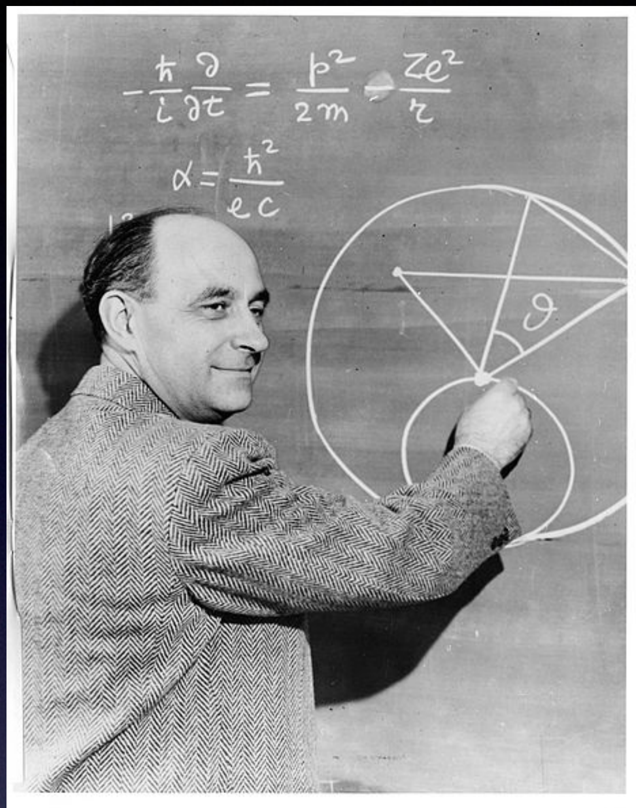
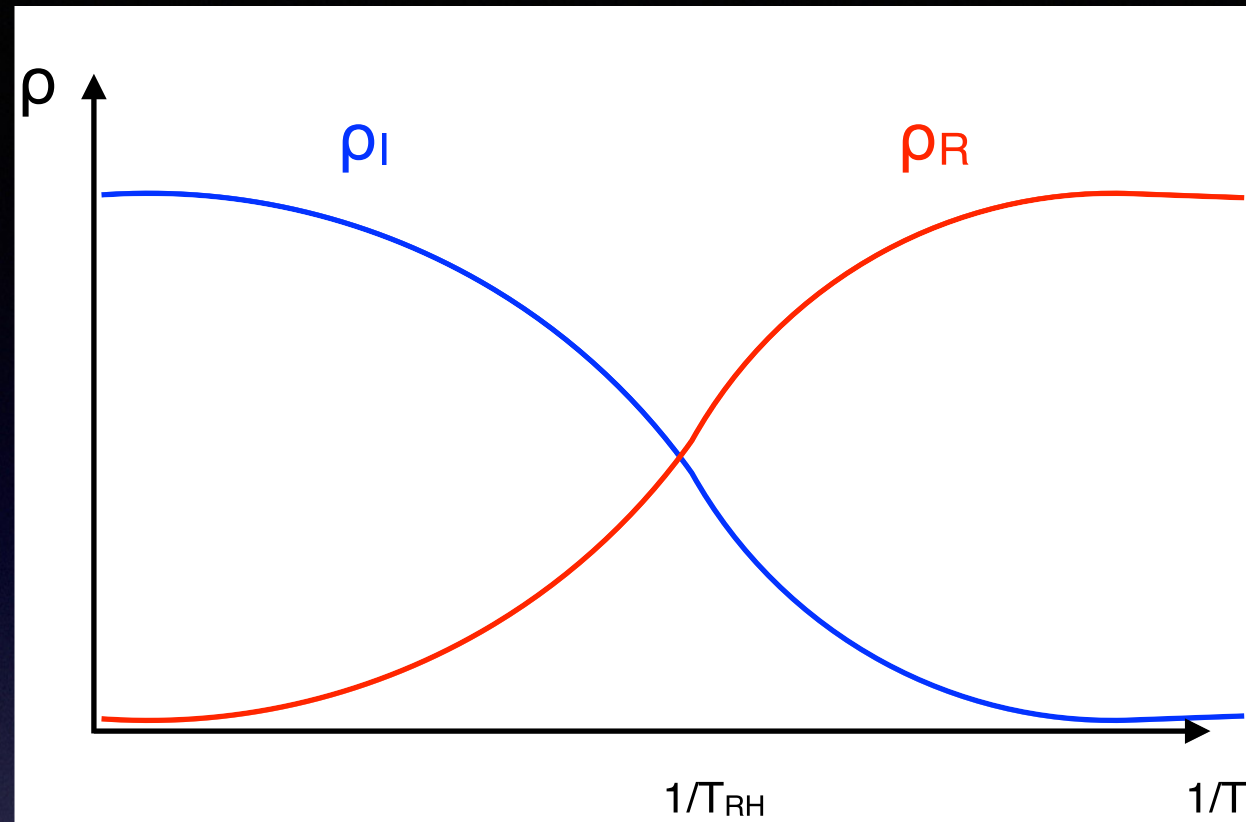
Thermalization and dark matter production





« Never underestimate the joy people derive from hearing something they already know.»
E. Fermi

Yann Mambrini

University of Paris-Saclay

Dark Side of the Universe, June 25th 2018, Annecy

MultiDark
Multimessenger Approach for Dark Matter Detection

D. Chowdhury, E. Dudas, M. Dutra, Y.M. in preparation

G. Bhattacharyya, M. Dutra, Y. M., M. Pierre ; 1806.00016

E. Dudas, T. Gherghetta, K. Kaneta, Y. M., Keith A. Olive ; arXiv:1805.07342

Nicolás Bernal, Maíra Dutra, Y. M., K. Olive, M. Peloso, M. Pierre ; Phys.Rev. D97 (2018) 115020 ; arXiv:1803.01866

E. Dudas, T. Gherghetta, Y. M., K.A. Olive ; Phys.Rev. D96 (2017) no.11, 115032 ; arXiv:1710.07341

M. A. G. Garcia, Y. M., K. A. Olive, M. Peloso ; Phys.Rev. D96 (2017) no.10, 103510 ; arXiv:1709.01549

Emilian Dudas, Y. M., Keith Olive Phys.Rev.Lett. 119 (2017) no.5, 051801; arXiv:1704.03008

The **non-observation** of any signal at direct and indirect detection experiments constrains the interaction cross section DM-SM to values below σ < 5x10^{-47} cm^2 ~ 10^{-18} GeV^{-2}

$$\simeq \frac{g_2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1 \text{ GeV}} \right)^2 \text{ GeV}^{-2}$$

$$= 4 \times 10^{-37} \left(\frac{m_\chi}{1 \text{ GeV}} \right)^2 \text{ cm}^2$$

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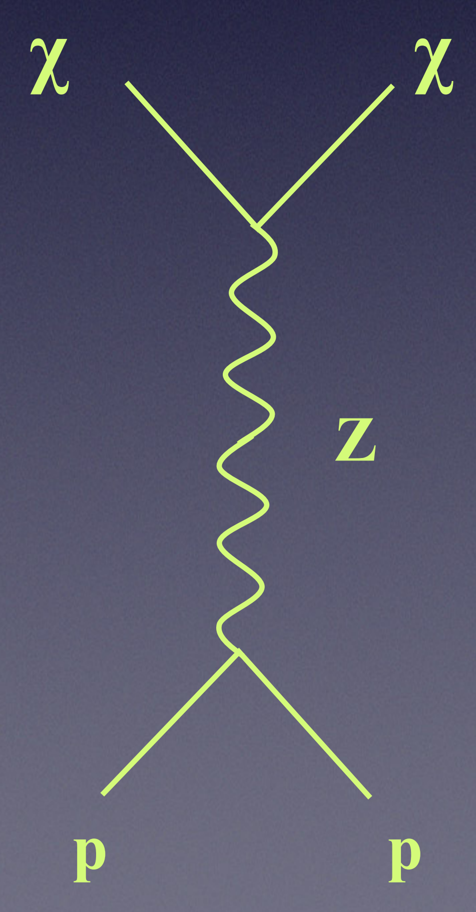
What do we expect for a WIMP :



$$\sigma_{EW}(\chi\, p \to \chi\, p) \simeq G_F^2 m_\chi^2$$

$$\simeq \frac{g_2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^2 \ \mathrm{GeV}^{-2}$$

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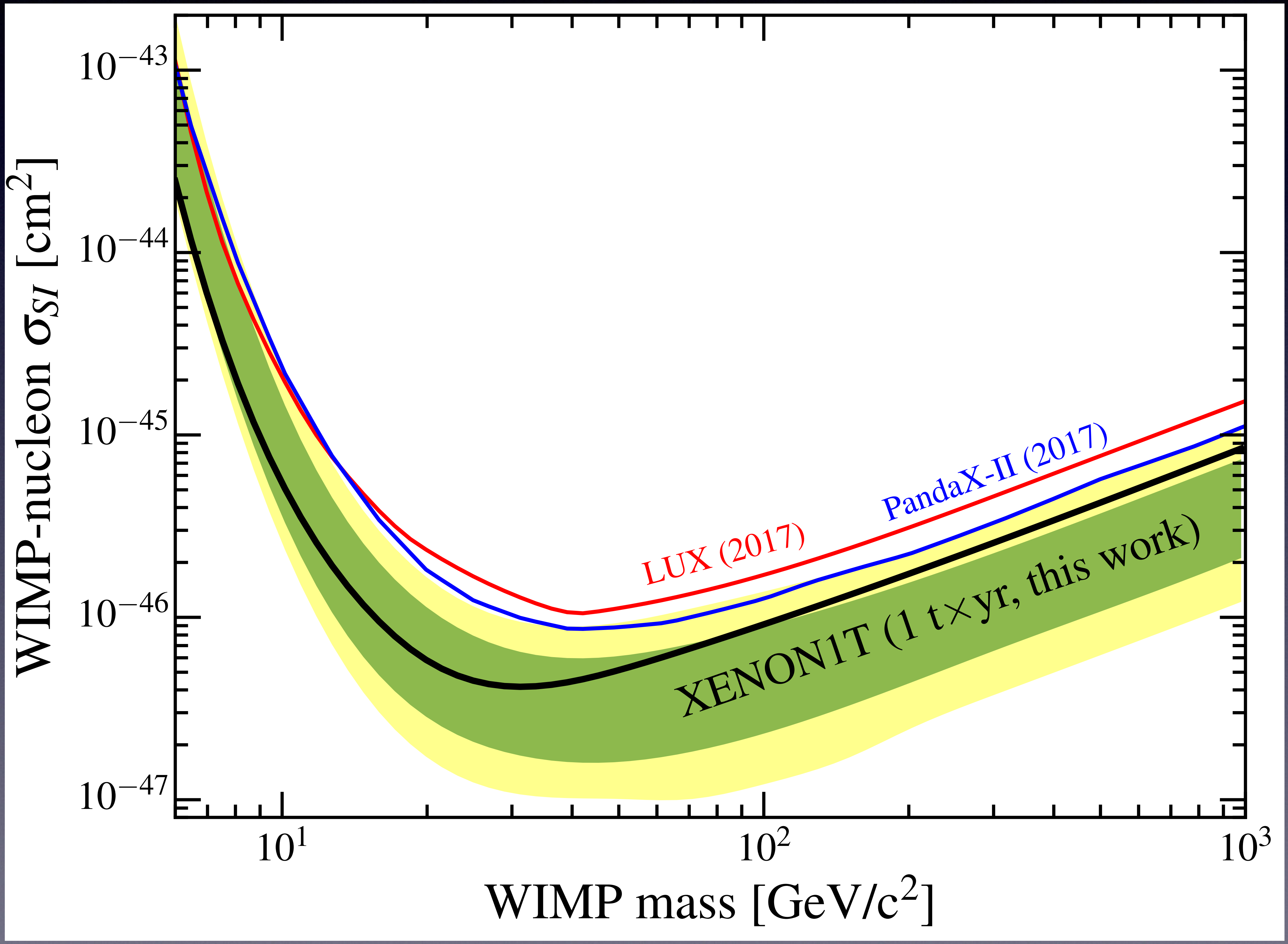


XENON1T; 1805.12562

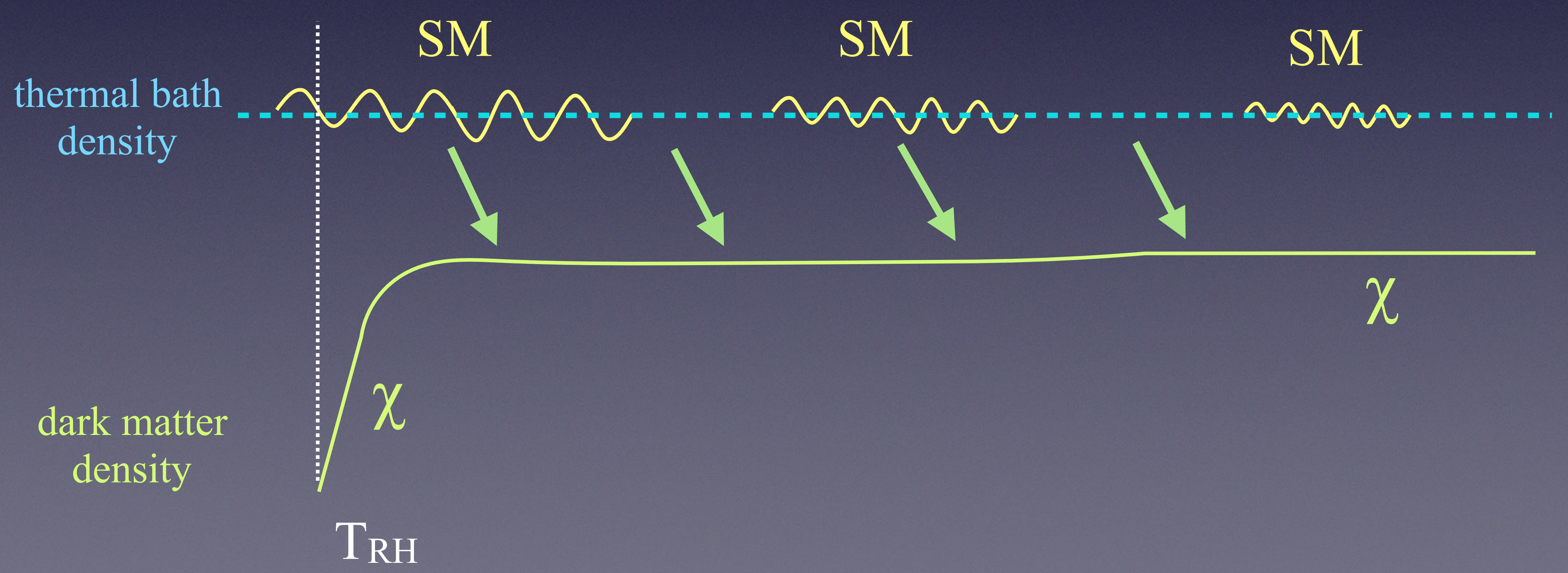
One way to solve the issue: FIMP

Production of dark matter in early Universe

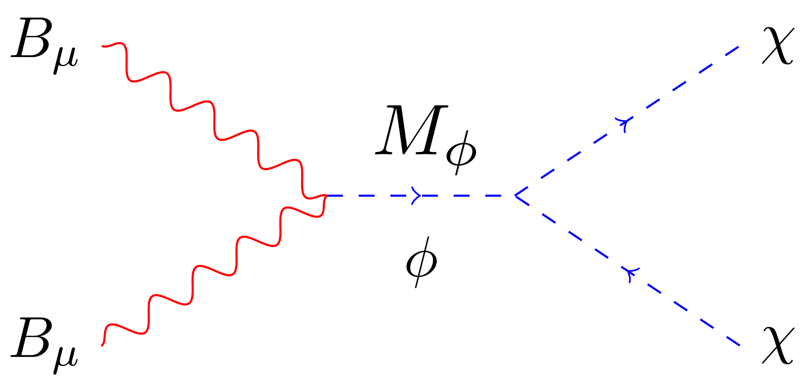
$$1 \; + \; 2 \quad \rightarrow \quad 3 \; + \; 4$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T)$$

