Cannibal Dark Matter

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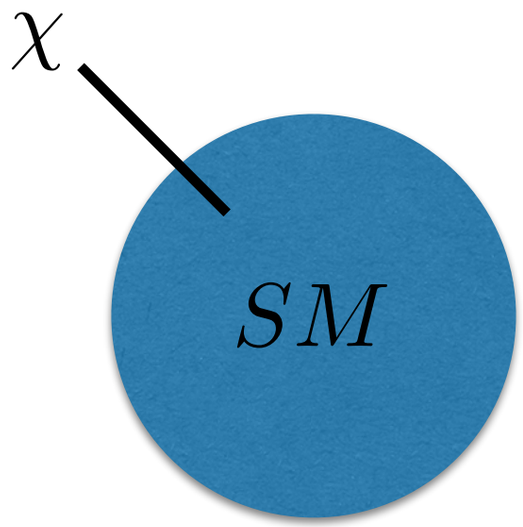
Based on: D. Pappadopulo, J. Ruderman, G. Trevisan ‘16
M.F., D. Pappadopulo, J. Ruderman, G. Trevisan ‘16

Why WIMP?

Cold dark matter



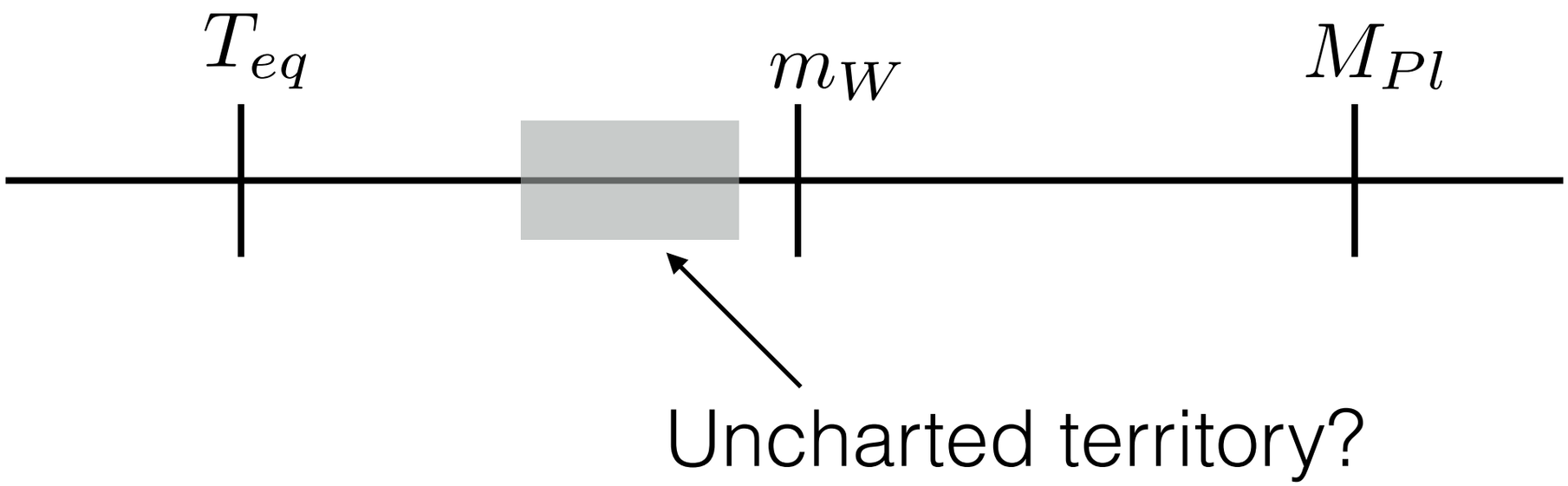
- Extremely successful
  (cold, pressureless, non interacting)

- Extremely simple

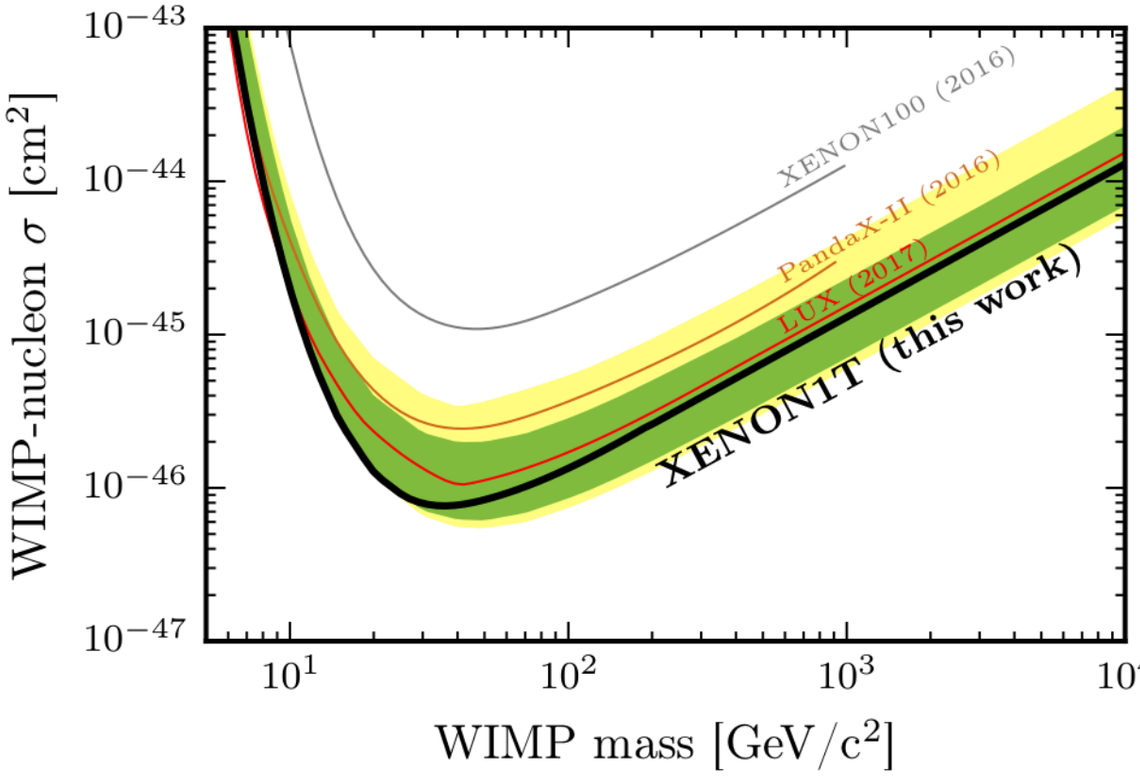
- WIMP miracle + Hierarchy problem

WIMP miracle?

- $\alpha_W \sqrt{T_{eq} M_{Pl}} \sim 1 \text{ TeV}$ "numerology"?
- No signs of solutions to the hierarchy problem at LHC
- Moreover…

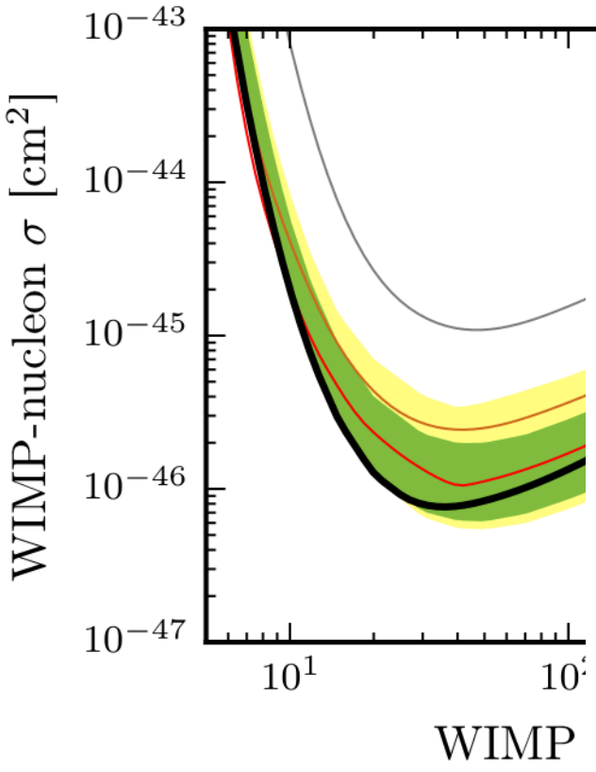


WIMP miracle?

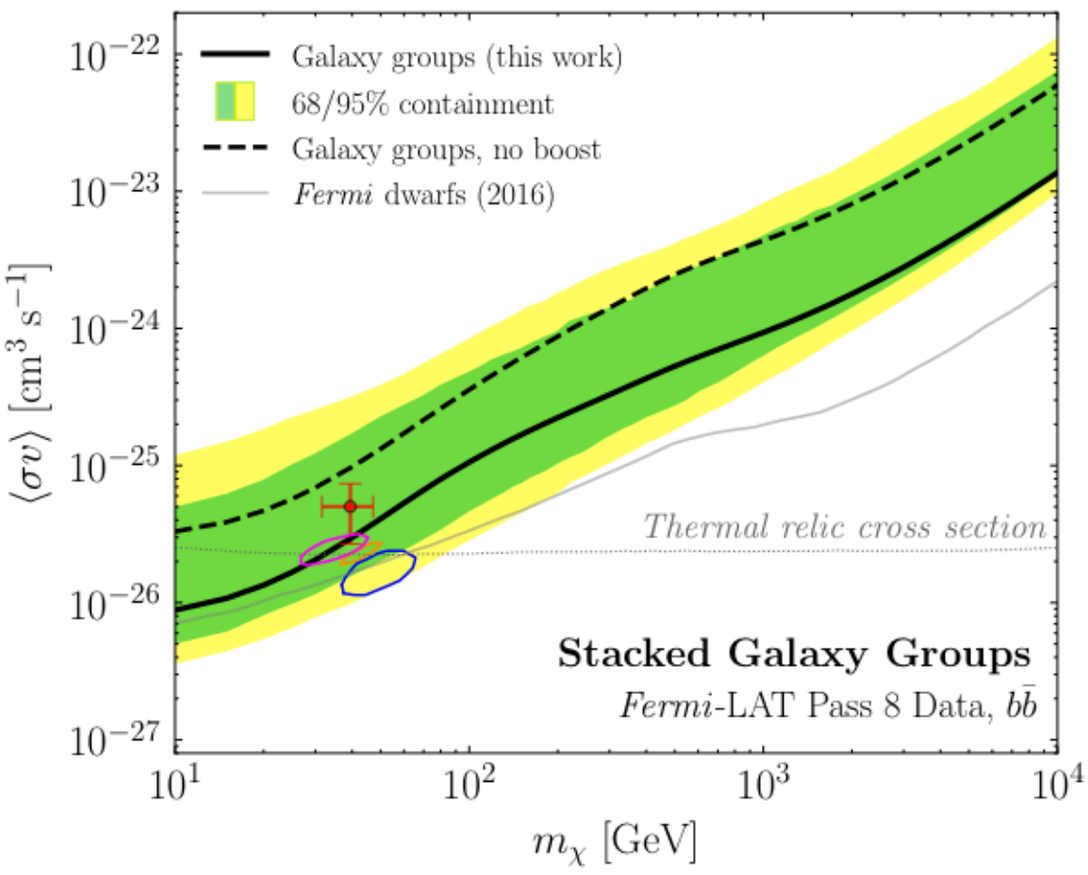


XENON 1T ’17

WIMP miracle?

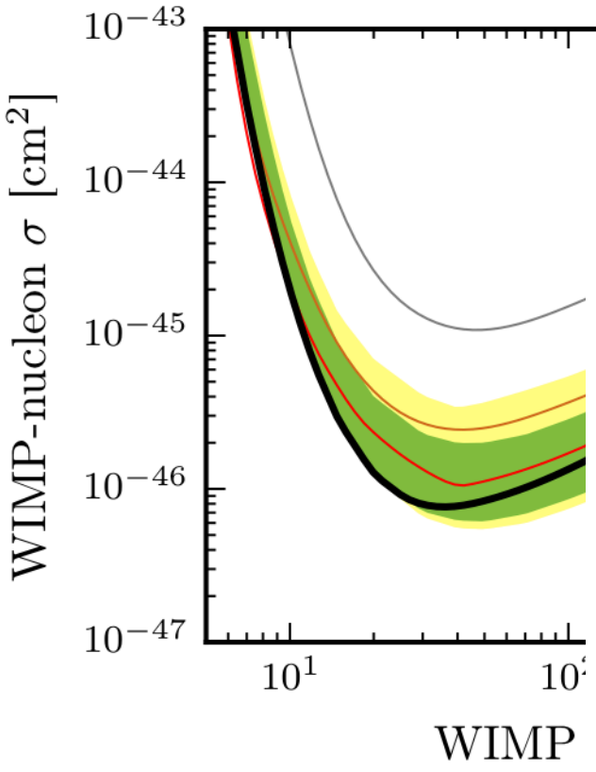


XENON 1T ’17

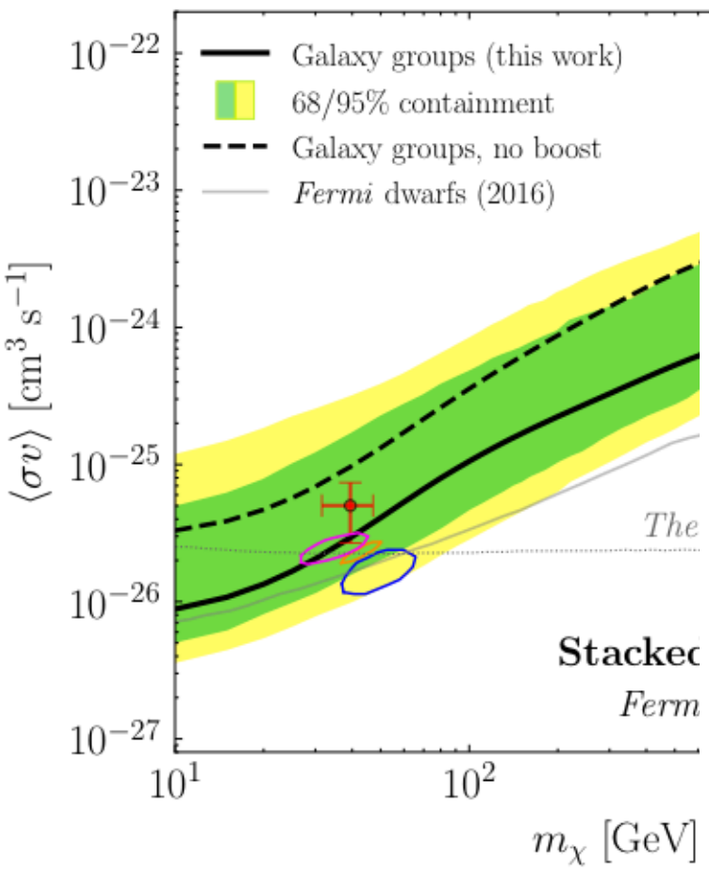


Lisanti et al. ‘17

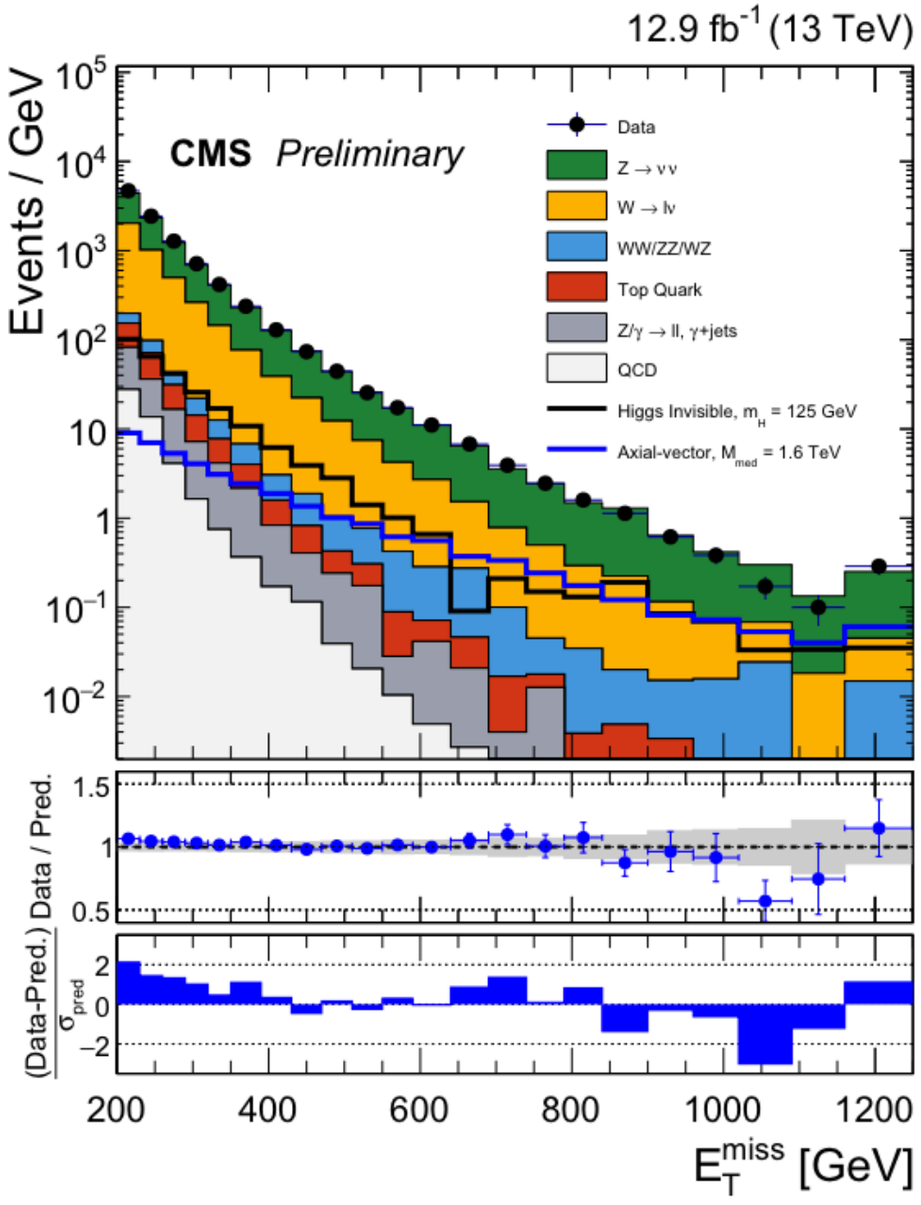
WIMP miracle?



XENON 1T ’17

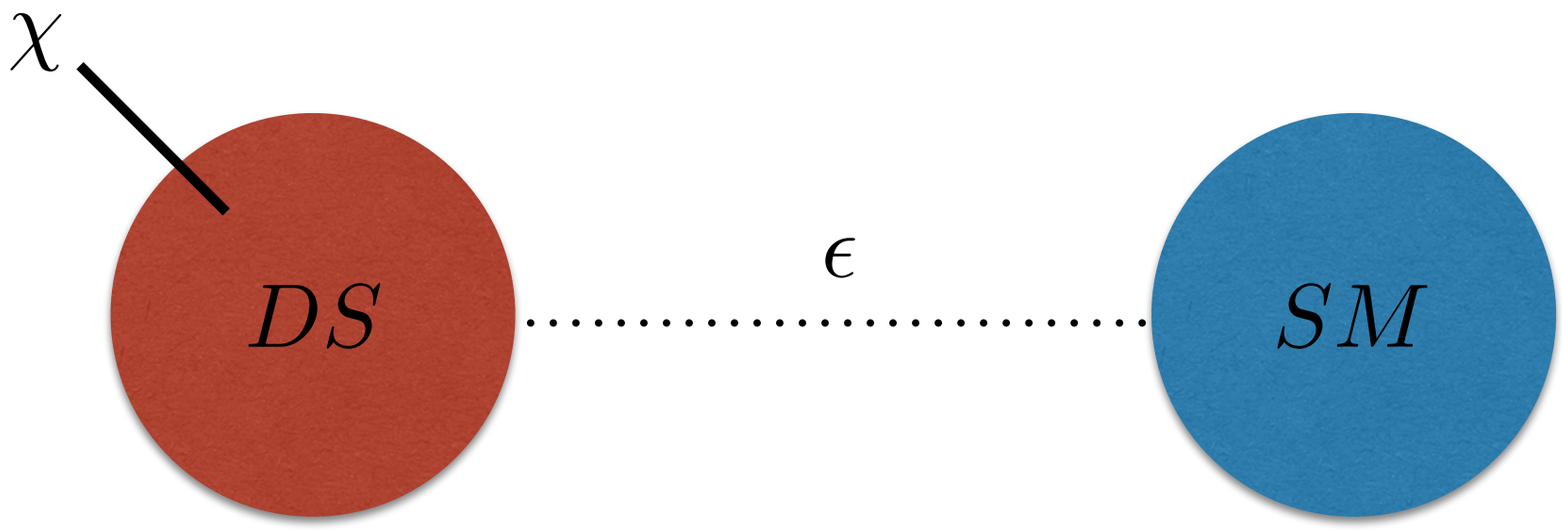


Lisanti et al. ‘17



CMS EXO-16-037-pas

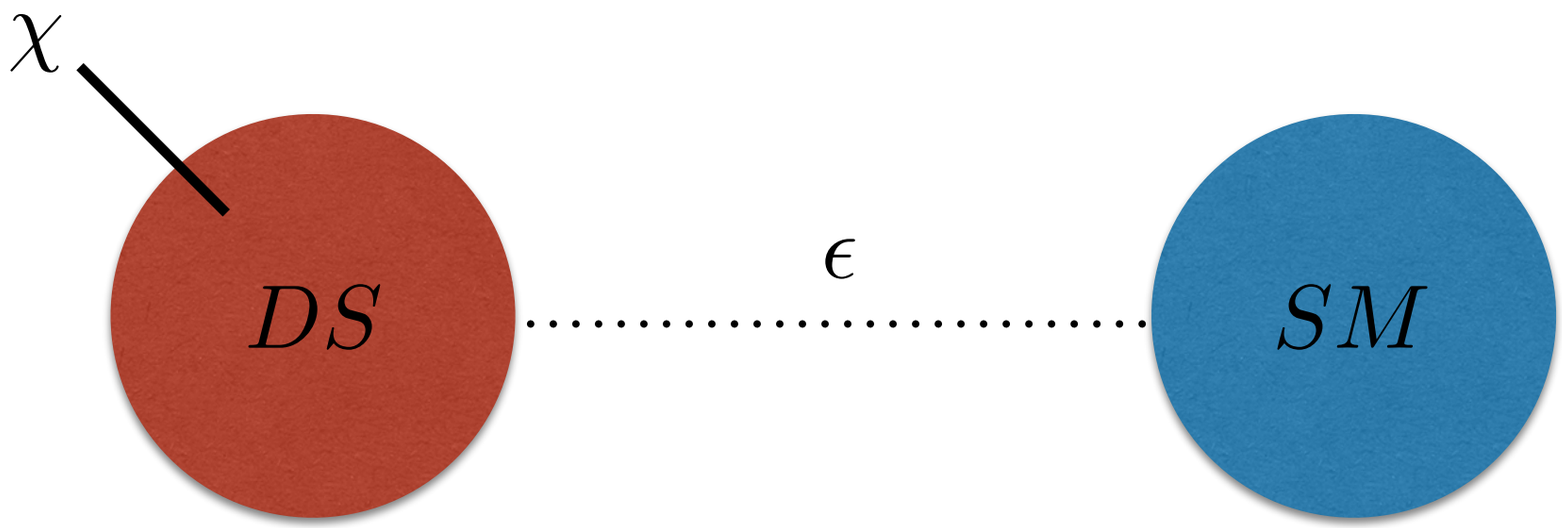
Beyond WIMP



Dark Sectors are well motivated

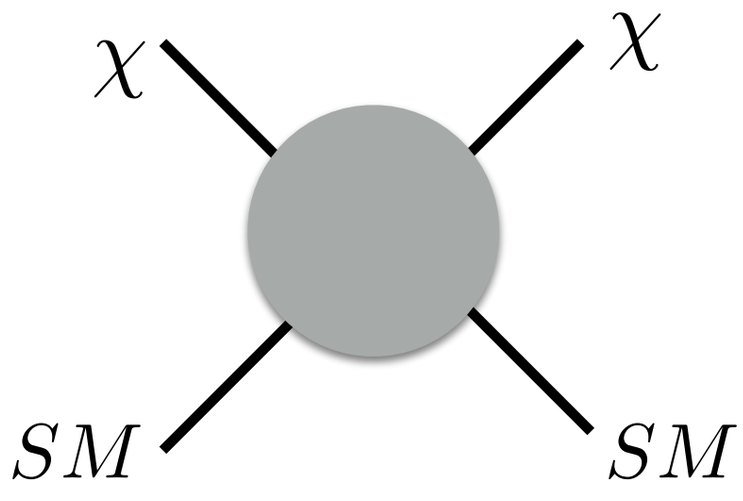
- Theoretically a more complex dark sector…
- Self interactions and light dark matter can affect structure formation, produce new experimental signatures

