Early Matter Domination from Long-Lived Particles in the Visible Sector

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Mitchell Conference on
Collider, Dark Matter, and Neutrino Physics 2022

MIFPA, Texas A&M University

May 24-27, 2012

Outline:

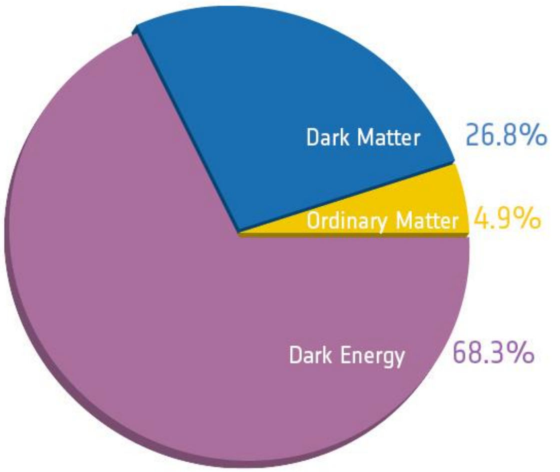
- Introduction
- Thermal histories with EMD
- EMD from the visible sector
- Prospects for LLP searches
- Conclusion and Outlook

Based on:

R.A., J. Osinski PRD 105, 023502 (2022)

Introduction:

The present universe according to observations:



BSM needed to explain 95% of the universe.

Important questions:

What is the nature of DM?

What is the origin of matter-antimatter asymmetry?

→ Particle Physics (BSM)

How did DM acquire its relic abundance?

How was the observed BAU generated?

→ Particle Physics (BSM) + Cosmology (thermal history)

What do we know about the early universe?

Thermal DM:

Starting in a RD universe:

$$\dot{n}_\chi + 3Hn_\chi =<\sigma_{ann} v>_f (n_{\chi,eq}^2 - n_\chi^2)$$

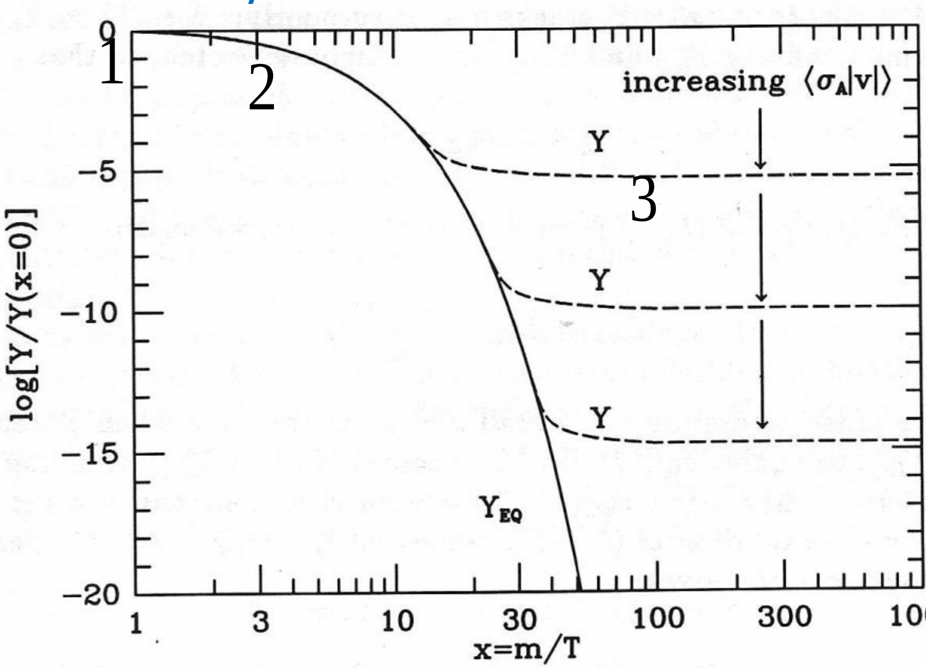
1) $T \gg m_\chi$: $\chi\chi \leftrightarrow f\bar{f} \implies n_\chi \propto T^3$

2) $T \lesssim m_\chi$: $\chi\chi \longrightarrow f\bar{f} \implies n_\chi \propto \exp(-\frac{m_\chi}{T})$

3) $T \approx T_f$: $\implies \frac{n_\chi}{s} = const.$

$$\boxed{<\sigma_{ann} v>_f = 3 \times 10^{-26}\, cm^3\, s^{-1}}$$

"The Early Universe" Kolb & Turner



WIMP miracle:

$$<\sigma_{ann} v>_f = \frac{\alpha_\chi^2}{m_\chi^2}$$

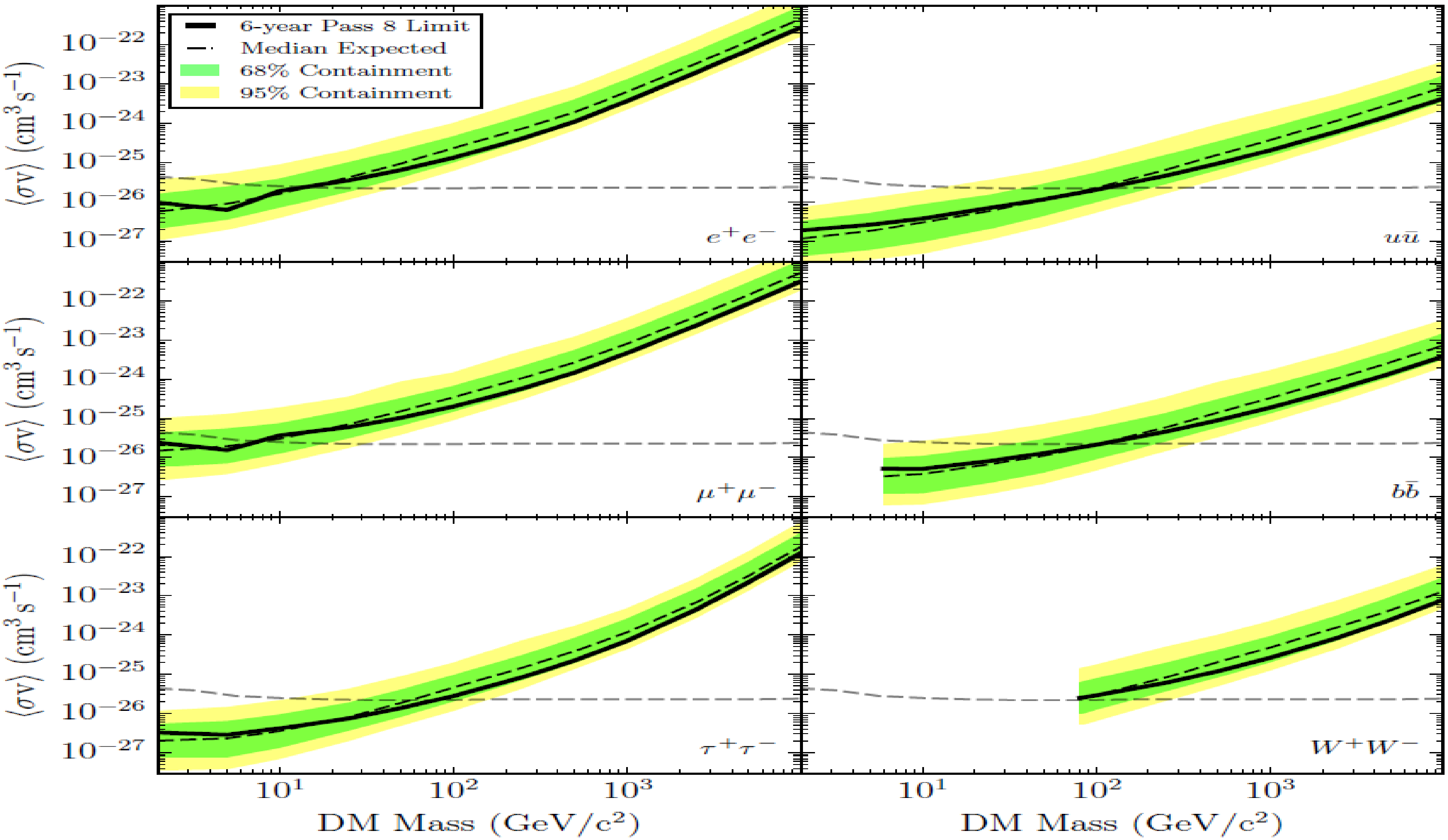
$$\alpha_\chi \sim O(10^{-2}), m_\chi \sim 10 - 10^3\ GeV$$

$$\Omega_\chi h^2 \sim 10^{-3} - 1$$

$$\boxed{t_f \lesssim 10^{-7}\ s}$$

Indirect detection experiments:

Fermi Collaboration PRL 115, 231301 (2015)



