UNIVERSITY OF LJUBLJANA
FMF Faculty of Mathematics and Physics
IJS

Diluted and Blast Frozen Dark Matter

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Light Dark World 2026, Carleton University, Ottawa

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Slovenian Research and Innovation Agency

Dark matter mass origin

Dark Matter needs to be cold = massive

Was it always cold?

How it became cold, can we see these effects?

Any relation to other physics?

Dark matter mass origin

1 Neutrino mass origin

Bezrukov, Hettmansperger, Lindner '09
MN, Senjanović, Zhang '12
MN, Zhang '23, '24

$$m_{\rm DM} \quad \leftrightarrow \quad m_\nu \neq 0$$

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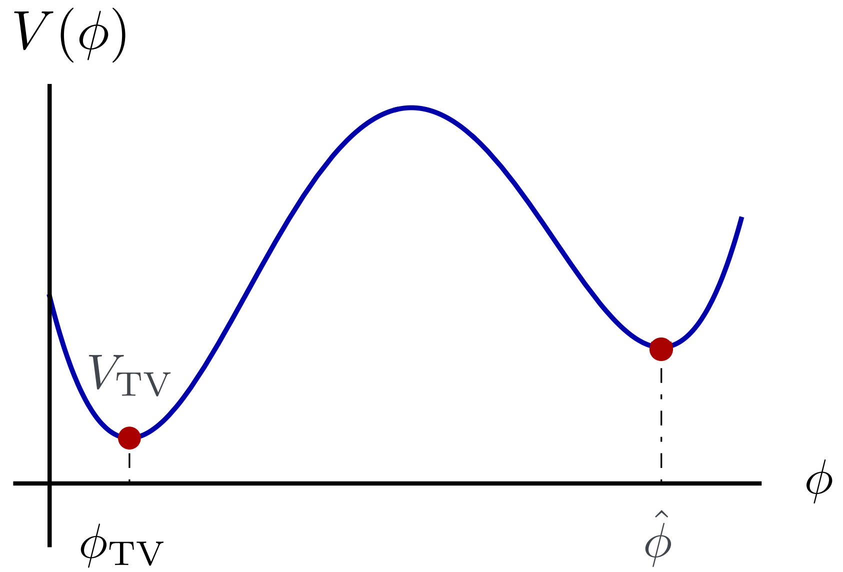
$$m_{\mathrm{DM}} \quad \leftrightarrow \quad m_\nu \neq 0$$

2 First order phase transition

MN, Zhang '25

$$m_{\mathrm{DM}} \quad \leftrightarrow$$



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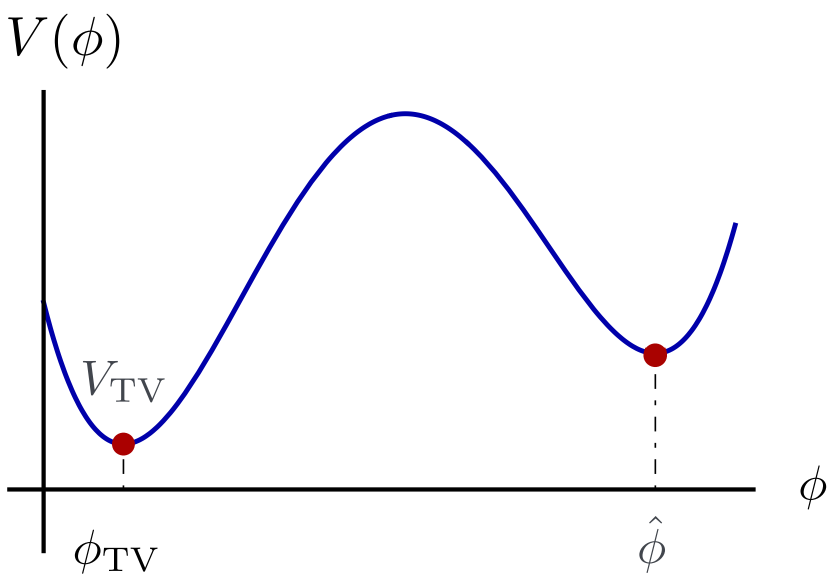
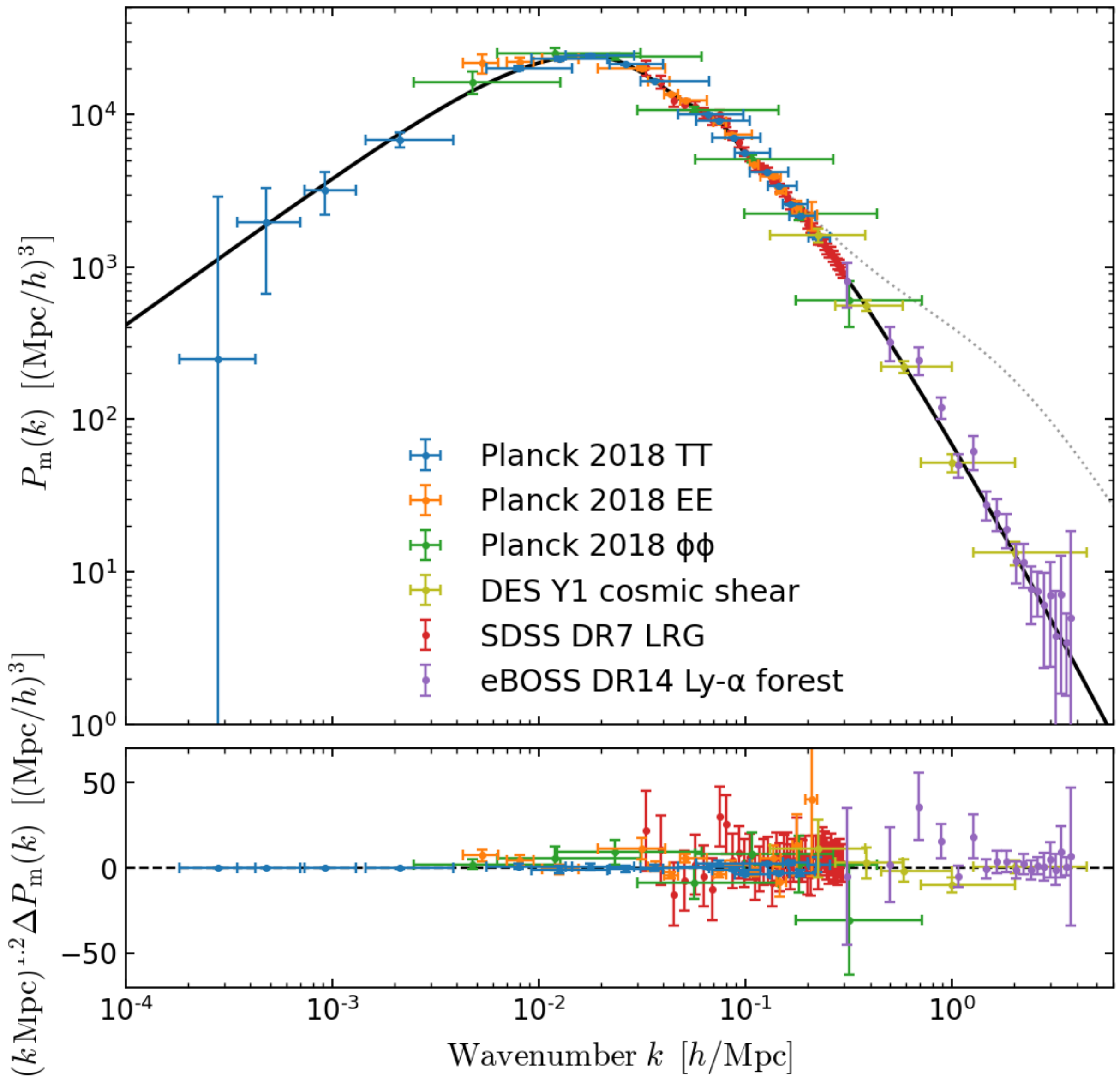




https://github.com/marius311/mpk_compilation

Neutrino mass origin: Left-Right symmetry

Pati-Salam

$$SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$$

Trinification

$$SU(3)^3$$

minimal Left-Right

Mohapatra, Pati '75
Senjanović, Mohapatra '75

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Symmetric fermions

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$Q_L = \left(3, 2, 1, \frac{1}{3}\right) , \qquad Q_R = \left(3, 1, 2, \frac{1}{3}\right)$$

$$L_L = \left(1, 2, 1, \frac{1}{3}\right) , \qquad L_R = \left(1, 1, 2, \frac{1}{3}\right)$$

LRSM scalars

$$\phi = (1,2,2,0)$$

$$\phi = \begin{pmatrix} \phi_1^{0*} & \phi_2^{+} \\ \phi_1^{-} & \phi_2^{0} \end{pmatrix}, \quad \langle\phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & -e^{i\alpha} v_2 \end{pmatrix}$$ bi-doublet

EWSB $$v^2 = v_1^2 + v_2^2\,, \quad 0 \le \tan\beta = \frac{v_2}{v_1} < 1$$

Doublets $$\chi_L = (1,2,1,1)\ , \quad \chi_R = (1,1,2,1)$$ Dirac ν

this talk

Triplets $$\Delta_L = (1,3,1,2)\ , \quad \Delta_R = (1,1,3,2)$$ Majorana N

Dark matter and dilutor

$$\langle\Delta_{L,R}\rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}, \quad v_L \lesssim \mathrm{GeV}\,, \quad v = 174\ \mathrm{GeV}\,, \quad v_R \gtrsim \mathrm{TeV}$$

$$L_R = \left(1, 1, 2, \frac{1}{3}\right) = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}$$

LRSM: Three Majorana neutrinos $N_{1,2,3}$ (3 for anomalies)

Dark Matter candidate(s)?

Neutral N_1 , Δ

(no ad-hoc symmetries)

Potentially stable

$N \to 3\nu,$ $\Delta \to W_R W_R$

$N \to \nu\gamma$ $\Delta \to \gamma\gamma$

Super-weak

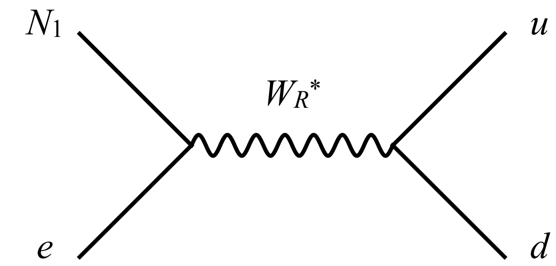
$$G_F \left(\frac{M_W}{M_{W_R}}\right)^4$$

Typical scales

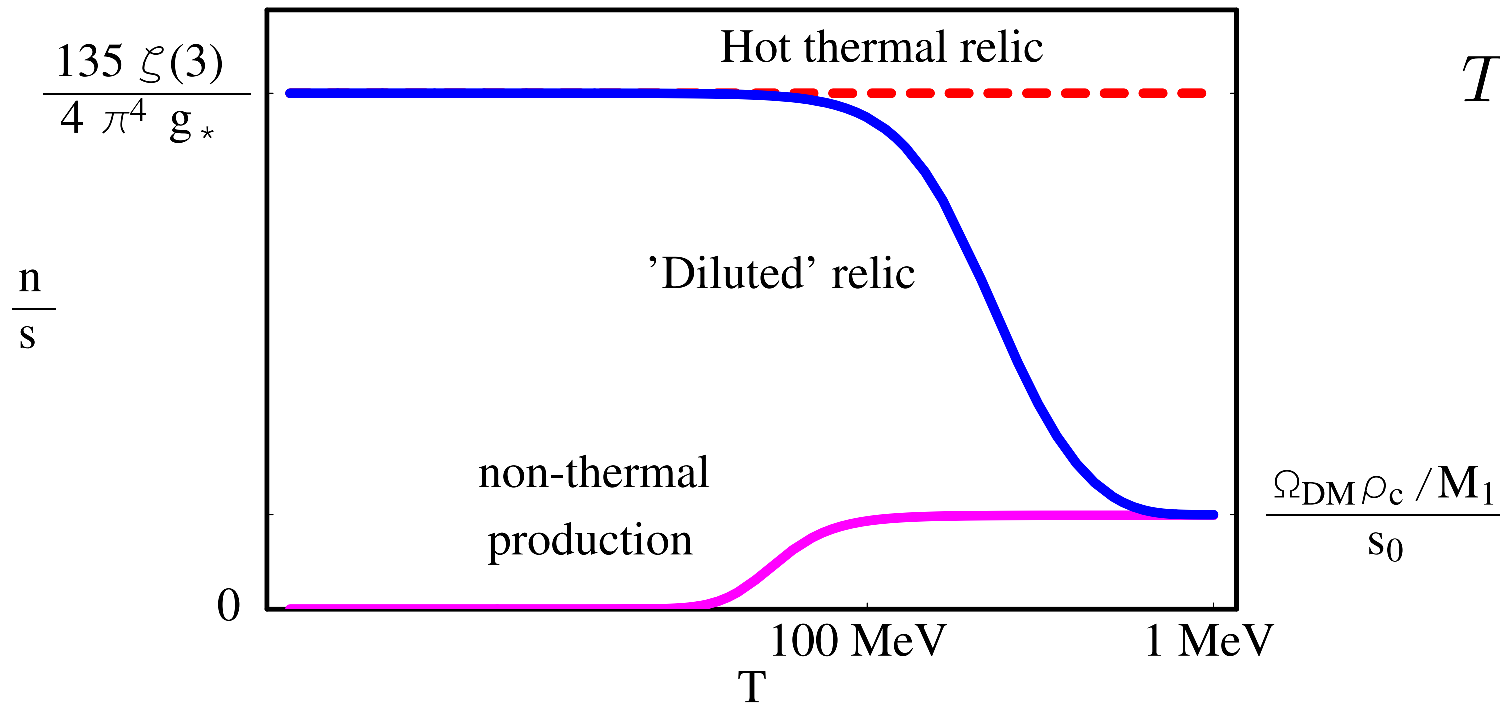
$m_N \lesssim m_\pi$ LHC $M_{W_R} \gtrsim 5 \text{ TeV}$ Nesti, MN, Popara '18 ATLAS, CMS

