Thermal Gravitational Contribution to Dark Matter Production

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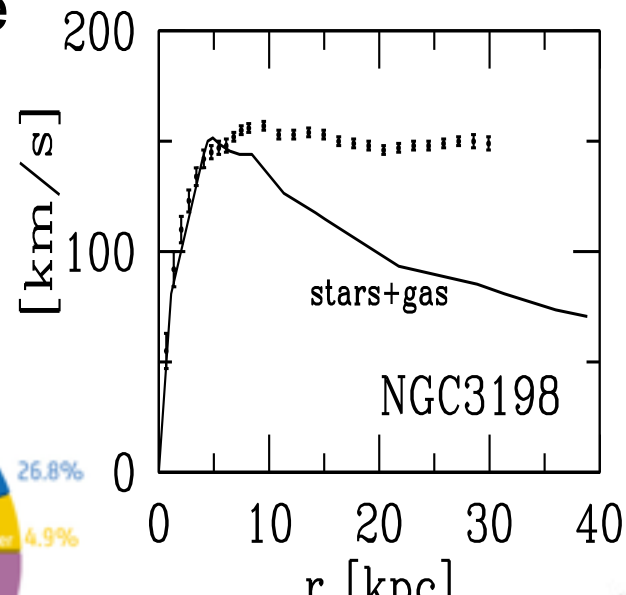
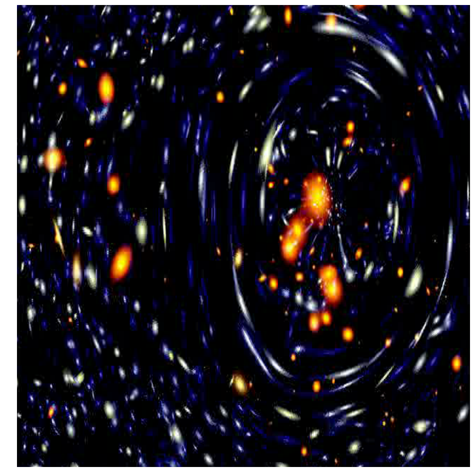
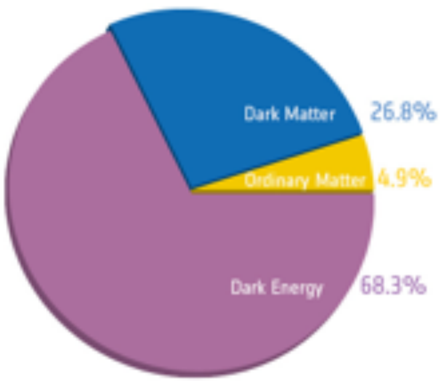
*YL.**Wu*** *& Y.**Tang**,* **1708.05138, 1604.04701**

Evidence of Dark Matter

- Galactic Rotation Curve
- Gravitational Lensing
- Large Scale Structure
- CMB anisotropies,
- …

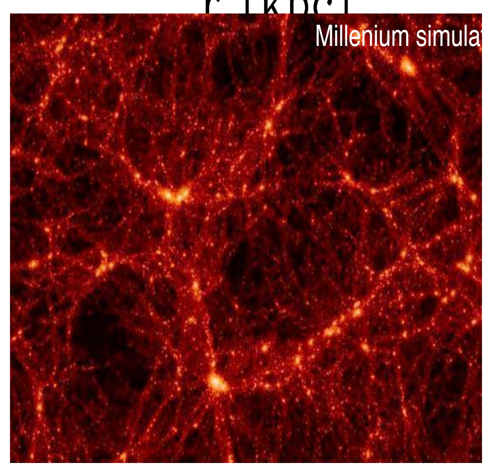


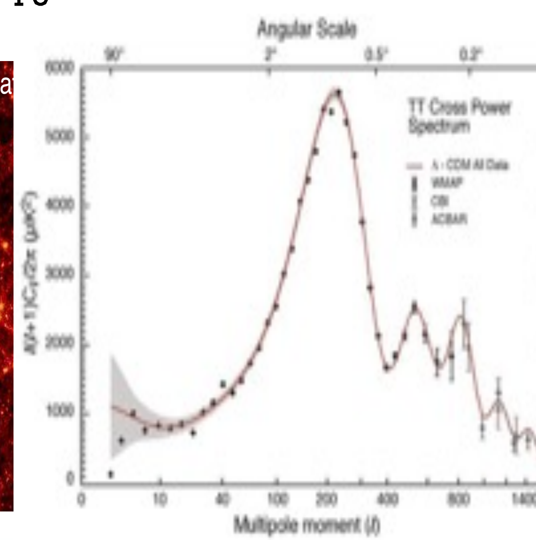




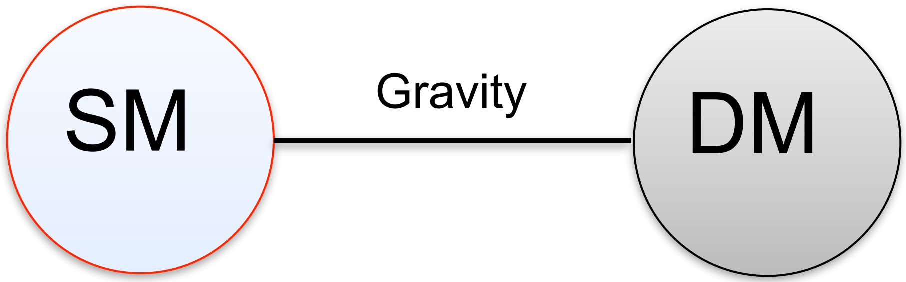
$$\Omega_X \simeq 0.26$$

All confirmed evidence indicates DM at least has gravitational interaction.





