Dark Matter *seeping* through *dynamic* Z′-portal

Avik Banerjee
Saha Institute of Nuclear Physics

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w/ Gautam Bhattacharyya, Debtosh Chowdhury, Yann Mambrini

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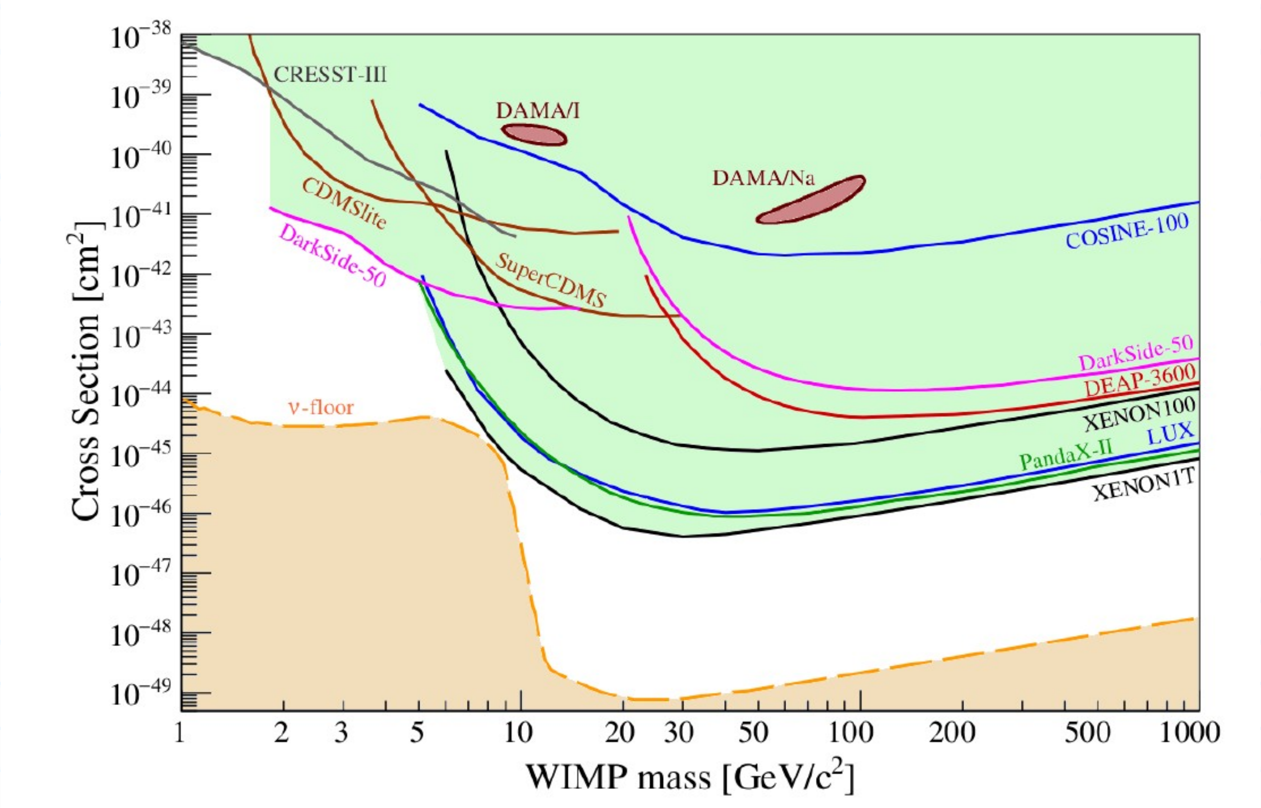
Whining WIMP

No signal for WIMP ➡ Only stronger limits

Still a Miracle ?



