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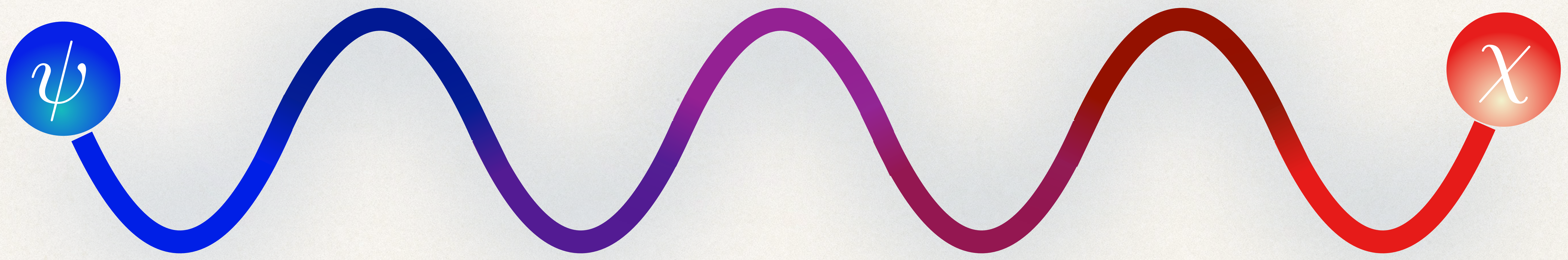

Production of ROMP Dark Matter

ALPS 2024

David Dunsky, Saniya Heeba, Josh Ruderman

Work in Progress

Motivation and Key Idea

Motivation and Key Idea

Rapidly

Motivation and Key Idea

Rapidly Oscillating

Motivation and Key Idea

Rapidly **O**scillating **M**assive

Motivation and Key Idea

Rapidly **O**scillating **M**assive **P**articles

Motivation and Key Idea

Rapidly **O**scillating **M**assive **P**articles

- Particle production by oscillating from one interaction state to another

Motivation and Key Idea

- Oscillations familiar from SM and BSM physics:

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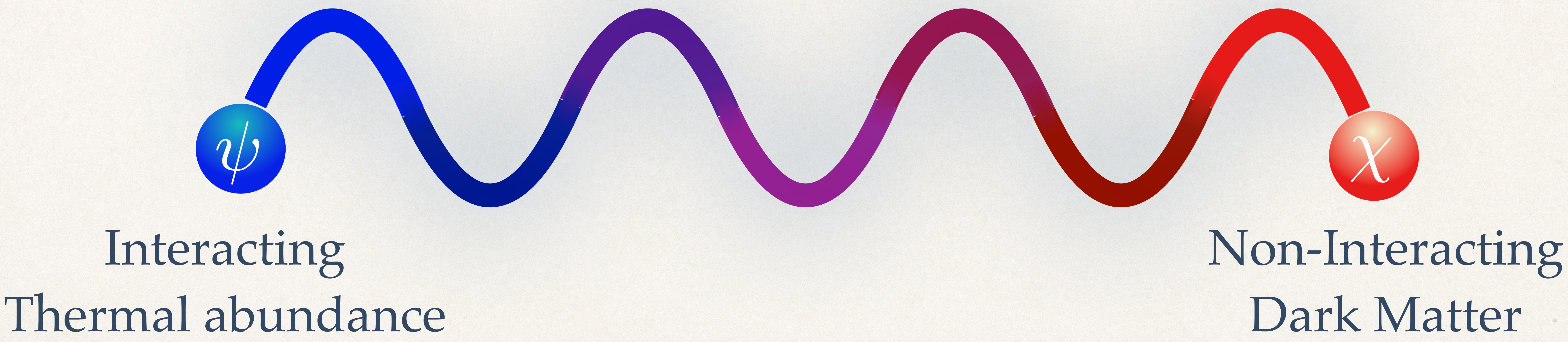
- Ubiquitous and potentially efficient production mechanism of dark matter
- Goal to generalize this framework. Necessary ingredients?

ROMP Ingredients

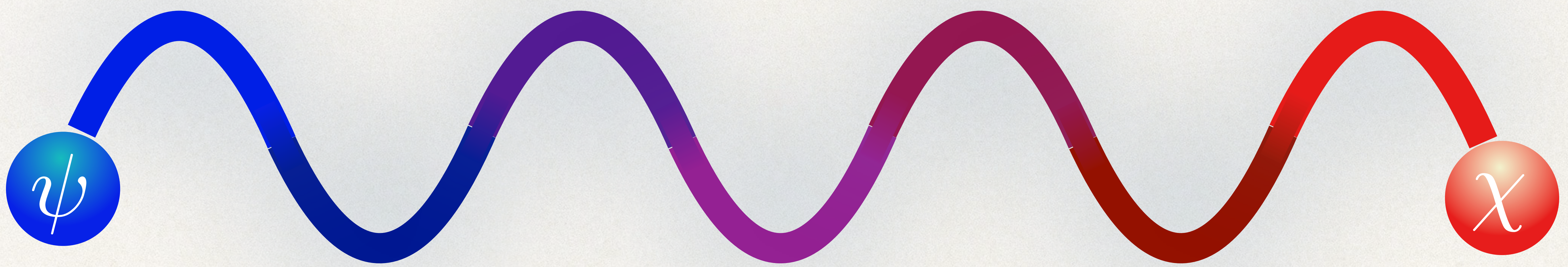
- Two state quantum system



$$\begin{pmatrix} \psi & \chi \end{pmatrix} \begin{pmatrix} m_\psi^2 & 0 \\ 0 & m_\chi^2 \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix}$$

ROMP Ingredients

- Two state quantum system



Interacting
Thermal abundance

Non-Interacting
Dark Matter

$$\begin{pmatrix}\psi & \chi\end{pmatrix}\begin{pmatrix}m_\psi^2 & m_{\psi\chi}^2 \\ m_{\psi\chi}^2 & m_\chi^2\end{pmatrix}\begin{pmatrix}\psi \\ \chi\end{pmatrix}$$

- Mass mixing: misalignment between interaction and mass basis

ROMP Ingredients

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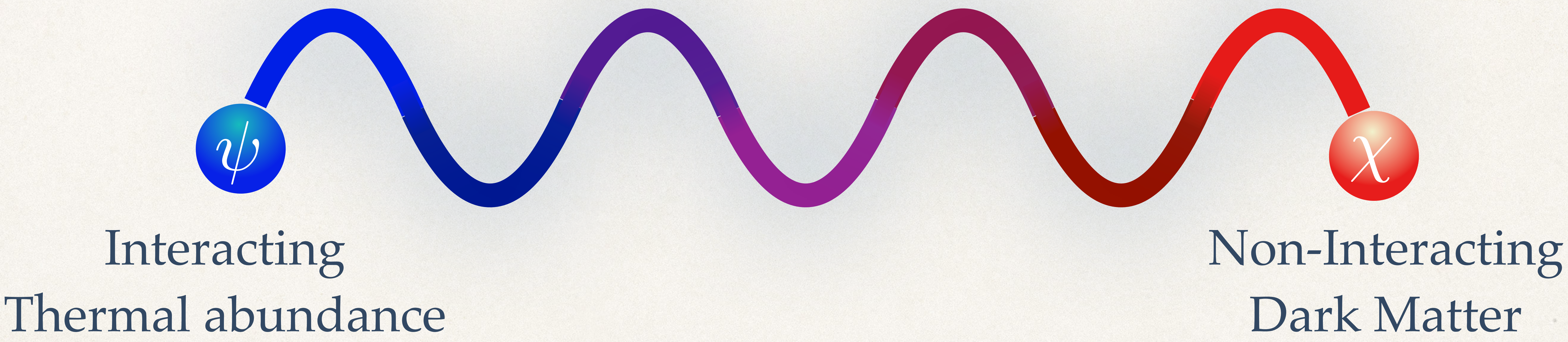

$$\begin{pmatrix}\psi & \chi\end{pmatrix}\begin{pmatrix} m_\psi^2 & m_{\psi\chi}^2 \\ m_{\psi\chi}^2 & m_\chi^2\end{pmatrix}\begin{pmatrix}\psi \\ \chi\end{pmatrix}$$

- Diagonalize by rotation matrix with vacuum mixing angle θ_0

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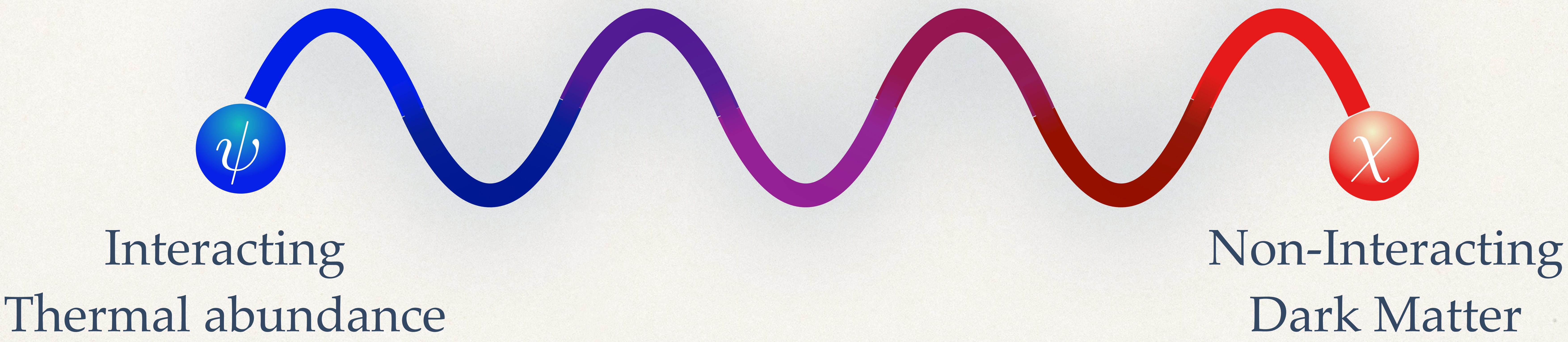


