Baryogenesis and Particle—Antiparticle Oscillations

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UC Irvine

SI, John March-Russell, *arXiv:1604.00009*

Sneak peek

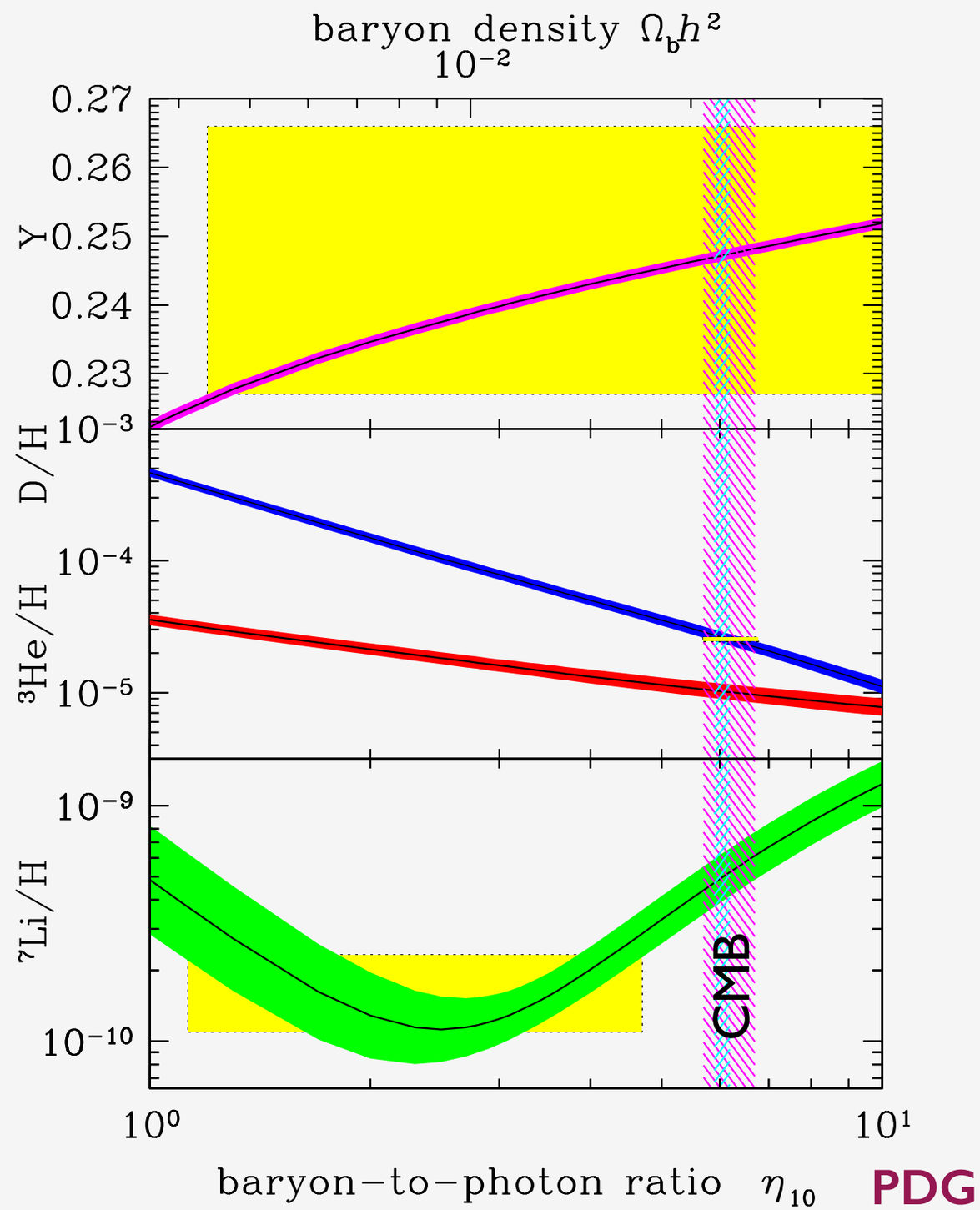
- There is more matter than antimatter - *baryogenesis*
- SM cannot explain this
  - There is baryon number violation
  - Not enough CP violation
  - No out-of-equilibrium processes
- CP violation is enhanced in particle—antiparticle oscillations
- Can these oscillations play a role in baryogenesis?

There is more matter than antimatter

$$\Omega_\Lambda \sim 0.69$$
$$\Omega_{\rm DM} \sim 0.27$$
$$\Omega_{\rm B} \sim 0.04$$

number of baryons:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$
$$\simeq 6 \times 10^{-10}$$



PDG

How Fermilab produces its baryons

How the Universe would do

Need to produce 1 extra quark for every 10 billion antiquarks!

Sakharov Conditions

Sakharov, *JETP Lett. 5, 24 (1967)*

Three conditions must be satisfied:

1) Baryon number (B) must be violated ✔

can't have a baryon asymmetry w/o violating baryon number!

2) C and CP must be violated ✘

a way to differentiate matter from antimatter

3) B and CP violating processes must happen out of equilibrium ✘

equilibrium destroys the produced baryon number

We need New Physics

Couple to the SM

Extra CP violation

Some out-of-equilibrium process

Old New Physics

Extra scalar fields → First-order phase transition

CP violation in the scalar sector

2HDM, MSSM, NMSSM, …

Leptogenesis → Out-of-equilibrium decays

CP violation from interference of tree-level and loop processes

Heavy right-handed neutrinos,…

Asymmetry in the dark sector ↔ Asymmetry in the visible sector

asymmetric dark matter

+ Affleck-Dine

We need New Physics

Couple to the SM

Let's re-visit SM CP violation

~~Extra~~ CP violation

Some out-of-equilibrium process

CP Violation in Neutral Meson Mixing

We see SM CP violation through neutral meson mixing

$K - \overline{K}$ $B_d - \overline{B}_d$ $B_s - \overline{B}_s$ $D - \overline{D}$

- A few Nobel prizes
- CKM matrix
- Top quark

Are particle—antiparticle oscillations special for CP violation?

Particle—Antiparticle Oscillations

Take a Dirac fermion with an approximately broken *U(1)* charge

$$-\mathcal{L}_{\rm mass} = M\,\overline{\psi}\,\psi + \frac{m}{2}(\overline{\psi^c}\,\psi + \overline{\psi}\,\psi^c)$$

Dirac mass

Majorana mass

with interactions

$$-\mathcal{L}_{\rm int} = g_1\,\overline{\psi}\,X\,Y + g_2\,\overline{\psi^c}\,X\,Y + \text{h.c.}$$

ψ : pseudo-Dirac fermion

We will want the final state XY to carry either baryon or lepton number

Particle—Antiparticle Oscillations

Hamiltonian: $\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$

$$\mathbf{M} = \begin{pmatrix} M & m \\ m & M \end{pmatrix}$$

$$\mathbf{\Gamma} \simeq \Gamma \begin{pmatrix} 1 & 2\,r\,e^{i\phi_\Gamma} \\ 2\,r\,e^{-i\phi_\Gamma} & 1 \end{pmatrix}$$

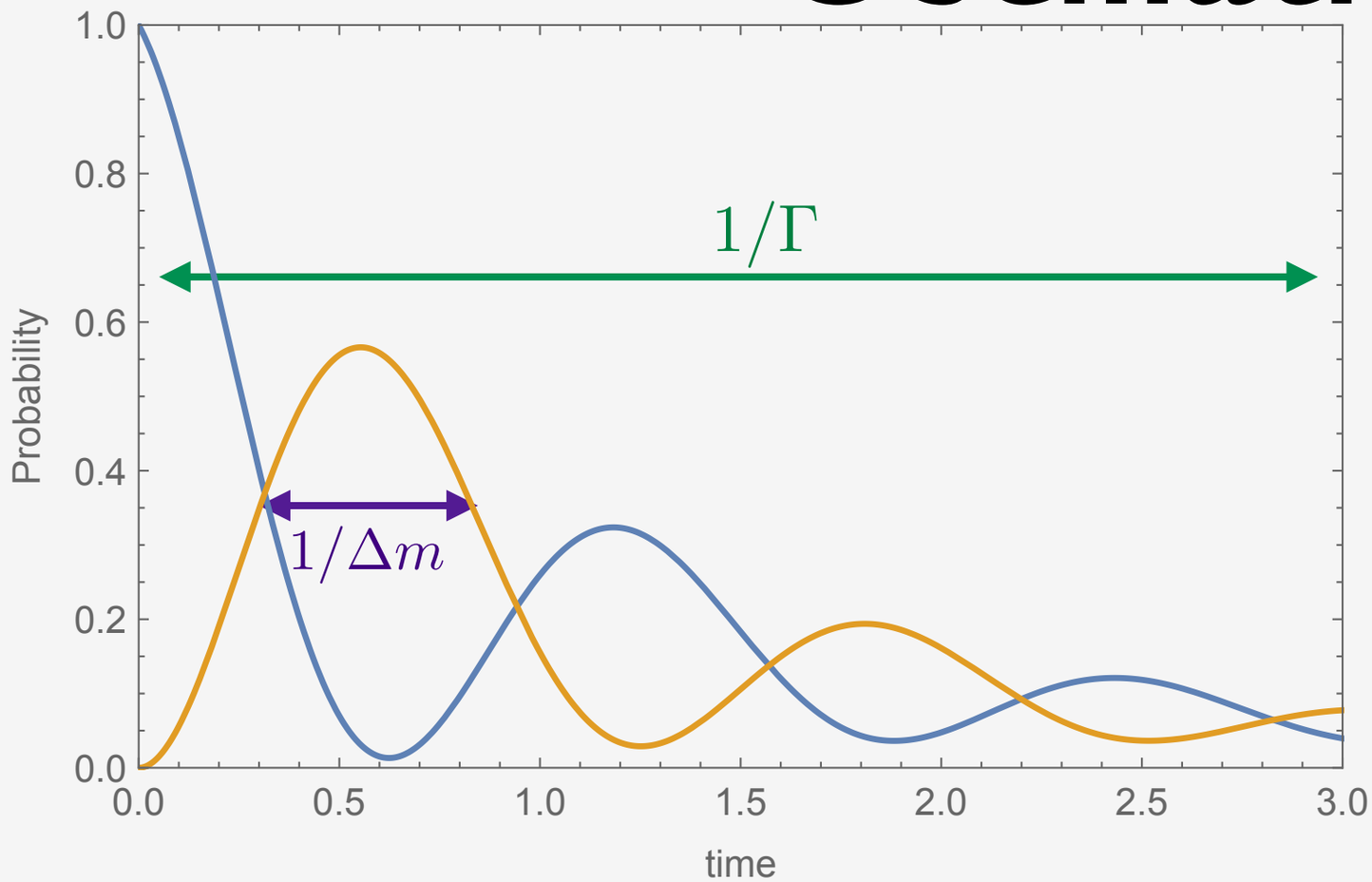
eigenvalues: $|\psi_{H,L}\rangle = p|\psi\rangle \pm q|\psi^c\rangle$

$$r = \frac{|g_2|}{|g_1|} \ll 1$$

mass states ≠ interaction states

→ OSCILLATIONS!