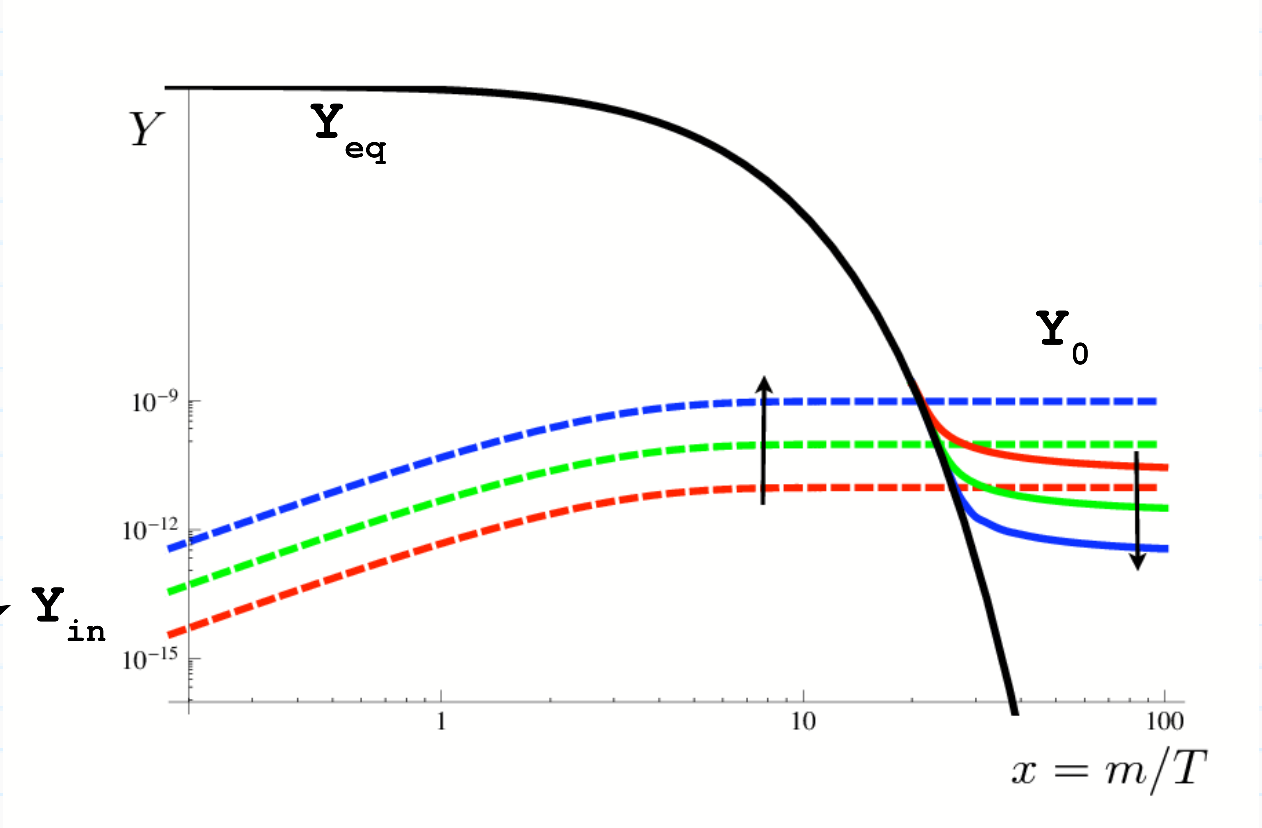
Taken from 1903.03026

Calls for alternate paradigm ➡ Ex: Freeze-in

Freeze-out vs. Freeze-in

DM-SM in thermal equilibrium

Freeze-out due to expansion



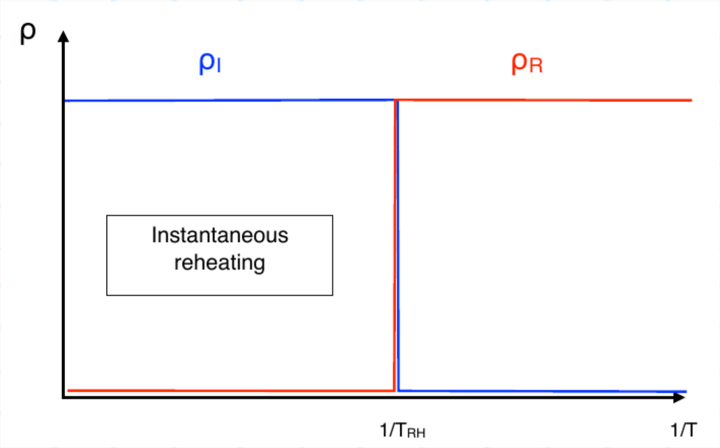
Assumption!

