

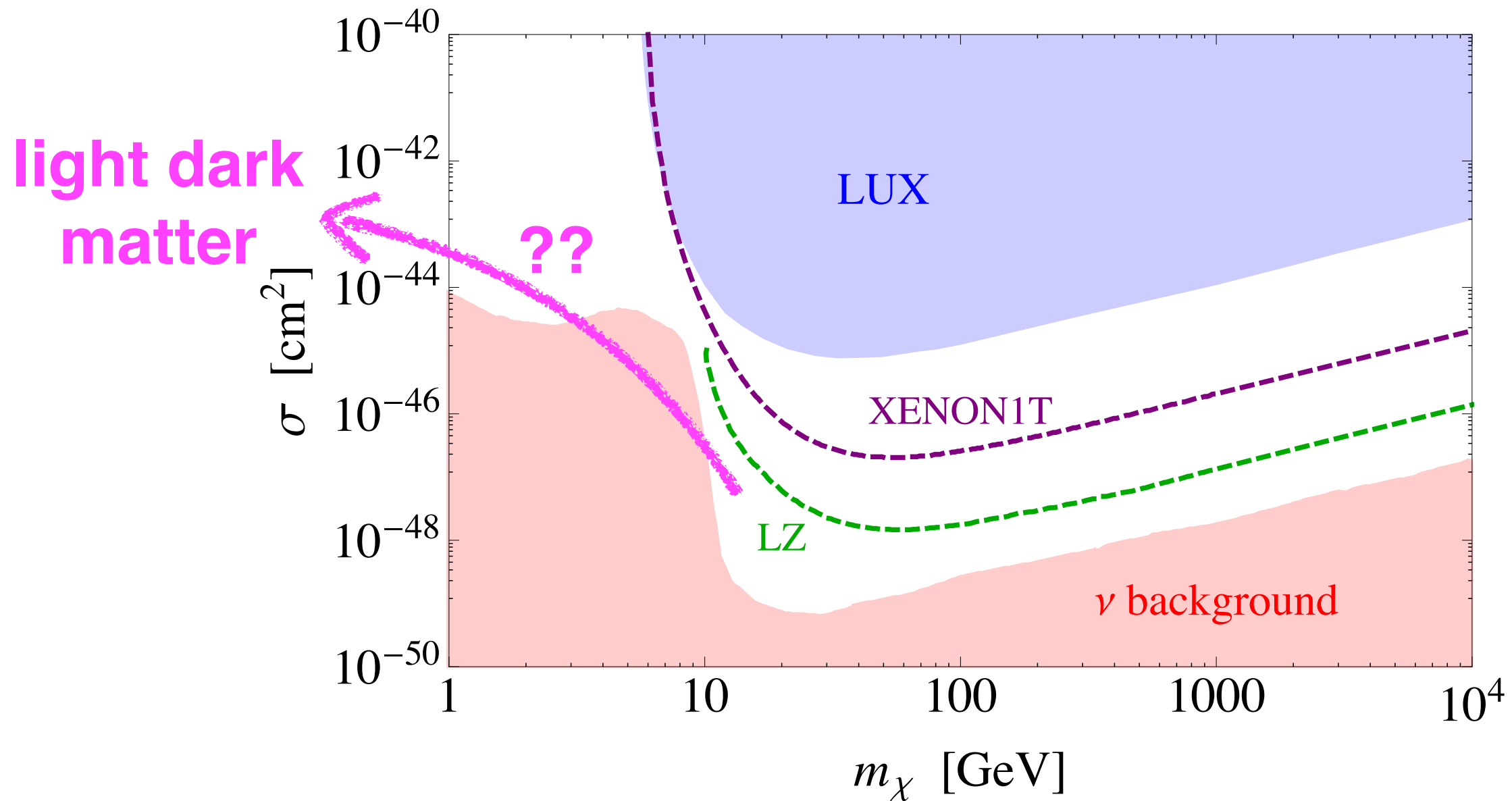


# Light Dark Matter from Boltzmann Factors

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

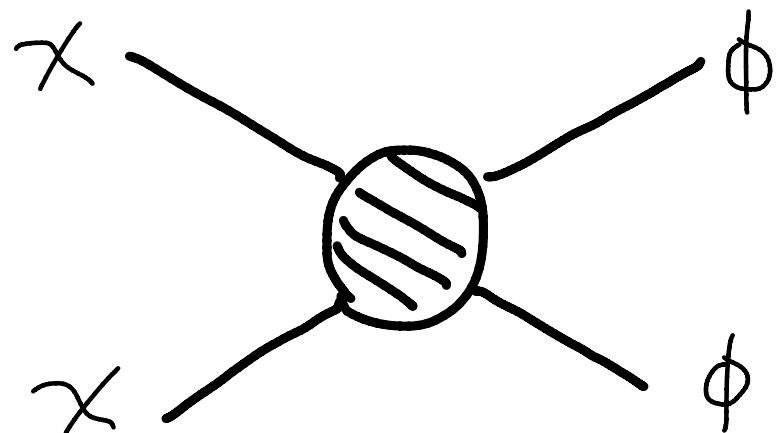
Raffaele D'Agnolo, JTR, *to appear*.

# Towards the Neutrino Floor in Direct Detection



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

# WIMP Miracle

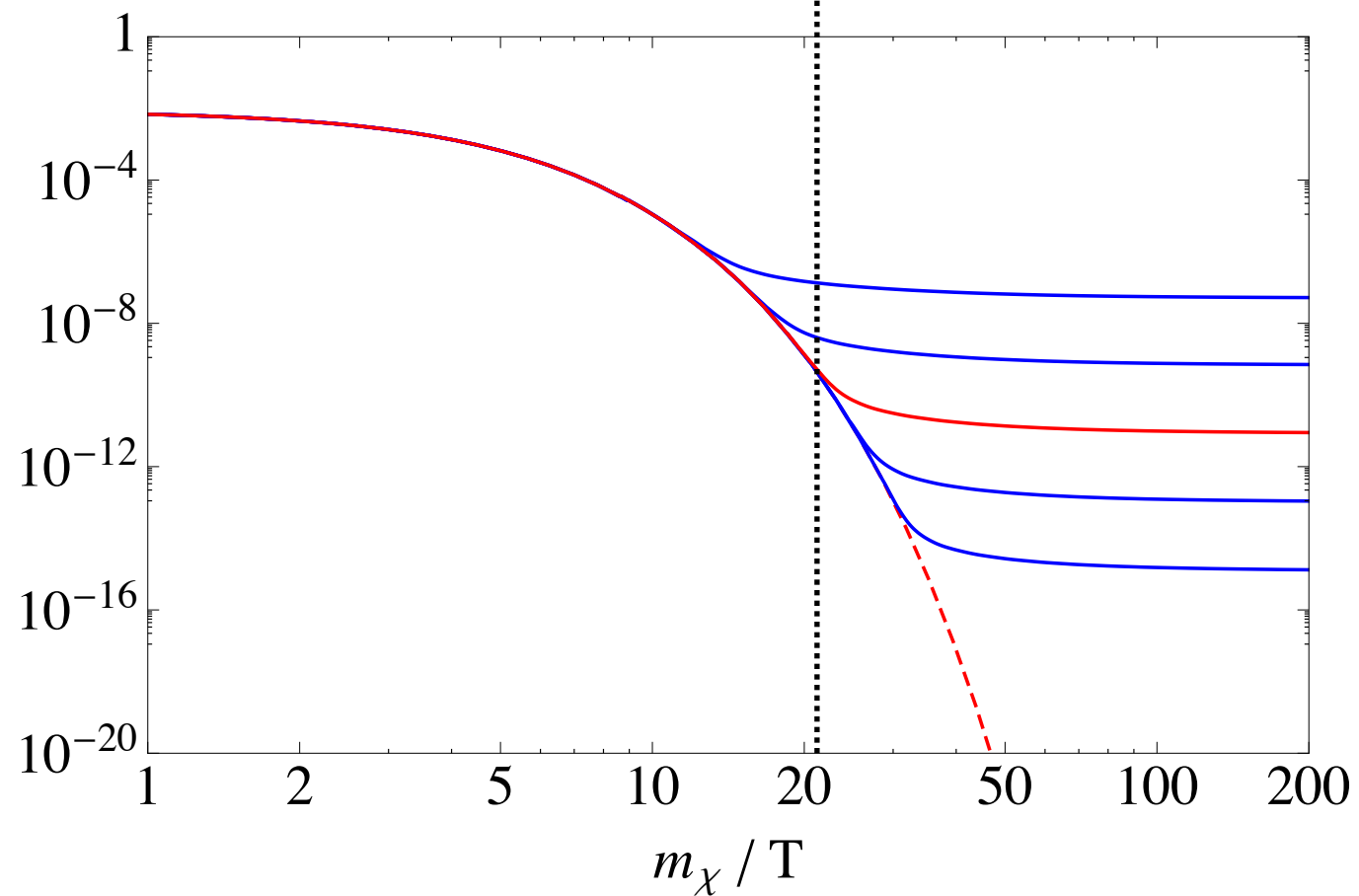


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle (n_\chi^2 - (n_\chi^{eq})^2)$$

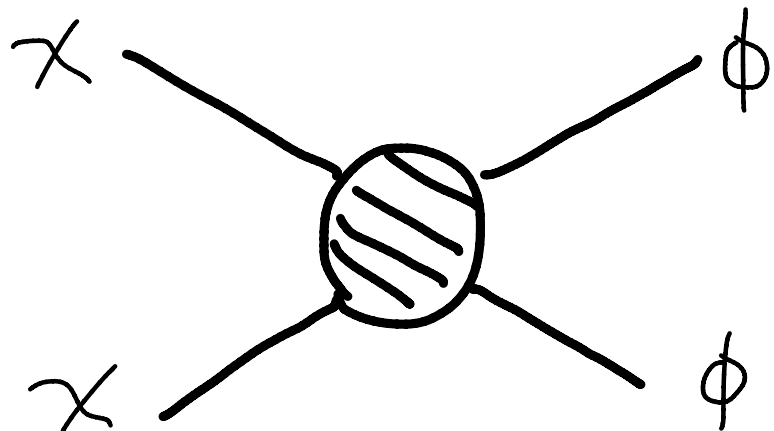
$$n_\chi \langle\sigma v\rangle \approx H$$

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

$Y_\chi$



# WIMP Miracle



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

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

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

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



**Three exceptions in the calculation of relic abundances**



Kim Griest

*Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, California 94720*

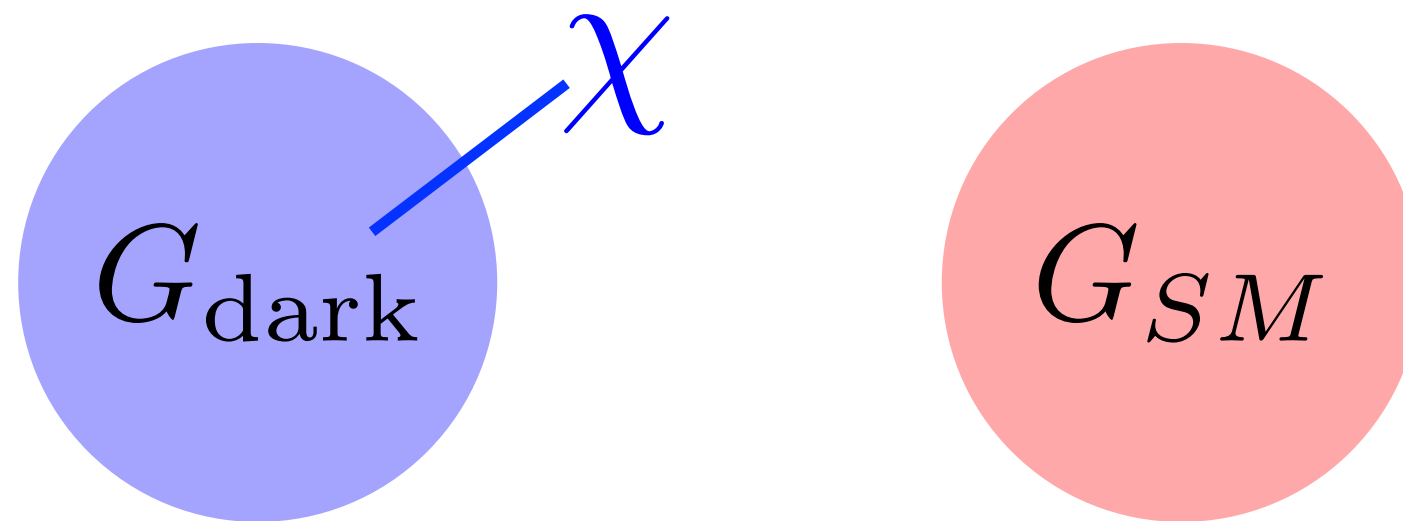
David Seckel

*Bartol Research Institute, University of Delaware, Newark, Delaware 19716*

(Received 15 November 1990)

1. coannihilation  so far mainly applied
2. forbidden channels  to weak-scale DM in
3. annihilation near pole SM sector

**goal:** explore possible cosmologies for thermal relics in hidden sectors



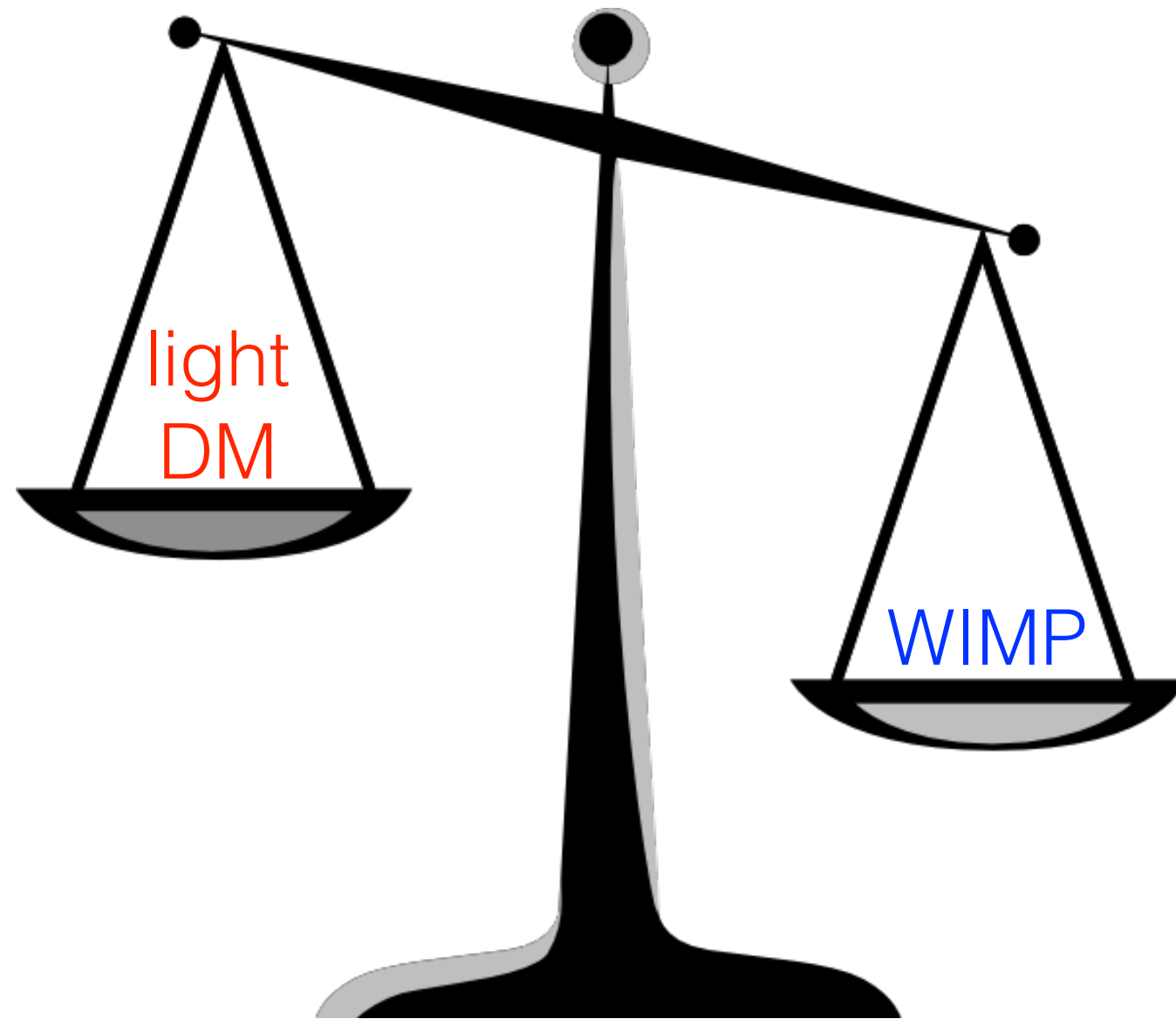
$$m_\chi \ll v$$

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

# plan

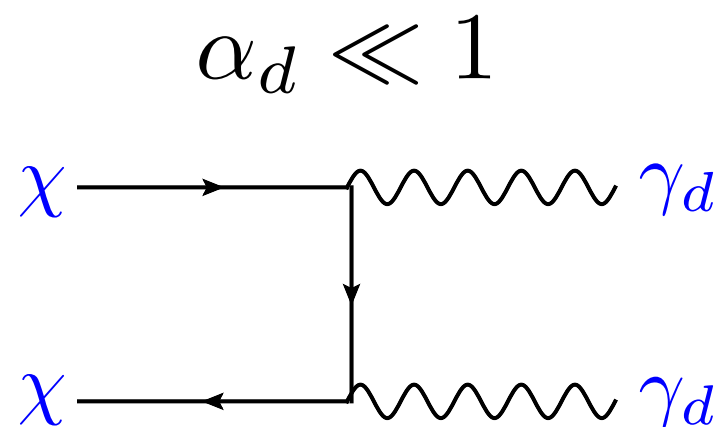
1. review: light dark matter
2. forbidden dark matter
3. generalized coannihilation

review: light dark matter



# light DM with weak cross section

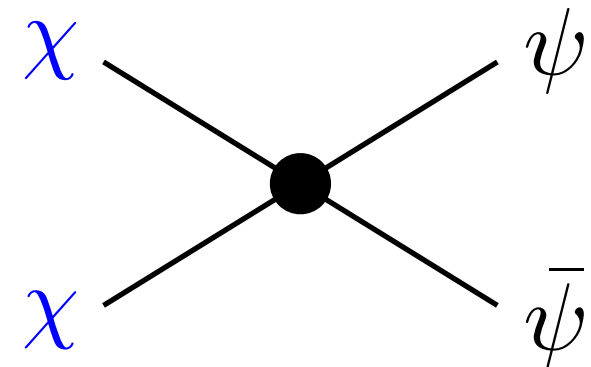
$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{m_Z^2}$$



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

(WIMPless miracle)

