Dark Matter as General Thermal Relics

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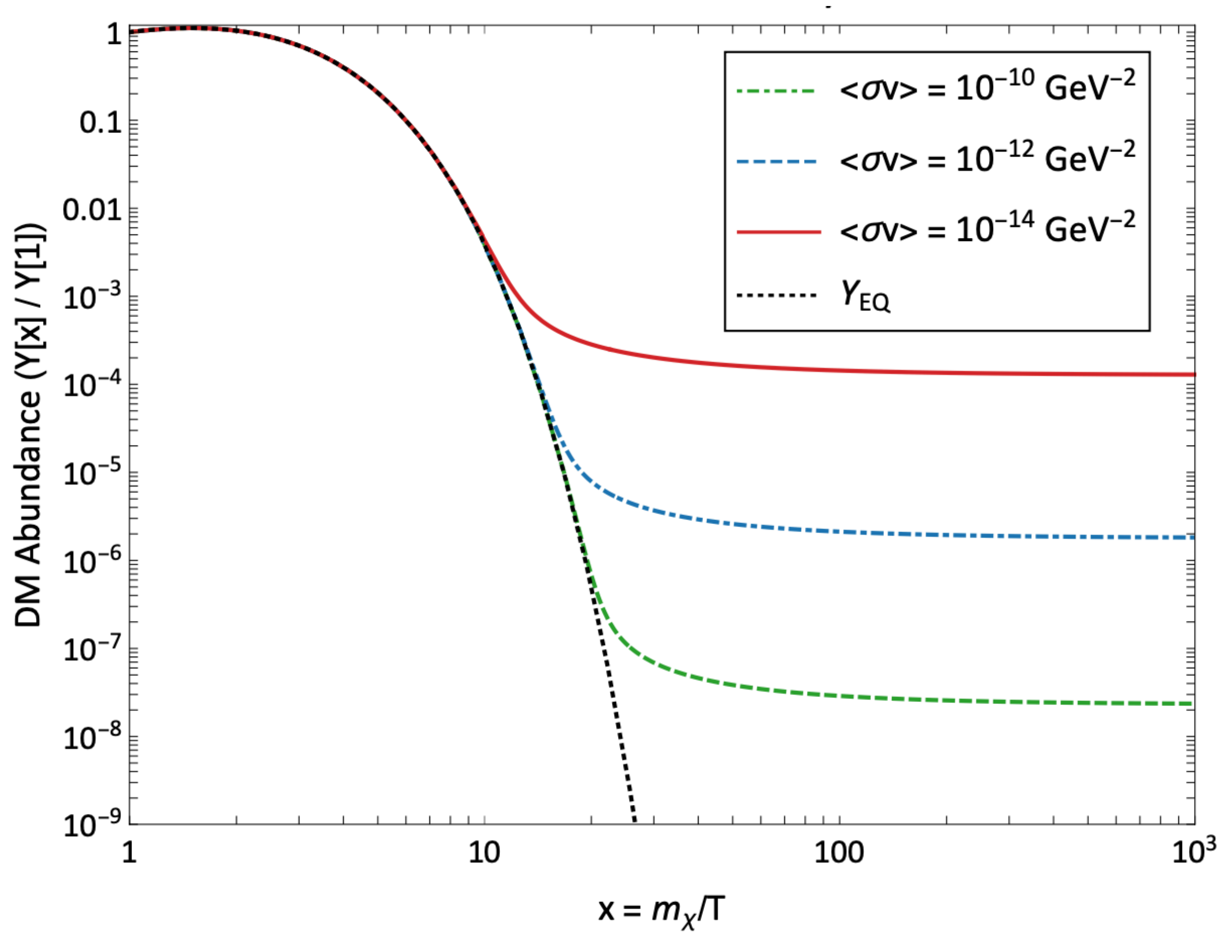
Dark Interactions Workshop - BNL - 2022

Relic Density as the Guideline

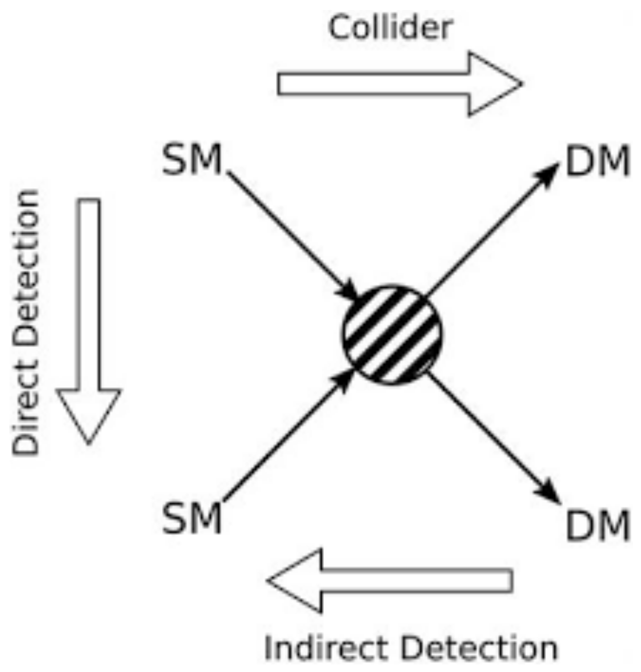
A baseline requirement for an appealing theory of dark matter is to address the origin of its abundance in the universe.



freeze out: $T \sim m/20$

dynamical, independent of initial condition, predictive

WIMP as a Wonderful Target



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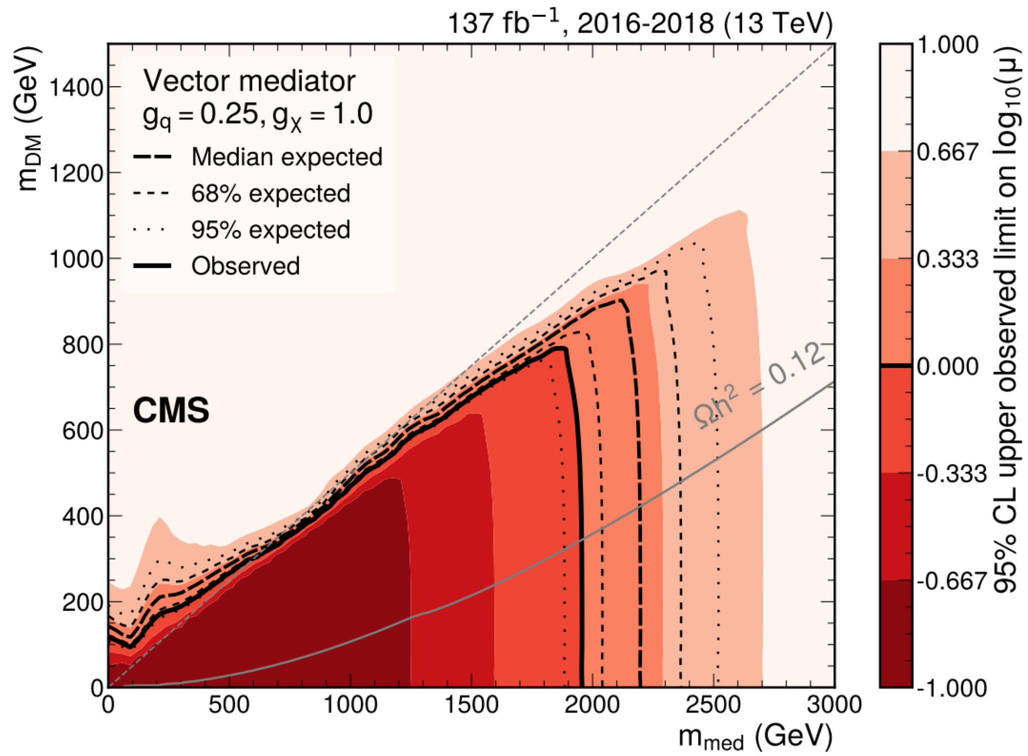