DM Scenarios



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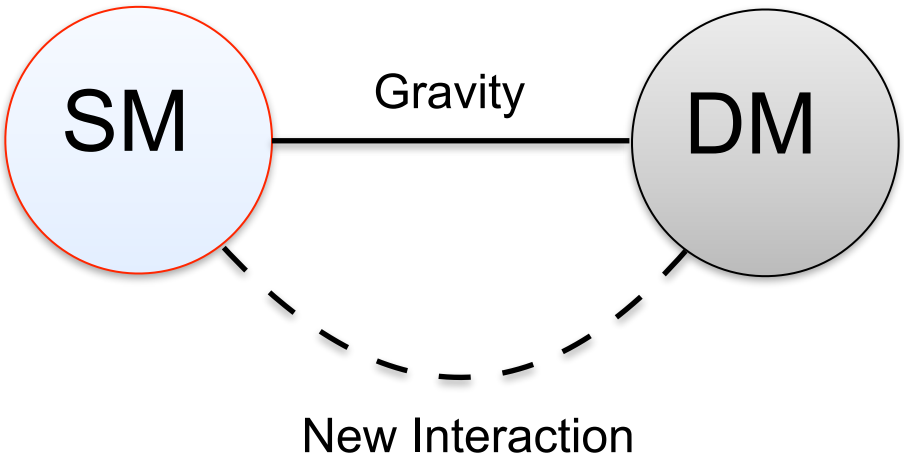

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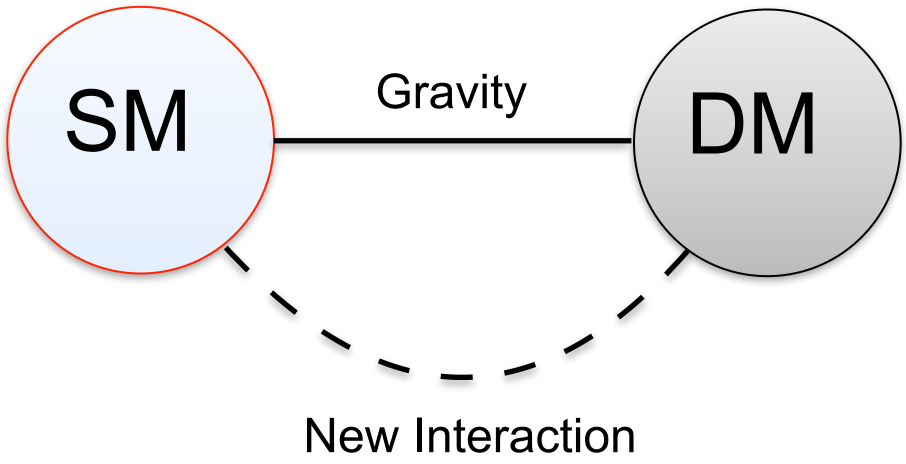
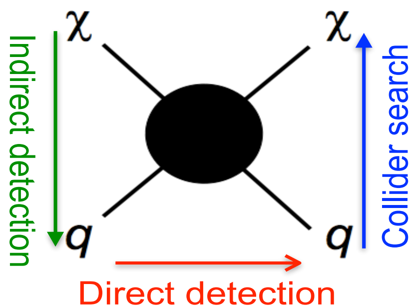
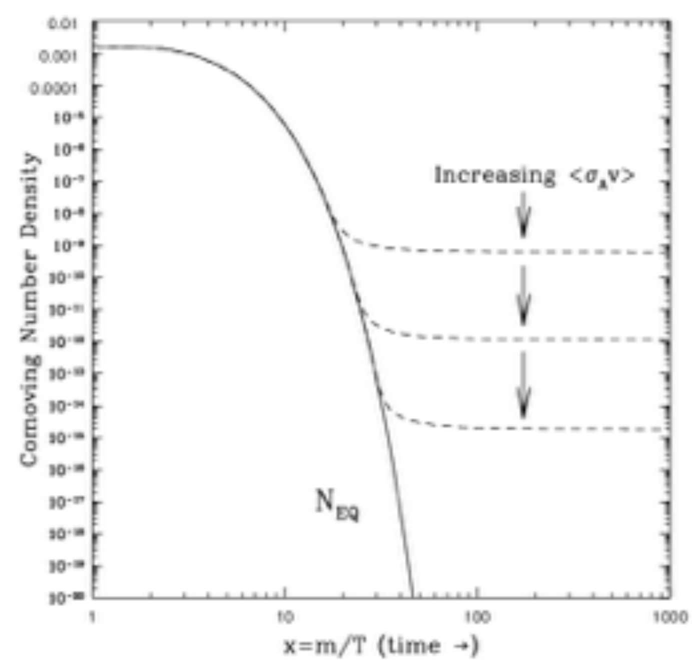


Weakly Interacting Massive Particle

- Mass around ~100GeV
- Coupling ~ 0.5
- Correct relic abundance Ω~0.3
- Searches for CDM
  - Collider qq > XXj
  - Direct Xq > Xq
  - Indirect XX > qq
- Theoretically interesting





