Cosmological 1st Order Phase Transitions: Bubble Growth & Energy Budget

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Outline

⇨ *Introduction to 1st Order Phase Transitions*:

- ⇒ *Bubble Nucleation & Growth "in a Nutshell".*
- ⇒ *Associated Cosmological Phenomena.*
- ⇒ *Relevant Quantities.*

⇨ *Formalism*:

⇒ *Studying Bubble Growth*:
- ❶ *Matching Equations Across the Bubble Wall.*
- ❷ *Fluid Equations for the Plasma.*
- ❶ + ❷ = ❸ *Fluid Solutions.*

⇒ *Distributing the Energy*: → ❹ *Efficiency Coefficients.*

⇒ *Fixing the Wall Velocity*: → ❺ *Higgs Equation of Motion.*

⇨ *Applications*:

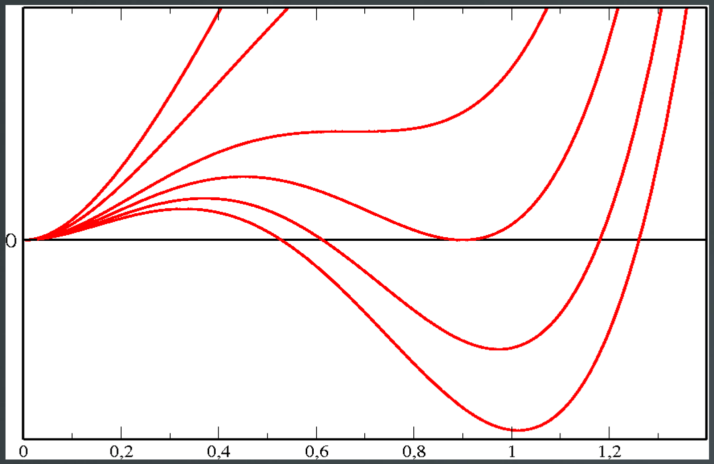
❻ *Steady State vs Acceleration (Runaway).*

❼ *Energy Budget.*

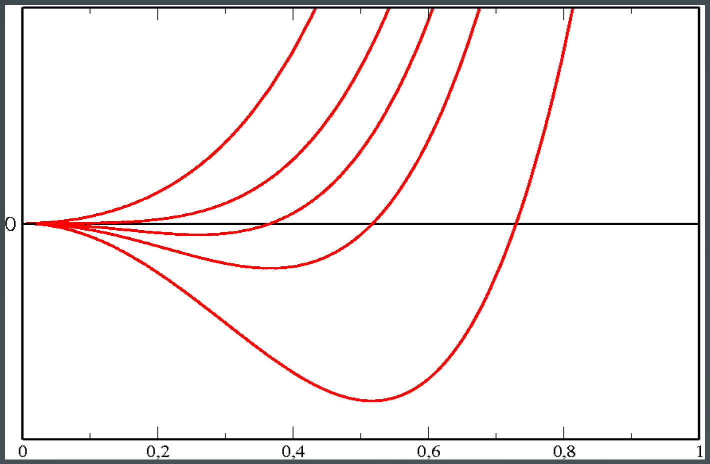
Why Bubbles?

Phase Transitions in the Early Universe (i.e. Electroweak Phase Transition)

1^{st} Order



2^{nd} Order



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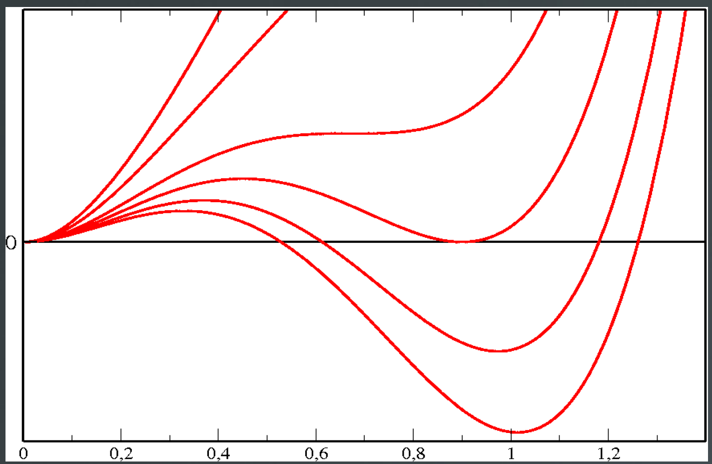
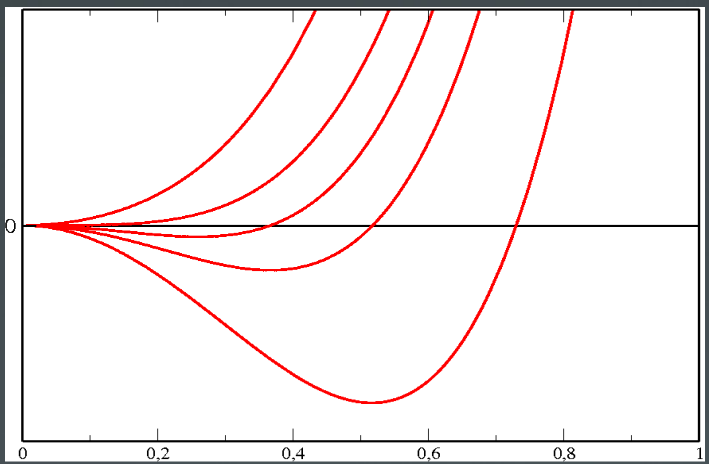
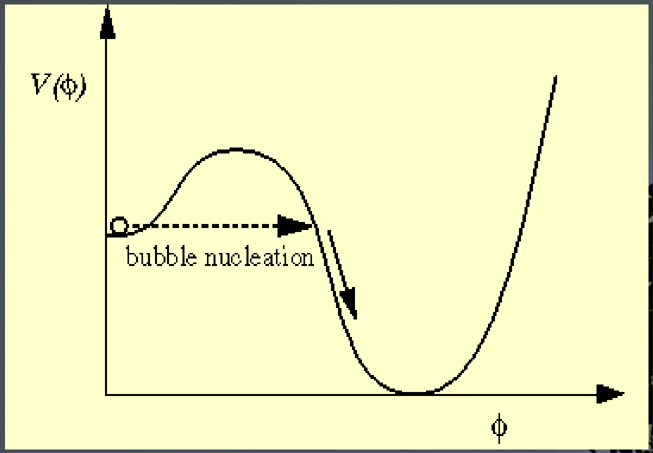


2nd Order



If Phase Transition is 1st Order

Nucleation of True Vacuum
Bubbles in False Vacuum Sea



Bubble Nucleation & Growth "in a Nutshell"

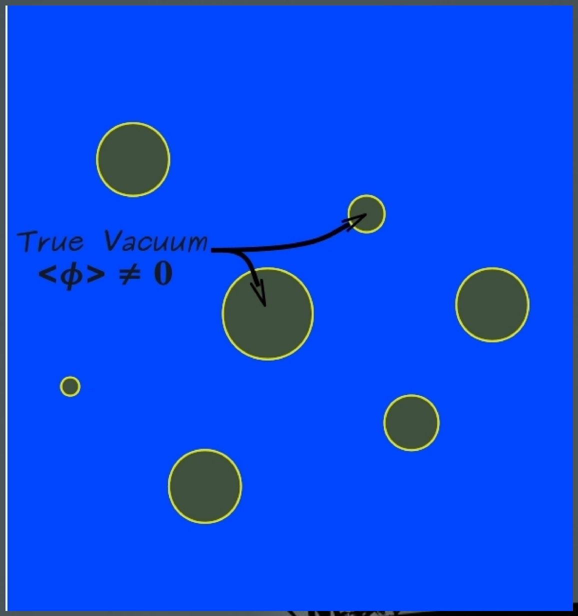
Nucleation:

