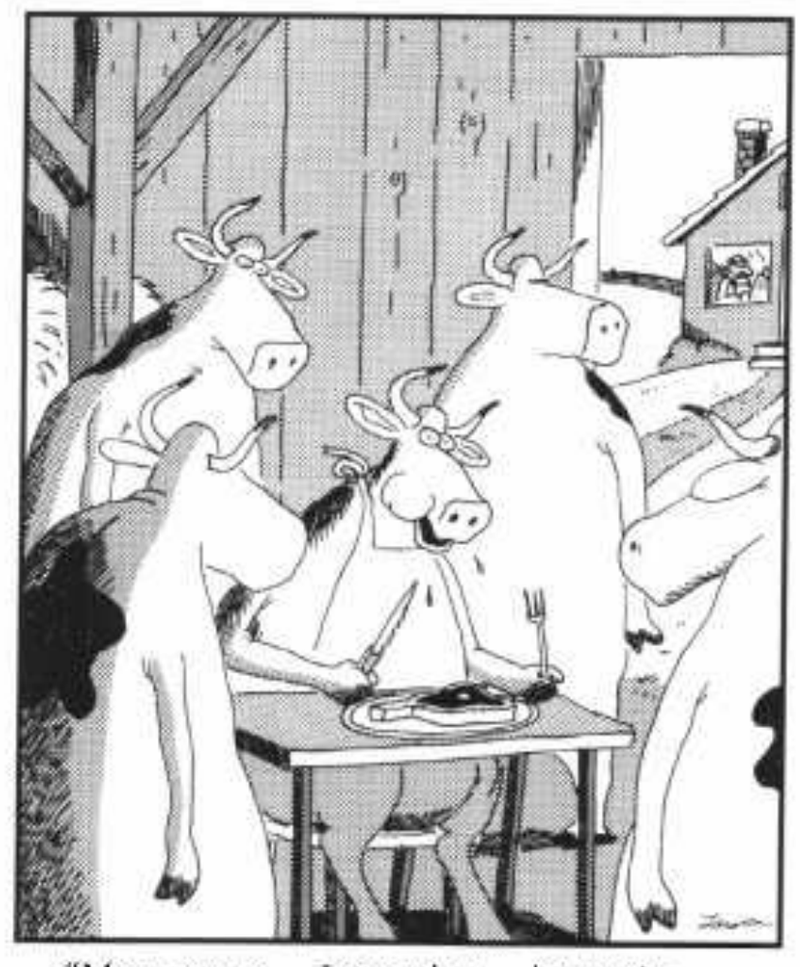
Cannibal Dark Matter

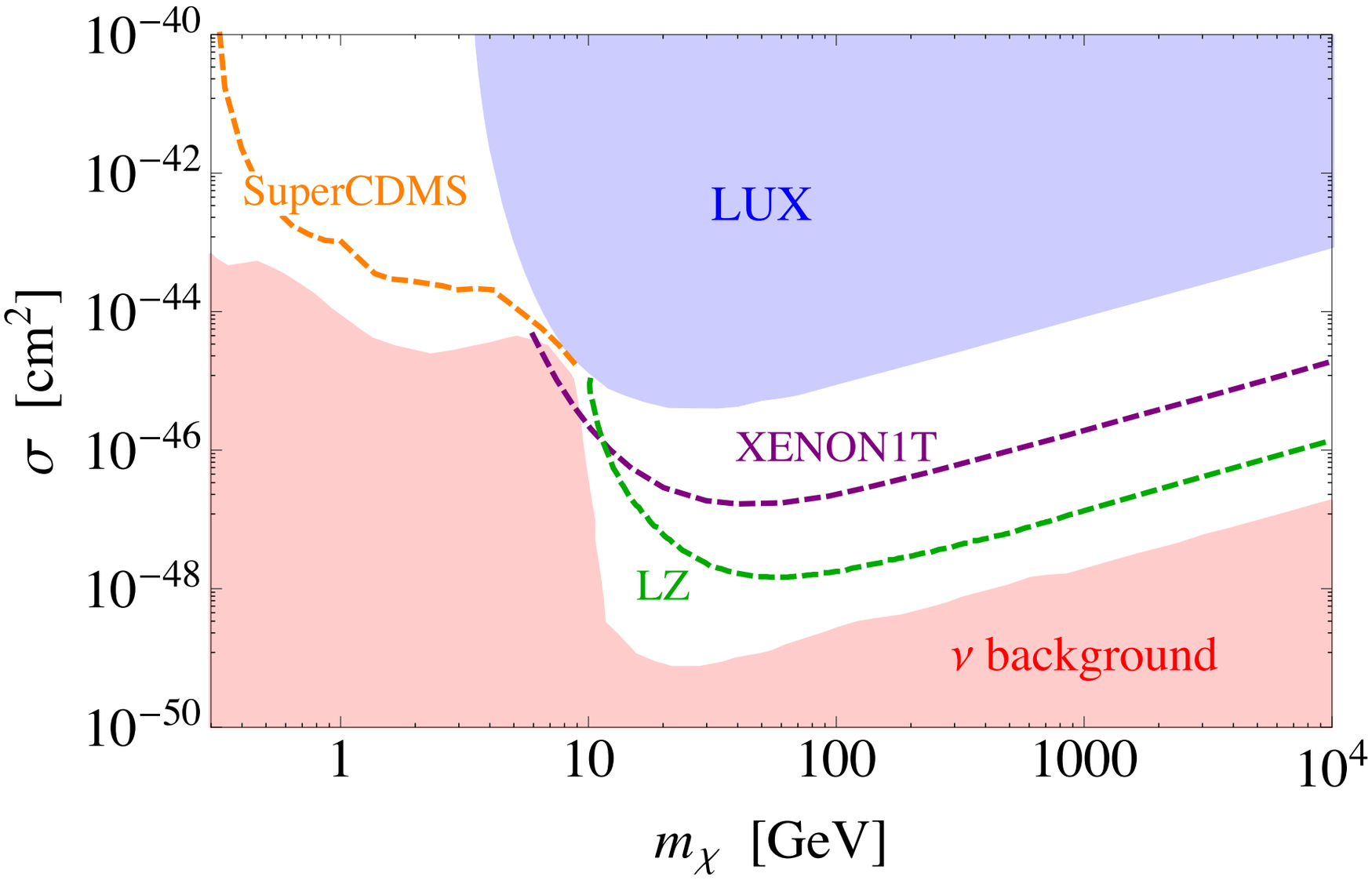
Josh Ruderman (NYU)
@Seoul 5/2/2016



"Mmmmmm … Interesting … interesting. … I'd say we taste a little like chicken."

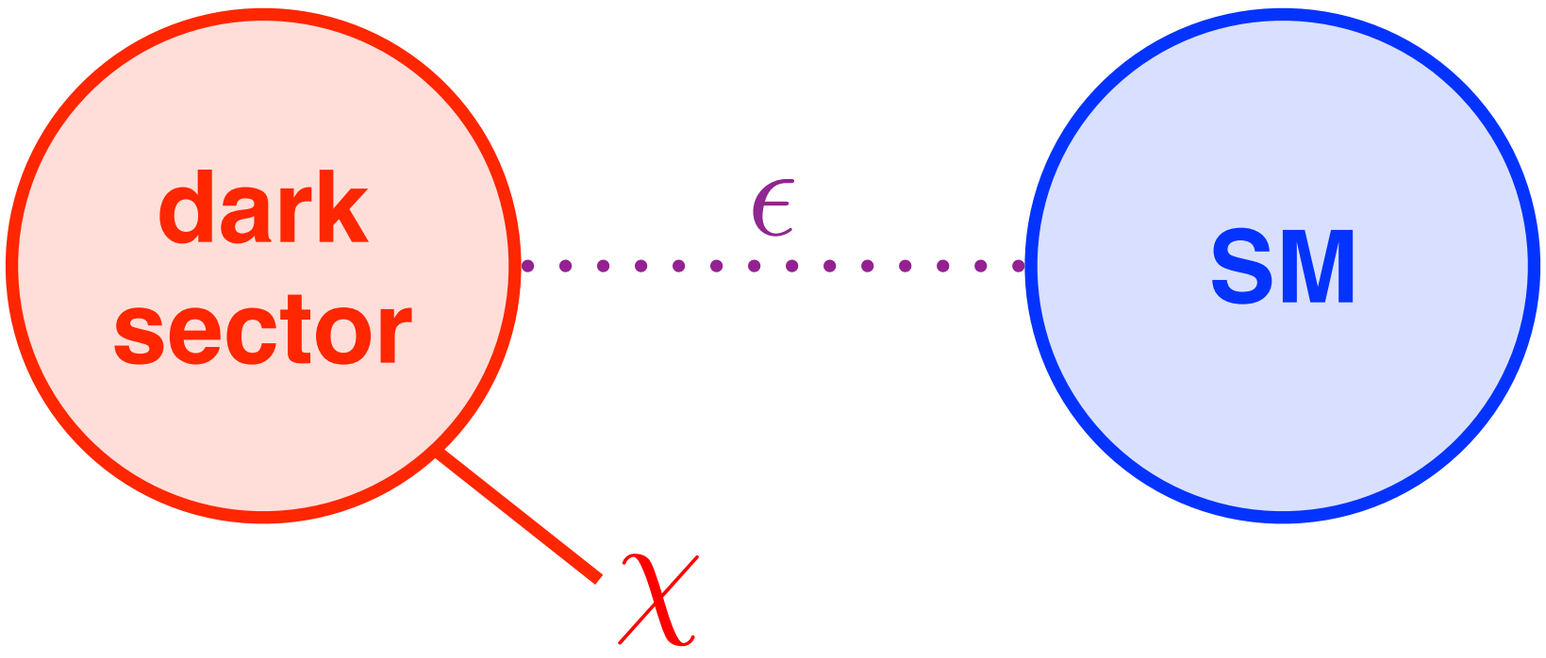
- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Towards the Neutrino Floor

