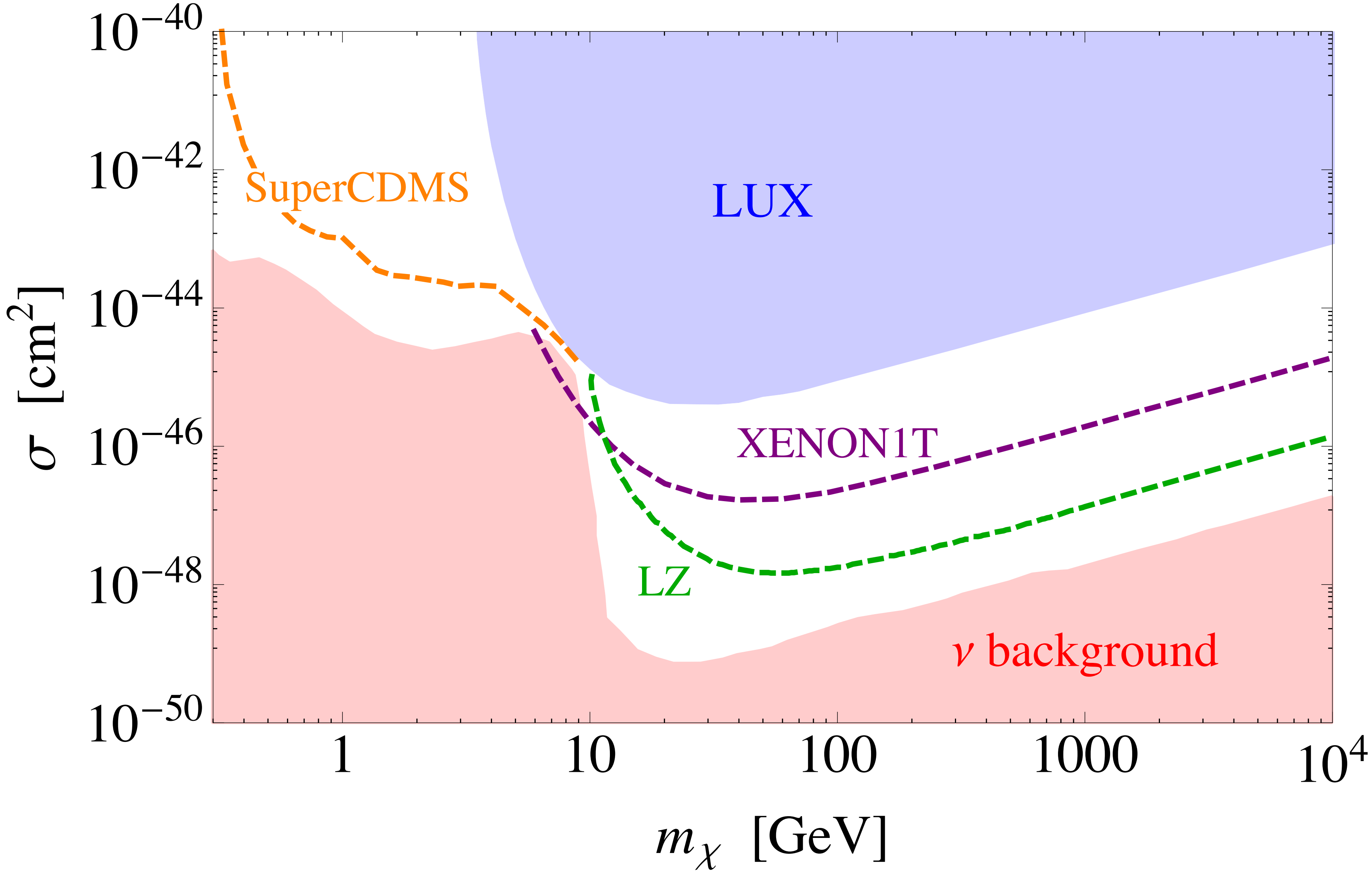
Dark Sectors with a Mass Gap

Josh Ruderman (NYU)
@Rutgers 5/17/2016

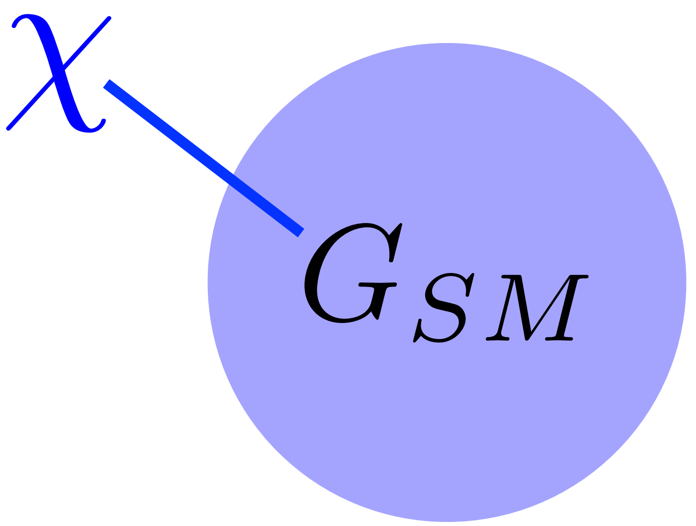
- Raffaele D'Agnolo, JTR, **1505.07107**
- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Towards the Neutrino Floor

