STUDYING DARK SECTOR IMPRINTS IN COSMOLOGY AND GROUND BASED EXPERIMENTS

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20.09.24

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LPTHE
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Outline

- Introduction

1. Evidence of dark matter
2. Particle dark matter (DM)
3. DM Production

- Non thermal DM
- CMB signature as DM probe

1a. Model A 1b. Results for model A JCAP 07 (2023) 012, Phys.Rev.D 106 (2022) 11*

- CMB signature as probe of BSM mediator

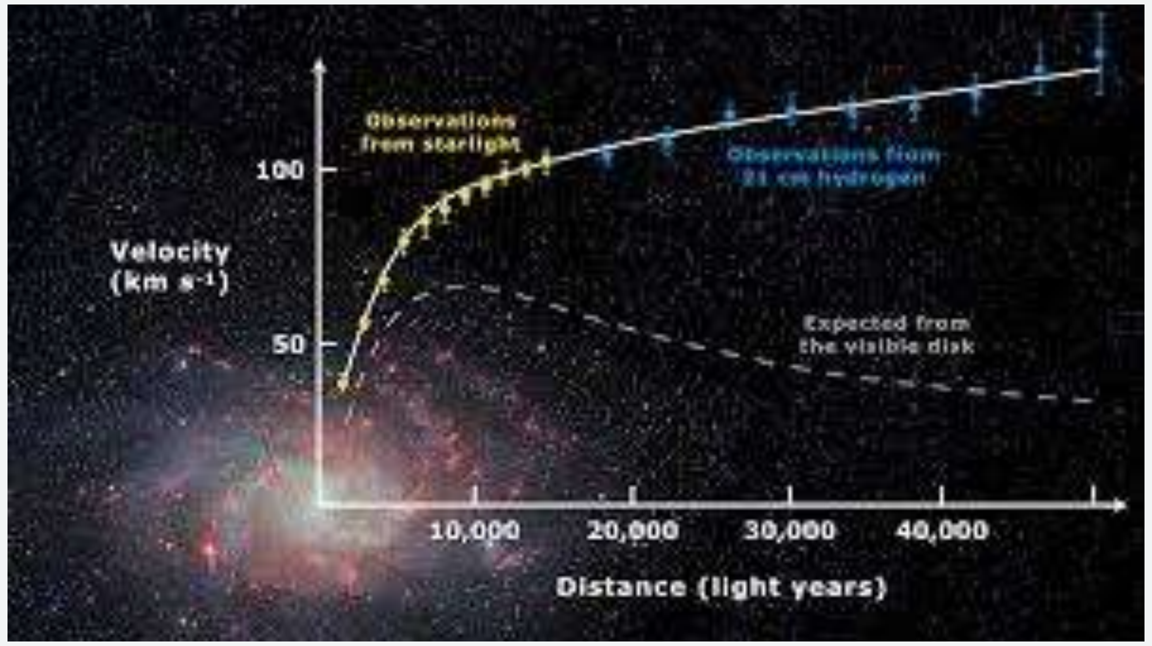
1. light Z′ in u(1)_x models Eur.Phys.J.C 84 (2024) 8, 853,
2. Neutrino decoupling in presence of Z′ 2404.10077 (Accepted in PRD) *

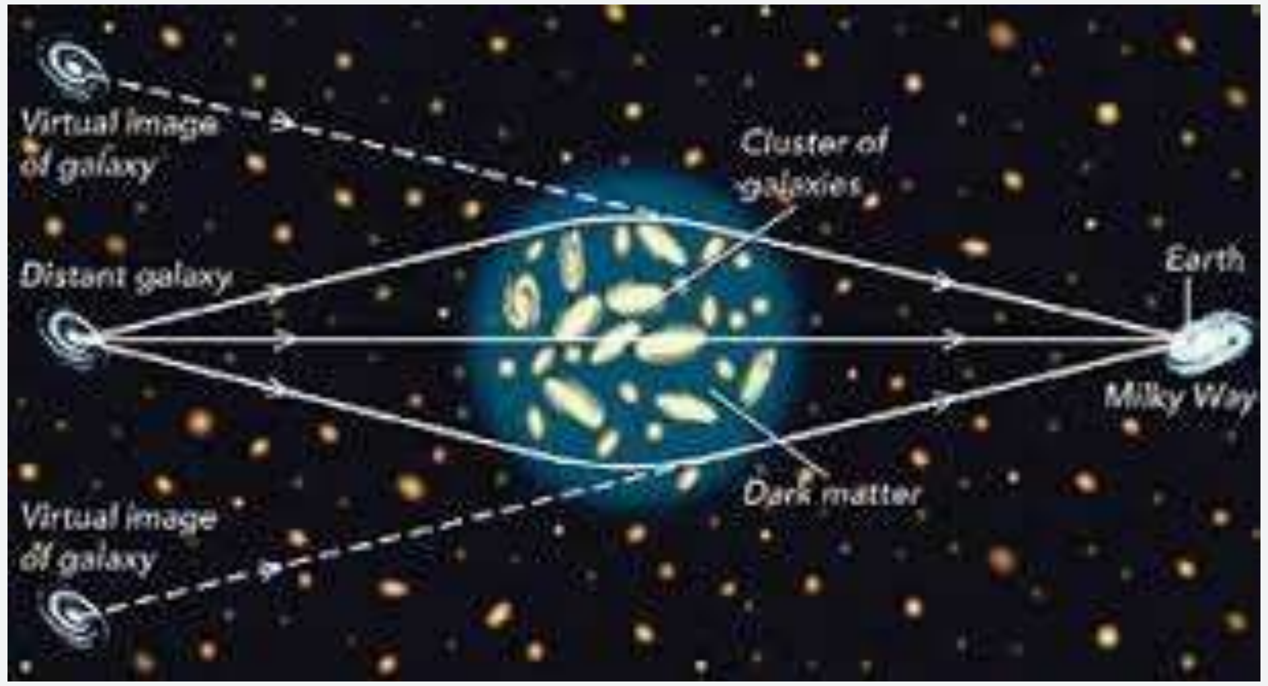
- Optically levitated nano-sphere probing

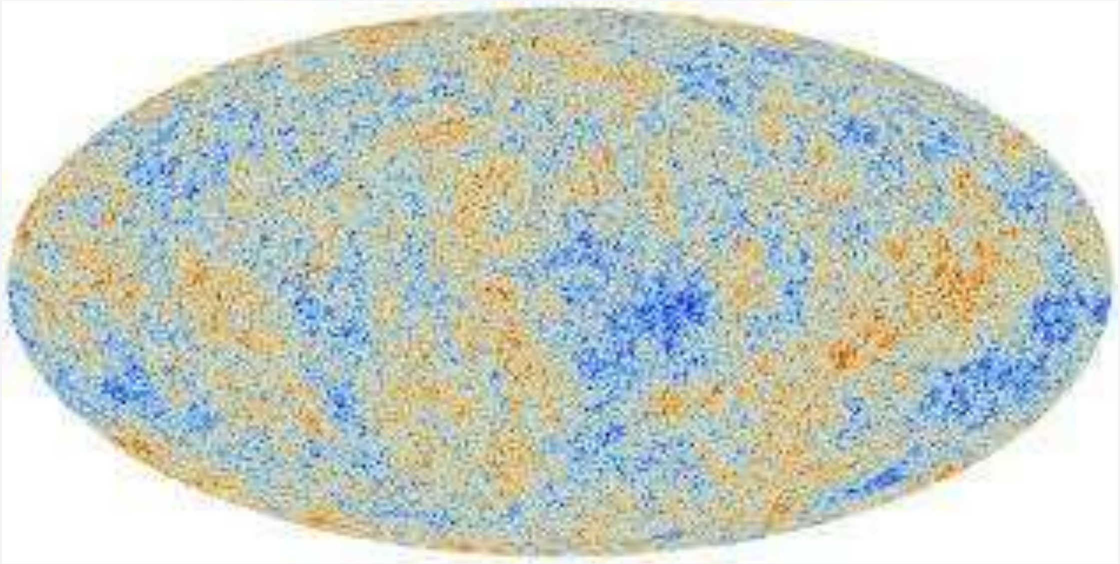
1. DM 2. ALP 2410.XXXXX

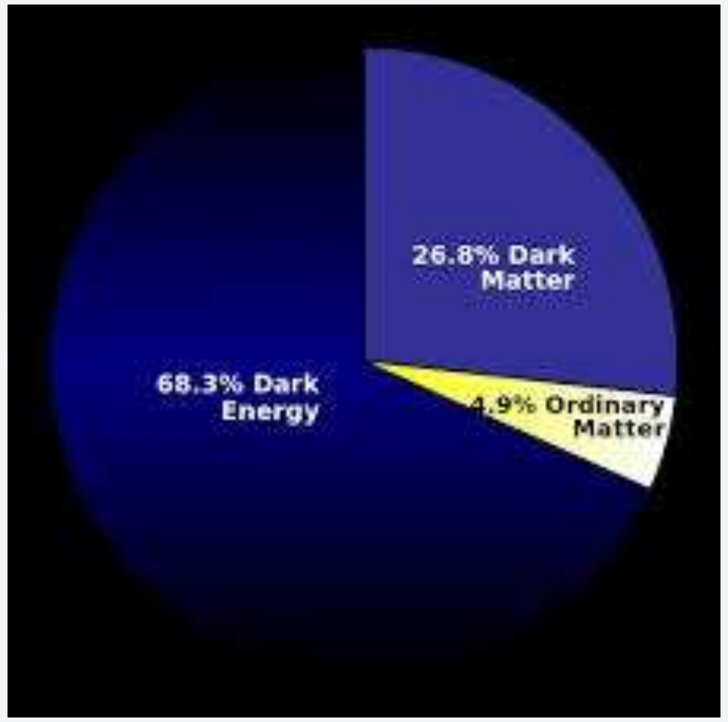
- Conclusion

Evidence of Dark matter









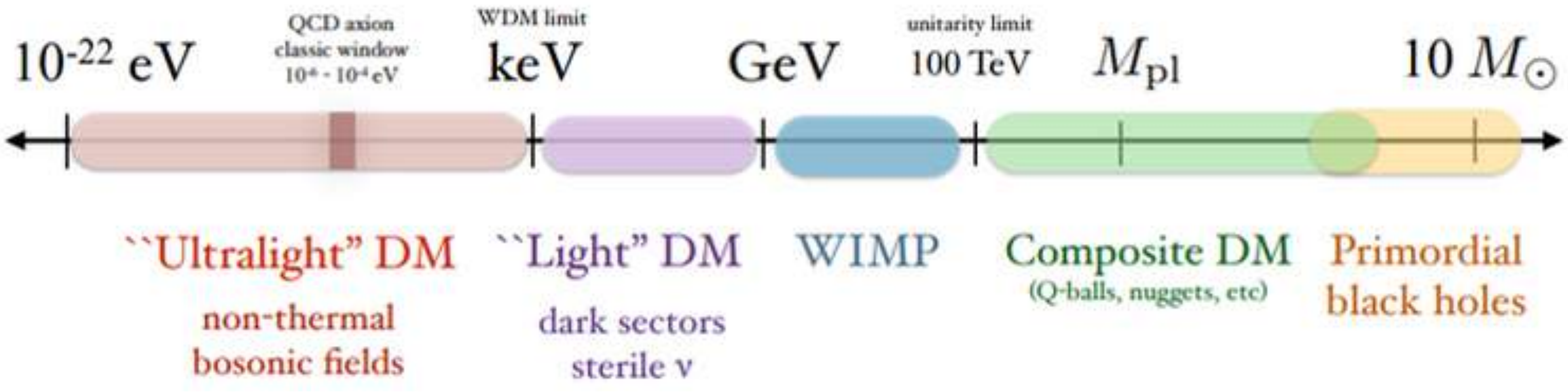
- Strongly suggest ~25% non-luminous, non baryonic DM
- SM fails to explain : begs for an extension

V.Rubin, WMAP, Planck 2018, M.Lisanti 2016

The puzzle of particle Dark matter

What we know:

- Interacts gravitationally
- Non luminous, electric charge very small
- Cold with mass<< momentum
- Collisionless at large scale



- Mass spanning from 1e-22 ev to the mass of least massive DM galaxy

M.Lisanti 2016, T. Lin 2019, Cirelli et al 2024

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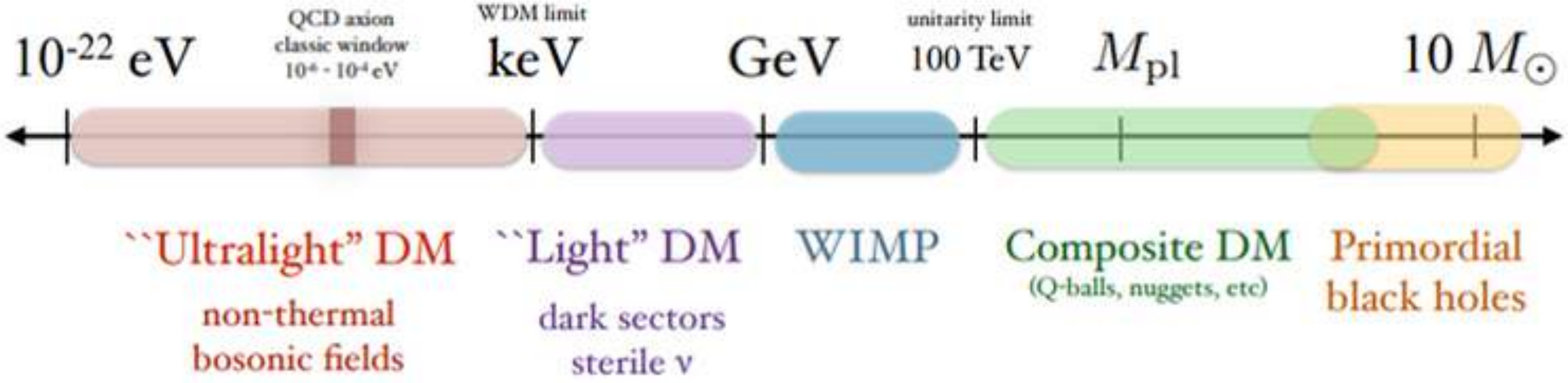

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What we don't know:

- Compact object or fundamental particle?
- Mass, Spin?
- interaction (with SM) other than Gravitational

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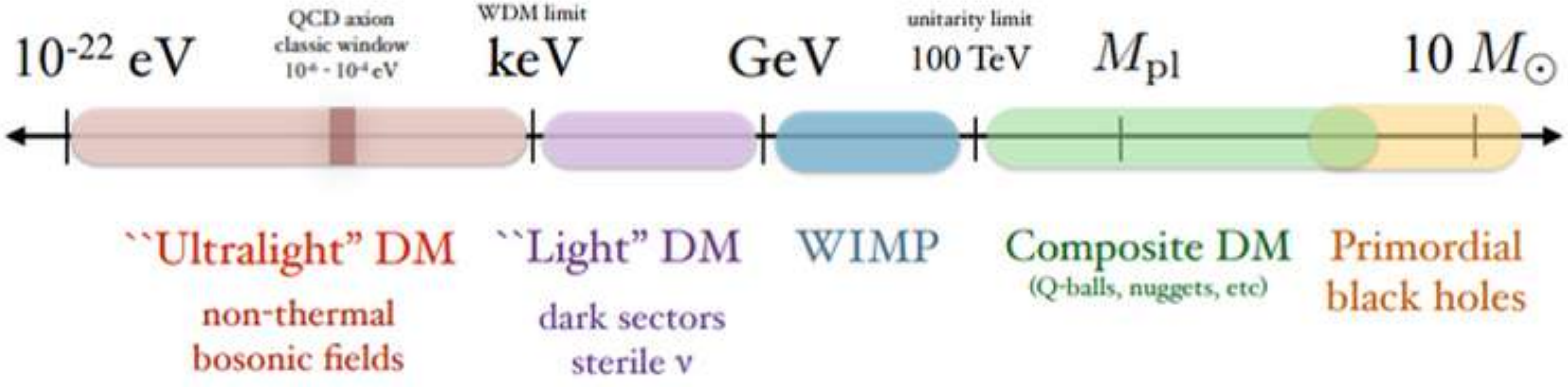

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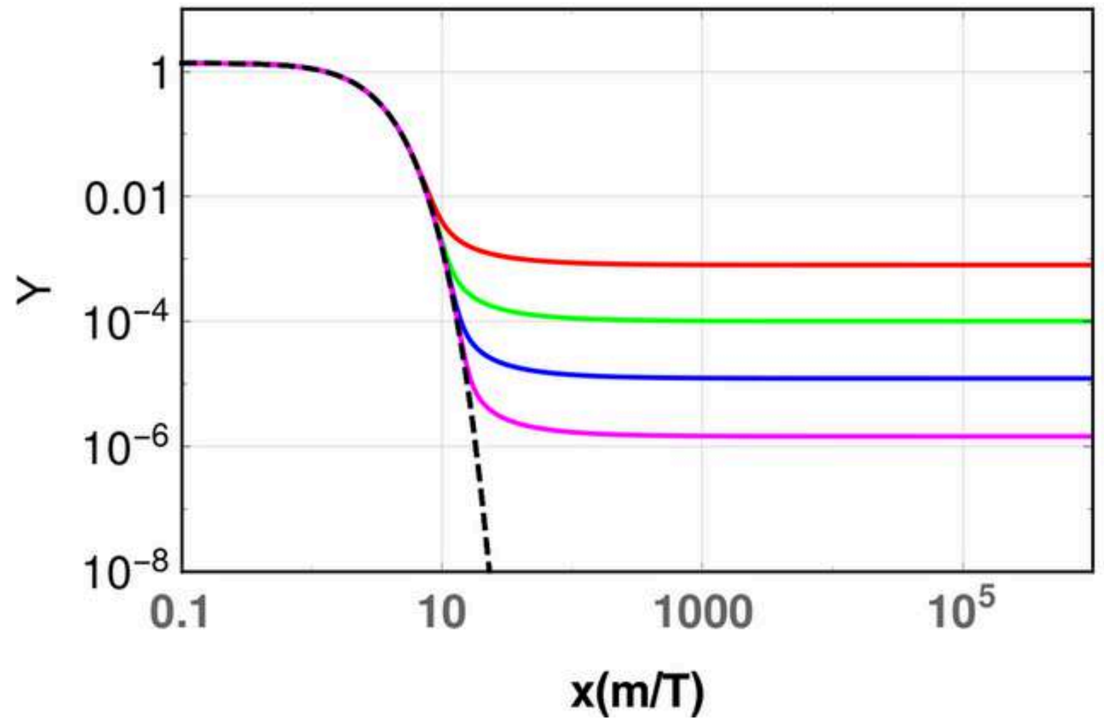
DM imprints can be related to production

M.Lisanti 2016, T. Lin 2019, Cirelli et al 2024

Dark matter production mechanisms

1.Thermal dark matter

- DM was in thermal equlibrium with SM bath at early time
- Kinetic eq. $\chi + SM \to \chi + SM$ ⟶ $T_\chi = T_{SM}$
- Chemical eq. $\chi + \chi \to SM + SM$ ⟶ $n_\chi = n_\chi^{eq.}$
- WIMP,SIMP and so on...



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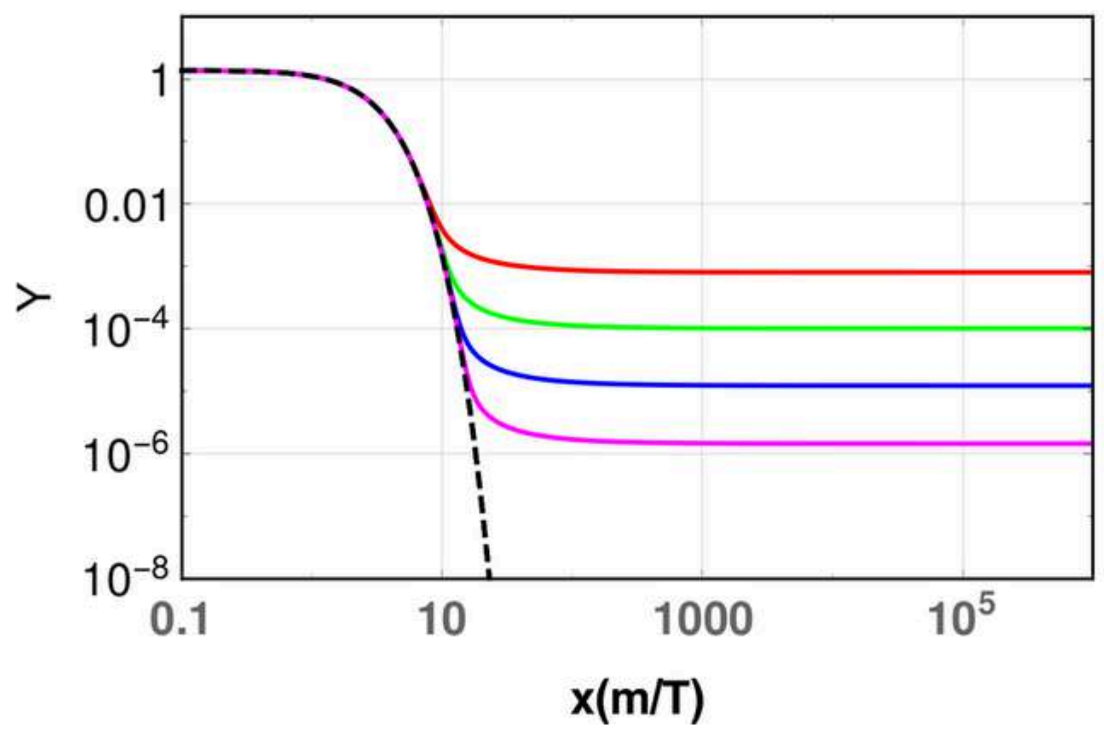
Can have imprints in Direct searches



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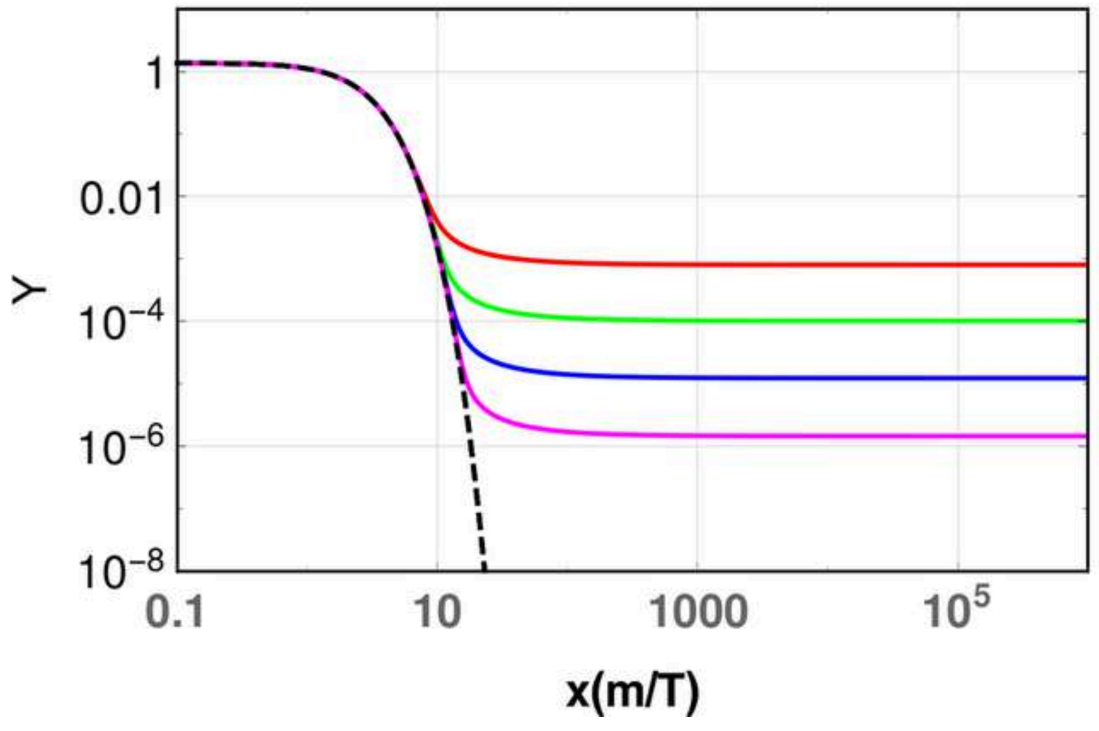
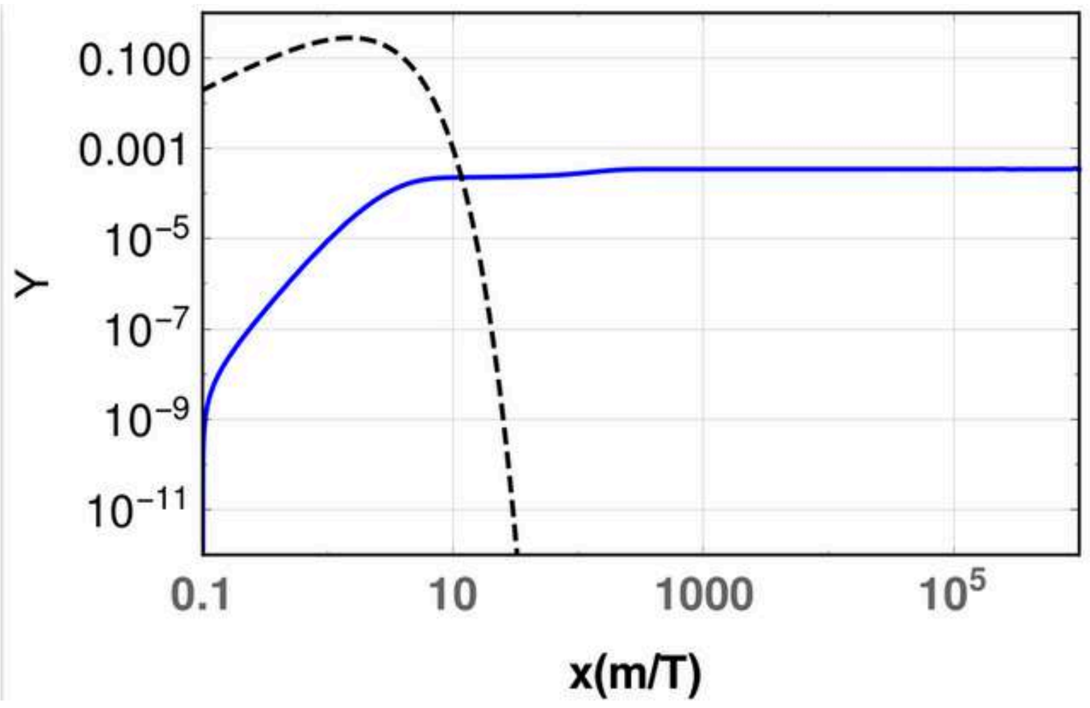


2.Non-thermal dark matter

- DM never attains equlibrium due to feeble interaction
- Initial abundance negligible
- Produced from decay/annihilation
- FIMP



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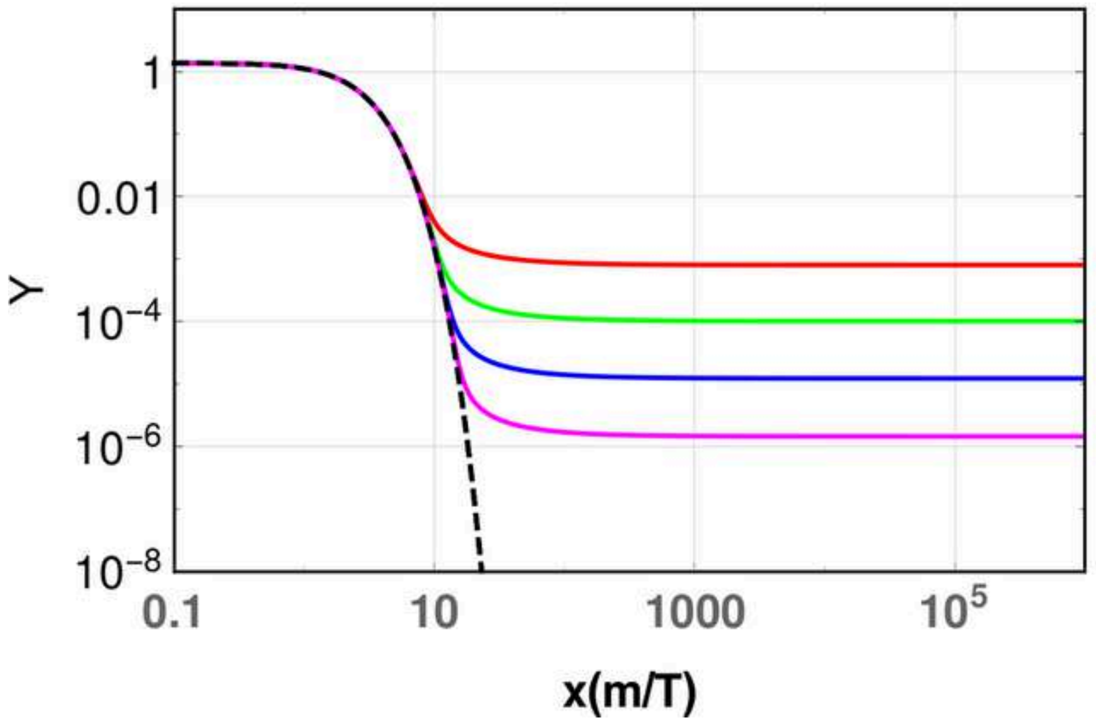

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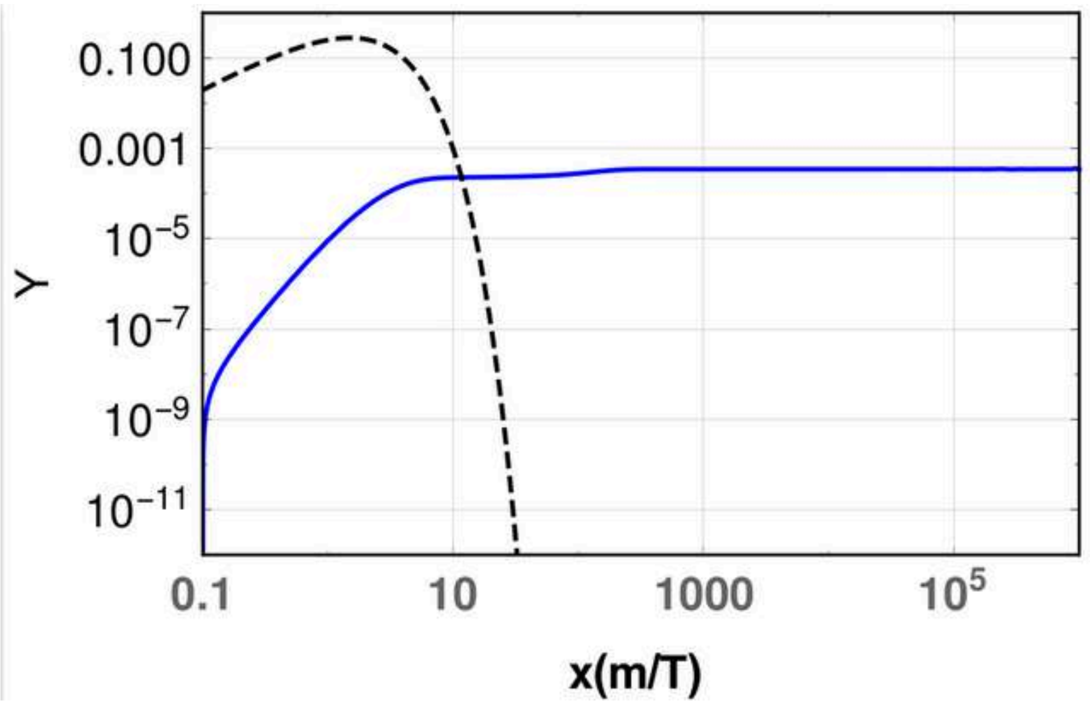

Non thermal dark matter

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Directly from SM bath

$$SM + SM \rightarrow \chi + \chi$$

Non thermal dark matter

Directly from SM bath

$$SM + SM \to \chi + \chi$$

One or More BSM particles

- Produced in steps

Non thermal dark matter

Directly from SM bath

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Collider probes

Long lived particle searches

Bharucha et al JHEP 2022,

D.k. Ghosh, A Ghoshal, SJ JHEP 2023

Dror et al PRD 2023

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SM $\to \phi$

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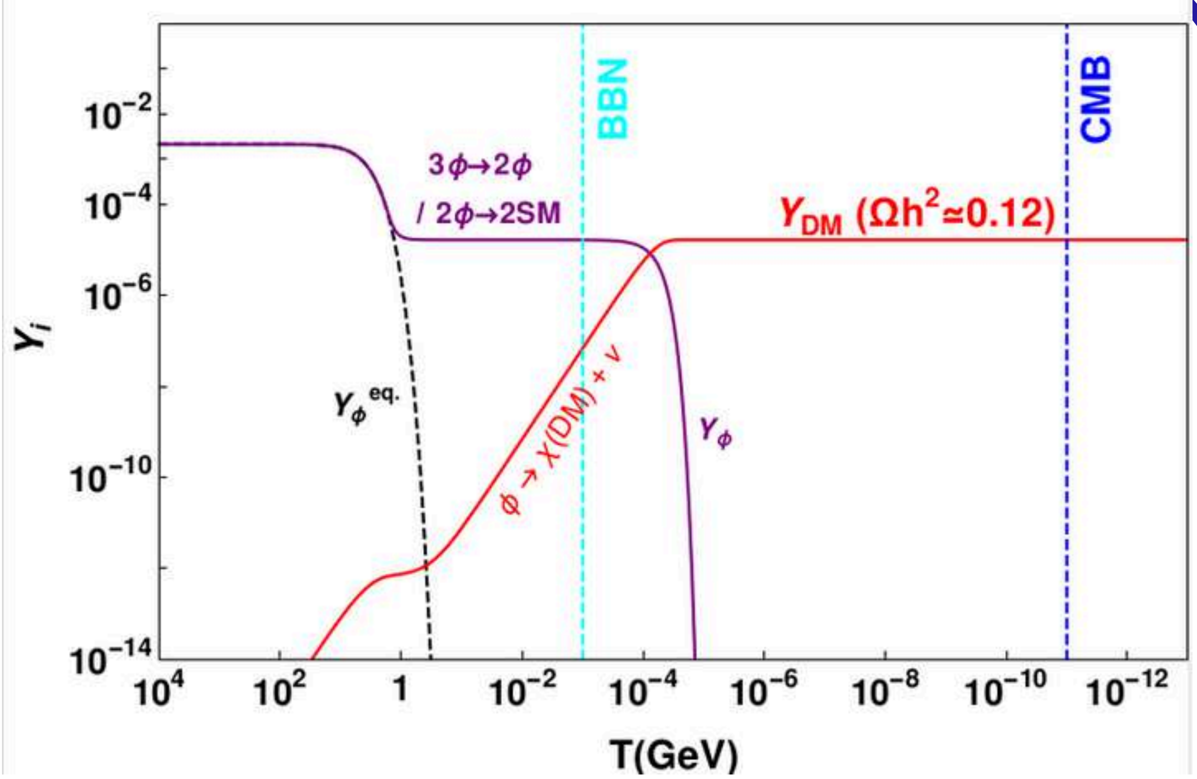

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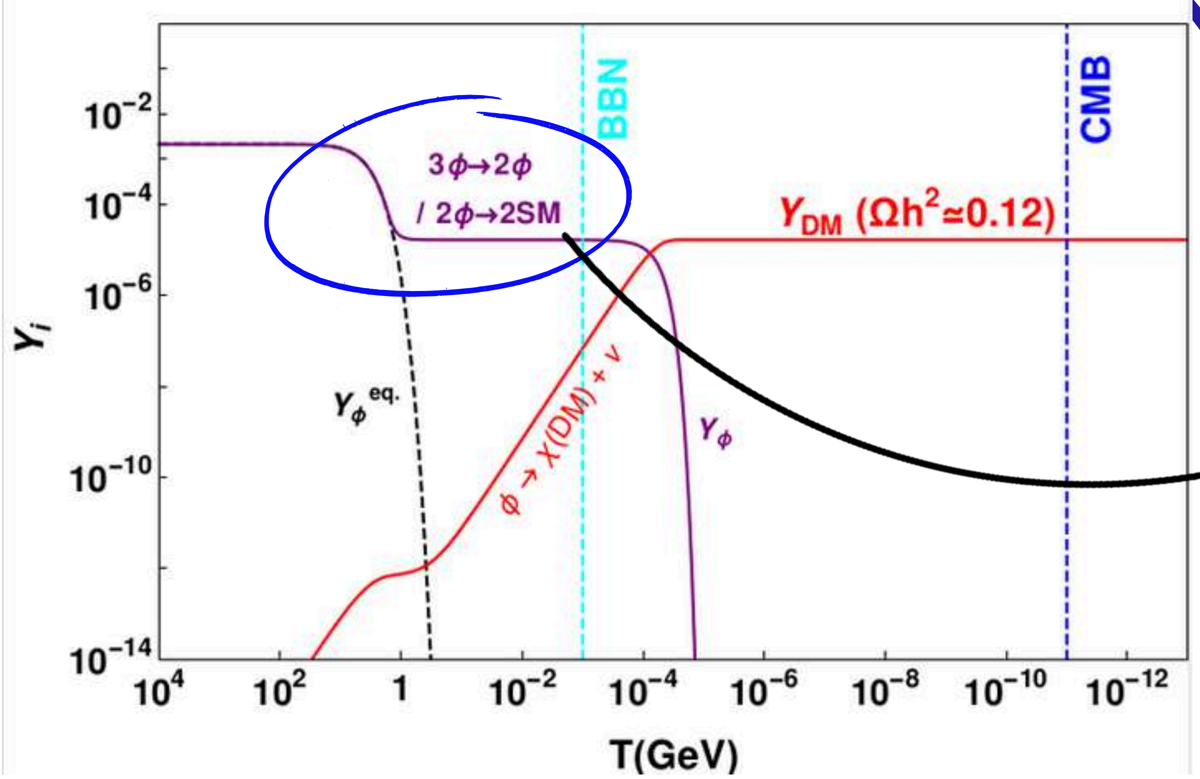

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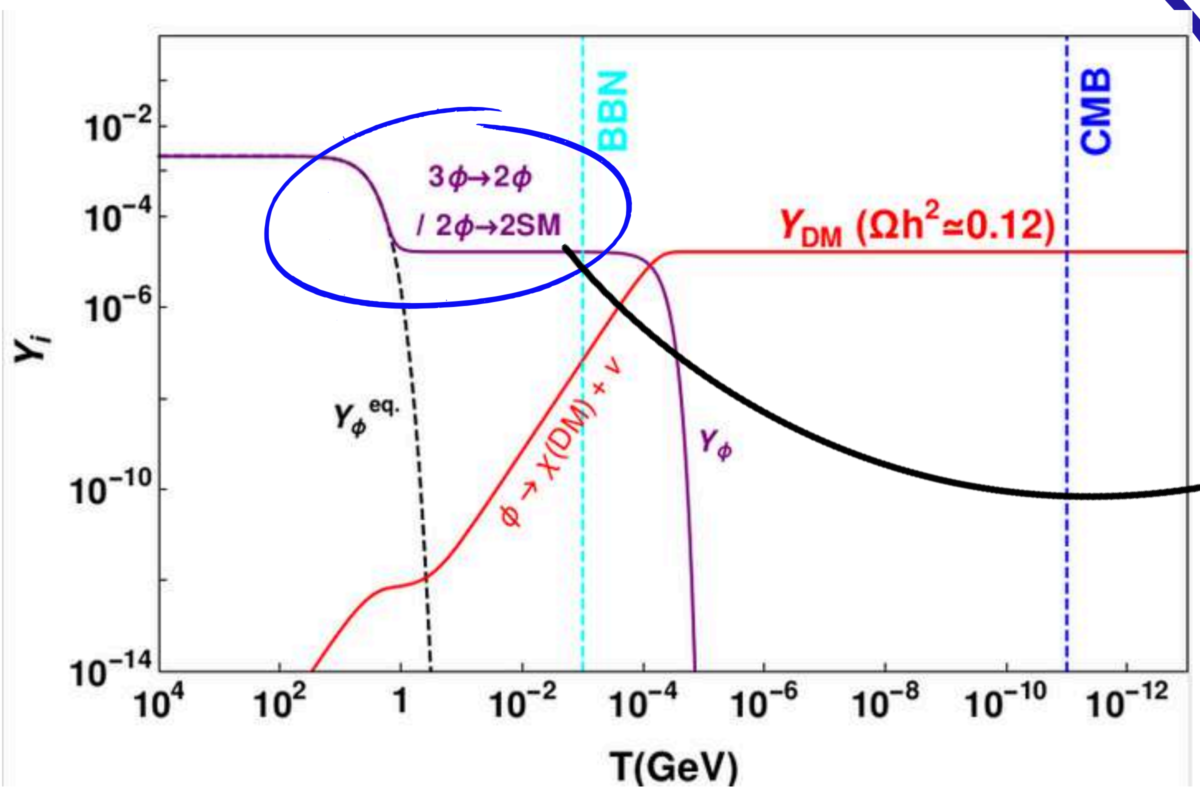

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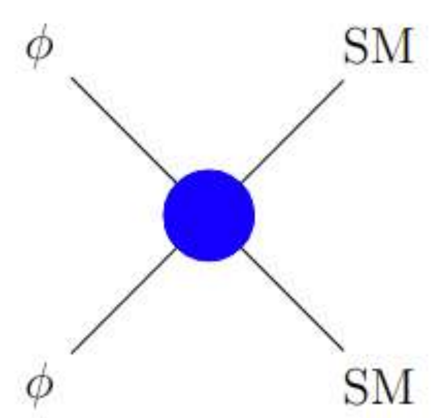

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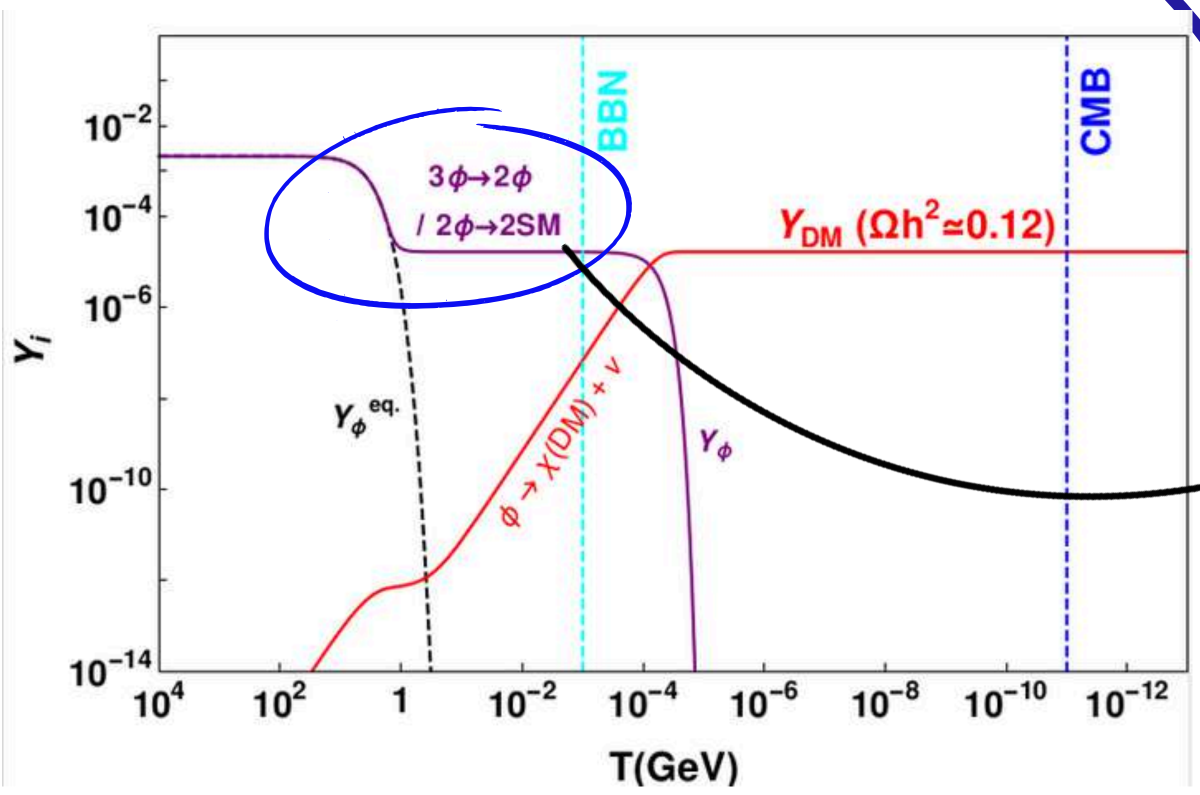

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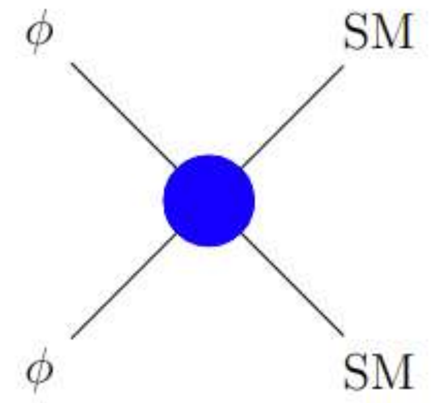
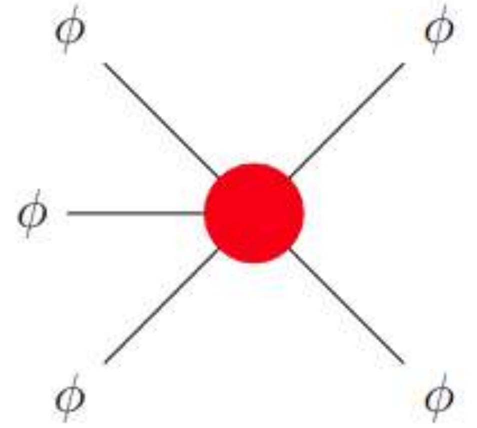


2.Self interaction



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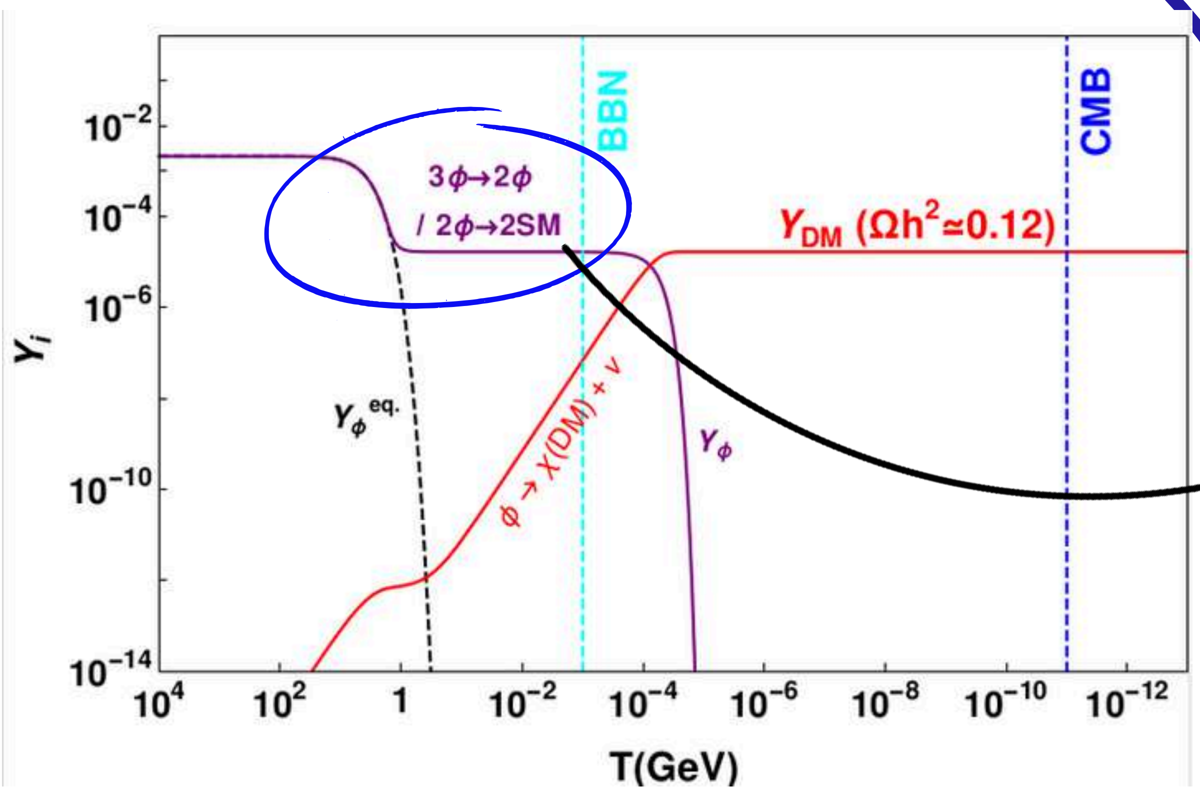

Q.Is it possible to probe such scenarios?---> Possible via CMB

If DM production affects N_{eff}

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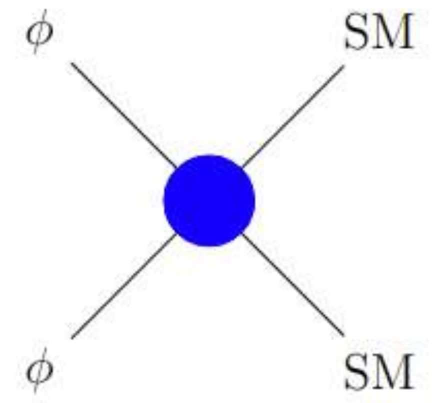