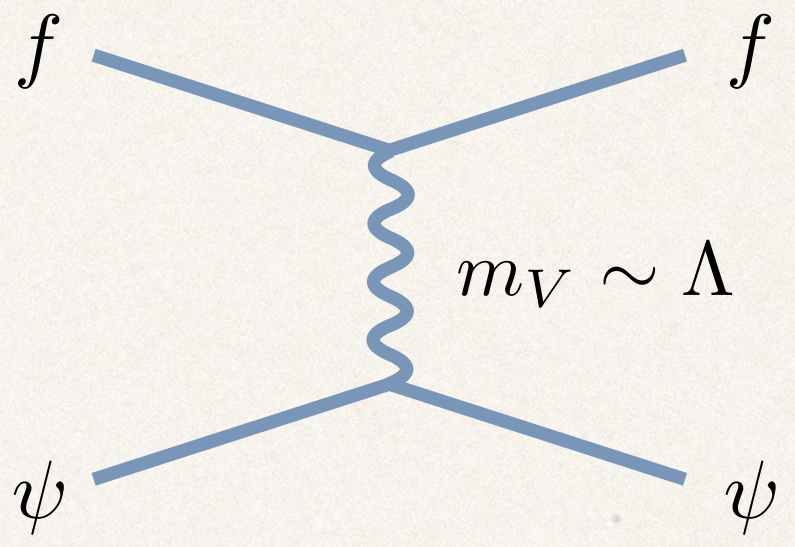
$$(\psi \quad \chi) \begin{pmatrix} m_\psi^2 + m_T^2 & m_{\psi\chi}^2 \\ m_{\psi\chi}^2 & m_\chi^2 \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix}$$

- Interactions that keep ψ in equilibrium also can generate thermal mass → $\theta(T)$

ROMP Example

- Many possibilities for operators/interactions that keep ψ in equilibrium

- As example, heavy vector exchange



- Important operators from EFT perspective:

$$\mathcal{L}_6 = \frac{1}{\Lambda^2}(\bar{f}\gamma^\mu P_L \psi) g_{\mu\nu} (\bar{\psi}\gamma^\nu P_L f)$$

4-Fermi like interaction

$$\mathcal{L}_8 = \frac{1}{\Lambda^4}(\bar{f}\gamma^\mu P_L \psi)(g_{\mu\nu}\partial^2 + \partial_\mu \partial_\nu)(\bar{\psi}\gamma^\nu P_L f)$$

Modification from heavy vector propagator

ROMP Production Time

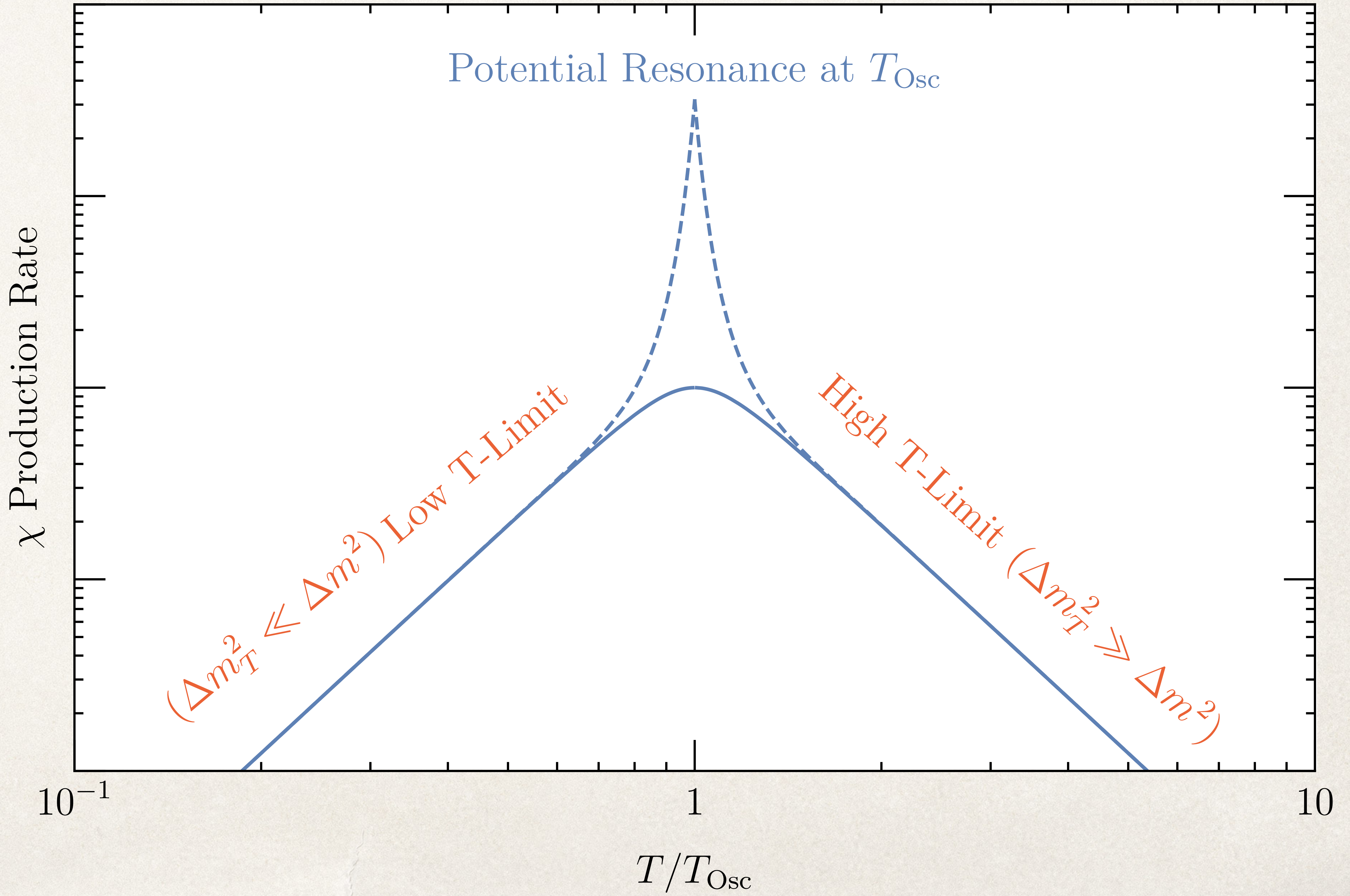
- Characteristic of ROMP dark matter that new temperature of production $T_{\rm osc}$

$$\mathbf{M}^2_{\rm eff} = \begin{pmatrix} m_\psi^2 + m_T^2 & m_{\psi\chi}^2 \\ m_{\psi\chi}^2 & m_\chi^2 \end{pmatrix}$$

$$\tan 2\theta = \frac{2m_{\psi\chi}^2}{m_T^2 + m_\psi^2 - m_\chi^2}$$

Can be large in early universe. Mixing suppressed!

$T_{\rm osc}$ when $|m_T^2| = m_\psi^2 - m_\chi^2$



Evolution Equation?

- How to capture:

    1. Oscillations

    2. Scattering

    3. Resonances

    4. In-medium (thermal) mass corrections

To determine relic abundance of χ dark matter?

Quantum Kinetic Equation

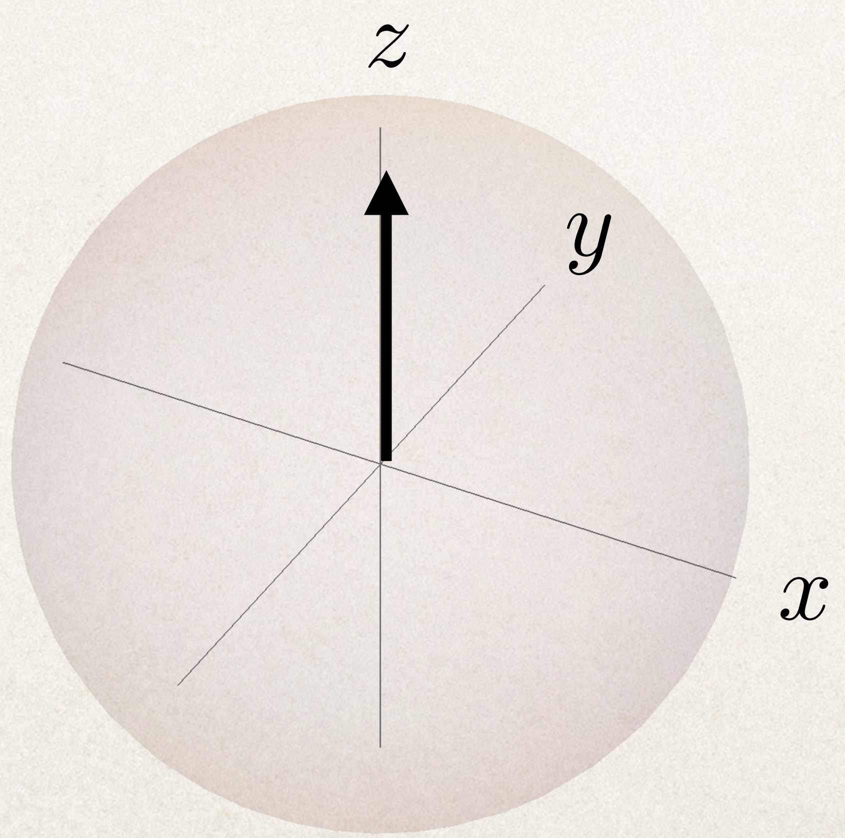
- Need evolution of density operator

$$i\partial_t \hat{\rho} = [\hat{H}, \hat{\rho}] \longrightarrow \frac{d\mathbf{P}}{dt} = \mathbf{V} \times \mathbf{P} - D\mathbf{P}_\perp + \dot{P}_0 \hat{\mathbf{z}}$$

