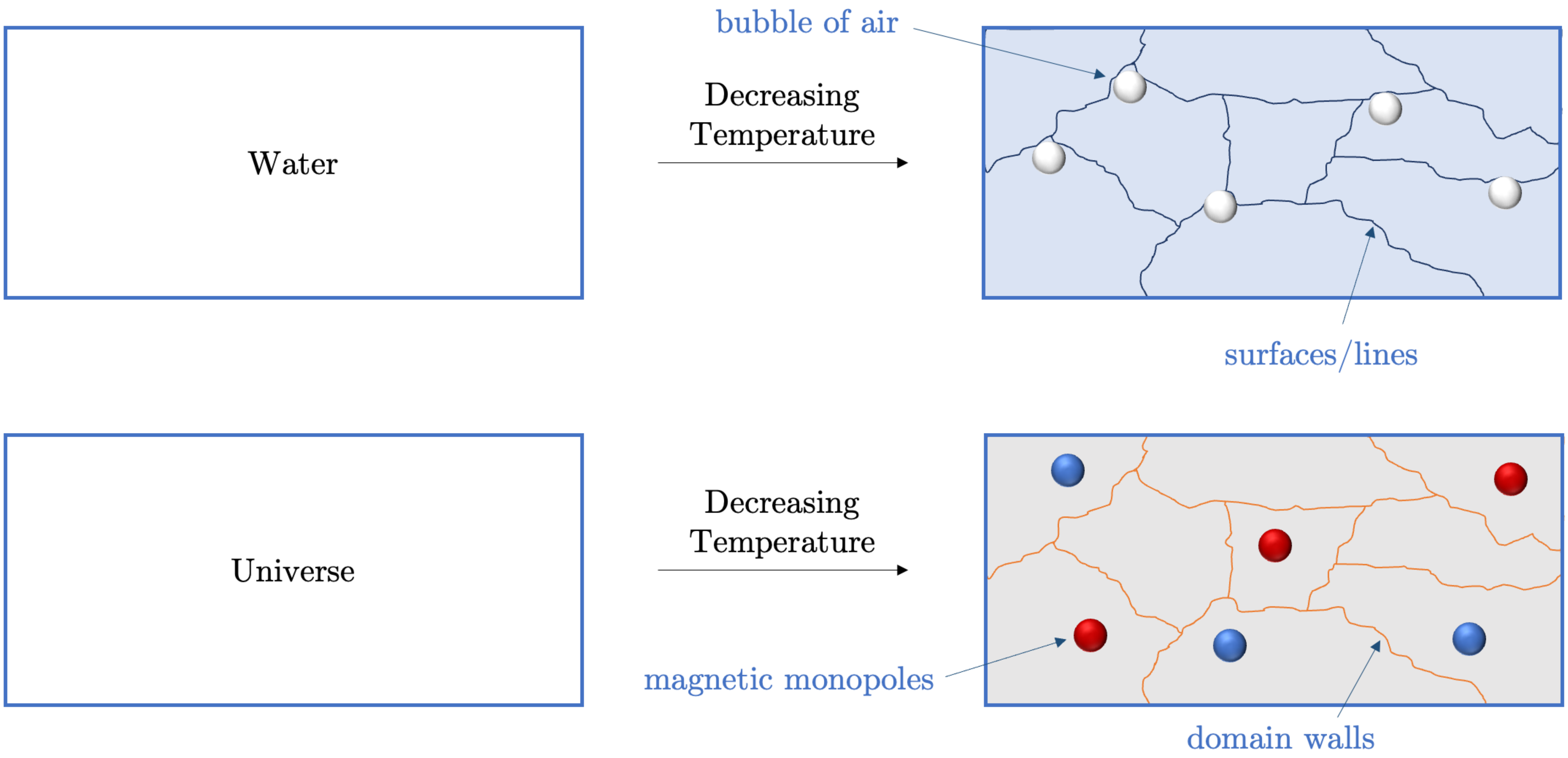
Confinement Slingshot and Gravitational Waves

Maximilian Bachmaier
(Cosmology Group by Gia Dvali)

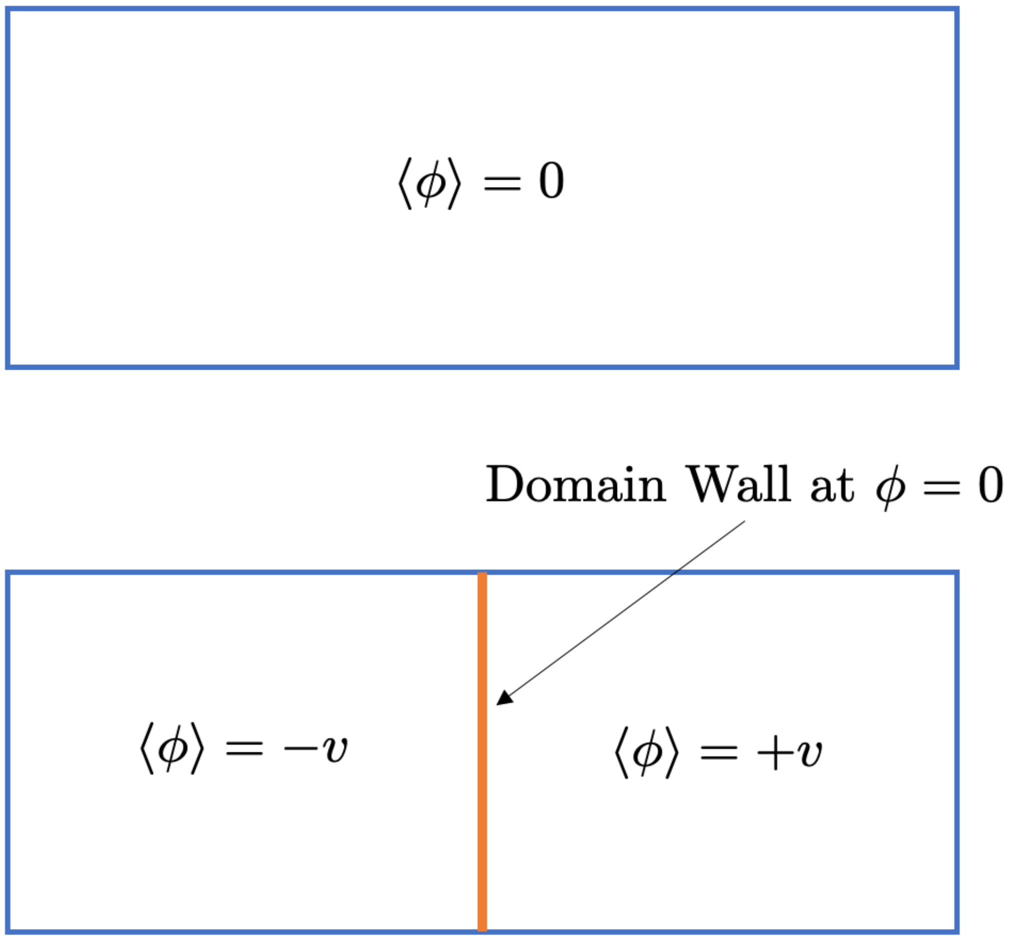
29 April 2024

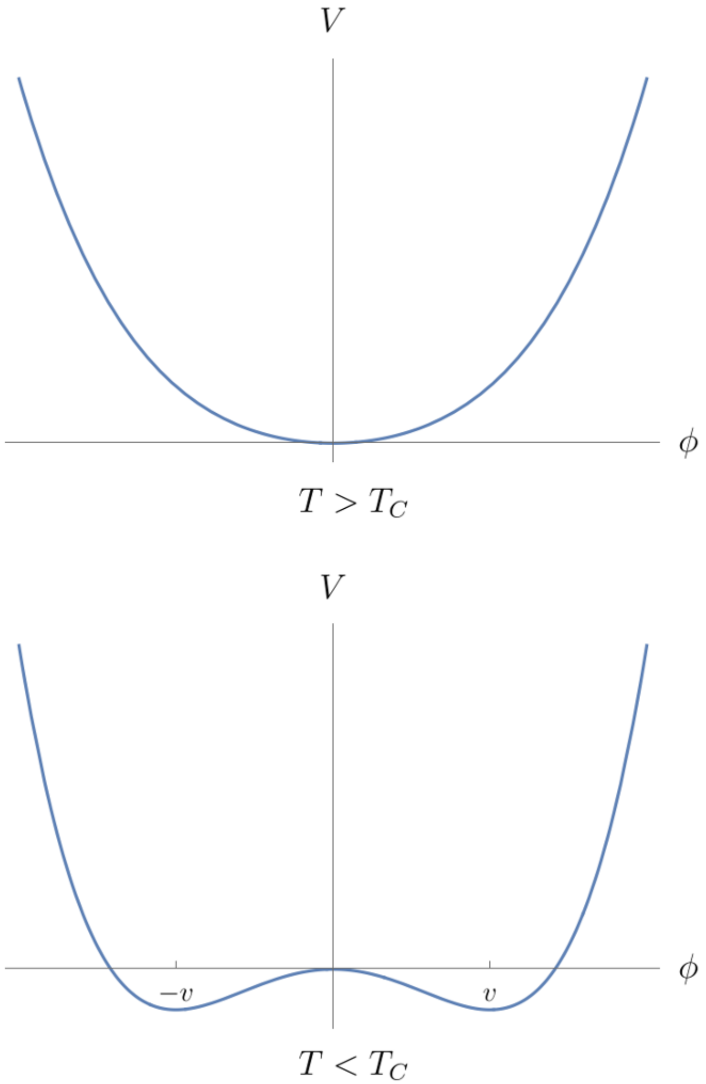
MPP IMPRS Colloquium

Motivation: Freezing of Water



What are Domain Walls?