$m_\Delta \ll M_{W_R}$ $M_{W_R} \gtrsim \text{few PeV}$ MN, Zhang '24

Over Production



Bezrukov, Hettmansperger, Lindner '09



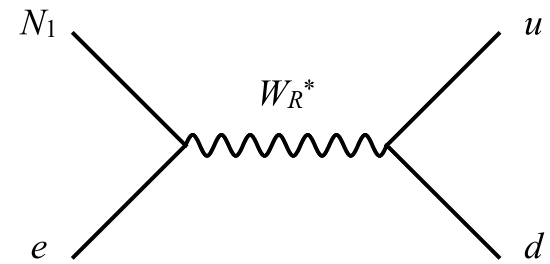
$$T_f = 400\ \text{MeV} \left(\frac{M_{W_R}}{5\ \text{MeV}}\right)^{4/3} \left(\frac{g_*}{70}\right)^{1/6}$$

relativistic freeze-out gives

too much dark matter

$$\Omega_N \simeq 3.3 \frac{m_N}{\text{keV}} \sim 12\,\Omega_{\text{DM}}$$

Over Production



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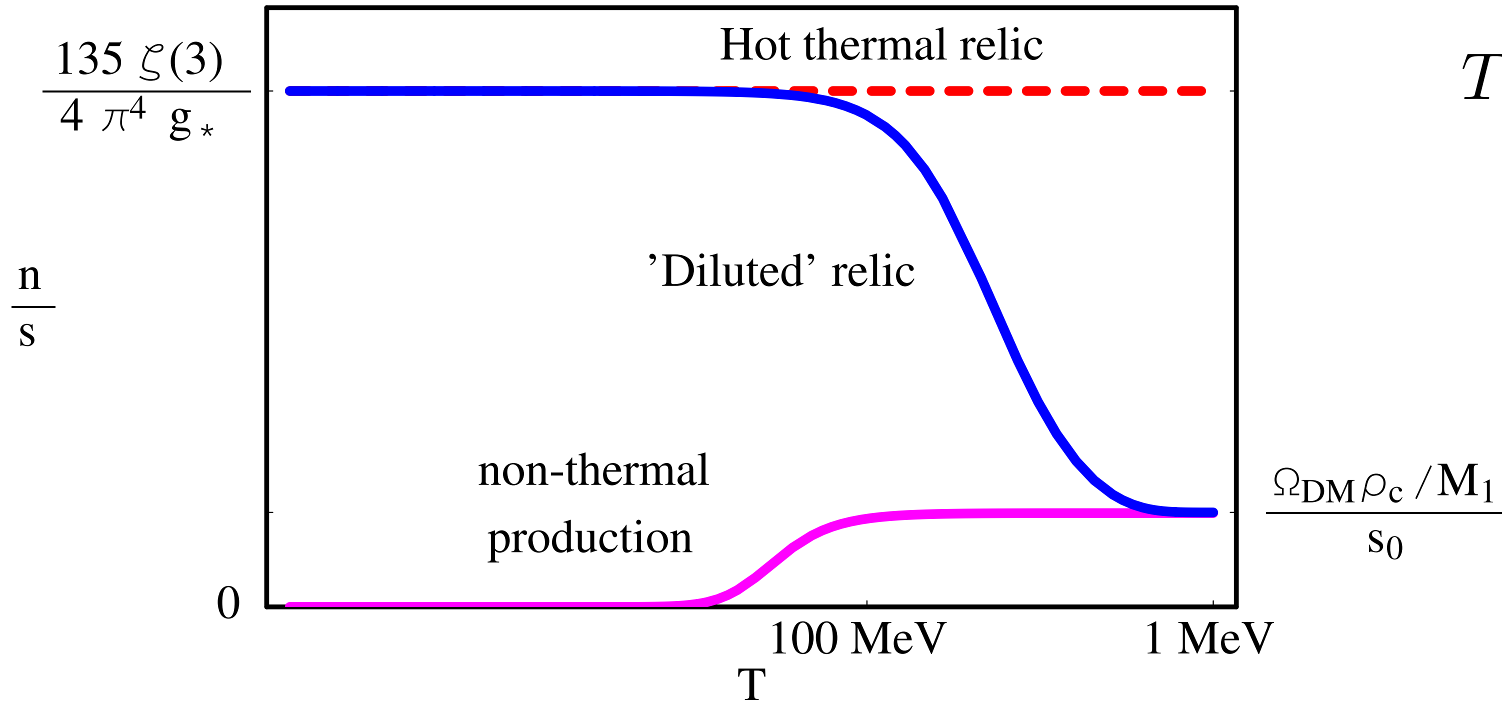

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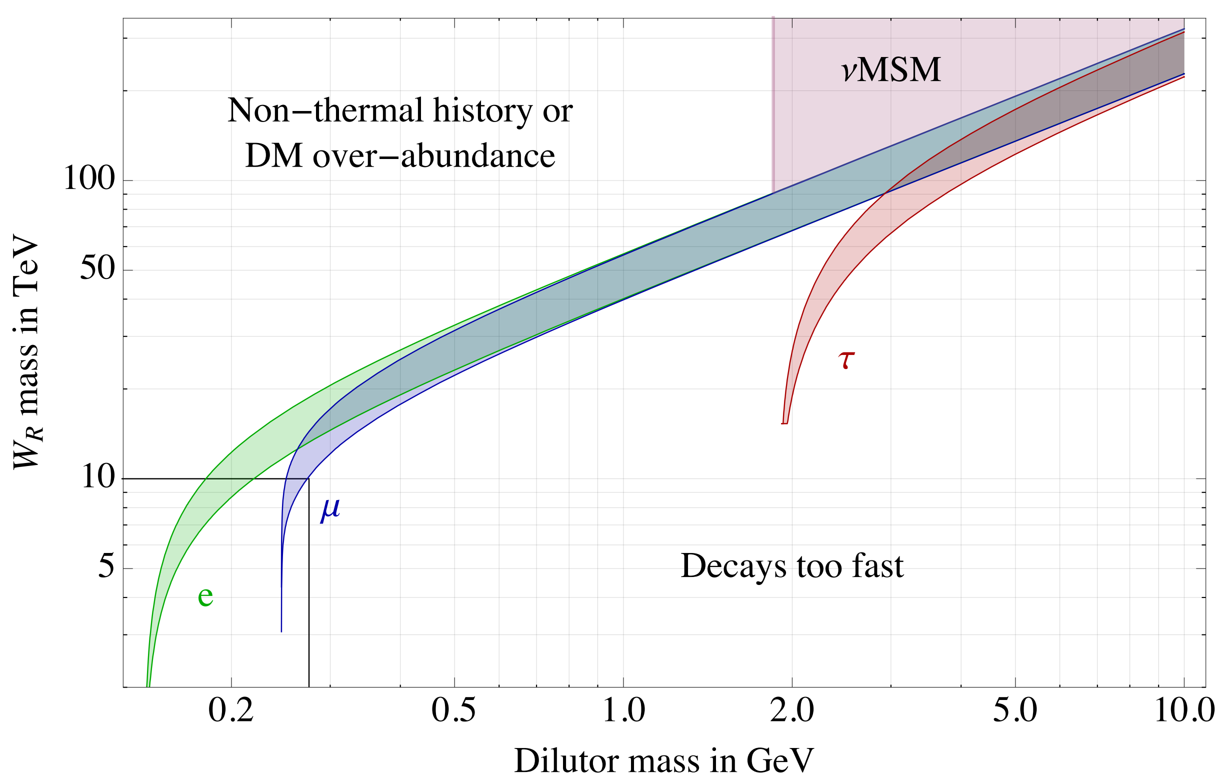
Scherrer, Turner '85 solve with entropy dilution, cool down DM



MN, Senjanović, Zhang '12,
King, Merle '12

targeting low LR scale

Dror, Dunsky, Hall, Harigaya '20

generic issue of dilutor DM repopulation

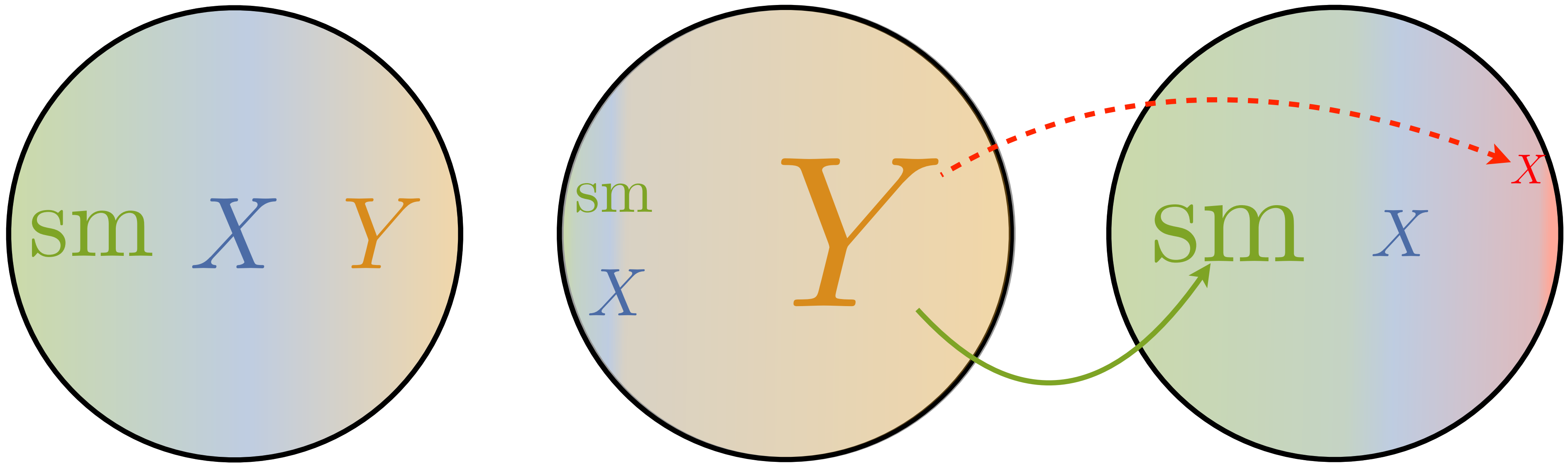
(~gravitino problem)

DM dilutor repopulation

Y = dilutor

MN, Zhang '23

X = DM



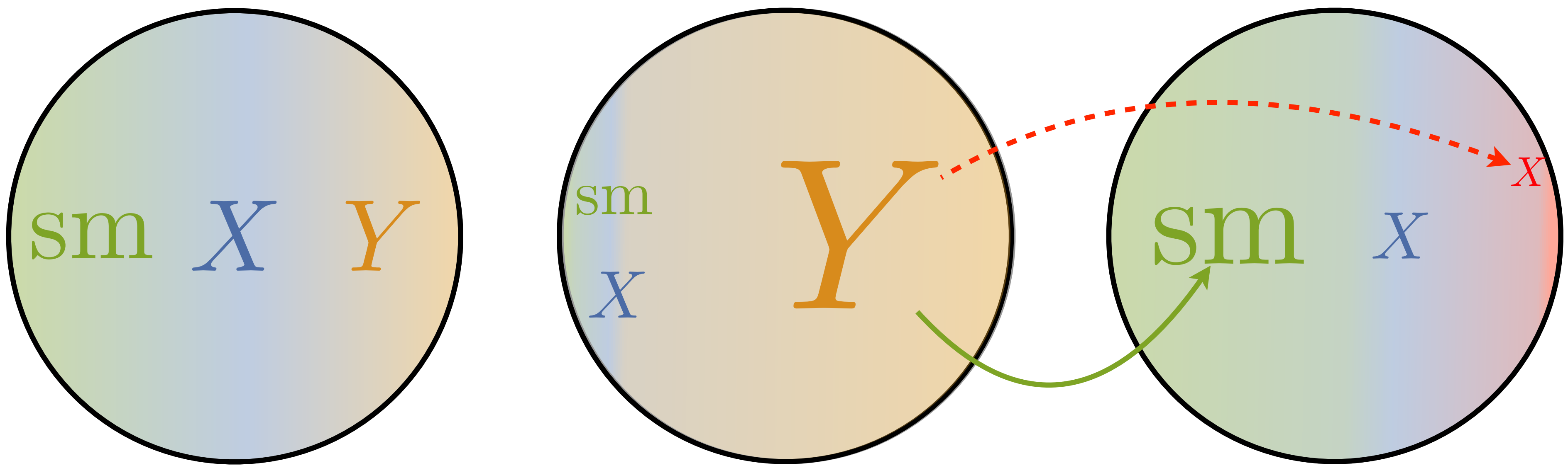
X = repopulated DM

DM dilutor repopulation

Y = dilutor

MN, Zhang '23

X = DM



X and Y freeze-out (relativistically) $Y_X = \frac{135\,\zeta(3)}{4\pi^4 g_*(T_{\rm fo})}$

X = repopulated DM

Y causes intermediate matter domination in H

$$Y \to n\,X + m\,SM$$
$n, m \in \mathbb{Z}^+$

Y dilutes only if it decays into the SM plasma

$$\Omega_X \simeq 0.26\,(1 + n{\rm Br}_X)\left(\frac{m_X}{1\,{\rm keV}}\right)\left(\frac{1\,{\rm GeV}}{m_Y}\right)\sqrt{\frac{1\,{\rm sec}}{\tau_Y}}$$

