Dynamics of confinement, slingshot, and primordial black holes as dark matter

Texas in Shanghai 2023

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Based on:

Dvali, Kühnel, MZ, 2108.09471

Dvali, Bermudez-Valbuena, MZ, 2210.14947

Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195

Motivation and Goal

- Confinement is expected to take place in the early Universe, e.g., in QCD, in several beyond Standard Model extensions (intermediate scales of Grand unified theories, dark sector, etc). What are their dynamical properties? What consequences could follow?

- Analysing the **confinement dynamics** within gauge theories in a controllable manner

- Confinement forces a specific dynamics that leads to the production of **gravitational waves**. Novel **"slingshot"** mechanism is an instance of this

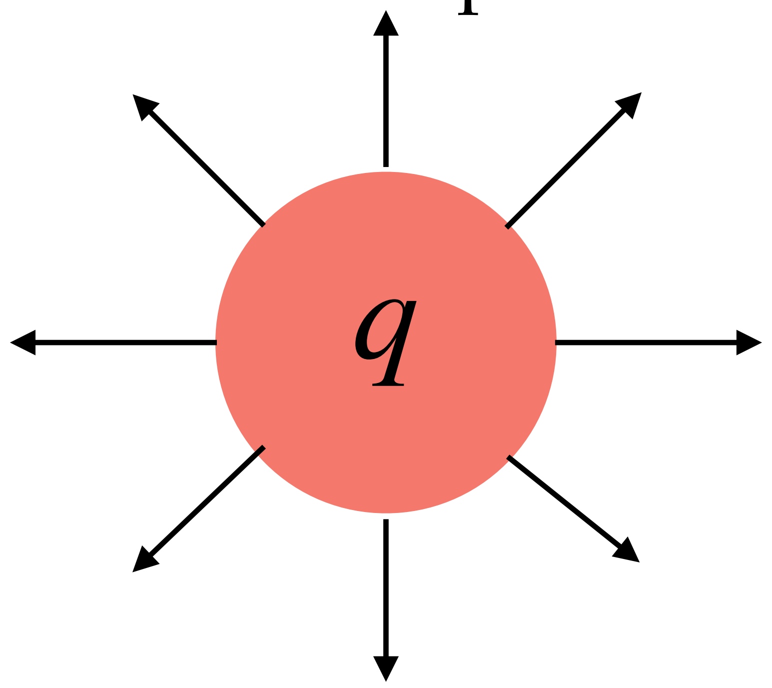
- Confinement dynamics can be responsible for the production of dark matter in the form of **primordial black holes**

- Field theoretical value given by an explicit realisation of **brane** dynamics

Motivation and Goal

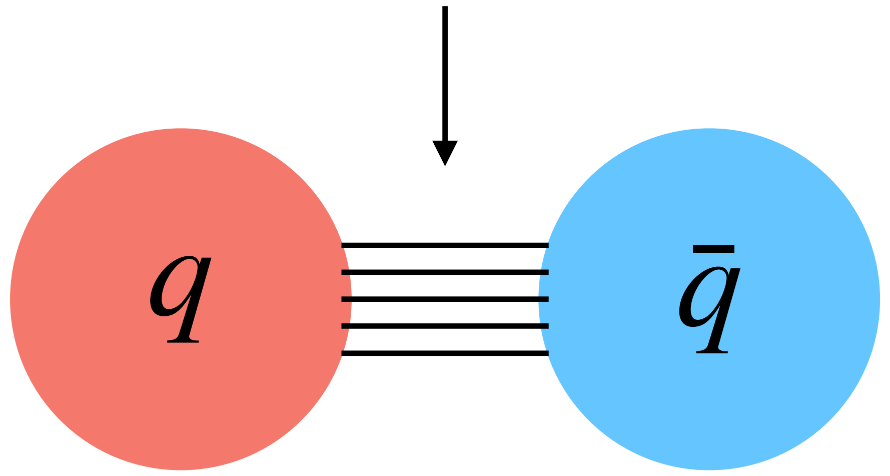
Unconfined

Coulomb phase

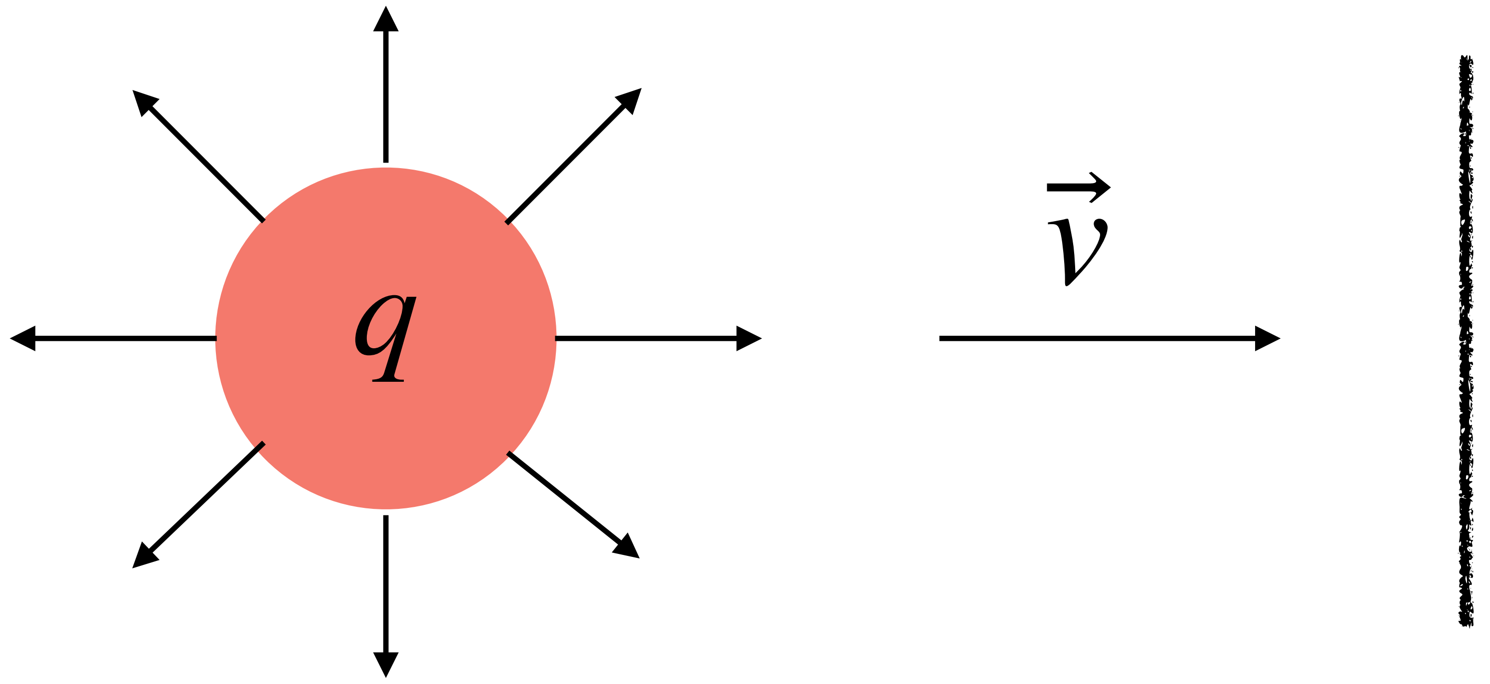


Confined

Color-electric flux tube

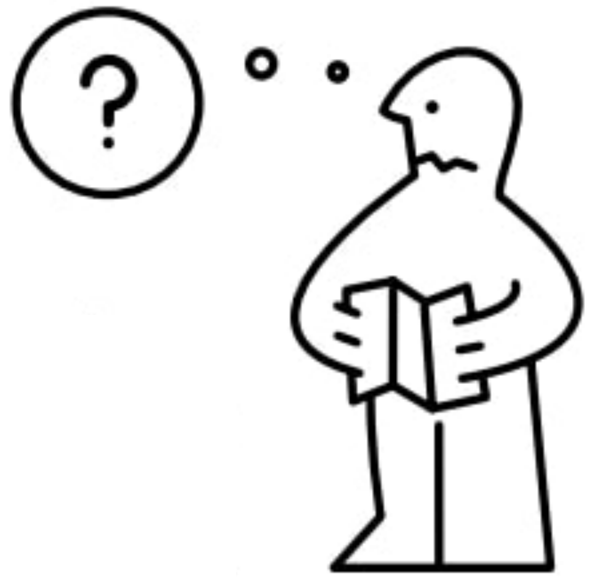


What happens in the dynamical case of a single unconfined quark interacting with a domain wall separating the two vacua?