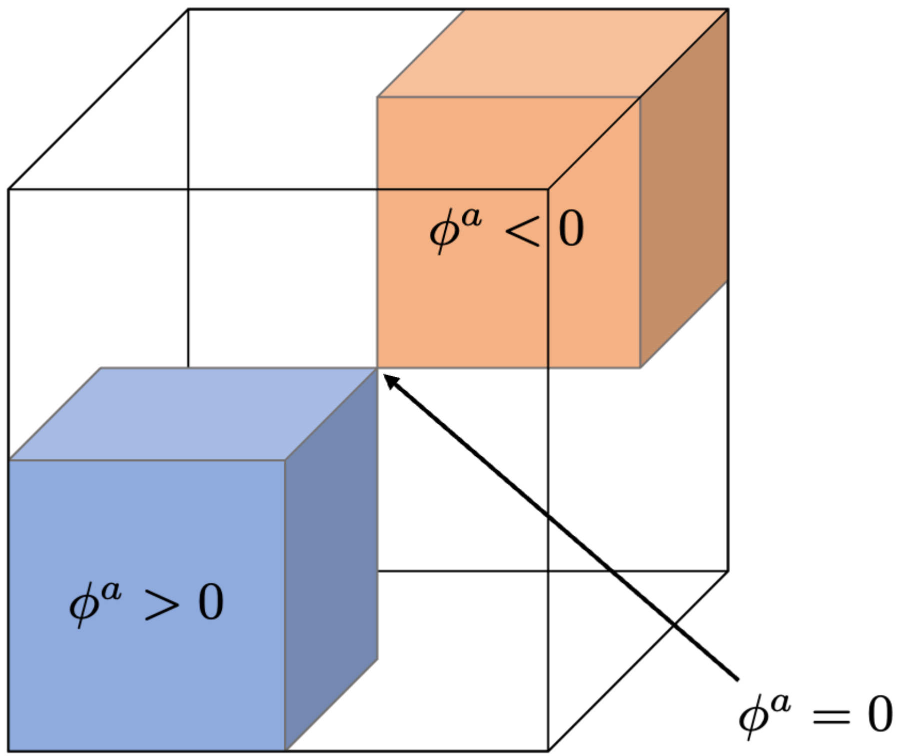


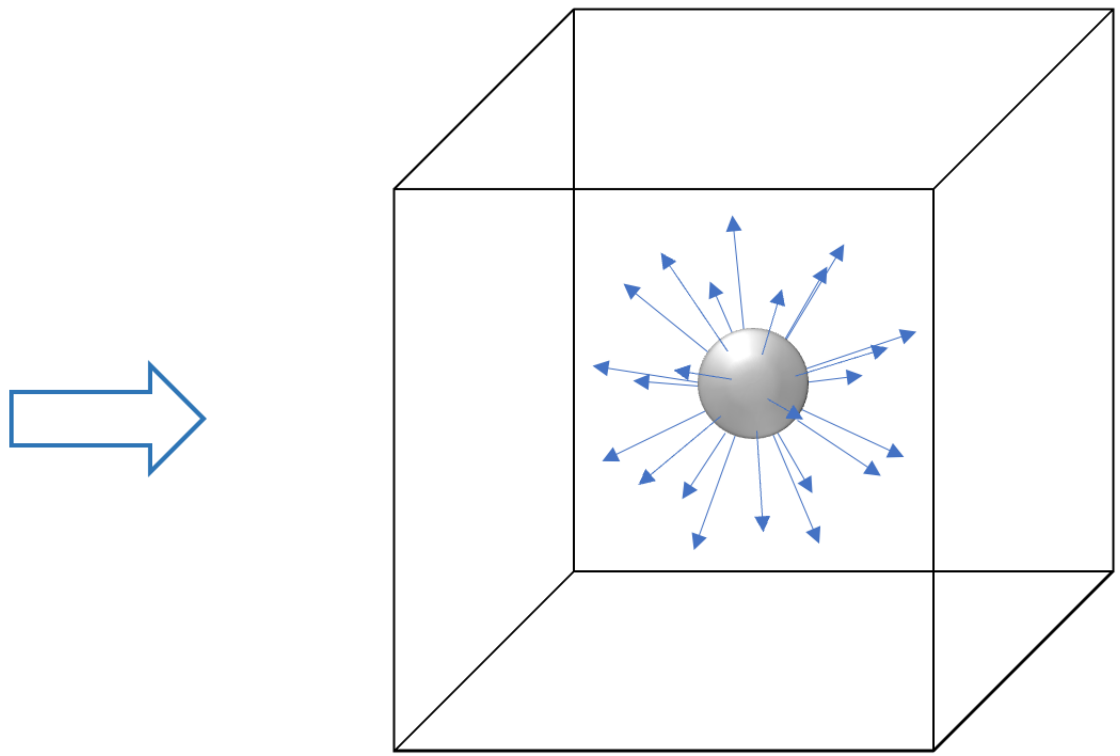


T. Kibble (1976)

What are Magnetic Monopoles?

