Heavy Dark Matter and
the Evolution of the Early Universe

Chang Sub Shin

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**based on Phys. Rev. D 101, 095019 (2020) by D. Chway, T.H. Jung, and C.S. Shin
and arXiv:2412.15864 by Tomasz Dutka(KIAS), Tae Hyun Jung(IBS), and Chang Sub Shin**

2025 CAU-IBS Beyond the Standard Model Workshop
Feb. 20, 2025 @ CAU

Outline

General Intro to Heavy Dark Matter Scenarios

  - Unitarity Bound, Constraints, and Production Mechanisms

Phase Transition for Dark Matter Productions

  - DM from Filtering effect and/or High energetic bubble collision etc.
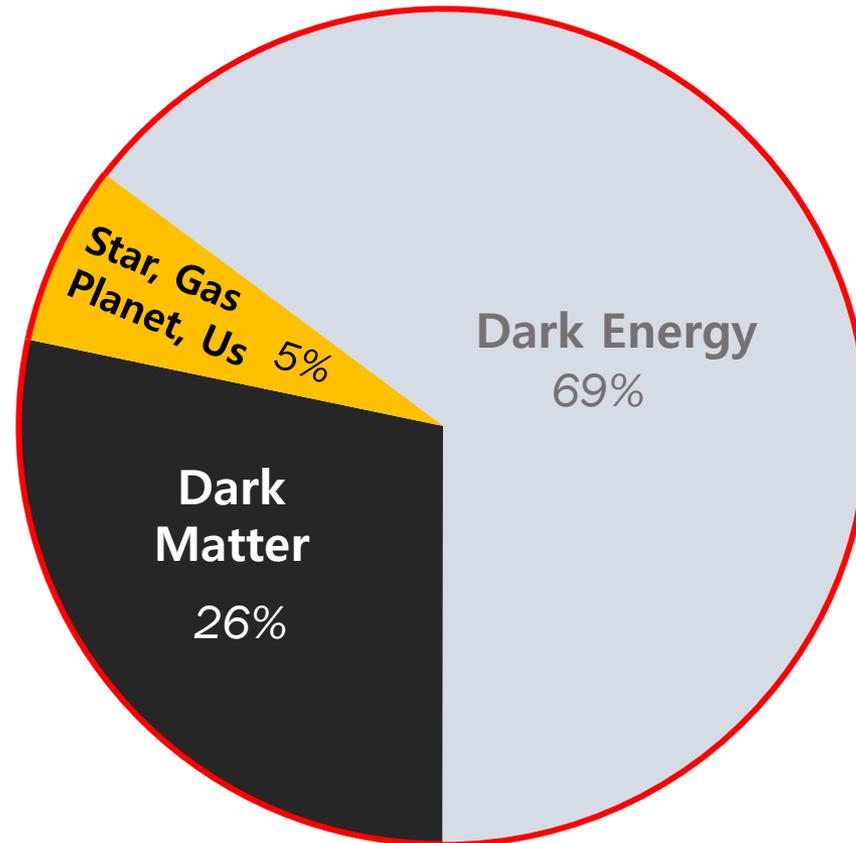

Fate of Supercooled Universe and First Order Phase Transition

  - Phase mixing (Spinodal decomposition) vs Nucleation and Growth

  - Lattice Simulations

Summary

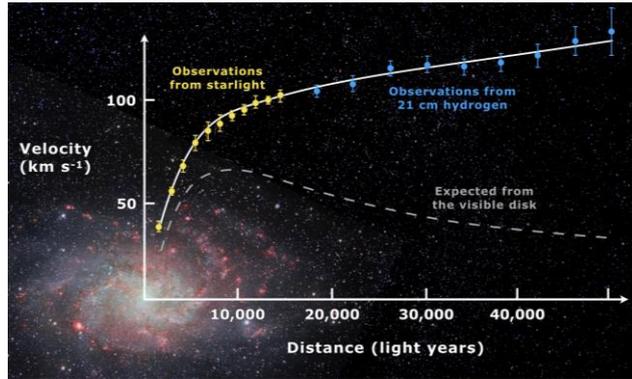# Introduction to Heavy Particle Dark Matter

Content of the Universe

Star, Gas Planet, Us 5%

Dark Matter 26%

Dark Energy 69%

It is very difficult to properly understand the origin of the each content from GR and the list of particles of the SM
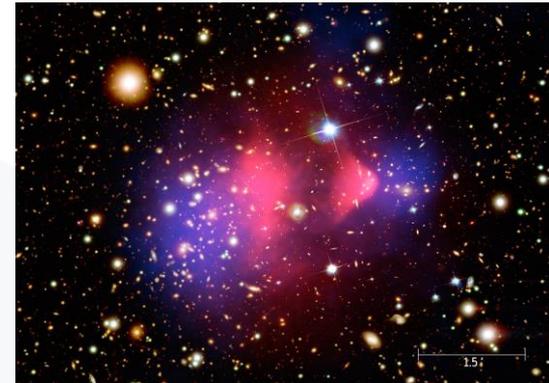
Content of the Universe - DM

Image of Galaxy Messier 33

Galaxy Scale

Image of Bullet Cluster 1E 0657-558

Galaxy Cluster Scale
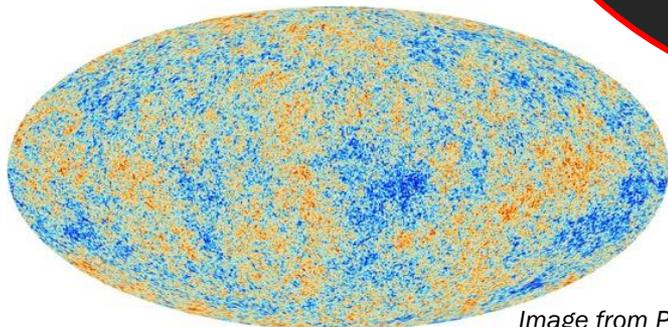
Dark Matter

26%

Image from PLACK
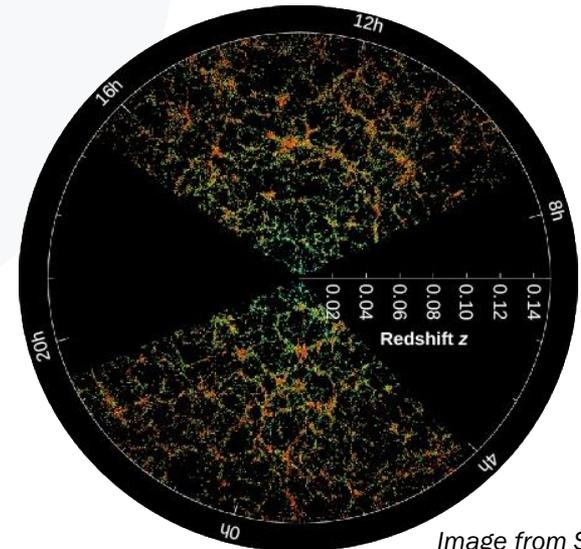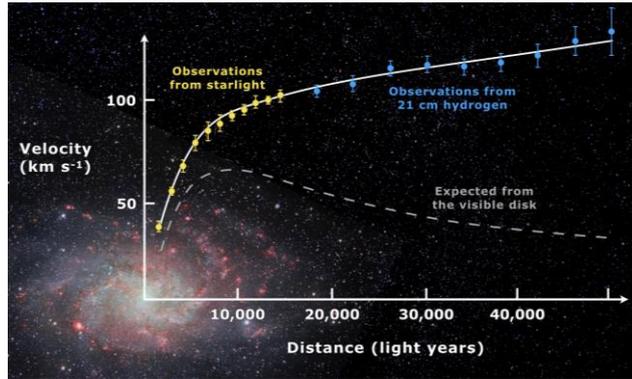
Cosmic Microwave Background

Image from SDSS

Large Scale Structure of the Universe

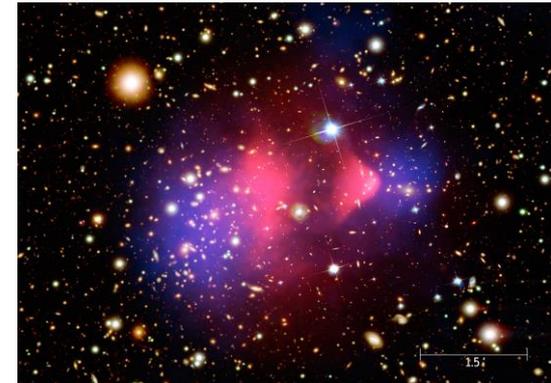# Content of the Universe - DM

Image of Galaxy Messier 33

Galaxy Scale

Image of Bullet Cluster 1E 0657-558

Galaxy Cluster Scale

<Dark Matter>

**Feels Gravity,
Cosmologically Stable,
No Light Emission, No EM Charge**

**CANNOT be explained by the
particle contents of the SM**

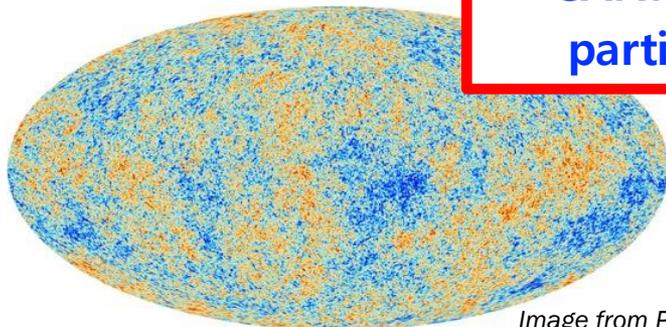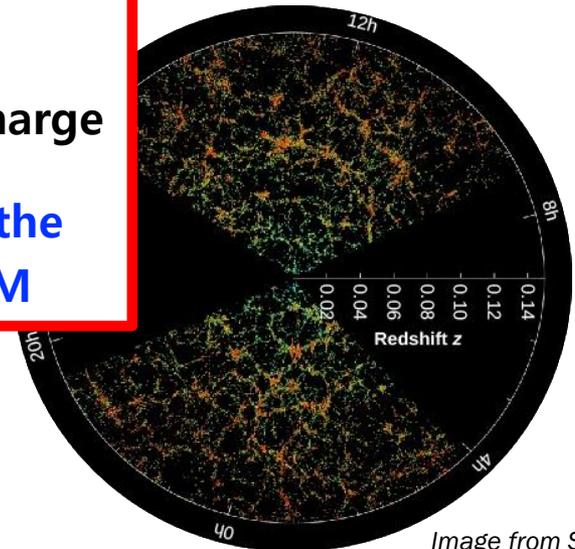**Cosmic Microwave Background**

Image from PLACK

Image from SDSS

Large Scale Structure of the Universe

What is the nature of dark matter?

