Early Matter Domination from LLPs in the Visible Sector

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arXiv:2108.13136

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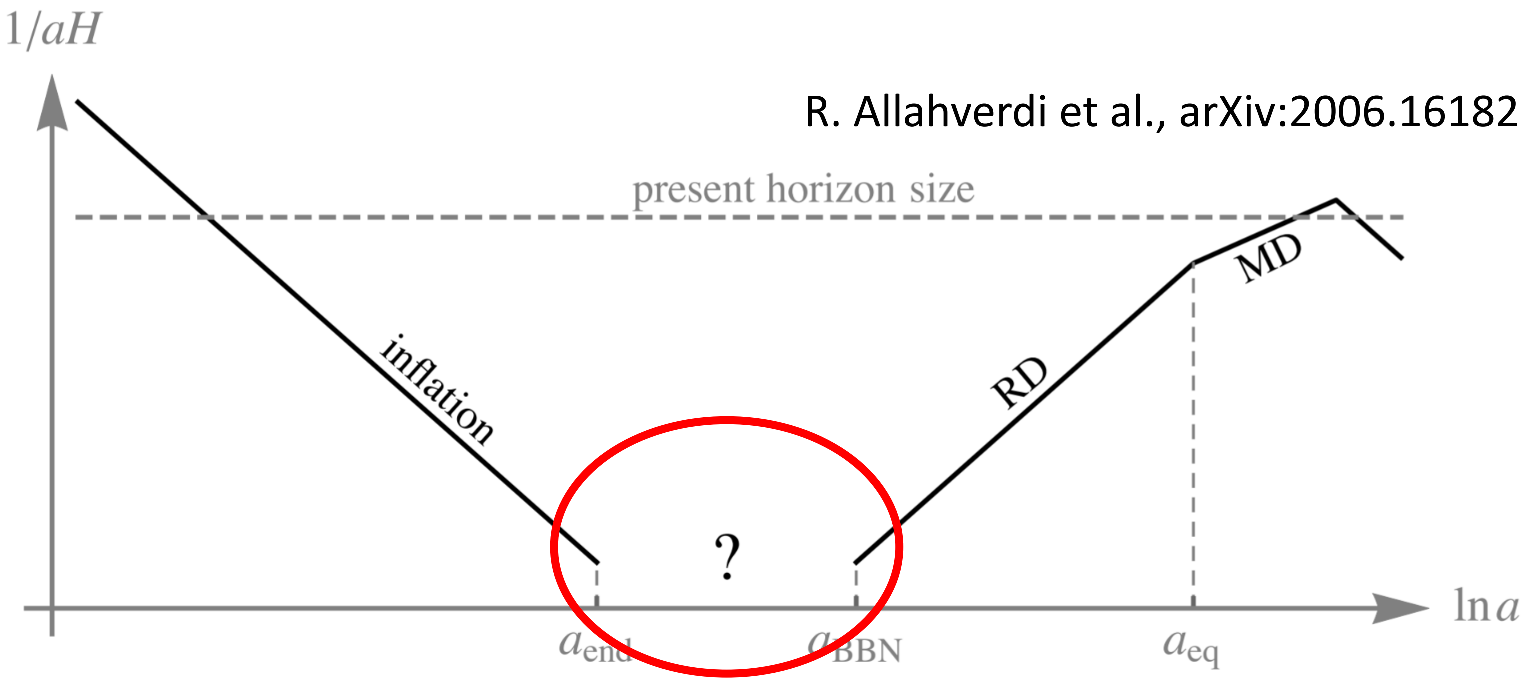
Early matter domination (EMD)

- History between inflation and BBN unknown
- Standard assumption is radiation domination (RD)
- EMD well-motivated class of nonstandard expansion (inflationary reheating, decoupled heavy particles, moduli, primordial black holes, ...)
- Constrained by BBN (must recover RD before $T \sim \mathrm{MeV}$)

- Can be probed with cosmological observations and DM indirect detection
- What about colliders?



R. Allahverdi et al., arXiv:2006.16182

The scenario

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

- *X* : scalar with Standard Model (SM) charges
- *N* : SM singlet (Majorana fermion) – the LLP
- ψ : SM fermions

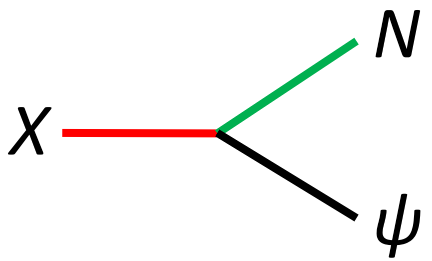
$m_X \gtrsim 1$ TeV
$m_N \sim$ weak
$m_N \ll m_X$

- Effective four-fermion interaction at low energies ($E \ll m_X$):

$$hh'^\dagger N\psi\psi\psi/m_X^2$$

- *X* starts in thermal equilibrium, decays to *N* which acquires thermal abundance, *N* freezes-out, dominates, and decays to SM with long lifetime → 5 conditions needed
- Can also accommodate observed dark matter relic abundance

Stages of the scenario's history



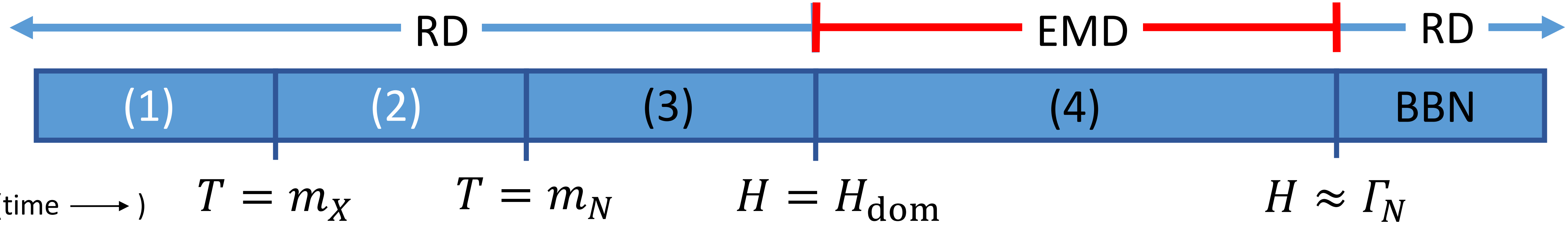
$$\mathbf{(1)}\ H \gtrsim H(T = m_X)$$

- Start RD at some high temperature
- *X* in thermal equilibrium due to interactions with SM
- *N* acquires thermal abundance from X decay, provided that:

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

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

- *N* is relativistic and in equilibrium



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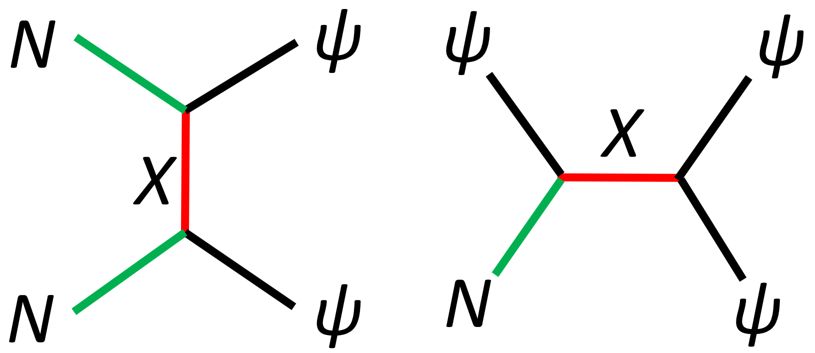