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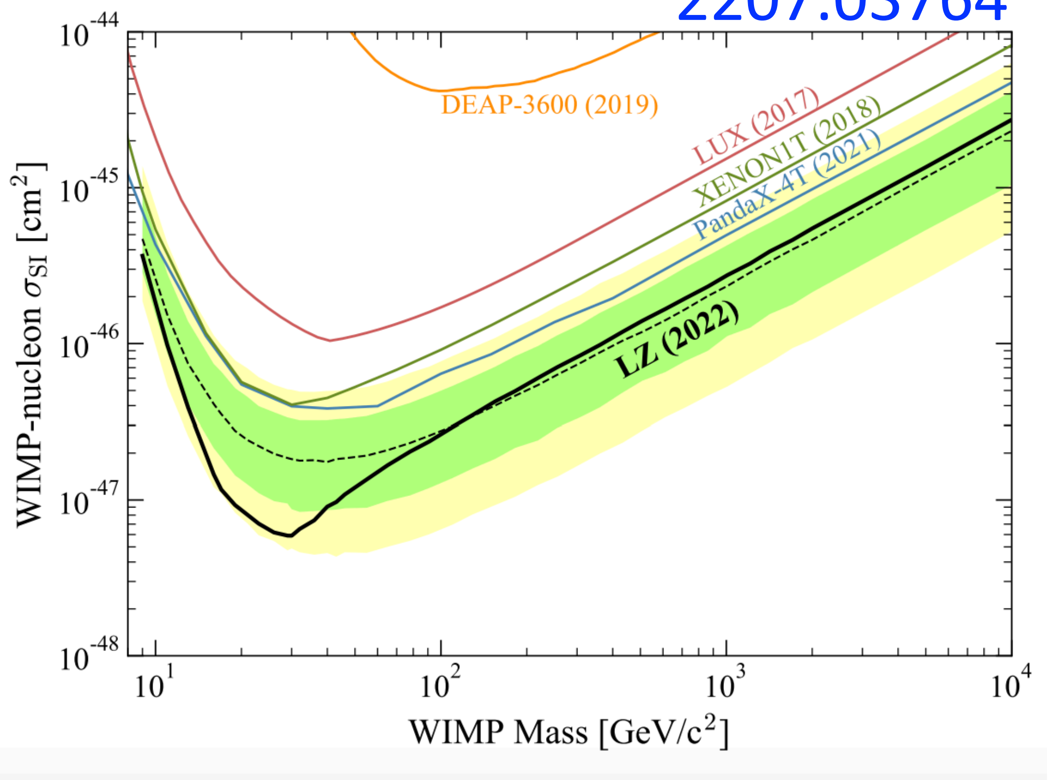
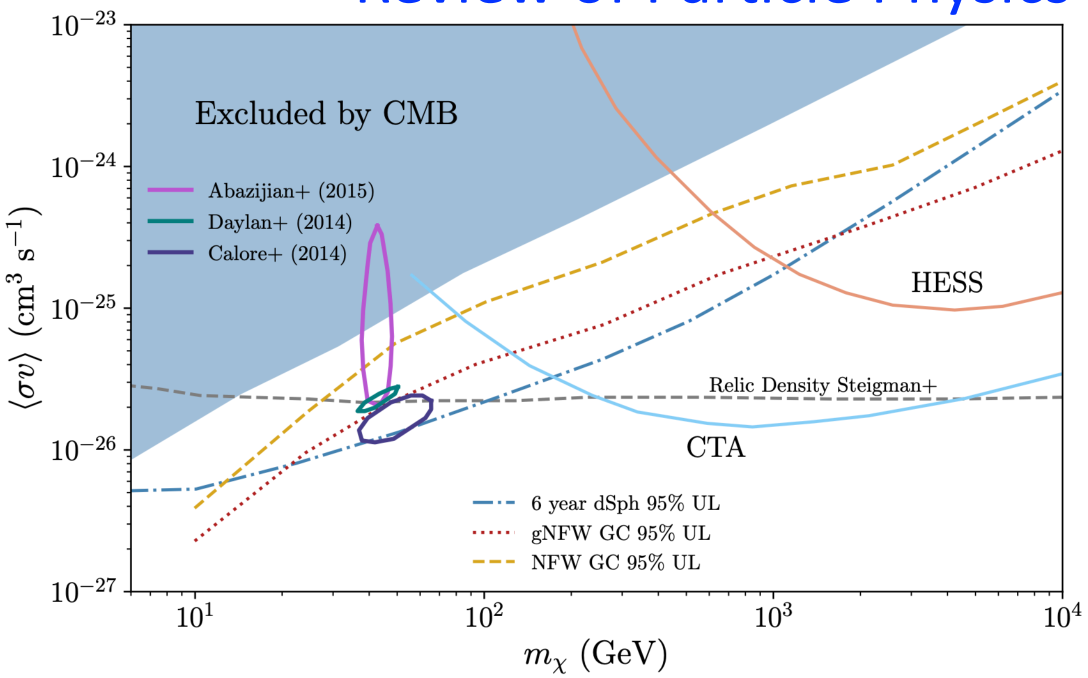


Review of Particle Physics



Zoo of Thermal Candidates

Many incarnations of thermal relic dark matter:

- WIMP / simple dark sector
- Co-annihilation
- Annihilation near poles
- Forbidden channels
- Sommerfeld enhancement
- Bound state effects
- SIMP 3→2 + elastic scattering
- ……

Mass Range of Thermal DM

Close connection between DM mass *M* and its relic density.

The good-old WIMP: 100 GeV - a few TeV scale. $\sigma v_{anni} \sim \frac{g^4}{M^2}$

Heavier: Griest-Kamionkowski unitarity limit, $M < 340$ TeV.

Lighter: Lee-Weinberg lower mass bound, $M > 2$ GeV. $\sigma v_{anni} \sim \frac{g^4 M^2}{M_W^4}$

Introducing a light mediator opens up sub-GeV mass window for thermal DM → dark sector models, an exciting frontier.

Cracking the Dark Sectors

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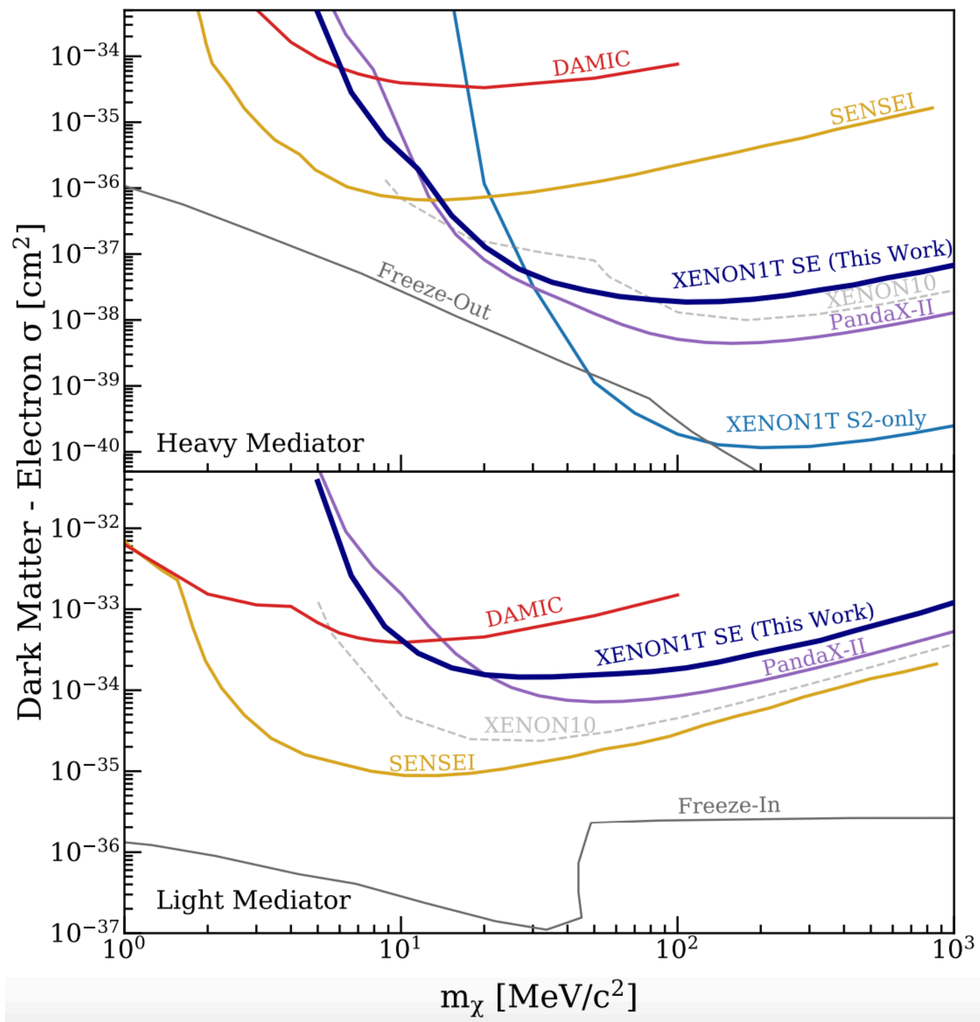