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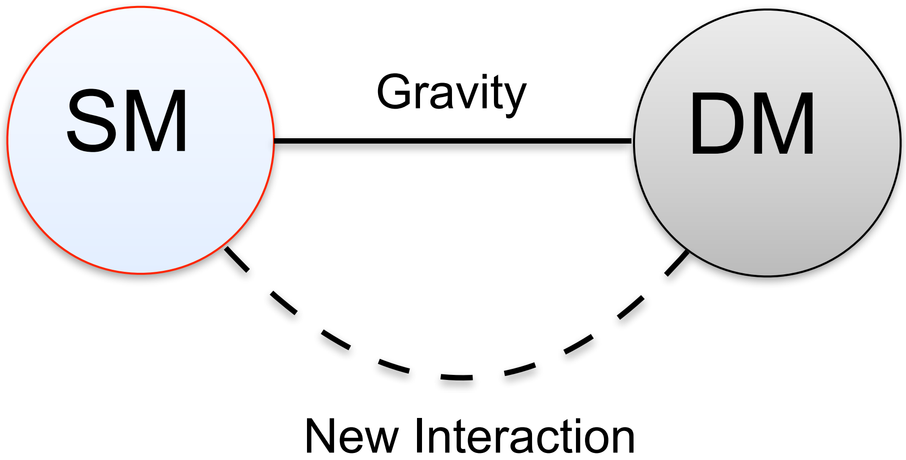
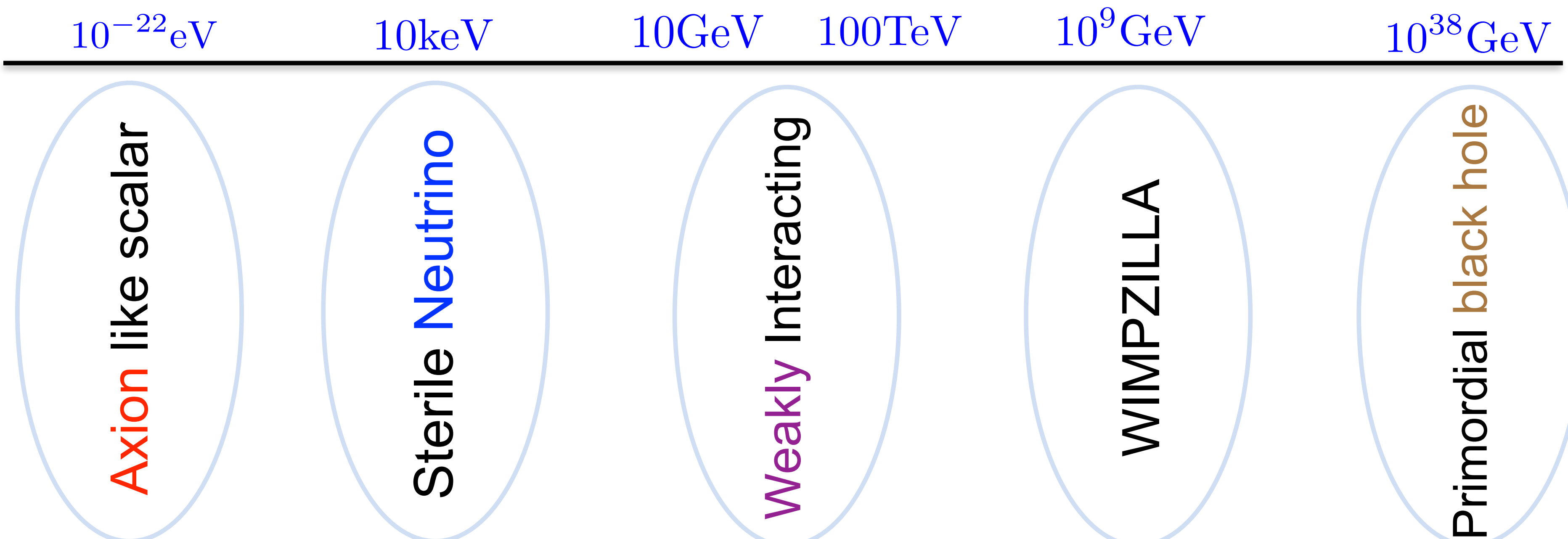
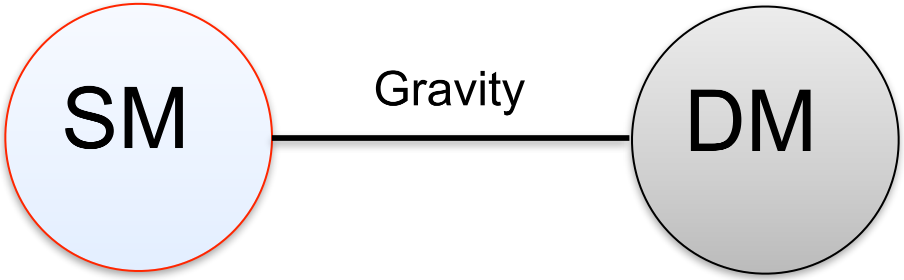
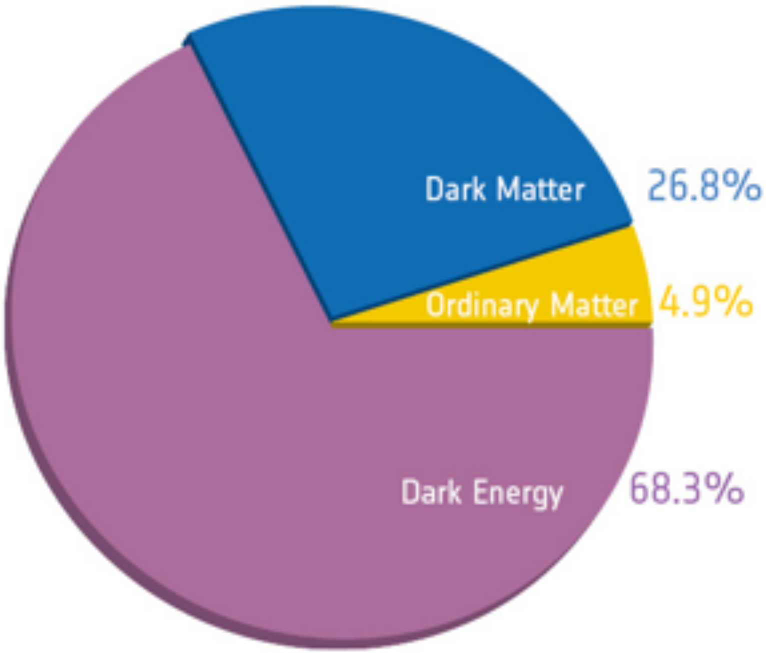




What if only Gravity?