Beyond WIMP



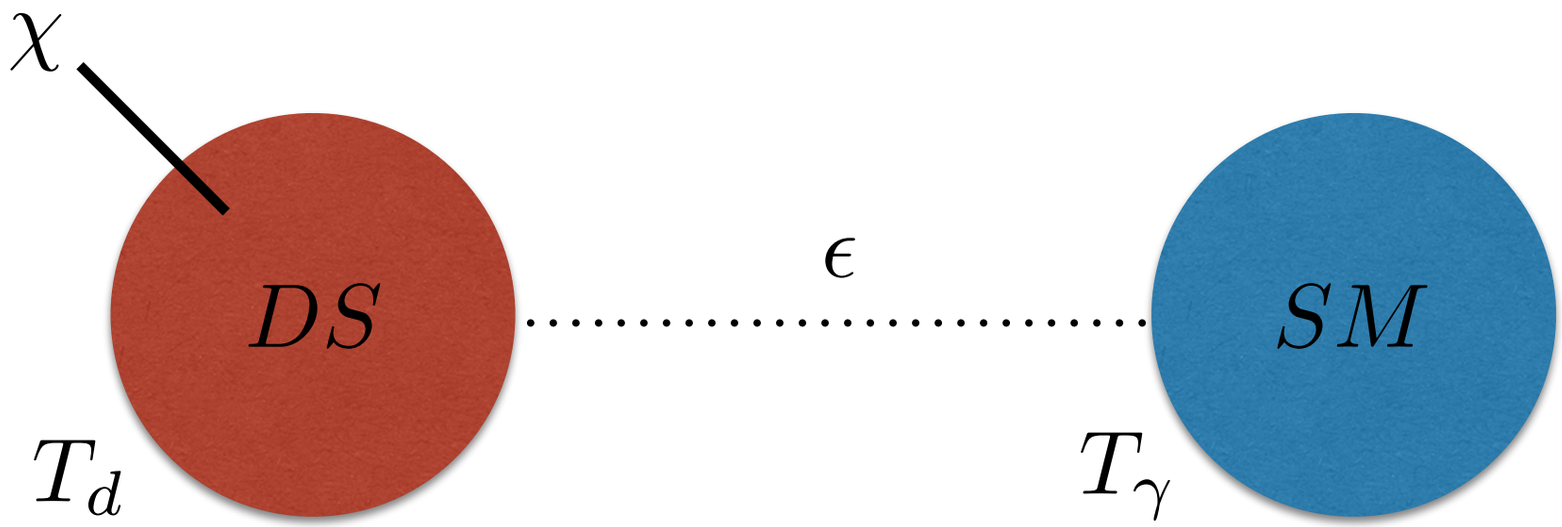
- SM and Dark Sector kinetically coupled

- WIMPless, Forbidden DM, SIMP (see Hitoshi's talk)



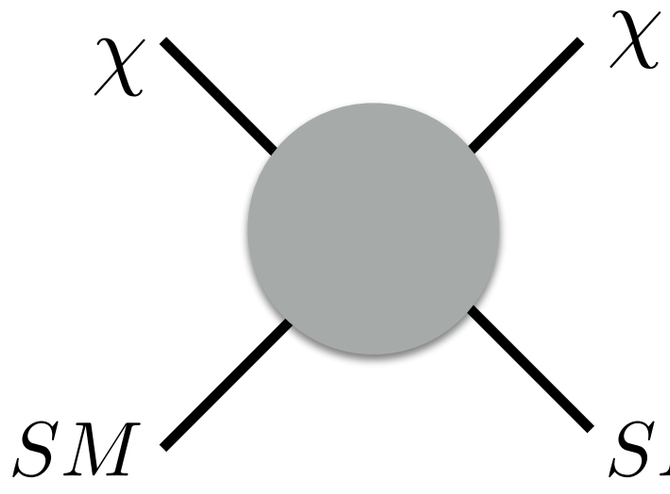
$$> H \qquad \epsilon \gtrsim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

Beyond WIMP



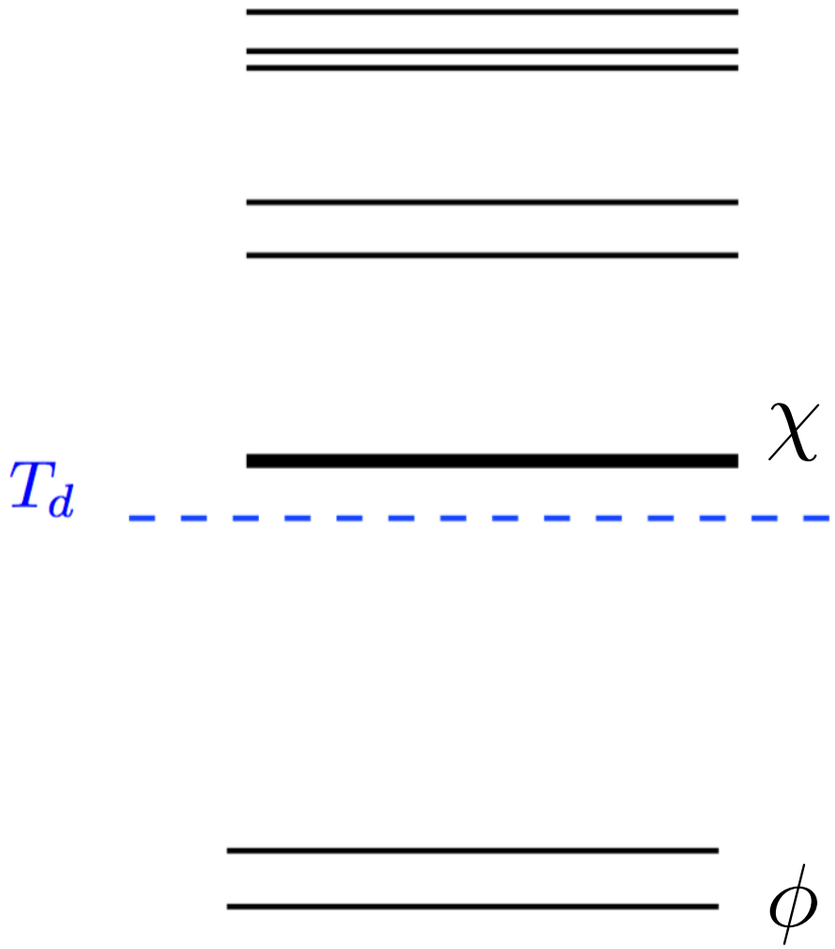
- SM and Dark Sector decoupled. Different temperature

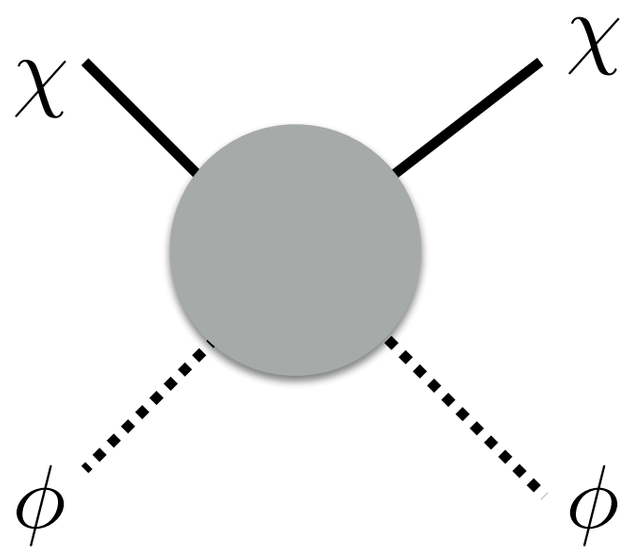
- Cannibal DM…

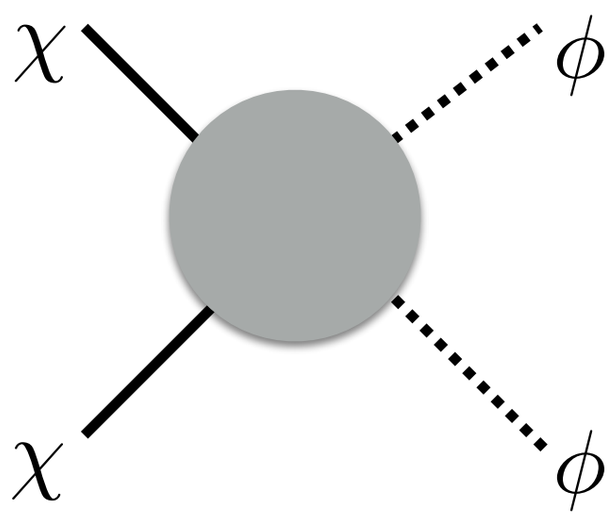


$$< H \qquad \epsilon \lesssim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

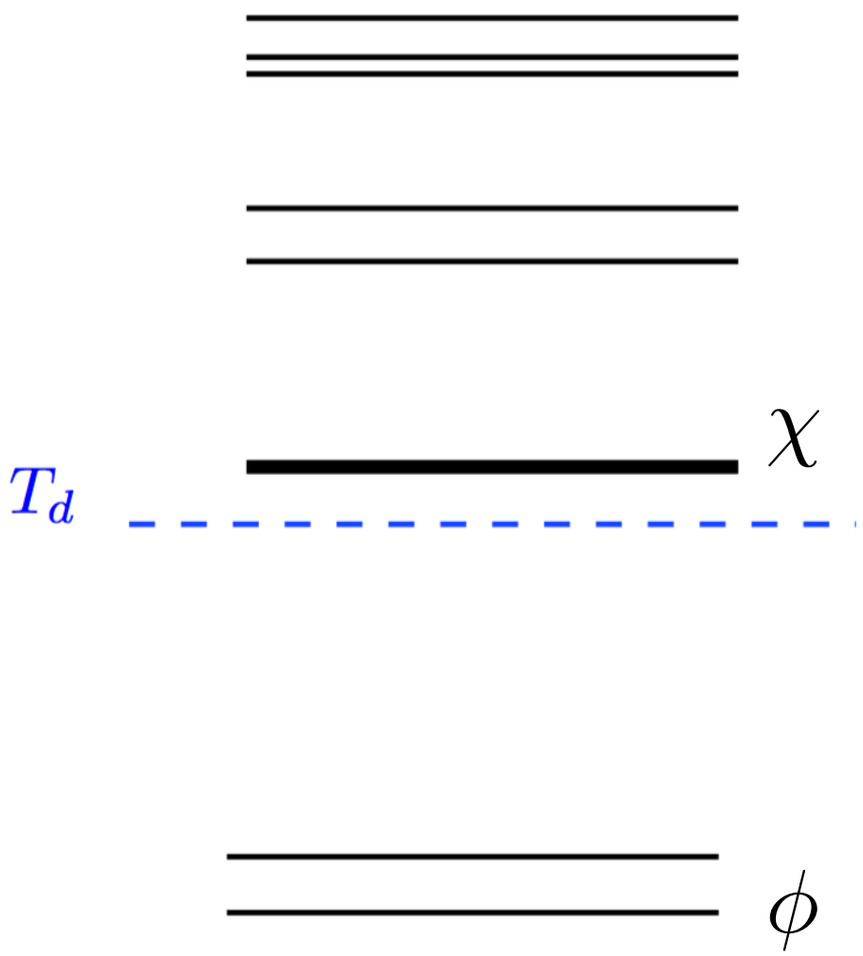
I. No gap







I. No gap



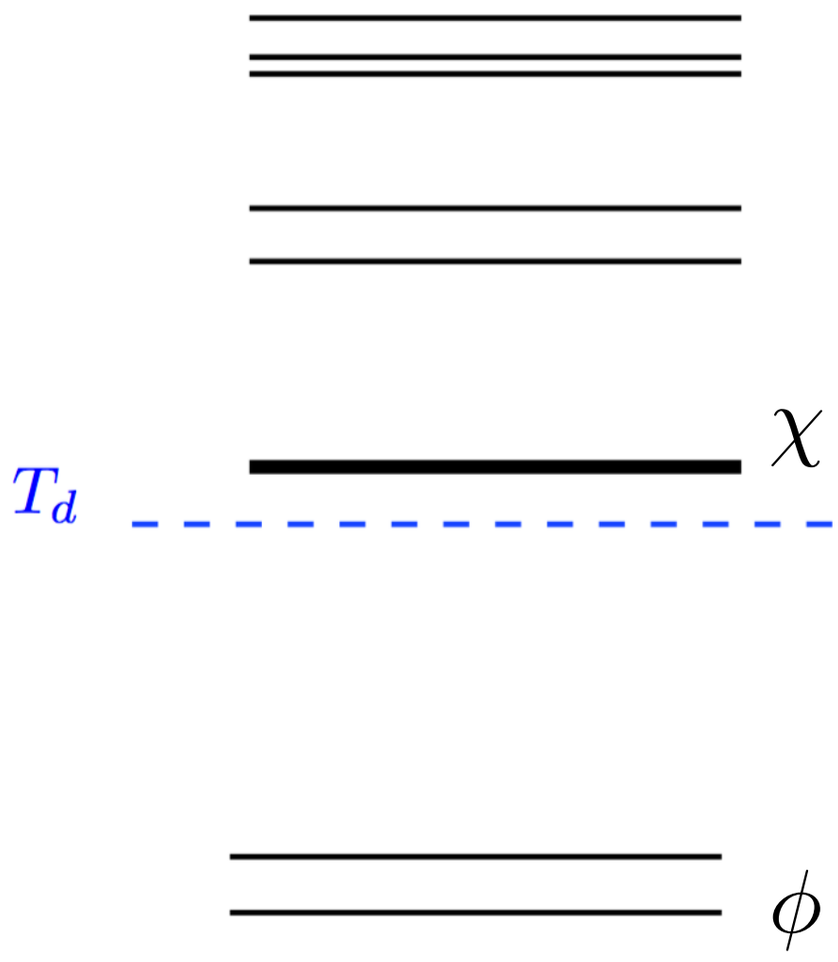
- At relevant freeze-out temperature $T_d \simeq m_\chi \gg m_\phi$
  ϕ is relativistic and by entropy conservation

$$T_d \propto \frac{1}{a}$$

- Entropies separately conserved

$$\xi \equiv \frac{s_{SM}}{s_d} = \frac{g_*^{SM} T_{SM}^3}{g_*^d T_d^3} = \text{const.}$$

I. No gap

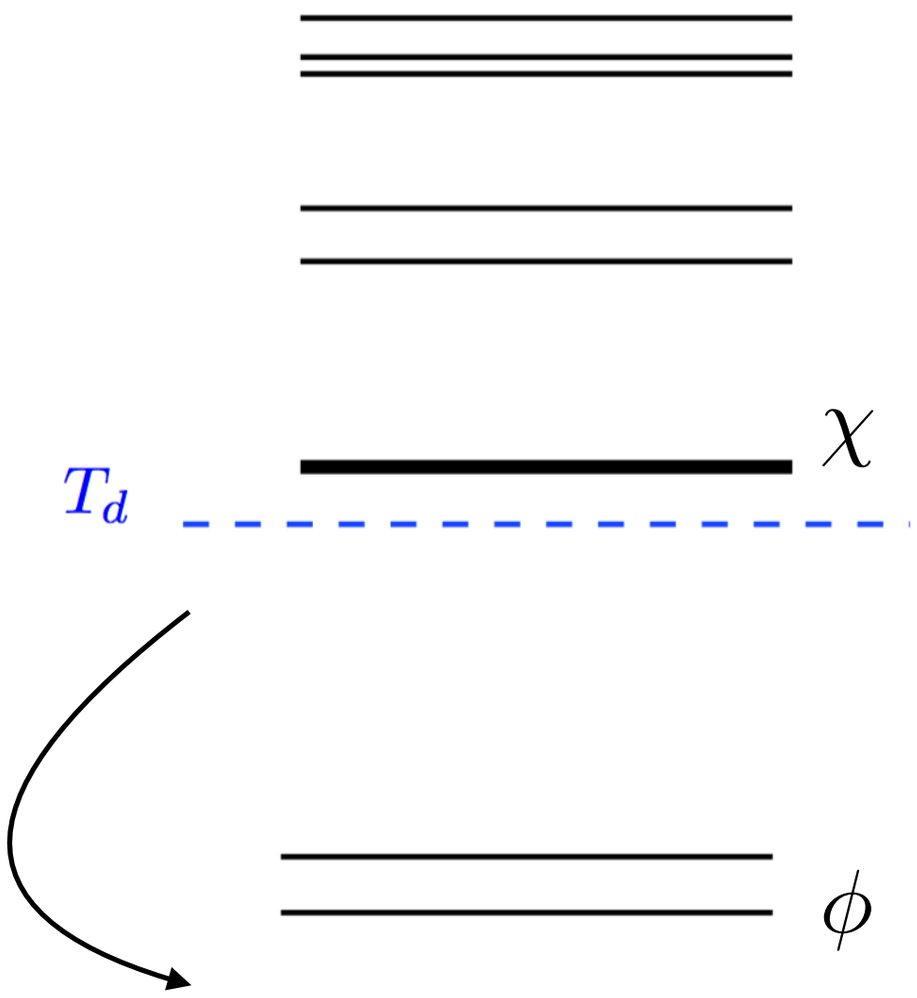


- Freeze-out of annihilations leads to

$$\frac{\Omega_X}{\Omega_{DM}} \approx 0.3 \frac{x_f}{\sqrt{g_*}} \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d}{T_{SM}}$$

- Ratio of temperatures enhancement

II. Gapped



- What happens if all the particles of the hidden sector become non relativistic?

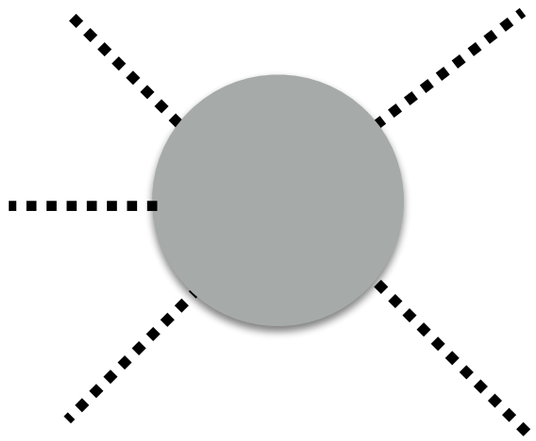
Cannibalism

Cannibalism 101

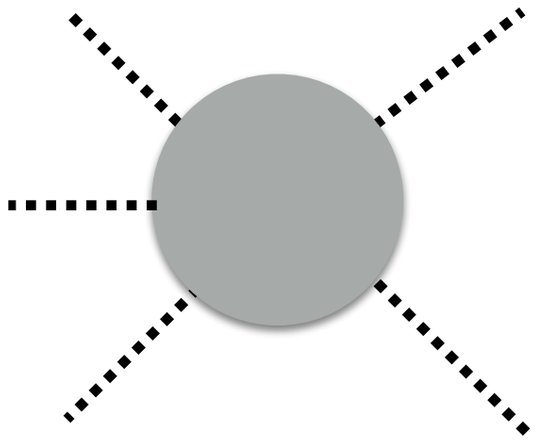
- Start with a simple example, one scalar field

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{m^2}{2}\phi^2 - \frac{A}{3!}\phi^3 - \frac{\lambda}{4!}\phi^4$$

- Number changing interactions active when $T_d < m_\phi$



Cannibalism 101

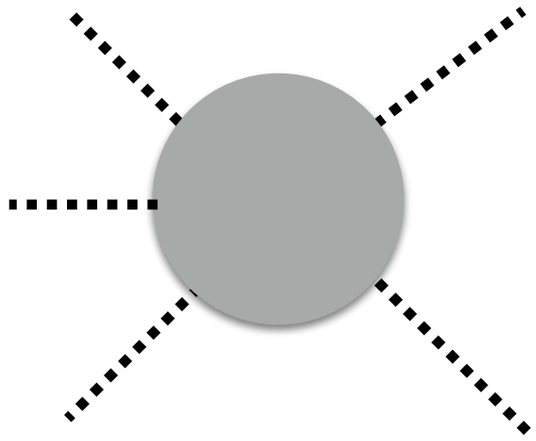


✓

$$s_\phi a^3 \approx \frac{\rho_\phi}{T_d} \propto m^3 \left(\frac{T_d}{m}\right)^{1/2} e^{-m/T_d} a^3 = \text{const.}$$

$$T_d \propto \frac{m}{\log a^3}$$

(No chemical potential)



