SIMP Miracles and WIMP Dead Ends: Navigating the Freeze-Out of MeV Dark Matter

Josef Pradler

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Navigating the Freeze-Out of MeV DM

1 SIMPs

natural habitat: 100 MeV mass scale

=> putting a new perspective on the “SIMP miracle”

arXiv:2401.12283 (PRL)

w/ Xiaoyong Chu, Marco Nikolic

2 WIMPs

natural habitat: EW mass scale

=> what is the lightest WIMP mass? The WIMP “dead end”.

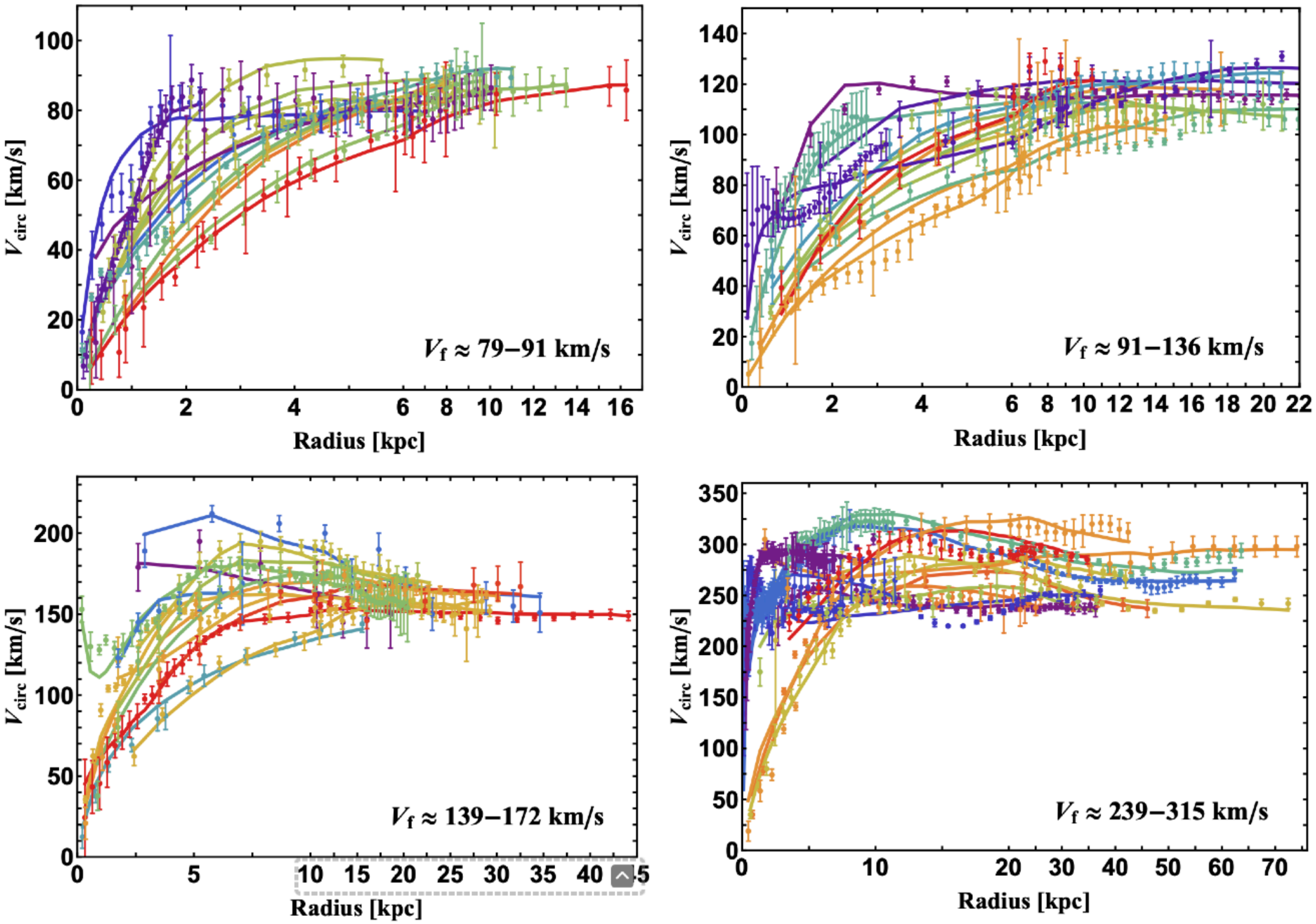
arXiv:2205.05714 (PRD)

arXiv:2310.06611 (PRD)

w/ Xiaoyong Chu, Jui-Lin Kuo

Motivation for SIMPs

Small scale structure problems in LCDM (core-cusp, diversity, …)



self-interactions lead to heat transfer in the halo, diversifying the halo density in the central regions of galaxies

natural habitat:

MeV mass scale paired with strong interactions

e.g. Ren, Kwa, Kaplinghat, Yu [2019]

$$\sigma/\mathrm{m} = 3\ \mathrm{cm}^2/\mathrm{g}$$

WIMPs

“Weakly Interacting Massive Particles”

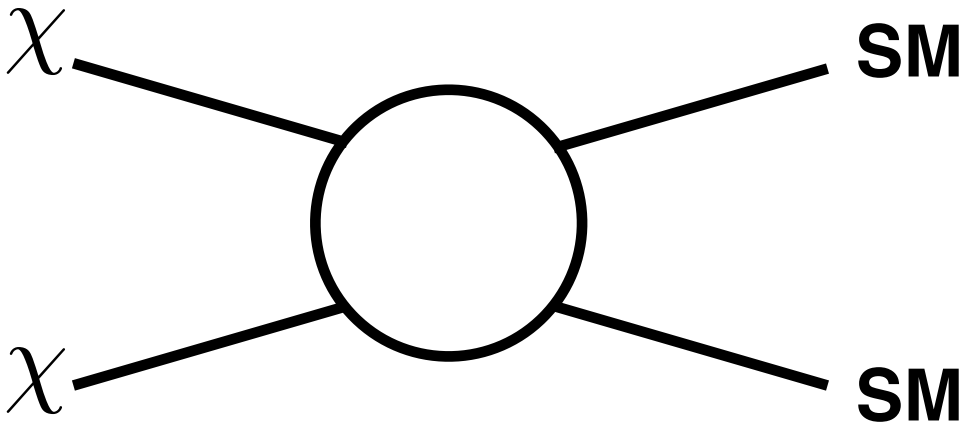
Freeze out when 2 -> 2 annihilation rate ~ Hubble rate

$$\Gamma_{2\to 2}(T_f) = \langle \sigma v \rangle n_\chi(T_f) \sim H(T_f)$$

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

$$n_\chi(T_f) = \frac{\rho_\chi(T_f)}{m_\chi} = \frac{T_{eq} m_\chi^2}{x_f^3}$$

$$H(T_f) \sim \frac{T_f^2}{M_P} = \frac{m_\chi^2}{x_f^2 M_P}$$



$$x_f = m_\chi / T_f \sim 20$$

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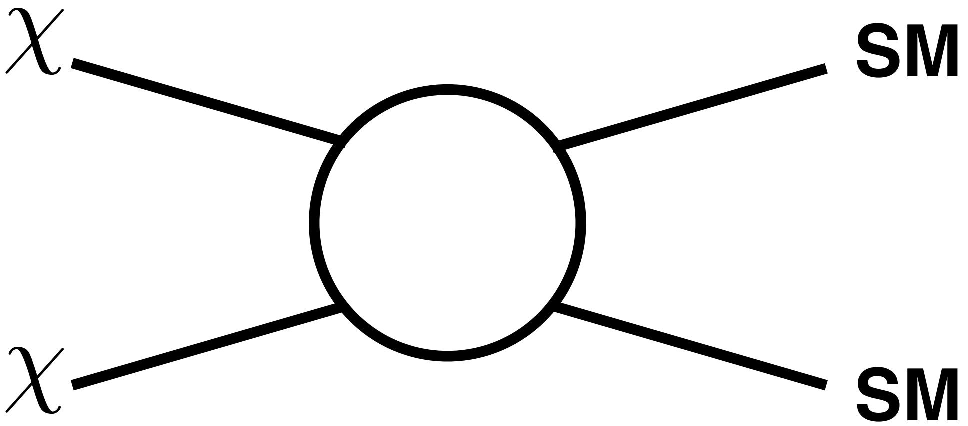


$$x_f = m_\chi / T_f \sim 20$$

$$\boxed{m_\chi \sim \frac{\alpha}{\sqrt{x_f}} \sqrt{T_{eq} M_P} \sim \alpha (30 \text{ TeV})}$$

=> points to electroweak scale

SIMPs

“Strongly Interacting Massive Particles”

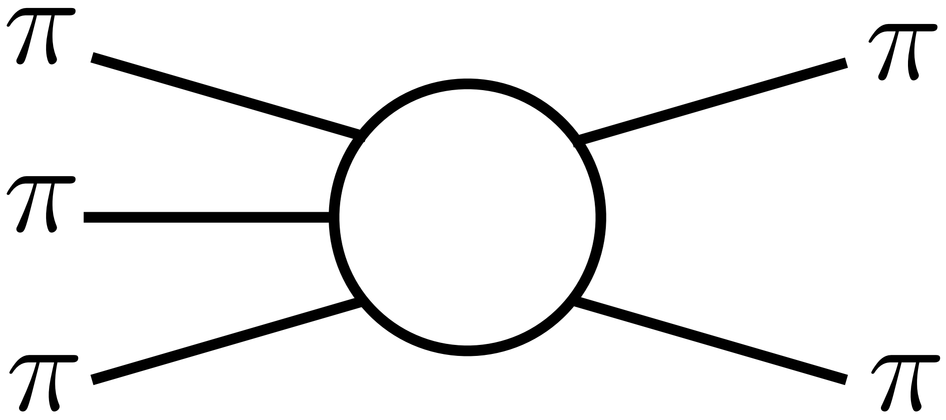
Freeze out when **3 -> 2** annihilation rate ~ Hubble rate

$$\Gamma_{3\to 2}(T_f) = \langle \sigma v^2 \rangle n_\pi^2(T_f) \sim H(T_f)$$

$$\langle \sigma v^2 \rangle \sim \frac{\alpha^3}{m_\chi^5}$$

collision term or

“cross section” of mass dimension -5



[Hochberg et al 2015, …]

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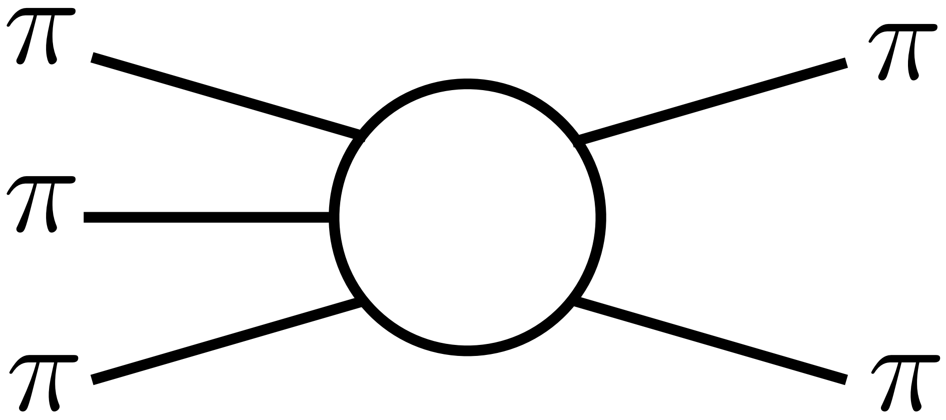


$$\boxed{m_\pi \sim \alpha (T_{eq}^2 M_P)^{1/3} \sim \alpha (100 \text{ MeV})}$$

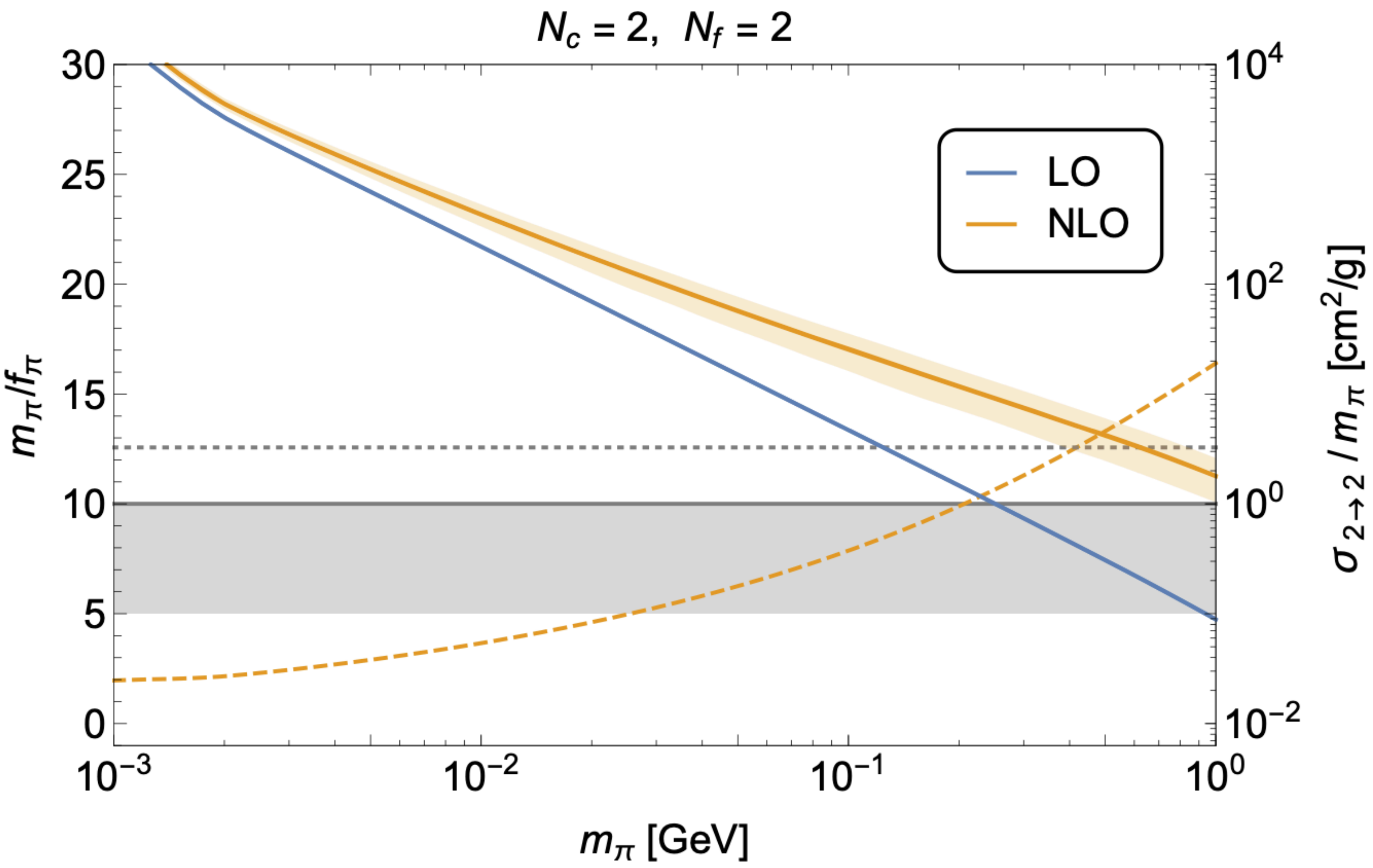
=> points to strong interactions

=> MeV scale DM

[Hochberg et al 2015, …]

A SIMP miracle?

