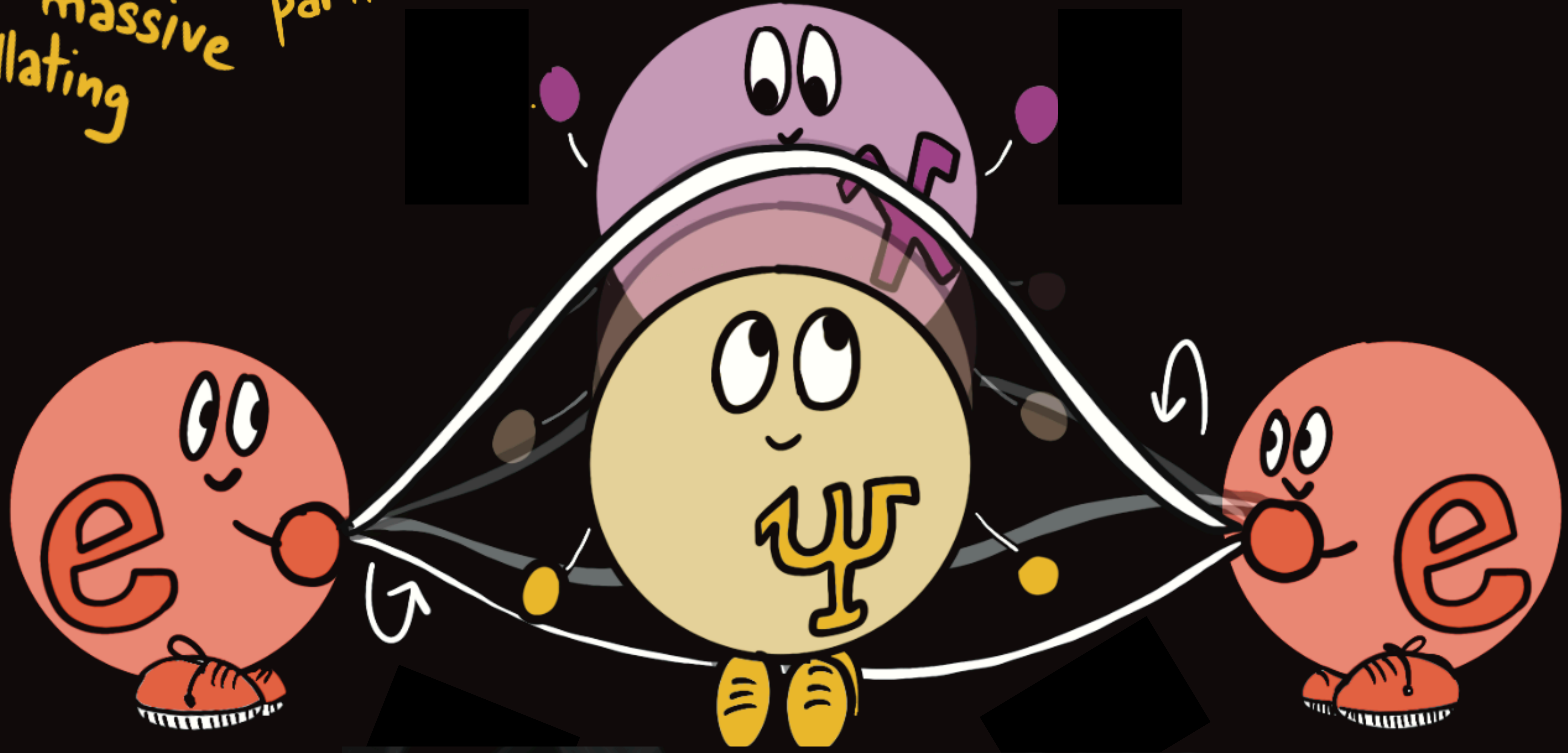
ROMP DARK MATTER

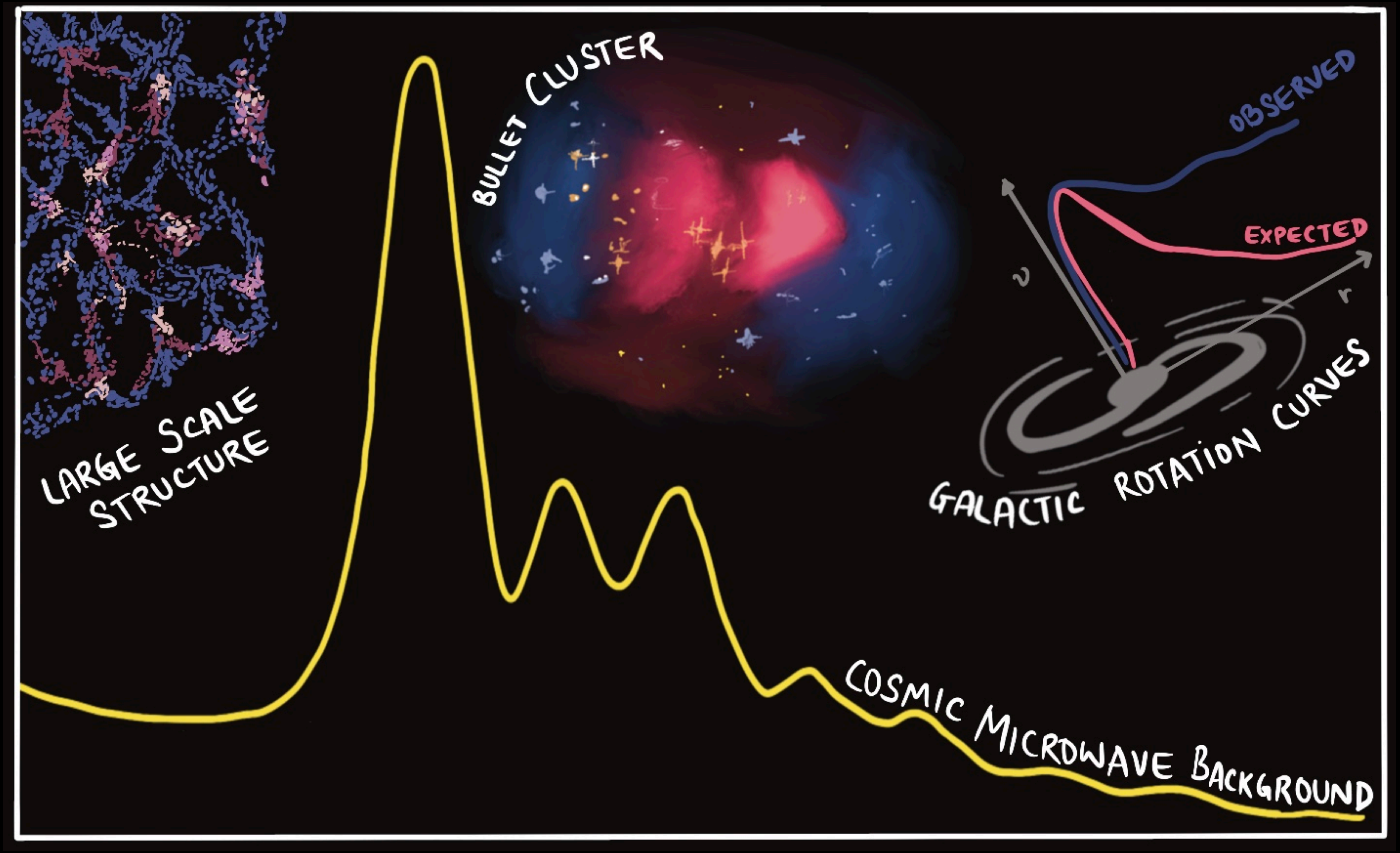
rapidly oscillating massive particle



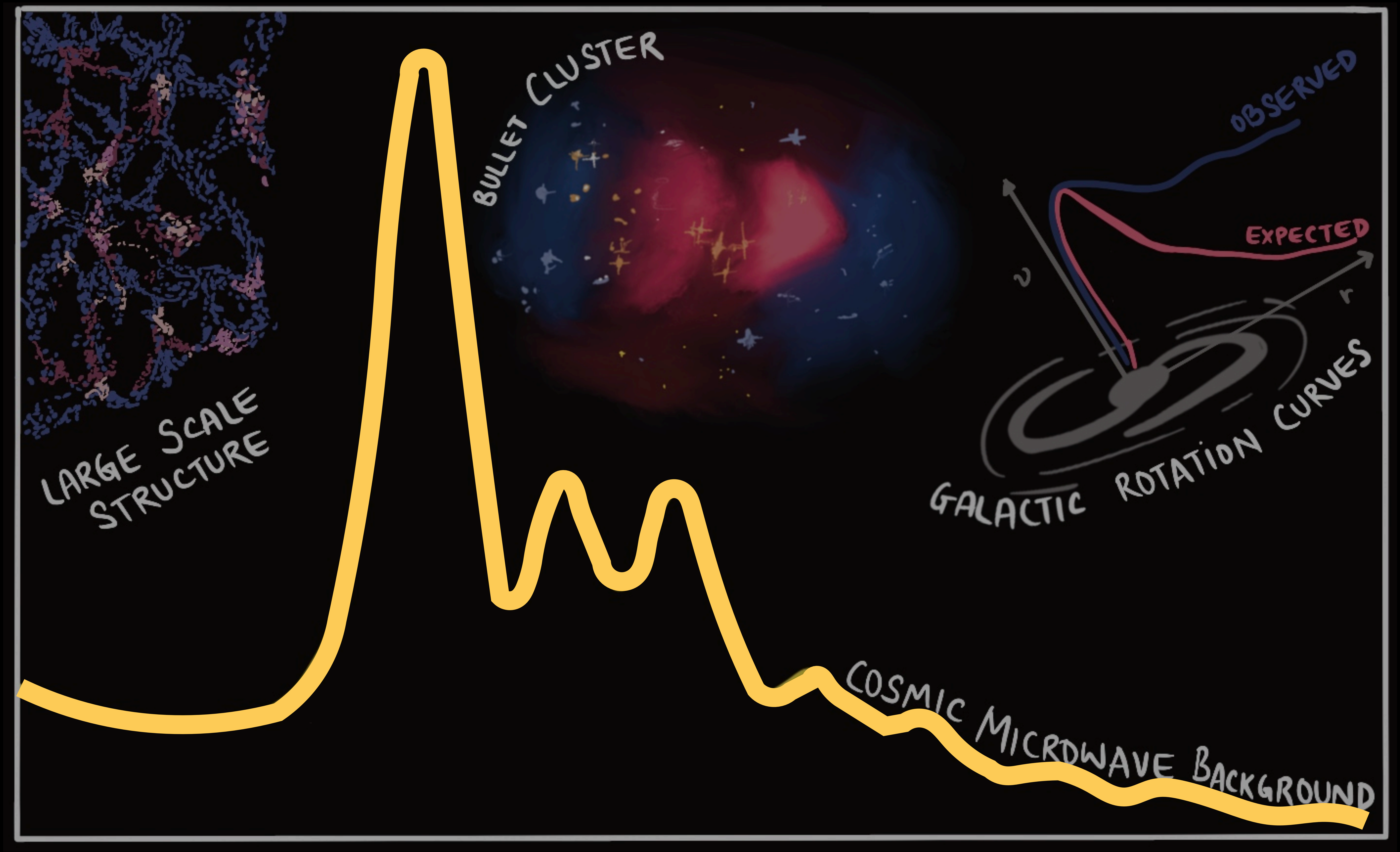
SANIYA HEEBA (McGILL U.)

Ongoing work w/ D. Dunsky & J. Ruderman (NYU)

WE KNOW THAT DARK MATTER EXISTS



FROM THE CMB: $\Omega_{\mathrm{DM}}h^2 = 0.12$

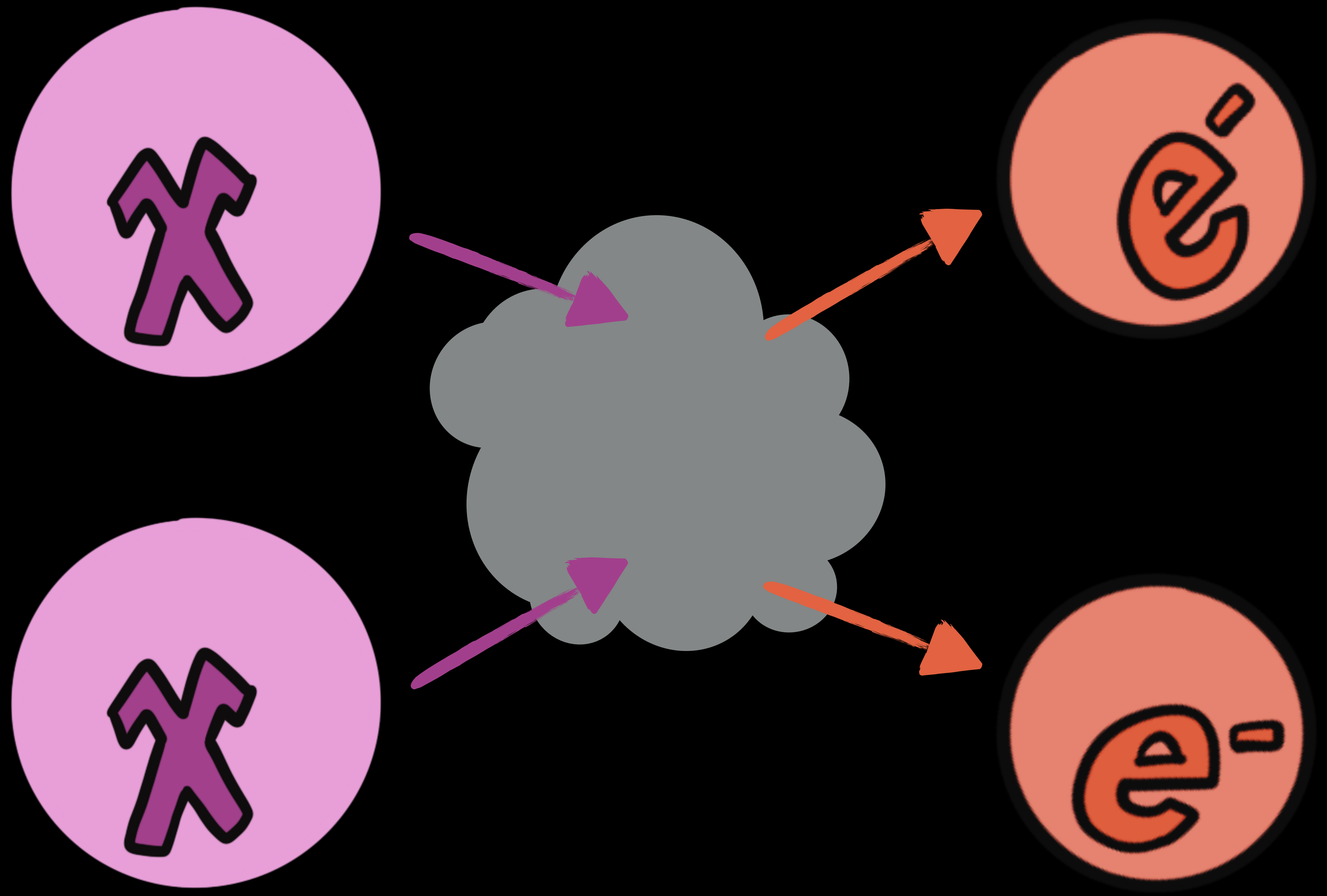


HOW IS DM PRODUCED IN THE EARLY UNIVERSE?

HOW IS DM PRODUCED IN THE EARLY UNIVERSE?

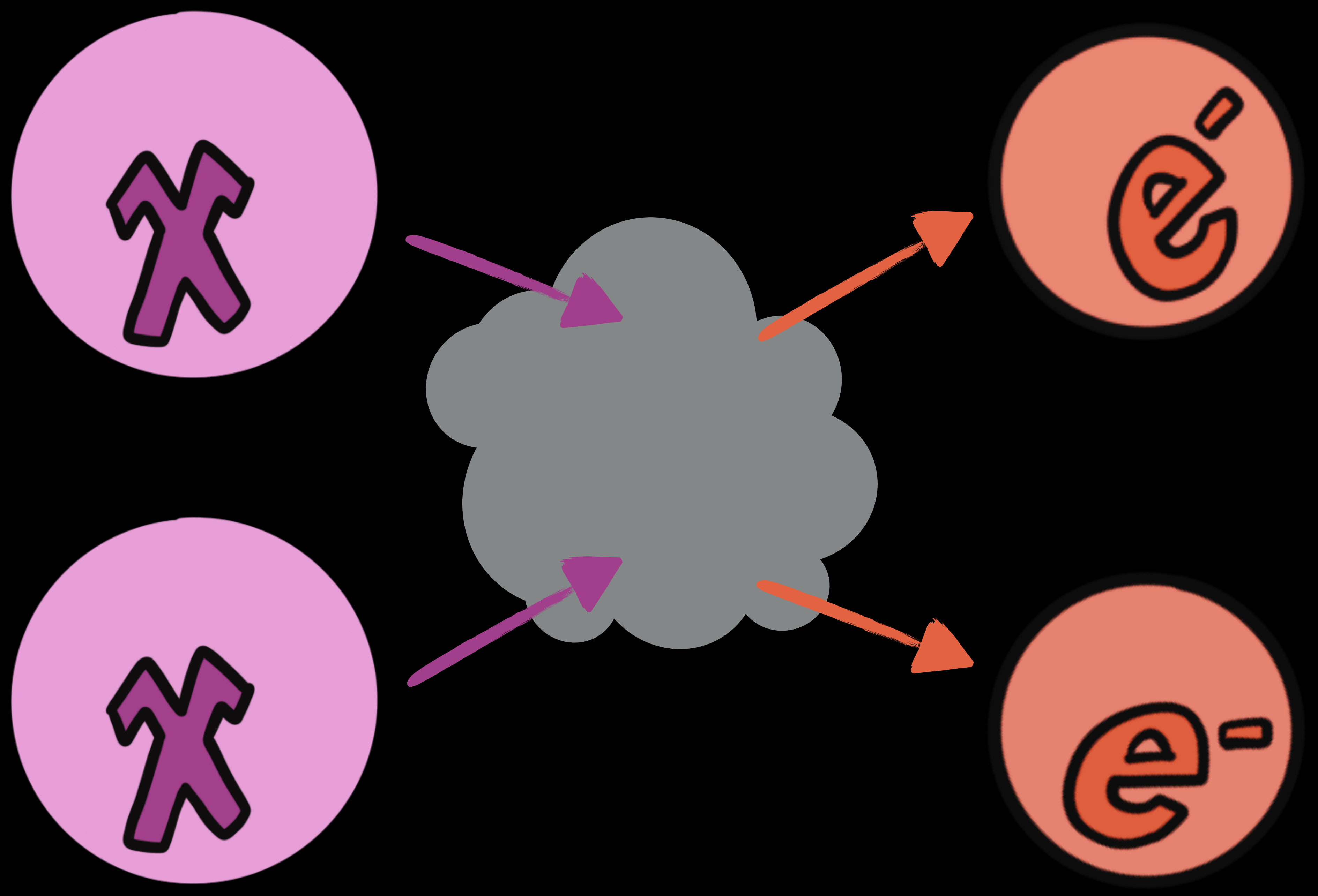
IF DARK MATTER IS THERMALLY COUPLED

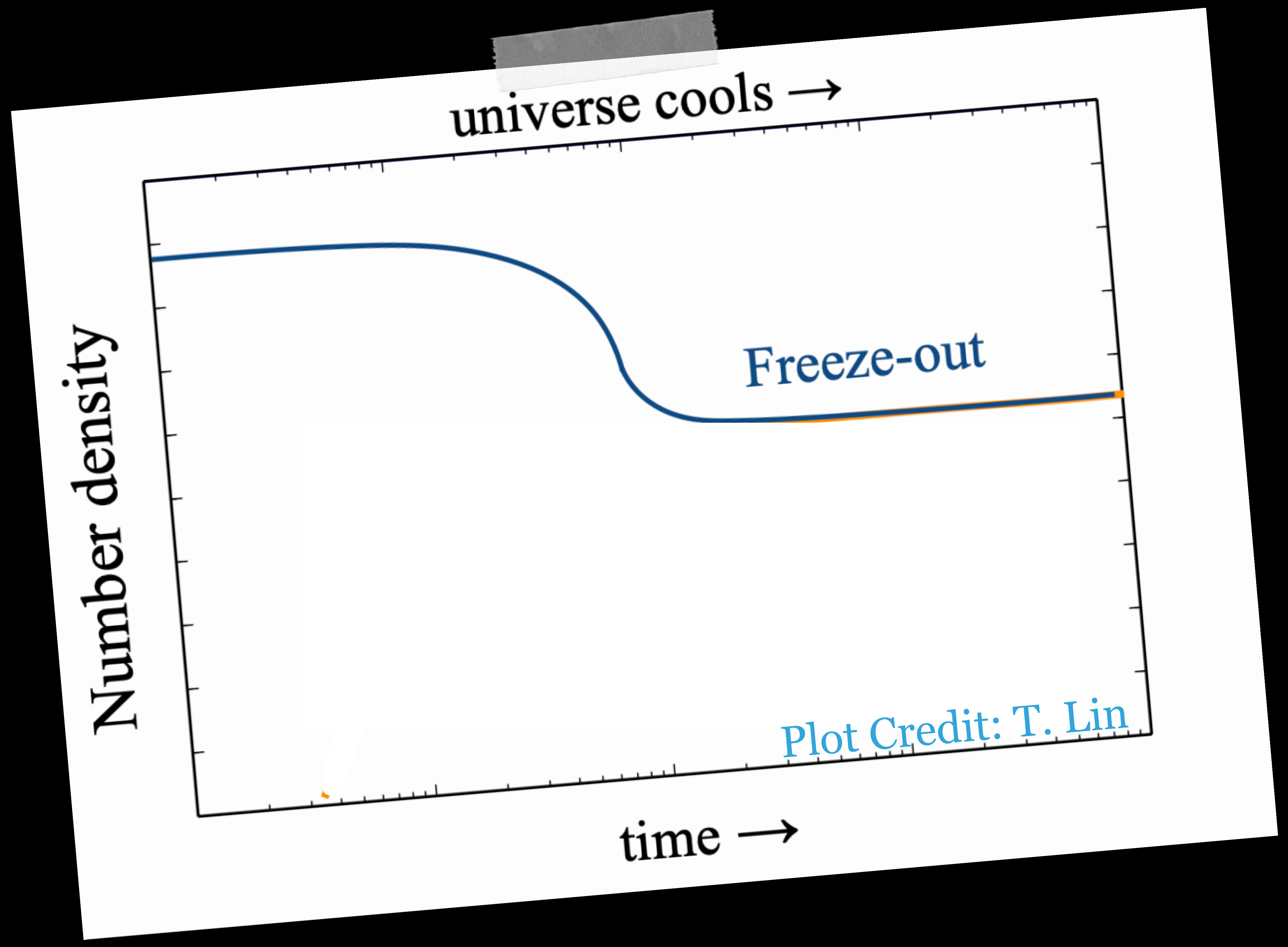
HOW IS DM PRODUCED IN THE EARLY UNIVERSE?



IF DARK MATTER IS THERMALLY COUPLED

HOW IS DM PRODUCED IN THE EARLY UNIVERSE?





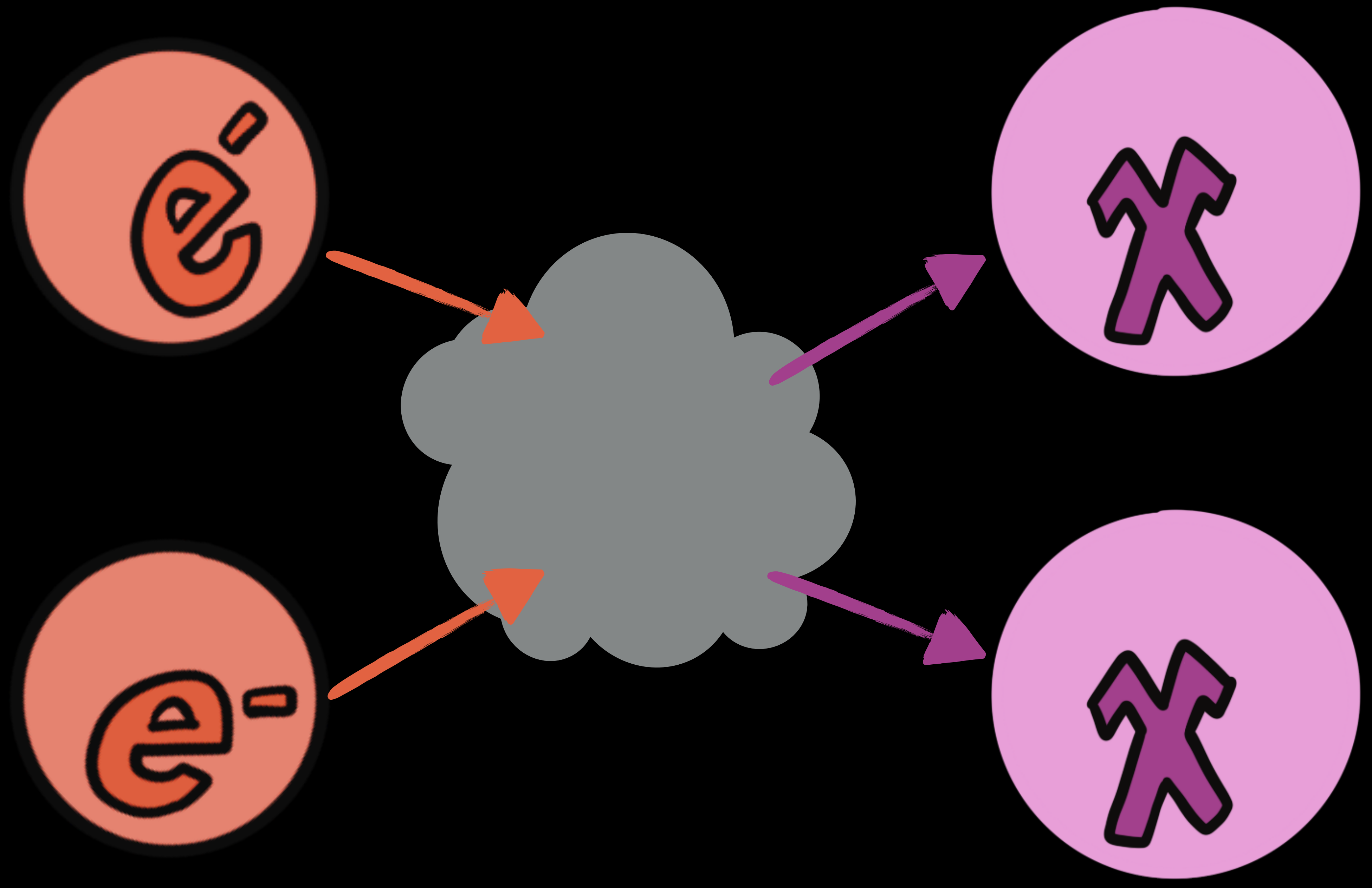
IF DARK MATTER IS THERMALLY COUPLED

HOW IS DM PRODUCED IN THE EARLY UNIVERSE?

HOW IS DM PRODUCED IN THE EARLY UNIVERSE?

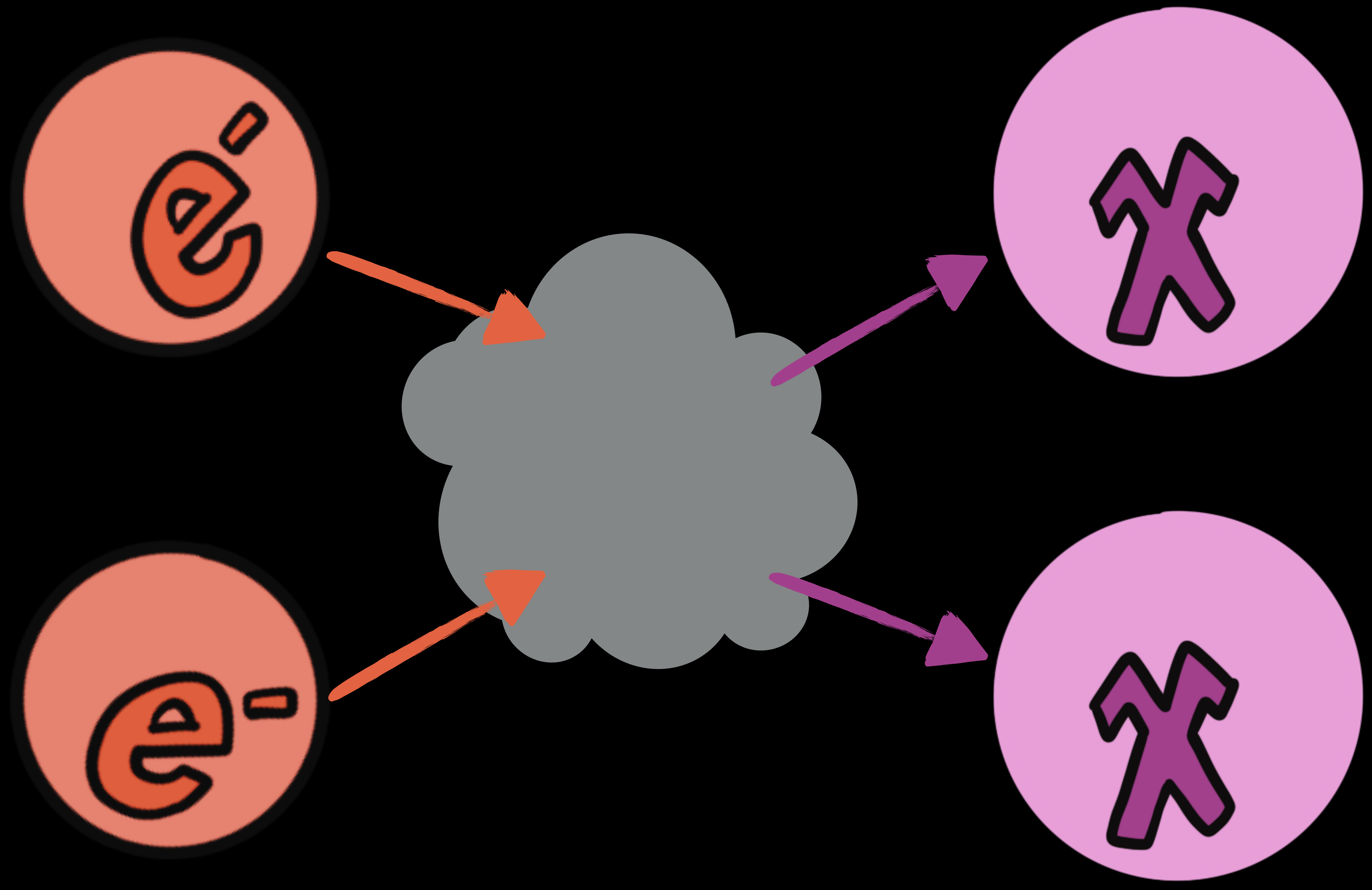
IF DARK MATTER IS THERMALLY DECOUPLED

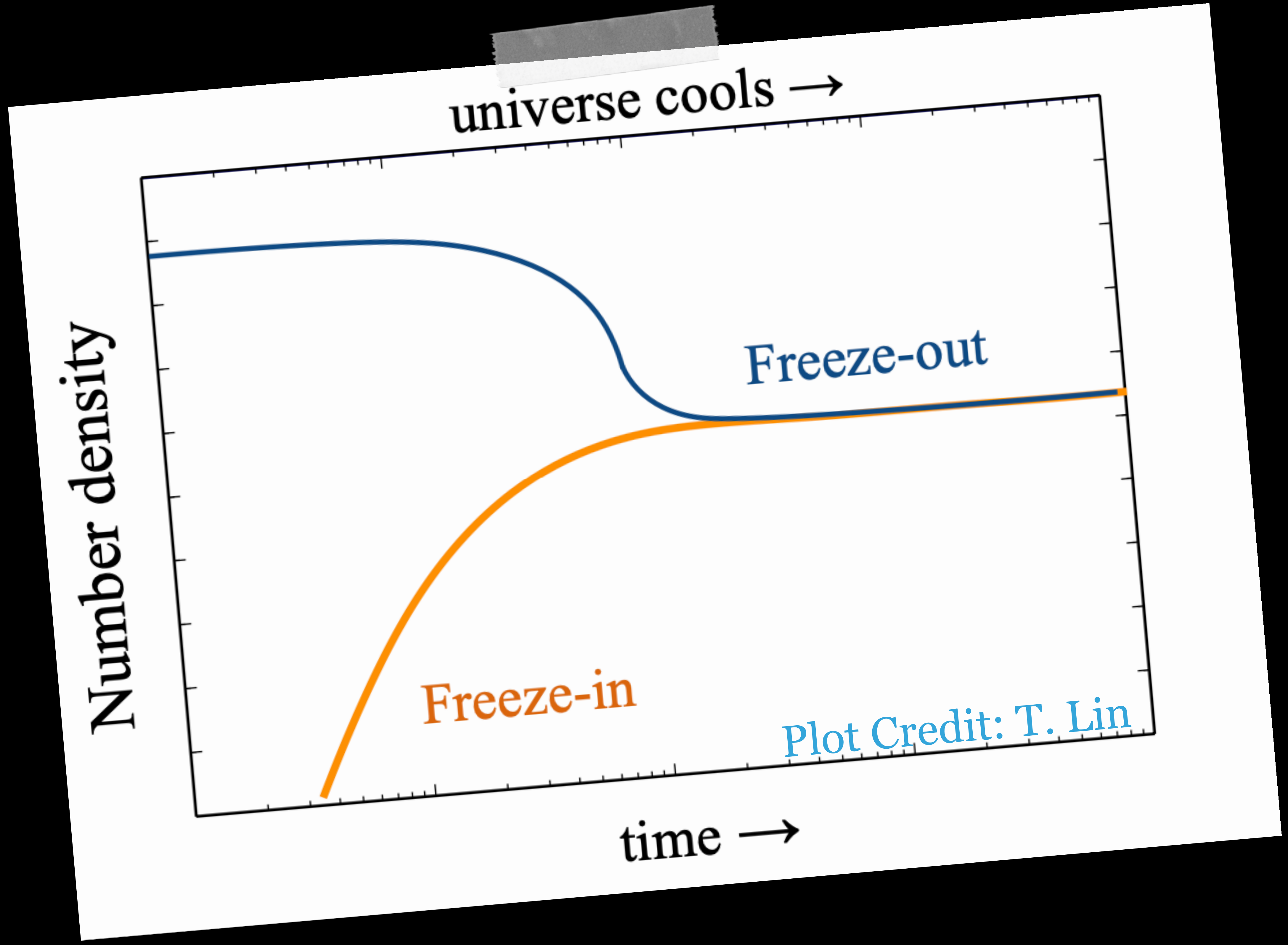
HOW IS DM PRODUCED IN THE EARLY UNIVERSE?



