Cosmological signatures of late time symmetry breaking

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Introduction and Motivation

- The universe likely experienced multiple transitions—GUT, electroweak, and QCD.
- After the 2012 Higgs discovery, it became evident that our universe may reside in a metastable false vacuum, implying possible Higgs-potential instability.
- Though such a vacuum can persist for billions of years, small primordial black holes may catalyze decay, nucleating true-vacuum bubbles that expand nearly at light speed but slightly slow due to friction.
- Such bubbles would produce heavy particles through vacuum mismatch at the wall, yielding observable photon and neutrino signatures that may precede the wall's arrival.
- We study here the astrophysical observational signature of the late time Electroweak and $SU(3)_c$ symmetry breaking in true vacuum bubble.
- Just like the Higgs field was necessary to break the electroweak symmetry, a new colored scalar field is necessary to break the $SU(3)_c$ symmetry respectively.

Particle Production due to vacuum mismatch

- Particle creation during first-order phase transitions can occur through several mechanisms. Here we adopt the **vacuum mismatch method**.[hep-th/9902127]
- To study vacuum–induced particle creation, we decompose the scalar field into background and fluctuations:

$$\phi = \phi_c + \chi, \qquad \partial_\tau^2 \chi + \nabla^2 \chi - V''(\phi_c)\chi = 0.$$

  Across the bubble wall, $V''(\phi_c)$ changes abruptly—from M^2 in the false vacuum to μ^2 in the true vacuum—causing a sudden shift in the fluctuation mass.
- The transition occurs at $\tau = \tilde{\tau} = -R_0$, where R_0 is the bubble radius and $a = 1/R_0$ the proper acceleration, setting the natural timescale for particle creation (analogous to Unruh radiation). [hep-th/0311263]
- Matching the fluctuation modes and their derivatives at $\tau = \tilde{\tau}$ yields Bogoliubov coefficients, from which the particle occupation number follows:

$$N_k = \left[\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{4\omega_+ R_0} - 1 \right]^{-1}, \qquad \omega_\pm = \sqrt{k^2 + (\mu, M)^2}.$$

Relativistic bubble-wall dynamics in a viscous medium

- The forces acting per unit area combine vacuum pressure, curvature, and friction:

$$F_{\text{net}} = \underbrace{\Delta V}_{\text{vacuum drive}} - \underbrace{\tfrac{2\sigma}{R}}_{\text{Laplace curvature}} - \underbrace{\eta\,\gamma v}_{\text{friction}} .$$

  The first term accelerates expansion; the latter two oppose it. [hep-ph/0001274]

- Equating inertia with total force gives the **relativistic thin-wall equation of motion**:

$$\boxed{\sigma\,\gamma^3 \frac{dv}{dt} = \Delta V - \frac{2\sigma}{R} - \eta\,\gamma v.}$$

  The γ^3 factor shows how inertia grows as $v \to c$.

- At large R, curvature becomes negligible. Force balance then fixes the **terminal velocity**:

$$\Delta V = \eta\,\gamma v \Rightarrow \gamma_{\rm term} \simeq \frac{\Delta V}{\eta}, \qquad v_{\rm term} \simeq 1 - \frac{1}{2\gamma_{\rm term}^2}.$$

  This establishes that realistic walls move *almost* but never exactly at the speed of light.

Proper-time formulation

- To connect with particle production, we express motion in the wall's **proper time** τ and rapidity y:

$$v = \tanh y, \quad \gamma = \cosh y, \quad \gamma v = \sinh y, \qquad \frac{dt}{d\tau} = \gamma, \ \frac{dR}{d\tau} = \sinh y.$$

- Expressing the dynamics in proper time τ with normalized drive and drag parameters $A = \Delta V/\sigma$ and $B = \eta/\sigma$, the wall's evolution follows

$$\boxed{\frac{dy}{d\tau} = A - \frac{2}{R(\tau)} - B \sinh y(\tau)} \quad \equiv \quad \alpha(\tau),$$

where $\alpha(\tau)$ is the wall's proper acceleration that governs the rate of particle production during vacuum decay.