Particle—Antiparticle Oscillations



important parameter:

$$x \equiv \frac{\Delta m}{\Gamma}$$

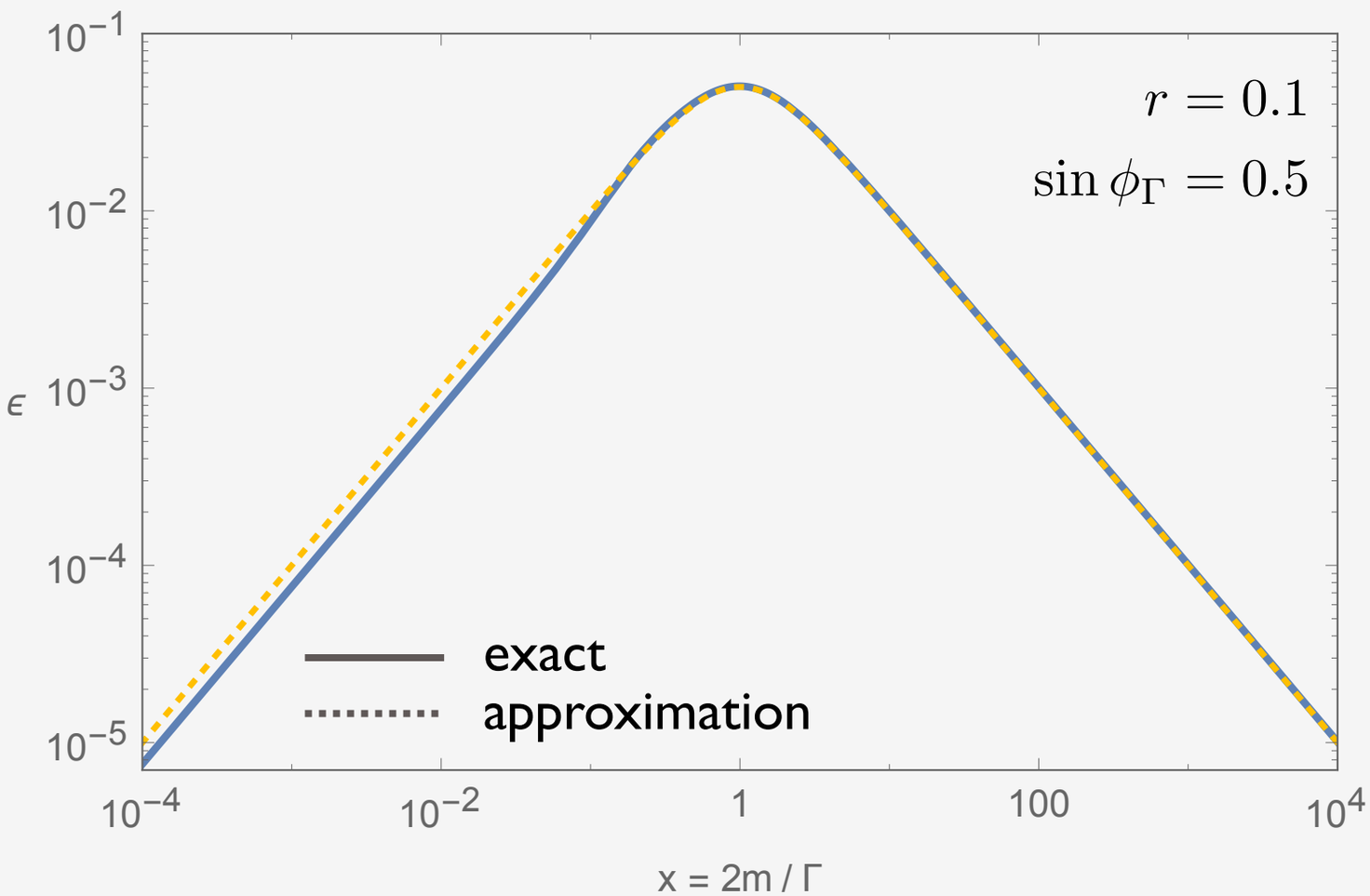
$$\Delta m = M_H - M_L \simeq 2m$$

Goldilocks principle for oscillations

$x \gg 1$	$x \sim 1$	$x \ll 1$
Too fast	Just right	Too slow

CP Violation in Oscillations

$$\epsilon = \int_0^\infty dt \, \frac{\Gamma(\psi/\psi^c \to f) - \Gamma(\psi/\psi^c \to \bar{f})}{\Gamma(\psi/\psi^c \to f) + \Gamma(\psi/\psi^c \to \bar{f})}$$



For $r = \frac{|g_2|}{|g_1|} \ll 1$

$$\epsilon \simeq \frac{2x\, r \sin\phi_\Gamma}{1 + x^2}$$

CP violation is maximized for $x \sim 1$

CP Violation ✔

$$\epsilon \simeq \frac{2x\, r \sin\phi_\Gamma}{1+x^2}$$

Baryon Number Violation ✔

Say the final state f has baryon number $+1$

e.g. RPV SUSY
$\tilde{g}\, u\, d\, d$

Baryon asymmetry is produced due to oscillations and decays:

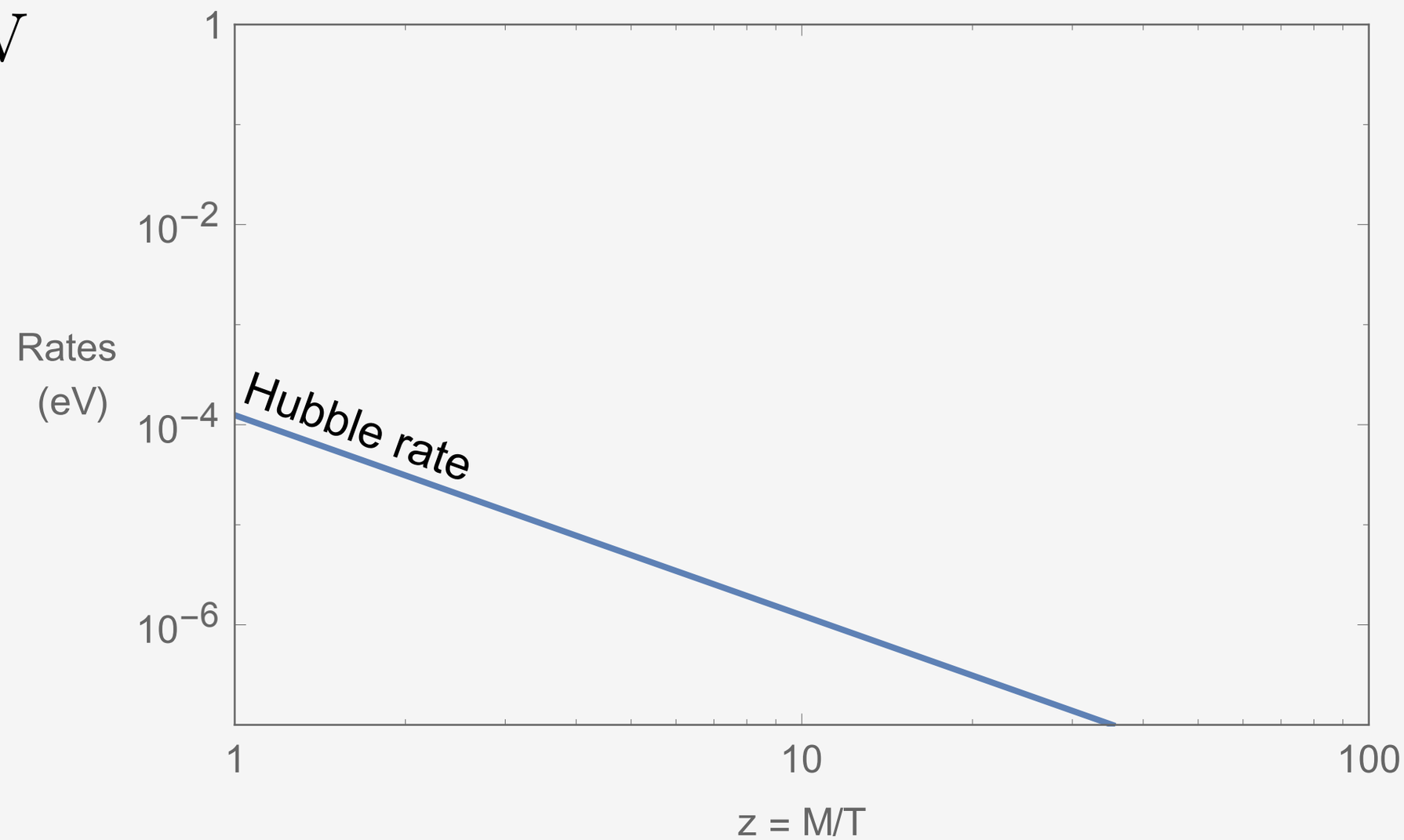
$$n_B - n_{\bar{B}} = \epsilon\, n_\psi$$

How to decay
out of thermal equilibrium?

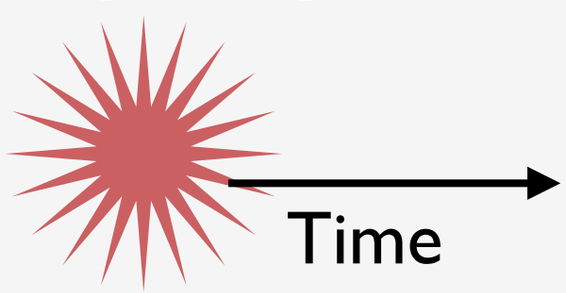
Oscillations
in the early Universe?

Oscillations in the early Universe are complicated

$M \sim 300$ GeV



Big Bang?



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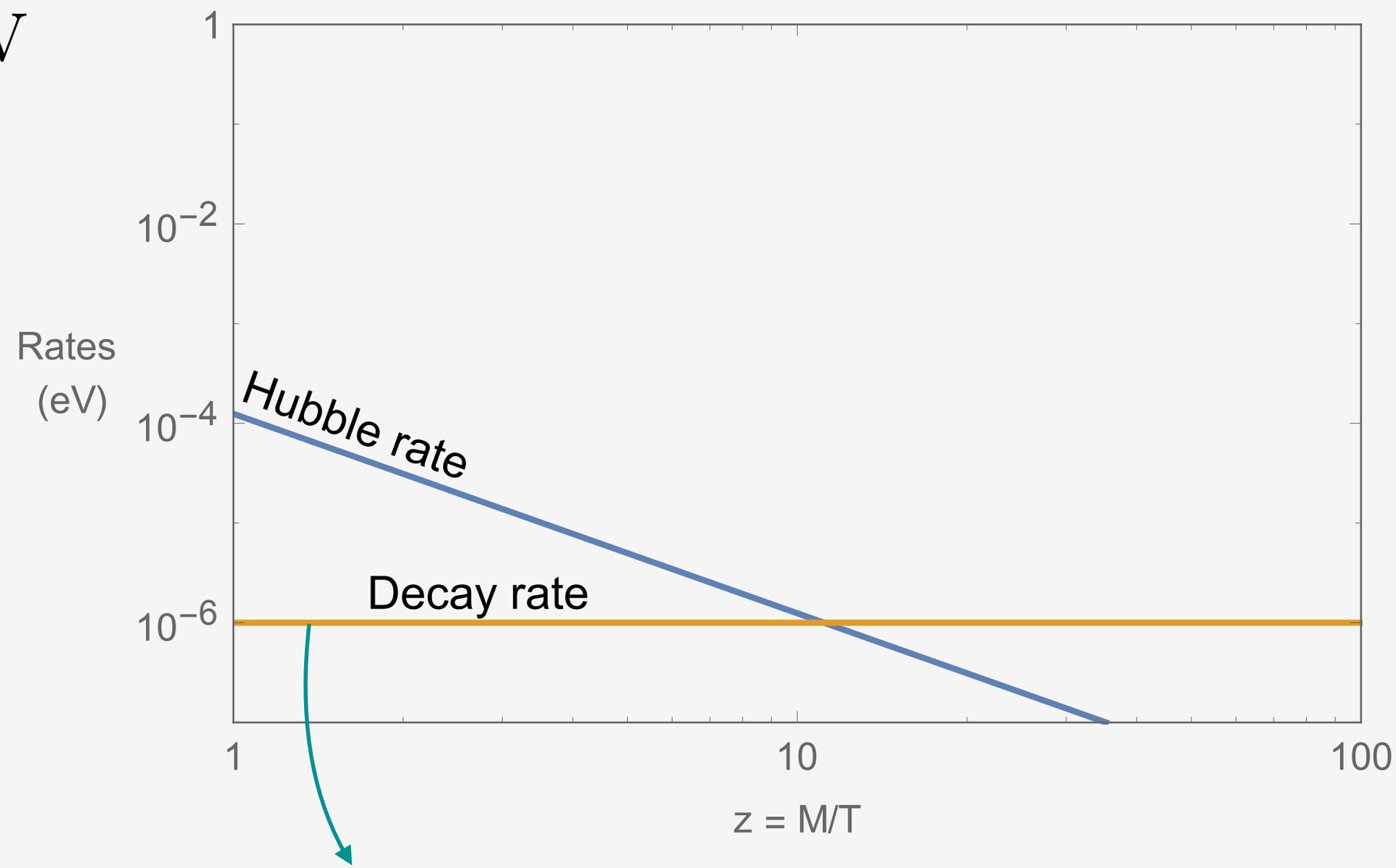

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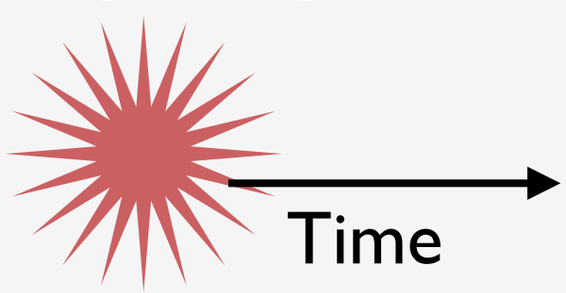