For DM masses *< 20 GeV*:

$$<\sigma_{ann} v>_f < 3\times 10^{-26}\ cm^3 s^{-1}$$

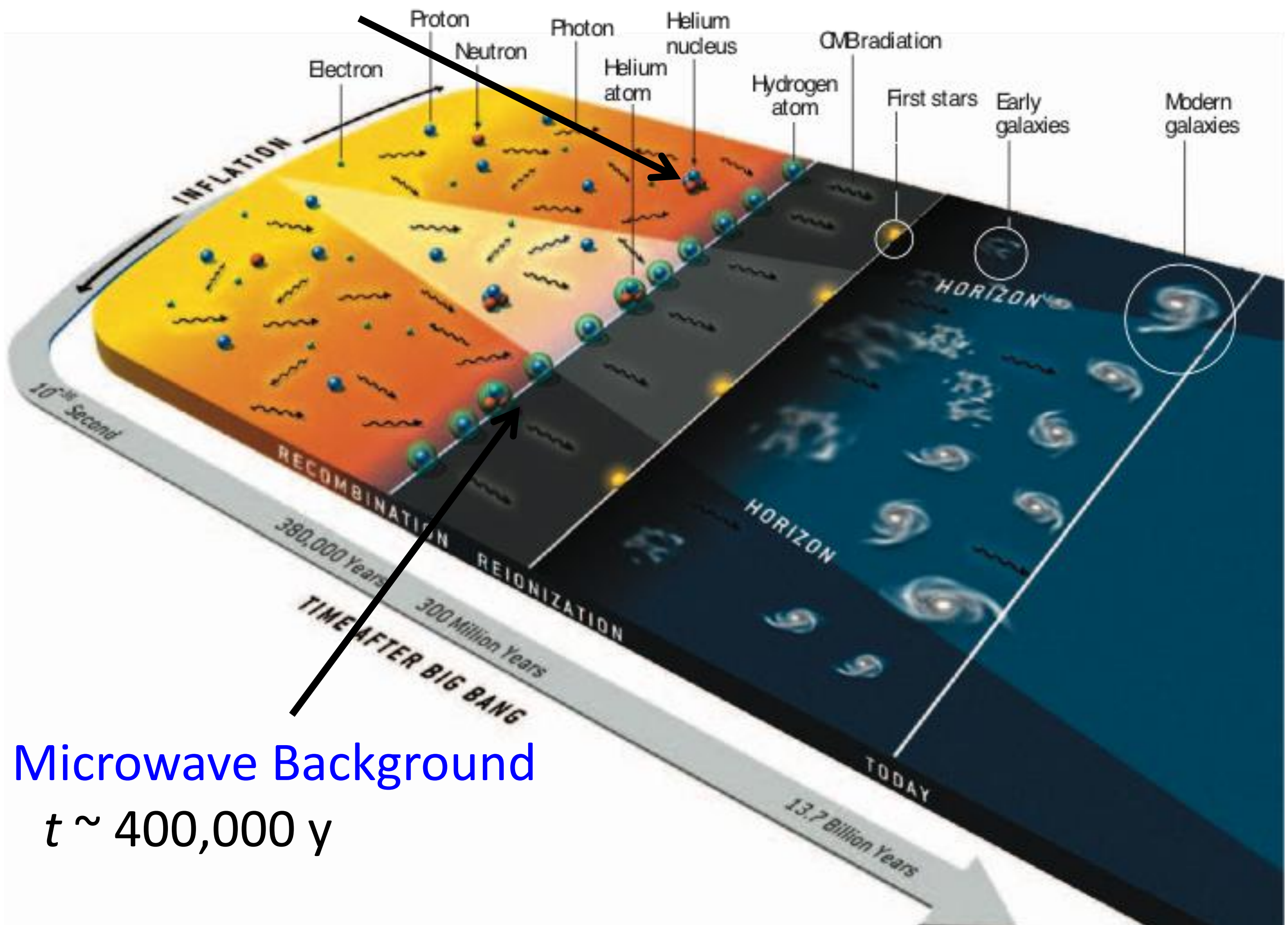
(assuming S-wave annihilation)

R. Leanne, T. Slatyer, J. Beacom, K. Ng PRD 98, 023016 (2018)

Observational probes of the early universe:

Big Bang Nucleosynthesis

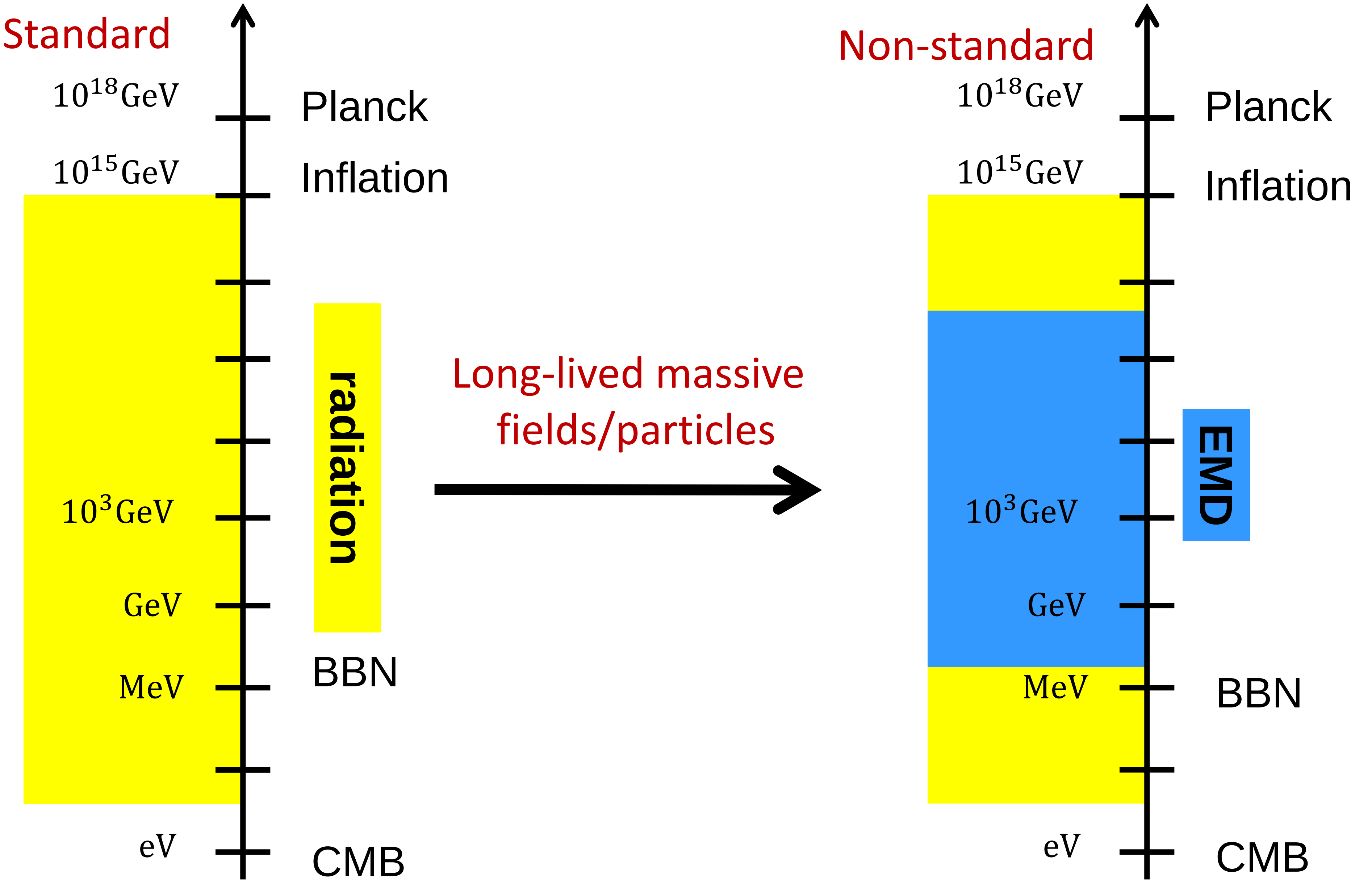
$t \sim 1$ s



Cosmic Microwave Background

$t \sim 400{,}000$ y

An alternative thermal history with EMD:



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

Thermal Histories with EMD:

Consider a scalar field ϕ with mass m_ϕ and decay width Γ_ϕ.