- The bubble reaches its terminal state on the characteristic timescale

$$\tau_{\mathrm{term}} = \frac{1}{B} = \frac{\sigma}{\eta}.$$

Instantaneous Particle production and integrated yield

- The vacuum mismatch near the wall produces particles via a mechanism analogous to the Unruh effect, controlled by $\alpha(\tau)$.
- For zero momentum ($k = 0$), the **instantaneous occupation number** is

$$N_{k=0}(\tau) = \left[\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{\frac{4\omega_+}{\alpha(\tau)}} - 1 \right]^{-1}, \qquad \omega_+ = \mu,\ \omega_- = M.$$

  Larger $\alpha(\tau)$ sharply enhances production; as $\alpha \to 0$, it shuts off.
- The **total number of particles** produced up to τ accumulates the instantaneous rate over the wall's expanding area:

$$\frac{dN_{\rm tot}}{d\tau} = N_{k=0}(\tau)\, 4\pi R(\tau)^2 \sinh y(\tau), \qquad N_{\rm tot}(0) = 0.$$

- The yield is governed by a competition between the exponential sensitivity to $\alpha(\tau)$ and the geometric amplification from $4\pi R^2$.

$SU(3)_C$ Symmetry Breaking: Phase Transition & Lagrangian

Adjoint-scalar Lagrangian [PhysRevD.19.1906]:

$$\mathcal{L} = -\tfrac{1}{2}\,\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}\,\mathrm{Tr}(D_\mu\Phi D^\mu\Phi) - V(\Phi).$$

Potential:

$$V(\Phi) = \frac{\mu^2}{4}\mathrm{Tr}\Phi^2 + \frac{\lambda_1}{16}(\mathrm{Tr}\Phi^2)^2 + \frac{\lambda_2}{6}\mathrm{Tr}\Phi^3 + V_0.$$

Diagonalizing Φ with $\psi_1 + \psi_2 + \psi_3 = 0$ gives $\psi_1 = \psi_2 = -\tfrac{1}{2}\psi_3 \equiv \psi$, so

$$V(\psi) = \tfrac{3}{2}\mu^2\psi^2 + \tfrac{9}{4}\lambda_1\psi^4 - \lambda_2\psi^3 + V_0.$$

Defining

$$\psi_0 = \frac{2\lambda_2}{9\lambda_1}, \qquad \epsilon_0 = \lambda_1 - \frac{2\mu^2}{3\psi_0^2},$$

the potential reduces to the compact double-well form [hep-ph/0703246]

$$\boxed{V(\psi) = \tfrac{9}{4}\lambda_1\,\psi^2(\psi-\psi_0)^2 - \tfrac{9}{4}\,\epsilon_0\,\psi_0^2\psi^2 + V_0}$$

with vacuum splitting

$$\delta V = \tfrac{9}{4}\,\epsilon_0\,\psi_0^4.$$

A small $\epsilon_0 > 0$ yields a metastable false vacuum; V_0 sets the false-vacuum energy at $(10^{-3}\,\mathrm{eV})^4$.

Characteristic Potential & Vacuum Tunneling

The potential exhibits a standard first–order structure:

- **False vacuum** at $\psi = 0$ (unbroken $SU(3)_c$) and **true vacuum** at $\psi \simeq \psi_0$.
- Vacuum splitting

$$\delta V = \tfrac{9}{4}\,\epsilon_0\,\psi_0^4$$

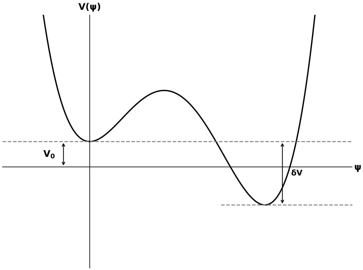
  drives the transition; $\epsilon_0 \lesssim 0.1$ ensures metastability.
- Vacuum longevity requires

$$\Gamma t_{\rm H}^4 \lesssim 1, \qquad t_{\rm H} \sim 10^{10}\ \text{yr},$$

  or equivalently

$$S_E \gtrsim 400,$$

  giving a lifetime longer than the age of the Universe.



