Dark Matter Bound State Formation in a Z_2 Model with Light Dark Photon and Dark Higgs Boson

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- In the literature:
- Sommerfeld Enhancement Calculations
- Dark Matter Bound State Formation through emitting a dark scalar
- Dark Matter Bound State Formation through emitting a dark photon
- arXiv:1611.01394 Kalliopi Petraki, Marieke Postma, Jordy de Vries, a Complete Classification?

Dark Matter Bound State Formation,
Dark Scalar+Dark Photon Combination?

Dark Higgs Mechanisms,
U(1)->Z_2 symmetry breaking.

Real y to conserve CP ↑

$$\mathscr{L} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi$$
$$+D_\mu\Phi^* D^\mu\Phi - \mu^2\Phi^*\Phi - \lambda|\Phi|^4 + (\frac{\sqrt{2}}{2}y\Phi\overline{\chi^C}\chi + \text{h.c.}),$$

↓ Appropriate Quantum Number Assignment. Crucial!

χ Is composed with χ_L and χ_R.

$$\Phi \to \frac{\sqrt{2}}{2}(v + R + iI)$$

$$\chi_1 = \frac{1}{\sqrt{2}}(\chi_L - \chi_R),$$

$$\chi_2 = \frac{i}{\sqrt{2}}(\chi_L + \chi_R)\,.$$

Mass Matrix:

$$\frac{1}{2}[\,\chi_1^T \;\; \chi_2^T\,] \begin{bmatrix} m - \delta m & 0 \\ 0 & m + \delta m \end{bmatrix} \begin{bmatrix} \chi_1 \\ \chi_2 \end{bmatrix} + \text{h.c.}.$$

Interactions:

$$\mathcal{L} \supset \frac{1}{2}[\,\chi_1^T \;\; \chi_2^T\,] \begin{bmatrix} -yR & yI \\ yI & yR \end{bmatrix} \begin{bmatrix} \chi_1 \\ \chi_2 \end{bmatrix} + \text{h.c.}.$$

$$\mathcal{L} \supset [\,\chi_1^\dagger \;\; \chi_2^\dagger\,] \begin{bmatrix} 0 & Q_\chi g A' \cdot \sigma \\ -Q_\chi g A' \cdot \sigma & 0 \end{bmatrix} \begin{bmatrix} \chi_1 \\ \chi_2 \end{bmatrix} + \text{h.c.}.$$

Two-component Schroedinger equations:

$$
\begin{aligned}
-\frac{\vec{\nabla}^2}{m_\chi}\psi_{\rm s}(\vec{x}) + V_{\rm s}\psi_{\rm s}(\vec{x}) &= E\psi_{\rm s}(\vec{x}), \\
-\frac{\vec{\nabla}^2}{m_\chi}\psi_{\rm d}(\vec{x}) + V_{\rm d}\psi_{\rm d}(\vec{x}) &= E\psi_{\rm d}(\vec{x}),
\end{aligned}
$$

Two-dimensional vector

2x2 matrix

$\chi_1\chi_1 \leftrightarrow \chi_2\chi_2$ R-Yukawa, attractive

R-contribution

Dark photon-contribution

$$V_{\mathrm{s},\alpha'} = \begin{bmatrix} -\frac{c_1 e^{-\frac{x}{\xi_1}}}{x} & -\frac{(c_2-c_1)e^{-\frac{x}{\xi_2}}}{x} \\ -\frac{(c_2-c_1)e^{-\frac{x}{\xi_2}}}{x} & -\frac{c_1 e^{-\frac{x}{\xi_1}}}{x} + \delta\gamma^2 \end{bmatrix} .$$

Dark Goldstone-contribution

Mass difference

Usually missing in the literature

$\chi_1\chi_2 \leftrightarrow \chi_2\chi_1$ R-Yukawa, repulsive

R-contribution

Dark photon-contribution

$$V_{\mathrm{d},\alpha'} = \begin{bmatrix} \frac{c_1 e^{-\frac{x}{\xi_1}}}{x} & \frac{(c_2+c_1)e^{-\frac{x}{\xi_2}}}{x} \\ \frac{(c_2+c_1)e^{-\frac{x}{\xi_2}}}{x} & \frac{c_1 e^{-\frac{x}{\xi_1}}}{x} \end{bmatrix} ,$$

Dark Goldstone-contribution

Solving the Schroedinger equation:

