Baryogenesis via Particle—Antiparticle Oscillations

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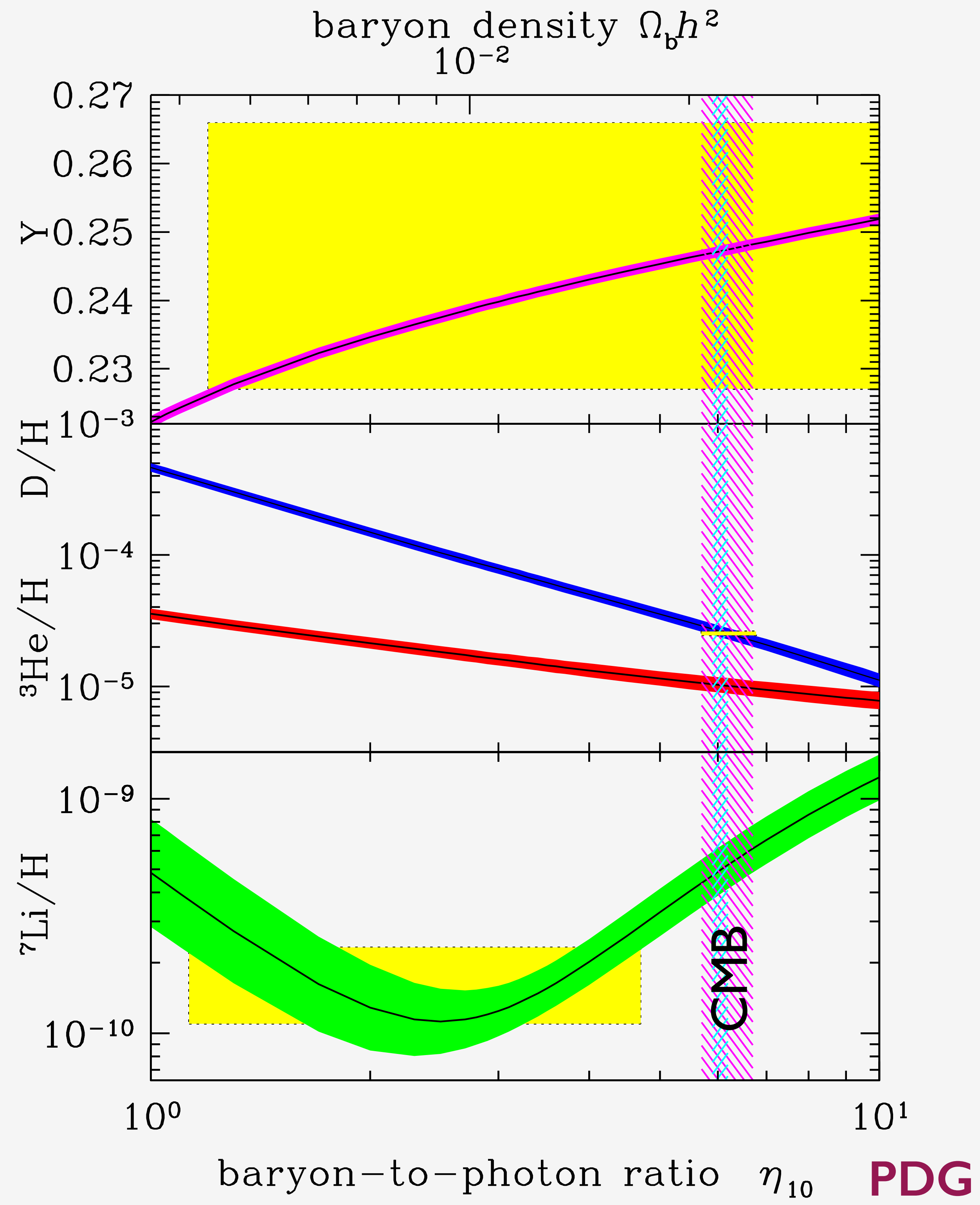
SI, John March-Russell, *arXiv:1604.00009*

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:

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



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

Couples to the SM

Extra CP violation

Some out-of-equilibrium process

We need New Physics

Couples to the SM

Let's re-visit SM CP violation

Extra CP violation

Some out-of-equilibrium process

Particle—Antiparticle Oscillations

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

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

Dirac mass   Majorana mass

with interactions

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

ψ : pseudo-Dirac fermion

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

Particle—Antiparticle Oscillations

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

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

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

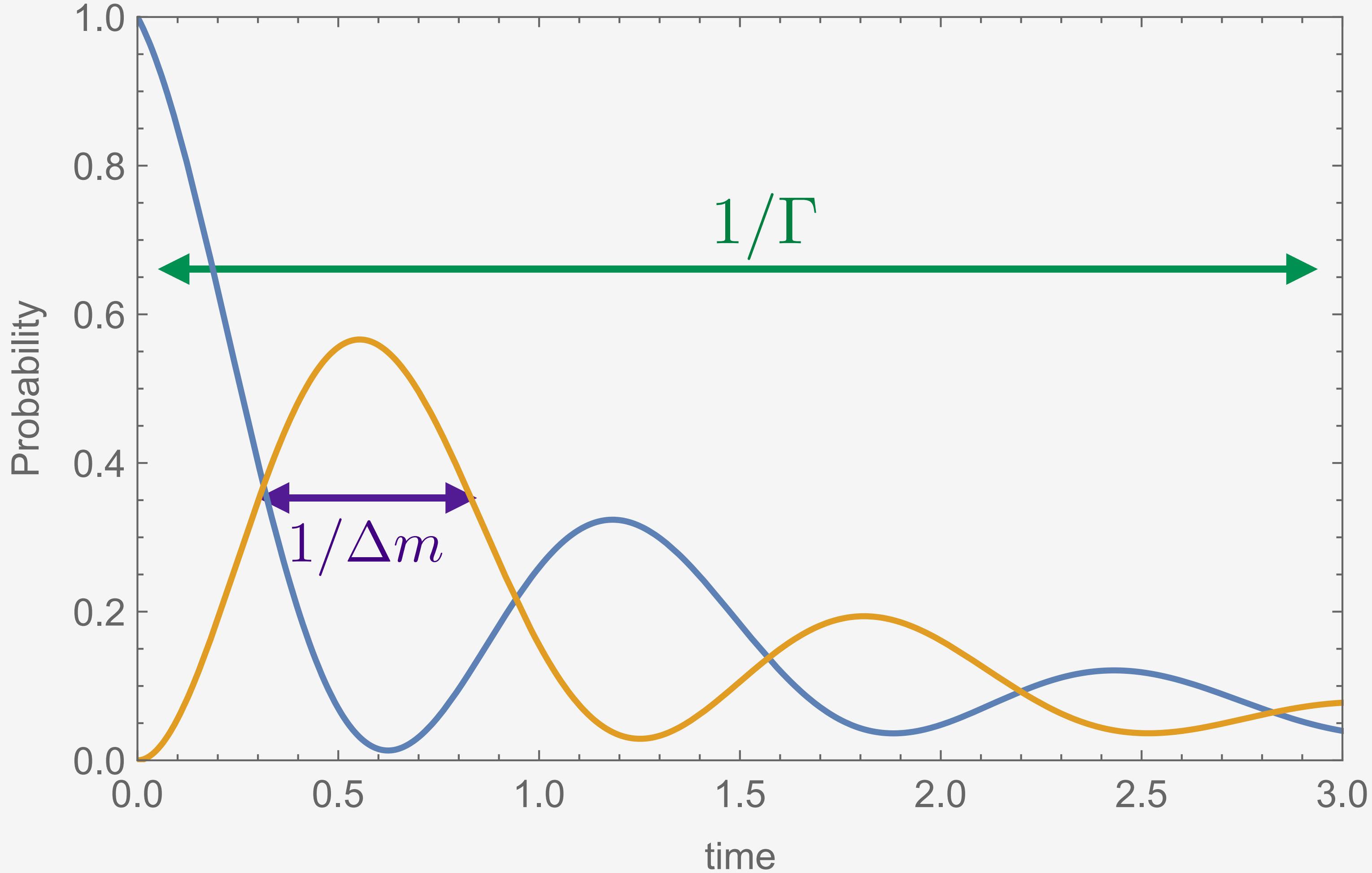
eigenvalues: $|\psi_{H,L}\rangle = p|\psi\rangle \pm q|\psi^c\rangle$

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

mass states ≠ interaction states

→ OSCILLATIONS!

Particle—Antiparticle Oscillations



important parameter:

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

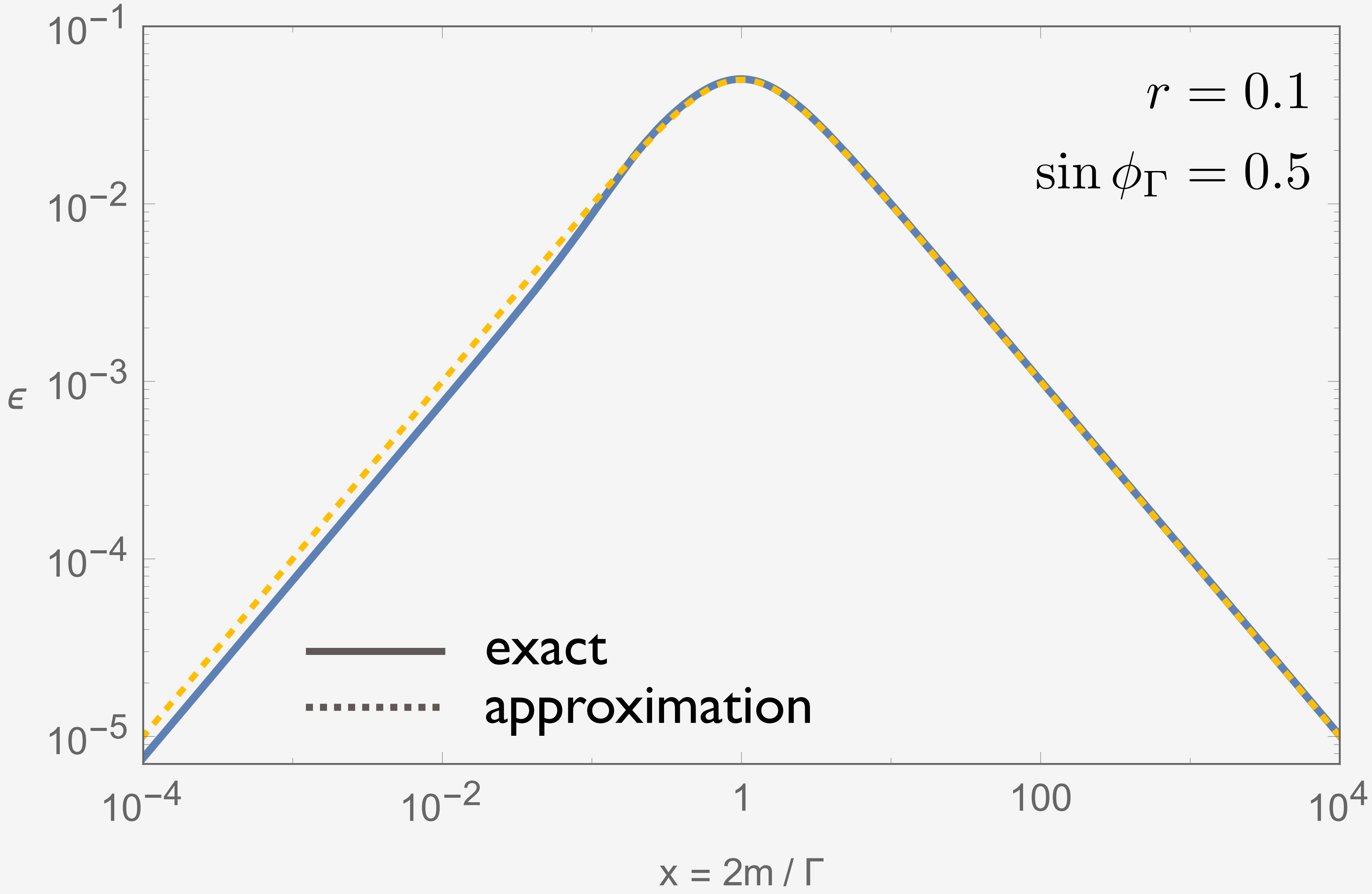
$$\Delta m = M_H - M_L \simeq 2m$$

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
$\tilde{g}\, u\, d\, d$

Out-of-equilibrium decays?