The unit of DM

Dark Matter Halo

Galaxy (Stars, Gases, Planets)

Dark Matter

What is the nature of dark matter?

Wave-like

Particle-like

Dark Matter Mass

Dark Matter

Compact & Macroscopic

How to interact with each other

How stable

How many different types

neutron

proton

electron

Any other interactions besides gravity

How to create

Candidates of DM for its mass

$$\bar{\rho}_{\mathrm{DM}} = M_{\mathrm{DM}}\, \bar{n}_{\mathrm{DM}} = (0.25 - 0.27)\bar{\rho}_{\mathrm{tot}} \simeq 1.2 \times 10^{-6} \mathrm{GeV/cm^3}$$

$$G = \frac{1}{M_{\mathrm{Pl}}^2} \quad \left(M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} \simeq 1.22 \times 10^{19} \mathrm{GeV} \right)$$

$$\bar{n}_{\mathrm{DM}} \lambda_{\mathrm{Compton}}^3 \gg 1 \qquad R_{\mathrm{BH}} = 2GM_{\mathrm{DM}} \ll \lambda_{\mathrm{Compton}} = \frac{1}{m_{\mathrm{DM}}} \ll \bar{n}_{\mathrm{DM}}^{-1/3} \qquad R_{\mathrm{BH}} \gg \lambda_{\mathrm{Compton}}$$

neutrino   electron   proton

$10^{-22}\mathrm{eV}$ μeV   keV $100\,\mathrm{GeV}$ $M_{\mathrm{Pl}} \simeq 10^{19} m_p$ $M_\odot \simeq 10^{57} m_p$

Fuzzy DM   *QCD axion*   *Warm DM*   *WIMP DM*   *Heavy DM*   *Primordial Black Hole,*
Sterile neutrino   *Ultra Compact Mini Halo*

Wave like (boson)   Particle like   Compact object

Candidates of DM for its mass and interactions

$$\bar{\rho}_{\mathrm{DM}} = M_{\mathrm{DM}}\,\bar{n}_{\mathrm{DM}} = (0.25 - 0.27)\bar{\rho}_{\mathrm{tot}} \simeq 1.2 \times 10^{-6}\mathrm{GeV/cm^3}$$

Interaction with SM particles other than gravity

?

Their Masses and Interactions determine

1) How they were produced in the early Universe

2) How we can detect them now

Interactions between (among) dark matters

neutrino   electron proton

| 10^{-22}eV | μeV | keV | 100 GeV | $M_{\mathrm{Pl}} \simeq 10^{19}m_p$ | $M_{\odot} \simeq 10^{57}m_p$ |

Fuzzy DM   *QCD axion*   *Warm DM*   *WIMP DM*   *Heavy DM*   *Primordial Black Hole,*
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Thermal Dark Matter

Weakly Interacting Massive Particle (WIMP) : $(0.1 \sim 1000)\ \mathrm{GeV}$

Dark matter density is determined by its annihilation cross-section

$$\Omega_{\mathrm{DM}} h^2 = 0.1 \left(\frac{3 \times 10^{-26}\,\mathrm{cm^3/s}}{\langle \sigma_{\chi\chi} v \rangle_T} \right)$$
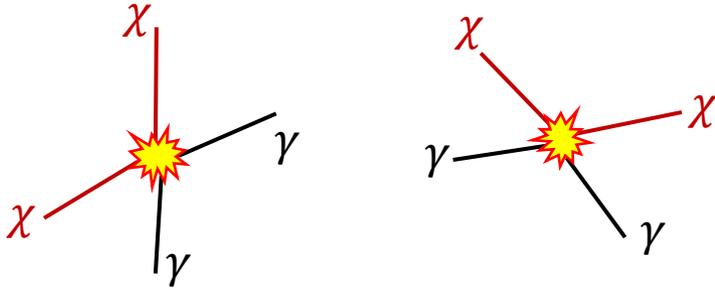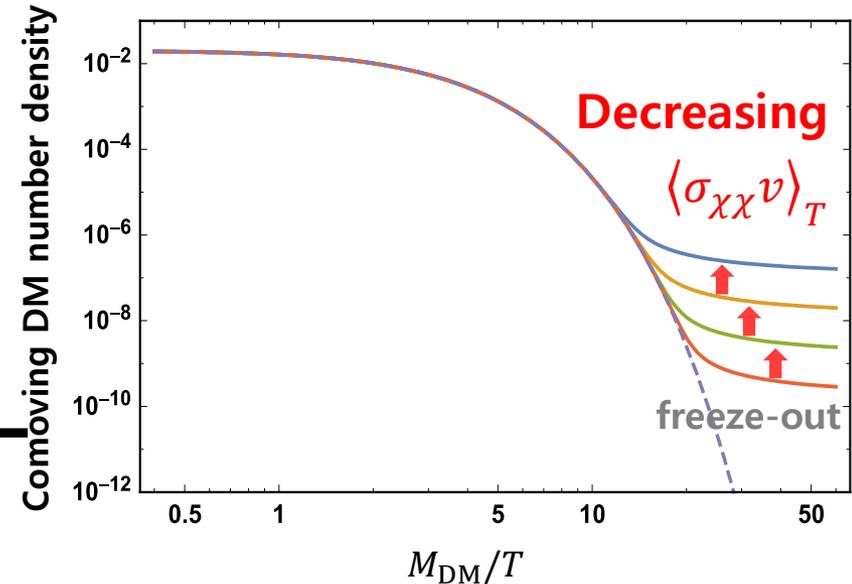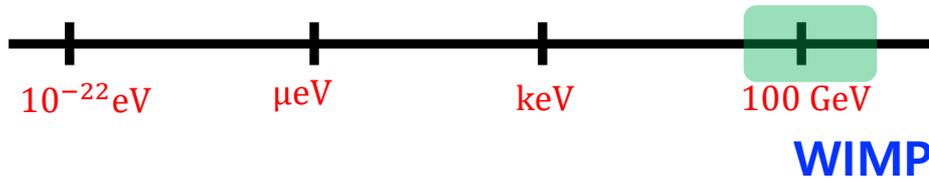
WIMP ($M_{\mathrm{DM}} \sim 100\ \mathrm{GeV}$, $\alpha_\chi \sim 0.01$) is one of the best candidates for DM

$10^{-22}\mathrm{eV}$ μeV   keV   100 GeV

WIMP

Decreasing $\langle \sigma_{\chi\chi} v \rangle_T$

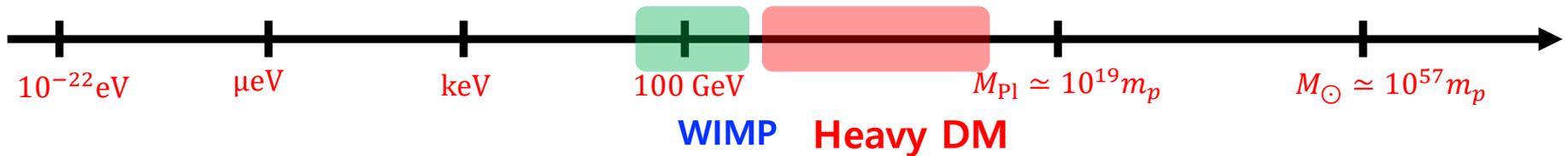freeze-out

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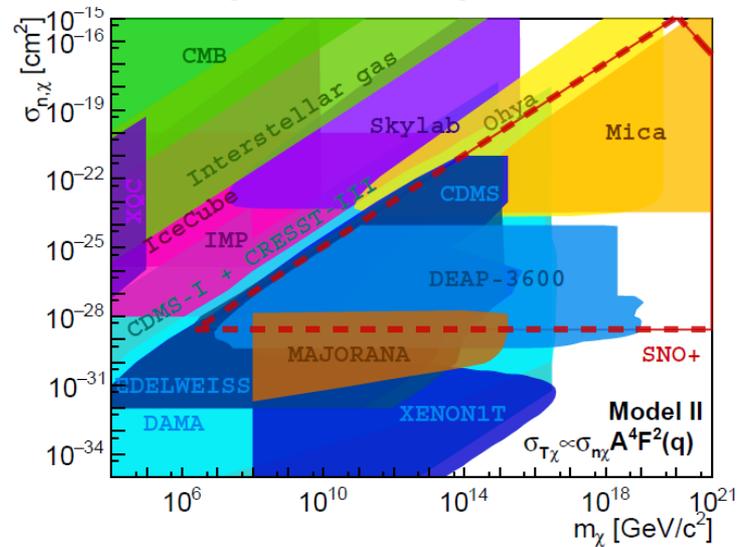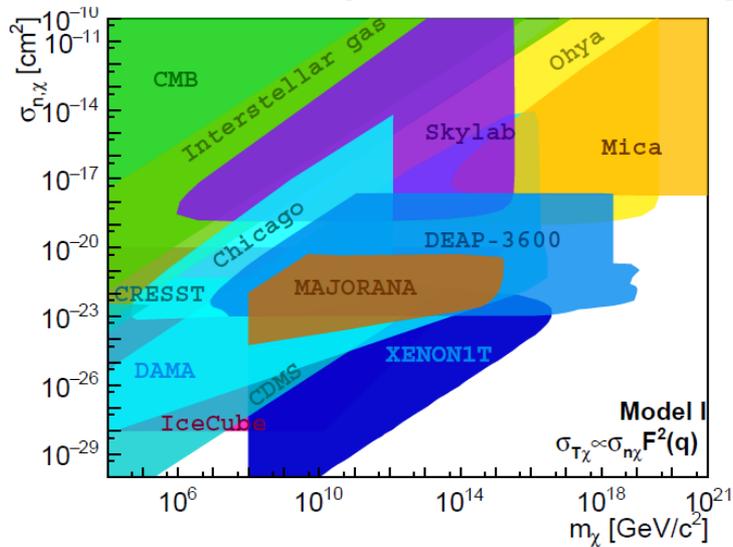**is one of the best candidates for DM**

