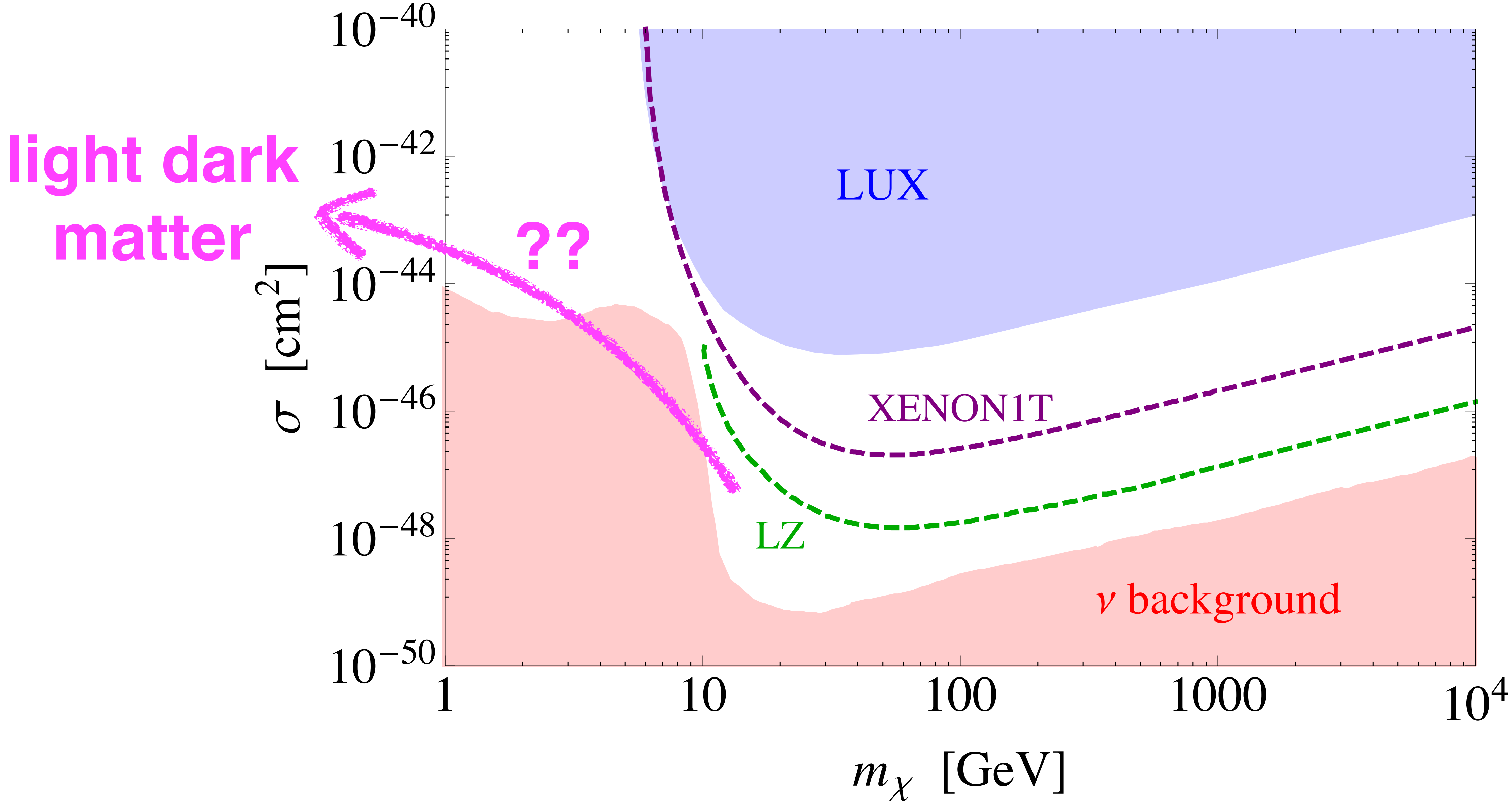
Light Dark Matter from Boltzmann Factors

Josh Ruderman (NYU)
@ Irvine 5/6/2015

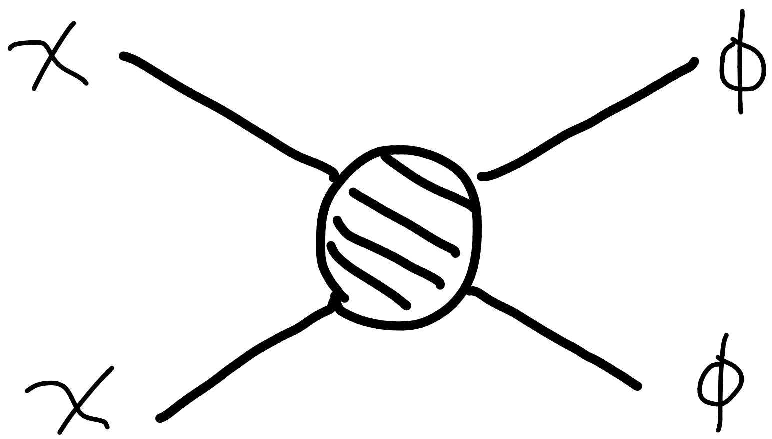
Raffaele D’Agnolo, JTR, *to appear.*

Towards the Neutrino Floor in Direct Detection



- LUX, **1310.8214**
- Billard, Figueroa-Feliciano, Strigari, **1307.5458**

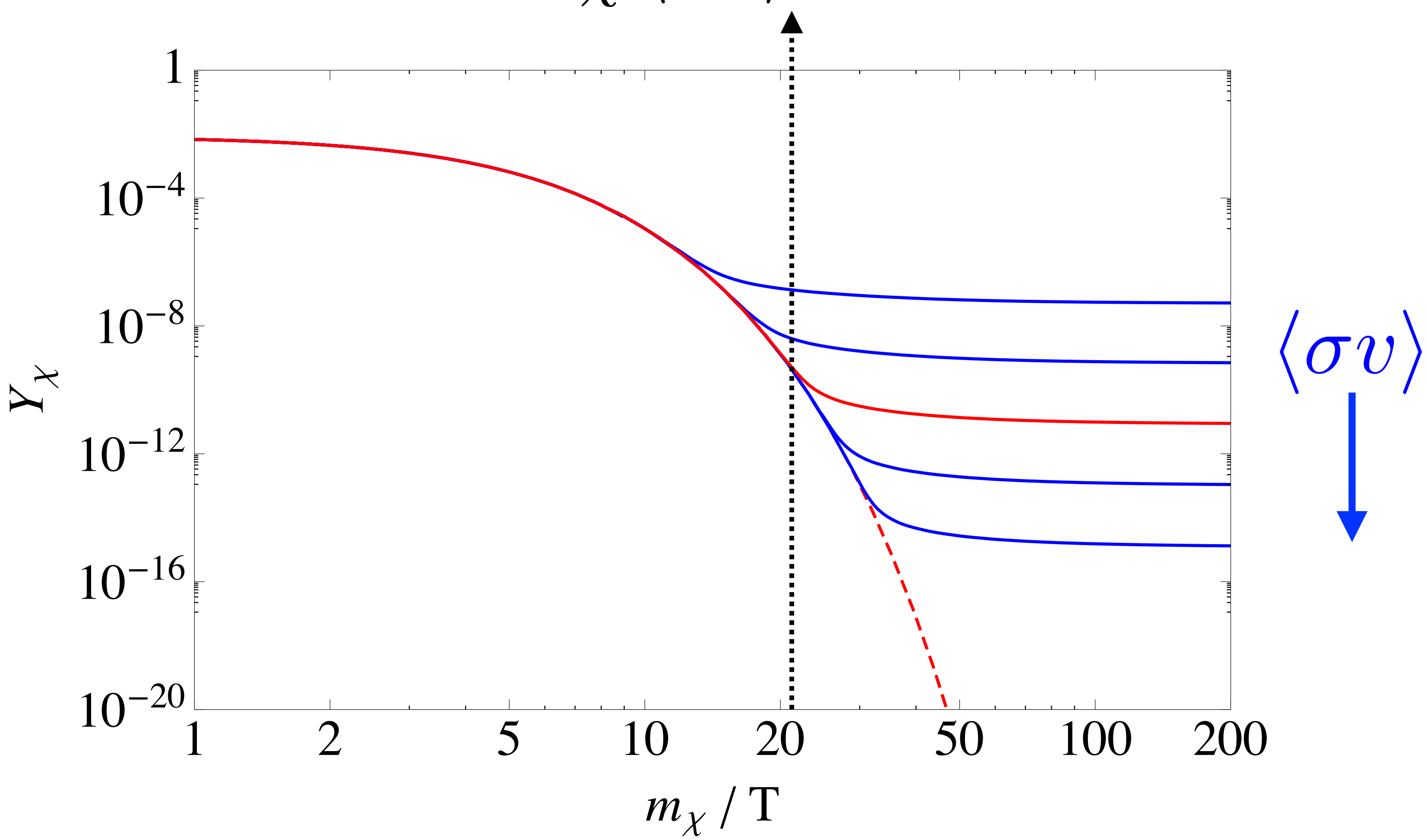
WIMP Miracle



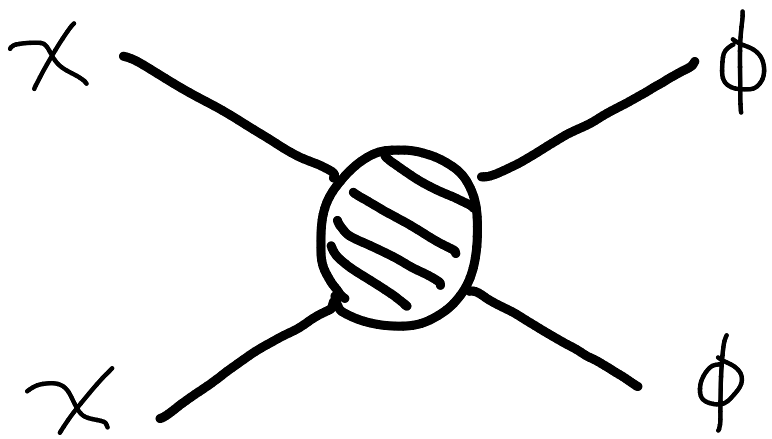
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

$$n_\chi \langle\sigma v\rangle \approx H$$

$$Y_\chi \equiv \frac{n_\chi}{s}$$



WIMP Miracle



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

$$n_\chi\langle\sigma v\rangle \approx H$$

$$\Omega_\chi h^2 \sim 0.1\frac{m_\chi Y_\chi}{T_{eq}} \sim 0.1\frac{m_\chi H}{T_{eq}\, s\,\langle\sigma v\rangle} \sim 0.1\frac{(T_{eq}M_{pl})^{-1}}{\langle\sigma v\rangle}$$

$$\sqrt{T_{eq}M_{pl}} \sim 60\ \text{TeV}$$

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Three exceptions in the calculation of relic abundances

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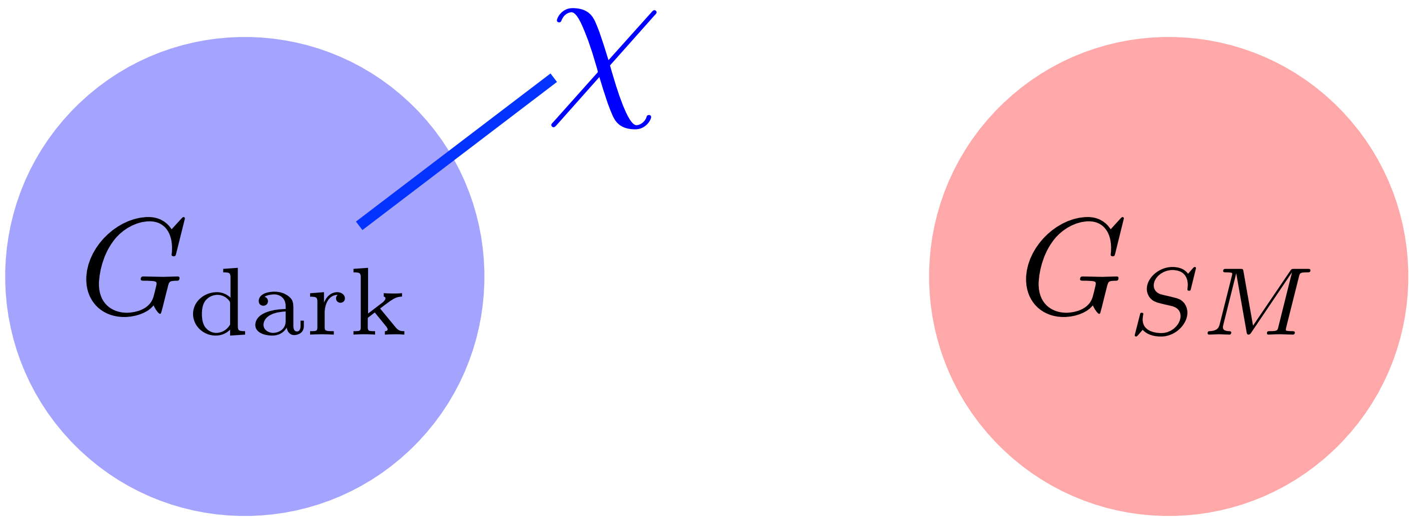
(Received 15 November 1990)

1. coannihilation ←
2. forbidden channels ←
3. annihilation near pole

so far mainly applied to weak-scale DM in SM sector

goal: explore possible cosmologies for thermal relics in hidden sectors



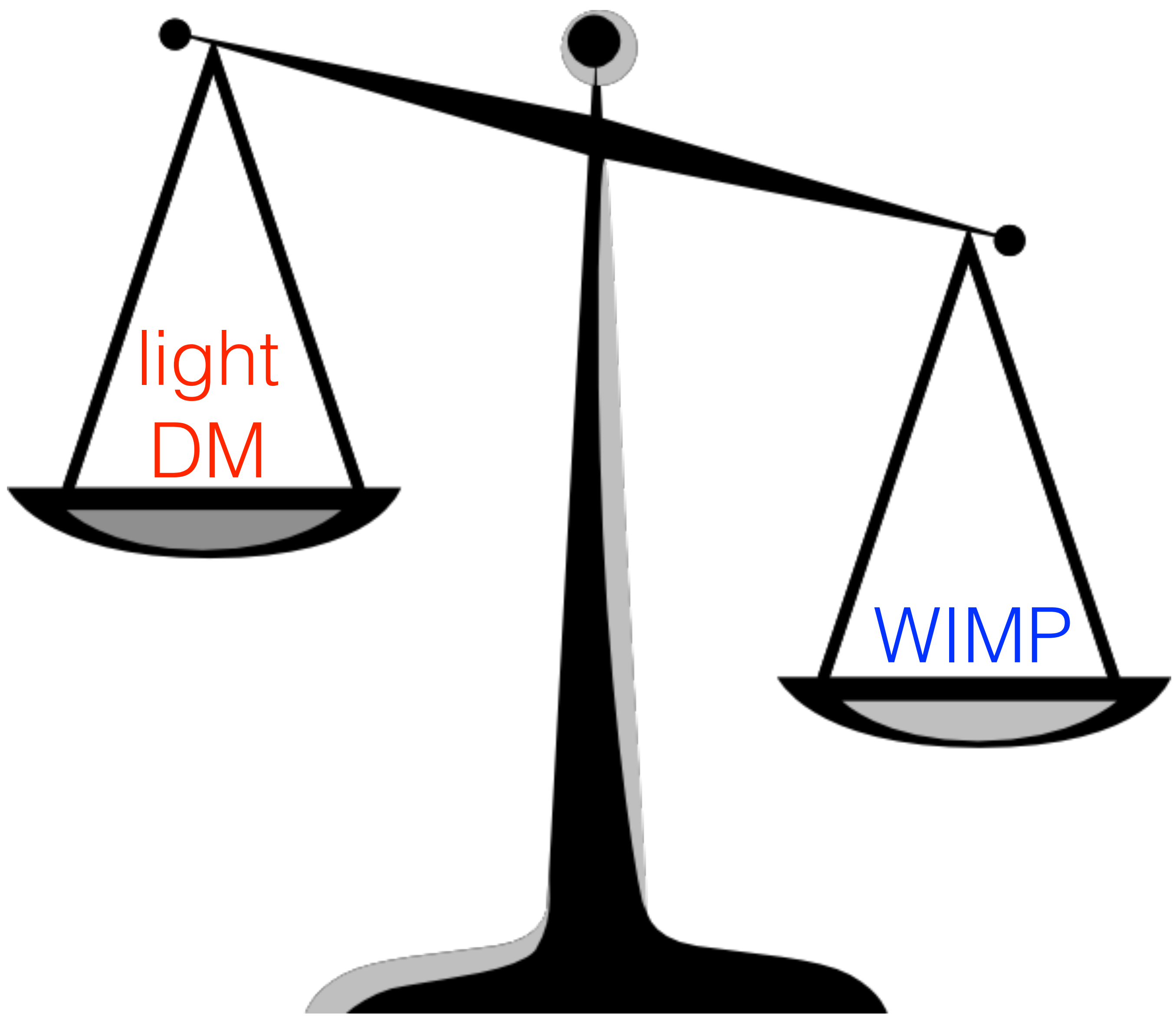
$$m_\chi \ll v$$

punchline: coannihilation and forbidden channels are generic mechanisms for light DM

plan

1. review: light dark matter
2. forbidden dark matter
3. generalized coannihilation

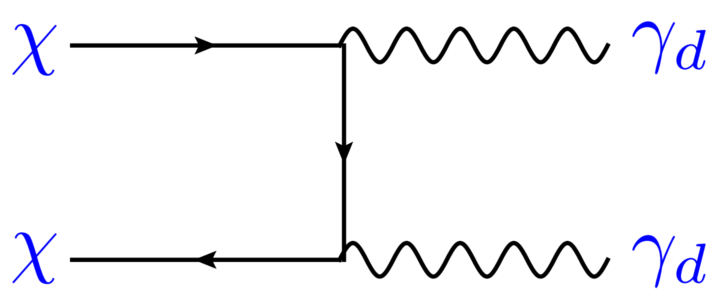
review: light dark matter



light DM with weak cross section

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{m_Z^2}$$

$$\alpha_d \ll 1$$

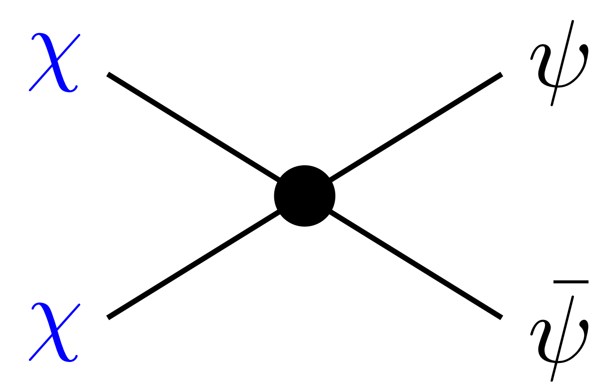


$$\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_\chi^2}$$

(WIMPless miracle)

- Feng, Kumar **0803.4196**

$$m_\chi \ll \Lambda$$



$$\langle \sigma v \rangle \sim \frac{m_\chi^2}{\Lambda^4}$$

- Lee, Weinberg 1977
- Boehm, Fayet **hep-ph/0305261**

asymmetric dark matter

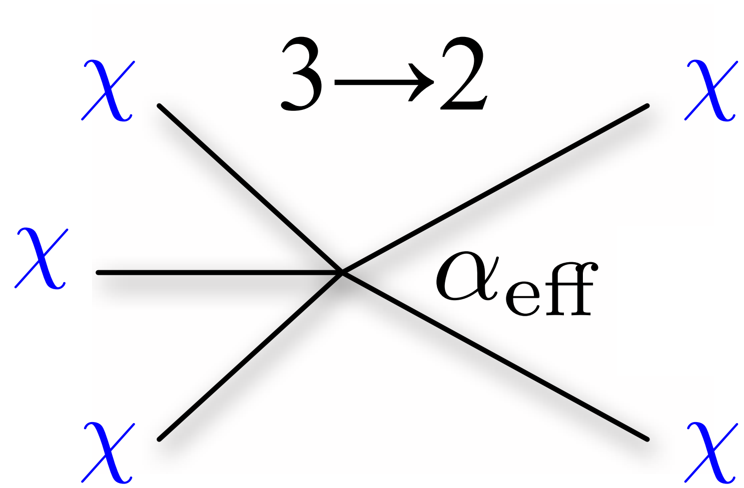
χ

χ χ

$$m_\chi \approx 5\ \mathrm{GeV} \left(\frac{n_B - n_{\bar{B}}}{n_\chi - n_{\bar{\chi}}} \right) \approx 5\ \mathrm{GeV} \left(\frac{2 \times 10^{-10}}{\left(n_\chi - n_{\bar{\chi}}\right)/s} \right)$$

