Nonthermal dark matter production from a light thermal scalar

Shao-Ping Li

Institute of High Energy Physics, Chinese Academy of Sciences

June 6, HPNP 2023@ Osaka U.

Based on: 2211.16802; 2301.02835

Outline

- Forbidden decay production of freeze-in DM from a light thermal scalar

- Scattering from forbidden scalar decay diagram

- Relative effects of forbidden decay and scattering

Forbidden Decay for Nonthermal DM Production

- In most situations, the nonthermal DM is produced from decay

$$A \to B + \mathrm{DM} \qquad \text{if} \qquad m_A > m_B + m_{\mathrm{DM}}$$

- When A is much lighter than DM, the vacuum decay is kinematically forbidden

$$A \nrightarrow B + \mathrm{DM} \qquad \text{if} \qquad m_A < m_B + m_{\mathrm{DM}}$$

Forbidden Decay for Nonthermal DM Production

- When A equilibrates in a thermal plasma, there exists a temperature regime for *thermally induced decay, or forbidden decay*

$$A \xrightarrow{\text{FD}} B + \text{DM} \qquad \text{if} \qquad m_A(T > T_c) > m_B + m_{\text{DM}}$$

↳ As a thermal correction to vacuum decay

$$m_A(T = 0) > m_B + m_{\text{DM}}$$

↳ As a purely thermal production of DM

$$m_A(T = 0) < m_B + m_{\text{DM}}$$

Scattering from Forbidden Decay Diagram

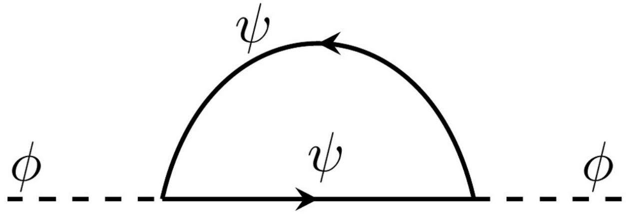
- Usually, scattering is suppressed by higher-order weak couplings and phase-space factors. However, *It is NOT always true in forbidden decay*!

- An example of forbidden scalar decay

$$\mathcal{L} = \underbrace{y_\chi \bar{\chi}\chi\phi}_{\text{DM production}} + \underbrace{y_\psi \bar{\psi}\psi\phi}_{\text{thermalization background}}$$

