Preheating in the Higgs as Inflaton Model

- Why is preheating interesting?
- Higgs as inflaton model
- Relevant physics:
  - ∗ nonadiabatic particle production
  - ∗ particle decay, thermalization of decay daughters
  - ∗ medium effects on nonadiabaticity
  - ∗ back reaction *etc*
- Conclusions

Preheating is interesting!

Energy must get out of Inflaton into “normal” thermal DOF

Maximum T achieved is important for many problems:

- leptogenesis (and baryogenesis)
- Gravitino production
- Other relic production and decay (moduli, etc)

T of reheating seems to be $very$ model dependent.

What is the “space of possibilities”?

Preheating is rich physics!

Models considered depend on physics of:

- Perturbative particle decay
- Parametric resonance
- Nonadiabatic particle production
- Tachyonic field evolution
- rescattering, feedback, backreaction

Very model dependent.

Unanswered Question

No detailed preheating study has been conducted in a scenario where reheating occurs directly into particles with nonabelian gauge interactions of realistic strength.

The physics could be quite different from what is studied:

- much stronger mutual interactions
- new, nonabelian phenomena?

What is the simplest such model?

Higgs as Inflaton

Bezrukov and Shaposhnikov, arXiv:0710.3755

Consider the addition of a Higgs-curvature interaction

$$S = \int d^4x \sqrt{-g} \left[\mathcal{L}_{\rm SM} + \left(\frac{M_{\rm P}^2}{2} + \xi H^\dagger H \right) R \right]$$

$$\mathcal{L}_{\rm SM} = g^{\mu\nu} D_\mu H^\dagger D_\nu H + \lambda (H^\dagger H)^2 + \dots$$

Here ξ is a permissible dimensionless coupling.

We will need $\xi \sim 10^5$ [SEE SLIDE 8!]

Further analysis easier in Einstein frame:

$$\Omega^2 \equiv \frac{M_{\rm P}^2 + \xi h^2}{M_{\rm P}^2}\,, \qquad (h^2 = 2H^\dagger H) \qquad \hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

Substituting, $(\ldots)R \to M_{\rm P}^2 \hat{R}$ plus $\partial_\mu \Omega$ type terms.

Canonically normalized Higgs χ

$$S_{\rm Einstein} = \int d^4x \sqrt{-\hat{g}} \left(\frac{M_{\rm P}^2}{2} \hat{R} + \frac{\hat{g}^{\mu\nu}}{2} D_\mu \chi D_\nu \chi + V(\chi) \right)$$

provided one defines (skipping some details)

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2 / M_{\rm P}^2}{\Omega^4}}\,, \qquad V(\chi) = \frac{1}{\Omega^4} \frac{\lambda}{4} (h^2(\chi))^2$$

Three regimes:

- $h \ll M_{\rm P}/\xi$: Everything normal.
- $\frac{M_{\rm P}}{\xi} < h < \frac{M_{\rm P}}{\sqrt{\xi}}$: here $\Omega \simeq 1$ but its derivatives matter!

$$\chi \sim \frac{\sqrt{\frac{3}{2}}\xi h^2}{M_{\rm P}} \qquad \text{and} \qquad V(\chi) \simeq \frac{\lambda M_{\rm P}^2}{6\xi^2}\chi^2$$

- $h > M_{\rm P}/\sqrt{\xi}$: Ω is large, $\chi \sim \sqrt{6} M_{\rm P} \ln(h)$, potential flattens out. Ideal slow-roll potential, $V \sim (\lambda/\xi^2) M_{\rm P}^4$

$\delta\rho/\rho$ right if $\xi = 44700\sqrt{\lambda}$; predicts $n_s \simeq 0.966$, $r = .0034$.

But is this nuts??