Why not?

Oscillations in the early Universe are complicated

Described by the time evolution of the density matrix

Oscillations

Vanishes if scatterings are *flavor* blind

$$zH\frac{d\mathbf{Y}}{dz} = -i(\mathbf{HY} - \mathbf{YH}^\dagger) - \frac{\Gamma_\pm}{2}[O_\pm, [O_\pm, \mathbf{Y}]] - s\langle\sigma v\rangle_\pm \left(\frac{1}{2}\{\mathbf{Y}, O_\pm \bar{\mathbf{Y}} O_\pm\} - Y_{\text{eq}}^2\right)$$

Annihilations

$\mathbf{H}$: Hamiltonian

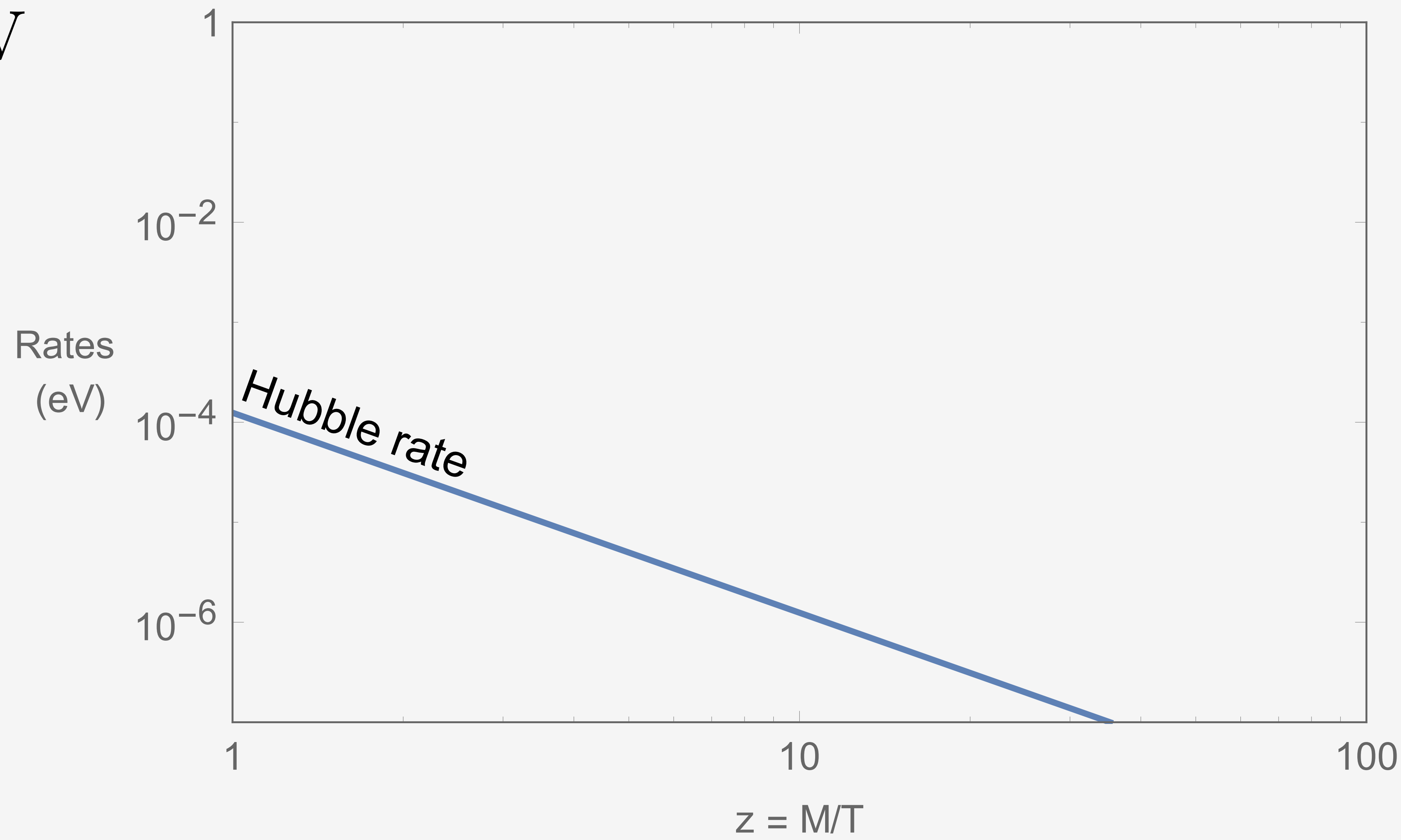
$\mathbf{Y}$: Density matrix

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

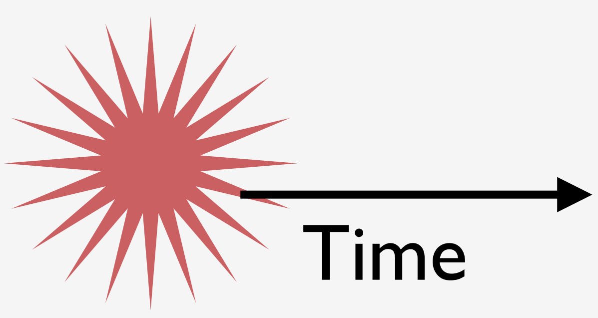
$z = M/T$ not redshift!

Oscillations in the early Universe are complicated

$M \sim 300\ \mathrm{GeV}$



Big Bang?