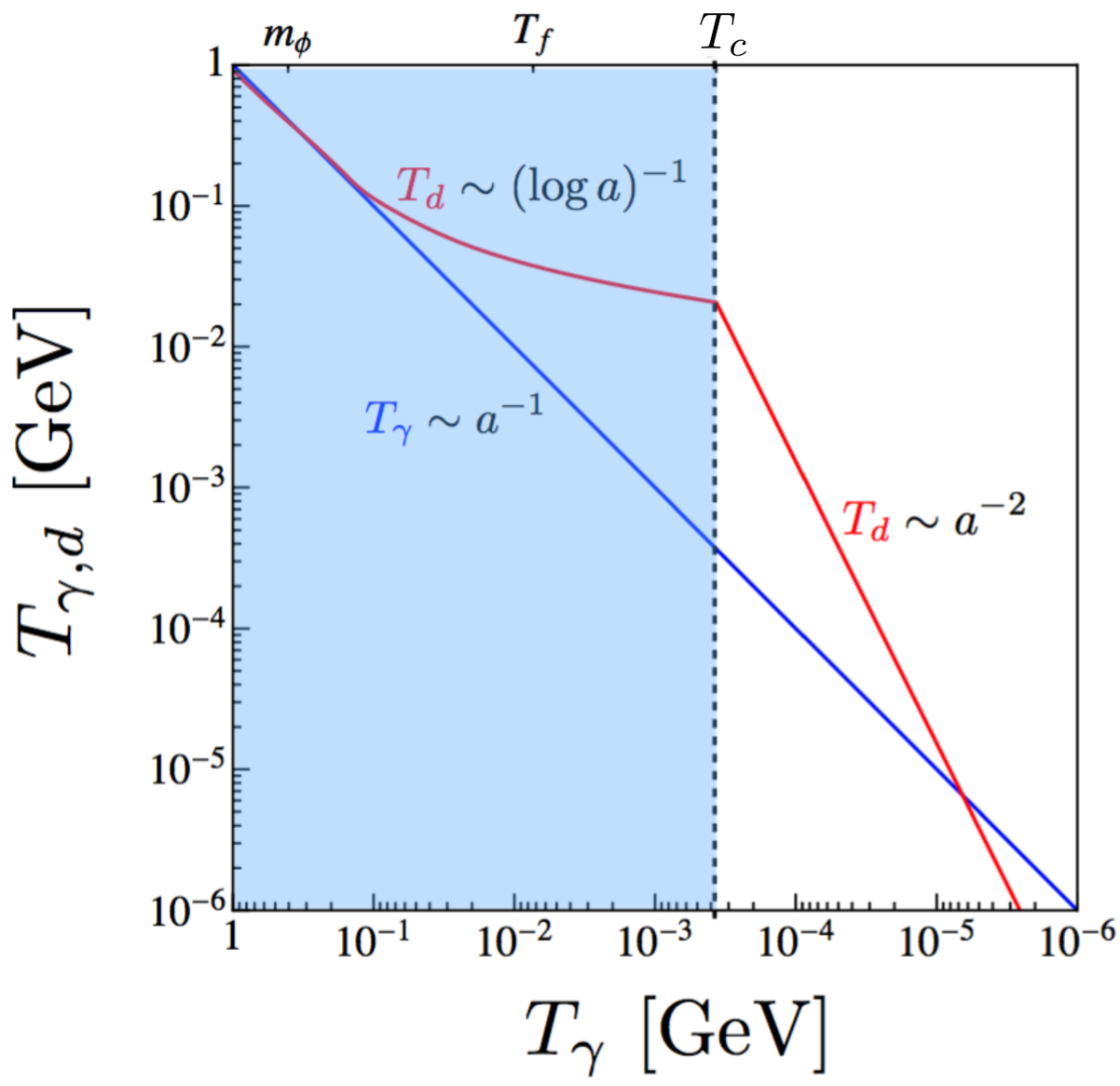
✗

$$s_\phi a^3 = \text{const.} \quad \text{and} \quad n_\phi a^3 = \text{const.}$$

$$T_d \propto \frac{1}{a^2}$$

Conservation of entropy

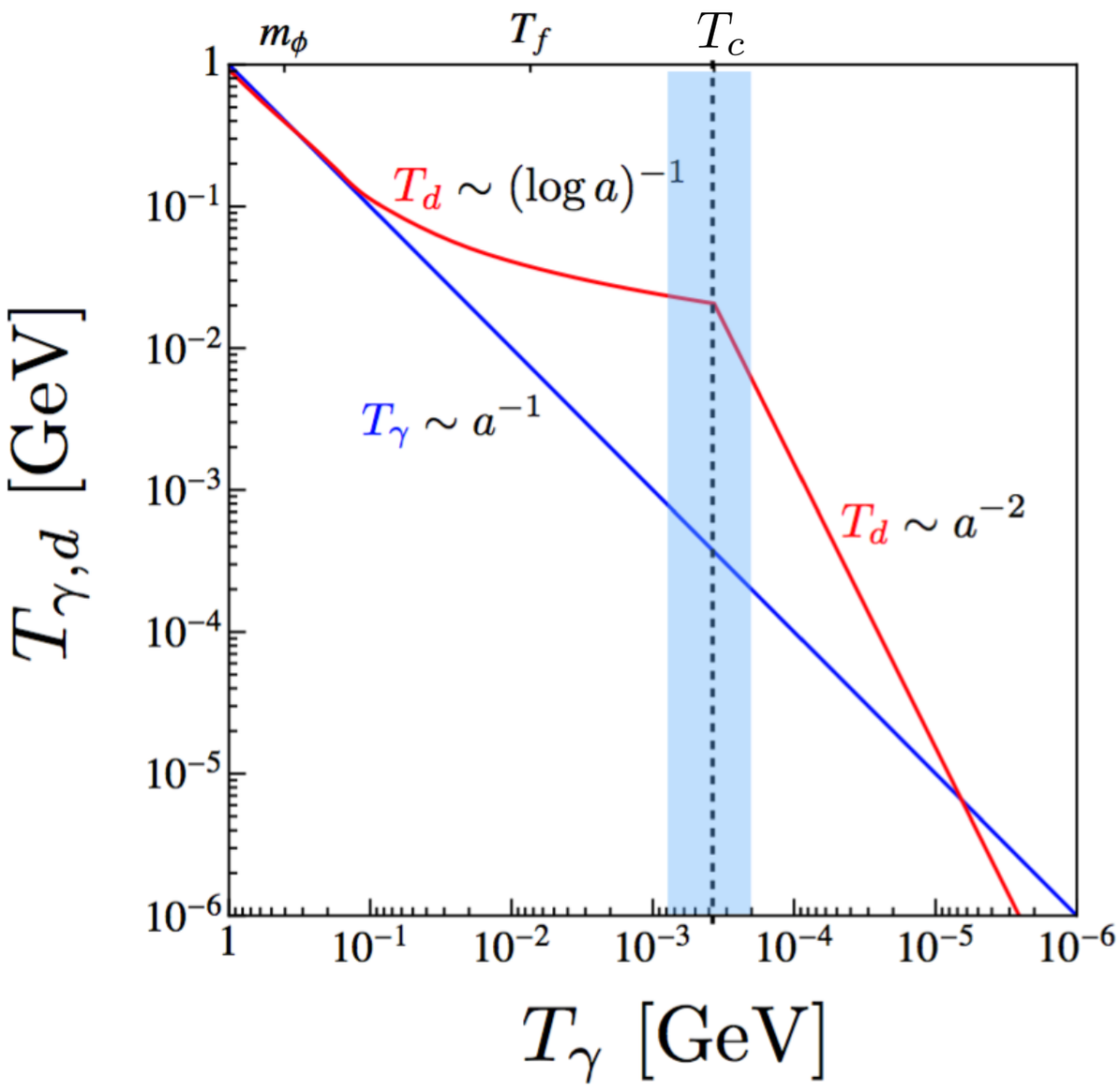
Cannibalism 101



- Dark sector exponentially hotter while number changing interactions are active

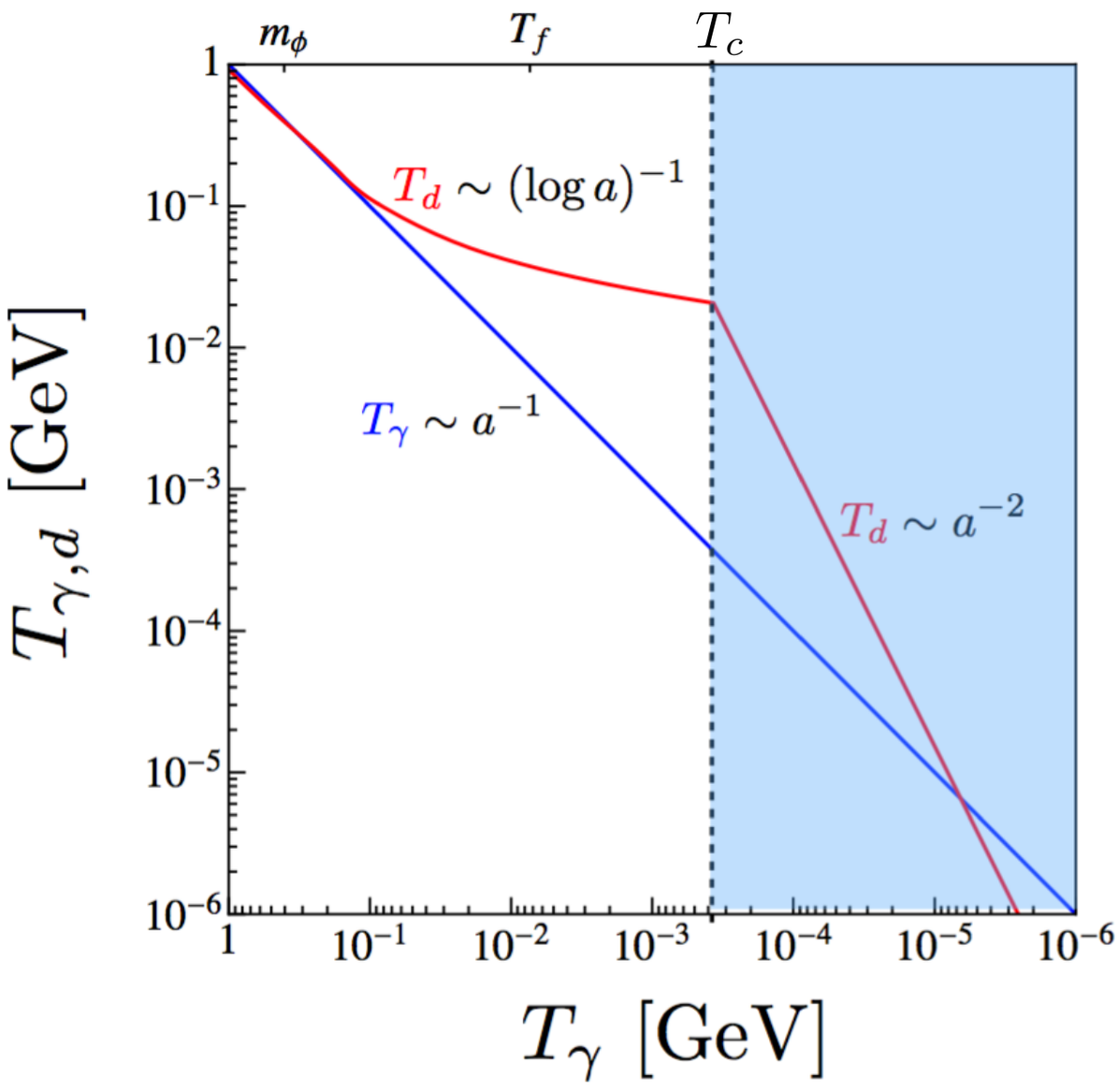
$$\frac{T_{SM}}{T_d} \approx \xi^{1/3} g_*^{1/3} \left(\frac{m}{T_d}\right)^{5/6} e^{-m/3T_d}$$

Cannibalism 101



- Cannibalism ends at T_c when $n_\phi^2 \langle \sigma v^2 \rangle \sim H$

Cannibalism 101



- After end of cannibalism the hidden sector temperature scales like that of a non-relativistic relic

Cannibalism 101

Can ϕ be dark matter?

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.

Cannibalism 101

Can ϕ be dark matter?

$$\frac{\Omega_\phi}{\Omega_{DM}} = \frac{m_\phi n_\phi}{s_{SM}} \frac{1}{0.4\,\mathrm{eV}} \approx \frac{m_\phi}{x_\phi \xi} \frac{1}{0.4\,\mathrm{eV}}$$

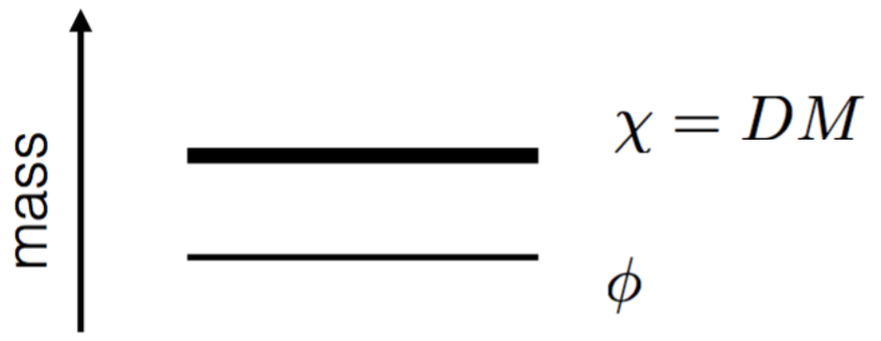
$x_\phi \sim 20 \div 50$ $\qquad$ $\xi \equiv \frac{s_{SM}}{s_d}$ $\qquad$ $\xi > 100$

$m_\phi = 1\ \mathrm{keV}$ if two sectors were in thermal equilibrium in the past.

DM is too warm and is excluded by Large Scale Structures.

Cannibal DM

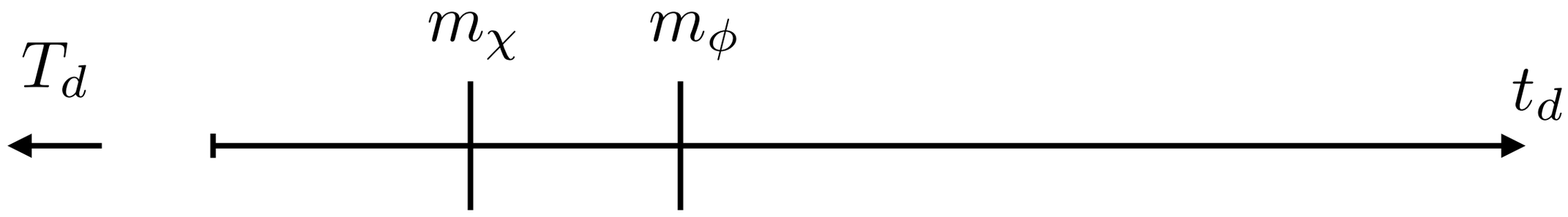
What if DM belongs to a Hidden Sector undergoing a cannibalism phase?



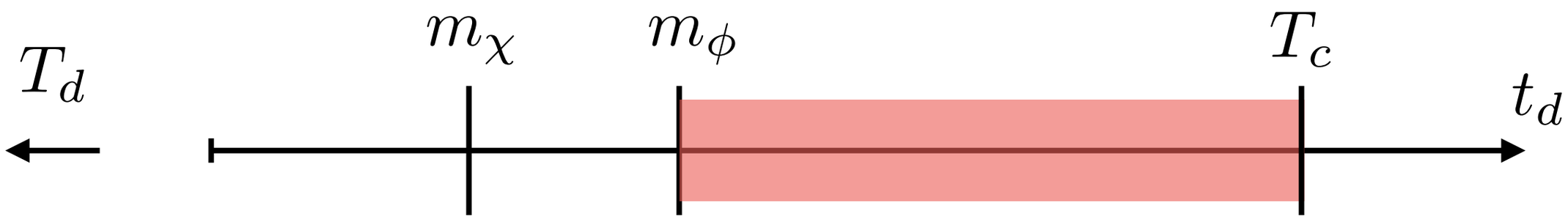
$$\mathcal{L}(\phi, \chi) = \mathcal{L}(\phi) + \bar{\chi}(i\partial - m_\chi)\chi - \frac{y}{2}\phi\bar{\chi}\chi$$

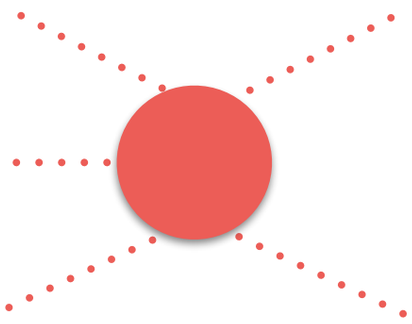
χ is DM from 2 to 2 freeze-out in a cannibalizing sector

Cannibal DM



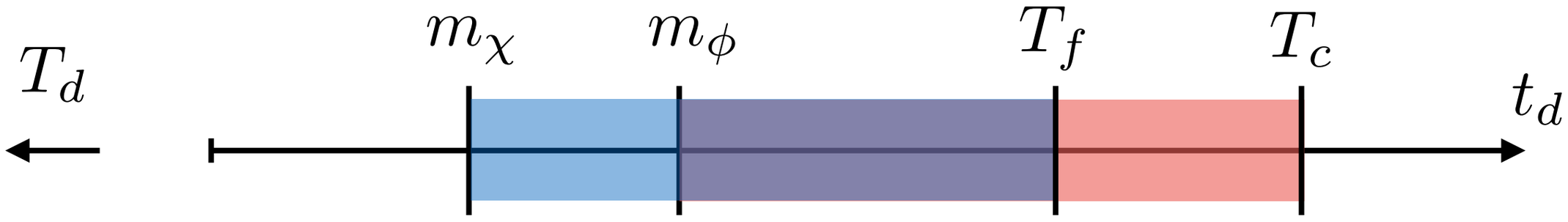
Cannibal DM

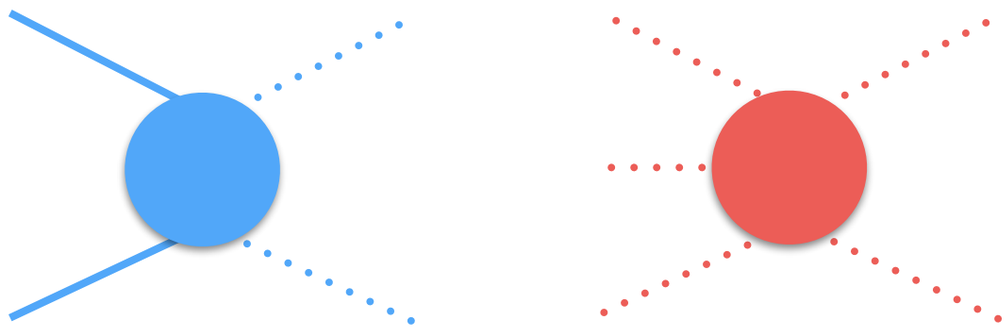




Dark Sector temperature exponentially higher than SM

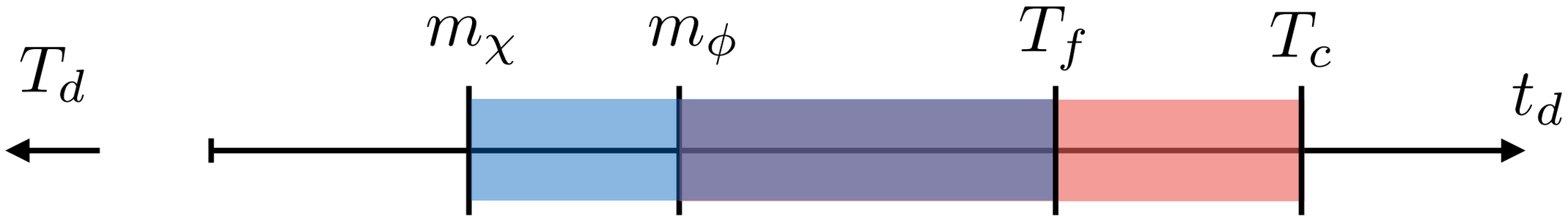
Cannibal DM

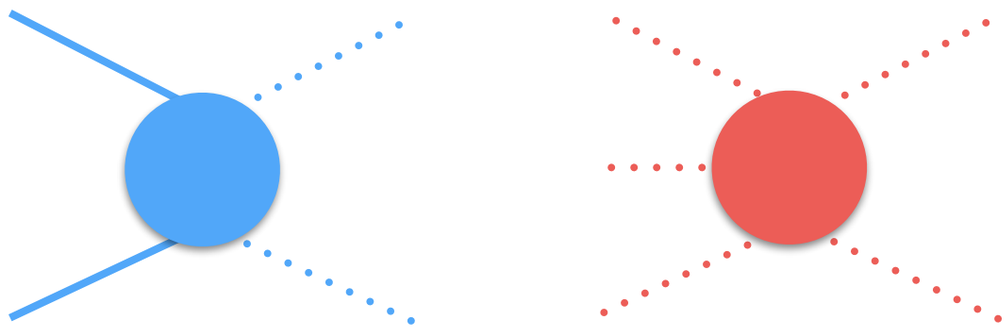




χ number changing interactions freeze-out during cannibalism when $n_\chi(T_d)\langle\sigma v\rangle = H(T_d)$

Cannibal DM





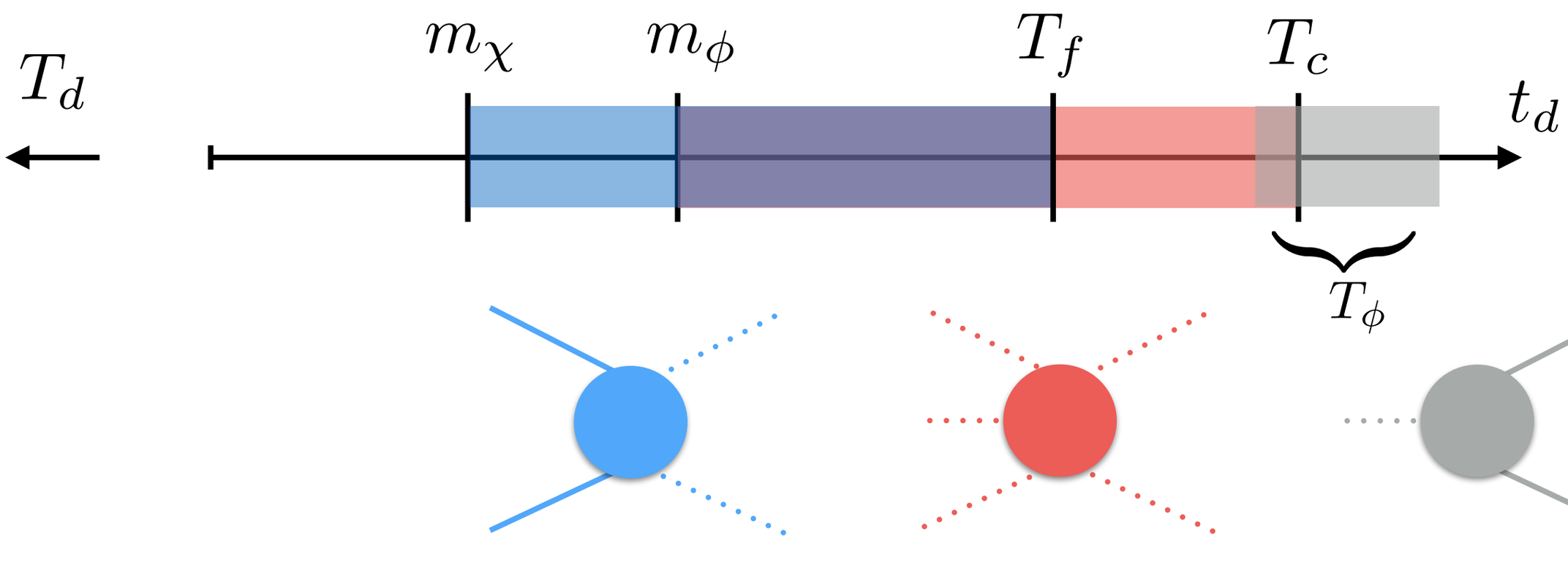
$$\frac{\Omega_\chi}{\Omega_{DM}} = \frac{m_\chi n_\chi}{s_{SM}} \frac{1}{0.4\,\mathrm{eV}} \approx 0.3 \frac{x_f}{g_*^{1/2}} \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d}{T_{SM}}$$

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

Exponential boost!