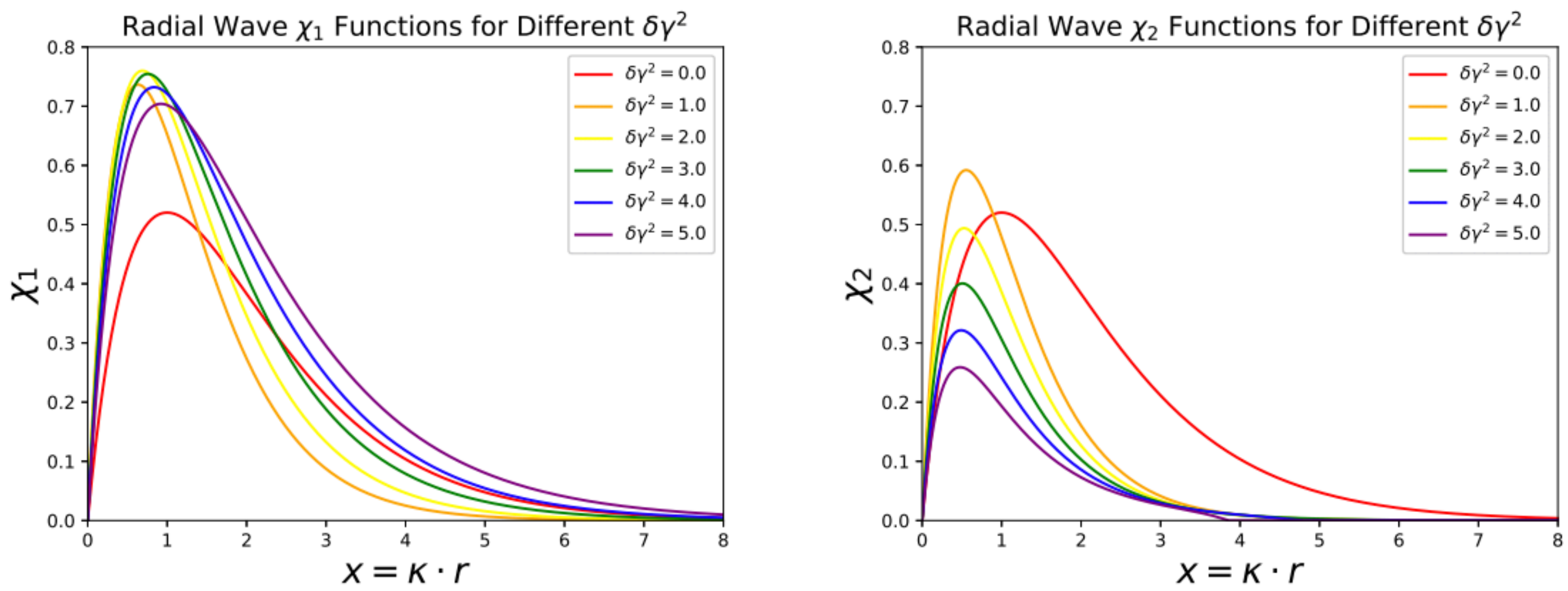


FIG. 1: Wave functions of the ground state for different $\delta\gamma^2$. Here we adopt $c_1 = 0.35$, $c_2 = 1$, $\xi_1 = 200$, $\xi_2 = 100$. We can see clearly that the χ_2 reduces as the $\delta\gamma^2$ accumulates. Here we only plot the $A > 0$ case, and the wave functions are normalized.