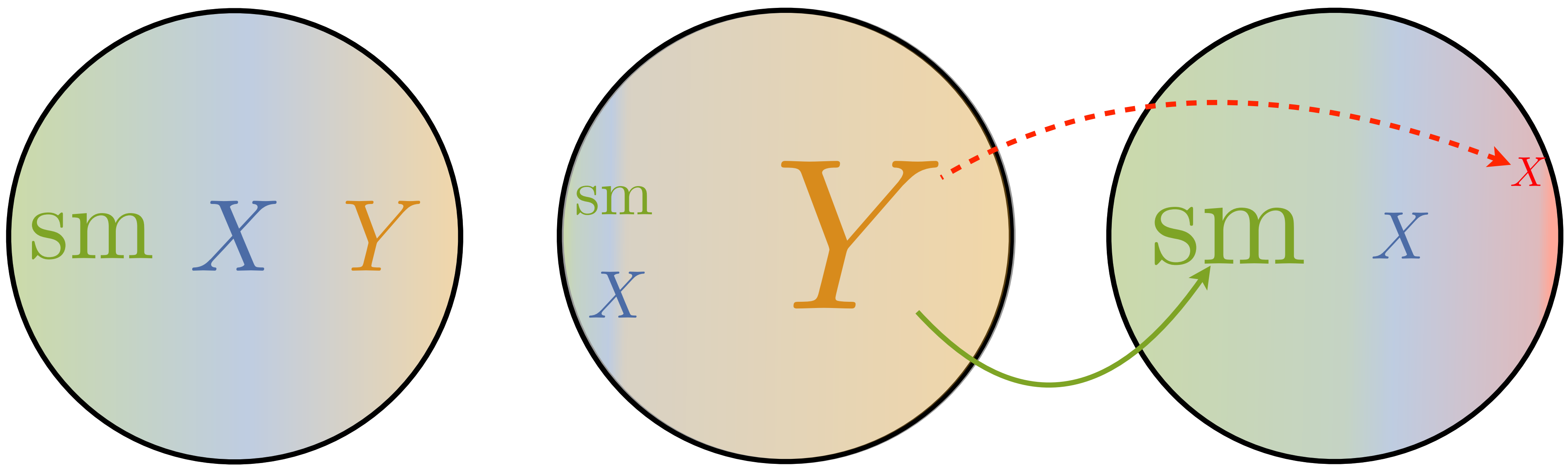
$$\boxed{{\rm Br}^{\rm max}_{Y\to X} = ?}$$

Not harmless to decay to X, cannot dilute away

not necessarily reducible

DM dilutor repopulation

MN, Zhang '23

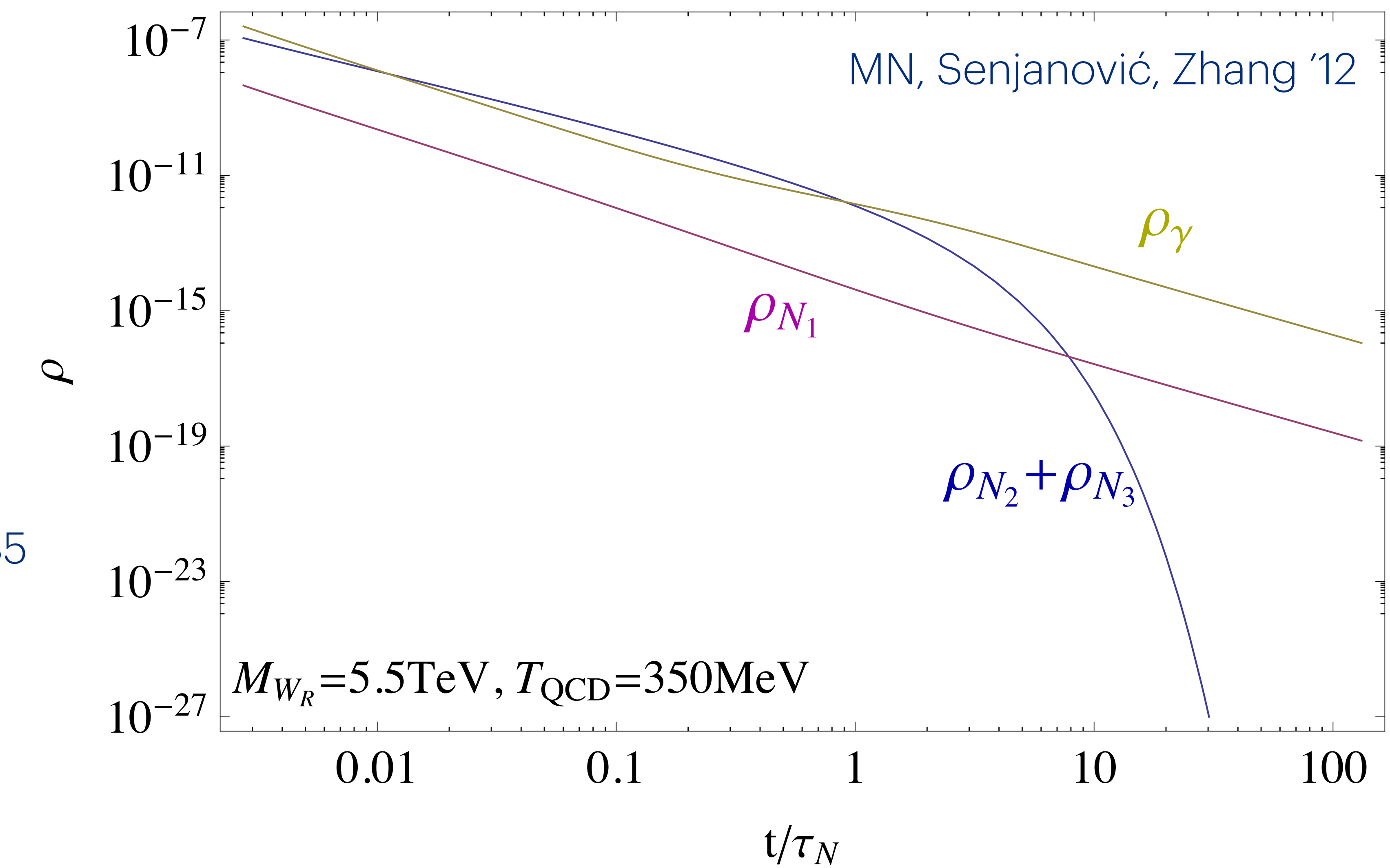


Boltzmann

$$\partial_t \rho_R + 4H\rho_R = \Gamma_2 \rho_2$$

$$\partial_t \rho_{N_1} + 4H\rho_{N_1} = 0$$

$$\partial_t \rho_{N_2} + 3H\rho_{N_2} = -\Gamma_2 \rho_2$$



Dilution factor Scherrer, Turner '85

$$\frac{s_>}{s_<} \simeq 1.7\, \frac{g_*(T_Y)^{1/4}\, m_Y Y_Y}{\sqrt{\Gamma_Y M_{\rm pl}}}$$

(Sudden decay approx. can do better)

DM dilutor repopulation

X = DM

X = repopulated DM

robustness of the phase space distribution, fixed DM mass $m_X = 10\,\mathrm{keV}$

LRSM $X = N_1\,,\quad Y = N_2, \Delta$

MN, Zhang '23

Single DM, 3 body

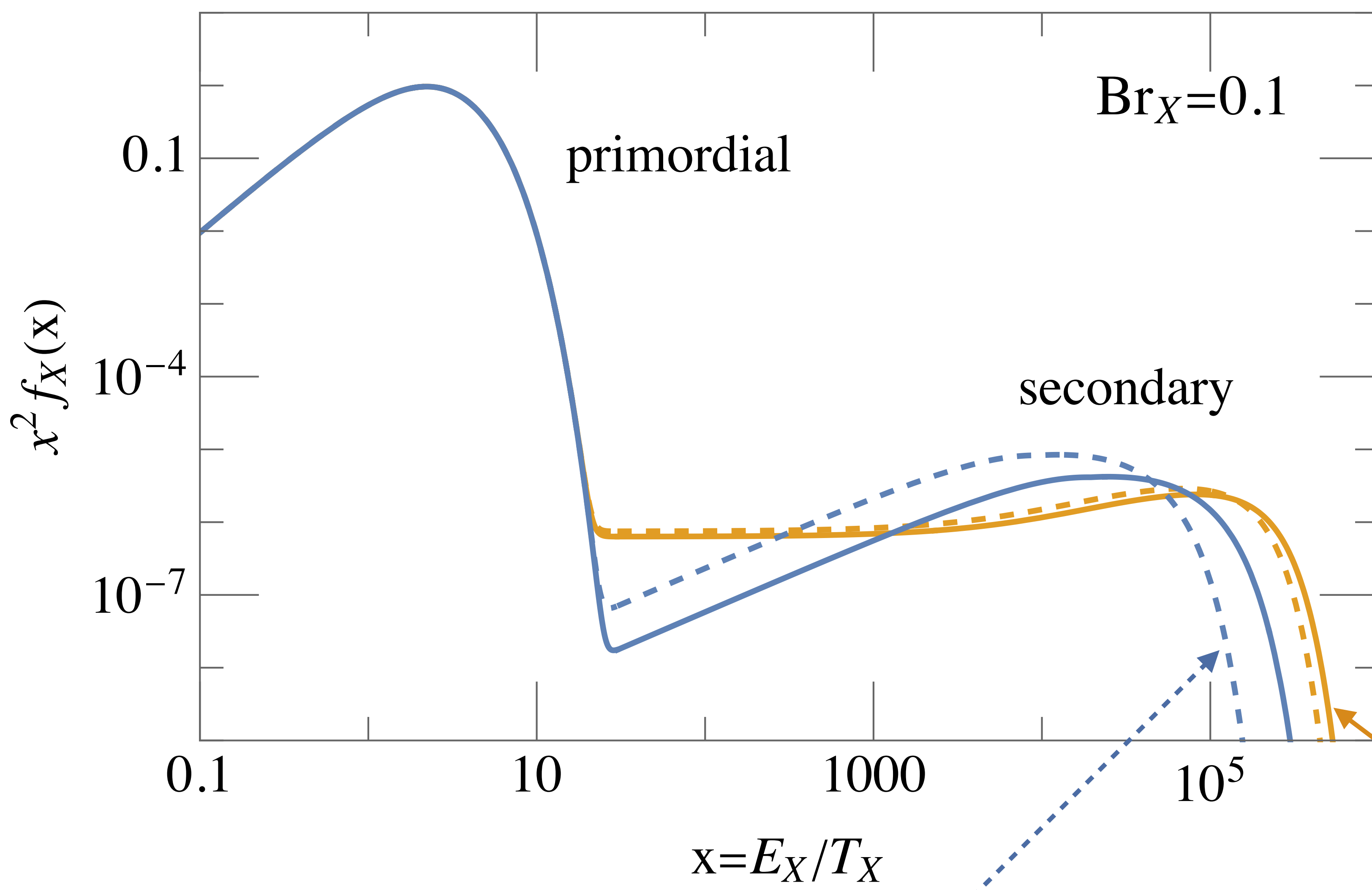
$n = 1$

$N_2 \to N_1 f f'$

Two DM, 2 body

$n = 2$

$\Delta \to N_1 N_1$



Heavy dilutor

$m_Y = 100\,\mathrm{GeV}$

Light dilutor

$m_Y = 1\,\mathrm{PeV}$

light Y, 3 body = least energetic

heavy Y, 2 body = most energetic

Secondary is *hot*, how much can *P(k)* take?

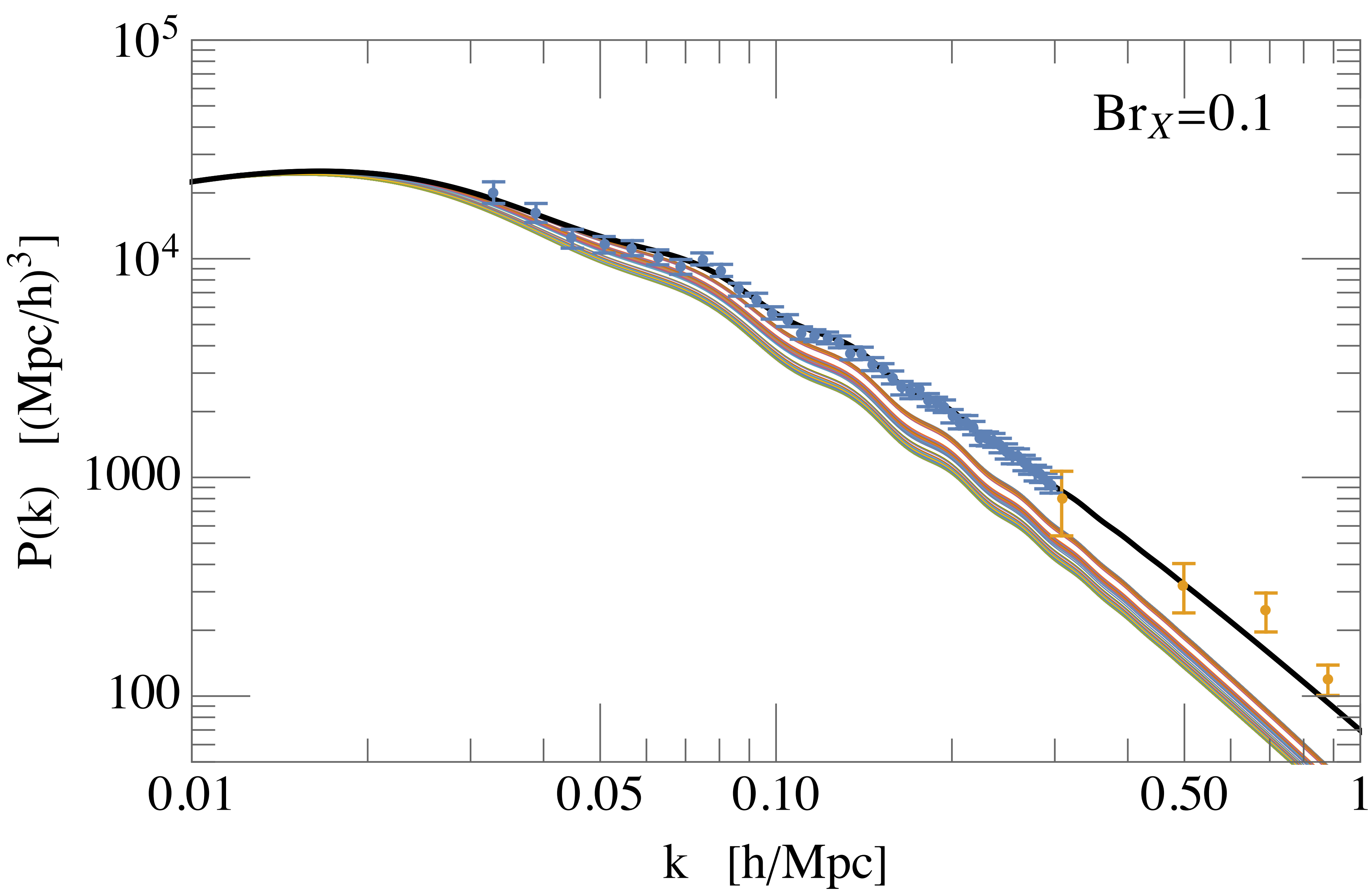
Hot DM repopulation vs. linear P(k)