Modulus fields in string theory are natural candidates for ϕ :

$$\Gamma_\phi = \frac{c}{2\pi} \frac{m_\phi^3}{M_P^2} \qquad c \sim O(1)$$

Dynamics in the early universe:

$H \gg m_\phi$: Displacement from the minimum during inflation

$H \simeq m_\phi$: Oscillations about the minimum start, dominate the universe

$H \simeq \Gamma_\phi$: Oscillations decay and form a RD universe

$$T_R \sim 0.1\ (\Gamma_\phi M_P)^{1/2} \sim \left(\frac{m_\phi}{50\ TeV}\right)^{\frac{3}{2}} \times 3\ MeV$$

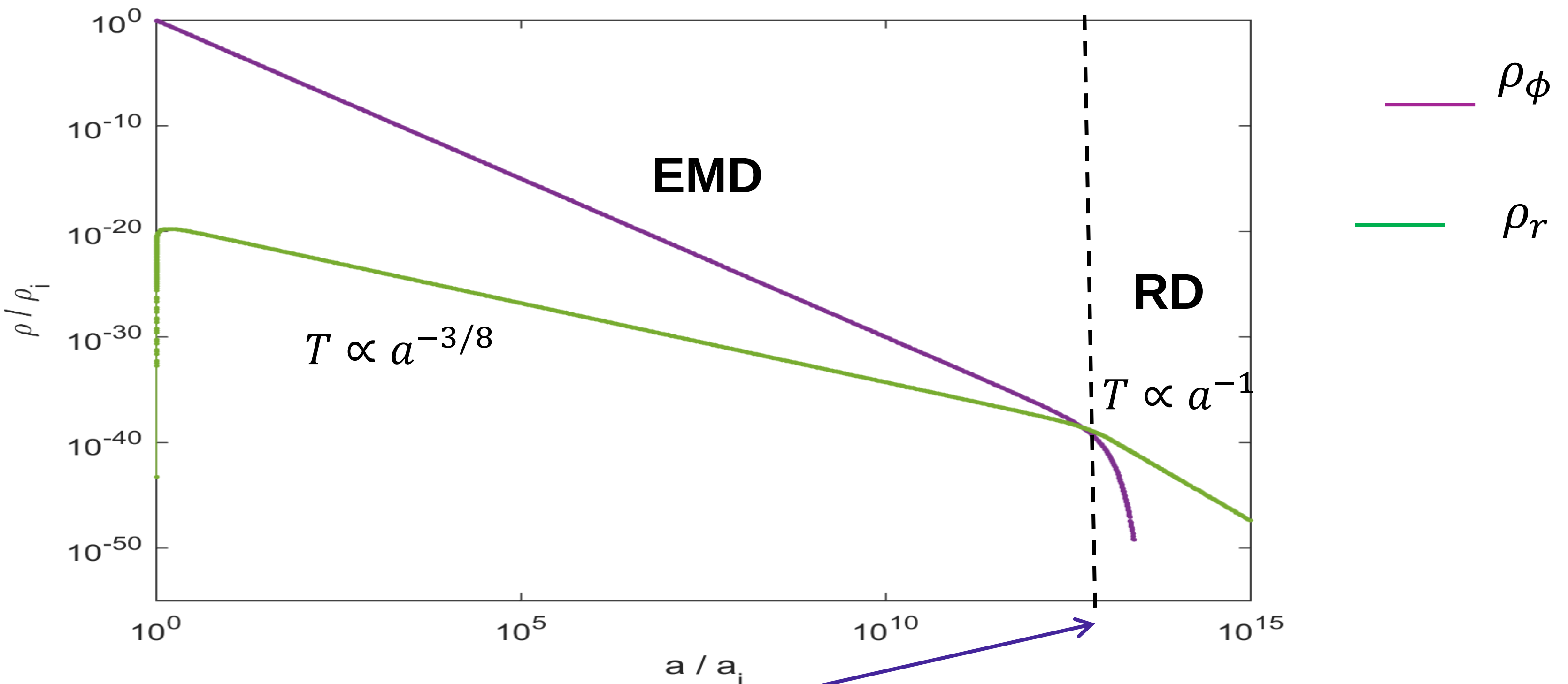
Evolution of matter and radiation energy densities:

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\dot{\rho}_r + 4H\rho_r = +\Gamma_\phi \rho_\phi$$

$$H^2 = \frac{\rho_\phi + \rho_r}{3M_P^2}$$

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$



BBN requires that:

$$T_R > 3\ MeV \Rightarrow \boxed{m_\phi > 50\ TeV}$$

Constraints:

(1) Obtaining the correct DM abundance.

$$\dot{n}_\chi + 3Hn_\chi = <\sigma_{ann} v>_f (n_{\chi,eq}^2 - n_\chi^2) + Br_\chi \Gamma_\phi n_\phi$$

Br_χ: number of DM quanta produced per decay of ϕ quanta

(2) Generating the observed baryon asymmetry.

$$\left(\frac{s_{after}}{s_{before}}\right) \sim \frac{M_P}{m_\phi} \quad (>> 10^{10})$$

(3) Gravitino production must be suppressed.

$\phi \rightarrow \tilde{G}\tilde{G}$ is the main source of gravitino production.

Helicity-1/2 gravitinos pose the main threat.

(4) Modulus decay must successfully reheat the visible sector.

No excess of DR, etc.

EMD from the Visible Sector:

Can we directly test the physics responsible for EMD in the lab?

Not possible for string moduli (large masses and very weak couplings).

A successful scenario where ϕ is in the visible sector?

This can also address issues with gravitino and DR production!

R.A., J. Osinski PRD 105, 023502 (2022)

Consider a minimal extension of the SM with two new fields X and N :

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm new} \, ,$$

$$\mathcal{L}_{\rm new} \supset h X N \psi + h' X^{\dagger} \psi \psi + {\rm h.c.}$$

ψ: SM fermions

X: Scalar with SM charges $\qquad m_N \ll m_X$

N: SM singlet Majorana fermion

Example:

$$\mathcal{L} \supset (h_i X N u_i^c + h'_{ij} X^* d_i^c d_j^c + \frac{1}{2} m_N N N + \text{h.c.}) + m_X^2 |X|^2$$

K. Bsabu, R. Mohapatra, S. Nasri PRL 98, 161301 (2007)

R.A., B. Dutta PRD 88, 023525 (2013)

X: Iso-singlet color-triplet scalar, *Y = 4/3*

u: Right-handed up-type quarks

d: Right-handed down-type quarks

4-fermion interaction at low energies $E \ll m_X$:

$$\frac{hh'}{m_X^2} Nudd$$

This operator results in *N* decay to three SM fermions.

Other possibilities: $NQLd$, $NLLe$

All of them violate baryon and/or lepton number.

N can drive an epoch of EMD! How?

Assuming RD at $T \gtrsim m_X$, subsequent stages are:

(1) $H \gtrsim H(T = m_X)$

RD: *X* in equilibrium, brings *N* into equilibrium via decays/inverse decays.

(2) $H(T = m_X) > H \gtrsim H(T = m_N)$

RD: *N* is relativistic with frozen comoving number density.

(3) $H(T = m_N) > H \gtrsim H_{\rm dom}$

RD: *N* becomes nonrelativistic, starts to dominate radiation.

(4) $H_{\rm dom} > H \gtrsim \Gamma_N$

EMD: *N* dominance, eventually ends when N decay establishes RD.

Necessary conditions for this scenario to work:

- *N* must reach equilibrium:

$$\Gamma_{X\to N} \gtrsim H(T = m_X)$$

- *N* self-annihilation and annihilation must be inefficient:

$$\Gamma_{NN\to\psi\psi^*} < H(T = m_N)$$

$$\Gamma_{N\psi\to\psi^*\psi^*} < H(T = m_N)$$

- *N* must dominate before decaying:

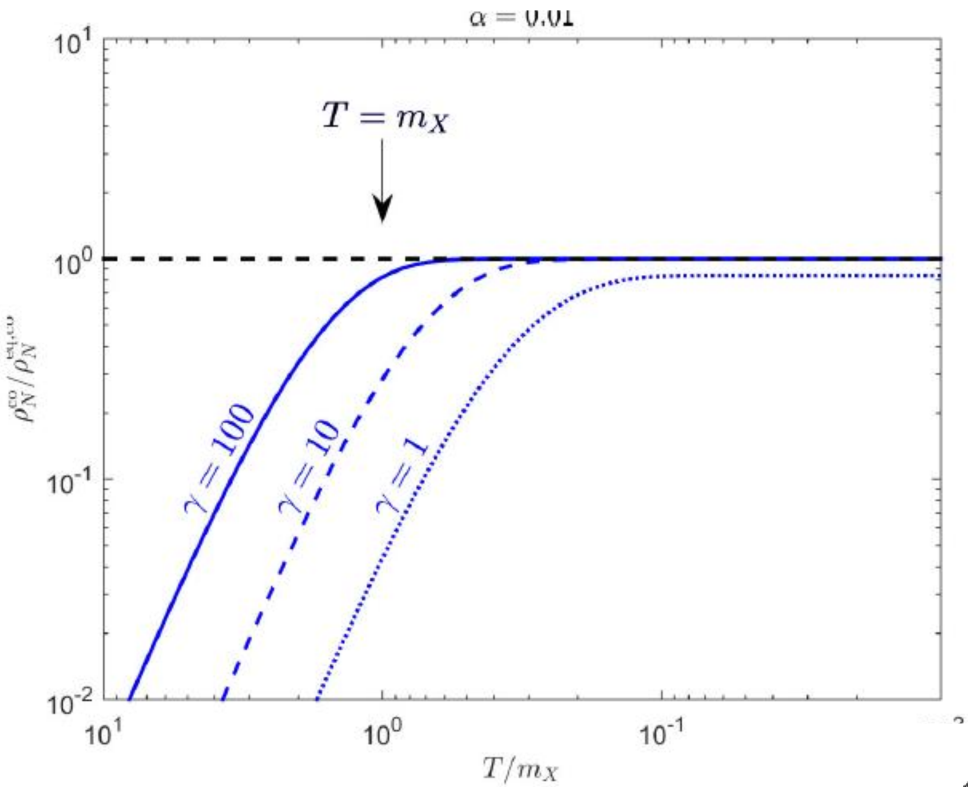
$$\Gamma_N < H_{\rm dom}$$

- *N* decay must happen before BBN:

$$\Gamma_N \gtrsim H_{\rm BBN} \sim 10\ {\rm s}^{-1}$$

Dilution factor:

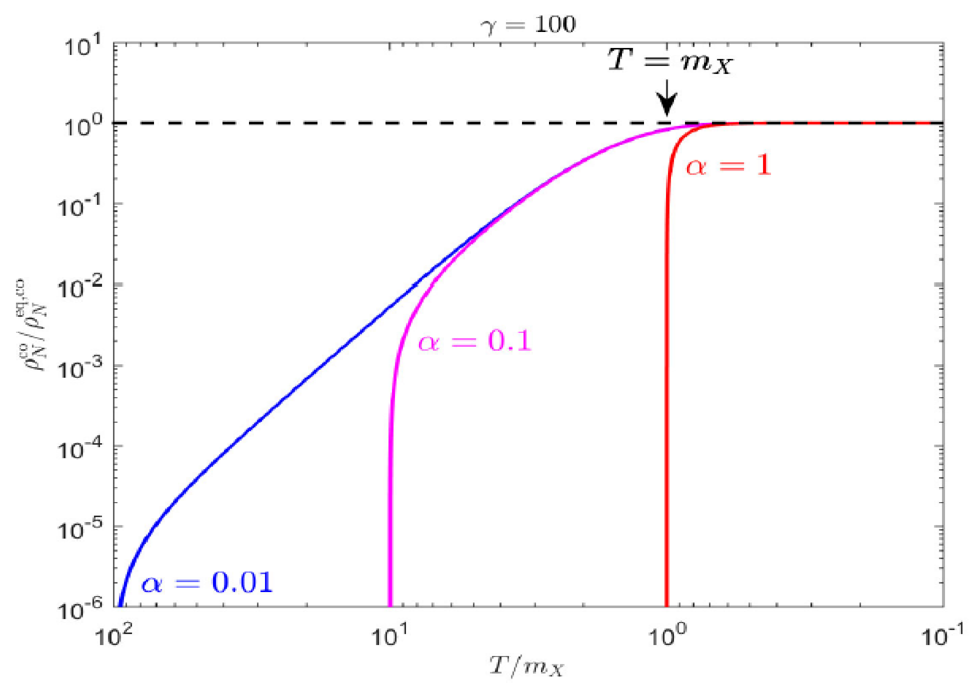
$$d \simeq \left(\frac{g_{*\rm dec}}{g_{*\rm dom}}\right)^{1/4} \left(\frac{H_{\rm dom}}{\Gamma_N}\right)^{1/2}$$



$$\alpha \equiv m_X/T_{\rm i}$$

$$\gamma \equiv \Gamma_{X\to N}/H(T = m_X)$$

Equilibrium is reached at
$T \gg m_X/10$ if $\alpha \gtrsim 1$.



For a given flavor combination of SM fermions:

$$\Gamma_{X\to N} \simeq \frac{|h|^2}{16\pi} m_X$$

$$\Gamma_{NN\to\psi\psi^*} \simeq C_1 \frac{|h|^4}{16\pi} \frac{E^2}{m_X^4} n_N$$

$$\Gamma_{N\psi\to\psi^*\psi^*} \simeq 3C_2 \frac{|h|^2|h'|^2}{16\pi} \frac{E^2}{m_X^4} n_\psi$$

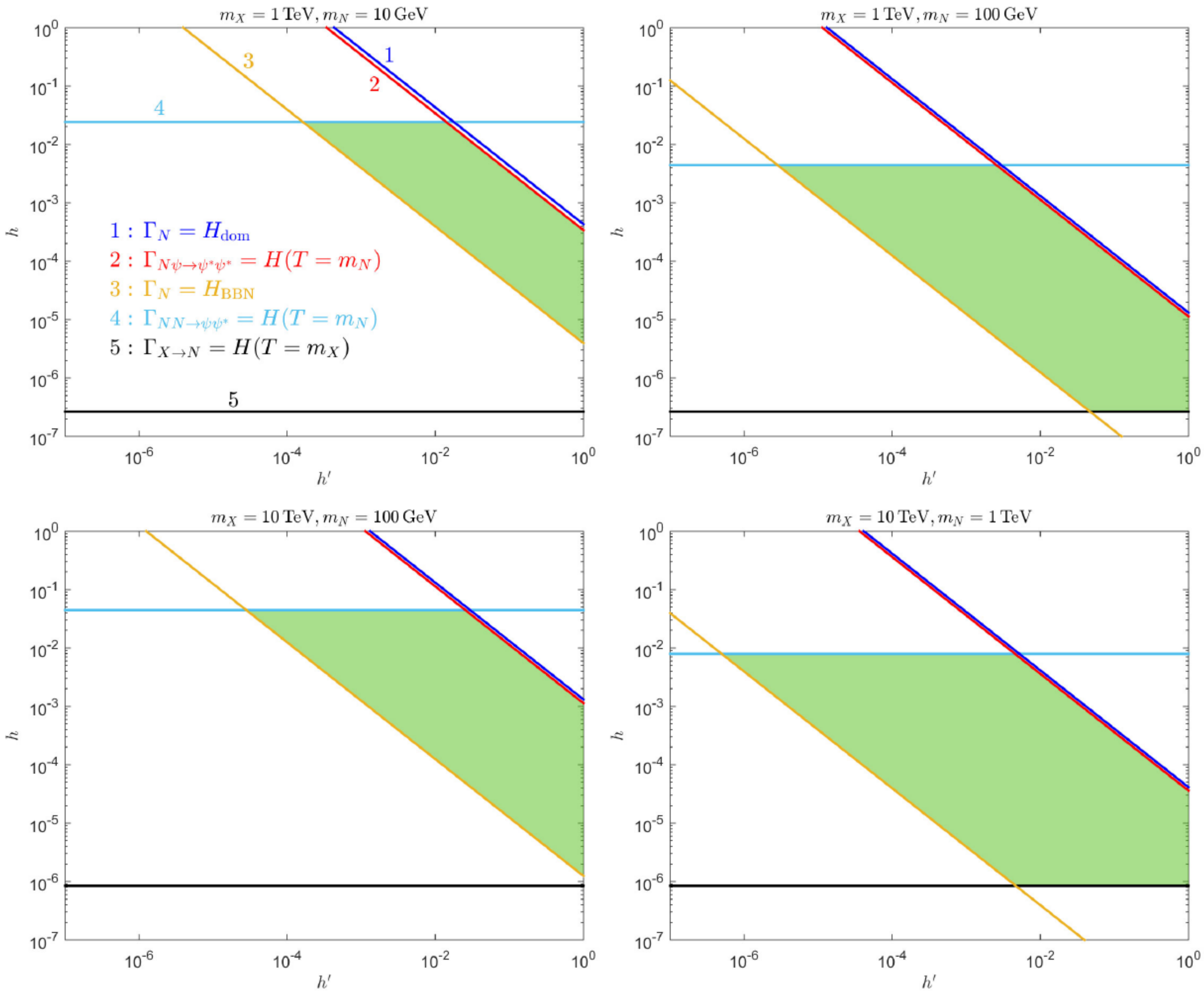
$$\Gamma_N = 2C_2 \frac{|h|^2|h'|^2}{128\cdot 192\pi^3} \frac{m_N^5}{m_X^4}$$

