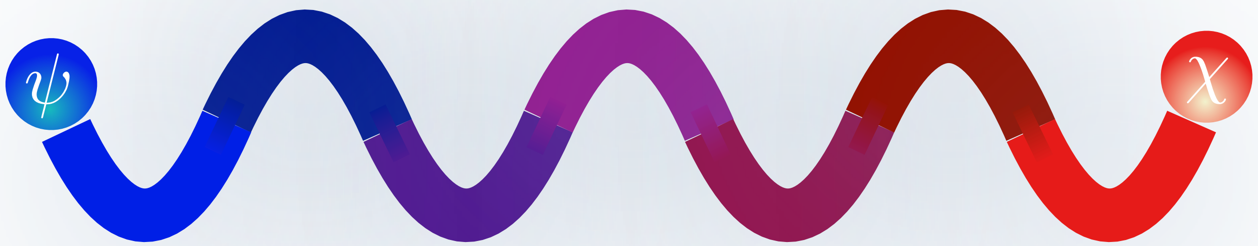
ROMP Dark Matter

Rapidly **O**scillating **M**assive **P**article

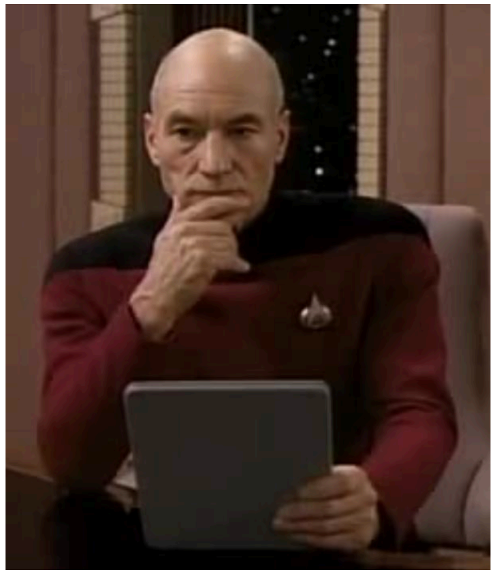


work in progress with:
David Dunsky and Saniya Heeba

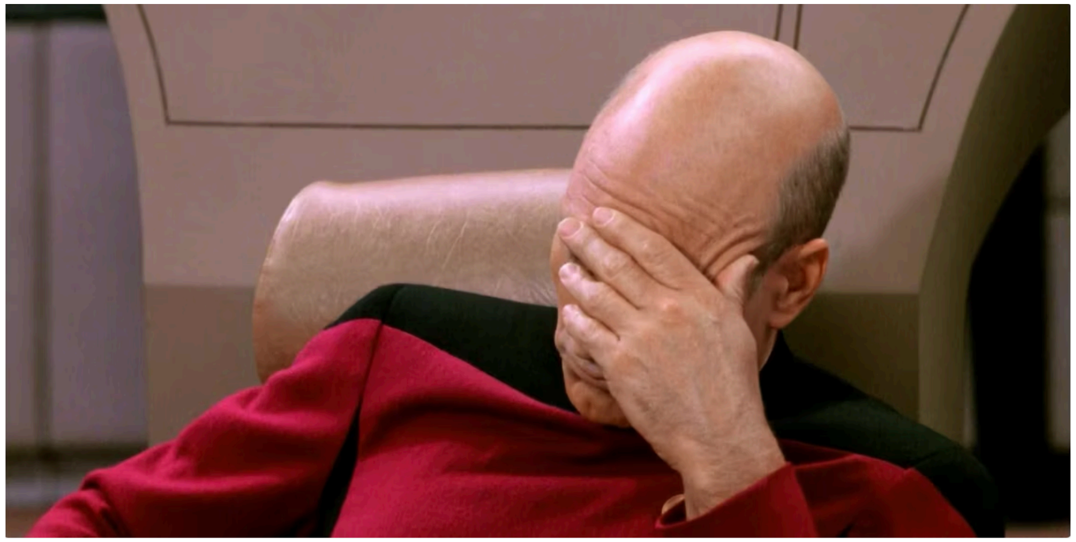
Josh Ruderman (NYU)
@PLANCK2024, 6/6

How was dark matter produced?

When was dark matter produced?

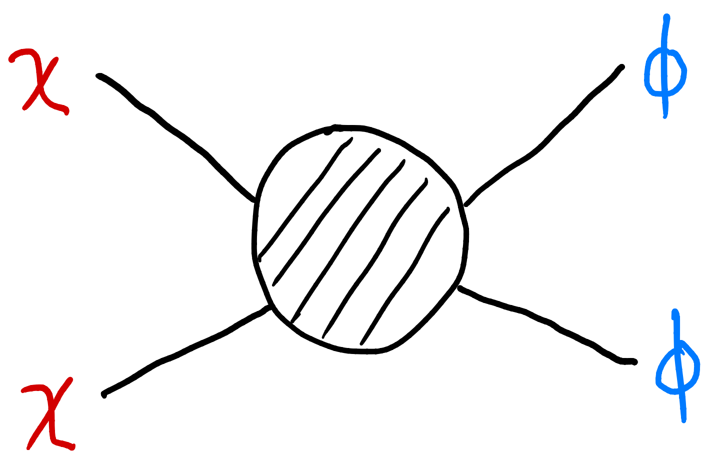


How can we test it?

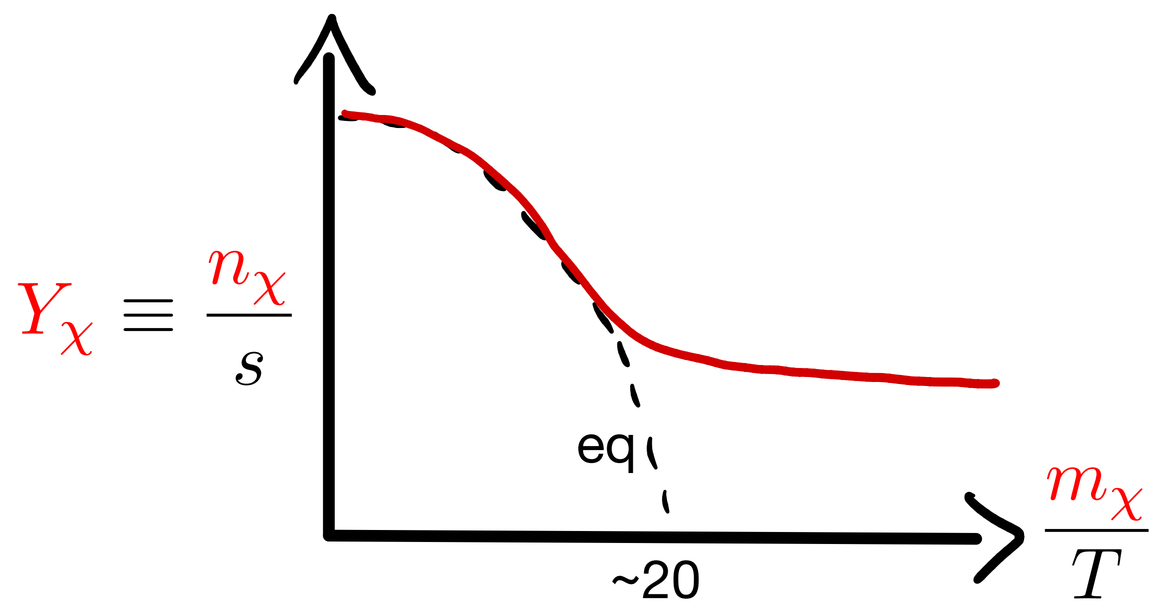


Freeze-Out vs. Freeze-In

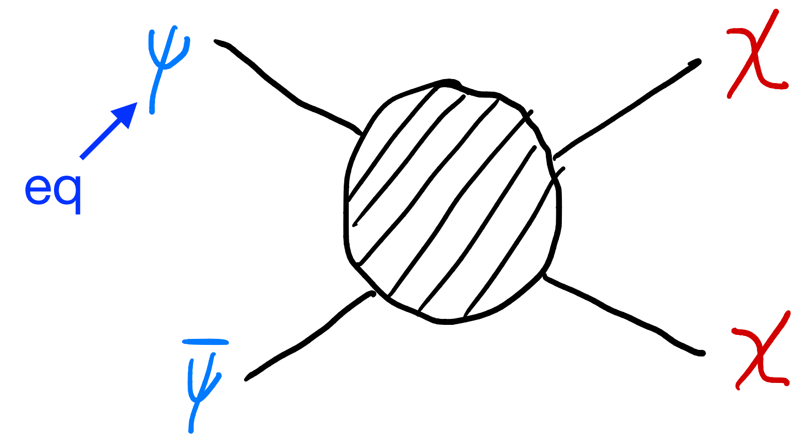
FO



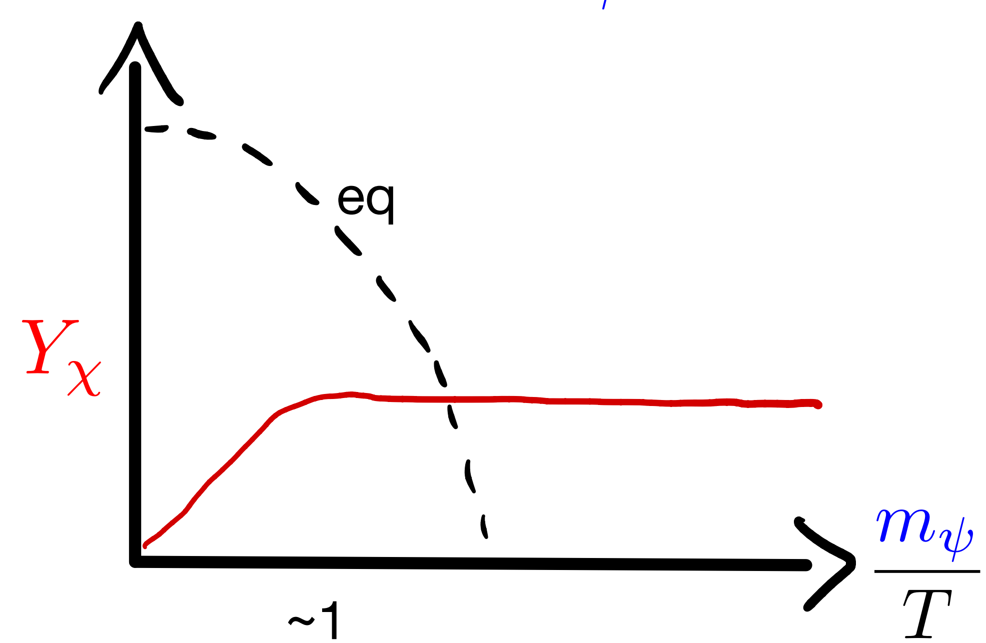
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - (n_\chi^{\rm eq})^2\right)$$