$$\textbf{(3)}\ \ H(T = m_N) > H \gtrsim H_{\text{dom}}$$

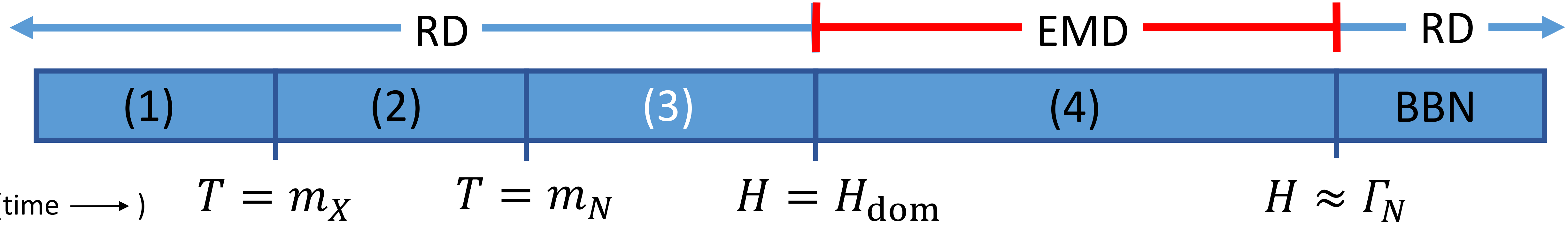
- *N* becomes nonrelativistic and freezes-out provided that scatterings/annihilations are inefficient:

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

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

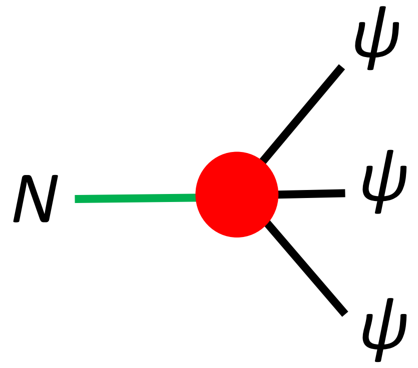
- *N* dominates over radiation, provided that lifetime is long enough:

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



Stages of the scenario's history

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

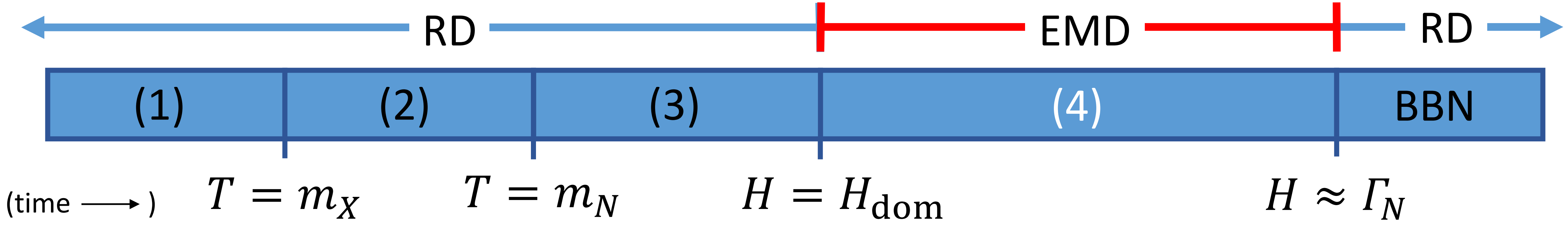


- EMD period driven by *N*, diluting prior abundances
- Must end before BBN, limiting *N* lifetime:

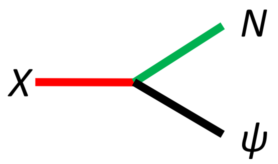
$$T_{\rm BBN} \simeq 4\ {\rm MeV}$$

T. Hasegawa et al., arXiv:1908.10189
P.F. de Salas et al., arXiv:1511.00672

$$\Gamma_N \gtrsim H_{\rm BBN} \sim \mathcal{O}(10)\ {\rm s}^{-1}$$

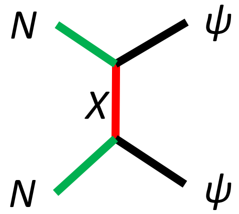


Conditions for successful scenario



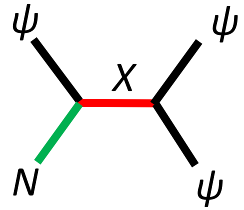
- *N* reaches equilibrium early on:

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



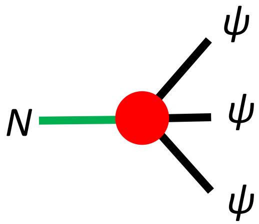
- *N* doesn't maintain equilibrium for too long:

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



- Long enough lifetime to dominate energy density:

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

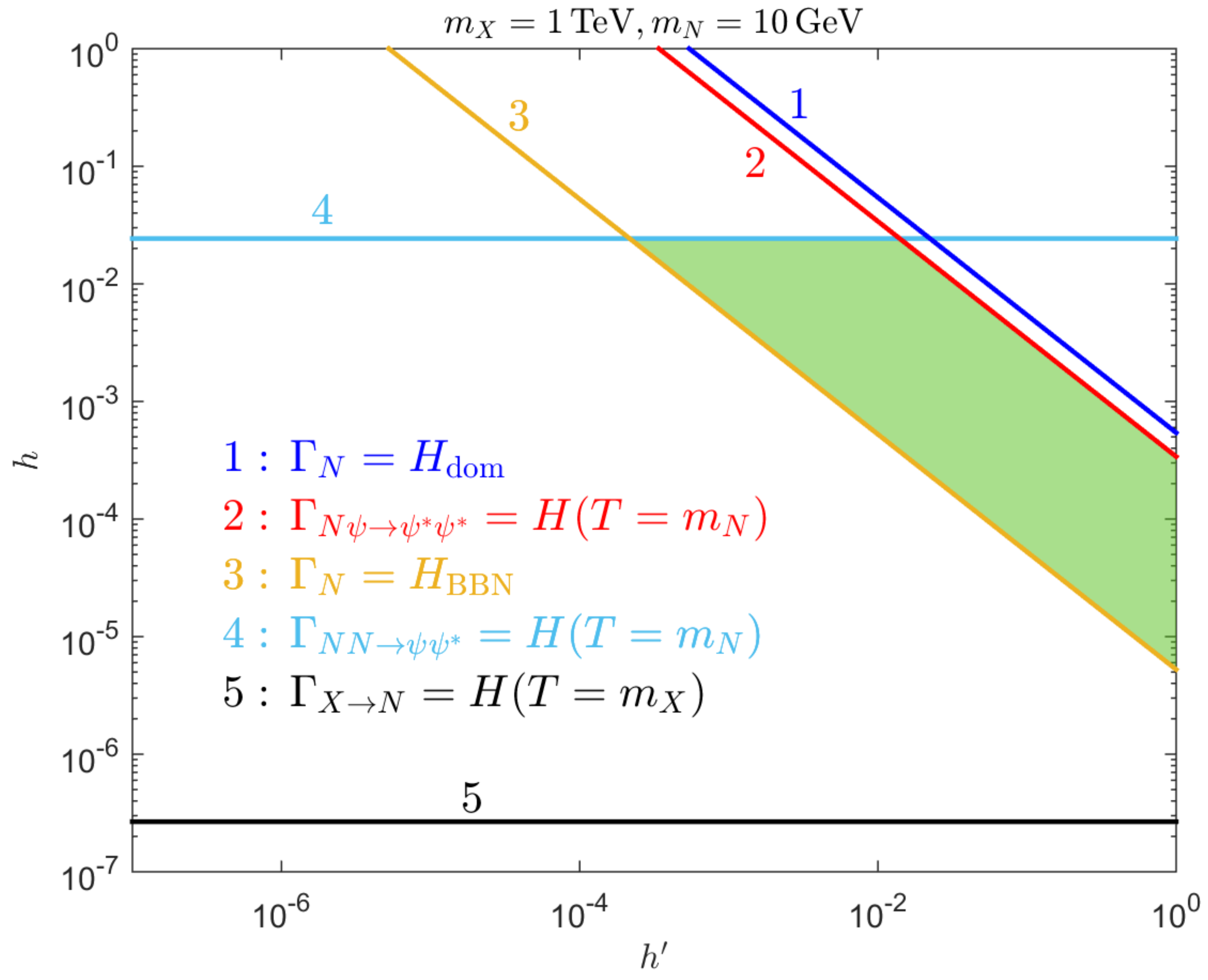


- But not too long… (BBN):

$$\Gamma_N \gtrsim H_{\rm BBN} \sim \mathcal{O}(10)\ \mathrm{s}^{-1}$$

- They can all be met simultaneously!

