Relic density and temperature evolution of a light dark sector

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最有动机的暗物质候选者：
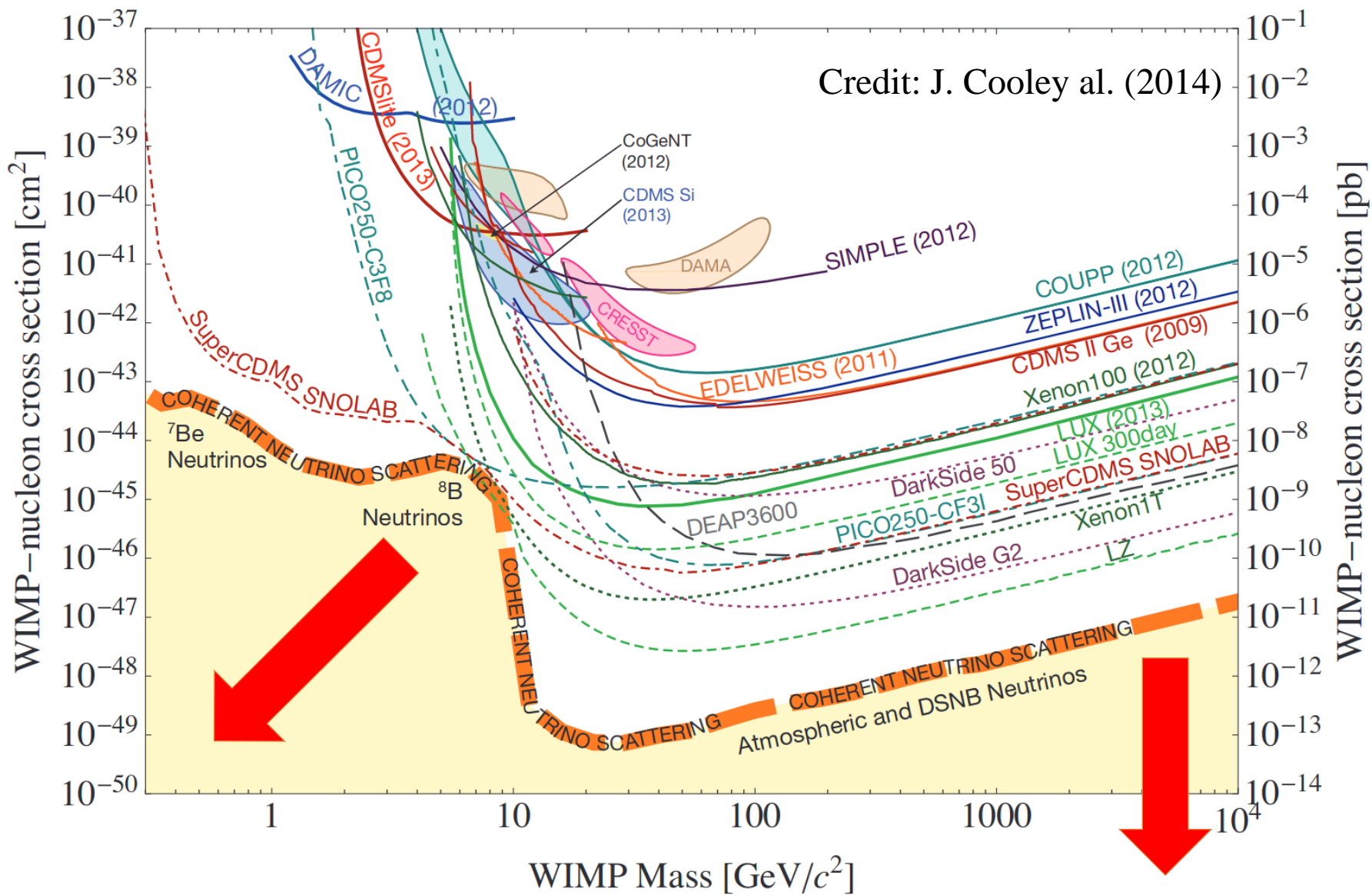Weakly Interacting Massive Particles (WIMPs)

- **实验没有发现任何结论性的信号**
- **新的参数空间的探索：**

a. 更**小**的**质量**

b. 更**小**的**耦合系数**

Credit: J. Cooley al. (2014)

遗迹密度对WIMPs质量的限制：

➢ **Lee-Weinberg bound**：$m \geq$ **2 GeV**

Cosmological Lower Bound on Heavy-Neutrino Masses

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(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

