Supersonic Electroweak Baryogenesis:

Achieving Baryogenesis from Fast Bubble Walls.

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PONT *Avignon.*

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Electroweak Phase Transition

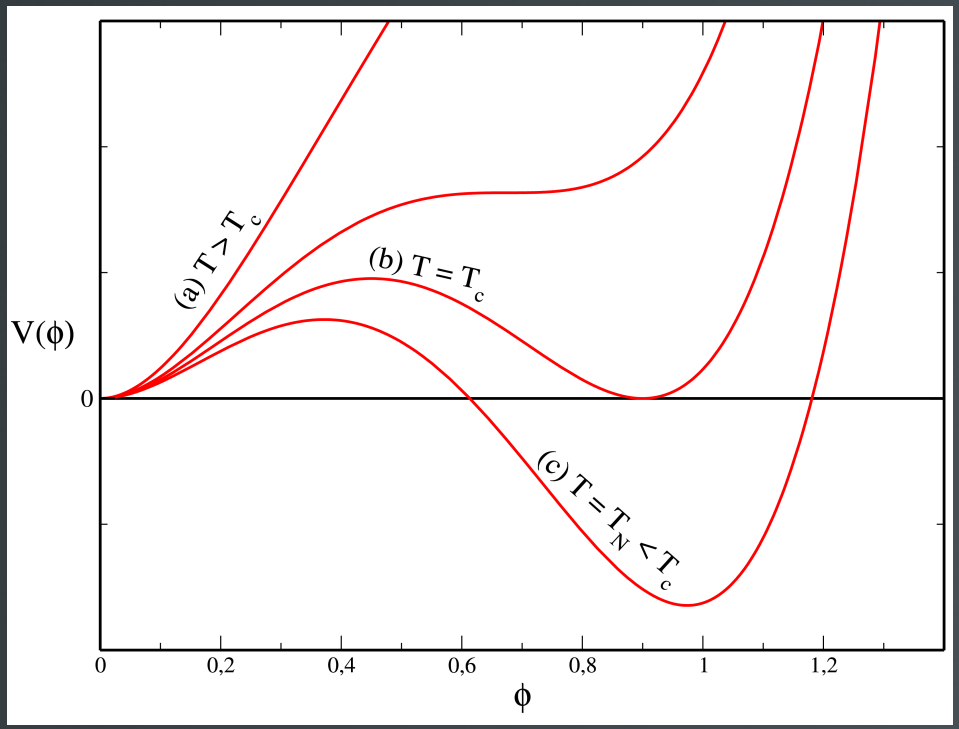
→ *EW Symmetry Broken at T = 0*

→ *EW Symmetry Restored at High T*

→ EW Phase Transition