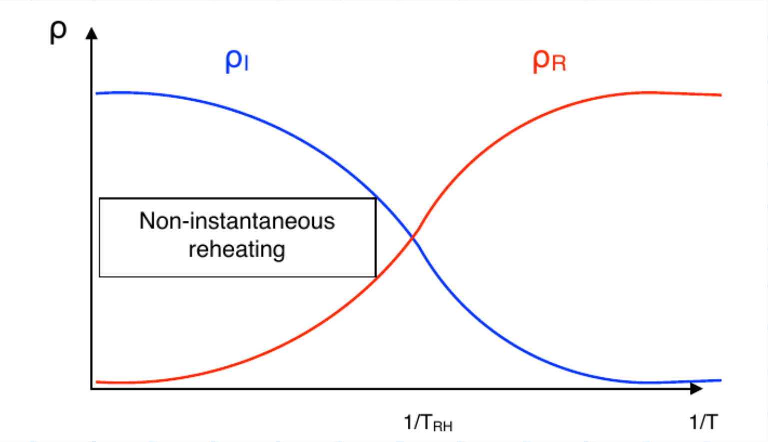
DM-SM coupling is small

DM not in thermal equilibrium

Freeze-in production from negligible initial abandunce

Non-instantaneous Reheating





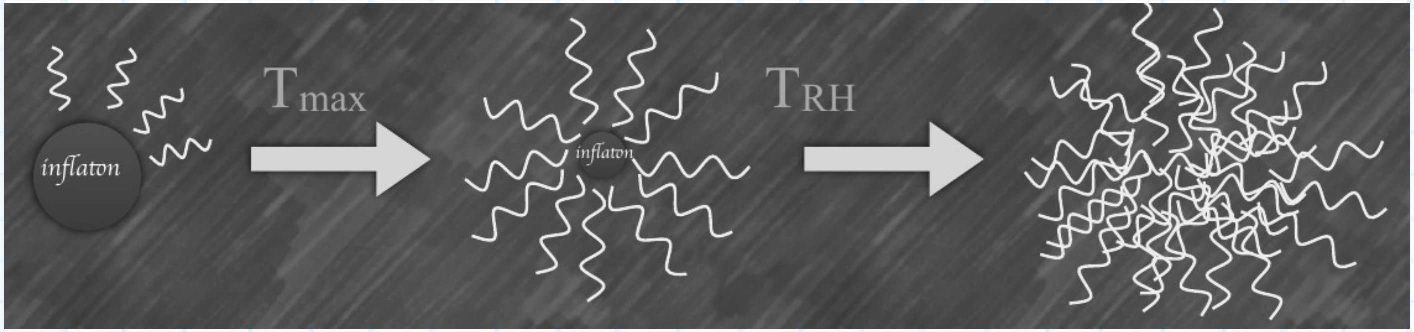


Figure courtesy: Y Mambrini

Giudice et al. (2001),
Garcia et al. (2017),
Chowdhury et al. (2018)
...

Inflaton dominated era: $T \propto a^{-3/8} \quad H \propto T^4 \implies Y_\chi \propto n_\chi / T^8$

Radiation dominated era: $T \propto a^{-1} \quad H \propto T^2 \implies Y_\chi \propto n_\chi / T^3$

Maximum temperature during reheating

$$T_{\rm MAX} \propto \left(\frac{m_\phi}{\Gamma_\phi}\right) T_{\rm RH} \gg T_{\rm RH}$$

UV vs. IR Freeze-in

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T)$$ ← **Rate of DM production**

$$\Omega h^2 \simeq \Omega h^2_{\mathrm{R}D} + \Omega h^2_{\mathrm{I}D}$$

$$\propto m_\chi \left[\int_{T_0}^{T_{\mathrm{RH}}} \frac{R(T)}{T^6} + 1.07\, T_{\mathrm{RH}}^7 \int_{T_{\mathrm{RH}}}^{T_{\mathrm{MAX}}} \frac{R(T)}{T^{13}} \right]$$

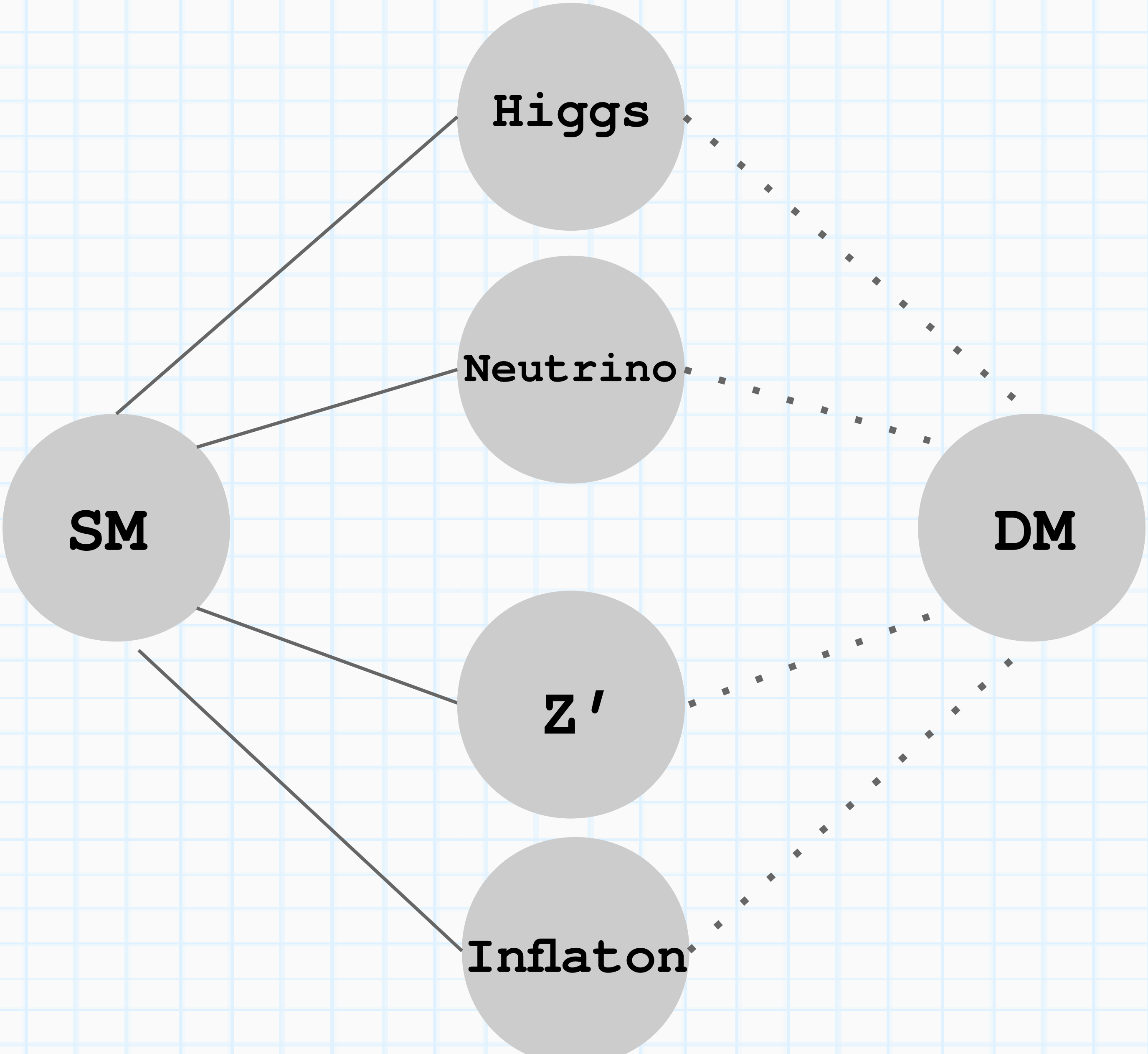
$$R(T) \sim \begin{cases} T^4 \\ \frac{T^8}{\Lambda^4} \\ \frac{T^{12}}{\Lambda^8} \end{cases} \Longrightarrow \frac{\Omega h^2_{\mathrm{ID}}}{\Omega h^2} \begin{cases} \ll 1\% \\ \sim 40\% \\ > 95\% \end{cases}$$