Successful relic density paired with sufficient self-scattering cross section

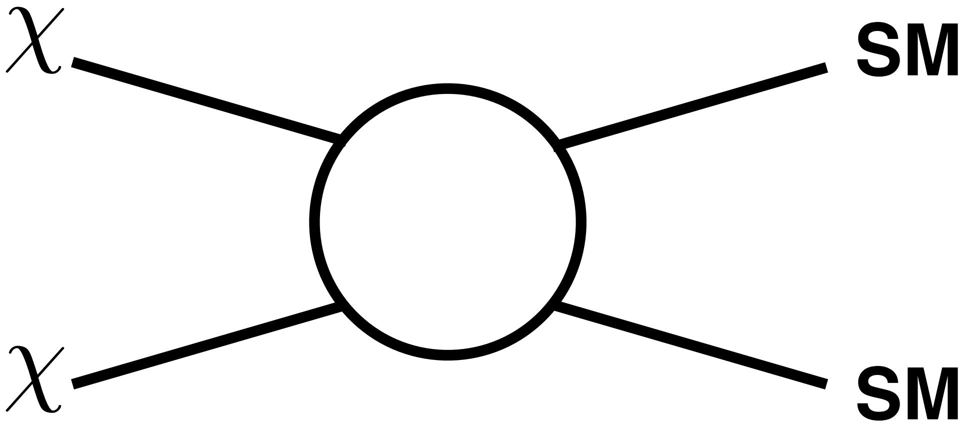


[Hansen, Langaeble, Sannino 2016]

tension in the joint "miracle" solution

WIMPs vs. SIMPs

$$m_\chi \sim \frac{\alpha}{\sqrt{x_f}} \sqrt{T_{eq} M_P} \sim \alpha(30\ \mathrm{TeV})$$



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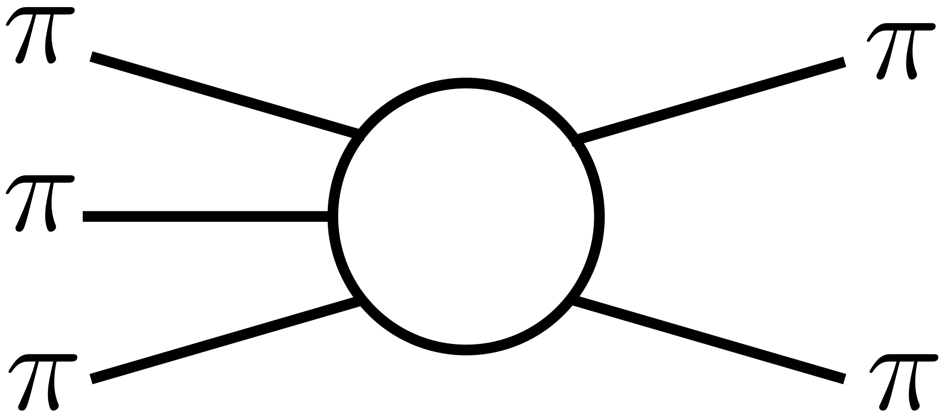

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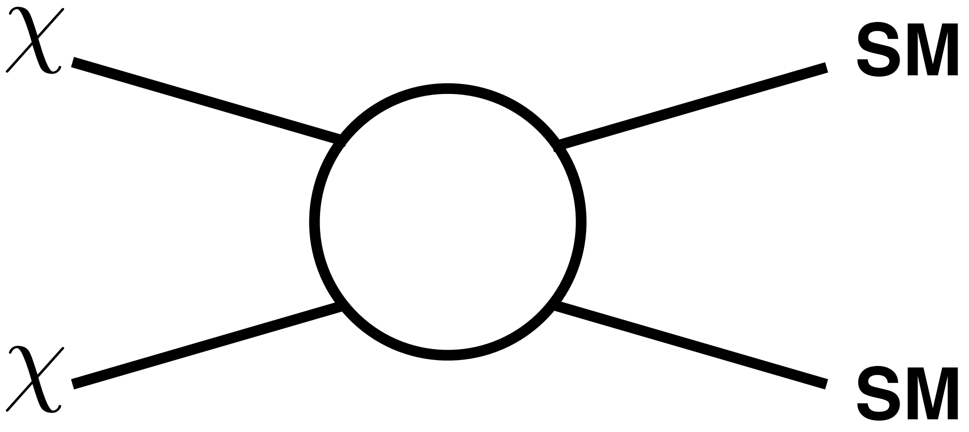
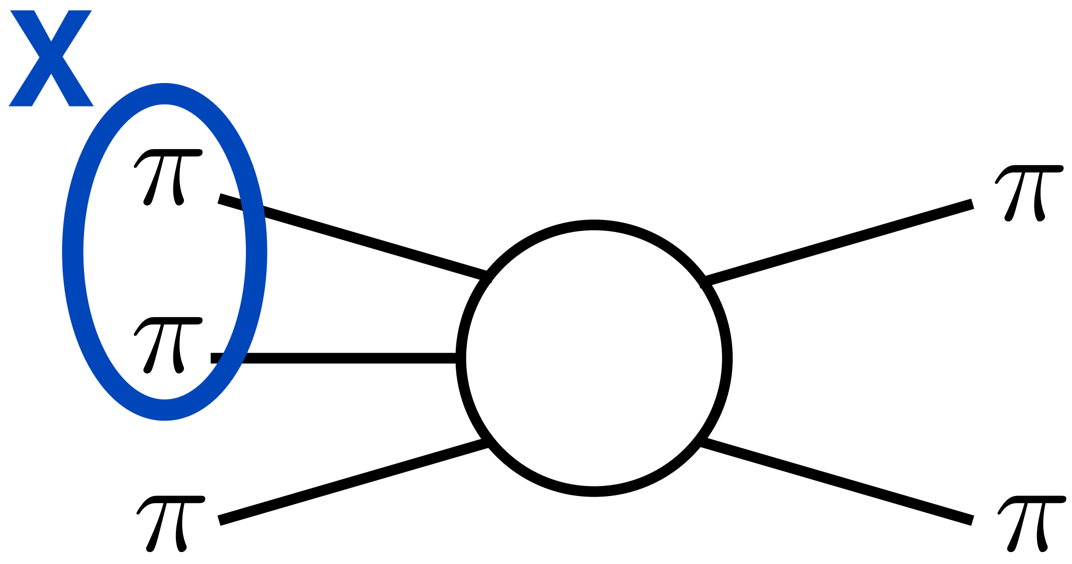


what if we make a stable bound state?



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SIMP prototype model

Dark Matter as Goldstone bosons of a confining dark sector

For example, two flavor $N_f = 2, \; Sp(4)_c$ gauge group

Kulkarni, Maas, Mee, Nikolic, JP, Zierler SciPost Phys. 14 (2023) 3, 044,

$$\mathcal{L}^{\mathrm{UV}} = -\frac{1}{2}\,\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \bar{u}\left(\gamma_\mu D_\mu + m_u\right)u + \bar{d}\left(\gamma_\mu D_\mu + m_d\right)d$$

Quarks are in pseudoreal representation of color group $(\tau^a)^T = S\tau^a S$

Flavor:

$$\Psi \equiv \begin{pmatrix} u_L \\ d_L \\ \sigma_2 S u_R^* \\ \sigma_2 S d_R^* \end{pmatrix}$$

=> $\mathcal{L}^{\mathrm{UV,f}}_{\mathrm{kin}} = i\Psi^\dagger \bar{\sigma}_\mu D^\mu \Psi.$

=> SU(4)

$$\bar{u}u + \bar{d}d = -\frac{1}{2}\Psi^T \sigma_2 S E \Psi + \text{ h.c.} \qquad (m_u = m_d)$$

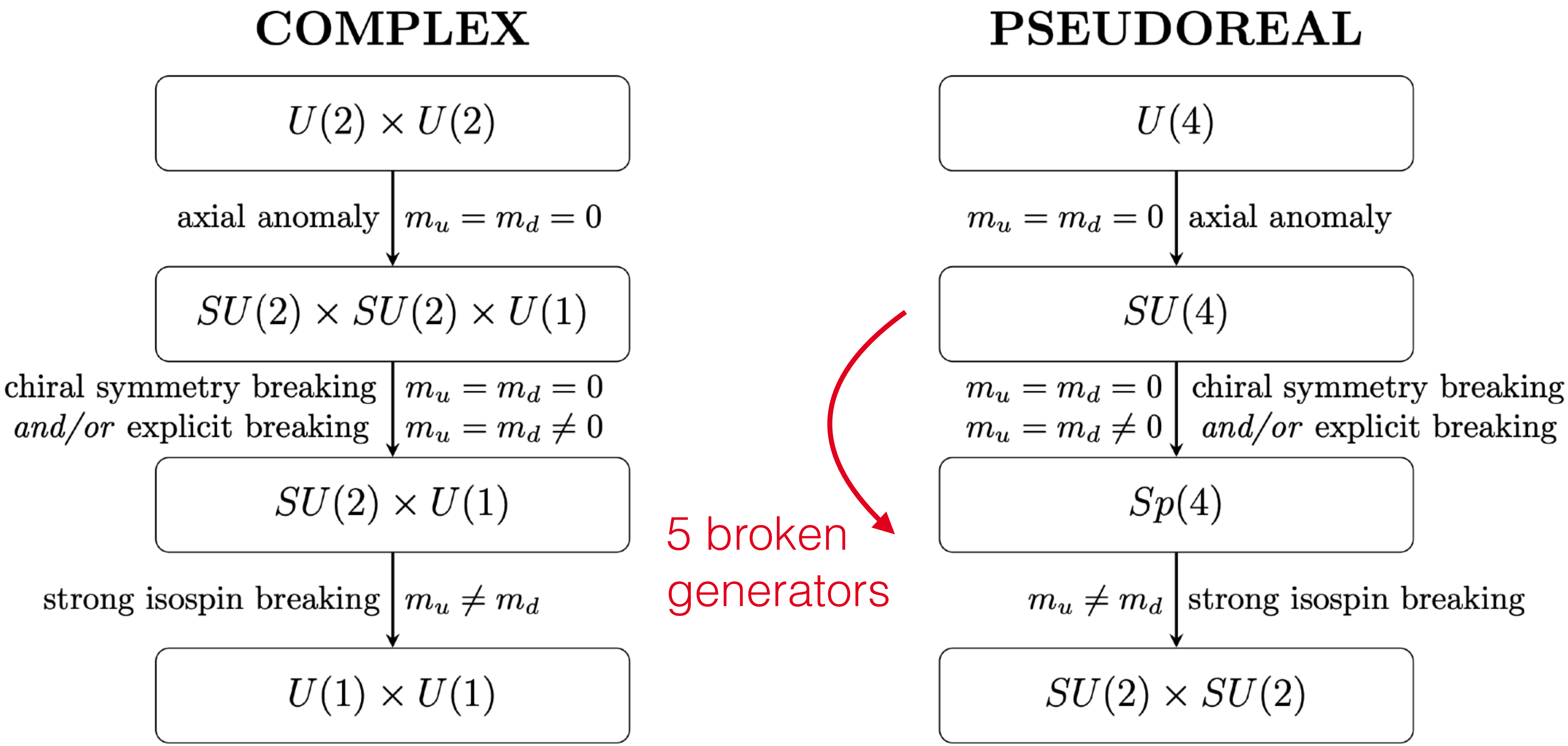
$$E = \begin{pmatrix} 0 & \mathbb{1}_{N_f} \\ -\mathbb{1}_{N_f} & 0 \end{pmatrix} \qquad U^T E U = E$$

=> Sp(4)

Flavor breaking pattern

QCD-like

this example



COMPLEX

$U(2) \times U(2)$

axial anomaly | $m_u = m_d = 0$

$SU(2) \times SU(2) \times U(1)$

chiral symmetry breaking | $m_u = m_d = 0$

and/or explicit breaking | $m_u = m_d \neq 0$

$SU(2) \times U(1)$

strong isospin breaking | $m_u \neq m_d$

$U(1) \times U(1)$

PSEUDOREAL

$U(4)$

$m_u = m_d = 0$ | axial anomaly

$SU(4)$

$m_u = m_d = 0$ | chiral symmetry breaking

$m_u = m_d \neq 0$ | *and/or* explicit breaking

$Sp(4)$

$m_u \neq m_d$ | strong isospin breaking

$SU(2) \times SU(2)$

5 broken generators

=> 5 Goldstone bosons

Prototype SIMP theory

Low energy description

chiral field $\Sigma = e^{i\pi/f_\pi}\Sigma_0 e^{i\pi^T/f_\pi}$

$$\pi = \sum_{n=1} \pi_n T^n \longleftarrow$$ broken generators

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu\Sigma\partial^\mu\Sigma^\dagger\right] - \frac{\mu^3}{2}\left(\mathrm{Tr}\left[M\Sigma\right] + \mathrm{Tr}\left[\Sigma^\dagger M^\dagger\right]\right) + \ldots .$$

$\big\downarrow$ expansion yields 4-point, 6-point, etc interactions

$$\mathcal{L}_{\rm int}^{\rm even} \supset -\frac{1}{3f_\pi^2}\,\mathrm{Tr}\left([\pi,\partial_\mu\pi][\pi,\partial^\mu\pi]\right) + \frac{m_\pi^2}{3f_\pi^2}\,\mathrm{Tr}\left[\pi^4\right]$$

even-numbered only

Wess-Zumino-Witten term when coset space has non-trivial fifth homotopy group

$$\mathcal{L}_{\rm int}^{\rm odd} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] .$$

odd-numbered

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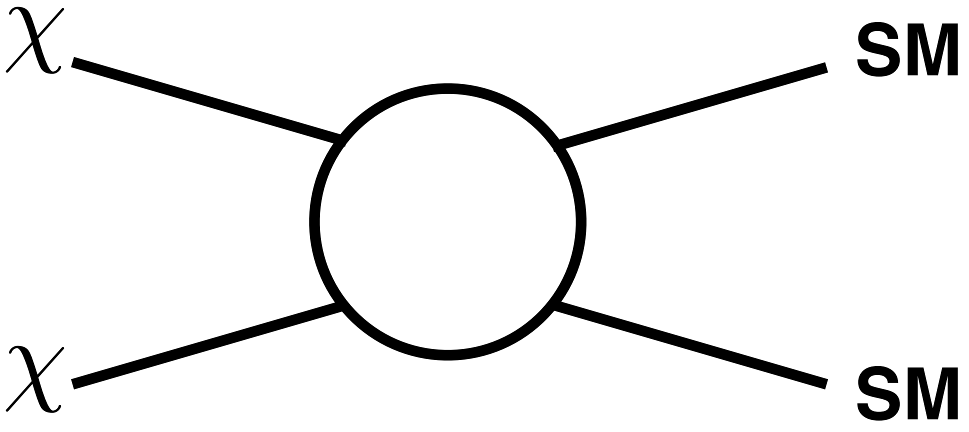

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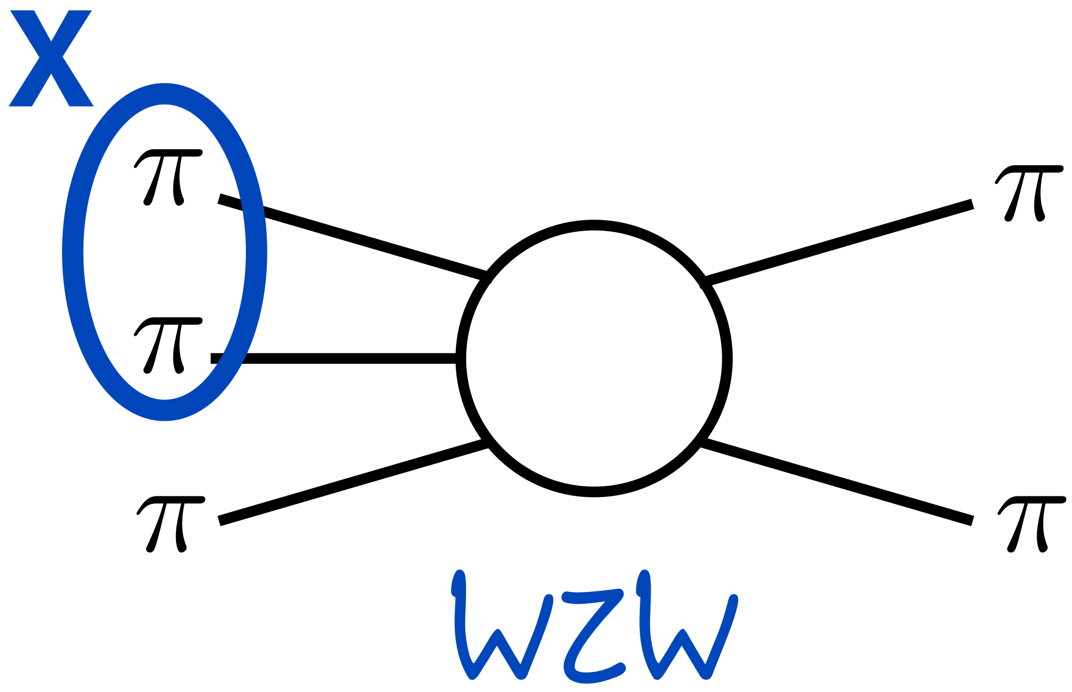


SIMP bound states

X = [π π] must exist

- considering SIMPs as pseudo-Nambu-Goldstone bosons of a strongly interacting theory we require a molecular state with negative binding energy such that $m_X \leq 2m_\pi$

  QCD with $m_q \ll \Lambda_{\rm strong}$ has a mass gap, hence not prospective

  => better consider a dark confining theory with $m_q \sim \Lambda_{\rm strong}$ and

  => make SIMP-onium

  => or take $m_q \gg \Lambda_{\rm strong}$: Glueball dark matter $J^{PC} = 0^{++}\text{or } 0^{-+}$ e.g. [Soni, Zhang, 2016]

$$V(G) = \frac{1}{4}\frac{m_G^2}{\Lambda_G^2}\left(G^4 \ln\left|\frac{G}{\Lambda_G}\right| - \frac{G^4}{4}\right)$$

  => yields odd G^3 interactions

  => 3-to-2 SIMP mechanism

  => make Glueball-onium

  for G-bound states see [Giacosa, Pilloni, Trotti 2021]

- one may also use a Yukawa force with sizable coupling; options exist

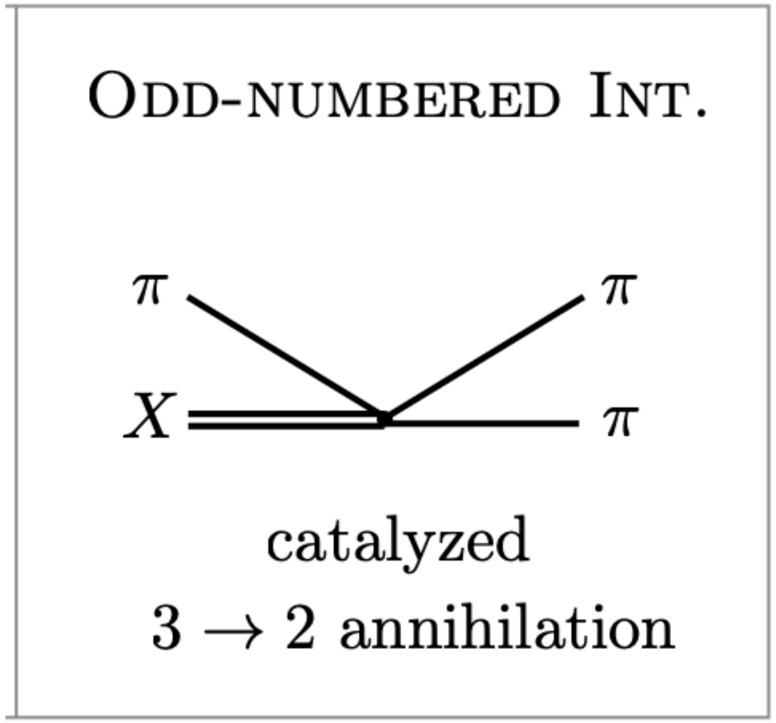
  e.g. [G. Kribs and E. Neil 2016, Y. Tsai, R. McGehee, H.Murayama 2020, R. Mahbubani, M. Redi and A. Tesi 2020, ….].

