Dark Matter and Baryogenesis from Long-Lived Particles in the Visible Sector

Rouzbeh Allahverdi

DEPARTMENT OF
PHYSICS & ASTRONOMY

Mitchell Conference on
Collider, Dark Matter, and Neutrino Physics 2023

MIFPA, Texas A&M University

May 16-19, 2023

Outline:

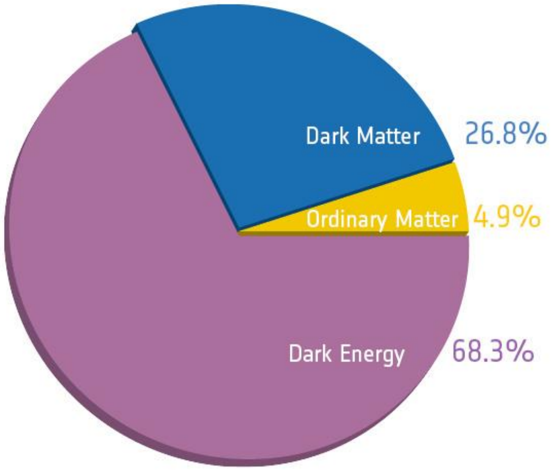
- Introduction
- Thermal histories with EMD
- The Model
- Results
- Conclusion

Based on:

R.A., N. Loc, J. Osinski 2212.11303 [hep-ph], PRD (in press)

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?

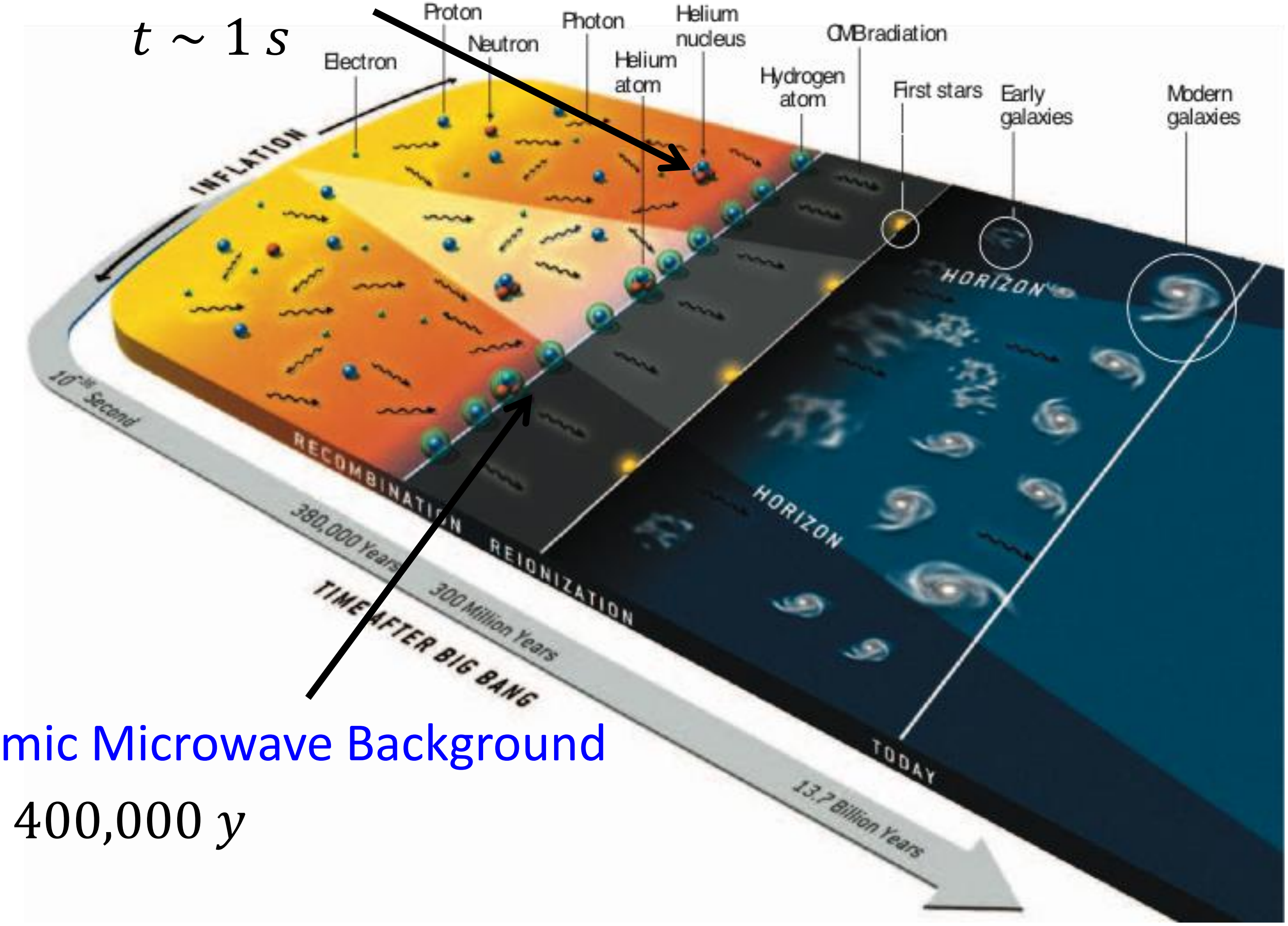
→ Particle Physics (BSM) + Cosmology (thermal history)

What do we know about the early universe?

