DEPARTMENT OF ELEMENTARY PARTICLE PHYSICS №40

MEPhI

IMPACT OF PRIMORDIAL PLASMA ON THE COLLAPSE OF BUBBLE WALLS AND PRIMORDIAL BLACK HOLE FORMATION

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8th INTERNATIONAL CONFERENCE ON PARTICLE PHYSICS AND ASTROPHYSICS

RELEVANCE OF THE WORK

Unsolved problems of cosmology

Dark matter:

- WIMP, axion, neutrino...;
- Primordial Black Holes.

Supermassive black holes at z>7:

- Seeds of Pop III;
- Star clusters;
- Direct collapse of a gas cloud;
- Primordial Black Holes.

Others...

Haiman (2012), arXiv:1203.6075

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Supermassive black holes at z>7:

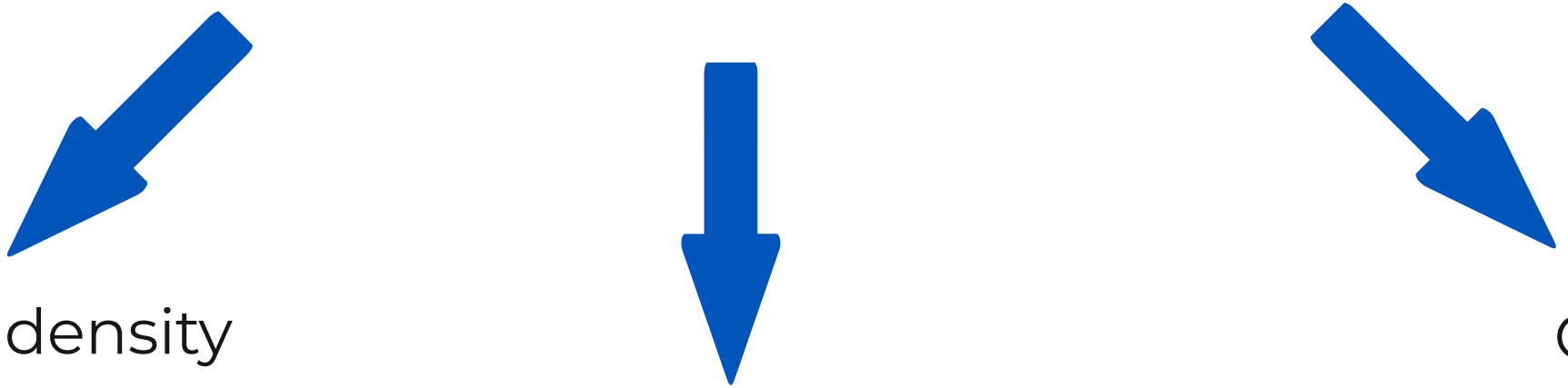
- ❏ Seeds of Pop III;
- ❏ Star clusters;
- ❏ Direct collapse of a gas cloud;
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RELEVANCE OF THE WORK

Models of Primordial Black Hole (PBH) formation



Inflationary density perturbations

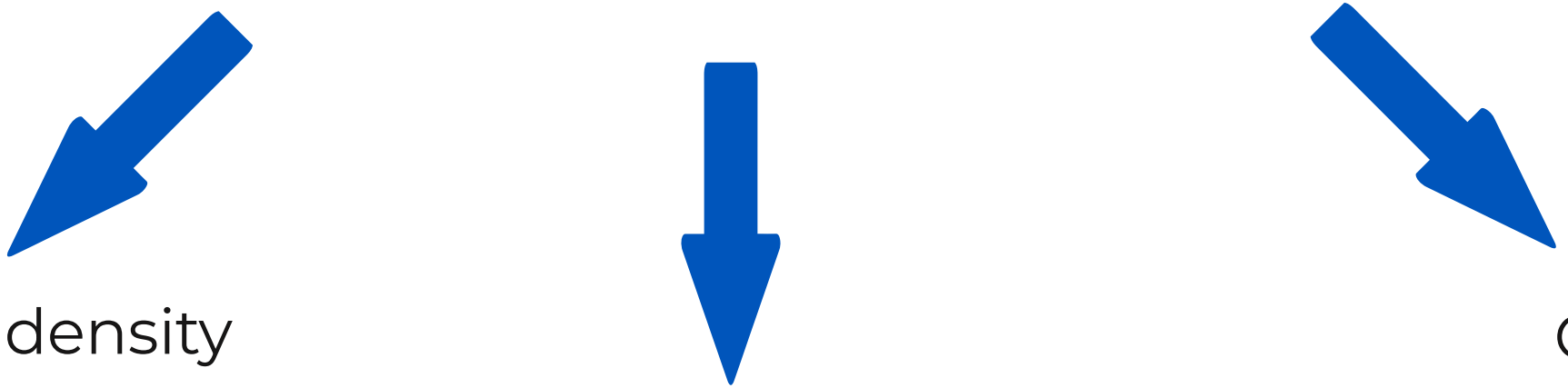
Topological defects & phase transitions

Others...