Allowed parameter space – couplings



$$\Gamma_{X\to N} \sim |h|^2 m_X$$

$$\Gamma_{NN\to\psi\psi^*} \sim |h|^4 \frac{m_N^5}{m_X^4}$$

$$\Gamma_{N\psi\to\psi^*\psi^*} \sim |h|^2 |h'|^2 \frac{m_N^5}{m_X^4}$$

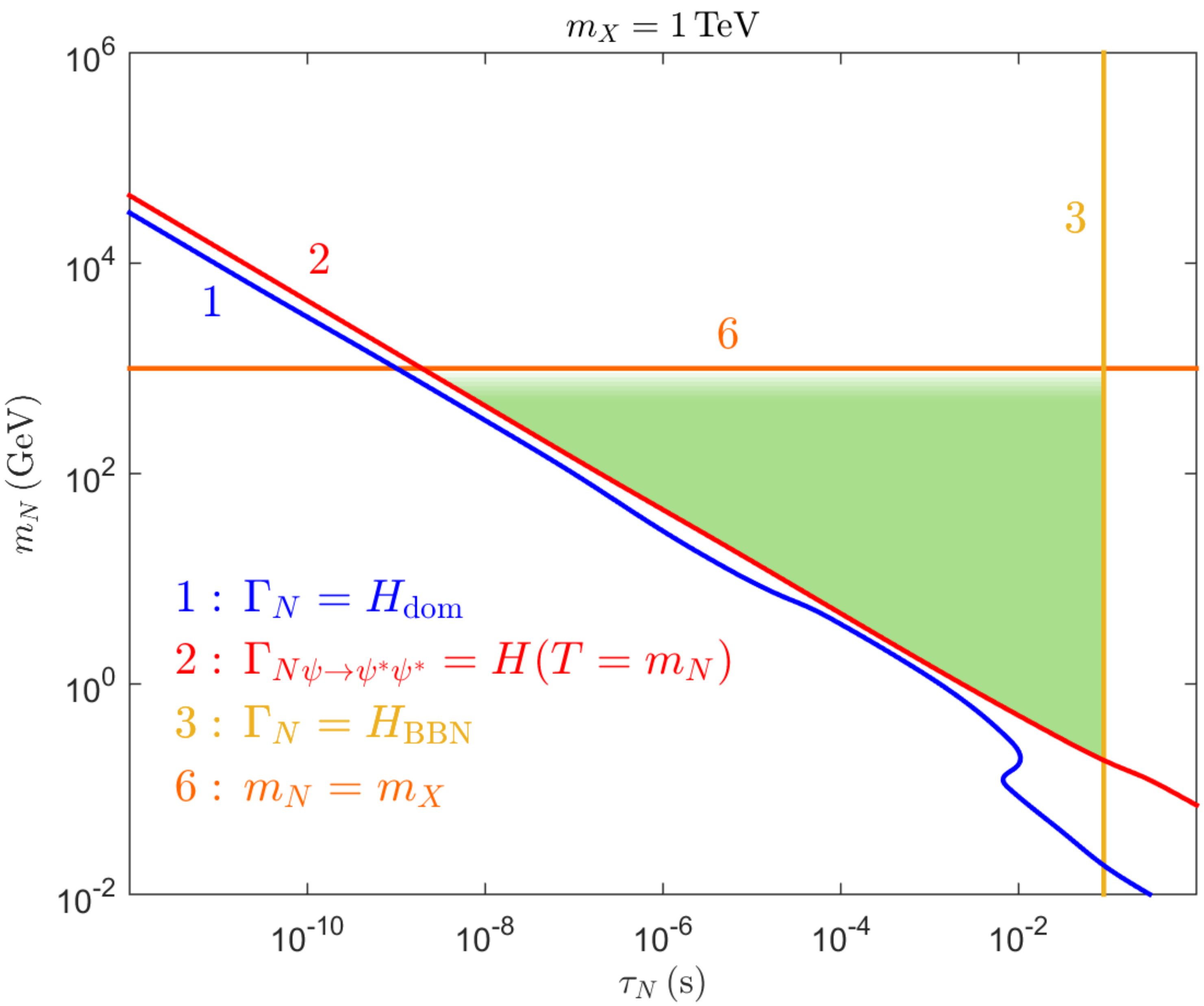
$$\Gamma_N \sim |h|^2 |h'|^2 \frac{m_N^5}{m_X^4}$$

Similar allowed region for

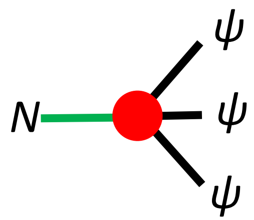
$m_X = 1 - 10$ TeV

$m_N = 10$ GeV $- 1$ TeV

Main parameter space of interest – mass vs lifetime



$\tau_N \equiv \Gamma_N^{-1}$



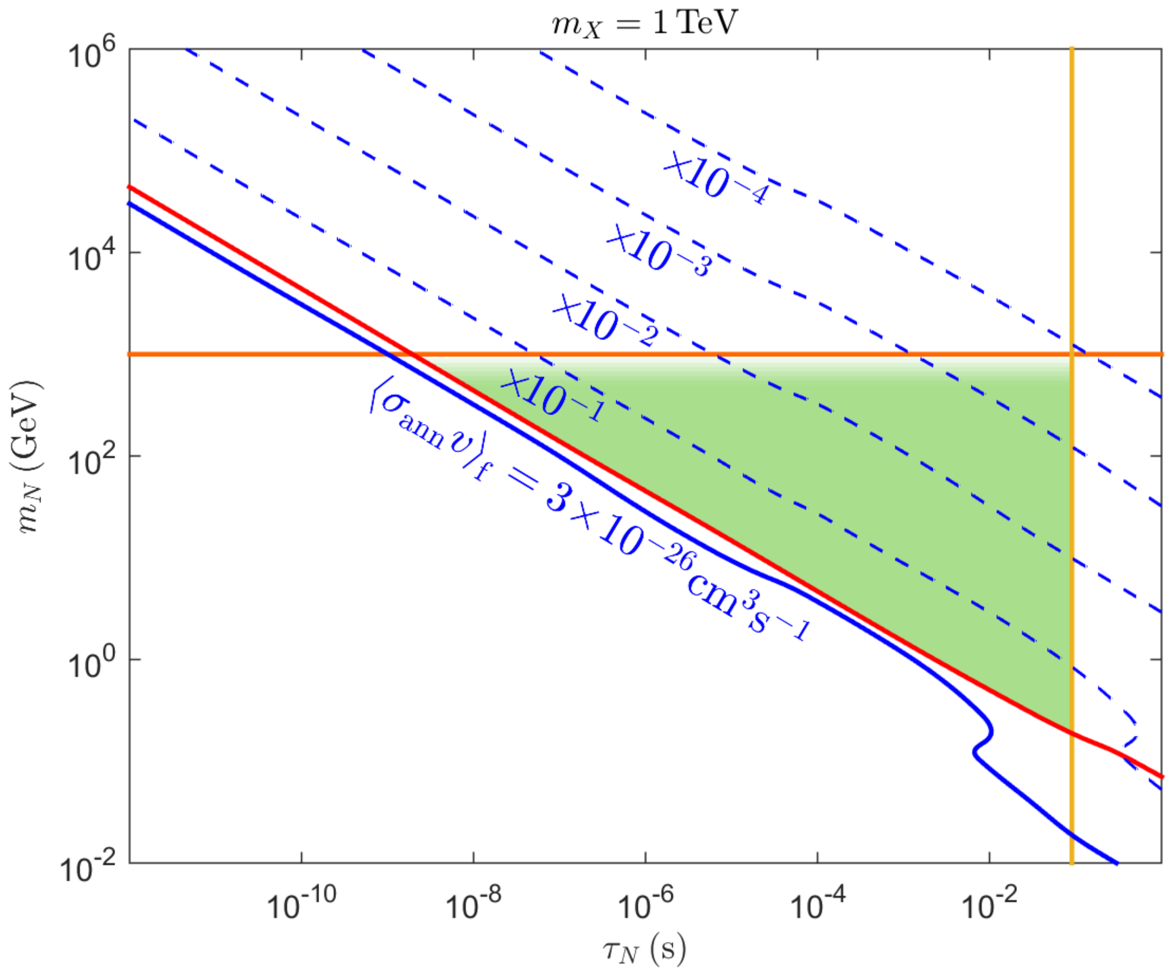
(three-body decay of *N* –> SM fermions)