10^{-22}eV μeV keV 100 GeV

WIMP

Decreasing

$\langle \sigma_{\chi\chi} v \rangle_T$

freeze-out

Comoving DM number density vs M_{DM}/T

Dark matter cross-section is limited by its mass and the velocity

The perturbative Unitarity bound: $\langle \sigma_{\chi\chi} v \rangle_T \leq \dfrac{4\pi}{M_{\mathrm{DM}}^2 \langle v \rangle_T}$ $\Omega_{\mathrm{DM}} h^2 \geq 0.1 \left(\dfrac{M_{\mathrm{DM}}}{130 \ \mathrm{TeV}} \right)^2$

[Griest, Kamionkowski PRL64 (615) 1990]

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Thermal Dark Matter

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WIMP   **Heavy DM**

HOWEVER, No hints for WIMP DM so far:
Strong motivation of the beyond WIMP paradigm

Direct/Indirect Detection of Heavy DM

Snowmass2021 Ultra-heavy particle dark matter arXiv:2203.06508

multi-scattering effect, tracklike signature for large scattering cross-sections

Cosmic-rays, neutrinos, photons from decaying heavy DMs

Heavy DM Beyond the Unitarity Bound

How can the Unitarity bound be overcome to allow various DM masses?

$$\Omega_{\mathrm{DM}} h^2 \geq 0.1 \left(\frac{M_{\mathrm{DM}}}{130 \text{ TeV}} \right)^2$$
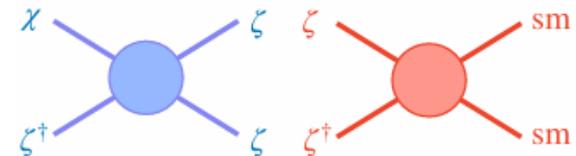
- Generated **nonthermally** during inflation, the end of inflation, preheating by quantum fluctuations, scatterings, or parametric resonances for $M_{DM} >, < H_{\mathrm{inf}}$
  [hep-ph/9805473, 9802238, 9809547, 0104100, 1804.07471, 2011.13458, 2206.08940, 2405.13883, ...]

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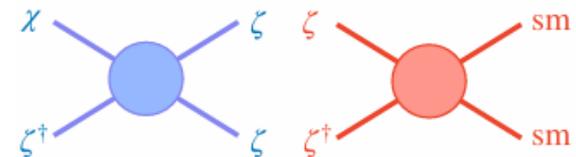 [1701.05859, 1811.03608, 2010.09762, …]

$$\Omega_{DM} h^2 \rightarrow \Omega_{DM} h^2 \times \frac{S_{\text{ini}}}{S_{\text{fin}}}$$

- **Sommerfeld enhancement** of annihilation cross-section with a light mediator
  [hep-ph/0610249, 1407.7874, 1703.00478, 1904.11503, 2110.13926, …]

- Coannihilation with lighter particles: **enhancement of annihilation rate** for DM
  [1906.00981, 2003.04900, …]

$$\Gamma_{\text{ann}} = \langle \sigma v \rangle n_\chi \rightarrow \Gamma_{ann} = \langle \sigma v \rangle n_\zeta : \Gamma_{\text{ann}} \rightarrow \Gamma_{\text{ann}} \times \frac{n_\zeta}{n_\chi} \quad \text{for } e.g.\ m_\zeta < m_\chi < 3 m_\zeta$$
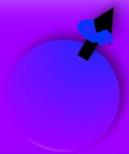
- Freeze-out in **dark sector thermal bath**
  [1609.02555, 1602.08490, 1905.05191, 1905.05191, 1912.05572, …]

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- **Phase Transition**

First Order Phase Transition for Dark Matter

Origin of Mass for particle DM: Expectation value of scalar field

Higgs field (giving mass to the elementary particles)

Nonzero expectation value of the scalar field imposes DM mass
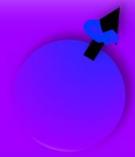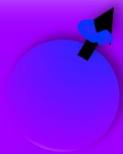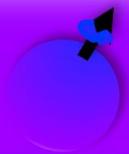
Scalar Field (giving DM Mass)
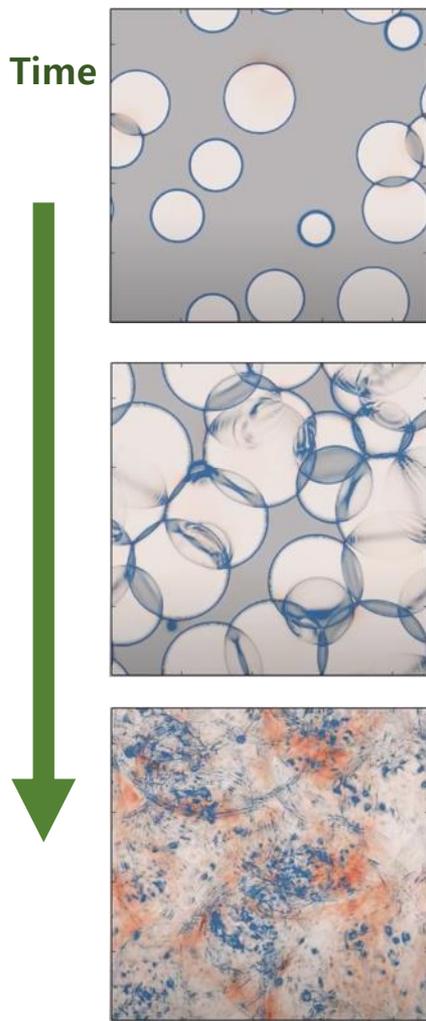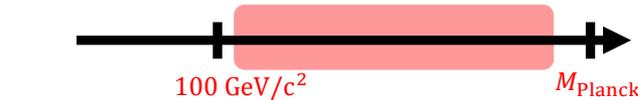
DM

Temperature drops: Vapor → Dew

Universe expands→ Temperature decreases → **Bubbles of scalar condensation form!**

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Scalar Field (giving DM Mass)

DM

Temperature drops: Vapor → Dew

Universe expands→ Temperature decreases → **Bubbles of scalar condensation collide!**

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Higgs field (giving mass to the elementary particles)

Nonzero expectation value of the scalar field imposes DM mass

Scalar Field (giving DM Mass)

Temperature drops: Vapor → Dew

Universe expands→ Temperature decreases → **Bubbles of scalar condensation fill the Universe** → **Cosmic 1st order phase transition**

Origin of DM mass & its abundance

Proposing the mechanism working in a wide range of DM mass

$100 \text{ GeV}/c^2$ M_{Planck}

Time

Filtering-out Mechanism

Exponential suppression of heavy DM relic by Filtering Effects

$$\rho_{\text{DM}} \rightarrow (\rho_{\text{DM}})_{\text{before}} e^{-M/2\gamma_w T_c} = \text{present value}$$

light particles
$(\gamma, e^{\pm}, \nu_i, q_i, \cdots)$

$\langle \phi \rangle = 0$

transmitted

annihilation

$\langle \phi \rangle \neq 0$

reflected

dark matter
(χ)

$\langle \phi \rangle \neq 0$

Cosmic 1st order phase transition
→ Production of Gravitational Waves

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D. Chway, T. H. Jung, CSS
Phys. Rev. D 101, 095019 (2020)

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Cosmic 1ˢᵗ order phase transition
→ Production of Gravitational Waves

Understanding the origin of DM by GW observations

Simulation from D. Cutting et al. 1802.05712

Stochastic Gravitational Waves

Proposing the mechanism working in a wide range of DM mass

$100 \text{ GeV}/c^2$ M_{Planck}

gravitational waves

GW observatory

Understanding the origin of DM by GW observations

Origin of DM mass & GW observations

Proposing the mechanism working in a wide range of DM mass

100 GeV/c² M_{Planck}

Mass=100PeV

Mass=100TeV

GW observatory

M. Ahmadvand 2108.00958

Understanding the origin of DM by GW observations

Heavy DM Production from First Order PT

DM Filtering Mechanism

Baker, Kopp, Long, [arXiv:1912.02830] for strong coupling and non-rel. bubble

D. Chway, T. H. Jung, **CSS** [arXiv:1912.04238] for weak coupling and rel. bubble

DM dilution/production from Supercooling related with confining/conformal sector

Hambye, Strumia, Teresi [arXiv:1805.01473], Baldes, Garcia-Cely [arXiv:1809.01198],

Baldes, Gouttenoire, Sala [arXiv: 2007.08440], Kierkla, Karam, Swiezewska [arXiv:2210.07075]

DM from Ultra-relativistic Bubble Wall and Plasma Interactions ($\phi \rightarrow$ DM+DM)

Azatov, Vanvlasselaer, Yin [arXiv:2101.05721], Ai, Fairbairn, Mimasu, You [arXiv:2406.20051]

DM from Ultra-rel. Bubble Collisions (local recovering of symmetry, high energetic pt collisions)

Falkowski, No [arXiv:1211.5615], Baldes, Dichtl, Gouttenoire, Sala [2306.15555]

Giudice, H. M. Lee, Pomarol, and Shakya [arXiv:2403.03252]

DM from the isolated Symmetric Phase (asymmetric DM, effect of squeezing)

Pontón, Bai, Jain [arXiv:1906.10739], Hong, Jung, Xie [arXiv:2008.04430],

Asadi, Kramer, Kuflik, Ridgway, Slatyer, Smirnov [arXiv: 2103.09827],

Gouttenoire, Kuflik, Liu [arXiv:2311.00029]

And many others

Thermal DM Beyond the Unitarity Bound

How can the Unitarity bound be overcome to allow various DM masses?

$$\Omega_{\mathrm{DM}} h^2 \geq 0.1 \left(\frac{M_{\mathrm{DM}}}{130 \ \mathrm{TeV}} \right)^2$$

What are the predictions for observables?

production of ultra-heavy dark matter

Snowmass2021 Ultra-heavy particle dark matter arXiv:2203.06508

DM Probe via Stellar Evolution

The mechanism working in a wide range of DM mass : Interaction with the SM particles

100 GeV/c^2 M_{Planck}

Dark Matter around the Star can be captured and accumulated in the core of the star because of negligible annihilation cross-section. It can trigger the earlier nuclear reaction in a certain stage of stellar evolution by new heating sources.