MN, Zhang '23

when is *X* hot? $T_{\rm NR} \sim 1\,{\rm eV}\,(n+m)\,g_*(T_{\rm RH})^{1/12}$

growth suppressed at scales below $H(T_{\rm NR}/{\rm Br}_X)$

quantitative CLASS runs $\Omega_X \simeq 0.26\,(1+n{\rm Br}_X)\left(\frac{m_X}{1\,{\rm keV}}\right)\left(\frac{1\,{\rm GeV}}{m_Y}\right)\sqrt{\frac{1\,{\rm sec}}{\tau_Y}}$



$m_X \in ({\rm keV}, {\rm MeV})$

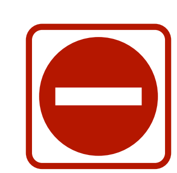
$m_Y \in ({\rm GeV}, 10^{16}\,{\rm GeV})$

Ly-A

SDSS DR7 LRG

LCDM

~WDM suppression

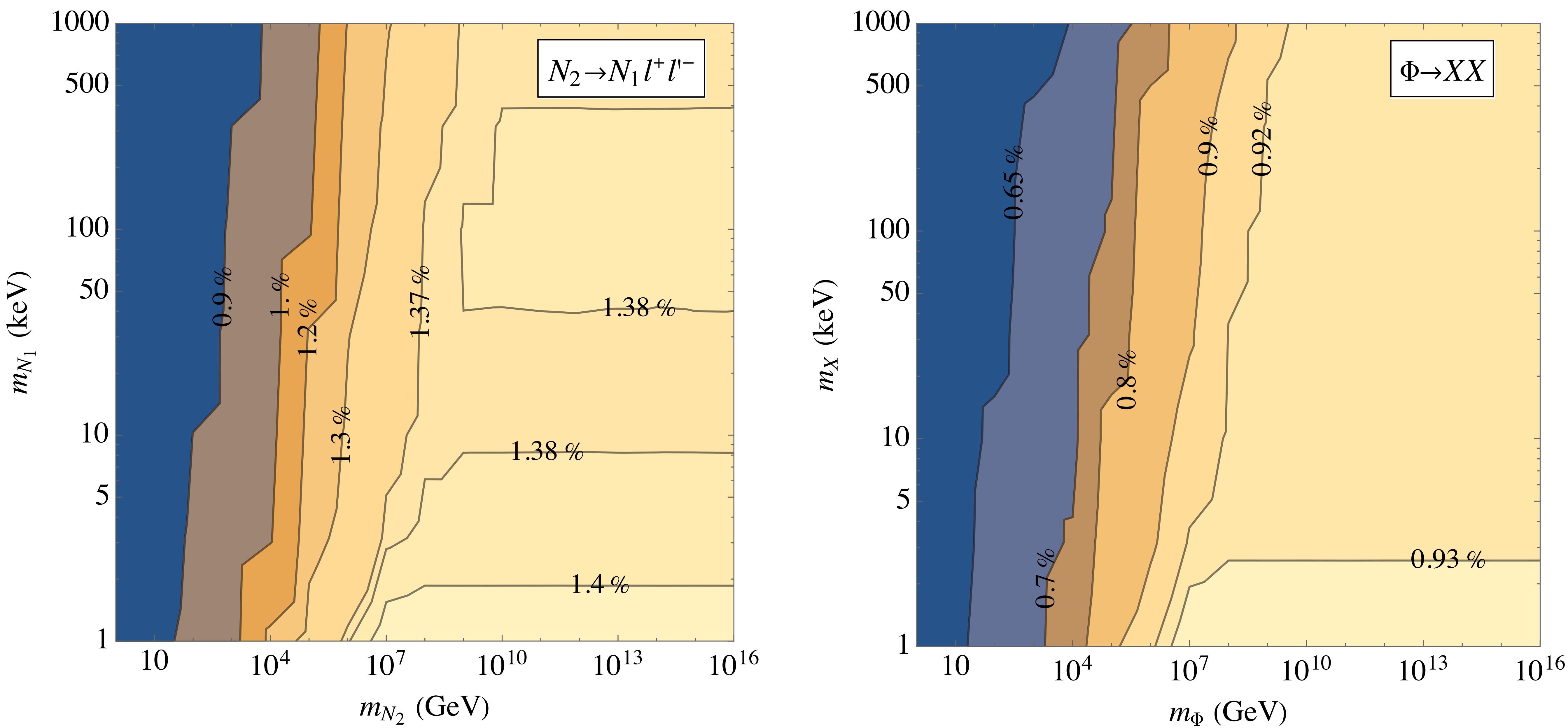


Hot DM repopulation bound

MN, Zhang '23

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

significant, ~loop level

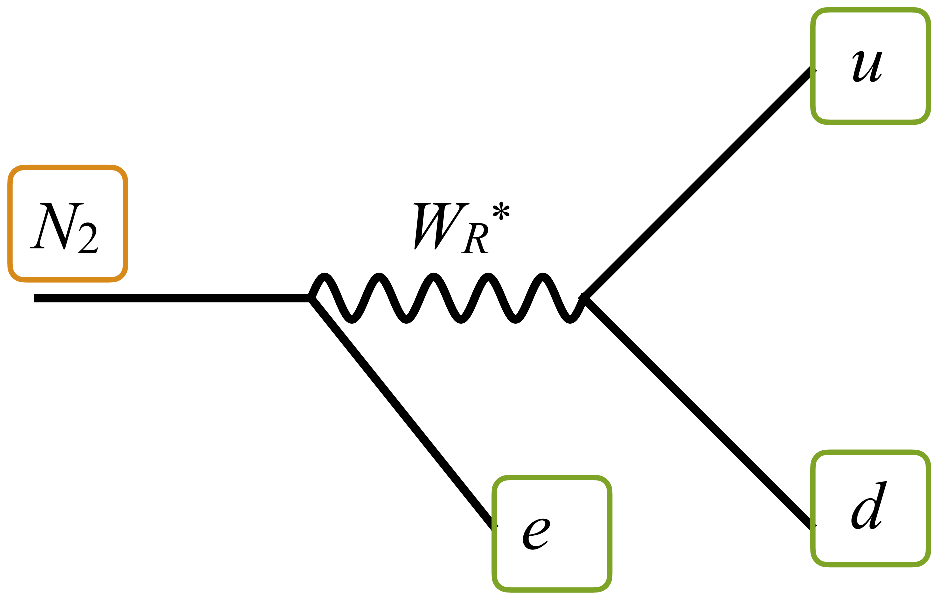


Remarkably robust, 2 and 3 body, across orders of magnitudes

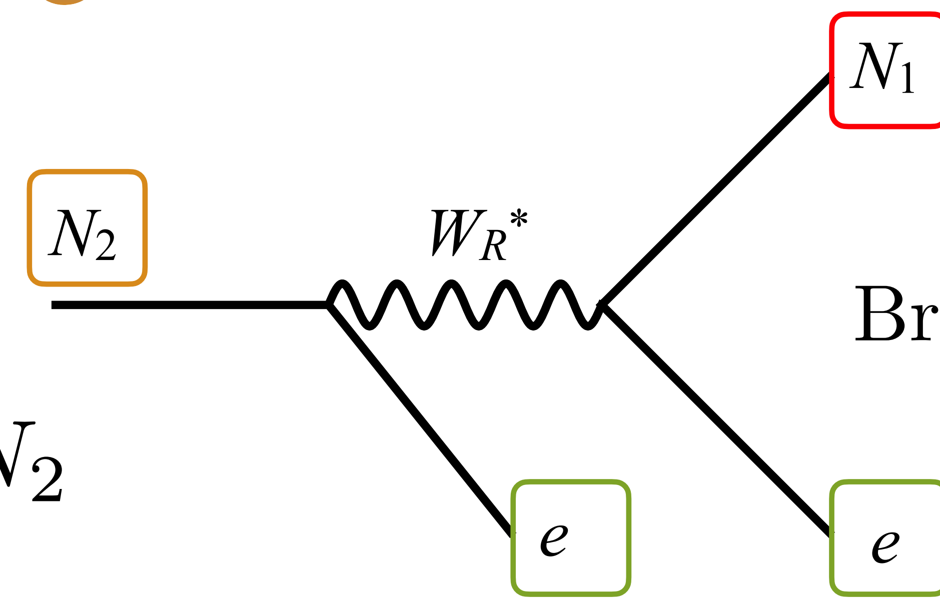
LRSM implications

$X = N_1$

MN, Zhang '24



$Y = N_2$



$\mathrm{Br}^{\mathrm{max}}_{Y \to X} \simeq 10\%$

Avoid X repopulation

a) flavor — MN, Senjanović, Zhang '12

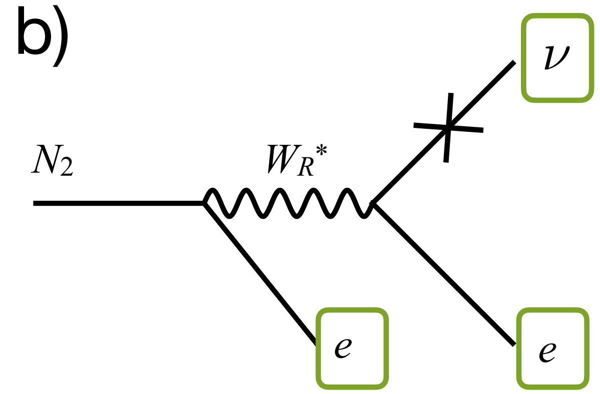
b) only Dirac

c) LR gauge mixing

d) scalar dilution

(b)–d): MN, Zhang '24)

b)



$$\Omega_{N_1} \gtrsim 2.9 \left(\frac{m_{N_1}}{6.5\,\mathrm{keV}}\right)\left(\frac{m_{N_2}}{1\,\mathrm{GeV}}\right)$$

b) Dirac no-go below M_W, also above

$$\theta_{N_2\nu} \gtrsim \sqrt{\frac{m_\nu}{m_{N_2}}}$$

seesaw

$$\tau_{N_2}^{-1} \gtrsim \frac{\mathfrak{m}\, G_F^2 m_{N_2}^5 \theta_{N_2\nu}^2}{96\pi^3} \gtrsim 10^{-23}\,\mathrm{GeV}\left(\frac{m_{N_2}}{1\,\mathrm{GeV}}\right)^4$$

lifetime

$$m_{N_2} \lesssim 90\,\mathrm{MeV}$$

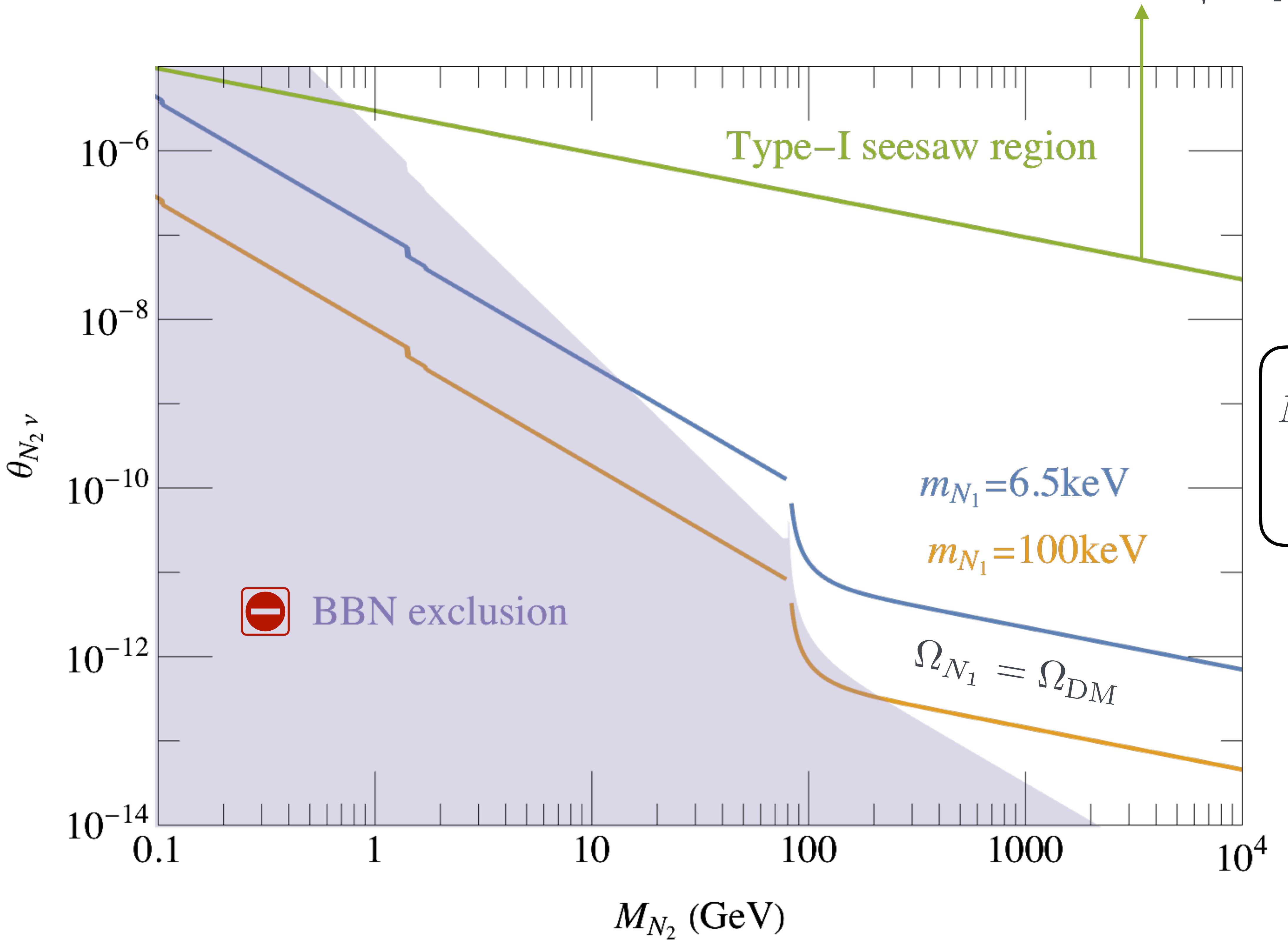
$$\tau_{N_2} \gtrsim 160\,\mathrm{sec}$$