→ Small Bubbles Nucleating Constantly Due to Fluctuations

→ When a Bubble Nucleates:

$$E_B = E_V + E_S = -\,{}^4\!/_3\,\pi R^3 \rho_V + 4\pi R^2 \rho_S$$

$$\frac{dE_B}{dR} < 0 \quad \Rightarrow \quad R > R_c$$

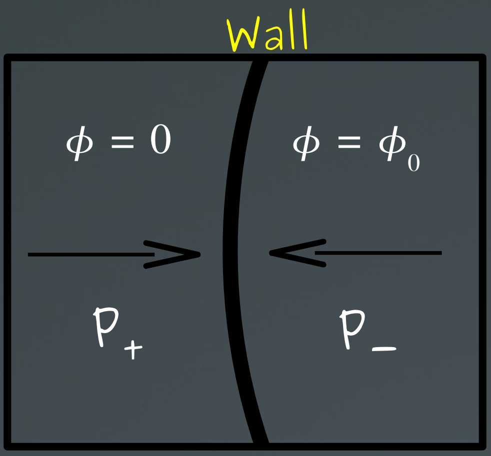


Bubble Nucleation & Growth "in a Nutshell"

Growth:

→ Why Does a Bubble Expand?

$$P_- - P_+ = V(0) - V(\phi_0) > 0$$



Net Pressure on Wall

⬇

Net Force on Wall

F_d

Bubble Nucleation & Growth "in a Nutshell"

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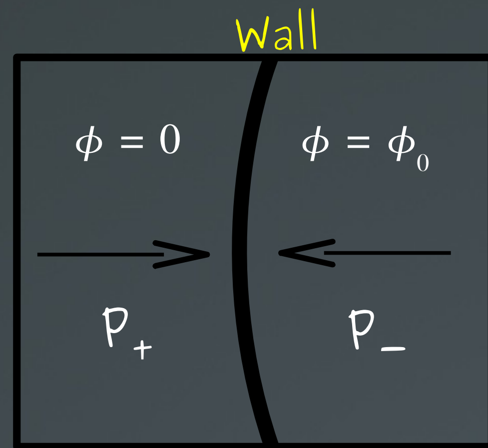


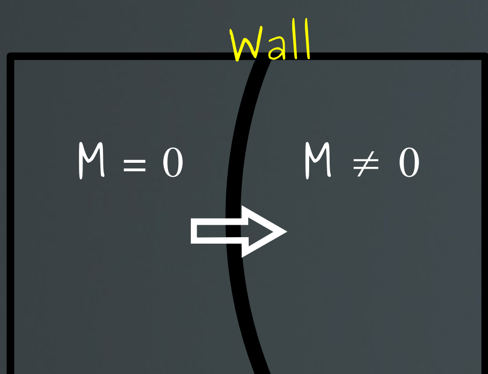
Net Pressure on Wall

⇓

Net Force on Wall

F_d

→ Bubbles Expand in Plasma → Friction!



Particles Gain Mass When Crossing Wall

Particle Distributions $f_a(p)$ ***Away from Equilibrium Close to Wall***

Friction Force F_{fr} Balances F_d

Bubble Growth in Cosmological Phase Transitions Relevant for:

→ ***Electroweak Baryogenesis.***

→ ***Production of a Stochastic Background of Gravitational Waves.***

→ ***Primordial Magnetic Fields.***

→ ***Etc...***

Electroweak Baryogenesis:

❶ 1st Order Phase Transition → Departure from Equilibrium (3rd Sakharov Condition)

↓

Suppresion of Sphaleron Rate in Broken Phase Γ^{b}_{Sph}

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

Electroweak Baryogenesis:

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Suppresion of Sphaleron Rate in Broken Phase Γ^{b}_{Sph}

$$<\phi>/T \geqslant 1$$

❷ Viable Baryogenesis:

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

→ $V_w < c_s$ (c_s ⇨ *Speed of Sound in Plasma*)

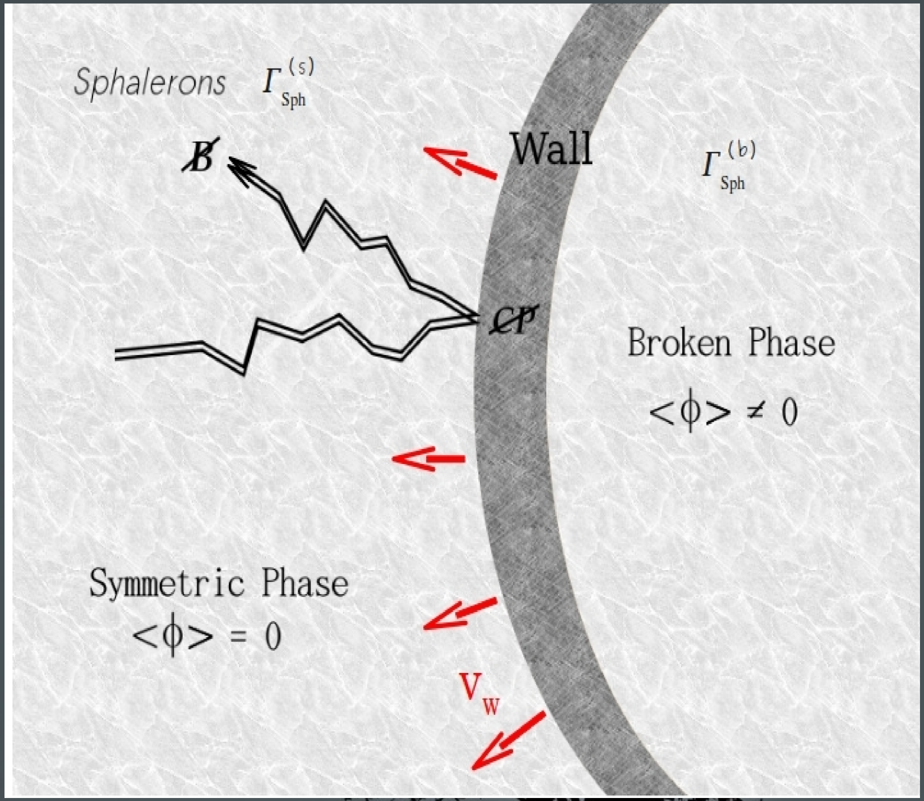
→ $\tau_{diff} = D/(V_w)^2$

$\Gamma^{s}_{Sph} \gg (\tau_{diff})^{-1}$ ↘

$\Gamma^{s}_{Sph} \ll (\tau_{diff})^{-1}$ ↗ *Suppressed* n_B

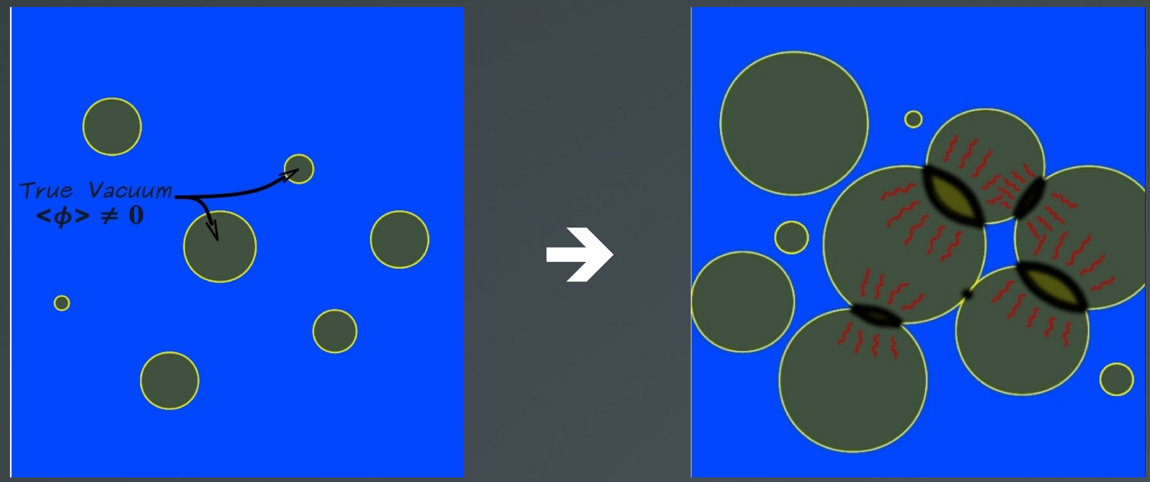
$\Gamma^{s}_{Sph} \simeq (\tau_{diff})^{-1}$ → $V_w \sim (few) \cdot 10^{-2}$

Favoured



Stochastic Background of Gravitational Waves:

Bubble Nucleation, Growth & Percolation.



