Dark Matter Dilution Mechanism and Large Scale Structure

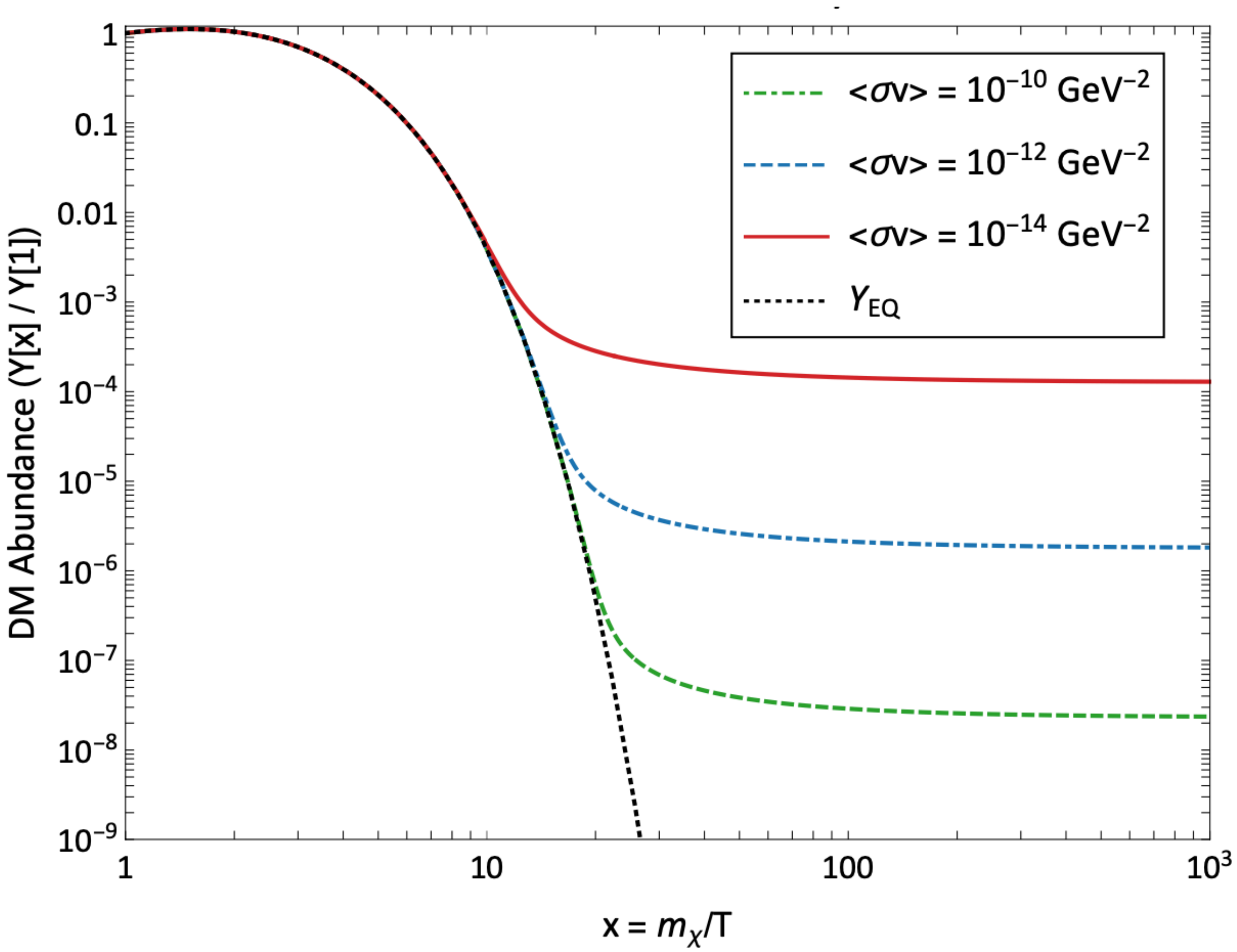
Yue Zhang

Carleton University

CAP Congress, University of New Brunswick

Fredericton NB, June 2023

WIMP Dark Matter

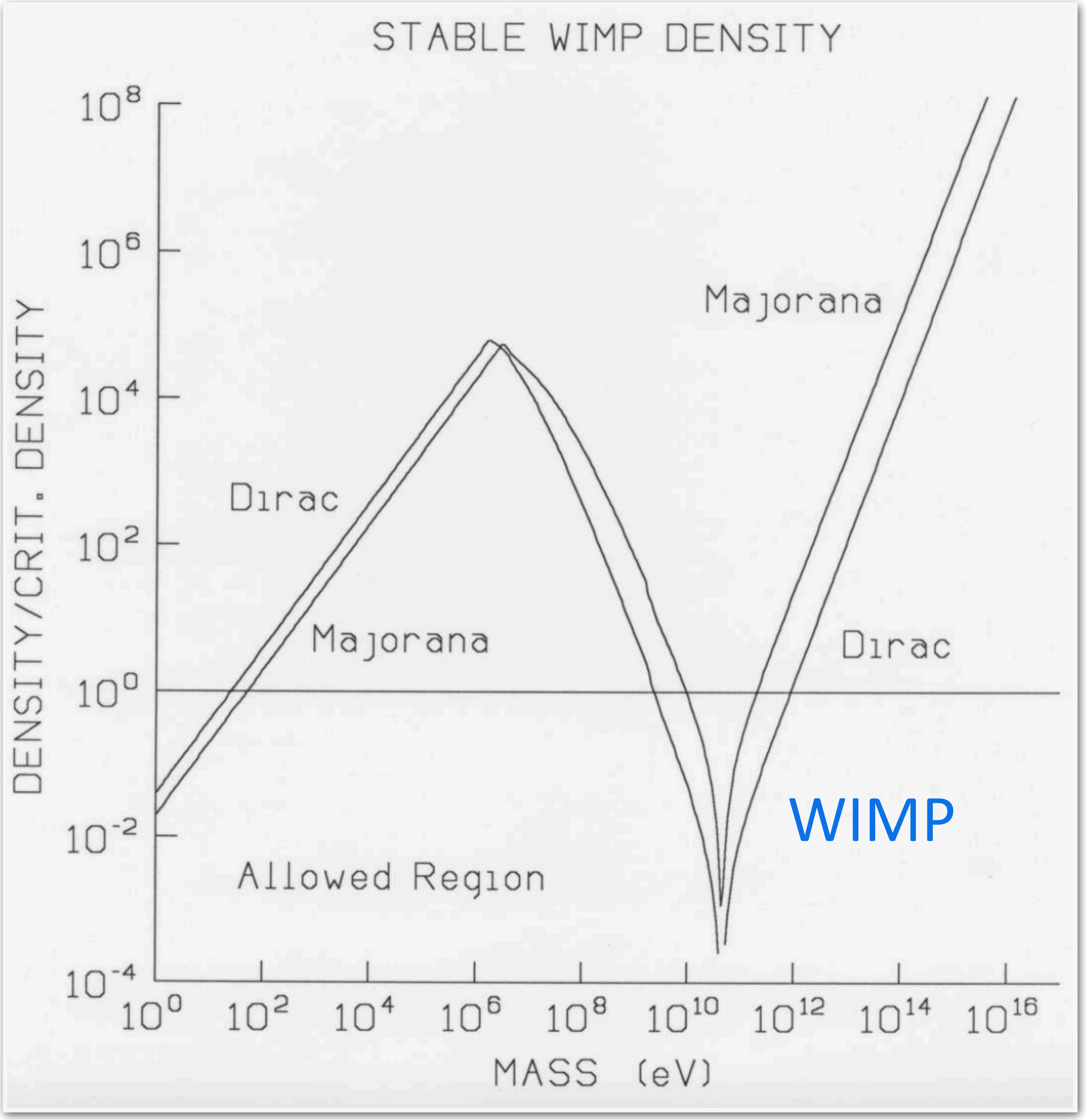


$$\Omega h^2 \sim \frac{1}{\langle \sigma v \rangle}$$