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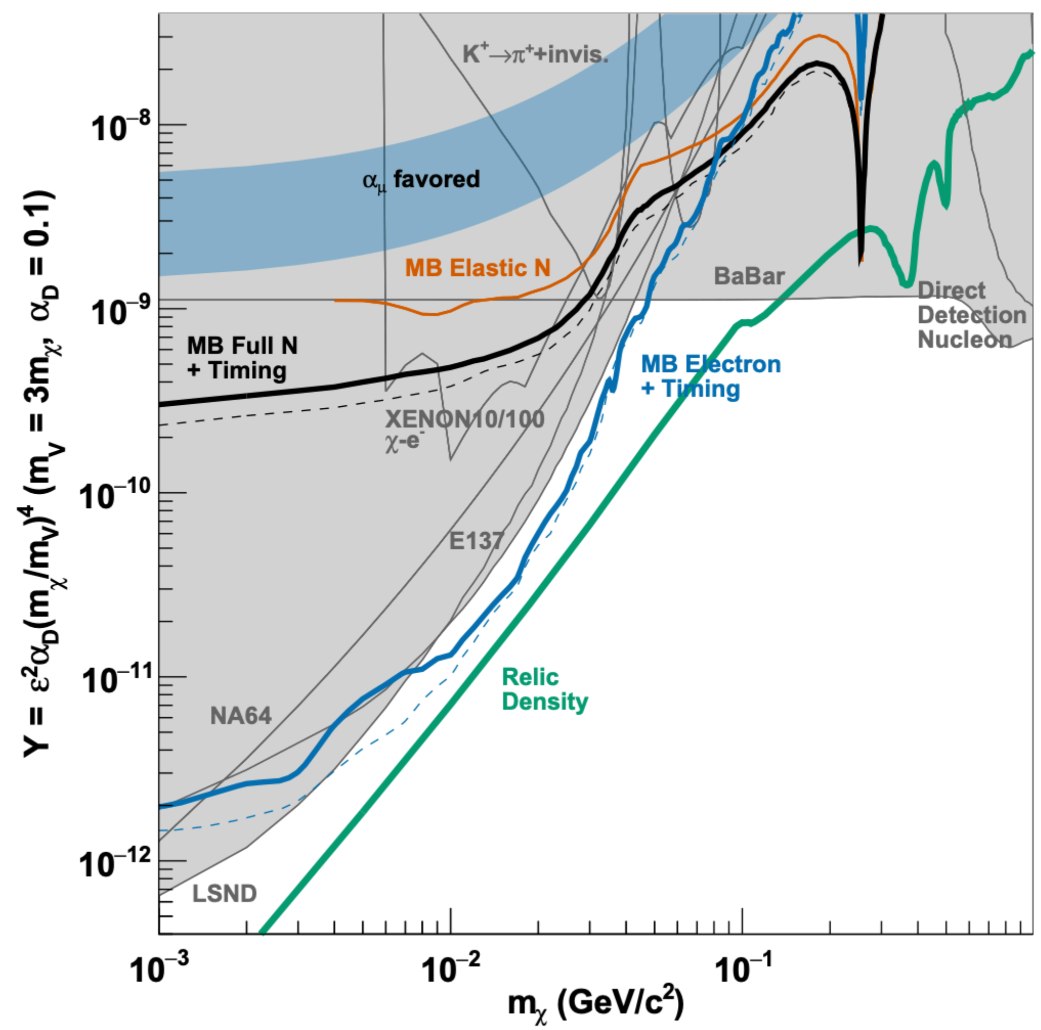
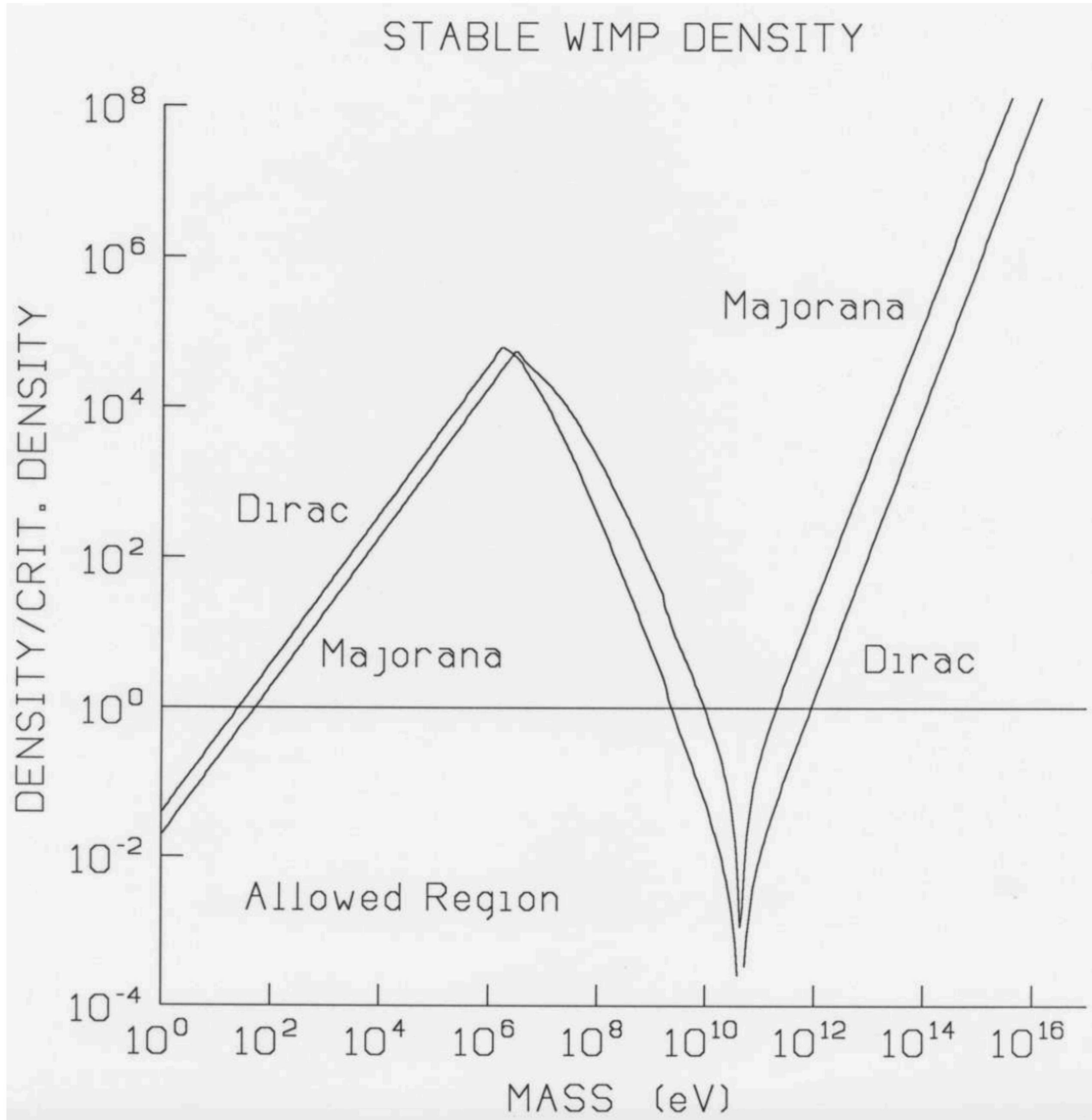


DM-e scattering

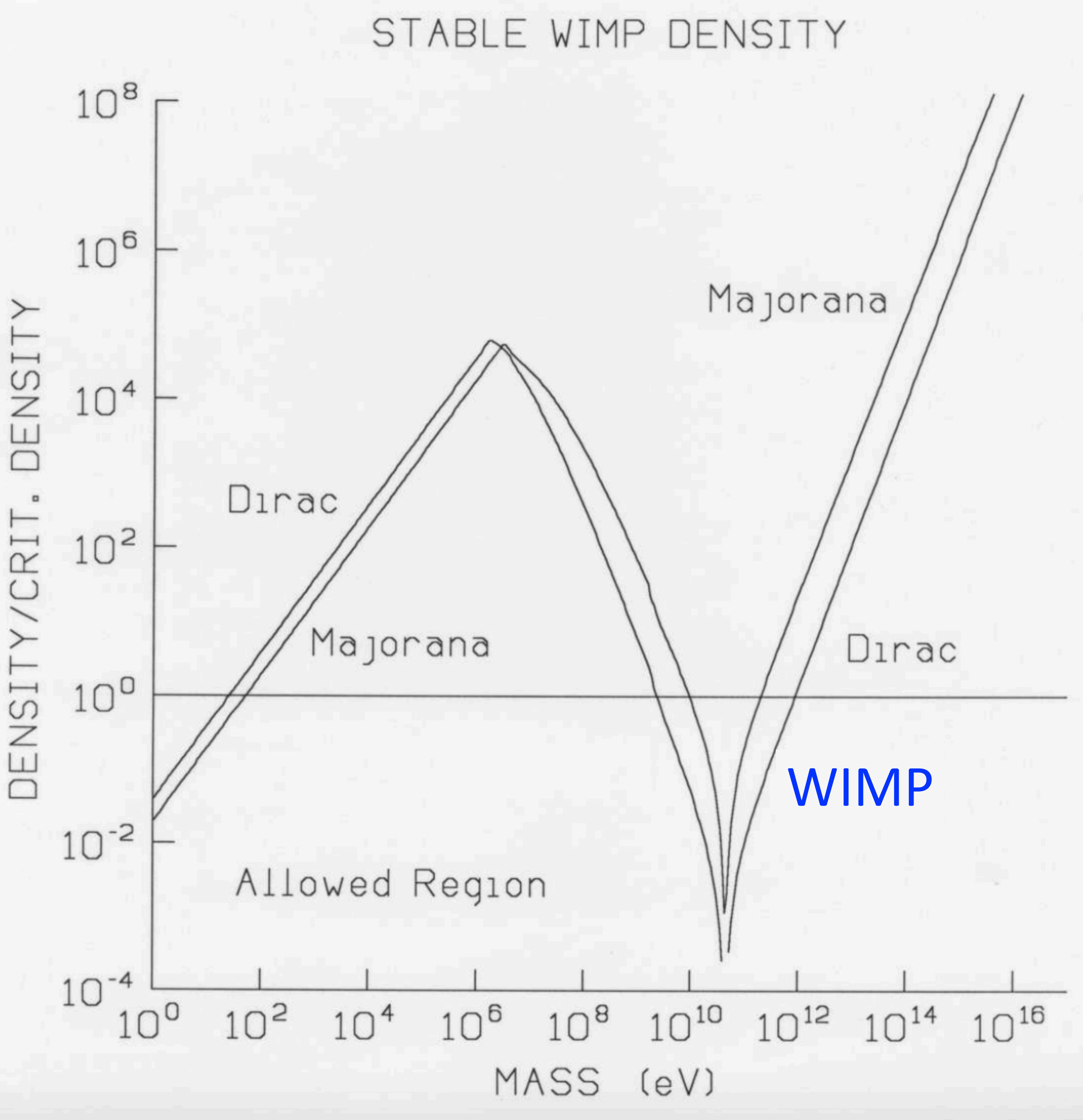
DM@ν experiments

Roadmap of Thermal Relics



John Terning (1985)