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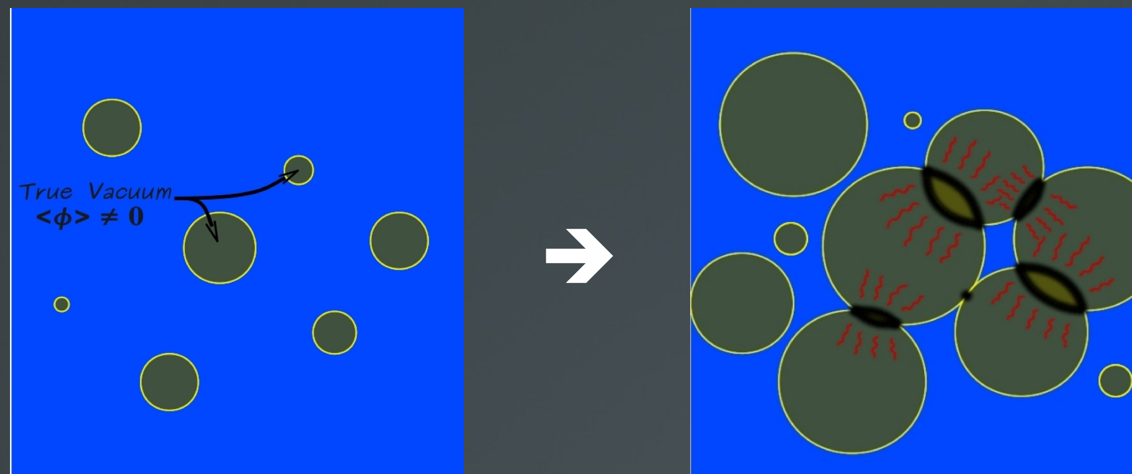


Possible Gravitational Wave sources:

Efficiency Coefficient for Converting Phase Transition Energy into Kinetic Energy for GW

⇨ Bubble Collisions:

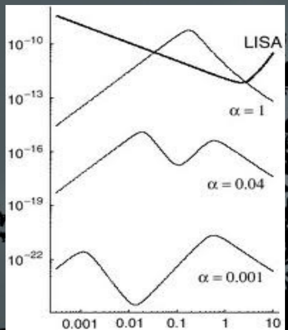
$$\Omega_{GW} \sim \kappa^2$$

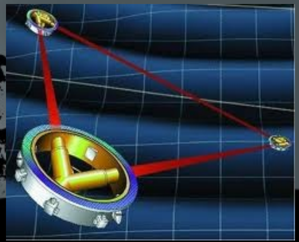
$$\Omega_{GW} \sim v_W^4$$

⇨ Turbulence in the Plasma.

⇨ Magnetic Fields.

Detectable by LISA?





Summary of Relevant Quantities

Phase Transition

- ➔ *EW Baryogenesis:* v_w $\langle\phi\rangle/T$
- ➔ *Gravitational Wave Production:* κ v_w α β

Bubble Growth

Summary of Relevant Quantities

Phase Transition

- *EW Baryogenesis:* $\mathbf{V_w}$ $\langle\phi\rangle/\mathbf{T}$
- *Gravitational Wave Production:* κ $\mathbf{V_w}$ α β

Bubble Growth

STUDY of BUBBLE GROWTH in 1st ORDER PHASE TRANSITIONS

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

$\Rightarrow$ *Study Plasma Behaviour* ($\mathbf{V_w}$ *Free Parameter*).

$\Rightarrow$ *Use Friction to fix* $\mathbf{V_w}$.

❶ *Matching Equations Across the Bubble Wall.*

Combined system **"Higgs Wall - Plasma"**:

$$T_{\mu\nu} = T^{\phi}_{\mu\nu} + T^{Plasma}_{\mu\nu} \begin{cases} T^{\phi}_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}\partial_\rho\phi\partial^\rho\phi - V_0(\phi)\right) \\ T^{Plasma}_{\mu\nu} = w u_\mu u_\nu - g_{\mu\nu} p \end{cases}$$

Energy-Momentum Conserved Across Bubble Wall ⟶ $\partial_\mu T_{\mu\nu} = 0$

+

Steady State (Wall Reference Frame) ⟶ $\partial_z T_{z0} = \partial_z T_{zz} = 0$

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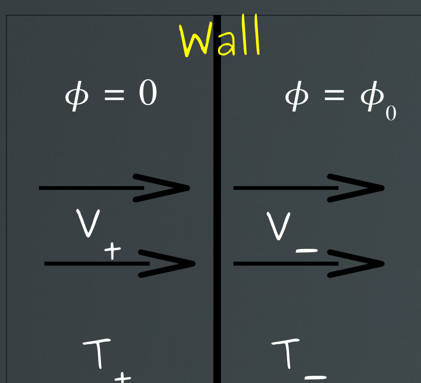


$$w_+ v_+^2 \gamma_+^2 + p_+ - V_0(0) = w_- v_-^2 \gamma_-^2 + p_- - V_0(\phi_0)$$

$$w_+ v_+ \gamma_+^2 = w_- v_- \gamma_-^2$$

Bag Approximation:

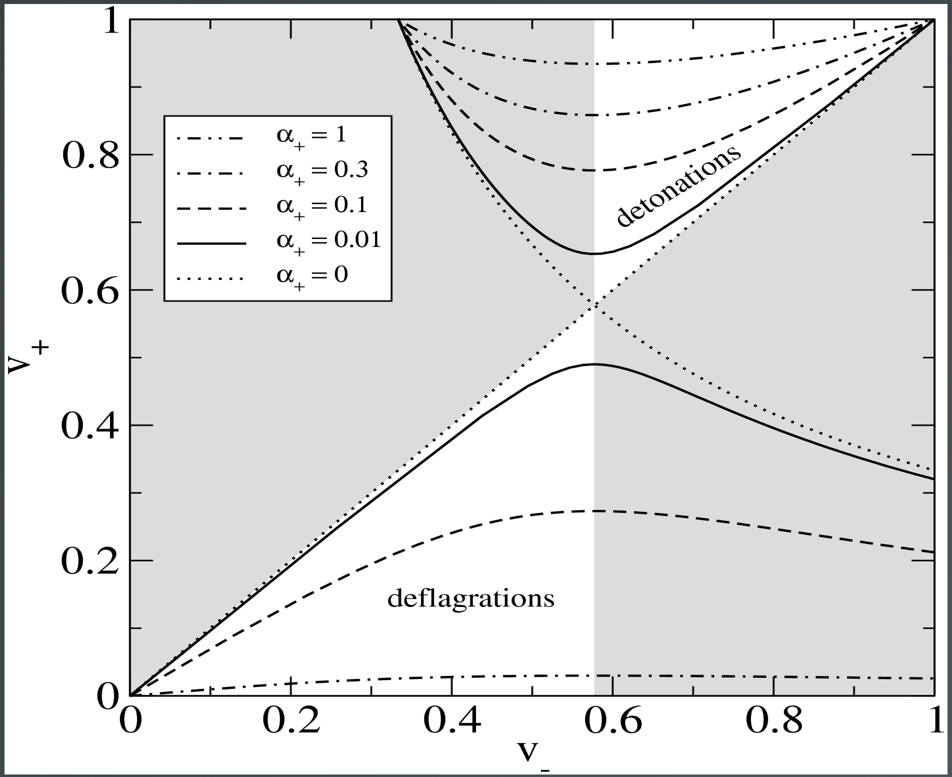
$$p_\pm = \frac{a_\pm}{3} T_\pm^4 \qquad a_\pm = \frac{\pi^2}{30} g_\pm \qquad V_0(0) - V_0(\phi_0) \equiv \epsilon$$

$$v_+ = \frac{1}{1+\alpha_+}\left(\frac{v_-}{2} + \frac{1}{6v_-} \pm \sqrt{\left(\frac{v_-}{2} + \frac{1}{6v_-}\right)^2 + \alpha_+^2 + \frac{2}{3}\alpha_+ - \frac{1}{3}}\right)$$