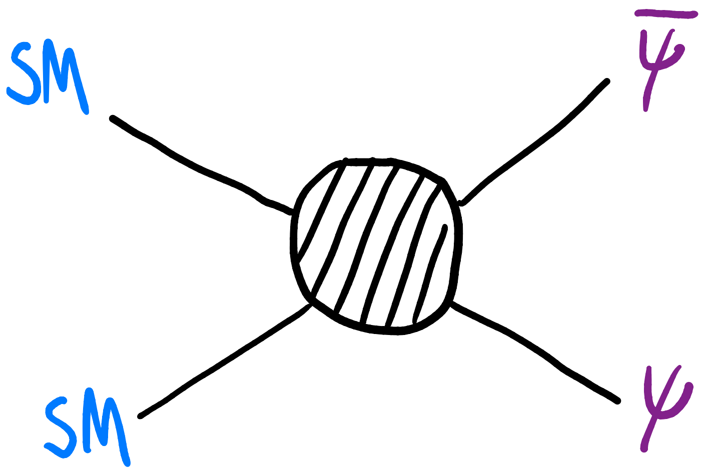
FI



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



Scattering on the Back of an Envelope



- operator dimension: $[\mathcal{O}] = d$

- thermally averaged cross-section: $\langle \sigma v \rangle \sim \dfrac{T^{2(d-4)-2}}{\Lambda^{2(d-4)}}$

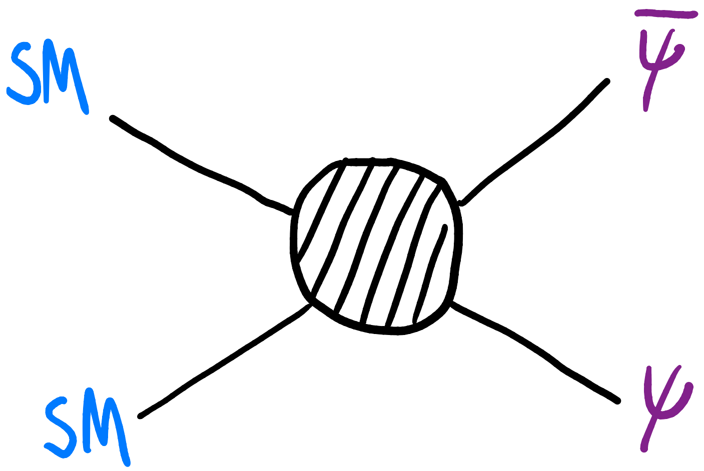
- scattering rate: $\Gamma = n_{\rm SM} \langle \sigma v \rangle \sim \dfrac{T^{(d-4)+1}}{\Lambda^{2(d-4)}}$

  $n_{\rm SM} \sim T^3$

- scattering per Hubble time: $\dfrac{\Gamma}{H} \sim \dfrac{M_{pl}}{\Lambda^{2(d-4)}} T^{2(d-4)-1}$

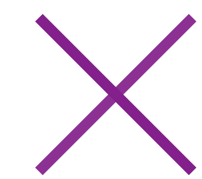
  $H \sim \dfrac{T^2}{M_{pl}}$

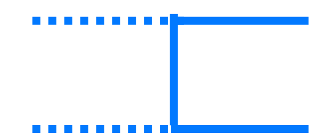
UV vs. IR Production



$[\mathcal{O}] = d$

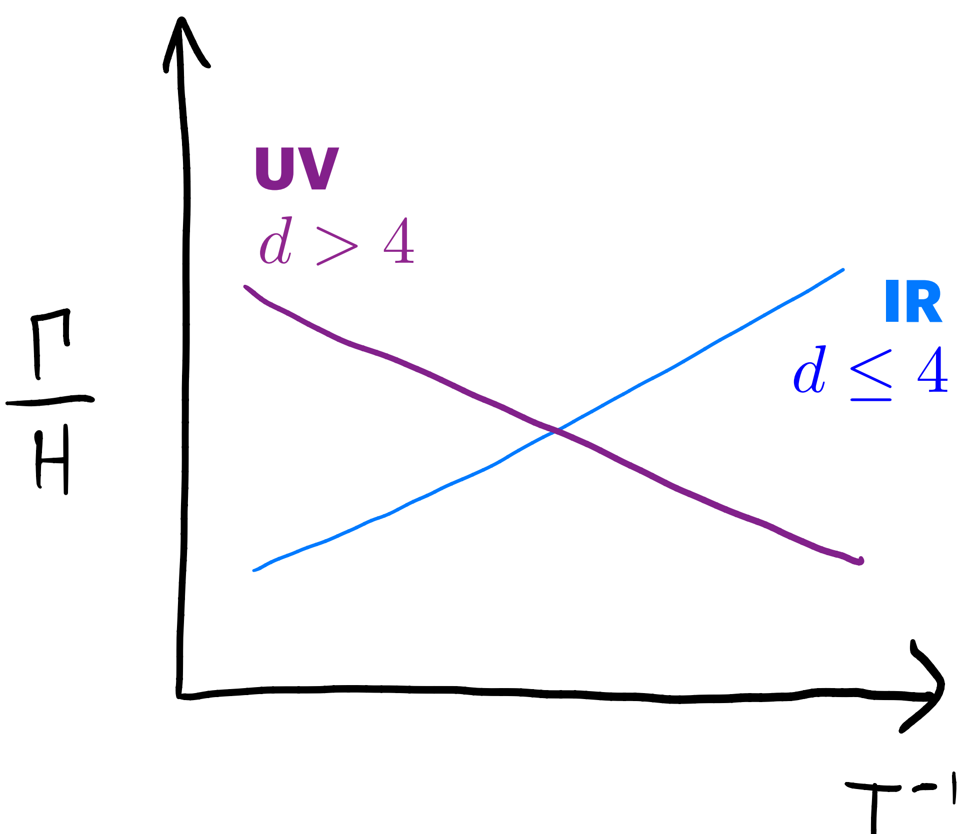
$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} T^{2(d-4)-1}$$

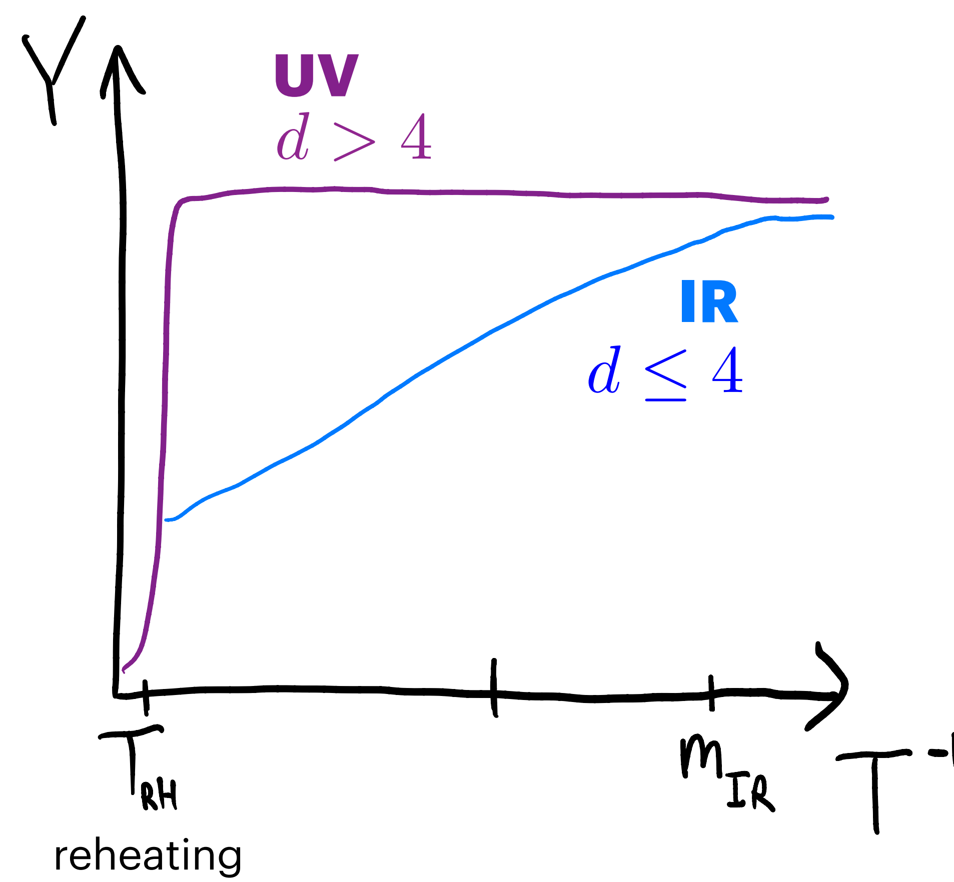
UV-dominated: $d > 4$ ex) 4-Fermi 

IR-dominated: $d \leq 4$ ex) Yukawa 

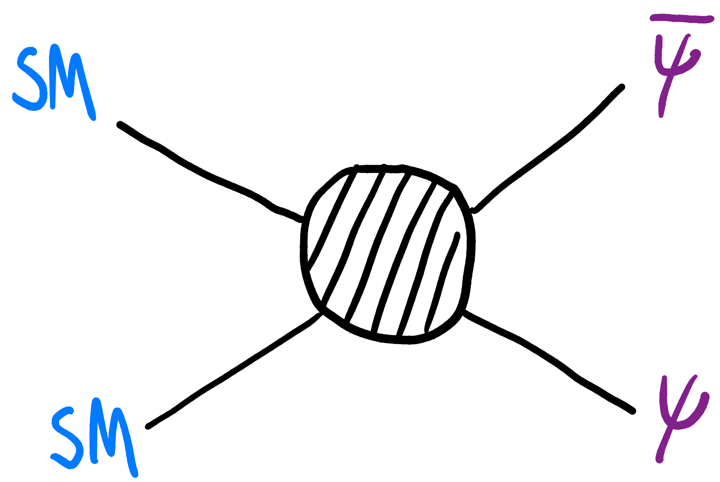
"freeze-in"