- Nussinov, **1985**
- Kaplan, Luty, Zurek, **0901.4117**

SIMP

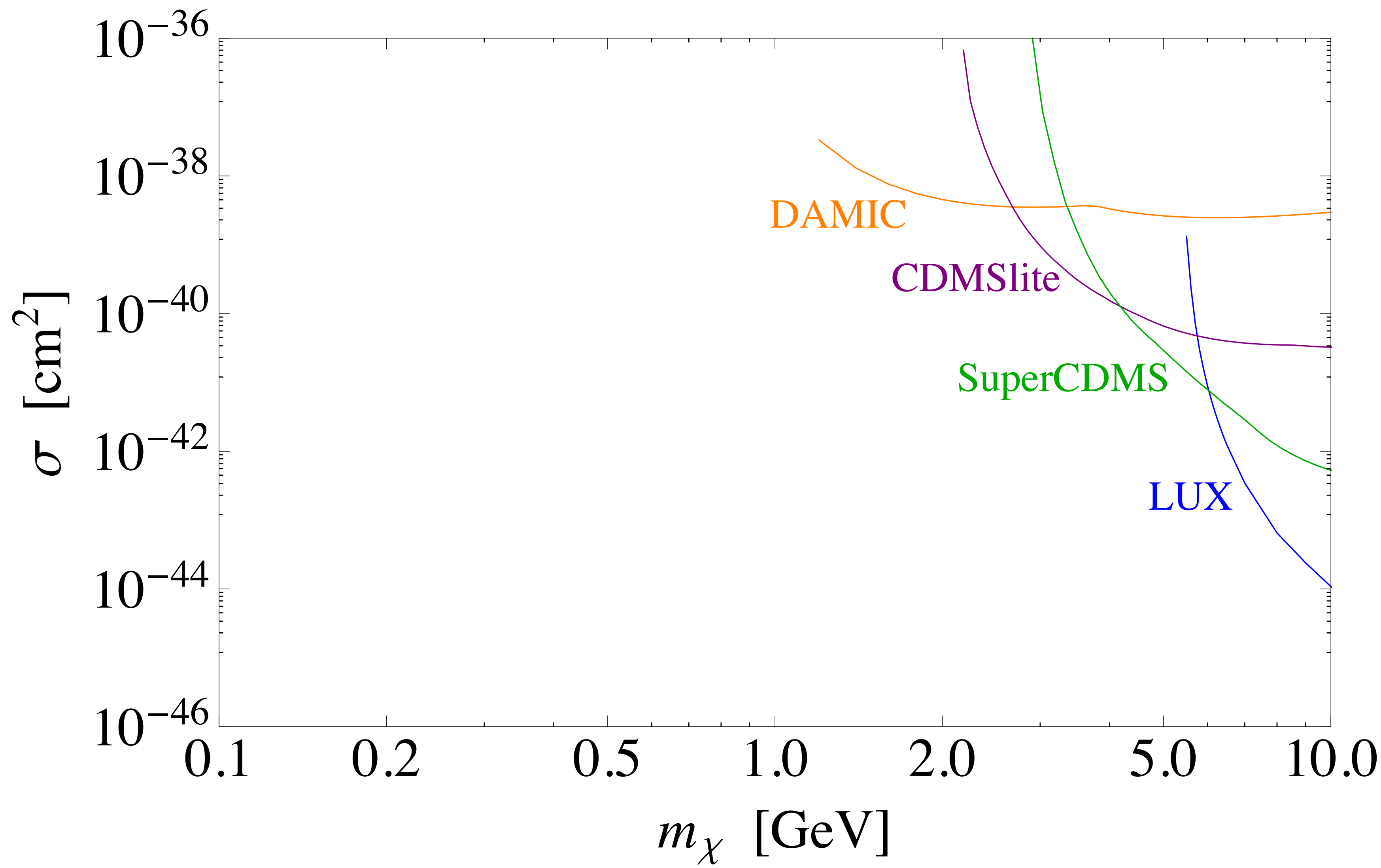


$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle_{3\to 2} \left(n_\chi^3 - n_\chi^2 n_\chi^{eq} \right)$$

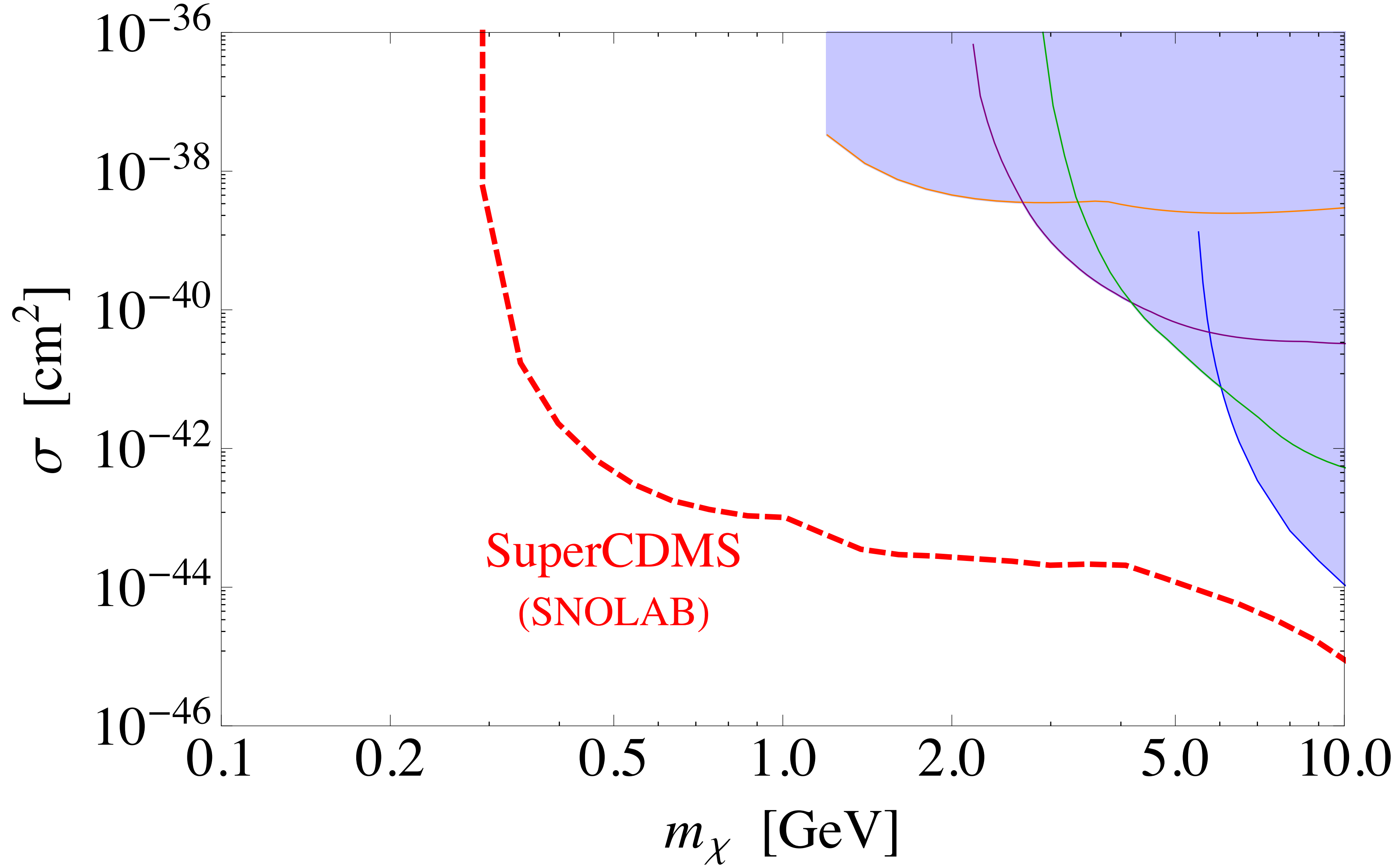
$$m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{pl} \right)^{1/3} \sim 100 \text{ MeV}$$

- Carlson, Hall, Machacek **1992**
- Hochberg, Kuflik, Volansky, Wacker, **1402.5143**

probing light dark matter

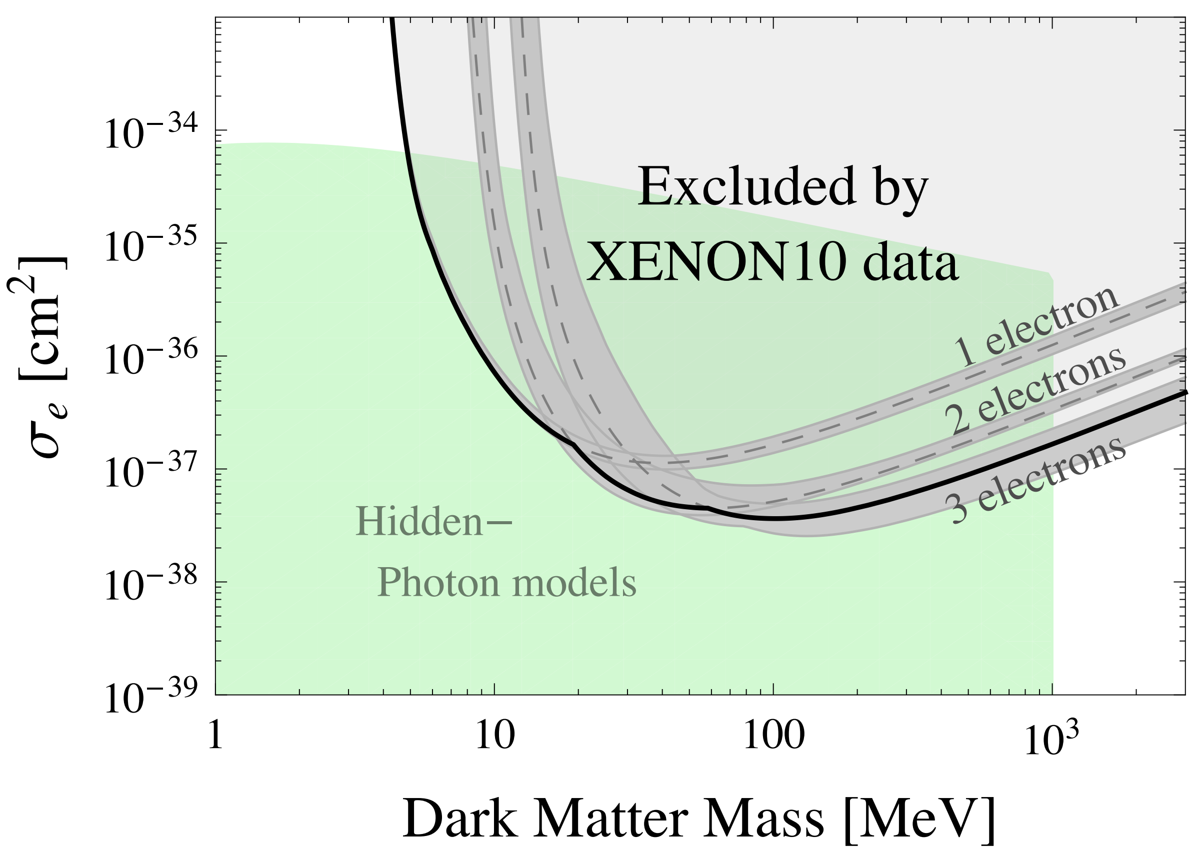


probing light dark matter



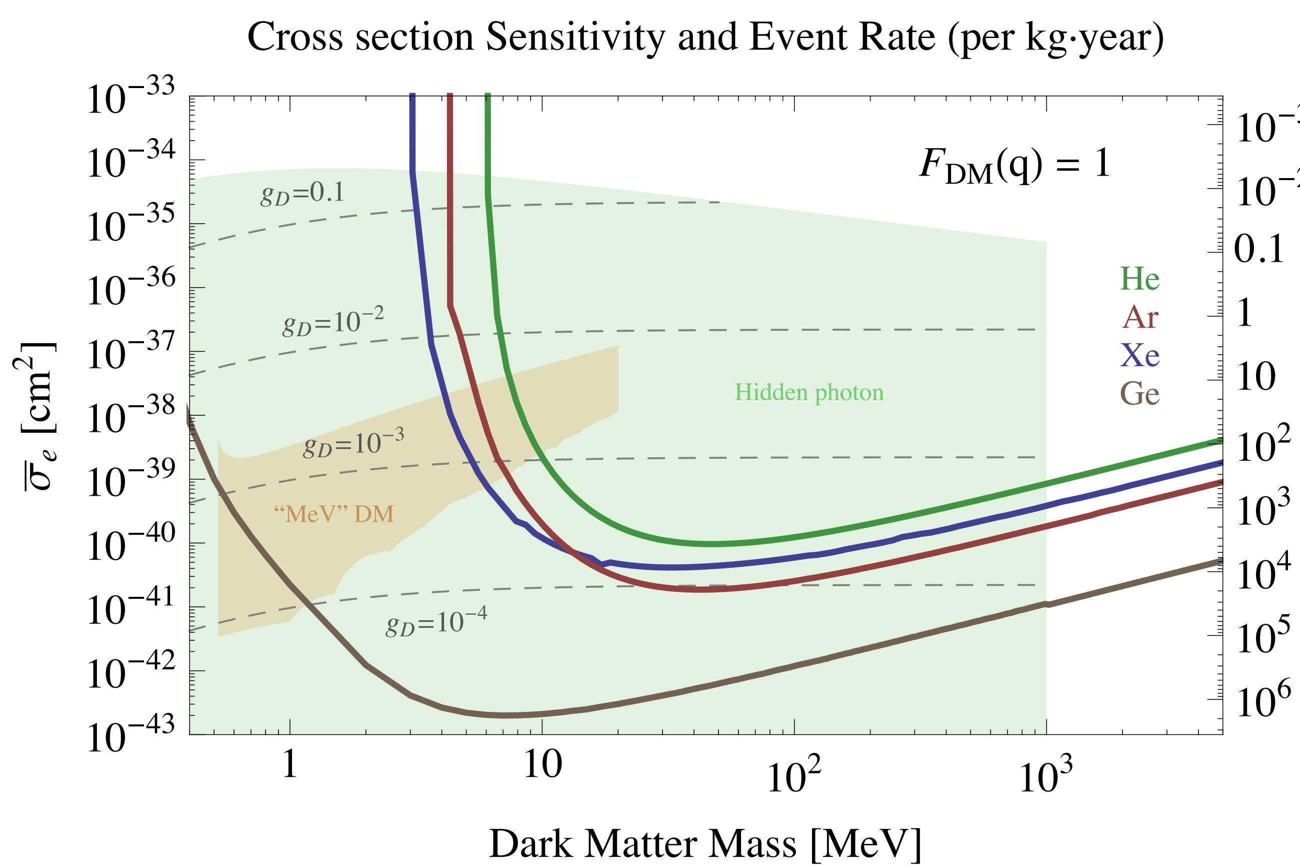
probing light dark matter

now



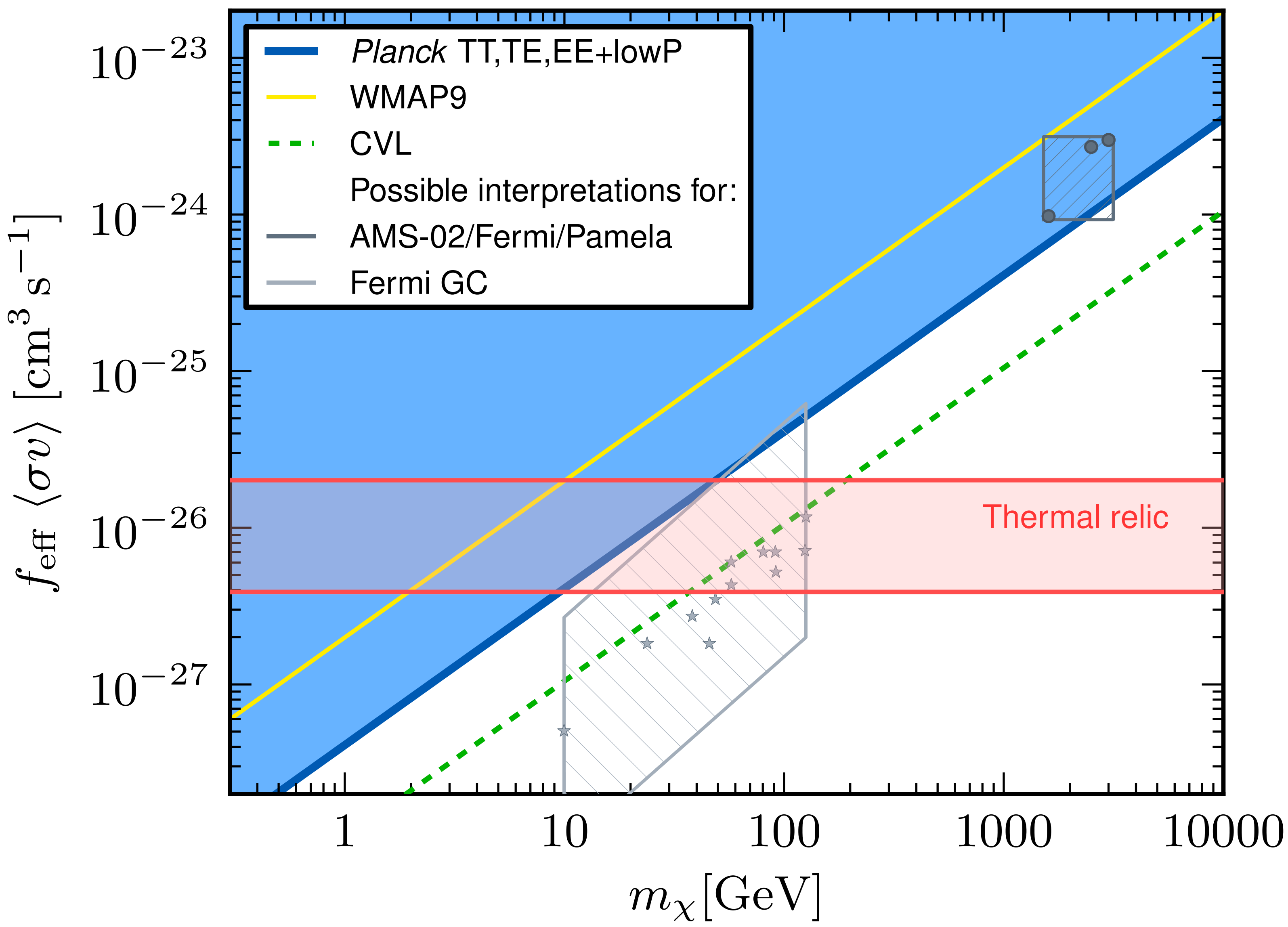
- Essig, Manalaysay, Mardon, Sorensen, Volansky **1206.2644**