- Gravitational interaction is very weak.
- One may wonder whether DM can be produced.
- We shall show gravity can be strong enough to play…



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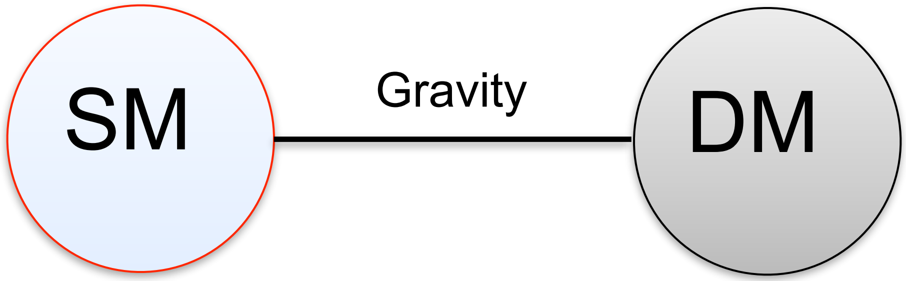
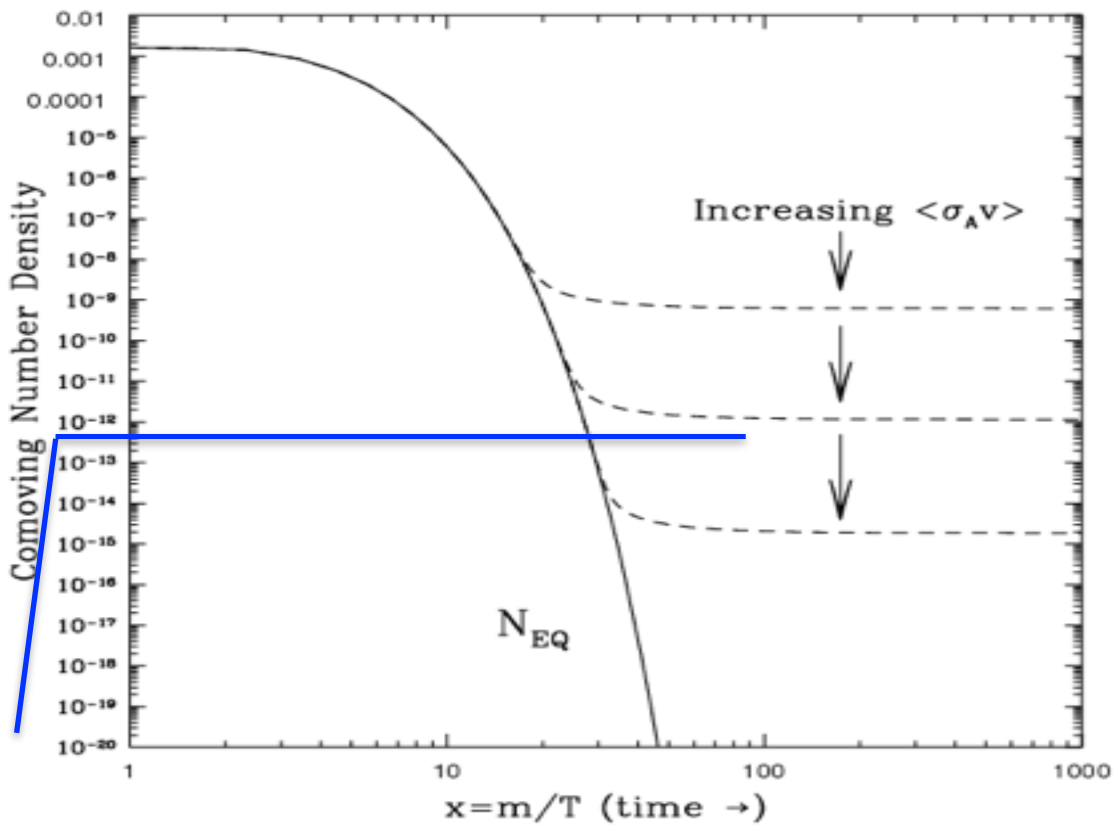




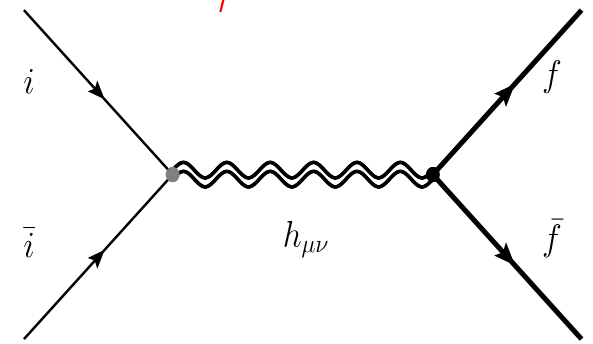
Gravitational Contributions

- Non-Thermal (*well-studied*)
  - Expansion of cosmic background
  - QFT in curved spacetime
  - Vacuum Fluctuation $n_X \propto H^3 \quad m_X \propto H$
    - Bogoliubov transformation

e.g. Ema, Jinno, Mukaida&Nakayama, 1502.02475,1604.08898 and refs. therein

- **Thermal scattering ($T > H$ or m_ϕ)**
  - EFT for *E<<M$_p$*

$$\mathcal{L}_{\rm int} = \frac{\kappa}{2} h_{\mu\nu} T^{\mu\nu},$$



$$\kappa = \sqrt{32\pi G} \sim \frac{1}{M_P}$$

Wu&Tang, 1604.04701, 1708.05138
Gary,Sandora,Sloth&Palessandro,1511.03278,1709.09688

EFT in Einstein's Gravity

- Einstein-Hilbert action

$$S=\int \mathcal{L}\, d^4x\ ,\quad \mathcal{L}=\sqrt{-g}\left[\frac{1}{16\pi G}R+L_m\right]$$