BBN

LRSM pure Dirac no-go

type I seesaw $\theta_{N_2\nu} \gtrsim \sqrt{\frac{m_\nu}{m_{N_2}}}$

MN, Zhang '24



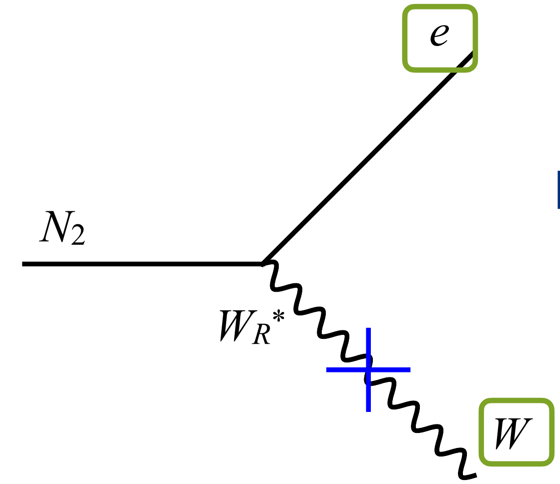
suppressed repopulation

$$M_{W_R} \gtrsim \frac{10\,\text{GeV}}{\sqrt{\theta_{N_2\nu}}} \gtrsim \text{PeV}$$

Type II seesaw can generate neutrino mass and allow for small mixing

LRSM solutions: LR mixing

MN, Zhang '24



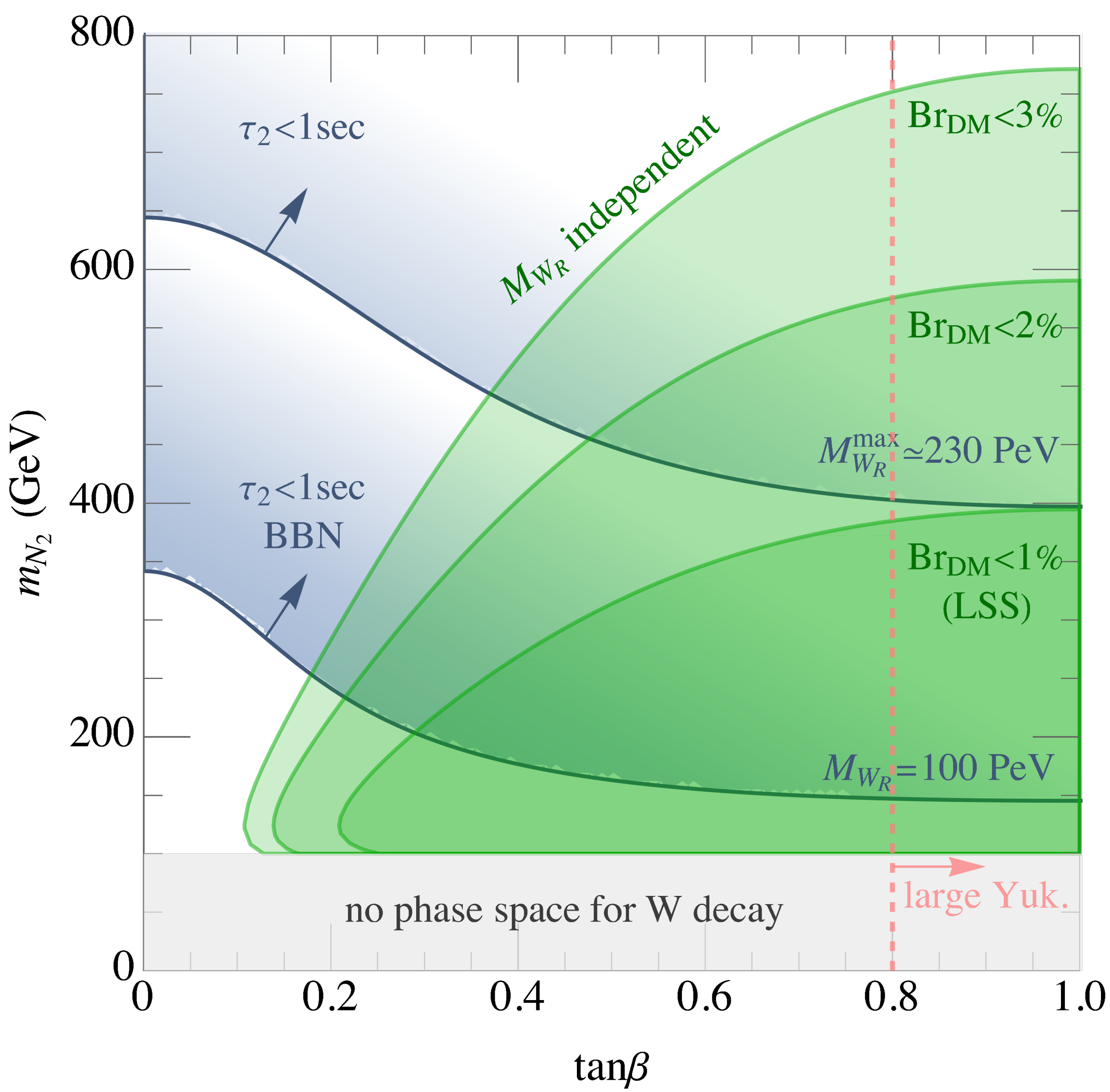
Gauge boson mixing $\xi_{\rm LR} \simeq s_{2\beta}\, e^{i\alpha} \left(\frac{M_W}{M_{W_R}}\right)^2$

Fast 2 body channel $\Gamma_{N_2\to \ell W} = \frac{g^2 |\xi_{\rm LR}|^2 m_{N_2}}{32\pi} \left(\frac{m_{N_2}}{M_W}\right)^2 \left(1-\frac{M_W^2}{m_{N_2}^2}\right)\left(1+\frac{M_W^2}{m_{N_2}^2}-\frac{2M_W^4}{m_{N_2}^4}\right)$

Seesaw Type II dominance

BBN 👍

careful with X-rays



LSS ⛔

LSS 👍

$Br_{Y\to X} < 1\%$

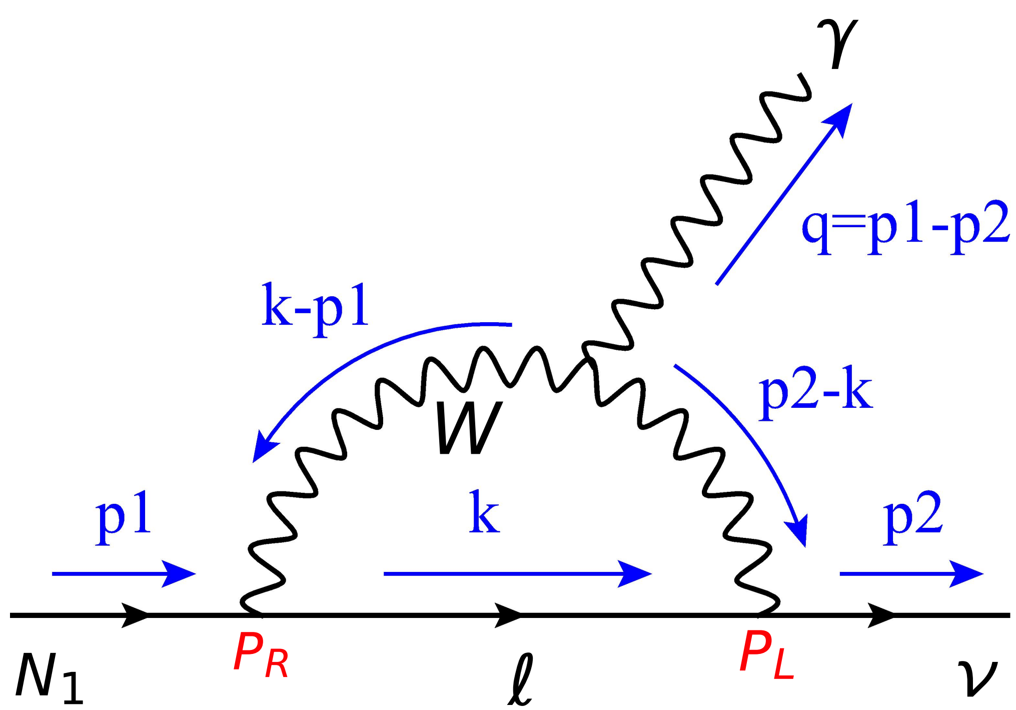
$M_{W_R} \gtrsim 100$ PeV

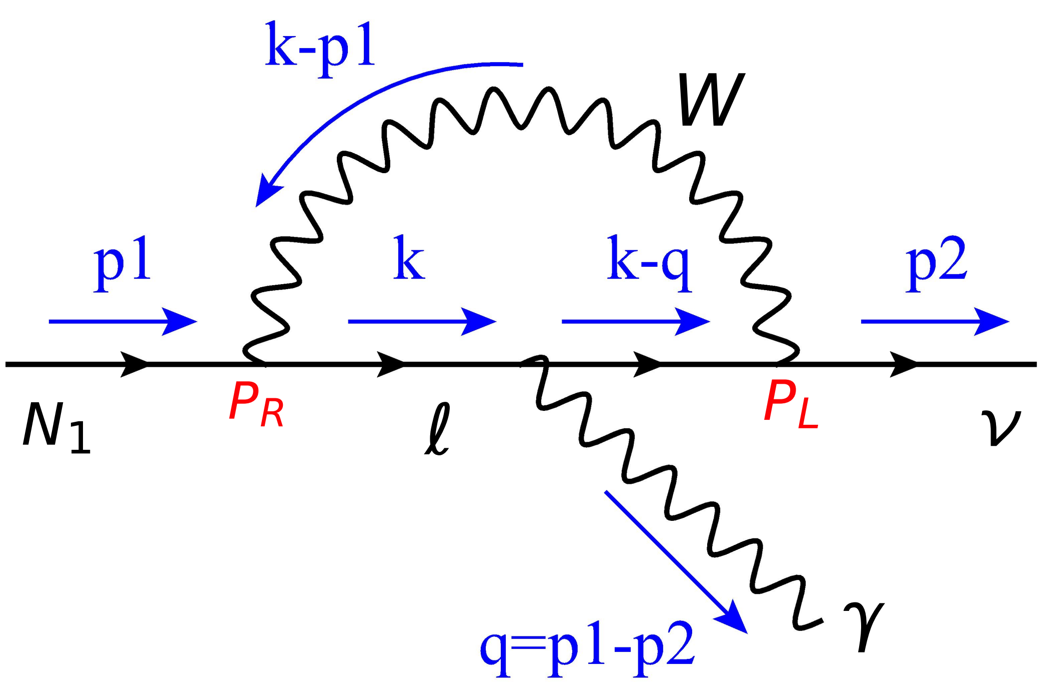
careful with Yukawas

LRSM solutions: LR mixing

MN, Zhang '24

Gauge boson mixing $\xi_{\rm LR} \simeq s_{2\beta}\, e^{i\alpha} \left(\frac{M_W}{M_{W_R}}\right)^2$





$$\Gamma_{N_1\to\nu\gamma} = \frac{\alpha\xi_{\rm LR}^2}{8\pi^4} G_F^2 m_{N_1}^3 \sum_\ell \left|\left(V_{\rm PMNS}^R\right)_{\ell 1}\right|^2 m_\ell^2$$