Roadmap of Thermal Relics



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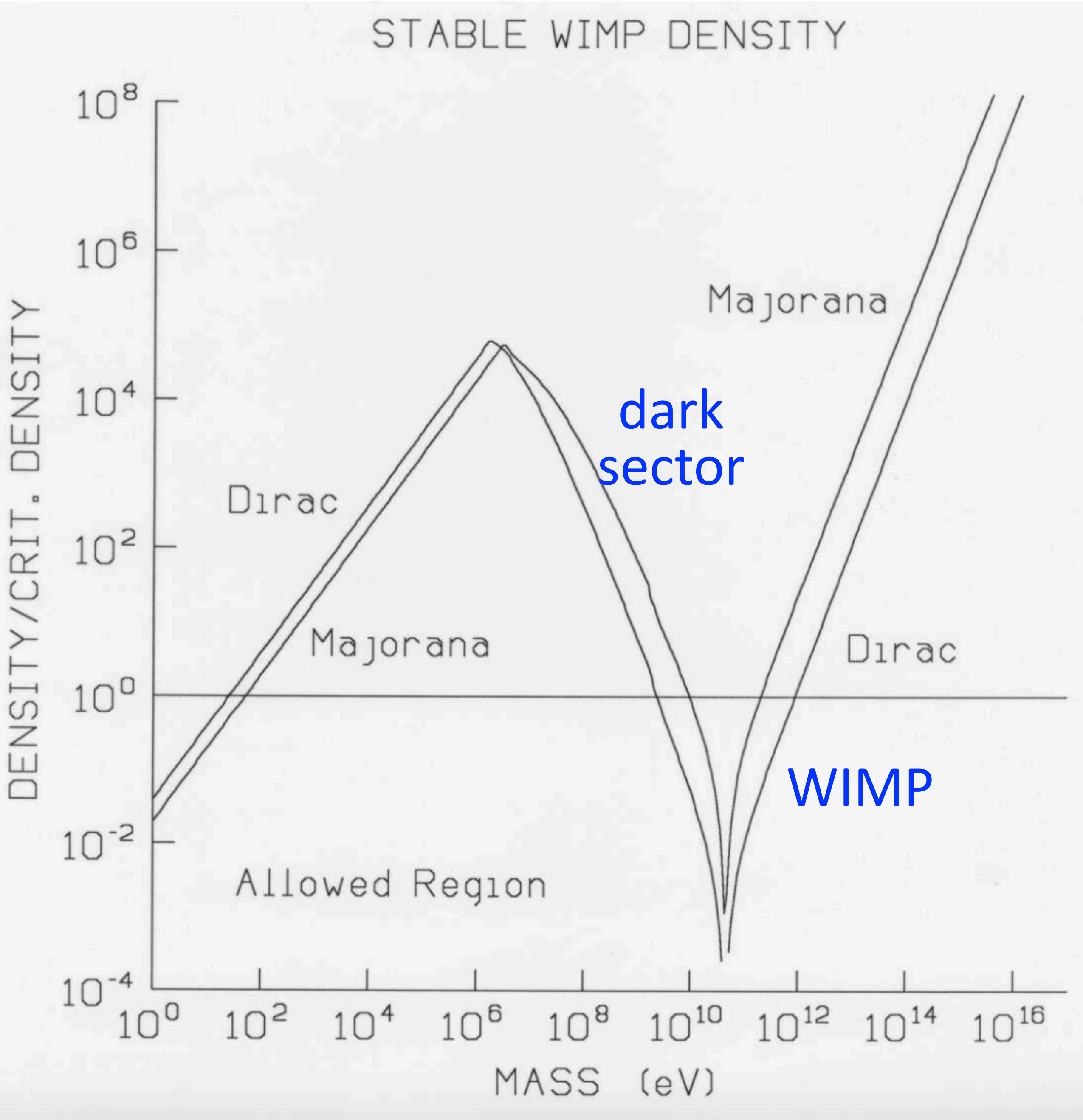

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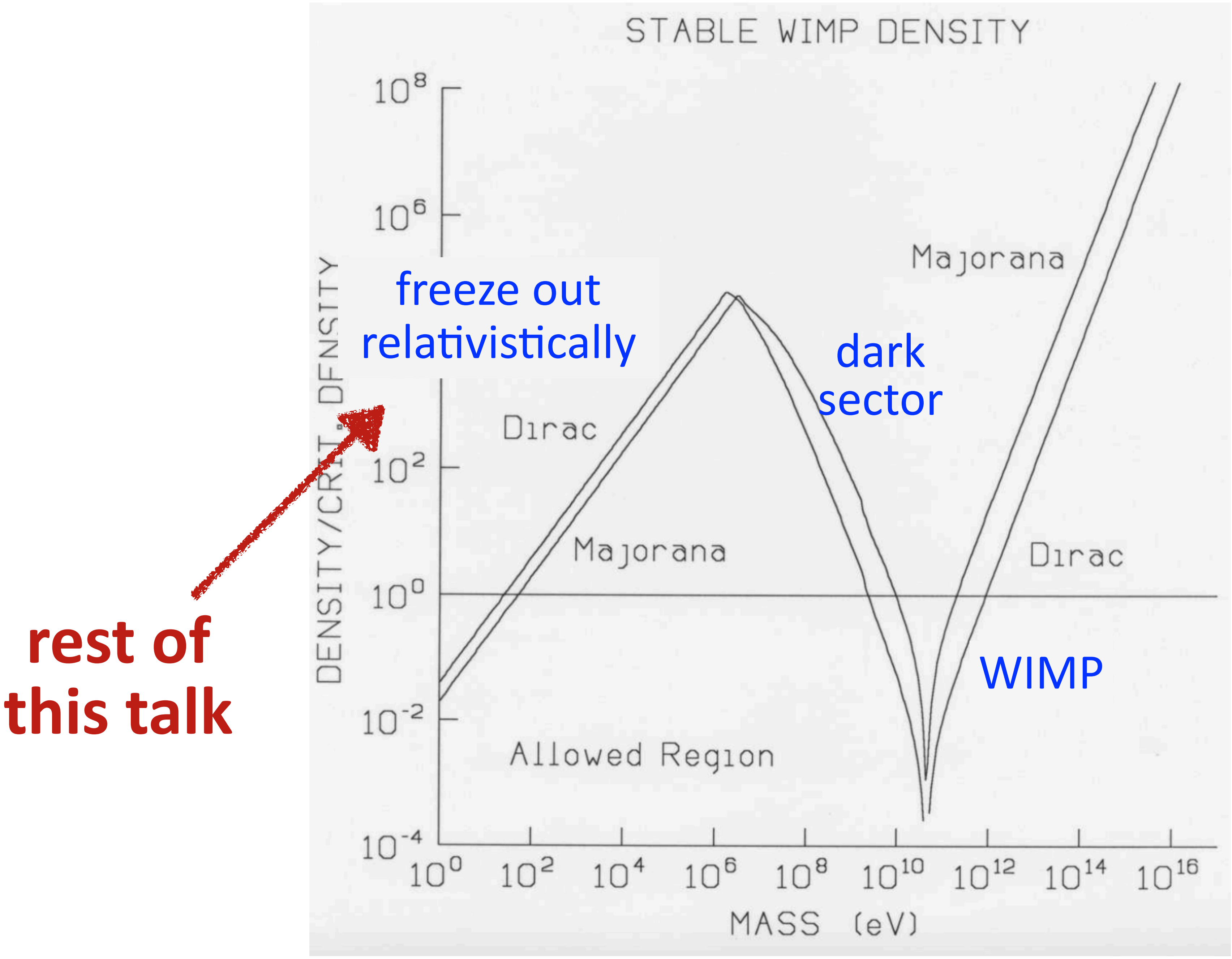
Roadmap of Thermal Relics



John Terning (1985)

Exercise with Active Neutrinos

An active neutrino freezes out relativistically around $T \sim$ MeV

$$\Omega_\nu h^2 = \frac{m_\nu}{93\,\mathrm{eV}} = 0.12\left(\frac{m_\nu}{11.2\,\mathrm{eV}}\right)$$

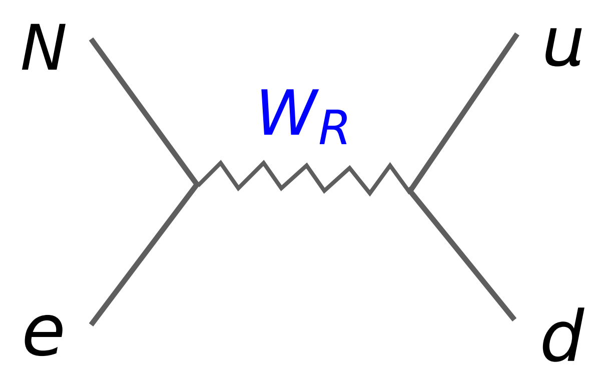
Relic density would work if m_ν = 11.2 eV, but in contradiction with upper bound from KATRIN and oscillation experiments.