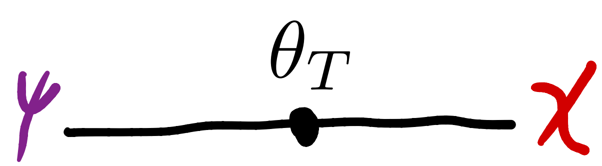
Hall, Jedamzik, March-Russell, West, **0911.1120**





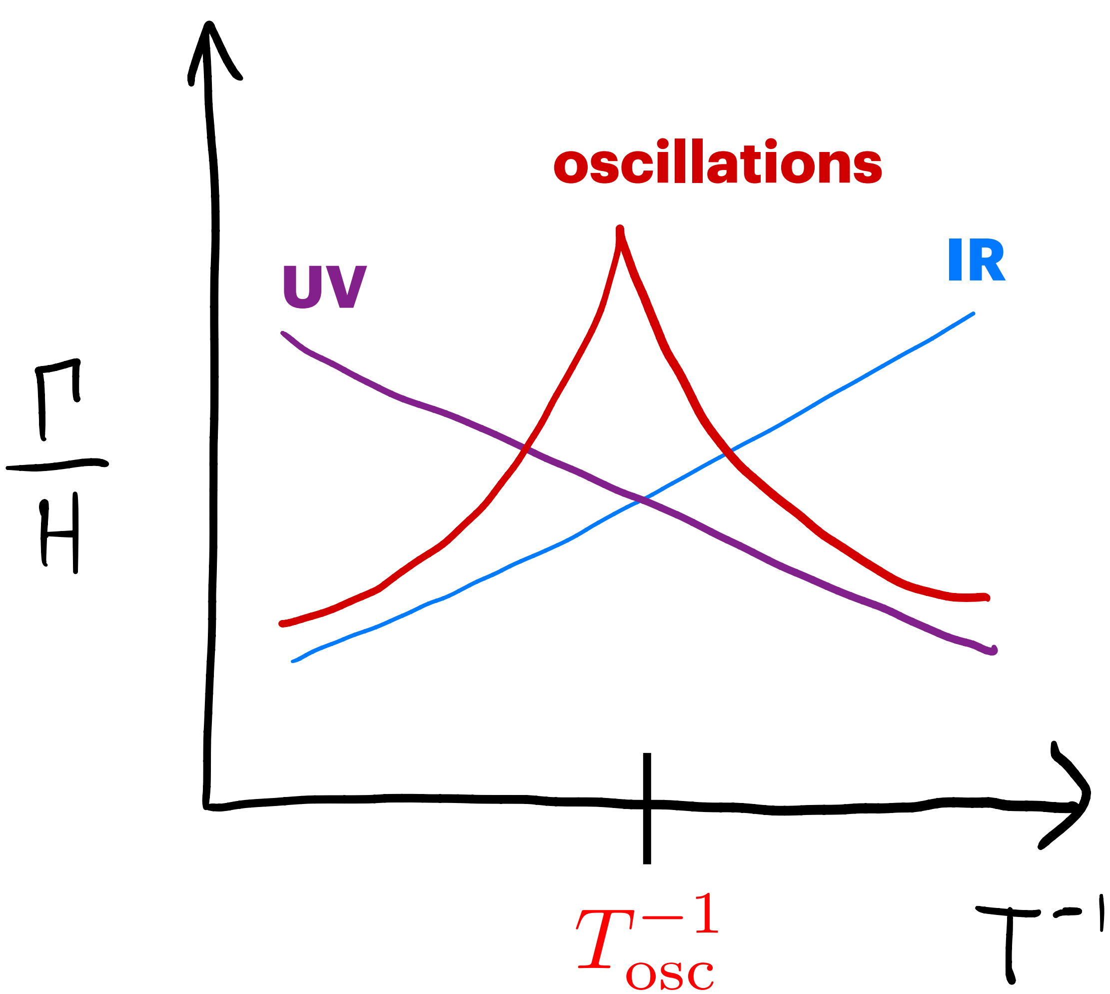
Production from Oscillations





$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} \theta_T^2 \, T^{2(d-4)-1}$$

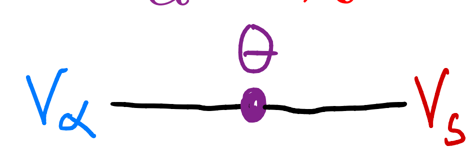
- at high temperatures: $\theta_T \propto T^{-n}$
- UV production shuts off when: $n \geq d-4$



ex) sterile neutrinos

(Dodelson & Widrow, **hep-ph/9303287**)

$$\psi = \nu_\alpha \qquad \chi = \nu_s$$



$$G_F \, \bar{\nu}_\alpha \gamma^\mu \nu_\alpha \, \bar{e}_L \gamma_\mu e_L$$

$$\begin{aligned} d &= 6 \\ n &= 6 \end{aligned} \longrightarrow \frac{\Gamma}{H} \propto T^{-9}$$

Plan

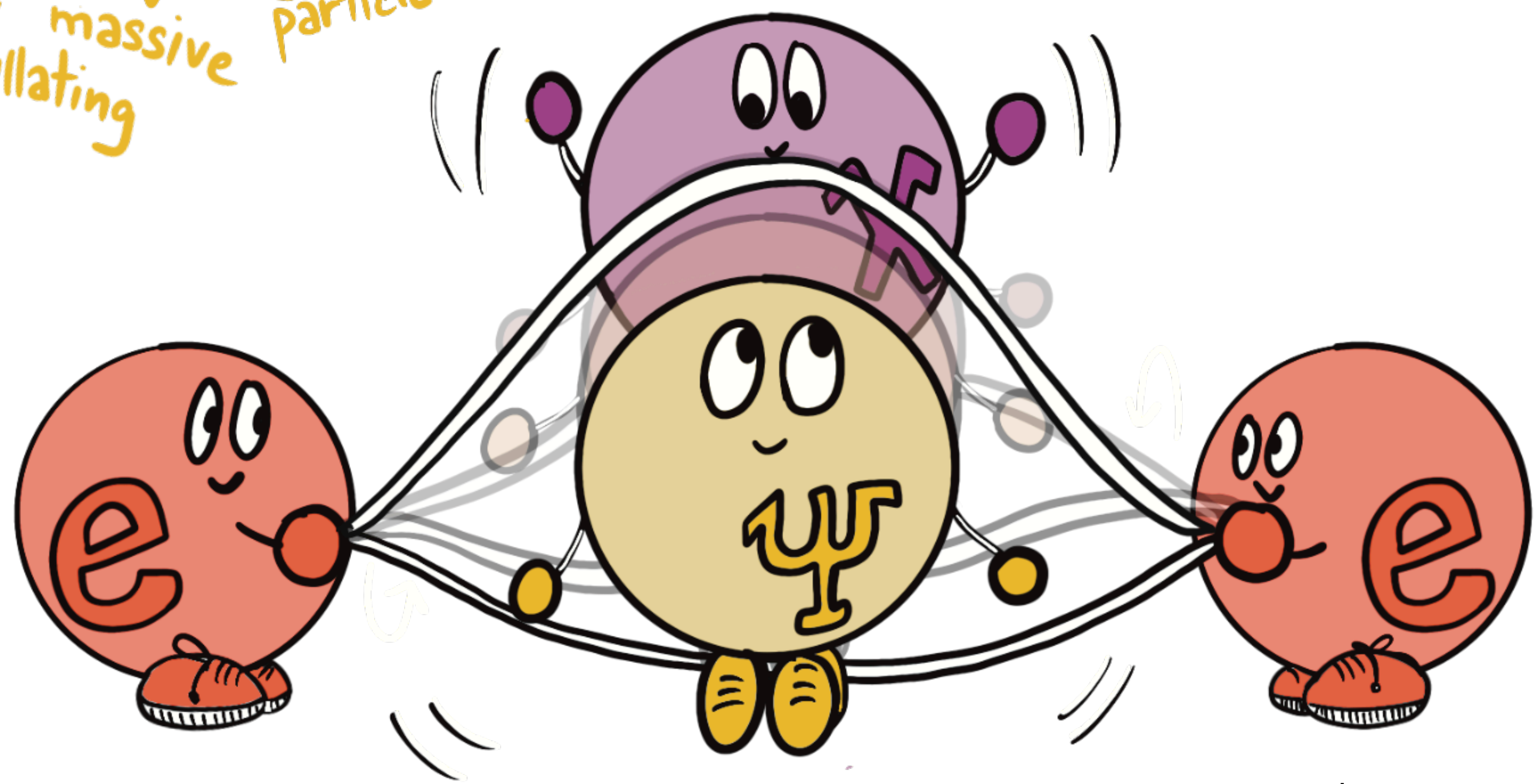
I. ROMP DM

II. Sterile Neutrino DM

III. Oscillations from BSM

1. ROMP DARK MATTER

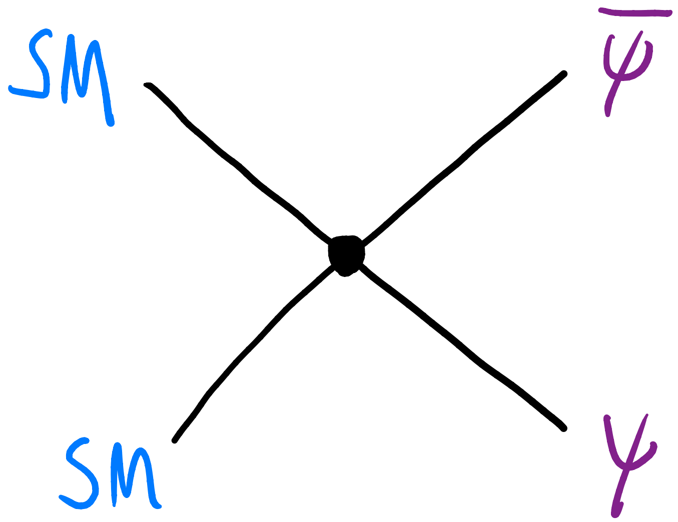
rapidly oscillating massive particle



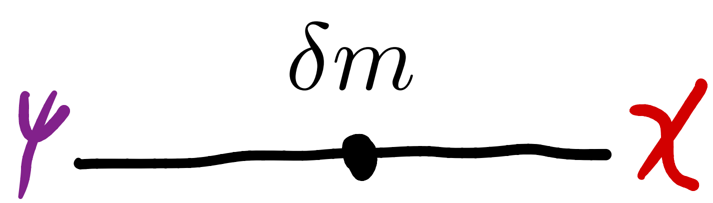
cartoon credit: Saniya

work in progress w/ David Dunsky and Saniya Heeba

ROMP Framework



$$\mathcal{L} \supset \frac{\mathcal{O}}{\Lambda^{d-4}}$$



$$\mathcal{L} \supset m_\psi \bar{\psi}\psi + m_\chi \bar{\chi}\chi + \delta m\, \bar{\psi}\chi + \mathrm{h.c.}$$