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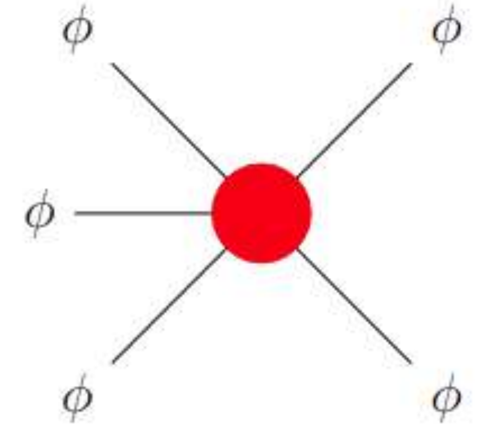
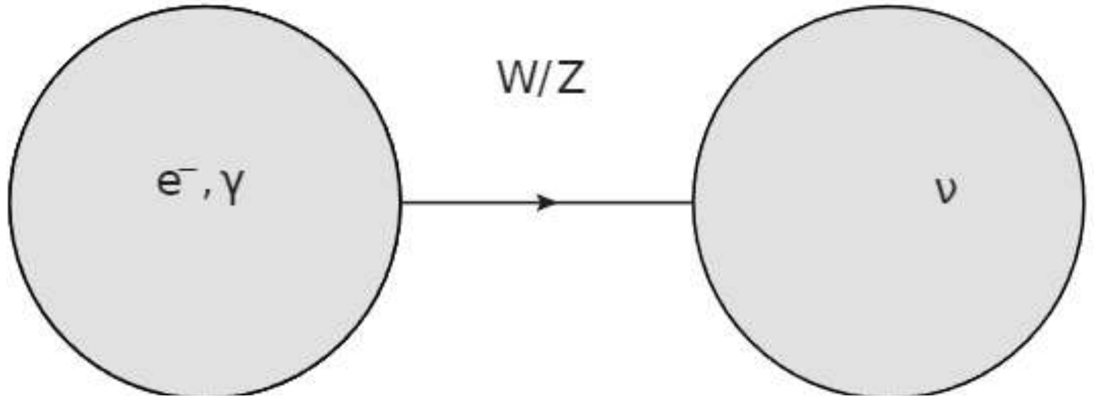


Contribution to N_{eff}

- $N_{eff}^{CMB} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{\rho_v}{\rho_\gamma}\right)_{CMB}$ where, $\rho_i \sim T_i^4$



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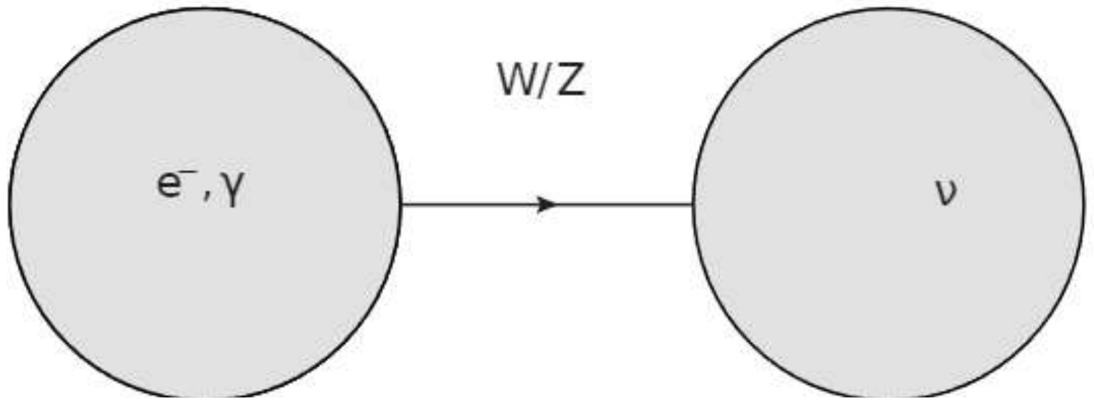

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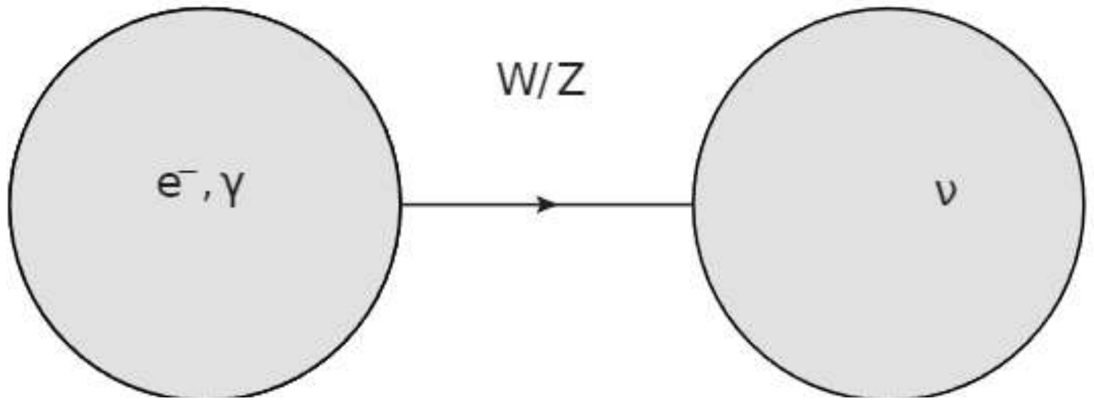

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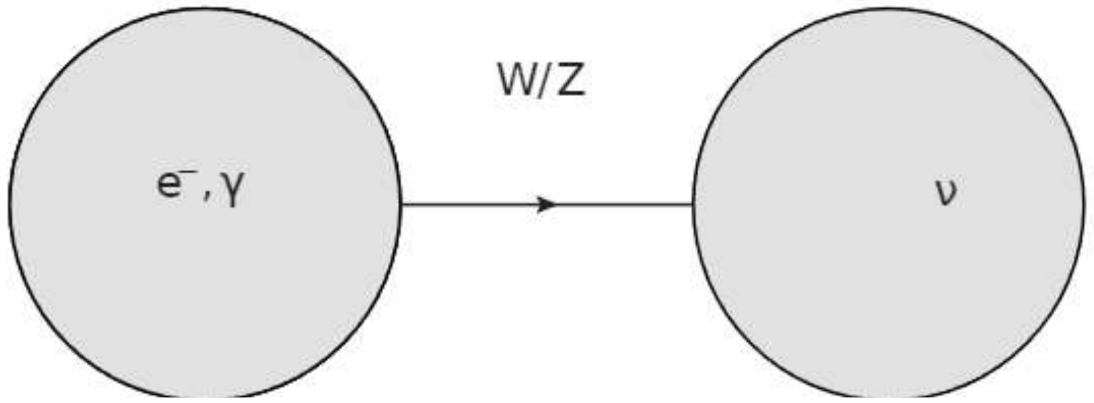

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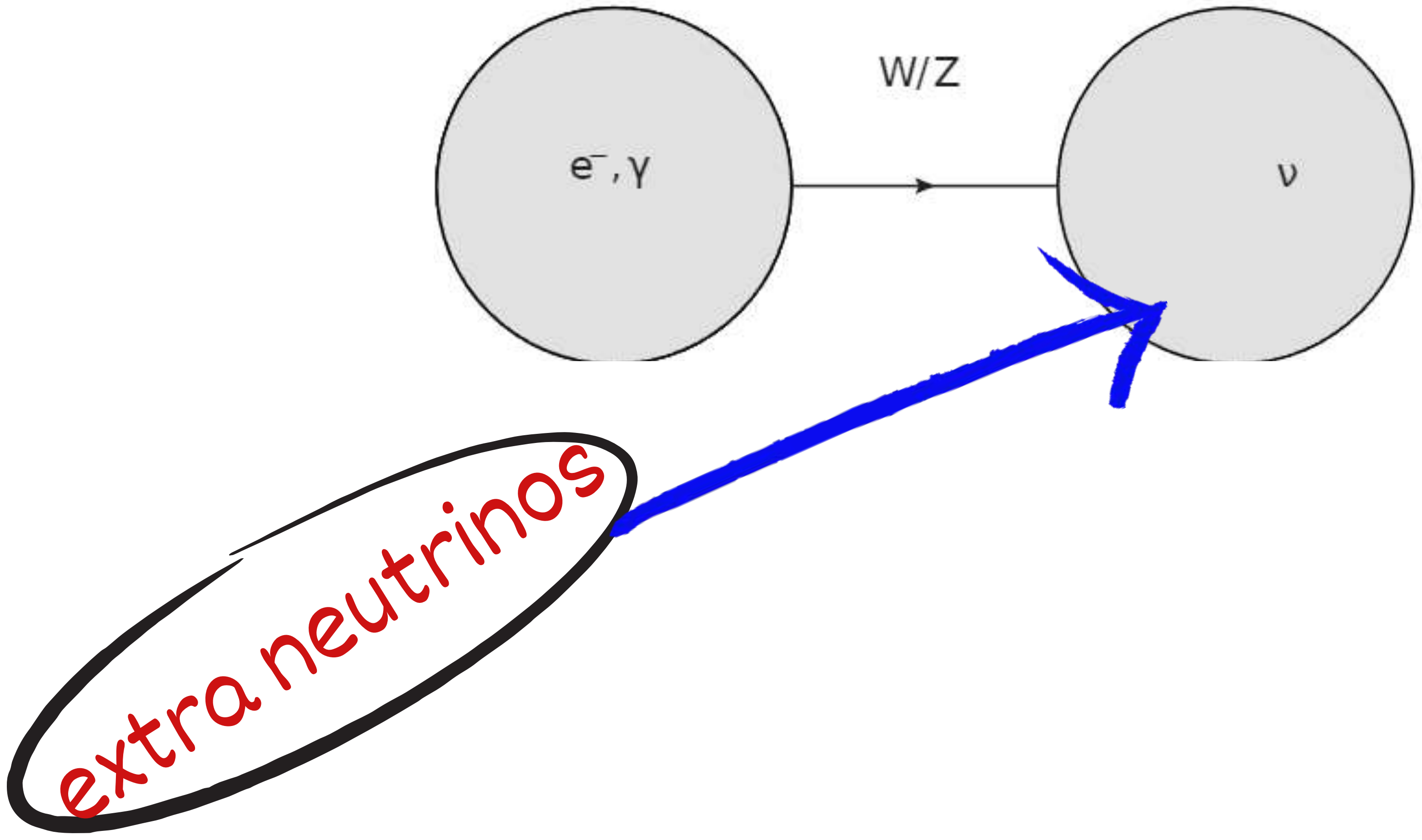

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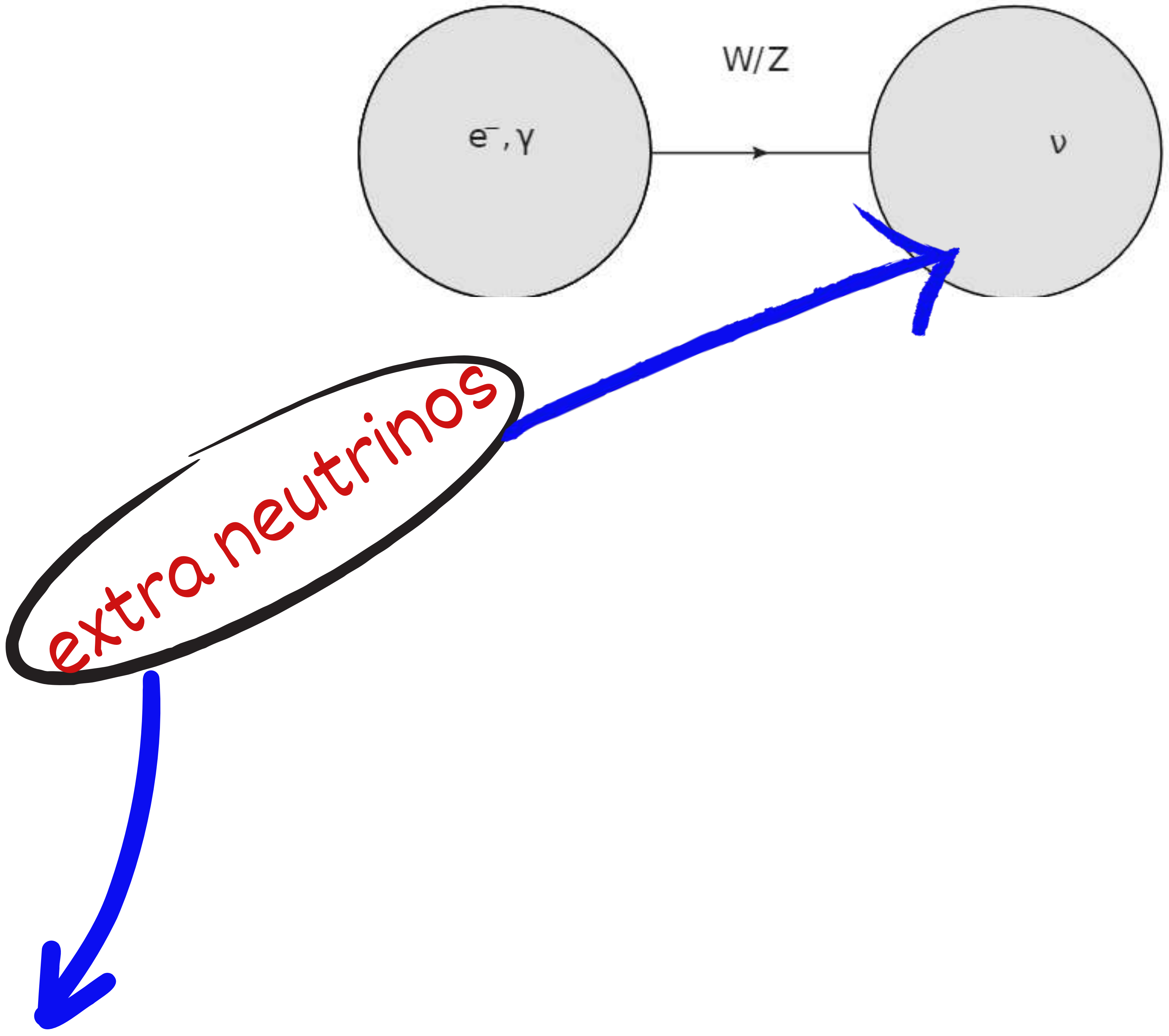

- $\frac{N'_{eff}}{N_{eff}^{SM}} = \left(\frac{\rho'_\nu}{\rho_\nu^{SM}}\right)_{CMB}$

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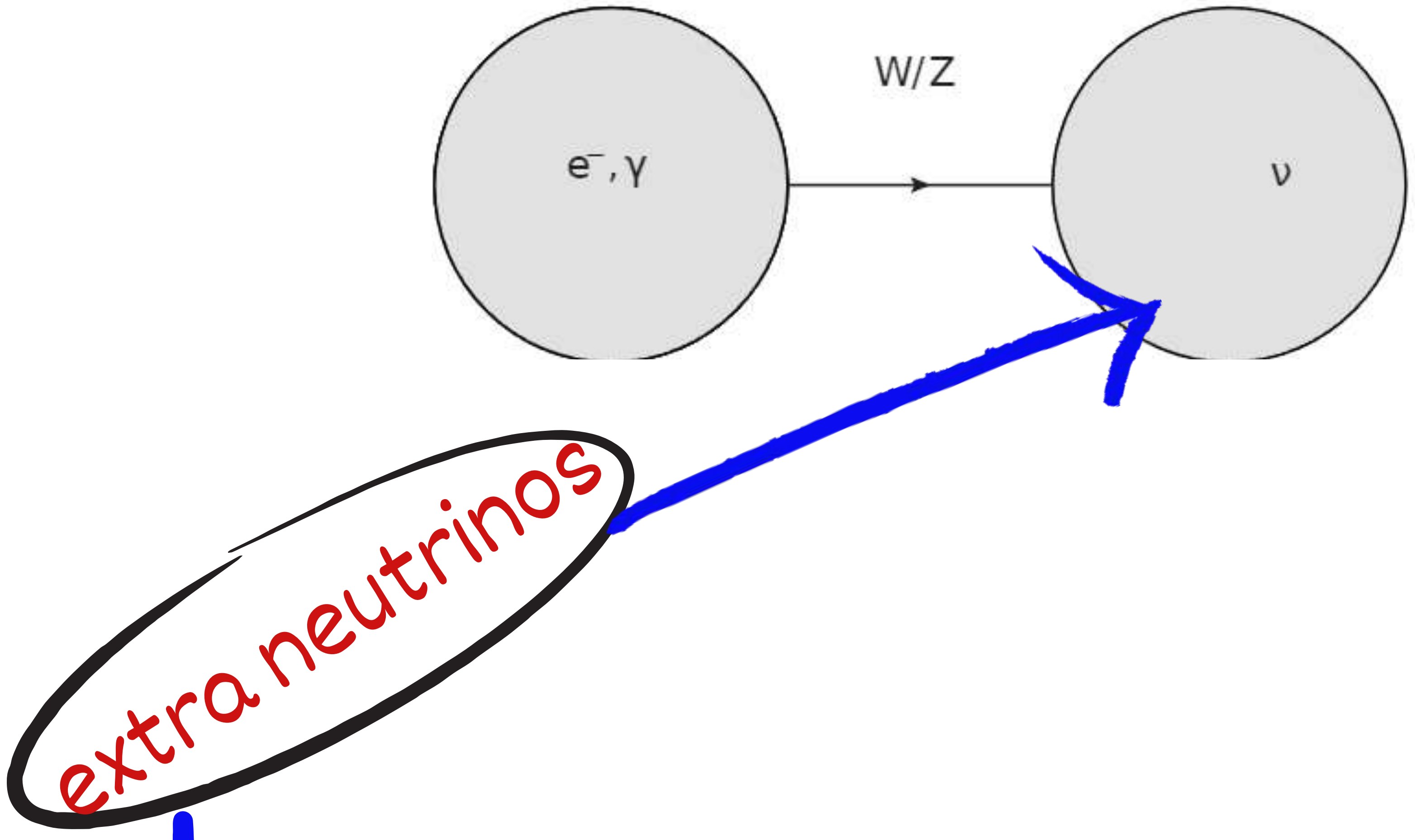

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- Boltzmann equations to track the energy densities

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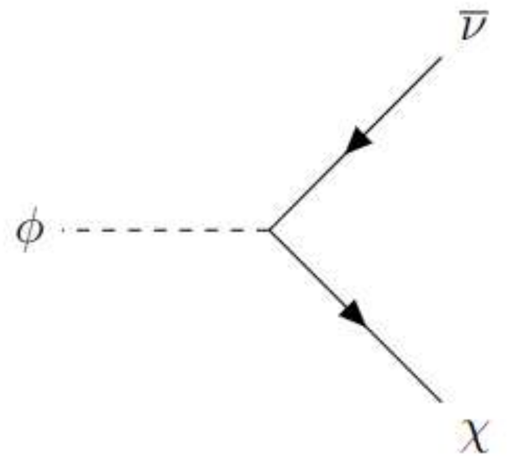

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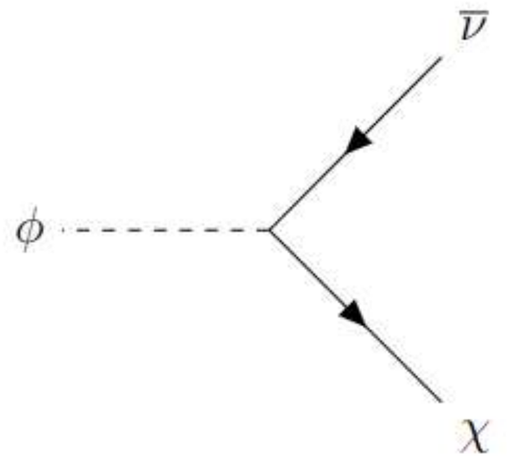

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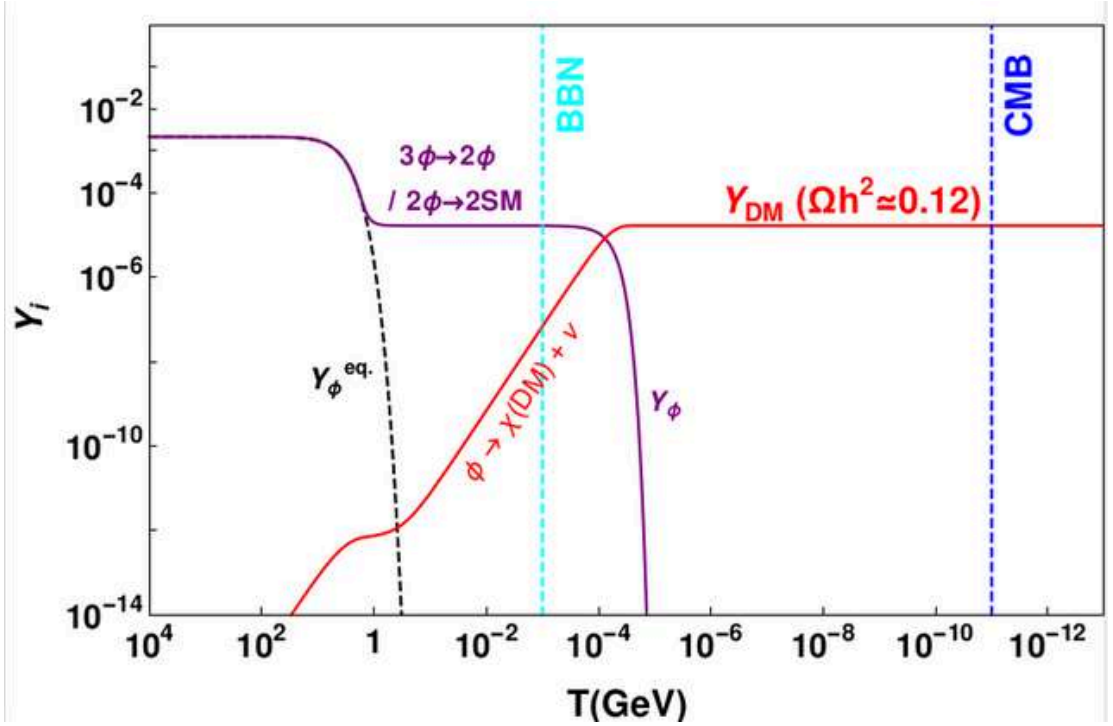

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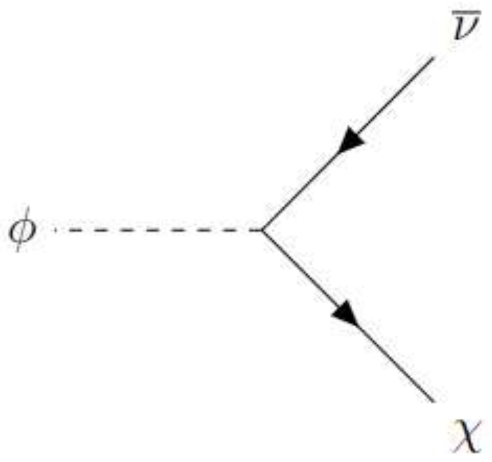

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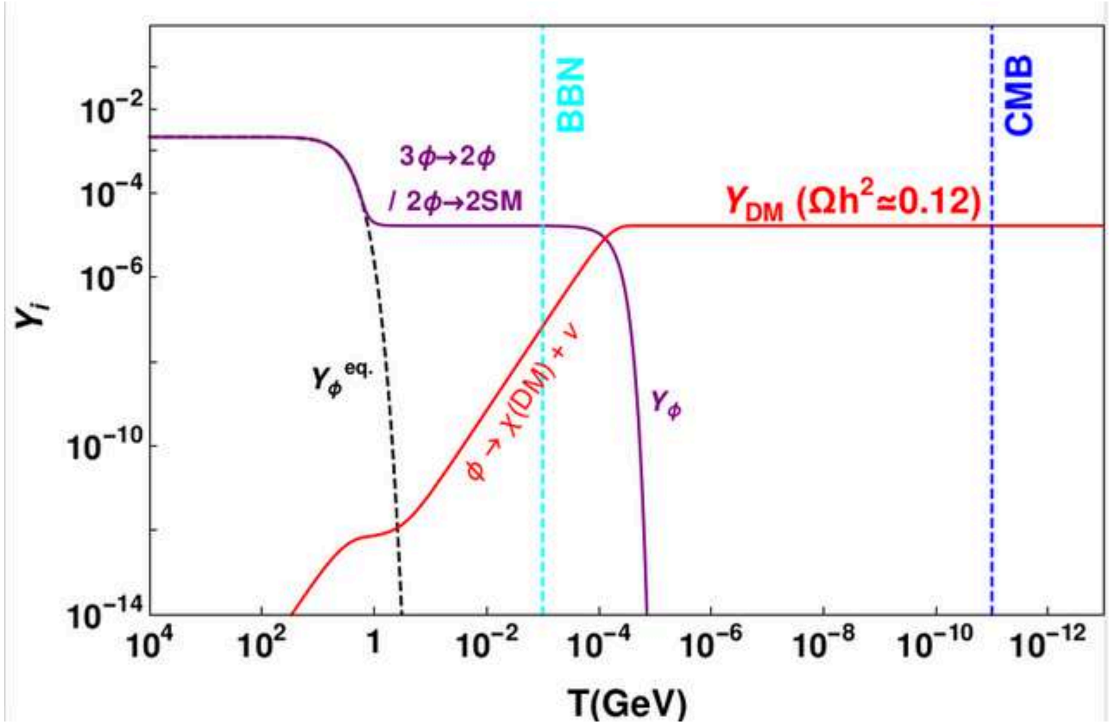

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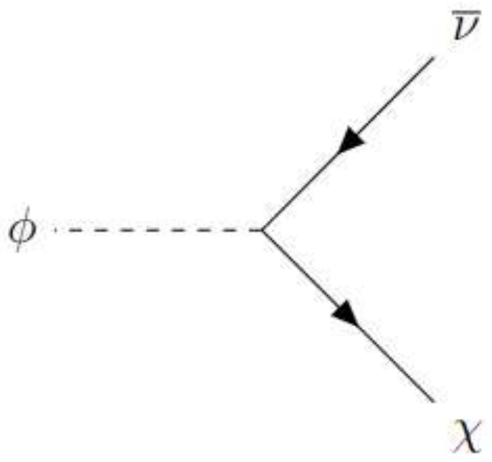

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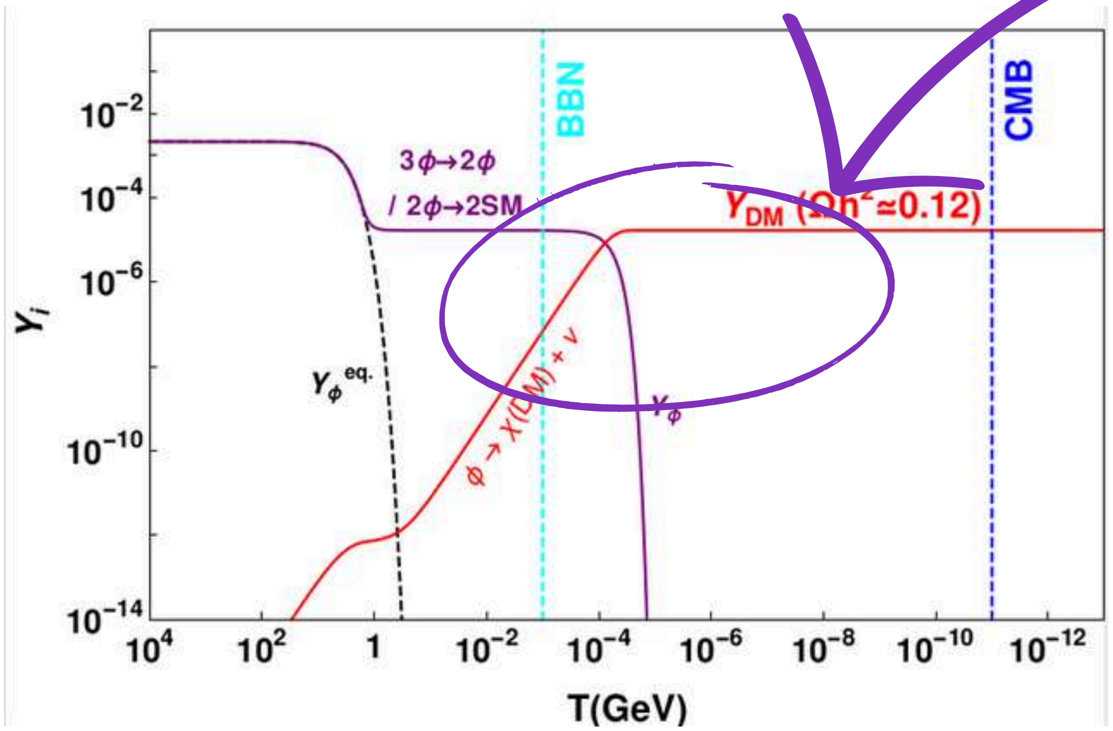

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D.k.Ghosh, P. Ghosh, SJ, JCAP2023

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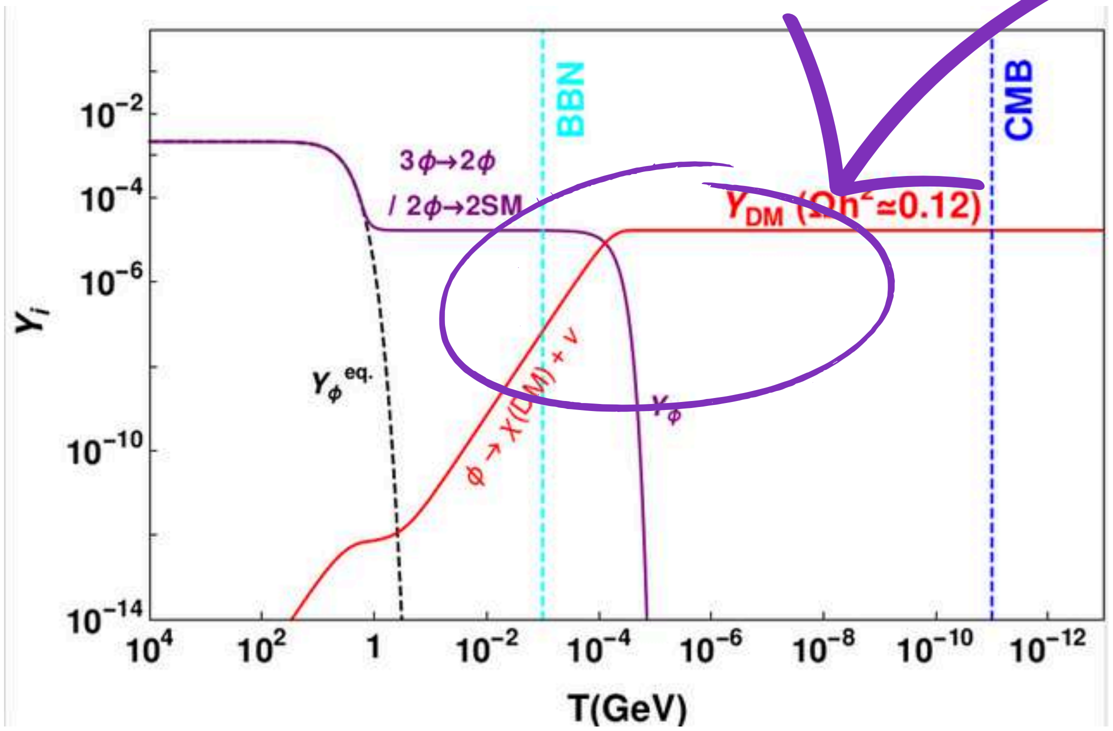

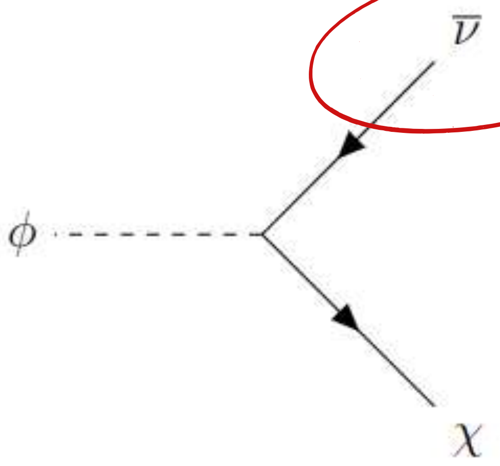

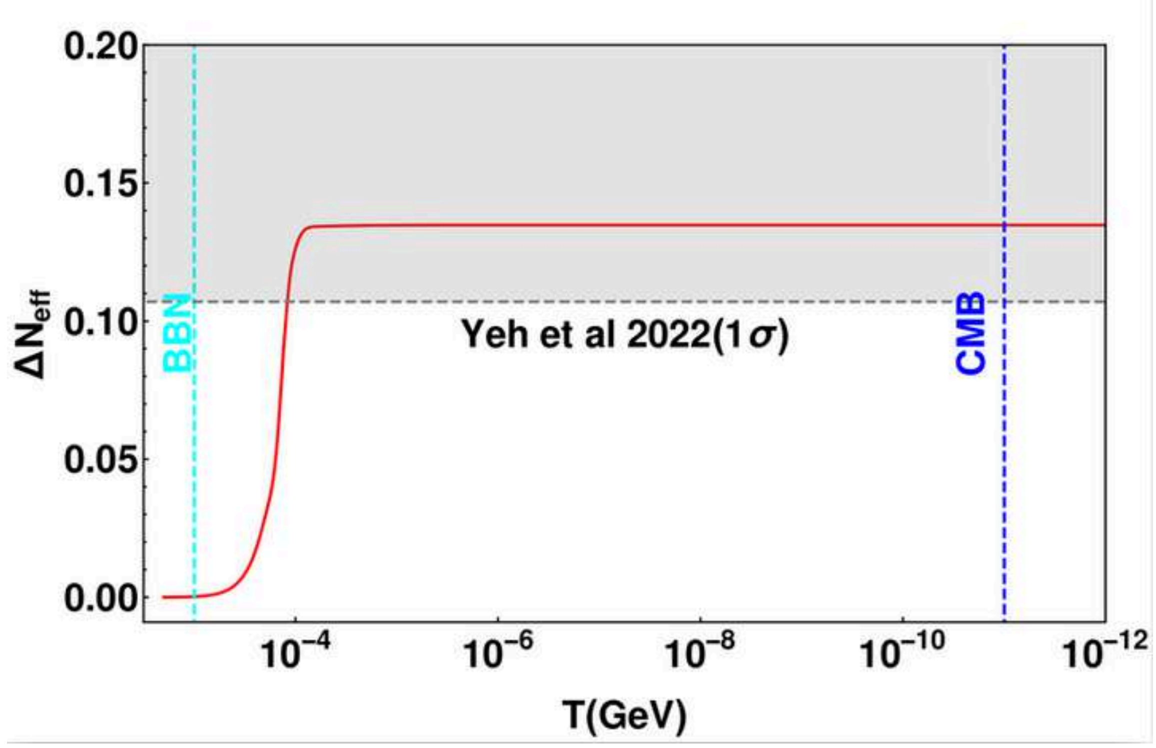

Boltzmann eqn: $d\rho'_\nu/dt + 4H\rho_\nu = \Gamma_{\phi\to\chi\,\nu}\,\rho_\phi$

The model

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- Type-I Seesaw Model + Z_3 odd complex scalar ϕ and fermion χ

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$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell\tilde{H}N_j + h.c.$$

$$\begin{aligned}\mathcal{L}_{\rm BSM} &\supset \mathcal{L}_{\rm DS} + \mathcal{L}_{\rm DS-H} + \mathcal{L}_{\rm DS-\nu} \\ &= \Big(|\partial_\mu\phi|^2 - \mu^2|\phi|^2 + i\bar{\chi}\gamma^\mu\partial_\mu\chi - M_{\rm DM}\bar{\chi}\chi - \lambda_\phi|\phi|^4 - \frac{\mu_\phi}{3!}(\phi^3+\phi^{*3}) \\ &\quad - y_{\phi\chi}\overline{\chi^c}\chi\phi\Big) + \Big(-\lambda_{\phi H}|H|^2|\phi|^2\Big) + \Big(-\sum_i y_{\phi N_i}\bar{\chi}\phi N_i + h.c.\Big) ,\end{aligned}$$

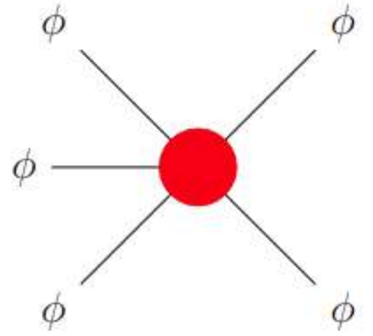
The model

- Type-I Seesaw Model + Z_3 odd complex scalar ϕ and fermion χ

$$\mathcal{L}_{\rm N} = \sum_i i\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{i,j}\frac{1}{2}M_{N_{ij}}\bar{N}_i^c N_j - \sum_{\ell,j} Y_{\ell j}\bar{L}_\ell\tilde{H}N_j + h.c.$$

$$\begin{aligned}\mathcal{L}_{\rm BSM} &\supset \mathcal{L}_{\rm DS} + \mathcal{L}_{\rm DS-H} + \mathcal{L}_{\rm DS-\nu} \\ &= \Big(|\partial_\mu\phi|^2 - \mu^2|\phi|^2 + i\bar{\chi}\gamma^\mu\partial_\mu\chi - M_{\rm DM}\bar{\chi}\chi - \lambda_\phi|\phi|^4 - \frac{\mu_\phi}{3!}(\phi^3 + \phi^{*3}) \\ &\quad - y_{\phi\chi}\overline{\chi^c}\chi\phi\Big) + \Big(-\lambda_{\phi H}|H|^2|\phi|^2\Big) + \Big(-\sum_i y_{\phi N_i}\bar{\chi}\phi N_i + h.c.\Big) ,\end{aligned}$$

Self scattering



$$\phi + \phi + \phi \Leftrightarrow \phi + \phi$$

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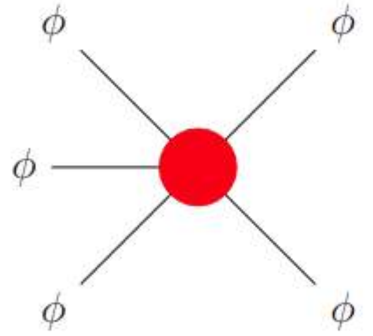

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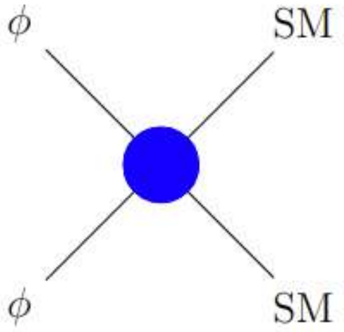
Annihilations



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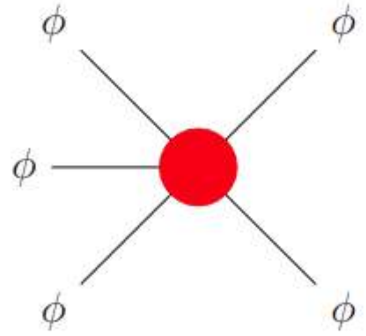

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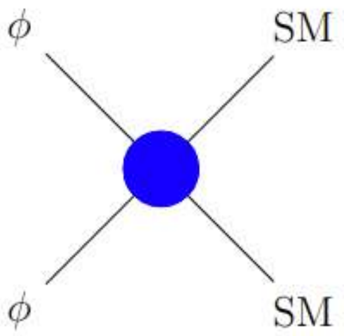
Annihilations



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$3 \to 2$: μ_ϕ, λ_ϕ

$2 \to 2$: $\lambda_{\phi H}$

The model

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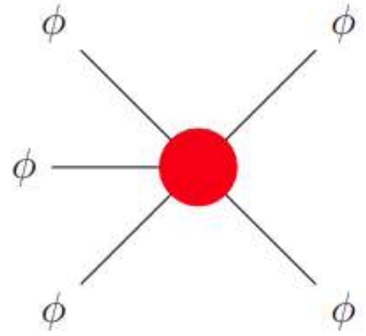

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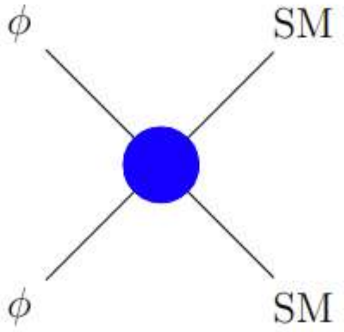
Annihilations



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Elastic scattering

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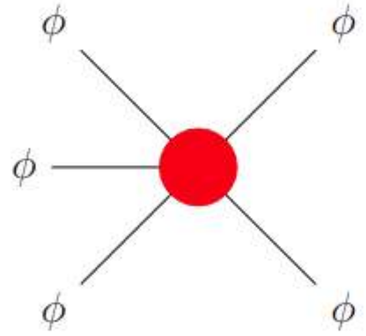

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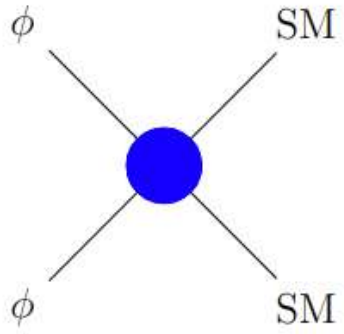
Annihilations



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$$T_\phi = T_{SM}$$

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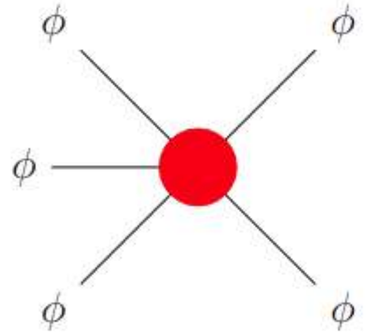
Self scattering



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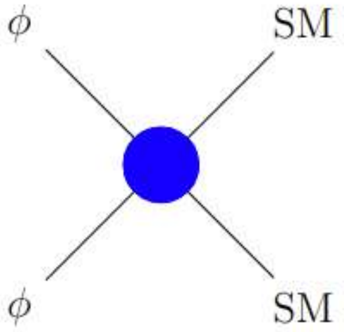
Annihilations



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$$T_\phi = T_{SM}$$

?

$3 \to 2$	:	μ_ϕ, λ_ϕ
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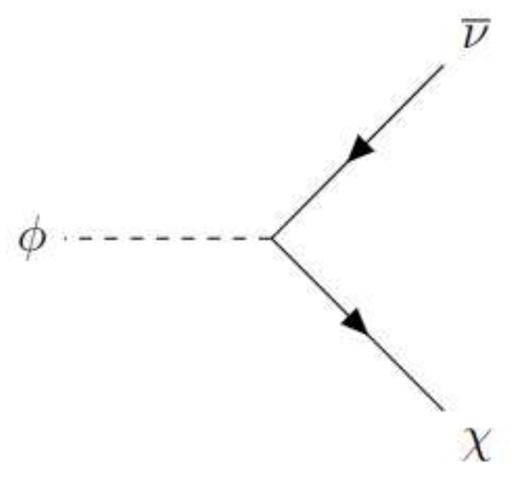
Dark matter production with CMB signature

- $\mathcal{L}^{\rm int}_{\rm DS-\nu} = y_1 \overline{\chi} \nu \phi + h.c.$

  where, $y_1 = \sum_i y_{\phi N_i} \theta^i_{\rm mix}$ with $M_\phi > M_\chi$



- Imprint in, $N_{eff} \Longrightarrow \tau_{BBN} < \tau_\phi < \tau_{CMB}$

  $\Longrightarrow y_1 \sim 10^{-12} - 10^{-14}$

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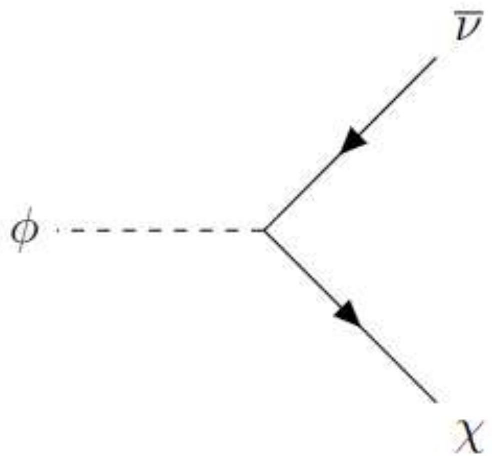

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- Boltzmann eq.

$$\frac{dY_\phi}{dx} = -0.116 \frac{g_s^2}{\sqrt{g_\rho}} \frac{M_\phi^4}{x^5} M_{pl} \langle \sigma v^2 \rangle_{3\phi \to 2\phi} \left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq} \right)$$

$$-0.264 \frac{g_s}{\sqrt{g_\rho}} \frac{M_\phi}{x^2} M_{pl} \langle \sigma v \rangle_{2\phi \to 2{\rm SM}} \left(Y_\phi^2 - Y_\phi^{eq2} \right) - \sqrt{\frac{45}{4\pi^3}} \langle \Gamma_{\phi \to \chi\nu} \rangle \frac{x}{M_\phi^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{4\pi^3}} \langle \Gamma \rangle_{\phi \to \chi\nu} \frac{x}{M_{sc}^2} \frac{M_{pl}}{\sqrt{g_\rho}} Y_\phi$$

Dynamics of dark sector

$$\frac{dY_\phi}{dx} = -0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\left\langle\sigma v^2\right\rangle_{3\phi\to2\phi}\left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right)$$

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Dynamics of dark sector

- Scenario-I

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \Gamma_{3\phi\to 2\phi} \gg \Gamma_{2\phi\to 2SM}$$

$$\frac{dY_\phi}{dx} = -0.116\frac{g_s^2}{\sqrt{g_\rho}}\frac{M_\phi^4}{x^5}M_{pl}\langle\sigma v^2\rangle_{3\phi\to 2\phi}\left(Y_\phi^3 - Y_\phi^2 Y_\phi^{eq}\right)$$
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Dynamics of dark sector

- Scenario-I

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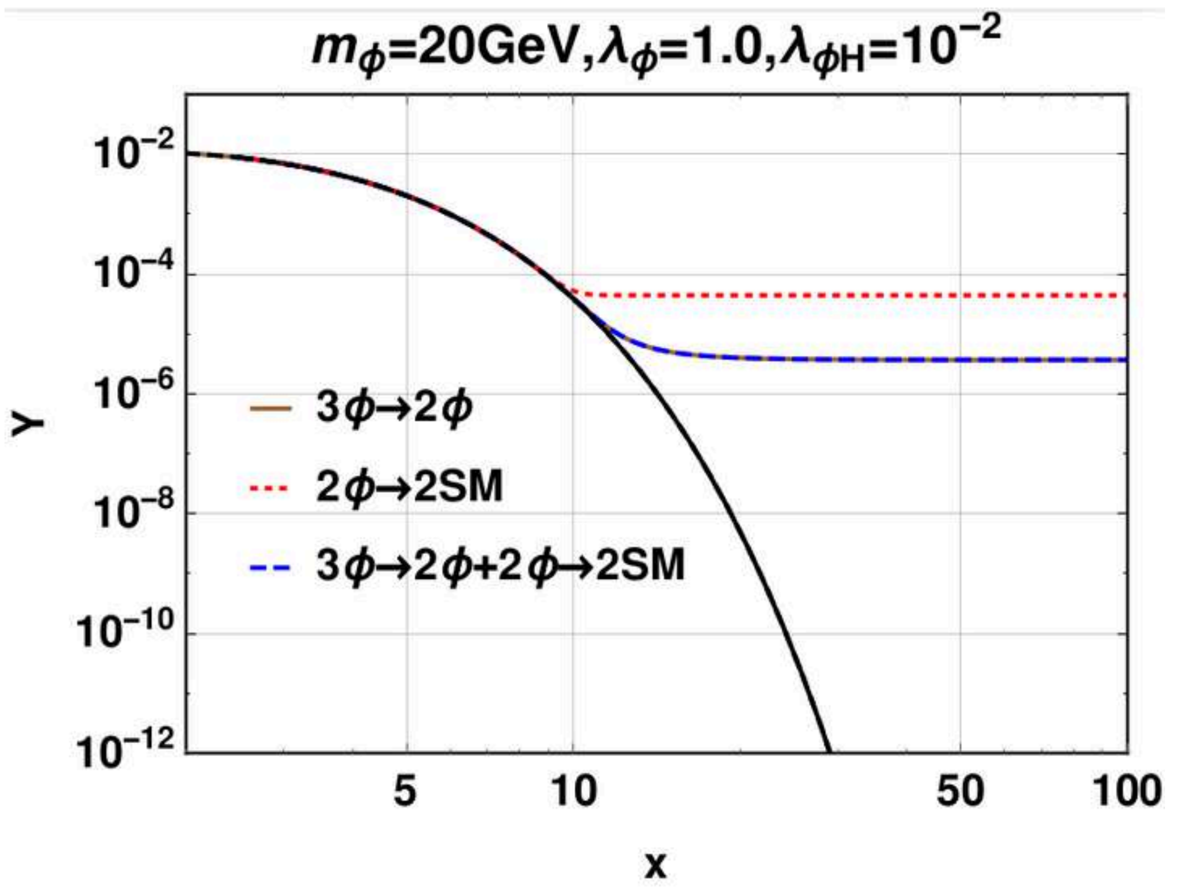

