DEPARTMENT OF ELEMENTARY PARTICLE PHYSICS №40

MEPhI

Interaction of primordial plasma with domain walls in the early Universe

Presented by
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XXIII INTERNATIONAL SEMINAR ON HIGH-ENERGY PHYSICS QUARKS 2026

THE RELEVANCE OF THE WORK

Closed, sphere-like domain walls (DWs) can lead to formation of Primordial Black Holes (PBHs).

Rubin et al., JETP 91 (2001) 921

PBHs could explain:

- ❑ the origin of quasars at z > 6;

  Maiolino et al., Nature 627 (2024) 59
- ❑ the origin of supermassive black holes;
- ❑ dark matter.

  Carr, Green, arXiv:2406.05736

THE AIM OF THE WORK

DW collapse can be a source of gravitational waves.

Sakharov et al., Phys. Rev. D 104 (2021) 043005

The purpose of this research is to explore possible effects of the hot particle plasma in the post-inflationary stage on:

- ❑ evolution of DWs;
- ❑ formation of PBHs;
- ❑ potential observational signatures of DWs.

WHAT IS A DOMAIN WALL?

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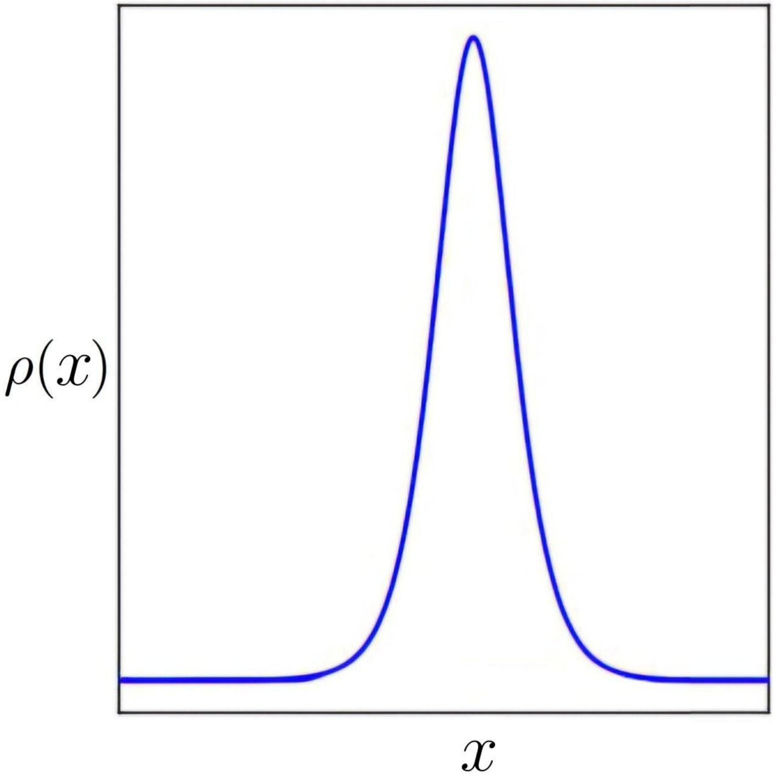
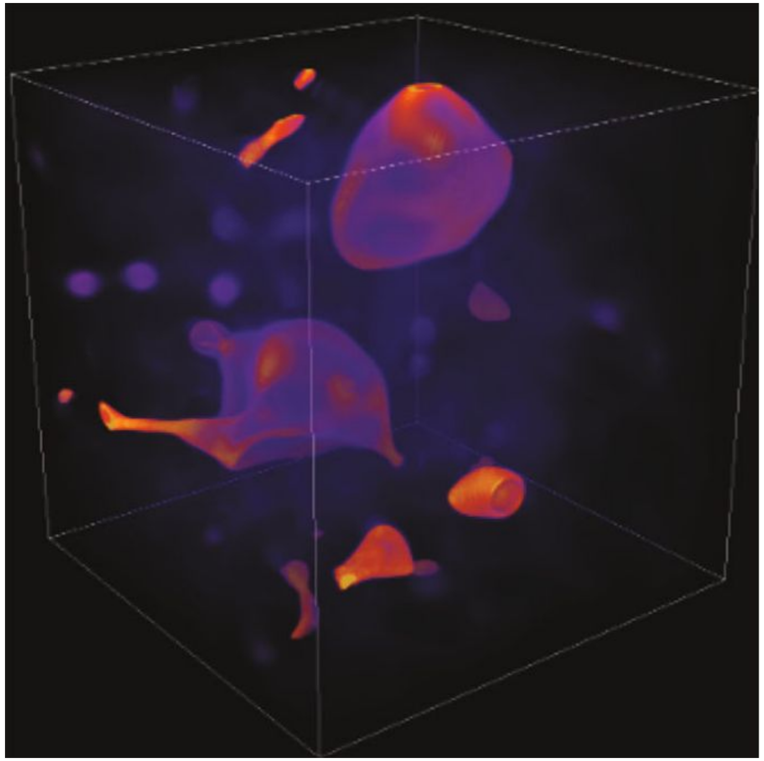
The domain wall is a nonzero energy density separating the vacuum states of the field



The energy density of the field that creates the wall

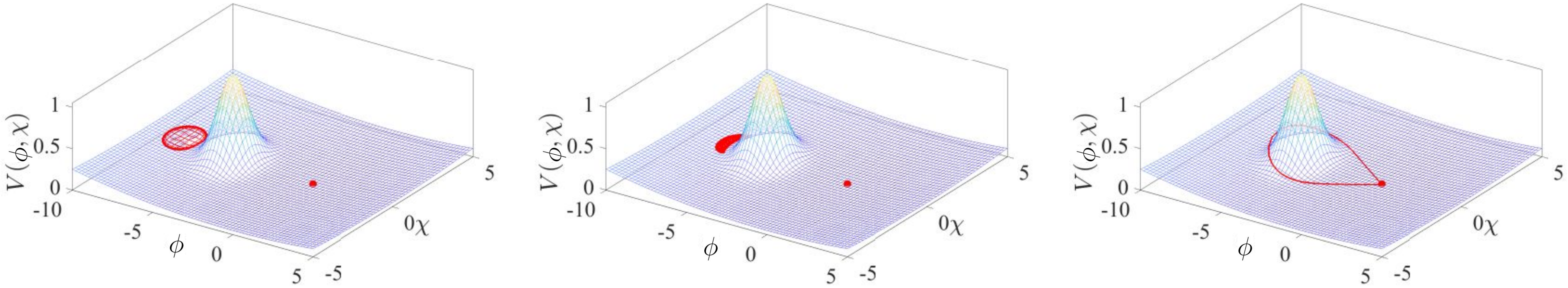


The energy density of the field in three-dimensional space

Kirillov et al., Phys. Lett. B 860 (2025) 139201

WHAT IS A DOMAIN WALL?

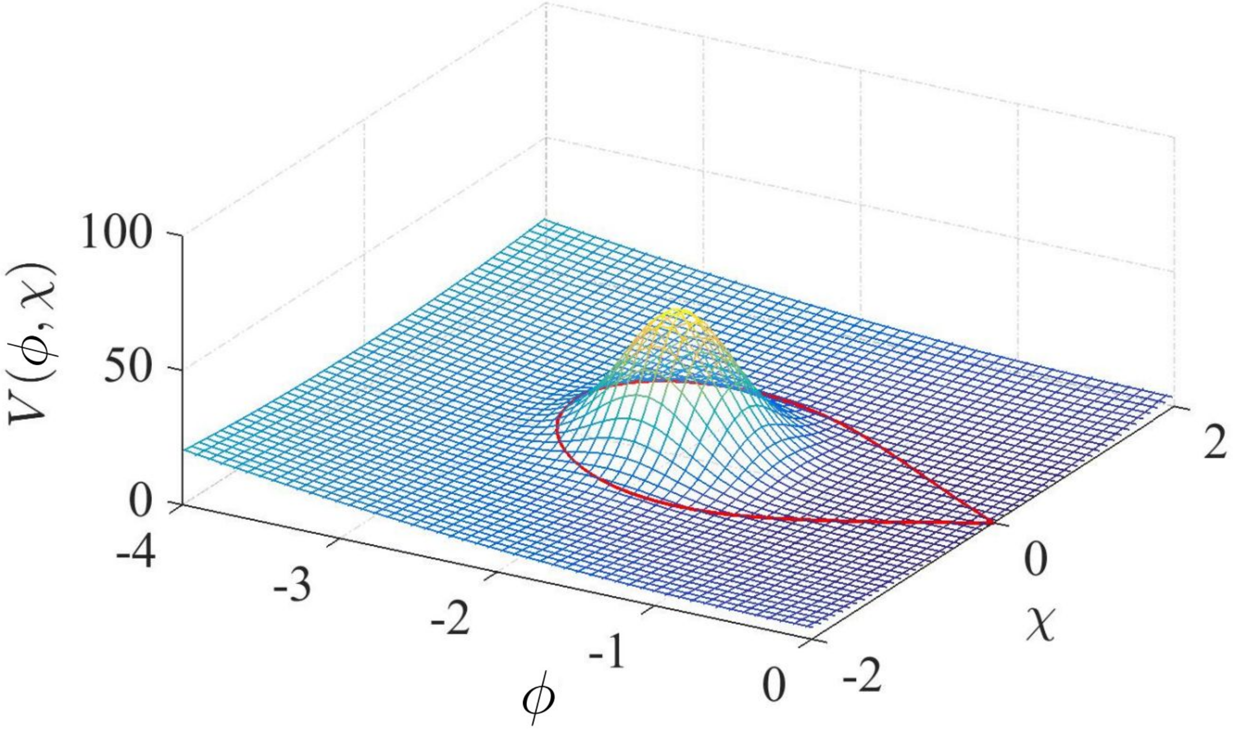
Quantum fluctuations produce spatially inhomogeneous initial fields that go around the local maximum and roll into the minimum, forming domain walls.



Formation of a domain wall at the inflation stage
Kirillov et al., Physics 3 (2021) 563

TWO-FIELD MODEL

$$V(\phi,\chi) = \frac{m^2}{2}(\phi^2+\chi^2) + \Lambda^4 \exp\left[-\frac{(\phi-\phi_0)^2+(\chi-\chi_0)^2}{2\sigma^2}\right],$$



Gani et al., JCAP 04 (2018) 042

where parameters determine the

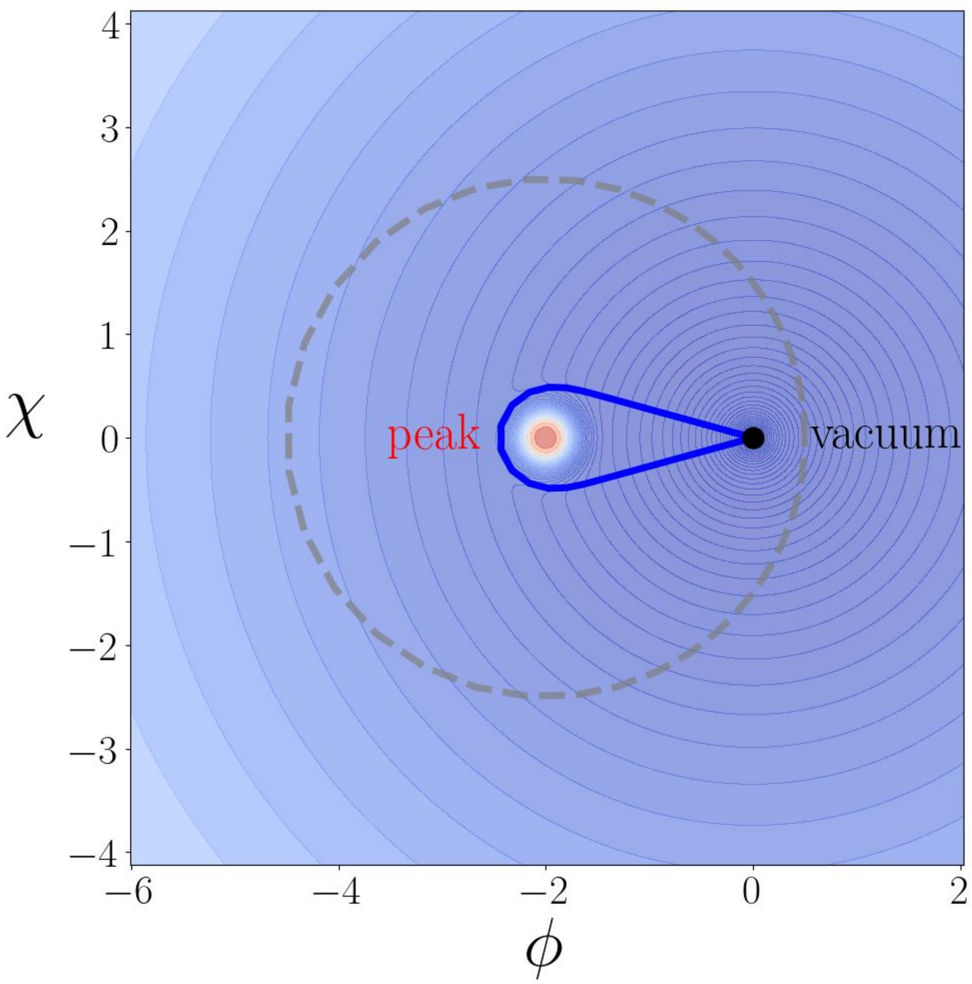
- height Λ
- width σ
- position of the peak ϕ_0, χ_0

INTERACTION OF DW WITH FERMIONS

Equations of motion of the fields

$$\ddot{\phi} + 3H\dot{\phi} - \nabla^2\phi = -\frac{\partial V}{\partial \phi}$$

$$\ddot{\chi} + 3H\dot{\chi} - \nabla^2\chi = -\frac{\partial V}{\partial \chi}$$



Interaction term for the one-dimensional approximation

$$\mathcal{L}_{\text{int}} = gU(x)\bar{\psi}\psi$$

where two barrier cases are possible

$$U(x) = \phi(x) + \chi(x) \quad \text{or} \quad U(x) = \frac{1}{\Lambda}(\phi^2(x) + \chi^2(x))$$