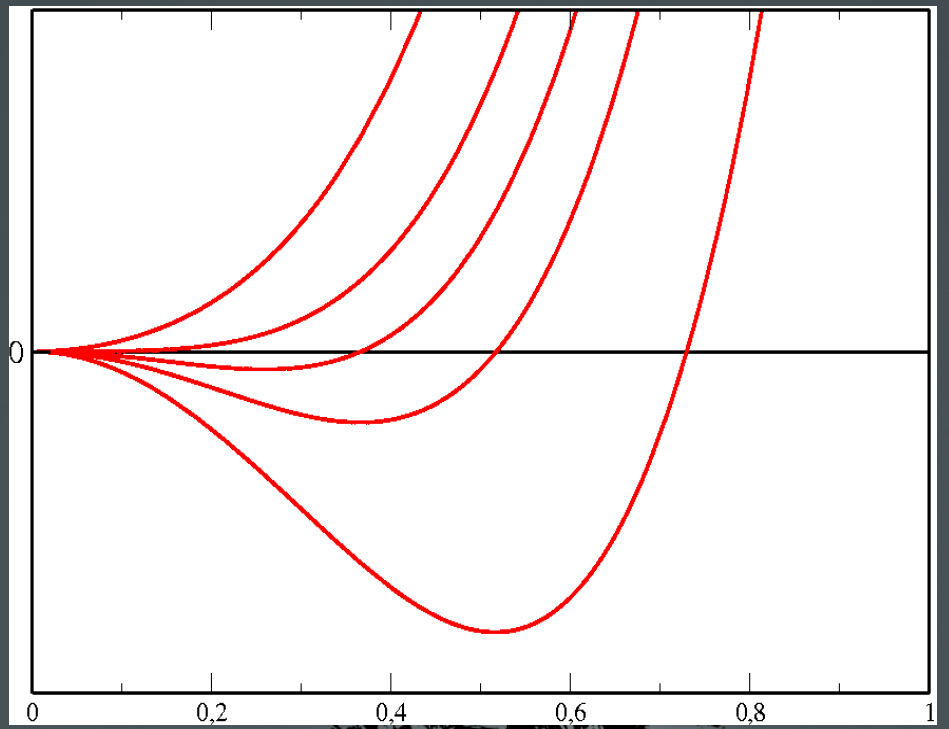
1st Order

$\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T)$ Discontinuous



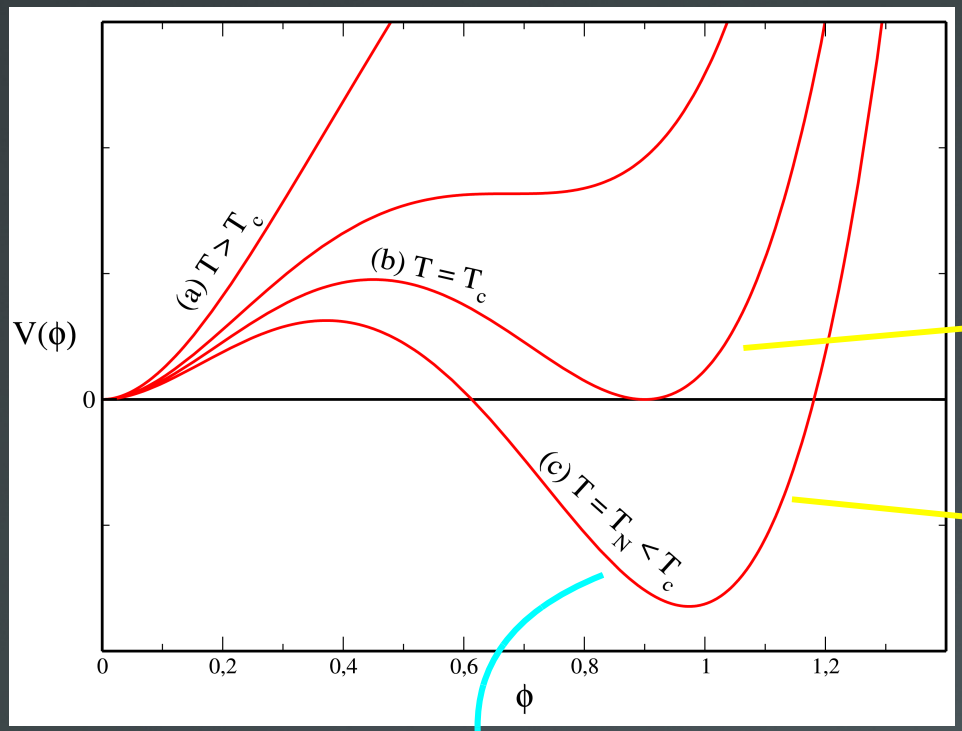
2nd Order

$\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T)$ Continuous



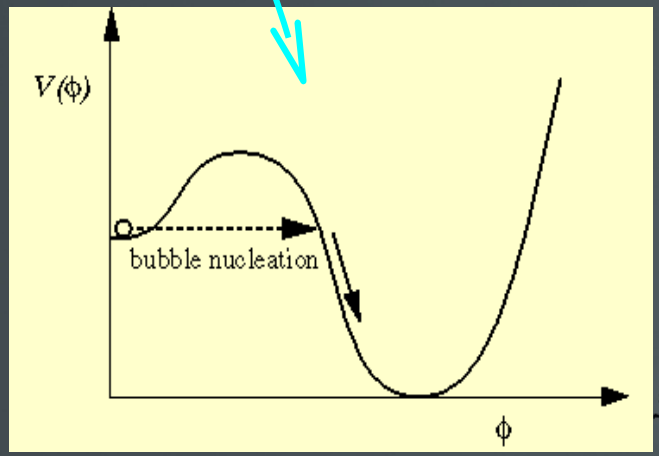
Electroweak Phase Transition

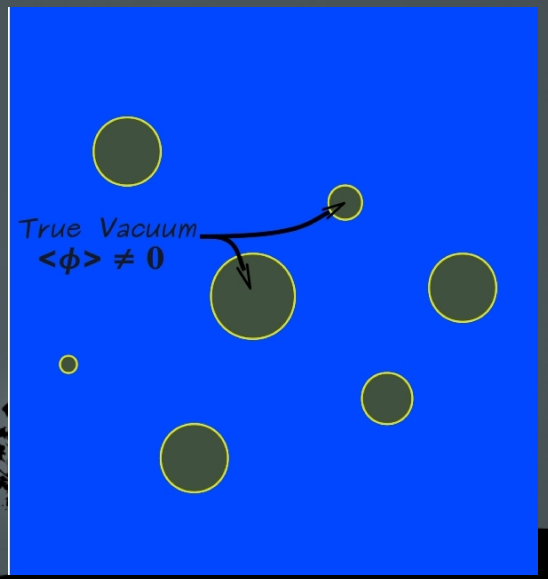
If 1st Order...