Out-of-equilibrium decay: $\Gamma \lesssim H(T \sim M)$

Oscillations in the early Universe are complicated

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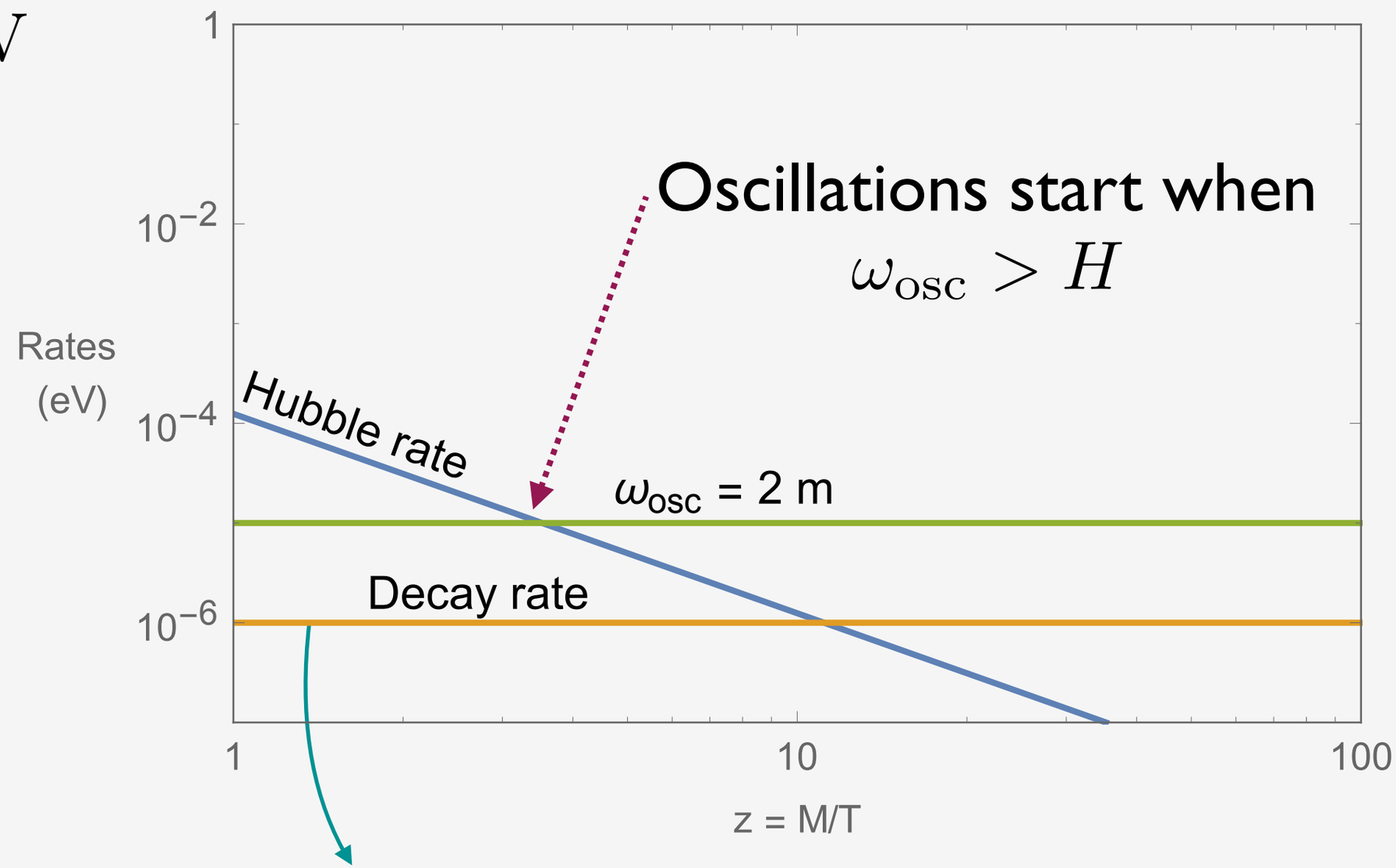

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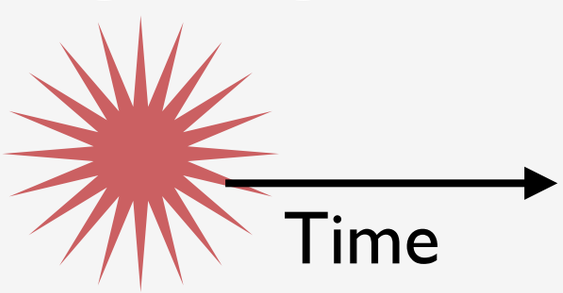

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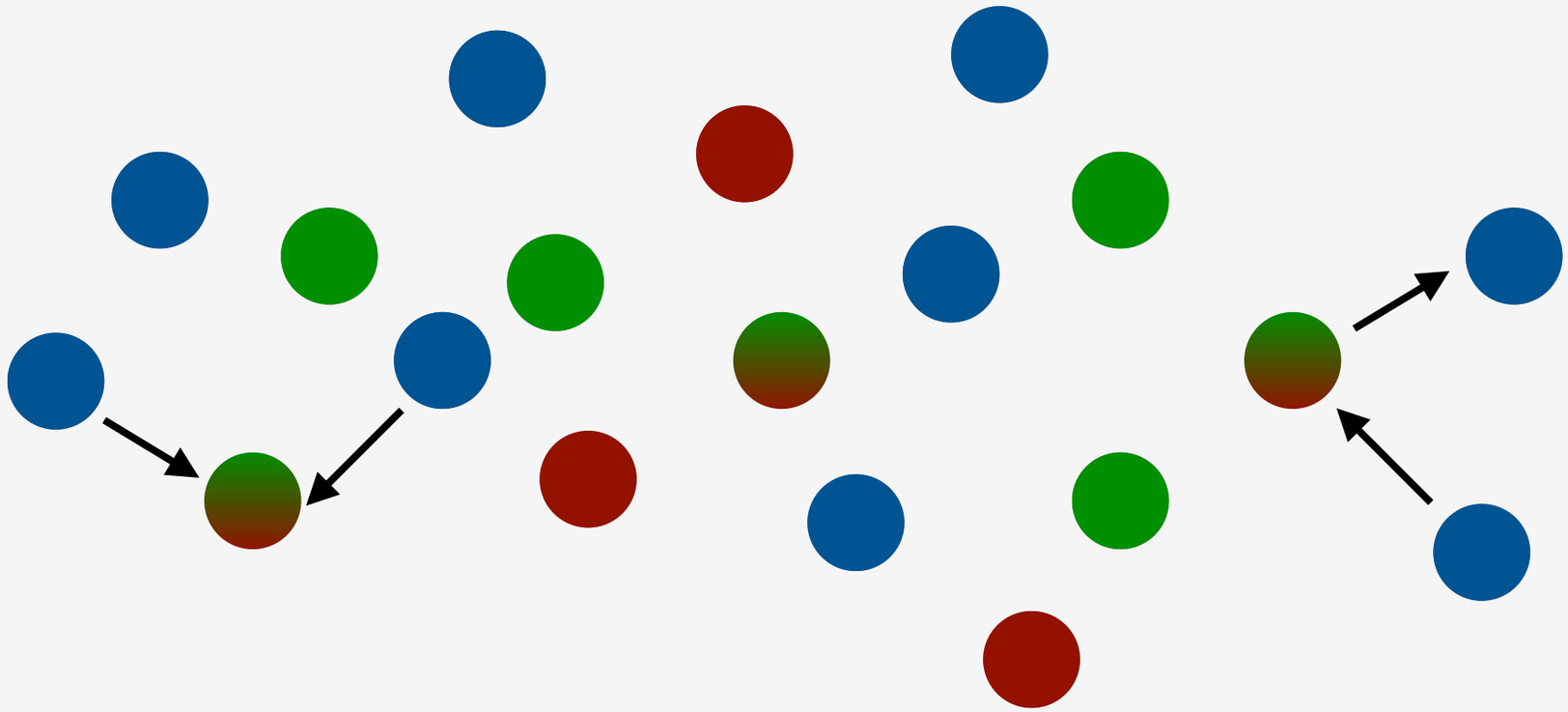
Oscillations in the early Universe are complicated



Particles/antiparticles are in a hot/dense plasma with interactions

$$-\mathcal{L}_{\rm scat} = \frac{1}{\Lambda^2}\bar{\psi}\,\Gamma^a\psi\,\bar{f}\,\Gamma_a f$$

Oscillations in the early Universe are complicated

What if interactions can tell the difference between a particle and antiparticle?

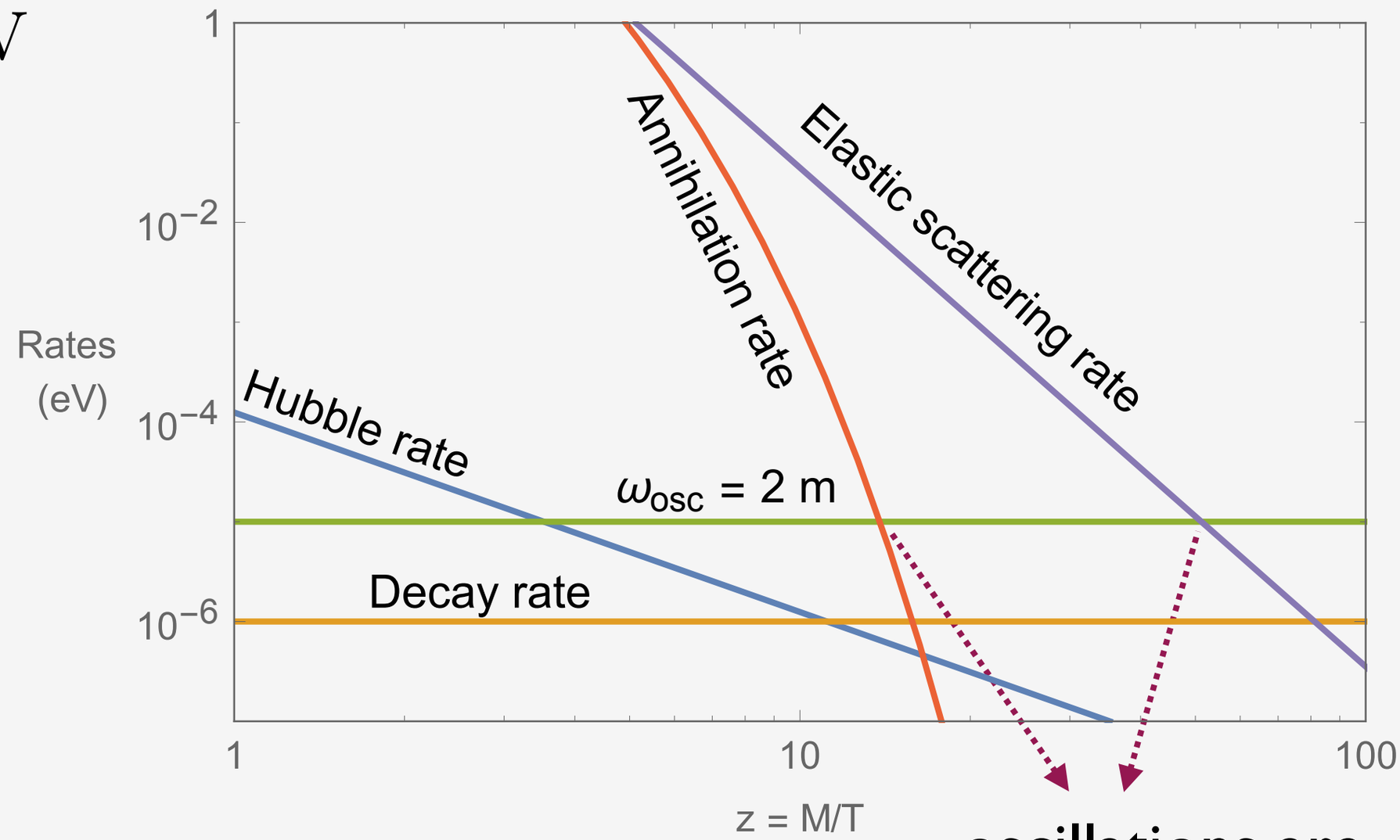
Quantum Zeno effect

Oscillations delayed till

$$\omega_{\rm osc} > \Gamma_{\rm ann}, \Gamma_{\rm scat}$$

Oscillations in the early Universe are complicated

$M \sim 300$ GeV



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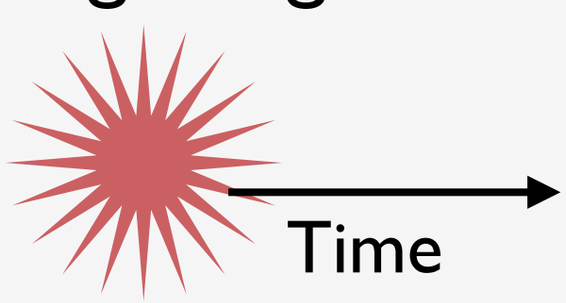


oscillations are further delayed

Oscillations in the early Universe are complicated

Described by the time evolution of the density matrix

Oscillations

Vanishes if scatterings are *flavor* blind

$$zH\frac{d\mathbf{Y}}{dz} = -i\left(\mathbf{HY} - \mathbf{YH}^\dagger\right) - \frac{\Gamma_\pm}{2}[O_\pm, [O_\pm, \mathbf{Y}]]$$

$$- s\langle\sigma v\rangle_\pm \left(\frac{1}{2}\{\mathbf{Y}, O_\pm \bar{\mathbf{Y}} O_\pm\} - Y_{\rm eq}^2\right)$$