Observational probes of the early universe:

Big Bang Nucleosynthesis

$t \sim 1\, s$



Cosmic Microwave Background

$t \sim 400{,}000\ y$

What was the state of the universe before 1 second?

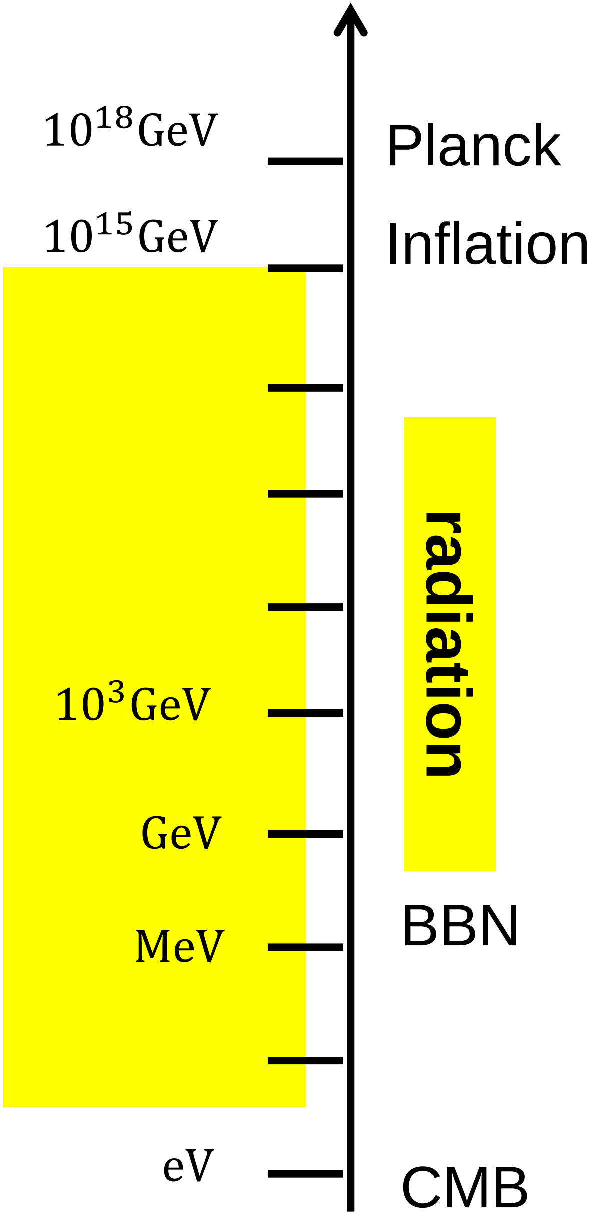
Standard thermal history:
Transition from inflation to hot big bang (reheating), then RD all the way to BBN.

Simple extrapolation from observations.
Predictive (thermal DM), but an assumption.

Under increasing scrutiny by experiment.
Hints/guidance from theory?

Alternative thermal histories!

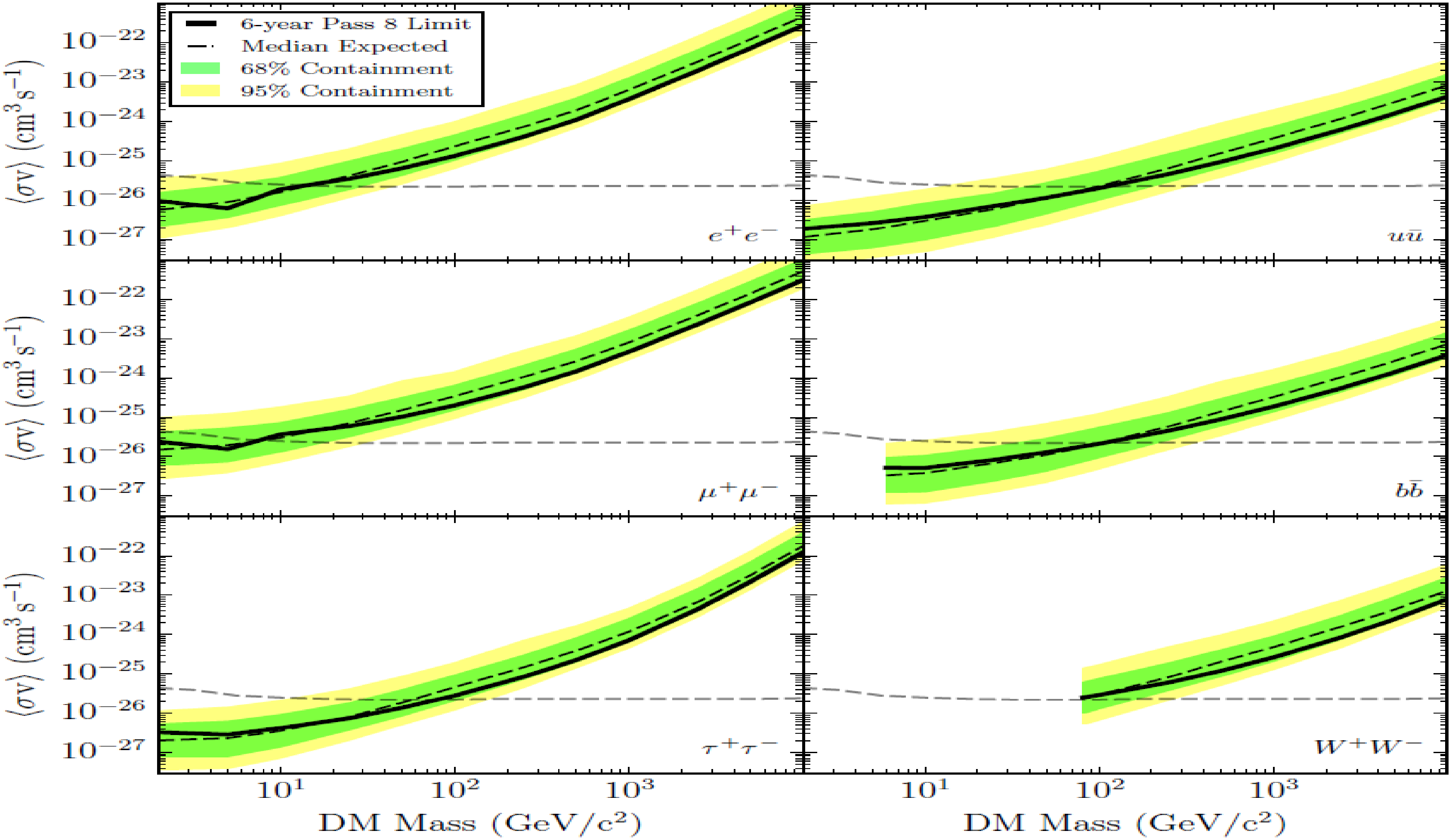
"The First Three Seconds" 2006.16182 [astro-ph.CO]