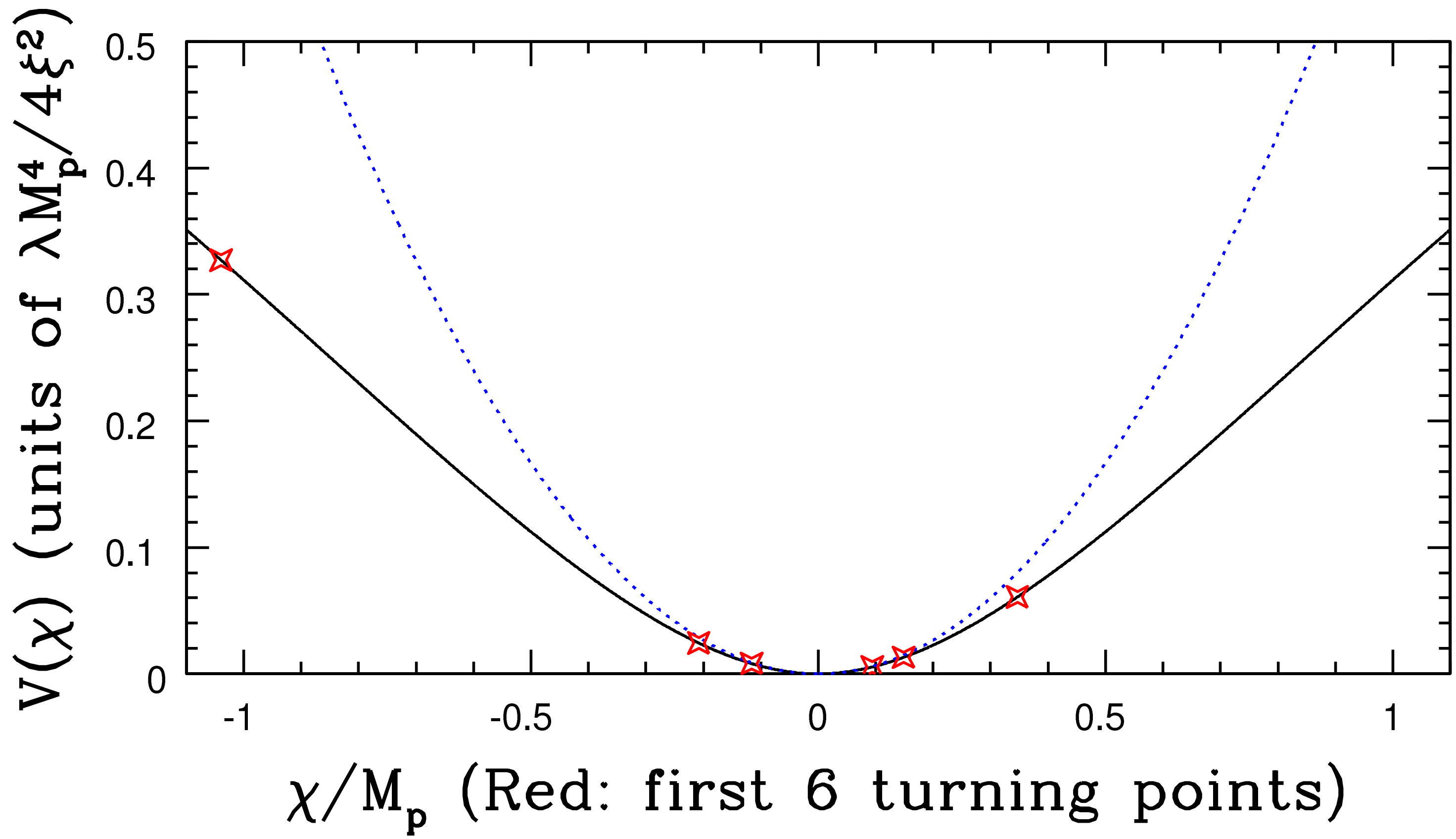
Model depends on a *large* rescaling between χ, h
arising from *large* Higgs-curvature coupling $\xi R h^2$.

- Bezrukov & Shaposhnikov: matter-only loops, stable.
- Burgess, Lee, Trott (arXiv:0902.4465): gravity-in-loops, not self-consistent.
- Barbon & Espinosa (arXiv:0903.0355): description not radiatively stable.

Burgess, Barbon *et.al.* probably right. We analyze anyway.

End of inflation

Field χ oscillating about potential minimum



Essentially quadratic after a few half-oscillations

Higgs VEV gives (un)usual masses to other particles:

$$m_W^2 = \frac{g^2}{4}h^2 = \frac{g^2}{\sqrt{24}\xi}|\chi|M_{\rm P} \gg m_h^2 = \frac{\lambda M_{\rm P}^2}{3\xi^2}$$

Mass squared is linear in $|\chi|$ which is strange.

$$\frac{m_Z^2}{m_W^2} = \frac{g'^2 + g^2}{g^2} \simeq 1.68\,, \qquad \frac{m_t^2}{m_W^2} = \frac{2y^2}{g^2} \simeq 1.24$$

where $\overline{\mu}_{\rm MS} \sim 10^{15}$GeV relevant scale.

Nonadiabatic evolution of W field excitations

W-field Excitation, wave number k, obeys SHO equation:

$$H = \frac{\dot{\phi}_k^2}{2} + \frac{k^2 + m^2(t)}{2}\phi_k^2$$

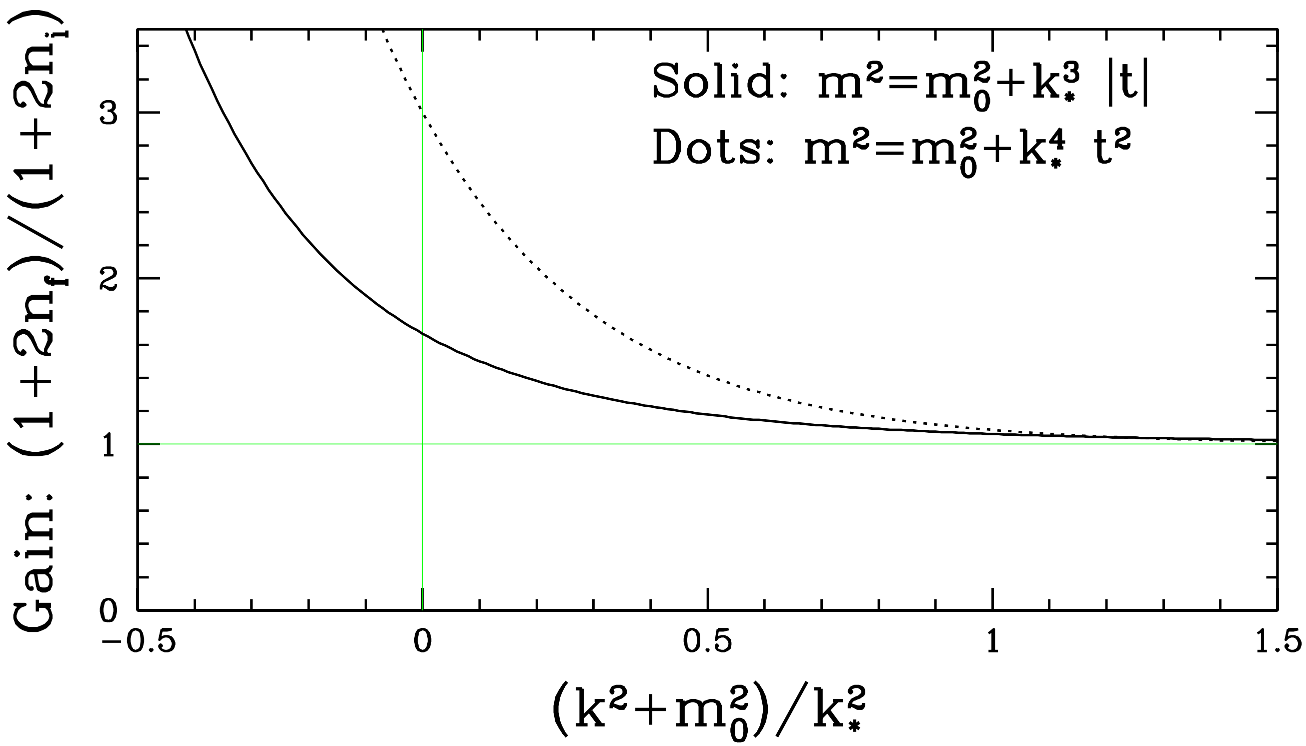
with $m^2(t) = \frac{g^2 M_{\rm P}\chi_0}{\sqrt{24}\xi}|\sin(m_h t)|$ (χ_0 peak χ value)

Evolution nonadiabatic near $\sin(m_h t) = 0$ if $k < k_*$, with $k_*^3 \equiv dm^2(t)/dt = m_W^2 m_h$.

Nonadiabatic evolution: $|0\rangle \Rightarrow |\text{squeezed}\rangle$

Random excited state: raises occupancy.

Occupancy change on evolving $m^2 = k_*^3 t$ through $t = 0$:

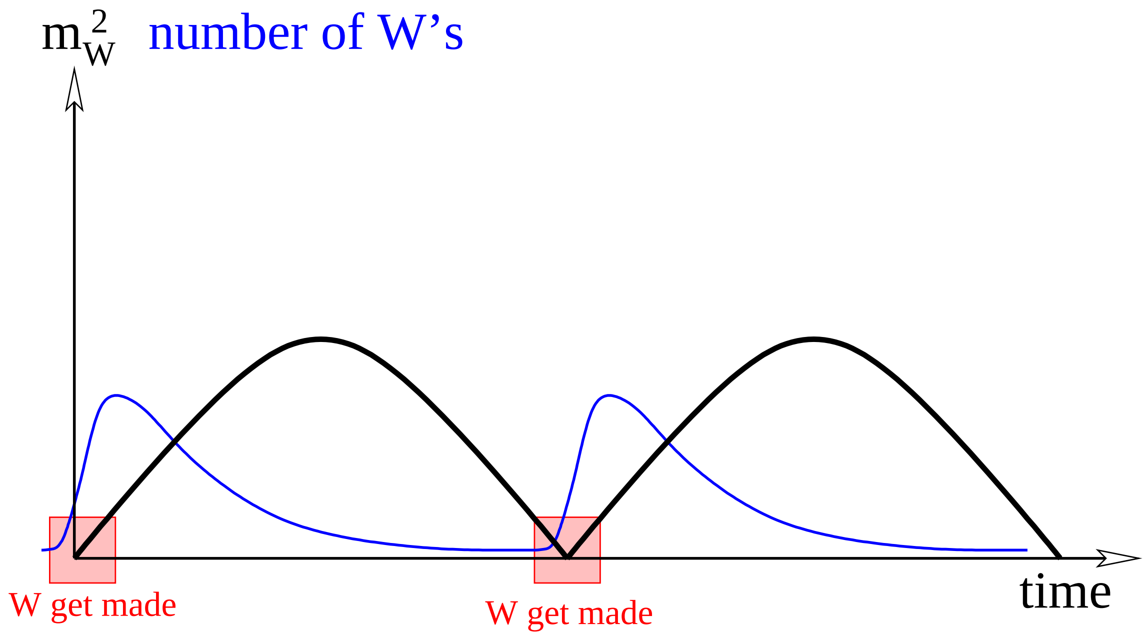


Modes with $k < 0.7k_*$ get appreciable amplification.

Less than in $m^2 \sim t^2$ case except at large k^2.

Early oscillations: $m_W > m_h/\alpha$: $\Gamma_W > m_h$

adiabatically generated W decay before next zero-crossing:



Occurs roughly first 80 oscillations.

After that, W stimulate more W, start to pile up.

Fate of W decay products?

W created when light, density $n_W \lesssim k_*^3$.

Decay when heavy, $m \gg k_*$: $p_{\rm decayproduct} \gg k_* \sim n_W^{1/3}$.