T_C

T_N





Nucleation of True Vacuum Bubbles in False Vacuum Sea

J. S. Langer, Ann. Phys. **54** (1969) 258

S. R. Coleman, Phys. Rev. D **15** (1977) 2929

A. D. Linde, Nucl. Phys. B **216** (1983) 421

Electroweak Baryogenesis

❶ 3 Sakharov conditions for Baryogenesis:

V. A. Kuzmin, V, A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B **155** (1985) 36

→ Baryon Number Violation ⇨ *Sphalerons*

$$\Gamma^{S}_{Sph} \sim \alpha_W^5 T^4$$

$$\Gamma^{b}_{Sph} \sim \mathrm{Exp}(-4\langle\phi\rangle/\alpha_W T)$$

→ C, CP Violation

→ Departure from Equilibrium ⇨ *1st Order Phase Transition*

↓

Suppresion of Sphaleron Rate in Broken Phase: $\langle\phi\rangle/T \geqslant 1$

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→ Baryon Number Violation ⇨ *Sphalerons* → $\Gamma^{S}_{Sph} \sim \alpha^{5}_{W} T^{4}$; $\Gamma^{b}_{Sph} \sim \mathrm{Exp}(-4\langle\phi\rangle/\alpha_{W} T)$

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→ Departure from Equilibrium ⇨ *1st Order Phase Transition*

↓

Suppresion of Sphaleron Rate in Broken Phase: $\langle\phi\rangle/T \geqslant 1$

❷ Viable Baryogenesis:

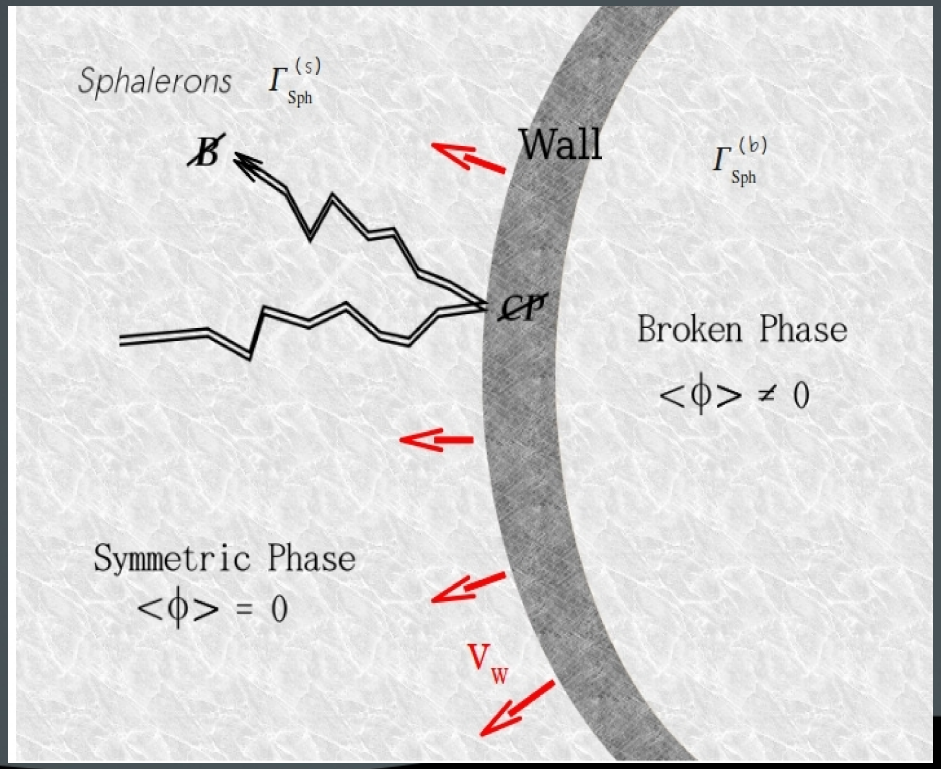
n_B *Generated by* $\not{C}\not{P}$ *Diffusion Ahead of Bubble Wall*

A. Cohen, D, Kaplan and A. Nelson, Nucl. Phys. B **373** (1992) 453

M. Joyce, T, Prokopec and N. Turok, Phys. Lett. B **338** (1994) 269

Effective Diffusion → $V_{\alpha t} < D/L_W \sim 0.1\text{-}0.3 < c_s$

($c_s = 0.577..$ ⇨ *Speed of Sound in Plasma*)

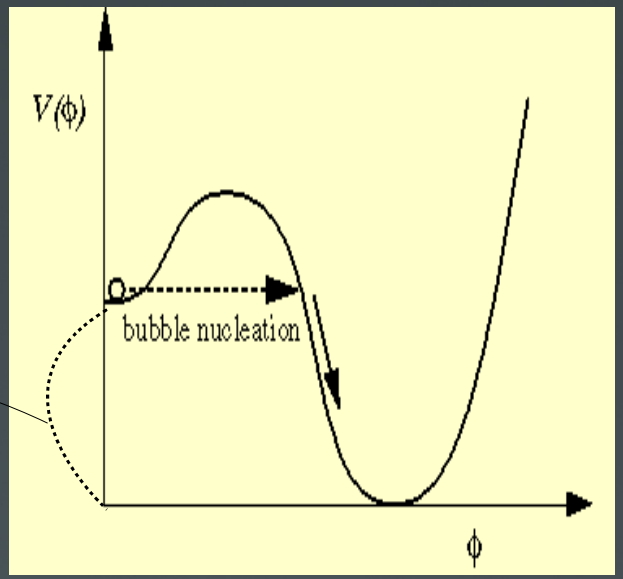


Motivation: Why Faster Walls?