$m_\chi \ll \Lambda$



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

- Feng, Kumar **0803.4196**

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

# asymmetric dark matter

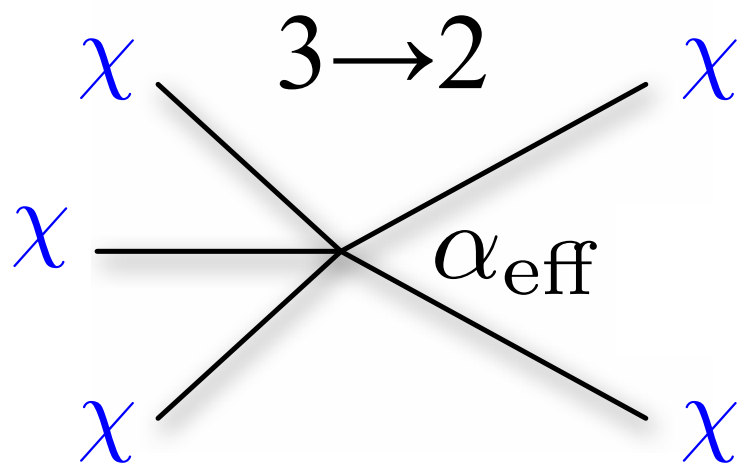
$\chi$

$\chi \chi$

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

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

# SIMP

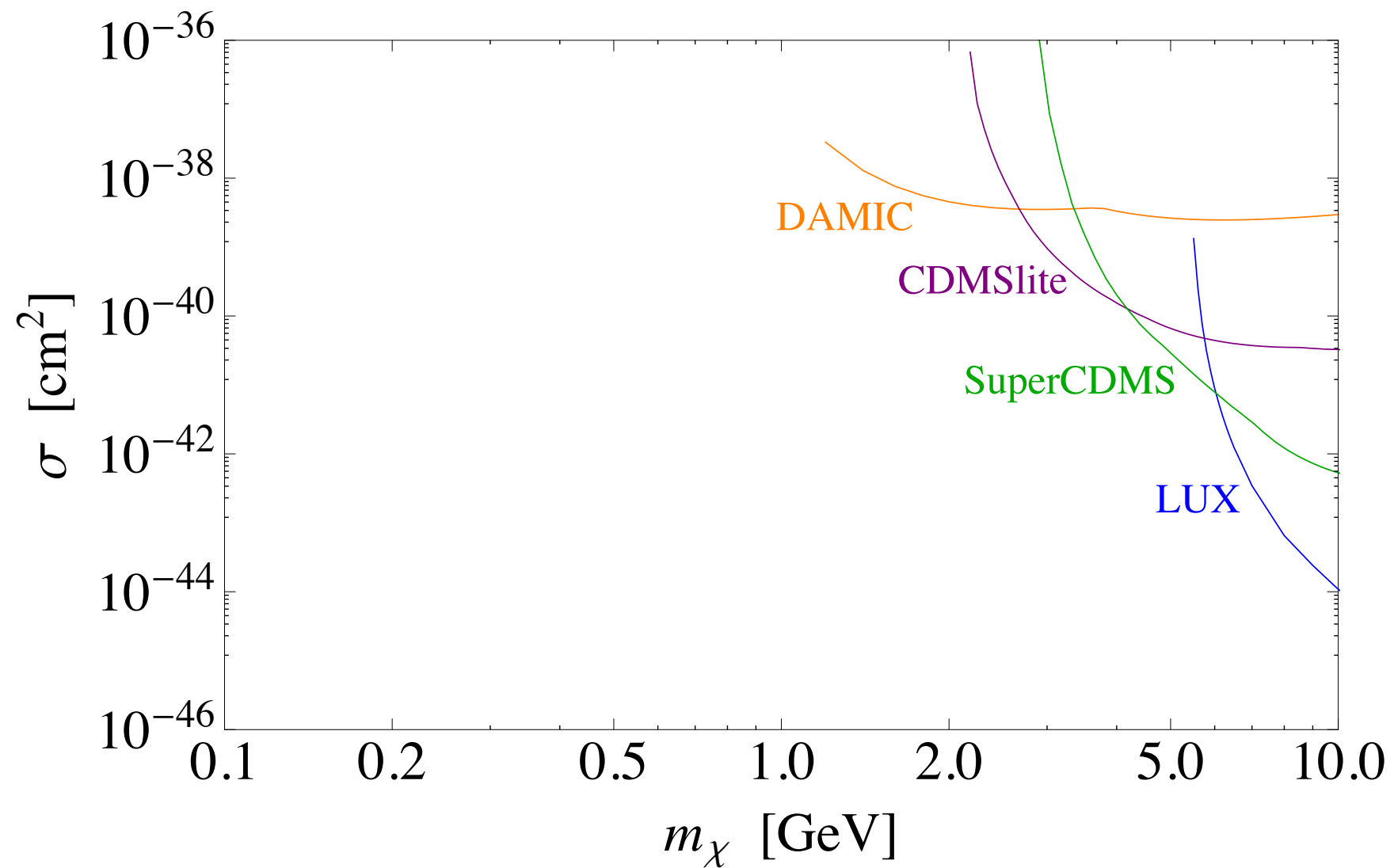


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle_{3\rightarrow 2} \left(n_\chi^3 - n_\chi^2 n_\chi^{eq}\right)$$

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

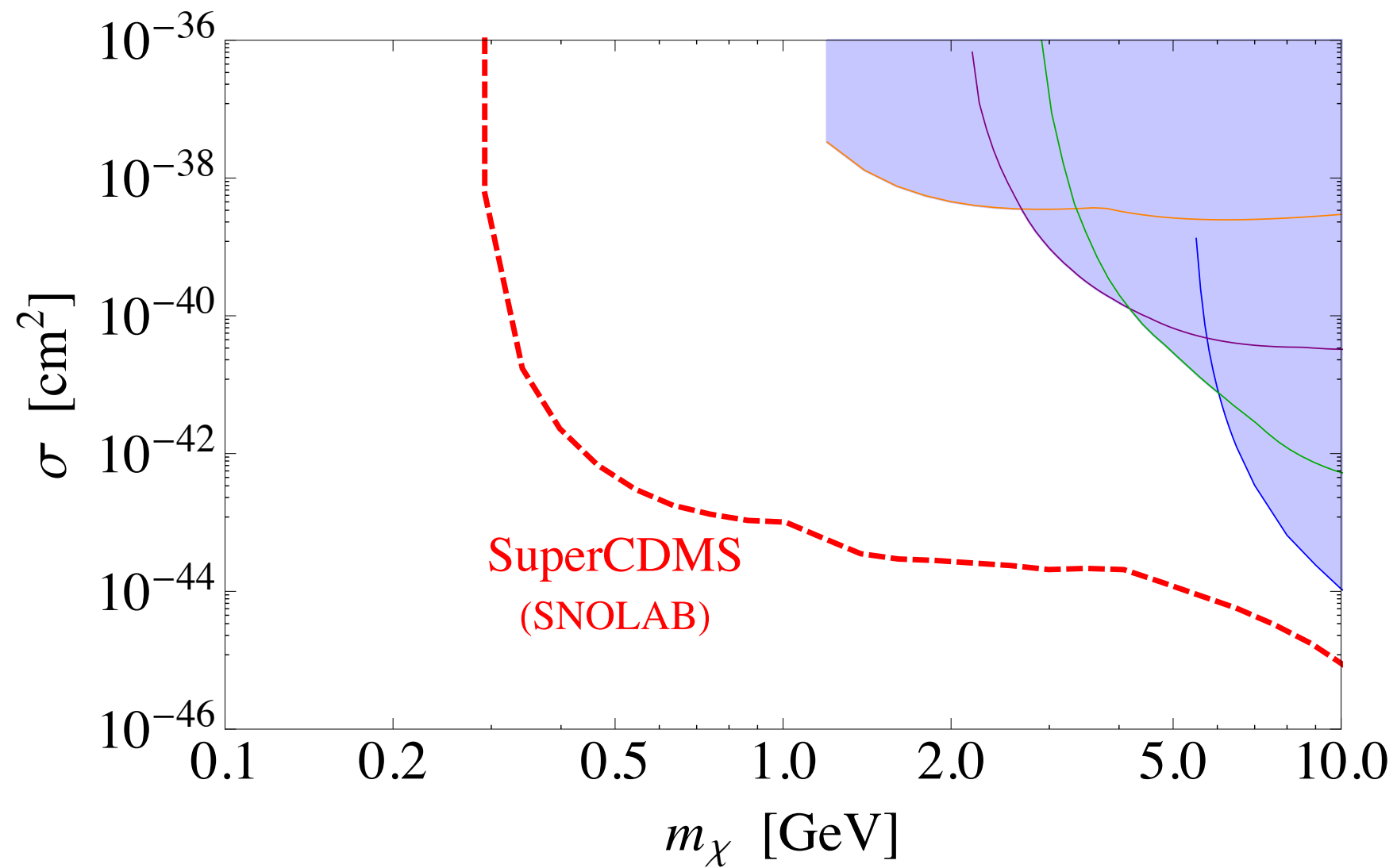
- Carlson, Hall, Machacek **1992**
- Hochberg, Kuflik, Volansky, Wacker, **1402.5143**

# probing light dark matter



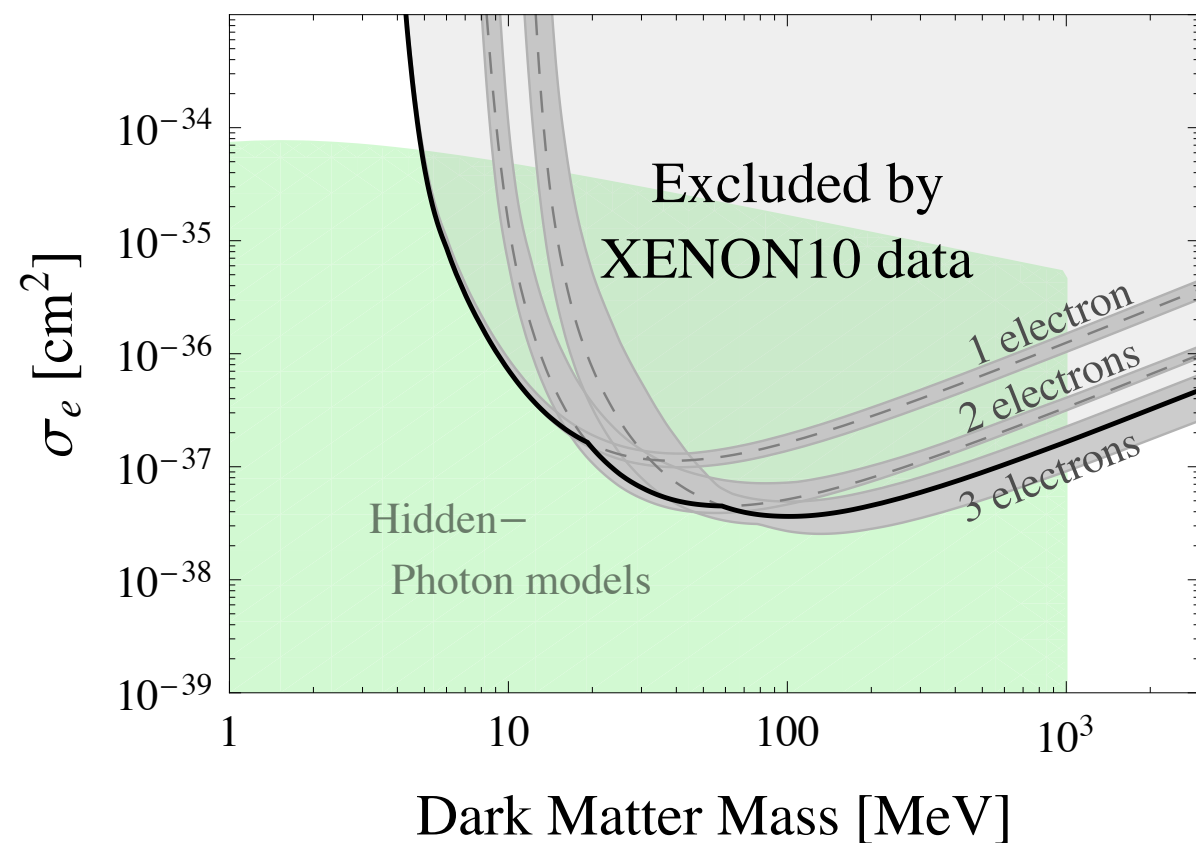


# probing light dark matter



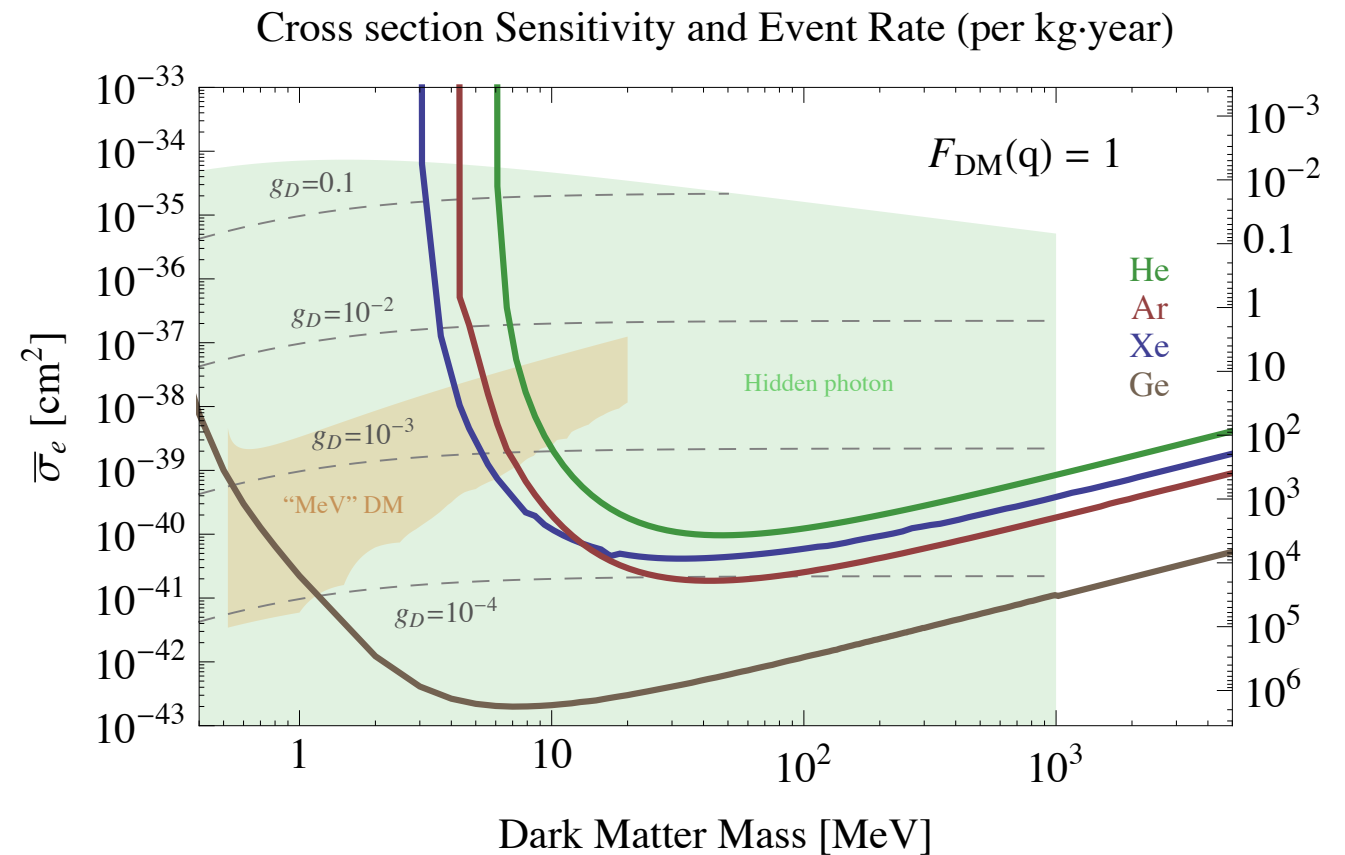
# probing light dark matter

**now**



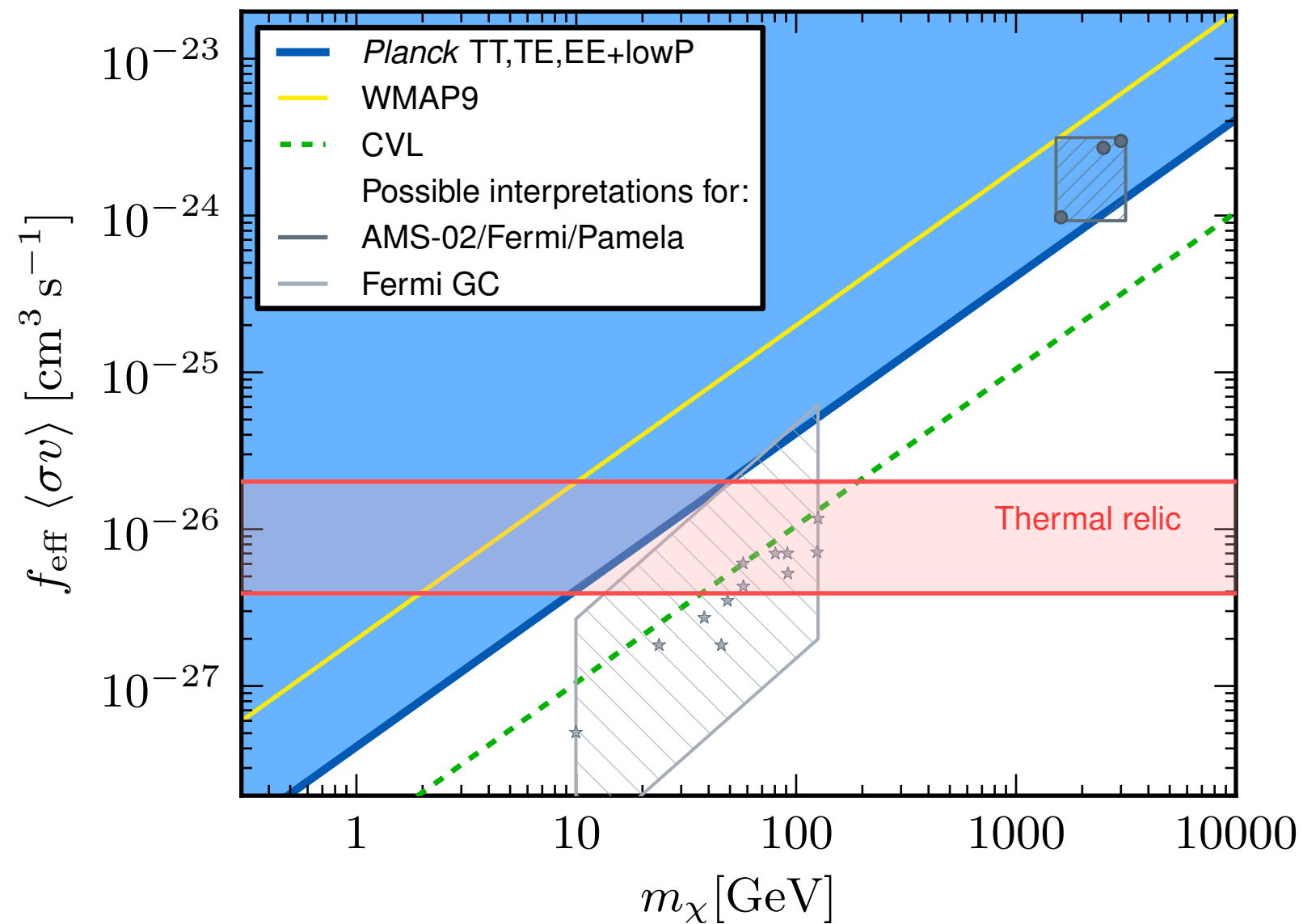
- Essig, Manalaysay, Mardon, Sorensen, Volansky **1206.2644**