IF DARK MATTER IS THERMALLY DECOUPLED

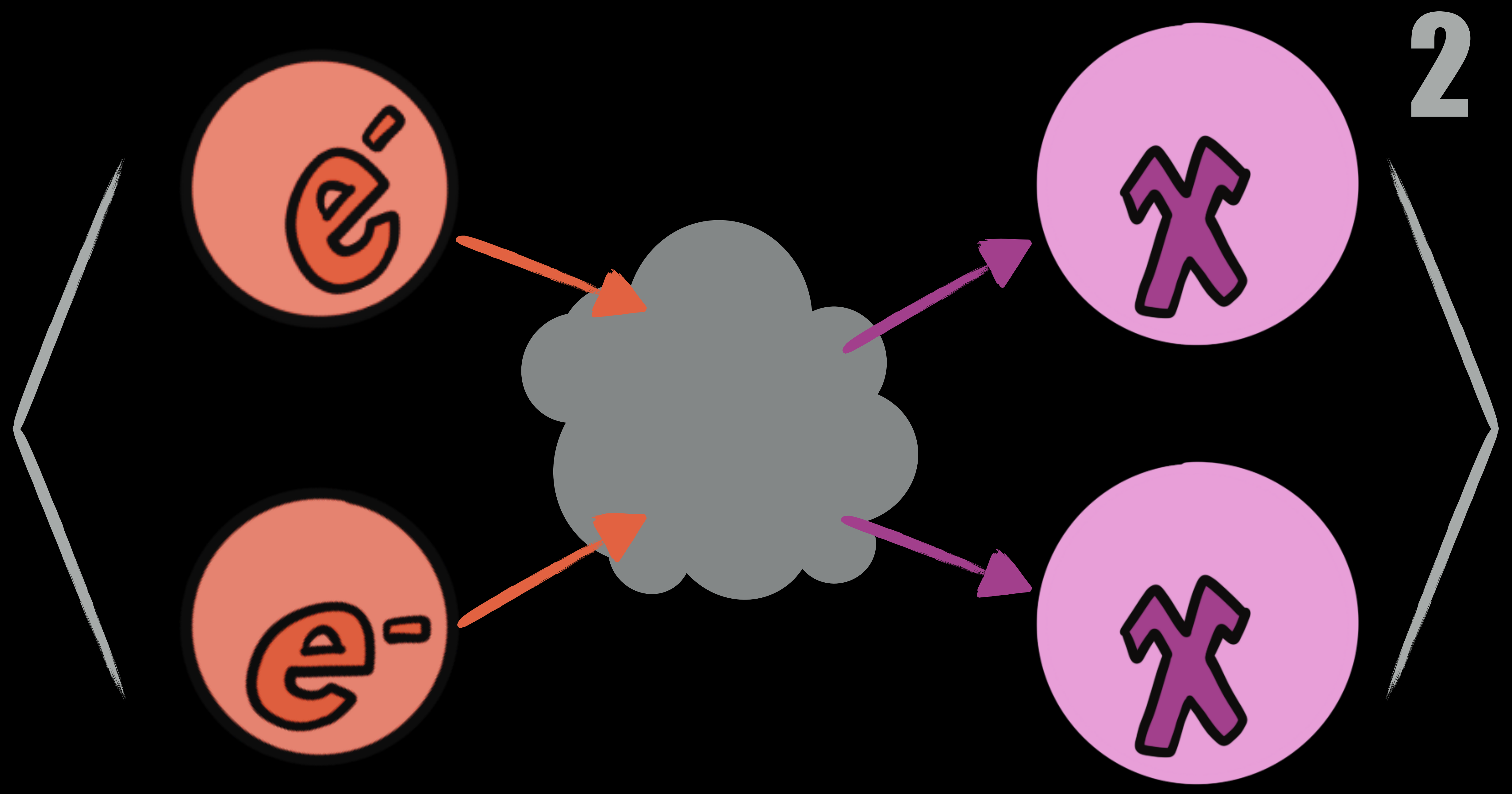
HOW IS DM PRODUCED IN THE EARLY UNIVERSE?





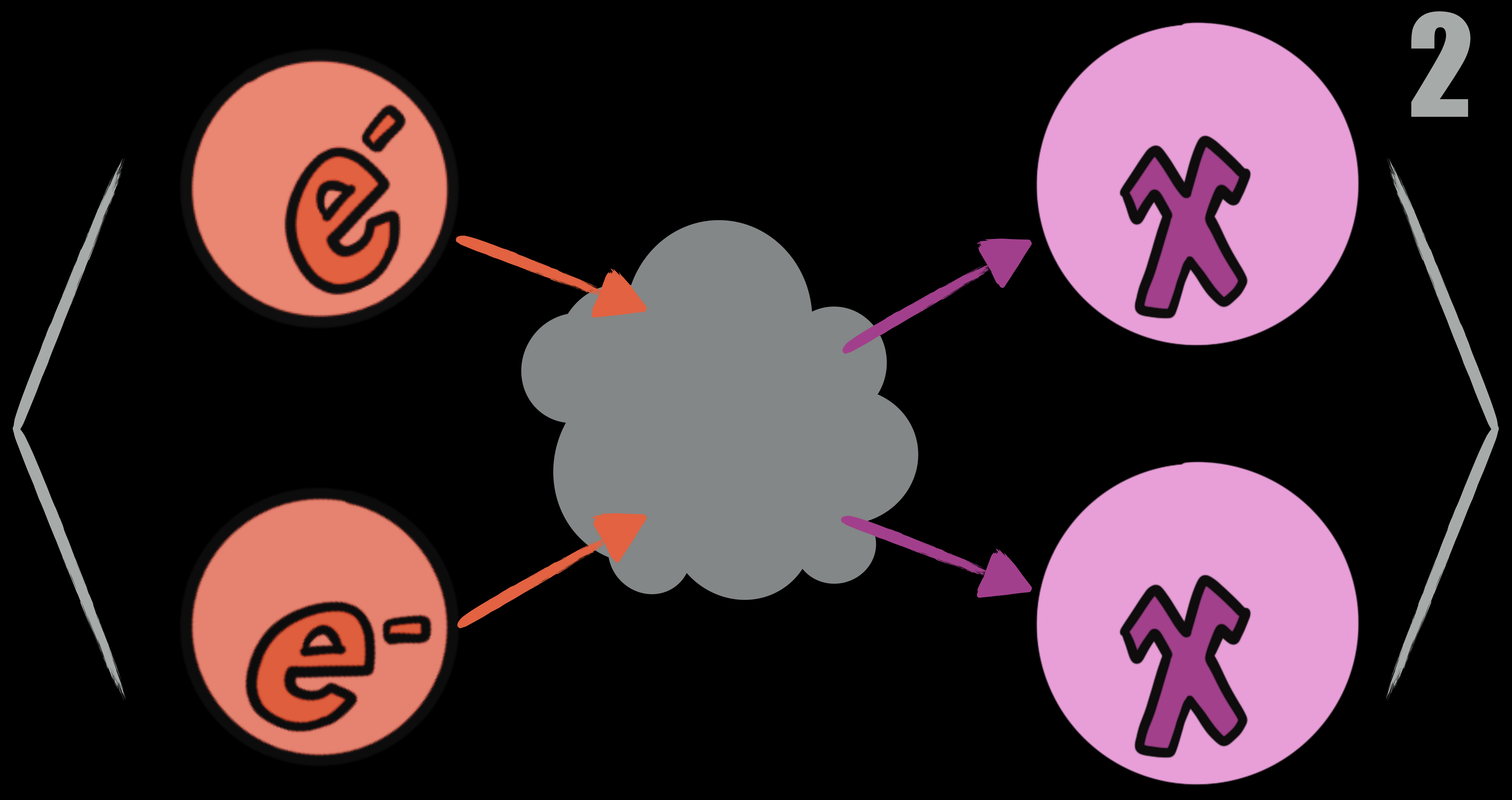
IF DARK MATTER IS THERMALLY DECOUPLED

KEY POINTS:



KEY POINTS:

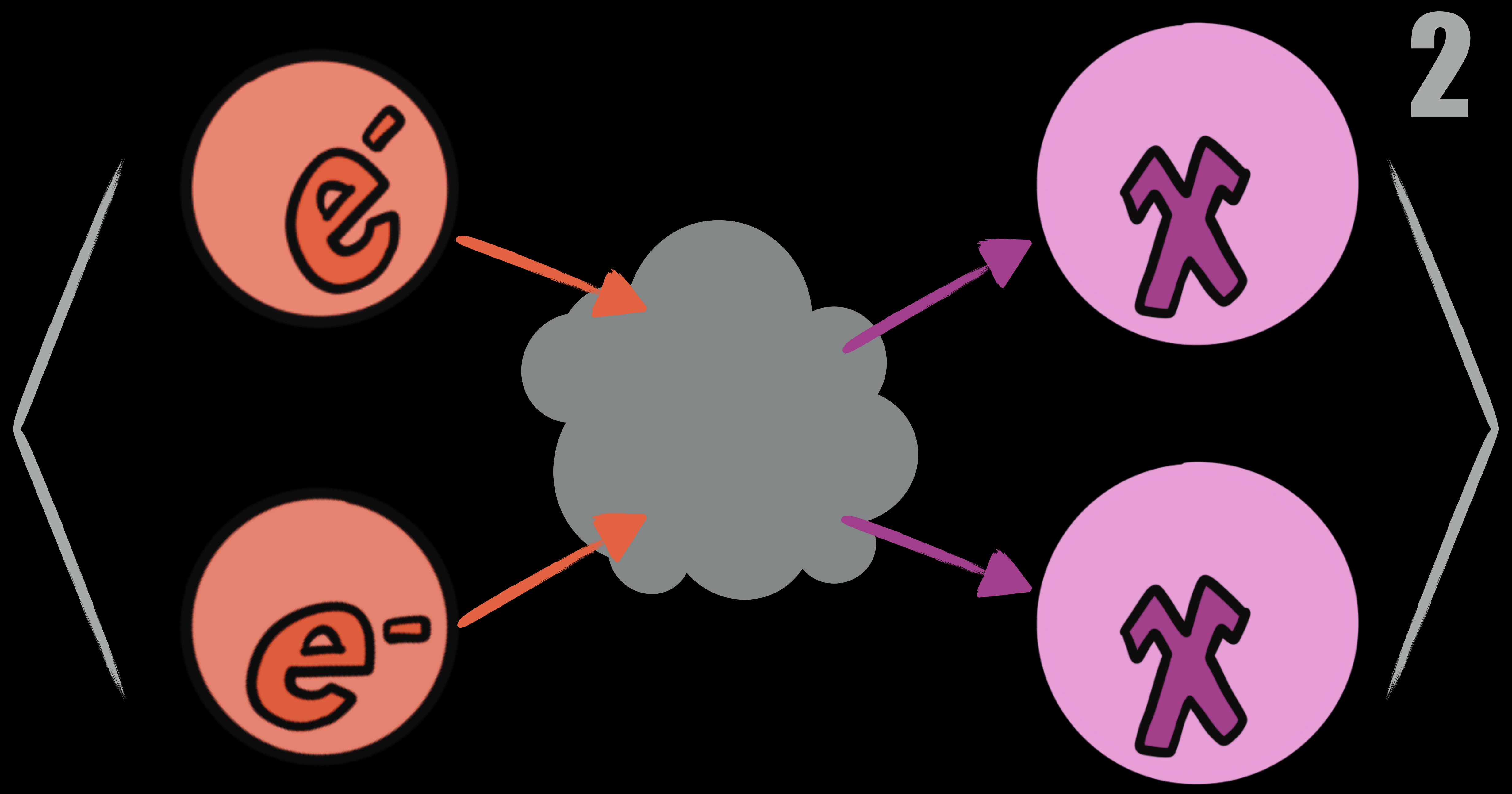
1. Interested in evolution of "quantum probabilities"



KEY POINTS:

1. Interested in evolution of "quantum probabilities"

2. Assume that everything happens in a vacuum

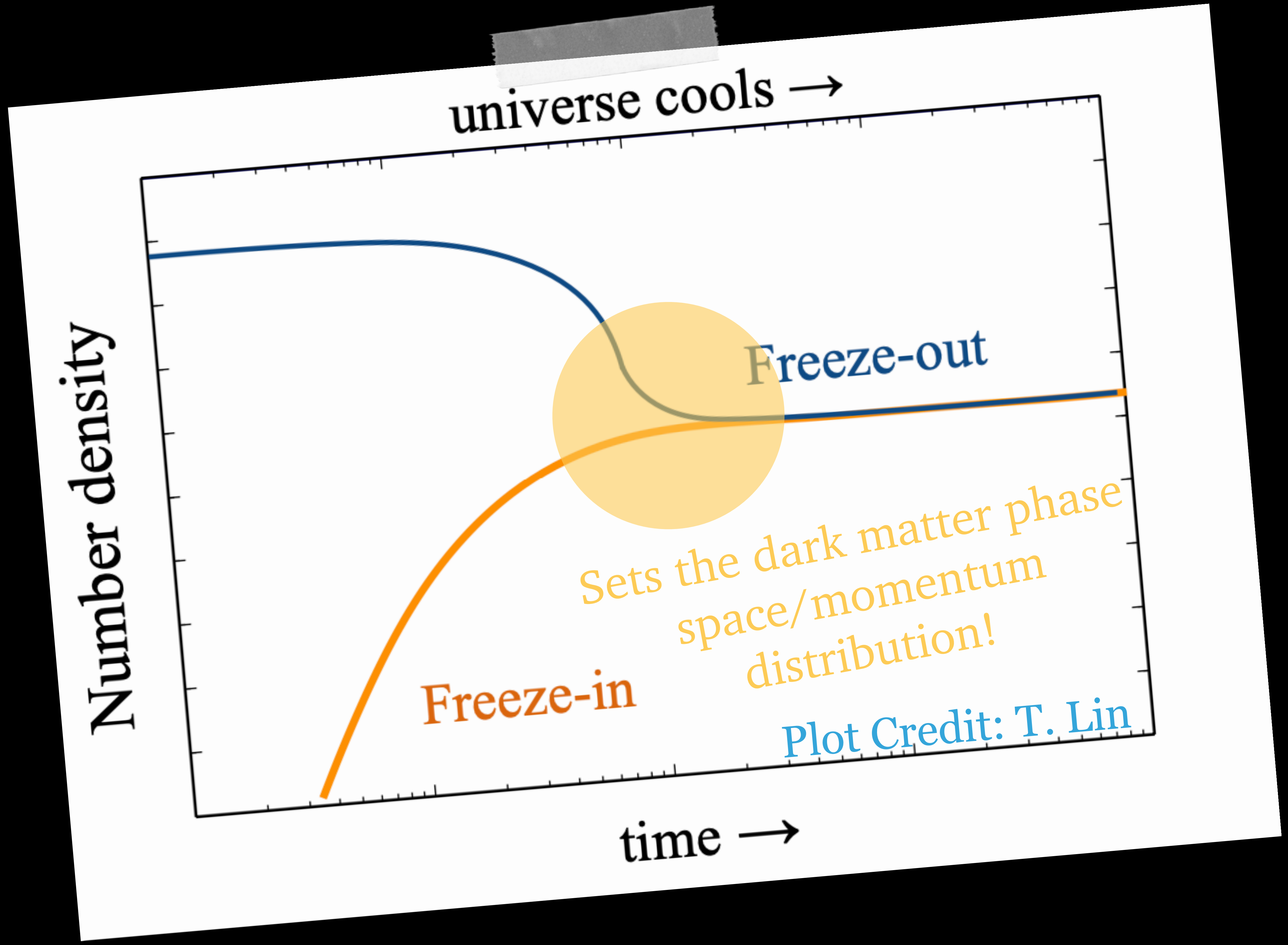


KEY POINTS:

1. Interested in evolution of "quantum probabilities"

2. Assume that everything happens in a vacuum

3. Temperature scale set by the mass of the heaviest interacting particle

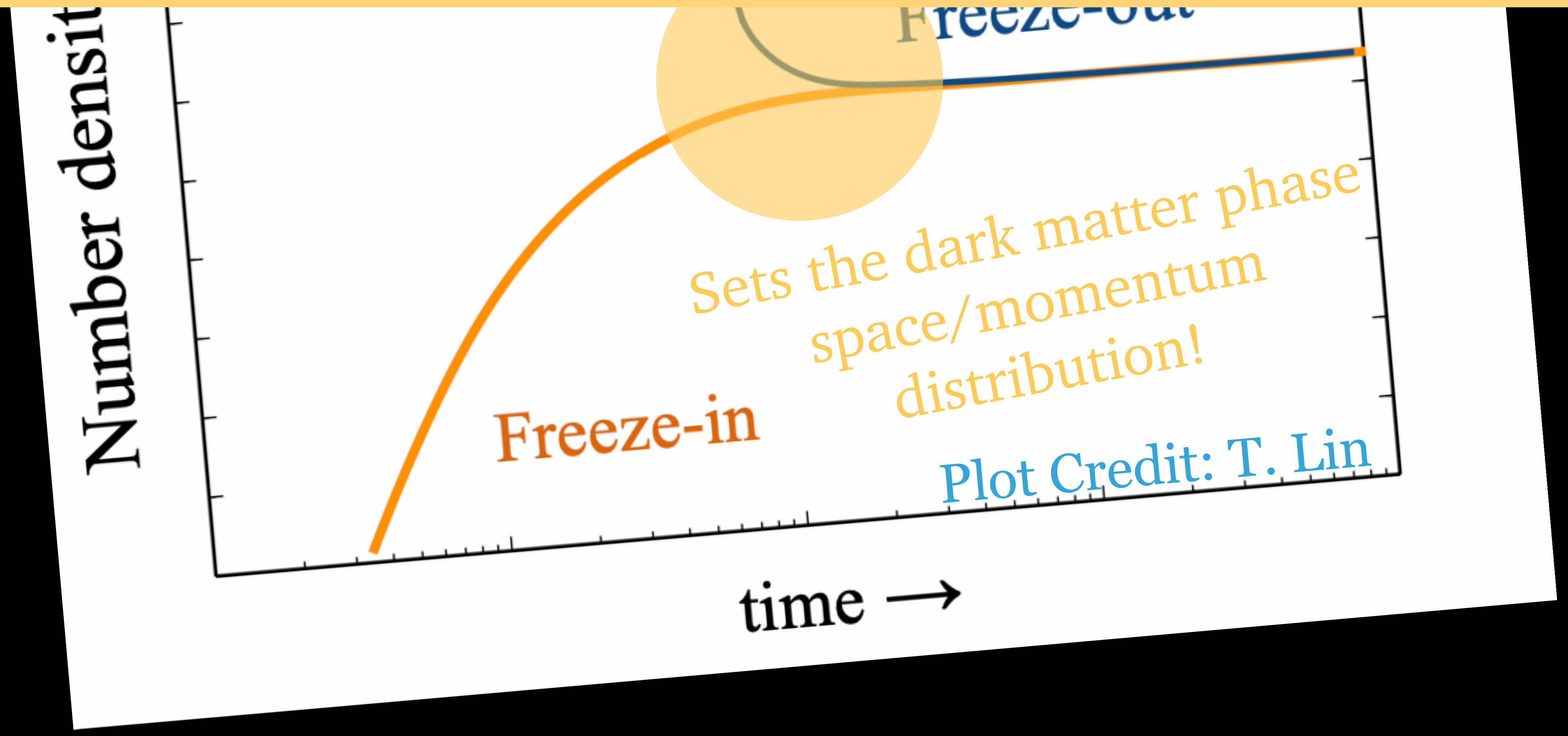


KEY POINTS:

When and how can we break these assumptions?

2. Assume that everything happens in a vacuum

3. Temperature scale set by the mass of the heaviest interacting particle



KEY POINTS:

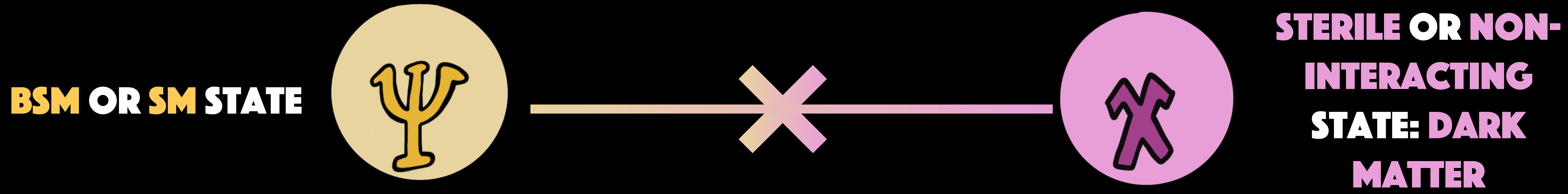
When and how can we break these assumptions?

2. Assume that everything happens in a

What does it mean for dark matter phenomenology?

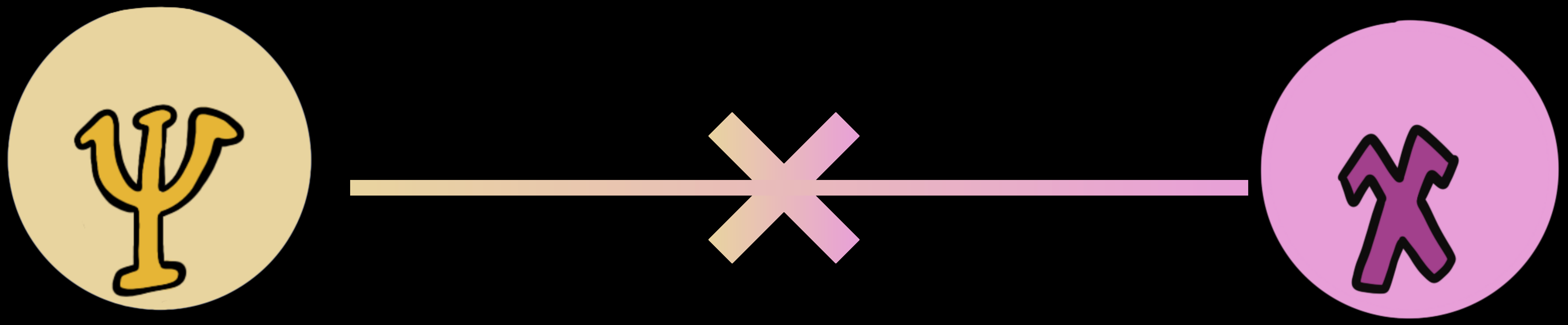
particle

CONSIDER: DARK MATTER MIXES WITH ANOTHER PARTICLE…



CONSIDER: DARK MATTER MIXES WITH ANOTHER PARTICLE...

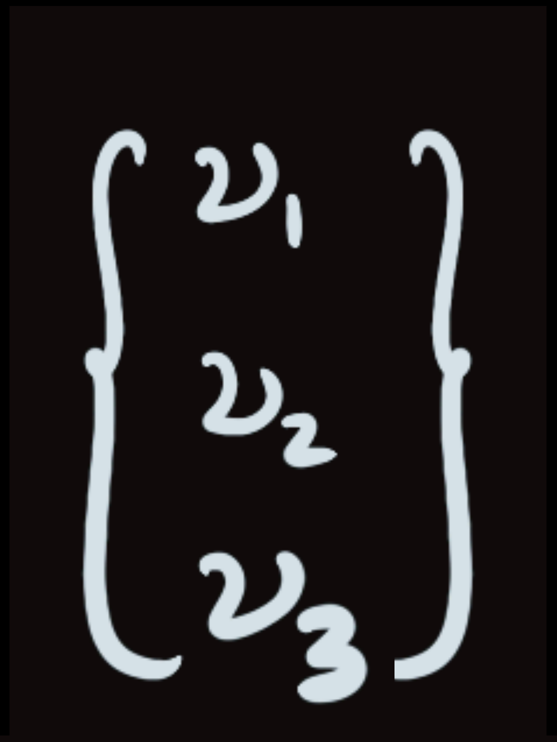
BSM OR SM STATE



STERILE OR NON-INTERACTING STATE: DARK MATTER

IN THE STANDARD MODEL:

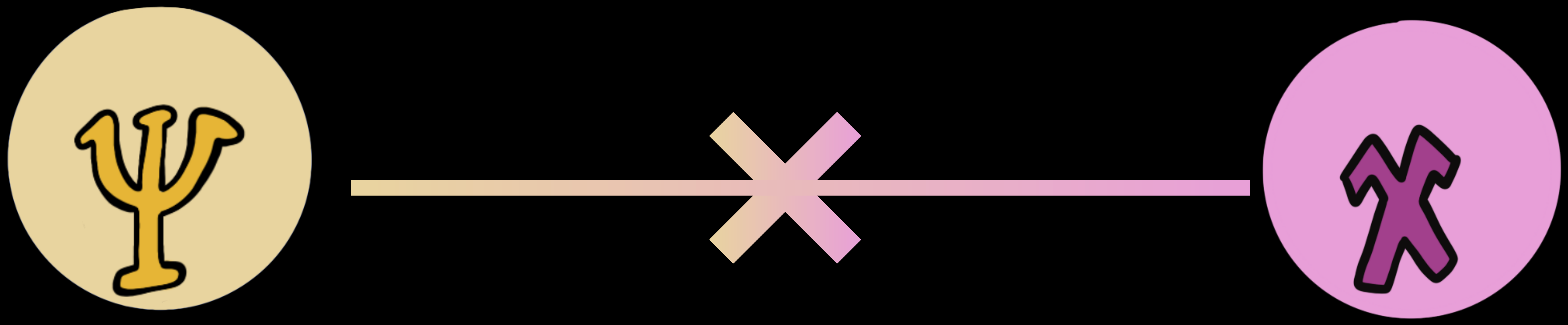
FLAVOR EIGENSTATES



MASS EIGENSTATES

CONSIDER: DARK MATTER MIXES WITH ANOTHER PARTICLE...

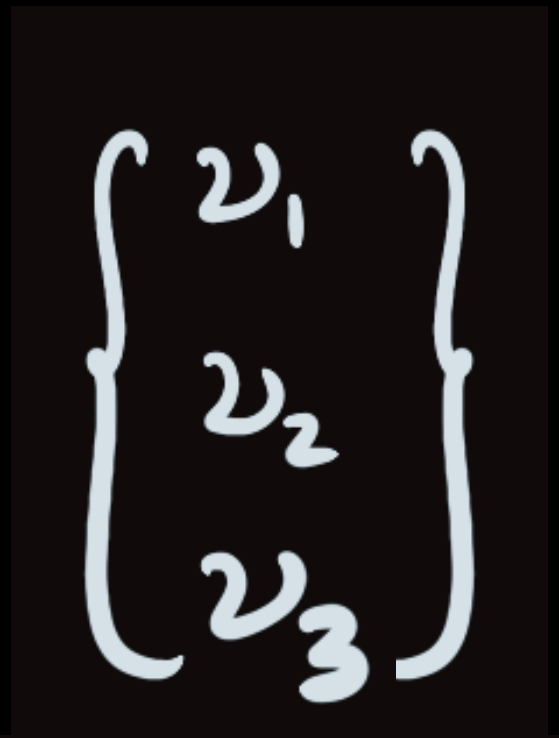
BSM OR SM STATE



STERILE OR NON-INTERACTING STATE: DARK MATTER

In The Standard Model:

Flavor Eigenstates

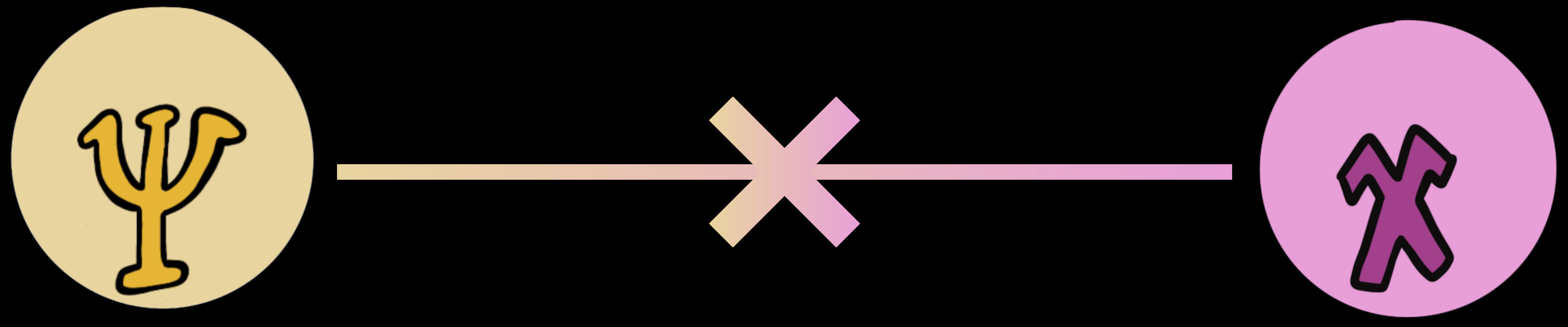


Mass Eigenstates

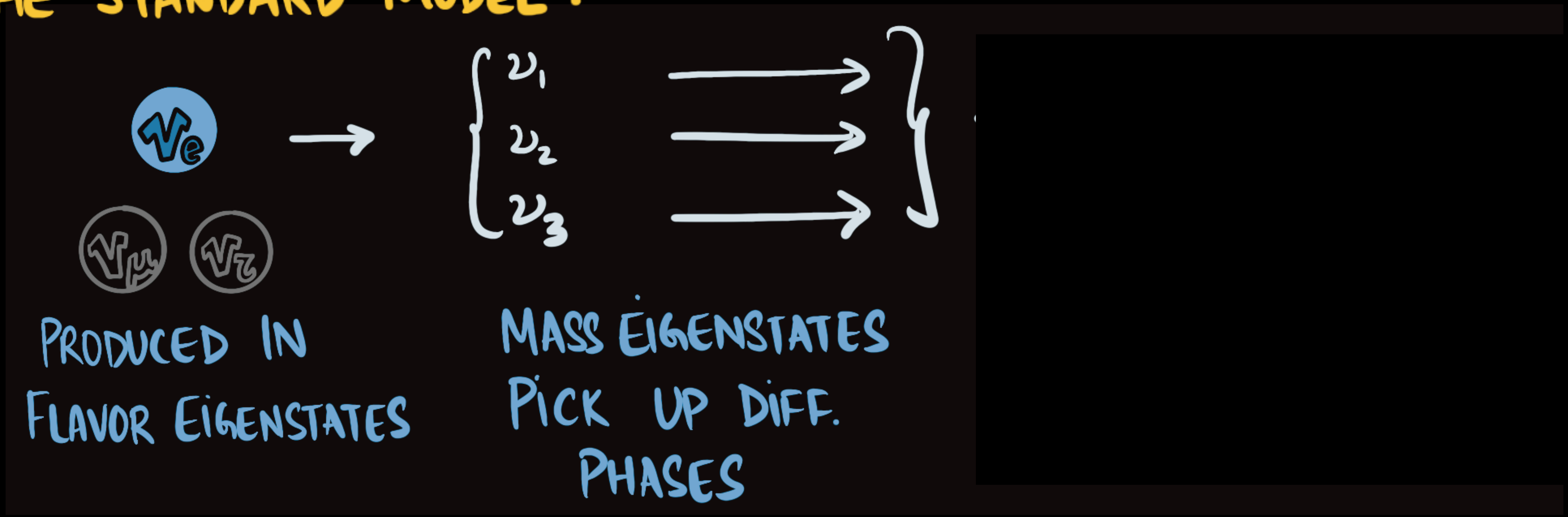
Beyond The Standard Model:

- Photon - Dark Photon
- Photon - Axions
- Neutrino - Sterile Neutrino
- ...

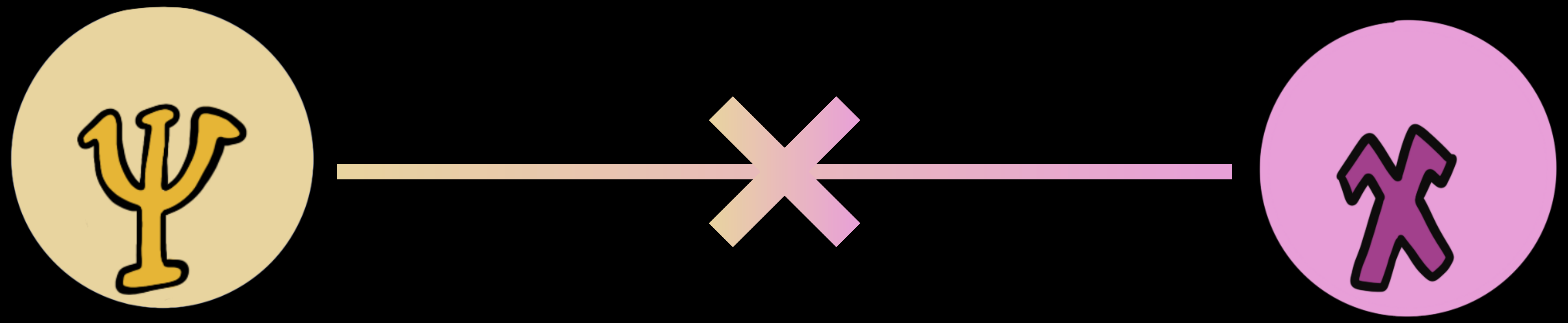
WHAT IF DARK MATTER MIXES WITH ANOTHER PARTICLE?



