Dark Matter Candidates And Models

IPA 2018
October 11 2018

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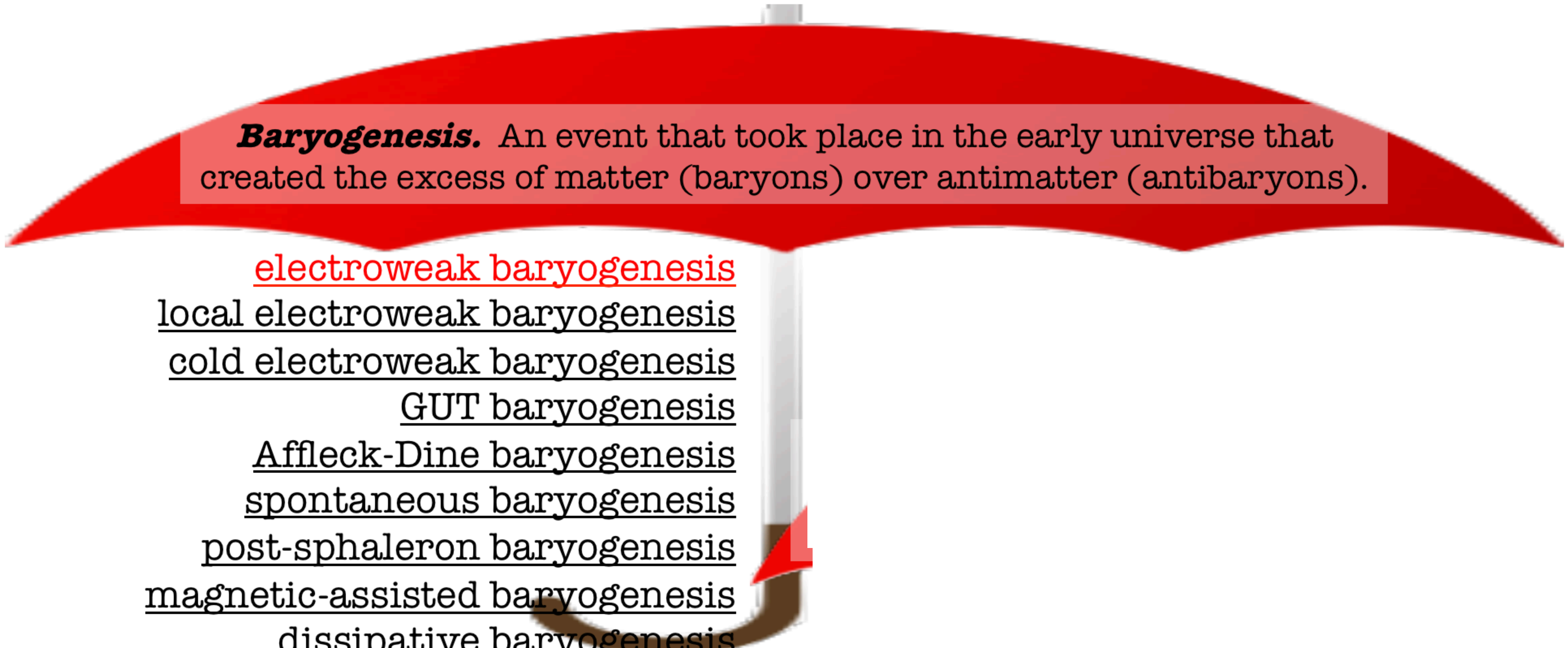
Dark Matter Lazy Intro

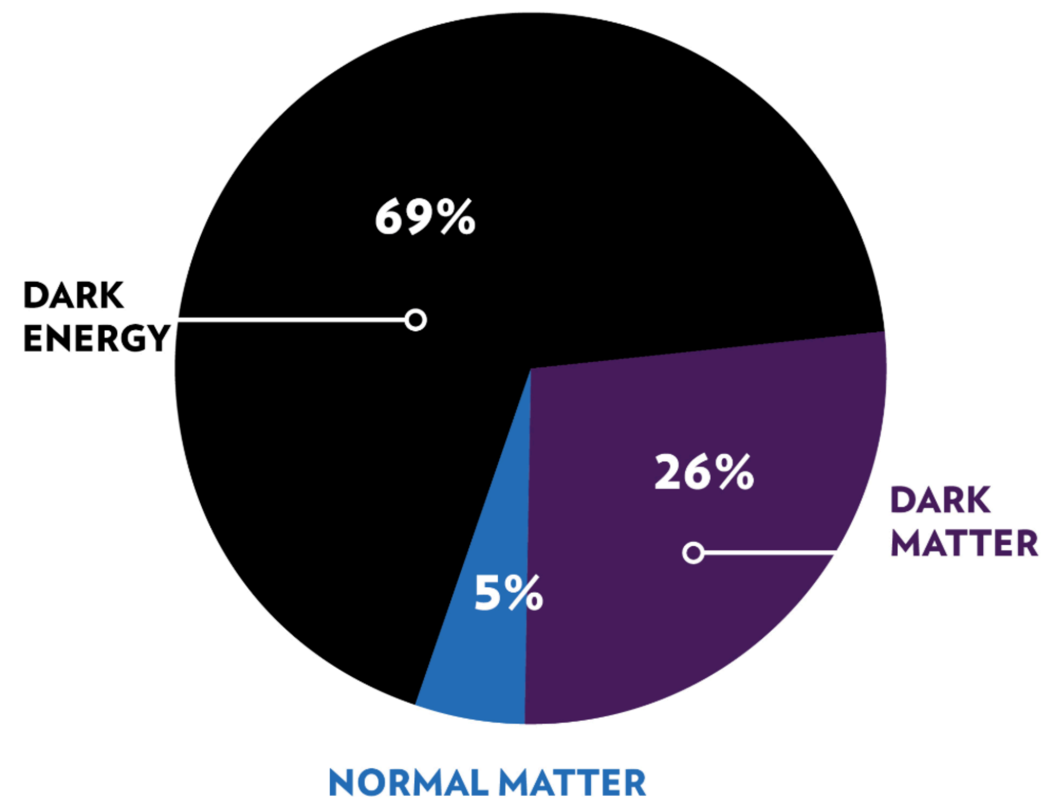


electroweak baryogenesis
local electroweak baryogenesis
cold electroweak baryogenesis
GUT baryogenesis
Affleck-Dine baryogenesis
spontaneous baryogenesis
post-sphaleron baryogenesis
magnetic-assisted baryogenesis
dissipative baryogenesis
warm baryogenesis
cloistered baryogenesis
Planck baryogenesis
WIMPy baryogenesis
cosmic string baryogenesis
axion domain wall baryogenesis
new GUT baryogenesis
PBH baryogenesis
supersonic baryogenesis
…

Courtesy of Andrew Long

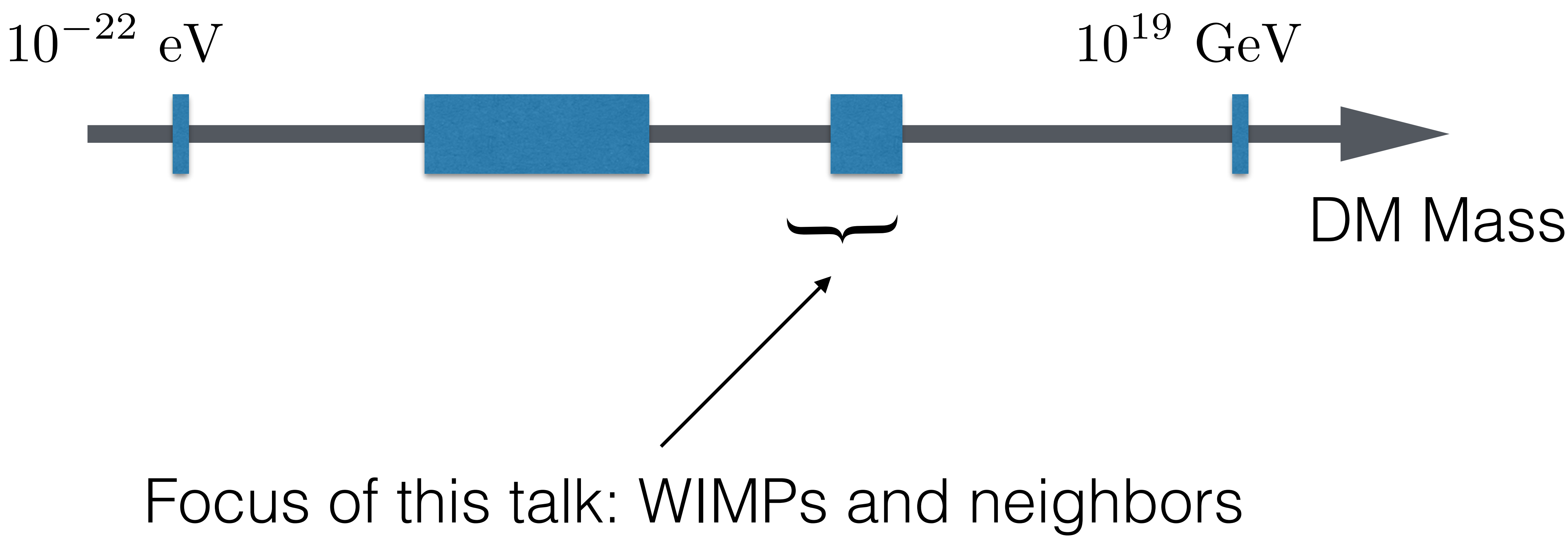
Dark Matter Lazy Intro

Dark Matter: something.
26% of the energy budget of the universe.

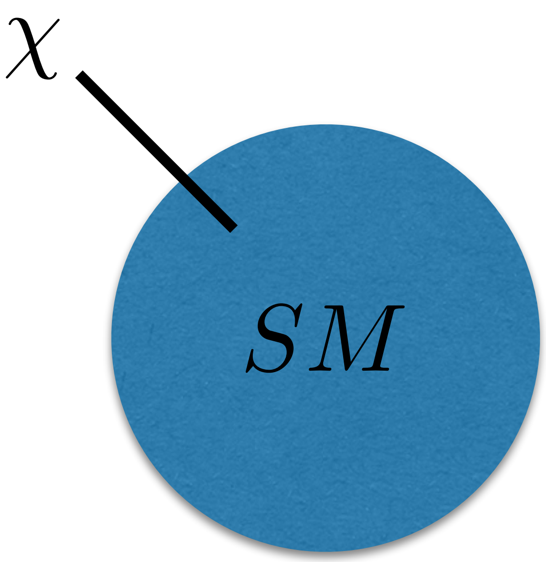


Courtesy of Andrew Long

Dark Matter Mass



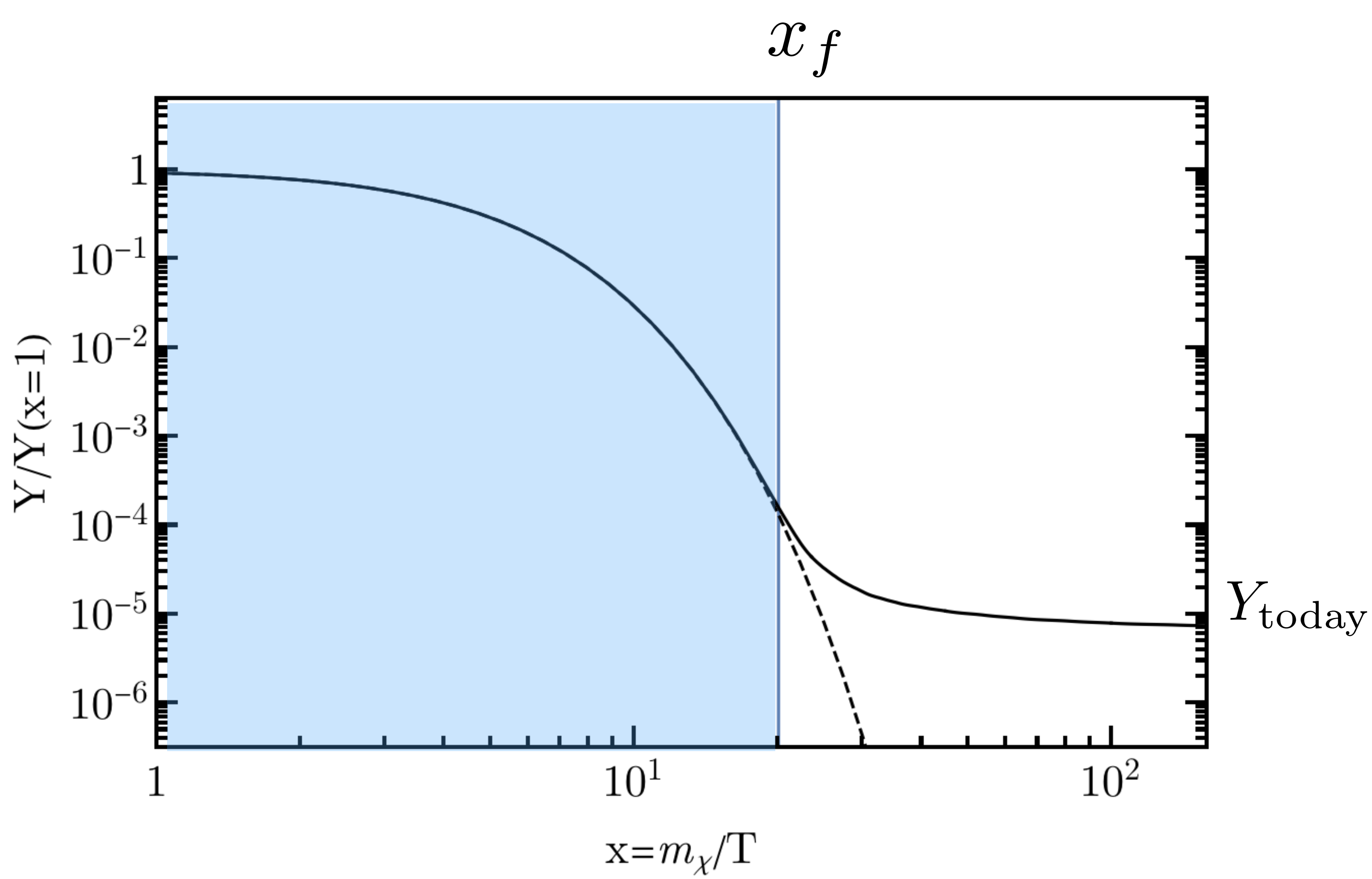
Why WIMP?



Cold dark matter

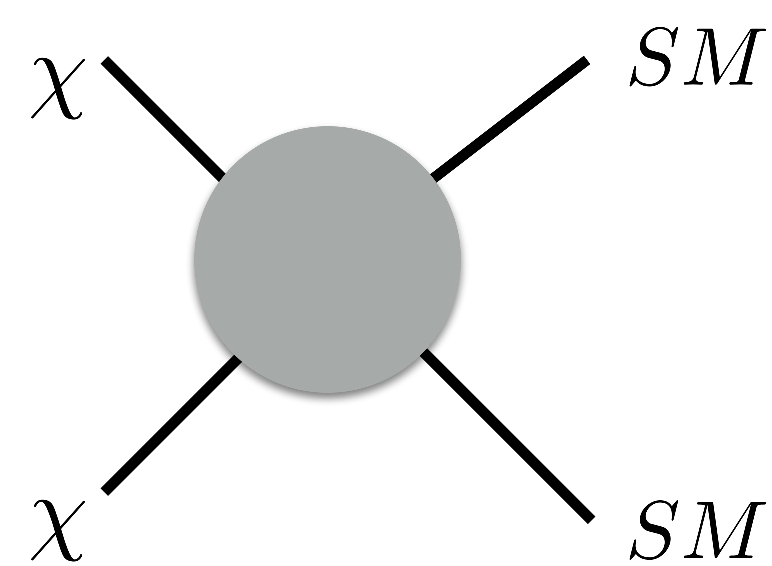
- Extremely successful
- Extremely simple
- WIMP miracle ~ Hierarchy problem?

WIMP Miracle

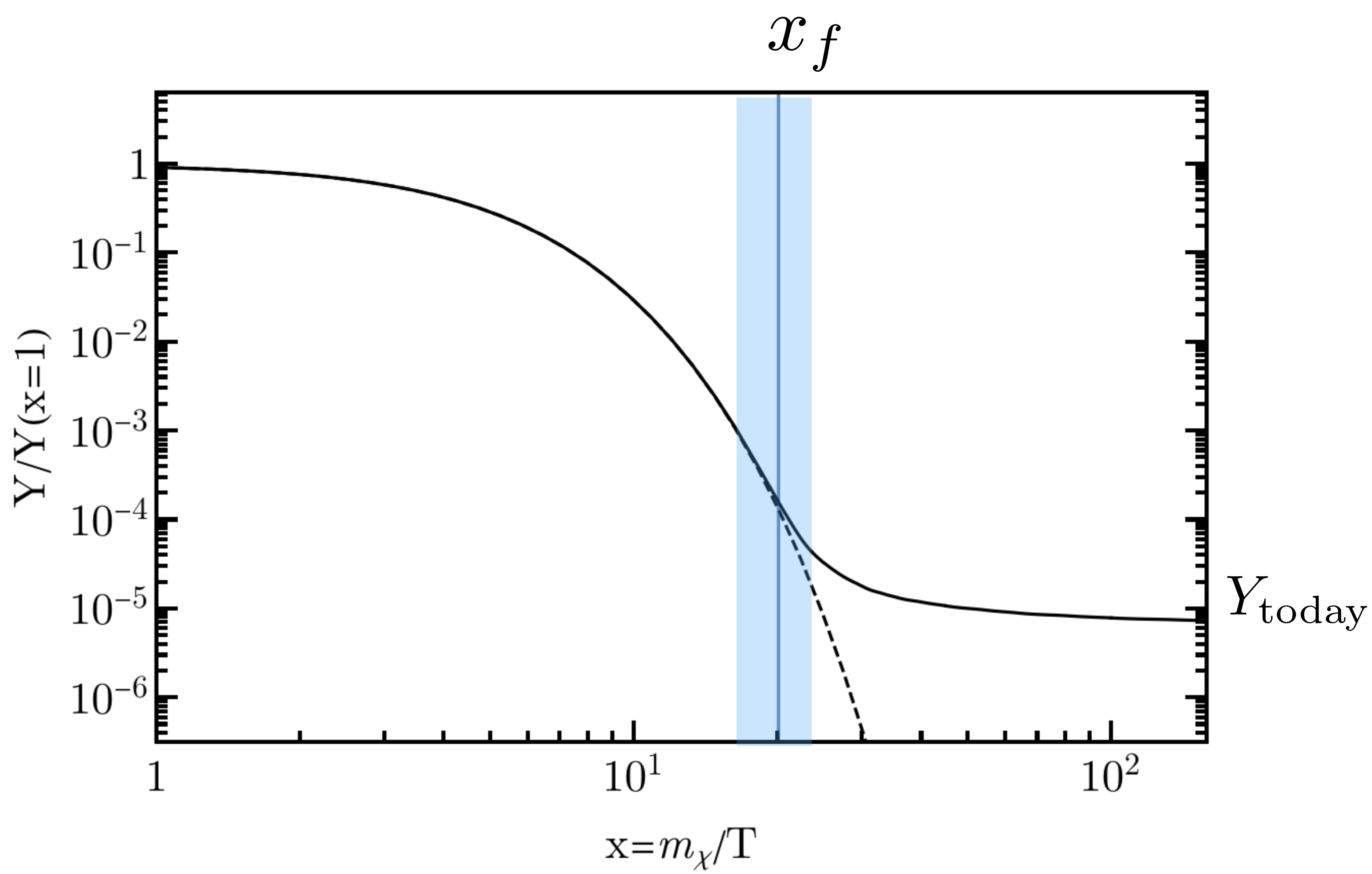


$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - (n_\chi^{eq})^2\right)$$

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



WIMP Miracle

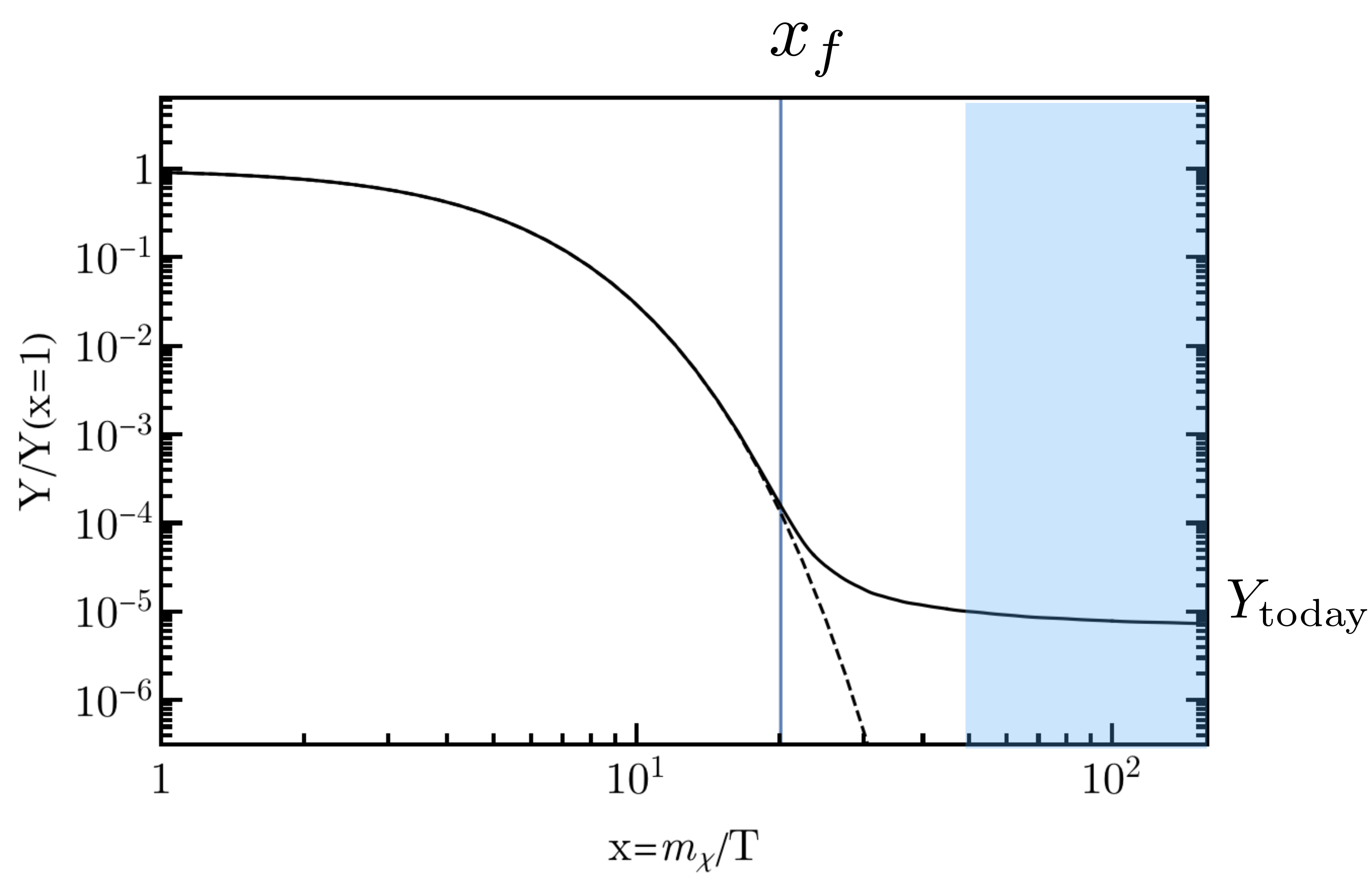


Freeze-out when $n_\chi \langle \sigma v \rangle \approx H$

$$Y \equiv \frac{n_\chi}{s} \sim e^{-m_\chi/T} \quad H \approx \sqrt{g_*}\frac{T^2}{M_{Pl}}$$

$$\Rightarrow \quad x_f \equiv \frac{m_\chi}{T_f} \sim \log\, m_\chi M_{Pl} \langle \sigma v \rangle$$

WIMP Miracle

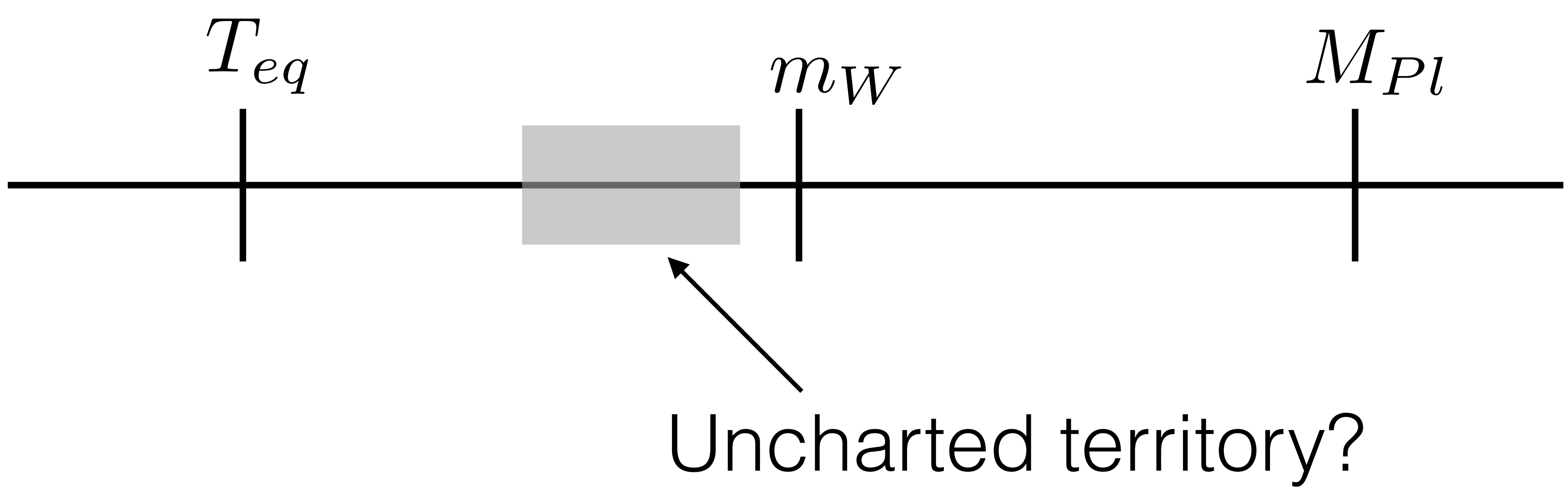


After freeze-out yield is fixed $Y \sim \frac{1}{m_\chi M_{Pl} \langle \sigma v \rangle}$