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Dynamics of dark sector

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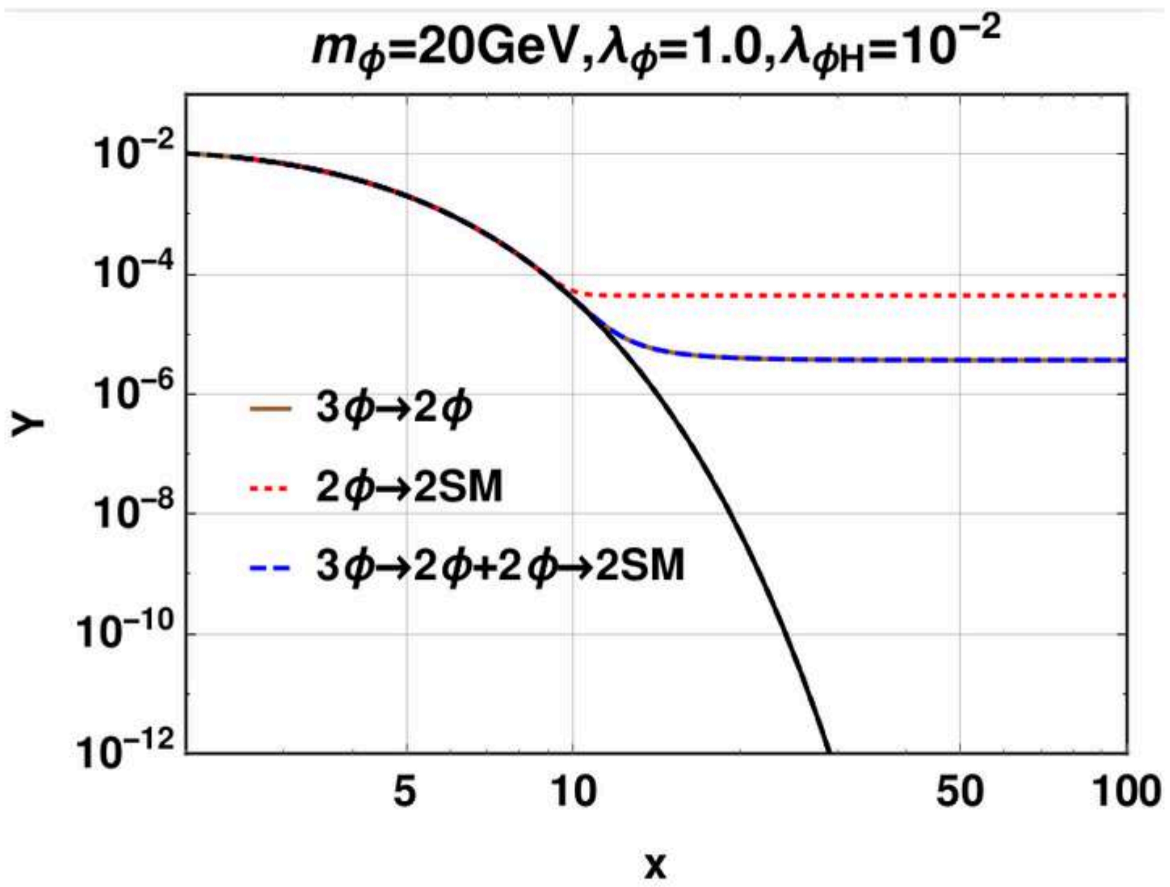
F.O.. $x_F^{tot} \approx x_F^{3\phi\to 2\phi}$



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Dynamics of dark sector

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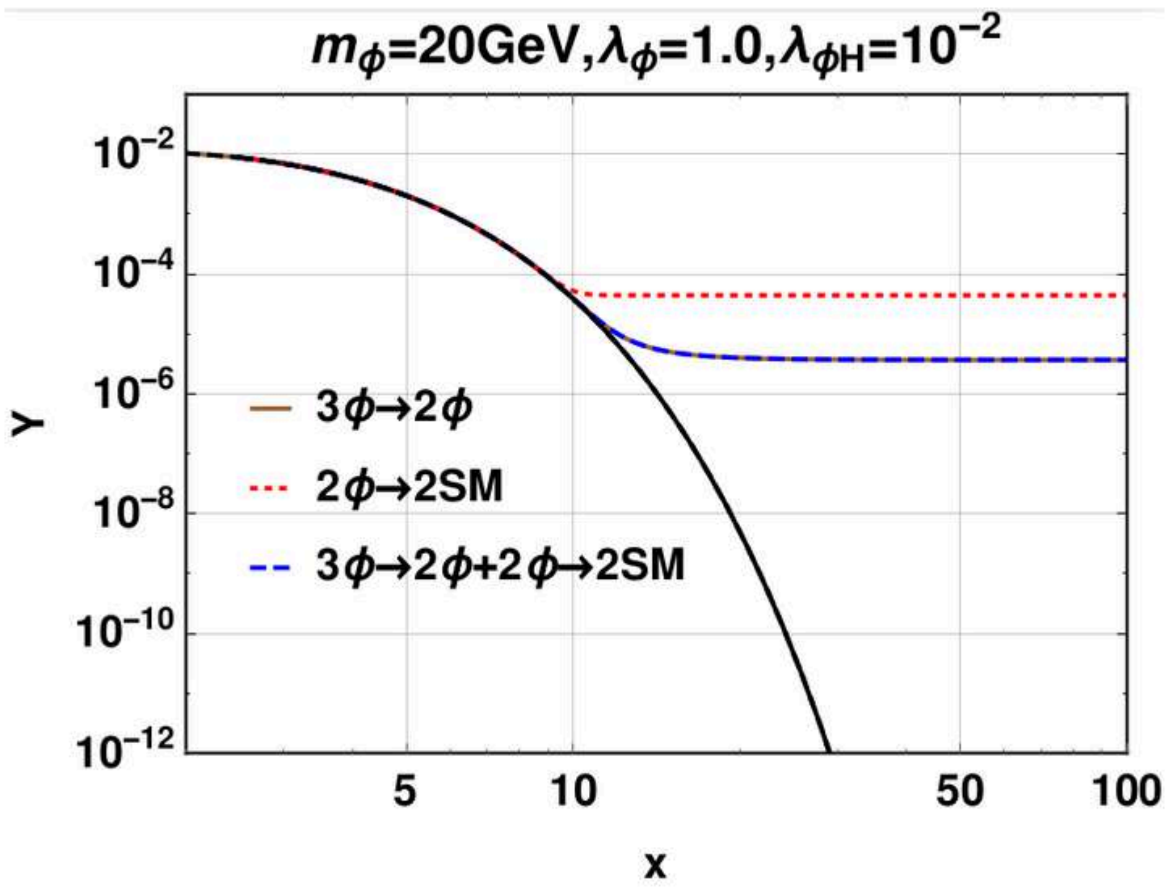

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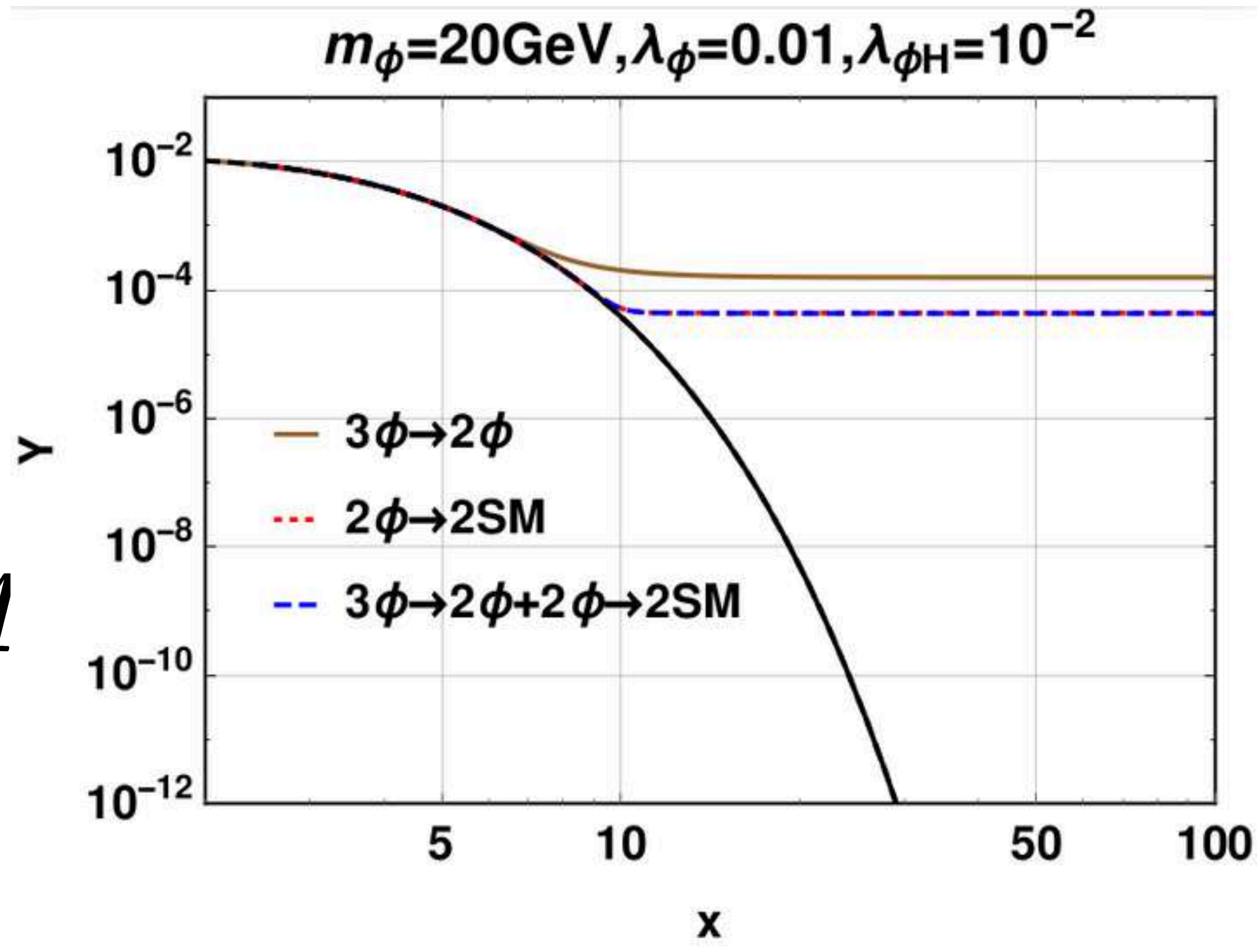
Dynamics of dark sector

- Scenario-II

$$\Gamma_{[\phi\, SM \to \phi\, SM]} > \Gamma_{2\phi \to 2\mathrm{SM}} \gg \Gamma_{3\phi \to 2\phi}$$

F.O.. $x_F^{tot} \approx x_F^{2\phi \to 2SM}$ $Y_\phi(x_F) \Rightarrow 2\phi \to 2SM$



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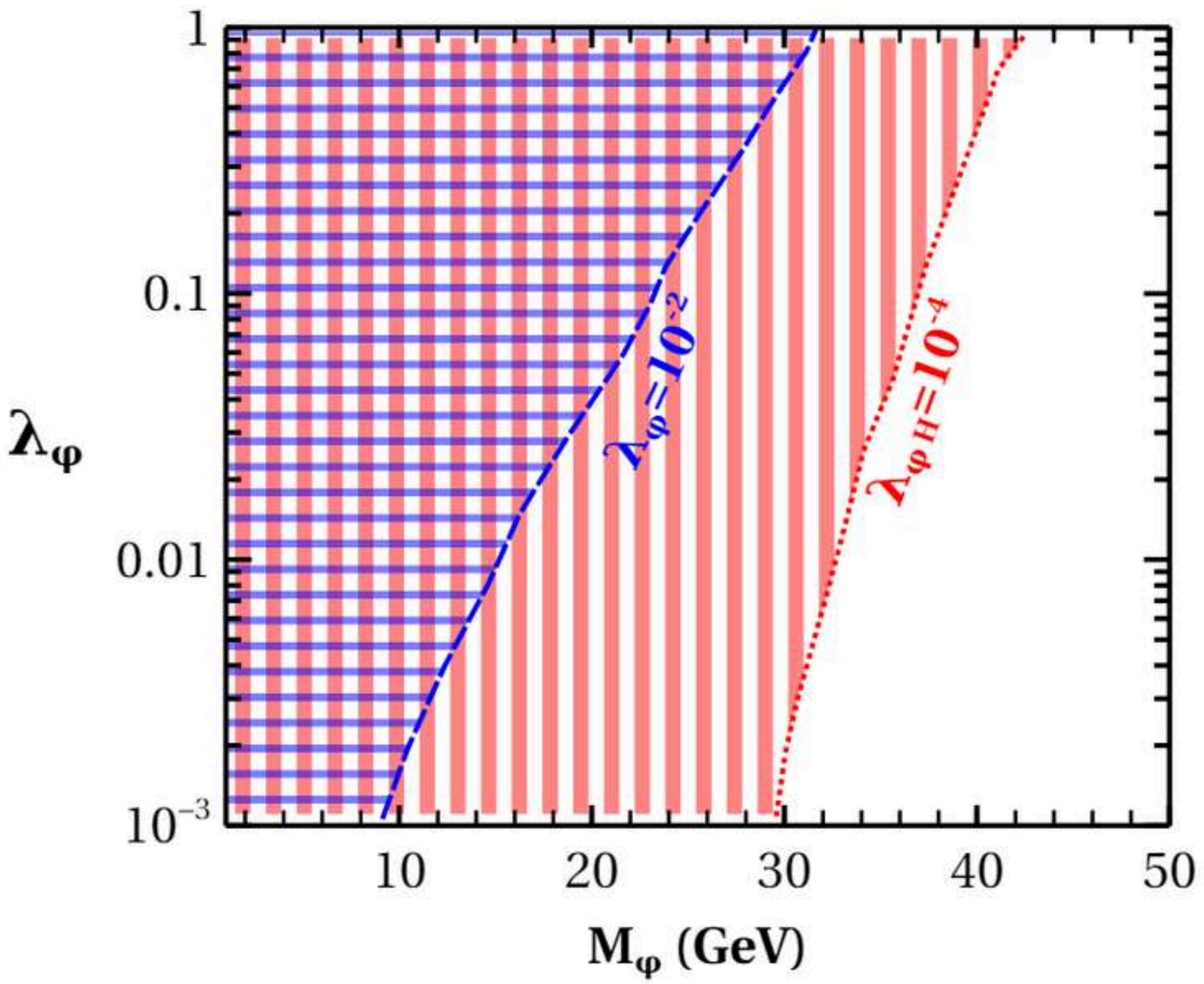
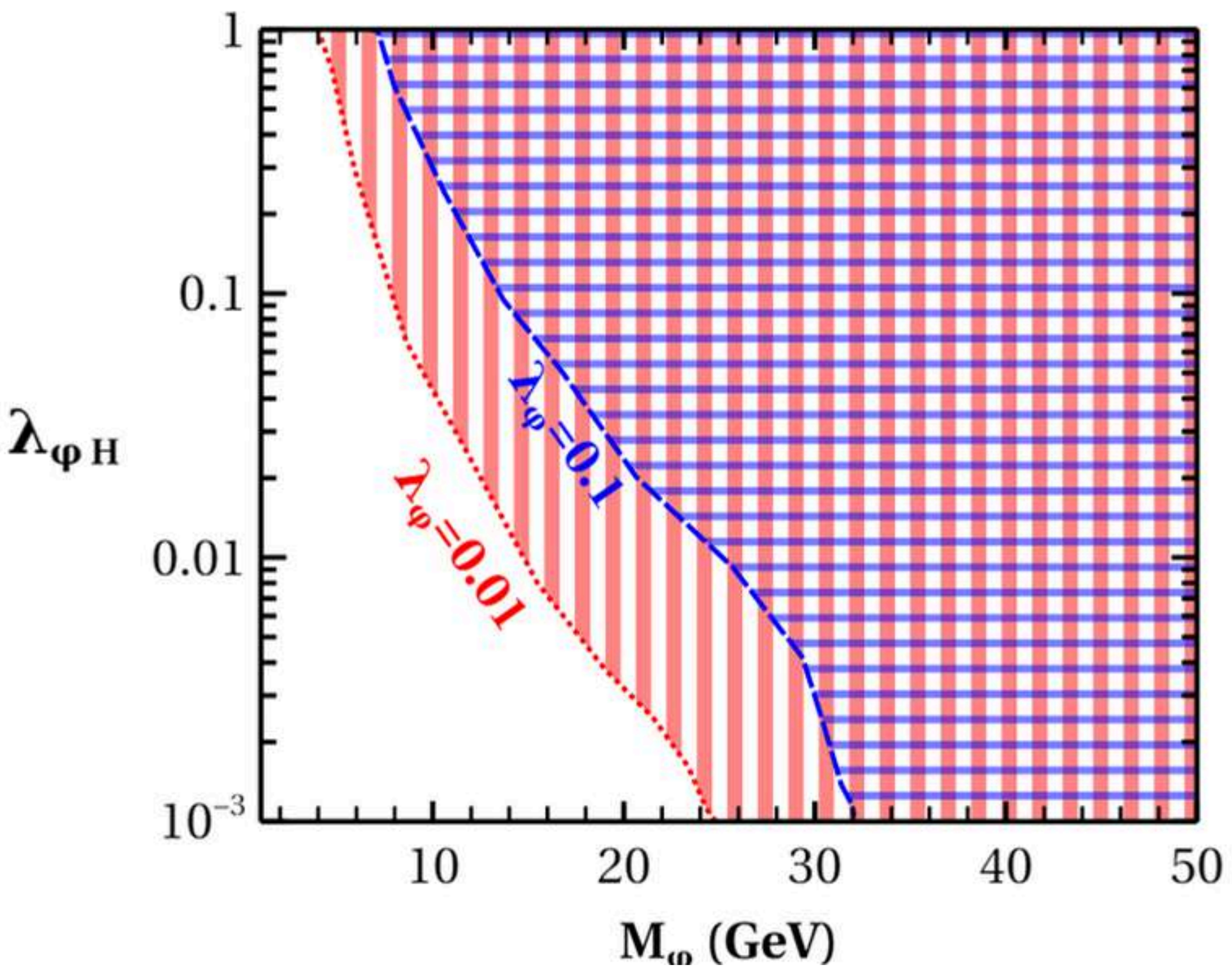
Parameter space of two scenarios

- Scenario-I



- Scenario-II



Numerical results

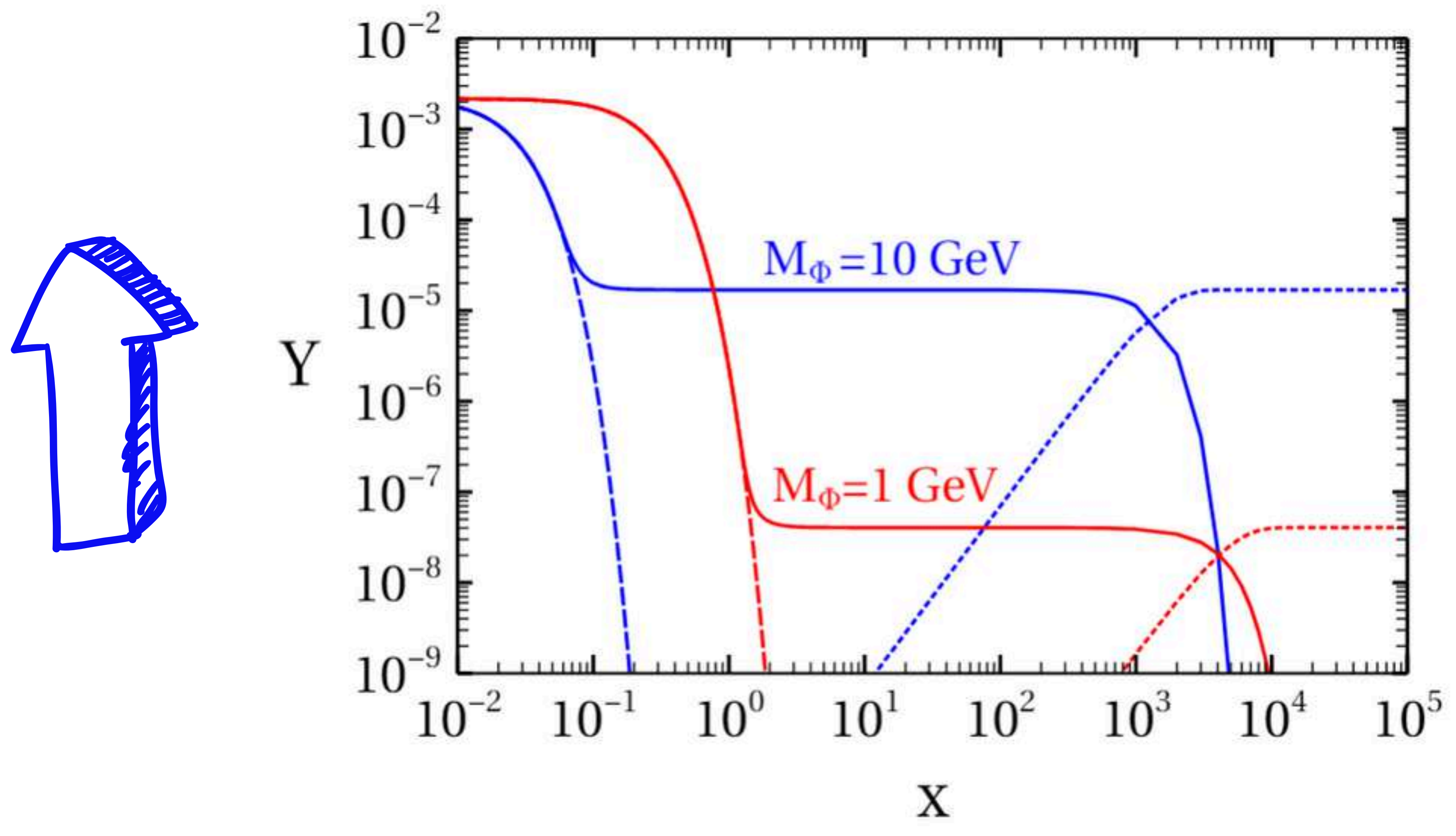
Self interacting HDS
Scenario-I

- Variation of mass

Numerical results

Self interacting HDS
Scenario-I

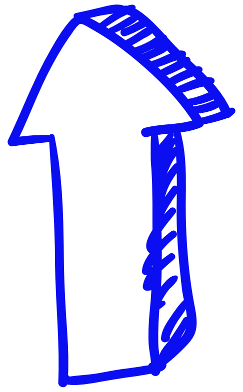
- Variation of mass

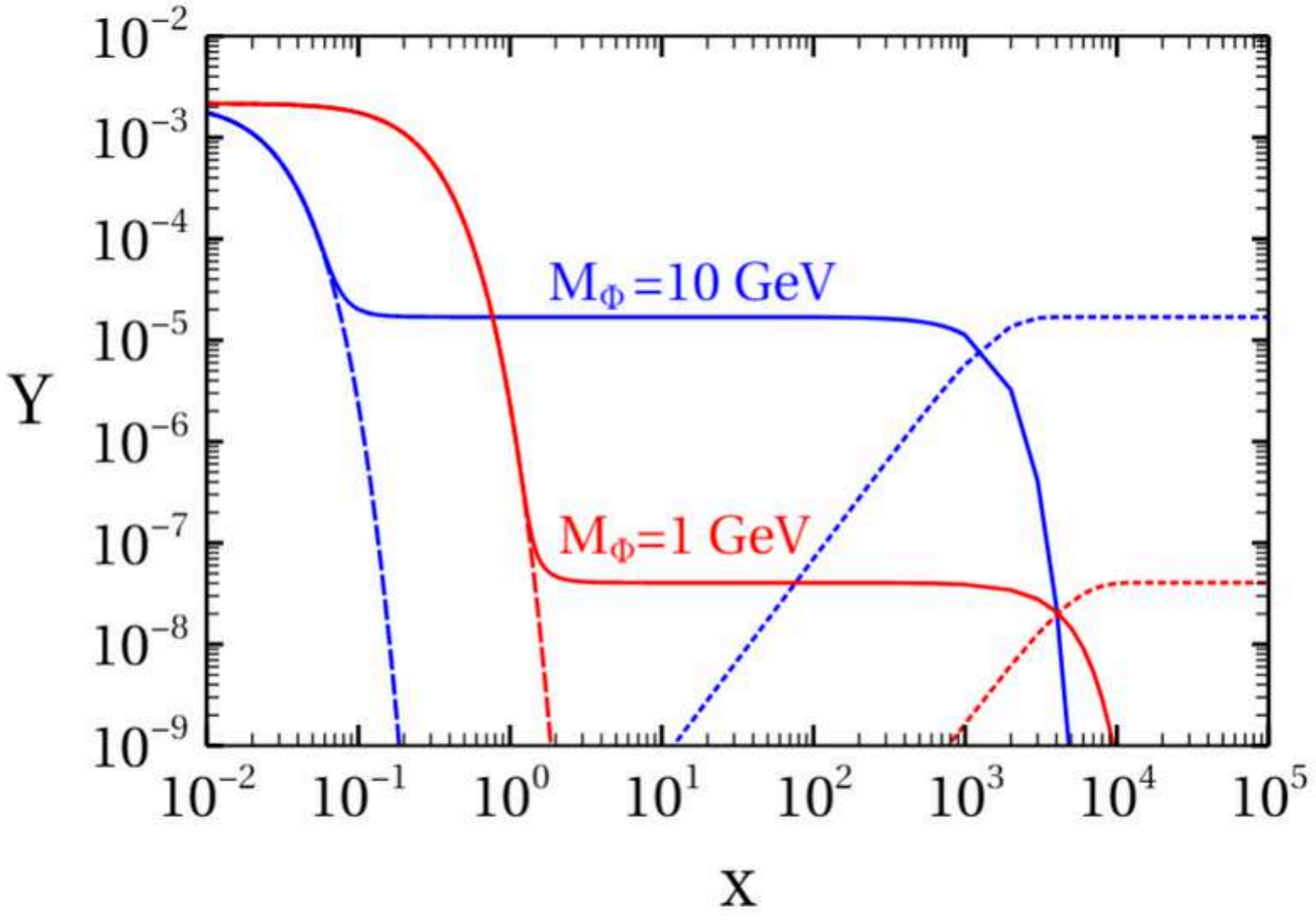


DM abundance

Numerical results

- Variation of mass





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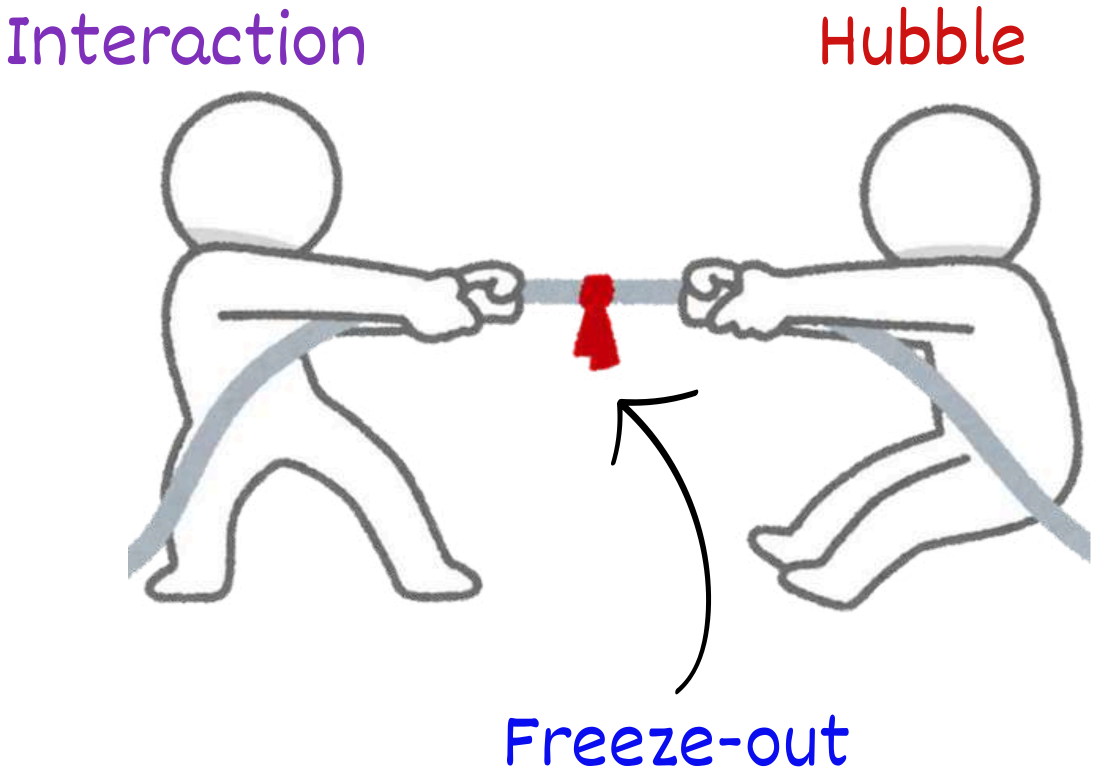
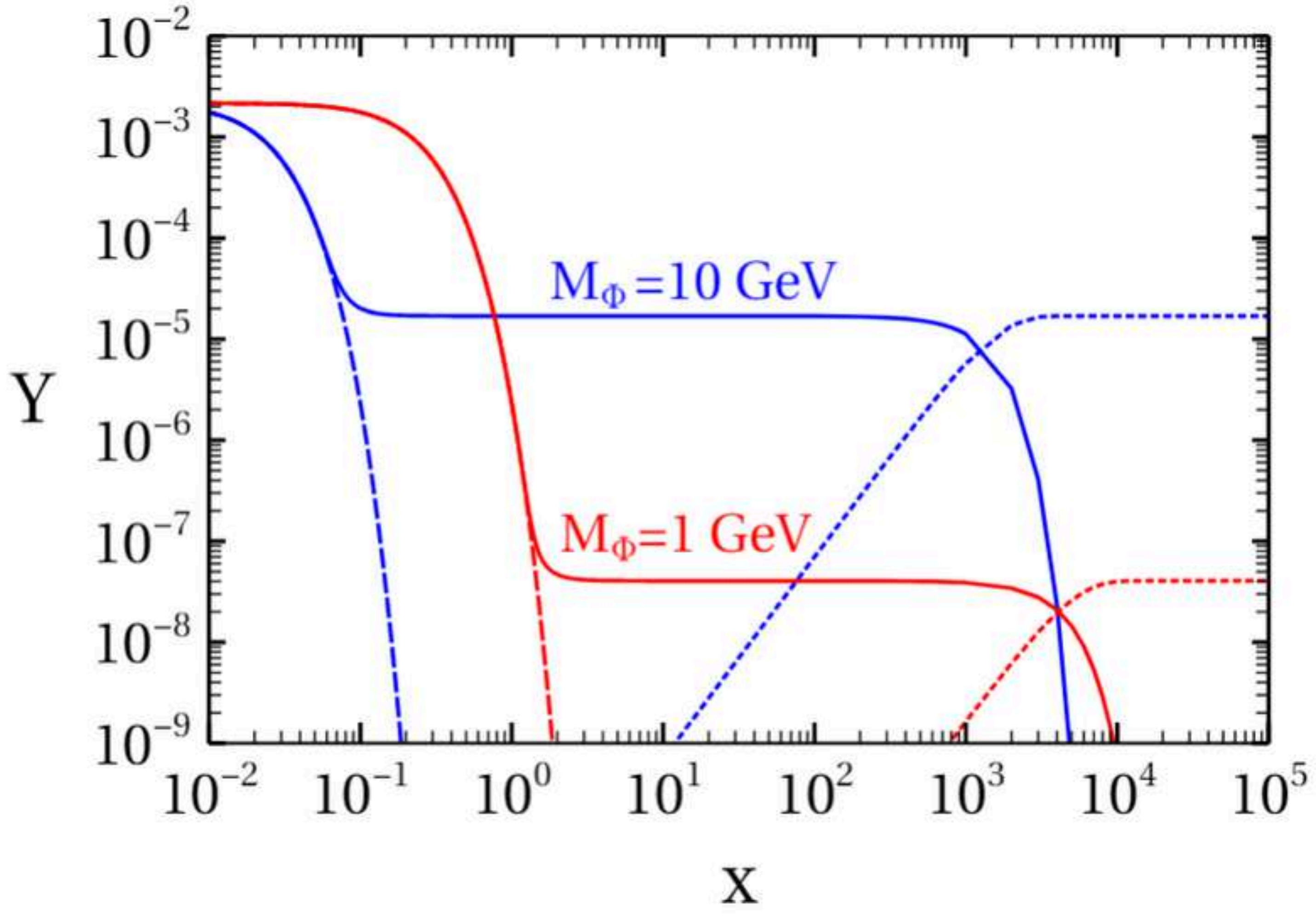


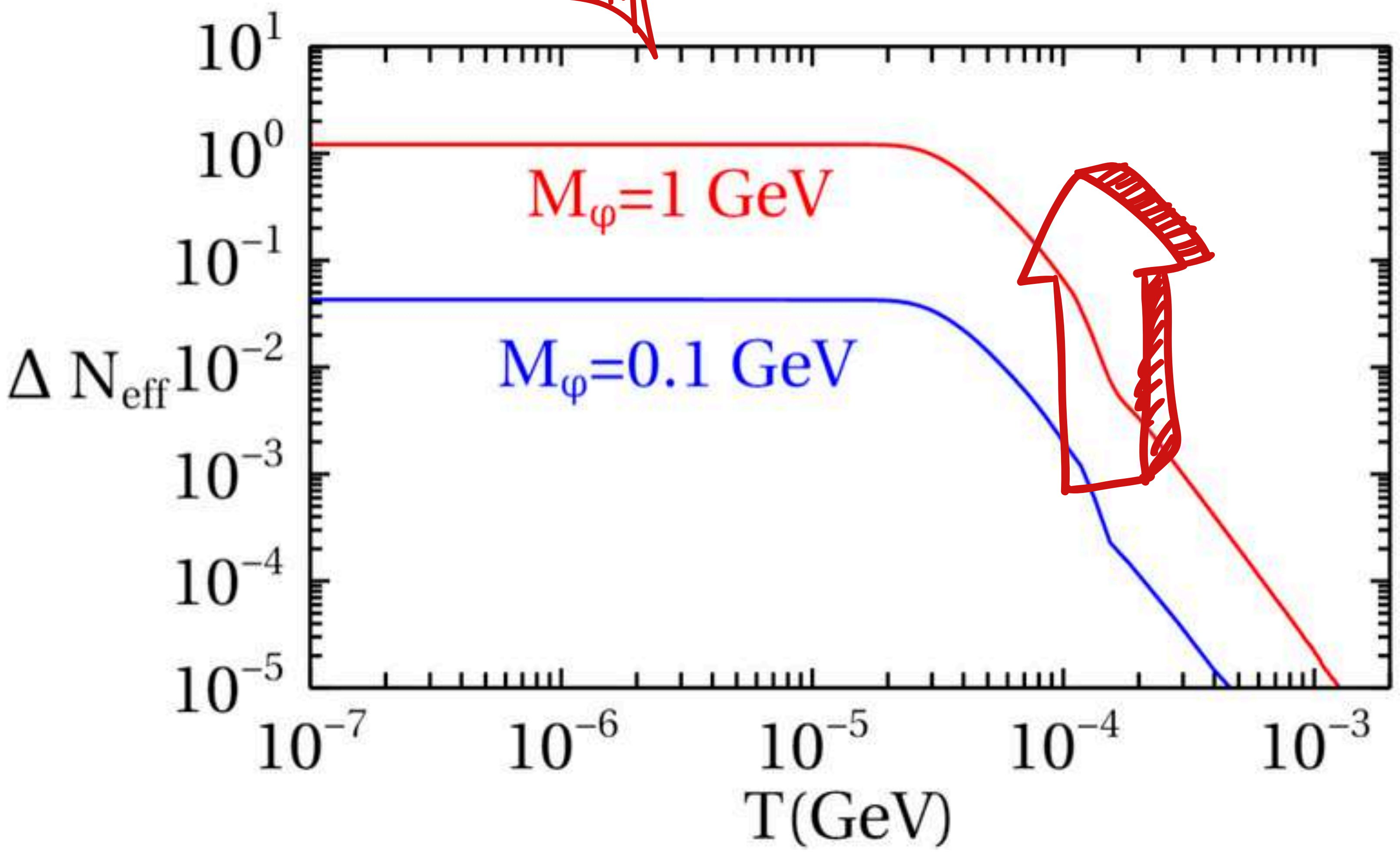
Numerical results

Self interacting HDS
Scenario-I

- Variation of mass

$\rho_\nu^{'} \sim Y_\phi$





DM abundance

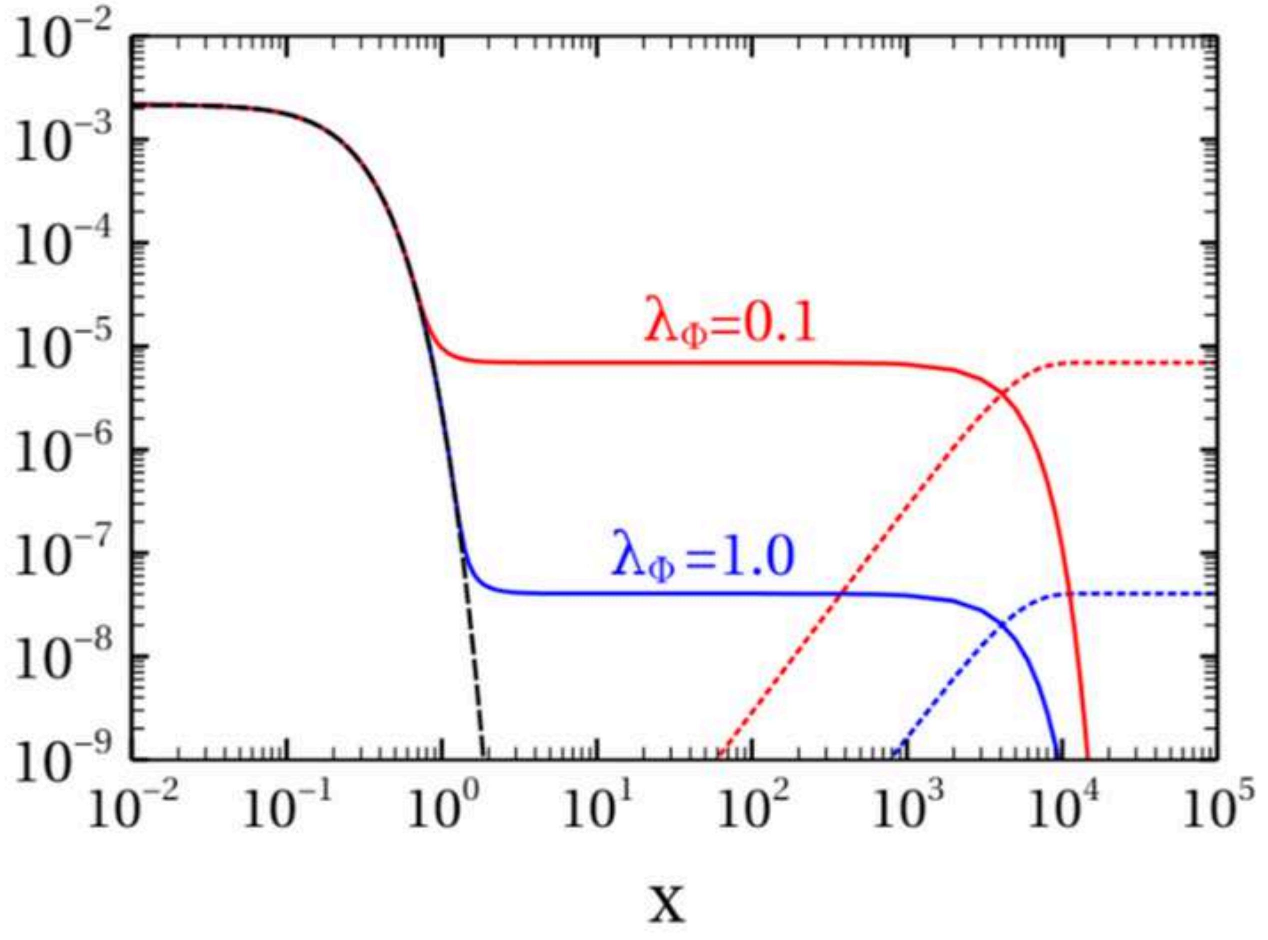
Contribution to $\rho_\nu^{'}$

Numerical results

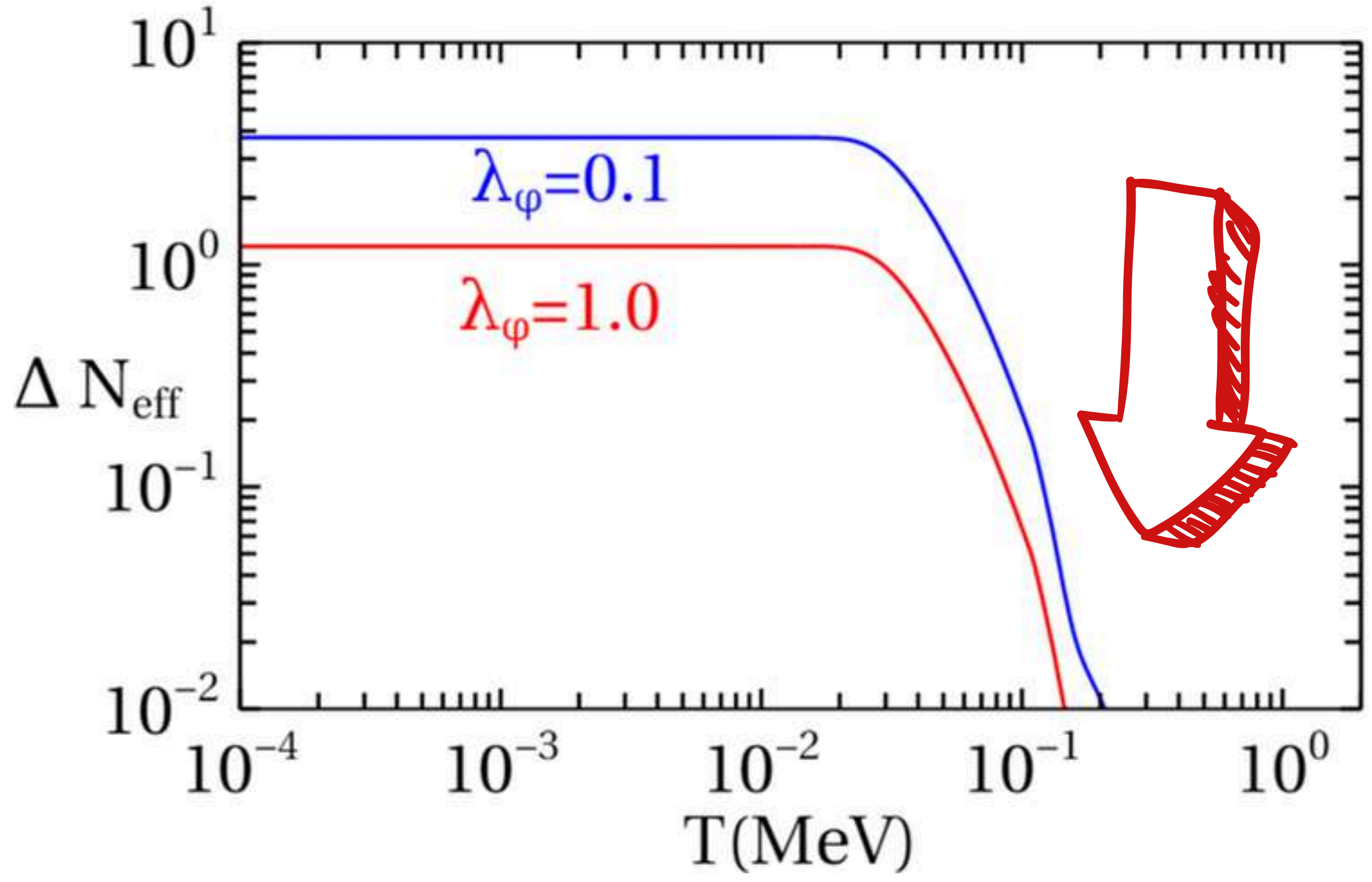
Self interacting HDS
Scenario-I

- Variation of coupling

$\rho_\nu' \sim Y_\phi$



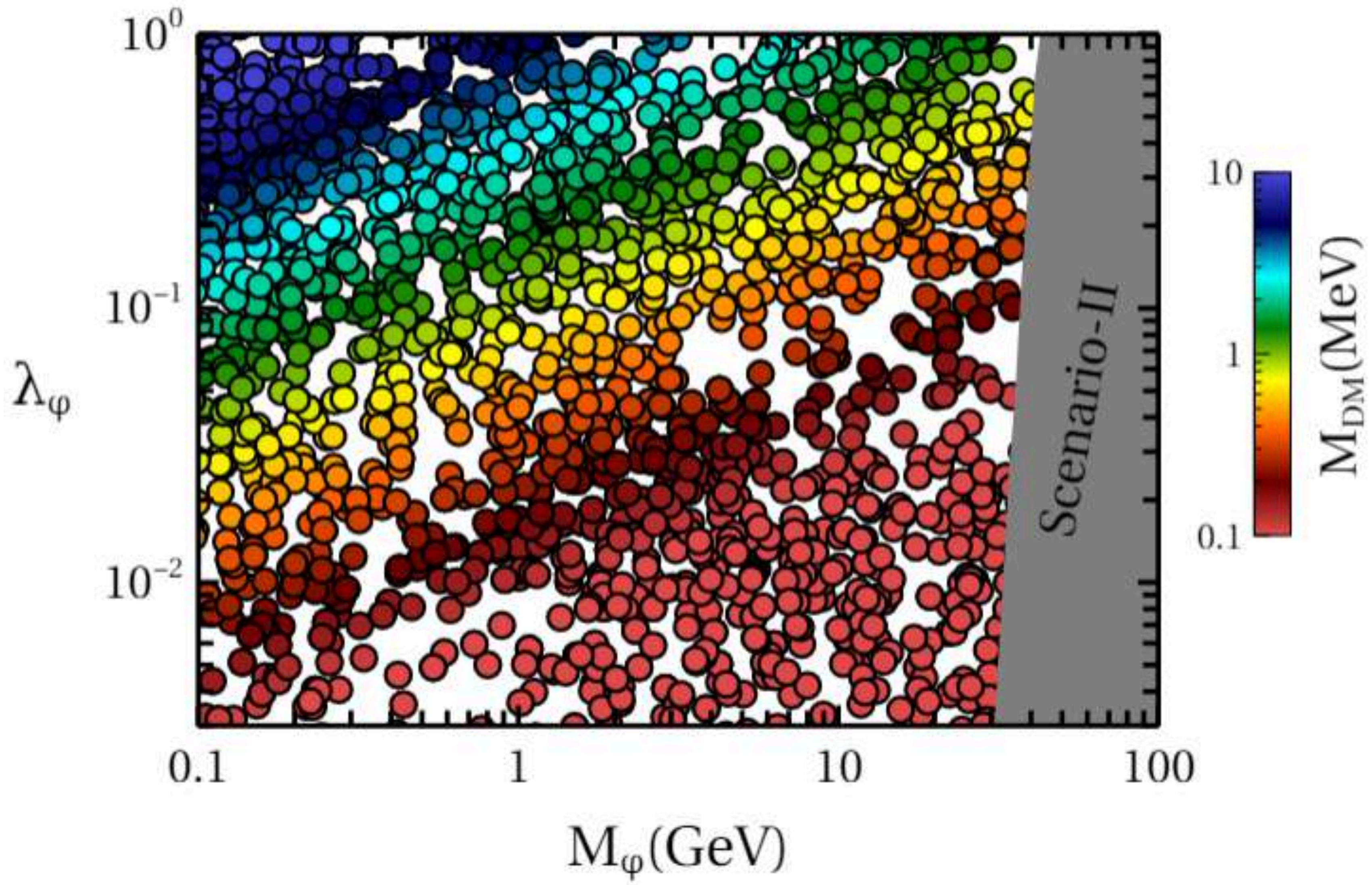
DM abundance



Contribution to ρ_ν'