Akhiezer et al '81; Stodolsky '87

ROMP polarization vector

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



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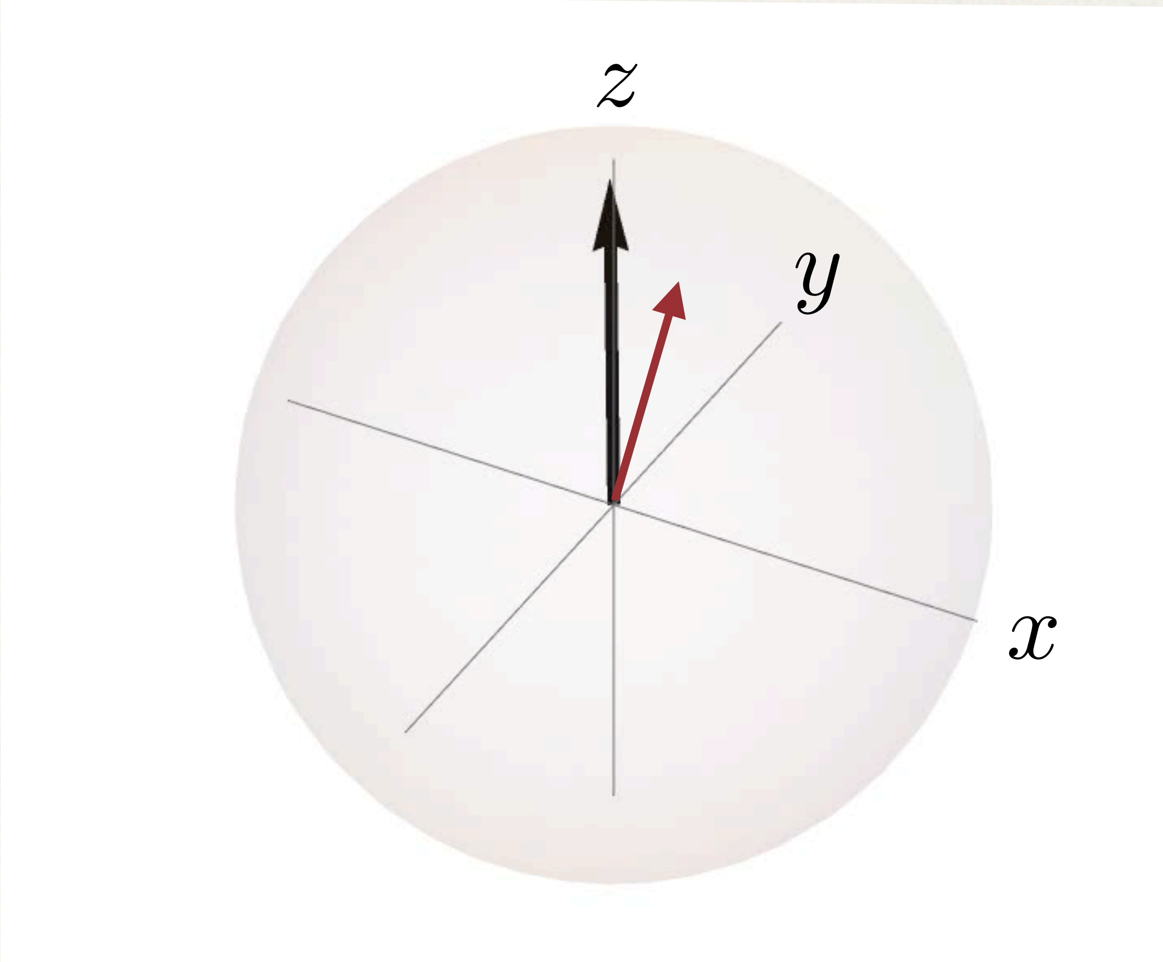
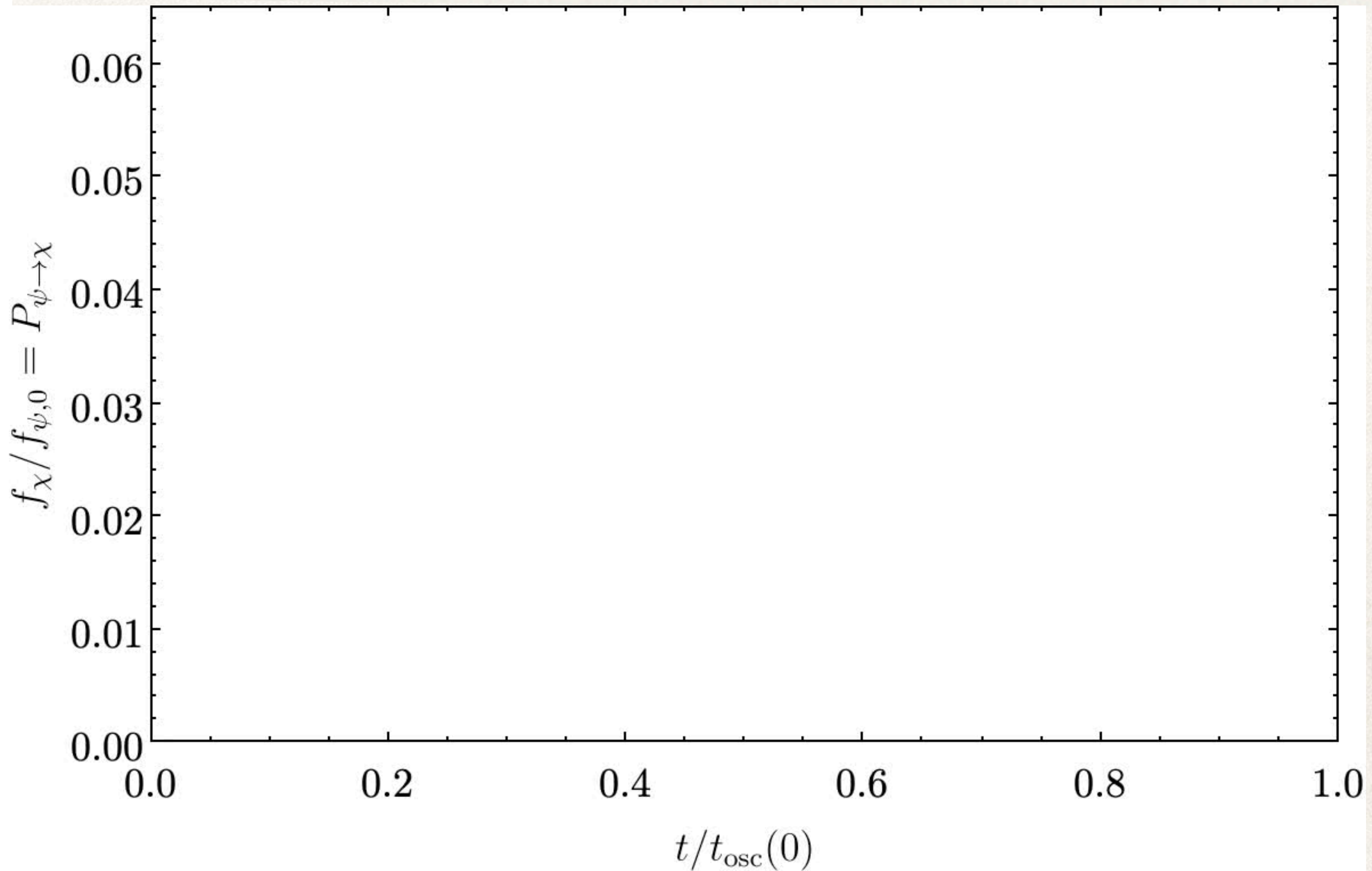
ROMP mixing vector. "Magnetic field" with $\mathbf{V} = \omega_{\rm osc}(\sin 2\theta \hat{\mathbf{x}} + \cos 2\theta \hat{\mathbf{z}})$





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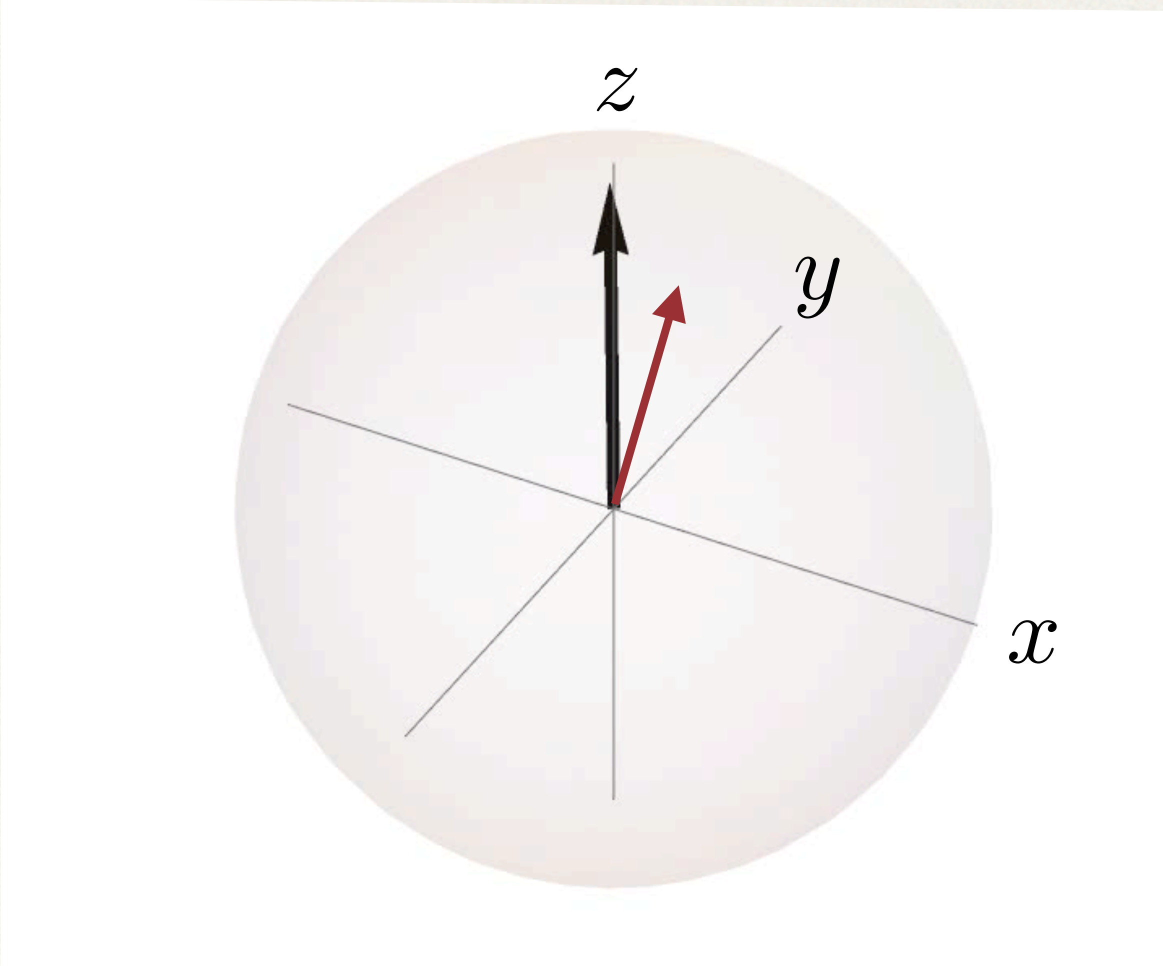