χ

χ

χ

Star

DM Clump

Ignition

New Stage of Stellar Evolution

Recent review of dark matter effects on compact stars such as White Dwarf, Neutron Stars Phys.Rept. 1052 (2024) 1-48 arXiv:2307.14435

Heavy DM in WD: 1505.04444, 1505.07464, 1805.07381, 1905.00395, 2203.09054, 2404.16272, etc.

Heavy DM in Red Giant (work in progress) with S. Ganguly, M. He, S. Yun (IBS), O. Straniero (INAF)

Order of Phase Transition and Simulation

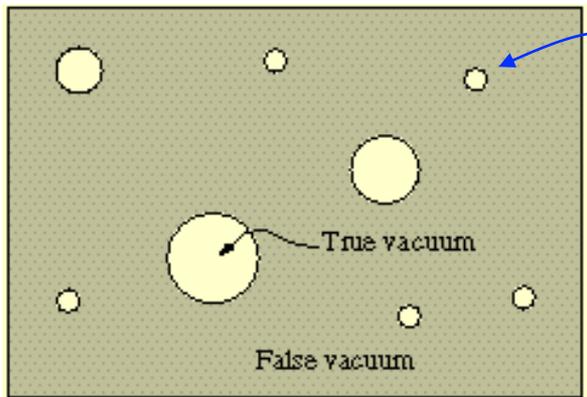*Tomasz Dutka, Tae Hyun Jung, and CSS arXiv:2412.15864*

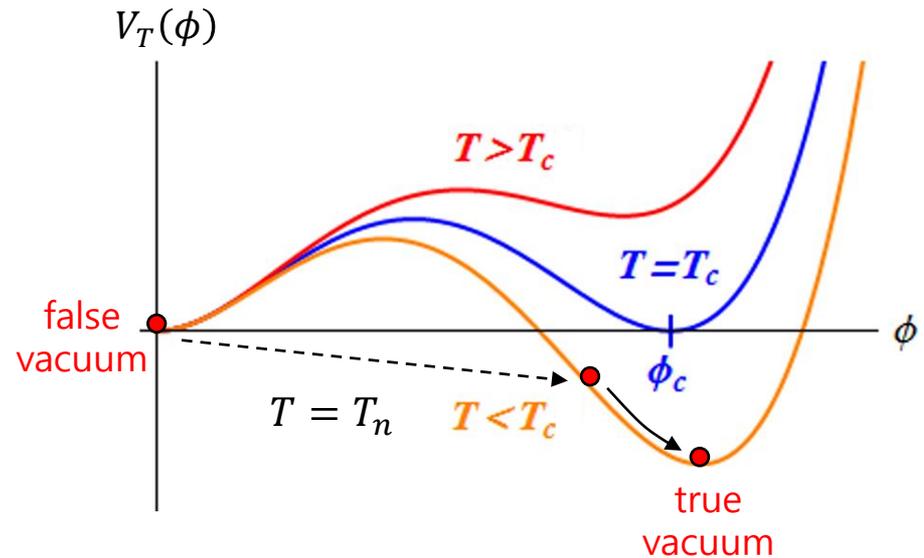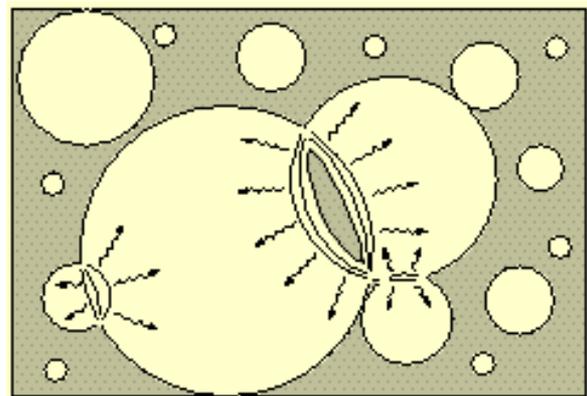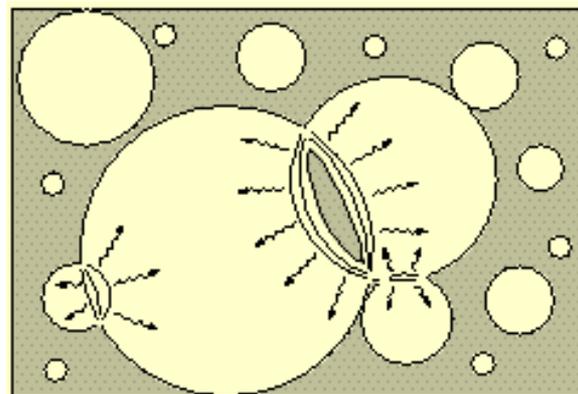# Condition for First Order Phase Transition

Equilibrium favors the state that minimizes the free energy at a given temperature T

$$f(T,\phi) = V_0(\phi) \pm \frac{g_i}{2\pi^2} T^4 J_{B,F}\left(\frac{m_i^2(\phi)}{T^2}\right) \qquad \text{where} \quad J_{B,F}(y^2) = \int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+y^2}}\right)$$

As the temperature decreases, a transition can occur from the symmetric phase to the broken phase (or vice versa). For the finite temperature effective potential $V_T(\phi) = f(T,\phi) - f(0,\phi)$
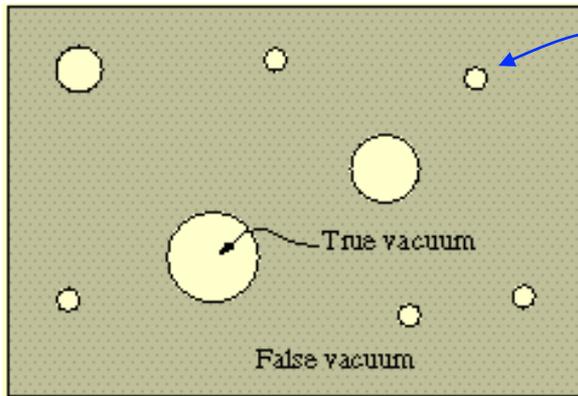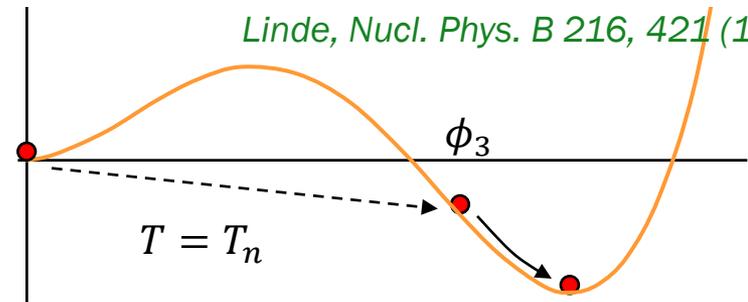
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First Order Phase Transition

33

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First Order Phase Transition

Condition for First Order Phase Transition

Equilibrium favors the state that minimizes the free energy at a given temperature T

$$f(T,\phi) = V_0(\phi) \pm \frac{g_i}{2\pi^2} T^4 J_{B,F}\left(\frac{m_i^2(\phi)}{T^2}\right) \qquad \text{where} \quad J_{B,F}(y^2) = \int_0^\infty dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+y^2}}\right)$$

As the temperature decreases, a transition can occur from the symmetric phase to the broken phase (or vice versa). For the finite temperature effective potential $V_T(\phi) = f(T,\phi) - f(0,\phi)$

Critical bubble with the field profile to give the bounce action S_3

$$\frac{\Gamma_n(T)}{\text{Vol}} \simeq \left(\frac{T}{2\pi}\right)\left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} \left(\frac{\det[-\partial^2 + V_T''(0)]}{\det'[-\partial^2 + V_T''(\phi_3)]}\right)^{1/2} \exp\left(-\frac{S_3}{T}\right)$$

Linde, Nucl. Phys. B 216, 421 (1983)

ϕ_3

$T = T_n$

True vacuum

False vacuum

Nucleation temperature

$$\frac{\Gamma(T_n)}{V} \sim T_n^4 \exp\left(-\frac{S_3}{T_n}\right) \quad = \quad H^4(T_n)$$
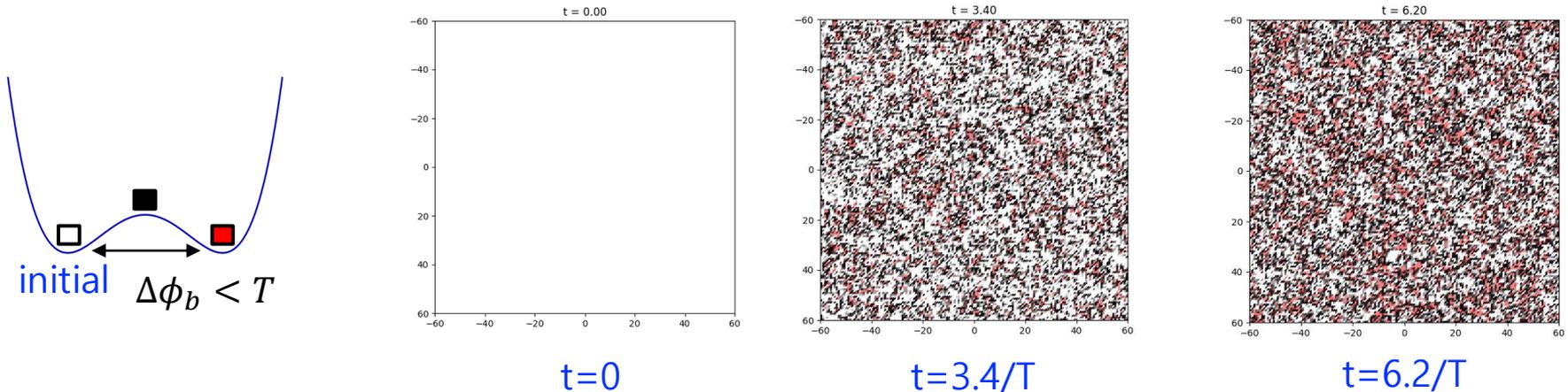
Condition for First Order Phase Transition

The nucleation rate is exponentially sensitive to the bounce action S_3 of the critical bubble.

$$\frac{\Gamma(T)}{V} \sim T^4 \exp\left(-\frac{S_3}{T}\right)$$

$S_3 = \infty$ at $T = T_c$

$S_3 = O(100)T$ at $T = T_n$

Bubble formations | **No phase transition**

$\frac{S_3}{T}$

$O(100)$

T_n T_c T

Condition for First Order Phase Transition

The nucleation rate is exponentially sensitive to the bounce action S_3 of the critical bubble.

$$\frac{\Gamma(T)}{V} \sim T^4 \exp\left(-\frac{S_3}{T}\right)$$

However, this bounce action approach may not be always true.