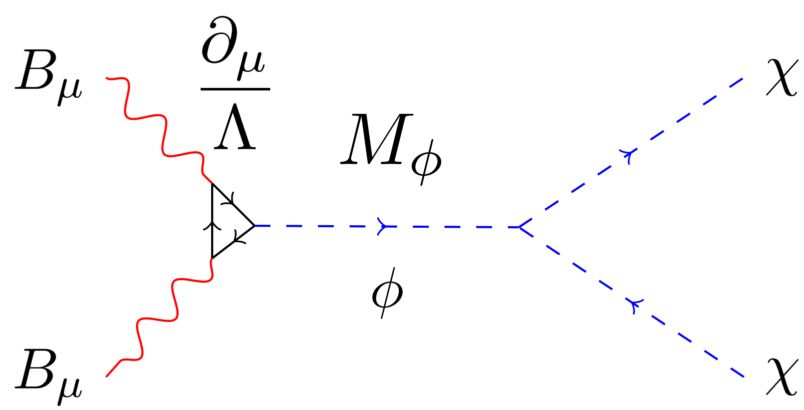
$$R(T) = n_{Eq}^2 \langle \sigma v \rangle = \int f_1 f_2 \frac{E_1 E_2 dE_1 dE_2 \; d\cos\theta_{12}}{1024\pi^6} \int |\mathcal{M}_{fi}|^2 d\Omega_{13} \propto \frac{T^{n+6}}{\Lambda^{n+2}}$$



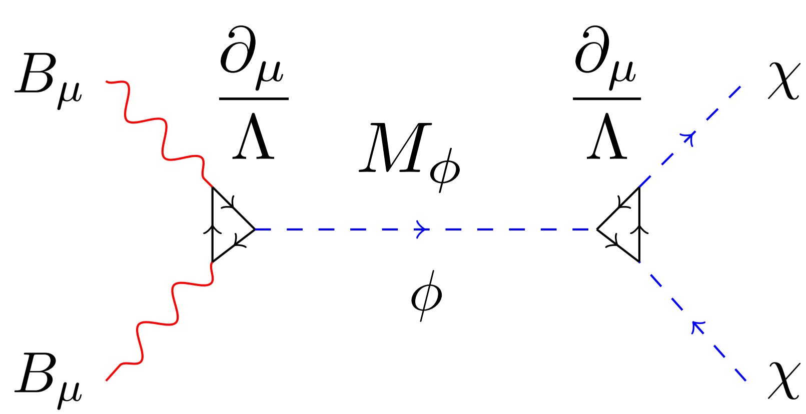
Example of rates



$$R(T) = \frac{T^{8}}{M_\phi^4}$$



$$R(T) = \frac{T^{10}}{M_\phi^4 \Lambda^2}$$



$$R(T) = \frac{T^{12}}{M_\phi^4 \Lambda^4}$$

In a radiation dominated Universe, instantaneous reheating

$$H^2 = \frac{8\pi}{3} G \rho_R = \frac{\rho_R}{3M_P^2} = \frac{\alpha T^4}{3M_P^2} \quad \Rightarrow \quad H = \sqrt{\frac{\alpha}{3}} \frac{T^2}{M_P}$$

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$$\boxed{R(T) = \frac{T^{6+n}}{\Lambda^{n+2}}}$$

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$$\boxed{R(T) = \frac{T^{6+n}}{\Lambda^{n+2}}}$$

Radiation dominated

$$\Omega = \frac{n(T_0) \times m}{\rho_c^0} \quad \Rightarrow \quad \Omega h^2 = 1.6 \times 10^8 \sqrt{\frac{3}{\alpha}} \frac{M_P}{(n+1)} \frac{T_{RH}^{n+1}}{\Lambda^{n+2}} \left(\frac{m}{1 \text{ GeV}} \right)$$

$$\boxed{\Omega h^2 = 0.12 \left(\frac{m}{(n+1) \text{ GeV}} \right) \left(\frac{T_{RH}}{10^{10} \text{ GeV}} \right)^{n+1} \left(\frac{10^{13} \text{ GeV}}{\Lambda} \right)^{n+2} \times 10^{11-3n}}$$

Non-instantaneous reheating: introducing the inflaton

Before the end of the reheating process, while the Universe was still dominated by the matter (inflaton), but temperature was higher than T_{RH}

M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549

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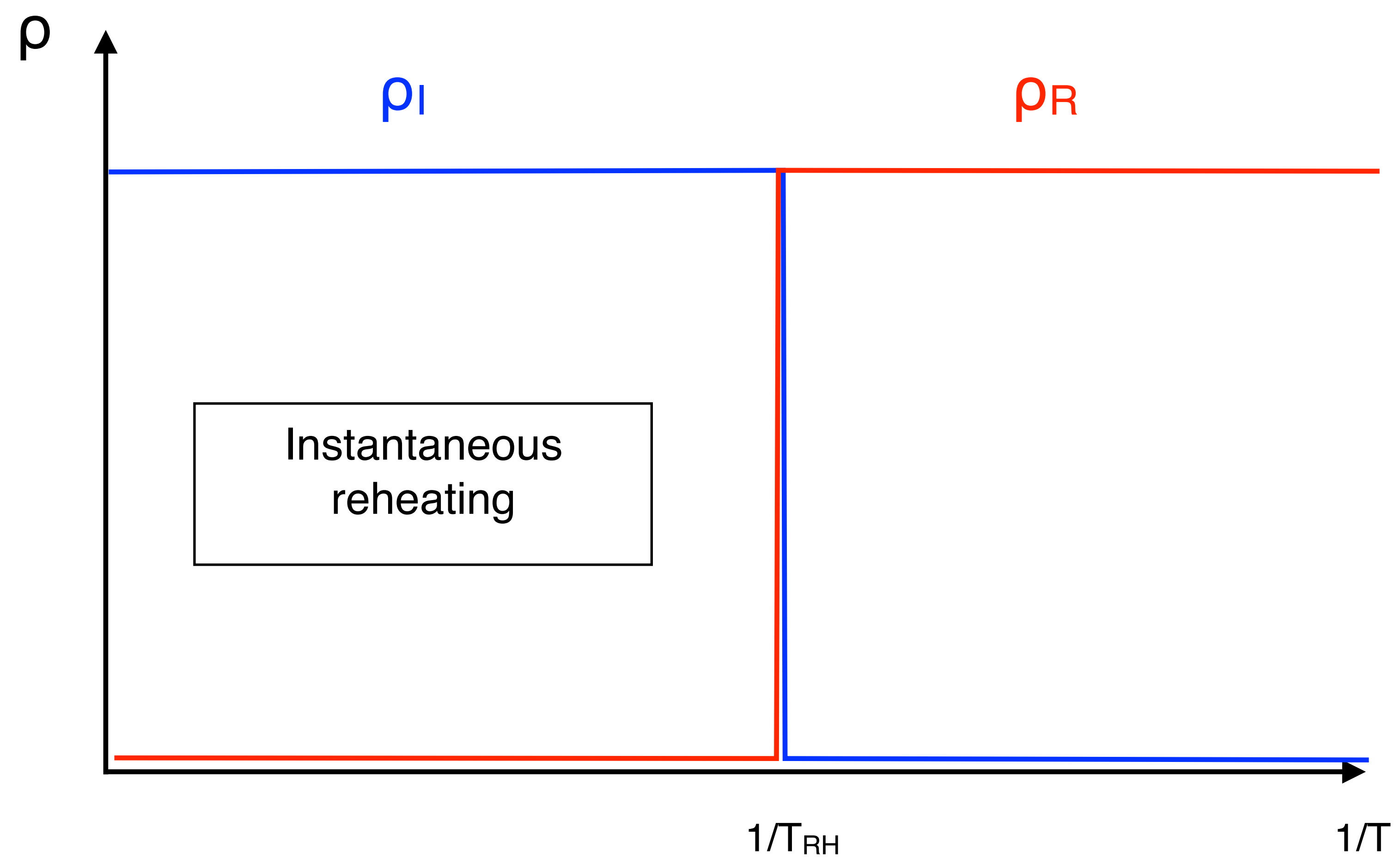
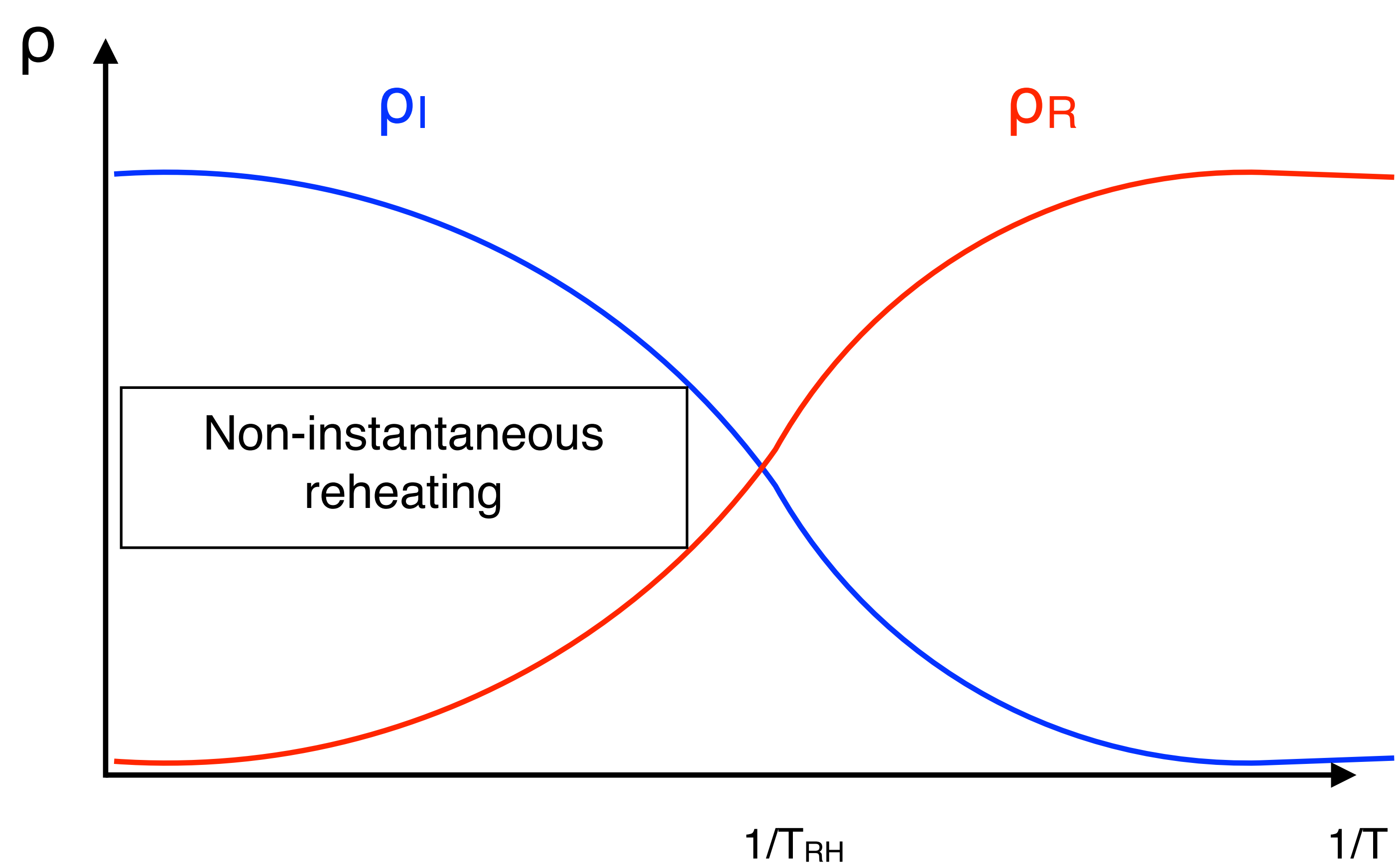
In other words, one should compare the total DM production releasing the hypothesis of instantaneous reheating

M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549



ρ
ρI
ρR
Instantaneous reheating
1/TRH
1/T



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Non-instantaneous reheating
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$$\frac{d\rho_I}{dt} + 3H\rho_I = -\Gamma_I \rho_I$$

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[$T = \beta a^{-1}$ in radiation dominated universe]

