Dark Matter Dilution Mechanism and Large Scale Structure

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Portorož Conference

April 2023

The Dark Matter Puzzle

$\Omega h^2 = 0.12$.

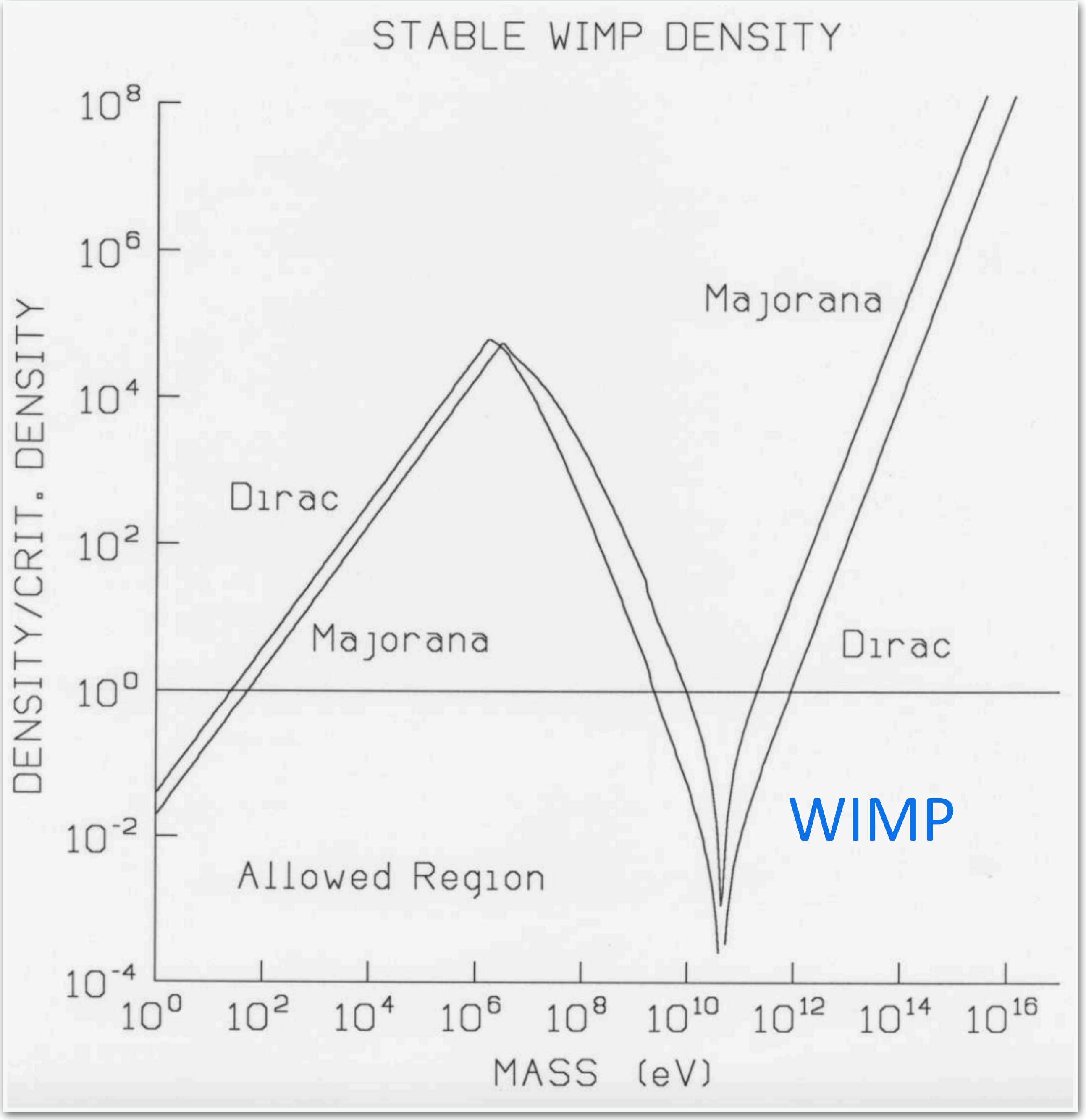
Origin vs Signal.

This talk will take observed relic density as guiding principle.

Many options.

Focus on those have once established thermal equilibrium with SM particles in very early universe.

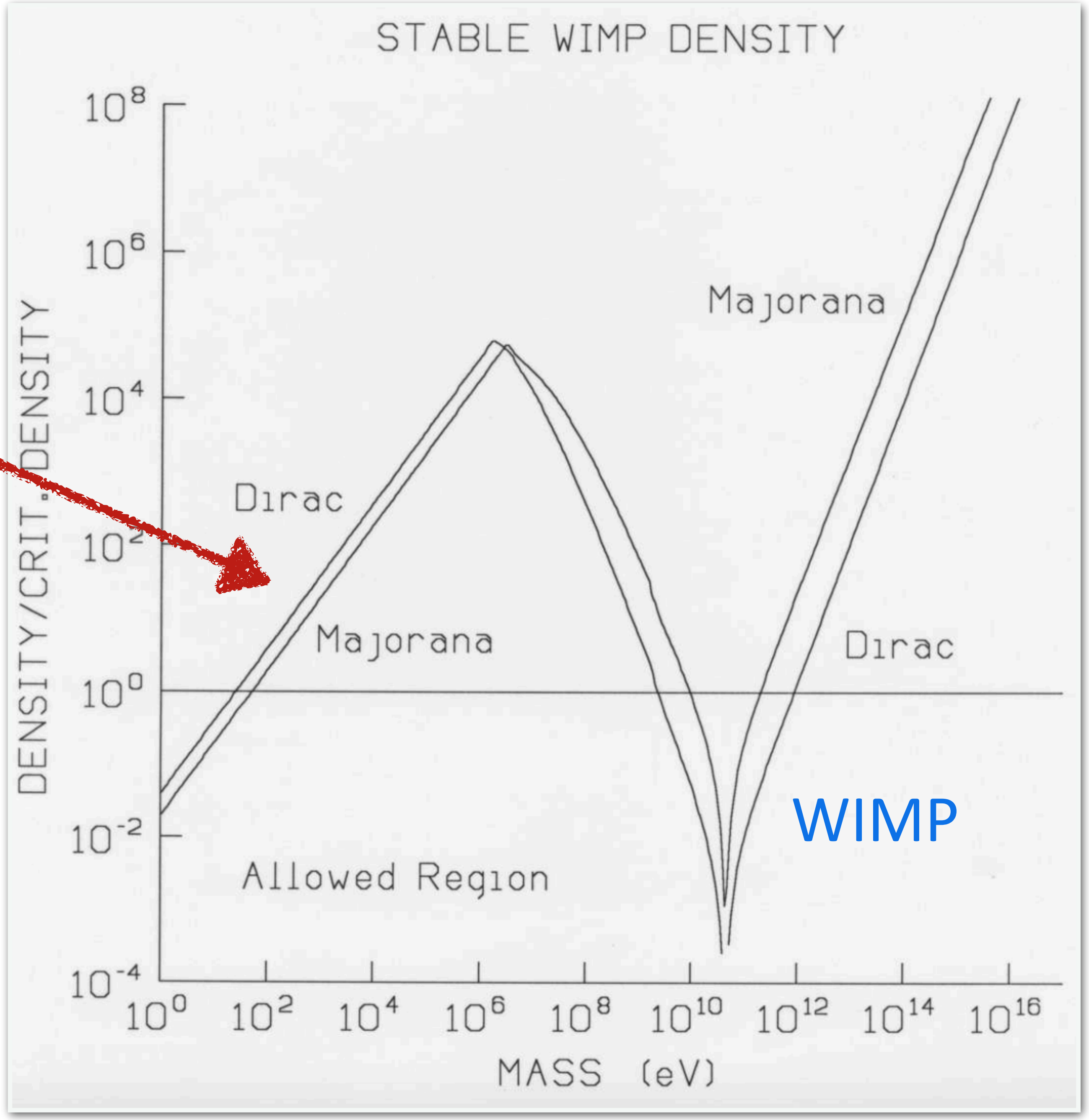
Roadmap of Thermal Relics



J. Terning (1985)

Roadmap of Thermal Relics

Freeze out relativistically (this talk)



J. Terning (1985)

Active Neutrinos

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

$$\Omega_\nu h^2 = \frac{m_\nu}{93\,\mathrm{eV}} \sim 0.12\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)$$

Relic density would work if $m_\nu \sim 10$ eV, but inconsistent with the known neutrino mass scale.