C_1, C_2 : multiplicity factors

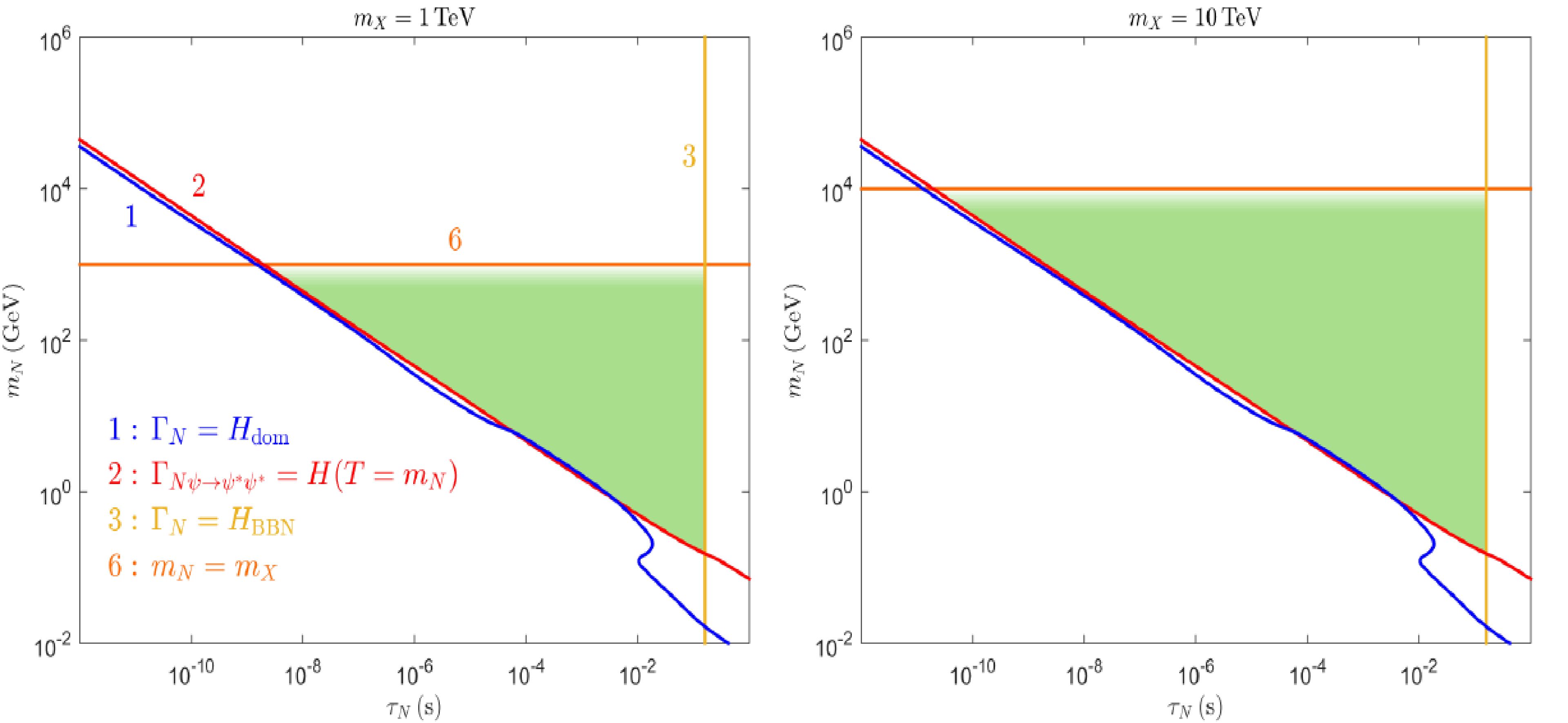
In the model mentioned above:

$C_1 = 3\,, C_2 = 6$

The allowed parameter space in $h - h'$ plane:



The allowed parameter space in the $m_N - \tau_N$ plane:



Conditions 4 & 5 are comfortably satisfied in the shaded regions here.

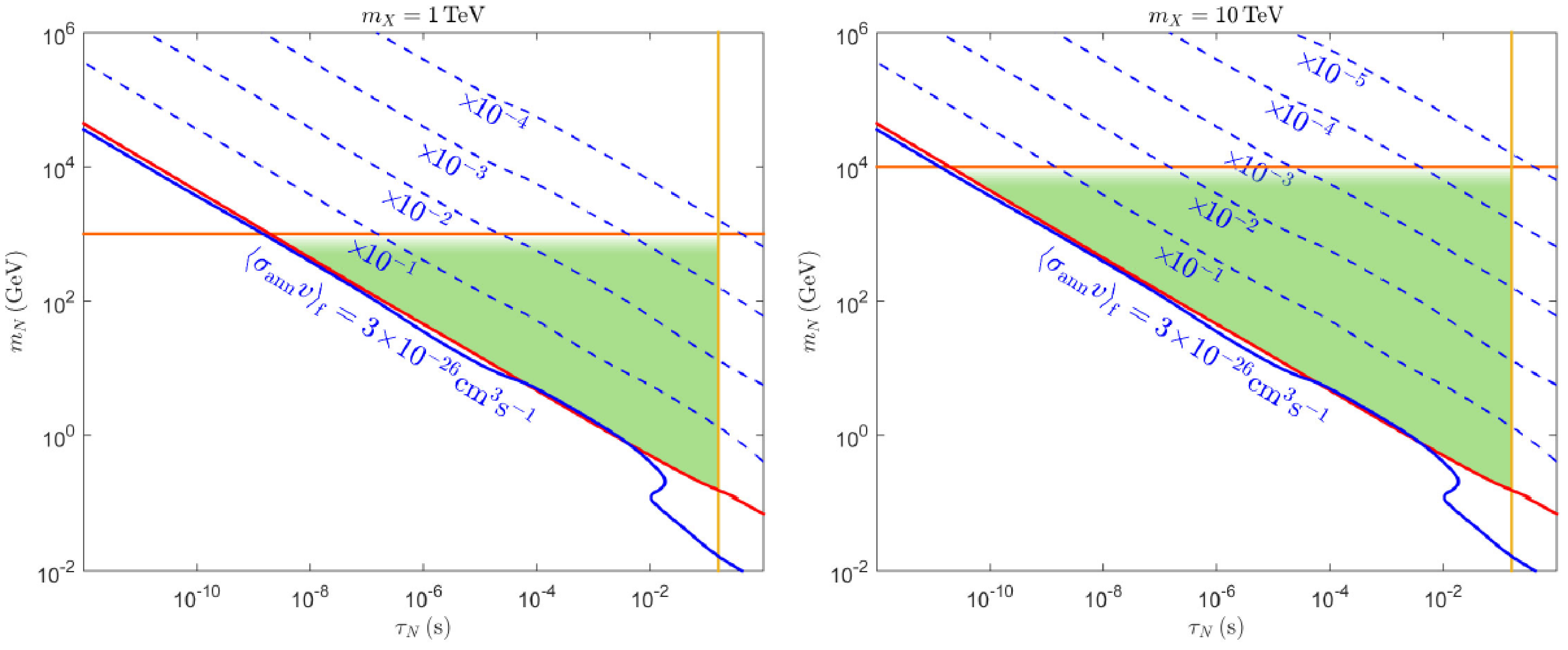
The resulting dilution factor is:

$$d \lesssim 10^5$$

DM relic abundance can be accommodated for small annihilation rates:

$$\left(\frac{n_{\rm DM}}{s}\right) = d^{-1} \times \frac{3\times 10^{-26}\ {\rm cm^3\ s^{-1}}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}} \times \left(\frac{n_{\rm DM}}{s}\right)_{\rm obs}$$

$$d = \frac{3\times 10^{-26}\ {\rm cm^3\ s^{-1}}}{\langle\sigma_{\rm ann} v\rangle_{\rm f}}$$