IR dominated production ($\ll 1\%$)

UV dominated production ($> 95\%$)

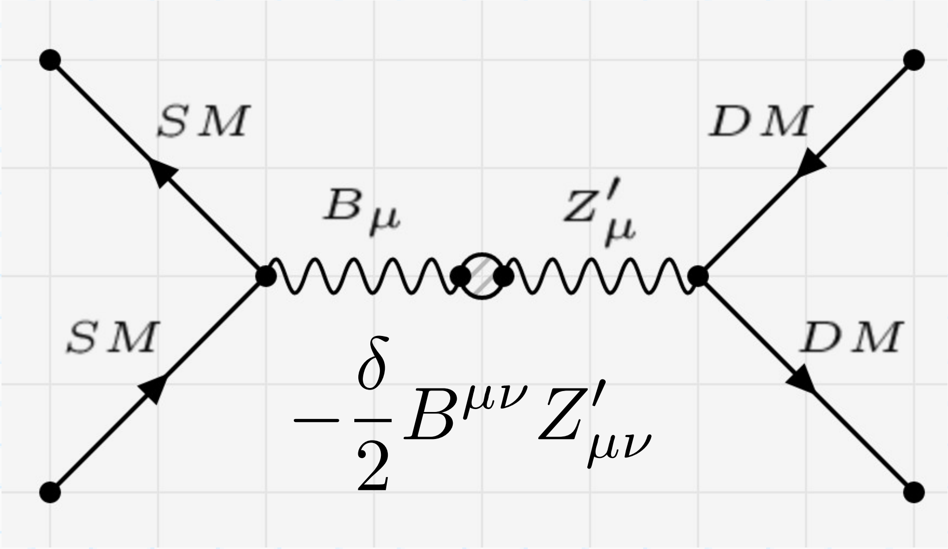
Assuming: $T_{\mathrm{MAX}} \sim 100 T_{\mathrm{RH}}$

Portals to the Dark sector



Kinetic mixing portal

$G_{SM} \times U(1)'$



DM: Dirac fermion charged under U(1)'

Z' receives mass by dark Higgs / Stuckelberg mechanism

Requirement of Freeze-in production: $\delta \ll 1$

How to generate a small mixing?

Generating *tiny* kinetic mixing

Dictated by symmetry:

- Non-Abelian parentage at UV forbids kinetic mixing

$$G \supset \mathrm{U}(1)' \quad \Longrightarrow \delta \to 0$$

- Discrete symmetries forbidding mixing

$$Z'_\mu \to -Z'_\mu, B_\mu \to -B_\mu \quad \Longrightarrow \delta \to 0$$

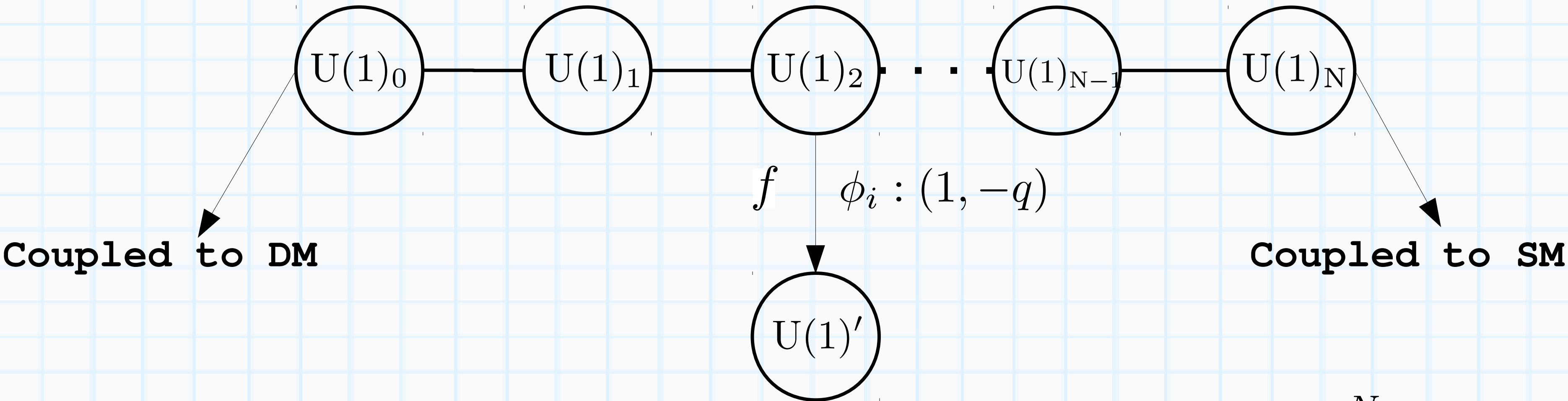
Small mixing is proportional to amount of symmetry breaking

Holdom (1986),
Dienes et al (1997)...

Clockworked mixing:

$$\delta \sim \frac{\mathcal{O}(1)}{q^N}, \qquad q \sim 3, \quad N \sim \mathcal{O}(10)$$

Clockworked kinetic mixing



$$\mathcal{L}_{\text{mass}} = \sum_{k=0}^{N-1} \frac{g_c^2 f^2}{2} \left(A_\mu^k - q A_\mu^{k+1}\right)^2$$

$$A_\mu^N = \frac{N_0}{q^N} Z'_\mu + \sum_{k=1}^{N} a_{Nk} \tilde{A}_\mu^k$$

$$A_\mu^0 = N_0 Z'_\mu + \sum_{k=1}^{N} a_{0k} \tilde{A}_\mu^k$$

$$-\frac{\delta}{2} B^{\mu\nu} A_{\mu\nu}^N \longrightarrow -\frac{\delta}{2} \frac{N_0}{q^N} B^{\mu\nu} Z'_{\mu\nu}$$

$$q = 3,\ N = 20 \implies \delta \sim 10^{-10}$$

Giudice et al. (2016)...,
Gherghetta et al. (2019)

Rate of DM production

$$\frac{dn_\chi}{dt} + 3Hn_\chi = R(T) \quad \Rightarrow \quad R(T) \sim T \int_{4m_\chi^2}^{\infty} ds \sqrt{s - 4m_\chi^2}\, K_1\left(\frac{\sqrt{s}}{T}\right) |\mathcal{M}|^2$$

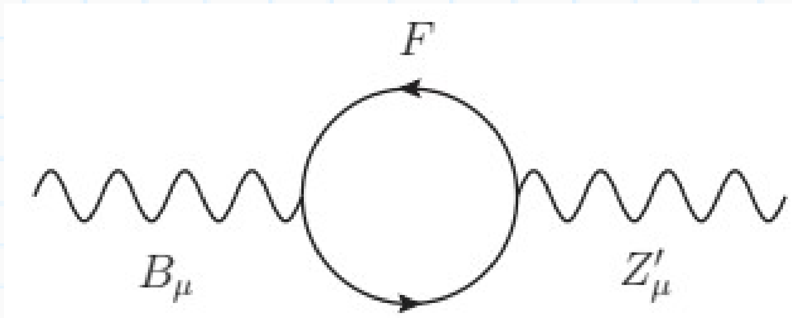
$$R(T) = \mathcal{C}^{\text{const}} \times \begin{cases} \delta^2 T^4\,, & (M_{Z'} \ll T) \\ \delta^2 M_{Z'}^4 \dfrac{T}{\Gamma_{Z'}} K_1\left(\dfrac{M_{Z'}}{T}\right)\,, & (M_{Z'} \sim T) \\ \delta^2 \dfrac{T^8}{M_{Z'}^4}\,, & (M_{Z'} \gg T) \end{cases}$$

DM production mostly after the end of reheating

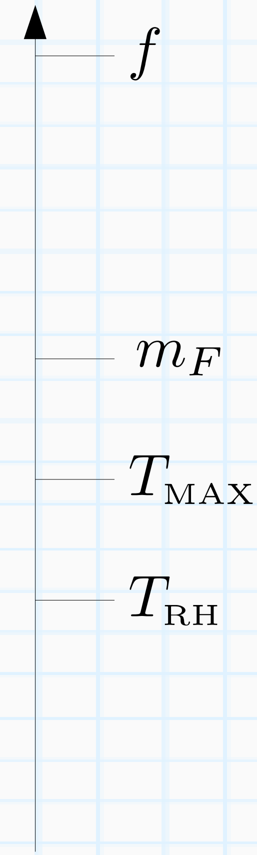
(IR dominated production)