This argument excludes active neutrinos from comprising all of dark matter in the universe.

Right-handed Neutrino DM

Motivated for generating nonzero neutrino masses.

Make them thermal relics: embed in anomaly-free gauge extensions of the SM: $U(1)_{B\text{-}L}$ or left-right symmetric model.



relativistic freeze out

Various structure formation limits exclude thermal relic DM lighter than keV scale → overproduction **→ need a dilution mechanism.**

Dilution with "Long-Lived" Particle

Relic density computations: for WIMP $\Omega = \frac{YMs_0}{\rho_0}, \quad Y = n/s$

Dilution: late entropy production from decay of a cosmologically long-lived particle. Reduces Y by an extra factor,

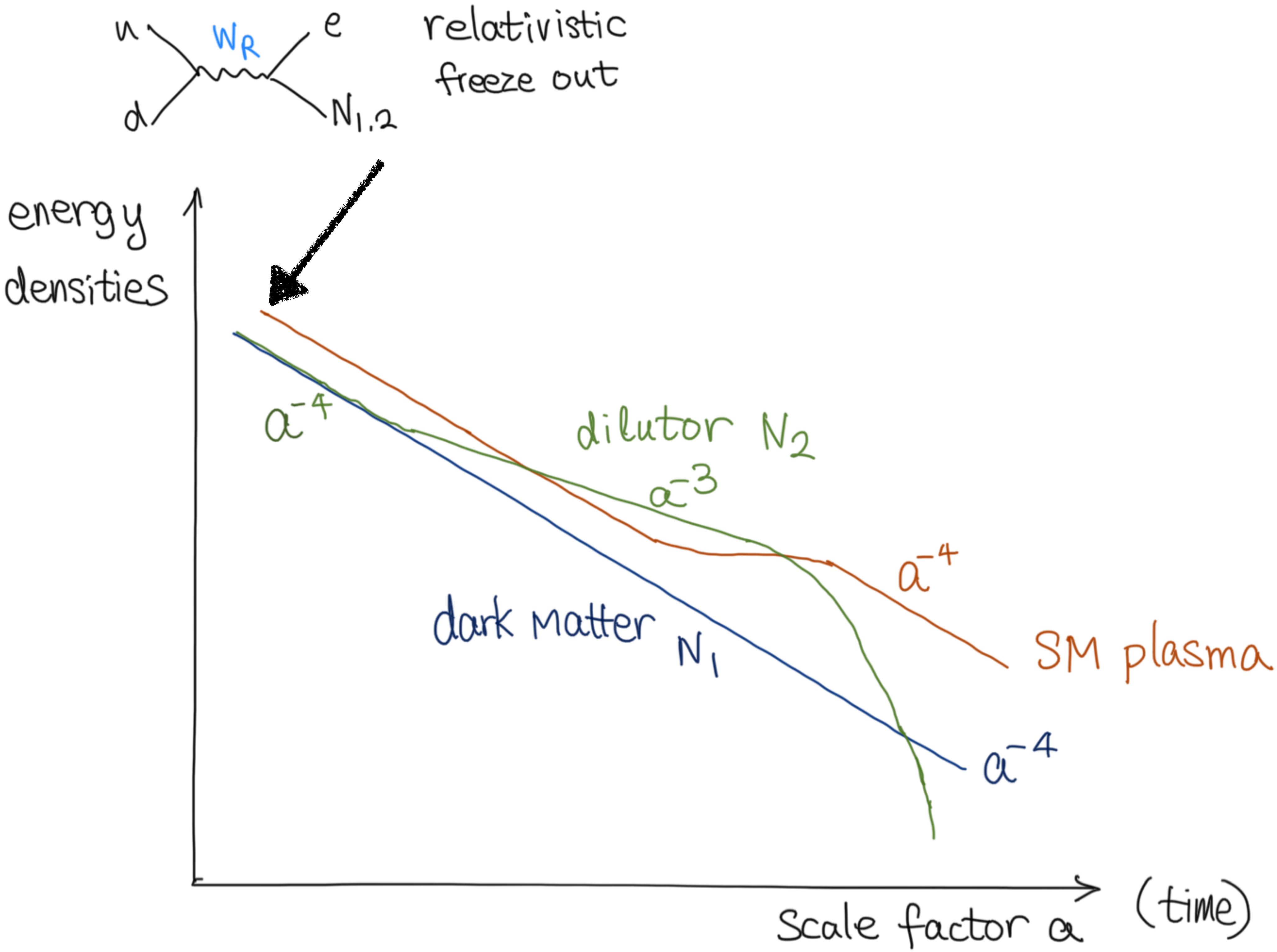
$$\Omega = \frac{YMs_0}{\rho_0}\frac{1}{\mathcal{S}} \qquad \text{need } \mathcal{S} \sim 10 - 100 \left(\frac{M}{1\,\mathrm{keV}}\right)$$

Lightest RH neutrino (N_1) serves as the dark matter.

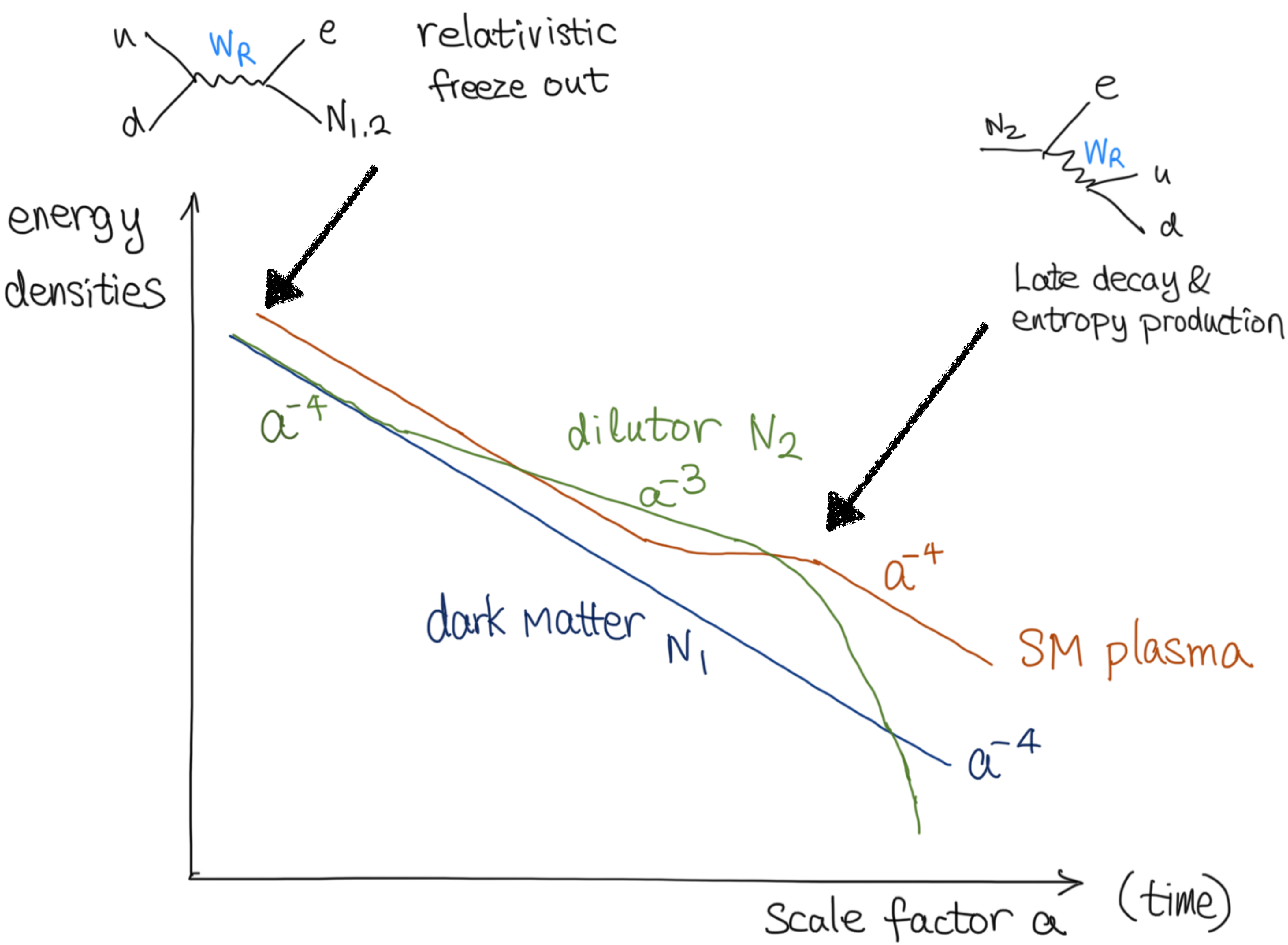
A heavier one (N_2) plays the role of long-lived particle (dilutor).