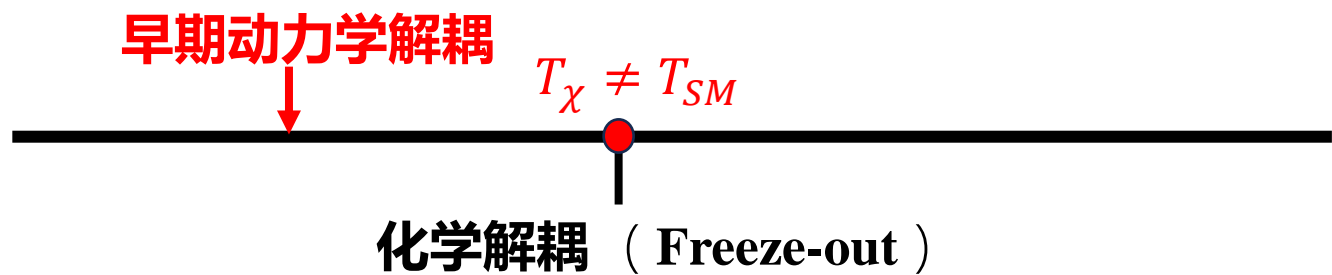想要逃过质量限制，只能引入**新的媒介粒子**

轻的 WIMPs （χ）+ 轻的 媒介子（ϕ）

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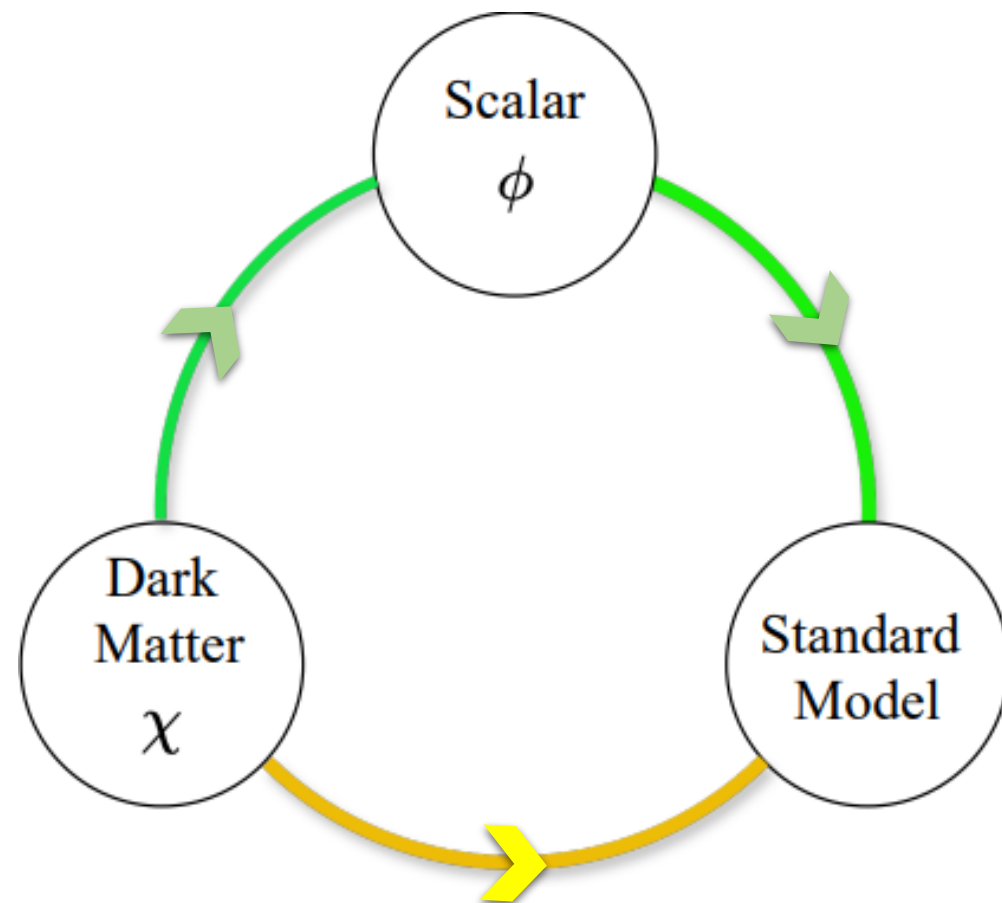
● **传统情形：**
热平衡态被有效维系