Escrivà et al. (2022), arXiv:2211.05767
Dokuchaev et al. (2026), arXiv:2610.10750

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AIM OF THE WORK

Domain Wall (DW) collapse can be a source of gravitational waves.

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

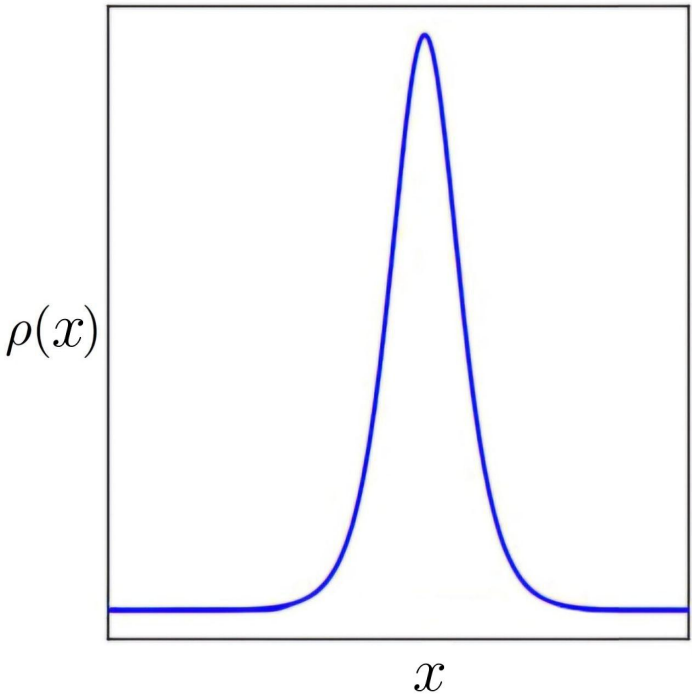
Dankovsky et al. (2025), Phys. Rev. D 112, 123521

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

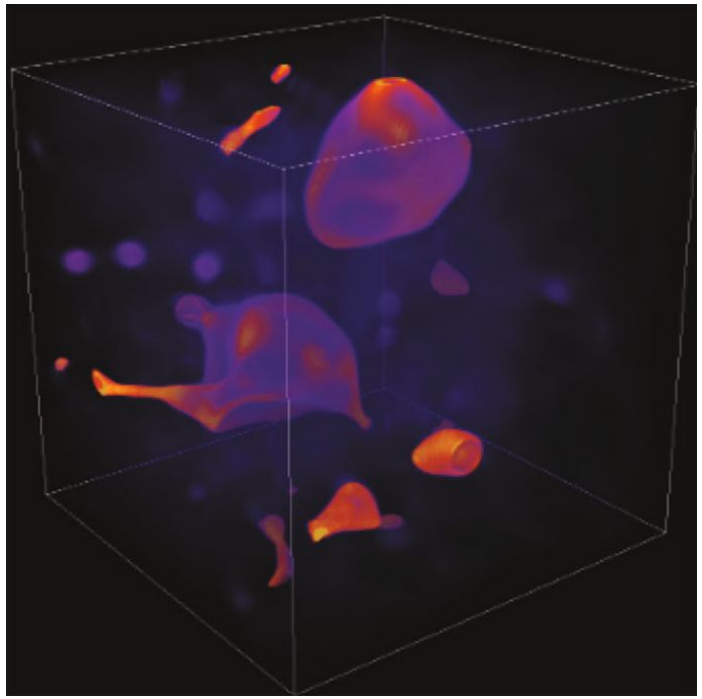
- ❏ evolution of DWs;
- ❏ formation of PBHs;
- ❏ potential observational signatures of DWs.

WHAT IS A DOMAIN WALL?