+ contribution via Dirac mixing, here sub-dominant

LRSM solutions: LR mixing

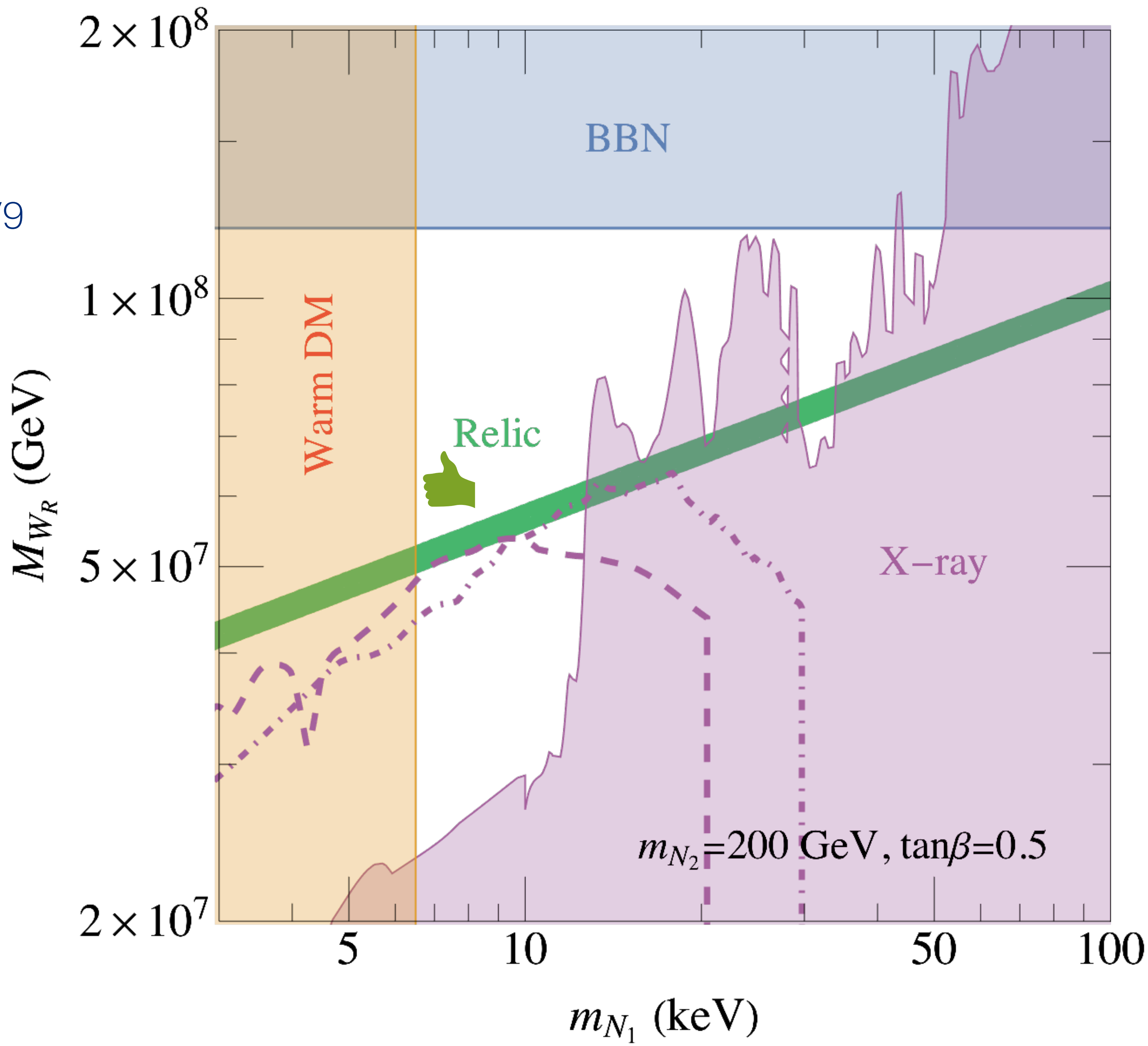
MN, Zhang '24

Phase space bound

Tremaine, Gunn '79
+... DES '20

Correct relic

Planck '18



BBN safe

e.g. Boyarsky et al '21

Probed by X-rays

e.g. Boyarsky et al '21

Future (not yet)

ATHENA
Neronov '15

XRISM '20 and '25
Dessert et al. '23

LRSM solutions: scalar dilutor

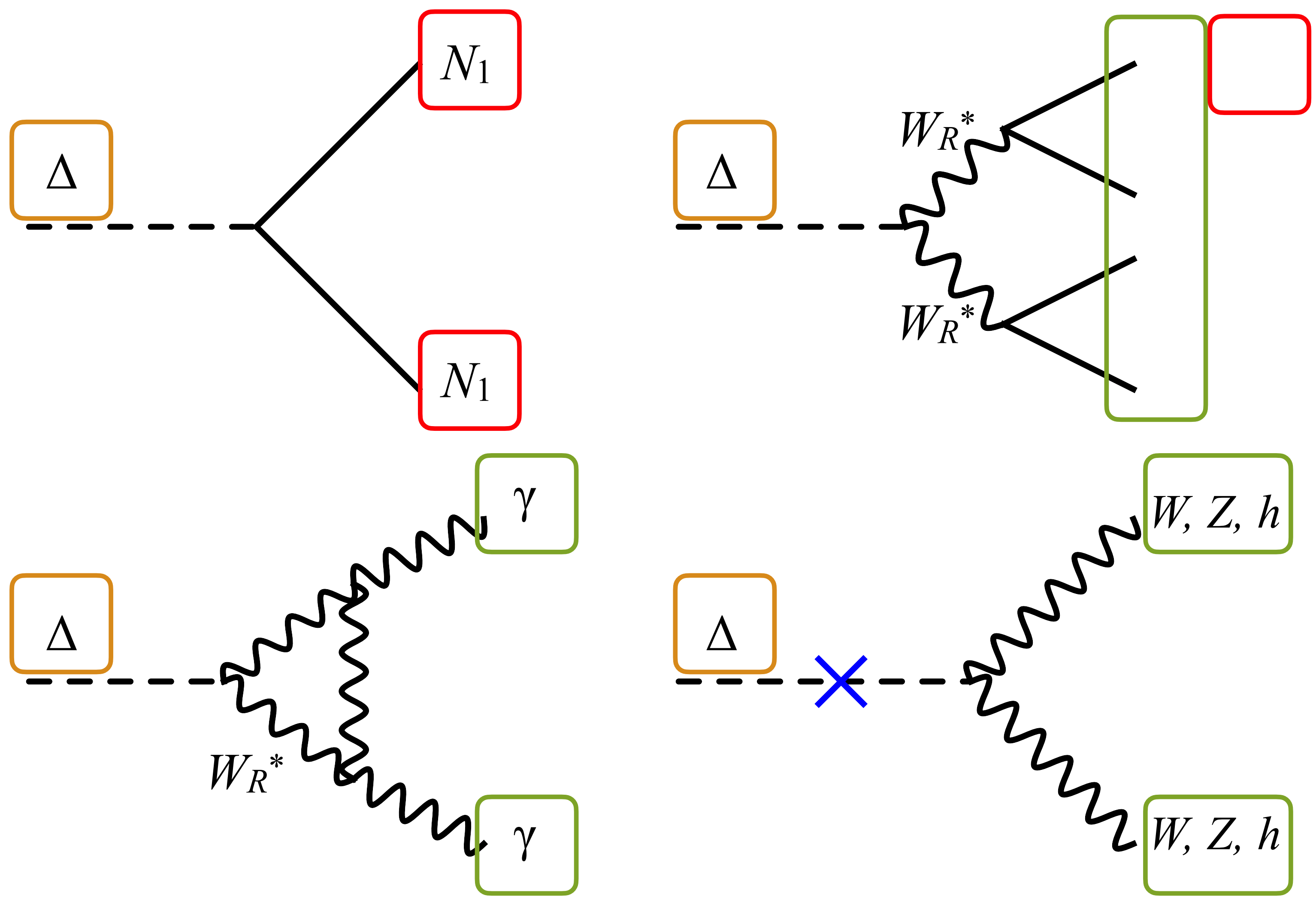
MN, Zhang '24

$$\bar{L}_L^c i\sigma_2 \Delta_L Y_L^M L_L + \bar{L}_R^c i\sigma_2 \Delta_R Y_R^M L_R \quad \Longrightarrow \quad M_N = \frac{v_R}{\sqrt{2}} Y_{\Delta_R}$$

triplet Δ can mix with the SM Higgs h : $\theta_{\Delta h} \neq 0$

Triplet is "Majorana" Higgs

Many diluting and some repopulating channel



$$\Gamma_{\Delta\to N_1N_1} = \frac{G_F M_W^2 m_{N_1}^2 M_\Delta}{4\sqrt{2}\pi M_{W_R}^2}, \qquad \Gamma_{\Delta\to W_R^* W_R^*} = \frac{5 G_F^3 M_W^6 M_\Delta^7}{576\sqrt{2}\pi^3 M_{W_R}^6}$$

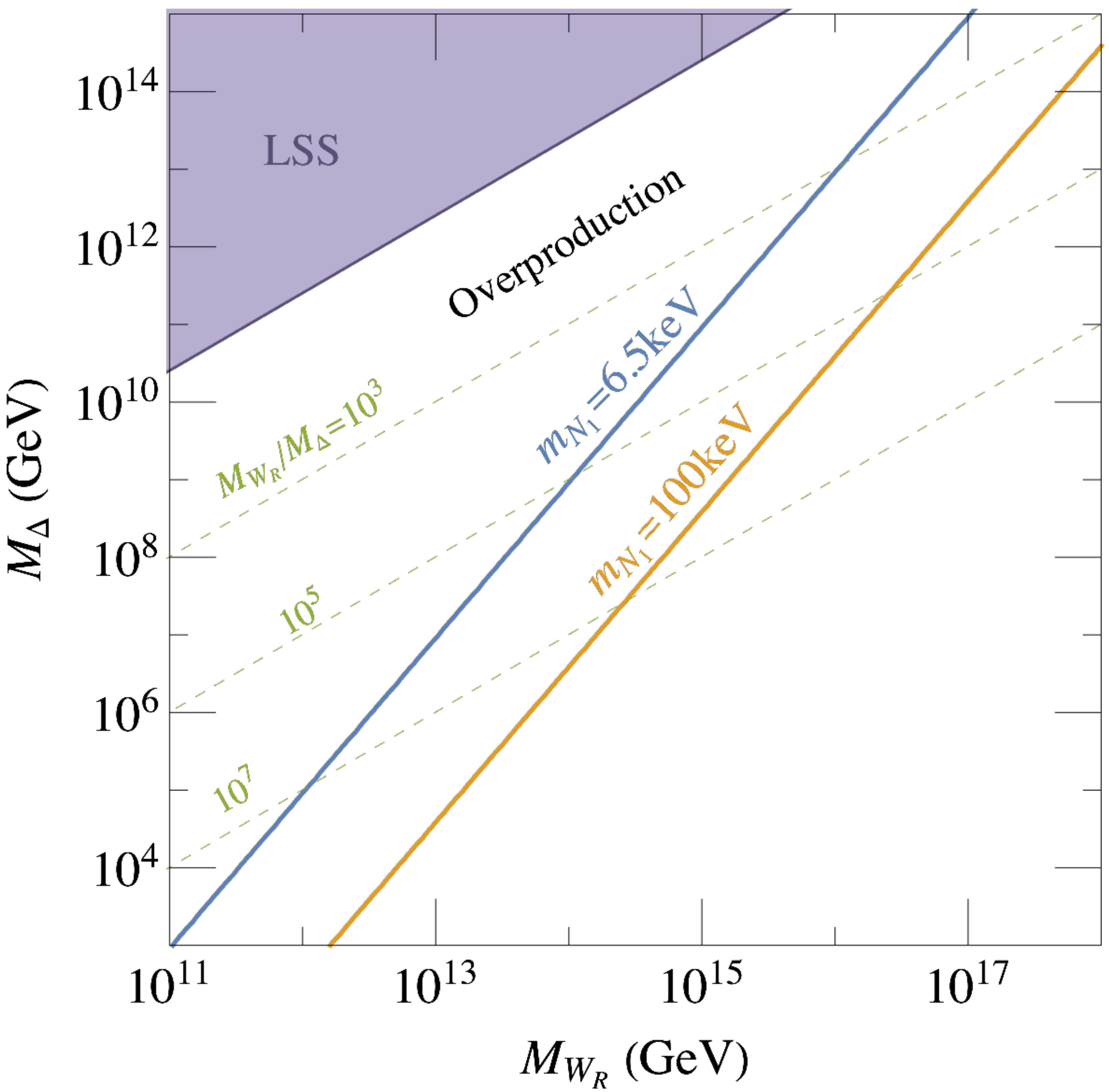
$$\Gamma_{\Delta\to\gamma\gamma} = \frac{49\alpha^2 G_F M_W^2 M_\Delta^3}{128\sqrt{2}\pi^3 M_{W_R}^2}, \qquad \Gamma_{\Delta\to h^*} \simeq \frac{\theta_{\Delta h}^2 G_F M_\Delta^3}{4\sqrt{2}\pi}$$

large hierarchy between N_1, Δ and M_{W_R}, vacuum stability — e.g. Weinberg '76

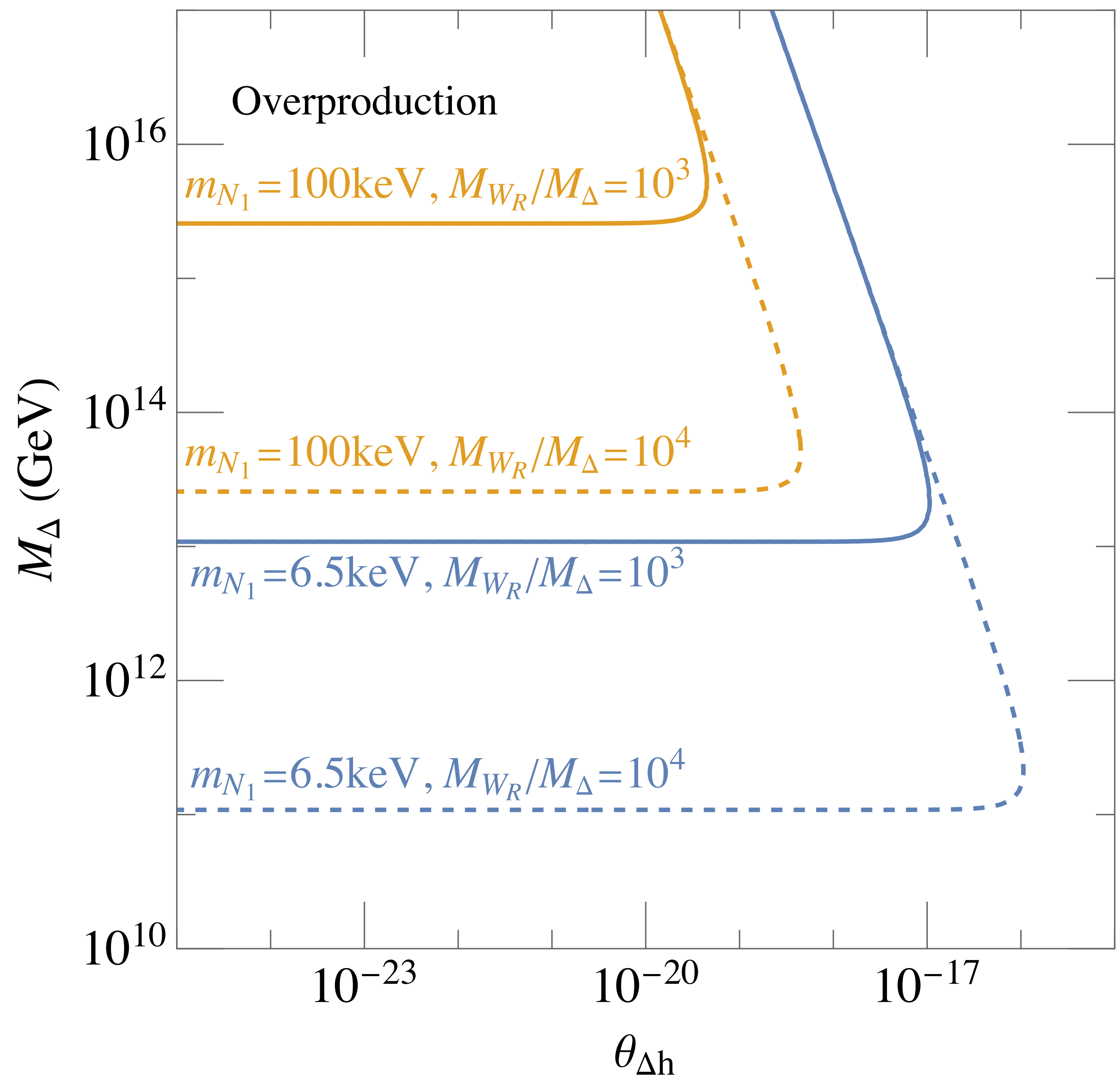
Δ can be dark matter — Dev, Heeck 25'

$$m_{N_1} \ll m_\Delta \ll M_{W_R}$$

no mixing



with tiny mixing



$$\frac{\Gamma_{\Delta\to N_1 N_1}}{\Gamma_{\Delta\to\gamma\gamma}} \simeq 1.2\times 10^{-7}\left(\frac{m_{N_1}}{M_\Delta}\right)^2 , \qquad \frac{\Gamma_{\Delta\to W_R^* W_R^*}}{\Gamma_{\Delta\to\gamma\gamma}} \simeq 2.3\times\left(\frac{M_\Delta}{M_{W_R}}\right)^4$$