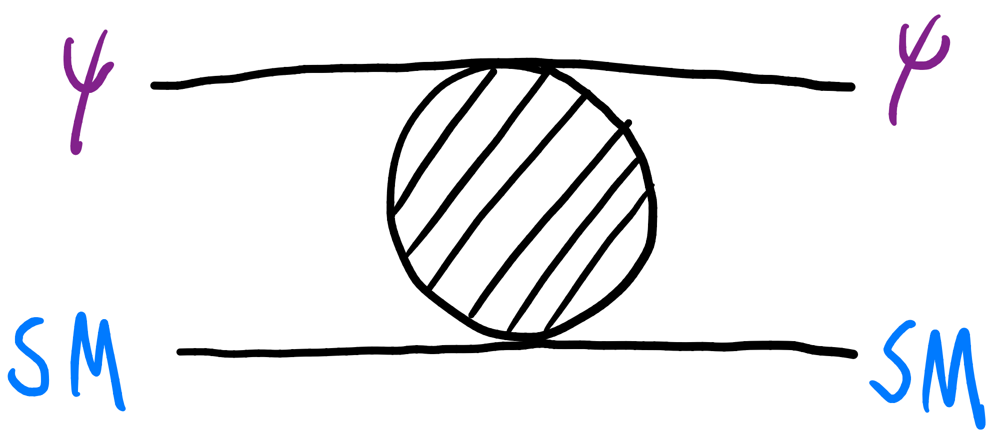
medium correction

$$\mathcal{M}^2_{\text{eff}} = \begin{pmatrix} m_\psi^2 + m_T^2 & \delta m^2 \\ \delta m^2 & m_\chi^2 \end{pmatrix} \qquad \tan 2\theta = \frac{2\delta m^2}{m_T^2 + m_\psi^2 - m_\chi^2}$$

resonant condition: $m_T^2 \approx m_\chi^2 - m_\psi^2$

Mixing in Medium

effective mass generated by forward scattering:



$$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\rm SM}}{2E_{SM}} \right\rangle$$

(sign determines resonant vs. non-resonant oscillations)

total scattering

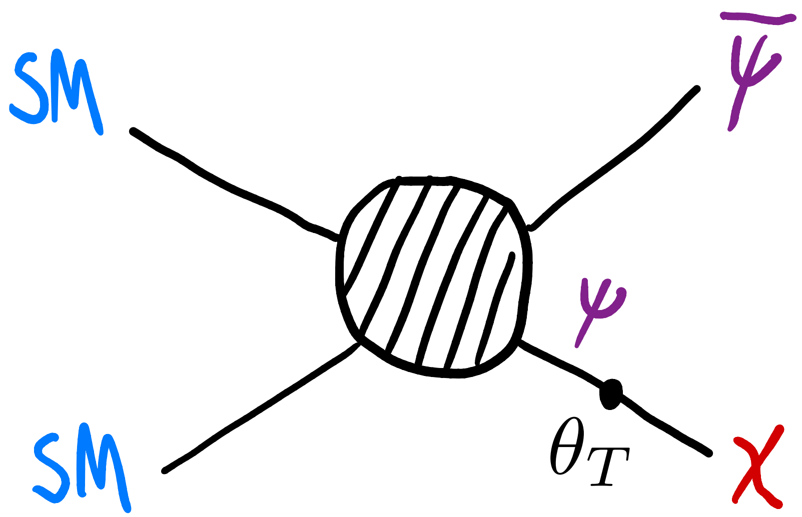
$$\mathcal{L} \supset \frac{\mathcal{O}}{\Lambda^{d-4}} + \frac{\mathcal{O}_F}{\Lambda^{d+\Delta-4}}$$

forward scattering

$$\Delta \geq 0$$

$$m_T^2 \sim \frac{m_\psi^\delta}{\Lambda^{d+\Delta-4}} T^{(d+\Delta-4)-\delta+2}$$

Oscillations at High Temperatures



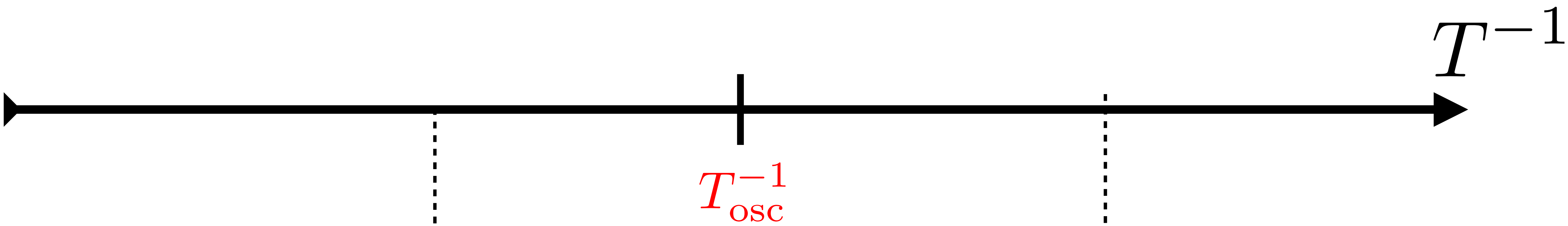
$$\frac{\Gamma}{H} \sim \frac{M_{pl}}{\Lambda^{2(d-4)}} \theta_T^2 \, T^{2(d-4)-1}$$

$$\theta_T \sim \frac{\delta m^2}{m_T^2} \sim \frac{\delta m^2 \Lambda^{d+\Delta-4}}{m_\psi^\delta} T^{-(d+\Delta-4)+\delta-2}$$

$$\frac{\Gamma}{H} \sim \frac{M_{pl} \Lambda^{2\Delta}}{m_\psi^{2\delta}} T^{-5-2\Delta+2\delta}$$

shuts off in UV if: $\delta - \Delta \leq 2$

Oscillation Temperature



high temperature:

$$\left|m_T^2\right| \gg \tilde{m}^2$$

$$\tilde{m}^2 \equiv \max(m_\psi^2, m_\chi^2)$$

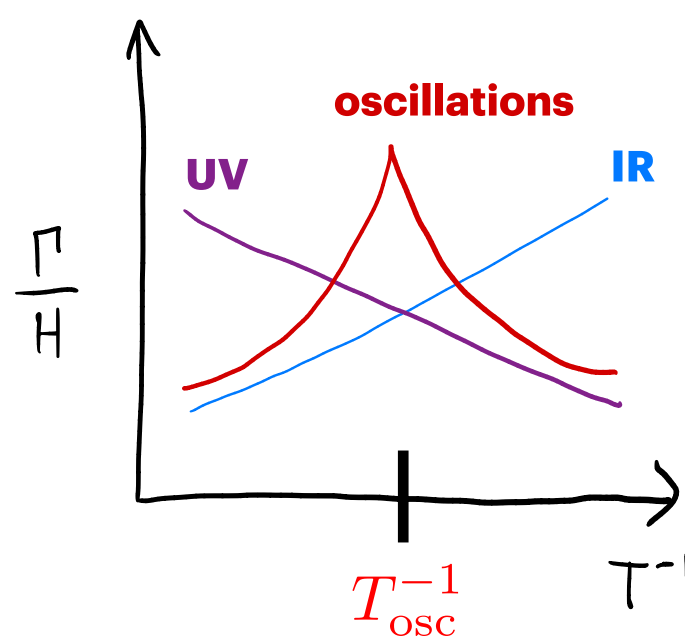
$$\theta_T \propto T^{-(d+\Delta-4)+\delta-2}$$

$$\frac{\Gamma}{H} \propto T^{-5-2\Delta+2\delta}$$

$$\left|m_{T_{\rm osc}}^2\right| = \tilde{m}^2$$

$$T_{\rm osc} \sim m_\psi^{-\delta/\alpha}\, \tilde{m}^{2/\alpha}\, \Lambda^{(\alpha+\delta-2)/\alpha}$$

where $\alpha \equiv (d+\Delta-4) - \delta + 2$



low temperature:

$$\left|m_T^2\right| \ll \tilde{m}^2$$

$$\theta_T \approx \theta_{\rm vac}$$

$$\frac{\Gamma}{H} \propto T^{2(d-4)-1}$$

Quantum Kinetic Equation

$$\frac{d\mathbf{P}}{dt} = \mathbf{V} \times \mathbf{P} - D\mathbf{P}_\perp + \dot{P}_0 \hat{\mathbf{z}}$$

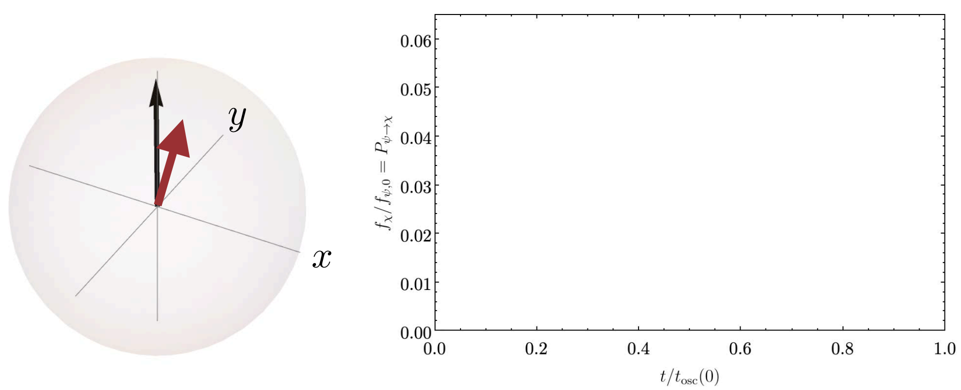
oscillations damping regeneration

Stodolsky, Phys. Rev. D **36**, 2273 (1987)