A domain wall is a field configuration separating the vacuum states of the field



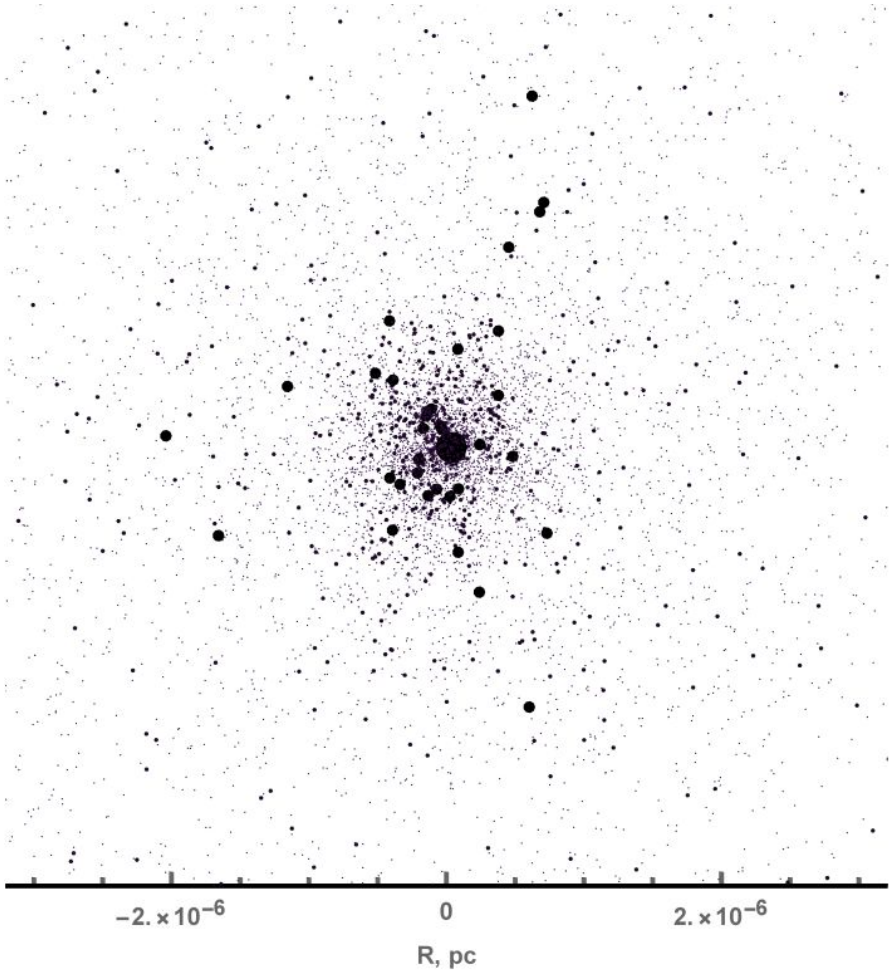
Field energy density across the wall



The energy density of the field in three-dimensional space

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

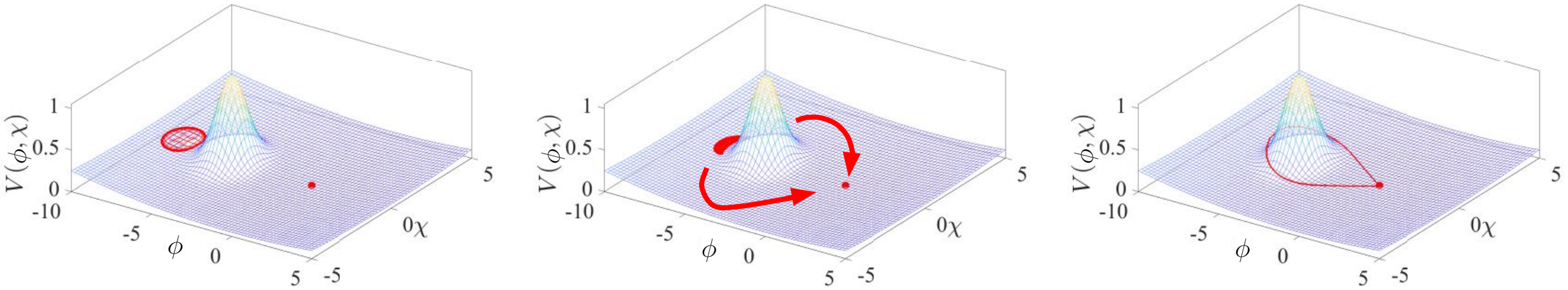
WHAT IS A DOMAIN WALL?



The spatial distribution of black holes within the cluster
Belotsky et al. (2019), Eur. Phys. J. C 79, 246

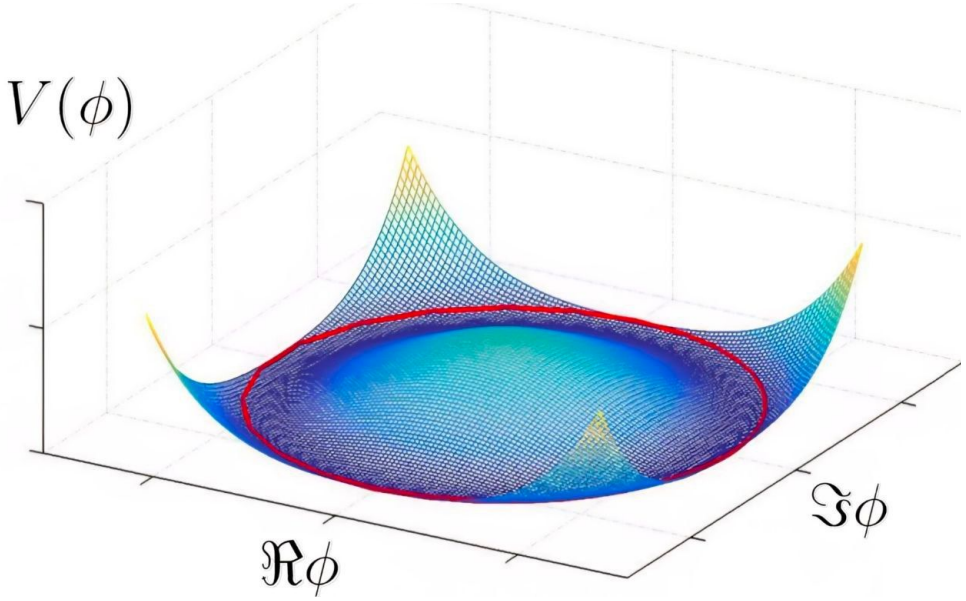
WHAT IS A DOMAIN WALL?