**later**



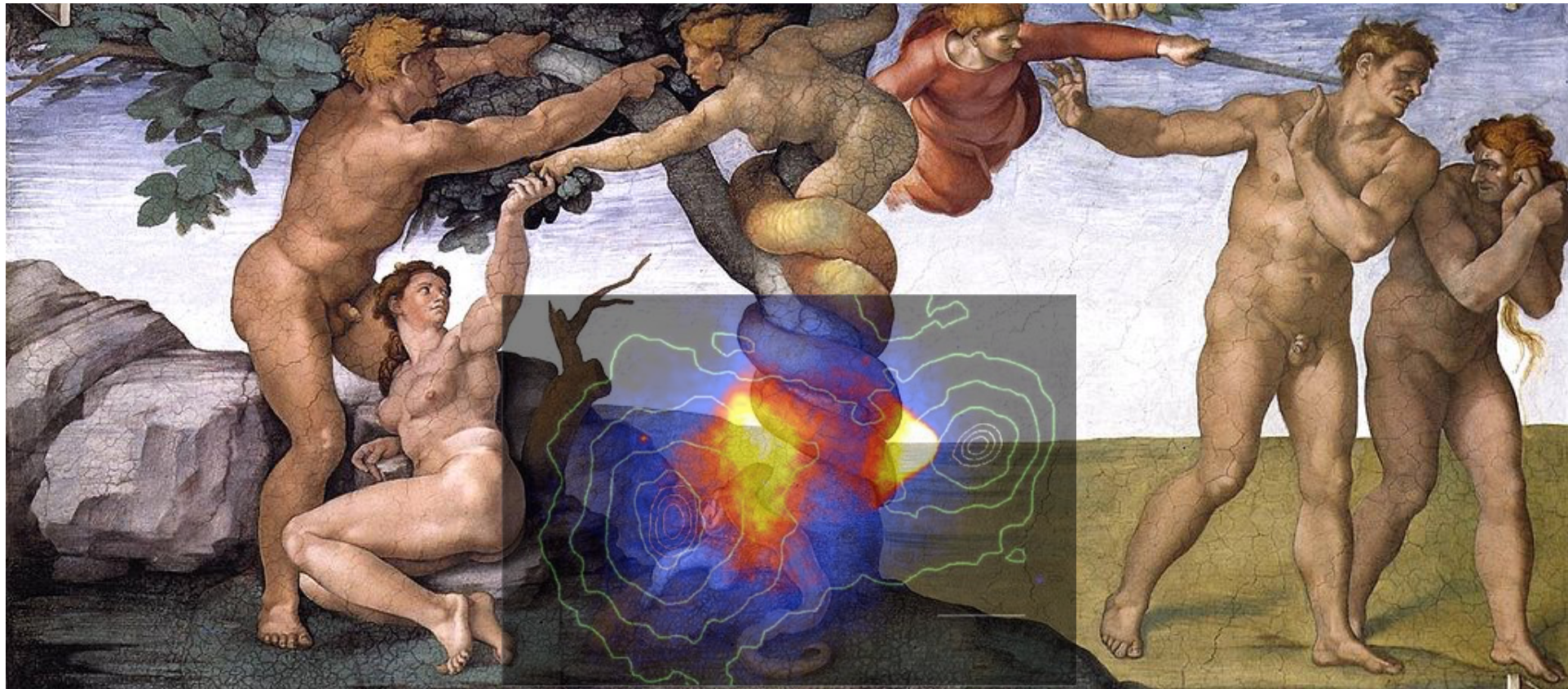
- Essig, Mardon, Volansky **1108.5383**

# CMB limit



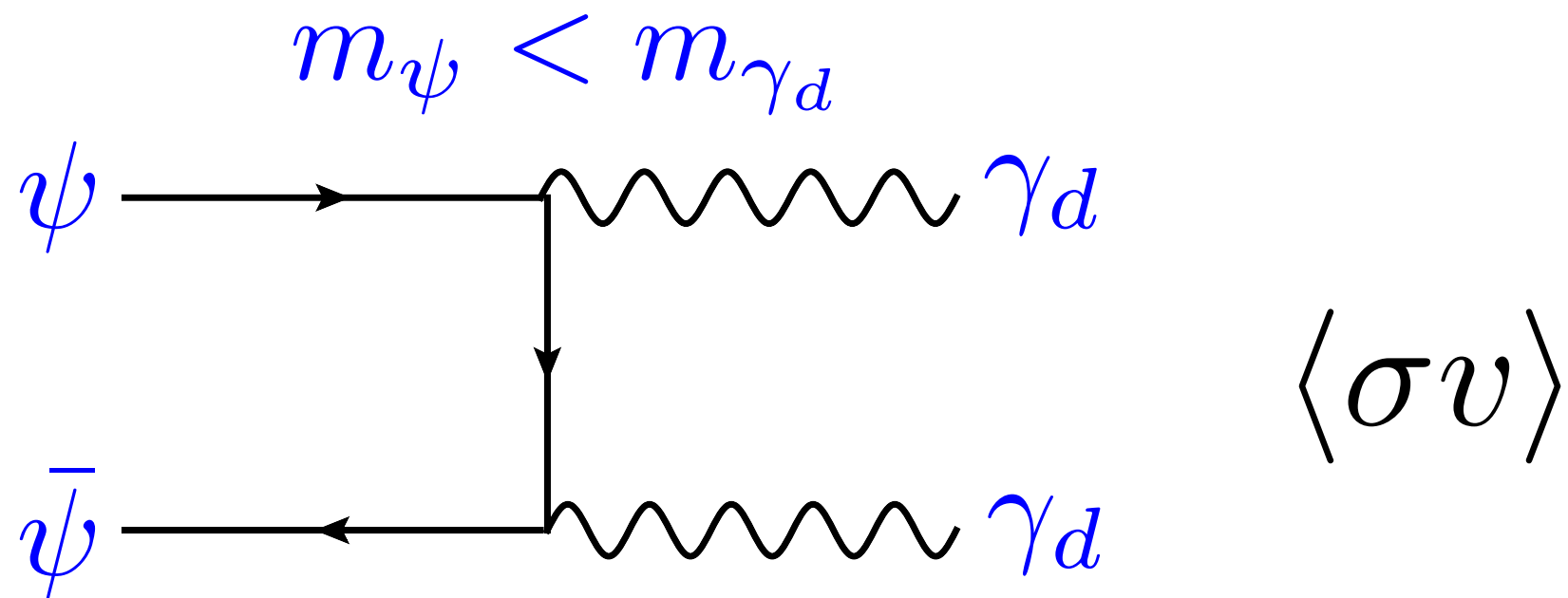
- Madhavacheril, Sehgal, Slatyer, **1310.3815**
- Planck, **1502.01589**

# Forbidden Dark Matter



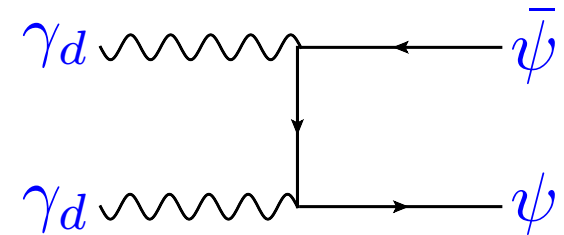
# example model

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

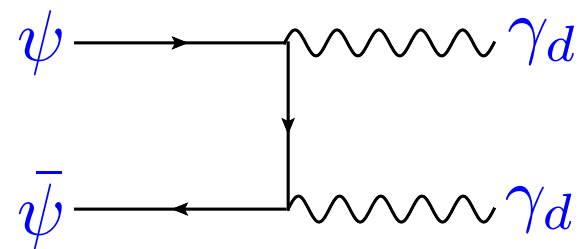


- evades CMB when:  $m_{\gamma_d} - m_\psi \gg T_{rec}$

# Boltzmann equation



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

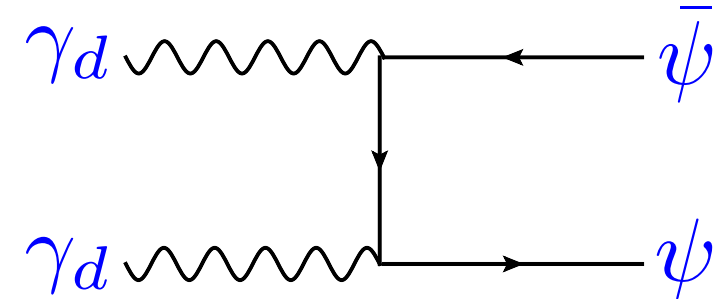


detailed  
balance:

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

# forbidden cross section

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



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

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

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

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

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



# forbidden relic density

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

## Three exceptions in the calculation of relic abundances

Kim Griest

*Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, California 94720*

David Seckel

*Bartol Research Institute, University of Delaware, Newark, Delaware 19716*

(Received 15 November 1990)

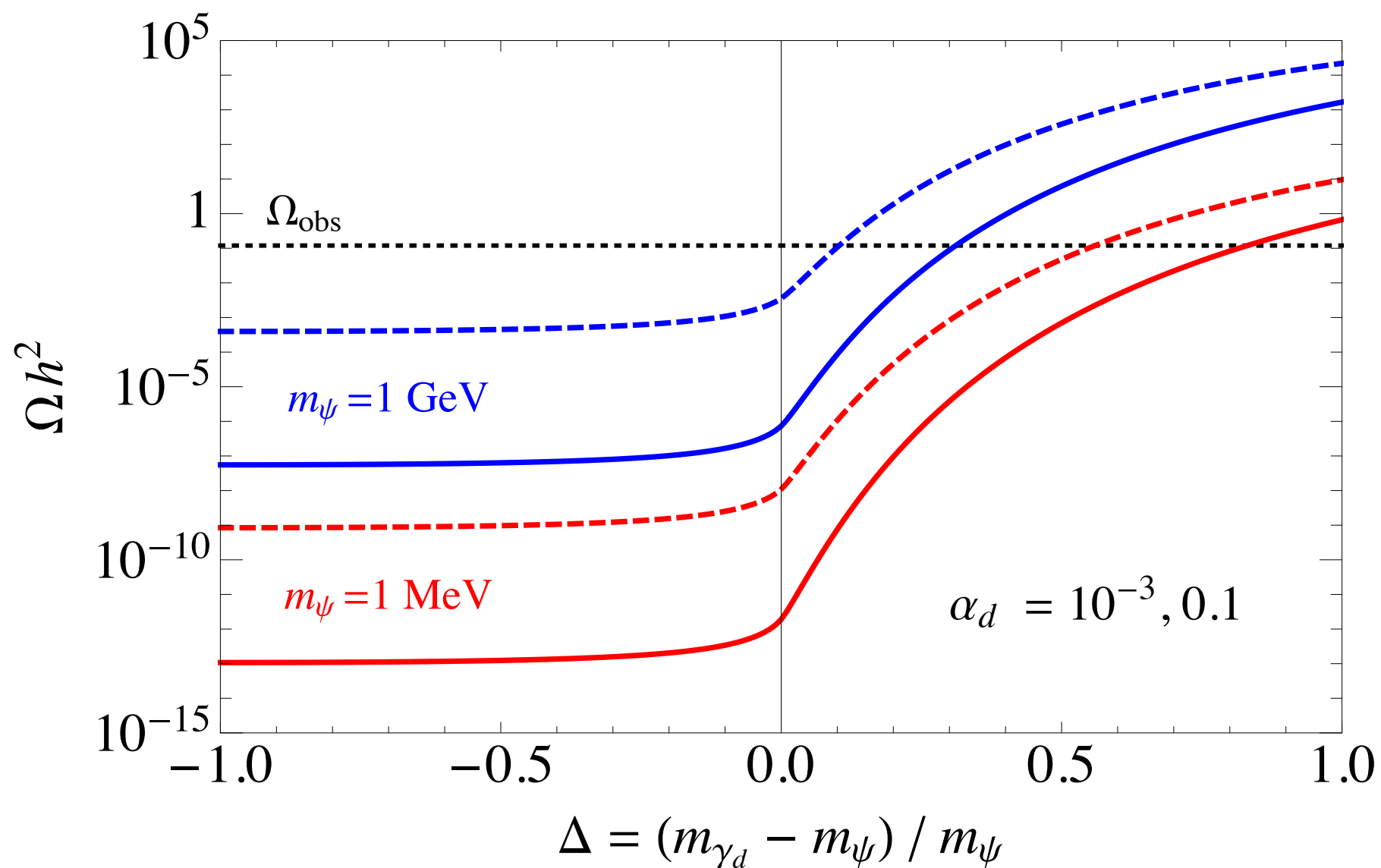
The calculation of relic abundances of elementary particles by following their annihilation and freeze-out in the early Universe has become an important and standard tool in discussing particle dark-matter candidates. We find three situations, all occurring in the literature, in which the standard methods 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  $\sim 5\text{--}15\%$ , 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

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

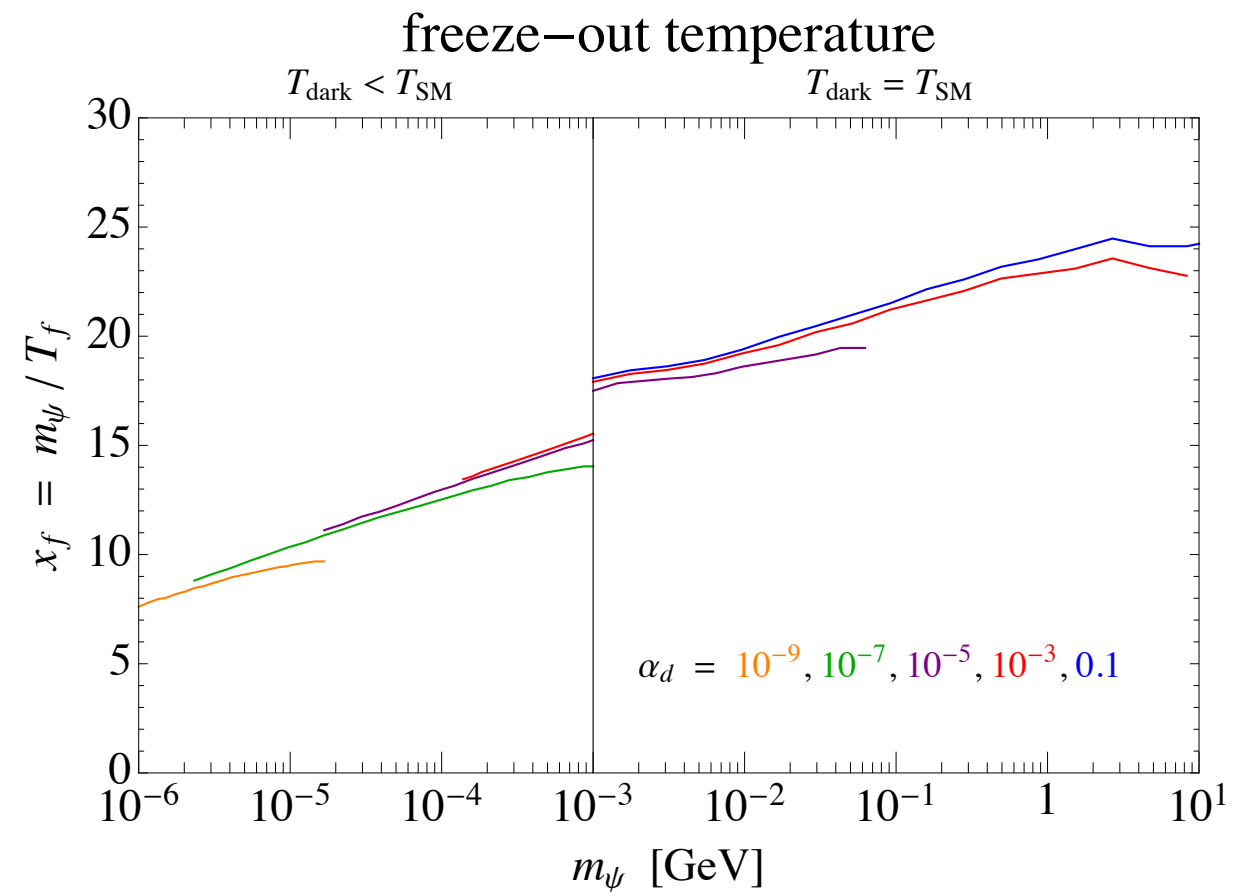
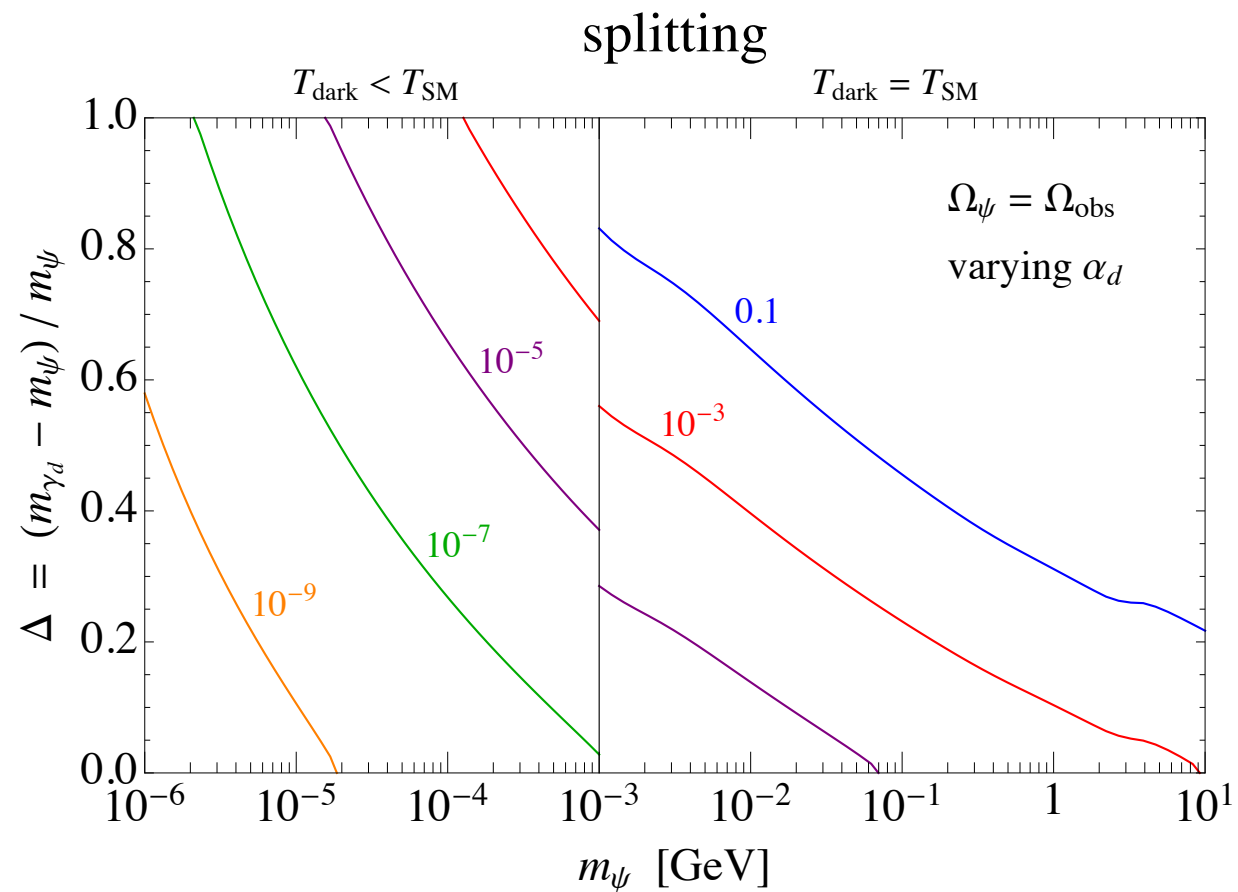
$$m_\psi \sim \alpha_d \sqrt{T_{eq} M_{pl}} e^{-2x_f \Delta}$$



