KINETIC MIXING IN THE DARK MATTER SECTOR

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KINETIC MIXING

$$U(1)_{DM} \subset G_{DM}$$

$$\mathcal{L}_{gauge\ mix} = -\frac{1}{4} W_{3\mu\nu} W_3^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\boldsymbol{\varepsilon}}{\mathbf{2}} \boldsymbol{B_{\mu\nu} b^{\mu\nu}} =$$

$$= -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu} + \frac{\boldsymbol{\varepsilon}}{\mathbf{2}} \left(\boldsymbol{cos(\theta_W)\, F_{\mu\nu} - sin(\theta_W)\, Z_{\mu\nu}} \right) \boldsymbol{b^{\mu\nu}}$$

KINETIC MIXING

- Changing basis:

$$b'_\mu = b_\mu + \varepsilon \, sin(\theta_W) \, Z_\mu$$
$$A'_\mu = A_\mu - \varepsilon \, cos(\theta_W) \, b_\mu$$

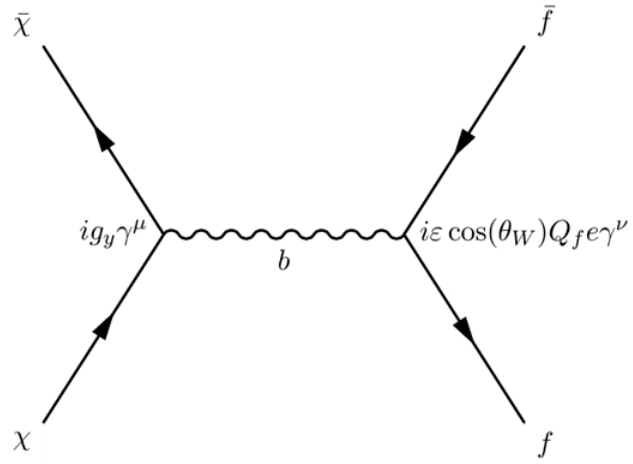
$$\mathcal{L}_{gauge\ mix} =$$
$$= -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} b_{\mu\nu} b^{\mu\nu}$$
$$+ \frac{\varepsilon^2}{4} sin^2(\theta_W) Z_{\mu\nu} Z^{\mu\nu} + \frac{\varepsilon^2}{4} cos^2(\theta_W) b_{\mu\nu} b^{\mu\nu} + \frac{\varepsilon^4}{4} sin^2(\theta_W) \, cos^2(\theta_W) \, Z_{\mu\nu} Z^{\mu\nu} - \frac{\varepsilon^3}{2} cos^2(\theta_W) \, sin^2(\theta_W) \, b_{\mu\nu} Z^{\mu\nu}$$

KINETIC MIXING

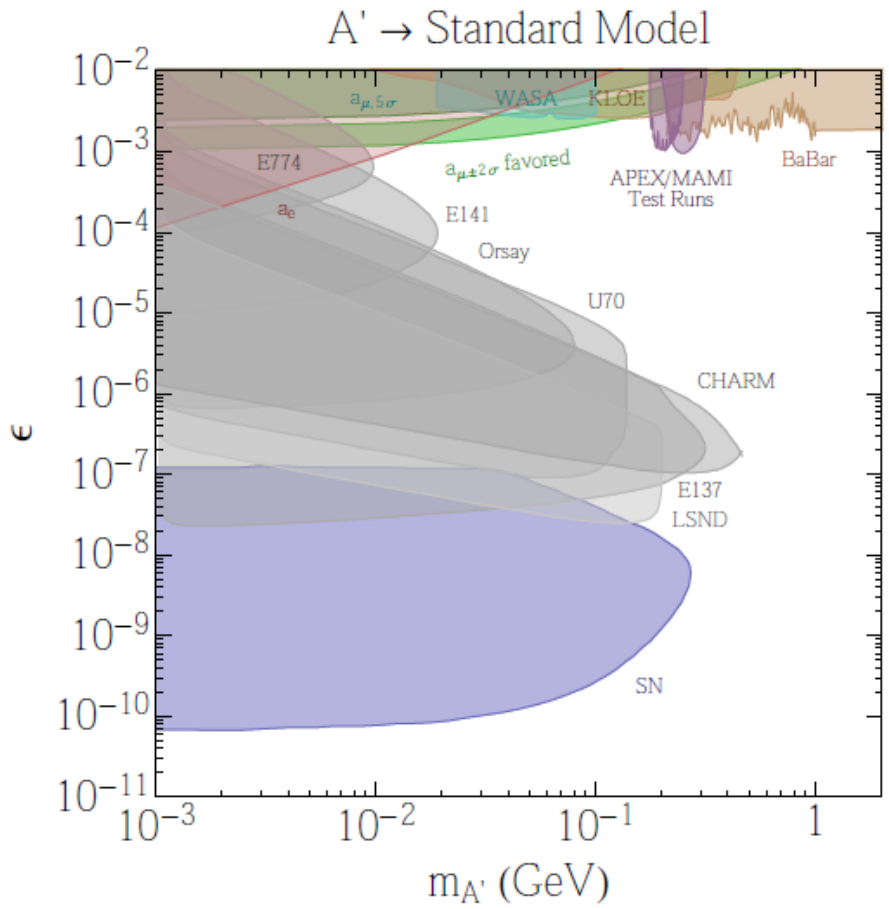
- $A_\mu J^\mu_{em} + Z_\mu J^\mu_Z + b_\mu J^\mu_b = A_\mu J^\mu_{em} + \varepsilon \cos(\theta_W)\, b_\mu J^\mu_{em} - \varepsilon^2 \cos(\theta_W) \sin(\theta_W)\, Z_\mu J^\mu_{em} + Z_\mu J^\mu_Z + b_\mu J^\mu_b - - \varepsilon \sin(\theta_W)\, Z_\mu J^\mu_b$