❶ Need $\langle\phi\rangle/T \geqslant 1$

→ Bigger $\langle\phi\rangle/T$ for Stronger Phase Transition (Bigger α_N)

$$\alpha_N = \frac{\varepsilon}{a T_N^4}$$



→ Bigger α_N means Bigger v_w

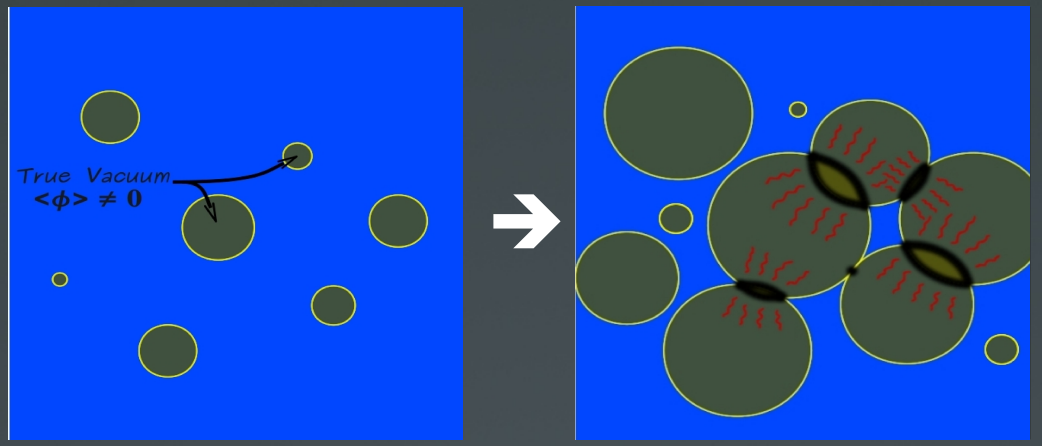
$$v_w \sim \frac{\alpha_N}{\eta}$$

Friction on the wall

Possible Tension Between $\langle\phi\rangle/T > 1$ and $v_w < 0.1 - 0.3$

Motivation: Why Faster Walls?

❷ Gravitational Wave Production



→ Bubble Collisions: $\Omega_{GW} \sim \kappa(\alpha_N, V_w)^2 \frac{\alpha_N^2}{(1+\alpha_N^2)} V_w^3$

Sizable GW Signal Needs Large V_w

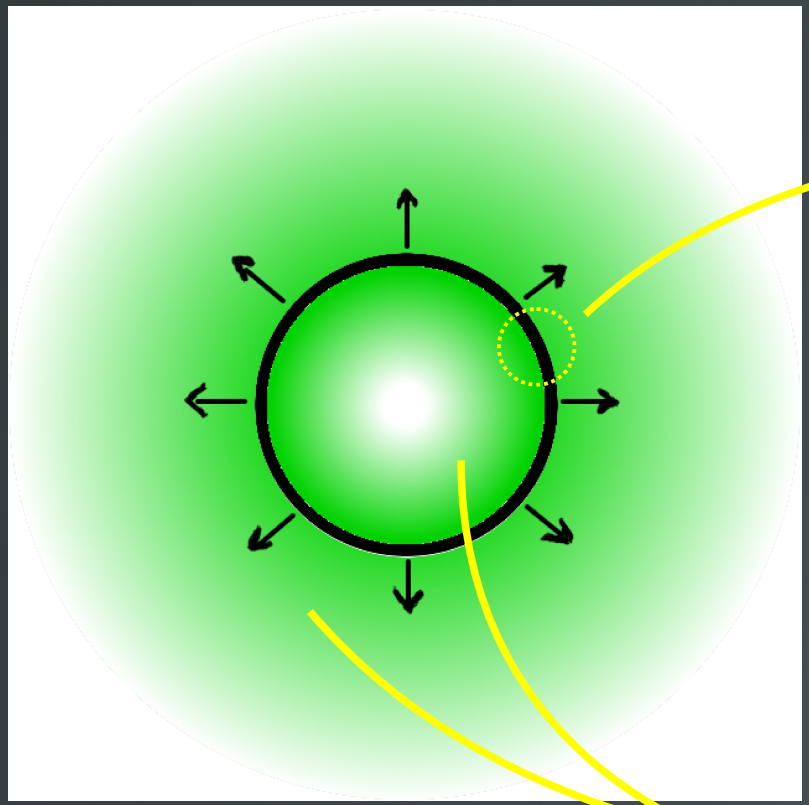
If GW Signal at Detection Experiment (LISA, BBO)...