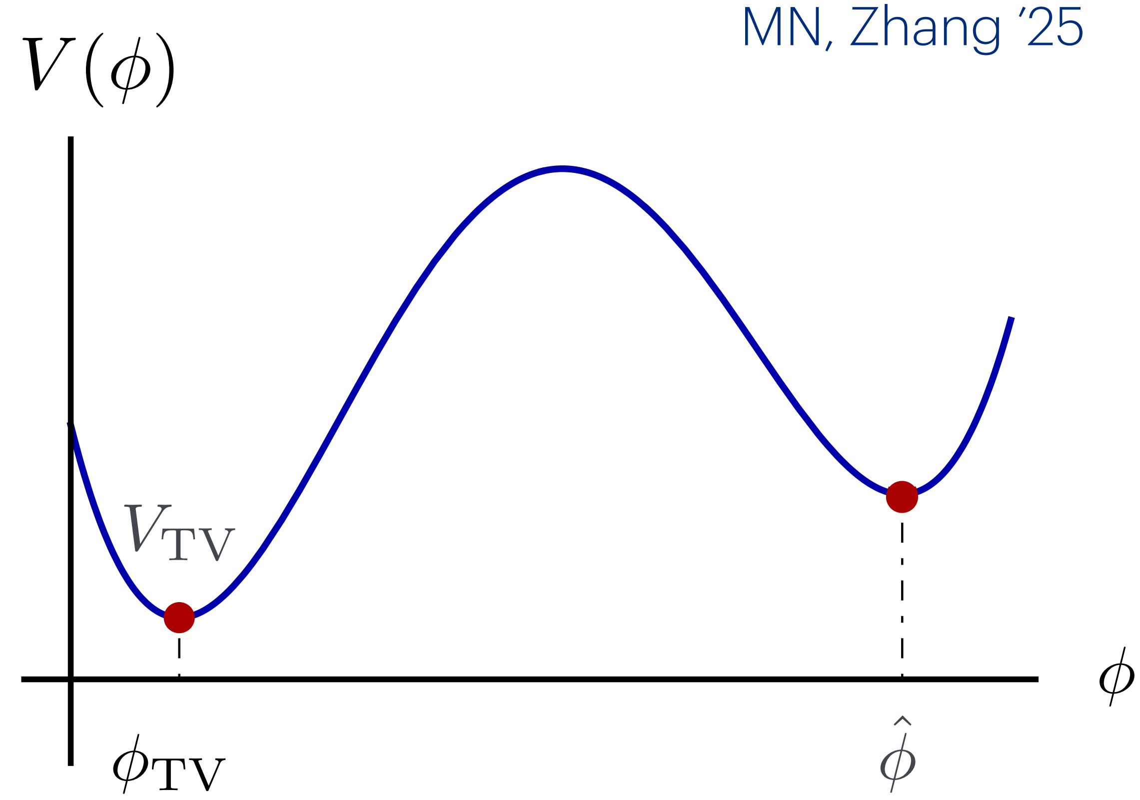
Blast-frozen Dark matter

MN, Zhang '25

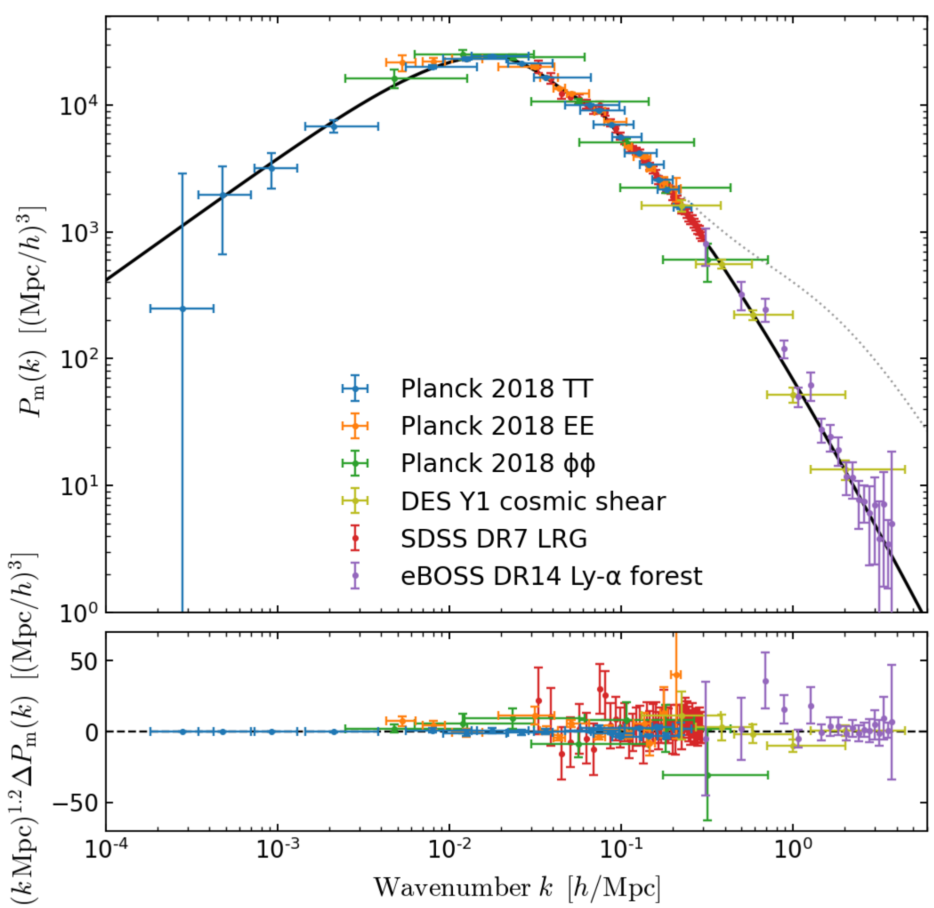
when does DM become massive?

$$m_X = m_0 + y\phi$$ fermions

$$m_X^2 = m_0^2 + \lambda\phi^2$$ scalars



massive DM needed by CMB and LSS



early

$$w \sim \frac{1}{3}$$

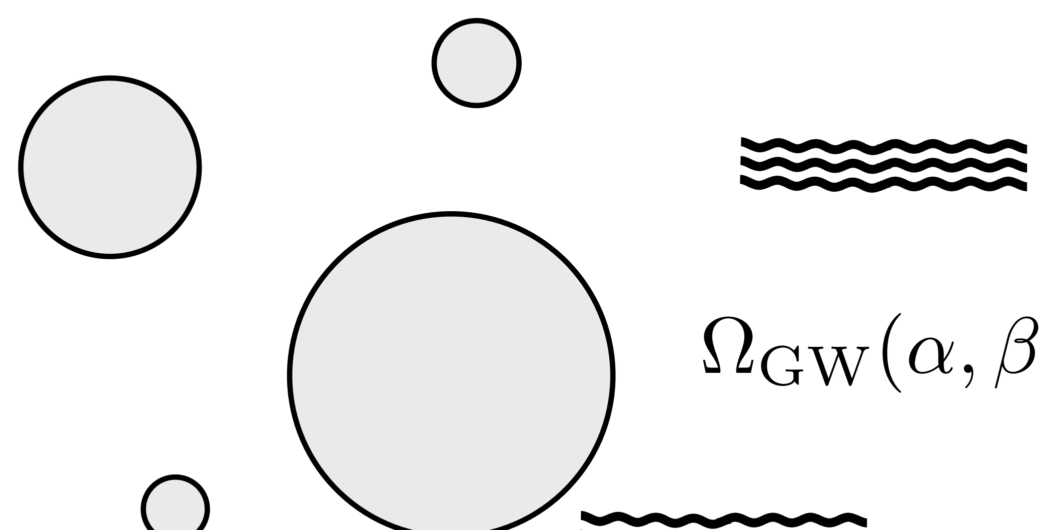
late

$$w \sim 0$$

First order phase transition T_*

$$T_* : \langle\phi\rangle = 0 \Rightarrow \langle\phi\rangle = \phi_0 \rightarrow v$$

Bubble collisions + plasma



$$\Omega_{\rm GW}(\alpha, \beta, v_w)$$

BFDM equation of state w

MN, Zhang '25

bounce action (FindBounce)

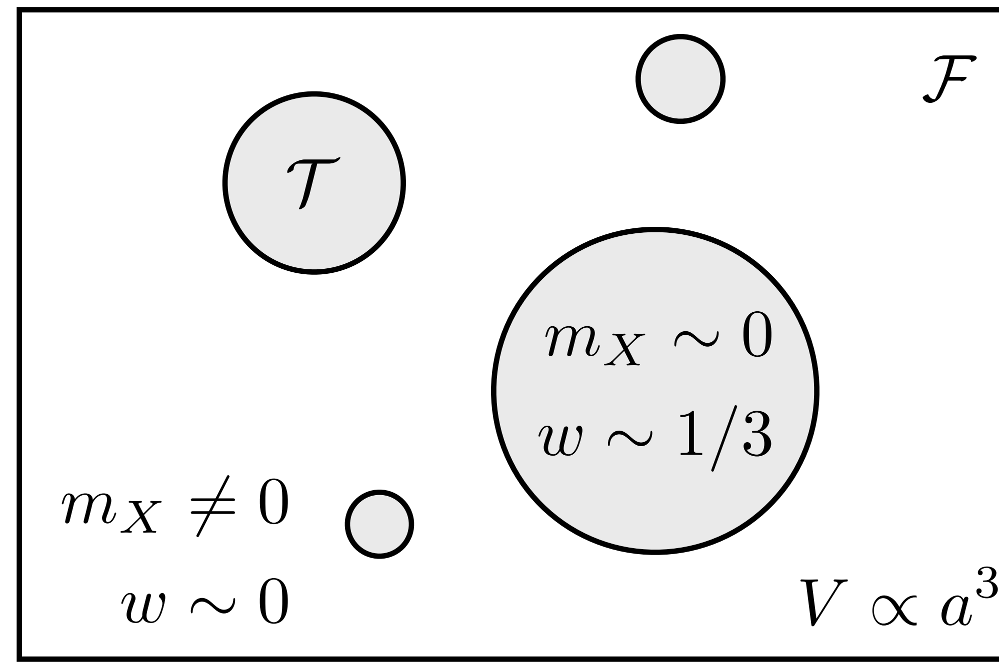
Nucleation possible below T_c

$$B \simeq \frac{S_3}{T} \qquad \beta \simeq -\frac{\mathrm{d}B}{\mathrm{d}t}$$

Nucleation rate $$\gamma = \frac{\Gamma}{V} = A\, e^{-B} \qquad A \sim T^4$$

determinants, SM

Volume fraction expansion Guth, Weinberg '83



$$\mathcal{F}(t) = \exp\left(-\int_{t_c}^{t} \mathrm{d}t_1 \gamma(t_1) a(t_1)^3 V(t_1, t)\right)$$

$$w(t) \simeq \frac{1}{3}\mathcal{F}(t) \simeq \frac{1}{3}\exp\left[-e^{\beta(t-t_*)}\Theta(t-t_c)\right]$$

Enqvist et al. '92, Caprini et al. '19

Double exponential transition, correlated with GW production e.g. PT2GWFinder

$$w(t) = \begin{cases} \frac{1}{3}\,, & t < t_-\,, \\ 0\,, & t > t_+\,, \end{cases} \qquad \dot{w}(t_-) = \dot{w}(t_+) = 0 \qquad \mathcal{F}(t_*) = 1/e$$

$\beta/H_* \to \infty \Rightarrow t_\mp \to t_*$ blast-frozen

$w(t, \vec{x}) \to w(t)$ homogeneous

BFDM perturbations δ

MN, Zhang '25

Keep the general *w* (numerics)

Ma, Bertschinger '95

$$\delta' = -(1+w)(\theta - 3\phi') - \frac{3a'}{a}\left(\frac{\delta p}{\delta\rho} - w\right)\delta$$

$$\theta' = -\frac{a'}{a}(1-3w)\theta - \frac{w'}{1+w}\theta + \frac{\delta p/\delta\rho}{1+w}k^2\delta + k^2\psi$$

Radiation $\quad \phi(k,\tau) = 2\mathcal{R}(k)\frac{\sin x - x\cos x}{x^3} \qquad x = \frac{k\tau}{\sqrt{3}} \qquad \phi = \psi \qquad \frac{\delta p}{\delta\rho} = w - \frac{w'}{3(1+w)a'/a}$