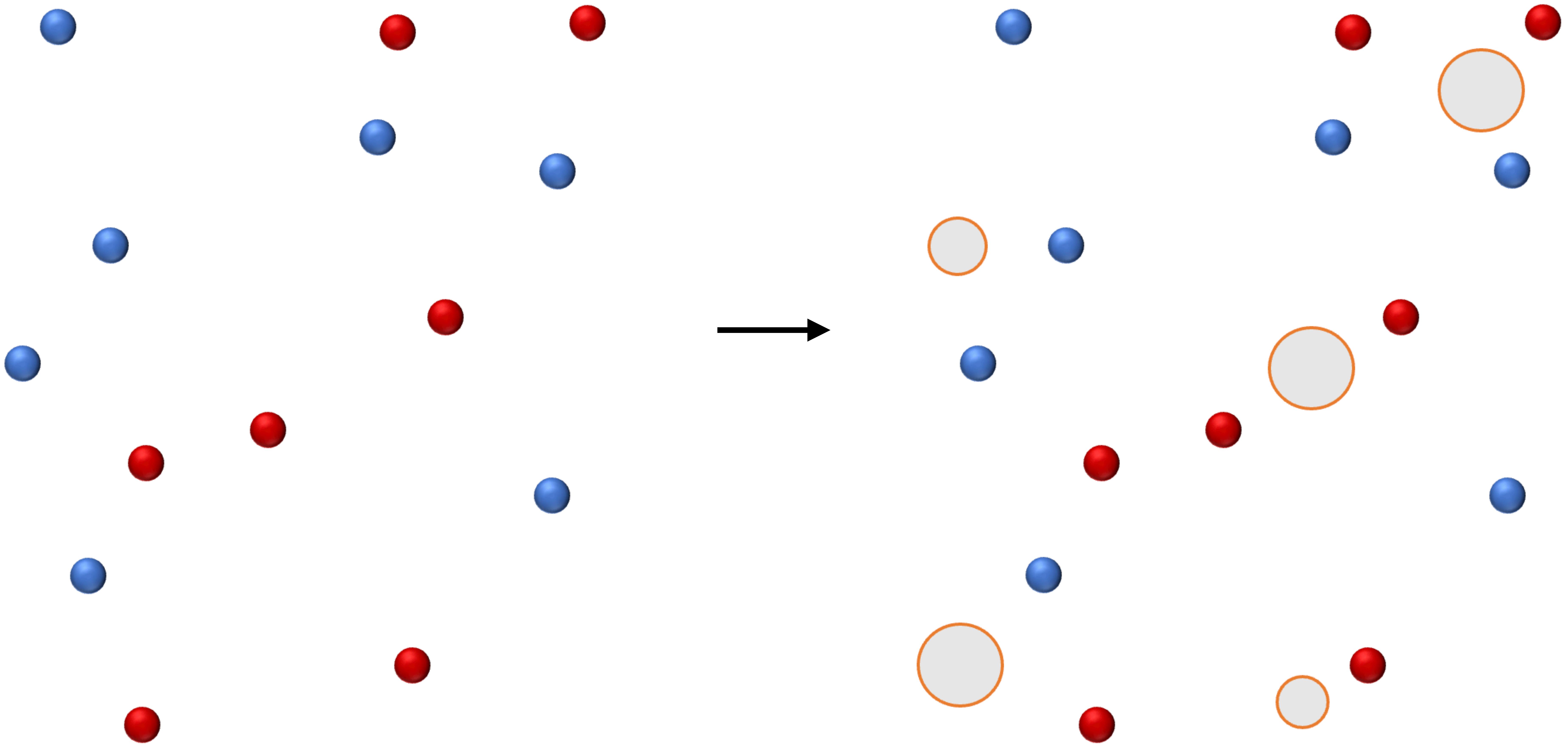


Domain wall

separating the regions

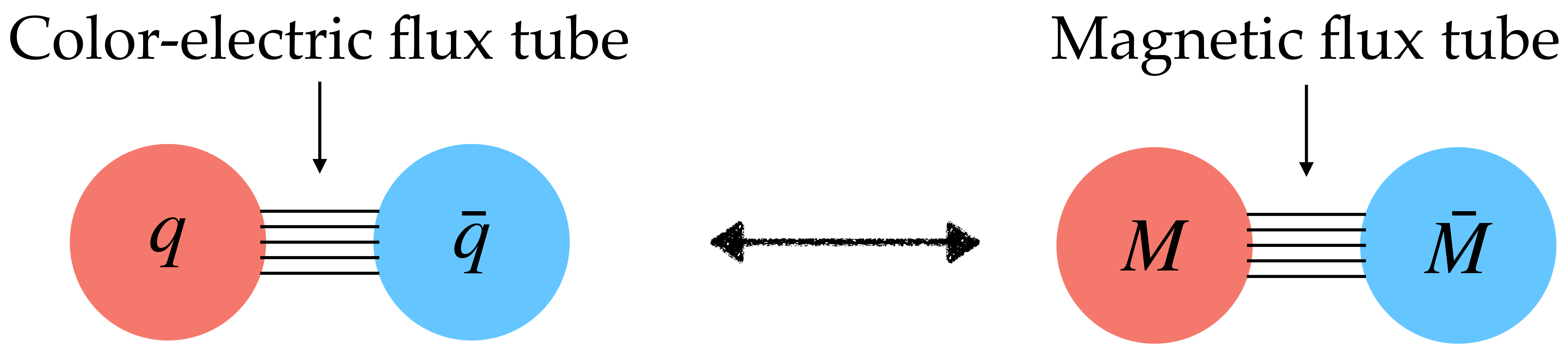


Motivation and Goal



Duality

There is a duality between colour electric confinement and magnetic confinement, Seiberg, Witten ‘94



- strongly coupled
- quantum system

- weakly coupled
- admits classical description
- realisation in terms of confined ’t Hooft Polyakov monopoles
- confinement is realised by Higgsing the $U(1)$ associated to the magnetic charge

System

$$\mathscr{L} = \mathrm{Tr}\left((D_\mu \phi)^\dagger (D^\mu \phi) \right) + (D_\mu \psi)^\dagger (D^\mu \psi) - \frac{1}{2}\mathrm{Tr}\left(G^{\mu\nu} G_{\mu\nu} \right) - U(\phi, \psi)$$

$$U(\phi, \psi) = U(\phi) + U(\psi) + \beta \psi^\dagger \phi \psi$$

SU(2) adjoint

SU(2) doublet

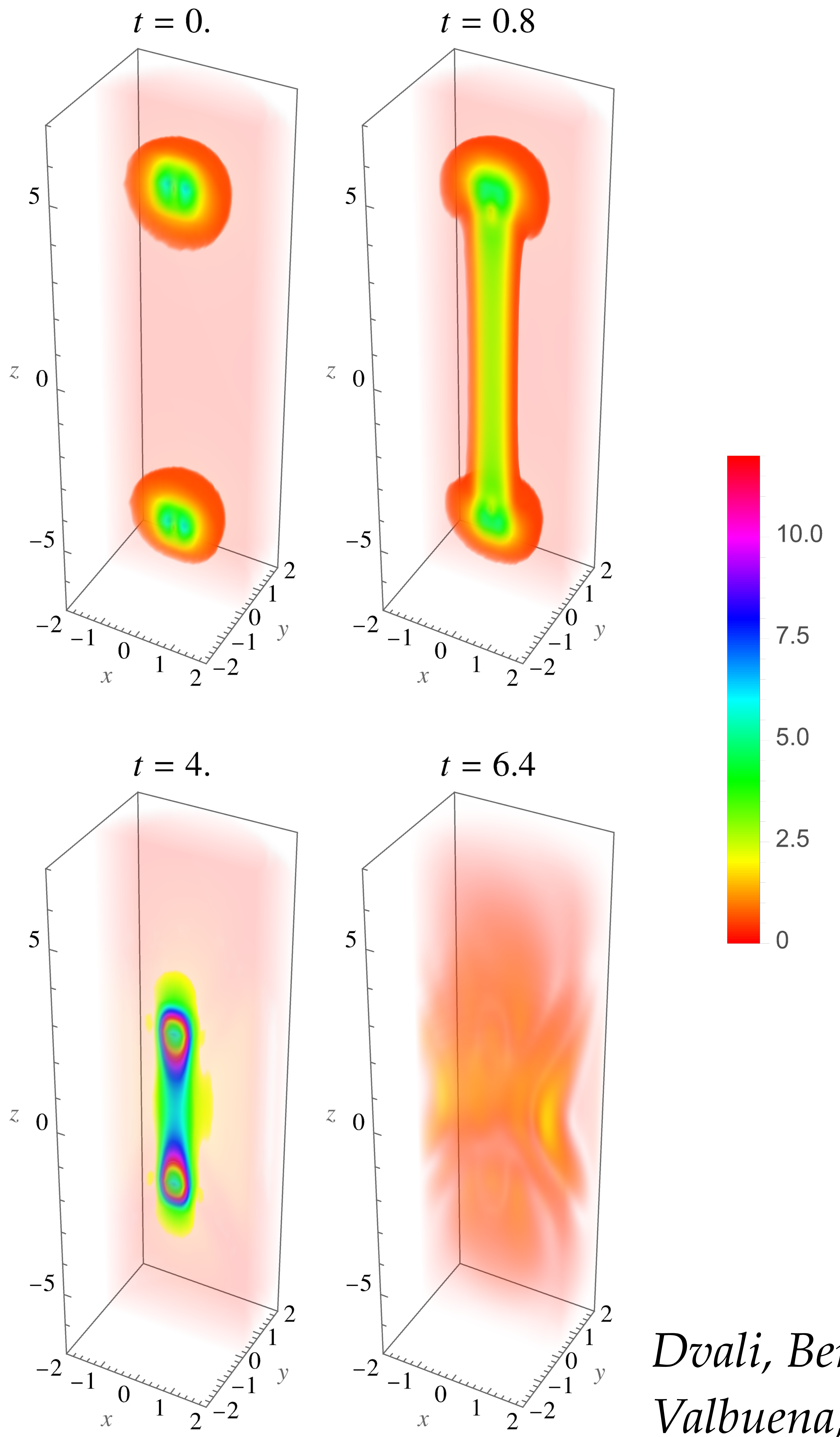
$$SU(2) \xrightarrow{\langle v_\phi \rangle} U(1) \xrightarrow{\langle v_\psi \rangle} 1$$

Massive "$W^\pm$"

Massive "A"

The system consists of a scalar adjoint, which provides monopole solution, and a scalar doublet, which makes the residual U(1) massive, leading to monopole confinement