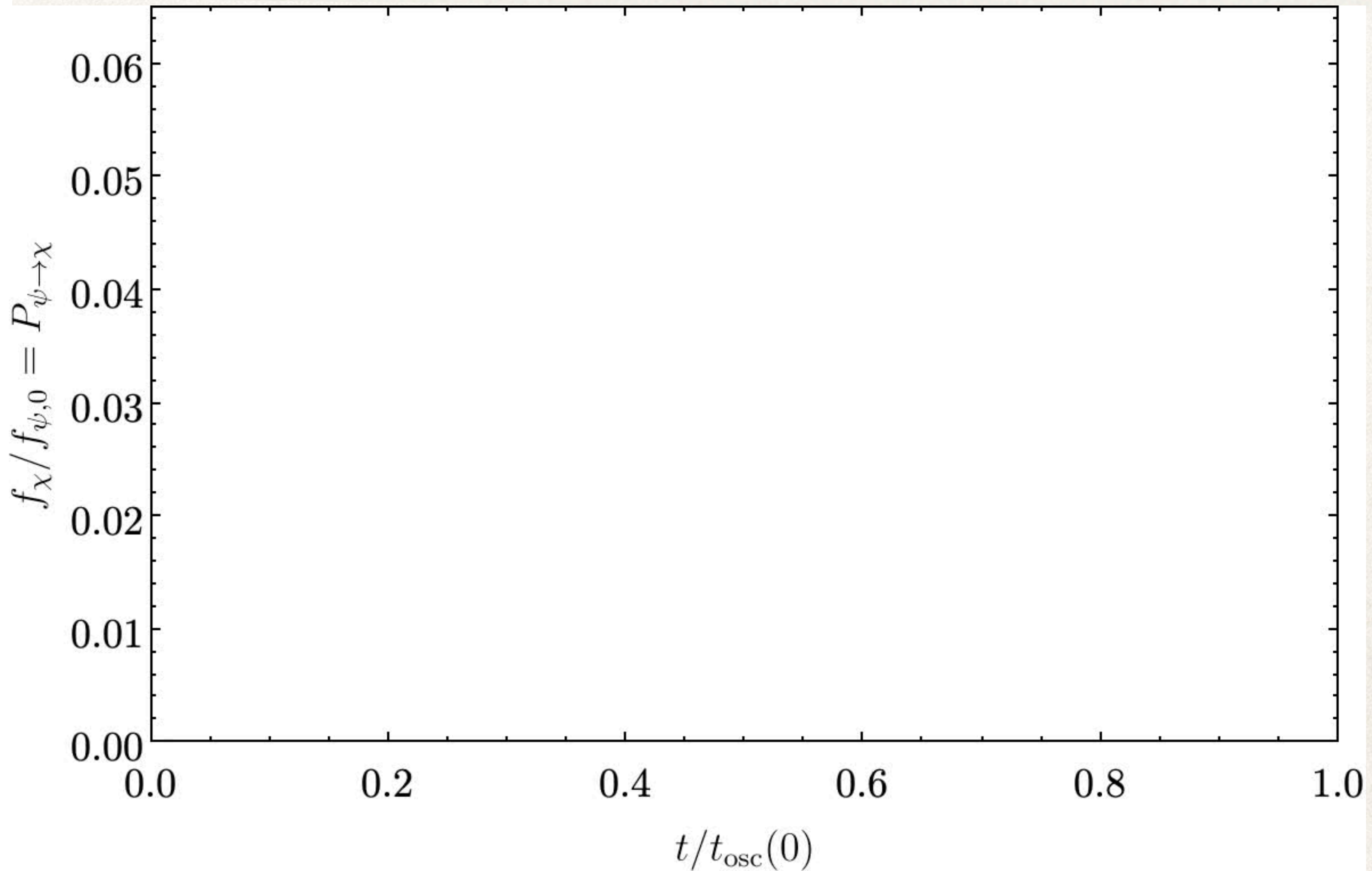

$$\frac{f_\chi}{f_{\psi,0}} = P_{\psi\to\chi} = \frac{1}{2}\sin^2 2\theta(1 - \cos\omega_{\rm osc} t)$$

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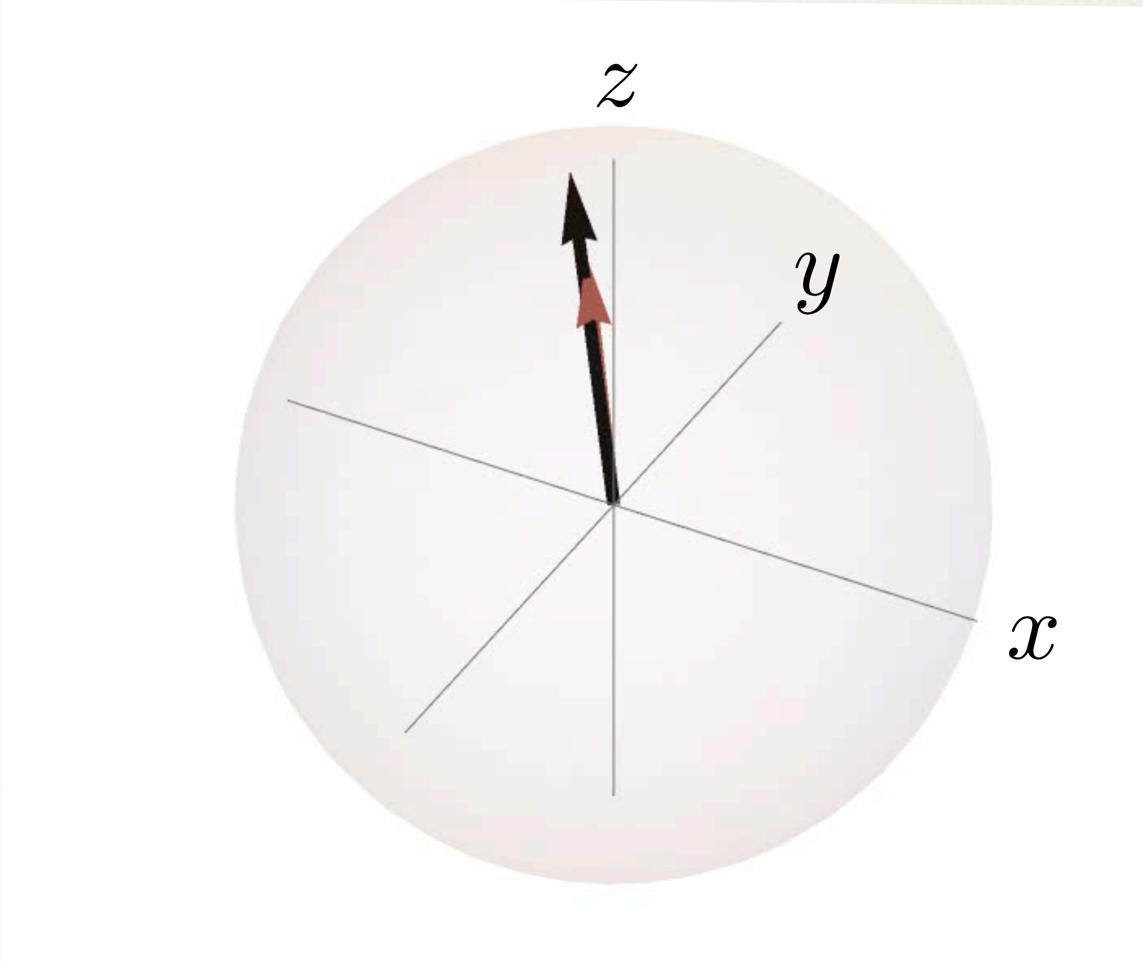
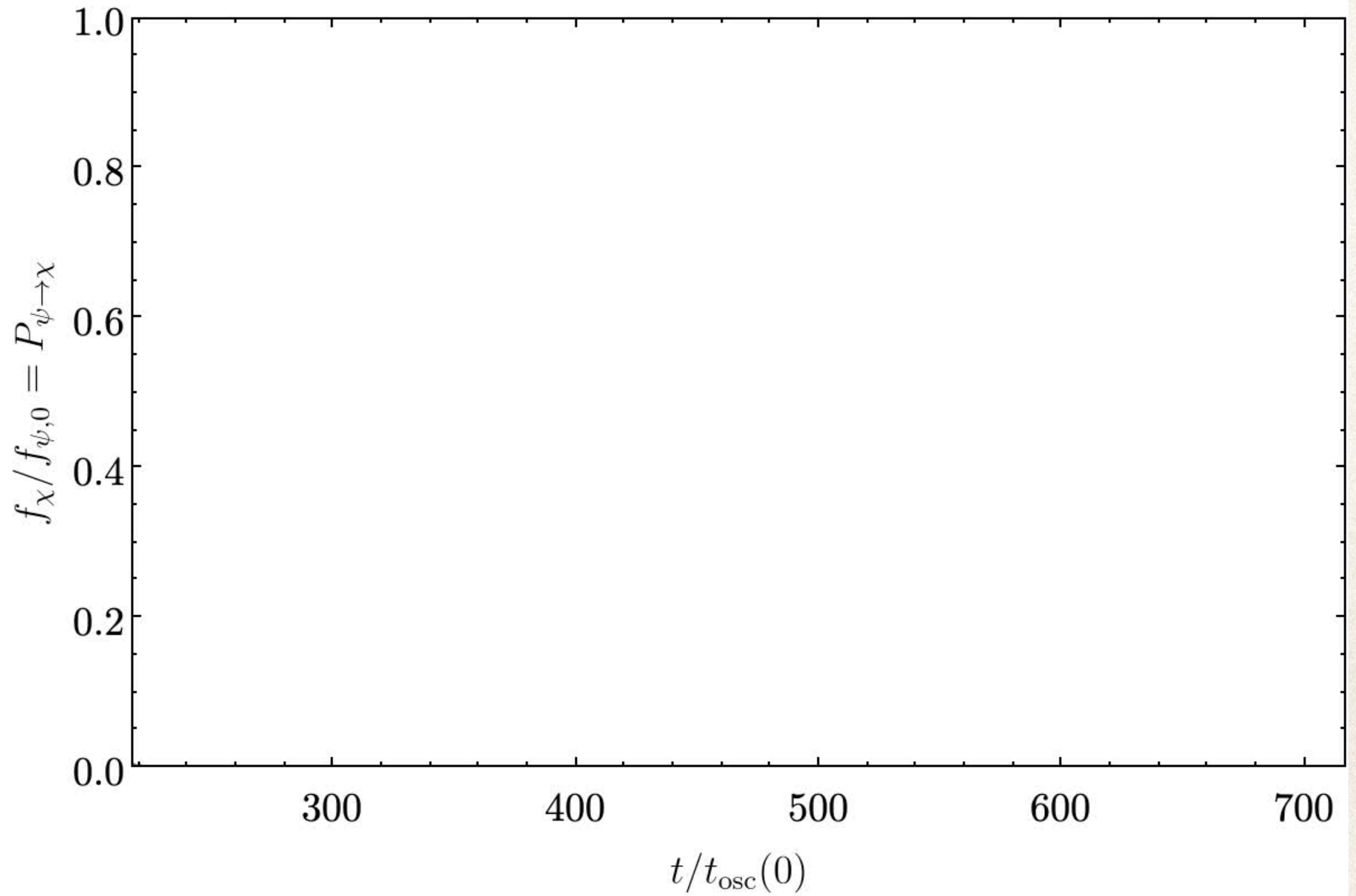
Time-dependent mixing angle