Oscillations in the early Universe are complicated

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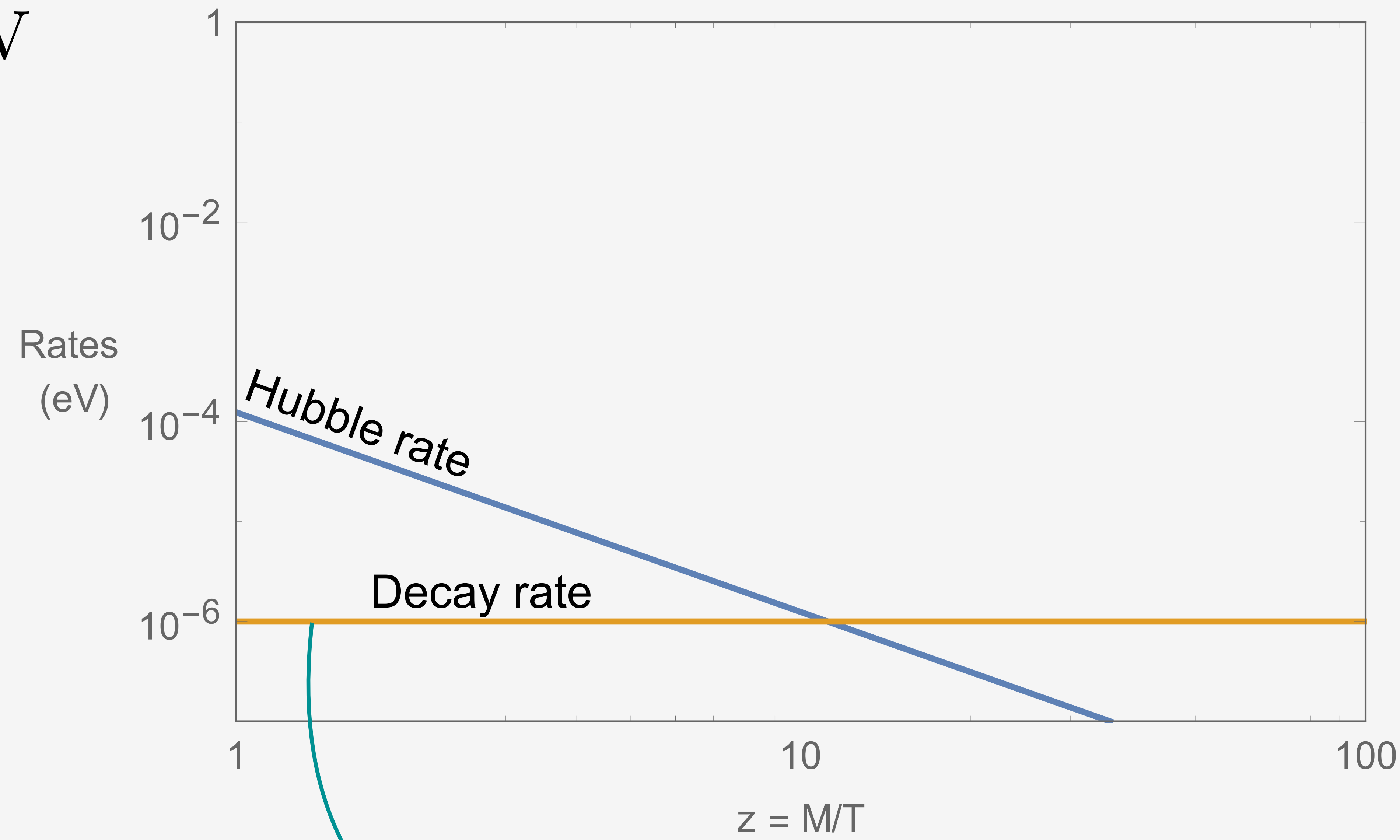