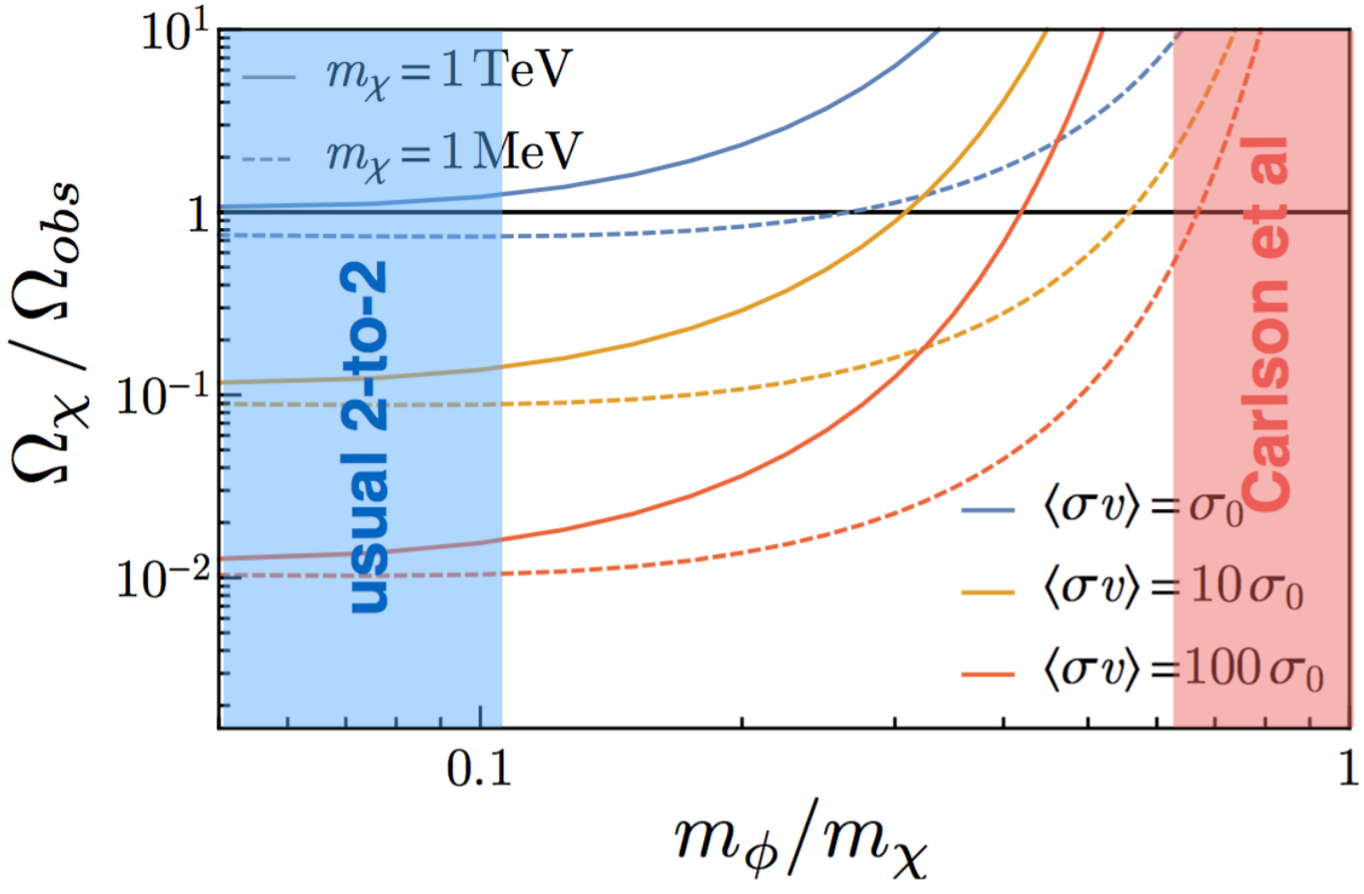
$$\frac{T_{SM}}{T_d} \approx \xi^{1/3} g_*^{1/3} \left(\frac{m}{T_d}\right)^{5/6} e^{-m/3T_d}$$

Cannibal DM



ϕ must eventually decay to SM (or to dark radiation)

Cannibal DM

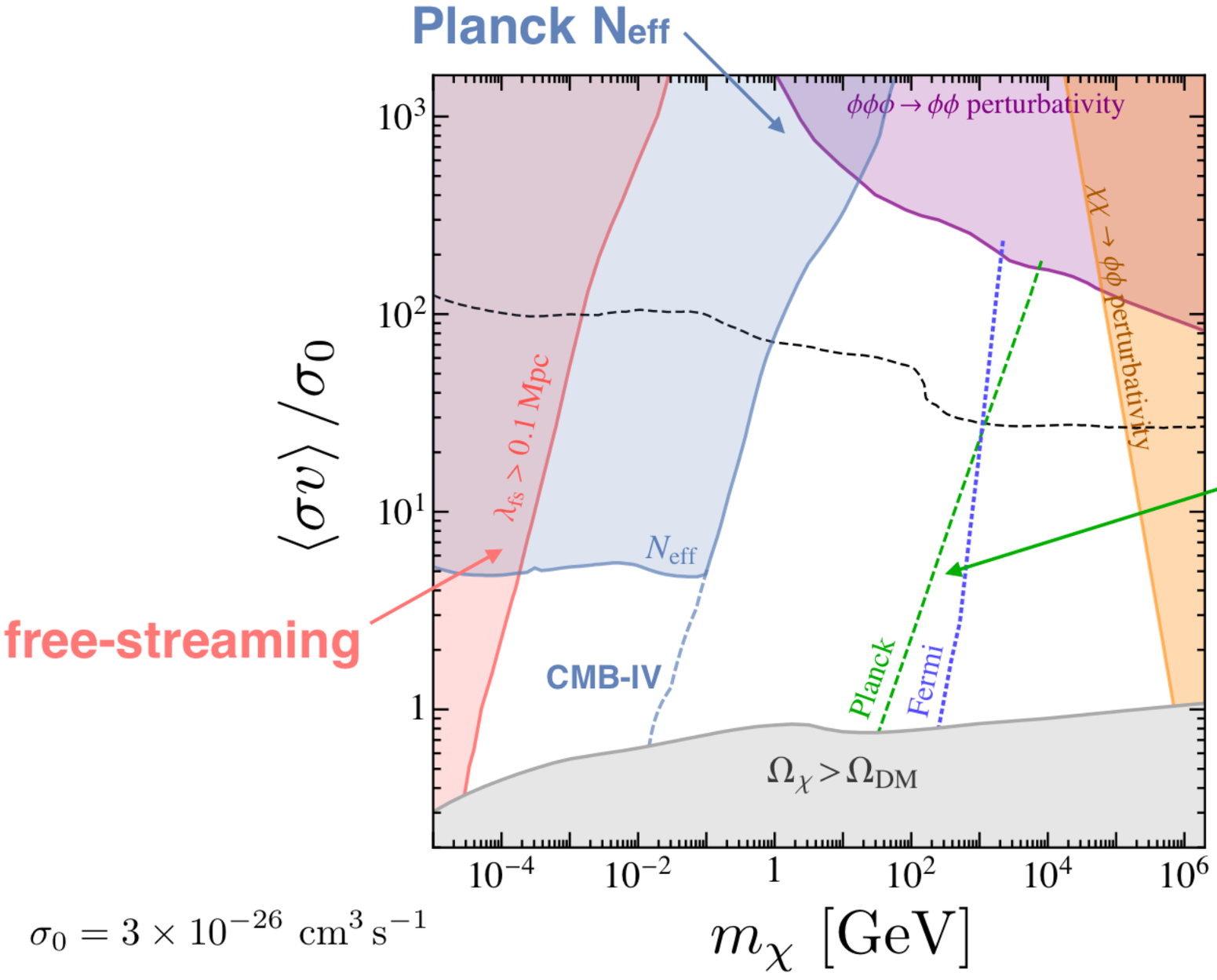


$$\frac{\Omega_\chi}{\Omega_{\chi,r=0}} \propto \left(m_\chi M_{Pl} \langle\sigma v\rangle\right)^{\frac{r/3}{1-2r/3}}$$

Cannibal DM Pheno

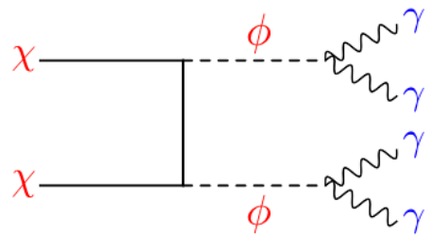
$$\xi \approx 39$$

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



free-streaming

indirect (s-wave)

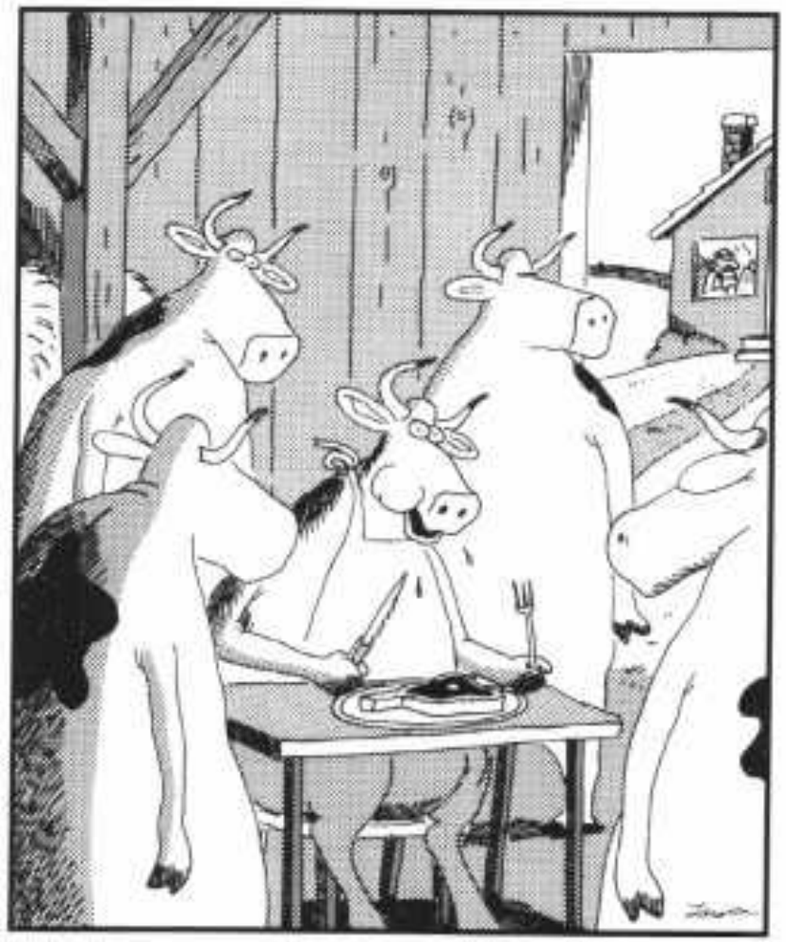


$\sigma_0 = 3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$

Conclusions

- Cannibalism is an interesting possibility, generic of hidden sectors with a mass scale

- Dark matter could arise from a cannibalizing sector, leading to:
    - Boosted annihilation rates
    - Implications for CMB and N_{eff}
    - Free streaming signatures

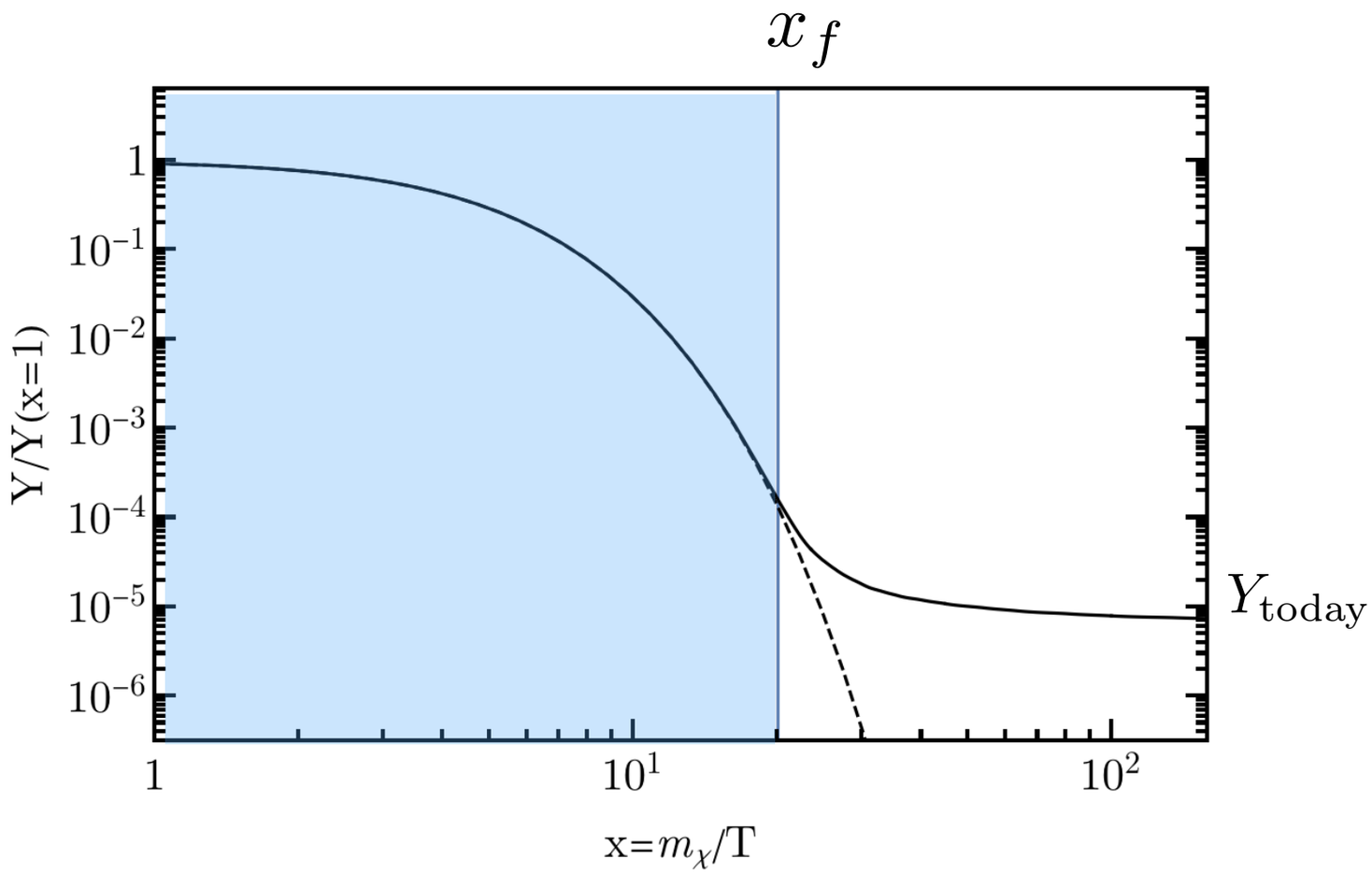


"Mmmmmm … Interesting … interesting. … I'd say we taste a little like chicken."

- Rich pheno with other phases…

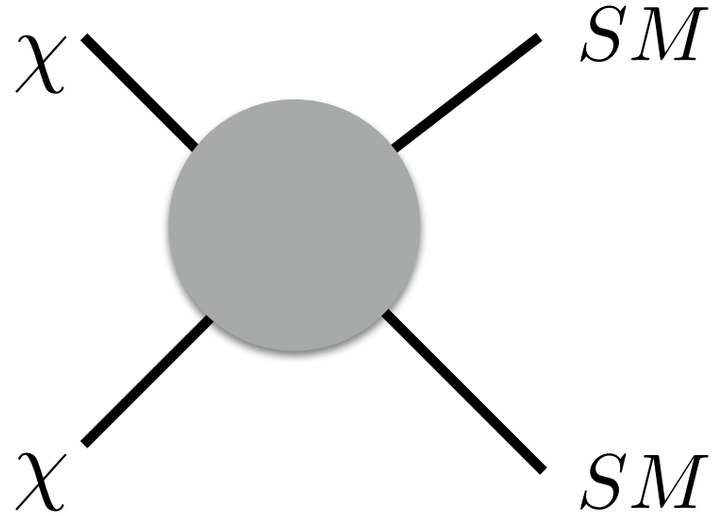
Backup

WIMP Miracle

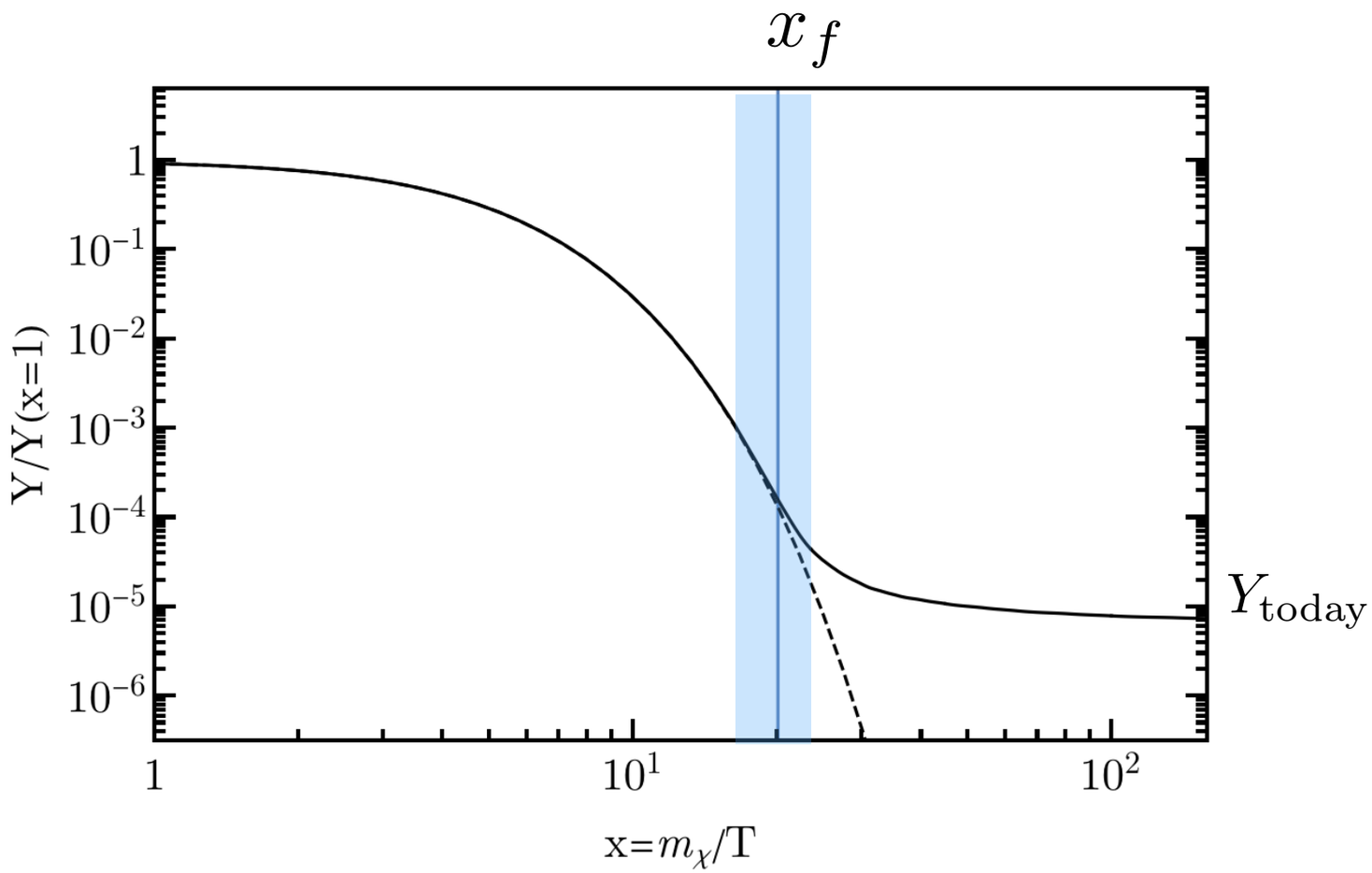


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

Thermal equilibrium $Y \equiv \dfrac{n_\chi}{s} \sim e^{-m_\chi/T}$



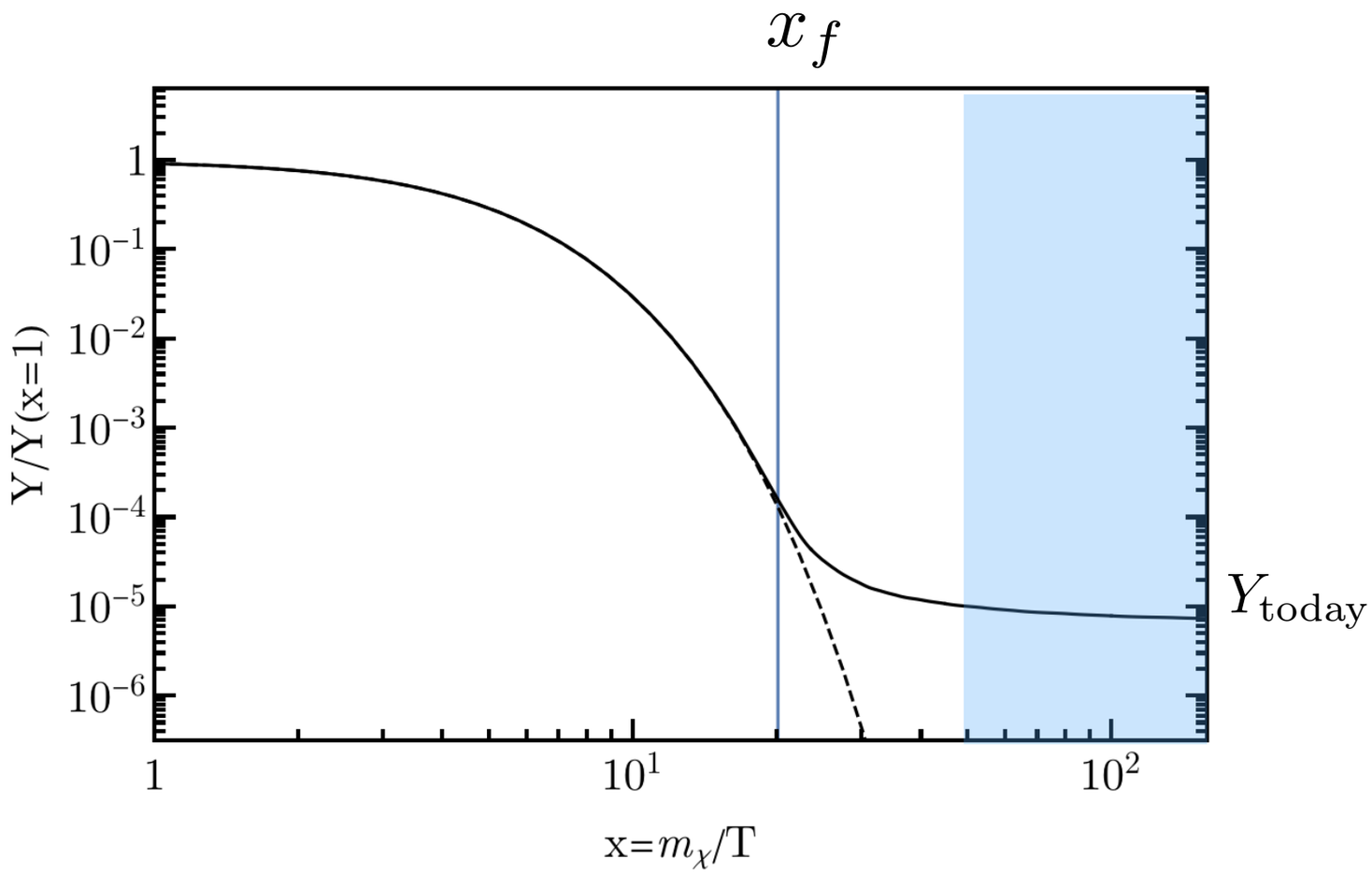
WIMP Miracle



Freeze-out when $n_\chi \langle \sigma v \rangle \approx H$

$$Y \equiv \frac{n_\chi}{s} \sim e^{-m_\chi/T} \quad H \approx \sqrt{g_*}\frac{T^2}{M_{Pl}} \quad \Rightarrow \quad x_f \equiv \frac{m_\chi}{T_f} \sim \log m_\chi M_{Pl} \langle \sigma v \rangle$$