4th active neutrino? — structure formation limits forbid thermal relic DM lighter than several keV scale — overproduction problem.

Something Else as Dark Matter

that still freeze out relativistically.

Reduce the dark matter relic abundance by “heating up” photons in the early universe.

$$\Omega h^2 \sim 100 \times 0.12 \left(\frac{M}{\mathrm{keV}}\right) \times \frac{1}{\mathcal{S}}$$

Textbook example of dilution via temperature dependence in g_*

$$\frac{1}{\mathcal{S}} = \left(\frac{10.75}{g_*(T_{\mathrm{dec}})}\right)$$

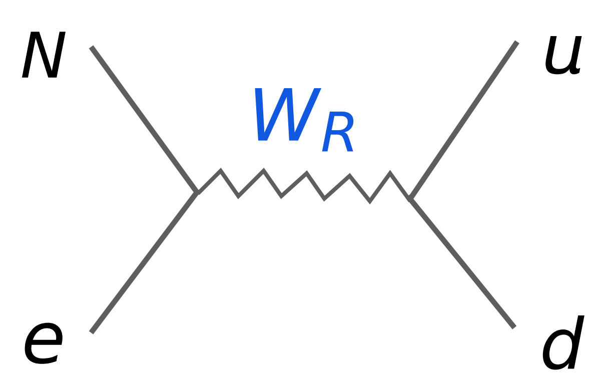
DM dilution via a “long-lived” particle.

Scherrer, Turner (1985)

Right-handed Neutrino as DM

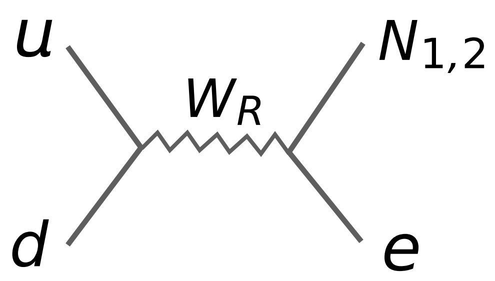
Motivated for generating nonzero neutrino masses.

Thermal relic scenario: embed in gauge extensions of the SM.
E.g. $U(1)_{B-L}$ or left-right symmetric model.

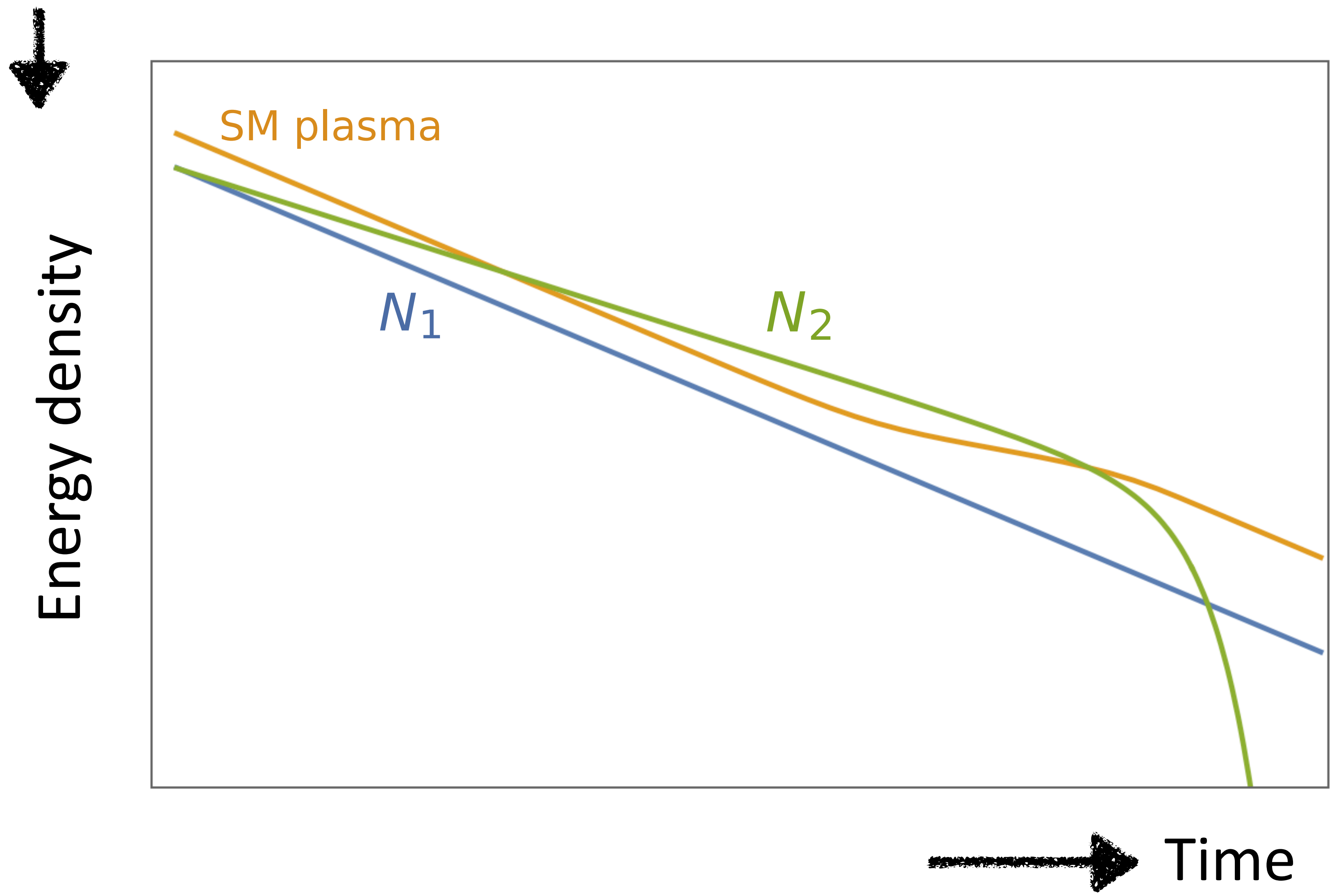


Large Hadron Collider: $M_{W_R} > 5$ TeV. *N* does decouple sooner than active neutrinos - still overproduced - needs dilution.