Bezrukov, Hettmansperger, Lindner (0912.4415)

Temporary Matter Domination

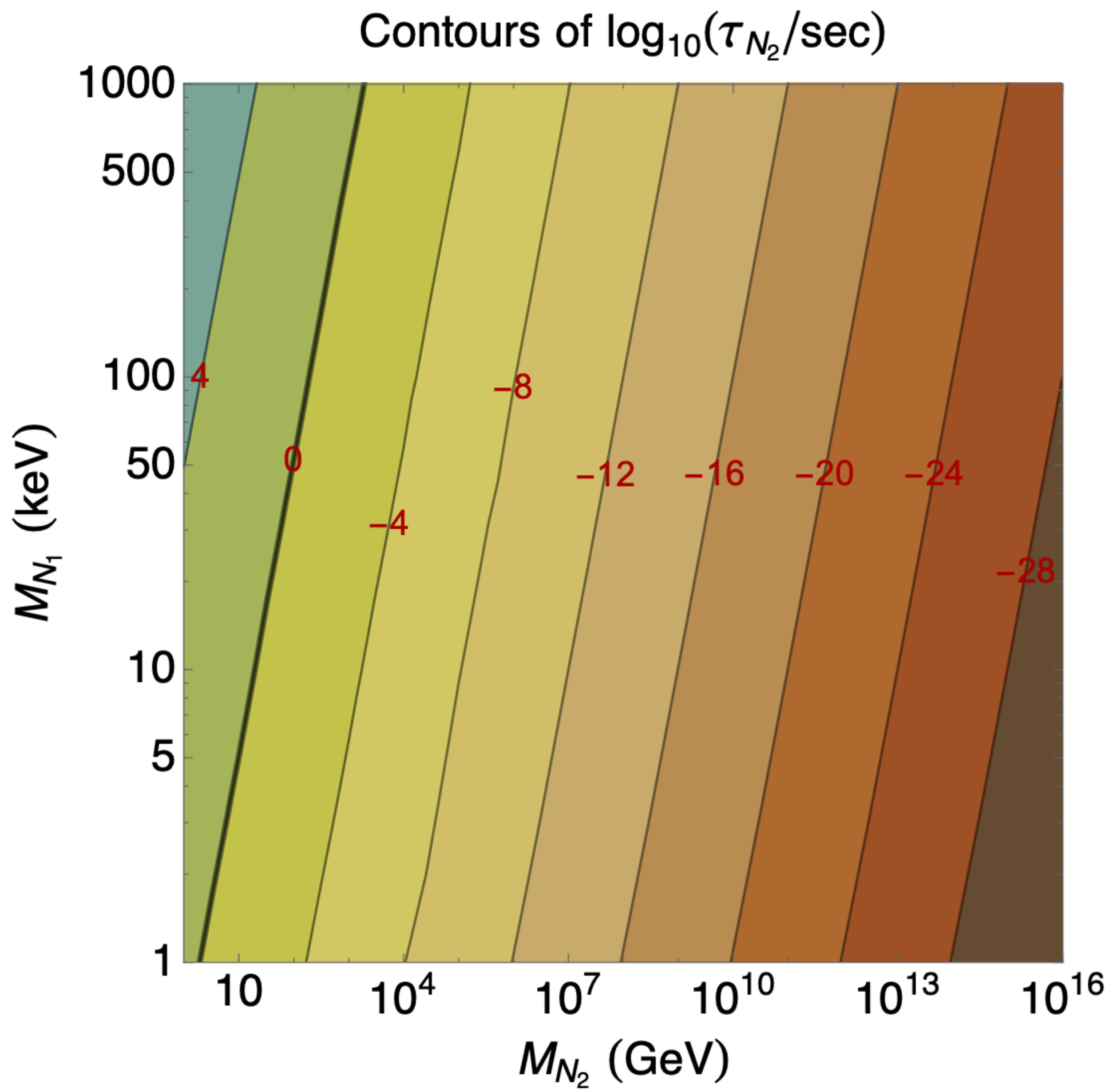


Temporary Matter Domination



Diluted Dark Matter Relic Density

$$\Omega \simeq 0.26 \left(\frac{M_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{1\,\mathrm{GeV}}{M_{N_2}}\right)\sqrt{\frac{1\,\mathrm{sec}}{\tau_{N_2}}}$$



Warm Dark Matter Constraints

While DM was still relativistic, it has a Fermi-Dirac distribution but features a lower temperature than active neutrinos,

$$\frac{T_{N_1}}{T_\nu} = 0.22 \left(\frac{1\,\mathrm{keV}}{M_{N_1}} \right)^{1/3}$$

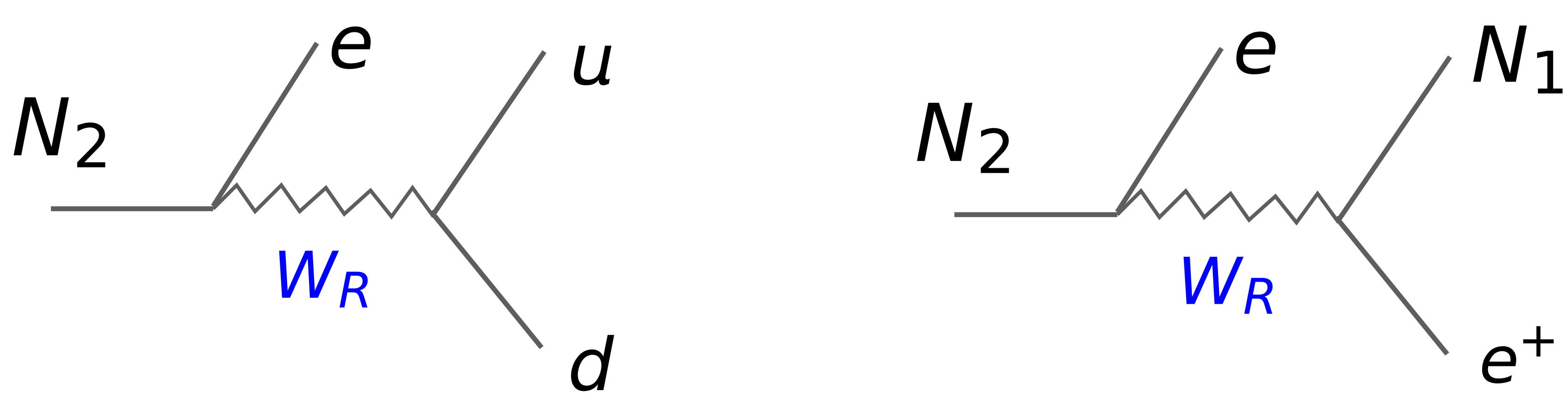
After dilution, N_1 is essentially a warm DM — free-streaming can smooth out observed small-scale structures in the universe (e.g. MilkyWay satellites, Lyman-α, strong lensing)

$$M_{\mathrm{WDM}} > 6.5\,\mathrm{keV}$$

DES Collaboration (2008.00022)

New Handle of Dilution Mechanisms

Dilutor-to-DM decay: if the right-handed current interaction mediated by W_R dominates decay of N_2, we run into a problem

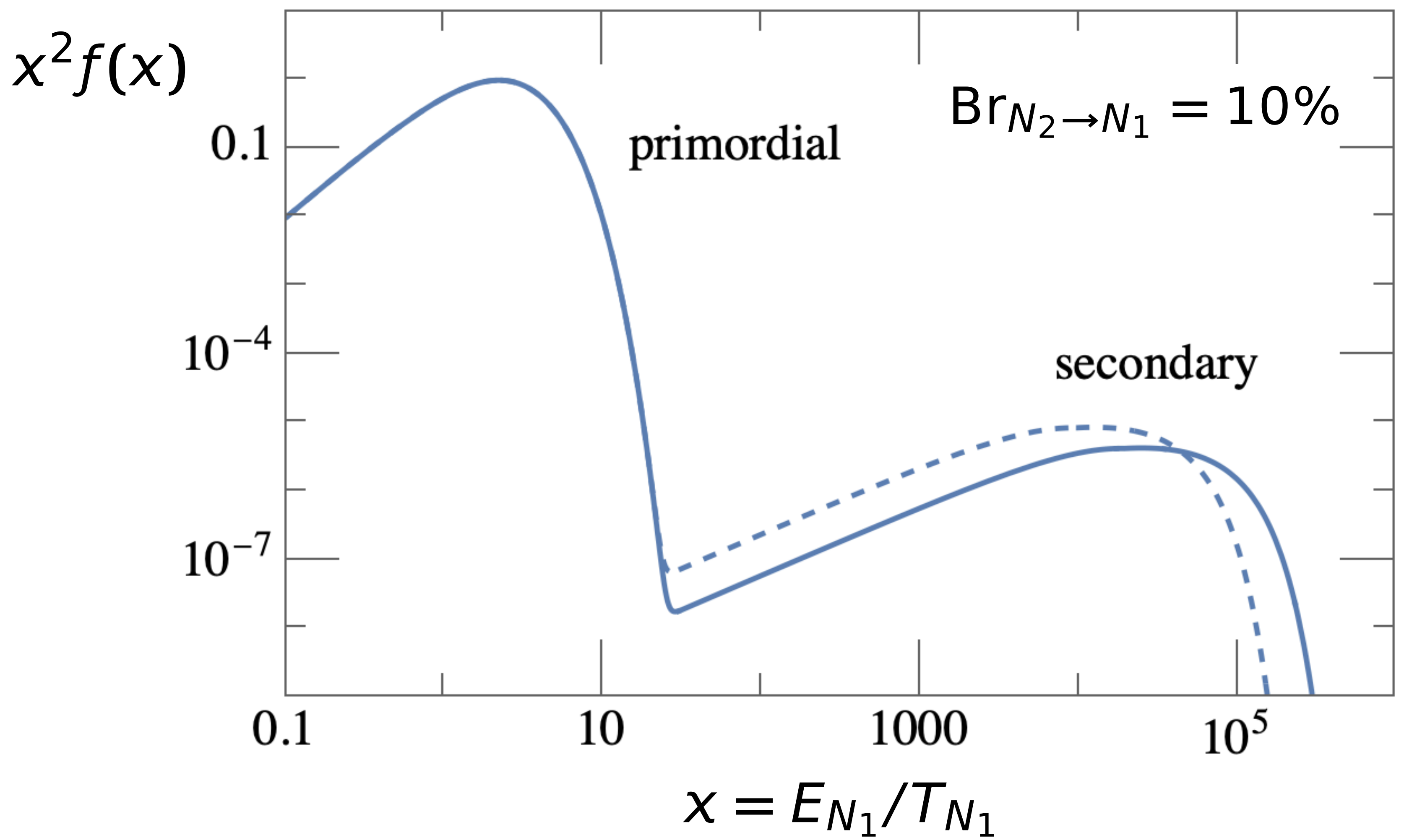


Sufficiently heavy N_2, second channel has decay Br = 1/10-1/7.