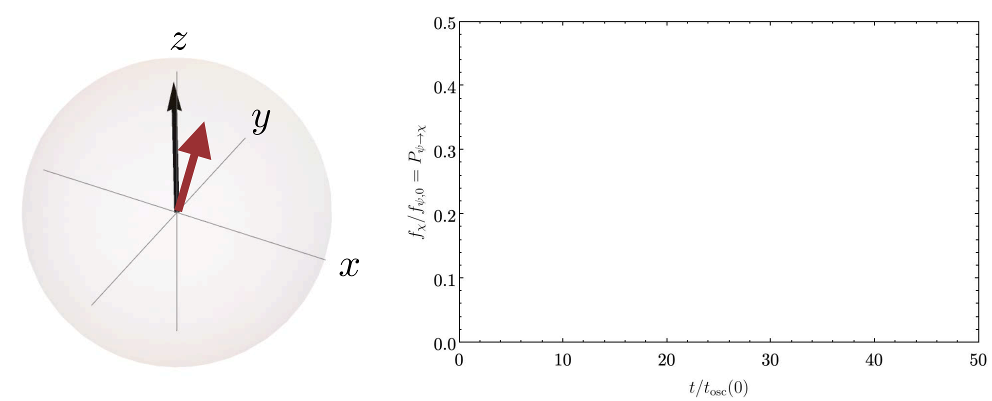
density matrix ⟶ phase space distribution functions $\boldsymbol{\rho} = \frac{1}{2}(P_0 \mathbb{1} + \mathbf{P} \cdot \boldsymbol{\sigma})$

$$P_z = \mathrm{tr}(\boldsymbol{\rho}\sigma_z) = \rho_{\psi\psi} - \rho_{\chi\chi} = f_\psi - f_\chi$$

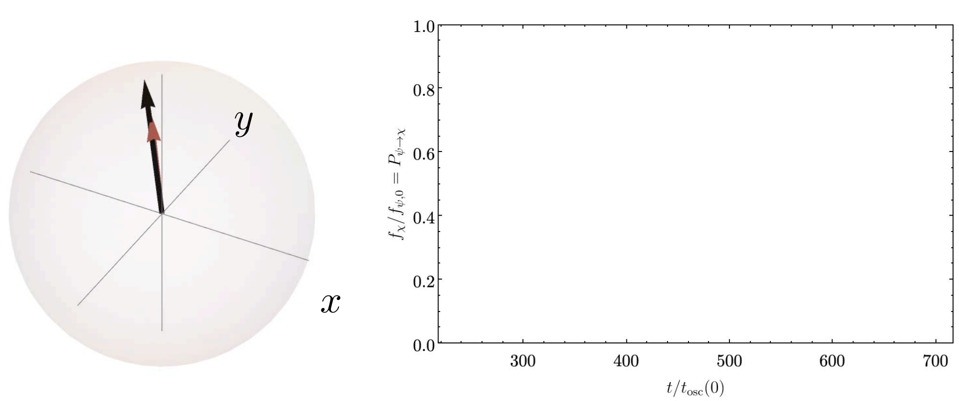
vacuum oscillations:



incoherent scattering:



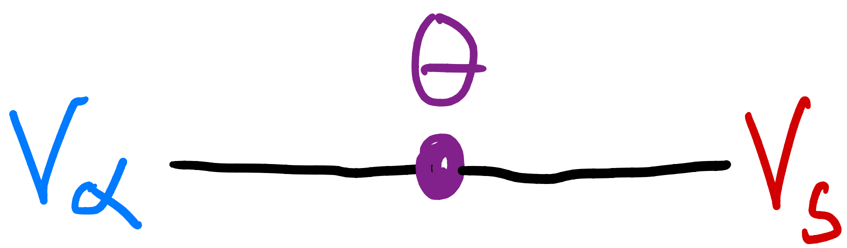
coherent level crossing:



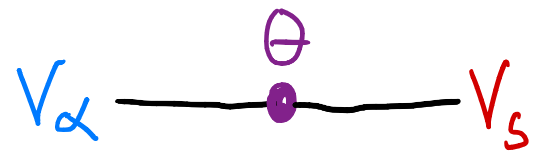
(Landau-Zener if non-adiabatic)

Boltzmann equation: $\dot{f}_\chi = \frac{1}{4}\Gamma_\psi \sin^2 2\theta (f_\psi - f_\chi)$

II. Sterile Neutrino DM



Dodelson-Widrow Mechanism

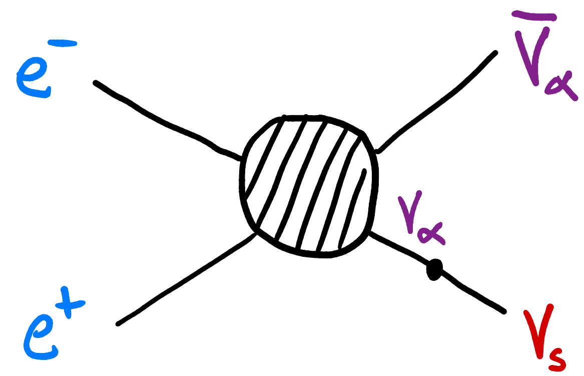


Dodelson & Widrow, **hep-ph/9303287**

total scattering:

$$G_F\,\bar{\nu}_\alpha\gamma^\mu\nu_\alpha\,\bar{e}_L\gamma_\mu e_L$$

$$d=6$$



$$\frac{\Gamma}{H}\sim M_{pl}G_F^2\,\theta_T^2 T^3$$

medium mass:

$$d=6 \qquad m_T^2 = G_F T(n_e - n_{\bar{e}})$$ vanishes in symmetric limit!

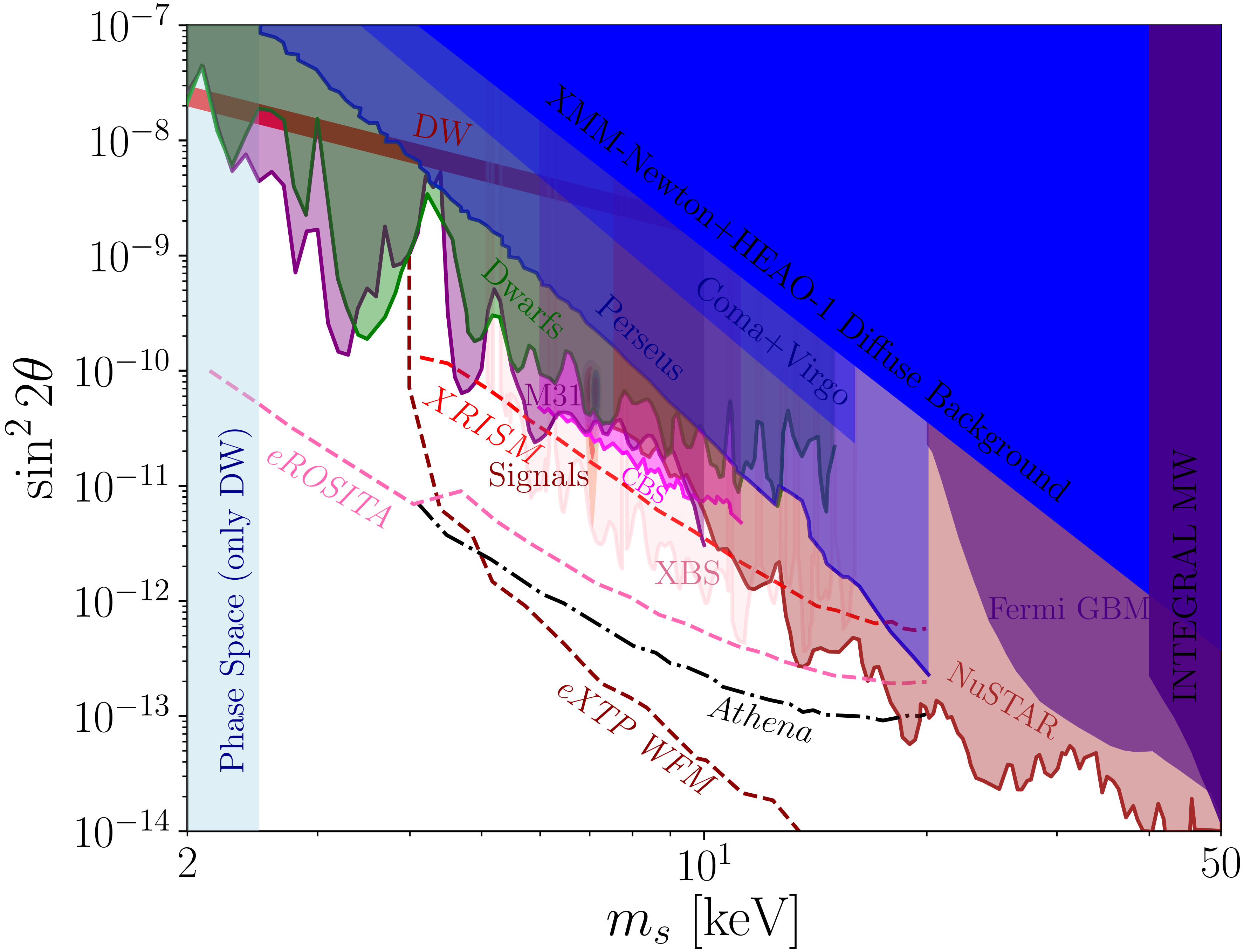
$$d=8 \qquad m_T^2 = -G_F^2 T^3(n_e + n_{\bar{e}}) \sim -G_F^2 T^6$$

$$G_F^2\,\bar{\nu}_\alpha\gamma^\mu\nu_\alpha\partial^\nu\partial_\nu\,\bar{e}_L\gamma_\mu e_L$$