# forbidden relic density

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

$$m_\psi \sim \alpha_d \sqrt{T_{eq} M_{pl}} e^{-2x_f \Delta}$$



# tuning?

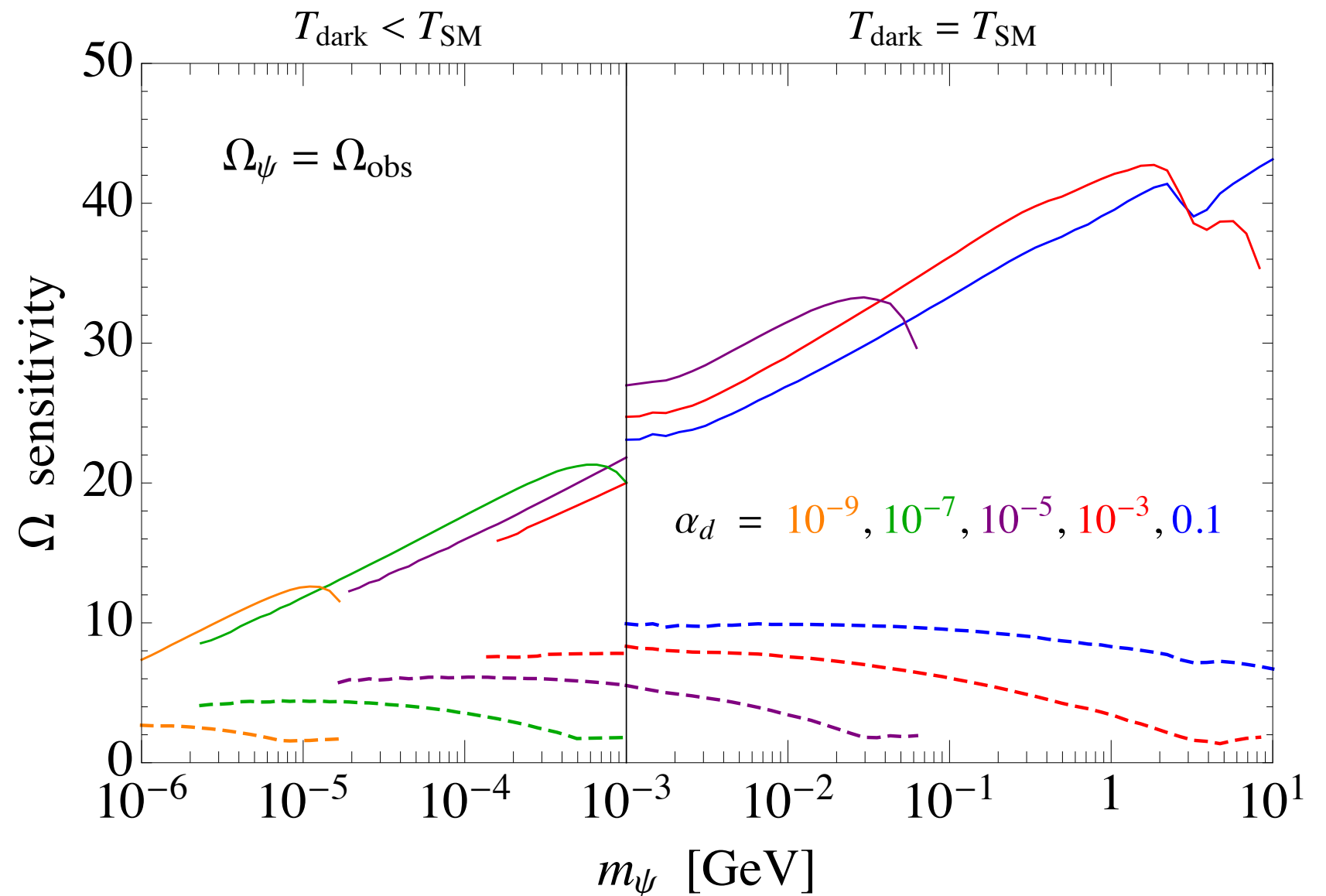
$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2} e^{2x_f \Delta}$$

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

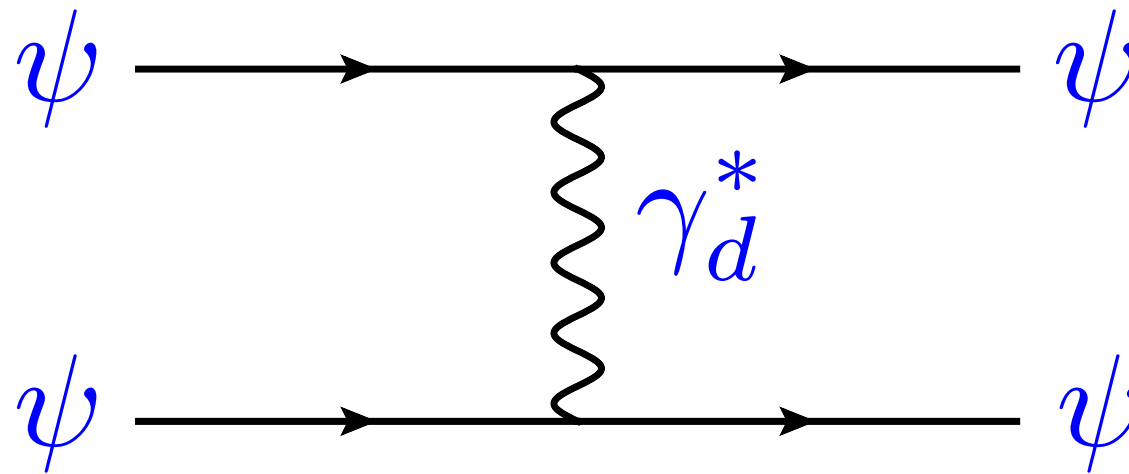
$$\frac{\partial \log \Omega}{\partial \log p_i}$$

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

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



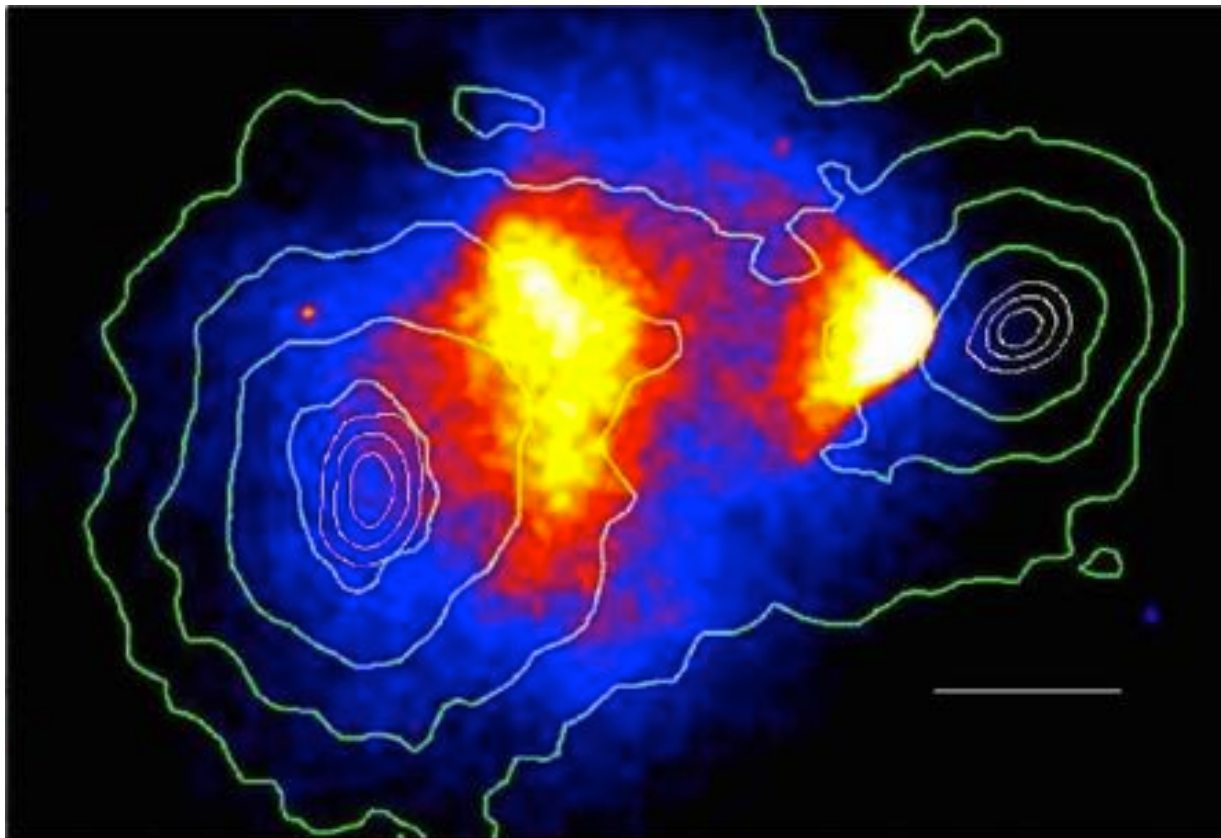
# self-interactions



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

# self-interactions

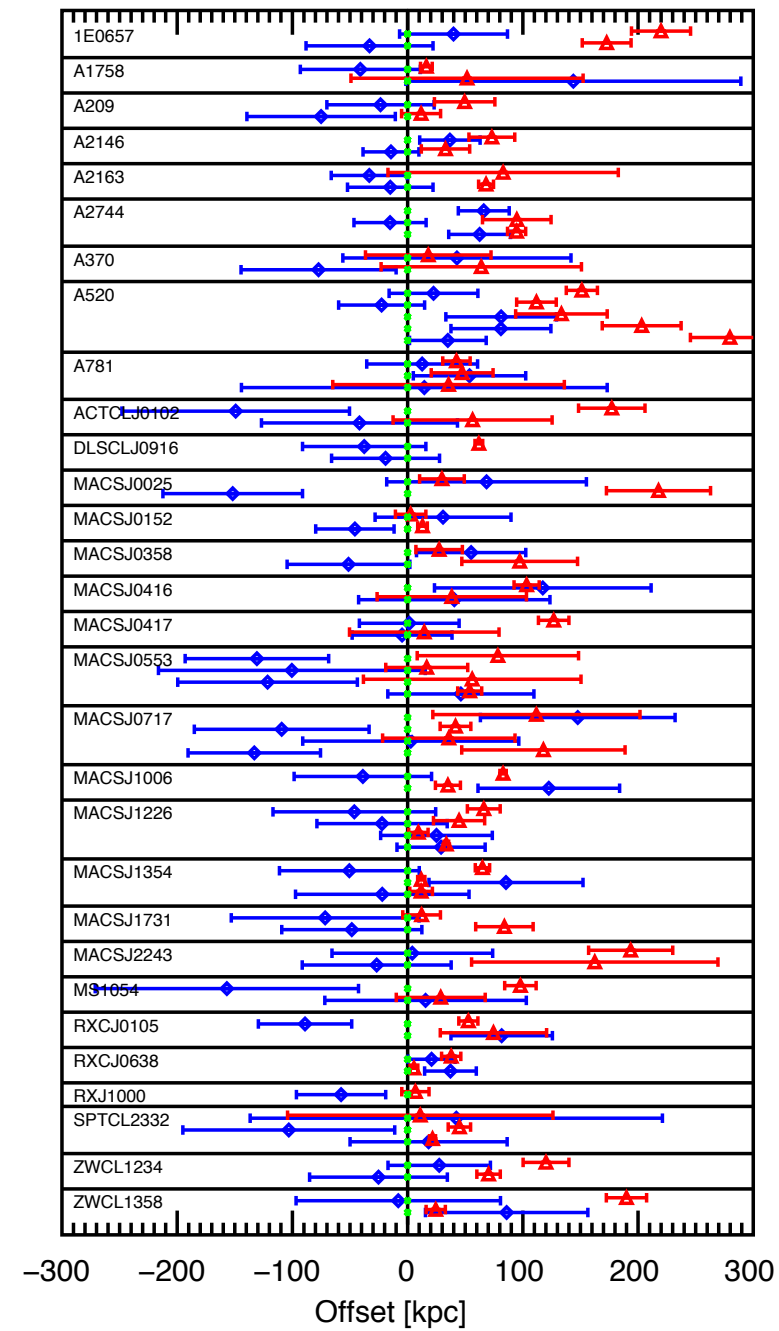
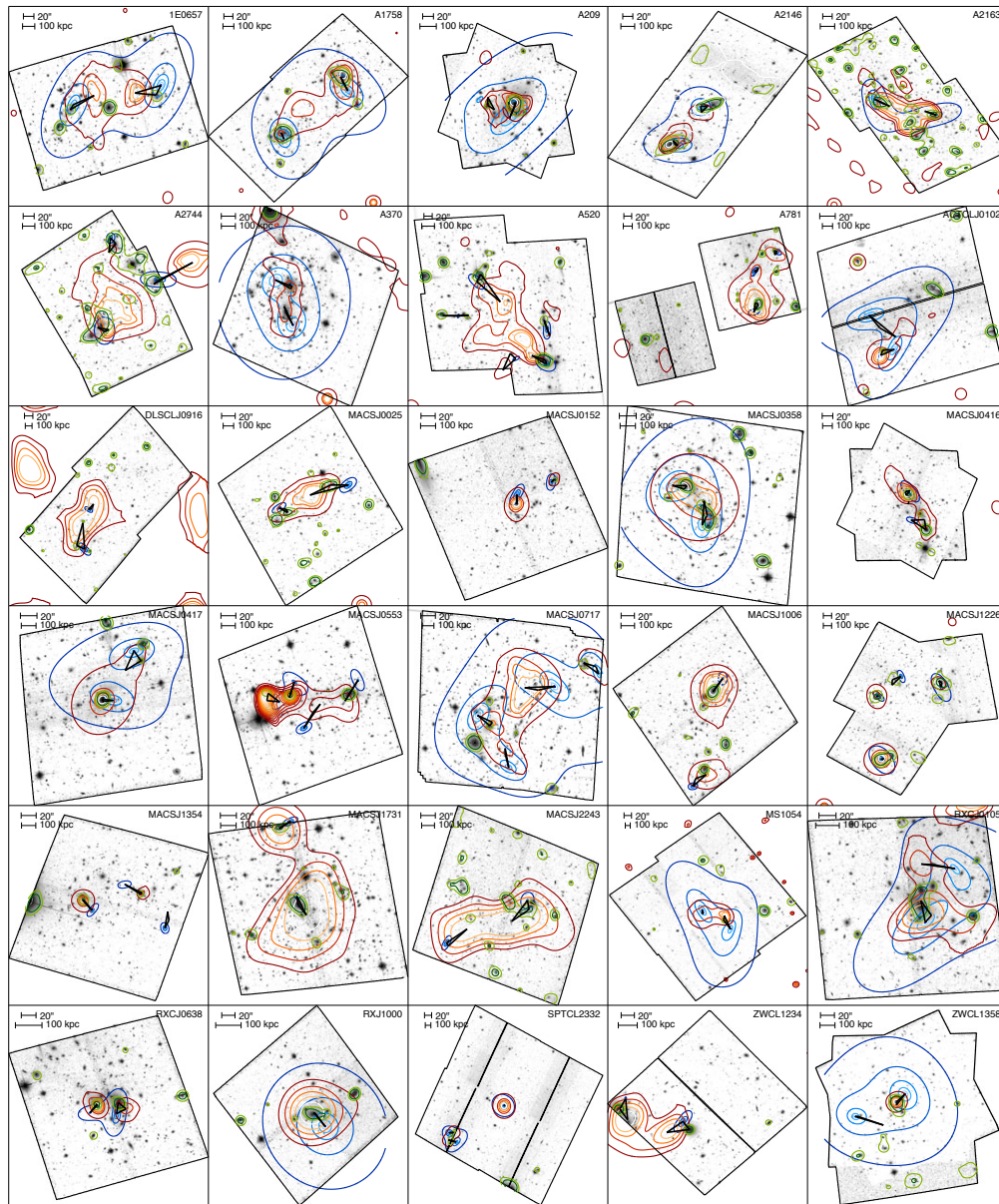
bullet cluster:



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

- Randall et al., **0704.0261**

# self-interactions



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

- Harvey et al., **1503.07675**

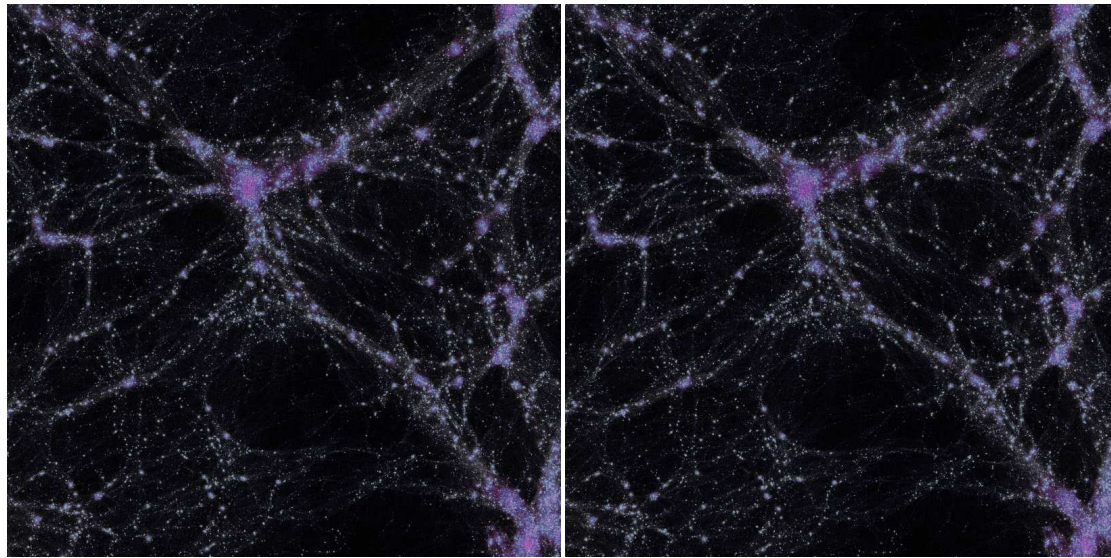


# self-interactions

CDM

SIDM

50 Mpc



0.2 Mpc



- core-cusp
- too big to fail

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

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

# self-interactions

sensitivity:

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

thermal annihilation rate:

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

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



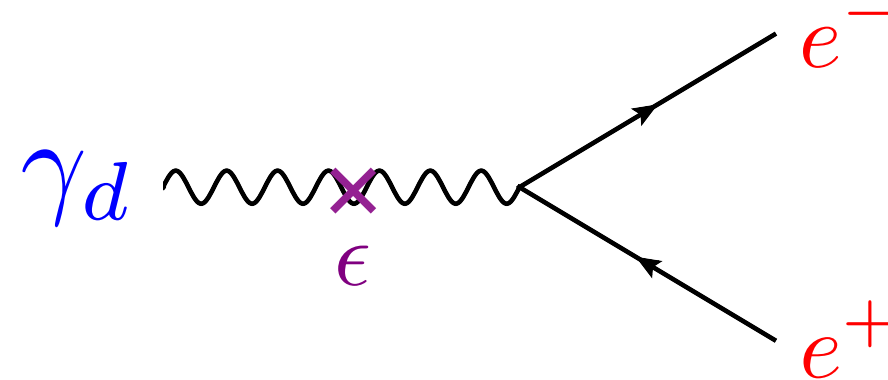
# self-interactions

The diagram shows two Feynman diagrams for self-interactions, separated by a diagonal slash. The left diagram, enclosed in large parentheses, shows two incoming particles labeled  $\psi$  (in blue) interacting via a vertical wavy line labeled  $\gamma_d^*$  (in blue), resulting in two outgoing particles labeled  $\psi$ . The right diagram, also in large parentheses, shows an incoming particle  $\psi$  and an incoming antiparticle  $\bar{\psi}$  (in blue) interacting via two vertical wavy lines labeled  $\gamma_d$  (in blue), resulting in an outgoing particle  $\psi$  and an outgoing antiparticle  $\bar{\psi}$ . To the right of the diagrams is a tilde symbol  $\sim$  followed by the expression  $\frac{e^{2x_f \Delta}}{m_\psi}$ .