Dark Matter Dilution Mechanism



relativistic freeze out



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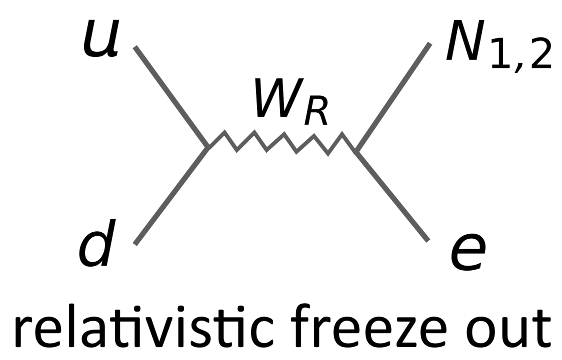

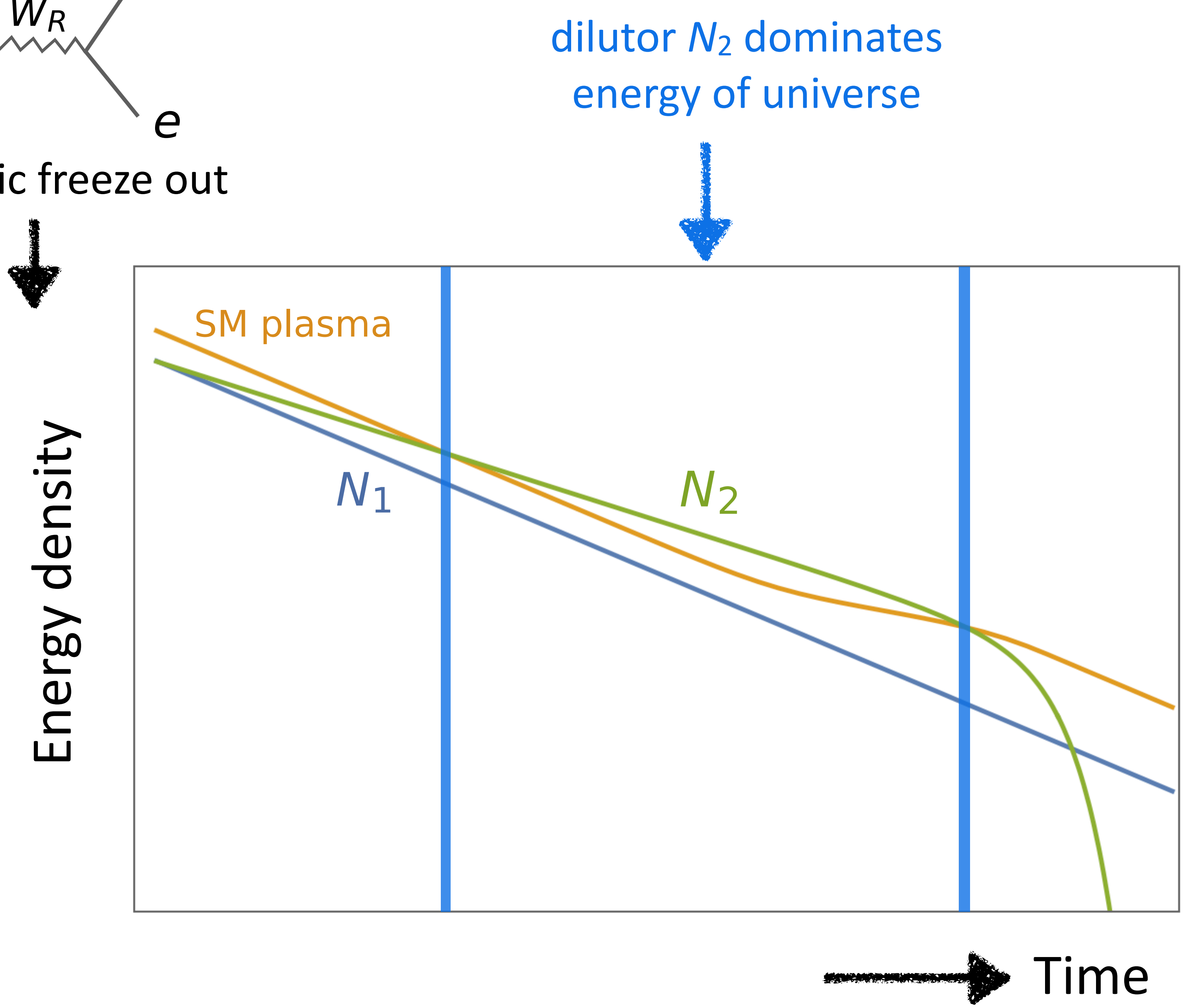

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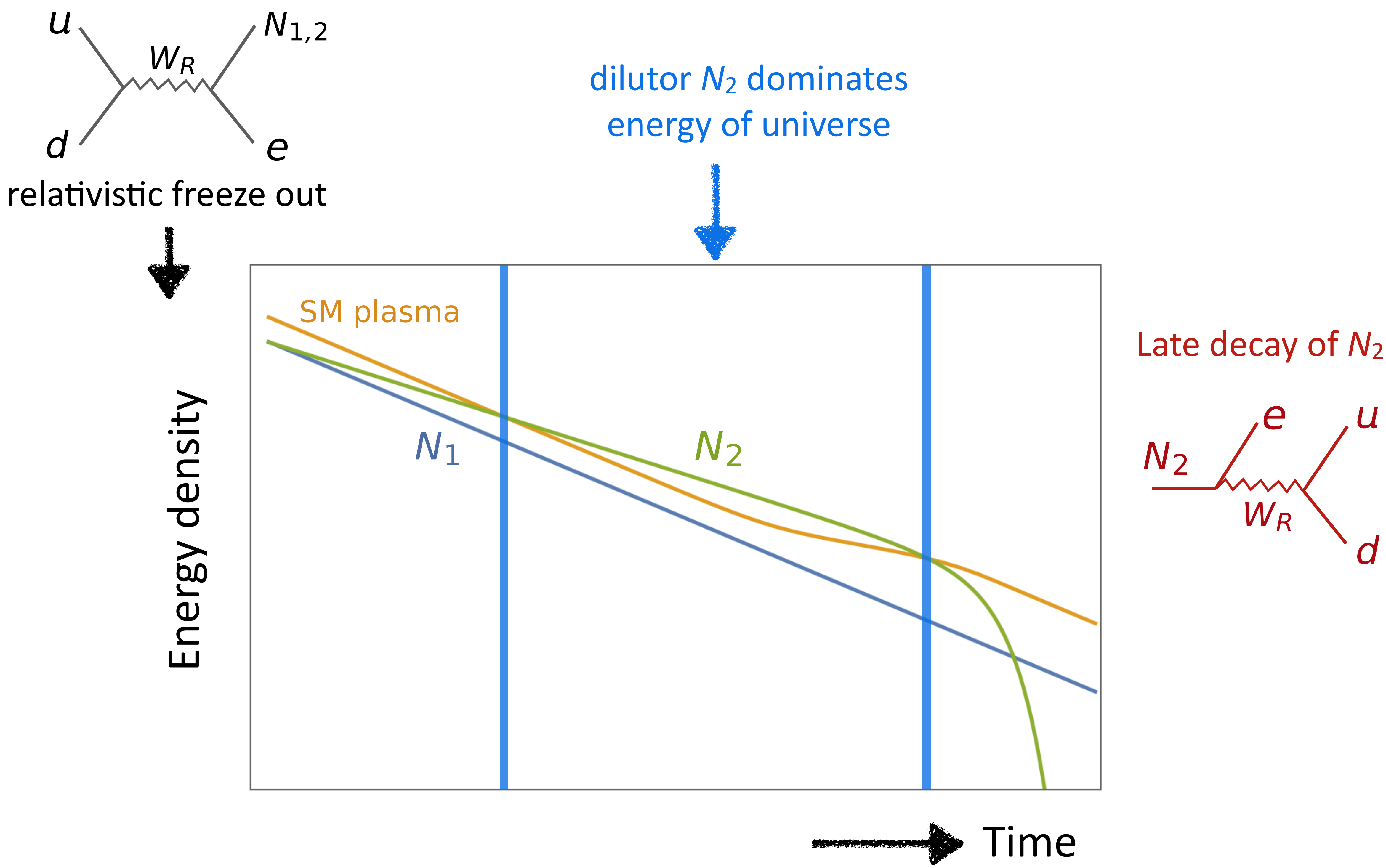
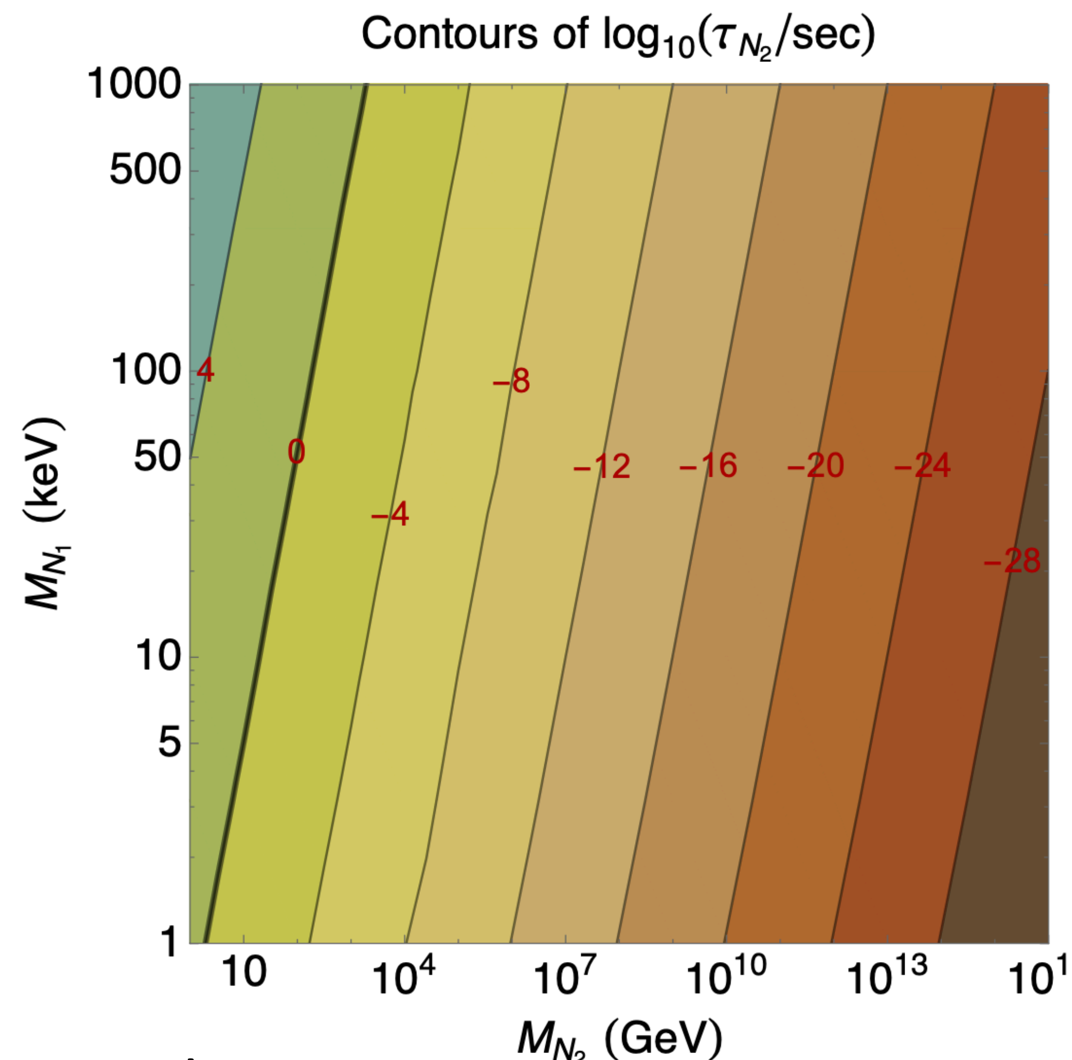


Diluted Dark Matter Relic Density

Such a mechanism has been shown to work in the left-right symmetric model.



Sudden decay approximation:

$$\Omega h^2 \simeq 0.12 \left(\frac{M_{N_1}}{1\,\mathrm{keV}}\right)\left(\frac{1\,\mathrm{GeV}}{M_{N_2}}\right)\sqrt{\frac{1\,\mathrm{sec}}{\tau_{N_2}}}$$

(Effectively 3 parameters, dilutor mass >> DM)