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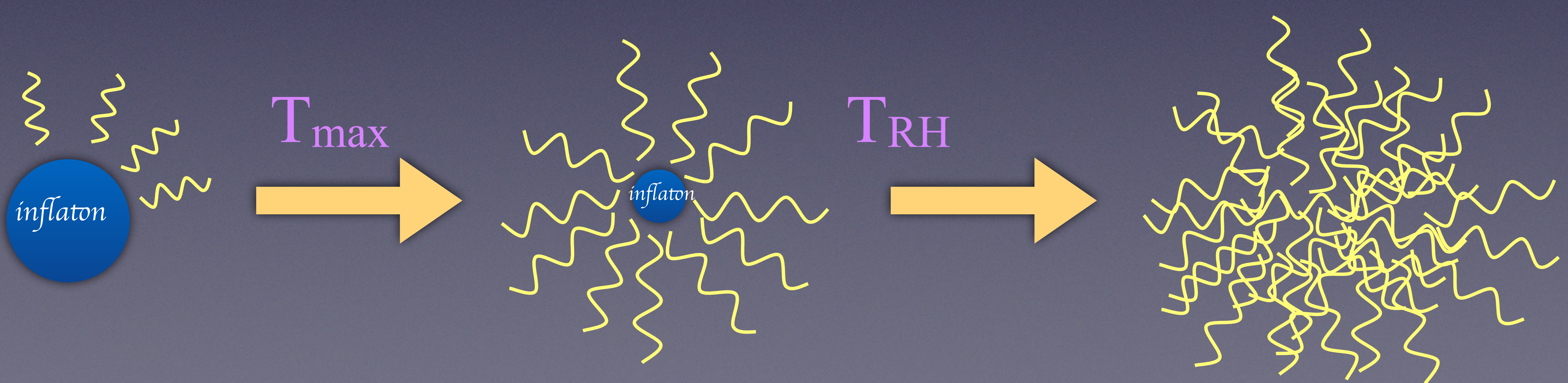
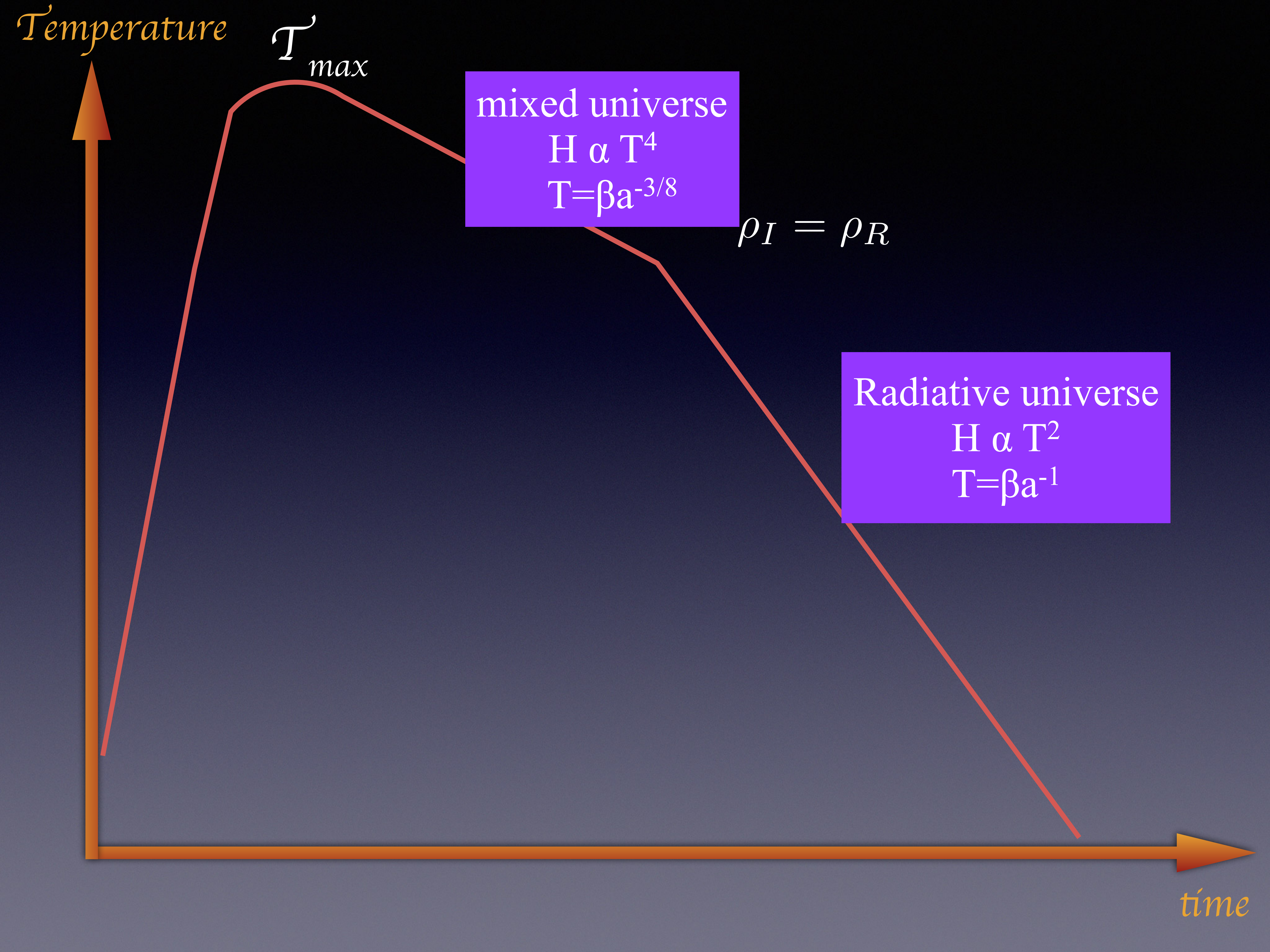
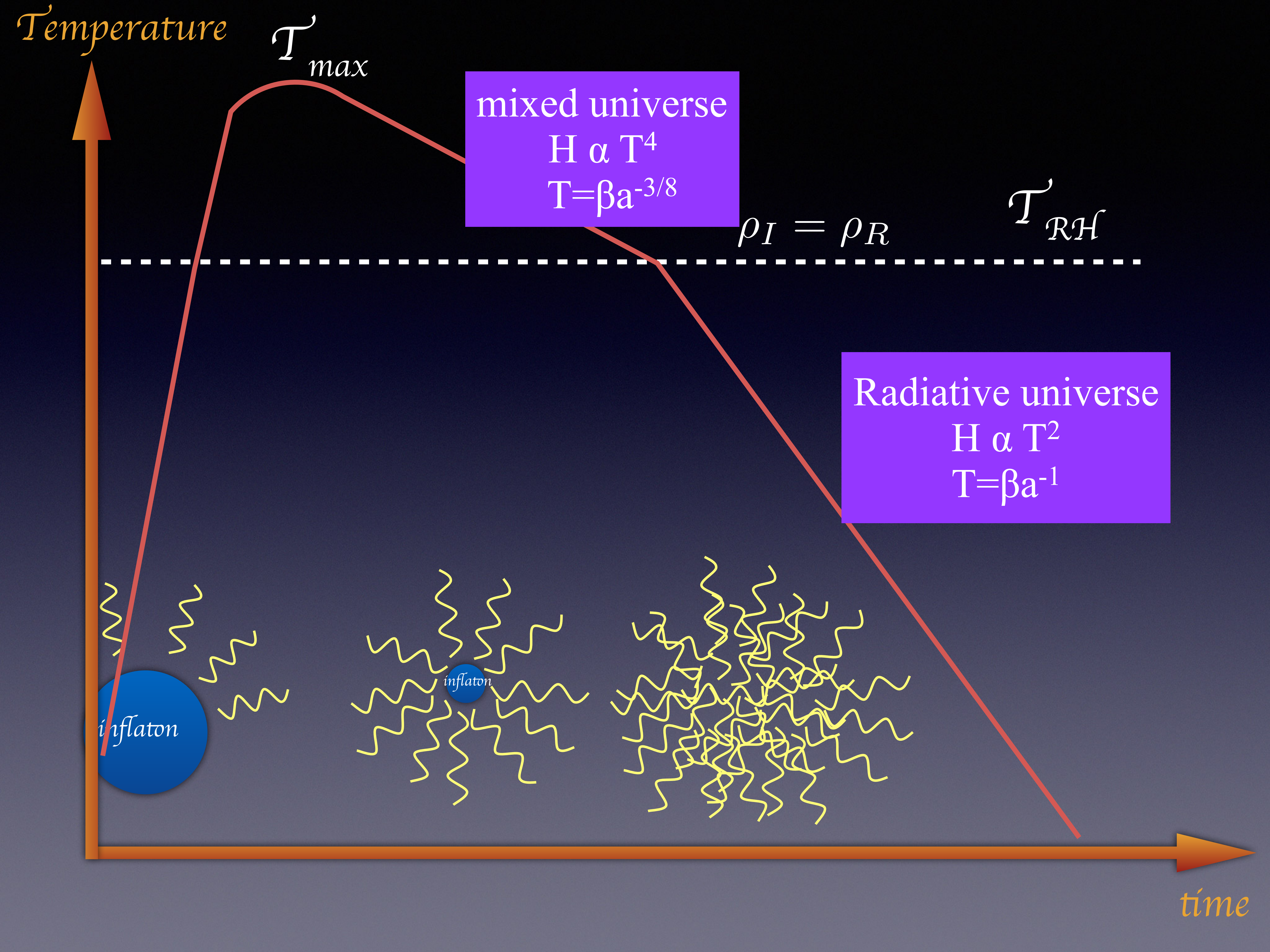




Temperature
T_{max}
mixed universe
H α T^4
$T=\beta a^{-3/8}$
$\rho_I = \rho_R$
Radiative universe
H α T^2
$T=\beta a^{-1}$
time



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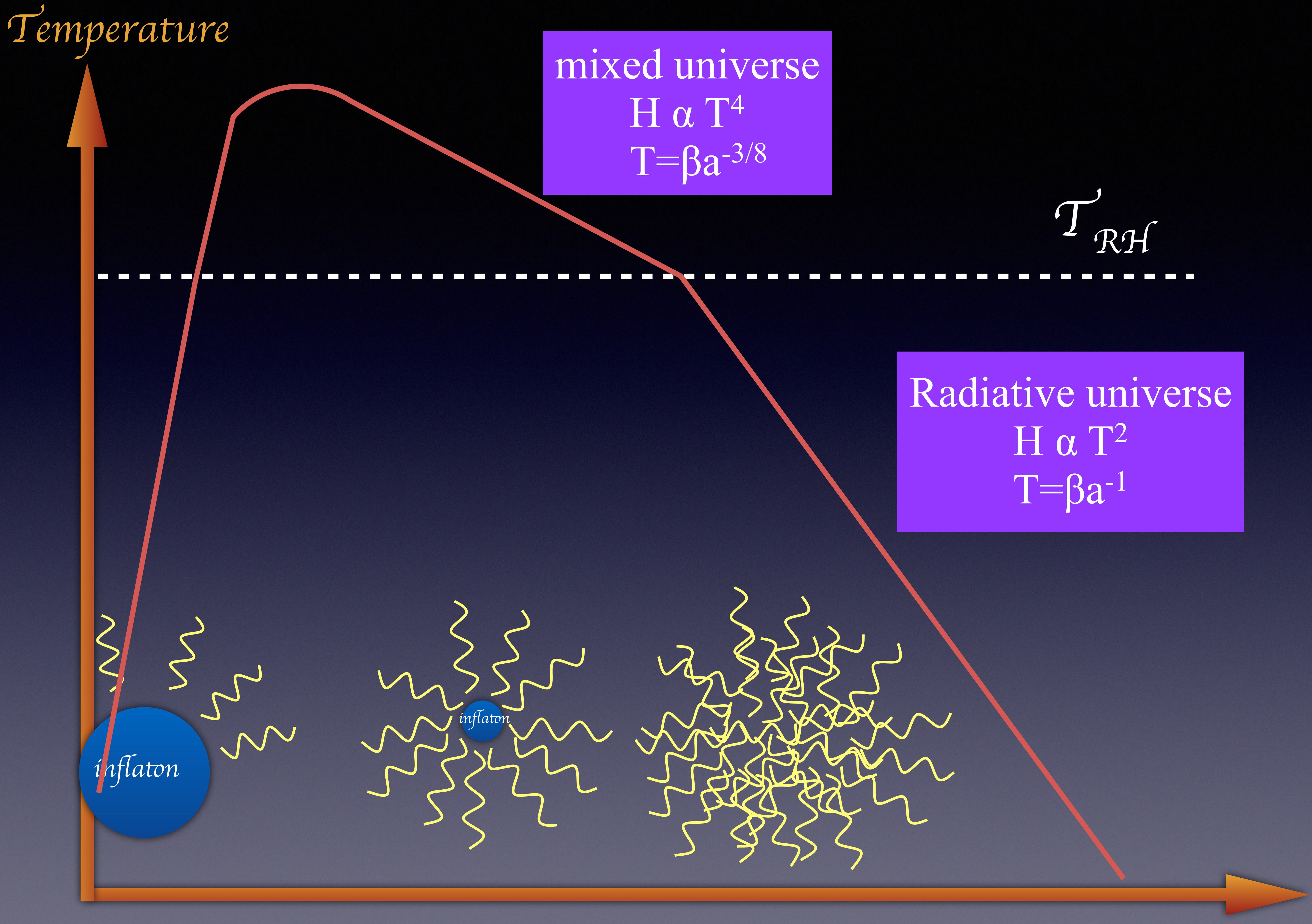
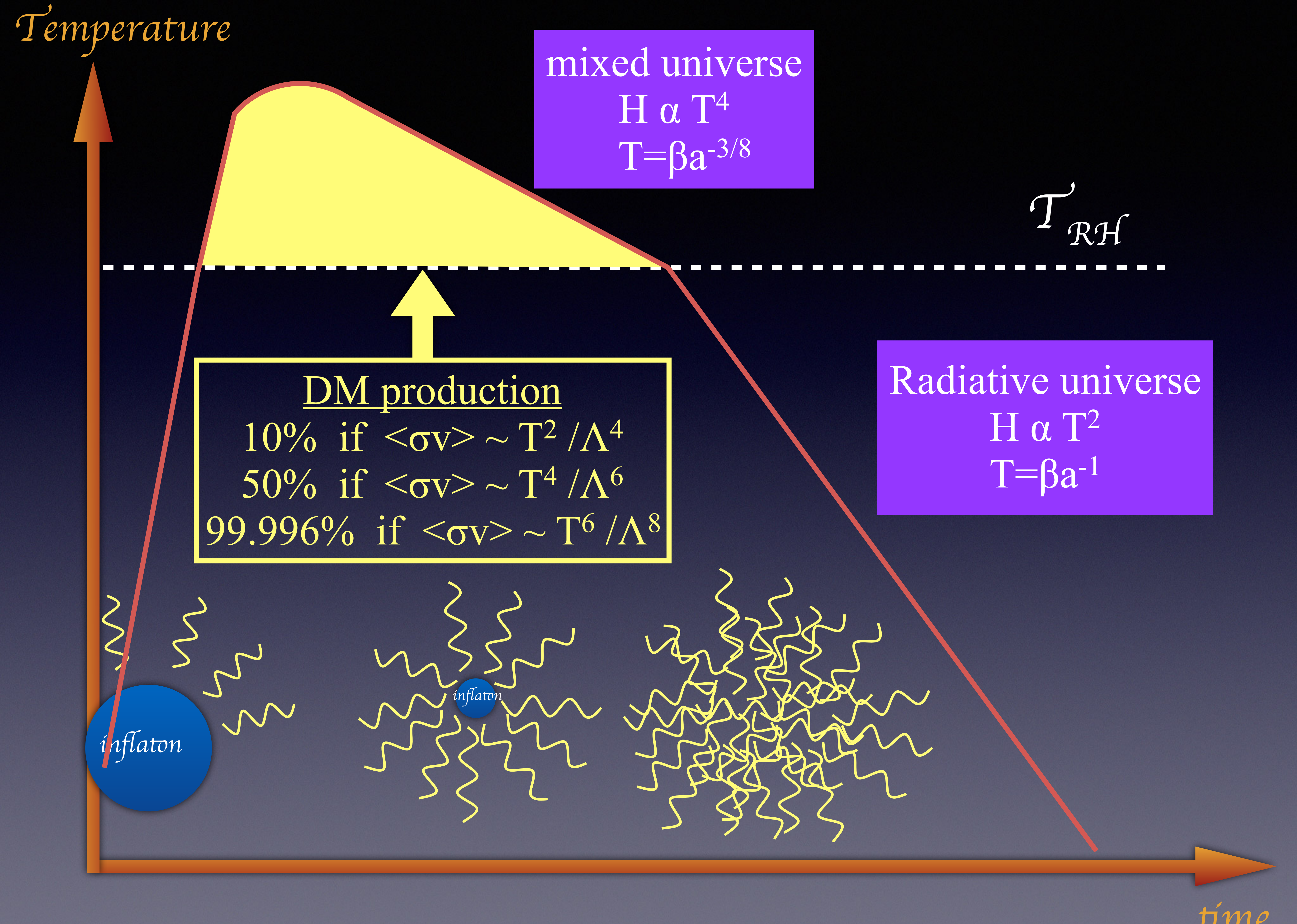


M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549 [hep-ph]



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Application to concrete models

Remark on goldstone/goldstino mode and the equivalence theorem

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$\boxed{\text{transverse modes}}$

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transverse modes

Longitudinal mode (« would-be » goldstone boson)

Application to concrete models

High scale SUSY

E. Dudas, T. Gherghetta, Y. M., K.A. Olive ; Phys.Rev. D96 (2017) no.11, 115032 ; arXiv:1710.07341

Emilian Dudas, Y. M., Keith Olive Phys.Rev.Lett. 119 (2017) no.5, 051801; arXiv:1704.03008

SO(10)

G. Bhattacharyya, M. Dutra, Y. M., M. Pierre ; 1806.00016

Massive spin 2

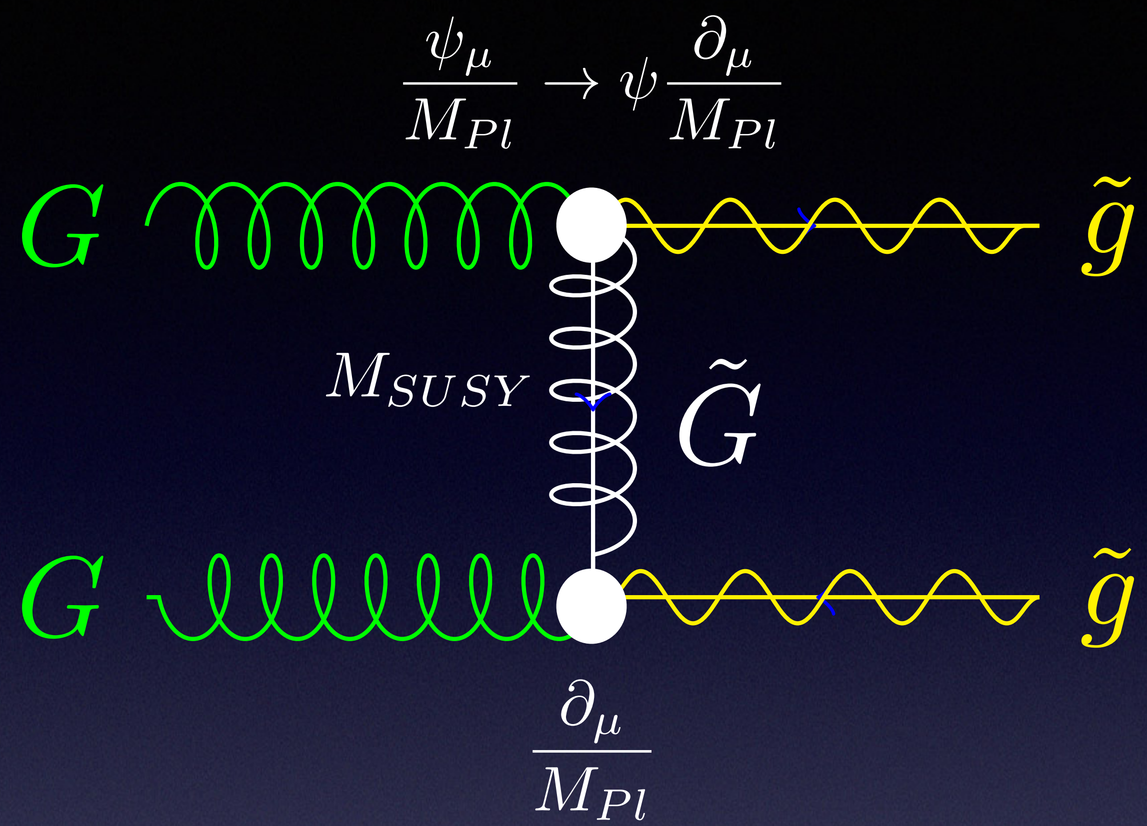
Nicolás Bernal, Maíra Dutra, Y. M., K. Olive, M. Peloso, M. Pierre ; Phys.Rev. D97 (2018) 115020 ; arXiv:1803.01866