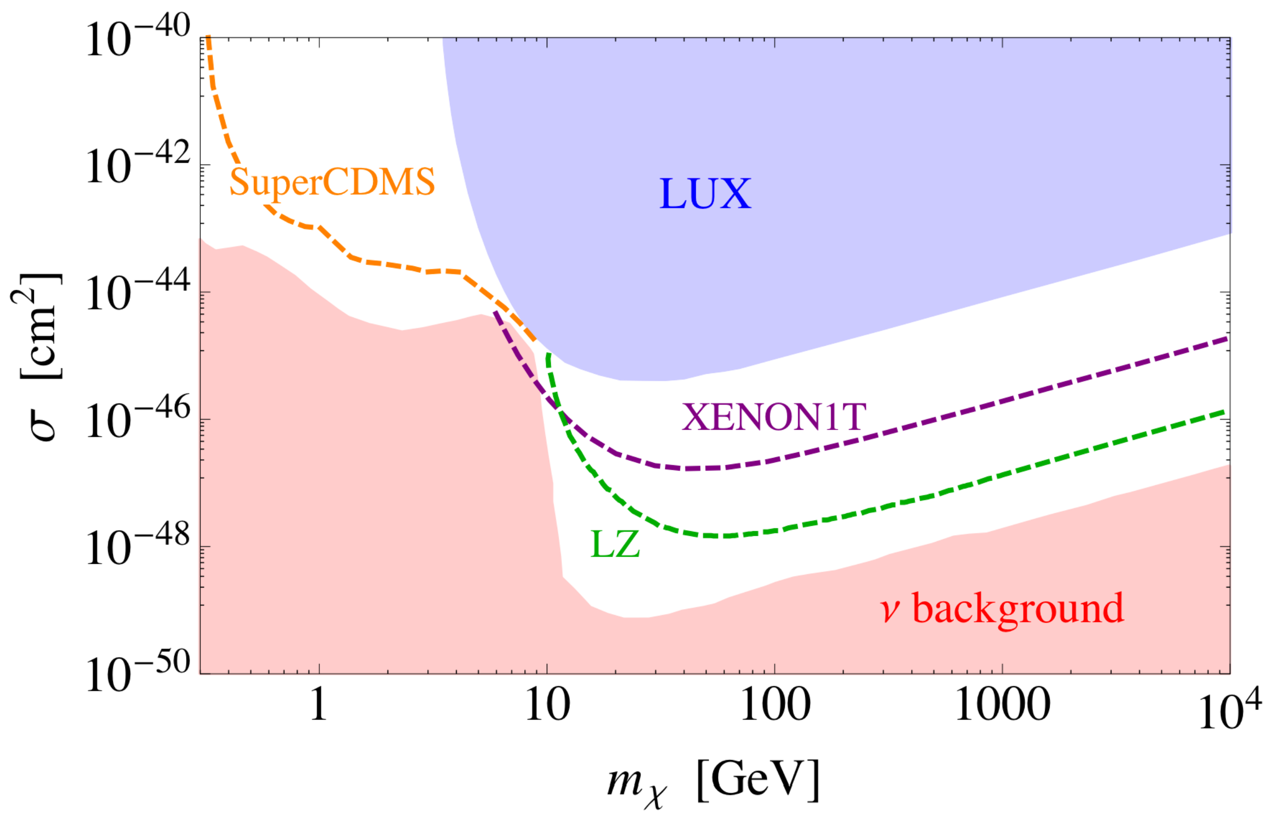
$T_{eq} \approx \frac{m_\chi n_\chi}{s}$ $\Rightarrow$ $m_\chi \sim \alpha \sqrt{T_{eq} M_{Pl}}$ for $\langle \sigma v \rangle \sim \frac{\alpha^2}{m_\chi^2}$

WIMP Miracle?

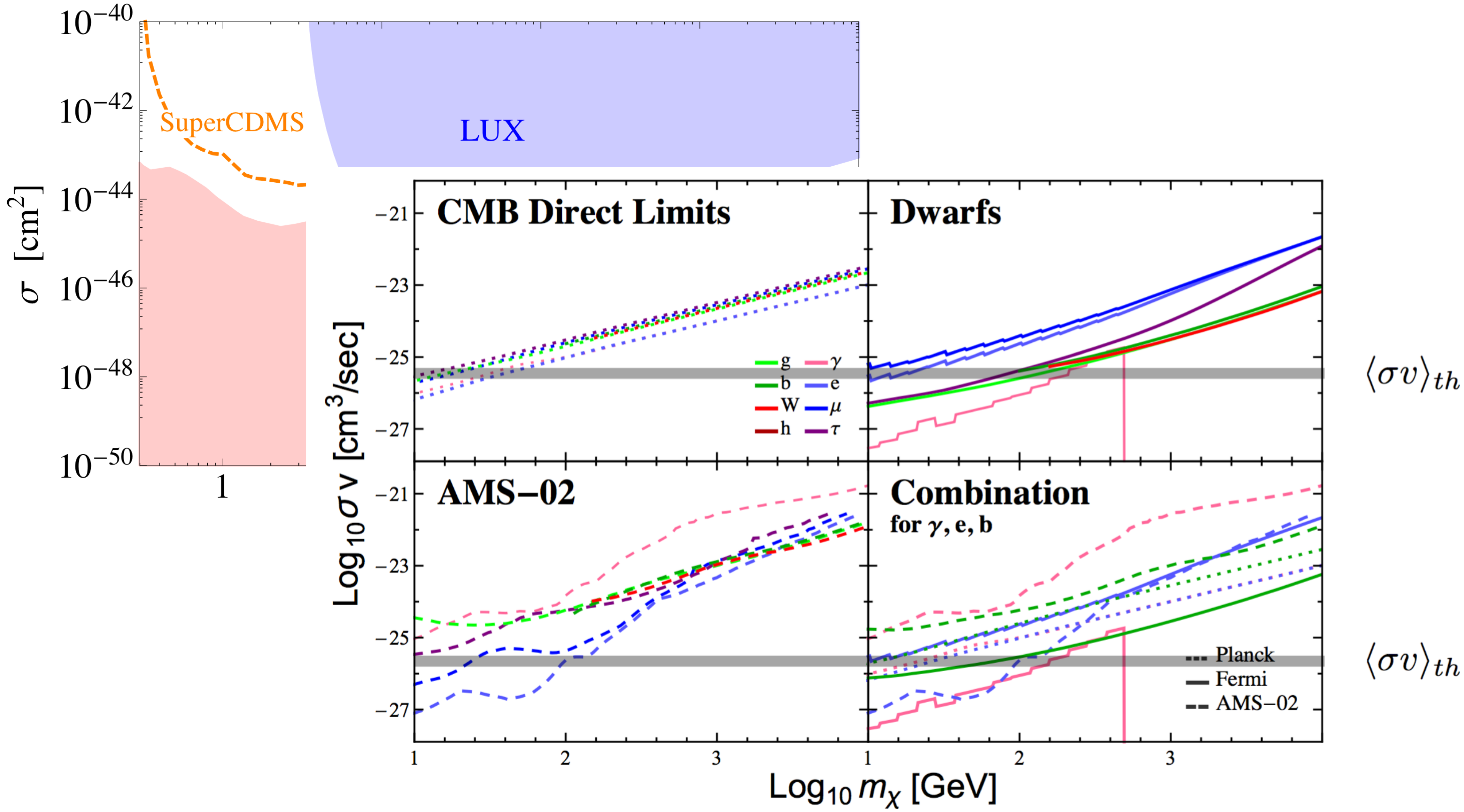
- $\alpha_W \sqrt{T_{eq} M_{Pl}} \sim 1 \text{ TeV}$ "numerology"?
- No signs of solutions to the hierarchy problem at LHC
- Moreover…



WIMP Miracle?

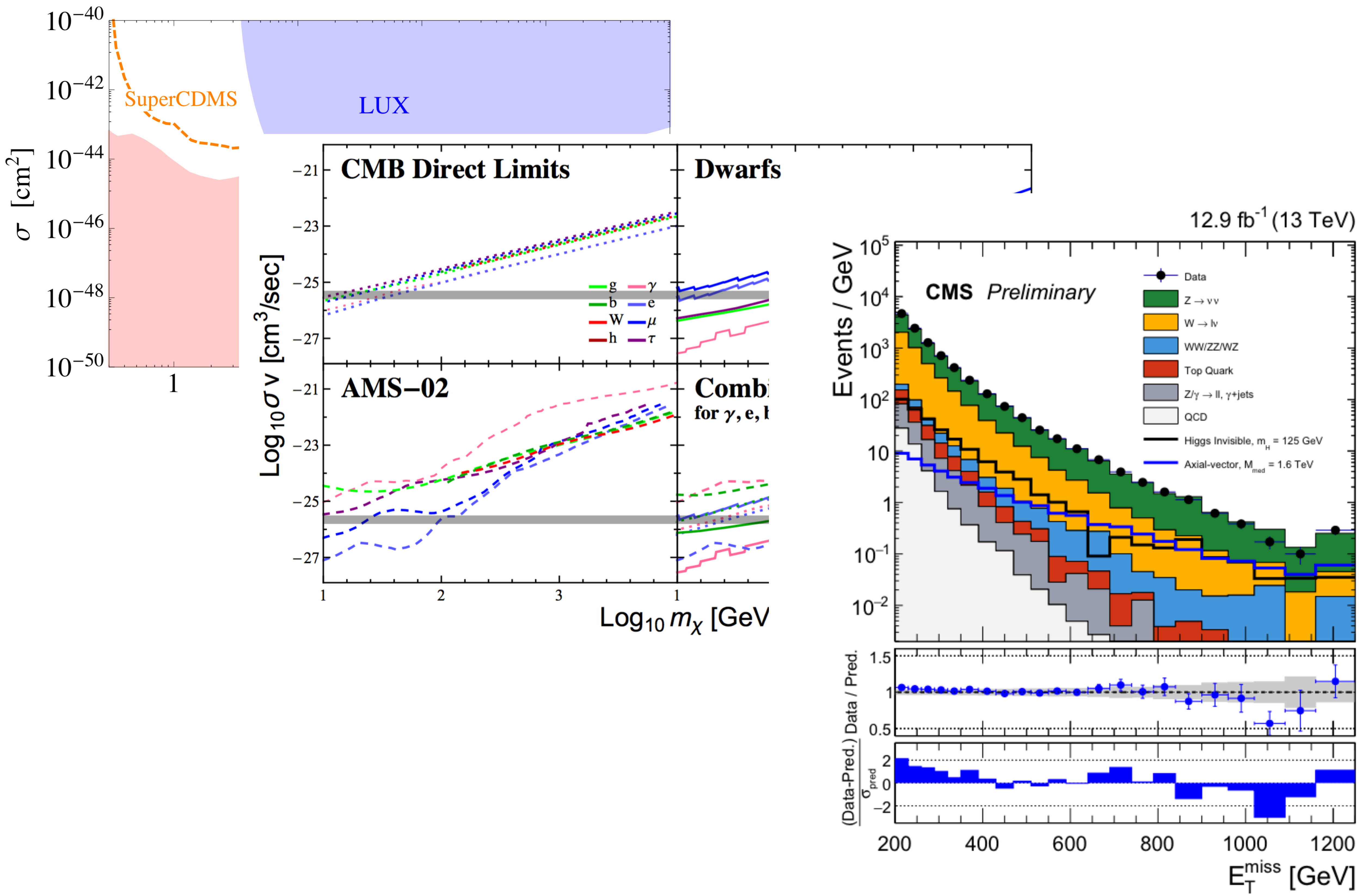


WIMP Miracle?



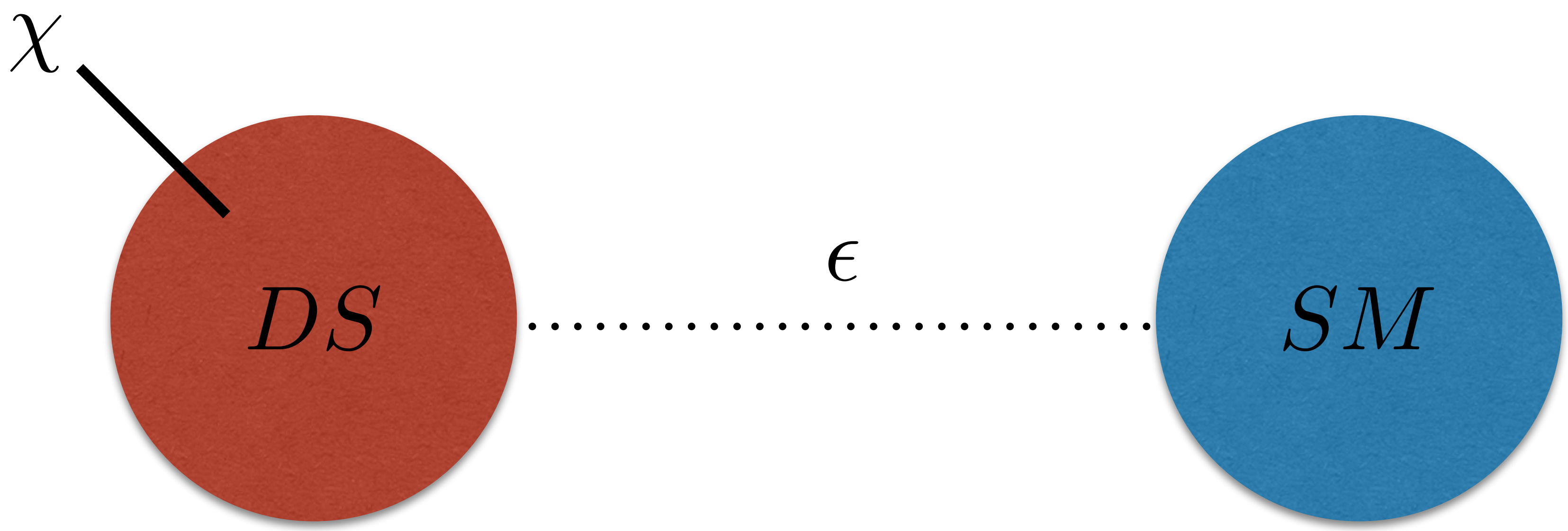
Elor, Rodd, Slatyer, Xue 15'

WIMP Miracle?

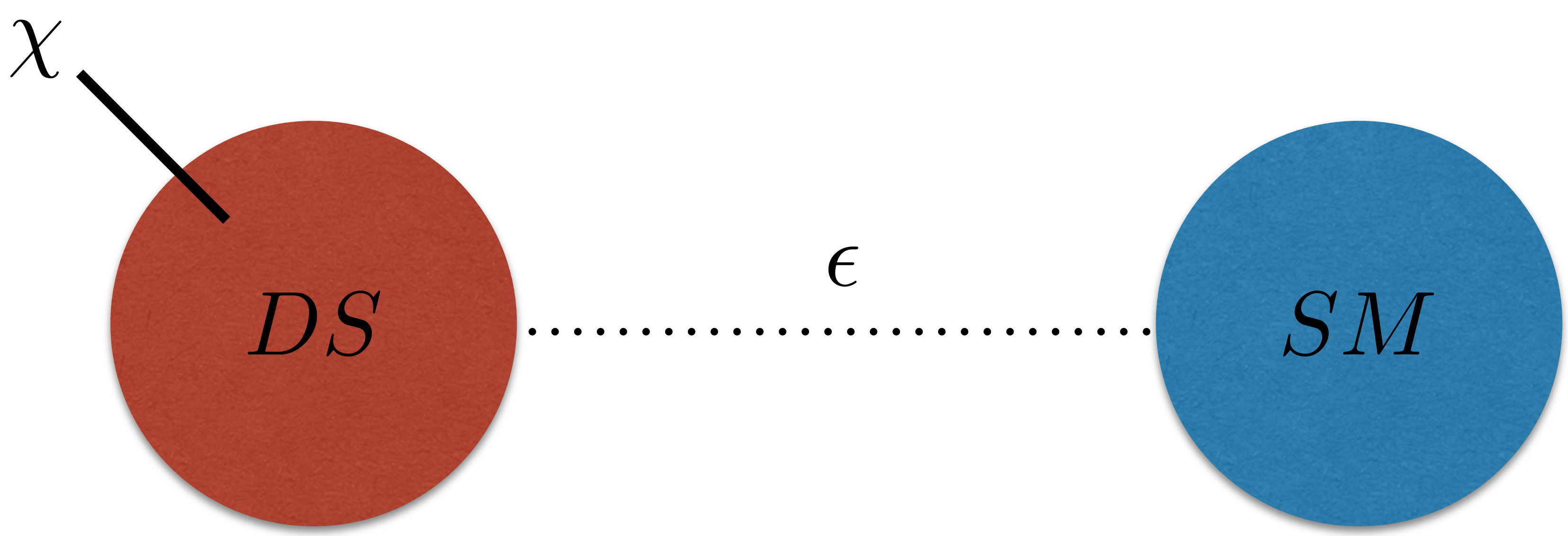


CMS EXO-16-037-pas

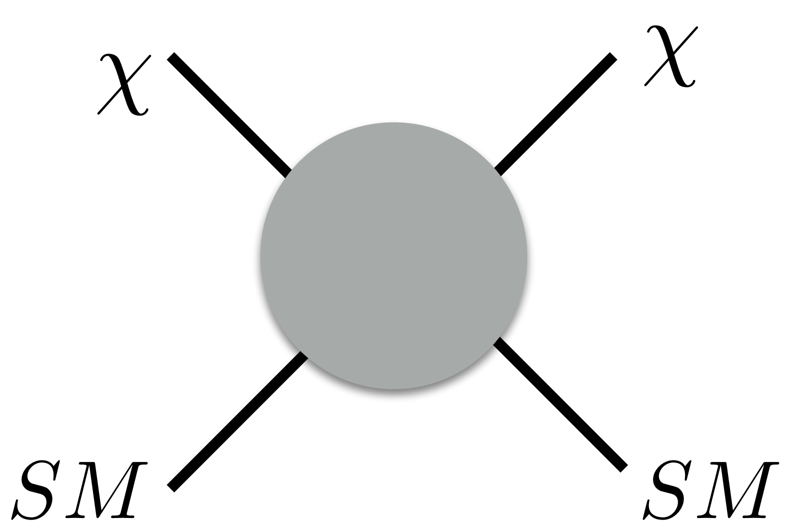
Beyond WIMP



Beyond WIMP



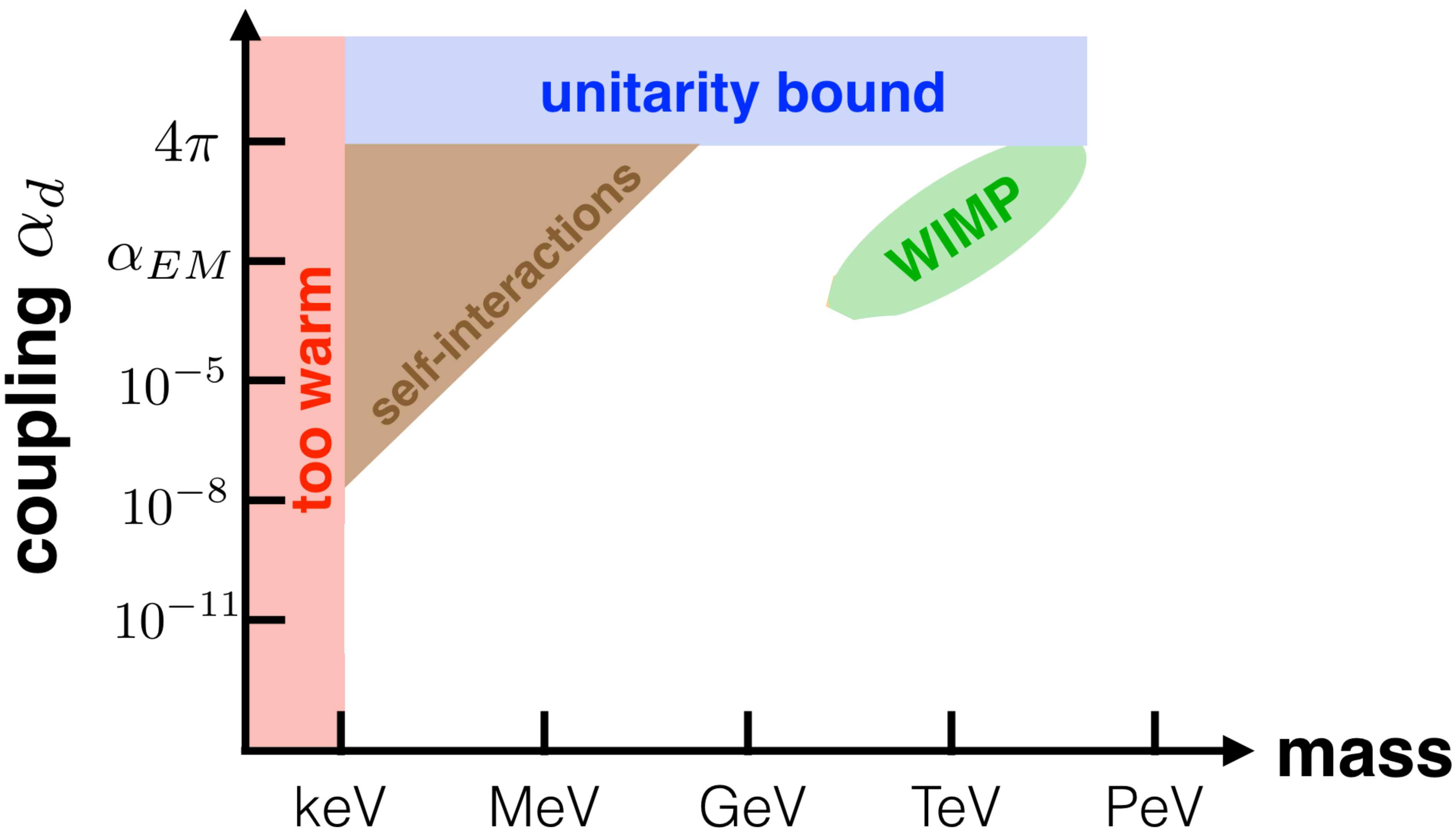
SM and Dark Sector kinetically coupled?



$> H$

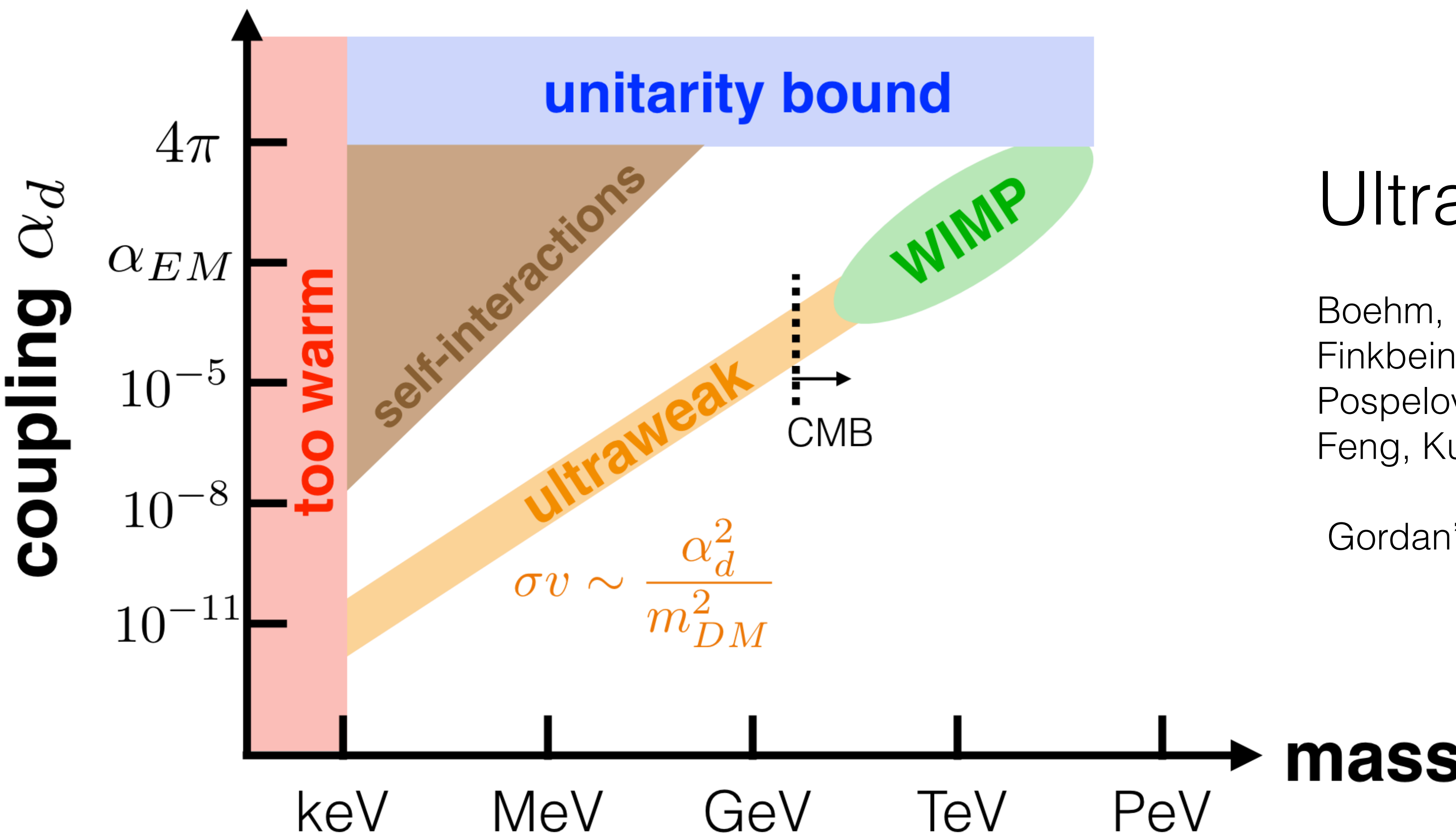
$$\epsilon \gtrsim 10^{-8} \sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

Beyond WIMPs



Courtesy of Josh Ruderman

Beyond WIMPs



Ultraweak DM

Boehm, Fayet '04
Finkbeiner, Weiner '07
Pospelov, Ritz, Voloshin '08
Feng, Kumar '08

Gordan's Talk

Courtesy of Josh Ruderman

Three Exceptions

How to populate the other regions?