Decay products: low density plasma of high energy particles

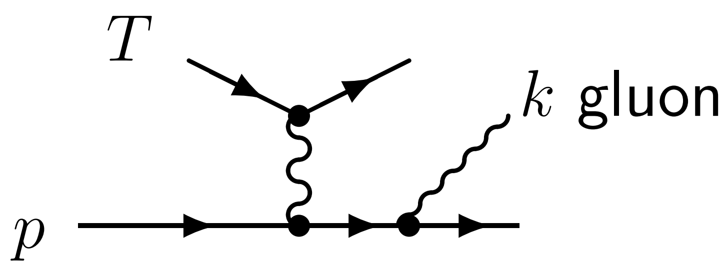
$$\epsilon \sim np \,, \qquad n \sim fp^3 \,, \quad f \ll 1$$

W decay is $2/3$ $q\bar{q}$, $1/3$ $l\nu_l$.

General question: how does such a plasma thermalize?

Plasma has a few soft particles. Form thermal bath $T \ll p$.

Scattering of hard p particles $dominated$ by scattering with T particles, NOT with each other.



Dominant process: elastic scattering off bath (T) particle

Main energy loss mechanism: Bremsstrahlung while scattering

k showers: Energy goes into T bath.

Subtleties

Sudakov logs: normally k distribution is $\int_0^p dk/k$.

Energy loss: $\int k dk/k$ dominated by $k \sim p$.

Dense medium: LPM suppression of large k by $(T/k)^{1/2}$.

Large k's take too long to shower: don't promptly add to T.

Requires slight extension of AMY/McGill jet energy loss method hep-ph/0209353, hep-ph/0309332, arXiv:0710.0605

$\alpha_{\rm s} = 1/40$: weak coupling justified first time!

Summary: decay products thermalize after about 80 oscillations.

Fraction of W decays is

$$\exp\left(-\int_0^{\pi/m_H}\Gamma_W dt\right) = \exp\left(-\frac{3\alpha_W}{4}\,\frac{m_{W,\mathrm{max}}}{m_h}\int_0^{\pi}\sqrt{\sin t}\,dt\right)$$

controlled by $m_W/m_h \sim \xi^{1/2}\chi_0/M_{\mathrm{P}}$.

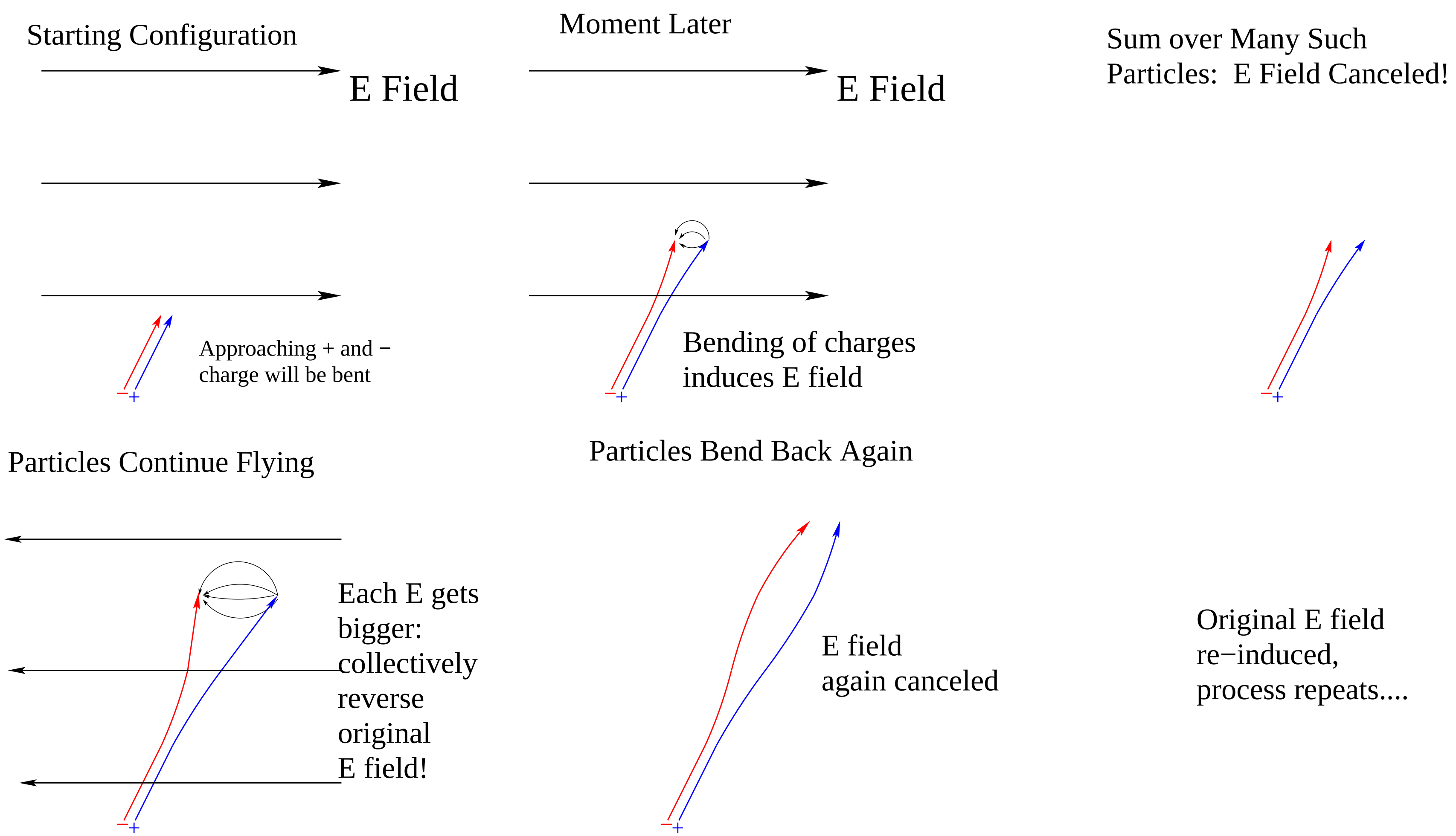
After about 80 oscillations, many W survive, stimulate (nonadiabatic) particle creation.