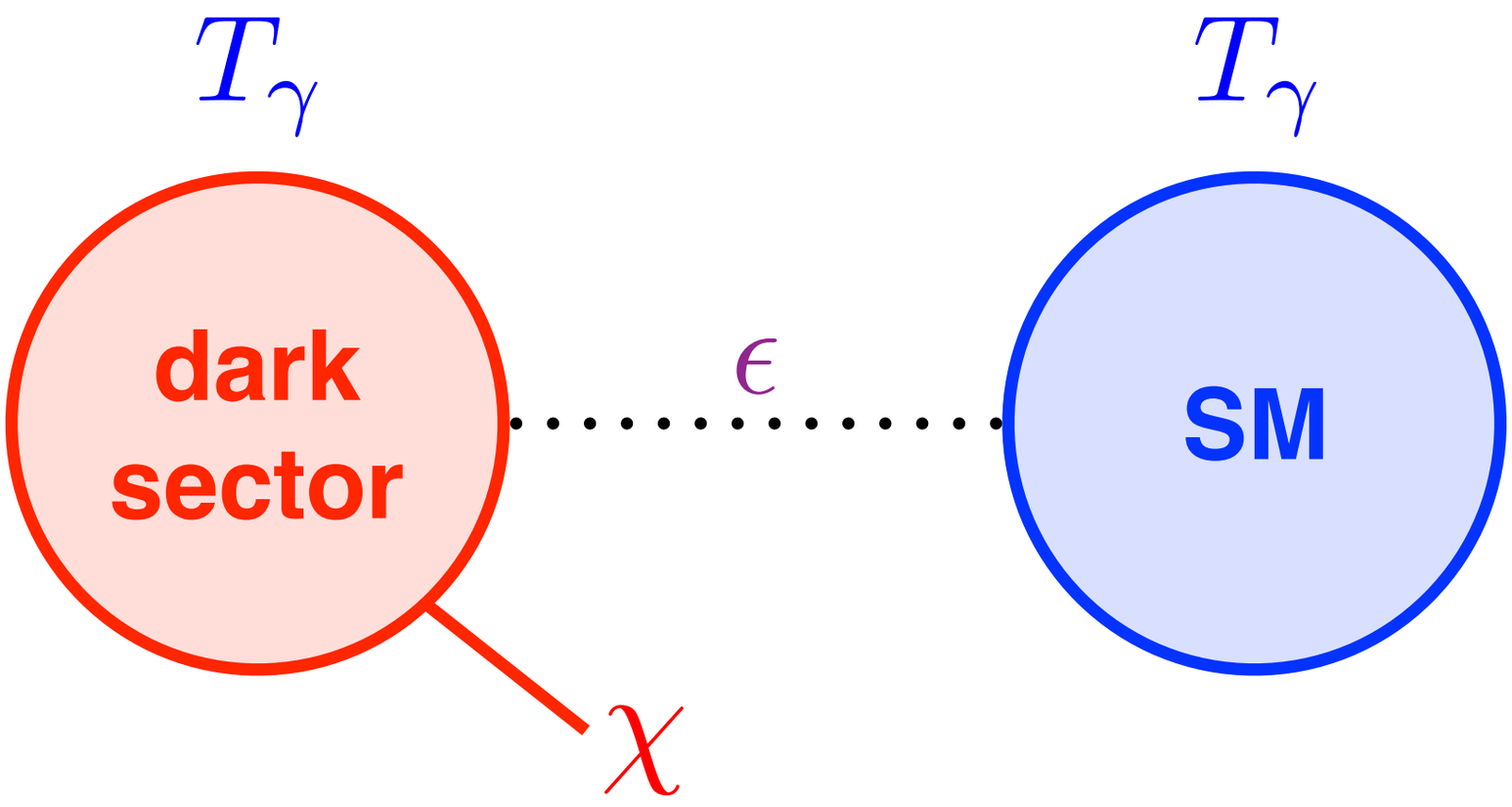


- XENON1T, **1512.07501**
- Snowmass, **1310.8327**

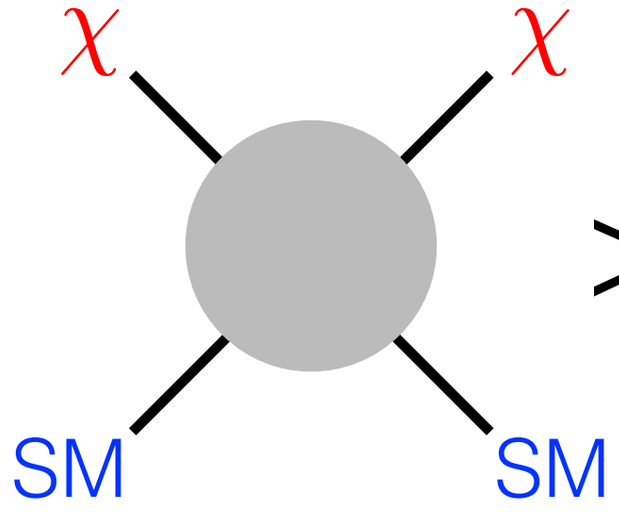
hidden sector dark matter



coupled sectors

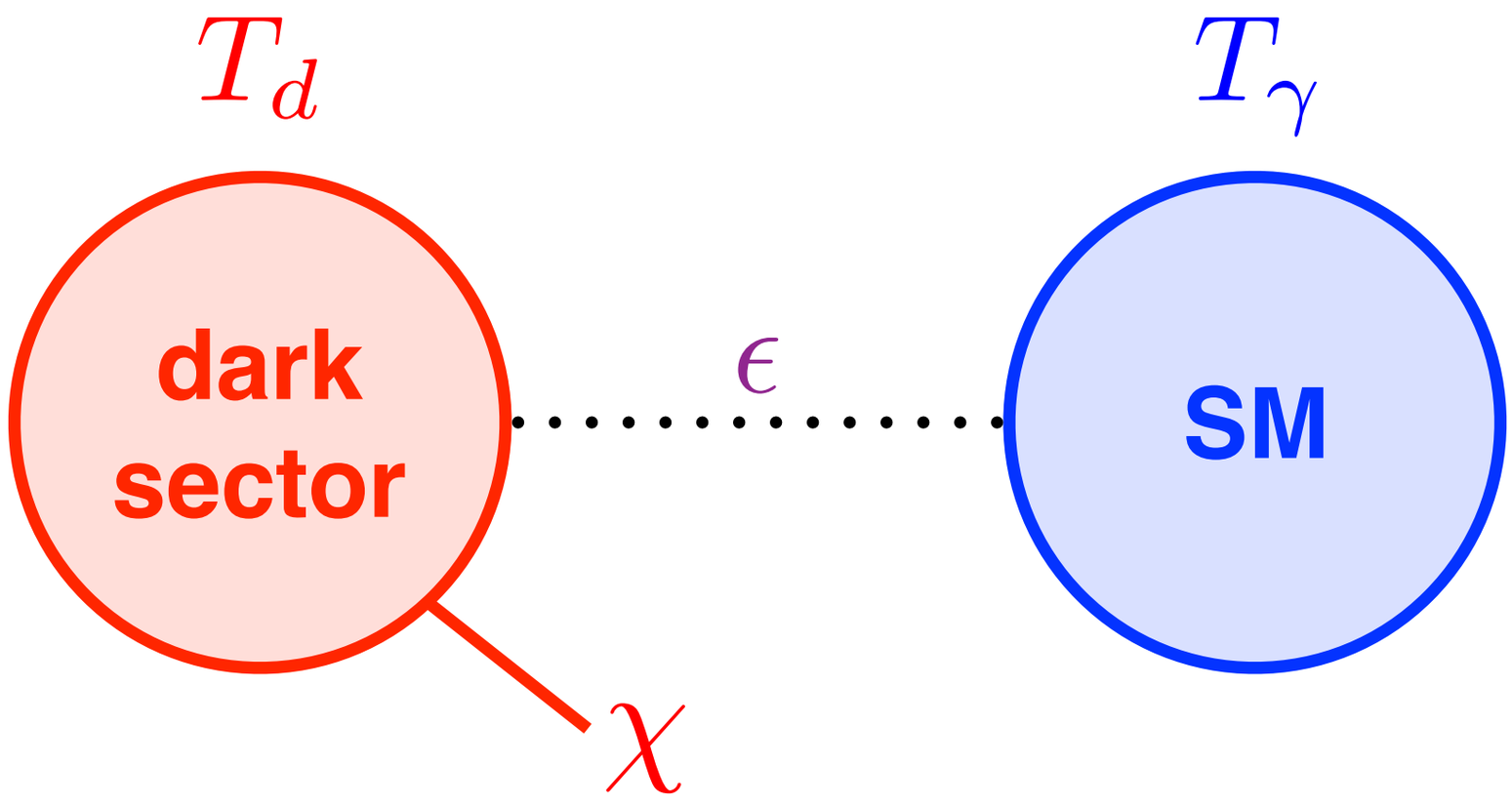


kinetic equilibrium:

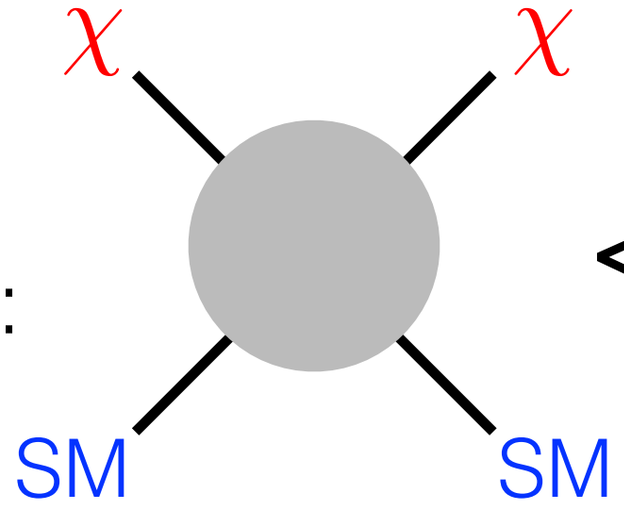


$$> H \qquad \epsilon \gtrsim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

decoupled sectors



kinetically decoupled:



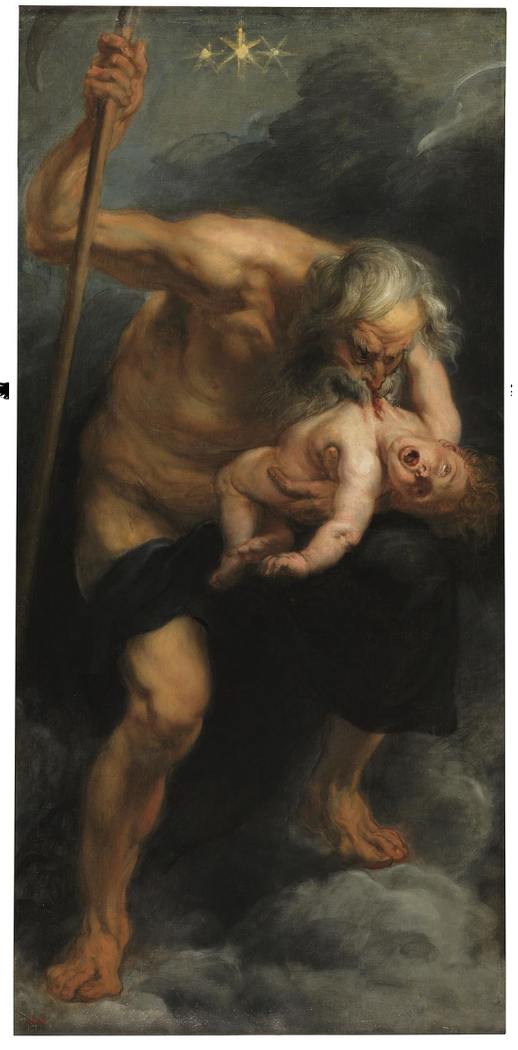