$$m_\phi(T=0) < 2m_\chi \qquad m_\phi(T>T_c) > 2m_\chi$$

Nonthermal DM $\quad m_\chi(T) \ll m_\chi(T=0)$

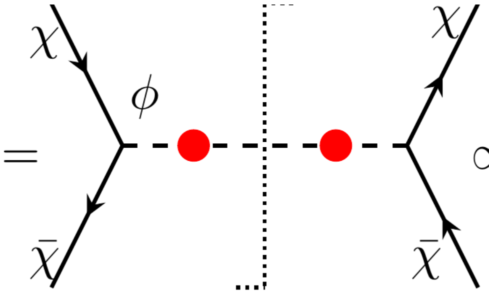


Thermal mass correction at finite T

$$m_\phi \equiv \kappa T$$

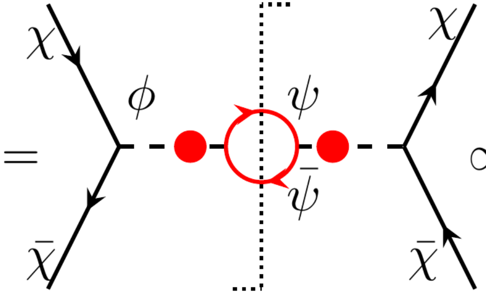
Scattering from Forbidden Decay Diagram

$$|\mathcal{M}|^2_{\phi\to 2\chi} =$$

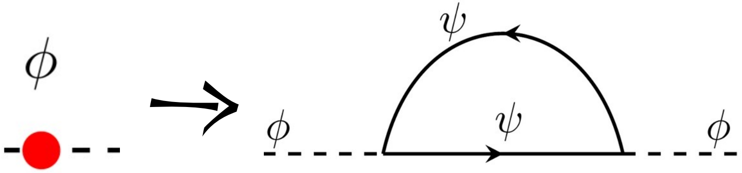


$$\propto y_\chi^2 \kappa^2$$

$$|\mathcal{M}|^2_{2\psi\to 2\chi} =$$



$$\propto y_\chi^2 y_\psi^2$$



$$m_\phi^2(T) \sim y_\psi^2 T^2$$

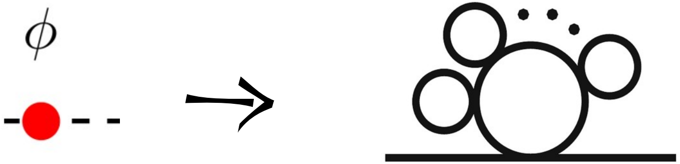
$$\kappa = \mathcal{O}(y_\psi)$$

Forbidden decay & scattering coexist, share the same order of couplings

A Special Exception

- If the scalar has only quartic interactions $\lambda\phi^4$

Luc Darmé, *et al*,1908.05685;
Partha Konar, *et al*, 2110.14411;



One-loop thermal mass correction with daisy rings

$$m_\phi^2(T) \sim \lambda T^2 \longrightarrow$$

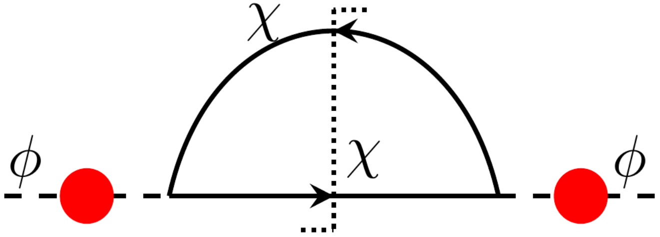
$$|\mathcal{M}|^2_{\phi\to 2\chi} \propto m_\phi^2 \sim y_\chi^2 \lambda$$

$$|\mathcal{M}|^2_{n\phi\to 2\chi} \sim y_\chi^2 \lambda^2$$ n=2 or 3

If the quartic coupling is small, the forbidden decay dominates the DM production

Forbidden Scalar Decay Rate

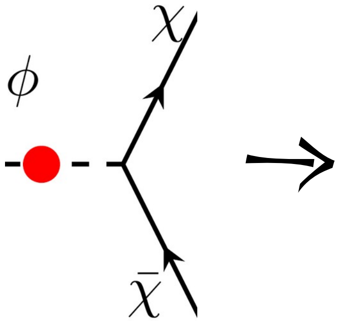
- Method 1: thermal field theory H.Weldon, PRD, 28 (1983) 2007



red blob: hard-thermal-loop resummation at finite T

$$E^2 \approx k^2 + m_\phi^2(T) \quad \text{for} \quad m_\phi(T=0) \ll m_\phi(T>0)$$

- Method 2: tree-level amplitude M. Drewes & J. U. Kang, 1510.05646



vacuum mass ⟶ thermal mass

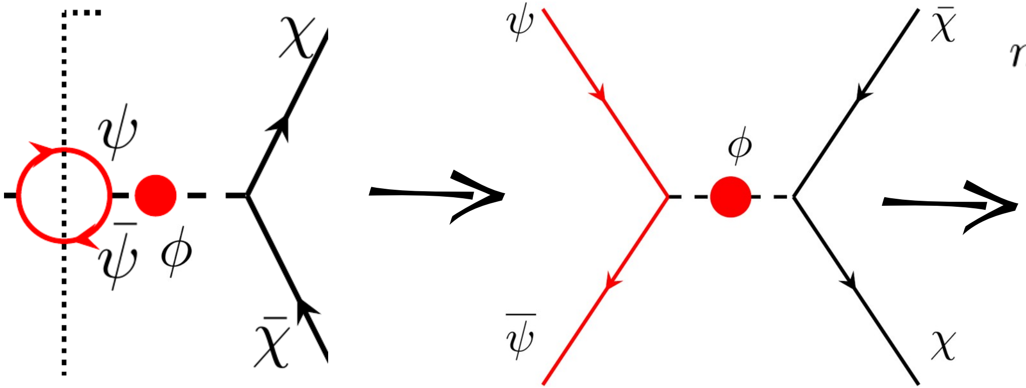
$$\Gamma_{\phi\to 2\chi} = \frac{y_\chi^2}{8\pi} m_\phi \left(1 - \frac{4m_\chi^2}{m_\phi^2}\right)^{3/2}$$

Caution: NOT for fermions!