later



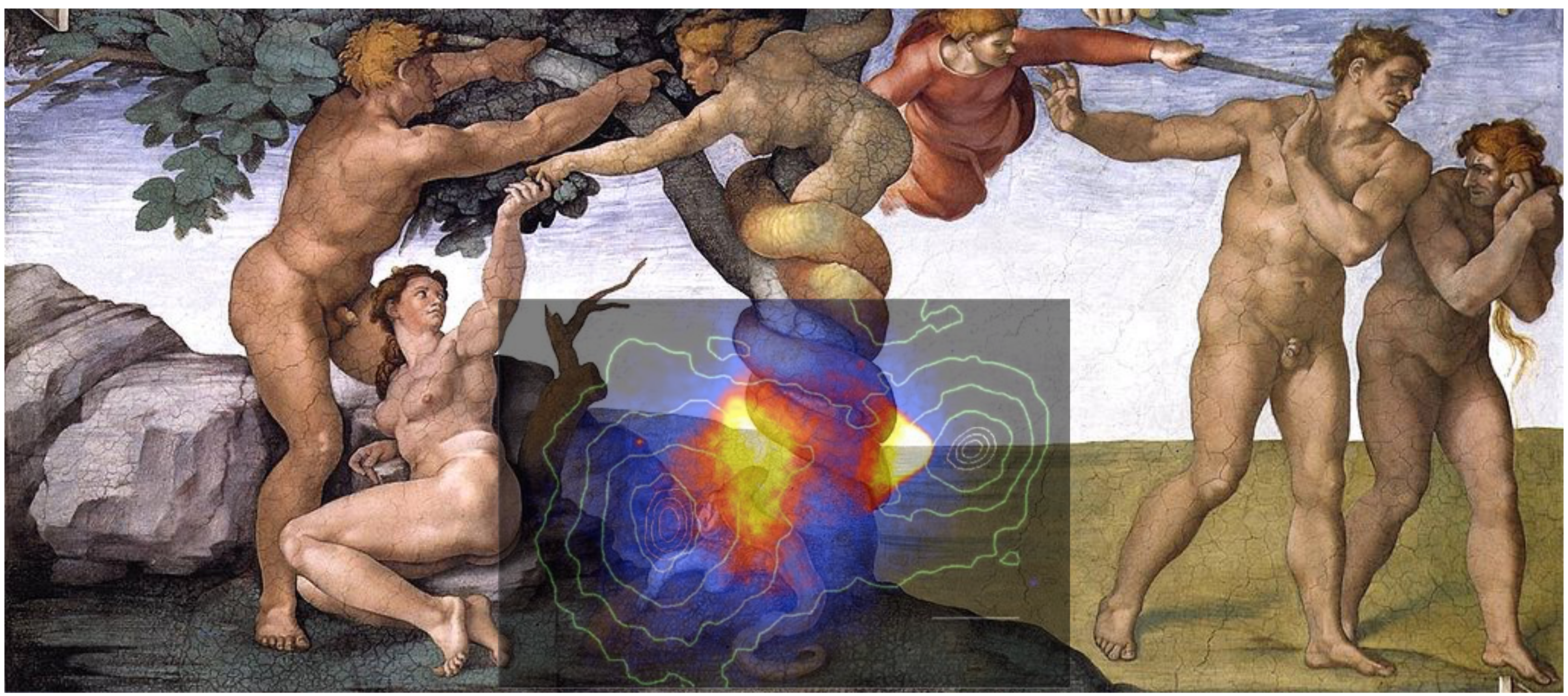
- Essig, Mardon, Volansky **1108.5383**

CMB limit



- Madhavacheril, Sehgal, Slatyer, **1310.3815**
- Planck, **1502.01589**

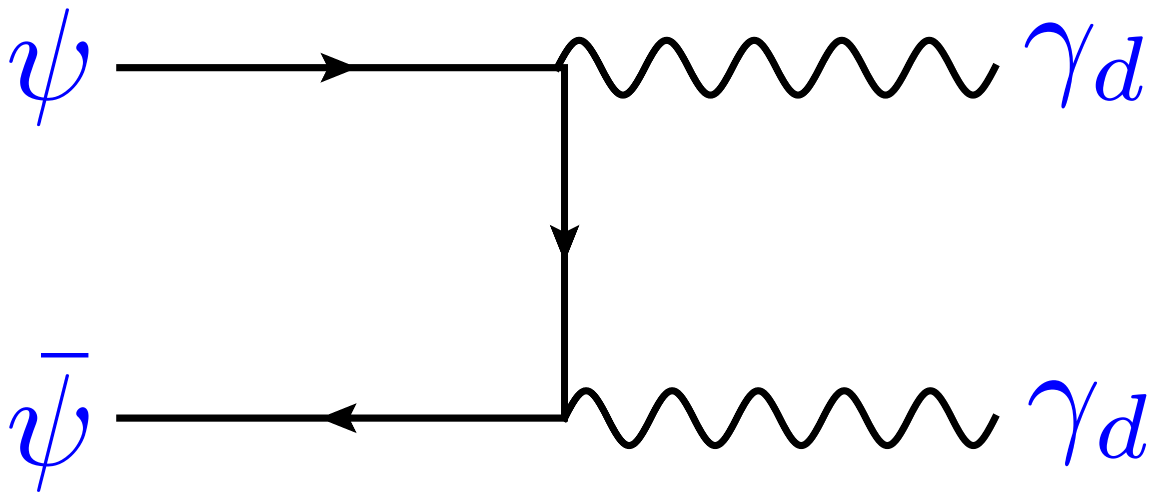
Forbidden Dark Matter



example model

$G_{SM} \times U(1)_d$

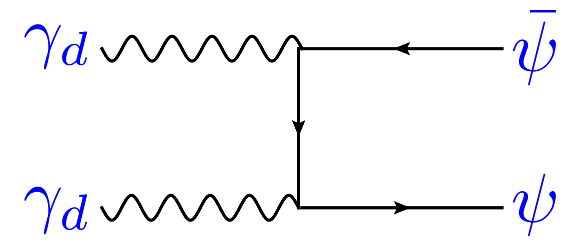
$m_\psi < m_{\gamma_d}$



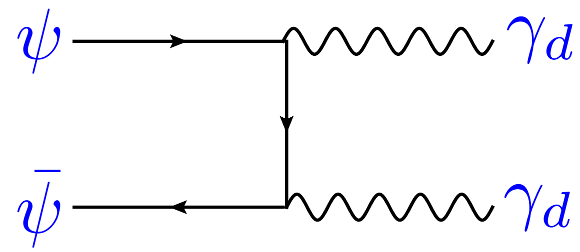
$\langle \sigma v \rangle$

- evades CMB when: $m_{\gamma_d} - m_\psi \gg T_{rec}$

Boltzmann equation



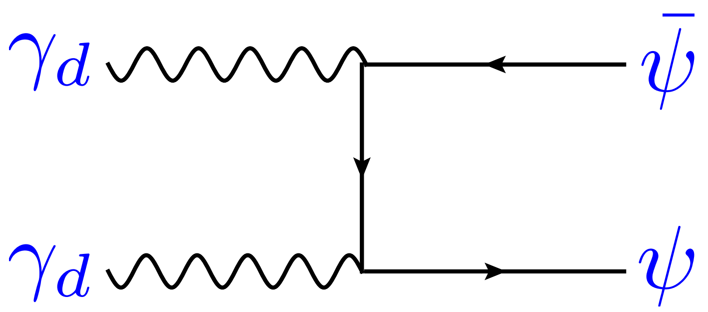
$$\dot{n}_\psi + 3Hn_\psi = -n_\psi^2 \left\langle \sigma v \right\rangle_{\psi\bar{\psi}} + n_{\gamma_d}^2 \left\langle \sigma v \right\rangle_{\gamma_d\gamma_d}$$



detailed balance: $$(n_\psi^{eq})^2 \left\langle \sigma v \right\rangle_{\psi\bar{\psi}} = (n_{\gamma_d}^{eq})^2 \left\langle \sigma v \right\rangle_{\gamma_d\gamma_d}$$

forbidden cross section

$$\langle \sigma v \rangle_{\psi\bar{\psi}} = \frac{(n^{eq}_{\gamma_d})^2}{(n^{eq}_{\psi})^2} \langle \sigma v \rangle_{\gamma_d \gamma_d}$$



$$n^{eq} = g \left(\frac{m\,T}{2\pi} \right)^{3/2} e^{-m/T}$$

$$\langle \sigma v \rangle_{\gamma_d \gamma_d} \approx \frac{\alpha_d^2}{m_{\gamma_d}^2}$$

$$\langle \sigma v \rangle_{\psi\bar{\psi}} \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2x\Delta}$$

$$\Delta \equiv \frac{m_{\gamma_d} - m_\psi}{m_\psi}$$

$$x \equiv \frac{m_\psi}{T}$$

forbidden relic density

$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2}\, e^{2x_f\Delta} \qquad\qquad m_\psi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-2x_f\Delta}$$

Three exceptions in the calculation of relic abundances

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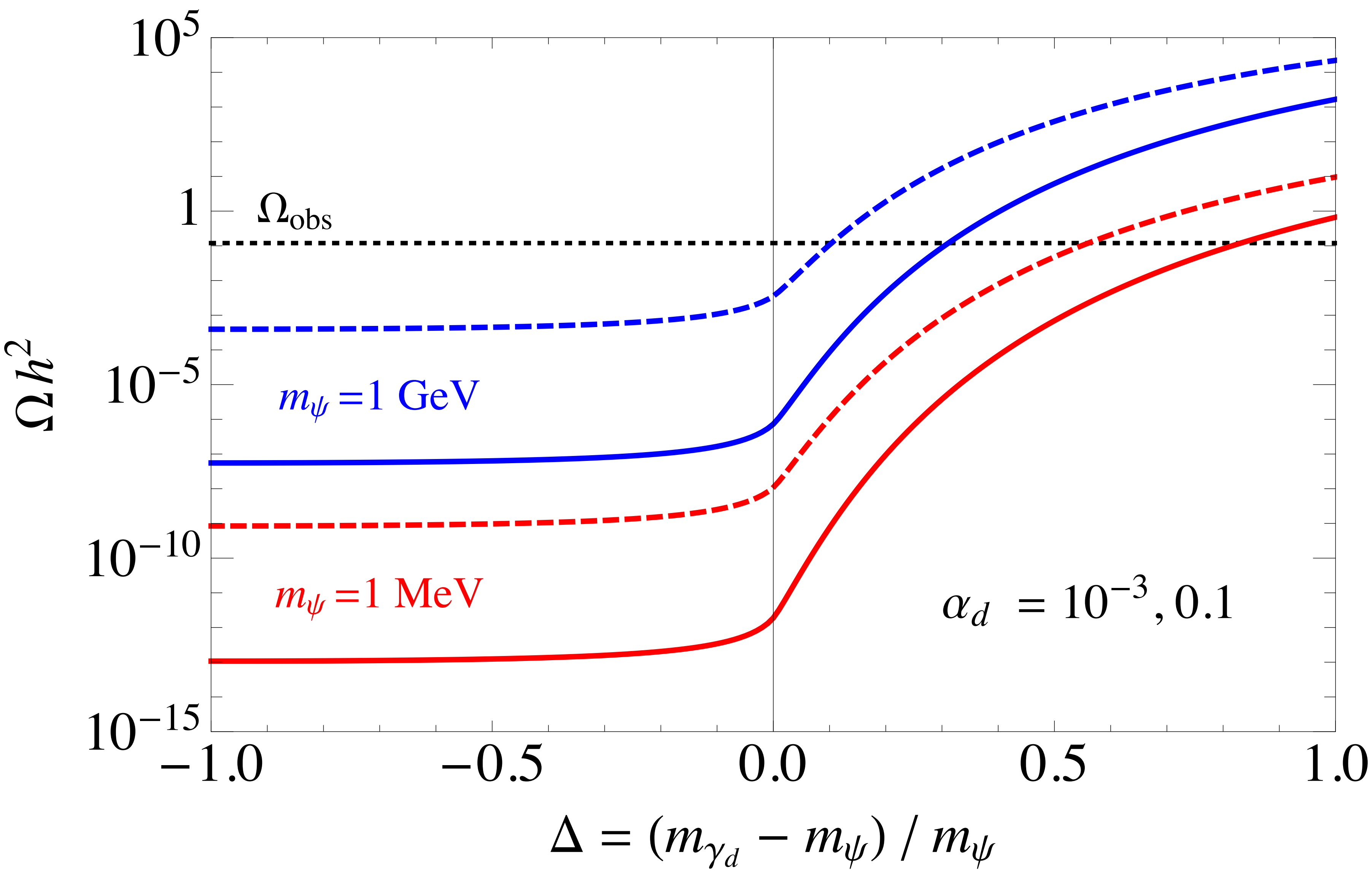
The calculation of relic abundances of elementary particles by following their annihilation and freeze-out in the early Universe has become an important and standard tool in discussing particle dark-matter candidates. We find three situations, all occurring in the literature, in which the standard methods of calculating relic abundances fail. The first situation occurs when another particle lies near in mass to the relic particle and shares a quantum number with it. An example is a light squark with neutralino dark matter. The additional particle must be included in the reaction network, since its annihilation can control the relic abundance. The second situation occurs when the relic particle lies near a mass threshold. Previously, annihilation into particles heavier than the relic particle was considered kinematically forbidden, but we show that if the mass difference is $\sim$5–15 %, these "forbidden" channels can dominate the cross section and determine the relic abundance. The third situation occurs when the annihilation takes place near a pole in the cross section. Proper treatment of the thermal averaging and the annihilation after freeze-out shows that the dip in relic abundance caused by a pole is not nearly as sharp or deep as previously thought.

forbidden relic density

$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2}\, e^{2x_f\Delta} \qquad\qquad m_\psi \sim \alpha_d \sqrt{T_{eq} M_{pl}}\, e^{-2x_f\Delta}$$



forbidden relic density

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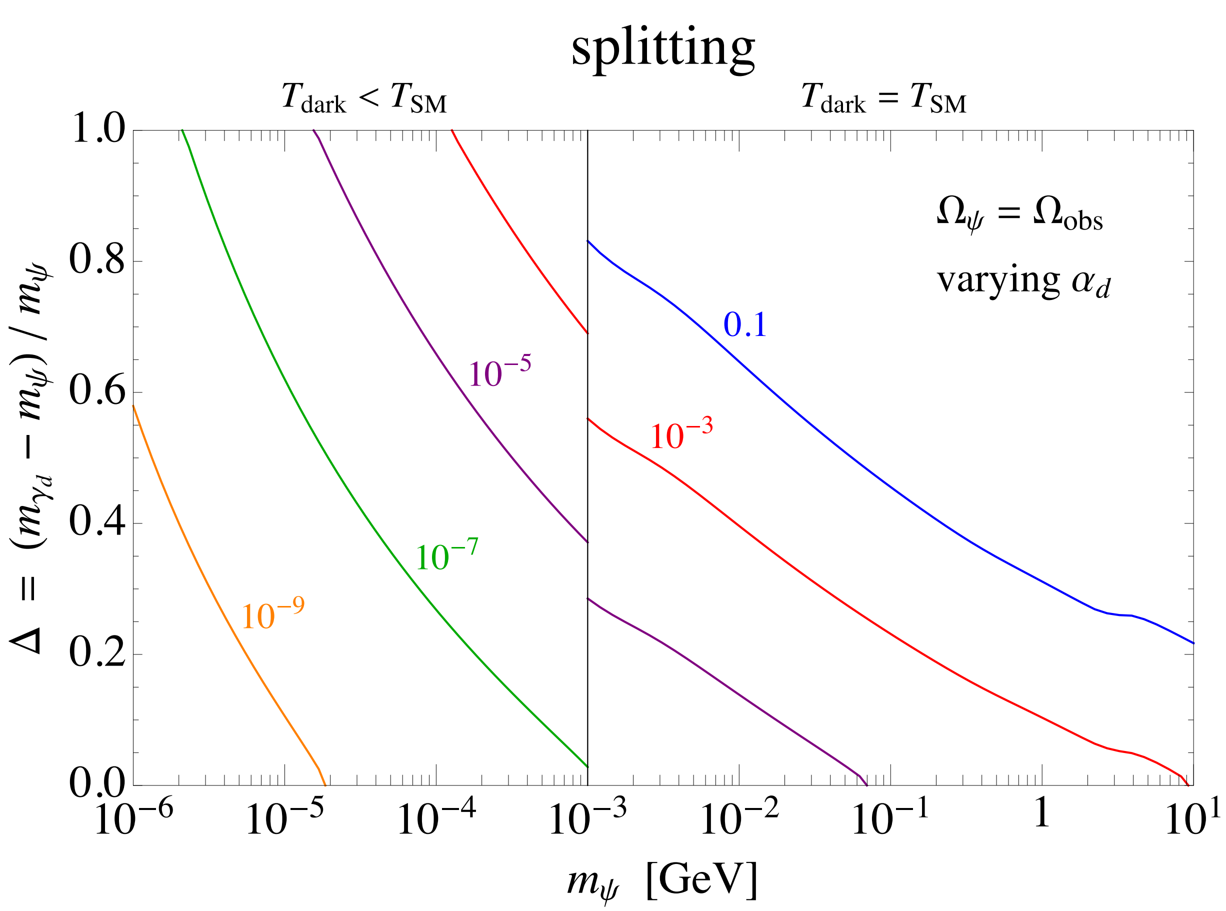
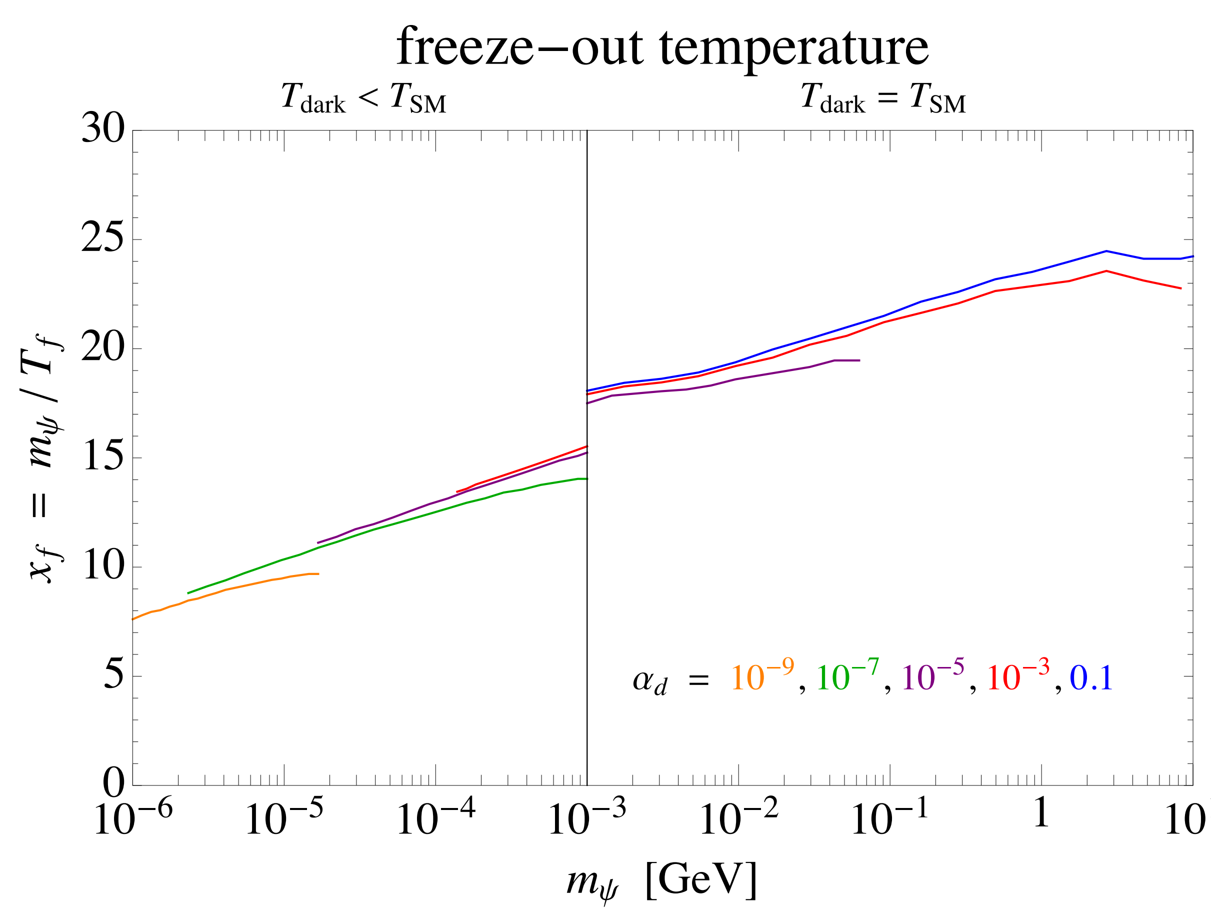




tuning?