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 post-inflationary stage
Kirillov et al., Physics 3 (2021) 563

AXION-LIKE PARTICLE MODEL



Red line represents DW in the field space

Complex scalar field

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

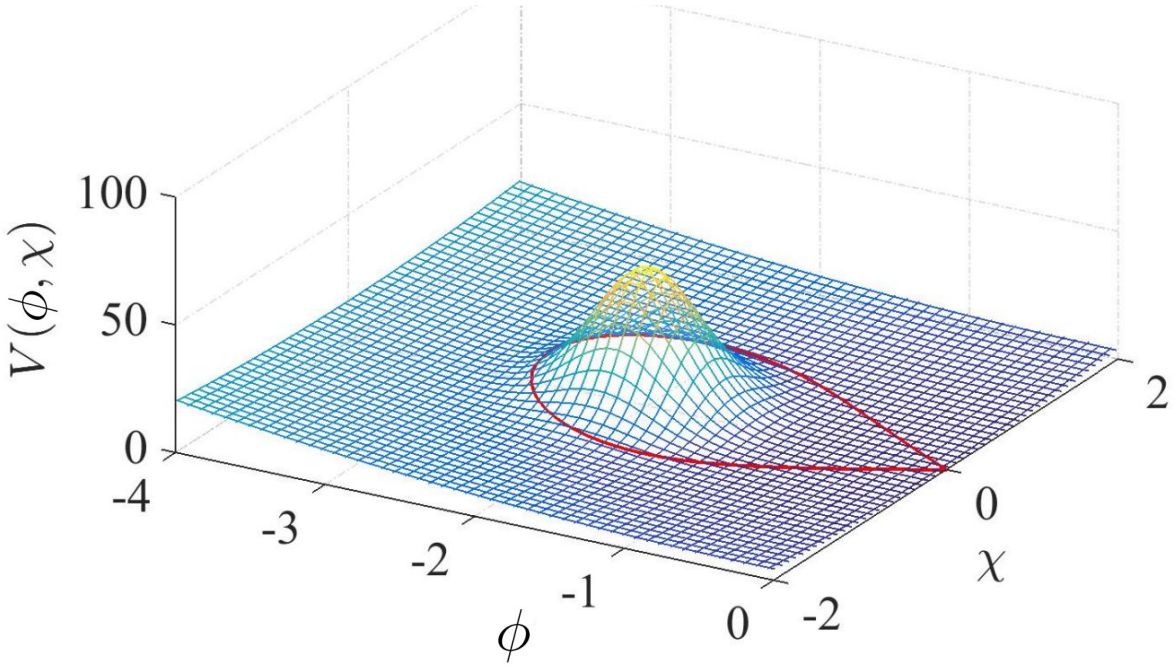
$$V(\varphi) = \lambda\left(\varphi^*\varphi - \frac{f^2}{2}\right)^2 + \Lambda_a^4(1-\cos(\theta))$$

Huang & Sikivie (1985), Phys. Rev. D 32, 1560

Blasi et al. (2023), JCAP 04, 008; arXiv:2210.14246

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 the parameters determine the

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

INTERACTION OF DW WITH PLASMA

Interaction term with fermions

$$\mathcal{L}_\psi = g_\psi(\phi+\chi)\bar{\psi}\psi$$

or

$$\mathcal{L}_\psi = \frac{g_\psi}{\Lambda}(\phi^2+\chi^2)\bar{\psi}\psi$$

Fermion threshold energy

$$T_{\psi\mathrm{th}} \sim \Lambda$$

Interaction term with photons

$$\mathcal{L}_\gamma = \frac{g_\gamma}{\Lambda}(\phi+\chi)F_{\mu\nu}F^{\mu\nu}$$

or

$$\mathcal{L}_\gamma = \frac{g_\gamma}{\Lambda^2}(\phi^2+\chi^2)F_{\mu\nu}F^{\mu\nu}$$