Bezrukov, Hettmansperger, Lindner (0912.4415)

Warm Dark Matter Constraints

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

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

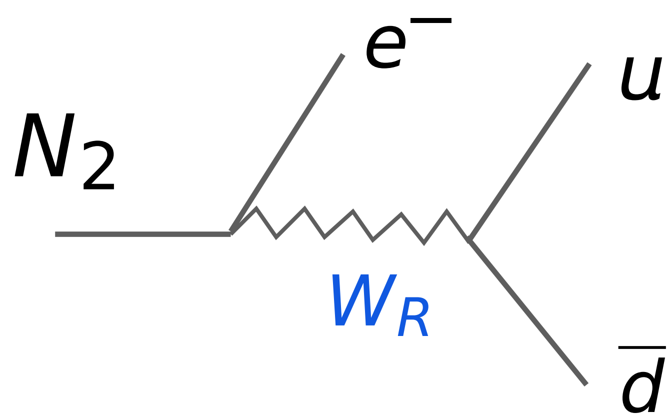
After dilution, N_1 is essentially a warm DM — free-streaming can smooth out observed small-scale structures in the universe (e.g. MilkyWay satellites, Lyman-α, strong lensing)

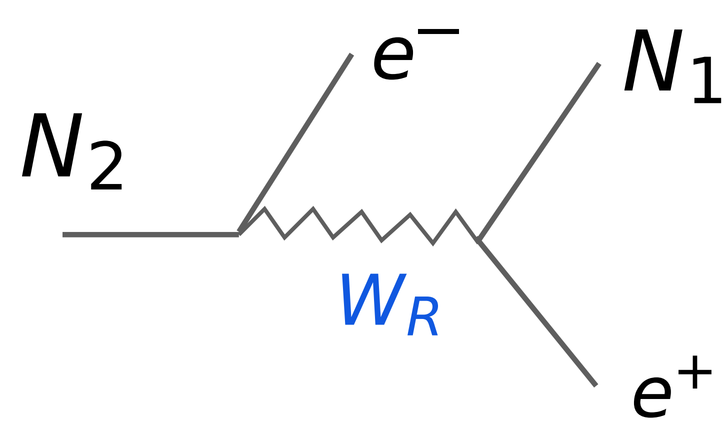
$$M_{\mathrm{WDM}} > 6.5\,\mathrm{keV}$$

DES Collaboration (2008.00022)

New Opportunities

Dilutor-to-DM decay: through right-handed current interaction, dilutor N_2 can also decay into N_1, inevitably.