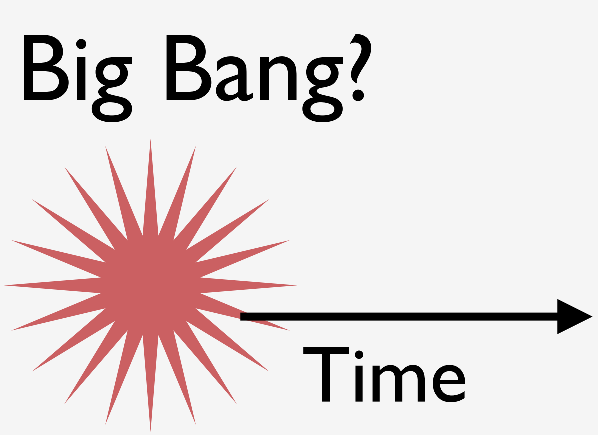

Out-of-equilibrium decay: $\Gamma \lesssim H(T \sim M)$

Oscillations in the early Universe are complicated

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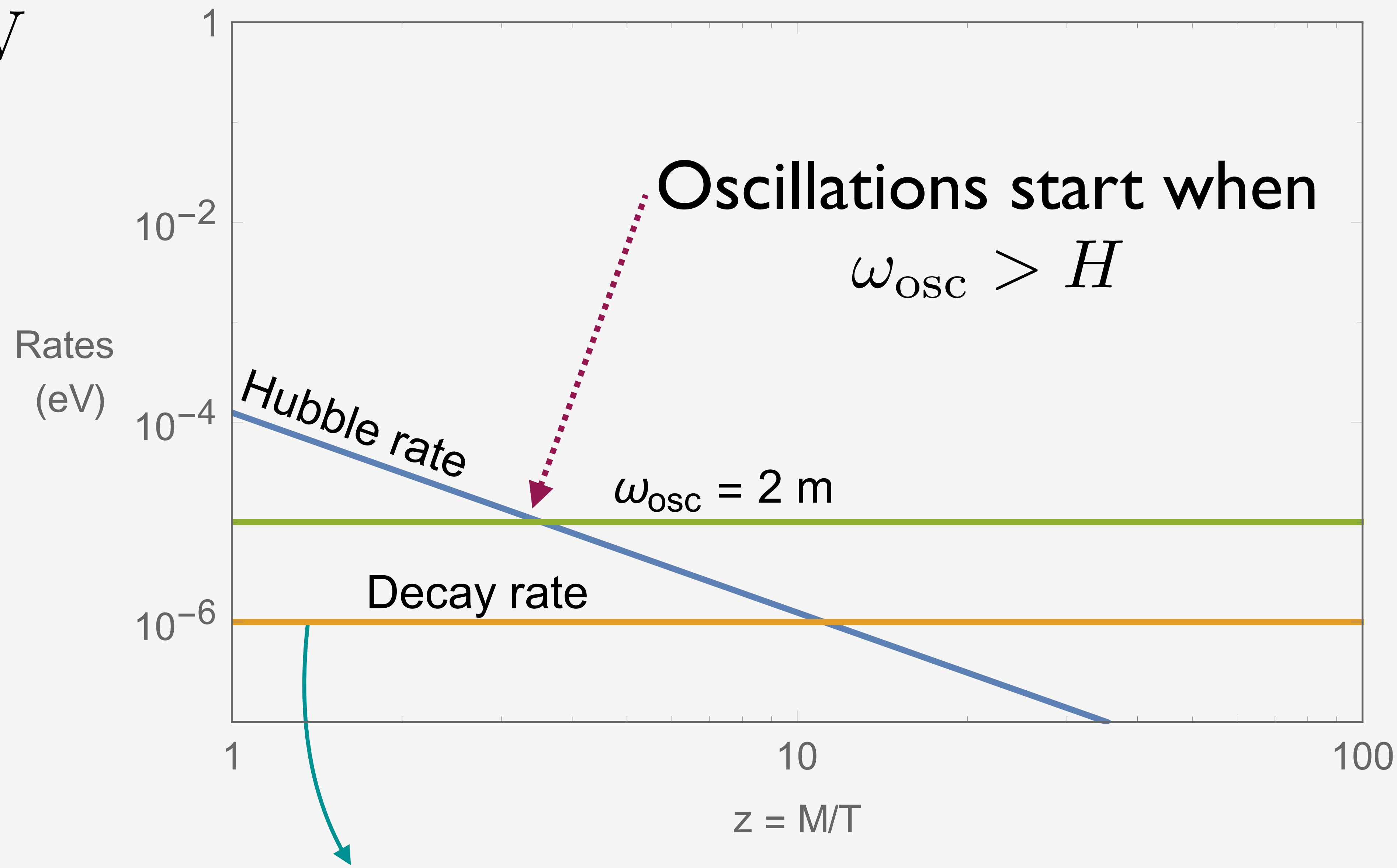

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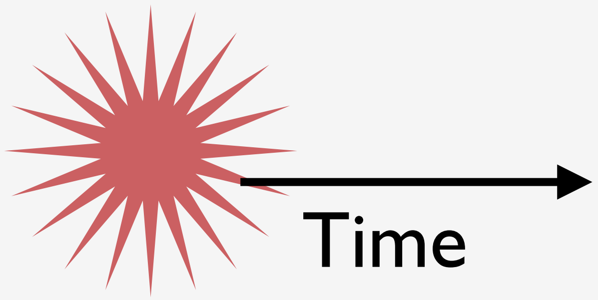

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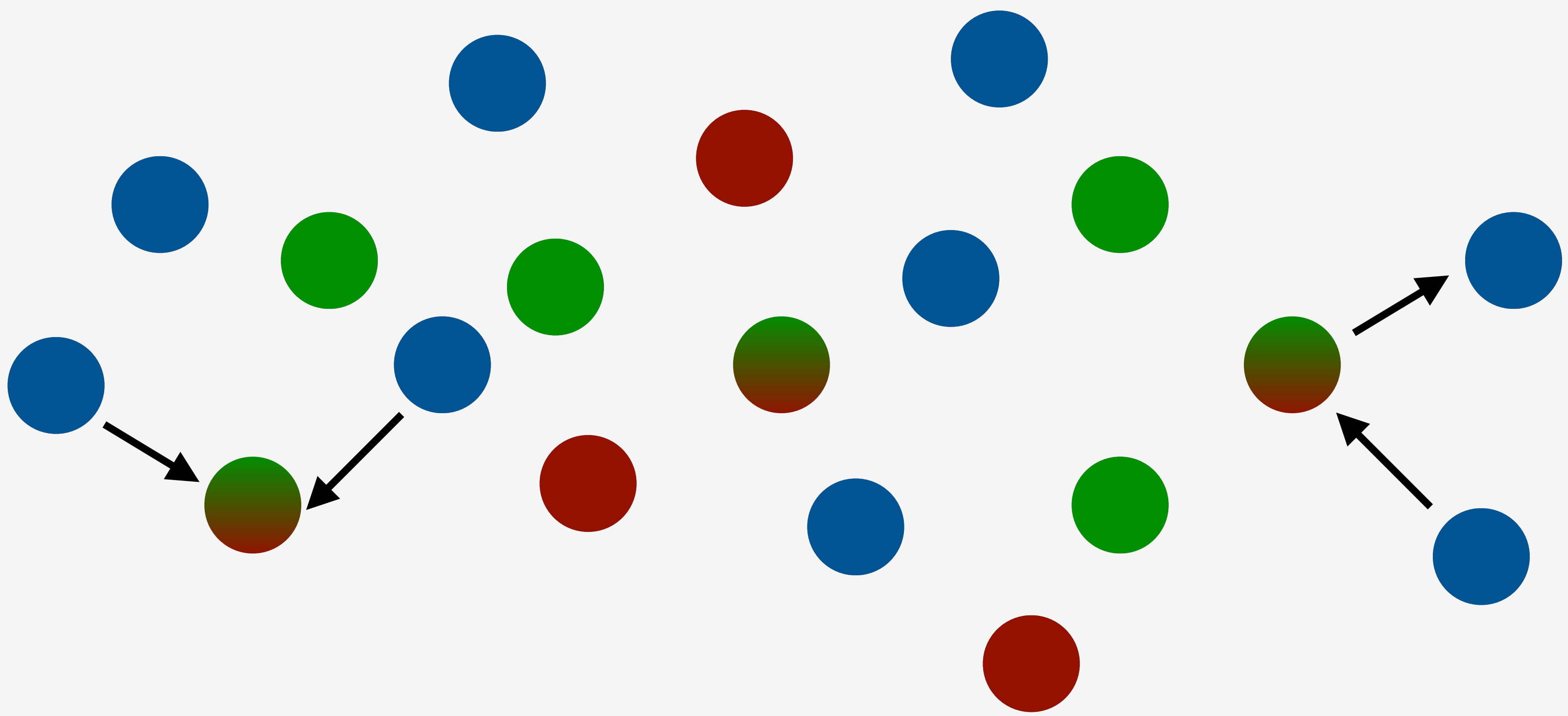
Oscillations in the early Universe are complicated