Phase Transition: $G \to \ldots \times U(1)$





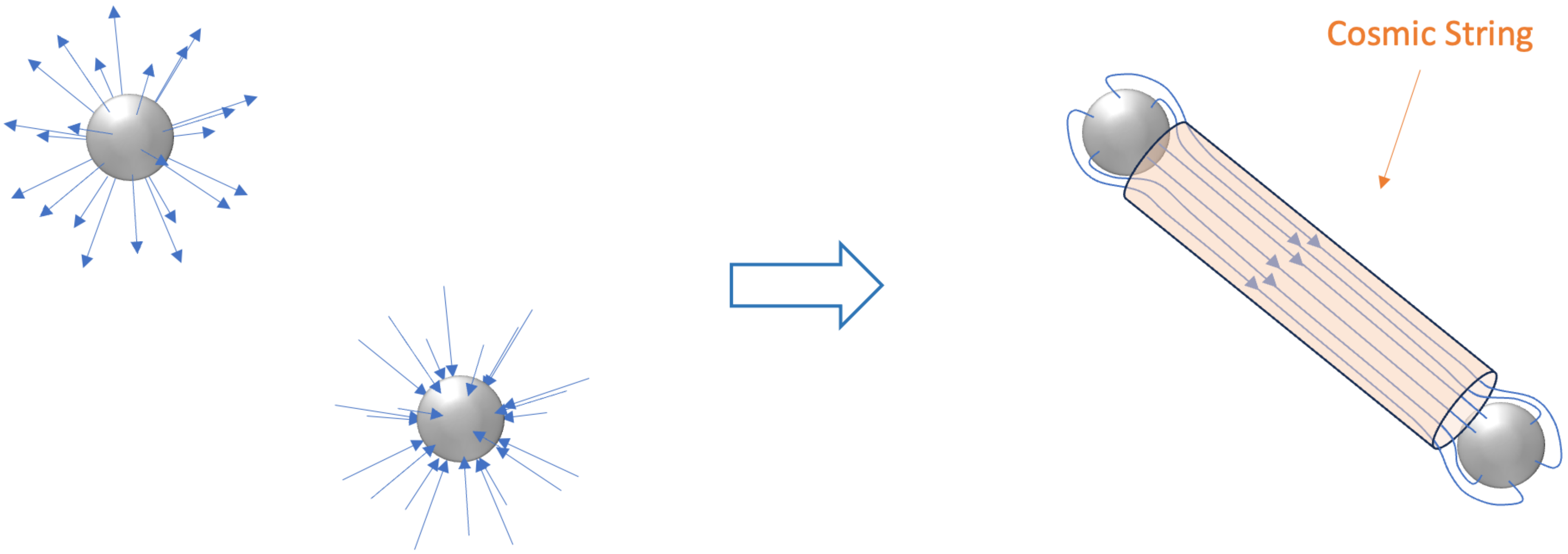
't Hooft-Polyakov
Magnetic Monopole

G. ‘t Hooft (1974)
A. Polyakov (1974)

Magnetic Monopoles Connected by a String

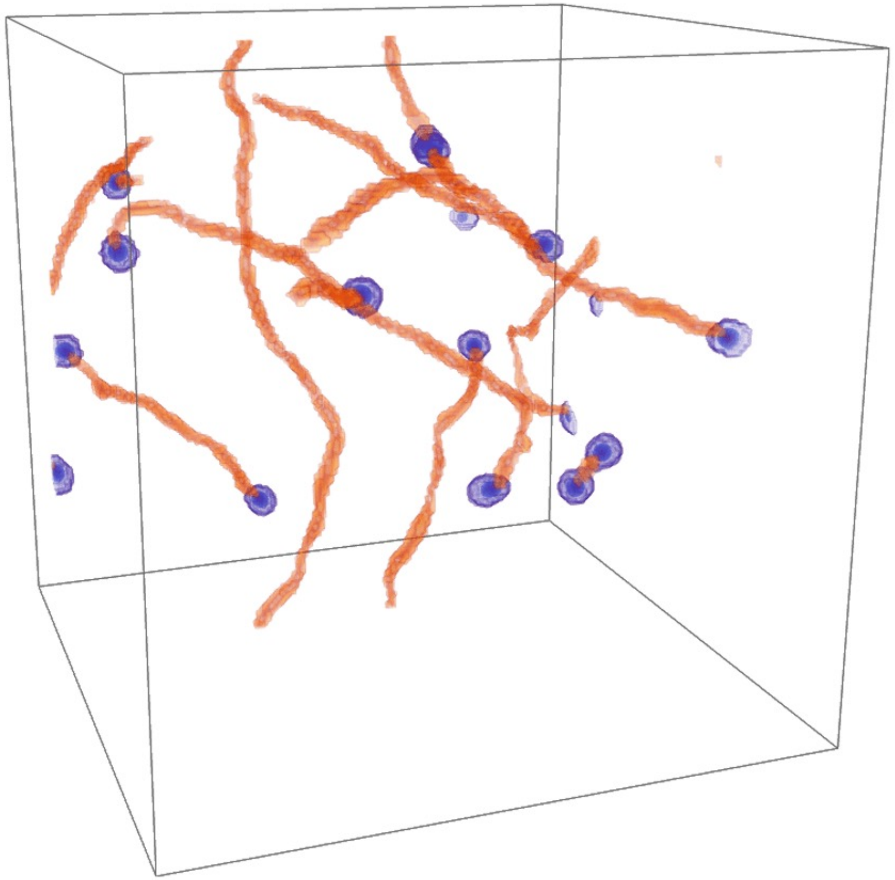
First Phase Transition: $G \to \ldots \times U(1)$

Second Phase Transition: $\ldots \times U(1) \to \ldots \times \cancel{U(1)}$



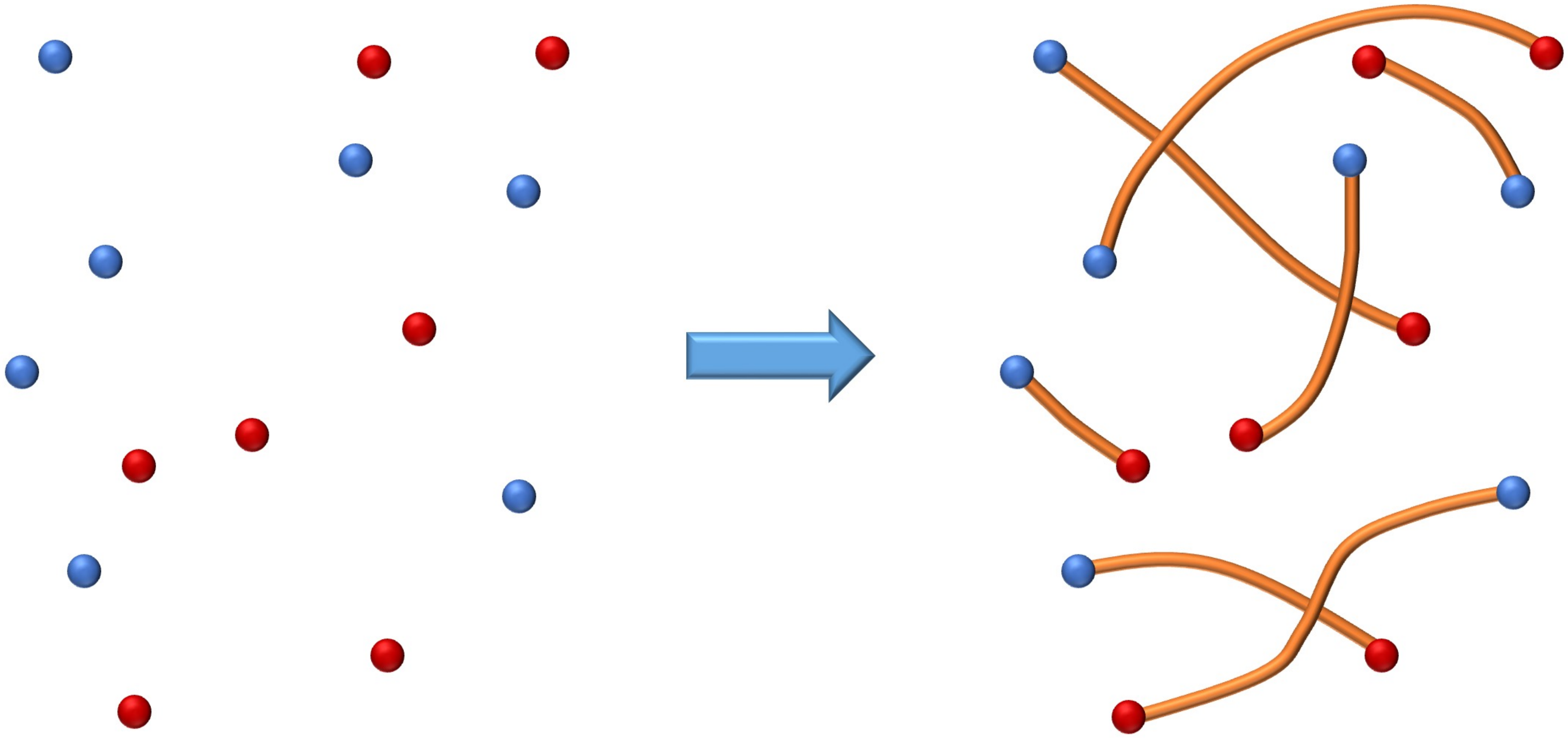
P. Langacker, S. Pi (1980)
X. Martin, A. Vilenkin (1997)
G. Dvali, J. S. Valbuena-Bermúdez, M. Zantedeschi (2022)