- $\mathcal{L}_{mass} = (b_\mu \quad Z_\mu) \begin{pmatrix} \frac{1}{2} m_b^2 & -\frac{1}{2} m_b^2 \varepsilon^2 \sin(\theta_W) \\ -\frac{1}{2} m_b^2 \varepsilon^2 \sin(\theta_W) & \frac{1}{2} m_Z^2 + \frac{1}{2} m_b^2 \varepsilon^2 \sin(\theta_W) \end{pmatrix} \begin{pmatrix} b_\mu \\ Z_\mu \end{pmatrix}$

- $\mathcal{L}_{coupling} = \boldsymbol{\varepsilon\, b_\mu \left(cos(\theta_W)\, J^\mu_{em} \right)} + \mathcal{O}\left(\frac{m_b^2}{m_Z^2}\right) J^\mu_Z - \varepsilon\, Z_\mu\, sin(\theta_W)\, J^\mu_b$



KINETIC MIXING



[R. Essig et al., arXiv:1311.0029 [hep-ph]]

DM GENESIS. FREEZE-OUT

- $Y_\chi \equiv \frac{n_\chi}{s}$
- $x \equiv \frac{m_\chi}{T}$
- $\Gamma_A \equiv \boldsymbol{n_\chi^{eq}\langle \sigma v_{M\phi l}\rangle}$

$$\frac{\boldsymbol{x}}{\boldsymbol{Y_\chi^{eq}}}\frac{\boldsymbol{dY_\chi}}{\boldsymbol{dx}} = -\frac{\boldsymbol{\Gamma_A}}{\boldsymbol{H(x)}}\left[\left(\frac{\boldsymbol{Y_\chi}}{\boldsymbol{Y_\chi^{eq}}}\right)^{\boldsymbol{2}} - \boldsymbol{1}\right]$$

- In first approximation:
  - $\boldsymbol{Y_\chi \backsimeq Y_\chi^{eq}}$, when $x \leq x_f$
  - $\boldsymbol{Y_\chi \backsimeq Y_\chi^{eq}(x_f)}$, when $x \geq x_f$
- $Y_{\chi,0} \backsimeq Y_{\chi,\infty} \equiv Y_\chi(x \to \infty) \backsimeq Y_\chi(x_f)$
- $\boldsymbol{\Omega_{\chi,0} = 2\frac{\rho_{\chi,0}}{\rho_{c,0}} \backsimeq 2\frac{m_\chi s_0 Y_{\chi,\infty}}{\rho_{c,0}}}$

[E. W. Kolb and M. S. Turner]

DM GENESIS. FREEZE-OUT

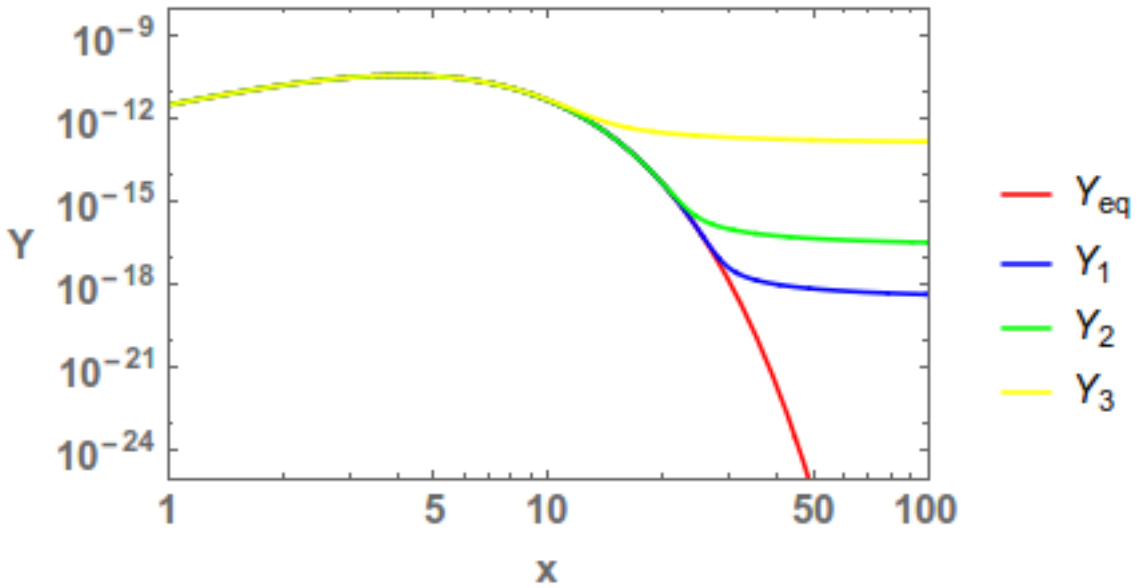
- Equilibrium:

$$Y_\chi^{eq} = \frac{45}{2\pi^4}\left(\frac{\pi}{8}\right)^{1/2}\frac{g_\chi}{g_{*,s}(T)}\, x^{3/2}\exp(-x)$$

- Plane waves expansion:

$$\langle \sigma v_{M\phi l}\rangle = \sigma_0 + \frac{\sigma_1}{x} + \cdots = \sum \sigma_n x^{-n}$$

$$\Omega_{\chi,0} \simeq 2\frac{s_0}{\rho_{\chi,0}}\frac{15}{\sqrt{5\pi}}\frac{\sqrt{g_{*(1)}}}{g_{*,s(x_f)}}\frac{x_f}{M_{Pl}\left(\sum \frac{\sigma_n}{n+1}x_f^{-n}\right)}$$



[E. W. Kolb and M. S. Turner]