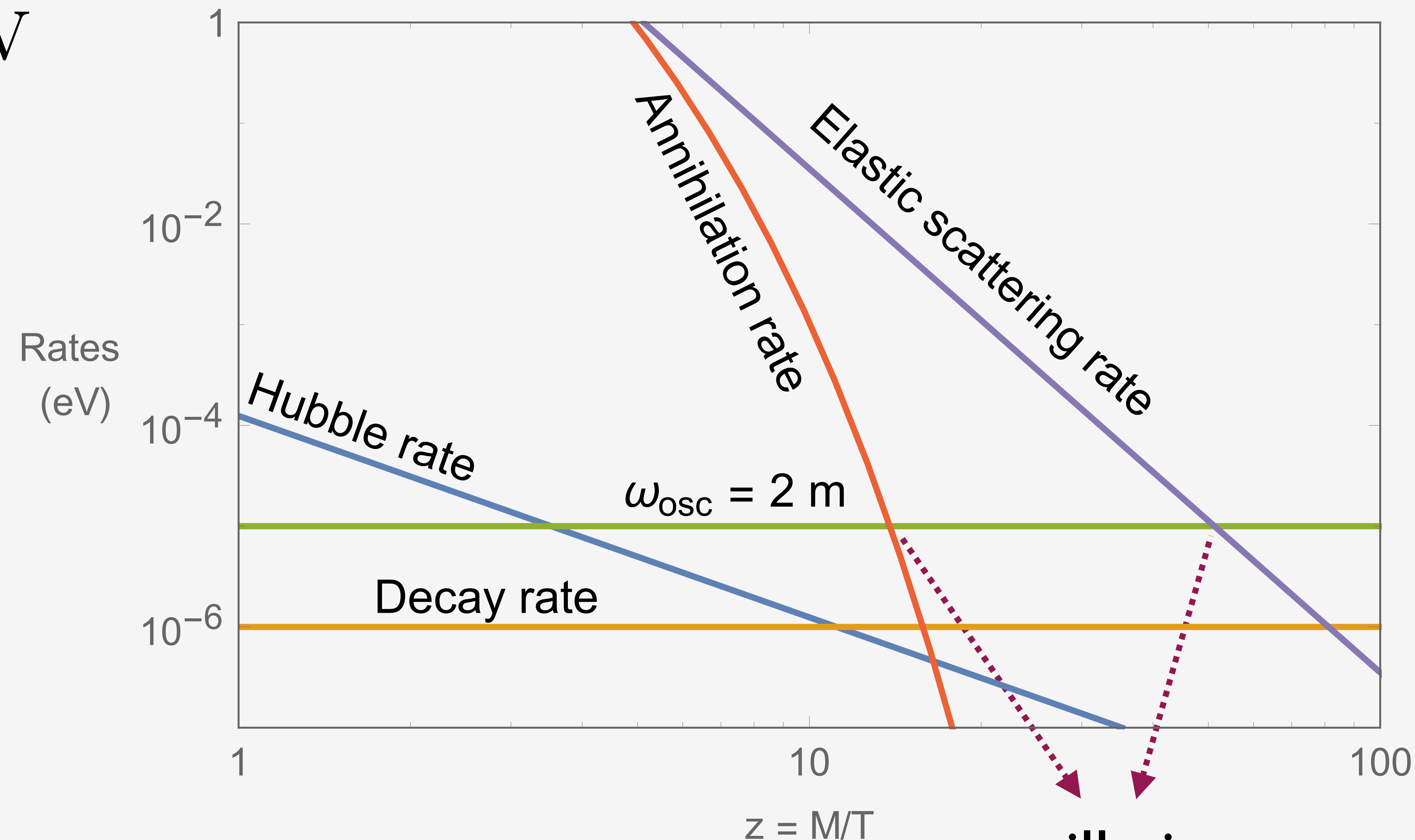


Particles/antiparticles are in a hot/dense plasma with interactions

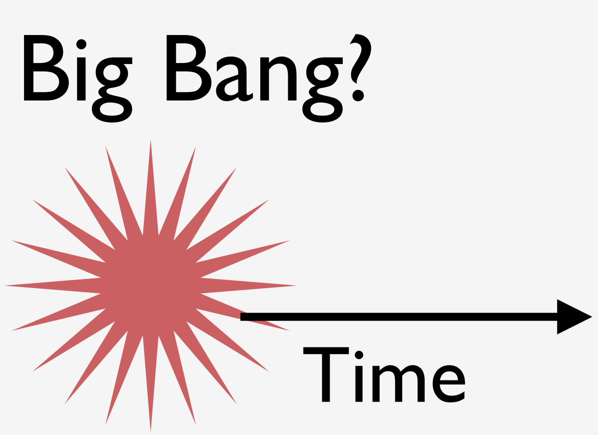
$$-\mathcal{L}_{\rm scat} = \frac{1}{\Lambda^2}\bar{\psi}\,\Gamma^a\psi\,\bar{f}\,\Gamma_a f$$