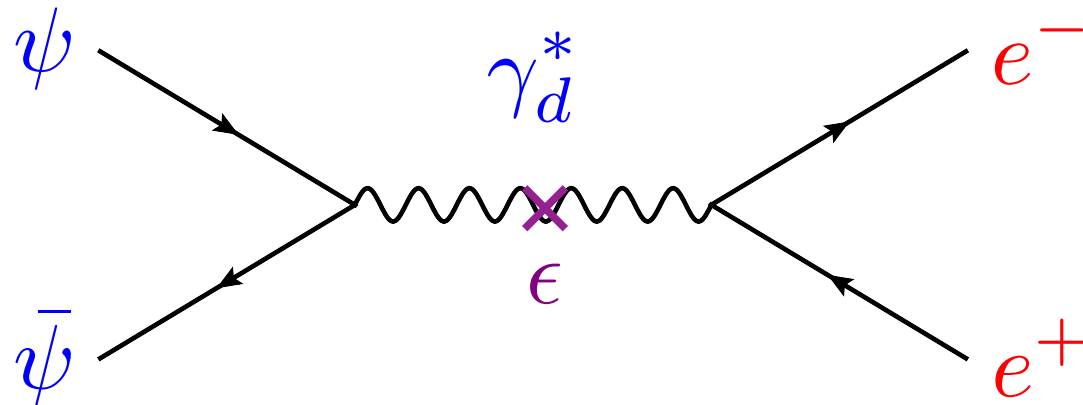
$$\frac{\sigma_{SI}}{m_\psi} \sim 0.2 \text{ cm}^2/\text{g} \times \left( \frac{10 \text{ MeV}}{m_\psi} \right)^3 \times \left( \frac{\alpha_d}{0.1} \right)^2$$

# coupling to SM

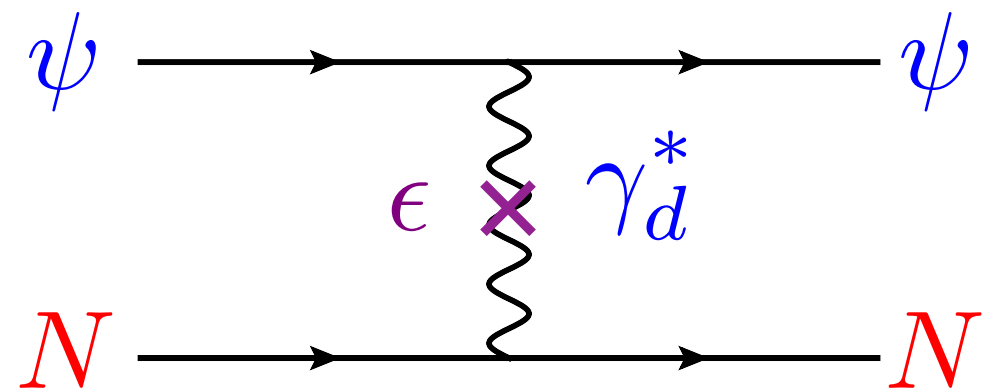
$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu}^d F^{\mu\nu}$$



indirect detection:

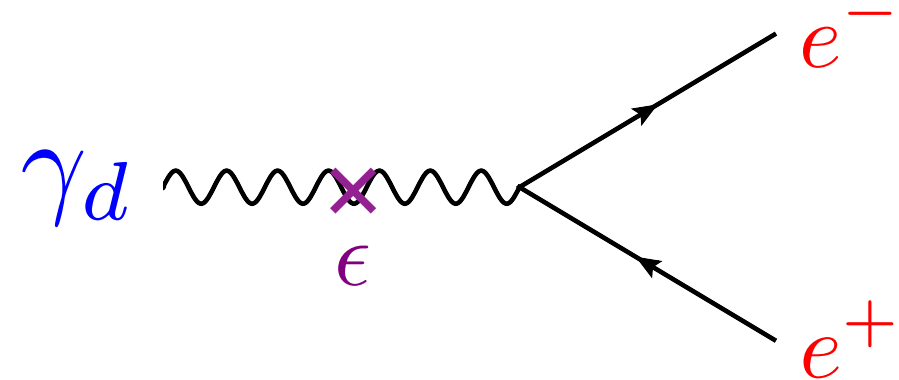


direct detection:



# coupling to SM

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

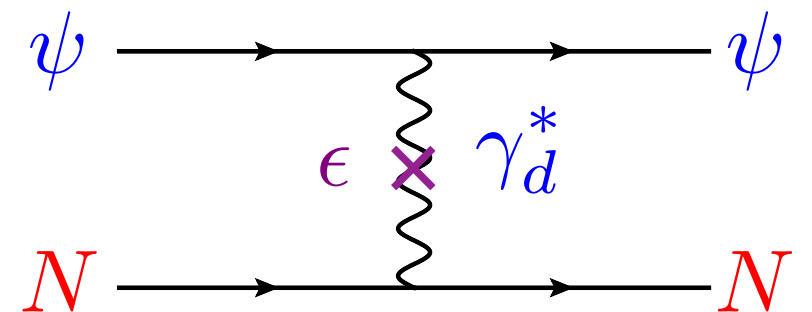
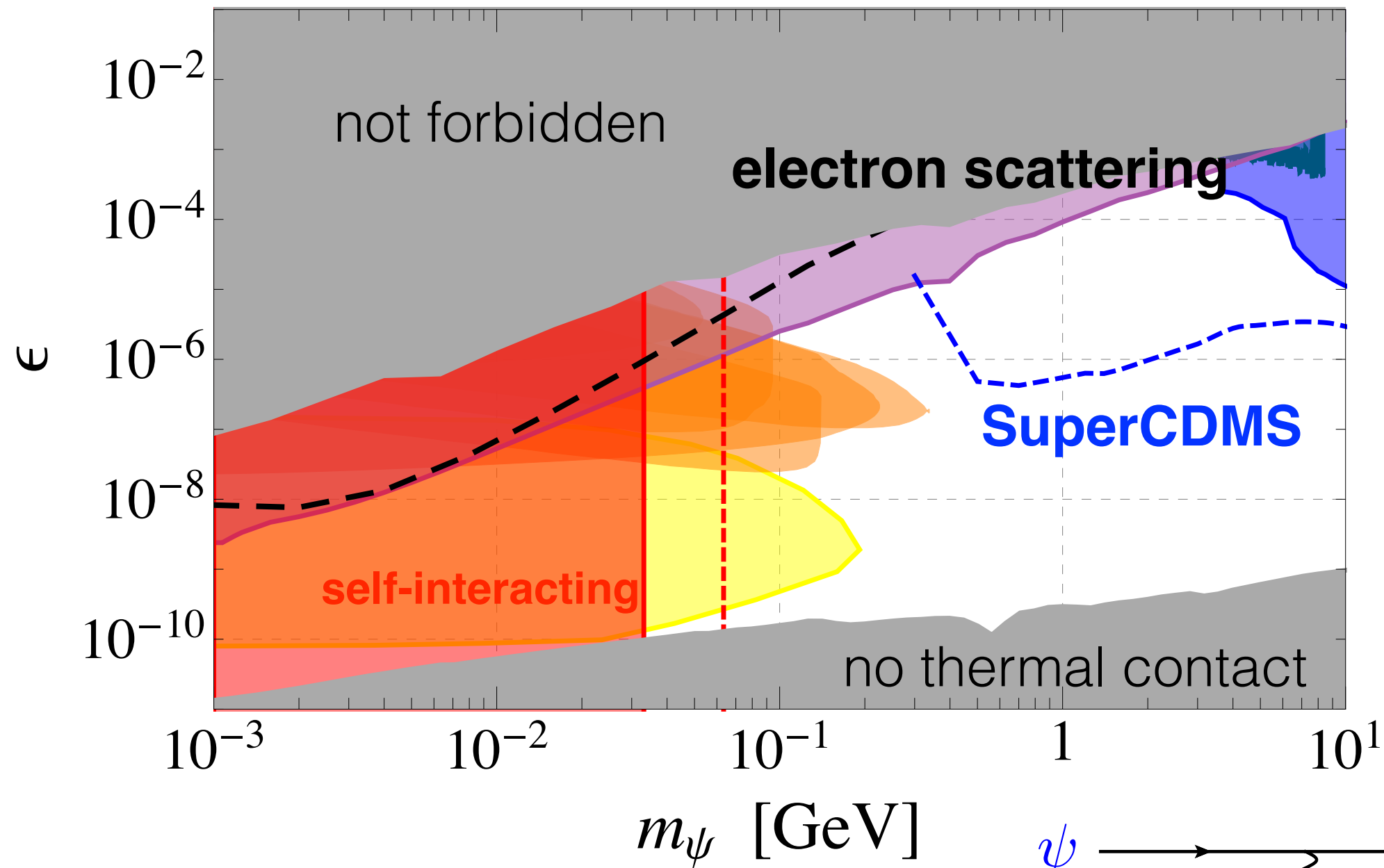


$$\left( \begin{array}{c} \psi \\ \bar{\psi} \end{array} \right) \xrightarrow{\gamma_d^*} \left( \begin{array}{c} e^- \\ e^+ \end{array} \right) < \left( \begin{array}{c} \psi \\ \bar{\psi} \end{array} \right) \xrightarrow{\gamma_d} \left( \begin{array}{c} \gamma_d \\ \gamma_d \end{array} \right)$$

The diagram shows two processes. On the left, a fermion-antifermion pair ( $\psi \bar{\psi}$ ) annihilates into a dark photon ( $\gamma_d^*$ ), which then decays into an electron-positron pair ( $e^- e^+$ ). On the right, a fermion-antifermion pair ( $\psi \bar{\psi}$ ) annihilates into two dark photons ( $\gamma_d \gamma_d$ ). The left process is shown with a purple 'x' and a purple  $\epsilon$  symbol, while the right process is shown with a blue  $\gamma_d$  label.

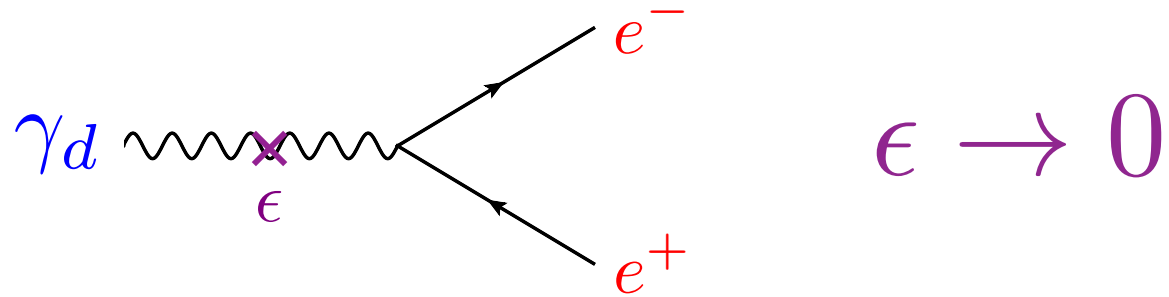
$$\epsilon^2 \frac{\alpha_d \alpha_{EM}}{m_\psi^2} < e^{-2x_f \Delta} \frac{\alpha_d^2}{m_\psi^2}$$

# direct detection reach



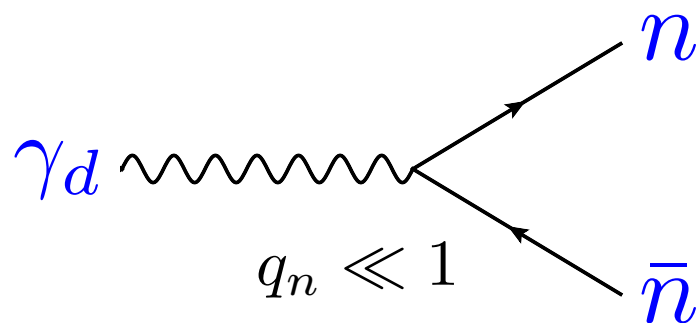
# decoupled from SM

turn off:



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

dark radiation:



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

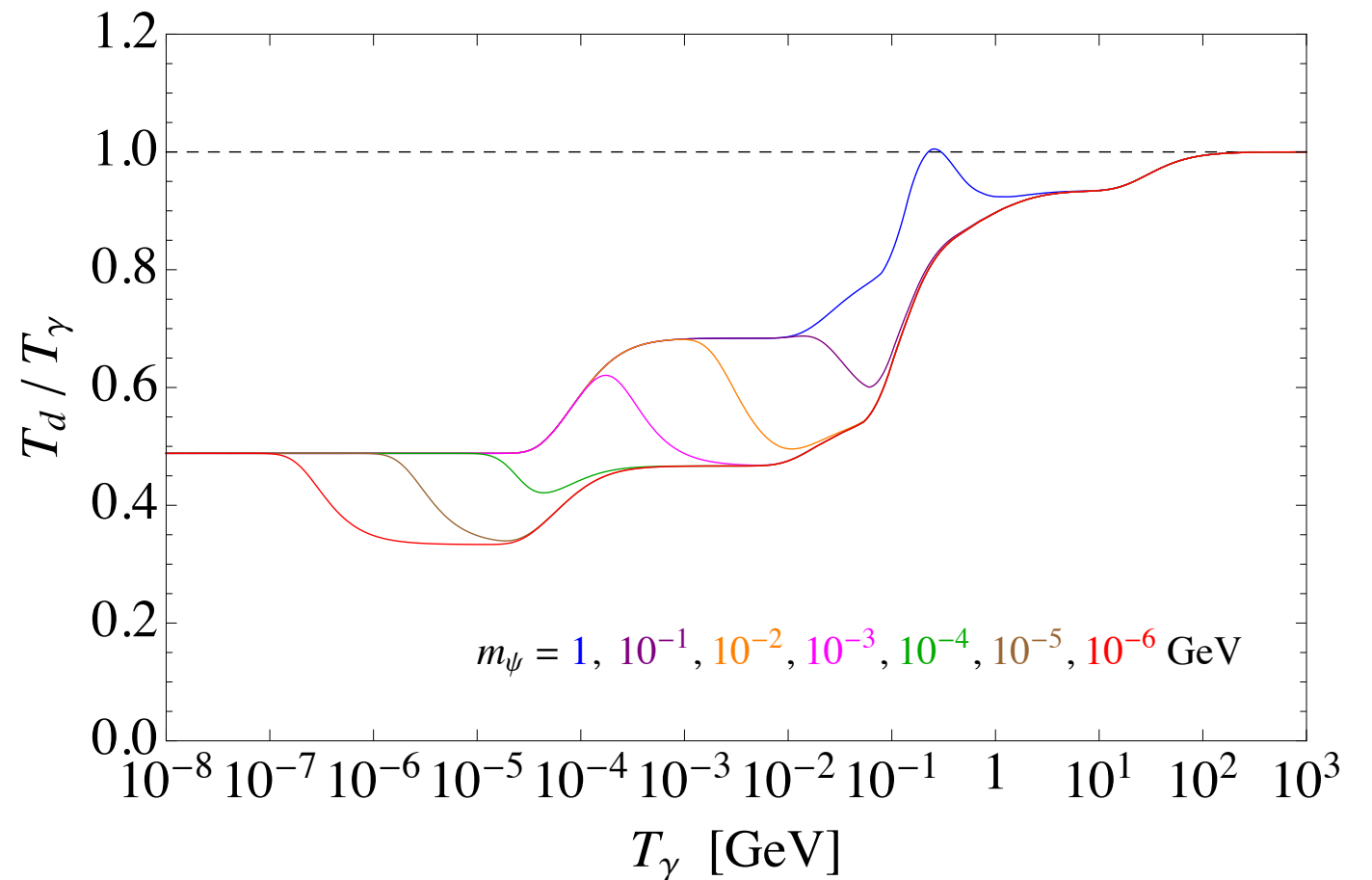
Viel et al. **astro-ph/0501562**

# 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:**

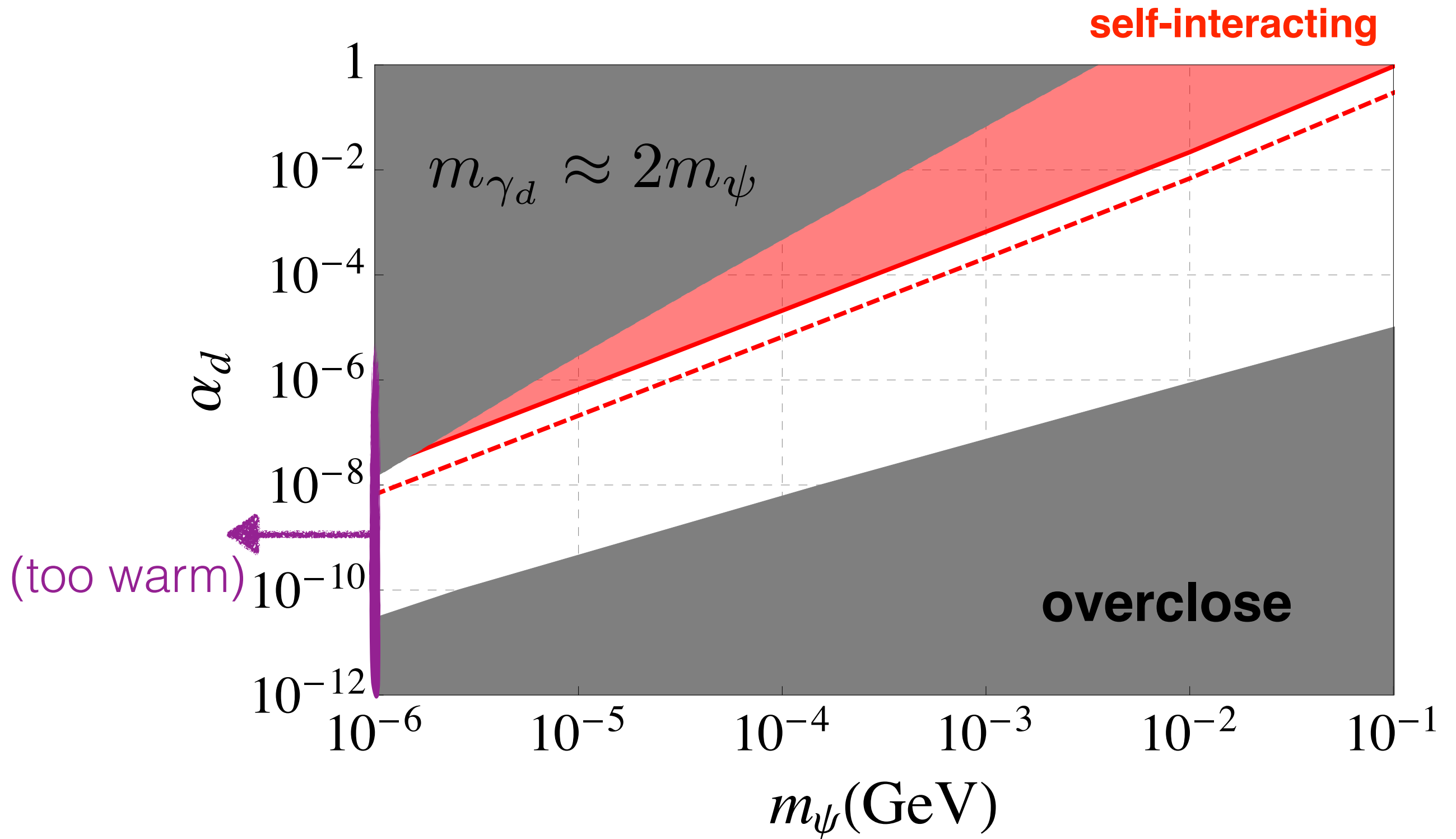
$$\Delta N_{eff} \approx 0.44 \quad (\Delta N_{eff} < 0.56)$$