DM GENESIS. FREEZE-IN

- Important features:
  - Interactions extremely weak → Thermally decoupled
  - Negligible initial abundance

- When $T > m_\chi$ (with $\lambda \ll 1$):
  - Quartic interaction: $Y_\chi \simeq \lambda^2 \, {M_{Pl}}/{T}$
  - Yukawa interaction: $Y_\chi \simeq \lambda^2 \, {M_{Pl}\, m_\chi^2}/{T^3}$

- When $T < m_\chi$: $Y_{\chi,0} \simeq \lambda^2 \, {M_{Pl}}/{m_\chi}$

[L. J. Hall et al., arXiv:0911.1120 [hep-ph]]

DM GENESIS. FREEZE-IN

- Initial condition:
  - $f_\chi \simeq 0$ and $f_{\bar{\chi}} \simeq 0$
- Assumptions:
  - $s \gg m_{bath}^2$
  - $f_i \simeq \exp\left({}^{-E_i}/_{T}\right)$

$$\boldsymbol{Y_{\chi,0} \simeq \frac{3}{2\pi}\sqrt{\frac{5}{\pi}}\frac{45\, M_{Pl}}{64\pi^4} g_f^2 \int_{T_0}^{T_{reh}} \frac{dT}{T^5} \int_{4\, m_\chi^2}^{\infty} ds\, \frac{\sigma(s) s^{3/2}}{g_{*S}(T)\sqrt{g_*(T)}} K_1\left(\frac{\sqrt{s}}{T}\right)}$$

[M. Blennow, E. Fernandez-Martinez and B. Zaldivar, arXiv:1309.7348 [hep-ph]]

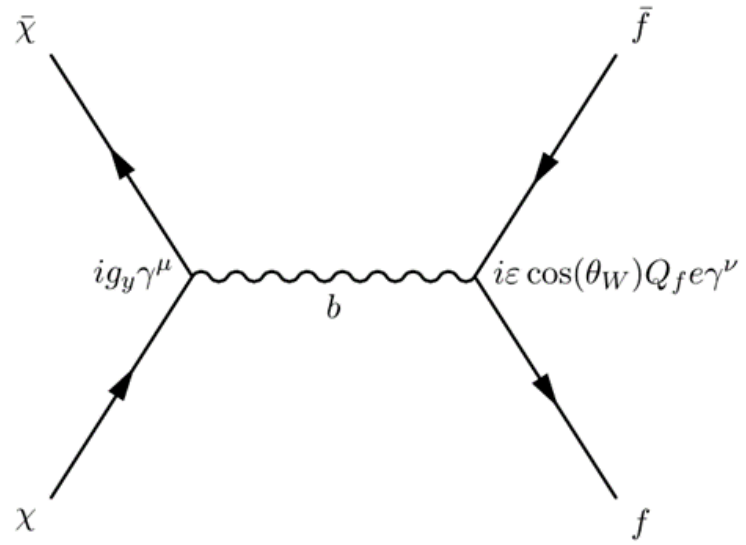
DM GENESIS. FREEZE-IN

- $s^{max} = (\mathcal{B}\, T)^2$
- $K_1 \simeq 1/{}_T^{\sqrt{s}}$
- $T^{max} \to \infty$
- $T^{min} = \frac{2}{\mathcal{B}} m_\chi$

$$\boldsymbol{\Omega_{\chi,0} \simeq 2 \frac{m_\chi s_0}{\rho_{c,0}} \frac{3}{2\pi} \sqrt{\frac{5}{\pi}} \frac{45\, M_{Pl}}{64\pi^6} \frac{g_f^2}{g_{*s}(m_\chi)\sqrt{g_*(m_\chi)}} \int_{\frac{2}{\mathcal{B}} m_\chi}^{\infty} \frac{dT}{T^4} \int_{4\, m_\chi^2}^{(\mathcal{B}\, T)^2} ds\, \sigma(s)\, s}$$

[M. Blennow, E. Fernandez-Martinez and B. Zaldivar, arXiv:1309.7348 [hep-ph]]

COMPUTATIONS AND RESULTS. FREEZE-OUT



$$\sigma_{\chi\bar{\chi}\to f\bar{f}} = \frac{F_c\, g_y^2\, \varepsilon^2 \cos^2(\theta_W)\; Q_f^2 e^2}{12\pi} \frac{|\vec{p}_i|}{|\vec{p}_f|} \frac{s^2 + 2s\left(m_f^2 + m_\chi^2\right) + 4\, m_f^2\, m_\chi^2}{s\,(s - m_b^2)^2}$$

$$s \simeq 4\, m_\chi^2 + m_\chi^2\, v_{M\phi l}^2$$

COMPUTATIONS AND RESULTS. FREEZE-OUT

$$a = \sum_f \frac{F_c\, g_y^2\, \varepsilon^2 \cos^2(\theta_W)\, Q_f^2 e^2}{12\pi} \frac{6\left(m_f^2 + 2\, m_\chi^2\right)\sqrt{m_\chi^2 - m_f^2}}{m_\chi \left(4\, m_\chi^2 - m_b^2\right)^2}$$

$$\boldsymbol{\sigma v_{M\phi l} \simeq a + b\, v_{M\phi l}^2}$$

$$b = \sum_f \frac{F_c\, g_y^2\, \varepsilon^2 \cos^2(\theta_W)\, Q_f^2 e^2}{12\pi} \frac{56\, m_f^4\, m_\chi^2 + 20\, m_f^2\, m_\chi^4 - 40\, m_\chi^6 - m_b^2\left(14\, m_\chi^4 - 7\, m_f^2\, m_\chi^2 + 2\, m_f^4\right)}{4\, m_\chi \left(4\, m_\chi^2 - m_b^2\right)^3 \sqrt{m_\chi^2 - m_f^2}}$$