Dynamics



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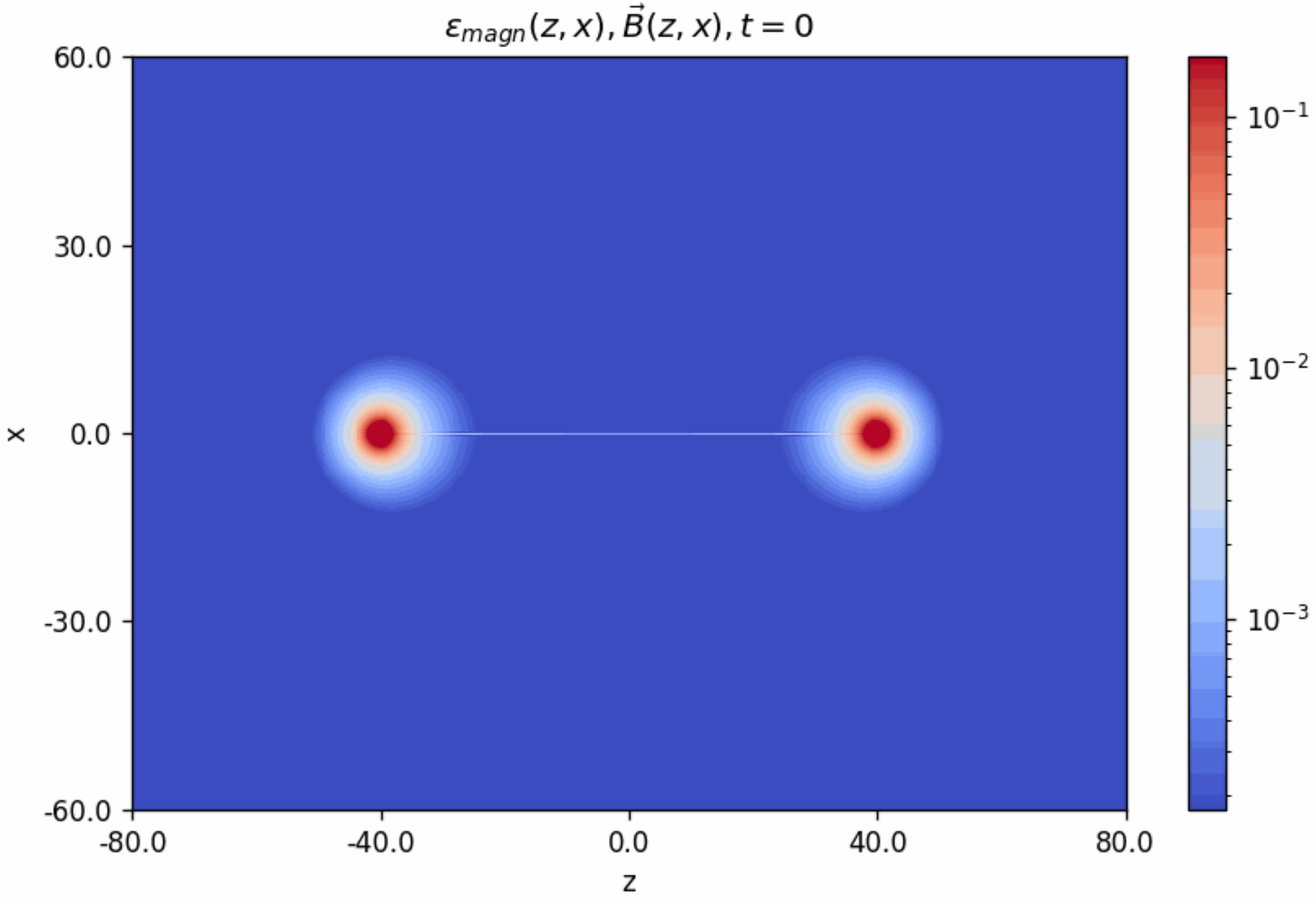
- Monopole-antimonopole pairs in confined region: their magnetic charge is confined into a string connecting them with tension Λ_c^2
- The string accelerated the monopoles towards each other with $a = \Lambda_c^2/m$ with the pair eventually annihilating
- The monopole can be twisted with respect to the antimonopole.
- In the maximal 'twist' case, the pair does not annihilate and a sphaleron-like configuration is attained instead

Dynamics



$\varepsilon_{magn}(z,x), \vec{B}(z,x), t=0$
60.0
30.0
0.0
-30.0
-60.0
x
-80.0
-40.0
0.0
40.0
80.0
z
10^{-1}
10^{-2}
10^{-3}

Slingshot setup

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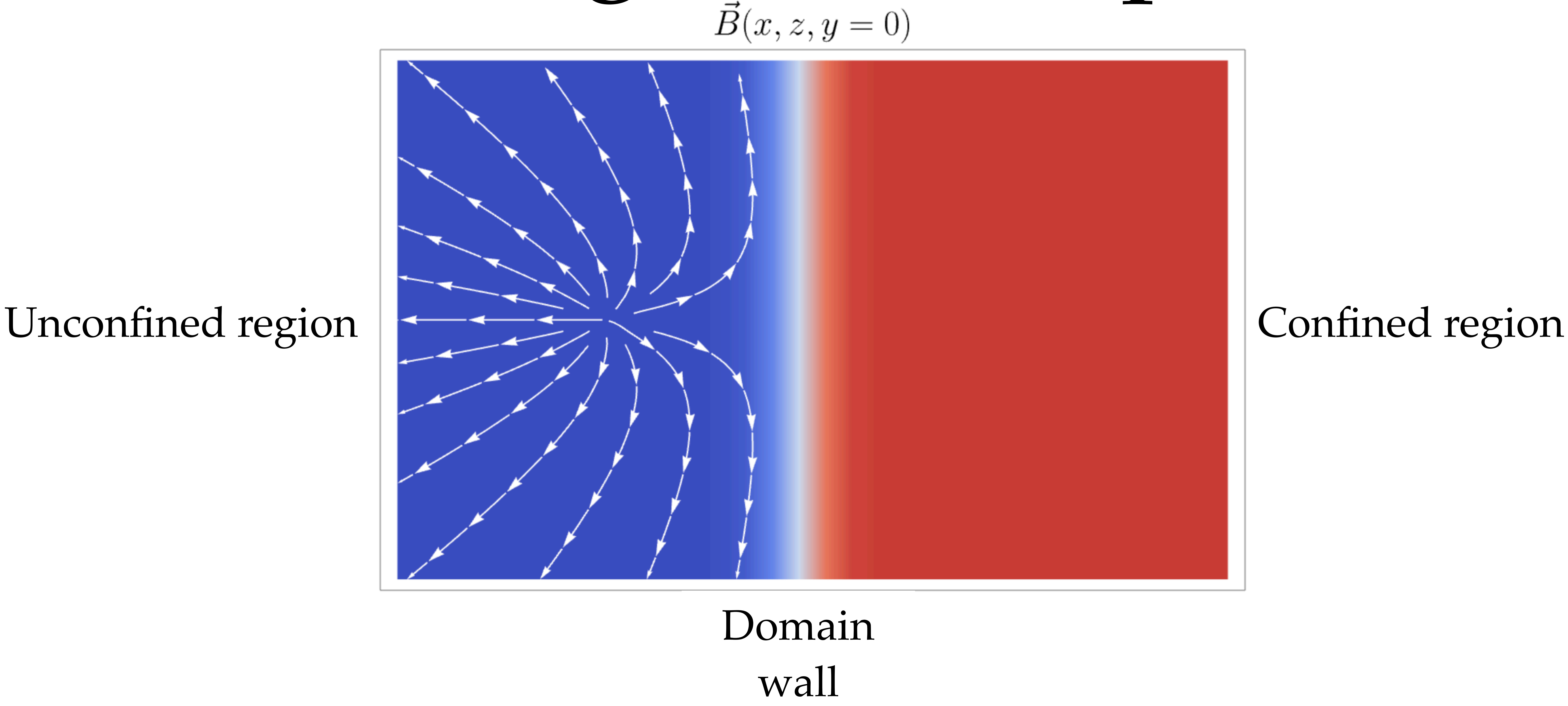
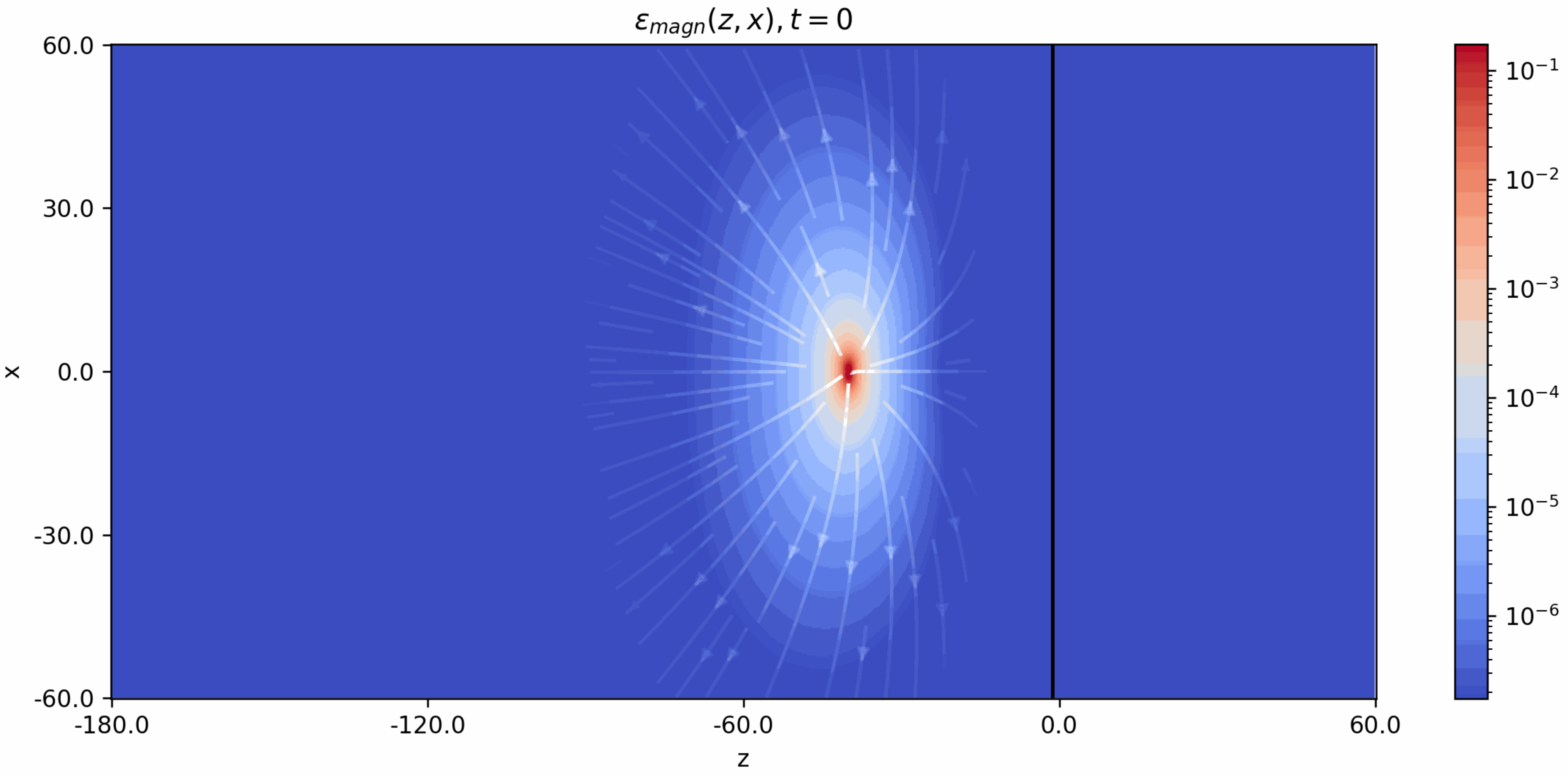