WIMP: Relic abundance as the guiding principle.

Dynamical, independent of initial condition, predictive

More General Thermal Relics

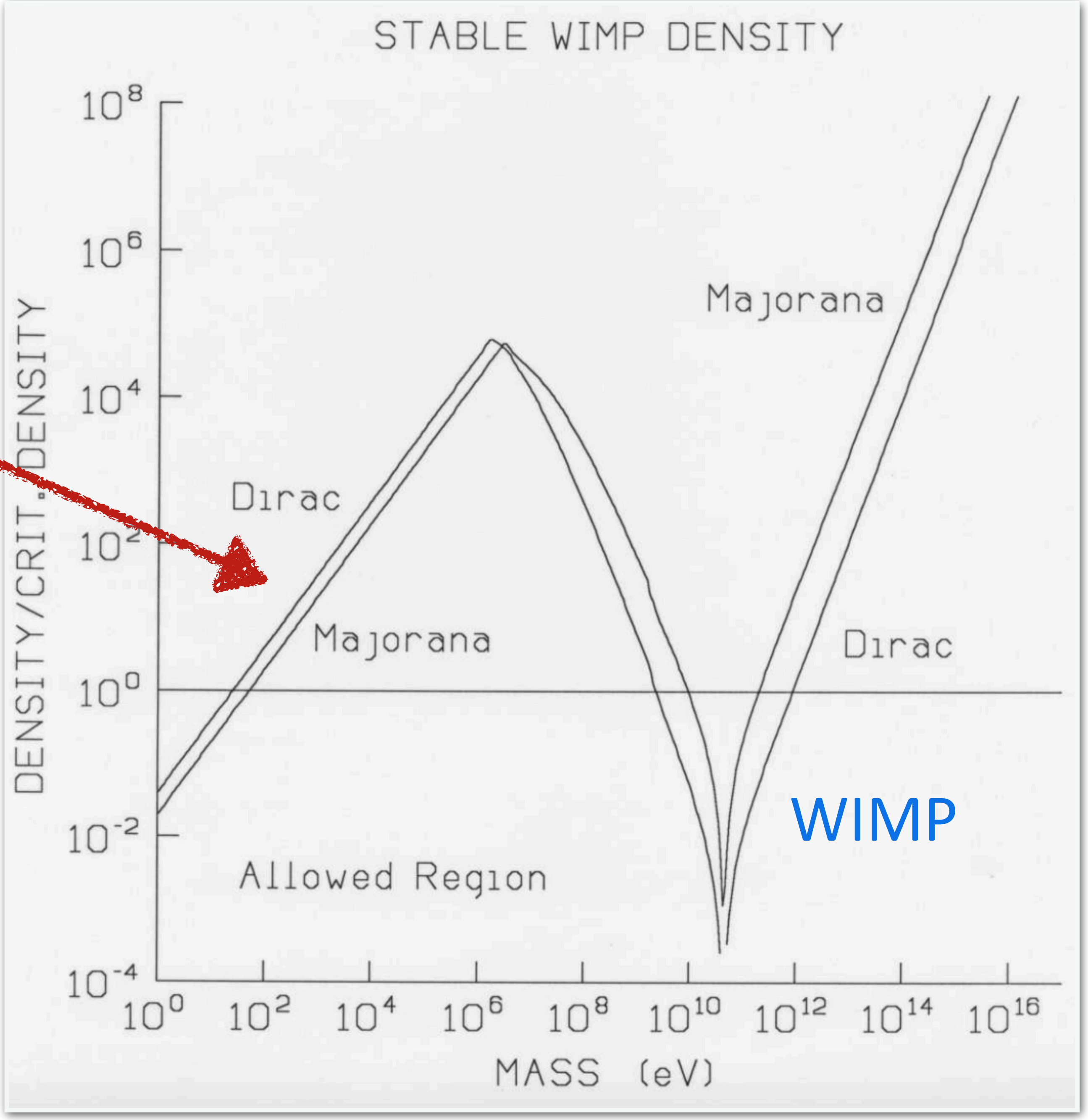


J. Terning (1985)

More General 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.