Second-Order Phase Transition

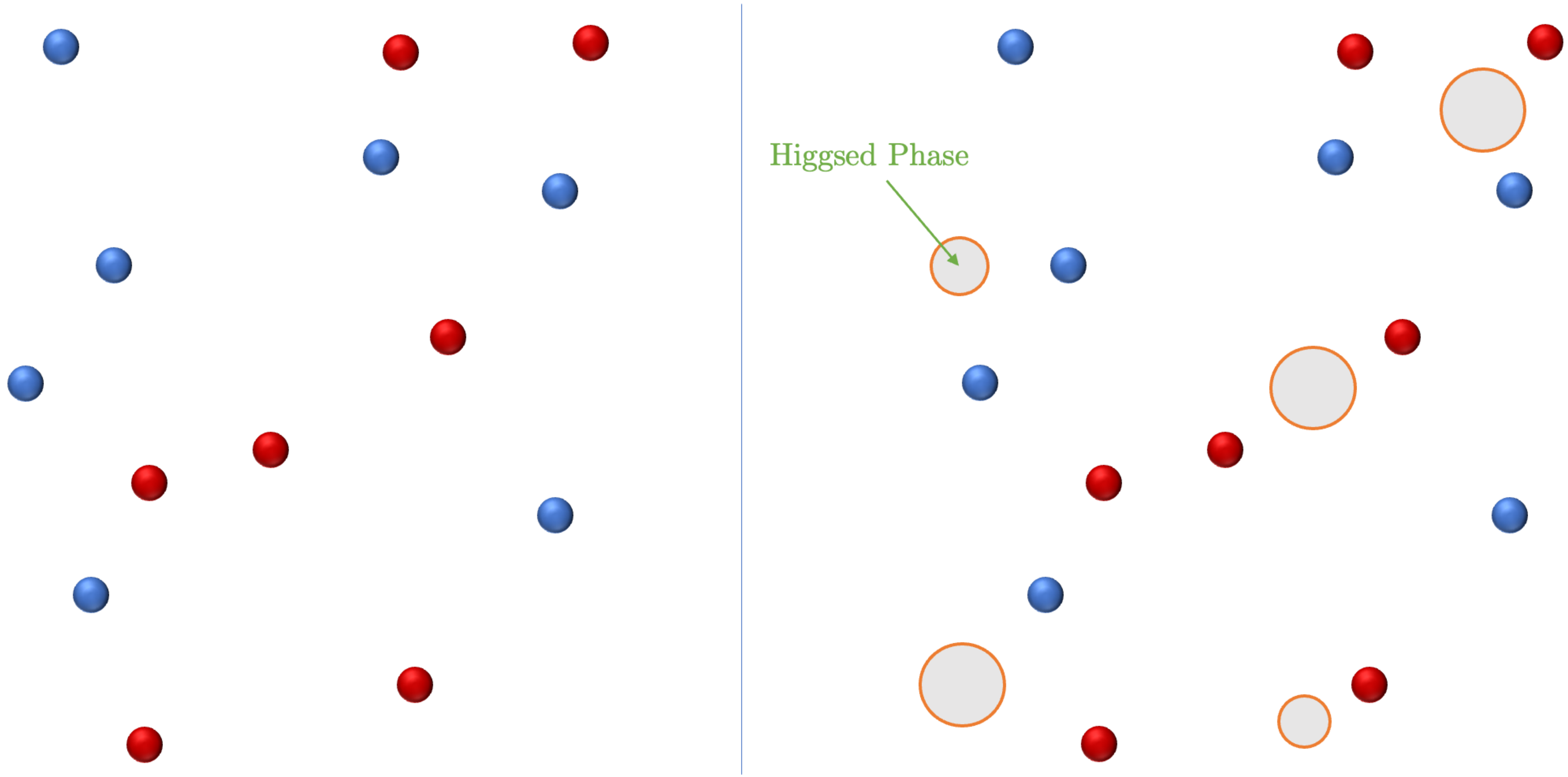


What happens in a first-order phase transition?

Second-Order Phase Transition



First-Order Phase Transition



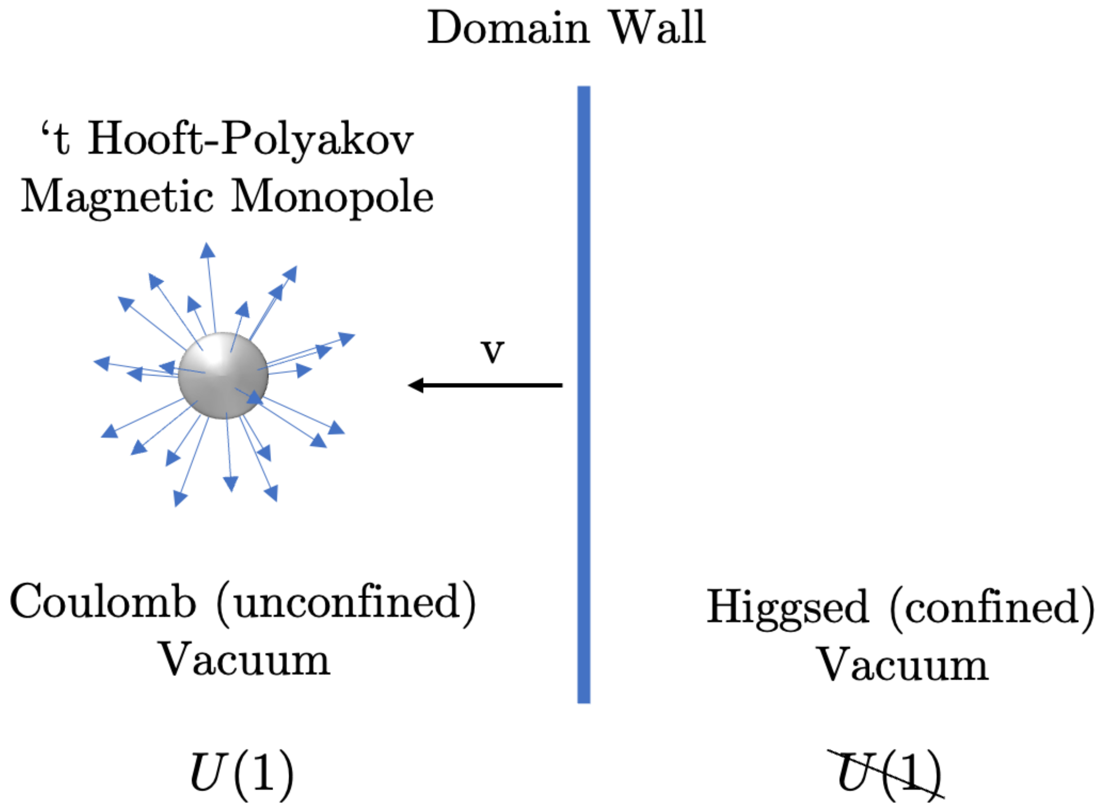
The Model

We consider an $SU(2)$ gauge theory with two scalar fields ϕ and ψ.

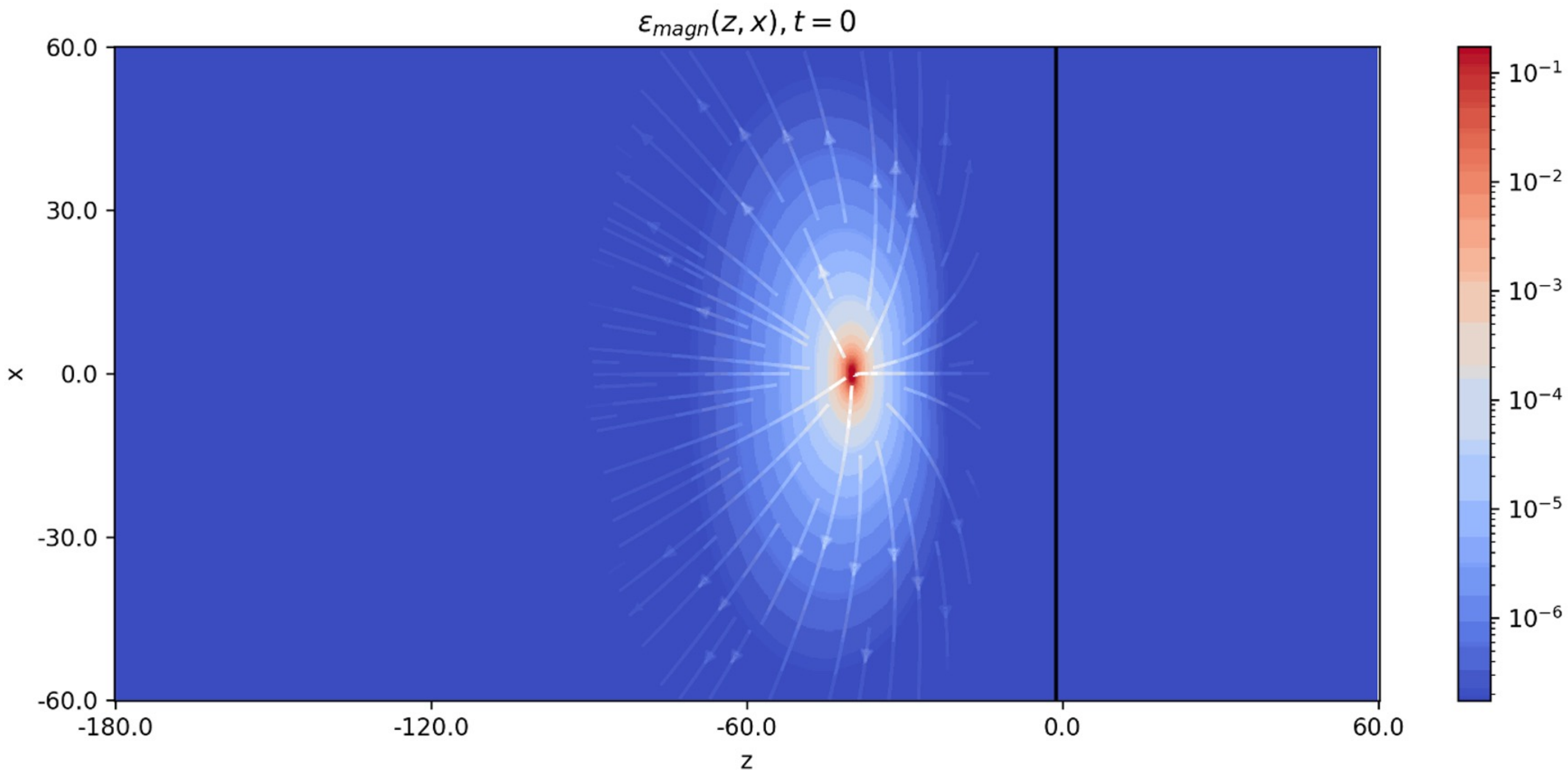
Breaking Pattern: $SU(2) \xrightarrow{\phi} U(1) \xrightarrow{\psi} 1$