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

Indirect detection experiments:

Fermi Collaboration PRL 115, 231301 (2015)



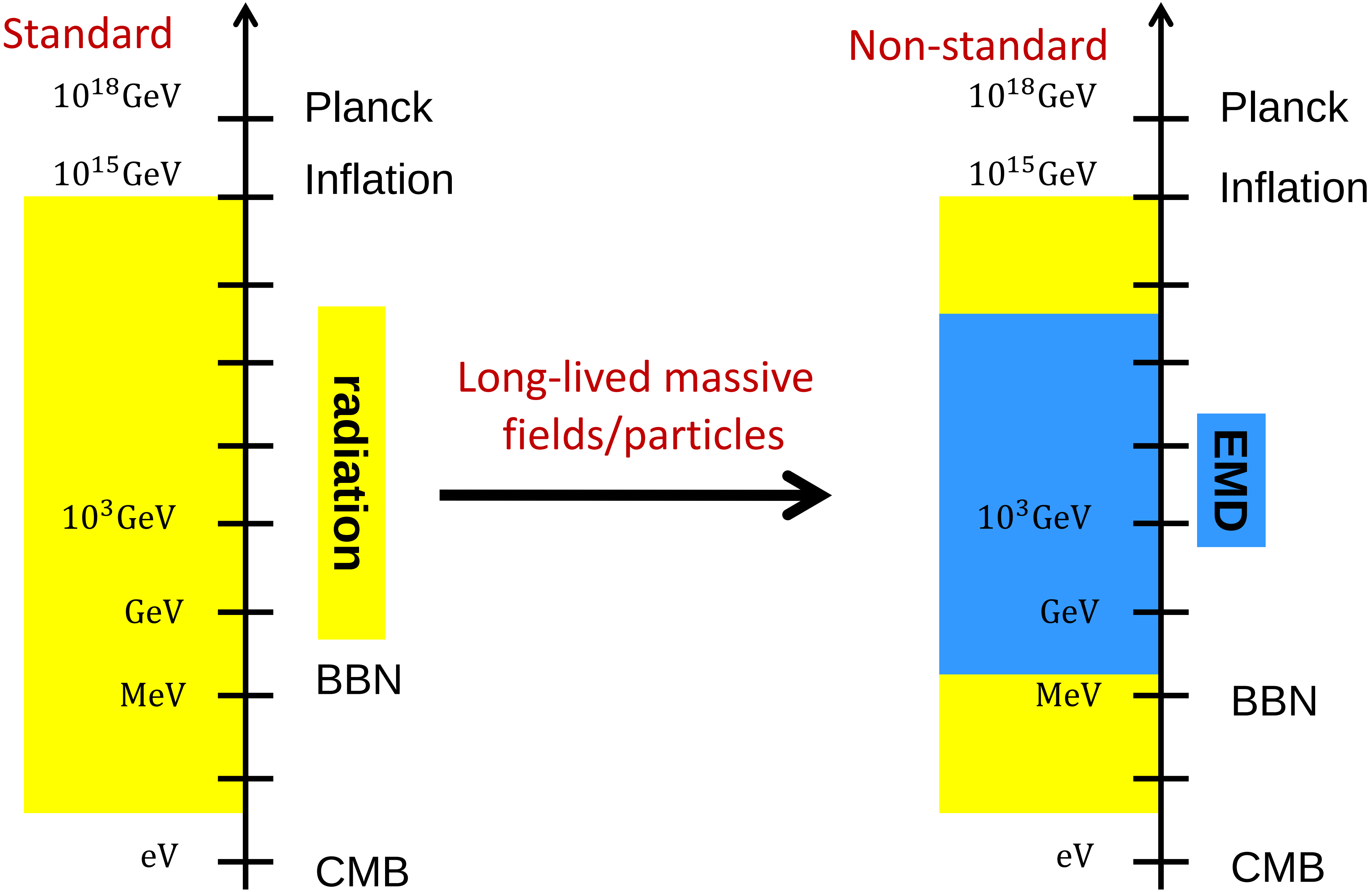
For DM masses *< 20 GeV*:

$$<\sigma_{ann} v>_f \ < 3\times10^{-26}\ cm^3 s^{-1}$$

(assuming S-wave annihilation)