Bound-state assisted freeze-out

Catalysis

Probability of two particles finding each other in a bound state vs. as free particles

$$\frac{n_X|\psi(0)|^2}{n_\pi^2} \approx 2\sqrt{2}\pi^{3/2}x_{\mathrm{f}}^{3/2}e^{\kappa x_{\mathrm{f}}}\frac{|\psi(0)|^2}{m_\pi^3}$$



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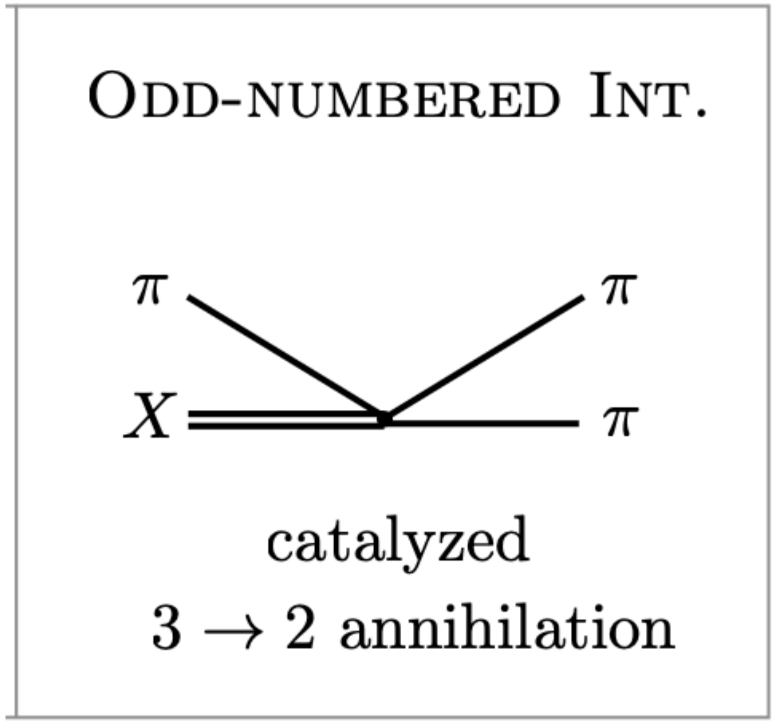
$$\frac{n_X|\psi(0)|^2}{n_\pi^2} \approx \underbrace{2\sqrt{2}\pi^{3/2}x_\mathrm{f}^{3/2}}_{\approx 10^3} e^{\kappa x_\mathrm{f}} \underbrace{\frac{|\psi(0)|^2}{m_\pi^3}}_{O(1)}$$

$$x_\mathrm{f} = 20.$$

$$\kappa \equiv E_B/m_\pi \sim 0.1$$



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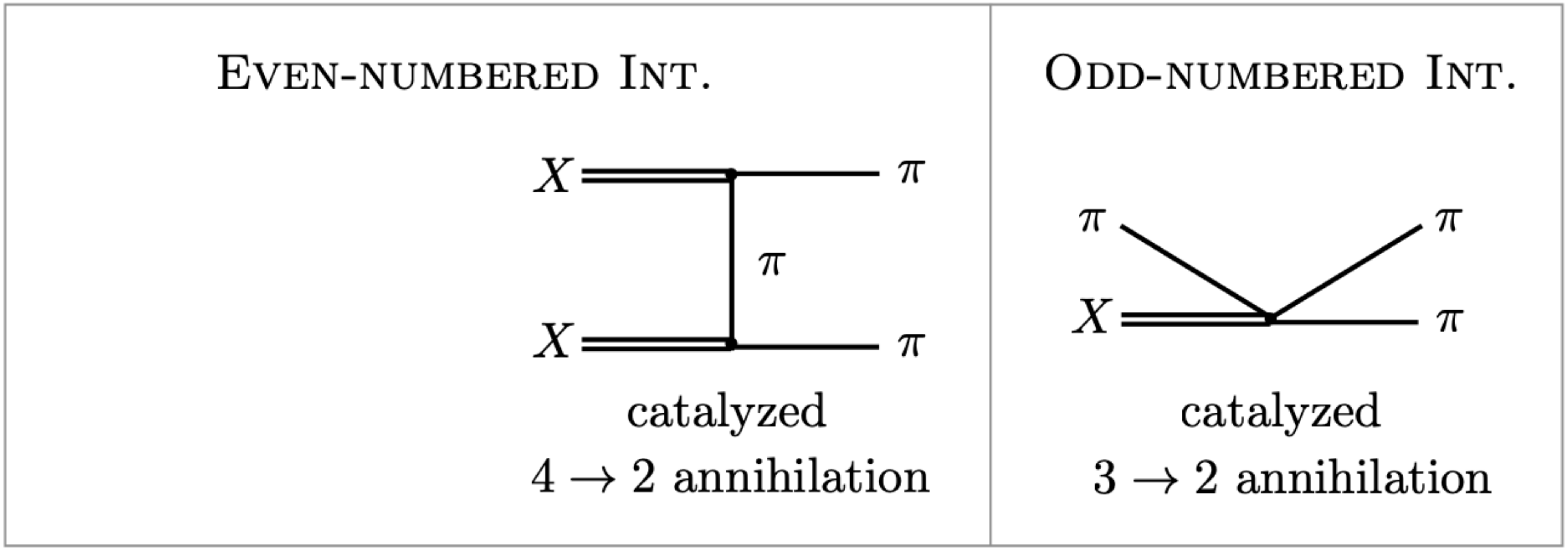
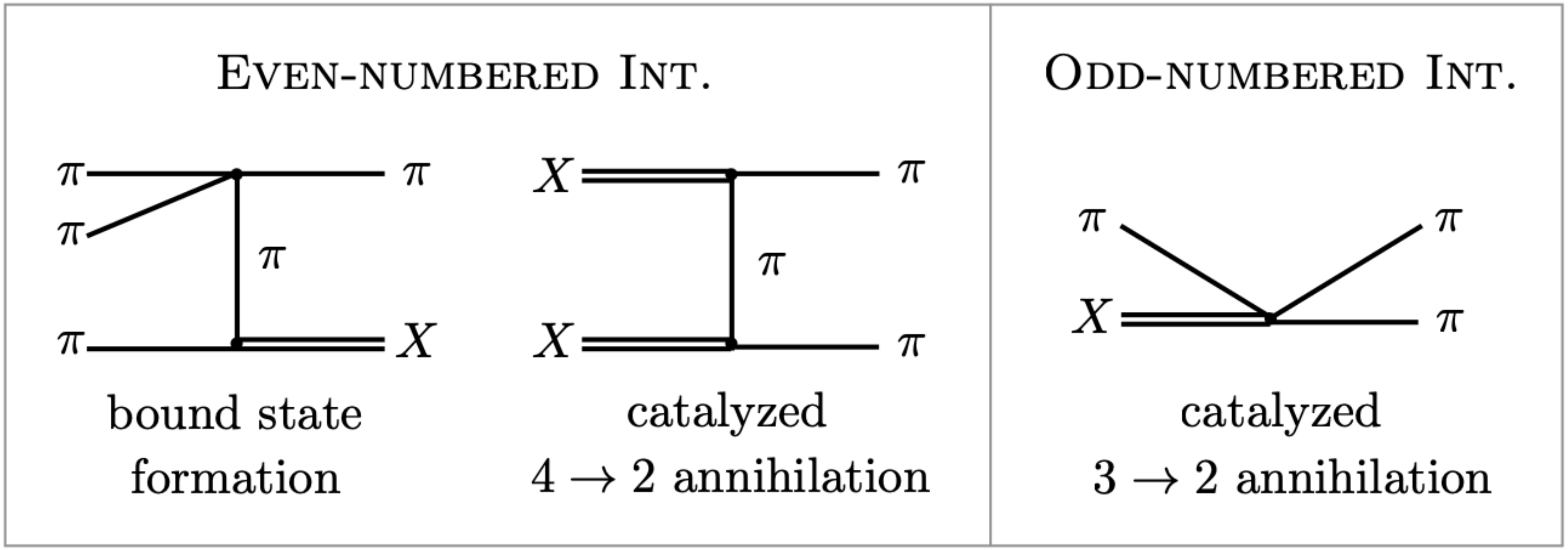


WZW-free SIMP mechanism

self-depletion of mass density in the early Universe possible
with even-numbered interactions only!

=> relaxes the requirement on the topological structure of the theory

Bound-state assisted freeze-out



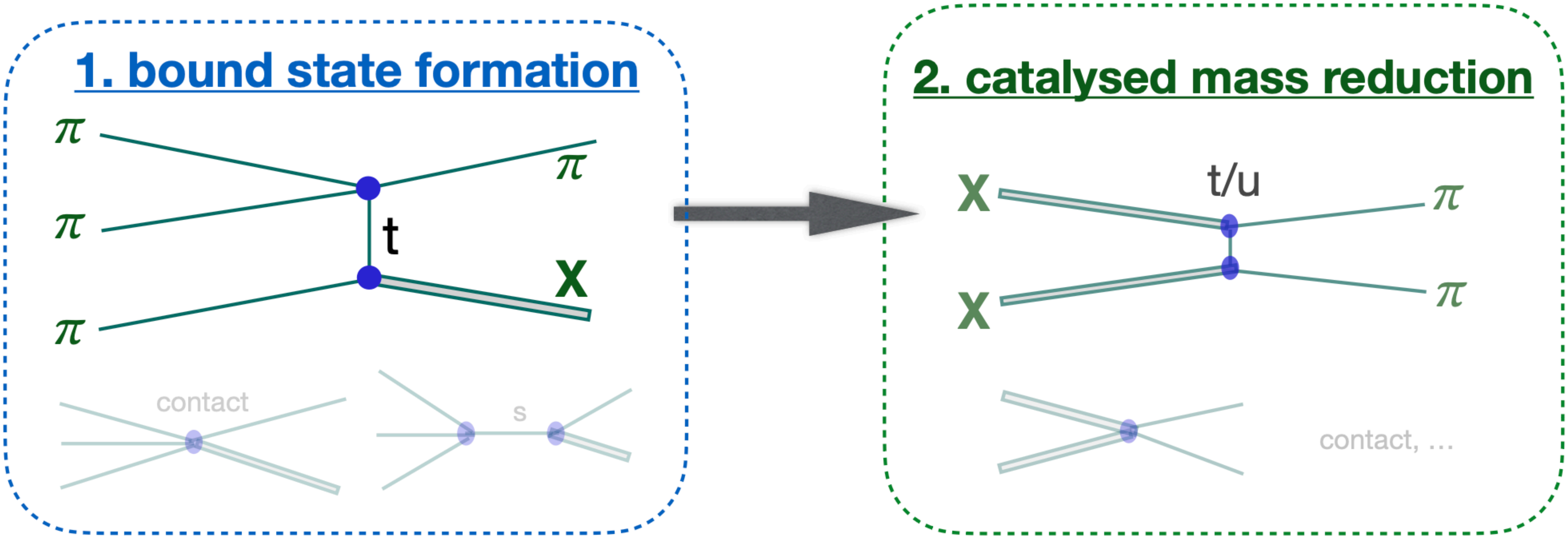
guaranteed X formation

Comparing the rates of X-formation to free

$$\frac{\Gamma_{3\pi\to X\pi}}{\Gamma_{3\pi\to 2\pi}} = \frac{\langle \sigma_{3\pi\to X\pi} v^2 \rangle}{\langle \sigma_{3\pi\to 2\pi} v^2 \rangle} \approx \frac{|\psi(0)|^2 f_\pi^2}{m_\pi^5} x_\mathrm{f}^2 .$$

easily exceeds unity

CASE 1: even-numbered interactions only



Working hypothesis:

X is a weakly bound (non-relativistic) state, such as a hadronic molecule

Bethe-Salpeter wave functions => non-relativistic Schroedinger equation

[e.g. K.Petraki, M.Postma, J.de Vries 2016, …]

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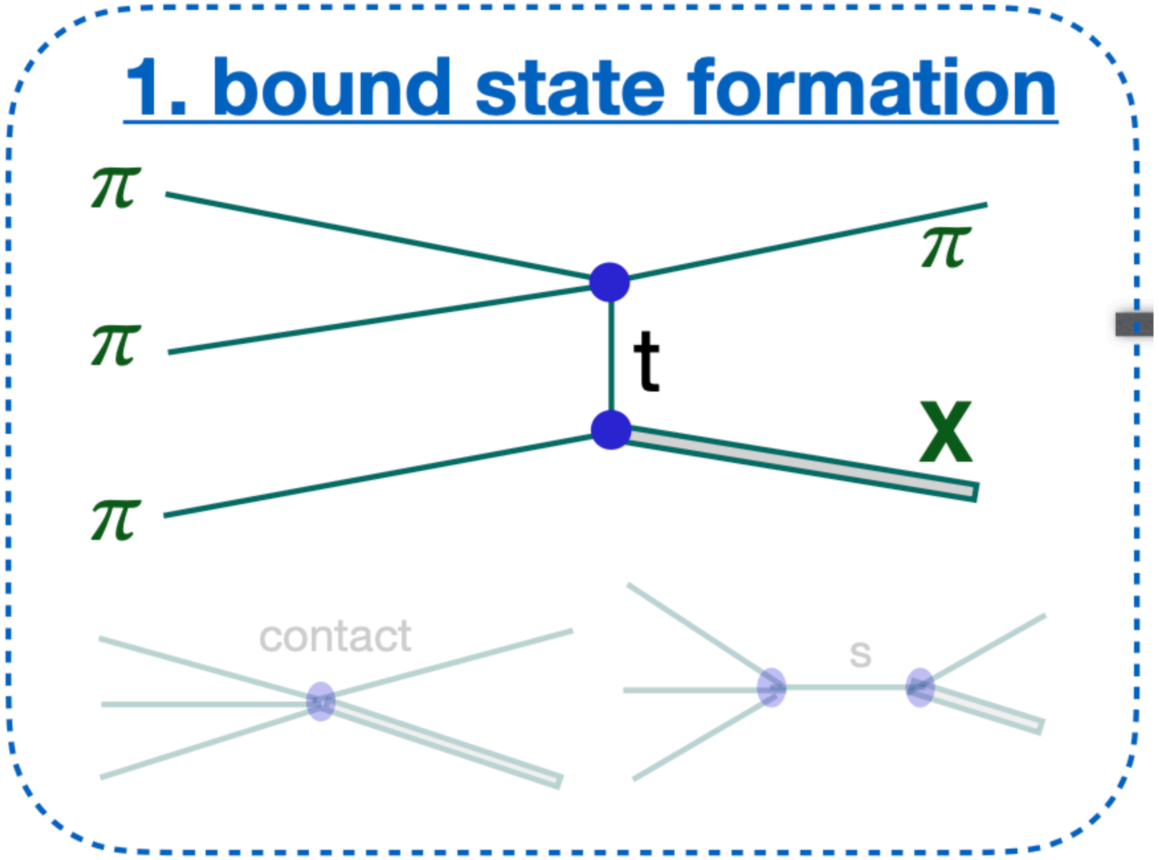

$$i\mathcal{M}(p_1,p_2,p_3 \to k,Q)_{3\pi\to\pi X}$$

$$\simeq \frac{\sqrt{2m_X}}{2m_\pi}\int \frac{d^3q}{(2\pi)^3}\int d^3r\, \psi^\star_X(\vec{r})\, e^{-i\vec{q}\vec{r}} \times i\mathcal{M}^{\text{free}}_{(p_1,p_2,p_3\to k,Q/2+q,Q/2-q)}$$

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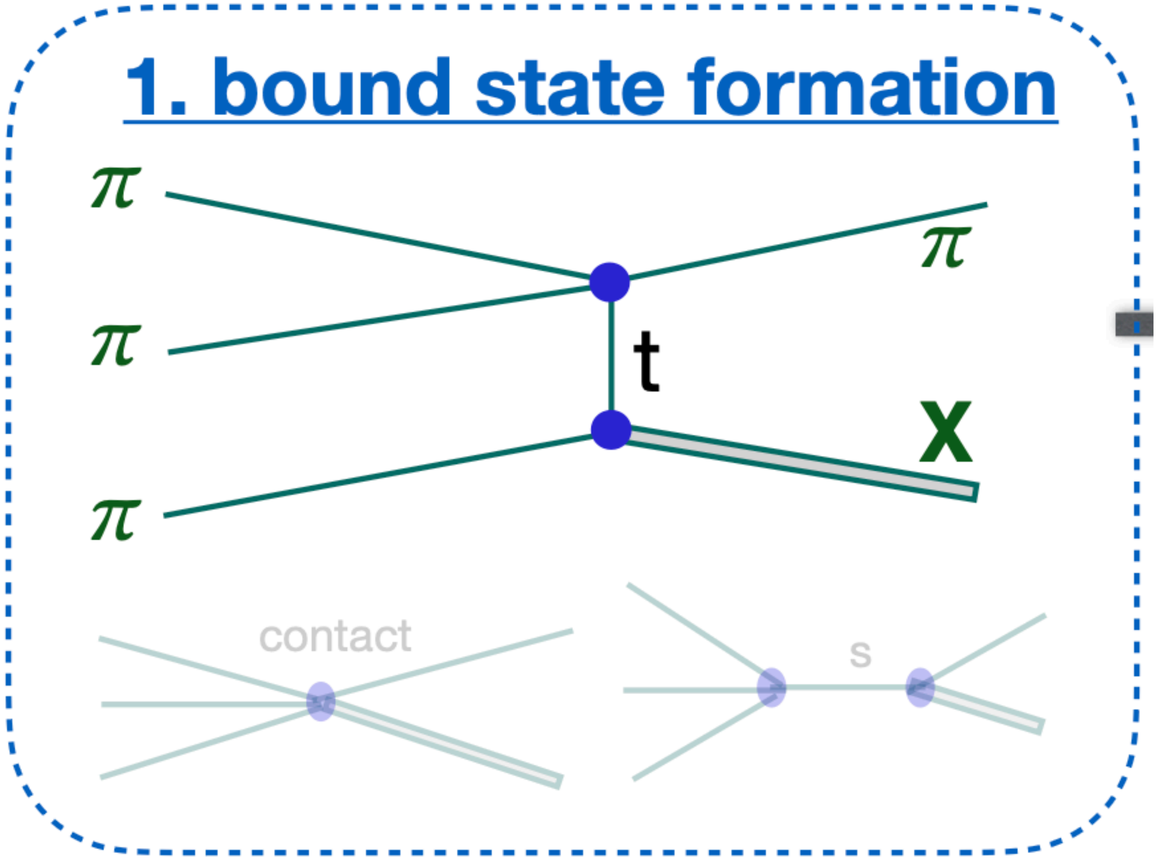


