Low Scale Baryogenesis from Hidden Bubble Collisions

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Outline

- Motivation: How low baryogenesis scale can be?
- Description of the new mechanism of baryogenesis
- Concrete model
- Closer look on moving parts:
  - Hidden valleys with runaway bubbles
  - Production of heavy particles in bubble collisions
  - Non-thermalization, out of equilibrium decays to the SM
- Signatures: neutron oscillations, gravitational waves…
- Outlook

Models of Baryogenesis — Crude Classification

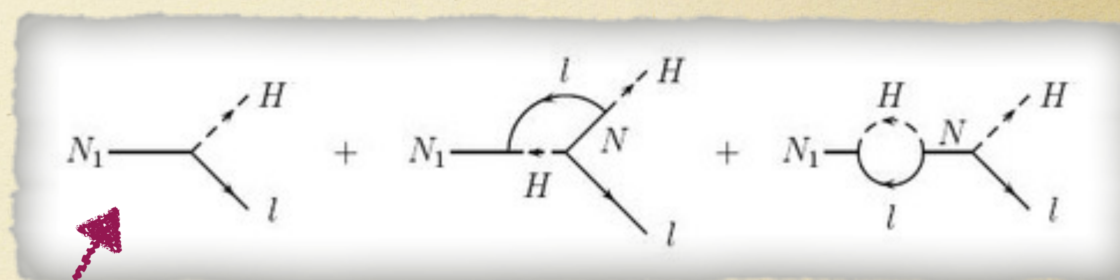
Sakharov conditions:

- BNV
- CPV
- out of equilibrium
  (or CPTV)

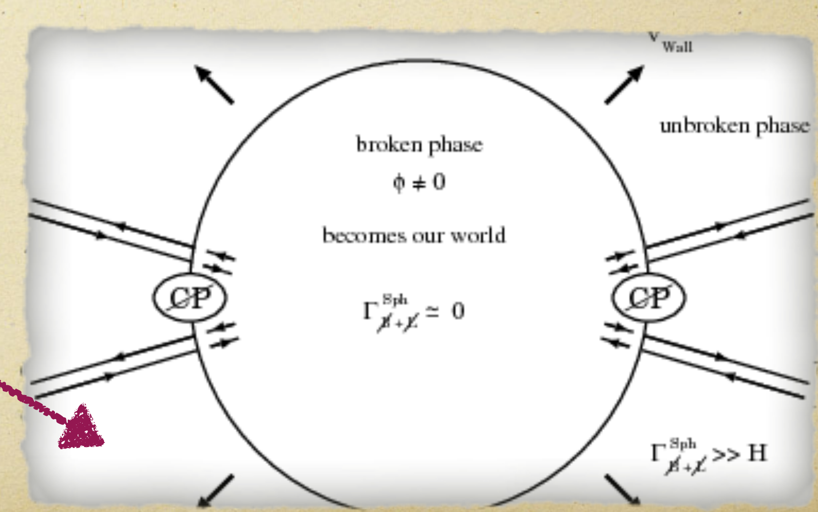
present in EW theory

need new sources

Scenario 1:

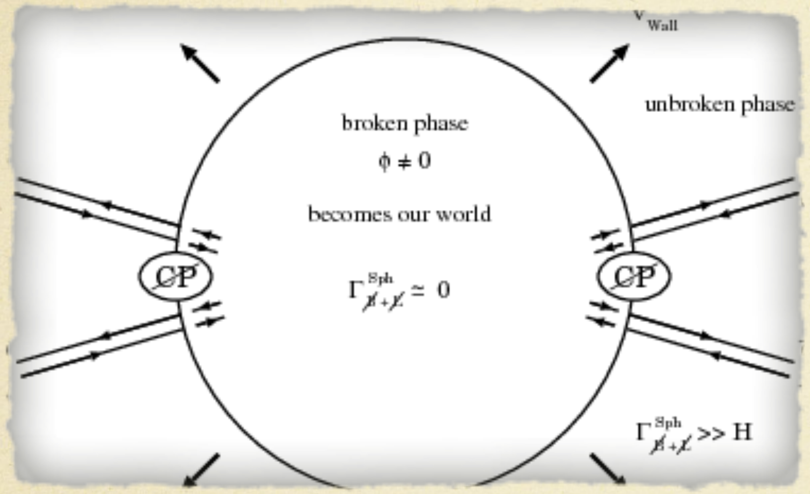


Scenario 2:



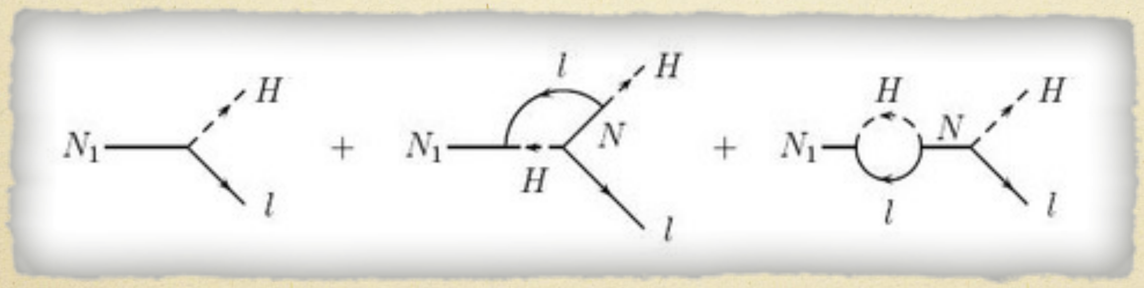
Scale of Baryogenesis

Scenario 2:



Typically EW scale, might be slightly higer if the SM has a complicated UV completion

Scenario 1:



Almost arbitrary. From higgs scale leptogenesis to WIMP scale

But... The particle should freeze out and decay out of equilibrium

Can We Reduce Baryoegenesis Scale?

- Obvious constraint — BBN. There is no easy way to go below 1 MeV and explain primordial element abundances

- Expanding bubbles: lowering the scale below ~100 GeV is probably impossible

- Decays out of equilibrium. In most of the models the decaying particles is assumed to freeze out at some point ➥ T ~ m. Are there any other options?

Why Low Scale?

- Inflation model with inefficient reheating — are they relevant?
- Theories with efficient baryon washout at (relatively) low energy — are they relevant?
- Experimental signatures. Are there new sources of BNV? Where should we expect the new sources of CPV? What is the relevant scale of the electron EDM?

Non-Thermal Production of Decaying Fermions

Processes at high-T: out-of-equilibrium decays (moduli).

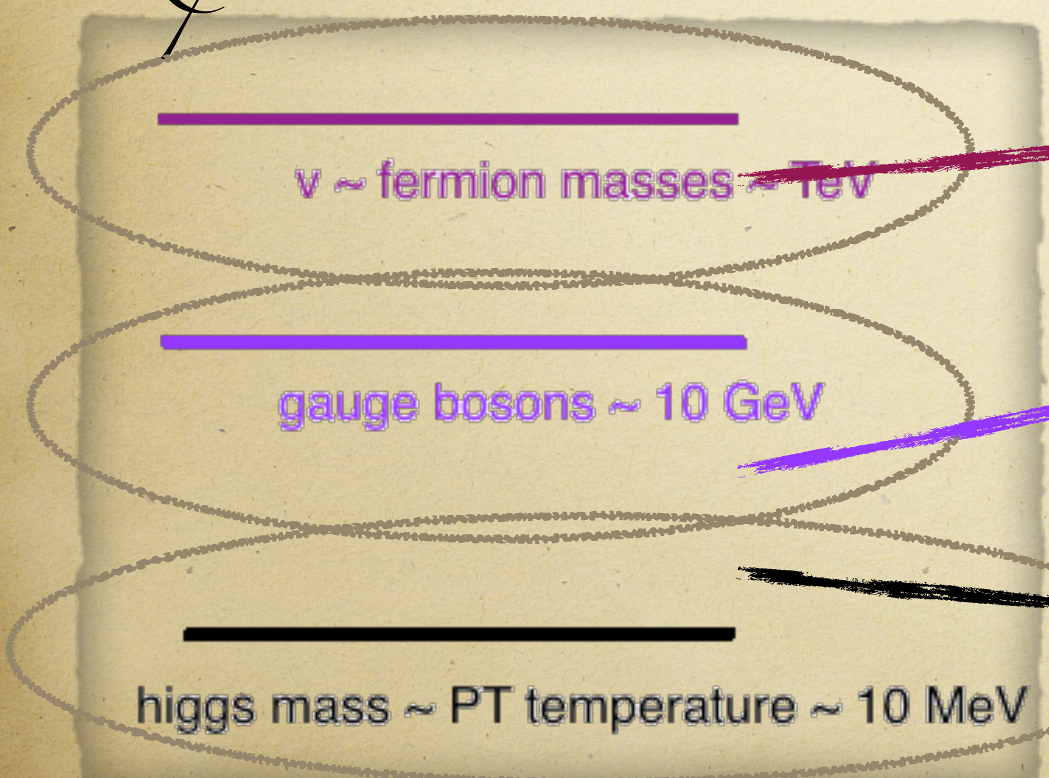
Low-T: only one process knows: bubble collisions in 1st order PT