Magnetic Monopoles

Cosmic Strings

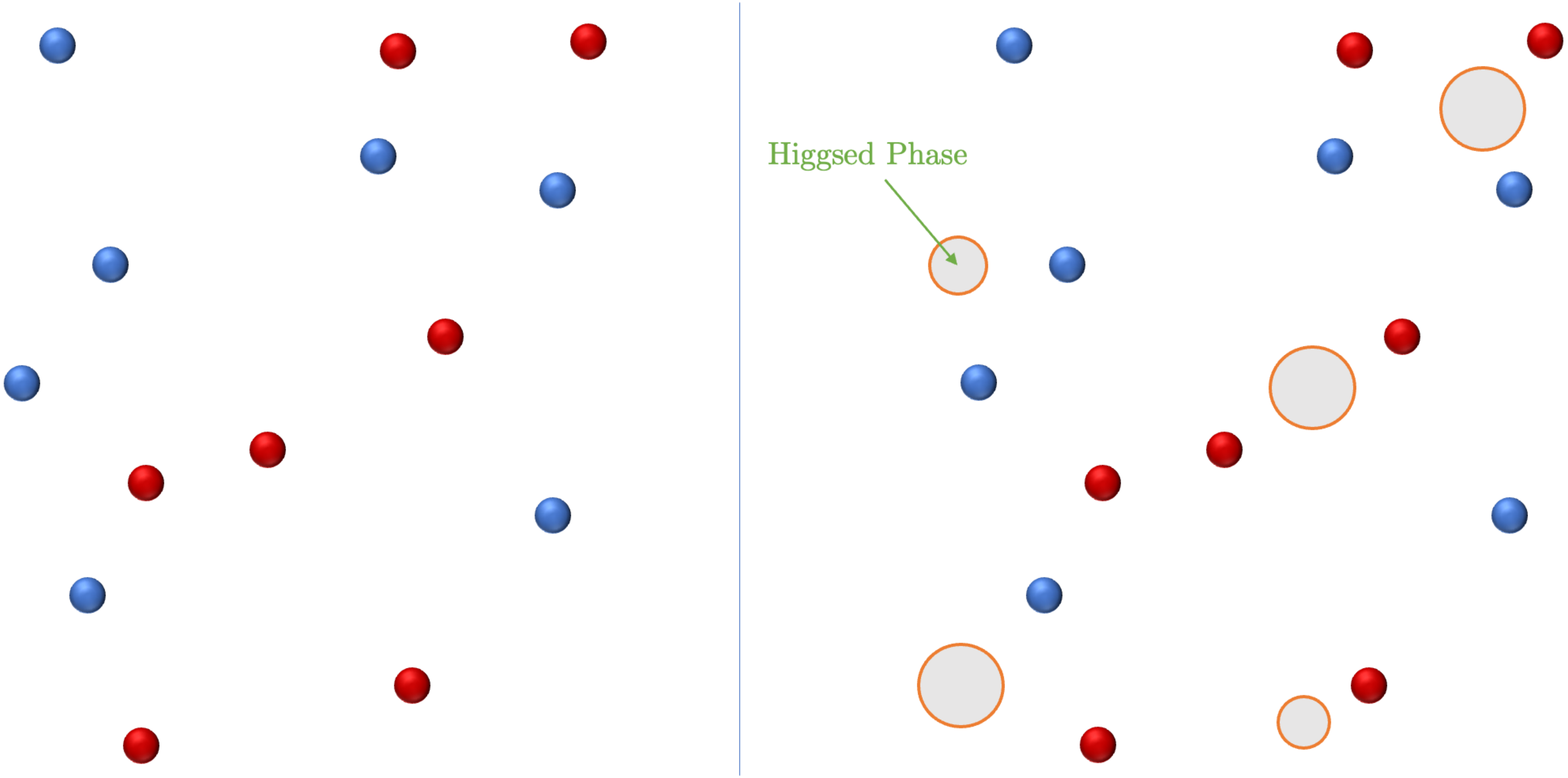


Confinement Slingshot

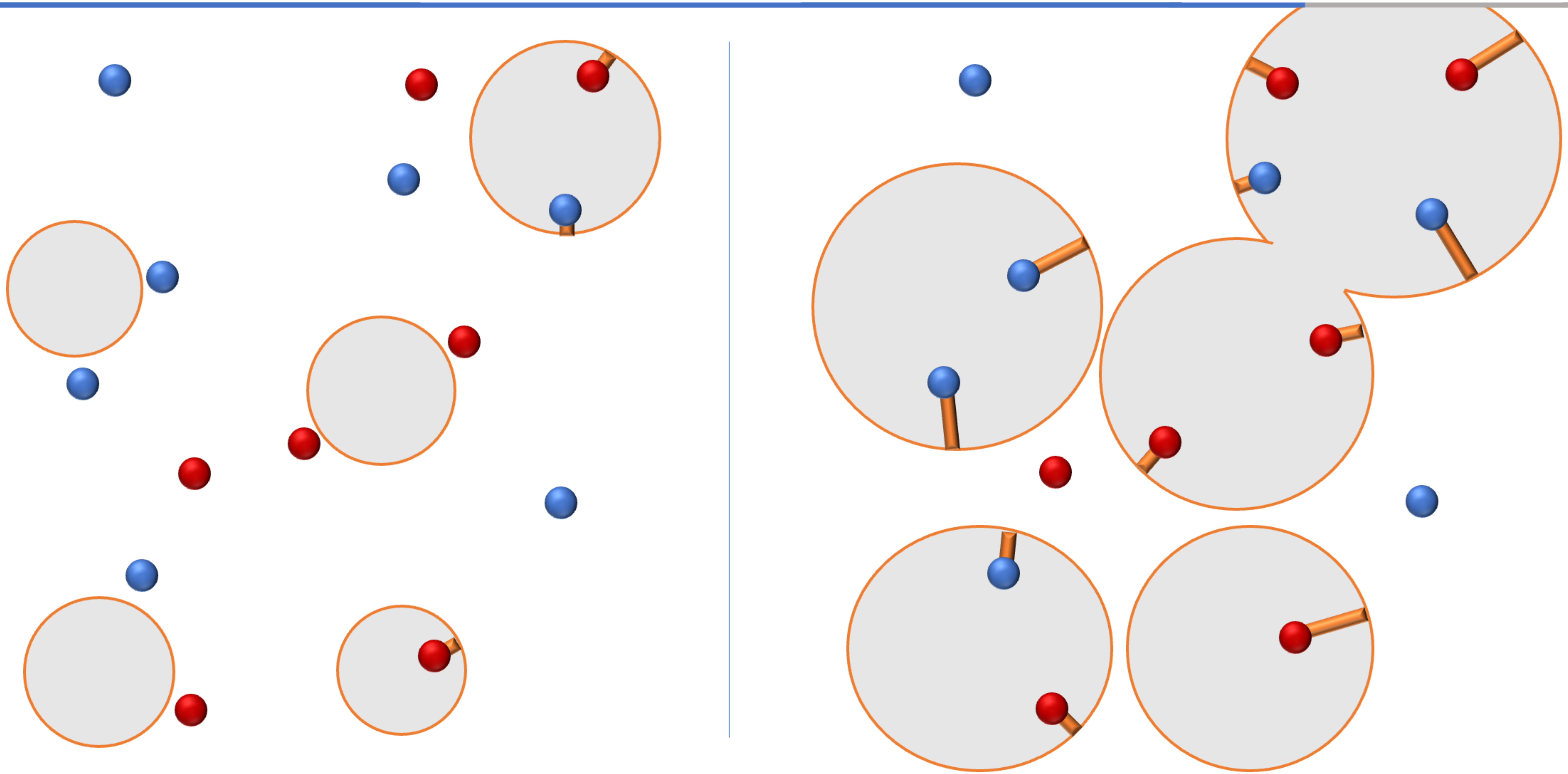


M. B., G. Dvali, J. S. Valbuena-Bermúdez, M. Zantedeschi (2023)

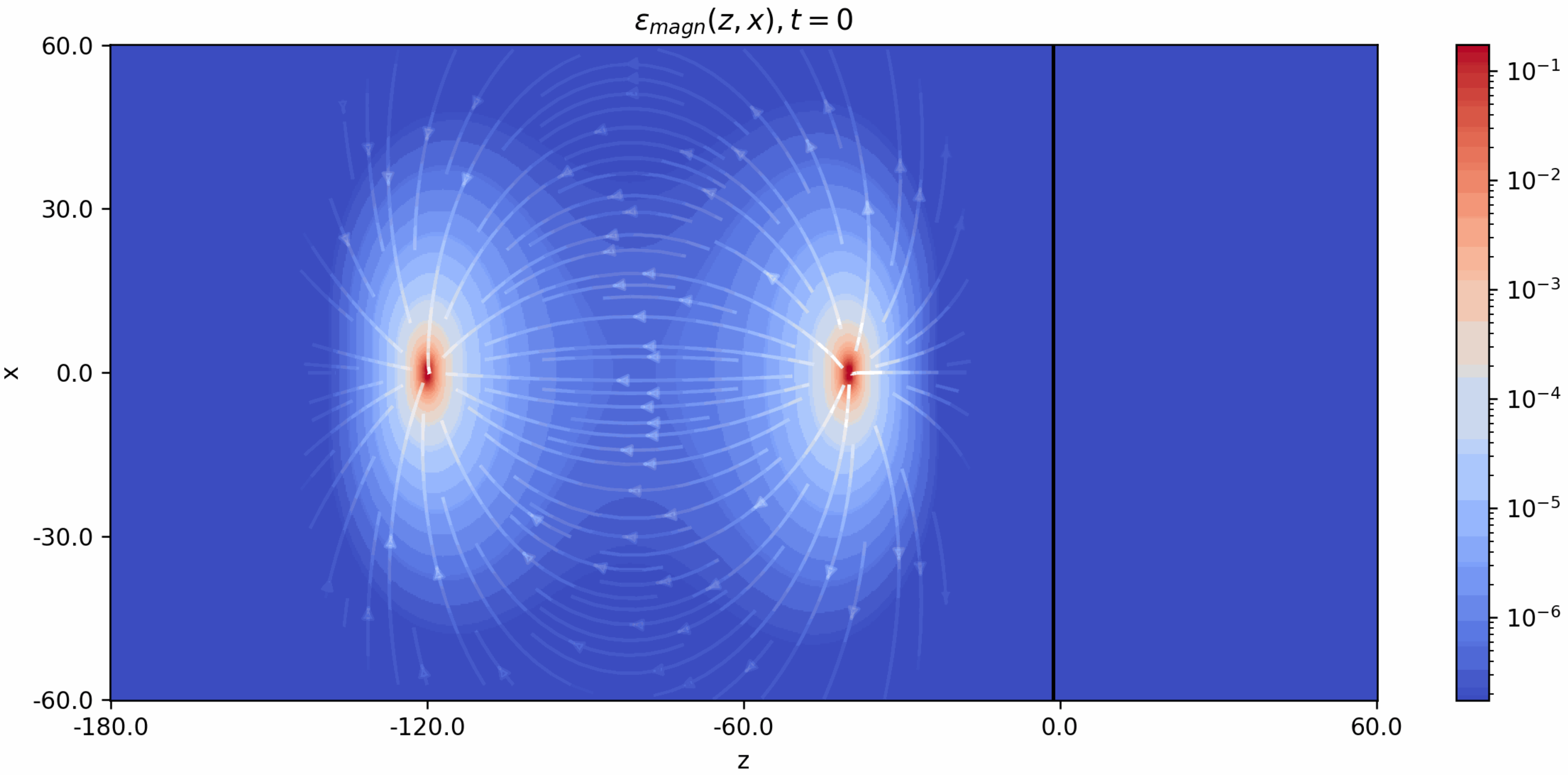
First-Order Phase Transition



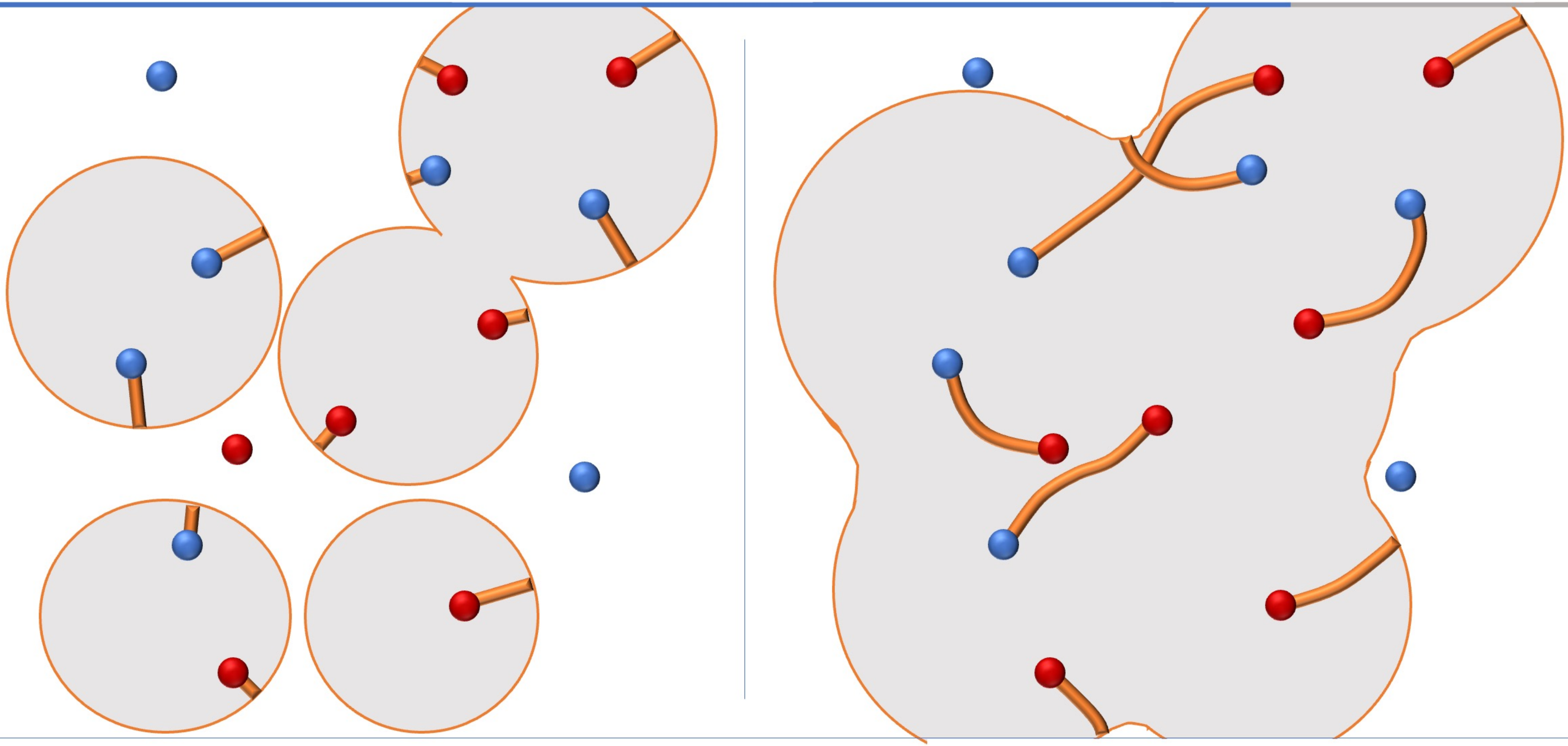
First-Order Phase Transition



Confinement Slingshot – Two Monopoles



First-Order Phase Transition

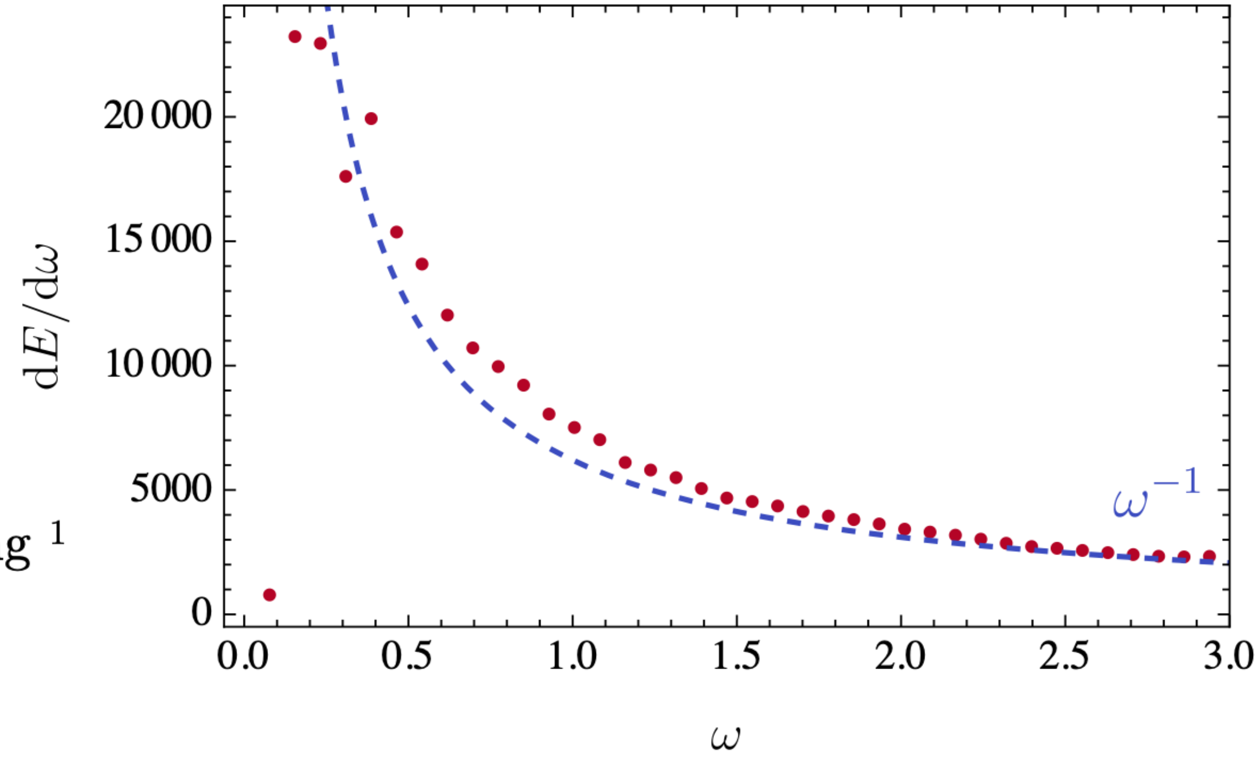


Confinement Slingshot – Gravitational Waves

The slingshot effect leads to the emission of gravitational waves