In the non-relativistic limit, one obtains a t-channel **resonance**:

$$\frac{s}{t - m_\pi^2} \propto \frac{m_\pi^2}{m_X^2 - 4m_\pi^2} \propto \frac{m_\pi}{E_B} \gg 1$$

radial wave function of X (s-wave)

$$\langle \sigma_{3\pi \to \pi X} v^2 \rangle \simeq \frac{57\,041}{1\,310\,720\sqrt{3}\pi^2} \frac{R_S^2(0)}{f_\pi^8} \left(\frac{m_\pi}{E_B} \right)^{3/2}$$

additional t-channel enhancement

CASE 1: even-numbered interactions only

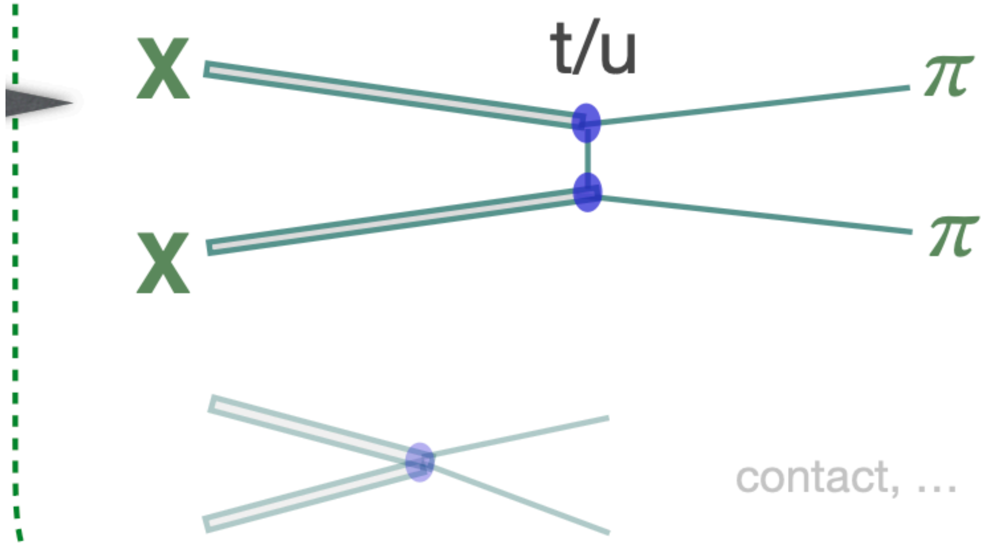
Mass-reduction rate

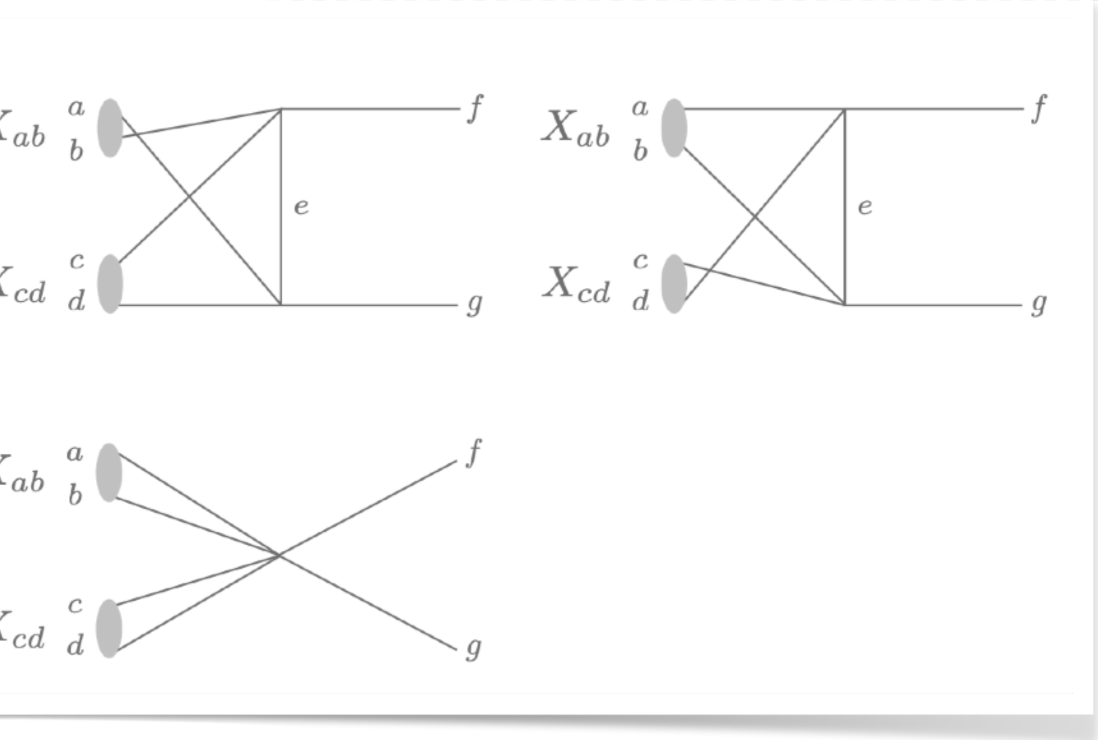
$$\Gamma_{XX\to\pi\pi} = \frac{n_{\rm X}^2 \, \langle\sigma_{XX\to\pi\pi}v\rangle}{n_\pi}$$

Cross section is s-wave

$$\langle\sigma_{XX\to\pi\pi}v\rangle \simeq \frac{2\,529\,757}{424\,673\,280\sqrt{3}\,\pi^3}\,\frac{R_S^4(0)}{f_\pi^8}$$

2. catalysed mass reduction





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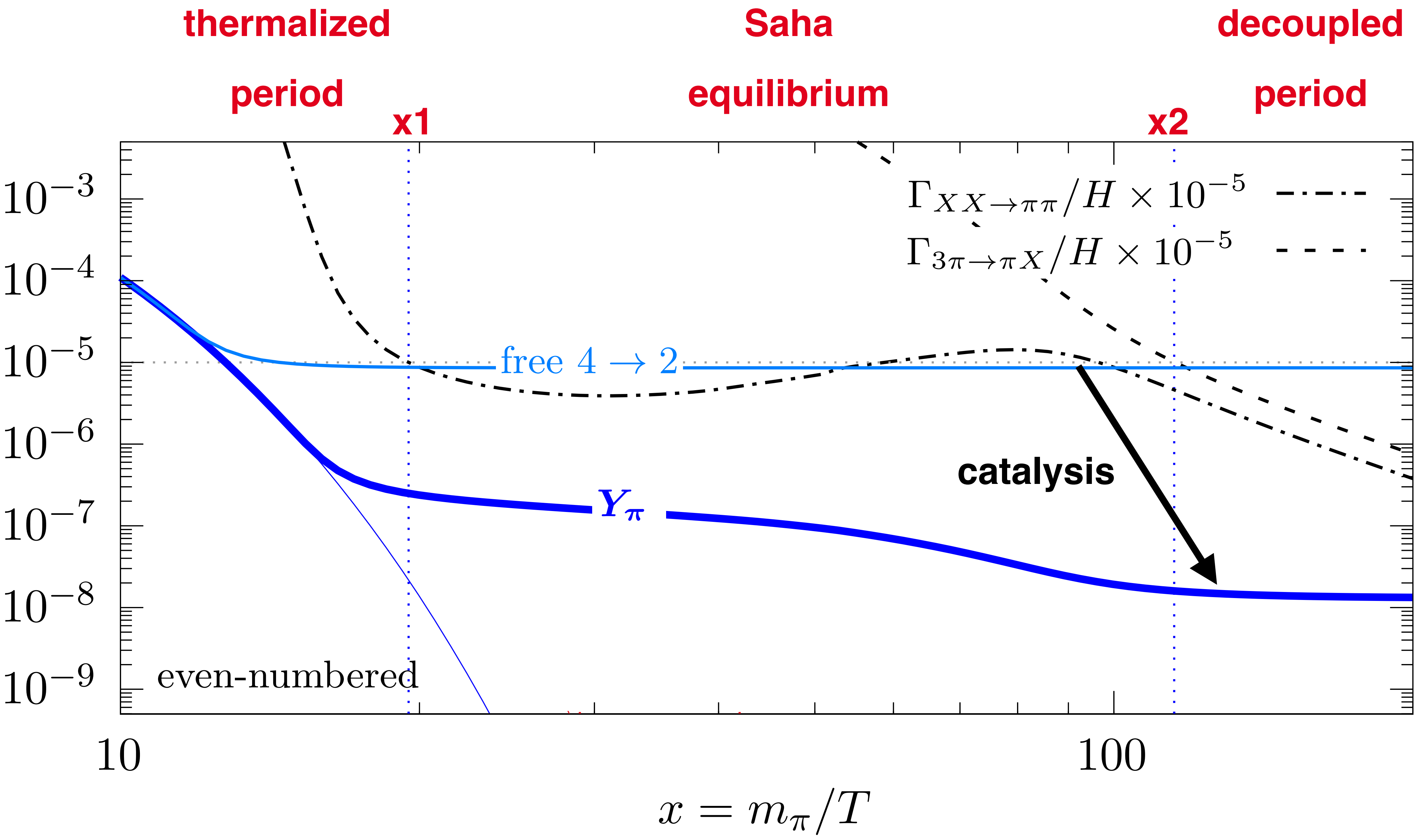
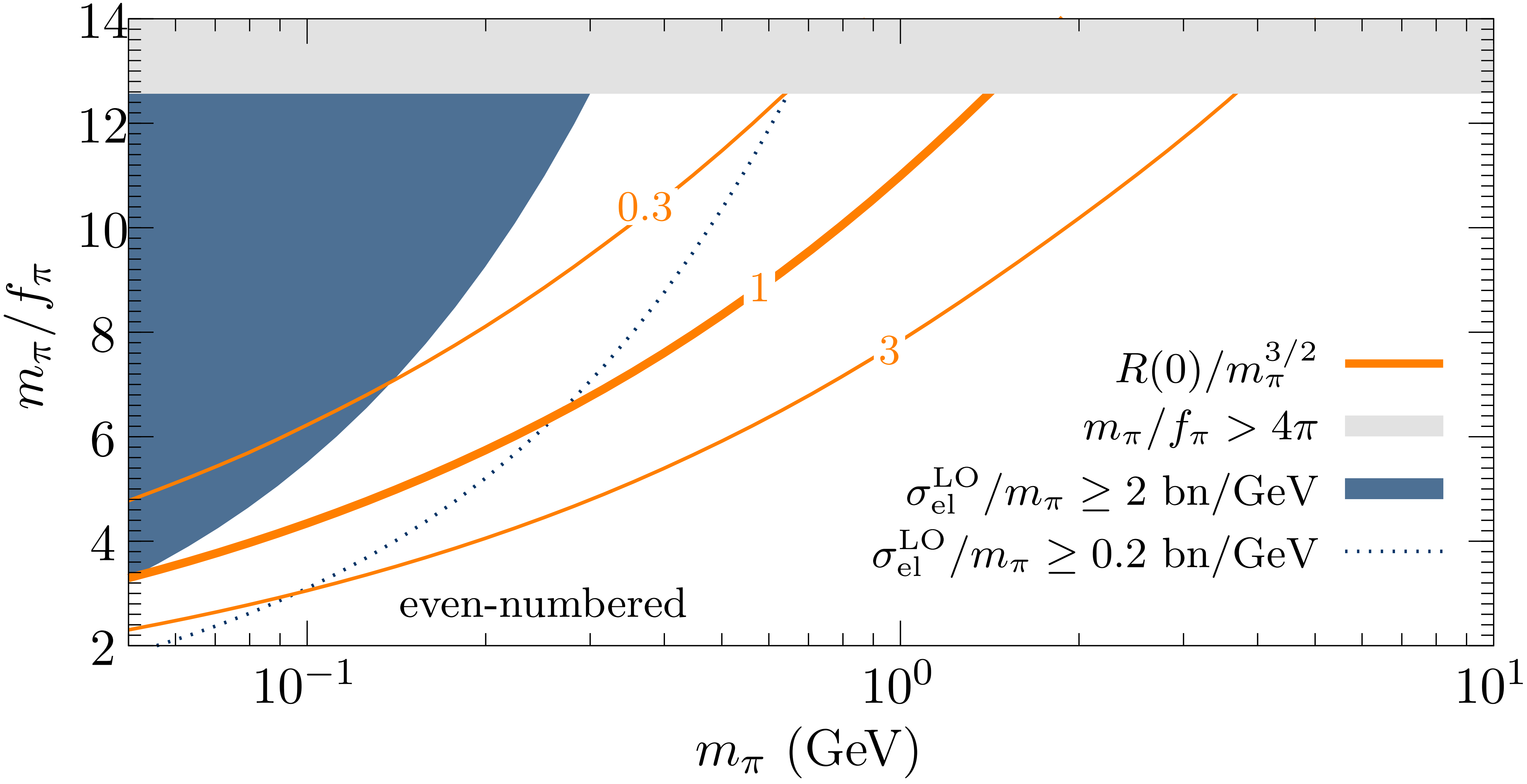


$$\Omega_\pi^{\mathrm{even}} \sim 0.2 \left(\frac{10^3}{\kappa^4 e^{\kappa x_2}} \frac{\mathrm{bn/GeV}}{\langle \sigma_{XX\to\pi\pi} v\rangle / m_\pi} \frac{m_\pi}{\mathrm{GeV}} \right)^{1/3}$$

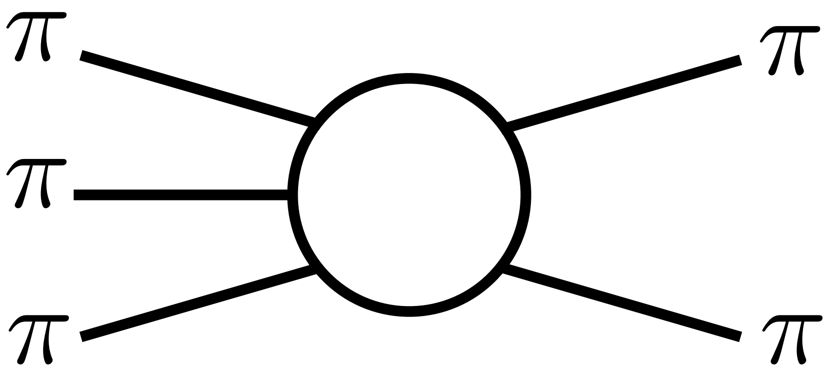
x2 - dependent!

Even SIMP miracles are possible!

coincidence of correct relic density + interesting self scattering ballpark



CASE 2: odd-numbered interactions



catalyzed
$3 \to 2$ annihilation

standard WZW annihilation **(d-wave)**

derivative of radial wave function of X **(p-wave)**

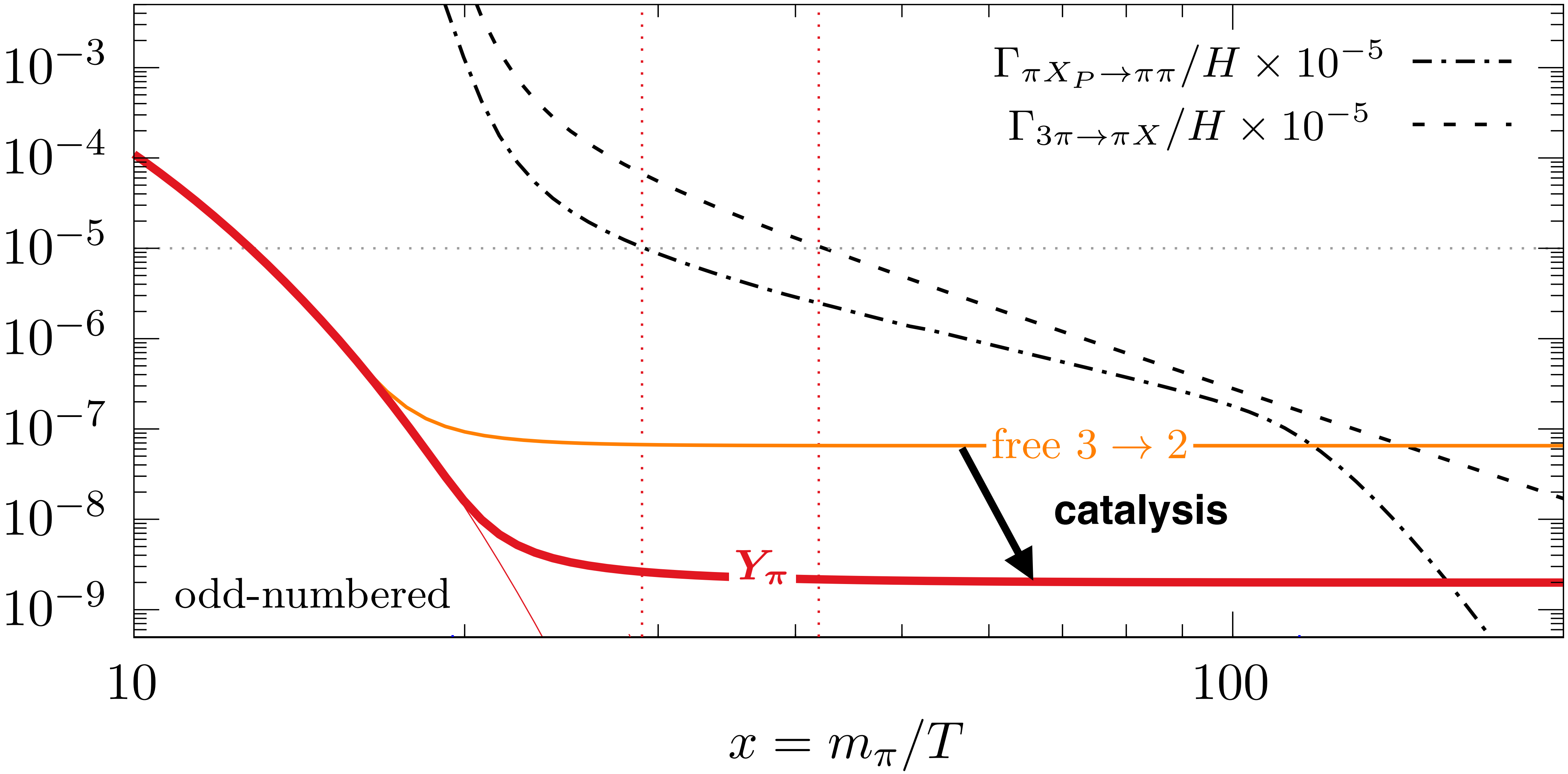
$$\left\langle \sigma_{3\pi\to 2\pi} v^2 \right\rangle = \frac{\sqrt{5} N_c^2 m_\pi^3 T^2}{12800 \pi^5 f_\pi^{10}}$$