With

$$\alpha_+ \equiv \frac{\epsilon}{a_+ T_+^4}$$

$$r \equiv \frac{a_+ T_+^4}{a_- T_-^4}$$



⇨ Detonations (+) ⟶ $v_+ > v_-$

⇨ Deflagrations (-) ⟶ $v_+ < v_-$

Only if $\alpha_+ < \frac{1}{3}$

$$v_+ = \frac{1}{1+\alpha_+}\left(\frac{v_-}{2}+\frac{1}{6v_-}\pm\sqrt{\left(\frac{v_-}{2}+\frac{1}{6v_-}\right)^2+\alpha_+^2+\frac{2}{3}\alpha_+-\frac{1}{3}}\right)$$

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$$\alpha_+ \equiv \frac{\epsilon}{a_+T_+^4}$$

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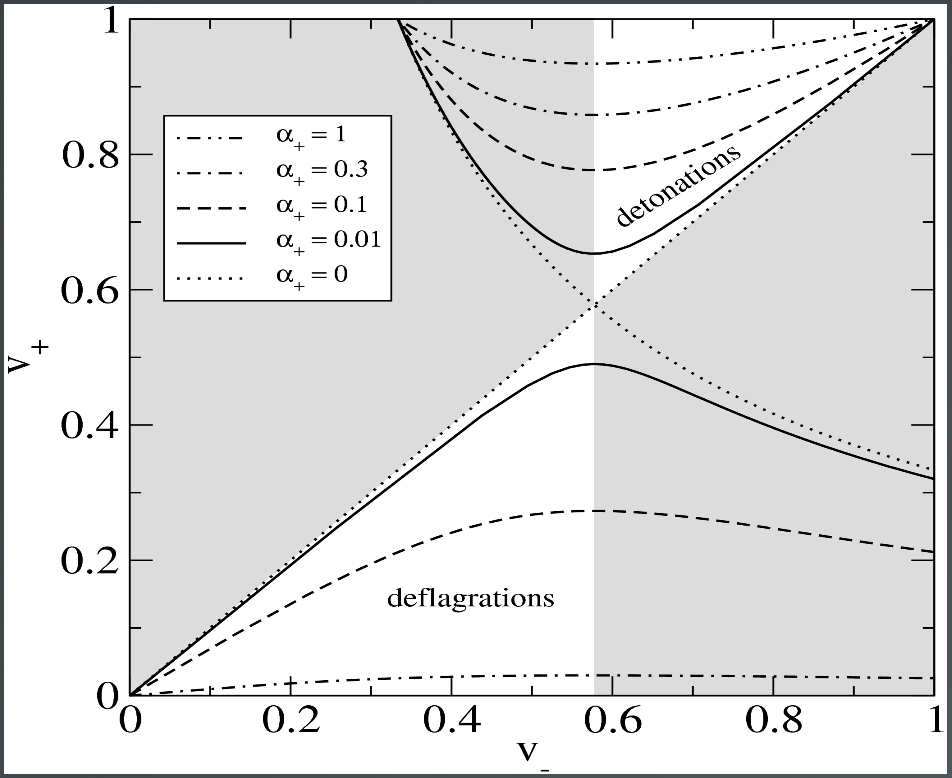


- ⇨ Detonations (+) → $v_+ > v_-$ → $r < \frac{1}{1+3\alpha_+}$
- ⇨ Deflagrations (-) → $v_+ < v_-$ → $r > \frac{1}{1+\alpha_+}\frac{1+\sqrt{\frac{2}{\alpha_+}+3}}{\sqrt{\frac{2}{\alpha_+}+3}-3}$

Only if $\alpha_+ < \frac{1}{3}$

❷ *Fluid Equations for the Plasma.*

Velocity Profile for the Plasma ⇒ Energy-Momentum Conservation

$$\partial_\mu T^{\mu\nu}_{Plasma} = 0 \qquad v(r,t) = v(\xi = r/t)$$

(Similarity Solution)

❷ *Fluid Equations for the Plasma.*

Velocity Profile for the Plasma ⇒ Energy-Momentum Conservation

$$\partial_\mu T^{\mu\nu}_{Plasma} = 0 \qquad v(r,t) = v(\xi = r/t)$$

(Similarity Solution)

⇩

$$\Rightarrow \quad \frac{1-\xi v(\xi)}{1-v^2(\xi)}\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v = 2\frac{v(\xi)}{\xi}$$

$$\mu(\xi, v) \equiv \frac{\xi - v(\xi)}{1-\xi v(\xi)}$$

$$\Rightarrow \quad \frac{\partial_\xi p}{w} = \gamma^2 \frac{\xi - v(\xi)}{1-\xi v(\xi)}\partial_\xi v \quad \longrightarrow \quad w(\xi) = w_0 \exp\left[\left(1+\frac{1}{c_s^2}\right)\int_{v_0}^{v(\xi)} \gamma^2 \mu \, dv\right]$$

Boundary Conditions v_+, v_- (❶) + *Fluid Equations* (❷)

❸ *Fluid Solutions.* $v(\xi)\ w(\xi)$

- ***Deflagrations***
  - Subsonic v_w. Fluid at Rest Behind Bubble Wall.
  - Compression Wave in Front of Wall. $T_+ > T_N$

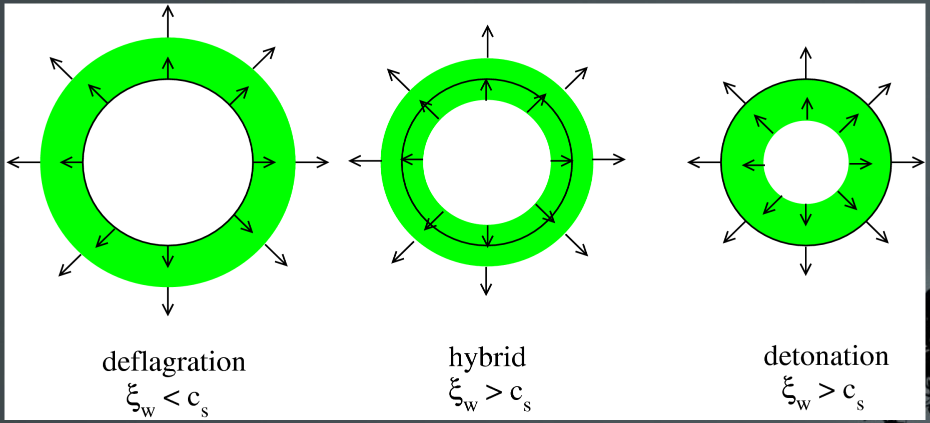
  $c_s > v_- = v_w > v_+$

- ***Detonations***
  - Supersonic v_w. Fluid at Rest in Front of Bubble Wall.
  - Rarefaction Wave Behind Wall. $T_+ = T_N$