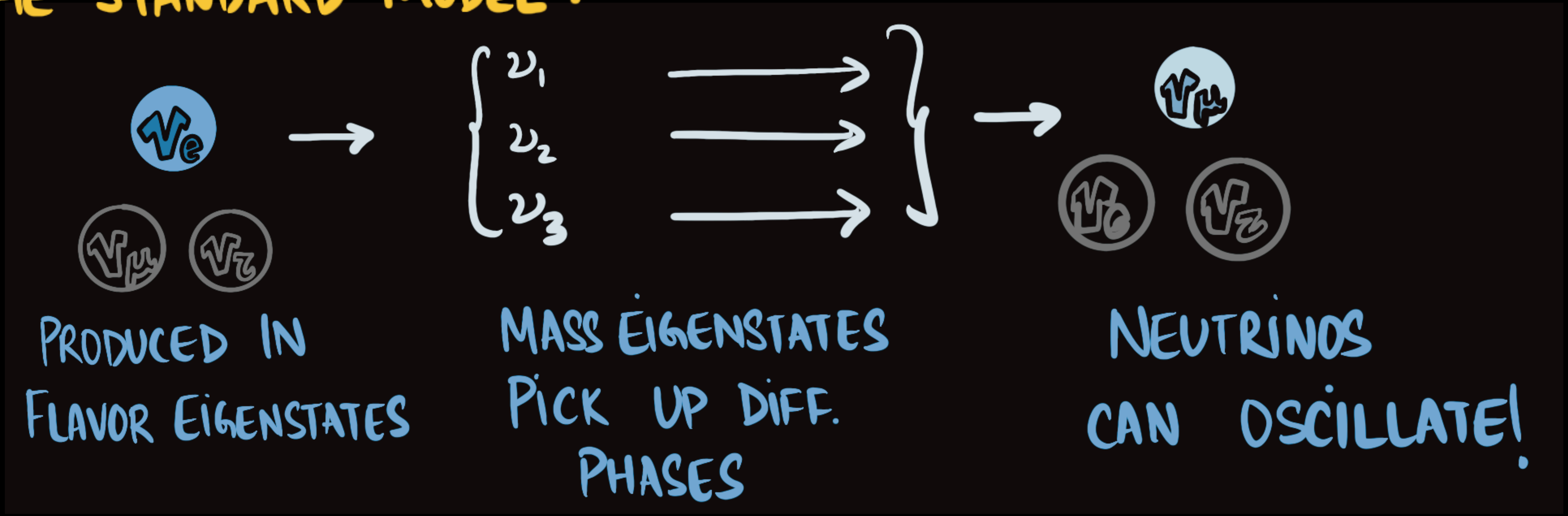
IN THE STANDARD MODEL:



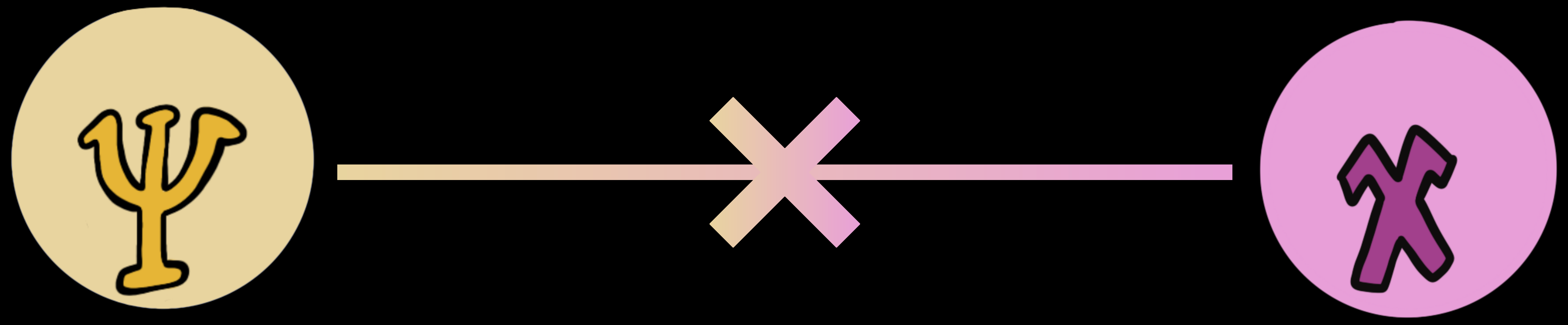
WHAT IF DARK MATTER MIXES WITH ANOTHER PARTICLE?



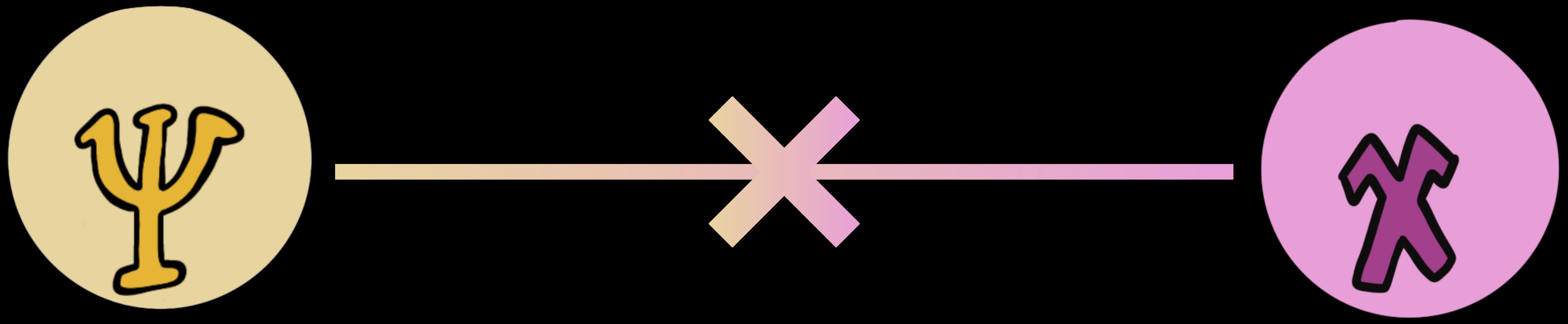
IN THE STANDARD MODEL:



DARK MATTER MAY ALSO BE SIMILARLY PRODUCED THROUGH OSCILLATIONS



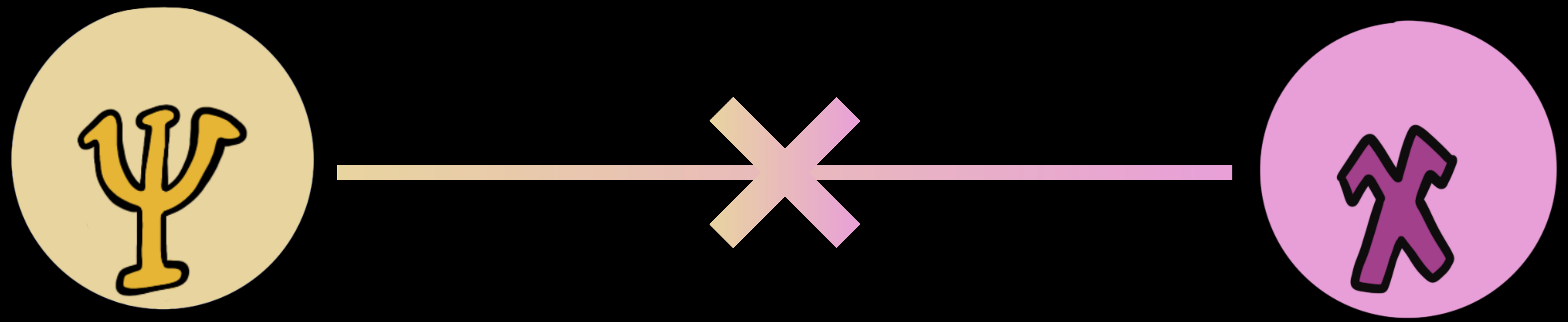
DARK MATTER MAY ALSO BE SIMILARLY PRODUCED THROUGH OSCILLATIONS



ROMPS!

(Rapidly Oscillating Massive Particles)

DARK MATTER MAY ALSO BE SIMILARLY PRODUCED THROUGH OSCILLATIONS

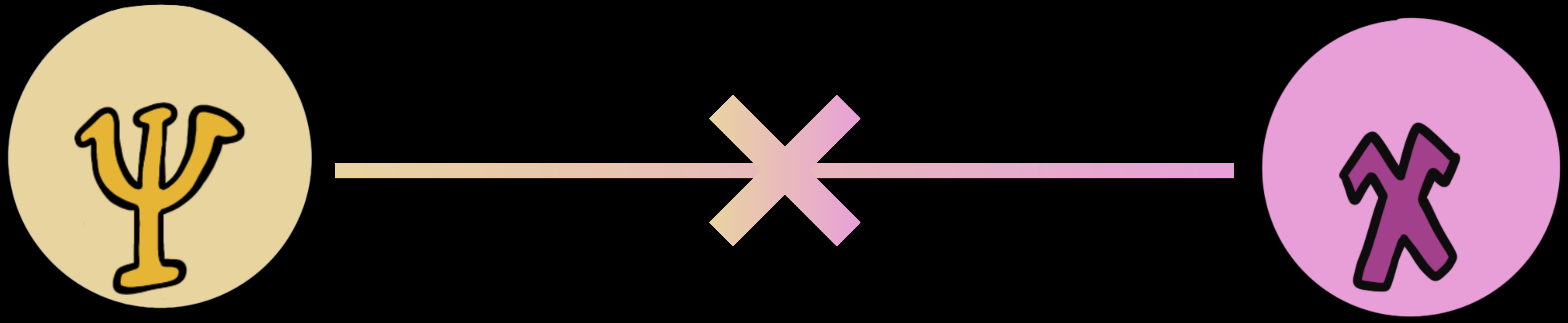


ROMPS!

(Rapidly Oscillating Massive Particles)

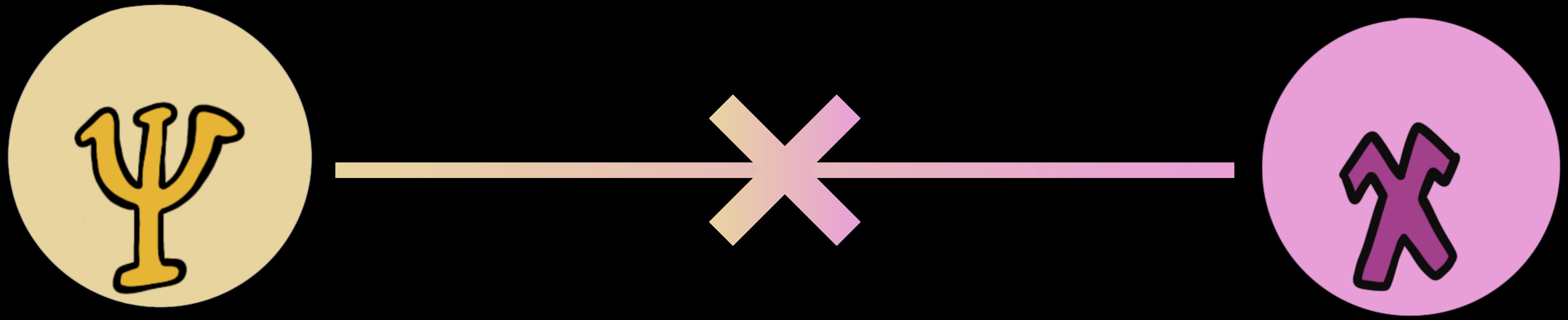
START OFF WITH ψ IN THE EARLY UNIVERSE, GENERATE A χ DENSITY

THE PROBABILITY OF CONVERSION IS QUANTIFIED BY THE AMOUNT OF MIXING



$$\mathscr{L}_{\psi-\chi} \supset m_{\psi\chi}\left(\bar{\psi}\chi + \mathrm{h.c.}\right)$$

THE PROBABILITY OF CONVERSION IS QUANTIFIED BY THE AMOUNT OF MIXING

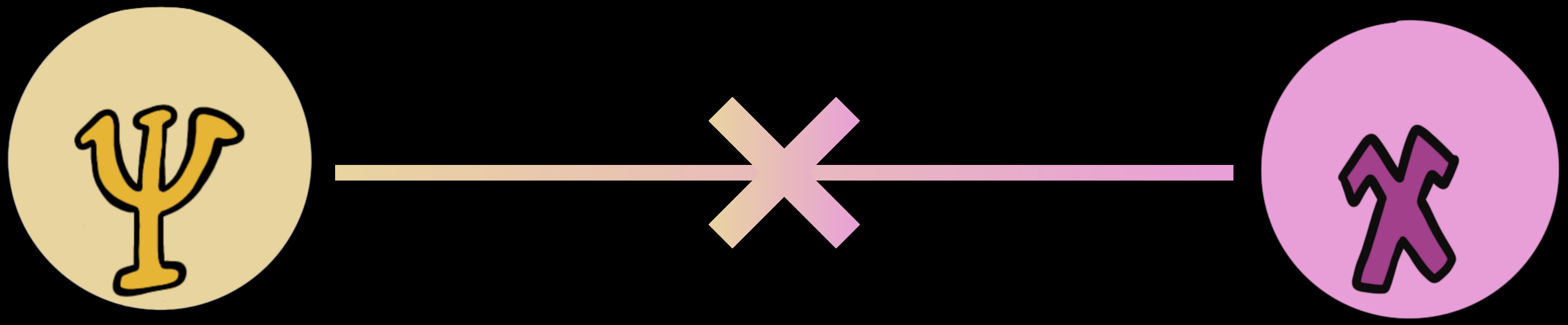


$$\mathscr{L}_{\psi-\chi} \supset m_{\psi\chi}\left(\bar{\psi}\chi + \mathrm{h.c.}\right)$$

Parameterize in terms of an angle

$$\begin{pmatrix} \psi \\ \chi \end{pmatrix}_{\text{flavor}} = \begin{pmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix}_{\text{mass}},$$

THE PROBABILITY OF CONVERSION IS QUANTIFIED BY THE AMOUNT OF MIXING

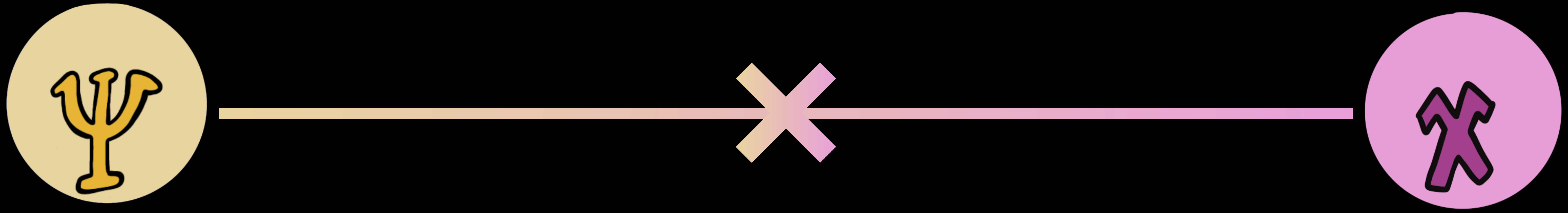


$$\mathscr{L}_{\psi-\chi} \supset m_{\psi\chi}\left(\bar{\psi}\chi + \mathrm{h.c.}\right)$$

Parameterize in terms of an angle

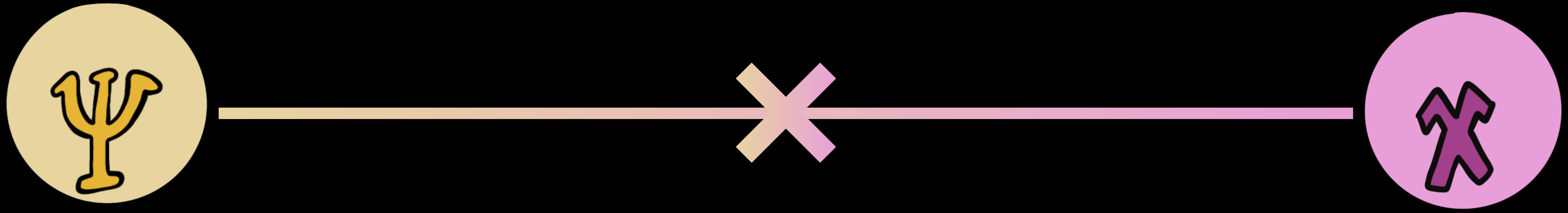
$$\begin{pmatrix}\psi \\ \chi\end{pmatrix}_{\text{flavor}} = \begin{pmatrix}\cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}\psi \\ \chi\end{pmatrix}_{\text{mass}},$$

$$\tan 2\theta_0 = \frac{2m_{\psi\chi}^2}{m_\psi^2 - m_\chi^2}$$



IN A VACUUM, ψ CONVERTS INTO χ WITH A PROBABILITY GIVEN BY

$$P_{\psi \to \chi} = \sin^2 2\theta_0 (1 - \cos \omega_{\text{osc}} t)$$

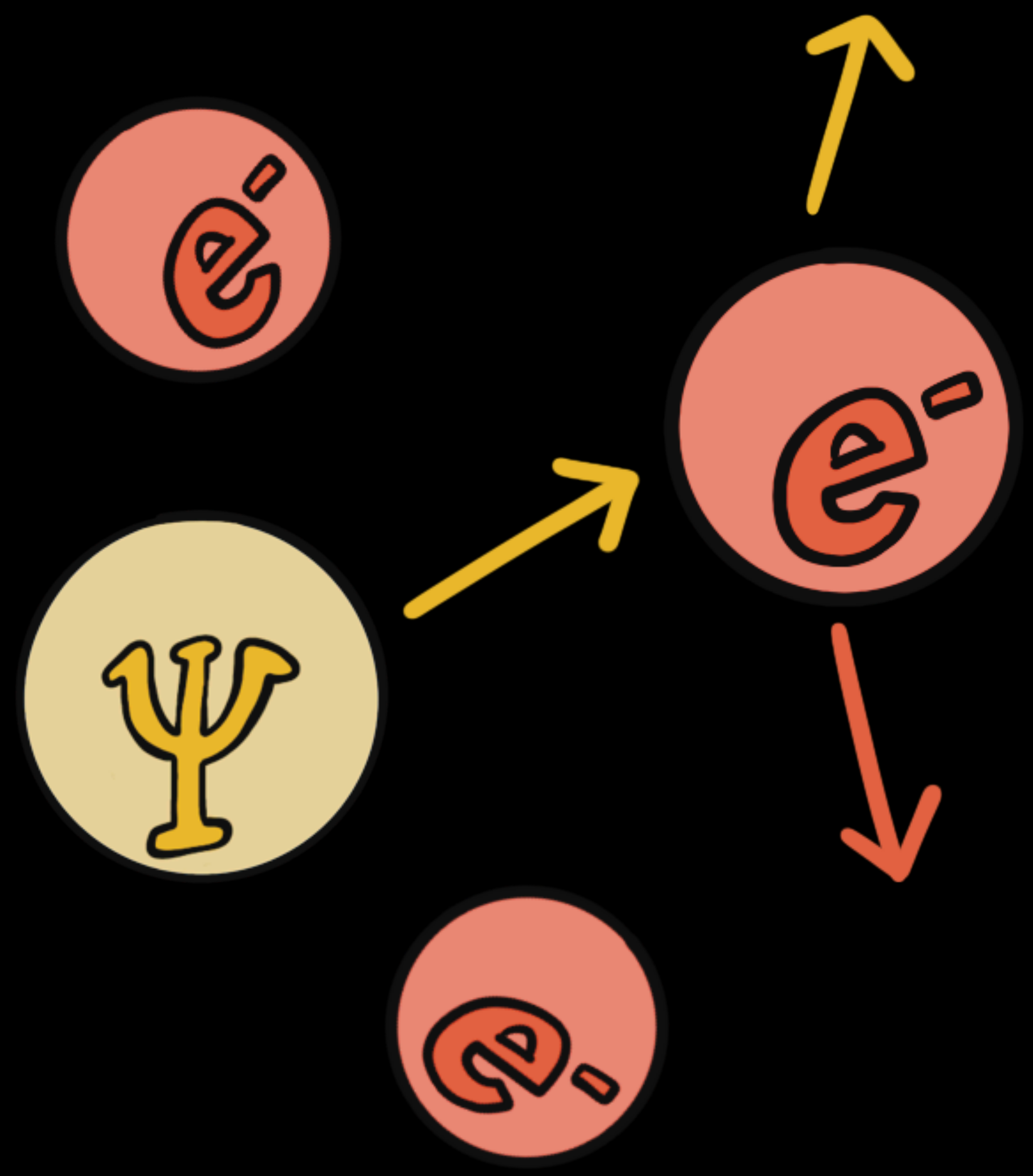


IN A VACUUM, ψ CONVERTS INTO χ WITH A PROBABILITY GIVEN BY

$$P_{\psi\to\chi} = \sin^2 2\theta_0 (1 - \cos \omega_{\text{osc}} t)$$

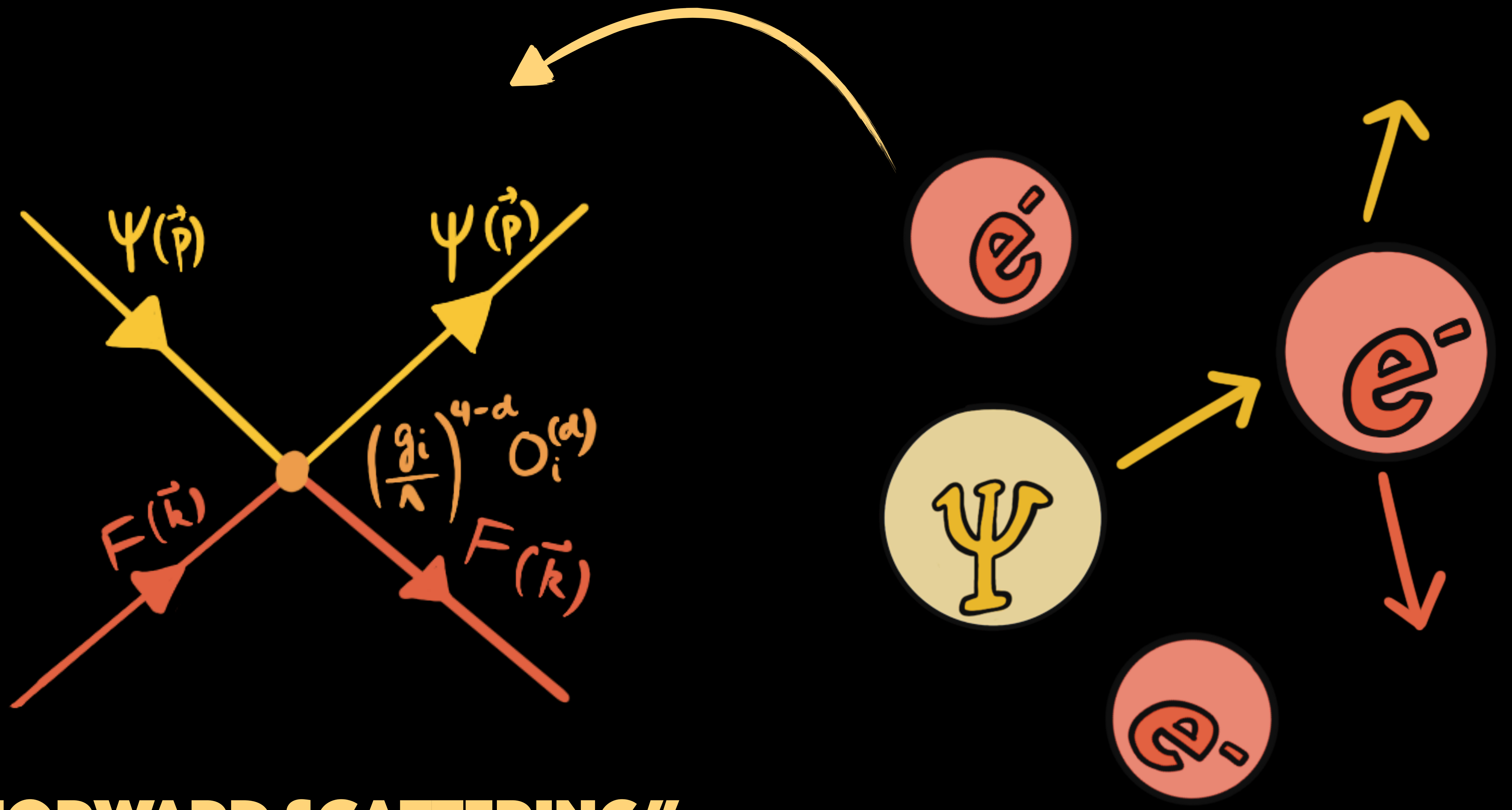
Oscillation frequency set by $\Delta m^2 = m_\psi^2 - m_\chi^2$

THE UNIVERSE IS NOT A VACUUM…



ψ INTERACTS WITH THE PARTICLES IN THE PLASMA

THE UNIVERSE IS NOT A VACUUM...

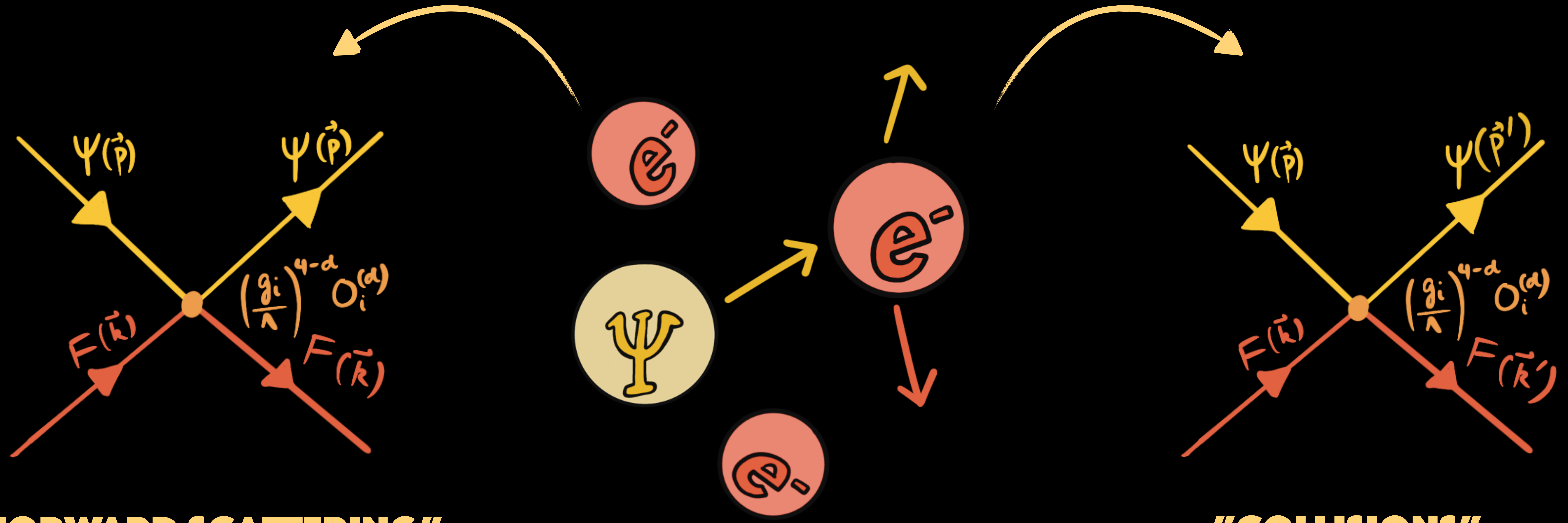


"FORWARD SCATTERING"

(ψ maintains its momentum)

ψ **INTERACTS WITH THE PARTICLES IN THE PLASMA**

THE UNIVERSE IS NOT A VACUUM…



"FORWARD SCATTERING"

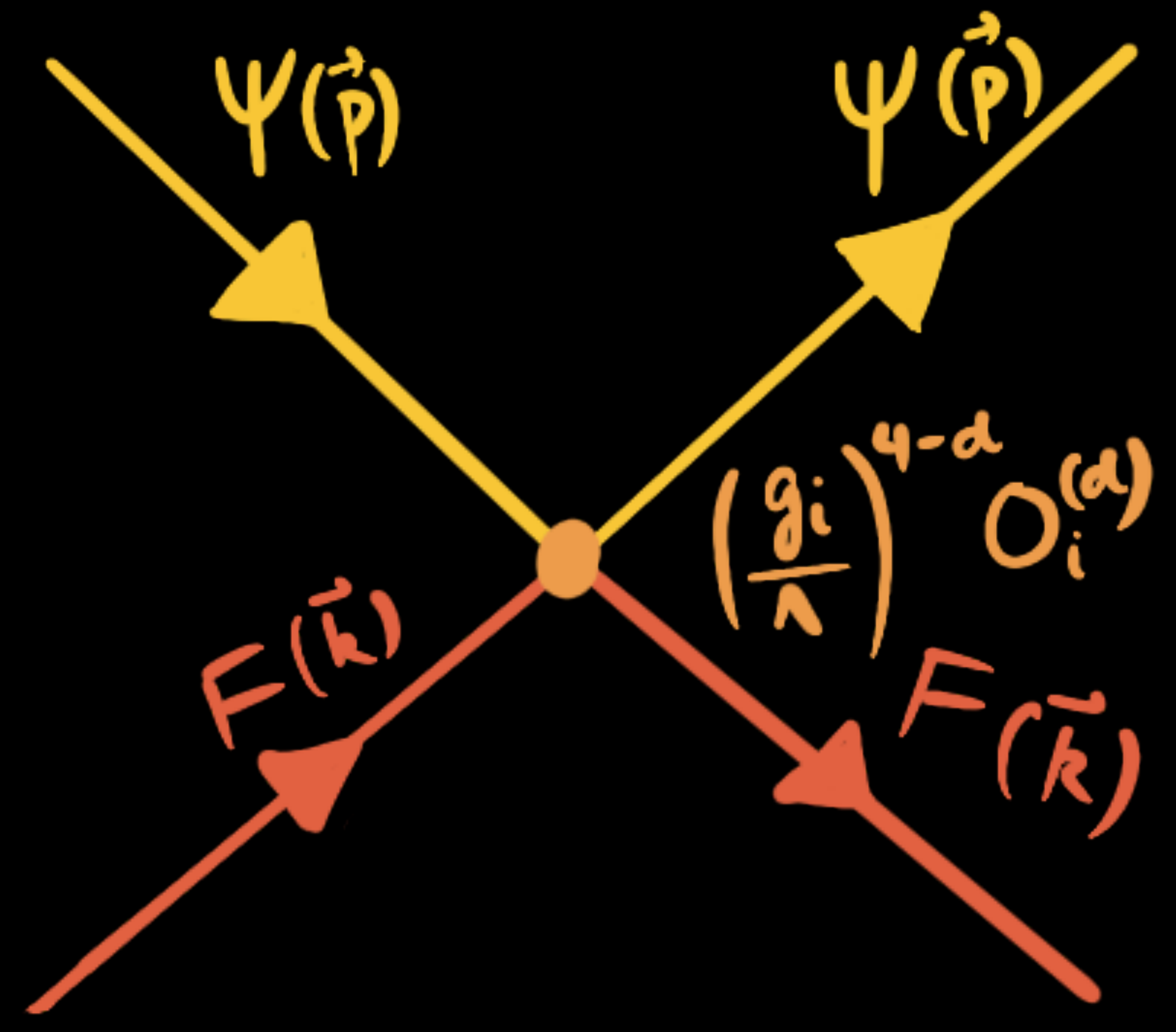
(ψ maintains its momentum)

ψ INTERACTS WITH THE PARTICLES IN THE PLASMA

"COLLISIONS"

(Such as annihilations)

FORWARD SCATTERING MODIFIES THE DISPERSION OF ψ…



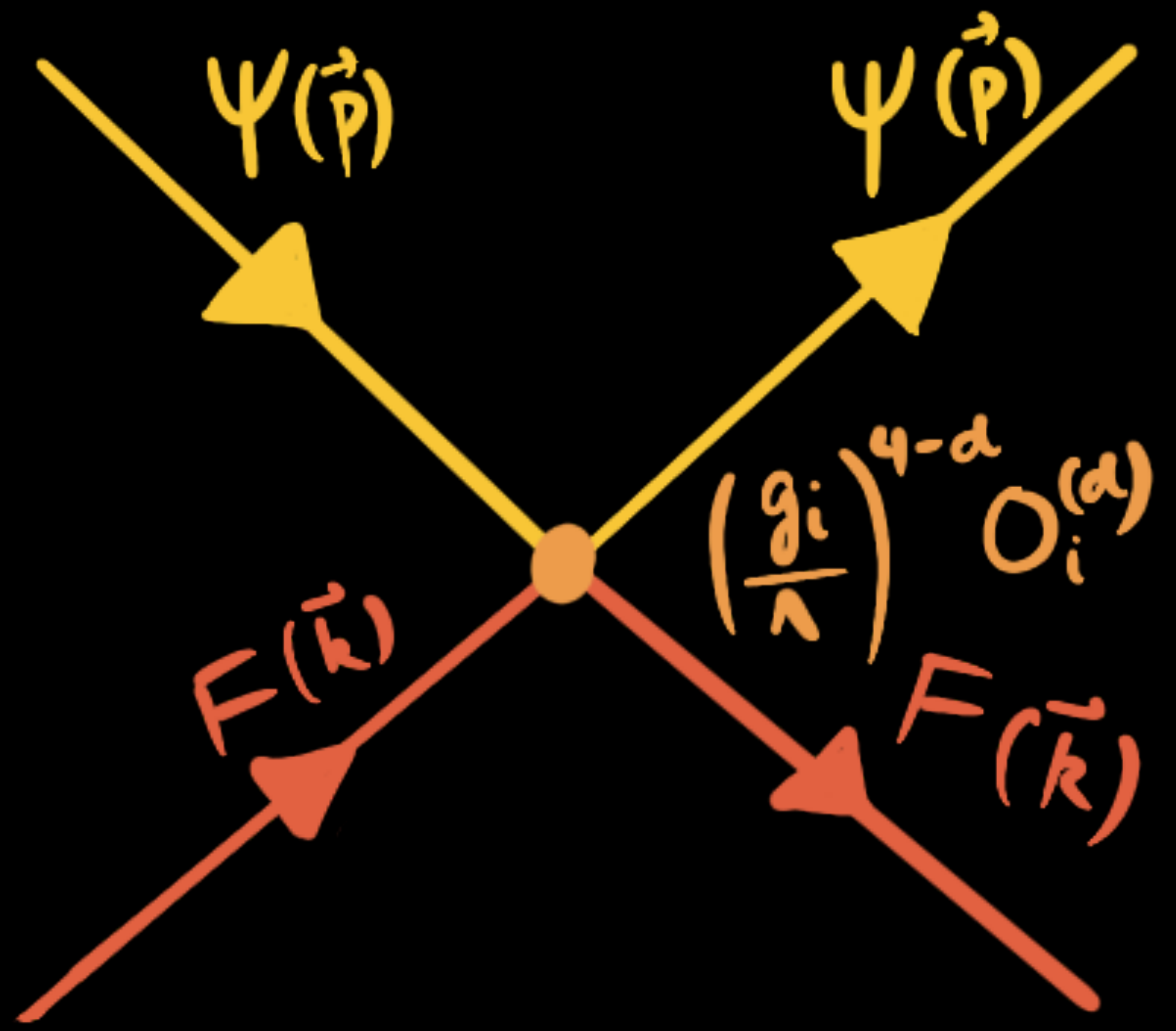
"FORWARD SCATTERING"

(ψ maintains its momentum)

…and therefore its effective mass in the plasma.

$$m^2_{\psi,\text{medium}} = m^2_\psi + \Delta m^2_T$$

FORWARD SCATTERING MODIFIES THE DISPERSION OF ψ...