$$\left\langle \sigma_{\pi X\to 2\pi} v \right\rangle = \frac{\sqrt{5} N_c^2 R'(0)^2 m_\pi^2}{512 \pi^6 f_\pi^{10}} T$$

p-wave X are available through collisional excitation

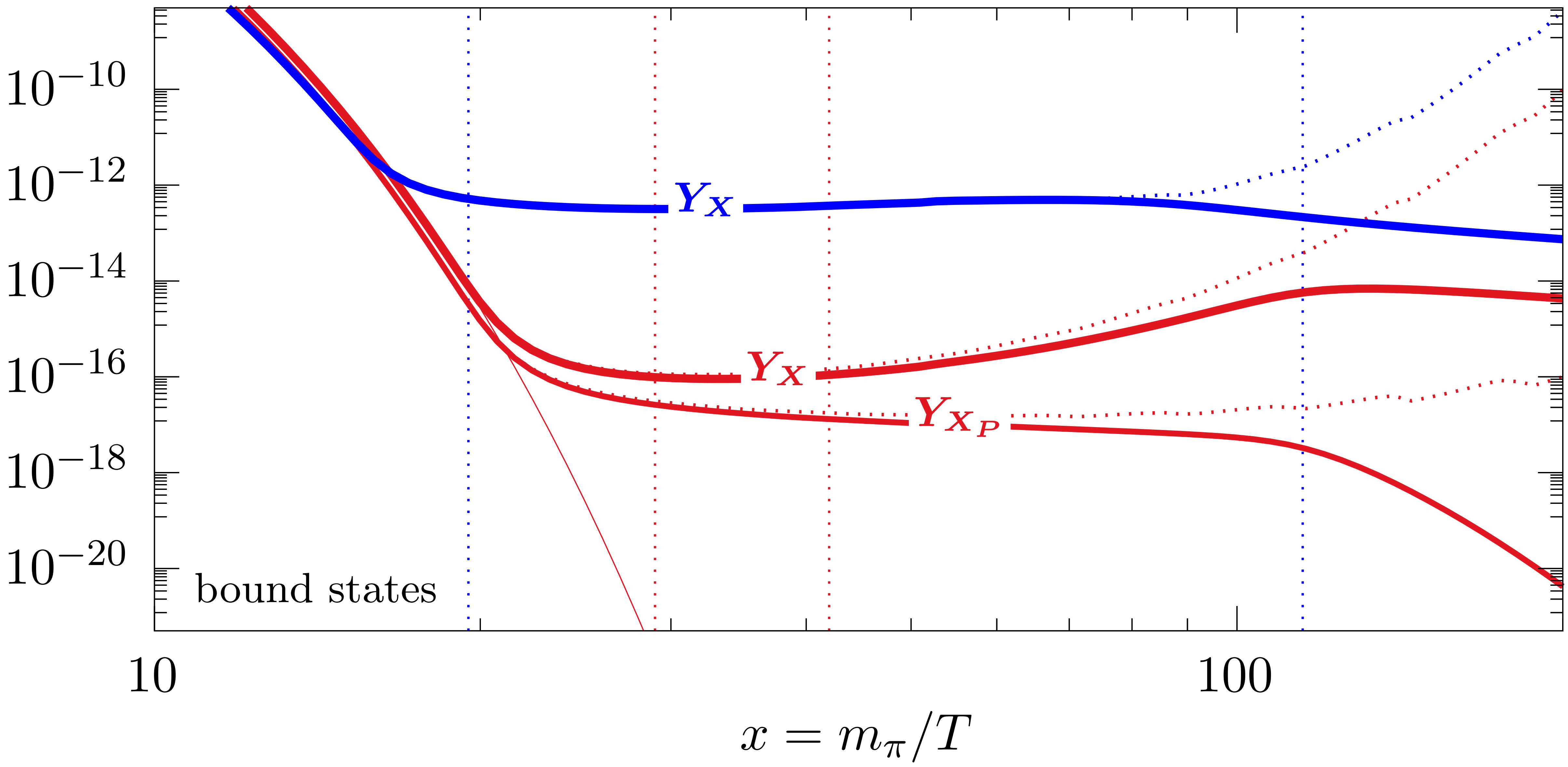
$$\frac{n_{X_P}}{n_{X_S}} = 3 e^{-|E_S - E_P| T / m_\pi}$$

CASE 2: odd-numbered interactions



$$\Omega_\pi^{\rm odd} \simeq 0.2 \left(\frac{x_1}{20}\right)^{5/4} \left(\frac{e^{-\kappa_P x_1}\, 10^{-3}\,{\rm bn/GeV}}{\langle \sigma_{\pi X_P \to \pi\pi} v\rangle / m_\pi}\right)^{1/2}$$

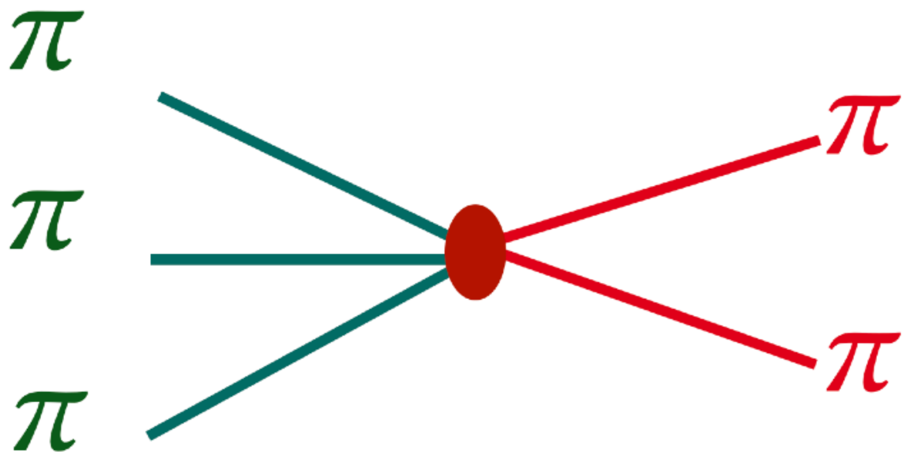
What bound states do?



two-body process remains efficient even after pions are frozen out

$$n_X \langle \sigma_{XX\to\pi\pi} v \rangle > H(x_2)$$

Coupling to Standard Model



SIMPs in isolation lead to
HOT dark matter (excluded)

SIMPs must come into kinetic equilibrium with the SM plasma (=share the same temperature)

$\pi\,\mathrm{SM}_i \to \pi\,\mathrm{SM}_i$ with $\Gamma_{\pi\,\mathrm{SM}} = \langle \sigma_{\pi\,\mathrm{SM}} c \rangle n_i > H$

=> typically enables $\pi\pi \to \mathrm{SM}_i\overline{\mathrm{SM}}_i$ but OK, because $n_i/n_\pi \gg 1$

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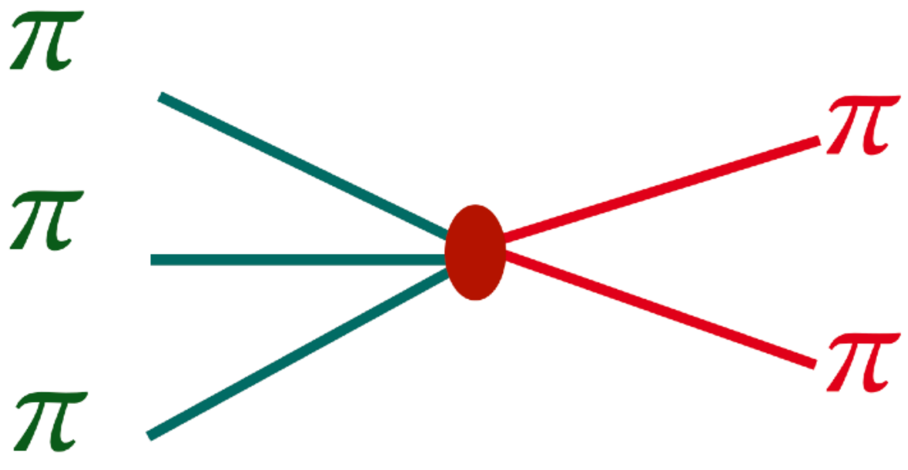

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HERE: destabilizes the bound state

$$X = [\pi\pi] \to \mathrm{SM}_i\overline{\mathrm{SM}}_i$$

Meta-stability of X

$$X = [\pi\pi] \to \mathrm{SM}_i\overline{\mathrm{SM}}_i$$

Noting that $|\psi(0)|^2 v$ has units of particle flux => $\Gamma_X \sim |\psi(0)|^2(\sigma_{\rm ann} v)$

$\Gamma_X/H < 1$ => $\sigma_{\rm ann} v \lesssim 10^{-3}\mathrm{pb}\; x^{-2} \left(\frac{m_\pi}{100\ \mathrm{MeV}}\right)^2 \frac{\mathrm{MeV}^3}{|\psi(0)|^2}$

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Taking $\sigma_{\pi\,\rm SM} c \sim \sigma_{\rm ann} v$, the stability requirement (X lives beyond freeze out) imposes upper limit on the elastic scattering rate that is needed to make Dark Matter “cold”.

$$1 \lesssim \frac{\Gamma_{\pi\,\rm SM}}{H} \lesssim \frac{10^6}{x^3}\left(\frac{m_\pi}{100\ \mathrm{MeV}}\right)^3 \frac{\mathrm{MeV}^3}{|\psi(0)|^2}$$

=> can easily be satisfied: retain kinetic equilibrium while maintaining sufficient longevity of X, paired with sub-Hubble two-body annihilation

=> no escalated model building requirements in comparison to original works on the SIMPs

=> previously explored phenomenology remains in place

X-catalyzed SIMP mechanism

When coupled to SM

additional X formation and breakup reactions may open

=> the detailed balancing condition

$$Y_X = \frac{Y_\pi^2 Y_X^{\rm eq}}{\left(Y_\pi^{\rm eq}\right)^2}$$

remains unaltered

=> If the new processes dominate over 3π ↔ πX, detailed balancing retains its validity longer

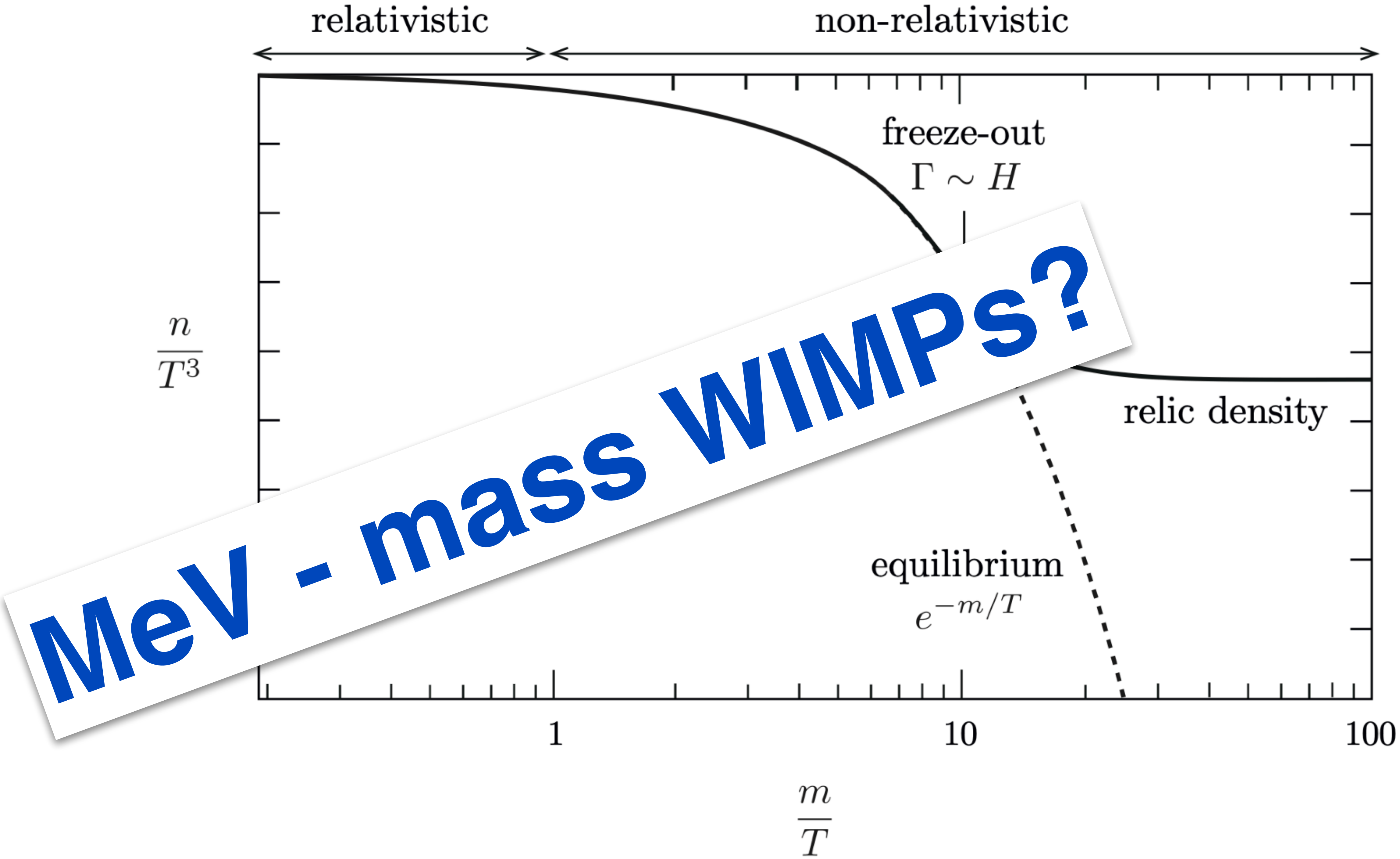
=> x2 will be larger, and **relic density smaller**

Introduction of **SM-interactions** harbor the potential to make **X-assisted freeze-out even more efficient**, without jeopardizing the overall picture!

2. WIMP dead end

Chu, Kuo, JP, PRD 2022
Chu, JP PRD 2024

What is the lightest thermal DM mass?



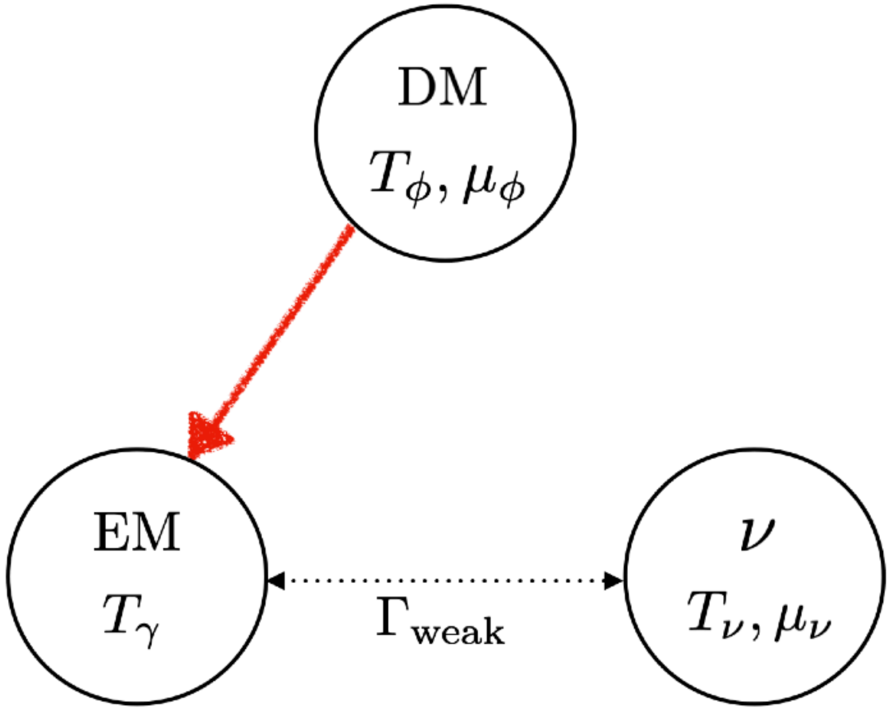
2. Thermal MeV DM

Chu, Kuo, JP, PRD 2022
Chu, JP PRD 2024

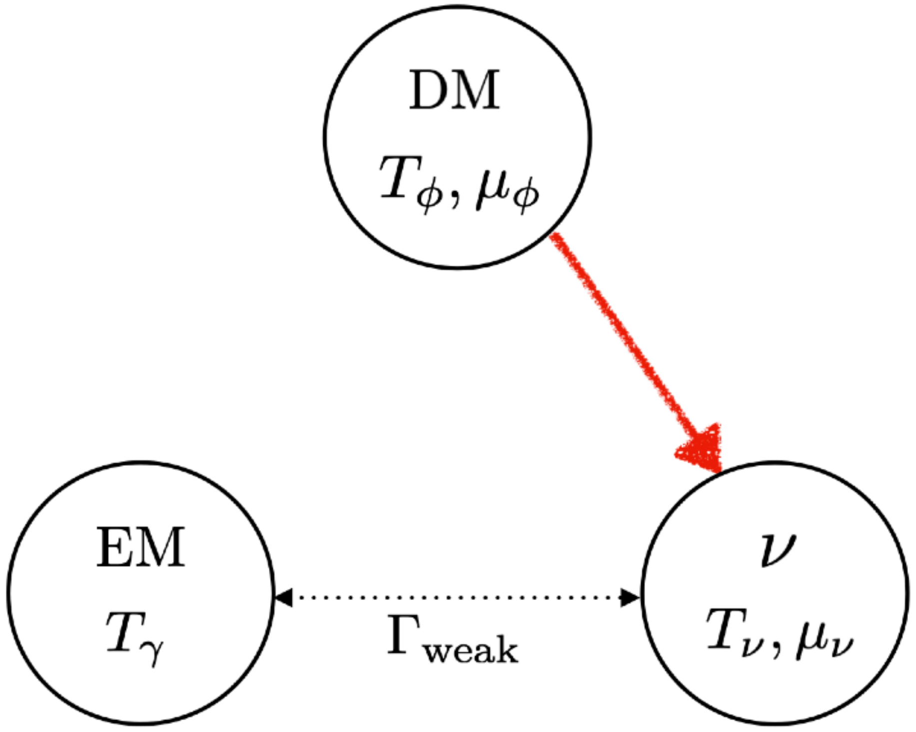
What is the lightest thermal DM mass?