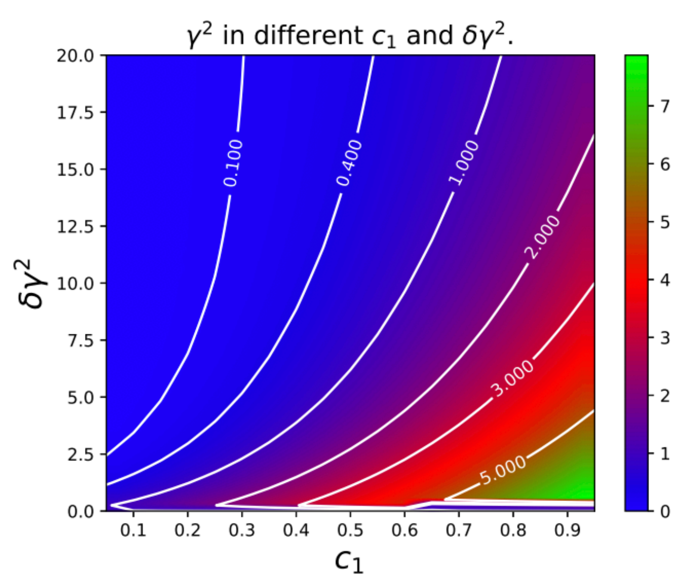
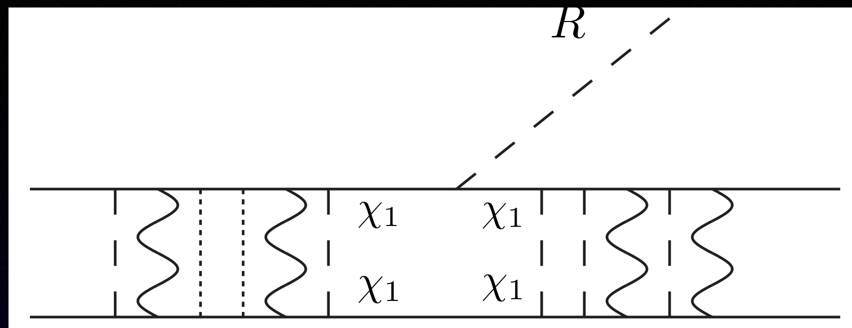
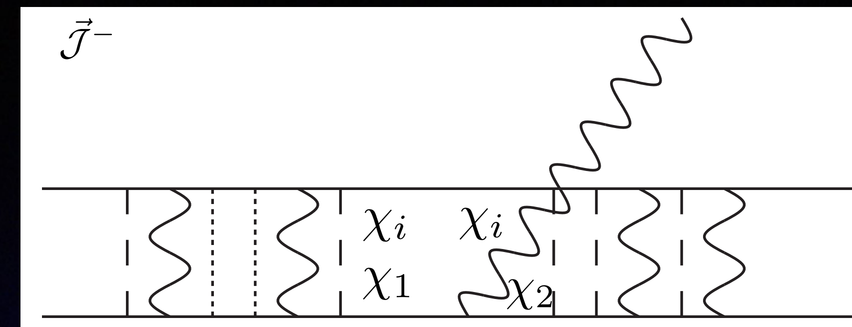


FIG. 2: γ^2, which indicates the bound-energy, versus different c_1 and $\delta\gamma^2$. Here c_2 is fixed to be 1, and $\xi_1 = 200$, $\xi_2 = 100$.



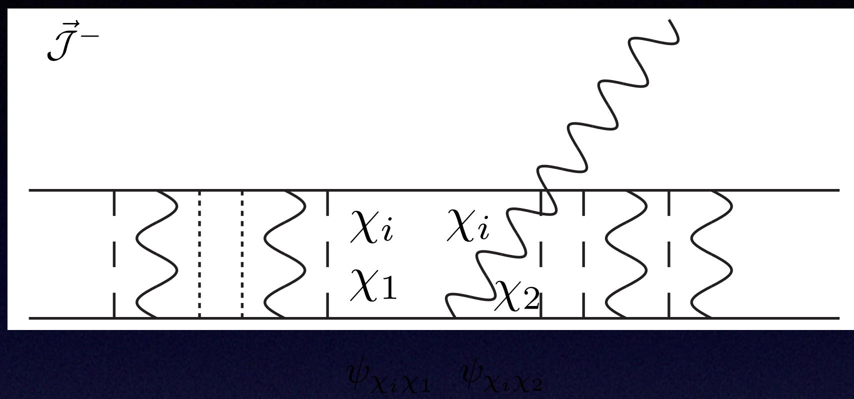


- We calculated the emission of R and γ' to form a dark matter bound state.

- Traditionally, lowest order of emitting a scalar will be eliminated by the orthogonality of the two wave functions.

- Lowest order of emitting a photon will be suppressed by "di-pole" coefficients.

Longitudinal dark photon/dark goldstone



Directly calculate the M0 requires the complete Bethe-Salpeter Wave functions!

Ward-Takahashi Identity in the Broken phase

$$\mathscr{M}^0 \leftrightarrow \mathscr{M}_{\text{GS}}$$

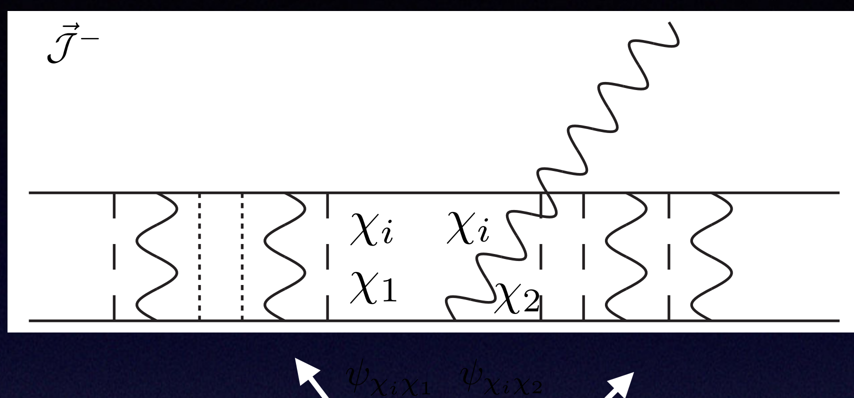
$$k_\mu \mathscr{M}^\mu = \Delta m \mathscr{M}_{\text{GS}}$$