Numerical results

Self interacting HDS

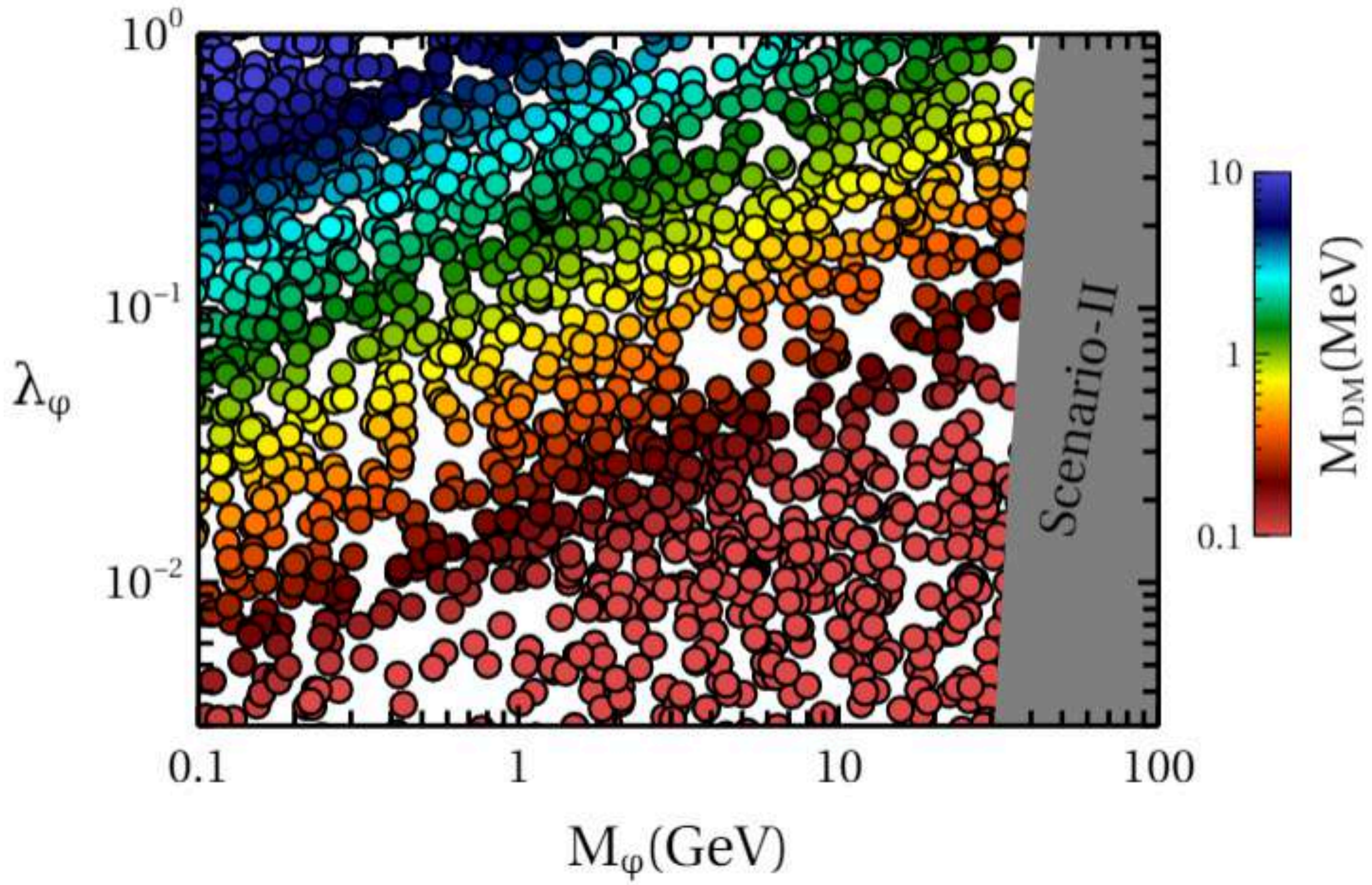


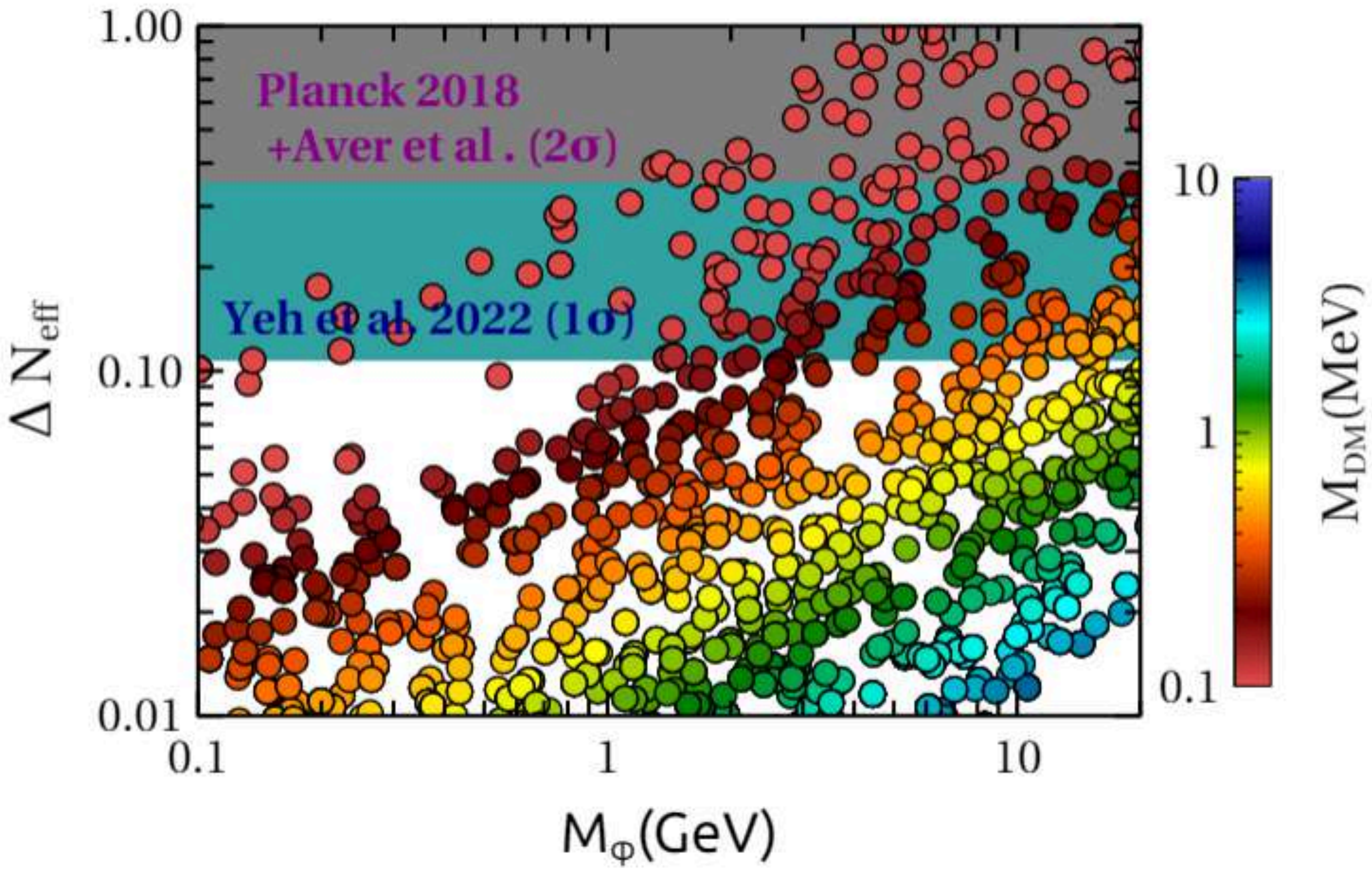
DM abundance

Numerical results

D.k.Ghosh, P. Ghosh, SJ, JCAP2023

Self interacting HDS



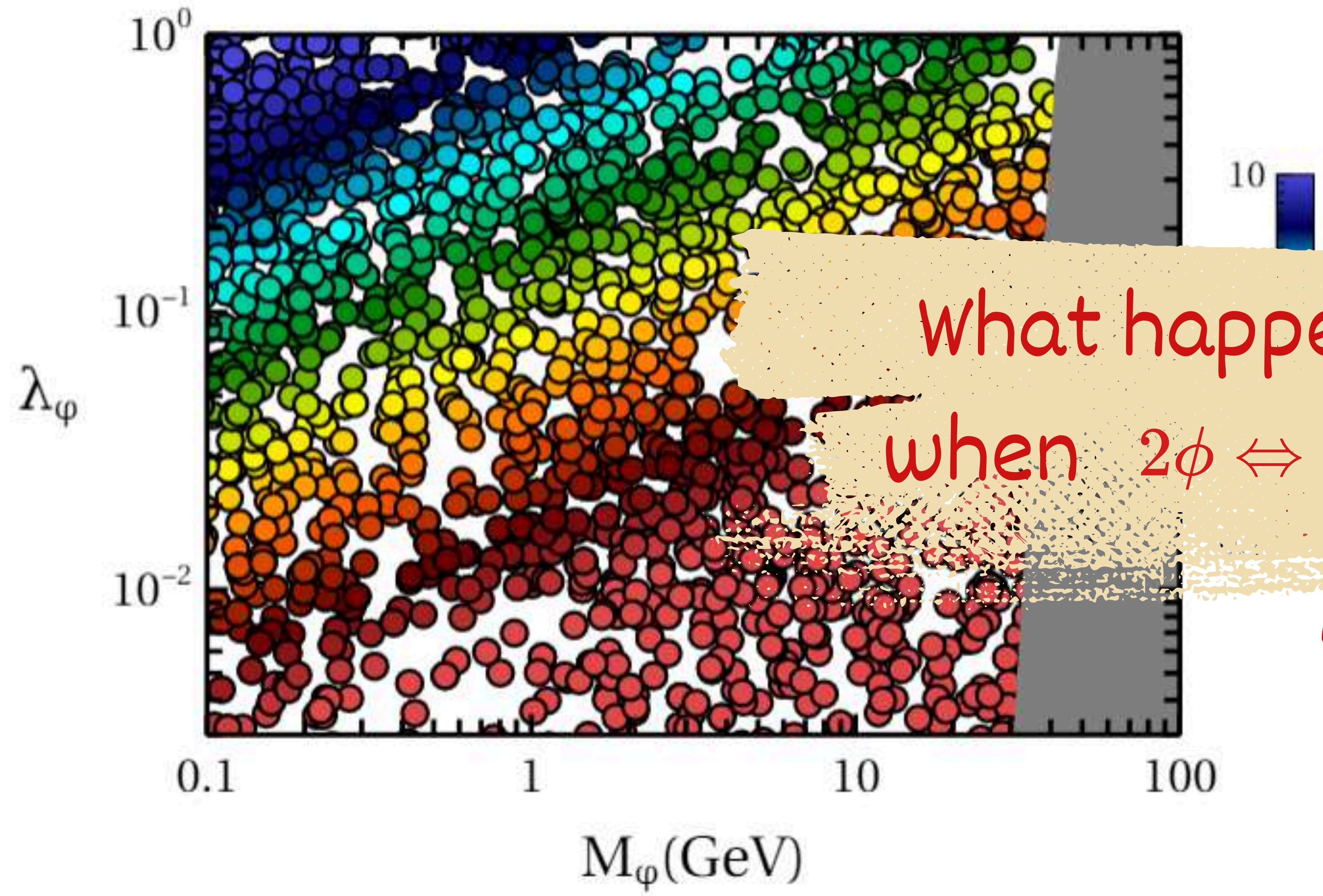


DM abundance

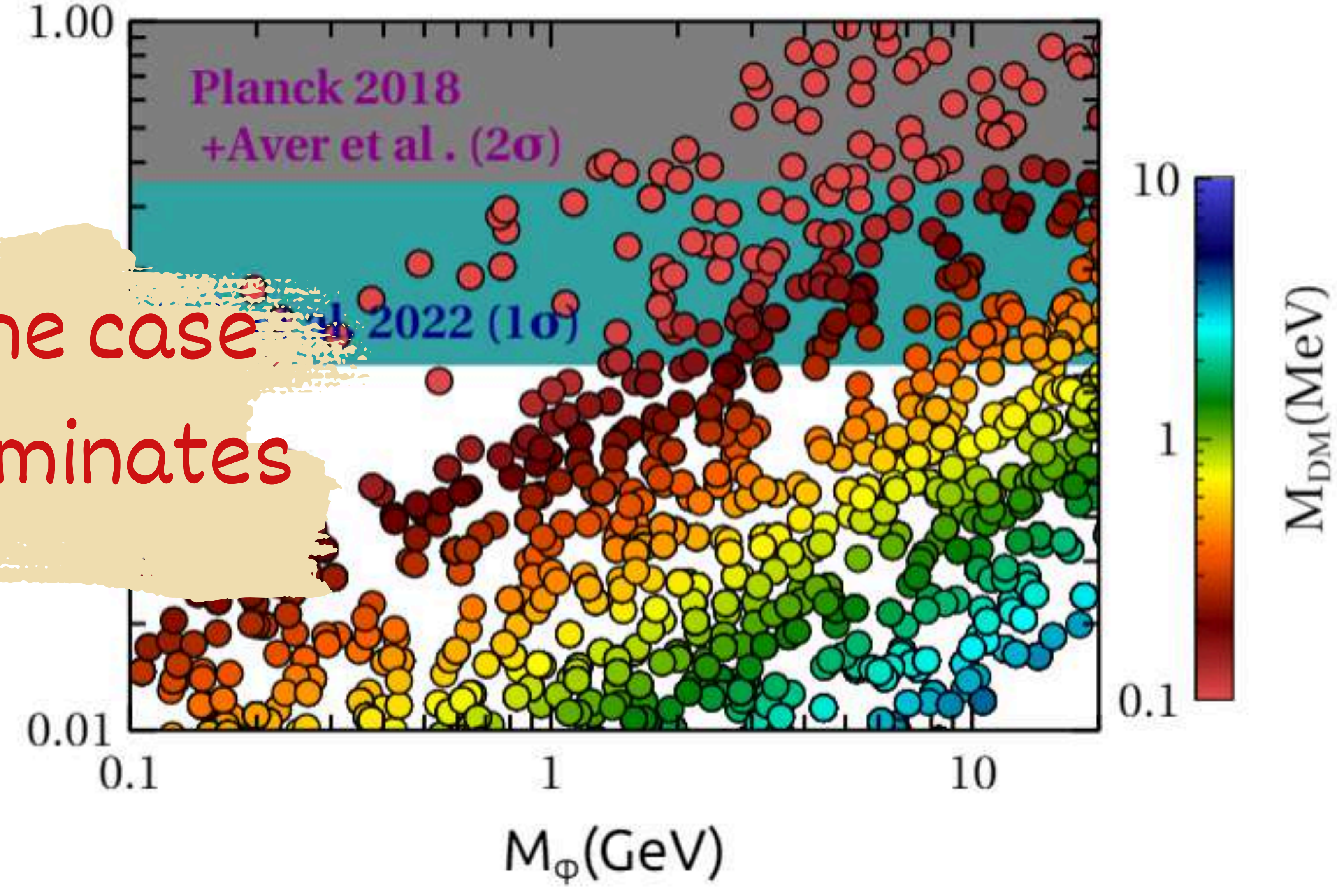
Contribution to N_{eff}

Numerical results

Self interacting HDS



What happens to the case when $2\phi \Leftrightarrow 2SM$ dominates ?

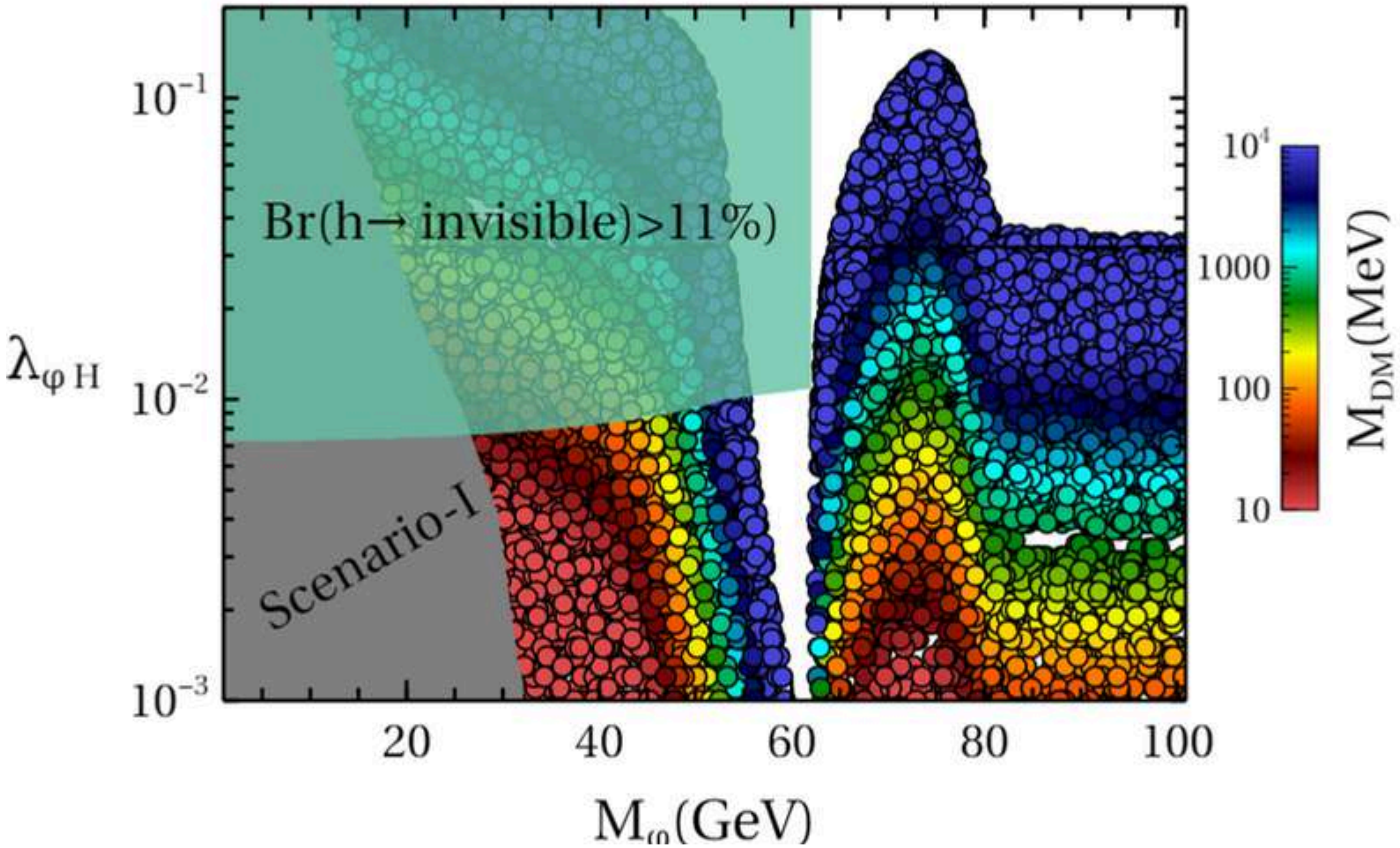


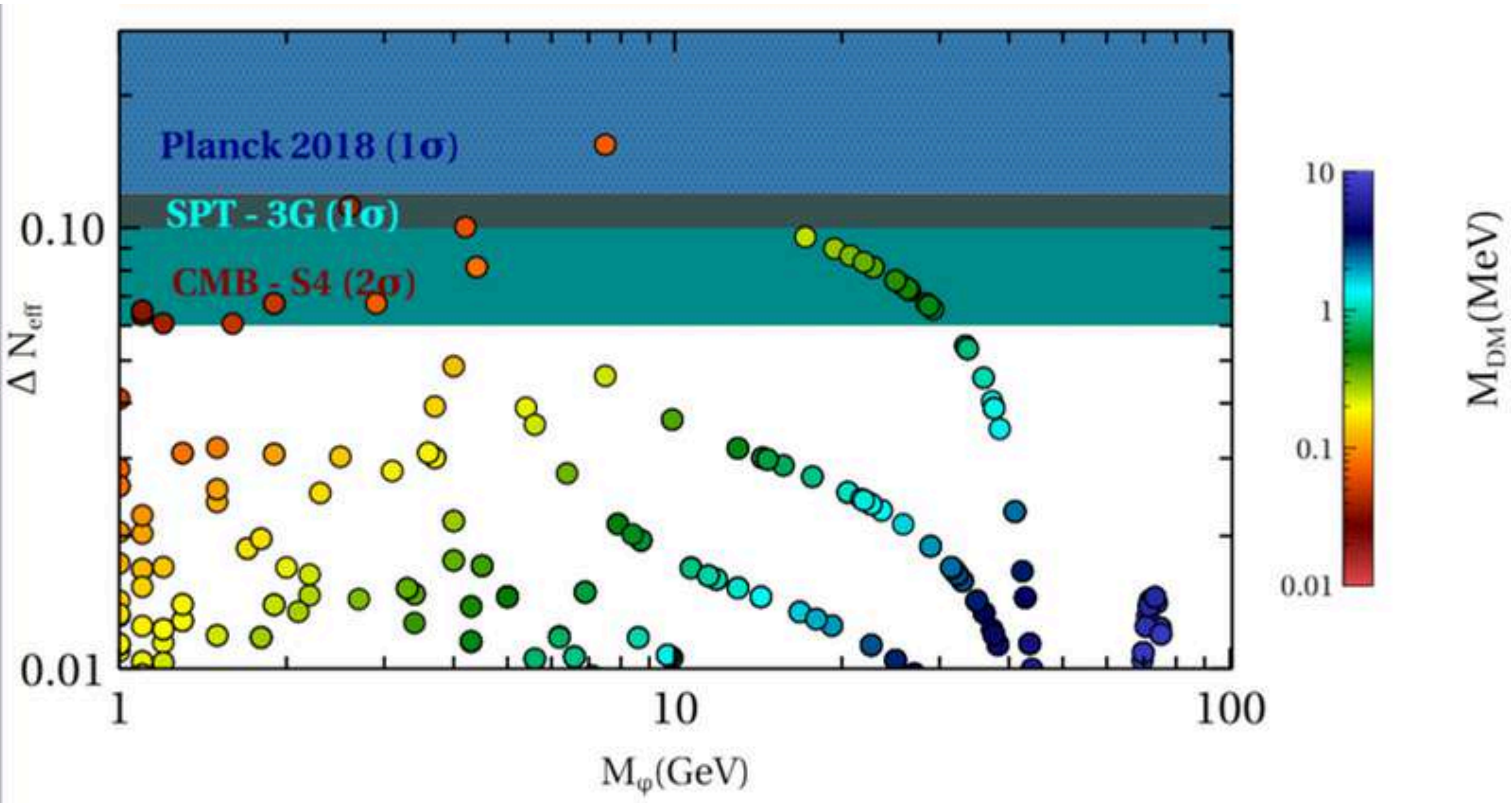
DM abundance

Contribution to N_{eff}

Numerical results for scenario-II

Weakly interacting HDS





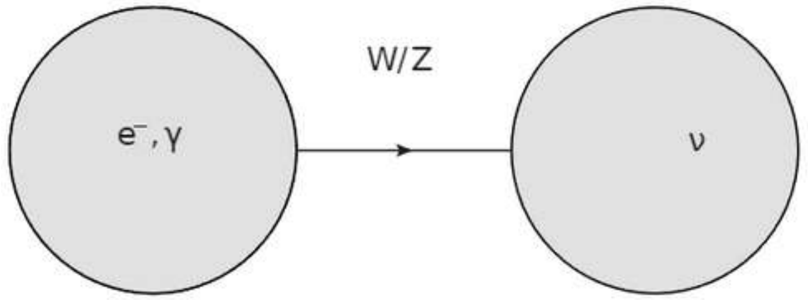
Different approach: Freeze-in DM in Scoto-Singlet Model

D.k.Ghosh, SJ, D. Nanda, PRD 2022

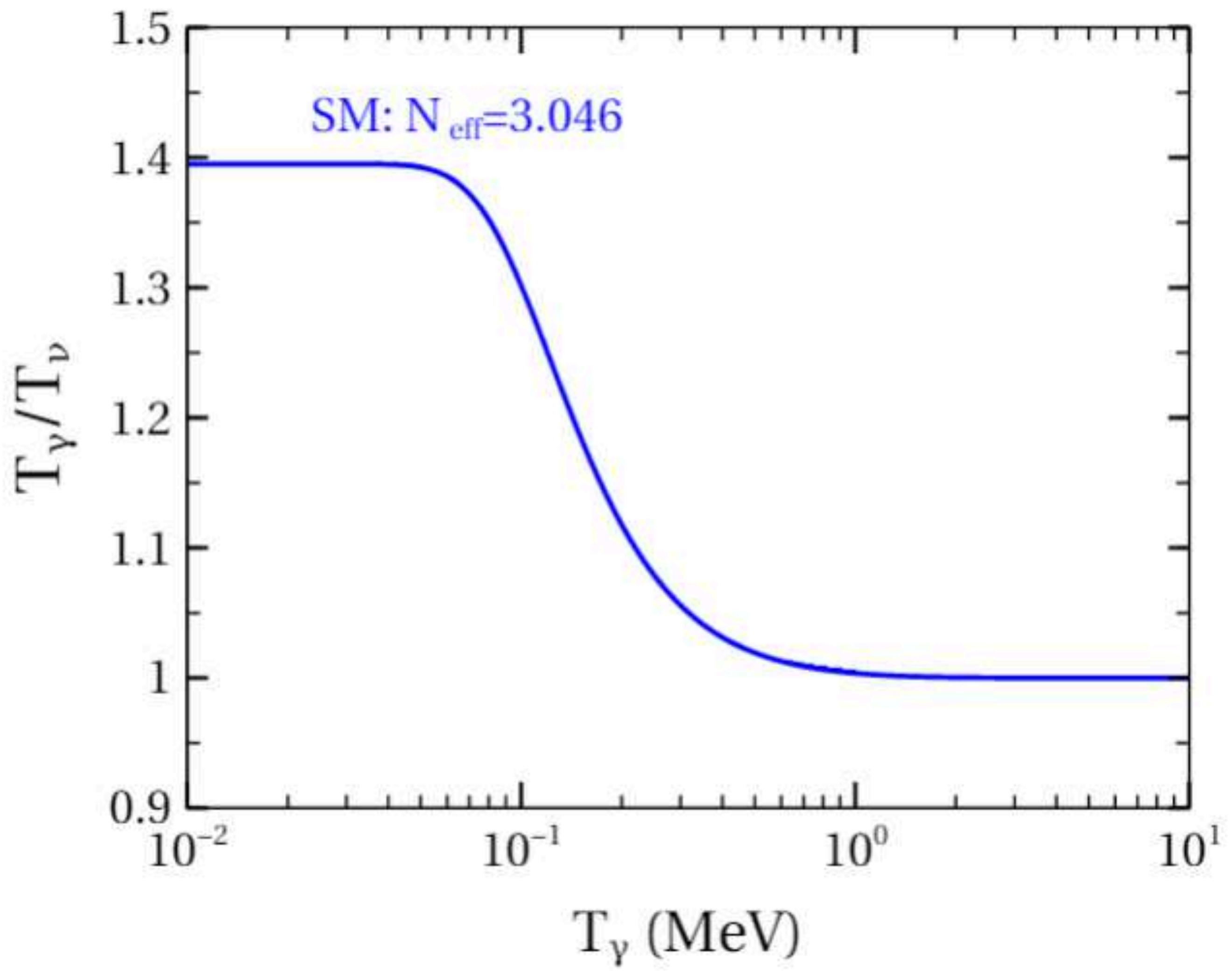
Decoupling/ Neff Phenomenology greatly impacted in the presence of a non standard cosmology in Pre-BBN era!

N_{eff} as a probe of light BSM mediators

- $N_{eff}^{CMB} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{\rho_v}{\rho_\gamma}\right)_{CMB}$
- SM Predicted value $N_{eff}^{CMB} = 3.046$



- BSM particle will change $T_{\nu,\gamma}$



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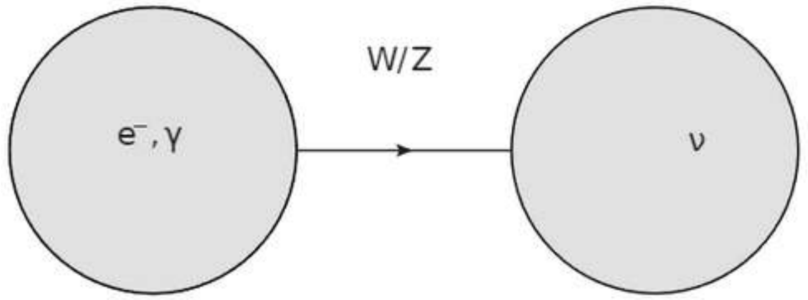

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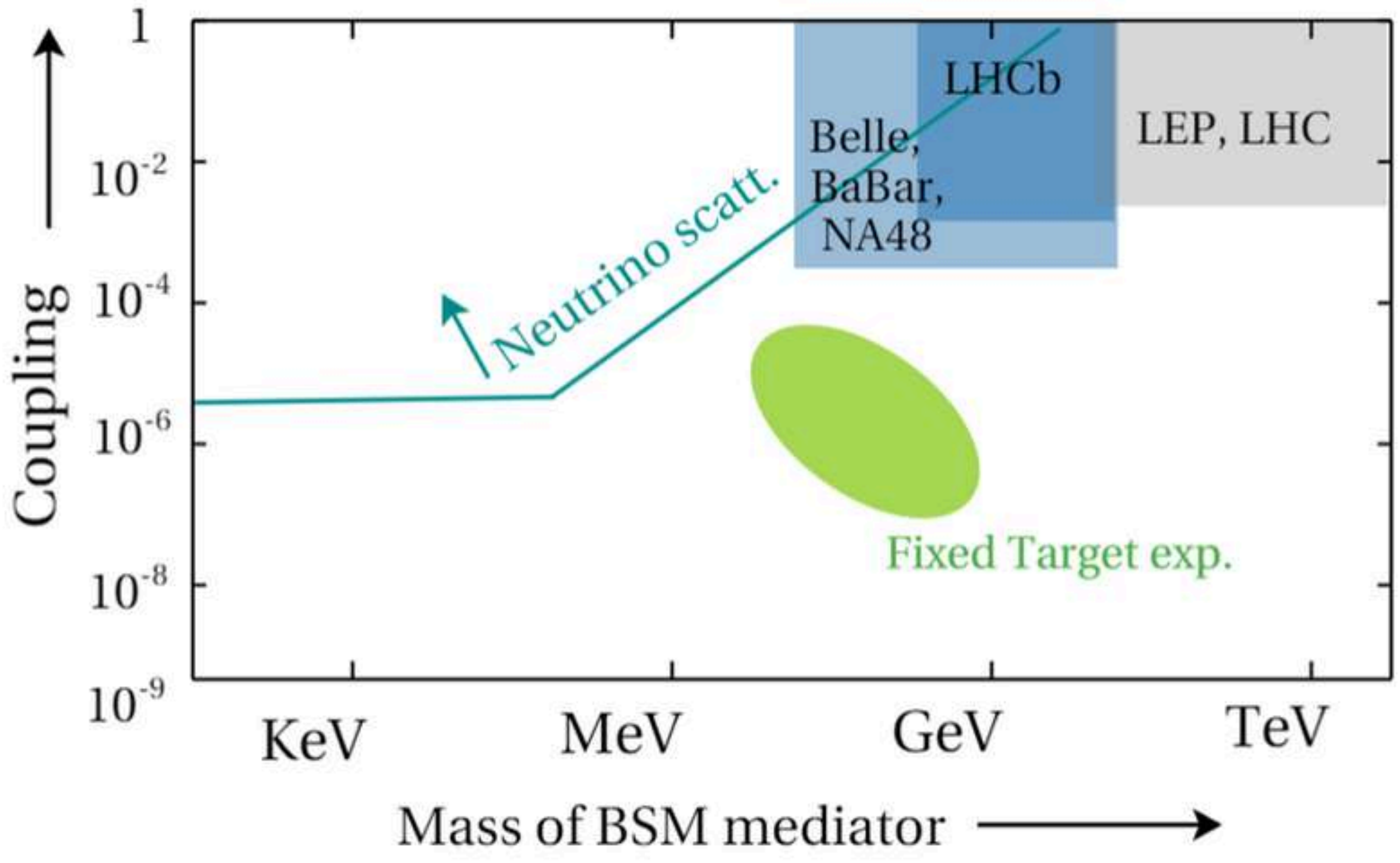

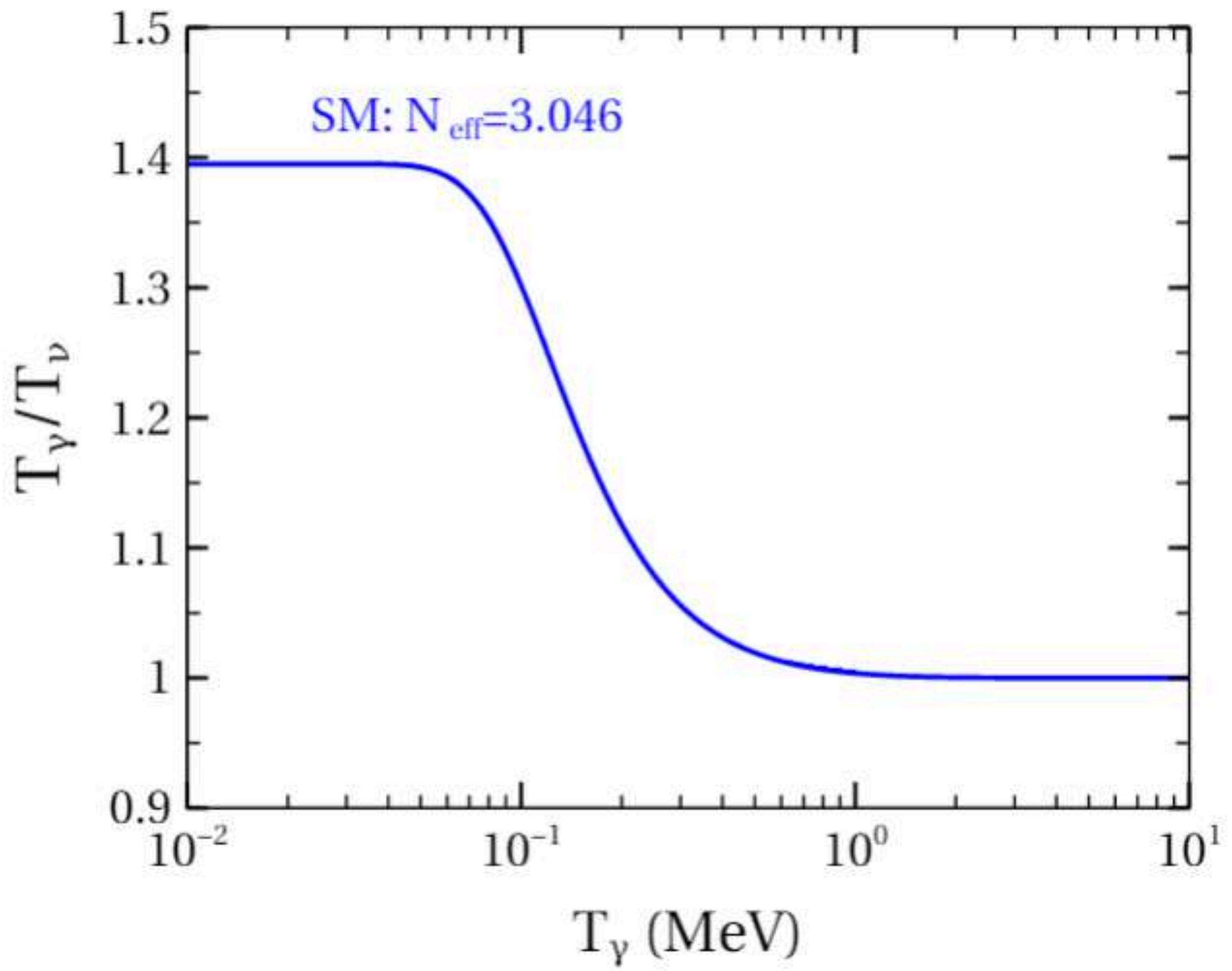

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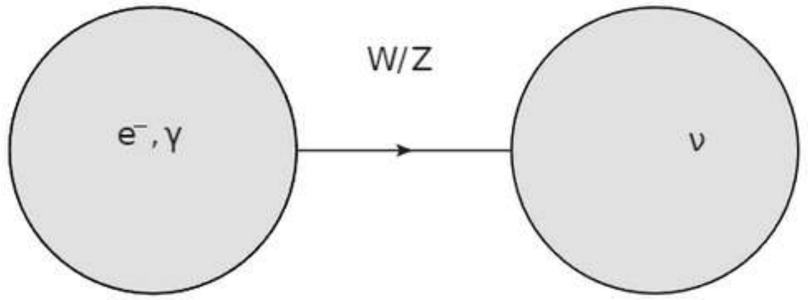

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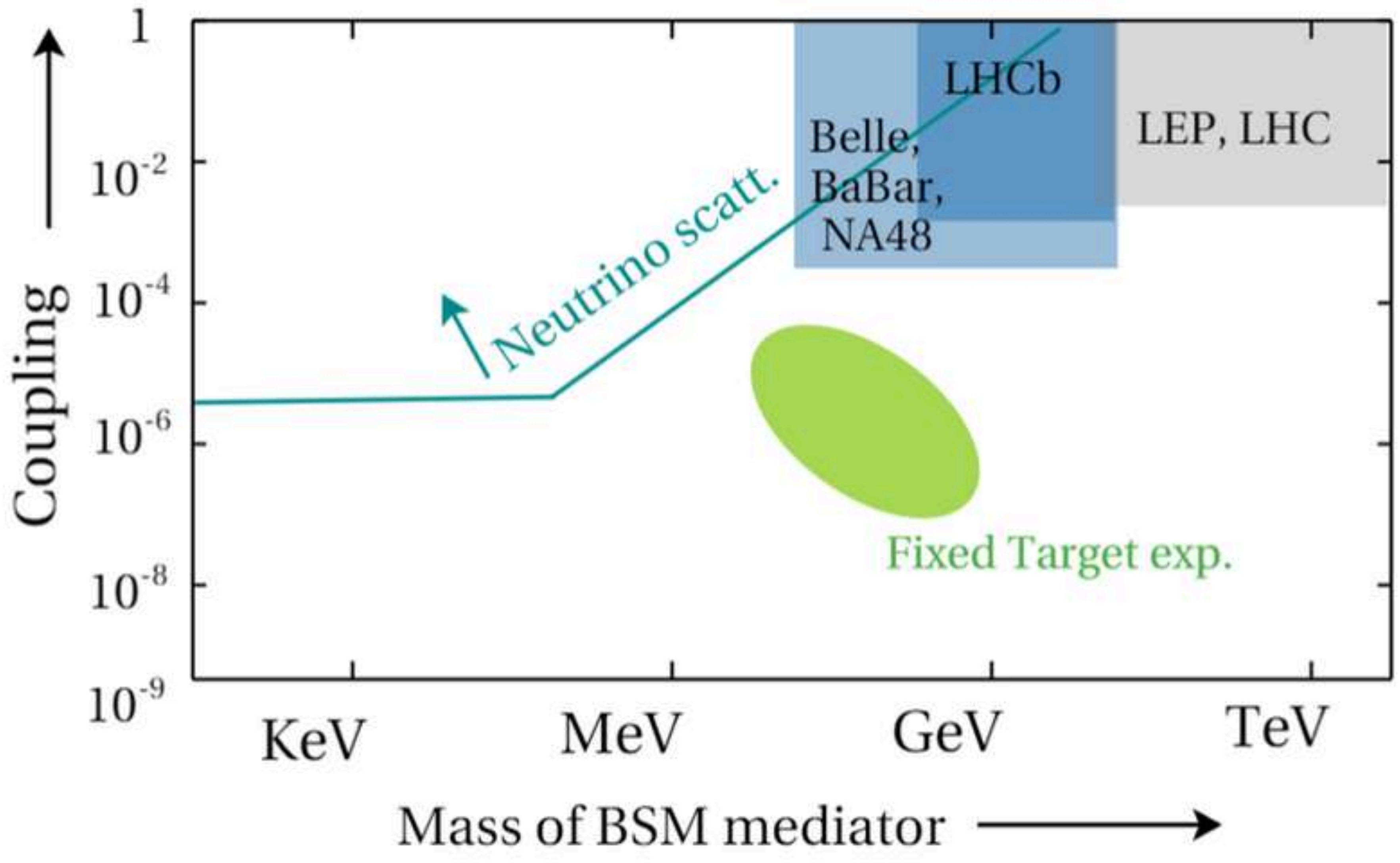

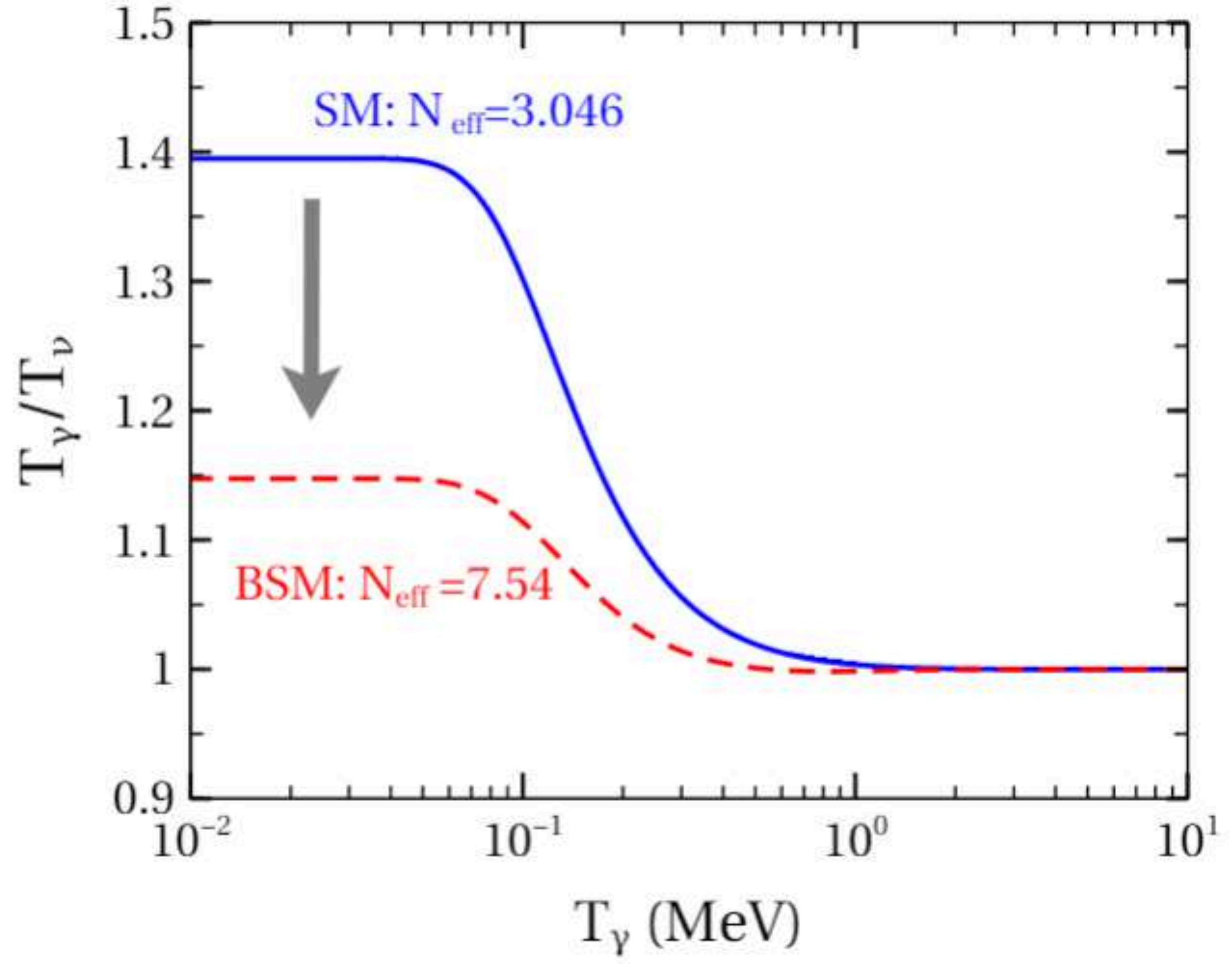

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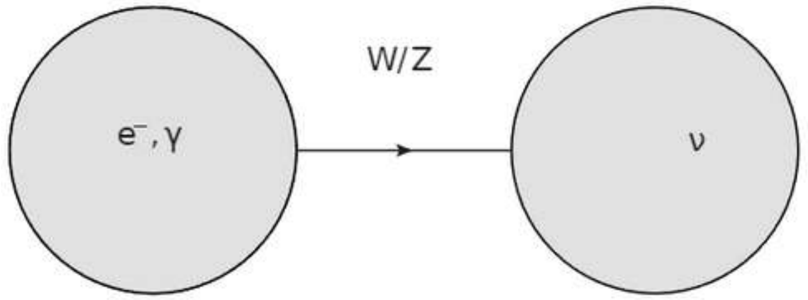

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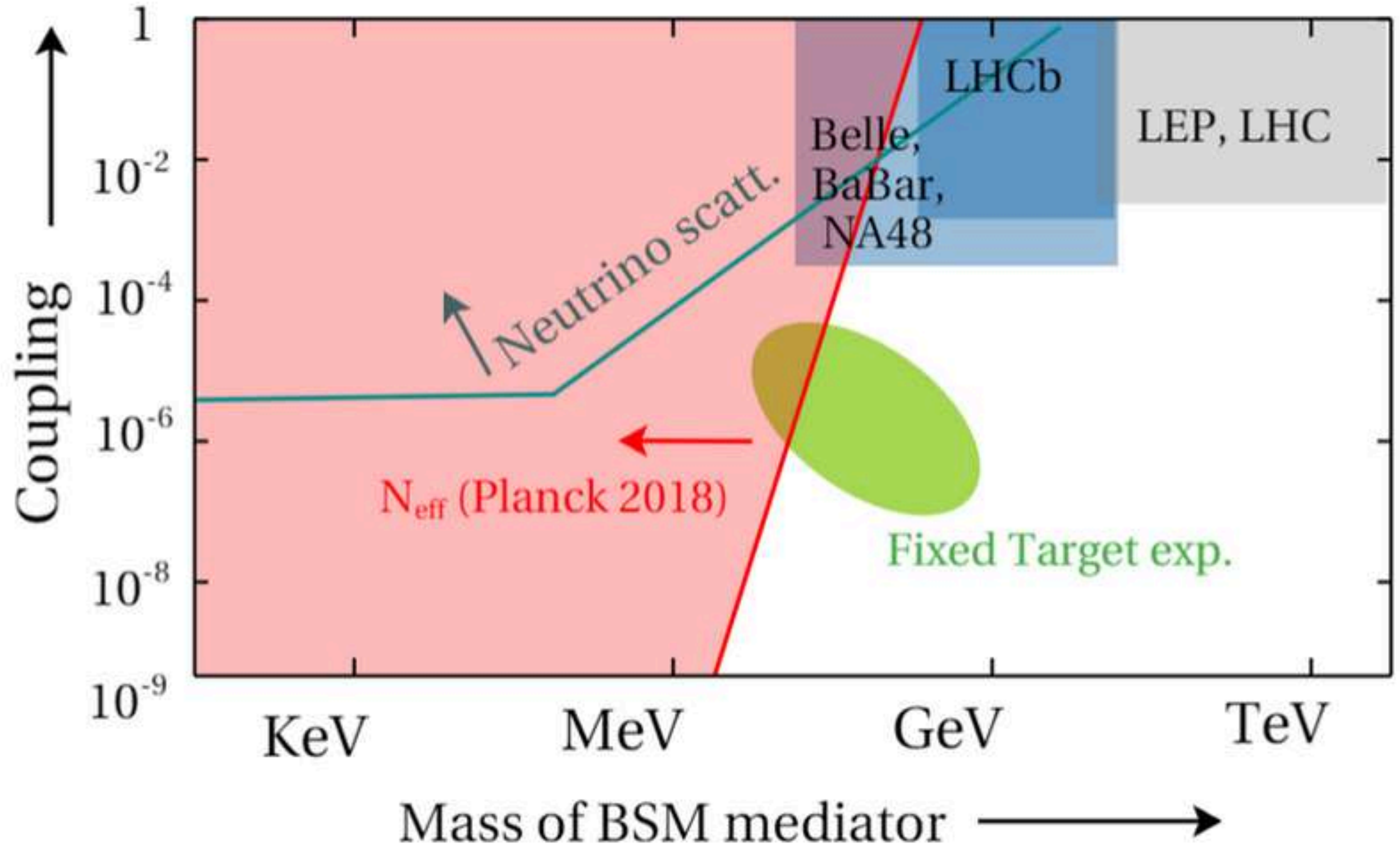

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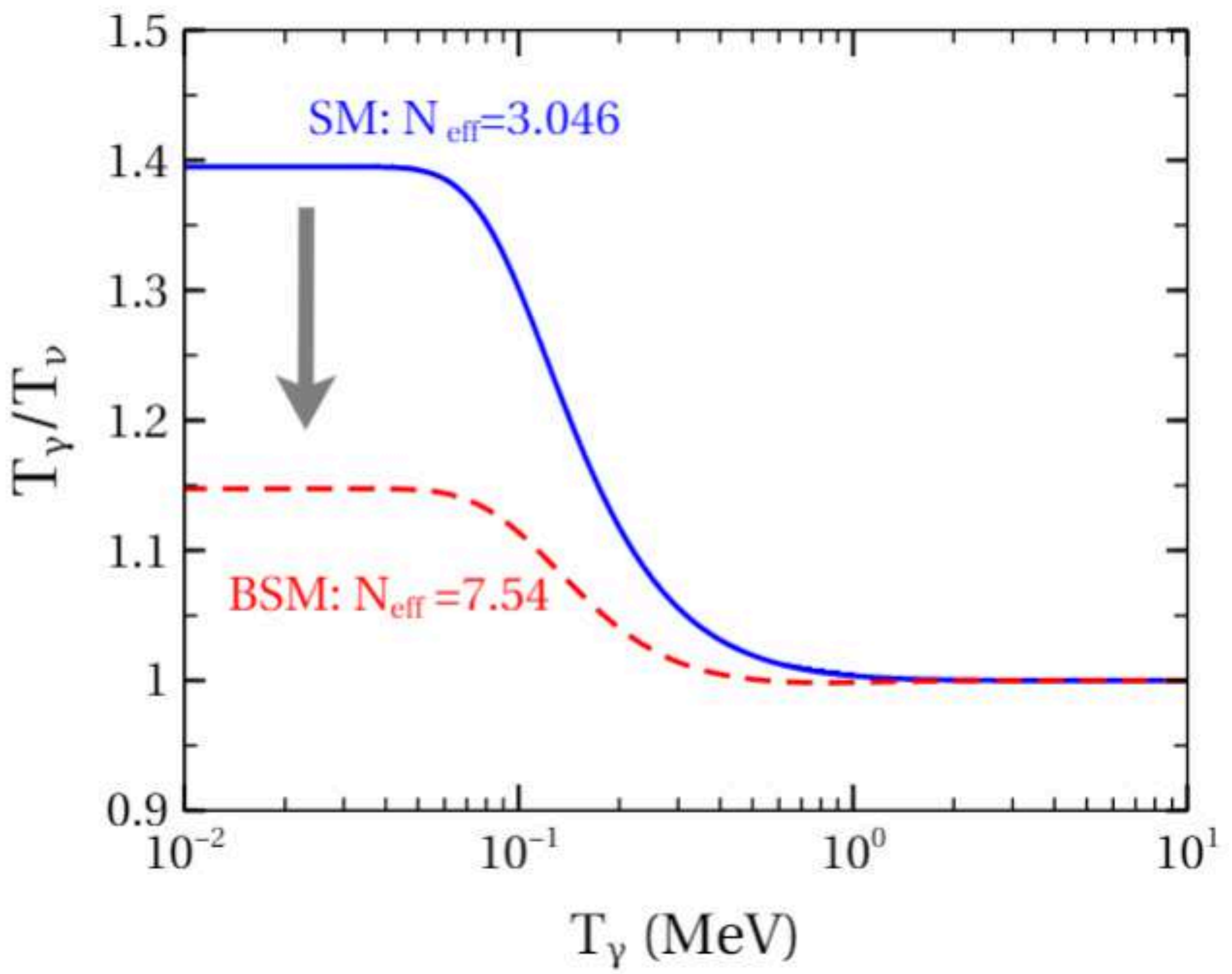


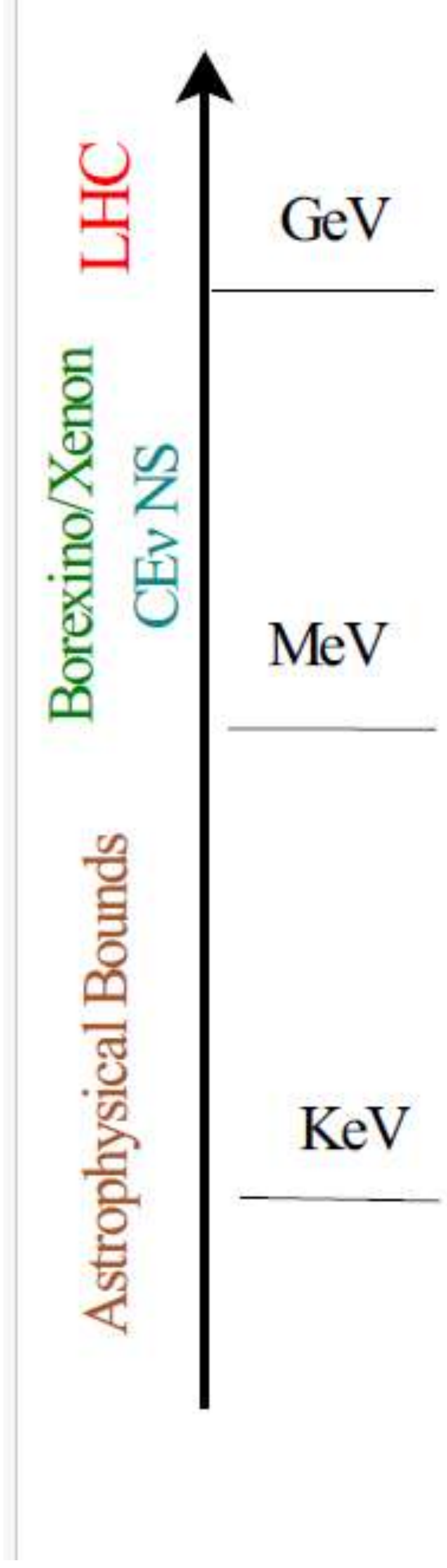
D.k.Ghosh, P.Ghosh, SJ, R.Srivastava, EPJC 2024

Z' from $U(1)_X$ gauge extension

- Charge assignments:

Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_X$
Q_i	$(3, 2, \frac{1}{3})$	$\mathbb{X}_{Q_i}$
u_i	$(3, 1, \frac{4}{3})$	$\mathbb{X}_{u_i}$
d_i	$(3, 1, -\frac{2}{3})$	$\mathbb{X}_{d_i}$
L_i	$(1, 2, -1)$	$\mathbb{X}_{L_i}$
ℓ_i	$(1, 1, -2)$	$\mathbb{X}_{\ell_i}$
ν_{R_i}	$(1, 1, 0)$	$\mathbb{X}_{\nu_i}$
Φ	$(1, 2, 1)$	$\mathbb{X}_\Phi$
σ	$(1, 1, 0)$	$\mathbb{X}_\sigma$

- Quark and lepton masses: $\mathbb{X}_{Q_i} = \mathbb{X}_{u_i} = \mathbb{X}_{d_i}$ and $\mathbb{X}_{L_i} = \mathbb{X}_{\ell_i} \equiv X_i$
- Charges across generations can be different. But problem in generating CKM matrix.