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

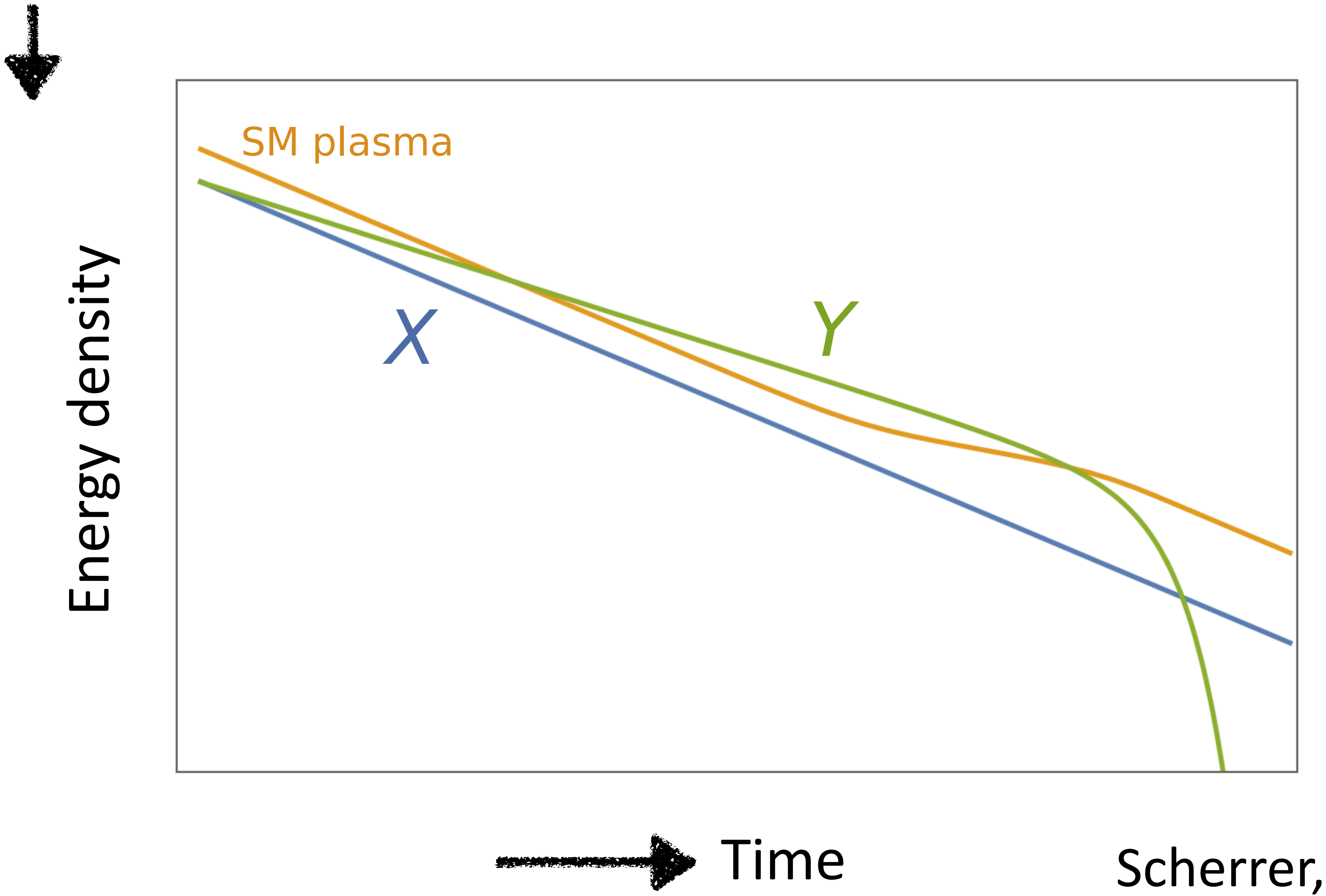
Textbook example of dilution via temperature dependence in g_*

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

DM dilution via a “long-lived” particle in early universe.

Dark Matter Dilution Mechanism

Both dark matter (*X*) and
the diluting particle (*Y*)
freeze out relativistically.

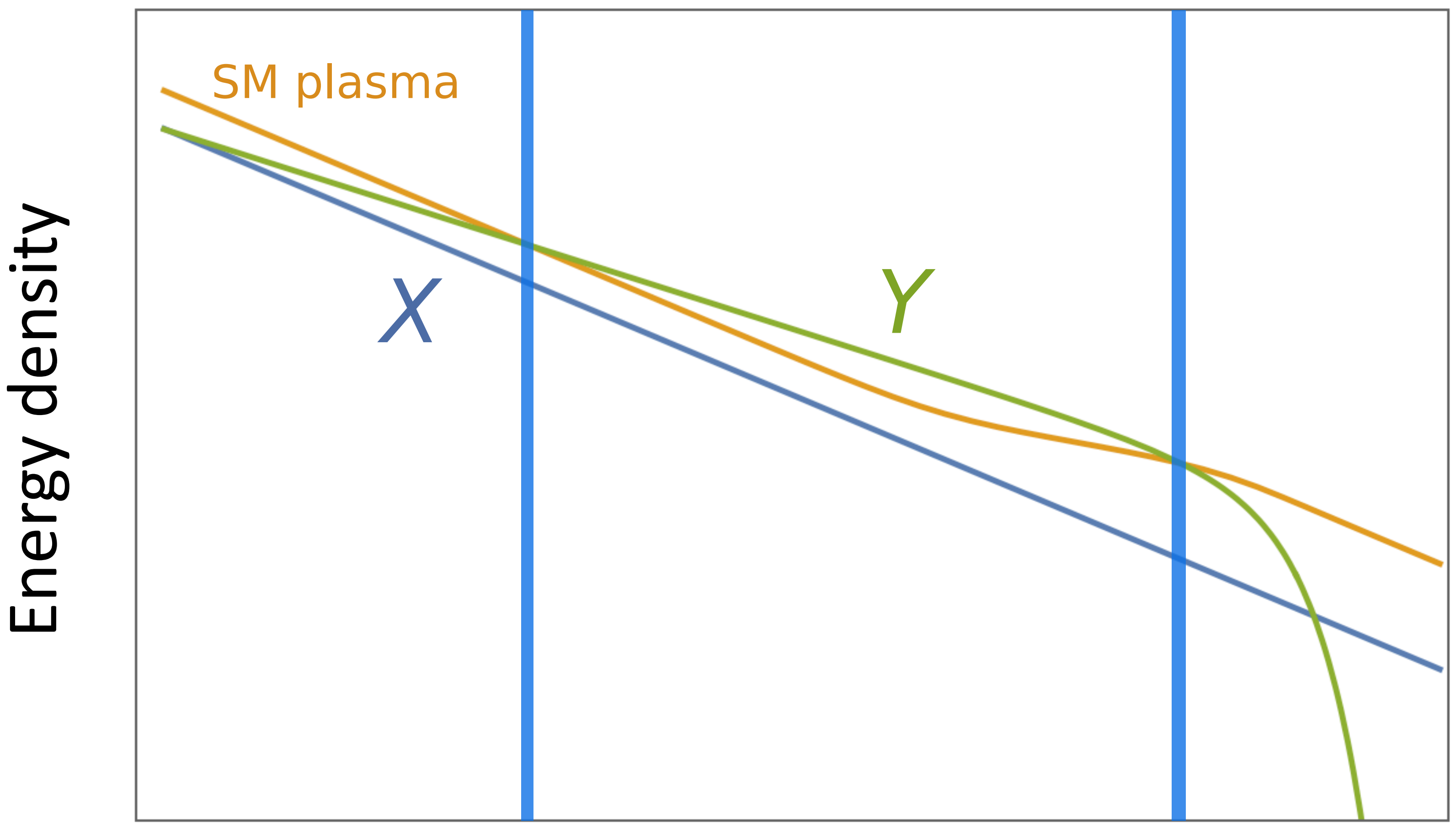


Scherrer, Turner (1985)

Dark Matter Dilution Mechanism

Both dark matter (*X*) and
the diluting particle (*Y*)
freeze out relativistically.

