Cosmological Constraints on MeV-scale New Mediators

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DM with Mediators

Recent DM theories “Dark Sector w/ tiny couplings”

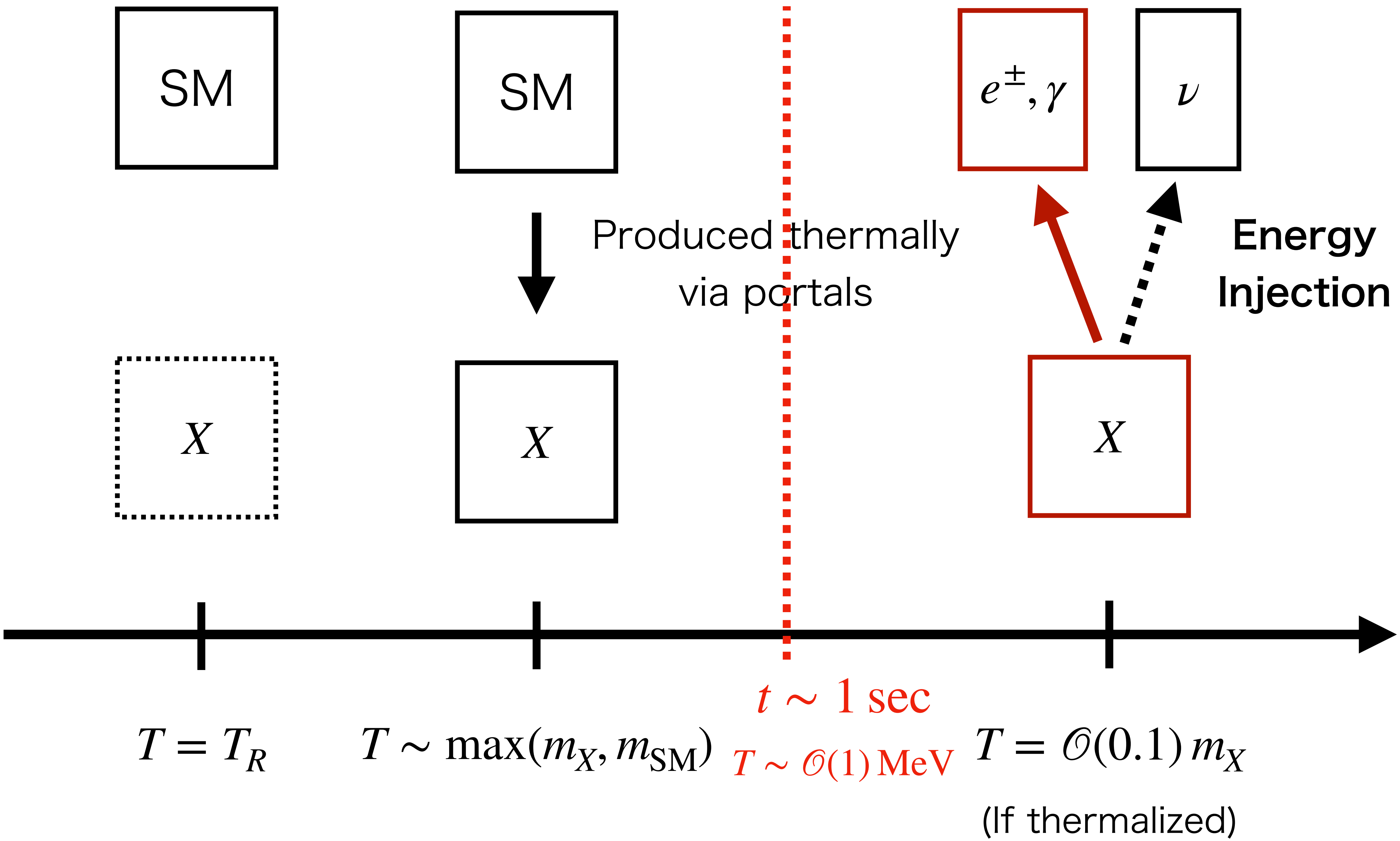
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm DS} + \underline{\mathscr{L}_{\rm portal}}\,,$$

1. Higgs $\quad \mathscr{L}_{\rm portal} = (\mu\phi + \lambda\phi^2)\,|H_{\rm SM}|^2 \quad$ 2112.11096
2. Vector $\quad \mathscr{L}_{\rm portal} = \varepsilon F'_{\mu\nu}F^{\mu\nu} \quad$ 1912.12152
3. Neutrino $\quad \mathscr{L}_{\rm portal} = yLHN$
4. Axion $\quad \mathscr{L}_{\rm portal} = \frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu},\ \frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu},\ \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi$

MeV~sub-GeV scale is discussed

Impact on Cosmology

Rule of thumb: Lifetime 1sec



Neff Observation

Definition of Neff:

$$N_{\rm eff} := \frac{8}{7}\left(\frac{11}{7}\right)^{4/3} \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma}\Bigg|_{T=T_{\rm CMB}}$$

Planck 2018

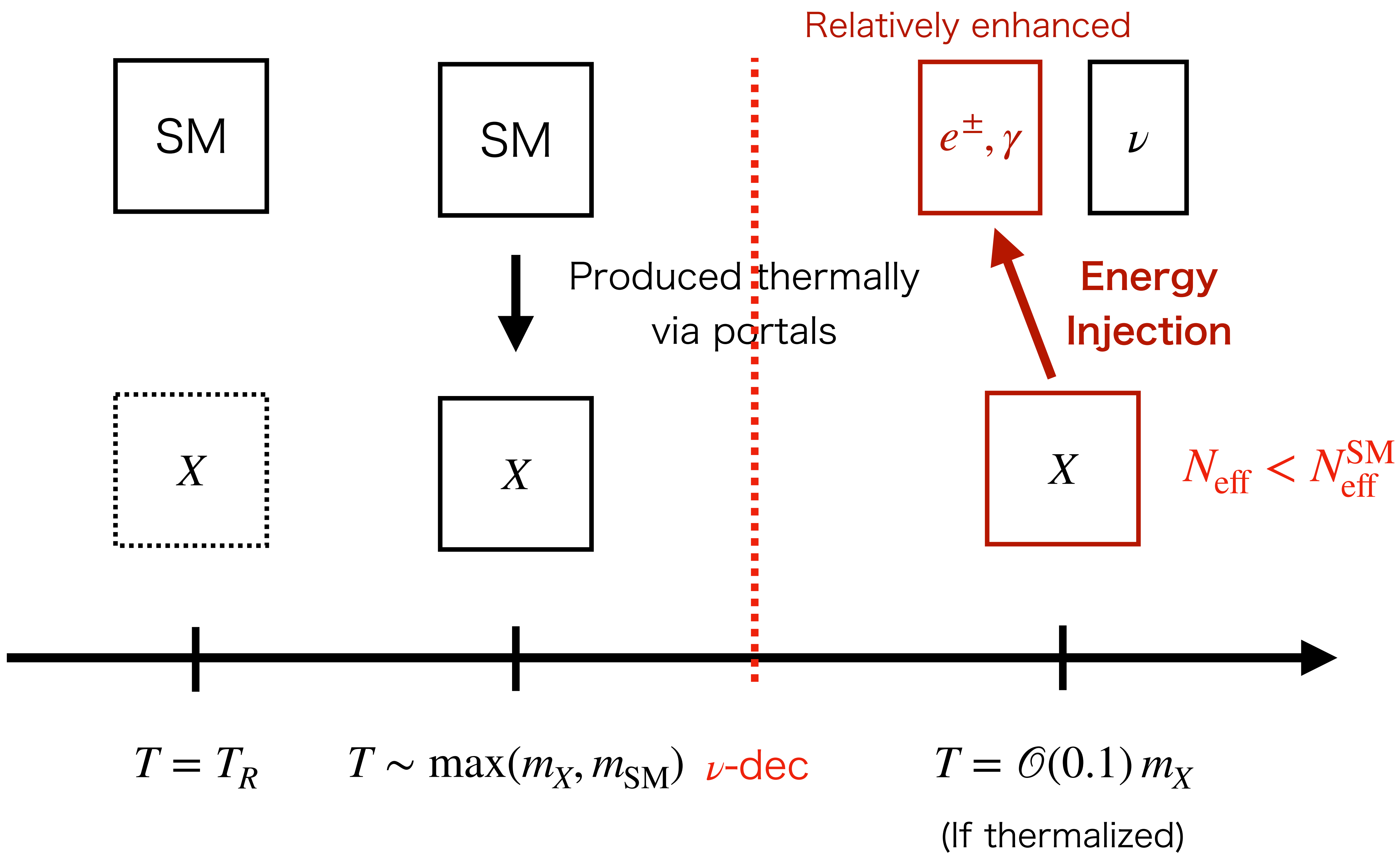
$N_{\rm eff} = 3.00^{+0.57}_{-0.53}$ (95%CL, TT+lowE)

$N_{\rm eff} = 2.92^{+0.36}_{-0.37}$ (95%CL, TT+TE+EE+lowE)