Three Exceptions
in the Calculation of Relic Abundances

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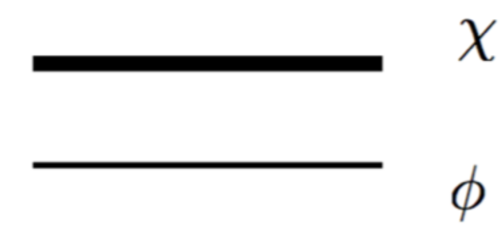
Griest, Seckel '91

Three Exceptions

How to populate the other regions?
Through annihilations:

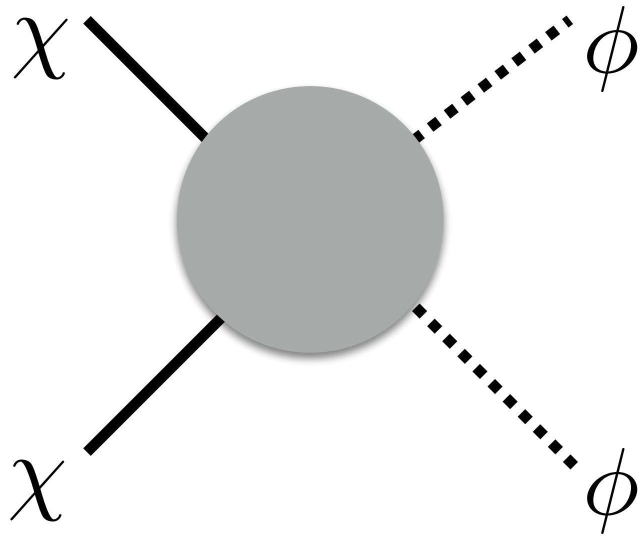


- near a pole in the cross section
- into heavier states
- among multiple species

Griest, Seckel ‘91

Forbidden

$m_\chi < m_\phi$



$$\delta = m_\phi - m_\chi$$

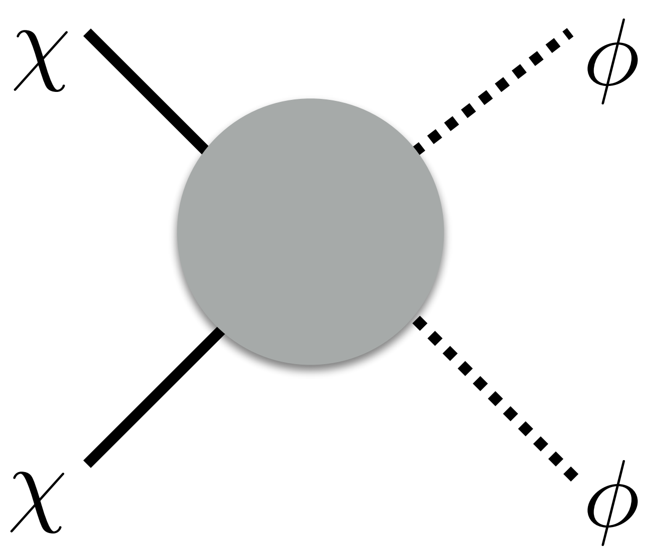
$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_\chi^2} e^{-2\delta/T}$$

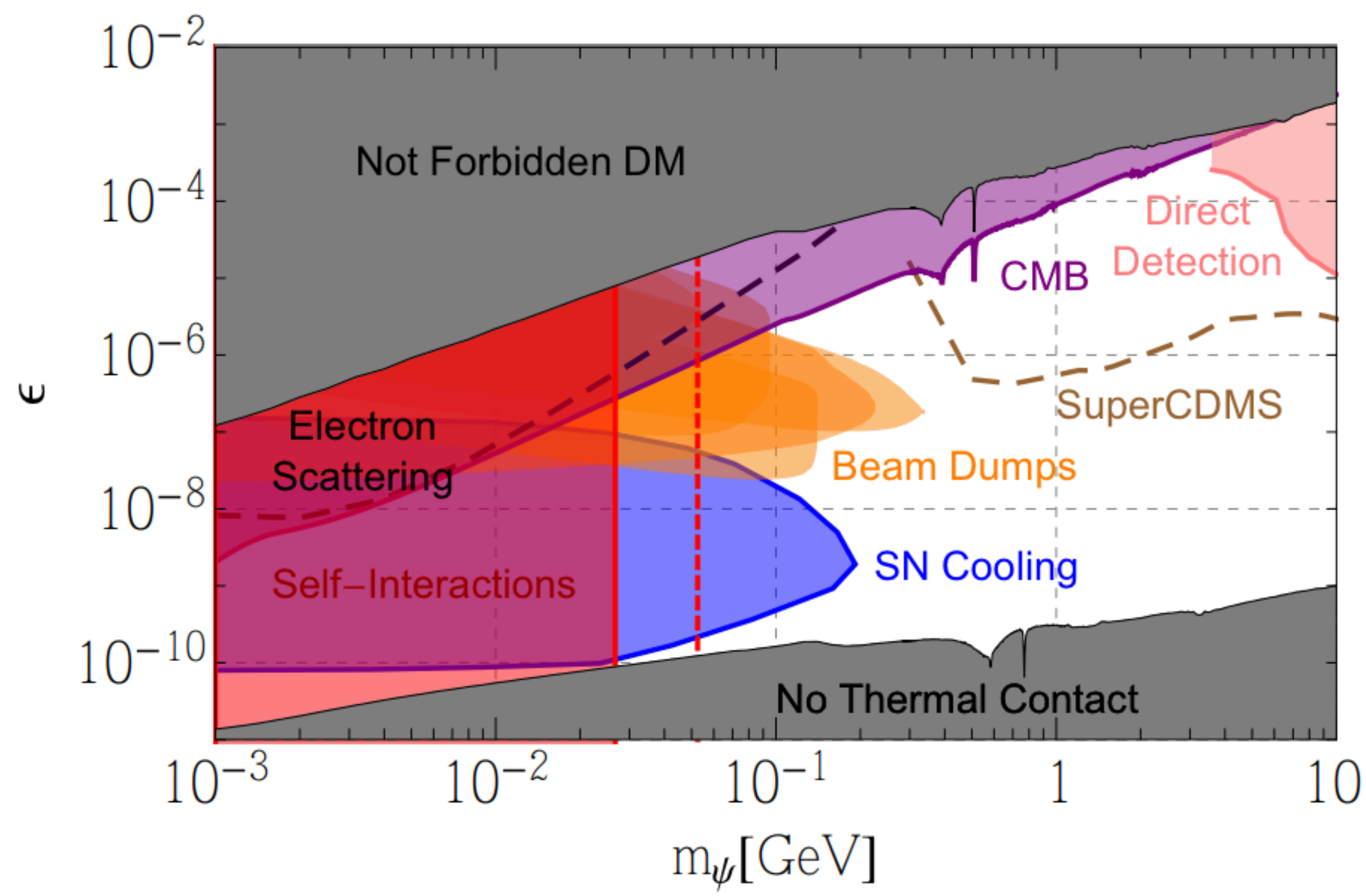
Forbidden channel suppression compensated by larger coupling

Griest, Seckel '91
D'Agnolo, Ruderman '15

Forbidden

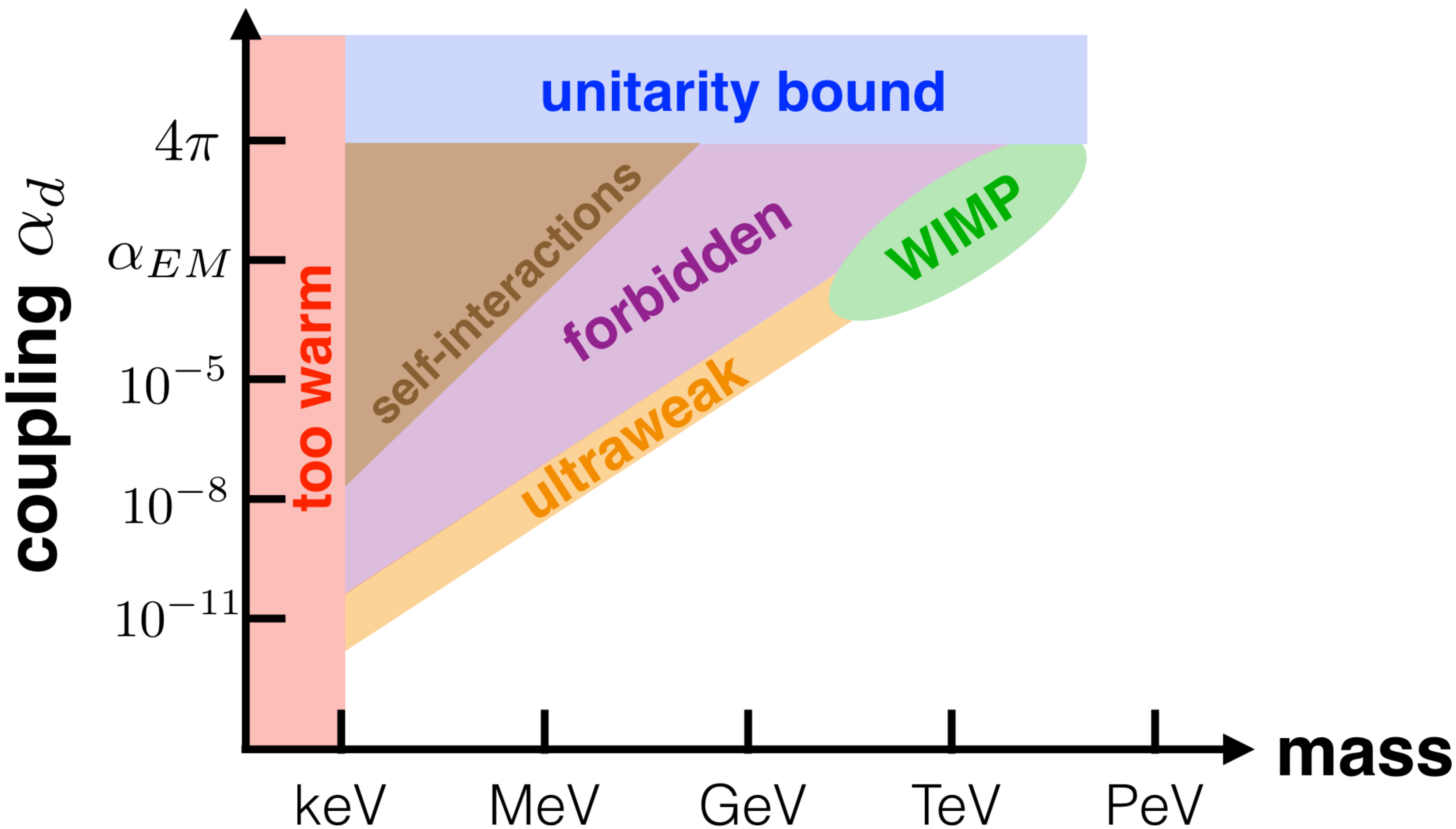
$m_\chi < m_\phi$





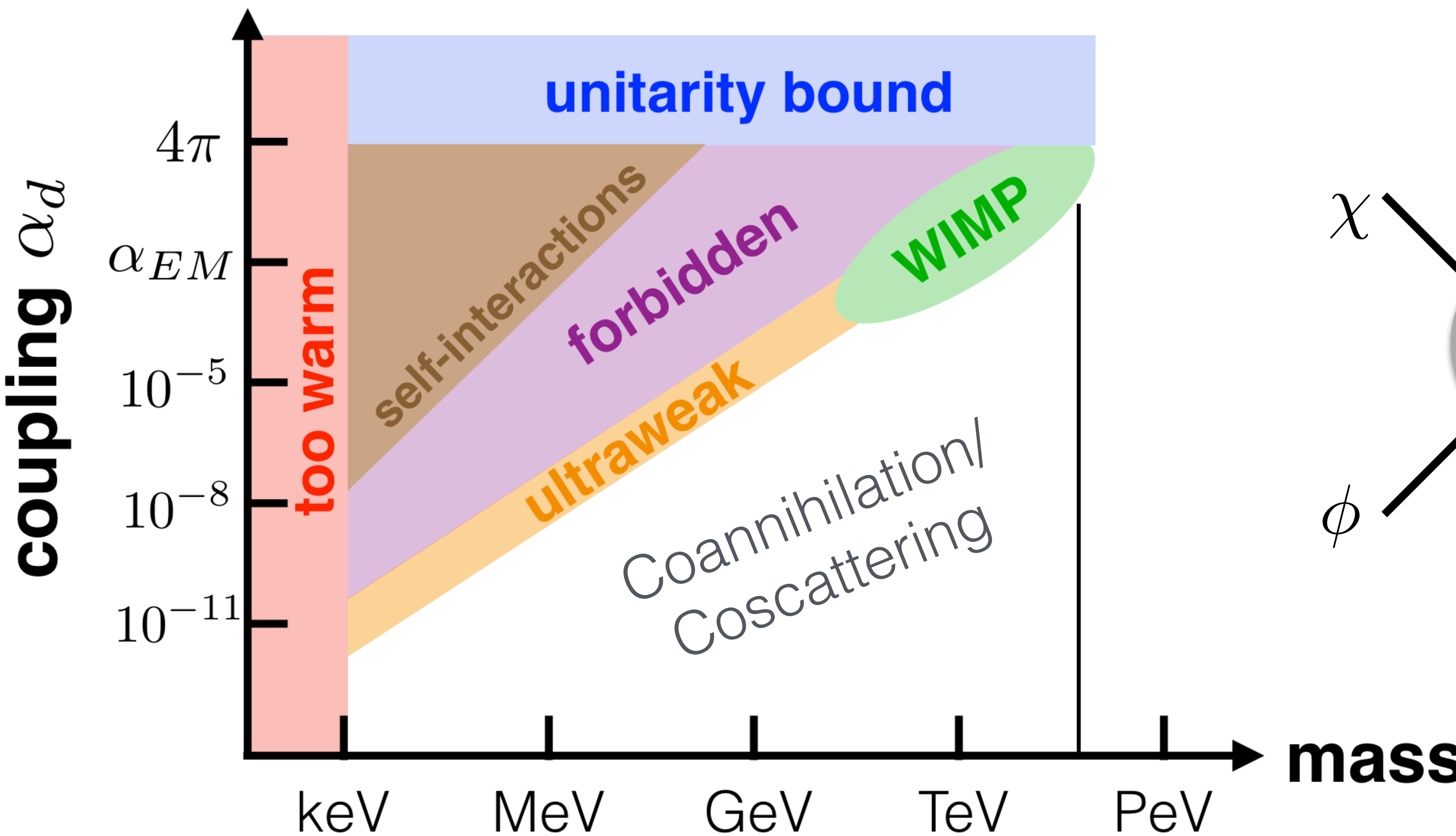
Griest, Seckel '91
D'Agnolo, Ruderman '15

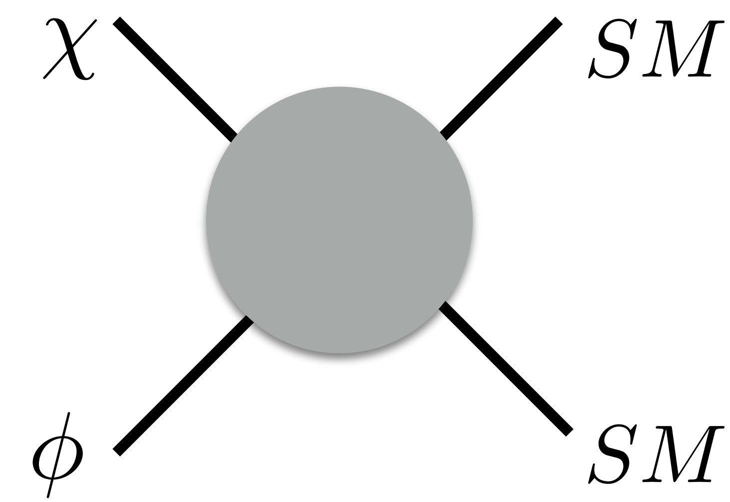
Beyond WIMPs



Griest, Seckel '91

Beyond WIMPs

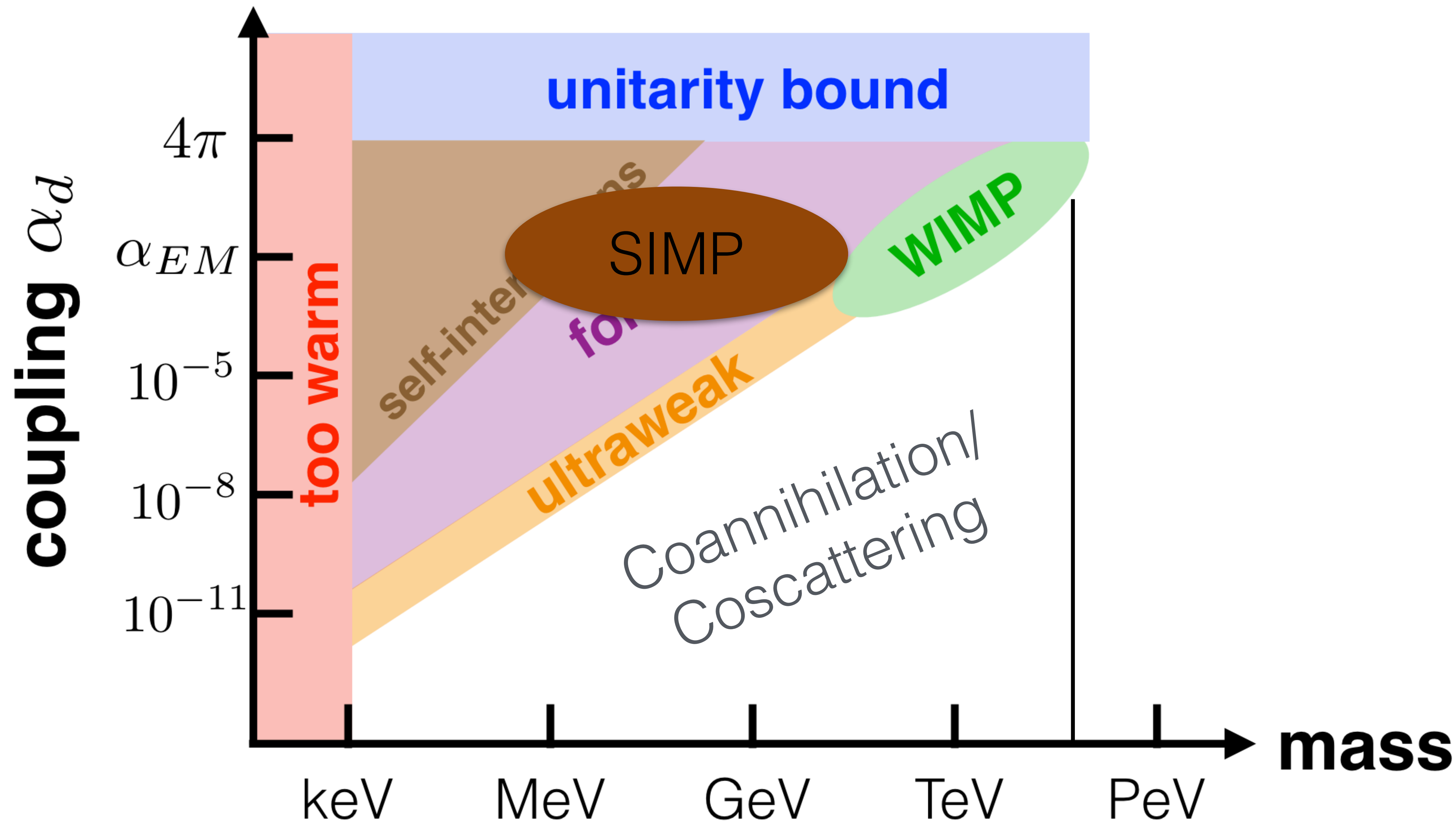




Arkani-Hamed, Delgado, Giudice '06
Tulin, Yu, Zurek '13
Bernal, Garcia-Cely, Rosenfeld '15
Ibarra, Pierce, Shah, Vogl '15