dilutor *Y* comes into domination
of total energy of the universe

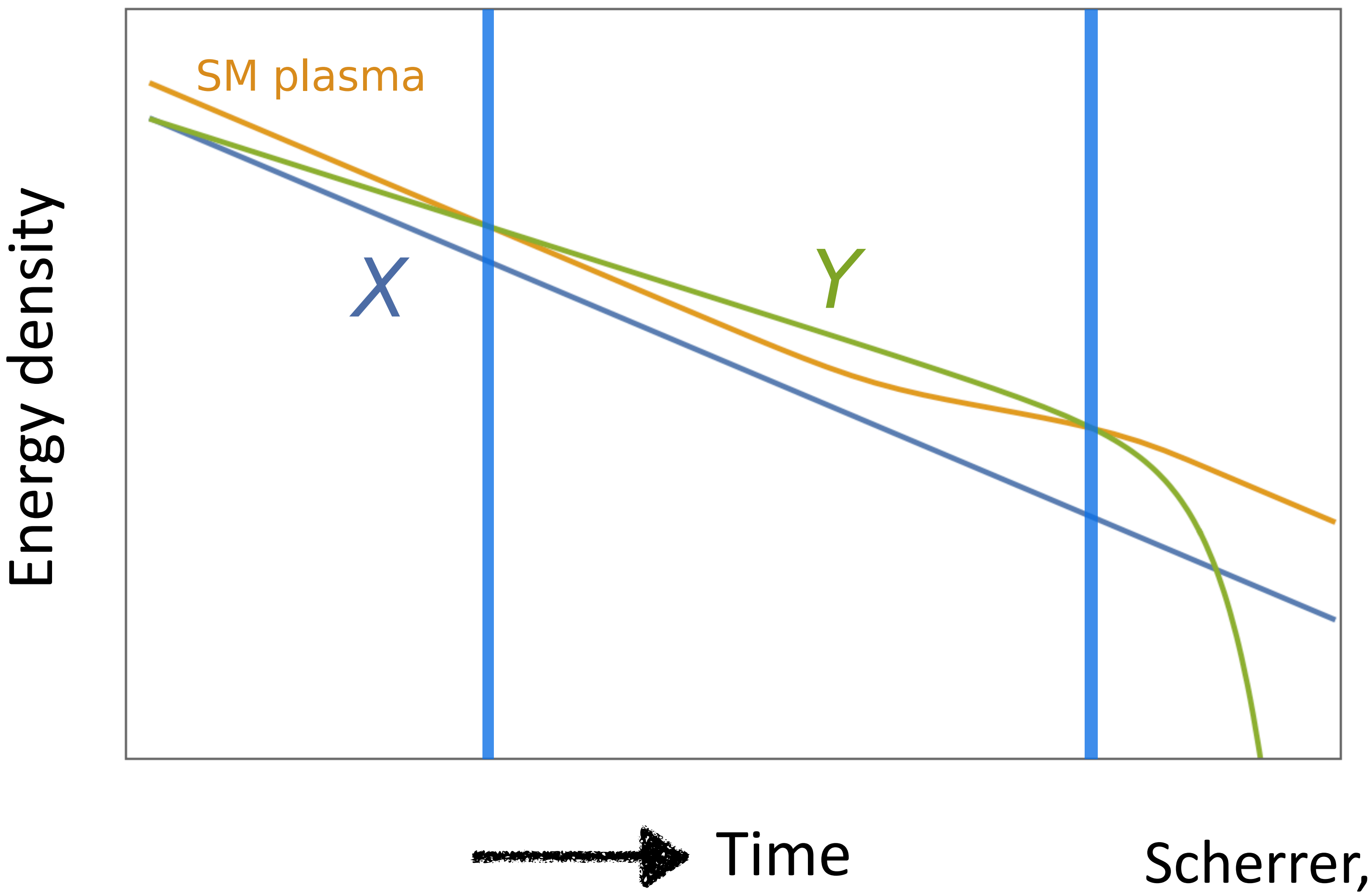


Scherrer, Turner (1985)

Dark Matter Dilution Mechanism

Both dark matter (*X*) and the diluting particle (*Y*) freeze out relativistically.

dilutor *Y* comes into domination of total energy of the universe



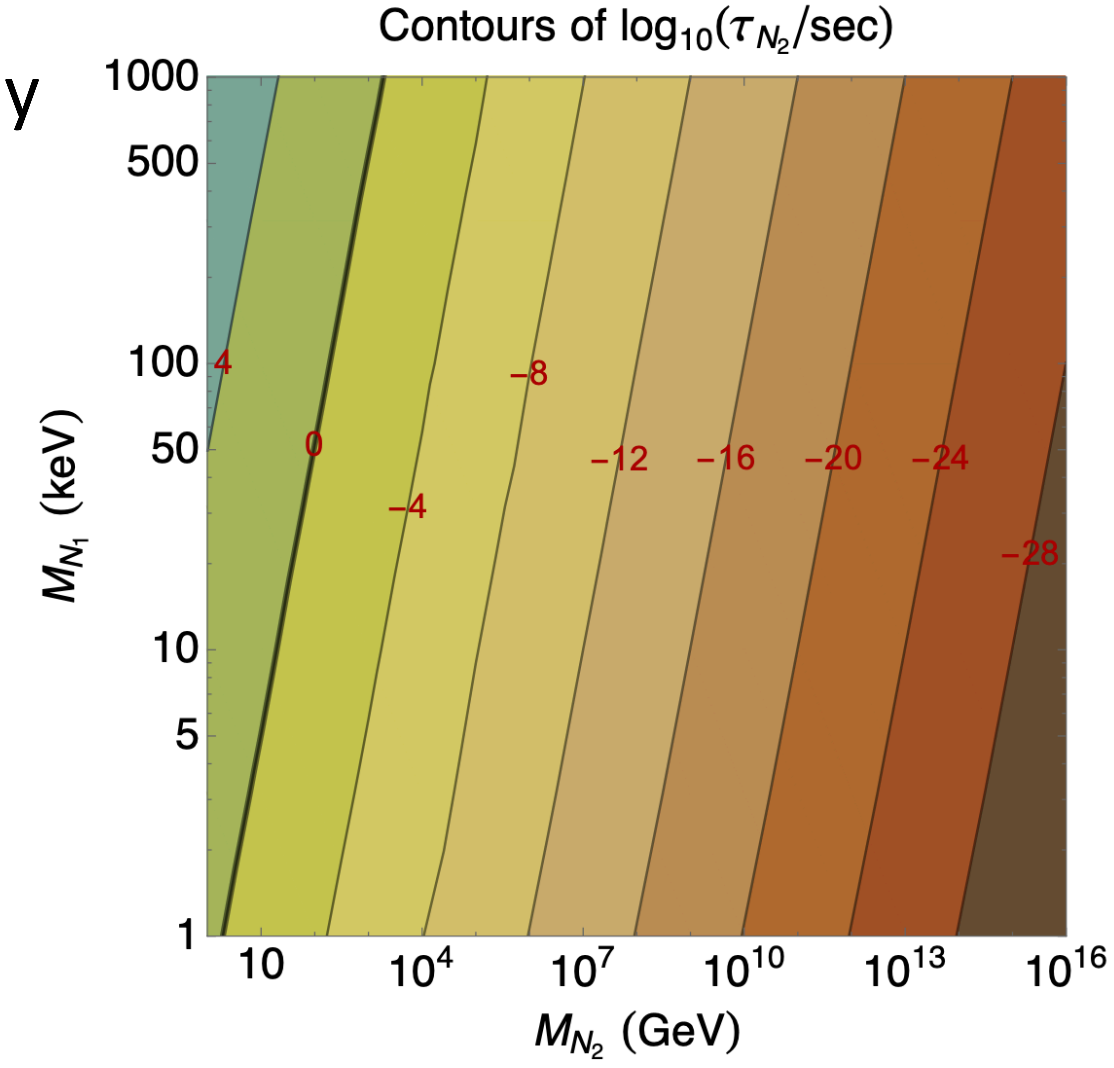
Decay of *Y* at a later time, mainly into Standard Model particles. Universe back to radiation dominated.