REFLECTION COEFFICIENT

$$U(x) = \phi(x) + \chi(x)$$

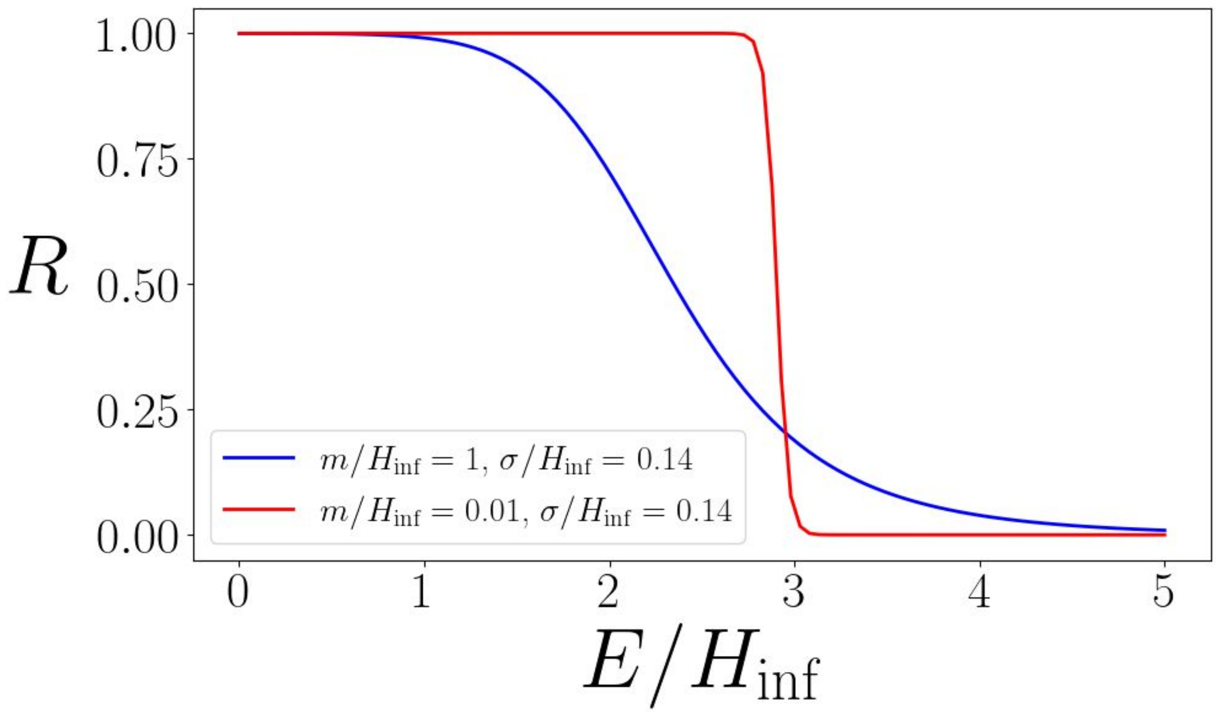


Fig.1 — Reflection coefficient of fermions

$m/H_{inf} = 1$, $\sigma/H_{inf} = 0.14$ - blue line

$m/H_{inf} = 0.01$, $\sigma/H_{inf} = 0.14$ - red line

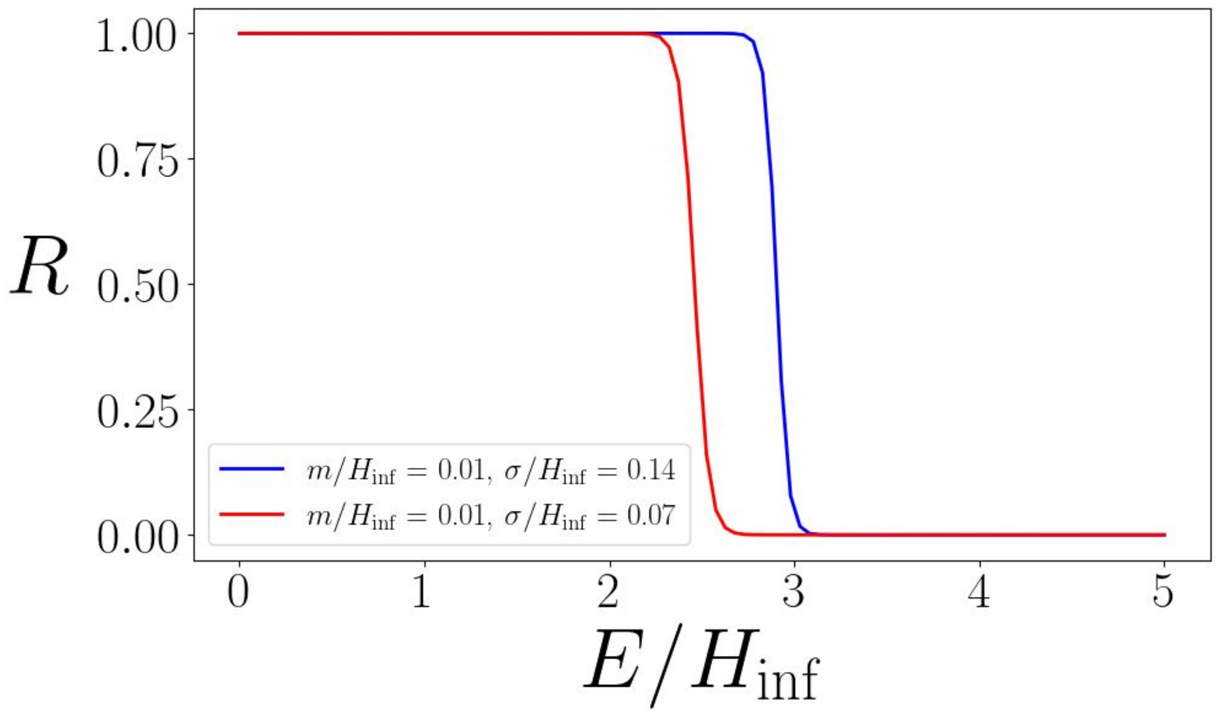
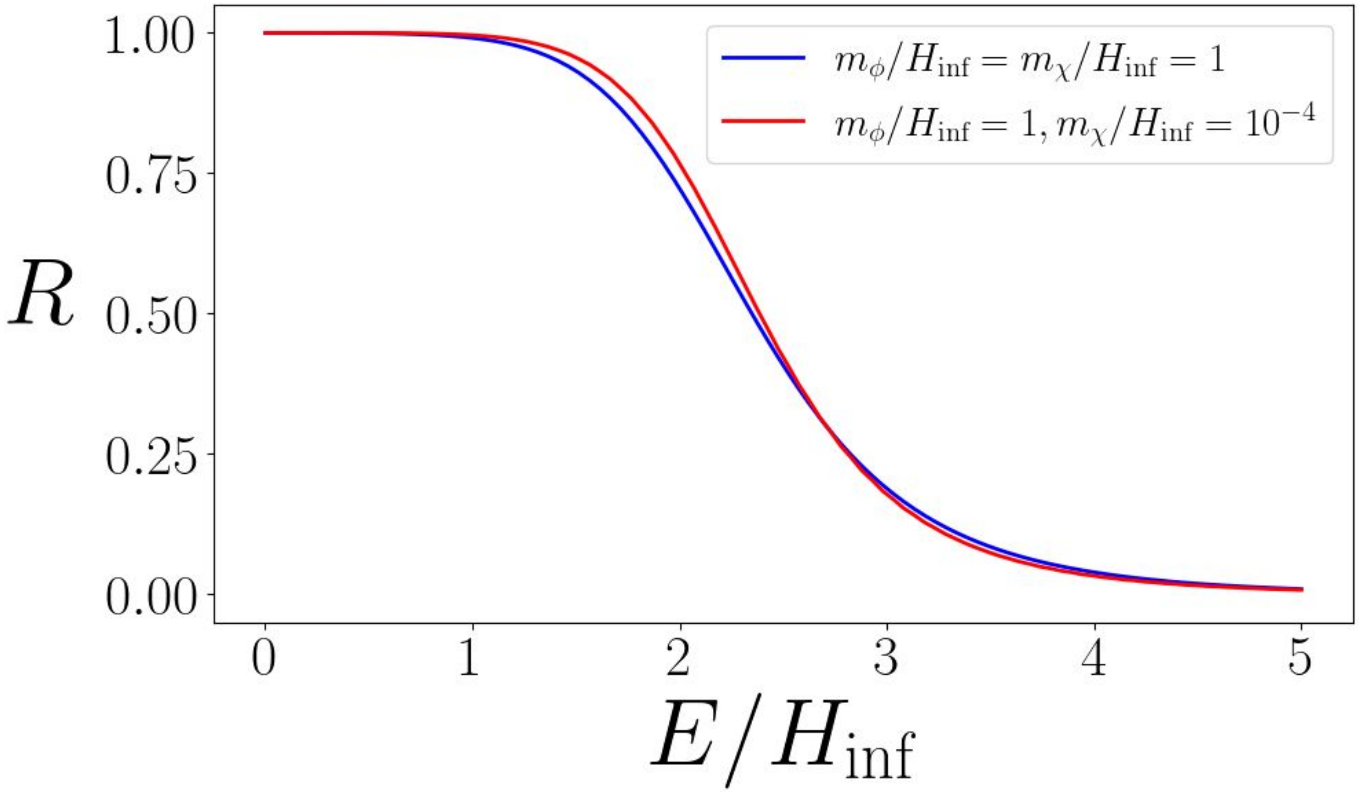


Fig.2 — Reflection coefficient of fermions

$m/H_{inf} = 0.01$, $\sigma/H_{inf} = 0.14$ - blue line

$m/H_{inf} = 0.01$, $\sigma/H_{inf} = 0.07$ - red line

REFLECTION COEFFICIENT



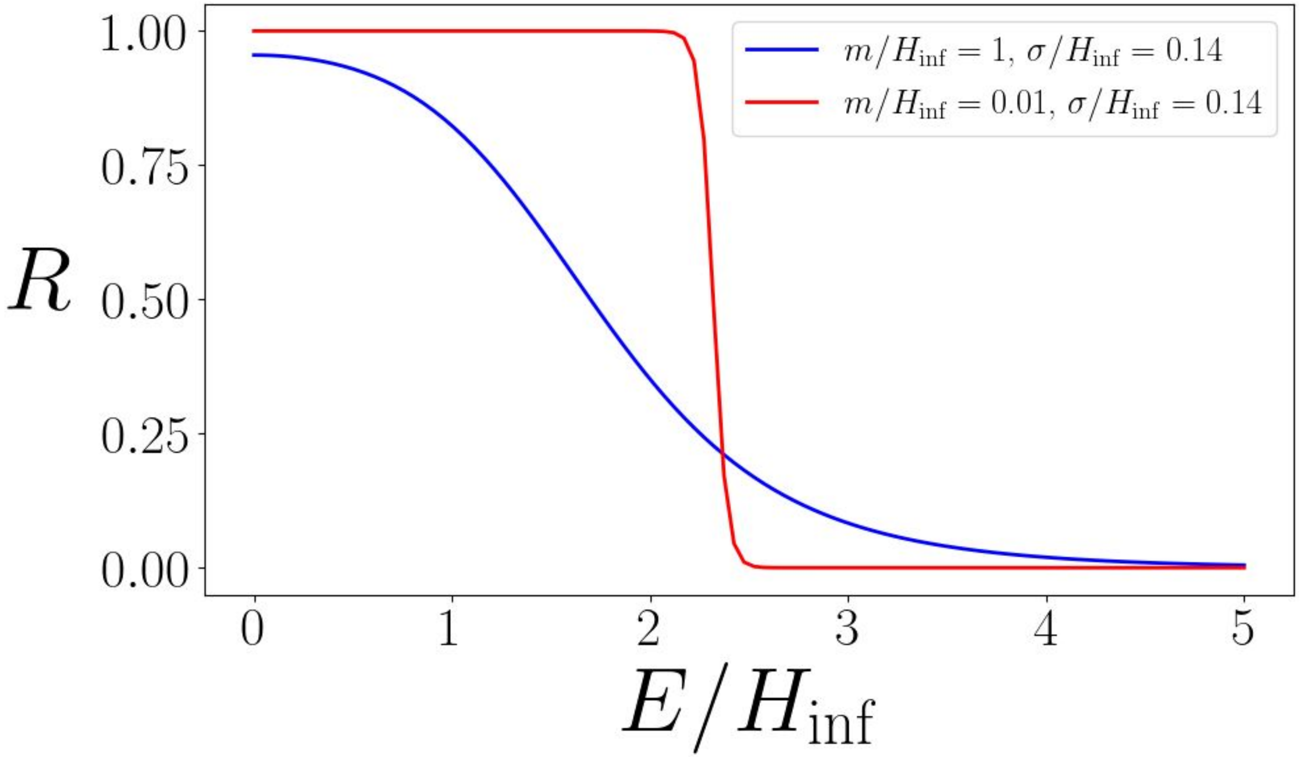
$$U(x) = \phi(x) + \chi(x)$$

Fig.3 — Reflection coefficient of fermions

$m_\phi/H_{inf} = m_\chi/H_{inf} = 1$ - blue line

$m_\phi/H_{inf} = 1$, $m_\chi/H_{inf} = 10^{-4}$ - red line

REFLECTION COEFFICIENT



$$U(x) = \frac{1}{\Lambda}(\phi^2(x) + \chi^2(x))$$

Fig.4 — Reflection coefficient of fermions

m/H_{inf} = 1, σ/H_{inf} = 0.14 - blue line

m/H_{inf} = 0.01, σ/H_{inf} = 0.14 - red line

INTERACTION OF DW WITH ELECTROMAGNETIC FIELD

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Lagrangian of the electromagnetic field with interaction

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}gU(x)F_{\mu\nu}F^{\mu\nu}$$

Possible cases

$$U(x) = \frac{1}{\Lambda}(\phi(x) + \chi(x)) \quad \text{or} \quad U(x) = \frac{1}{\Lambda^2}(\phi^2(x) + \chi^2(x))$$

Electromagnetic properties of the medium

$$\epsilon(x) = 1 + U(x); \quad \mu(x) = \frac{1}{1 + U(x)}$$

Refractive index

$$n = \sqrt{\epsilon\mu} = 1$$

INTERACTION OF DW WITH ELECTROMAGNETIC FIELD

Electromagnetic properties of the medium

$$Z(x) = \sqrt{\frac{\mu}{\epsilon}} = \frac{1}{1 + U(x)}$$

Photons pass through the barrier when the wavelength is much smaller than the barrier scale

$$\lambda \ll d$$

Threshold reflection temperature

$$T_{\rm th} \sim g m U_0$$

Landau, Lifshitz, Electrodynamics of Continuous Media (Vol. 8)

TWO FIELD MODEL

For the following parameters:

- Fermions are trapped inside the wall;
- Photons pass through the wall.

Approximations to be used:

- The domain wall has a spherical shape;
- Primordial plasma is an ideal monatomic gas with a pressure of $P = nT$.

EVOLUTION OF DW

The equation of motion for a spherical wall in **physical coordinates**

Deng et al., JCAP 04 (2017) 050

$$v = \dot{R} - HR$$

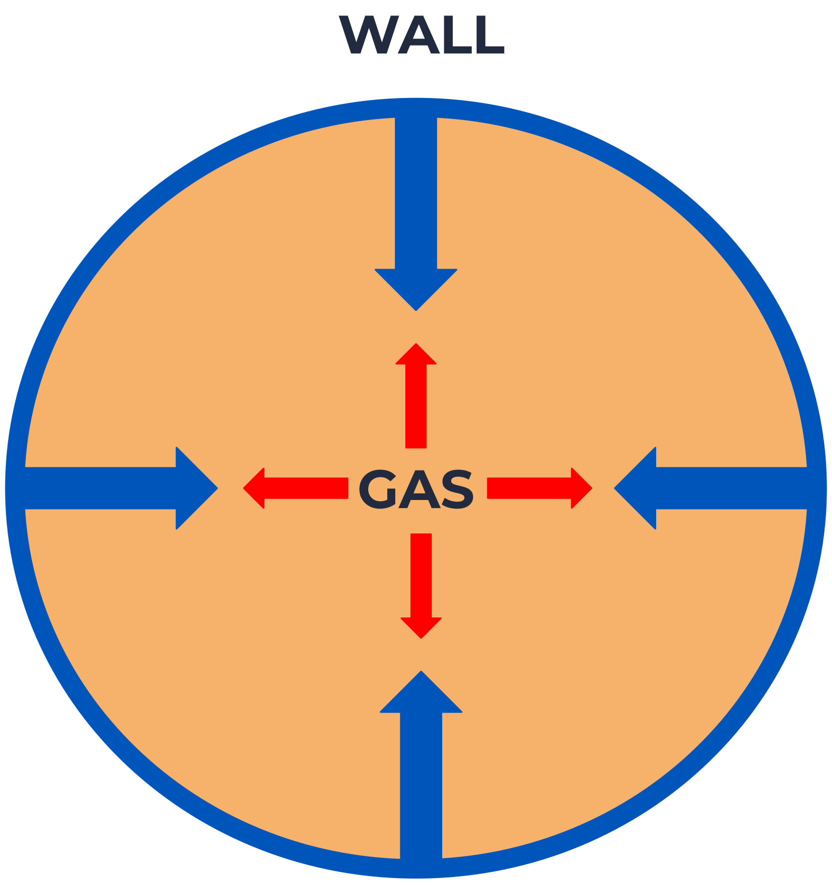
$$\dot{v} = (1 - v^2)\left(-\frac{2}{R} - 3Hv + \frac{P_0}{\mu}\right)$$