⬇

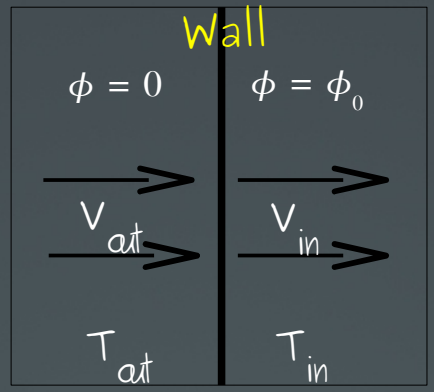
Electroweak Baryogenesis Ruled Out?

Bubble Growth & Plasma Behaviour

Bubble Growth Will Perturb Plasma ➔ *Bubble Expansion Modes*



Wall + Plasma Close to Wall



$$\partial_\mu \left(T^{\mu\nu}_{\phi} + T^{\mu\nu}_{\text{Plasma}} \right) = 0$$

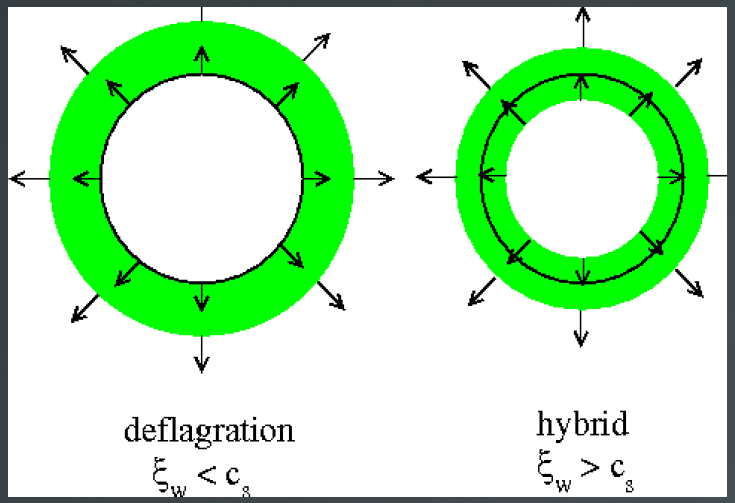
Plasma Away from Wall

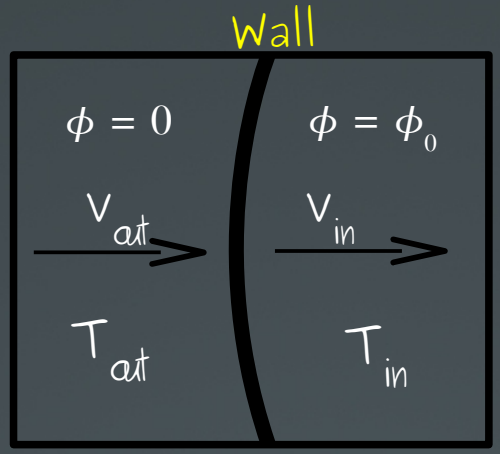
$$\partial_\mu T^{\mu\nu}_{\text{Plasma}} = 0$$

Bubble Expansion Modes (I)

P. J. Steinhardt, Phys. Rev. D **25** (1982) 2074

H. Kurki-Suonio and M. Laine, Phys. Rev. D **51** (1995) 5431





➔ ***Deflagrations***

$c_s > V_w > V_{out}$

Subsonic V_w

Compression Wave in Front of Wall

➔ ***Hybrids***

$V_w > c_s > V_{out}$

Supersonic V_w

Both Compression & Rarefaction Wave

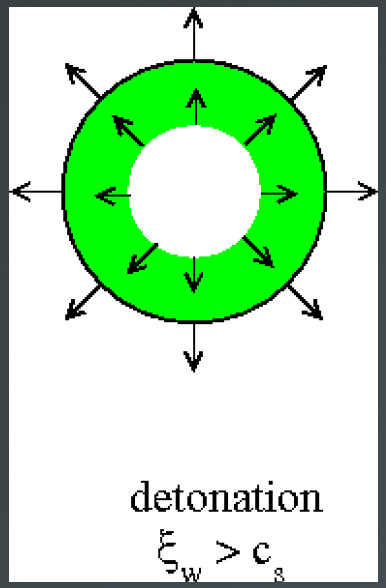
$V_w > V_{out}$

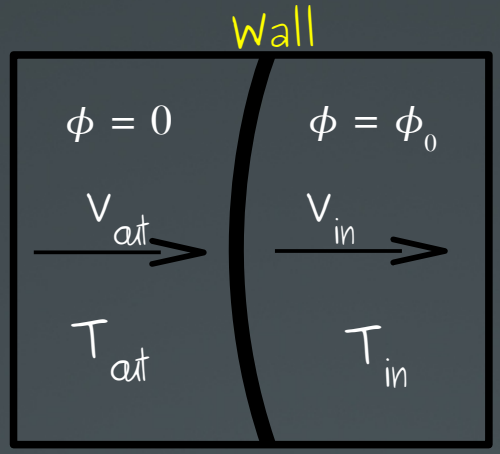
$T_{out} > T_N$

Bubble Expansion Modes (II)