S.-P. Li, 2301.02835

Scattering Rate

on-shell cut



$$m_\psi(T=0) \ll m_\chi, m_\phi(T=0) \ll m_\chi$$

$$\sigma_{2\psi\to 2\chi} = \frac{y_\chi^2 y_\psi^2}{4\pi\sqrt{s}} \frac{(s-4m_\chi^2)^{3/2}}{[s-\mathrm{Re}\Pi_R^\phi]^2 + [\mathrm{Im}\Pi_R^\phi]^2}$$

- If resonance present, include the thermal corrections to off-shell mediator.

Boltzmann Equation for DM Production

$$\dot{n}_\chi + 3Hn_\chi = 2\gamma_{\phi\to 2\chi} + 2\gamma_{2\psi\to 2\chi}$$

forbidden decay — scattering

$$\gamma_{\phi\to 2\chi} = \frac{\kappa^3 y_\chi^2 K_1(\kappa)}{16\pi^3}\left(1-\frac{4m_\chi^2}{\kappa^2 T^2}\right)^{3/2} T^4$$

Vacuum-like dispersion relation

$m_\phi \equiv \kappa T$

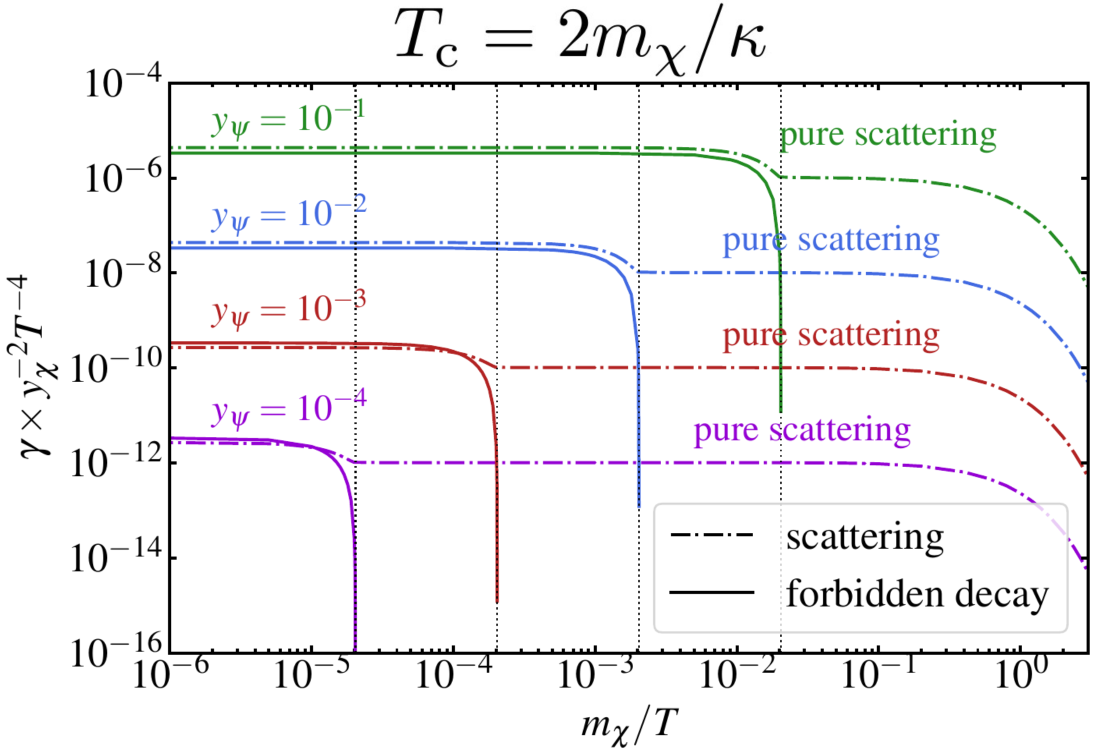
$E^2 - k^2 = \mathrm{Re}_R^\phi,\ \kappa = y_\psi/6$

$\propto y_\chi^2 y_\psi^2$

$$\gamma_{2\psi\to 2\chi} \approx \frac{T}{32\pi^4}\int_{4m_\chi^2}^{\infty} ds\,\sigma_{2\psi\to 2\chi}\, s^{3/2} K_1(\sqrt{s}/T) \quad \propto y_\chi^2 y_\psi^2$$