- EFT for $E<<M_p$ ← Justified after inflation

$$\mathcal{L}_{\rm int}=\frac{\kappa}{2}h_{\mu\nu}T^{\mu\nu},$$

Energy-Momentum Tensor

$$T_S^{\mu\nu}=-\eta^{\mu\nu}\partial^\alpha S^\dagger\partial_\alpha S+\eta^{\mu\nu}m_S^2S^\dagger S+\partial^\mu S^\dagger\partial^\nu S+\partial^\nu S^\dagger\partial^\mu S,$$

$$T_F^{\mu\nu}=-\eta^{\mu\nu}\left(\overline{F}i\partial\!\!\!/ F-m_F\overline{F}F\right)+\frac{1}{2}\overline{F}i\gamma^\mu\partial^\nu F+\frac{1}{2}\overline{F}i\gamma^\nu\partial^\mu F$$
$$+\frac{1}{2}\eta^{\mu\nu}\partial^\alpha\left(\overline{F}i\gamma_\alpha F\right)-\frac{1}{4}\partial^\mu\left(\overline{F}i\gamma^\nu F\right)-\frac{1}{4}\partial^\nu\left(\overline{F}i\gamma^\mu F\right),$$

$$T_V^{\mu\nu}=\eta^{\mu\nu}\left(\frac{1}{4}F^{\alpha\beta}F_{\alpha\beta}-\frac{1}{2}m_V^2V^\alpha V_\alpha\right)-\left(F^{\mu\alpha}F^\nu{}_\alpha-m_V^2V^\mu V^\nu\right),$$

$$T_\gamma^{\mu\nu}=\frac{1}{4}\eta^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta}-F^{\mu\alpha}F^\nu{}_\alpha.$$

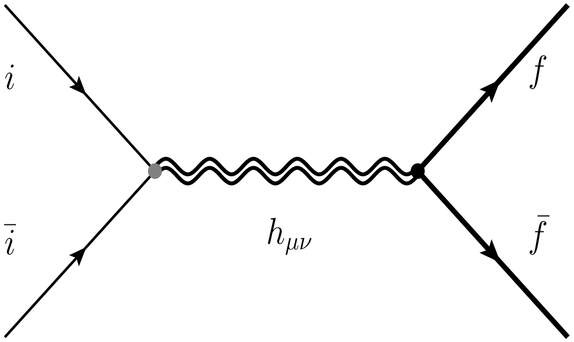
Non-minimal coupling

$$\zeta S^\dagger SR\to 2\zeta(\partial^\mu\partial^\nu-\eta^{\mu\nu}\partial_\alpha\partial^\alpha)S^\dagger S$$

Annihilation Processes

- Boltzmann Equation

$$\dot{n} + 3Hn \equiv \frac{d\left(a^3 n\right)}{a^3 dt} = \mathcal{C}_{col}$$



- Reduced to

$$\frac{d\left(a^3 n\right)}{a^3 dt} = \frac{g^2 T}{32\pi^4} \int ds\, \sigma \sqrt{s}(s - 4m^2) K_1 \left(\frac{\sqrt{s}}{T}\right),$$

- The core

$$\sigma = \frac{\kappa^4}{32\pi s \left(S g_i^2\right)} \frac{|\vec{p}_f|}{|\vec{p}_i|} \mathcal{A}$$

Massless limit
$\sigma \propto \kappa^4 s$
Wu&Tang **1604.04701**

$$|\vec{p}_i| = \sqrt{s^2/4 - m^2},\ |\vec{p}_f| = \sqrt{s^2/4 - M^2}$$

Various Contributions

- Scalar

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$$\mathcal{A}(S \to S) = \frac{7m^4M^4}{30s^2} - \frac{m^2M^2}{30s}\left(m^2+M^2\right),$$
$$+\frac{1}{40}\left(m^4+4m^2M^2+M^4\right)+\frac{s}{120}\left(m^2+M^2\right)+\frac{s^2}{240},$$
$$\mathcal{A}(F \to S) = -\frac{7m^4M^4}{15s^2} - \frac{m^2M^2}{60s}(M^2-4m^2)$$
$$+\frac{1}{60}\left(2M^4+3m^2M^2-3m^4\right)-\frac{s}{240}(4M^2-m^2)+\frac{s^2}{480},$$
$$\mathcal{A}(V \to S) = \frac{101m^4M^4}{30s^2} - \frac{m^2M^2}{10s}\left(11M^2+m^2\right)$$
$$+\frac{1}{120}\left(19M^4+76m^2M^2+49m^4\right)-\frac{7s}{120}\left(m^2+M^2\right)+\frac{s^2}{80},$$
$$\mathcal{A}(\gamma \to S) = \frac{1}{120}\left(s-4M^2\right)^2,$$

Various Contributions

- Fermion

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$$\mathcal{A}(F\to F)=\frac{14m^4M^4}{15s^2}+\frac{m^2M^2}{30s}\left(m^2+M^2\right),$$
$$-\frac{1}{120}\left(8m^4-3m^2M^2+8M^4\right)-\frac{s}{120}\left(m^2+M^2\right)+\frac{s^2}{160},$$
$$\mathcal{A}(V\to F)=-\frac{101m^4M^4}{15s^2}+\frac{m^2M^2}{20s}\left(44M^2-m^2\right)$$
$$-\frac{1}{60}\left(19M^4-19m^2M^2-26m^4\right)-\frac{s}{240}\left(7M^2+52m^2\right)+\frac{13s^2}{480},$$
$$\mathcal{A}(\gamma\to F)=\frac{1}{120}\left(s-4M^2\right)\left(3s+8M^2\right),$$

- Vector

$$\mathcal{A}(V\to V)=\frac{2983m^4M^4}{30s^2}-\frac{293m^2M^2}{10s}\left(m^2+M^2\right),$$
$$+\frac{1}{120}\left(257m^4+1188m^2M^2+257M^4\right)-\frac{37s}{40}\left(m^2+M^2\right)+\frac{29s^2}{240},$$
$$\mathcal{A}(\gamma\to V)=\frac{13}{120}\left(s-4M^2\right)^2,$$
$$\mathcal{A}(\gamma\to\gamma)=\frac{s^2}{10}.$$