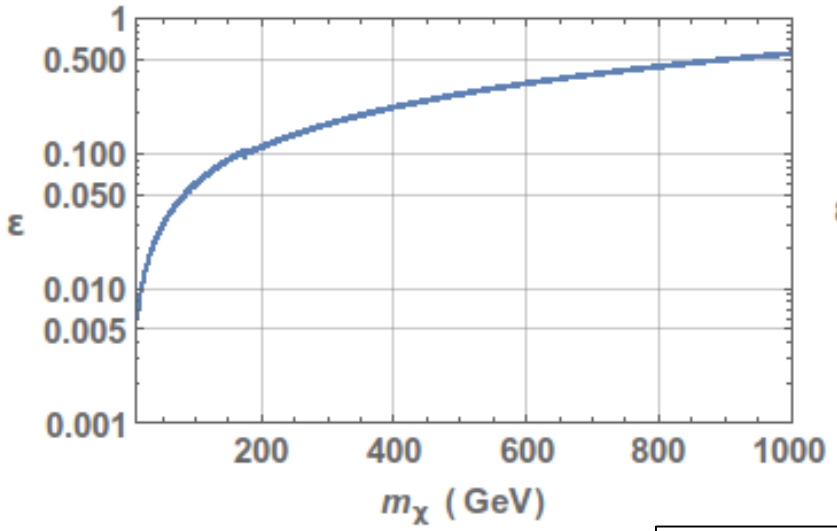
COMPUTATIONS AND RESULTS. FREEZE-OUT

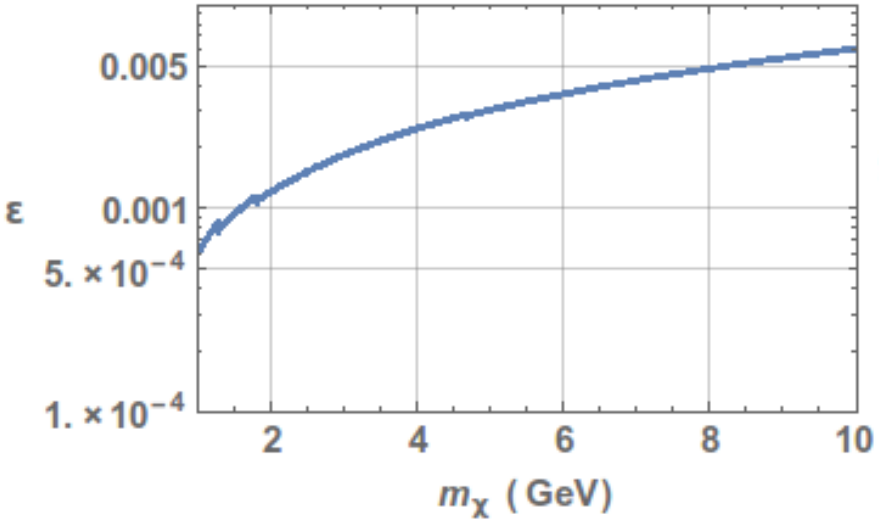
$$\langle \sigma \, v_{M\phi l} \rangle \simeq a + 12\, b\, \frac{1}{x}$$

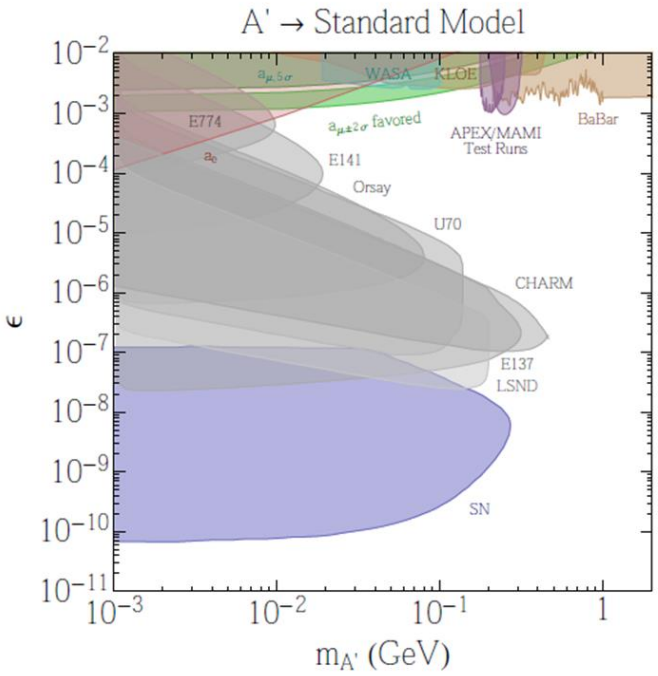
$$\boldsymbol{\Omega_{\chi,0} \simeq 2 \frac{15}{\sqrt{5\,\pi}} \frac{\sqrt{g_*(1)}}{g_{*s}(x_f)} \frac{s_0}{\rho_{c,0}} \frac{x_f}{M_{Pl}\left(a + \frac{12b}{2}\frac{1}{x_f}\right)}}$$

- Assumptions
  - $x_f \simeq 20$
  - When $T \sim m_\chi$: $g_{*s} = g_* \simeq \mathrm{g}_{*SM} + \mathrm{g_b}$
  - $\alpha(m_W^2) = \frac{e^2}{4\pi} \simeq 1/128$
  - $g_y = 1$
- Measured values
  - $\rho_{c,0} = 1.05375 \times 10^{-5} h^2 \ \mathrm{GeV\,cm^{-3}}$
  - $s_0 = 2891.2 \ \mathrm{cm^{-3}}$
  - $\boldsymbol{\Omega_{\chi,0}\, h^2 = 0.1186 \pm 0.0020}$