Scherrer, Turner (1985)

Diluted Dark Matter Relic Density

Sudden decay approximation: effectively 3 parameters, dilutor mass >> DM

$$\Omega h^2 \simeq 0.12 \left(\frac{M_X}{1\,\mathrm{keV}}\right)\left(\frac{1\,\mathrm{GeV}}{M_Y}\right)\sqrt{\frac{1\,\mathrm{sec}}{\tau_Y}}$$



Wide range of viable parameter space.

A number of dark matter models resort to dilution mechanism: Sterile neutrino, Gravitino, twin-Higgs models, strongly coupled dark sectors …

Warm Dark Matter Constraints

While DM was still relativistic, it follows a thermal distribution but the temperature is much lower than the photon,

$$\frac{T_X}{T_\gamma} = 0.16 \left(\frac{1\,keV}{M_X} \right)^{1/3}$$

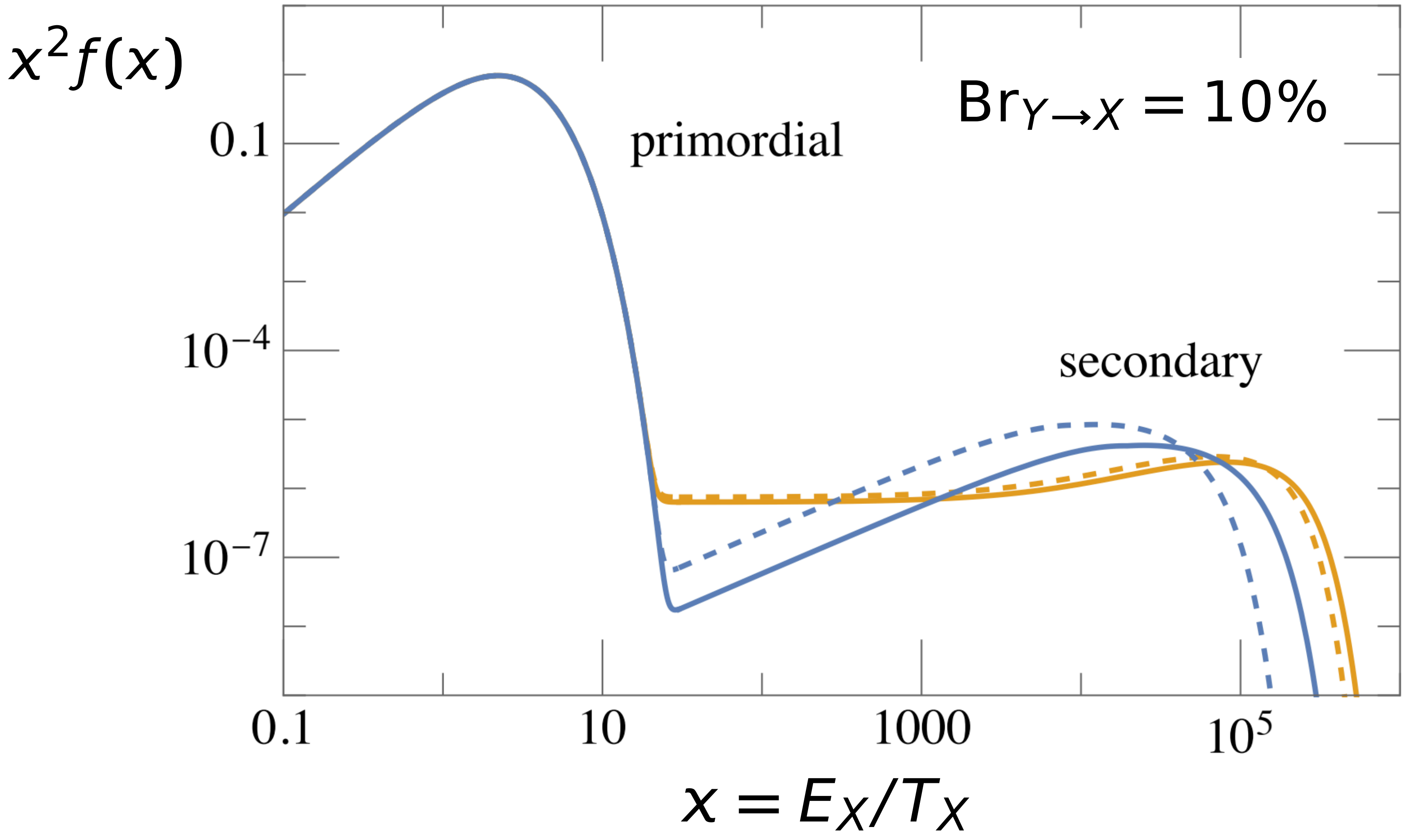
After dilution, N_1 is essentially a warm DM — free-streaming can smooth out observed small-scale structures in the universe (e.g. MilkyWay satellites, Lyman-α, strong lensing)

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

DES Collaboration (2008.00022, PRL)