Set the asymptotic *w* (analytics) $\quad \delta(k,\tau) = \mathcal{R}(k)\mathcal{G}_{\mp}(x)$

$\delta(k,0) = -2\phi(k,0)\,,\, \delta'(k,0) = 0$

adiabatic

$w = \frac{1}{3} \qquad \mathcal{G}_-(x) = 4\cos x + 8\frac{(1-x^2)\sin x - x\cos x}{x^3}$ — oscillations + damping

$w = 0 \qquad \mathcal{G}_+(x) = c_1 + c_2\ln x + 6\mathrm{Ci}(x) + 6\frac{(1-x^2)\sin x - x\cos x}{x^3}$ — log growth + damped osc.

fix by matching

Ballistic DM Das, Dasgupta, Khatri '18

Perturbations δ_{BFDM}

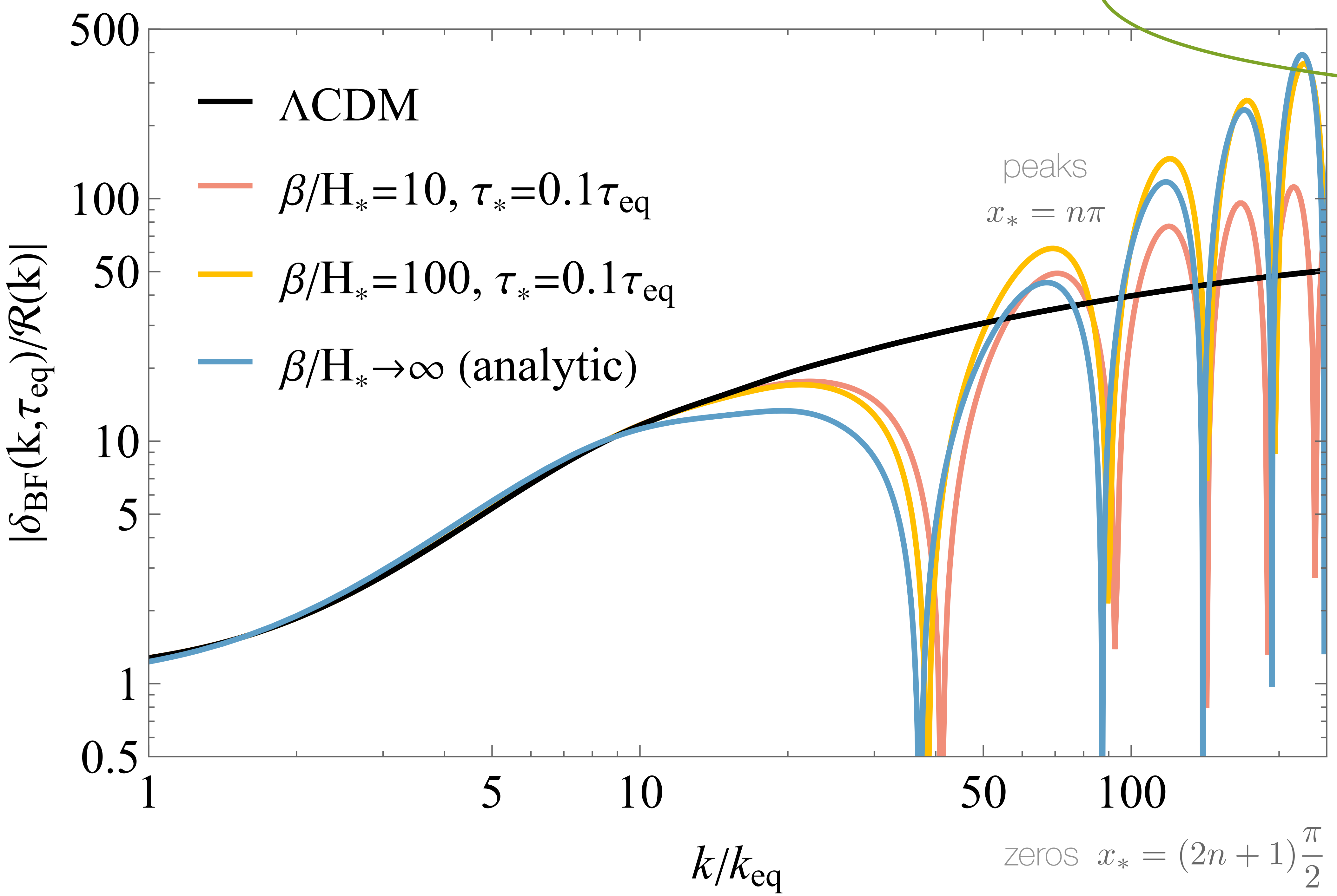
MN, Zhang '25

instantaneous matching $\delta(\tau) = \frac{3}{4}\left(1 + w(\tau)\right)\delta(\tau_-)$

sub-horizon $\delta(x) \simeq -x_*^2 \cos x_* \log\left(\frac{x}{x_*}\right)\mathcal{R}(k)\,,\; x > x_* \gg 1$

usual log growth

oscillations from boundary with *m=0*, enhanced large *k*



Oscillates above LCDM

Specific small scale features

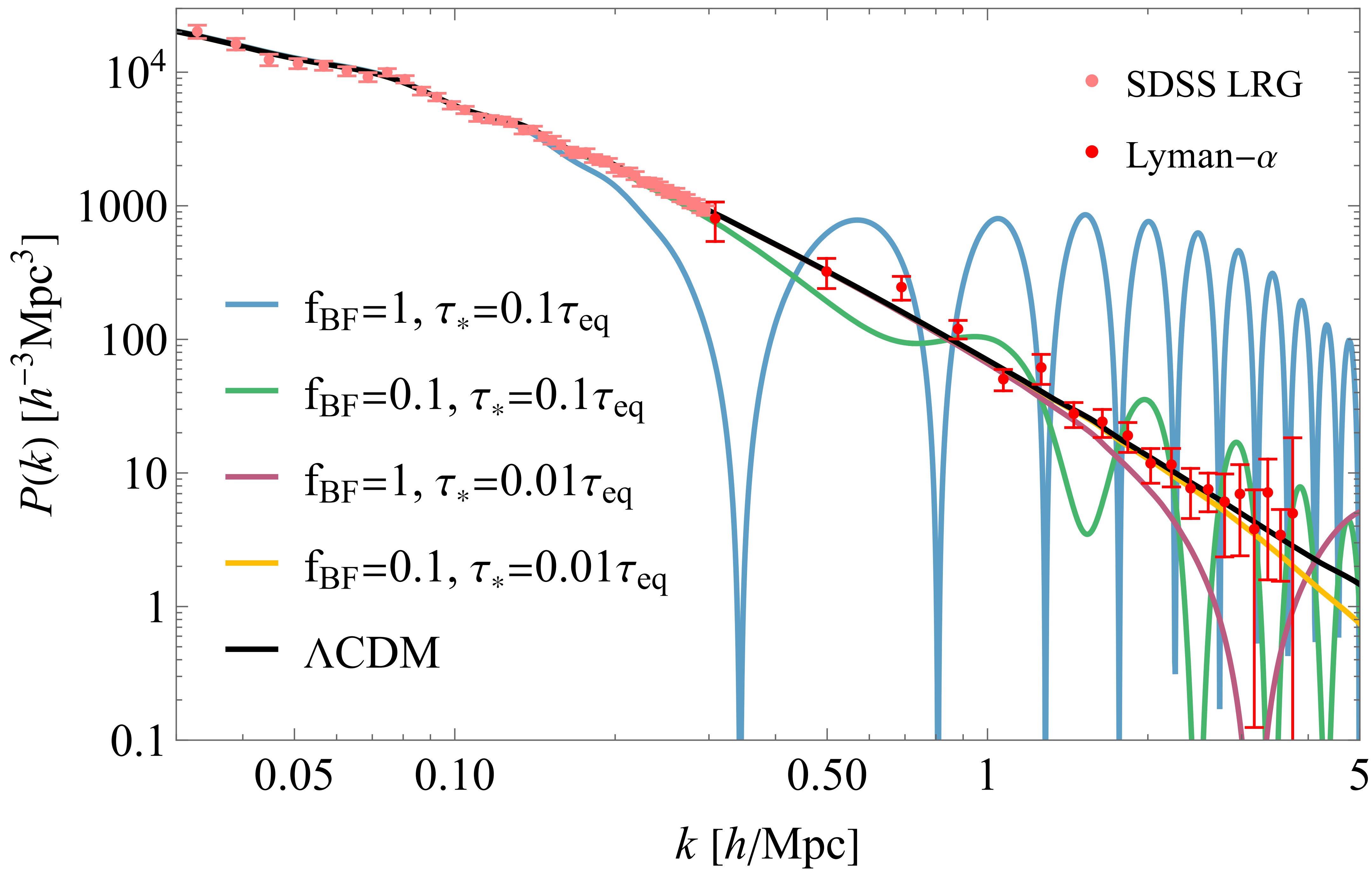
DM structure formation measures FOPT duration

Fractional BFDM $f_{\rm BF}$

MN, Zhang '25

$$P(k) = P_{\Lambda\rm CDM}(k) \left| \frac{f_{\rm BF}\delta_{\rm BF} + (1-f_{\rm BF})\delta_{\rm CDM}}{\delta_{\Lambda\rm CDM}} \right|^2$$

Totality of BFDM possible if early enough: $f_{\rm BF} = 1 \quad \tau_* \lesssim \tau_{\rm eq}/100$

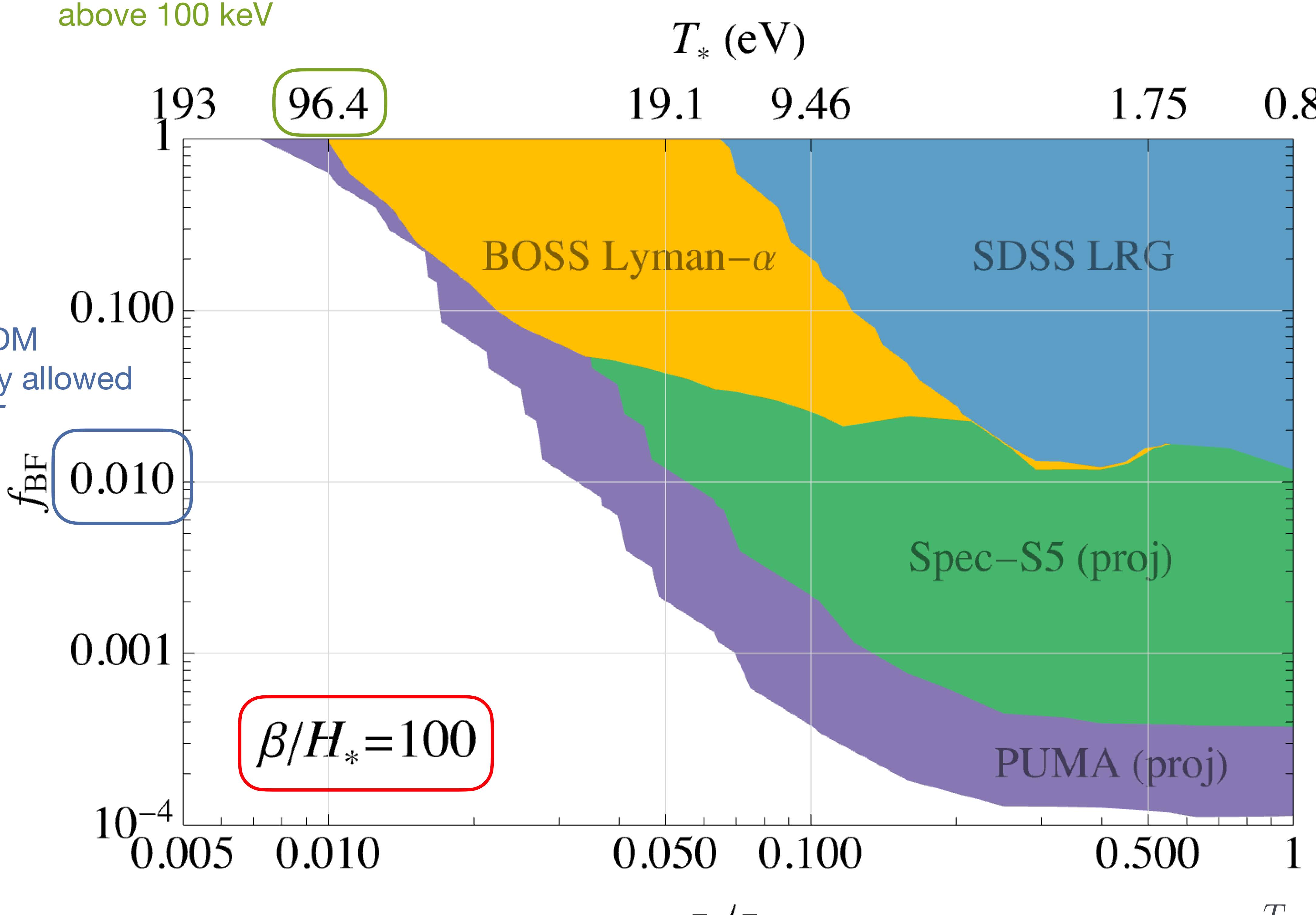


Nucleation T_*

MN, Zhang '25

Total BFDM allowed above 100 keV

1% BFDM currently allowed at any T



Future sensitivity at 10^{-4}

Fast transition

$$\Delta N_{\rm eff} \simeq 0.14\, f_{\rm BF}\, \frac{T_{\rm eq}}{T_*}$$

Summary

1 Dark Matter can be diluted Majorana neutrino

The price: high scale of LR breaking

Observables cosmological, LSS imprints, X-rays

2 Dark Matter can be tied to a dark sector FOPT

Brings together GW creation and DM mass origin

Oscillating imprints growing at small scales

LIGHT DARK WORLD 2026

July 28th - July 31st
Carleton University
Ottawa, Canada

Thank you!