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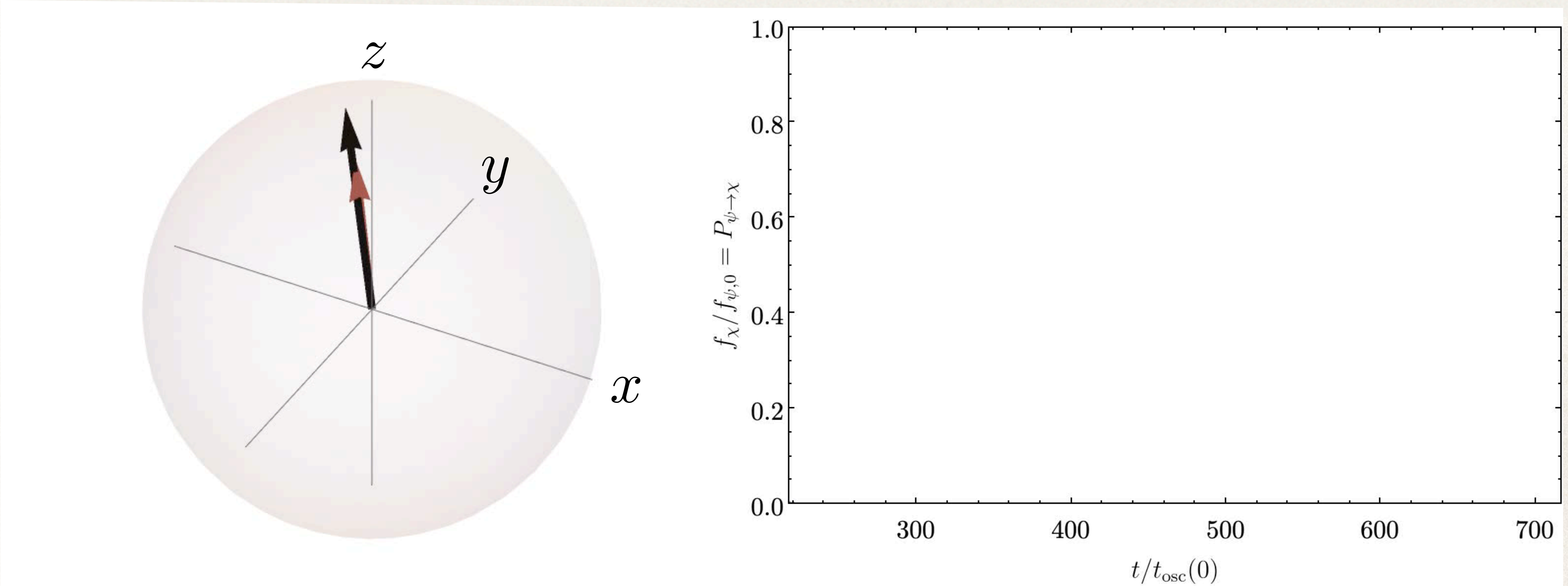

$$\frac{f_\chi}{f_{\psi,0}} = P_{\psi\to\chi} = 1 - \exp(-\pi\gamma/2)$$

$$\gamma = \frac{\delta t_{\rm res}}{\Delta t_{\rm osc}|_{t_{\rm res}}}$$

> 1 Adiabatic

< 1 Non-Adiabatic

Landau '32; Zener '33

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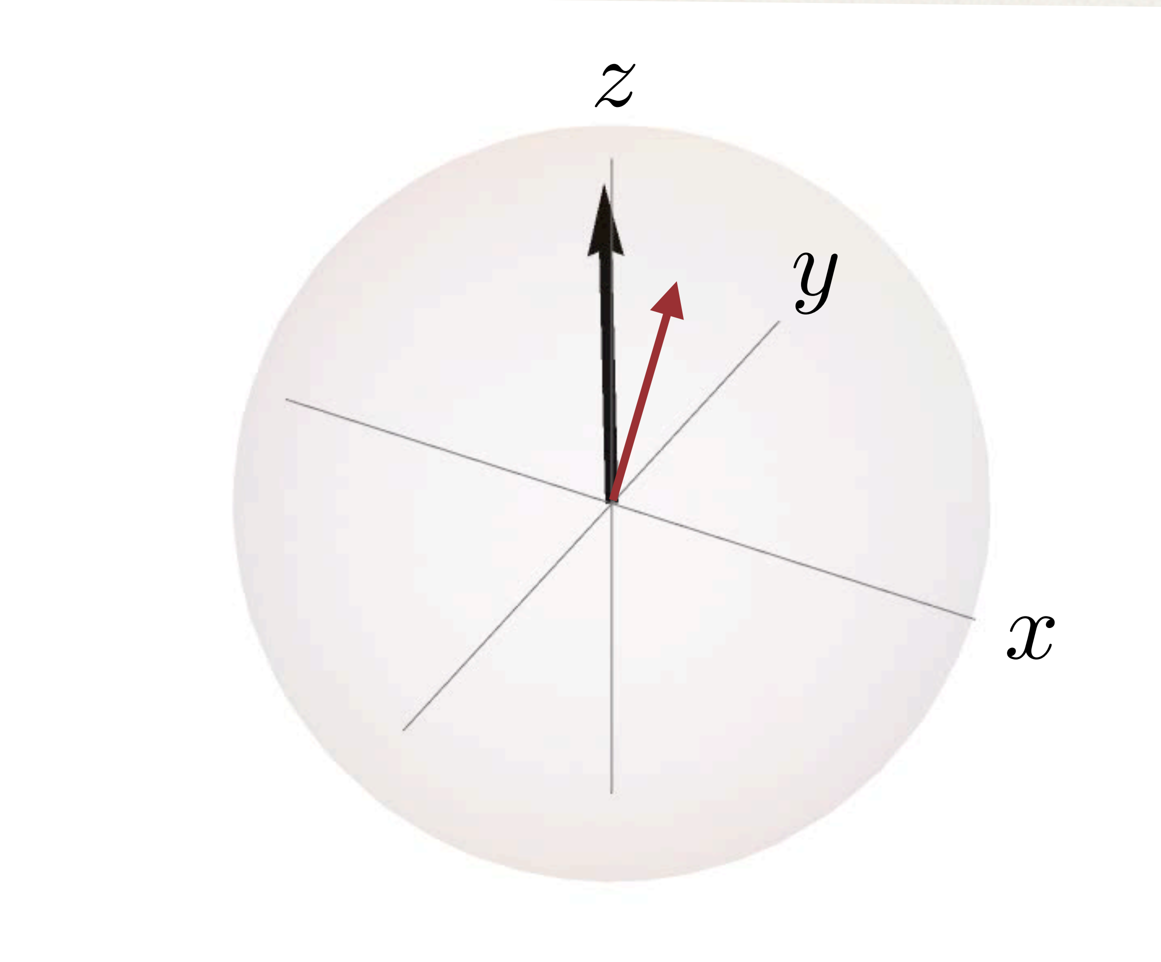
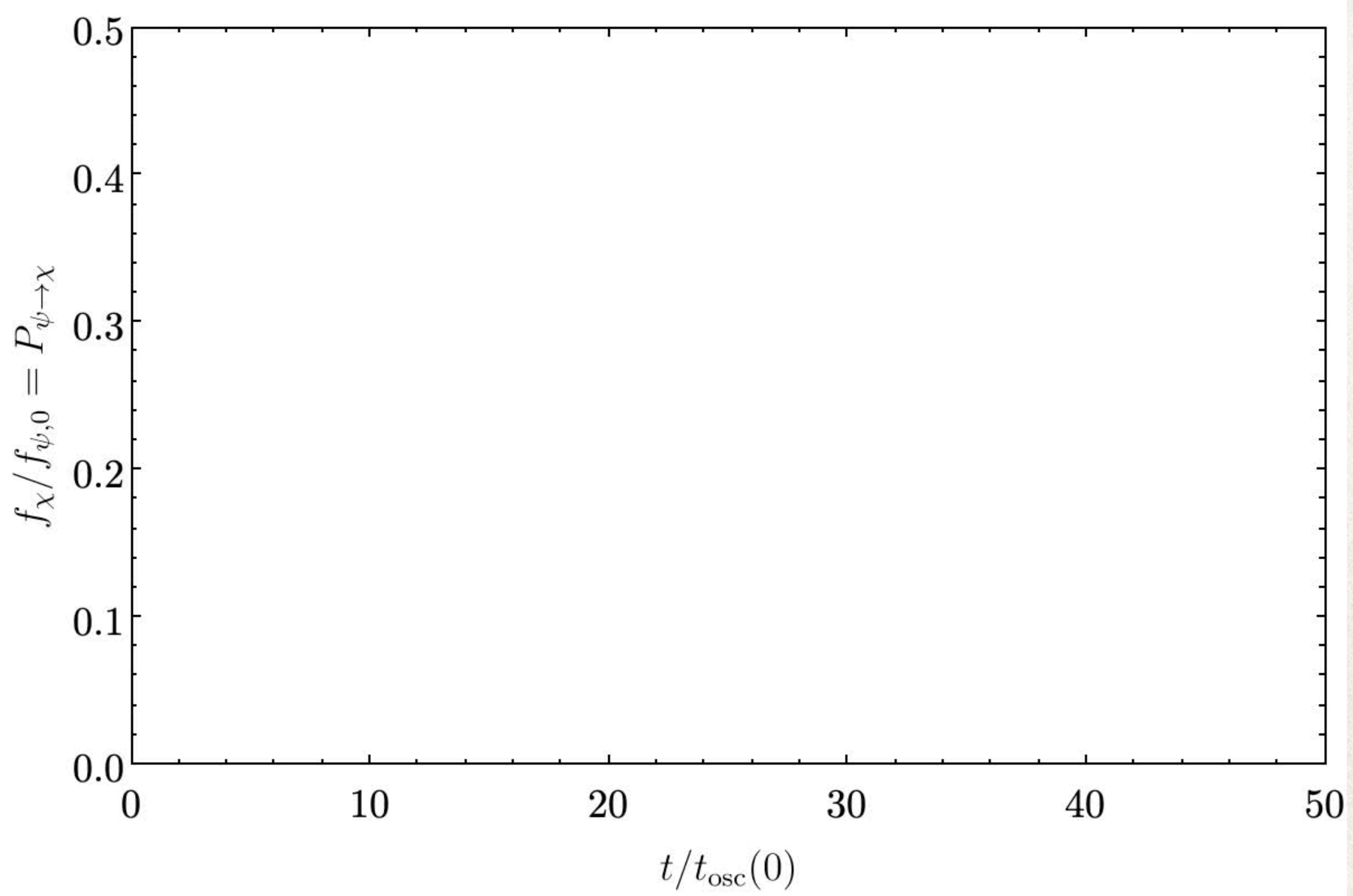
$$D = \frac{1}{2}\Gamma_\psi$$