$$< H \qquad \epsilon \lesssim 10^{-8} \sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

Hidden Sector Taxonomy

non-gapped

gapped

cannibalism



T_d

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

  - Feng, Tu, Yu **0808.2318**

plan

1. Cannibalism
2. Cannibal Dark Matter

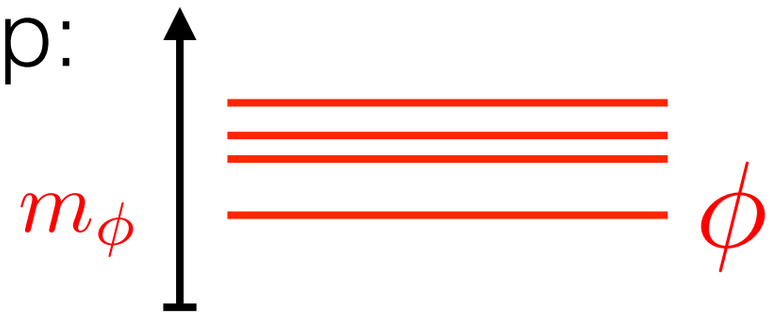
Cannibalism

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:

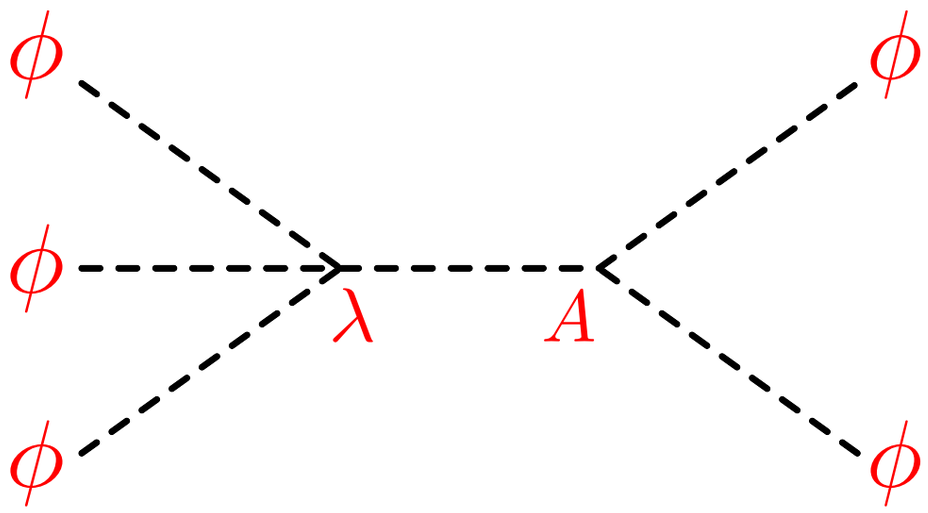
$$T_d < m_\phi$$

4. no chemical potential:

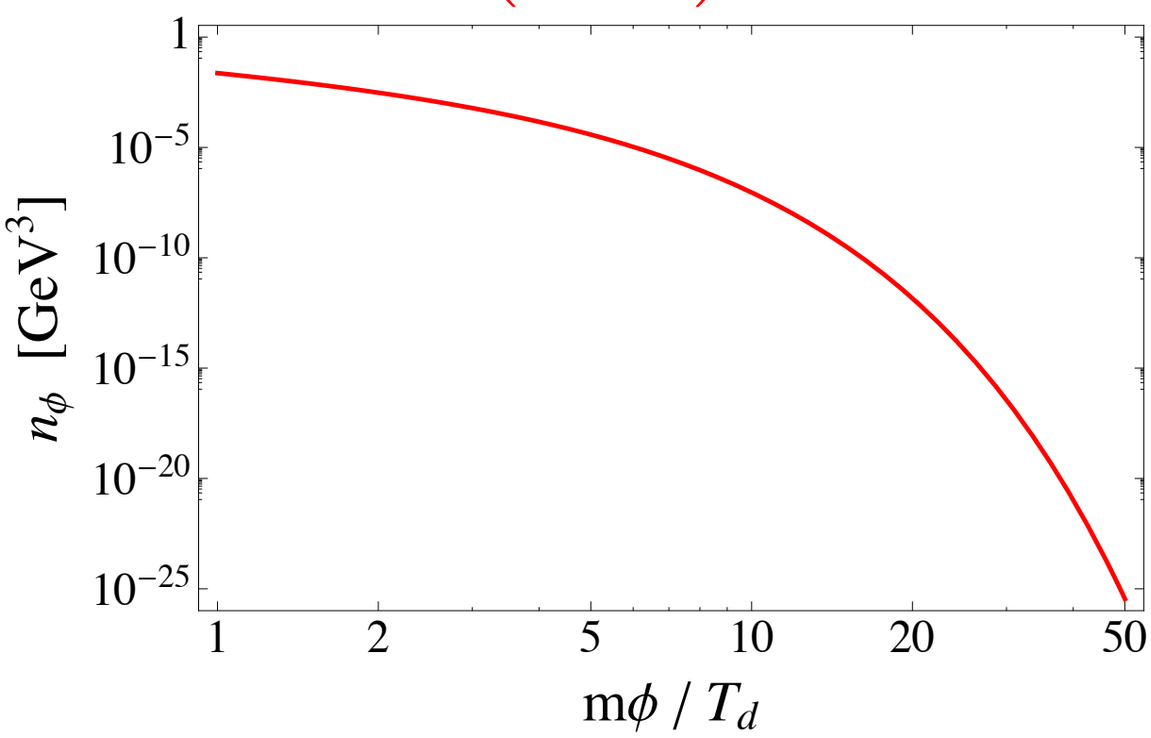
$$\mu_\phi = 0$$

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:

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

- 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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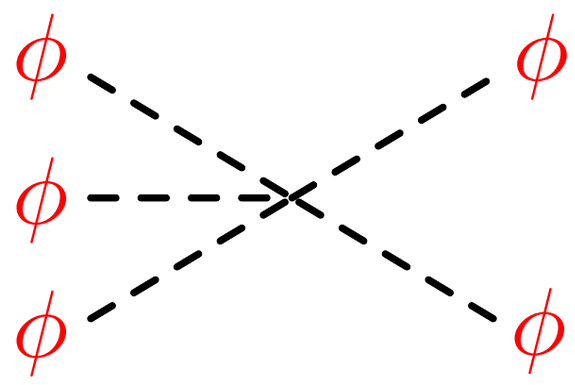
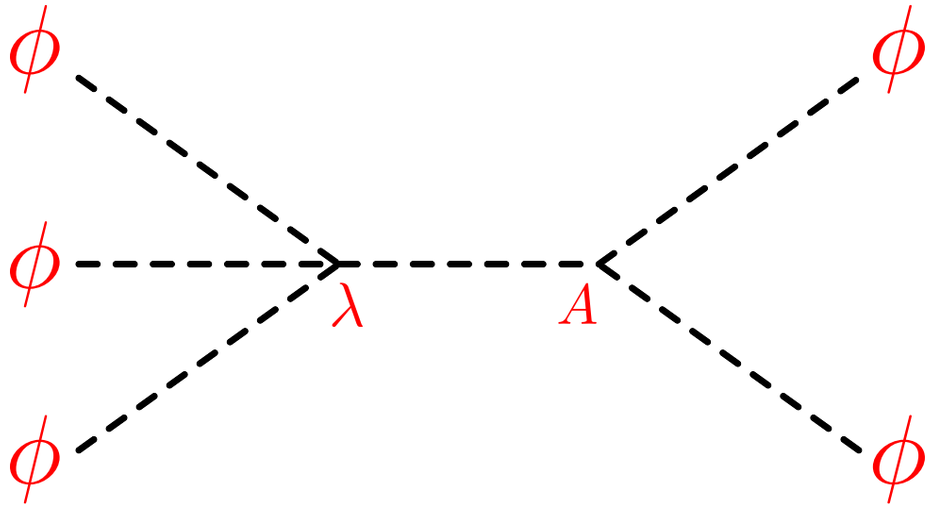
the number density of particles. Hence number changing processes like $3 \to 2$ or $4 \to 2$ will tend to deplete the number of dark matter particles. But these processes take nonrelativistic particles in and produce (fewer) relativistic particles out, so that the outgoing particles have much more kinetic energy than the mean $(3/2)T'$. Hence subsequent $2 \to 2$ 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

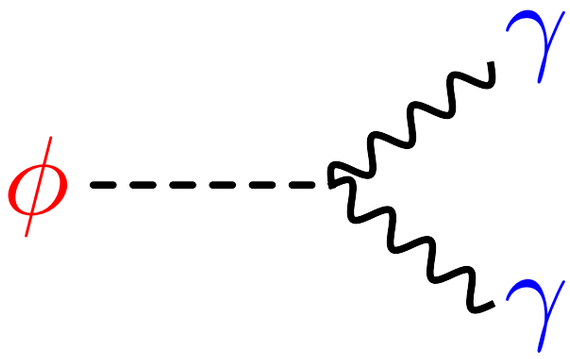
$\phi\phi\phi \to \phi\phi$ decoupling



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

ϕ decays

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



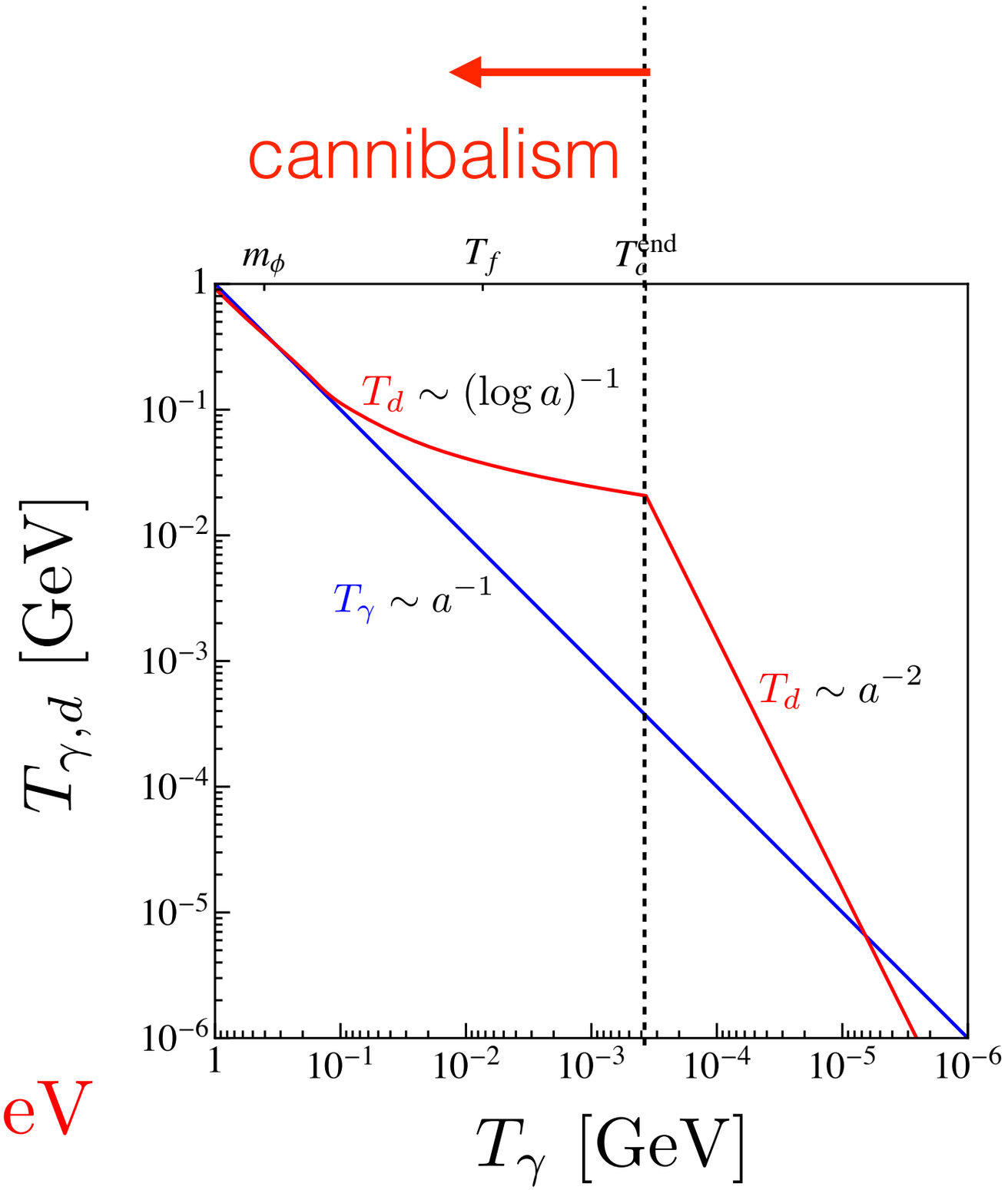
- during cannibalism:

$$\Gamma_\phi \ll H$$

- end of cannibalism:

$$\Gamma_\phi \approx H$$

Cannibalism

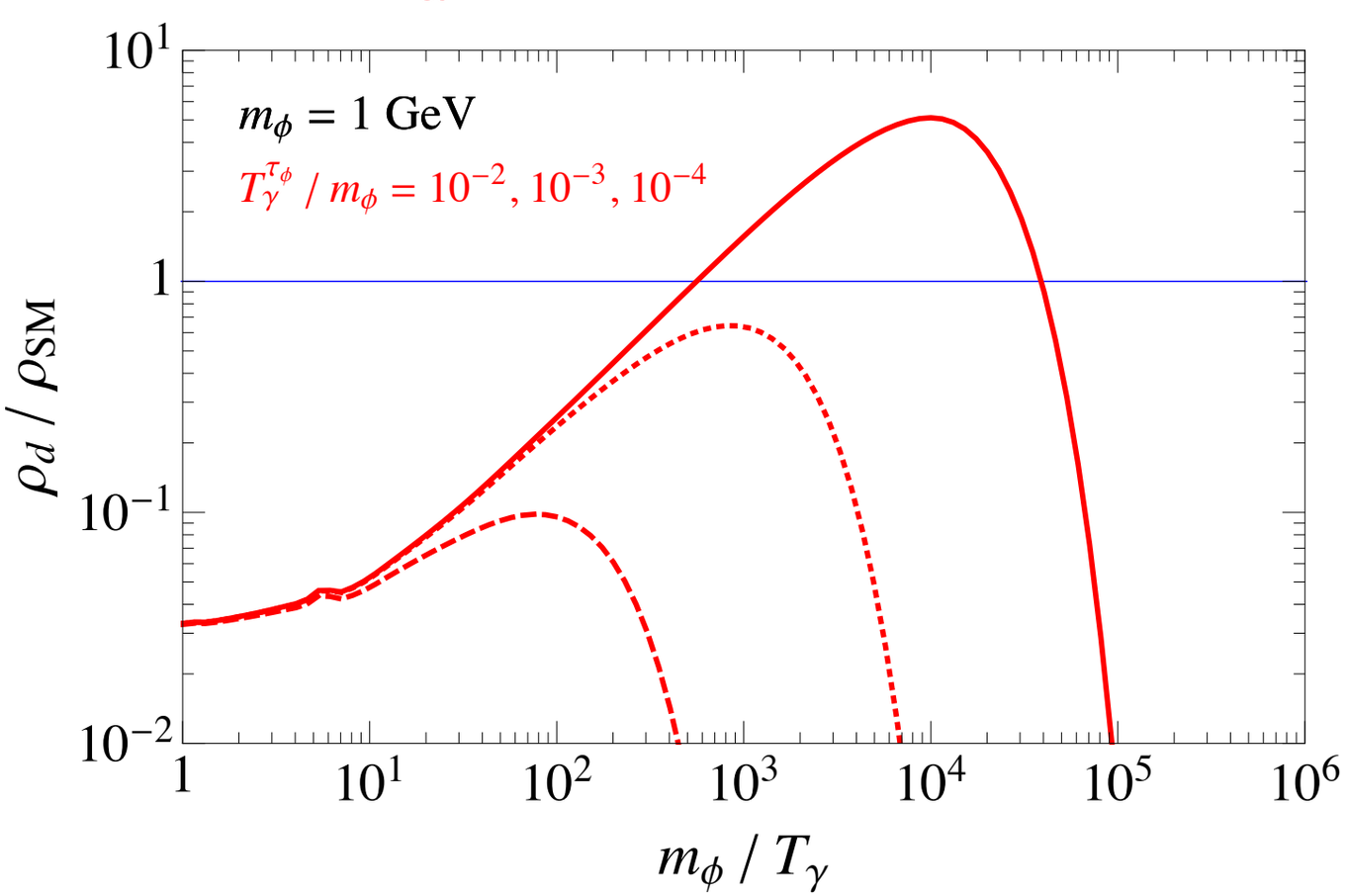


$m_\phi = 0.4$ GeV

ϕ Domination

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

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



ϕ Dark Matter?

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

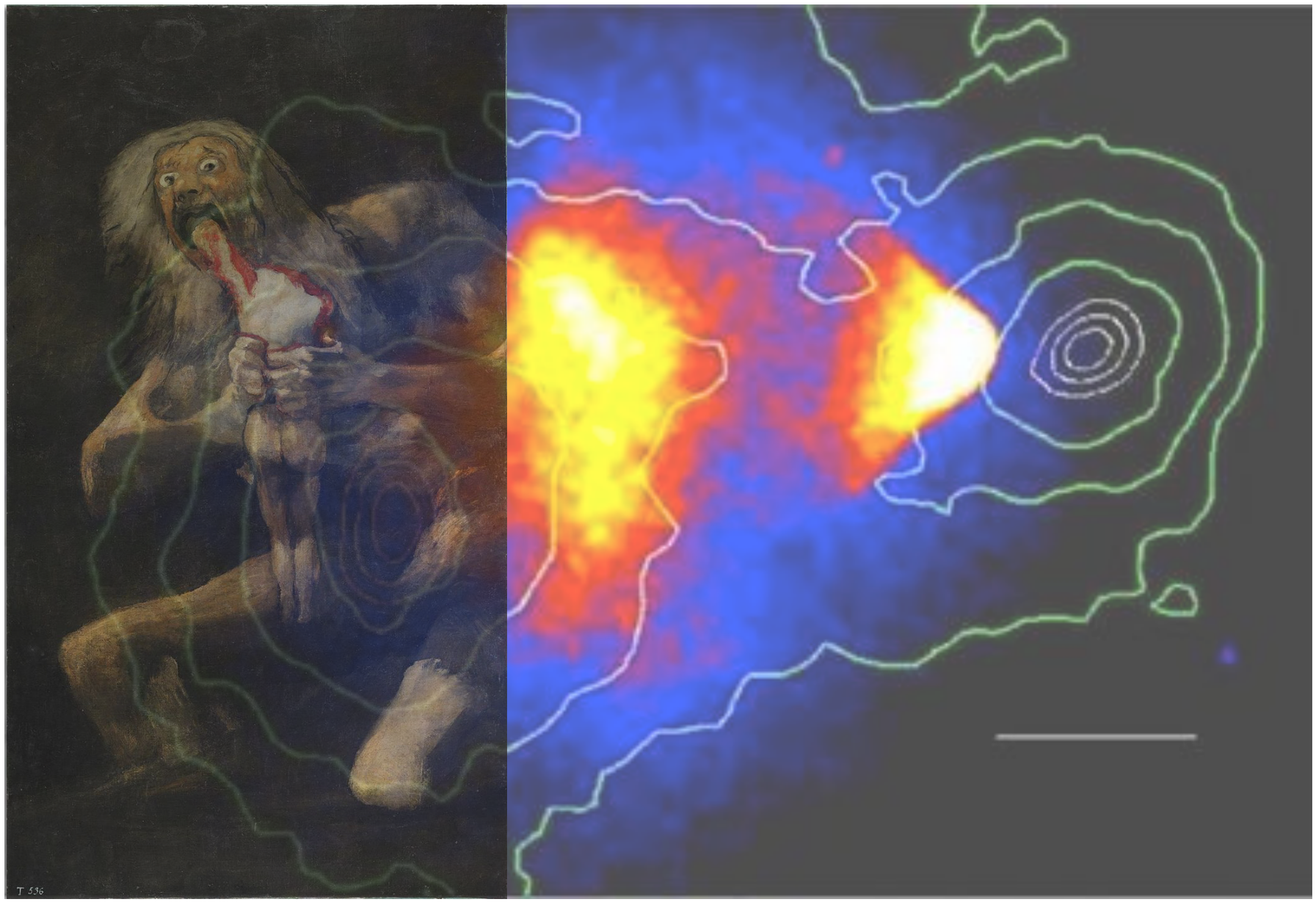
$$x_f = \frac{m_\phi}{T_d^f} \qquad \xi = \frac{s_{SM}}{s_d}$$

- 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



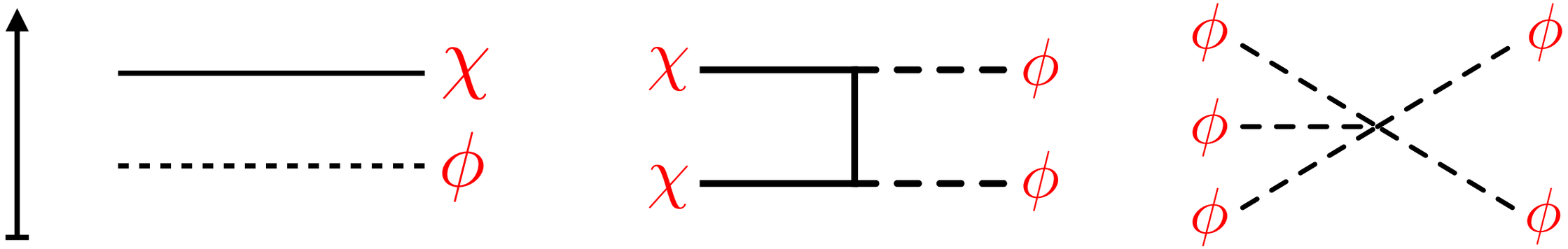
Cannibal Dark Matter

- Suppose ϕ is not dark matter

- What if cannibalizing ϕ is the **background** for the production of dark matter: χ?