**BBN:**

$$(D/H)_p$$

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

forbidden with dark radiation



# Generalized Coannihilation

NO RADIO ..... "THE FIGHT" ..... NO HOME TV

**MADISON SQ. GARDEN** | **MON. MARCH 8<sup>TH</sup>**  
31st ST. TO 33rd STREET ON 7th AVE. AT 8:30 P.M.

15 ROUNDS FOR THE HEAVYWEIGHT CHAMPIONSHIP OF THE WORLD

**coannihilation**

PHILA. - UNDEFEATED WORLD HEAVYWEIGHT CHAMPION  
1964 OLYMPIC CHAMPION

**VS.**

**inelastic  
freezeout**

LOUISVILLE - UNDEFEATED FORMER HEAVYWEIGHT CHAMPION  
1960 OLYMPIC CHAMPION

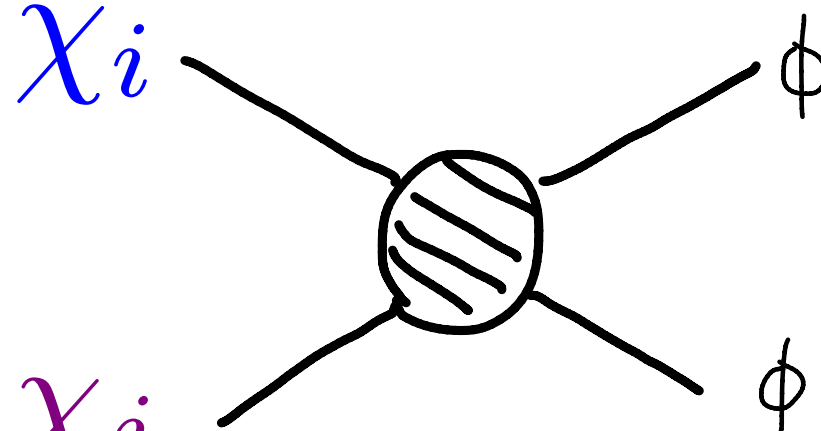
PRICES: RINGSIDE & LOGE \$150.00 • 1st PROM. \$100.00  
2nd PROM. \$75.00, \$50.00, \$40.00 • MEZZANINE \$20.00

A vintage boxing poster for a fight at Madison Square Garden. The poster features two boxers, one on the left and one on the right, both in boxing stances. The background is a solid yellow color. The text is in various colors and fonts, including red, black, and white. The top of the poster has a red banner with white text. The main title of the fight is in large black letters. The names of the boxers and their titles are in smaller black letters. The date and time of the fight are in large black letters. The word "coannihilation" is written in large red letters across the middle of the poster. The words "inelastic" and "freezeout" are written in large black letters below "coannihilation". The bottom of the poster has a red banner with white text listing the prices for different seating areas.



# coannihilation

$\chi_i \leftrightarrow \chi_j$  in equilibrium

$$\sum_{ij} \left( \begin{array}{c} \chi_i \\ \chi_j \end{array} \right) \rightarrow \phi \phi$$


$$\langle \sigma_{eff} v \rangle = \frac{\sum_{ij} w_i w_j \langle \sigma_{ij} v \rangle}{\sum_i w_i}$$

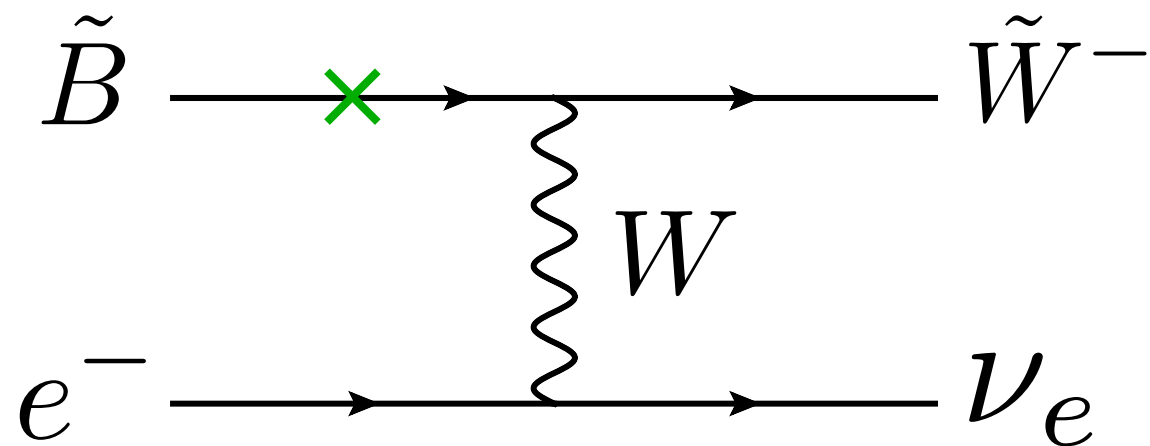
$$w_i = \left( \frac{m_i}{m_1} \right)^{3/2} e^{-x \left( \frac{m_i}{m_1} - 1 \right)}$$

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

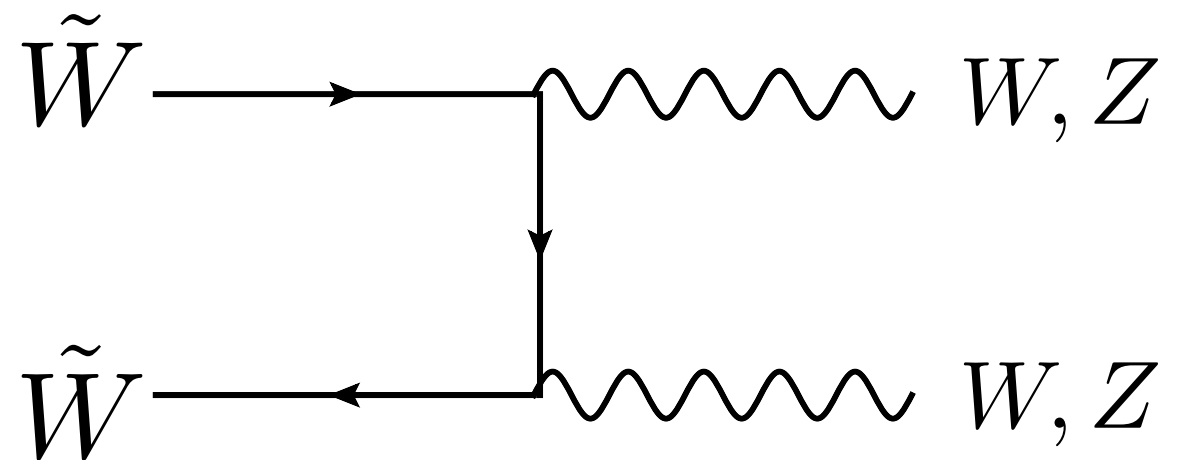
# coannihilation

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

equilibriate:



annihilate:



# example model

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

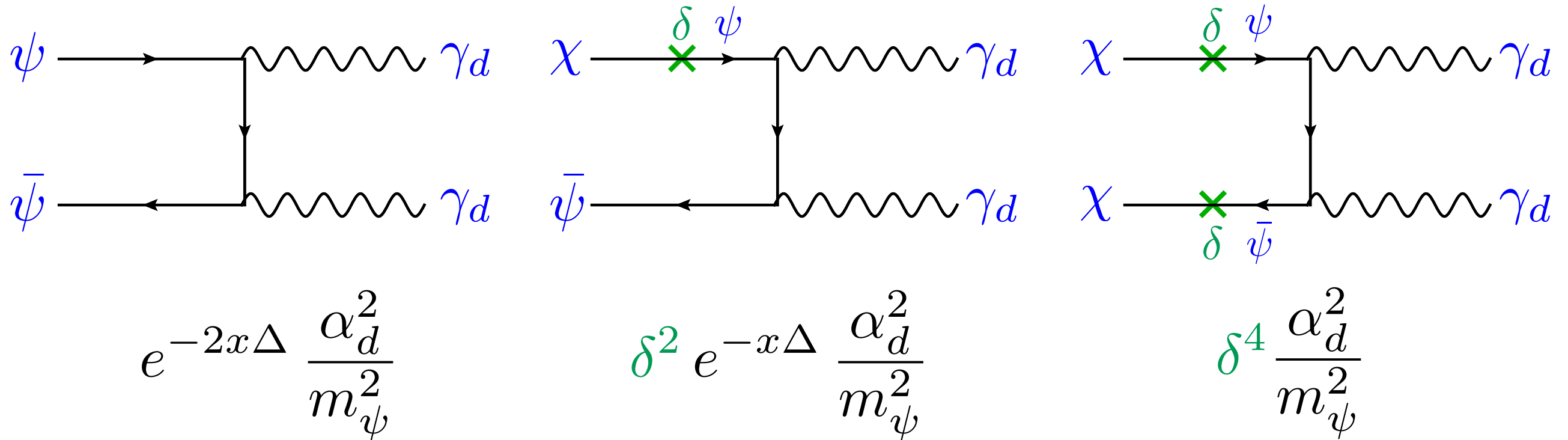
	$\chi$	$\psi$	$\phi$
$U(1)_d$	<b>0</b>	<b>+1</b>	<b>-1</b>

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

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

$$\begin{array}{c} \psi \\ \hline \hline \gamma_d \end{array} \chi$$

# annihilation



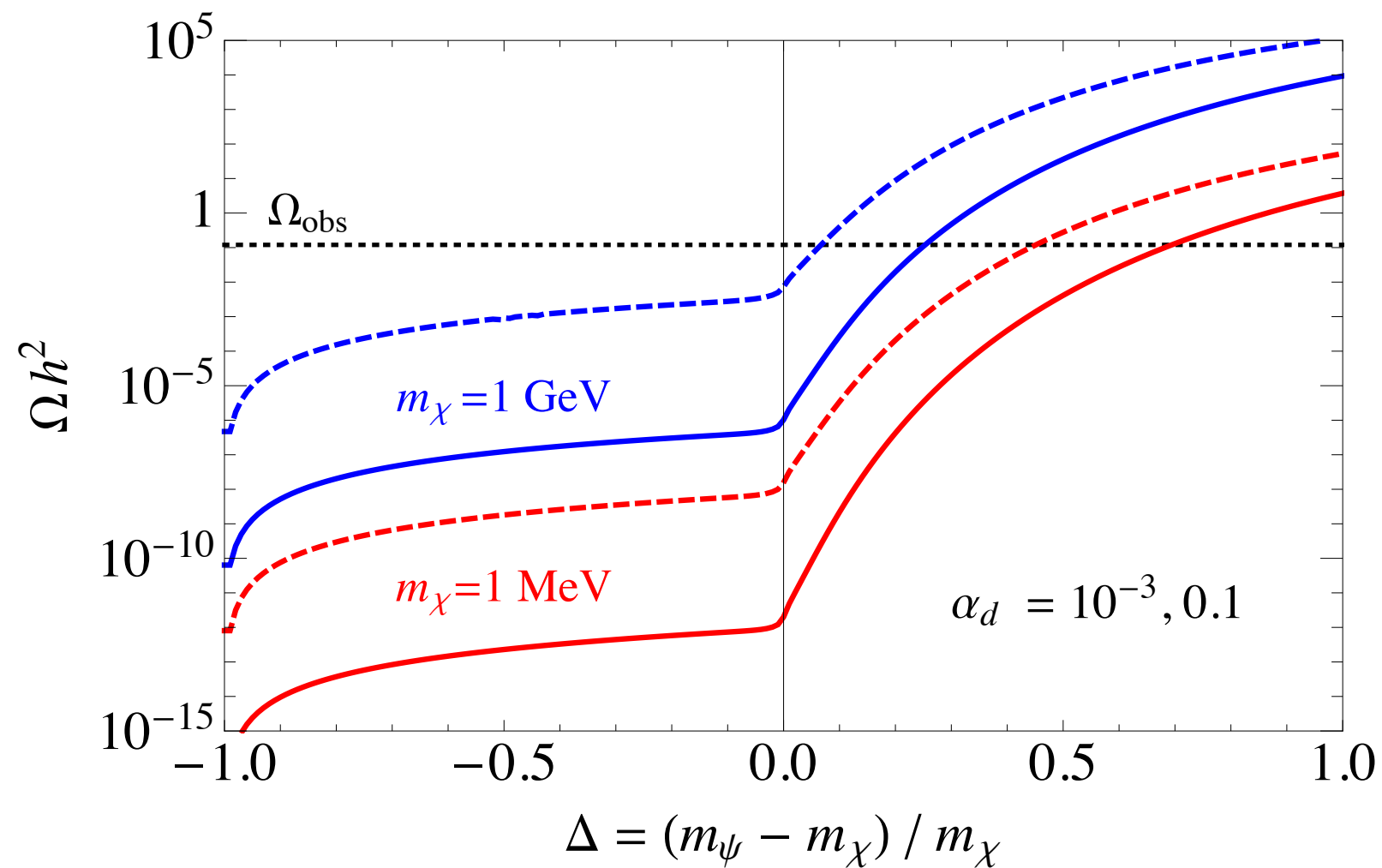
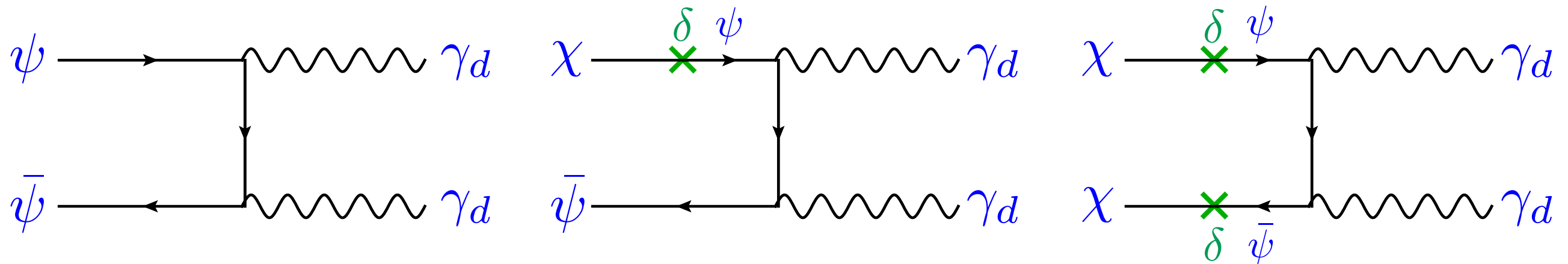
**coannihilation:**  $\delta^2 \lesssim e^{-x_f \Delta}$

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

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

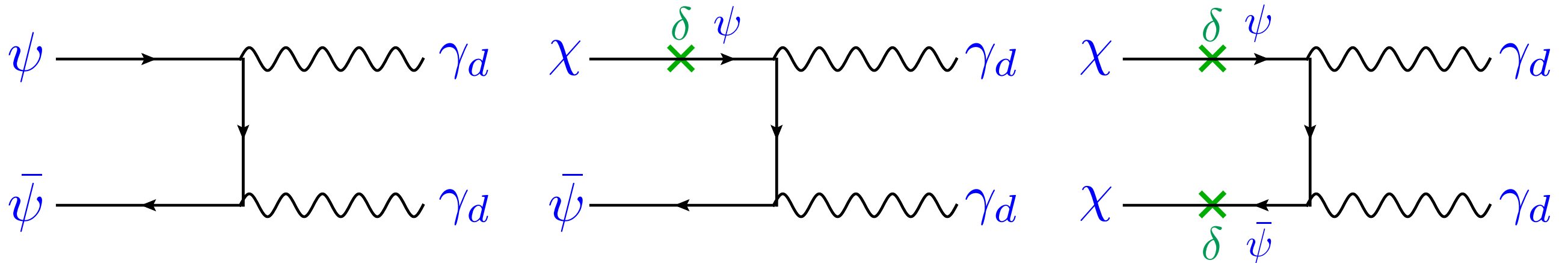
$$\delta \equiv \frac{y \langle \phi \rangle}{m_\chi}$$