Well known that MeV-DM subject to Neff bound from heating by annihilation

Previous treatments had to assume a branching either into EM-sector OR neutrinos:



OR



see e.g. [M. Escudero 2019, Depta et al. 2019, Sabti et al. 2020]

2. Thermal MeV DM

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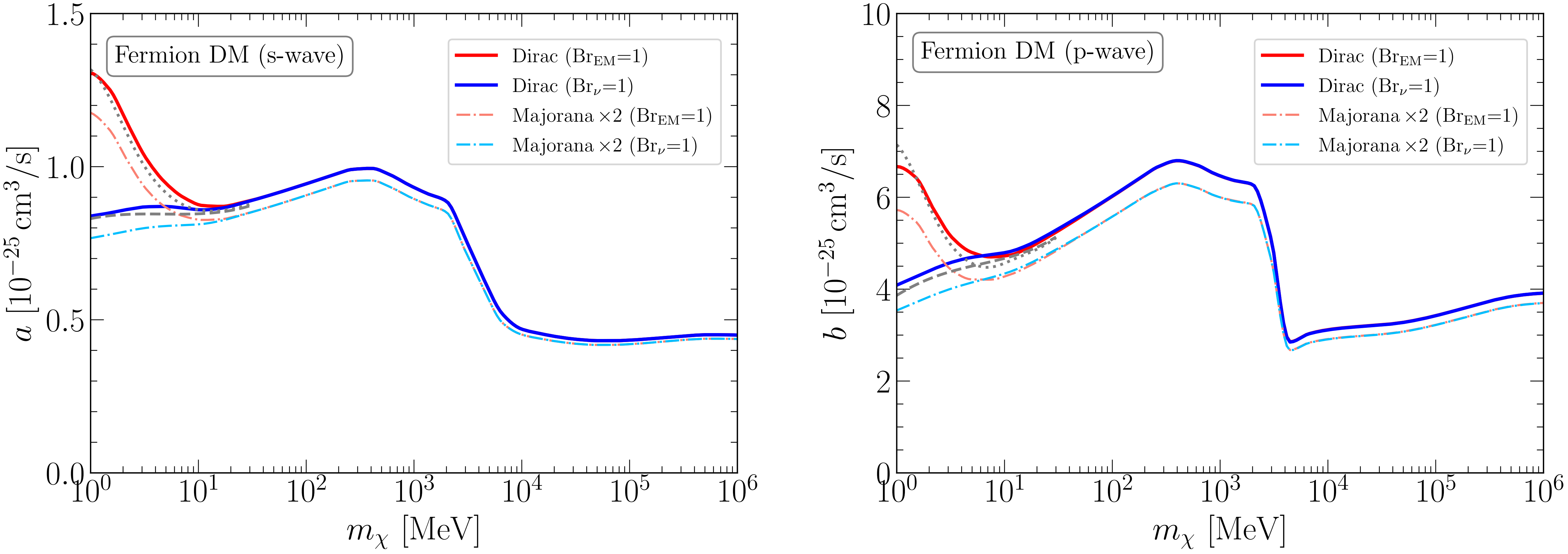

$$\langle \sigma_{\rm ann} v \rangle = a + b\,(6T/m_{\phi,\chi})$$

2. Thermal MeV DM

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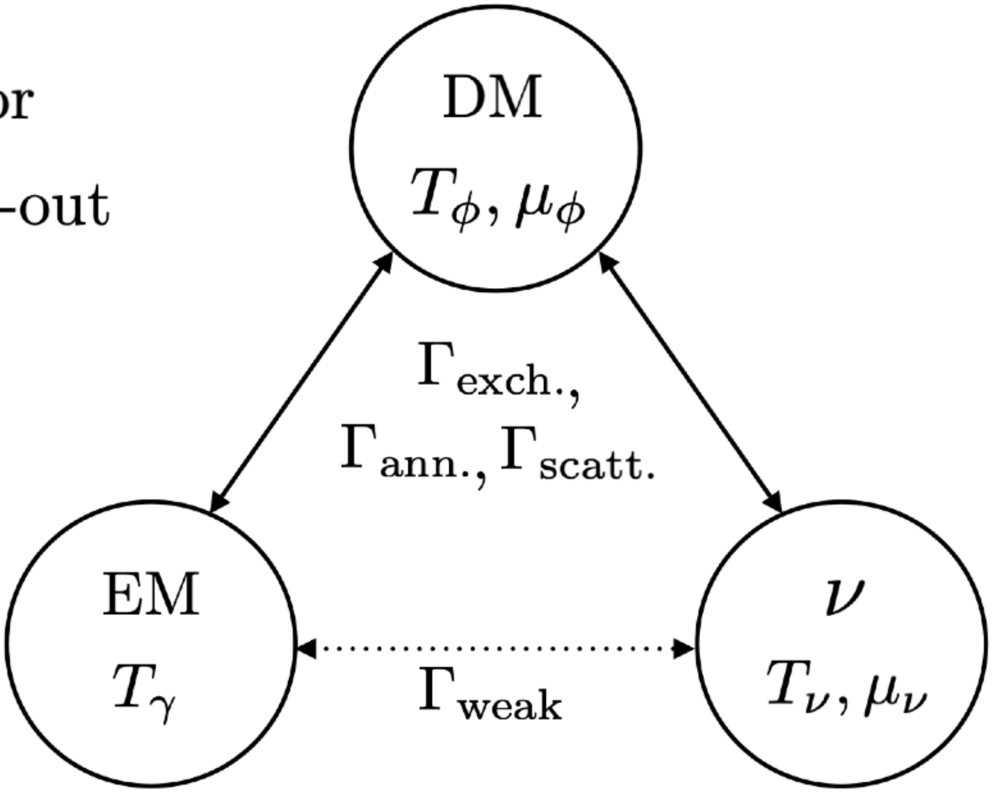
In the full picture, joint treatment of the three coupled sectors is necessary

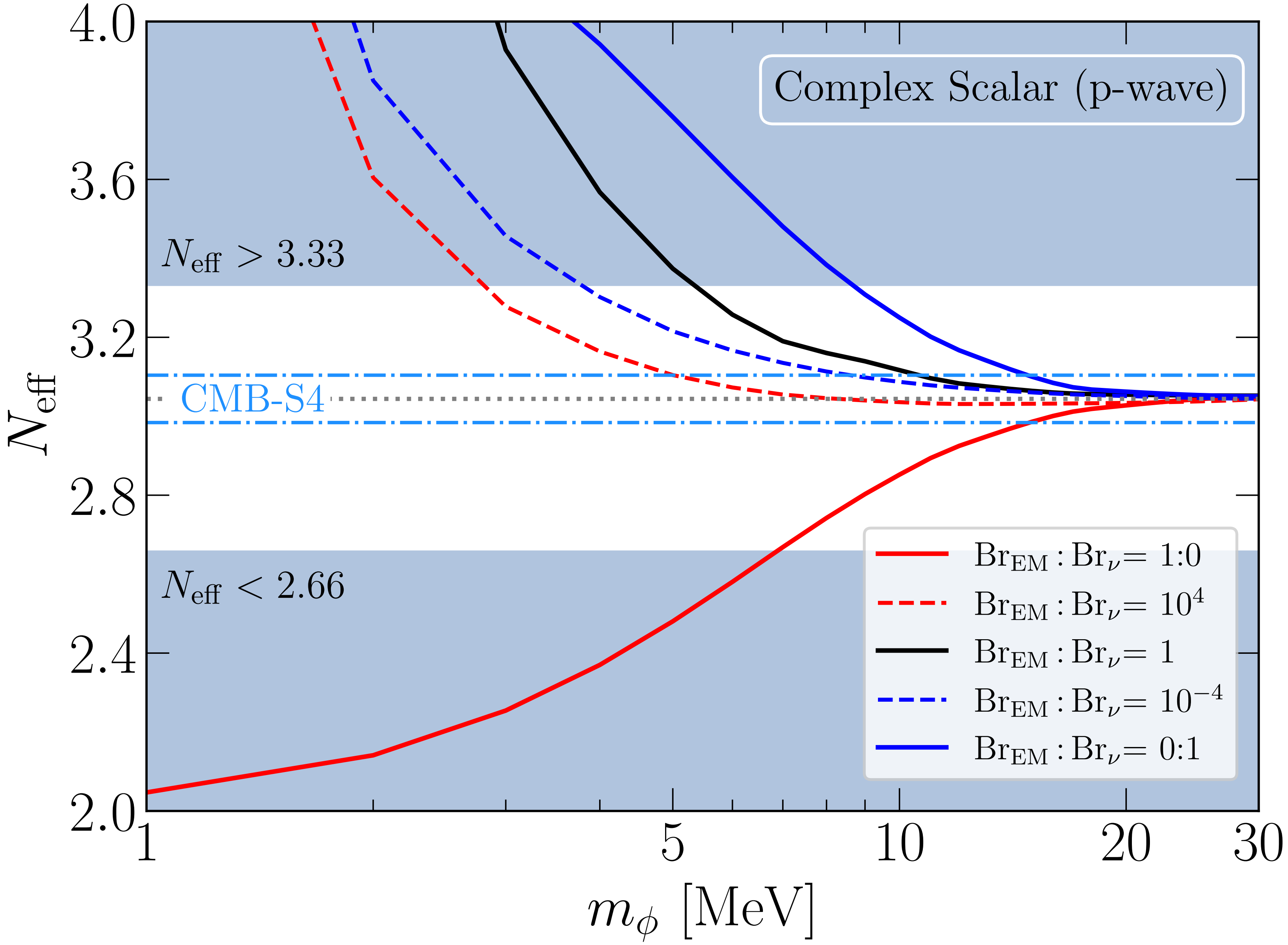
three-sector
DM freeze-out



$$\Gamma_{\rm weak} \equiv n_e G_F^2 T_\gamma^2 \, ,$$
$$\Gamma_{\rm ann.} \equiv n_\phi \langle \sigma_{\rm ann.} v \rangle \, ,$$
$$\Gamma_{{\rm exch.},i} \equiv n_\phi^2 \langle \sigma_{{\rm ann.},i} v \delta E \rangle / \rho_i \, ,$$
$$\Gamma_{{\rm scatt.},i} \equiv n_i \langle \sigma^{\phi i}_{\rm scatt.} v \rangle \, .$$

Light DM freeze out

What is the lightest thermal DM mass?

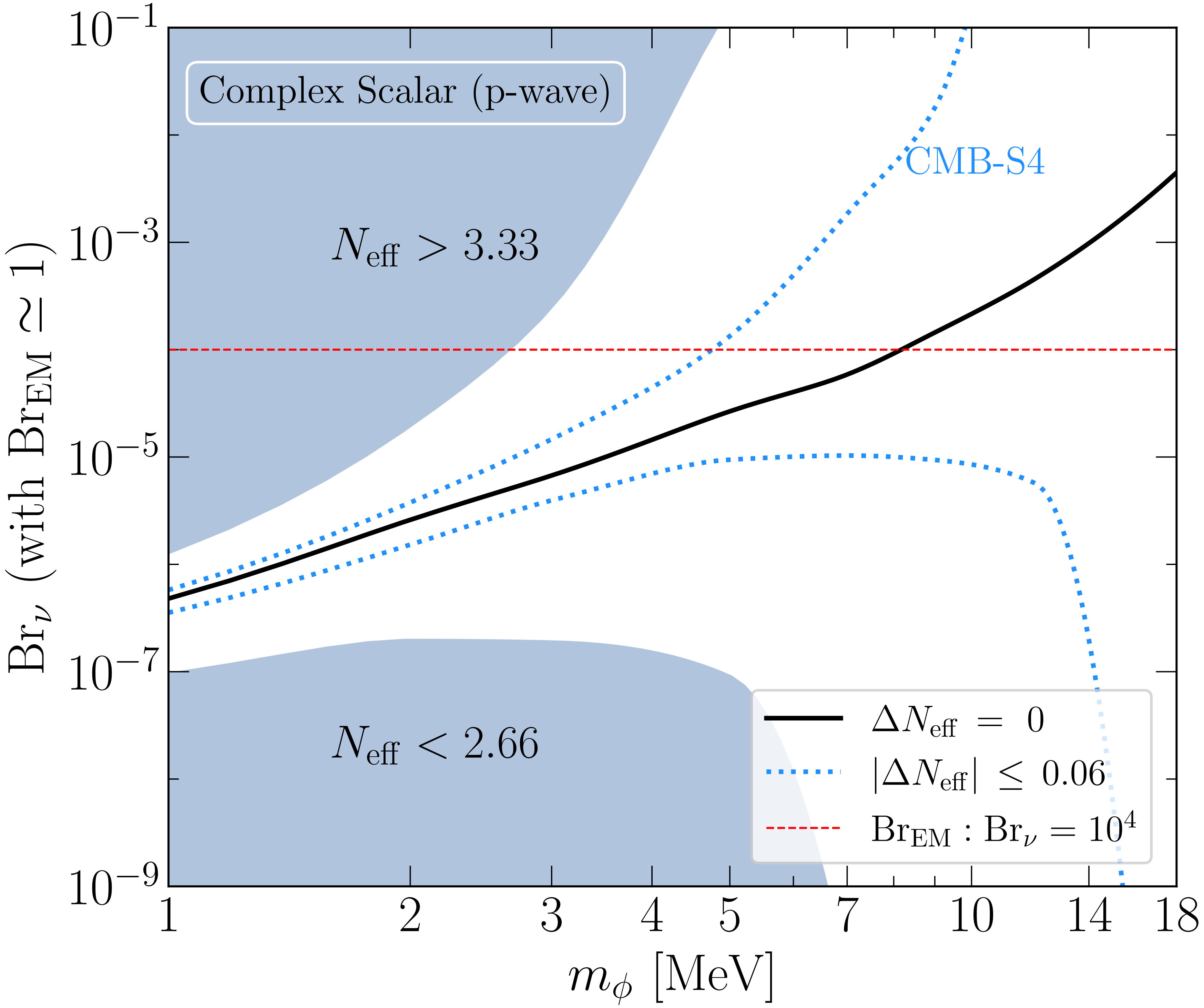


Example: p-wave annihilation

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Evading Neff bound

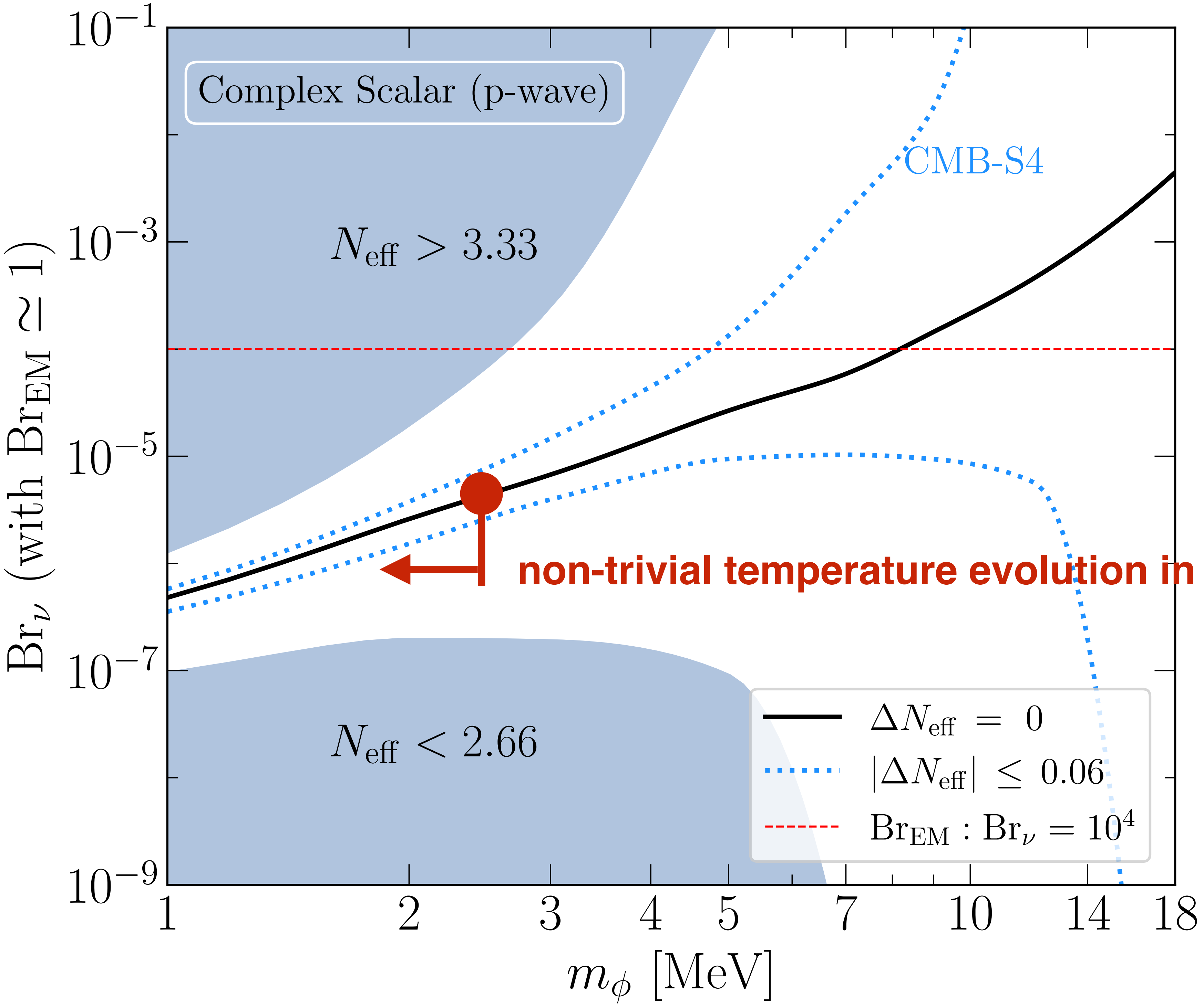
How low can you go?