Only dependence on m_X is in $m_N = m_X$ line

Implications for dark matter (DM)

- Scenario can accommodate DM abundance for both large and small annihilation rates (relative to thermal WIMPs)

- Small: $\langle \sigma_{\rm ann} v \rangle_{\rm f} < 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$
- Thermal overproduction in standard RD history
- If $m_N < m_{\rm DM}$, DM freezes-out prior to EMD and gets diluted



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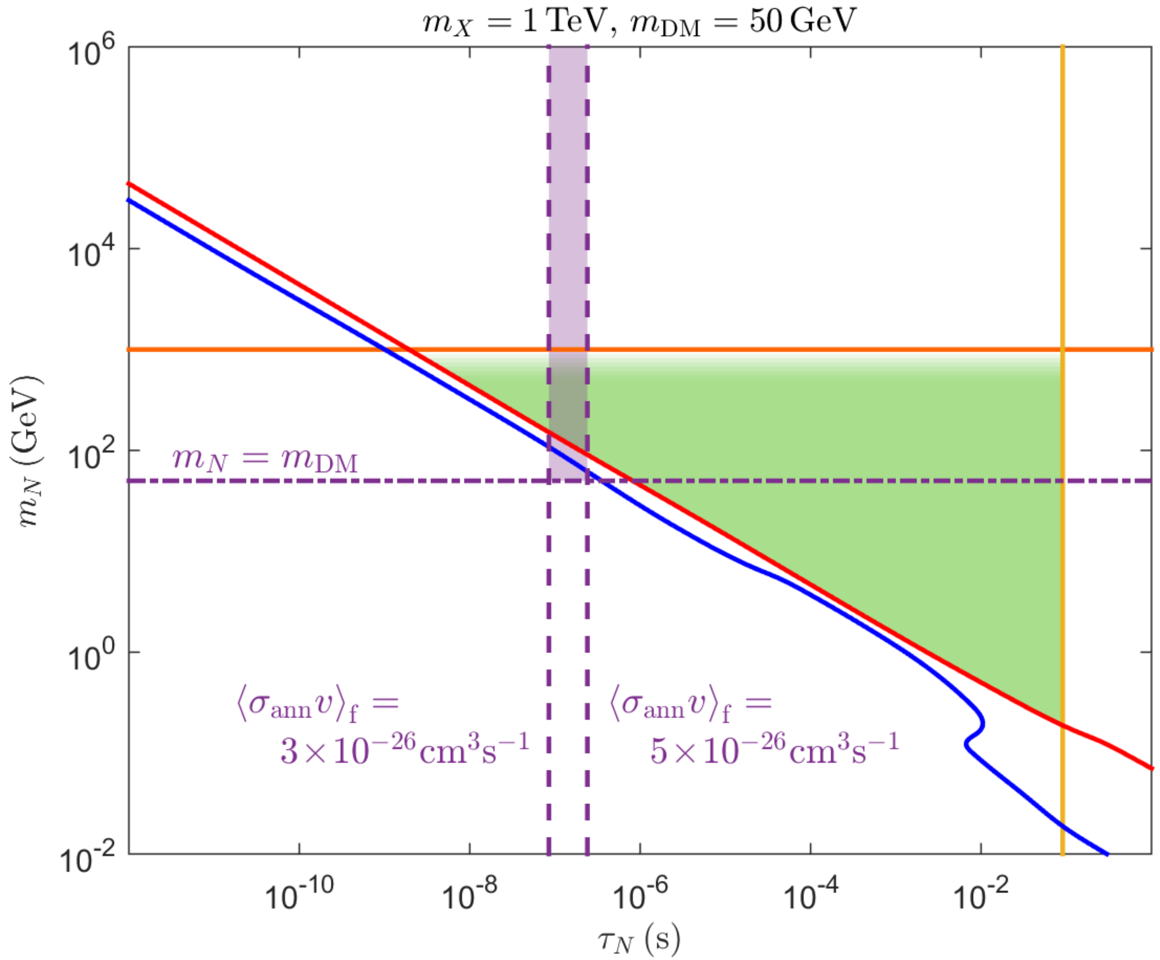

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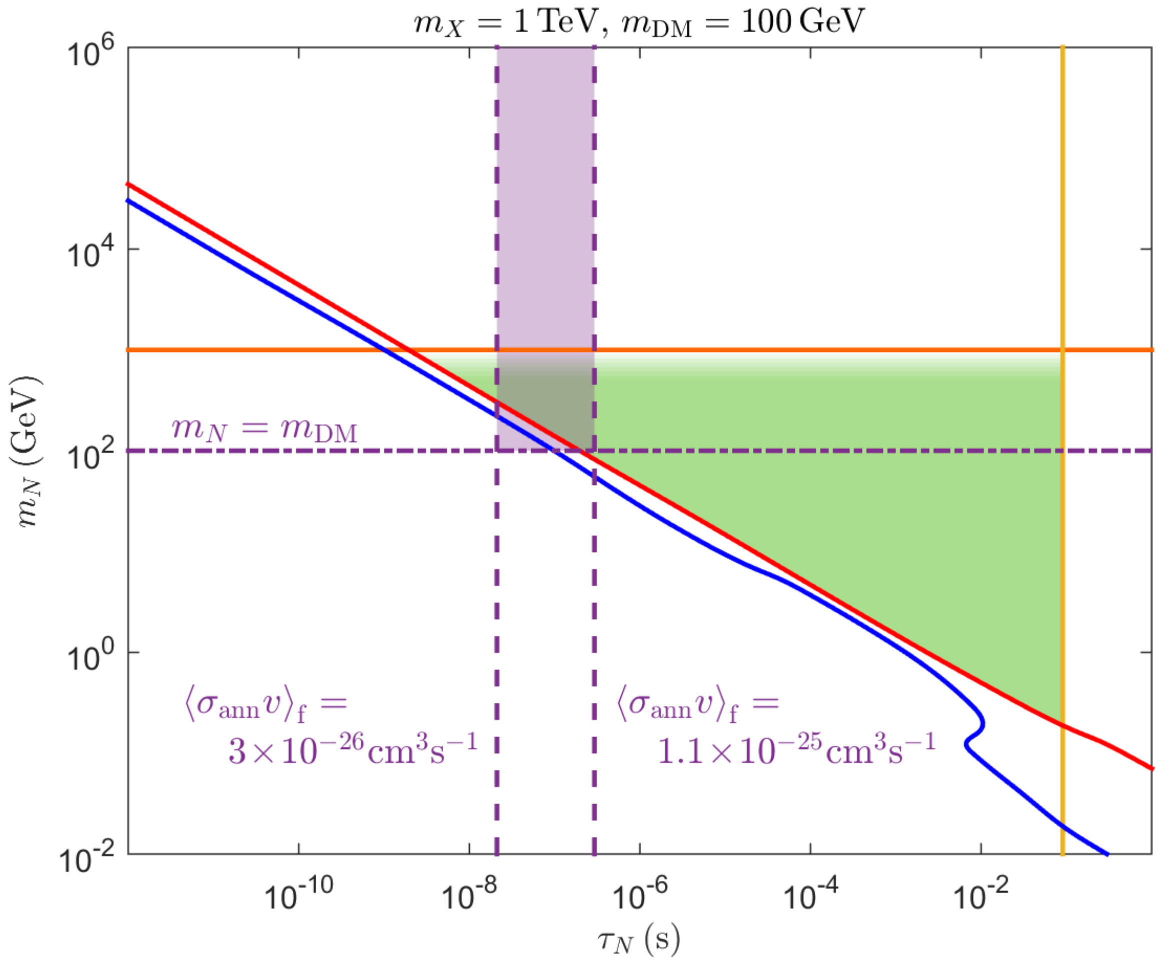