New Opportunities

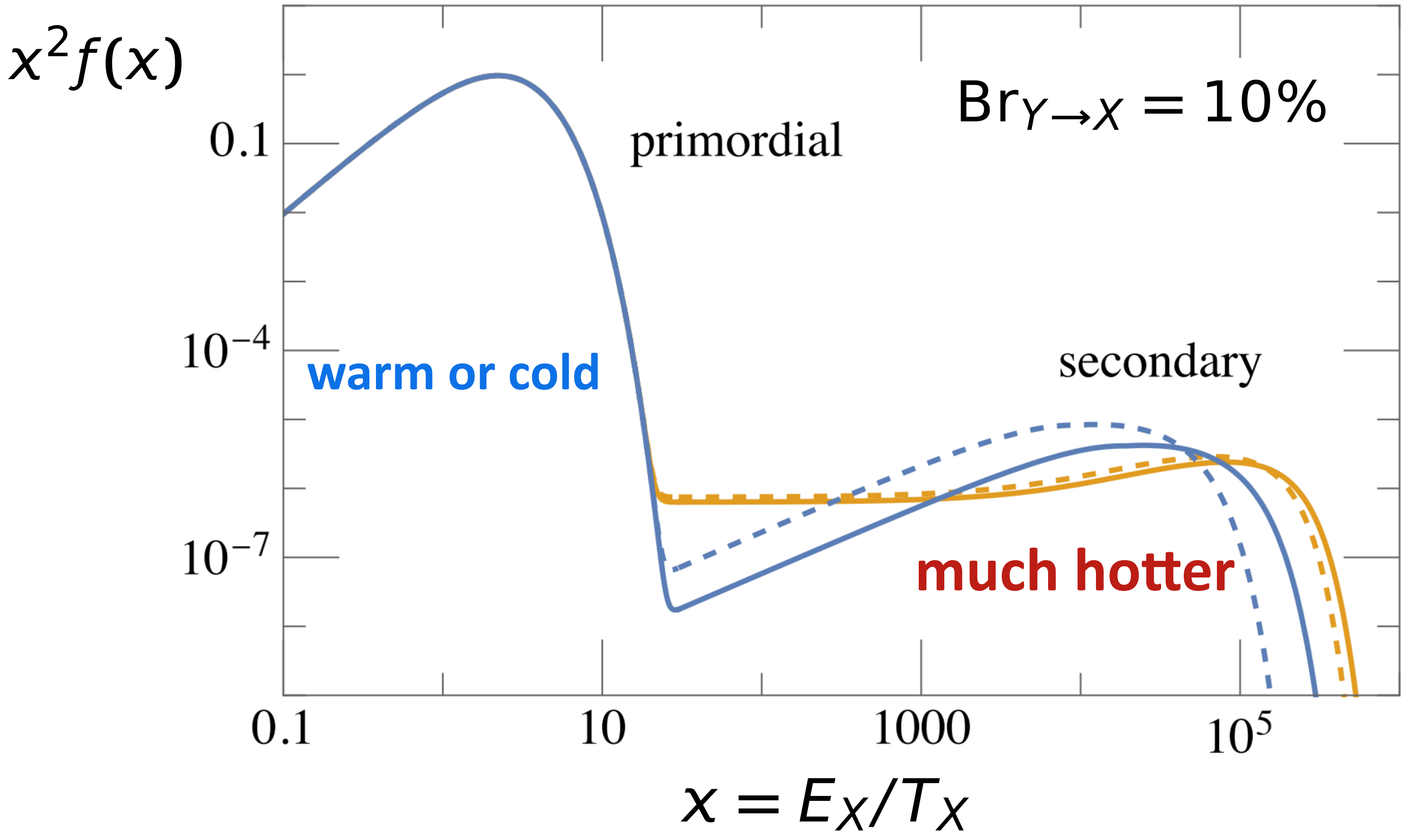
The diluting particle could decay into (very energetic) dark matter.



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

New Opportunities

The diluting particle could decay into (very energetic) dark matter.



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

Fate of Secondary Dark Matter

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

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

Fate of Secondary Dark Matter

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

Another look at relic density $\Omega h^2 \simeq 0.12 \left(\frac{M_X}{1\,\mathrm{keV}}\right)\left(\frac{1\,\mathrm{GeV}}{M_Y}\right)\left(\frac{T_{\rm RH}}{1\,\mathrm{MeV}}\right)$

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

Early On

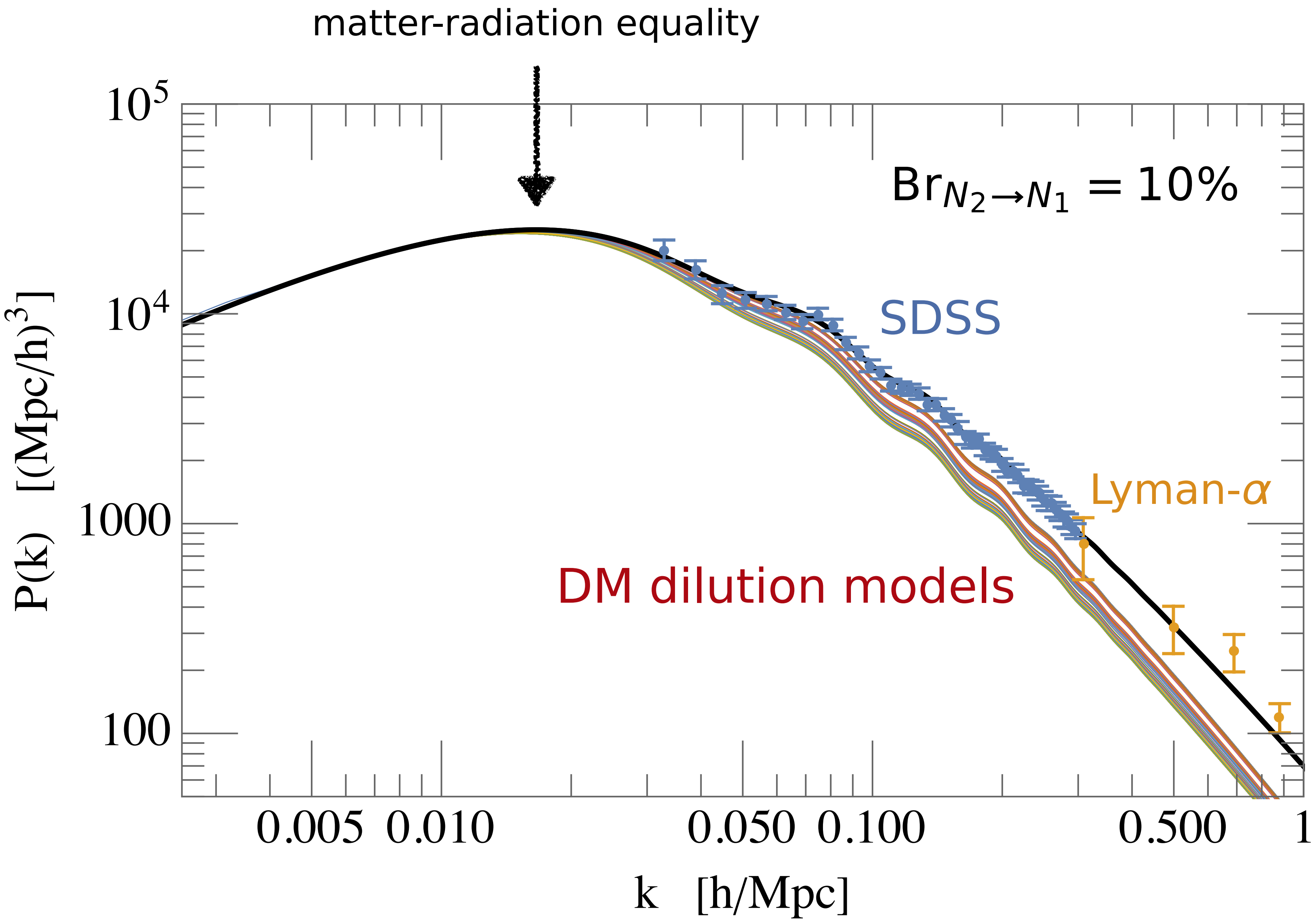
Energy density of radiation red-shifts faster than matter.