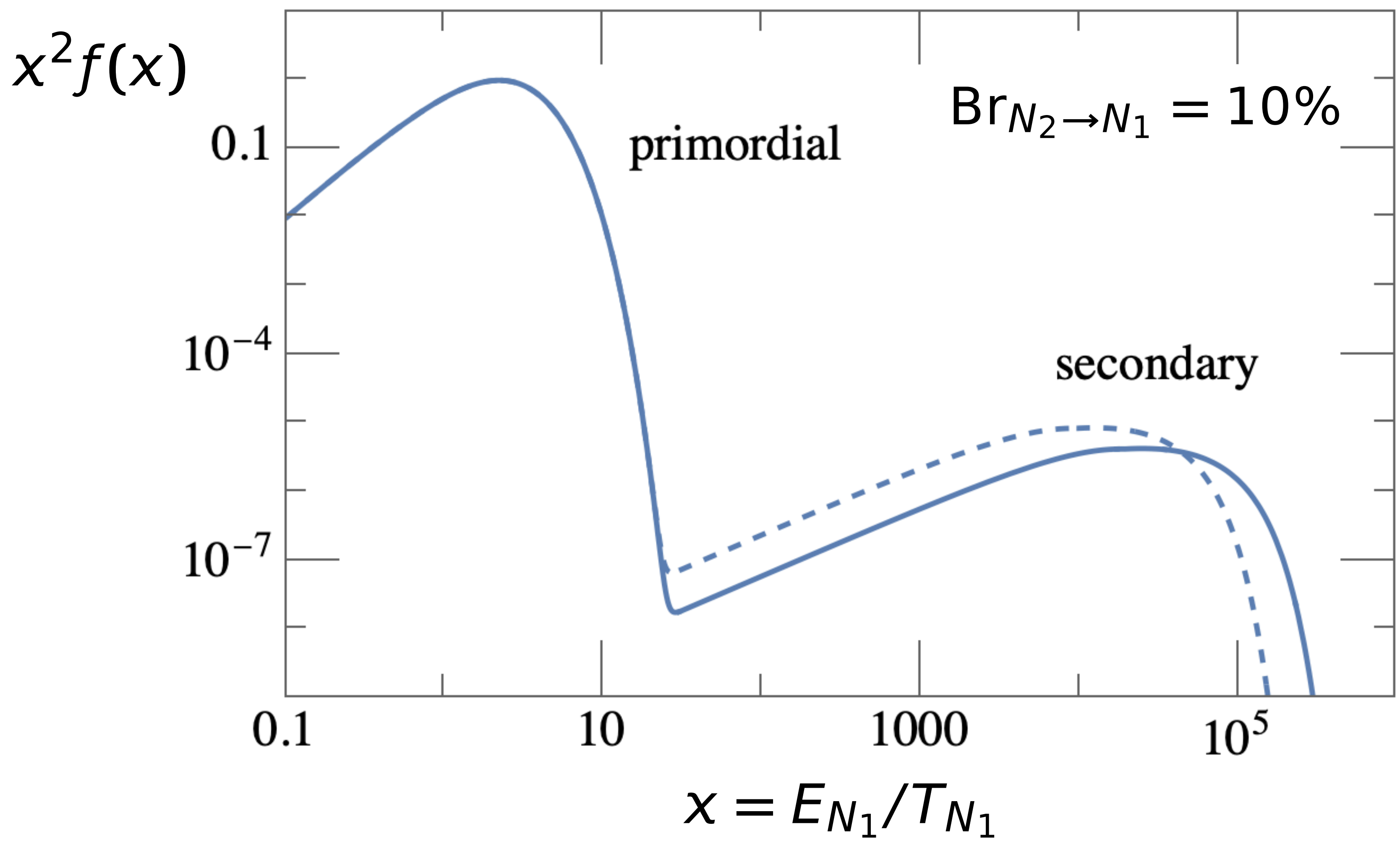




Sufficiently heavy N_2, second channel has decay Br = 1/10-1/7.

Phase Space Distribution

Secondary component of DM from dilutor way more energetic.



Miha Nemevsek and Yue Zhang (2206.11293)

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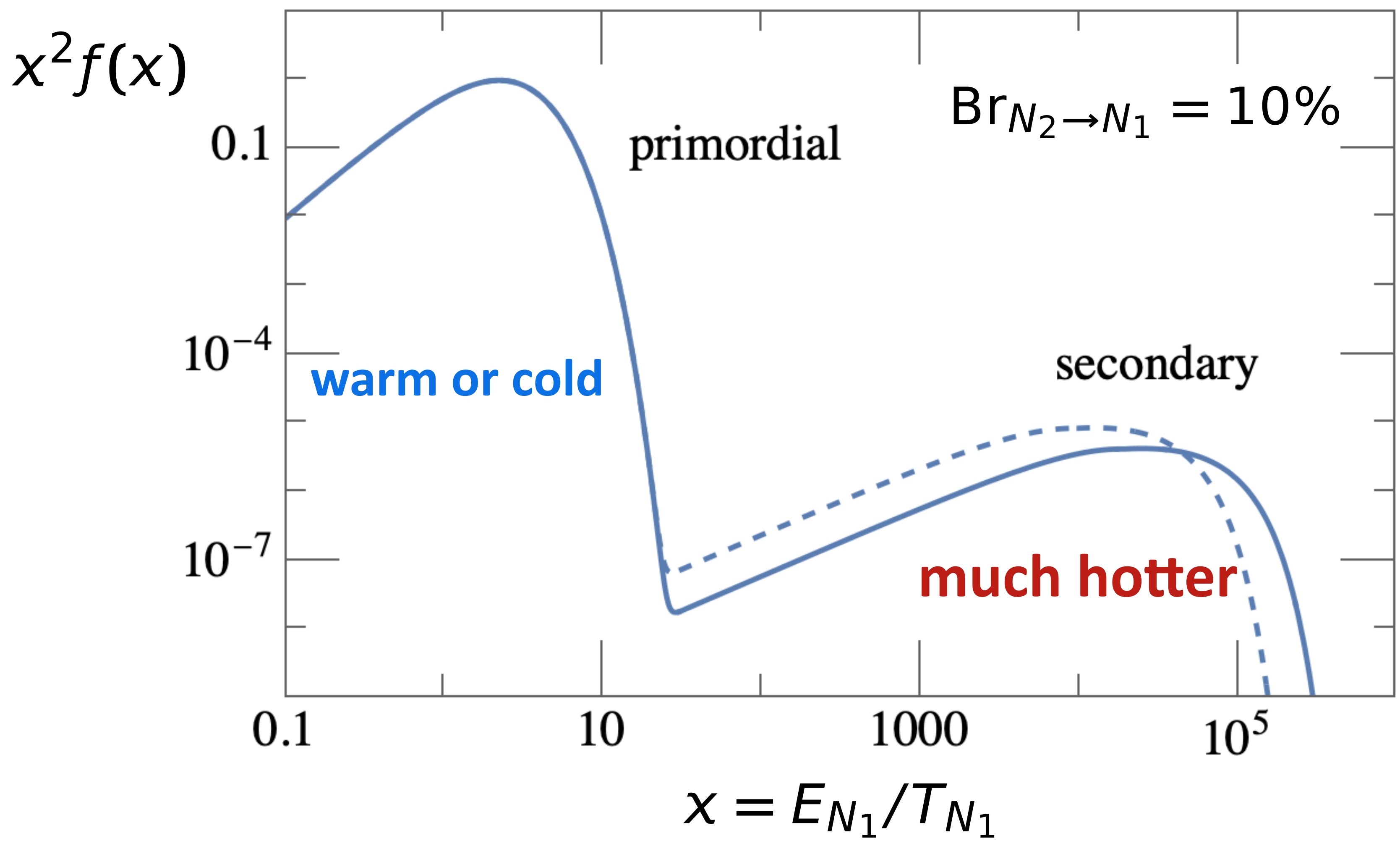

Miha Nemevsek and Yue Zhang (2206.11293)

Fate of Secondary Dark Matter

	Energy of secondary DM (N_1)	Temperature of photon background
Immediately after dilutor (N_2) decay	$\sim M_{N2}$	$T_{\rm RH}$
Secondary DM just turns non-relativistic	$\sim M_{N1}$	$T_{\rm NR} \sim T_{\rm RH} \dfrac{M_{N_1}}{M_{N_2}}$

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Another look at relic density $\quad \Omega h^2 \simeq 0.12 \left(\dfrac{M_{N_1}}{1\,\mathrm{keV}}\right)\left(\dfrac{1\,\mathrm{GeV}}{M_{N_2}}\right)\left(\dfrac{T_{\rm RH}}{1\,\mathrm{MeV}}\right)$

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→ $\boldsymbol{T_{\rm NR} \sim 0.3}$ **eV** — independent of any parameters M_{N1}, M_{N2}, τ_{N2}, up to a super mild $g_*(T_{\rm RH})^{\frac{1}{12}}$ dependence.