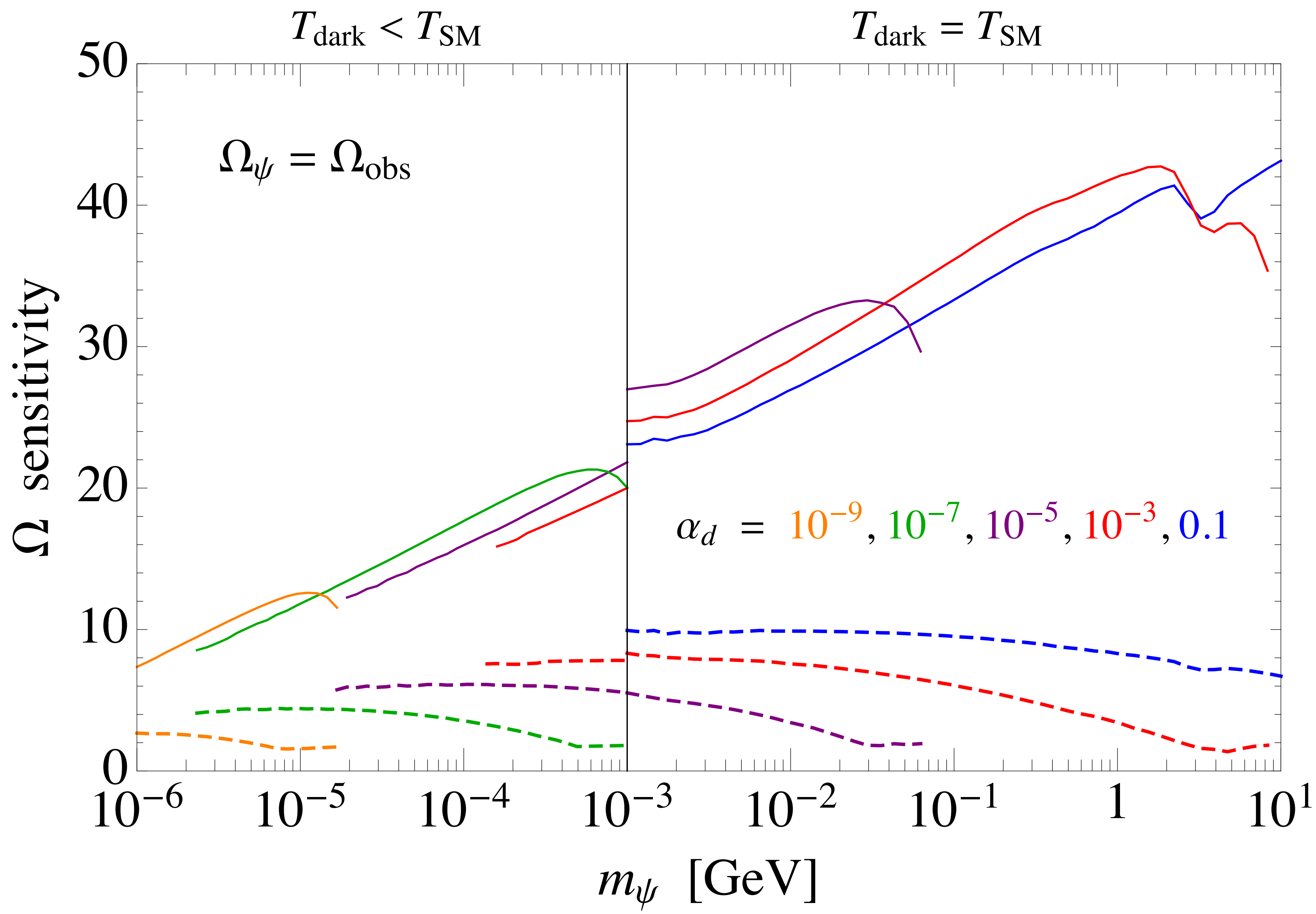
$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2}\, e^{2x_f\Delta}$$

$$\Lambda_{QCD} \approx \Lambda_{UV}\, e^{-\frac{2\pi}{b_3\alpha_3(\Lambda_{UV})}}$$

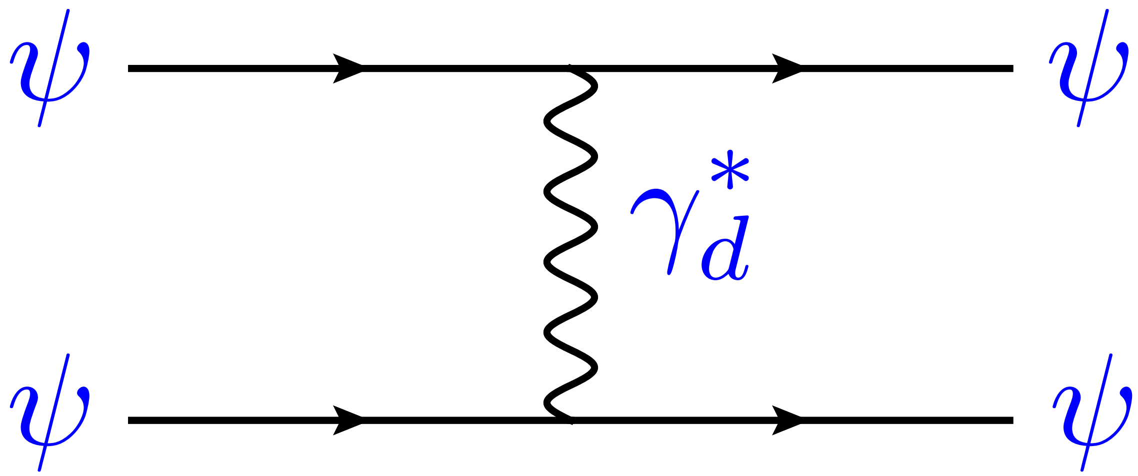
$$\frac{\partial \log \Omega}{\partial \log p_i}$$

$$p_i = (m_\psi, m_{\gamma_d})$$

$$(m_\psi, \Delta)$$



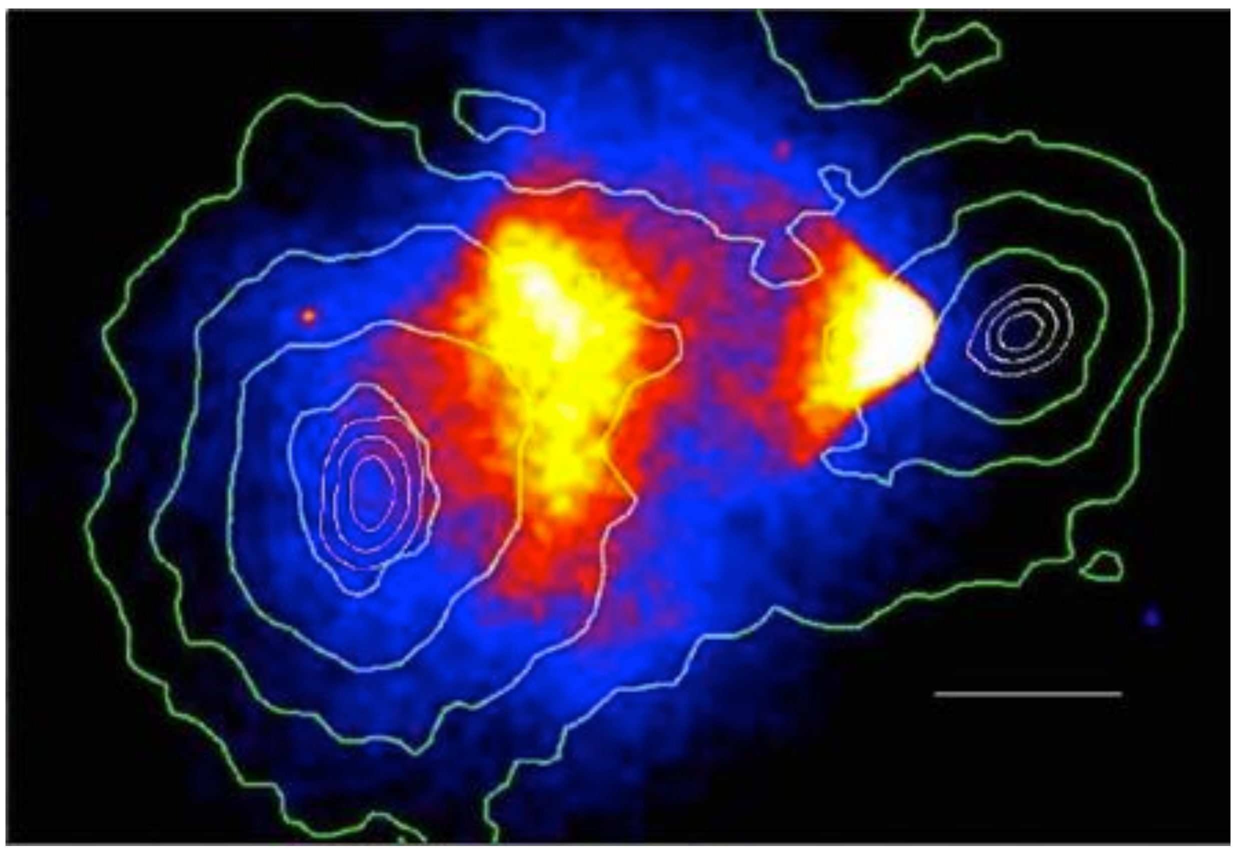
self-interactions



$$\frac{\sigma_{SI}}{m_\psi} = \frac{10\pi}{3} g_\Delta \frac{\alpha_d^2}{m_\psi^3}$$

self-interactions

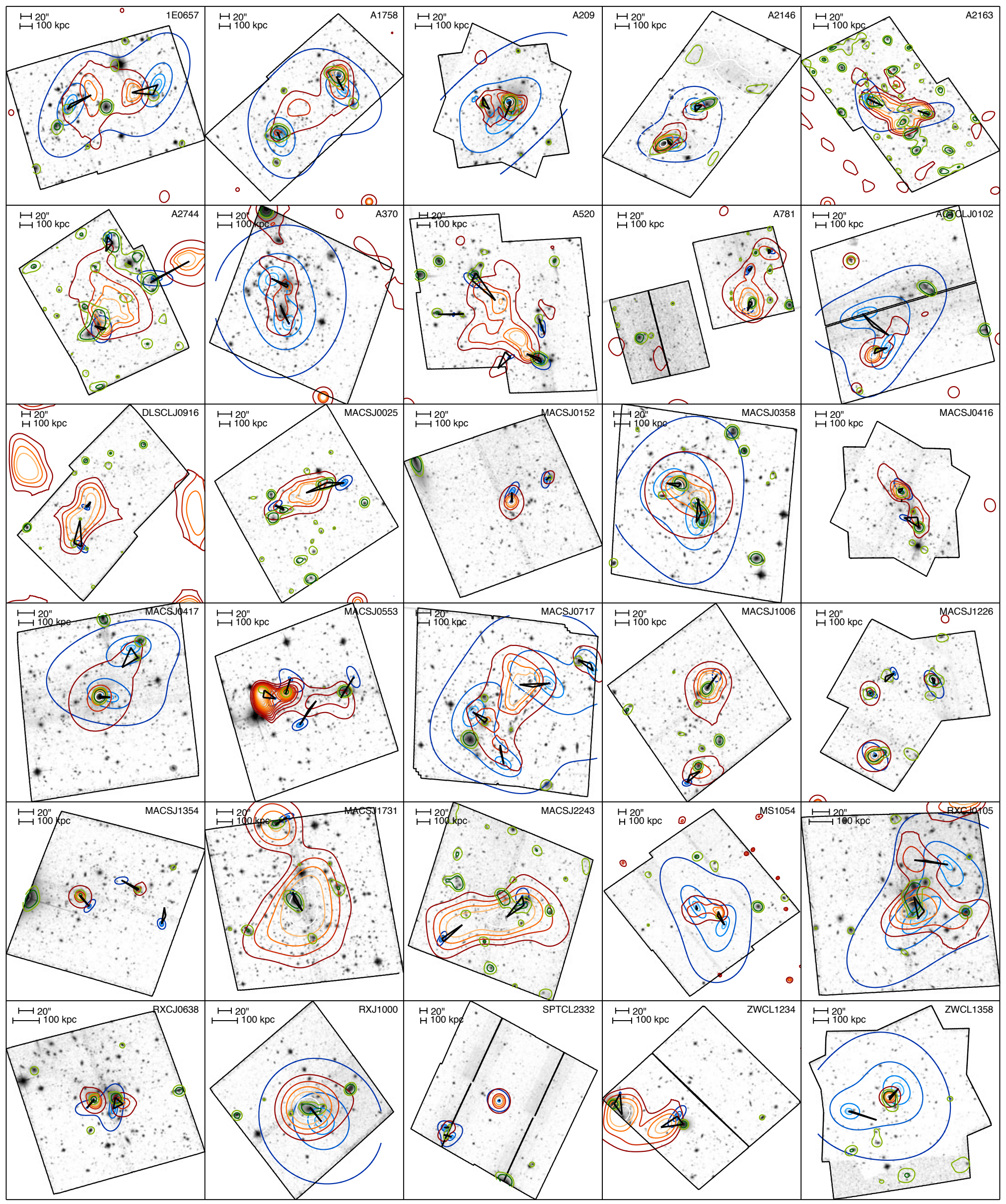
bullet cluster:

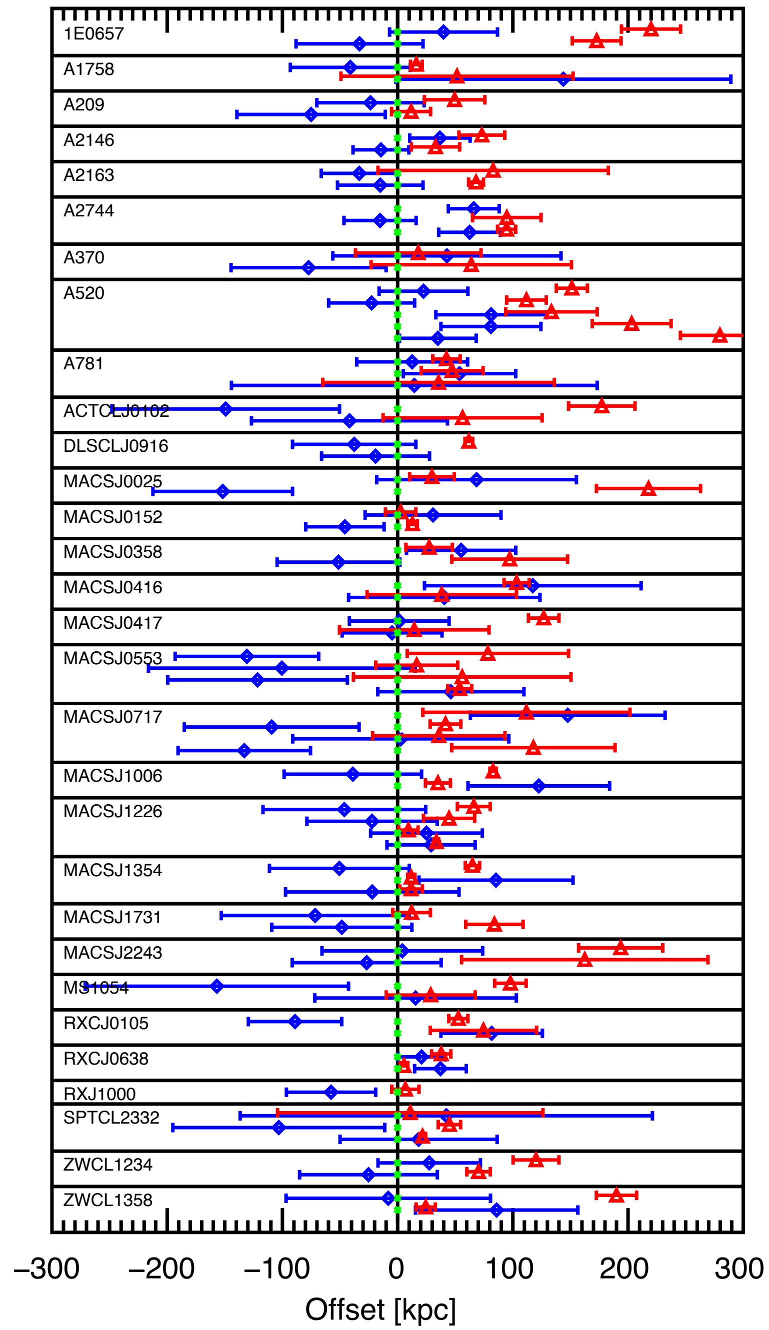


$$\frac{\sigma_{SI}}{m_\psi} < 1.25\ \mathrm{cm}^2/\mathrm{g}$$

- Randall et al., **0704.0261**

self-interactions

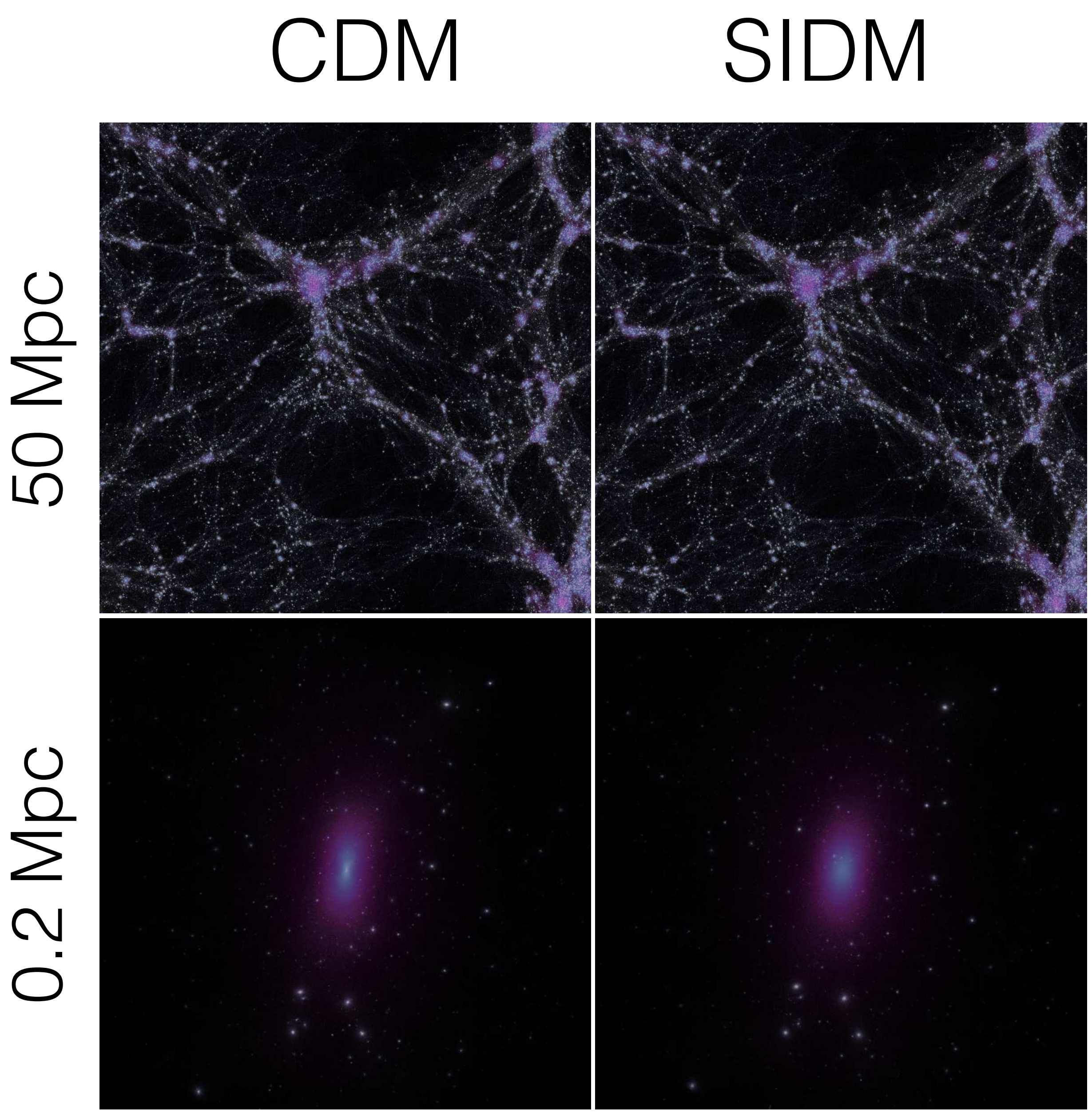




$$\frac{\sigma_{SI}}{m_\psi} < 0.47\ \mathrm{cm}^2/\mathrm{g}$$

- Harvey et al., **1503.07675**

self-interactions



- core-cusp
- too big to fail

$$\frac{\sigma_{SI}}{m_{\psi}} \sim 0.1\,\mathrm{cm}^2/g$$

- Rocha et al., **1208.3025**, Peter et al., **1208.3026**

self-interactions

sensitivity:

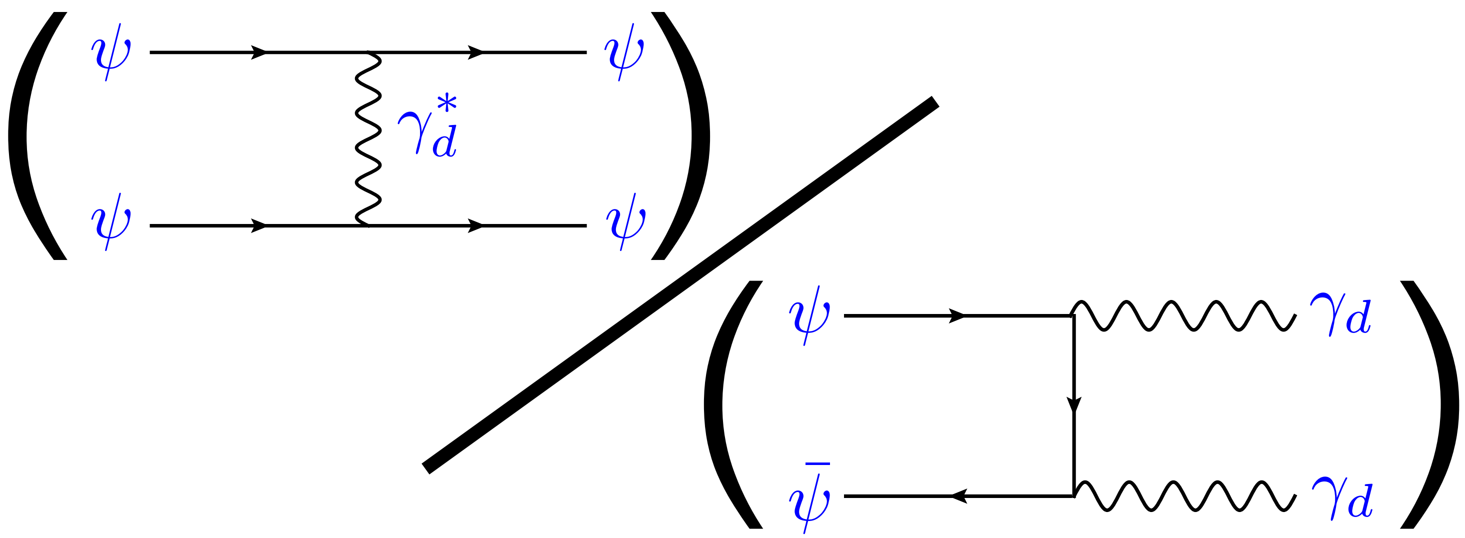
$$\frac{\sigma_{SI}}{m_\psi} \sim 1\ \mathrm{cm}^2/g \sim 5 \times 10^{-6}\ \mathrm{MeV}^{-3}$$

thermal annihilation rate:

$$\langle \sigma v \rangle \sim 3 \times 10^{-3}\ \mathrm{TeV}^{-2}$$

ratio: $$\frac{\sigma_{SI}}{\langle \sigma v \rangle} \sim 10^{12} \left(\frac{1\ \mathrm{GeV}}{m_\psi} \right)$$

self-interactions

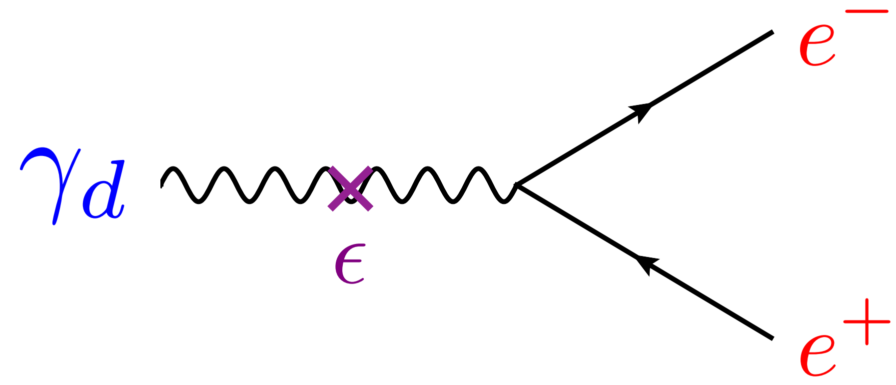


$$\sim \frac{e^{2x_f\Delta}}{m_\psi}$$

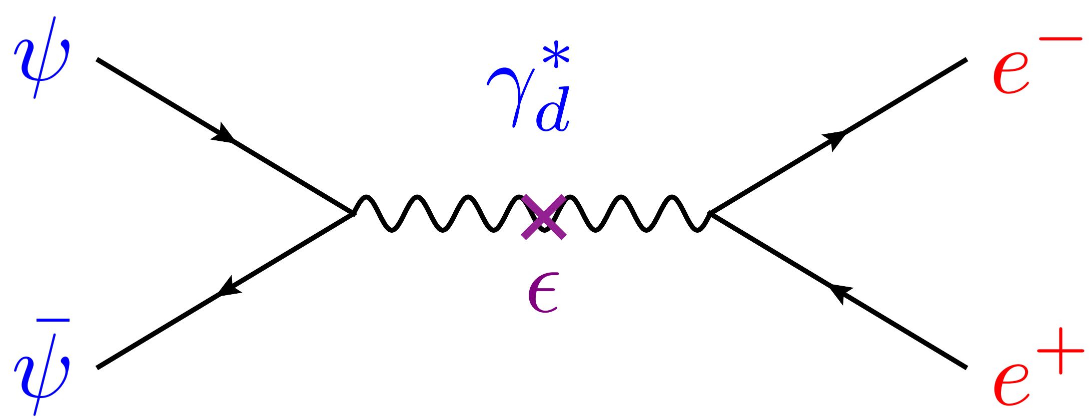
$$\frac{\sigma_{SI}}{m_\psi} \sim 0.2\ \mathrm{cm}^2/\mathrm{g} \times \left(\frac{10\ \mathrm{MeV}}{m_\psi}\right)^3 \times \left(\frac{\alpha_d}{0.1}\right)^2$$

coupling to SM

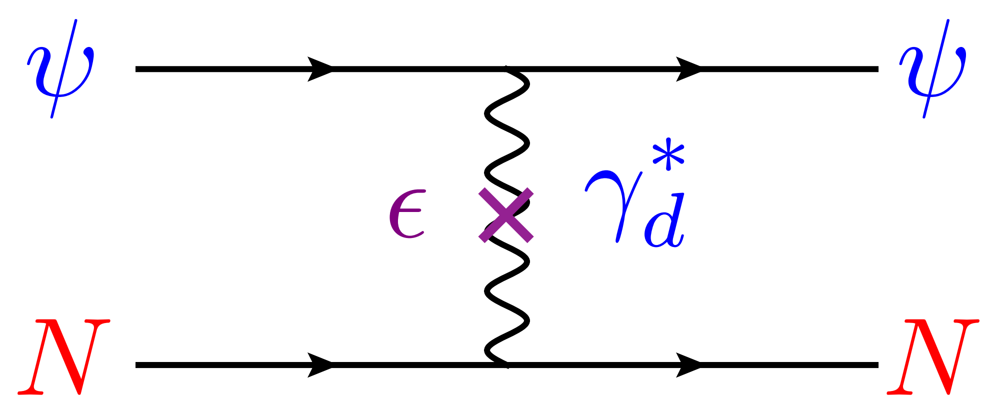
$$\mathcal{L} \supset \frac{\epsilon}{2} F^d_{\mu\nu} F^{\mu\nu}$$



indirect detection:

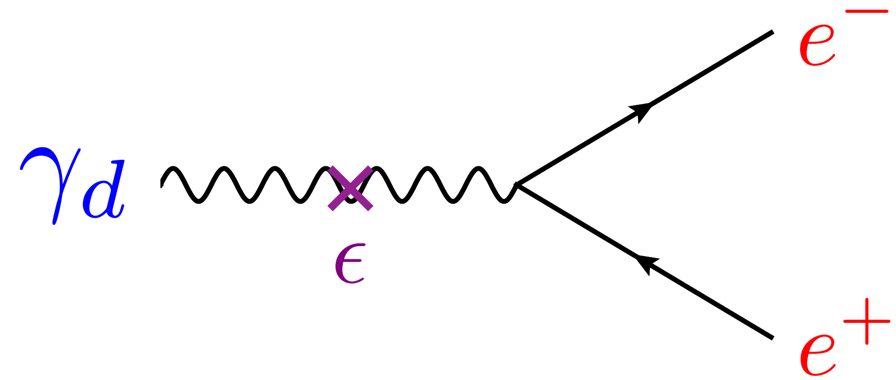


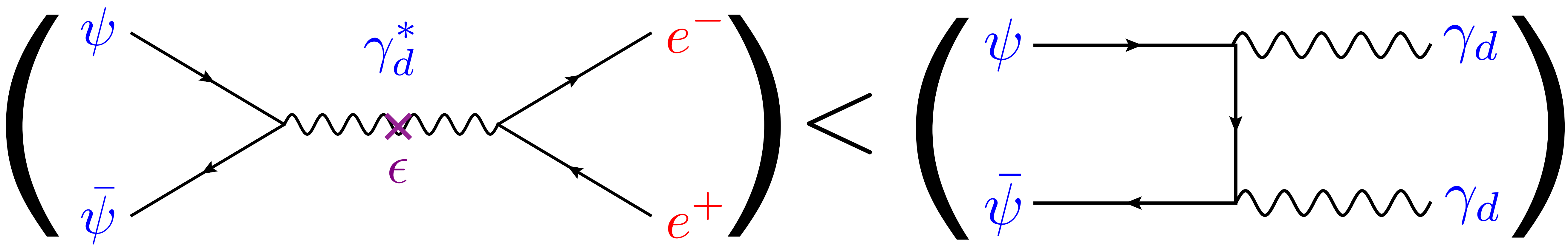
direct detection:



coupling to SM

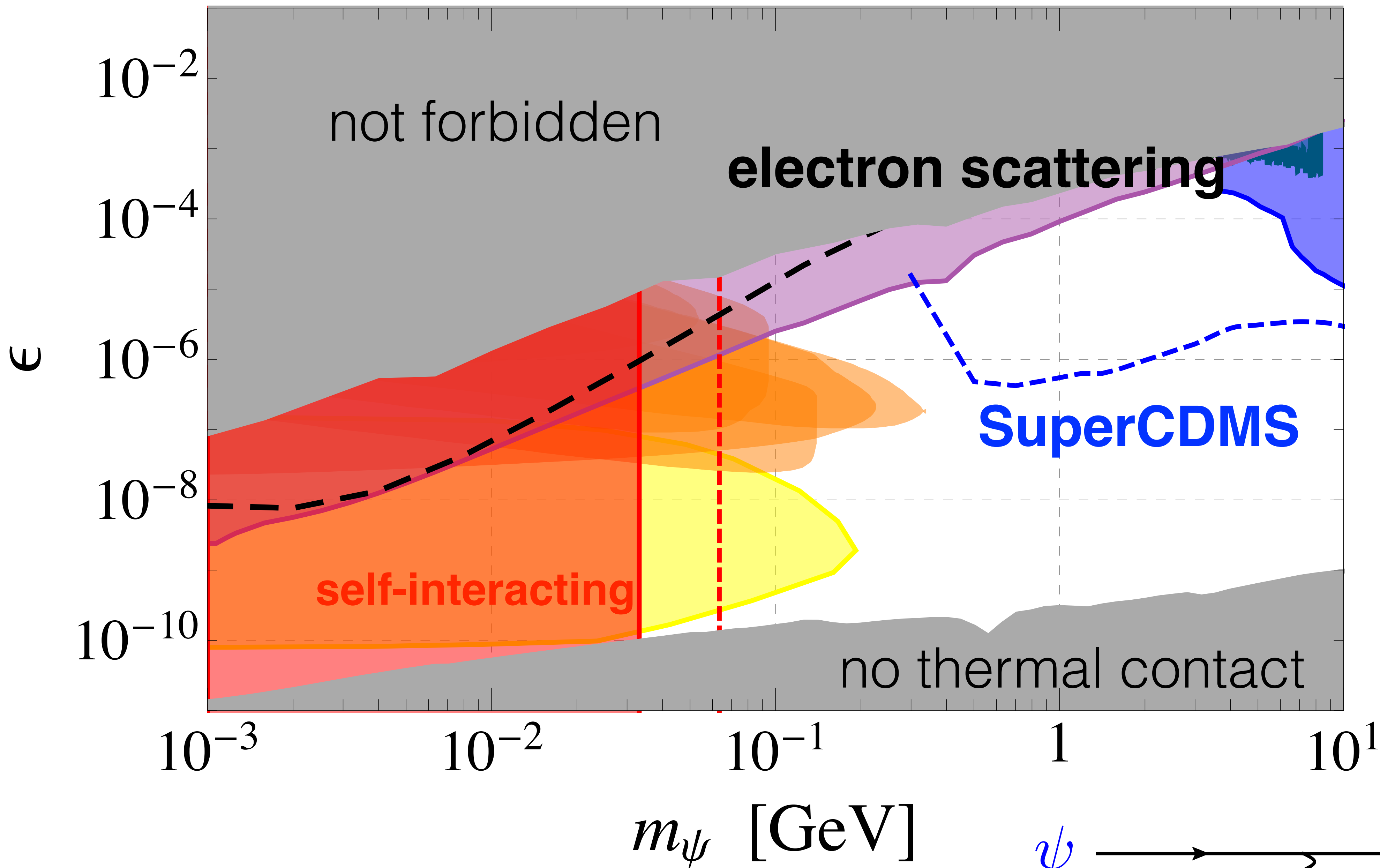
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{d}_{\mu\nu} F^{\mu\nu}$$

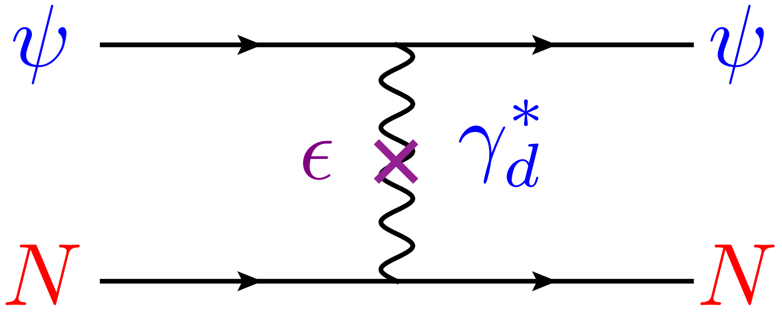




$$\epsilon^2 \frac{\alpha_d \alpha_{EM}}{m_\psi^2} < e^{-2x_f \Delta} \frac{\alpha_d^2}{m_\psi^2}$$

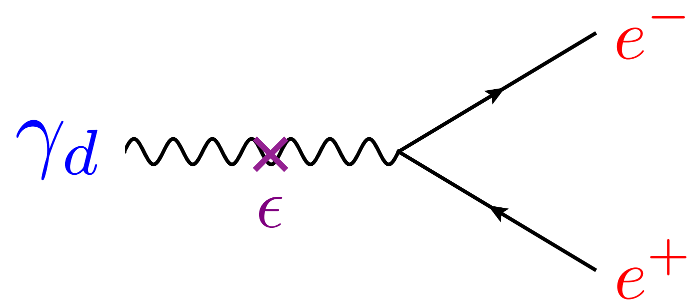
direct detection reach





decoupled from SM

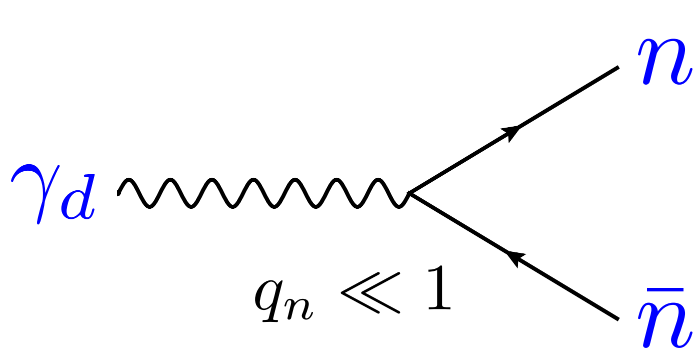
turn off:



$$\epsilon \to 0$$

how to maintain? $n_{\gamma_d} = n_{\gamma_d}^{eq}$

dark radiation:



$$\Omega_n h^2 \approx 0.06 \left(\frac{T_d}{T_\gamma}\right)^3 \left(\frac{m_n}{1\ \mathrm{eV}}\right) \lesssim 0.1\, \Omega_{\mathrm{DM}} h^2$$

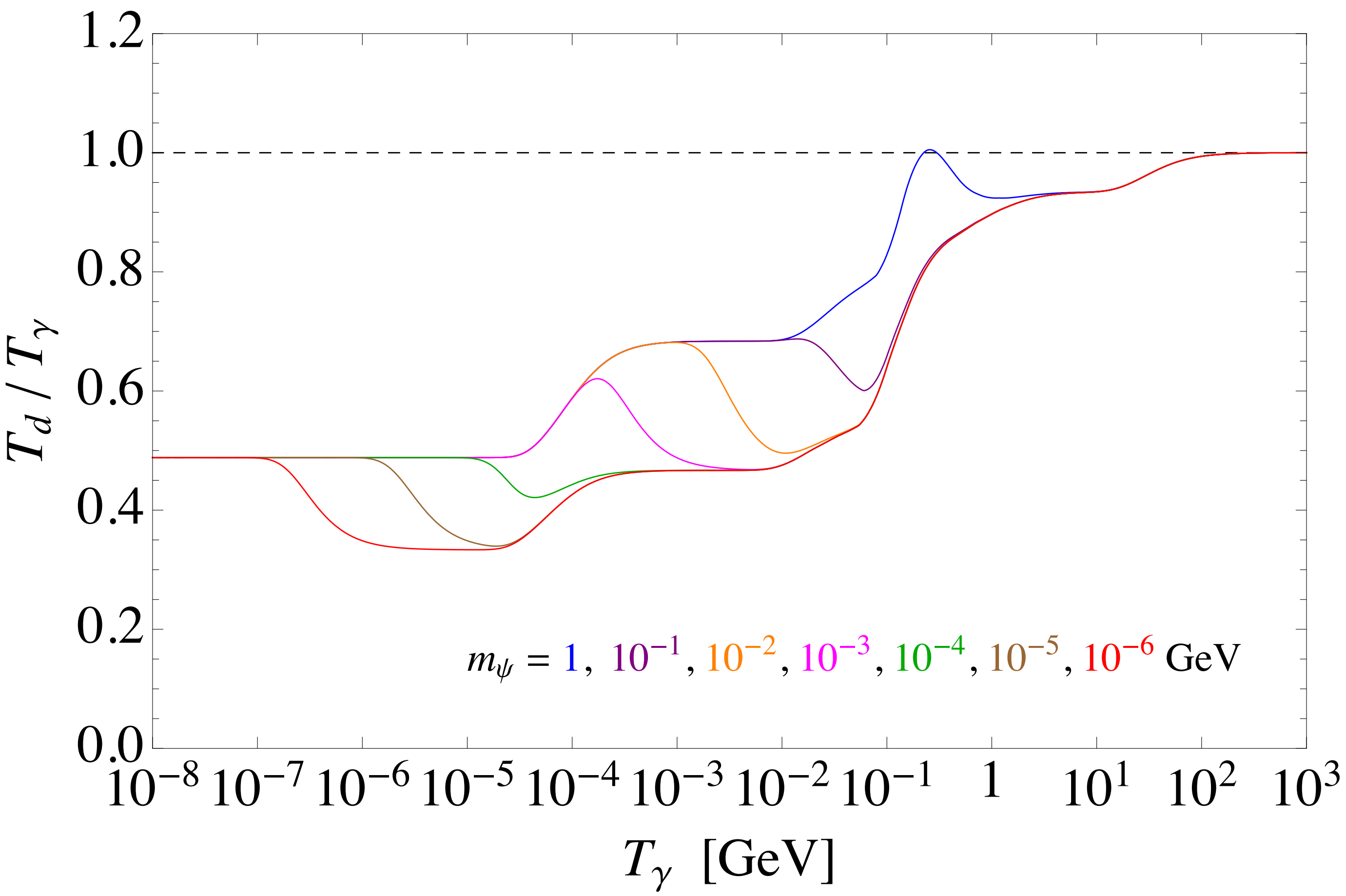
Viel et al. **astro-ph/0501562**

dark radiation

conservation of entropy:

$$\frac{g_{*S}^{d}(T_d)\,T_d^3}{g_{*S}^{d}(T_0)\,T_0^3} = \frac{g_{*S}^{SM}(T_{SM})\,T_{SM}^3}{g_{*S}^{d}(T_0)\,T_0^3}$$