（如：**DarkSUSY, micrOMEGAs**）

$T_\chi = T_{SM}$

动力学解耦

化学解耦 （**Freeze-out**）
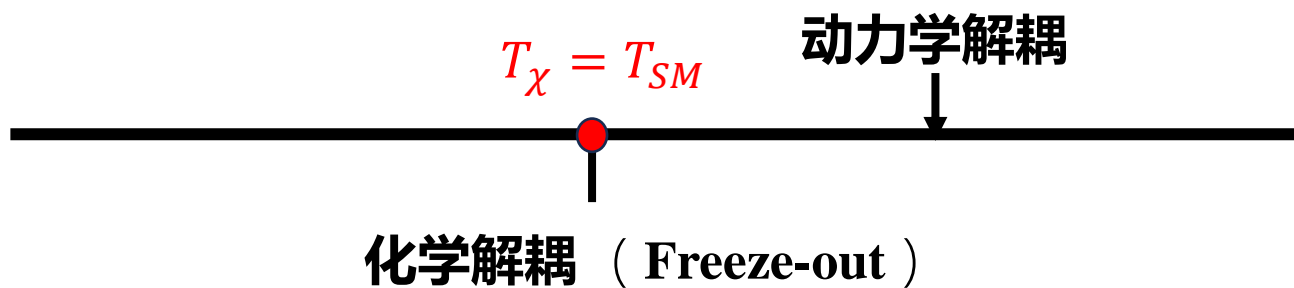
仅需考察**数密度**演化

更小的质量与耦合系数 ➤ **更弱的反应**

● **实际情形：**
热平衡态被破坏

早期动力学解耦

$T_\chi \neq T_{SM}$

化学解耦 （**Freeze-out**）

温度的演化与**数密度**的演化均需要考察
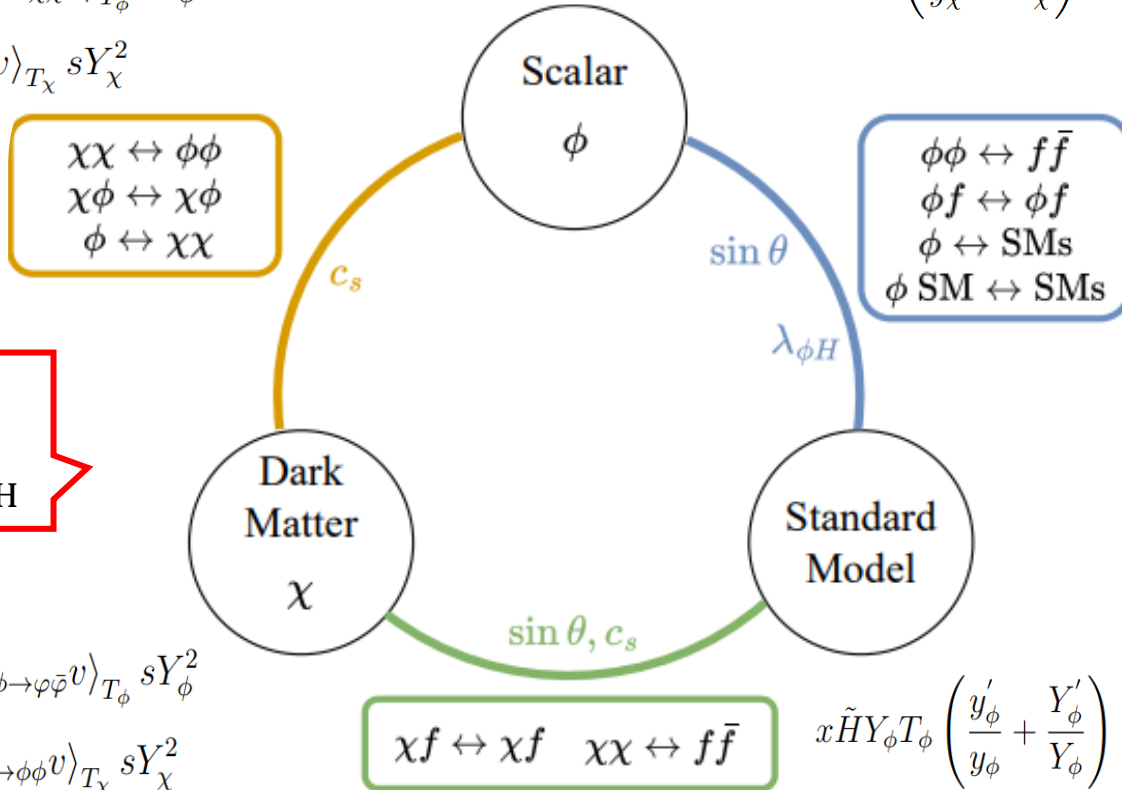
四个独立的演化变量： $N_\chi \quad N_\phi \quad T_\chi \quad T_\phi$

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$$x\tilde{H}Y'_\chi = \langle\sigma_{\varphi\bar\varphi\to\chi\chi}v\rangle_T sY^2_{\varphi,\text{eq}} - \langle\sigma_{\chi\chi\to\varphi\bar\varphi}v\rangle_{T_\chi} sY^2_\chi$$
$$- \langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} sY^2_\chi + \langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi} sY^2_\phi$$
$$+ \langle\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi} Y_\phi - \langle\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi} sY^2_\chi$$

$$x\tilde{H}Y_\chi T_\chi \left(\frac{y'_\chi}{y_\chi} + \frac{Y'_\chi}{Y_\chi}\right) = \frac{H}{3}\left\langle\frac{\mathbf{p}^4_\chi}{E^3_\chi}\right\rangle Y_\chi + \langle T_\chi\sigma_{\varphi\bar\varphi\to\chi\chi}v\rangle_T sY^2_{\varphi,\text{eq}} - \langle T_\chi\sigma_{\chi\chi\to\varphi\bar\varphi}v\rangle_{T_\chi} sY^2_\chi$$
$$- \langle T_\chi\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} sY^2_\chi + \langle T_\chi\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi} sY^2_\phi$$
$$+ \langle T_\chi\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi} Y_\phi - \langle T_\chi\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi} sY^2_\chi$$
$$+ \mathcal{S}_{\chi\phi}(T_\chi,T_\phi)sY_\chi Y_\phi + \mathcal{S}_{\chi\varphi}(T_\chi,T)sY_\chi Y_{\varphi,\text{eq}}$$

Scalar ϕ

$$\chi\chi \leftrightarrow \phi\phi$$
$$\chi\phi \leftrightarrow \chi\phi$$
$$\phi \leftrightarrow \chi\chi$$

$$\phi\phi \leftrightarrow f\bar{f}$$
$$\phi f \leftrightarrow \phi f$$
$$\phi \leftrightarrow \text{SMs}$$
$$\phi\,\text{SM} \leftrightarrow \text{SMs}$$