Tension force

Hubble flow

Particle pressure

EVOLUTION OF DW



The change in the number density (neglecting reactions that change number of particles)

$$\dot{n_{0j}} = -3\frac{\dot{R}}{R}n_{0j}$$

Plasma composition $j = p, n, e, \nu$

The First Law of Thermodynamics

$$\frac{d}{dt}U_0 = -P_0\frac{dV_0}{dt} - 4\pi R^2\sigma T_0^4$$

EVOLUTION OF DW

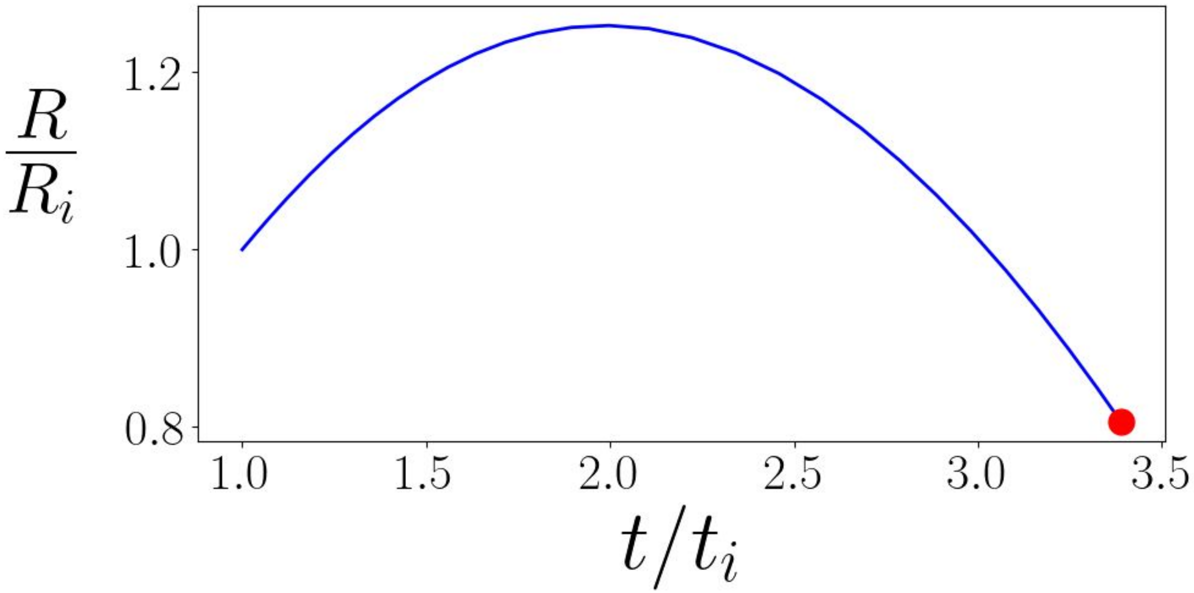


Fig.5 — Evolution of the wall's radius

$R_i = 10^{10}$ cm

$t_i = 0.5$ s

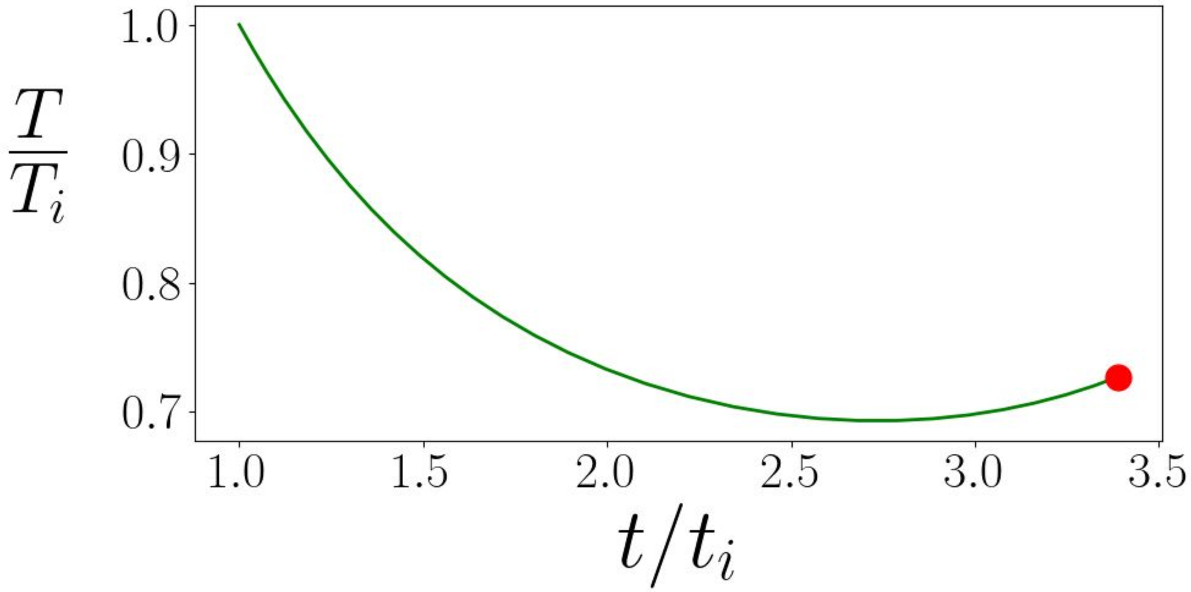
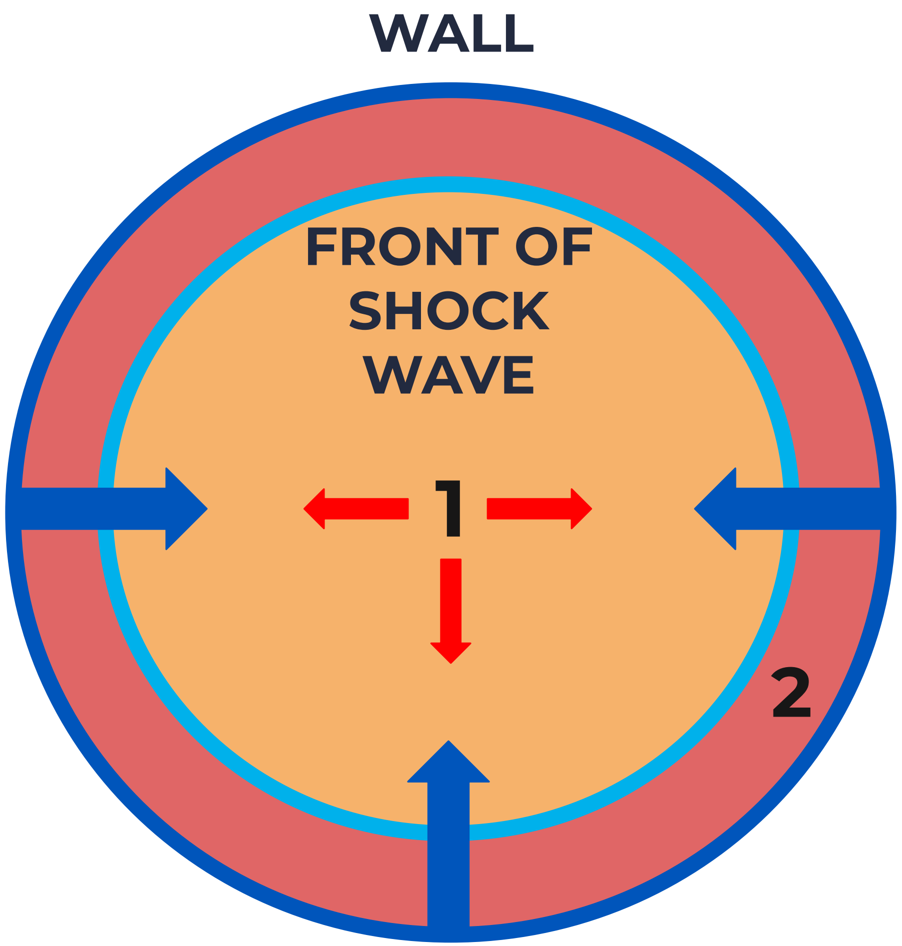


Fig.6 — Evolution of gas temperature

$T_i = 1.5$ MeV

SHOCK WAVE FORMATION



The first law of thermodynamics for layer 2 — the layer between the wall and the front of shock wave

$$\frac{dU_2}{dt} = -P_2\frac{dV_2}{dt} - 4\pi R^2\sigma T_2^4 - \dot{N}_1 \cdot \frac{\varepsilon_1 + P_1}{n_1}$$

Changes in the number density in layer 2 occurs due to:

- changes in the volume;
- flow of matter from layer 1.

Landau, Lifshitz, Fluid Mechanics (Vol. 6)