Photon threshold energy

$$T_{\gamma\mathrm{th}} \sim m$$

EVOLUTION OF DW

Equation of motion for a spherical wall in **physical coordinates**

Deng et al., JCAP 04 (2017) 050

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

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

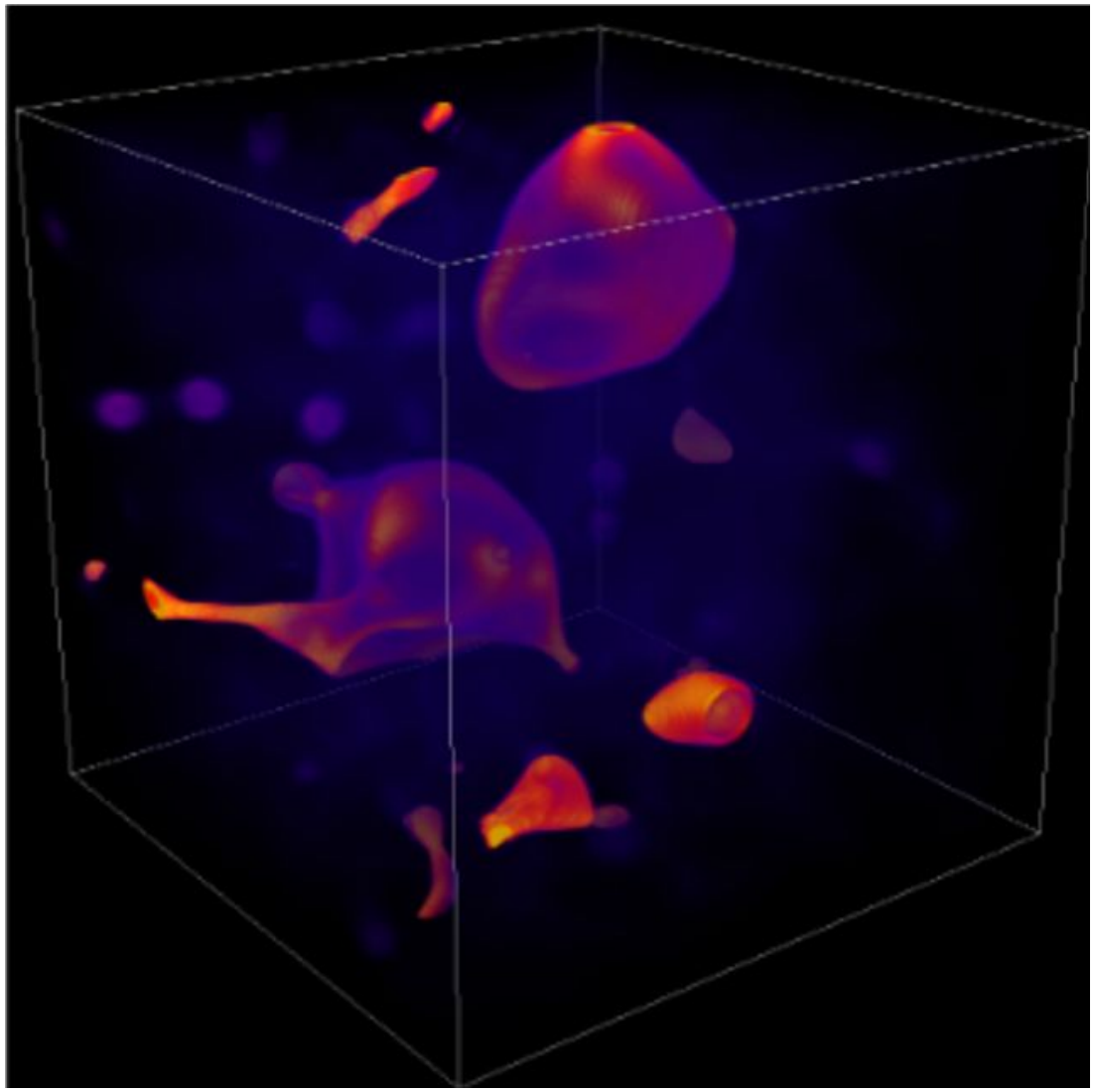
Tension force

Hubble flow

Particle pressure

μ — DW surface energy density