COMPUTATIONS AND RESULTS. FREEZE-OUT

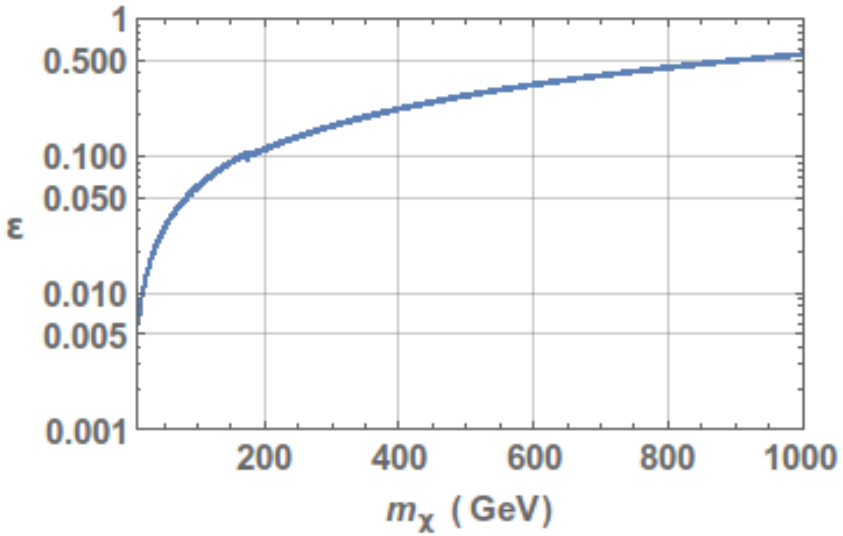


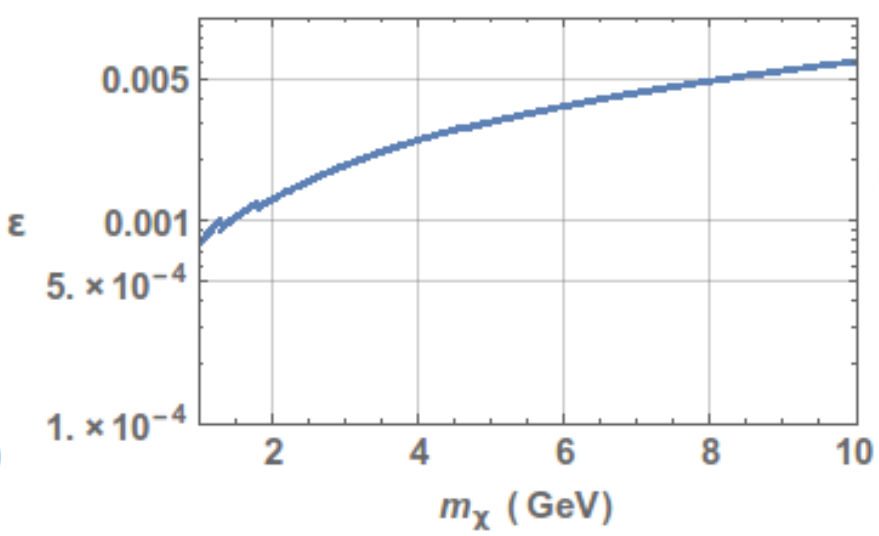


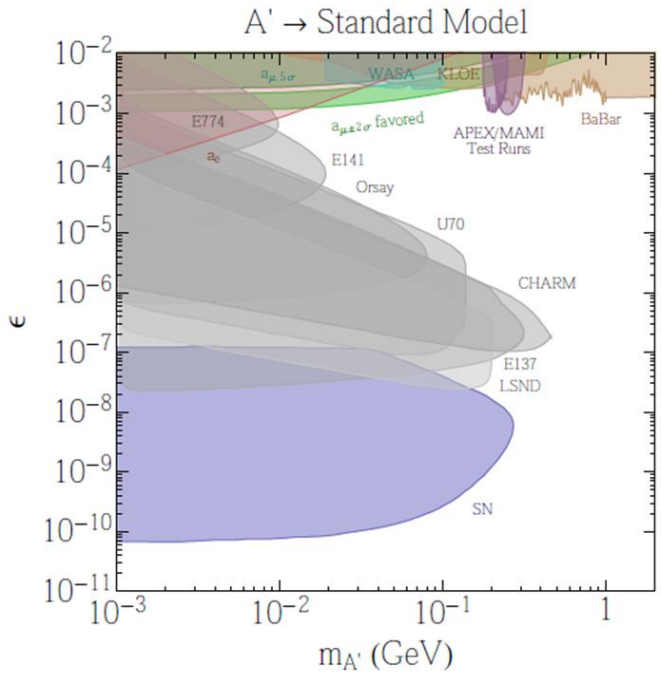


$m_b = 1$ GeV

COMPUTATIONS AND RESULTS. FREEZE-OUT

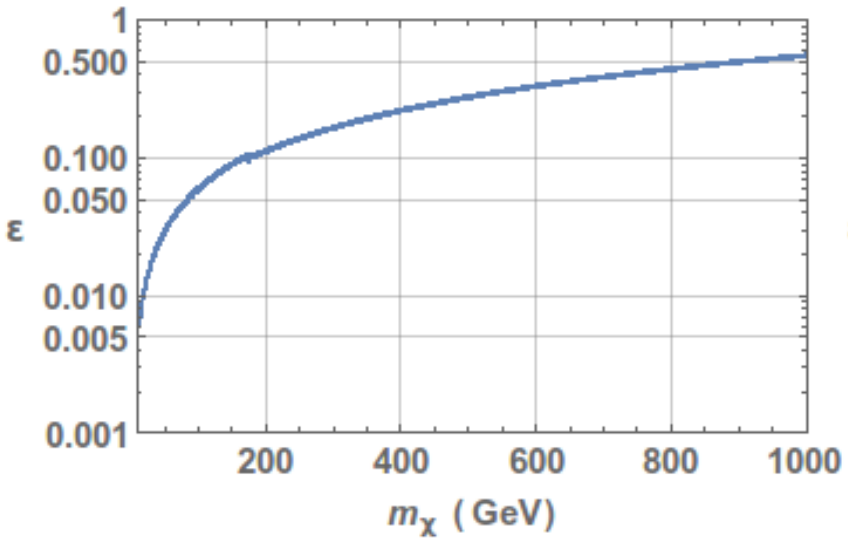


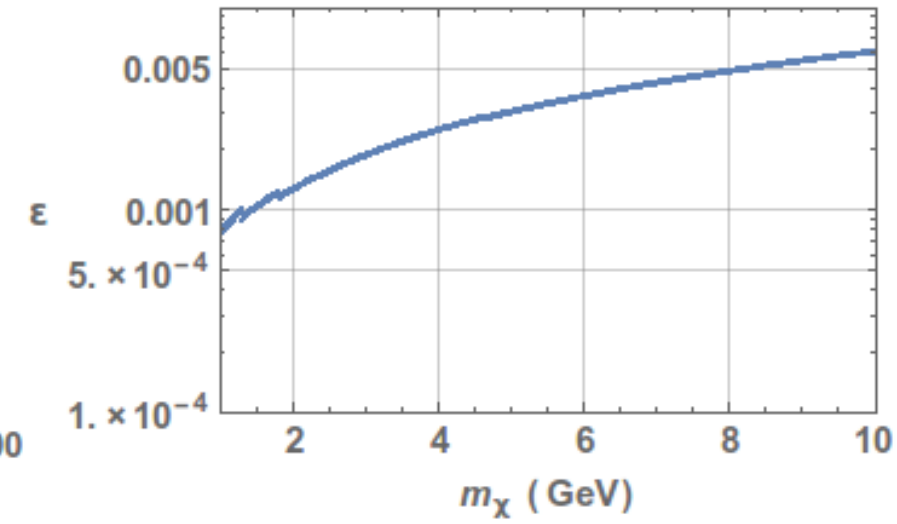


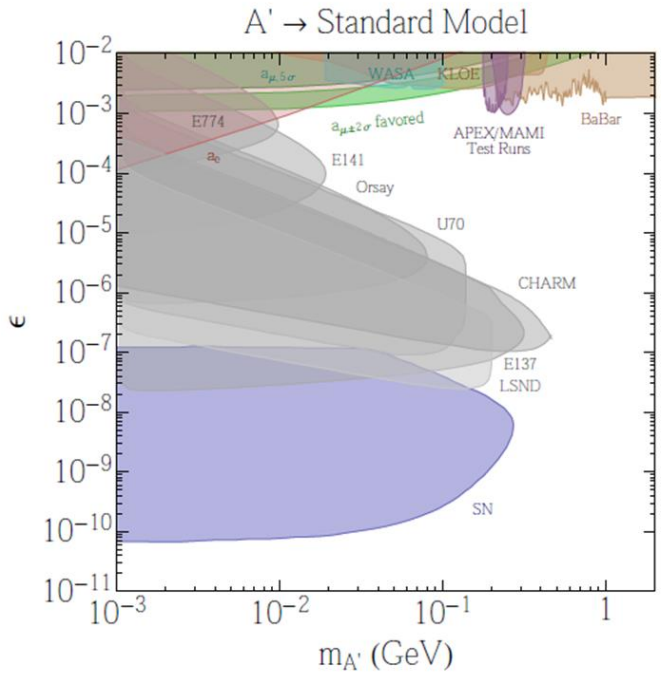


$m_b = 100$ MeV

COMPUTATIONS AND RESULTS. FREEZE-OUT

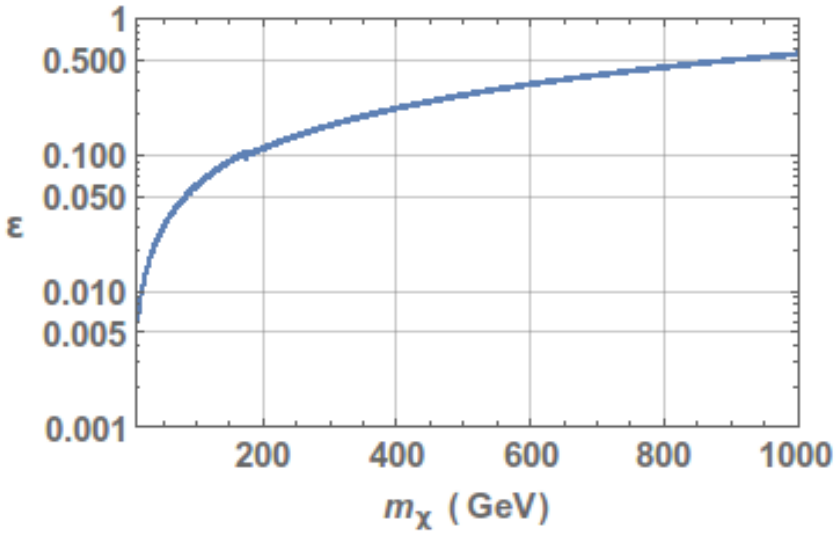