# annihilation

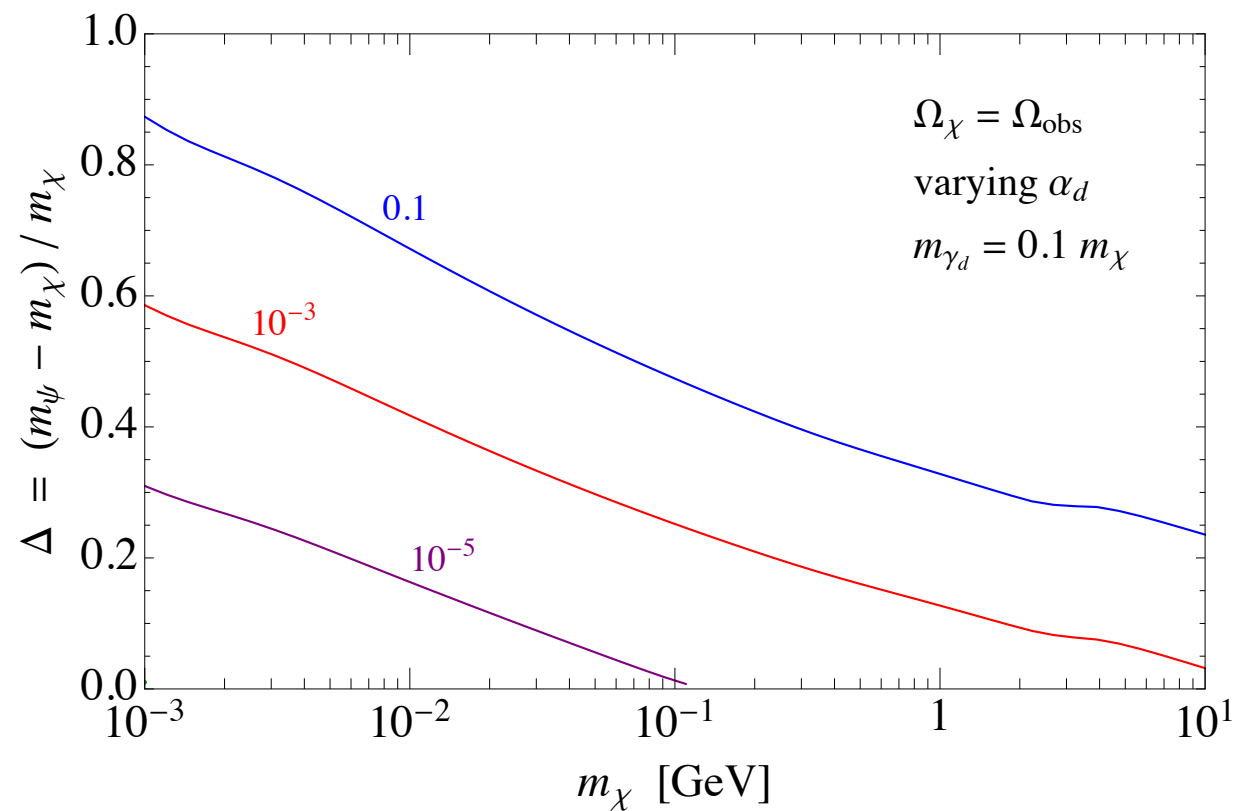


$$\delta = \frac{y \langle \phi \rangle}{m_\chi} = 10^{-5}$$

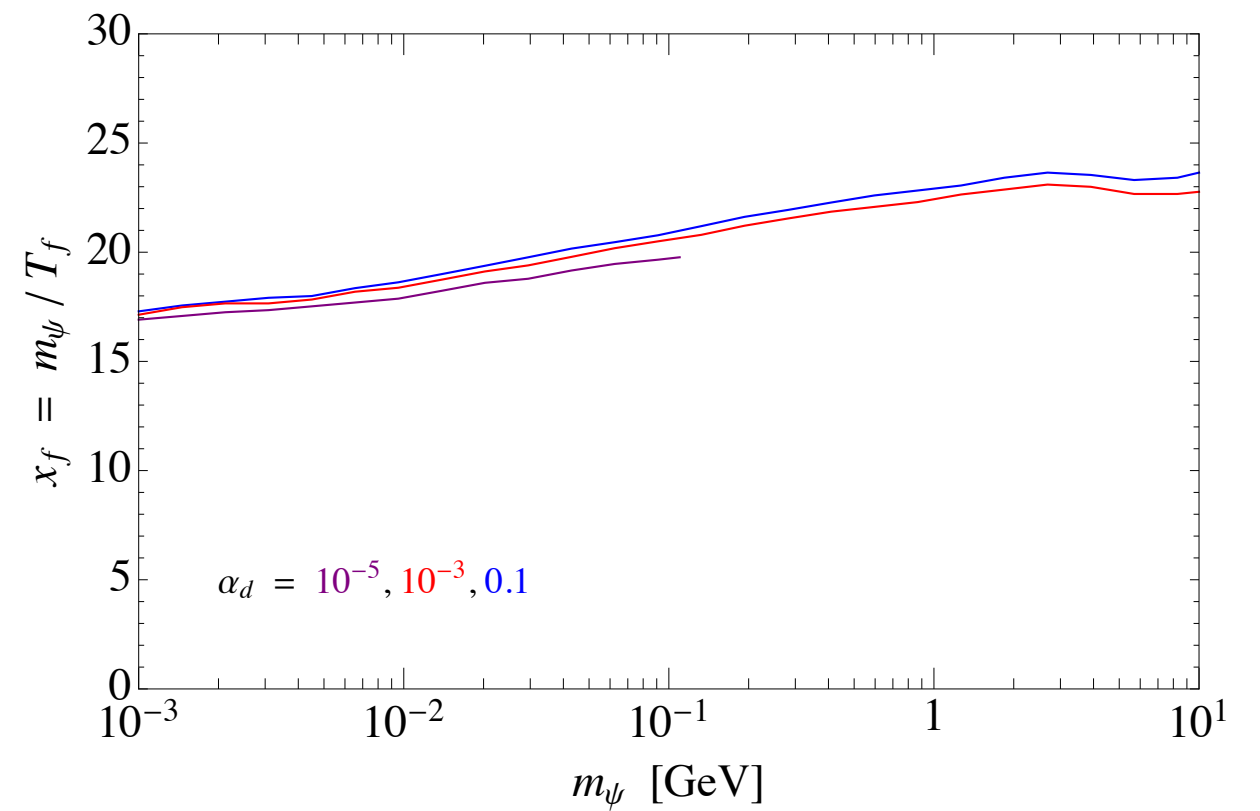
# annihilation



splitting



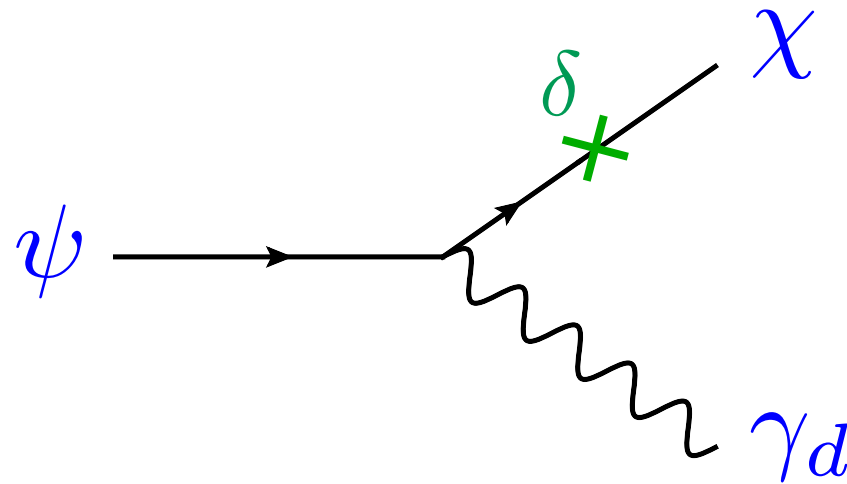
freeze-out temperature



# $\chi/\psi$ equilibrium

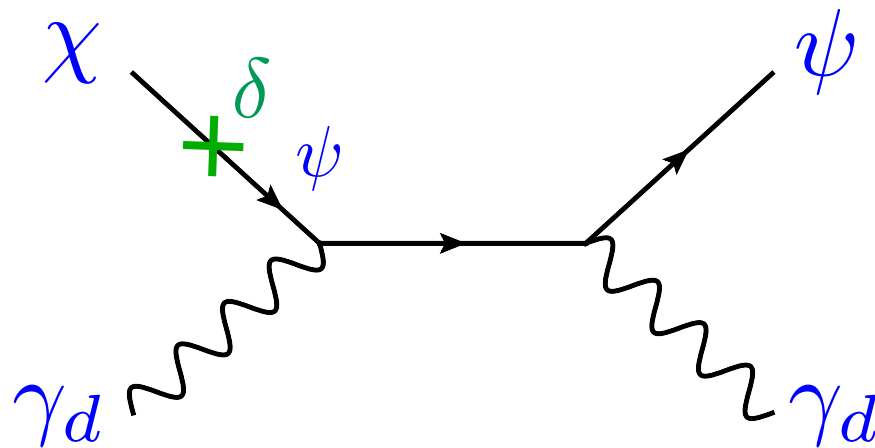
decay:

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



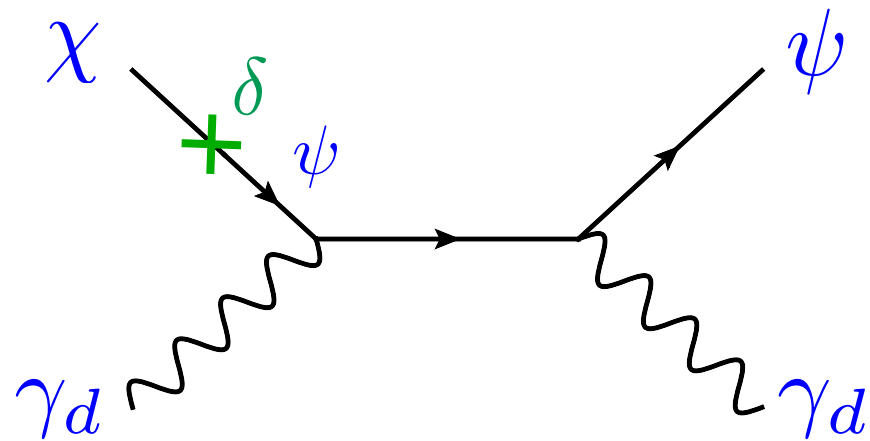
inelastic scattering:

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



# generalized coannihilation

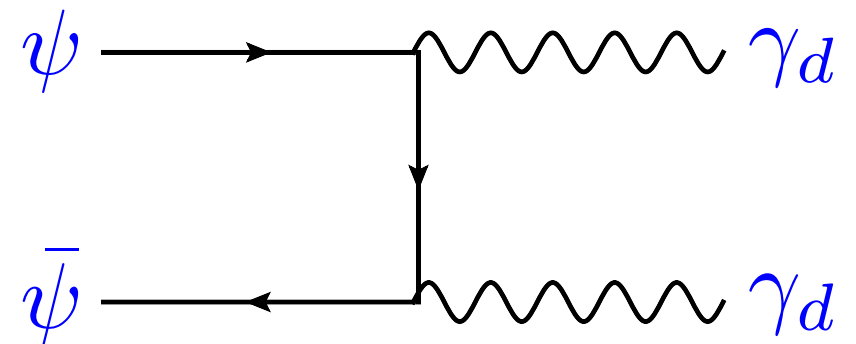
inelastic freezeout



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

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

coannihilation



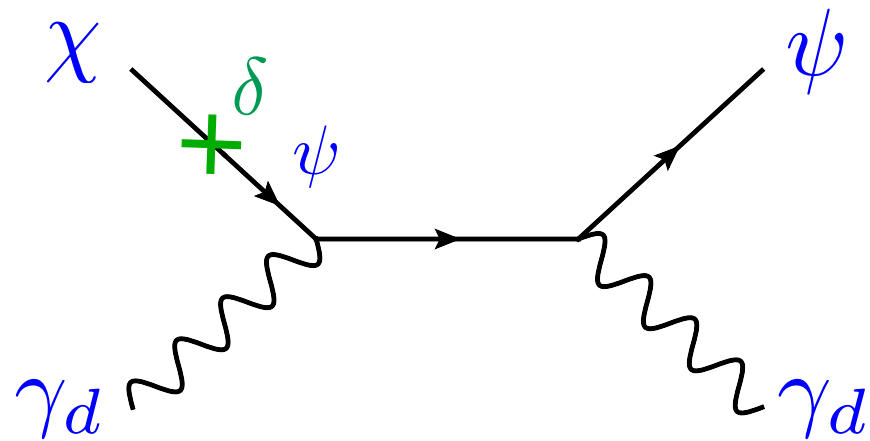
$$n_\psi^{eq} \langle \sigma_{eff} v \rangle \sim e^{-(1+3\Delta)x} \frac{\alpha_d^2}{m_\psi^2}$$