Oscillations in the early Universe are complicated

$M \sim 300 \text{ GeV}$

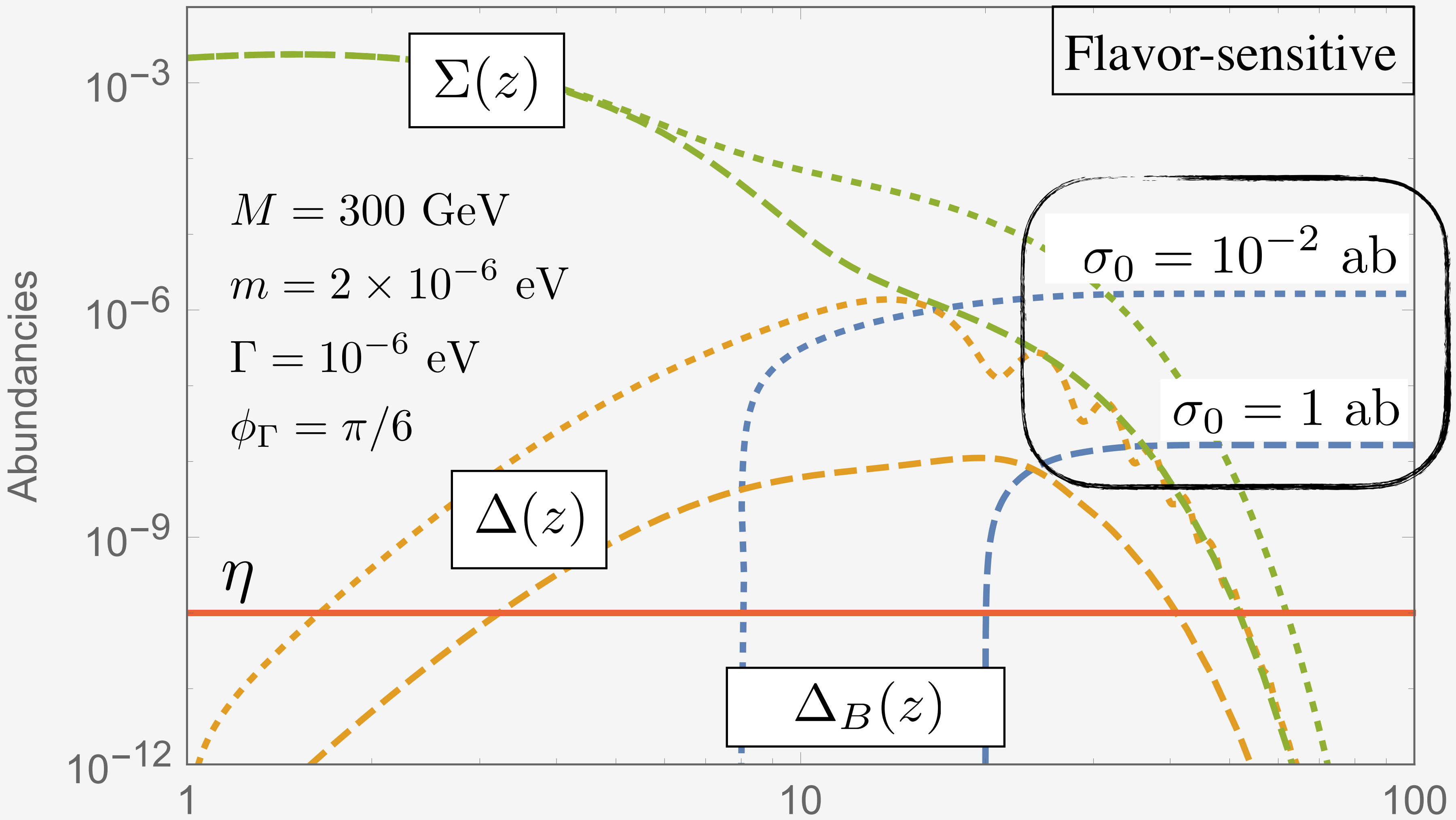


oscillations are further delayed



Let there be baryons!

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



BARYONS!!!

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

What kind of model?

Oscillations ⟷ Pseudo-Dirac fermions

Approximately broken $U(1)$ symmetry

↓

$U(1)_R$ -symmetric SUSY with a pseudo-Dirac bino!

Pseudo-Dirac bino oscillations

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

Let's also consider R-parity violation

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

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

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

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

$u\, d\, d$

$u\, d\, d$

Pseudo-Dirac bino oscillations

Oscillation Hamiltonian:

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

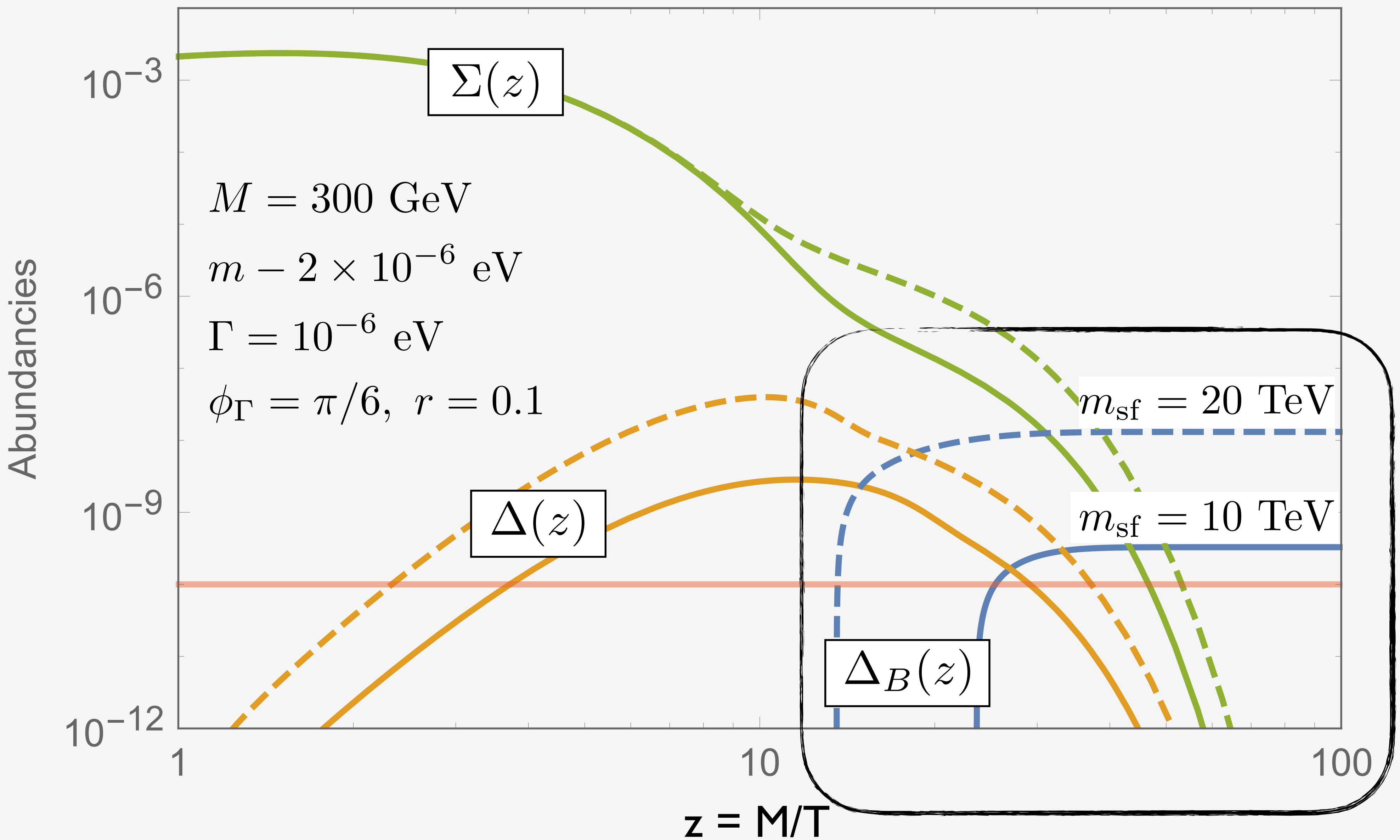
$$\Gamma \simeq \frac{M^5}{(32\pi)^3}|G_{\tilde{B}}|^2 \qquad r = \frac{|G_S|}{|G_{\tilde{B}}|} \ll 1$$