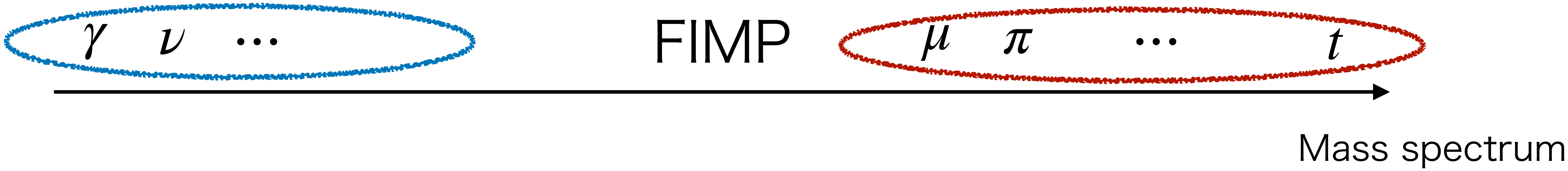
$N_{\rm eff} = 2.89^{+0.36}_{-0.38}$ (95%CL, TT+TE+EE+lowE+lensing)

$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95%CL, TT+TE+EE+lowE+lensing+BAO)

Neff with Light Mediator



FIMP Production



Relevant for $T \sim m_{\text{FIMP}}$

"(Conventional) freeze-in"

Relevant for $T > m_{\text{SM}}$

"UV freeze-in"

Example: $f\bar{f} \to X$

$$\frac{n_\phi}{s_{\text{SM}}} \sim \left.\frac{\Gamma\, n_f^{\text{eq}} H^{-1}}{s_{\text{SM}}}\right|_{T\sim m_X} \propto \varepsilon^2 \xi^2 \frac{M_{\text{Pl}}}{m_X}$$

Example: $f\bar{f} \to XV \ (V = \gamma, g)$

$$\frac{n_\phi}{s_{\text{SM}}} \sim \left.\frac{\sigma_f\, (n_f^{\text{eq}})^2 H^{-1}}{s_{\text{SM}}}\right|_{T\sim m_f} \propto \varepsilon^2 \xi^2 \frac{M_{\text{Pl}}}{m_f}$$

(ξ is some SM coupling: $\mathscr{L}_{\text{SM}-\text{med}} = \xi \mathcal{O}_{\text{SM}} \cdot \varepsilon X$)

FIMP Production

Dark photon

$$\mathscr{L}_{\rm SM-med} = e\bar{f}\gamma^\mu f \cdot \varepsilon A'_\mu$$

ξ is universal

Production from heavy state is negligible:

$$\left.\frac{n_{\gamma'}}{s_{\rm SM}}\right|_{\rm FI} > \left.\frac{n_{\gamma'}}{s_{\rm SM}}\right|_{\rm UVFI}$$

For $2m_e < m_{\gamma'} < 2m_\mu$,

$e^-e^+ \to \gamma'$ is dominant

Dark scalar

$$\mathscr{L}_{\rm SM-med} = \frac{m_f}{v}\bar{f}f \cdot \varepsilon\phi$$

ξ is non-universal

Production from heavy state is not negligible:

$$\left.\frac{n_\phi}{s_{\rm SM}}\right|_{\rm UVFI} \propto \varepsilon^2 \frac{m_f M_{\rm Pl}}{v^2}$$

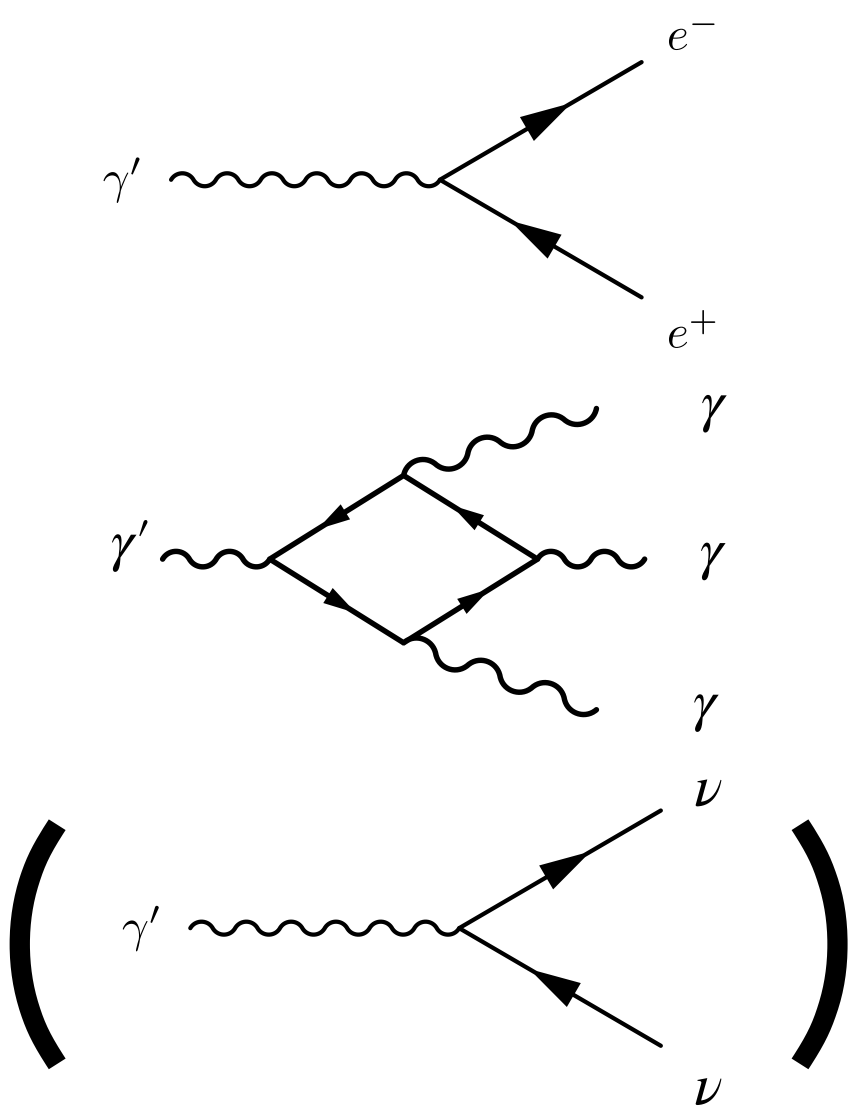
All processes should be considered even for $m_\phi \sim \mathrm{MeV}$

FIMP Decay

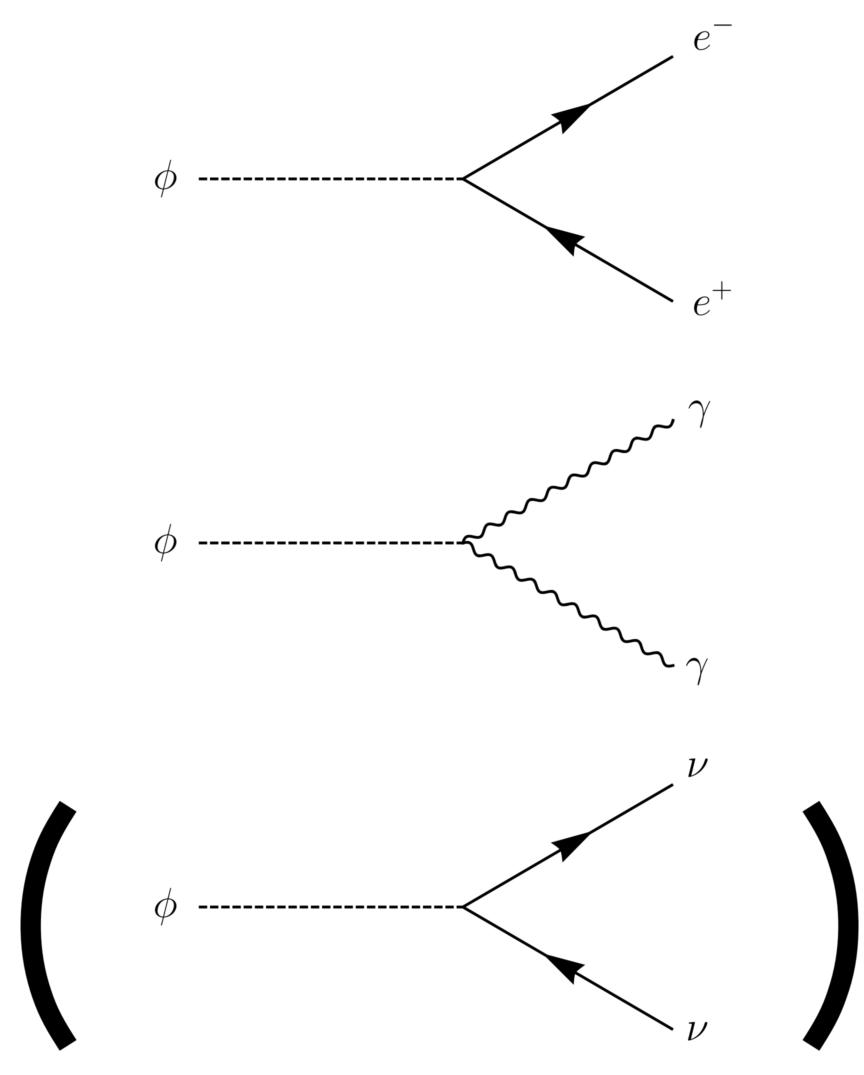
Mass spectrum

Provide decay modes

Dark photon



Dark scalar



Concrete Setup

Dark photon

$$\mathscr{L}_{\text{mix}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{\gamma'}^2}{2}A'_\mu A'^\mu + ej^\mu_{\text{EM}}A_\mu$$

$$\Rightarrow \mathscr{L}_{\text{SM-med}} = \varepsilon e j^\mu_{\text{EM}} A'_\mu$$