Annihilations

$\mathbf{H}$: Hamiltonian

$\mathbf{Y}$: Density matrix

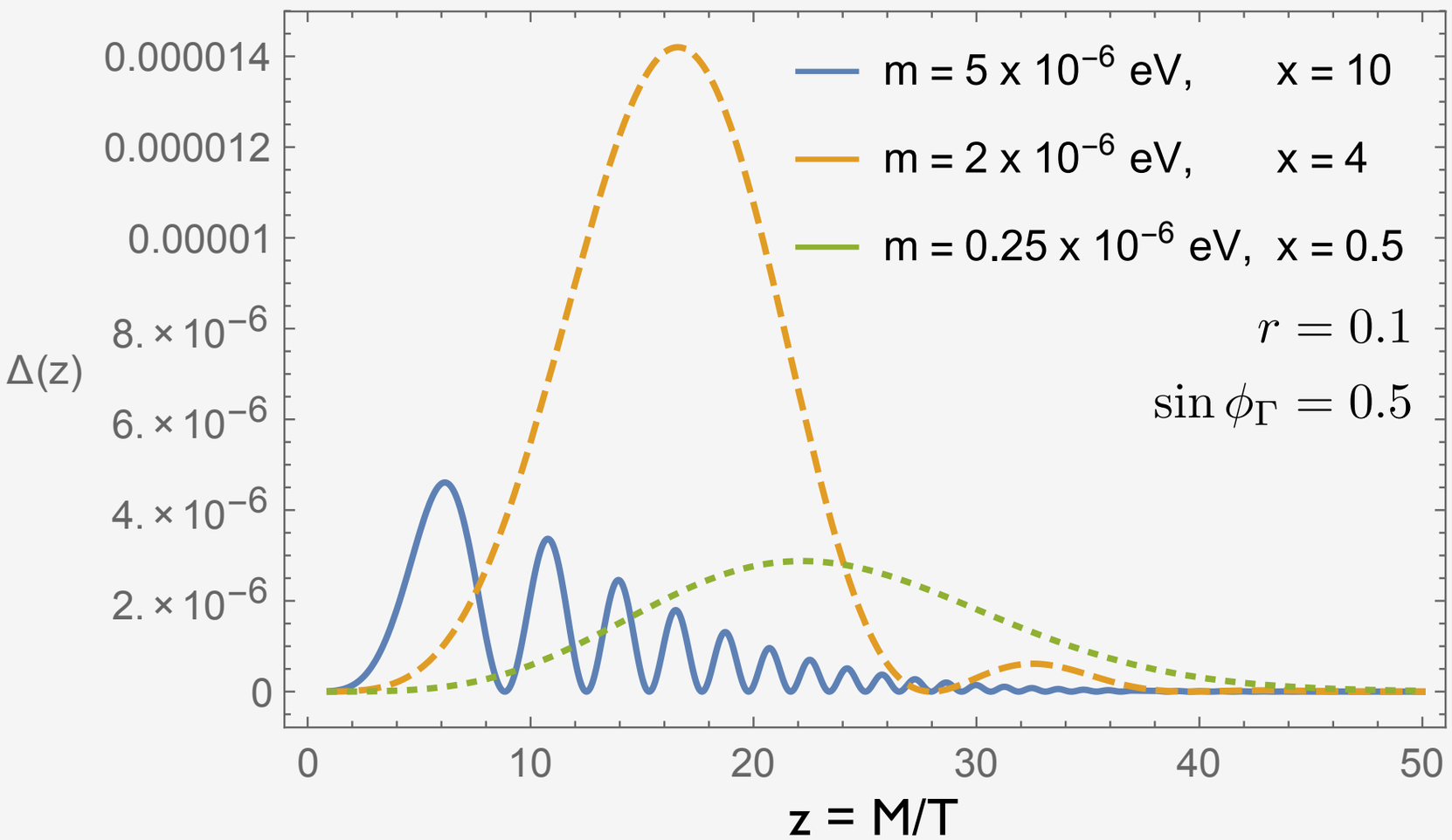
$O_\pm = \mathrm{diag}(1, \pm 1)$

$z = M/T$ not redshift!

Oscillations + Decays

$\Delta(z) \equiv Y_\psi - Y_{\psi^c}$: particle asymmetry

$M = 300 \text{ GeV}, \ \Gamma = 10^{-6} \text{ eV}$



Symmetric initial conditions: $\Delta(0) = 0$

Oscillations are delayed for smaller m

Smaller asymmetry

$$\Delta(z) = \epsilon\, Y_{\rm eq}(1) \exp\left(-\frac{\Gamma}{2H(z)}\right) \sin^2\left(\frac{m}{2H(z)}\right)$$

Oscillations + Decays + Annihilations/Scatterings

Two types of interactions

flavor-blind	flavor-sensitive
$\psi \to \psi^c : \quad \mathcal{L} \to \mathcal{L}$	$\mathcal{L} \to -\mathcal{L}$

e.g. scalar

$$-\mathcal{L} = \frac{1}{\Lambda^2} \bar{\psi}\psi \, \bar{f} f$$

e.g. vector

$$-\mathcal{L} = \frac{1}{\Lambda^2} \bar{\psi} \, \gamma^\mu \, \psi \bar{f} \, \gamma_\mu \, f$$

f : (massless) fermion $\quad \Lambda$: interaction scale

Elastic scatterings/Annihilations delay oscillations

Ignoring decays, particle asymmetry is given by

$$y = z^2$$

$$z = M/T$$

$$\frac{d^2\Delta(y)}{dy^2} + 2\,\xi\,\omega_0\,\frac{d\Delta(y)}{dy} + \omega_0^2\,\Delta(y) = 0$$

$$\Delta(z) \equiv Y_\psi - Y_{\psi^c} \qquad \omega_0 \equiv \frac{m}{yH}, \quad \xi \equiv \frac{\Gamma^S_{\rm ann}/\Gamma^V_{\rm scat}}{2m}$$

$\xi \gg 1$ overdamped, no oscillations

$\xi < 1$ underdamped, system oscillates

Elastic scatterings/Annihilations delay oscillations

flavor-sensitive interactions

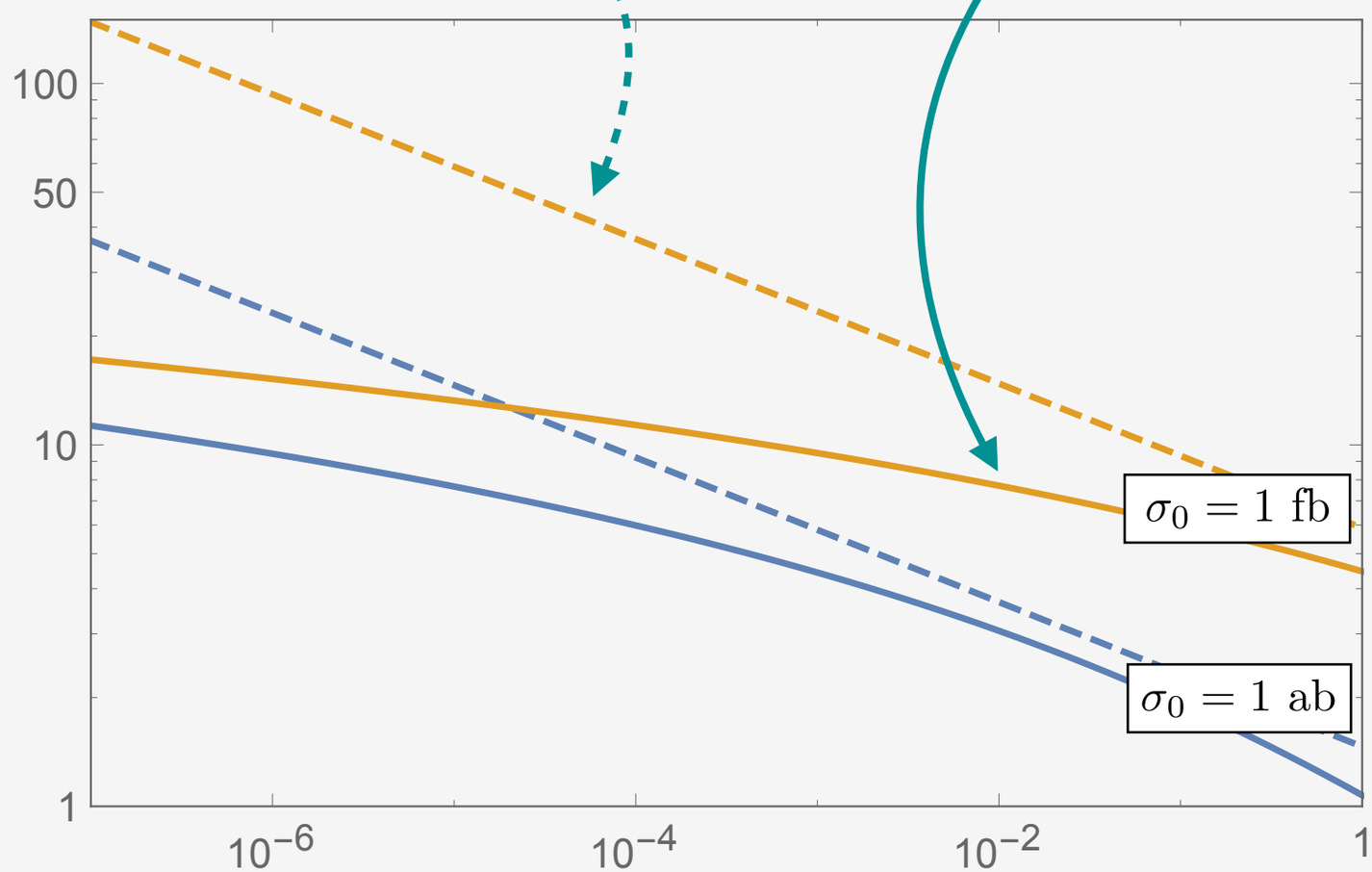
$$\omega_{\rm osc} = \Gamma_{\rm scat}(z_{\rm osc})$$