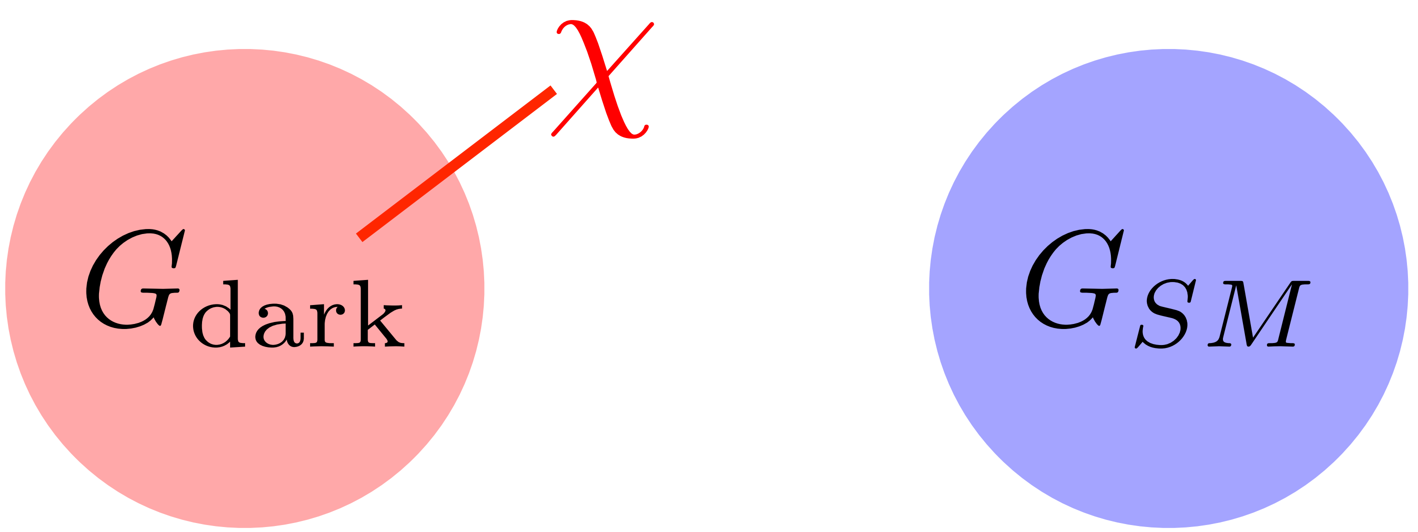


- XENON1T, **1512.07501**
- Snowmass, **1310.8327**

Weakly Interacting Dark Matter

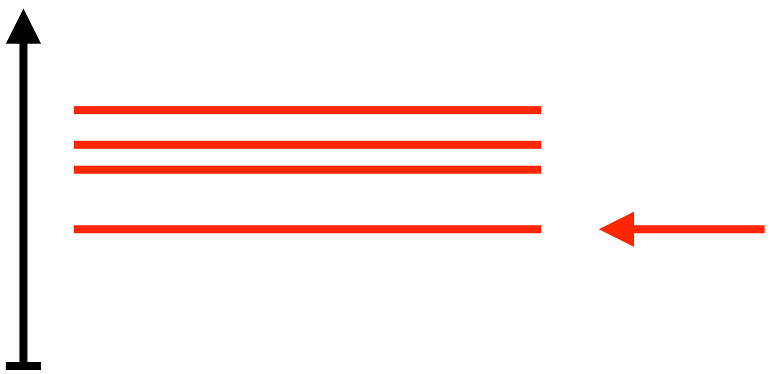


Hidden Sector Dark Matter



goal: explore possible cosmologies for thermal relics in hidden sectors

Gapped Hidden Sector



LDP - Lightest Dark Particle

$$m_{LDP} > 0$$

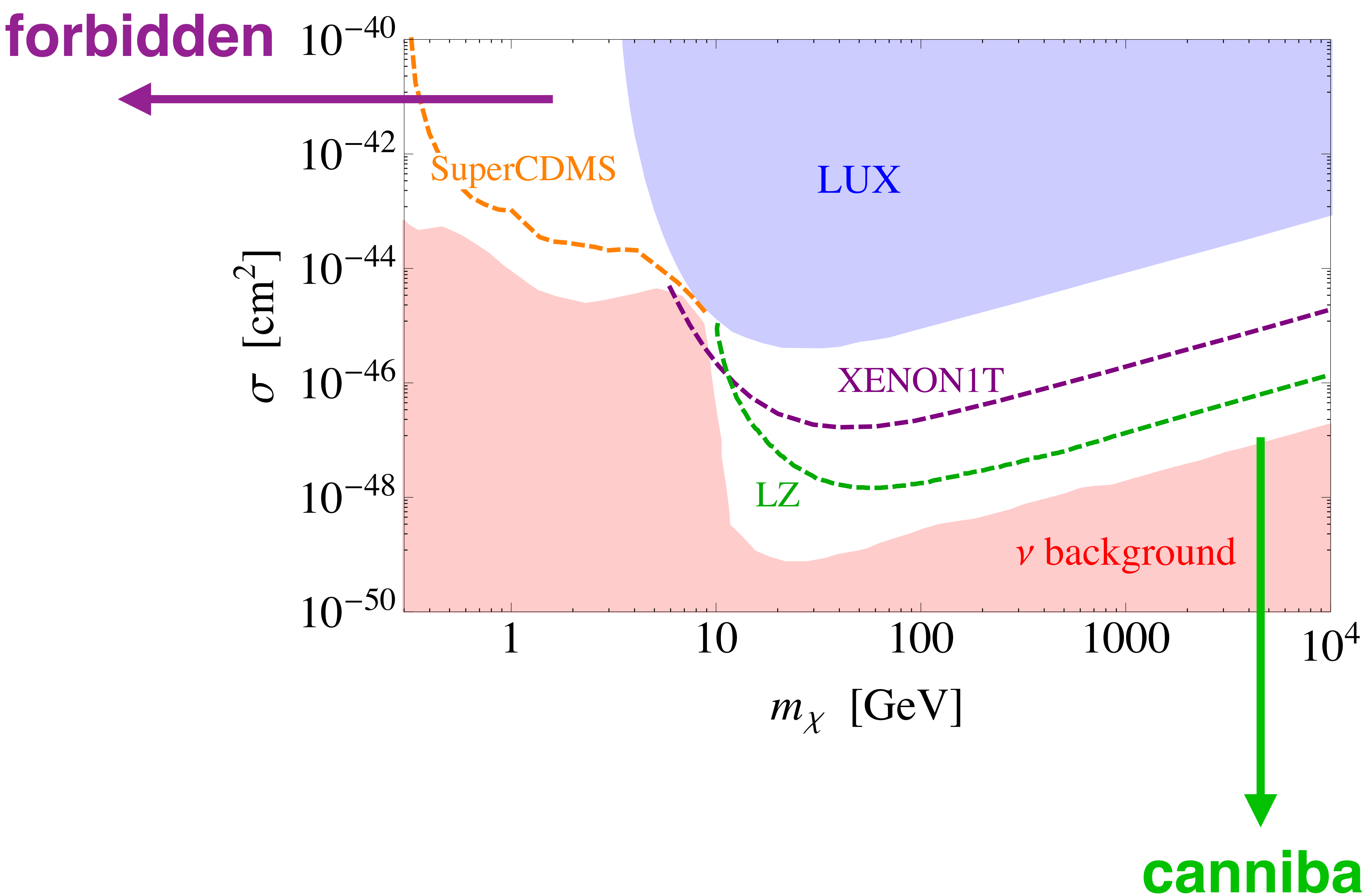
Forbidden DM

- LDP = DM

Cannibal DM

- LDP nonrelativistic at DM freezeout
- dark sector thermally decoupled from SM

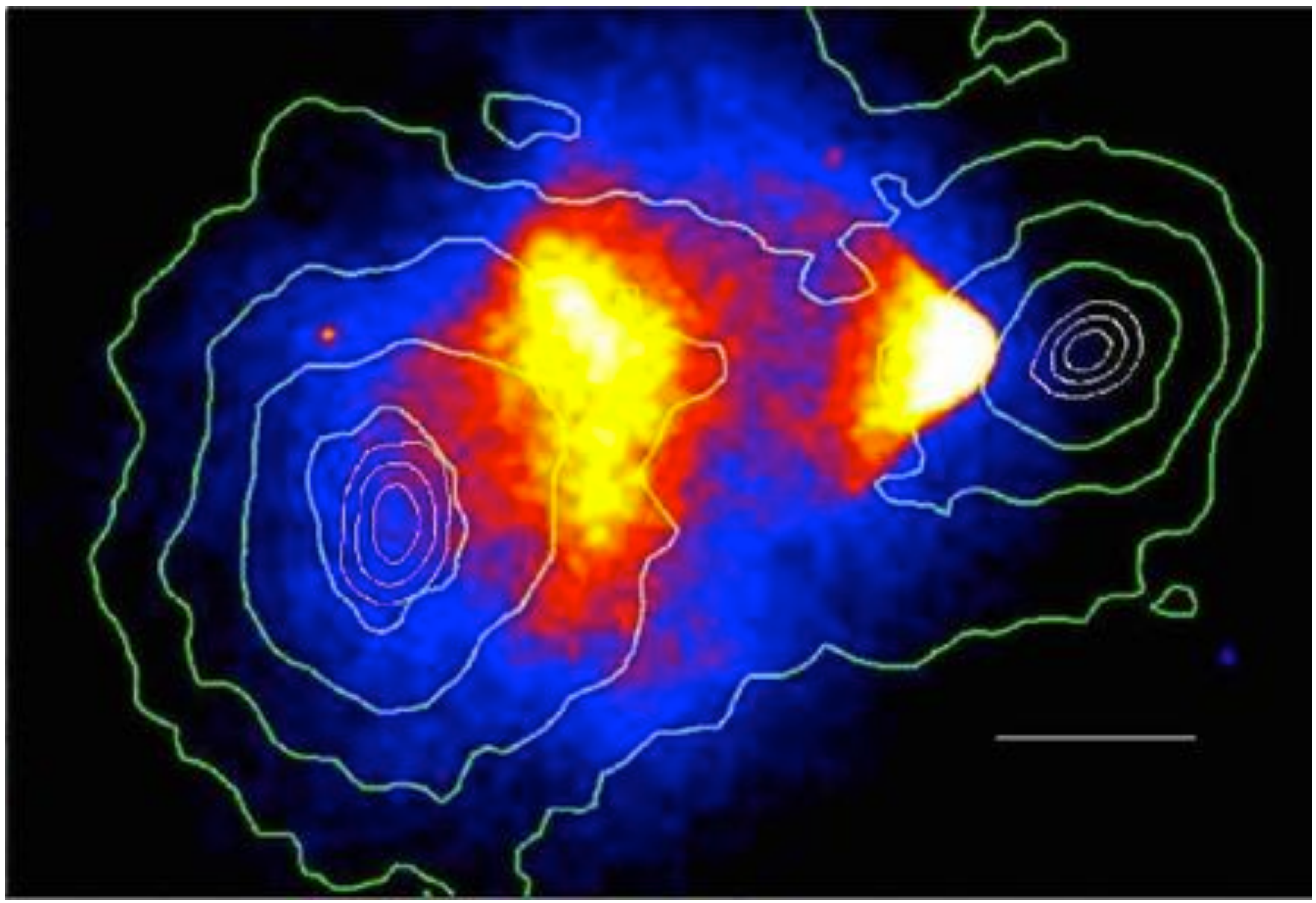
Towards the Neutrino Floor



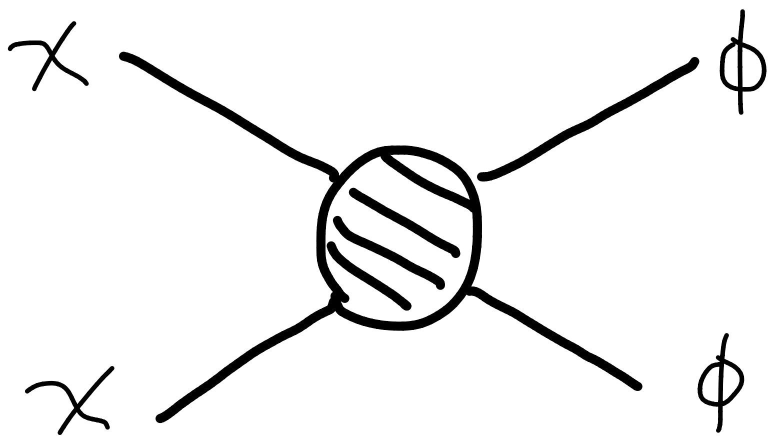
plan

1. WIMP Warmup
2. Forbidden Dark Matter
3. Cannibal Dark Matter

1. WIMP Warmup



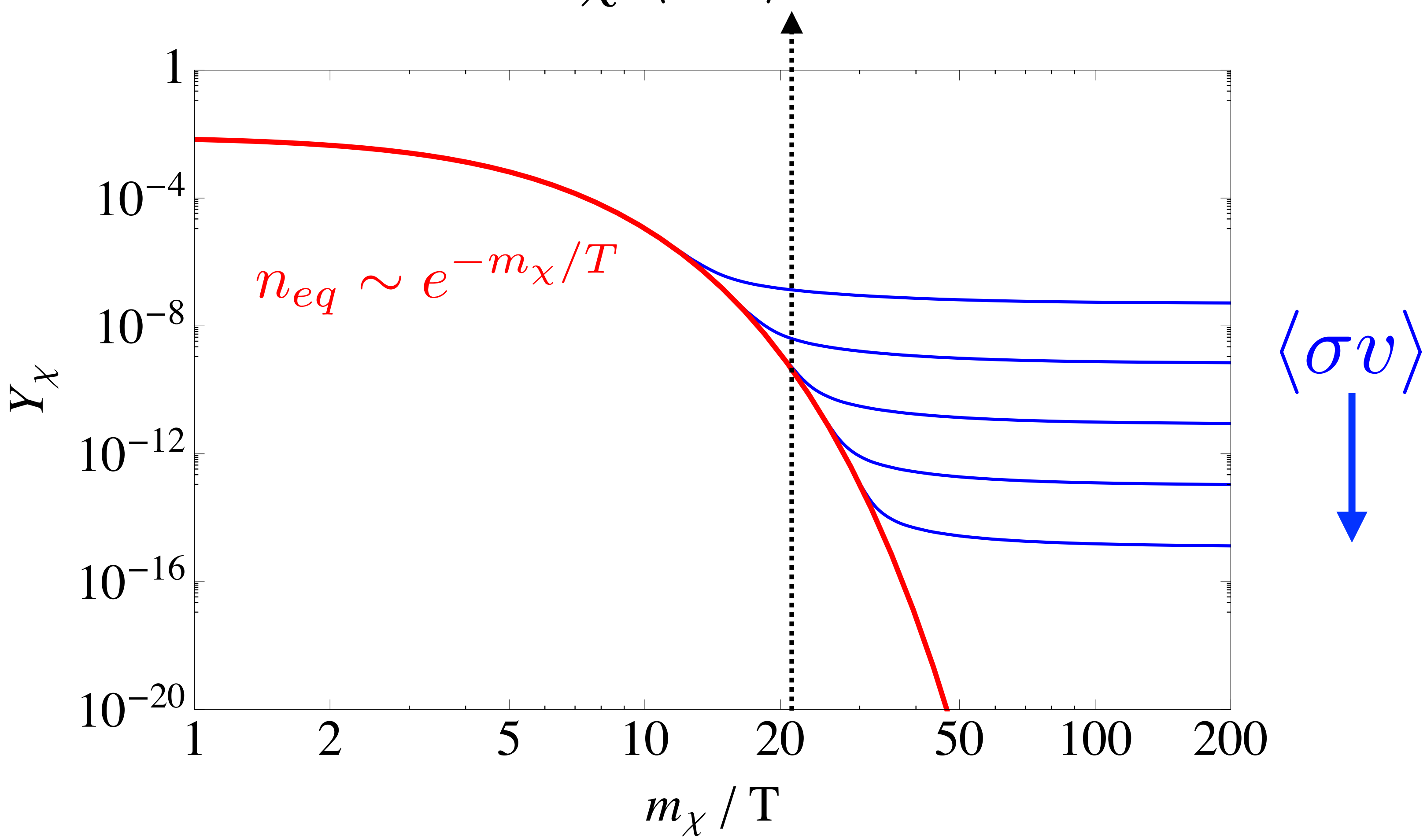
WIMP “Miracle”



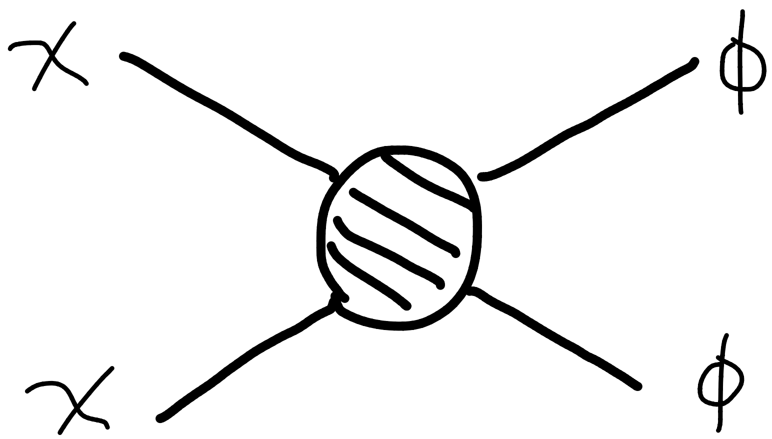
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

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

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



WIMP "Miracle"



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

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

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

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

Models of Light (Thermal) DM

$$m_{DM} \ll m_h$$

Models of Light (Thermal) DM

1. weakly coupled

- Pospelov, Ritz, Voloshin **0711.4866**
- Feng, Kumar **0803.4196**

$$\langle \sigma v \rangle \sim \frac{\alpha_d^2}{m_\chi^2} \qquad \alpha_d \ll 1$$

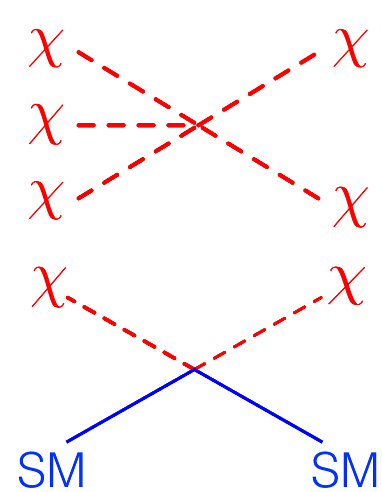
2. asymmetric

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

$$m_\chi \approx 5 \text{ GeV} \left(\frac{n_B - n_{\bar{B}}}{n_\chi - n_{\bar{\chi}}} \right)$$

3. SIMPs

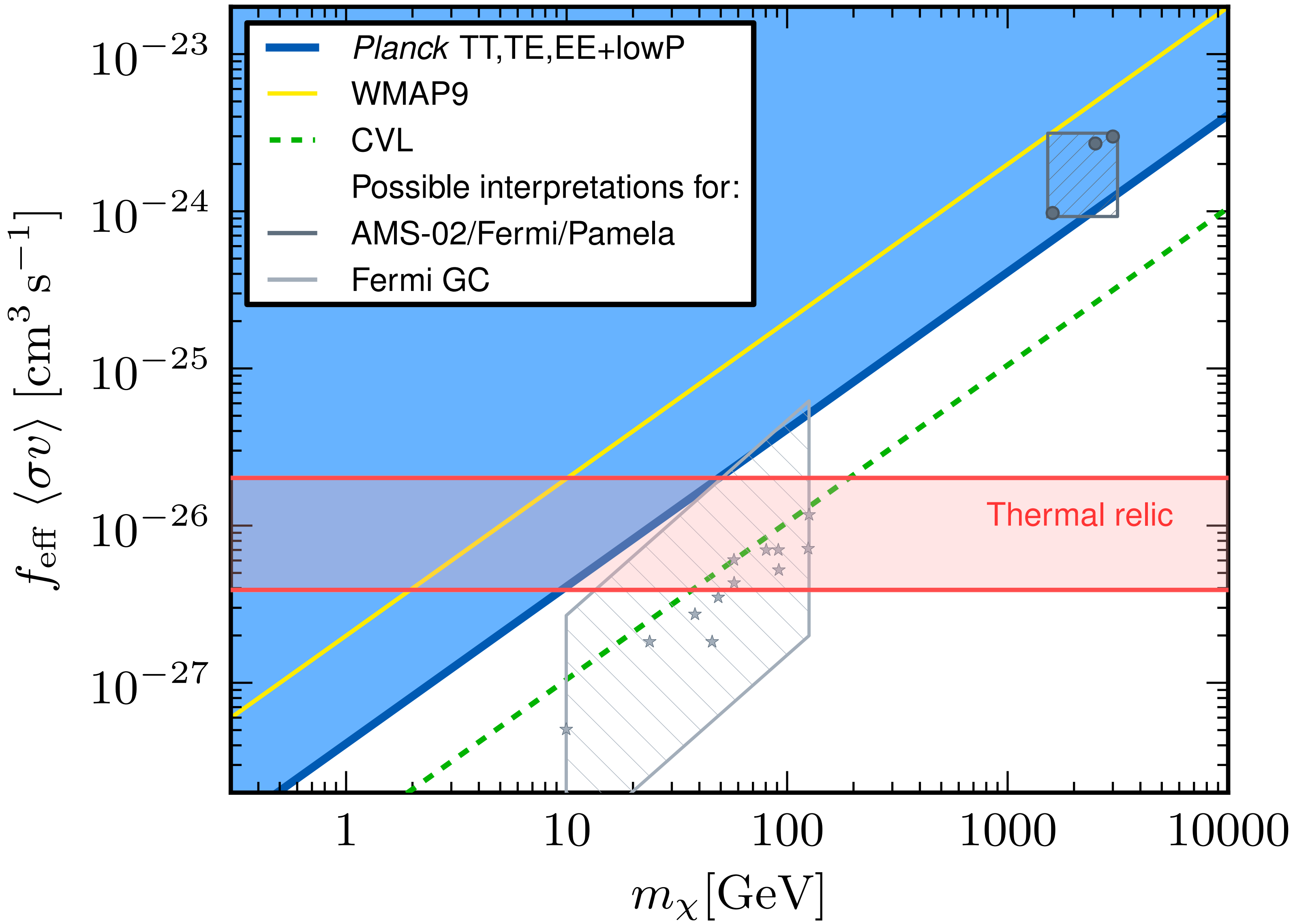
- Hochberg, Kuflik, Volansky, Wacker, **1402.5143**



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

$$\sim 100 \text{ MeV}$$

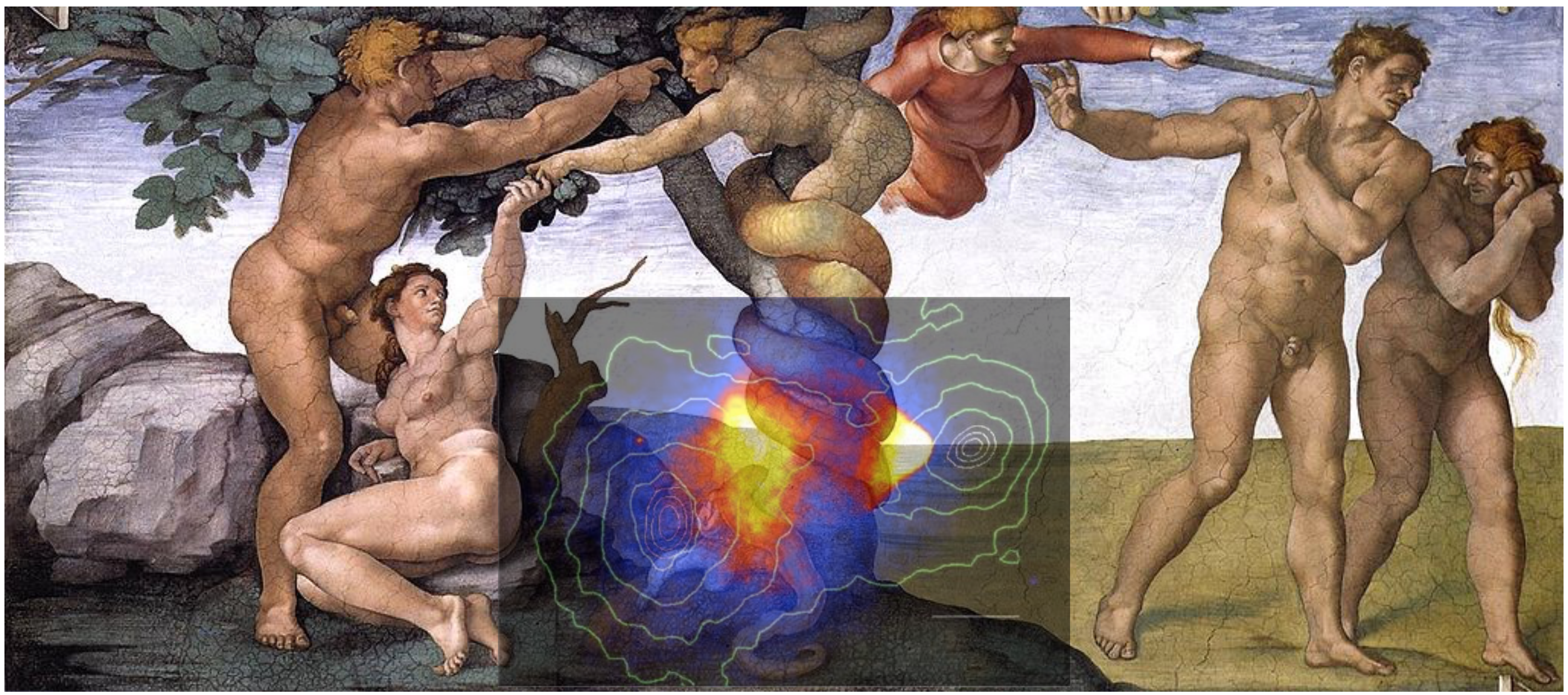
CMB limit



s-wave

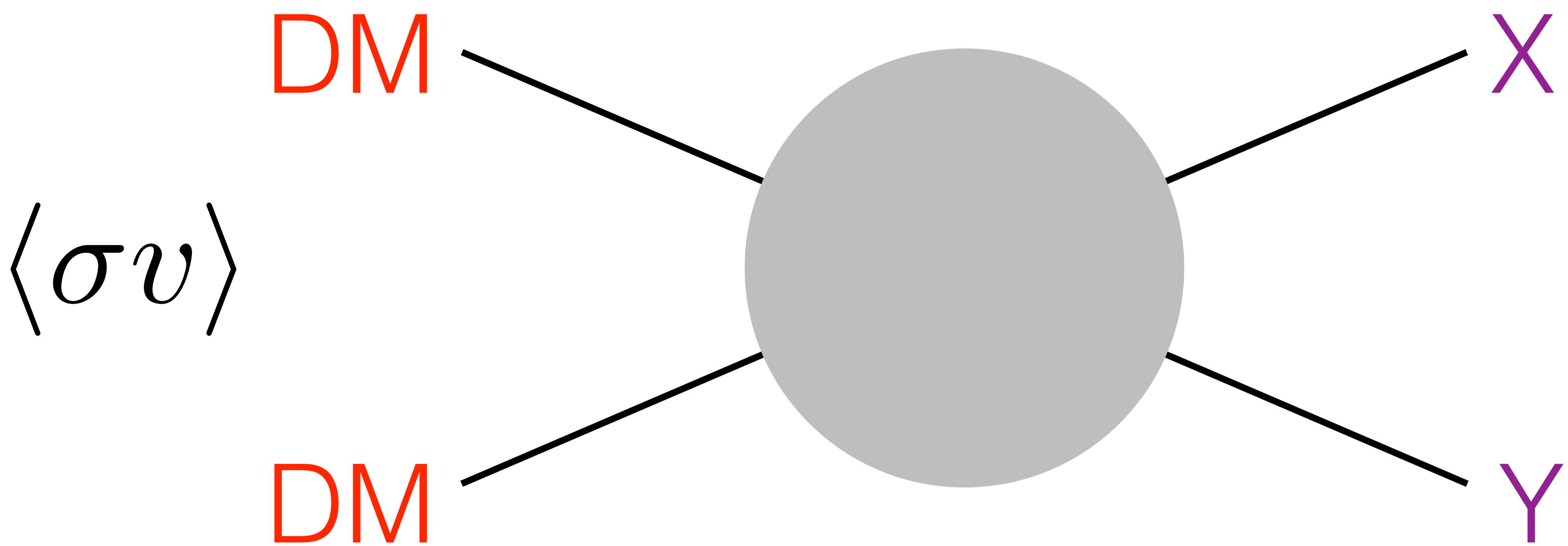
- Planck, **1502.01589**

2. Forbidden Dark Matter



- Raffaele D'Agnolo, JTR, **1505.07107**

Forbidden Dark Matter



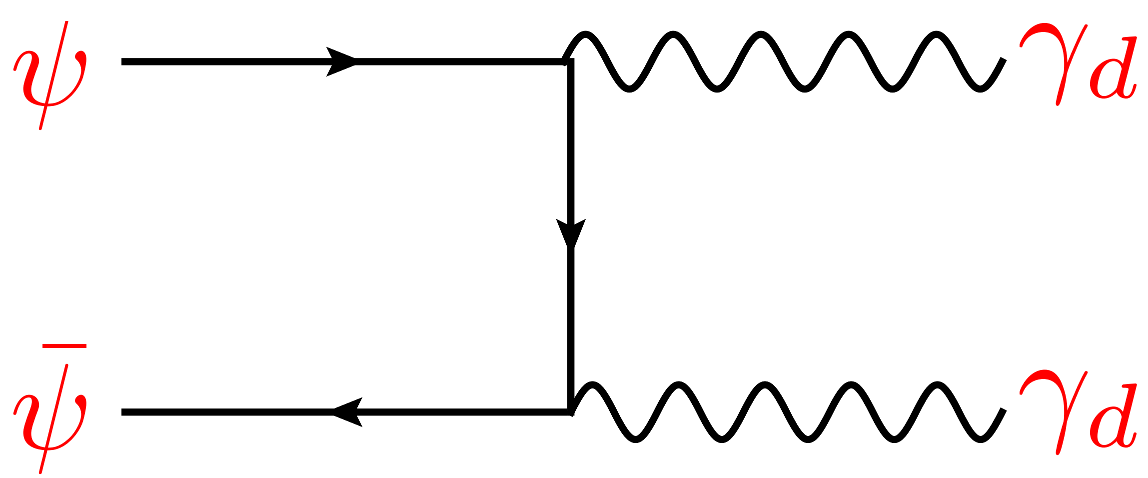
$$2m_{DM} < m_X + m_Y$$

- Griest and Seckel, **1991:** “Forbidden Channel”
- evades CMB when: $T_{\rm rec} \ll m_X + m_Y - 2m_{DM}$

example model

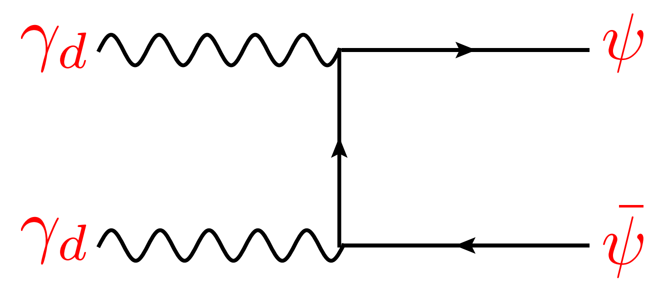
$$G_{SM} \times U(1)_d$$

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

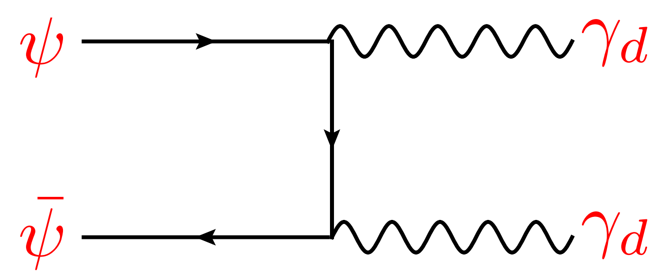


$$\langle \sigma v \rangle$$

forbidden cross section



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

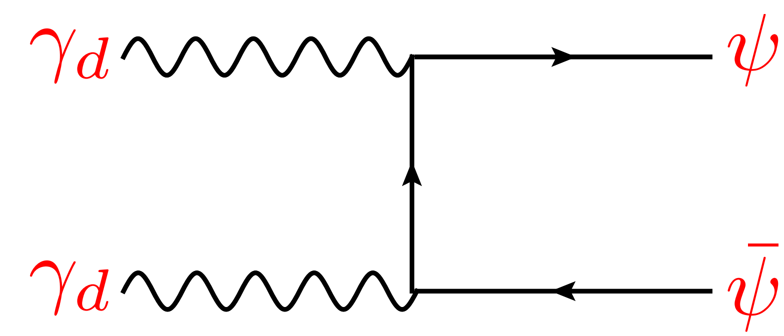


detailed balance: $(n_\psi^{\mathrm{eq}})^2 \langle \sigma v \rangle_{\psi\bar{\psi}} = (n_{\gamma_d}^{\mathrm{eq}})^2 \langle \sigma v \rangle_{\gamma_d \gamma_d}$