P. J. Steinhardt, Phys. Rev. D **25** (1982) 2074

M. Laine, Phys. Rev. D **49** (1994) 3847





➔ ***Detonations***

$V_w = V_{out} > c_s$

Supersonic V_w

Rarefaction Wave Behind Wall
(No compression Front)

$V_w = V_{out}$

$T_{in} > T_{out} = T_N$

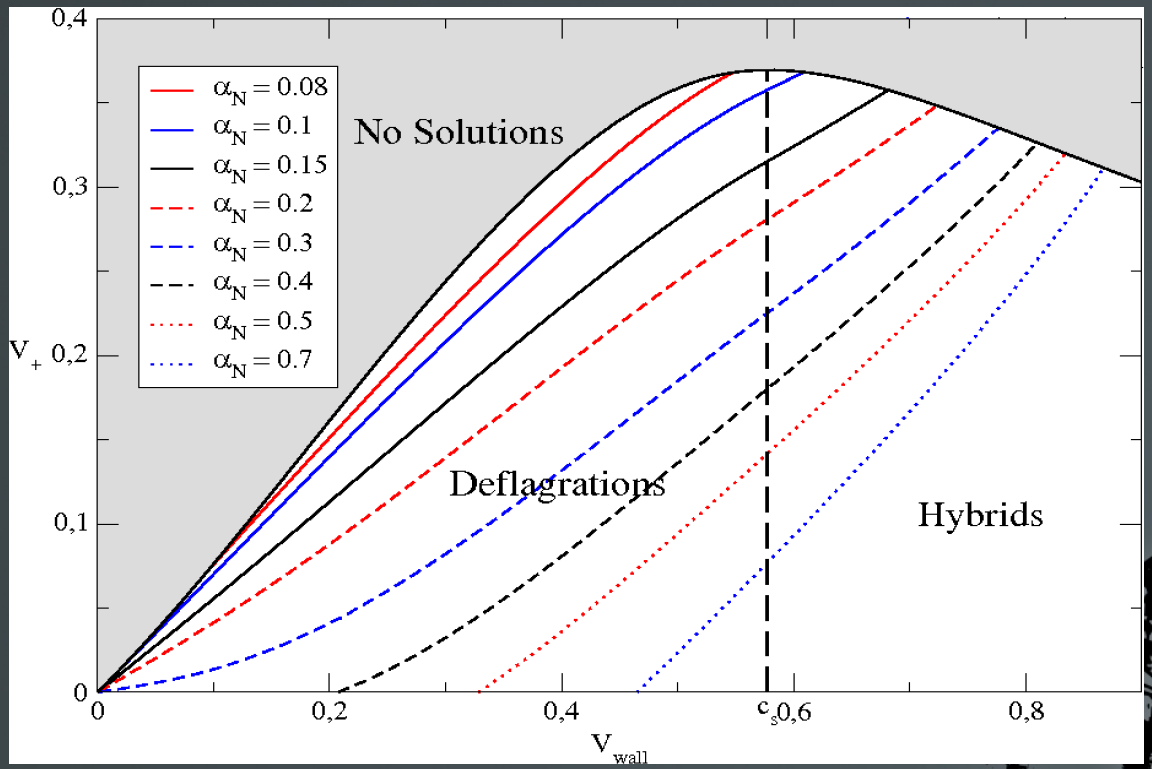
EW Baryogenesis + Sizable GW Signals?

J. M. N, arXiv:1103.2159

Viable EW Baryogenesis ⇨ *Upper Bound on Relative Velocity Between Bubble Wall and Plasma in Front* $v_{at} < 0.1 - 0.2$

Compression Wave in front of Bubble Wall → $v_{at} < v_w$ ($v_{at} \ll v_w$ for strong transitions)