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

A well-motivated alternative thermal history:



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 of 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

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

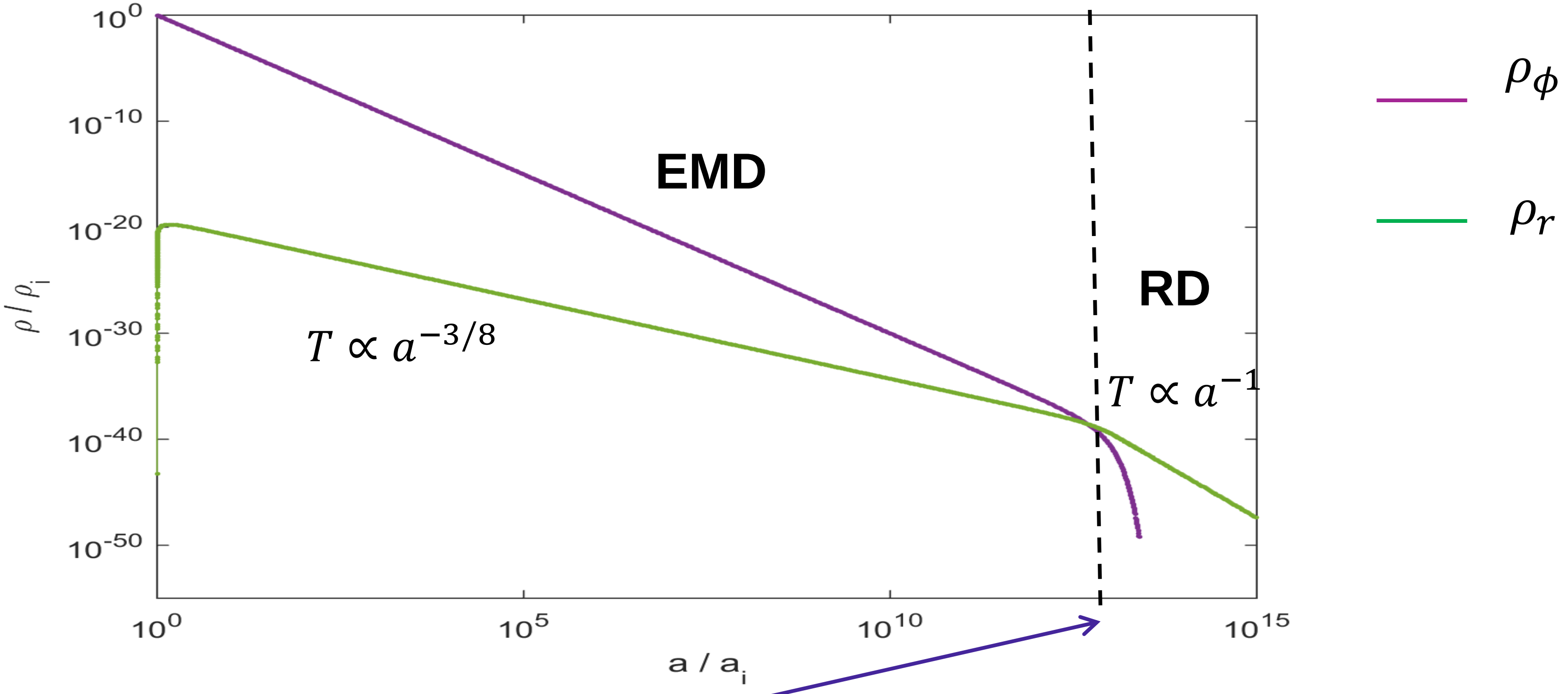
Evolution of matter and radiation energy densities:

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

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

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

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



BBN requires that:

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

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.

$\phi \to \tilde{G}\tilde{G}$ 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?

Can naturally address the gravitino and DR production issues!

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

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

$$\mathcal{L}_{new} \supset hXN\psi + h' X^* \psi\psi + h.c.$$

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

ψ: SM fermions

X: Scalar with SM charges

$$m_N \ll m_X$$

N: SM singlet Majorana fermion

The Model:

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

R.A., N. Loc, J. Osinski 2212.11303 [hep-ph], PRD (in press)

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

N, χ: SM singlet Majorana fermions $m_\chi \approx m_p \ll m_N \ll m_X$

u, d: Right-handed up-type and down-type quarks

Supersymmetric version without χ : to address DM and baryogenesis.

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

Model without χ : EMD driven by N .

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

Model with no N : natural GeV DM if $m_p - m_e \leq m_\chi \leq m_p + m_e$.

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

Thermal overproduction ⟶ nonthermal mechanism needed.

N can drive an epoch of EMD!