Cannibal Dark Matter

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



mass

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

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

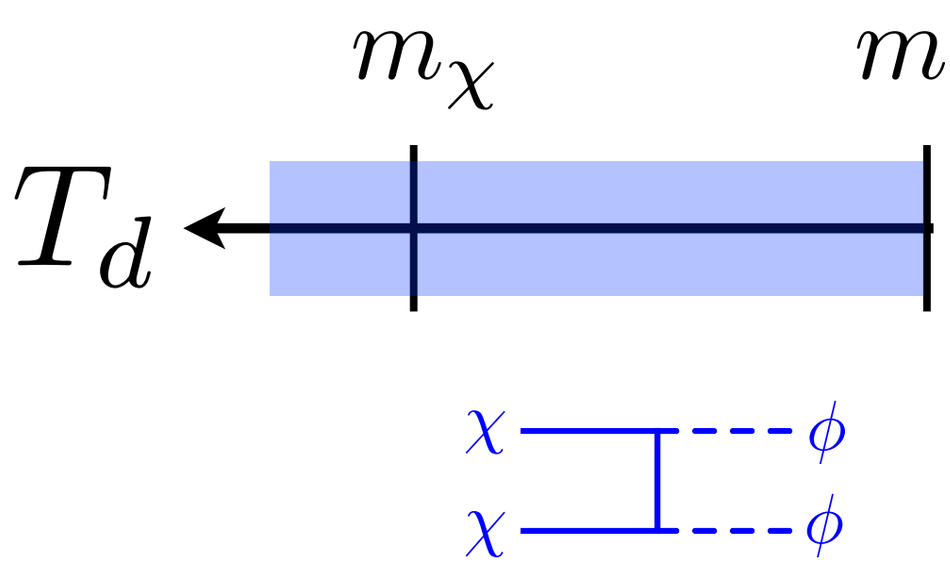
- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

1)

χ annihilations are in equilibrium

ϕ is relativistic



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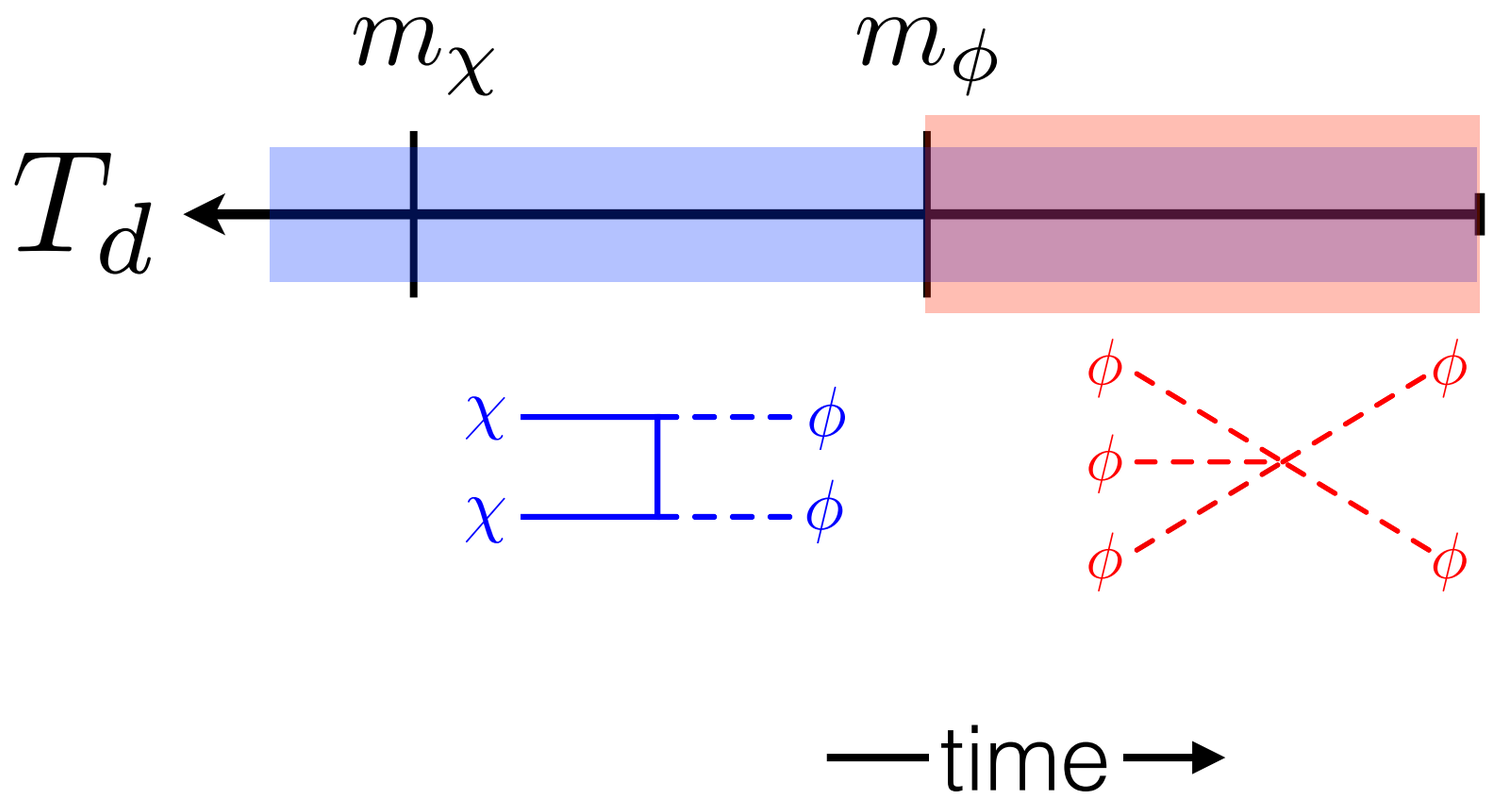
Cannibal Dark Matter