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

forbidden cross section

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



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

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

$$\boxed{\langle \sigma v \rangle_{\psi\bar\psi} \sim \frac{\alpha_d^2}{m_\psi^2} e^{-2x\Delta}}$$

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

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

forbidden relic density

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

Three exceptions in the calculation of relic abundances

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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
2. forbidden channels
3. annihilation near pole

forbidden relic density

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

Three exceptions in the calculation of relic abundances

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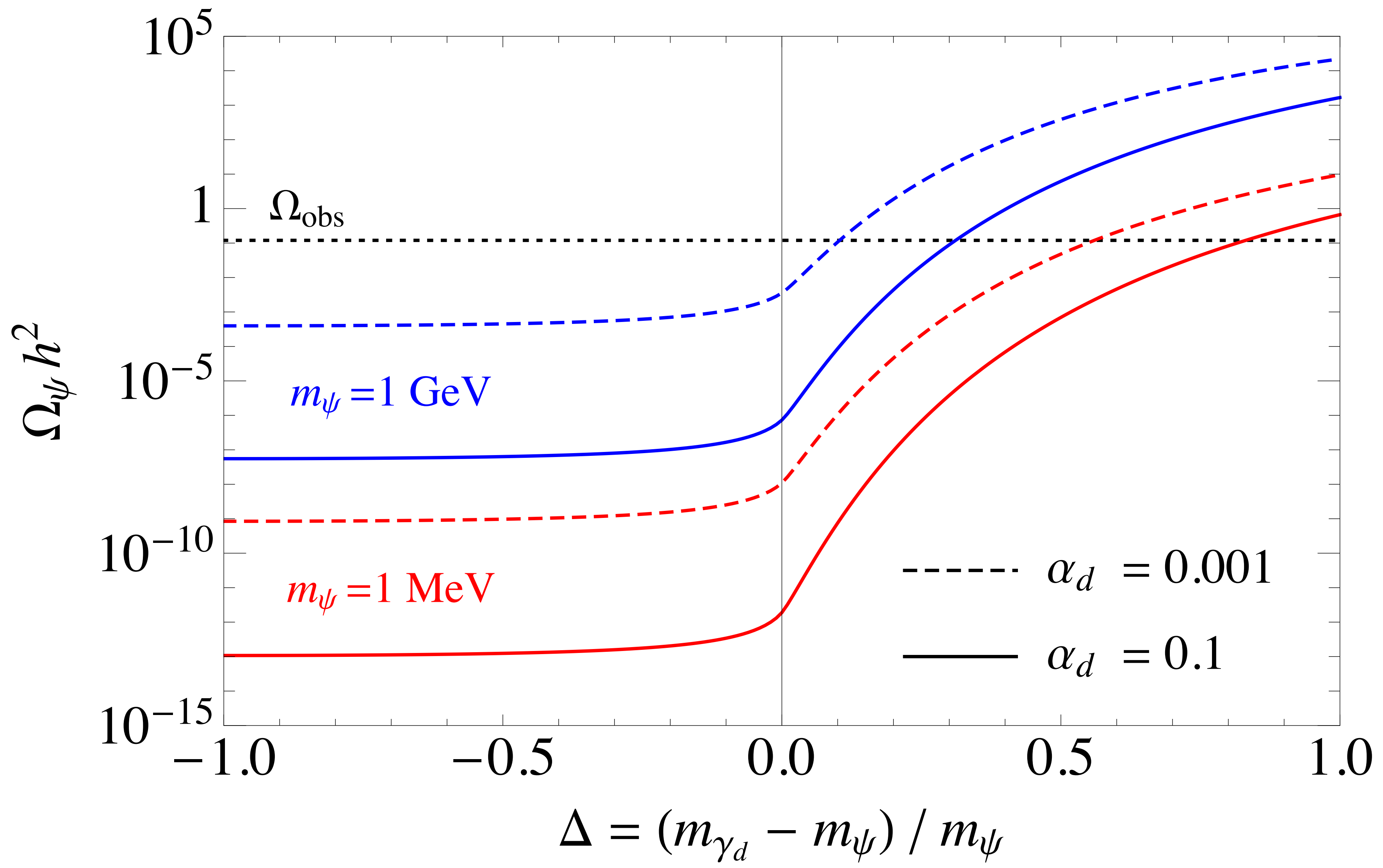
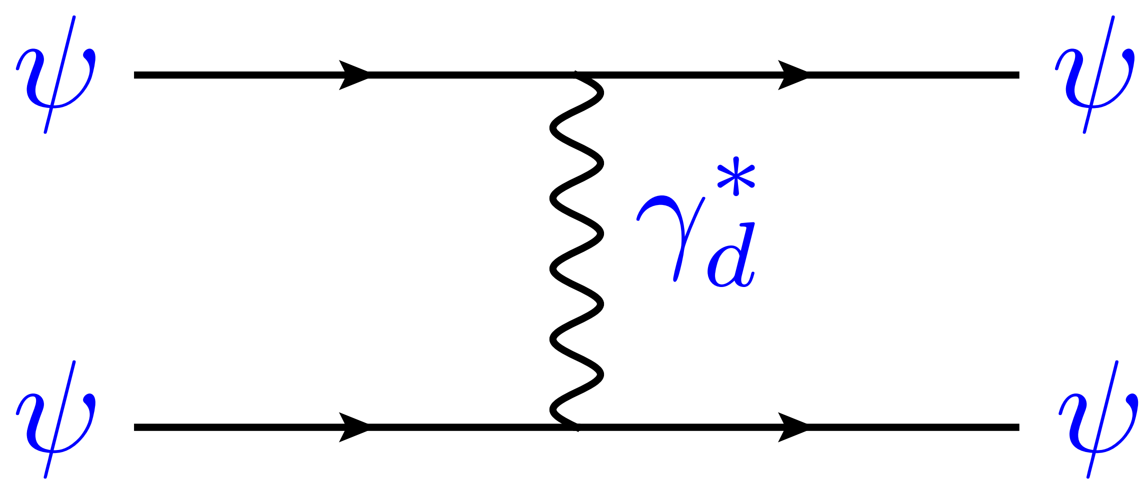
The calculation of relic abundances of elementary particles by following their annihilation and freeze-out in the early Universe has become an important and standard tool in discussing particle dark-matter candidates. We find three situations, all occurring in the literature, in which the standard methods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

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



self-interactions

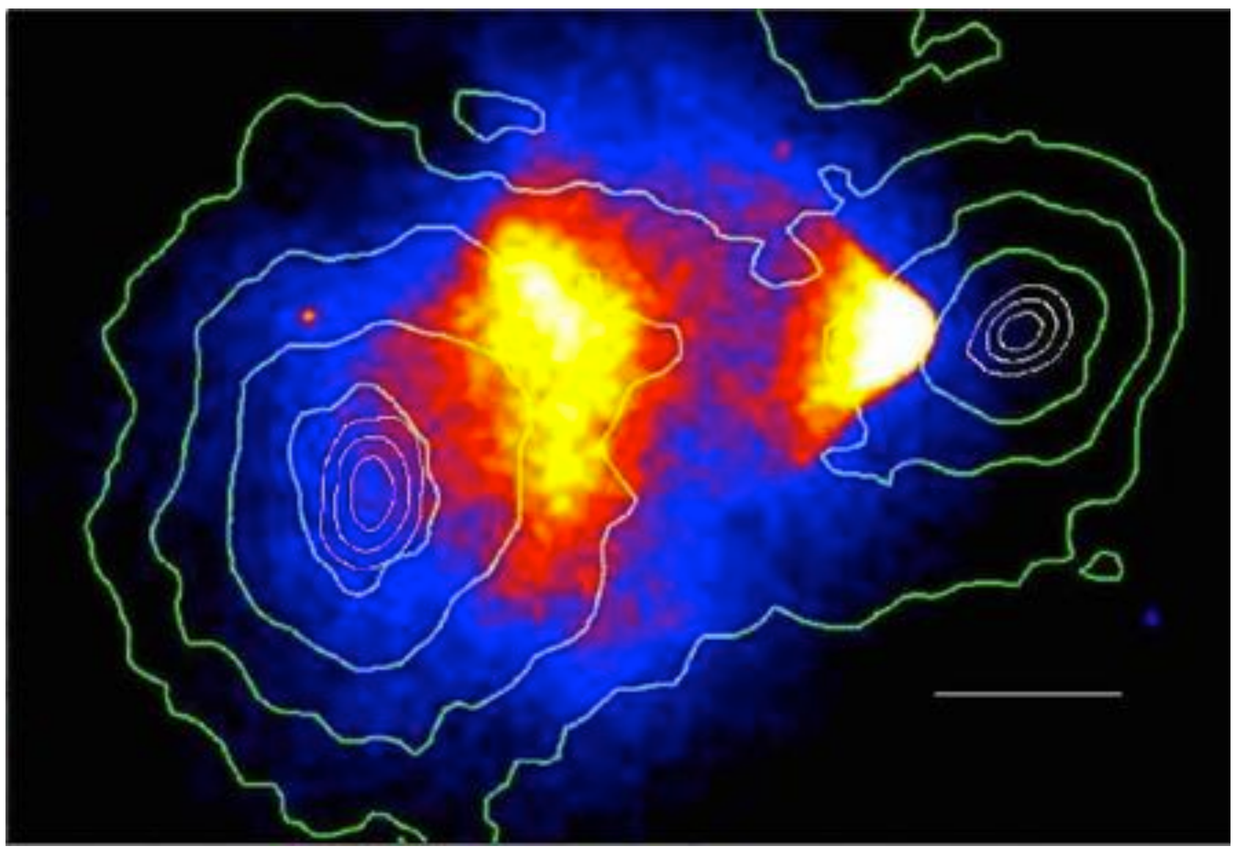


$$\frac{\sigma_{SI}}{m_\psi} \sim \frac{\alpha_d^2}{m_\psi^3}$$

(velocity independent)

self-interactions

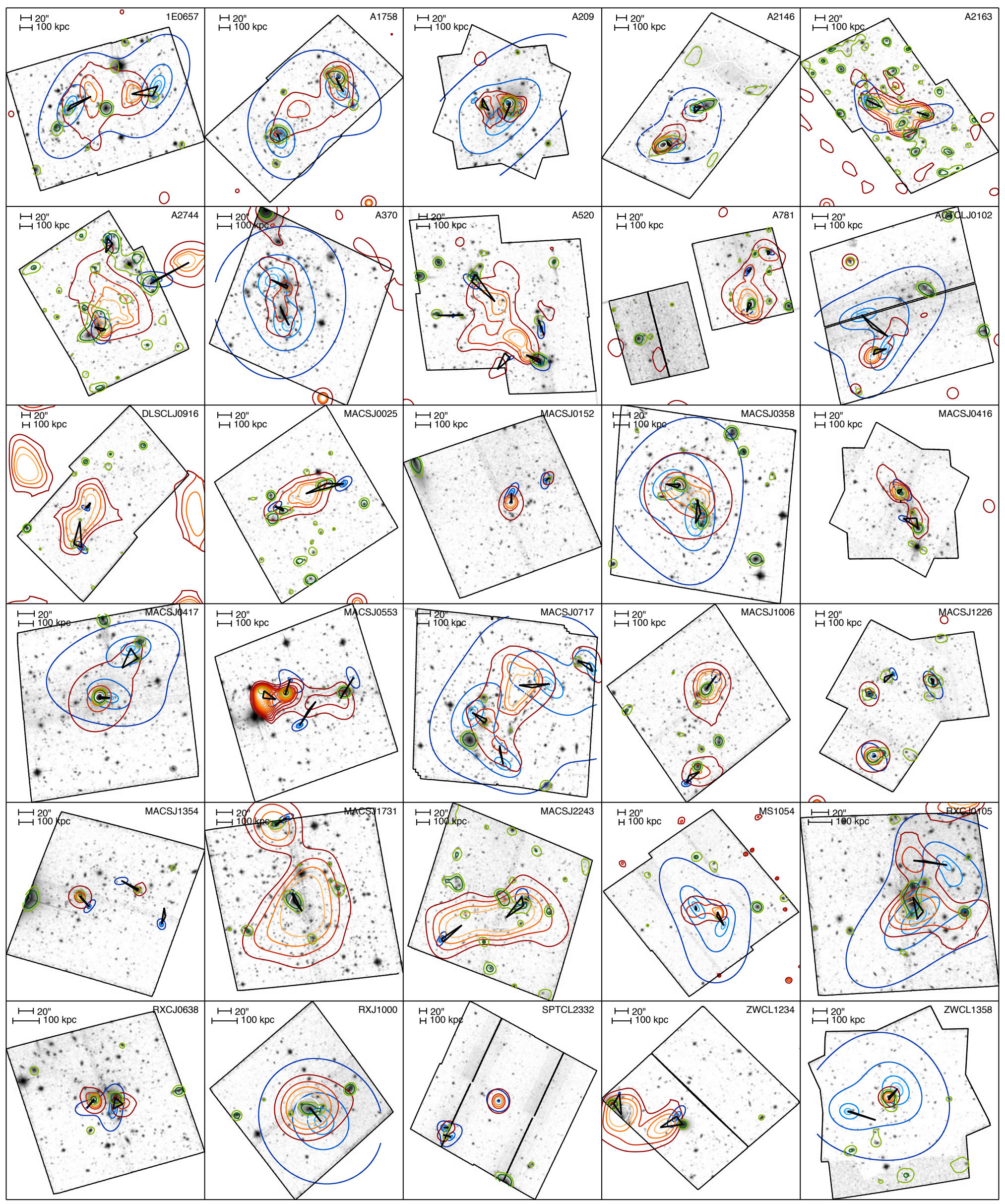
bullet cluster:

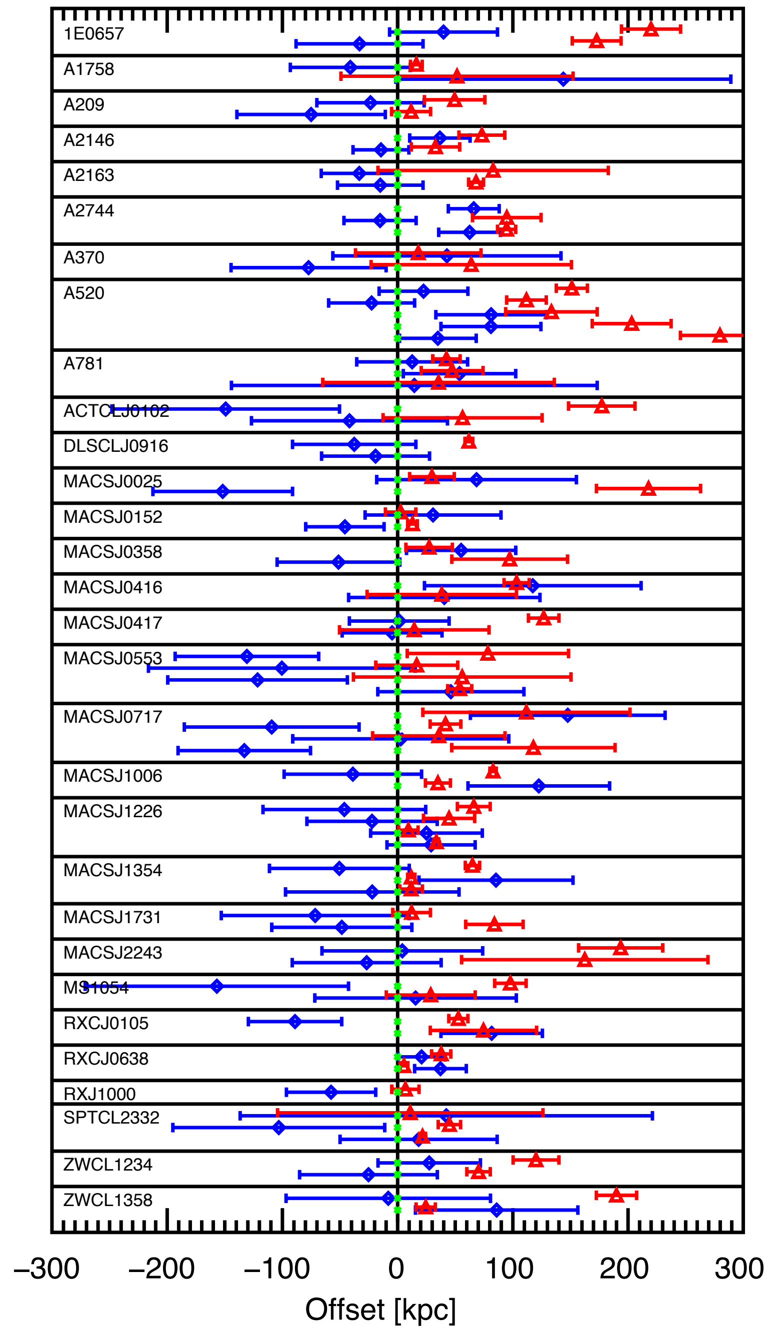


$$\frac{\sigma_{SI}}{m_\psi} < 1.25\ \mathrm{cm}^2/\mathrm{g}$$

- 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

sensitivity:

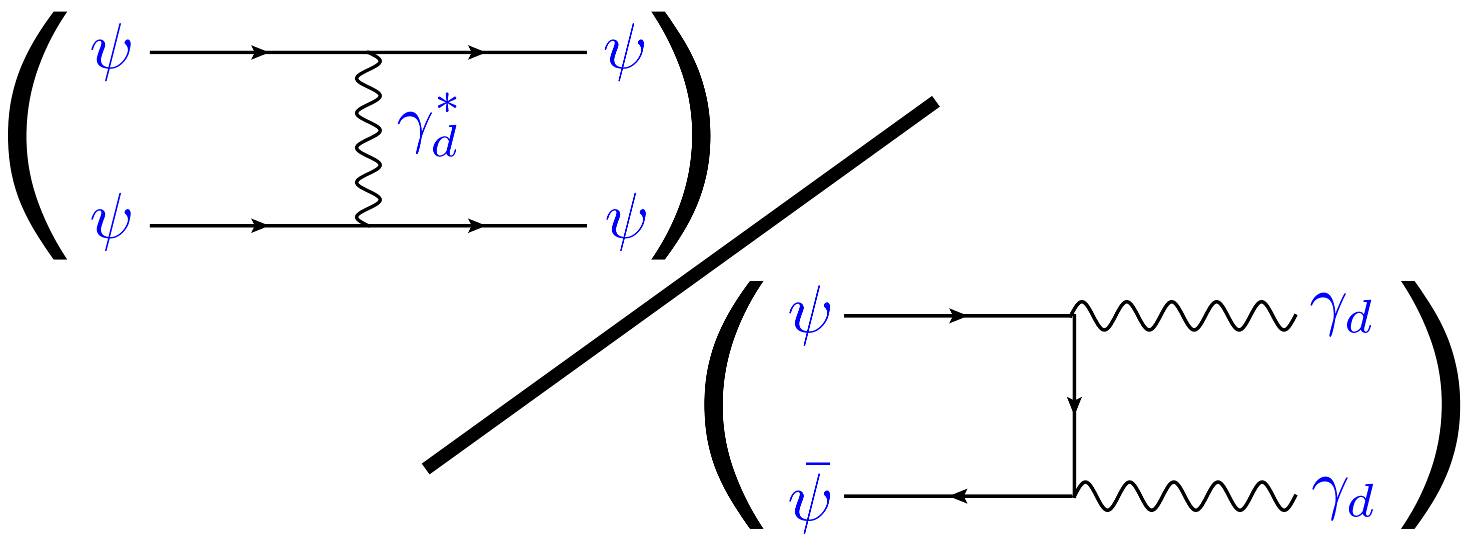
$$\frac{\sigma_{SI}}{m_\psi} \sim 1\ \mathrm{cm}^2/g \sim 5 \times 10^{-6}\ \mathrm{MeV}^{-3}$$

thermal annihilation rate:

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

ratio: $$\frac{\sigma_{SI}}{\langle \sigma v \rangle} \sim 10^9 \left(\frac{m_\psi}{1\ \mathrm{MeV}} \right)$$

self-interactions

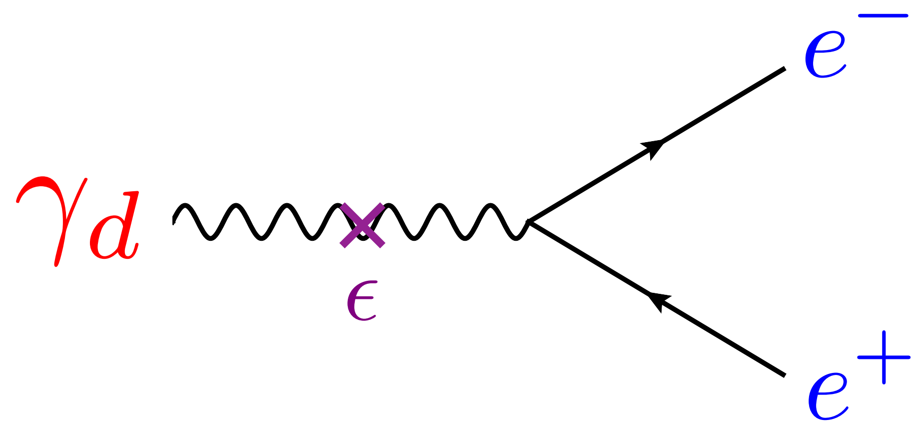


$$\propto \quad e^{2x_f \Delta}$$

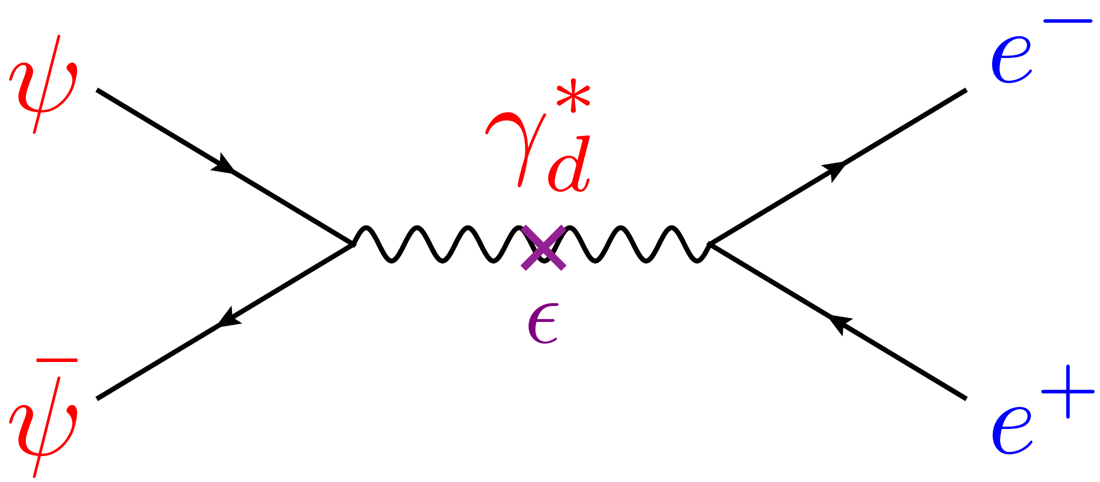
$$\frac{\sigma_{SI}}{m_\psi} \sim 10\ \mathrm{cm}^2/\mathrm{g} \times \left(\frac{10\ \mathrm{MeV}}{m_\psi}\right)^3 \times \left(\frac{\alpha_d}{0.1}\right)^2$$

coupling to SM

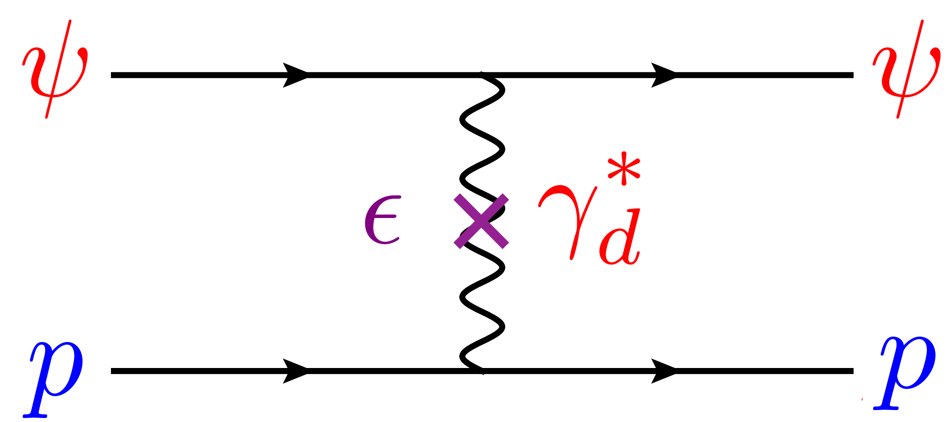
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{d}_{\mu\nu} F^{\mu\nu}$$



indirect detection:

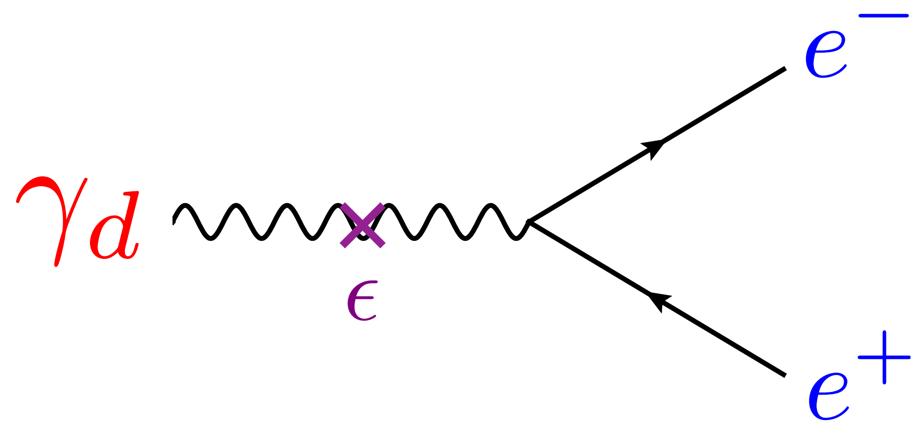


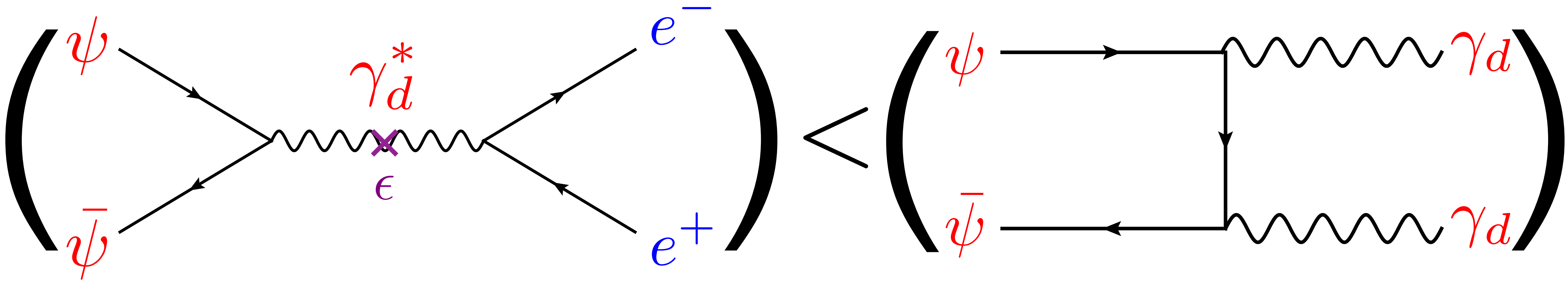
direct detection:



coupling to SM

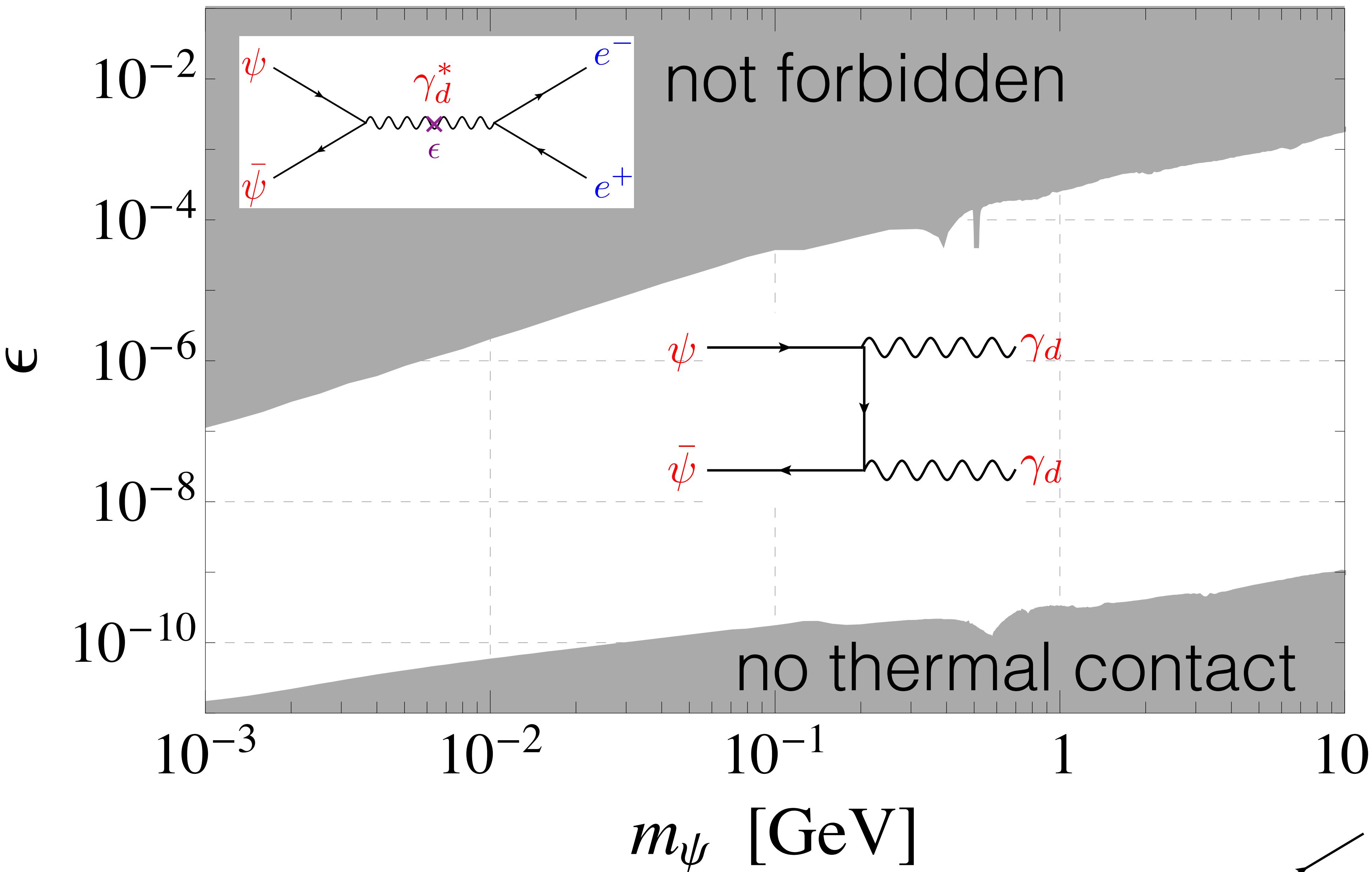
$$\mathcal{L} \supset \frac{\epsilon}{2} F^d_{\mu\nu} F^{\mu\nu}$$

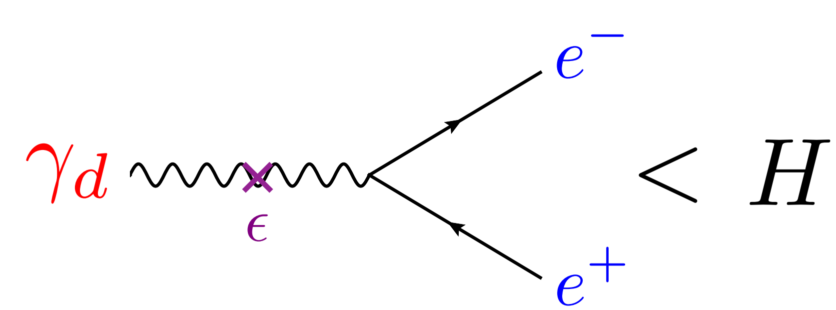




$$\epsilon^2 \, \frac{\alpha_d \alpha_{EM}}{m_\psi^2} \; < \; e^{-2x_f \Delta} \, \frac{\alpha_d^2}{m_\psi^2}$$