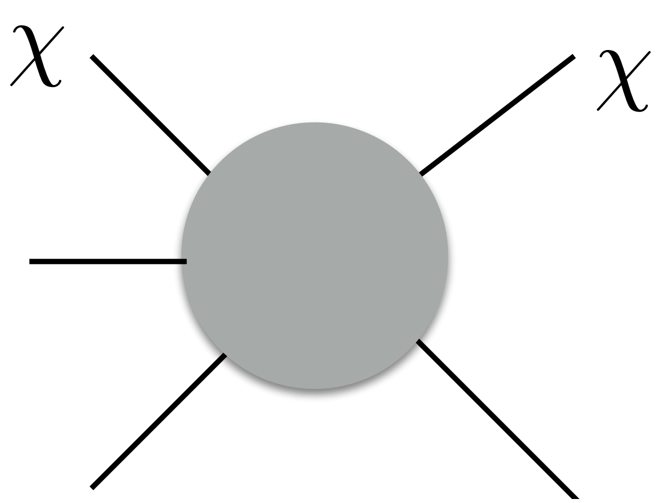
D'Agnolo, Pappadopulo, Ruderman '17

Beyond WIMPs



SIMP

Introduce 3 to 2 scattering

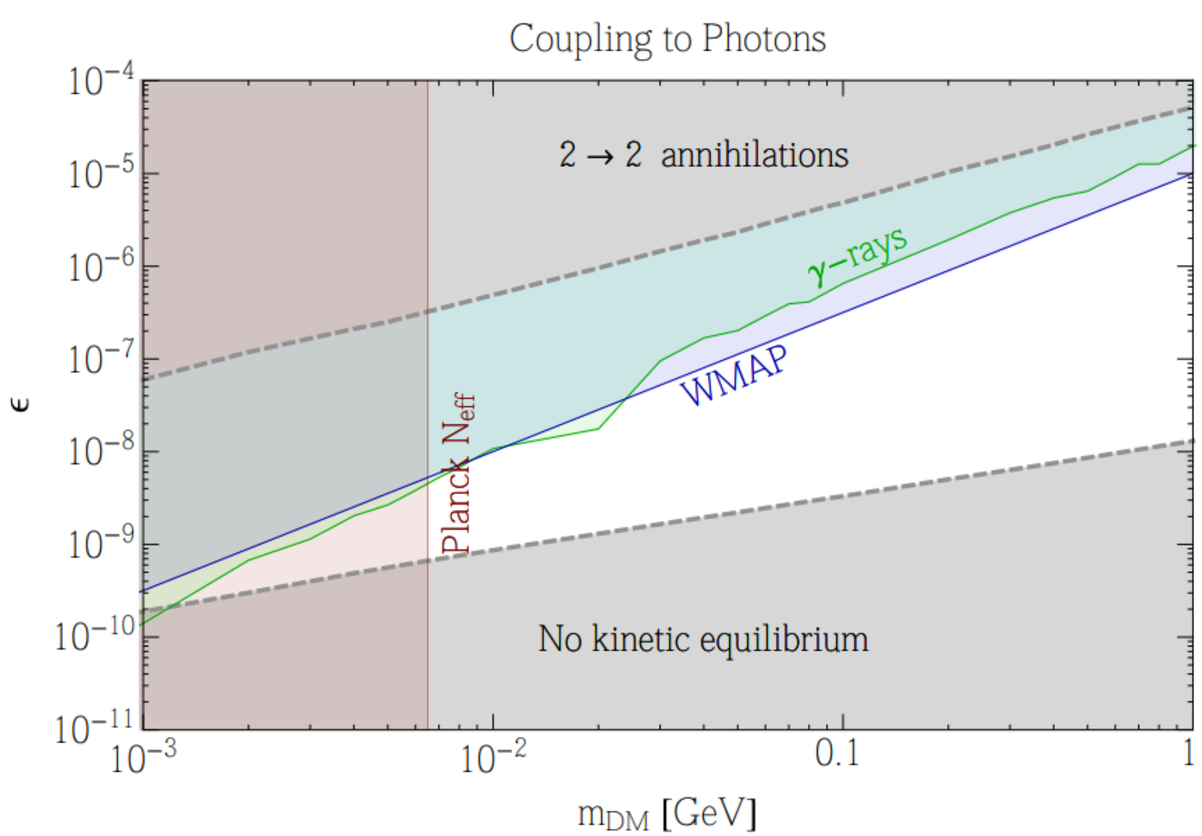


$$m_\chi \sim \alpha (T_{eq}^2 M_{Pl})^{1/3}$$

$$m_\chi = 40 \text{ MeV} \quad \text{for} \quad \alpha = 1$$

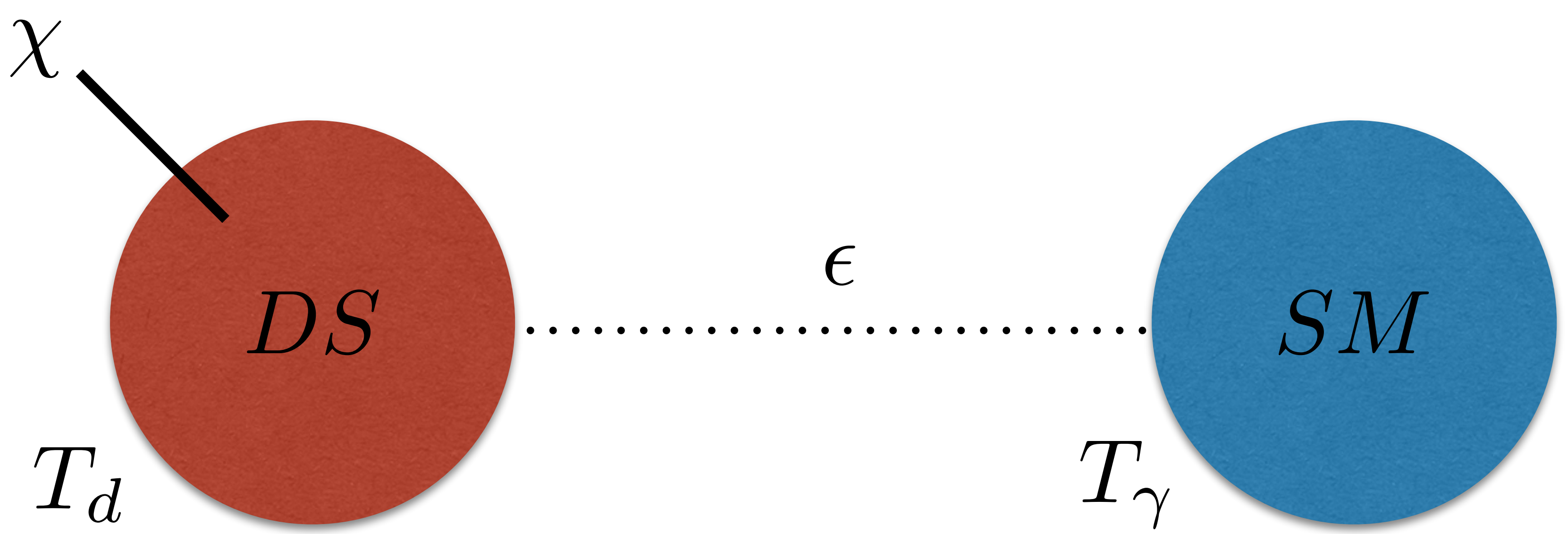
instead of

$$m_\chi \sim \alpha \sqrt{T_{eq} M_{Pl}}$$

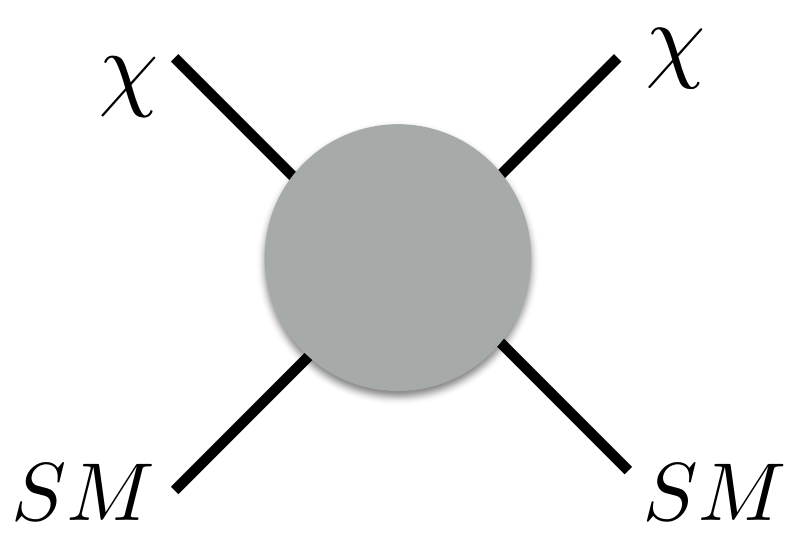


Hochberg, Kuflik, Volansky, Wacker ’14
…

Thermally decoupled sectors



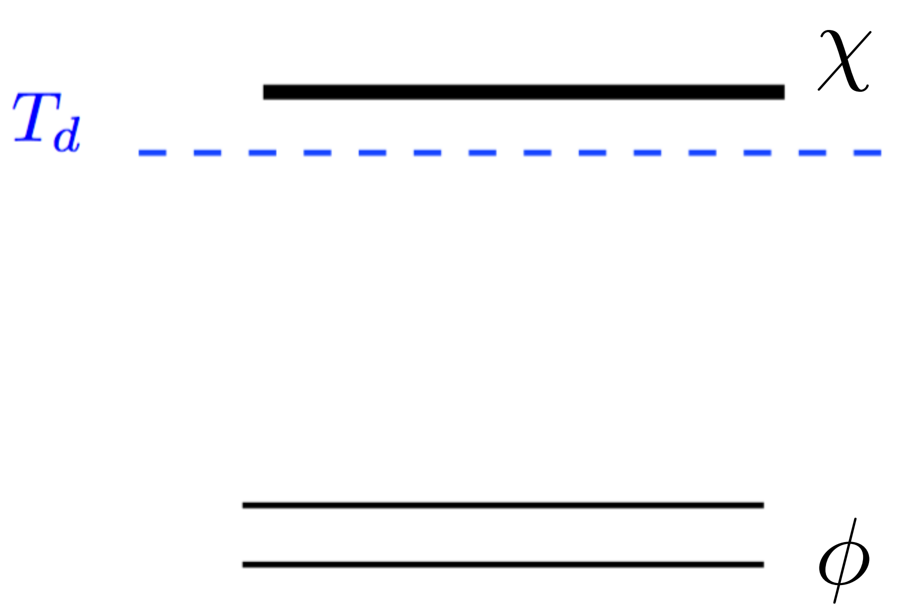
SM and Dark Sector decoupled. Different temperature

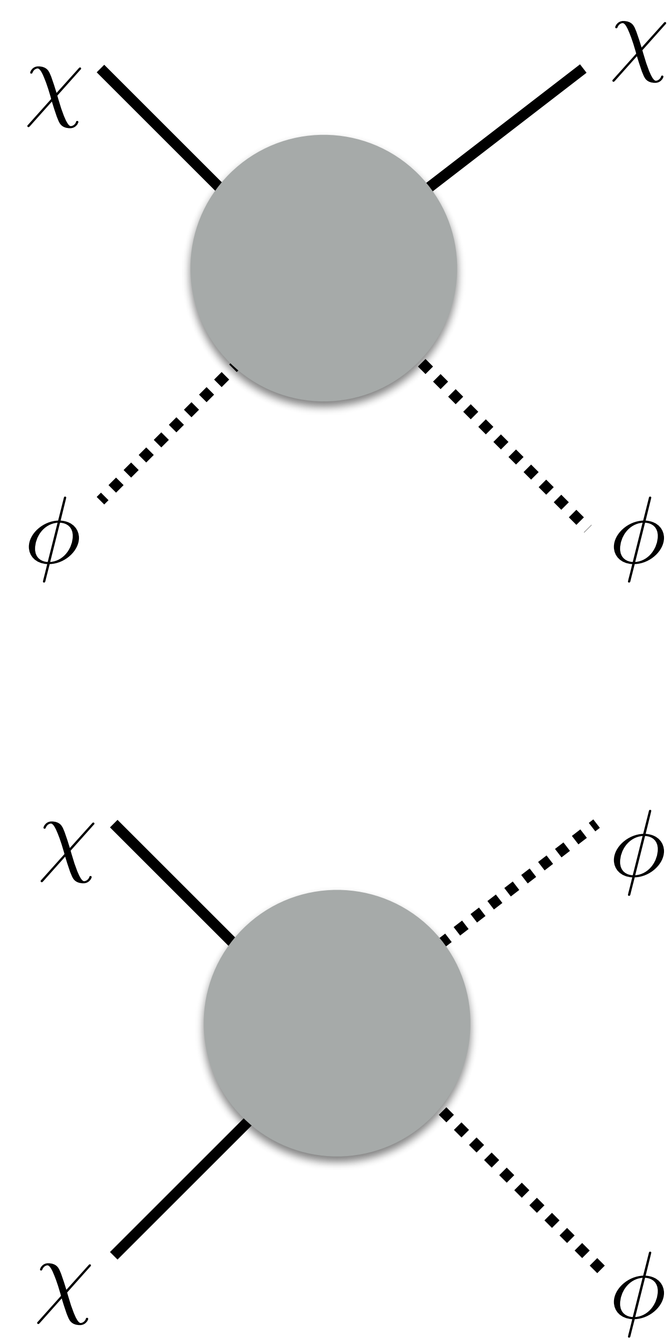


$< H$

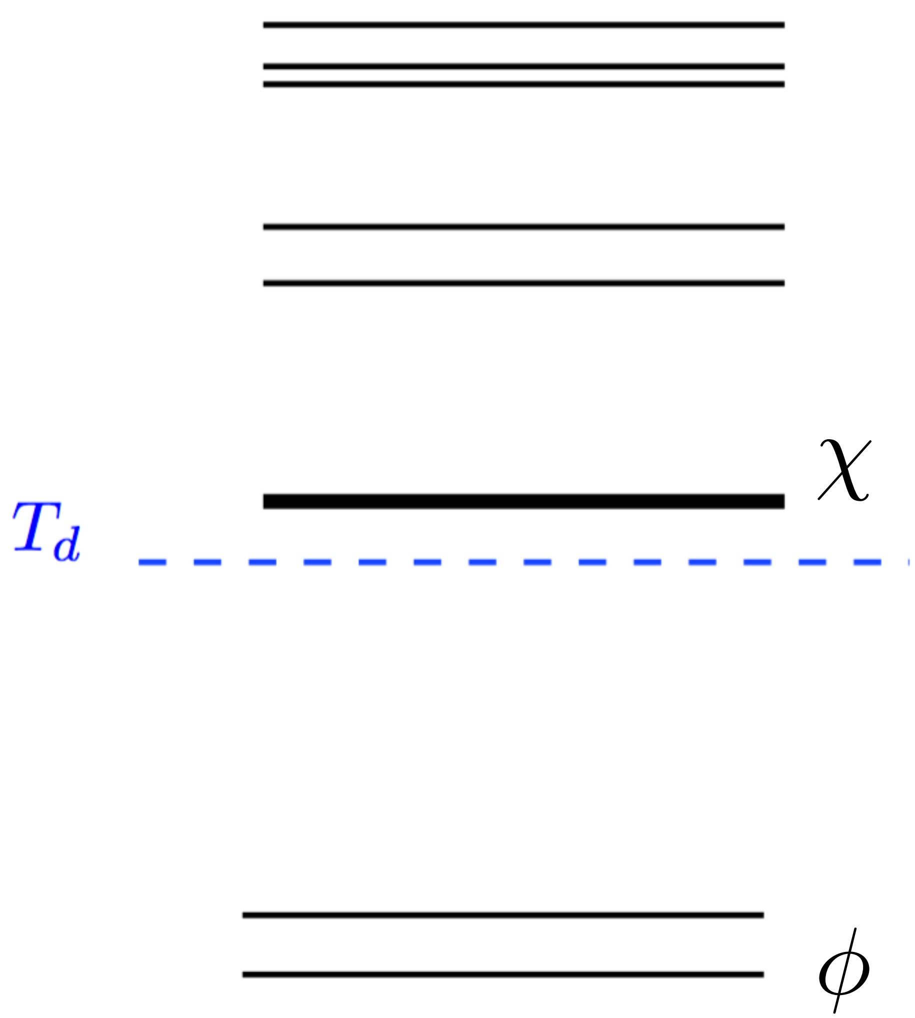
$$\epsilon \lesssim 10^{-8}\sqrt{\frac{T}{1\ \mathrm{GeV}}}$$

I. No gap





I. No gap



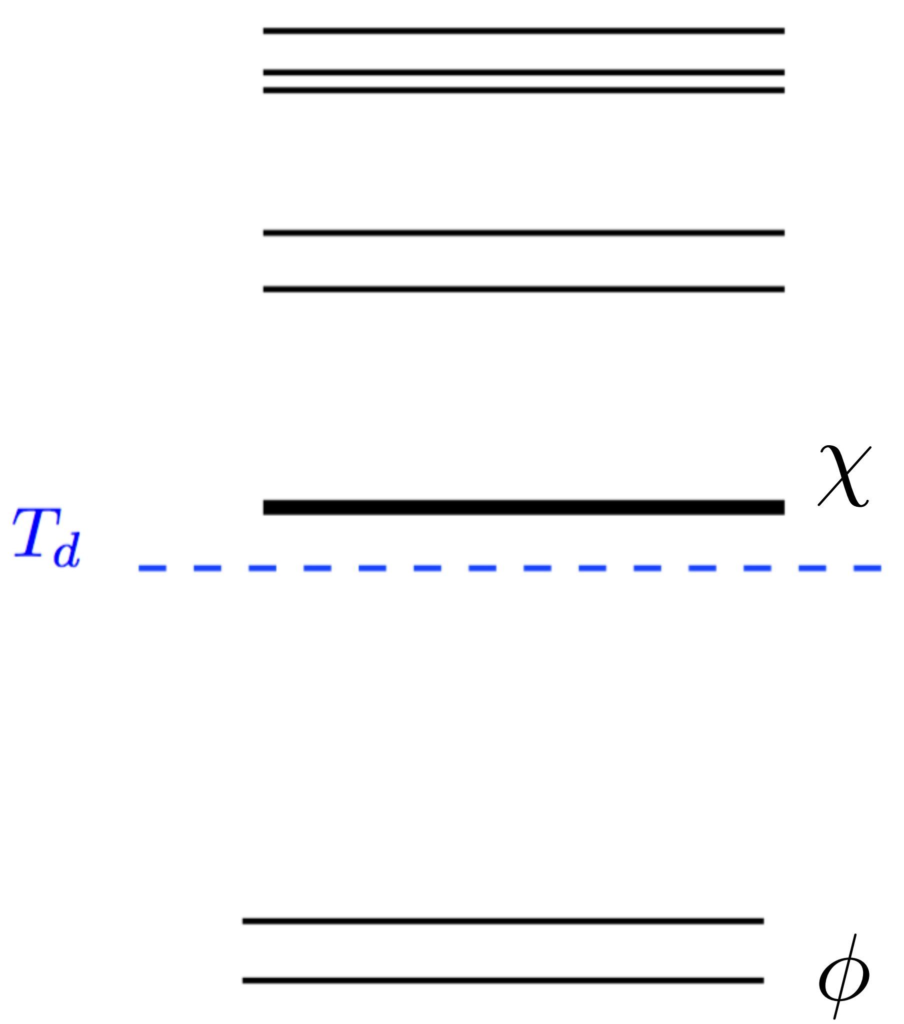
- At relevant freeze-out temperature $T_d \simeq m_\chi \gg m_\phi$ ϕ is relativistic and by entropy conservation

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

- 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

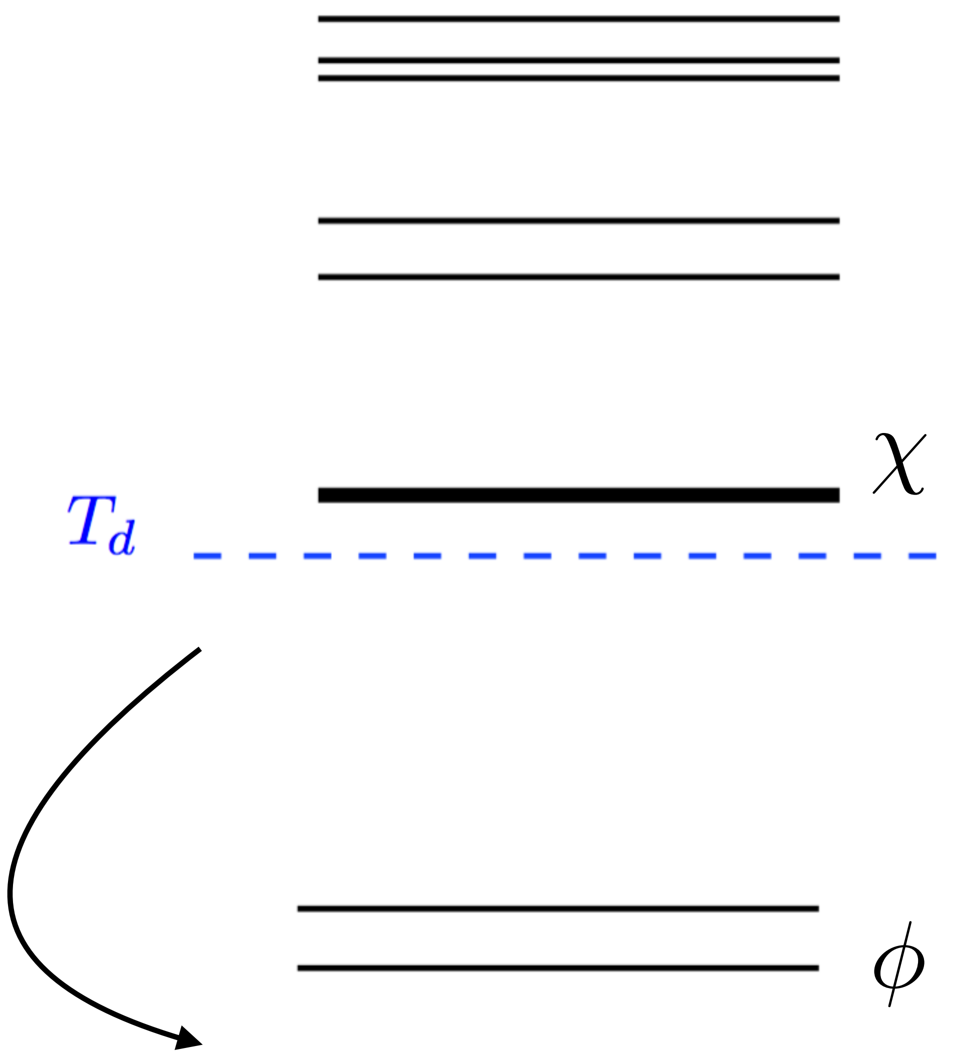


- Freeze-out as of annihilations leads to

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

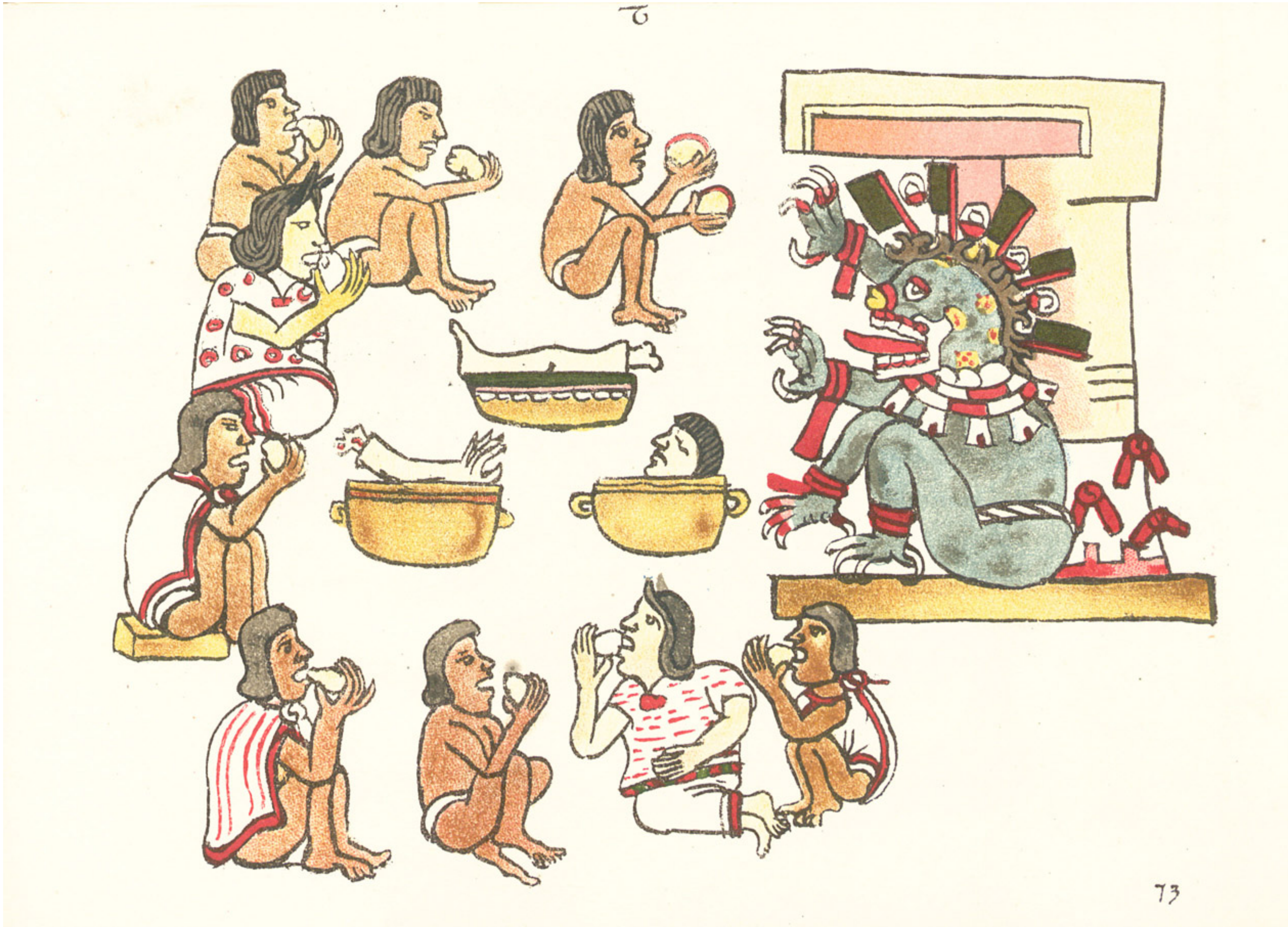
- Ratio of temperatures enhancement

II. Gapped



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

Cannibalism



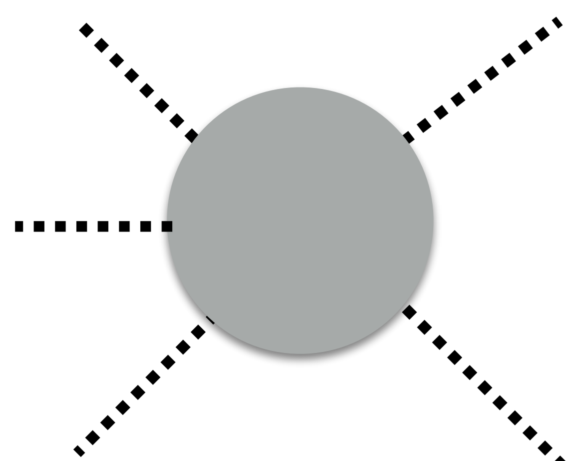
Cannibalism 101

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

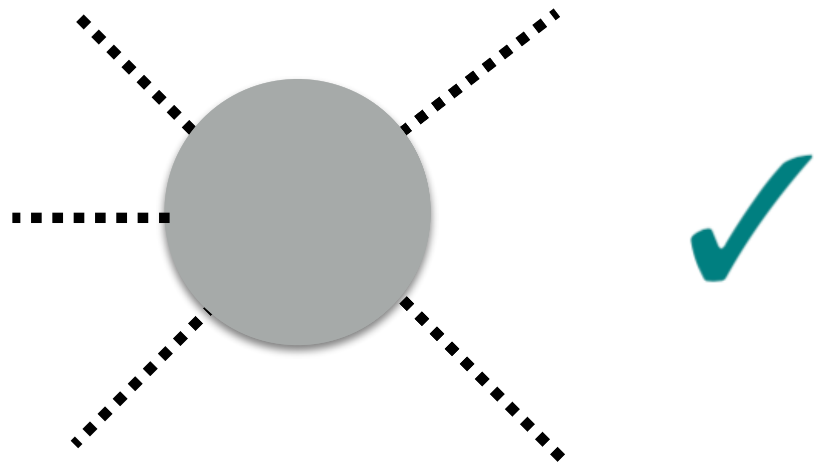
- Start with a simple example, one scalar field

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

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



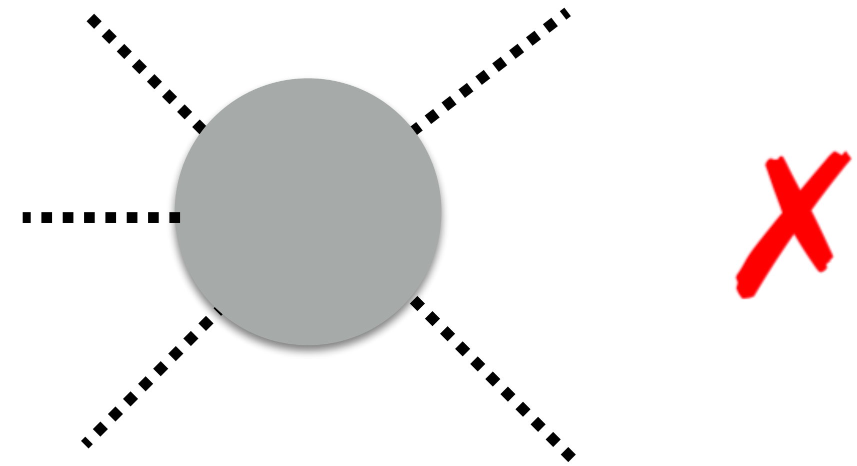
Cannibalism 101



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

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

(No chemical potential)