For instance, if the field distance of the potential barrier is smaller than the background temperature ($\Delta\phi_b < T$), thermal fluctuations that cannot be captured by the critical bubble formation can induce **the phase mixing between two phases,** even at the critical temperature.

initial $\Delta\phi_b < T$

t=0

Condition for First Order Phase Transition

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initial $\Delta\phi_b < T$

t=0   t=3.4/T   t=6.2/T

the phase mixing between symmetry and broken phases

Borrill, Gleiser Phys.Rev. D51 (1995) 4111-4121

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Condition for First Order Phase Transition

Non-equilibrium thermal fluctuation becomes important when $\Delta\phi_b < T$

In this case, **no bubbles form**, and the two phases undergo strong mixing before the transition occurs—a process known as **spinodal decomposition**. **As $T < T_c$, the broken phase gradually and smoothly fills the Universe.**
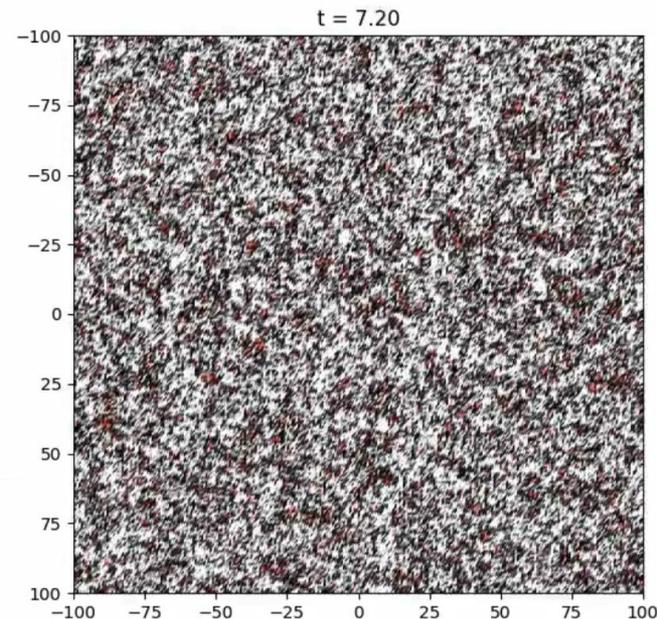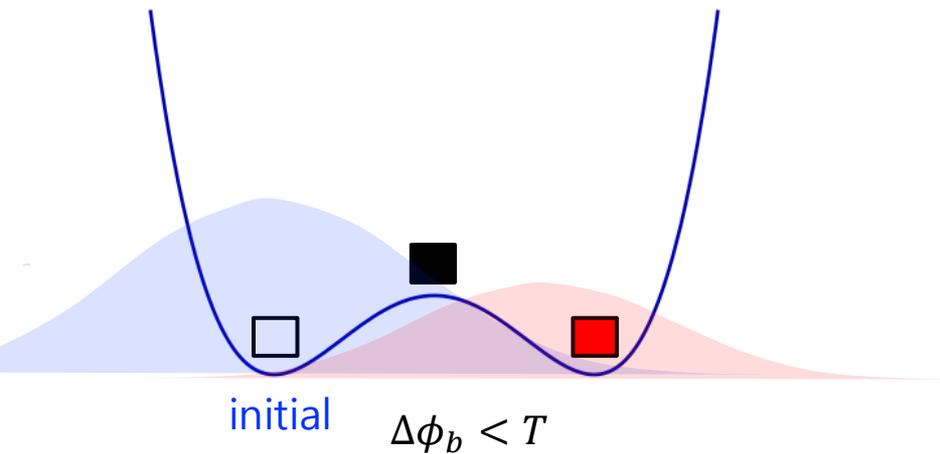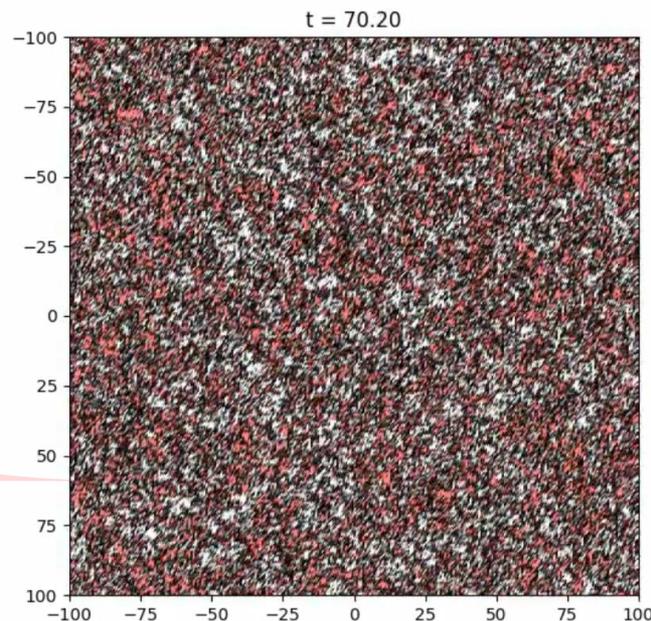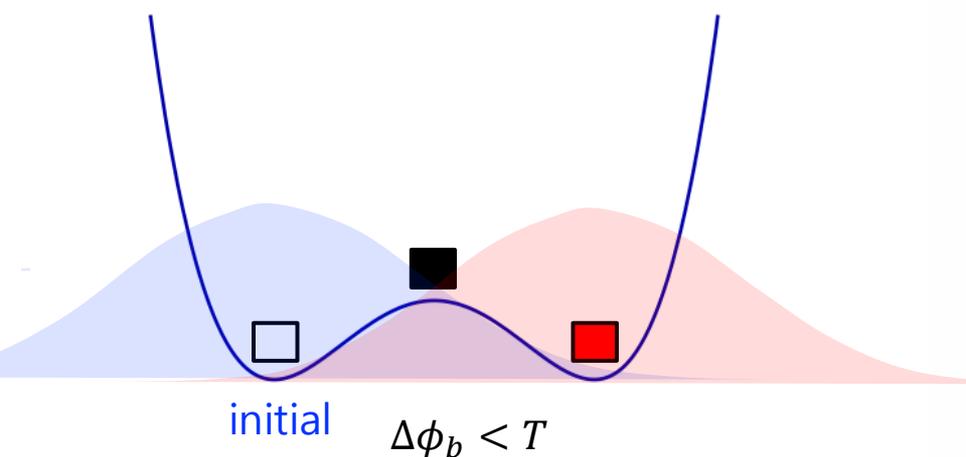

Simulation by Tomasz Dutka

the phase mixing between symmetry **and** broken **phases**

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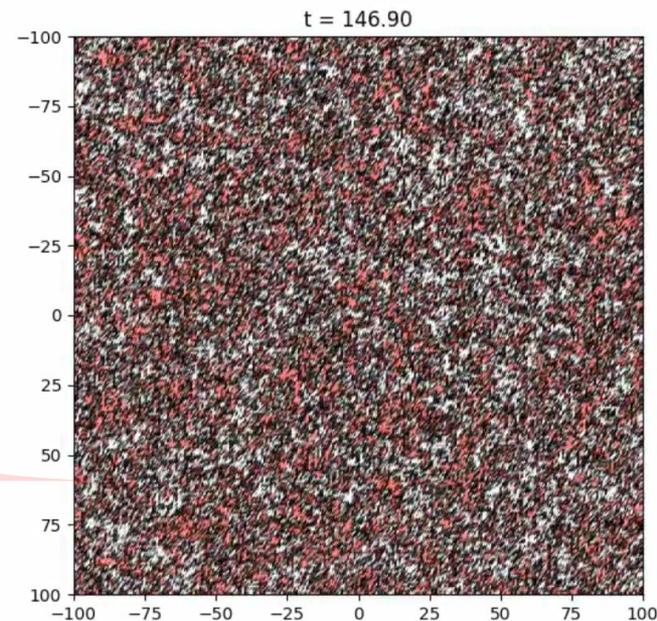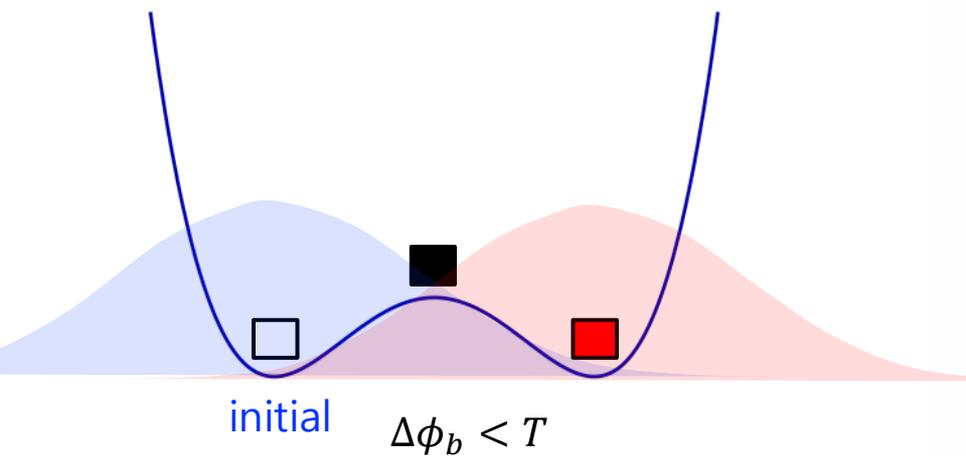

initial $\Delta\phi_b < T$

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the phase mixing between symmetry and broken phases