Early On

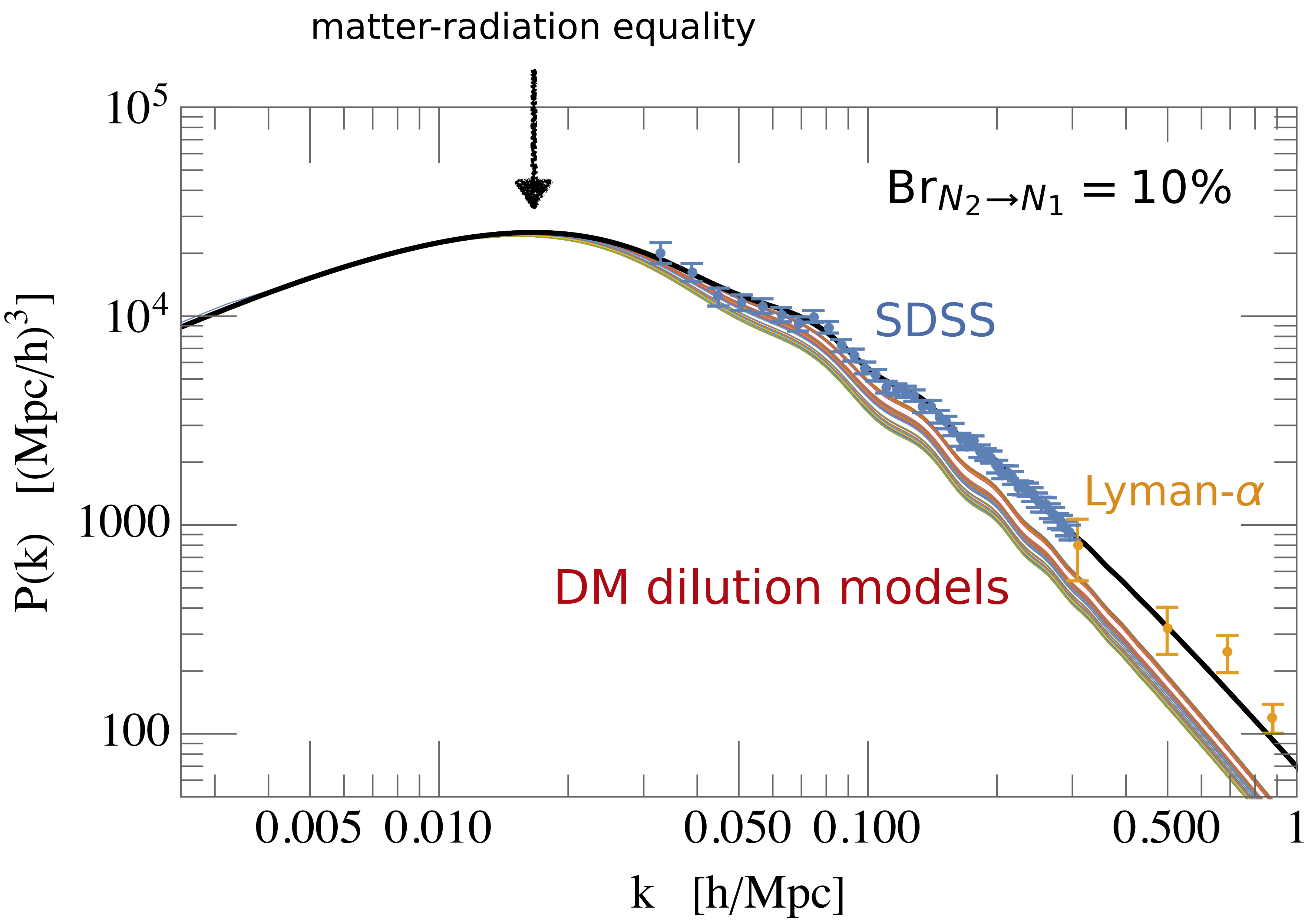
Energy density of radiation red-shifts faster than matter.

If a fraction $\mathrm{Br}_{N_2 \to N_1}$ of dark matter in the universe is made of the hot secondary components, the whole DM fluid would behave like radiation at temperatures above

$$T > \frac{0.3\,\mathrm{eV}}{\mathrm{Br}_{N_2 \to N_1}}$$

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

Length Scales of Damping



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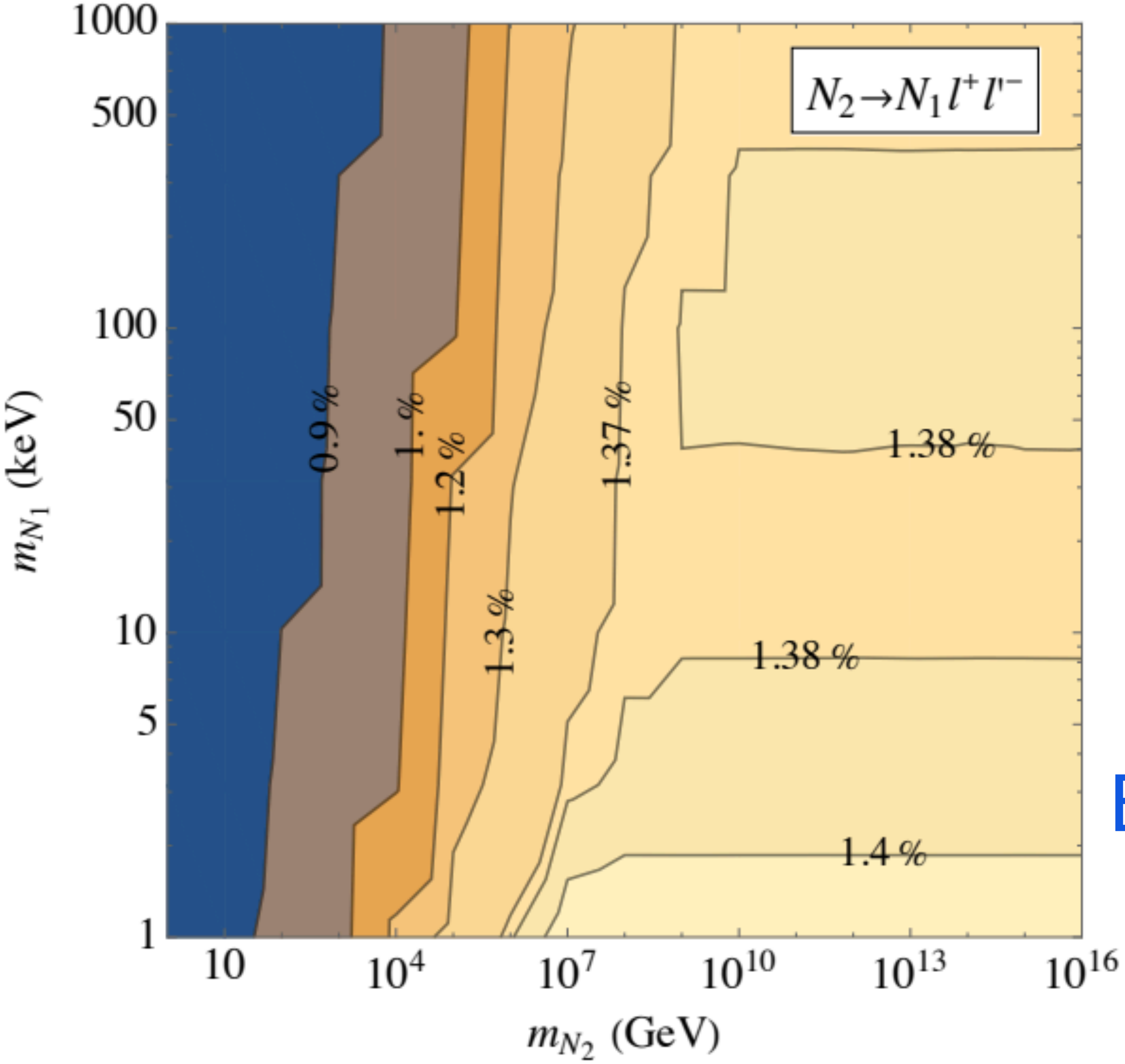
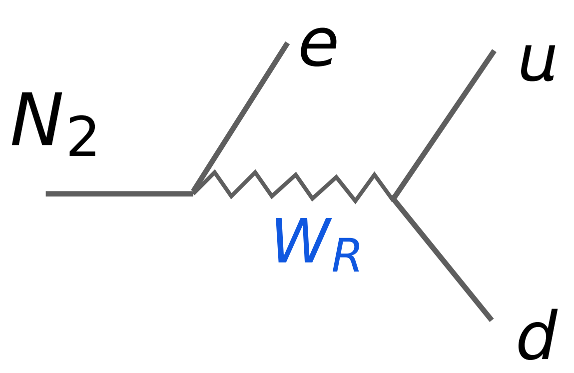
Large Scale Structure Constraint