$$\mathscr{M}^0 = \frac{k_i \mathscr{M}^i + \Delta m \mathscr{M}_{\text{GS}}}{k^0}$$

Easily acquired from Schroedinger wave Functions

This connects the longitudinal polarization With the Goldstone emission diagrams.

Longitudinal dark photon/dark goldstone



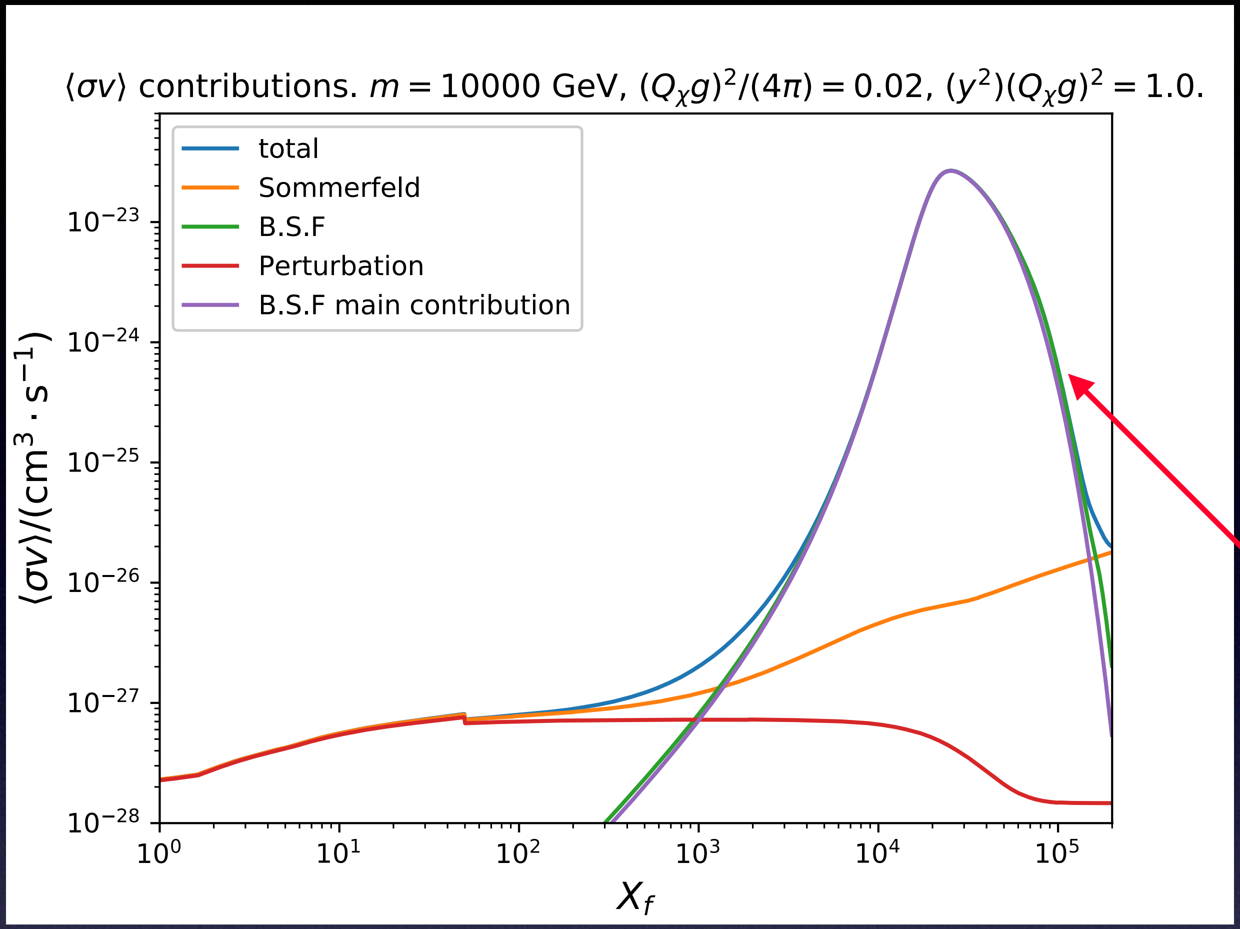
Different potential
->Different Schroedinger equation
->non-orthogonality of wave functions!