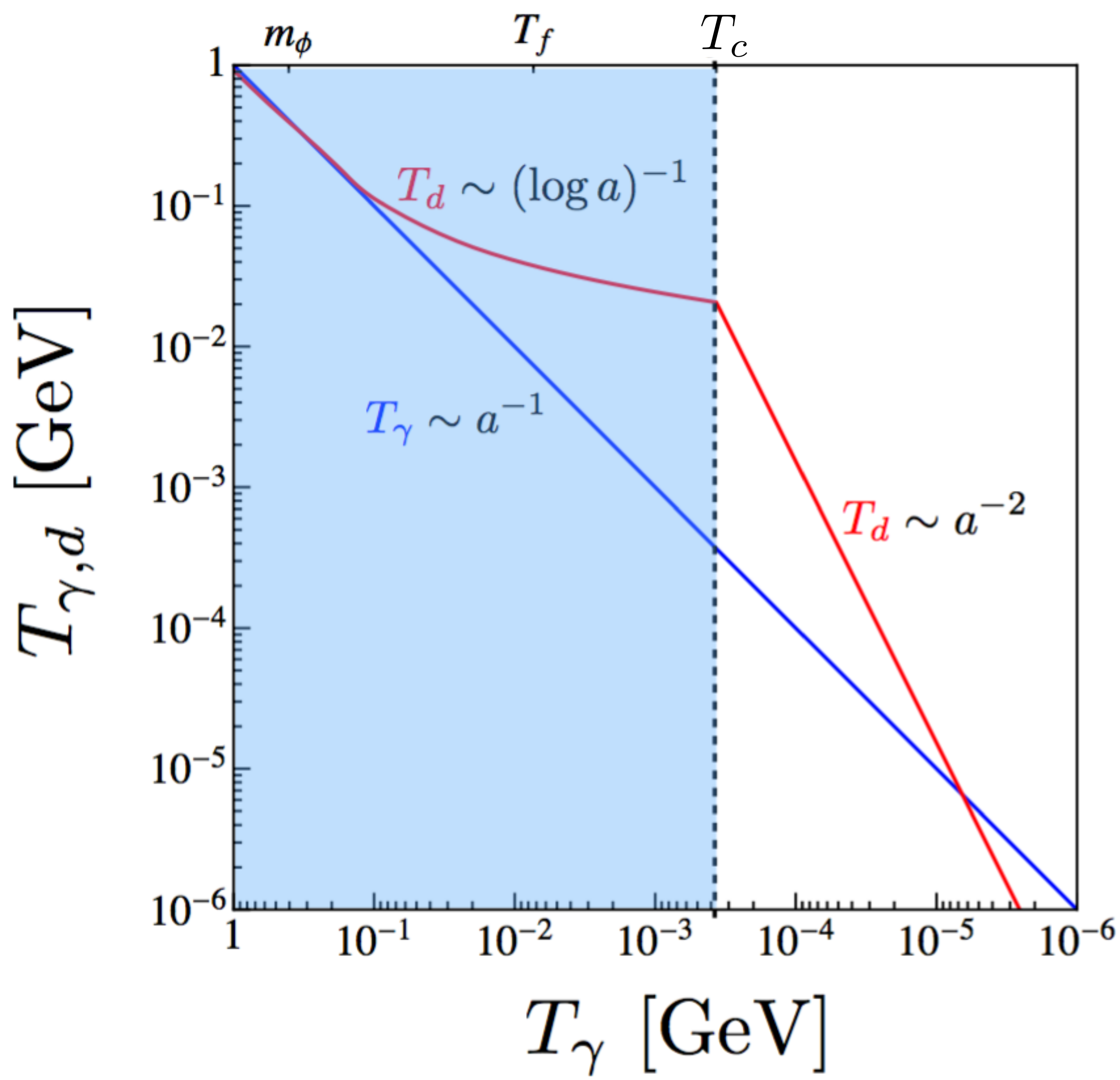


$$s_\phi a^3 = \text{const.} \quad \text{and} \quad n_\phi a^3 = \text{const.}$$

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

Conservation of entropy

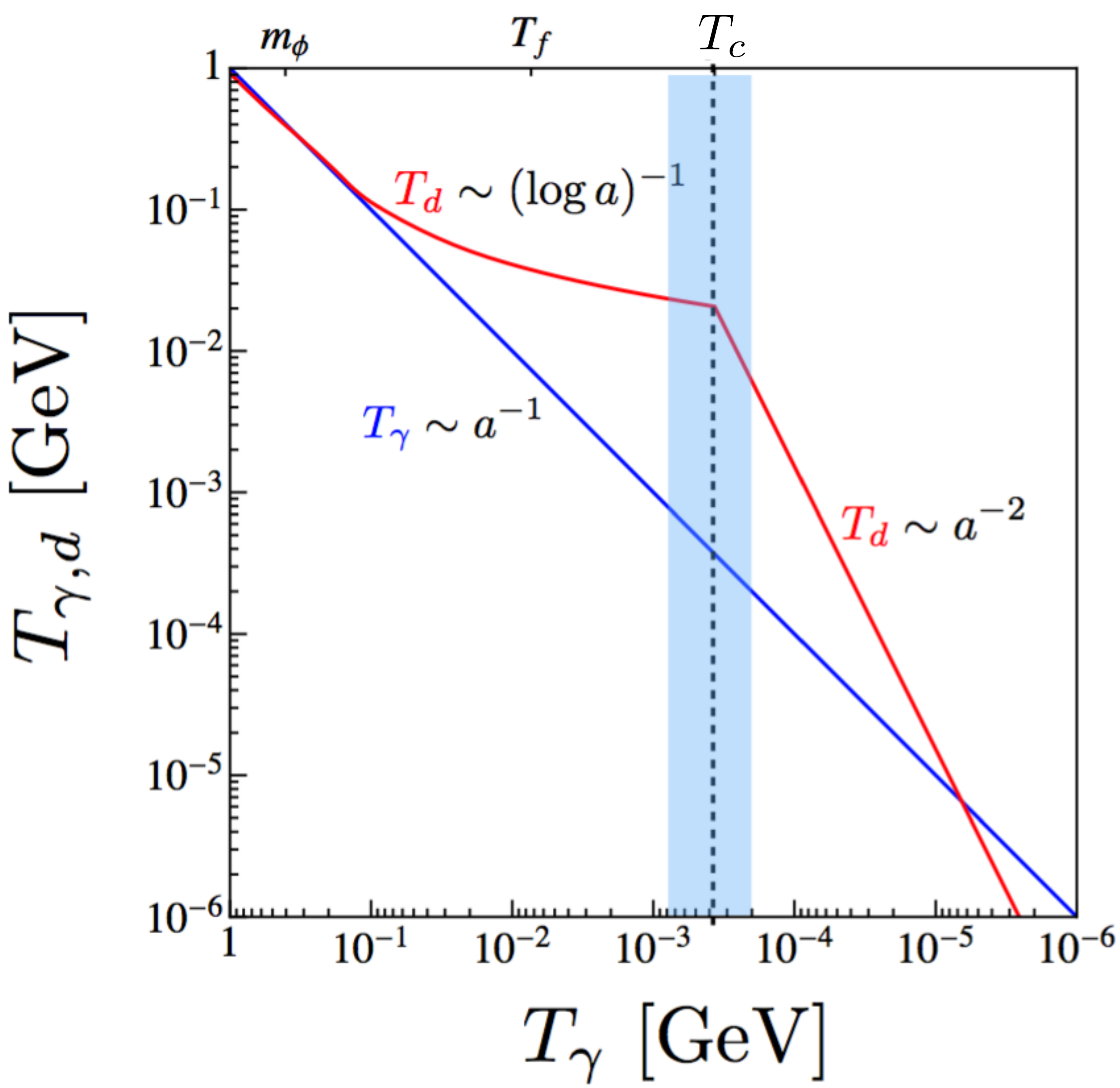
Cannibalism 101



- DS exponentially hotter while number changing interactions are active

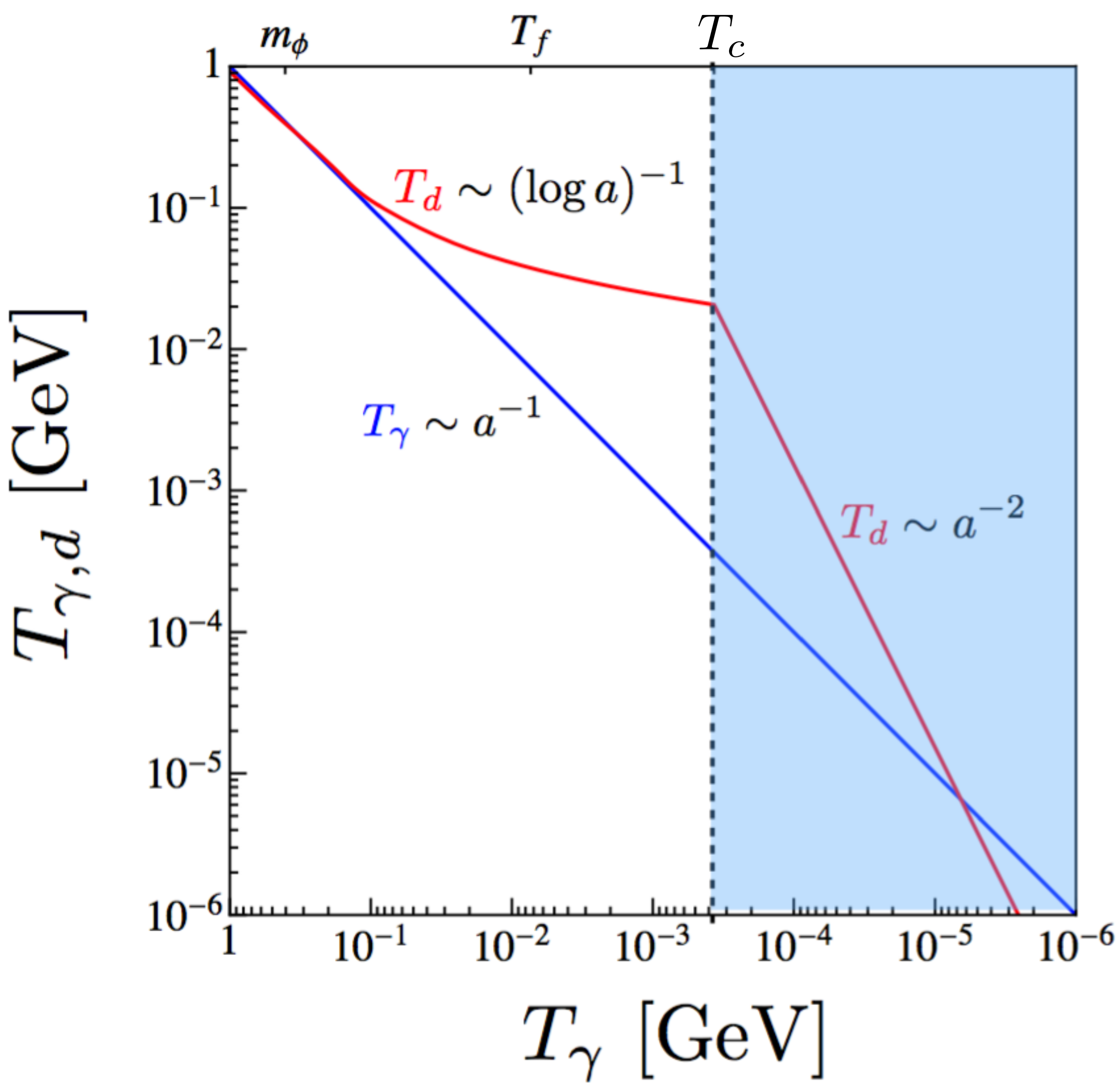
$$\frac{T_{SM}}{T_d} \approx \xi^{1/3} g_*^{1/3} \left(\frac{m}{T_d}\right)^{5/6} e^{-m/3T_d}$$

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 $3 \rightarrow 2$ 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.

Cannibalism 101

Can ϕ be dark matter?

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

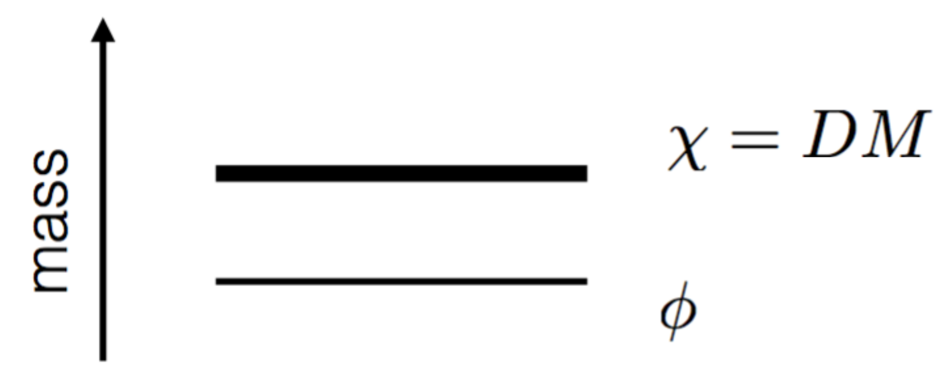
$$x_\phi \sim 20 \div 50 \qquad \xi \equiv \frac{s_{SM}}{s_d} \qquad \xi > 100$$

$m_\phi = 1\ \mathrm{keV}$ 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?

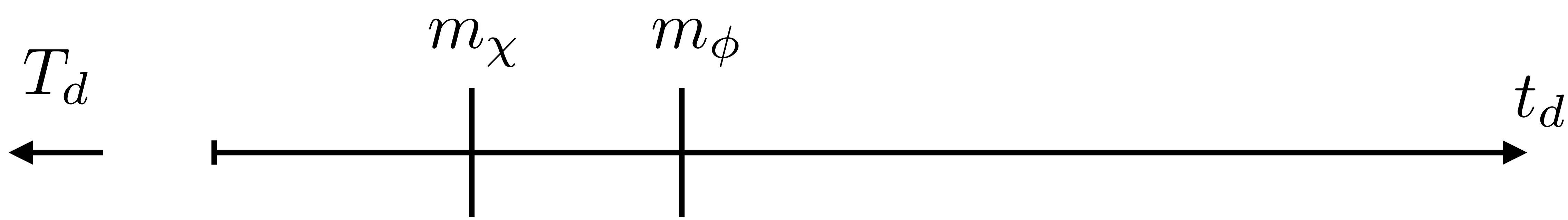


$$\mathcal{L}(\phi,\chi) = \mathcal{L}(\phi) + \bar{\chi}(i\partial - m_\chi)\chi - \frac{y}{2}\phi\bar{\chi}\chi$$

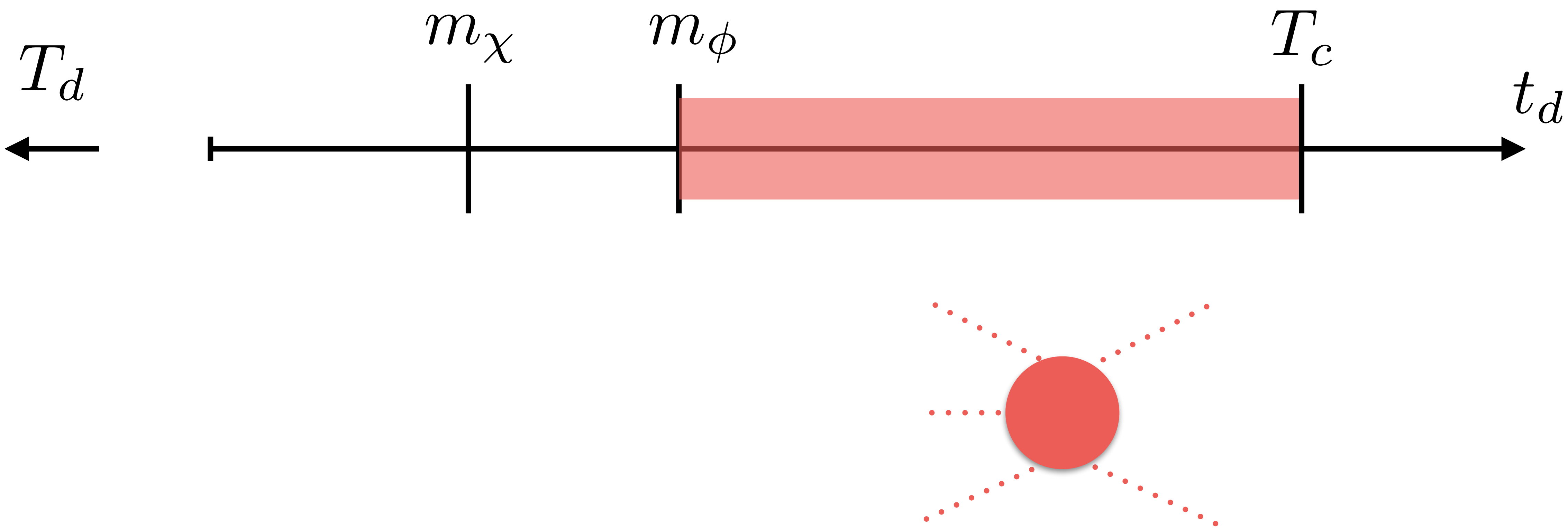
χ is DM from 2 to 2 freeze-out in a cannibalizing sector

Pappadopulo, Ruderman, Trevisan ’16
Farina, Pappadopulo, Ruderman, Trevisan ‘16

Cannibal DM

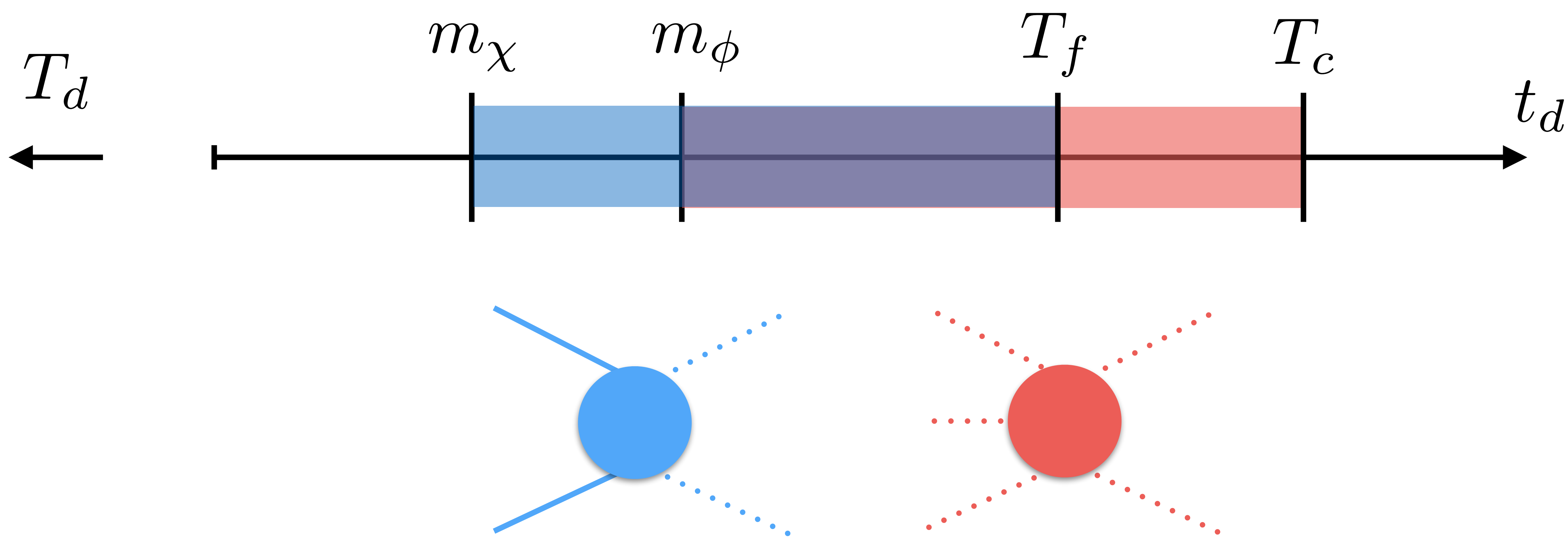


Cannibal DM



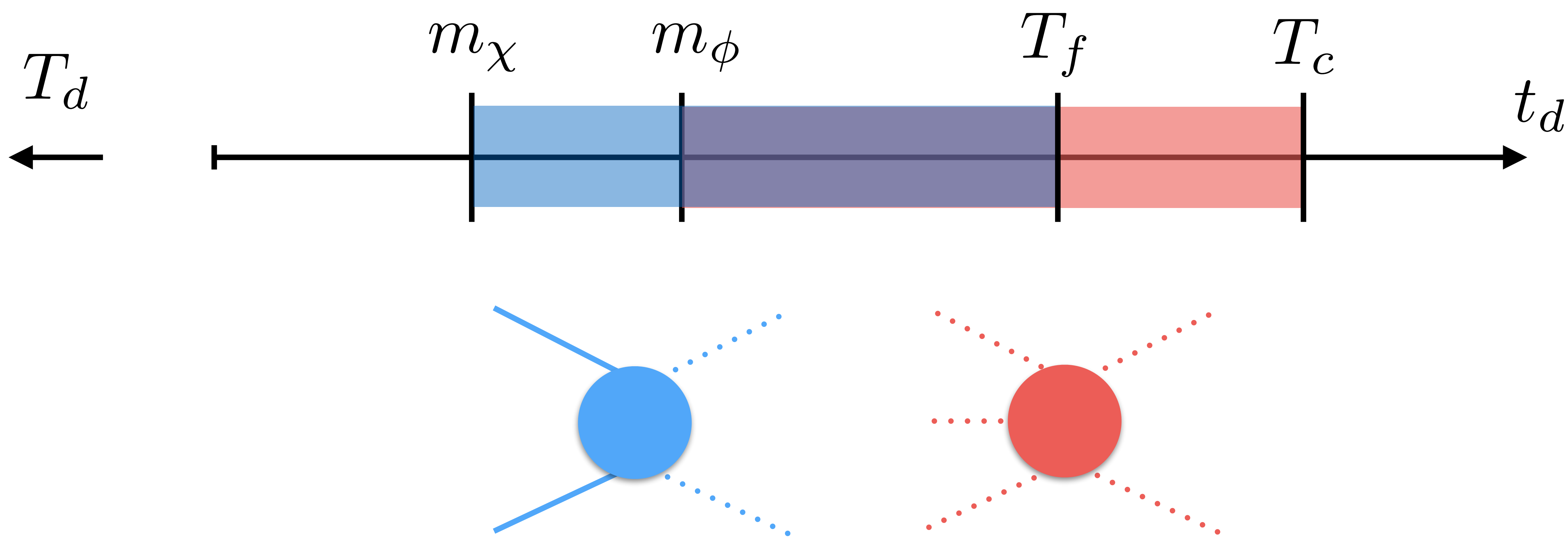
Dark Sector temperature exponentially higher than SM

Cannibal DM



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

Cannibal DM

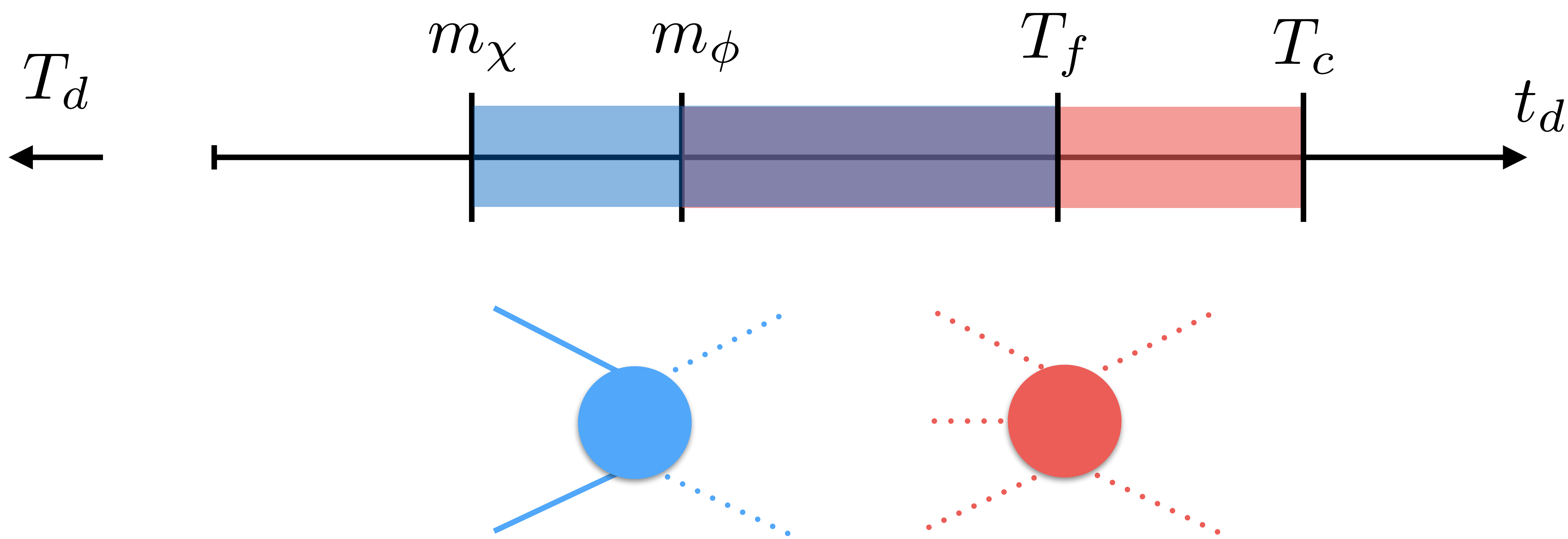


$$\frac{\Omega_\chi}{\Omega_{DM}} = \frac{m_\chi n_\chi}{s_{SM}} \frac{1}{0.4\,\mathrm{eV}} \approx 0.3 \frac{x_f}{g_*^{1/2}} \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d}{T_{SM}}$$

$$x_f \equiv \frac{m_\chi}{T_d^f} \approx 10 \div 50$$

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

Cannibal DM



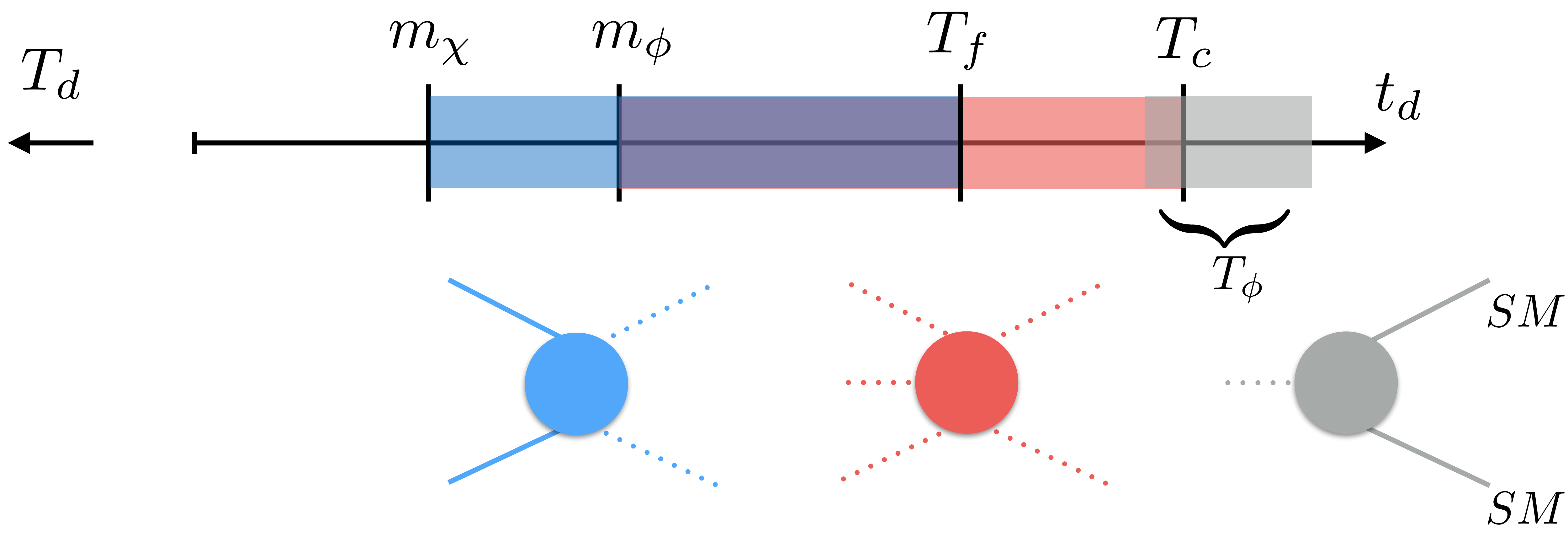
$$\frac{\Omega_\chi}{\Omega_{DM}} = \frac{m_\chi n_\chi}{s_{SM}} \frac{1}{0.4\,\mathrm{eV}} \approx 0.3 \frac{x_f}{g_*^{1/2}} \frac{\sigma_0}{\langle \sigma v \rangle} \frac{T_d}{T_{SM}}$$

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

Exponential boost!