- Scattering & forbidden decay share the same order of couplings

Comparison between Scattering and Decay



- At high T

Thermal correction to mediator included, resonant effect compensates suppression of phase-space factors

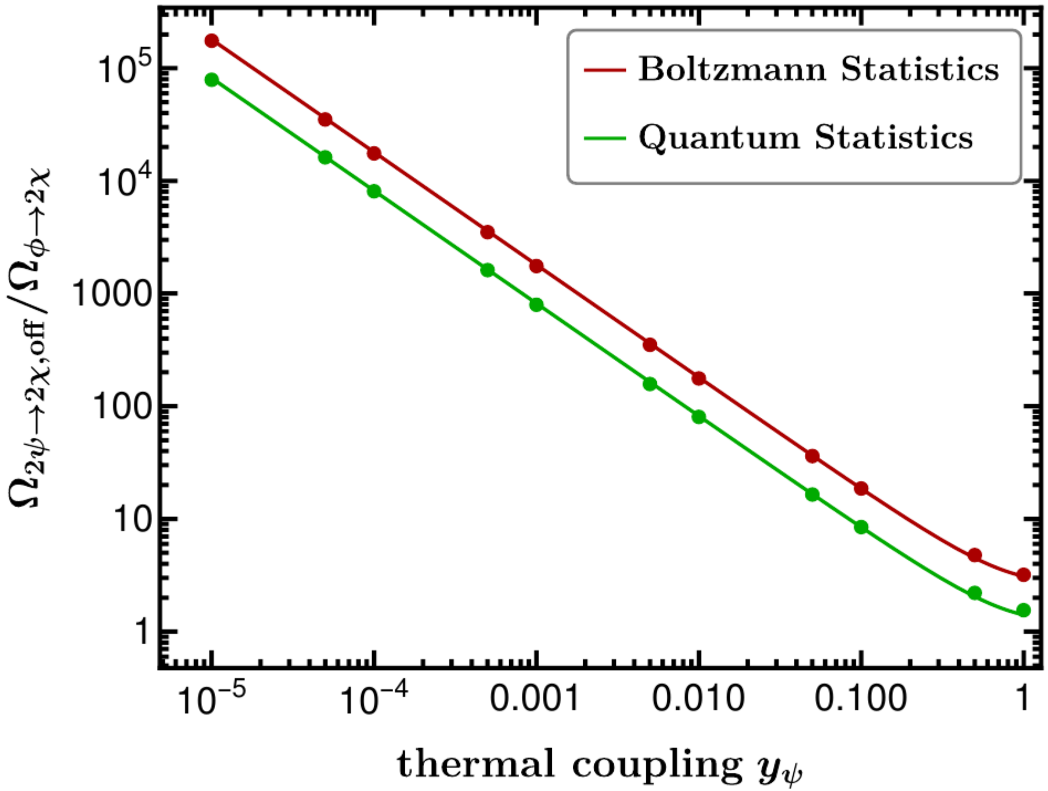
$$\gamma_{2\psi\to 2\chi} \approx 1.3\gamma_{\phi\to\chi}$$

for $y_\psi = 0.1 - 0.01$

- After critical T

Only scattering exists, a longer duration than the forbidden decay

DM Relic Density in Scalar Forbidden Decay



- Fitted formula (Boltzmann)

$$\frac{\Omega_{2\psi\to 2\chi}}{\Omega_{\phi\to 2\chi}} \approx 0.8 y_\psi + 1.8 y_\psi^{-1} + 0.5$$

- For large thermal coupling, both channels are comparable

$$\frac{\Omega_{\mathrm{decay}}}{\Omega_{\mathrm{tot}}} \approx 20\% \quad \text{for} \quad y_\psi = 0.5$$

- For small thermal coupling, the scattering takes over

$$\frac{\Omega_{2\psi\to 2\chi}}{\Omega_{\phi\to 2\chi}} \simeq 10^3 \quad \text{for} \quad y_\psi = 10^{-3}$$

Summary

Where to consider forbidden scalar decay?

↳ ✔ Heavy DM production from a light scalar mediator

When forbidden scalar decay matters?