NUMERICAL SOLUTION

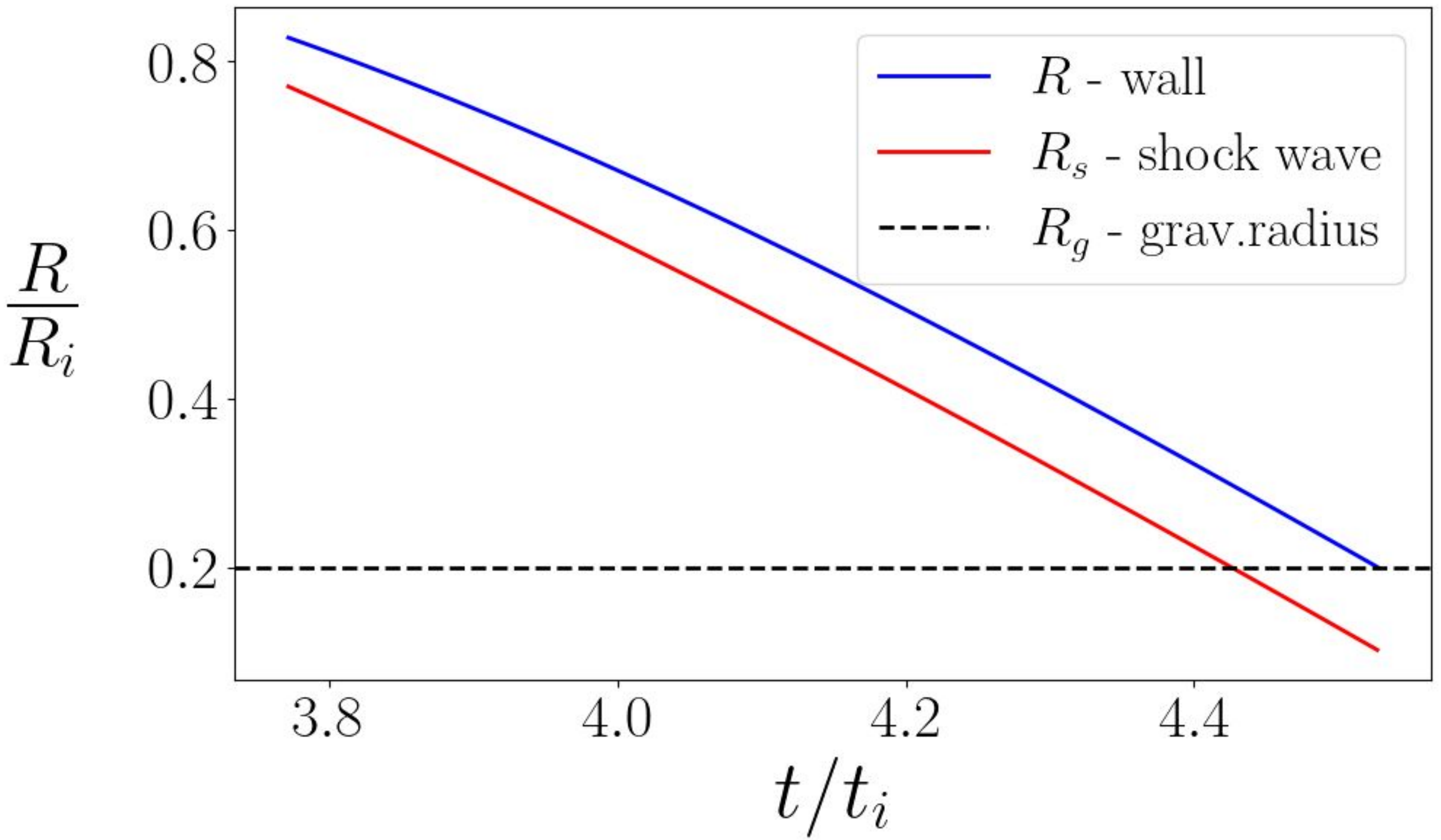


Fig.7 — Evolution of the DW radius and shock wave

NUMERICAL SOLUTION

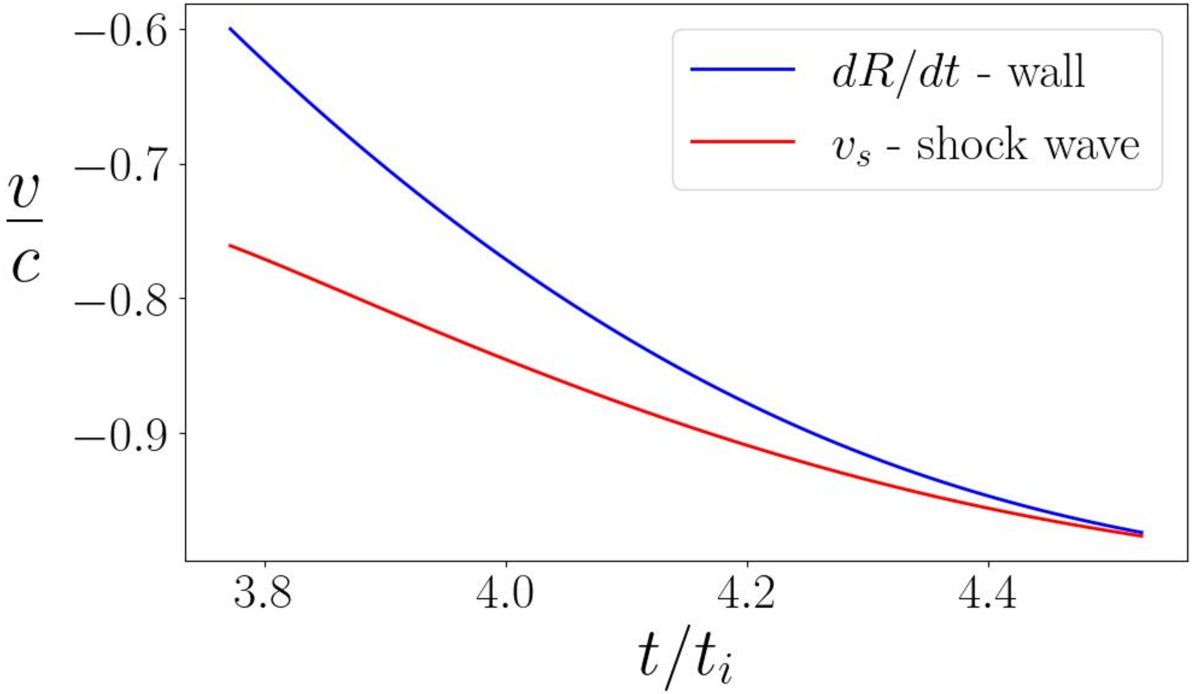


Fig.8 — Velocity evolution of the shock wave and DW

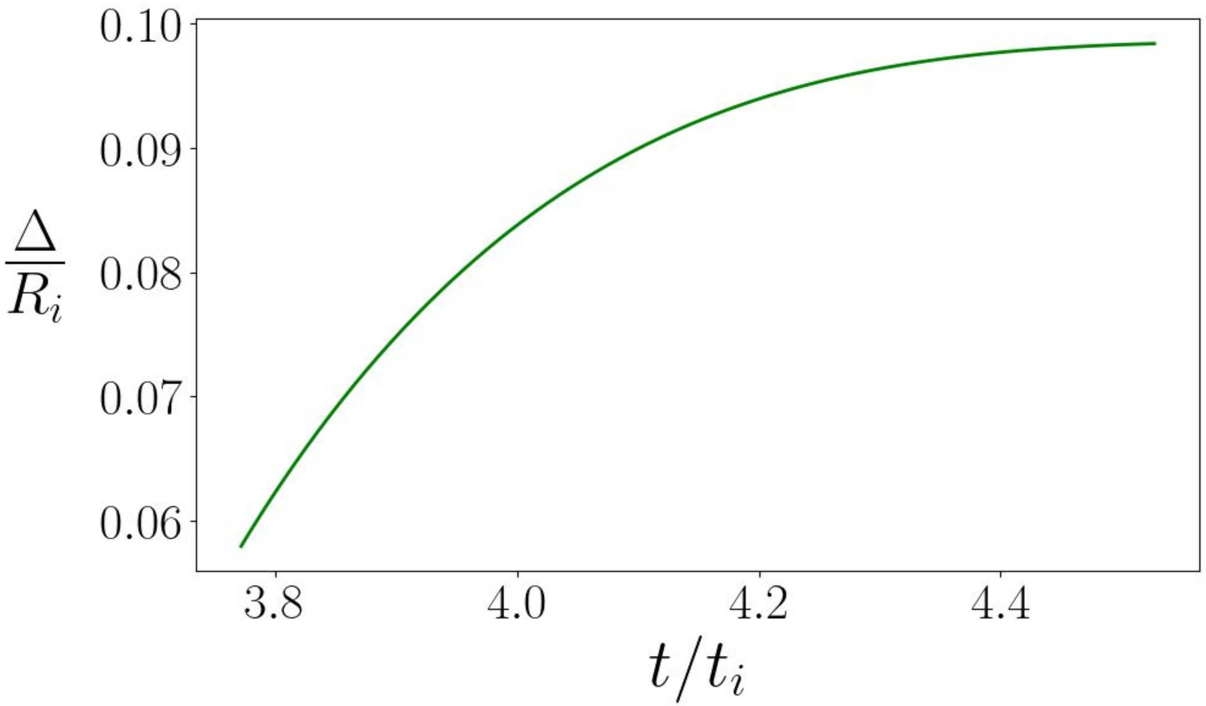


Fig.9 — Evolution of layer 2 thickness

NUMERICAL SOLUTION

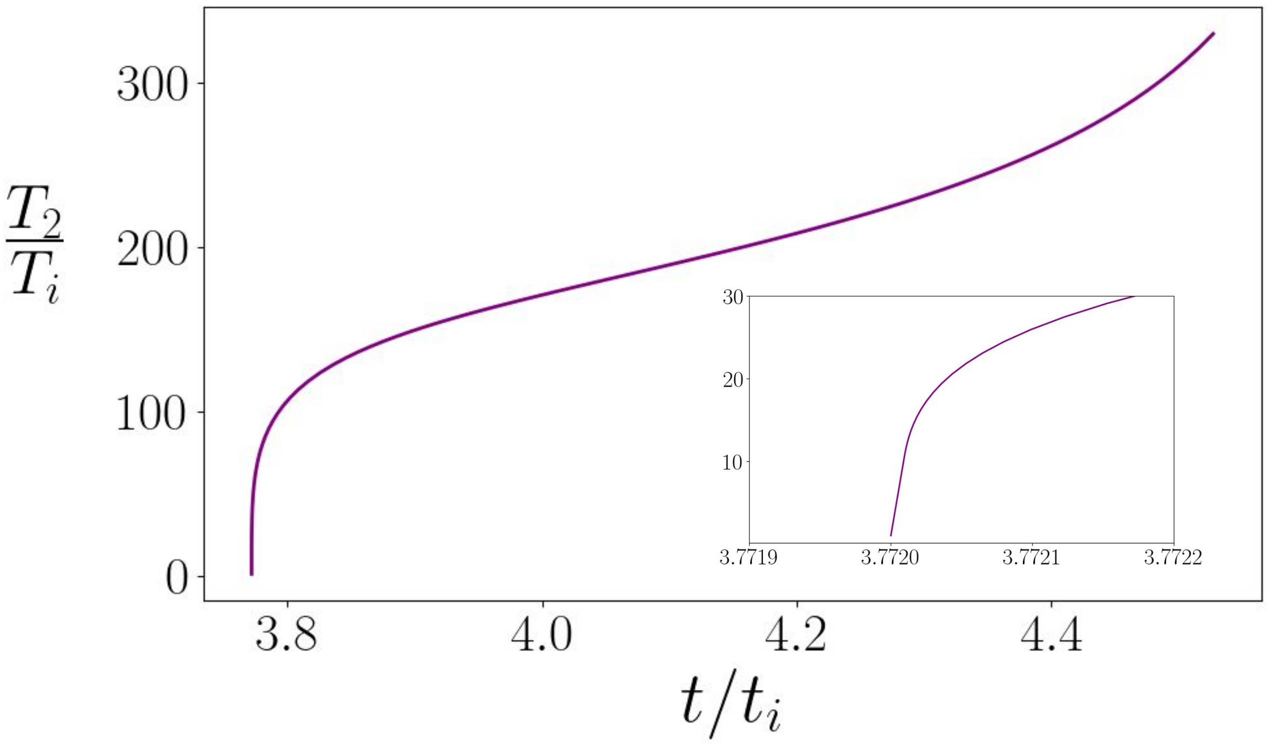


Fig.10 — Temperature evolution in layer 2

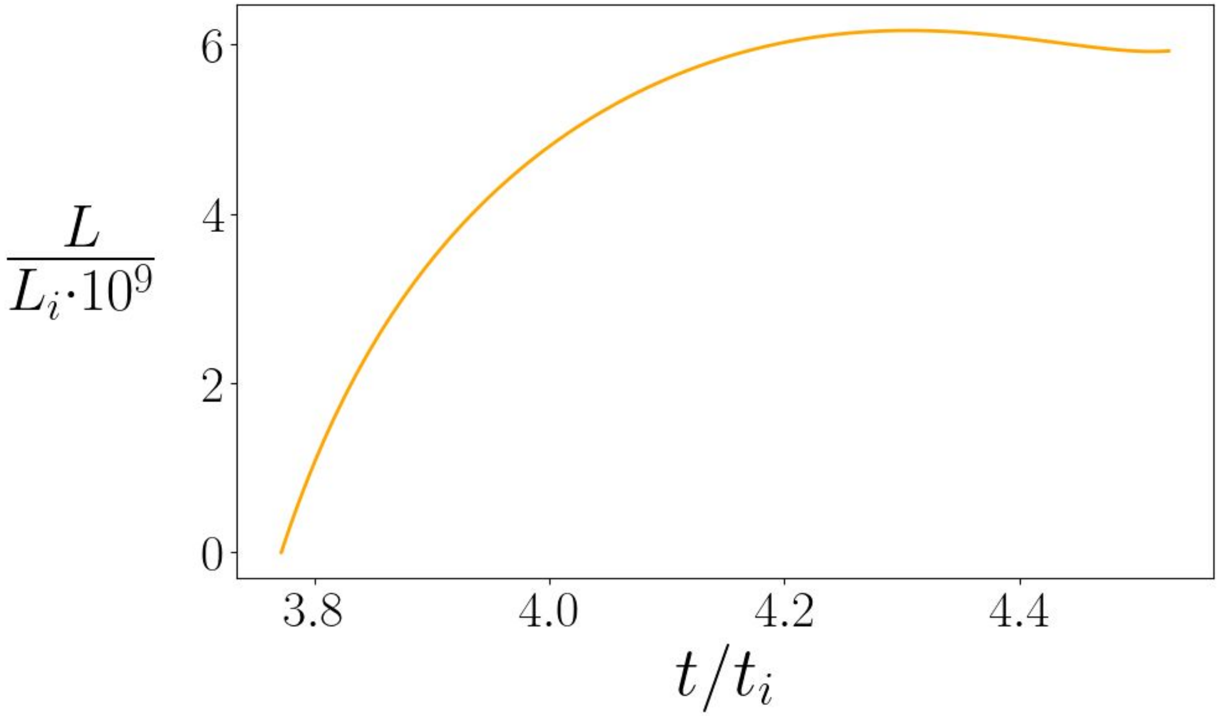


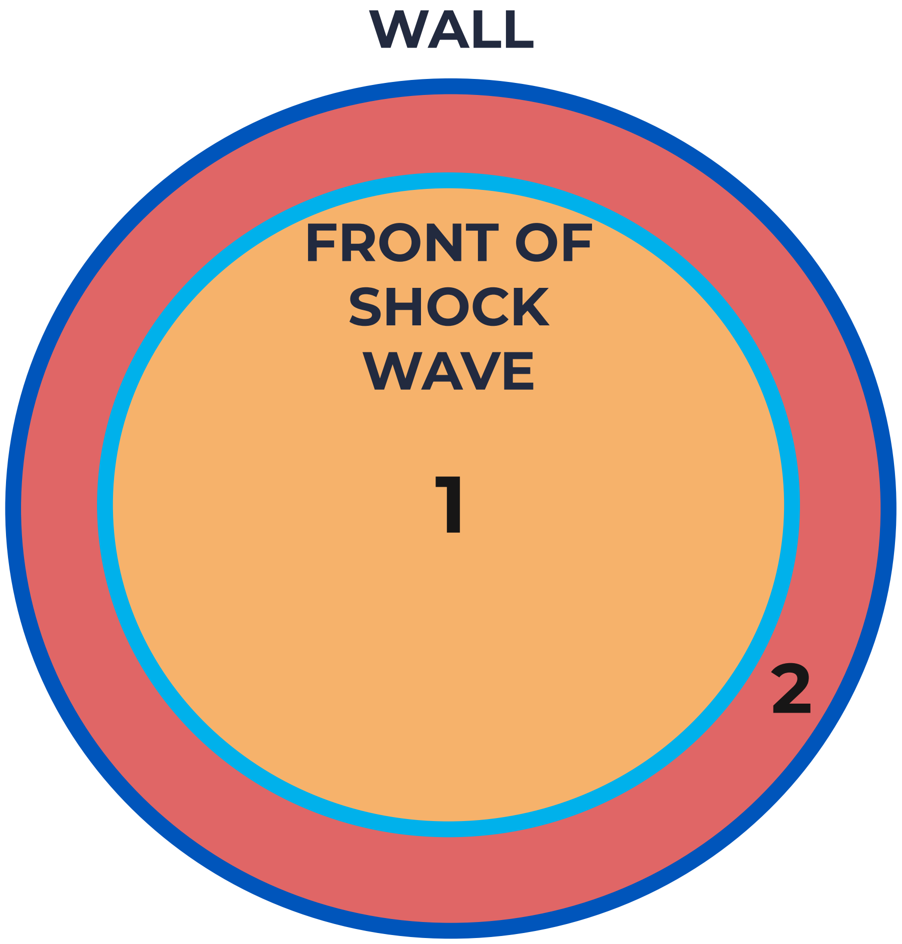
Fig.11 — Evolution of luminosity

NUMERICAL SOLUTION

	Time of crossing the horizon	Time of the black hole formation
Wall radius R	1	0.2
Temperature in layer 2 T_2	1	329
Luminosity L	1	$6 \cdot 10^9$

Table 1 — Statistics of results in dimensionless units

LAYER HOMOGENEOUS ANALYSIS



In the numerical solution, layer 2 was assumed to be homogeneous.

A layer can be considered homogeneous if

$$\frac{d\Delta}{dt} < c_s \sim 0.57$$

LAYER HOMOGENEOUS ANALYSIS

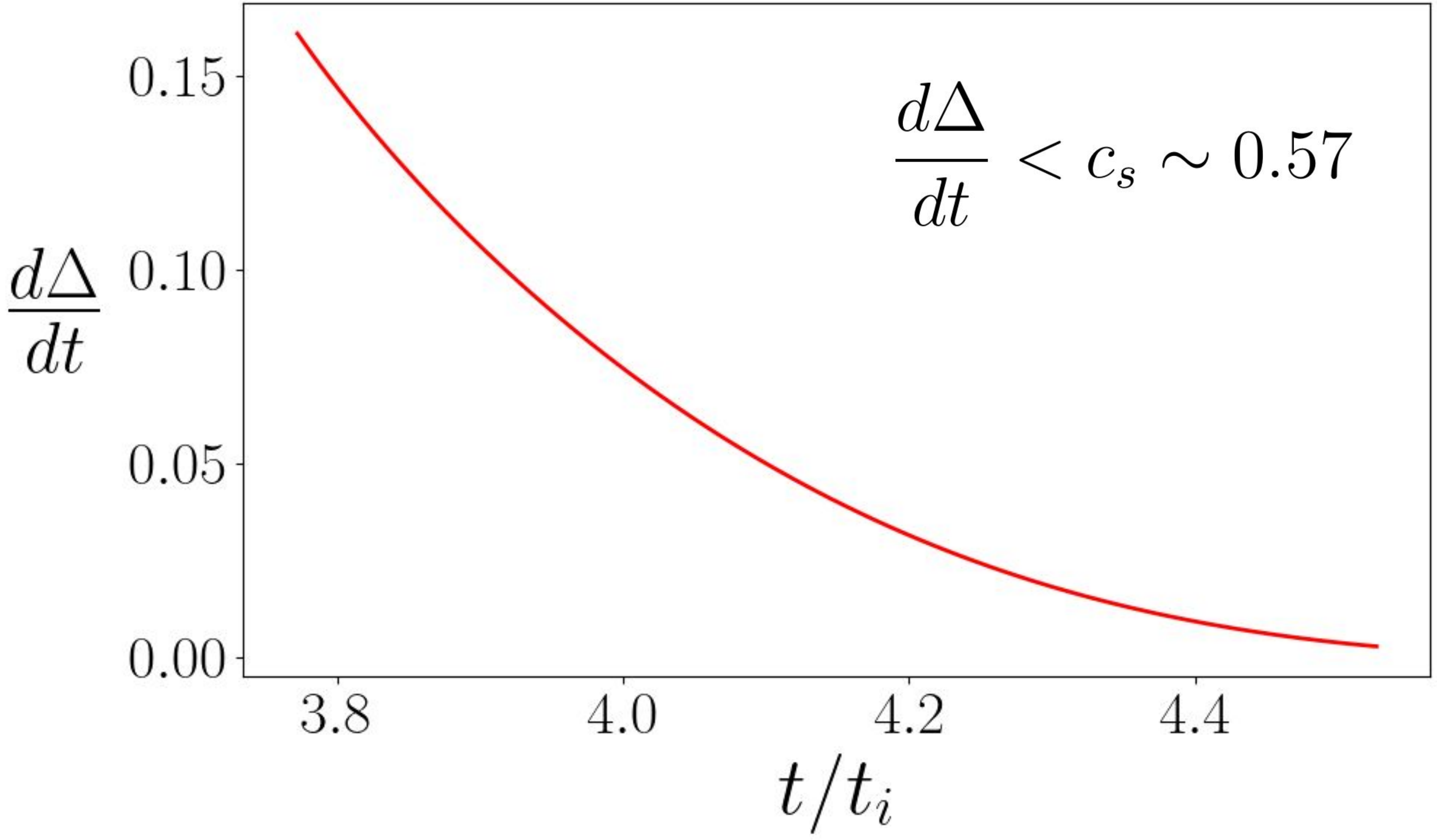
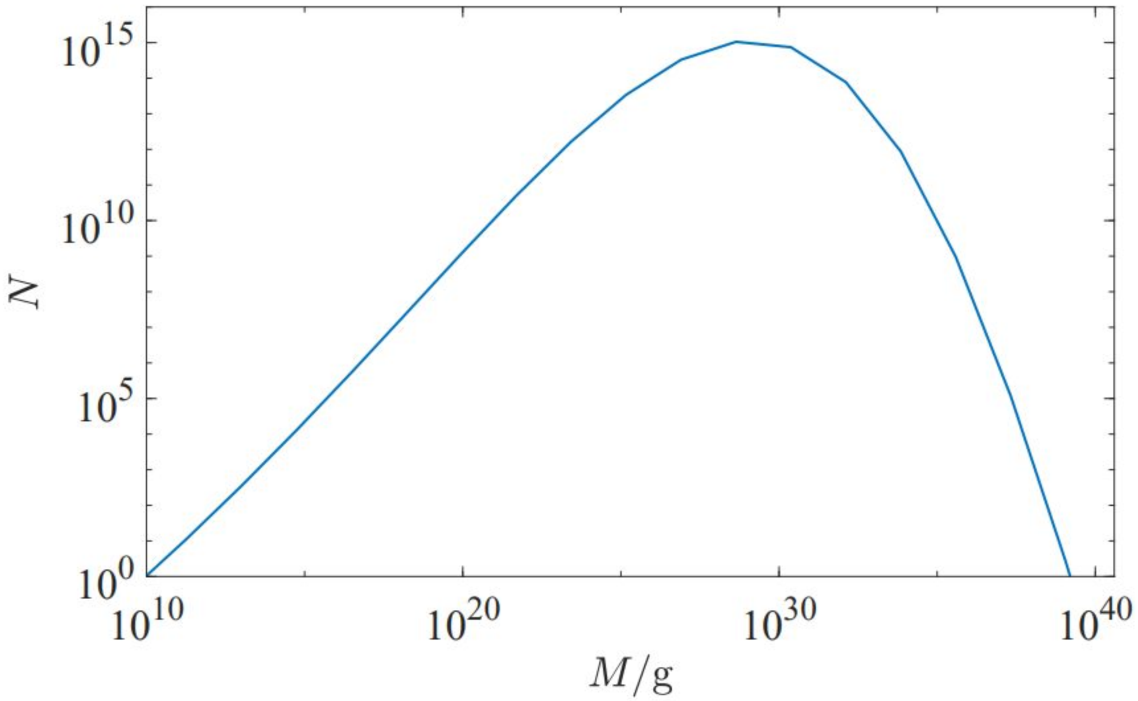