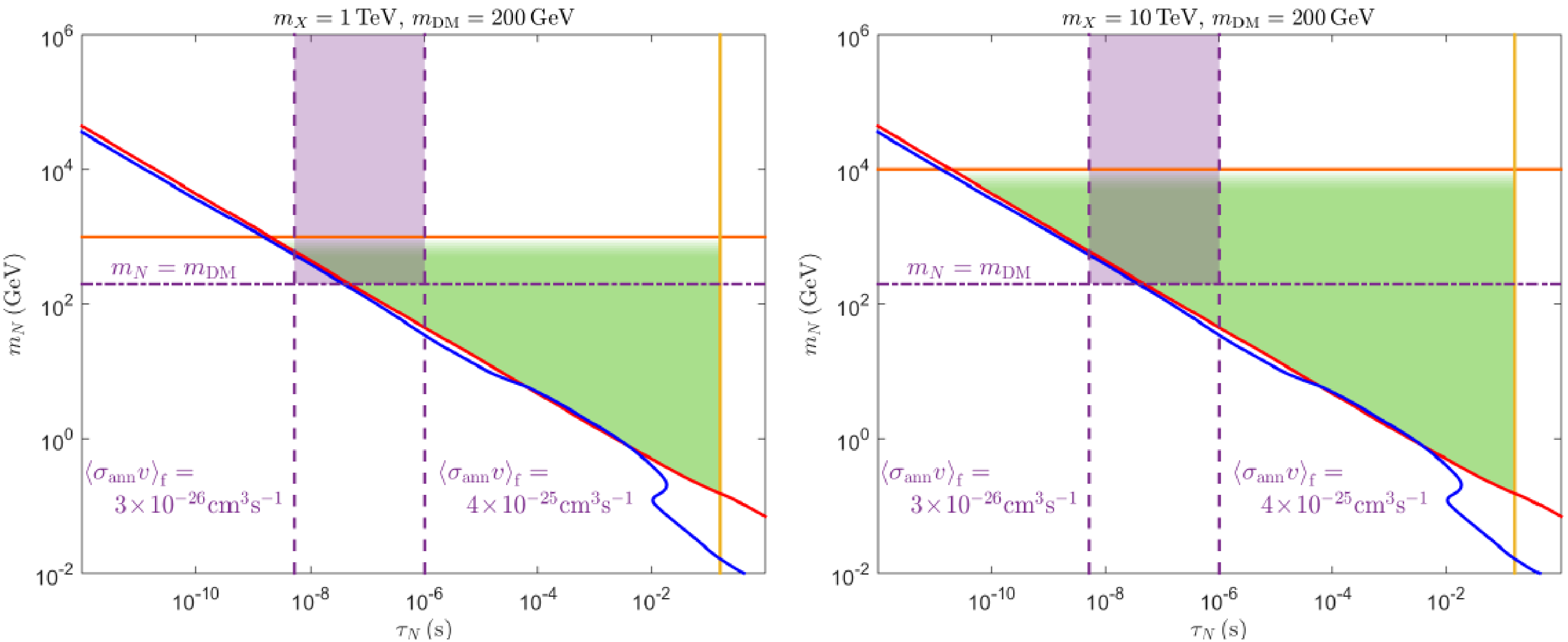


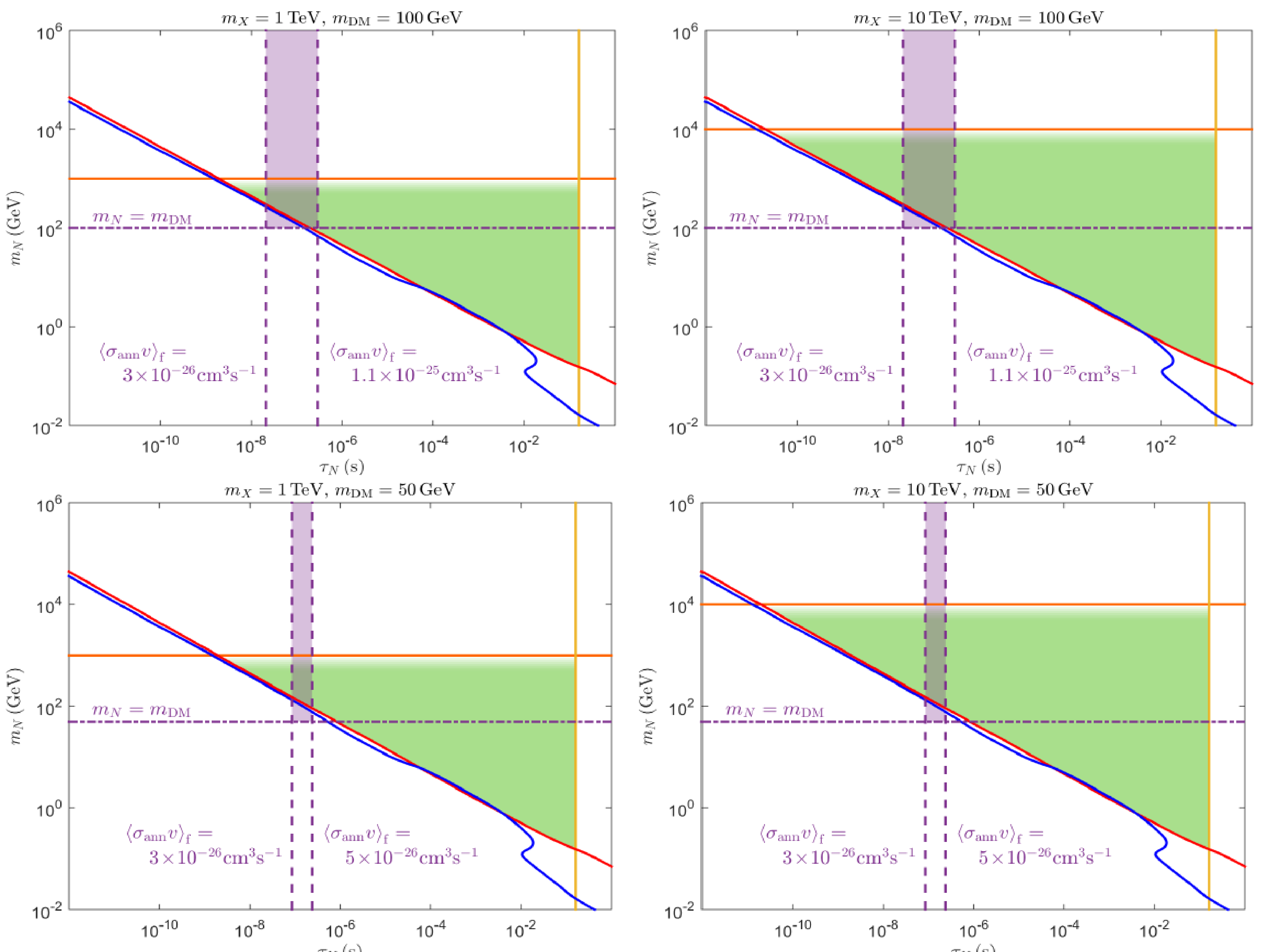
And for large annihilation rates too:

$$\left(\frac{n_{\rm DM}}{s}\right) = \frac{T_{\rm f}}{T_{\rm dec}} \times \frac{3\times 10^{-26}\ {\rm cm^3\ s^{-1}}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}} \times \left(\frac{n_{\rm DM}}{s}\right)_{\rm obs}$$

$$T_{\rm dec} = \frac{3\times 10^{-26}\ {\rm cm^3\ s^{-1}}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}} \times T_{\rm f}$$

$$T_{\rm f} \sim m_{\rm DM}/20$$





$m_X = 1\,\mathrm{TeV},\ m_{\mathrm{DM}} = 100\,\mathrm{GeV}$
$m_X = 10\,\mathrm{TeV},\ m_{\mathrm{DM}} = 100\,\mathrm{GeV}$
$m_X = 1\,\mathrm{TeV},\ m_{\mathrm{DM}} = 50\,\mathrm{GeV}$
$m_X = 10\,\mathrm{TeV},\ m_{\mathrm{DM}} = 50\,\mathrm{GeV}$
m_N (GeV)
τ_N (s)
$m_N = m_{\mathrm{DM}}$
$\langle\sigma_{\mathrm{ann}}v\rangle_{\mathrm{f}} = 3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$
$\langle\sigma_{\mathrm{ann}}v\rangle_{\mathrm{f}} = 1.1\times10^{-25}\mathrm{cm}^3\mathrm{s}^{-1}$
$\langle\sigma_{\mathrm{ann}}v\rangle_{\mathrm{f}} = 5\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

Prospects for LLP Searches:

N is an example of a neutral LLP.

N decay length at colliders is given by:

$$l_N = \bar{b} c \tau_N$$

The average boost factor from *X* decay is:

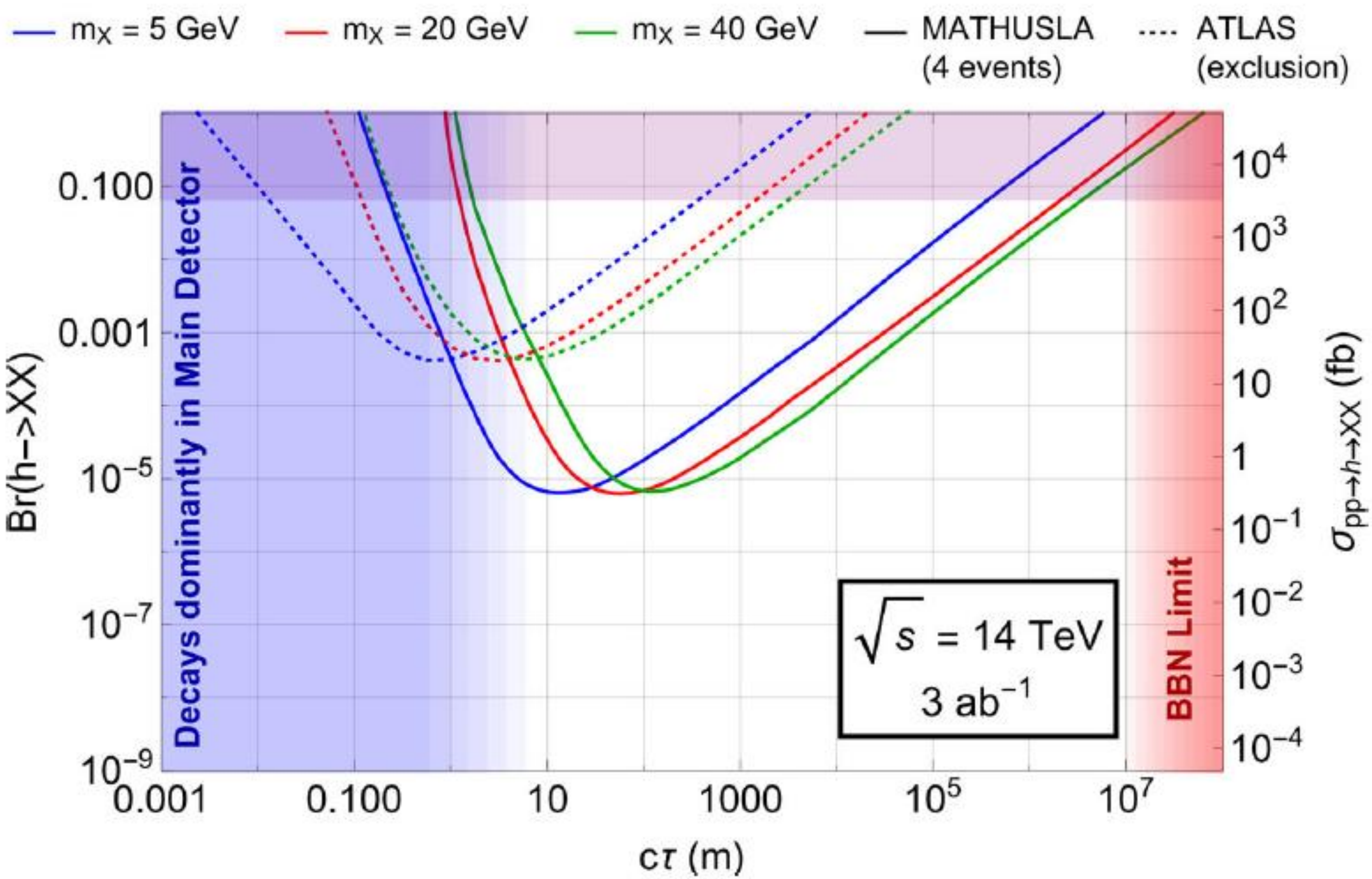
$$\bar{b} \sim m_X / 2 m_N$$

Neutral LLPs with $l_N > 100\ \mathrm{m}$ are difficult to be detected at the LHC main detectors.

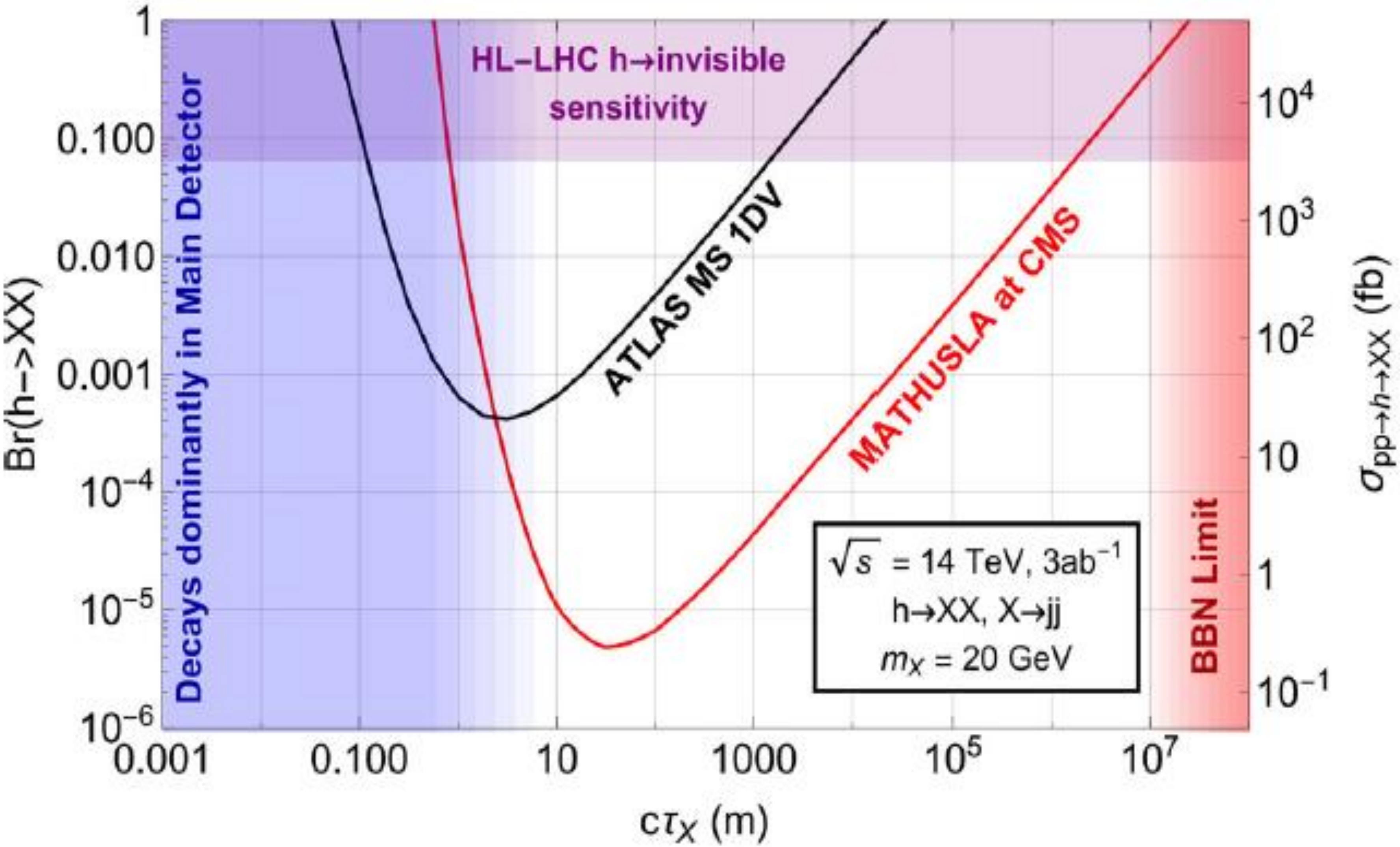
However, dedicated searches will look for LLPs with l_N corresponding to $\tau_N \sim 0.1\ \mathrm{sec}$.

Example: MATHUSLA (MAssive Timing Hodoscope for Ultra Stable neutraL pArticles).

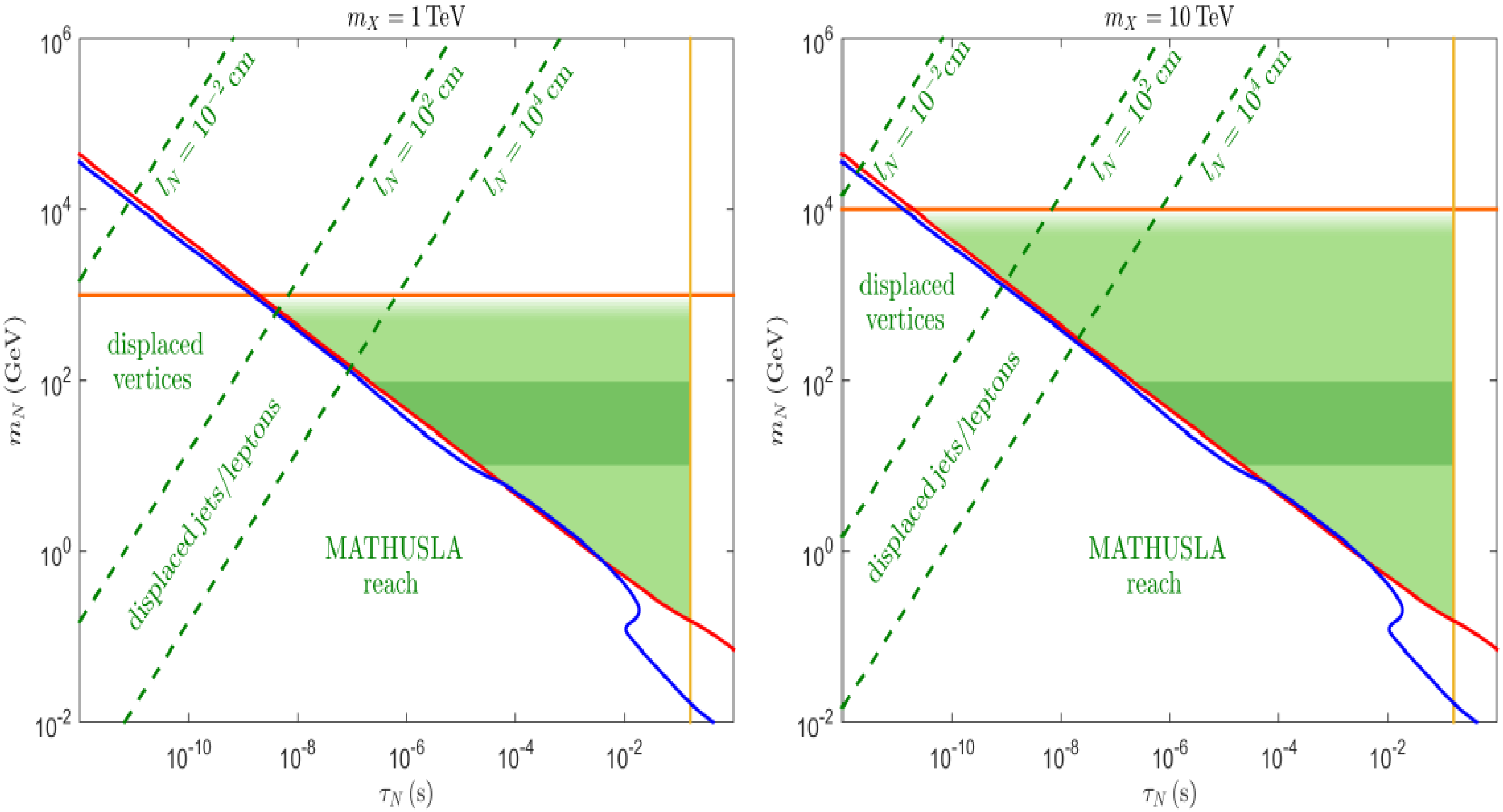
J. Chou, D. Curtin, H. Lubatti PLB 767, 29 (2017)