W number starts growing exponentially.

What cuts off exponential growth?

How does presence of bath and other W bosons feed back on nonadiabaticity condition for m_W zero-crossing?

Example of plasma's effect on W's: Plasma oscillations



Full W evolution determined by action:

$$S_A = \frac{m^2(t)}{2} A^\mu A_\mu + \frac{1}{4} F_{ij}^2 - \frac{1}{2} F_{i0}^2 - A_\mu J^\mu$$
$$J_x^a = \left(m^2(t) + k^2 + \partial_t^2 \right) A_x^a$$

Current is sum of currents from particles in plasma:

$$J_x^a = \int \frac{d\Omega_{\mathbf{v}}}{4\pi} v_x \, \delta f^a(\mathbf{v})$$

(retarded) δf^a is induced by past E fields

$$(D_t + \mathbf{v} \cdot \mathbf{D}) \, \delta f^a(\mathbf{v}) = m_{\rm D}^2 \mathbf{v} \cdot \mathbf{E}^a$$

Note straight-line propagation.

Particle propagation Green function:

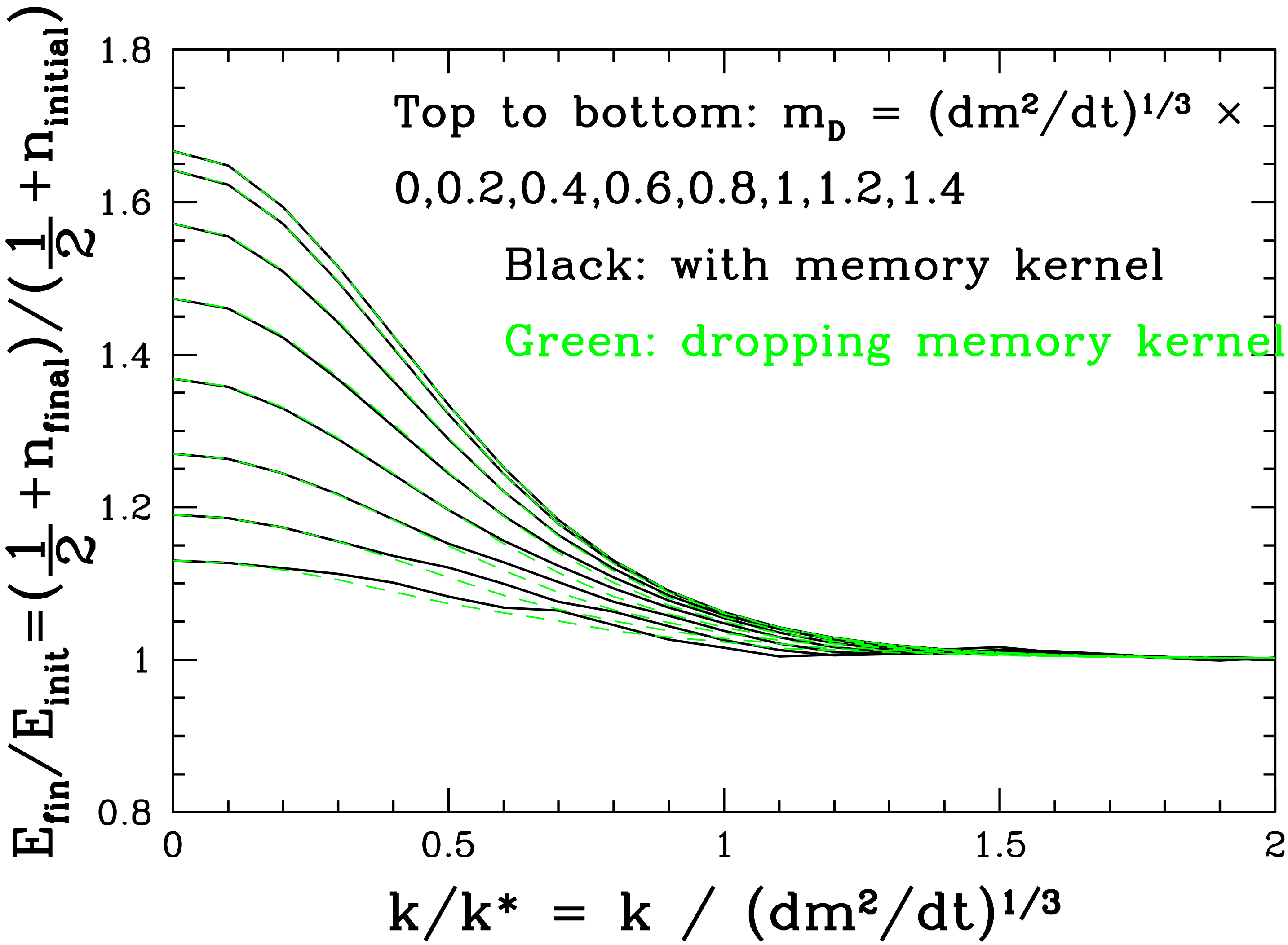
$$\delta f^a(\mathbf{x}, t, \mathbf{v}) = m_{\rm D}^2 \int_0^\infty dl \; \mathbf{v} \cdot \mathbf{E}^a(\mathbf{x} - l\mathbf{v}, t - l)$$