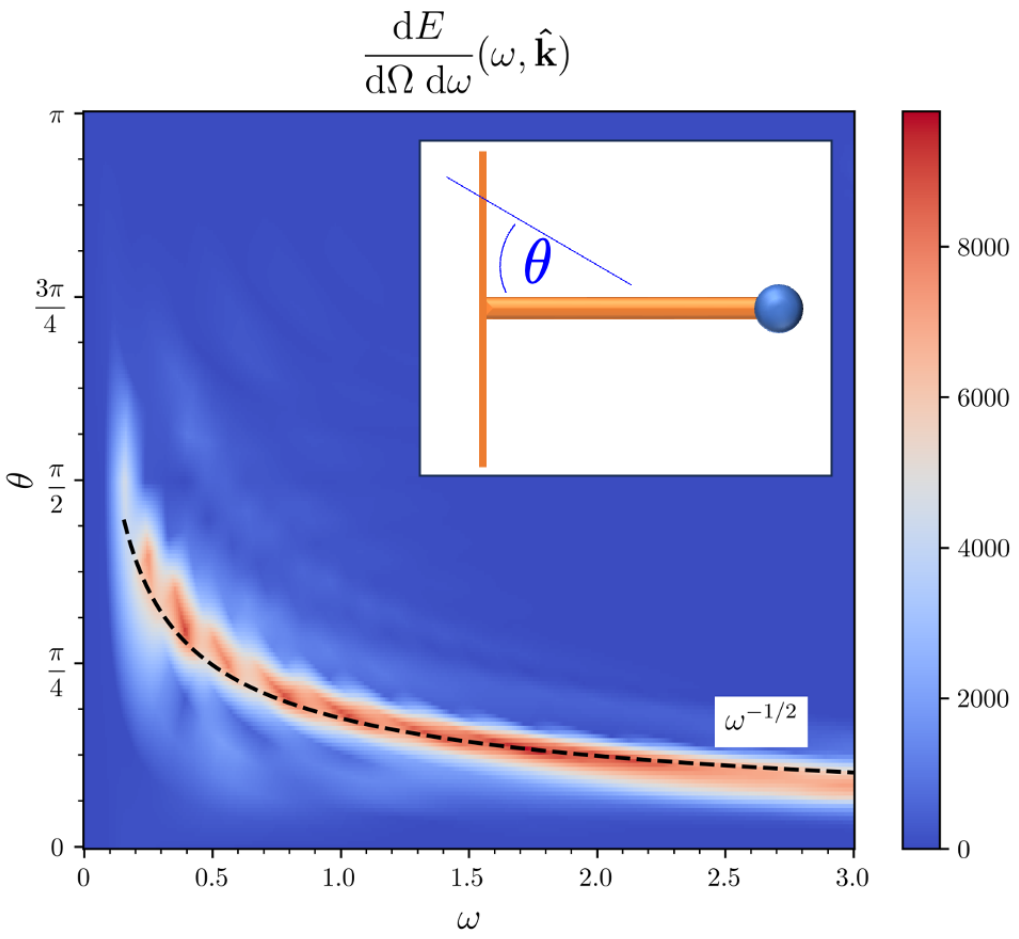
The energy spectrum decays with ω^{-1}

$\rightarrow$ Similar to two monopoles connected by a string [1]



[1] X. Martin, A. Vilenkin (1997) / G. Dvali, J. S. Valbuena-Bermúdez, M. Zantedeschi (2022)

Confinement Slingshot – Gravitational Waves



The angle of emission depends on the frequency

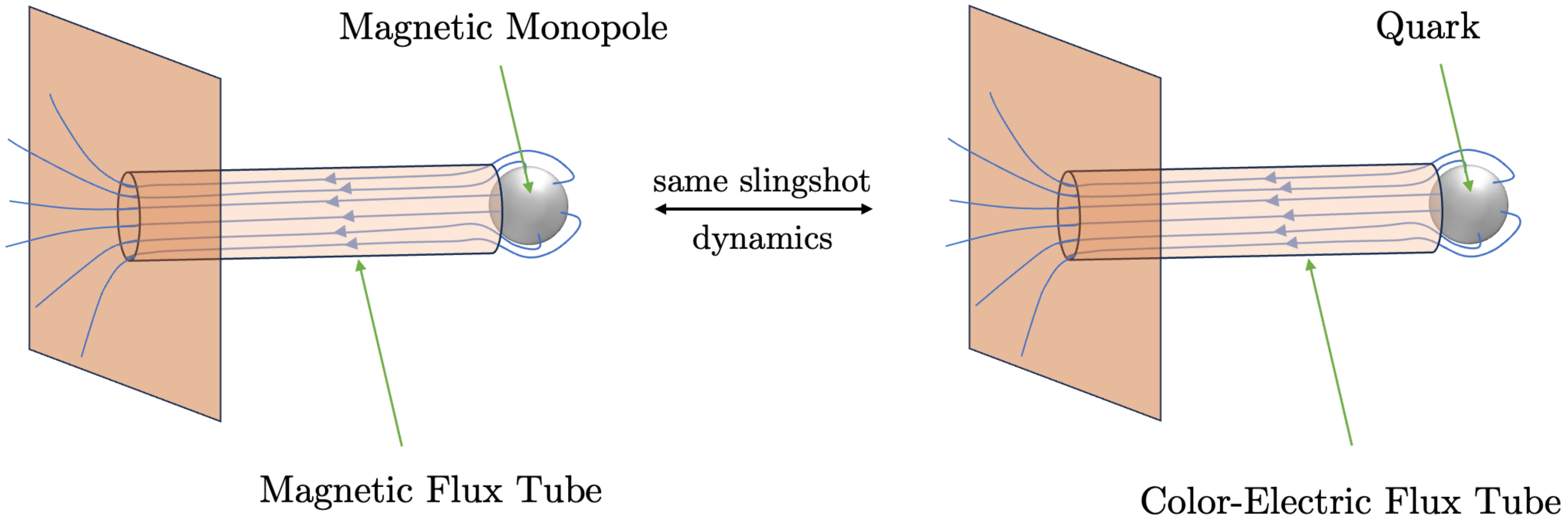
Most of the radiation is emitted in the direction of acceleration

→ Again similar to two monopoles connected by a string [1]

[1] L. Leblond, B. Shlaer, X. Siemens (2009)

Confinement Slingshot – Quark Confinement

The similar slingshot effect is expected in a "dual" picture when a heavy quark crosses into a confined vacuum of QCD.



(In the case of light quarks, quark-antiquark pairs can emerge and break the string.)

Summary

We analyzed an effect that can appear in first-order phase transitions involving magnetic monopoles/quarks

This slingshot effect can also happen for vortices/strings in 2+1/3+1 dimensions

Slingshot effect leads to the emission of gravitational waves
$\rightarrow$ observable?