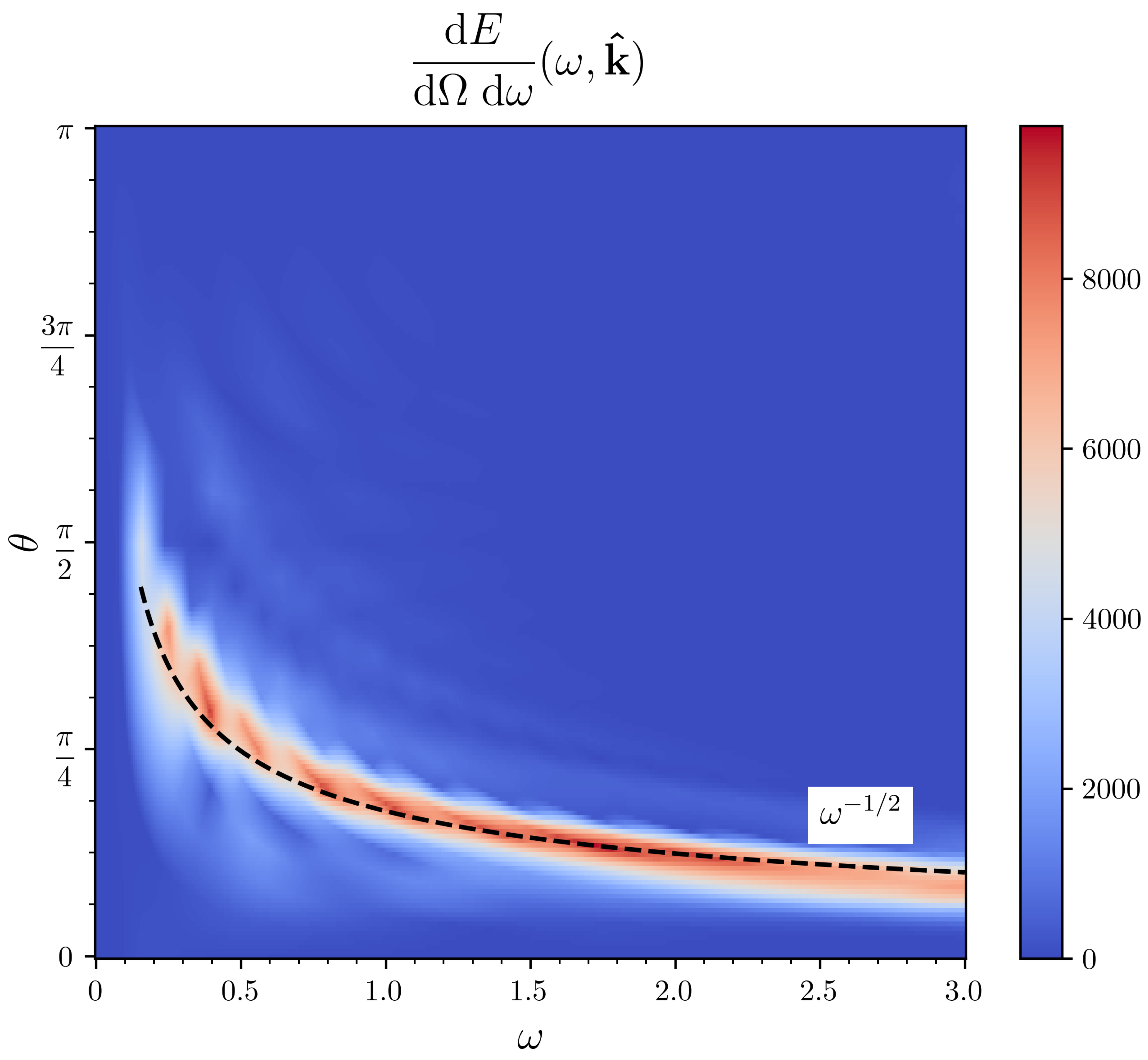
Monopole starts in unconfined region and display a Coulomb-like magnetic field. At the layer interface, the magnetic lines are repelled, analogously to Meissner effect.

Slingshot Dynamics

Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195



Gravitational Waves from Slingshot



Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195

$$\frac{dE_n}{d\Omega\, d\omega} = \frac{G\,\omega_n^2}{\pi}\left(T^*_{\mu\nu}(\omega_n, \mathbf{k})T^{\mu\nu}(\omega_n, \mathbf{k}) - \frac{1}{2}\,|\,T^{\mu}_{\mu}(\omega_n, \mathbf{k})\,|^2\right)$$

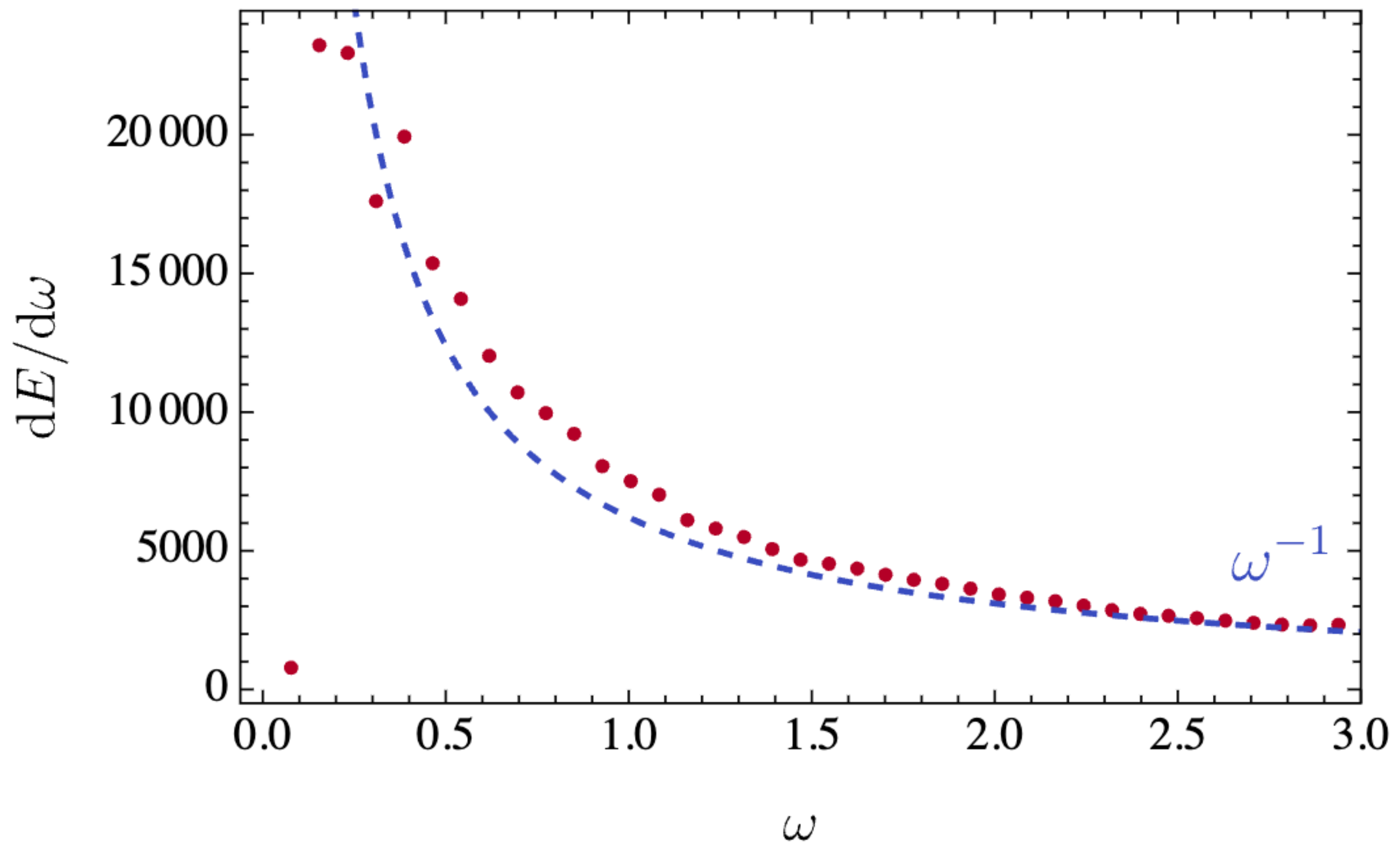
Emission takes place in a beaming angle with scaling

$$\theta \propto \omega^{-1/2}$$

This is typical behaviour of monopole accelerated by a string, as found in the point-like analysis of a monopole-antimonopole pair connected by a string *Martin, Vilenkin '96 + Leblond, Shlaer, Siemens '09*