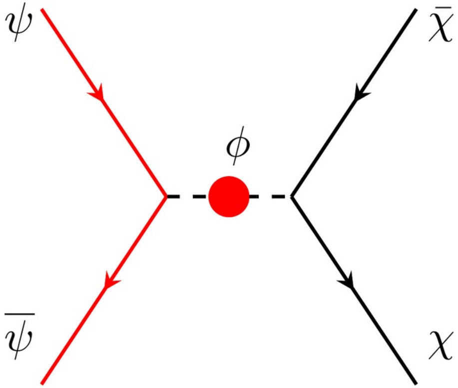
↳ ✔ Not-too-weak corrections to the light mediator $\mathcal{O}(0.1-1)$
✔ Strong quartic self-coupling

How to implement forbidden scalar decay?

↳ ✔ Tee-level amplitude with a vacuum-like dispersion (neither for fermions nor possibly for vectors)

Thanks for your attention!

Backup: Scattering Rate w/wo Thermal Propagator



Scalar dispersion relation: $E^2 \approx k^2 + m_\phi^2(T)$ $\quad m_\phi(T) = \frac{y_\psi}{\sqrt{6}} T$

fermion dispersion relation--two modes:

$$\omega_1 \approx k \qquad E_\psi^2 - k^2 \approx 2m_\psi^2(T) \qquad m_\psi(T) = \frac{y_\psi}{4} T$$

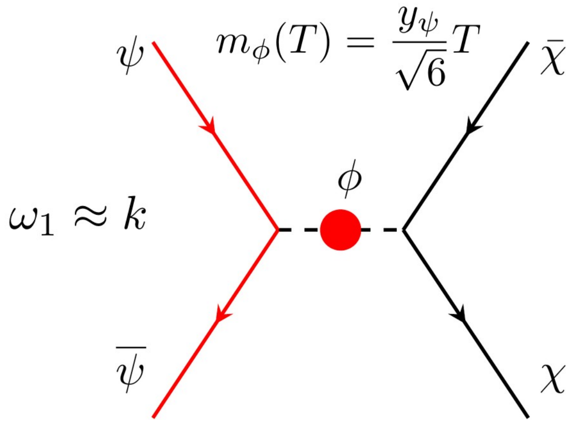
Check if there is an on-shell crossing point $\quad (P_1 + P_2)^2 = s \sim m_\phi^2(T)$

↳ Only the massless mode allows an on-shell crossing in the collinear regime:

$$\theta \equiv \cos^{-1}(\vec{p}_1 \cdot \vec{p}_2 / p_1 p_2) \sim \mathcal{O}(y_\psi)$$

Backup: Scattering Rate w/wo Thermal Propagator

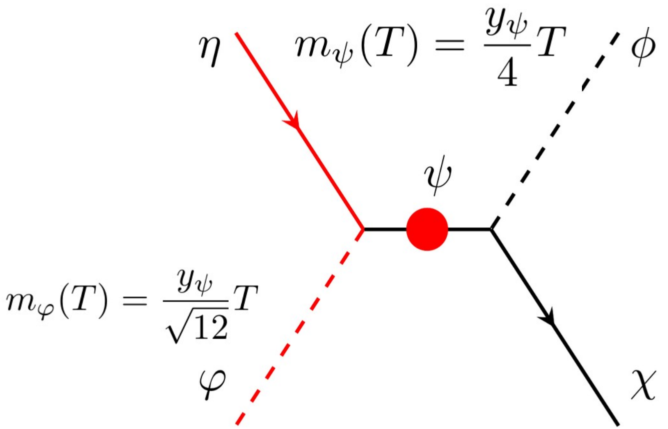
- For scalar mediator



Allow on-shell scalar propagation. Thermal propagator included.

$$\sigma_{2\psi\to 2\chi} = \frac{y_\chi^2 y_\psi^2}{4\pi\sqrt{s}} \frac{(s - 4m_\chi^2)^{3/2}}{[s - \mathrm{Re}\Pi_R^\phi]^2 + [\mathrm{Im}\Pi_R^\phi]^2}$$

- For fermion mediator



No on-shell fermion propagation. Thermal propagator neglected.

$$\sigma_{\varphi\eta\to\chi\phi} = \frac{y_\chi^2 y_\psi^2}{32\pi s}(1 - \frac{m_\phi^2}{s})^2$$