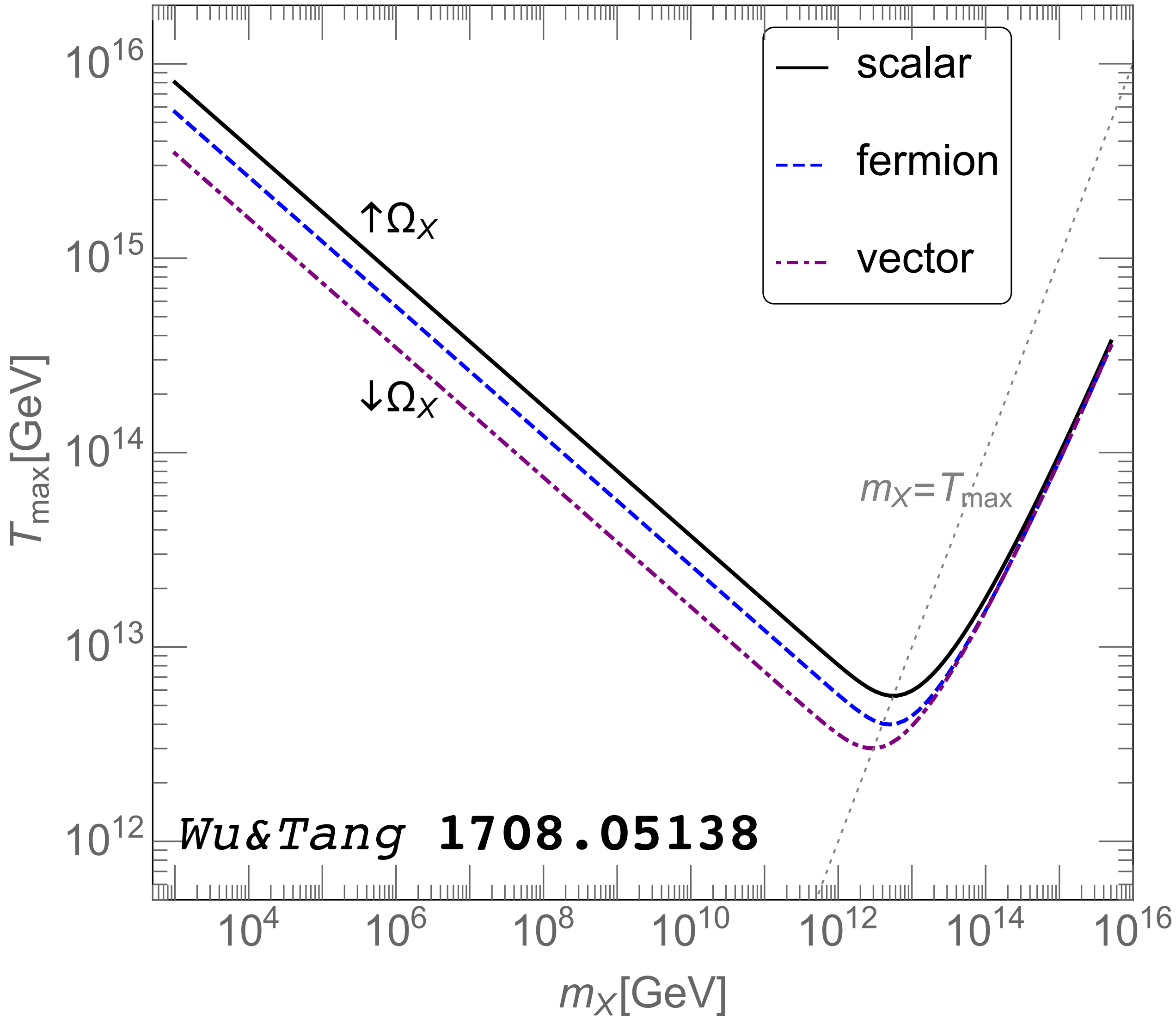
Parameter Space

- Dark Matter *X*,

  $\Omega_X = 0.258$

- Below DM m_X, *power-law; Above, log*

- Similar for diff spins.



Effects of Inflation

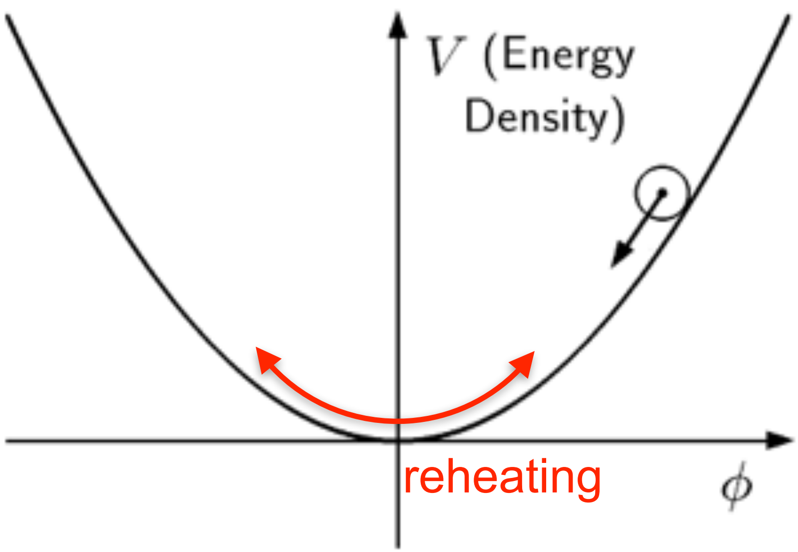
- The temperature after inflation is determined by the reheating process, usually the decay of the inflaton.