WIMP Miracle

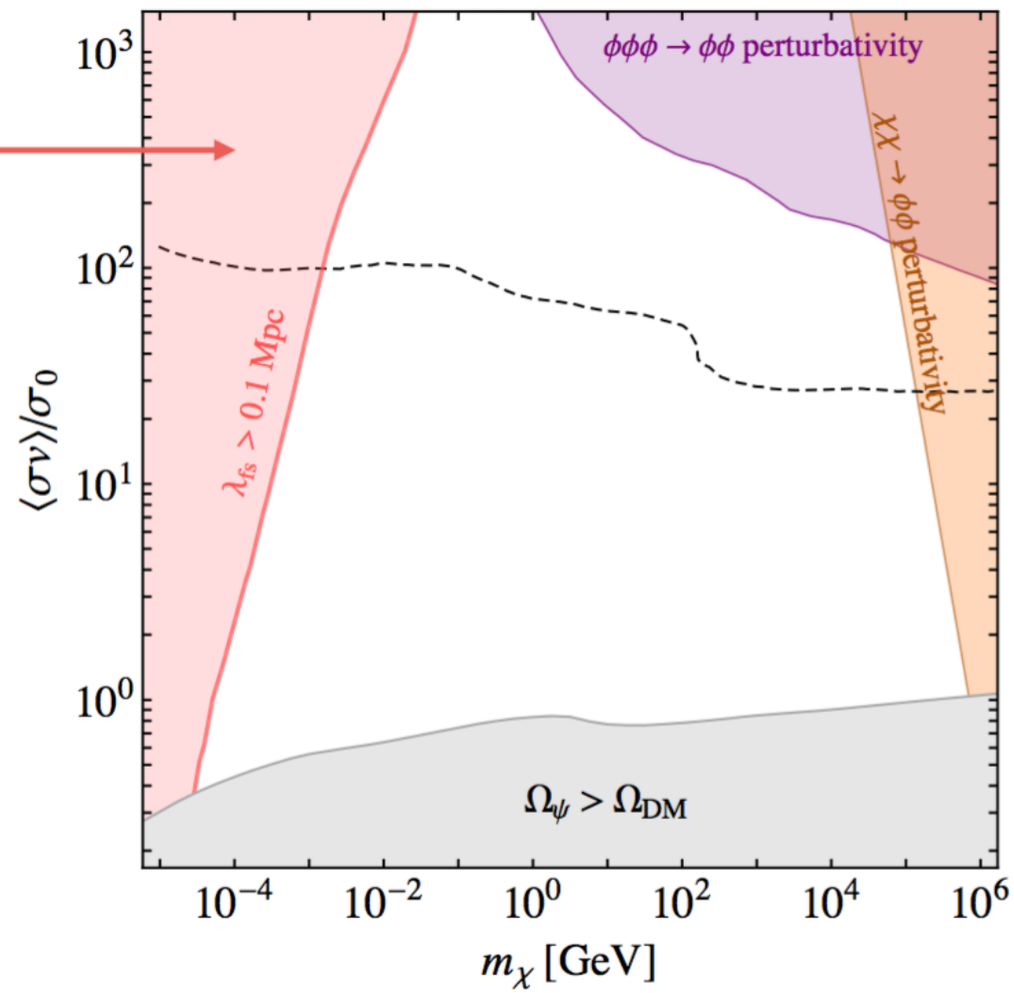


After freeze-out yield is fixed $Y \sim \dfrac{1}{m_\chi M_{Pl} \langle \sigma v \rangle}$

$T_{eq} \approx \dfrac{m_\chi n_\chi}{s}$ → $m_\chi \sim \alpha \sqrt{T_{eq} M_{Pl}}$ for $\langle \sigma v \rangle \sim \dfrac{\alpha^2}{m_\chi^2}$

$\phi \to \gamma\gamma$

free-streaming



$$\xi = \frac{g_{*SM}}{g_{*\phi} + g_{*\chi}} \approx 39$$

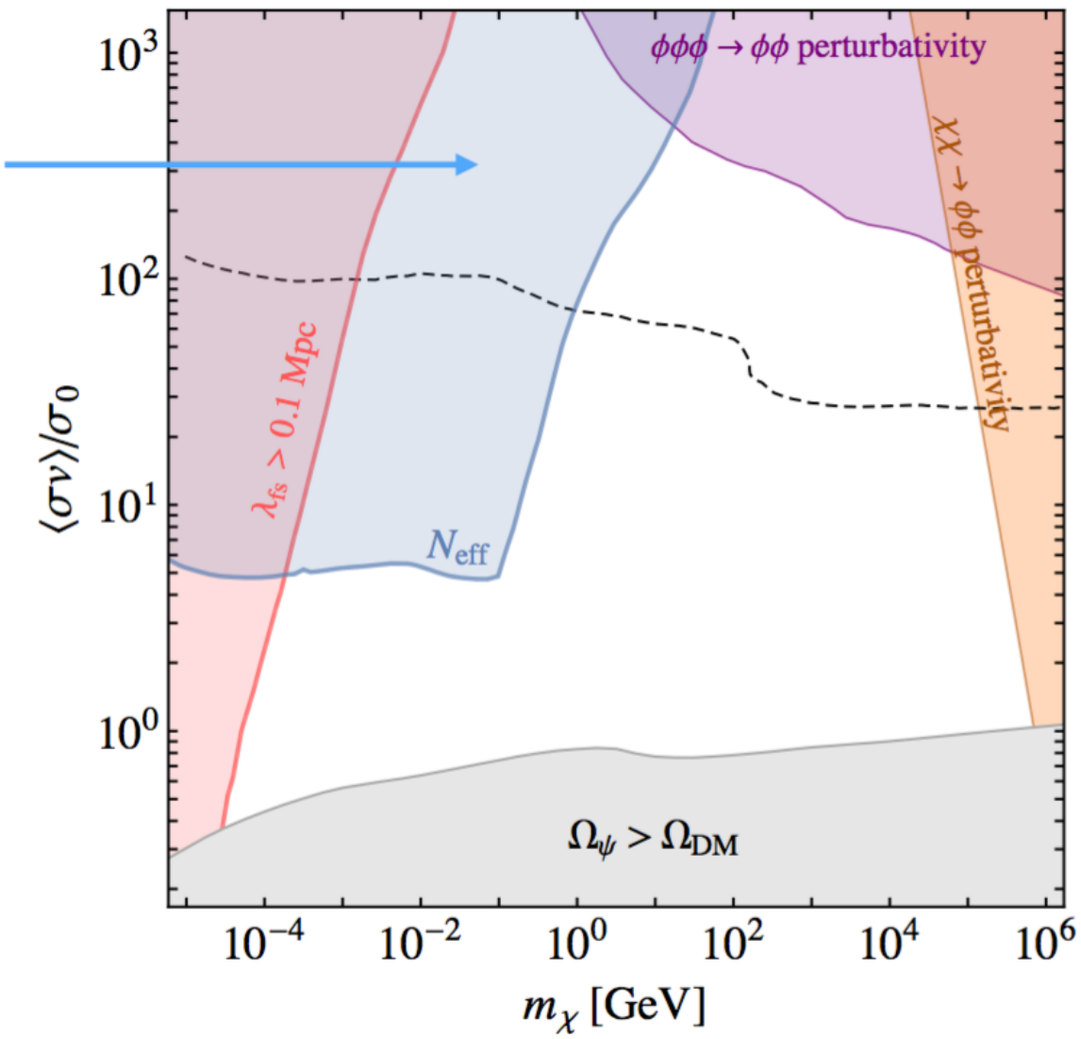
$$\Gamma_\phi = H_f \approx \frac{T_k^2}{M_{Pl}}$$

$$\lambda_{\rm fs} \approx 100\,{\rm Mpc}\,\frac{1}{\sqrt{x_f}}\,\frac{\log T_k^{\rm eV}}{T_k^{\rm eV}} \qquad \lambda_{\rm fs} < 0.1\,{\rm Mpc} \quad [Ly\alpha]$$

At FO the velocity dispersion of chi is the same of a WIMP but the SM is much colder: free streaming effective for higher masses

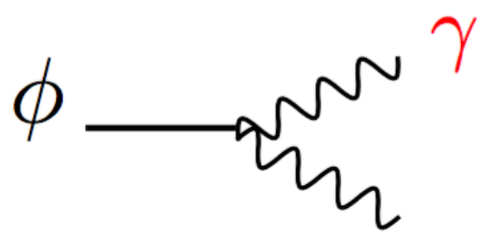
$\phi \to \gamma\gamma$

Planck Neff



$$\xi = \frac{g_{*SM}}{g_{*\phi} + g_{*\chi}} \approx 39$$

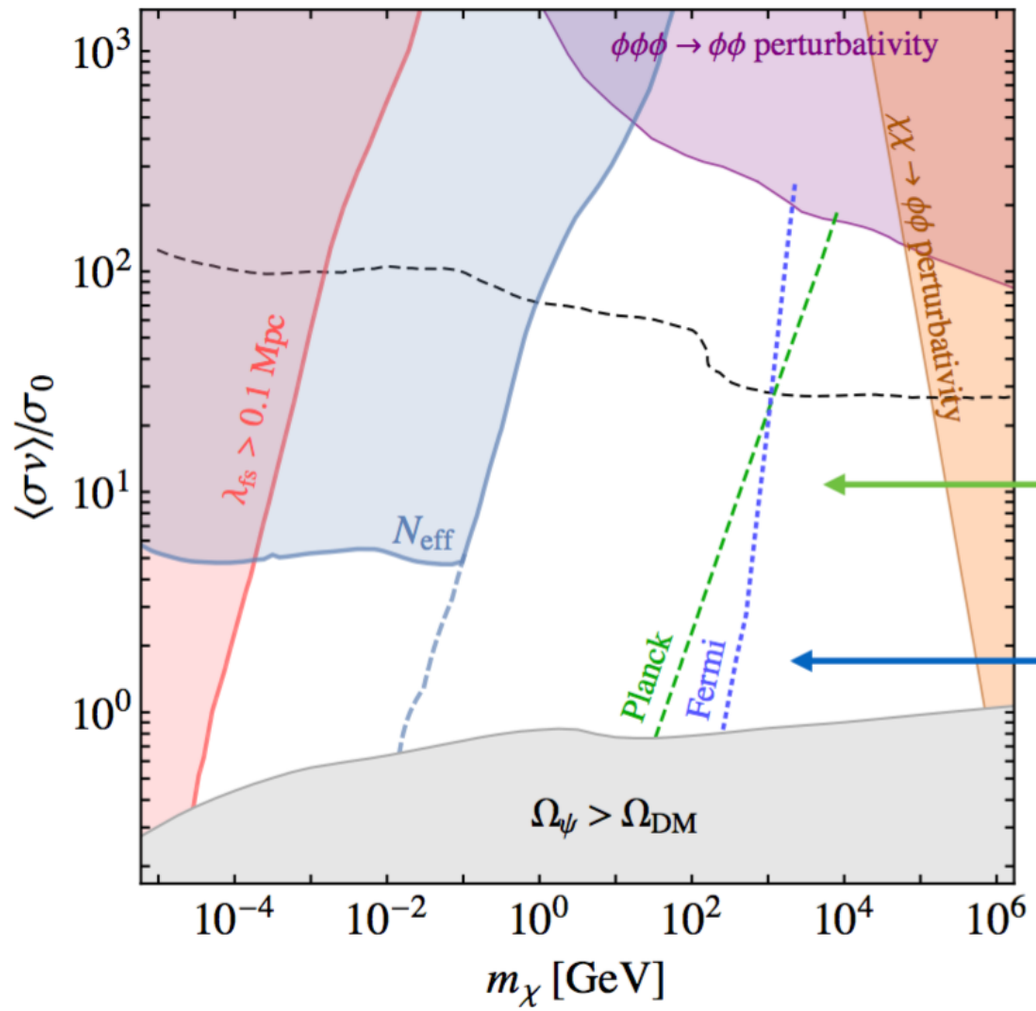
$$\Gamma_\phi = H_f$$



$$N_{\rm eff} = 3.15 \pm 0.23 \quad [Planck]$$

When ϕ decays to photon it effectively decreases Neff, heating up the photons relatively to the neutrinos.

$\phi \to \gamma\gamma$

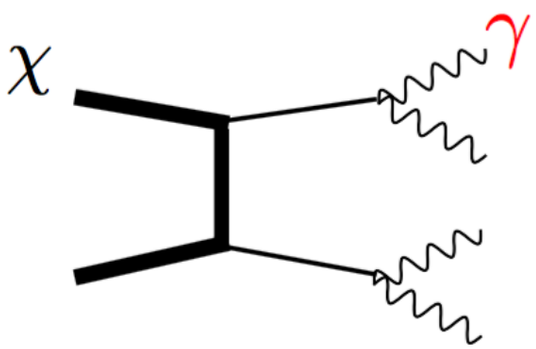


$$\xi = \frac{g_{*SM}}{g_{*\phi} + g_{*\chi}} \approx 39$$

$$\Gamma_\phi = H_f$$

Planck ionization

Fermi dSph



Indirect detection bounds are very constraining if one assumes s-wave annihilation

Freeze-out can happen during while ϕ is dominating the energy density of the universe.

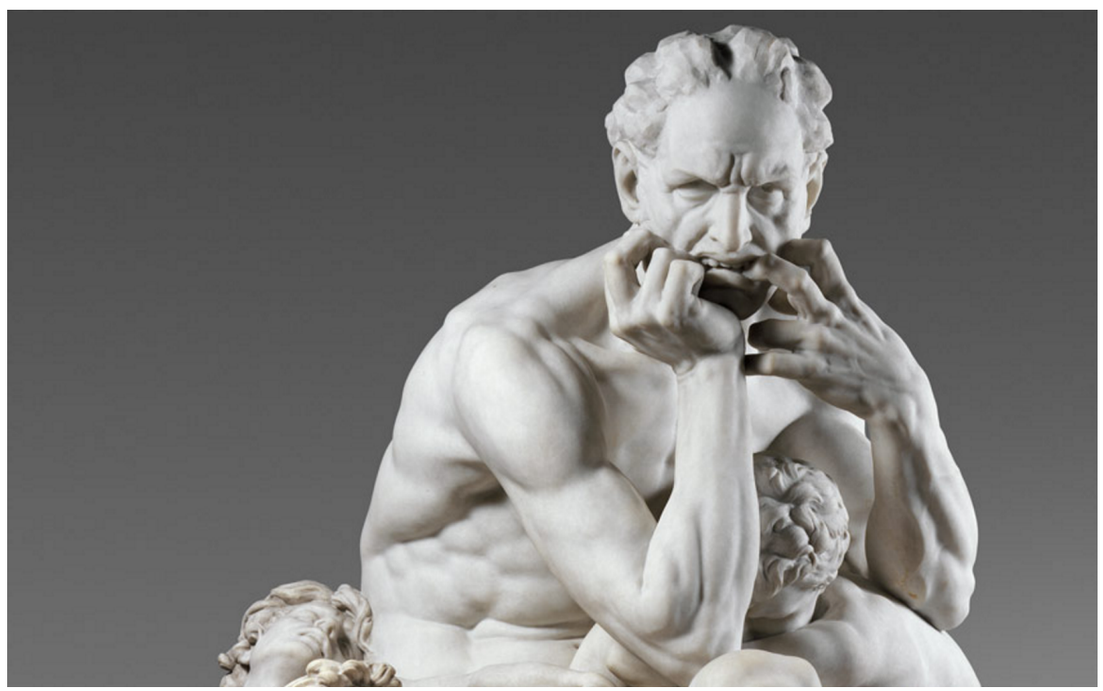
$$\frac{\Omega_\chi}{\Omega_{DM}} \approx 0.3 \frac{x_f}{g_*^{1/2}} \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d^{3/2}}{\xi^{1/2} T_{SM}^{3/2} D}$$

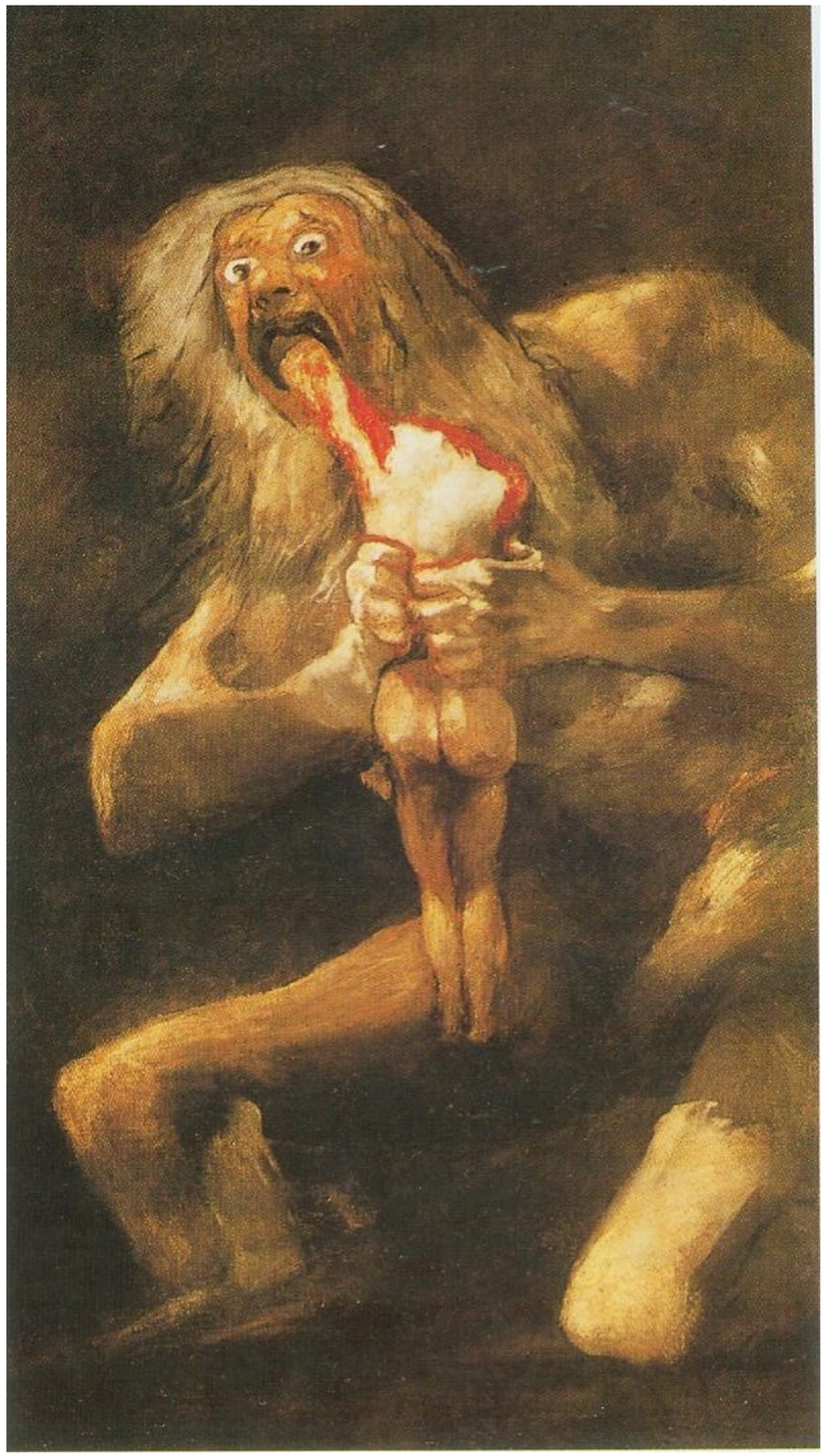
D measures the dilution due to entropy generation after ϕ decay.

$$D \approx \frac{T_{SM}^E}{T_{RH}} \qquad\qquad T_{RH} \approx g_*^{-1/4} \Gamma_\phi^{1/2} M_{Pl}^{1/2}$$

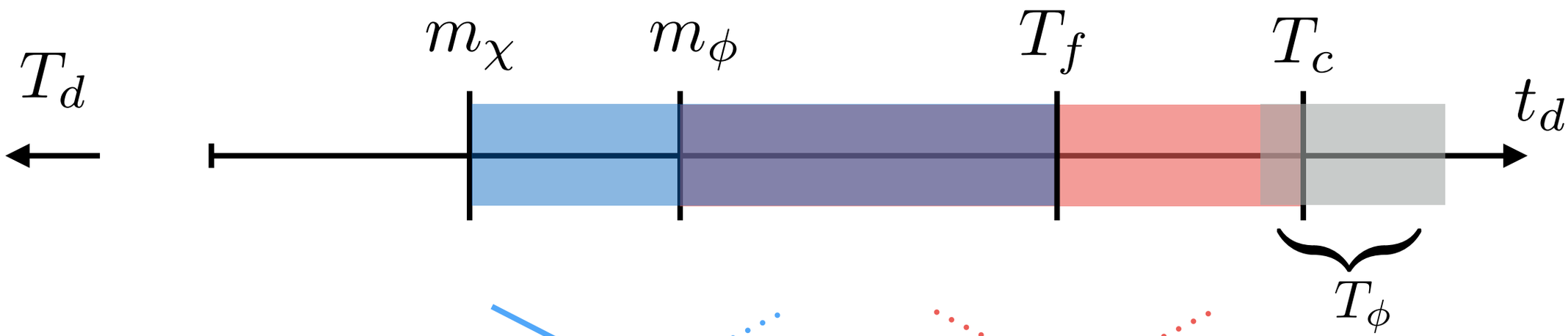
Notice that D is different from 1 only if ϕ decays to SM.