Assuming RD at $T \gtrsim m_X$:

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

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

(2) $H(T = m_N) \lesssim H \lesssim H(T = m_X)$

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

(3) $H_{dom} \lesssim H \lesssim H(T = m_X)$

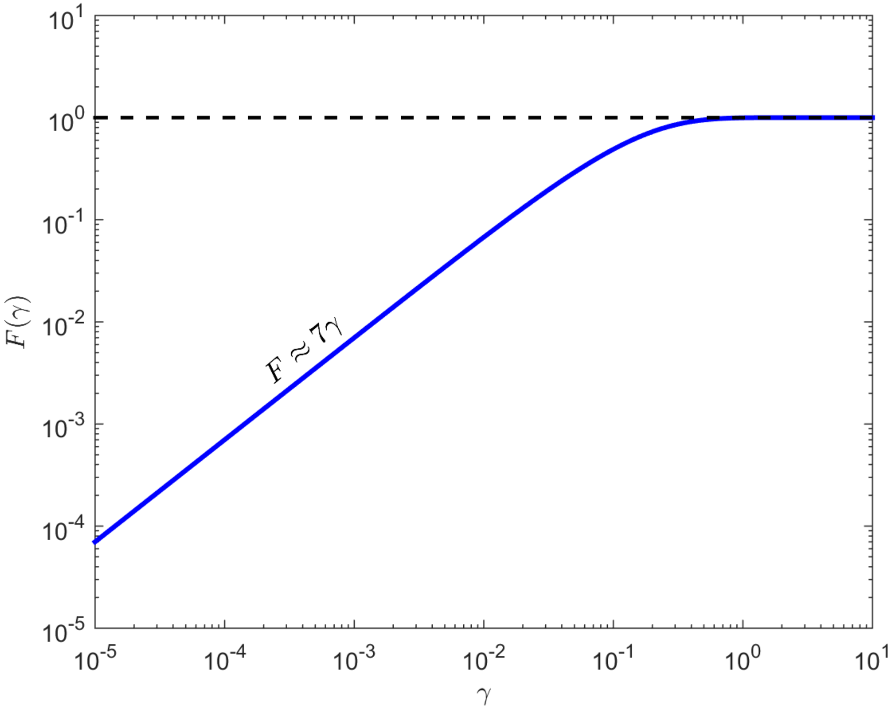
RD: *N* becomes nonrelativistic, starts to dominate radiation.

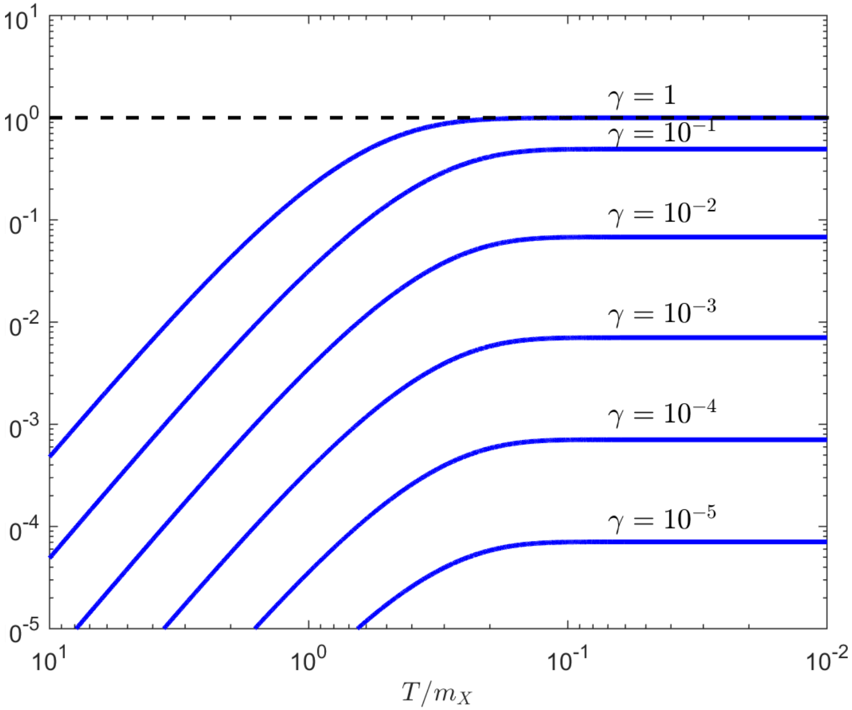
(4) $\Gamma_N \lesssim H \lesssim H_{dom}$

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

$$F_{N,\chi}(\gamma_{N,\chi}, T) \equiv \frac{n_{N,\chi}}{n_{N,\chi}^{eq}}$$

$$\gamma_{N,\chi} \equiv \frac{\Gamma_{X\to N,\chi}}{H(T = m_X)}$$





Necessary conditions for having an EMD epoch:

- *N* must reach equilibrium:

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

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

$$\Gamma_{NN\to u\bar{u}} < H(T = m_N)$$

$$\Gamma_{Nq\to \bar{q}\bar{q}} < H(T = m_N)$$

- *N* must dominate before decaying:

$$\Gamma_N \lesssim H_{dom}$$

- *N* decay must happen before BBN:

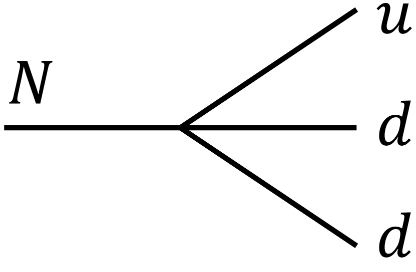
$$\Gamma_N \gtrsim H_{BBN} \sim 10\, s^{-1}$$