« string inspired » moduli fields

D. Chowdhury, E. Dudas, M. Dutra, Y.M. in preparation

High scale supergravity

see talk Keith Olive



$$R(T) = \frac{T^{12}}{M_{SUSY}^4 M_{Pl}^4}$$

K. Benakli, Y. Chen, E. Dudas and Y. M.; Phys.Rev. D95 (2017) [arXiv:1701.06574]

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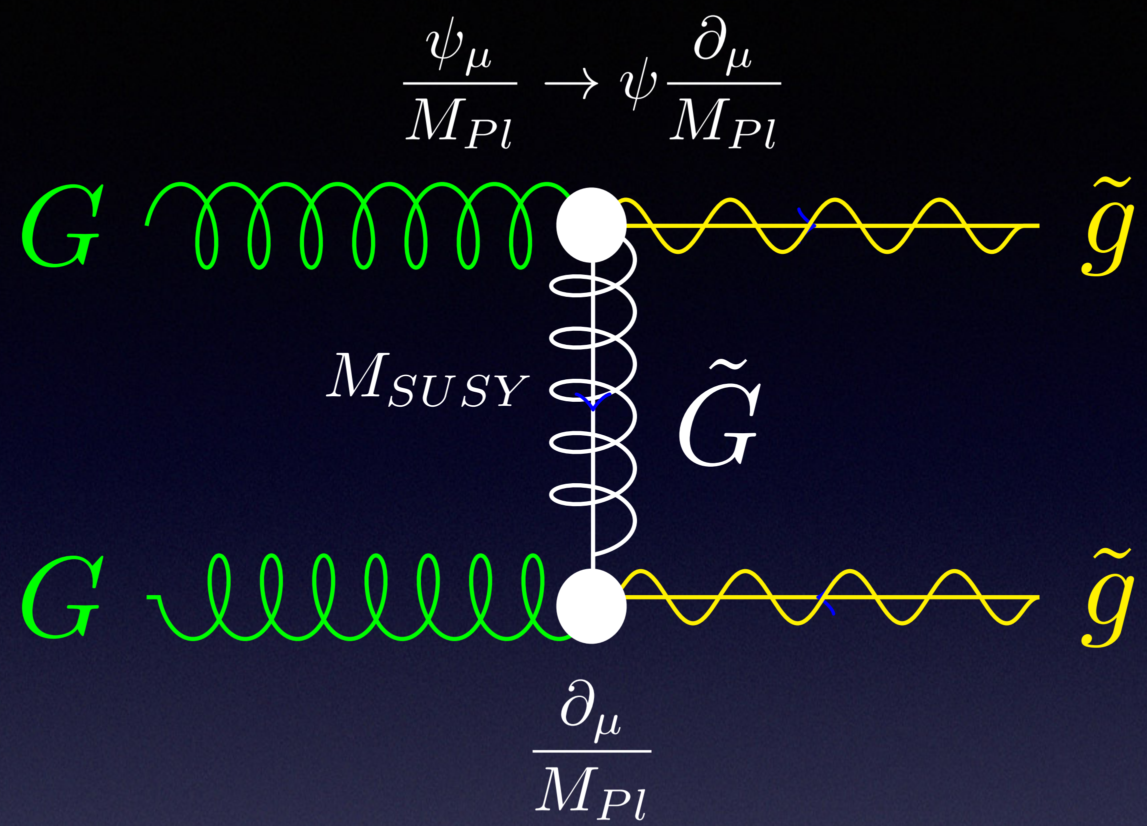

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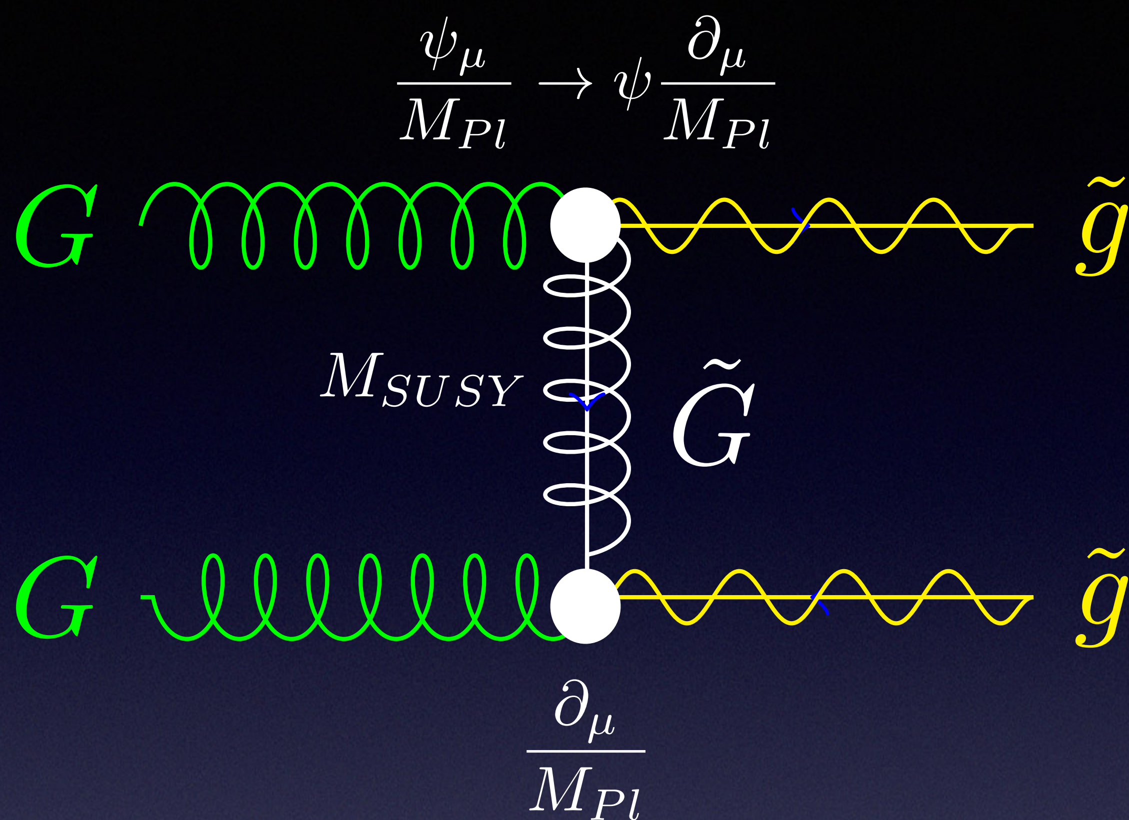

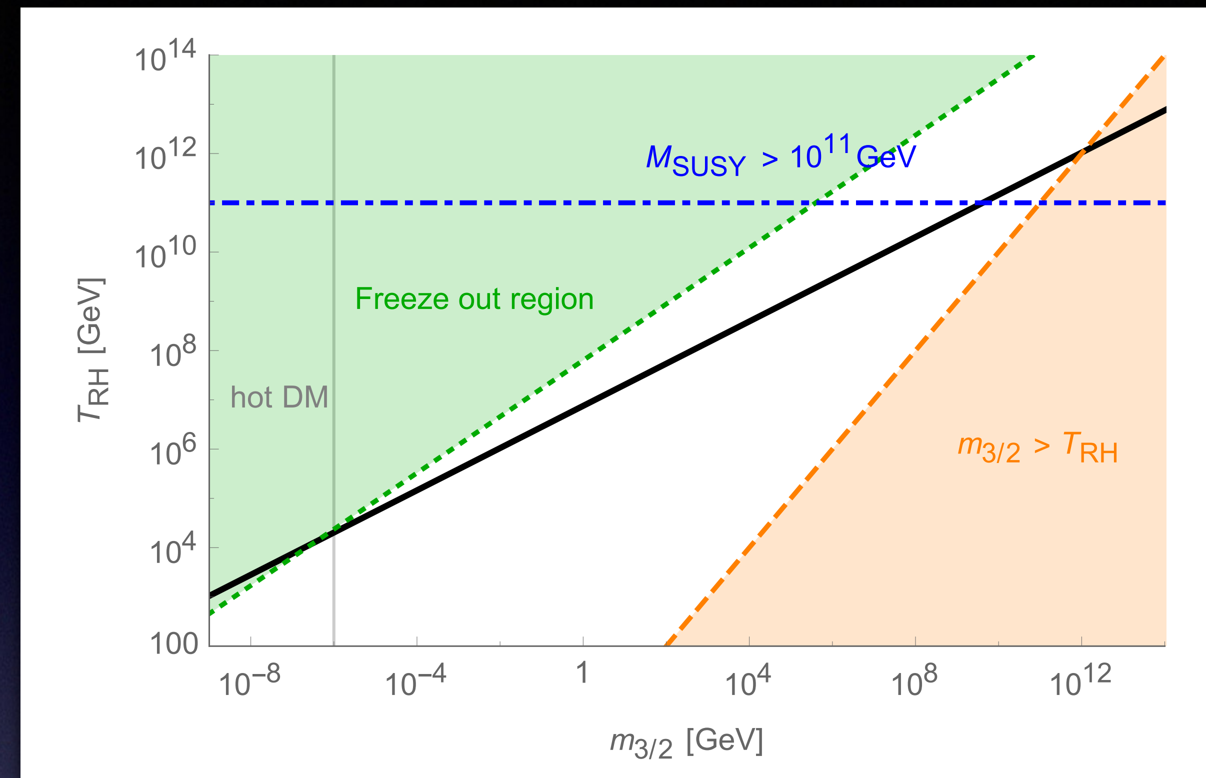

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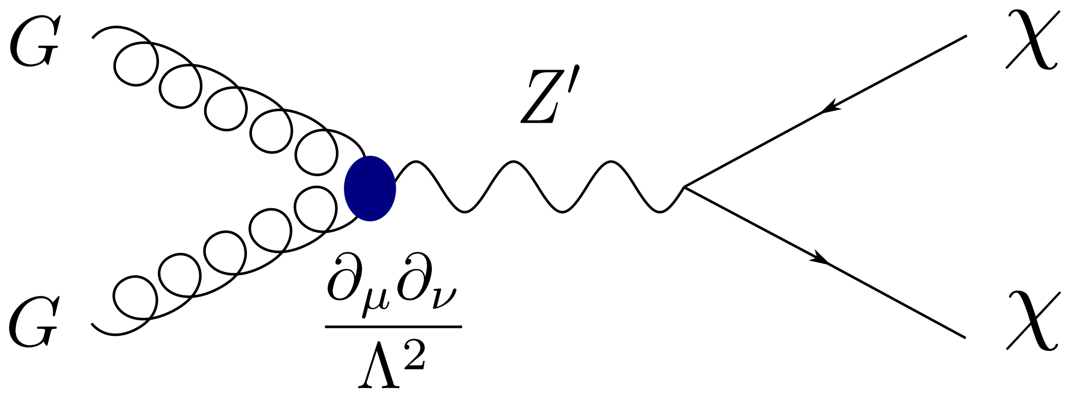
Spin-1 mediator

G. Bhattacharyya, M. Dutra, Y. M., M. Pierre ; 1806.00016

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2}\partial^\alpha Z'_\alpha \epsilon^{\mu\nu\rho\sigma}\text{Tr}[G^a_{\mu\nu}G^a_{\rho\sigma}]$$



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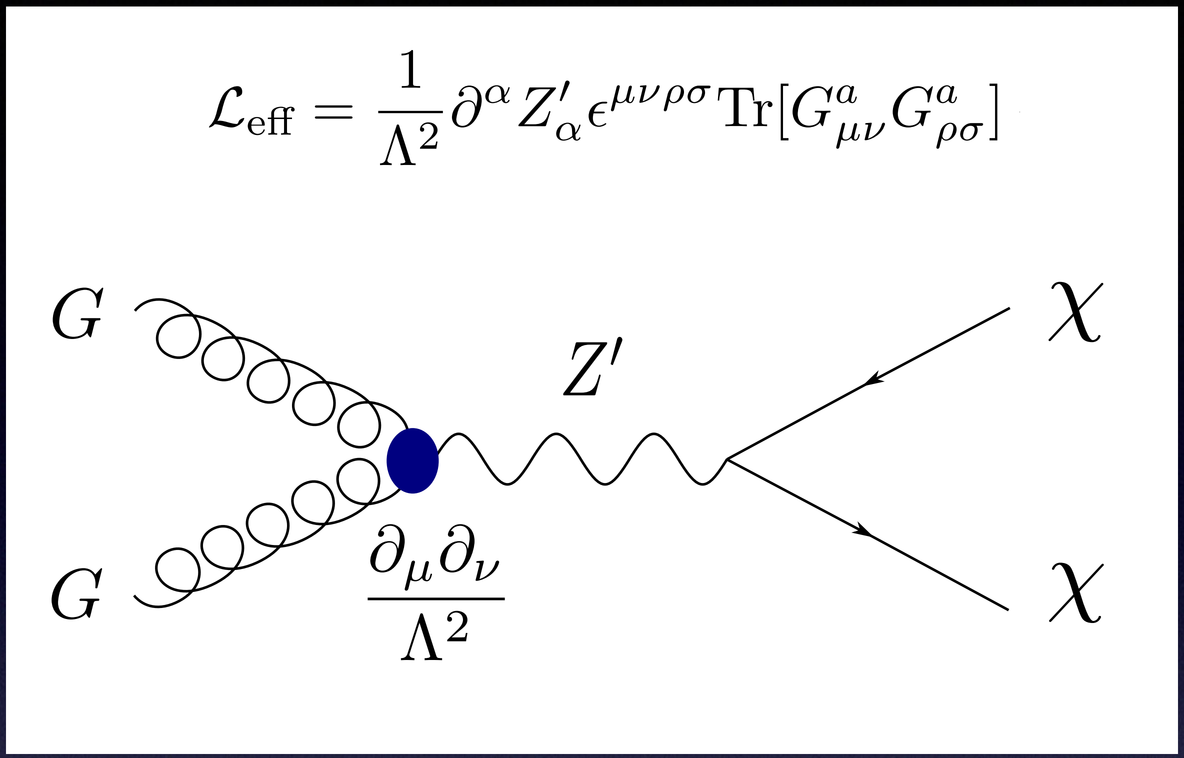

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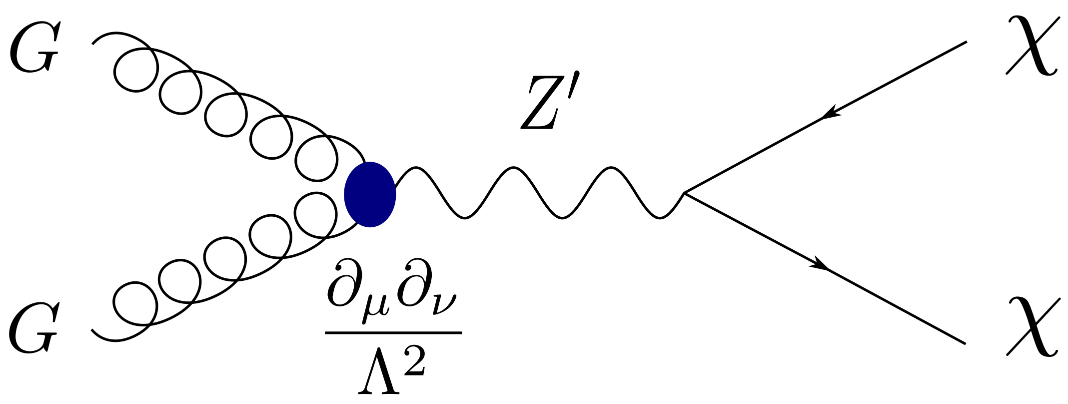