Fig.12 — Evolution of layer 2 thickness

COMPARISON OF FIELD MODELS

In two field model $V(\phi, \chi) = \frac{m^2}{2}(\phi^2 + \chi^2) + \Lambda^4 \exp\left[-\frac{(\phi - \phi_0)^2 + (\chi - \chi_0)^2}{2\sigma^2}\right]$

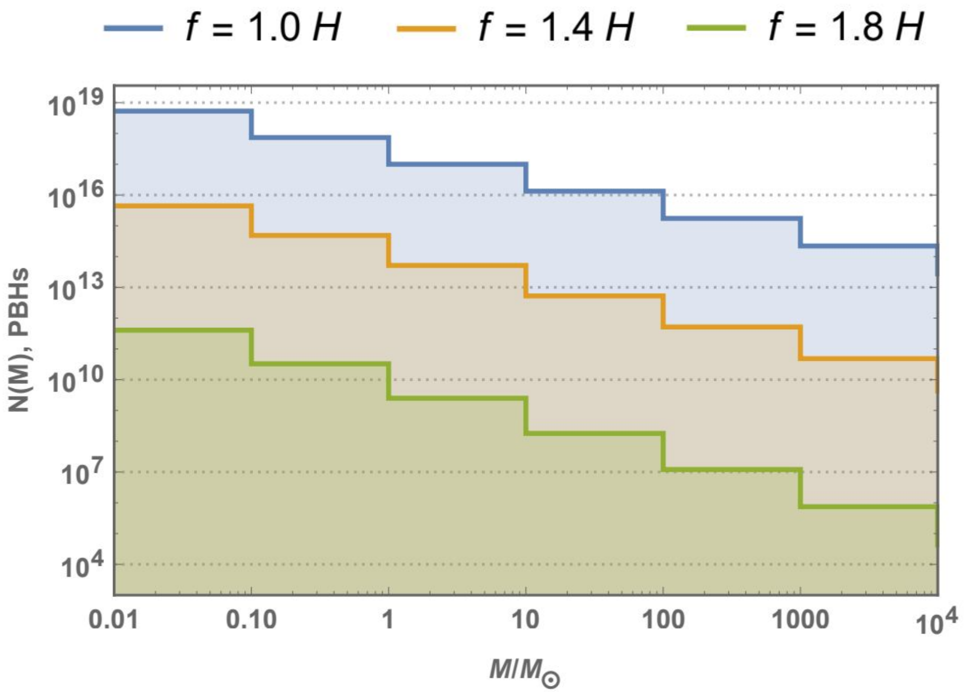


The PBHs mass distribution formed from DWs
Kirillov, Rubin, Front. Astron. Space Sci. 8 (2021) 777661

- ❑ Fermions are locked inside the DW;
- ❑ The wall is transparent to photons without polarization.

COMPARISON OF FIELD MODELS

In ALP model $$V = \frac{1}{4}\left(\phi^*\phi - \frac{f^2}{2}\right)^2 + \Lambda^4(1-\cos(\theta))$$



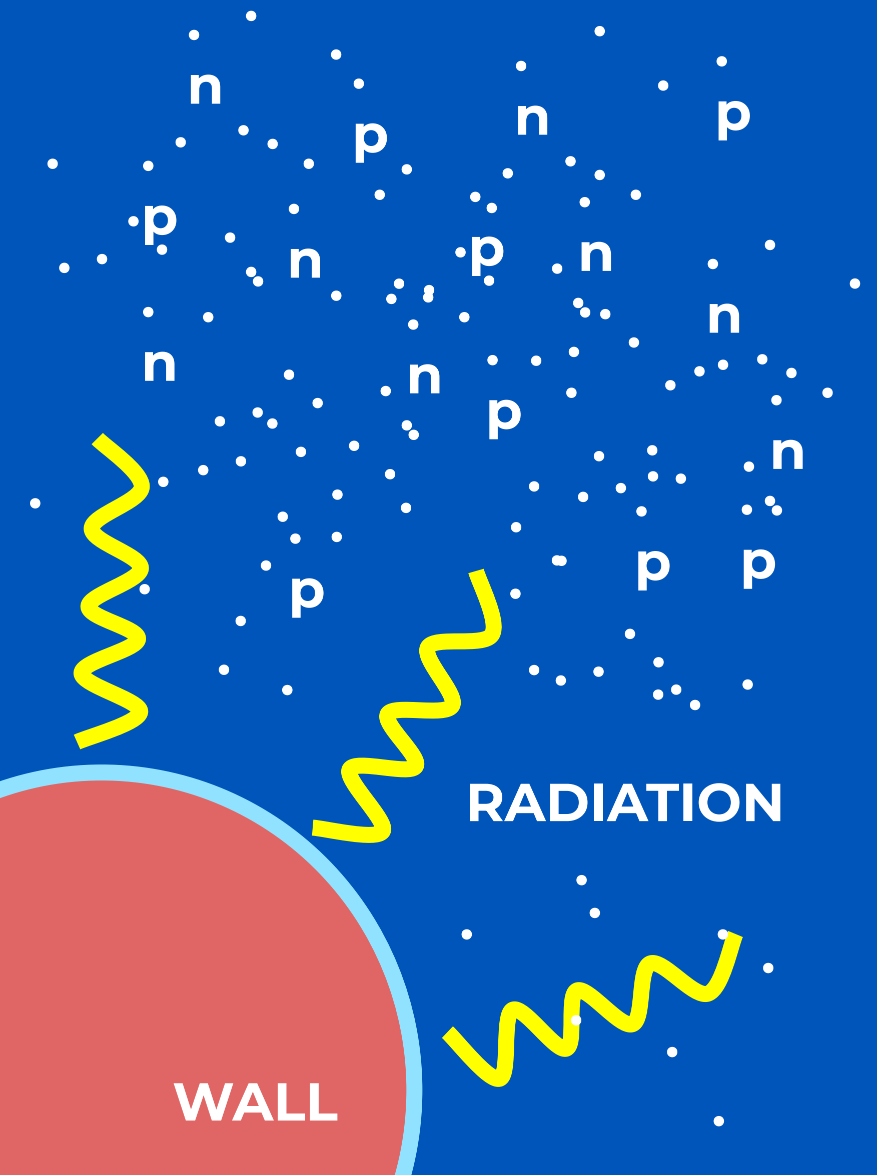
The PBHs mass distribution formed from DWs
Belotsky et al., Eur. Phys. J. C 79 (2019) 246

- Fermions pass through the wall;
  Rubin et al., JETP 91 (2001) 921
  Blasi et al., JCAP 04 (2023) 008

$$P \propto \frac{\Lambda^8}{f^4} \longrightarrow \frac{T_2}{T_1} \ll 1$$

- The wall is transparent to photons, and polarization is possible.
  Blasi, JHEP 05 (2025) 013

RESULTS



If DW collapse <u>before</u> BBN

↓

Gas heating outside the wall

↓

Local return to n ↔ p equilibrium

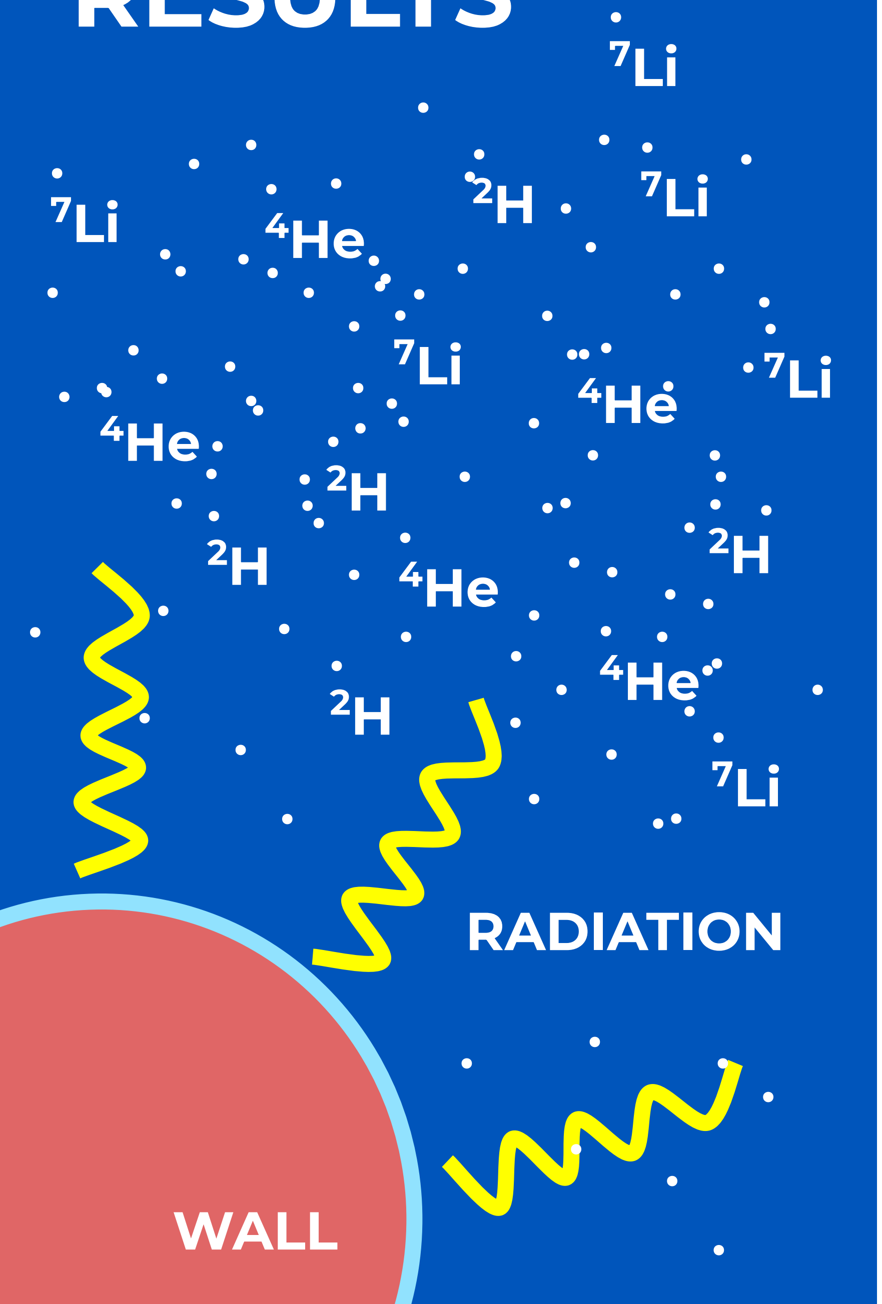
↓

n/p freezes out at a different value

↓

Local anomaly of primordial abundances

RESULTS



If DW collapse <u>after</u> BBN

↓

Gas heating outside the wall

↓

Photodissociation destroys ^{2}H

↓

Proton reactions destroy ^{7}Li

↓

^{4}He remains intact

THANK YOU FOR YOUR ATTENTION

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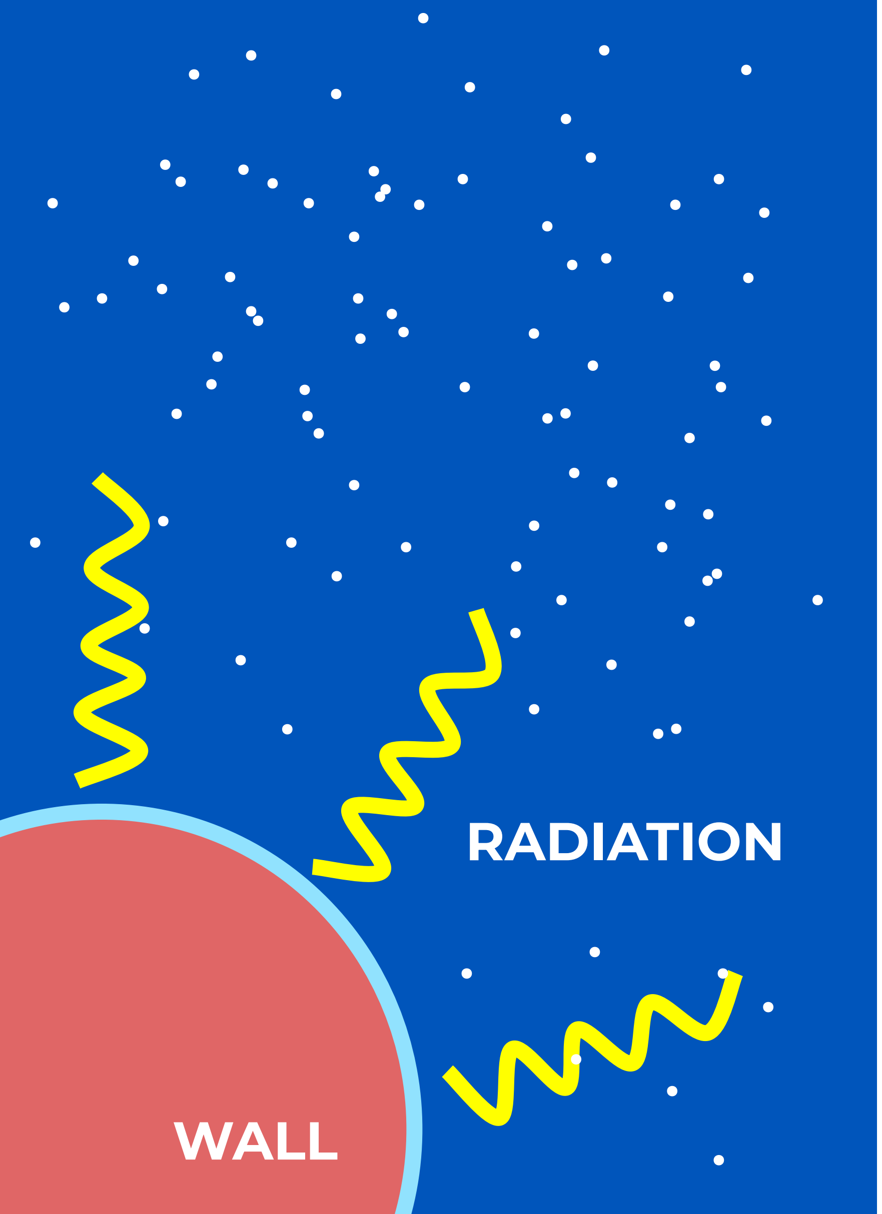
National Research
Nuclear University

ADDITIONAL SLIDES

RESULTS



If DW collapse <u>after</u> BBN

$$T_{\rm bg} = 0.01 \text{ MeV}$$

$$T_{\rm DW} = 330 \times T_{\rm bg} \approx 3.3 \text{ MeV}$$

D	$d + \gamma \to p + n$
D	$d + p \to {}^3\text{He} + \gamma$
D	$d + d \to {}^3\text{He} + n$
D	$d + d \to {}^3\text{H} + p$

^{3}He	${}^3\text{He} + \gamma \to d + p$
^{3}He	${}^3\text{He} + d \to {}^4\text{He} + p$
^{3}He	${}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + 2p$