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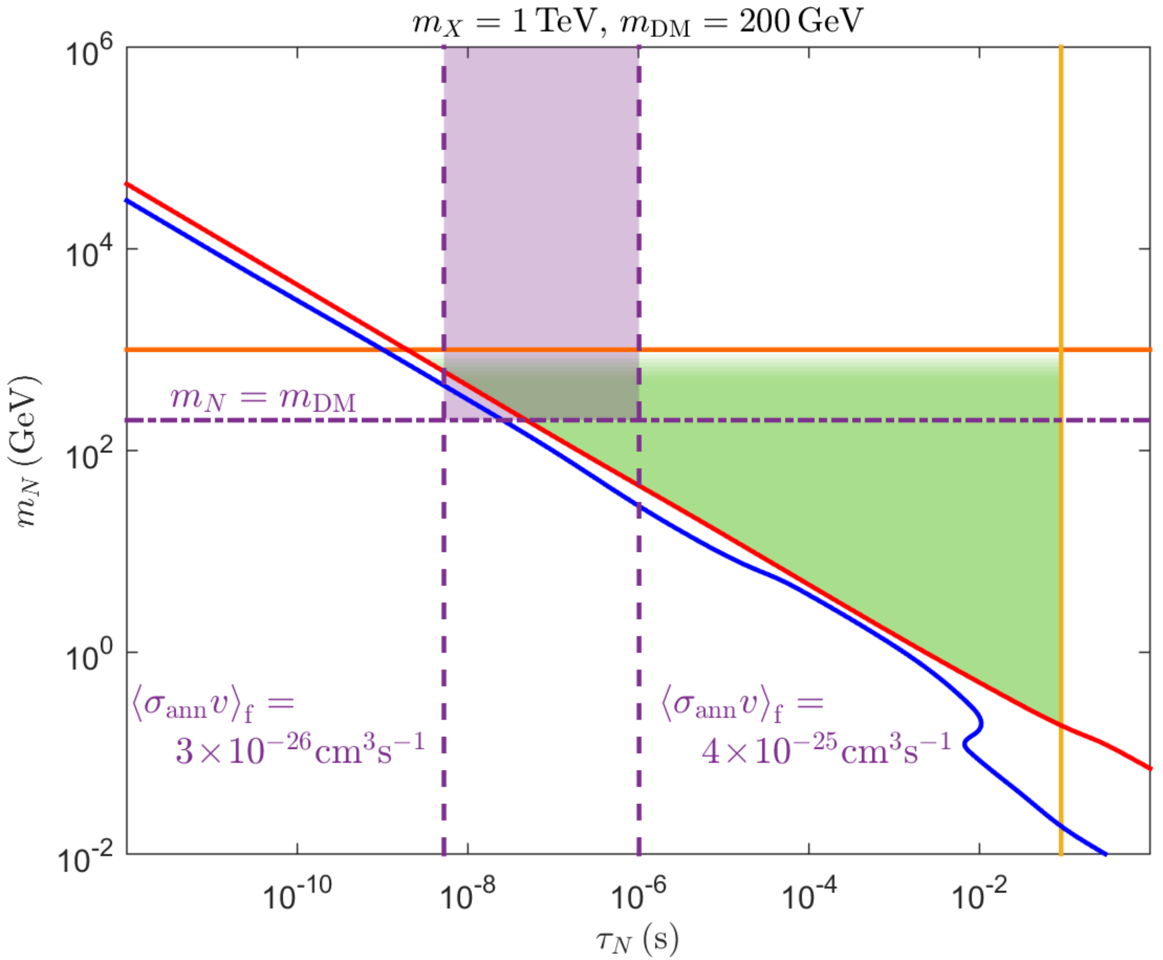


Collider prospects

- N (LLP) production from X decay
- N decay to 3 SM fermions
- N mass and lifetime give start and end of EMD phase

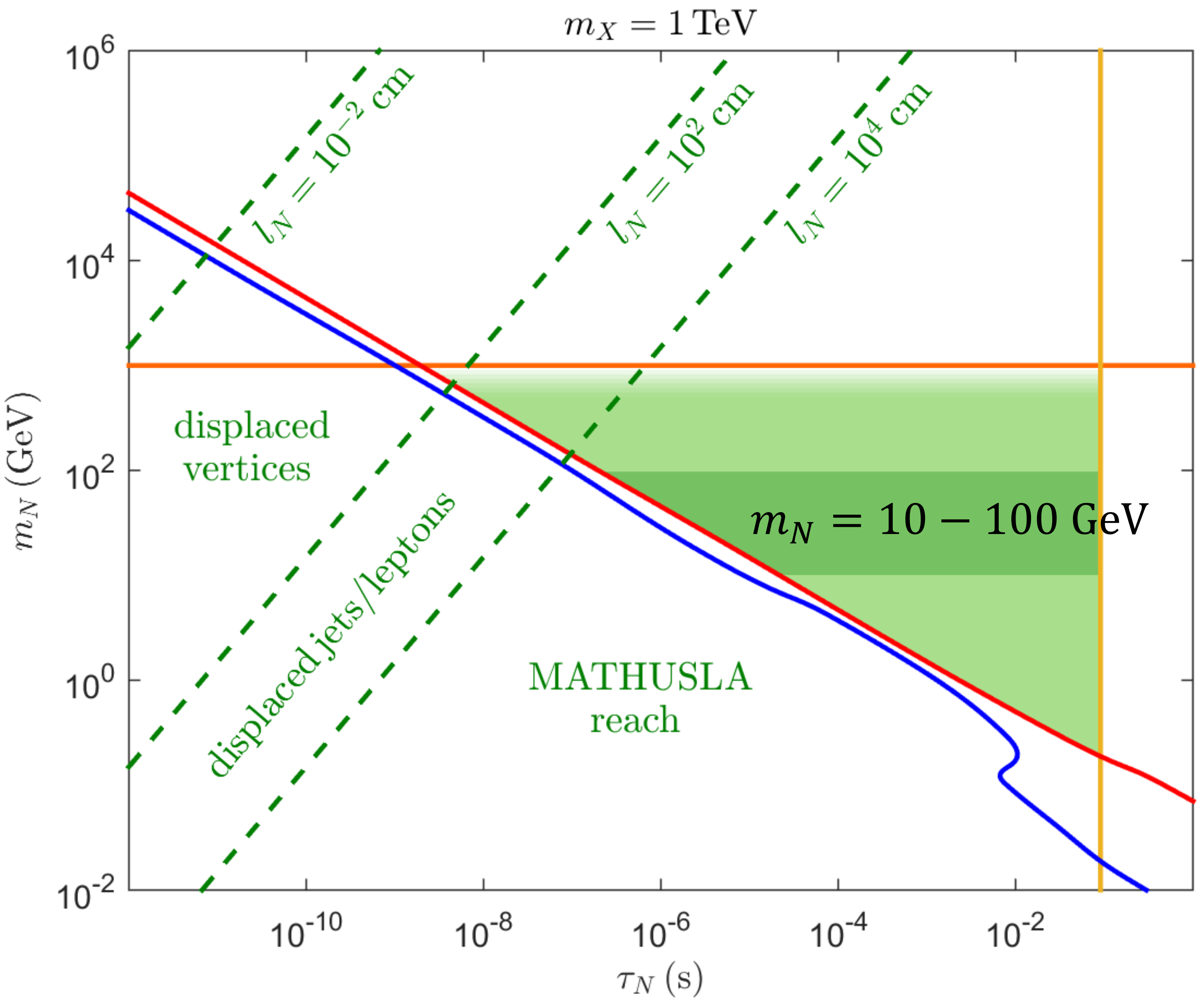
$$\boxed{m_N} \sim \sqrt{M_\mathrm{P} H_\mathrm{dom}} \sim T_\mathrm{dom}$$