Miha Nemevsek and Yue Zhang (2206.11293)

Phase Space Distribution

Secondary component of DM from dilutor way more energetic.



Miha Nemevsek and Yue Zhang (2206.11293)

Length Scales of Damping

Immediately after dilutor decays away, secondary DM has energy $E \sim M_{N2}$, turns non-relativistic after (M_{N2}/M_{N1}) of expansion.

Another look at the diluted relic density

$$T_{\rm NR} \sim T_{\rm RH} \frac{M_{N_1}}{M_{N_2}}$$

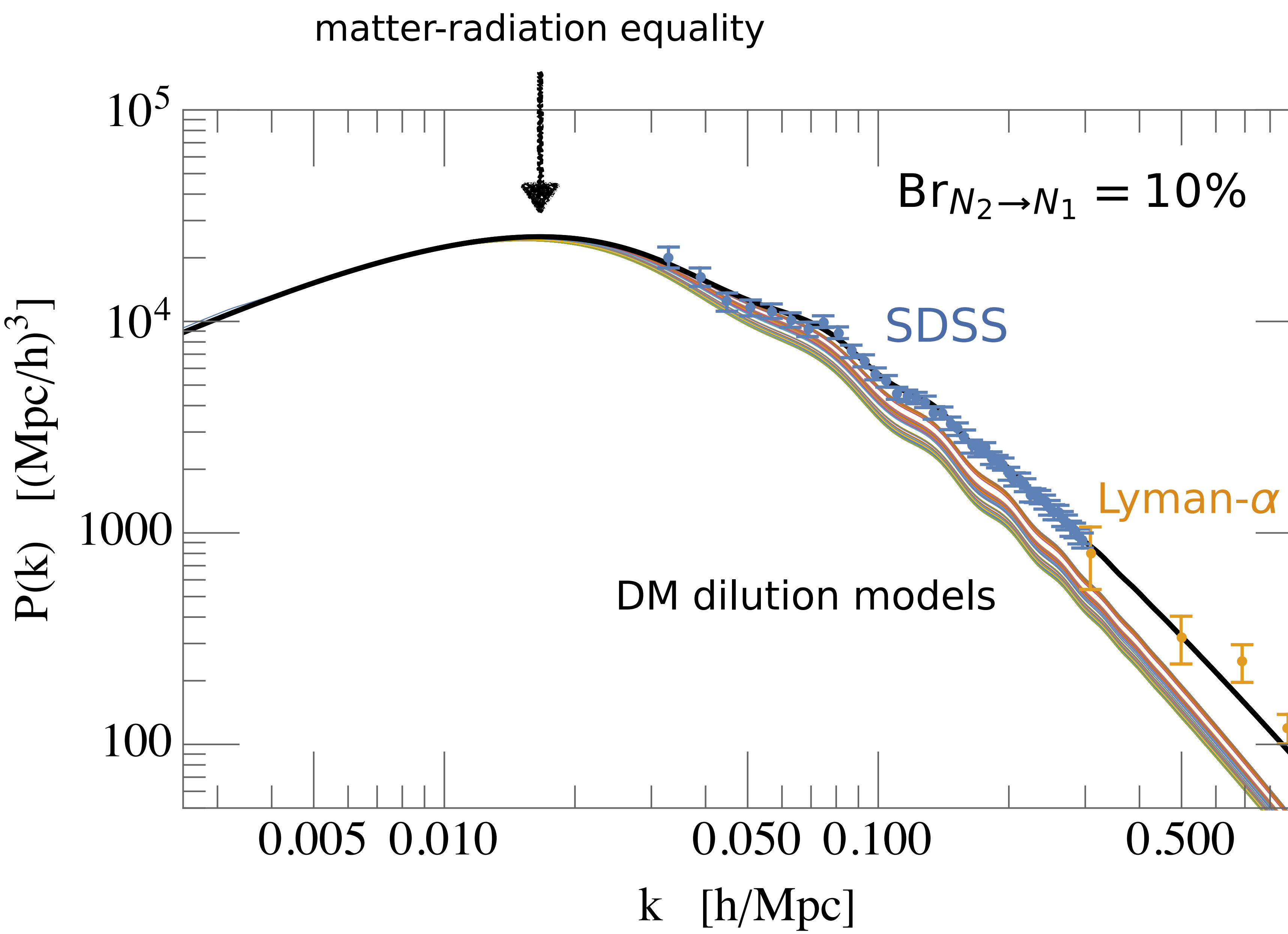
$$\Omega \simeq 0.26 \left(\frac{M_{N_1}}{1\,\text{keV}} \right) \left(\frac{1\,\text{GeV}}{M_{N_2}} \right) \left(\frac{T_{\rm RH}}{1\,\text{MeV}} \right)$$

Relic density dictates that secondary DM always turns NR at eV temperature, independent of any parameters M_{N1}, M_{N2}, τ_{N2}.

DM fluid is radiation-like at temperatures $T > 0.26\,\text{eV} / \text{Br}_{\text{N}_2 \to \text{N}_1}$

Reference point: photon temperature at matter-radiation equality $T \sim 0.3$ eV.

Primordial Matter Power Spectrum



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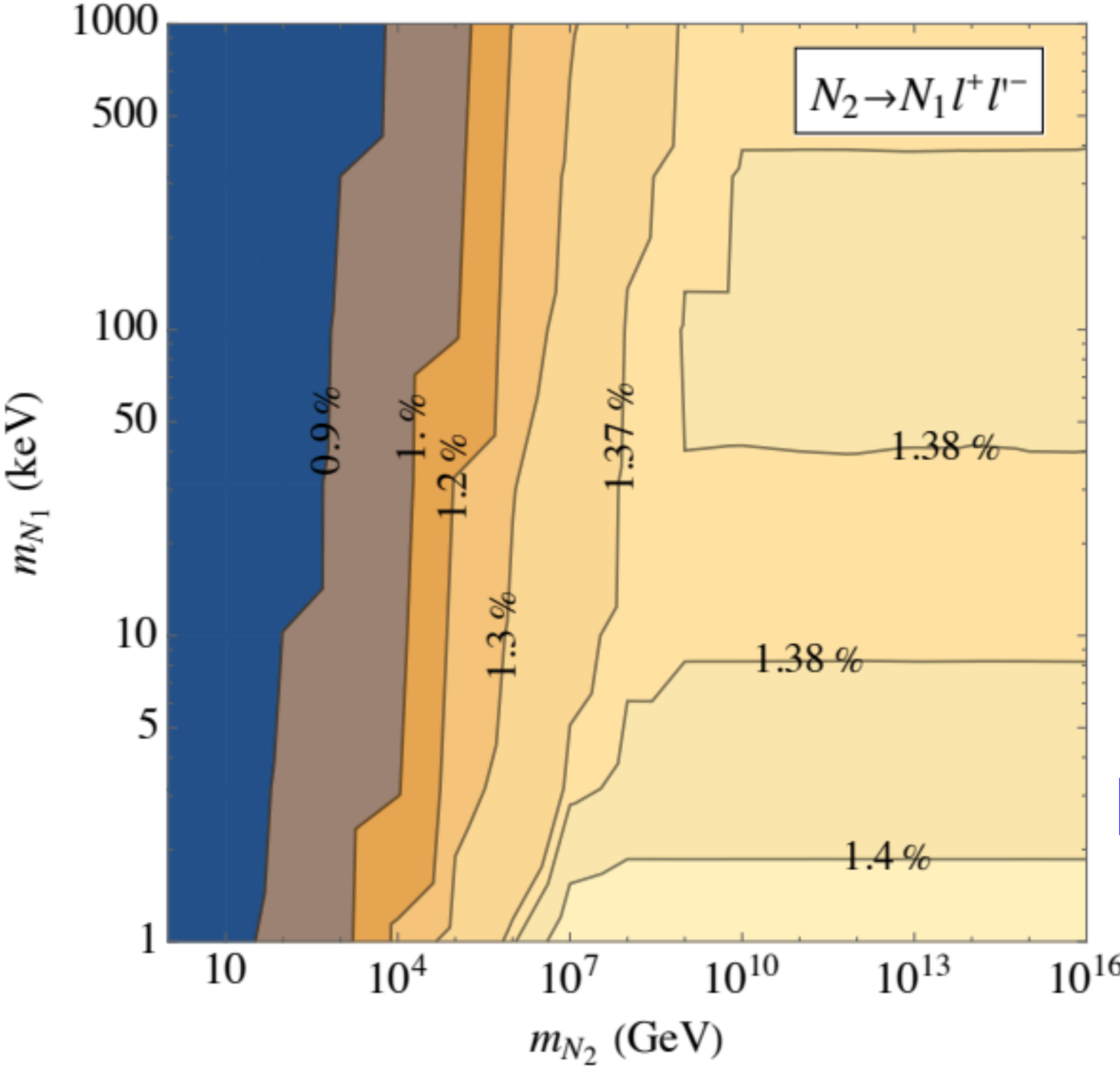
Large Scale Structure Constraint