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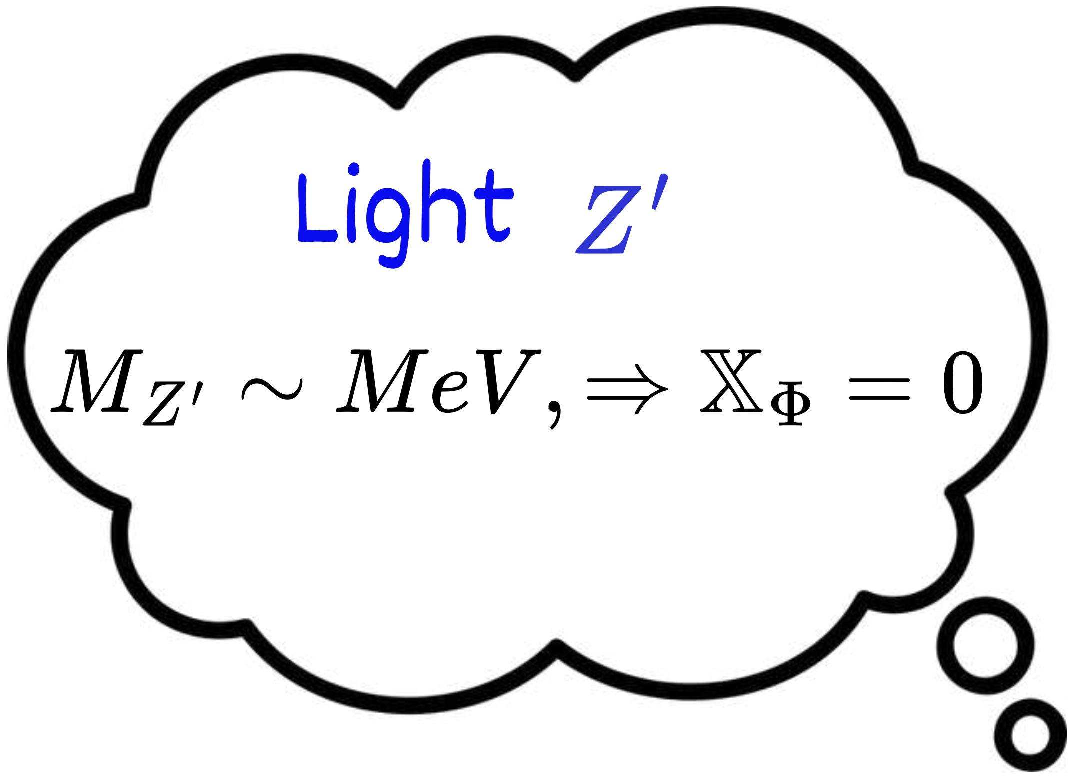

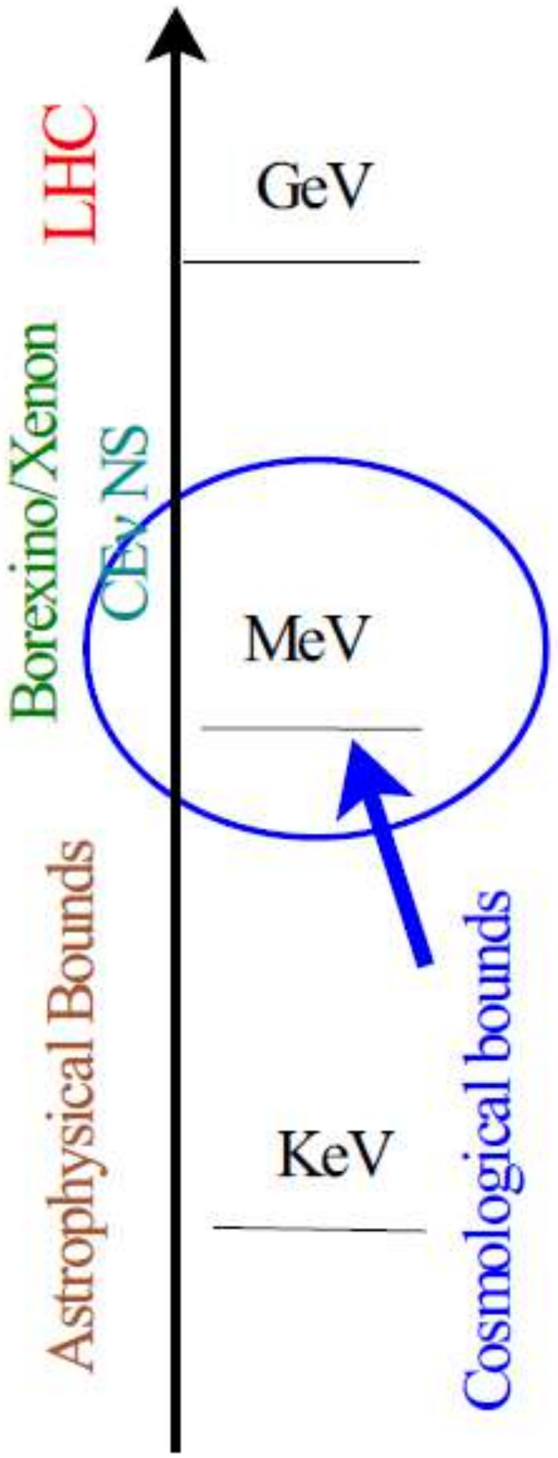

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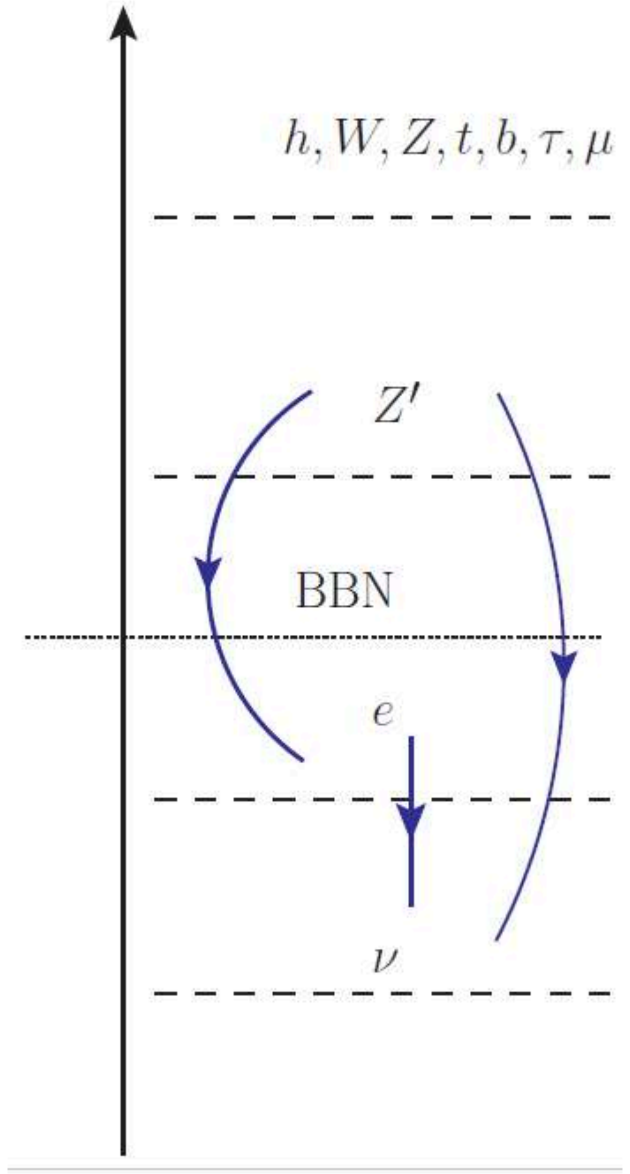
ν_L decoupling in presence of light Z'

- Relevant particles



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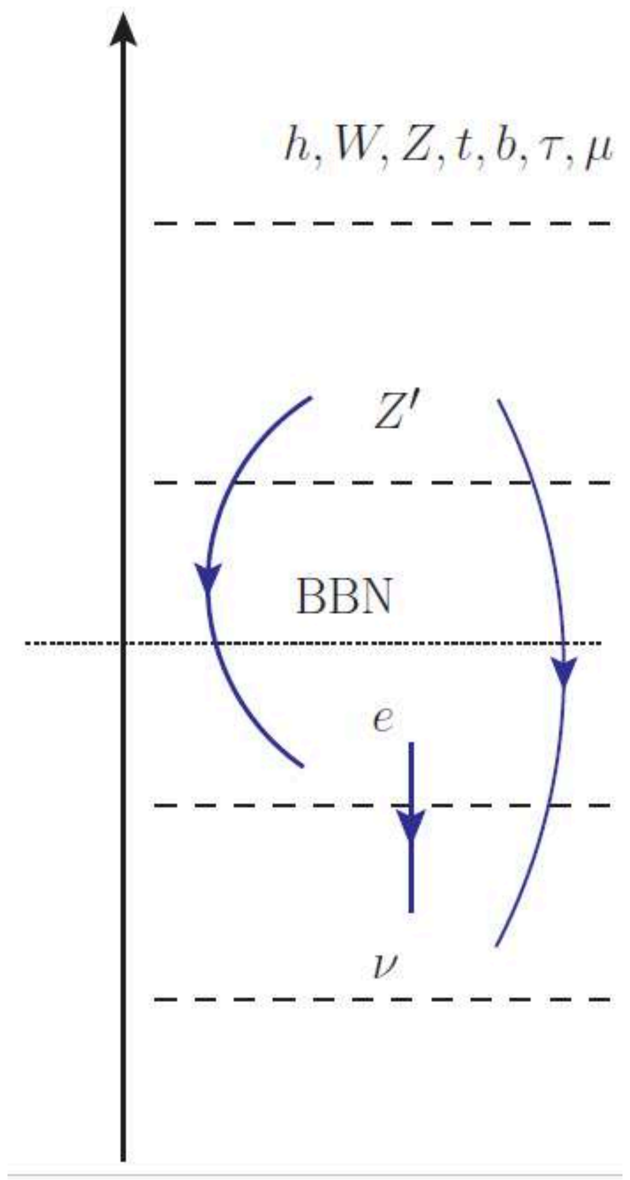

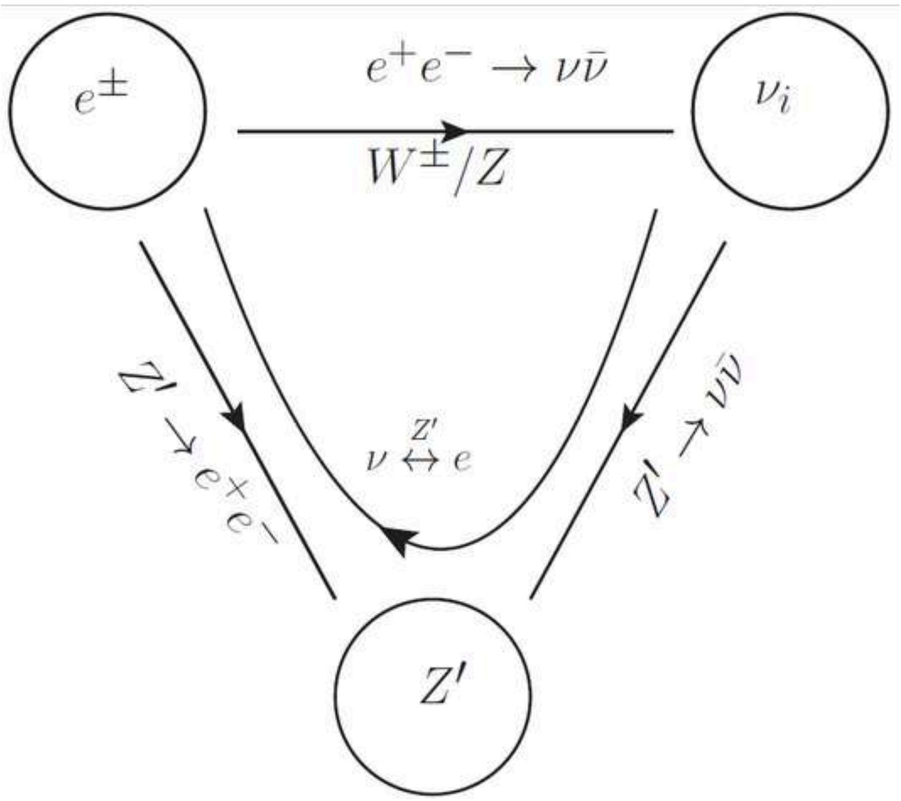

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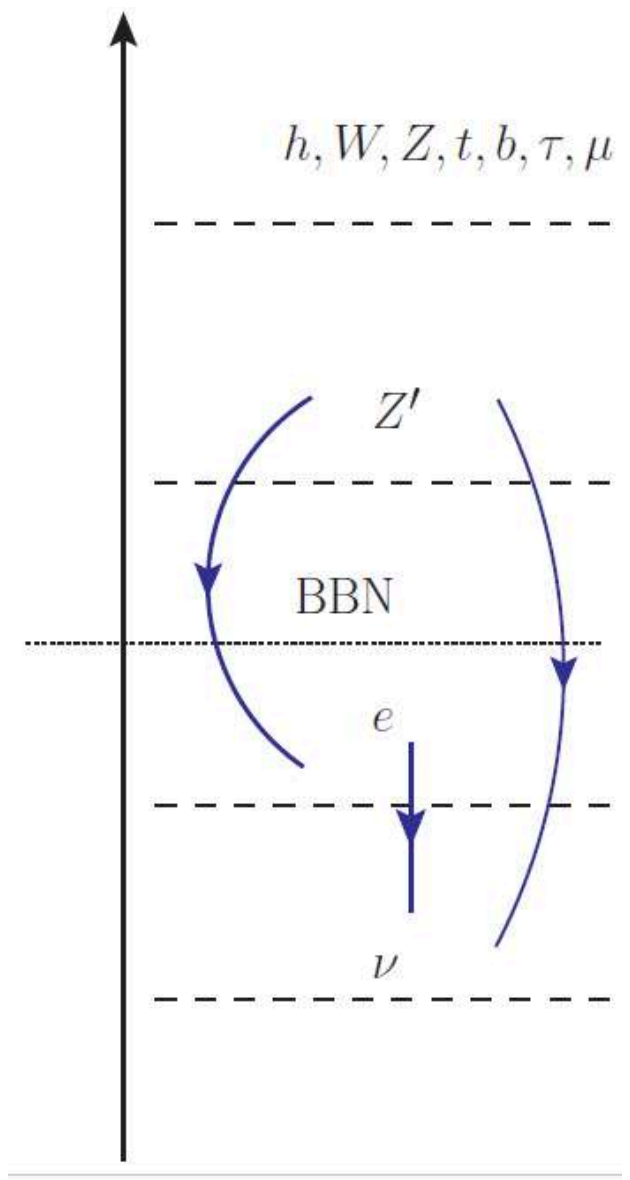

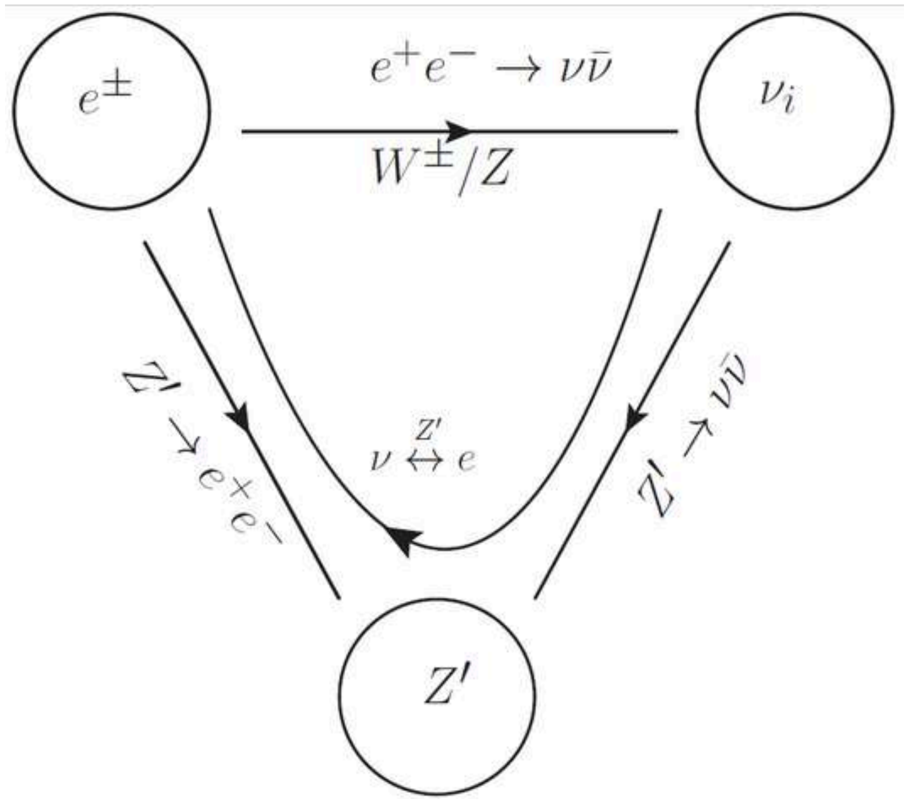

- Relevant processes

1. **SM contributions:** (W/Z)
   $\nu_i\bar{\nu}_i \leftrightarrow e^+e^-$, $\nu_i e^\pm \leftrightarrow \nu_i e^\pm$
2. **BSM contributions to γ bath:** Z'
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3. **BSM contributions to ν bath:** Z'
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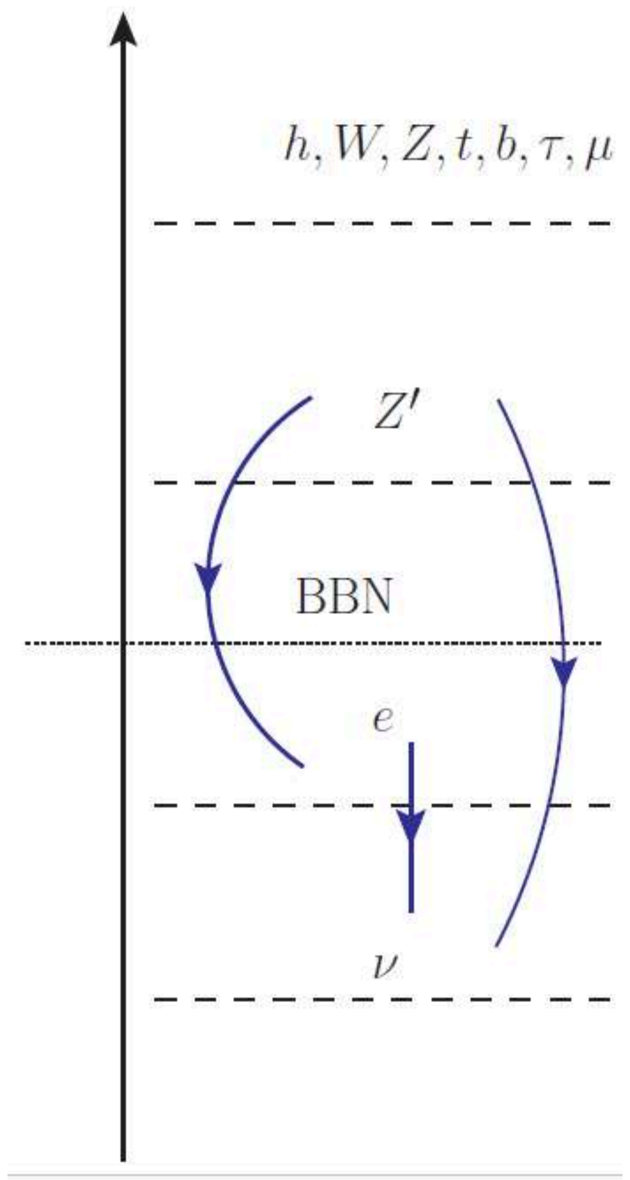

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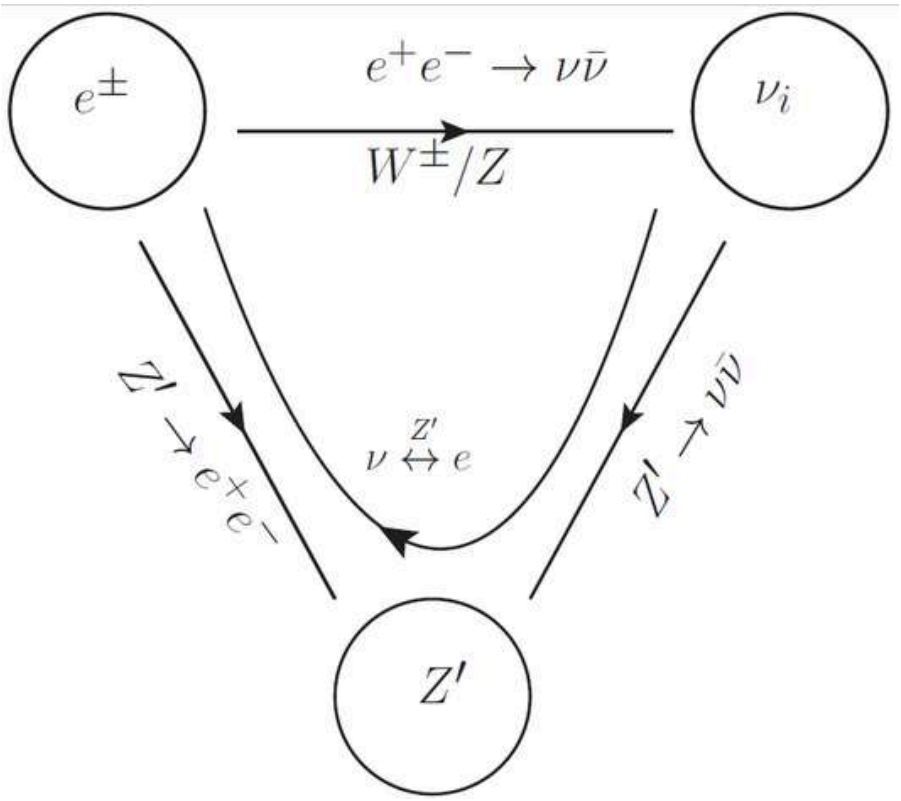

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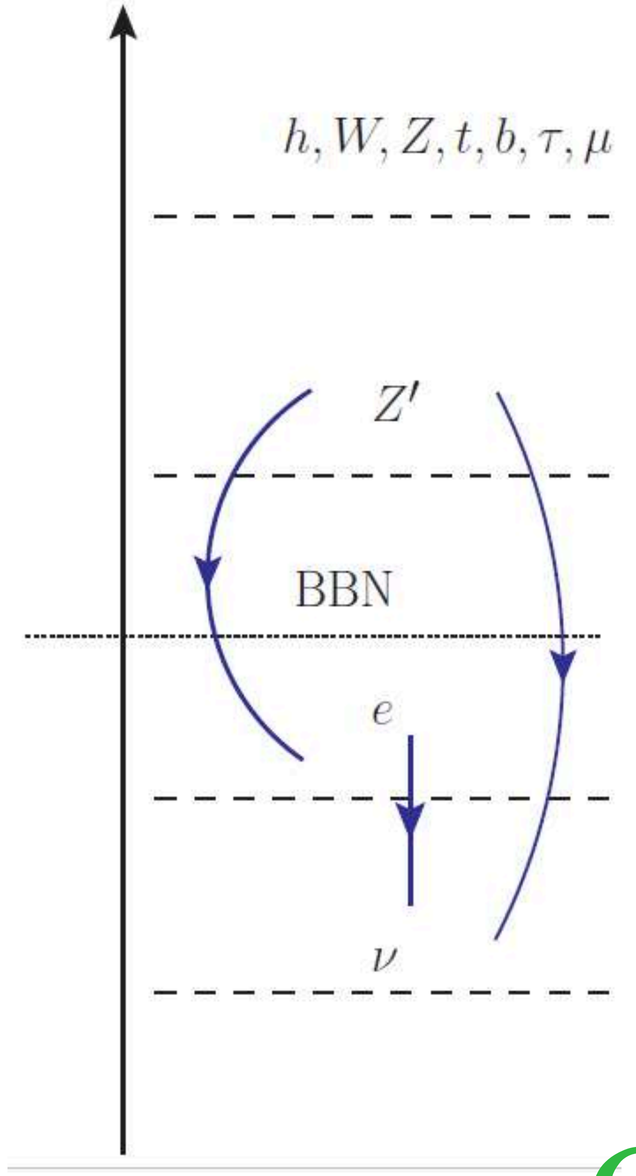

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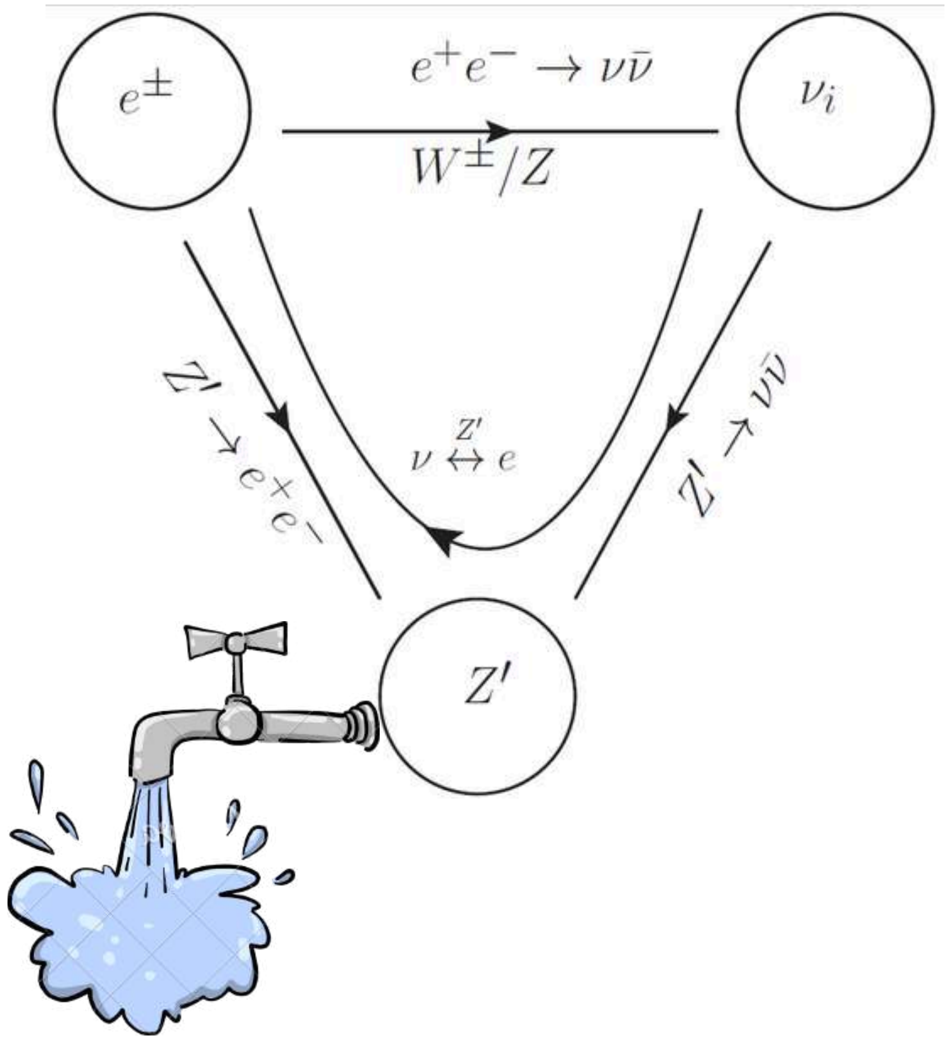

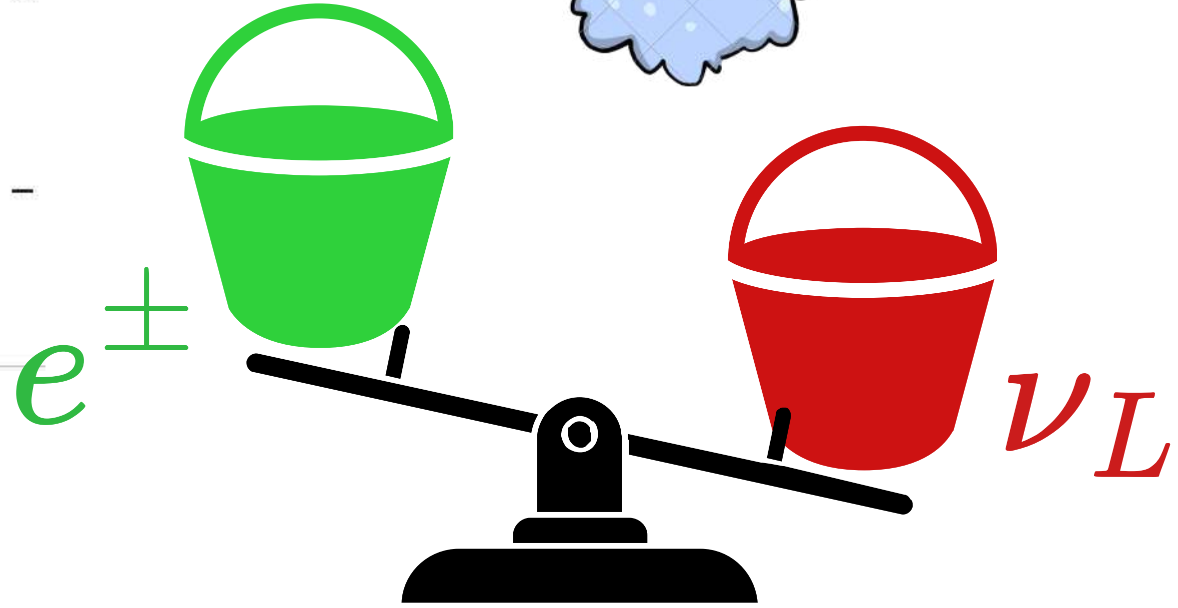

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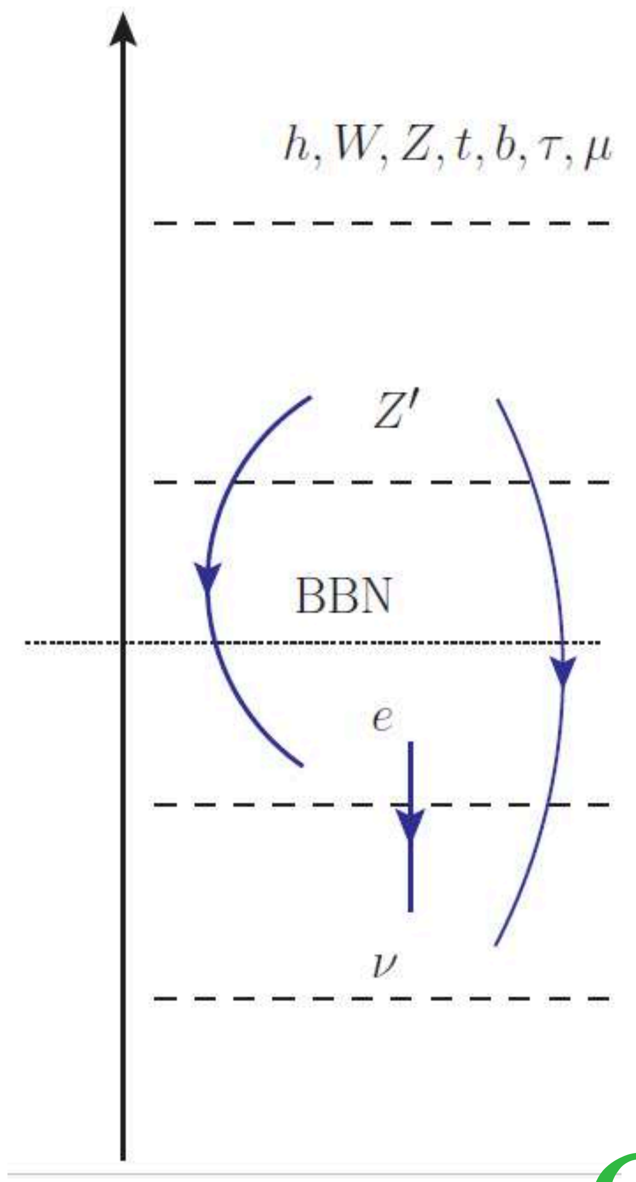

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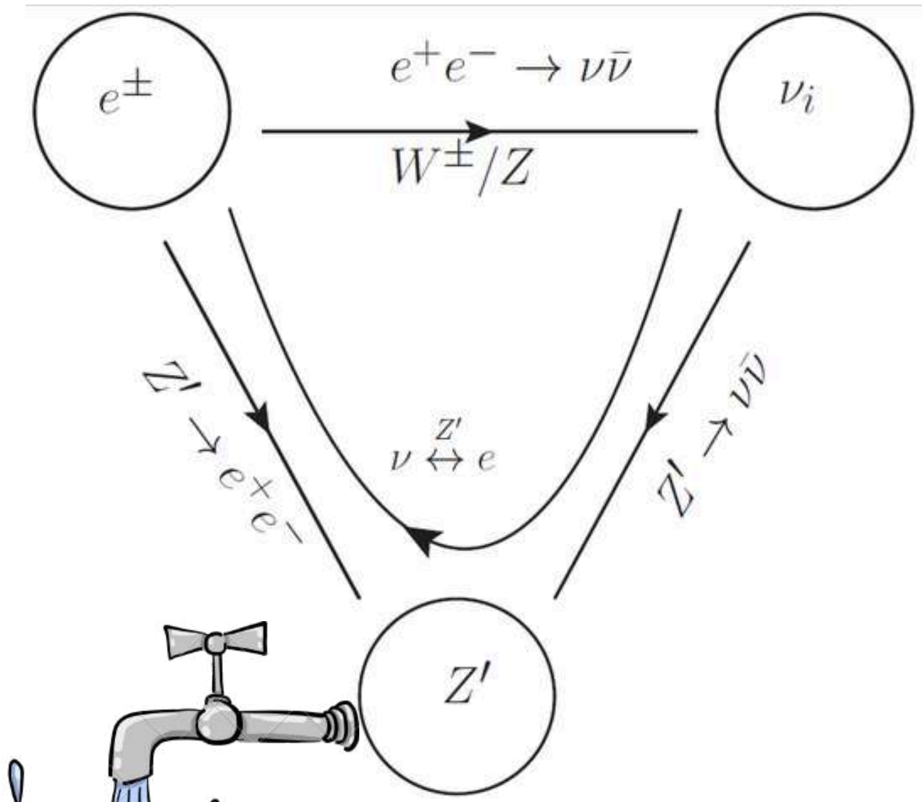

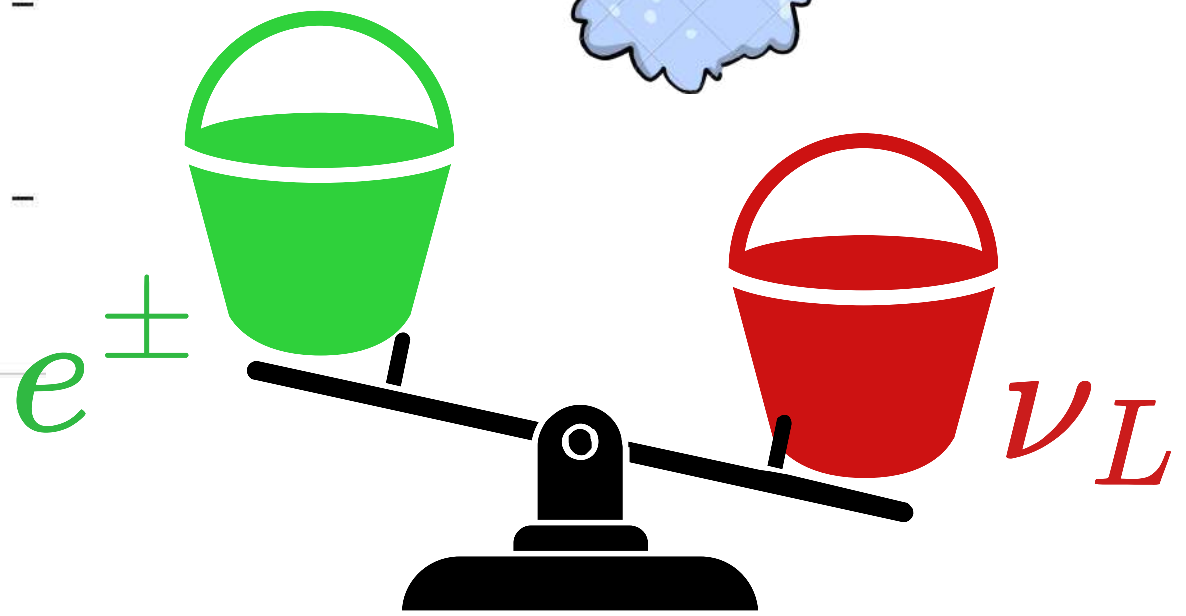

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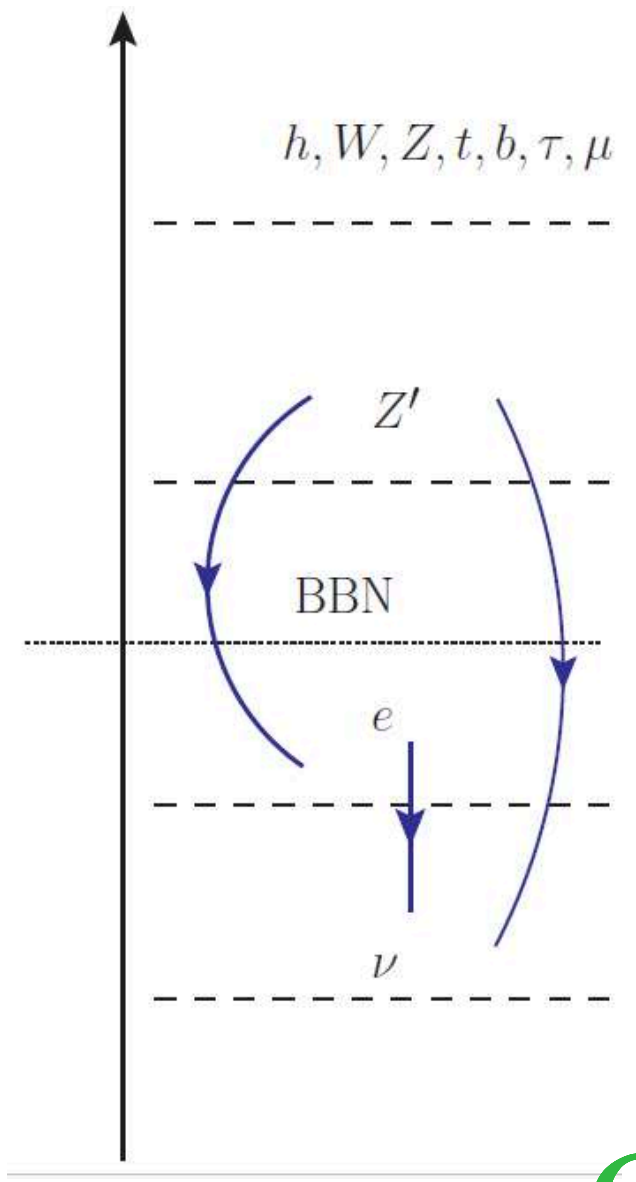

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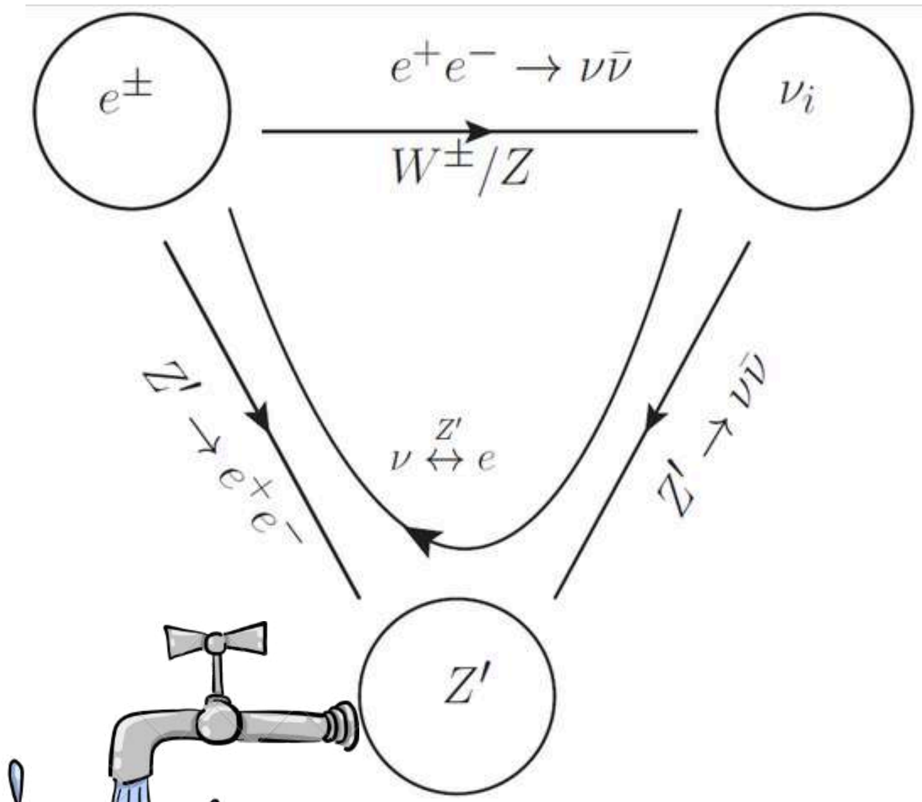

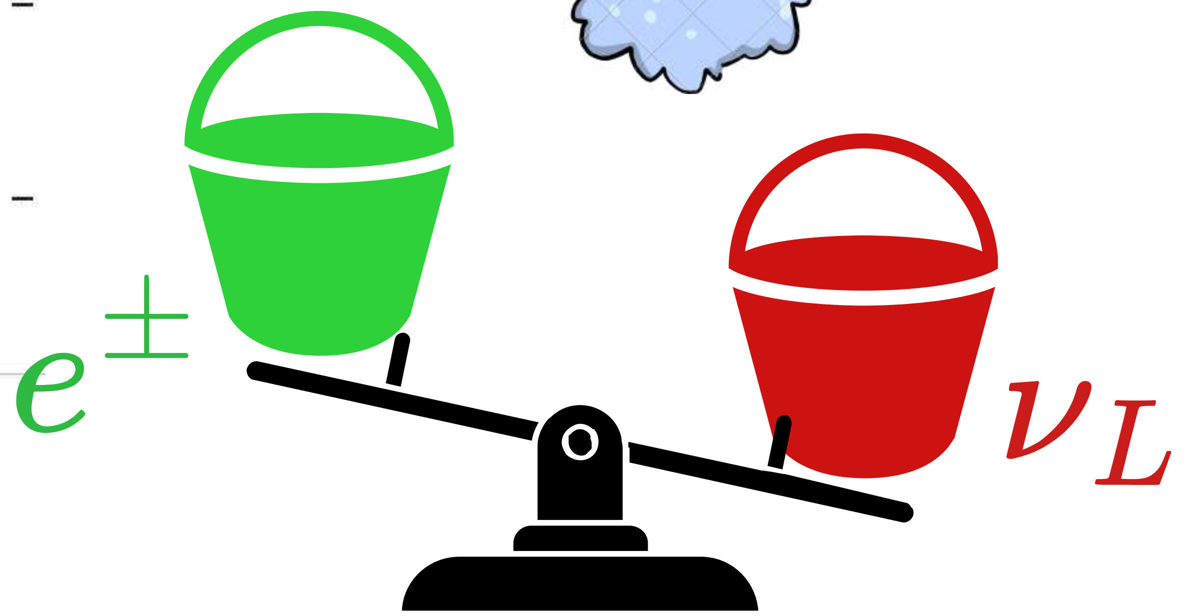

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Evaluation of temperature ratios

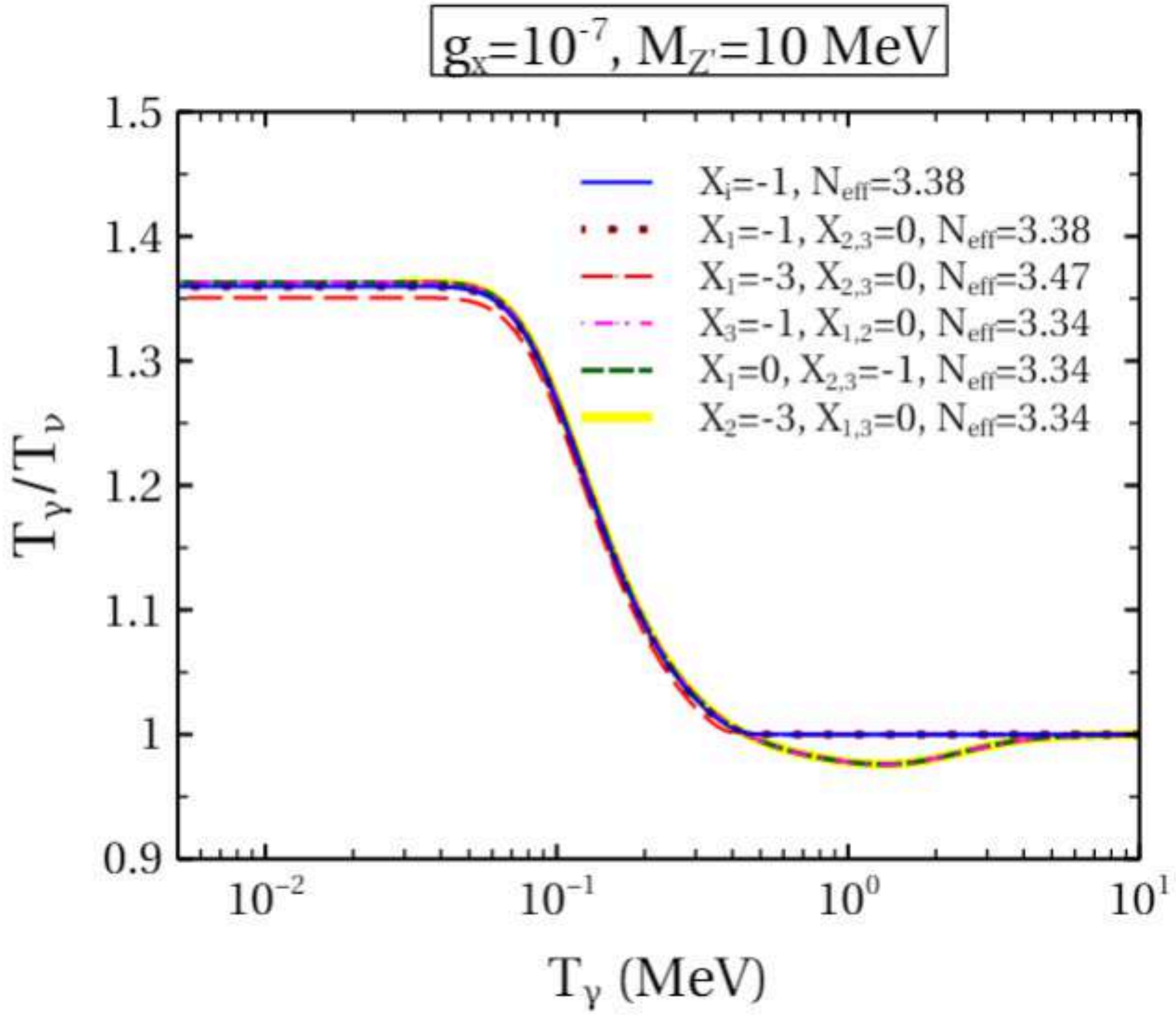
- Relevant interaction $\mathcal{L}_{int} \supset Z'_\alpha J^\alpha_{\mathbb{X}}$

$$J^\alpha_{\mathbb{X}} \supset g_X \left(X_3 \bar{\tau}\gamma^\alpha \tau + X_3 \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau + X_2 \bar{\mu}\gamma^\alpha \mu + X_2 \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu \right)$$
$$+ g_X \left(X_1 \bar{e}\gamma^\alpha e + X_1 \bar{\nu}_e \gamma^\alpha P_L \nu_e \right)$$