Hard Thermal Loop (neglecting color rotation).

$$\begin{aligned} J_x &= \int \frac{d\Omega_{\mathbf{v}}}{4\pi} v_x \, m_{\rm D}^2 \int_0^\infty dl \; v_x \partial_t A_x(t-l) e^{-iv_z kl} \\ &= \frac{m_{\rm D}^2}{3} A_x(t) + m_{\rm D}^2 \int_0^\infty \frac{dt'}{t'} A_x(t-t') \times \\ &\qquad \times \left[\frac{3\cos(kt')}{k^2 t'^2} + \frac{(k^2 t'^2 - 3)\sin(kt')}{k^3 t'^3} \right] \end{aligned}$$

Leads to integro-differential equation of motion for A_x!

New nonadiabatic amplification of W's:



Plasma effect is almost $m^2 \to m^2 + \omega_{\rm pl}^2$ with $\omega_{\rm pl}^2 = m_{\rm D}^2/3$.

So what is $\omega_{\rm pl}^2$?

- Thermal bath contribution, $m_W > 3T$: $g^2T^2/4$
- Thermal bath, $m_W < 3T$: $\frac{11}{18}g^2T^2$ (W in bath)
- Other IR W bosons: $3g^2 n_W/m_W$.
  What m_W? At $\chi = 0$, use $m_W = \omega_{\rm pl}$.

Note: IR bosons feed back on each other to make each other feel more massive. Production is self-limiting

Other feedbacks ($3W \to 2W$ *etc*) comparable but smaller

Back-reaction on Higgs field

W bosons contribute thermal mass to Higgs field:

$$\begin{aligned} V(\chi) &= V_{\rm vac}(\chi) + V_{\rm bath}(\chi) \\ \frac{dV_{\rm bath}}{d\chi} &= \int \frac{d^3k}{(2\pi)^3}(6) f_W(k) \frac{dE_k}{d\chi} \end{aligned}$$

Every half-oscillation begins with more W's
Ends with fewer W's. Damps χ oscillations.

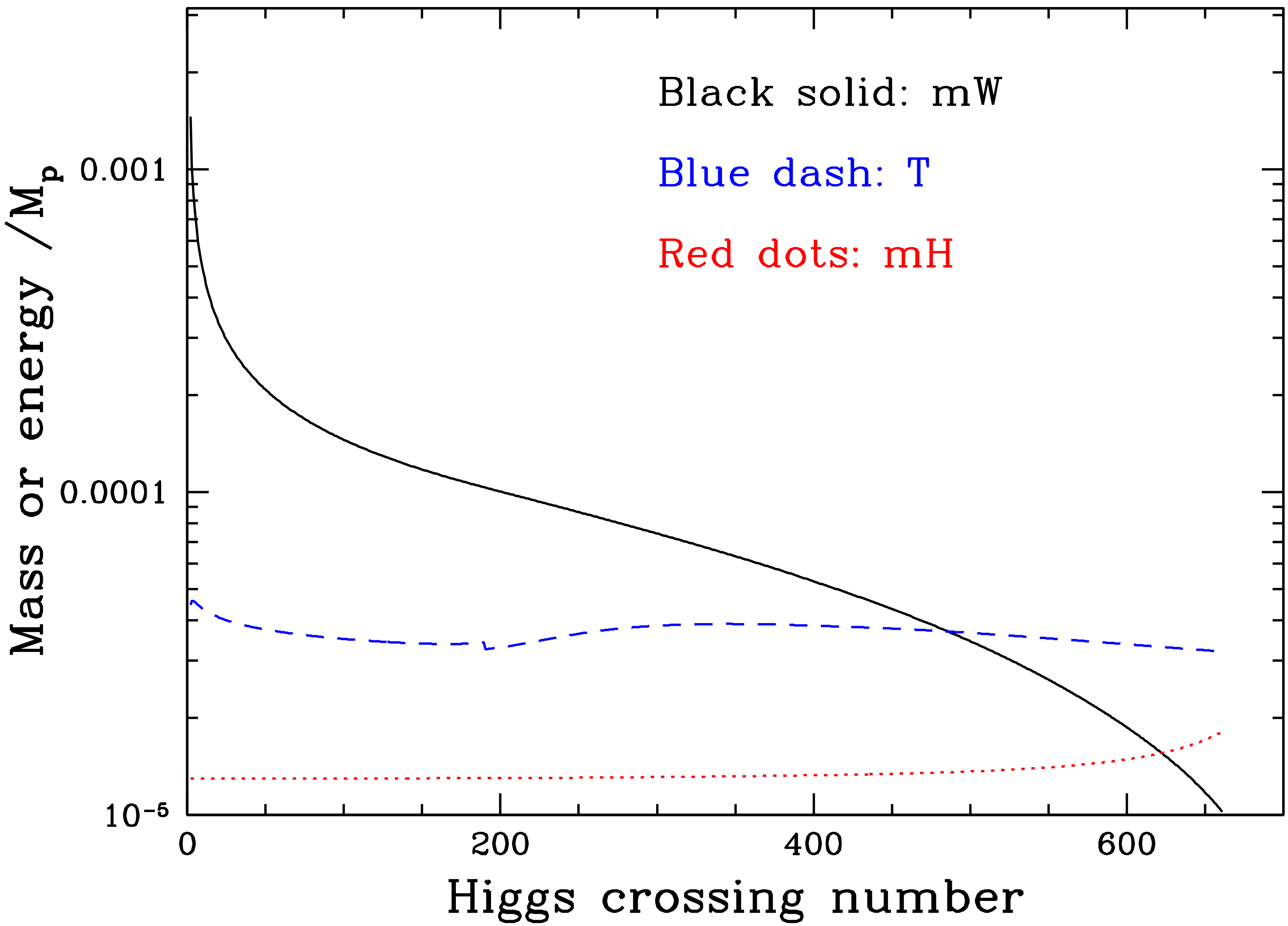
Account for by bath energy gain via W decays.