$\sin\theta$

$\lambda_{\phi H}$

c_s

五个自由参数：

$$m_\chi \quad m_\phi \quad \sin\theta \quad c_s \quad \lambda_{\phi H}$$

Dark Matter χ

Standard Model

$\sin\theta, c_s$

$$\chi f \leftrightarrow \chi f \quad \chi\chi \leftrightarrow f\bar{f}$$

聚焦于**三种**典型的情形：
a. Forbidden： $m_\chi < m_\phi$
b. Resonance： $2m_\chi \approx m_\phi$
c. Secluded： $m_\chi \gg m_\phi$

$$x\tilde{H}Y'_\phi = \langle\sigma_{\varphi\bar\varphi\to\phi\phi}v\rangle_T sY^2_{\varphi,\text{eq}} - \langle\sigma_{\phi\phi\to\varphi\bar\varphi}v\rangle_{T_\phi} sY^2_\phi$$
$$- \langle\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi} sY^2_\phi + \langle\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} sY^2_\chi$$
$$- \langle\Gamma_{\phi\to\varphi\bar\varphi}\rangle_{T_\phi} Y_\phi + \langle\sigma_{\varphi\bar\varphi\to\phi}v\rangle_T sY^2_{\varphi,\text{eq}}$$
$$- \langle\Gamma_{\phi\to\chi\chi}\rangle_{T_\phi} Y_\phi + \langle\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi} sY^2_\chi$$
$$+ \sum_{\varphi_2,\varphi_3,\varphi_4}\left[\langle\sigma_{\varphi_3\varphi_4\to\phi\varphi_2}v\rangle_T\ sY_{\varphi_3,\text{eq}}Y_{4,\text{eq}} - \langle\sigma_{\phi\varphi_2\to\varphi_3\varphi_4}v\rangle_{(T_\phi,T)}\ sY_{\varphi_2,\text{eq}}Y_\phi\right]$$