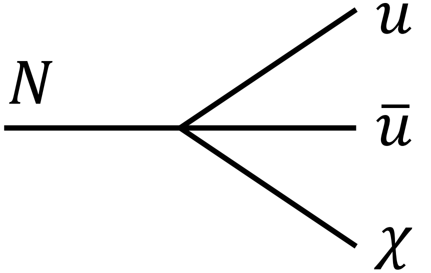
Dilution factor: $d \simeq 10^{-2} F(\gamma_N) \dfrac{m_N}{T_R}$

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

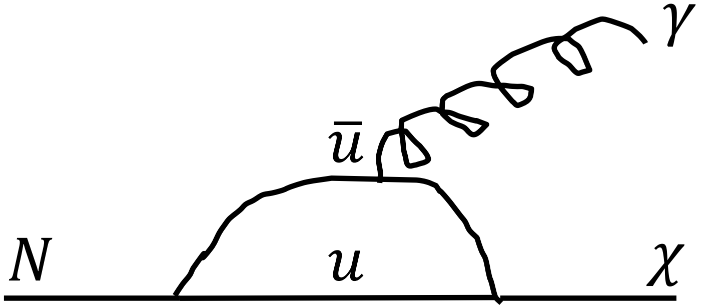
$$\Gamma_N = \Gamma_N^{2-body} + \Gamma_N^{3-body}$$

$$\Gamma_N^{3-body} \simeq 12 \times \frac{h^2 h'^2}{128 \times 192\pi^3} \frac{m_N^5}{m_X^4}$$





$$\Gamma_N^{2-body} \simeq \alpha_{em} \times \frac{h^2 h''^2}{32\pi^4} \frac{m_N^3}{m_X^2}$$



$$\Gamma_{NN\to u\bar{u}} \simeq 3 \times \frac{h^4}{16\pi} \frac{E^2}{m_X^4} n_N$$

$$\Gamma_{Nq\to \bar{q}\bar{q}} \simeq 18 \times \frac{h^2 h'^2}{16\pi} \frac{E^2}{m_X^4} n_q$$

DM relic abundance:

$$\frac{n_\chi}{s} \approx \frac{4 \times 10^{-3} F(\gamma_\chi)}{d} + Br_{N\to\chi} Y_N \approx 5 \times 10^{-10}$$

X decay & dilution by EMD

N decay

Desired value

$$Y_N \equiv \frac{3T_R}{4m_N}$$

$$d \simeq 10^{-2} F(\gamma_N) \frac{m_N}{T_R} \qquad\qquad Br_{N\to\chi} \equiv \frac{\Gamma_{N\to u\bar{u}\chi} + \Gamma_{N\to\chi\gamma}}{\Gamma_N}$$

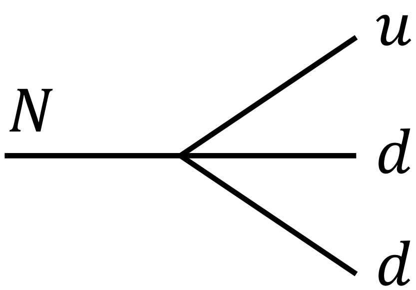
For $m_N \lesssim O(TeV)$, we need:

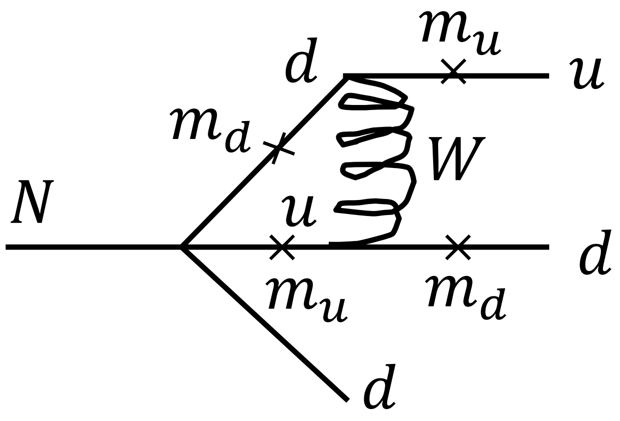
$$F(\gamma_\chi) \ll 1 \qquad\qquad Br_{N\to\chi} \ll 1 \qquad\qquad \longrightarrow$$

Freeze-in production

Baryon asymmetry:

Three-body decays with the help of electroweak loops:





$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \epsilon_B Y_N \frac{\Gamma_{N\to udd} + \Gamma_{N\to\bar{u}\bar{d}\bar{d}}}{\Gamma_N} \approx 9 \times 10^{-11}$$

$$\epsilon_B \sim \frac{\alpha_2}{4} \frac{m_c m_s m_t m_b}{m_W^2 m_N^2}$$

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

The maximum asymmetry is obtained for $m_N \sim 100\ GeV$.

Prospects for LLP searches:

N is an example of a neutral LLP.

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)

The most important MATHUSLA target: hadronically decaying LLPs with mass in the 10-100 GeV range.