➡ Start of EMD

$$\boxed{\tau_N} \equiv \Gamma_N^{-1} \sim H_\mathrm{dec}^{-1} \sim M_\mathrm{P}/T_\mathrm{dec}^2$$

➡ End of EMD, start of RD for BBN

$$l_N = \bar{b} c \tau_N \qquad \bar{b} \sim m_X / 2 m_N$$



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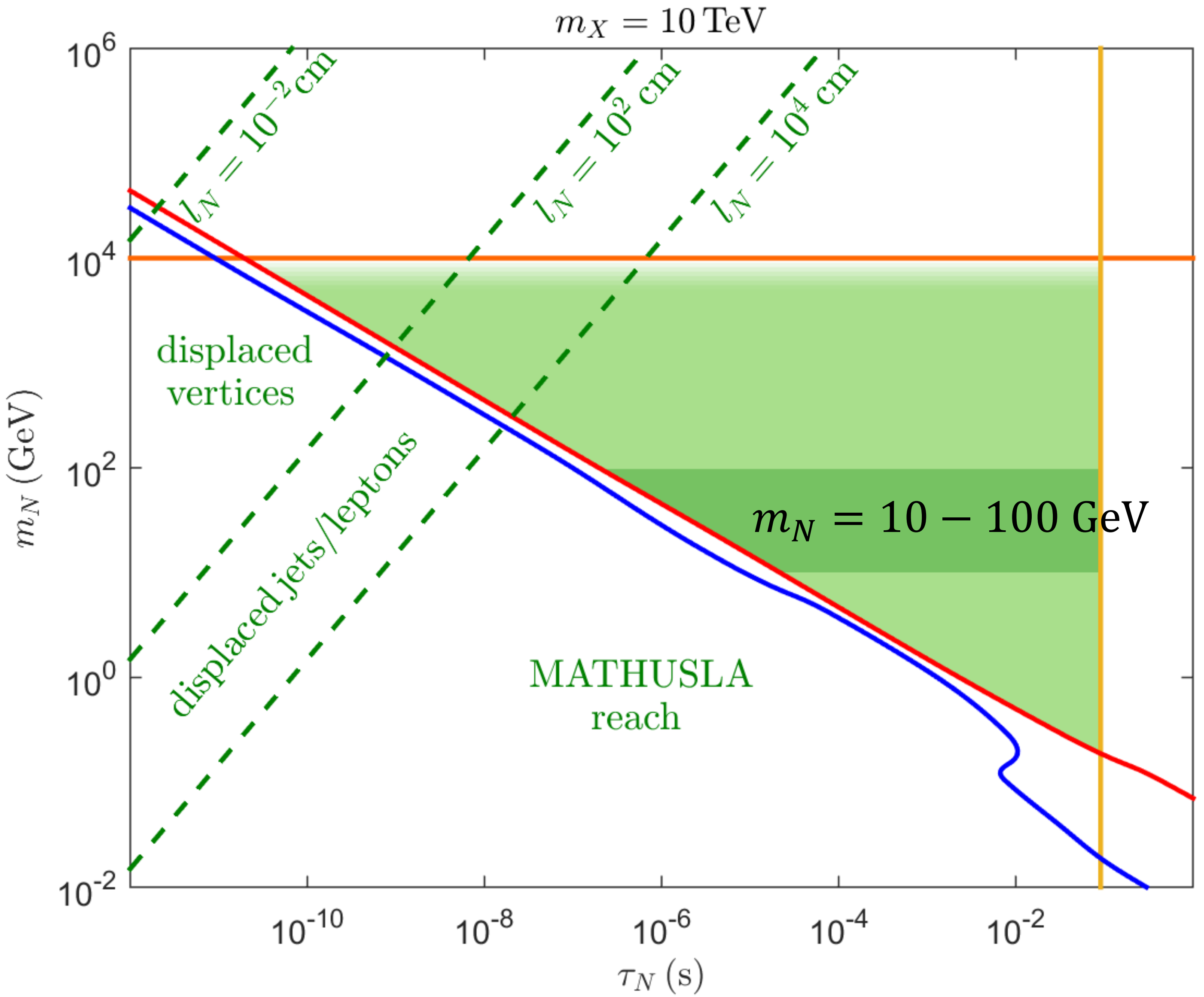


Summary

- Weak-scale LLP can drive EMD period rather naturally (thermal bath)
- Cosmological history conditions are not difficult to satisfy
- LLP lifetime can be quite long (up to BBN), mass relatively high

- Connection between collider observables and pre-BBN era

Thank you!

Backup

Some probes of EMD

- Indirect detection signals of DM annihilation in microhalos boosted due to EMD:

  M. Sten Delos et al., arXiv:1910.08553

  C. Blanco et al., arXiv:1906.00010

  A.L. Erickcek et al., arXiv:1510.04291

  A.L. Erickcek, arXiv:1504.03335

- DM free-streaming from relativistic velocities at production makes it harder to form MW satellite galaxies and can alter Lyman-α forest:

  C. Miller et al., arXiv:1908.10369

Rates in more detail

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

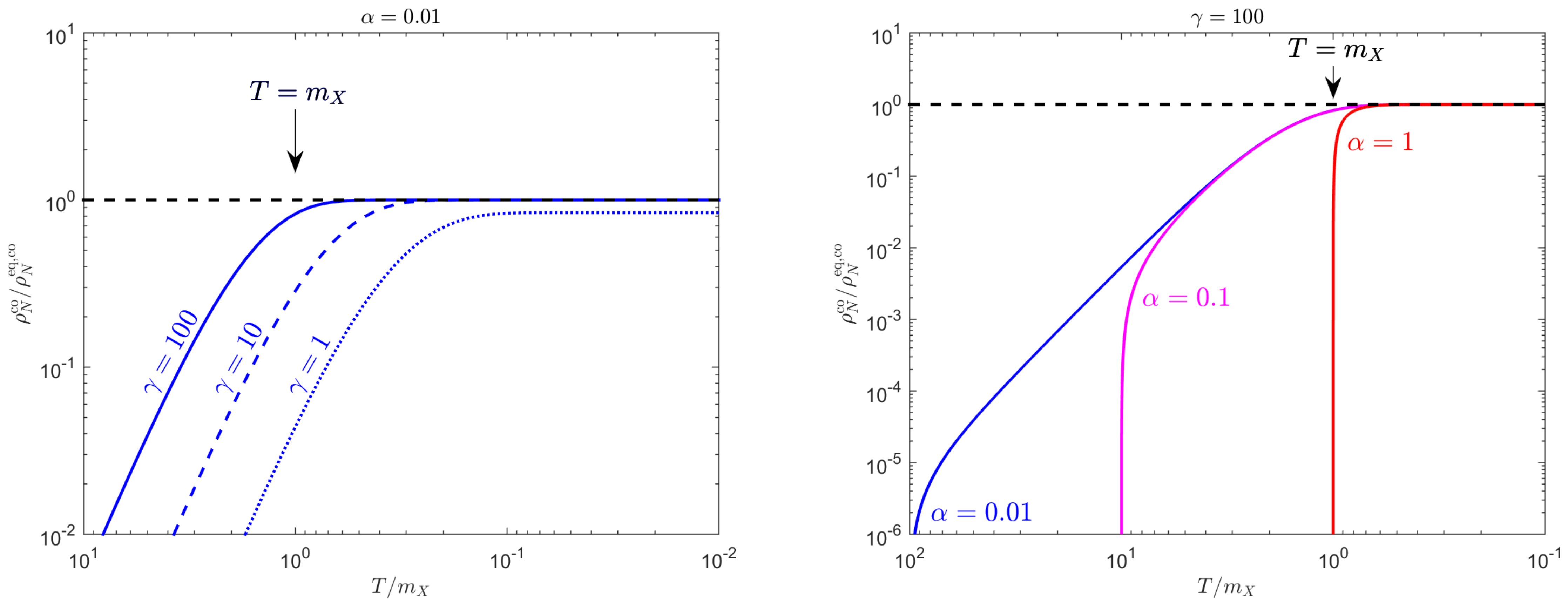
$$\Gamma_N = 2C_2 \frac{|h|^2|h'|^2}{128\cdot 192\pi^3}\frac{m_N^5}{m_X^4} \qquad \Gamma_{N\psi\to\psi^*\psi^*} \simeq 3C_2 \frac{|h|^2|h'|^2}{16\pi}\frac{E^2}{m_X^4} n_\psi$$

- ψ SM fermions of a specific chirality
- Consider *X* coupling to given flavor combinations in *N*ψ and $\psi\psi$ for simplicity (need to sum over all flavor combinations for full)
- *C*'s are *O*(1) model-dependent multiplicity factors
- *n*'s are fermionic relativistic equilibrium number densities
- $E \sim m_N$ (evaluated at $T = m_N$ because of decoupling condition)

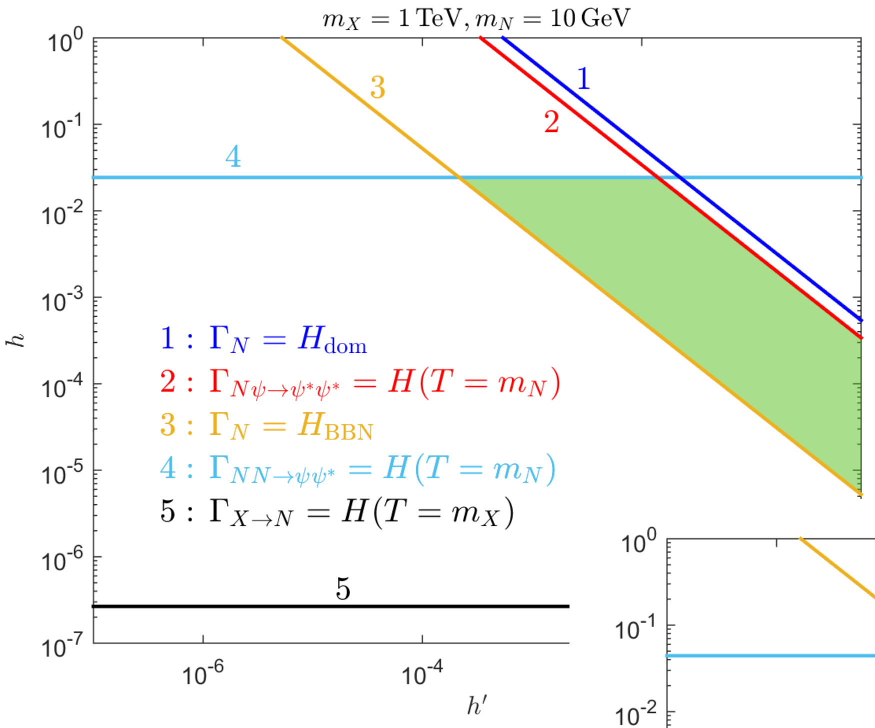
Reaching equilibrium in early Universe

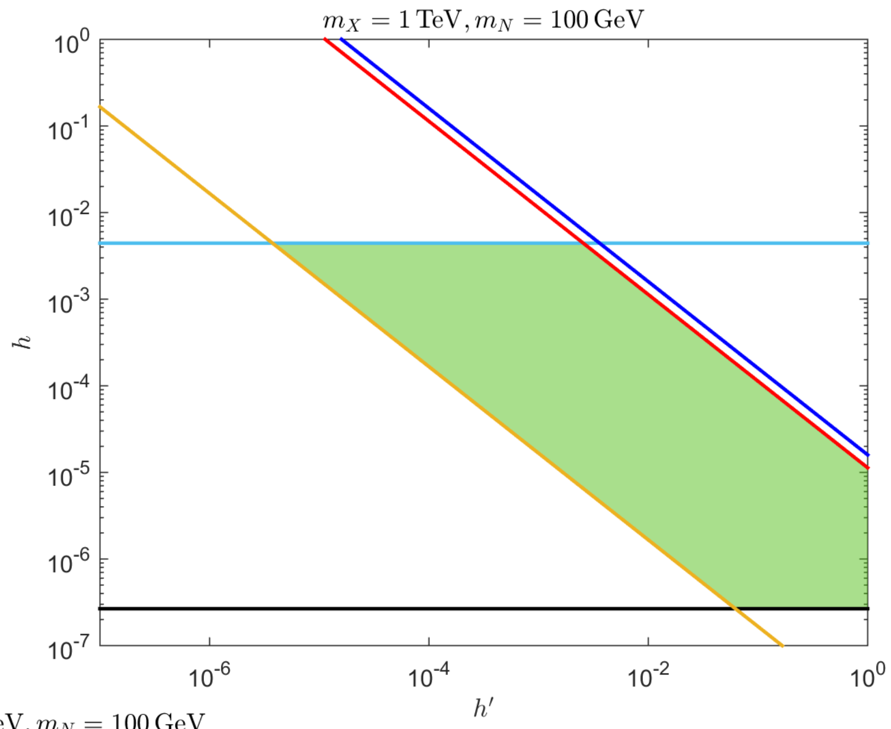
- Thermal abundance of *N* maximizes duration of EMD
- Boltzmann suppression if *X* (or *N*) becomes nonrelativistic while maintaining equilibrium
- Comoving energy densities normalized to equilibrium shown below