flavor-blind interactions

$$\omega_{\rm osc} = \Gamma_{\rm ann}(z_{\rm osc})$$

when oscillations start

z_{osc}

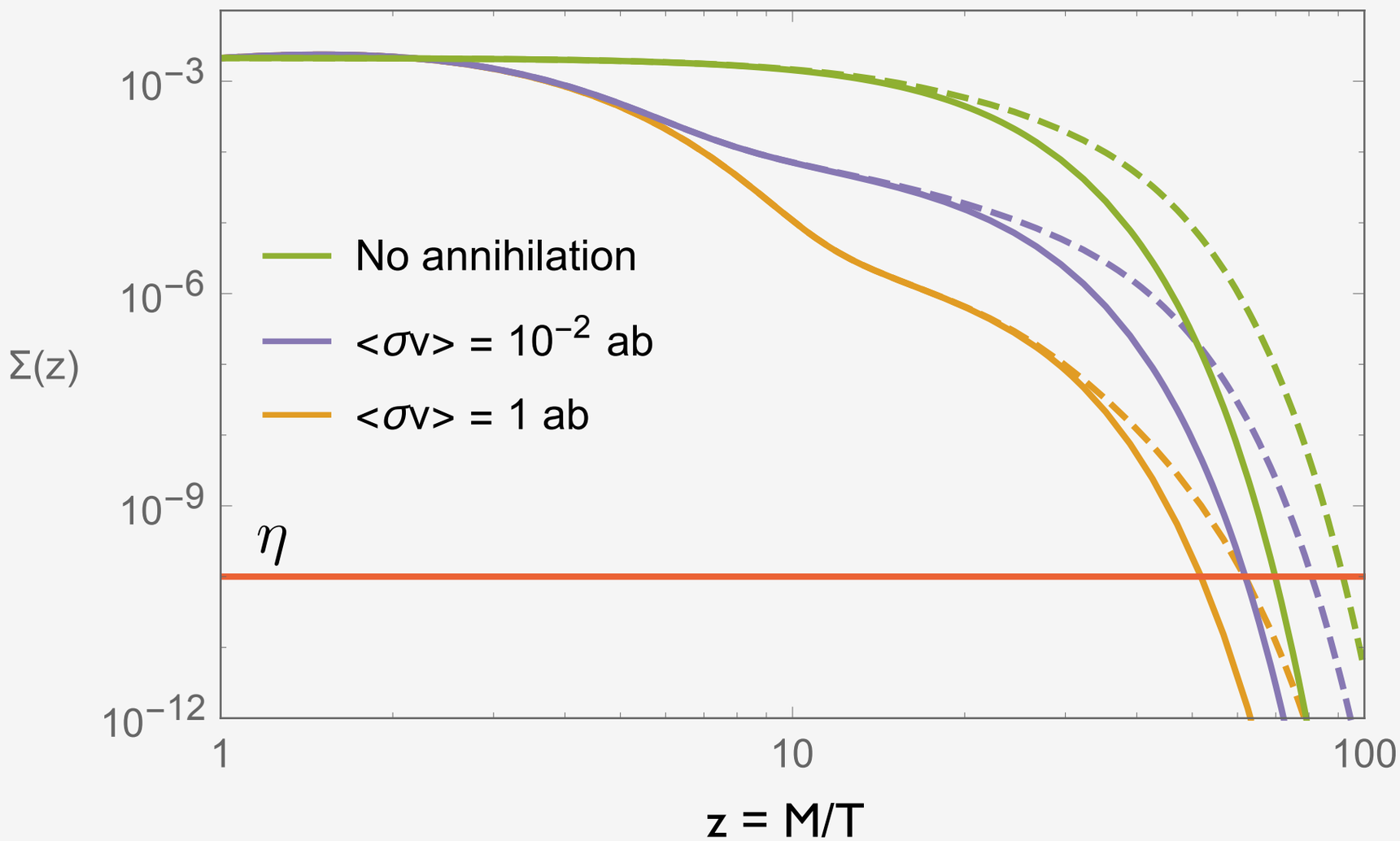


z = M/T

mass difference (eV)

Oscillations + Decays + Annihilations/Scatterings

$\Sigma(z) \equiv Y_\psi + Y_{\psi^c}$: total number of particles



$M = 300$ GeV

$m - 2 \times 10^{-6}$ eV

$\Gamma = 10^{-6}$ eV

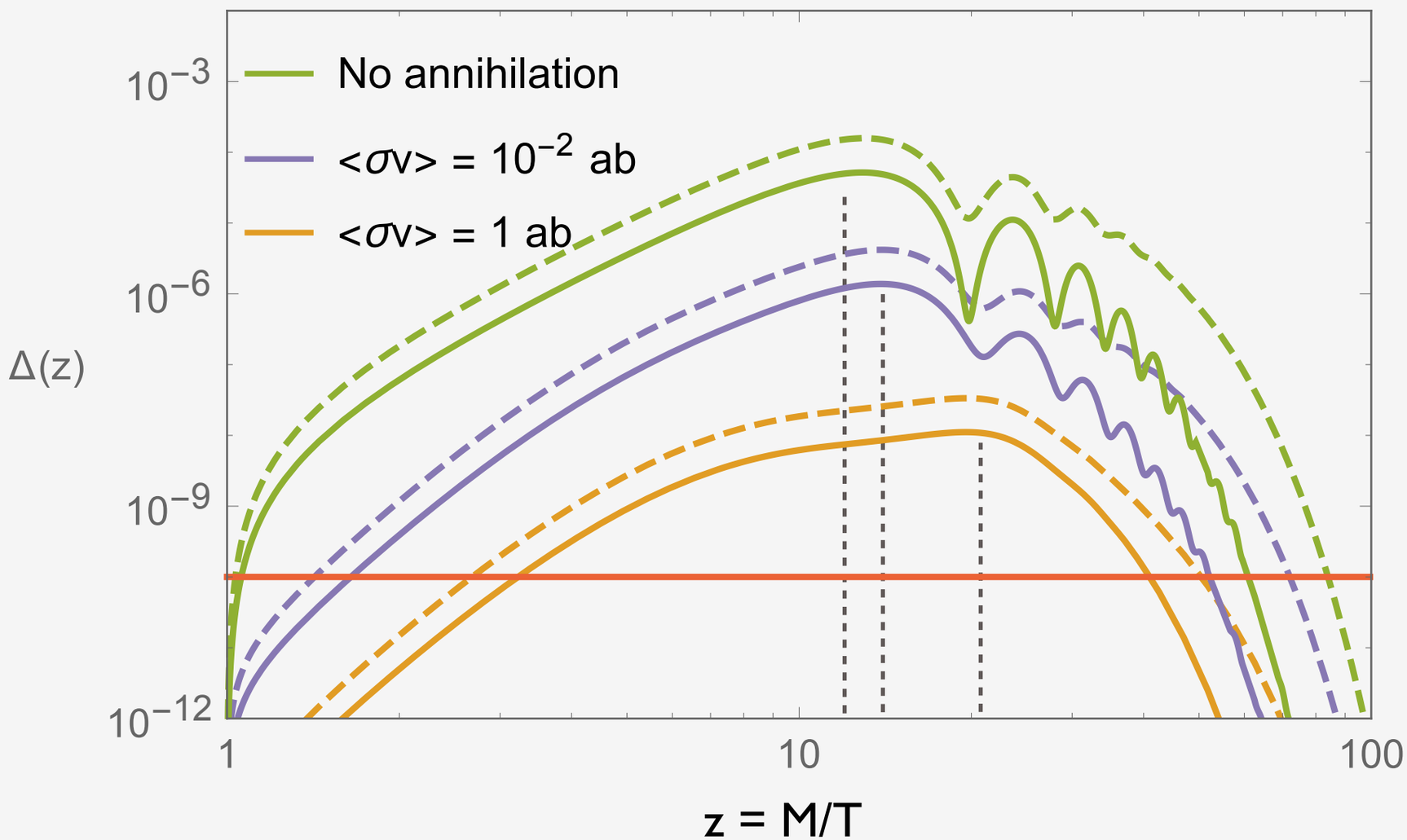
$\sin\phi_\Gamma = 0.5$

$r = 0.1 - 0.3$

flavor-sensitive

Oscillations + Decays + Annihilations/Scatterings

$$\Delta(z) \simeq \epsilon\, Y_{\rm eq}(z_{\rm osc}) \exp\left(-\frac{\Gamma}{2H(z)}\right) \sin^2\left(\frac{m}{2H(z)}\right)$$



$M = 300$ GeV

$m - 2 \times 10^{-6}$ eV

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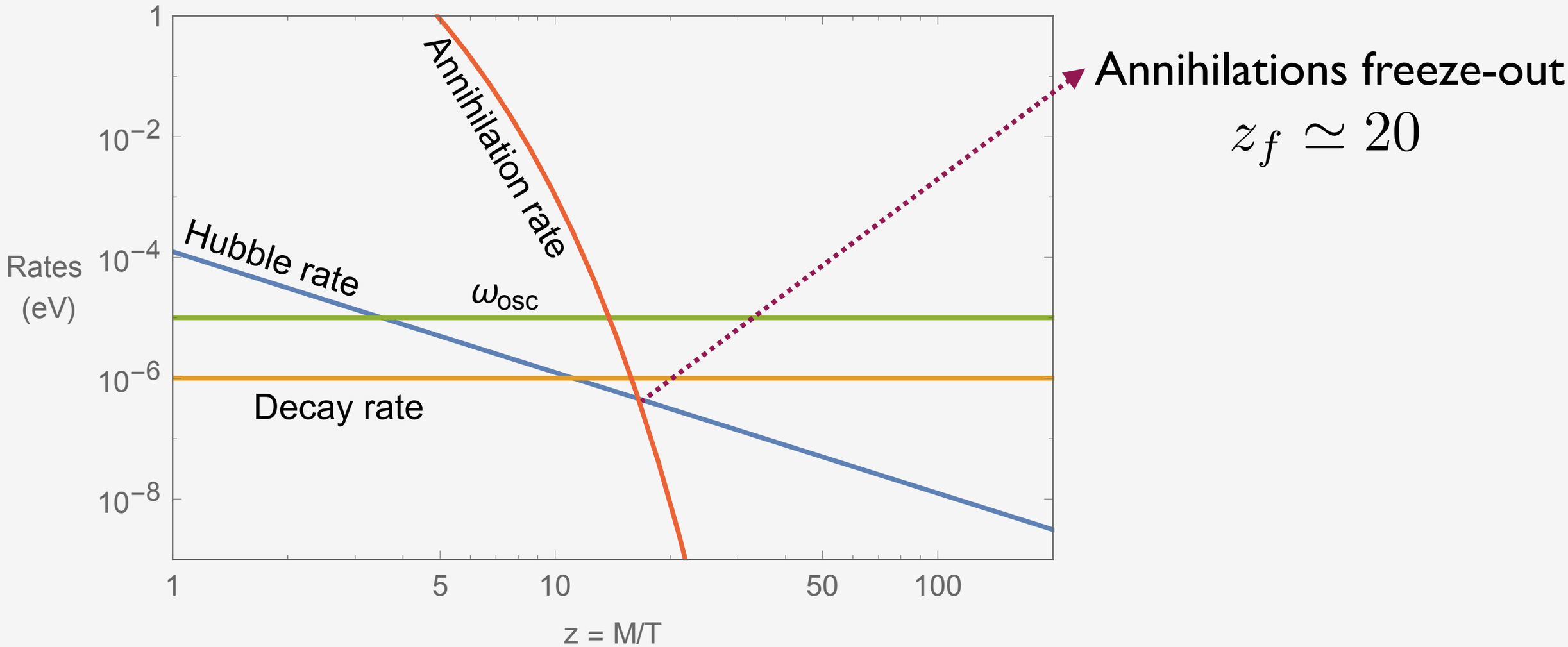
$\sin\phi_\Gamma = 0.5$

$r = 0.1 - 0.3$

Oscillations are delayed

Smaller asymmetry

How about baryon asymmetry?