Dynamic portal for UV freeze-in

Adding a hybrid fermion: $\mathcal{L}_{\text{hybrid}} = \bar{F}(i\partial\!\!\!/ - m - g' Q' B\!\!\!/ - g_D Q_D Z\!\!\!/') F$



$$\delta_{\text{mix}} \sim \begin{cases} -\dfrac{g' Q' g_D Q_D}{12\pi^2} \ln\left(\dfrac{p^2}{m_F^2}\right), & (p^2 \gg m_F^2) \\ -\dfrac{g' Q' g_D Q_D}{60\pi^2} \dfrac{p^2}{m_F^2}, & (p^2 \ll m_F^2) \end{cases}$$



Decoupling of heavy particles

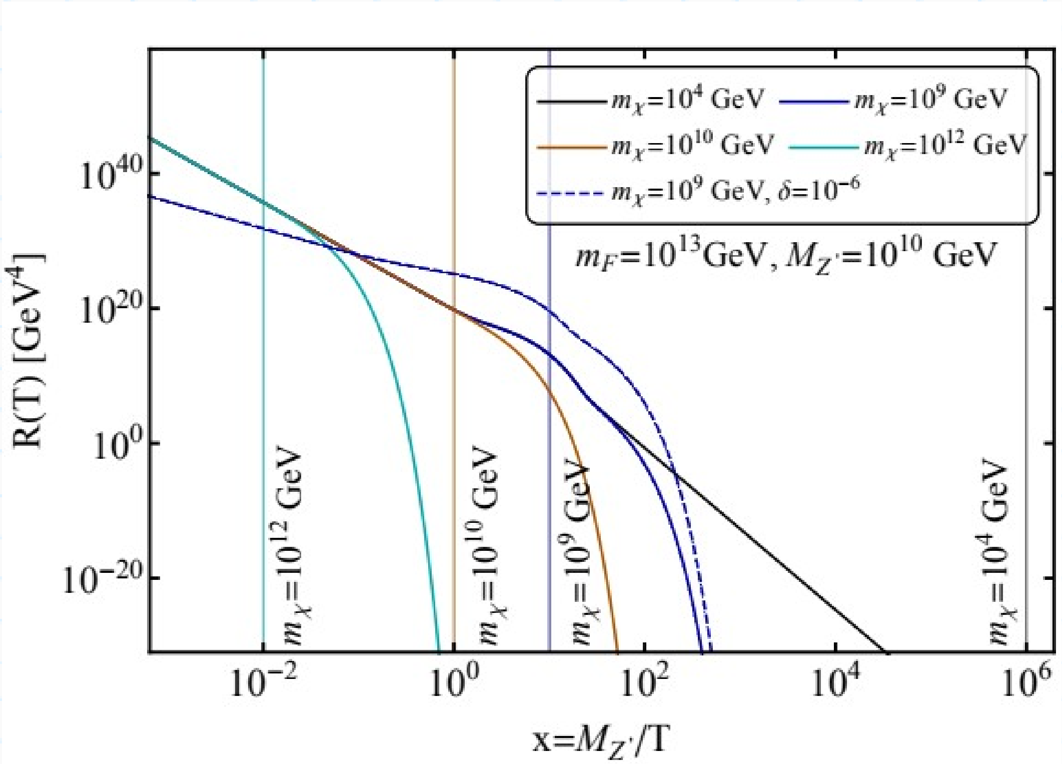
Recall the origin of Lamb Shift in QED

AB, G Bhattacharyya, D Chowdhury, Y Mambrini 1905.11407