"FORWARD SCATTERING"

(ψ maintains its momentum)

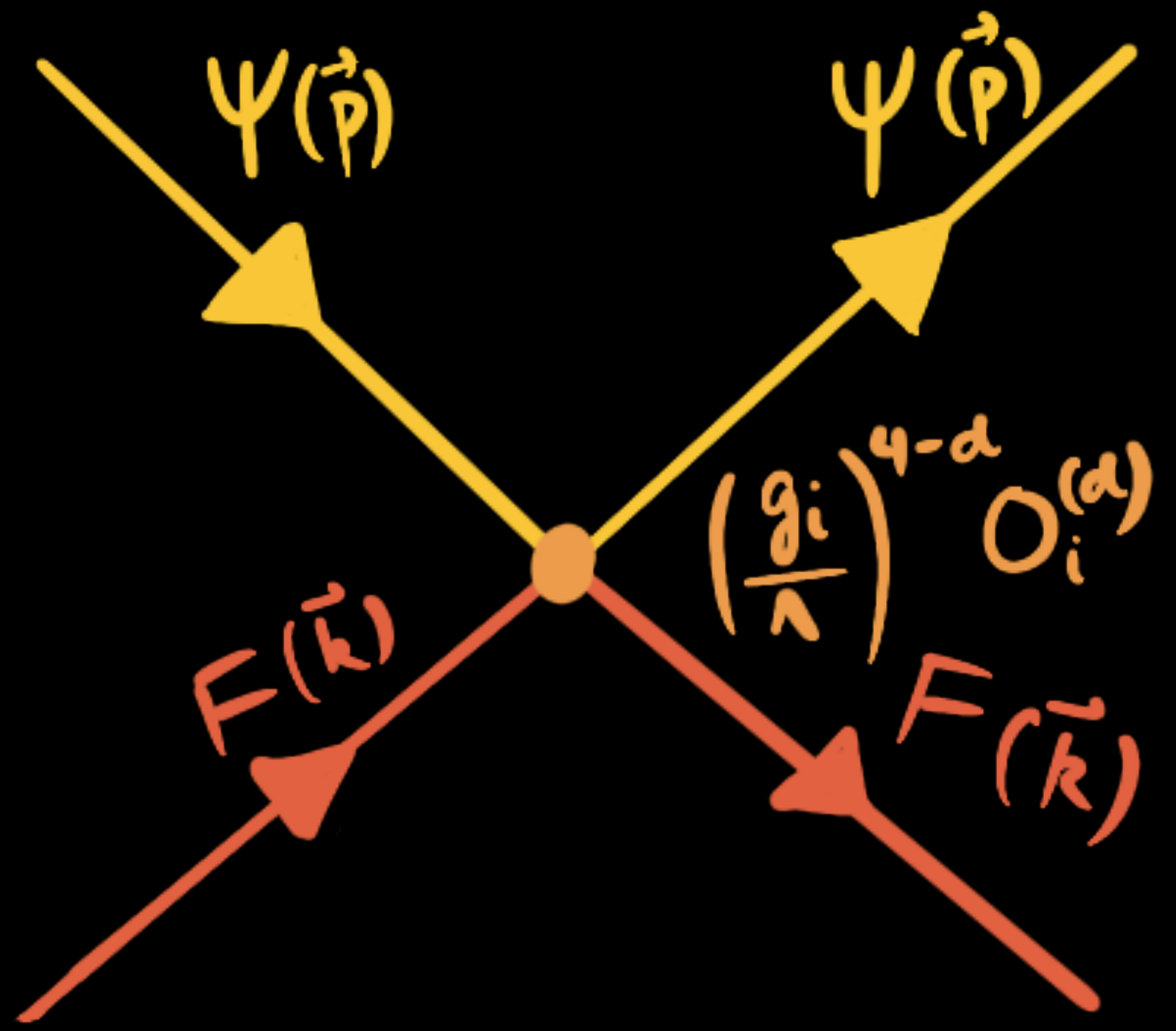
...and therefore its effective mass in the plasma.

$$m^2_{\psi,\mathrm{medium}} = m^2_\psi + \Delta m^2_T$$

IN-MEDIUM MIXING ANGLE MODIFIED!

$$\tan 2\theta_m = \frac{2m^2_{\psi\chi}}{m^2_\psi + \Delta m^2_T - m^2_\chi}$$

FORWARD SCATTERING MODIFIES THE DISPERSION OF ψ...



"FORWARD SCATTERING"

(ψ maintains its momentum)

...and therefore its effective mass in the plasma.

$$m^2_{\psi,\mathrm{medium}} = m^2_\psi + \Delta m^2_T$$

IN-MEDIUM MIXING ANGLE MODIFIED!

$$\tan 2\theta_m = \frac{2m^2_{\psi\chi}}{m^2_\psi + \Delta m^2_T - m^2_\chi}$$

Function of temperature!

(background fermion density)

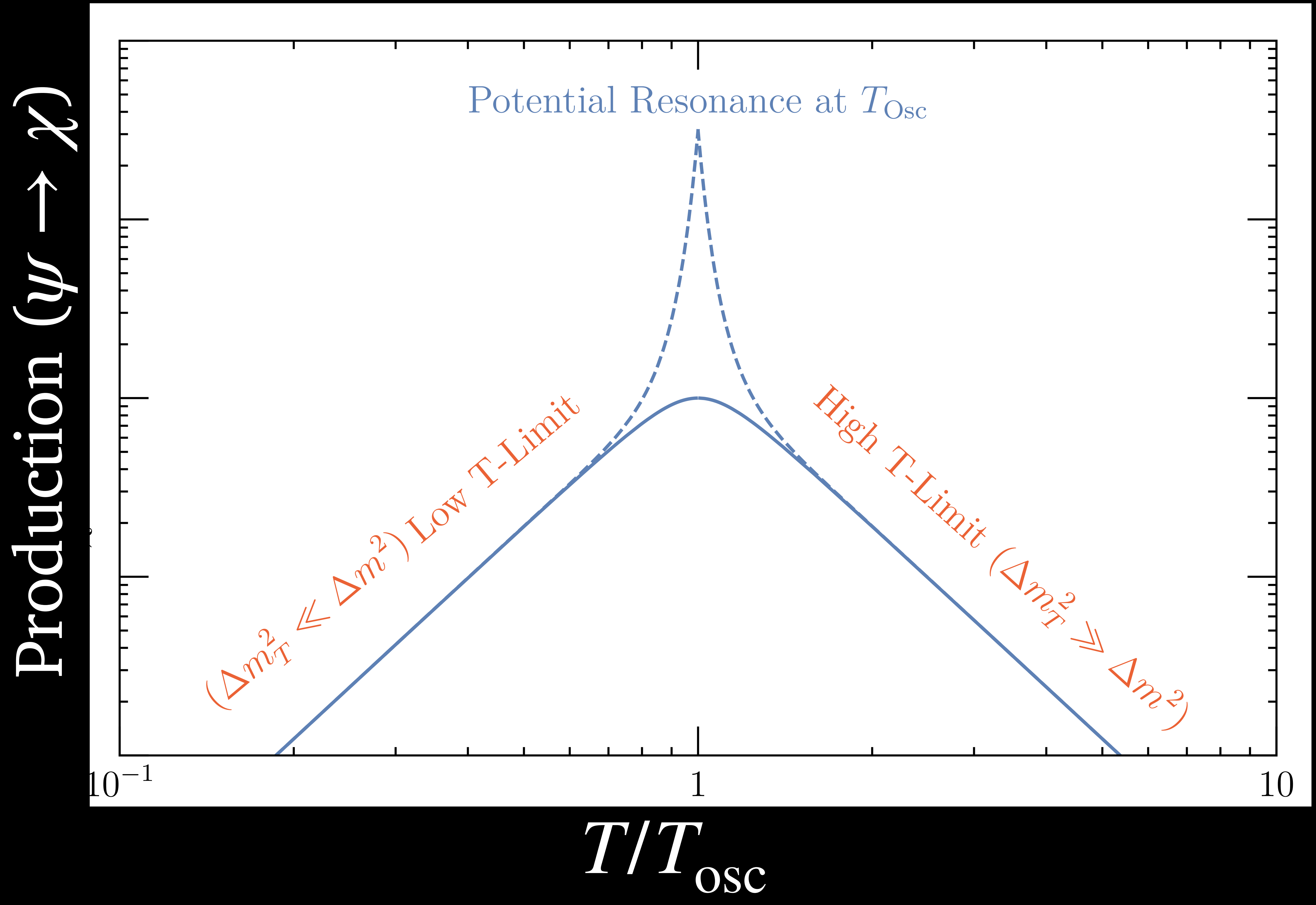
...POTENTIALLY ENHANCING THE MIXING ANGLE

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

RESONANT ENHANCEMENT AT T_{osc}, WHEN

$$\Delta m_T^2 = m_\psi^2 - m_\chi^2$$

...Potentially enhancing the mixing angle

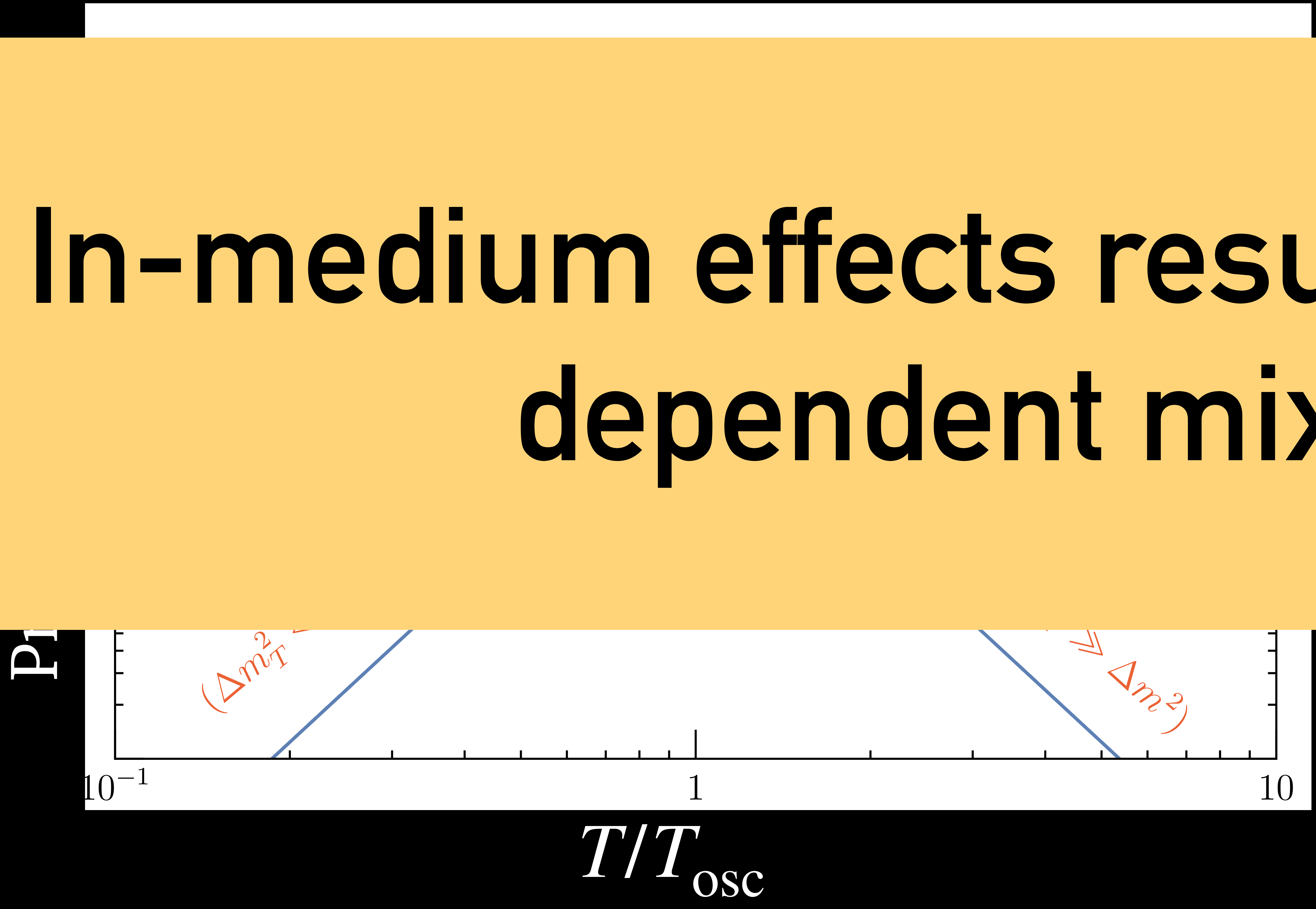


$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_\psi^2 + \Delta m_T^2 - m_\chi^2}$$

Resonant enhancement at $T_{\rm osc}$, when

$$\Delta m_T^2 = m_\psi^2 - m_\chi^2$$

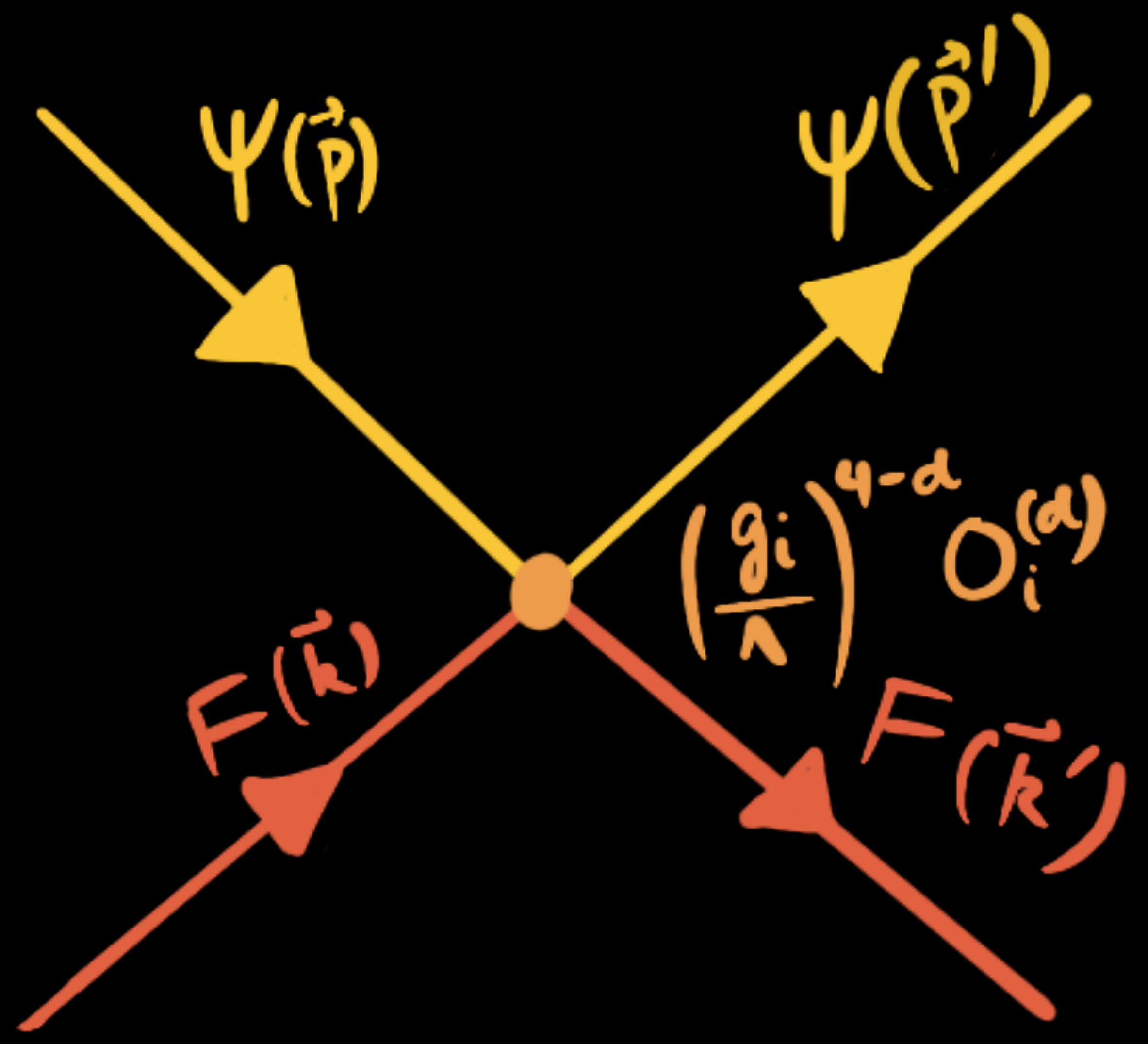
…Potentially enhancing the mixing angle



In-medium effects result in a temperature dependent mixing angle!

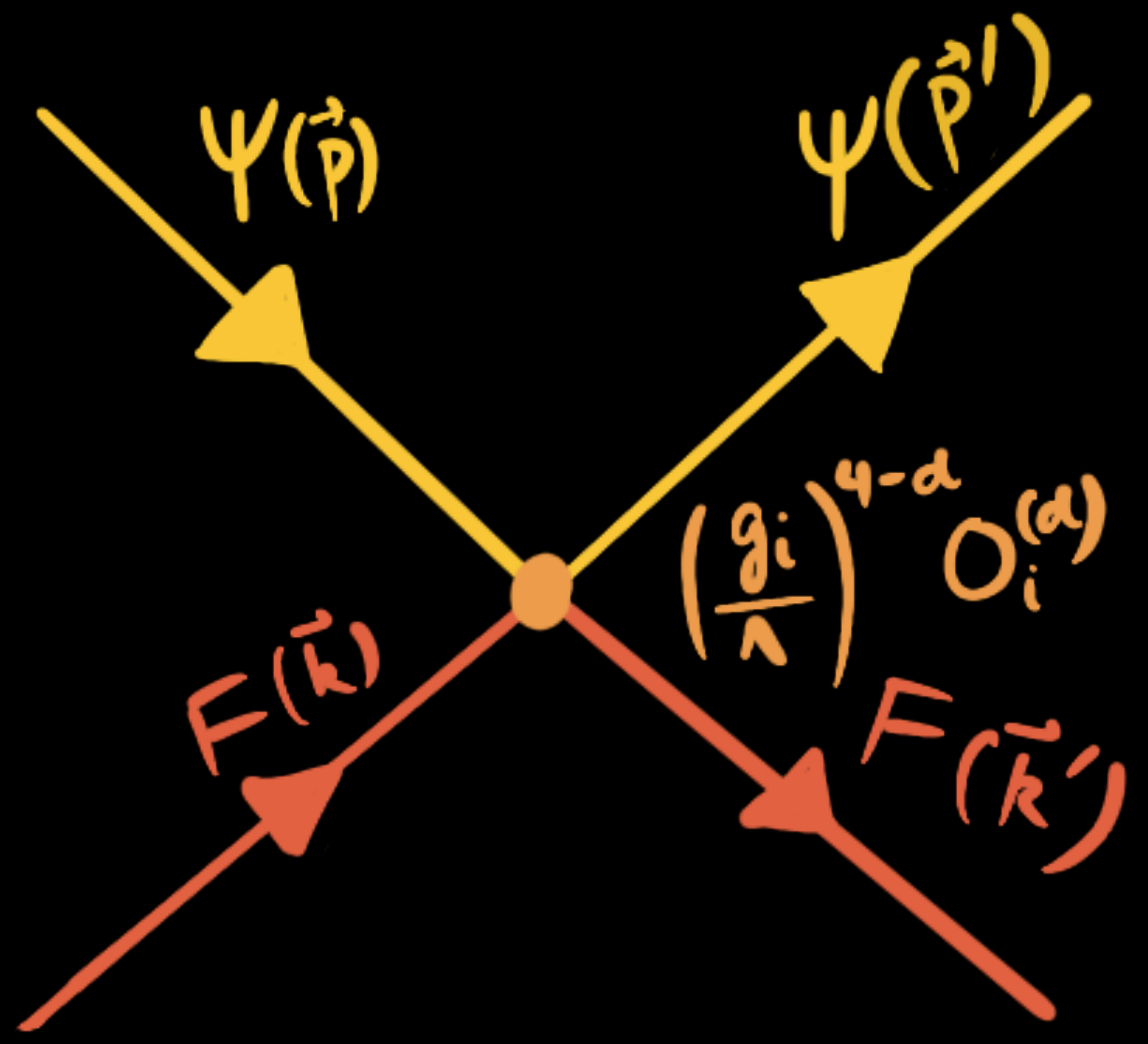
$$\Delta m_T^2 = m_\psi^2 - m_\chi^2$$

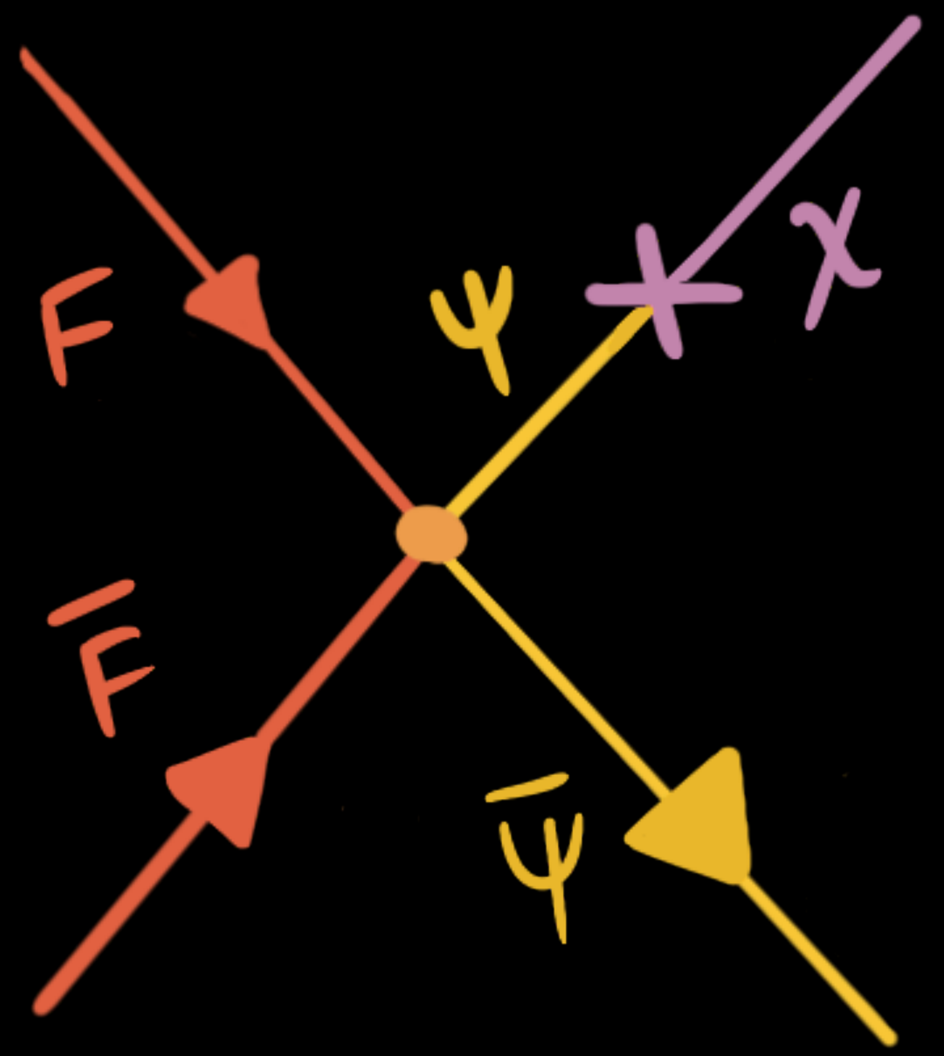
COLLISIONS SPOIL THE COHERENCE BETWEEN ψ AND χ



.. AND **DAMP** THE COHERENT OSCILLATIONS

COLLISIONS SPOIL THE COHERENCE BETWEEN ψ AND χ



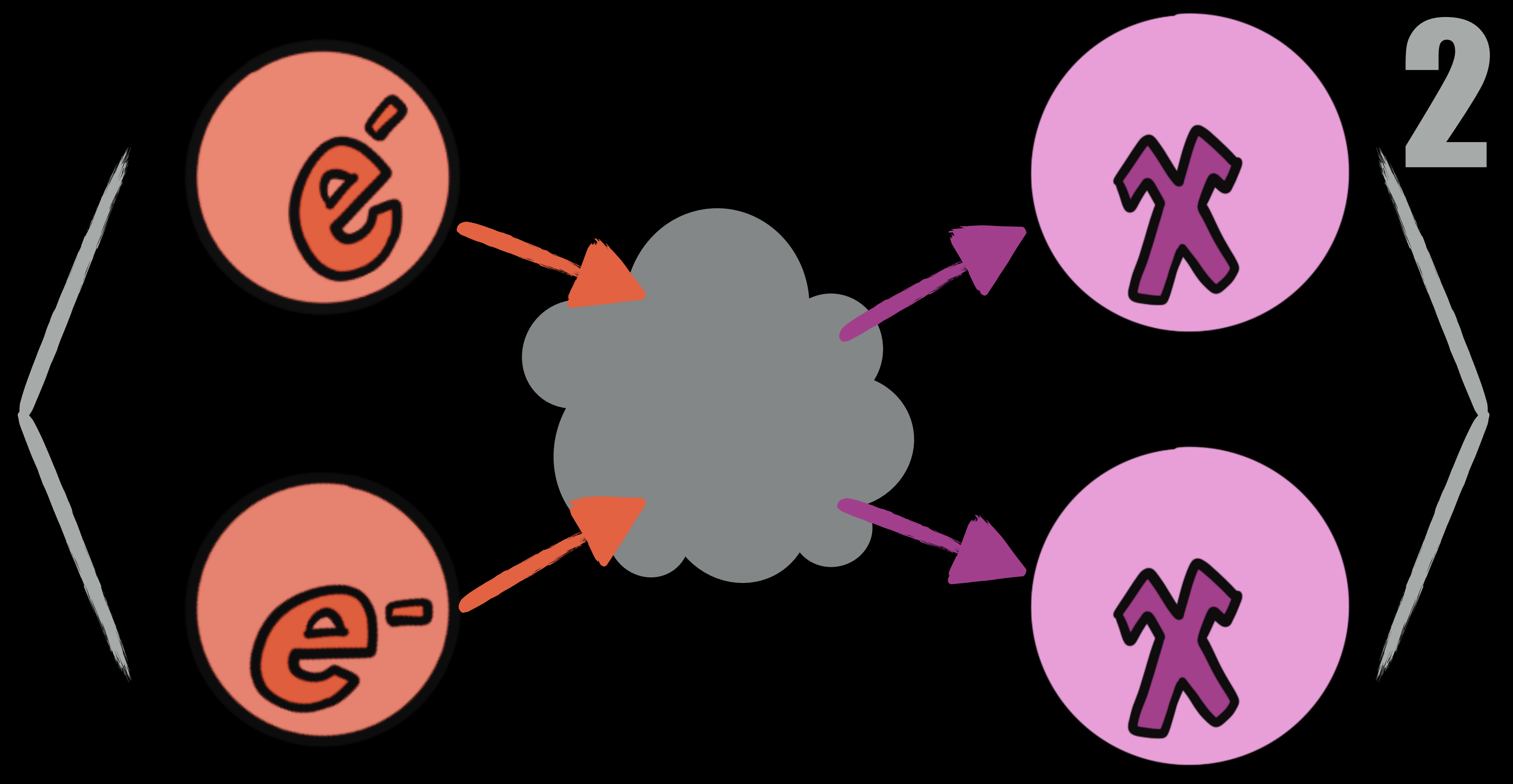


.. AND **DAMP** THE COHERENT OSCILLATIONS

BUT CAN ALSO INDUCE CONVERSIONS!

SCATTERING INDUCED INCOHERENT PRODUCTION

ROMPS ARE INTERESTING DARK MATTER CANDIDATES PHENOMENOLOGICALLY DIFFERENT FROM FREEZE-IN AND FREEZE-OUT



FREEZE-IN/FREEZE-OUT

- Track quantum amplitudes,
Oscillations are coherent processes!

