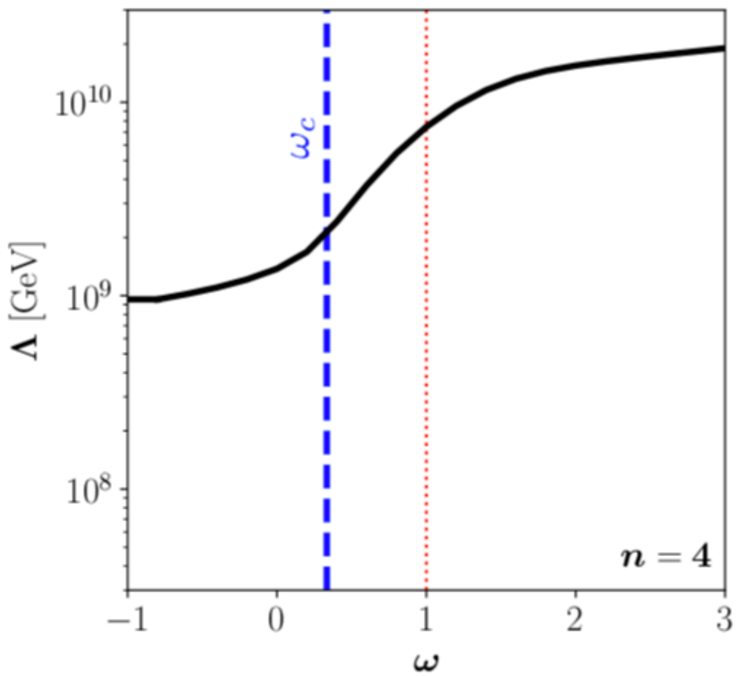
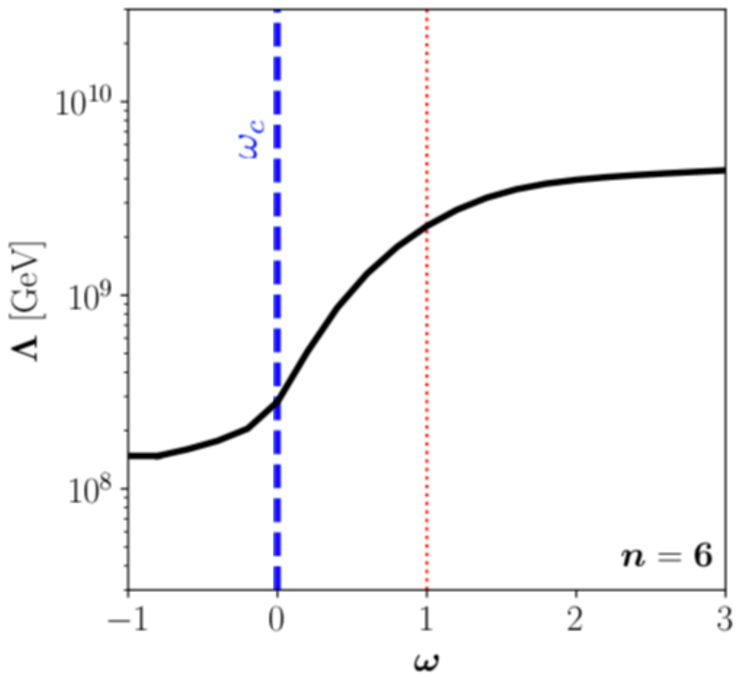
Increasing operator dimension *n*