^{7}Li	${}^7\text{Li} + p \to {}^4\text{He} + {}^4\text{He}$

SIMILAR MODELS

- Baryogenesis during reheating in natural inflation

  A. Dolgov et al., Phys. Rev. D 56 (1997) 6155

- Multi-stream inflation

  M. Li and Y. Wang, JCAP 07 (2009) 033

- Hybrid inflation

  A. Linde, Phys. Rev. D 49 (1994) 748

REFLECTION COEFFICIENT

$$\gamma^0 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \gamma^1 = i\sigma_z = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}, \quad \psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

$$\psi(t,x) = e^{-iEt}\psi(x)$$

$$\psi_1' = -V\psi_1 + E\psi_2$$

$$\psi_2' = -E\psi_1 + V\psi_2$$

REFLECTION COEFFICIENT

$$\psi_1 = ae^{iEx} + be^{-iEx}$$
$$\psi_2 = iae^{iEx} - ibe^{-iEx}$$

Right — Only the transmitted wave **Left—** Superposition of the incident and reflected waves

$$\begin{pmatrix}\psi_1(x_R)\\ \psi_2(x_R)\end{pmatrix} = \begin{pmatrix}1\\ i\end{pmatrix} e^{iEx_R}$$

$$\psi_1(x_L) = a\, e^{iEx_L} + b\, e^{-iEx_L}, \qquad \psi_2(x_L) = ia\, e^{iEx_L} - ib\, e^{-iEx_L}$$

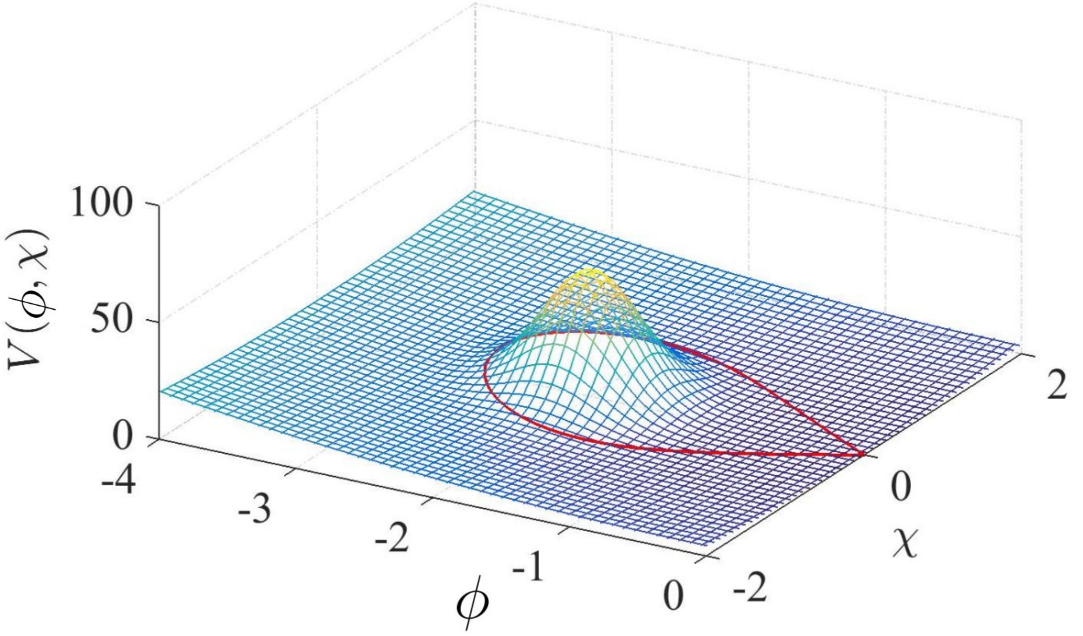
$$a = \frac{\psi_1(x_L) - i\psi_2(x_L)}{2}\, e^{-iEx_L}$$
$$b = \frac{\psi_1(x_L) + i\psi_2(x_L)}{2}\, e^{iEx_L}$$

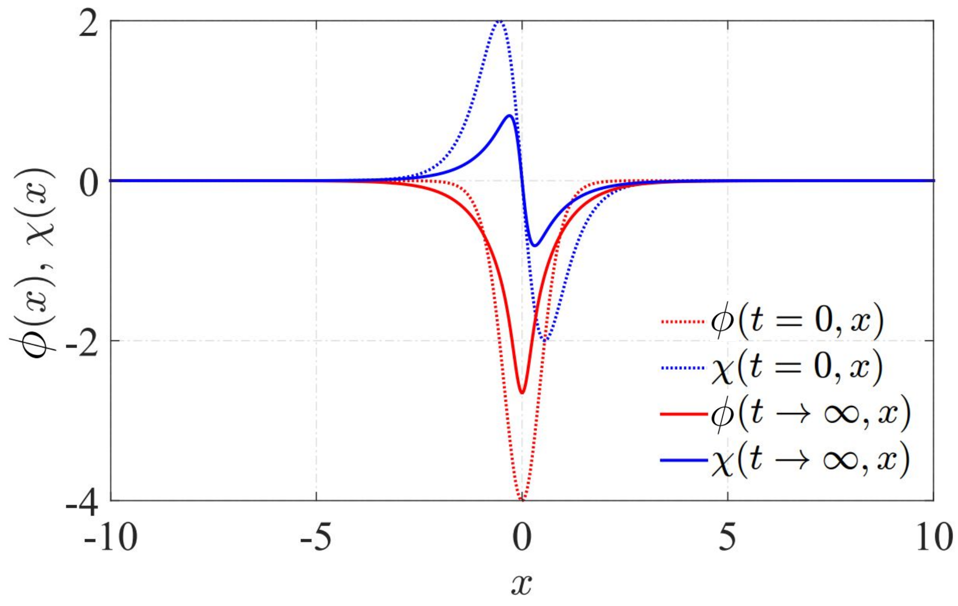
$$R = \left|\frac{b}{a}\right|^2 = \left|\frac{\psi_1(x_L) + i\psi_2(x_L)}{\psi_1(x_L) - i\psi_2(x_L)}\right|^2$$

TWO-FIELD MODEL

$$V(\phi,\chi)=\frac{m^2}{2}(\phi^2+\chi^2)+\Lambda^4\exp\left[-\frac{(\phi-\phi_0)^2+(\chi-\chi_0)^2}{2\sigma^2}\right],$$

$\mu \sim m(\phi_0^2+\chi_0^2)$ - surface energy density



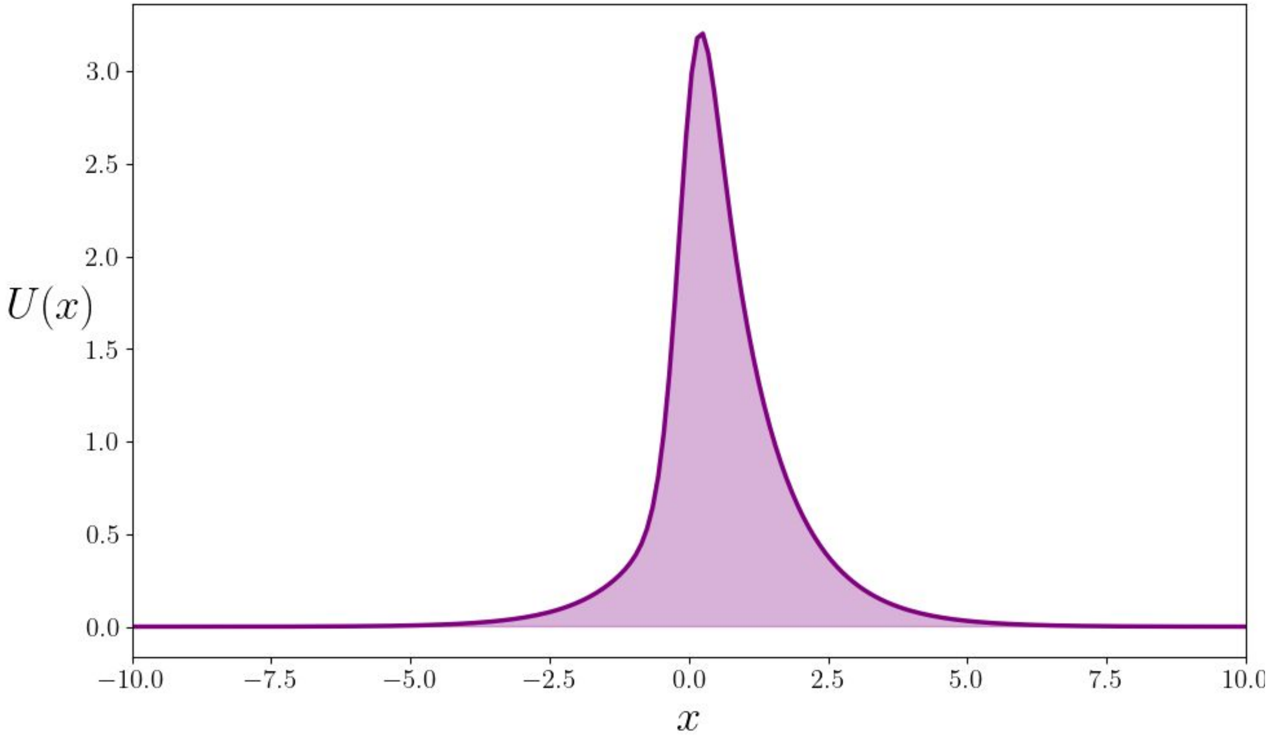


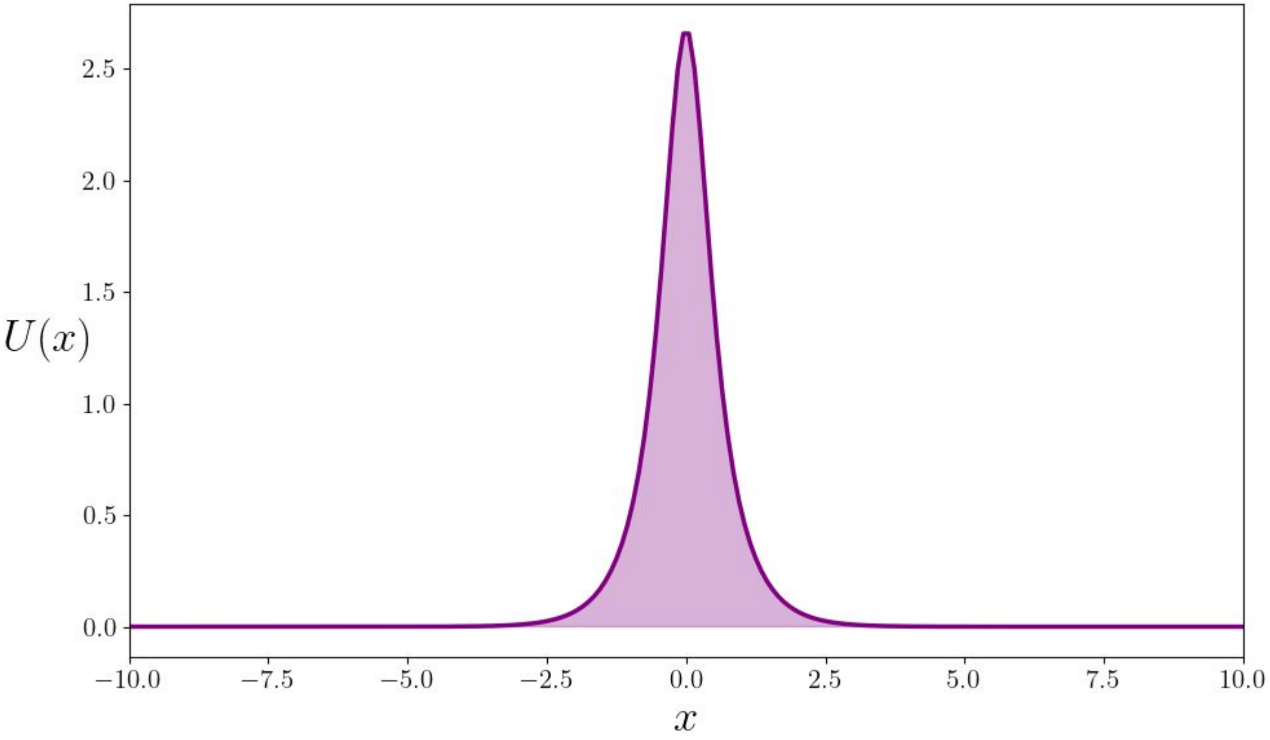
Gani et al., JCAP 04 (2018) 042

REFLECTION COEFFICIENT

$$U(x) = \phi(x) + \chi(x)$$

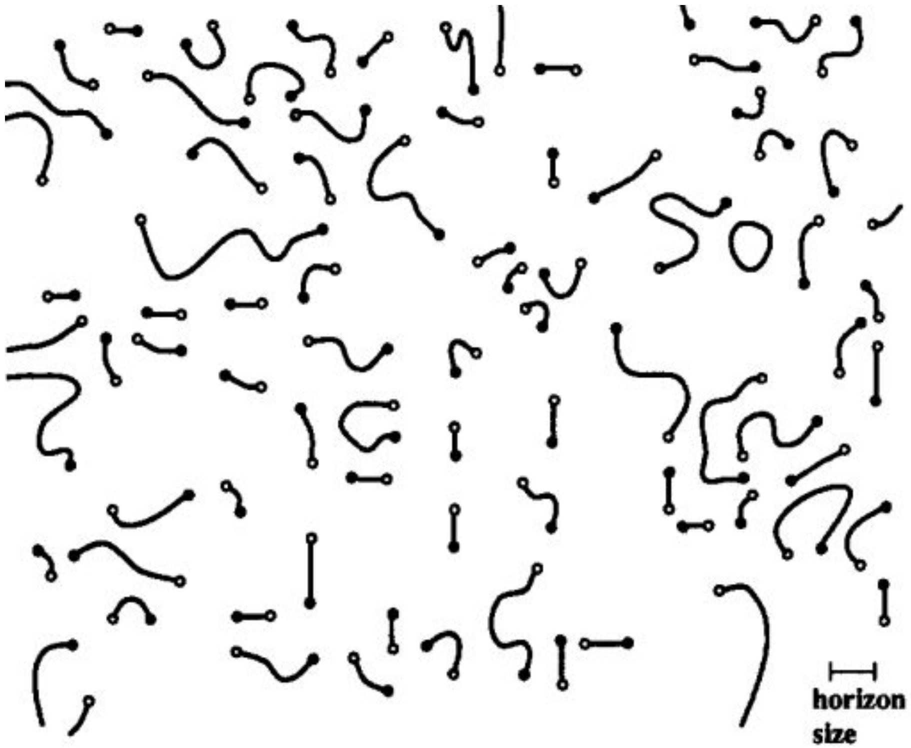
$$U(x) = \frac{1}{\Lambda}(\phi^2(x) + \chi^2(x))$$





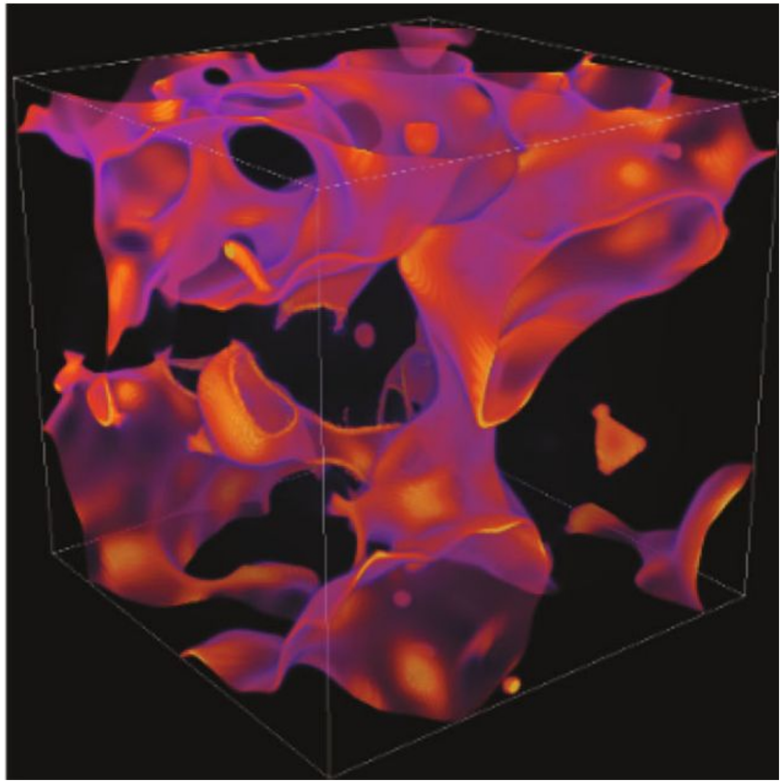
COMPARISON OF FIELD MODELS

In ALP model



The string-wall network
S. Chang et al., Nuclear Physics B 72 (1999) 99-104

In two field model



The soliton foam cluster in three-dimensional space
Kirillov et al., Phys. Lett. B 860 (2025) 139201