- Feng, Tu, Yu **0808.2318**



CMB:

Planck:

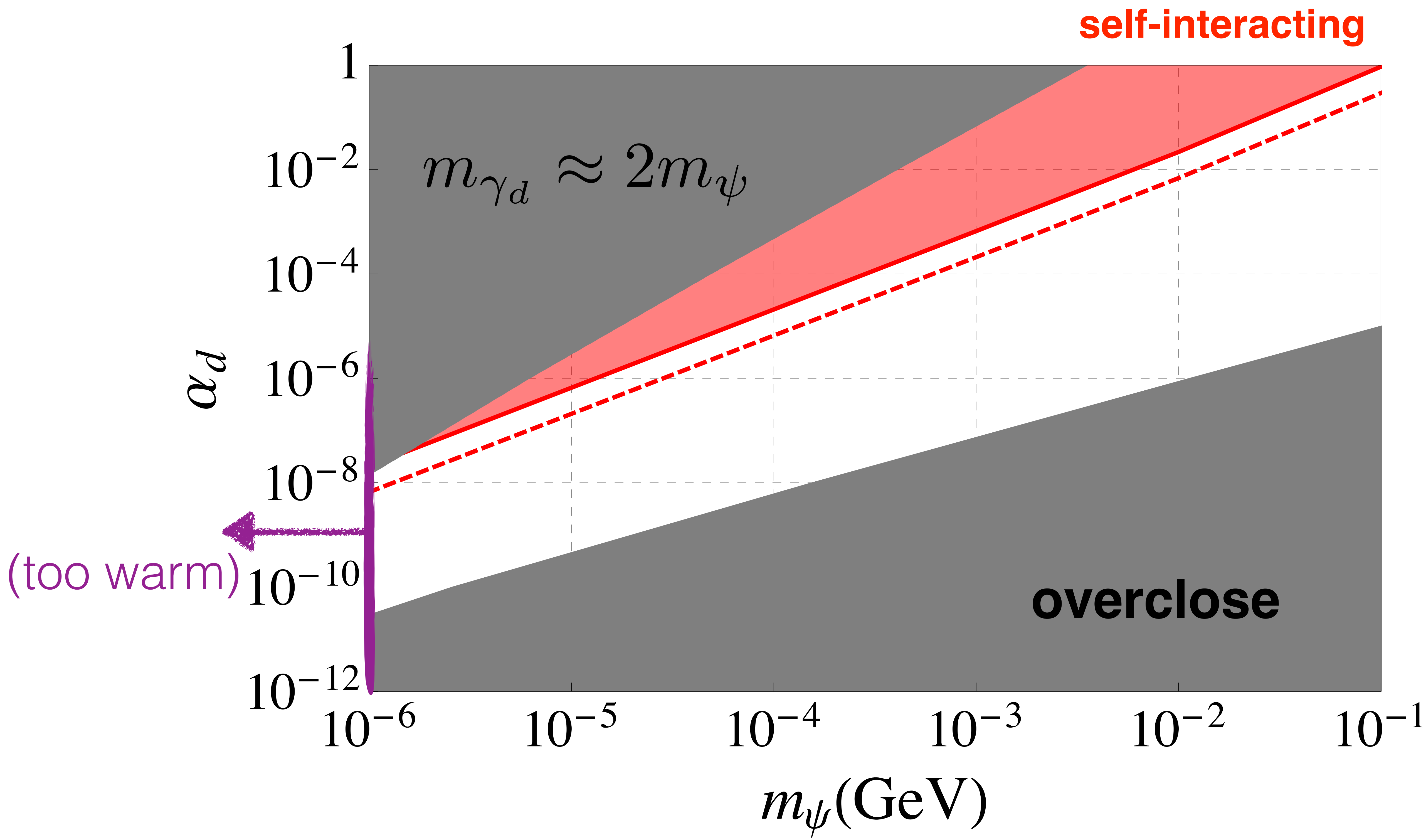
$$\Delta N_{eff} \approx 0.44 \quad (\Delta N_{eff} < 0.56)$$

BBN:

$$(D/H)_p$$

$$\Delta N_{eff} \lesssim 0.43 \quad (\Delta N_{eff} < 0.85)$$

forbidden with dark radiation

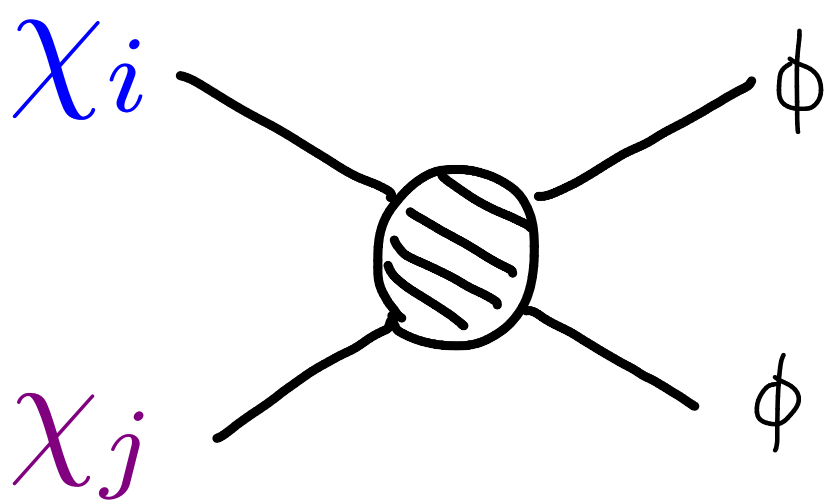


Generalized Coannihilation

coannihilation

$\chi_i \leftrightarrow \chi_j$ in equilibrium

$$\Sigma_{ij}$$



$$\langle \sigma_{eff}\, v \rangle = \frac{\Sigma_{ij}\, w_i w_j \,\langle \sigma_{ij} v \rangle}{\Sigma_i\, w_i}$$

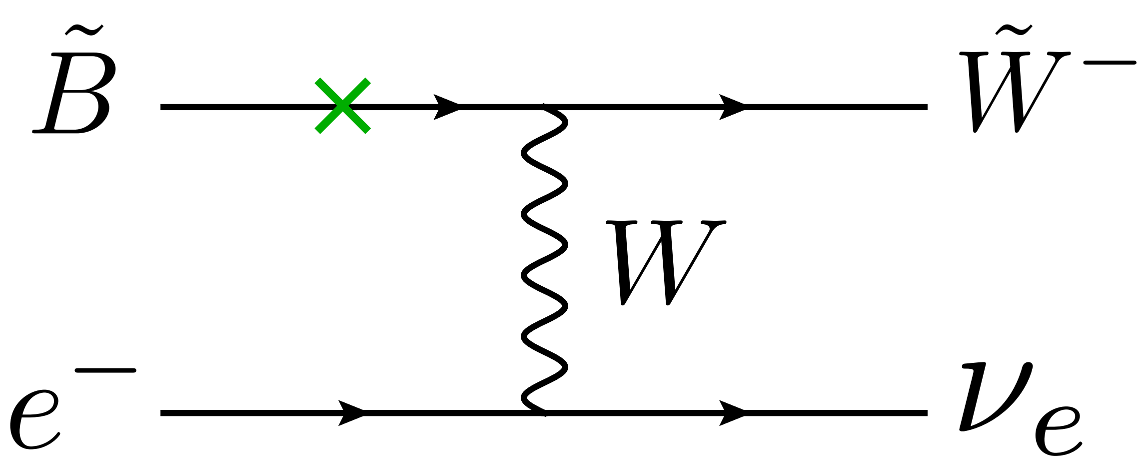
$$w_i = \left(\frac{m_i}{m_1}\right)^{3/2} e^{-x\left(\frac{m_i}{m_1}-1\right)}$$

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2\right) \qquad n = \Sigma_i\, n_i$$

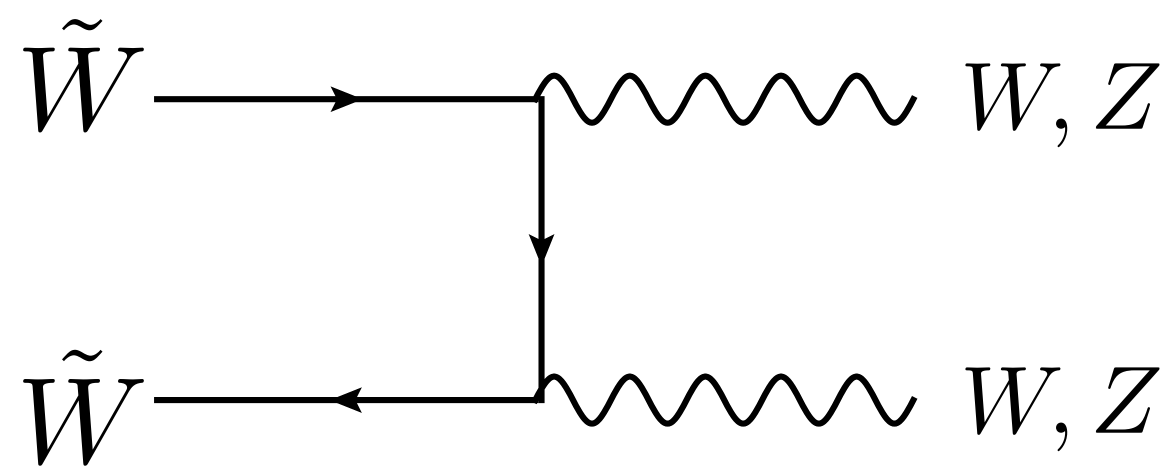
coannihilation

ex) $\tilde{B}/\tilde{W}$

equilibriate:



annihilate:



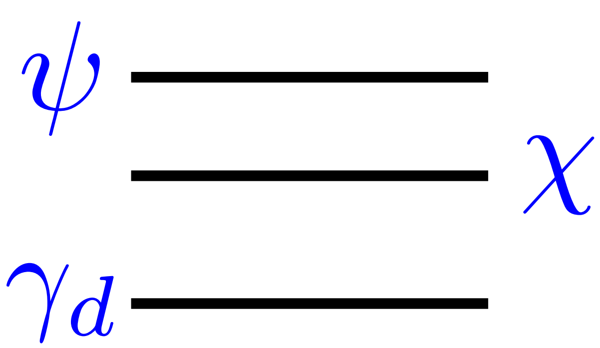
example model

$$G_{SM} \times U(1)_d$$

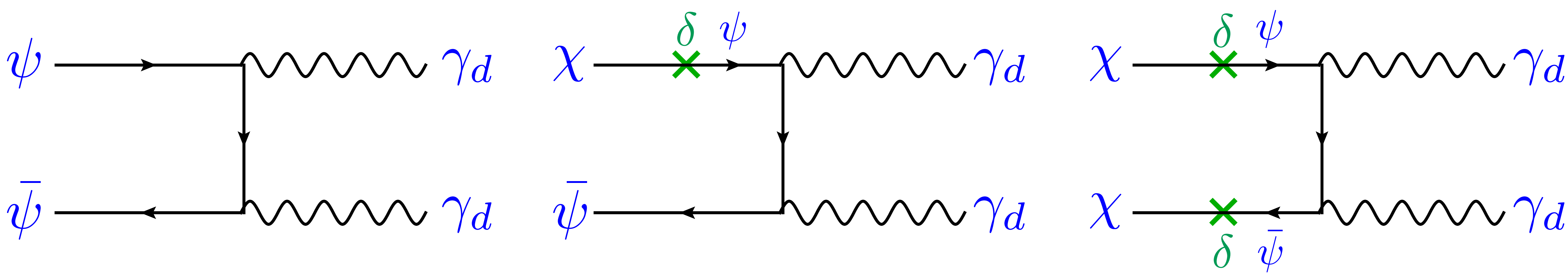
	χ	ψ	ϕ
$U(1)_d$	**0**	**+1**	**-1**

$$\mathcal{L} \supset -y\,\chi\phi\psi - \bar{y}\,\chi\phi^*\bar{\psi} - \frac{1}{2}m_\chi^2\chi^2 - m_\psi\psi\bar{\psi}$$

$$y\langle\phi\rangle \ll m_{\chi,\psi}$$



annihilation



$$e^{-2x\Delta}\,\frac{\alpha_d^2}{m_\psi^2} \qquad \delta^2\, e^{-x\Delta}\,\frac{\alpha_d^2}{m_\psi^2} \qquad \delta^4\,\frac{\alpha_d^2}{m_\psi^2}$$

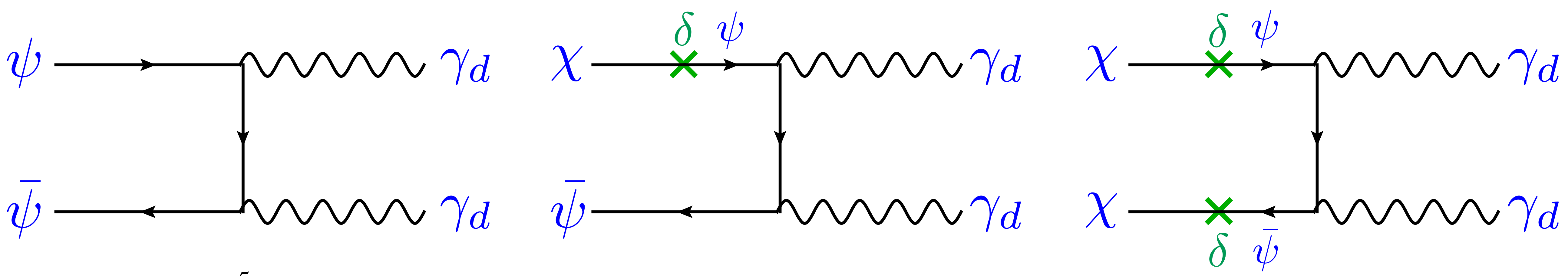
coannihilation: $\delta^2 \lesssim e^{-x_f\Delta}$

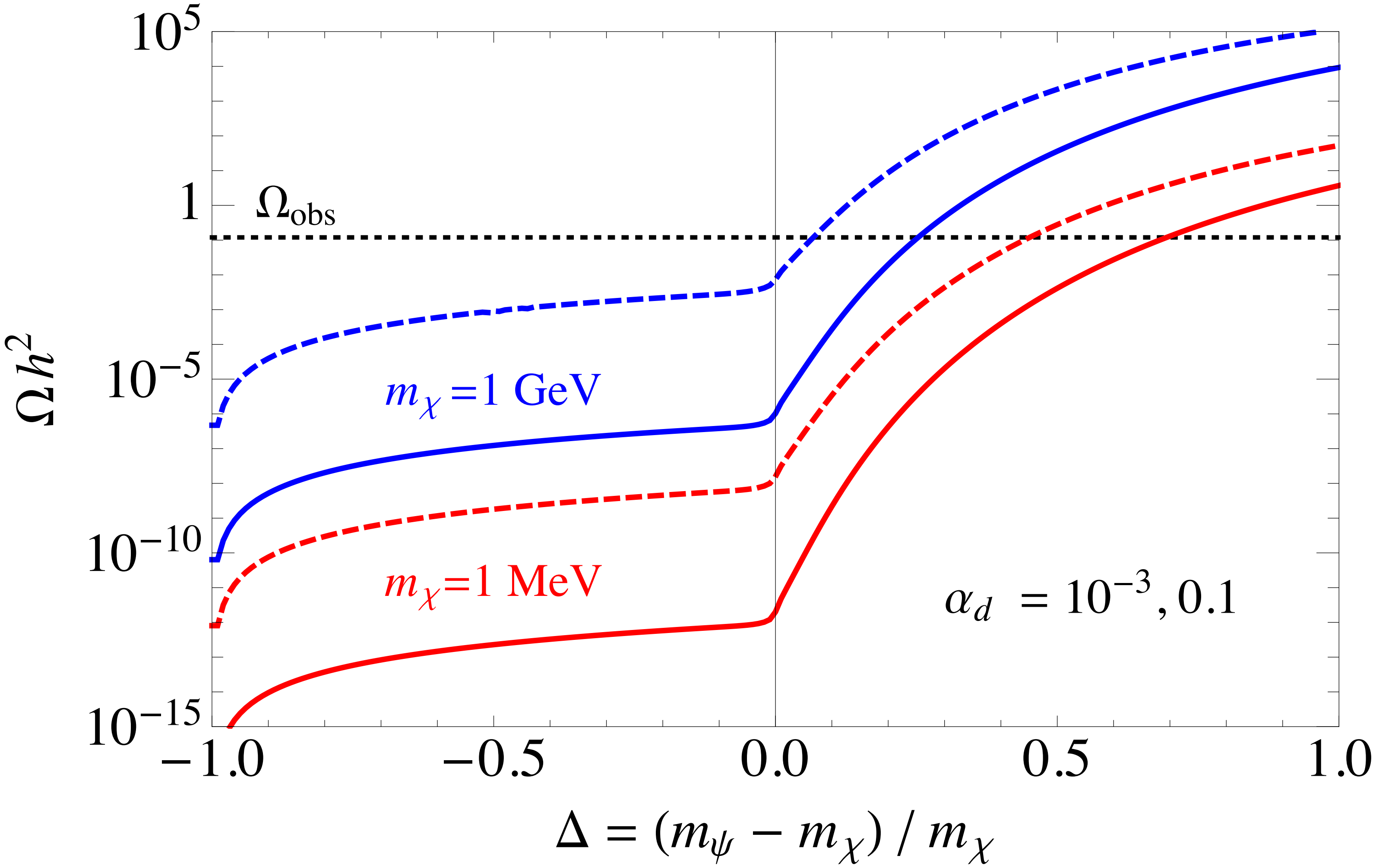
$$\Delta \equiv \frac{m_\psi - m_\chi}{m_\chi}$$