Fine-tuned branching into neutrinos evades Neff constraint.

Evading Neff bound

How low can you go?



non-trivial temperature evolution in conflict with BBN

Fine-tuned branching into neutrinos evades Neff constraint.

Application:

thermal DM affecting 21cm cosmology with millicharged DM (=> see paper)

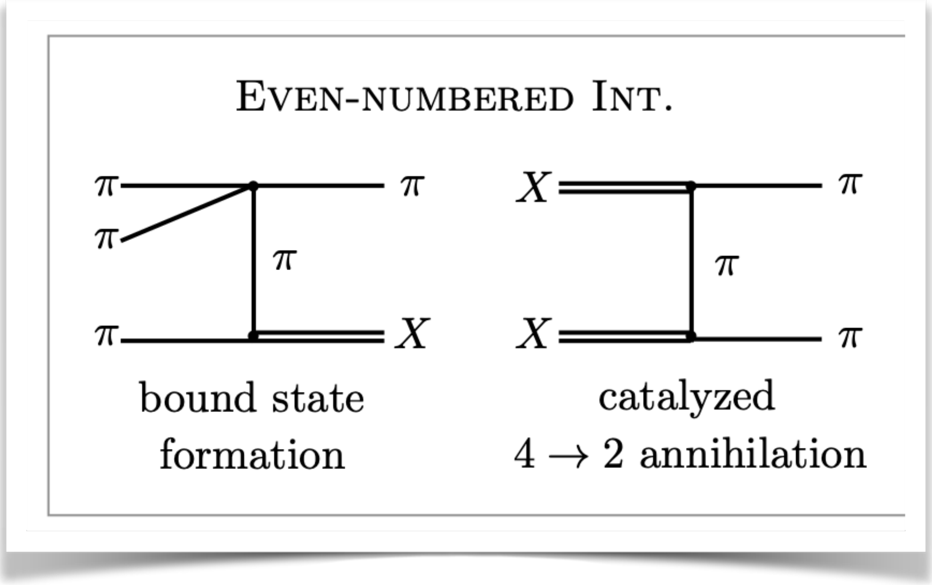
Summary

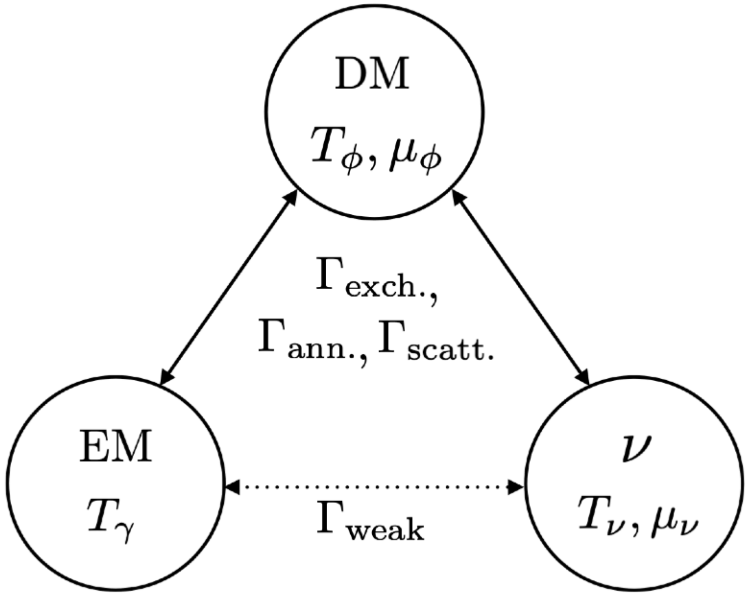
Freeze-out of MeV-mass DM candidates

- Small-scale structure problems pertinent to LCDM may be a hint for DM self-interactions, naturally realized in theories with strongly interacting particles (SIMPs)
- When SIMPs regulate their relic abundance in N->2 processes, bound states — should they exist — significantly alter the standard picture.
- Even-numbered SIMP-mechanism is possible

……………………

- A comprehensive assessment of thermal MeV-scale DM necessitates a three-sector treatment of vastly changing rates => systematic formulation
- nice application for DM affecting 21cm cosmology

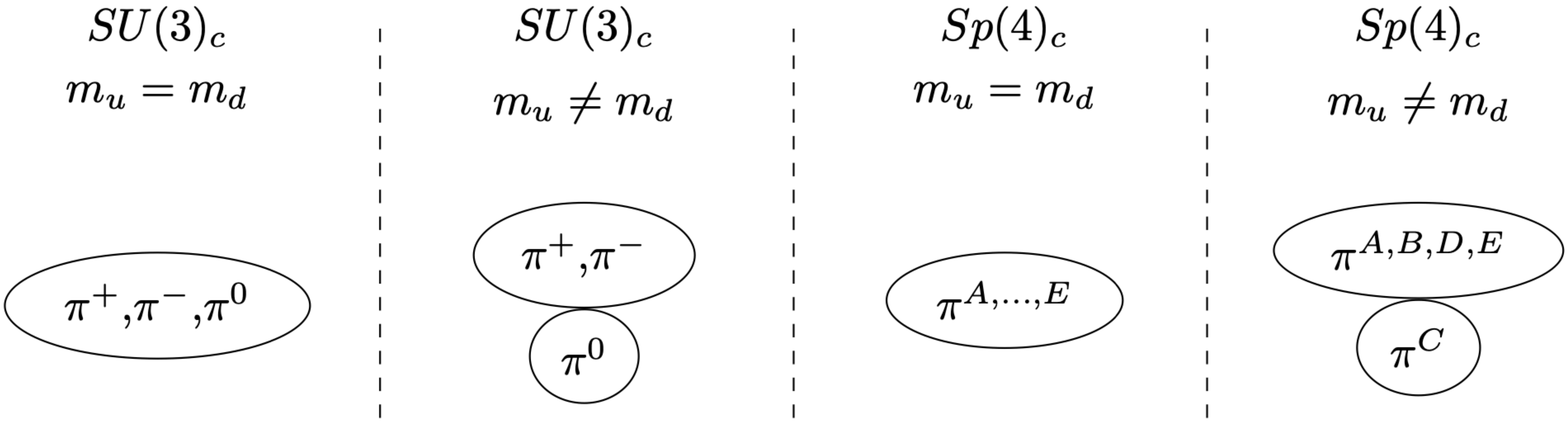




Thank you

Backup slides

Meson multiplet structure



$$\pi^D = \bar{d}\gamma_5 S C \bar{u}^T$$

$$\pi^E = d^T S C \gamma_5 u$$

$$\pi = \sum_{i=1,\ldots,5} \pi_a T^a = \sum_{N=A,\ldots,E} \pi_N T^N = \frac{1}{2}\begin{pmatrix} \pi^C & \pi^B & 0 & \pi^E \\ \pi^A & -\pi^C & -\pi^E & 0 \\ 0 & -\pi^D & \pi^C & \pi^A \\ \pi^D & 0 & \pi^B & -\pi^C \end{pmatrix}$$

=> 5 Goldstone bosons

Bound-state assisted freeze-out

Expectations/guesses for $|\psi(0)|^2$

In analogy to QED, one may posit a scale a_B “Bohr radius”

For perturbative couplings α $\quad a_B \sim 1/(\alpha\mu) = 2/(\alpha m_\pi) \geq 2/m_\pi$

Radial profiles (for n=1)

$$R_s(r) \simeq R_s(0)\, e^{-(r/2a_B)}, \qquad R_p(r) \simeq R'_p(0)\, r\, e^{-(r/2a_B)}\,,$$

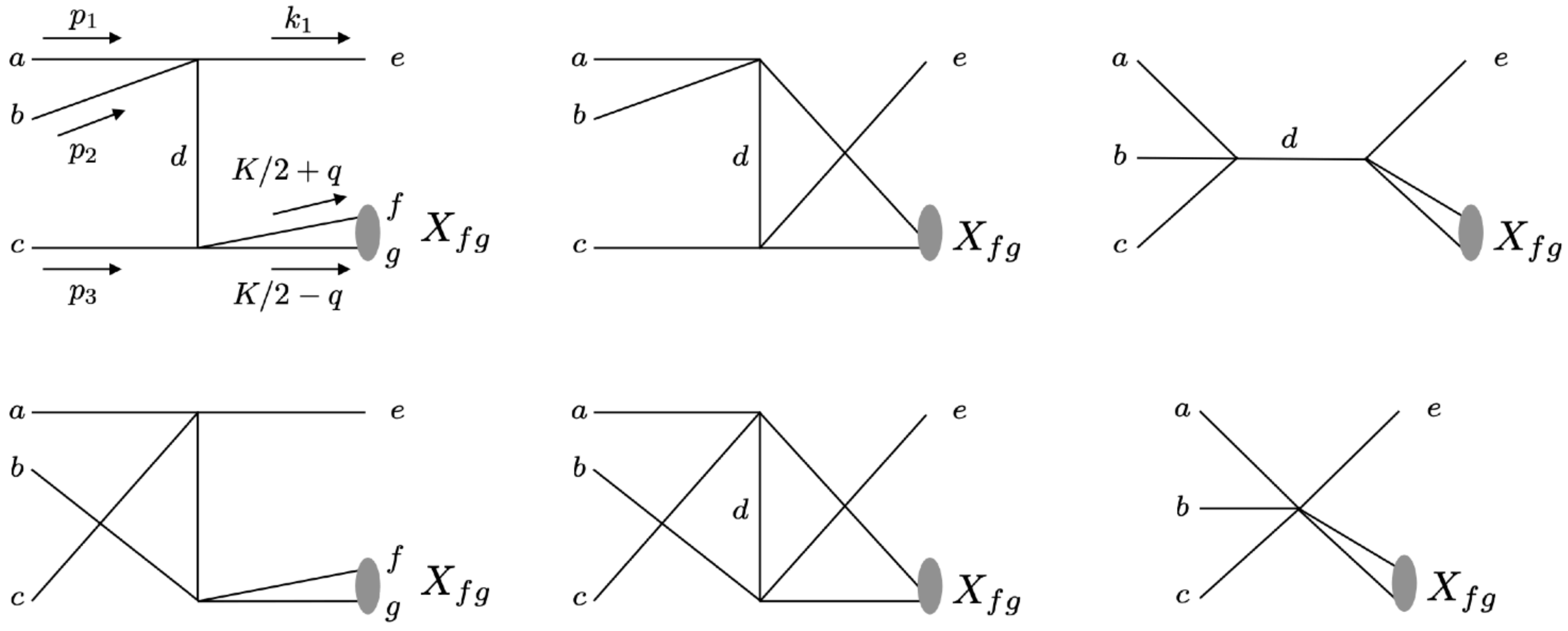
s-wave (l=0) p-wave (l=1)

$$R_s(0) = \frac{1}{\sqrt{2a_B^3}} \sim 0.25(\alpha m_\pi)^{3/2}, \quad R'_p(0) = \frac{1}{\sqrt{24a_B^5}} \sim 0.035(\alpha m_\pi)^{5/2}$$

=> $|\psi(0)|/m_\pi^{3/2} \sim 0.9\alpha^{3/2}$

Bound state formation

X-formation



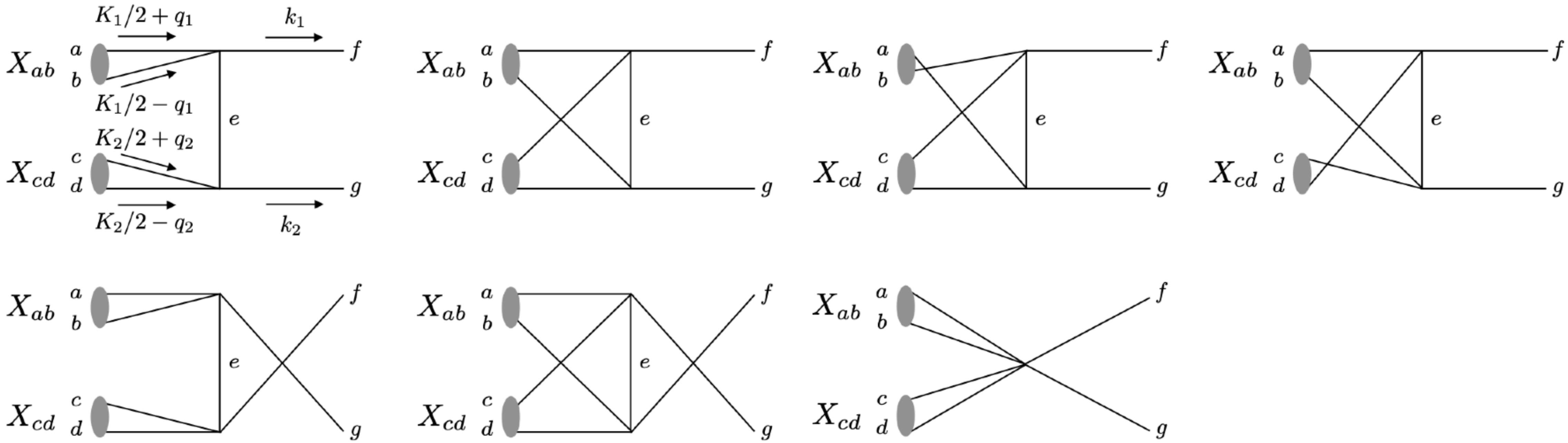
radial wave function of X (s-wave)

$$\langle \sigma_{3\pi\to\pi X} v^2 \rangle \simeq \frac{57\,041}{1\,310\,720\sqrt{3}\pi^2} \frac{R_S^2(0)}{f_\pi^8} \left(\frac{m_\pi}{E_B} \right)^{3/2}$$

additional t-channel enhancement

Bound state-assisted annihilation

XX annihilation



$$\langle \sigma_{XX\to\pi\pi} v \rangle \simeq \frac{2\,529\,757}{424\,673\,280\sqrt{3}\,\pi^3}\frac{R_S^4(0)}{f_\pi^8}$$

catalyzed 3->2

derivative of X wavefunction in p-state!

$$\langle \sigma_{\pi X\to\pi\pi} v \rangle \simeq \frac{\sqrt{5}N_c^2 m_\pi^3}{512\pi^6 f_\pi^{10} x} R_P'^2(0)$$

2. Thermal MeV DM

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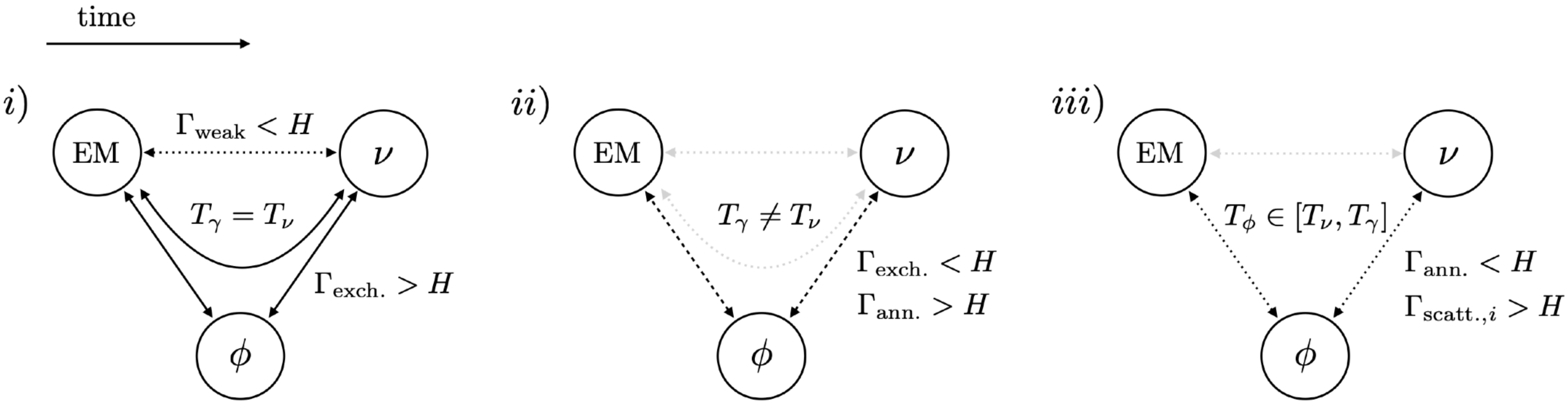