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

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

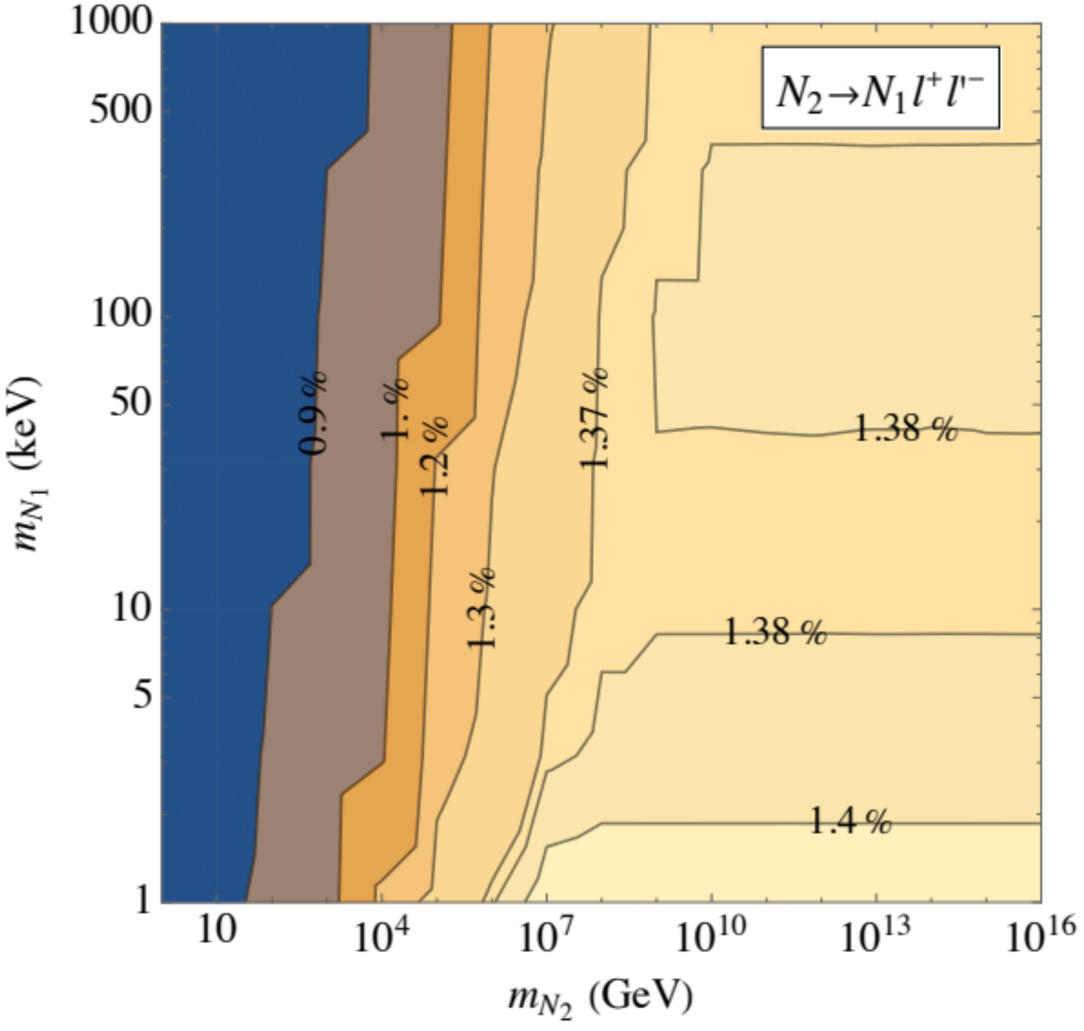
Note: photon temperature at matter-radiation equality $T \sim 0.3$ eV.