$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2}\, e^{2x_f\Delta}$$

$$\delta \equiv \frac{y\langle\phi\rangle}{m_\chi}$$

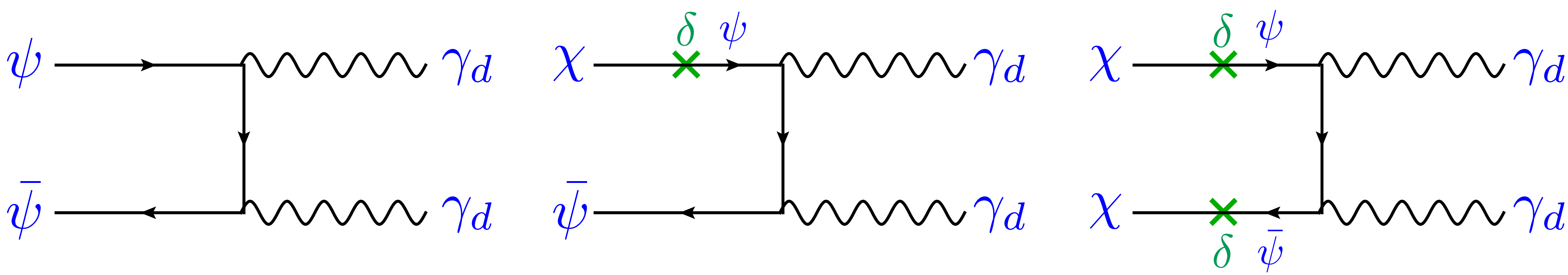
annihilation



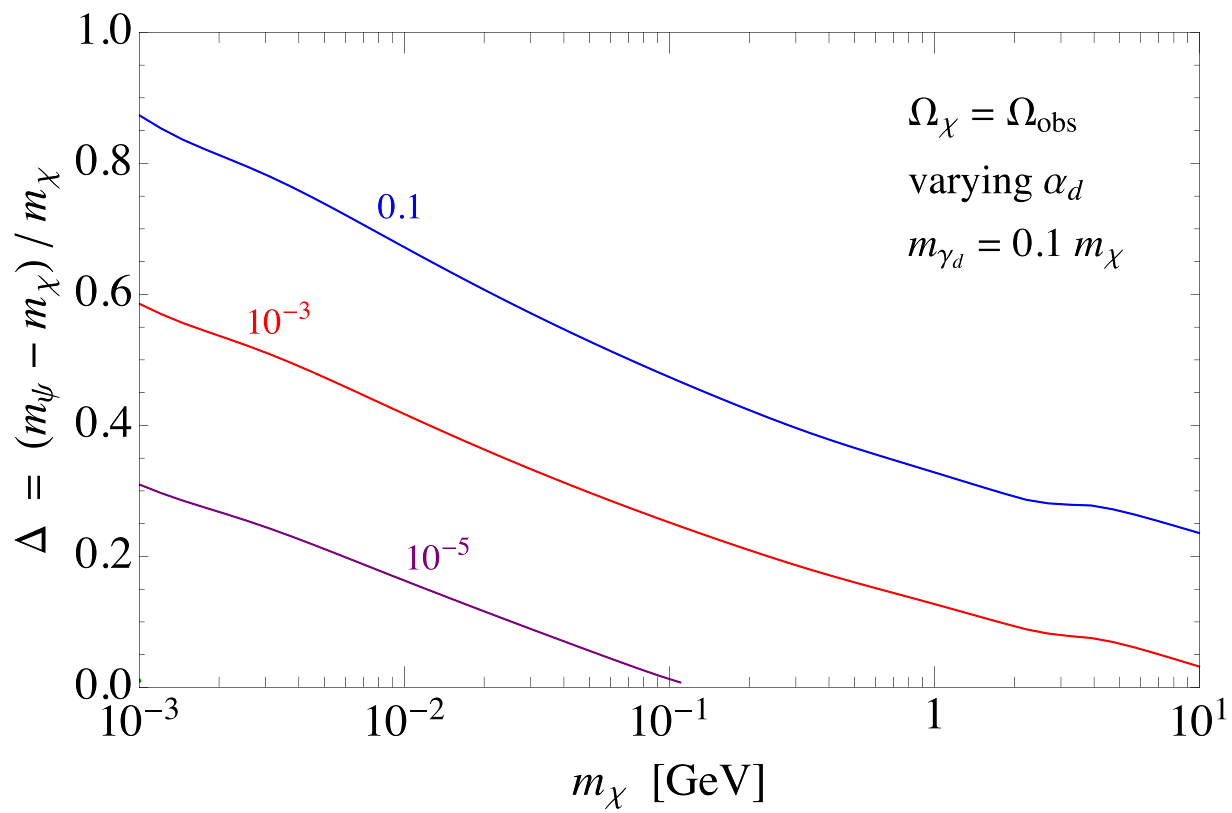


$$\delta = \frac{y \langle \phi \rangle}{m_\chi} = 10^{-5}$$

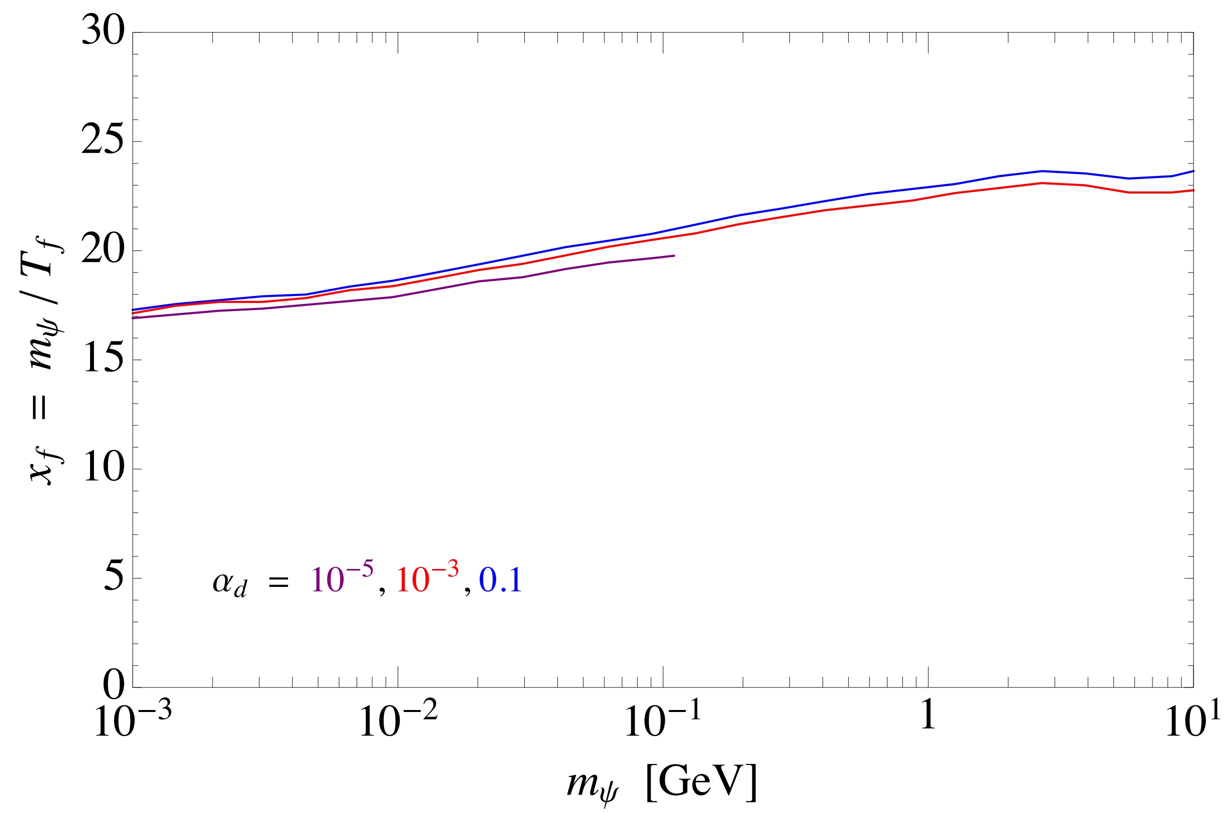
annihilation



splitting

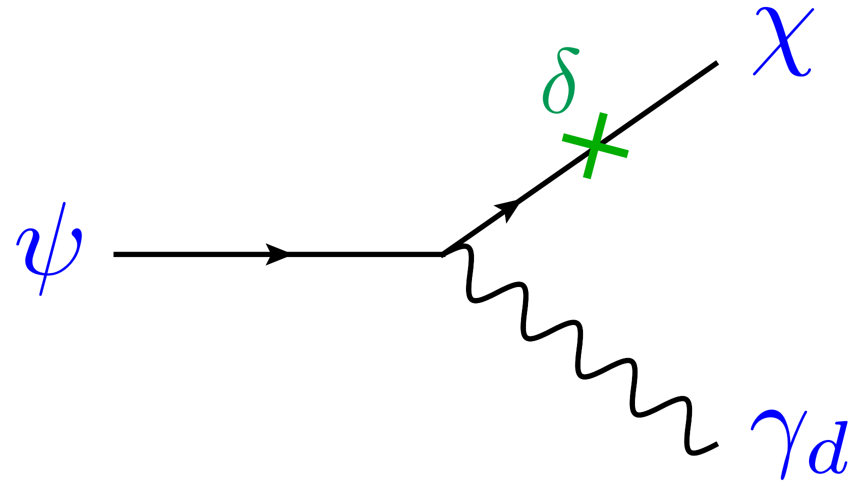


freeze−out temperature



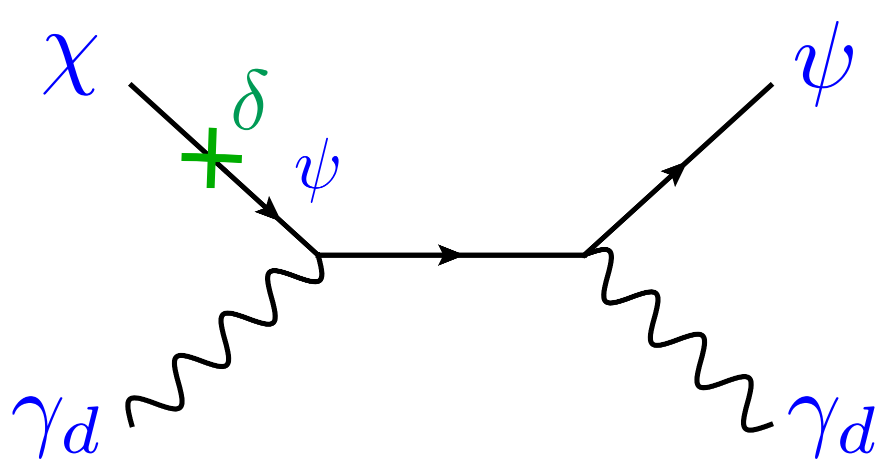
χ/ψ equilibrium

decay:



$$m_\psi > m_\chi + m_{\gamma_d}$$

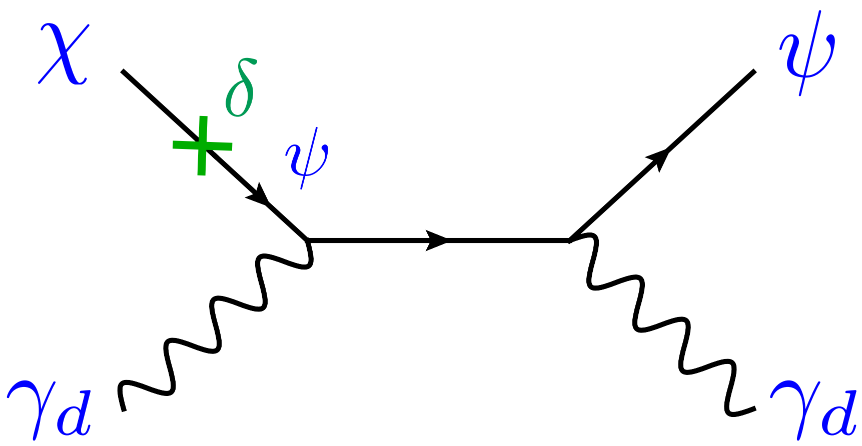
inelastic scattering:



$$m_\psi < m_\chi + m_{\gamma_d}$$

generalized coannihilation

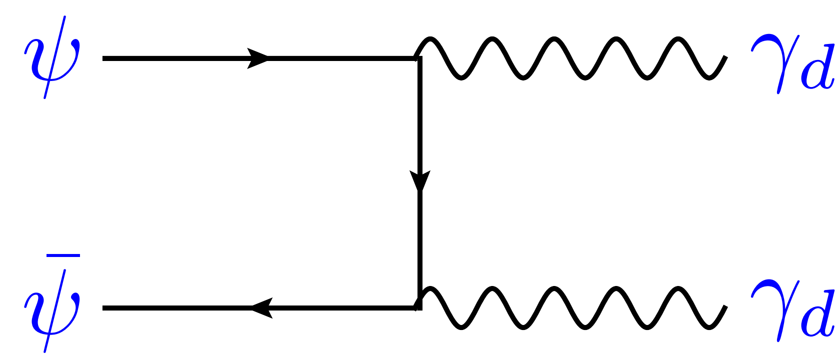
inelastic freezeout



$$n_{\gamma_d}^{eq} \langle \sigma_{in} v \rangle \sim \delta^2 \, e^{-(m_{\gamma_d}/m_\chi + \Delta)x} \, \frac{\alpha_d^2}{m_\psi^2}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -n_{\gamma_d}^{eq} \langle \sigma_{in} v \rangle \left(n_\chi - n_\chi^{eq} \right)$$

coannihilation

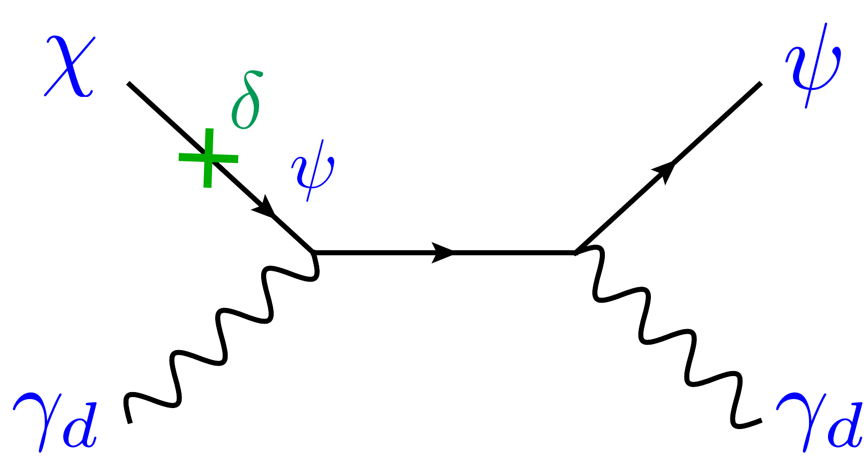


$$n_\psi^{eq} \langle \sigma_{eff} v \rangle \sim e^{-(1+3\Delta)x} \, \frac{\alpha_d^2}{m_\psi^2}$$

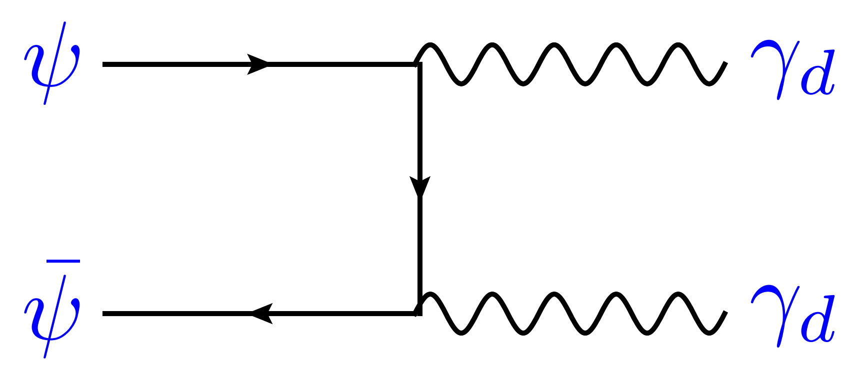
$$\frac{dn}{dt} + 3Hn = - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