计算总花费~**200000**核时

$$x\tilde{H}Y_\phi T_\phi \left(\frac{y'_\phi}{y_\phi} + \frac{Y'_\phi}{Y_\phi}\right) = \frac{H}{3}\left\langle\frac{\mathbf{p}^4_\phi}{E^3_\phi}\right\rangle Y_\phi + \langle T_\phi\sigma_{\varphi\bar\varphi\to\phi\phi}v\rangle_T sY^2_{\varphi,\text{eq}} - \langle T_\phi\sigma_{\phi\phi\to\varphi\bar\varphi}v\rangle_{T_\phi} sY^2_\phi$$
$$- \langle T_\phi\sigma_{\phi\phi\to\chi\chi}v\rangle_{T_\phi} sY^2_\phi + \langle T_\phi\sigma_{\chi\chi\to\phi\phi}v\rangle_{T_\chi} sY^2_\chi$$
$$- \langle T_\phi\Gamma_\phi\rangle_{T_\phi} Y_\phi + \langle T_\phi\sigma_{\chi\chi\to\phi}v\rangle_{T_\chi} sY^2_\chi + \langle T_\phi\sigma_{\varphi\bar\varphi\to\phi}v\rangle_T sY^2_{\varphi,\text{eq}}$$
$$+ \mathcal{S}_{\phi\chi}(T_\phi,T_\chi)sY_\chi Y_\phi + \mathcal{S}_{\phi\varphi}(T_\phi,T)sY_\phi Y_{\varphi,\text{eq}}$$
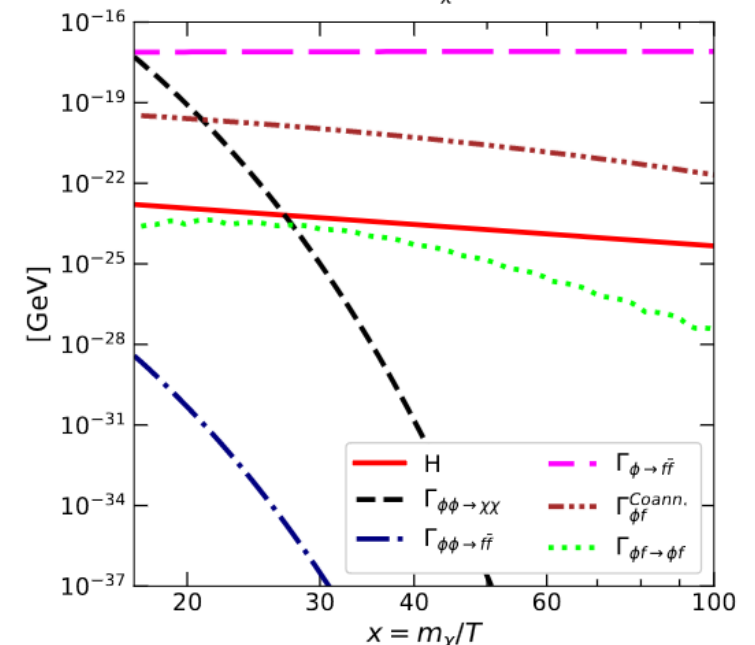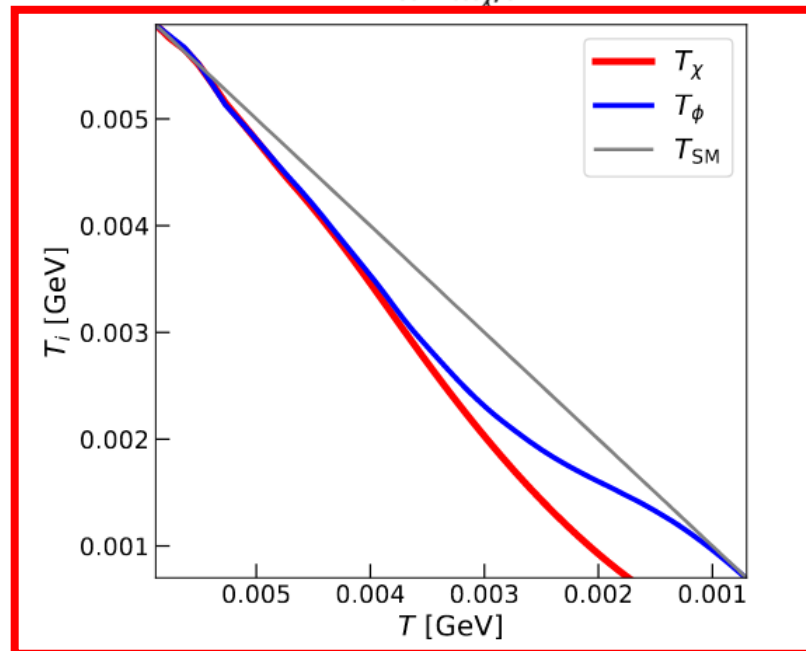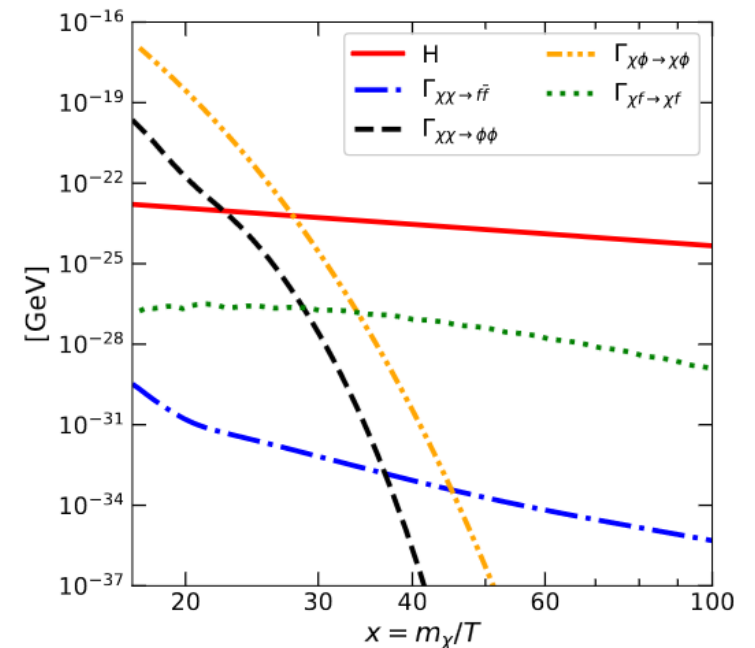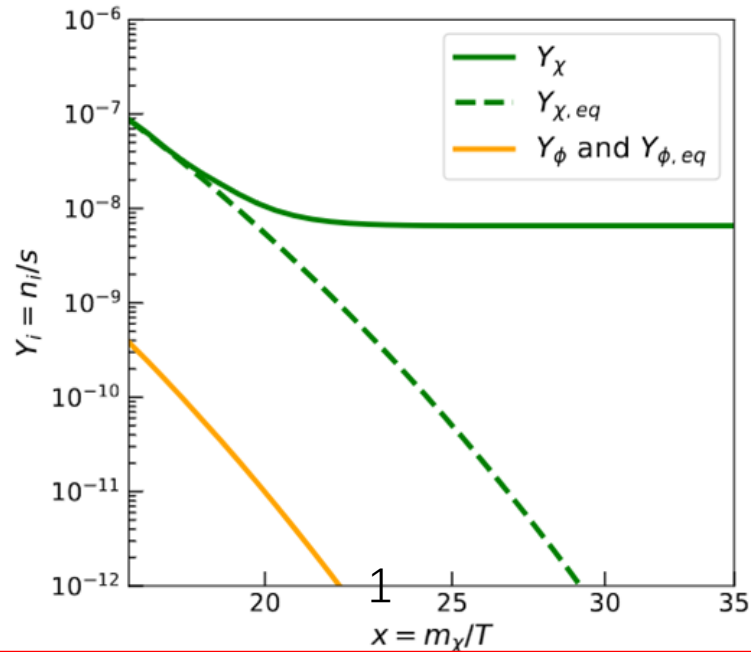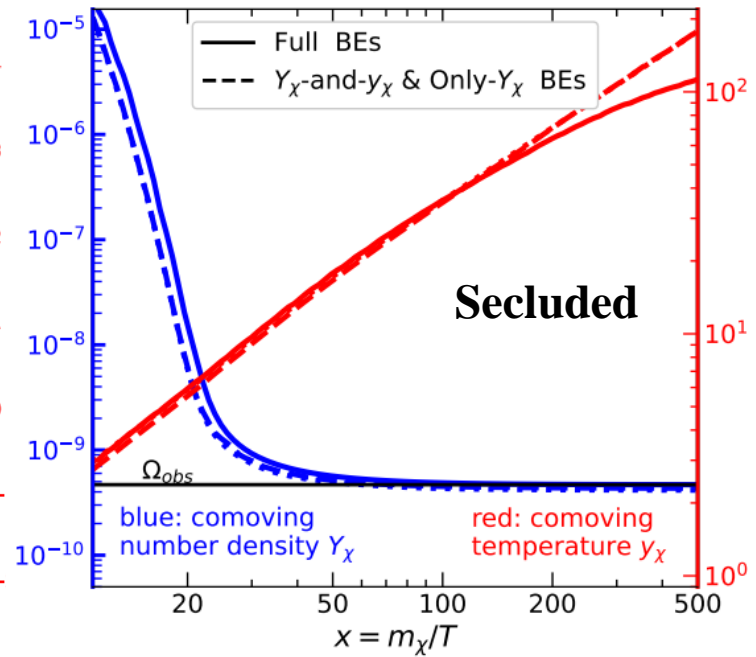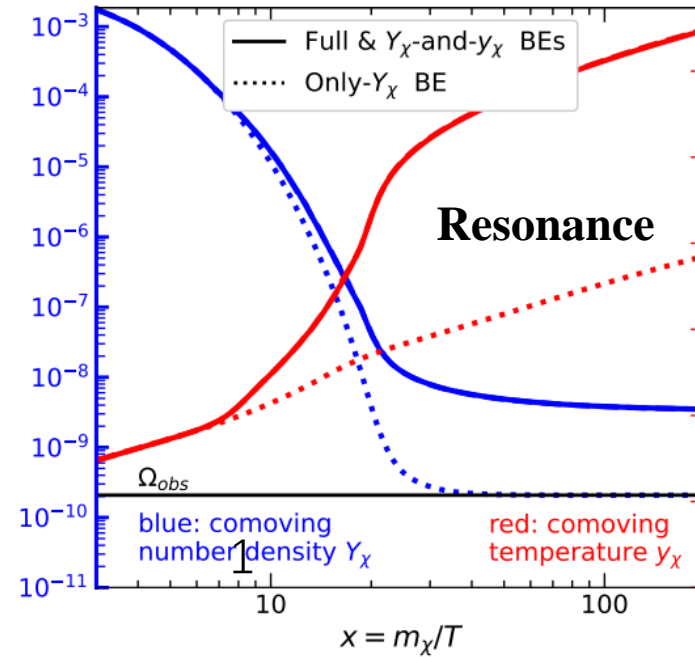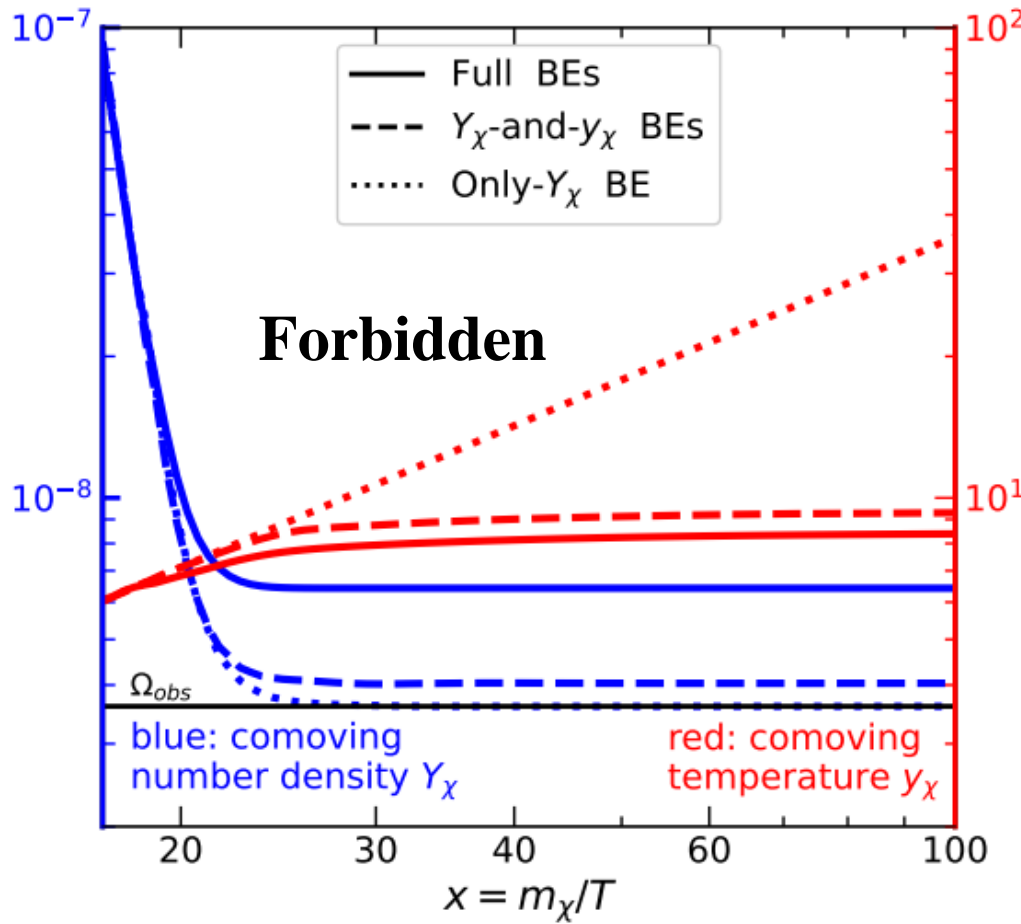$$+ \sum_{\varphi_2,\varphi_3,\varphi_4} s\left[\langle T_\phi\sigma_{\varphi_3\varphi_4\to\phi\varphi_2}v\rangle_T\ Y_{\varphi_3,\text{eq}}Y_{\varphi_4,\text{eq}} - \langle T_\phi\sigma_{\phi\varphi_2\to\varphi_3\varphi_4}v\rangle_{(T_\phi,T)}\ Y_{\varphi_2,\text{eq}}Y_\phi\right]$$