ROMPS

ROMPS ARE INTERESTING DARK MATTER CANDIDATES PHENOMENOLOGICALLY DIFFERENT FROM FREEZE-IN AND FREEZE-OUT

Assume that everything happens in a vacuum

FREEZE-IN/FREEZE-OUT

- Incorporate the effect of finite temperature and density of the background

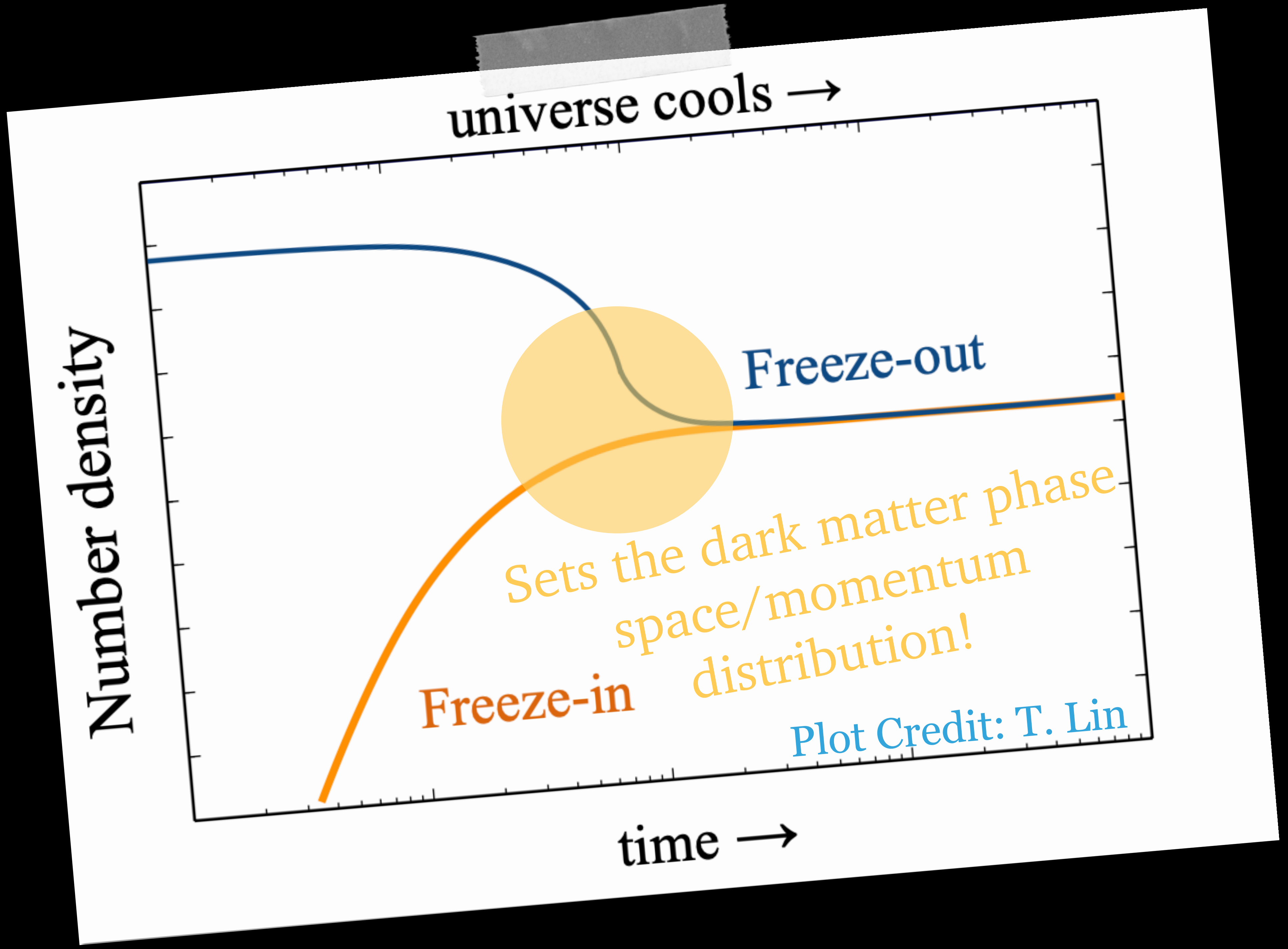
ROMPS

ROMPS ARE INTERESTING DARK MATTER CANDIDATES PHENOMENOLOGICALLY DIFFERENT FROM FREEZE-IN AND FREEZE-OUT

FREEZE-IN/FREEZE-OUT

ROMPS

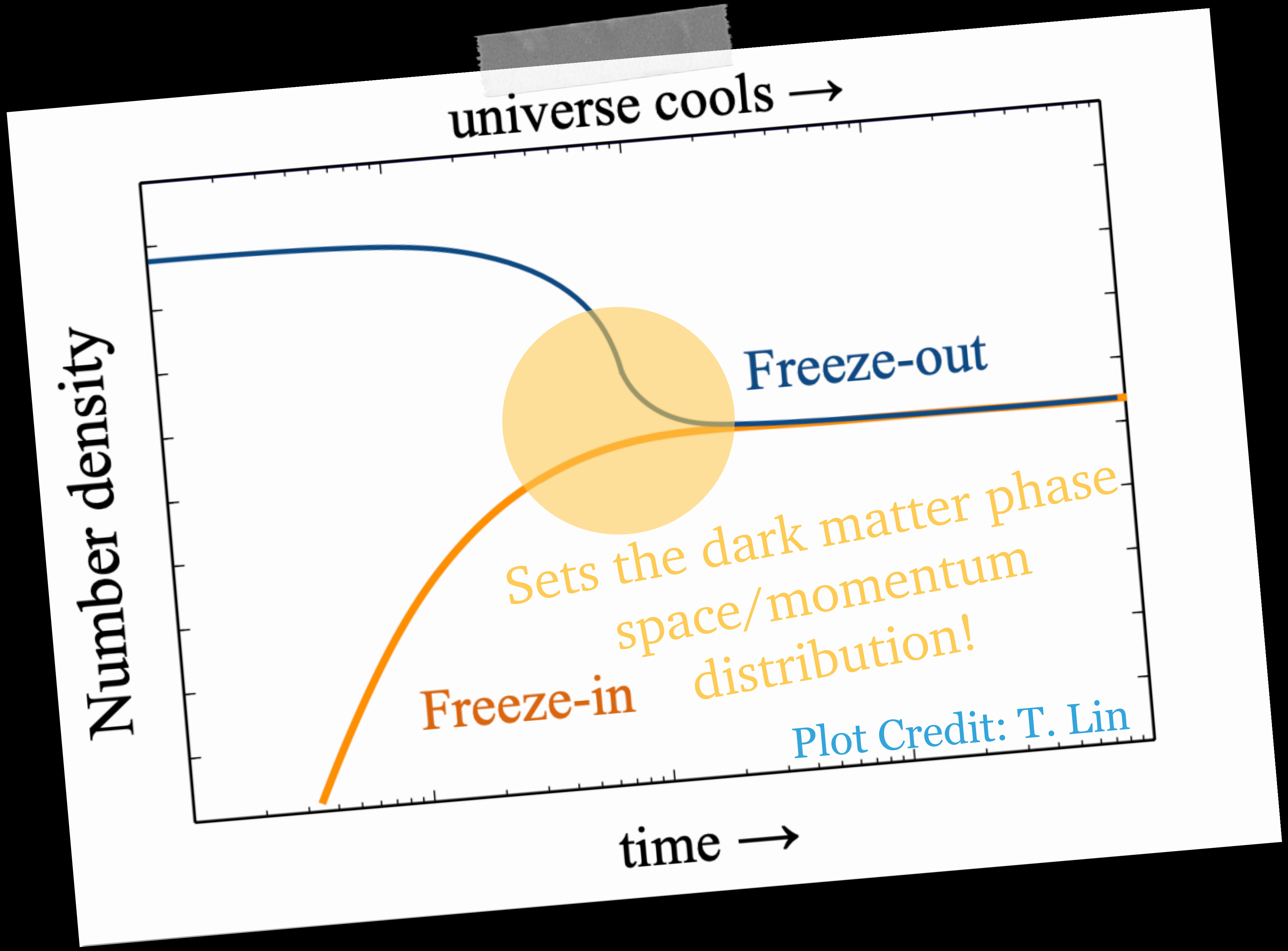
ROMPS ARE INTERESTING DARK MATTER CANDIDATES PHENOMENOLOGICALLY DIFFERENT FROM FREEZE-IN AND FREEZE-OUT



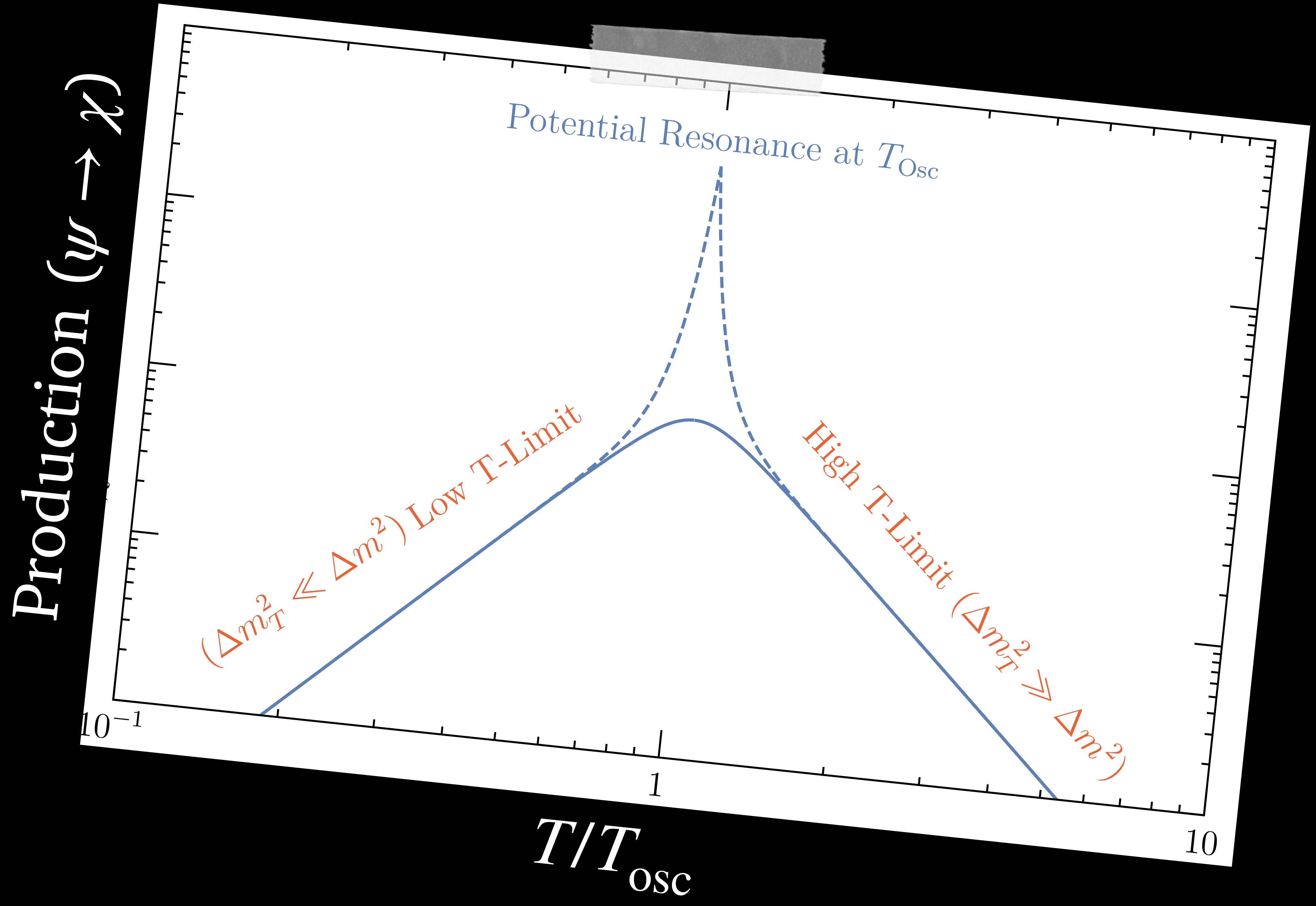
FREEZE-IN/FREEZE-OUT

ROMPS

ROMPS ARE INTERESTING DARK MATTER CANDIDATES PHENOMENOLOGICALLY DIFFERENT FROM FREEZE-IN AND FREEZE-OUT



FREEZE-IN/FREEZE-OUT

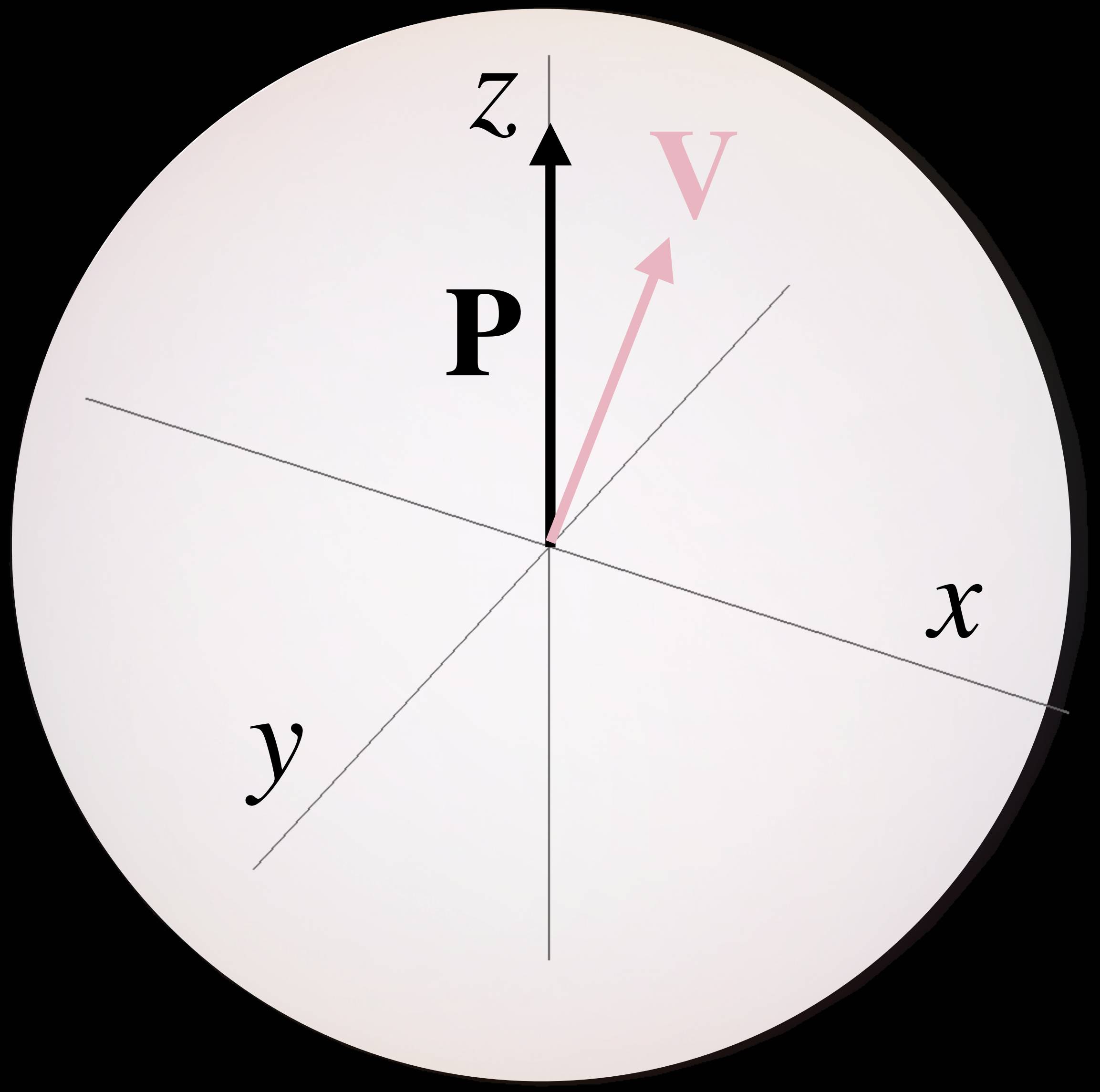


ROMPS

BUT HOW DOES ONE CALCULATE THE DARK MATTER RELIC ABUNDANCE ACCOUNTING FOR

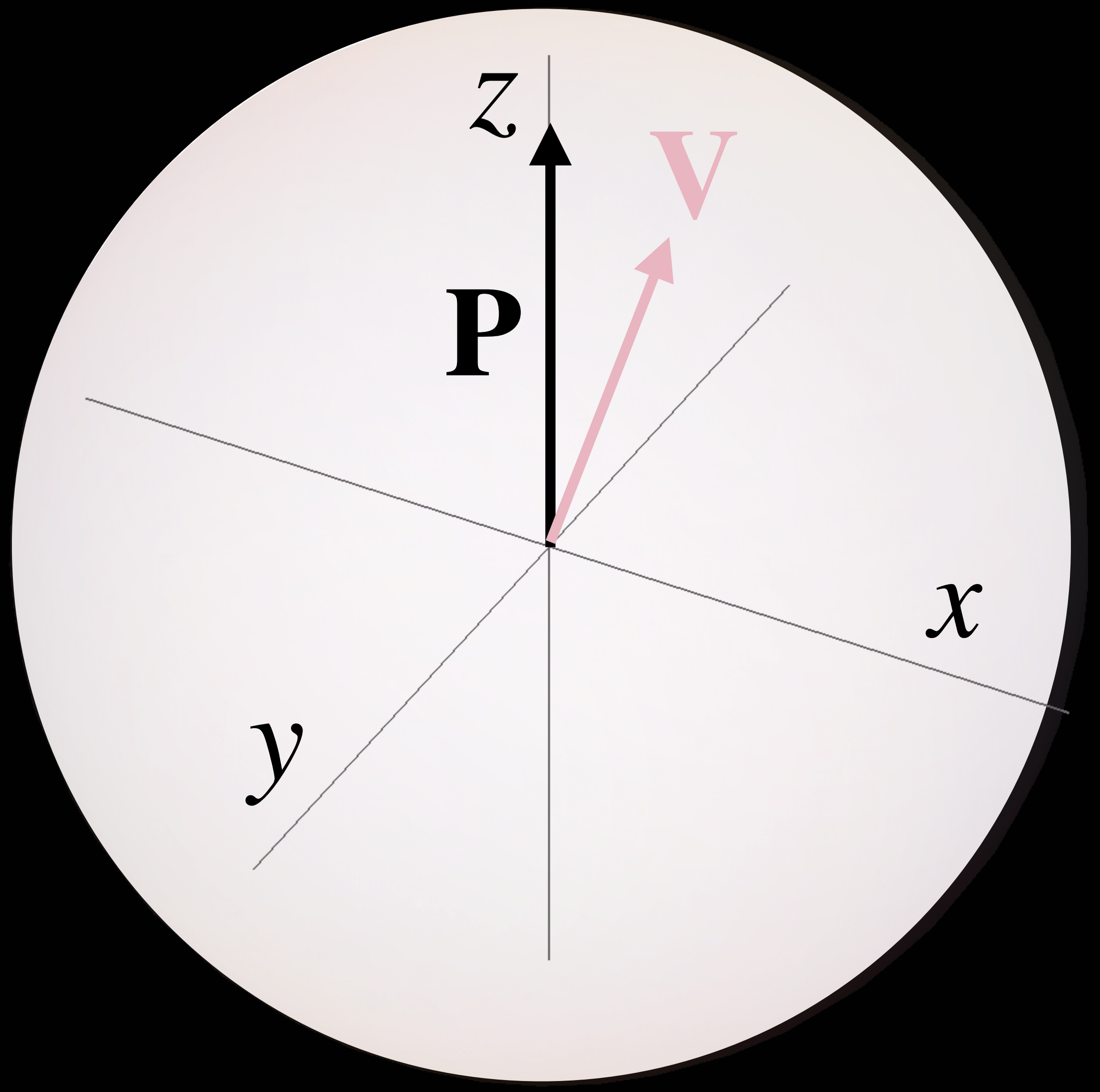
- COHERENT AND INCOHERENT EFFECTS
- INTERACTIONS WITH THE BACKGROUND
- RESONANCES IN THE PARAMETER SPACE

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_{\mathrm{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION

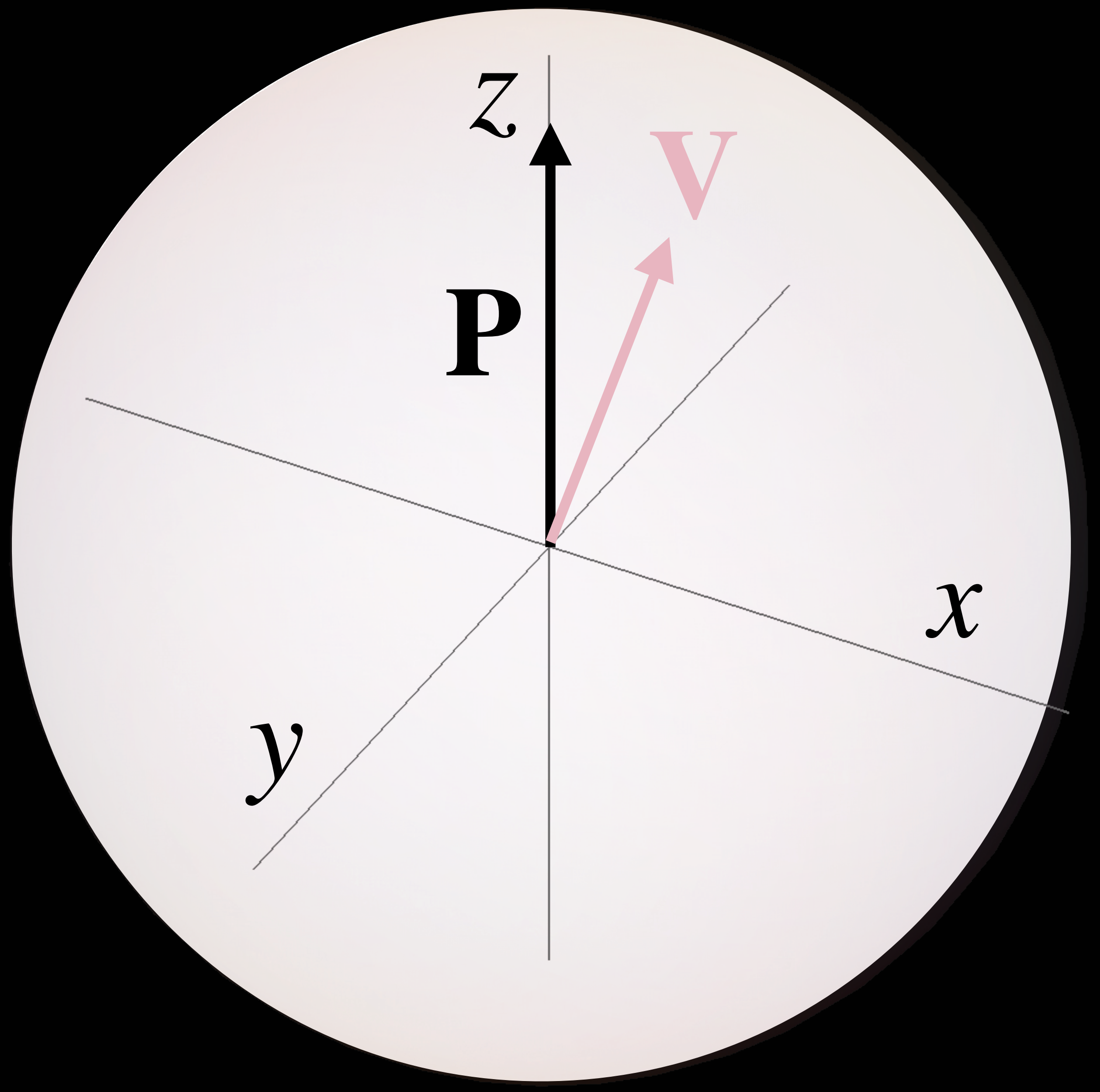


ROMP polarization with

$$P_z = f_\psi(p) - f_\chi(p)$$

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_\mathrm{T} + \dot{P}_0\,\hat{\mathbf{z}}$$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



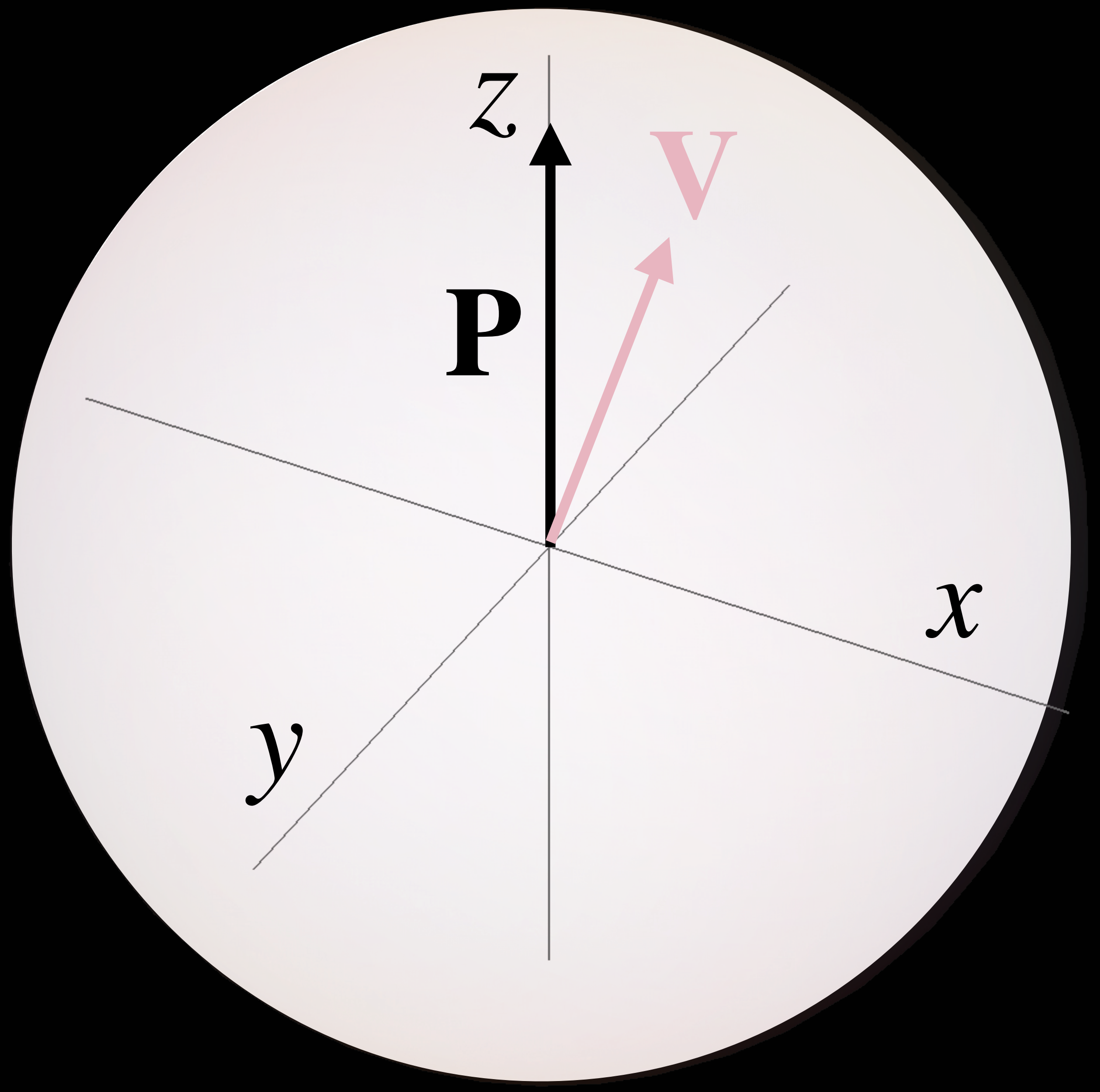
ROMP polarization with

$$P_z = f_\psi(p) - f_\chi(p)$$

$$P_0 = f_\psi(p) + f_\chi(p)$$

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_\mathbf{T} + \dot{P}_0\,\hat{\mathbf{z}}$$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



ROMP polarization with

$P_z = f_\psi(p) - f_\chi(p)$

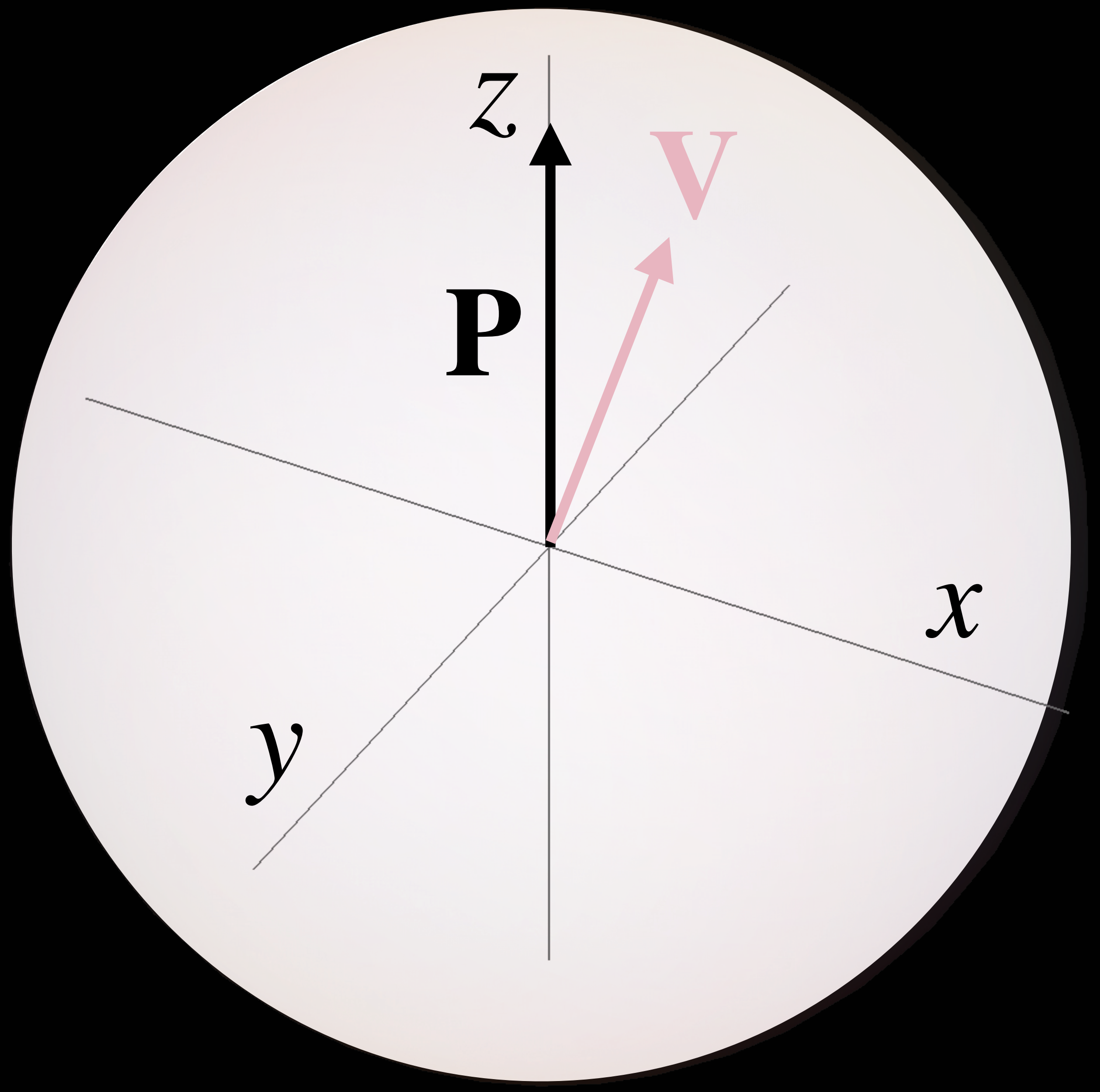
$P_0 = f_\psi(p) + f_\chi(p)$

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_\mathbf{T} + \dot{P}_0\,\hat{\mathbf{z}}$$

ROMP mixing

$\mathbf{V} = \omega_{\mathrm{osc}}\,(\sin 2\theta\,\hat{\mathbf{x}} + \cos 2\theta\,\hat{\mathbf{z}})$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



ROMP polarization with

$P_z = f_\psi(p) - f_\chi(p)$

$P_0 = f_\psi(p) + f_\chi(p)$

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_\mathbf{T} + \dot{P}_0\,\hat{\mathbf{z}}$$

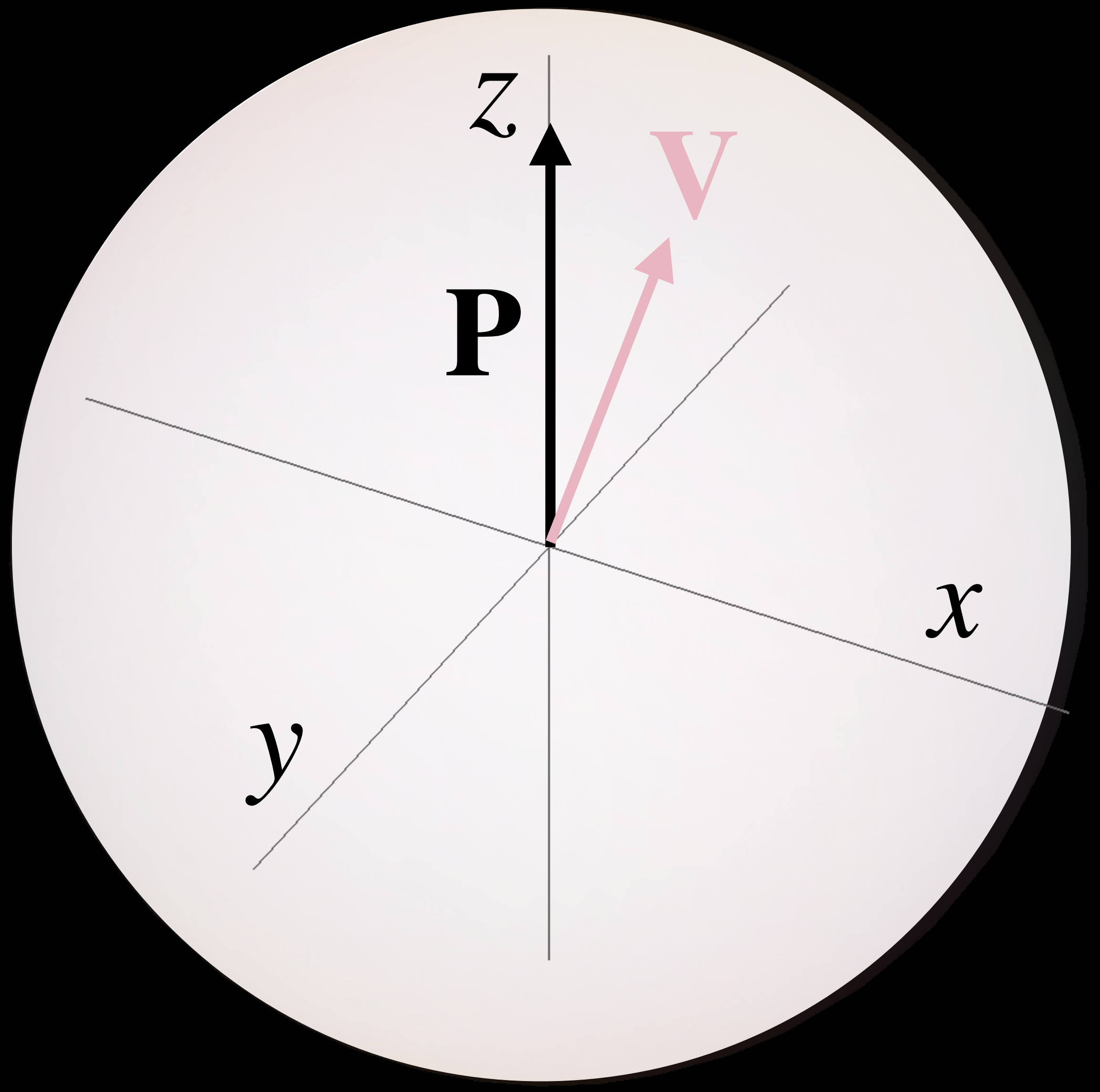
ROMP mixing

$\mathbf{V} = \omega_{\rm osc}\,(\sin 2\theta\,\hat{\mathbf{x}} + \cos 2\theta\,\hat{\mathbf{z}})$