INTERACTION OF DW WITH ELECTROMAGNETIC FIELD

Lagrangian of the free electromagnetic field

$$\mathcal{L} = \frac{1}{2}\left(\epsilon \mathbf{E}^2 - \frac{1}{\mu}\mathbf{B}^2\right)$$

The case of interaction

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V(x)F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left((1+V)\mathbf{E}^2 - (1+V)\mathbf{B}^2\right)$$

Comparing these two cases

$$\epsilon = 1 + V(x) \quad \frac{1}{\mu} = 1 + V(x) \quad \boxed{n = \sqrt{\epsilon\mu} = 1} \quad Z(x) = \sqrt{\frac{\mu}{\epsilon}} = \frac{1}{1+V(x)}$$

INTERACTION OF DW WITH ELECTROMAGNETIC FIELD

$$\mathcal{L} = -\frac{1}{4}\left(1 + V(x)\right) F_{\mu\nu} F^{\mu\nu}$$

$$E_y(x,t) = E(x) e^{-i\omega t}, \; H_z(x,t) = H(x) e^{-i\omega t}$$

$$V \to 0$$

$$\frac{d}{dx}\Big((1+V)E'\Big) + \omega^2 (1+V) E = 0$$

$$(1) \cdot E'' + 0 \cdot E' + \omega^2 (1) \cdot E = 0 \implies E'' + \omega^2 E = 0$$

$$E(x) = \frac{\mathcal{E}(x)}{\sqrt{1 + V(x)}}$$

$$\mathcal{E}'' + \left[\omega^2 - U(x)\right] \mathcal{E} = 0 \qquad U(x) = \frac{V''}{2(1+V)} - \frac{(V')^2}{4(1+V)^2}$$

$$k(x) = \sqrt{\omega^2 - U(x)}, \qquad \left|\frac{k'(x)}{k^2(x)}\right| \ll 1 \qquad \lambda \ll d$$

$$V' \sim V_0/d \qquad V'' \sim V_0/d^2 \qquad d \sim 1/m$$

$$\boxed{T_{\text{th}} \sim g m U_0}$$

HYDRODYNAMICS OF THE SHOCK WAVE

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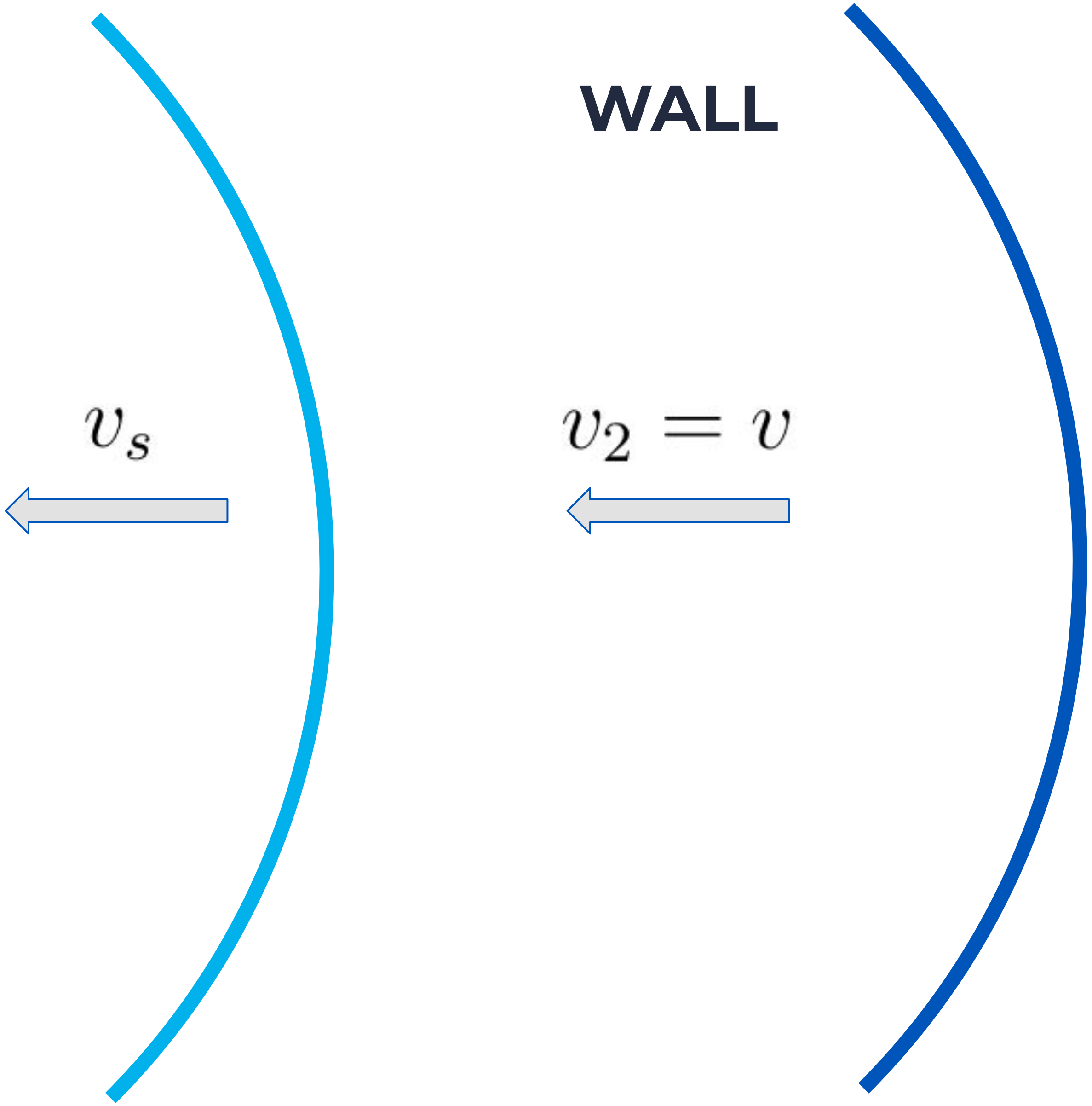
Rankine-Hugoniot conditions in the rest system of the shock wave front $v_s' = 0$

$$\begin{cases} n_1\gamma_1' v_1' = n_2\gamma_2' v_2' \\ (\varepsilon_1 + p_1)v_1'^2\gamma_1'^2 + p_1 = (\varepsilon_2 + p_2)v_2'^2\gamma_2'^2 + p_2 \\ (\varepsilon_1 + p_1)\gamma_1'^2 v_1' = (\varepsilon_2 + p_2)\gamma_2'^2 v_2' \end{cases}$$

Landau, Lifshitz, Fluid Mechanics (Vol. 6)

HYDRODYNAMICS OF THE SHOCK WAVE

The rest frame of the bubble's center

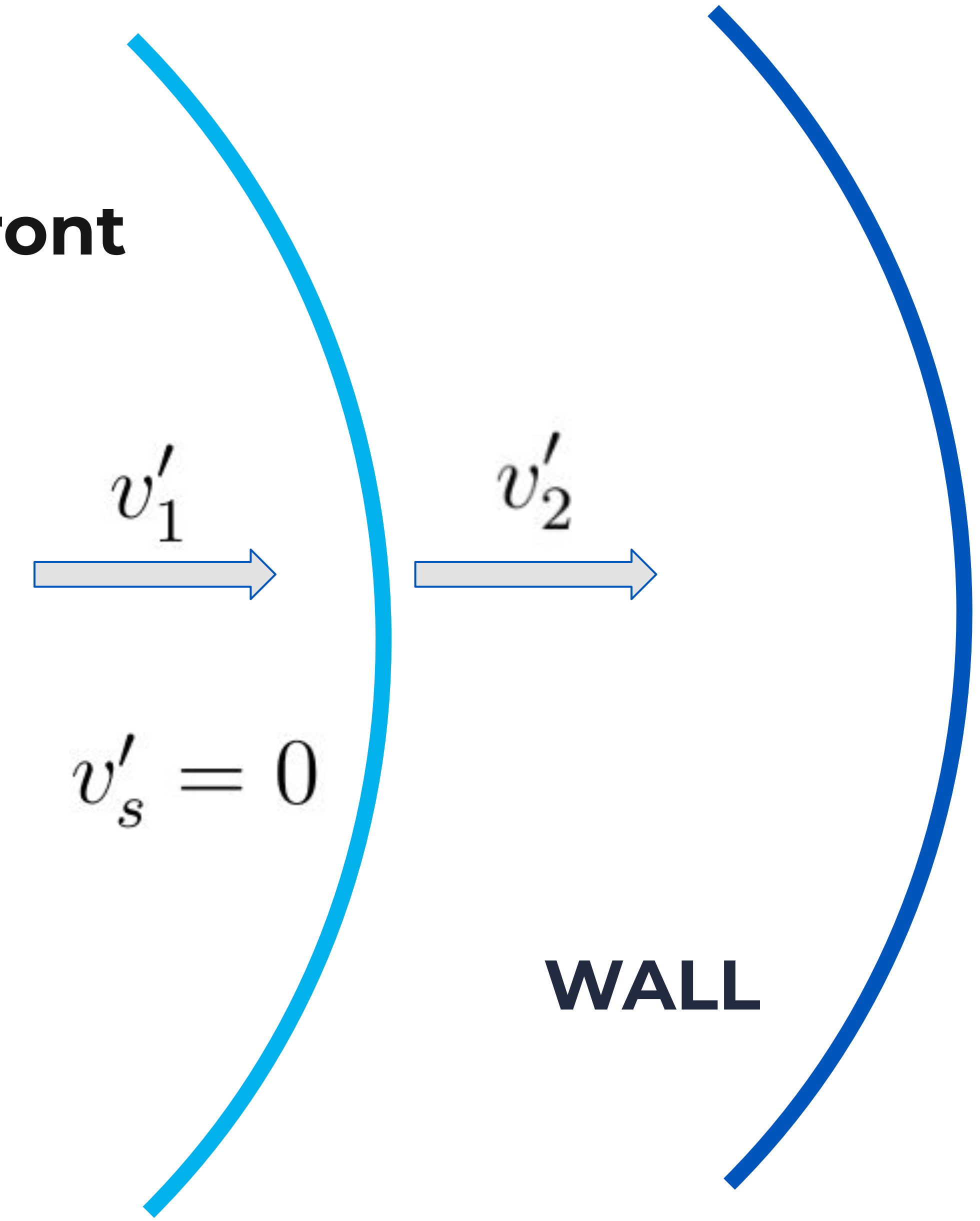


HYDRODYNAMICS OF THE SHOCK WAVE

The rest system of the shock wave front

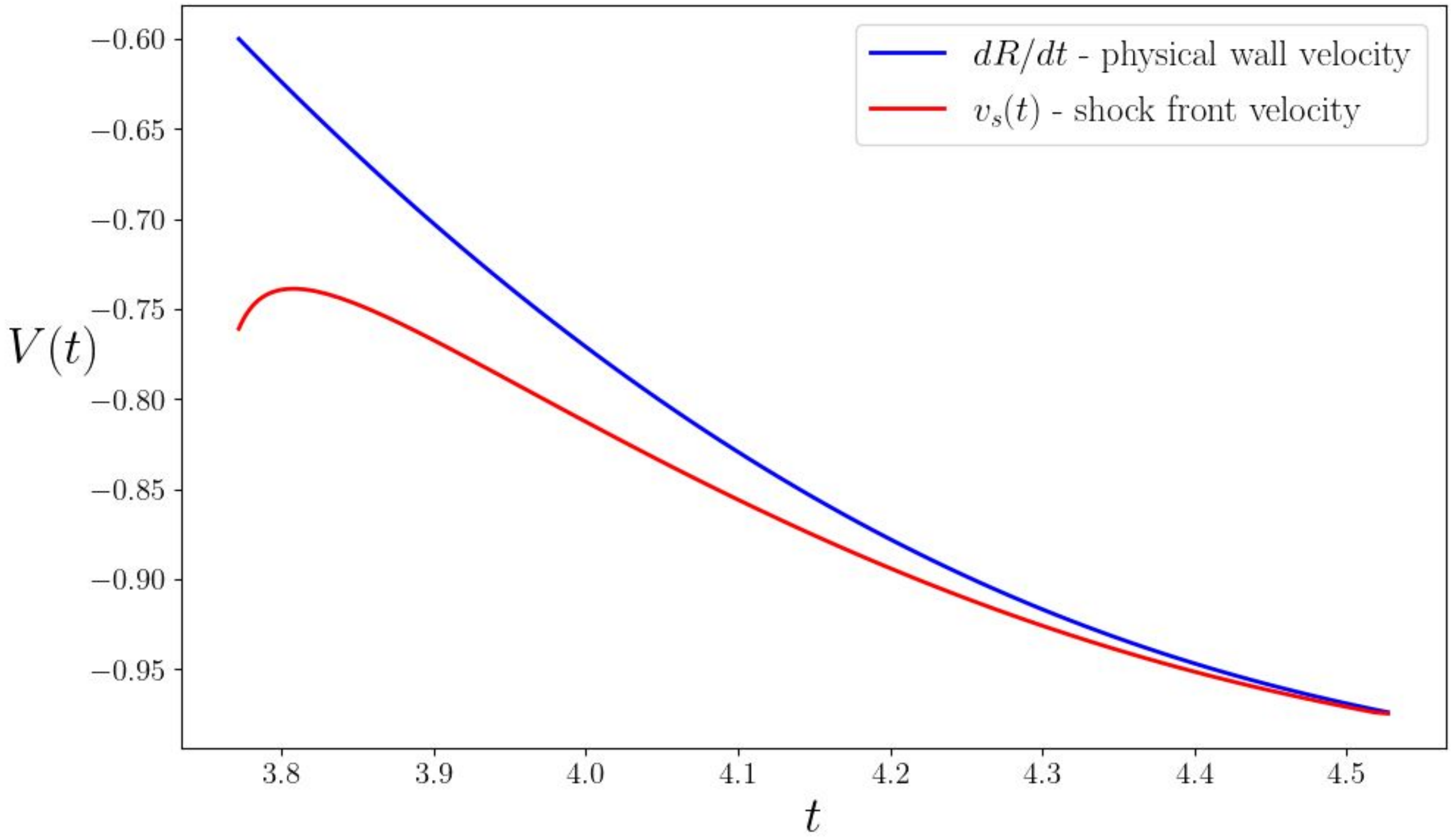
$$v_2' = \frac{v_2 - v_s}{1 - v_2 v_s}$$

$$v_1' = -v_s$$



UNKNOWN ANOMALY

$$\frac{\Delta_i}{R_i} < 0.07$$



NUMERICAL SOLUTION

MEPhI

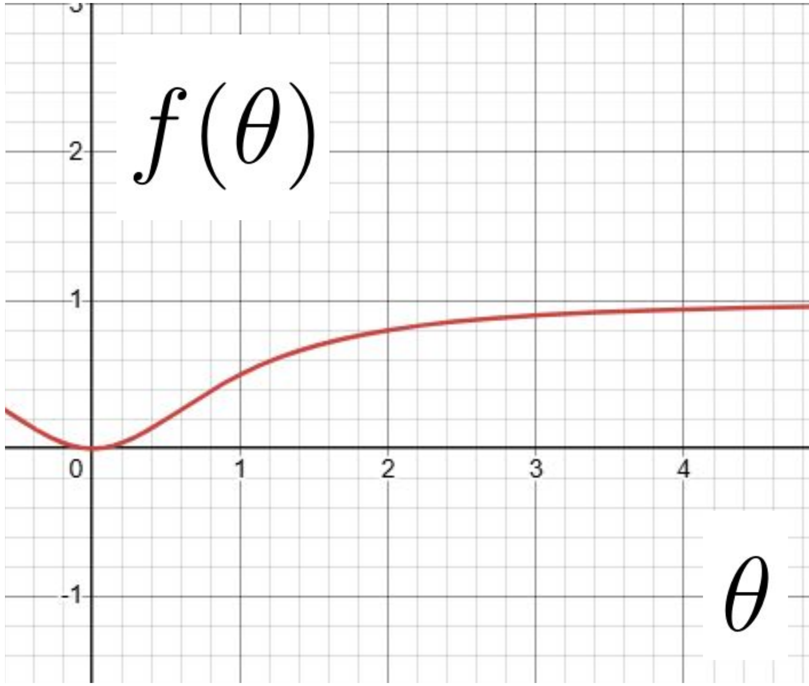
Accounting for electron gas degeneracy

$$\theta = \frac{T_2}{T_F} = \frac{T_2}{(3\pi^2 n_e)^{1/3}} = \begin{cases} <1 \text{ gas is degenerate} \\ >1 \text{ gas is non-degenerate} \end{cases}$$