Rate again

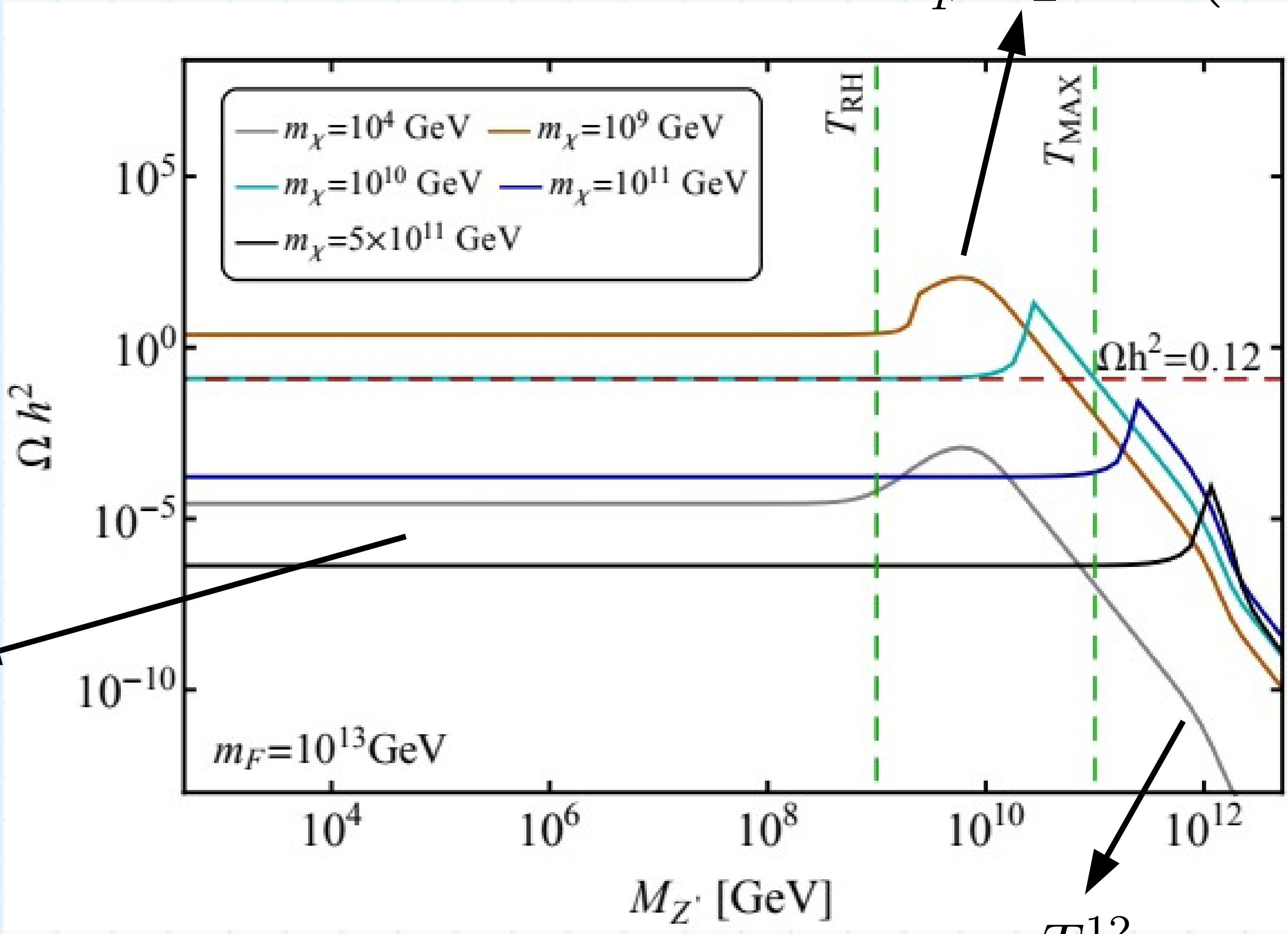
$$R(T) = \frac{\mathcal{C}}{(4\pi)^4} \times \begin{cases} \dfrac{T^8}{m_F^4} \\ \dfrac{M_{Z'}^8}{m_F^4}\dfrac{T}{\Gamma_{Z'}}K_1\left(\dfrac{M_{Z'}}{T}\right) \\ \dfrac{T^{12}}{m_F^4 M_{Z'}^4} \end{cases}$$

$$\mathcal{C}^{\rm const} \times \begin{cases} \delta^2 T^4\,, & (M_{Z'} \ll T) \\ \delta^2 M_{Z'}^4 \dfrac{T}{\Gamma_{Z'}} K_1\left(\dfrac{M_{Z'}}{T}\right)\,, & (M_{Z'} \sim T) \\ \delta^2 \dfrac{T^8}{M_{Z'}^4}\,, & (M_{Z'} \gg T) \end{cases}$$