Damping

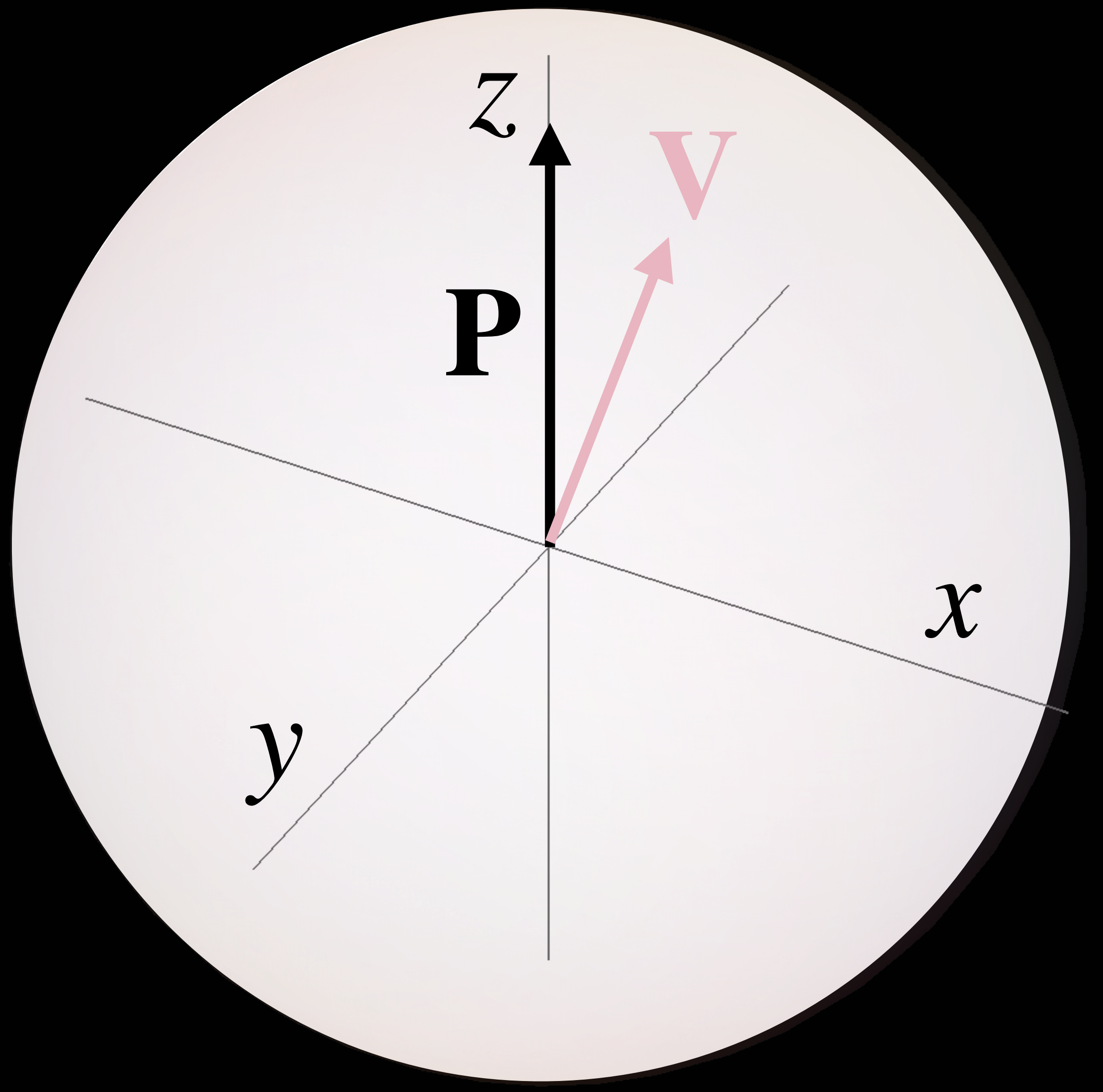
$D \sim \Gamma_{\psi \to \rm everything}$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_{\mathrm{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION

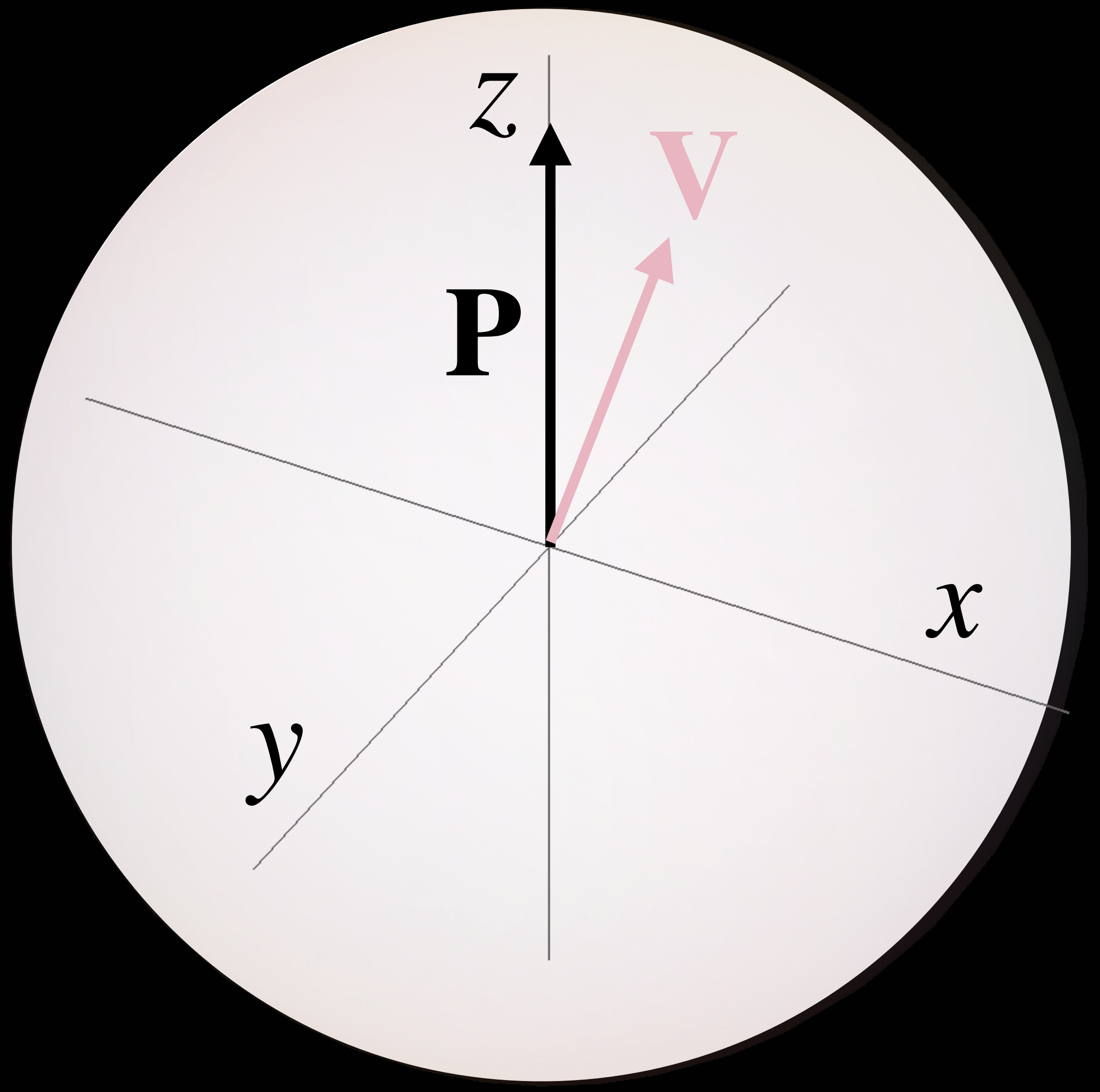


$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \underbrace{\mathbf{V} \times \mathbf{P}} - D\,\mathbf{P}_\mathrm{T} + \dot{P}_0\,\hat{\mathbf{z}}$$

Accounts for
coherent
effects

(quantum amplitudes)

SOLVE A QUANTUM KINETIC EQUATION FOR ROMP POLARIZATION



Accounts for incoherent effects

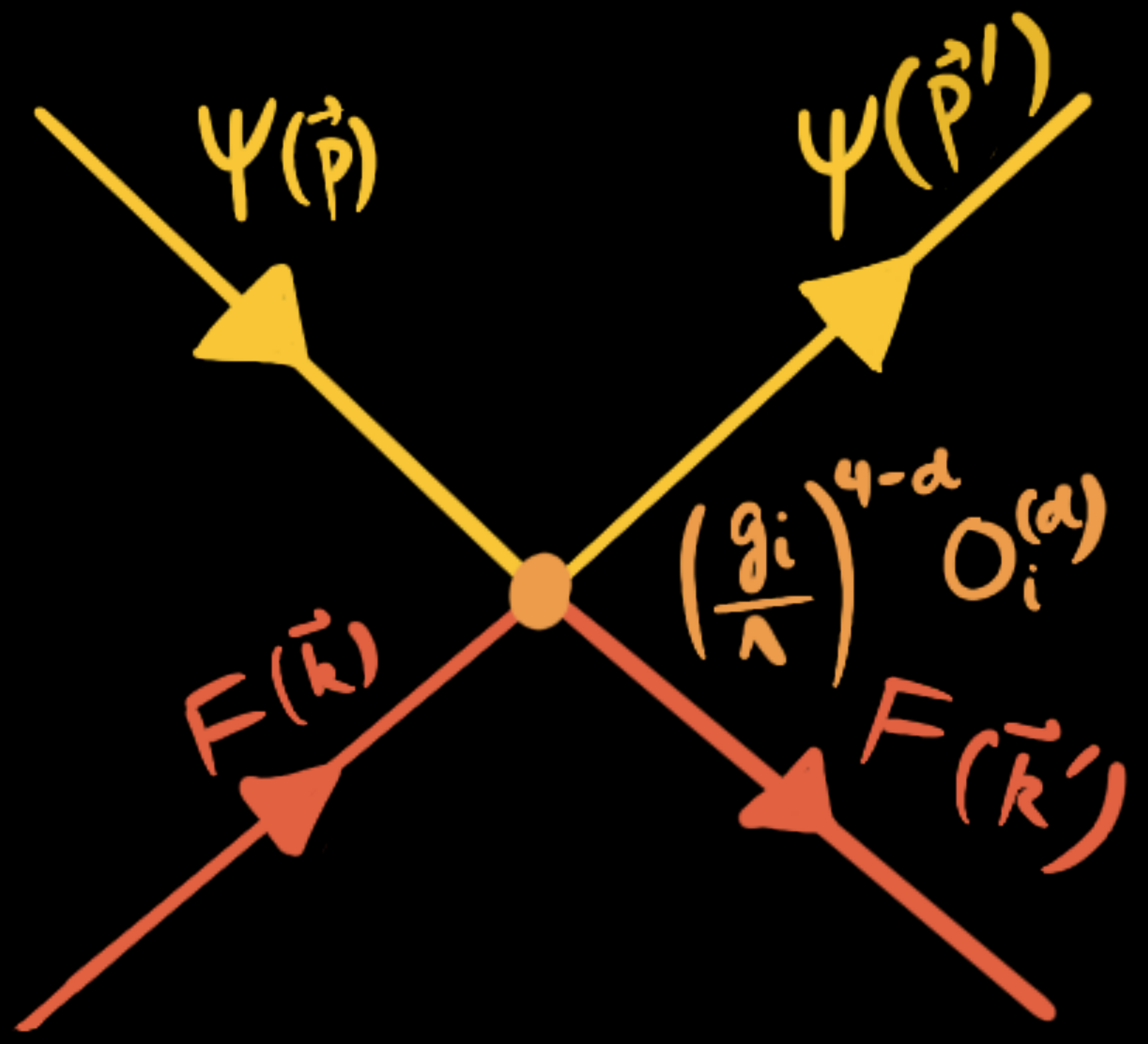
(quantum probability)

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V} \times \mathbf{P} - D\,\mathbf{P}_{\mathbf{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$

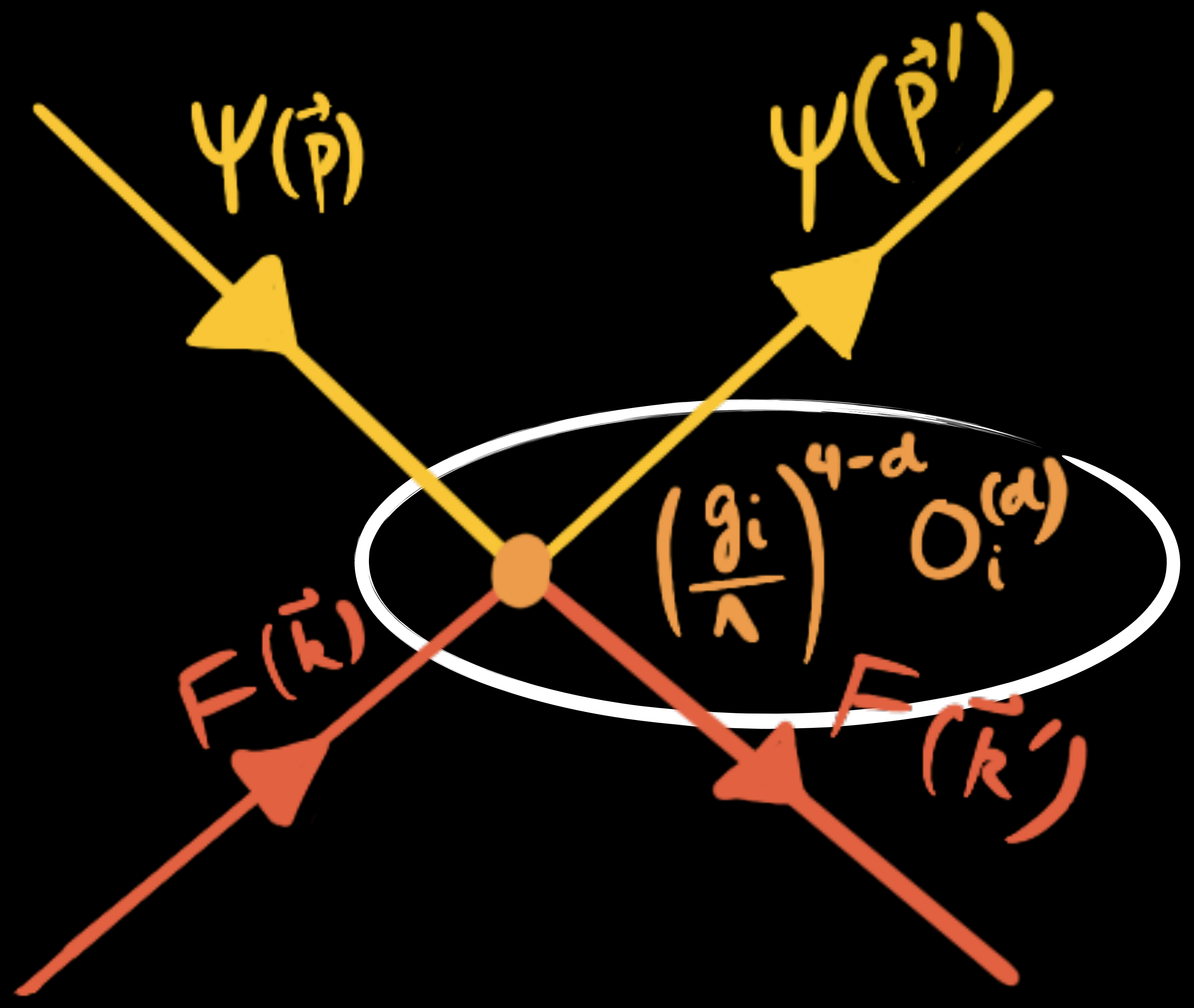
Accounts for coherent effects

(quantum amplitudes)

NEED TO QUANTIFY:



NEED TO QUANTIFY:



FINALLY TIME TO TALK ABOUT COUPLINGS!

VECTOR INTERACTIONS: PHENOMENOLOGY

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

DIM 6: $\mathscr{L}_V^{(6)} = (\bar{\psi}\gamma^\mu F)g_{\mu\nu}(\bar{F}\gamma^\nu\psi)$:

May be small!

$$\Delta m_T^2 \sim \frac{T^2}{\Lambda^2}\frac{1}{T}(n_F - n_{\bar{F}})$$

VECTOR INTERACTIONS: PHENOMENOLOGY

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

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

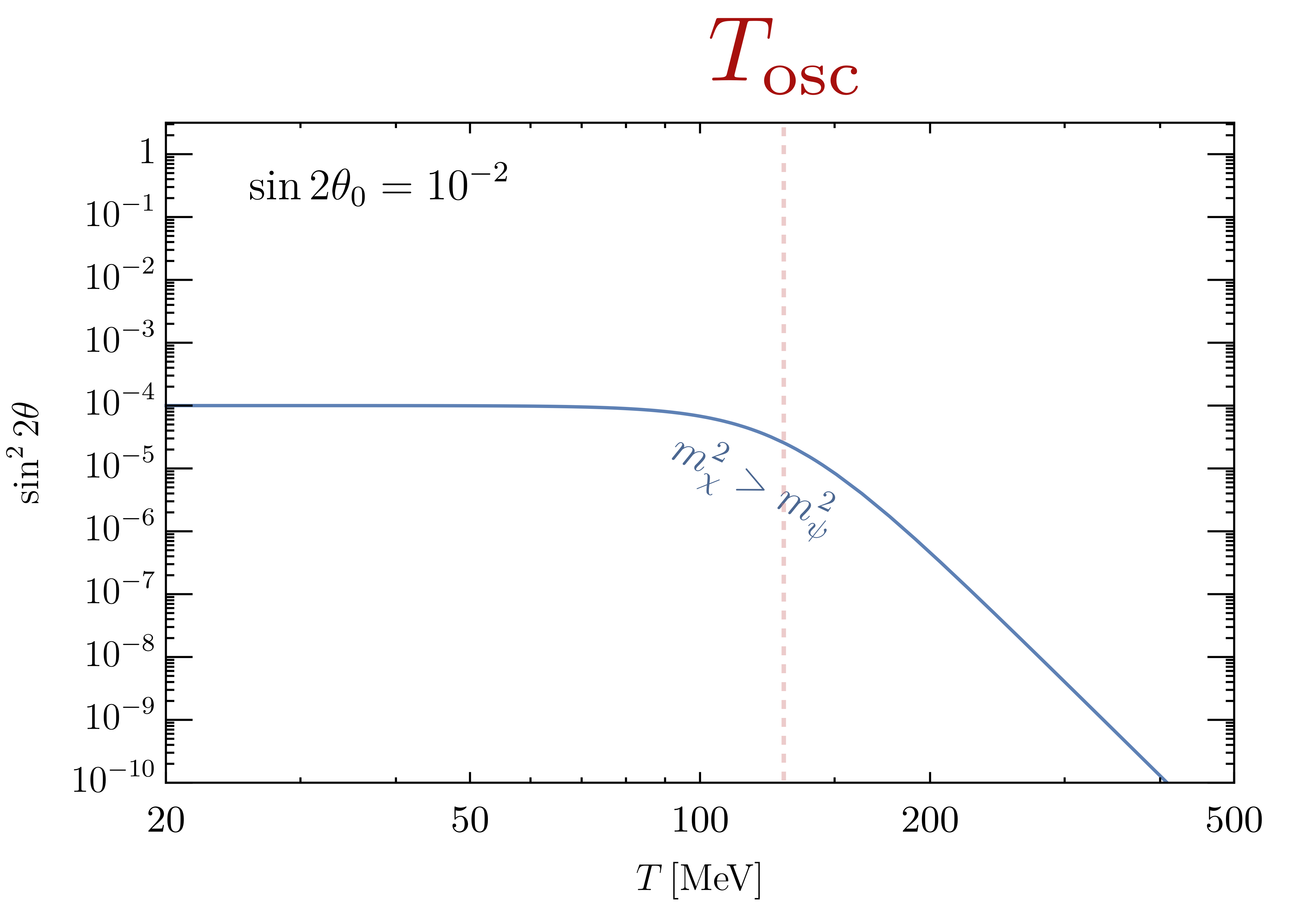
Vector Interactions: Phenomenology

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

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 > m_\psi^2$: No Resonance!

Scattering induced incoherent production!



VECTOR INTERACTIONS: PHENOMENOLOGY

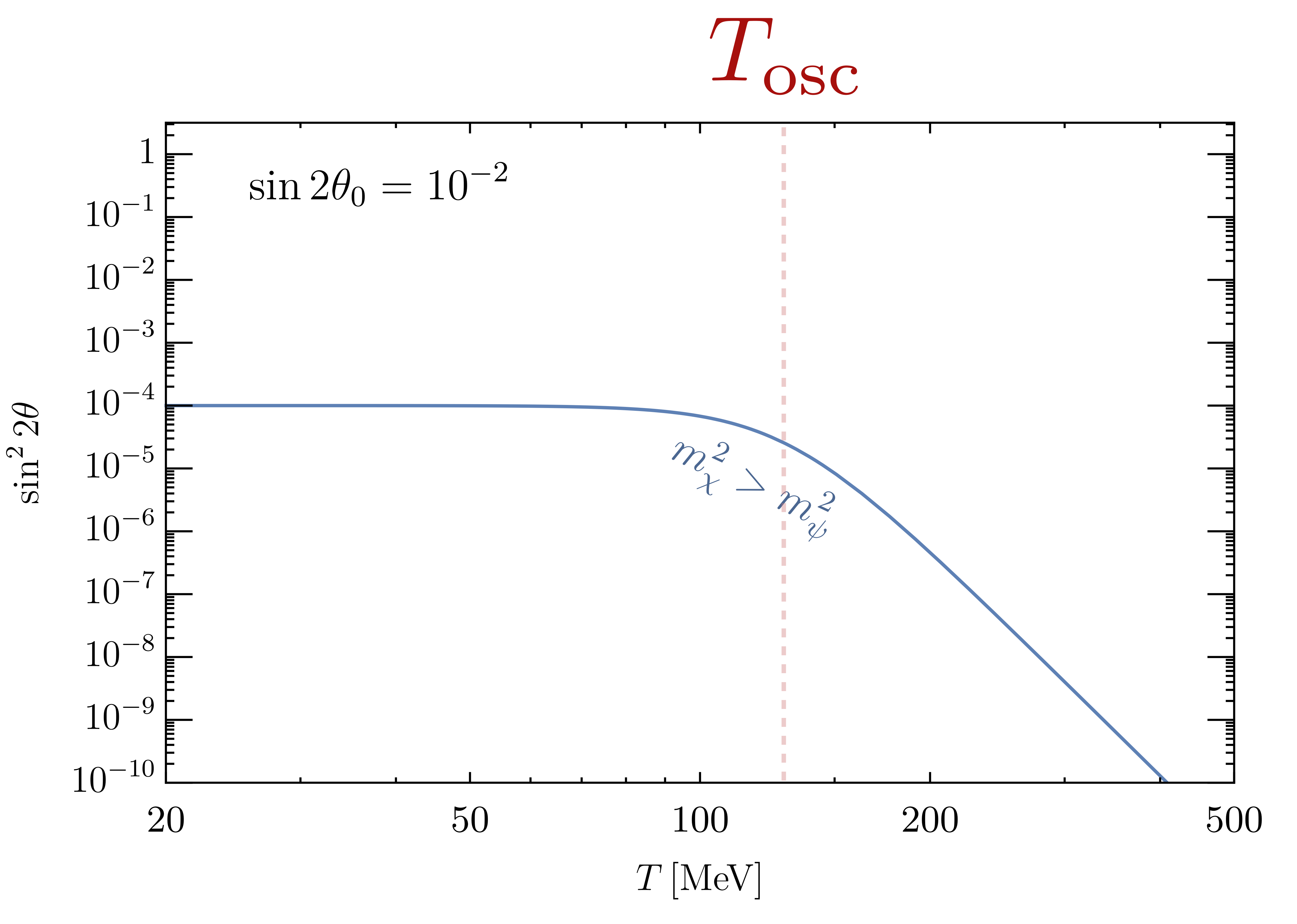
$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_\psi^2 + \Delta m_T^2 - m_\chi^2}$$

DIM 8: $\mathcal{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu \psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 > m_\psi^2$: No Resonance!

Scattering induced incoherent production!

χ may decay: account for lifetime of χ



VECTOR INTERACTIONS: PHENOMENOLOGY

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

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 > m_\psi^2$: No Resonance!

Scattering induced incoherent production!

χ may decay: account for lifetime of χ

Vector Interactions: Phenomenology

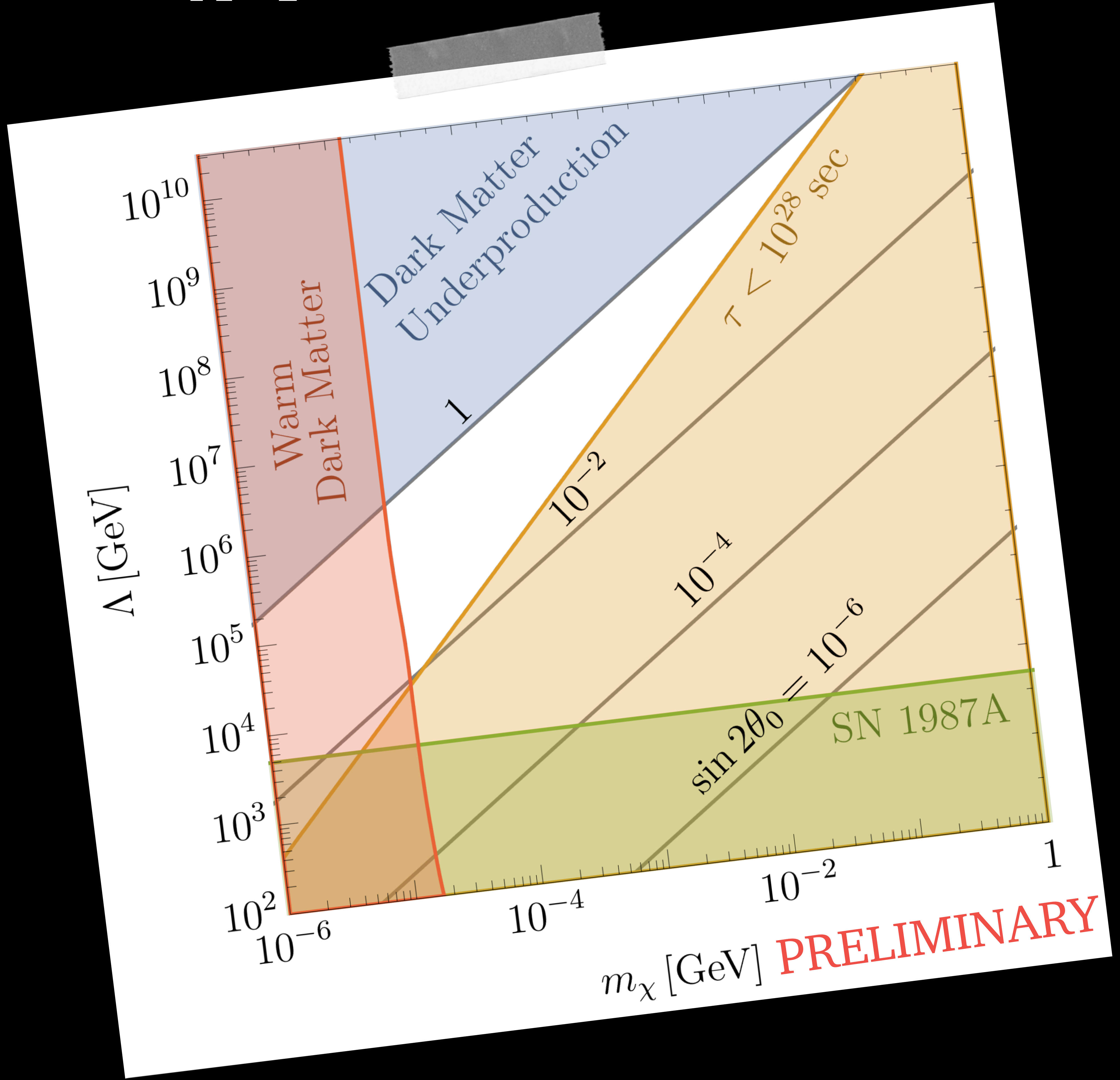
$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_\psi^2 + \Delta m_T^2 - m_\chi^2}$$

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\quad \Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 > m_\psi^2$: No Resonance!

Scattering induced incoherent production!

χ may decay: account for lifetime of χ



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

VECTOR INTERACTIONS:

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

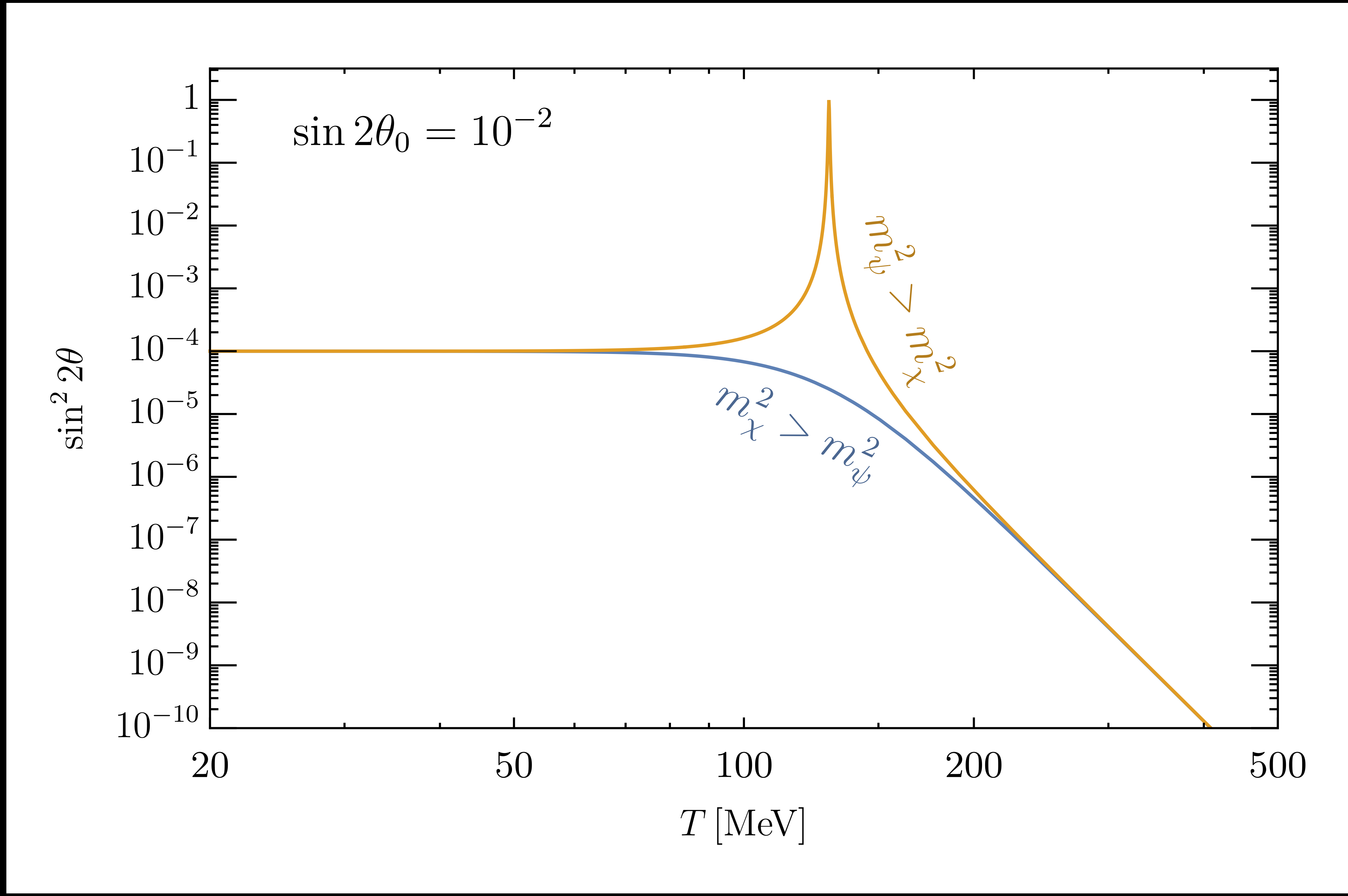
If $m_\chi^2 < m_\psi^2$: Resonance

VECTOR INTERACTIONS:

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

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 < m_\psi^2$: Resonance



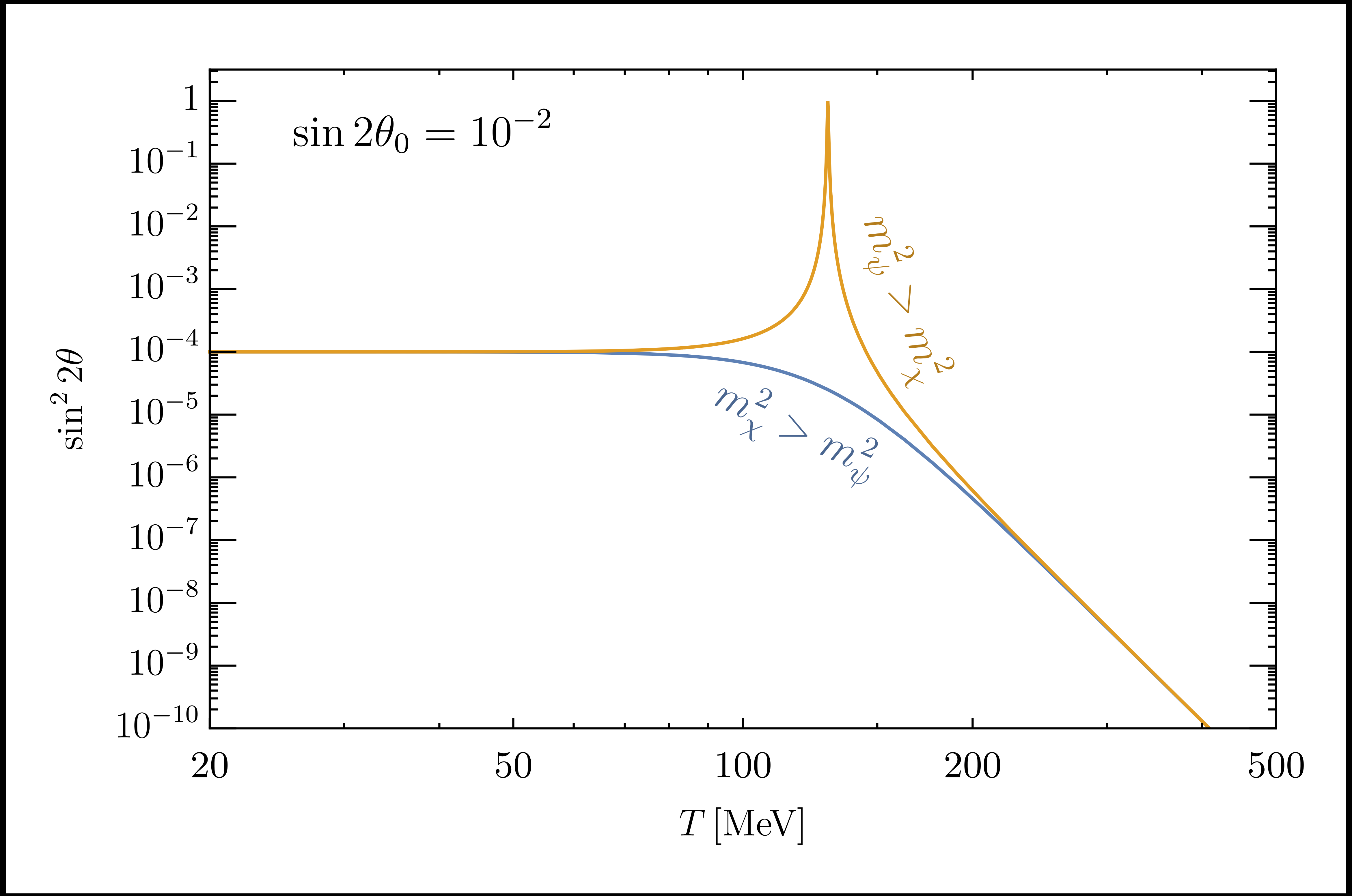
VECTOR INTERACTIONS:

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

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu \psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 < m_\psi^2$: Resonance

Both coherent (oscillations) and incoherent (scattering induced) production



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

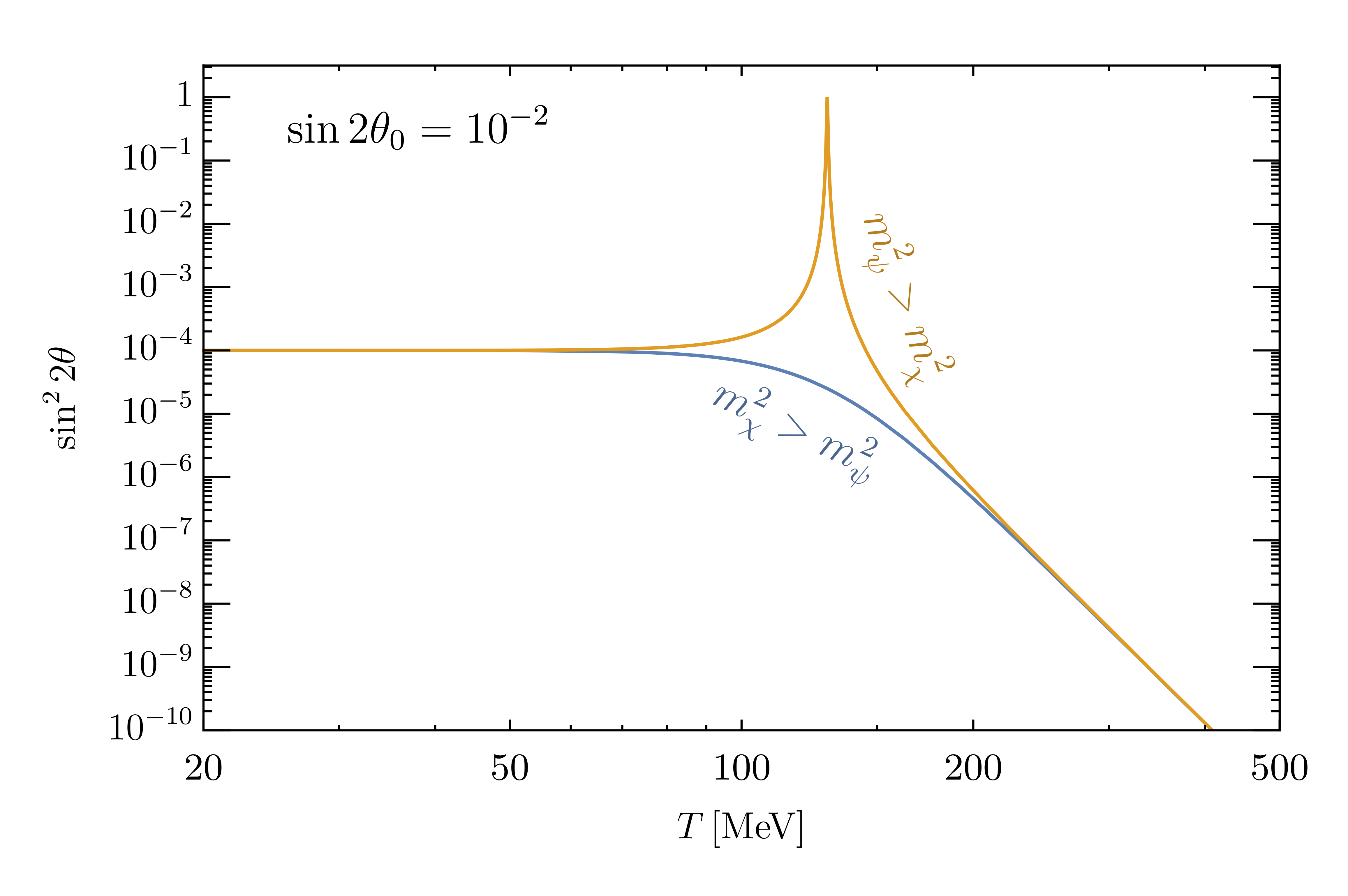
VECTOR INTERACTIONS:

DIM 8: $\mathcal{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 < m_\psi^2$: Resonance

Both coherent (oscillations) and incoherent (scattering induced) production

ψ may decay: account for freeze-out and decay



VECTOR INTERACTIONS:

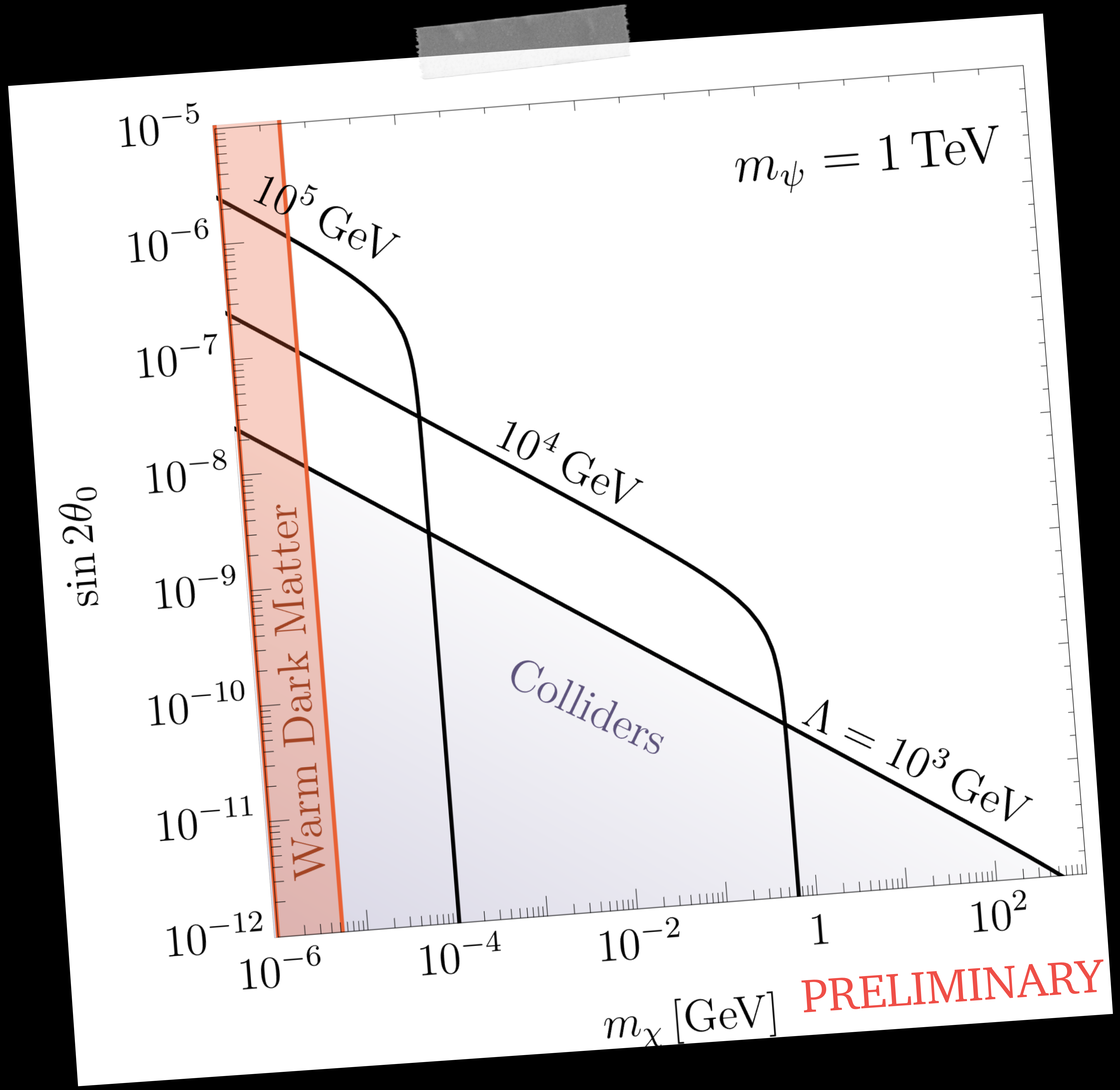
$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_\psi^2 + \Delta m_T^2 - m_\chi^2}$$

DIM 8: $\mathscr{L}_V^{(6)} = \frac{1}{\Lambda^4}(\bar{\psi}\gamma^\mu F)(g_{\mu\nu}q^2 + q_\mu q_\nu)(\bar{F}\gamma^\nu\psi)$: $\Delta m_T^2 \sim -\frac{T^4}{\Lambda^4}\frac{1}{T}(n_F + n_{\bar{F}})$

If $m_\chi^2 < m_\psi^2$: Resonance

Both coherent (oscillations) and incoherent (scattering induced) production

ψ may decay: account for freeze-out and decay



TAKEAWAYS

TAKEAWAYS

1. OSCILLATIONS CAN BE AN EFFICIENT MECHANISM FOR DARK MATTER PRODUCTION

TAKEAWAYS

1. OSCILLATIONS CAN BE AN EFFICIENT MECHANISM FOR DARK MATTER PRODUCTION

2. ROMPS ARE PHENOMENOLOGICALLY DIFFERENT FROM TRADITIONAL DARK MATTER CANDIDATES!

TAKEAWAYS

1. **OSCILLATIONS CAN BE AN EFFICIENT MECHANISM FOR DARK MATTER PRODUCTION**

2. **ROMPS ARE PHENOMENOLOGICALLY DIFFERENT FROM TRADITIONAL DARK MATTER CANDIDATES!**

- Production sensitive to coherent effects!
- New temperature scale for production!
- Impact on DM momentum distribution!

TAKEAWAYS

1. OSCILLATIONS CAN BE AN EFFICIENT MECHANISM FOR DARK MATTER PRODUCTION

2. ROMPS ARE PHENOMENOLOGICALLY DIFFERENT FROM TRADITIONAL DARK MATTER CANDIDATES!

- Production sensitive to coherent effects!
- New temperature scale for production!
- Impact on DM momentum distribution!

3. THE ROMP FRAMEWORK CAN BE EASILY GENERALIZED TO WELL-ESTABLISHED DARK MATTER MODELS

OUTLOOK

OUTLOOK

1. ESTABLISH THE PHENOMENOLOGY OF OTHER EFFECTIVE OPERATORS SUCH AS SCALAR FOUR-FERMI OPERATORS

2. WORK OUT CONSTRAINTS:

   A. STRUCTURE FORMATION

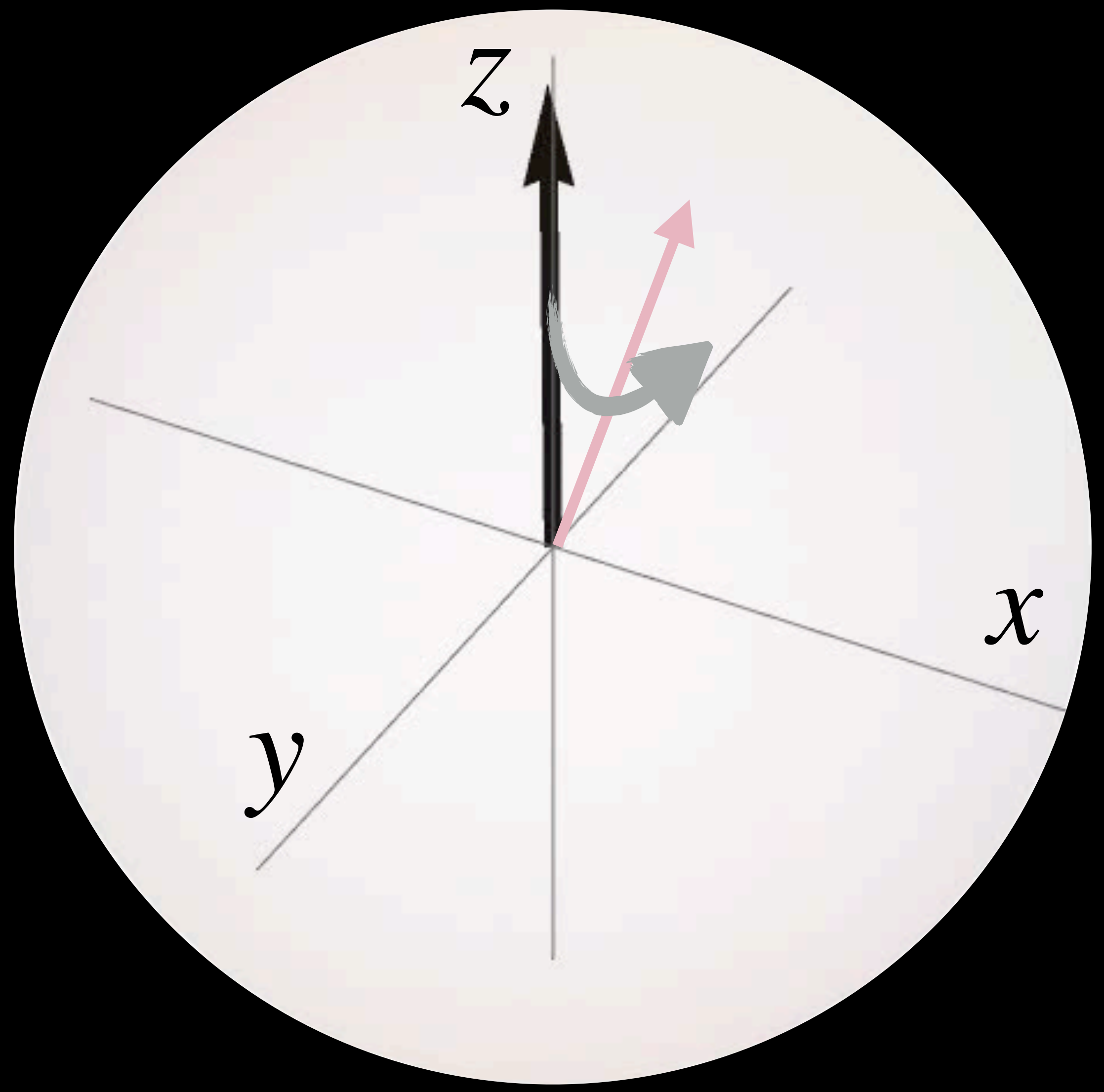
   B. COLLIDER SEARCHES

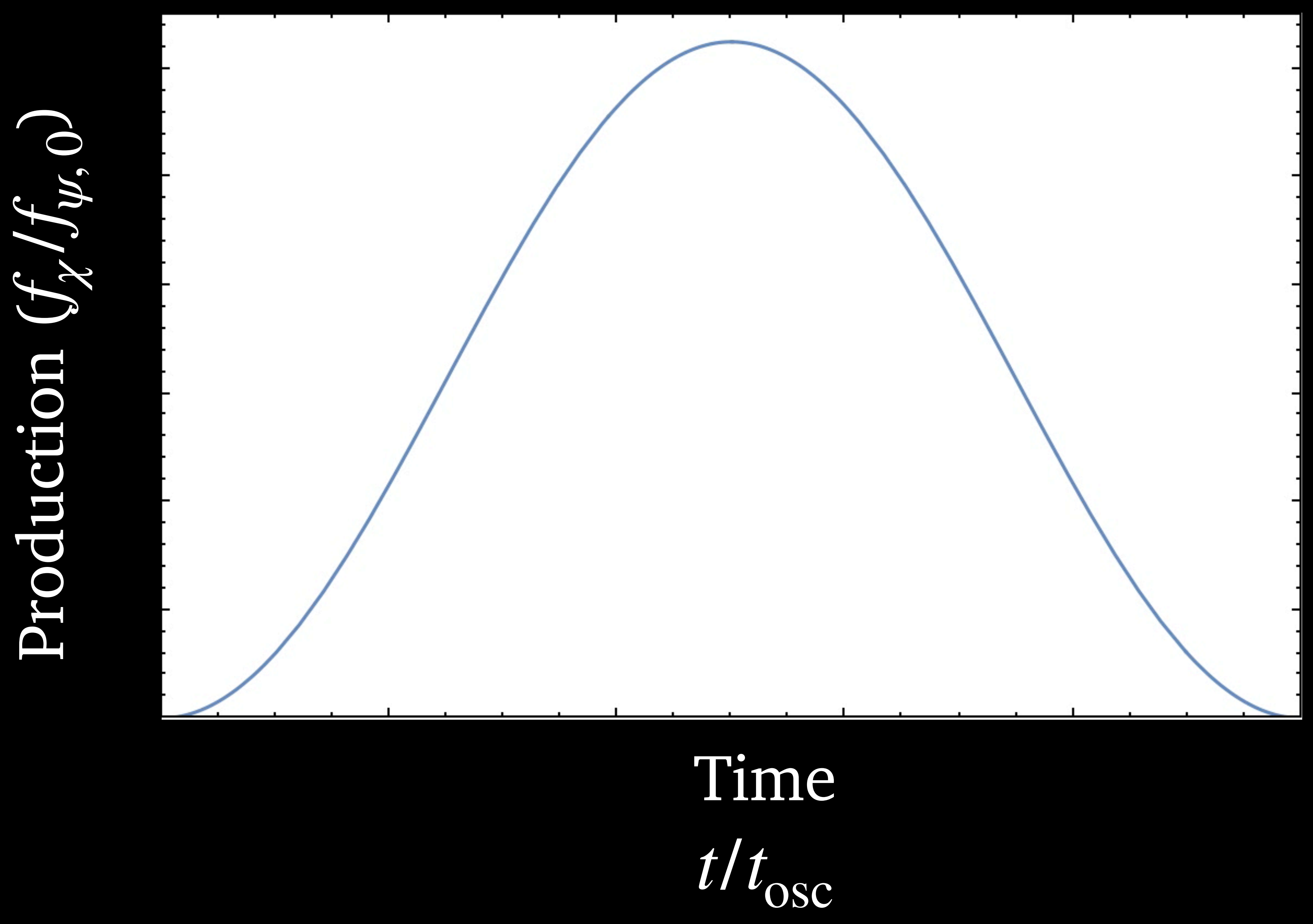
   C. INDIRECT SEARCHES FOR DECAYS

(fin.)

IN A VACUUM:

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

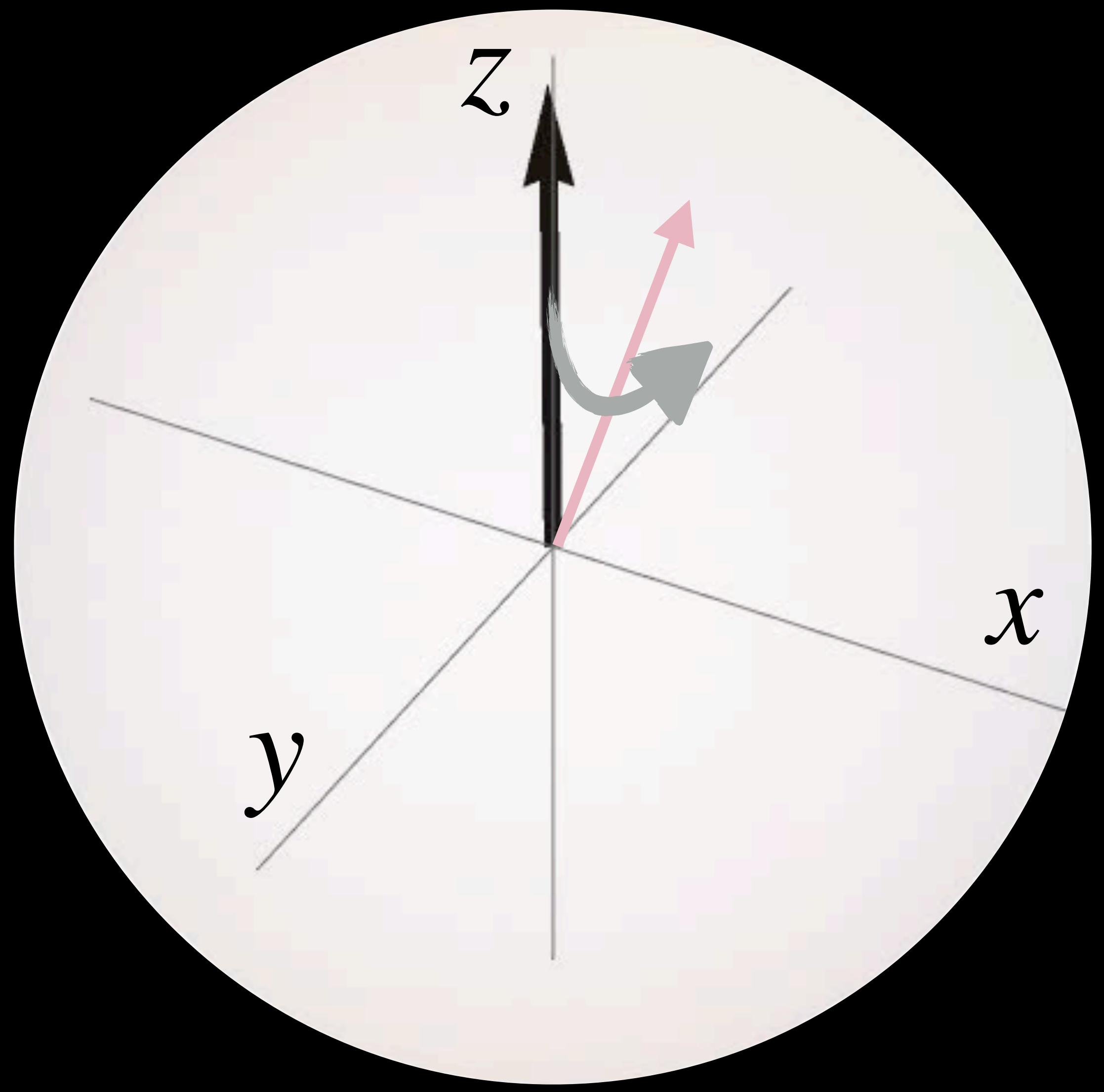


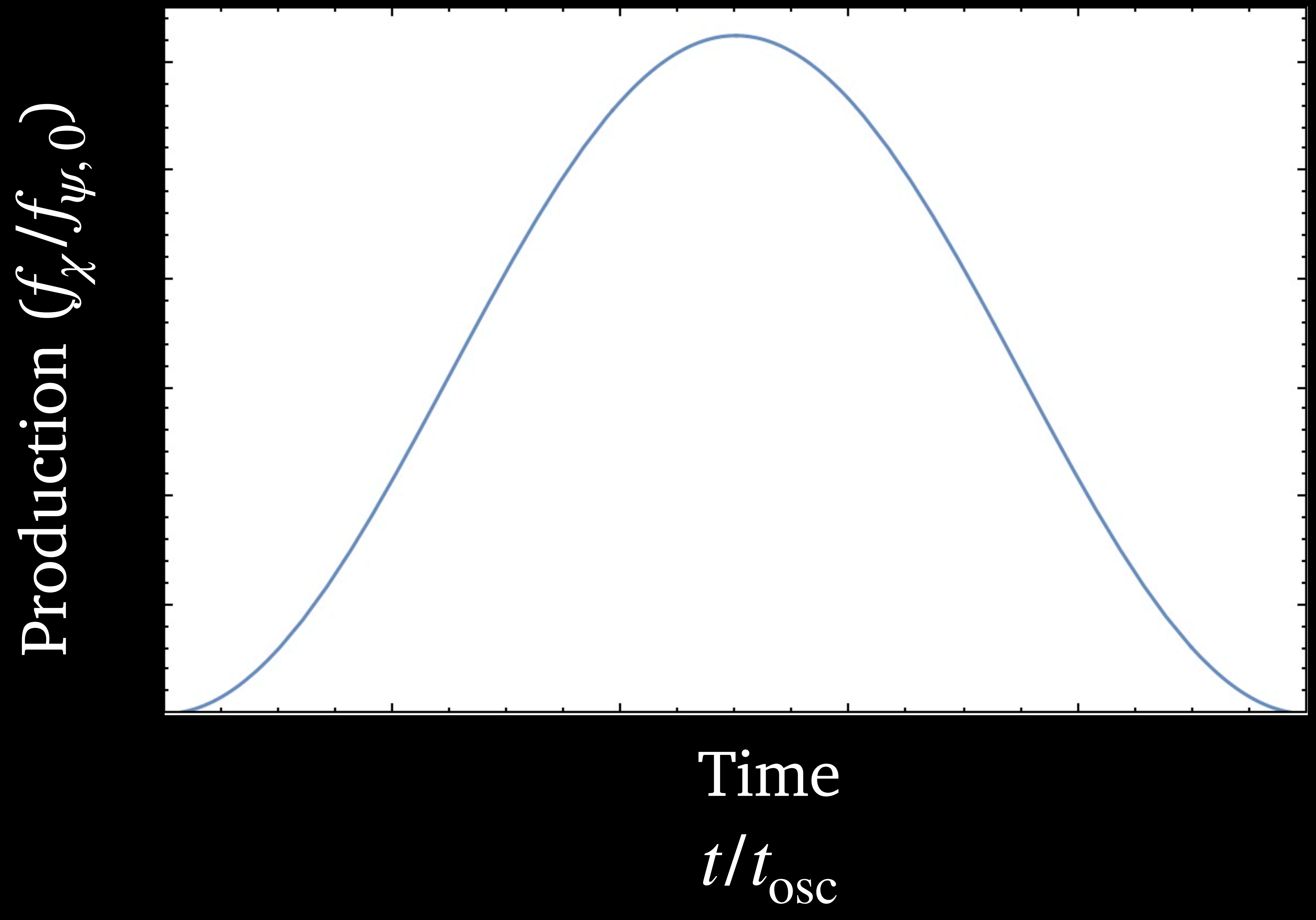


Animation Credit: D. Dunsky

IN A VACUUM:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\text{vac}} \times \mathbf{P} - D\mathbf{P}_{\mathrm{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$

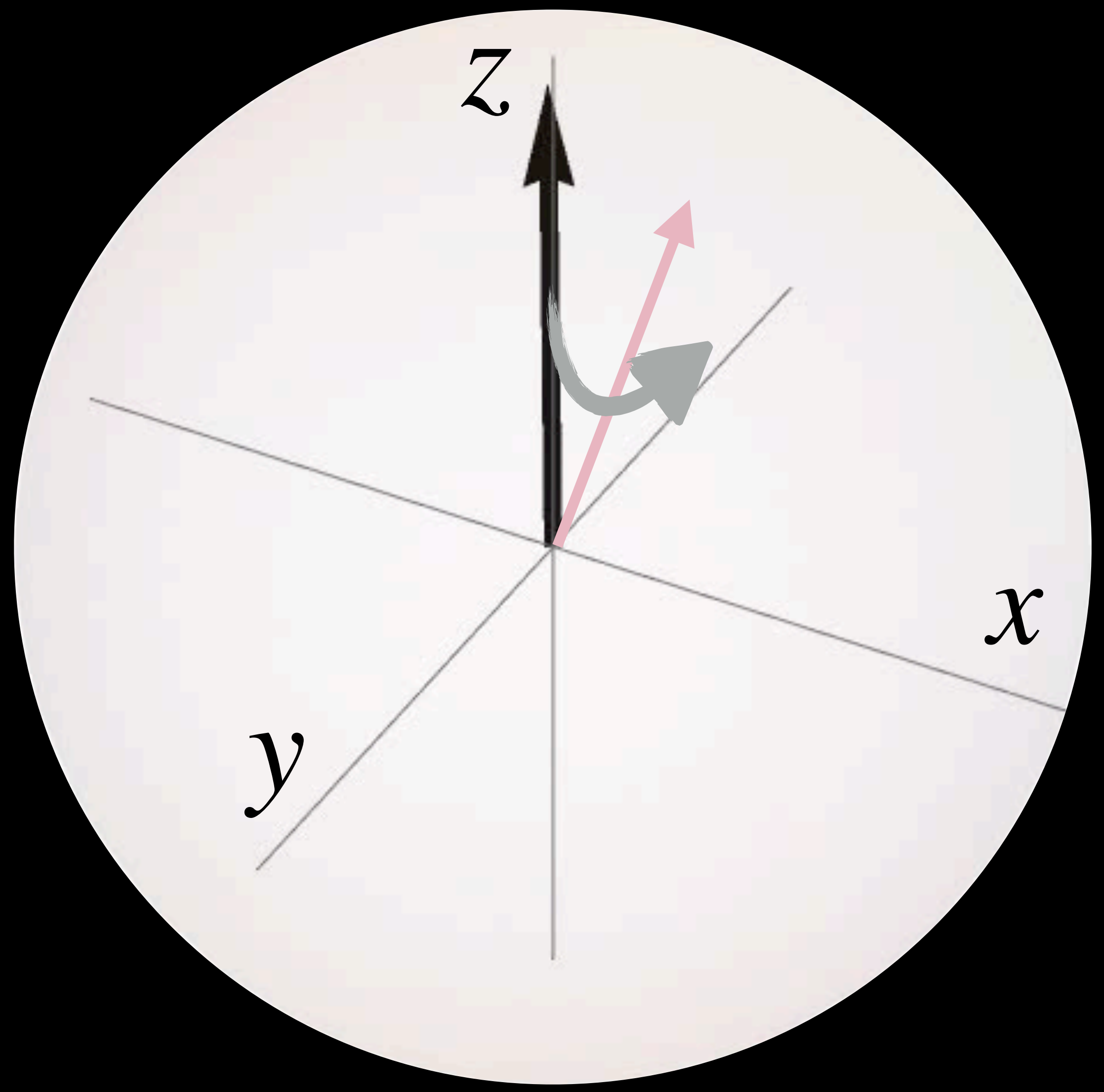


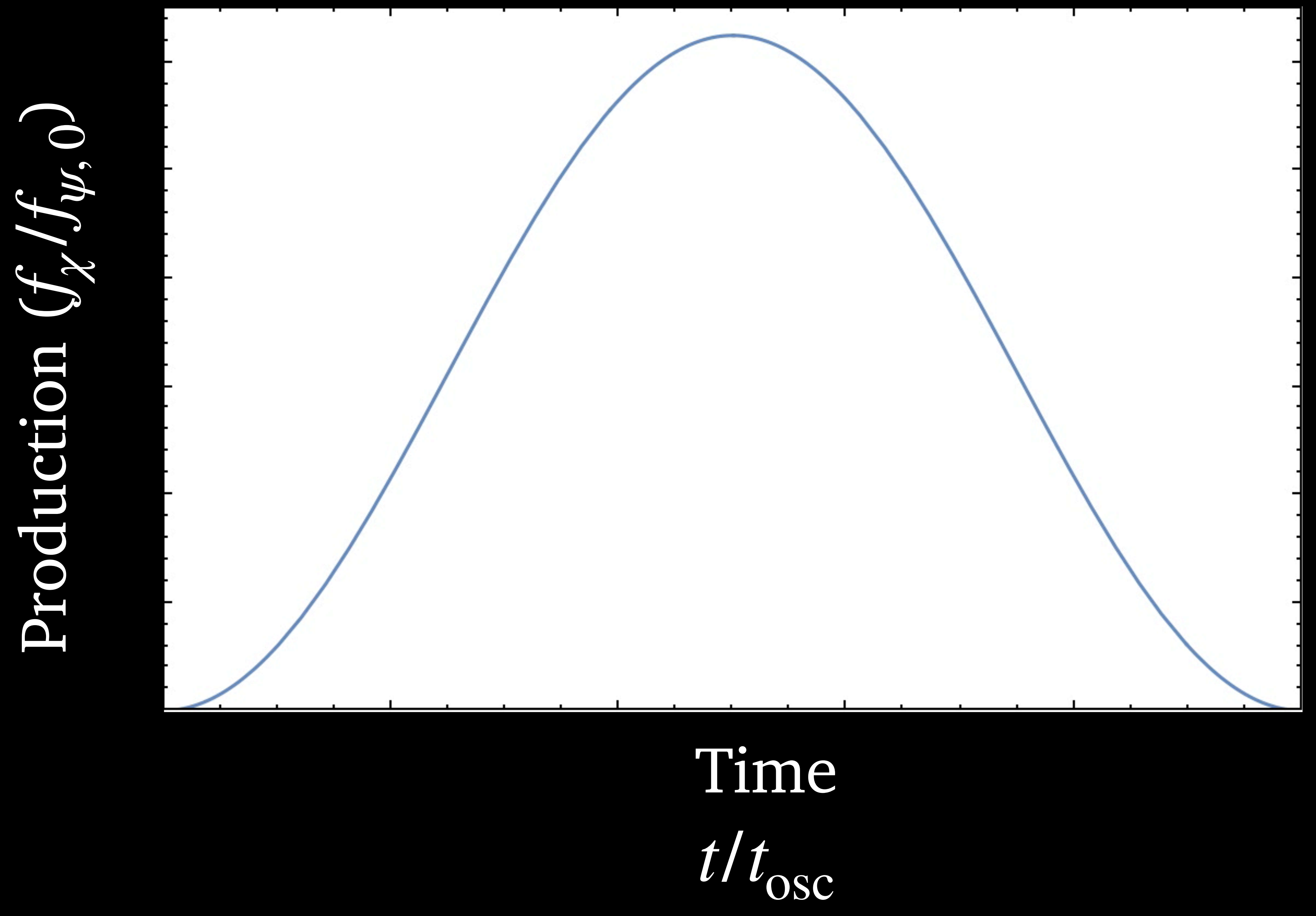


Animation Credit: D. Dunsky

IN A VACUUM:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\mathrm{vac}} \times \mathbf{P} - D\mathbf{P}_{\mathrm{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$