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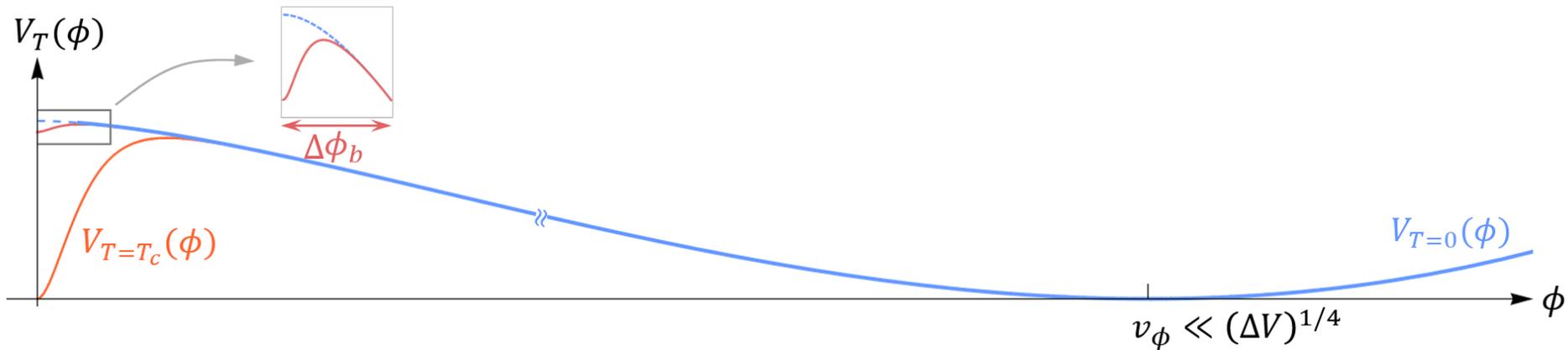

Simulation by Tomasz Dutka

the phase mixing between symmetry and broken phases

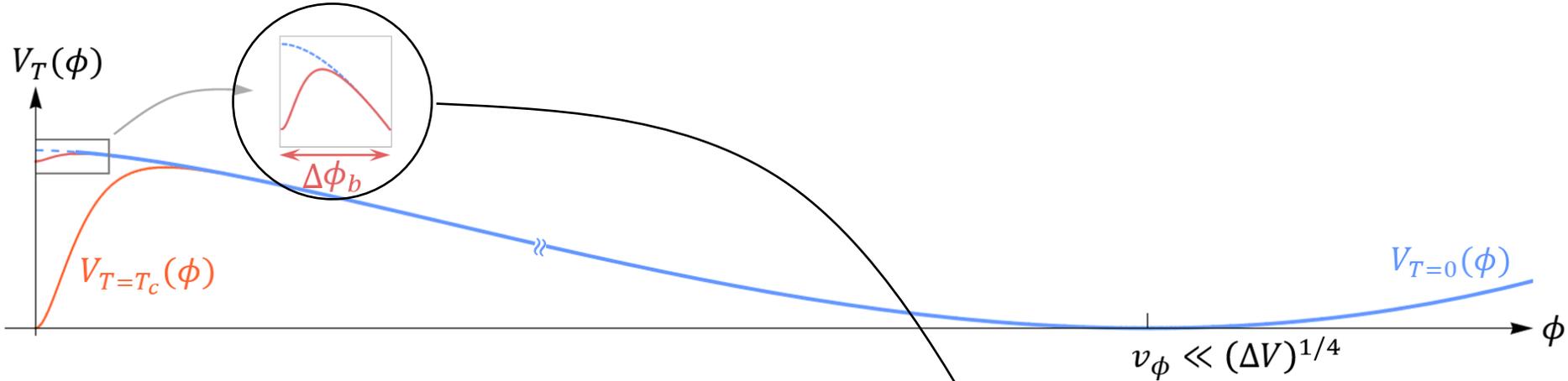# Condition for First Order Phase Transition

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Supercooled Phase Transition

For a strong first-order PT—favorable for mechanisms like heavy DM generation via filtering or energetic collisions—**a supercooled transition with a flat potential is typically preferred**. In this scenario, the true vacuum field value is significantly larger than the critical/nucleation temp.

It is quite natural to expect **this phase transition to be first-order**, as the transition occurs before the potential barrier disappears.
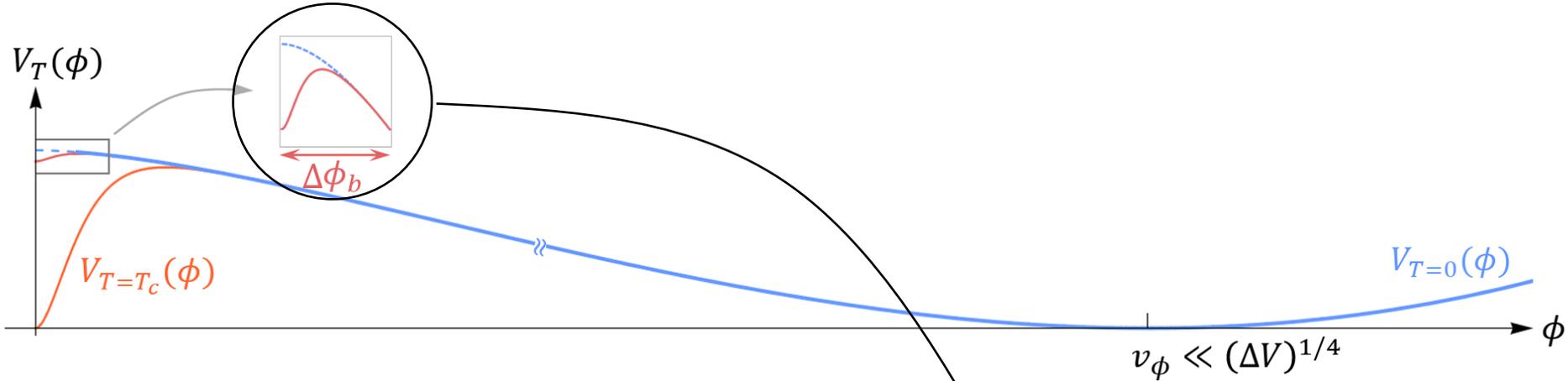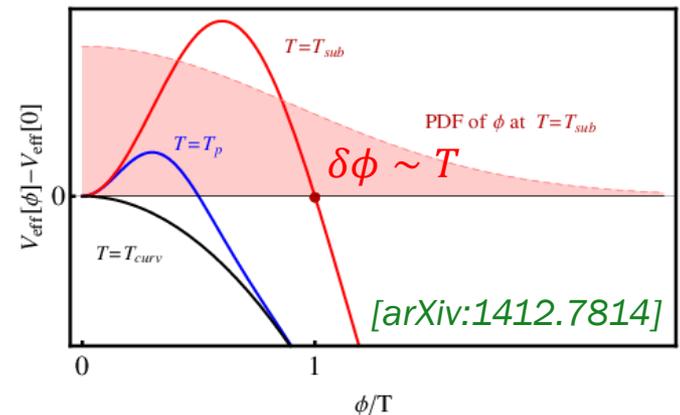
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schematic summary of potential shapes around the origin (not to scale)

$T = T_{sub}$

PDF of ϕ at $T = T_{sub}$

$T = T_p$

$\delta\phi \sim T$

$T = T_{curv}$

$V_{eff}[\phi] - V_{eff}[0]$

ϕ/T

[arXiv:1412.7814]

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$$v_\phi \ll (\Delta V)^{1/4}$$

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However, there is some ambiguity, as the field distance for the potential barrier can be smaller than the temperature, $\Delta\phi_b < T$. In this case, thermal fluctuations can easily overcome the barrier. The question: **Is the transition still first order**? It may seem as if the field evolves from the top of the unstable potential without forming bubbles.

schematic summary of potential shapes around the origin (not to scale)

$T = T_{sub}$
PDF of ϕ at $T = T_{sub}$
$T = T_p$
$\delta\phi \sim T$
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[arXiv:1412.7814]