Forbidden DM：

- $m_\chi = 0.10\ \text{GeV}$
- $m_\phi = 0.13\ \text{GeV}$
- $\sin\theta = 0.001$
- $c_s = 0.1$
- $\lambda_{\phi H} = 1.0$

复杂的相互作用下有趣的温度演化关系，揭示出考虑温度演化的必要性

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Erros to $Only\text{-}Y_\chi$	2 BEs	4 BEs
Forbidden DM	10%	72%
Resonance DM	1000%	1000%
Secluded DM	---	9%

Planck error is around 1%
(TT + TE + EE + lowE + lensing)

1. 该工作针对于**质量轻于**李-温伯格约束的暗物质，考虑了一种简单模型，其中包含有一种新的轻媒介粒子。

2. 我们发展了一套包含有轻暗物质、轻媒介子和标准模型在内的四个完全耦合的玻尔兹曼方程。

3. **精确**计算出了暗物质和媒介子的**数密度**与**温度**的演化以及暗物质的**遗迹密度**。

4. 通过对照实验测量得到的遗迹密度的误差，我们发现如果**不把温度演化**考虑在内，所造成的误差将会**严重影响**人们对暗物质参数空间的判断。
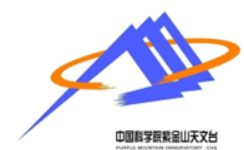
感 谢 耐 心 聆 听