Dark scalar

$$V_{\text{int}} = V_H(H) + V_{\text{mix}}(H,s) + V_s(s) \ ,$$

$$V_{\text{mix}}(H,s) = \frac{\lambda_{Hs}}{2}s^2|H|^2 + \mu_{Hs}s|H|^2 \ ,$$

$$V_s(s) = \frac{m_s^2}{2}s^2 + \frac{\mu_s}{6}s^3 + \frac{\lambda_s}{24}s^4 \ .$$

$$\Rightarrow \mathscr{L}_{\text{SM-med}} = s_\theta \frac{m_f}{v}\phi\bar{f}f$$

(+ self interactions)

Concrete Setup

$$\frac{\partial f_X}{\partial t} - H p_X \frac{\partial f_X}{\partial p_X} = - \sum_{\text{processes}} I(p_X, T) \times \left(f_X(p_X) - f_X^{\text{eq}}(p_X, T) \right)$$

$X = \gamma'$

$$e^+ e^- \leftrightarrow \gamma'$$
$$e^- e^+ \leftrightarrow \gamma' \gamma$$
$$e^\pm \gamma \rightarrow e^\pm \gamma'$$

$(\gamma\gamma\gamma \leftrightarrow \gamma')$

$X = \phi \ (T_R \lesssim 100 \text{ GeV})$

$$e^+ e^- \leftrightarrow \phi$$
$$l^- l^+ \leftrightarrow \phi \gamma \qquad (l = e, \mu, \tau)$$
$$l^\pm \gamma \rightarrow l^\pm \phi$$

$$M^- M^+ \leftrightarrow \phi \gamma$$
$$M^\pm \gamma \rightarrow M^\pm \phi \qquad (M = \pi, K)$$

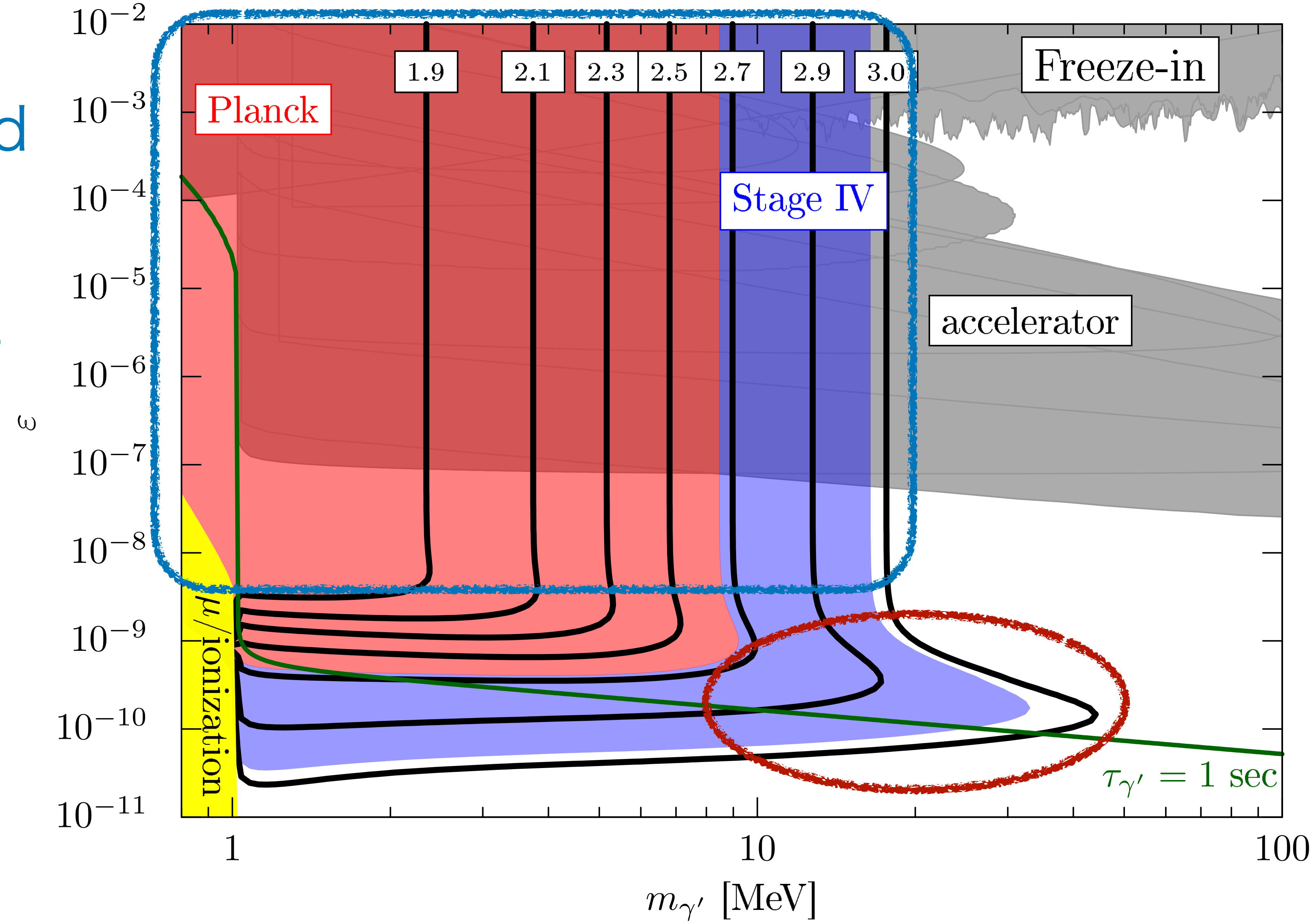
$$q^- q^+ \rightarrow \phi g$$
$$q^\pm g \rightarrow q^\pm \phi \qquad (q = c, b, t)$$

Parameter Scan (dark photon)

$$f_{\gamma'}(p, T_{\rm init}) = 0$$

γ' is thermalized

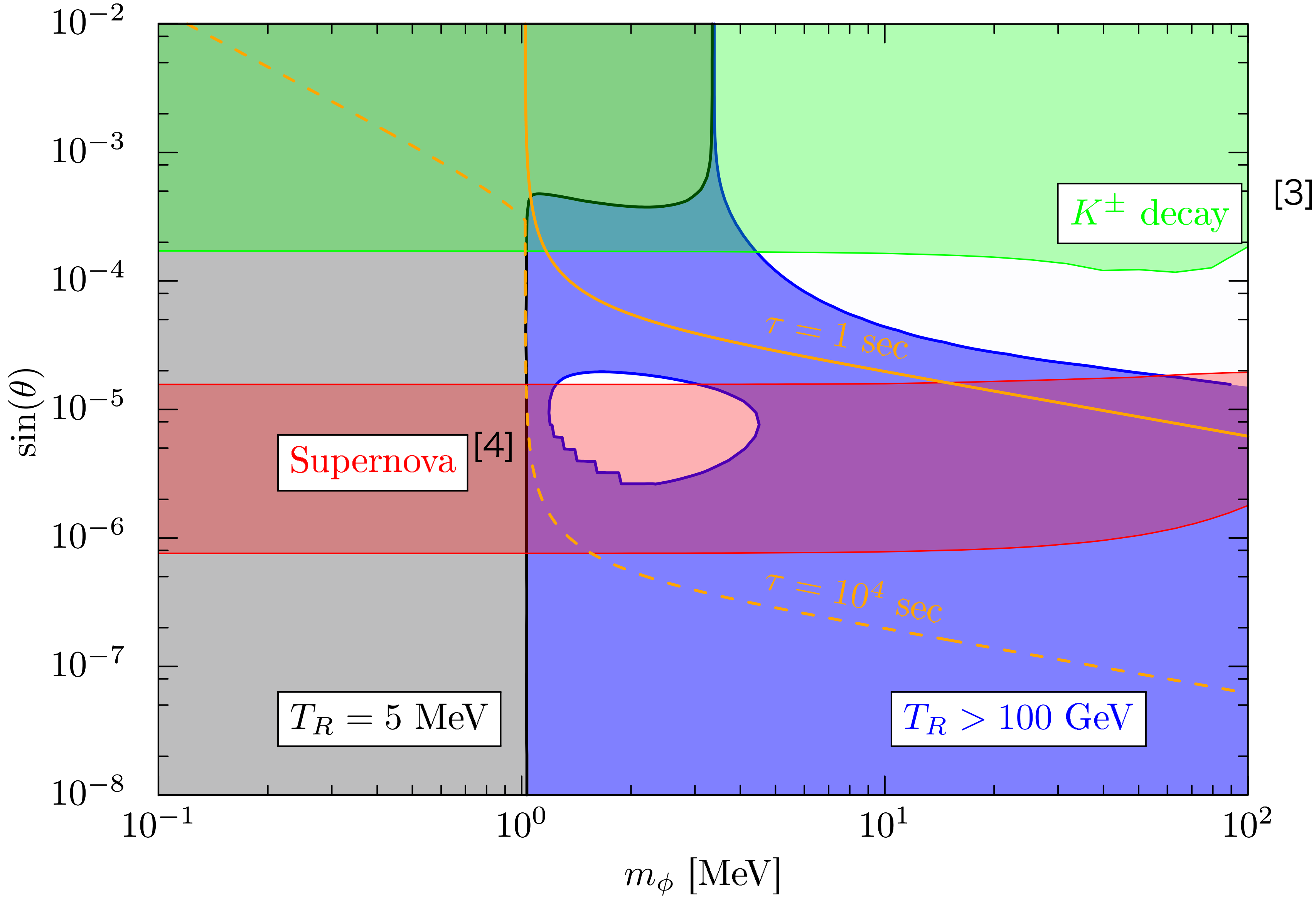
Independent of UV physics



Out-of-equilibrium decay

Parameter Scan (dark scalar)