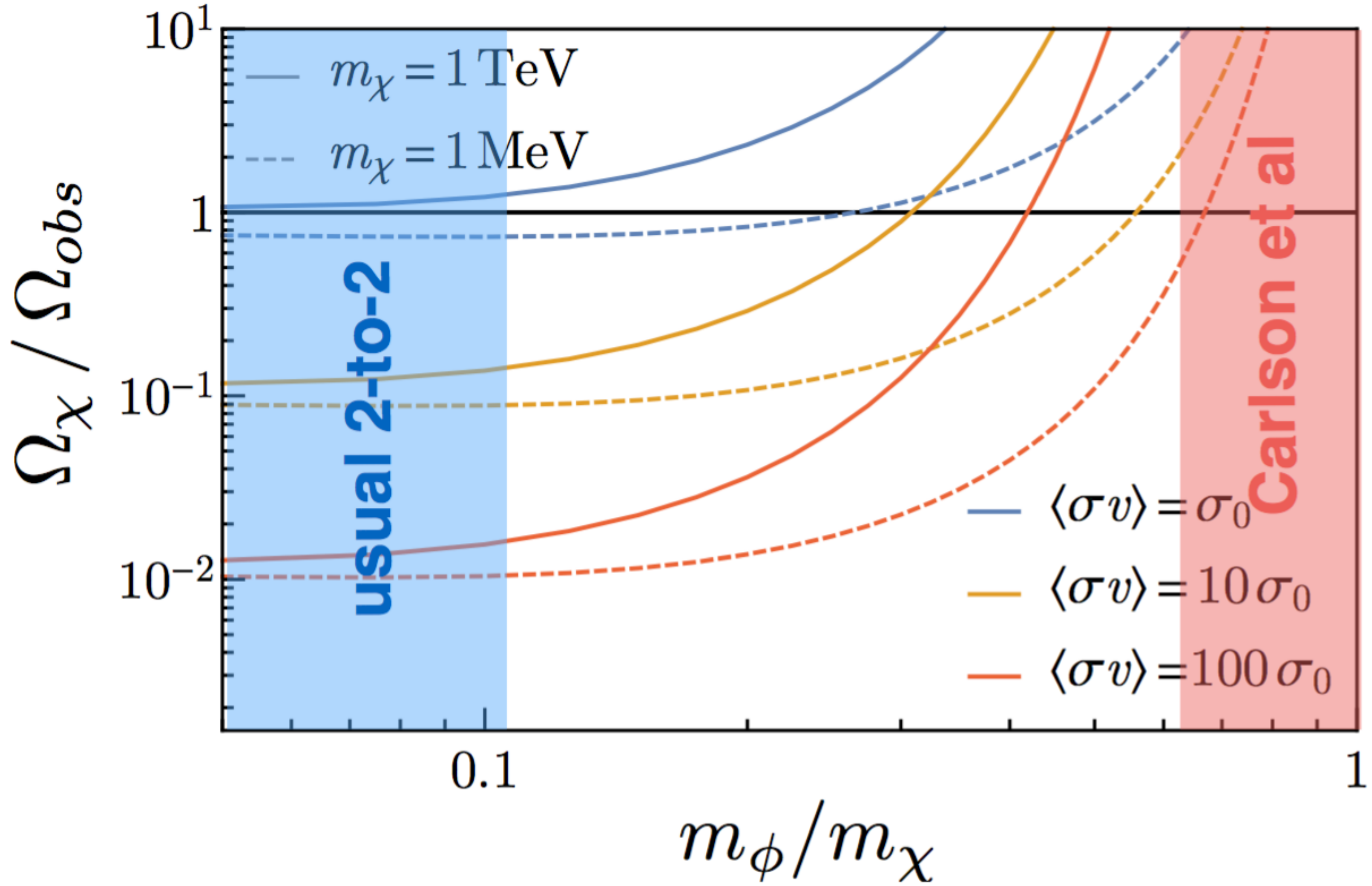
$$\frac{T_{SM}}{T_d} \approx \xi^{1/3} g_*^{1/3} \left(\frac{m}{T_d}\right)^{5/6} e^{-m/3T_d}$$

Cannibal DM



Other orderings viable…

Cannibal DM

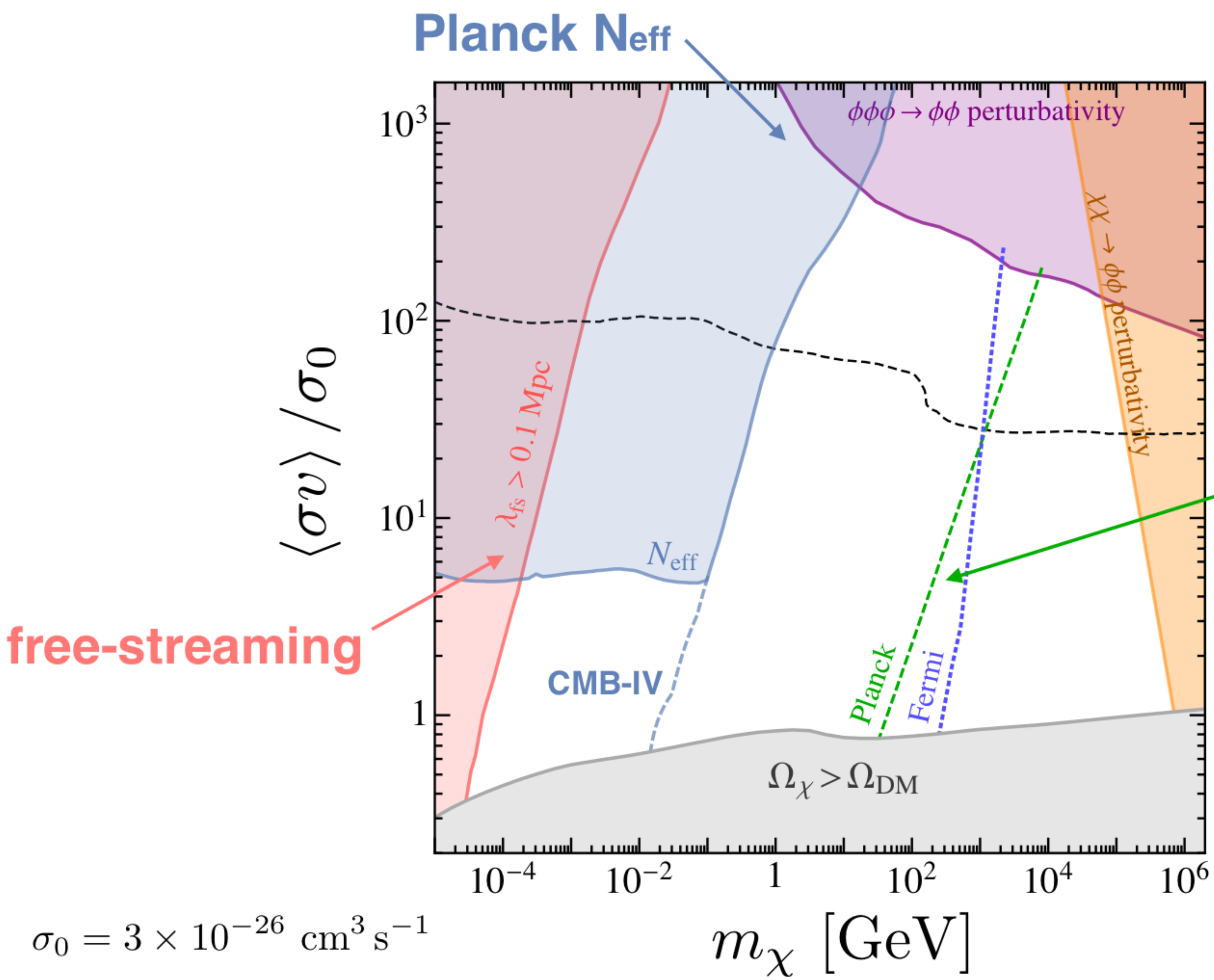


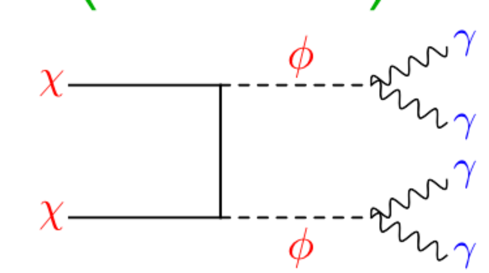
$$\frac{\Omega_\chi}{\Omega_{\chi,r=0}} \propto \left(m_\chi M_{Pl} \langle\sigma v\rangle\right)^{\frac{r/3}{1-2r/3}}$$

Cannibal DM Pheno

$\xi \approx 39$

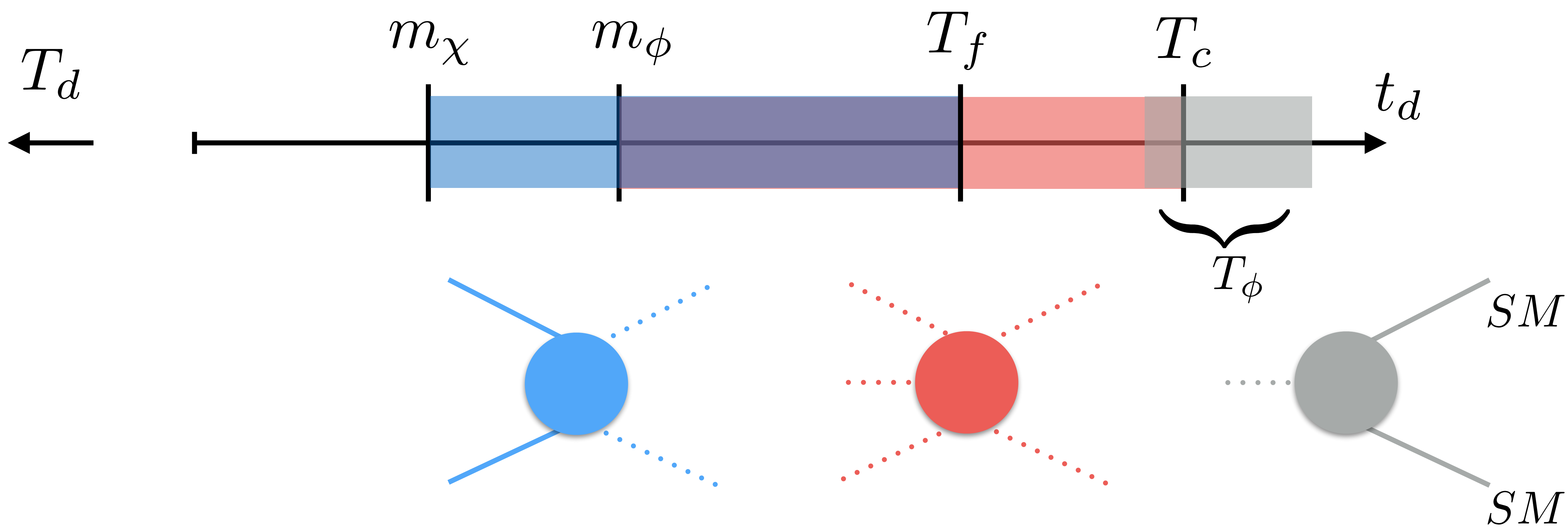
$\tau_\phi \sim H_f^{-1}$





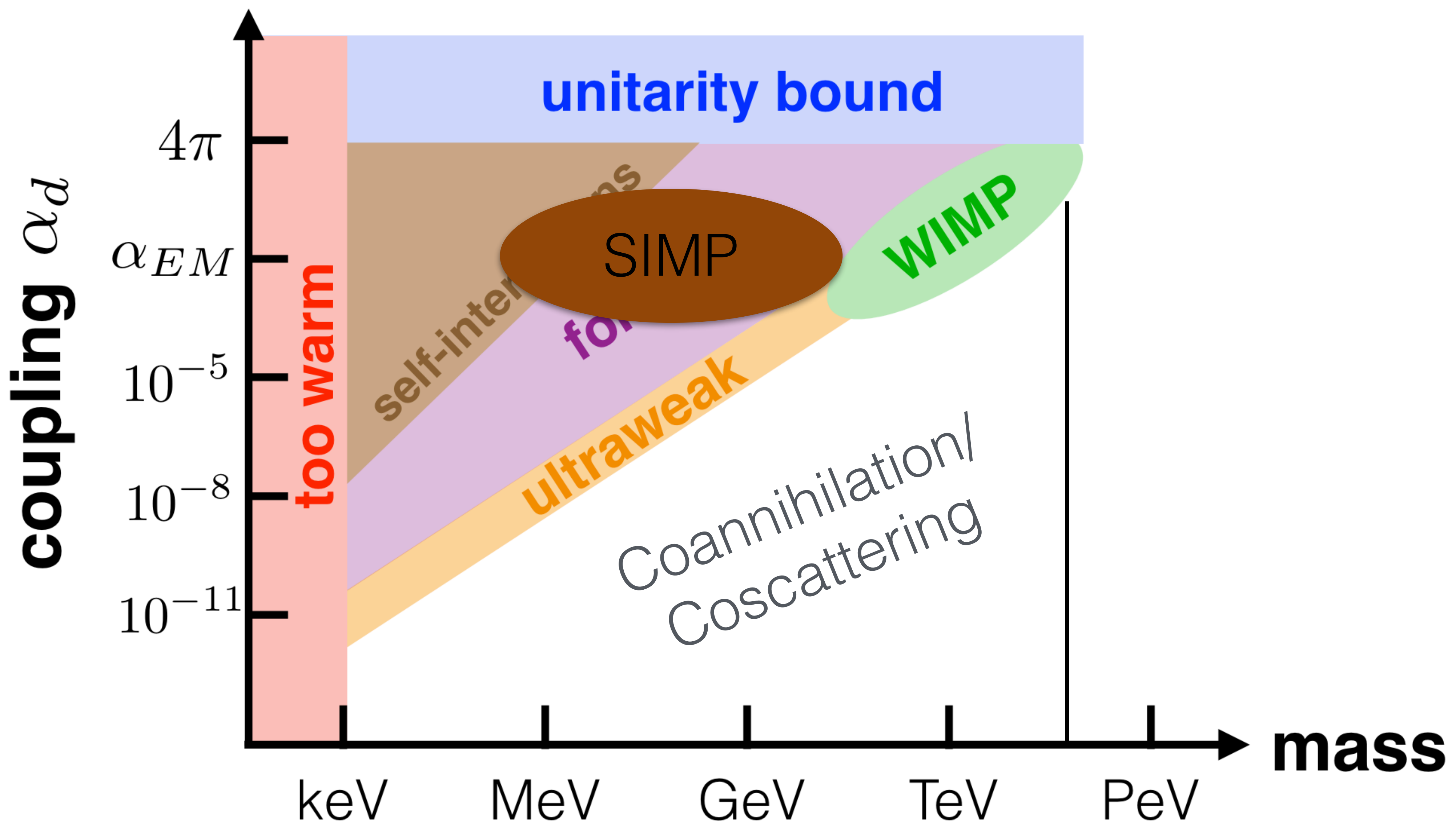
$\sigma_0 = 3 \times 10^{-26}\ \mathrm{cm^3\, s^{-1}}$

Cannibal DM



Other orderings viable…

Recap



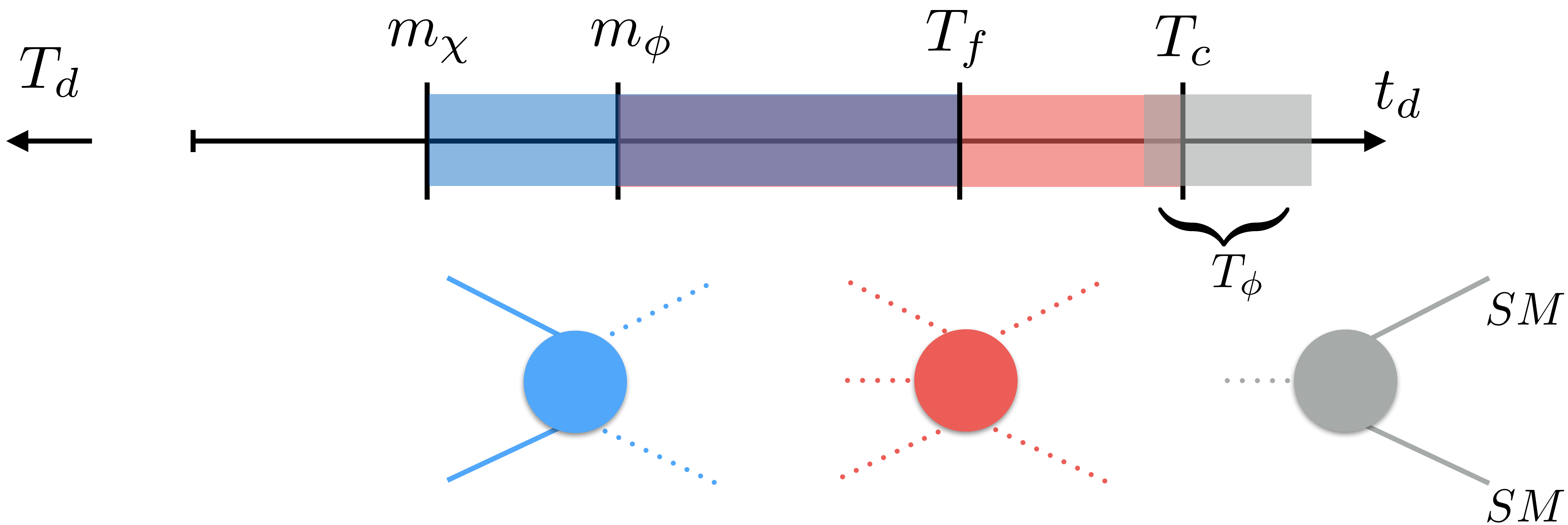
coupling α_d
4π
α_{EM}
10^{-5}
10^{-8}
10^{-11}
unitarity bound
too warm
self-inter
ns
SIMP
fo
WIMP
ultraweak
Coannihilation/
Coscattering
keV
MeV
GeV
TeV
PeV
mass

Conclusions

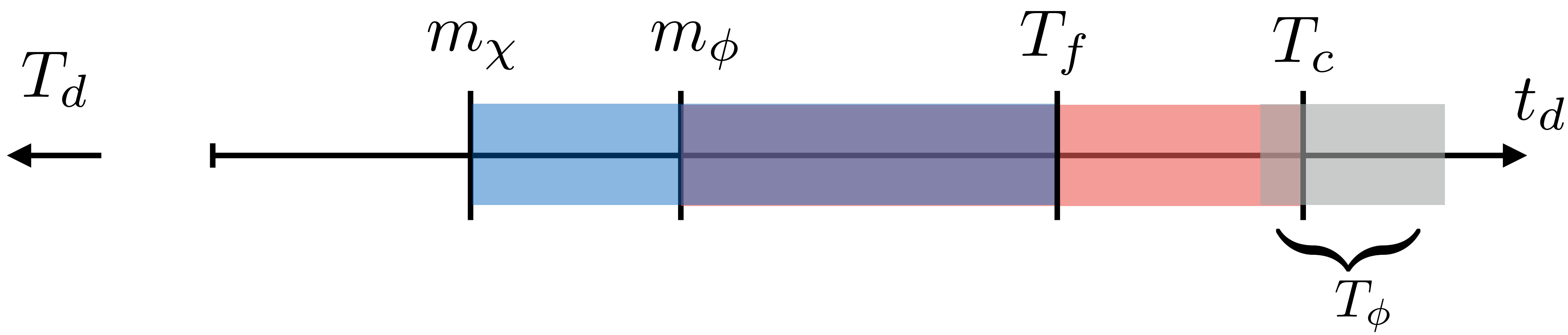
- Way too many models to cover:
  Asymmetric DM, Axions, Freeze-In, Primordial Black Holes, fuzzy DM, superfluid DM…
- Dark matter could arise from a non minimal dark sector with rich phenomenology

Backup

Three time scales

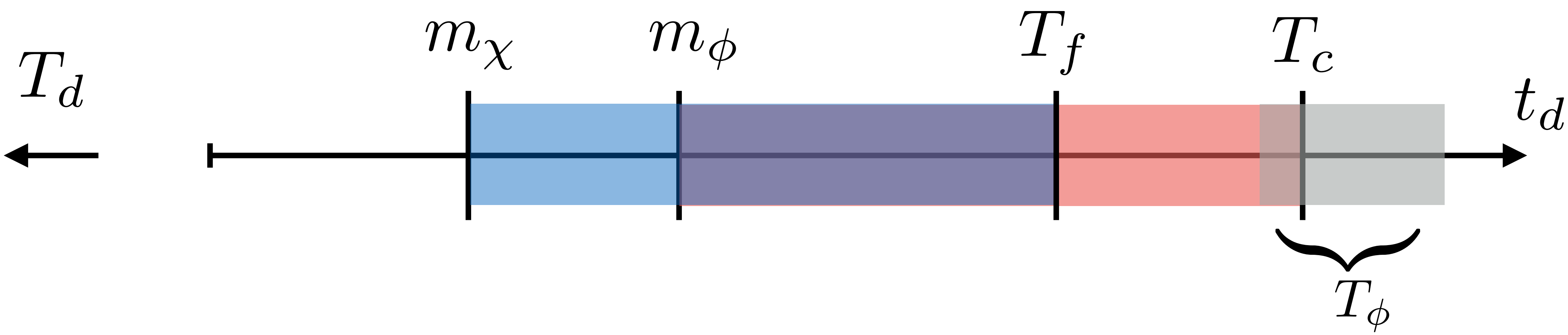


Three time scales

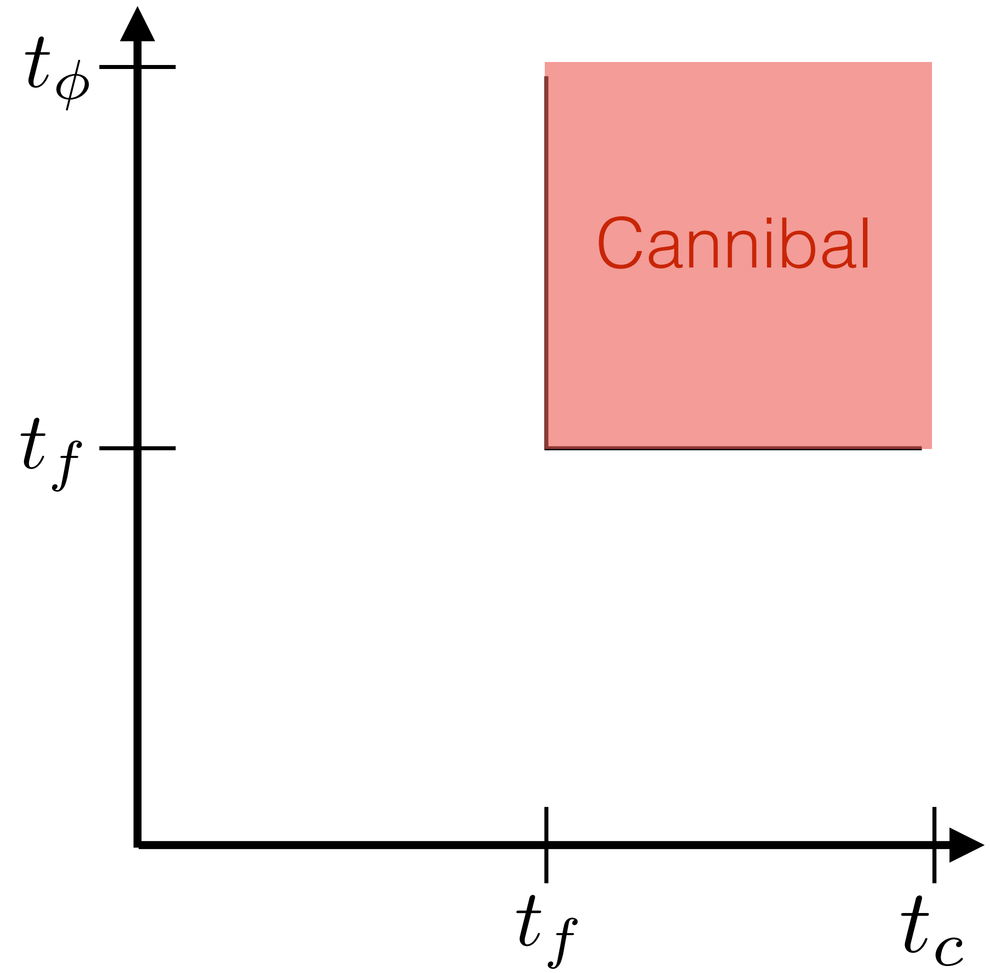


- t_f : time at which DM 2 to 2 freeze-out (stable ϕ limit)
- t_c : time at which 3 to 2 freeze-out (stable ϕ limit)
- t_ϕ : ϕ lifetime