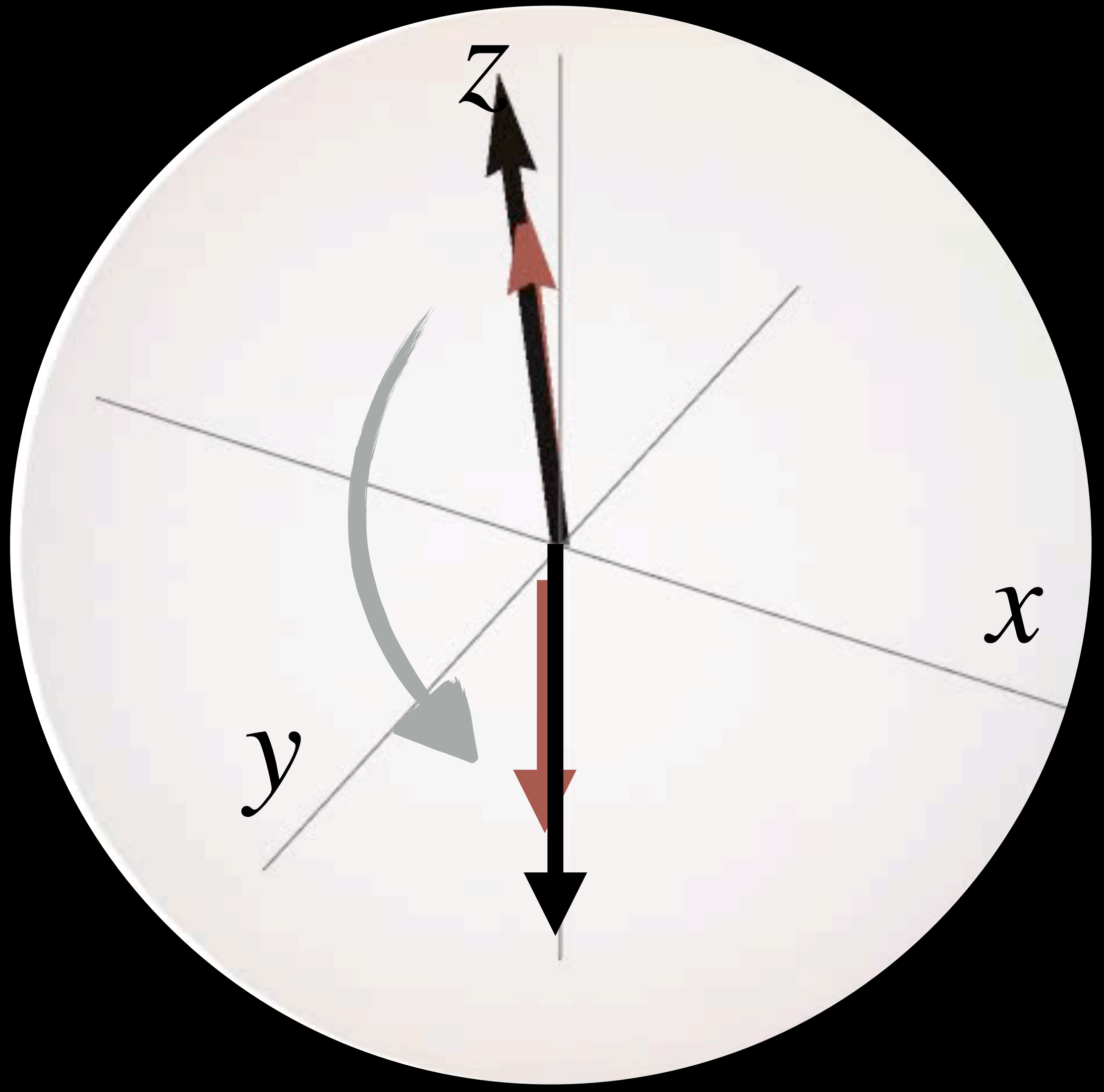


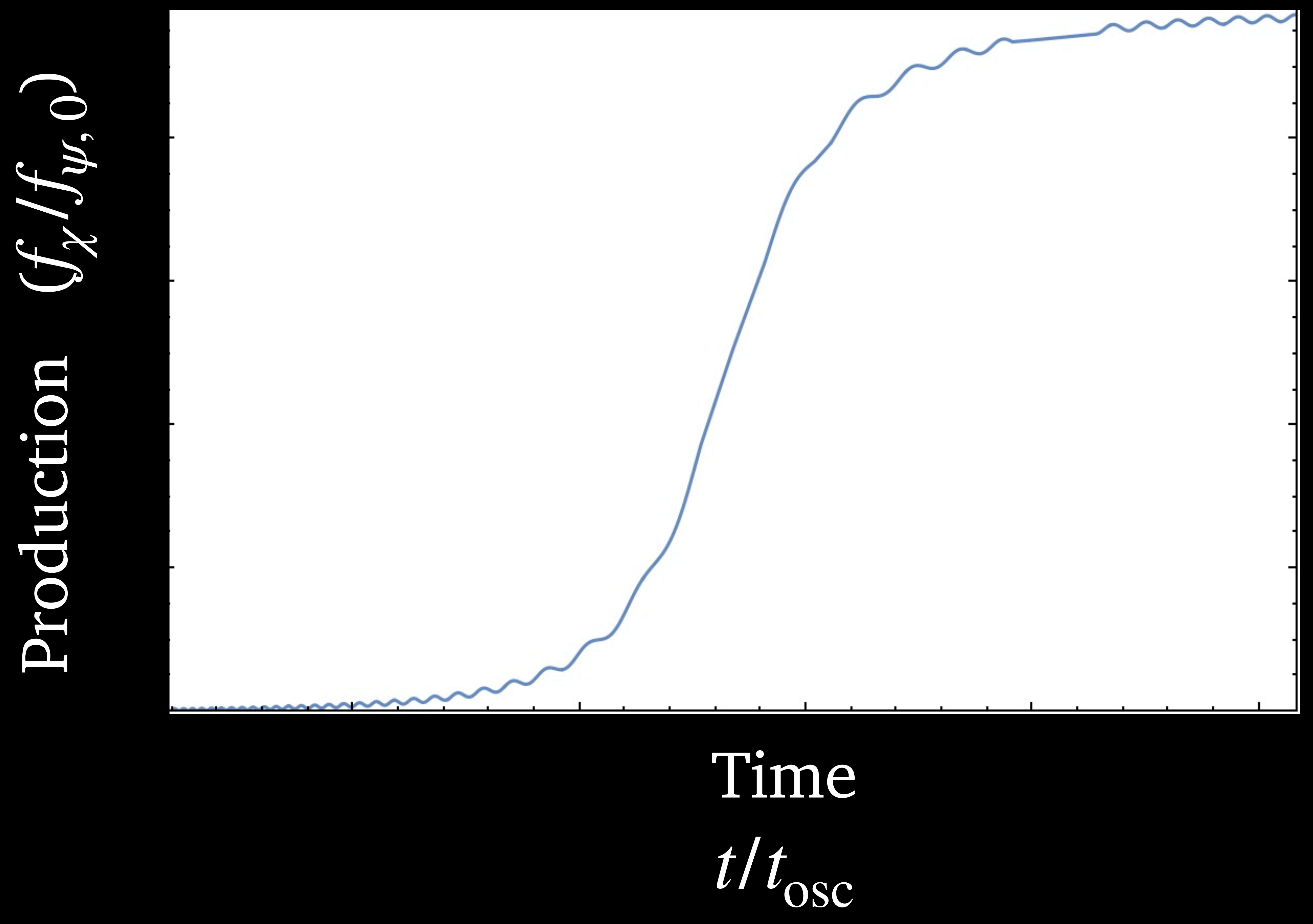


ψ oscillates into χ with a probability given by: $\frac{f_\chi}{f_{\psi,0}} = P_{\psi\to\chi} \sim \sin^2\theta_{\mathrm{vac}}\,(1 - \cos\omega_{\mathrm{osc}}t)$

Animation Credit: D. Dunsky

IN A MEDIUM, WITHOUT COLLISIONS: $\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\mathrm{med}} \times \mathbf{P} \cancel{- D\mathbf{P}_{\perp} +} \dot{P}_0 \hat{\mathbf{z}}$



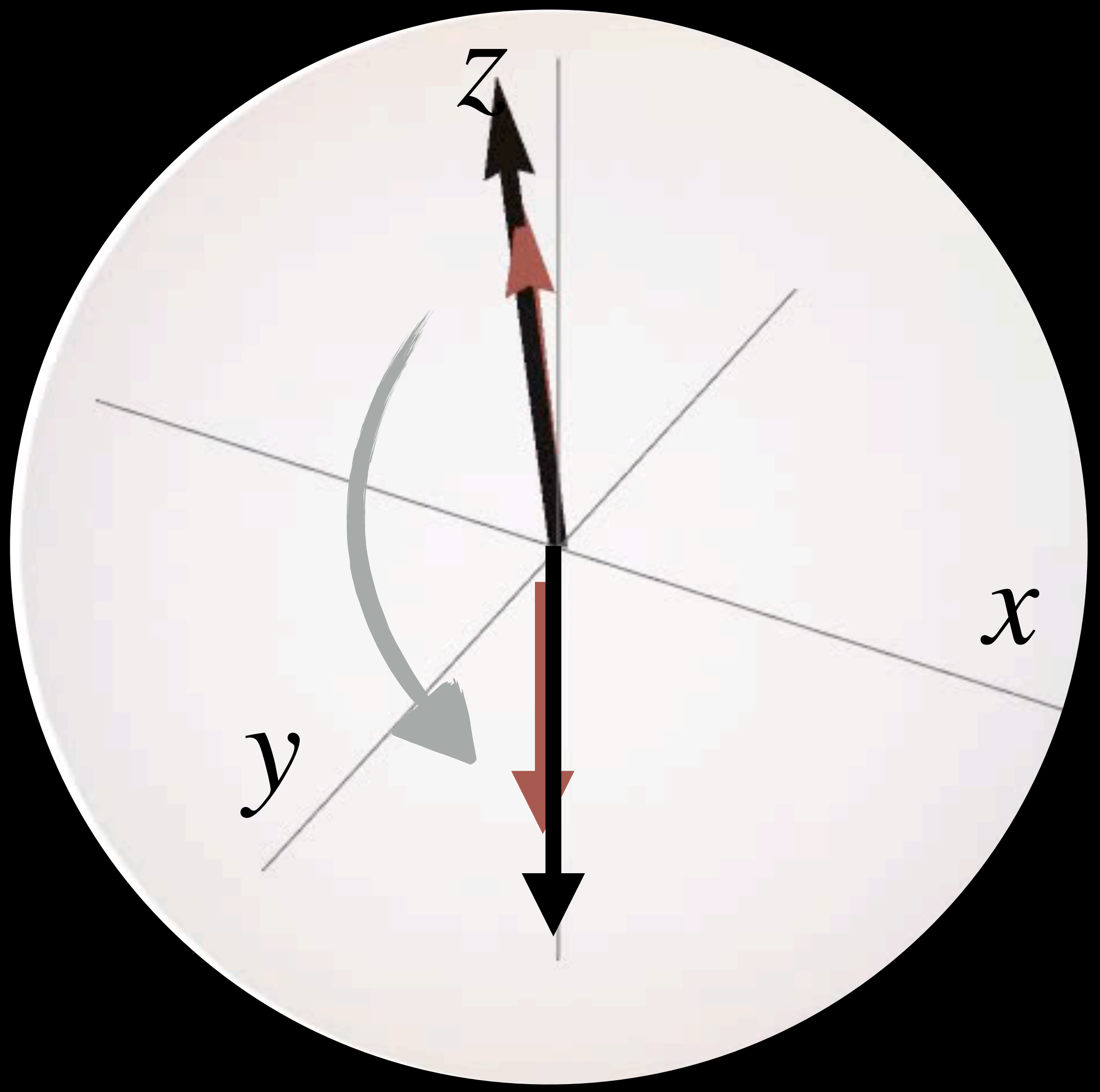


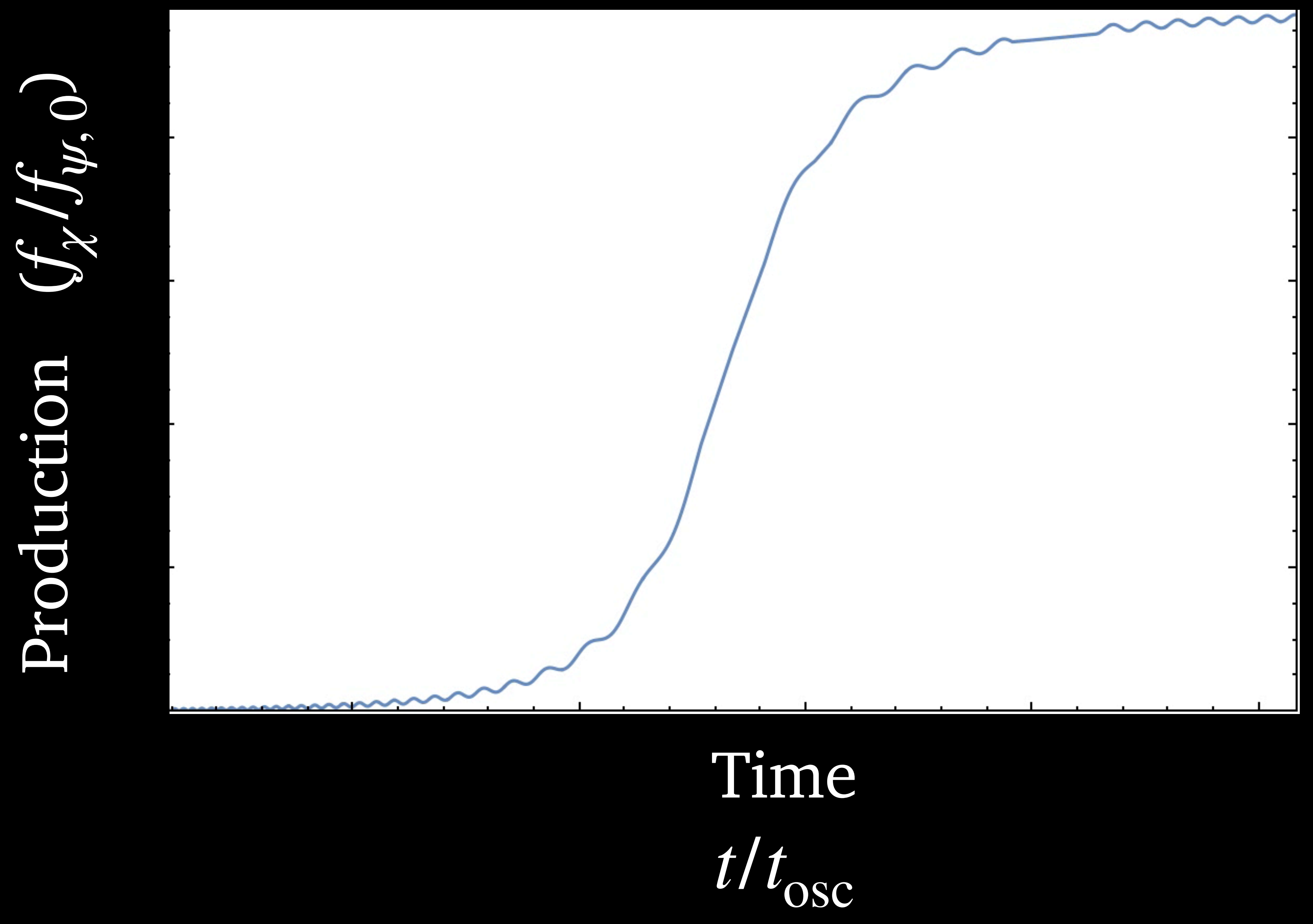
Mixing angle is a function of temperature, and may cross a resonance!

If $\delta t_{\mathrm{res}} > t_{\mathrm{osc}}$ adiabatic conversion!

Animation Credit: D. Dunsky

IN A MEDIUM, WITHOUT COLLISIONS: $\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\mathrm{med}} \times \mathbf{P} - D\mathbf{P}_{\perp} + \dot{P}_0 \, \hat{\mathbf{z}}$





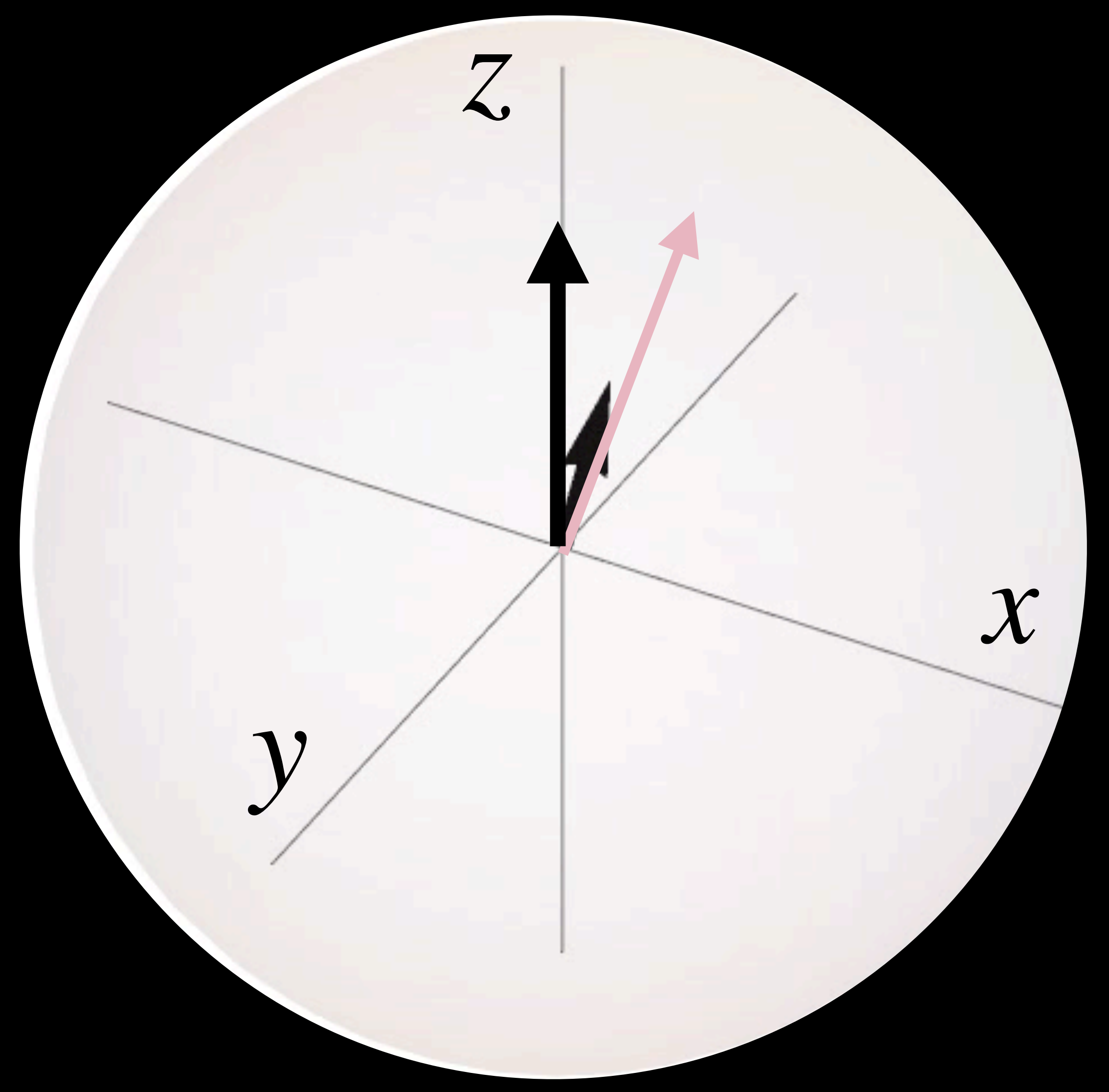
Mixing angle is a function of temperature, and may cross a resonance!

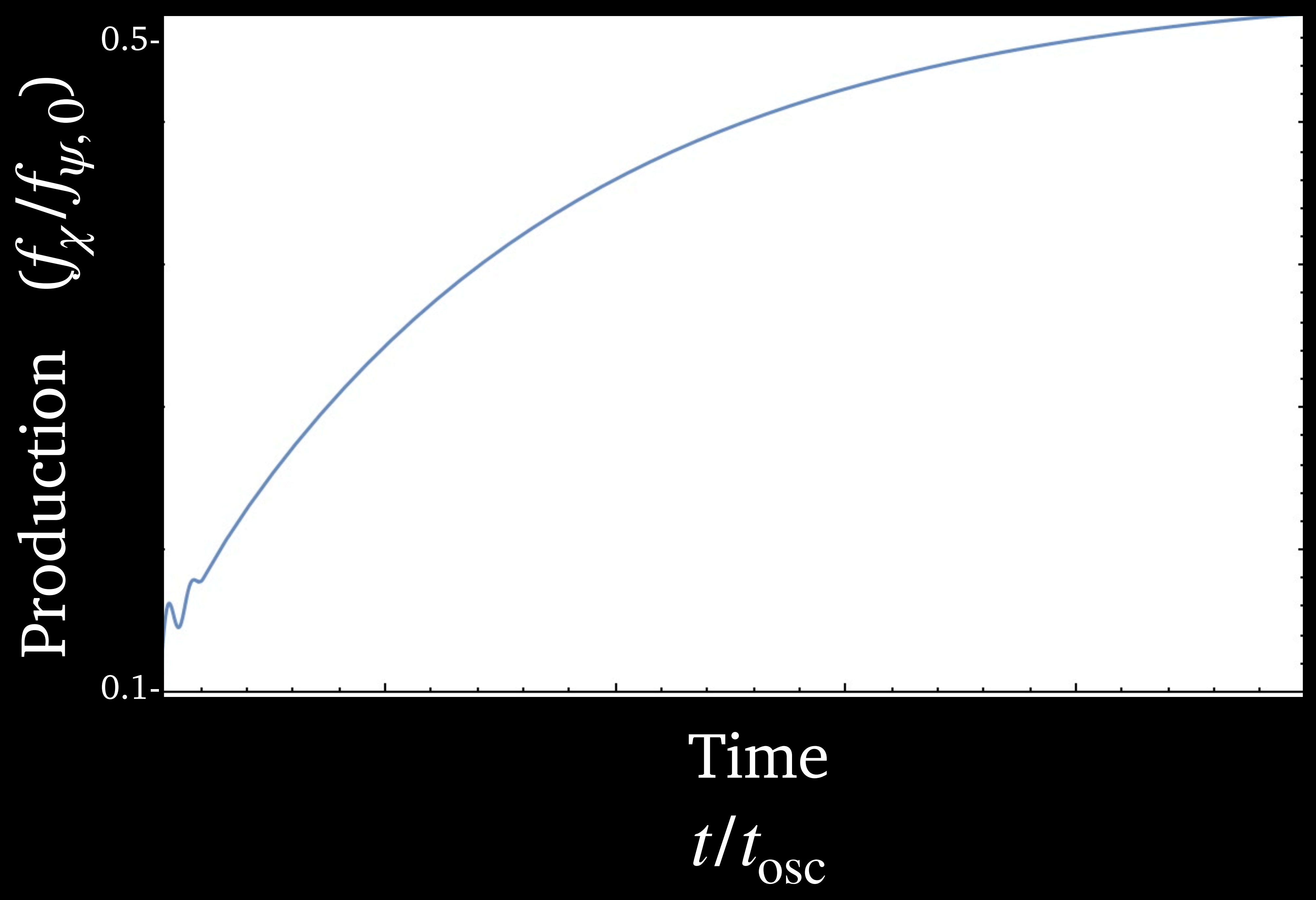
If $\delta t_{\mathrm{res}} > t_{\mathrm{osc}}$ adiabatic conversion!

Animation Credit: D. Dunsky

ADDING COLLISIONS:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\mathrm{vac}} \times \mathbf{P} - D\,\mathbf{P}_{\mathbf{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$



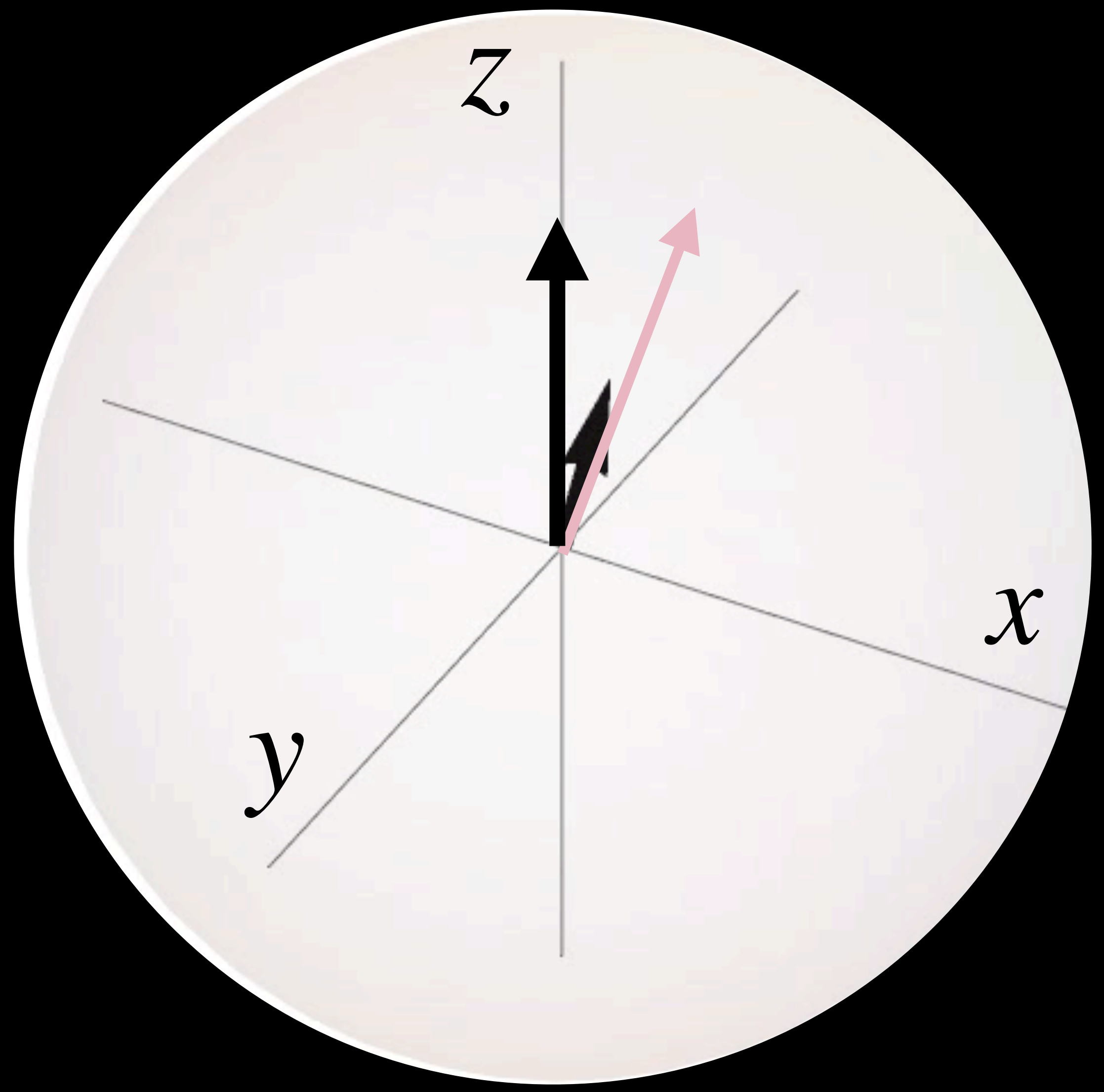


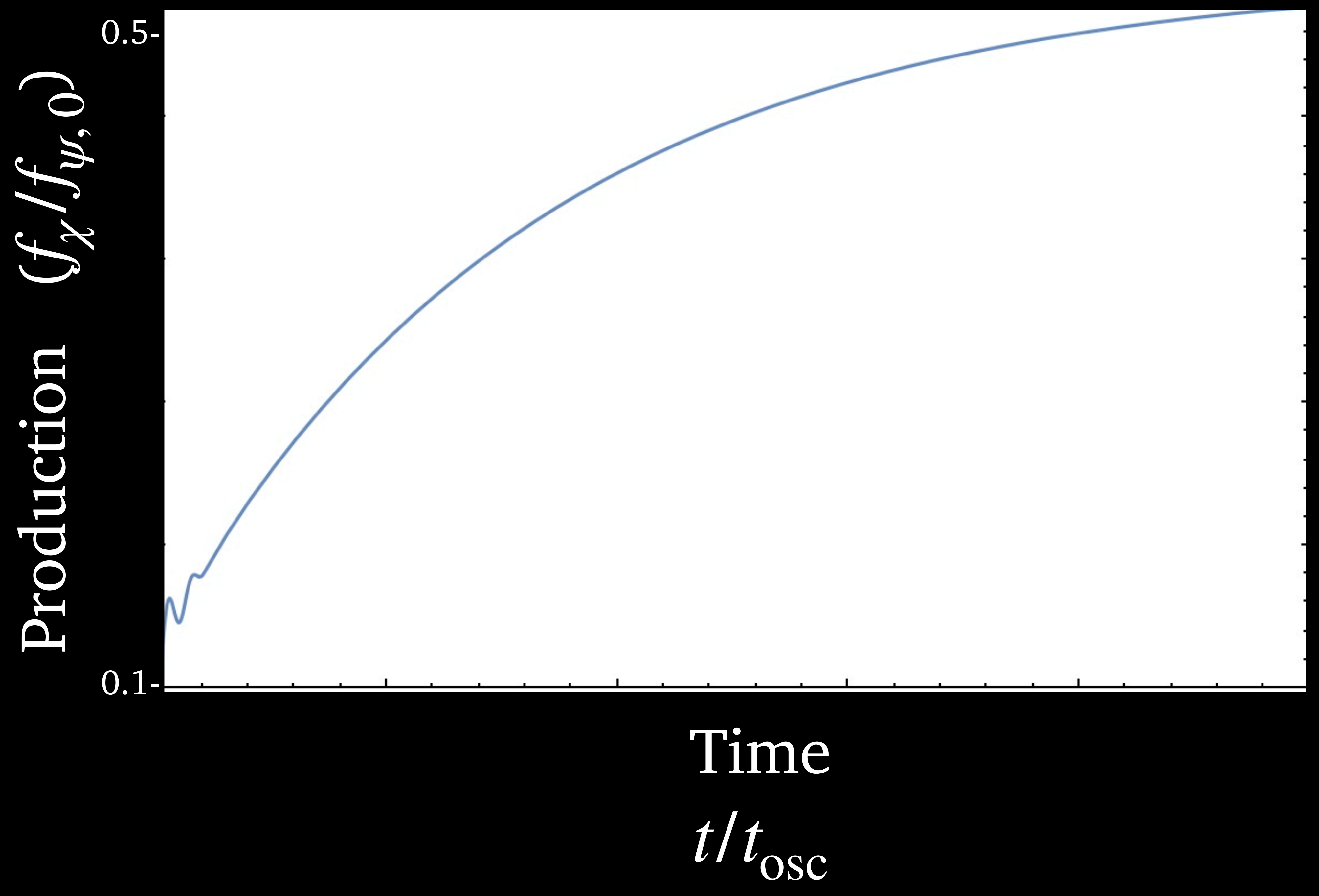
Collisions cause the two states to "decohere" and become equally populated

Animation Credit: D. Dunsky

ADDING COLLISIONS:

$$\frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \mathbf{V}_{\mathrm{vac}} \times \mathbf{P} - D\,\mathbf{P}_{\mathbf{T}} + \dot{P}_0\,\hat{\mathbf{z}}$$





Collisions cause the two states to “decohere” and become equally populated

Animation Credit: D. Dunsky