- Liouville equation

$$\frac{\partial f(p,t)}{\partial t} - Hp \frac{\partial f(p,t)}{\partial p} = \mathcal{C}[\, f \,]$$

- After integrating => temperature eqn.s for $T_\nu, T_\gamma, T_{Z'}$



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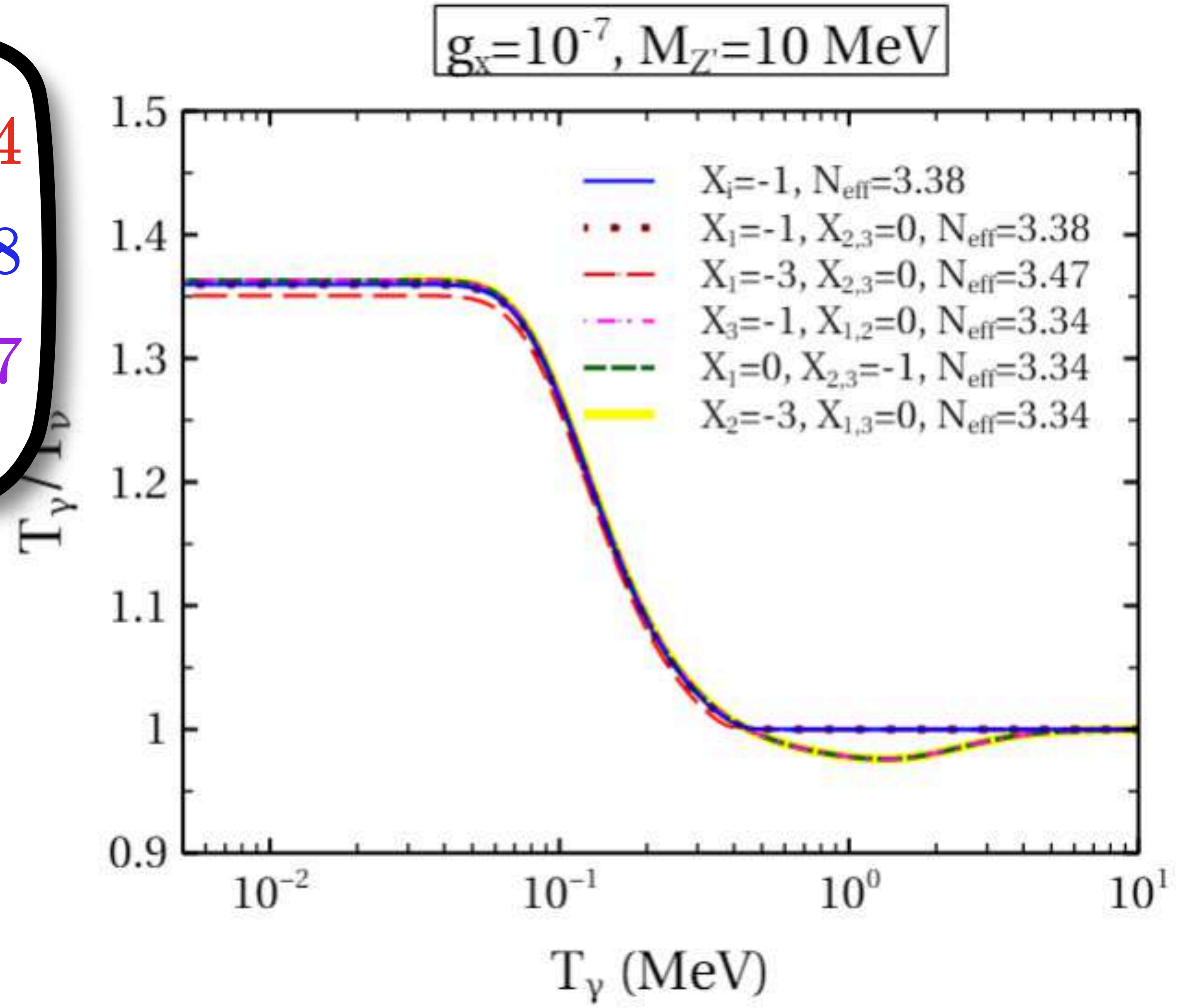
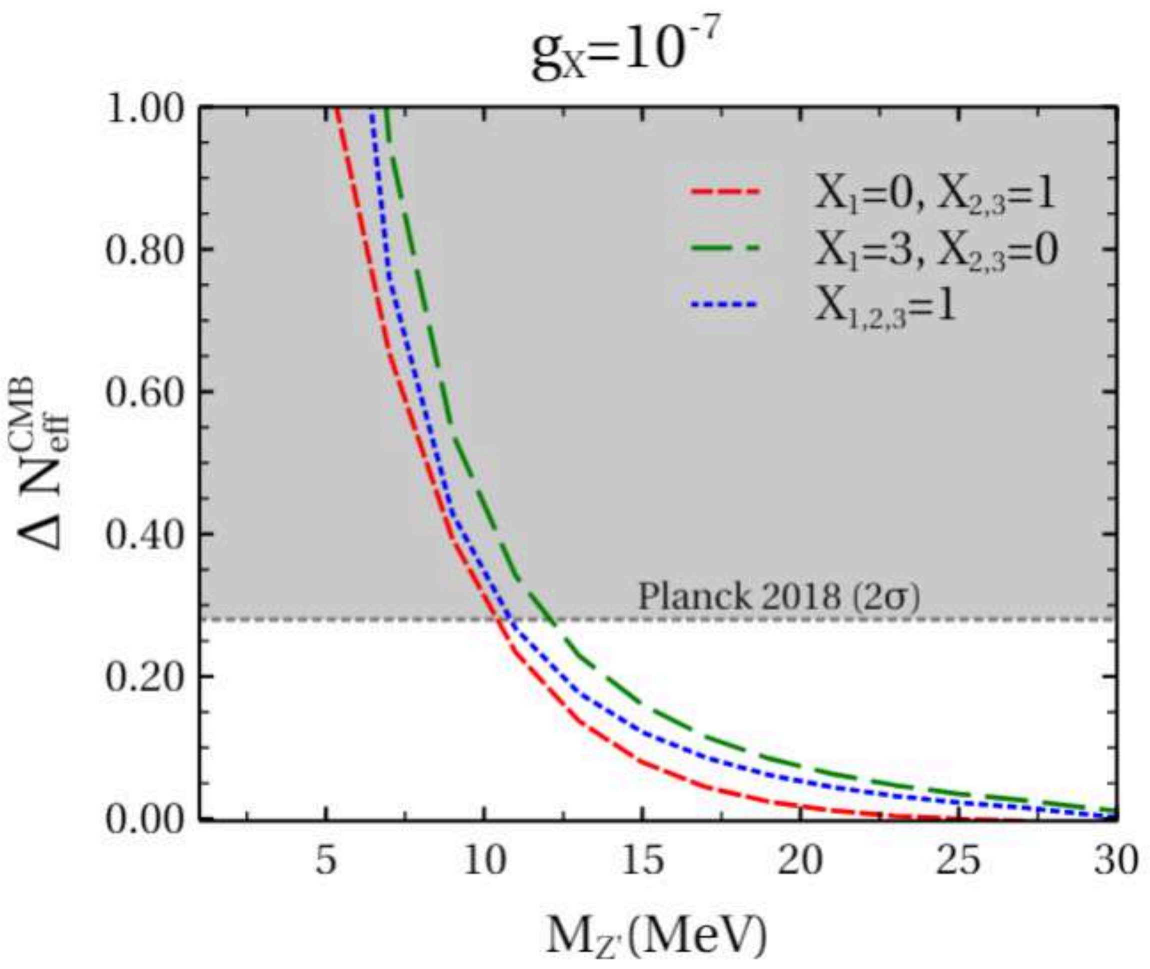
$1. X_1 = 0, N_{eff} = 3.34$

$2. X_1 = 1, N_{eff} = 3.38$

$3. X_1 = 3, N_{eff} = 3.47$



Classification of light Z' models



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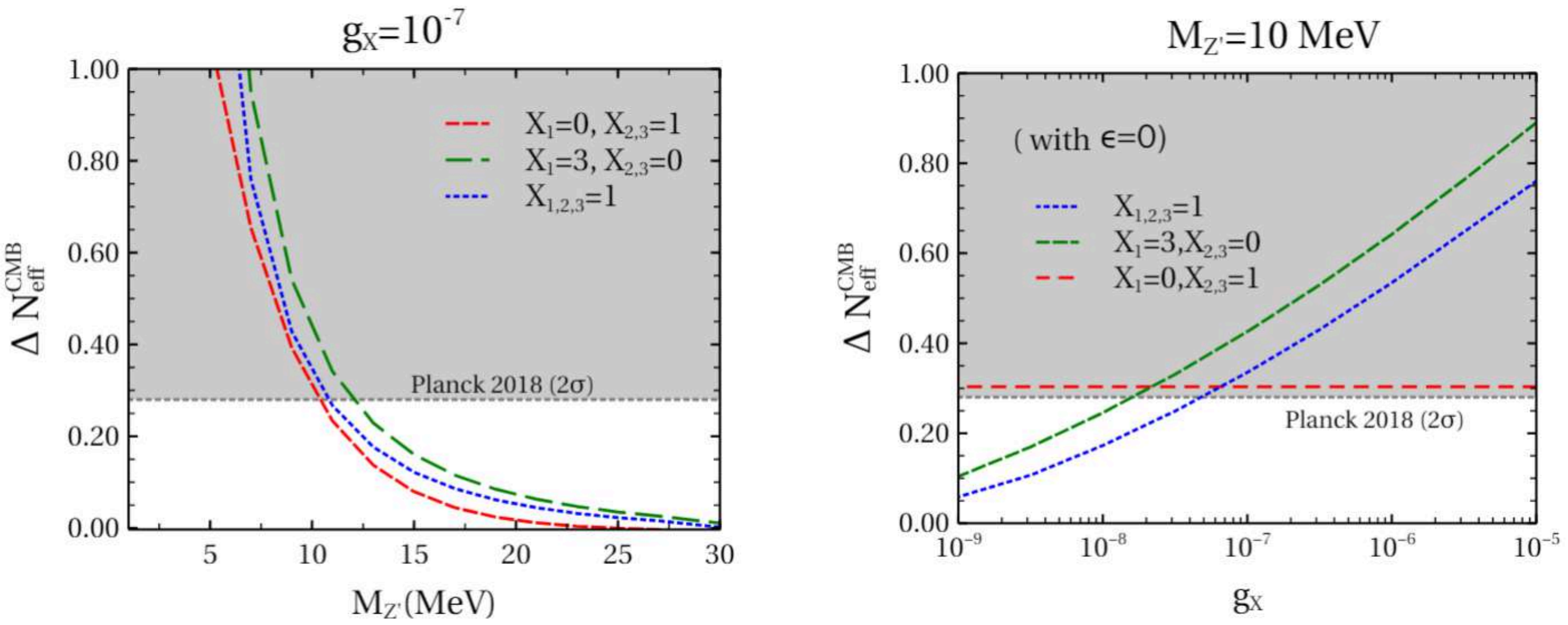

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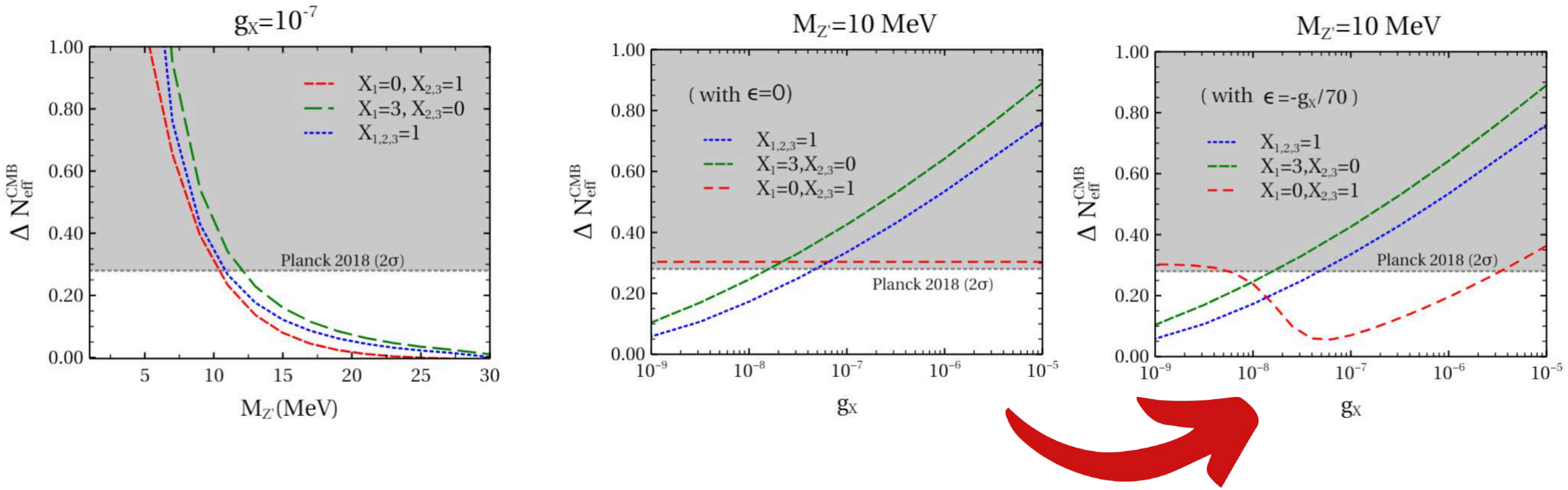
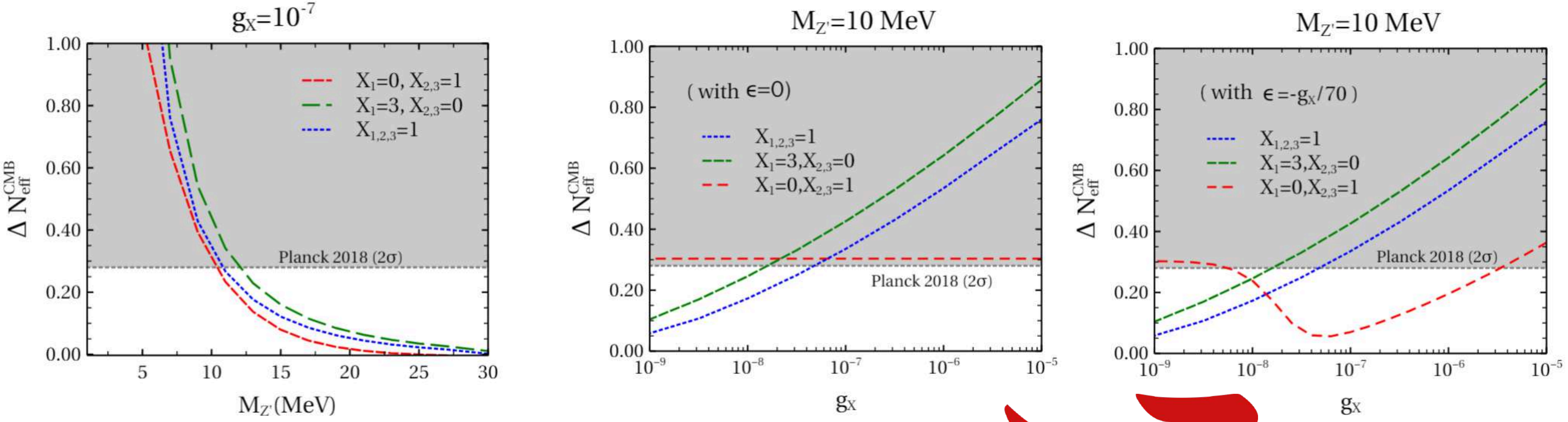


$$\mathcal{L} \supset (\epsilon e) Z_\mu \bar{e} \gamma^\mu e$$

Induced coupling

Classification of light Z' models



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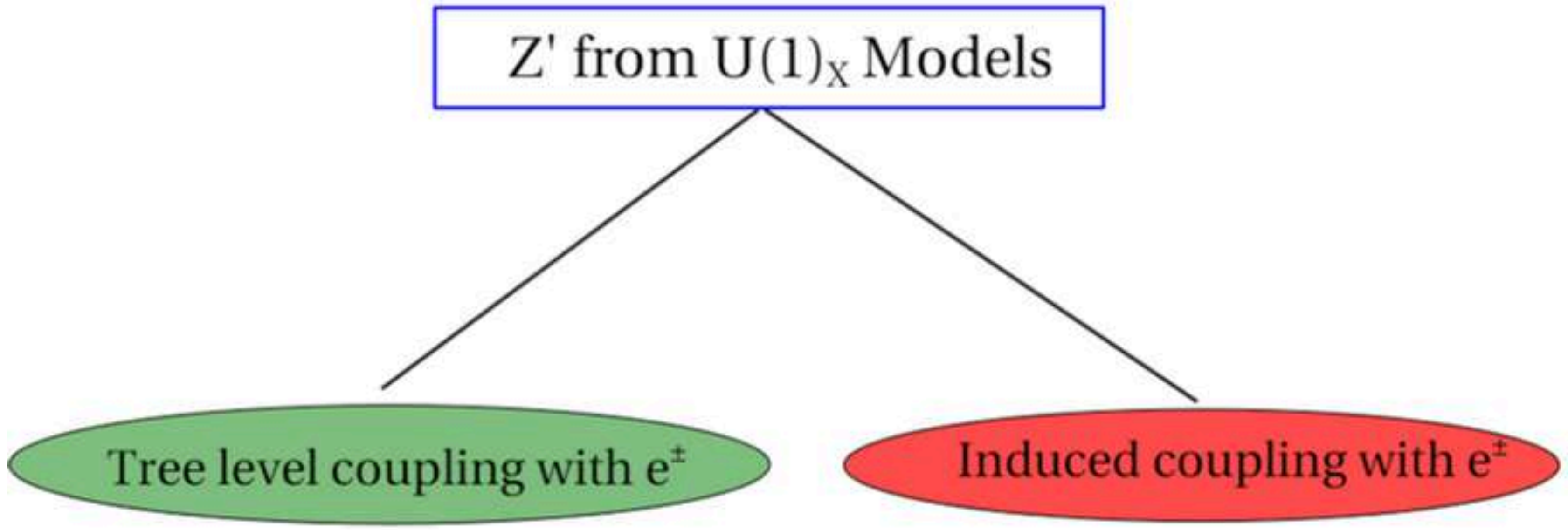
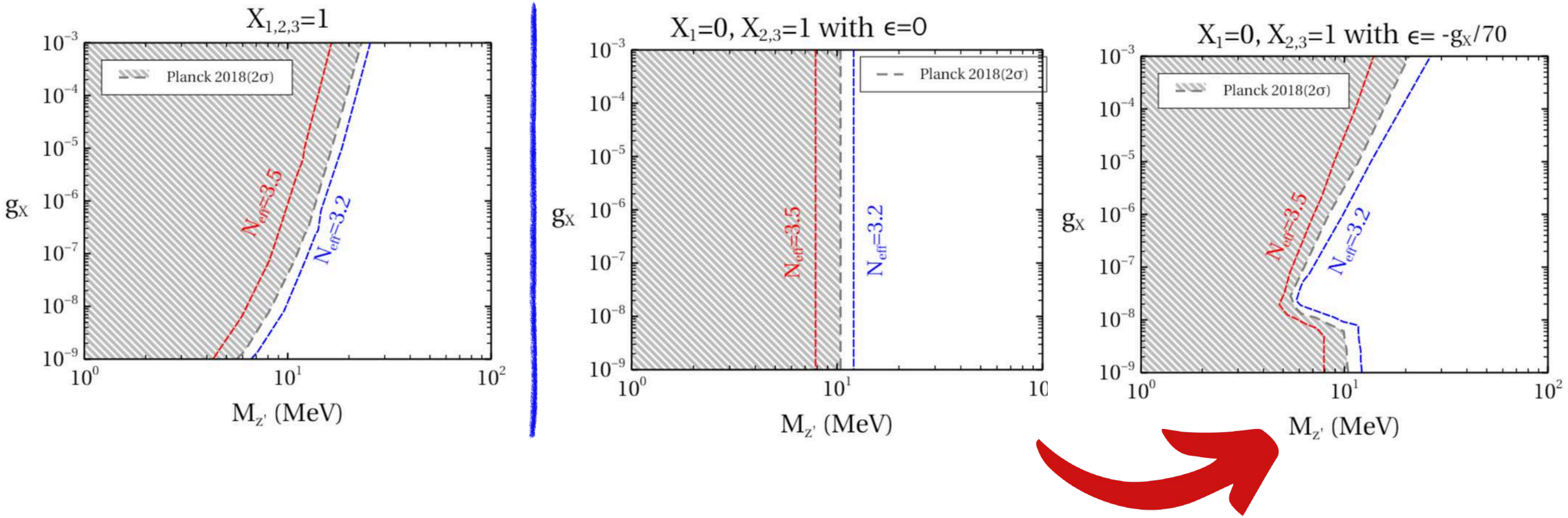


Constraint on the Z' parameter space



Including induced coupling

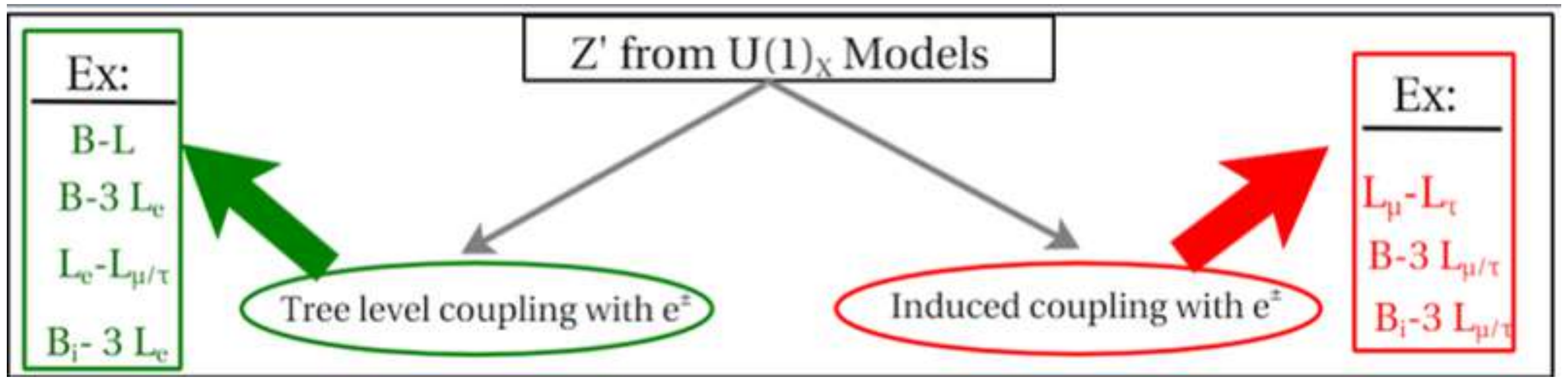
D.k.Ghosh, P.Ghosh, SJ, R.Srivastava, EPJC 2024

Imprints of popular $U(1)_X$ models

Models	$\mathbb{X}_{Q_i}(\mathbb{X}_{u_i} = \mathbb{X}_{d_i})$	$\mathbb{X}_{L_1}$	$\mathbb{X}_{L_2}$	$\mathbb{X}_{L_3}$
$\mathbf{B-L}$	$(1/3,\ 1/3,\ 1/3)$	-1	-1	-1
$\mathbf{B-3L_e}$	$(1/3,\ 1/3,\ 1/3)$	-3	0	0
$B-3L_\mu$	$(1/3,\ 1/3,\ 1/3)$	0	-3	0
$B-3L_\tau$	$(1/3,\ 1/3,\ 1/3)$	0	0	-3
$\mathbf{L_e-L_\mu}$	$(0,0,0)$	1	-1	0
$\mathbf{L_e-L_\tau}$	$(0,0,0)$	1	0	-1
$L_\mu-L_\tau$	$(0,0,0)$	0	1	-1
$\mathbf{B_1-3L_e}$	$(1,0,0)$	-3	0	0
$\mathbf{B_2-3L_e}$	$(0,1,0)$	-3	0	0
$\mathbf{B_3-3L_e}$	$(0,1,0)$	-3	0	0
B_1-3L_μ	$(1,0,0)$	0	-3	0
B_2-3L_μ	$(0,1,0)$	0	-3	0
B_3-3L_μ	$(0,1,0)$	0	-3	0
B_1-3L_τ	$(1,0,0)$	0	0	-3
B_2-3L_τ	$(0,1,0)$	0	0	-3
B_3-3L_τ	$(0,1,0)$	0	0	-3

Imprints of popular $U(1)_X$ models

Models	$\mathbb{X}_{Q_i}(\mathbb{X}_{u_i} = \mathbb{X}_{d_i})$	$\mathbb{X}_{L_1}$	$\mathbb{X}_{L_2}$	$\mathbb{X}_{L_3}$
$\mathbf{B-L}$	$(1/3,\ 1/3,\ 1/3)$	-1	-1	-1
$\mathbf{B-3L_e}$	$(1/3,\ 1/3,\ 1/3)$	-3	0	0
$B-3L_\mu$	$(1/3,\ 1/3,\ 1/3)$	0	-3	0
$B-3L_\tau$	$(1/3,\ 1/3,\ 1/3)$	0	0	-3
$\mathbf{L_e-L_\mu}$	$(0,0,0)$	1	-1	0
$\mathbf{L_e-L_\tau}$	$(0,0,0)$	1	0	-1
$L_\mu-L_\tau$	$(0,0,0)$	0	1	-1
$\mathbf{B_1-3L_e}$	$(1,0,0)$	-3	0	0
$\mathbf{B_2-3L_e}$	$(0,1,0)$	-3	0	0
$\mathbf{B_3-3L_e}$	$(0,1,0)$	-3	0	0
B_1-3L_μ	$(1,0,0)$	0	-3	0
B_2-3L_μ	$(0,1,0)$	0	-3	0
B_3-3L_μ	$(0,1,0)$	0	-3	0
B_1-3L_τ	$(1,0,0)$	0	0	-3
B_2-3L_τ	$(0,1,0)$	0	0	-3
B_3-3L_τ	$(0,1,0)$	0	0	-3



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$\mathbf{B-3L_e}$	$(1/3,\ 1/3,\ 1/3)$	-3	0	0
$B-3L_\mu$	$(1/3,\ 1/3,\ 1/3)$	0	-3	0
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B_3-3L_μ	$(0,1,0)$	0	-3	0
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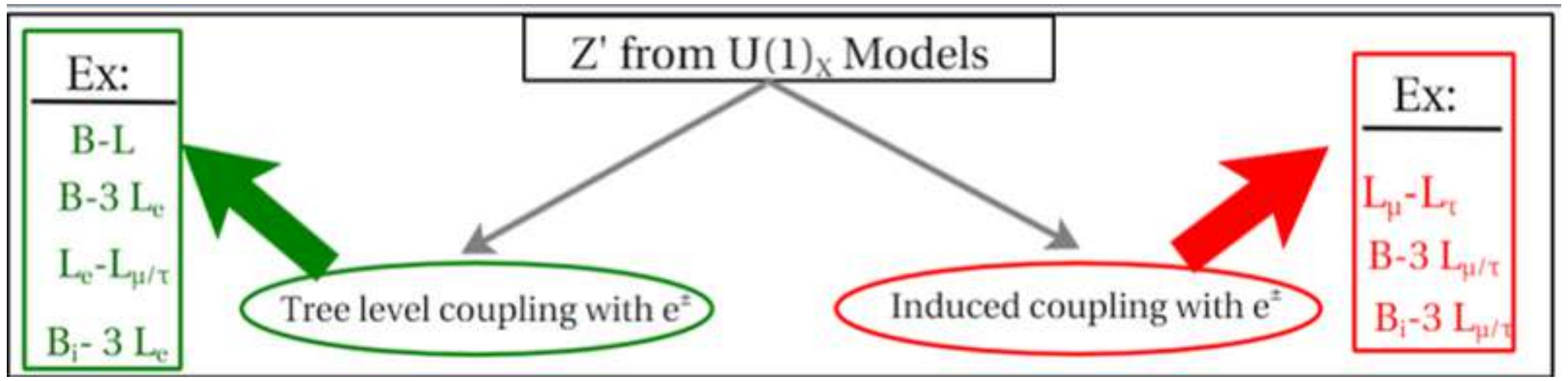


- With Tree level $Z'e^+e^-$ vertex

$$1. B-L, L_e-L_\mu, L_e-L_\tau \Longrightarrow |X_1|=1$$

$$2. B-3L_e, B_i-3L_e \Longrightarrow |X_1|=3$$

- Without Tree level $Z'e^+e^-$ vertex

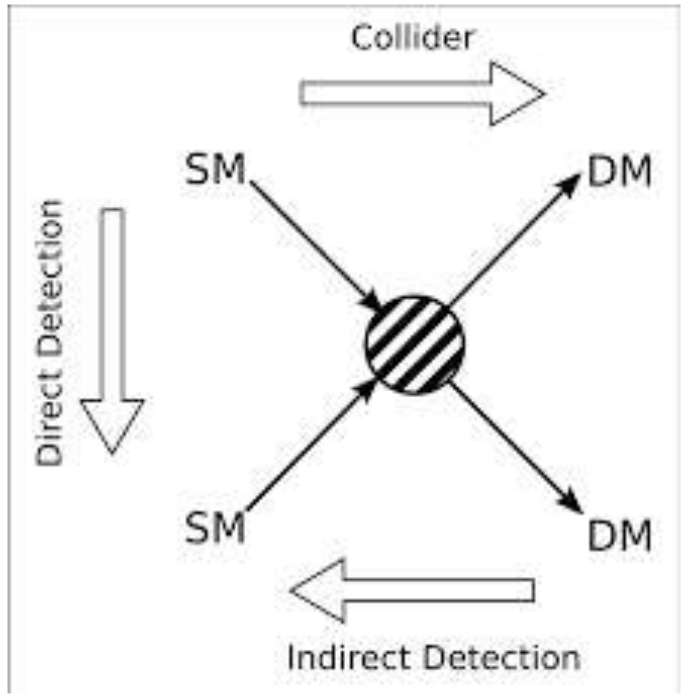
$$1. B-3L_\mu, B-3L_\tau, L_\mu-L_\tau, B_i-3L_\mu, B_i-3L_\tau$$

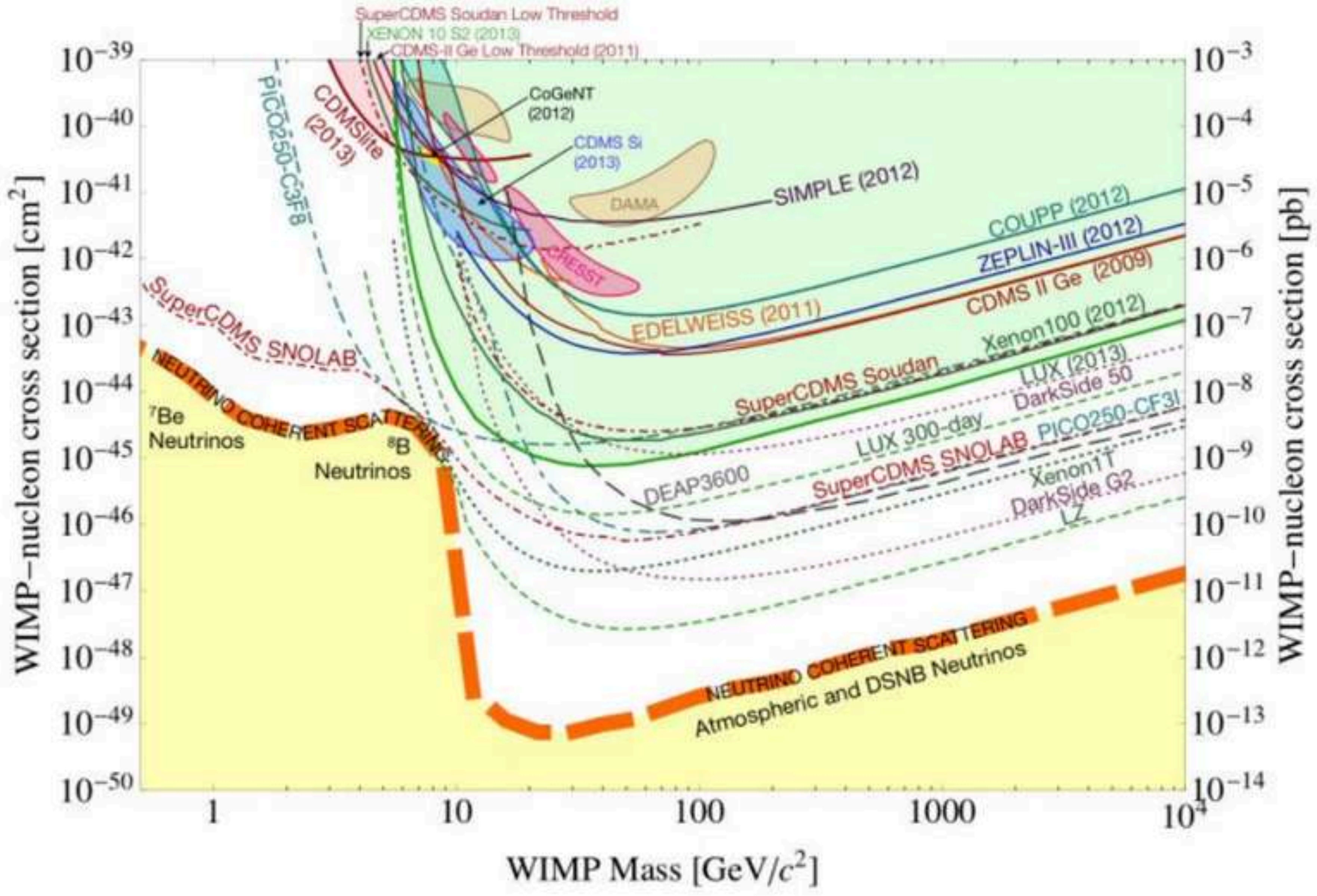
D.k.Ghosh, P.Ghosh, SJ, R.Srivastava, 2404.1007 (accepted in PRD.....)

Summary

- CMB bound can probe significant parameter space of nonthermal DM if its production contains extra radiation
- The effect can get enhanced in presence of a nonstandard epoch in the pre-BBN era
- CMB bound on $N_{\rm eff}$ can place stringent bounds on $U(1)_X$ in low mass region of Z'
- It can be used to constrain BSM models complementary to the bounds obtained from ground based experiments

Directly detecting Dark matter





Pushing towards neutrino floor
at GeV scale

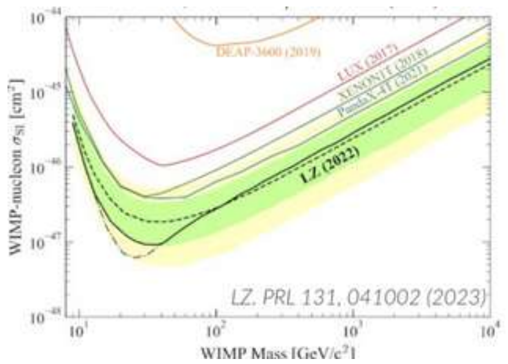
Hunting Dark matter from direct search

Cross section (cm^2)

10^{-20}

10^{-30}

10^{-40}

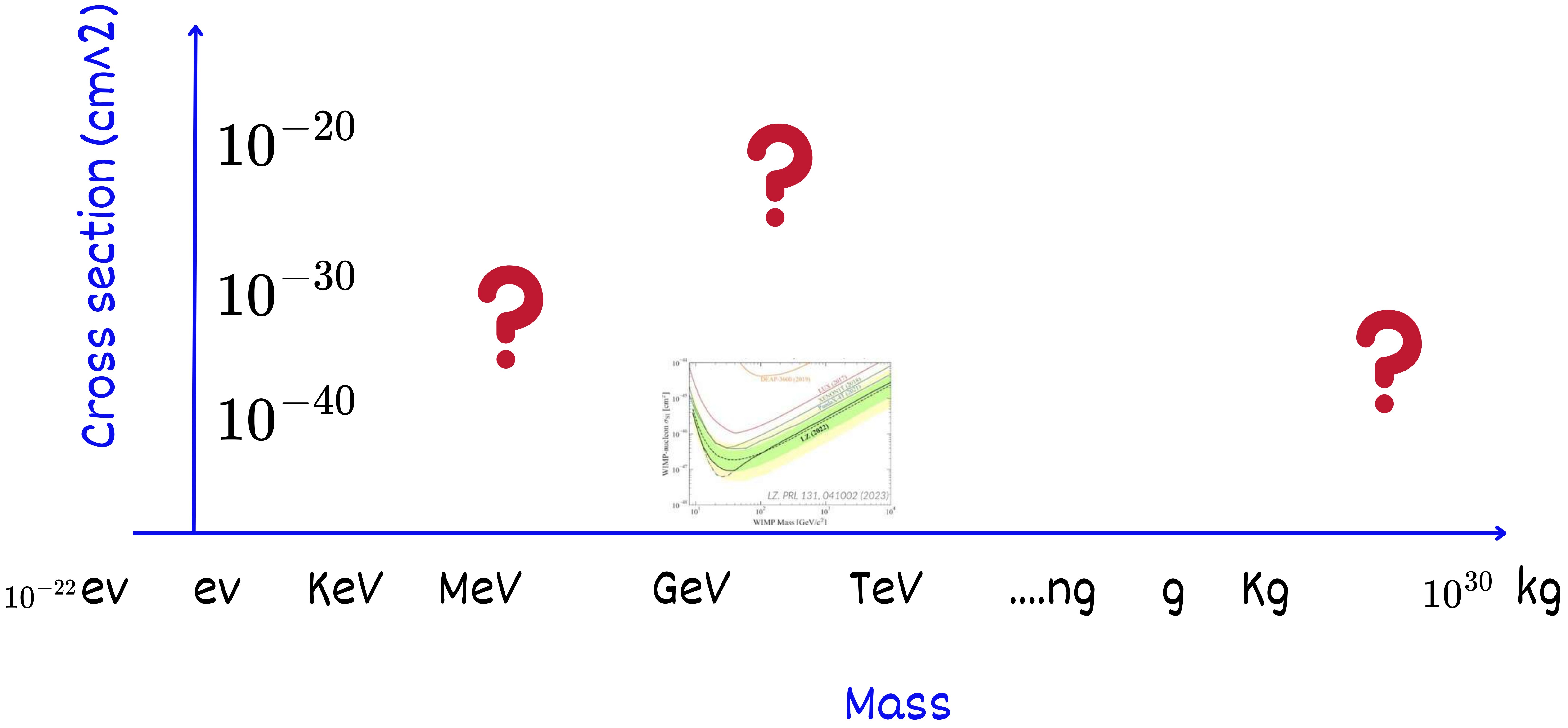


10^{-22} ev   ev   KeV   MeV   GeV   TeV   ....ng   g   Kg 10^{30} kg

Mass

Inspired from N. Raj , WDMAP, 2024

Hunting Dark matter



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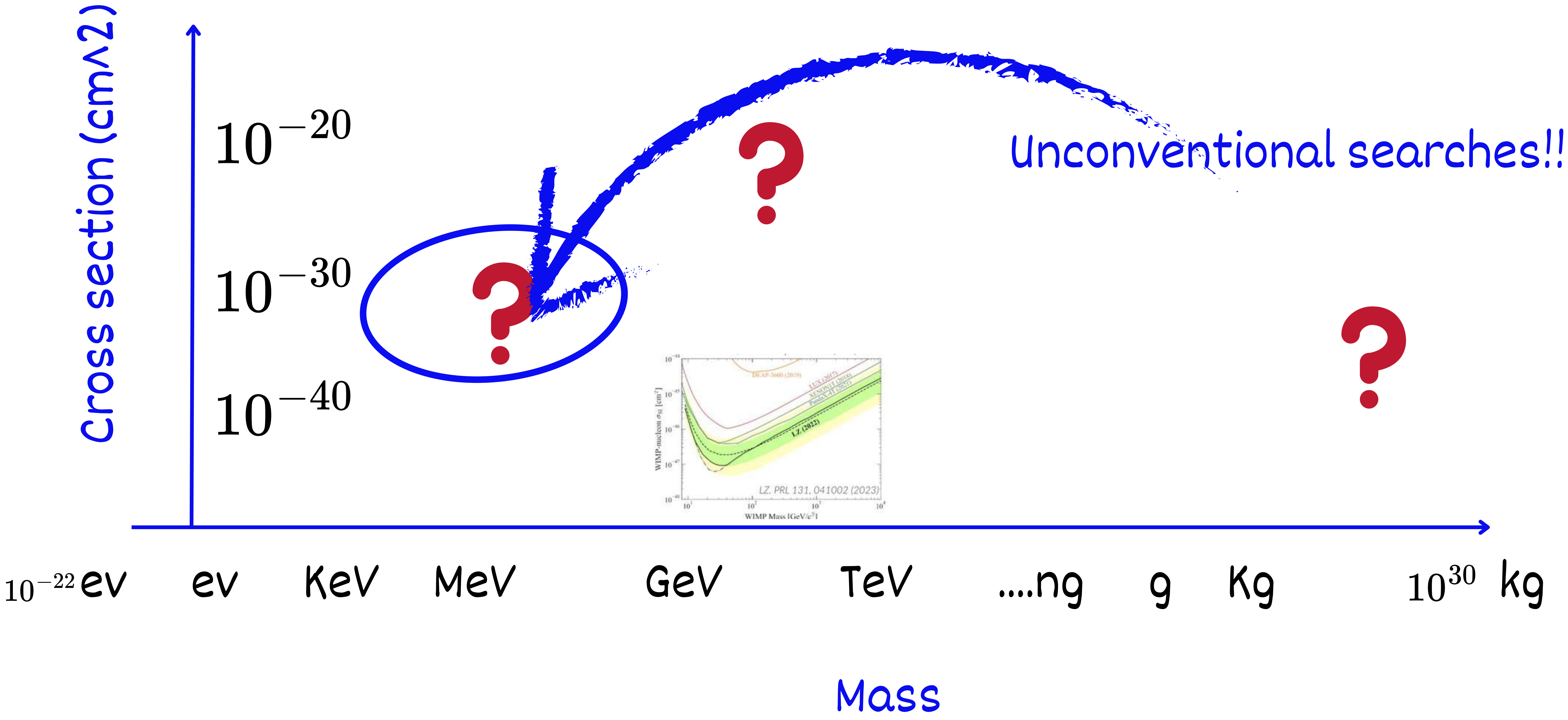
Hunting Dark matter



Inspired from N. Raj, WDMAP, 2024

Hunting Sub-GeV Dark matter

- Event rate $\chi + N \to \chi + N$

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{M_\chi} \int_{v_{min}}^{\infty} d^3v \, \frac{d\sigma_{\chi N}}{dE_R} v f(\vec{v})$$

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$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

$$M_\chi \sim 100 \text{ MeV}, \ E_R = 1 \text{ keV},$$

$$v_{min} = 10^{-2} c$$

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$$f(v) = \frac{1}{N_0} \exp\left(-\frac{v^2}{v_0^2}\right) \Theta(v_{esc} - |v|)$$

$$v_0 \approx 230km/s(10^{-3}c), \; v_{esc} \approx 600km/s$$

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- Low momentum/kinetic energy ---> main challenge to detect light DM

Hunting Sub-GeV DM

Hunting Sub-GeV DM

- Lighter Target

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Electron recoil experiments in Xenon, LZ, Sensei etc.