Late in preheating, m_h^2 rises due to bath. Accelerates completion of thermalization.

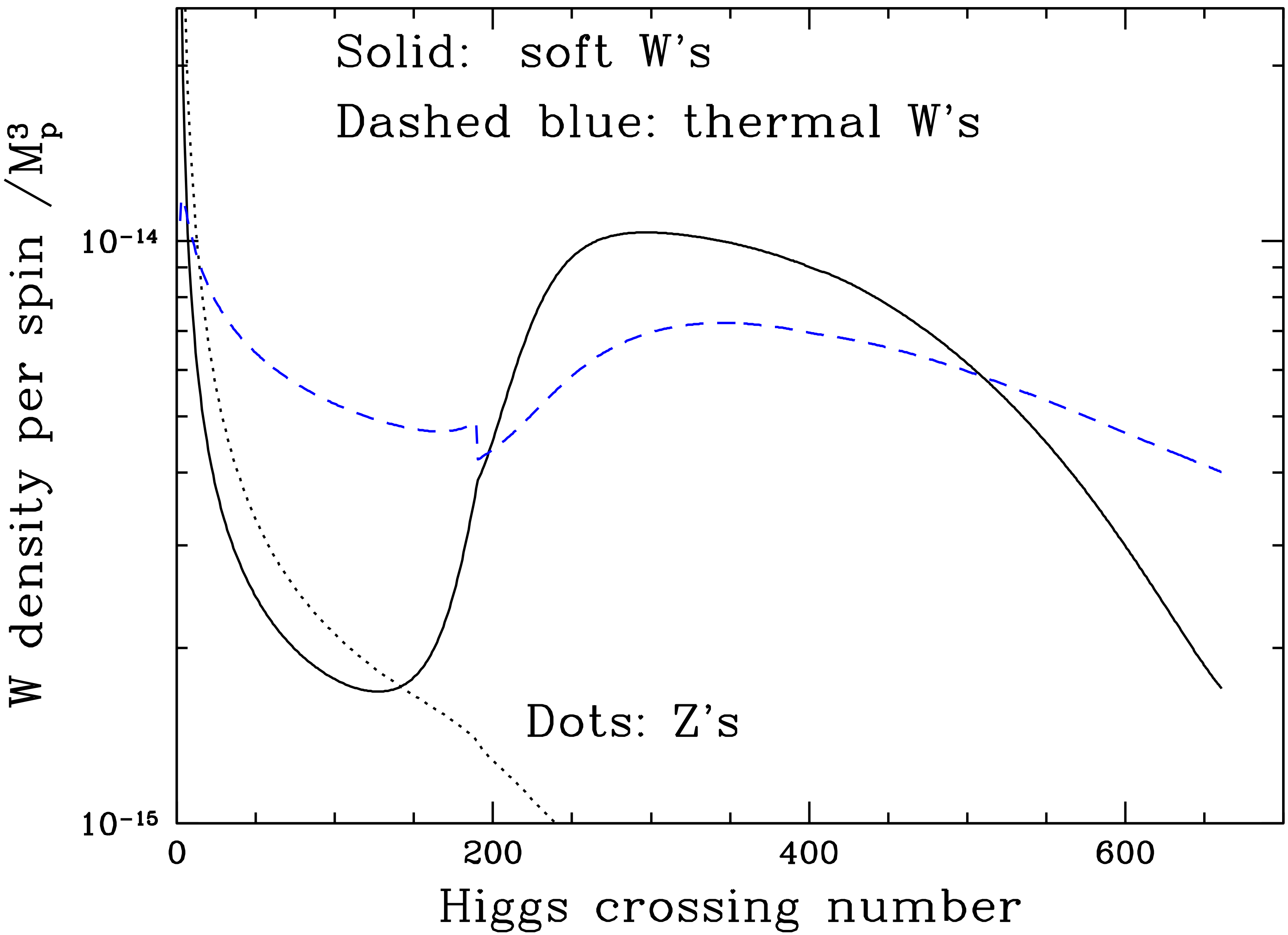
Roll everything together:

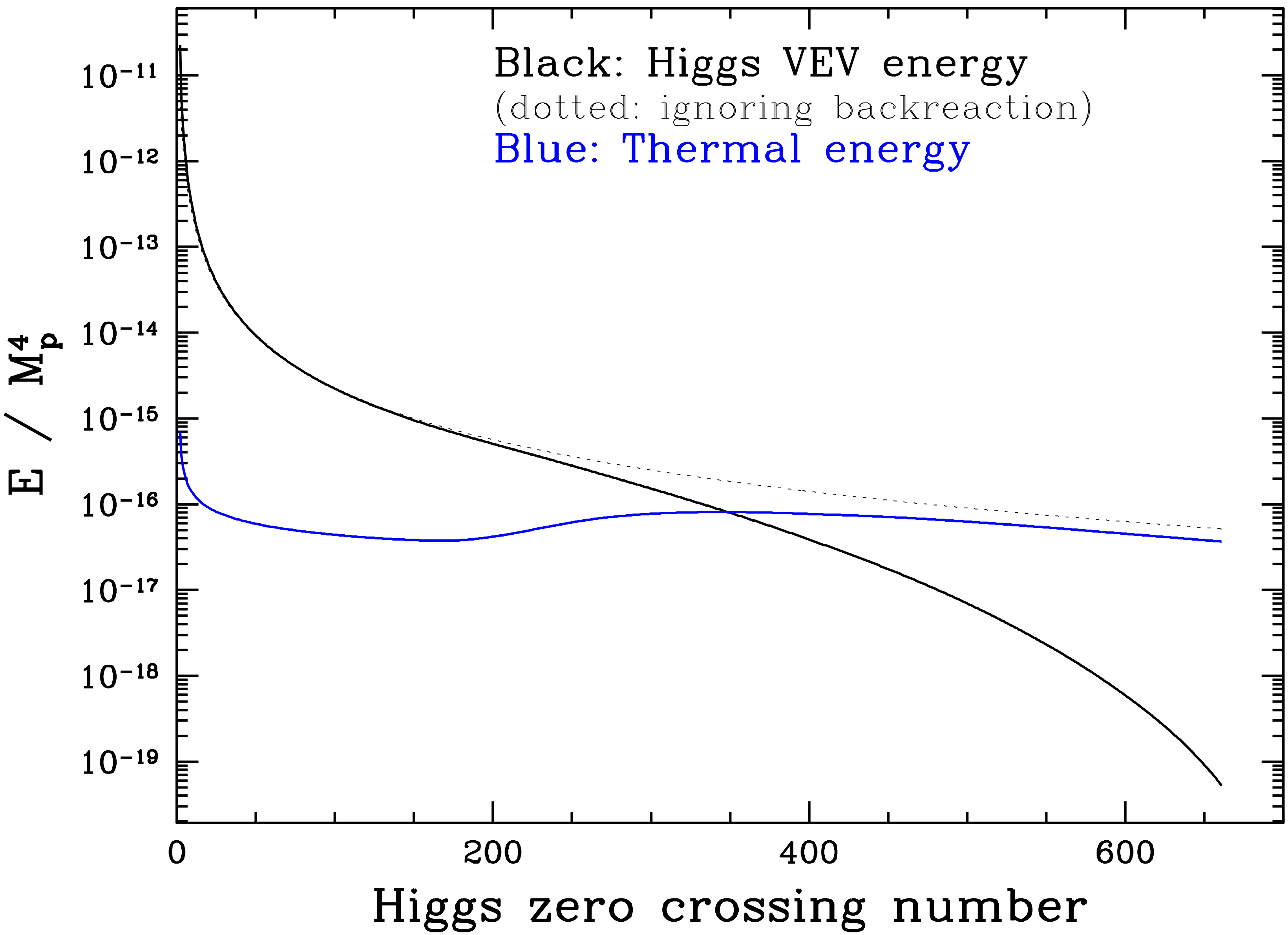
- Bath-corrected Particle production on zero-crossing
- W particle decay, energy gain to bath
- Hubble expansion diluting T and χ_{max}
- W feedback on χ_{max}

Determine evolution of χ, bath, soft W's as function of time (number of half-oscillations of h)



Black solid: mW
Blue dash: T
Red dots: mH
Mass or energy /M_p
0.001
0.0001
10^{-5}
0
200
400
600
Higgs crossing number


Solid: soft W's
Dashed blue: thermal W's
Dots: Z's
W density per spin $/M_p^3$
10^{-14}
10^{-15}
0
200
400
600
Higgs crossing number



Black: Higgs VEV energy
(dotted: ignoring backreaction)
Blue: Thermal energy
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
E / M_p^4
0
200
400
600
Higgs zero crossing number

Results

- First, weak thermal bath develops
- At ~ 100 oscillations, soft W's start to pile up.
- Self-limit around 250 oscillations
- Thermal bath dominates energy after ~ 350 half-oscillations
- Higgs field rapidly dies away after 500 half-oscillations

Very rich set of physics contributes