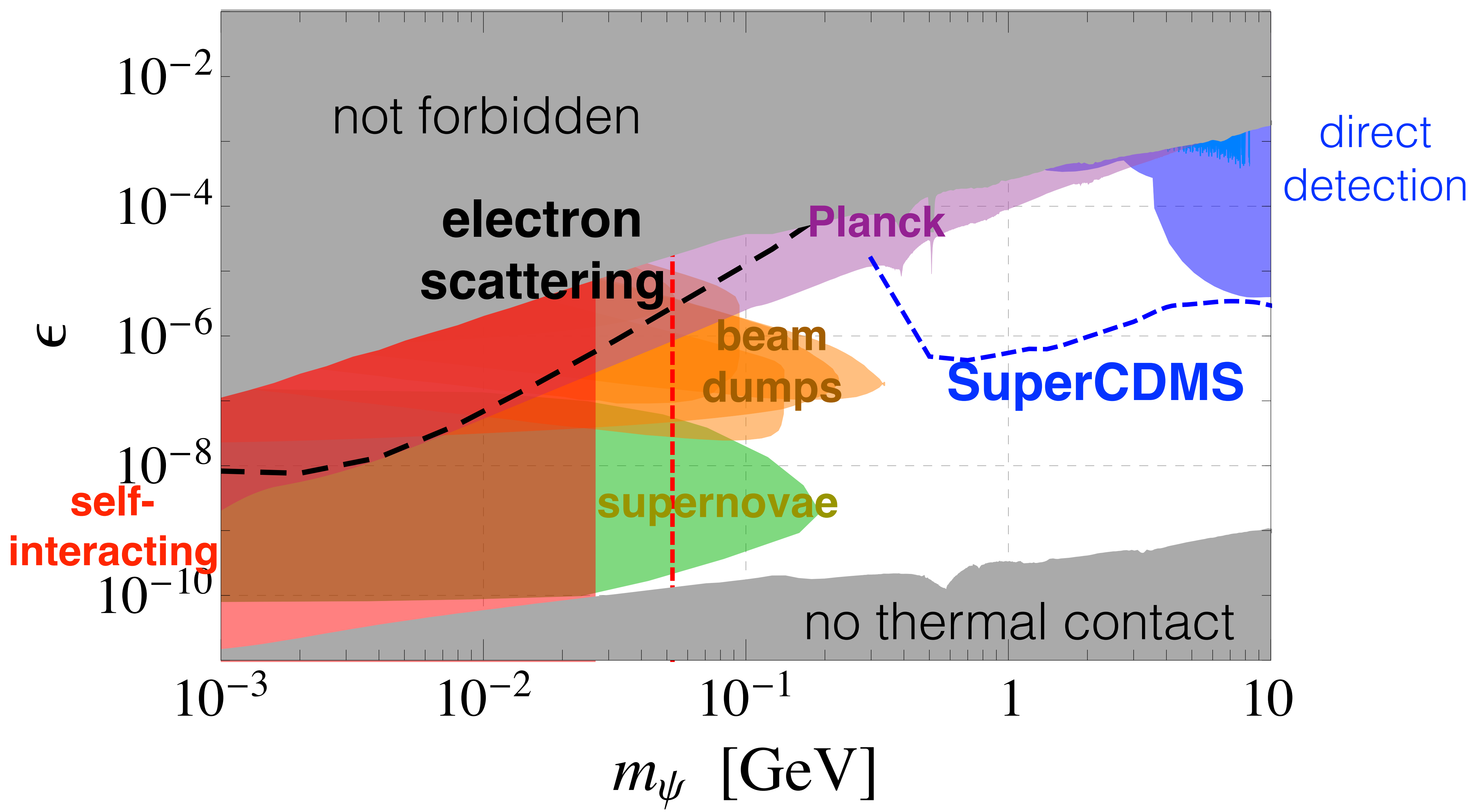
forbidden parameter space





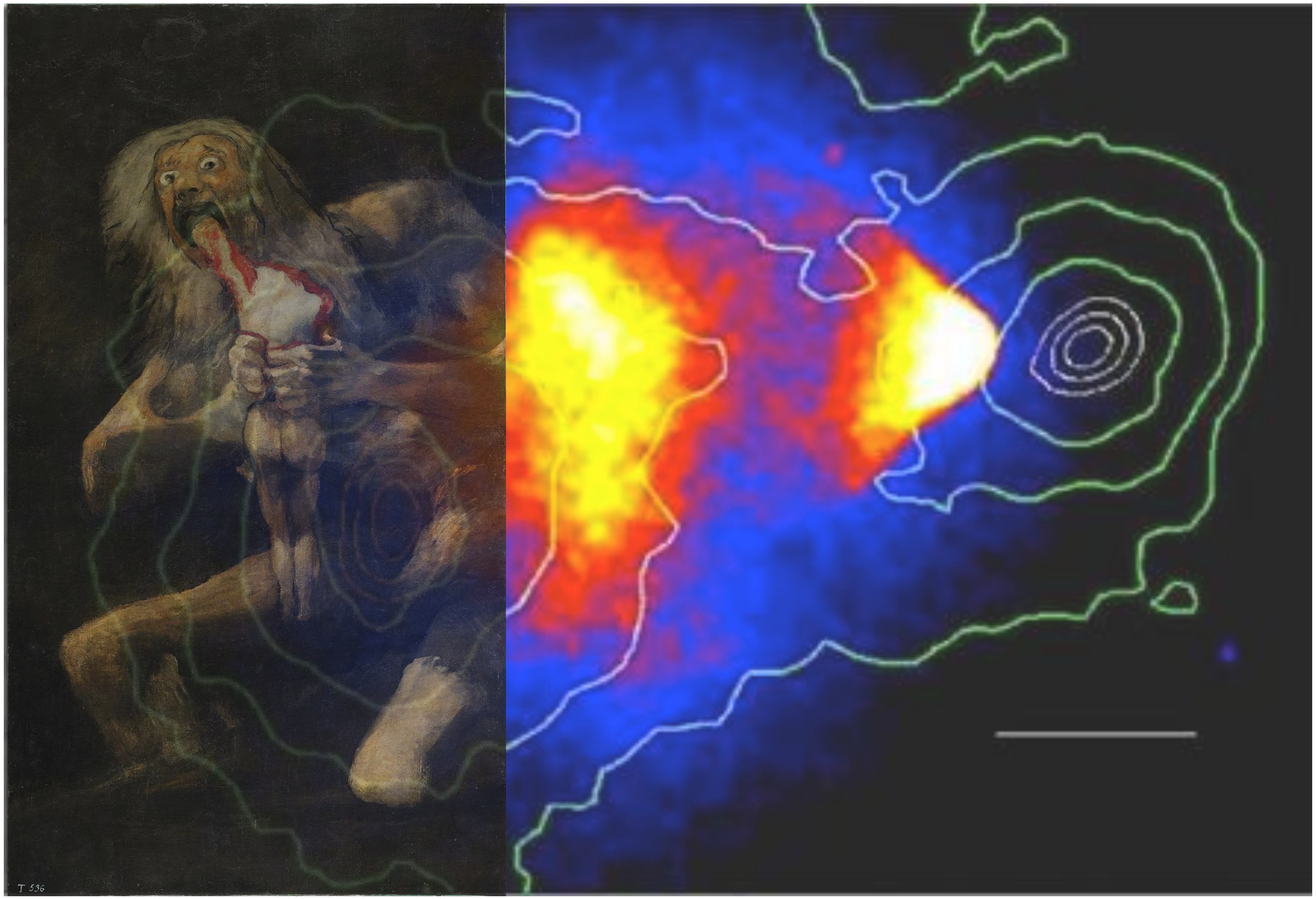
$\alpha_d = 0.1$

direct detection reach



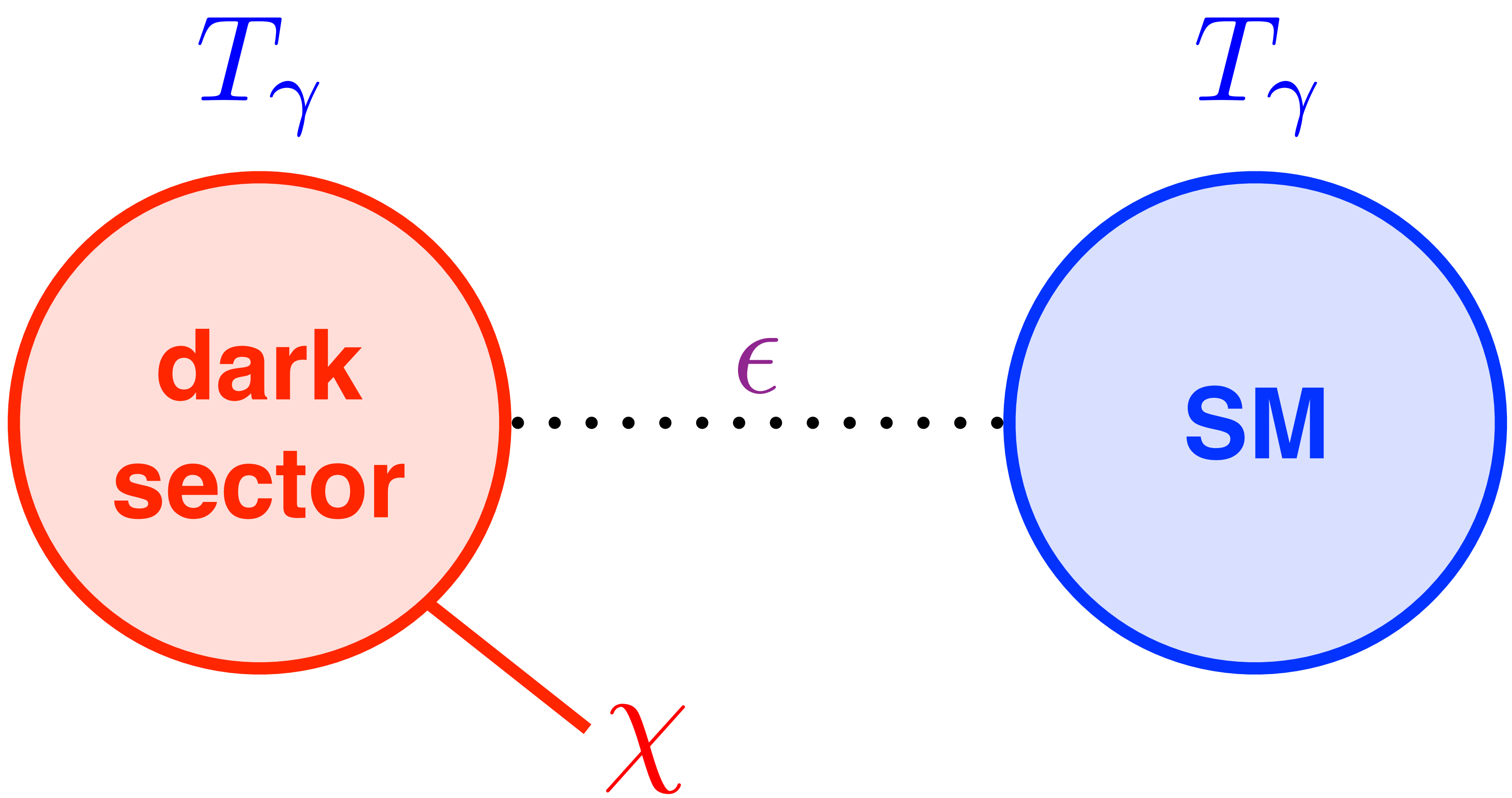
- Essig, Mardon, Volansky **1108.5383**
- Snowmass, **1310.8327**

3. Cannibal Dark Matter

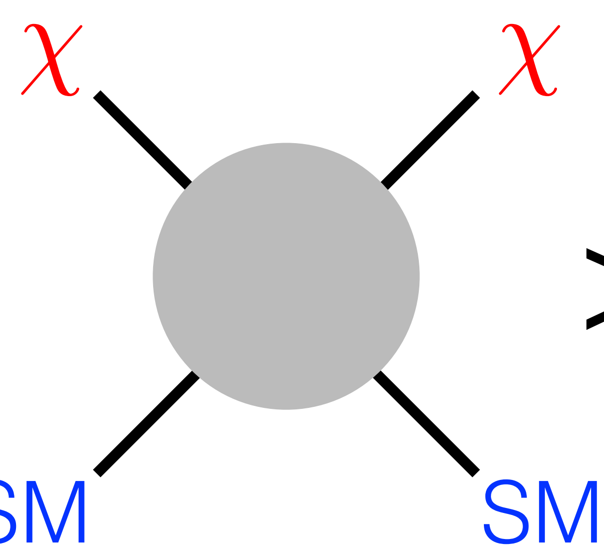


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

coupled sectors



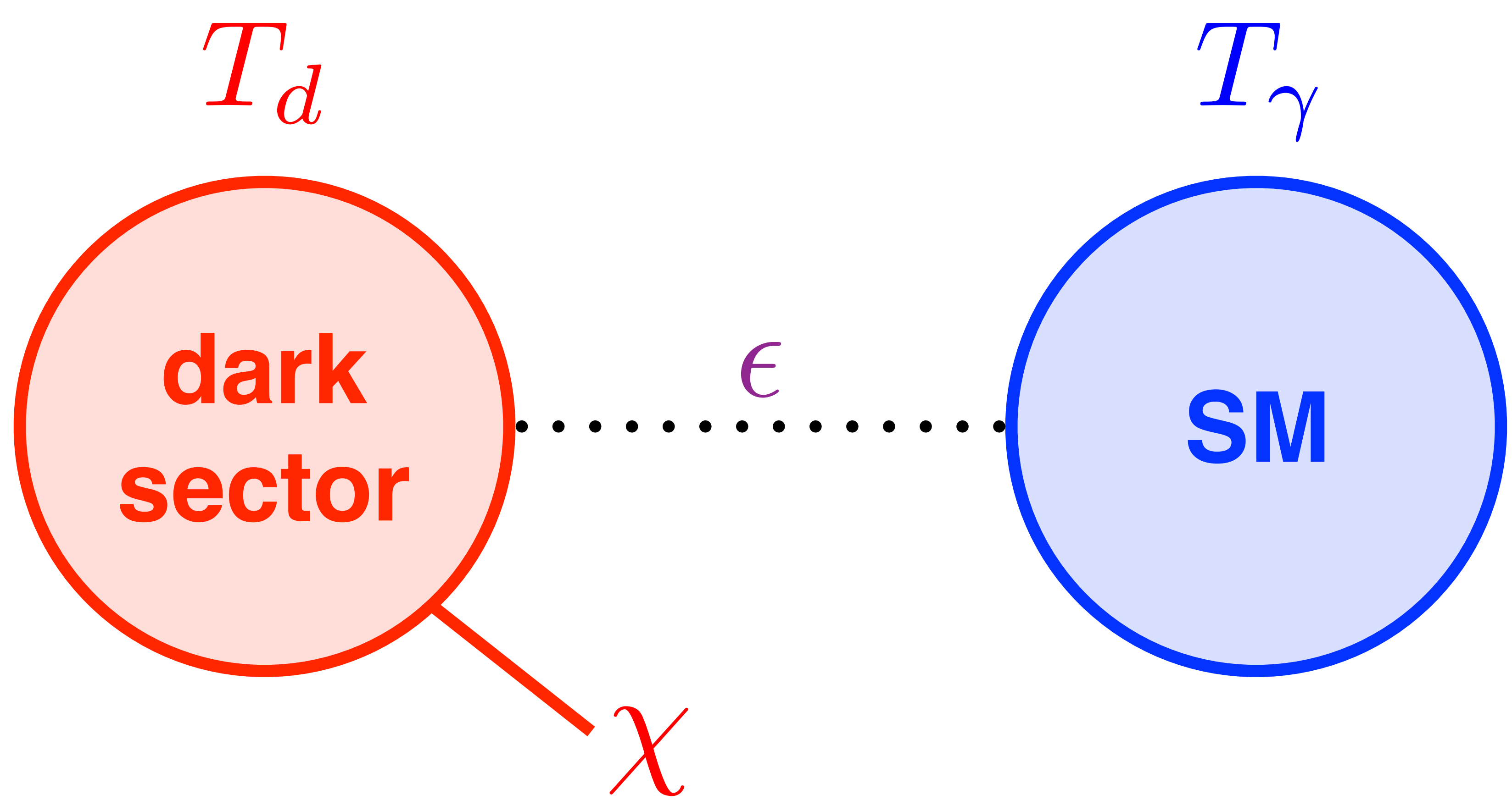
kinetically coupled:



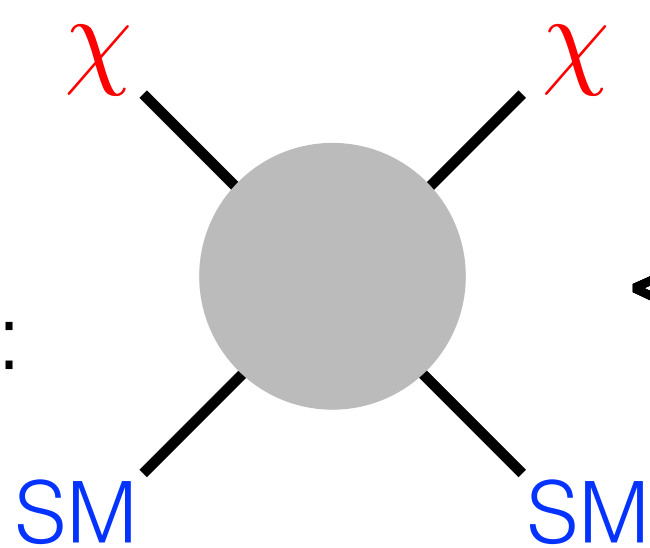
$> H$

$$\epsilon \gtrsim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

decoupled sectors



kinetically decoupled:



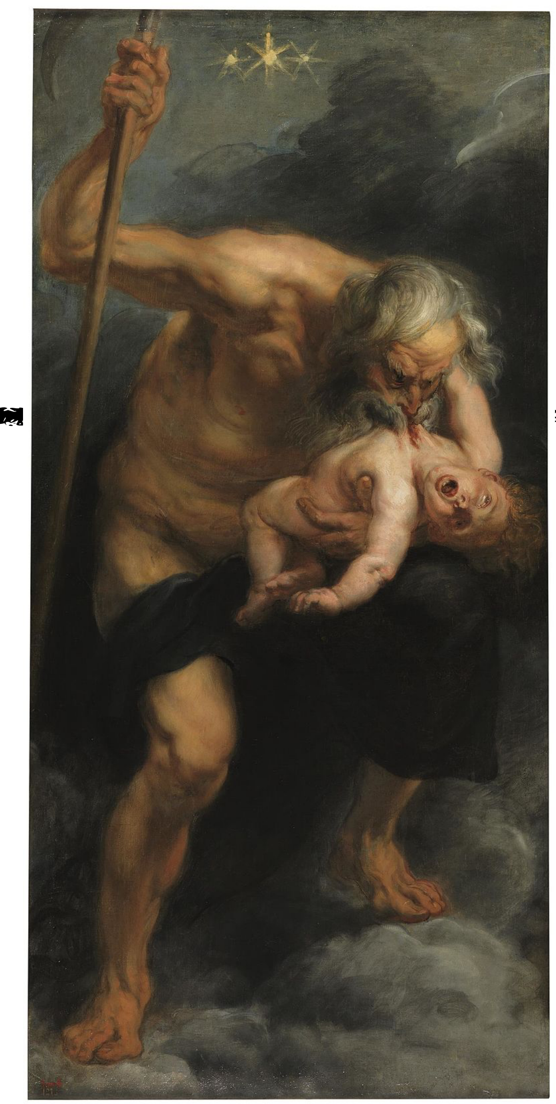
$< H$

$\epsilon \lesssim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$

Hidden Sector Taxonomy

non-gapped **gapped**

cannibalism



Non-Gapped Hidden Sector

- entropy per comoving volume is separately conserved:

$$s_d = \frac{2\pi^2}{45}\, g_{*S}^{d}\, T_d^3 \qquad\qquad s_{SM} = \frac{2\pi^2}{45}\, g_{*S}^{SM}\, T_\gamma^3$$

$$\xi = \frac{s_{SM}}{s_d}$$

- temperature ratio: $\frac{T_\gamma}{T_d} = \xi^{1/3} \left(\frac{g_{*S}^{d}}{g_{*S}^{SM}} \right)^{1/3} \sim \mathcal{O}(1)$

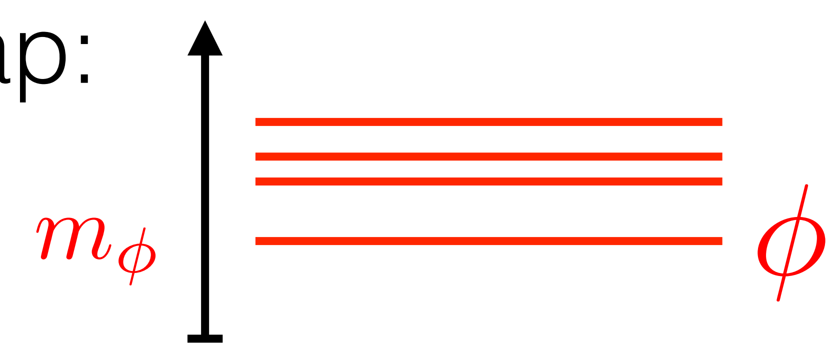
- Feng, Tu, Yu **0808.2318**

Cannibalism Conditions

1. hidden sector is kinetically decoupled from SM:

$$T_d \neq T_\gamma$$

2. hidden sector has a mass gap:



3. number changing interactions are in equilibrium when the hidden sector is non-relativistic:

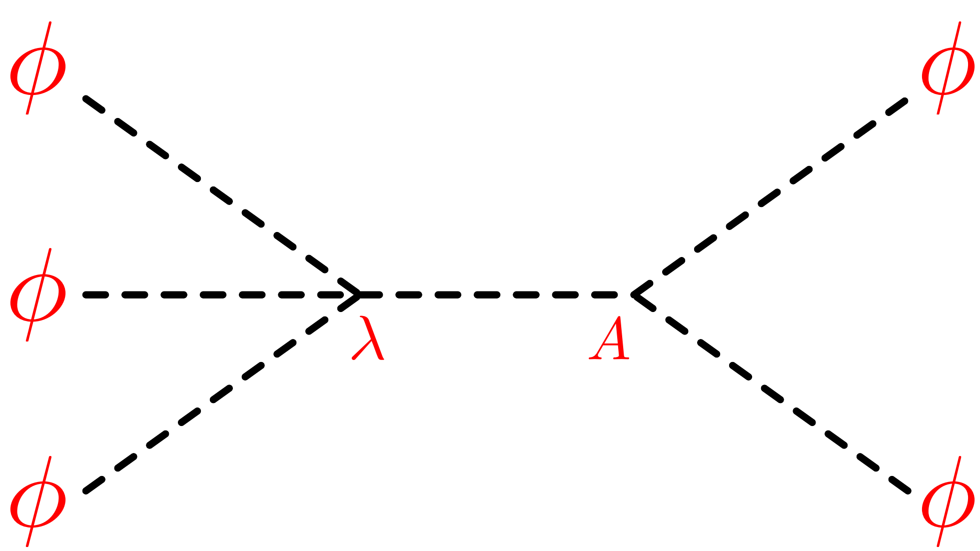
$$T_d < m_\phi$$

4. no chemical potential:

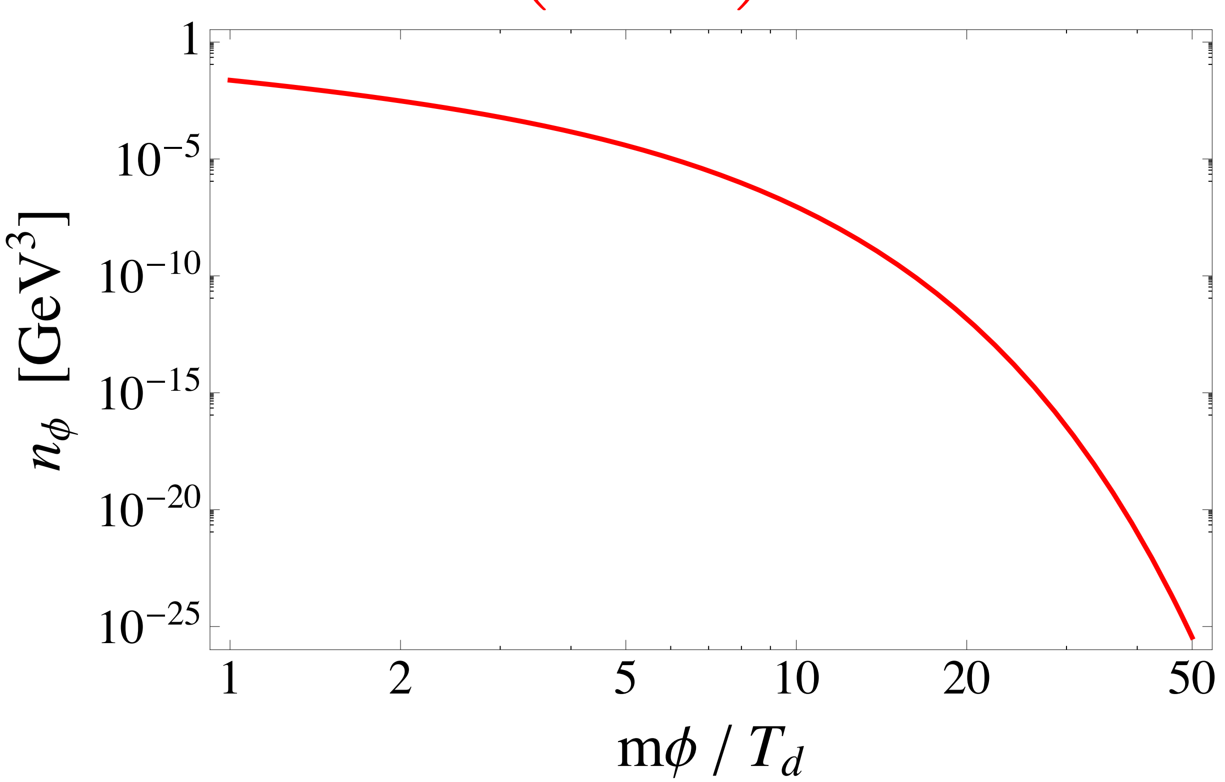
$$\mu_\phi = 0$$

Simplest Hidden Sector

$$V_d = \frac{m_\phi^2}{2}\phi^2 + \frac{A}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4$$



$$n_\phi^{eq} = \left(\frac{m_\phi T_d}{2\pi}\right)^{3/2} e^{-m_\phi/T_d}$$



Cannibal Sector Temperature

- entropy:

$$s_d = \frac{\rho_d + p_d}{T_d} \approx \frac{m_\phi n_\phi}{T_d} \approx \frac{m_\phi^{5/2} T_d^{1/2}}{(2\pi)^{3/2}} e^{-m_\phi/T_d} \qquad s_{SM} = \frac{2\pi^2}{45} g_{*S}^{SM} T_\gamma^3$$

- temperature ratio:

$$\xi = \frac{s_{SM}}{s_d} \quad \longrightarrow \quad \frac{T_\gamma}{T_d} \approx 0.5\, \xi^{1/3} \left(g_*^{SM}\right)^{-1/3} \left(\frac{m_\phi}{T_d}\right)^{5/6} \boxed{e^{-m_\phi/3T_d}}$$

- temperature vs. scale factor:

$$T_\gamma \sim \frac{1}{a} \qquad T_d \sim \frac{1}{\log a}$$

SELF-INTERACTING DARK MATTER

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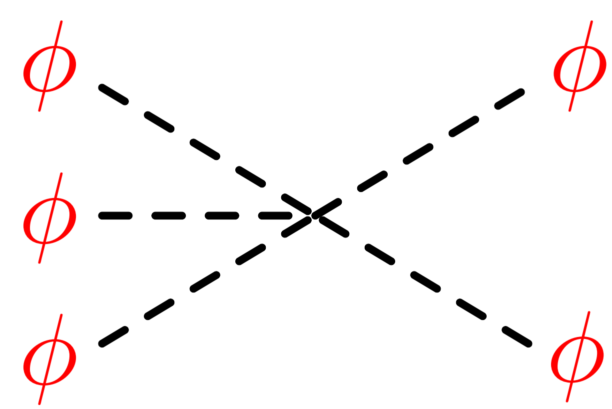
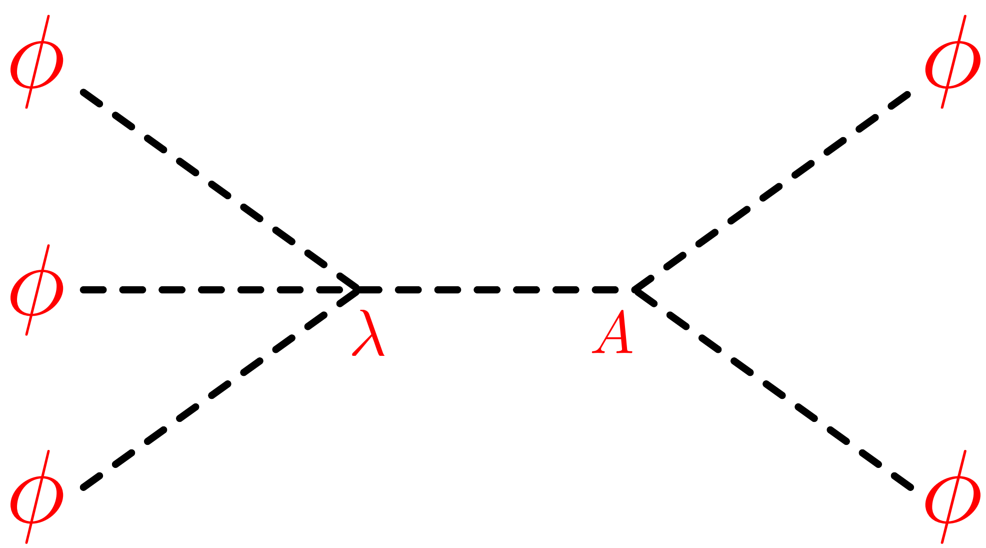
Received 1992 March 17; accepted 1992 April 20

the number density of particles. Hence number changing processes like $3 \rightarrow 2$ or $4 \rightarrow 2$ will tend to deplete the number of dark matter particles. But these processes take nonrelativistic particles in and produce (fewer) relativistic particles out, so that the outgoing particles have much more kinetic energy than the mean $(3/2)T'$. Hence subsequent $2 \rightarrow 2$ processes will transfer the kinetic energy of these few particles to all the dark matter, increasing the temperature. So as the universe expands, the dark matter cannibalizes itself to keep warm.



End of Cannibalism

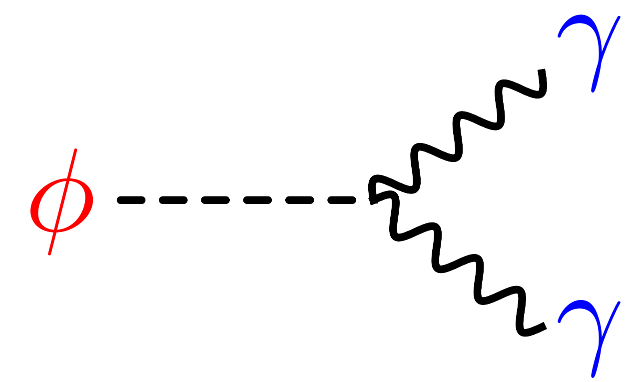
$\phi\phi\phi \to \phi\phi$ decoupling



$$n_\phi^2 \left\langle \sigma v^2 \right\rangle \approx H$$

ϕ decays

$$\frac{\phi\, F^2}{M}$$



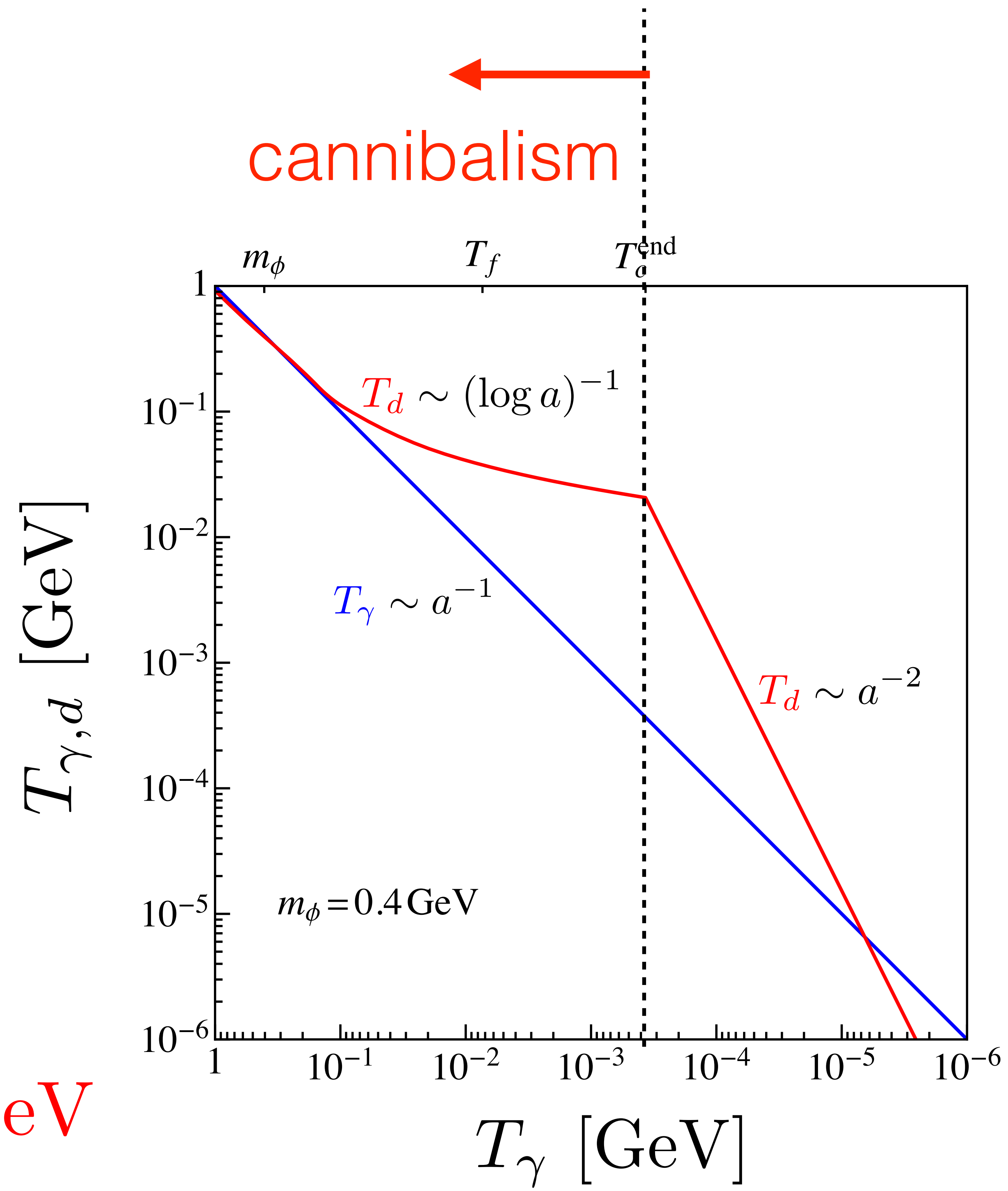
- during cannibalism:

$$\Gamma_\phi \ll H$$

- end of cannibalism:

$$\Gamma_\phi \approx H$$

Cannibalism

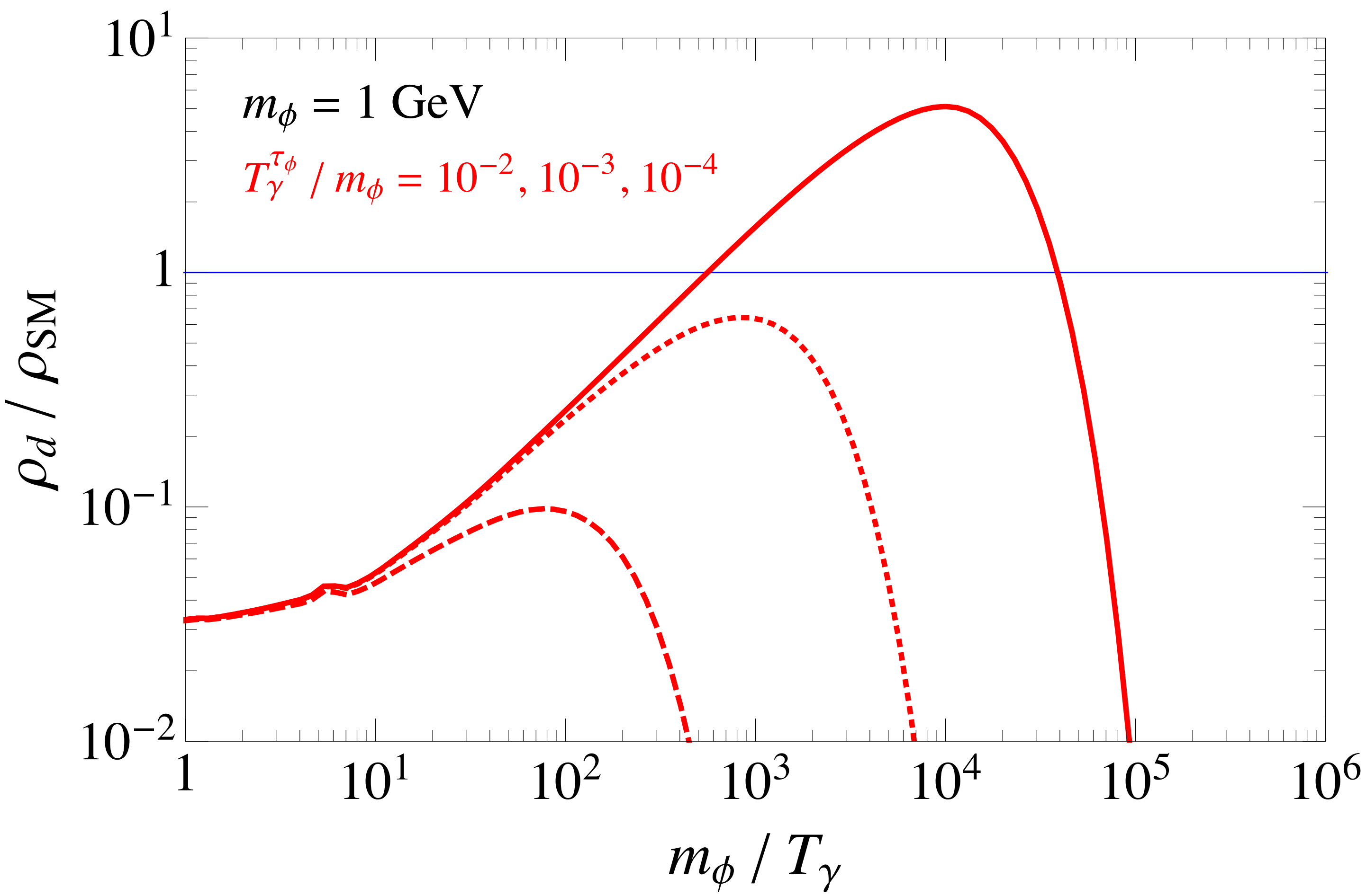


$m_\phi = 0.4$ GeV

ϕ Domination

- hidden vs. SM energy: $$\frac{\rho_d}{\rho_{SM}} = \frac{s_d T_d}{(4/3) s_{SM} T_\gamma} \propto e^{3m_\phi/T_d}$$

- ϕ dominates if: $$\frac{T_\gamma}{T_d} < \frac{4}{3}\xi^{-1} \qquad \xi = \frac{s_{SM}}{s_d}$$



ϕ Dark Matter?

$$\Omega_\phi h^2 \approx \frac{m_\phi n_\phi}{s_{SM}} (3.5 \text{ eV})^{-1} = \frac{m_\phi}{x_f \xi} (3.5 \text{ eV})^{-1}$$

$$x_f = \frac{m_\phi}{T_d^f} \qquad \xi = \frac{s_{SM}}{s_d}$$

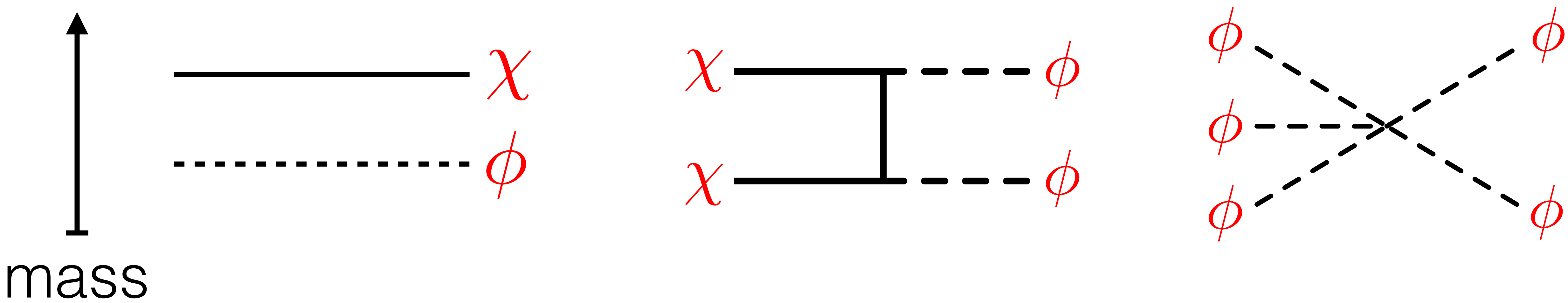
- Carlson, Hall, Machacek, **1992**.