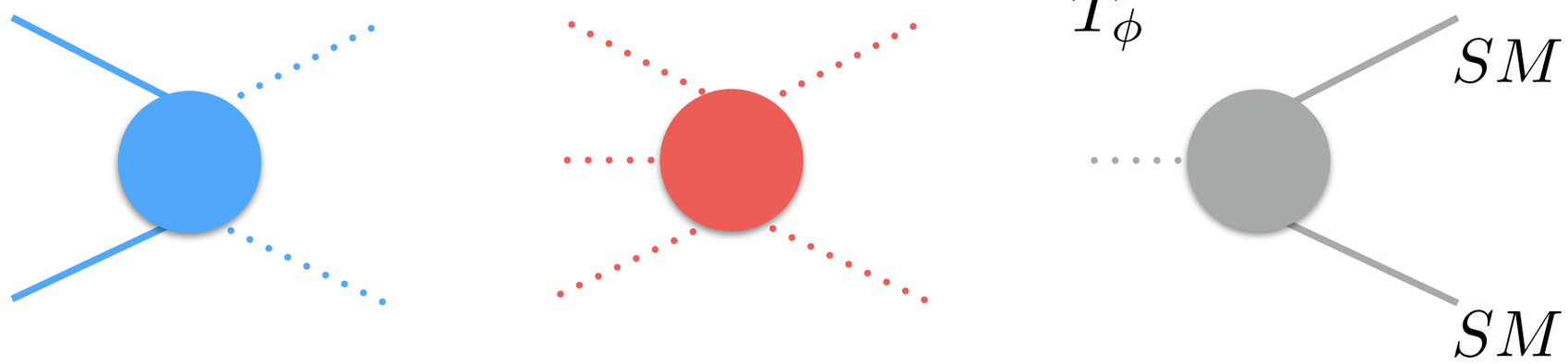
Phases of Cannibal DM



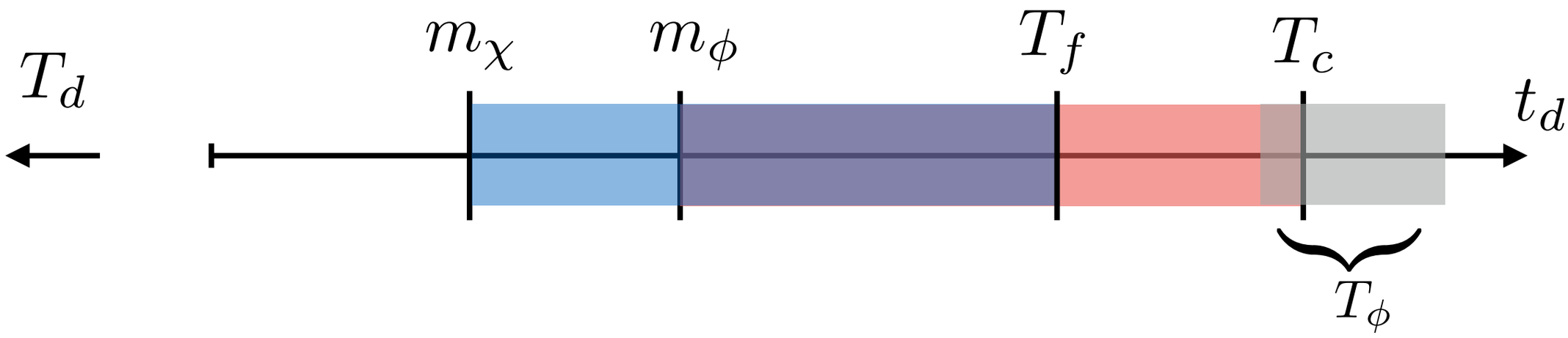


Three time scales



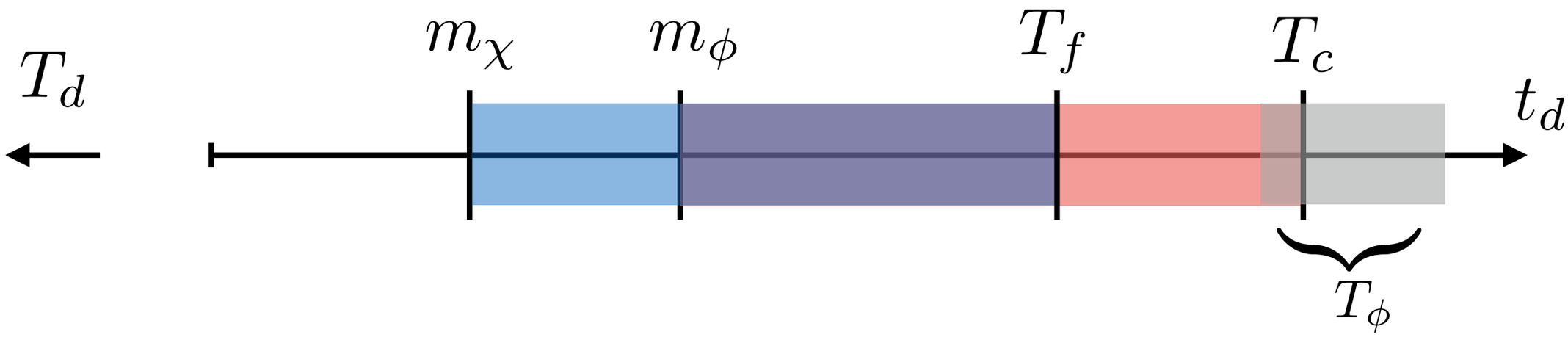


Three time scales

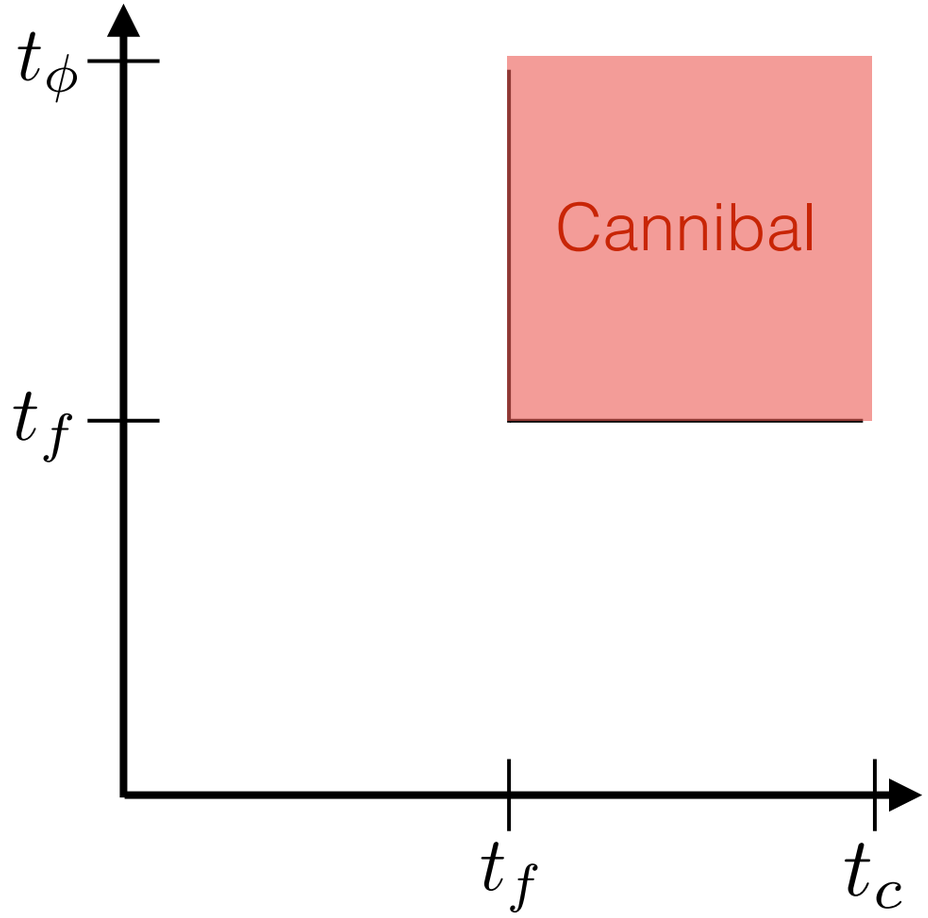


- t_f : time at which DM 2 to 2 freeze-out (stable ϕ limit)
- t_c : time at which 3 to 2 freeze-out (stable ϕ limit)
- t_ϕ : ϕ lifetime

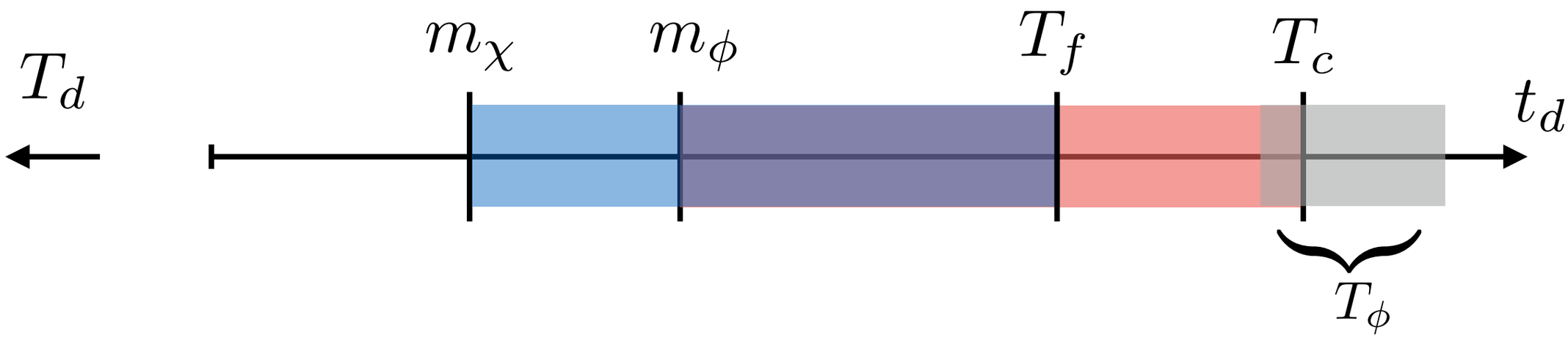
Three phases (I)



- Cannibal: $t_f \ll t_c,\ t_\phi$

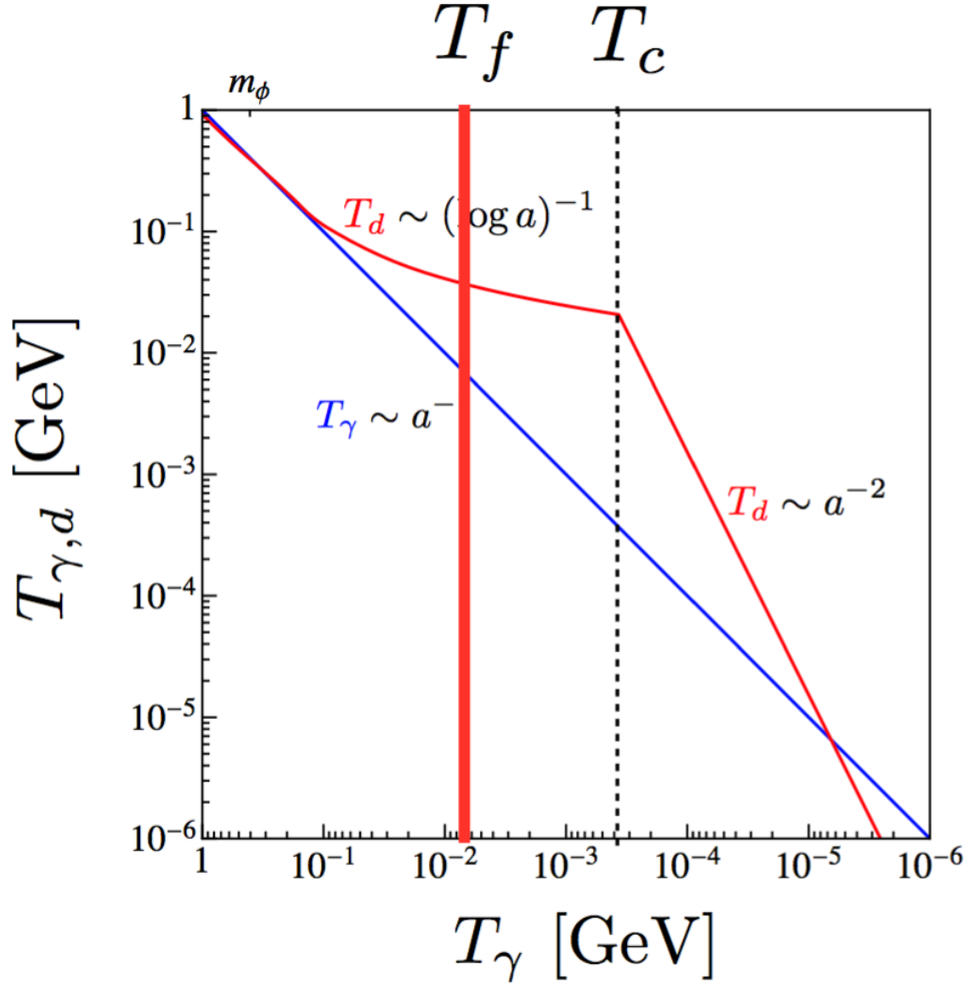


Three phases (I)

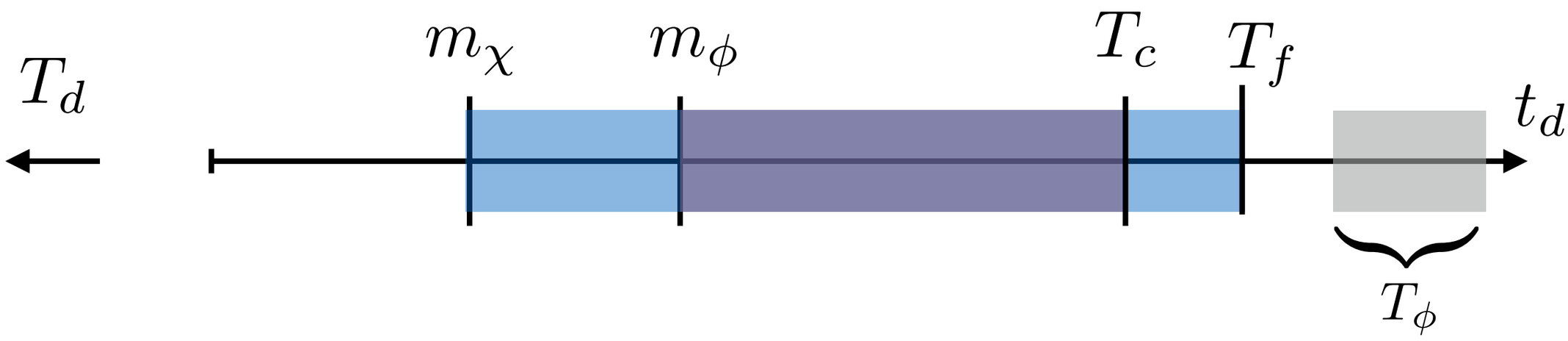


- Cannibal: $t_f \ll t_c,\ t_\phi$

$$Y_\chi \propto (m_\chi M_P \sigma_2)^{-\frac{1-r}{1-2/3\,r}}$$

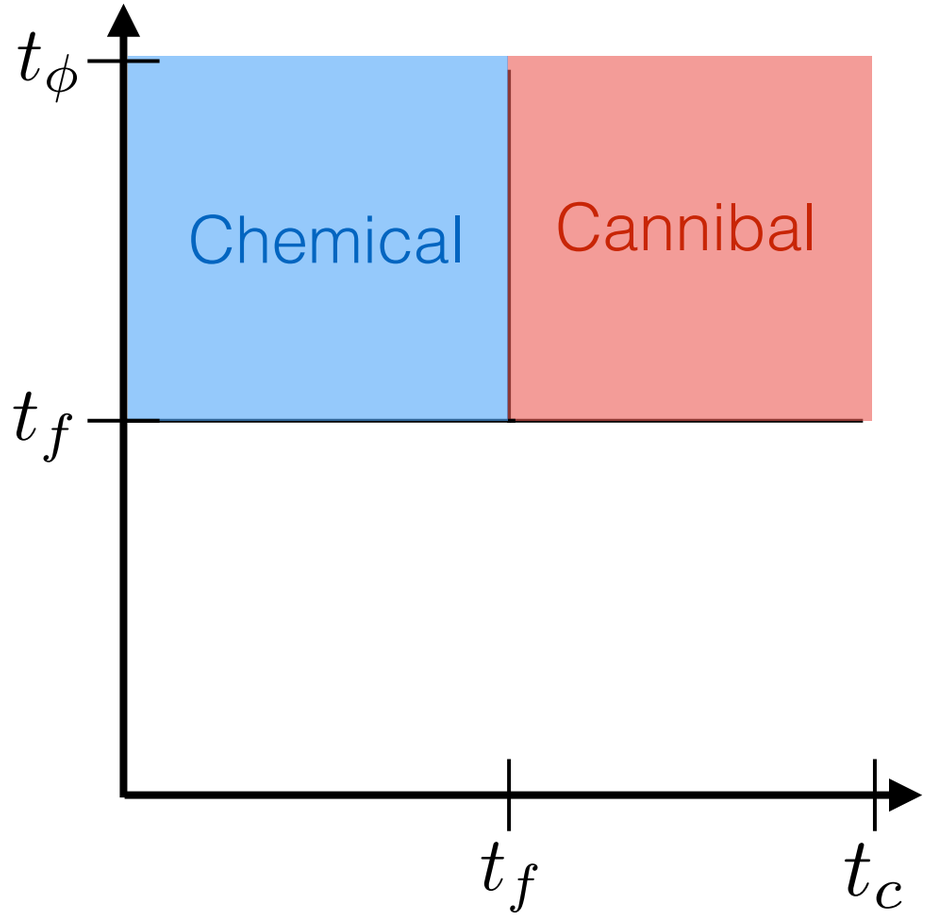


Three phases (II)

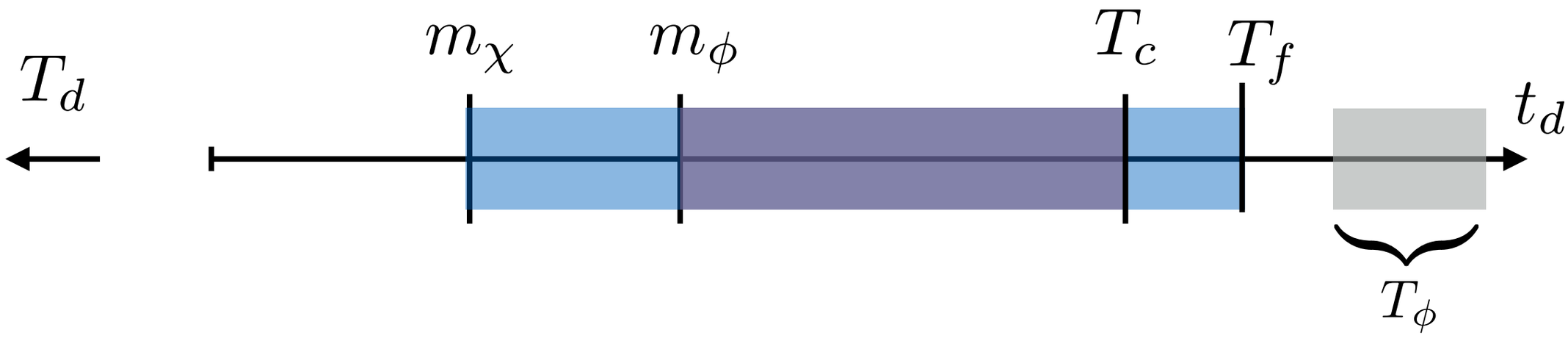


- Chemical: $t_c \ll t_f \ll t_\phi$

  Why chemical?
  After t_c total number of dark particles is conserved
  Chemical potential introduced as usual non-relativistic relics

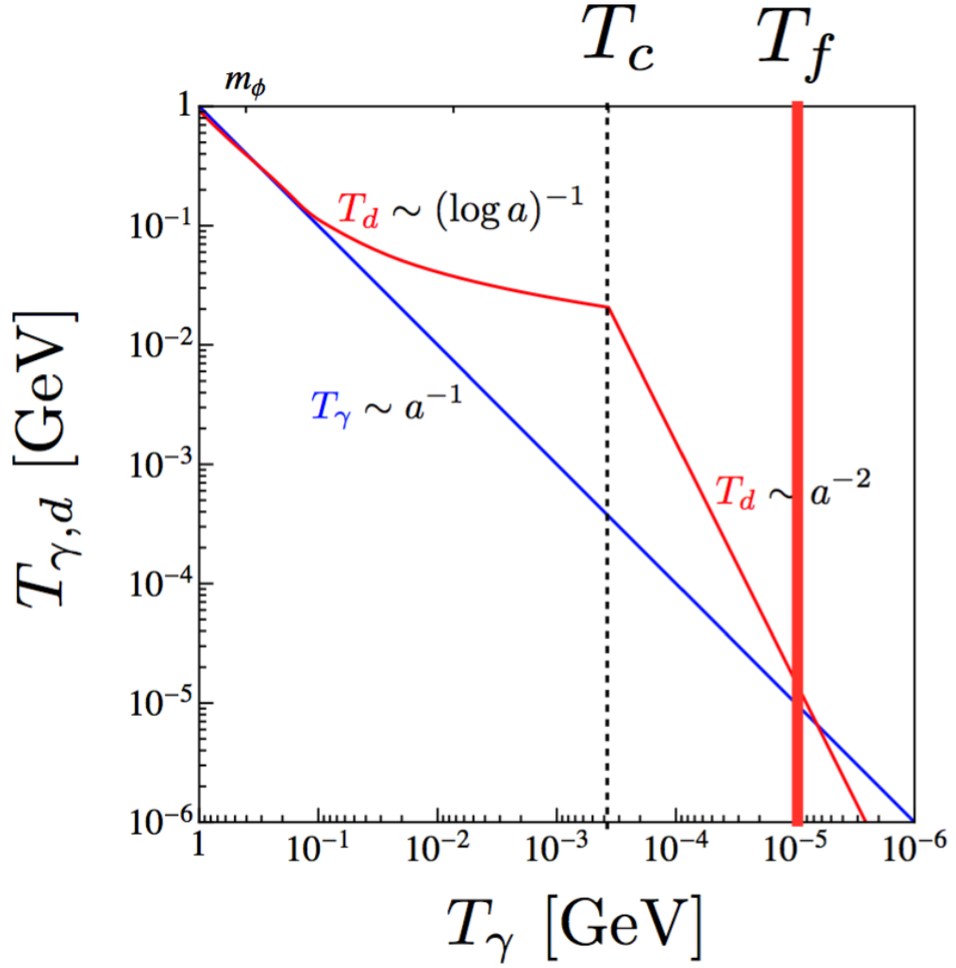


Three phases (II)