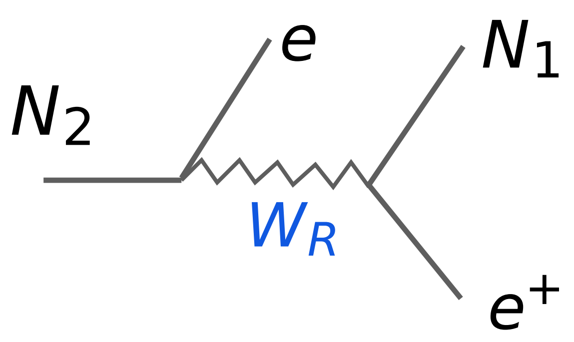
$\mathrm{Br}_{N_2 \to N_1} \lesssim 1\%$

Miha Nemevsek and Yue Zhang (2206.11293)

Implication for the Left-Right Model

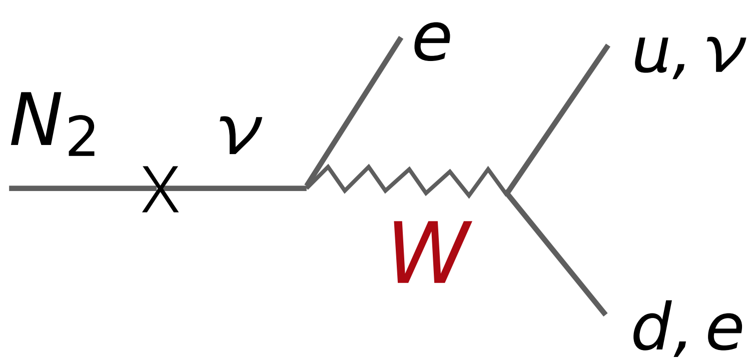


Entropy production (good)



Producing hot dark matter (bad)

Viable dilution mechanism exists if N_2 participates in the seesaw mechanism

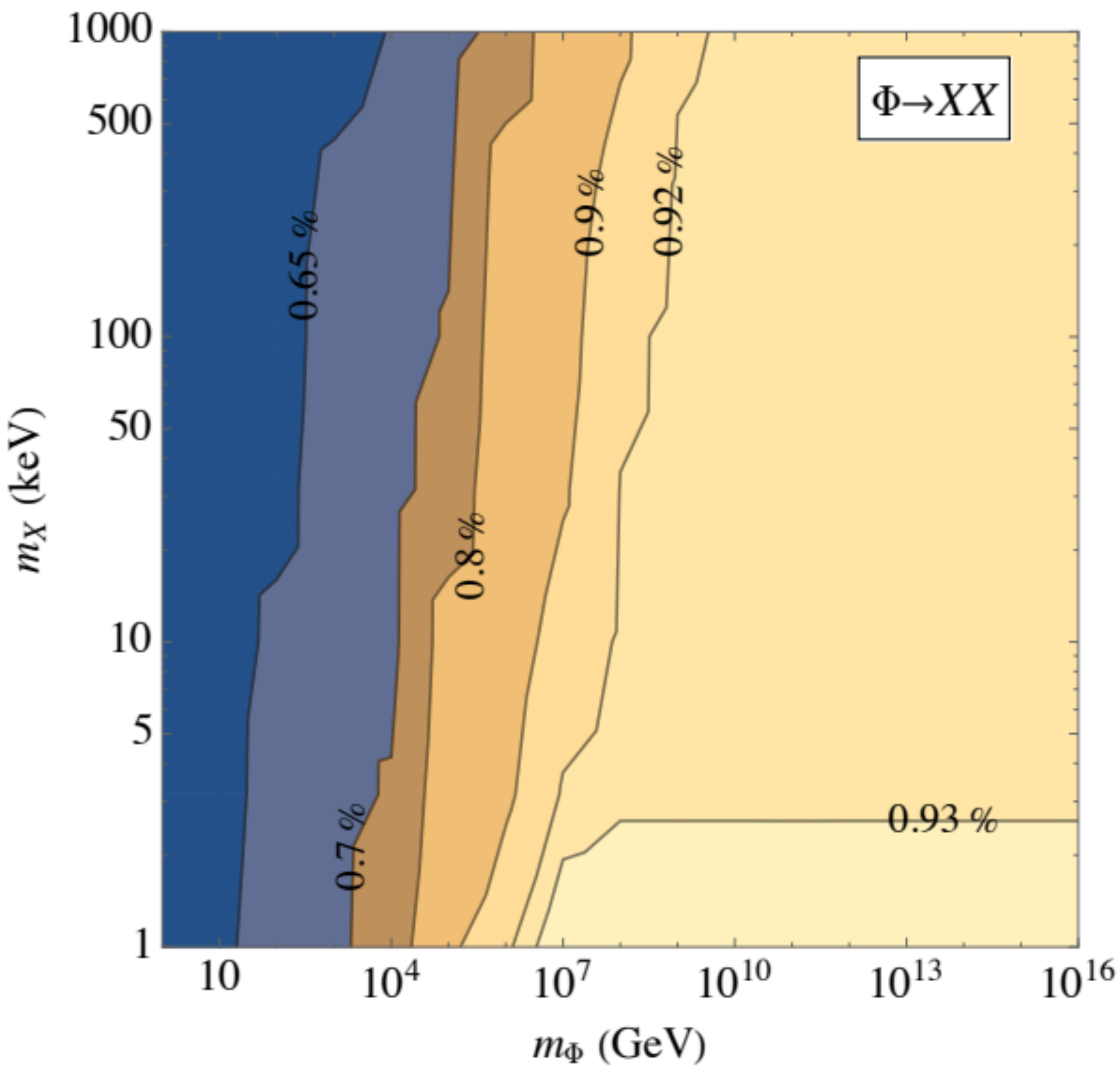


LSS sets lower bound on W_R boson mass

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

Generic Upper Bound

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



Always require:

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

Implications

A number of dark matter models resort to dilution mechanism:

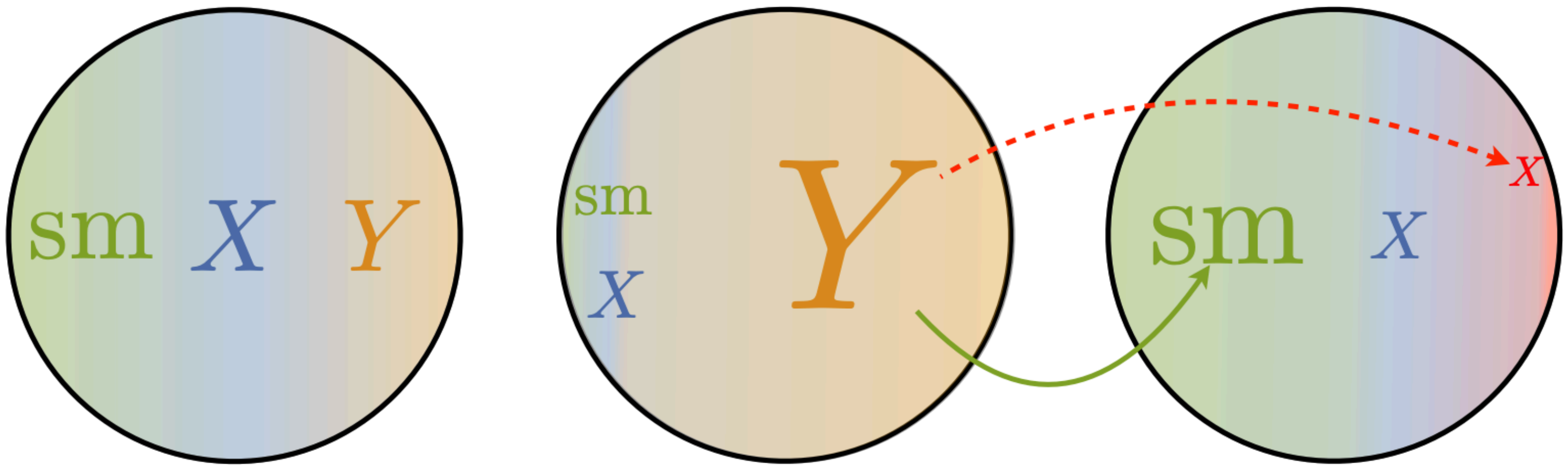
Gravitino, twin-Higgs models, strongly coupled dark sectors …

Beware: *Baltz, Murayama (astro-ph/0108172); Hasenkamp, Kersten (1008.1740); Chacko, Craig, Fox, Harnik (1611.07975); Soni, Xiao, Zhang (1704.02347); Asadi, Kramer, Kuflik, Slatyer, Smirnov (2203.15813) ……*

Decay of diluting particle to other light and free-streaming stuff would be subject to a similar LSS bound.

Conclusion

This talk focuses on thermal relic dark matter that originates from entropy dilution mechanism, points out novel, powerful cosmological probe using the large scale structure.



Thanks!

Bonus

Prediction for ΔN_{eff}

Primordial component as a thermal relic:

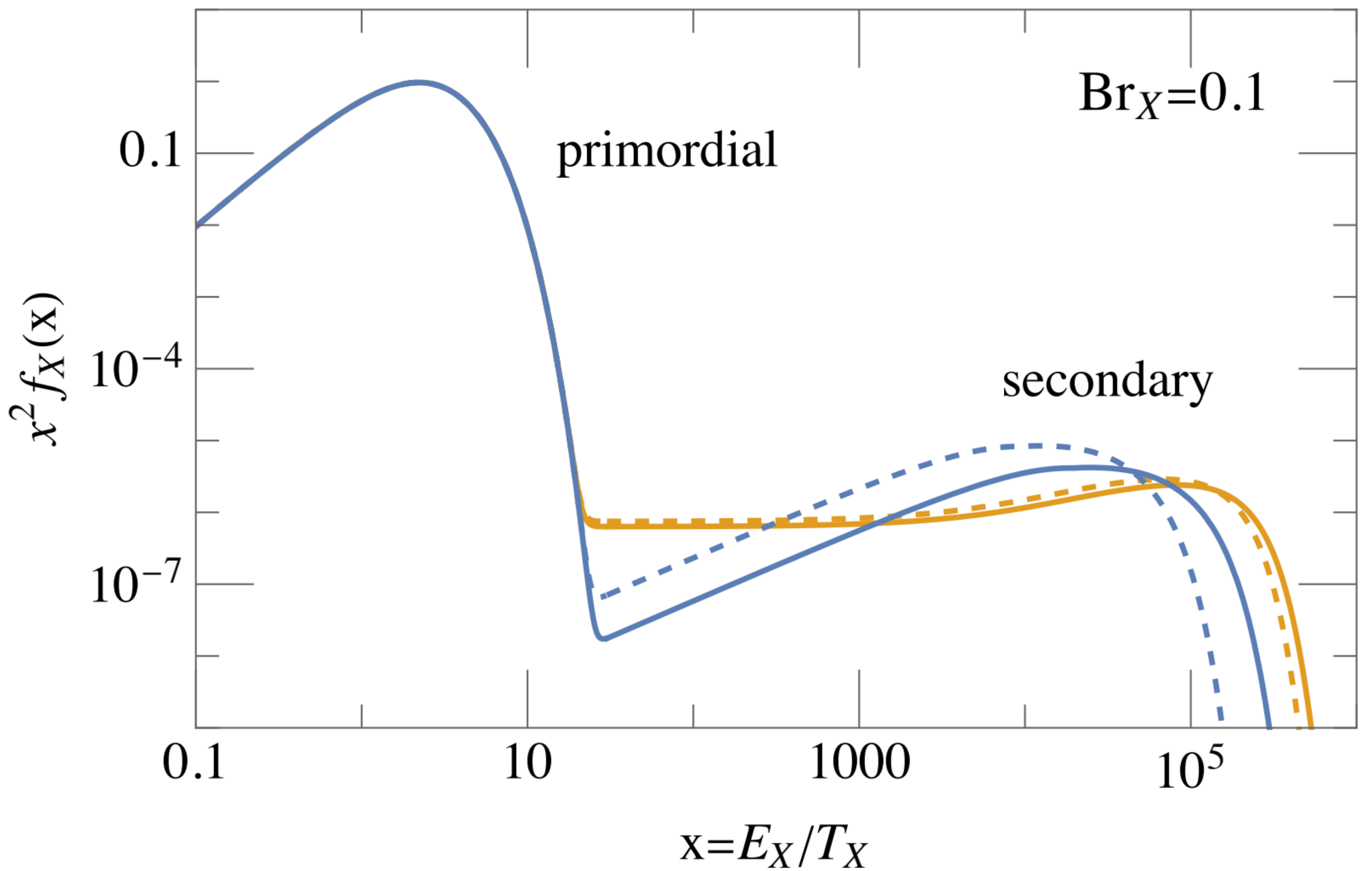
$$\Delta N_{\mathrm{eff}} = \frac{T_{N_1}^4}{T_\nu^4} = 0.22^4 \left(\frac{1\,\mathrm{keV}}{M_{N_1}} \right)^{4/3} \lesssim 2 \times 10^{-3}$$

Secondary component form dilutor decay:

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

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

Phase Space Distributions



Blue: two-body. Orange: three-body decay.