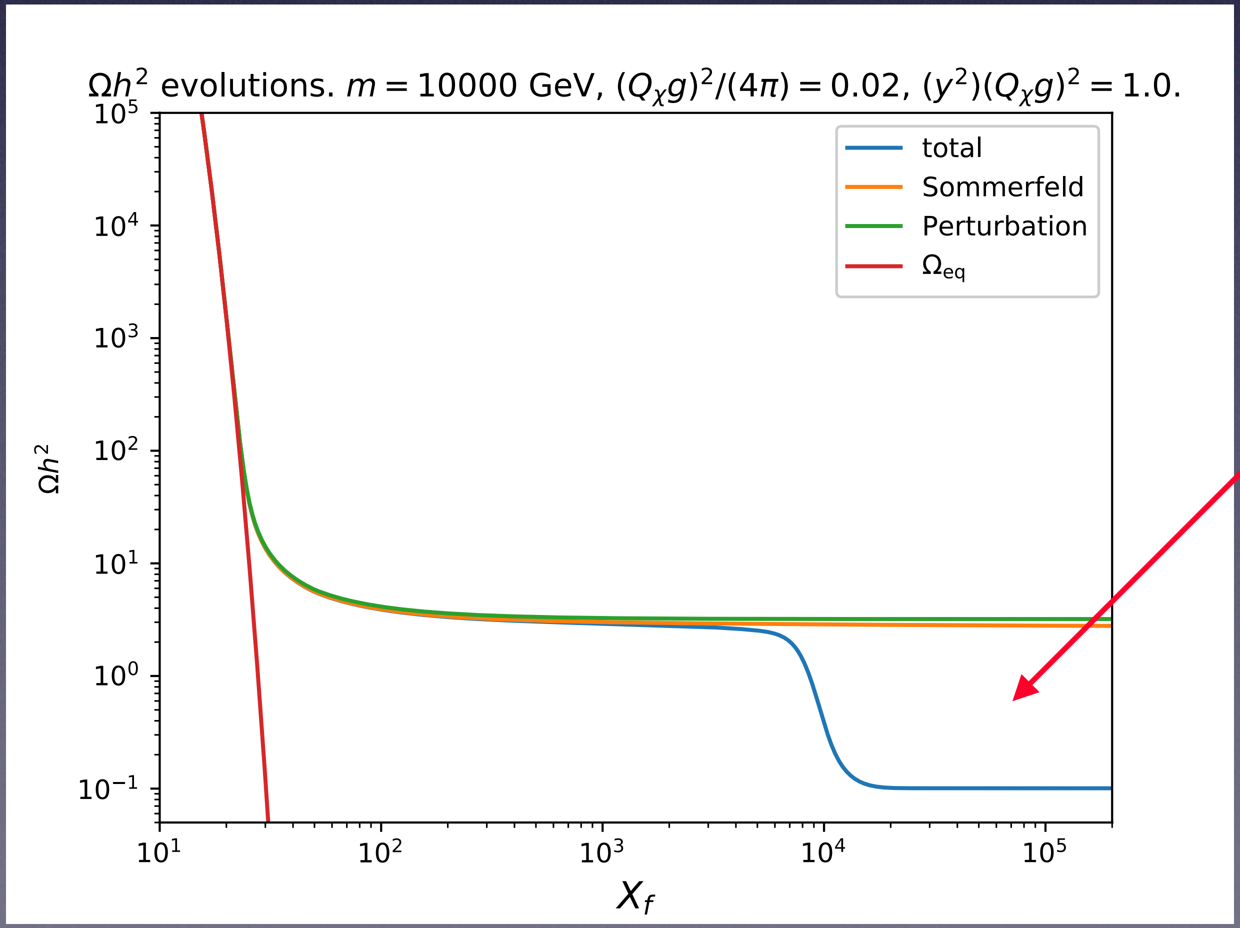
$$\mathcal{M}_{\text{GS, s->d, or d->s},\vec{k}} = 2g\sqrt{2\mu}(2m)\left(\mathcal{I}^+_{\text{s->d, or d->s},\vec{k},nlm}\left(\frac{\vec{p}_{\gamma'}}{2}\right) + \mathcal{I}^-_{\text{s->d, or d->s},\vec{k},nlm}\left(\frac{\vec{p}_{\gamma'}}{2}\right)\right)$$

Zero-th order “mono-pole” contribution becomes nonzero!