CMB ($N_{\rm eff}, Y, \mu$ distortion[1]) + BBN + X-ray[2]



[1] J. Chluba, Mon. Not. Roy. Astron. Soc. 460, 227 (2016), arXiv:1603.02496

[2] R. Essig, et.al., JHEP 11, 193 (2013), arXiv:1309.4091

[3] Constraints on $\mathrm{Br}(K^+ \to \pi^+\phi)$ by NA62 & E949

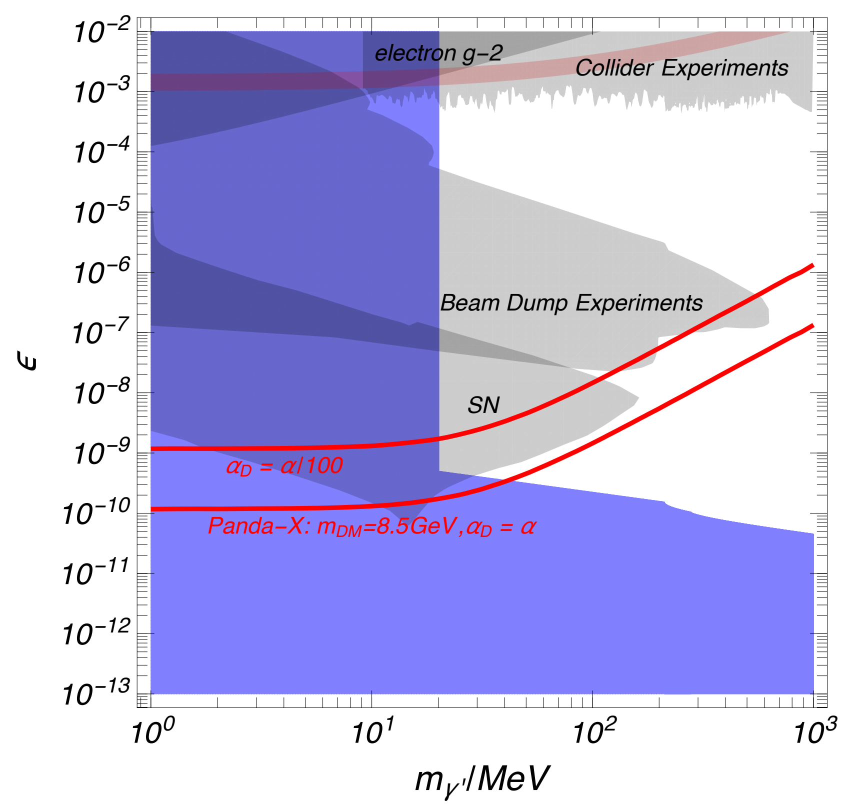
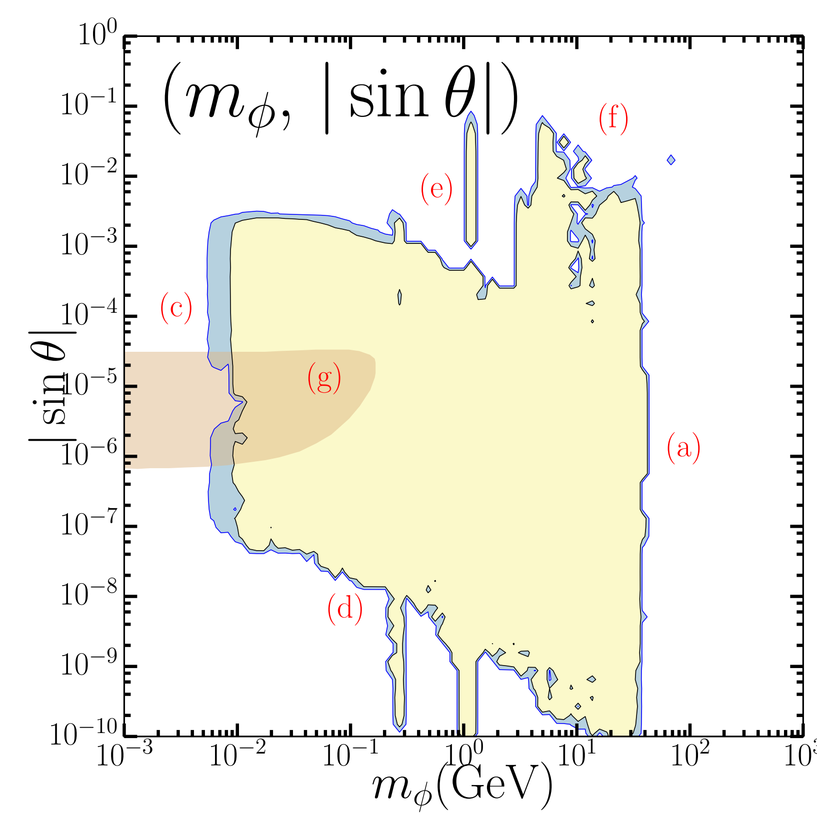
[4]G. Krnjaic, PRD 94, 073009 (2016), arXiv:1512.04119

Summary

- Unstable new mediators inject energy into thermal plasma. They can be constrained by cosmology if the lifetime is longer than about 1sec.
- Neff can be smaller than the SM value if long-lived electro-philic mediators exist.
- The dark photon, which couples to SM states via the universal gauge coupling, can be robustly constrained by the CMB Neff.
- The dark scalar, which couples to SM states via the non-universal Yukawa couplings, can be produced significantly by heavy particles.

Back Up

Example Models

Model	Composite ADM [1]	SM singlet Majorana WIMP [2]
DS Symmetry	$\mathrm{SU}(3)' \times \mathrm{U}(1)'$	$\mathbb{Z}_2 \quad (\chi \to -\chi,\ \phi \to \phi)$
Mediator	Dark photon	Dark scalar
Parameter space		

[1] M. Ibe, A. Kamada, S. Kobayashi, W. Nakano, JHEP 11 (2018) 203

[2] S. Matsumoto, Y. S. Tsai, P. Tseng, JHEP 07 (2019) 050

Recap on ν decoupling

Neutrino-electron interaction

$$\mathscr{L}_{\nu-e} = 2\sqrt{2}G_{\mathrm{F}}(J^{\dagger\mu}J_{\mu} + J_Z^{\mu}J_{Z\mu})$$

This is relevant only above

$$T > (G_{\mathrm{F}}^2 M_{\mathrm{Pl}})^{-1/3} \sim \mathcal{O}(1)\,\mathrm{MeV}.$$

Entropy conservation at e^-e^+ annihilation

$$\left(2 + \frac{7}{8} \times 2 \times 2\right) z_i^3 = 2z_f^3, \ \ (z = Ta)$$

Since $T_\nu \propto a^{-1}$,

$$\frac{z_f}{z_{\nu f}} = \frac{T_f}{T_{\nu f}} = \left(\frac{11}{4}\right)^{1/3} \simeq 1.4$$

Remarks on Neff

Remark 1

Neff is often defined by

$$N_{\text{eff}} := \frac{8}{7}\left(\frac{11}{7}\right)^{4/3}\frac{\rho_\nu + \rho_{\text{BSM}}}{\rho_\gamma}$$

(e.g. in the context of time-dependent Neff)

This does not necessarily coincide with the original one, because ρ_{BSM} can behave like matter.

We can apply the constraints from Planck data only to the original Neff.