UV behavior: $\theta_T \propto T^{-6} \longrightarrow \dfrac{\Gamma}{H}\propto T^{-9}$

oscillation temperature: $T_{\rm osc}\sim\left(\dfrac{m_{\nu_s}}{G_F}\right)^{1/3}\sim 130\,\mathrm{MeV}\left(\dfrac{m_{\nu_s}}{1\,\mathrm{keV}}\right)^{1/3}$

Sterile Neutrino Parameter Space

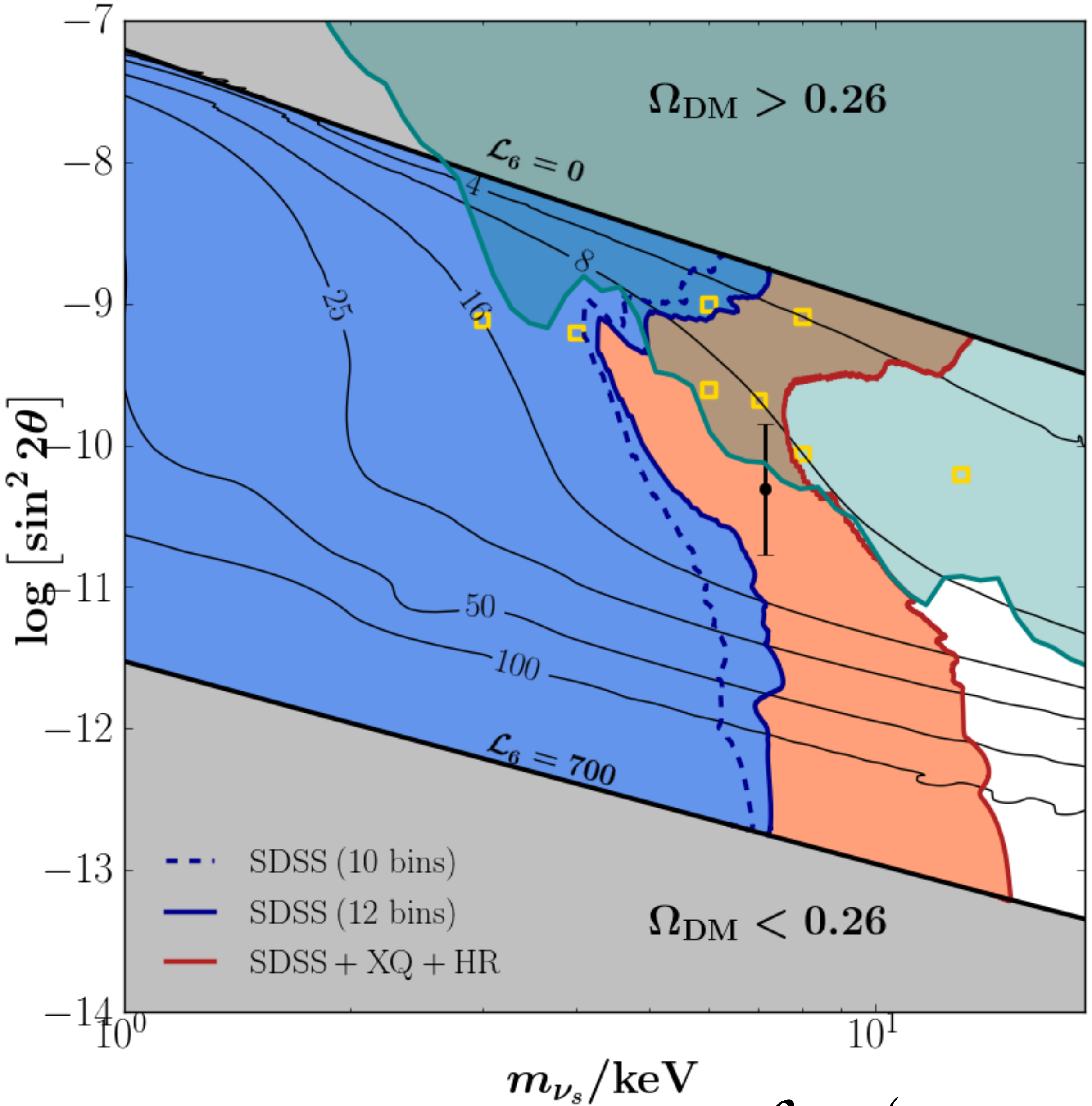


Abazajian *et. al.*, Snowmass, **2203.07377**

Shi-Fuller Mechanism

large lepton asymmetry allows for dimension-6 operator to dominate forward scattering

Shi, Fuller, **astro-ph/9810076**



$$\mathcal{L} = (n_{\nu_e} - n_{\bar{\nu}_e})/s$$

Baur *et. al.*, **1706.03118**

$$m_T^2 = G_F T(n_e - n_{\bar{e}}) \sim G_F(\Delta L)\, T^4$$

$$\theta_T \propto T^{-4} \qquad T_{\rm osc} \sim \frac{m_{\nu_s}^{1/2}}{G_F^{1/4} \Delta L^{1/4}}$$

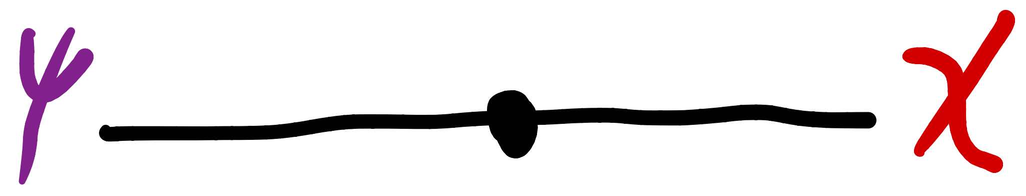
- necessary lepton asymmetry:

$$Y_\nu - Y_{\bar{\nu}} \sim 10^{-6} - 10^{-3}$$

- observed baryon asymmetry:

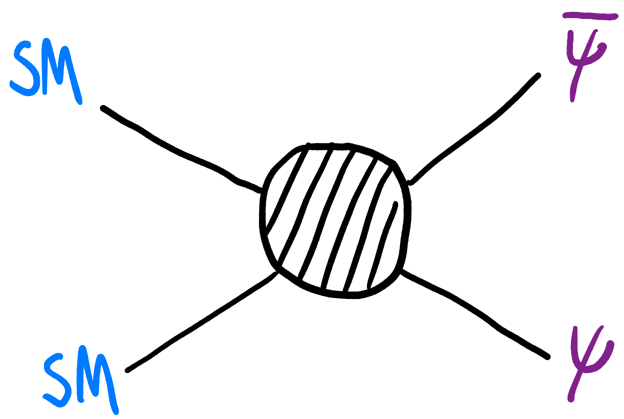
$$Y_B - Y_{\bar{B}} = 8.7 \times 10^{-11}$$

III. Oscillations from BSM



ROMP Recipe

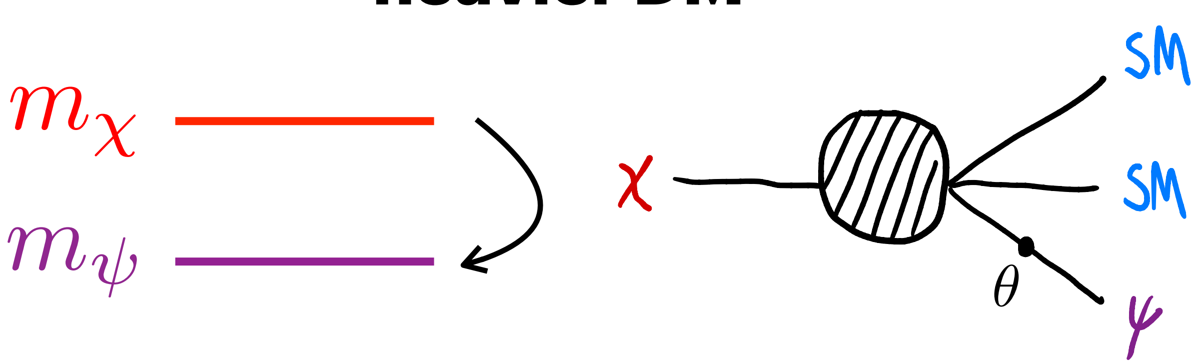
1) select one or more operators that couple ψ to the thermal bath



$$\mathcal{L} \supset \frac{\mathcal{O}}{\Lambda^{d-4}} + c_F \frac{\mathcal{O}_F}{\Lambda^{d+\Delta-4}} + \ldots$$

2) choose vacuum spectrum $\mathcal{L} \supset m_\psi \bar{\psi}\psi + m_\chi \bar{\chi}\chi + \delta m\, \bar{\psi}\chi + \text{h.c.}$

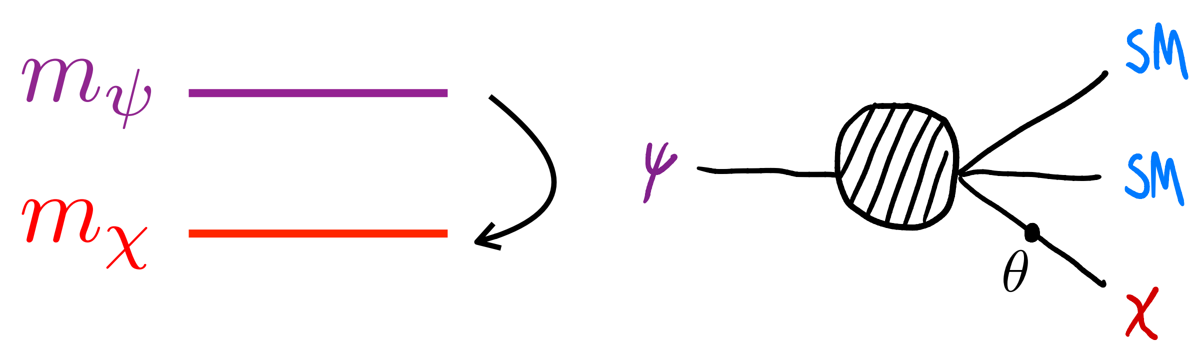
heavier DM



ex) sterile neutrino

- dark matter is unstable
- ψ contributes to DM or dark radiation

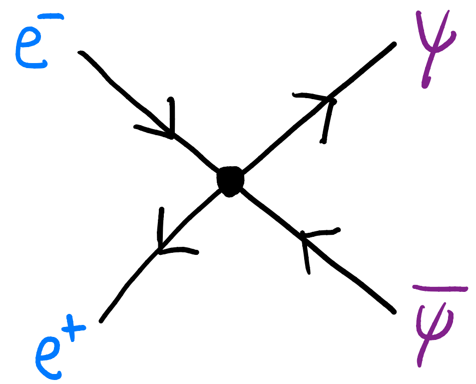
lighter DM



- dark matter can be stable
- ψ decays (after decoupling) contribute to DM abundance