Gravitational Waves from Slingshot

Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195



Angularly integrated spectrum scales approximately as

$$\frac{\mathrm{d}E}{\mathrm{d}\omega} \propto \omega^{-1}$$

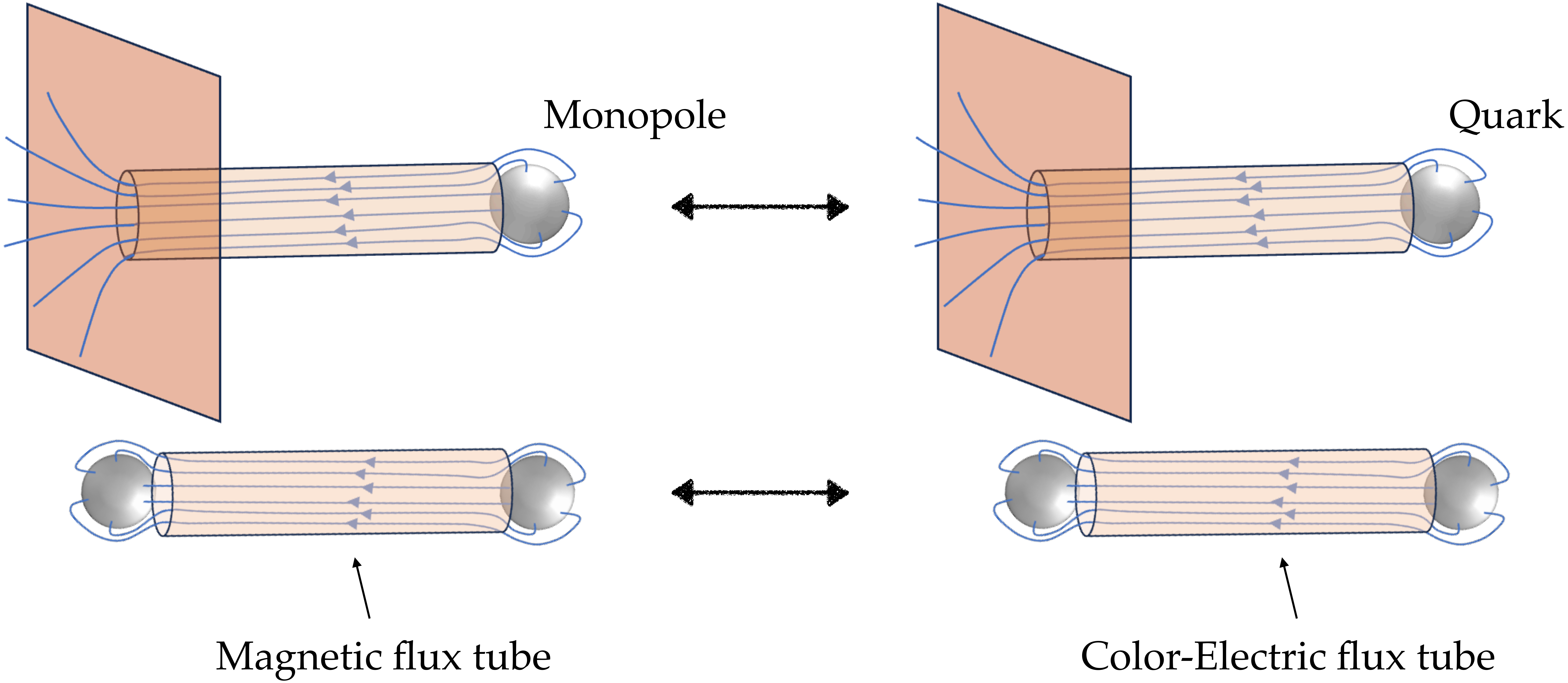
This is analogous to the behaviour we found for a confined monopole-antimonopole pair previously mentioned.

More in general we get $P_n \simeq G_N \Lambda_c^4/n$

For example, for $\Lambda_c \sim 10^9$GeV, $\Omega_{\mathrm{GW}} \gtrsim 10^{-10}$ at $f \sim 10^{-3}$Hz in the right ballpark for LISA

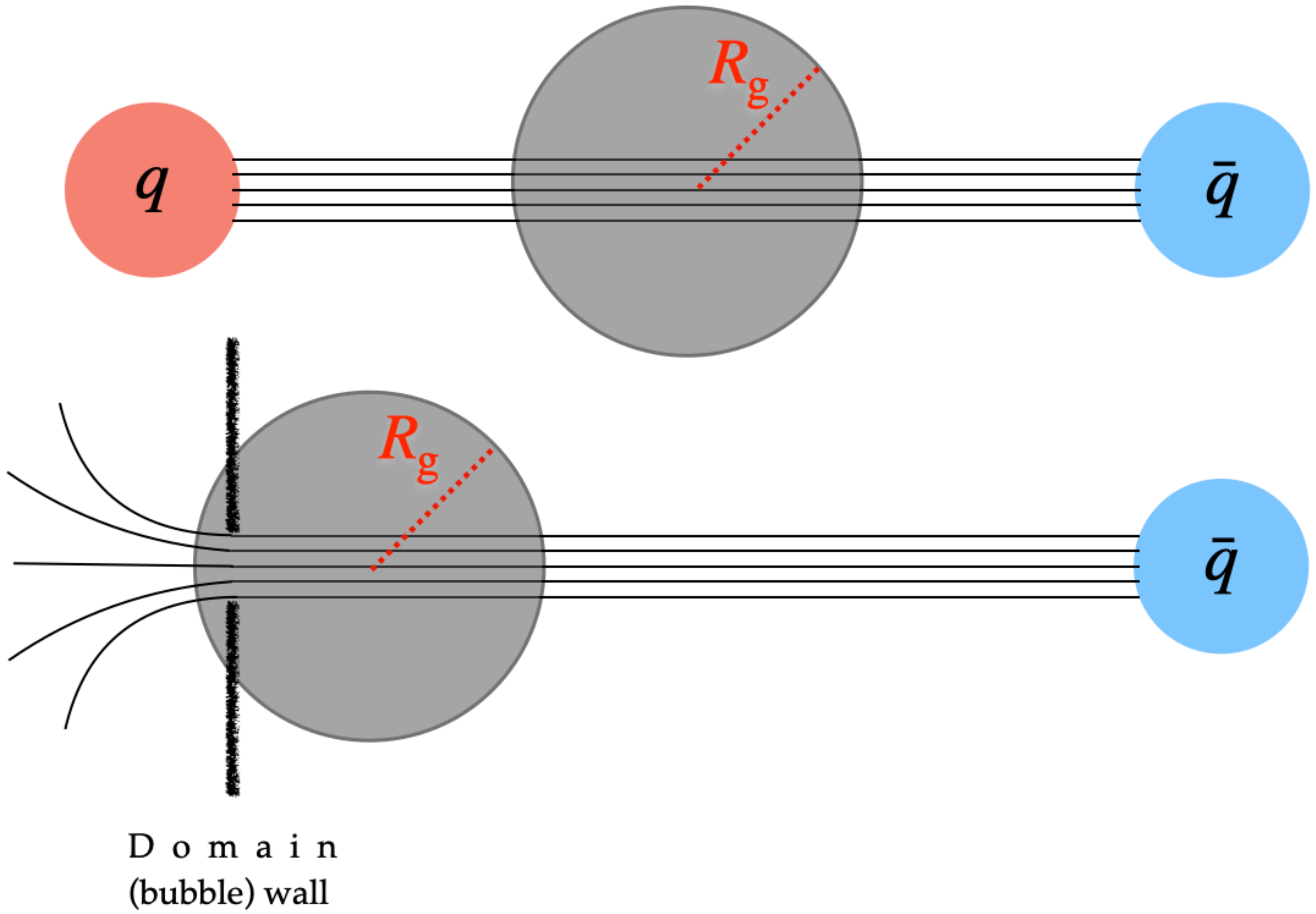
Dual picture

The similar slingshot effect is expected in the “dual” picture when a heavy quark crosses into the confined vacuum



Black hole production

The long elongated string stored significant energy: possibility for primordial black holes production, regardless of whether the string ends on a monopole or a domain wall