Remarks on Neff

Remark 2

The original Neff is different from 3 in SM:

$$N_{\rm eff}^{\rm SM} = 3.044$$

[J. J. Bennett et.al., JCAP 04 (2021) 073, arXiv: 2012.02726]

Due to

- ☑ Delay of ν decoupling (dominant)
- ☑ Finite temperature QED correction
- ☑ Neutrino oscillation

In order to treat these effect,
we need the Quantum Kinetic Equation (QKE)

Remarks on Neff

Remark 3

When considering neutrino-phobic BSM,
we can avoid to treat the non-thermal effect of neutrino

$$N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$$

Including non-thermal effect due to SM ($N_{\rm eff}^{\rm SM}$)

Impact on Neff due to BSM ($\Delta N_{\rm eff}$)

$$\Delta N_{\rm eff} = \tilde{N}_{\rm eff} - \tilde{N}_{\rm eff}\Big|_{\text{portal coupling}\to 0}$$

$\tilde{N}_{\rm eff}$: Neff w/o non-thermal effects

Effective Couplings

Trace of energy-momentum tensor can be expressed by normal products in Green's functions (like $\langle 0|H\Theta^\mu_\mu|0\rangle$): [Collins, Duncan and Joglekar, 1977]

Trace of energy-momentum tensor in Green's functions

$$\Theta^\mu_\mu = \bar{q}Mq - \frac{b\alpha_s}{8\pi}G^a_{\mu\nu}G^{a\mu\nu}, \ \kappa = \frac{2n_h}{3b}, \ b = \frac{1}{3}(11N_c - 2N_f)$$

Explicit breaking   Quantum effect

Conversely, this means we can rewrite the effective couplings as:

$$\mathscr{L} \supset -\frac{H}{v}\bar{q}Mq + n_h\frac{H}{v}\frac{\alpha_s}{12\pi}G^a_{\mu\nu}G^{a\mu\nu}$$
$$= -\frac{H}{v}\left\{\kappa\Theta^\mu_\mu + (1-\kappa)\bar{q}Mq\right\}$$

[Leutwyler & Shifman, 1989]

Effective Couplings

The corresponding operators in ChPT are obtained by the following replacement

$$\Theta^\mu_\mu\Big|_{3+3\,\mathrm{QCD}} \to \Theta^\mu_\mu\Big|_{\mathrm{ChPT}}, \qquad \bar{q}Mq \to \frac{1}{2}Bf_\pi^2\,\mathrm{tr}(MU + \mathrm{h.c.})$$

At the lowest order

$$\mathcal{L}_{\mathrm{ChPT}} = f_\pi^2\,\mathrm{tr}(\partial_\mu U^{-1}\partial^\mu U) - \frac{1}{2}Bf_\pi^2\,\mathrm{tr}(MU + \mathrm{h.c.})$$

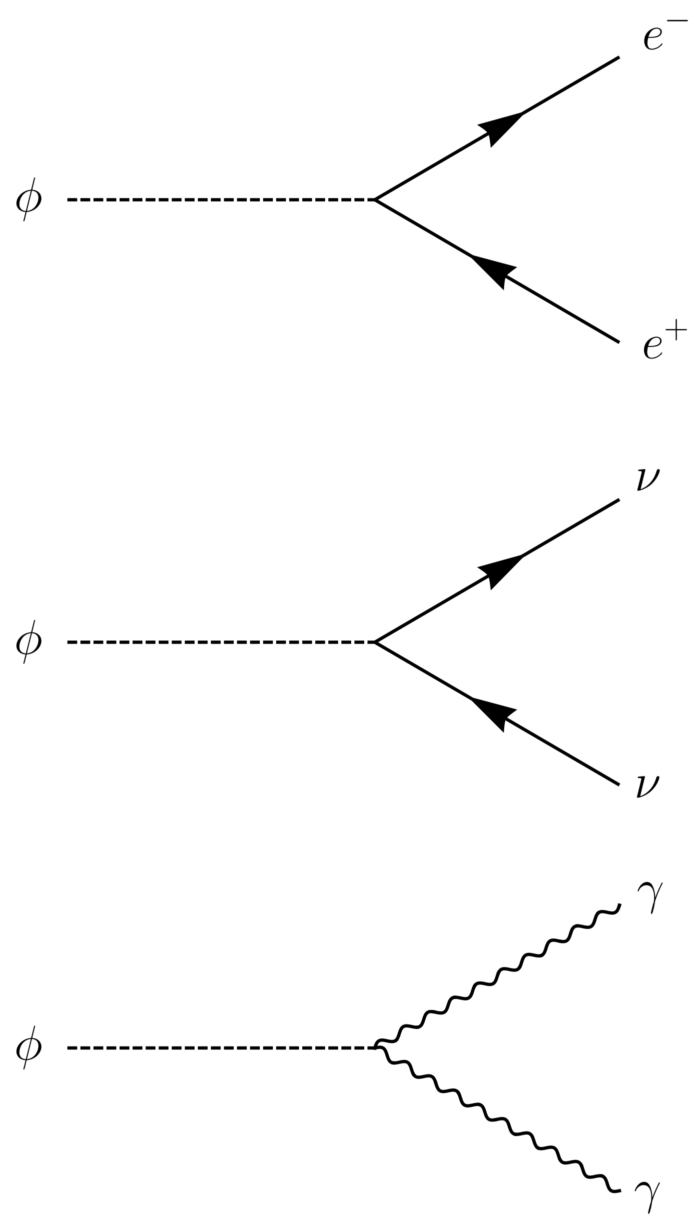
$$\Theta^{\mathrm{ChPT}}_{\mu\nu} = 2f_\pi^2\,\mathrm{tr}(\partial_\mu U^{-1}\partial_\nu U) - g_{\mu\nu}\mathcal{L}_{\mathrm{eff}}$$

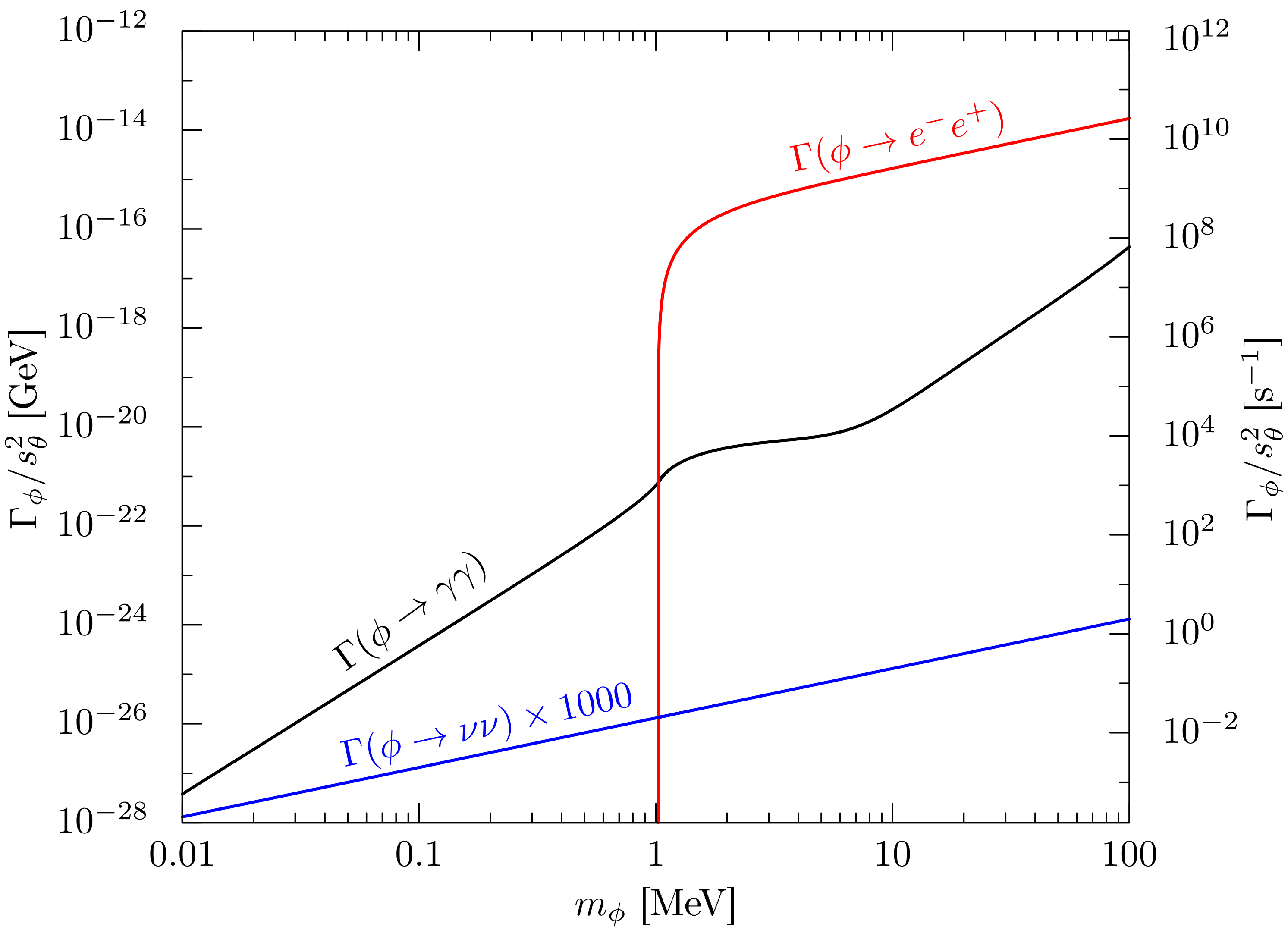
$$\boxed{\mathcal{L}_{HPP} = \frac{H}{v}\left\{2\kappa\partial_\mu P^+\partial^\mu P^- - (1+3\kappa)m_P^2P^+P^-\right\}} \qquad P = \pi \text{ or } K$$

[Leutwyler & Shifman, 1989]

Decay Channels (dark scalar)