- Bubbles should be ultra-relativistic (“runaway”)
- Collisions should be fairly elastic
- Fermions mass should be ~ to order parameter in the broken phase (but much heavier than T of the PT)
- Need parametric separation between the T of the PT and order parameter

Existence Proof: a Model

SU(2) gauge group in the hidden sector with a small "higgs" quartic coupling $\lambda << 1$. $m_h << v$ and $T_{crit} \sim m_h$. The thermal potential should be suitable for the 1st order PT ➠ strong interactions with the higgs: $g^2 >> \lambda$ (gauge driven PT)

Representative mass scales:



Energy carried by the expanding bubbles

Responsible for driving the PT (strong) 1st order

PT temperature. Above this scale the system is in ubroken phase

Fermions

Colliding bubbles cannot produce efficiently particles heavier than the order parameter in the unbroken phase: $m_f \sim v$.

Two generations of the SU(2) doublets: L_i . Minimal amount of matter needed to cancel anomalies. Add also two generation of singlet fermions e_i.

$$\mathcal{L} \supset y_{ij} \Phi L_i e_j$$

Not enough. In order to decay into the SM and produce asymmetry, fermions should be Majorana

Majorana Fermions and Decays into the SM

Having Dirac fermions is not enough:

$$\mathcal{L} \supset y_{ij}\Phi L_i e_j + m_L \epsilon_{ij}\epsilon^{ab} L_a^i L_b^j + (m_e)_{ij} e_i e_j \ .$$

after diagonalization — 4 Majorana fermions; assume yv ~ $m_{e,\,L}$.

Possible couplings to the SM:

$$\mathcal{L} \supset \frac{1}{\Lambda^2}\left(\eta''_{ijk}\psi Q_i Q_j D_k^\dagger + \lambda''_{ijk}\psi U_i D_j D_k\right)$$