with annihilations + elastic scatterings:

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

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

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?
- Neutron — antineutron oscillations???

backup slides

Oscillations+Decays

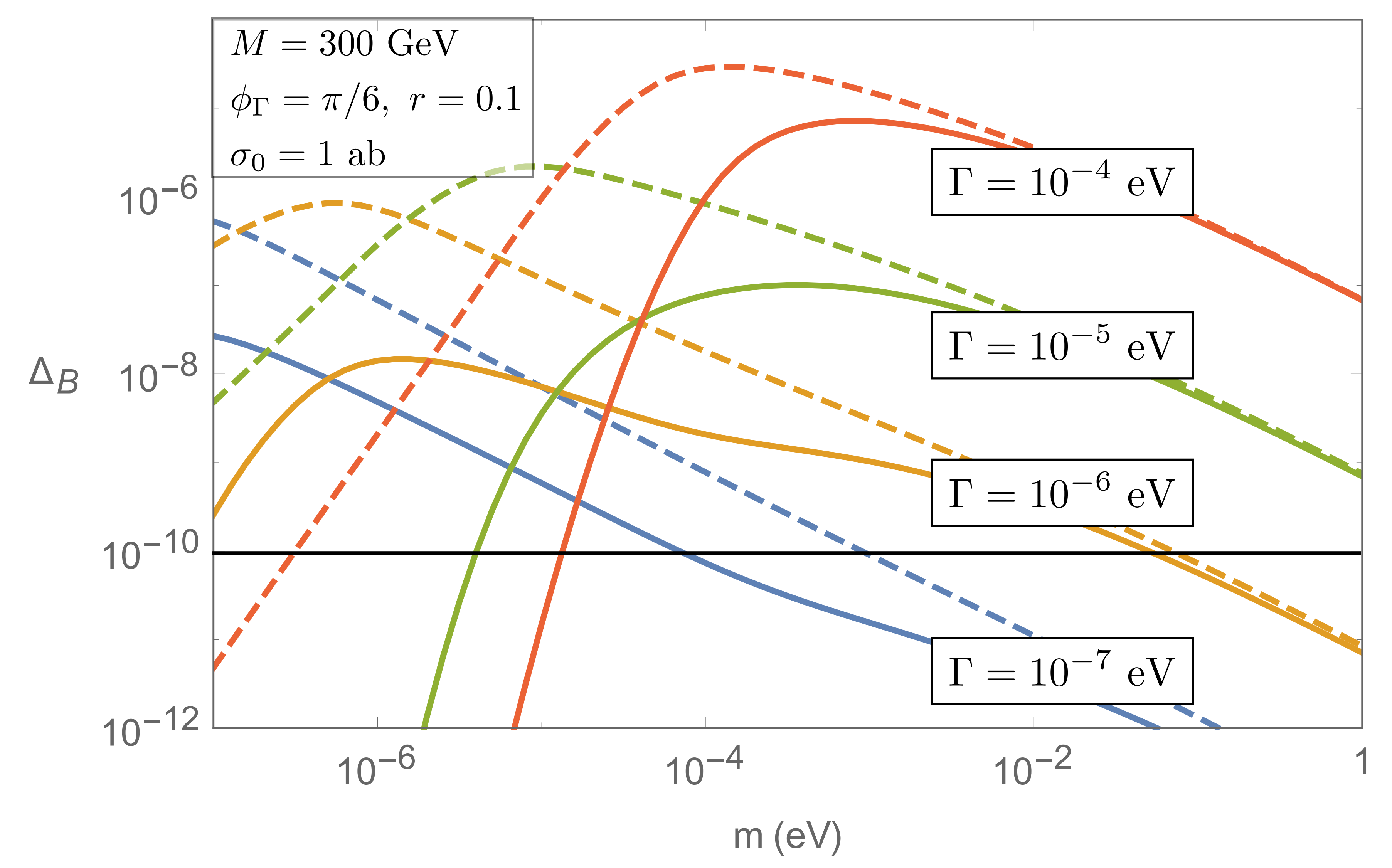
$$\frac{d^2\Delta(y)}{dy^2} + 2\,\xi\,\omega_0\,\frac{d\Delta(y)}{dy} + \omega_0^2\,\Delta(y) = -\epsilon\,\omega_0^2\,\Sigma(y)$$

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

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