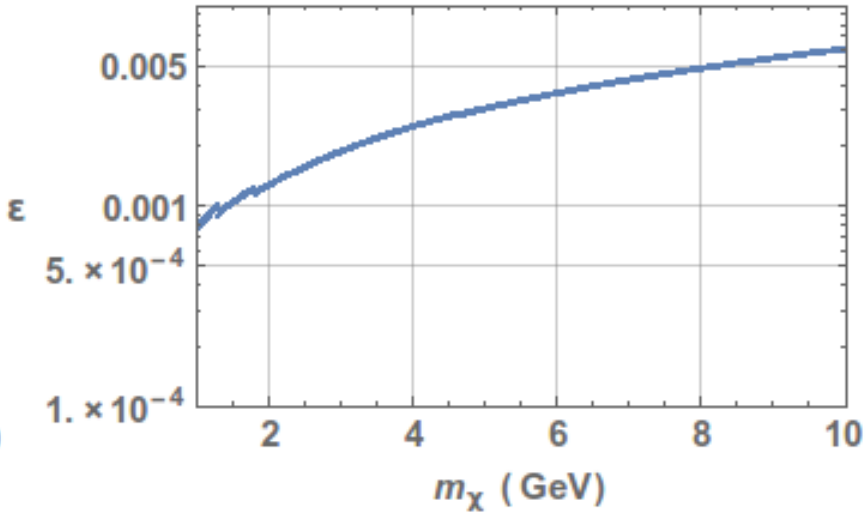


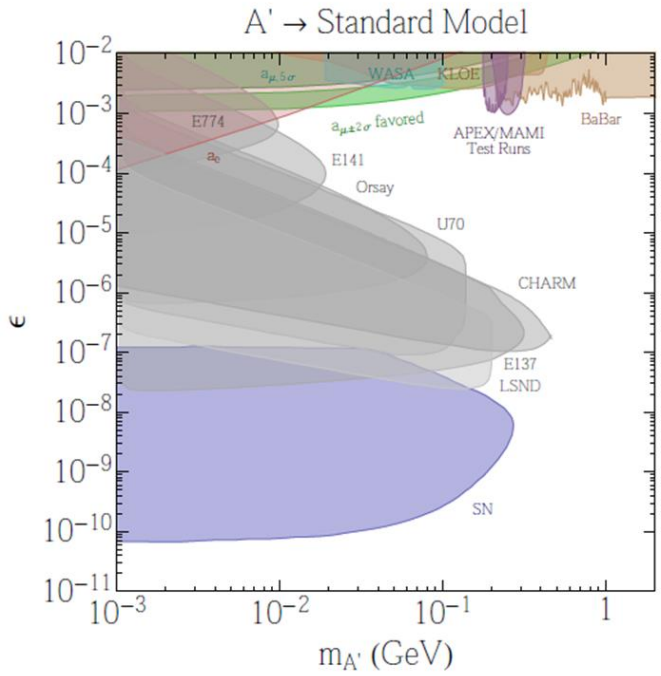


$m_b = 10$ MeV

COMPUTATIONS AND RESULTS. FREEZE-OUT







$m_b = 1\ \mathrm{MeV}$

COMPUTATIONS AND RESULTS. FREEZE-IN

- Cross section

$$\sigma_{f\bar{f}\to\chi\bar{\chi}} = \frac{1}{g_f^2}\frac{F_c\, g_y^2\, \varepsilon^2\, cos^2(\theta_W)\; Q_f^2 e^2}{3\pi}\frac{|\vec{p}_i|}{|\vec{p}_f|}\frac{s^2 + 2s\left(m_f^2 + m_\chi^2\right) + 4\, m_f^2\, m_\chi^2}{s\,(s - m_b^2)^2}$$