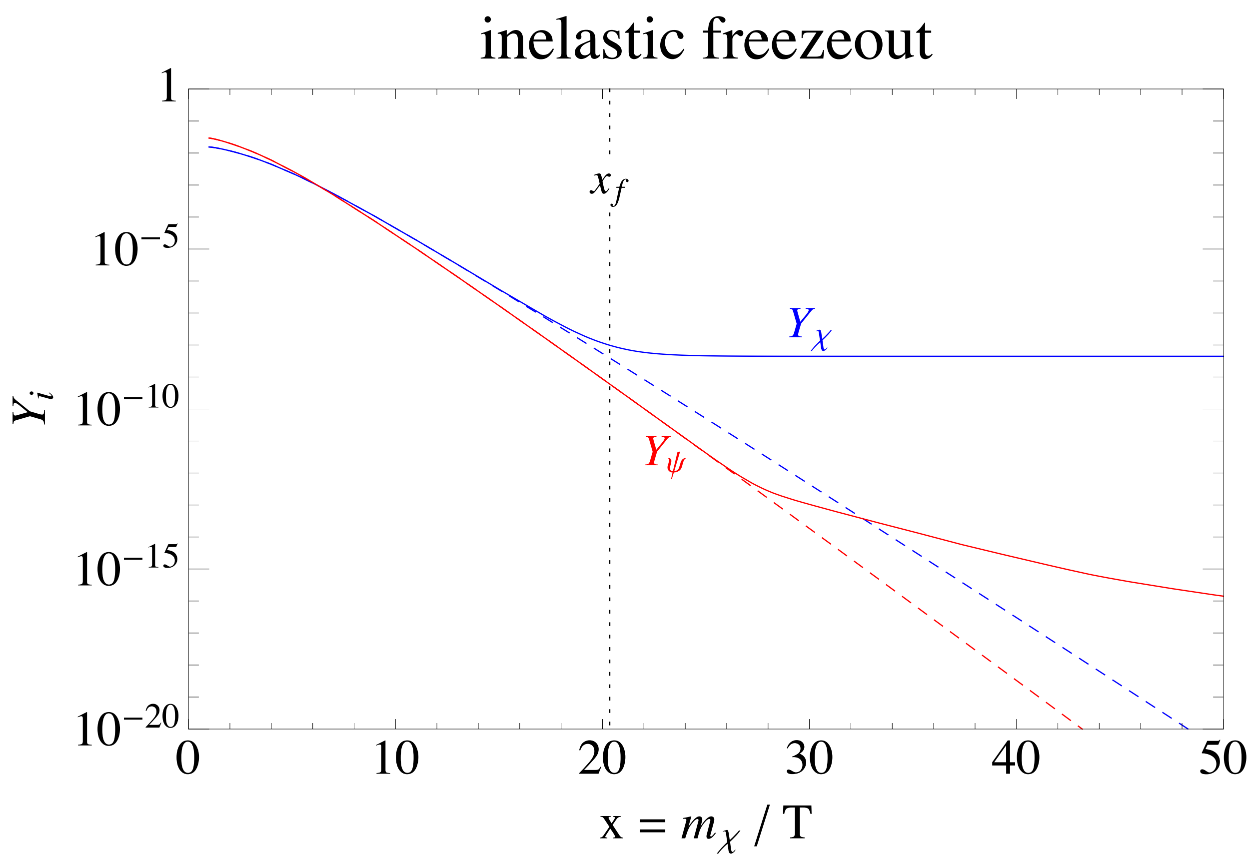
generalized coannihilation

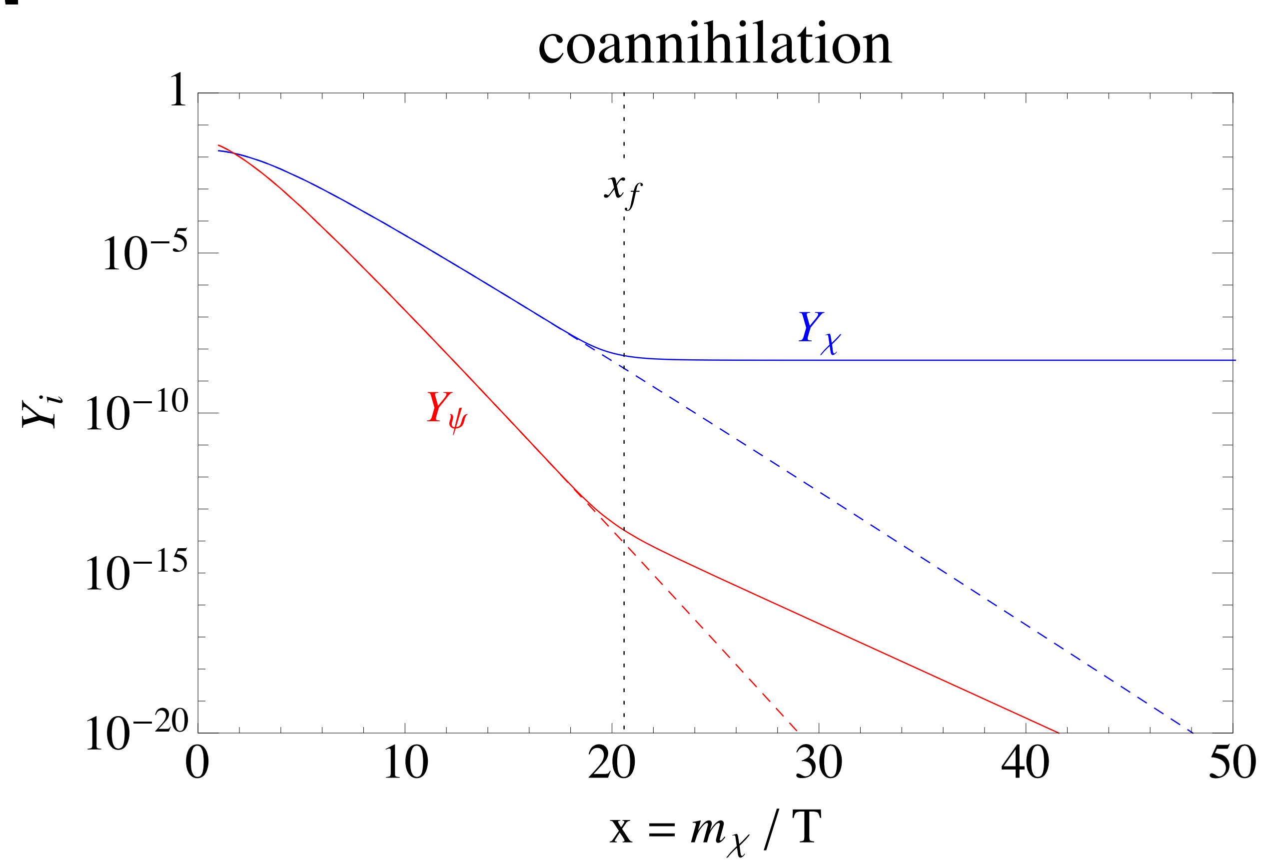
inelastic freezeout



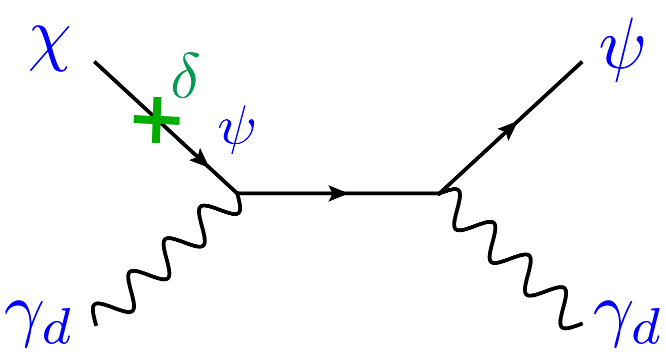
coannihilation

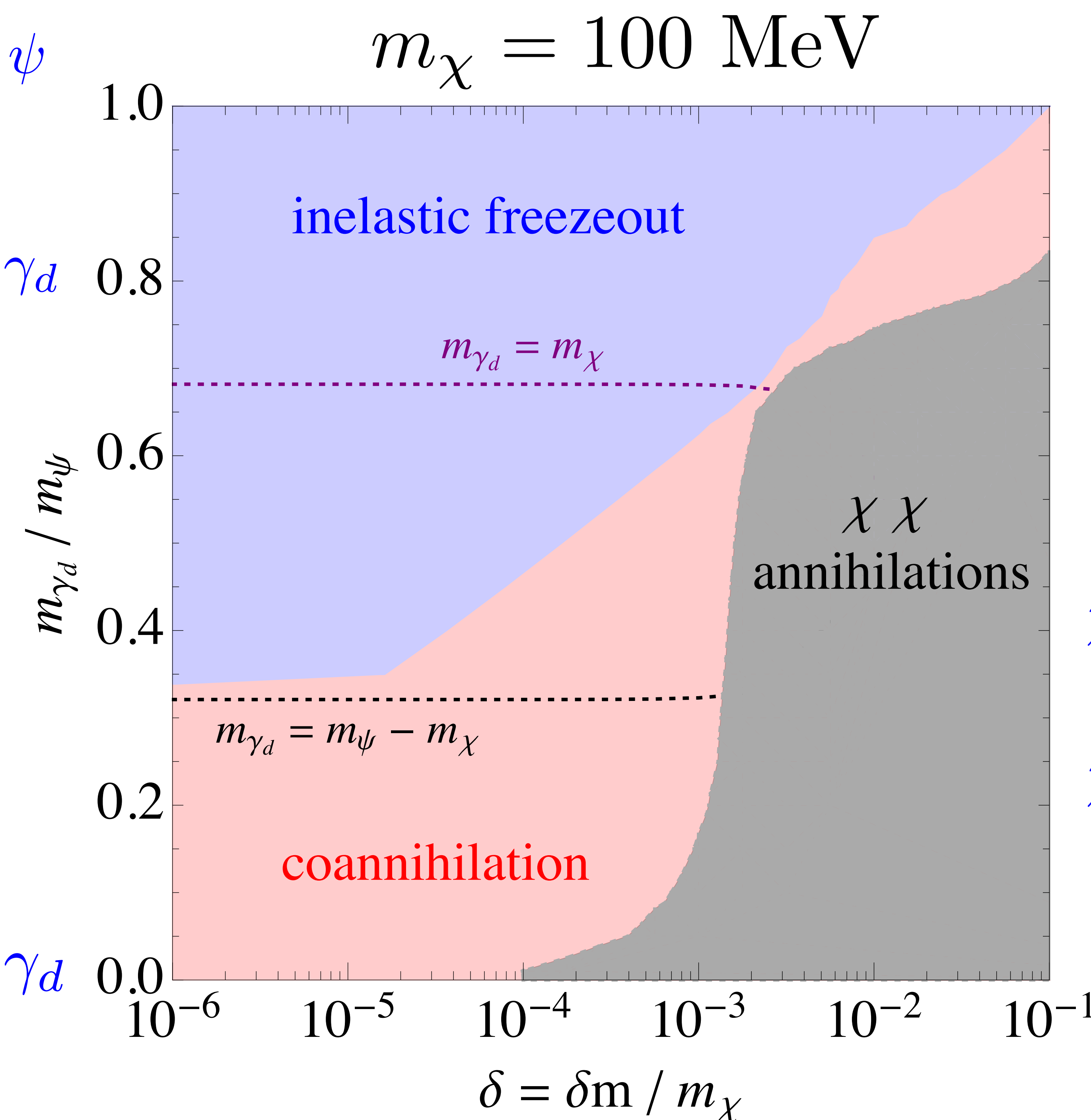


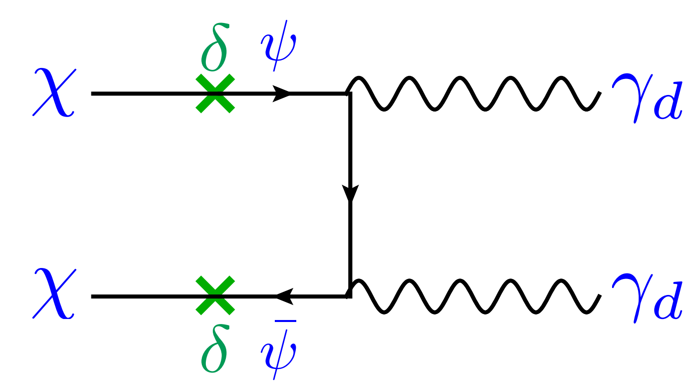


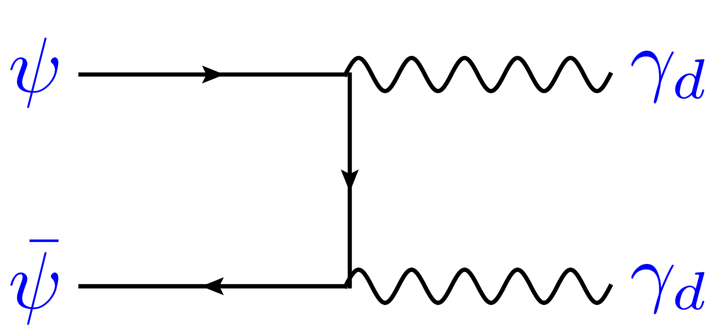


generalized coannihilation





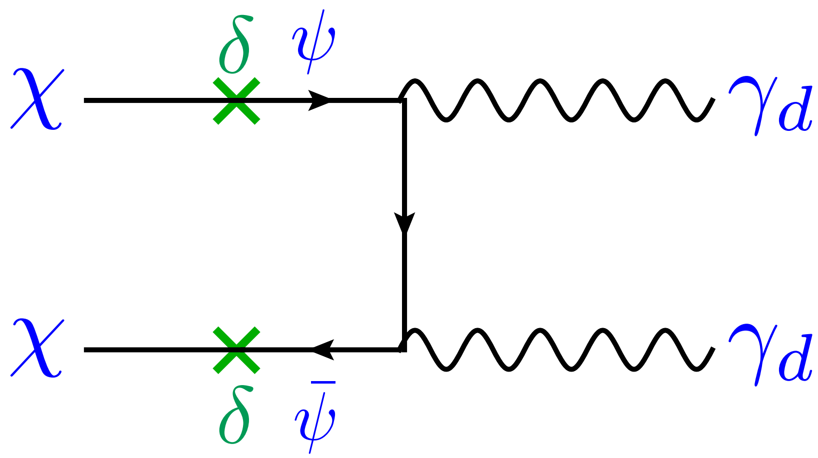




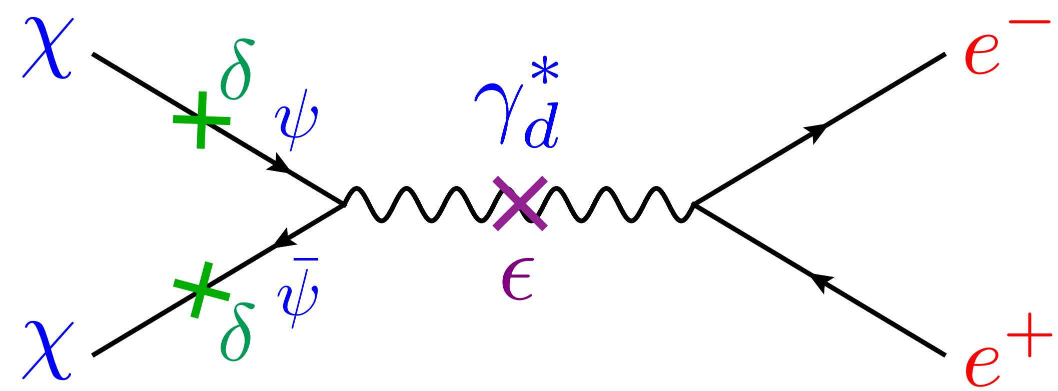
pheno

$$\mathcal{L} \supset \frac{\epsilon}{2} F^{d}_{\mu\nu} F^{\mu\nu}$$

indirect detection:

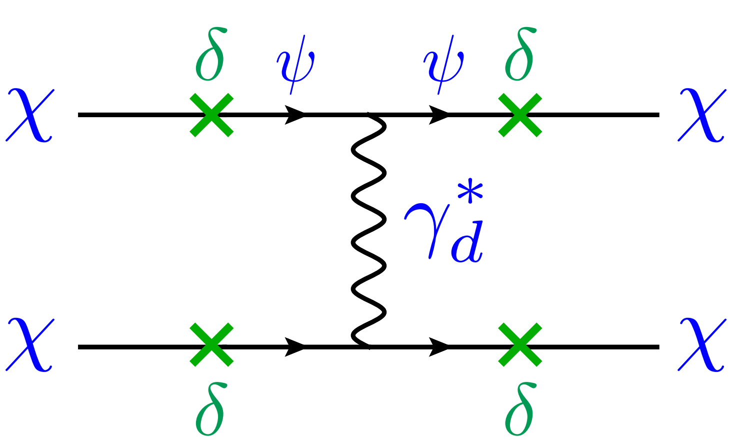


$m_\chi > m_{\gamma_d}$

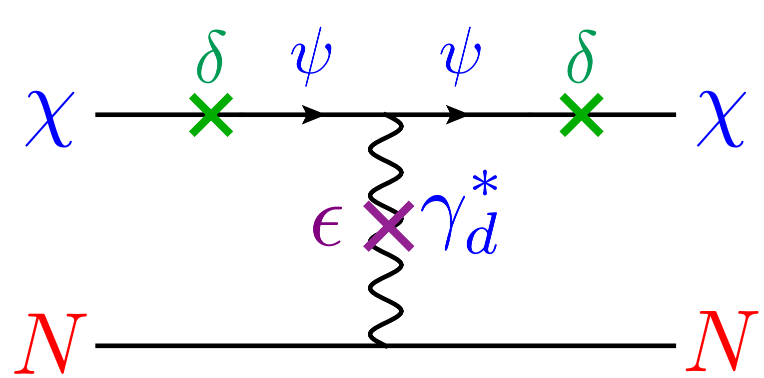


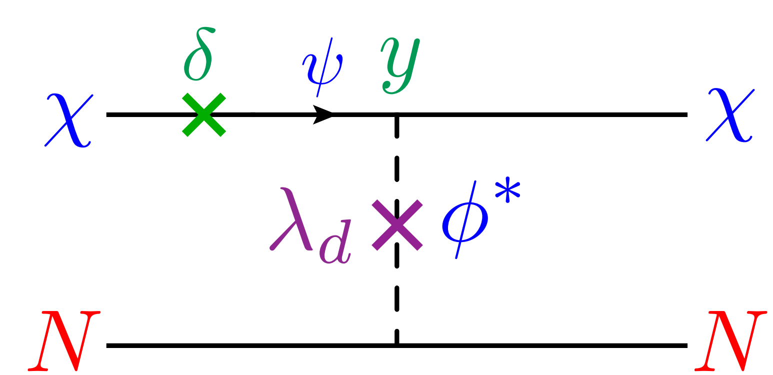
$m_\chi < m_{\gamma_d}$

self interaction:

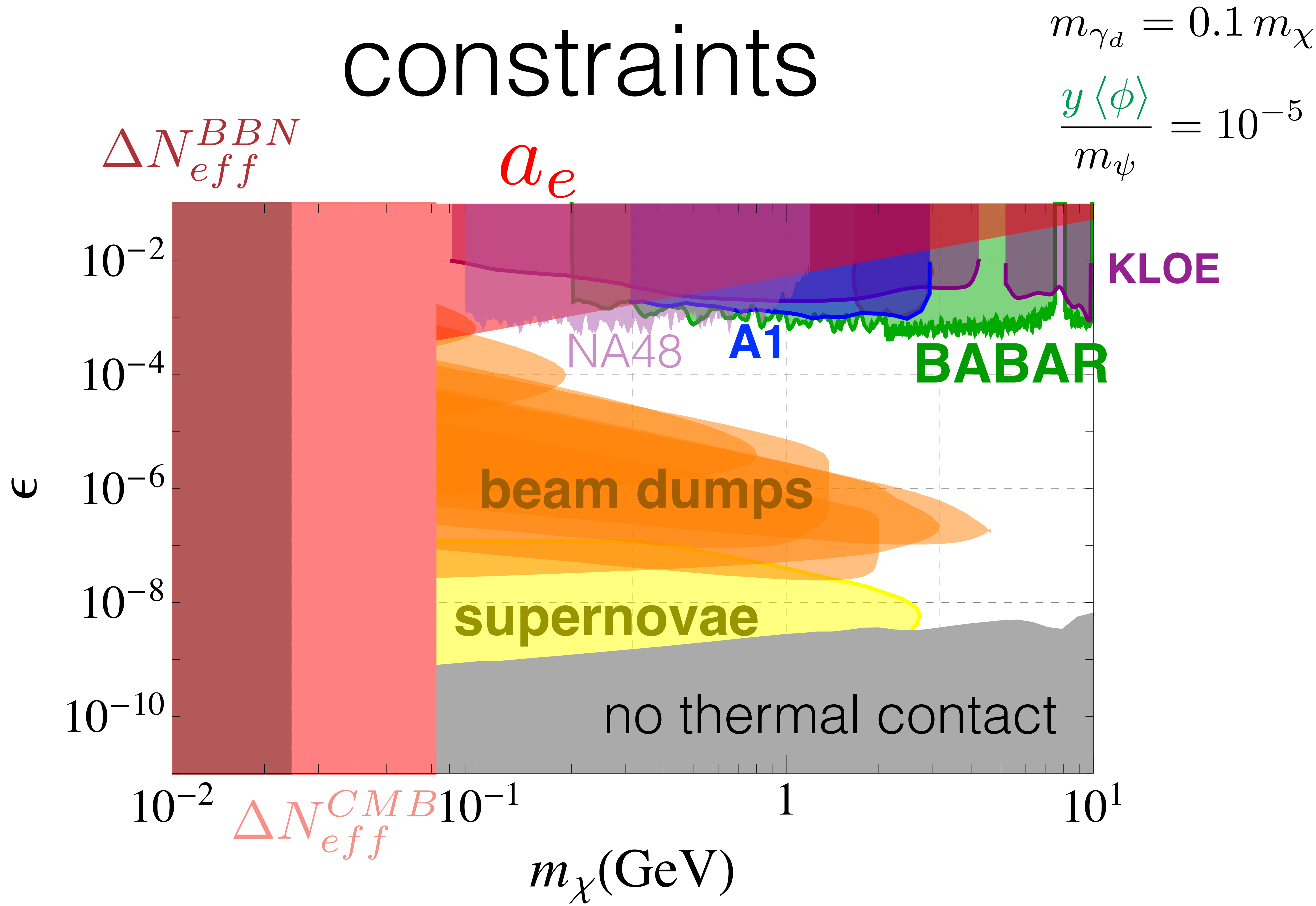


direct detection:





constraints

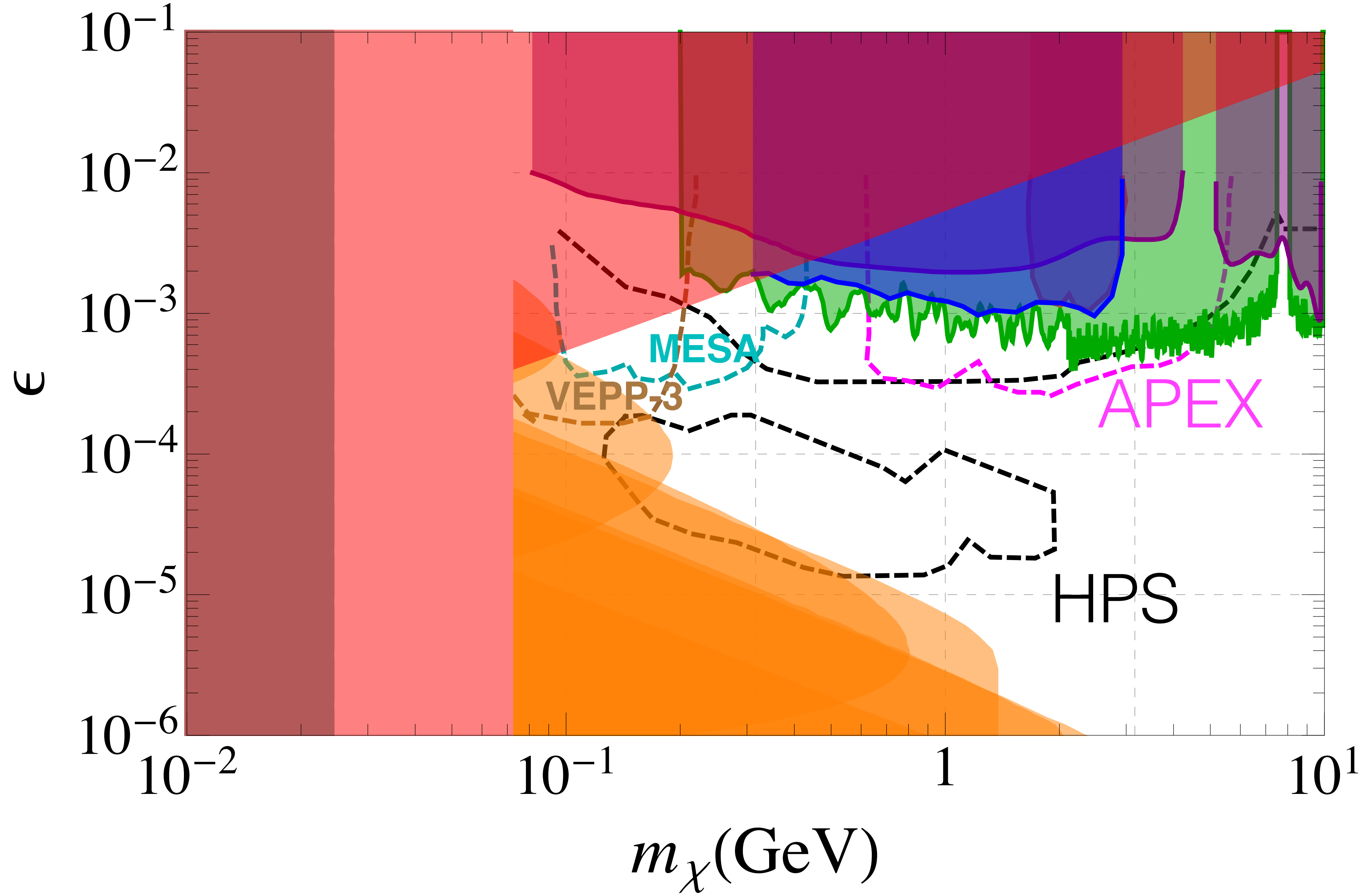


- Babar, **1406.2980**
- Snowmass, **1311.0029**

constraints

$$m_{\gamma_d} = 0.1\, m_\chi$$

$$\frac{y\,\langle\phi\rangle}{m_\psi} = 10^{-5}$$



- Snowmass, **1311.0029**

take away

- finite temperature $\Rightarrow$ Boltzmann factor $\Rightarrow$ light DM

ex) forbidden DM, co-annihilation, inelastic freezeout, …

pheno:

- evades CMB
- low mass direct detection, self-interactions, hidden photon, …