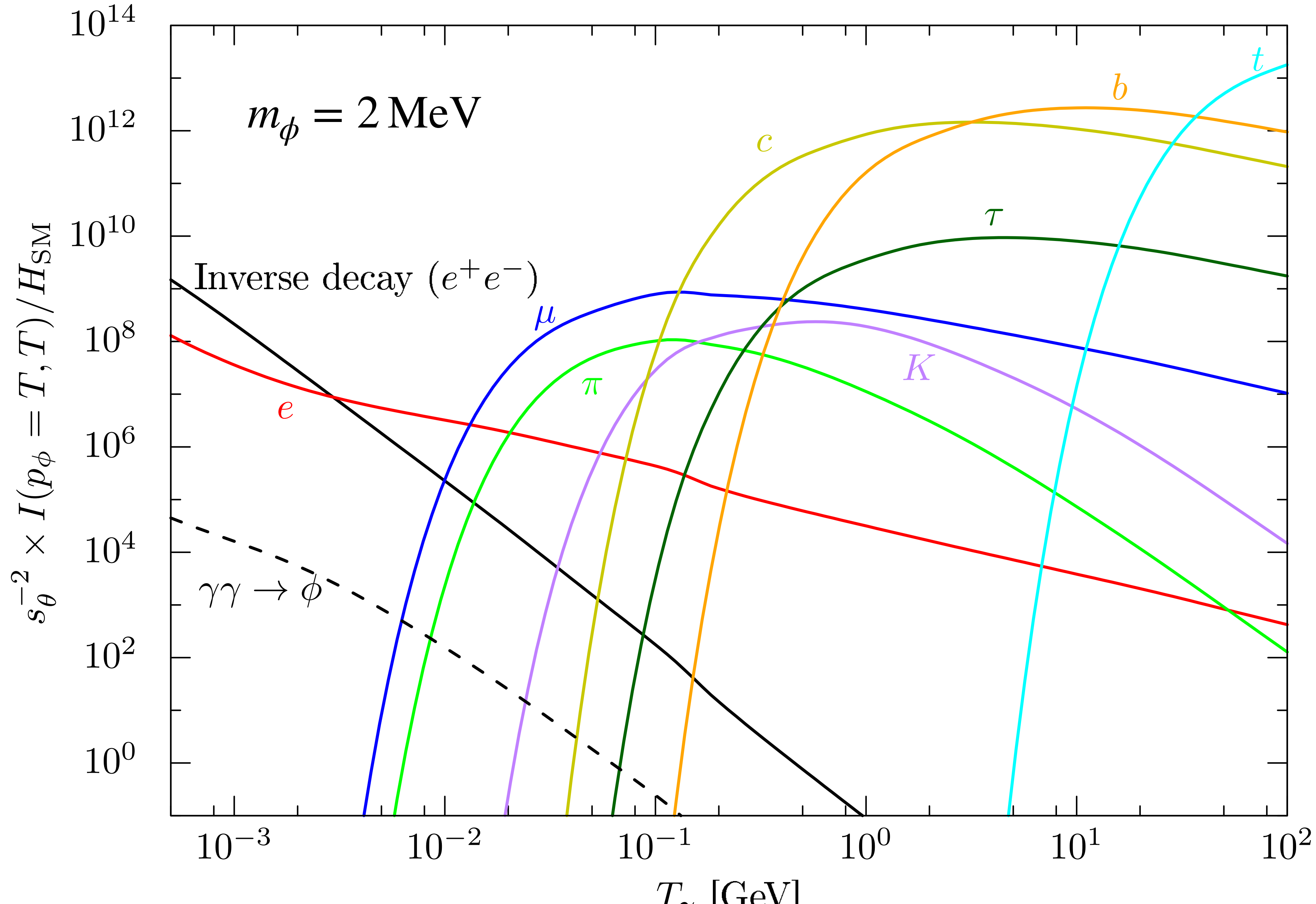
Decay channels (For neutrinos, see-saw is assumed)





Dark Scalar Production

Production rate of each process $\frac{\partial f_\phi}{\partial t} - Hp_\phi \frac{\partial f_\phi}{\partial p_\phi} = -I(p_\phi, T)(f_\phi - f_\phi^{\rm eq})$



Production History

Determination of decoupling/freeze-in temperature

$$R(T) := \frac{\int \frac{d^3\mathbf{p}_\phi}{(2\pi)^3} I(p_\phi, T) f_\phi^{\mathrm{BE}}(p_\phi, T)}{H\big|_{\rho_\phi=0,\, T_\gamma=T} \times n_\phi^{\mathrm{eq}}(T)}$$

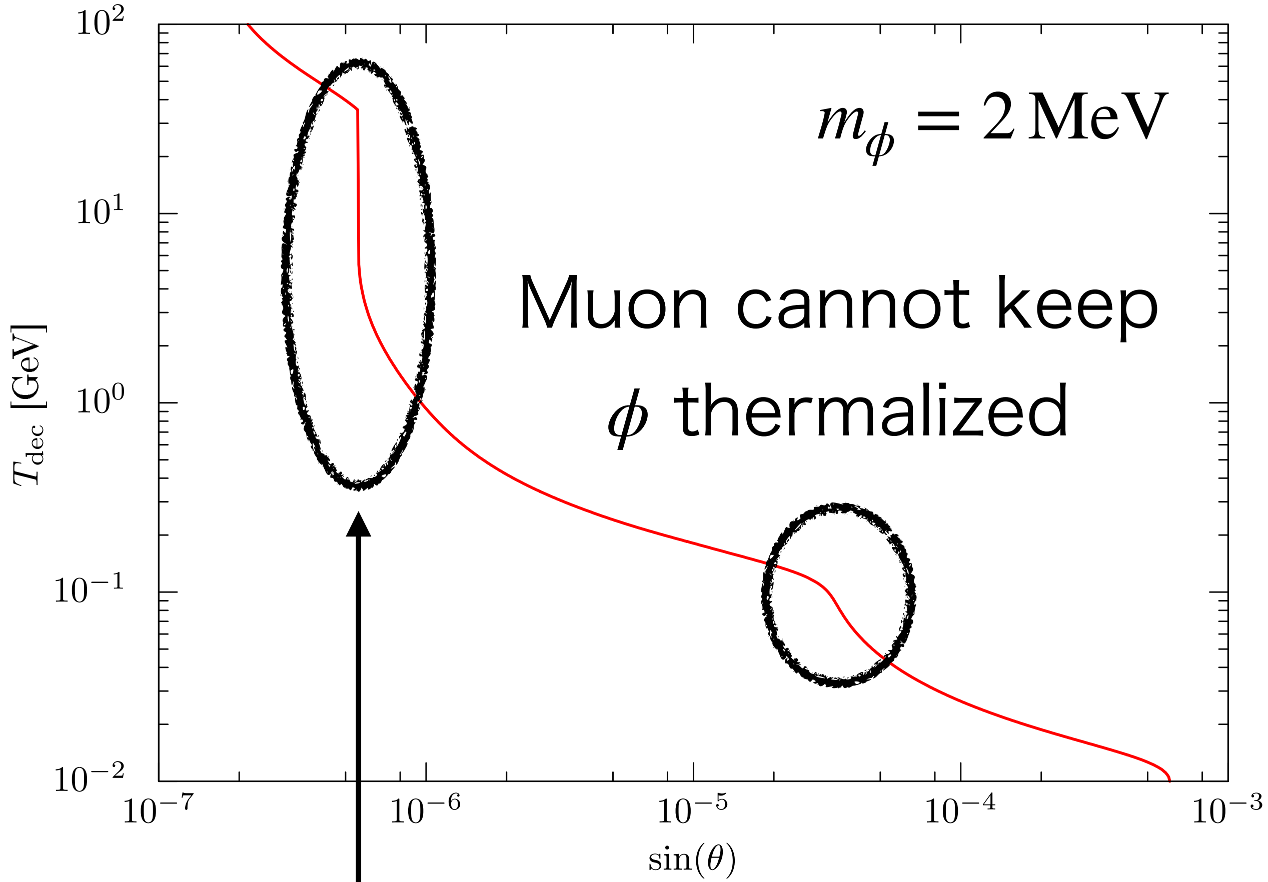
T_{dec} (UV decoupling temperature)