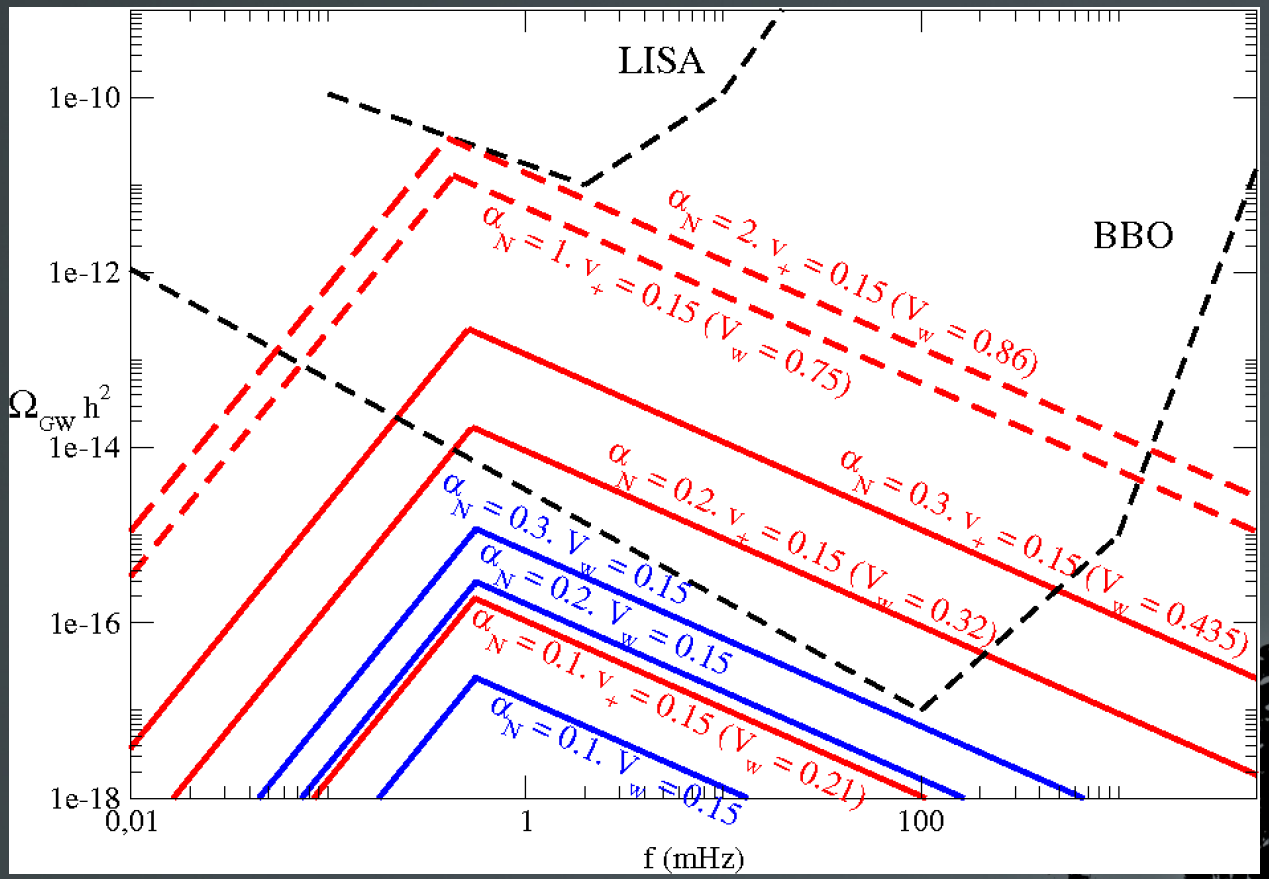
(Deflagrations & Hybrids)



$v_{at} < 0.1 - 0.2$ & Large v_w, Large α_N ⟶ Possible!

Viable EW Baryogenesis

Sizable GW Signal



Supersonic Electroweak Baryogenesis

C. Caprini and J. M. N, *In preparation*

Detonations ($V_w = V_{at} > c_s$) ⟶ *Diffusion Ahead of Bubble Wall Suppresed*

Electroweak Baryogenesis Possible?

Supersonic Electroweak Baryogenesis

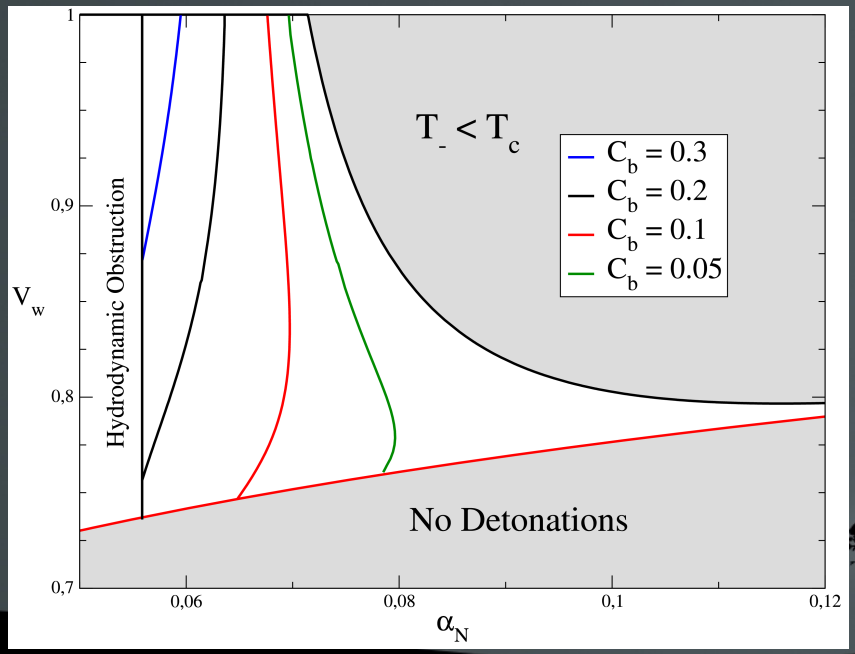
C. Caprini and J. M. N, *In preparation*