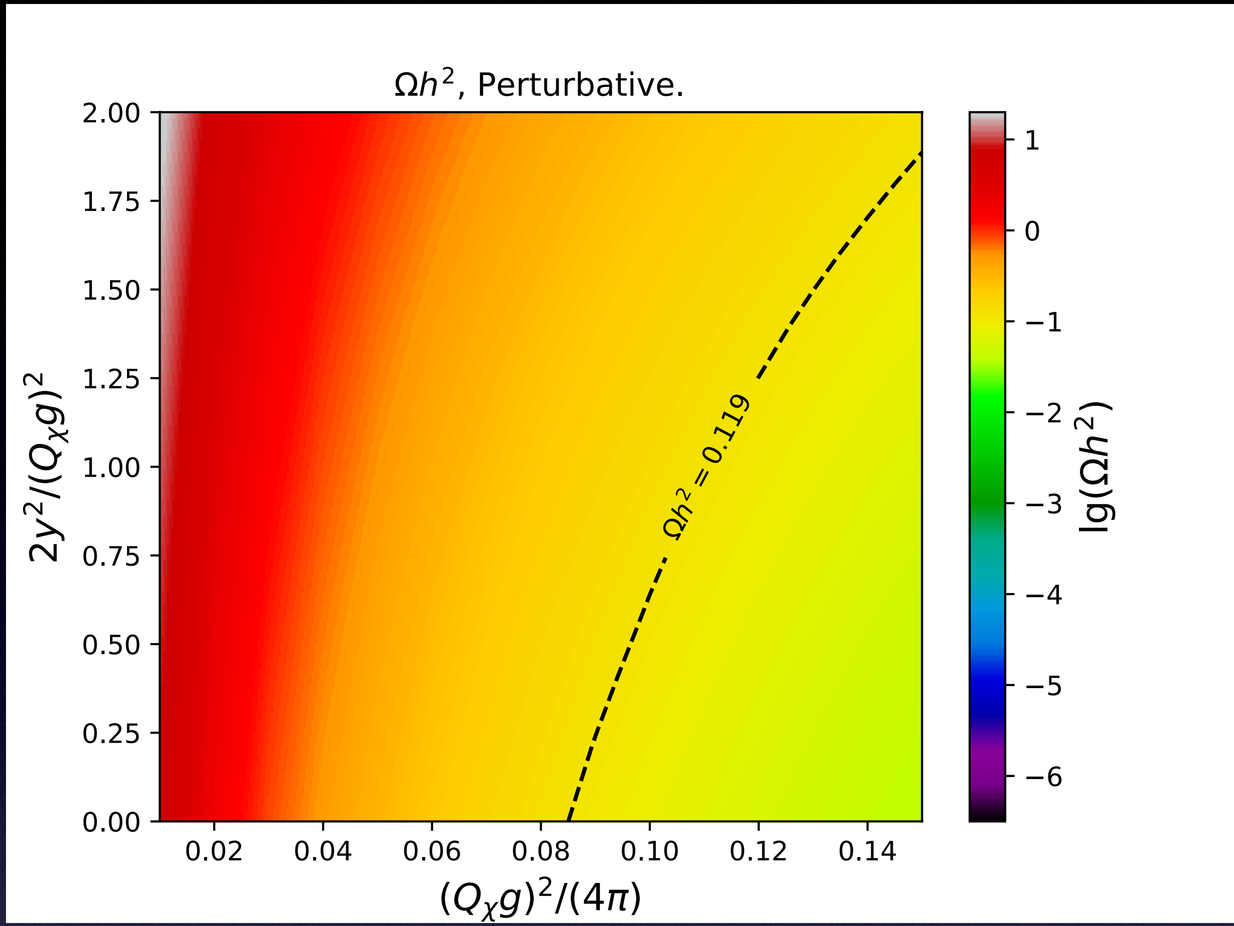
- Dark Matter Bound State formation through emitting a longitudinal γ' , or equivalently, a dark Goldstone boson I , is crucial!