Relic abundance-I

$$\frac{M_{Z'}^8}{m_F^4}\frac{T}{\Gamma_{Z'}}K_1\left(\frac{M_{Z'}}{T}\right)$$

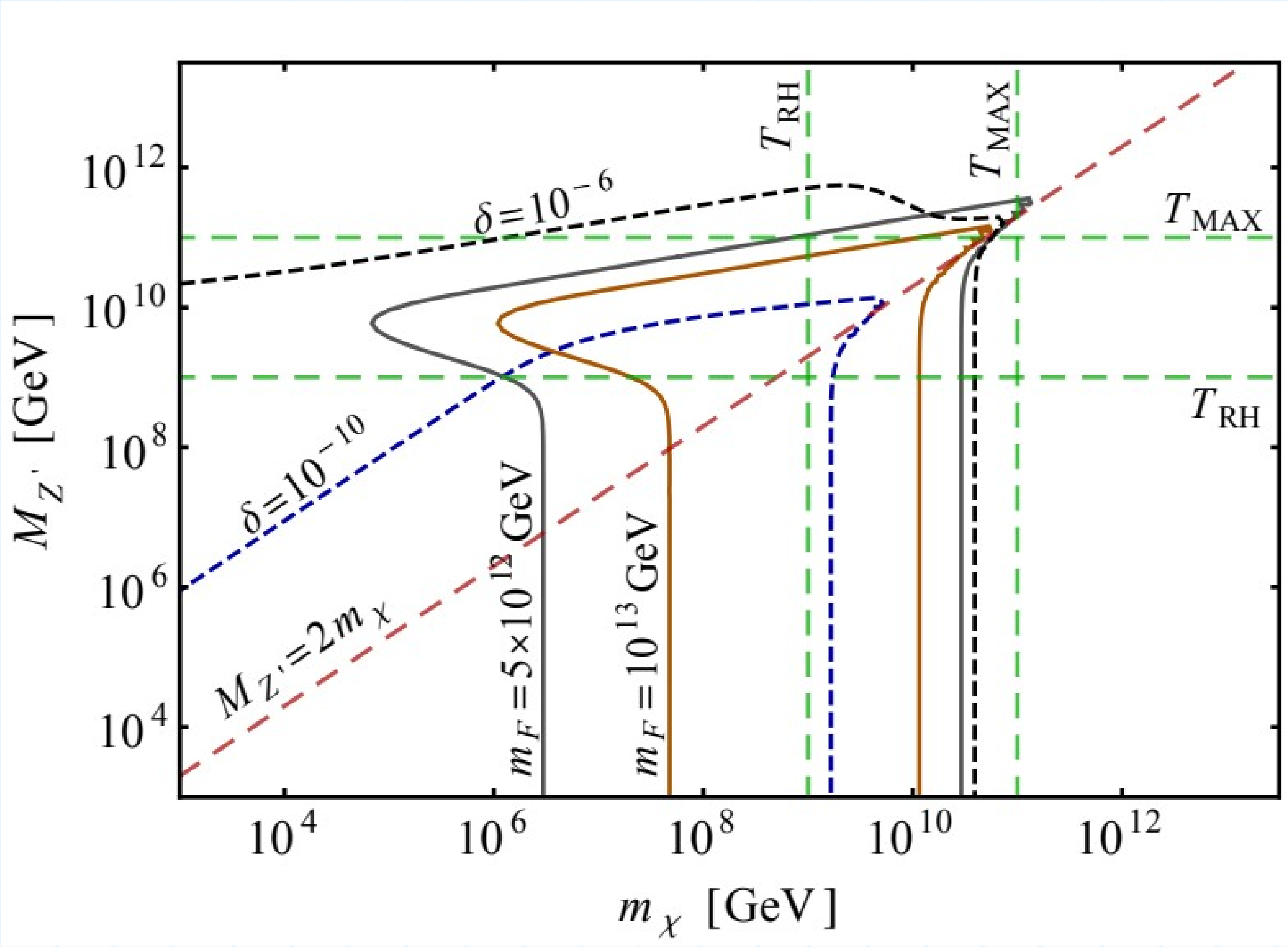


$$\frac{T^8}{m_F^4}$$

$$\frac{T^{12}}{m_F^4 M_{Z'}^4}$$

Relic abundance-II

$$\Omega h^2 \propto m_\chi n_\chi$$



Summary and questions

- UV freeze-in of DM during early phase of reheating
- Freeze-in requires small kinetic mixing : clockwork
- Momentum dependent mixing: integrate out loops of heavy hybrid fermion

Questions

- Initial conditions?
- Experimental signatures? GW from dark phase transition?
- Thermal effects?
- Freeze-out with dynamic mixing?

Thank you!

Backup

Full set of Boltzmann Equations

$$\frac{\mathrm{d}\rho_\gamma}{\mathrm{d}t} \approx -4H\,\rho_\gamma + \Gamma_\phi\,\rho_\phi$$

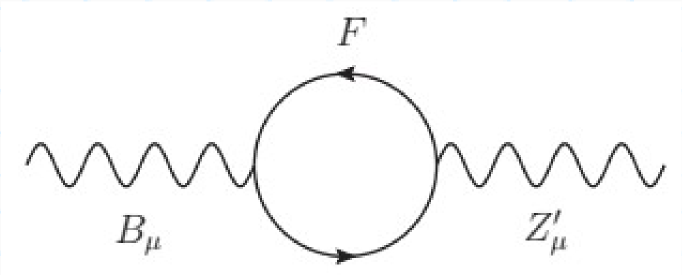
$$\frac{\mathrm{d}\rho_\phi}{\mathrm{d}t} = -3H\,\rho_\phi - \Gamma_\phi\,\rho_\phi$$

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} = -3Hn_\chi + R(T)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} = -H(T)T$$ ← **Radiation dominated era**

$$\frac{\mathrm{d}}{\mathrm{d}t} = -\frac{3}{8}H(T)T$$ ← **Inflaton dominated era**

Loop calculation



$$i\Pi^{\mu\nu}_{Z'B}(p^2) = i\Pi_{Z'B}(p^2)\left(p^2\eta^{\mu\nu} - p^\mu p^\nu\right)$$

$$\Pi_{Z'B}(p^2) \simeq -\frac{(g'Q')(g_D Q_D)}{12\pi^2}\left[\frac{1}{\hat{\epsilon}} + \log\left(\frac{\mu^2}{m_F^2}\right) + \frac{p^2}{5m_F^2} + \mathcal{O}\left(\frac{p^4}{m_F^4}\right)\right] .$$

$$\delta_{\rm ren}(0) = \Pi_{Z'B}(0) - \delta_{\rm CT} = 0$$

$$\delta_{\rm ren}(p^2) = \Pi_{Z'B}(p^2) - \Pi_{Z'B}(0) \simeq -\frac{(g'Q')(g_D Q_D)}{60\pi^2}\frac{p^2}{m_F^2} + \mathcal{O}\left(\frac{p^4}{m_F^4}\right)$$