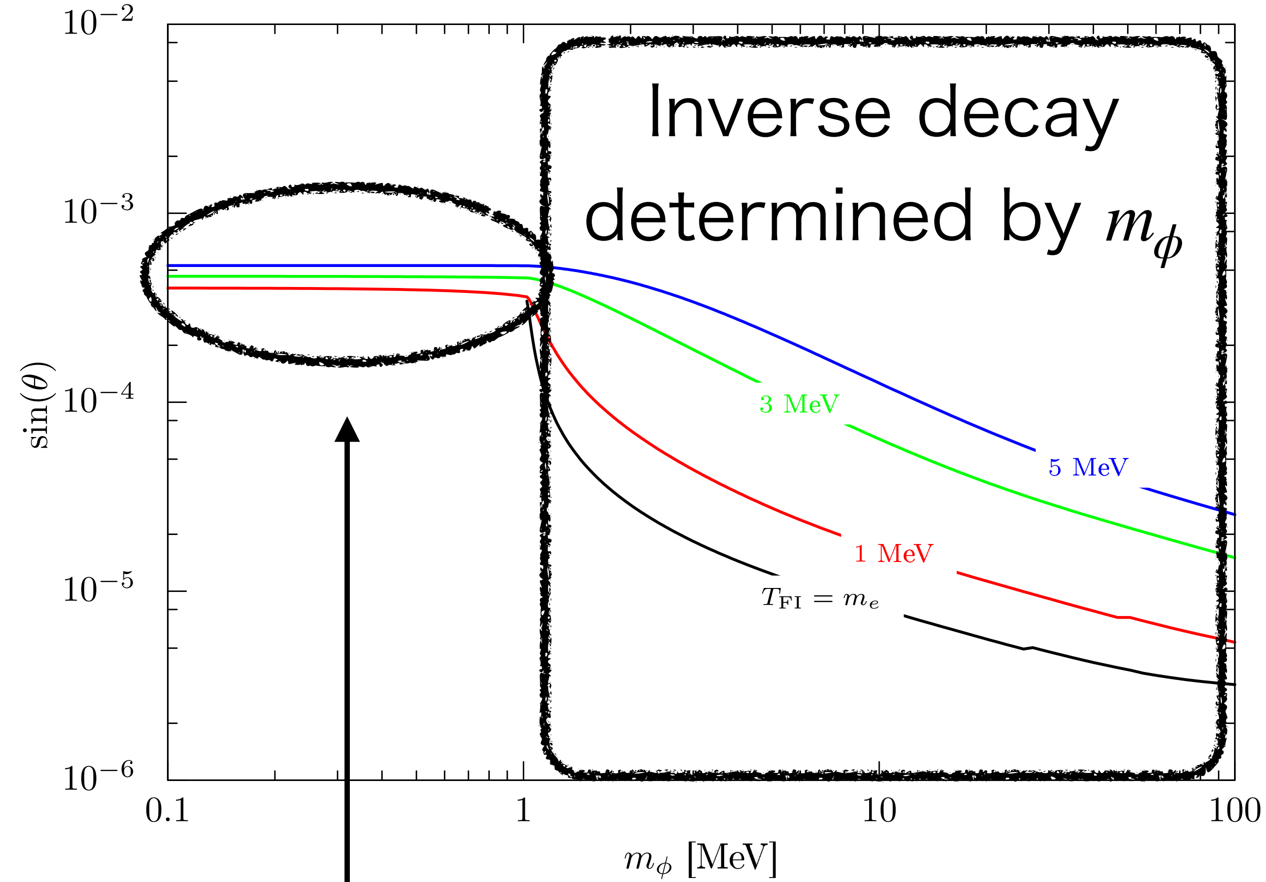
$$:\Leftrightarrow R(T_{\mathrm{dec}}) = 1 \wedge dR/dT\Big|_{T=T_{\mathrm{dec}}} > 0$$

T_{FI} (Freeze-in temperature)

$$:\Leftrightarrow R(T_{\mathrm{FI}}) = 1 \wedge dR/dT\Big|_{T=T_{\mathrm{FI}}} < 0$$

Dark Scalar Production





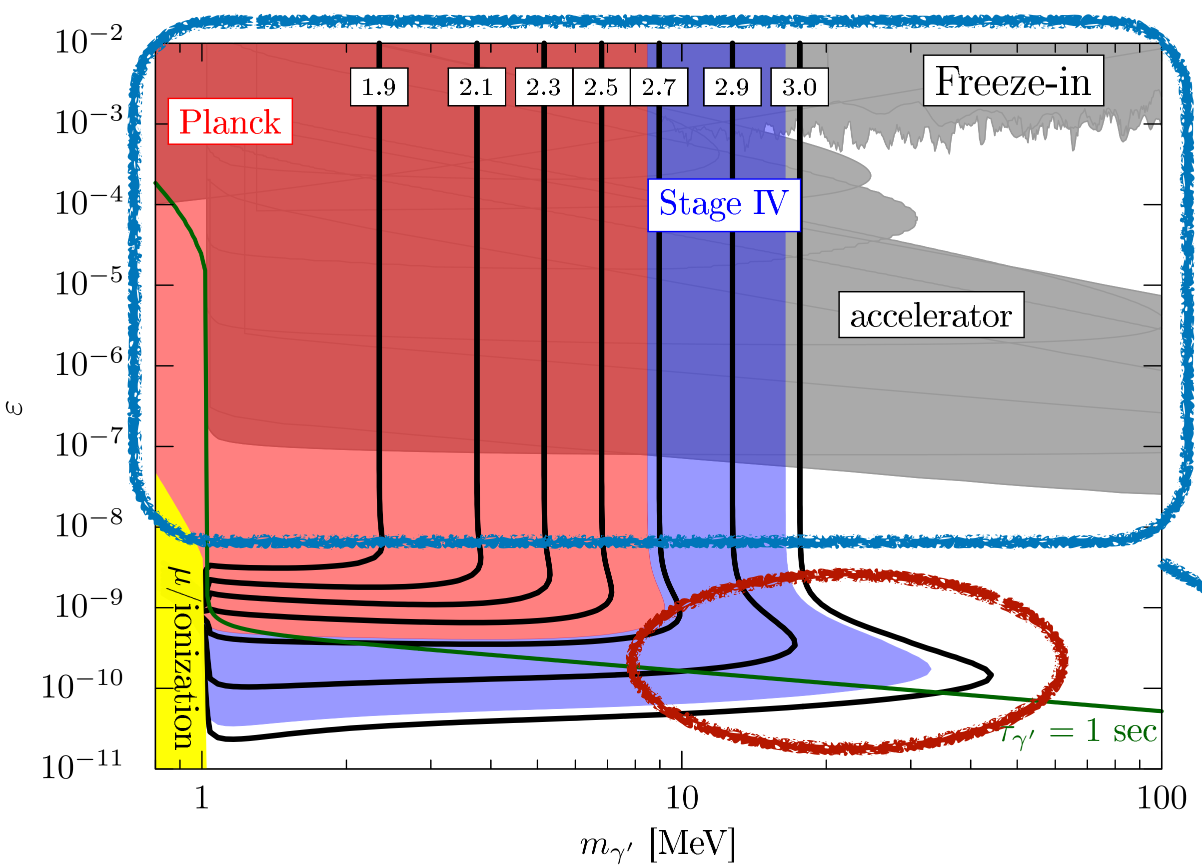
Charm quark cannot keep
ϕ thermalized

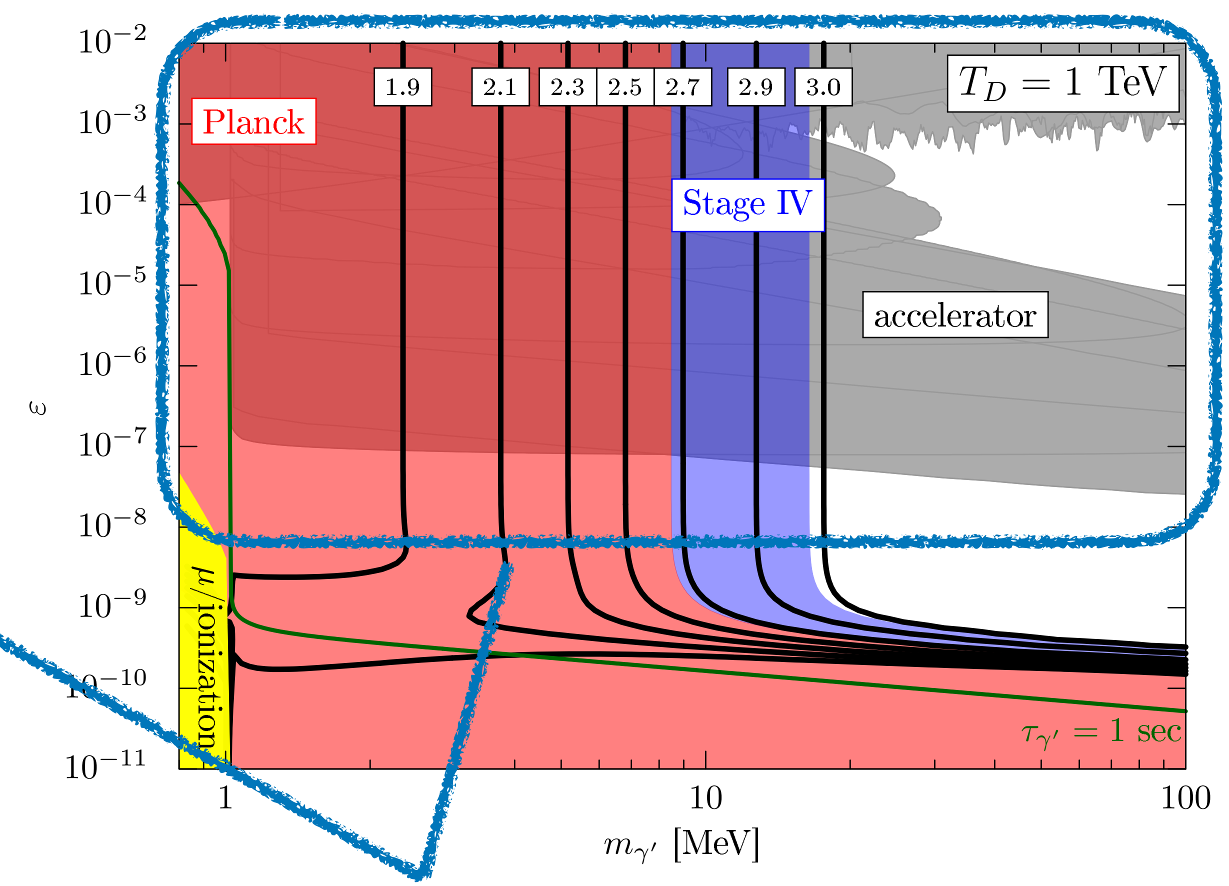
Scatterings from $e^\pm$
determined by m_e