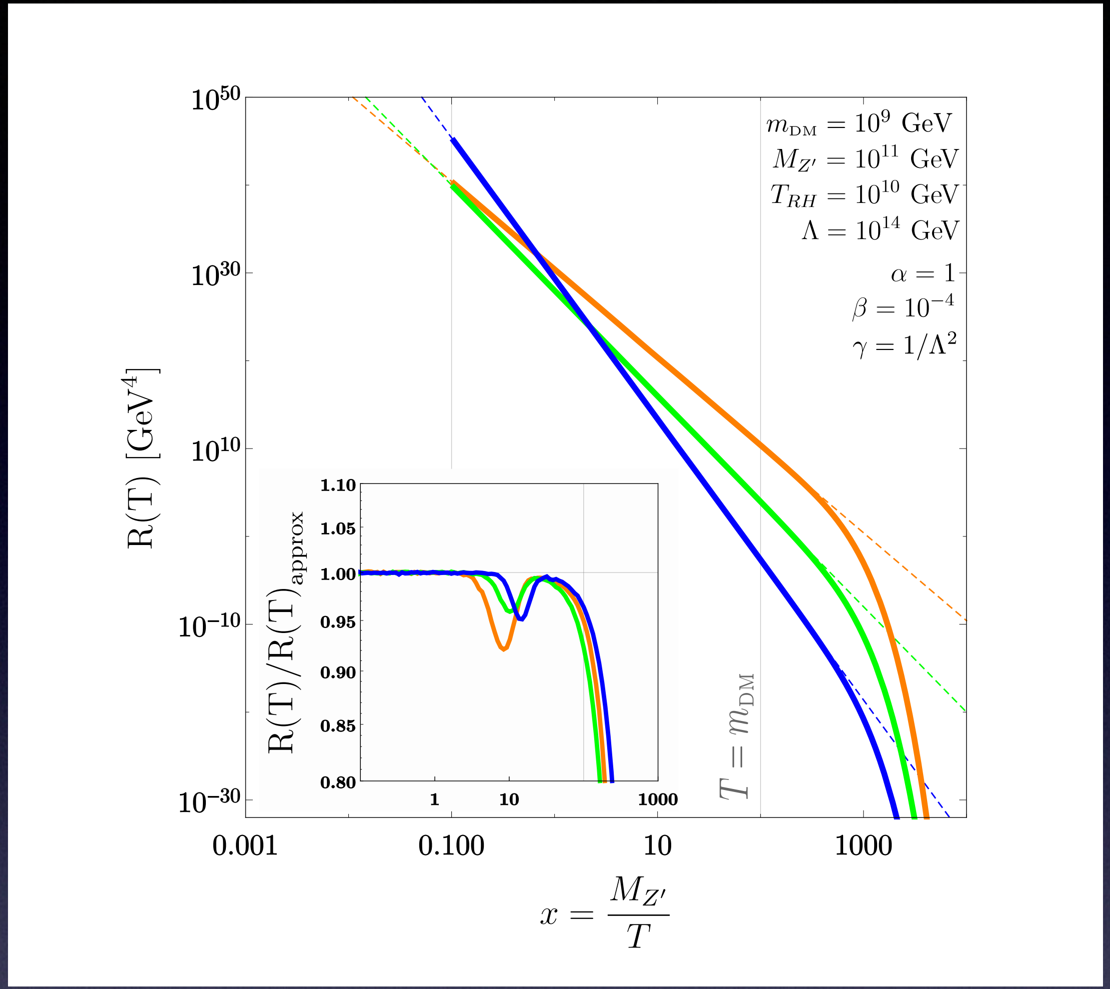

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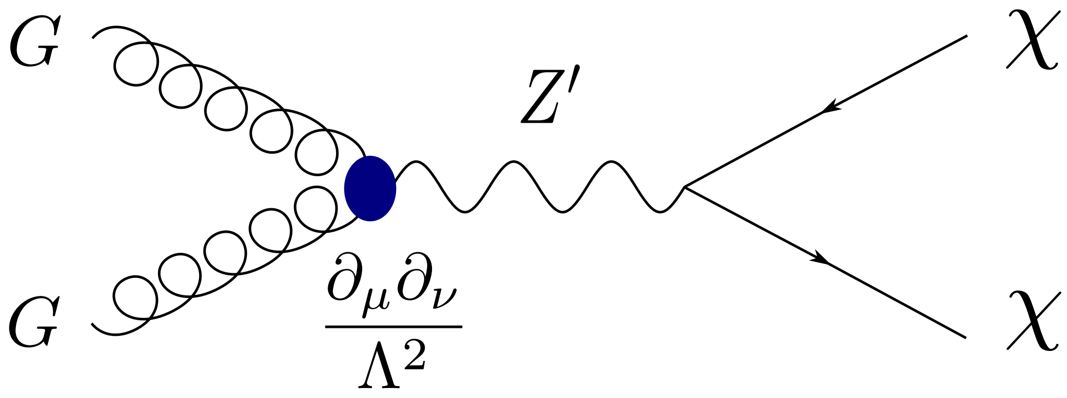

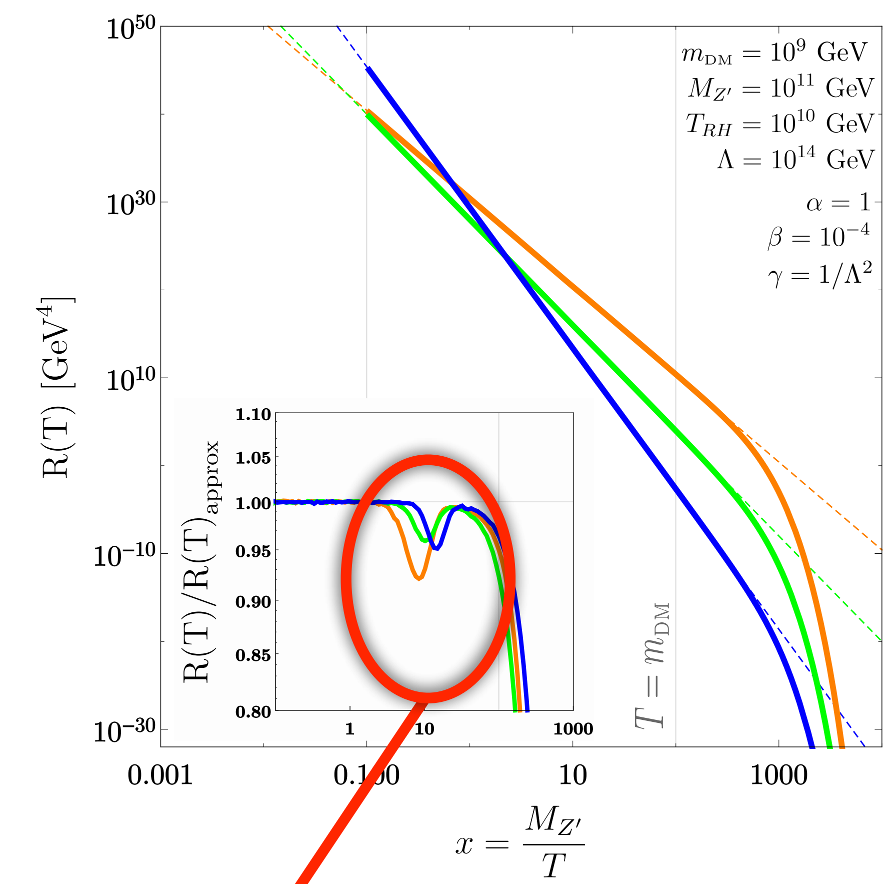

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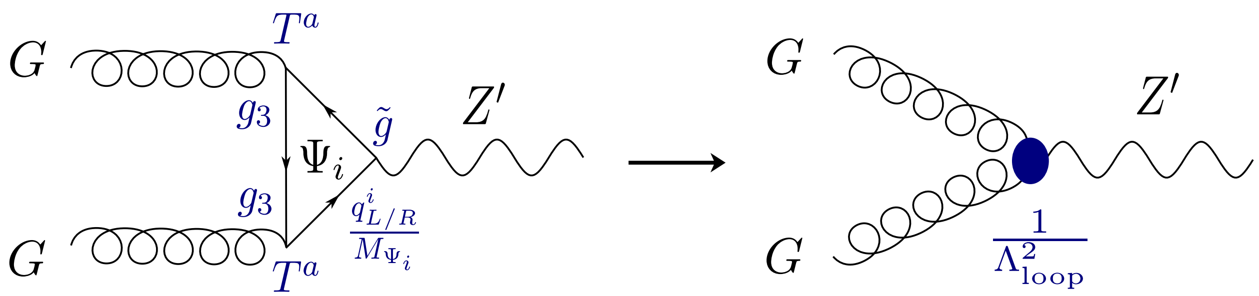
$\boxed{\text{Landau Yang}}$

$$\boxed{\Omega h^2 = 0.12 \left(\frac{m_\chi}{6\times 10^{10}\ \text{GeV}}\right)^3 \left(\frac{10^{14}\ \text{GeV}}{M_{Z'}}\right)^4 \left(\frac{10^{16}\ \text{GeV}}{\Lambda}\right)^4 \left(\frac{T_{RH}}{10^{12}\ \text{GeV}}\right)^5}$$

A microscopic realization : SO(10)



$$\frac{1}{\Lambda^2_{\mathrm{loop}}} = \frac{g_3^2\ \tilde{g}}{96\pi^2}\sum_i \frac{q^i_L - q^i_R}{M^2_{\Psi_i}}\mathrm{Tr}[T^a T^a].$$

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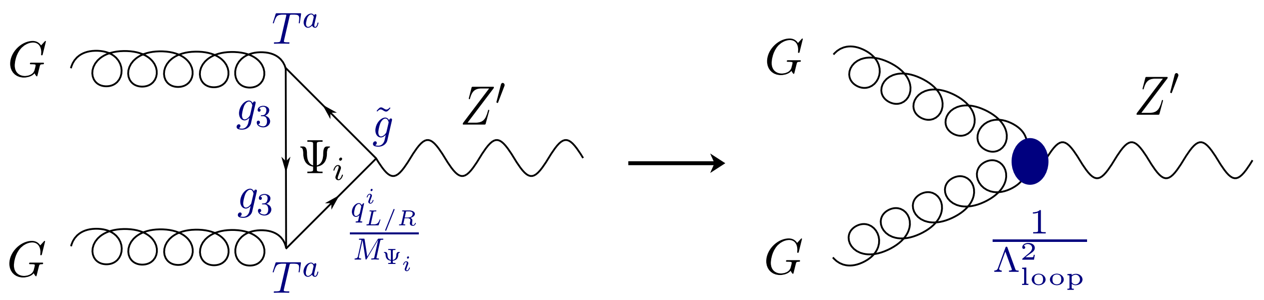

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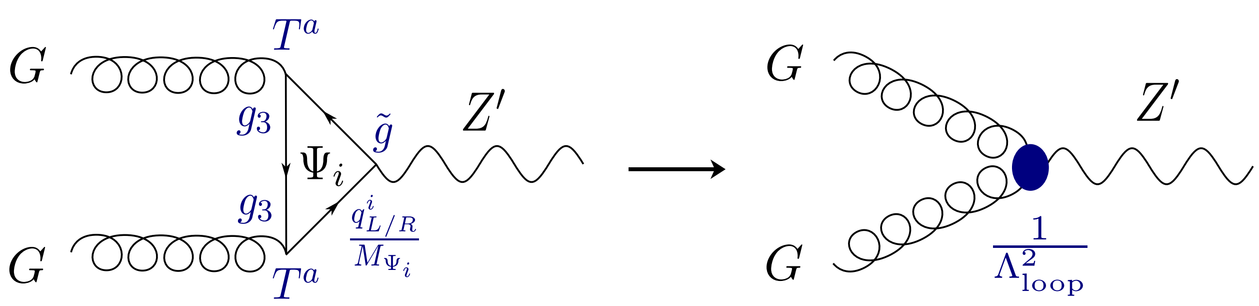

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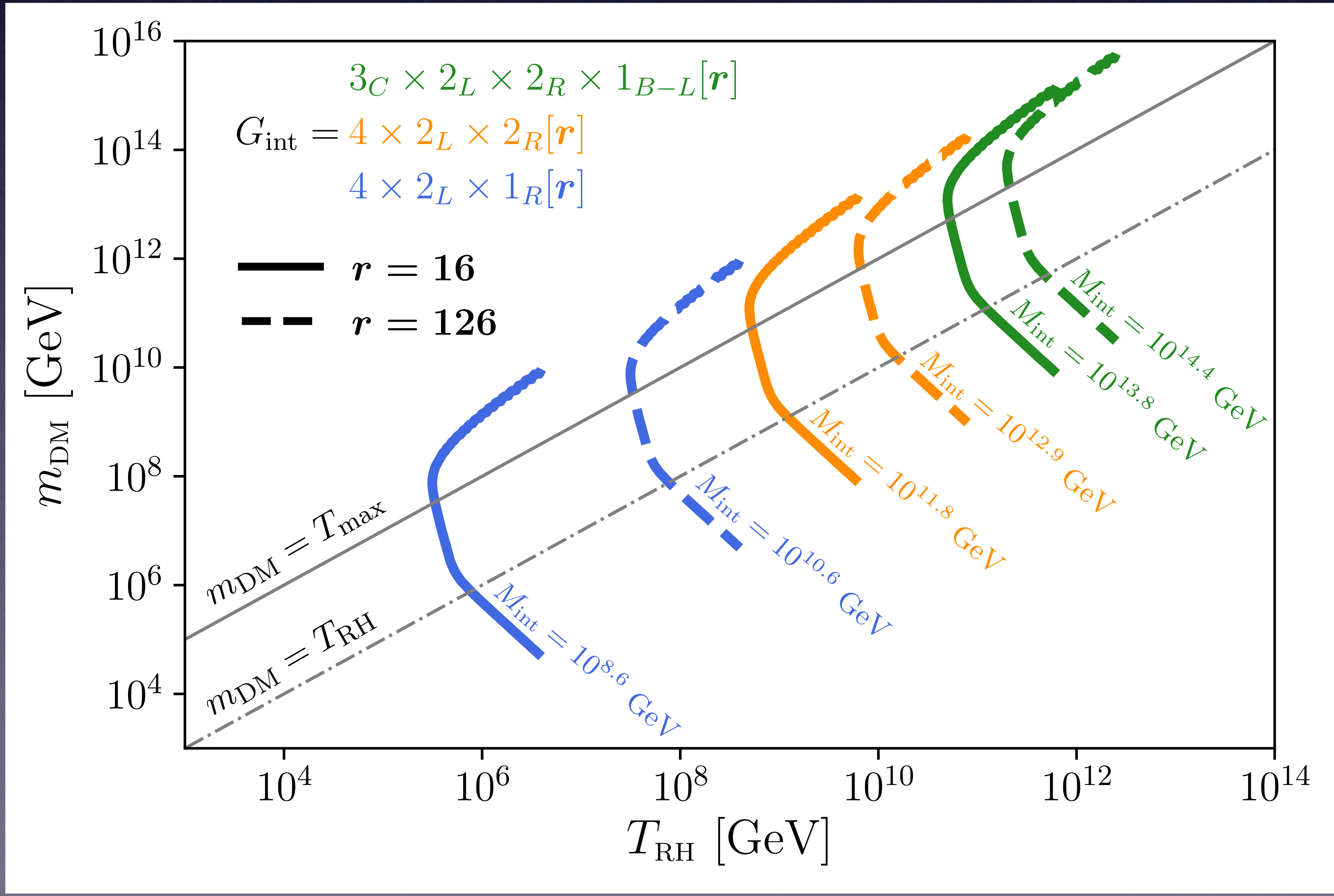

Spin-2 mediator

Nicolás Bernal, Maíra Dutra, Y. M., K. Olive, M. Peloso, M. Pierre ; Phys.Rev. D97 (2018) 115020 ; arXiv:1803.01866

$$\mathcal{L}^1_{\rm int} = \frac{1}{2M_P} h_{\mu\nu} \left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\rm X}\right)$$