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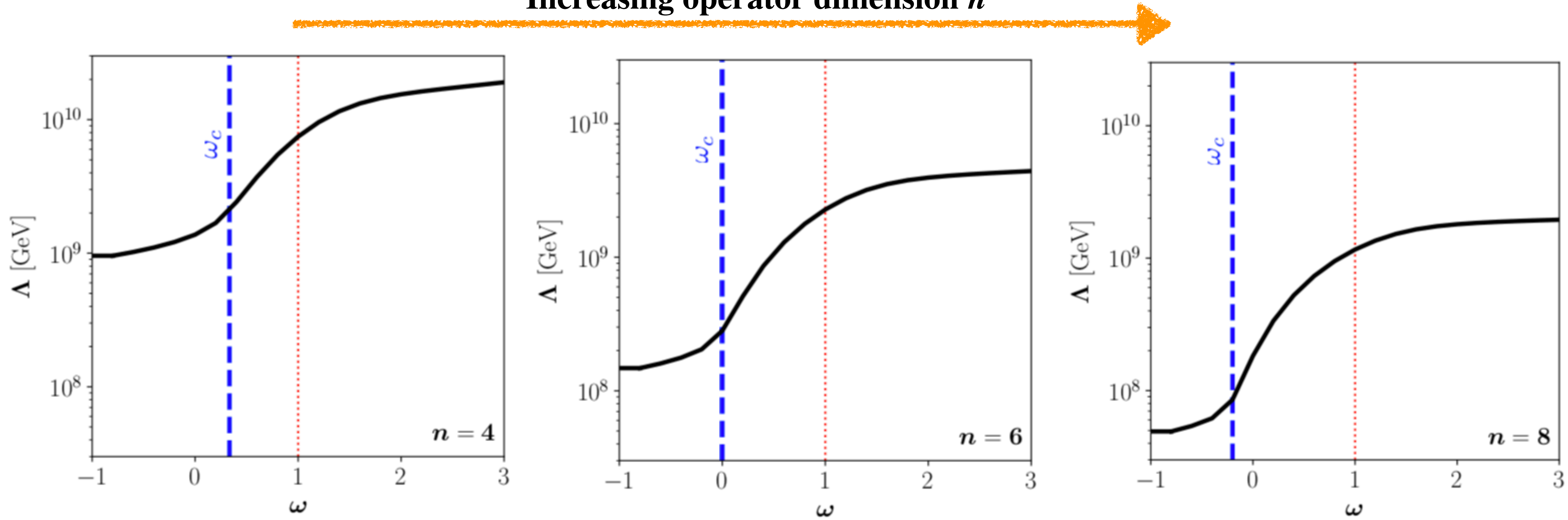
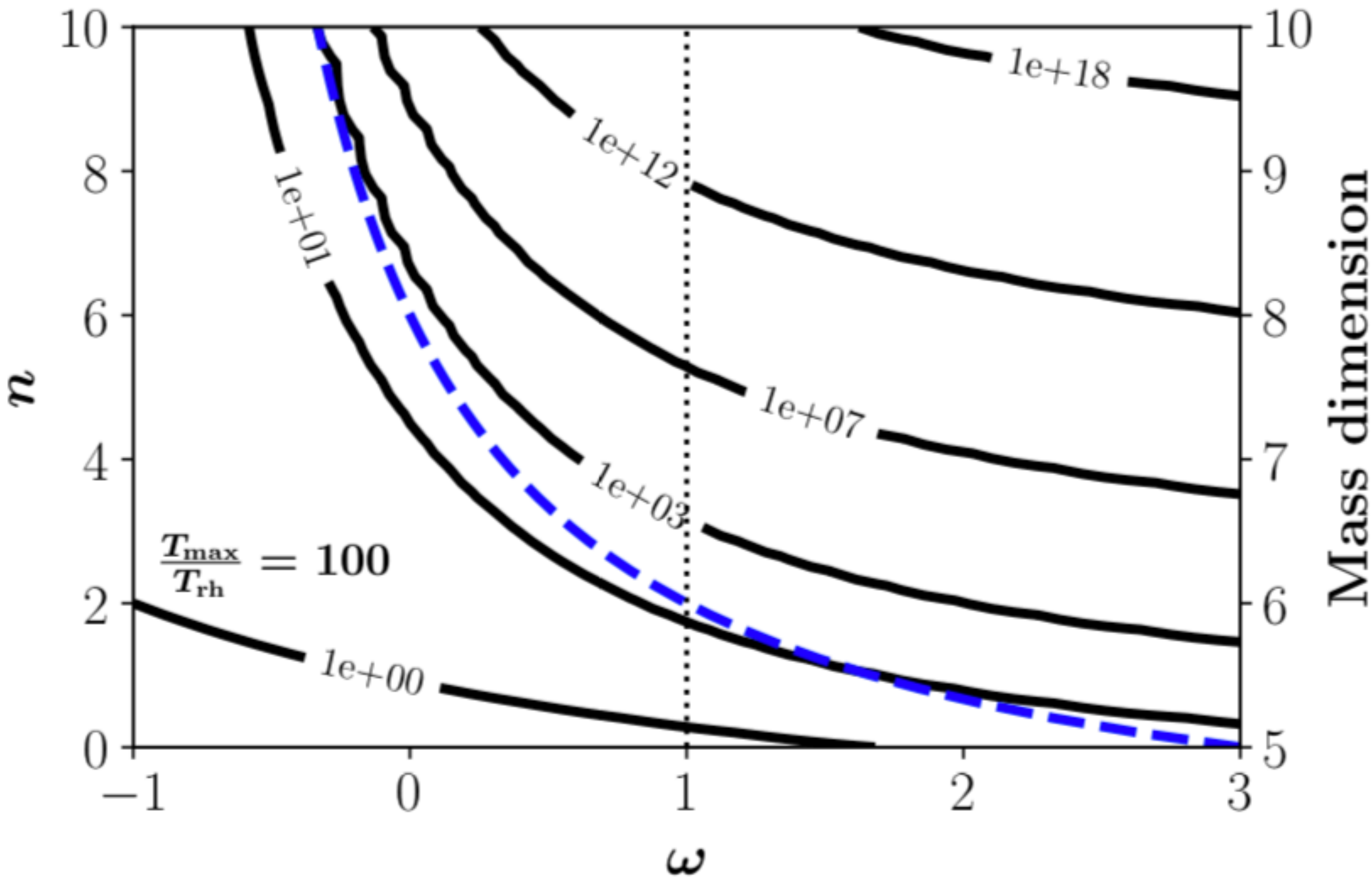


Boosting to large abundance



Useful for motivated dark matter candidates which are **underproduced**.
For example gravitino dark matter in high scale supersymmetry scenarios.

Bernal, Elahi, Maldonado, & JU [1909.07992]

Conclusion

- **Cosmological events** and can drastically alter expectations for DM.
- Dilution permit correct relic density for **heavier DM** or **smaller couplings**.
- This can **revive the Higgs portal** (and other excluded classic models).
- Conversely, **underproduced DM** can be enhanced via reheating effects.
- Non standard cosmology occurs in many **motivated BSM scenarios**.

Thank you.