D. Curtin *et al* Rep. Prog. Physics 82, 116201 (2019)



MATHUSLA Collaboration 2009.01693 [physics.ins-det]



The dark shaded band corresponds to the most important MATHUSLA target for hadronically decaying LLPs.

It overlaps with the DM allowed regions!

In our case, X production and decay at the LHC must be studied.

The sensitivity curves must then be modified accordingly.

What are the implications of a detection in LLP searches?

τ_N is directly related to T_R :

$$T_R \sim (\Gamma_N M_P)^{1/2}$$

Highest temperature of the universe in the RD phase relevant for BBN!

m_N is related to the onset of EMD:

$$H_{\rm dom} \simeq \frac{4g_{*{\rm dom}}^{2/3}}{g_{*N}^{8/3}} H(T = m_N)$$

Duration of the preceding EMD phase!

Conclusion and Outlook:

- Nonstandard thermal histories with EMD are well motivated and have interesting consequences.
- A scenario of EMD from the visible sector can arise naturally in minimal extensions of the SM.
- A sub-TeV LLP can acquire thermal abundance and dominate the energy density of the universe.
- The scenario can accommodate the correct DM abundance, may also lead to baryogenesis.
- Proposed LLP searches, like MATHUSLA, can be used to reconstruct thermal history just prior to BBN.
- A detailed study needed: build explicit models, analyze the discovery prospect, embed in UV complete models.

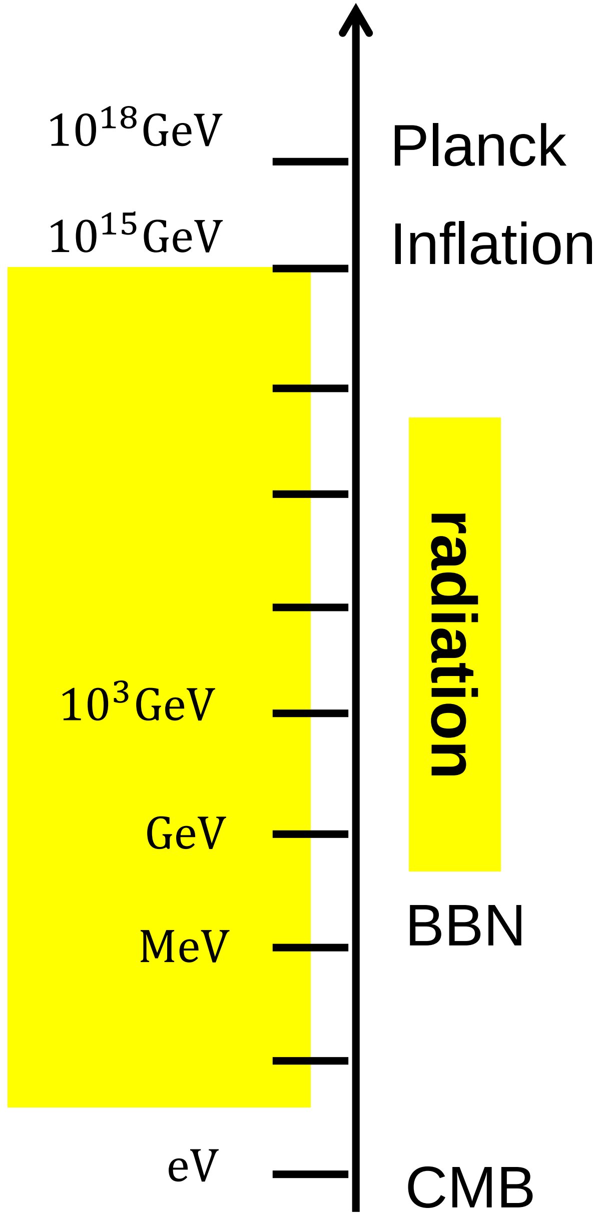
Backup Slides

What was the state of the universe before 1 second?

Standard thermal history:
Transition from inflation to hot big bang (reheating), RD phase all the way to BBN.

A simple extrapolation from observations, but an assumption.

Can we confirm or disprove it?



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

Thermal DM is an attractive scenario:

- Predictive
- Robust

However, it is coming under increasing pressure by DM searches.

What can theory tell us we about the thermal history?

We need particle physics models of the early universe that describe evolution from inflation all the way to BBN.

A class of well-motivated theories based on string constructions lead to nonstandard histories with EMD.

Studying alternatives thermal histories is well motivated.

Moduli decay reheats the universe and releases huge entropy:

$$\frac{s_{after}}{s_{before}} = \left(\frac{s_R}{s_0} \frac{a_R^3}{a_0^3} \right) = \left(\frac{\rho_R}{\rho_0} \frac{a_R^4}{a_0^4} \right)^{3/4}$$

$$\Gamma_\phi < H < m_\phi : \;\; a \propto t^{2/3}$$

$$\frac{s_{after}}{s_{before}} \sim \left(\frac{\rho_R}{\rho_0} \left(\frac{m_\phi}{\Gamma_\phi} \right)^{8/3} \right)^{3/4} \sim \frac{M_P}{m_\phi} \;\; (>> 10^{10})$$

Late reheating washes out any relic abundance generated prior to EMD.

Constraints:

(1) Obtaining the correct DM abundance.

$$\dot{n}_\chi + 3Hn_\chi = <\sigma_{ann} v>_f (n_{\chi,eq}^2 - n_\chi^2) + Br_\chi \Gamma_\phi n_\phi$$

Br_χ: number of DM quanta produced per decay of ϕ quanta

- Production from the instantaneous thermal bath (1st term on the RH).

G. Giudice, E. Kolb, A. Riotto PRD 64, 043512 (2001)

A. Erickcek PRD 92, 103505 (2015)

…

- Production from direct decay (2nd term on the RH).

G. Gelmini, P. Gondolo PRD 74, 023510 (2006)

R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)

…

- Production from the interplay between the two terms.

M. Kawasaki, T. Moroi, T. Yanagida PLB 370, 52 (1996)

T. Moroi, L. Randall NPB 570, 455 (2000)

…

(2) Generating the observed baryon asymmetry.

Recall the dilution factor due to modulus decay:

$$\left(\frac{s_{after}}{s_{before}}\right) \sim \frac{M_P}{m_\phi} \quad (>> 10^{10})$$

Any pre-existing asymmetry will be washed out.

- Baryogenesis at the end of EMD:

Non-thermal post-sphaleron baryogenesis

R.A., B. Dutta, K. Sinha PRD 81, 053538 (2010)

…

- Baryogenesis mechanism with associated entropy production:

Affleck-Dine baryogenesis

G. Kane, J. Shao, S. Watson, H-B Yu JCAP 1111, 012 (2011)

R.A., M. Cicoli, F. Muia JHEP 1606, 153 (2016)

…

(3) Gravitino production must be suppressed.

$\phi \to \tilde{G}\tilde{G}$ is the main source of gravitino production.

M. Endo, K. Hamaguchi, F. Takahashi PRL 96, 211301 (2006)

Helicity-1/2 gravitinos pose the main threat.

M. Dine, R. Kitano, A. Morisse, Y. Shirman PRD 73, 123518 (2006)

(4) Modulus decay must successfully reheat the visible sector.

No excess of DR, etc.

Challenge: successful realization in explicit models.

R.A., M. Cicoli, B. Dutta, K. Sinha PRD 88, 095015 (2013)

R.A., M. Cicoli, B. Dutta, K. Sinha JCAP 10, 002 (2014)

R.A., I. Broeckel, M. Cicoli, J. Osinski JHEP 02, 026 (2021)

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