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$$\begin{aligned}
T^0_{\mu\nu} &= \frac{1}{2}\left(\partial_\mu\phi\,\partial_\nu\phi + \partial_\nu\phi\,\partial_\mu\phi - g_{\mu\nu}\partial^\alpha\phi\,\partial_\alpha\phi\right) , \\
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T^1_{\mu\nu} &= \frac{1}{2}\left[F^\alpha_\mu F_{\nu\alpha} + F^\alpha_\nu F_{\mu\alpha} - \frac{1}{2} g_{\mu\nu} F^{\alpha\beta} F_{\alpha\beta}\right] . \qquad (5)
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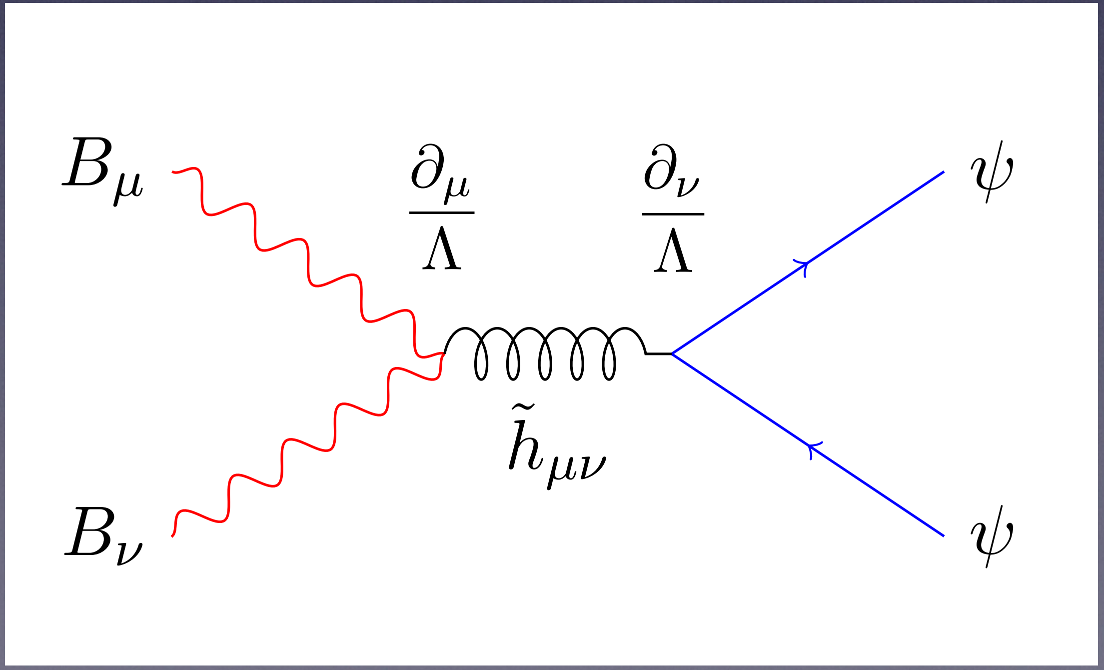
$$R(T) \propto \frac{T^{12}}{\Lambda^4 M^4_{\tilde{h}}}$$



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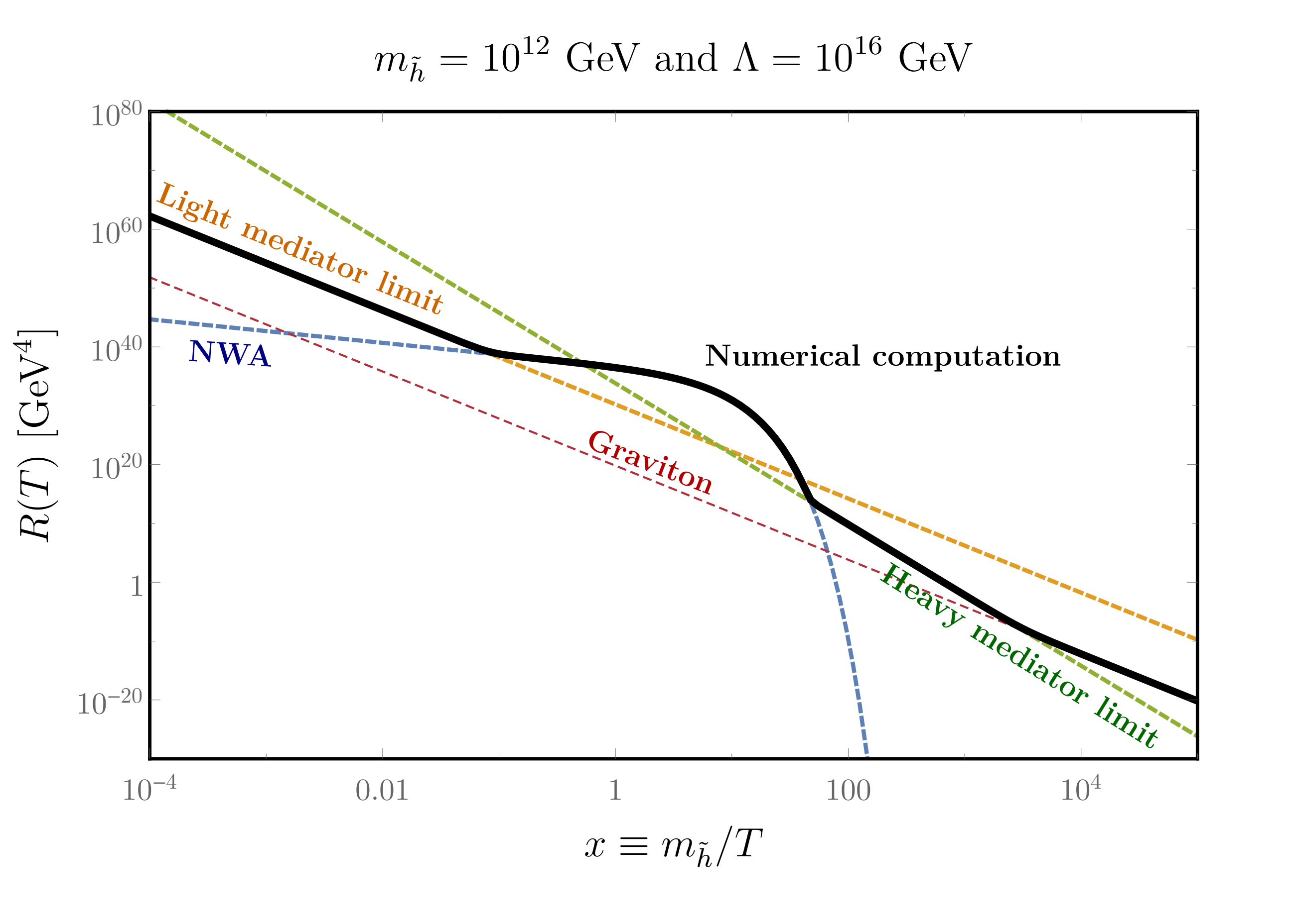

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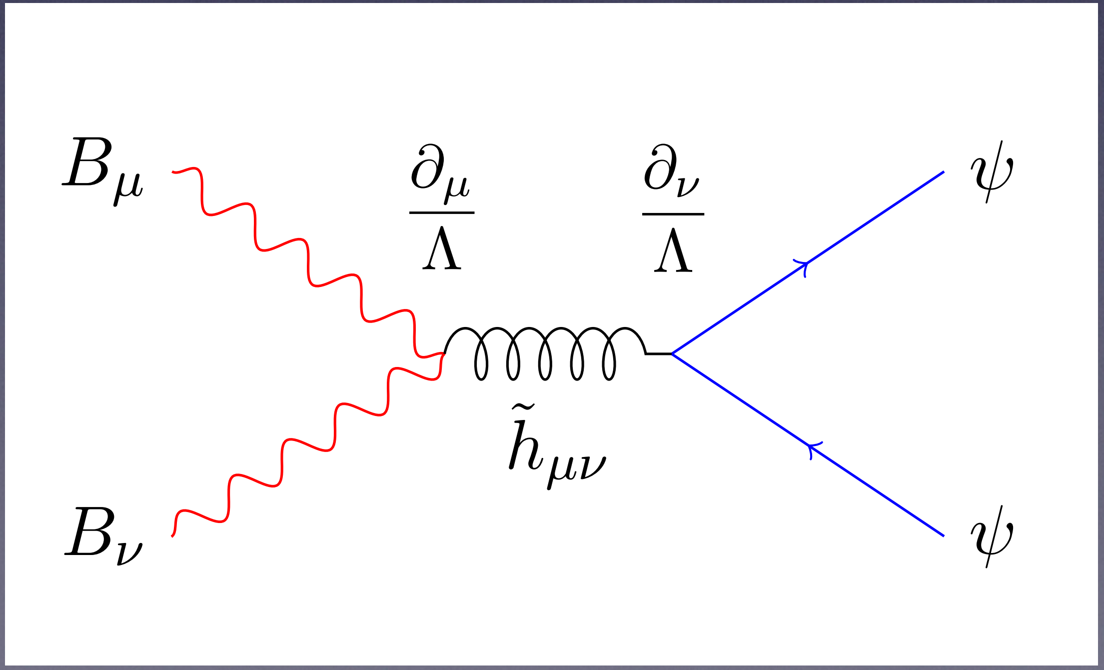

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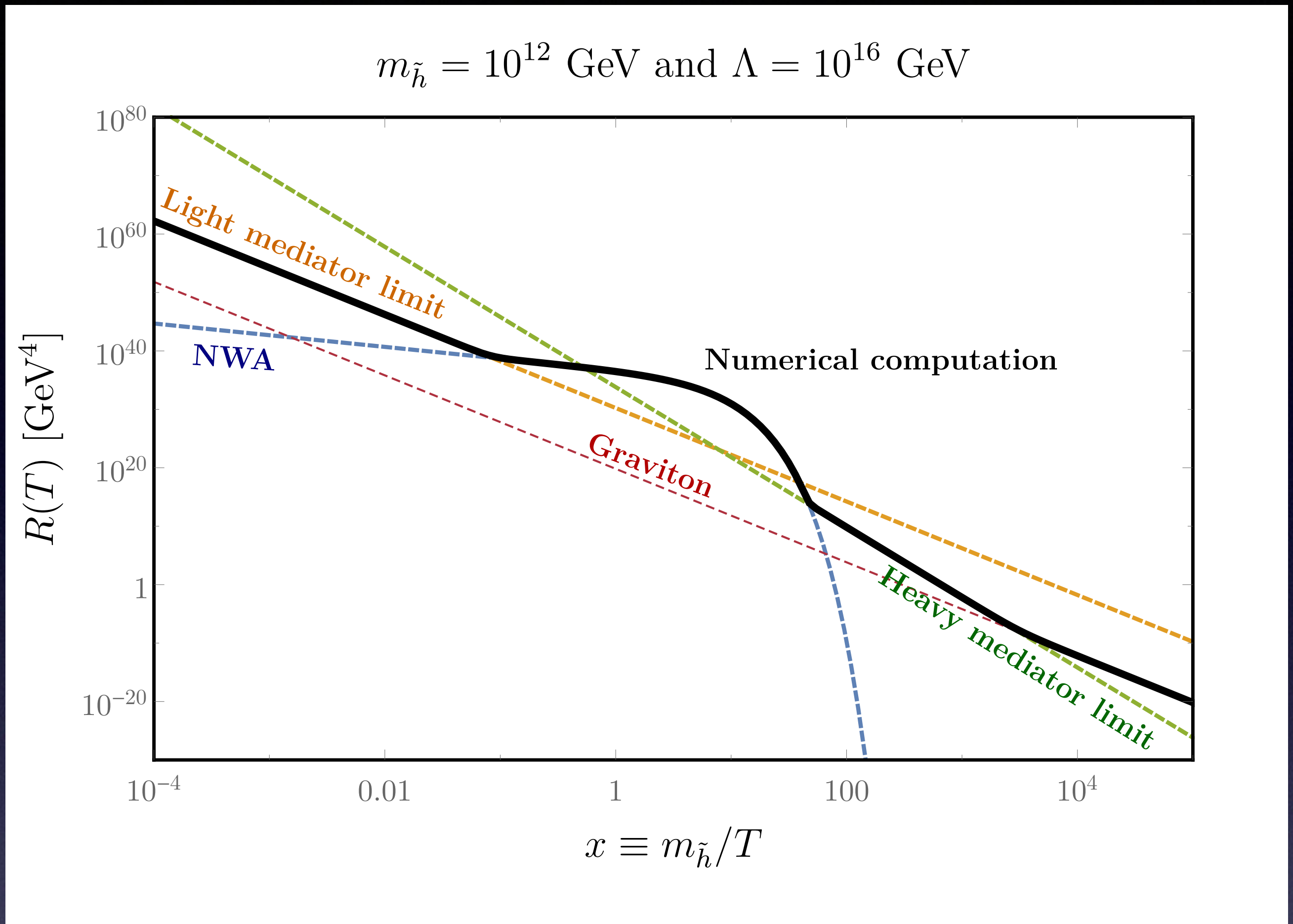
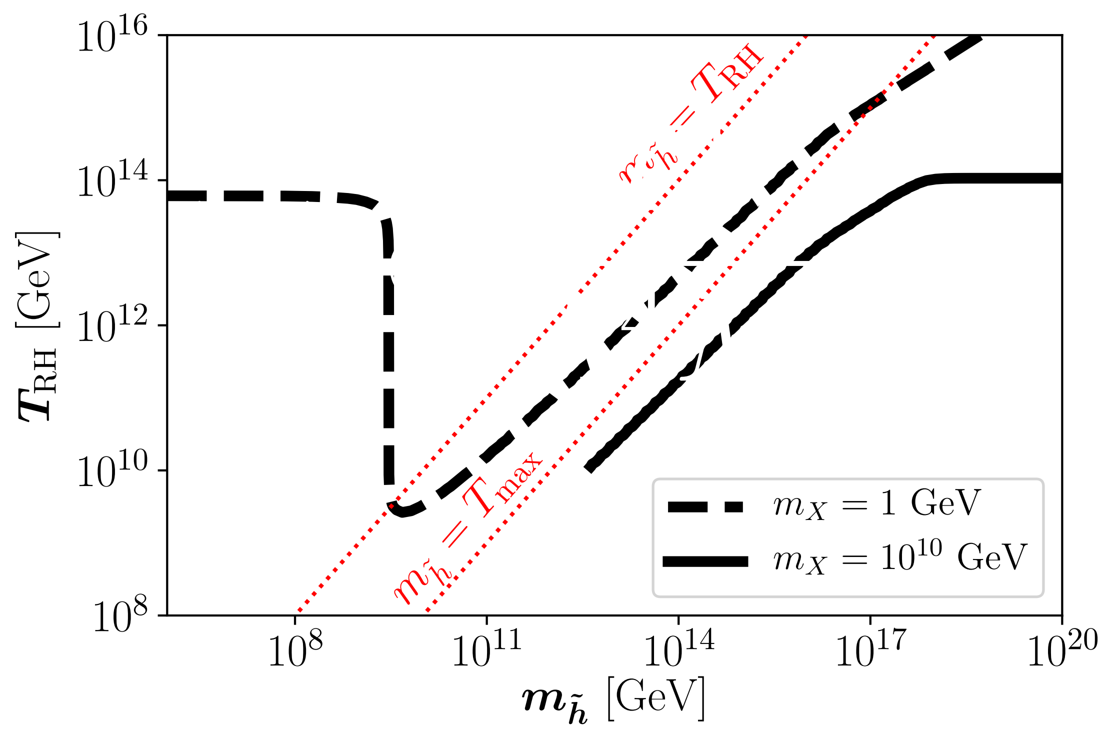
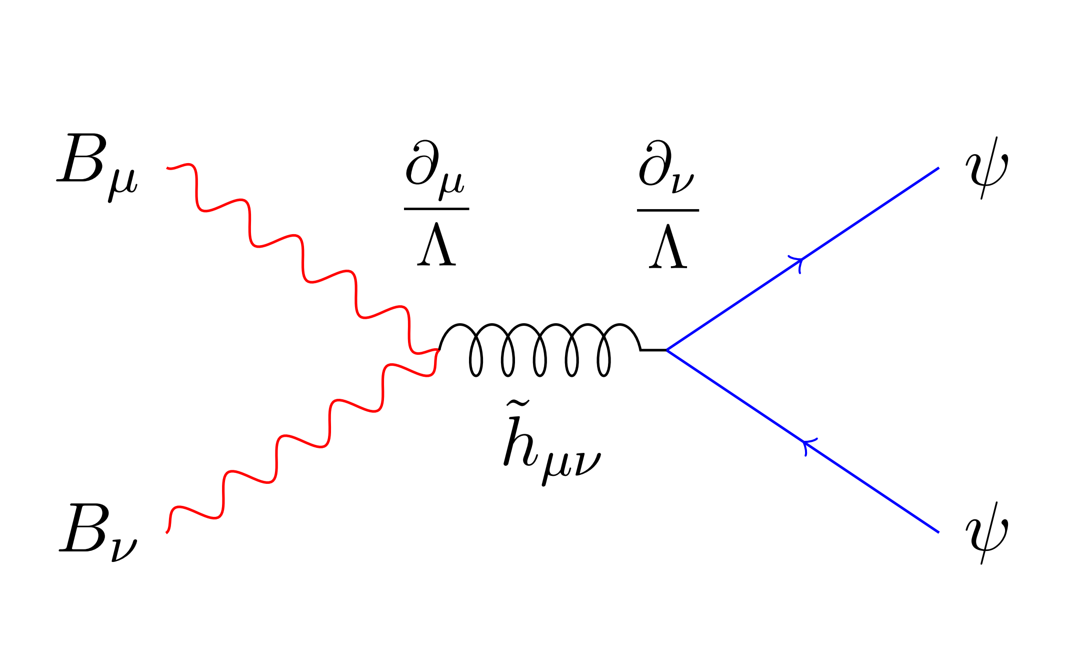