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



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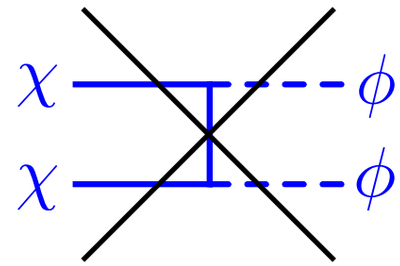
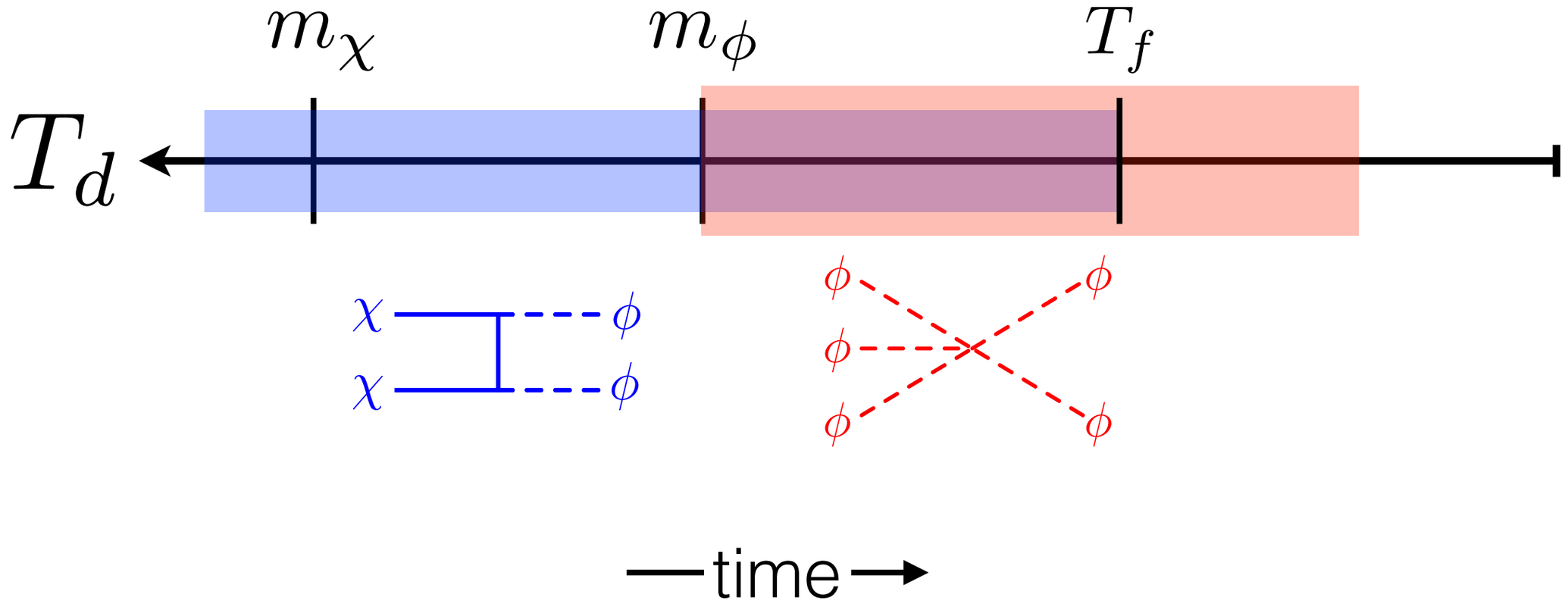
Cannibal Dark Matter

3) χ annihilations freezeout**:**



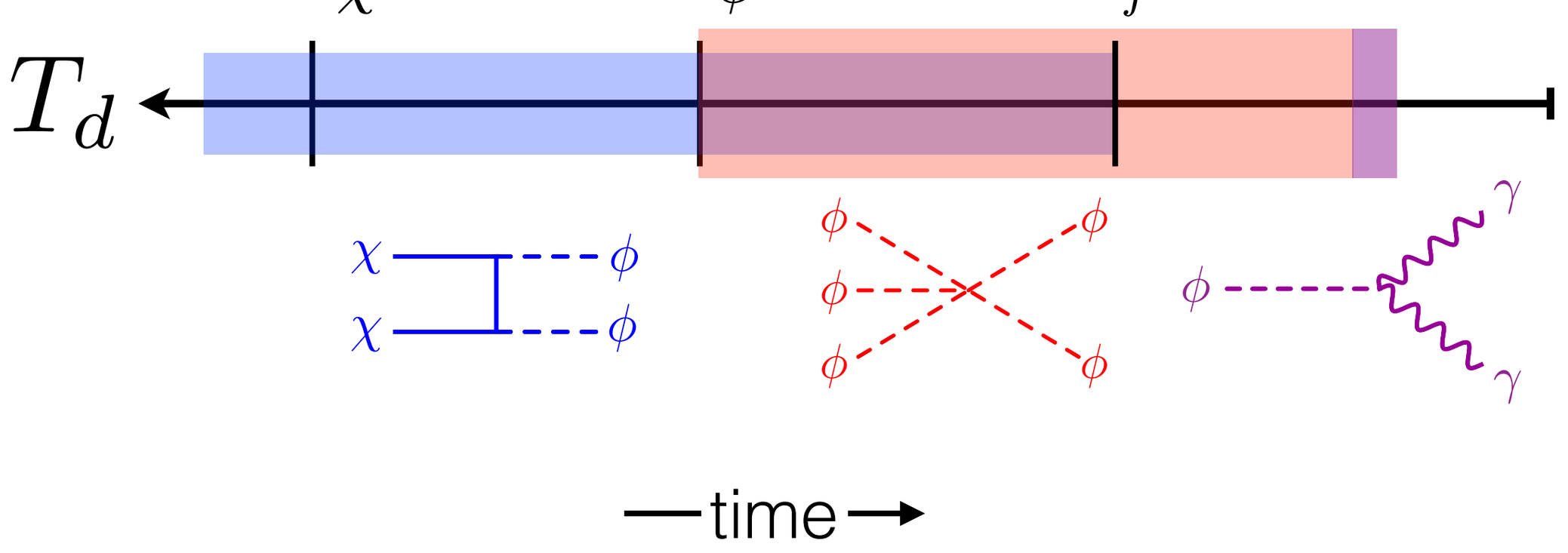


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Cannibal Dark Matter

4) cannibalism ends when**:**

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

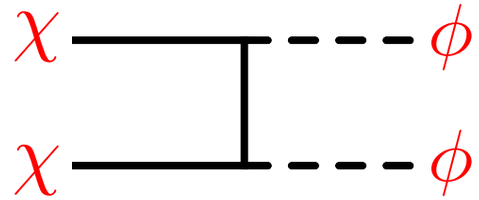


- Duccio Pappadopulo, JTR, Gabriele Trevisan, **1602.04219**

Relic Density

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

freezeout:



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

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

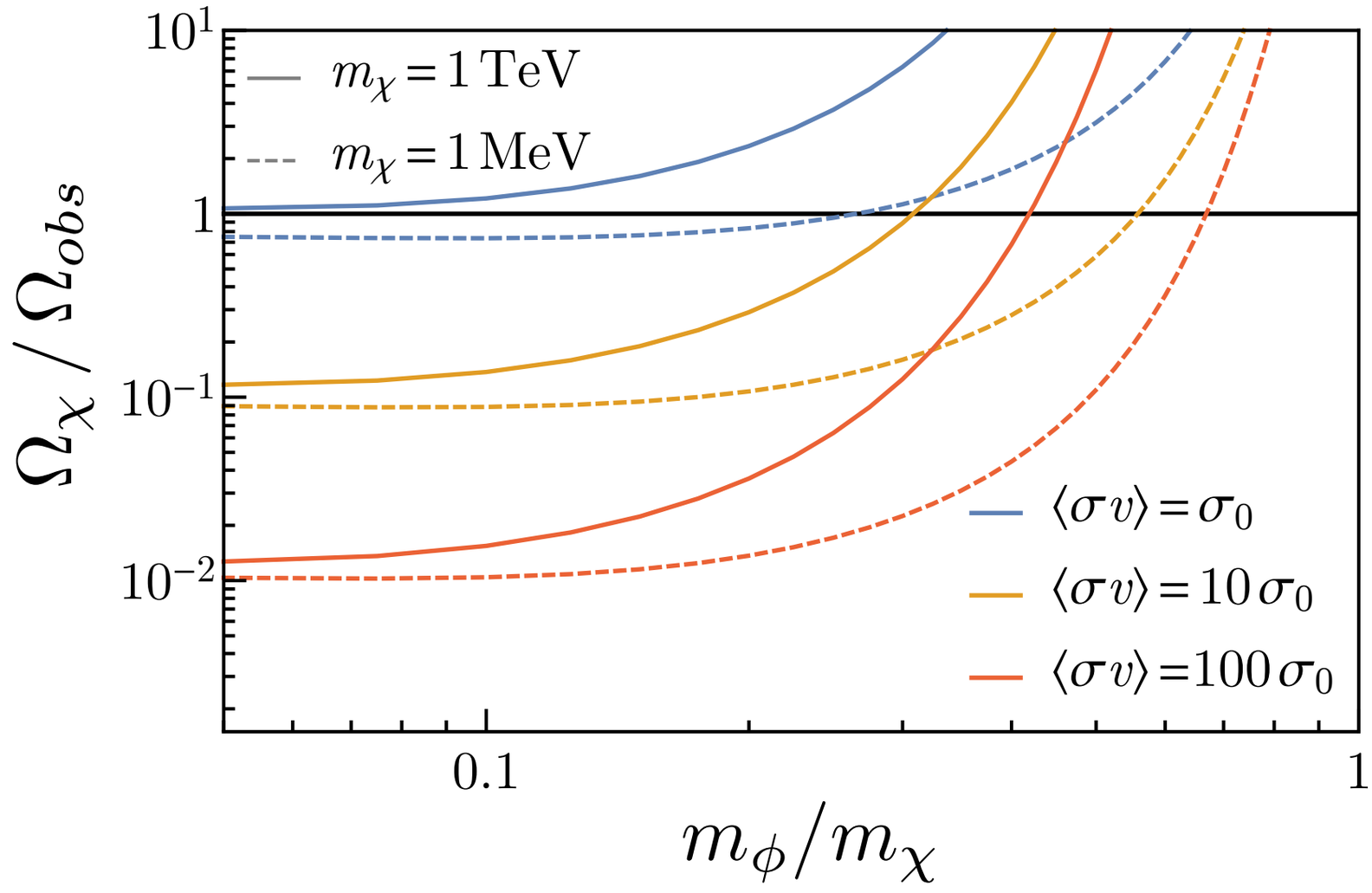
$$x_f \equiv \frac{m_\chi}{T_d^f}$$

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

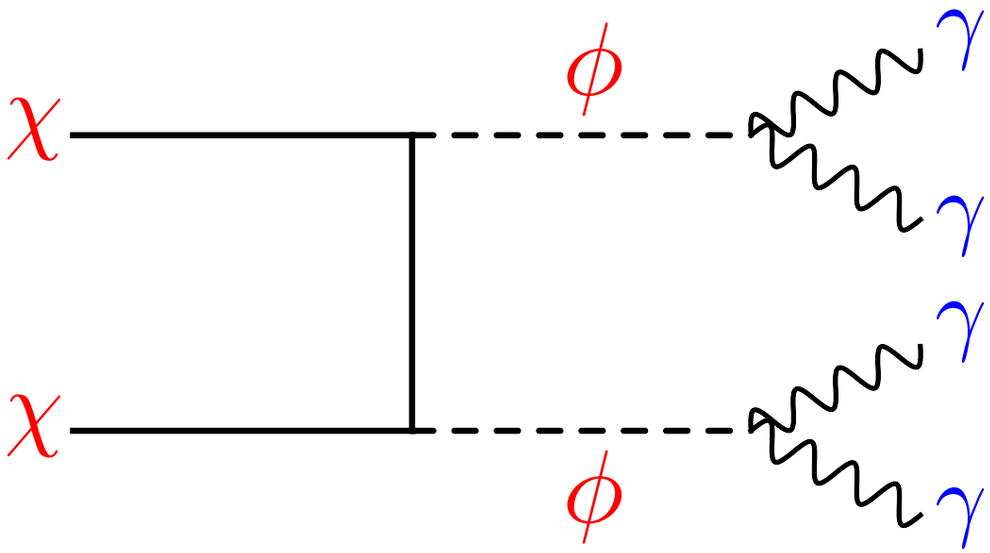
$$\sigma_0 = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

Relic Density

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



Indirect Detection



boosted cross:

$$\langle \sigma v \rangle \sim \sigma_0 \, e^{m_\phi / 3 T_d^f}$$

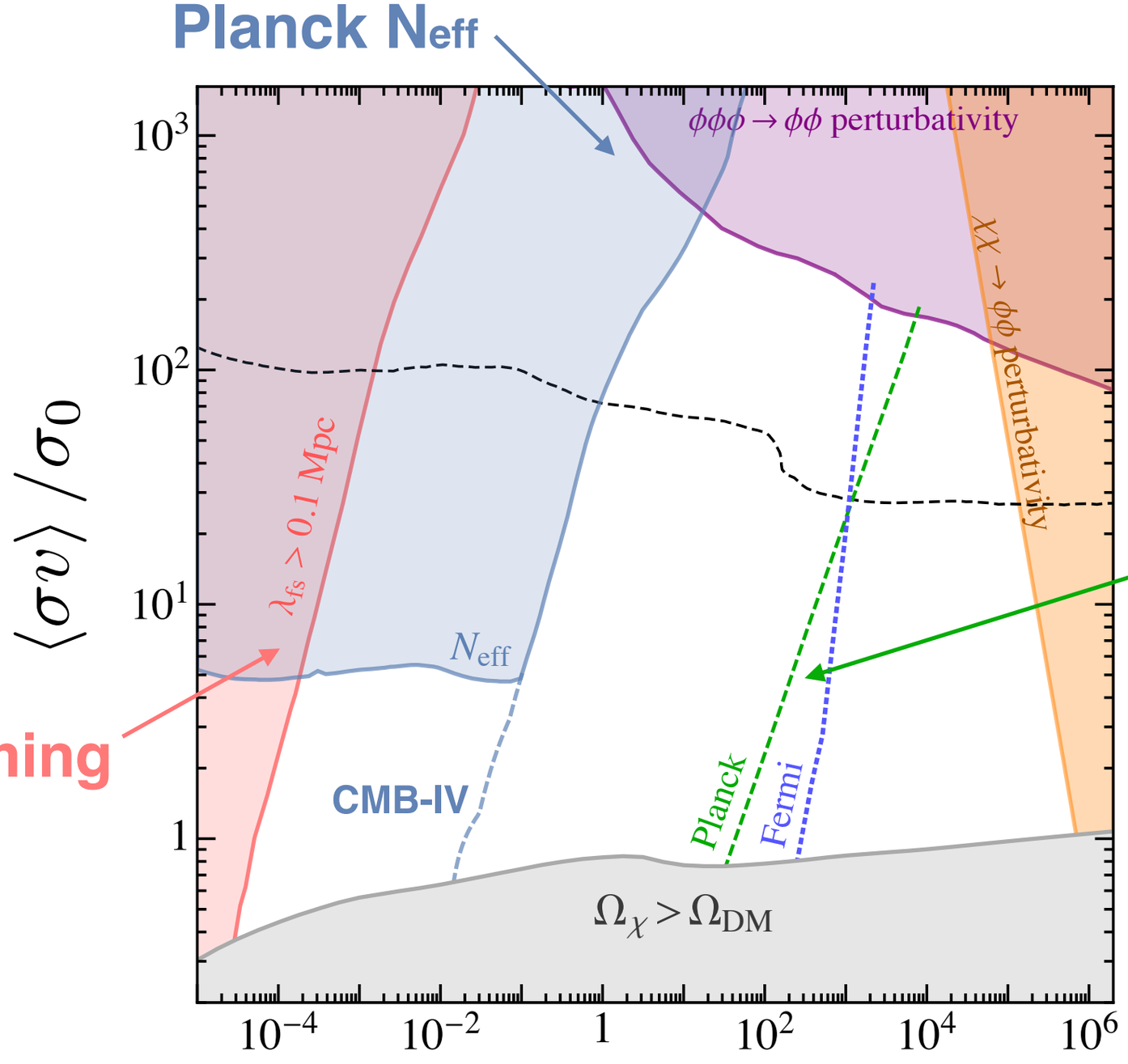
$$\frac{y}{2} \, \phi \, \chi^2$$

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

Cannibal DM Pheno

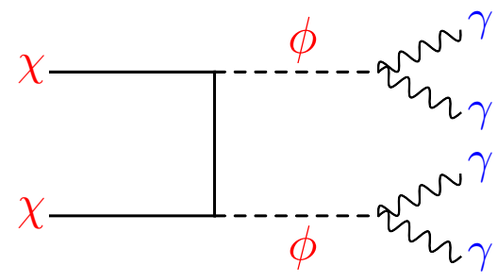
$$\xi \approx 39$$

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



free-streaming

indirect
(s-wave)

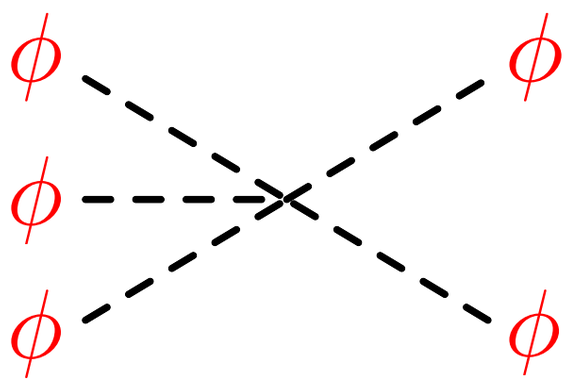


Elor, Rodd, Slatyer, Xue,
1511.08787

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

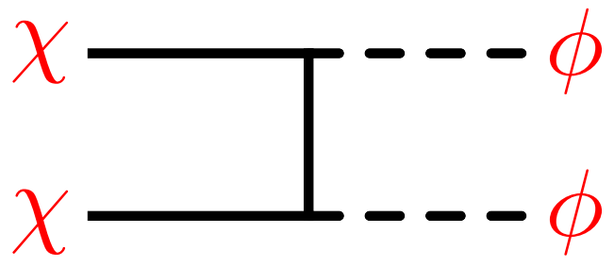
take away

- a hidden sector with a mass gap generically undergoes a phase of **cannibalism**



$$\frac{T_\gamma}{T_d} \propto e^{-m_\phi/3T_d}$$

- **cannibal dark matter**: 2-to-2 freezeout in a cannibalizing sector



- **pheno:** - boosted annihilation **σ**