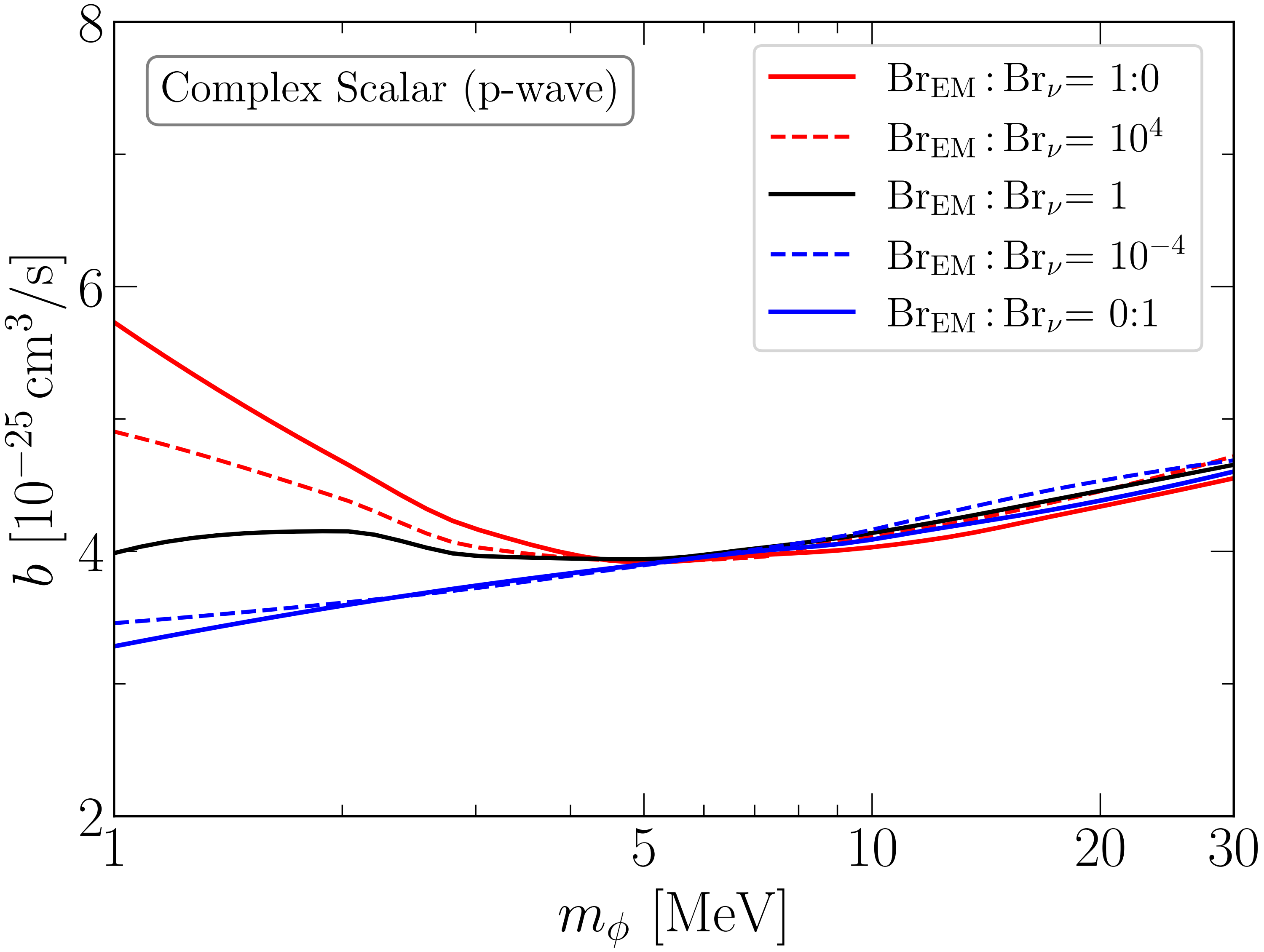
all sectors thermalized

neutrino-electron decoupling

ϕ freeze-out

Light DM freeze out

Thermal cross section



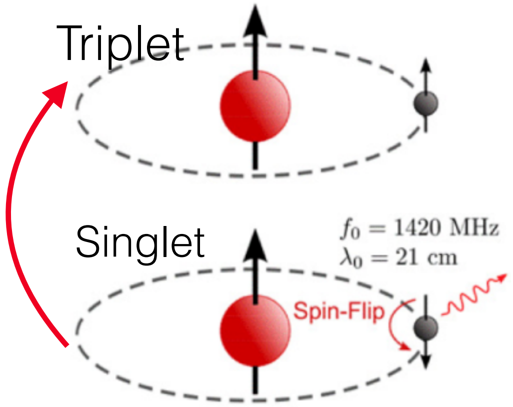
Example: p-wave annihilation

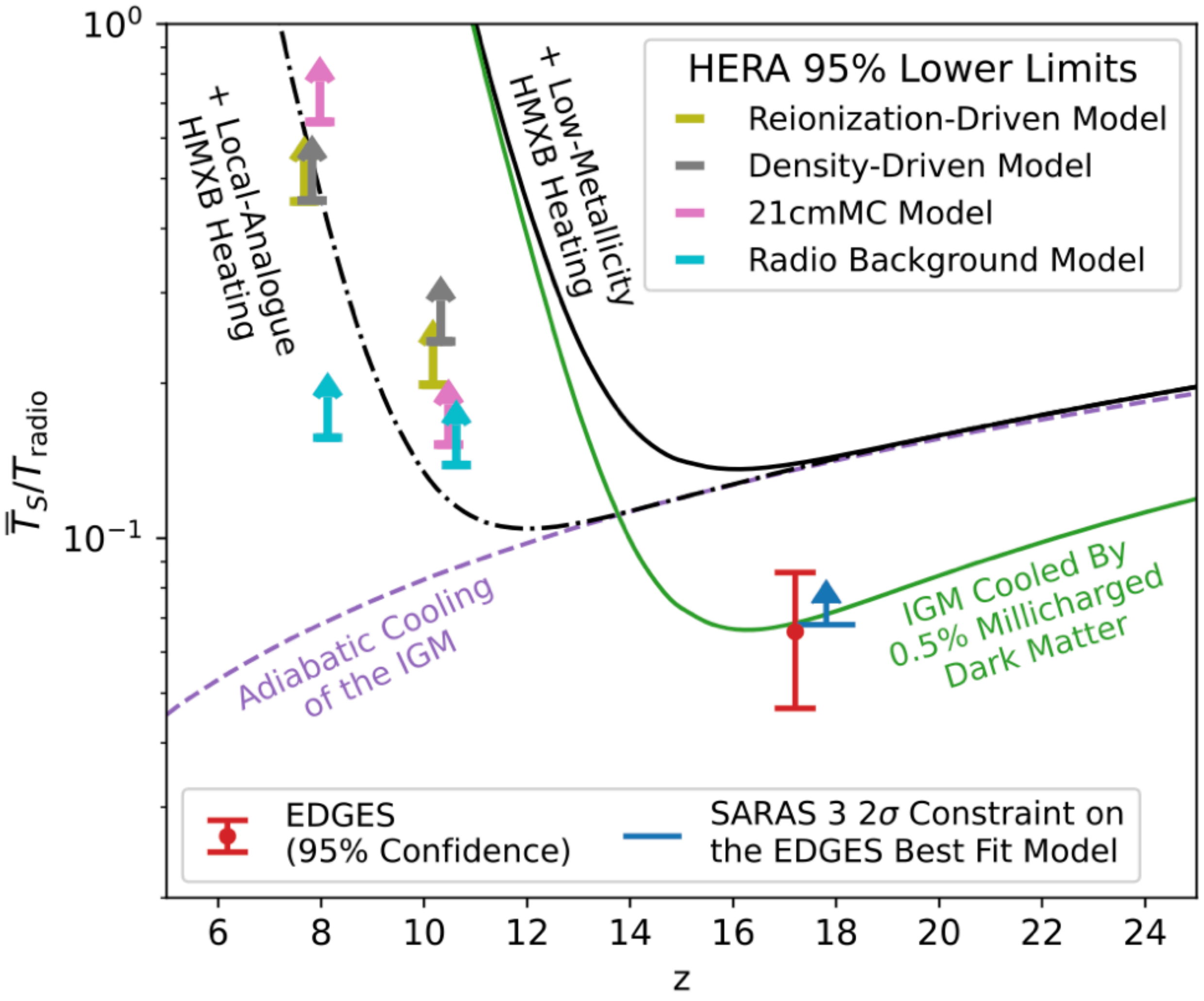
$$\mathcal{L}^{\rm int}_{Z'} = g_\phi^2 Z'^\mu Z'_\mu \phi^* \phi - i g_\phi Z'^\mu (\phi^* \overset{\leftrightarrow}{\partial}_\mu \phi) - g_l Z'^\mu \bar{l} \gamma_\mu l \,.$$

see these morning's talks

21cm application

Weaker mass bounds from Neff can be useful:





[HERA 2210.04912]

21cm sensitivity to baryon cooled down from scattering off MeV dark matter after CMB

=> use 1/velocity^4 enhancement of Rutherford-type scattering of baryons on DM

Models of milli-charged sub-% dark matter can do this but:

- **no valid thermal freeze-out;**
- **strong bounds from CMB/BBN;**

[e.g. Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski 1807.11482]

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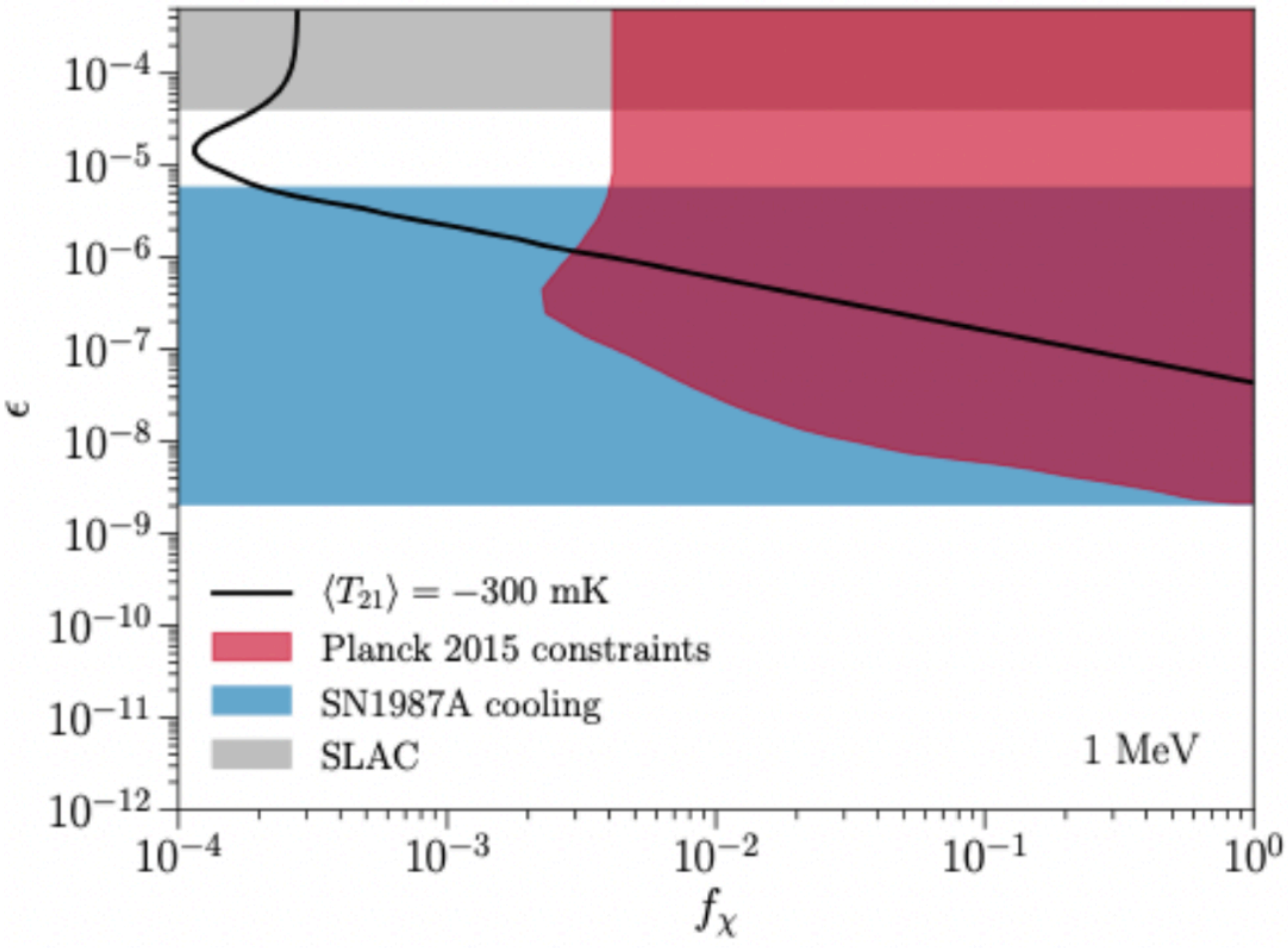

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21cm application

Provide a valid model: **add neutrino annihilation**

$$i\epsilon e\gamma^{\mu} J_{\chi} + i y_A A(\bar{\chi}\gamma_5\chi) + i y_{\nu} A(\bar{\nu}_l\gamma_5\nu_l)$$

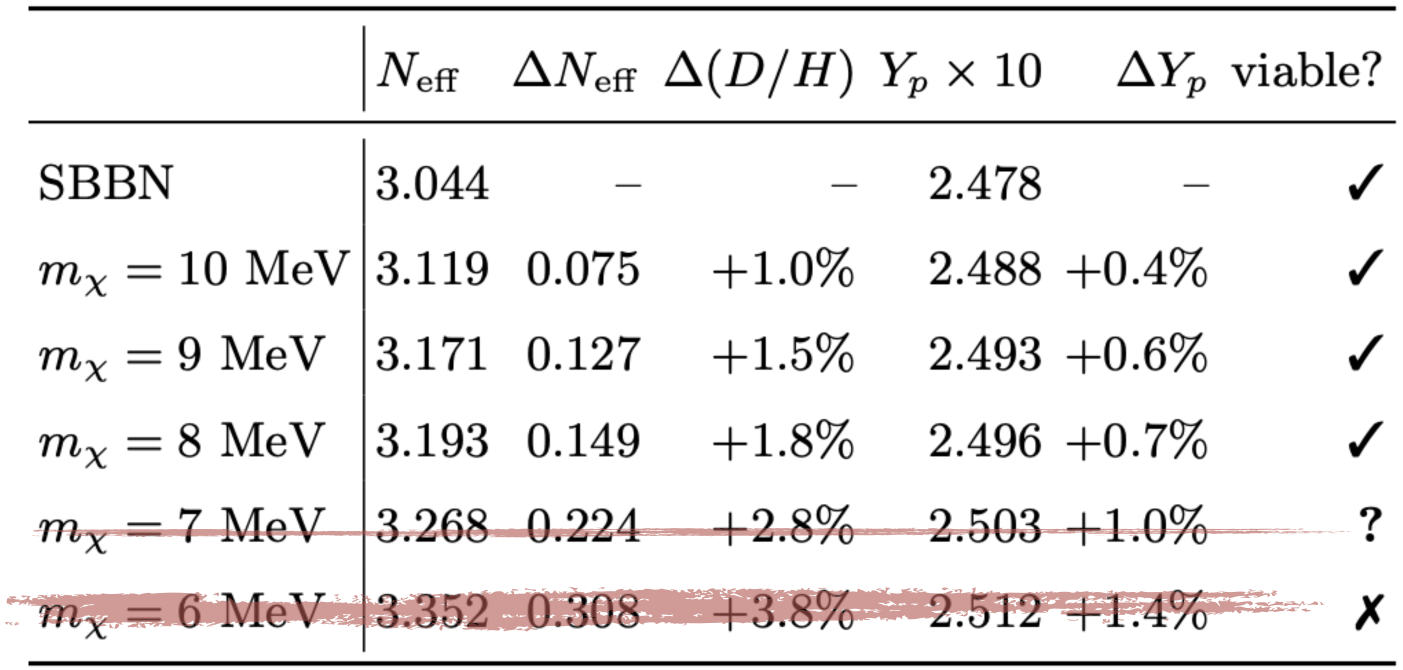
millicharge

(effective) neutrino interactions

annihilation

$\mathrm{Br}_{\mathrm{EM}} : \mathrm{Br}_{\nu} \sim 10^{-2}$

=> dominant annihilation into neutrinos, makes thermal sub-% dark matter component



	$N_{\rm eff}$	$\Delta N_{\rm eff}$	$\Delta(D/H)$	$Y_p \times 10$	ΔY_p	viable?
SBBN	3.044	–	–	2.478	–	✓
$m_\chi = 10$ MeV	3.119	0.075	+1.0%	2.488	+0.4%	✓
$m_\chi = 9$ MeV	3.171	0.127	+1.5%	2.493	+0.6%	✓
$m_\chi = 8$ MeV	3.193	0.149	+1.8%	2.496	+0.7%	✓
~~$m_\chi = 7$ MeV~~	~~3.268~~	~~0.224~~	~~+2.8%~~	~~2.503~~	~~+1.0%~~	?
~~$m_\chi = 6$ MeV~~	~~3.352~~	~~0.308~~	~~+3.8%~~	~~2.512~~	~~+1.4%~~	✗

=> working model affecting 21cm passing all constraints

(incl. ν mfp, ν self-interactions, constraints on mediator from flavor physics,…)