(Reduces $|\mathbf{P}|$, making ROMP a mixed state)





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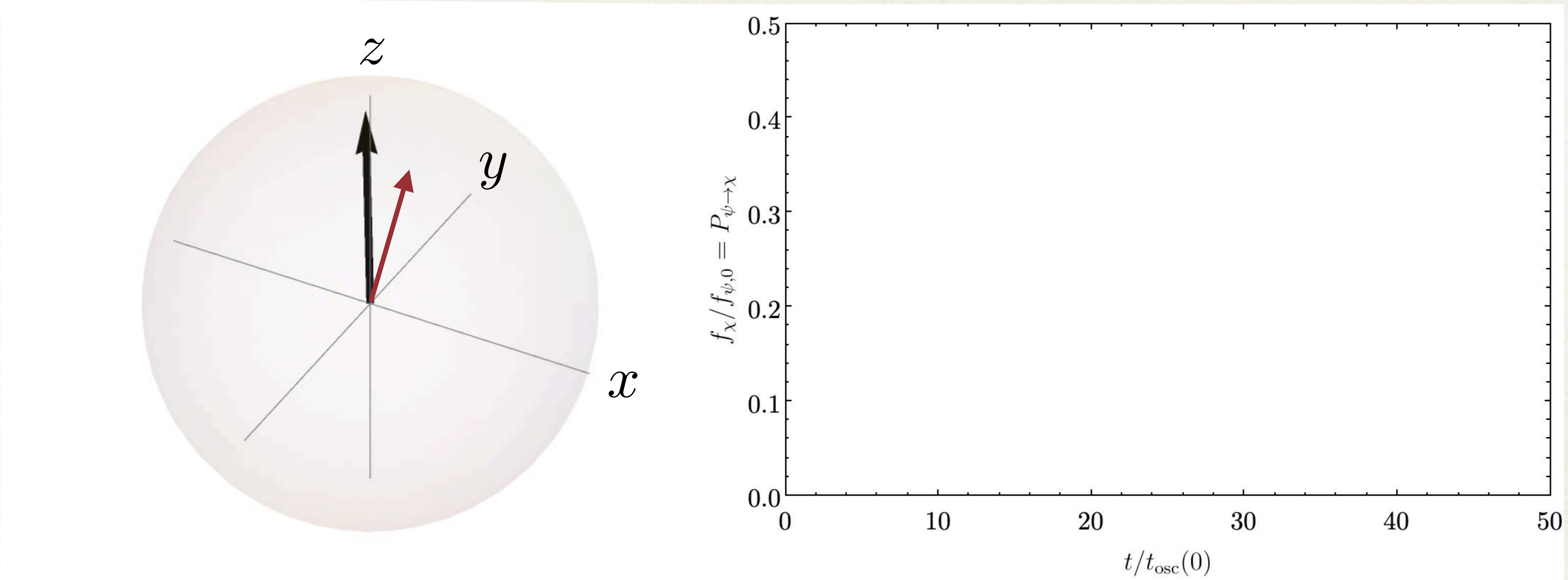


$$\dot{f}_\chi = \frac{1}{4}\Gamma_\psi \sin^2 2\theta (f_\psi - f_\chi)$$

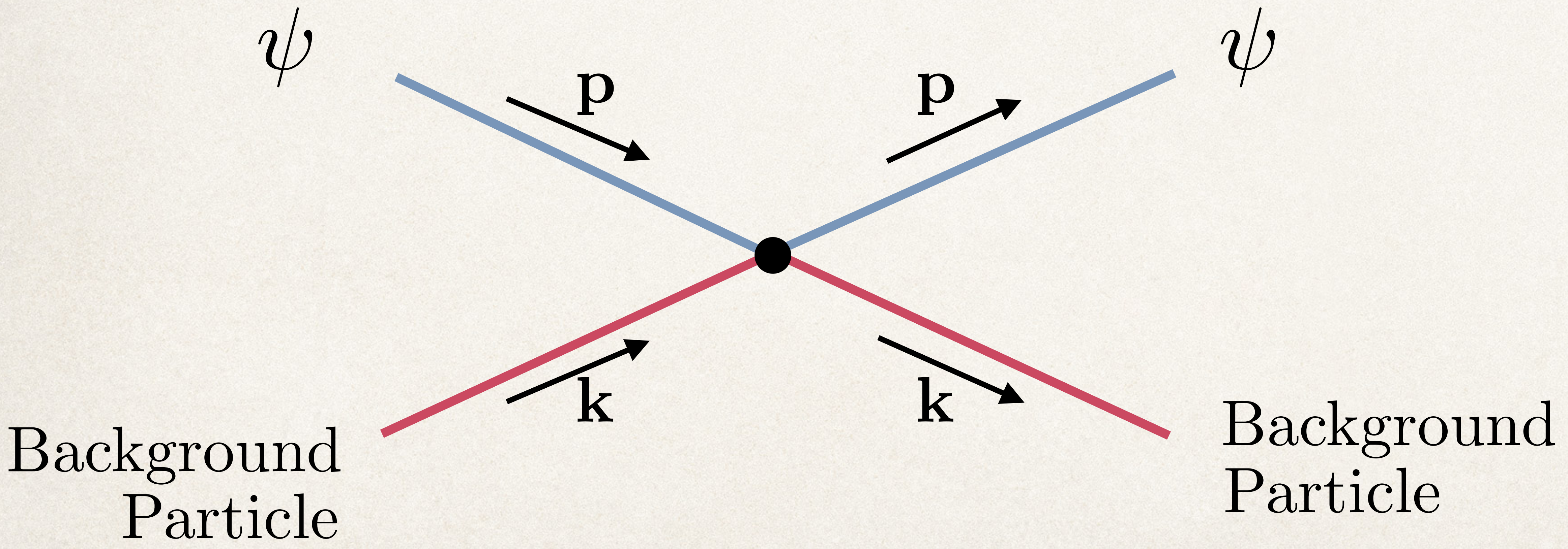
$\times$ suppression factor when damping strong

$+$ transient oscillatory factor

In-Medium Masses

$$\mathbf{M}^2_{\text{eff}} = \begin{pmatrix} m_\psi^2 + m_T^2 & m_{\psi\chi}^2 \\ m_{\psi\chi}^2 & m_\chi^2 \end{pmatrix}$$