By taking $\Psi \Rightarrow e$ we get potentially two different CPV phases

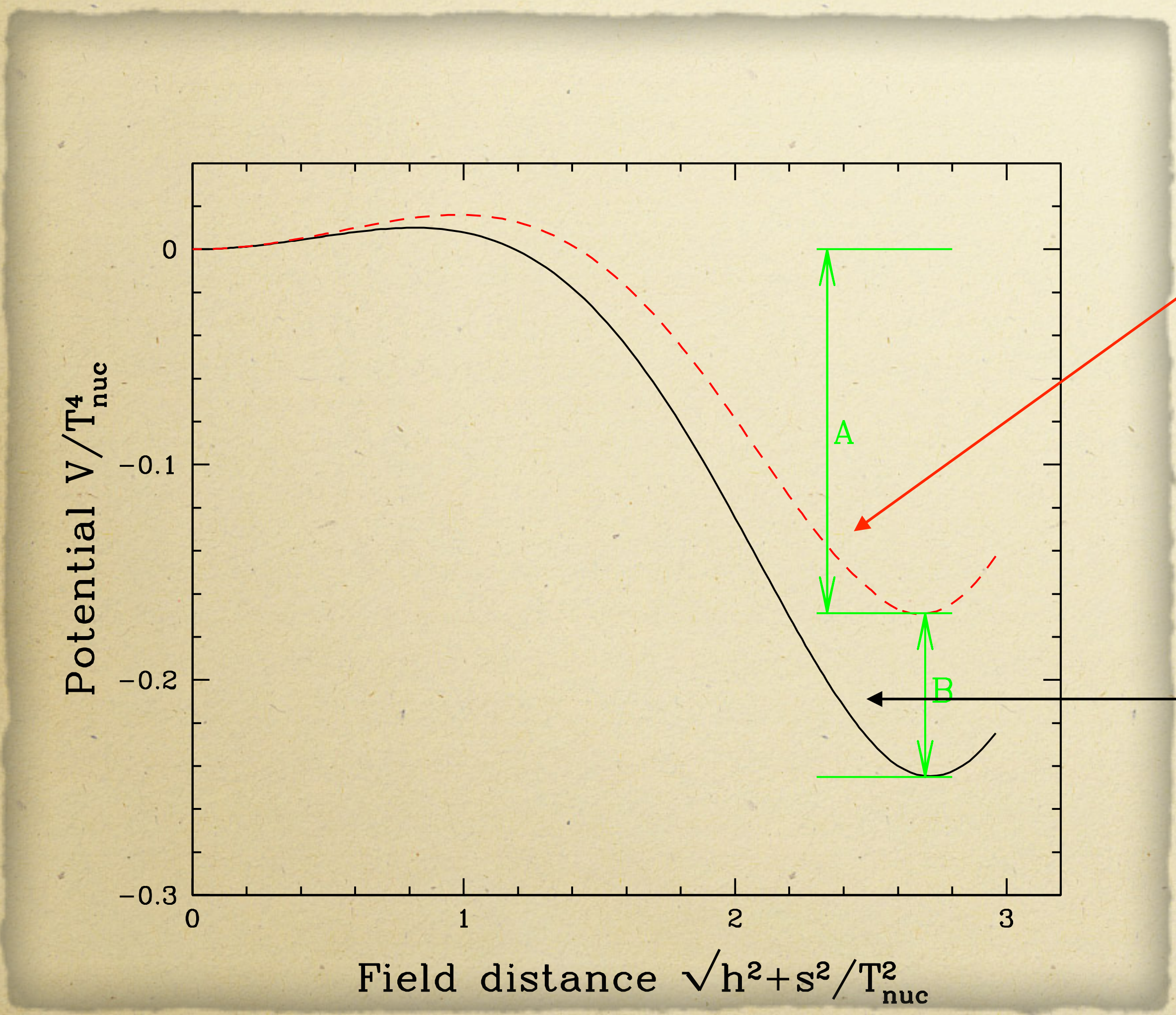
Detailed Questions to Address

- The dark higgs by construction is the lightest dark particle. It should decay fast enough to the SM (without asymmetries)
- The dark W's are dark-stable. Should either decay fast enough or not to be overproduced as the possible DM
- By construction we get neutron-antineutron oscillation operator. The bound on this operator is ~100 TeV.

When Do Bubbles Run Away?

Bodeker, Moore; 2009

Criterion



Mean free field approximation

Full thermal potential

Why Mean Free Field?

Bodeker, Moore; 2009

The difference between the values of the thermal potential at different higgs points:

$$\delta V_T = \sum_a \int \frac{d^3p}{(2\pi)^3} f_B(E_{p,h,a}) \frac{dE_{p,h,a}}{dh} \delta h = \sum_a \int \frac{d^3p}{(2\pi)^3} \frac{f_B(E_{p,h,a})}{2E_{p,h,a}} \frac{dm_a^2}{dh} \delta h \,,$$

particle occupancies

$$E_{p,h,a} = \sqrt{p^2 + m_a^2(h,s)}$$

Limit $m^2(h_1) - m^2(h_2) \ll T^2$ but the masses are not small

$$V_T(h_2) - V_T(h_1) \simeq \sum_a \left(m_a^2(h_2) - m_a^2(h_1) \right) \int \frac{d^3p}{(2\pi)^3} \frac{f_B(E_{p,h_1,a})}{2E_{p,h_1,a}} \,.$$

equivalent to expanding to the second order in h

Why Mean Free Field?

Bodeker, Moore; 2009

Pressure on plasma (per unit area) in limit ɣ >> 1:

$$\frac{F}{A} = \sum_a (m_a^2(h_2) - m_a^2(h_1)) \int \frac{d^3p}{(2\pi)^3 2E_{p,h_1,a}} f_a(p, \mathrm{in}) + \mathcal{O}(1/\gamma^2)\,.$$

Occupancies in the unbroken state — unperturbed plasma.

This expression is identical to the mean free field approximation. Basic assumption: in the ultra-relativistic limit the occupancies of the plasma in the unbroken phase particles approaching the wall get no signal about the approaching wall, and their occupancies are those of the equilibrium state.

Momentum of incoming particle is ɣT, reflections from the walls are exponentially suppressed.