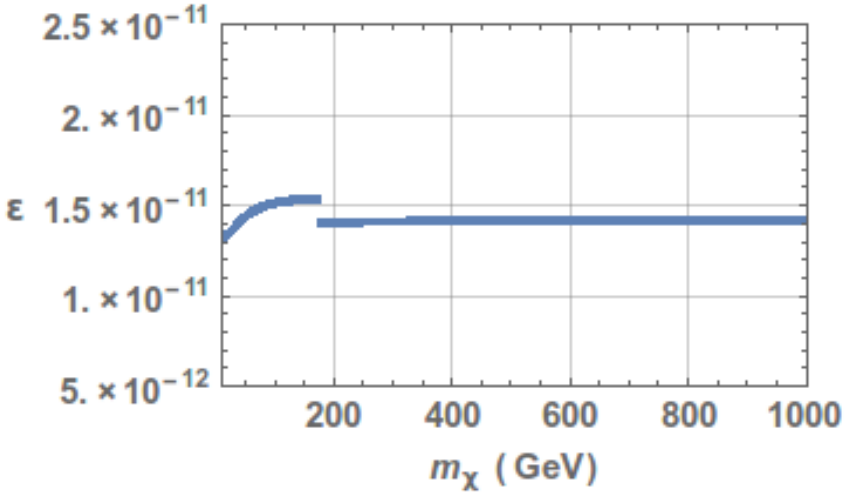
- Relic density

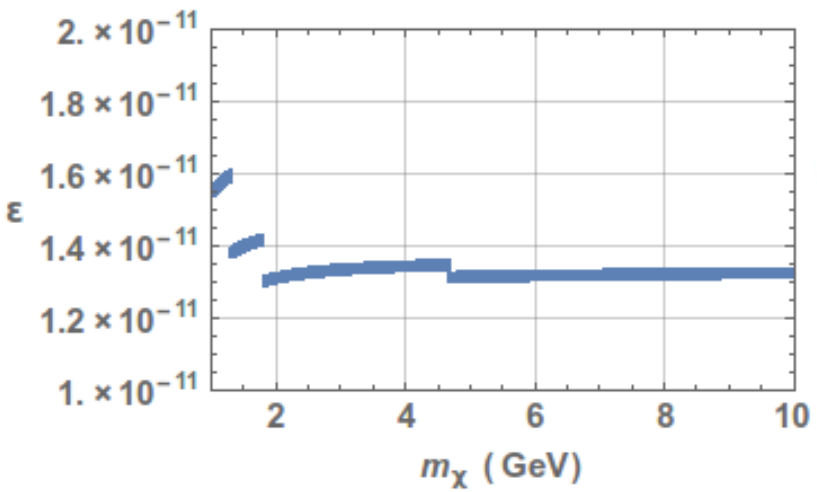
$$\Omega_{\chi,0} \simeq 2\frac{m_\chi s_0}{\rho_{c,0}}\frac{3}{2\pi}\sqrt{\frac{5}{\pi}}\frac{45\, M_{Pl}}{64\pi^6}\frac{g_f^2}{g_{*s}(m_\chi)\sqrt{g_*(m_\chi)}}\int_{\frac{2}{\mathcal{B}}m_\chi}^{\infty}\frac{dT}{T^4}\int_{4\, m_\chi^2}^{(\mathcal{B}\, T)^2} ds\; \sigma(s)\; s$$