Parameter Scan (dark photon)

$$f_{\gamma'}(p, T_{\rm init}) = 0$$

$$f_{\gamma'}(p, T_{\rm init}) = f_{\gamma'}\left(\frac{a(T_{\rm init})}{a(T_{\rm D})}p, T_{\rm D}\right)$$



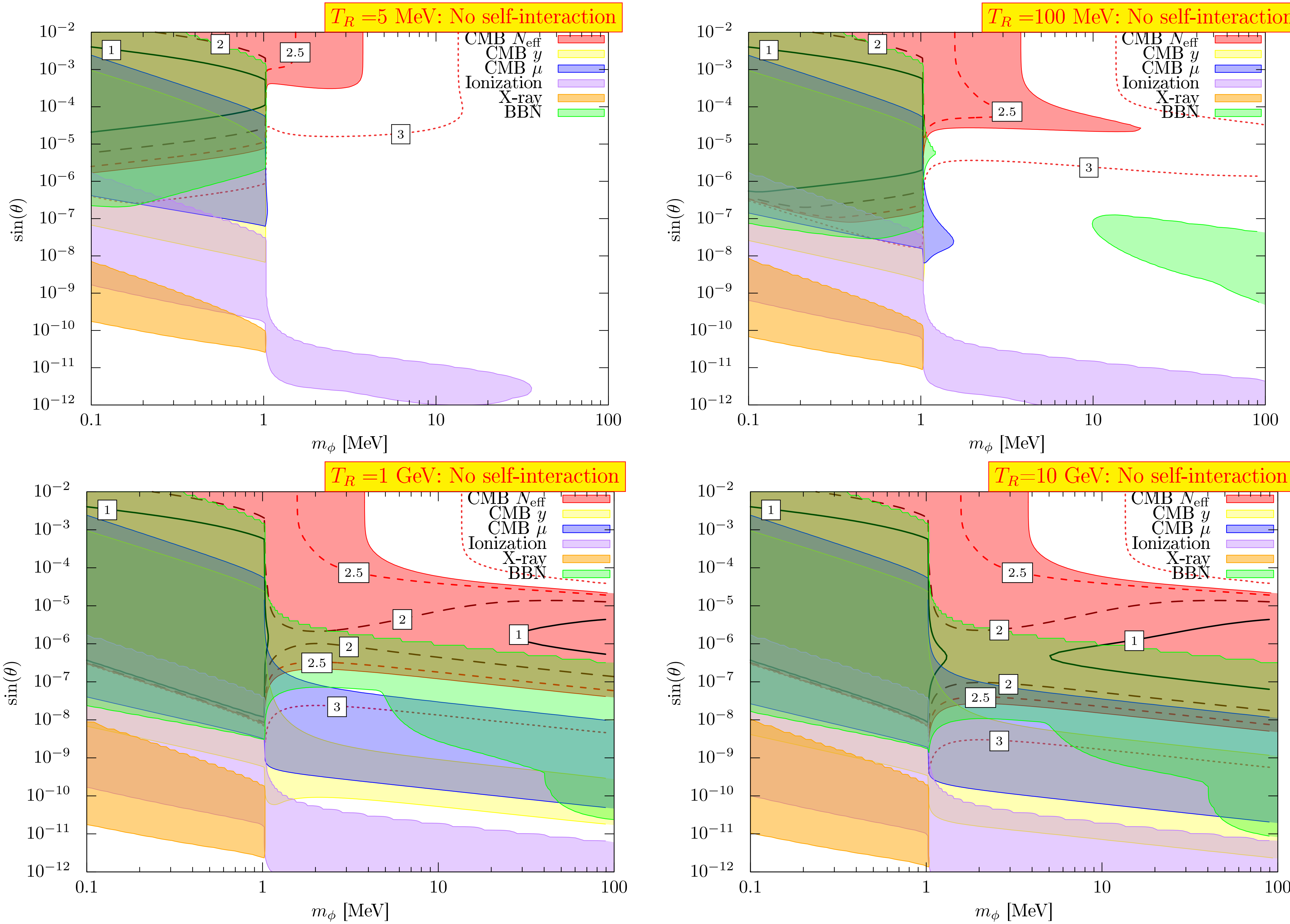


Out-of-equilibrium decay

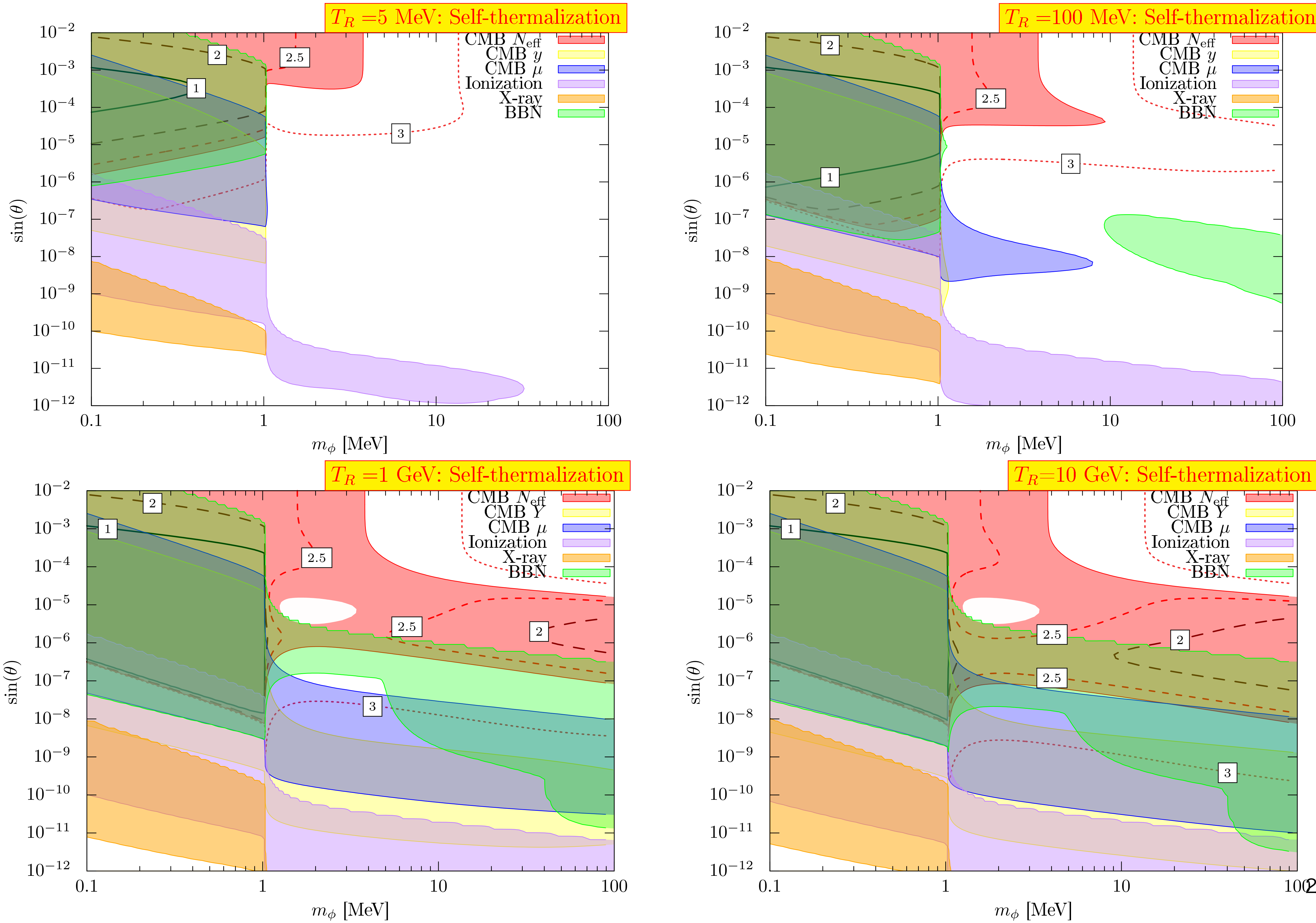
γ' is thermalized

Constraints are independent of UV physics

Parameter Scan (dark scalar)



Parameter Scan w/ SI



Summary of Effect of SI

1. $Y_\phi \gg \mathrm{O}(10^{-15})$ for the parameter space of our interest.
   Hence the scalar reaches the chemical equilibrium.
2. The scalar energy density decreases rapidly due to number-changing processes.
   This makes impacts on cosmology smaller.
3. On the other hand, when the number of scalar is quite small, they behave like non-relativistic particles.
   This enhances their impacts on cosmology.
4. Anyway, self-interactions freeze out at low temperature.
   Then the scalar becomes a free particle.