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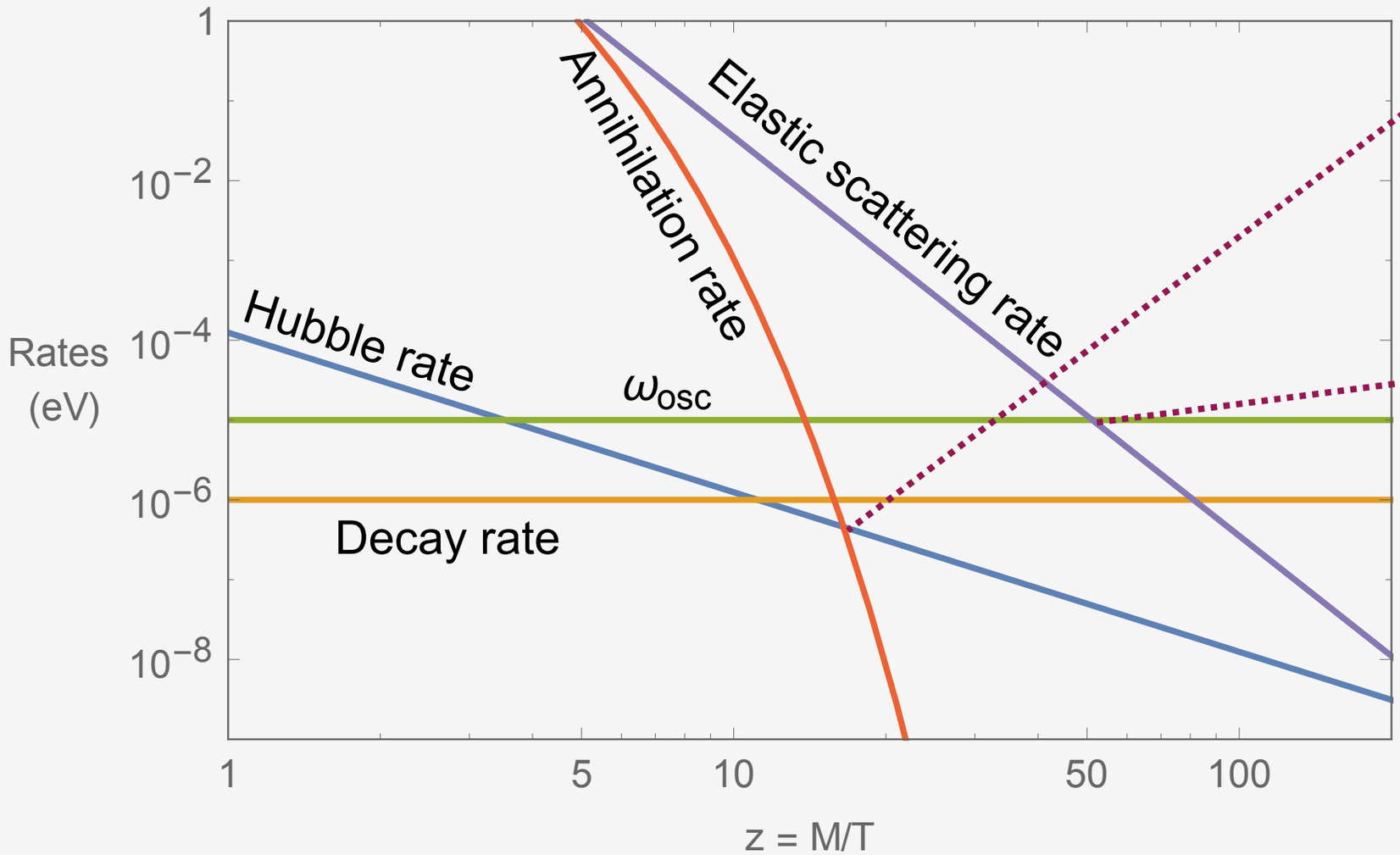


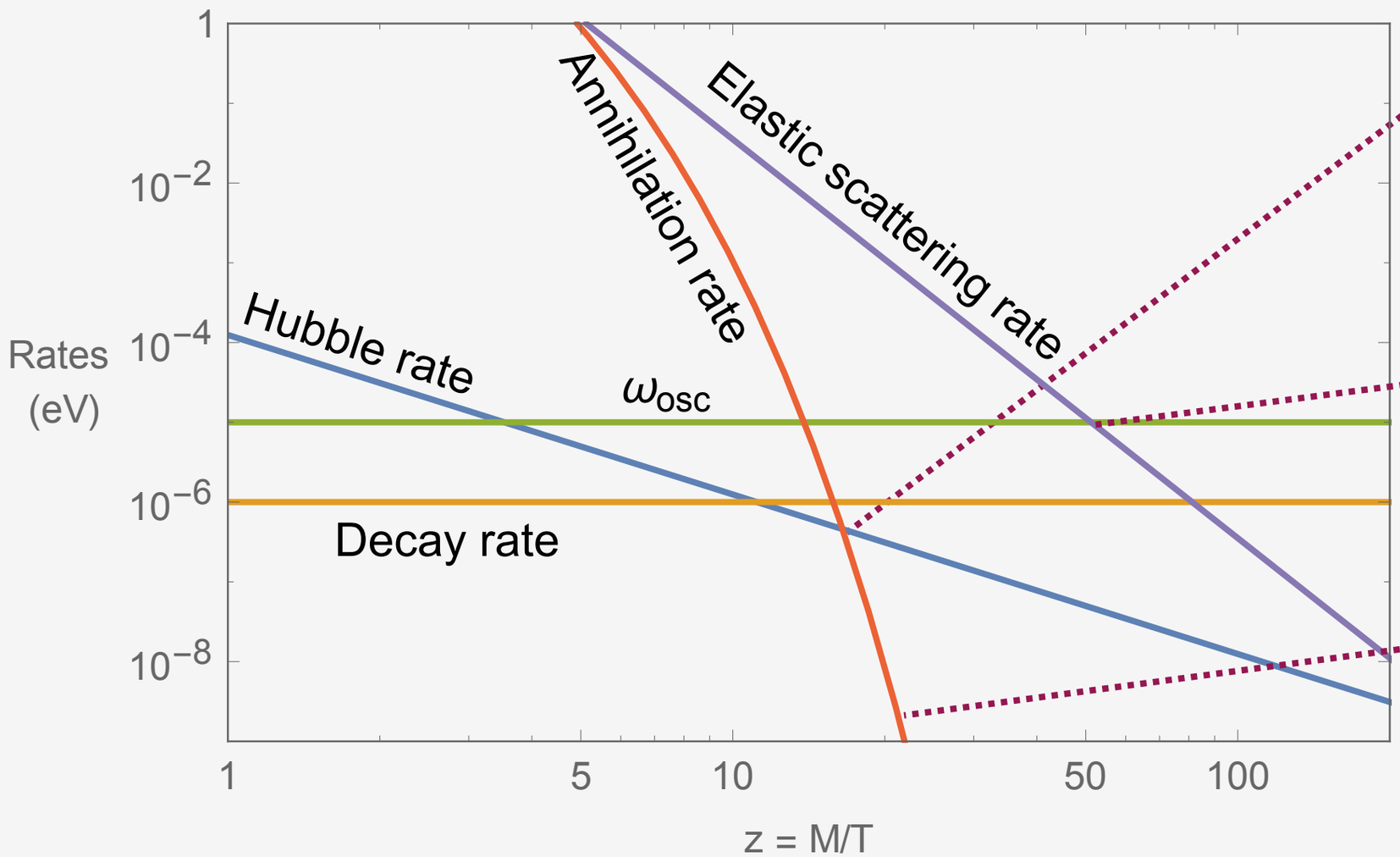
Annihilations freeze-out

$z_f \simeq 20$

Oscillations start

$z_{\rm osc} \simeq 60$

How about baryon asymmetry?



Annihilations freeze-out

$$z_f \simeq 20$$

Oscillations start

$$z_{\rm osc} \simeq 60$$

Annihilations are Boltzmann suppressed

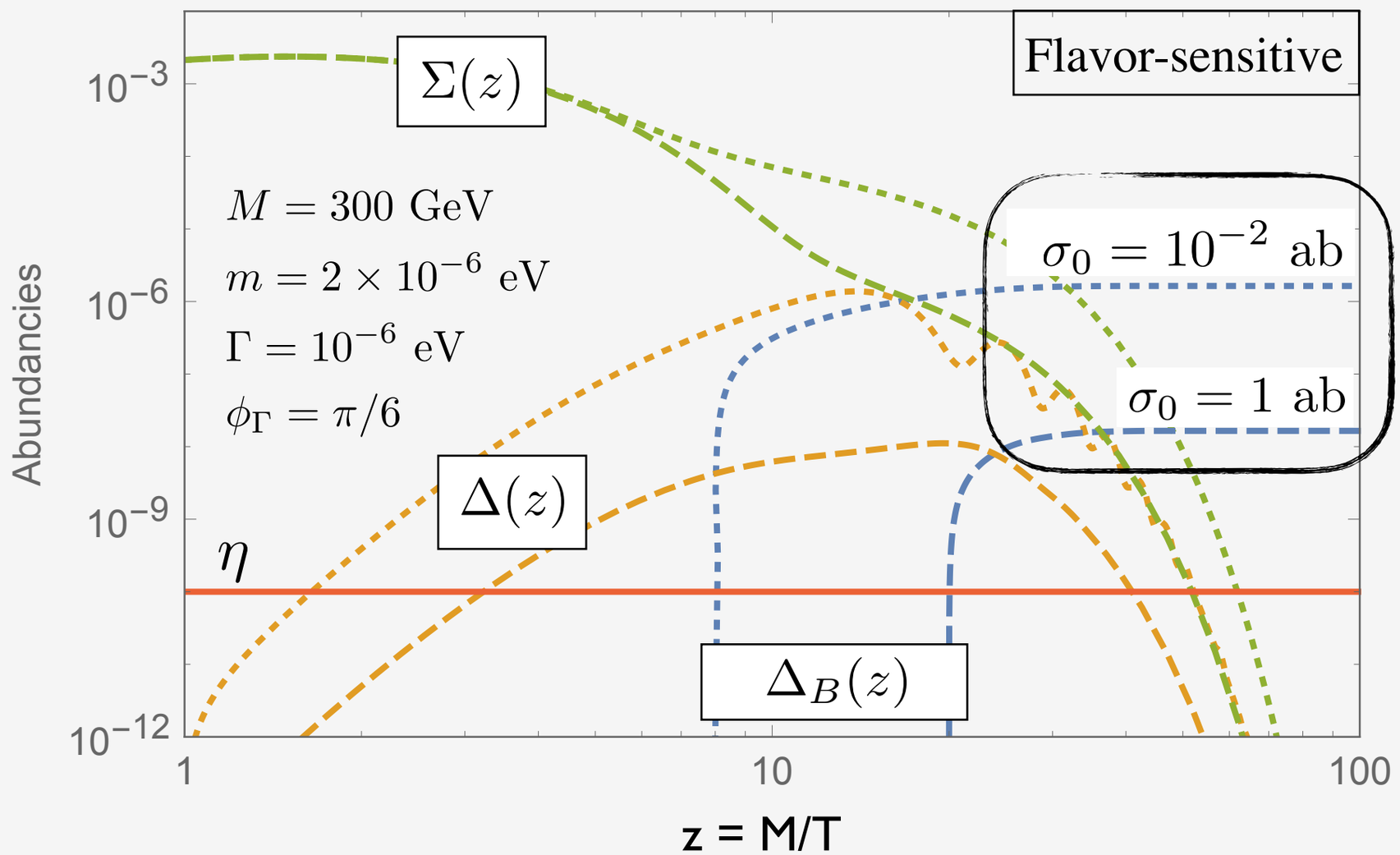
$$\Gamma_{\rm ann} \ll \Gamma$$

Oscillate a few times → Produce the baryon asymmetry

$$\eta \simeq \epsilon\, \Sigma(z_{\rm osc}) \sim 10^{-10}$$

Let there be baryons!

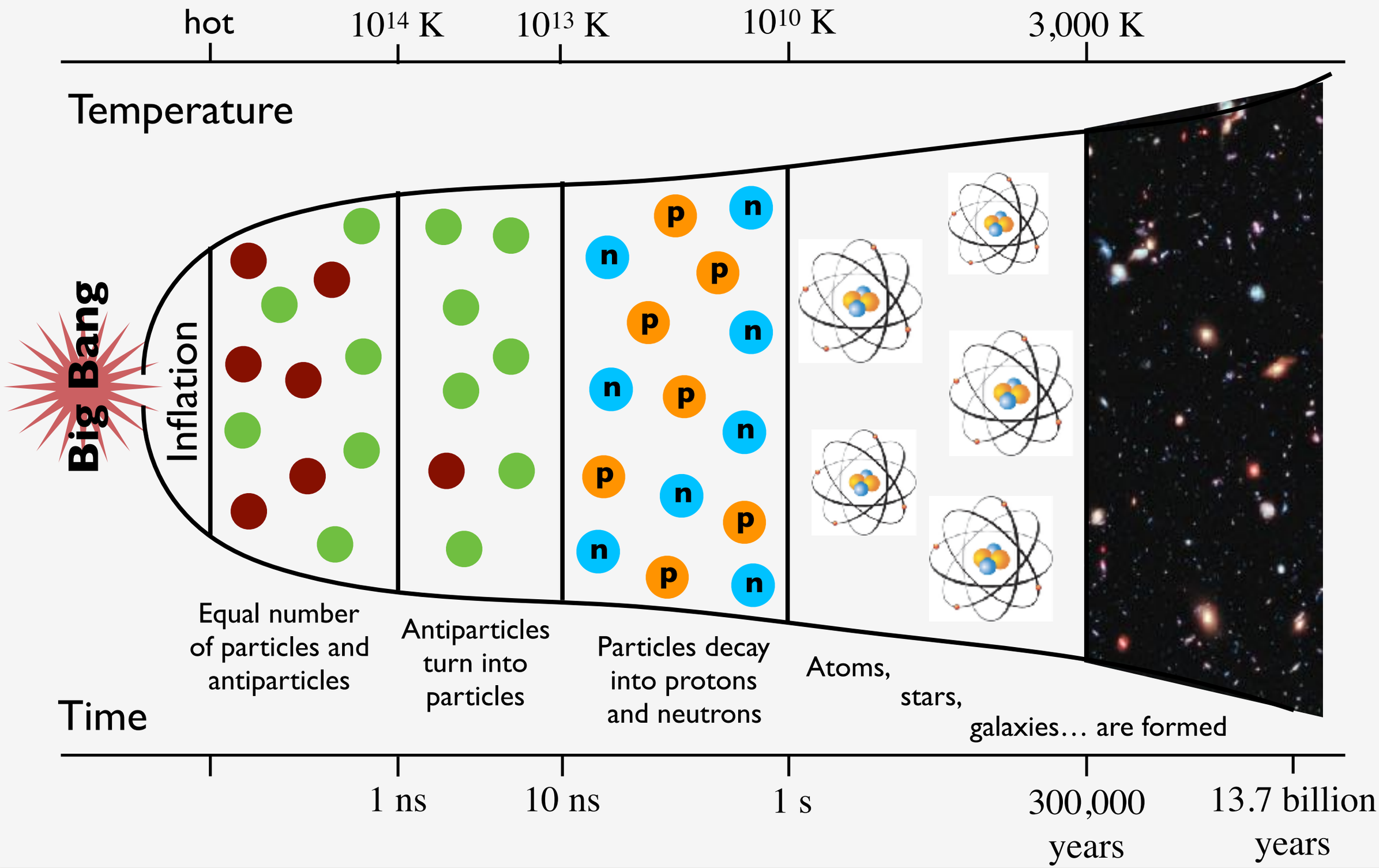
For $z > z_{\rm osc}$ baryon asymmetry is given by: $\dfrac{d\Delta_B(z)}{dz} \simeq \dfrac{\epsilon\,\Gamma}{zH}\,\Sigma(z)$