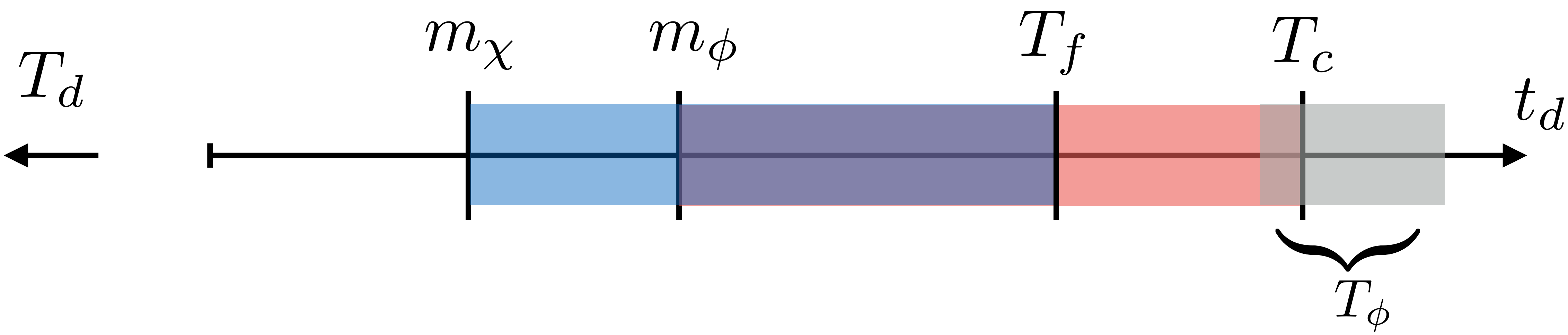
Three phases (I)



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

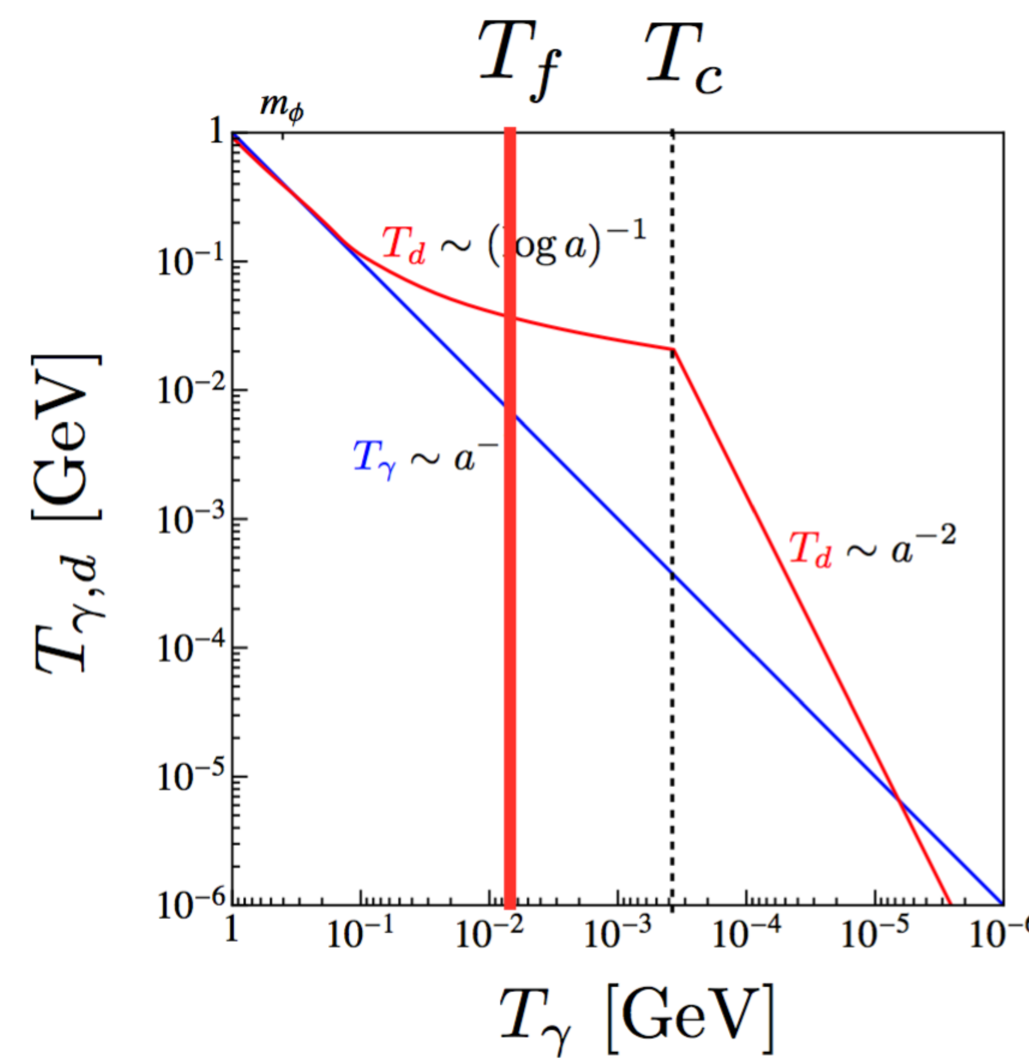


Three phases (I)

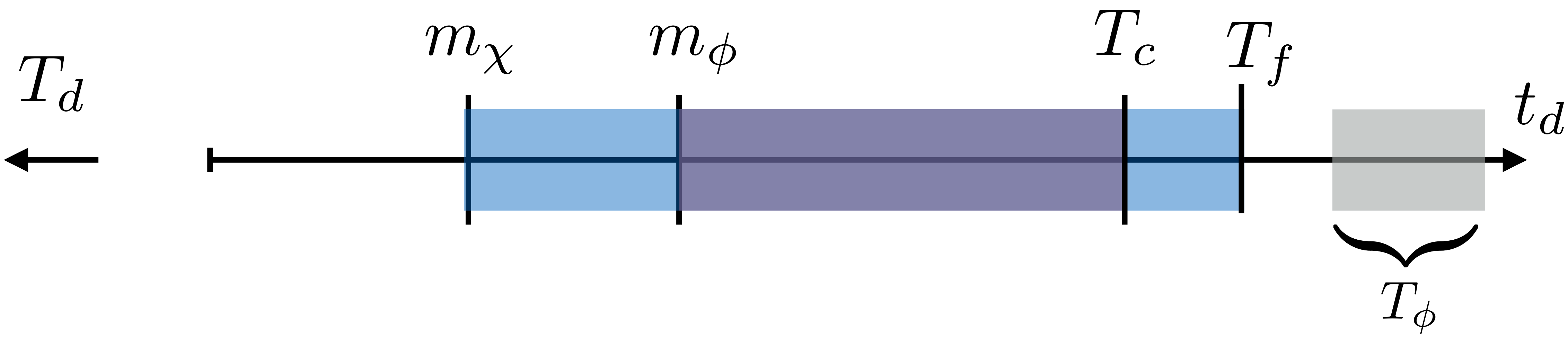


- Cannibal: $t_f \ll t_c,\ t_\phi$

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

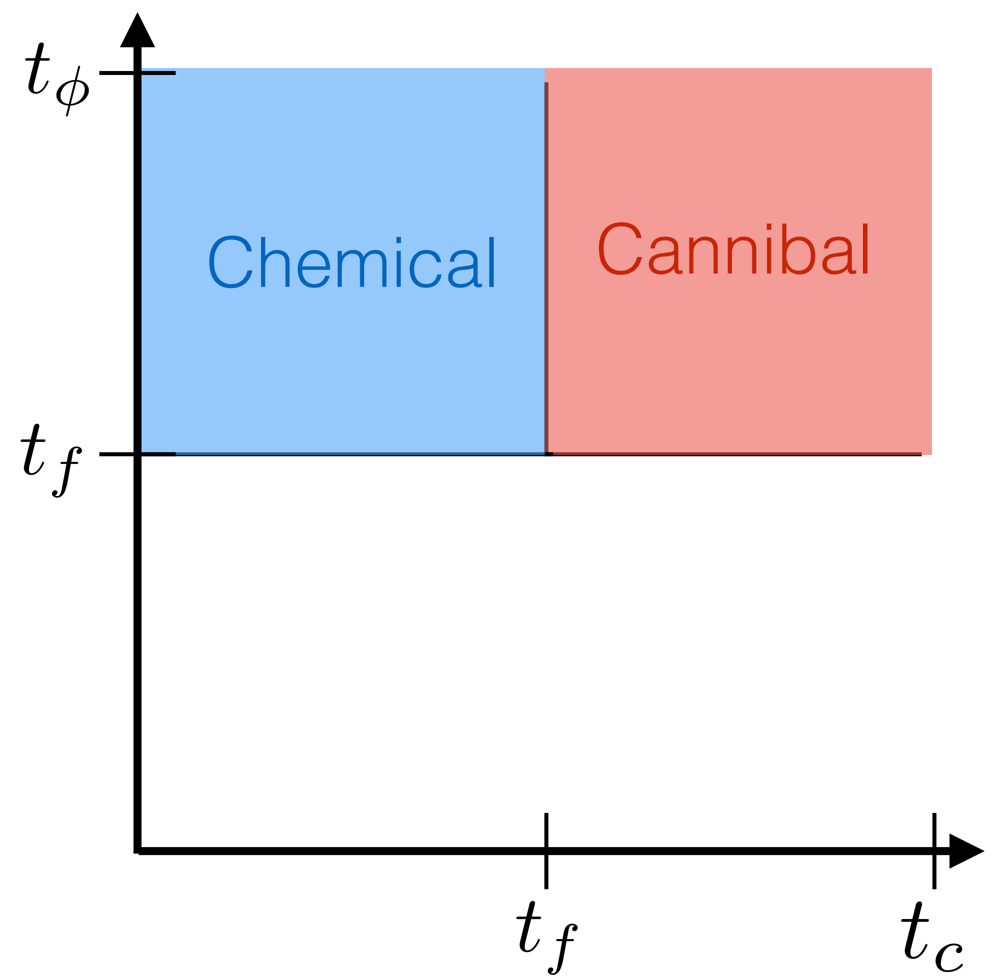


Three phases (II)

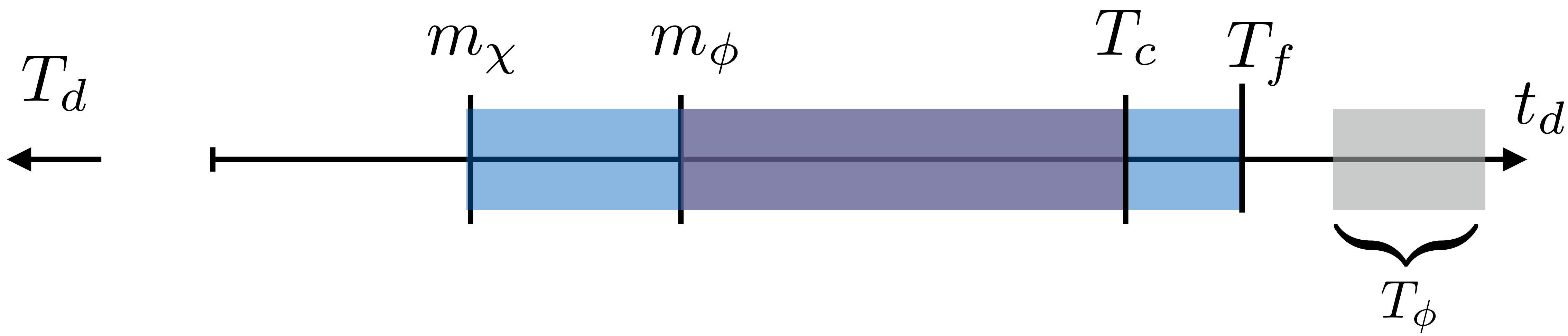


- Chemical: $t_c \ll t_f \ll t_\phi$

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

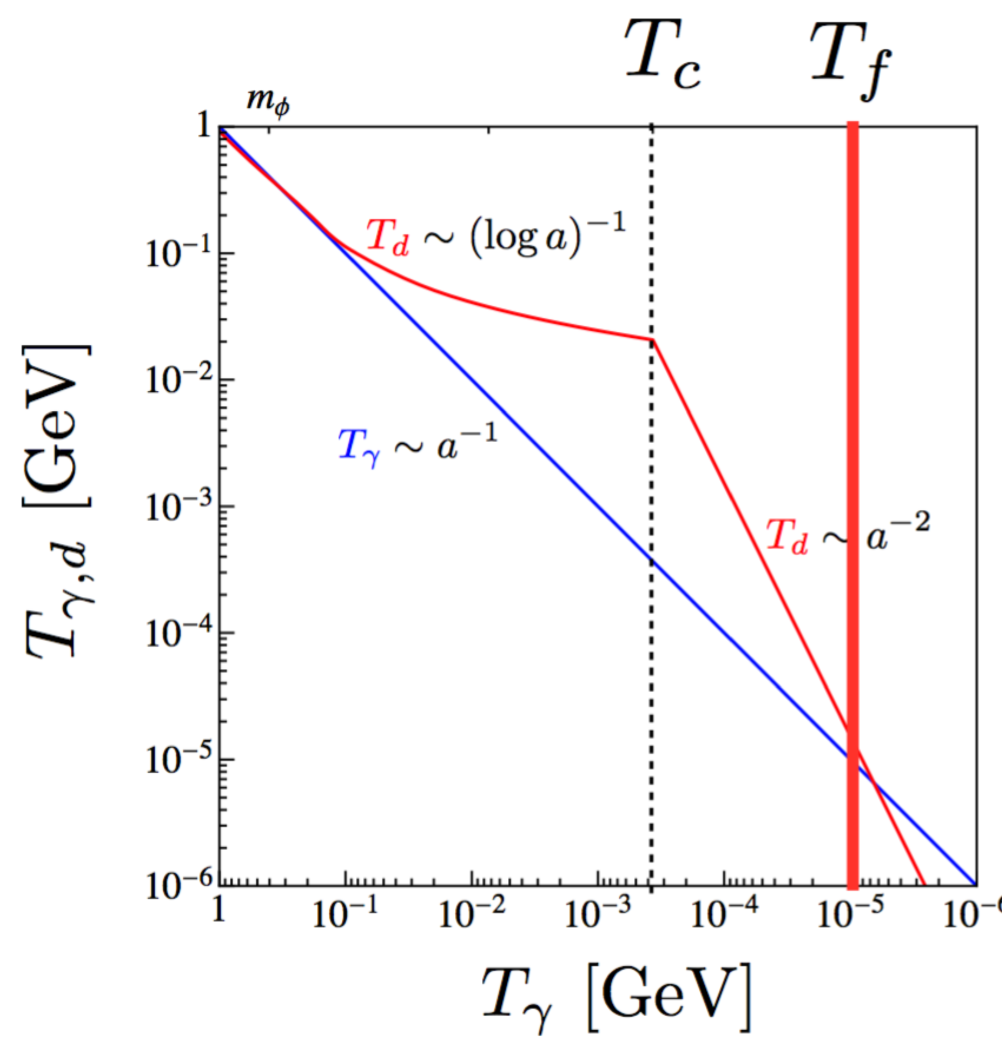


Three phases (II)

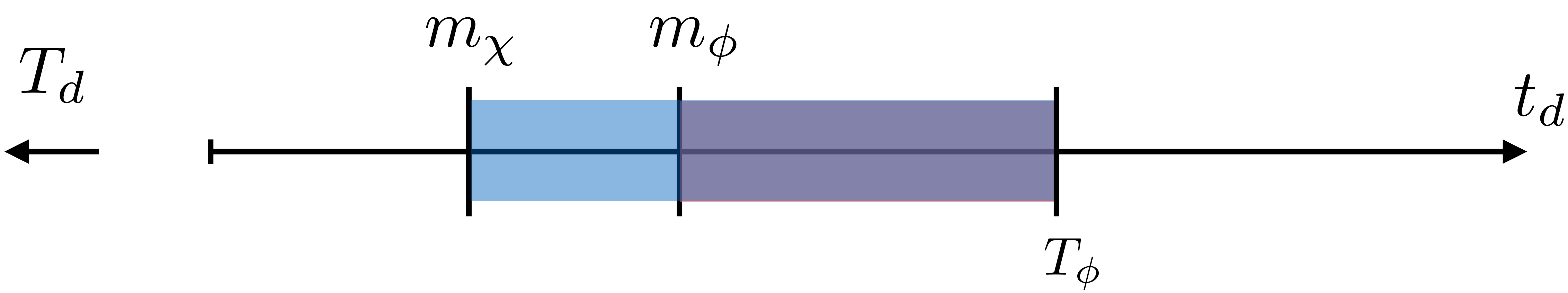


- Chemical: $t_c \ll t_f \ll t_\phi$

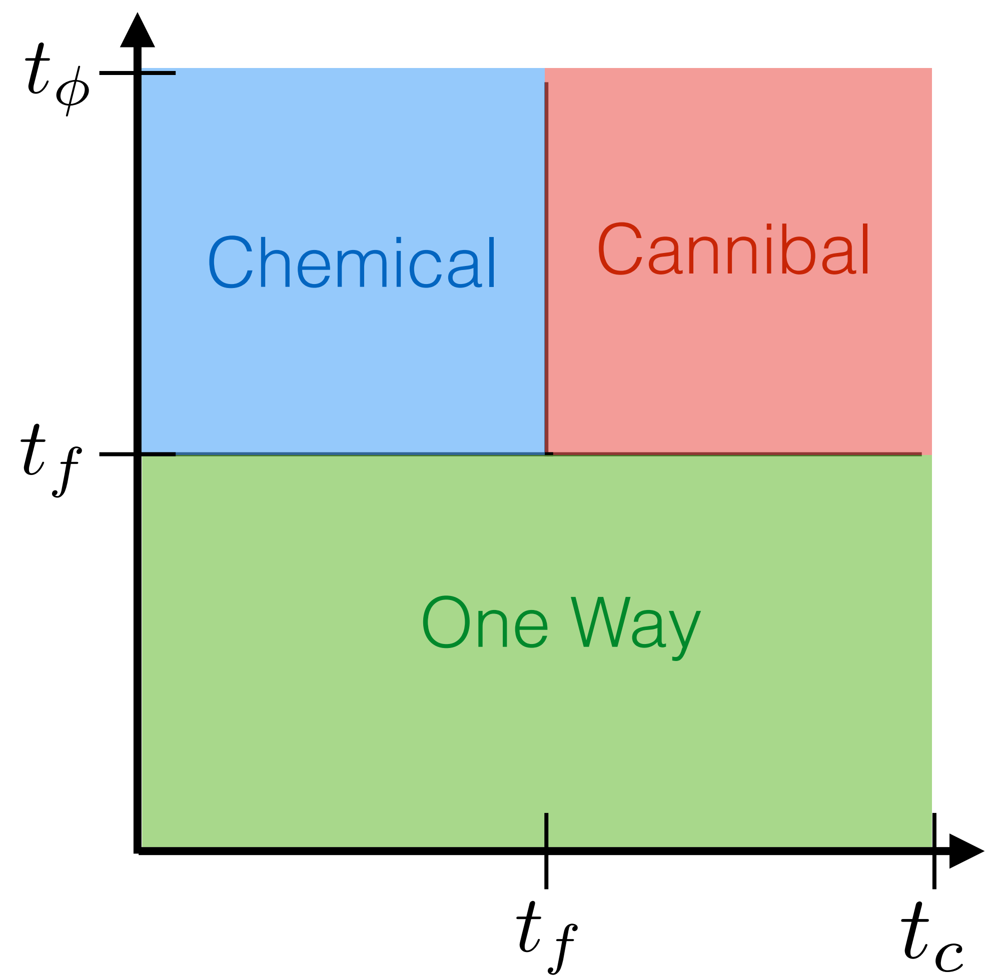
$$Y_\chi \propto \frac{(m_0^4 M_P \sigma_3)^{1/4}}{m_\chi M_P \sigma_2}$$



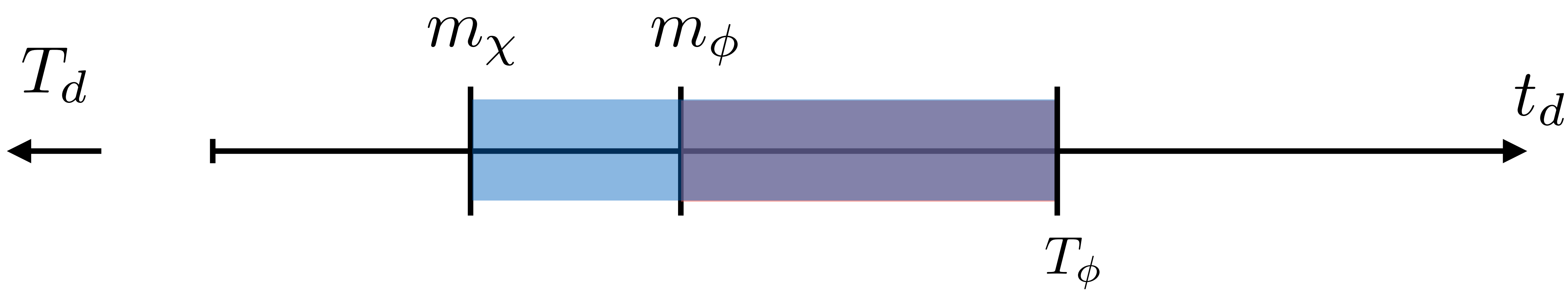
Three phases (III)



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

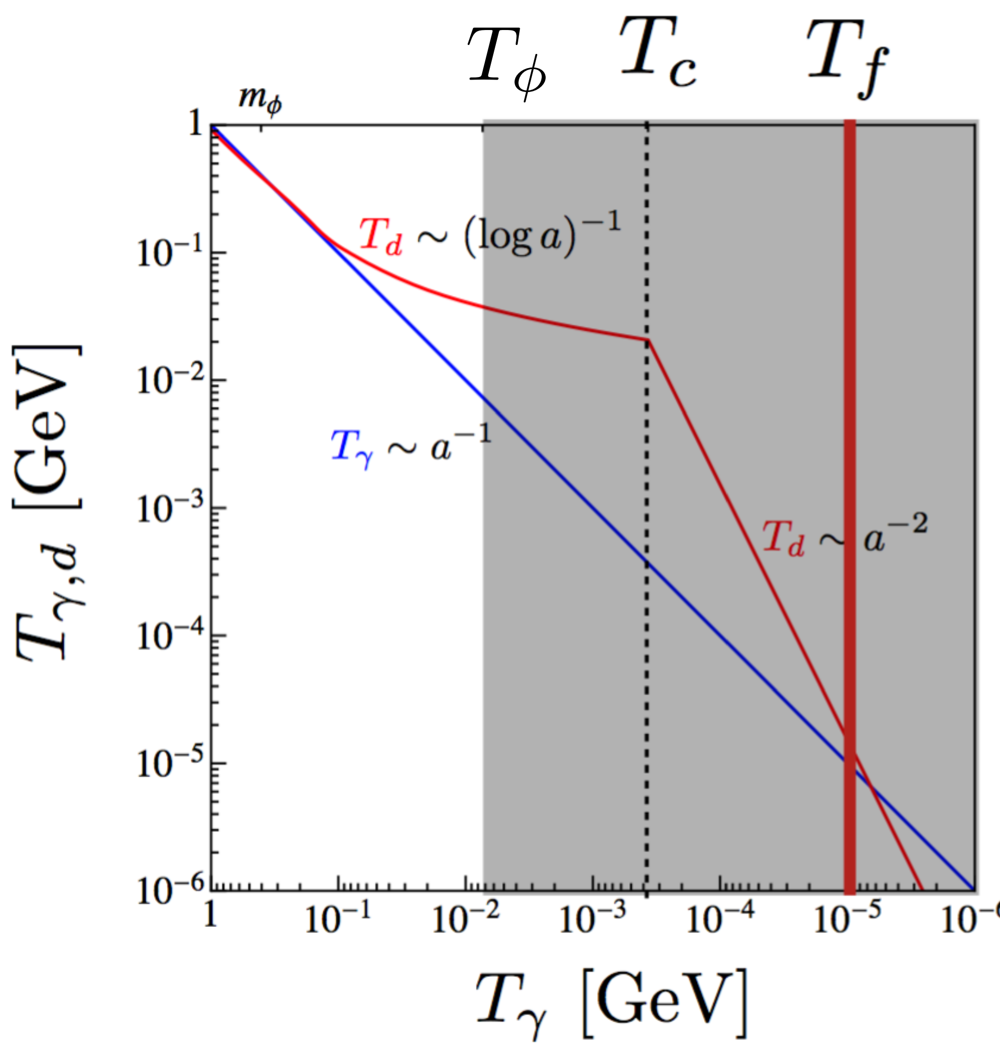


Three phases (III)