Adjoint $SU(3)$ Breaking: Vacuum Structure Summary

- We take the adjoint Higgs in a diagonal vacuum configuration

$$\langle \Phi \rangle \equiv v = \mathrm{diag}(a, b, c), \qquad a + b + c = 0,$$

so that the potential on this VEV subspace is

$$V(a, b, c) = \frac{\mu^2}{4}(a^2 + b^2 + c^2) + \frac{\lambda_1}{16}(a^2 + b^2 + c^2)^2 + \frac{\lambda_2}{2}\, abc.$$

Potential choice	Vacuum alignment	Unbroken H	Massive/Massless gluons	Massive/Massless scalars
$\lambda_2 \neq 0$ (cubic present)	$a = b \neq c$	$U(2)$	4 massive, 4 massless	4 massive, 4 eaten
$\lambda_2 = 0$, $\mu^2 > 0$	$a = b = 0$ (trivial)	$SU(3)$	0 massive, 8 massless	8 massive, 0 eaten
$\lambda_2 = 0$, $\mu^2 < 0$	$a \neq b \neq c$ (generic)	$U(1) \times U(1)$	6 massive, 2 massless	2 massive, 6 eaten

Overview of TeV-Scale Color States

- The color gauge group $SU(3)_c$ is broken to $U(2)$ by an adjoint scalar Φ acquiring a VEV $\langle \Phi \rangle = \psi_0 = \mathcal{O}(\text{TeV})$. This splits the gluon spectrum into **four massive** and **four massless** states.
- The **massive gluons** obtain $M_G \sim g_s\, \psi_0$ and, much like the electroweak $W^{\pm}$, they do not form glueballs. Instead, they can form multi-TeV bound states through the residual unbroken interaction, with characteristic size $\Lambda_{\rm QCD}^{-1}$.
- The **massless gluons** belong to the unbroken $U(2)$ subgroup and confine into ordinary QCD glueballs with hadronic-scale masses.
- Inside the **true vacuum** bubble, colored excitations propagate freely without hadronizing; in the **false vacuum**, they hadronize into $SU(3)_c$ singlets before decaying. This difference governs the observable photon and neutrino signals.

Particle Creation: Scalar Spectrum

Scalar masses:

$$M^2 = \tfrac{9}{2}\psi_0^2(\lambda_1 - \epsilon_0) \;\Rightarrow\; M = 2.000 \text{ TeV},$$

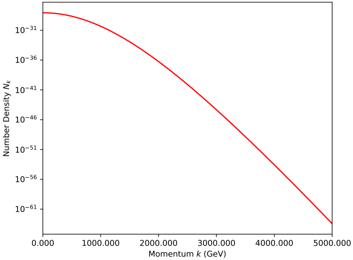
$$\mu^2 = \tfrac{9}{2}\psi_0^2\left(\lambda_1 + 5\epsilon_0 + 6\frac{\epsilon_0^2}{\lambda_1}\right) \;\Rightarrow\; \mu = 2.550 \text{ TeV}.$$

Occupation number:

$$N_k = \frac{1}{\frac{(\omega_+ + \omega_-)^2}{(\omega_+ - \omega_-)^2} e^{4\omega_+ R_0} - 1},$$

$$\omega_- = \sqrt{k^2 + M^2}, \qquad \omega_+ = \sqrt{k^2 + \mu^2},$$

with $R_0 \approx 6.3 \text{ TeV}^{-1}$.



Particle Creation: Massive Gluon Spectrum

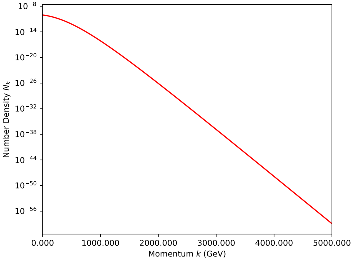
Gluon masses: massless outside ($M = 0$), massive inside ($\mu = 1$ TeV).

Number density per mode:

$$n_{\mathrm{gluon}}(k) = 8 \times 2\, N_k = 16\, N_k\,,$$

accounting for 8 colors and 2 transverse polarizations.

- Production suppressed for $k < \mu$ since gluons are massless outside.
- Exponential fall–off for $k \gg \mu$ due to $e^{-4\omega + R_0}$.