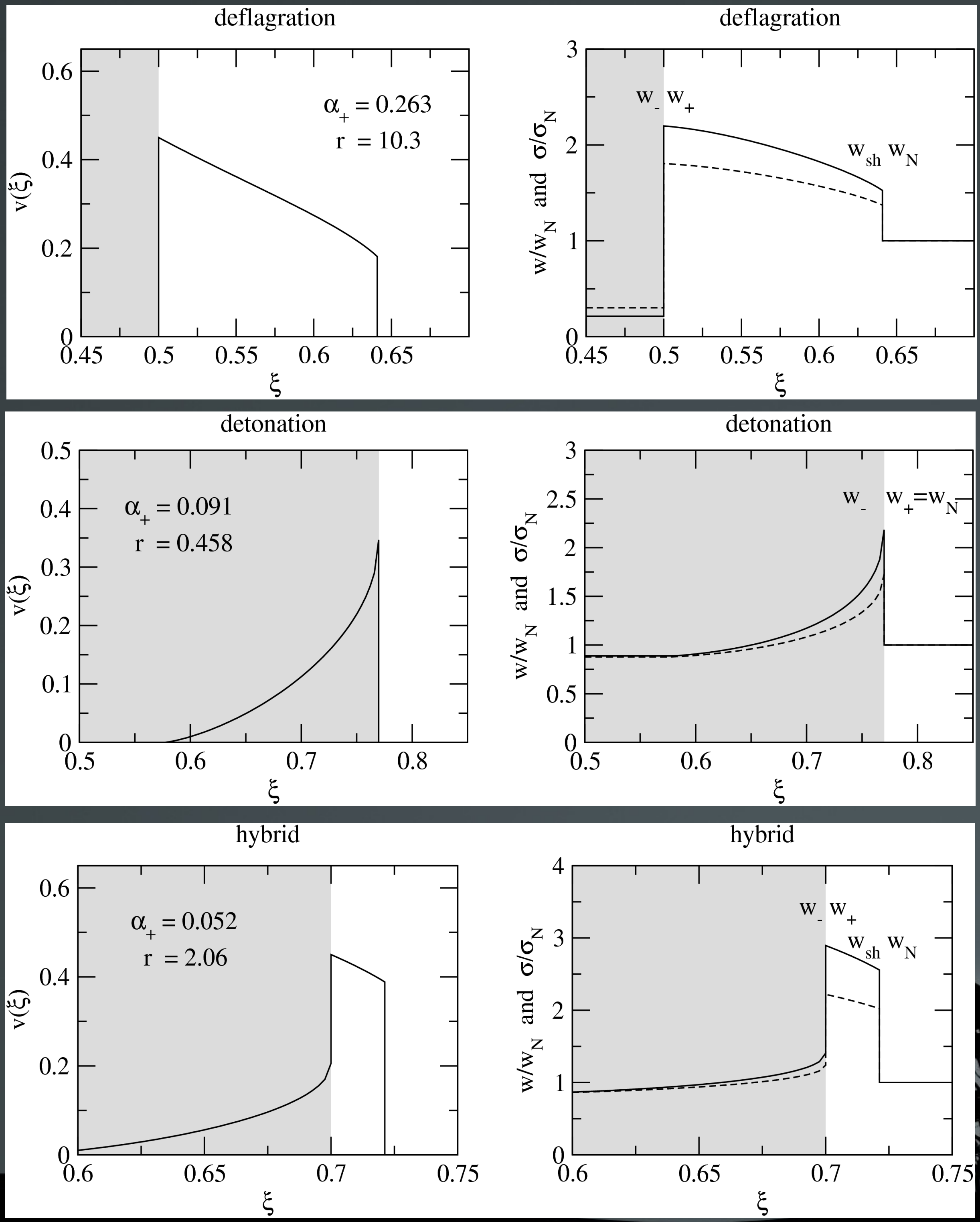
  $v_w = v_+ > v_- > c_s$

- ***Hybrids*** → Both Compression and Rarefaction Wave.

  $v_w > c_s = v_- > v_+$

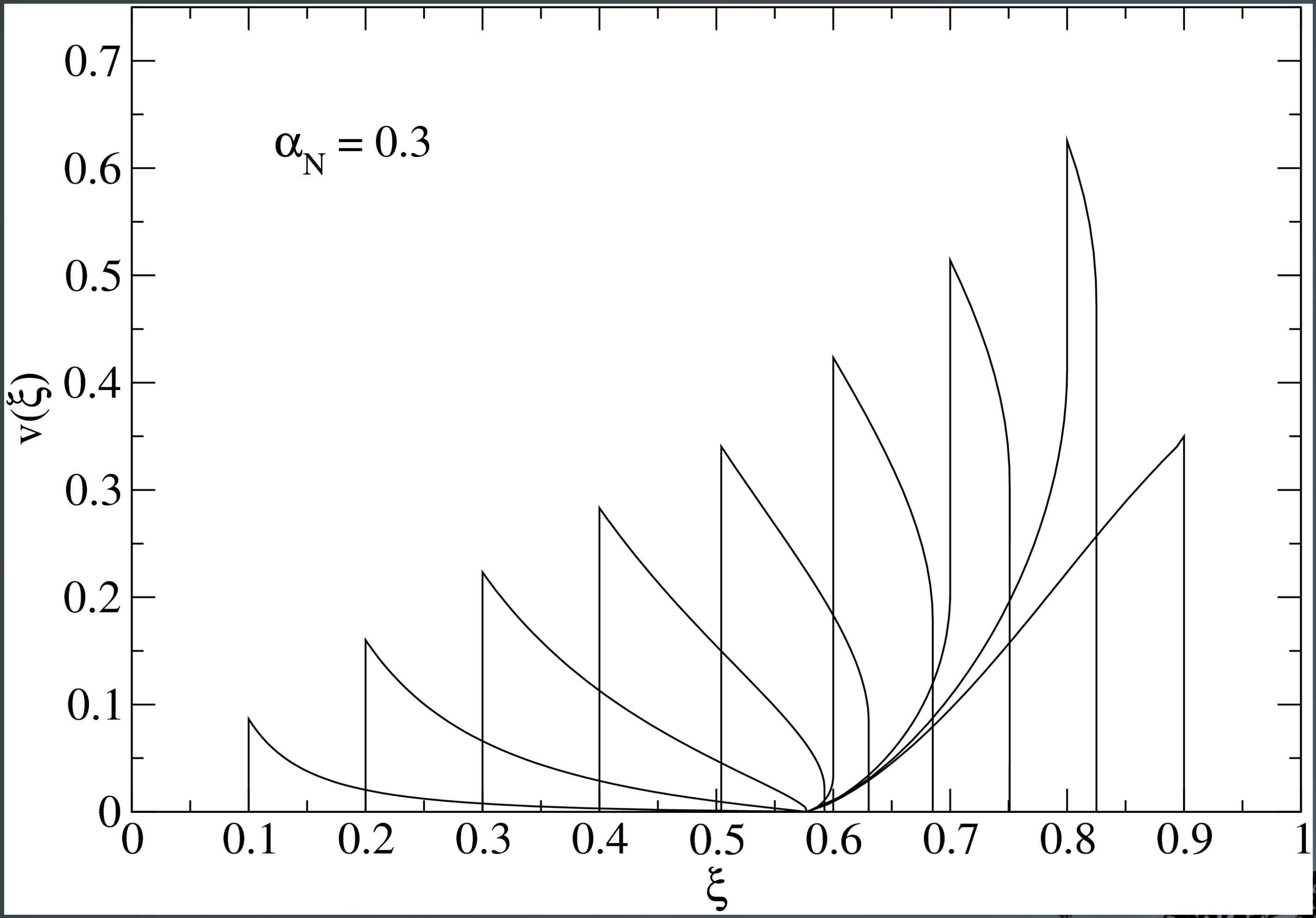


Fluid Profiles



As Wall Velocity increases: (α_N = cte)

- ⇨ ***Deflagrations Evolve Into Hybrids***
- ⇨ ***Hybrids Evolve Into Detonations***



❹ *Efficiency Coefficients.* $\kappa(\xi_w, \alpha_N)$

Gravitational Wave Production from Bubble Collisions Depends on:

$$\int T(r)\, r^2 dr = \int w(r)\, \frac{v^2(r)}{1 - v^2(r)}\, r^2 dr$$

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⇒ ***Vacuum Bubbles: Perfect Conversion of Available Energy into Kinetic Energy***

$$\int T(r)\, r^2 dr = \frac{1}{3} \rho_{\rm vac} R^3_{Bubble}$$

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⇒ ***Vacuum Bubbles: Perfect Conversion of Available Energy into Kinetic Energy***

$$\int T(r)\, r^2 dr = \frac{1}{3}\rho_{\rm vac} R^3_{Bubble}$$

⇒ ***Bubbles in Plasma: Conversion of Available Energy into Kinetic Energy is*** **NOT Perfect**