Forward Scattering



$$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\text{bg}}}{2E_{\text{bg}}(\mathbf{k})} \right\rangle = \int \frac{\mathcal{M}(0)}{2E_{\text{bg}}(\mathbf{k})} f_{\text{bg}}(\mathbf{k}) \frac{d^3\mathbf{k}}{(2\pi)^3}$$

Foldy '45; Langacker, Liu '92

In-Medium Masses

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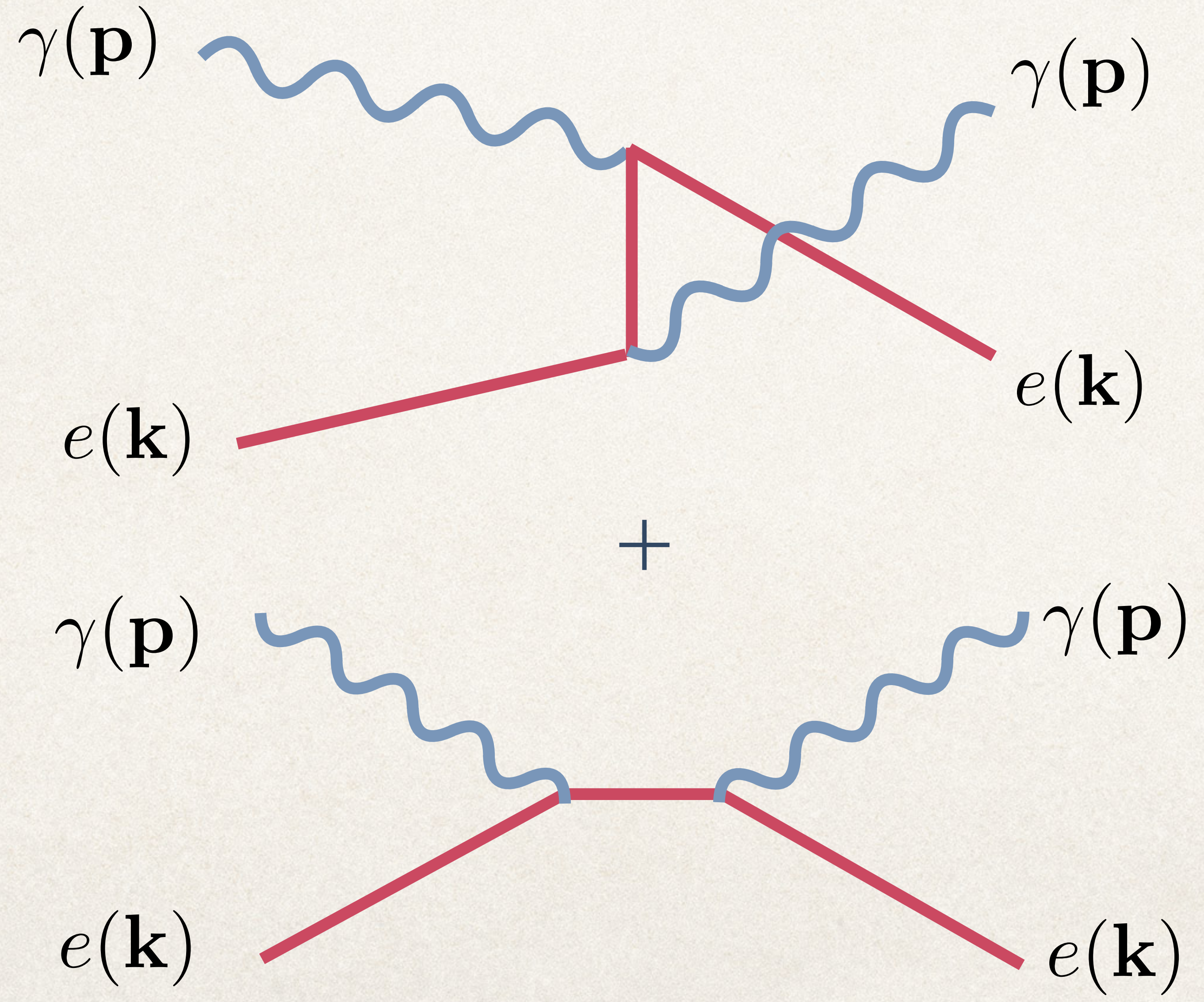
Example: Photon Forward Scattering



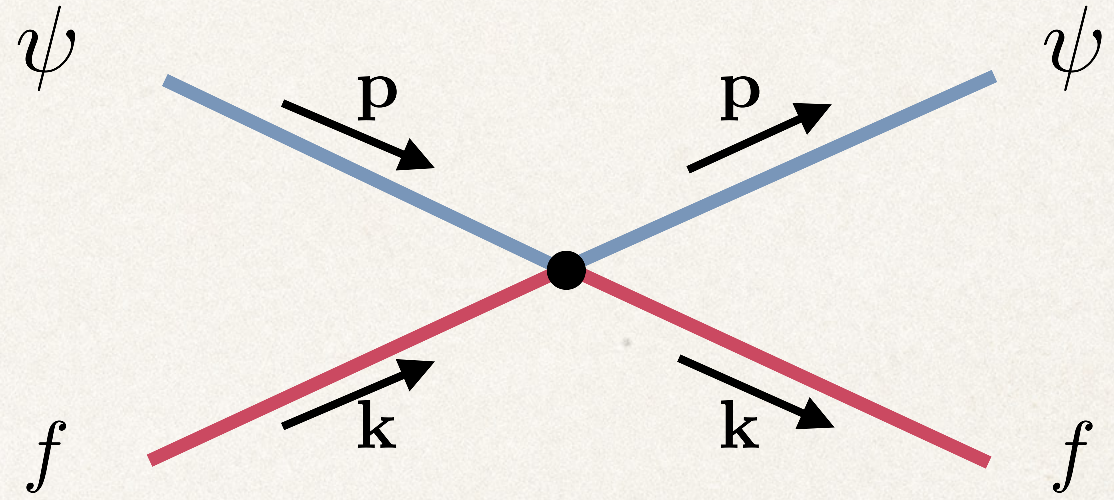
$$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\text{bg}}}{2E_{\text{bg}}(\mathbf{k})} \right\rangle \sim \frac{\alpha n_e}{m_e}$$

(Non-relativistic plasma limit)

Example ROMP Calculation: Thermal Mass

$$\mathcal{L}_6 = \frac{1}{\Lambda^2}(\bar{f}\gamma^\mu P_L \psi) g_{\mu\nu} (\bar{\psi}\gamma^\nu P_L f) \qquad \mathcal{L}_8 = \frac{1}{\Lambda^4}(\bar{f}\gamma^\mu P_L \psi)(g_{\mu\nu} q^2 + q_\mu q_\nu)(\bar{\psi}\gamma^\nu P_L f)$$

Dim-6 $$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\text{bg}}}{2E_{\text{bg}}(\mathbf{k})} \right\rangle \sim \frac{T^2}{\Lambda^2}\frac{1}{T} n_f$$



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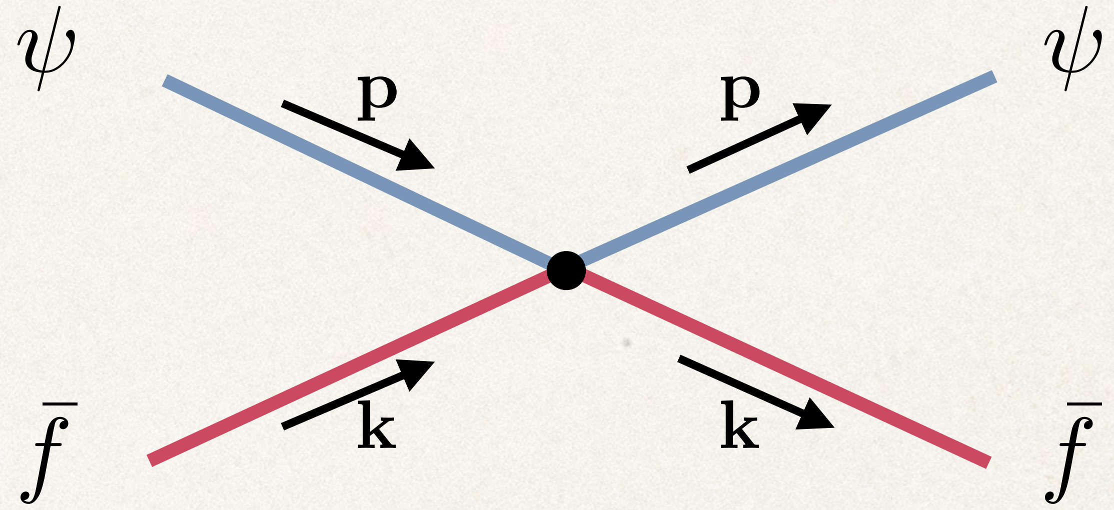

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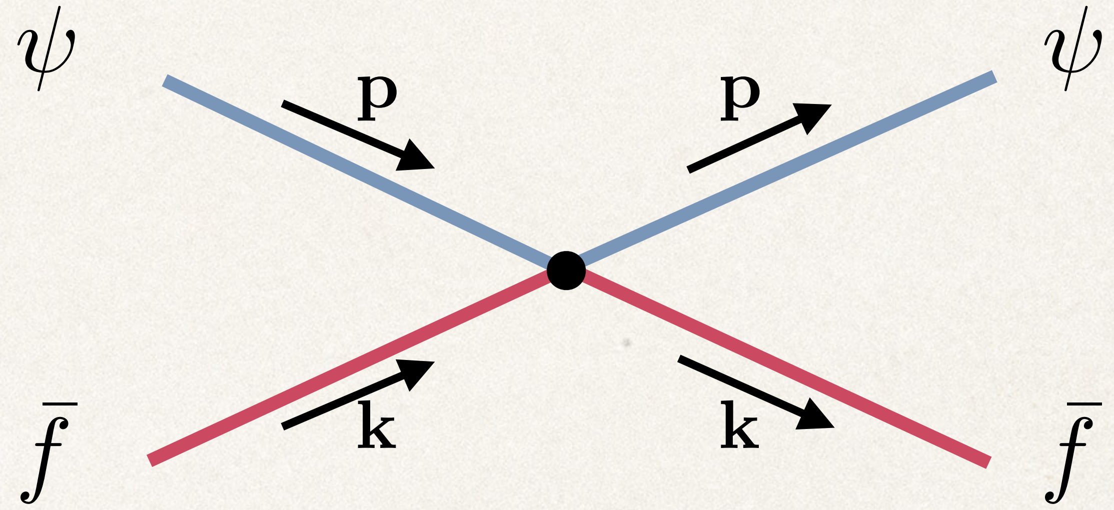