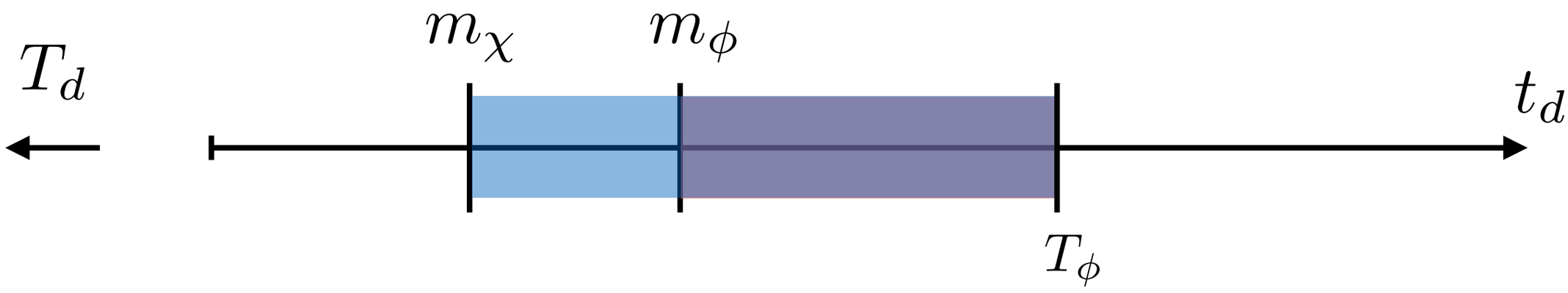


- Chemical: $t_c \ll t_f \ll t_\phi$

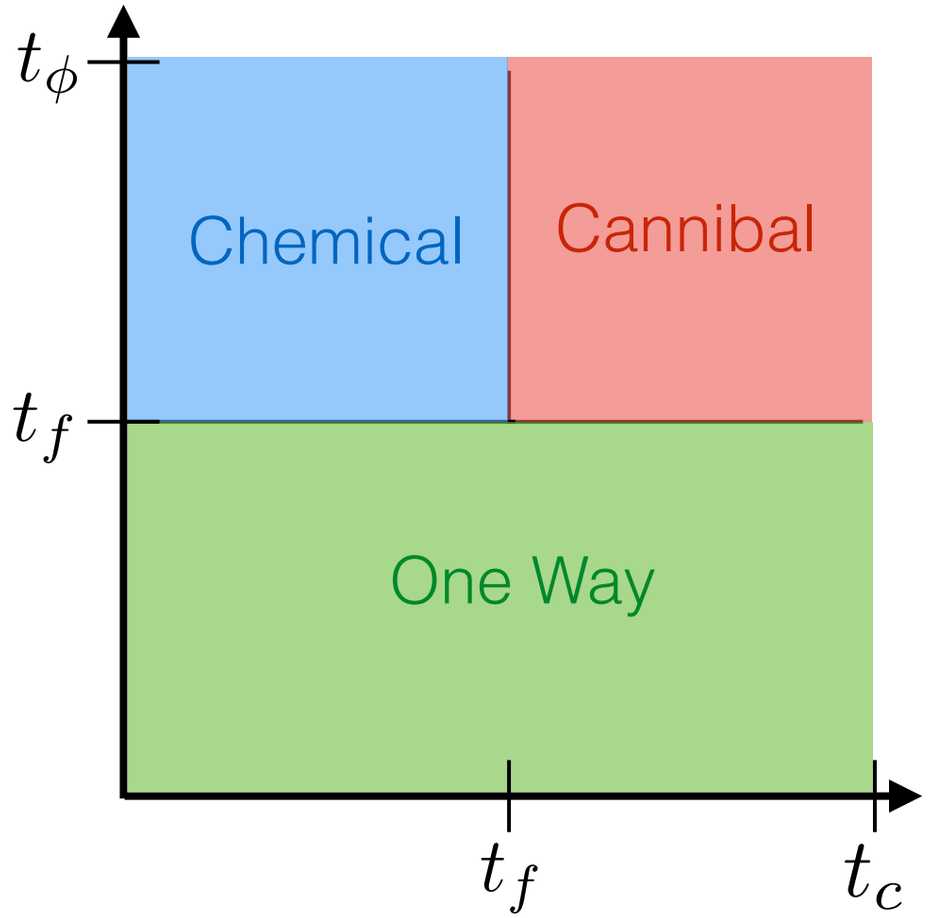
$$Y_\chi \propto \frac{(m_0^4 M_P \sigma_3)^{1/4}}{m_\chi M_P \sigma_2}$$



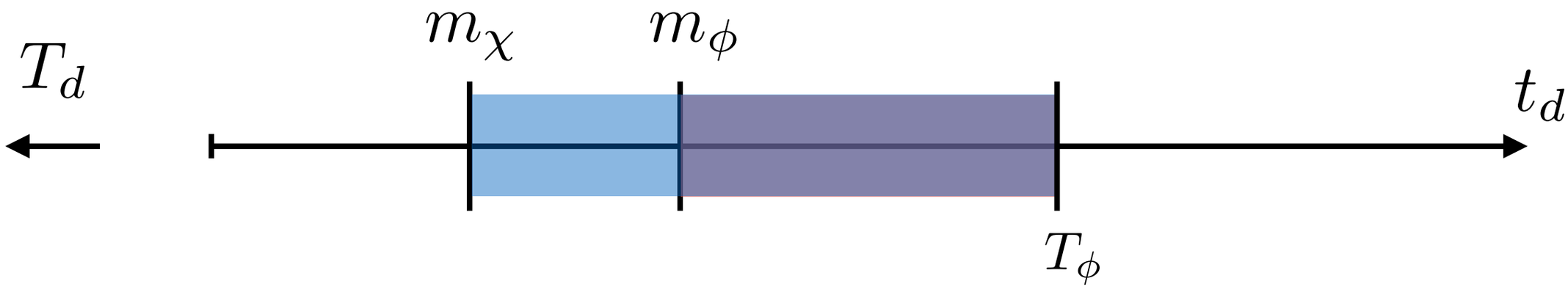
Three phases (III)



- One Way: $t_\phi \ll t_f$

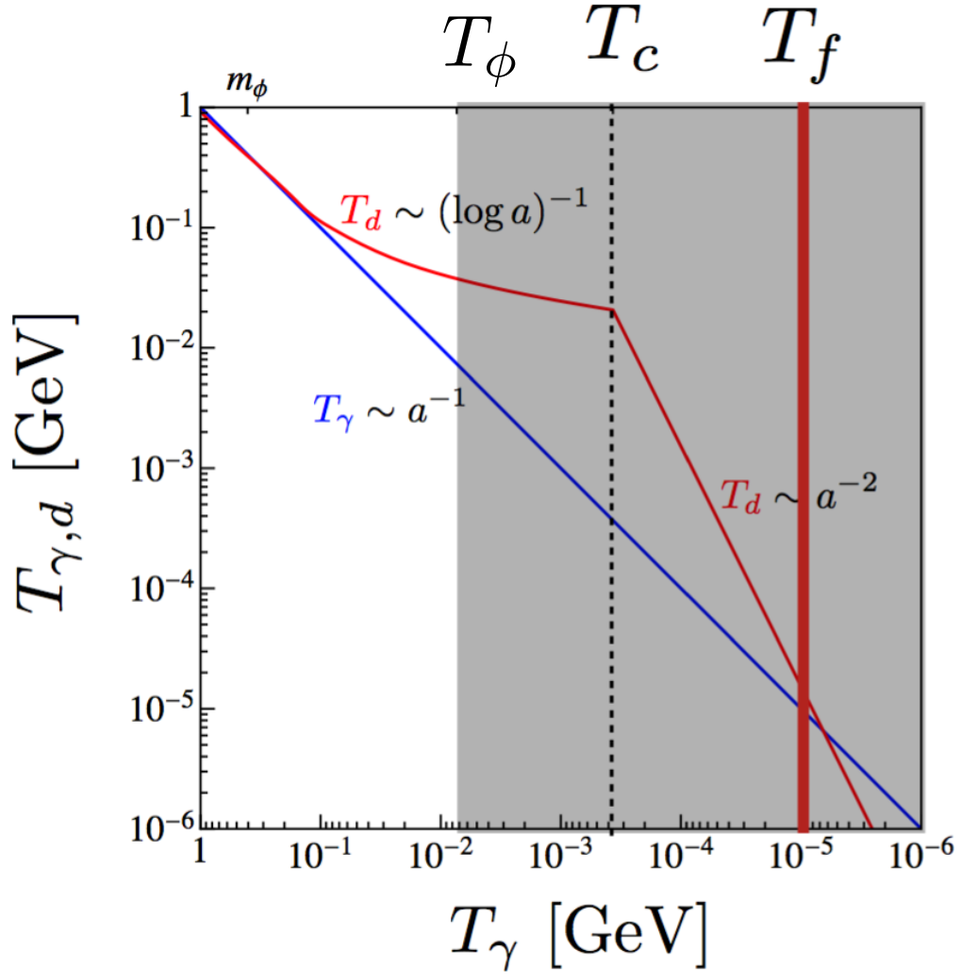


Three phases (III)

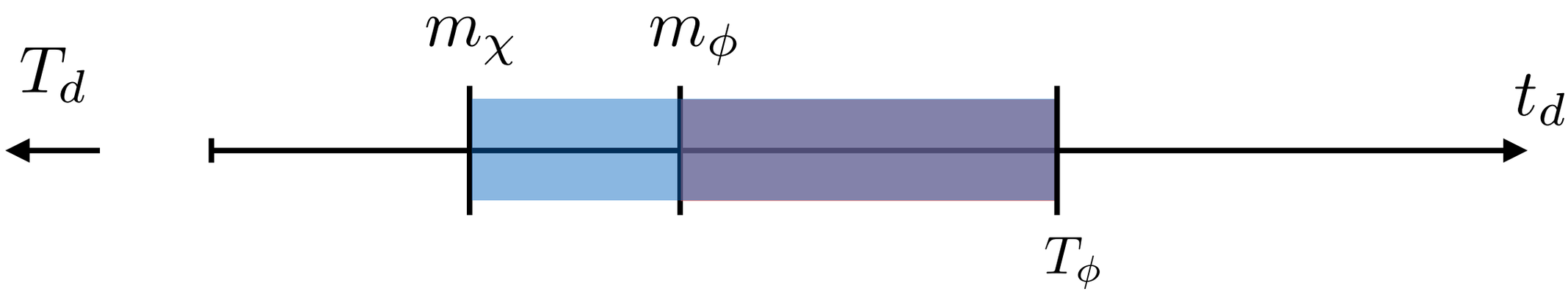


- One Way: $t_\phi \ll t_f$

$$Y_\chi \propto \frac{1}{\Gamma_\phi^{1/2} M_P^{3/2} \sigma_2}$$



Three phases (III)



- One Way: $t_\phi \ll t_f$

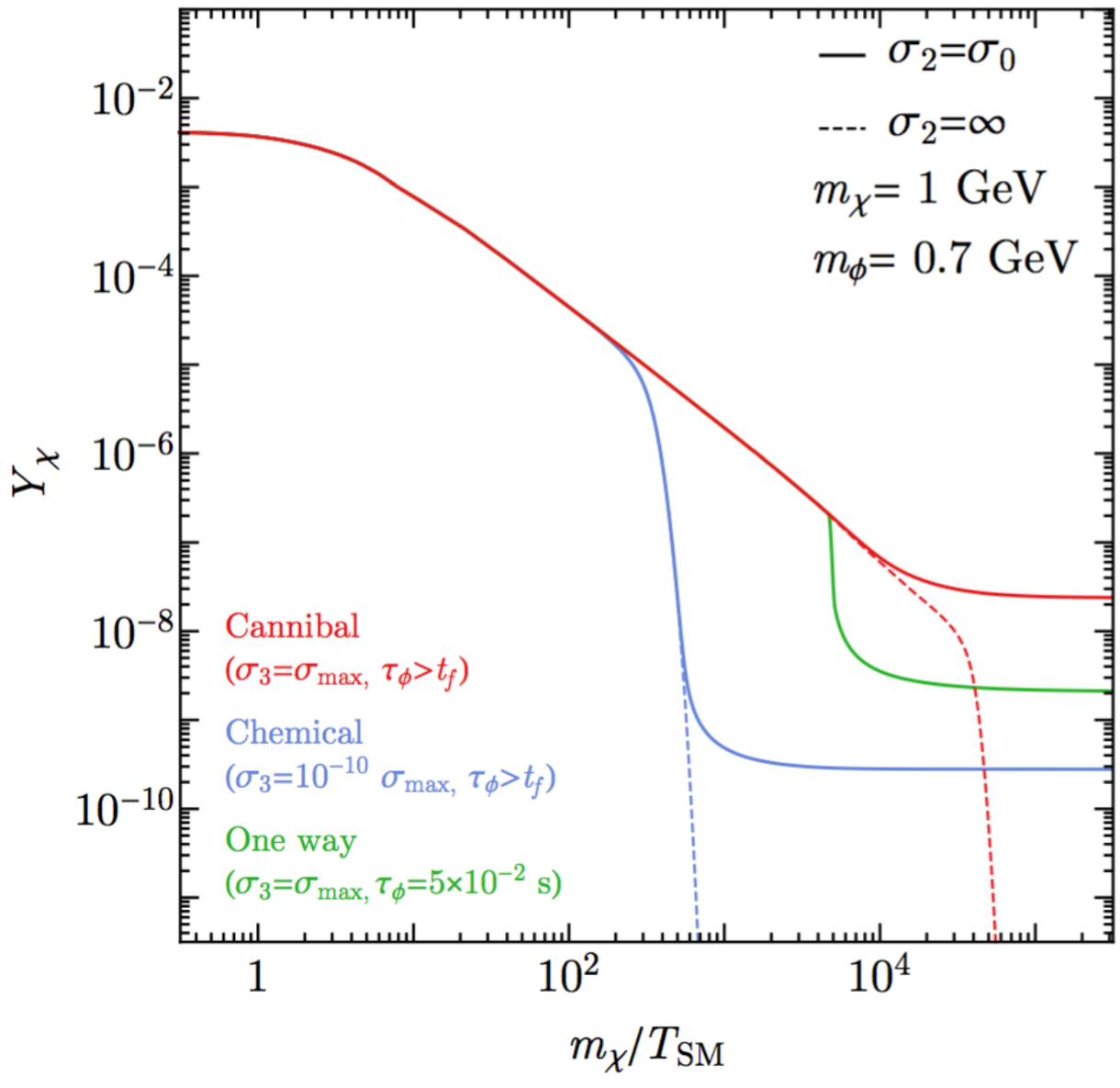
$$Y_\chi \propto \frac{1}{\Gamma_\phi^{1/2} M_P^{3/2} \sigma_2}$$

Requires out of equilibrium physics.

Set $n_\phi = 0$ at T_ϕ as an approximate treatment.

Sub-case studied by Dror, Kuflik, Ng 16'

Three phases (I+II+III)

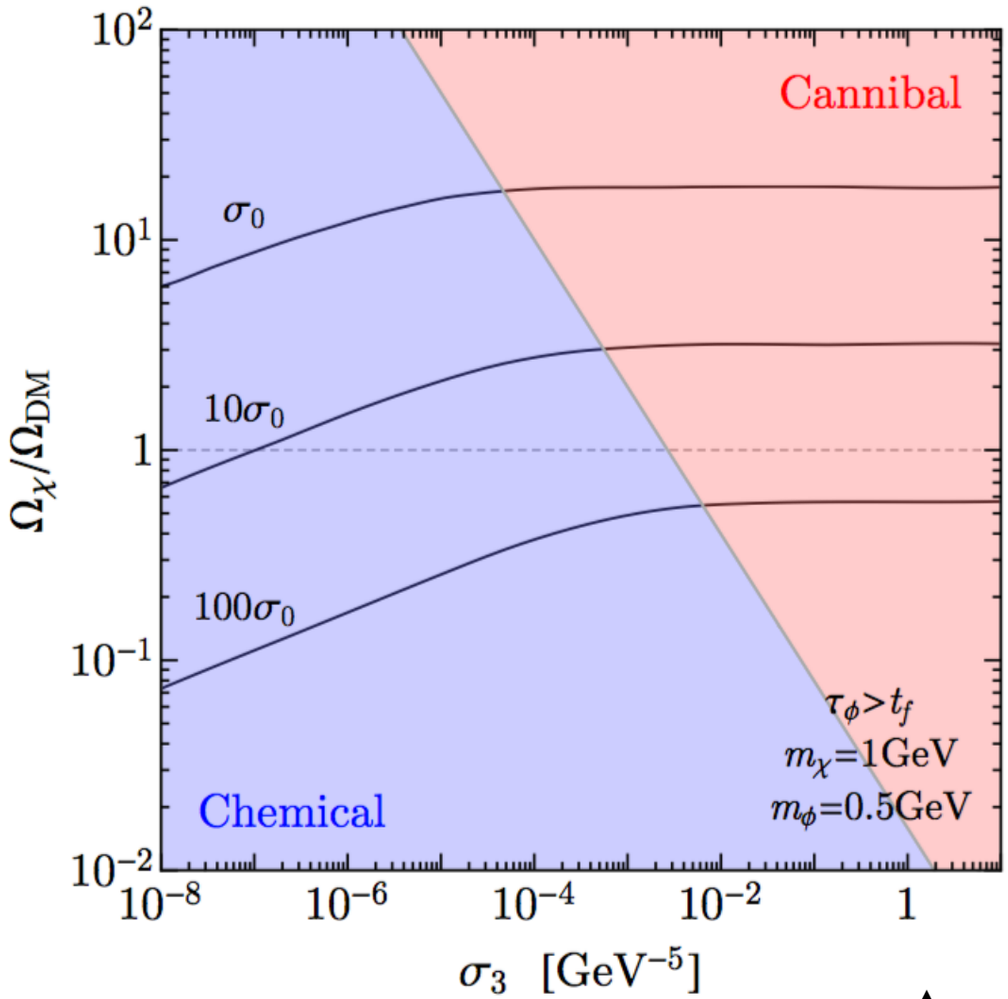


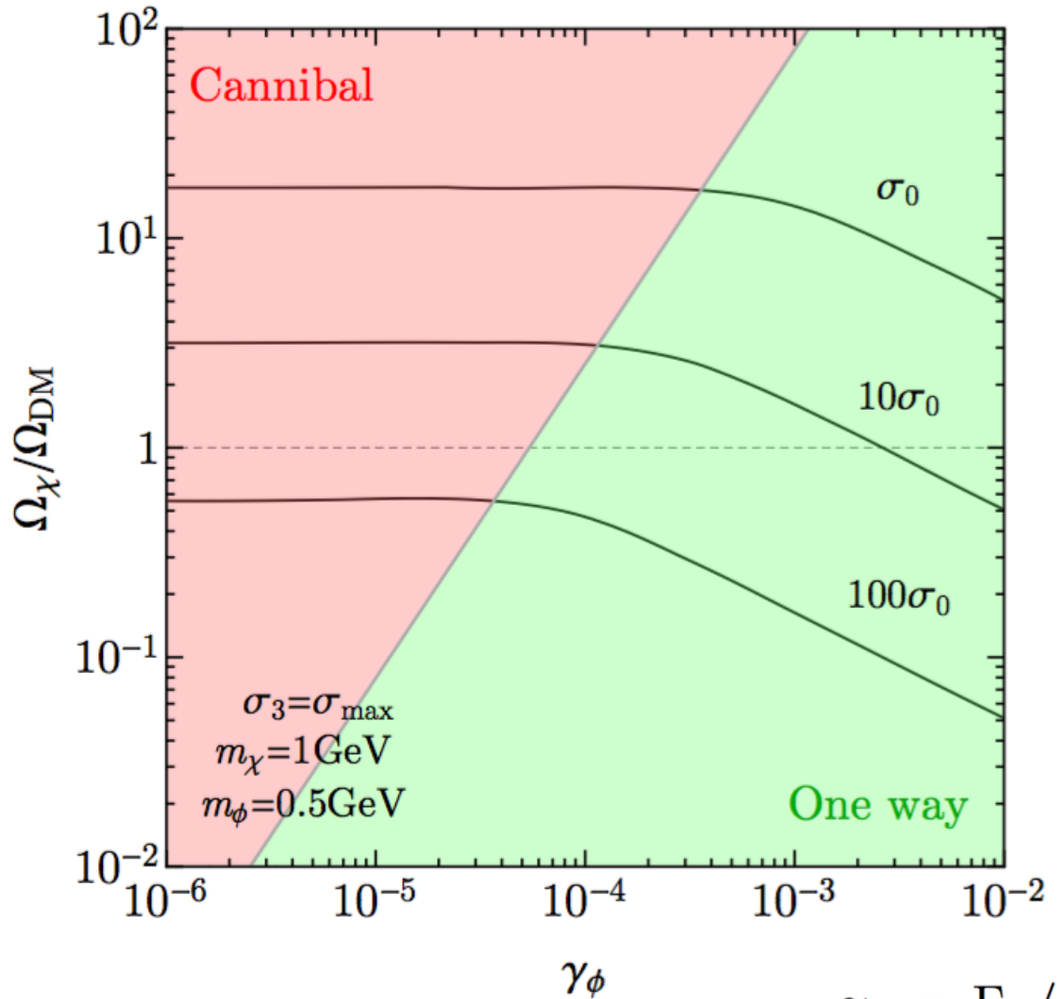
Three phases (I+II+III)

$$Y_\chi \propto \frac{(m_0^4 M_P \sigma_3)^{1/4}}{m_\chi M_P \sigma_2}$$

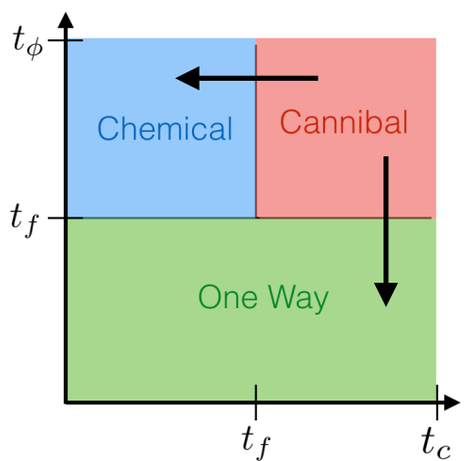
$$Y_\chi \propto (m_\chi M_P \sigma_2)^{-\frac{1-r}{1-2/3\,r}}$$