→ ***Efficiency Coefficient*** κ

M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D **49** (1994) 2837

$$\int T(r)\, r^2 dr = \kappa \frac{\epsilon}{3} R^3_{Bubble} \longrightarrow \kappa = \frac{3}{\epsilon\, \xi_w^3 \int w(\xi)\, \frac{v^2(\xi)}{1-v^2(\xi)} \xi^2 d\xi}$$

Energy not Transformed into Kinetic Bulk Motion, Used to Increase Thermal Energy of Plasma

Previously, **Chapman – Jouguet** *Condition Assumed:* $v_- = c_s$

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

Jouguet Detonations $\rightarrow$ $$\xi_w = \xi_J = \frac{1}{1+\alpha_N}\left(\sqrt{\alpha_N^2 + \frac{2}{3}\alpha_N} + \sqrt{\frac{1}{3}}\right)$$

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$$\kappa(\xi_w, \alpha_N) \to \kappa(\alpha_N) = \frac{\sqrt{\alpha_N}}{0,135 + \sqrt{0,98 + \alpha_N}}$$

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$$\Downarrow$$

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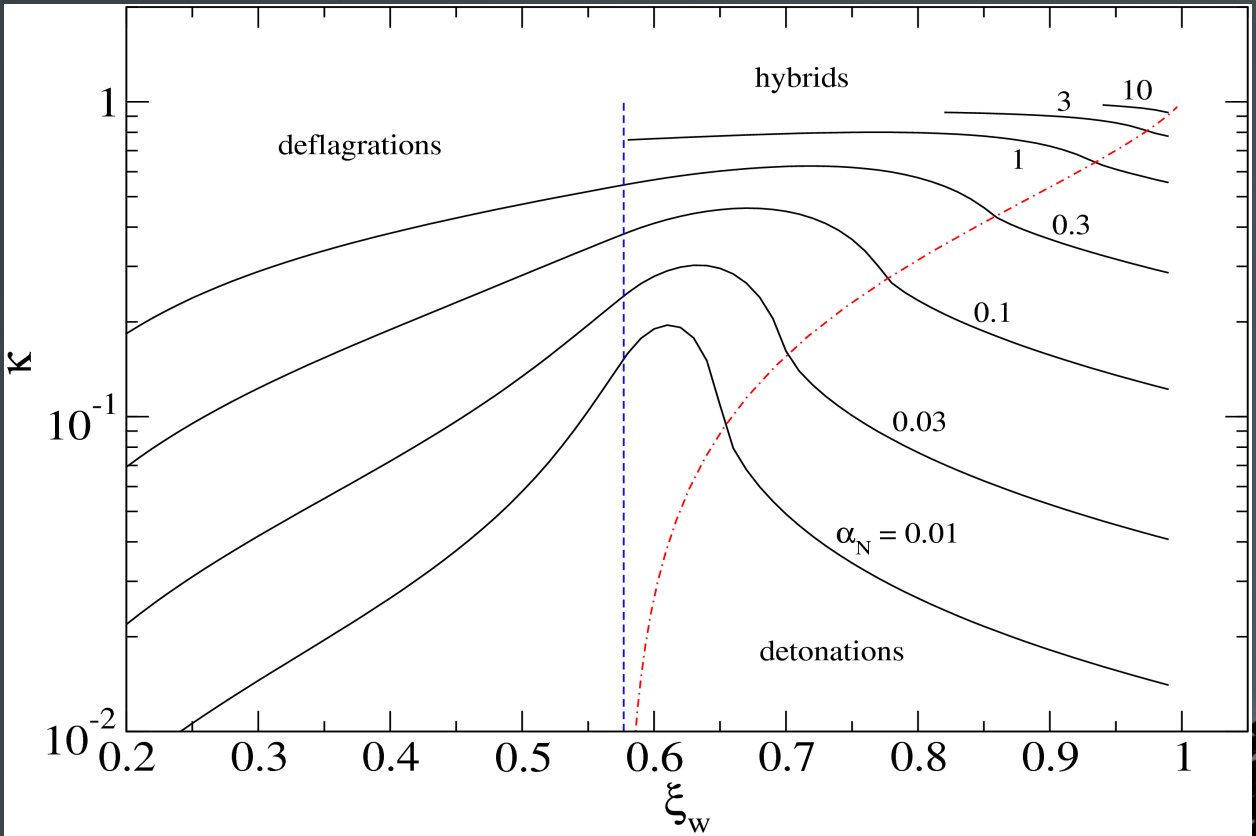
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D **49** (1994) 2837

However, Chapman – Jouguet Condition
- *Chemical Combustion* ☑
- *Cosmological Phase Transitions* ☒

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

Previous Result $\kappa(\alpha_N)$ Extended to the (ξ_w, α_N) Plane.

J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 1006:028 (2010)



❺ *Higgs Equation of Motion.* *(Needed to Fix ξ_w)*

G. D. Moore and T. Prokopec, Phys. Rev. D **52** (1995) 7182-7204

J. Ignatius, K. Kajantie, H. Kurki-Suonio and M. Laine, Phys. Rev. D **49** (1994) 3854-3868

So far, ξ_w is a Free Parameter ⇨ Need to Determine it.

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Higgs EoM:

$$\partial_\mu \partial^\mu \phi + \frac{\partial \mathcal{F}}{\partial \phi} - \mathcal{K}(\phi) = 0 \qquad \mathcal{K}(\phi) = -\sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} \delta f_i(p) = 0$$

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$$F_{dr} = \int dz\, \partial_z \phi \frac{\partial \mathcal{F}}{\partial \phi}$$

Driving Force

$$F_{fr} = \int dz\, \partial_z \phi \mathcal{K}(\phi)$$

Friction Force

Departure from Equilibrium of Particle Distributions close to the Wall

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$$F_{dr} = \int dz\, \partial_z \phi \frac{\partial \mathcal{F}}{\partial \phi}$$

Driving Force

$$F_{fr} = \int dz\, \partial_z \phi \mathcal{K}(\phi)$$

Friction Force → Departure from Equilibrium of Particle Distributions close to the Wall

- *If* $F_{dr} = F_{fr}$ (*Friction Balances Pressure*) → *Steady State*
- *If* $F_{dr} > F_{fr}$ → *Acceleration*

❻ *Steady State* vs *Acceleration (Runaway) I.*

Previously Believed: $F_{fr} \sim \gamma_w \xi_w \;\rightarrow\; \lim_{\xi_w \to 1} F_{fr} = \infty$

True for $\xi_w \ll 1 \quad (F_{fr} \sim \gamma_w \xi_w \sim \xi_w)$

G. D. Moore and T. Prokopec, Phys. Rev. D **52** (1995) 7182-7204

❻ Steady State vs Acceleration (Runaway) I.

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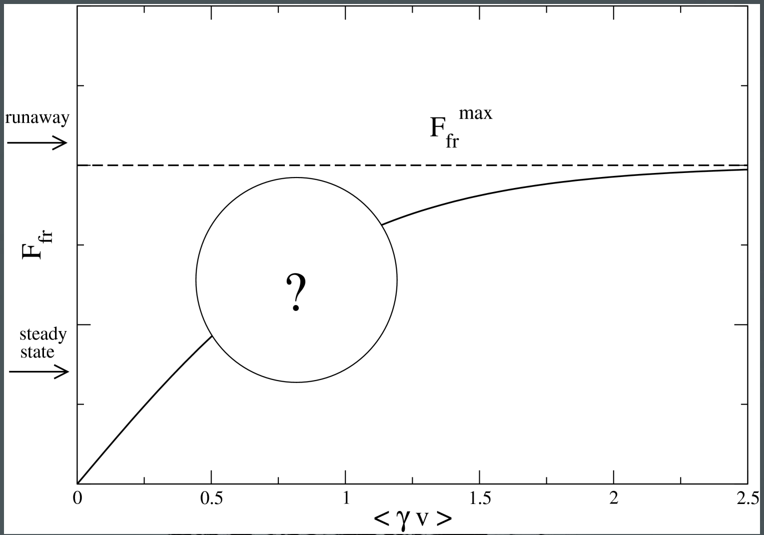
However: $\xi_w \to 1 \rightarrow F_{fr} \to F_{fr}^{max} = \text{cte}$ (Up to Possible Log(γ_w) Corrections)

D. Bodeker and G. D. Moore, JCAP 0905:009 (2009)

- *If* $F_{dr} < F_{fr}^{max} \rightarrow$ *Steady State*
  (*Friction Balances Pressure*)
- *If* $F_{dr} > F_{fr}^{max} \rightarrow$ *Runaway Bubble Wall*
  (*Acceleration*)



Steady State vs Acceleration (Runaway) II.