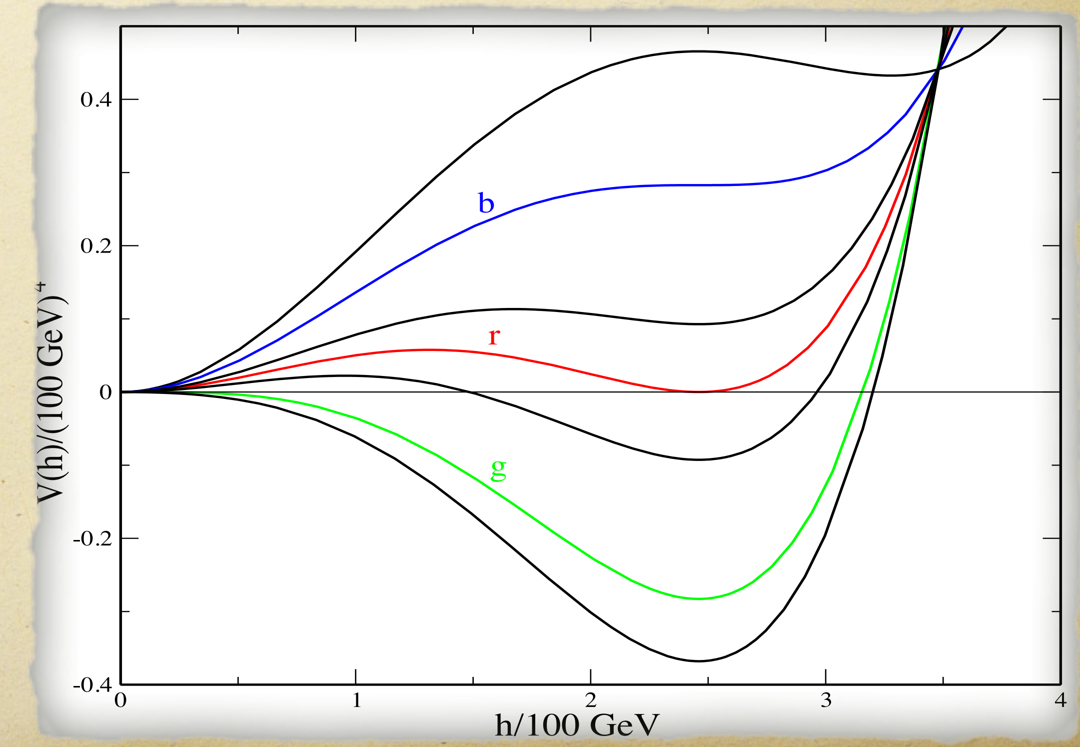
Runaway Bubbles without Singlets

- Strong modification of the zero-T potential (achieved by singlets in BM scenario)
- Significant supercooling (have to calculate)

In original Bodeker-Moore scenario it was a scalar which strongly modified the potential.

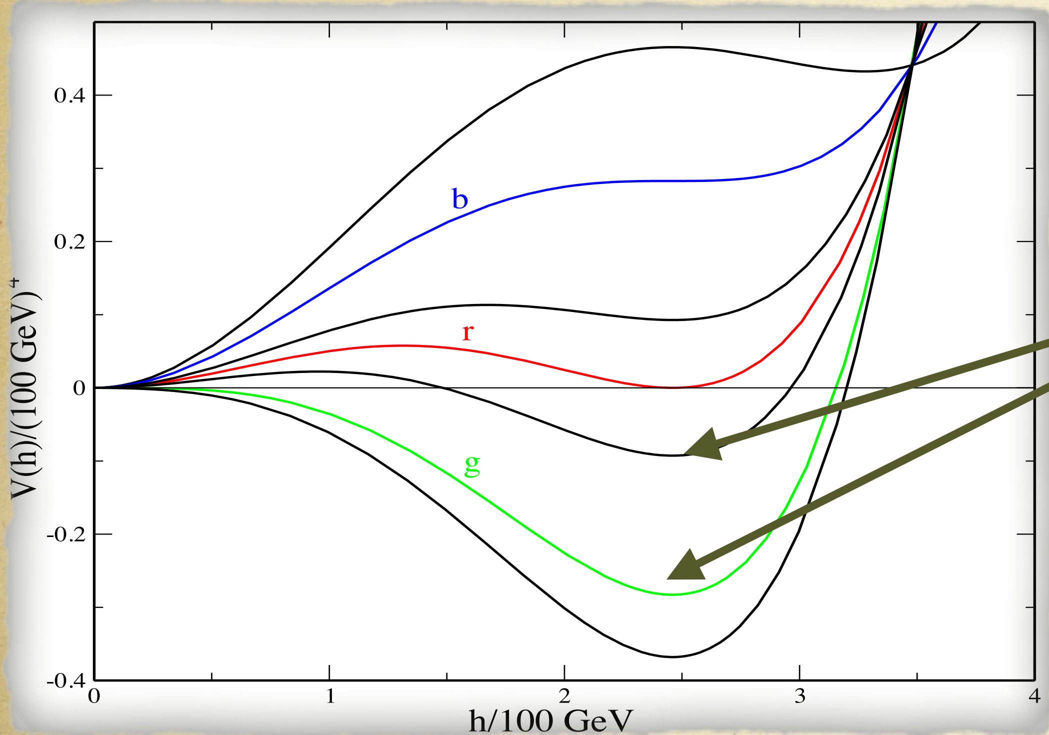
original idea of Espinosa-Quiros; 2007

V(T = 0) due to CW modifiction (with singlets in EQ case)