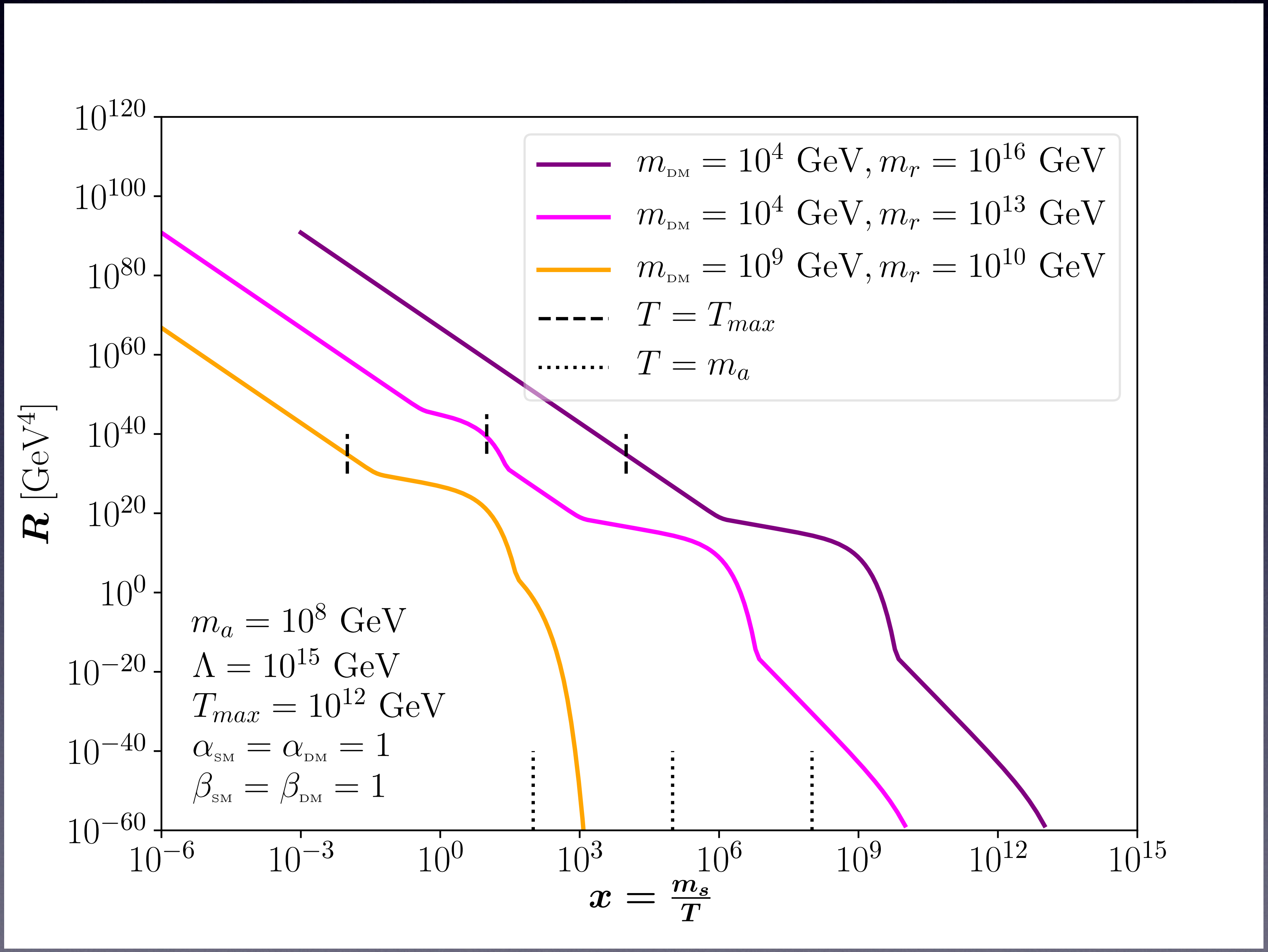


Moduli mediator

see talk Debtosh Chowdhury

In string motivated construction, the moduli fields T couple to the SM fields Φ following

$$\mathcal{L} = \frac{1}{\Lambda} T |D_\mu \Phi|^2$$



D. Chowdhury, E. Dudas, M. Dutra, Y.M. in preparation

Non-instant thermalization

see talk Marcos Garcia

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they annihilate almost immediately after being produced by the inflaton (thus at a much larger energy, around $M_I/2$)

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see talk Marcos Garcia

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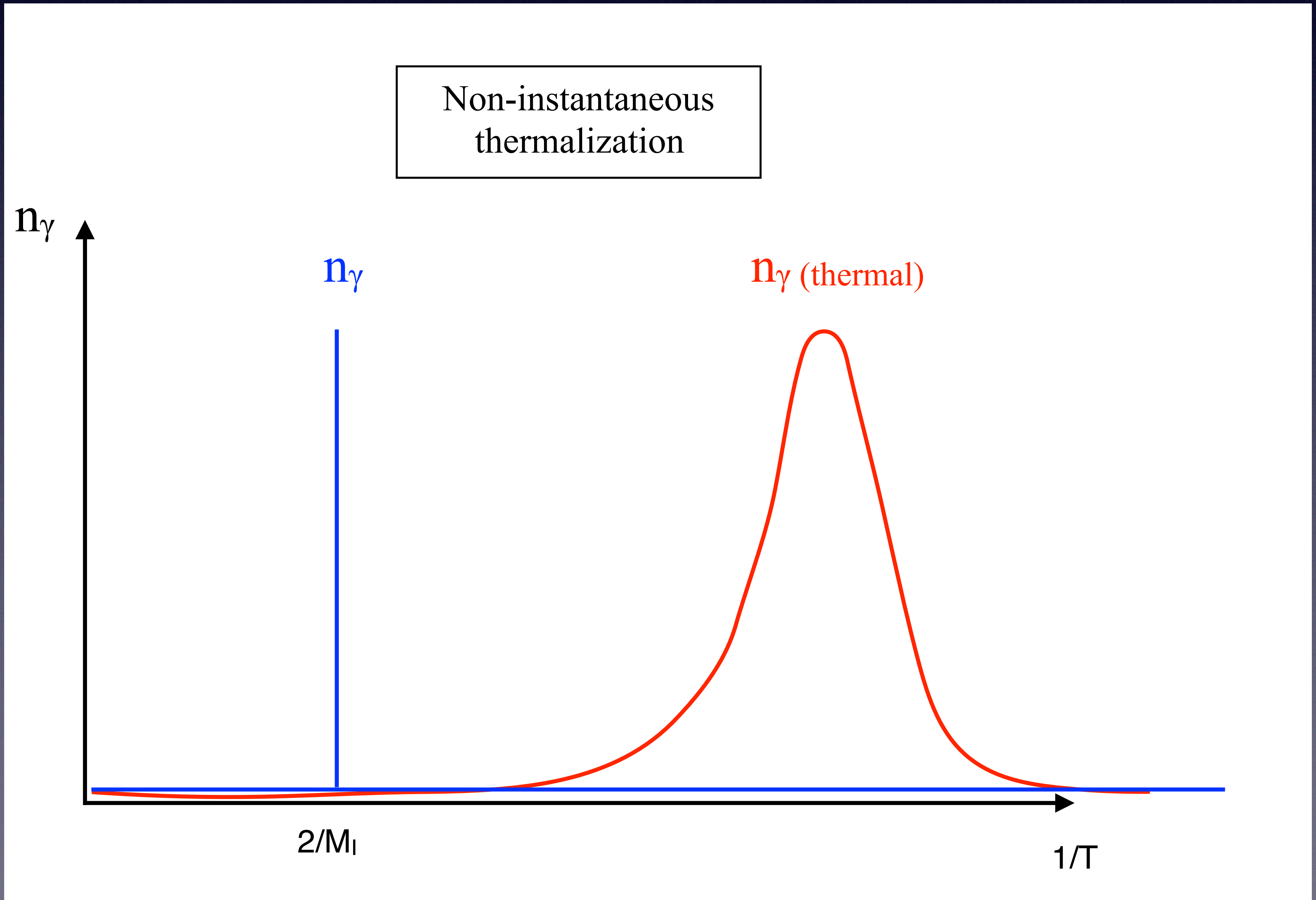

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see talk Marcos Garcia

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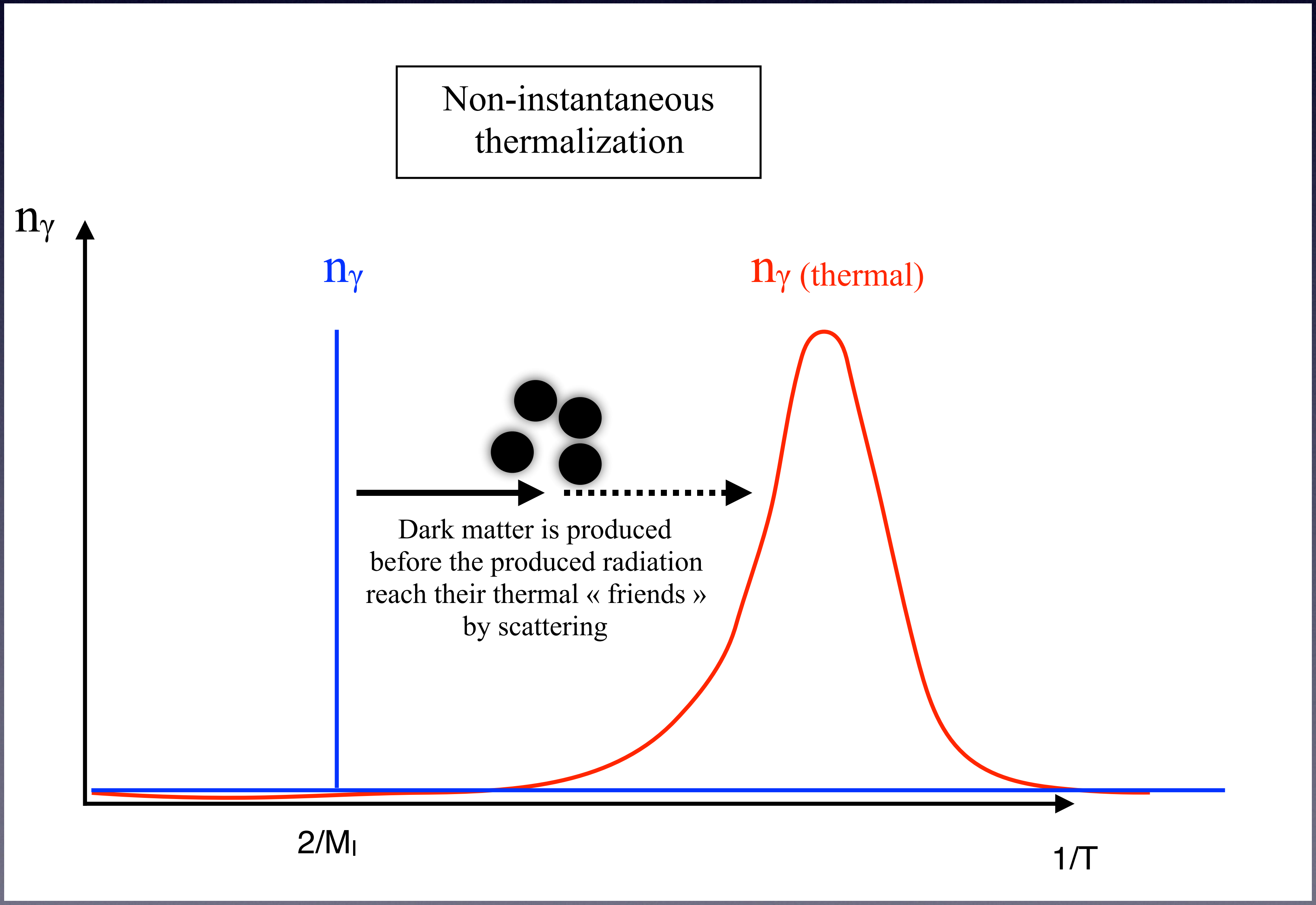
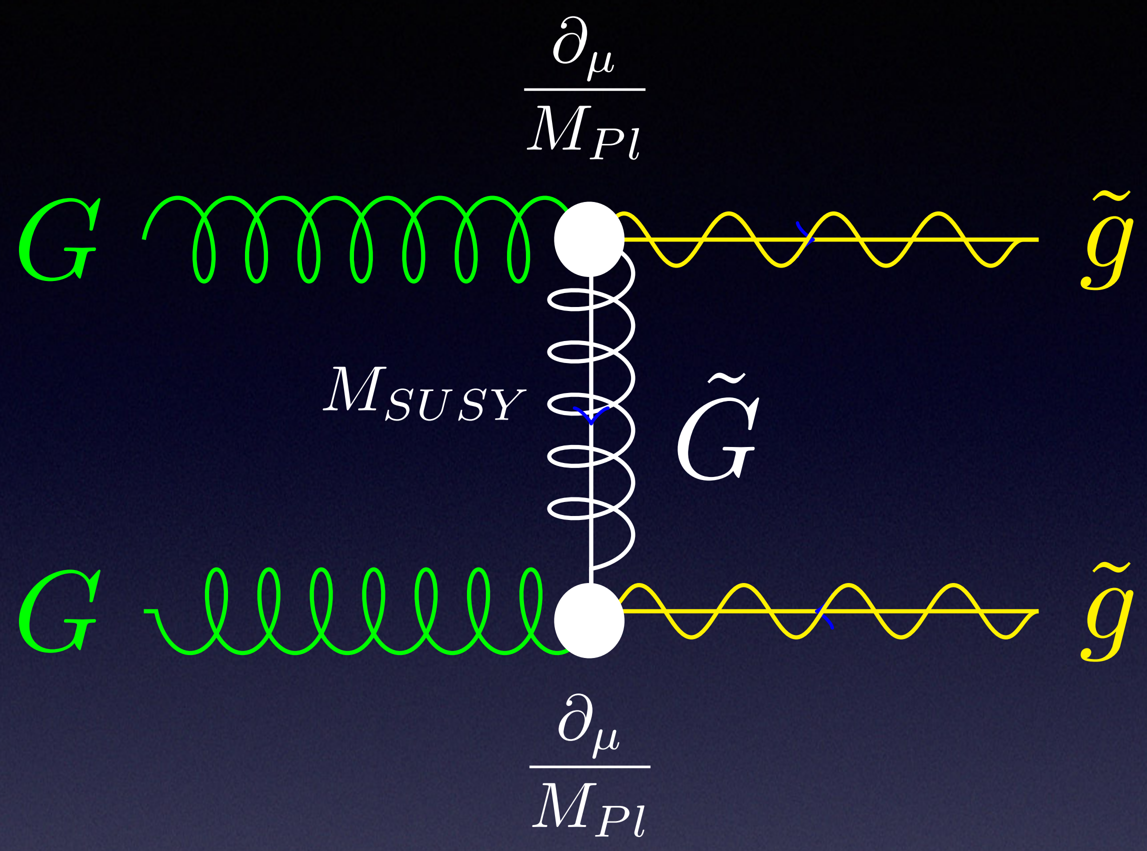
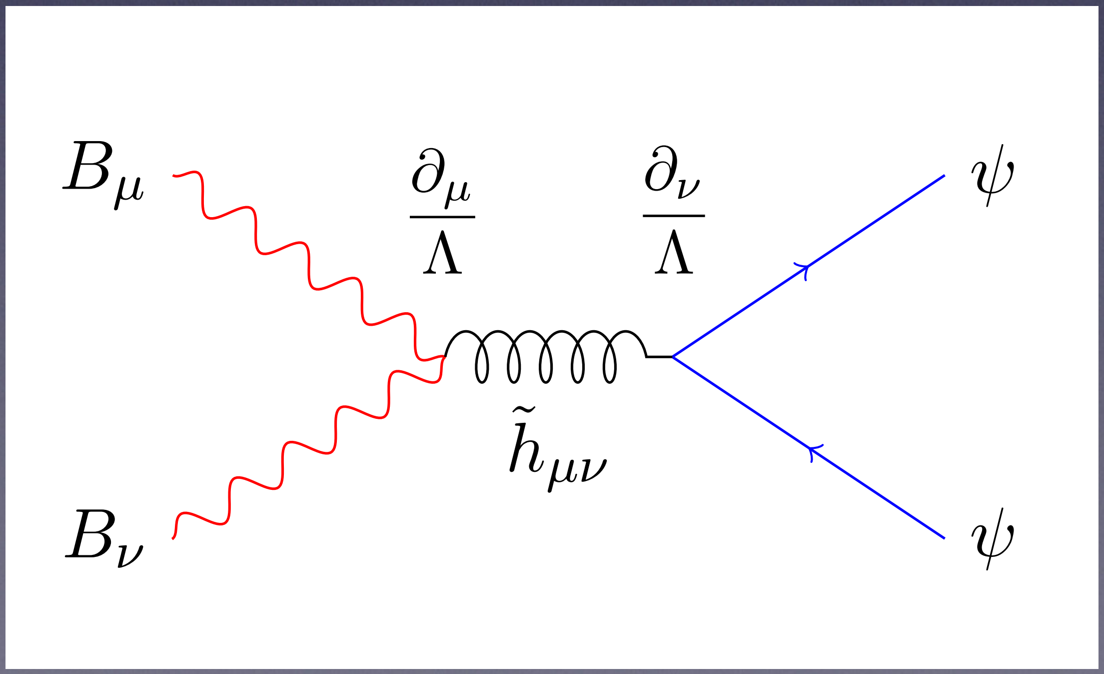
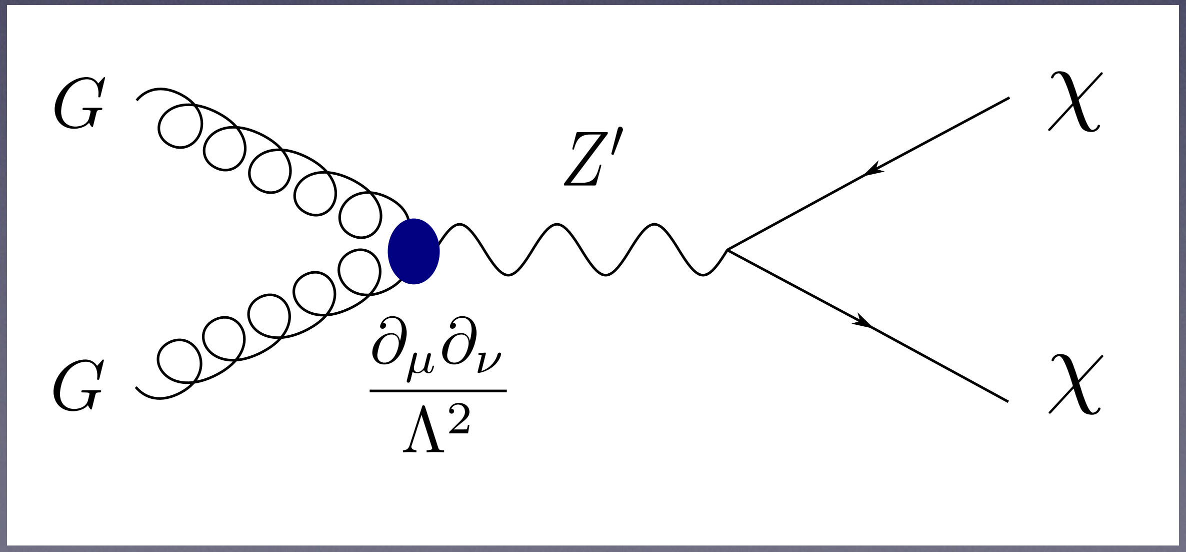