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Simulation
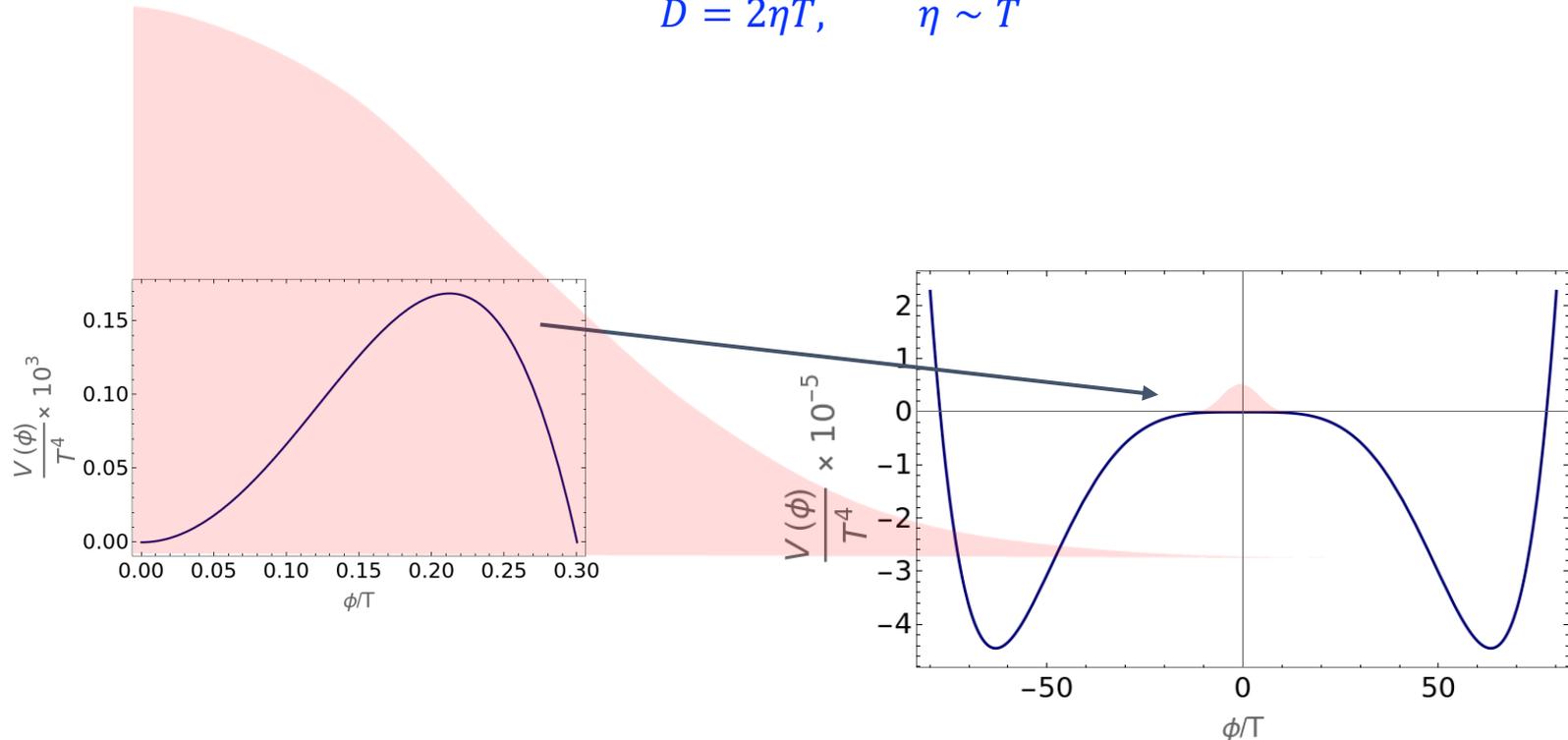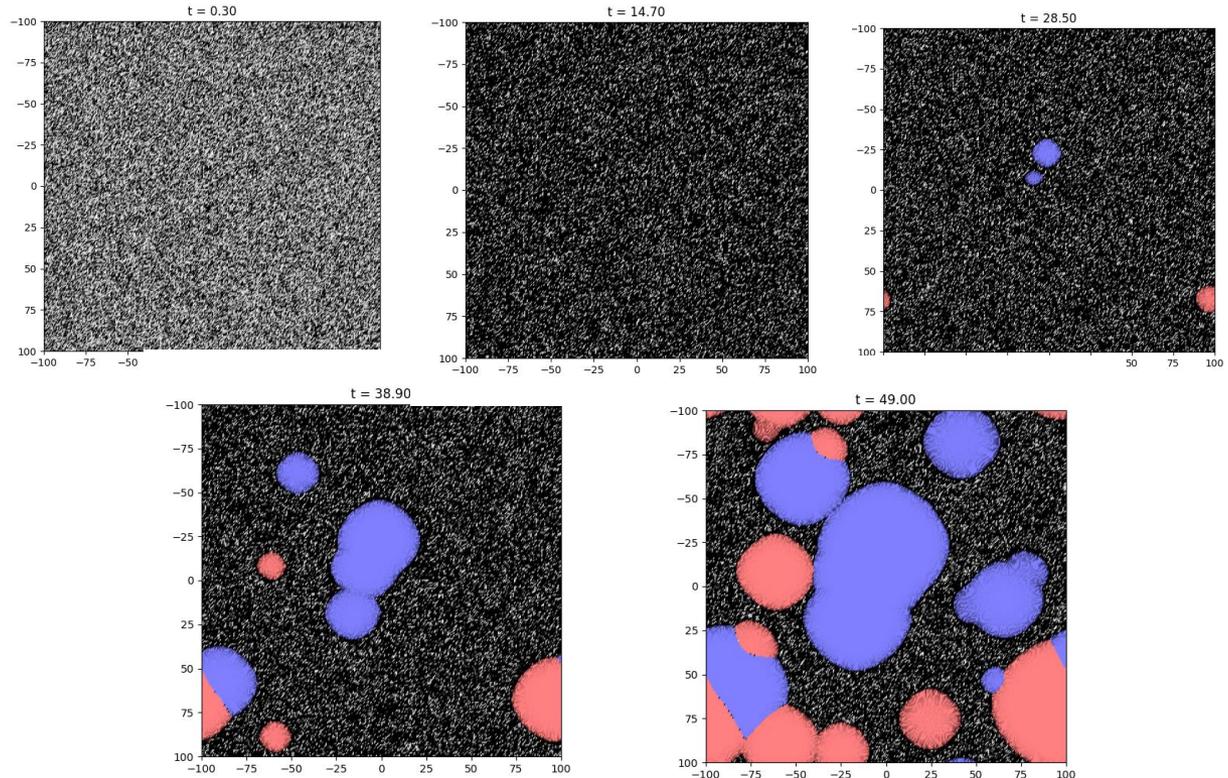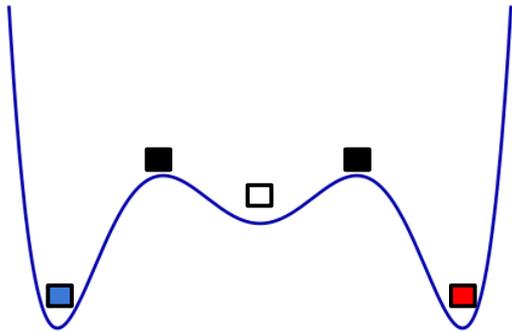
We directly solve the 3+1dimensional **Langevin equation** in the lattice ($N_{\text{lattice}}^3 \sim (200 - 400)^3$)

$$\partial_t^2 \phi(\boldsymbol{x}, t) + \eta \partial_t \phi(\boldsymbol{x}, t) - \nabla^2 \phi(\boldsymbol{x}, t) + \partial_\phi V_T(\phi) = \xi(\boldsymbol{x}, t)$$

with the **fluctuation**-**dissipation** theorem

$$\langle \xi(\boldsymbol{x}, t) \xi(\boldsymbol{x}', t') \rangle_T = D\delta(t - t')\delta^3(\boldsymbol{x} - \boldsymbol{x}')$$

$$D = 2\eta T, \qquad \eta \sim T$$

$V_T(\phi)$

Noise (thermal fluctuation)

$\phi_b \sim (0.1 - 0.5)T$

$v_\phi \gg T$

Simulation

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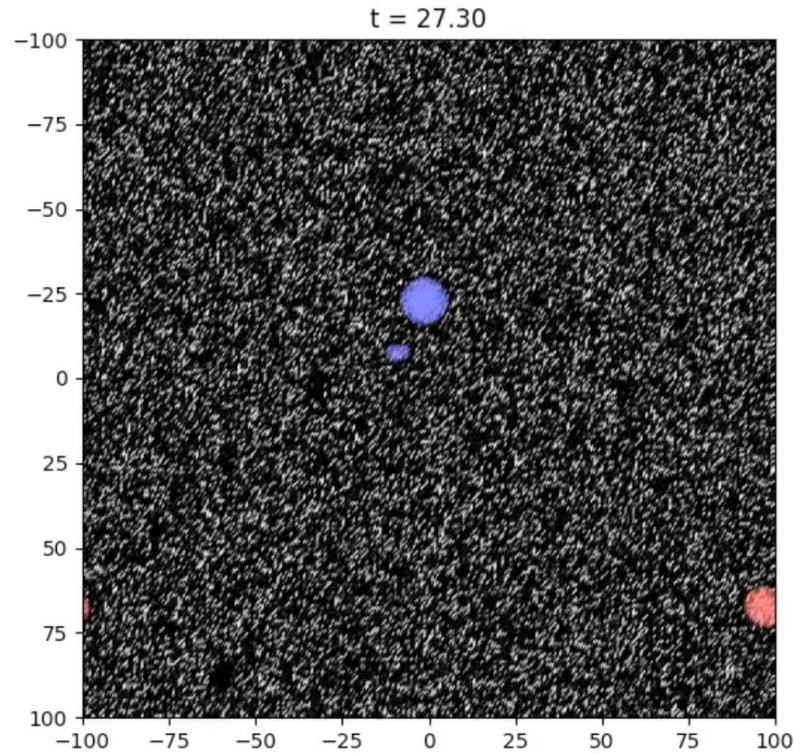**Simulation supports bubble nucleation prediction**