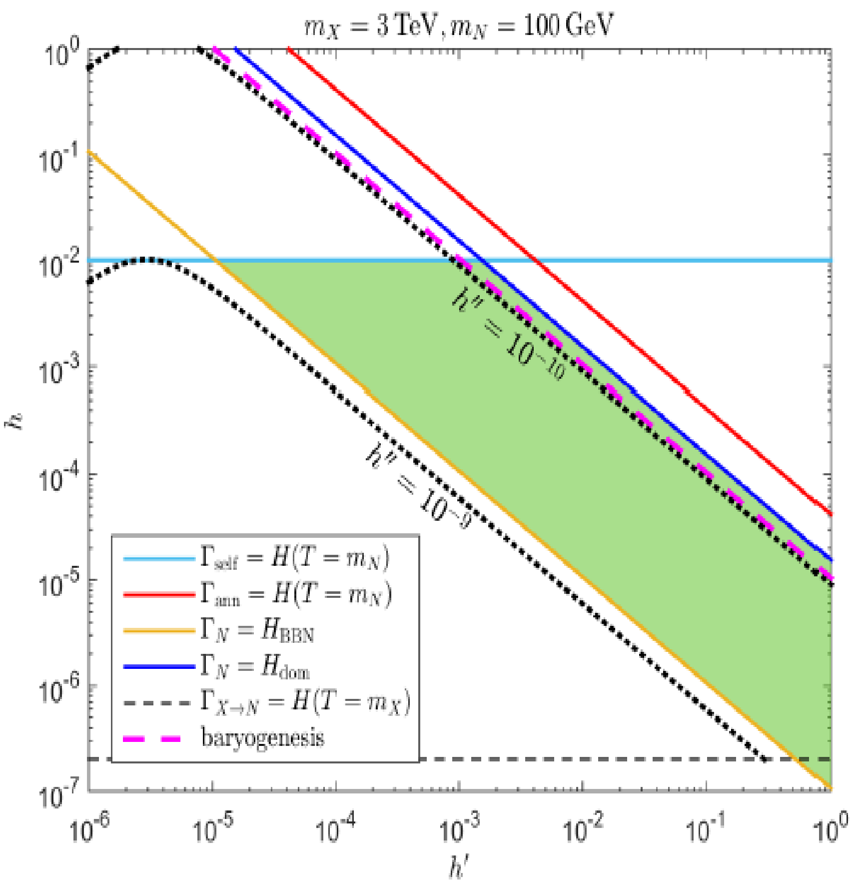
C. Alpigiani et al. [MATHUSLA Collaboration] 2009.01693 [physics.ins-det]

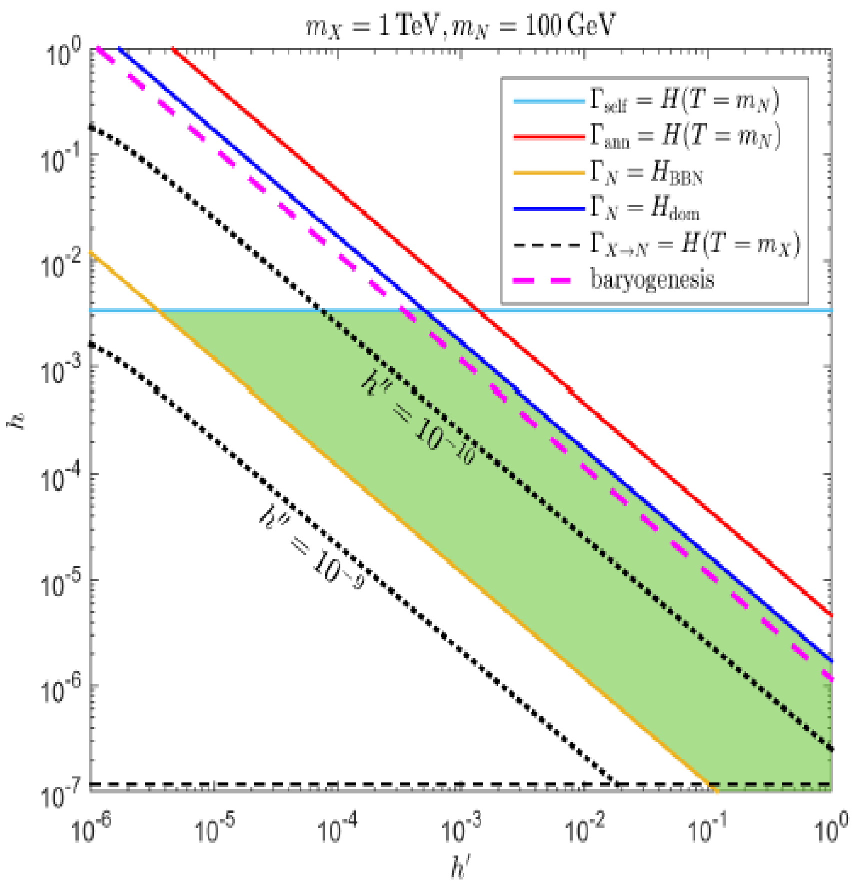
Our N nicely lies in this region!

Results:

The allowed parameter space (DM and baryogenesis only):

R.A., N. Loc, J. Osinski 2212.11303 [hep-ph]





Corresponding decay length of *N*:

$$4 \times 10^3\, m \lesssim l_N \lesssim 1.5 \times 10^8\, m$$

$$1.6 \times 10^3\, m \lesssim l_N \lesssim 6 \times 10^7\, m$$

Low energy probes: $\Delta B = 2$ processes.