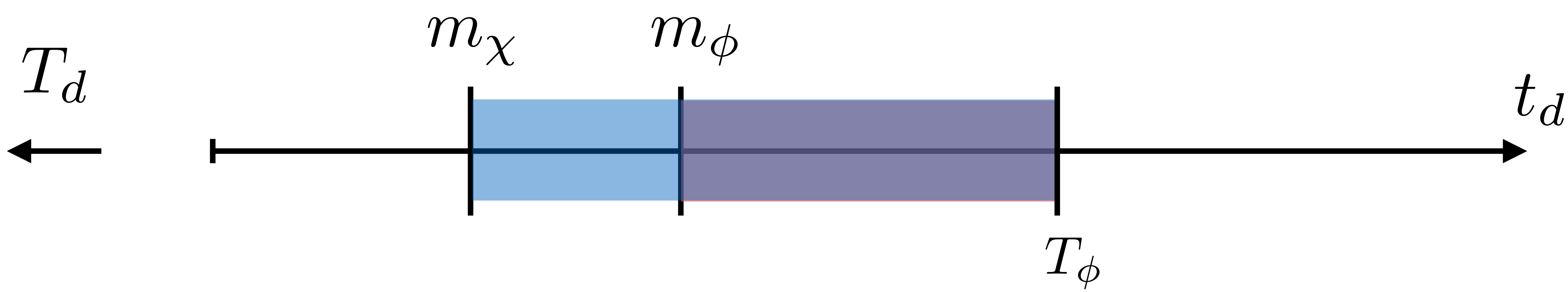


- One Way: $t_\phi \ll t_f$

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



Three phases (III)



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

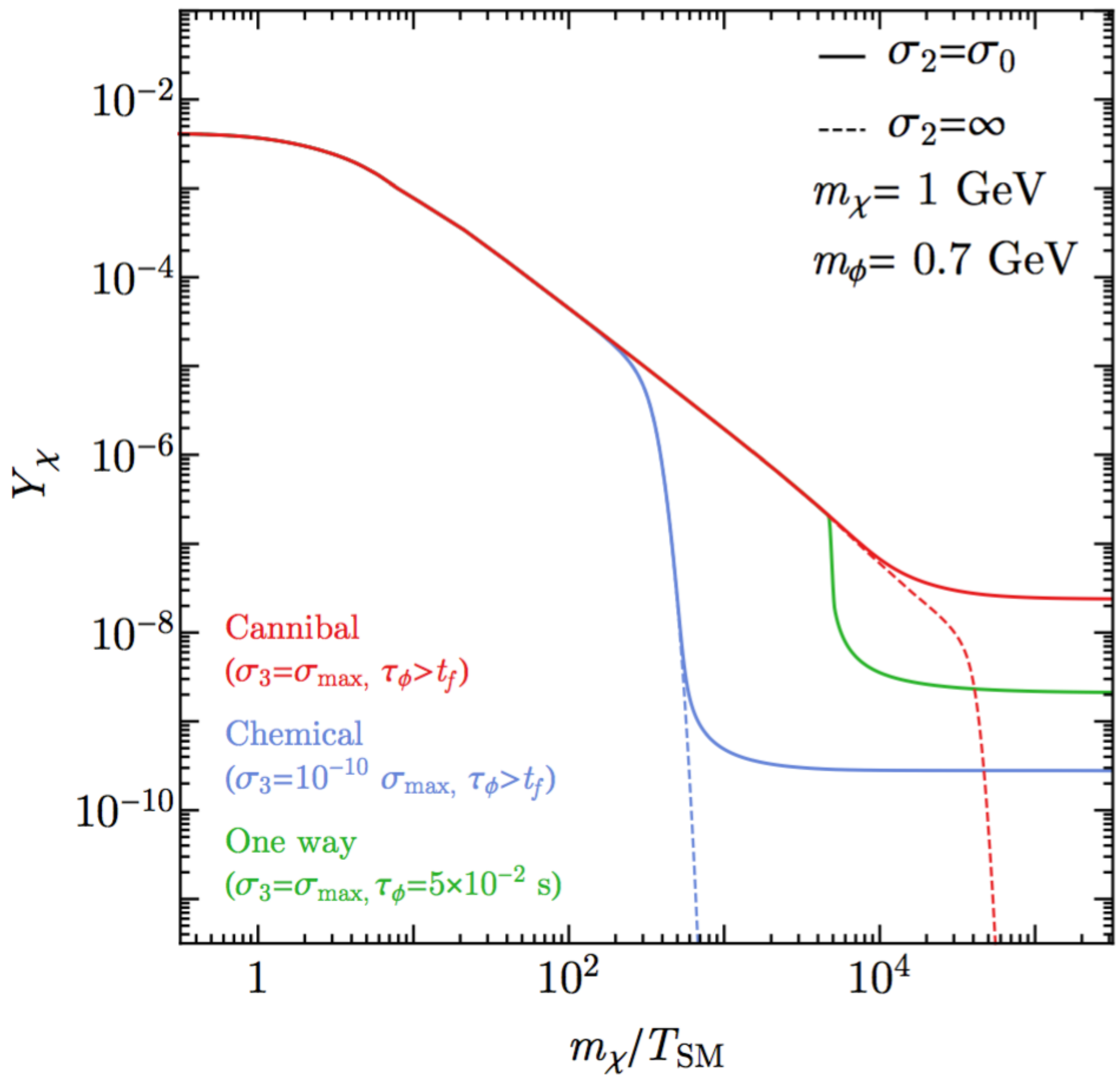
Requires out of equilibrium physics.

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

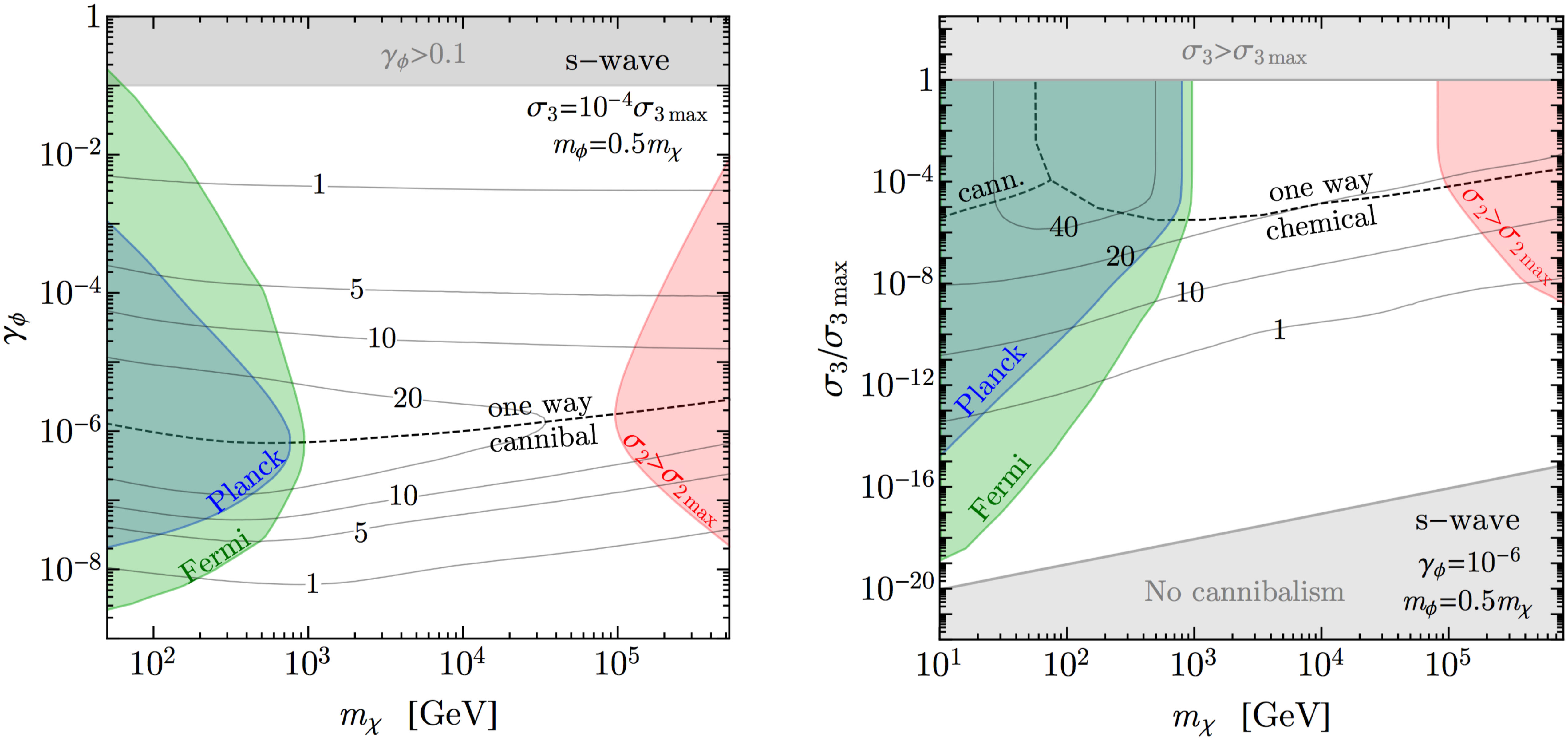
Set $n_\phi = 0$ at T_ϕ as an approximate treatment.

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

Three phases (I+II+III)

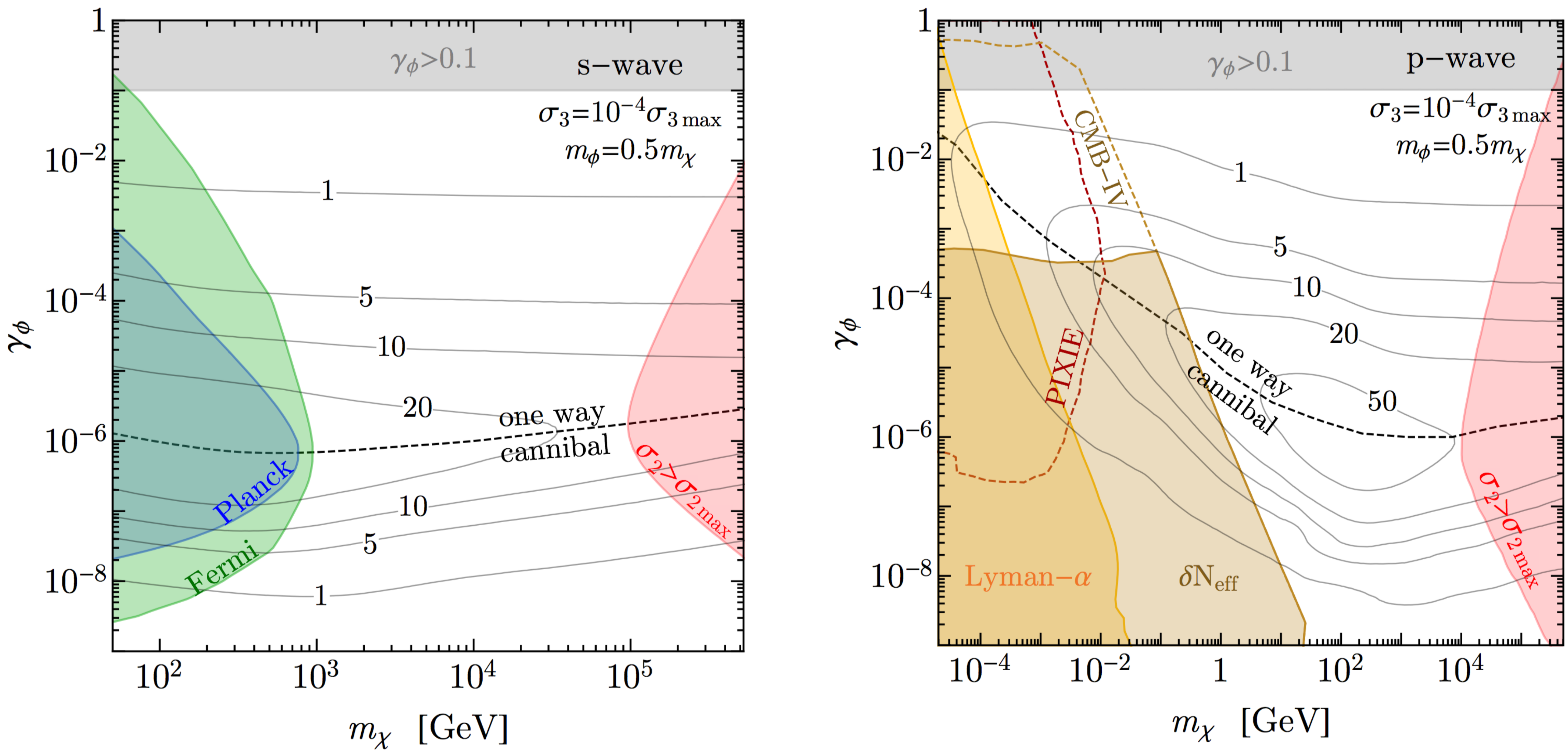


Phases Pheno



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

Phases Pheno



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

Otherwise…

ϕ must eventually decay to SM (or to dark radiation). Otherwise it typically dominates the dark sector energy density

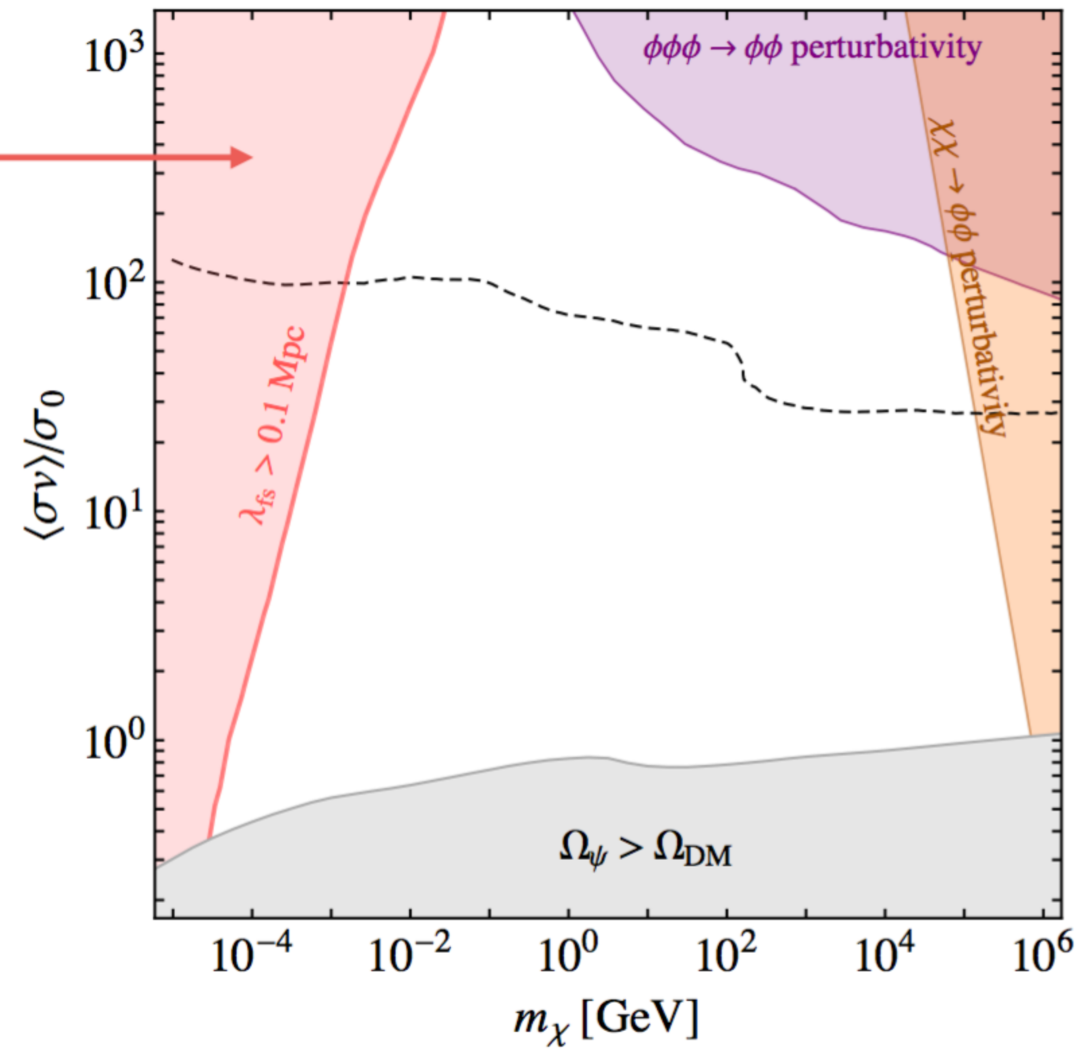
$$\frac{\rho_\phi}{\rho_\chi} \approx \frac{1}{2}\left(\frac{m_\chi}{m_\phi}\right)^{5/2} e^{(m_\chi - m_\phi)/T_d}$$

Moreover ϕ can dominate the energy density of the universe, from exponential temperature ratio (an early matter domination phase is allowed though…)

$$\frac{\rho_d}{\rho_{SM}} = \frac{3}{4}\frac{s_d T_d}{s_{SM} T_{SM}} \longrightarrow \frac{T_{SM}^E}{T_d^E} = \frac{4}{3}\frac{1}{\xi}$$

$\phi \to \gamma\gamma$

free-streaming



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

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

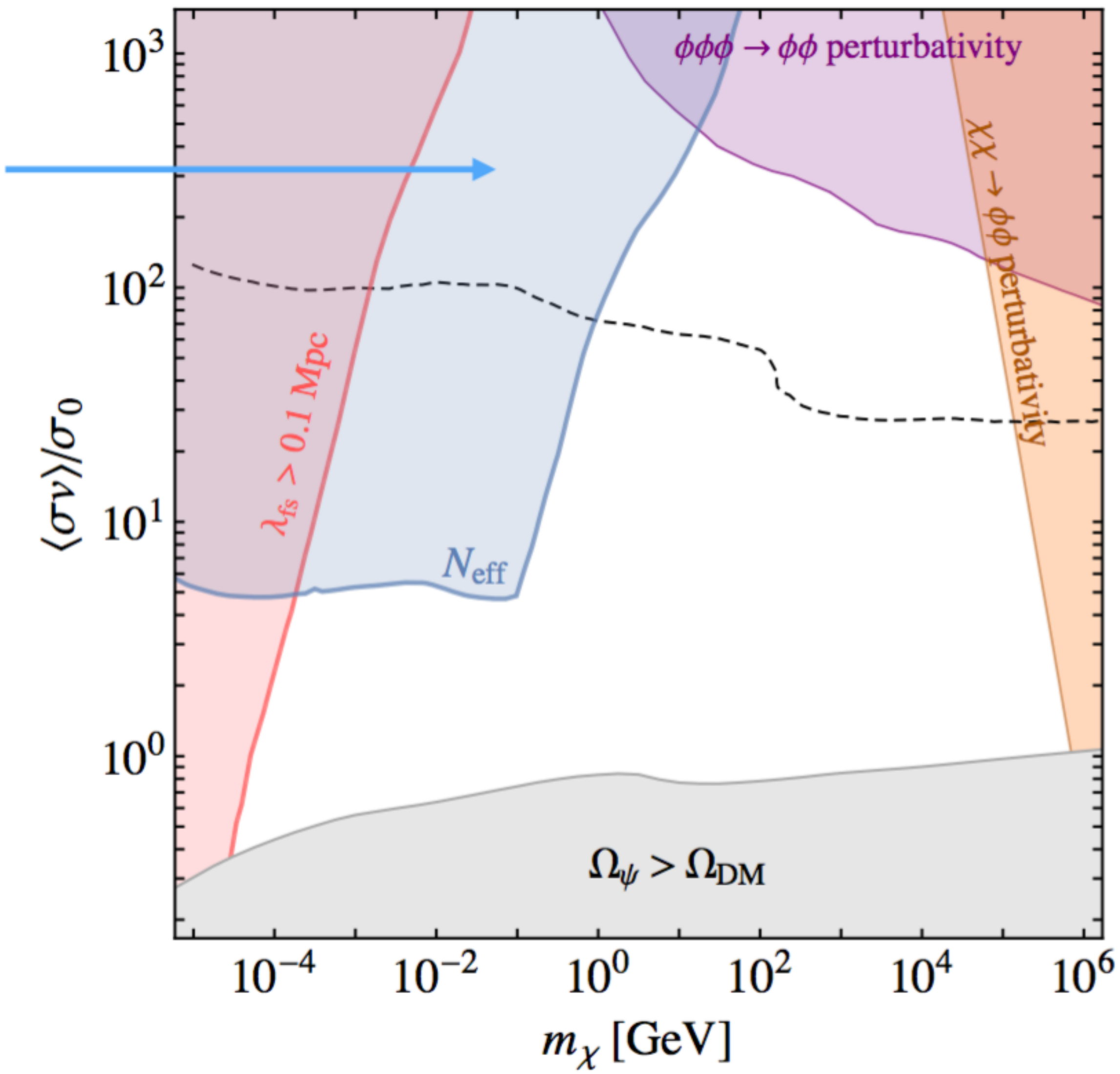
$$\lambda_{\rm fs} \approx 100\,{\rm Mpc}\,\frac{1}{\sqrt{x_f}}\,\frac{\log T_k^{\rm eV}}{T_k^{\rm eV}}$$

$$\lambda_{\rm fs} < 0.1\,{\rm Mpc} \quad [Ly\alpha]$$

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

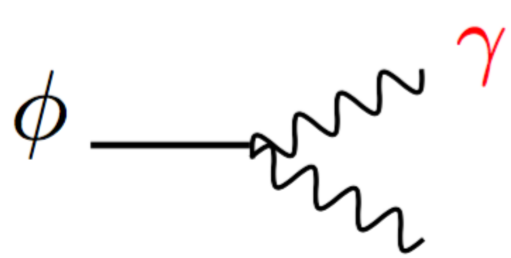
$\phi \rightarrow \gamma\gamma$

Planck Neff



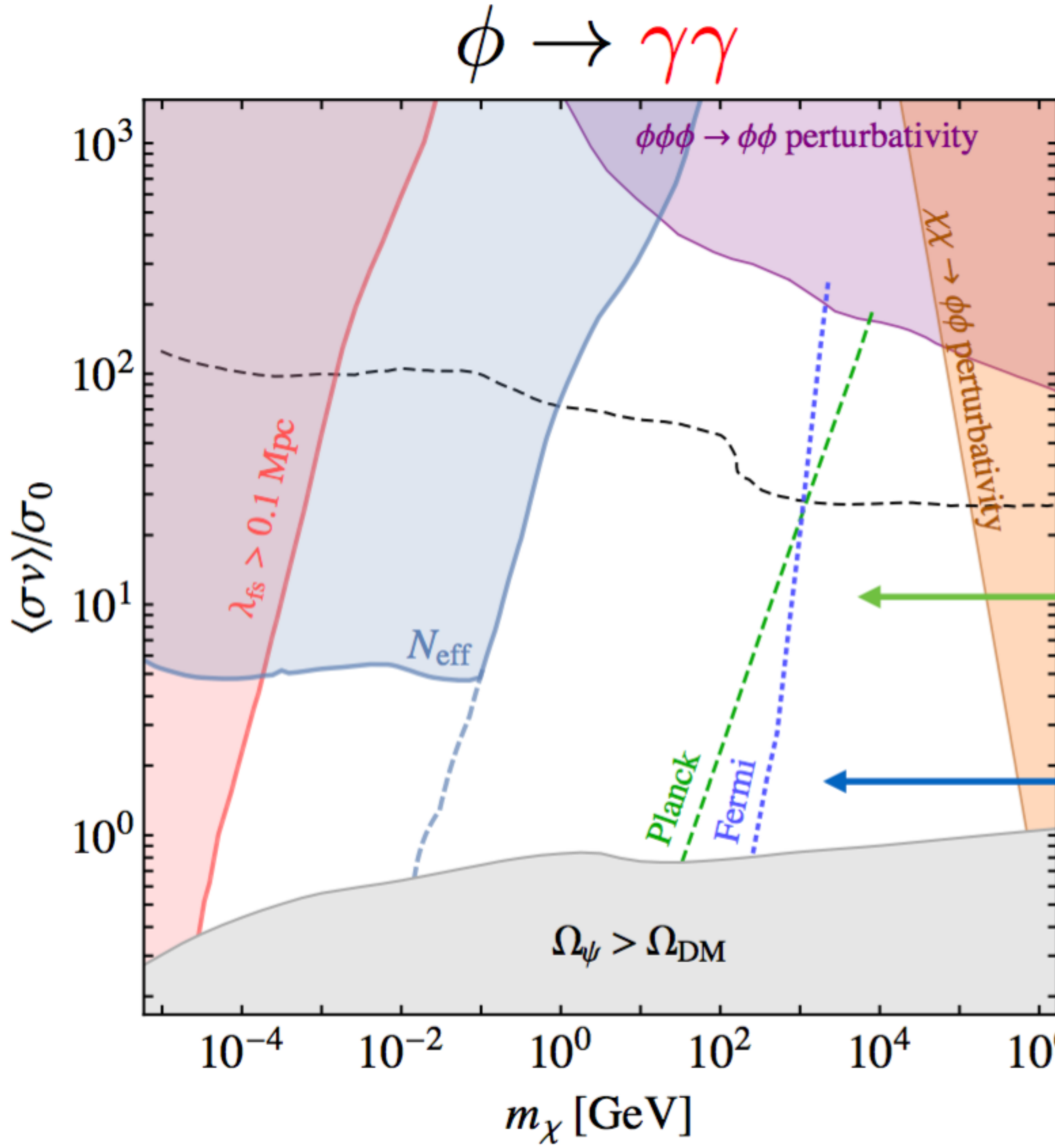
$$\xi = \frac{g_{*SM}}{g_{*\phi} + g_{*\chi}} \approx 39$$

$$\Gamma_\phi = H_f$$



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

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

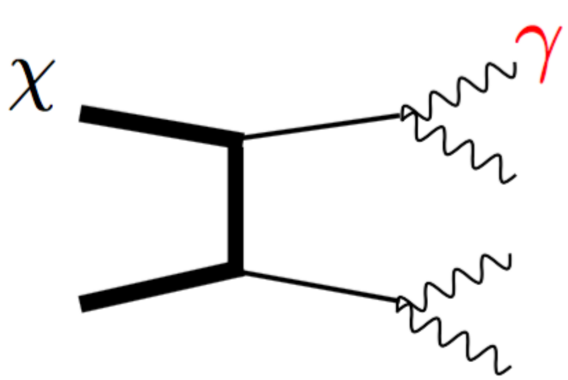


$$\xi = \frac{g_{*SM}}{g_{*\phi} + g_{*\chi}} \approx 39$$

$$\Gamma_\phi = H_f$$

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.

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

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