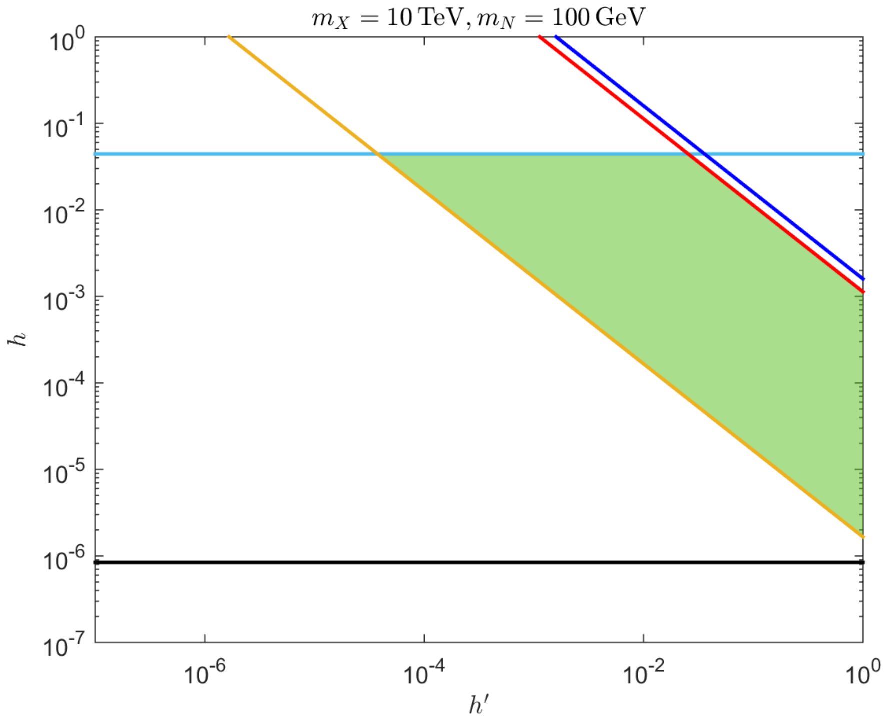
$$\gamma \equiv \Gamma_{X\to N}/H(T=m_X) \qquad \alpha \equiv m_X/T_{\rm i}$$

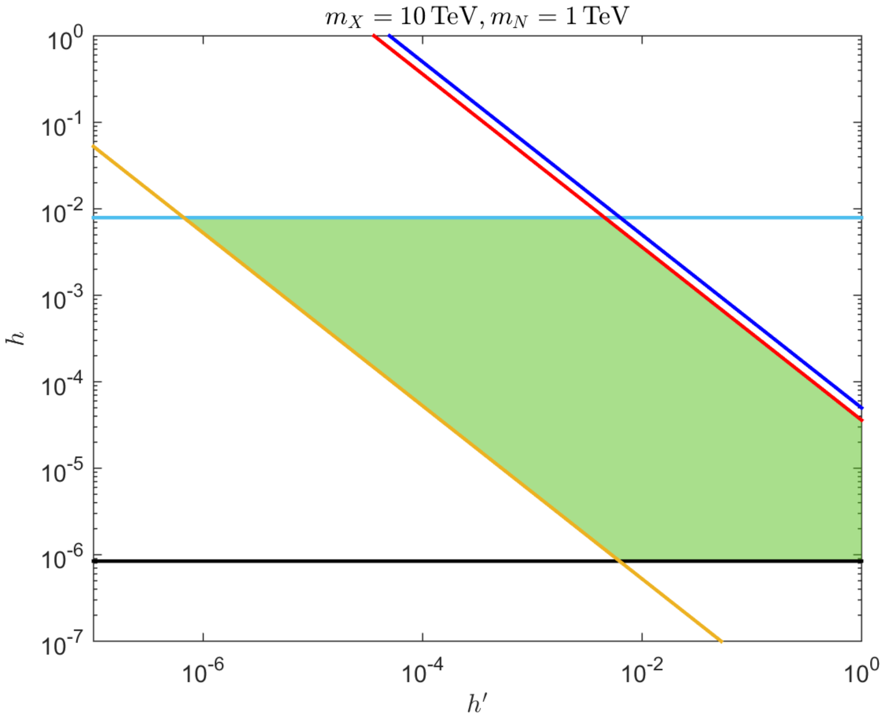


More h – h' plane

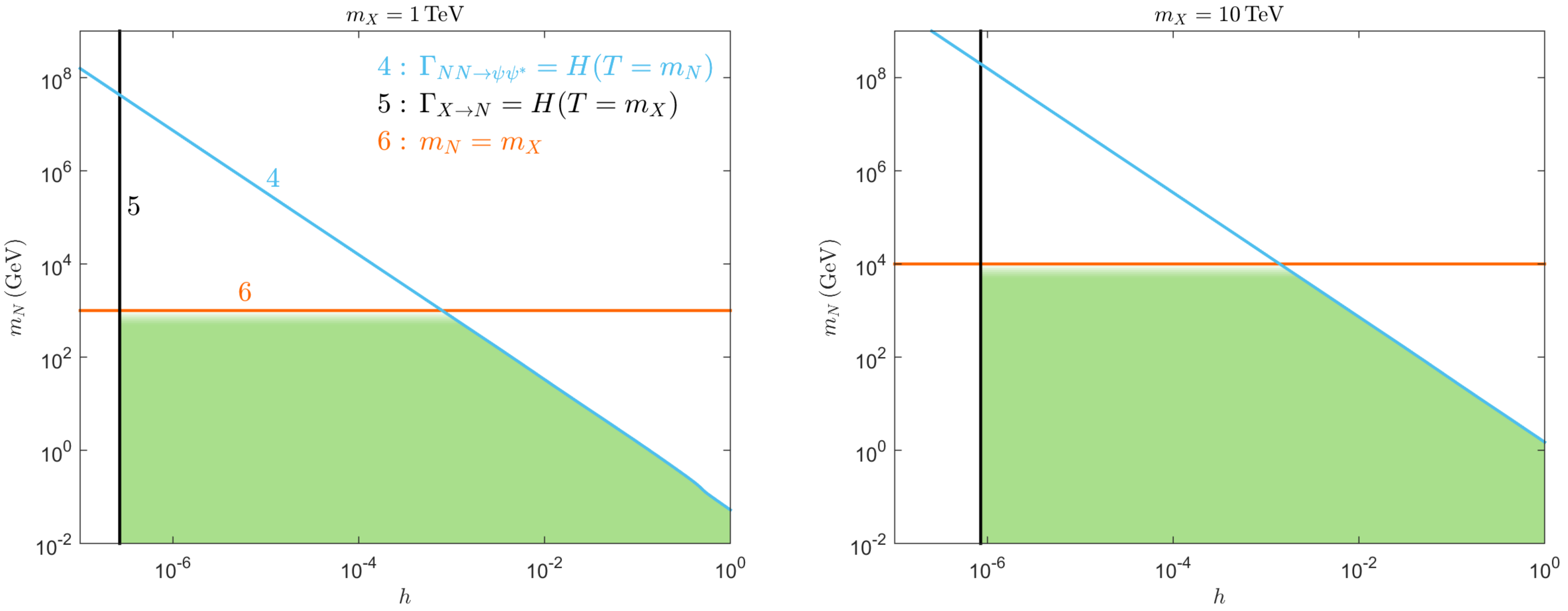








Relating the two parameter spaces



An explicit model

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

- *i*, *j*, *k* flavor indices
- *u*/*d* left-handed up/down-type antiquarks
- *X* iso-singlet color-triplet scalar with hypercharge +4/3
- Effective four-fermion interaction at low energies: $N u_i^c d_j^c d_k^c$
- *N* decay can source baryon asymmetry
- Also has DM candidates
- Testable at colliders

Model:
R. Allahverdi and B. Dutta, arXiv:1304.0711
K.S. Babu et al., arXiv:hep-ph:0612357
R. Allahverdi et al., arXiv:1305.0287

Testability:
B.Dutta et al., arXiv:1401.1825
R. Allahverdi et al., arXiv:1507.02271
R. Allahverdi et al., arXiv:1712.02713
P.S. Bhupal Dev et al., arXiv:1504.07196