$$\ddot{\phi} + 3H\dot{\phi} + \Gamma_\phi \dot{\phi} + V'(\phi) = 0,$$

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

$$T_R = \sqrt{\Gamma_\phi M_P} \quad \text{maybe } T_R > m_\phi$$

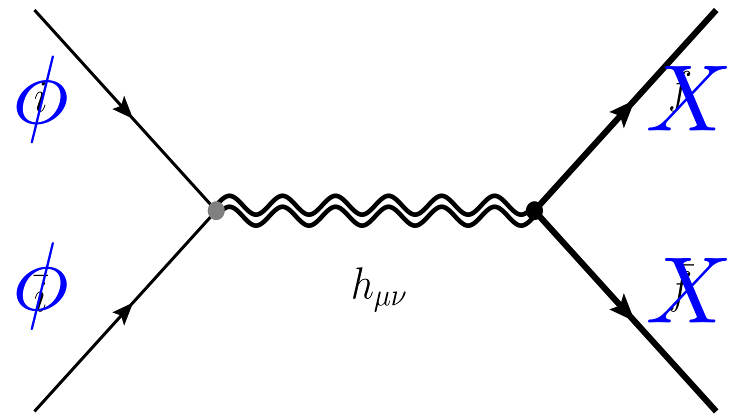
- Another important effect is from *inflaton annihilation*



Annihilation from Inflaton

- The energy density during inflation is much lower than Planck scale

$$\sigma = \frac{\kappa^4}{32\pi s \left(S g_i^2\right)} \frac{|\vec{p}_f|}{|\vec{p}_i|} \mathcal{A}$$



$m = m_\phi$ $\qquad$ $M = M_X$

- Scalar $\mathcal{A} = \frac{1}{32}\left[2(1-6\zeta)m^2 + M^2\right]^2$
- Fermion $\frac{1}{16} M^2 \left(m^2 - M^2\right)$
- Vector $\frac{1}{32}\left(4m^4 - 4m^2M^2 + 3M^4\right)$
- Massless vector 0

helicity suppression

Wu&Tang **1708.05138**

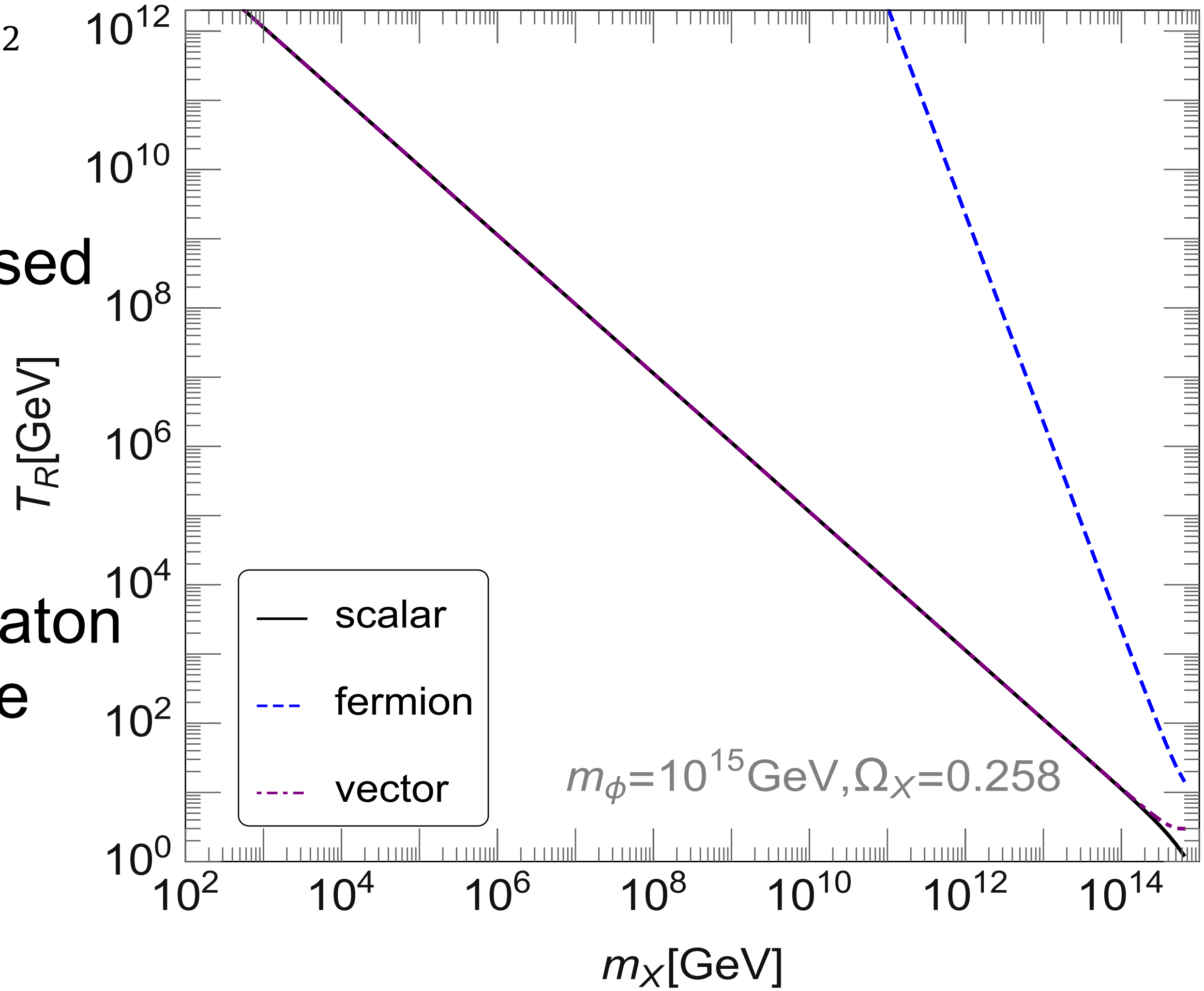
Parameter Space

- For massive scalar and vector

$$Y_X \simeq \frac{H_*}{M_P^2} T_R \simeq \frac{m_\phi}{M_P}\left(\frac{\Gamma_\phi}{M_P}\right)^{1/2}$$