EVOLUTION OF DW



Criterion for the bubble to stay spherical during collapse

$$R_i > R_{\rm crit}(m, \Lambda)$$

Widrow (1989), Phys. Rev. D 39, 3576
Kitajima (2025), arXiv:2510.22759

BOUNCE CRITERION

Equation of motion for a spherical wall

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

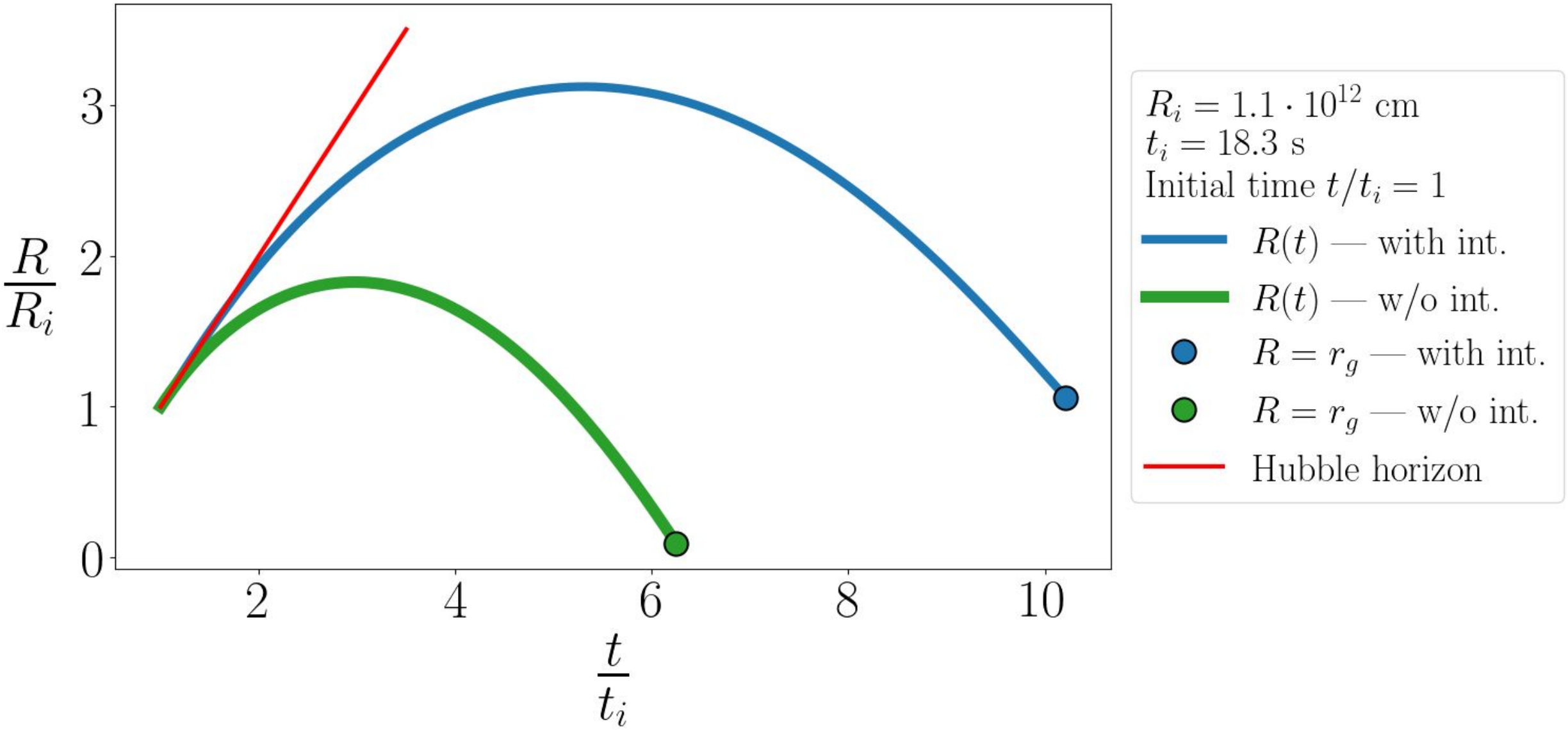
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Bounce criterion