Phenomenology of a Color-Octet Scalar G_H

$$M_{G_H} = 2.5\ \mathrm{TeV}, \quad u = \langle \Phi \rangle = 1\ \mathrm{TeV}.$$

Tree-level decay to quarks: [arXiv:1306.2248]

$$\Gamma(G_H \to q\bar{q}) = \frac{C_F M_{G_H}}{8\pi} \left(\frac{m_q}{v}\right)^2 \left(1 - \frac{4m_q^2}{M_{G_H}^2}\right)^{3/2}.$$

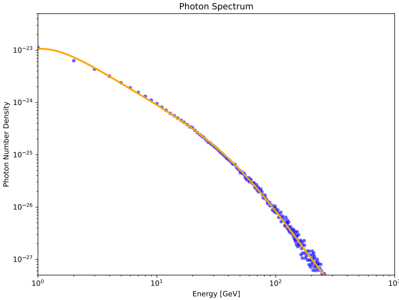
Loop-induced gluon decay:[arXiv:1306.2248]

$$\Gamma(G_H \to gg) = \frac{5\alpha_s^2}{1536\pi^3} \frac{\mu^2}{M_{G_H}} \left(\frac{\pi^2}{9} - 1\right)^2.$$

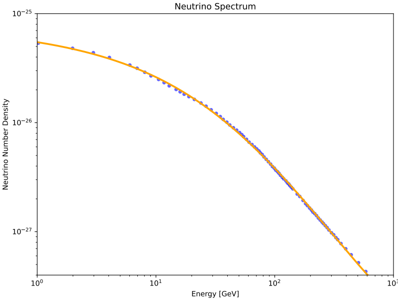
Channel	Γ [GeV]	BR [%]
$u\bar{u}$	1.06×10^{-8}	< 0.01
$d\bar{d}$	4.84×10^{-8}	< 0.01
$s\bar{s}$	2.02×10^{-5}	< 0.01
$c\bar{c}$	3.53×10^{-3}	0.006
$b\bar{b}$	3.83×10^{-2}	0.060
$t\bar{t}$	6.37×10^{1}	99.934
gg	3.18×10^{-6}	< 0.01
Total	6.38×10^{1}	100

Table: Partial widths and branching ratios of the color–octet scalar G_H at 2.5 TeV.

Color-Octet Photon & Neutrino Spectra



Photon Spectrum



Neutrino Spectrum

- $N_k \simeq 3.7 \times 10^{-24}$ color-octets per GeV^{-3}.
- Photons from neutral meson decays; neutrinos from semileptonic modes.

Phenomenology of a Massive Gluon

$$M_G = g_s\,\psi_0 \approx 1\ \mathrm{TeV}.$$

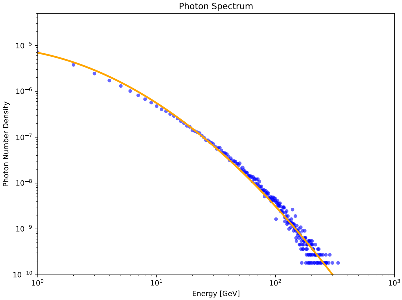
Tree-level partial width:

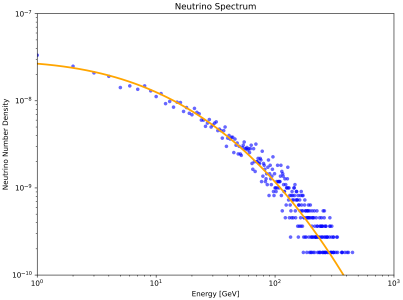
$$\Gamma(G \to q\bar{q}) = \frac{\alpha_s}{2}\,M_G\left(1 + 2\frac{m_q^2}{M_G^2}\right)\sqrt{1 - \frac{4m_q^2}{M_G^2}}.$$

Quark	Γ [GeV]	BR [%]
$u\bar{u}$	59.20	16.68
$d\bar{d}$	59.20	16.68
$s\bar{s}$	59.20	16.68
$c\bar{c}$	59.20	16.68
$b\bar{b}$	59.20	16.68
$t\bar{t}$	58.87	16.59
Total	354.87	100

Table: Massive gluon partial widths & BRs (1 TeV).

Massive Gluon Photon & Neutrino Spectra





Photon Spectrum **Neutrino Spectrum**

- $n_k \simeq 7.4 \times 10^{-8}$ gluons per GeV^{-3}.
- High-energy photons & neutrinos as key observational signals.