- Quarks accelerate towards each other $a = \Lambda_c^2/m_q$ and become relativistic

$$E \simeq \Lambda_c^2 l \simeq M_{PBH}, \quad R_g \gg \Lambda_c^{-1}$$

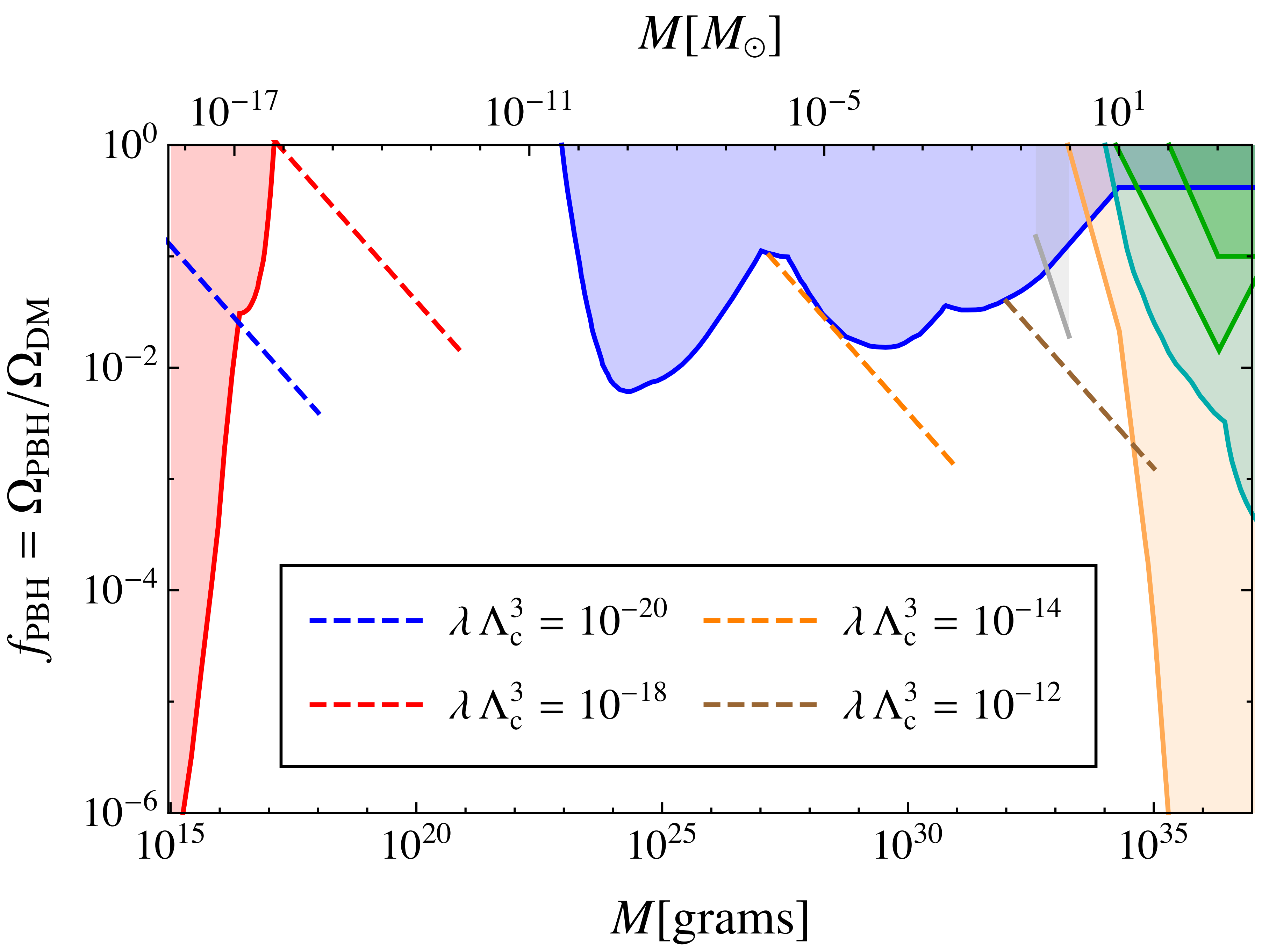
- Eventually, system might find itself within its own Schwarzschild radius, leading to black hole formation.

Dvali, Kühnel, MZ, 2108.09471

See also T Matsuda arXiv:hep-ph/0509061

Primordial black holes

Dvali, Kühnel, MZ, 2108.09471



Monochromatic spectrum

$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}} \propto \lambda\, \Lambda_{\rm c}^3\, M_{\rm PBH}^{-1/2}$$

⟶ λ characterises the nucleation rate of quarks during the inflationary era

⟶ Filled areas are phenomenological constraints (evaporation, dynamical,…)

⟶ No exponential sensitivity on density fluctuations

⟶ Seeds for supermassive black holes in the galactic centres

⟶ Maximally rotating sub-solar PBHs production

⟶ Possible embedding with known QCD as long as $\Lambda_{\rm c} < m_{\rm q}$ (assumption required)

⟶ Interesting stochastic background with flat $\Omega_{\rm GW} \propto \lambda\, \Lambda_c^4$

Outlook

Confining phase transitions can lead to rich dynamics, which produces gravitational waves, that could characterise the early Universe

Novel monopole ''slingshot" mechanism is an example of this. **Duality** also informs us that the same dynamic takes place in the case of confined heavy **quarks**.

Confinement dynamics can lead to **production** of dark matter in the form of **primordial black holes**

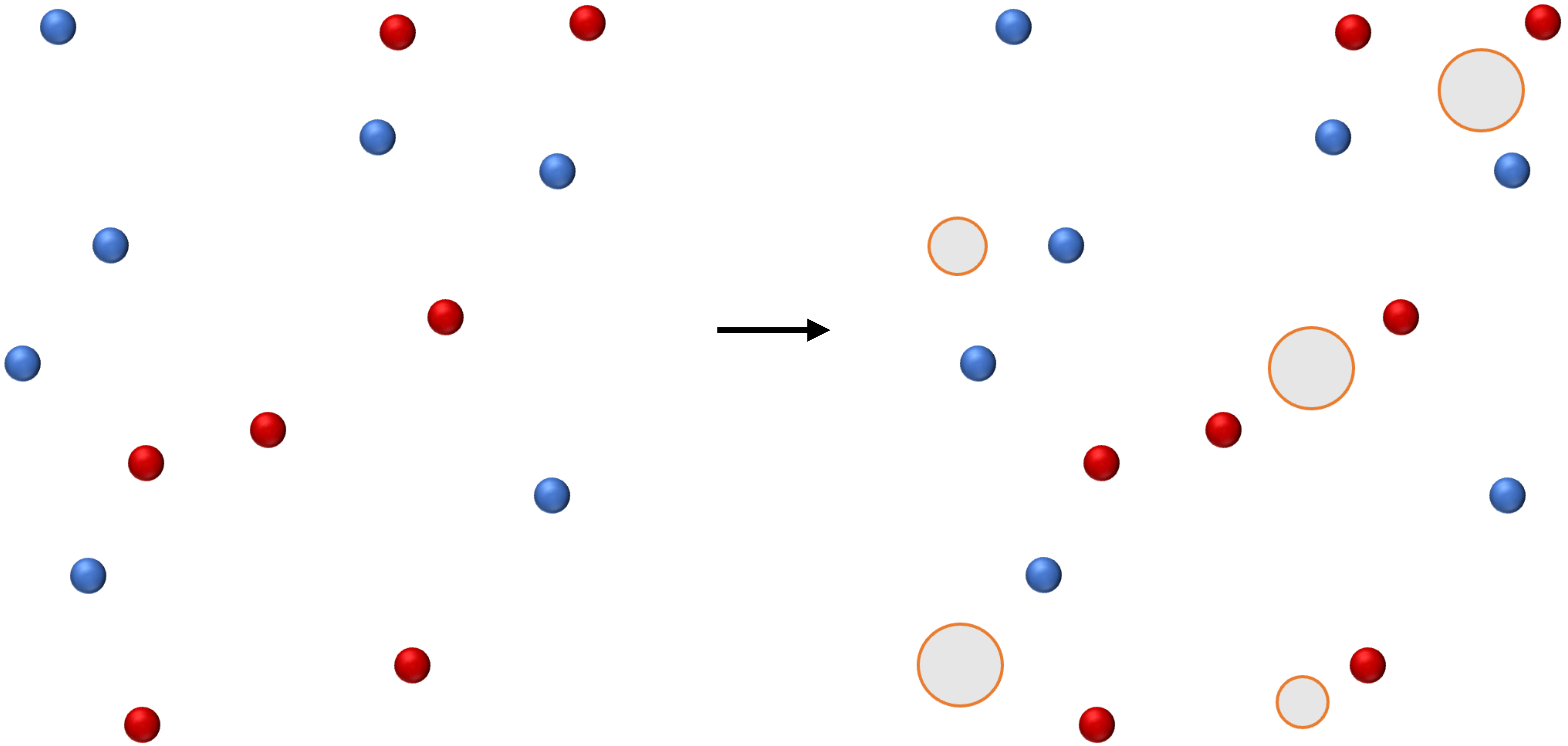
The mechanism has a field theoretical value as it is an explicit realisation of **branes** of different co-dimensionality interacting

So far we have discussed the case of a monopole slingshot. Can the same effect take place with **topological defects of different co-dimension**? For example, a **string would deform the bubble wall on a line** (as opposed to the case of a monopole, which deforms it in a point).