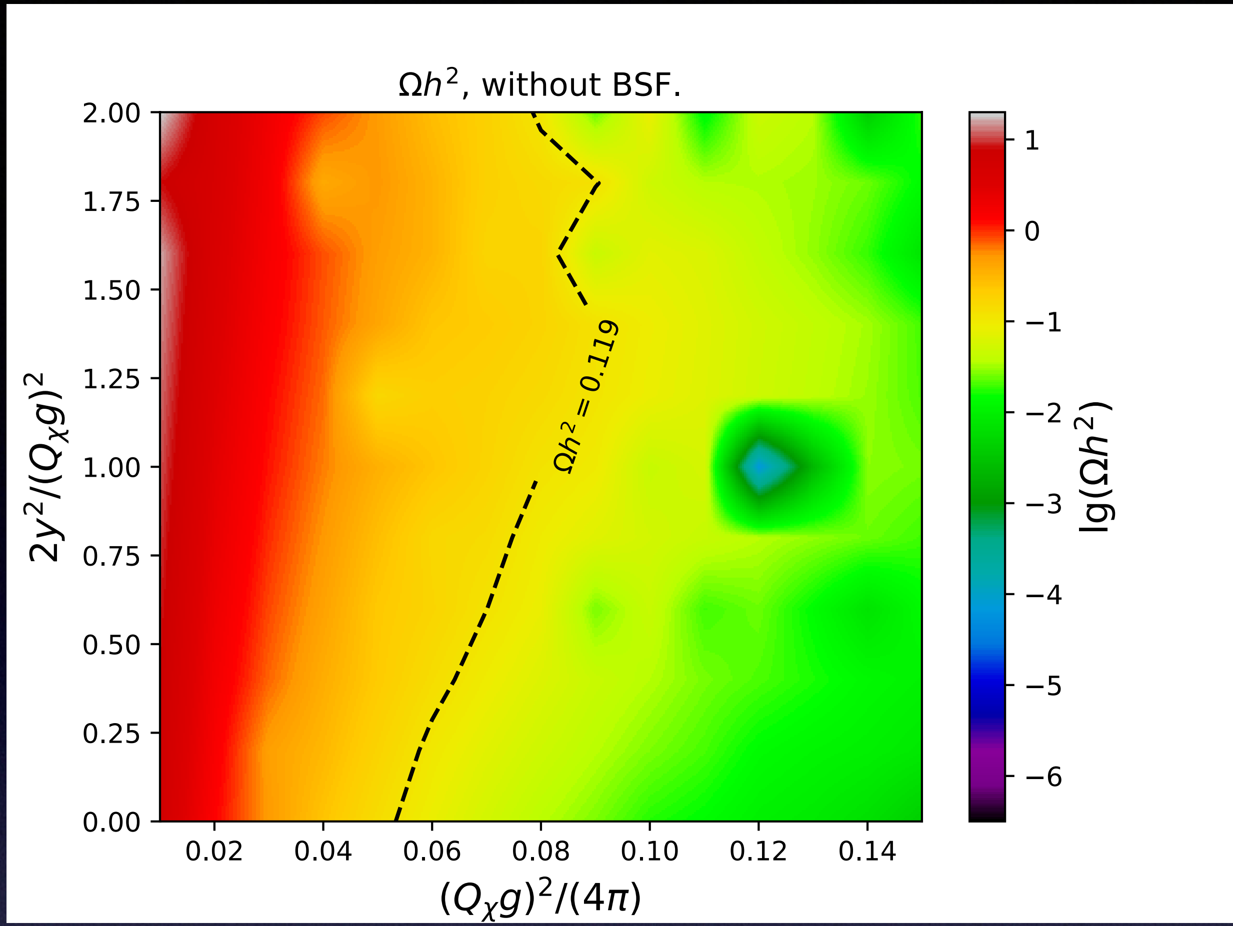
Results:





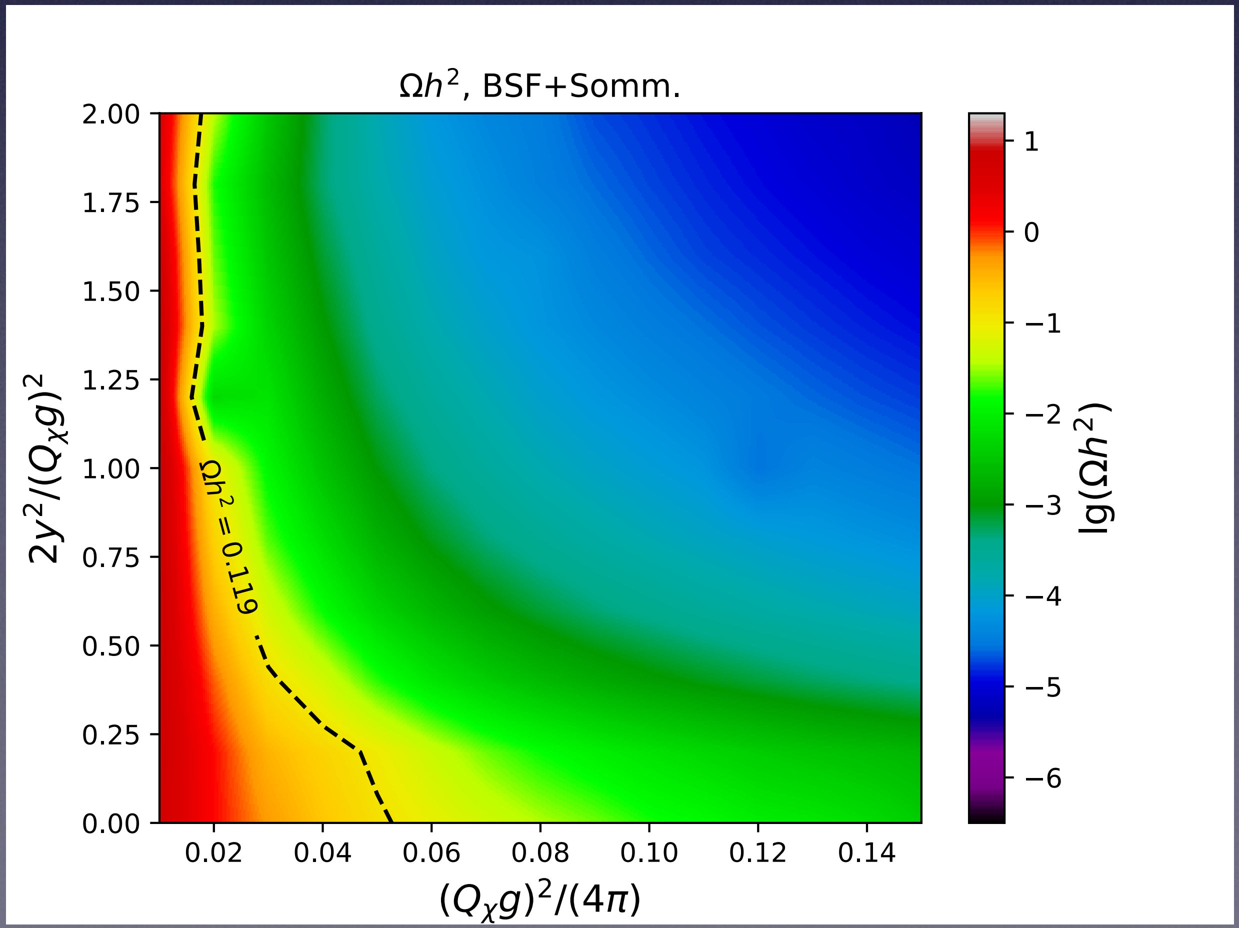
Re-annihilation





Perturbative

Sommerfeld



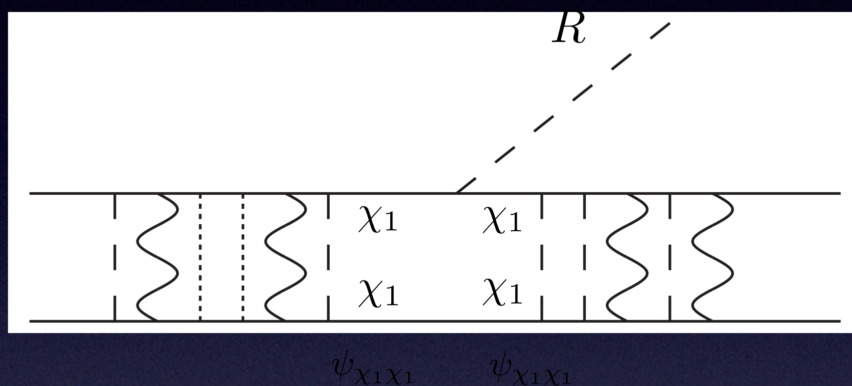
BSF+Somm.

- Direct detection bounds can be easily evaded.
- Indirect detection is not disturbed, because only initial states with different dark components $\chi_1\chi_2$ are amplified.
- CMB recombination bounds can be evaded, because strong gauge coupling need different components, and same-component Yukawa couplings are moderate for a week Sommerfeld enhancement.

Conclusion

- Yukawa interactions can be repulsive.
- Goldstone contribution can significantly alter the potential and the bound state formation cross section.
- Re-annihilation process induced by bound state formation emitting a Goldstone boson is important.

Future research prospect



This can also large because $\chi_1\chi_1 R$ $\chi_2\chi_2 R$

coupling constants are different by an opposite sign!

This might affect the indirect detection and ruin the CMB bounds. Future research?