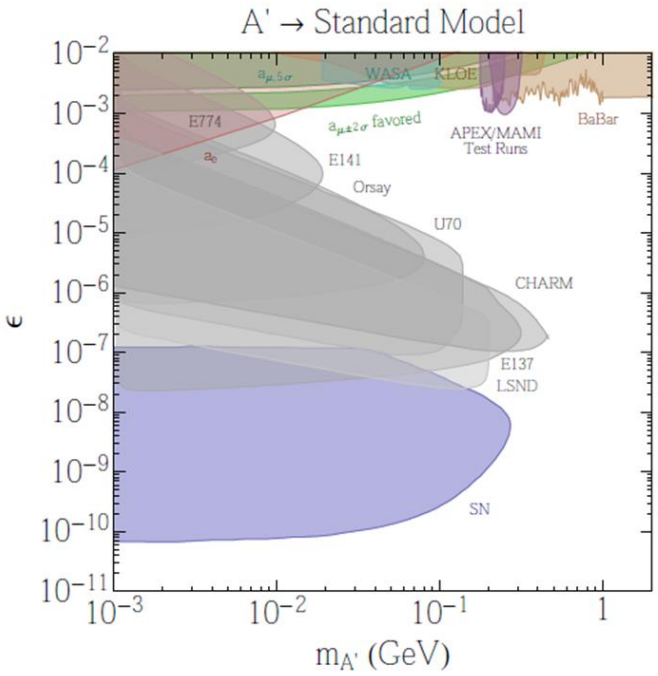
$$\Omega_{\chi,0} \simeq 2\frac{s_0}{\rho_{c,0}}\frac{3}{2\pi}\sqrt{\frac{5}{\pi}}\frac{45\, M_{Pl}}{64\pi^6}\sum_f \frac{F_c\, g_y^2\, \varepsilon^2\, cos^2(\theta_W)\; Q_f^2 e^2}{g_{*s}(m_\chi)\sqrt{g_*(m_\chi)}}\frac{\mathcal{B}^3}{32}$$

[M. Blennow, E. Fernandez-Martinez and B. Zaldivar, arXiv:1309.7348 [hep-ph]]

COMPUTATIONS AND RESULTS. FREEZE-IN

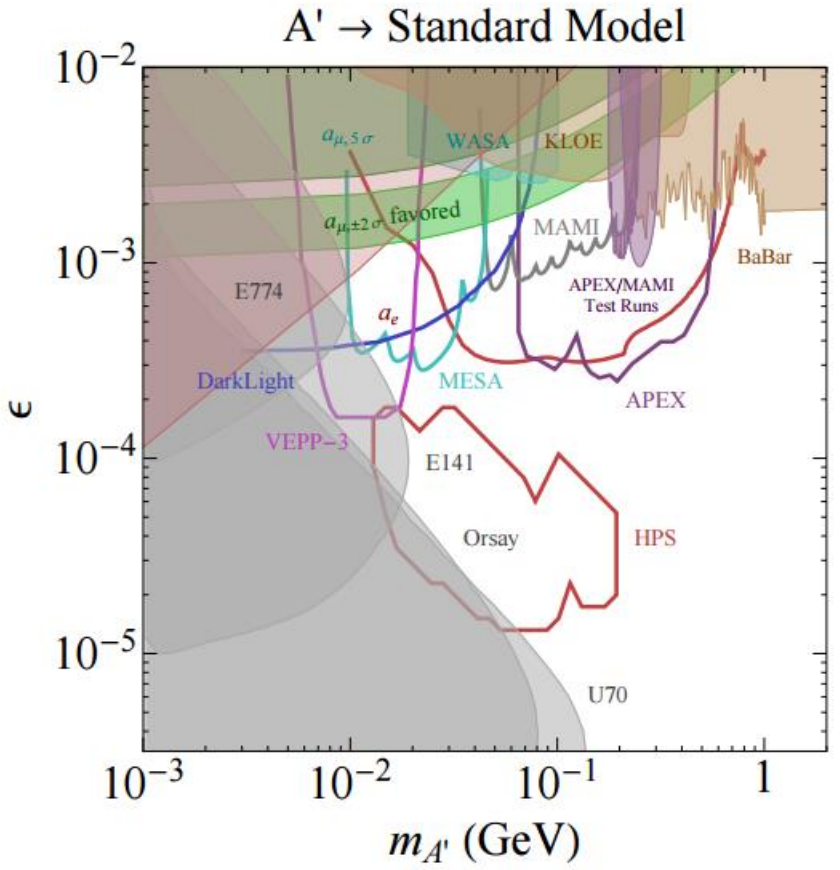






SEARCHING HIDDEN PHOTONS

- Accelerators
  - MAMI
  - MESA
- Fixed target experiments (electrons)
  - APEX
  - Darklight
  - HPS
- Fixed target experiments (positrons)
  - VEPP-3
- Fixed target experiments (protons)



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