Detonations ($v_w = v_{at} > c_s$) ⟶ *Diffusion Ahead of Bubble Wall Suppresed*

Electroweak Baryogenesis Possible?

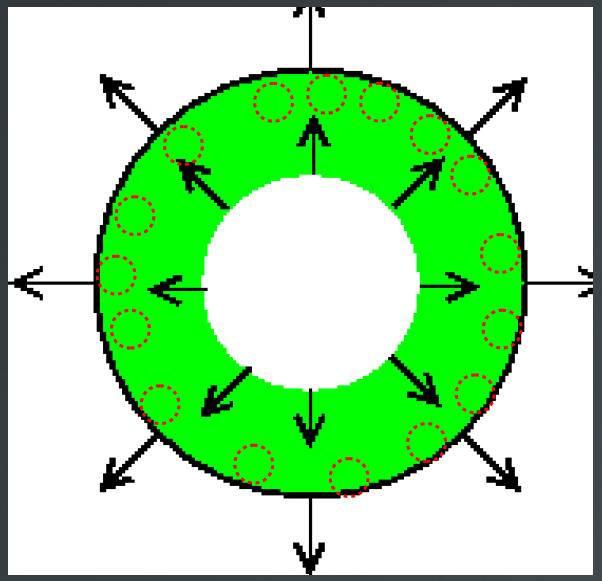
⇨ *Plasma Heating Behind Bubble Wall:* $T_{in} > T_N$ ⟶ $T_{in} > T_c$?

C_b = *% of Corona with* $T > T_c$

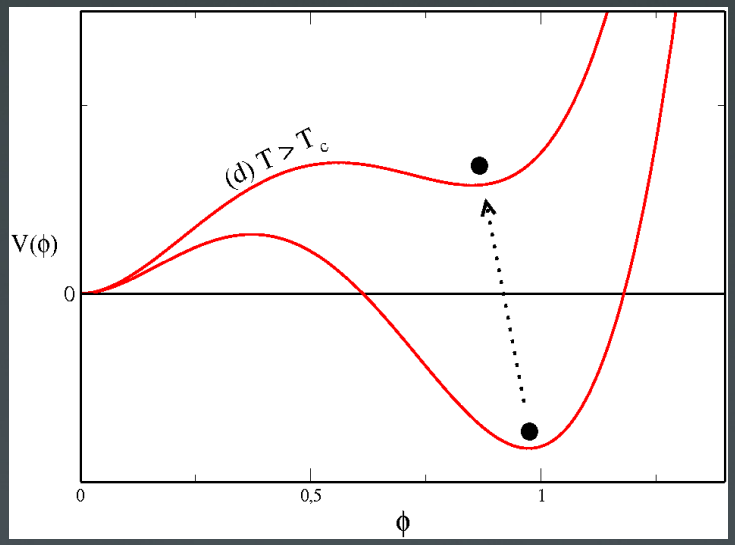


If $T_{in} > T_c$

Locally (close to Wall)



Nucleation of Symmetric Bubbles in Thin Shell Behind Bubble Wall



Sphalerons Unsuppressed Inside Symmetric Bubbles

Relevant Velocity $V \sim V_{Plasma} \ll V_W$

Supersonic Electroweak Baryogenesis May Be Possible

Conclusions

Electroweak Baryogenesis from Fast Bubble Walls may be Possible

❶ Deflagrations & Hybrids ⇨ Compression Wave Ahead of Bubble Wall: $v_w \to v_{at}$

→ Usual Mechanism for EW Baryogenesis at Work + Large Wall Velocities (GW)

❷ Detonations ⇨ Heating of Plasma Behind Bubble Wall $T_{in} > T_c$

→ Symmetric Bubble Nucleation Behind Bubble Wall

→ Electroweak Baryogenesis Inside Symmetric Bubbles (Sphalerons Active)

→ "Different" Mechanism for EW Baryogenesis + Large Wall Velocities (GW)

→ EW Baryogenesis NOT Ruled Out if Detection of Sizable GW Signal.

→ EW Baryogenesis Natural for (Moderately) Strong 1st Order Phase Transitions.