The effect is also possible if we strongly modify the zero-T potential

Gauge-Driven Runaway Bubbles

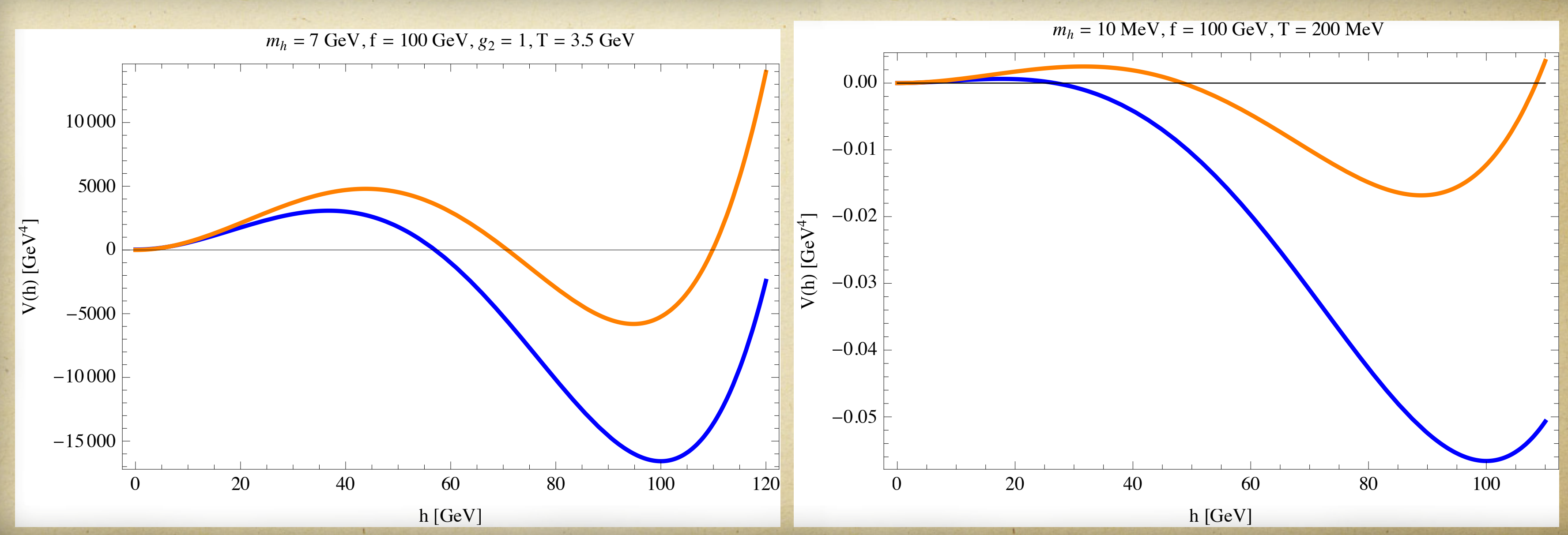


Similar effect can be achieved due to the gauge bosons if

$$\lambda \sim \frac{g^2}{16\pi^2}$$

The potential can be very flat near the origin at T = 0 or the origin can even be a local minimum

Points, which satisfy Bodeker-Moore criterion due to modification via CW potentia



Supercooling

It is not enough to verify that Bodeker-Moore criterion holds. We should also make sure that the PT does not happen at higher-T, namely that we indeed supercool.

Tunnelling probability per unit time per unit volume:

$$P \sim A(T) \cdot \exp(-\frac{S_3}{T}) \ .$$

Linde's approximation:

bubble radius extremizes this expression

$$S_3 \approx -\frac{4\pi}{3} r^3 \Delta V + 4\pi r^2 \int_0^{\phi_0} \sqrt{2V(\phi, T)} d\phi$$

This approximation is valid only for very weak 1st order PT. But it can be shown that true S_3 is bigger than Linde's approximation, and we always overestimate T_{nuc}