Hunting Sub-GeV DM

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- Accelarating DM to higher velocities

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Boosted DM:

1. Cosmic p, e scattering
2. Solar reflected
3. Multicomponent
4. DSNB etc.

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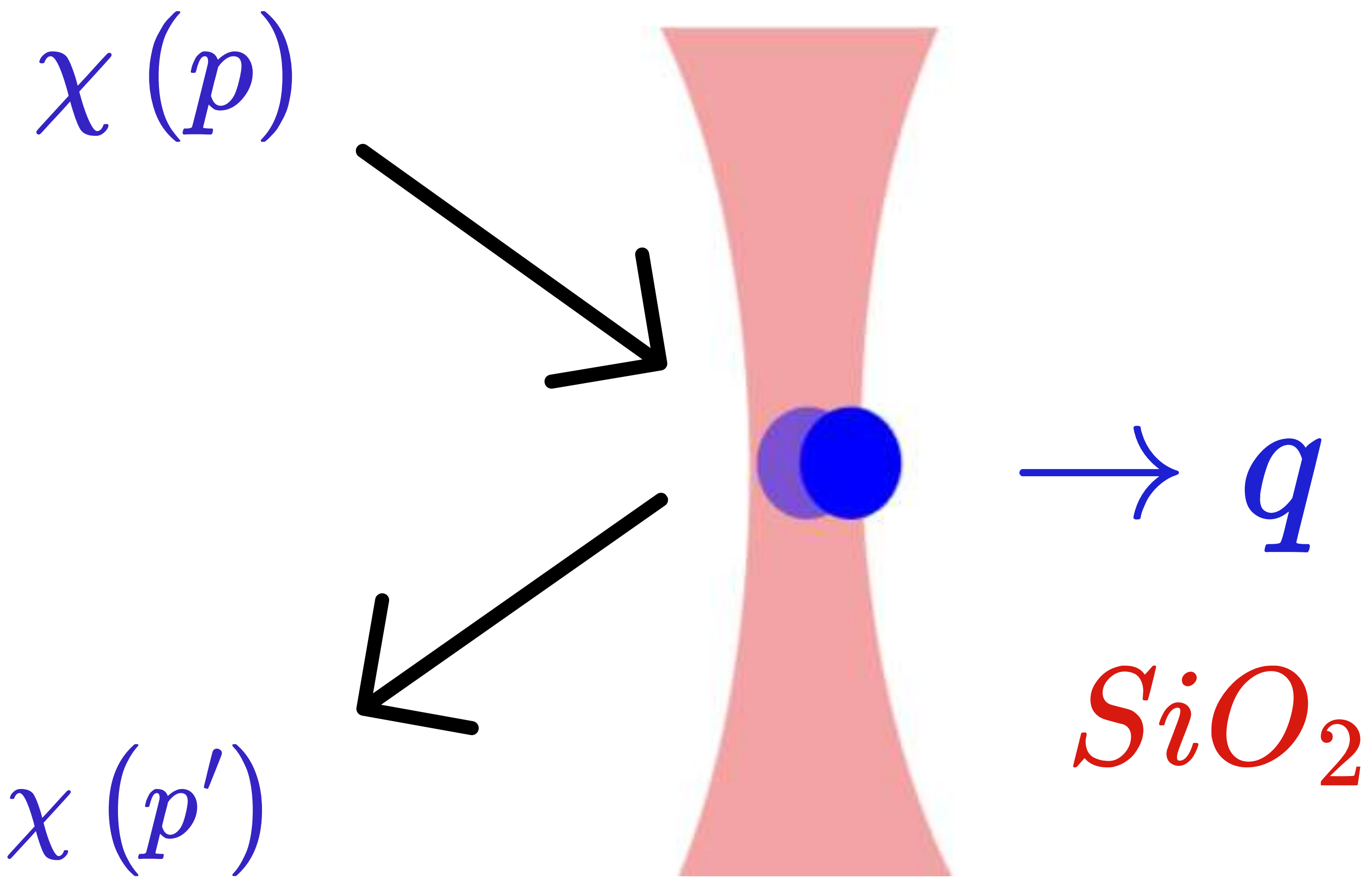
DM in optically levitated nanosphere



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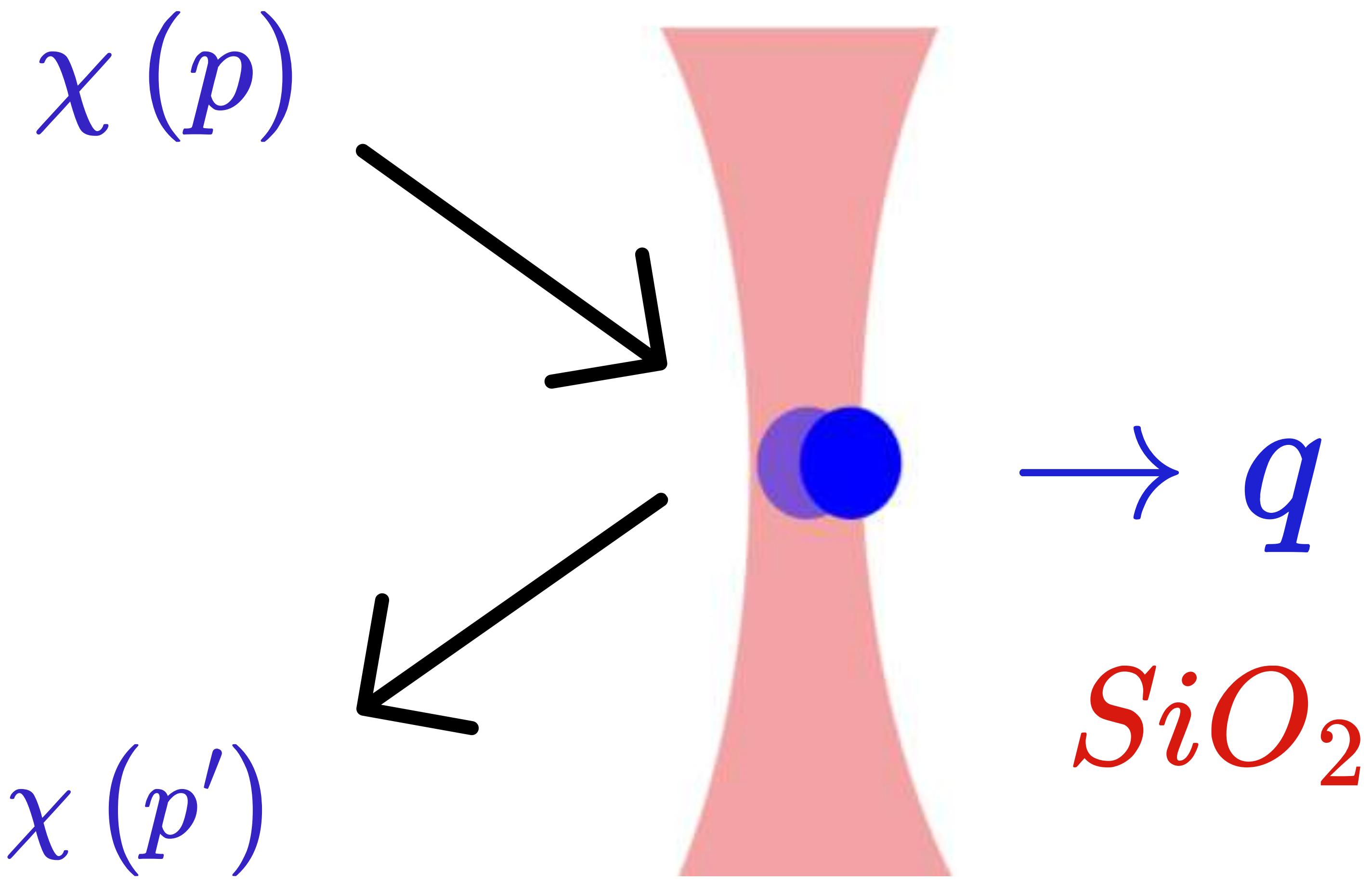
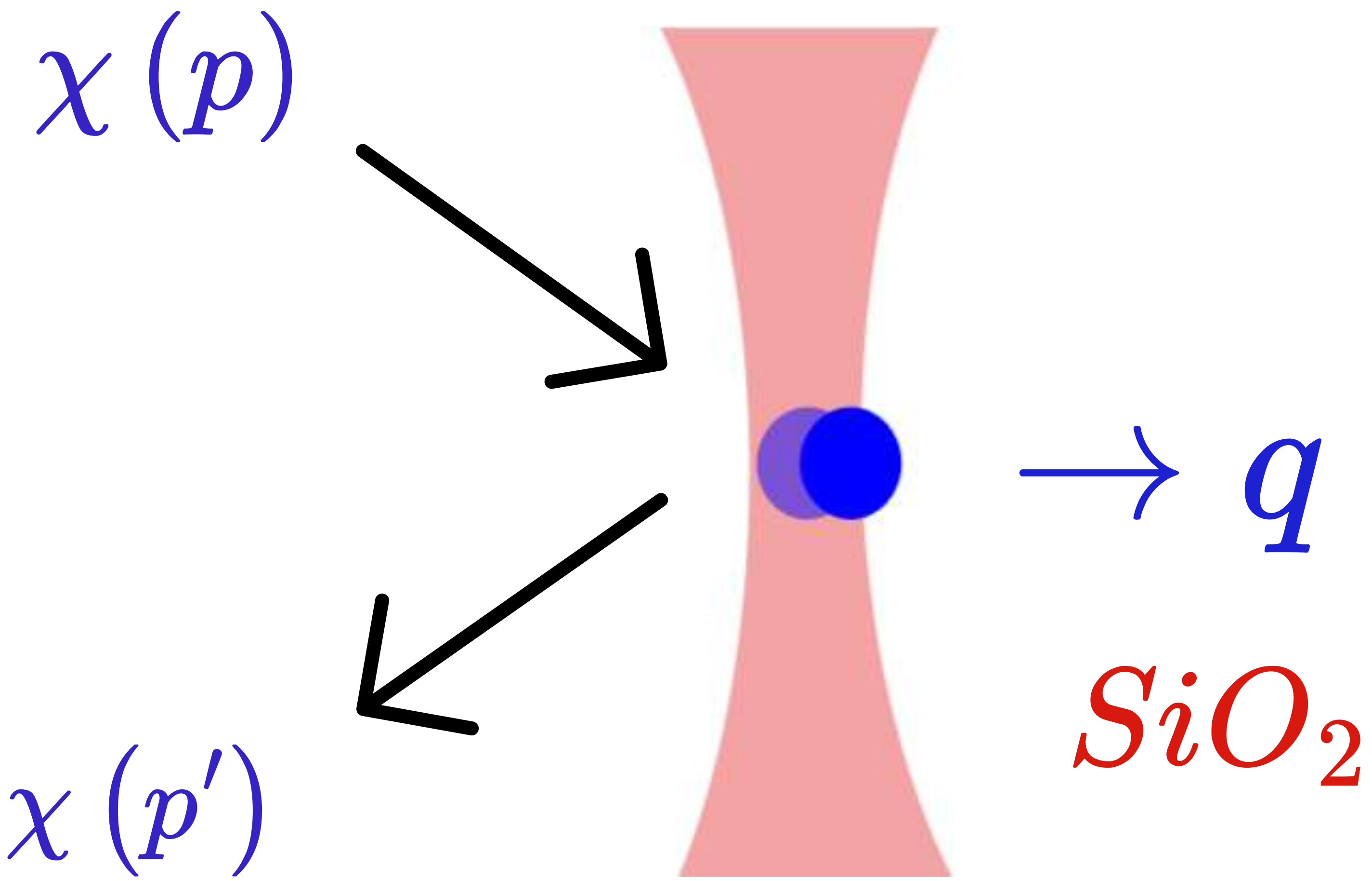


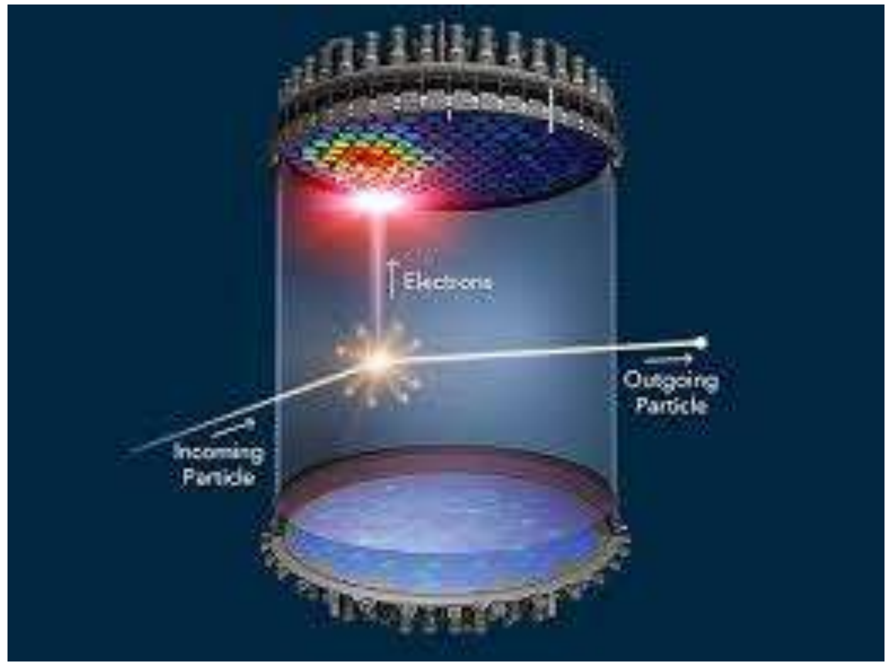
$$m \sim 10^{-15} gm$$

$$N_T \sim 10^9$$

$$r_s \sim 100nm$$

DM in optically levitated nanosphere





Xe

$$m \sim 10^{-15} gm$$

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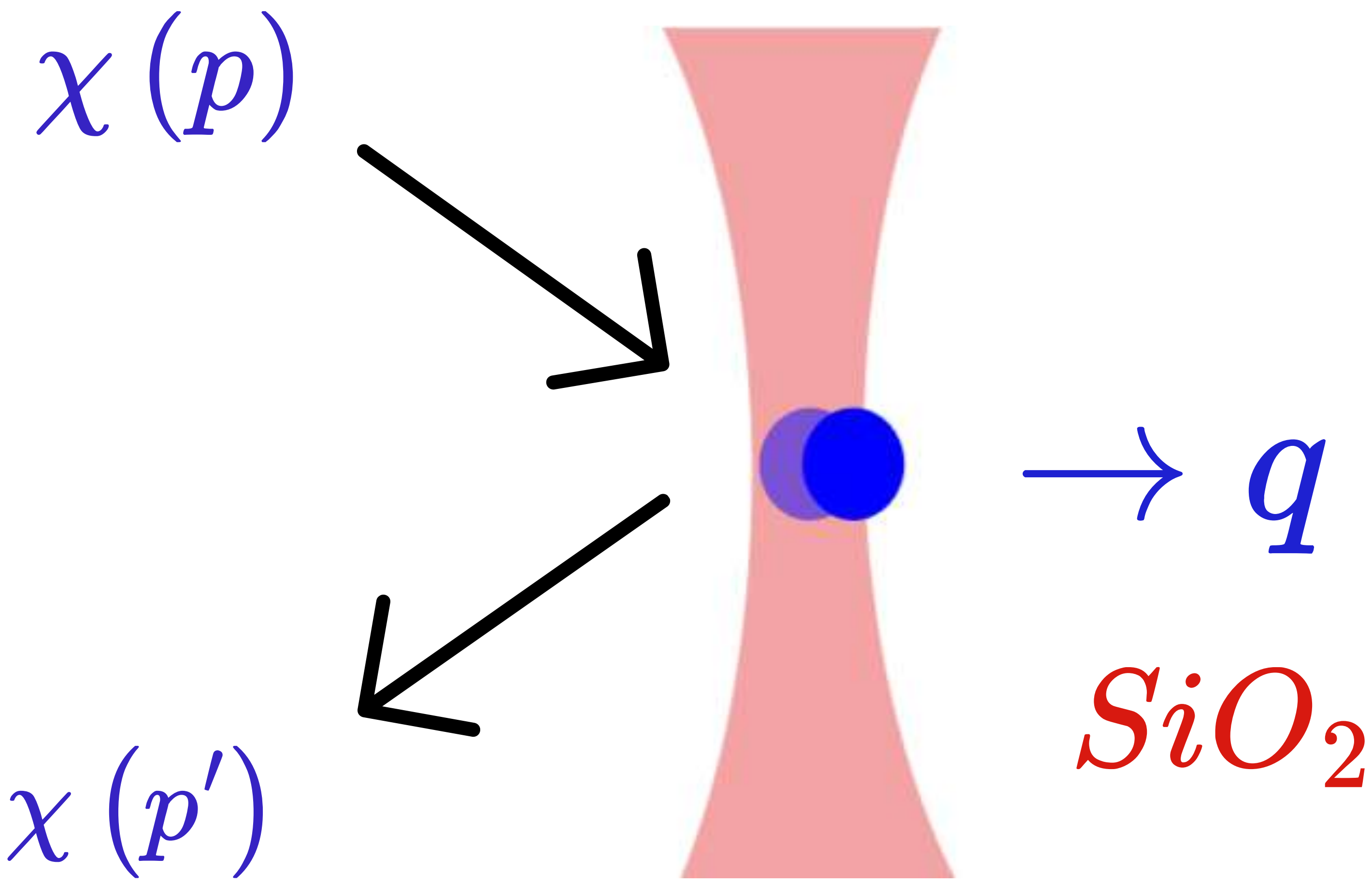
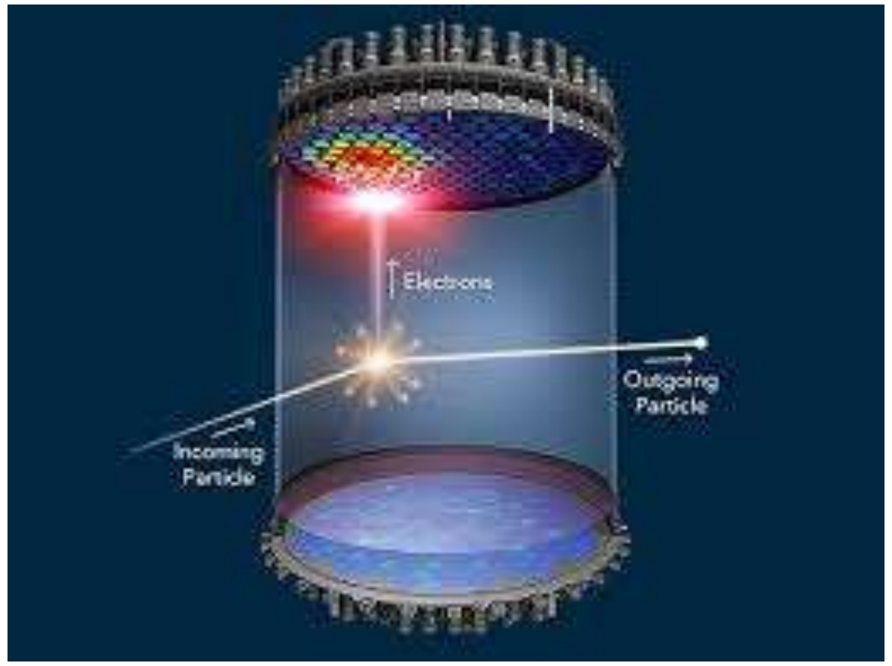
$$m \sim 10^{6} gm$$

$$N_T \sim 10^{27}$$

DM in optically levitated nanosphere



SiO_2



Xe

- Target size small

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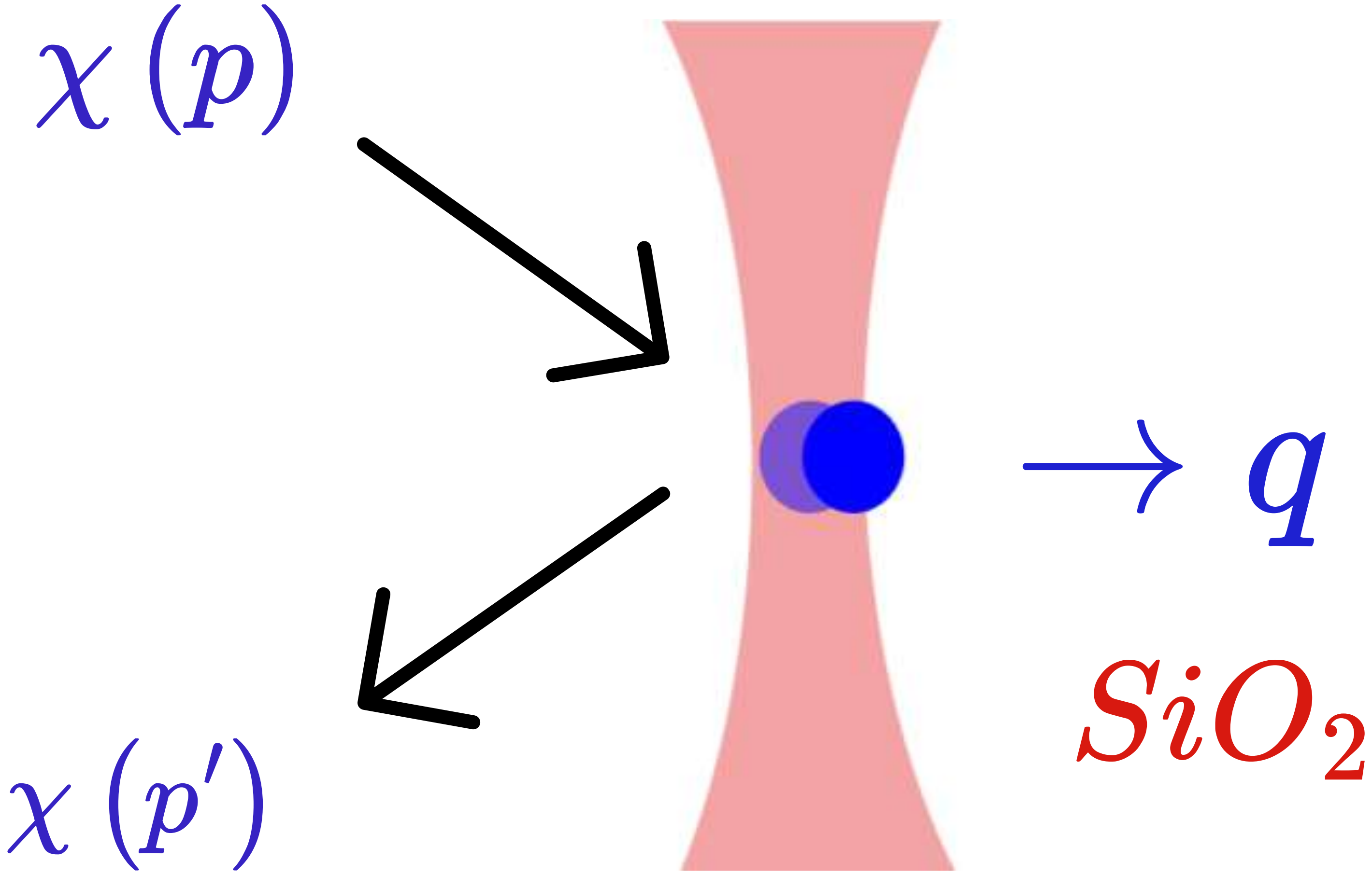

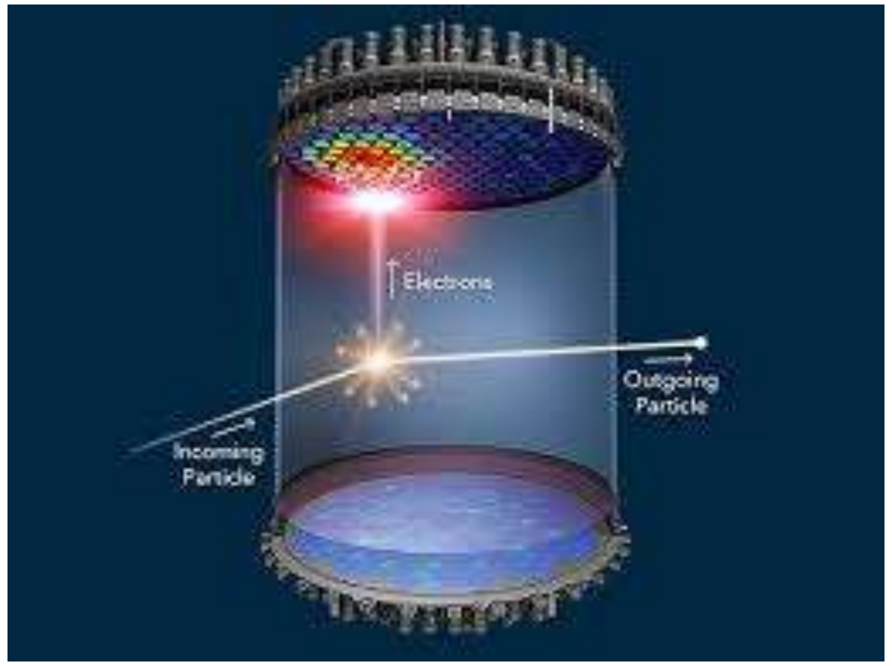

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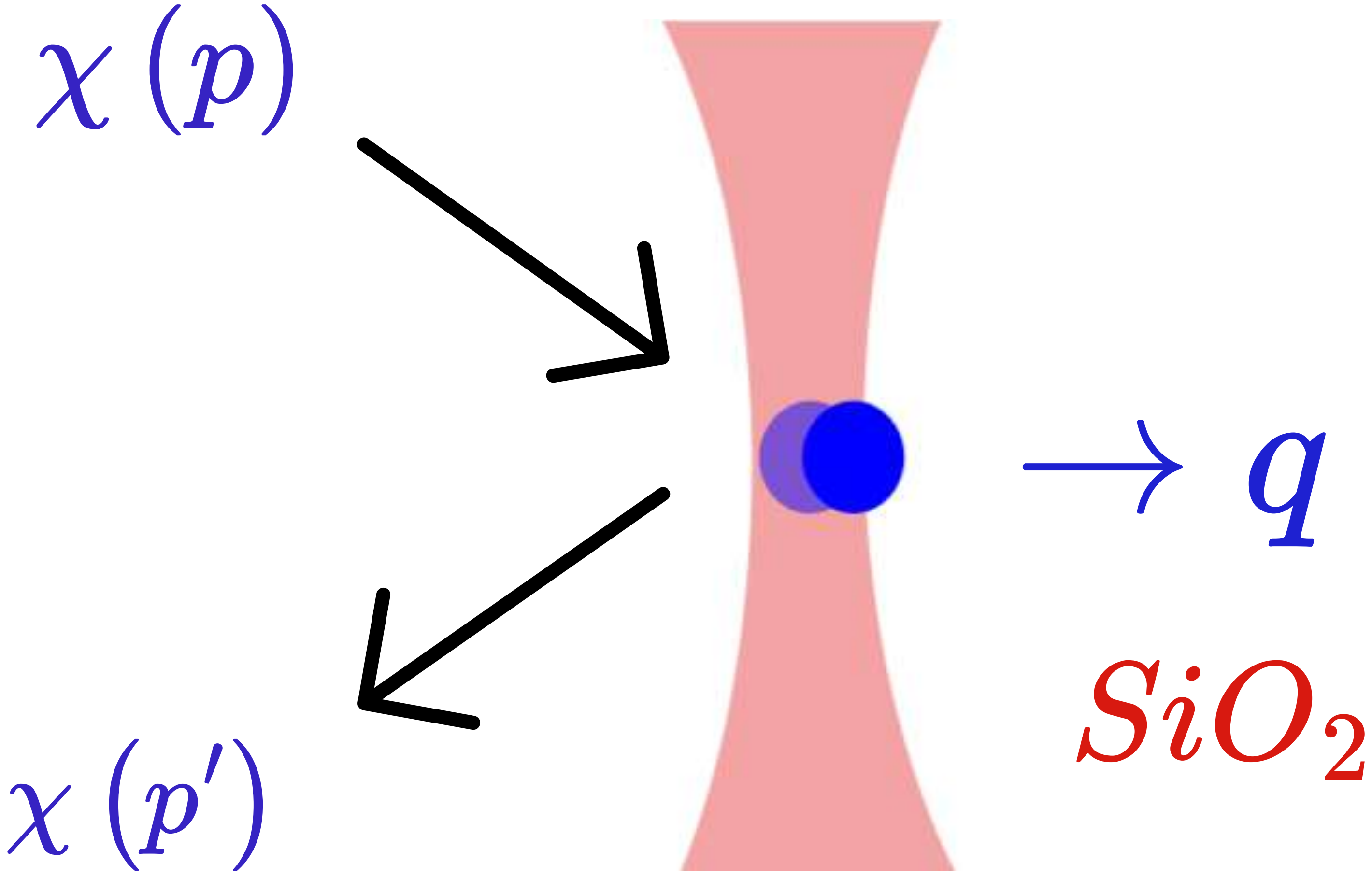
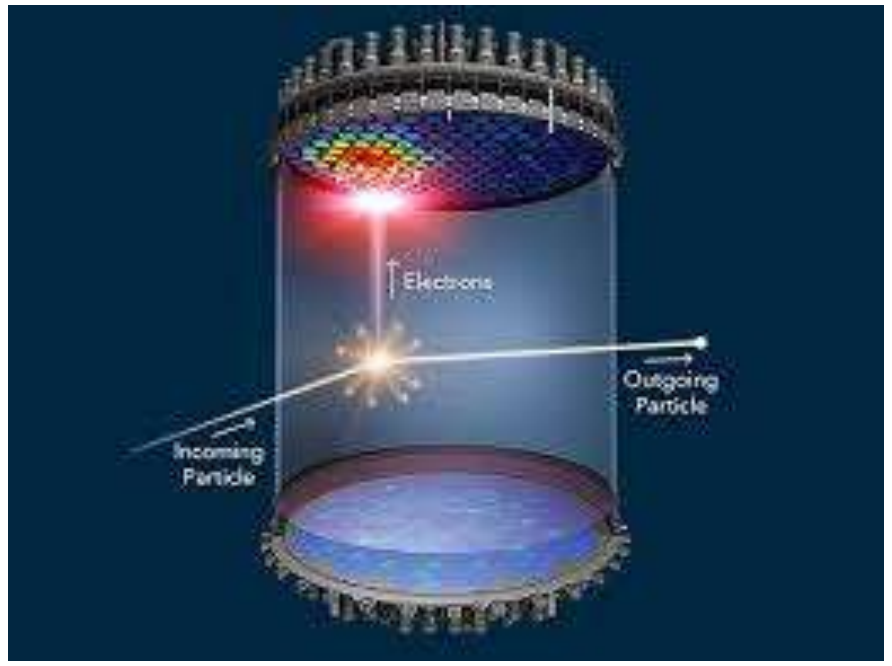
Measure → recoil energy

DM in optically levitated nanosphere





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recoil momentum ⟵ Measure ⟶ recoil energy

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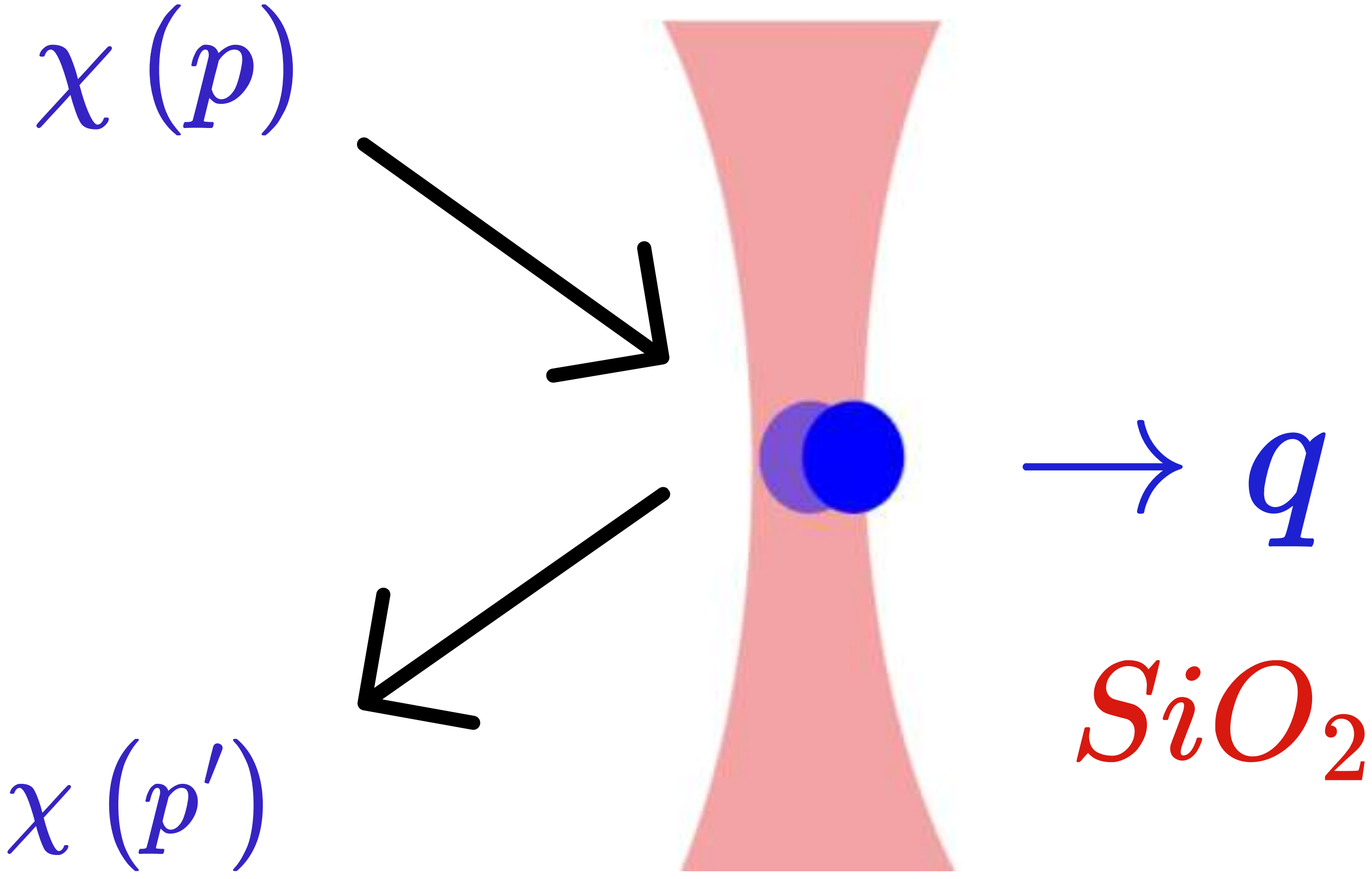

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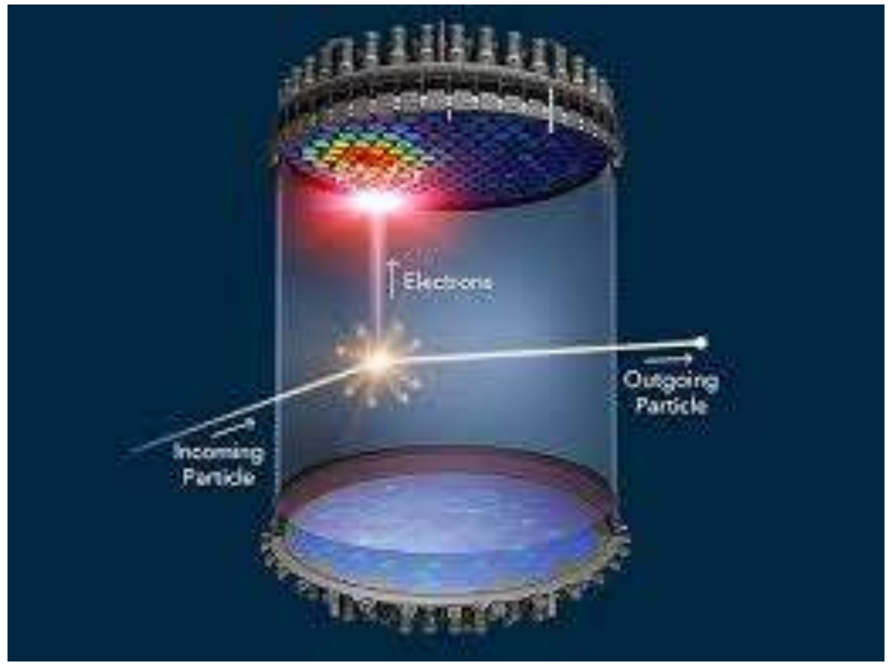

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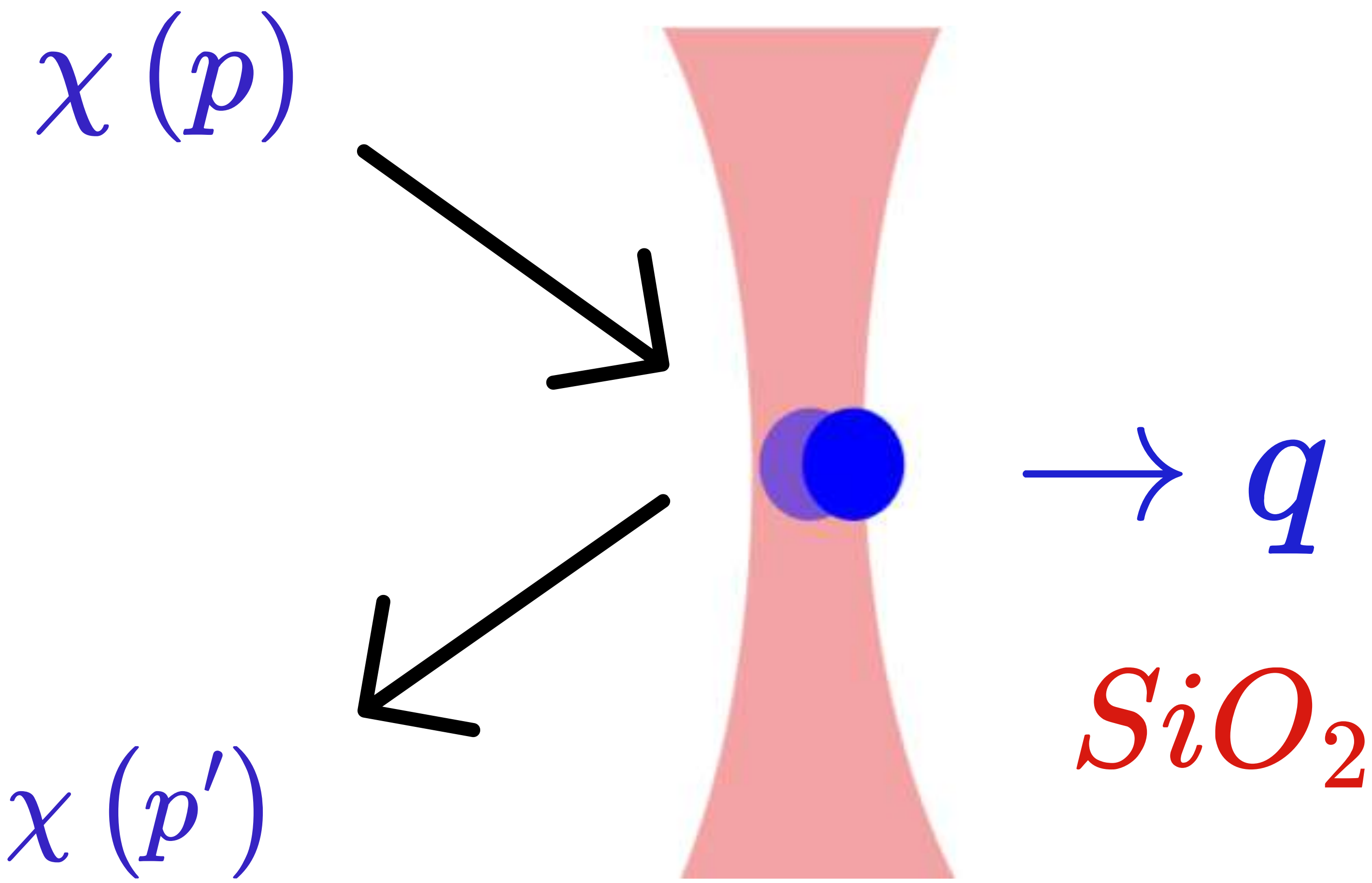

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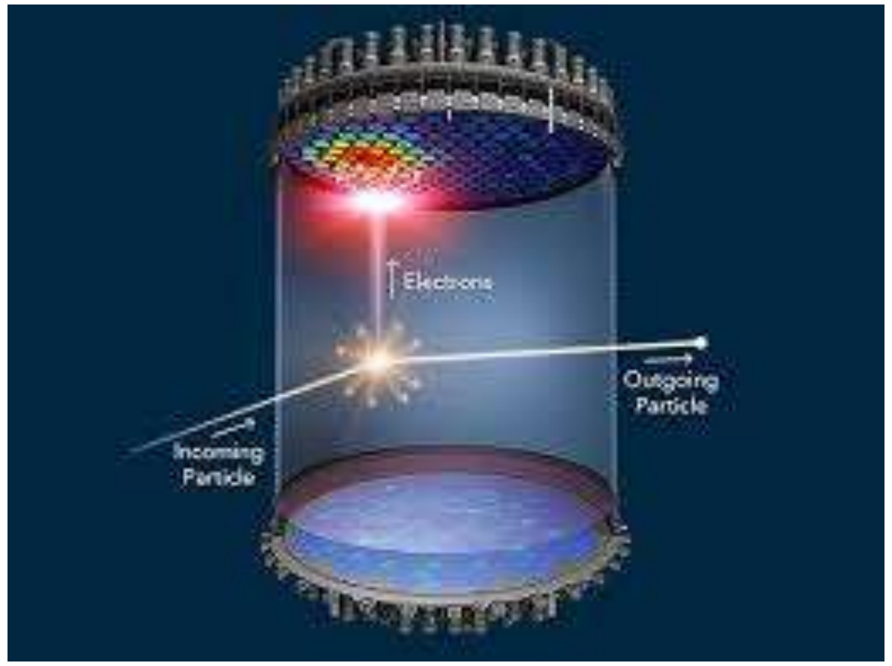

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Calculation of event rate

$$\frac{dR}{dq} = \frac{\rho_\chi}{m_\chi}\frac{\sigma}{2\mu^2} q\,\eta(v) S(q)$$

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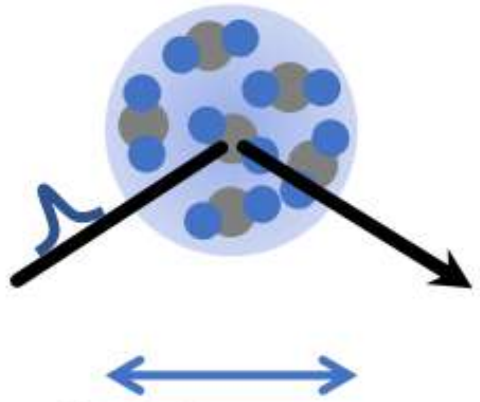
$2\pi/q \sim r_{\mathrm{nuc}}$



200 nm

$m_T \sim 10^{-15} gm$ $\qquad$ $N_T \sim 10^9$

G. Afek, D. Carney, D Moore, PRL 2021

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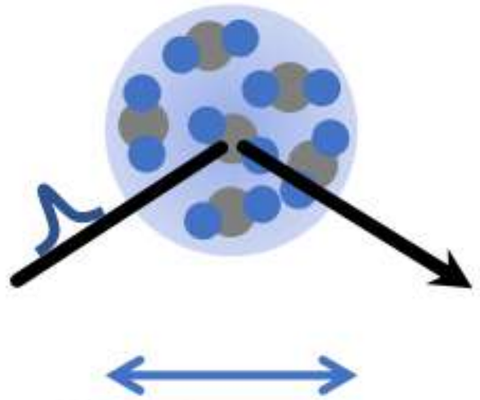

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- Scattering at nuclear scale q~10 kev

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G. Afek, D. Carney, D Moore, PRL 2021

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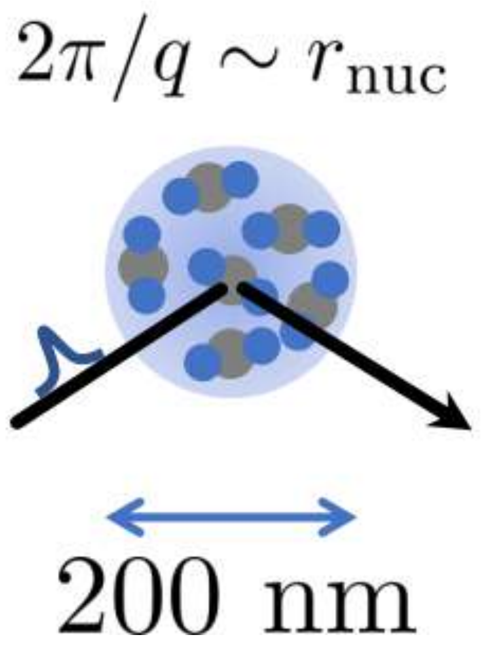

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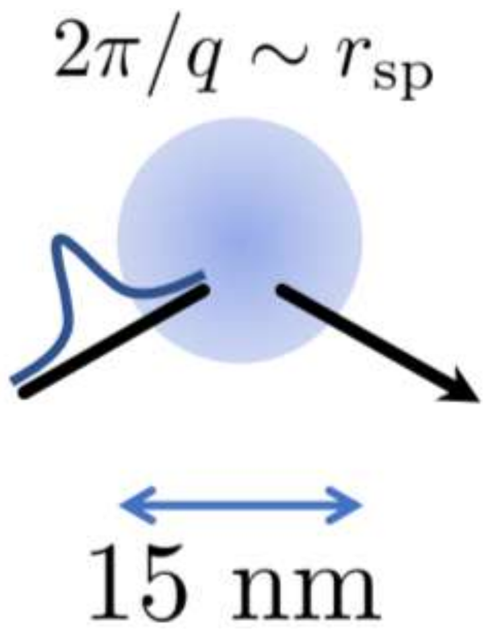

$m_T \sim 10^{-18} gm$ $\quad N_T \sim 10^6$

G. Afek, D. Carney, D Moore, PRL 2021

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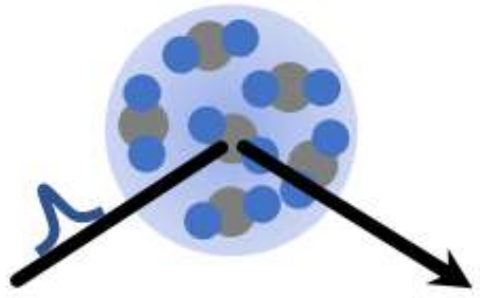


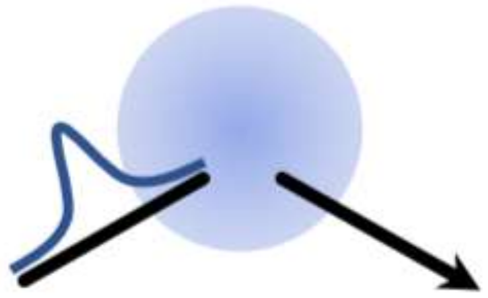
200 nm

- Scattering at nuclear scale $q \sim 10$ kev

$m_T \sim 10^{-15} gm$ $N_T \sim 10^9$

- Scattering over entire sphere $q < 0.1$ kev

$2\pi/q \sim r_{\text{sp}}$



15 nm

$m_T \sim 10^{-18} gm$ $N_T \sim 10^6$

G. Afek, D. Carney, D Moore, PRL 2021

Calculation of event rate

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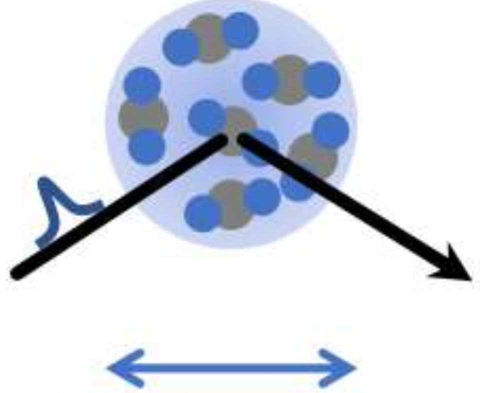
$\sim \times 10^{12}$

$2\pi/q \sim r_{\rm nuc}$



200 nm

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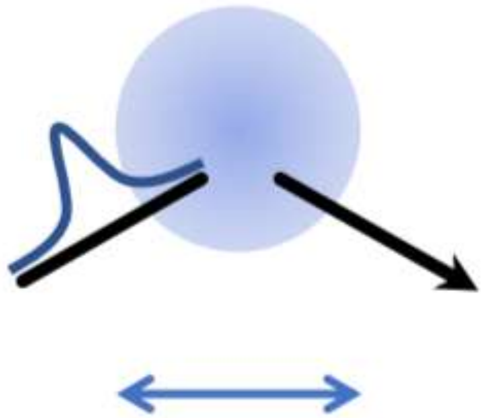
$N_T \sim 10^9$

- Scattering over entire sphere q<0.1 kev

$2\pi/q \sim r_{\rm sp}$



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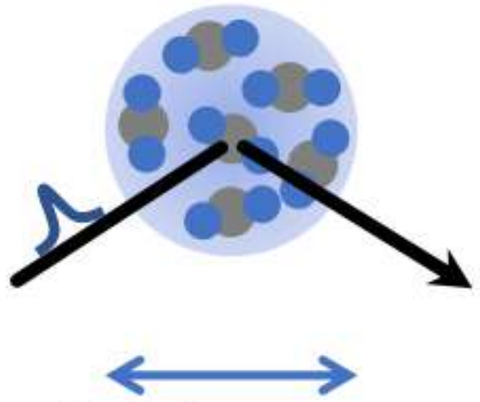
smaller sphere
lower threshold

$\sim \times 10^{12}$

$2\pi/q \sim r_{\text{nuc}}$



200 nm

$m_T \sim 10^{-15} gm$

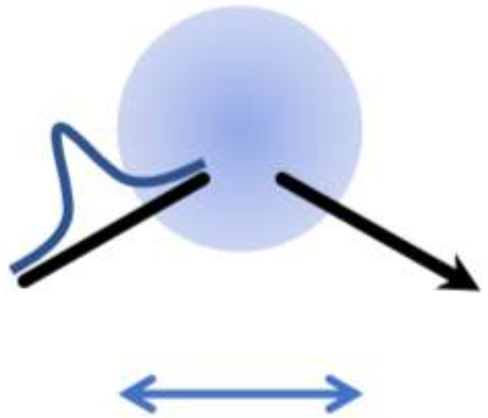
- Scattering at nuclear scale $q \sim 10$ kev

$N_T \sim 10^9$

- Scattering over entire sphere $q < 0.1$ kev

$m_T \sim 10^{-18} gm$

$2\pi/q \sim r_{\text{sp}}$



15 nm

$N_T \sim 10^6$

G. Afek, D. Carney, D Moore, PRL 2021

Calculation of event rate

- Threshold : Standard Quantum limit (SQL) $\sigma_{SQL} = \sqrt{m_{sp}\omega}$
- Large Sphere: $q_{th} = 1.8 \times 10^4 eV$

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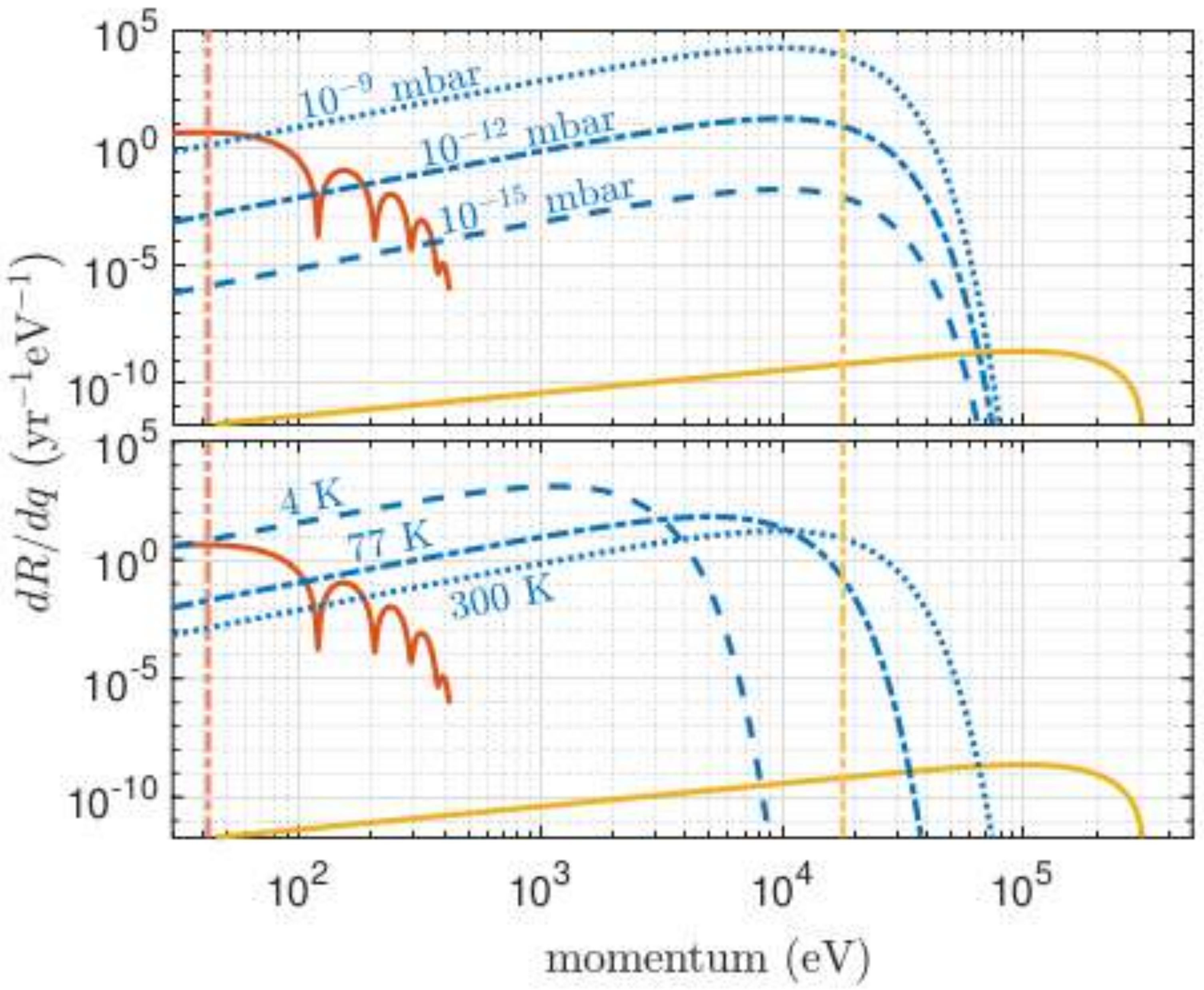