- ϕ is too warm: $m_\phi = x_f \, \xi \times 0.4 \text{ eV} \lesssim 1 \text{ keV}$

(except for large ξ)

Cannibal Dark Matter

- DM from 2-to-2 freezeout in a cannibalizing sector:



$$V = \frac{m_\chi^2}{2}\chi^2 + \frac{y}{2}\phi\chi^2 + \mathrm{h.c.}$$

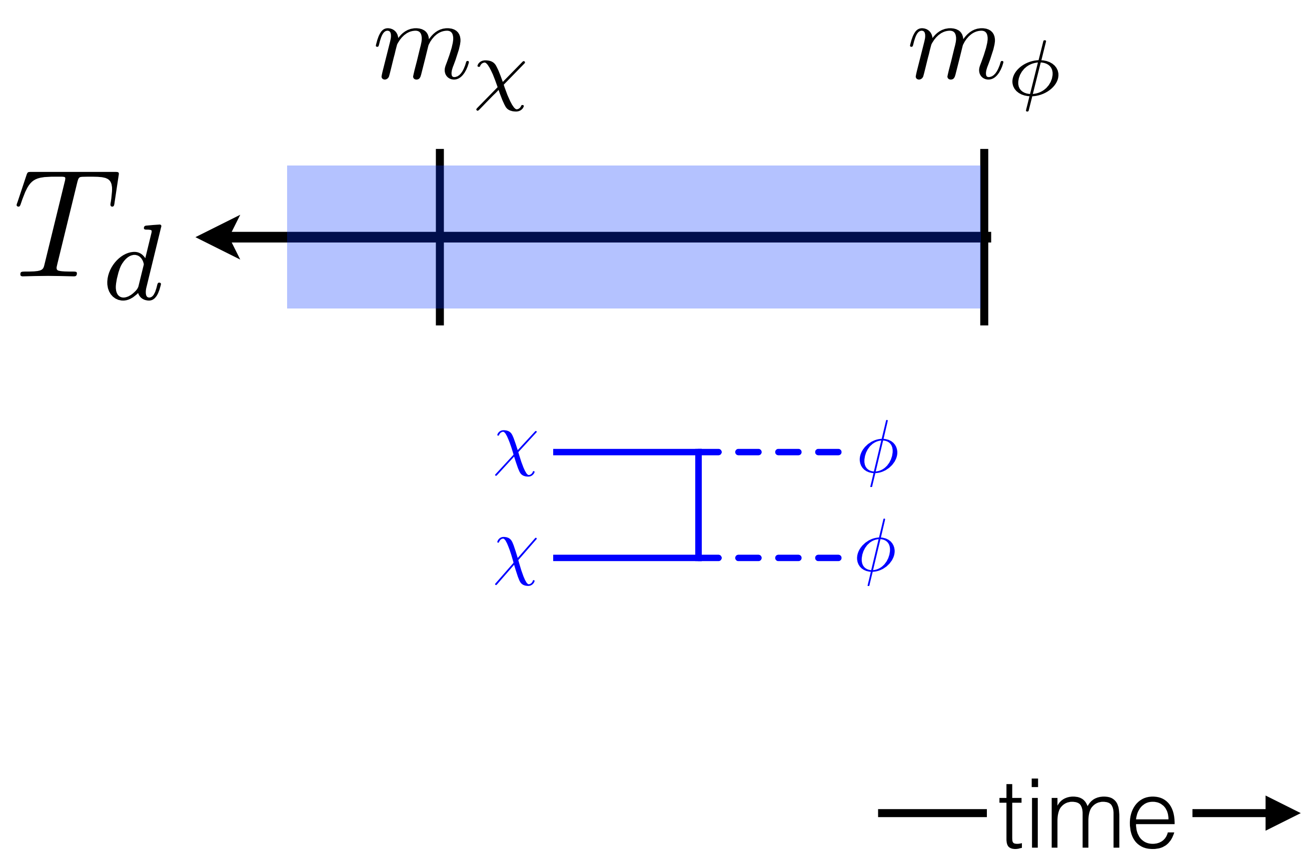
$$+ \frac{m_\phi^2}{2}\phi^2 + \frac{A}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4$$

- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

1) χ annihilations are in equilibrium

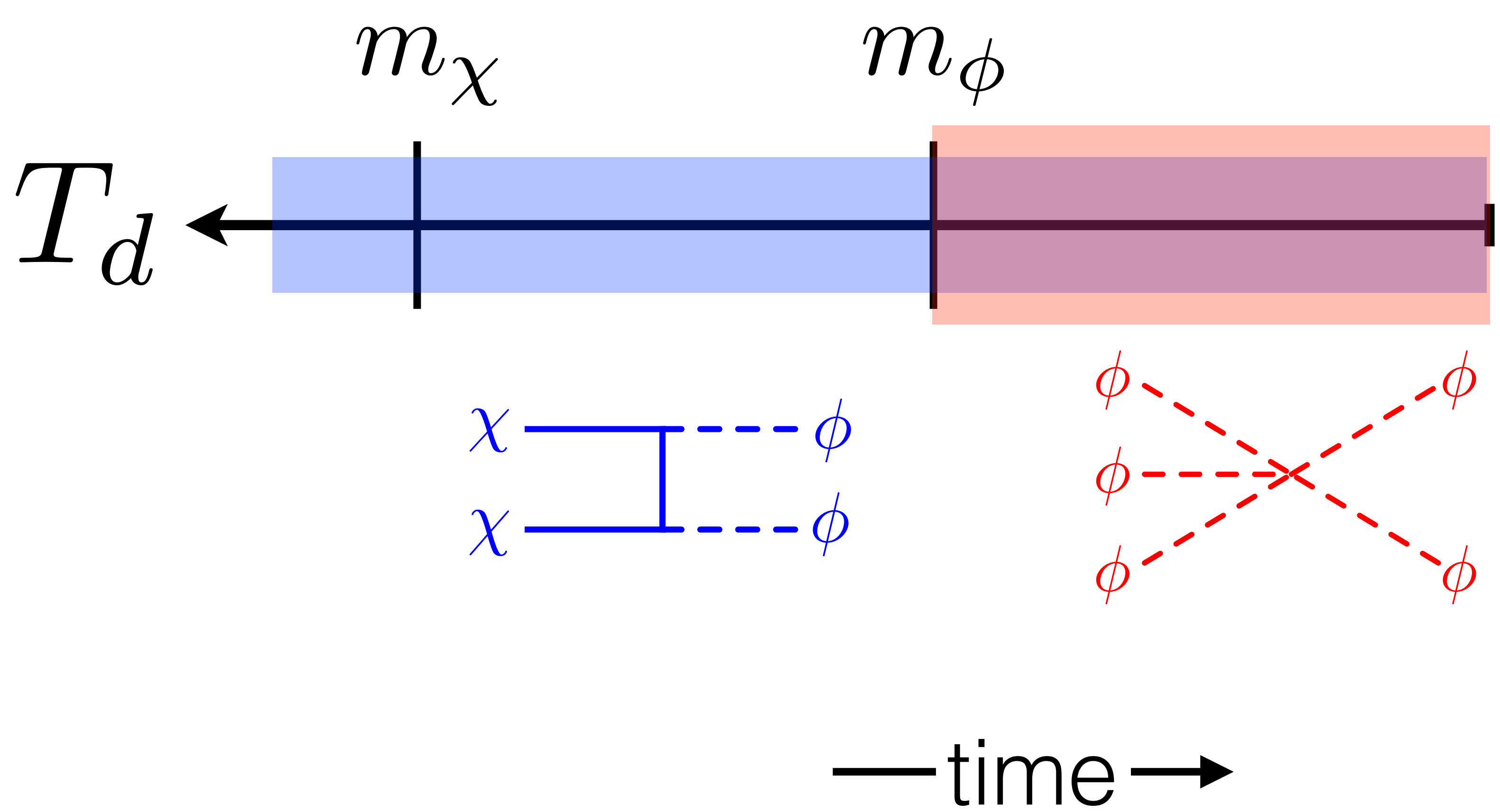
ϕ is relativistic



- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

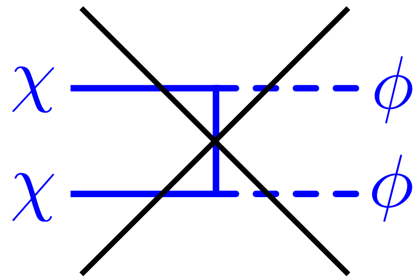
2) cannibalism starts when**:** $T_d < m_\phi$

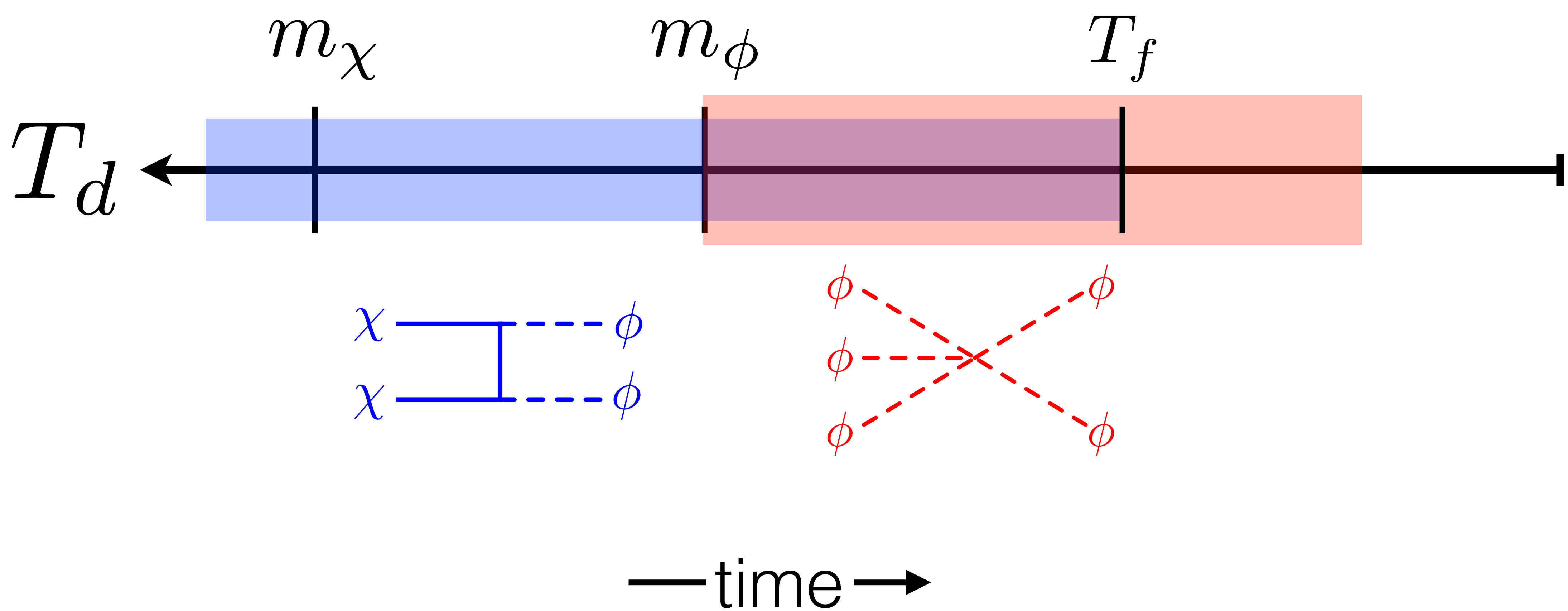


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

3) χ annihilations freezeout**:**



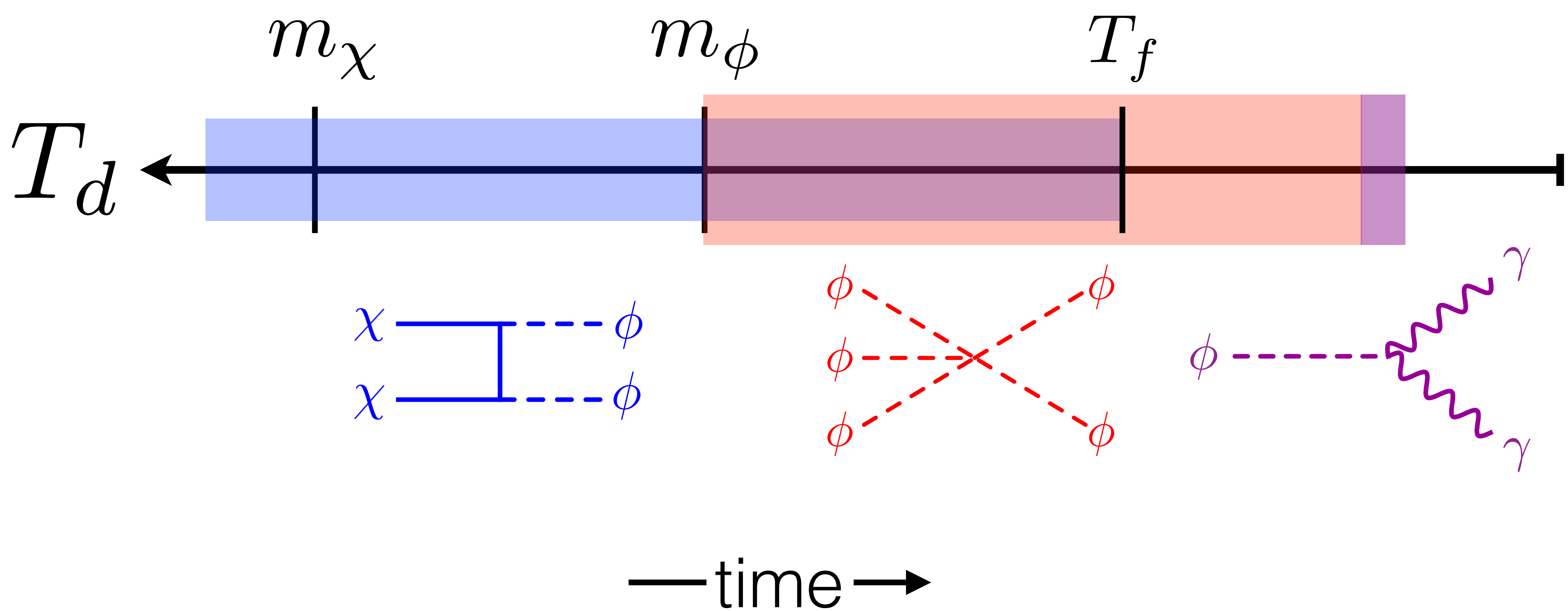


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

4) cannibalism ends when**:**

- ϕ decays
- $\phi\phi\phi \to \phi\phi$ freezeout

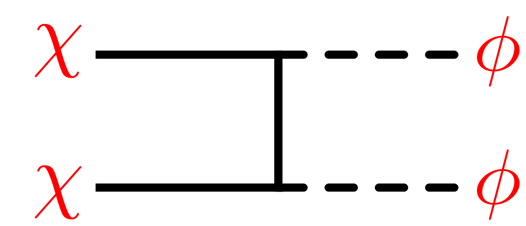


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Relic Density

$$\Omega_\chi h^2 \approx \frac{m_\chi n_\chi}{s_{SM}} \, (3.5 \text{ eV})^{-1}$$

freezeout:



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

$$\frac{\Omega_\chi}{\Omega_{obs}} \approx 0.3 \, (g_*^{SM})^{-1/2} \, x_f \, \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d}{T_\gamma} \sim \frac{\sigma_0}{\langle \sigma v \rangle} e^{3 m_\phi / T_d^f}$$