Feng, Rajaraman, Takayama, **hep-ph/0302215**

ex 1) vector 4-Fermi



$$\mathcal{L} \supset \frac{\bar{e}_L \gamma^\mu e_L \, \bar{\psi}_L \gamma_\mu \psi_L}{\Lambda^2} + c_8 \frac{\bar{e}_L \gamma^\mu e_L \partial^\nu \partial_\nu \bar{\psi}_L \gamma_\mu \psi_L}{\Lambda^4}$$

- medium ψ mass: $m_T^2 \sim -\frac{c_8}{\Lambda^4} T^6$ (assuming small asymmetries)
- UV production: $\frac{\Gamma}{H} \sim \frac{M_{pl} (\delta m)^4 \Lambda^4}{c_8^2} T^{-9}$
- oscillation temperature: $T_{\rm osc} \approx 5\,{\rm GeV} \left(\frac{\max\{m_\psi, m_\chi\}}{1\,{\rm MeV}} \right)^{1/3} \left(\frac{\Lambda}{1\,{\rm TeV}} \right)^{2/3}$
- spectrum:

m_χ ———
m_ψ ———

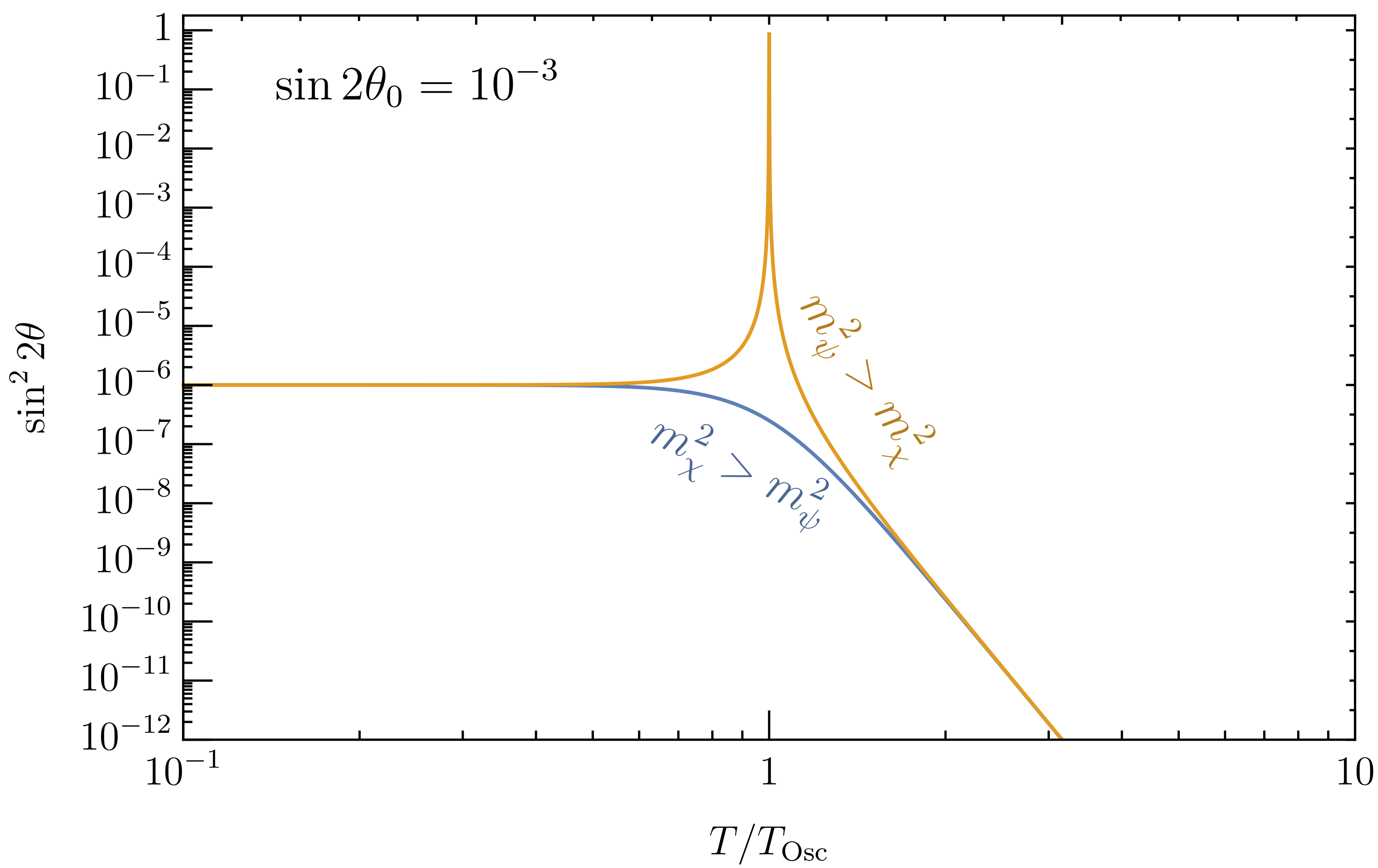
non-resonant $(c_8 > 0)$

-or-

m_ψ ———
m_χ ———

resonant! $(c_8 > 0)$

ex 1) vector 4-Fermi



- spectrum:

m_χ ——— m_ψ ———

-or-

m_ψ ——— m_χ ———

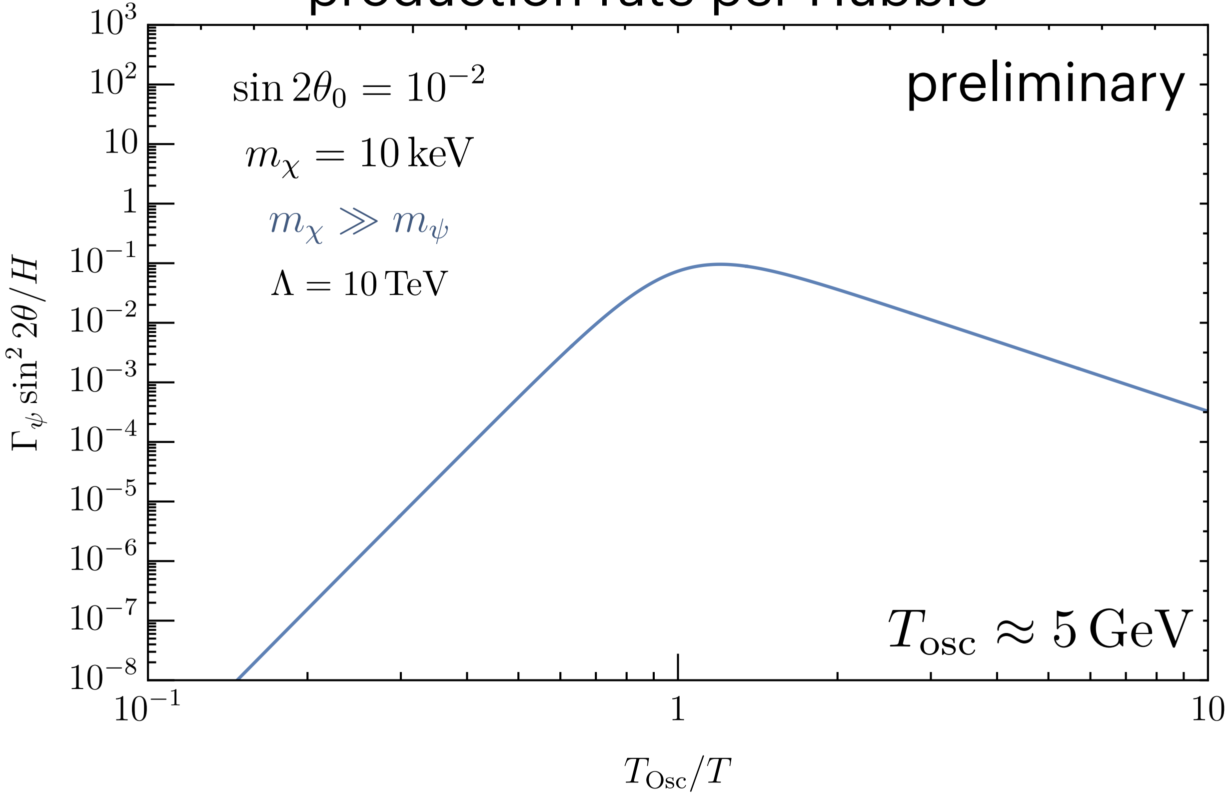
non-resonant $(c_8 > 0)$

resonant! $(c_8 > 0)$

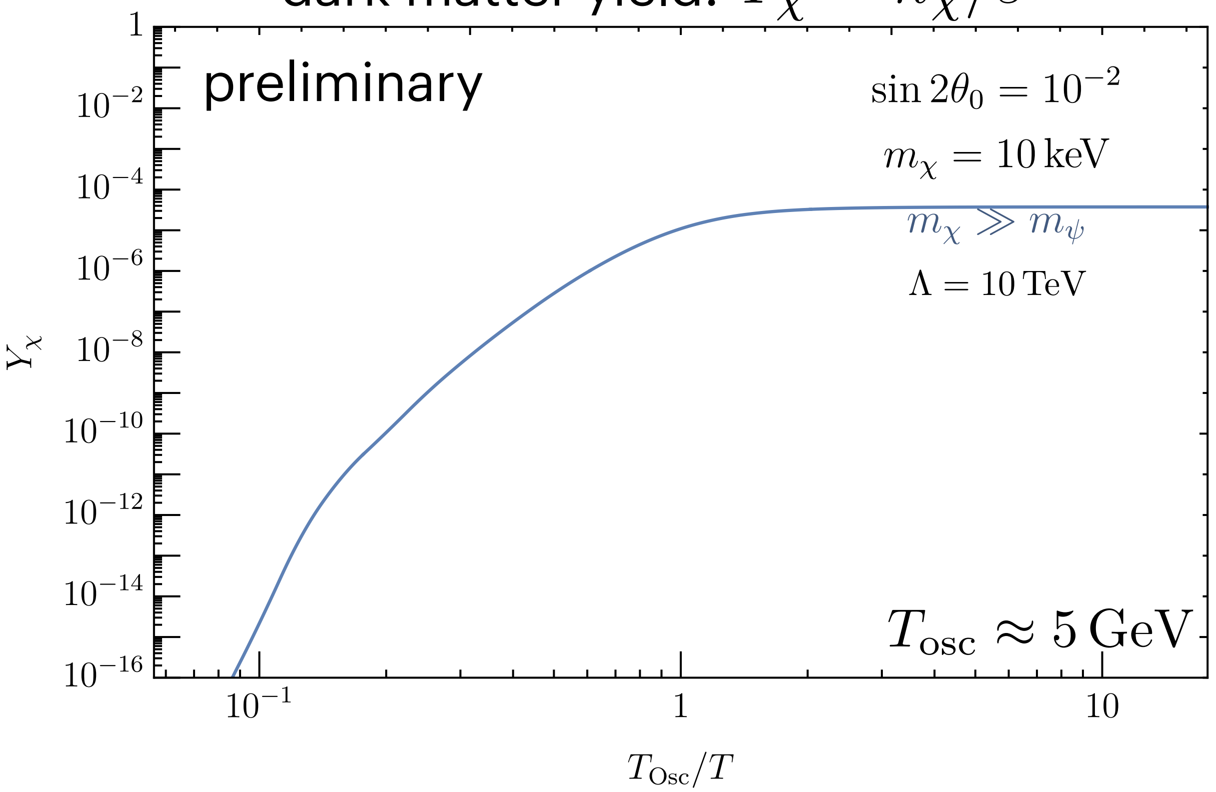
ex 1) vector 4-Fermi

non-resonant production: $m_\chi > m_\psi$

production rate per Hubble

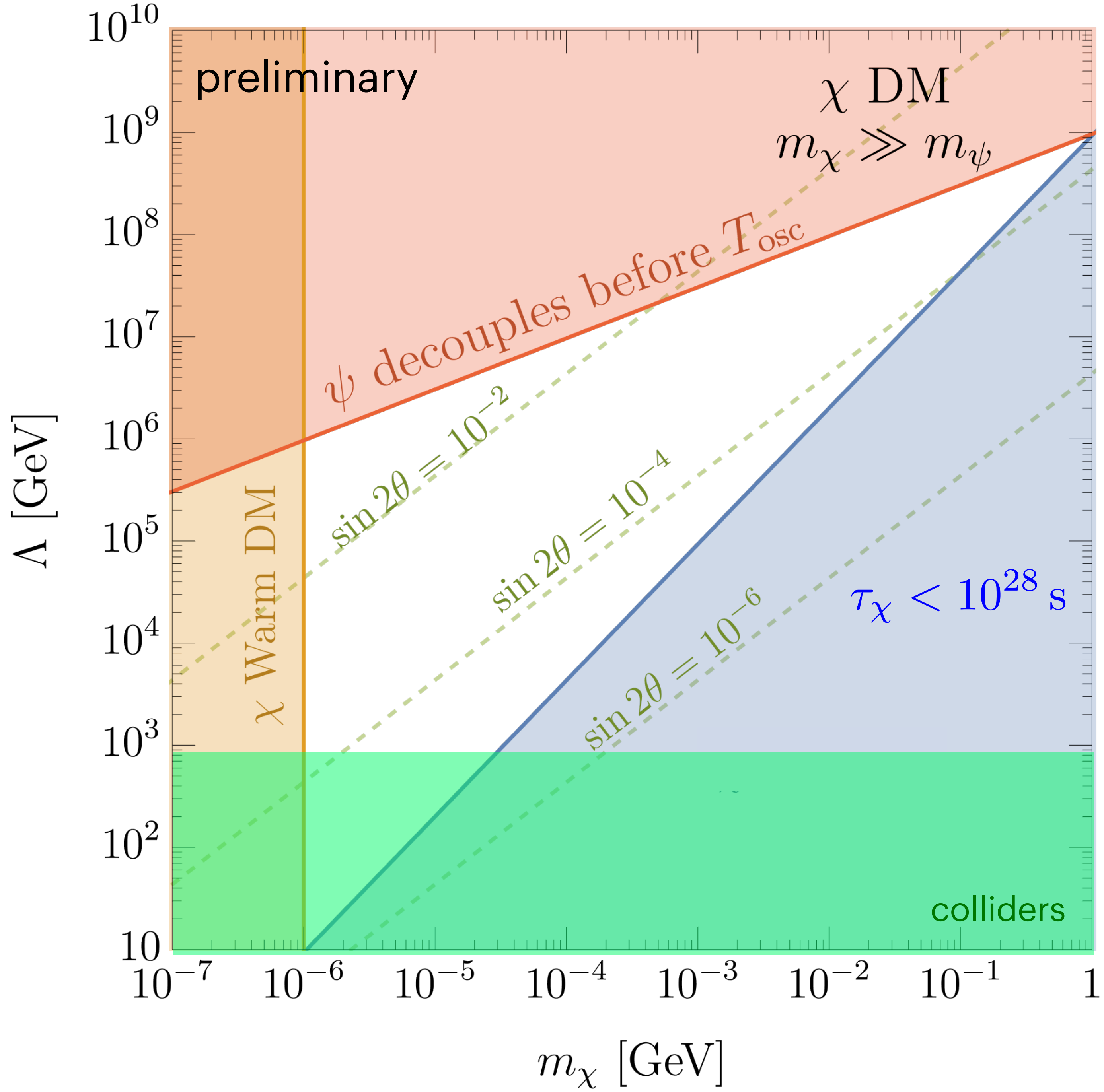


dark matter yield: $Y_\chi = n_\chi / s$

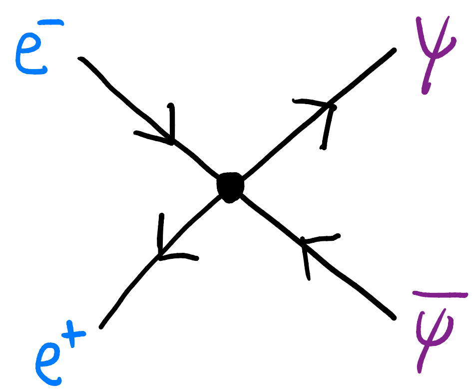


ex 1) vector 4-Fermi

non-resonant production



ex 2) scalar 4-Fermi



$$\mathcal{L} \supset \frac{\bar{e}e\,\bar{\psi}\psi}{\Lambda^2}$$

- medium ψ mass: $m_T^2 \sim \frac{m_\psi}{\Lambda^2} T^3$
- UV production: $\frac{\Gamma}{H} \sim \frac{M_{pl}(\delta m)^4}{m_\psi^2} T^{-3}$
- oscillation temperature:

$$T_{\rm osc} \approx 5\,\mathrm{GeV} \left(\frac{\max\{m_\psi, m_\chi\}}{1\,\mathrm{MeV}}\right)^{2/3} \left(\frac{m_\psi}{1\,\mathrm{MeV}}\right)^{-1/3} \left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^{2/3}$$

- spectrum:

m_χ ——
m_ψ ——

resonant!

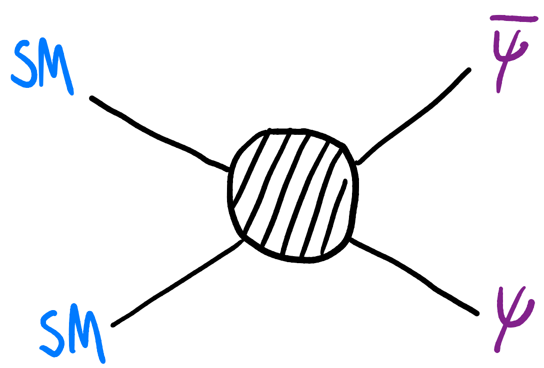
-or-

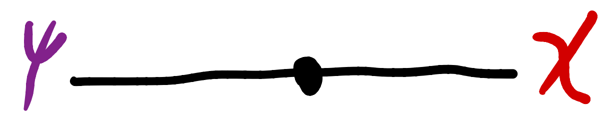
m_ψ ——
m_χ ——

non-resonant

Take Away

- Dark Matter could be a **ROMP** (= **R**apidly **O**scillating **M**assive **P**article)

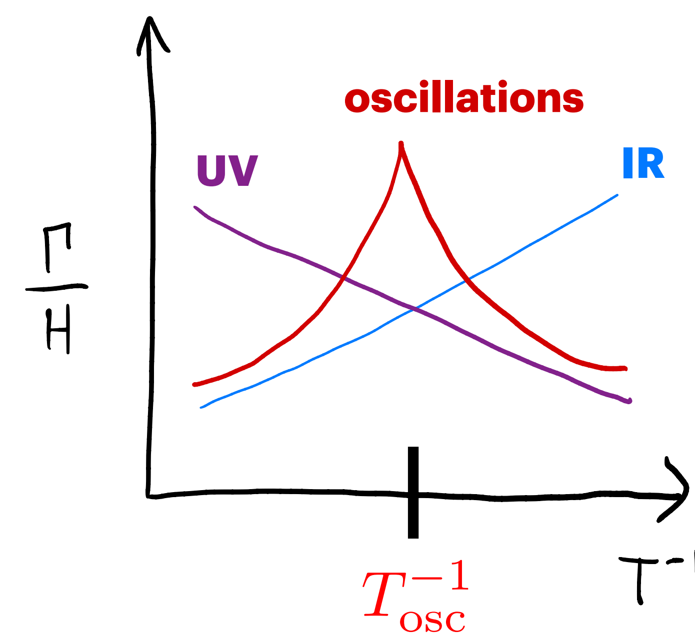




- ROMPs allow for DM produced by a higher dim. operator, insensitive to reheating dynamics

- ROMPs pick a new cosmic epoch:

$$T_{\rm osc} \approx 5\,{\rm GeV} \left(\frac{\max\{m_\psi, m_\chi\}}{1\,{\rm MeV}}\right)^{1/3} \left(\frac{\Lambda}{1\,{\rm TeV}}\right)^{2/3}$$



- many possible realizations, that differ vastly from sterile neutrinos