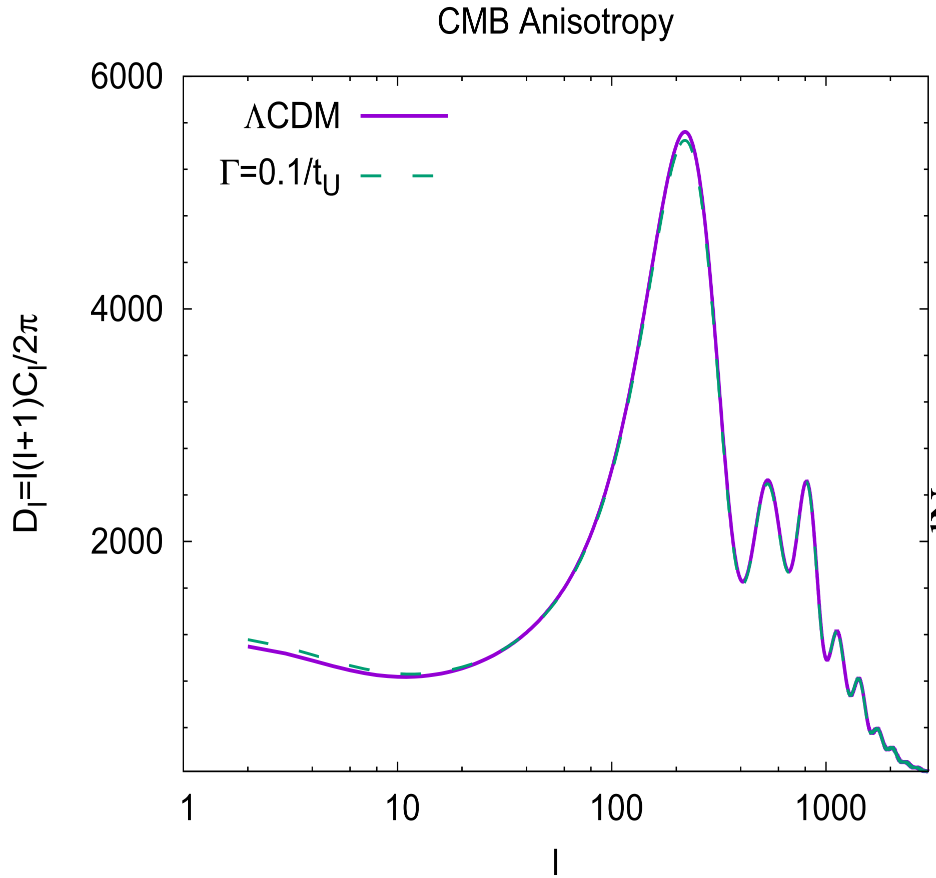
- Fermion is suppressed by a factor M_f^2/m_ϕ^2

- Production from inflaton annihilation could be dominant



Possible Signatures

- If stable, no signal in Direct/Indirect/Collider…
- If unstable, decay products can be shown as anomalies in astrophysical observables



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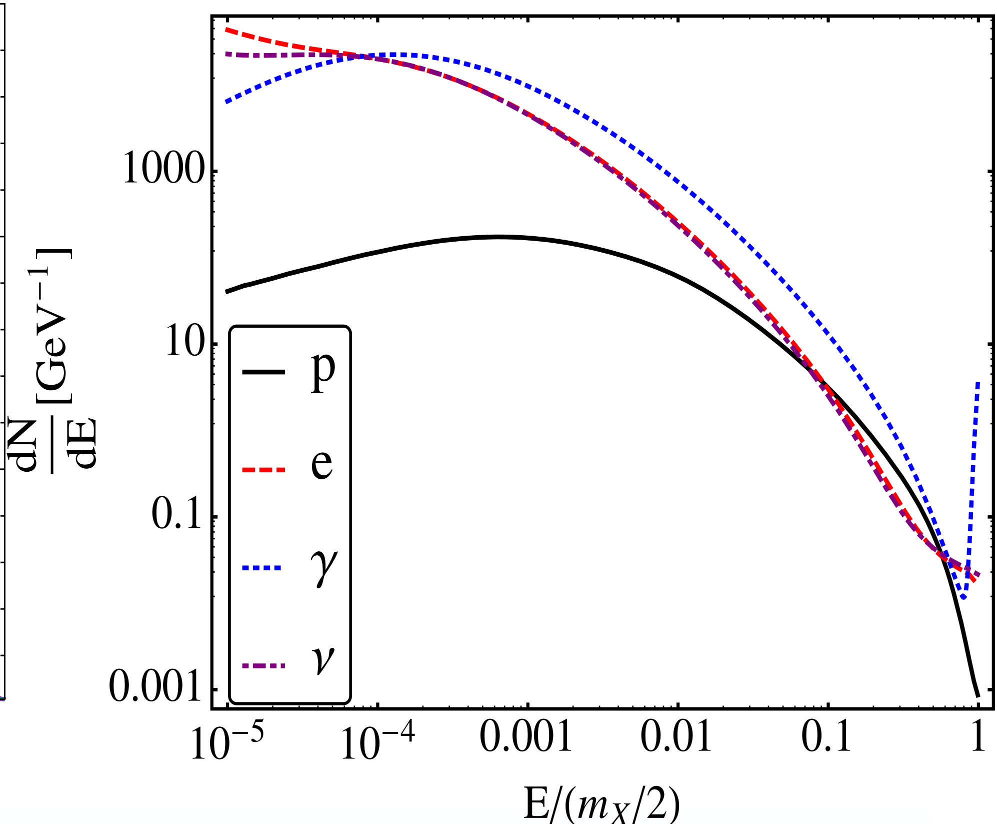

Summary

- *Gravitational contributions* to dark matter production can be important for ***non-WIMP*** case
- We consider the contribution due to thermal ***SM*** particles' gravitational annihilation
- Inflation plays two important roles
  - Reheating temperature
  - Inflaton's gravitational annihilation
- Possible astrophysical signatures if DM decay.

Thanks for your attention.