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Simulation

Tomasz Dutka, Tae Hyun Jung, and CSS *arXiv:2412.15864*

Simulation supports bubble nucleation prediction

Simulation

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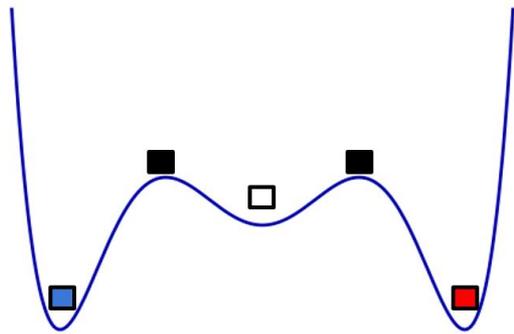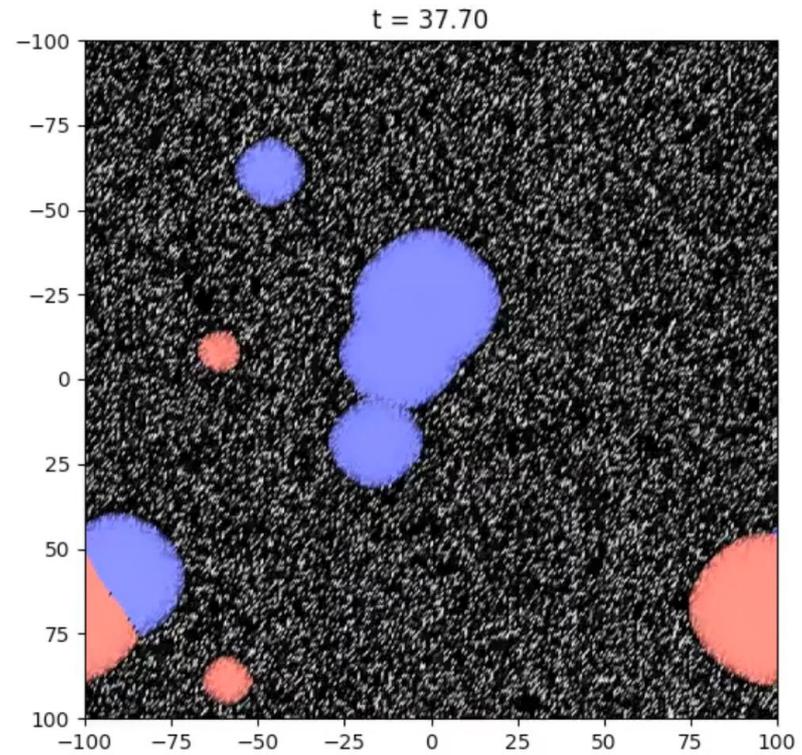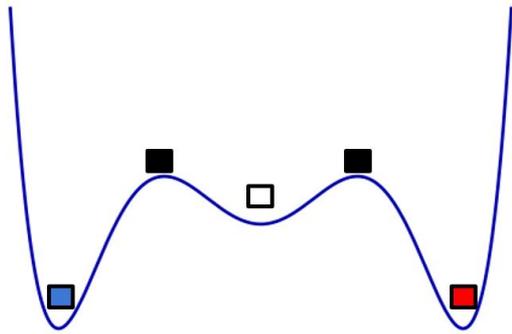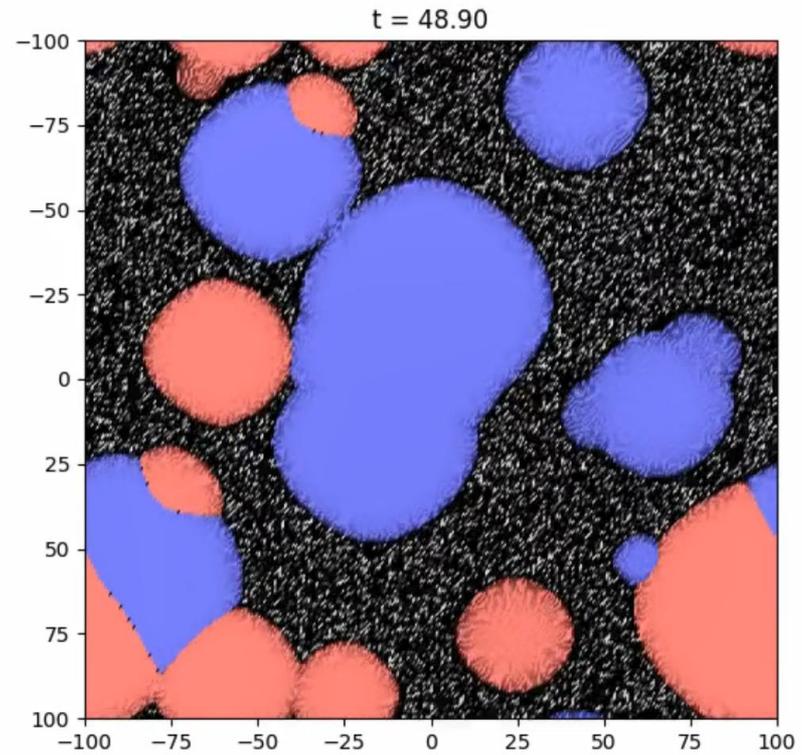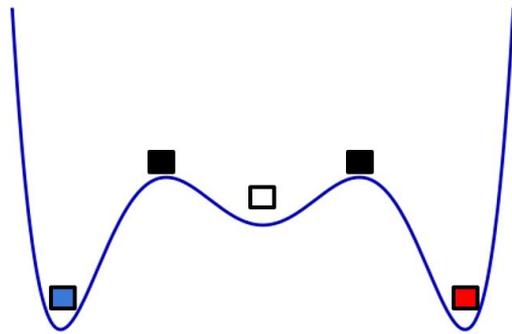
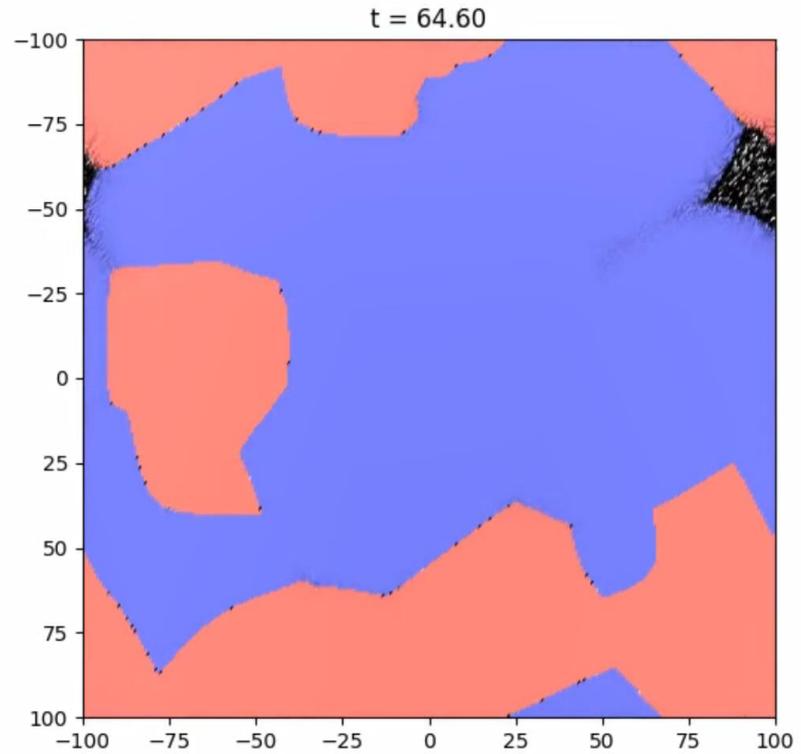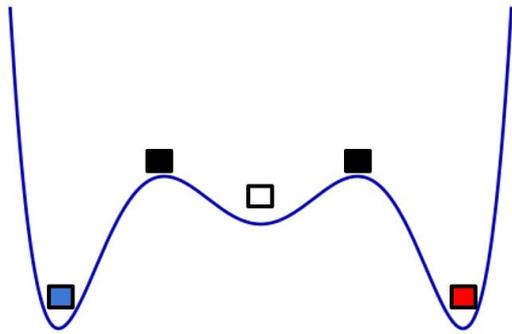# Simulation

t = 14.90

Tomasz Dutka, Tae Hyun Jung, and CSS arXiv:2412.15864

Simulation

Tomasz Dutka, Tae Hyun Jung, and **CSS** *arXiv:2412.15864*

Simulation

Tomasz Dutka, Tae Hyun Jung, and **CSS** *arXiv:2412.15864*

Simulation

t = 48.90

Tomasz Dutka, Tae Hyun Jung, and **CSS** *arXiv:2412.15864*
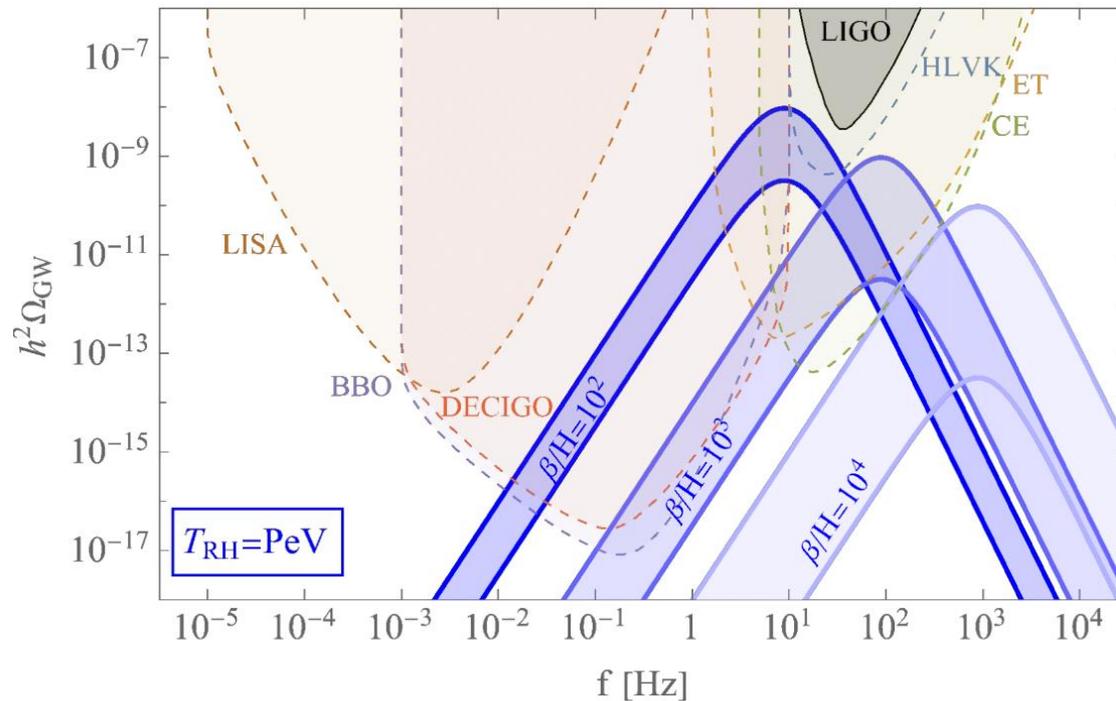
Simulation

Tomasz Dutka, Tae Hyun Jung, and **CSS** *arXiv:2412.15864*

Expected GW Signal

Further study is needed to determine whether the nucleation rate, the evolution of the true vacuum fraction, and the bubble wall velocity are consistent with our analytical understanding.

Nevertheless, we have strong evidence that a first-order phase transition is a generic feature of such a flat potential. The expected gravitational wave signal is as follows:

Summary

Heavy dark matter and its phenomenological implications are gaining significant attention.

We have explored various heavy dark matter production scenarios when sizable interactions with Standard Model particles exist, highlighting the role of a first-order phase transition.

Through simulations, we investigated whether thermal fluctuations—such as noise and friction in field dynamics—can actually induce bubble formation and expansion, i.e. first order phase transition, rather than spinodal decomposition, for various examples

A systematic study of first-order phase transitions enables more accurate predictions of dark matter phenomenology and gravitational wave signals.