Phenomenological Approach:

$$\mathcal{K}(\phi) = T_N \tilde{\eta} \frac{u^\mu \partial_\mu \phi}{\sqrt{1 + (\lambda_\mu u^\mu)^2}}$$

Possible Runaway Behaviour

$\tilde{\eta}$ Friction Parameter (Calculable from Theory)

$$\delta \in \left(1, \frac{1}{r}\right)$$

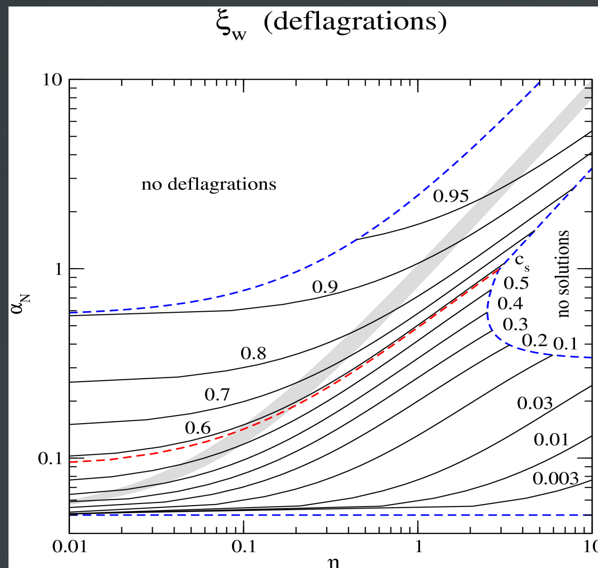
Higgs EoM (in Wall frame):

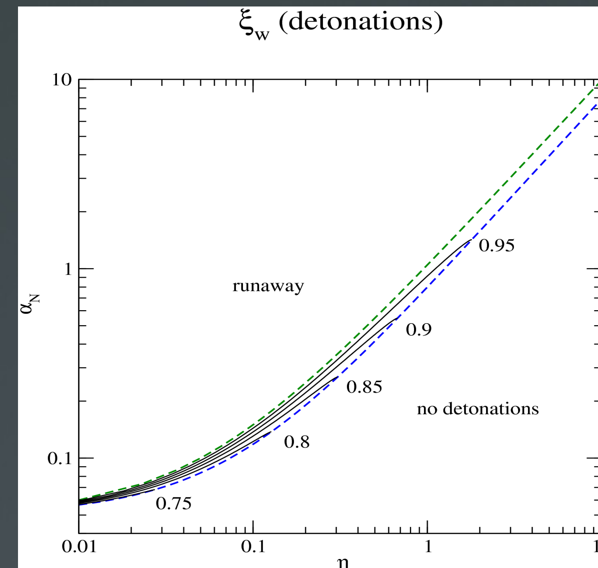
$$\partial_z^2 \phi - \frac{\partial \mathcal{F}}{\partial \phi} = T_N \tilde{\eta} v \partial_z \phi \quad \longrightarrow \quad \alpha_+ - \delta \alpha_c = \eta \frac{\alpha_+}{\alpha_N} \langle v \rangle$$

J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 1006:028 (2010)

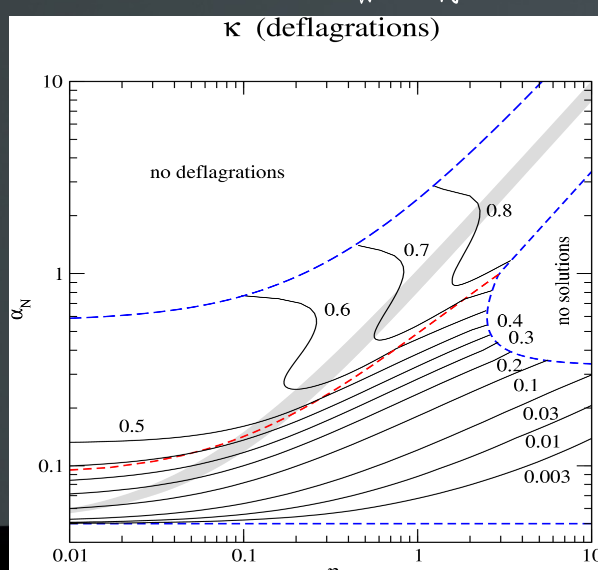
Steady State vs Acceleration (Runaway) III.