$$f(\theta) = \frac{\theta^2}{\theta^2+1}, \in [0,1]$$

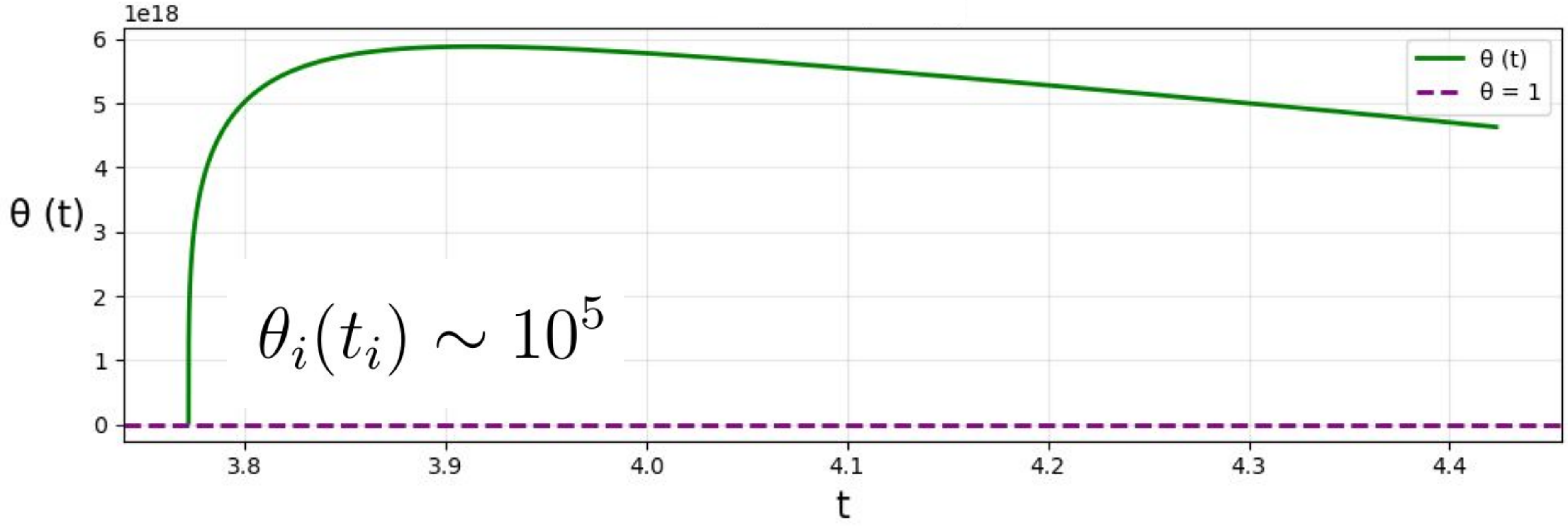
$$P_{2e} = n_{2e} T_2 f(\theta) + \frac{(3\pi^2)^{1/3}}{4} n_{2e}^{4/3} (1 - f(\theta))$$

$$\epsilon_{2e} = (n_{2e} m_e + n_{2e} T_2) f(\theta) + \frac{1}{3} \frac{(3\pi^2)^{1/3}}{4} n_{2e}^{4/3} (1 - f(\theta))$$



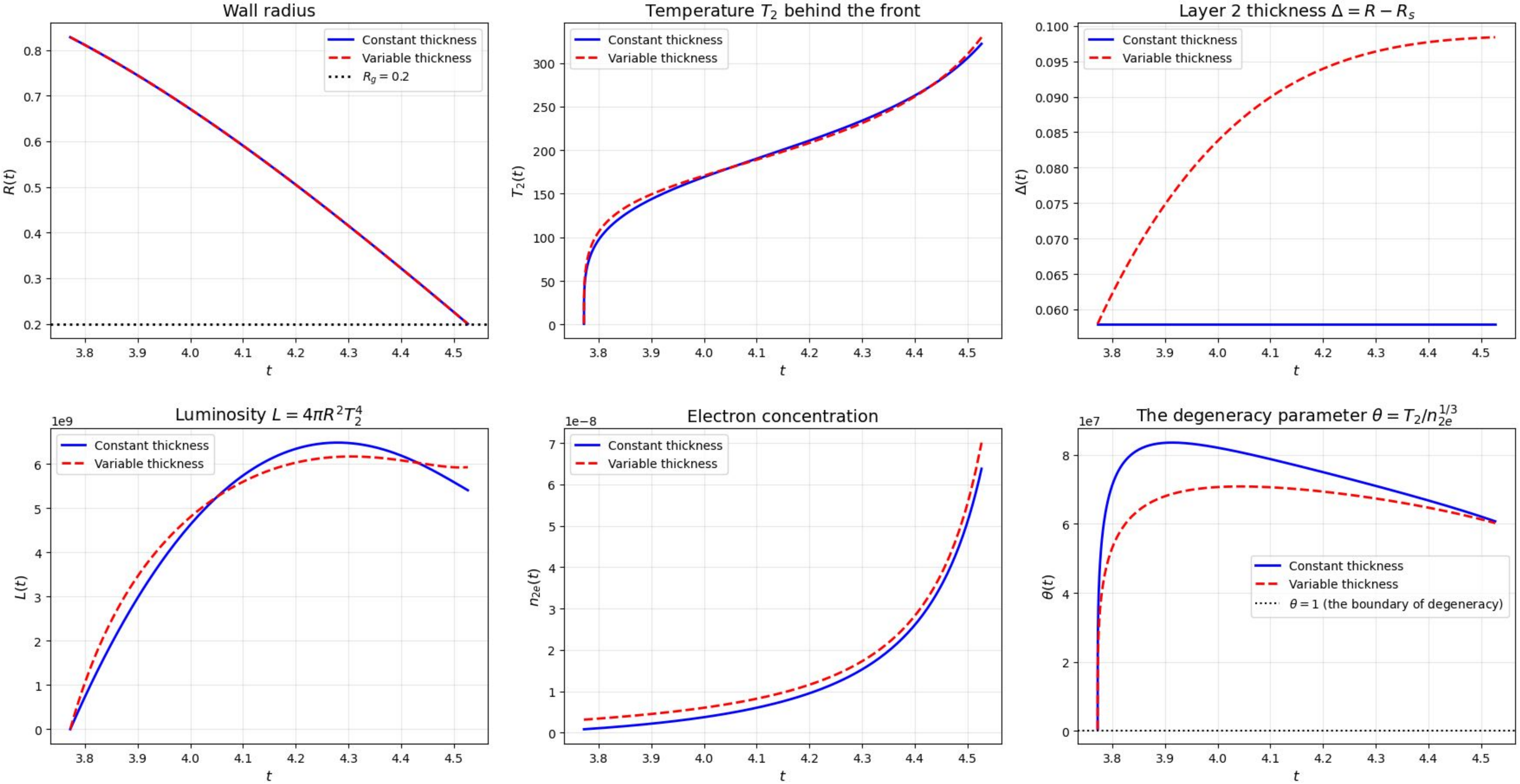
NUMERICAL SOLUTION

Accounting for electron gas degeneracy



$$\theta = \frac{T_2}{T_F} = \frac{T_2}{(3\pi^2 n_e)^{1/3}} = \begin{cases} <1 \text{ gas is degenerate} \\ >1 \text{ gas is non-degenerate} \end{cases}$$

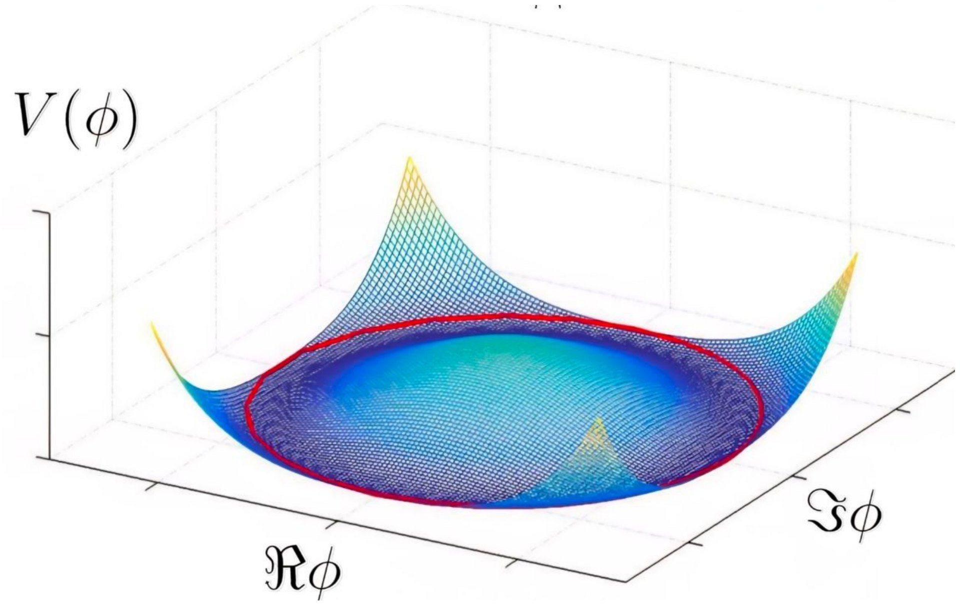
NUMERICAL SOLUTION



ALP MODEL

$$\phi = \rho e^{i\theta}$$

$$V = \frac{1}{4}\left(\phi^*\phi - \frac{f^2}{2}\right)^2 + \Lambda^4(1 - \cos(\theta))$$



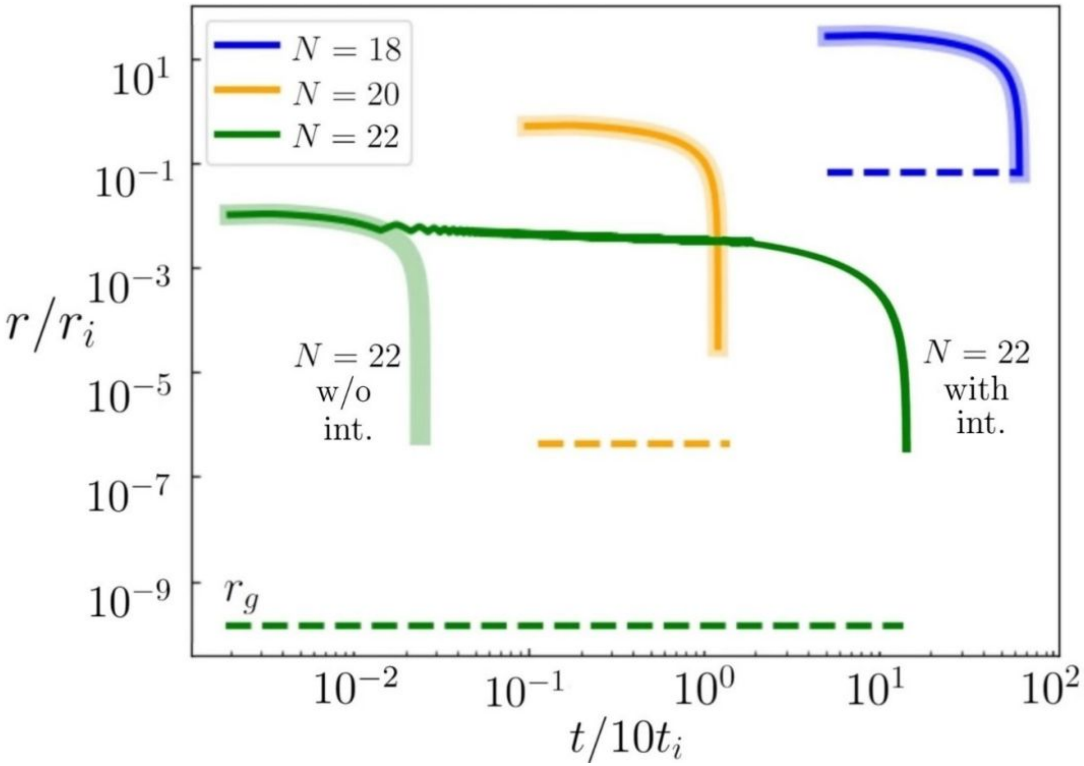
$$\theta(x) = 4\arctan\left[\exp\left(\frac{2x}{d}\right)\right]$$

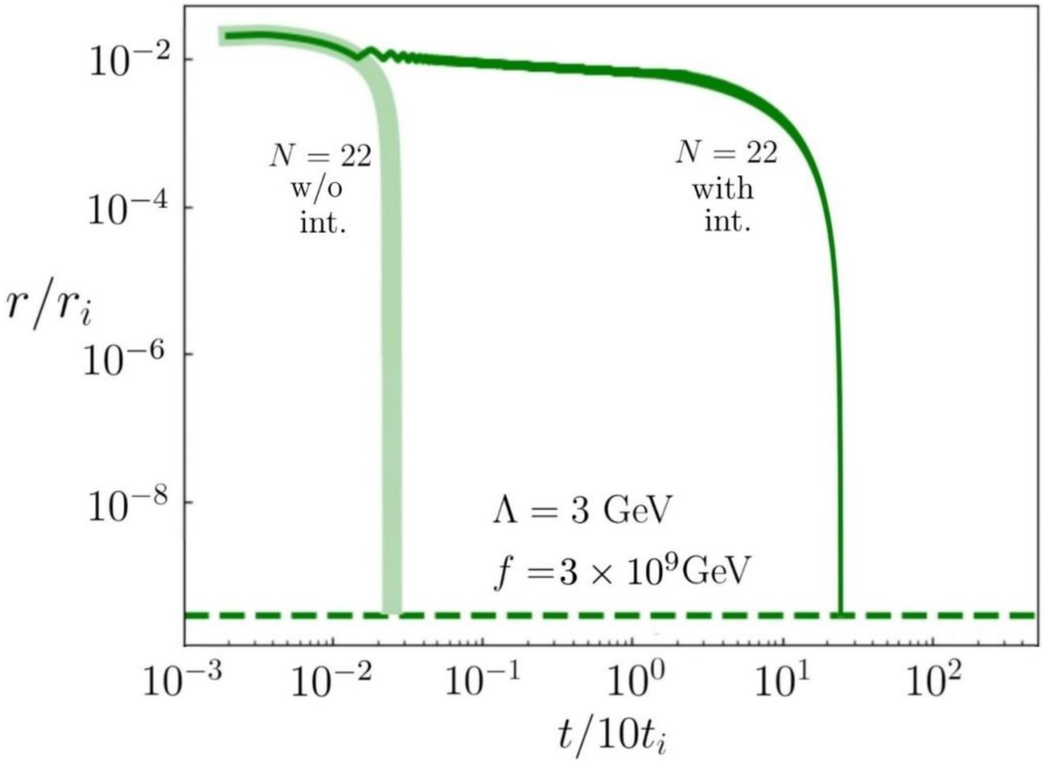
$$\mathcal{L}_{\text{int}} = \partial_\nu\theta\bar{\psi}\gamma^5\gamma^\nu\psi$$

PREVIOUS RESULTS

$$V = \frac{1}{4}\left(\phi^*\phi - \frac{f^2}{2}\right)^2 + \Lambda^4(1 - \cos\theta)$$

$$\mathcal{L}_{\text{int}} = \frac{1}{2}\alpha_0(\phi + \phi^*)\varphi^2$$





The radius of the DW in the case of interaction and without

Filippov, Kirillov, Phys. Atom. Nucl. 88 (2025) 540

THE END