G. Afek, D. Carney, D Moore, PRL 2021

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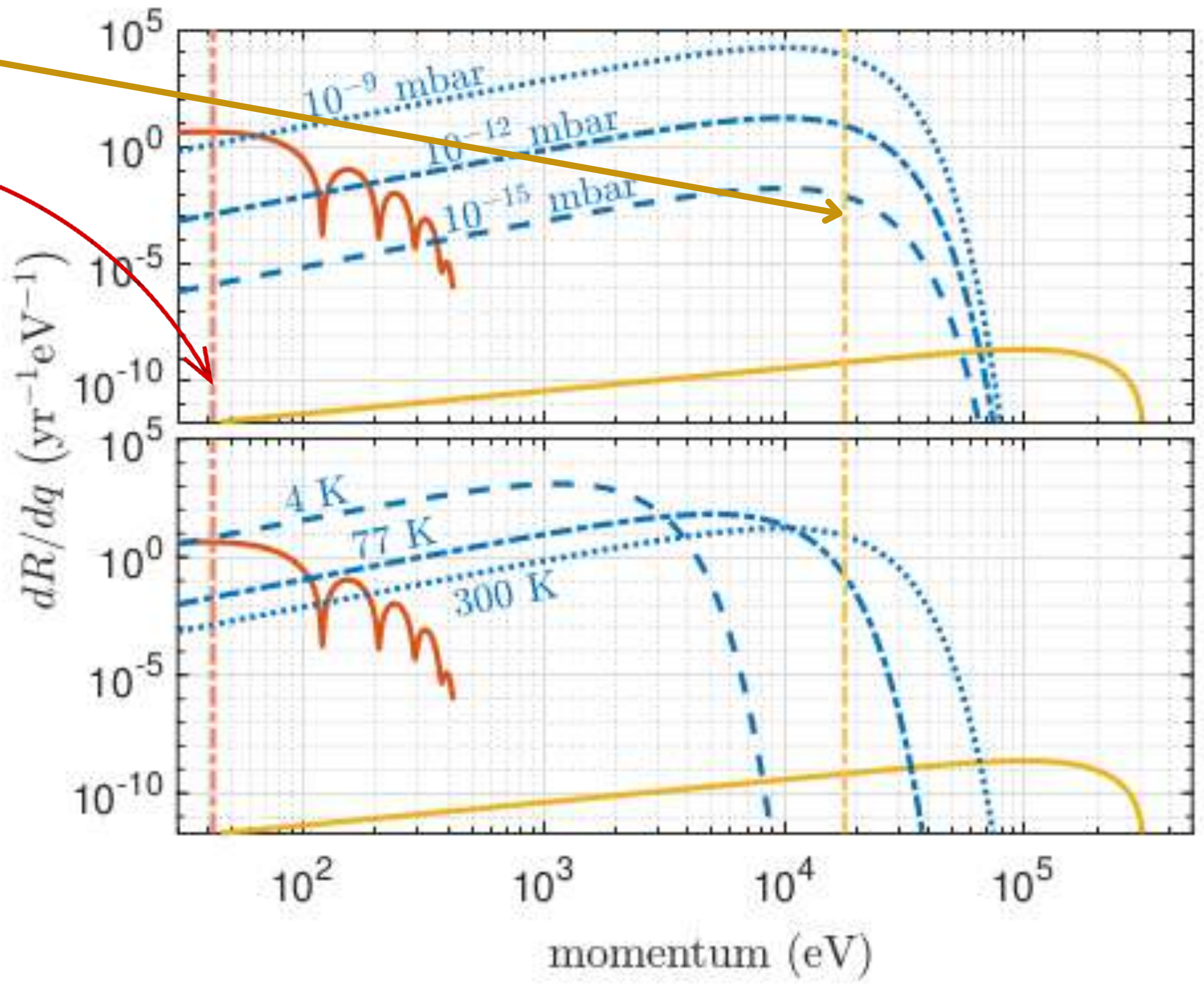
$m_\chi = 60 MeV$ $\qquad$ $m_\chi = 80 keV$

$\sigma_{\chi N} = 10^{-31} cm^2$ $\qquad$ $\sigma_{\chi N} = 10^{-28} cm^2$



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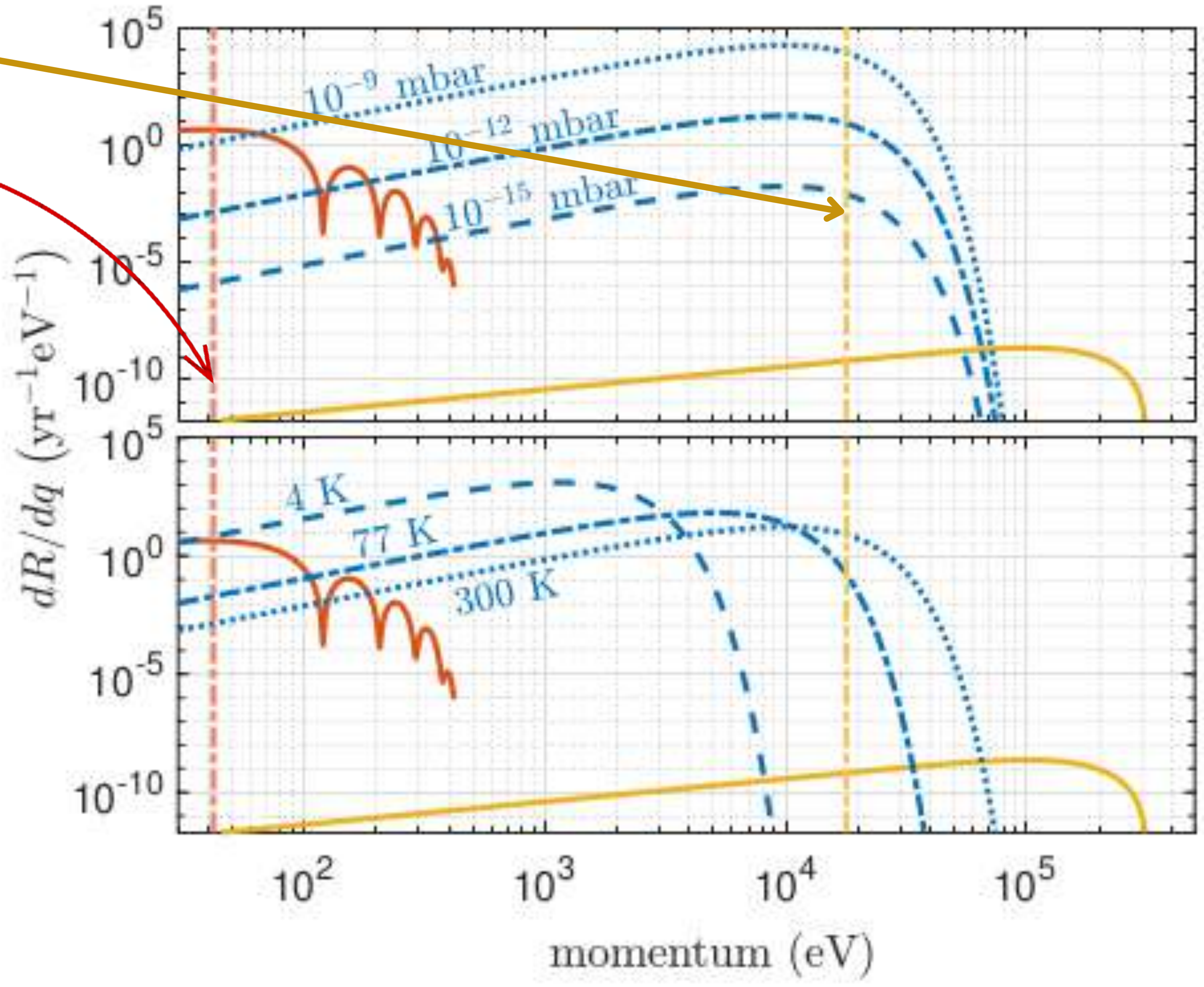
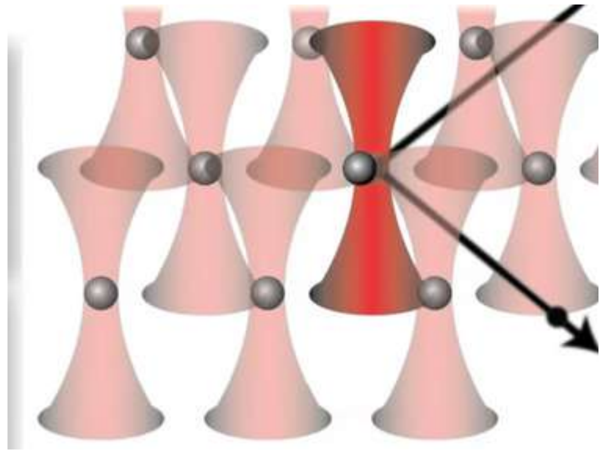
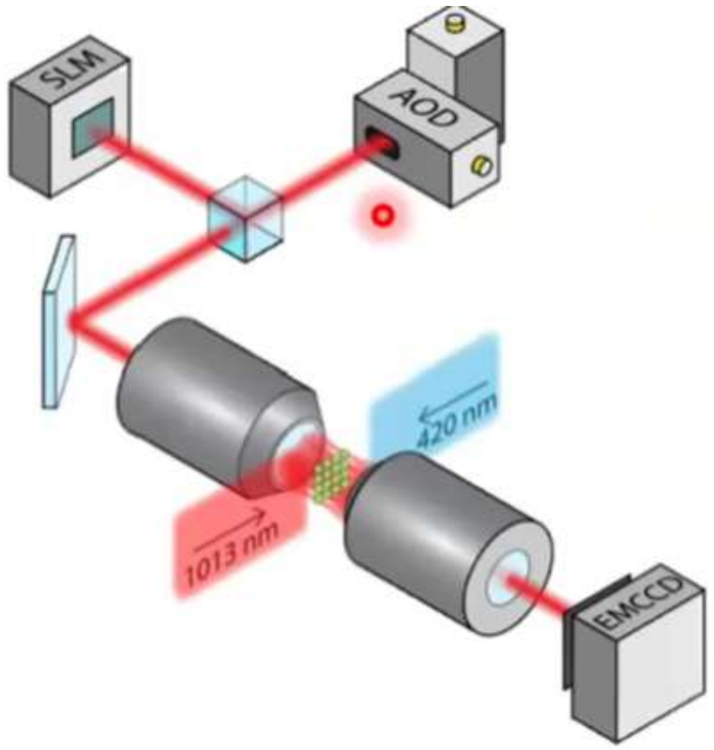


Large arrays of such sphere can enhance the rate (6400 1D array already achieved

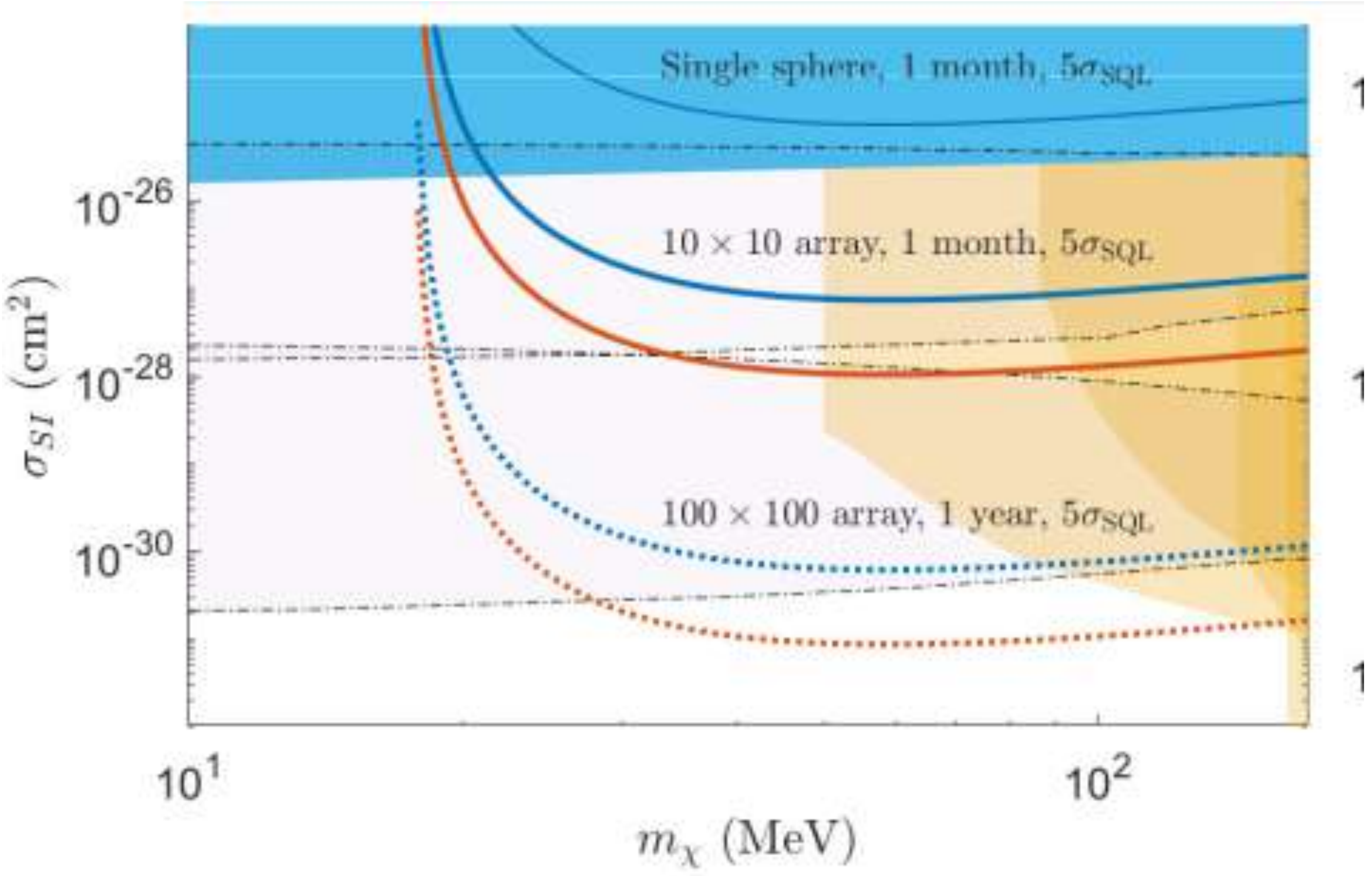




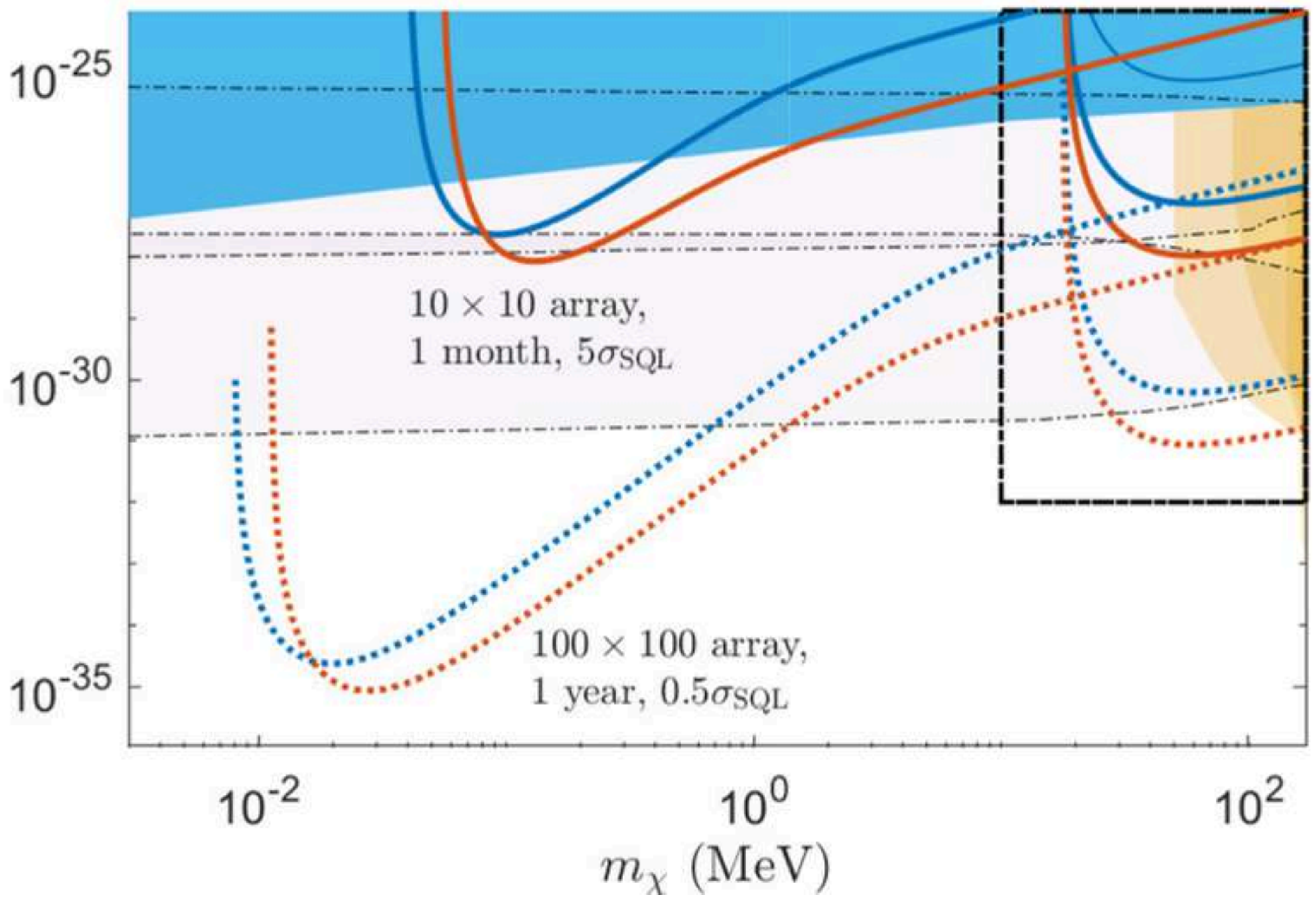
Lester et al PRL 2015

Manetsch et al 2403.12021

Fermion DM constraints



Large sphere



Small sphere

G. Afek, D. Carney, D Moore, PRL 2021

Light BSM particles:ALP

- Strong CP Problem:

$$\mathscr{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - \left(\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \mathrm{h.c.}\right) \qquad \theta_{\mathrm{QCD}} = \theta + \arg\left[\det\left[M_u M_d\right]\right]$$

Neutron EDM constrains! $\theta_{\mathrm{QCD}} \lesssim 1.3 \times 10^{-10}$

- $U(1)_{PQ}$ symmetry: The goldstone after SSB is called "Axion"

  QCD scale Chiral symmetry breaking leads to tiny mass -> pNGB

Pecci, Quinn, 1997

- Plethora of BSM model predicts such pseudoscalar not necessarily related to Strong CP=> Broadly called Axion like particles (ALP).

Probing ALPs

- In EFT approach one can have effective couplings ALP& SM

$$\mathcal{L}_{ae} \supset -ig_{ae}\bar{e}\gamma^5 ea - i\bar{N}\gamma^5(g^0_{aN}I + \sigma_3 g^3_{aN})Na - \frac{1}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$ ....+other gauge bosons

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Caputo, Raffelt 2401.13728

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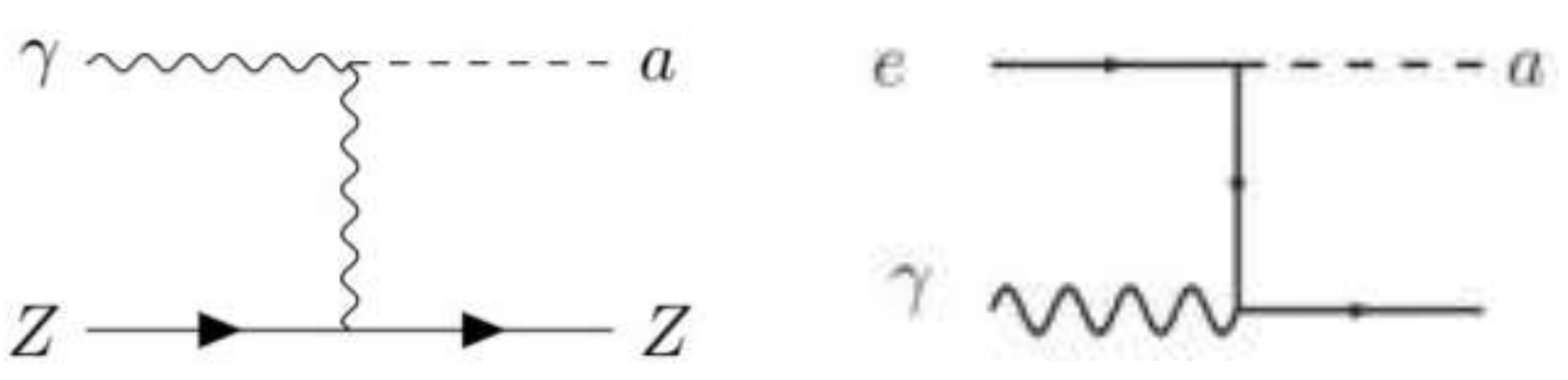

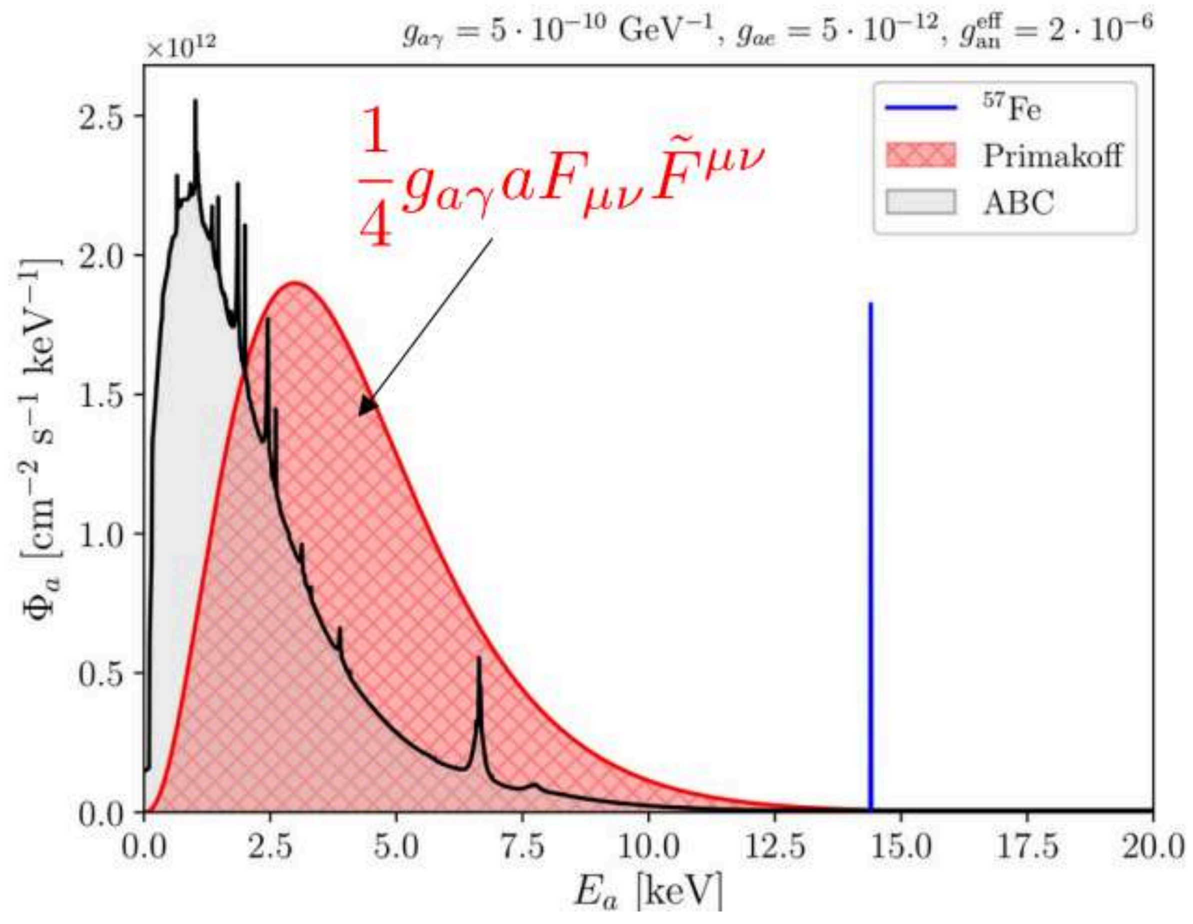

J.B. Dent B. Dutta, J.L. Newstead, A. Thompson, PRL 2020

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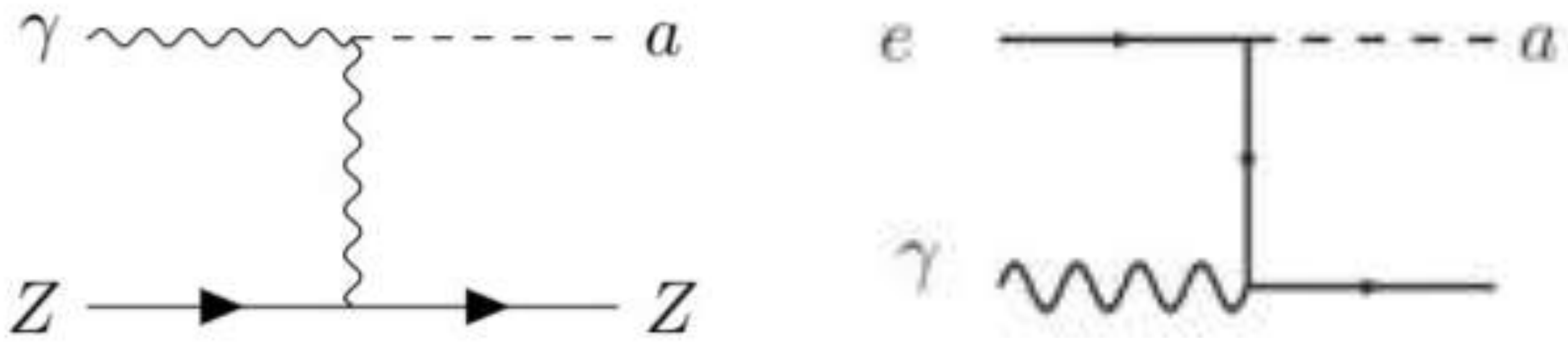

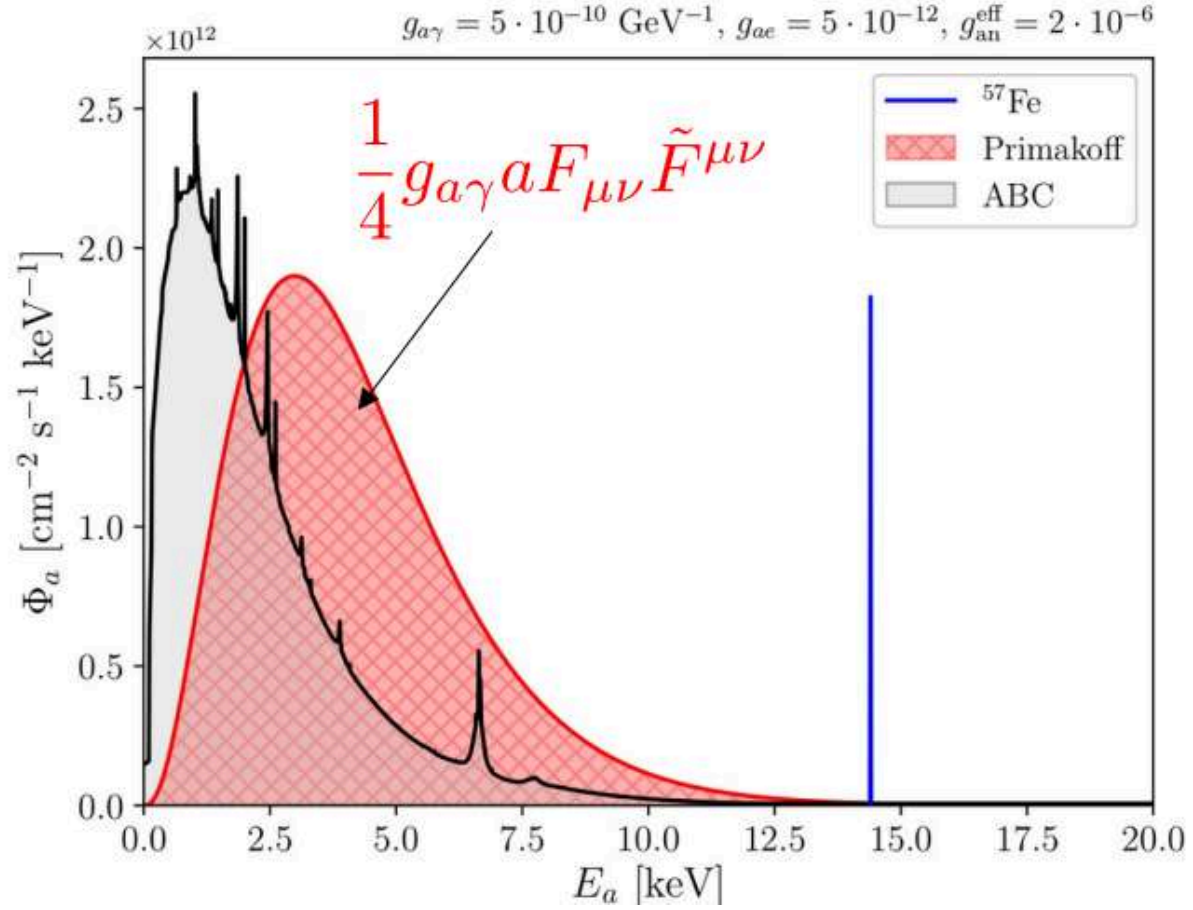

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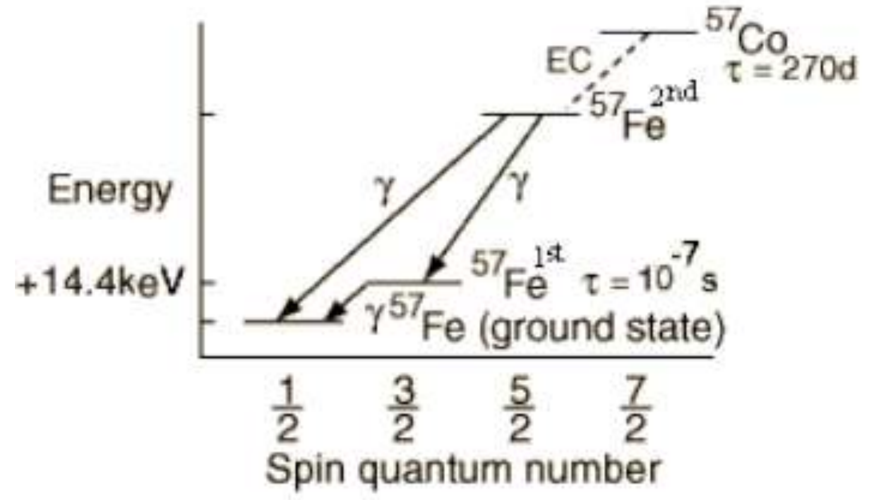
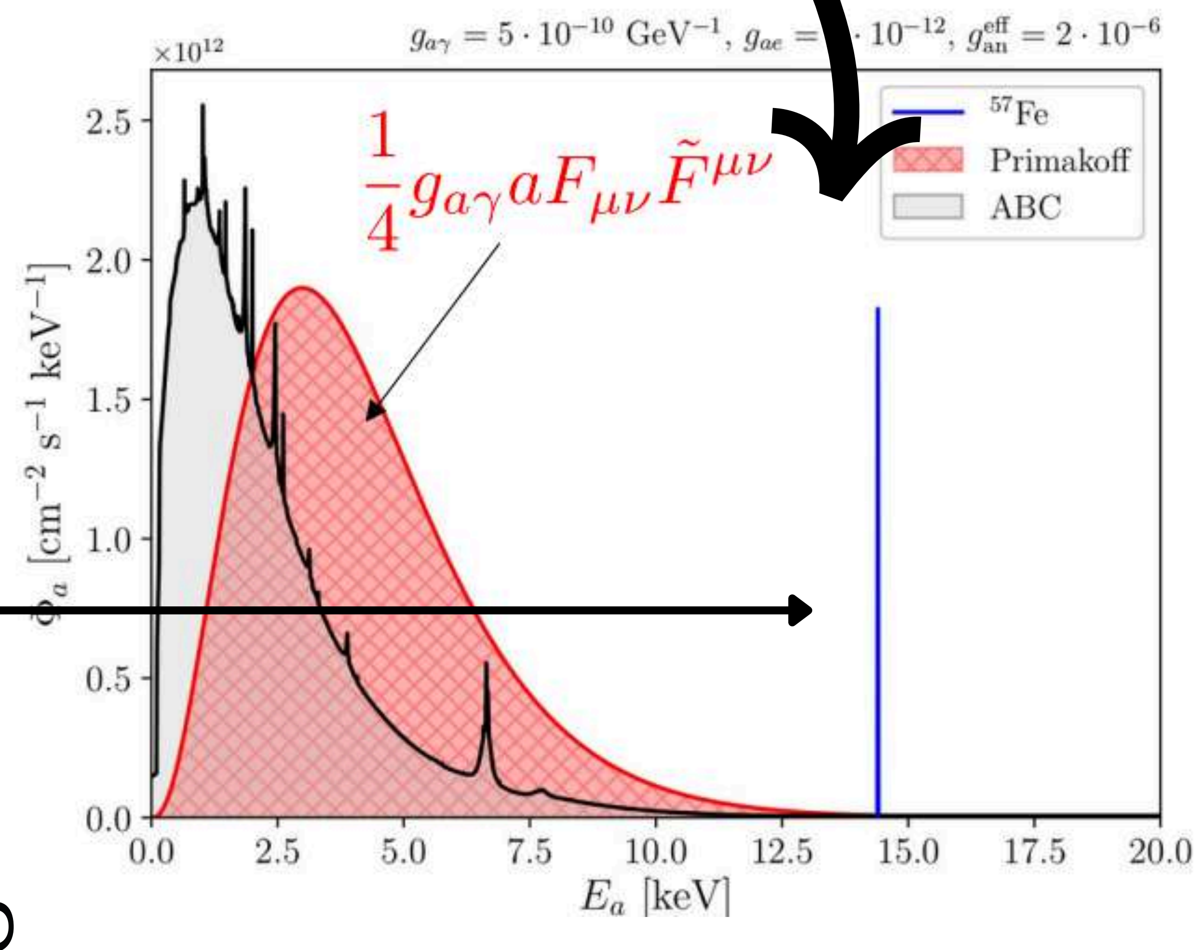
- ALP can also emit from the nuclear deexcitations: ~14.4 keV





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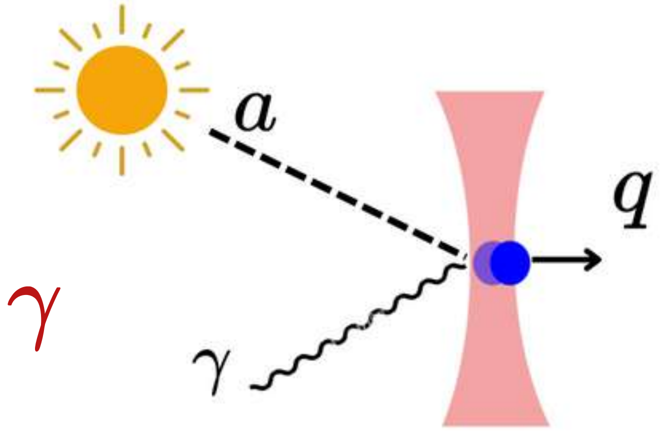

Ideal for levitated large spheres!

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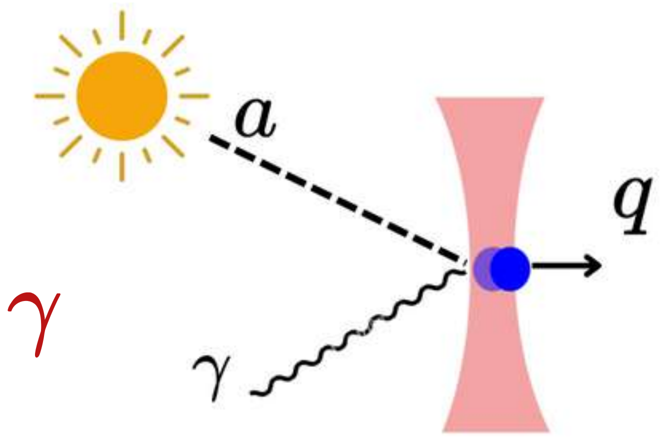

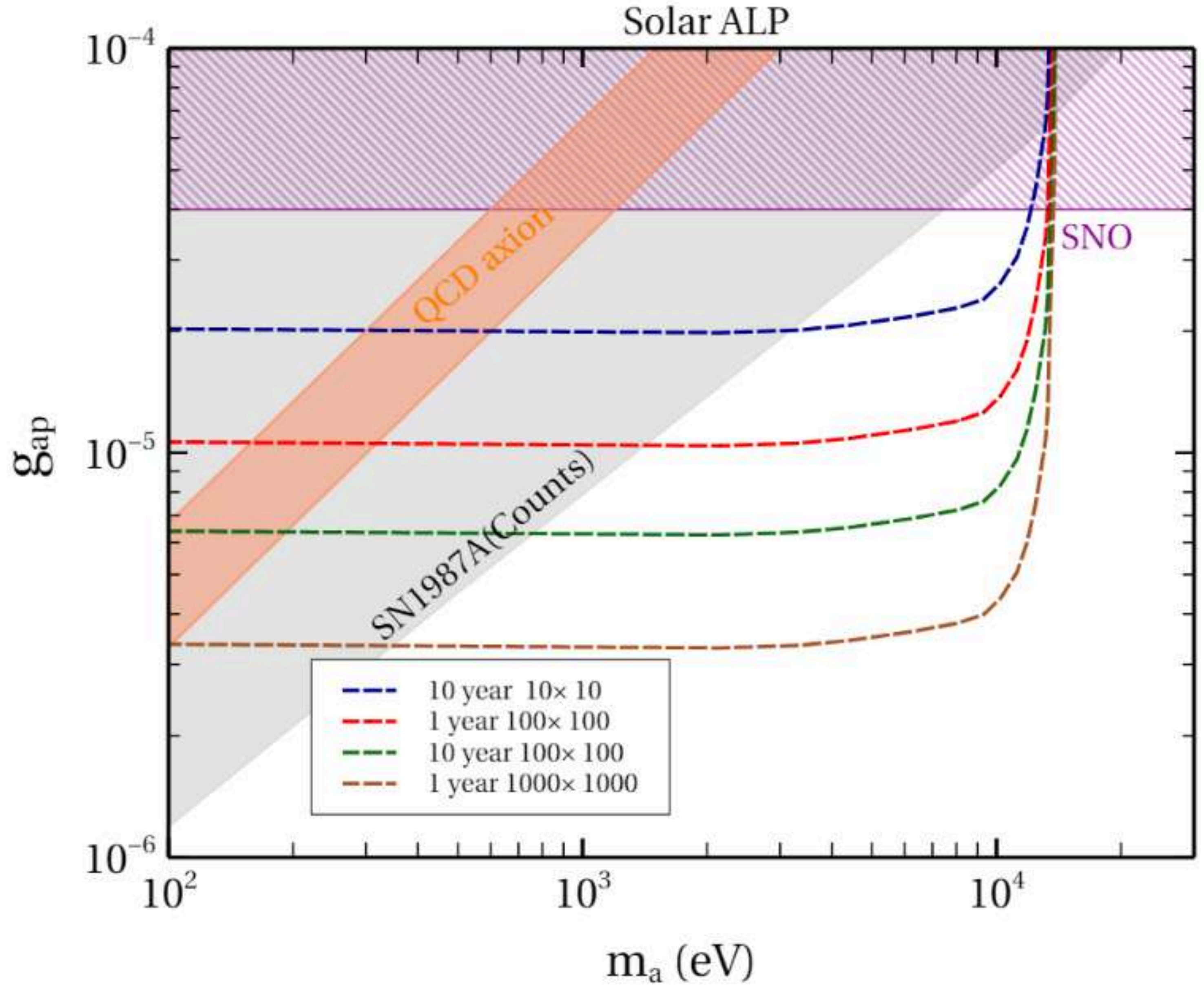

B. Dutta, D.k.Ghosh, SJ, 2410.XXXX

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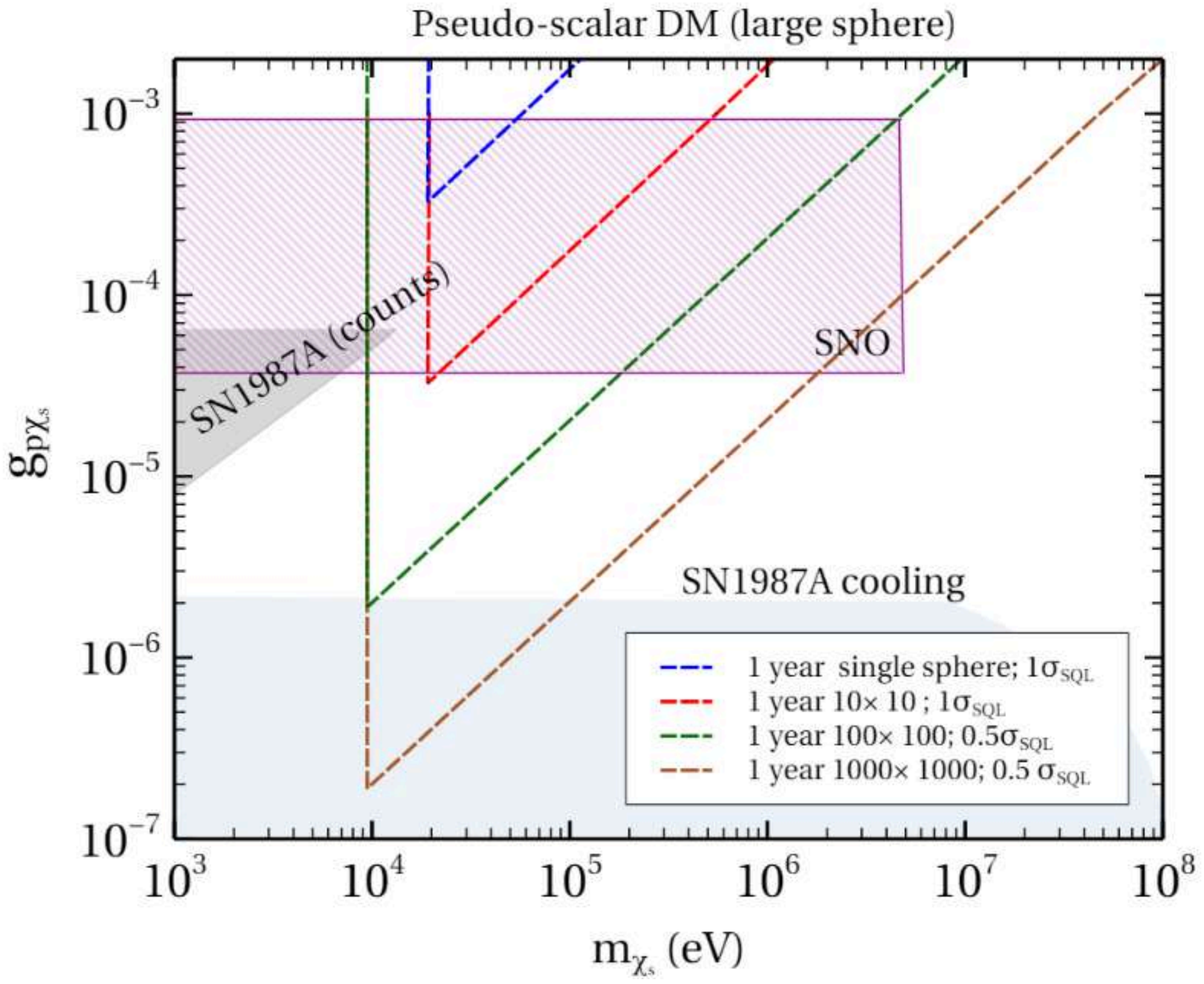

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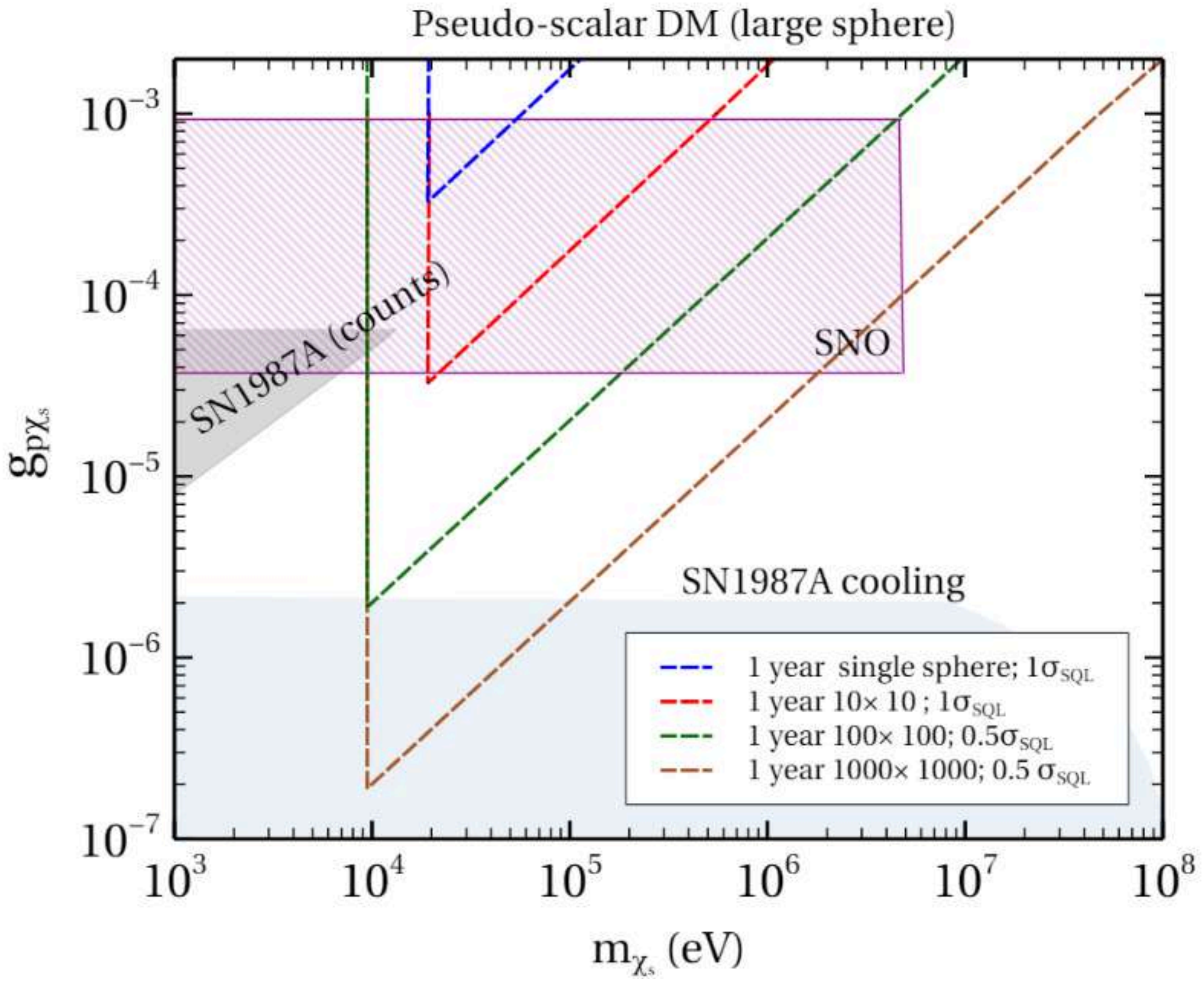

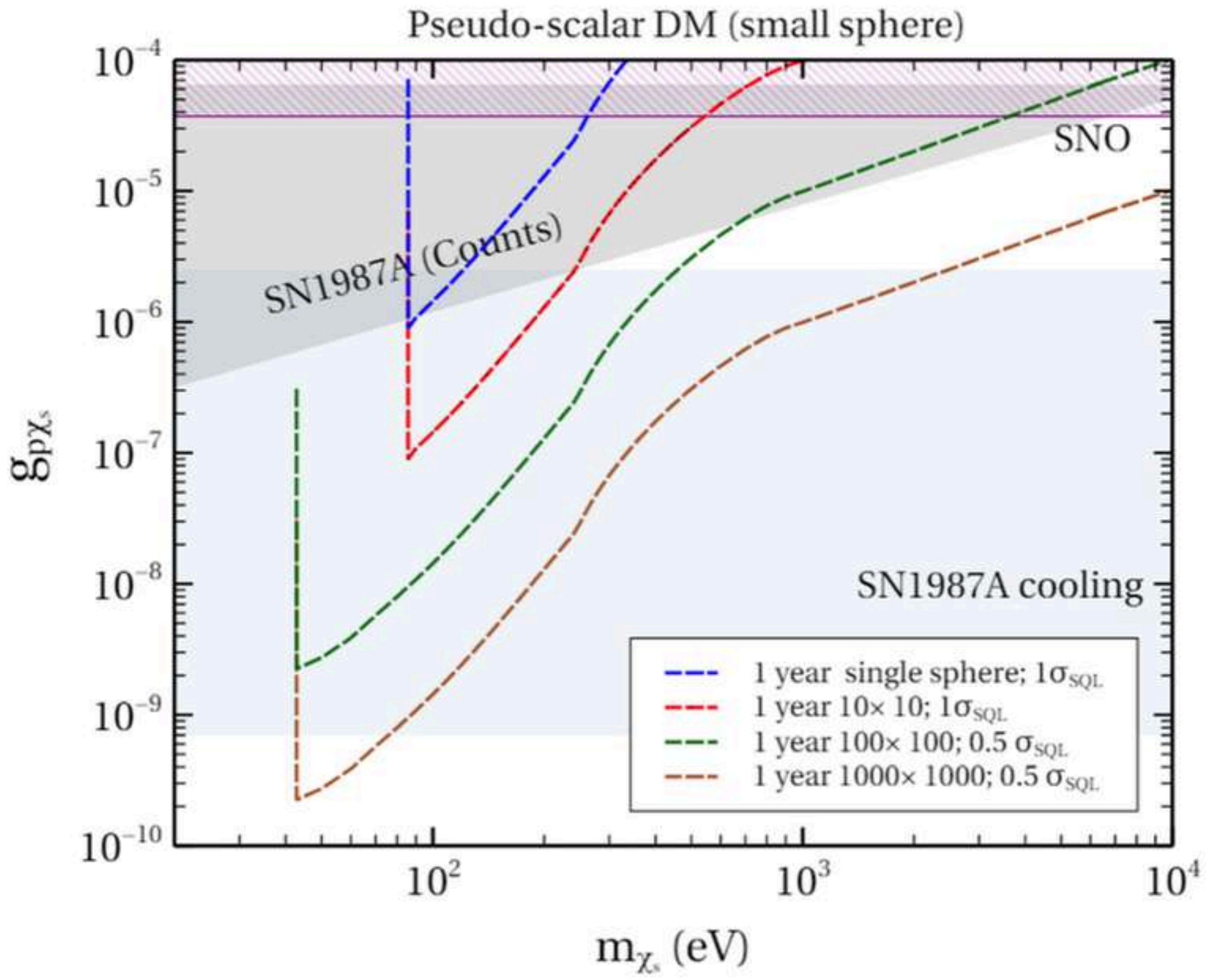

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And so you can do for scalar, vector….

Conclusion

- Levitated sphere set up can probe galactic low mass dark matter
- It can also probe solely the nucleon coupling of 14.4 keV solar ALP
- Can be used to probe plethora of light (low energetic) BSM particle

  Ex: Earth bound DM

Thank you