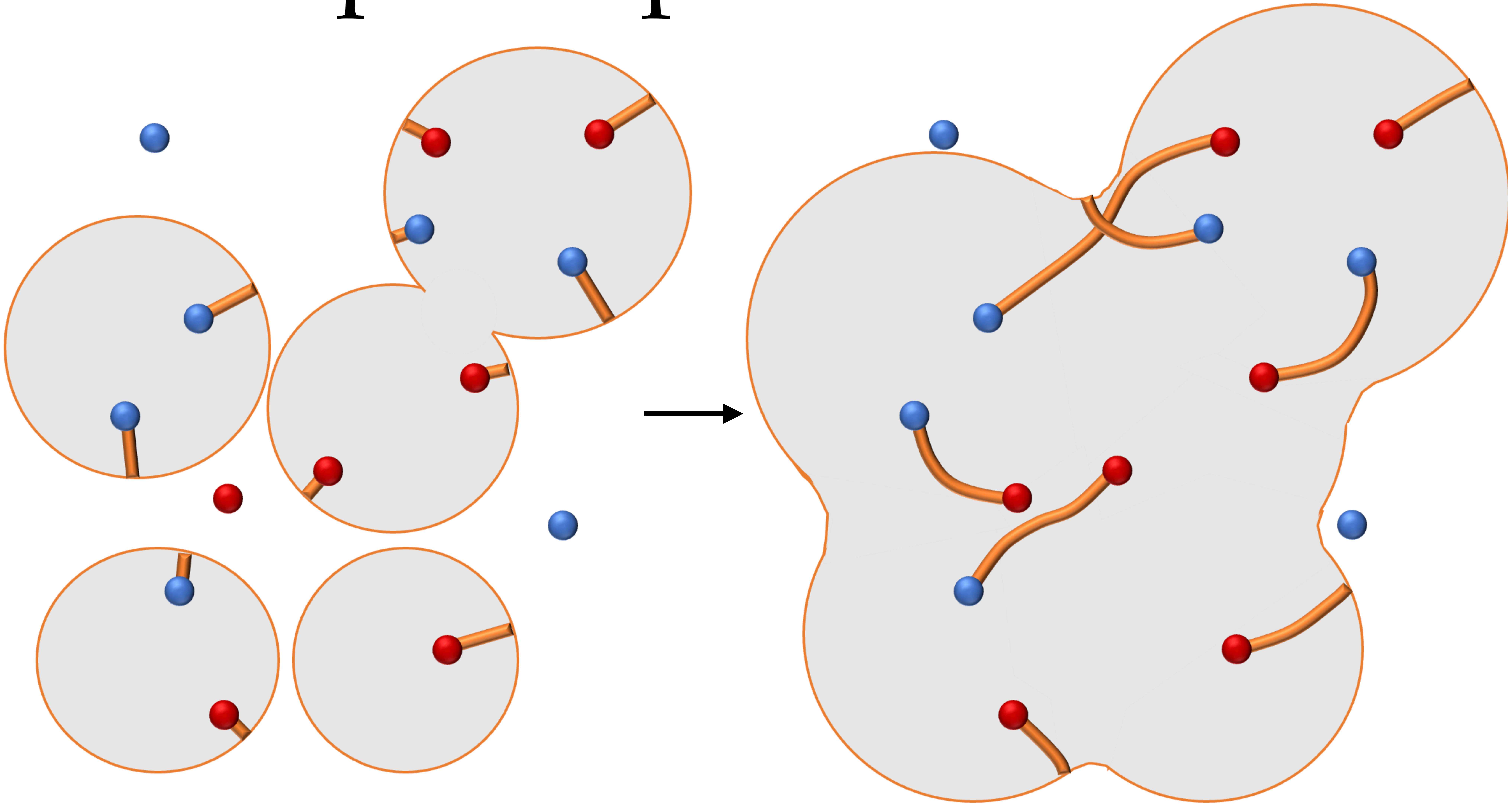
Thank you!

Backup

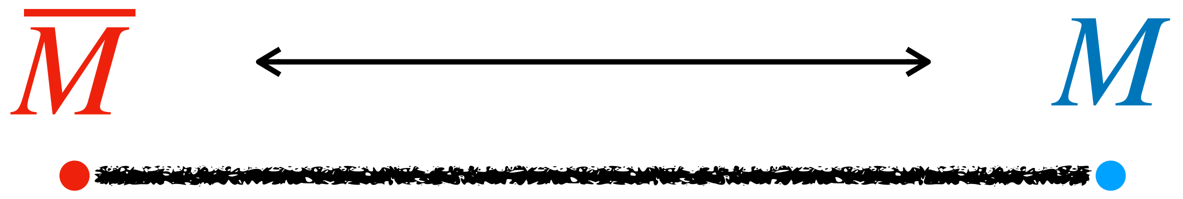
Example of phase transition

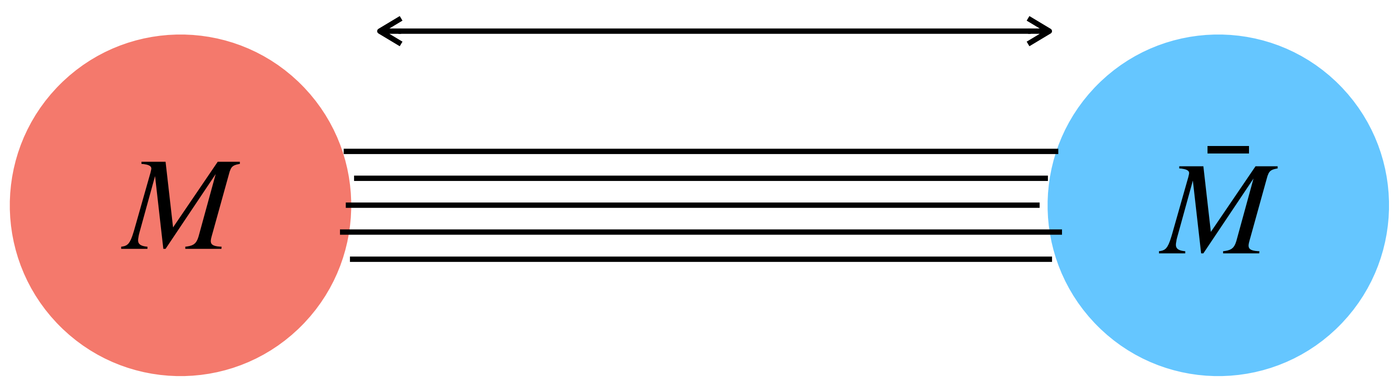


Example of phase transition



Point-like result





Point-like limit previously studied by *Martin, Vilenkin '96*

$$S = -\, m_M \int \mathrm{d}s_1 - m_M \int \mathrm{d}s_2 - \Lambda^2 \int \mathrm{d}\Sigma$$

- Which admits solution of constantly accelerating, oscillating monopoles, with $a = \Lambda^2 / m_M$

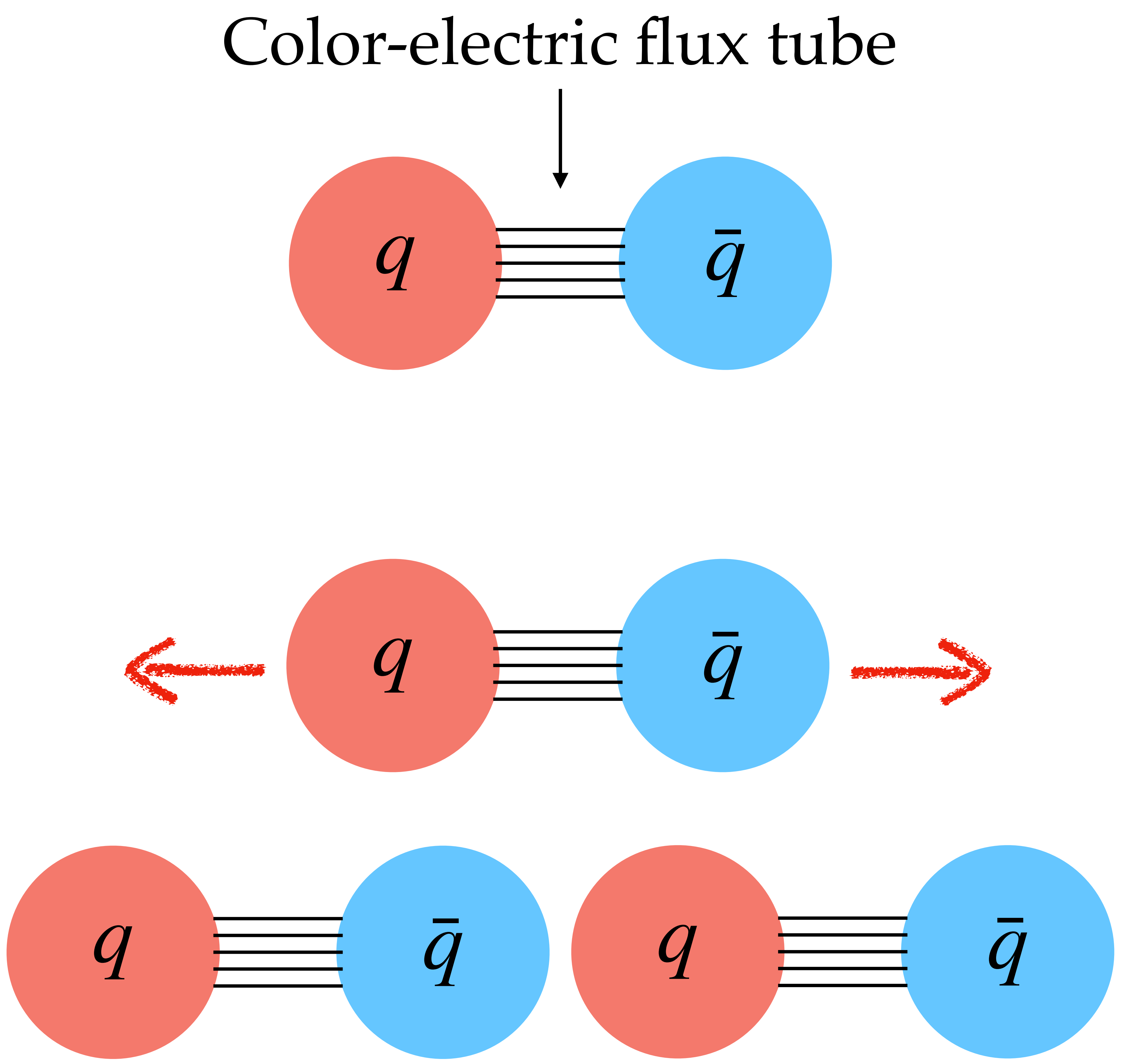
- Gravitational radiation with power

$$P_\mathrm{n} \sim \frac{G_N \Lambda_\mathrm{c}^4}{n}, \quad \omega_\mathrm{n} = 2\pi n/d,$$