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

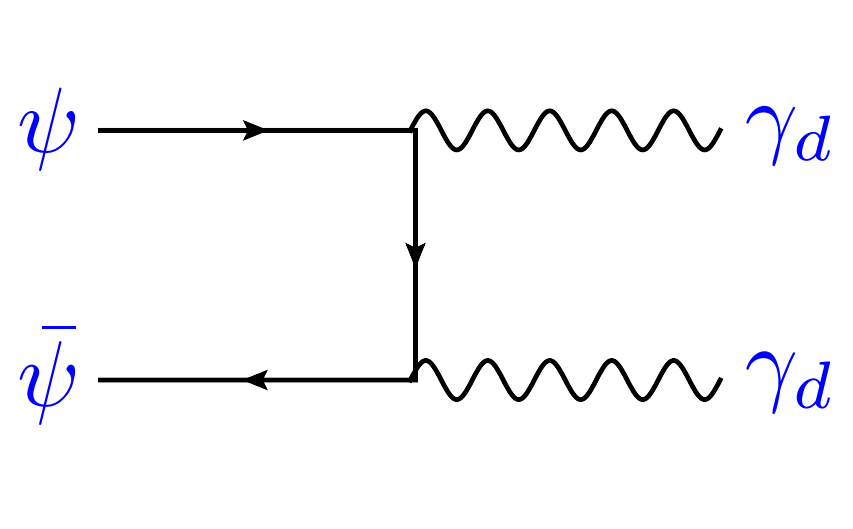


# generalized coannihilation

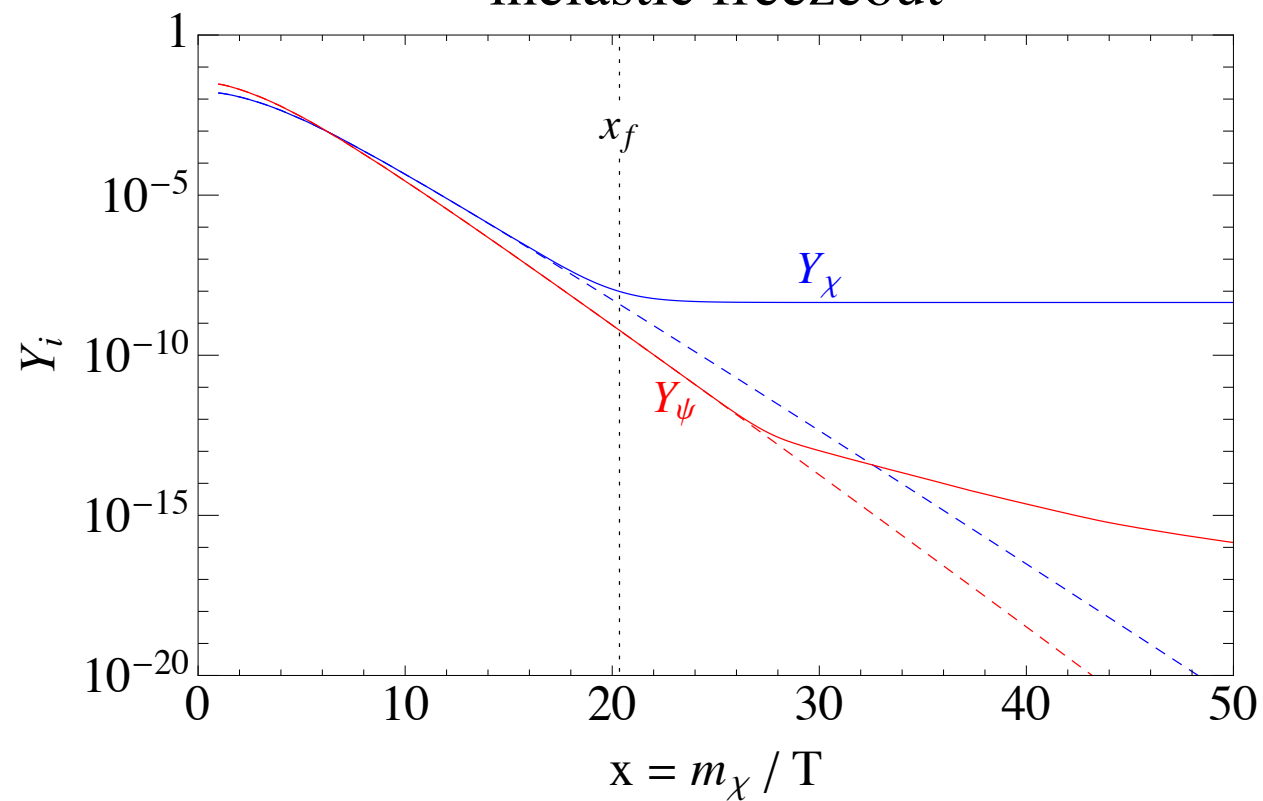
inelastic freezeout



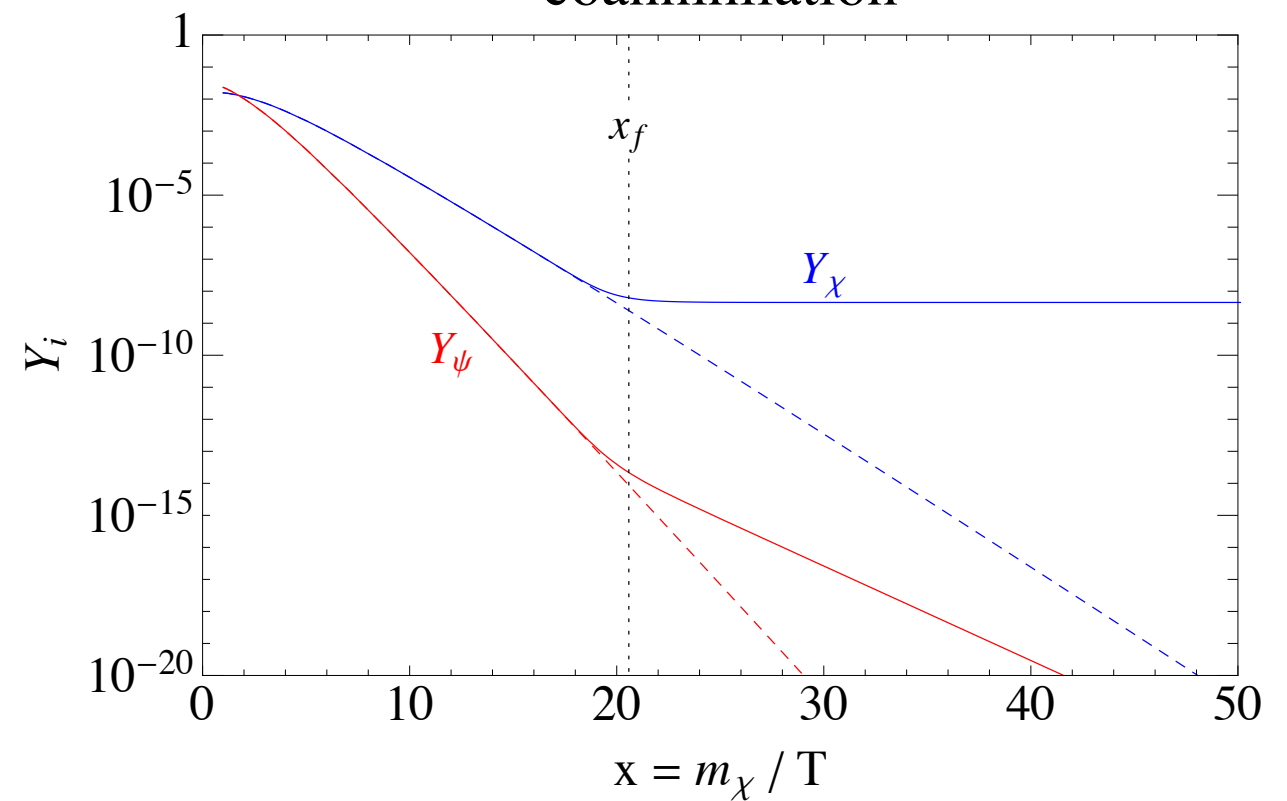
coannihilation



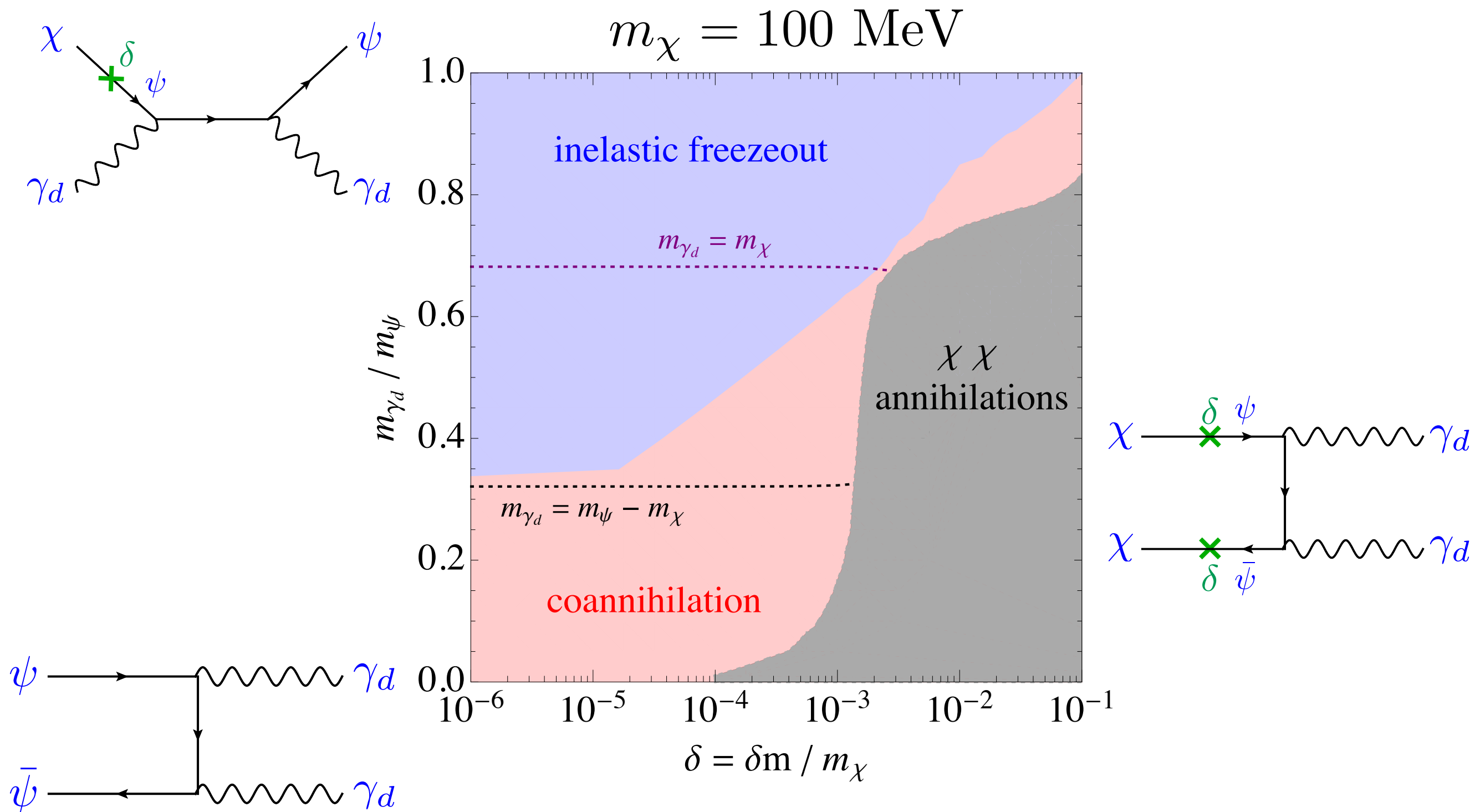
inelastic freezeout



coannihilation



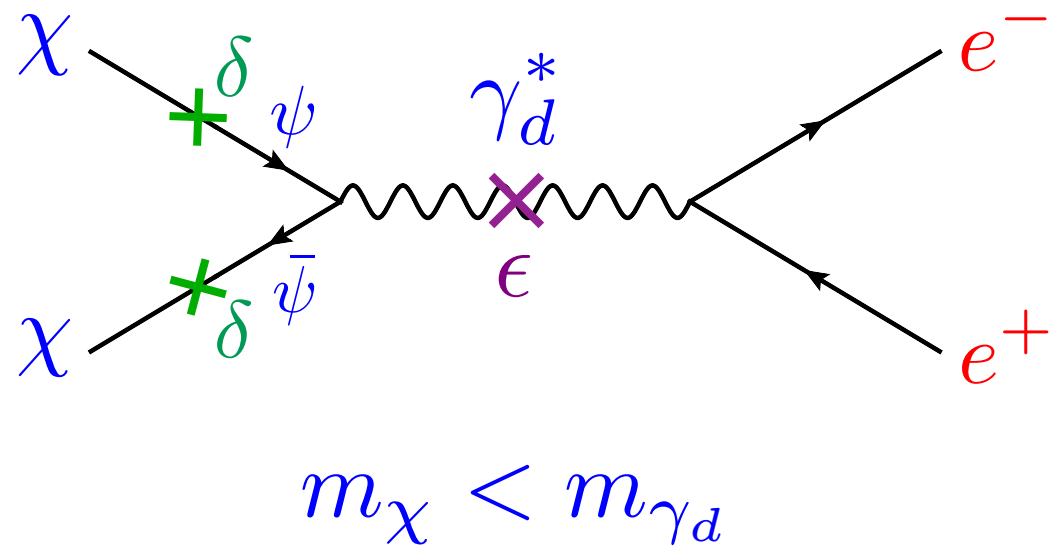
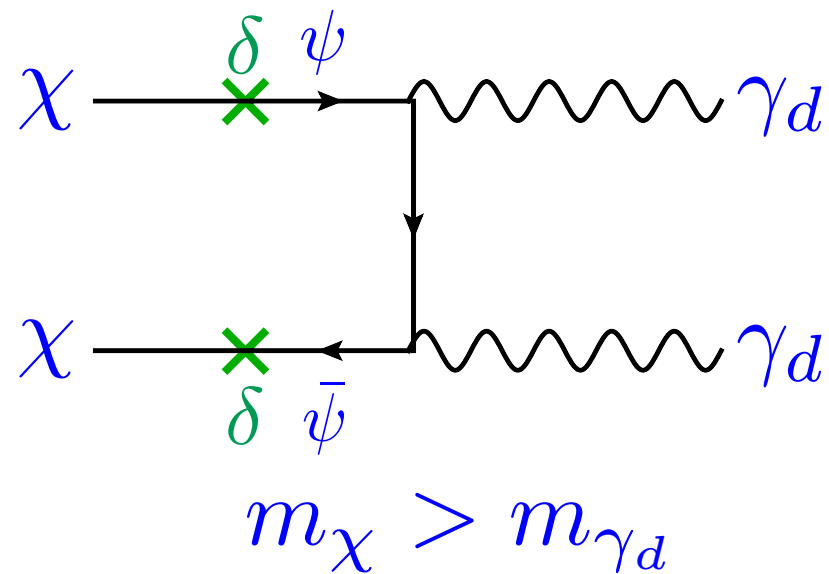
# generalized coannihilation



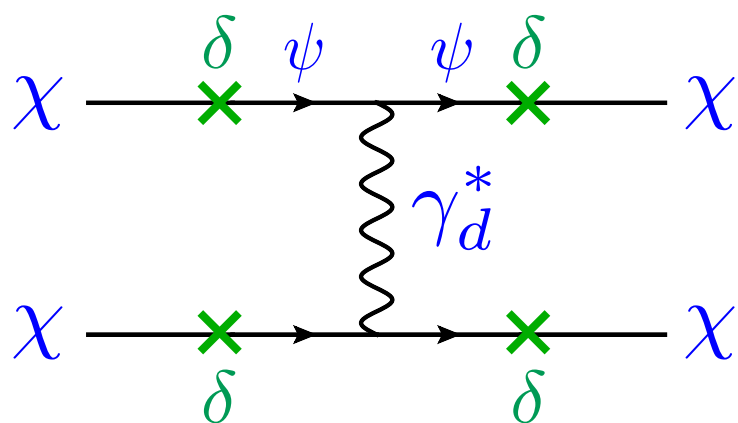
# pheno

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

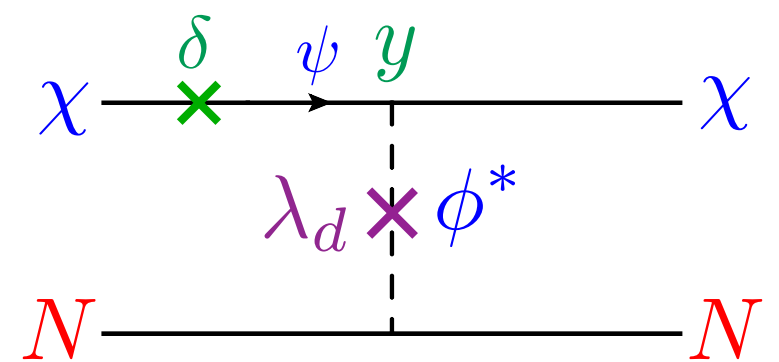
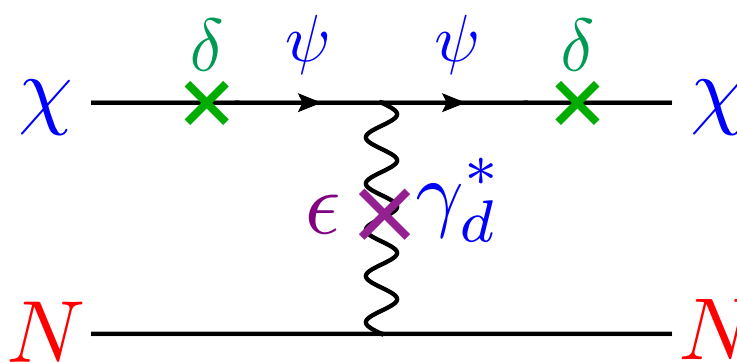
**indirect detection:**



**self interaction:**



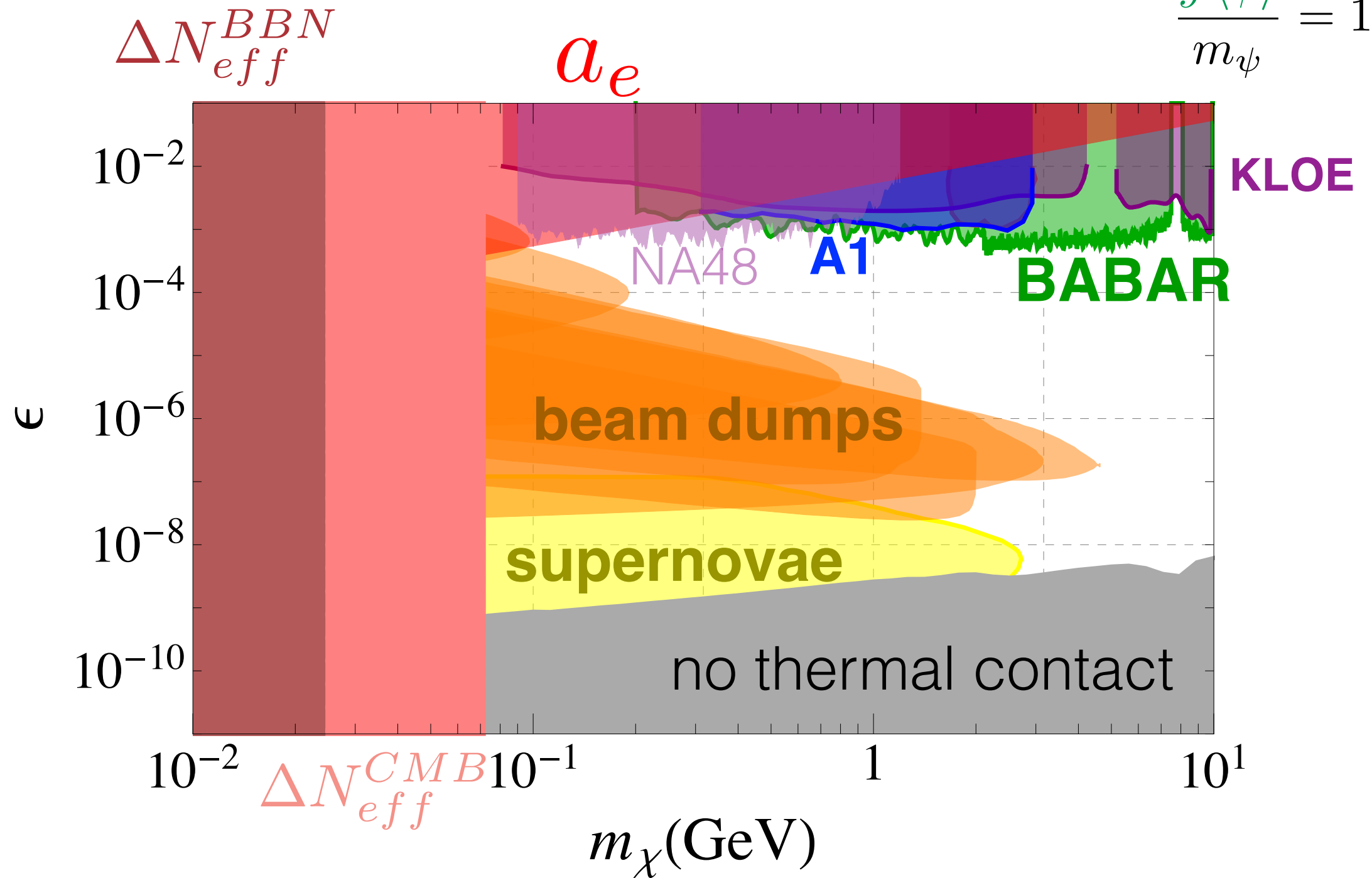
**direct detection:**



# constraints

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

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

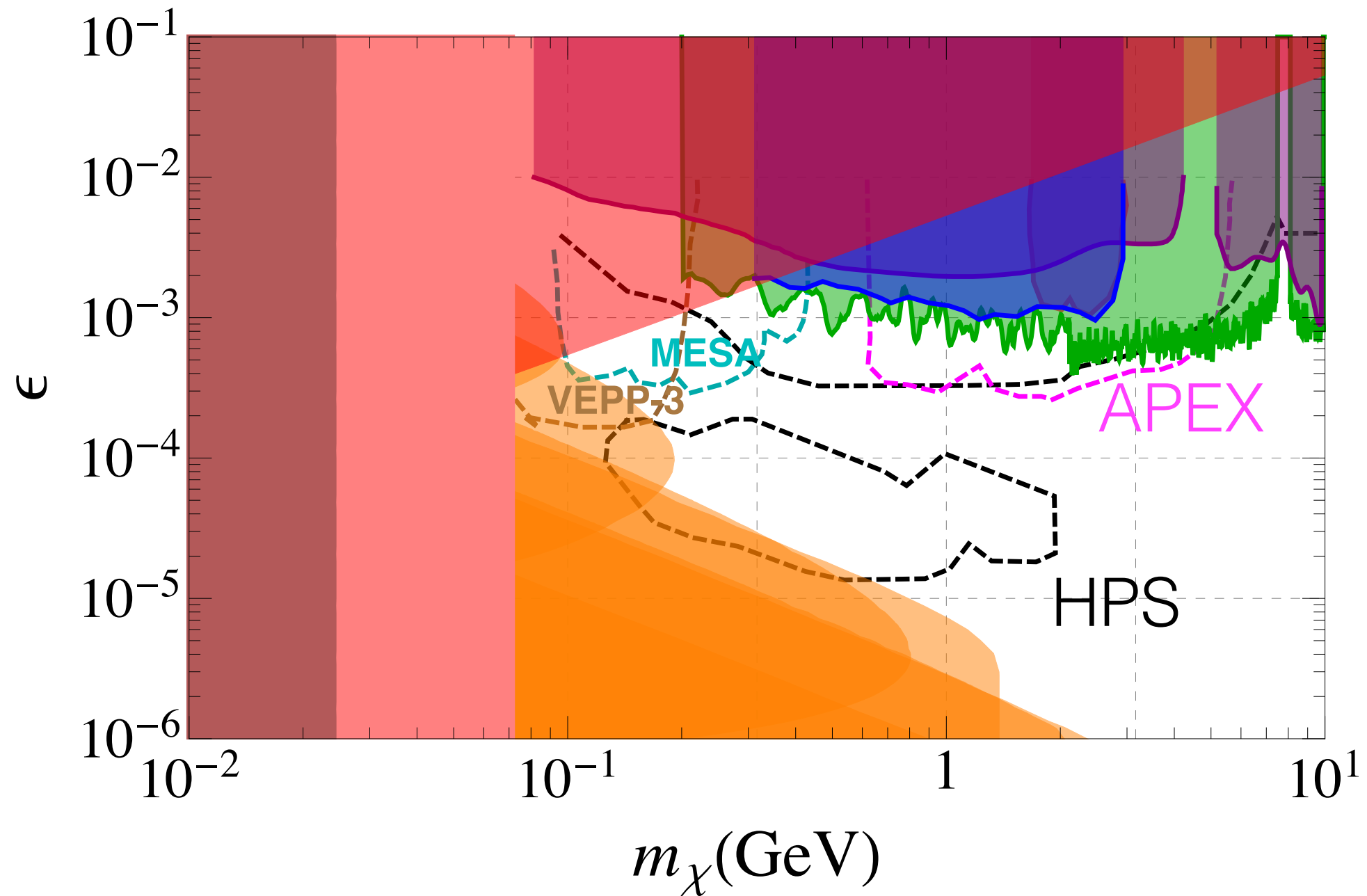


- Babar, **1406.2980**
- Snowmass, **1311.0029**

# 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, ...