Dim-8 $$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\text{bg}}}{2E_{\text{bg}}(\mathbf{k})} \right\rangle \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_f + n_{\bar{f}})$$

$$\tan 2\theta = \frac{\sin 2\theta_0}{\cos 2\theta_0 + \frac{m_T^2}{m_1^2 - m_2^2}}$$

Example ROMP Calculation: Incoherent Production

- For ROMPs, production maximized when $m_T^2 = m_1^2 - m_2^2 \qquad (T = T_{\rm osc})$

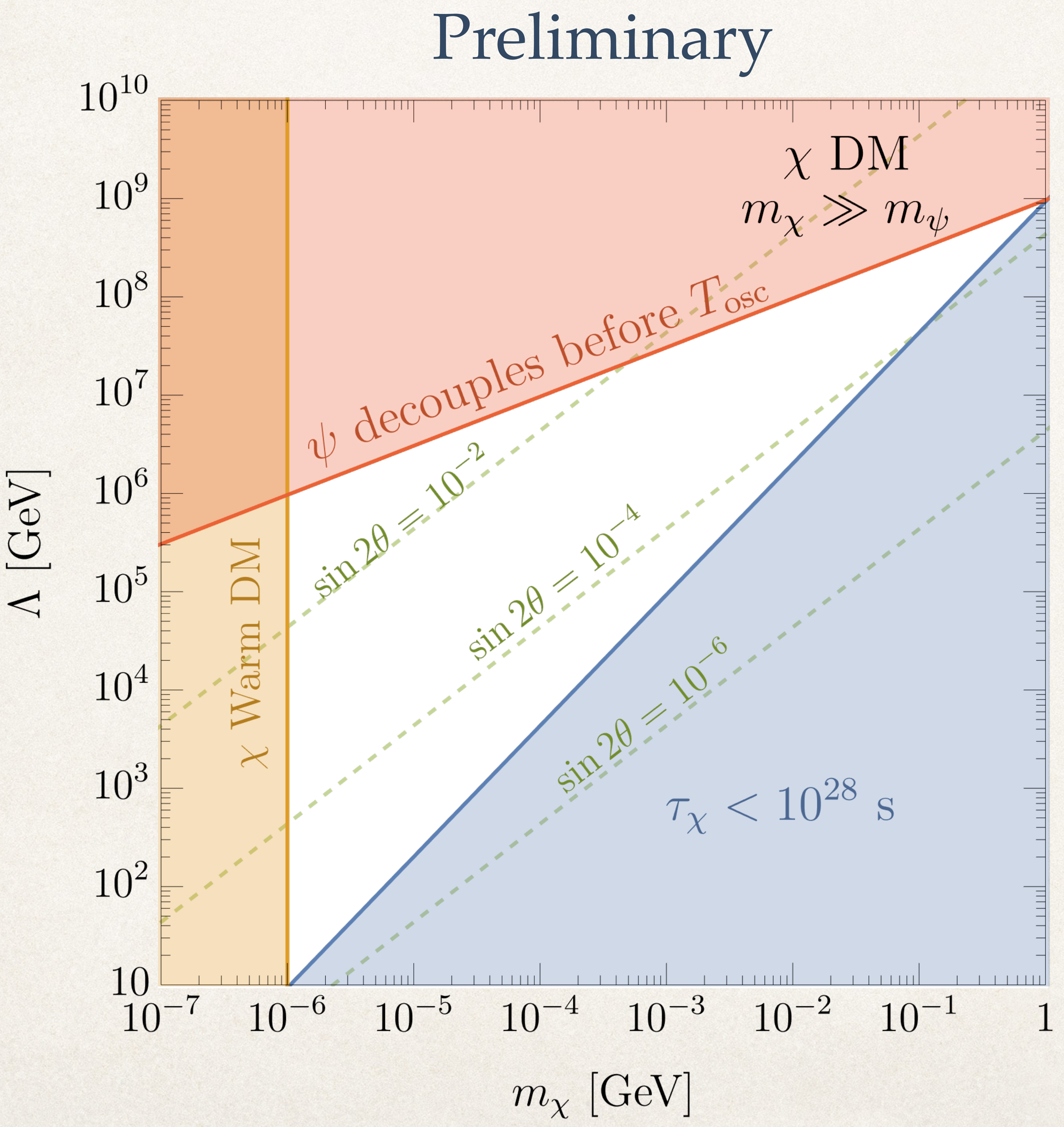
Dim-8 $$m_T^2 = \left\langle \frac{\mathcal{M}(0)\, n_{\rm bg}}{2E_{\rm bg}(\mathbf{k})} \right\rangle \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_f + n_{\bar{f}})$$

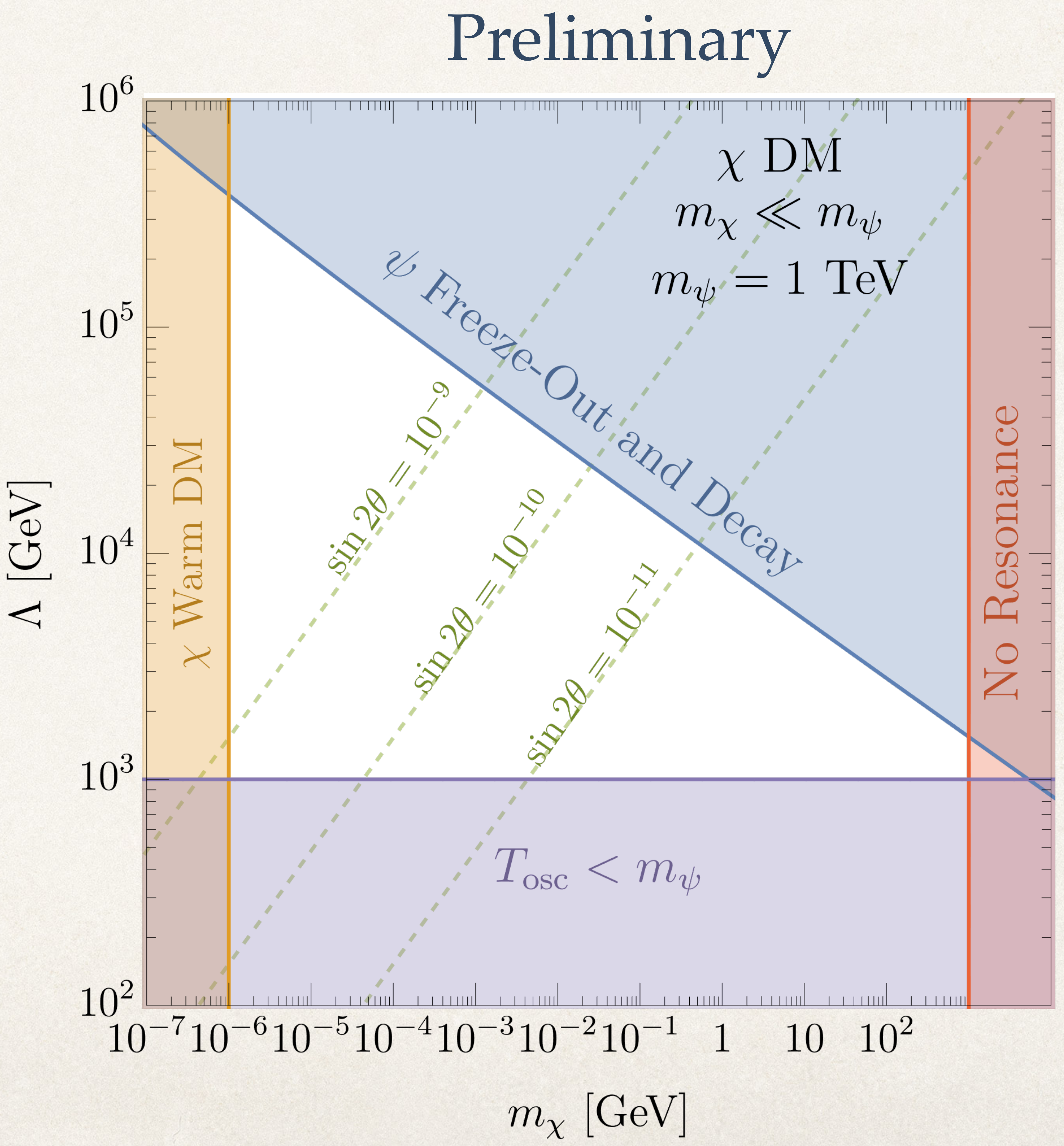
↓

$$T_{\rm osc} \sim 500\,{\rm MeV}\left(\frac{\Lambda}{100\,{\rm GeV}}\right)^{2/3}\left(\frac{{\rm Max}\{m_\psi, m_\chi\}}{100\,{\rm keV}}\right)^{1/3}$$

- Boltzmann limit of QKE ⟶ $Y_\chi \approx Y_\psi \frac{\Gamma_\psi \sin^2 2\theta_0}{H}\Big|_{T_{\rm osc}}$

Example ROMP Calculation: Parameter Space





Summary

- Simple framework for calculating production of ROMPs in early universe
- New temperature where production dominates, T_{osc}, where $m_T^2 = m_1^2 - m_2^2$
- Quantum mechanical effects like Landau-Zener also arise in ROMP models
- Variety of other interesting operators to consider, like scalar exchange
- Potential signals: photons from ROMP decays, warmness, collider bounds for small Λ