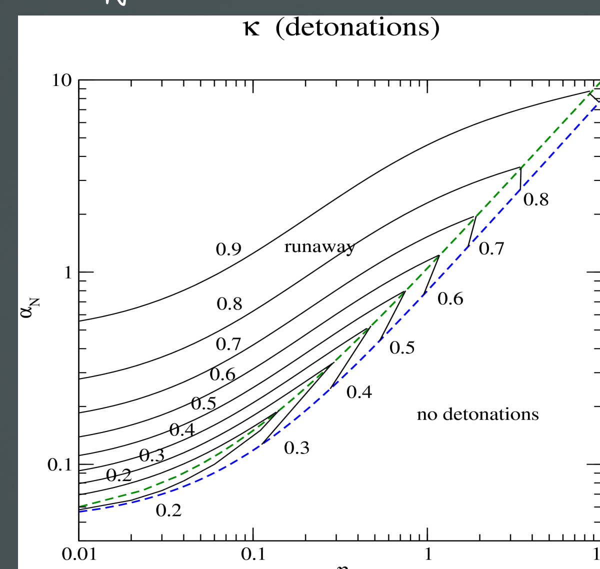
ξ_w in the (η, α_N) Plane





$\kappa(\xi_w, \alpha_N)$ in the (η, α_N) Plane



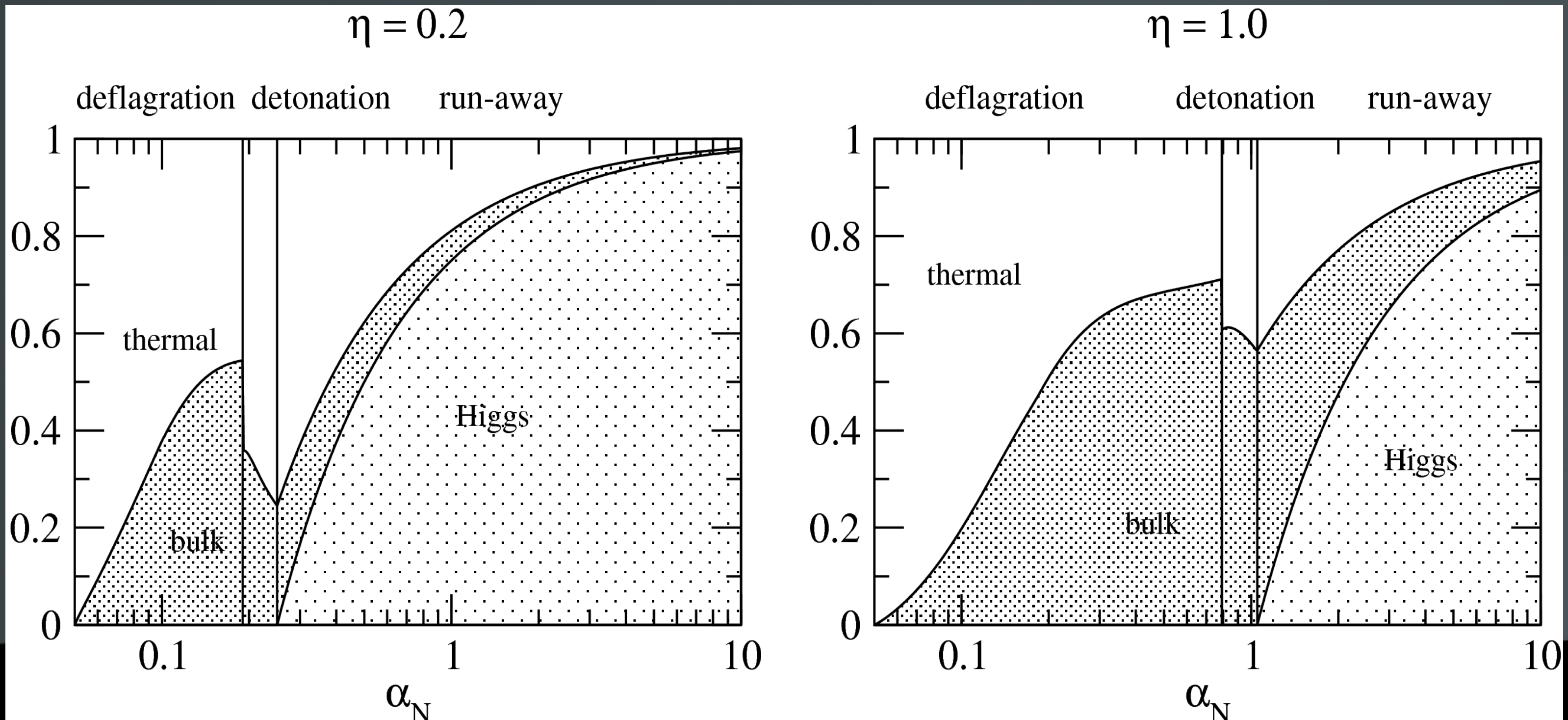


❼ *Energy Budget.*

J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 1006:028 (2010)

$\alpha_N < \alpha_\infty$ → $\kappa(\xi_w, \alpha_N)$ *Plasma Bulk Motion*

→ $1 - \kappa(\xi_w, \alpha_N)$ *Plasma Thermal Energy*



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$\alpha_N < \alpha_\infty$

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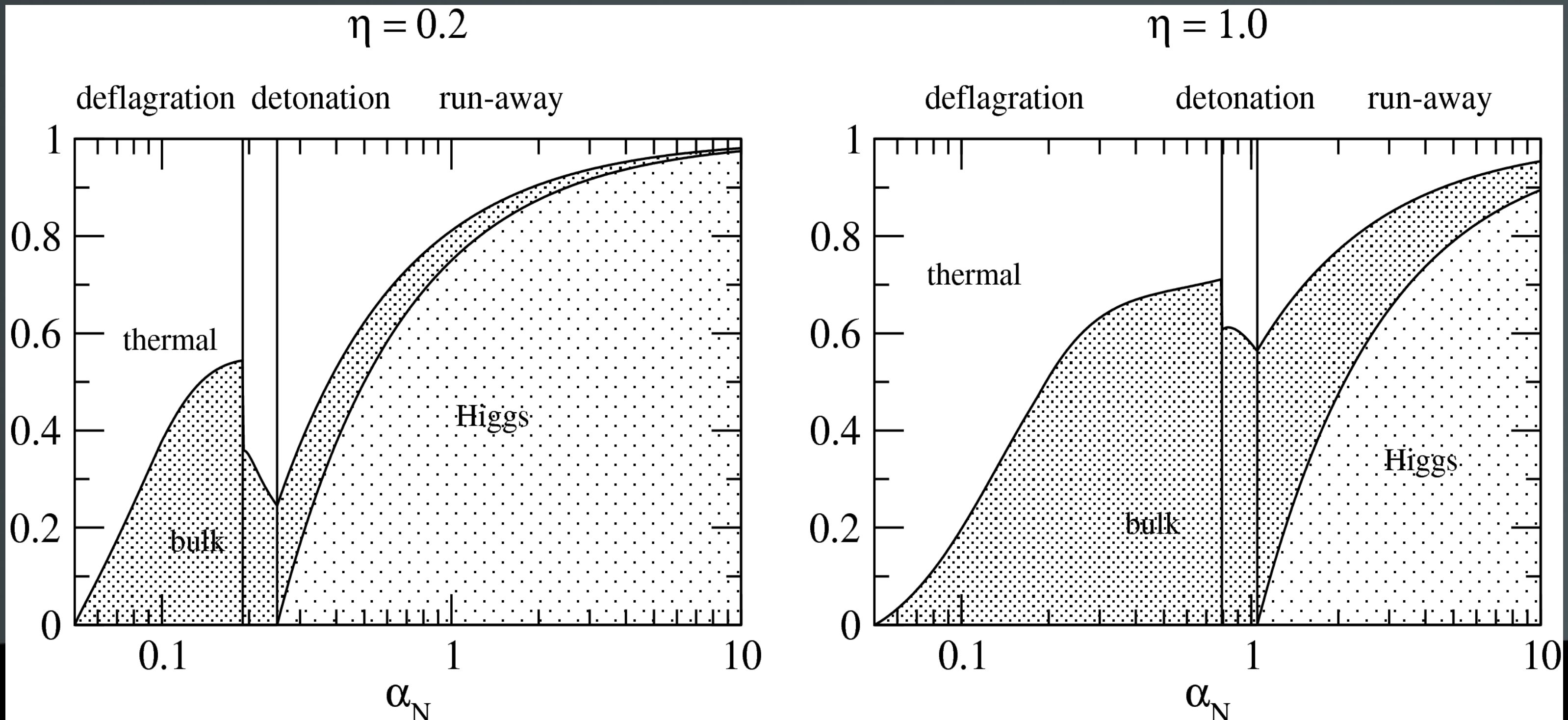
- → $1 - \kappa(\xi_w, \alpha_N)$ *Plasma Thermal Energy*

$\alpha_N > \alpha_\infty$

- → $\alpha_N - \alpha_\infty$ *Higgs Field (Wall Acceleration)*, with $\kappa = 1$
- → α_∞ *Plasma Bulk Motion + Thermal Energy*, with κ_∞



Bonus: *Possible Hydrodynamic Obstruction.*

T. Konstandin and J. M. No, ArXiv:1011.3735

Steady State Solution ⟶

$$F_{dr} = \int dz\, \partial_z \phi \frac{\partial \mathcal{F}}{\partial \phi} = \int dz\, \partial_z \phi\, \mathcal{K}(\phi) = F_{fr}$$

Suppose Subsonic ξ_w ⇨ ***Deflagration*** $(T_+ > T_N)$

⇨ As Wall Moves, Reheats Plasma in Front $(T_+ > T_N)$.

⇨ As ξ_w Increases, T_+ Raises ($T_+ \uparrow$ if $\xi_w \uparrow$).

⇨ As T_+ Raises, F_d Decreases ($F_d \downarrow$ if $T_+ \uparrow$).

If Heating Effect Drives $T \to T_c$ ⇨

$$F_{dr} \simeq \mathcal{F}_- - \mathcal{F}_+ \longrightarrow 0$$

Average T on the Bubble Wall

If $F_d \to 0$ for $\xi_w < c_s$ ***Hydrodynamic Obstruction!!***

Conclusions

❶ Efficiency coefficient $\kappa(\xi_w, \alpha_N)$ Obtained → Energy Budget of Phase Transitions

❷ Runaway Bubble Walls → Energy Stored in the Higgs Field

↓

Qualitative Modification of the Energy Budget

***Possible Consequences for Gravitational Wave Spectrum* (Turbulence)**

❸ Possible Hydrodynamic Obstruction to Supersonic ξ_w

→ Allows to Estimate Subsonic ξ_w Without Knowing Friction

→ Favors Electroweak Baryogenesis Scenarios

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Thank You!