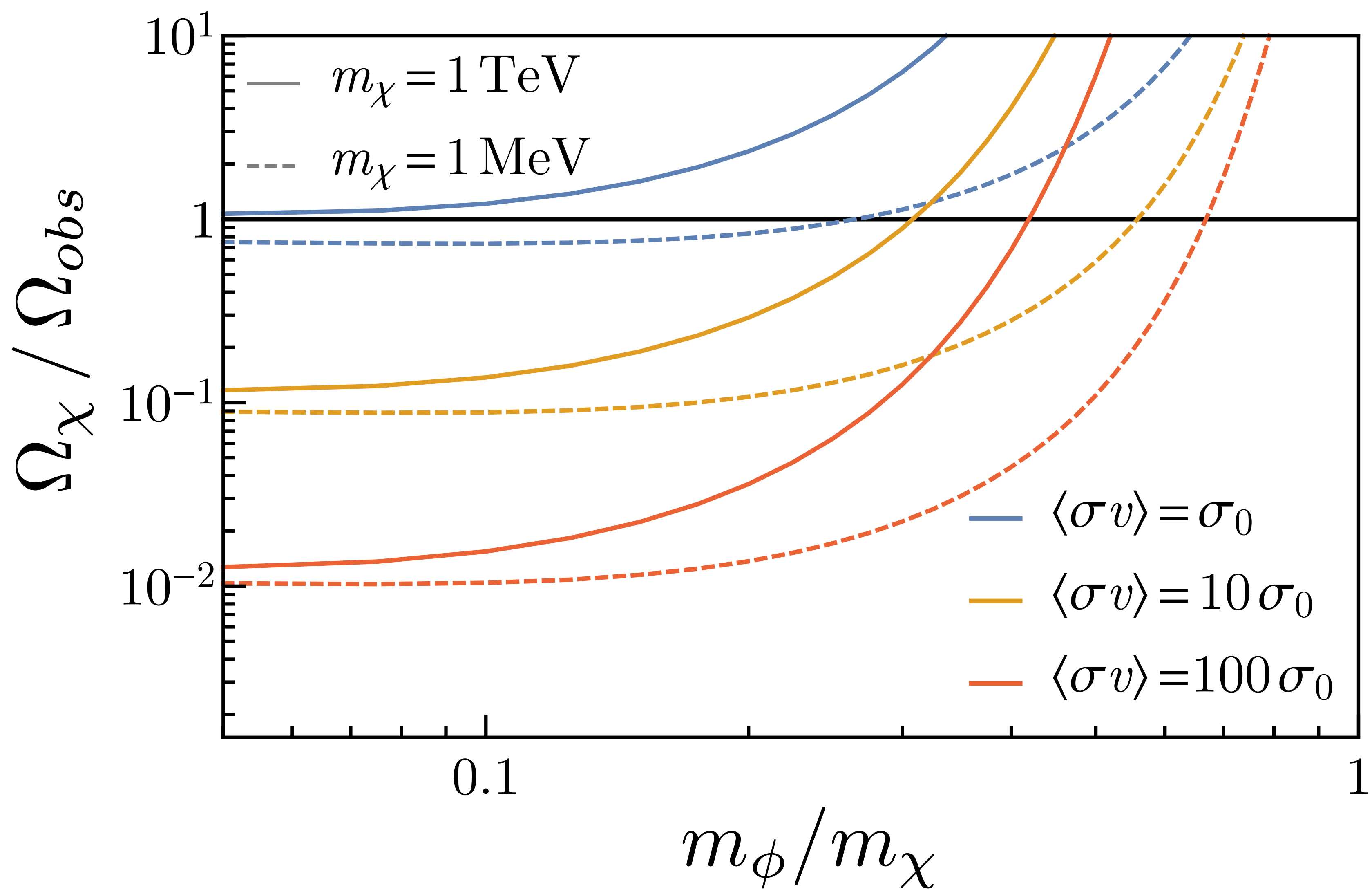
$$x_f \equiv \frac{m_\chi}{T_d^f}$$

$$\frac{T_d}{T_\gamma} \sim e^{m_\phi / 3 T_d^f}$$

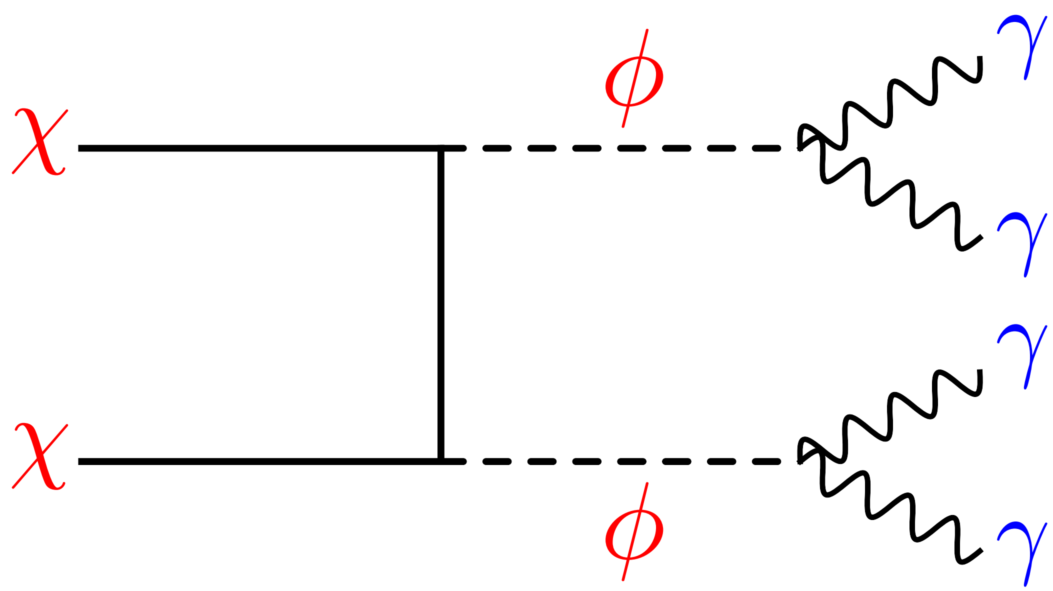
$$\sigma_0 = 3 \times 10^{-26} \text{ cm}^3 \, \text{s}^{-1}$$

Relic Density

$$\Omega_\chi \propto \langle \sigma v \rangle^{-1} \; e^{3m_\phi/T_d^f}$$



Indirect Detection



$$\boxed{\begin{array}{c}\text{boosted cross:}\\ \langle \sigma v \rangle \sim \sigma_0 \, e^{m_\phi / 3T_d^f}\end{array}}$$

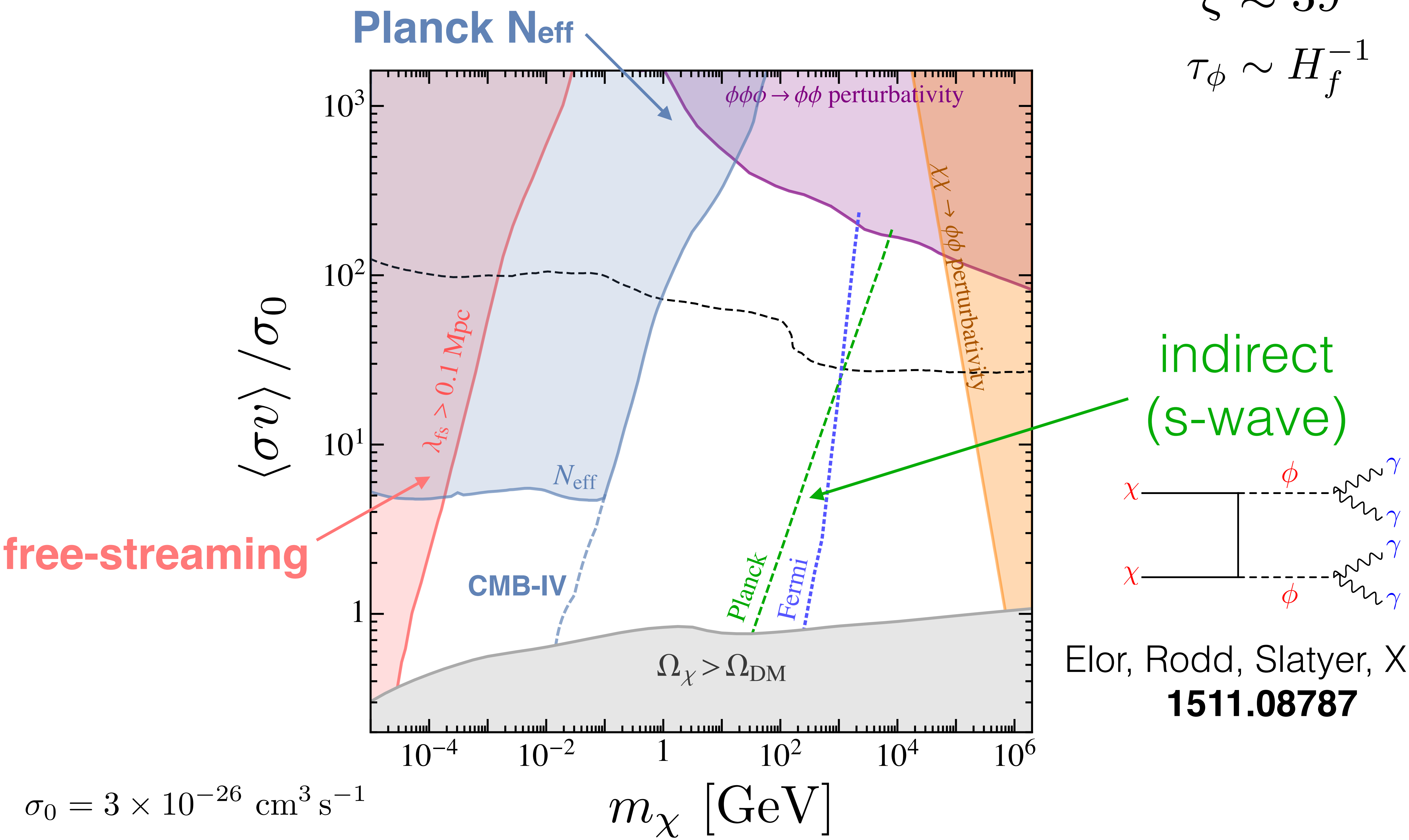
$$\frac{y}{2}\,\phi\,\chi^2$$

- s-wave: $\arg(y) \neq 0, \pi$
- p-wave: $\arg(y) = 0, \pi$

Cannibal DM Pheno

$\xi \approx 39$

$\tau_\phi \sim H_f^{-1}$

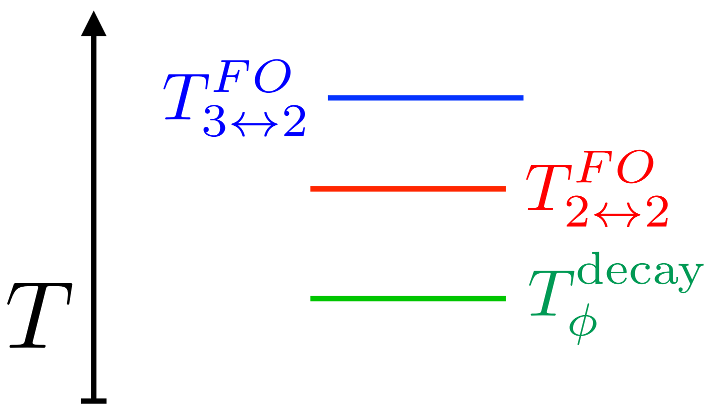


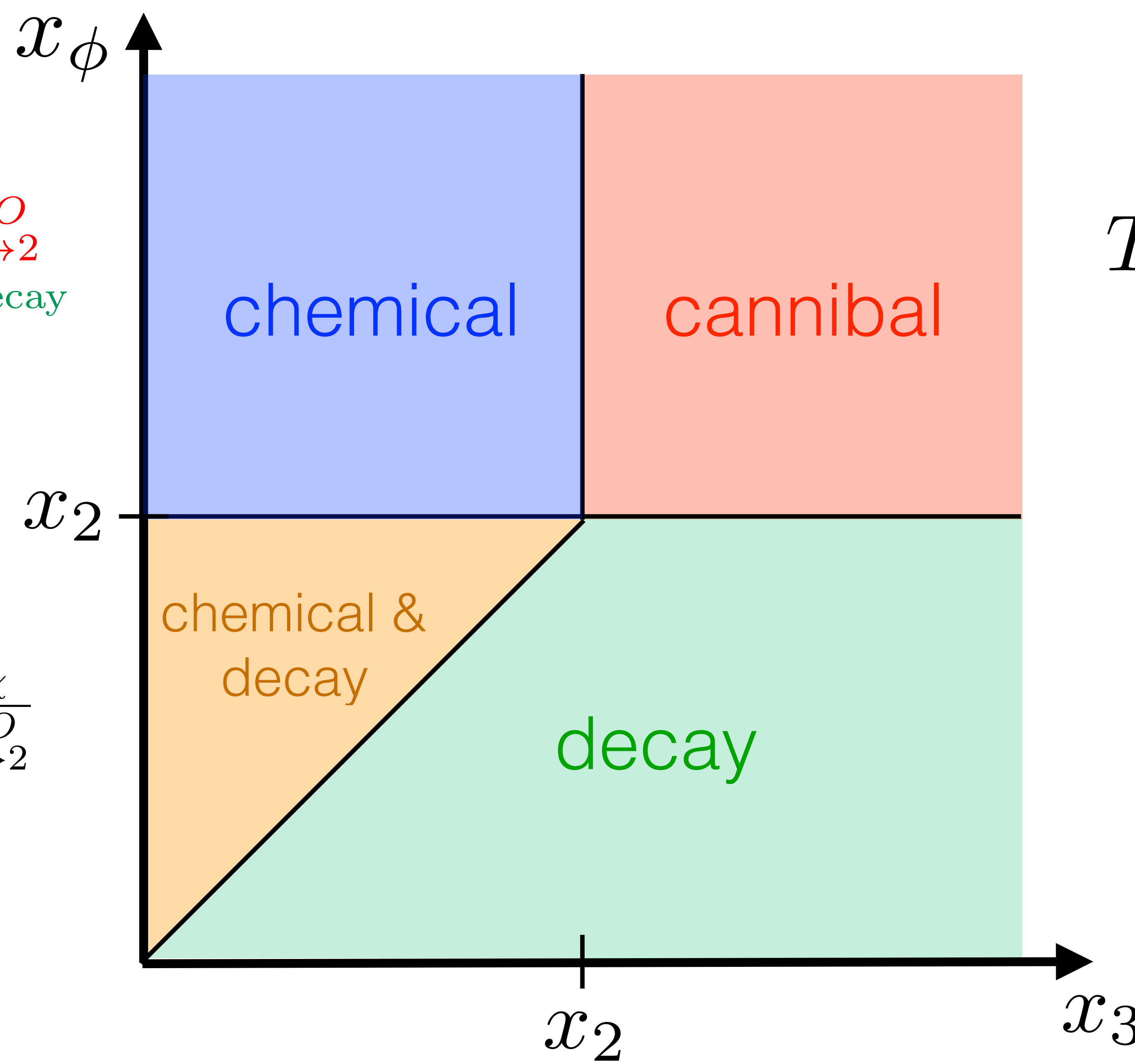
Elor, Rodd, Slatyer, Xue, **1511.08787**

$\sigma_0 = 3 \times 10^{-26}\ \mathrm{cm^3\,s^{-1}}$

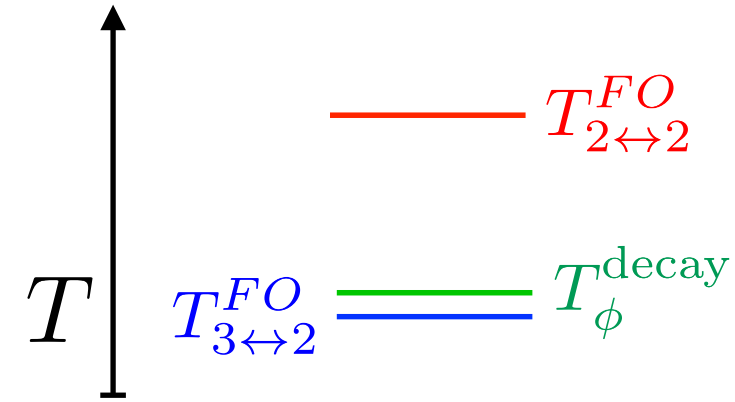
Dark Sector Phases

chemical:

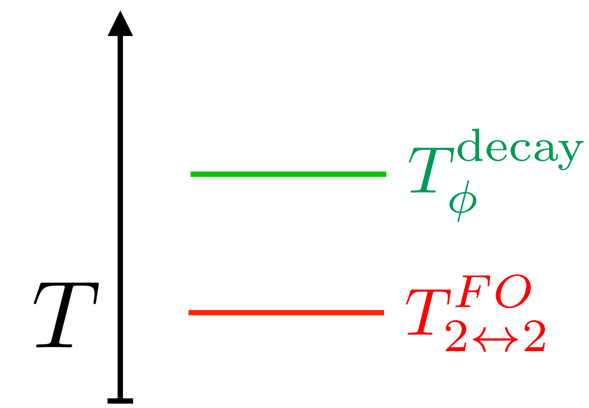




cannibal:



decay:



$$x_2 = \frac{m_\chi}{T^{FO}_{2\leftrightarrow 2}} \qquad x_3 = \frac{m_\chi}{T^{FO}_{3\leftrightarrow 2}}$$

$$x_\phi = \frac{m_\chi}{T^{\rm decay}_{\phi}}$$

- Marco Farina, Duccio Pappadopulo, JTR, Gabriele Trevisan, *to appear.*

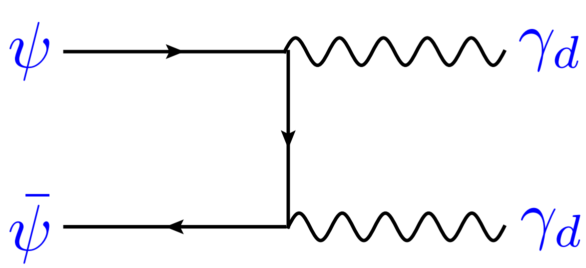
take away

Forbidden DM

Cannibal DM

take away

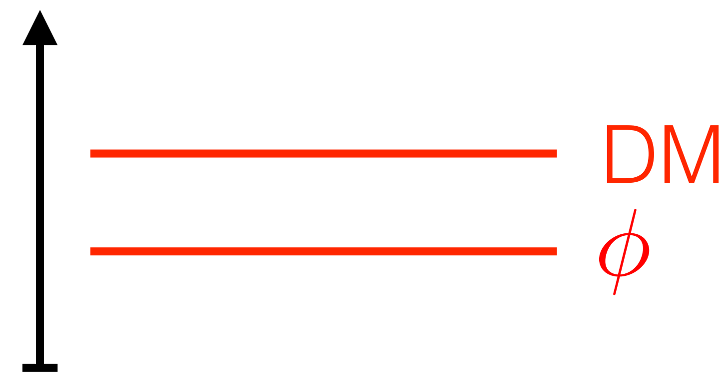
Forbidden DM

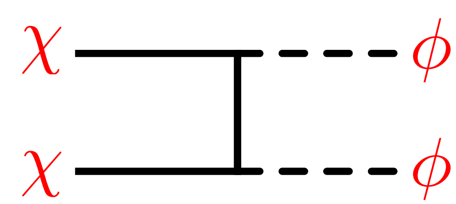


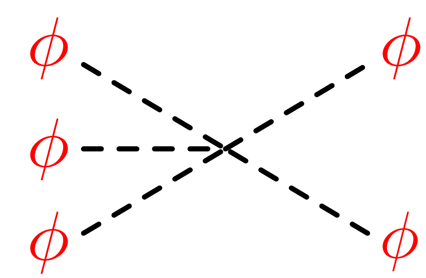
$$\Omega \propto \frac{m_\psi^2}{\alpha_d^2}\, e^{2x_f\Delta}$$

- light DM
- evades CMB
- self-interactions

Cannibal DM







$$\Omega_\chi \propto \langle \sigma v \rangle^{-1}\; e^{3m_\phi/T_d^f}$$

- boosted σ
- N_{eff}