Forbidden DM : $m_\chi = 0.1$ Gev, $m_\phi = 0.13$ GeV, $\sin\theta = 10^{-3}$, $c_s = 0.1$ and $\lambda_{\phi H} = 1.0$
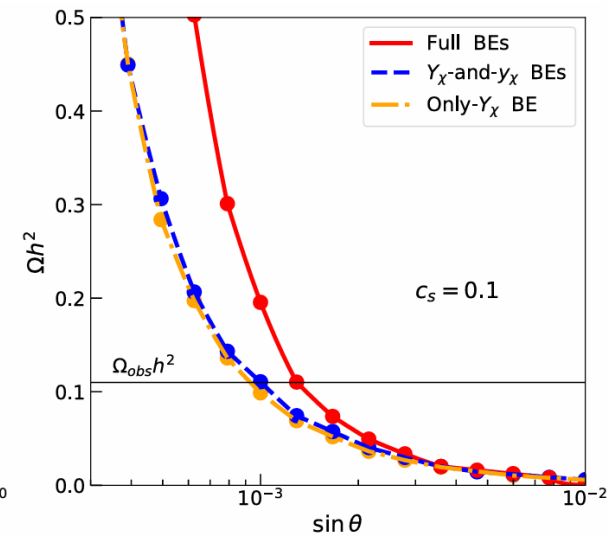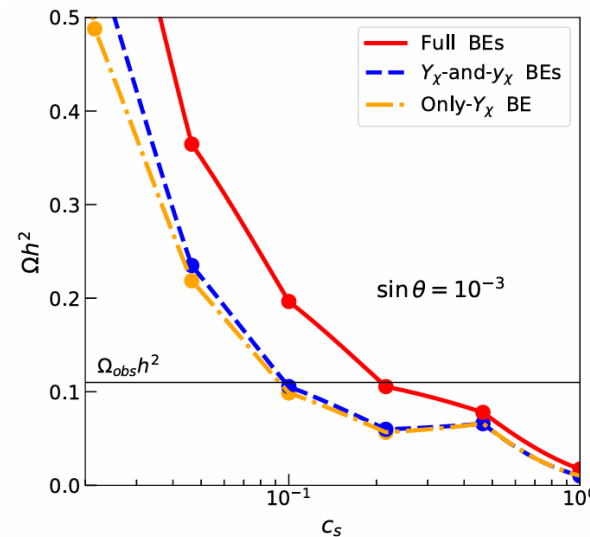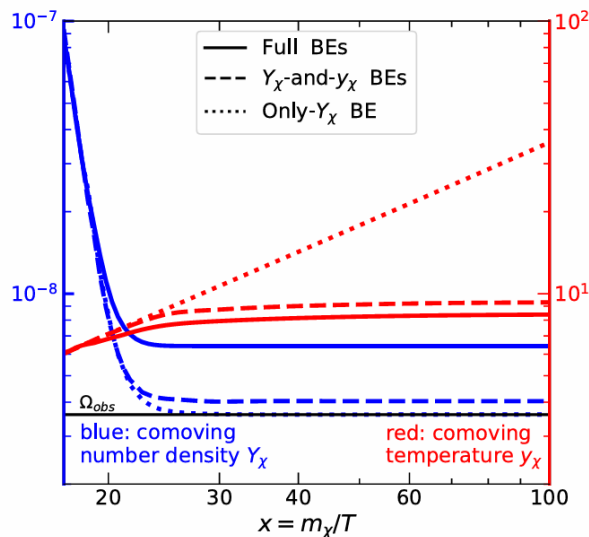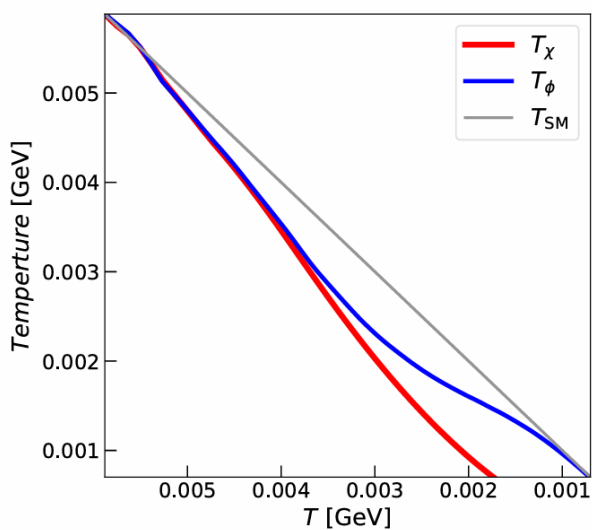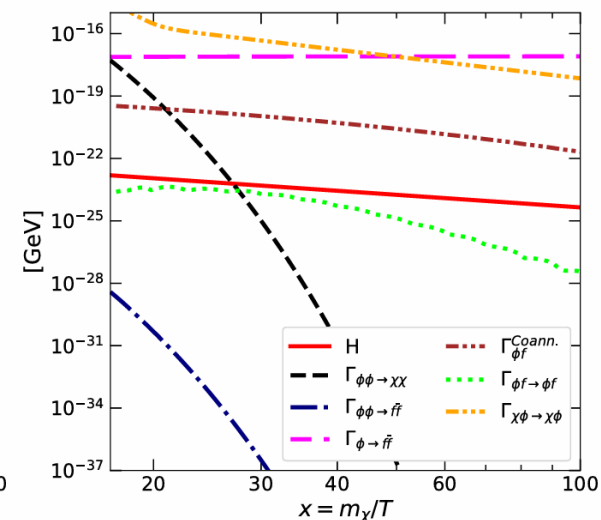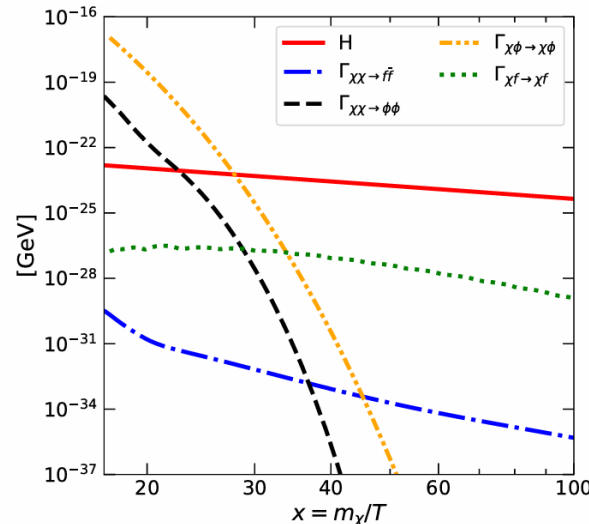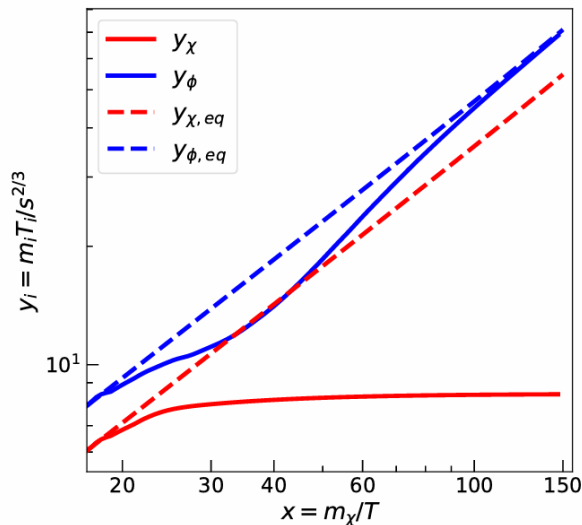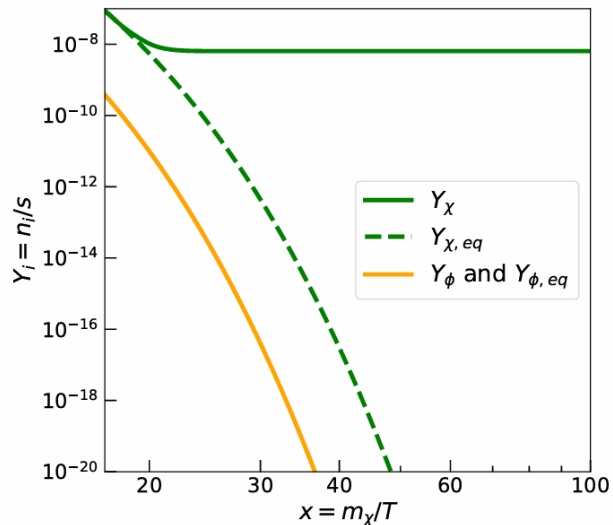
Resonance DM : $m_\chi = 2.2$ Gev, $m_\phi = 4.7$ GeV, $\sin\theta = 0.01$, $c_s = 10^{-3}$ and $\lambda_{\phi H} = 1.0$

附页：Secluded DM