Conclusion

The computation of dark matter abundance in early universe should be treated with care, especially in models where new physics appears at high scale (~10^{10} GeV), implying derivative, and thus temperature-dependent processes.

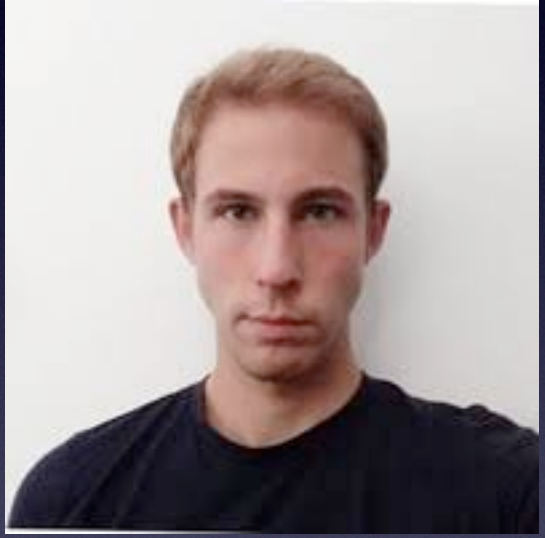






The workers

Maira Dutra



Mathias Pierre

Marcos Garcia

```
H^2 = \left( \frac{\dot a}{a} \right)^2 = \frac{8 \pi G}{3} \rho_{rad}(T) = \frac{8 \pi G}{3} \frac{\pi^2}{15} T^4
\\
aT = \mathrm{cste} ~~~~ \Rightarrow ~~~~ \frac{da}{a} = - \frac{dT}{T}
\\
\frac{dT}{T^3}= -\sqrt{\frac{8 \pi^3 G}{45}} dt ~~~~\Rightarrow ~~~~ t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32
\pi^3}} \simeq 0.2 \frac{M_{PL}}{T^2}
\\
t \simeq 3 \times 10^{27}~\mathrm{GeV^{-1}} \sim 200 ~\mathrm{seconds}
\\
n(t_D) \sigma v ~ t_D \simeq 1 ~~~~\Rightarrow n(t_D) \simeq \frac{1}{\sigma v t_D}
\\
v = \sqrt{\frac{3 T_D}{m_p}}\times c \simeq 5 \times 10^8 ~\mathrm{cm ~s^{-1}}
\\
T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9~\mathrm{K})}\right)^{1/3} 10^9~\mathrm{K} = \left( \frac{10^{-30}}
{1.78 \times 10^{-6}~\mathrm{g/cm^3}} \right)^{1/3}10^9~\mathrm{K} \simeq 8 ~\mathrm{K}


\psi_\mu \sim i \sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu \psi

H = h e^{i \frac{\theta}{<H>}} ~~\Rightarrow ~~ W_\mu = i \frac{1}{<H>} \partial_\mu \theta

\mathrm{with}~~ m_{3/2} = \frac{<F>}{\sqrt{3}M_{Pl}}

{\cal L} = \frac{i m_{\tilde G}}{8 \sqrt{6}~ m_{3/2} ~ M_{Pl}} {\color{yellow} \bar\psi} ~  [\gamma_\mu, \gamma_\nu]
{\color{red} \tilde G} ~ {\color{green} G_{\mu \nu}}


\Omega_{3/2} h^2 \sim 0.3 \left( \frac{1 ~\mathrm{GeV}}{m_{3/2}} \right) \left( \frac{T_{\mathrm{RH}}}{10^{10}~
\mathrm{GeV}} \right) \sum
\left( \frac{m_{\tilde G}}{100~\mathrm{GeV}} \right)^2


\Omega_{3/2} h^2 = {\color{yellow} \Omega_{3/2}^{scat} h^2 } + {\color{red}\Omega_{3/2}^{decay} h^2} ~~ \propto~~
{\color{yellow} \frac{T_{RH}\sum  m_{\tilde G^2}}{m_{3/2}^2 M_{Pl}}} +{\color{red} \frac{ \sum M^3_{\tilde Q}}
{m^2_{3/2} M_{Pl}} }
```

The equations

n_{e^-} + n_{e^+} = n_{\nu} + n_{\bar \nu} = \frac{3}{2} n_{\gamma}

```
n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}


\frac{\ddot a}{a} = - \frac{4 \pi G}{3}  \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi
G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c


n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}


\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f
\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }



\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1
~~~~~~~~
\Rightarrow \langle \sigma v \rangle > 10^{-9} h^{-2} ~\mathrm{GeV^{-2}}


\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}



\frac{dY_{a}}{dx_s} =\left( \frac{45}{g_* \pi} \right)^{3/2} \frac{1}{4 \pi^2} \frac{M_P}{m_{a}^5}x_s^4 R

{\color{white} \chi^0_1=} {\color{red} c_B \tilde B + c_1 \tilde H_1 + c_2 \tilde H_2} {\color{yellow} + c_W \tilde
W}
```

The equations

```
Y_{\tilde G} = \frac{n_{\tilde G}}{n_\gamma} \simeq 10^{-8} \left( \frac{m_{3/2}}{1 ~
\mathrm{GeV}} \right)
```

```
g_{s+3/2}^d \times (T_{3/2}^d)^3 \times V(T^d_{3/2}) = \left[ 4 \times \frac{7}{8} \times (T_{3/2}^0)^3 + 3 \times 2
\times \frac{7}{8}(T_\nu^0)^3 + 2 \times (T_\gamma^0)^3 \right] \times V(T_\gamma^0)
```

```
(T_{3/2}^0)^3 = \frac{1}{g^d_s}\frac{43}{11}(T_\gamma^0)^3 ~~\Rightarrow  ~~ \Omega h^2 = \frac{\rho_{3/2}}
{\rho_c^0} \simeq \frac{210}{g_s^d} \left(\frac{m_{3/2}}{1~\mathrm{keV}} \right) \lesssim 1 ~~ \Rightarrow ~~m_{3/2}
\lesssim 100 ~\mathrm{eV} ~~[g^d_s \lesssim 200]
```

```
\Gamma_{3/2}= \alpha_{3} \frac{m_{3/2}^3}{M_{\mathrm{Pl}}} ~; ~~\tau_{3/2} < 1~s ~~  \Rightarrow ~~ m_{3/2} > 10~
\mathrm{TeV} ~~\Rightarrow ~~ \sqrt{F} \simeq \sqrt{ m_{3/2} M_{\mathrm{Pl}}} \gtrsim 10^{11}~\mathrm{GeV}
```

```
{\color{yellow} X + \tilde \gamma \rightarrow X + \tilde g}
```

```
{\cal L}
=\frac{1}{4 M_{\mathrm{Pl}}}
{\color{yellow} \bar{\psi}^\alpha} \gamma_\alpha[\gamma^\mu,\gamma^\nu ] ~{\color{red} \tilde G} ~{\color{green}
G_{\mu \nu}}
```

```
\psi_\mu \sim i \sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \psi
```

```
{\color{green} \Omega^{FO}_{3/2} = \Omega_{\tilde G} \times \frac{m_{3/2}}{m_{\tilde G}} \propto \frac{1}{\langle
\sigma v \rangle} \frac{m_{3/2}}{m_{\tilde G}} \simeq \frac{1}{\alpha_3} m_{\tilde G} \times m_{3/2}}
```

```
{\color{yellow} \Omega_{3/2}^{\mathrm{scat}} \propto \frac{T_{RH} m_{\tilde G}^2}{m_{3/2}} }~~\Rightarrow ~~
\Omega_{3/2} \propto ~ {\color{yellow} \frac{T_{RH} m_{\tilde G}^2}{m_{3/2}}} +{\color{green} m_{\tilde G} \times
m_{3/2}}
```

FIMP

```
\frac{dn}{dt} = \langle \sigma v \rangle n_\gamma^2= R
~~\Rightarrow ~~\frac{d Y}{dT}= \frac{R(T)}{H ~T ~ s}
\\
{\color{yellow} \mathrm{with} ~~ H(T) = 1.66 ~ g_*(T) \frac{T^2}{M_{Pl}}
~~ \mathrm{and} ~ ~s = \frac{2 \pi^2}{45}g_*(T) ~T^3}mes m_{3/2}}
```

```
R(T) = \int \frac{E_1dE_1 E_2dE_2~ d \cos\theta_{12}}{(e^{E1/T}-1)(e^{E_2/T}-1)}\int
\frac{|{\cal M}|_{\gamma \gamma \rightarrow \psi \psi}^2}{1024 \pi^6} d\Omega

{\cal L} = (\frac{1}{\Lambda_1} \phi B_{\mu \nu} B^{\mu \nu} + y_\psi \phi~ \bar \psi_L \psi_R + h.c.) + \mu_\phi^2
|\phi|^2 - \lambda_\phi |\phi|^4

\Omega h^2 = 0.1 ~\lambda_\phi~
\left(\frac{m_\psi}{10^9 ~\mathrm{GeV}} \right)^3
\left(\frac{T_{RH}}{10^{10} ~\mathrm{GeV}} \right)^5
\left(\frac{10^{13}~\mathrm{GeV}}{M_s} \right)^6
\left(\frac{10^{14}~\mathrm{GeV}}{\Lambda_1} \right)^2
```

```
{\cal L} = {\color{yellow} (\frac{1}{\Lambda_1} \phi B_{\mu \nu} B^{\mu \nu} + y_\psi \phi~ \bar \psi_L \psi_R +
h.c.) + \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^4}
\\
 {\color{green} +( y_F \phi ~\bar F_L F_R + h.c.)}

\Omega h^2 = 0.1 ~(g_1^2 \sum Y_F^2)^2\left(\frac{\lambda_\phi}{4} \right)^4
\left( \frac{m_\psi}{10^9 ~\mathrm{GeV}} \right)^3
\left( \frac{T_{RH}}{10^{10}~\mathrm{GeV}} \right)^5
\left( \frac{10^{13}~\mathrm{GeV}}{m_s} \right)^8

T_{RH}= \left( \frac{10}{g_s} \right)^{1/4}
\left( \frac{2 \Gamma_s M_{Pl}}{\pi c}\right)^{1/2}
\\
\simeq 2.3 \times 10^{12}~
(g_1^2 \sum_F Y_F^2)~\sqrt{\lambda_\phi}
\left( \frac{m_s}{10^{13}~\mathrm{GeV}} \right)^{1/2}
~ \mathrm{GeV}
```

The equations

FIMP

```
{\cal M}= \lambda ~\frac{s}{p^2-M_M^2} \simeq \lambda \frac{s}{M_M^2}~~\Rightarrow ~~ R(T)\sim
\frac{T^8}{M_M^4}
\\
\Rightarrow  ~~ \Omega h^2 = 0.1 ~\lambda^2 \left( \frac{M_{dm}}{1~\mathrm{TeV}} \right)
\left( \frac{T_{RH}}{10^{10}~\mathrm{GeV}} \right)^3
\left( \frac{10^{10}}{M_M} \right)^4
```

```
\Omega_{3/2}h^2 \simeq 0.11 \left( \frac{0.1 ~ \mathrm{EeV}}{m_{3/2}} \right)^3 \left( \frac{T_{RH}}{2 \times
10^{10}} \right)^7 {\color{red} \times \frac{56}{5} \ln \left(\frac{T_{max}}{{T_{RH}}}\right)}
```

```
R(T) = n_{Eq}^2\langle \sigma v \rangle =  \int f_1 f_2 \frac{E_1 E_2 dE_1 dE_2 ~d\cos \theta_{12}}{1024 \pi^6} \int
|{\cal M}_{fi}|^2 d \Omega_{13}  \propto \frac{T^{n+6}}{\Lambda^{n+2}}
```