$\mathrm{Br}_{N_2 \to N_1} \lesssim 1\%$

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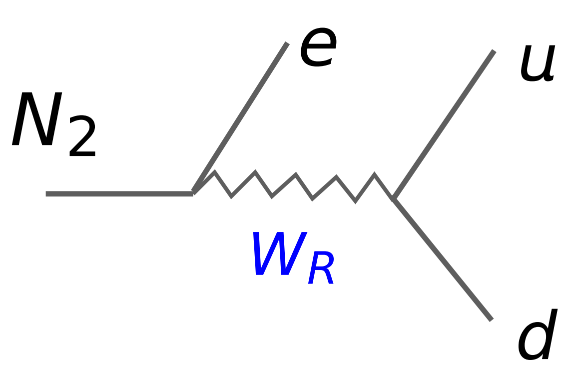
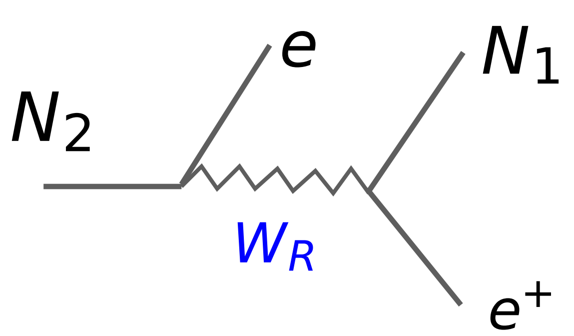
Lifting the Constraint in LR Model

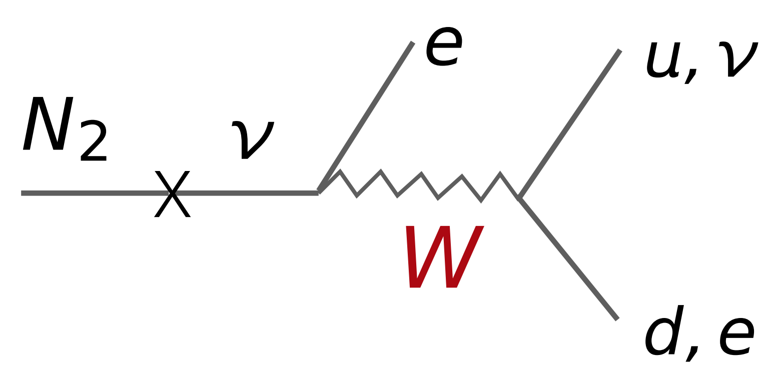


Entropy production (good)



Produces ultra-energetic DM (bad)

Viable dilution mechanism exists if N_2 participates in the seesaw mechanism



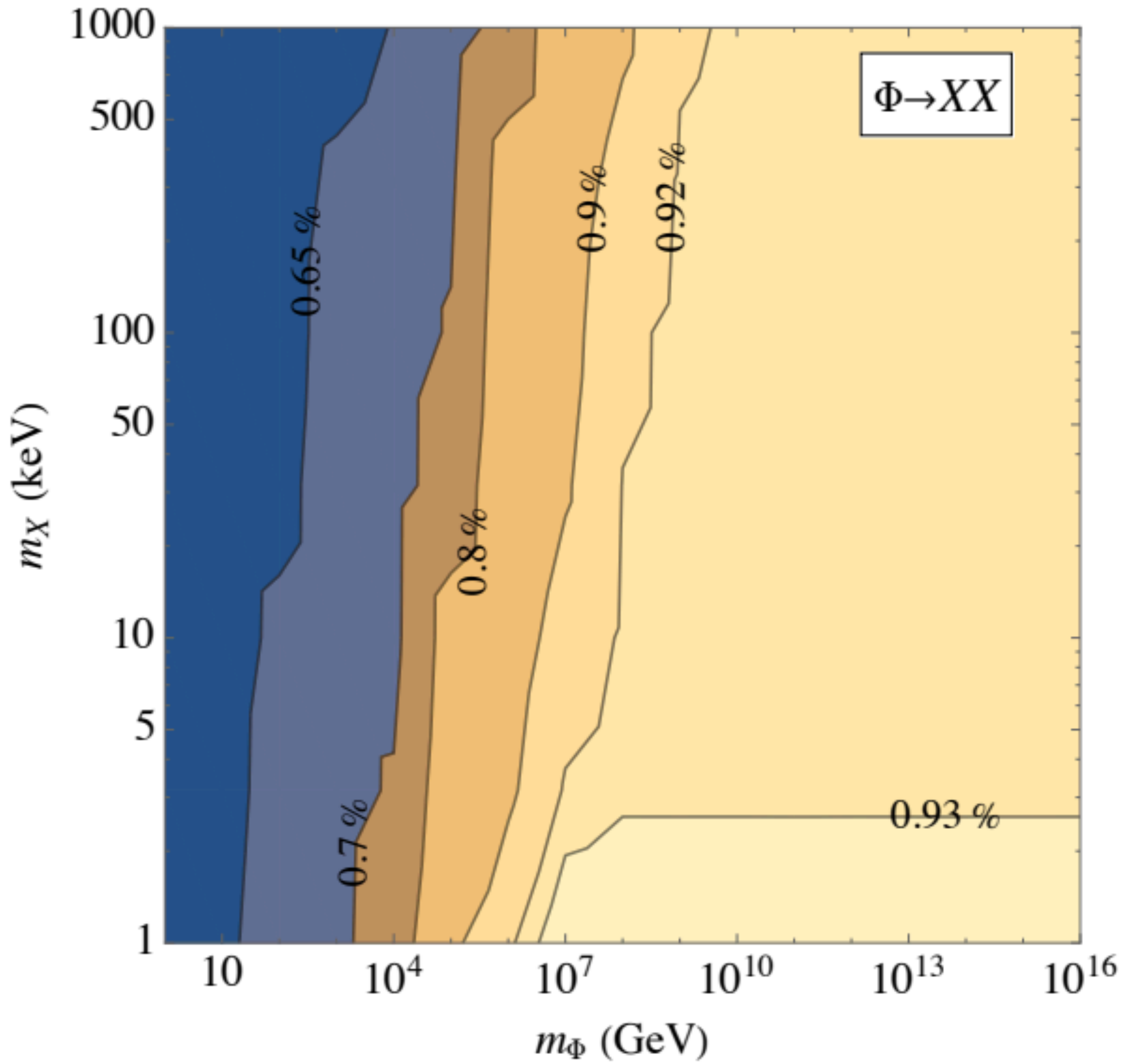
$$\theta \sim \sqrt{m_\nu / M_{N_2}}$$

Lower bound on mass of W_R boson

$$M_{W_R} \gtrsim 55\,\mathrm{TeV} \left(\frac{M_{N_2}}{1\,\mathrm{GeV}} \right)^{1/4}$$

Generic Upper Bound

Similar upper bound on dilutor → DM decay applies to other scenarios



Always need:

$\mathrm{Br}_{\mathrm{dilutor}\to\mathrm{DM}} \lesssim 1\%$

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Other DM Candidates

… that also require a dilution mechanism:

Gravitino dark matter from low-scale gauge mediated SUSY breaking:

Baltz, Murayama (astro-ph/0108172)
Hasenkamp, Kersten (1008.1740)

SU(N) Glueball dark matter:

Soni, Xiao, Zhang (1704.02347)

Conclusion

This talk presents a broad roadmap for dark matter as general thermal relic of the early universe.

After a briefly overview of WIMP and dark sector that already have an extensive search program, we discuss thermal relic dark matter with a dilution mechanism.

Point out new cosmological probes of dilution mechanisms with large scale structure — nicely complement terrestrial efforts.

Thanks!

backup

$\Delta N_{\rm eff}$

Primordial component as a thermal relic:

$$\Delta N_{\rm eff} = \frac{T_{N_1}^4}{T_\nu^4} = 0.22^4 \left(\frac{1\,\mathrm{keV}}{M_{N_1}}\right)^{4/3} \lesssim 2 \times 10^{-3}$$

Secondary component form dilutor decay:

$$\Delta N_{\rm eff} = \frac{43}{7} \frac{y\mathrm{Br}_{N_2 \to N_1}}{1 - y\mathrm{Br}_{N_2 \to N_1}} \left(\frac{43}{4 g_*(T_{\rm RH})}\right)^{4/3} \lesssim 0.022$$

y=7/20 is fraction of energy carried by N_1 in each $N_2 \to N_1$ decay.

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