(1) Double proton decay.

$$\tau_{pp\to K^+K^+} > 1.7 \times 10^{32} y$$

P. S. B. Dev, R. N. Mohapatra Phys. Rev. D 92, 016007 (2015)

$$h_1 h'_{12} \lesssim 3 \times 10^{-6} \quad (m_X = 3\ TeV, m_N = 100\ GeV)$$

$$h_1 h'_{12} \lesssim 3 \times 10^{-7} \quad (m_X = 1\ TeV, m_N = 100\ GeV)$$

(2) Neutron-antineutron oscillations.

$$3 \times 10^{8}\ s \leq \tau_{n-\bar{n}} \leq 5 \times 10^{10} s$$

current limit

next generation experiments

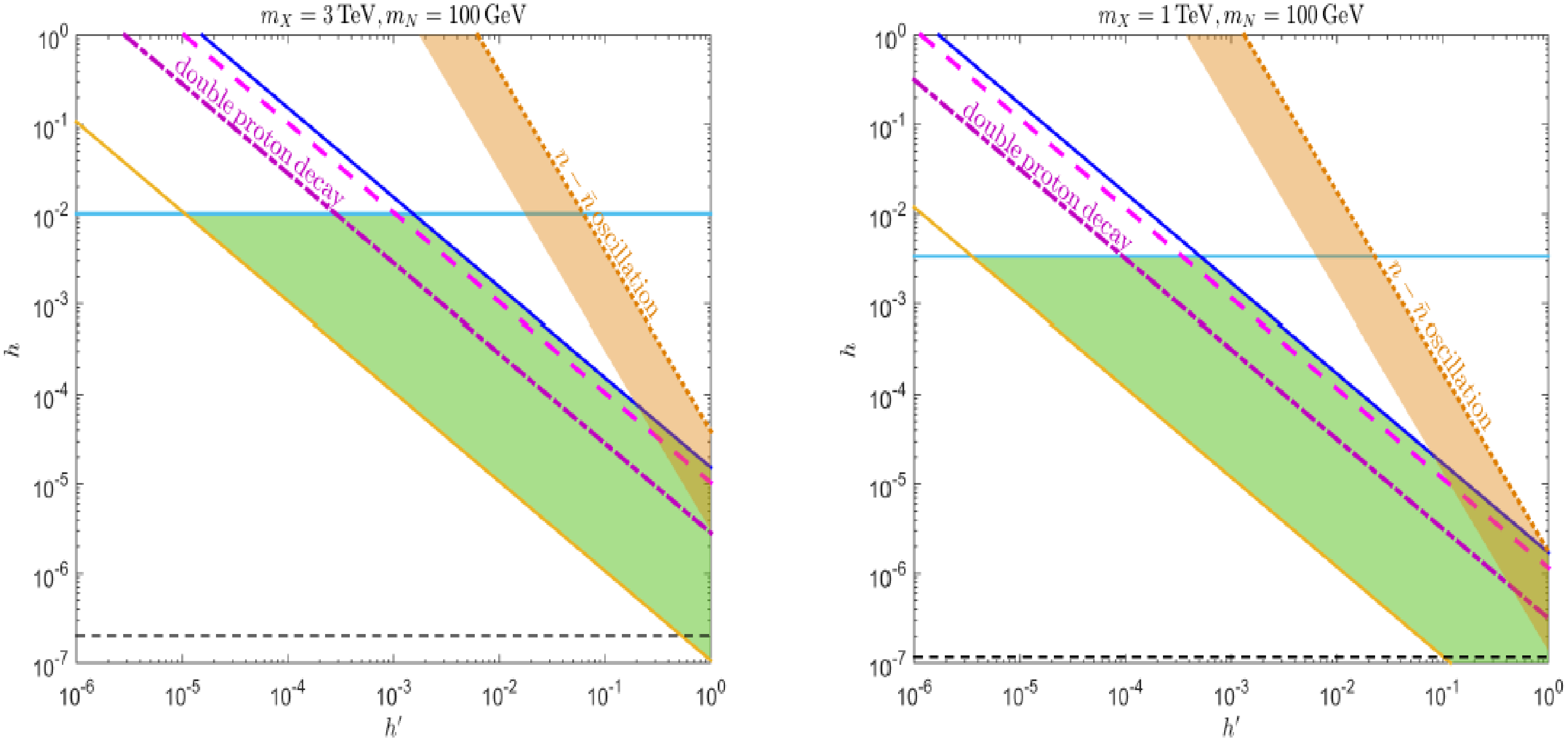
R. A., P. S. B. Dev, B. Dutta Phys. Lett. B 779, 262 (2018)

$$3 \times 10^{-6} \lesssim h_1 h'^2_{13} \lesssim 4 \times 10^{-5} \quad (m_X = 3\ TeV, m_N = 100\ GeV)$$

$$10^{-7} \lesssim h_1 h'^2_{13} \lesssim 2 \times 10^{-6} \qquad (m_X = 1\ TeV, m_N = 100\ GeV)$$

The allowed parameter space (low energy constraints added):

R.A., N. Loc, J. Osinski 2212.11303 [hep-ph]



All requirements and bounds can be satisfied simultaneously.

The small *h* and large *h'* corner is particularly predictive!

Conclusion:

- Nonstandard thermal histories with EMD are well motivated.
- EMD may be driven by LLPs in the visible sector.
- An explicit model with a hadronically decaying LLP presented.
- It can lead to the correct DM abundance and successful baryogenesis.
- It can be probed by the proposed LLP searches like MATHUSLA.
- It is also within the reach of future $n - \bar{n}$ oscillation experiments.