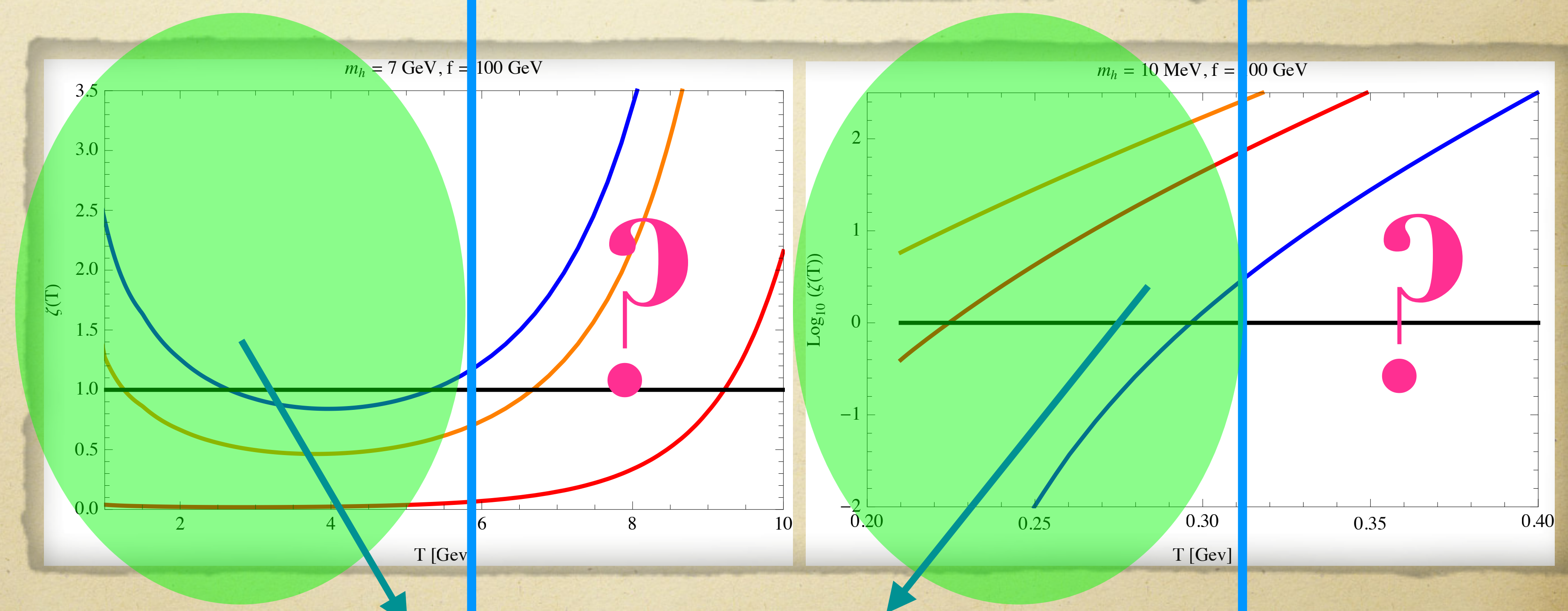
Linde's Bound on Nucleation Temperature

Linde's approximation overestimates the T_{nuc} ⇨ use it as a bound on nucleation temperatures

Nucleation condition:

$$\frac{S_3}{T} \sim 5 \log\left(\frac{M_{pl}}{T_c}\right) .$$

$$\zeta \equiv \frac{S_3/T}{5 \log(M_{pl}/T)} .$$



Suitable for runaway bubbles

Heavy Particles Production from the Runaway Bubbles

Watkins and Widrow; 1992; Konstandin and Servant; 2011; Falkowski and No; 2112

Probability of particle production $\mathcal{P} = 2\,\mathrm{Im}\left(\Gamma\left[h\right]\right)$

effective action

The effective action is calculated using the explicit higgs profile in thermal potential at the nucleation temperature. Collisions are either elastic (the bubble planar wave retreats back after the collision and restores the symmetric phase) or partially inelastic.

Particles Production

Falkowski and No; 2112

Particle produced per unit area:

$$\frac{\mathcal{N}}{A} = \frac{1}{2\,\pi^2}\int_0^\infty d\chi\, f(\chi)\,\mathrm{Im}\left(\tilde{\Gamma}^{(2)}\,(\chi)\right)$$