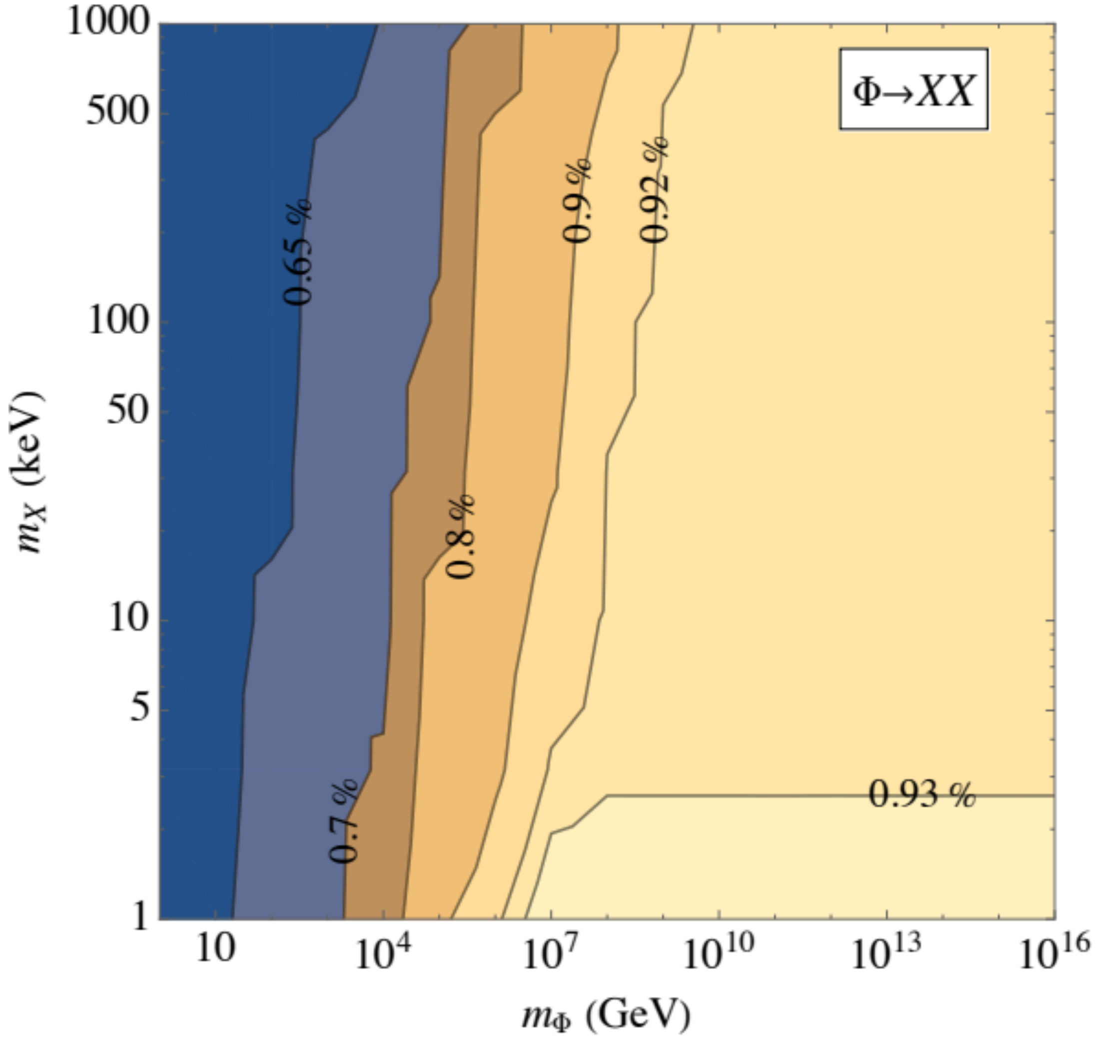
Length Scales of Damping



Miha Nemevsek and Yue Zhang (2206.11293, PRL)

Large Scale Structure Constraint





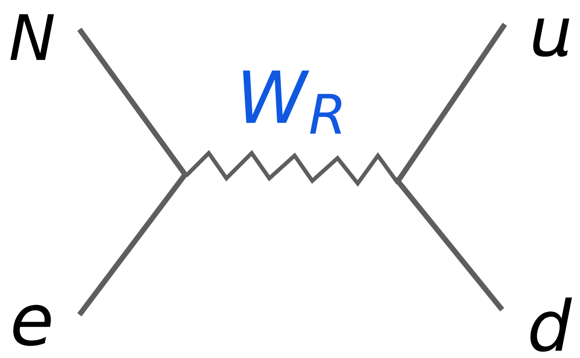
$$\mathrm{Br}_{Y \to X} \lesssim 1\%$$

Miha Nemevsek and Yue Zhang (2206.11293, PRL)

Right-handed Neutrino as DM

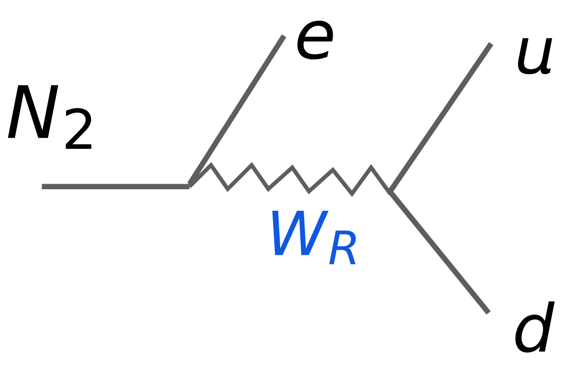
Well motivated for generating nonzero neutrino masses.

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

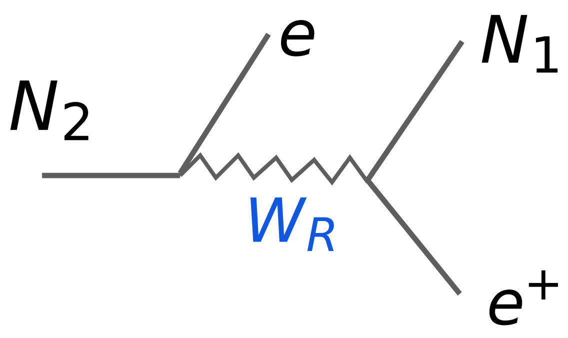


Large Hadron Collider: $M_{W_R} > 5$ TeV. All N does decouple sooner than active neutrinos - overproduced - needs dilution.

Implication for the Left-Right Model

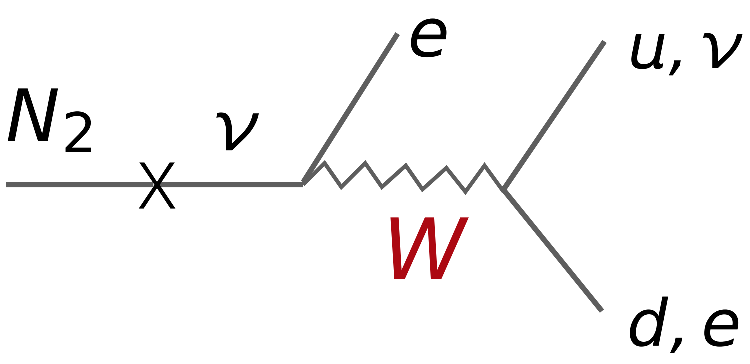


Entropy production (good)



Producing hot dark matter (bad)

Viable dilution mechanism exists if N_2 participates in the seesaw mechanism



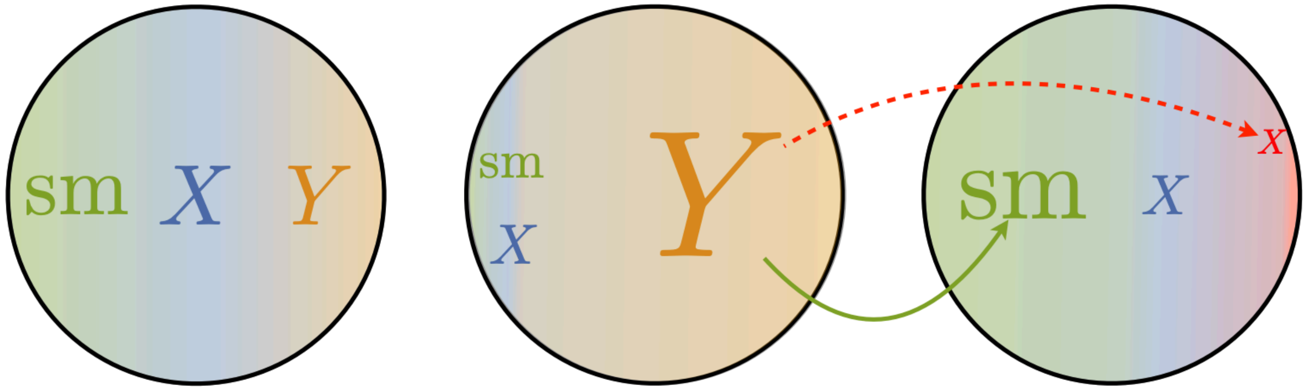
LSS sets lower bound on W_R boson mass

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

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.

We derive a useful constraint on dilutor to DM decay branching ratio that can be used to constrain various models.



Thanks!

Bonus

Prediction for ΔN_{eff}

Primordial component as a thermal relic:

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

Secondary component form dilutor decay:

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

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

Miha Nemevsek and Yue Zhang (2206.11293, PRL)