$$Y_\chi \propto \frac{1}{\Gamma_\phi^{1/2} M_P^{3/2} \sigma_2}$$

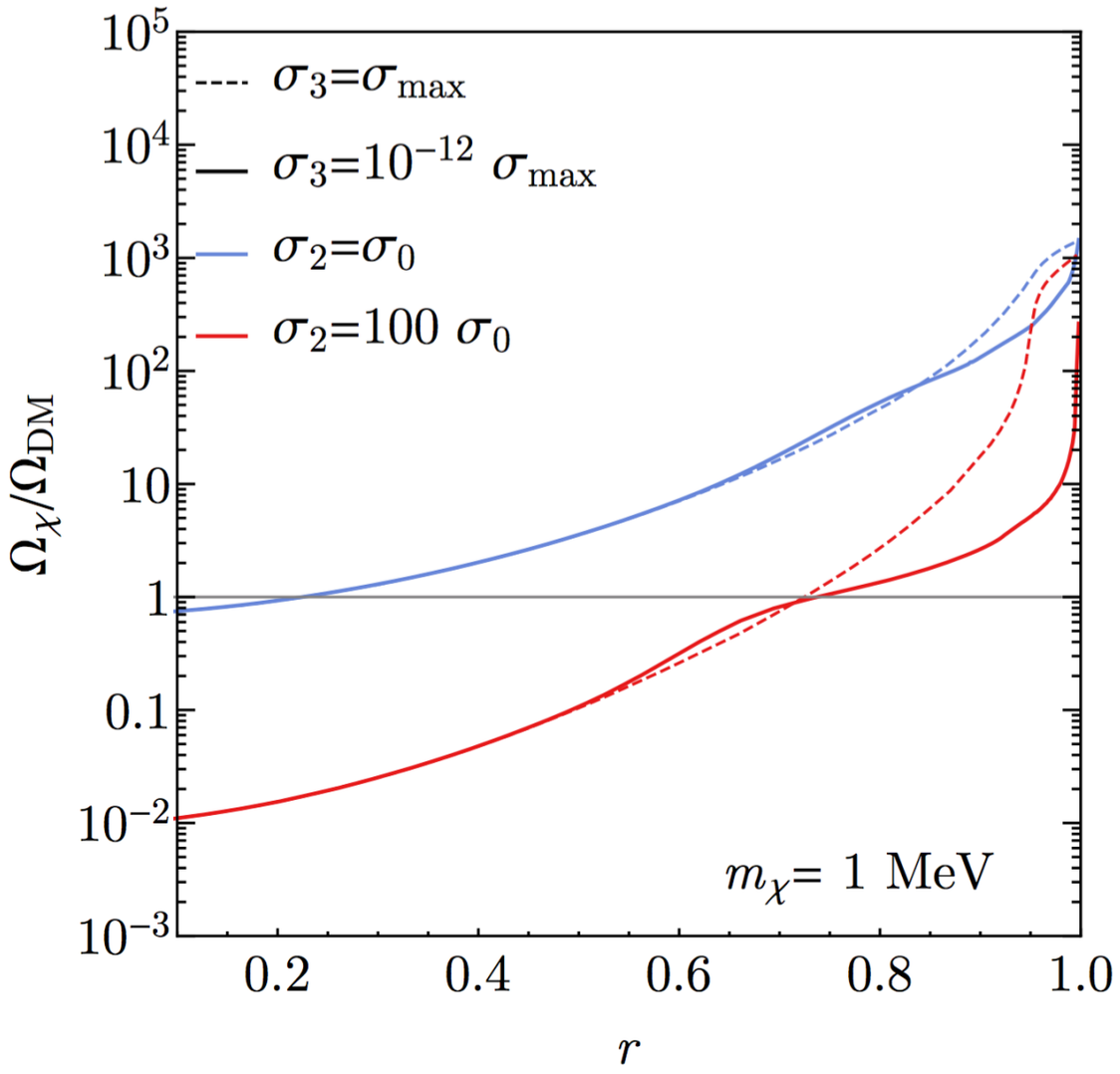


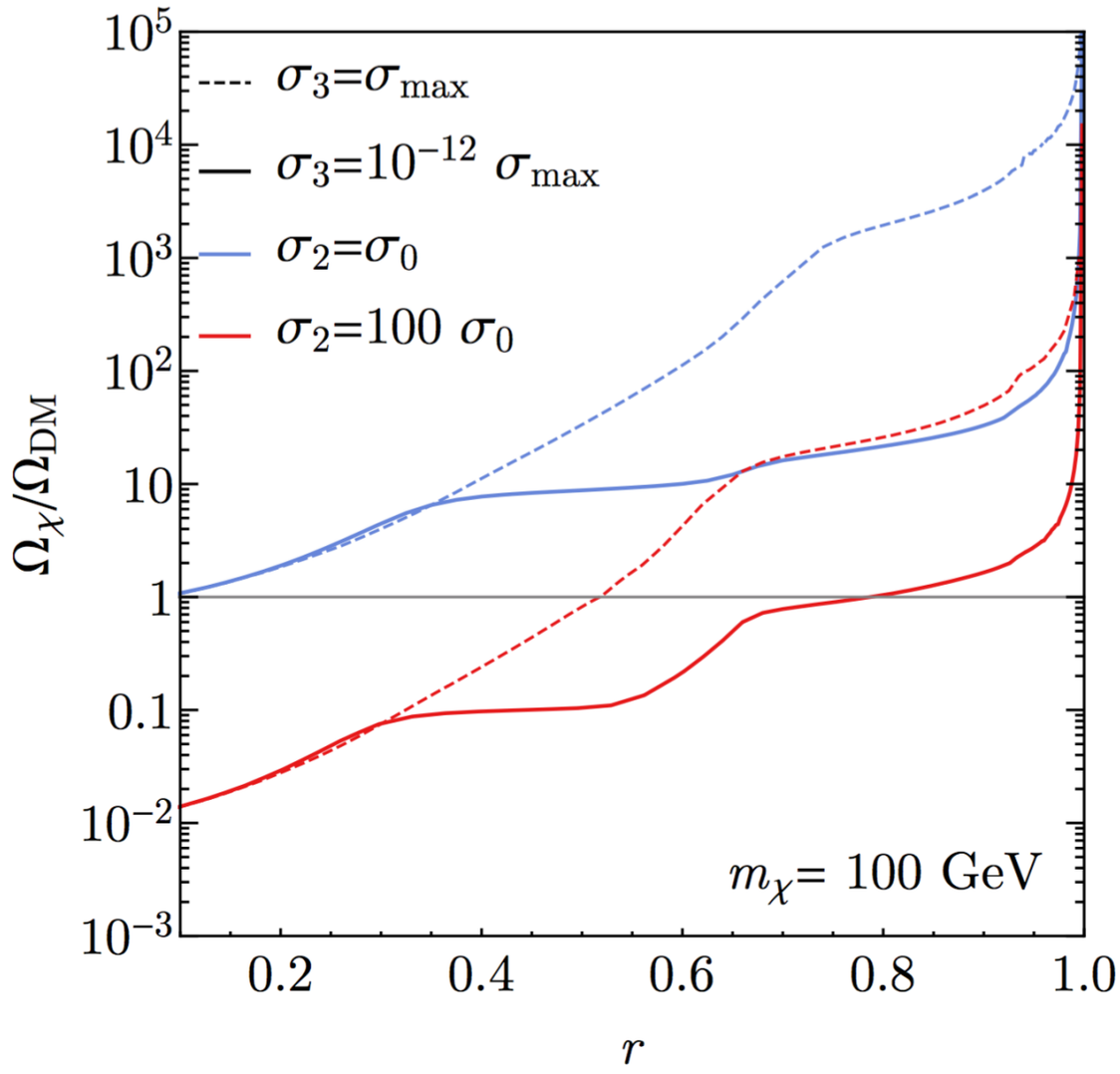


$$\gamma_\phi = \Gamma_\phi / H(m_\phi)$$

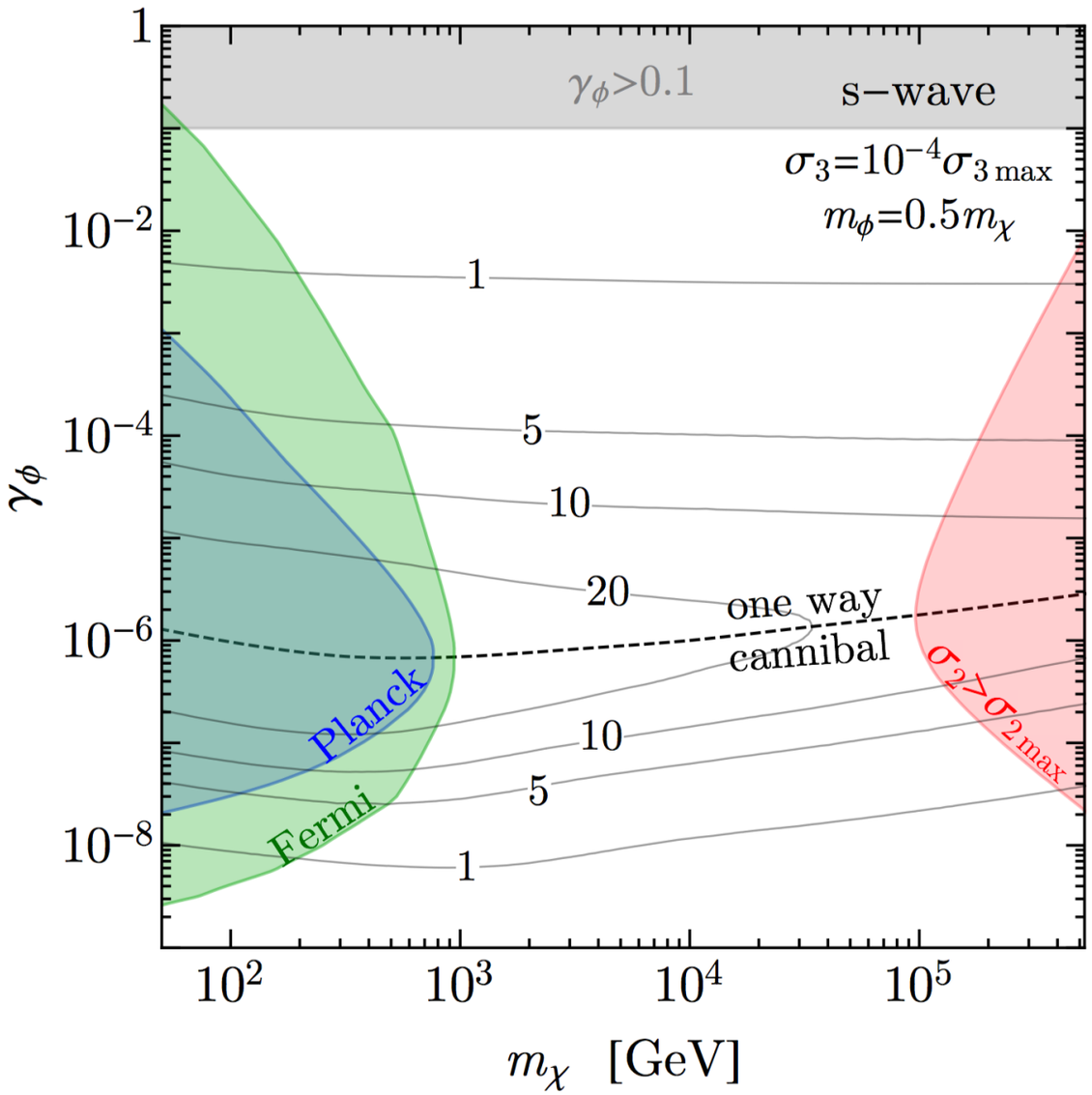


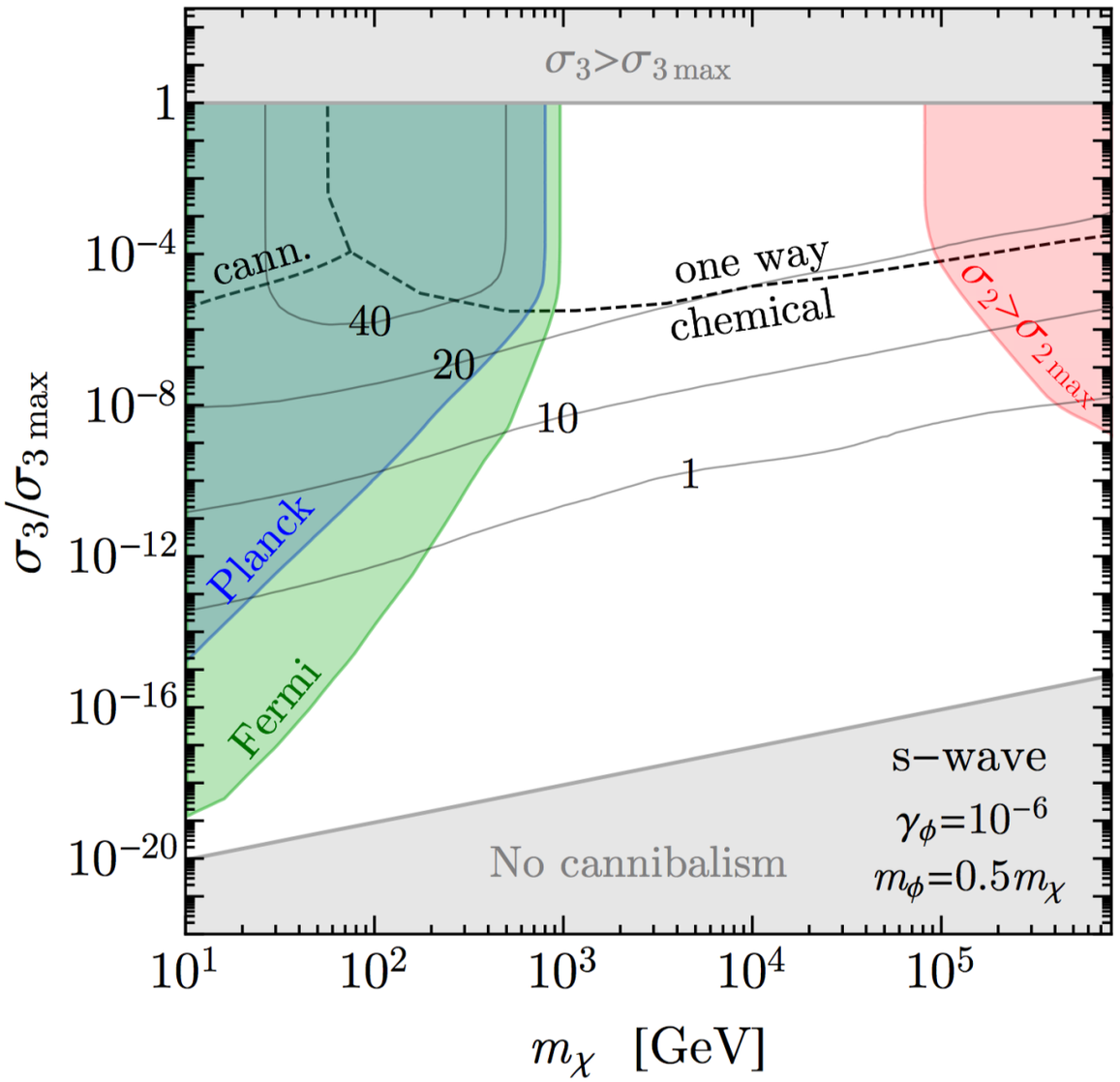
Three phases (I+II+III)





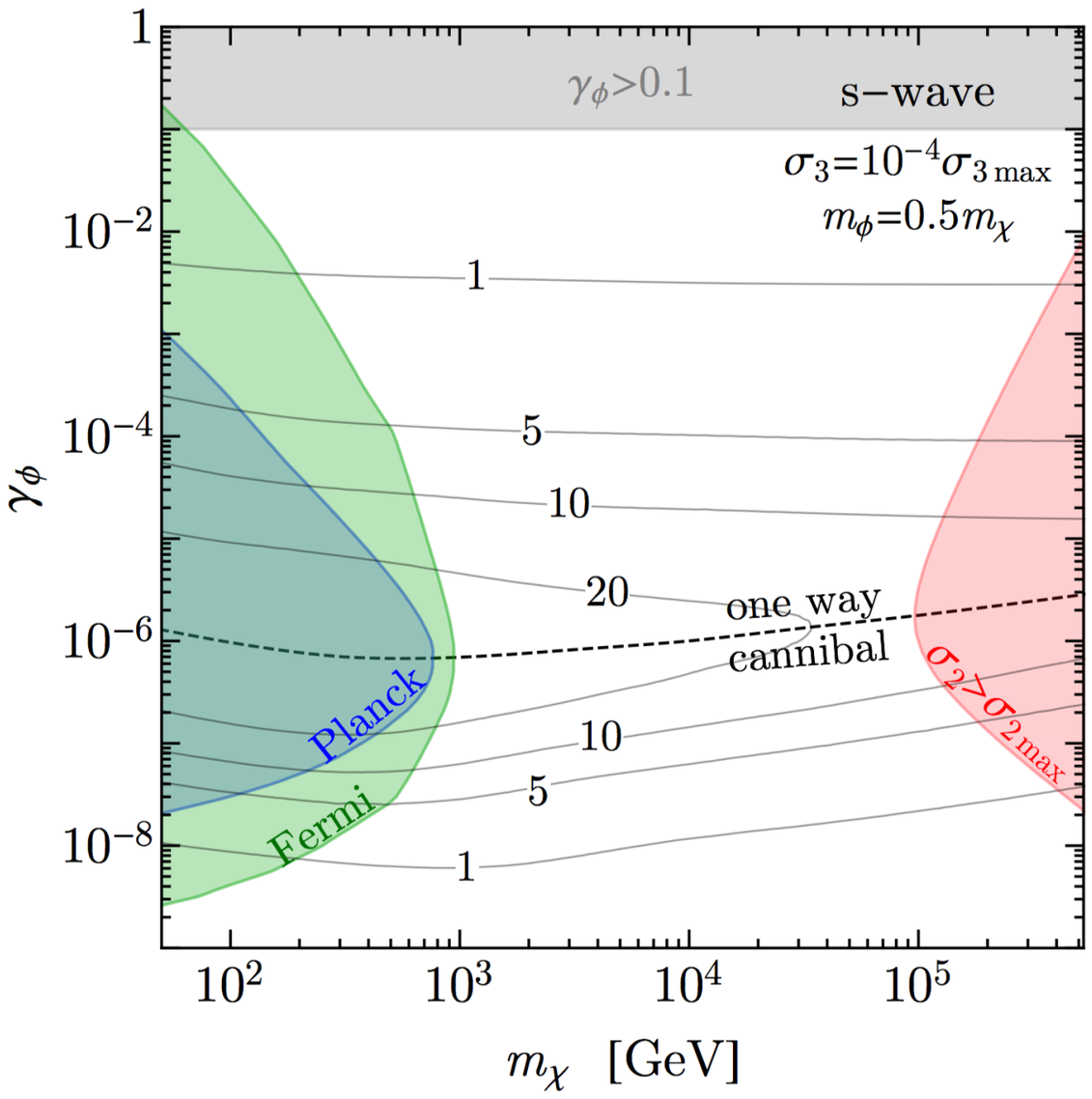
Phases Pheno

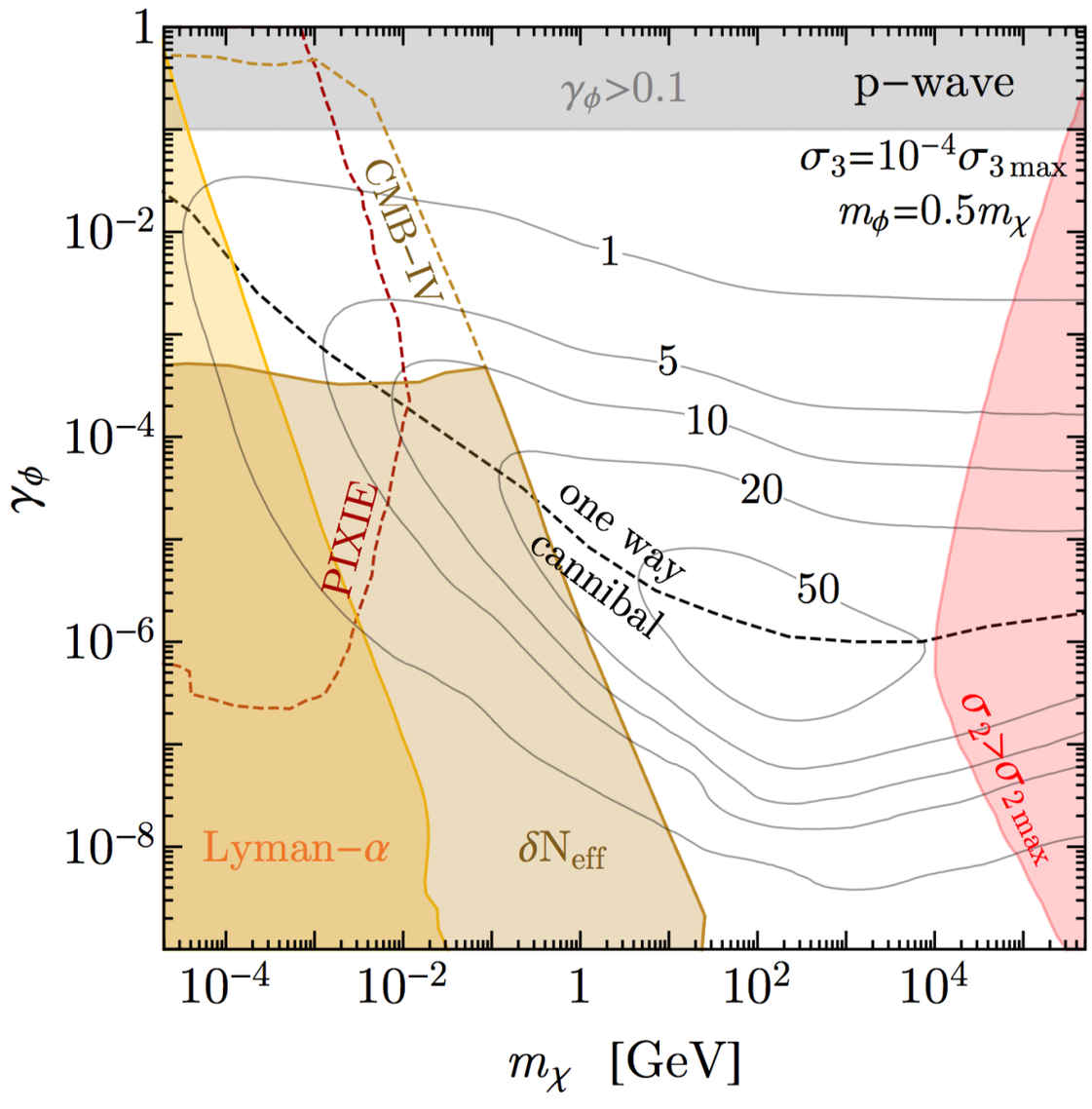




- Take Away: all phases imply boosted annihilation cross section. Rich pheno.

Phases Pheno





- Take Away: all phases imply boosted annihilation cross section. Rich pheno.