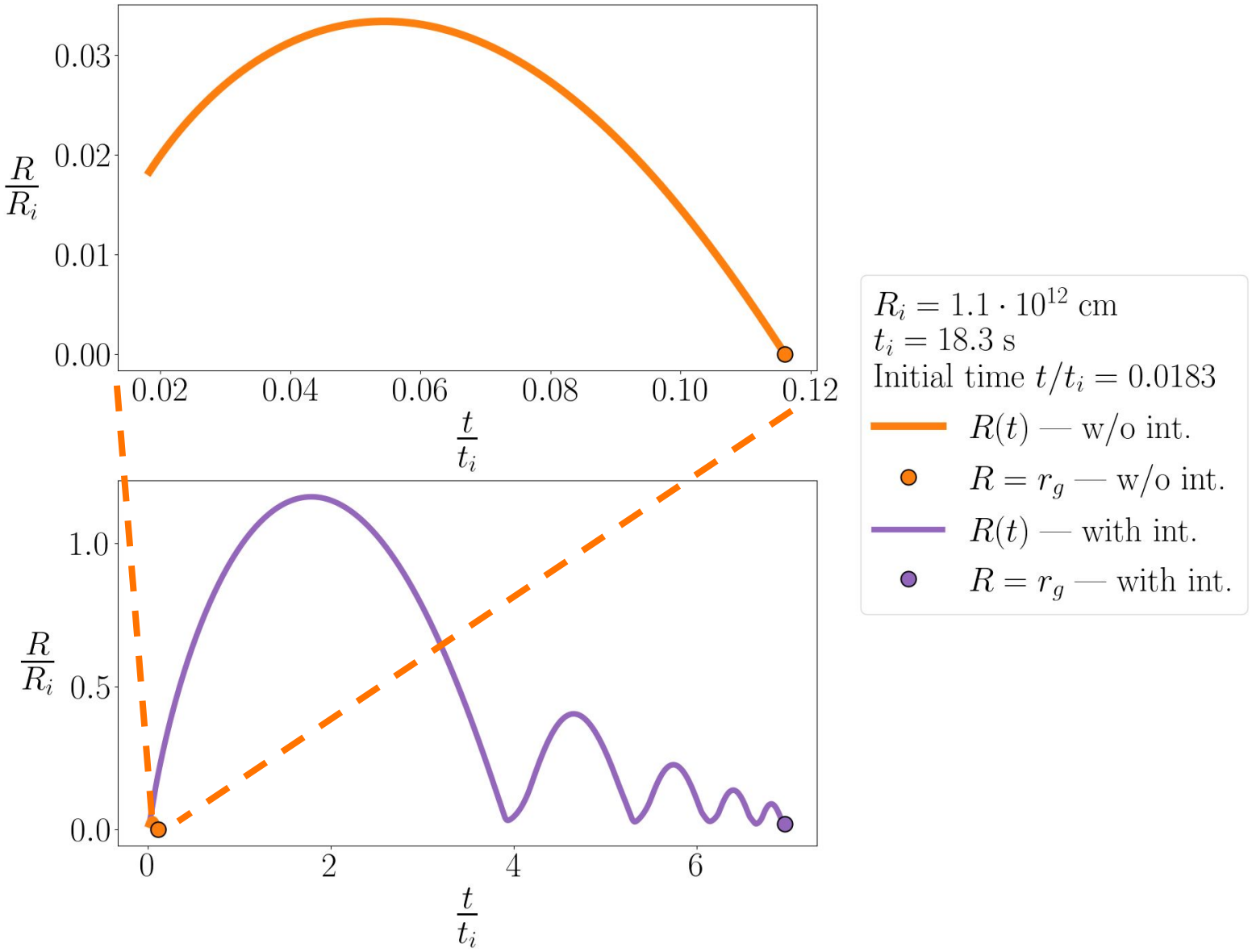
$$P > \frac{2\mu}{R_{\min}} \quad \Rightarrow \quad R_{\min} > R_g$$

Hydrodynamic simulation is performed using the Kurganov–Tadmor scheme (with MUSCL reconstruction and a Minmod limiter) **Kurganov & Tadmor (2000), J. Comput. Phys. 160, 241**

RESULTS OF THE NUMERICAL SOLUTION



RESULTS OF THE NUMERICAL SOLUTION



RESULTS

For a single DW shock wave heating:

- **60-85%**

Shifts n/p ratio:

- **10-20%**

Destroys/produces elements:

- **D, ^{7}Be, ^{7}Li, ^{3}He, ^{4}He**

Shock wave heating



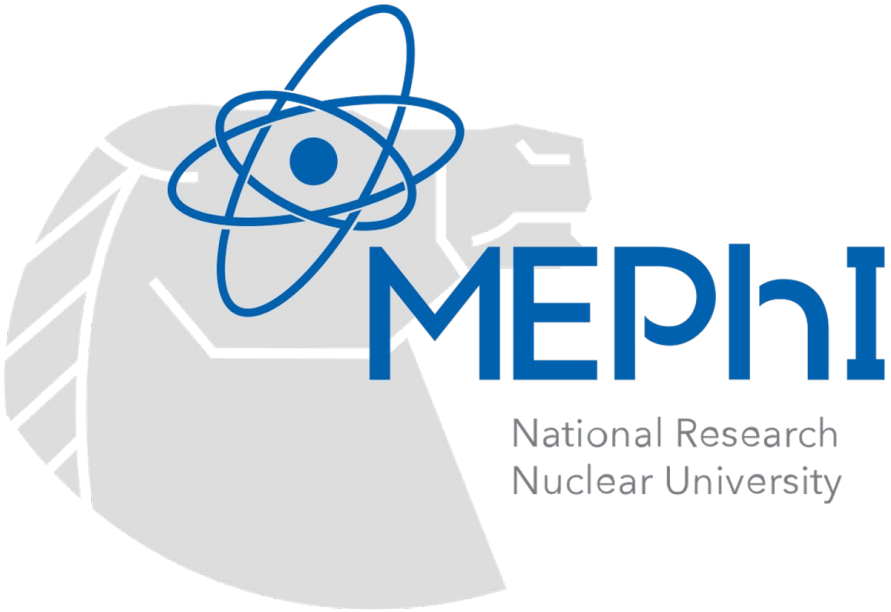
- Destroys/produces elements
- Shifts n/p ratio