Integrated Particle Yields & Vacuum Energy

- Terminal deficit $\delta \equiv 1 - v_{\rm term}$: smaller $\delta \Rightarrow$ faster walls, longer ultra-relativistic phase, larger yields.

δ	η [TeV^4]	$\tau_{\rm term}$ [TeV^{-1}]	$R_{\rm fin}$ [TeV^{-1}]	Scalar $N_{\rm tot}^{\rm (int)}$	Gluons $N_{\rm tot}^{\rm (int)}$
10^{-12}	2.260×10^{-7}	1.487×10^{6}	1.051×10^{12}	6.101×10^{6}	4.881×10^{7}
10^{-11}	7.148×10^{-7}	4.702×10^{5}	1.051×10^{11}	1.928×10^{5}	1.542×10^{6}
10^{-10}	2.261×10^{-6}	1.487×10^{5}	1.051×10^{10}	6.087×10^{3}	4.869×10^{4}

δ	$R_{\rm fin}$ [TeV^{-1}]	$E_{\rm vac}$ [TeV]
10^{-12}	1.051×10^{12}	6.7×10^{35}
10^{-11}	1.051×10^{11}	6.7×10^{32}
10^{-10}	1.051×10^{10}	6.7×10^{29}

Photon & Neutrino Spectra vs. Energy

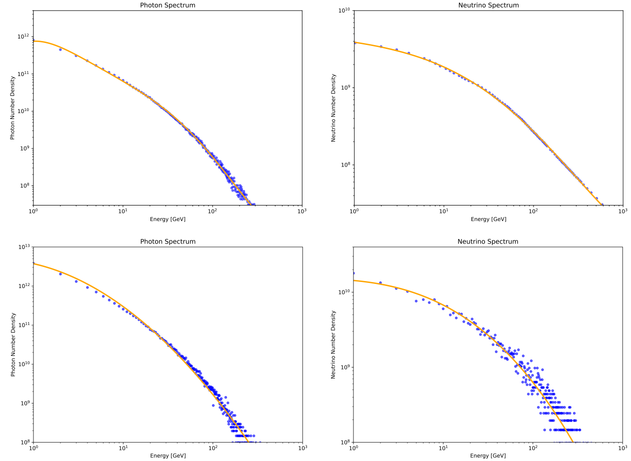


Figure: Photon and neutrino spectra from decays of a 2.5 TeV color octet and a 1 TeV massive gluon. Curves shown for $\delta = 10^{-12}$.

Arrival delay: photons / neutrinos vs. bubble wall

- Because friction limits $v_{\text{wall}} < c$, photons and neutrinos emitted during expansion can arrive *before* the wall itself.
- At low redshift, we can write the flat-space expression

$$\Delta t \simeq \delta \frac{D}{c},$$

where D is the proper distance to the source.
- Even a tiny velocity deficit produces substantial advance times:

Velocity Deficit δ	Distance (ly)	Time Delay
1.0×10^{-10}	1.0×10^{9}	35 d, 7 h, 23 m, 55.25 s
1.0×10^{-11}	1.0×10^{9}	3 d, 12 h, 44 m, 23.52 s
1.0×10^{-12}	1.0×10^{9}	0 d, 8 h, 28 m, 26.35 s

- Therefore, γ-ray and neutrino bursts could precede the wall by days to years, potentially offering an observable early-warning signature of vacuum decay.

Conclusions and Outlook

- As the bubble expands, the vacuum shifts from false to true, generating particles continuously. The spectra shown are *local* and must be redshifted to compare with observations.
- The wall, a coherent state of different quanta, interacts with surrounding plasma, interstellar matter, and even its own decay products, further reducing its speed.
- A late-time first-order phase transition may leave multi-messenger imprints—gravitational waves, and gamma-ray or neutrino bursts—detectable by next-generation observatories.
- Beyond vacuum–mismatch production, we are now quantifying the number of particles produced *thermally* due to frictional dissipation.
- The key question is whether this thermal yield exceeds the vacuum–mismatch yield in realistic parameter space.
- A natural next step is to extend this framework to the fermion sector, determining how quarks reorganize under the broken SU(3) symmetry and what novel bound states or phenomenological signatures emerge.

Question???