BARYONS!!!

$\Delta_B = Y_B - Y_{\overline{B}}$: baryon asymmetry

My history of the Universe



What kind of model?

Oscillations ⟷ Pseudo-Dirac fermions

Approximately broken $U(1)$ symmetry

DM theories with a global $U(1)$?

global symmetries are broken
by gravity

Hall, Randall, Nuc.Phys.B-352.2 1991
Kribs, Poppitz, Weiner, arXiv: 0712.2039
Frugiuele, Gregoire, arXiv:1107.4634

SI, McKeen, Nelson, arXiv: *1407.8193*
SI, John March-Russell, *arXiv:1604.00009*
Pilar Coloma, SI, arXiv:1606.06372

My favorite model for everything!

$U(1)_R$ -symmetric SUSY

Has Dirac gauginos

Dirac gauginos are awesome - less tuning for heavier stops

Solves SUSY CP and flavor problems, …

$U(1)_R$ symmetric SUSY

Sfermions have +1 R-charge

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
$Q = \tilde{q} + \theta\, q$	3	2	$1/6$	1
$\bar{U} = \tilde{\bar{u}} + \theta\, \bar{u}$	$\bar{3}$	1	-$2/3$	1
$\bar{D} = \tilde{\bar{d}} + \theta\, \bar{d}$	$\bar{3}$	1	$1/3$	1
$\Phi_{\bar{D}} = \phi_{\bar{D}} + \theta\, \psi_{\bar{D}}$	$\bar{3}$	1	$1/3$	1
$\Phi_D = \phi_D + \theta\, \psi_D$	3	1	-$1/3$	1
$W_{\tilde{B},\alpha} \supset \tilde{B}_\alpha$	1	1	0	1
$\Phi_S = \phi_s + \theta\, S$	1	1	0	0

Bino has +1 R-charge
Singlino (S) has -1 R-charge

(pseudo)-Dirac gauginos!

$U(1)_R$ symmetric SUSY

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
$Q = \tilde{q} + \theta\, q$	3	2	$1/6$	1
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$\Phi_S = \phi_s + \theta\, S$	1	1	0	0

New superfields → non-gauge couplings for Dirac partners

Pseudo-Dirac gauginos

Fox, Nelson, Weiner, hep-ph/0206096

Take the bino and the singlino:

$$\tilde{B} \equiv (1,1,0)_{+1}$$
$$S \equiv (1,1,0)_{-1}$$

$$-\mathcal{L}_{\rm mass} \supset M_D\, \tilde{B} S + M_D^* \tilde{B}^\dagger S^\dagger$$

$U(1)_R$ must be broken

…because (anomaly mediation)

(Small) Majorana mass for the bino

$$m_{\tilde{B}} = \frac{\beta(g)}{g} F_\phi$$

some conformal parameter

$$\frac{m_{3/2}^3}{16\pi^2 M_{\rm Pl}^2} \lesssim |F_\phi| \lesssim m_{3/2}$$

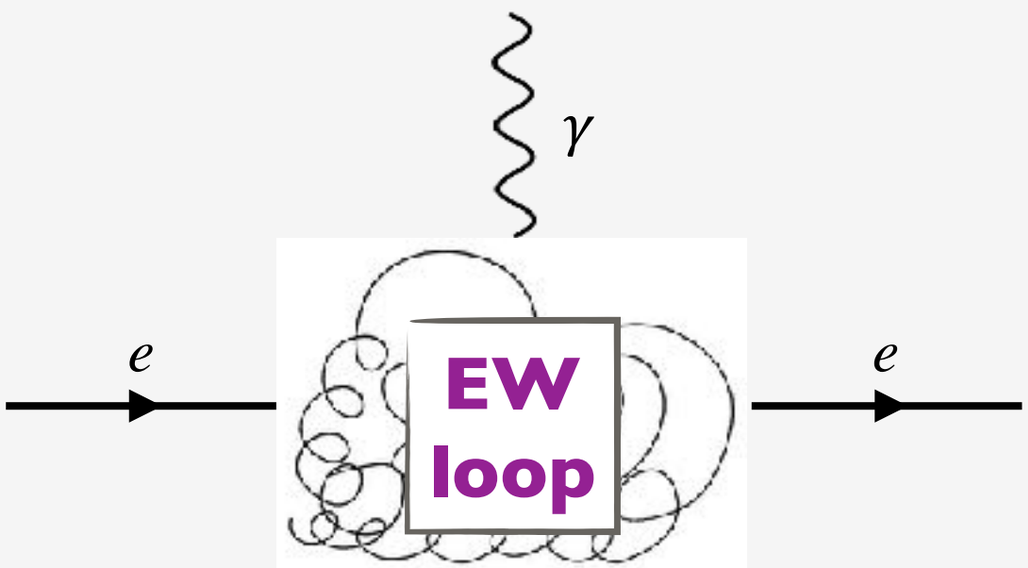
Arkani-Hamed, *et al, hep-ph/0409232*

SUSY CP Problem

Electron electric dipole moment: $d_e \leq 0.87\text{x}10^{-28}\ e\cdot\text{cm}$

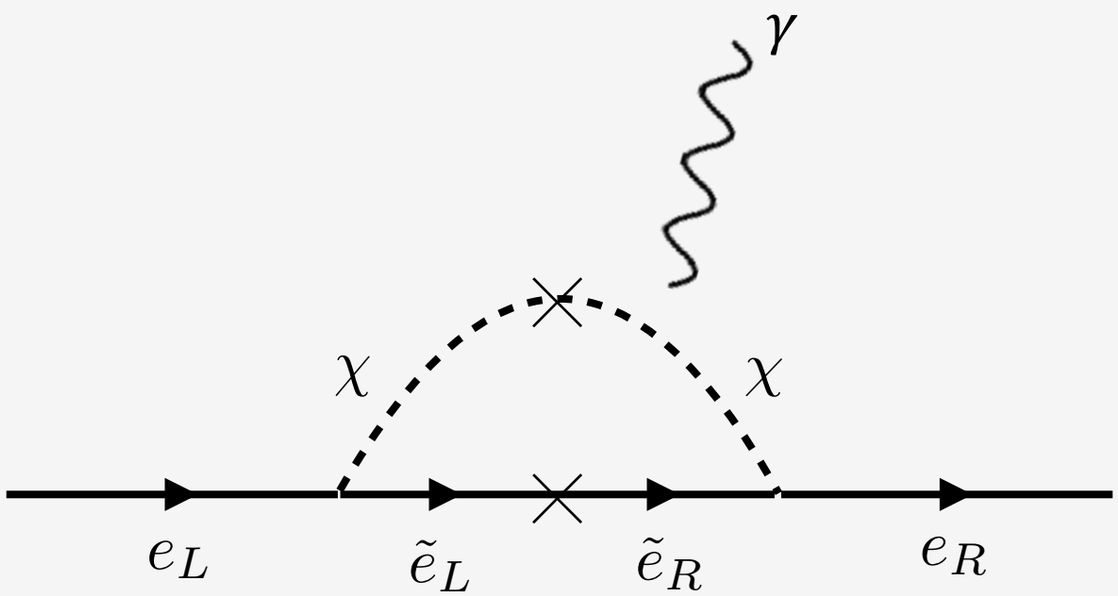
ACME, Science 343 (2014)

What we have in the SM:



$d_e \leq 10^{-38}\ e\cdot\text{cm}$

What SUSY has:

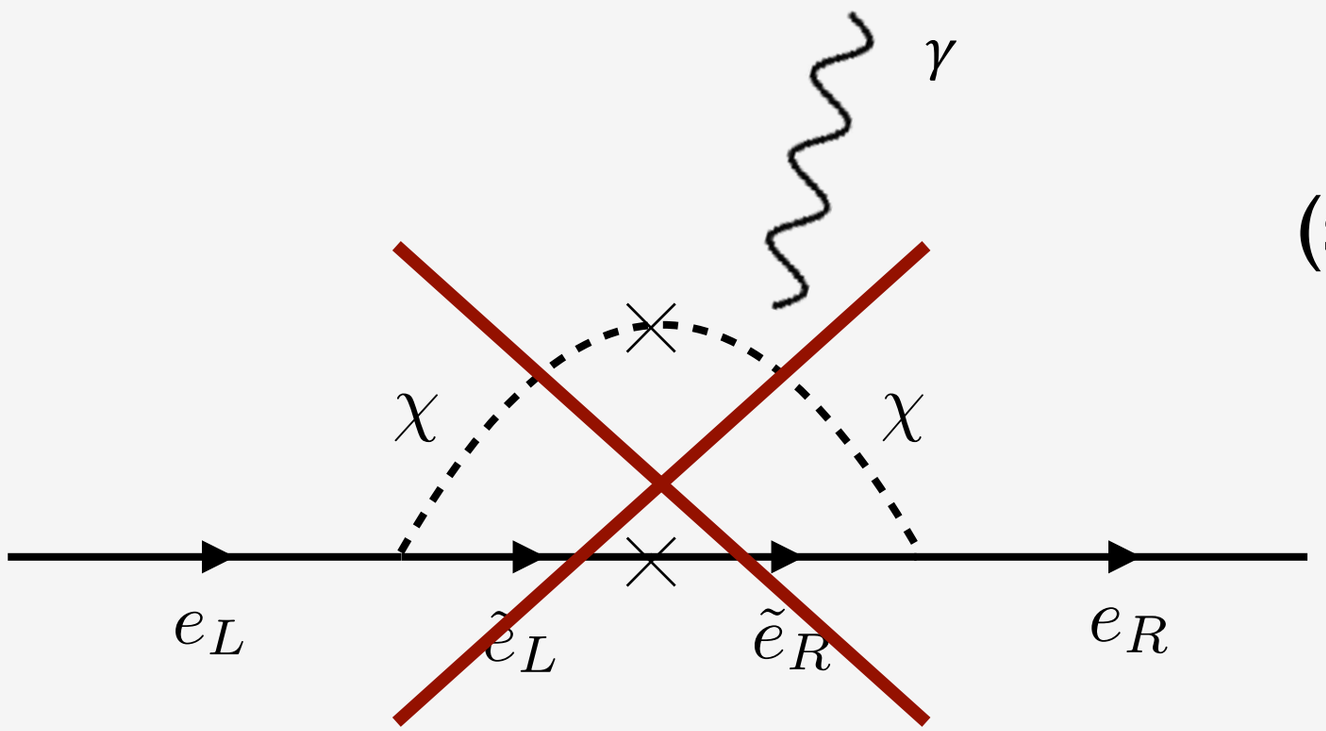


SUSY CP problem

SUSY CP Problem: Solved

Due to the $U_R(1)$ symmetry:

- No (very small) Majorana gaugino masses
- No left-right mixing for sfermions



(similar story for the flavour problem)

We can have large CP violating parameters w/o affecting EDMs

Pseudo-Dirac bino oscillations

Mass terms: $$-\mathcal{L}_{\rm mass} \to M_D BS + \frac{1}{2}\left(m_{\tilde{B}}\tilde{B}\tilde{B} + m_S SS\right) + \text{h.c.}$$

Let's also consider R-parity violation

$$-\mathcal{L}_{\rm eff} = G_{\tilde{B}}\tilde{B}\,\bar{u}\bar{d}\bar{d} + G_S S\,\bar{u}\bar{d}\bar{d} + \text{h.c.}$$

$$G_B \sim \frac{g_Y\,\lambda''}{m_{\rm sf}^2} \quad G_S \sim \frac{g_S\,\lambda''}{m_\phi^2}$$

Remember from before:

$$-\mathcal{L}_{\rm mass} = M\,\overline{\psi}\,\psi + \frac{m}{2}(\overline{\psi^c}\,\psi + \overline{\psi}\,\psi^c)$$

bino

antibino

with interactions

$$-\mathcal{L}_{\rm int} = g_1\,\overline{\psi}\,XY + g_2\,\overline{\psi^c}\,XY + \text{h.c.}$$

$u\,d\,d$

$u\,d\,d$

Pseudo-Dirac bino oscillations

Oscillation Hamiltonian:

$$\mathcal{H} = \begin{pmatrix} M_D & m \\ m & M_D \end{pmatrix} - \frac{i}{2}\Gamma \begin{pmatrix} 1 & 2re^{i\phi_\Gamma} \\ 2re^{-i\phi_\Gamma} & 1 \end{pmatrix}$$

$$\Gamma \simeq \frac{M^5}{(32\pi)^3}|G_{\tilde{B}}|^2 \qquad r = \frac{|G_S|}{|G_{\tilde{B}}|} \ll 1$$

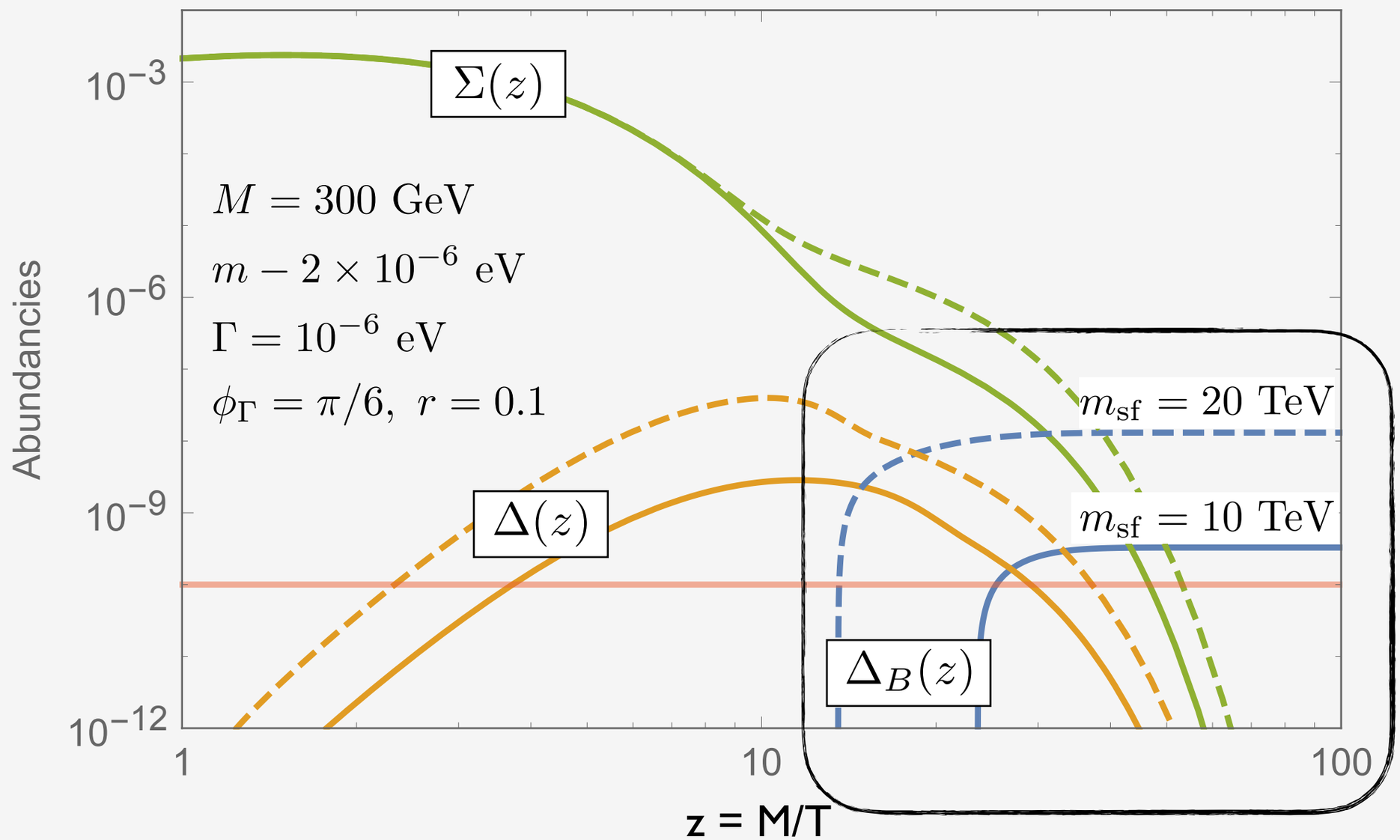
with annihilations + elastic scatterings:

$$-\mathcal{L}_{\rm scat} = \frac{g_Y^2}{m_{\rm sf}^2}\bar{\psi}\gamma_\mu P_L \psi\, \bar{F}\gamma^\mu(g_V + g_A\gamma_5)F$$

flavor sensitive, oscillations are delayed, etc etc

$$g_{V,A} = \frac{Y_R^2 \pm Y_L^2}{2} \qquad F = \begin{pmatrix} f_L \\ f_R^\dagger \end{pmatrix}$$

Let there be baryons!



BARYONS!!!

Outlook

- Sfermions are a few TeV (no lighter than ~ 3 TeV)
- O(100 GeV - TeV) particles ➡ Colliders!
- Decay rate < 10^{-4} eV ➡ travels > mm displaced vertices!
- How about lepton number violation? same-sign lepton asymmetry?
- Connection to asymmetric DM?

backup slides

Time dependent oscillations

$$|\psi(t)\rangle = g_+(t)|\psi\rangle - \frac{q}{p} g_-(t)|\psi^c\rangle,$$
$$|\psi^c(t)\rangle = g_+(t)|\psi^c\rangle - \frac{p}{q} g_-(t)|\psi\rangle$$

$$g_\pm(t) = \frac{1}{2}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} \pm e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)$$

Oscillations+Decays

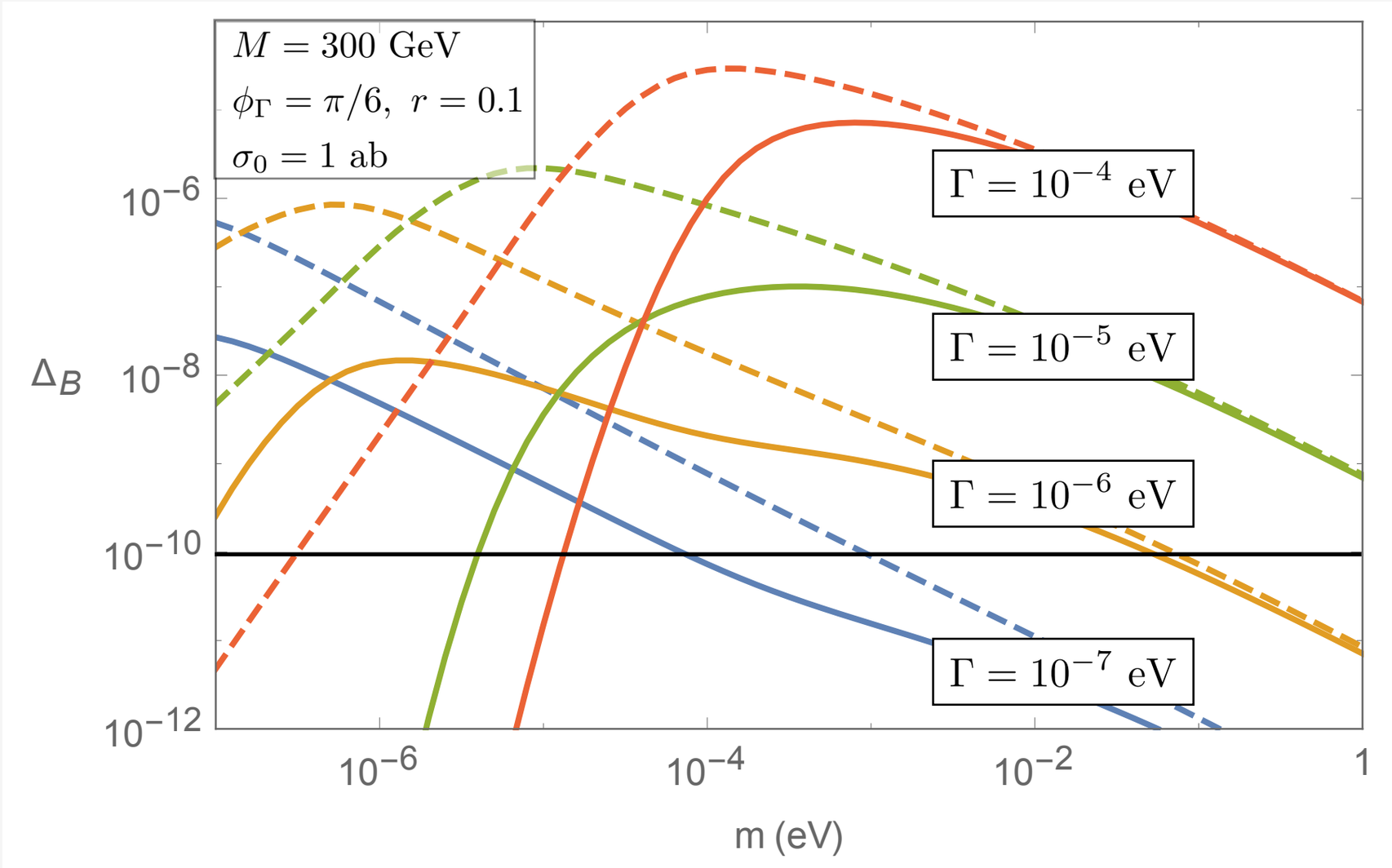
$$\frac{d^2\Delta(y)}{dy^2} + 2\,\xi\,\omega_0\,\frac{d\Delta(y)}{dy} + \omega_0^2\,\Delta(y) = -\epsilon\,\omega_0^2\,\Sigma(y)$$

For: $$\Sigma(z) = 2\,Y_{\rm eq}(1)\exp\left(-\frac{\Gamma}{2H(z)}\right) \quad \text{for} \quad z > 1$$

Solution is

$$\Delta(z) \simeq A\,\epsilon Y_{\rm eq}(1)\exp\left(-\frac{\Gamma}{2H(z)}\right)\sin^2\left(\frac{m}{2H(z)} + \delta\right)$$

Different mass difference



Oscillation start times

Hubble

$$z_{\rm osc} \sim 6\sqrt{\frac{2\times 10^{-6}\ {\rm eV}}{m}}\left(\frac{M}{300\ {\rm GeV}}\right)$$

Flavor-blind

$$z_{\rm osc} \sim \ln\left[10^7\left(\frac{M}{300\ {\rm GeV}}\right)^3\left(\frac{2\times 10^{-6}\ {\rm eV}}{m}\right)\left(\frac{\sigma_0}{1\ {\rm fb}}\right)\right]$$

Flavor-sensitive

$$z_{\rm osc} \simeq 80\left(\frac{M}{300\ {\rm GeV}}\right)^{3/5}\left(\frac{2\times 10^{-6}\ {\rm eV}}{m}\right)^{1/5}\left(\frac{\sigma_0}{1\ {\rm fb}}\right)^{1/5}$$

Elastic scatterings delay oscillations