Locally changes chemical composition

THANK YOU FOR YOUR ATTENTION

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ADDITIONAL SLIDES

SHOCK WAVE FORMATION

Shock-wave propagation distance

$$R_{\mathrm{sh}} \propto \Gamma_{\mathrm{w}} R_i^{0.6}$$

Γ_{w} — DW Lorentz factor

Relative heating

$$\frac{T_{\mathrm{sh}}}{T_{\mathrm{b}}} \sim \Gamma_{\mathrm{w}}$$

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Complex scalar field

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

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

Interaction term with fermions

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

Huang & Sikivie (1985), Phys. Rev. D 32, 1560

Interaction term with photons

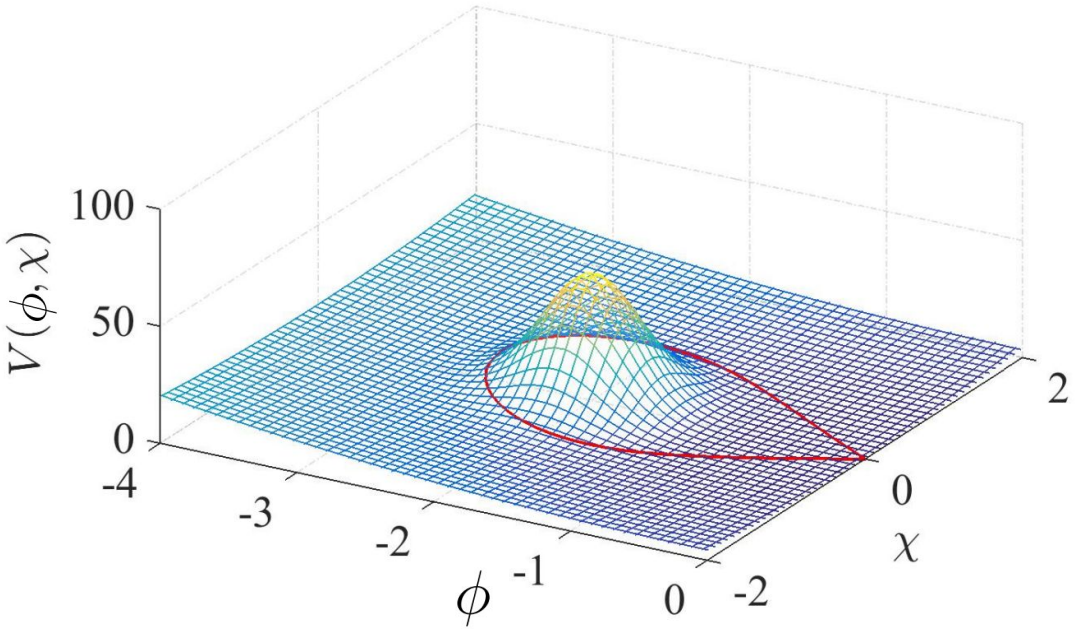
$$\mathcal{L}_{a\gamma} = \theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

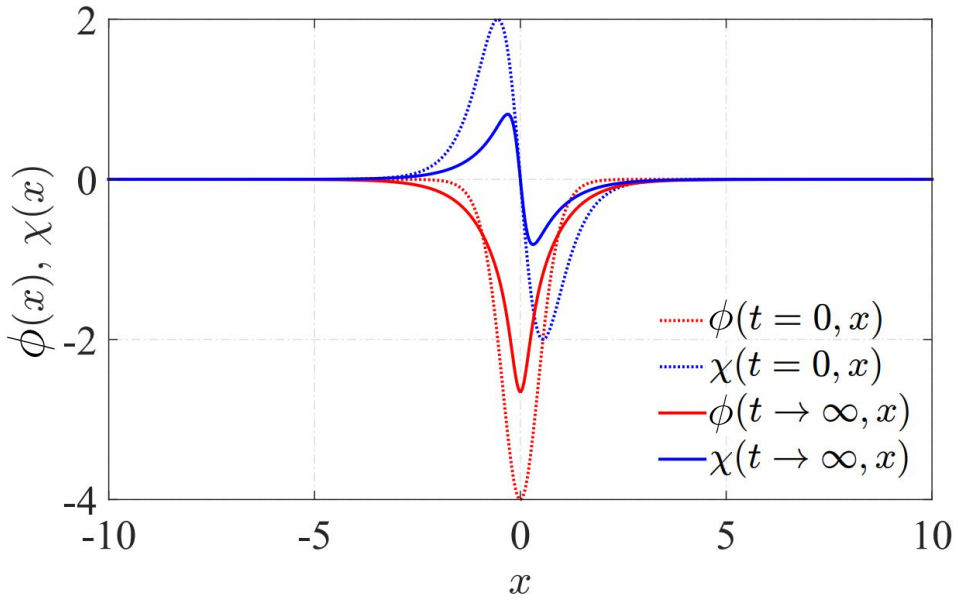
Blasi et al. (2023), JCAP 04, 008; arXiv:2210.14246

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

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





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

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THE END