Thank you!

More Videos on YouTube  Maximilian Bachmaier

Backup

The Model

We consider an $SU(2)$ gauge theory with the following potential

$$V(\phi) = \lambda_\phi \left(\phi^a\phi^a - v_\phi^2\right)^2 + \lambda_\psi \left(\psi^\dagger\psi - v_\psi^2\right)^2 \left(\psi^\dagger\psi\right) + \beta\psi^\dagger\phi\psi$$

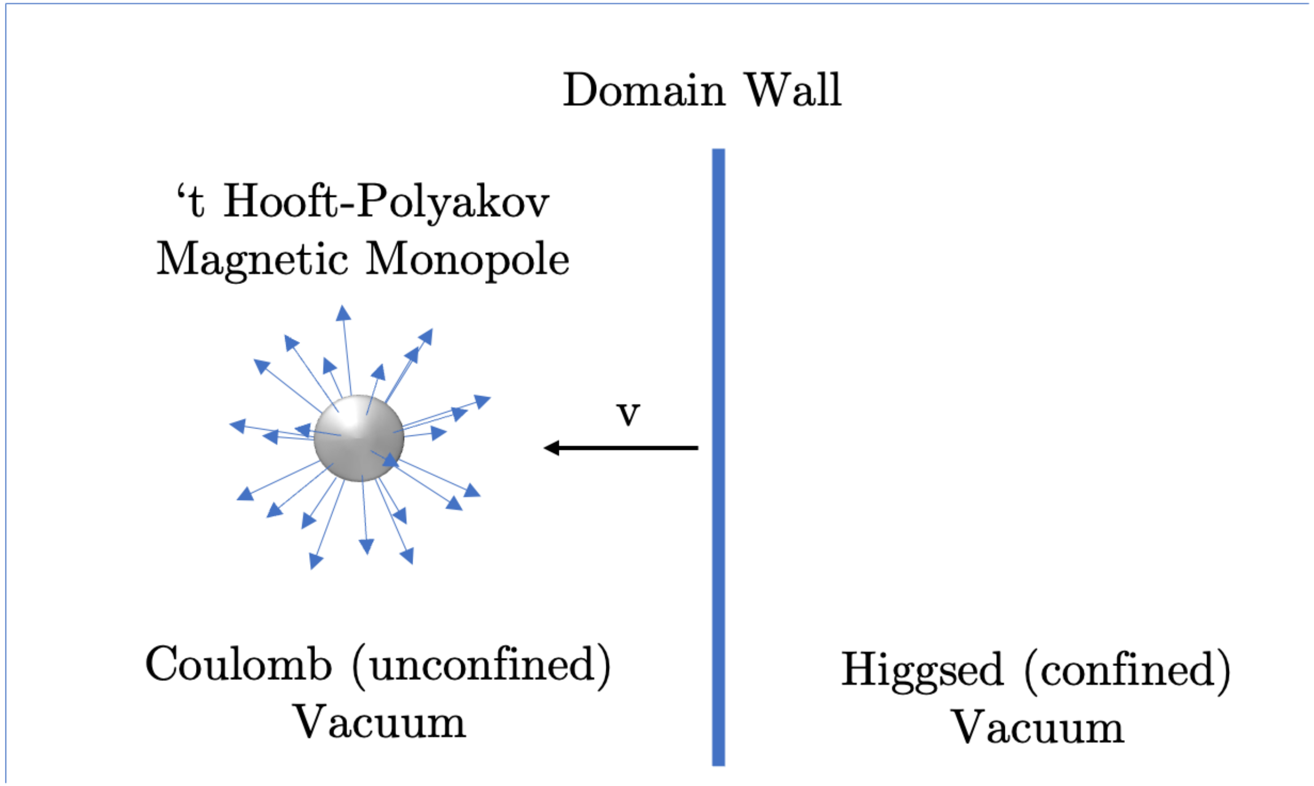
ϕ: $SU(2)$ adjoint
ψ: $SU(2)$ fundamental

$\langle\phi^a\phi^a\rangle = v_\phi^2 \rightarrow SU(2)$ breaks down to $U(1)$
$\rightarrow$ Magnetic Monopoles

Disconnected Vacuum Manifold for ψ
$\rightarrow$ Domain Walls

$\langle\psi^\dagger\psi\rangle = v_\psi^2 \rightarrow U(1)$ breaks down to 1
$\rightarrow$ Cosmics Strings

Breaking Pattern: $SU(2) \xrightarrow{\phi} U(1) \xrightarrow{\psi} 1$



Numerical Simulation

Python Package Numba:

- Translates Python and NumPy code into fast machine code
- Easy implementation of parallelization

Numerical Simulation – Axial Symmetry

Axial Symmetry:

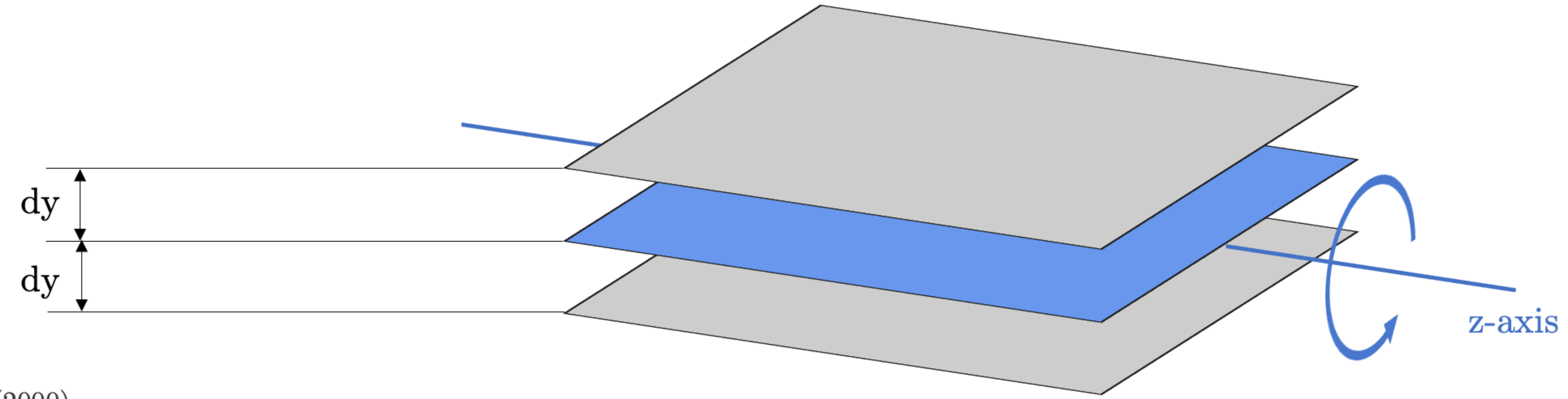
$$\phi^1 = xf_1 + yf_2 \qquad \phi^2 = yf_1 - xf_2 \qquad \phi^3 = f_3$$

$$W_x^1 = xyf_4 + y^2 f_5 + f_6 \qquad W_x^2 = -x^2 f_4 - xyf_5 + f_7 \qquad W_x^3 = xf_8 + yf_9$$

$$W_y^1 = y^2 f_4 - xyf_5 - f_7 \qquad W_y^2 = -xyf_4 + x^2 f_5 + f_6 \qquad W_y^3 = yf_8 - xf_9$$

$$W_z^1 = xf_{10} + yf_{11} \qquad W_z^2 = -xf_{11} + yf_{10} \qquad W_z^3 = 0$$

$$W_t^1 = xf_{12} + yf_{13} \qquad W_t^2 = -xf_{13} + yf_{12} \qquad W_t^3 = 0$$



L. Pogosian, T. Vachaspati (2000)

Confinement Slingshot – Gravitational Waves

The gravitational radiation spectrum can be calculated by Weinberg's formula:

$$\frac{\mathrm{d}E}{\mathrm{d}\Omega\,\mathrm{d}\omega} = \frac{G\,\omega^2}{2\pi^2}\Lambda_{ij,lm}(\hat{\mathbf{k}})T^{ij*}(\mathbf{k},\omega)T^{lm}(\mathbf{k},\omega)\,, \tag{1}$$

with

$$\Lambda_{ij,lm}(\hat{\mathbf{k}}) \equiv P_{il}(\hat{\mathbf{k}})P_{jm}(\hat{\mathbf{k}}) - \frac{1}{2}P_{ij}(\hat{\mathbf{k}})P_{lm}(\hat{\mathbf{k}})\,, \tag{2}$$

where $P_{ij}(\hat{\mathbf{k}}) = \delta_{ij} - \hat{k}_i\hat{k}_j$.

S. Weinberg (1972)

Slingshot Effect for Vortices