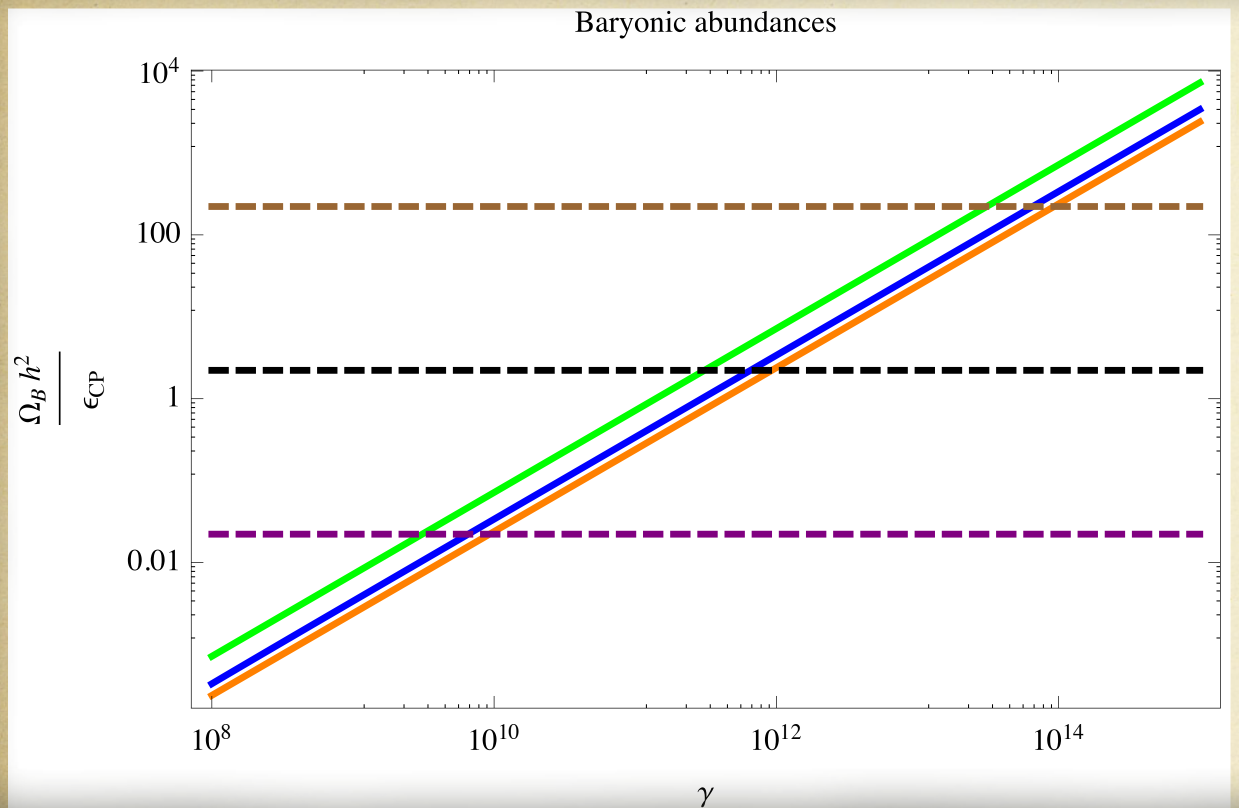
function which carries the information about the efficiency of the collisions

two-point 1PI Green function

$$\mathrm{Im}\left(\tilde{\Gamma}^{(2)}\,(\chi)\right) = \frac{1}{2}\sum_\alpha \int d\Pi_\alpha \left|\overline{\mathcal{M}}(h \to \alpha)\right|^2 \Theta\left[\chi - \chi_{\rm min}\right]$$

In small quartic limit production starts being inefficient for particles with mass ~ v (fully elastic case) and ~m_h (fully inelastic)

How Many Baryons Can We Produce?



- Orange — T=10 GeV, v = 1 TeV, y = 1
- Green — T = 10 GeV, v = 2 TeV, y = 1.5
- Blue — T = 50 MeV, v= 500 GeV, y = 1

What values of γ are reasonable?

Theoretical bound $$\gamma_{max} \sim \frac{\beta^{-1}}{H^{-1}} \frac{v}{M_{pl}} \sim 10^{17} \frac{\text{GeV}}{v}$$

Practically these velocities are hard to reach because of the friction term ~ log(γ)

Open Questions About Particles Production

- Are the collisions elastic or largely inelastic in our case?
- What are realistic values of the bubble velocity (γ) when all friction effects are properly taken into account?
- Any further parameter space beyond what is allowed by Bodeker-Moore criterion?

Remarks on Experimental Signatures

- Gravitation wave (1st order PT)
- Neutron oscillations

$$\frac{\psi UDD}{\Lambda^2} \Longrightarrow \frac{UDDU^\dagger D^\dagger D^\dagger}{m_\psi \Lambda^4}$$

Right now the bound ~ 100 TeV — not very high and much weaker than the bound on Λ (decay within 1 sec)

Remarks on Model-Dependent Experimental Signatures

$$\mathcal{L} \supset \frac{1}{\Lambda^2}\left(\eta''_{ijk}\psi Q_i Q_j D_k^\dagger + \lambda''_{ijk}\psi U_i D_j D_k\right)$$

Interactions suggest colored bosonic mediator. Small Λ ➡ small couplings to the SM. Possibly shows up as an R-hadron at the LHC. Cannot be much heavier than the Ψ (to have efficient baryon production)

The dark higgs should decay. The most natural candidate:

$$\mathcal{L} = \lambda|H|^2|\Phi|^2$$

exotic higgs decays. But model dependent…

Conclusions

- There is a simple mechanism to produce the baryonic asymmetry at temperatures as low as BBN
- The mechanism heavily relies on the strong 1st order PT in the hidden sector with runaway bubbles
- Generic signals of this kind of mechanism: primordial gravitational wave from 1st order PT and neutron-antineutron oscillations
- The parameter space of these kind of models and how fine-tuned they are is yet to be explored
- Still unclear if this kind of phenomenon is possible in confinement PT
- Less generic signatures will have to do with the dark particle decays (dark higgs decays ⇔ exotic visible higgs decays), new colored (long lived) particles with masses close to the hidden fermions