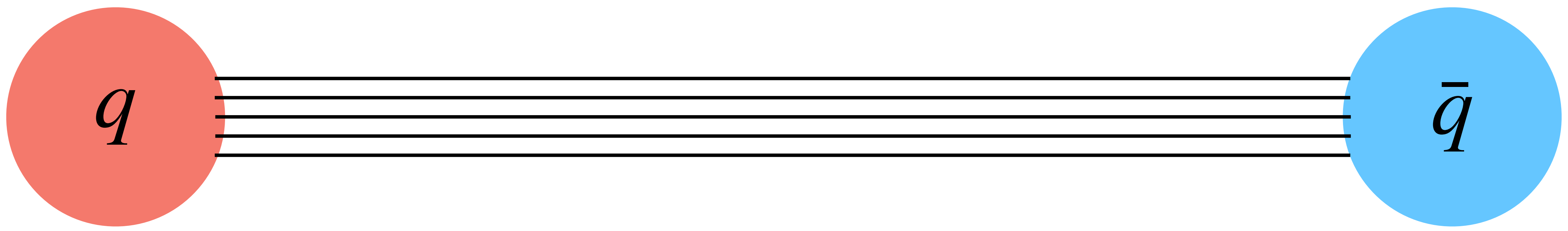
We looked at this in an explicit realisation with 't Hooft Polyakov monopoles

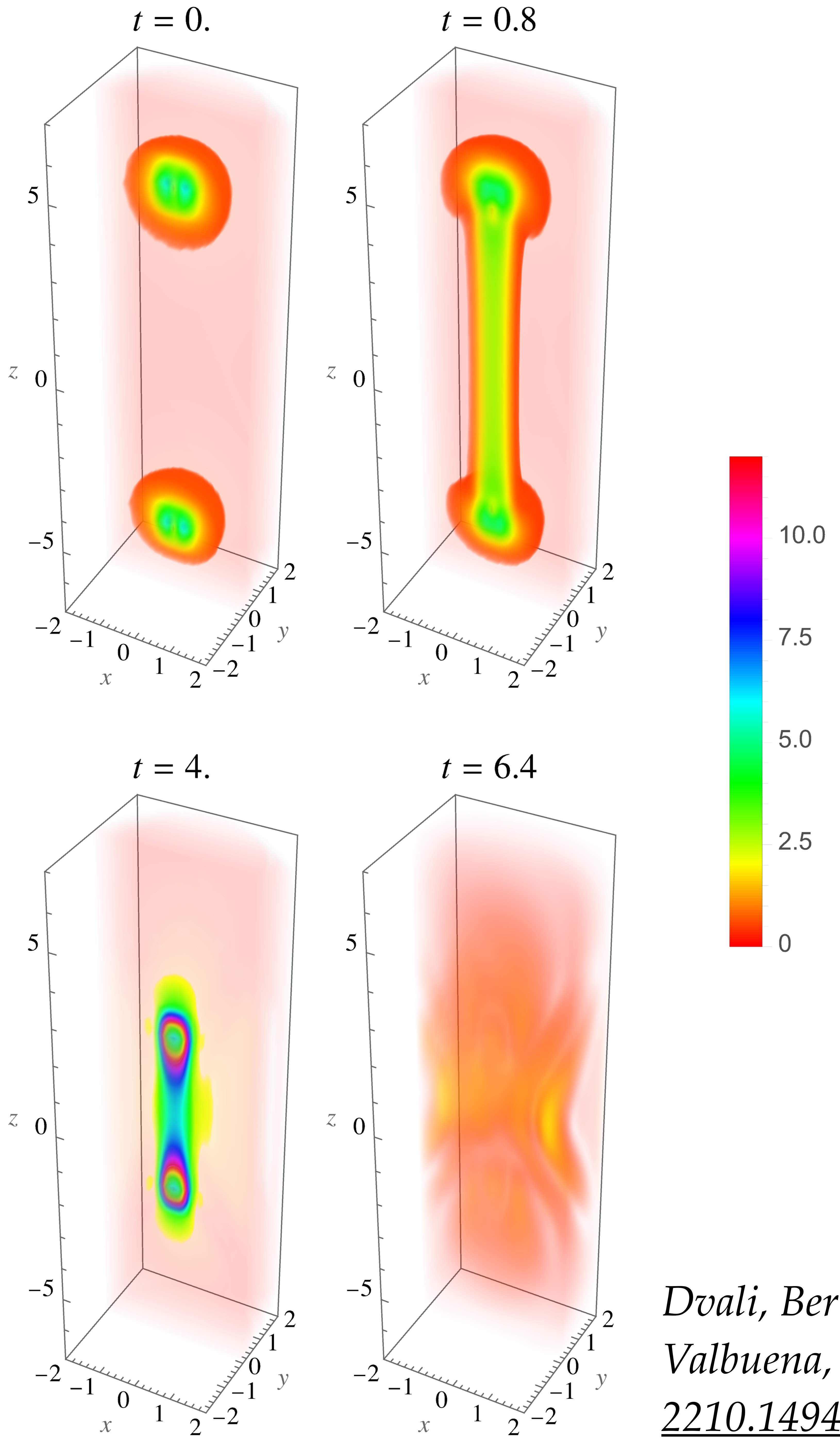
Dvali, Bermudez-Valbuena, MZ, 2210.14947

More on Confinement



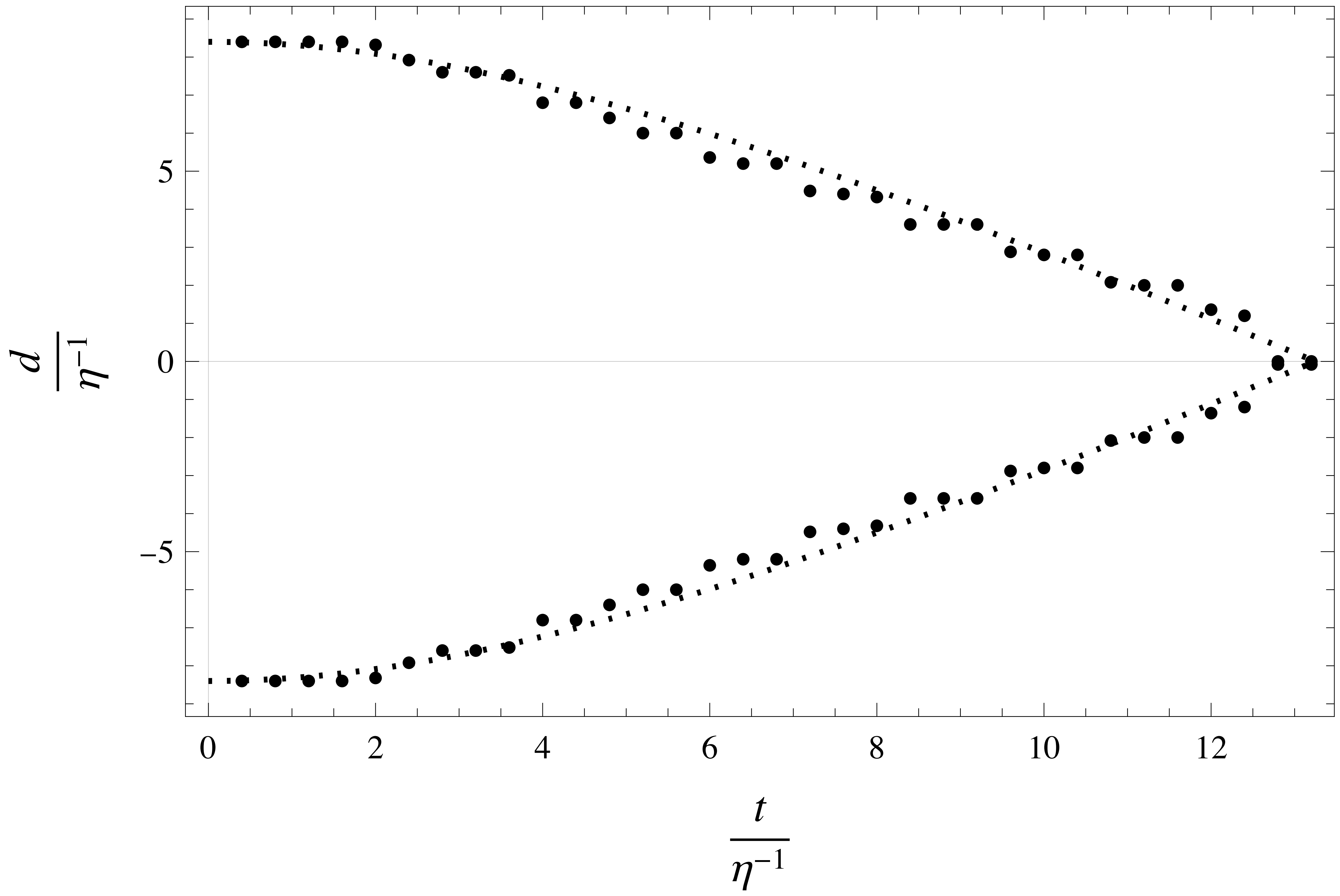
- Colour-charged particles (quarks and gluons) cannot be isolated. States are colourless below the confinement scale Λ_c
- Flux tubes of colour (strings) connect quarks
- Property of gauge theories (e.g., QCD)
- Separating quarks → nucleation of pairs
- $P_{\text{tunnel}} \propto e^{-\pi \left(M_q/\Lambda_c\right)^2}$ → if $M_q > \Lambda_c$ we could stretch an exponentially long string





Dynamics

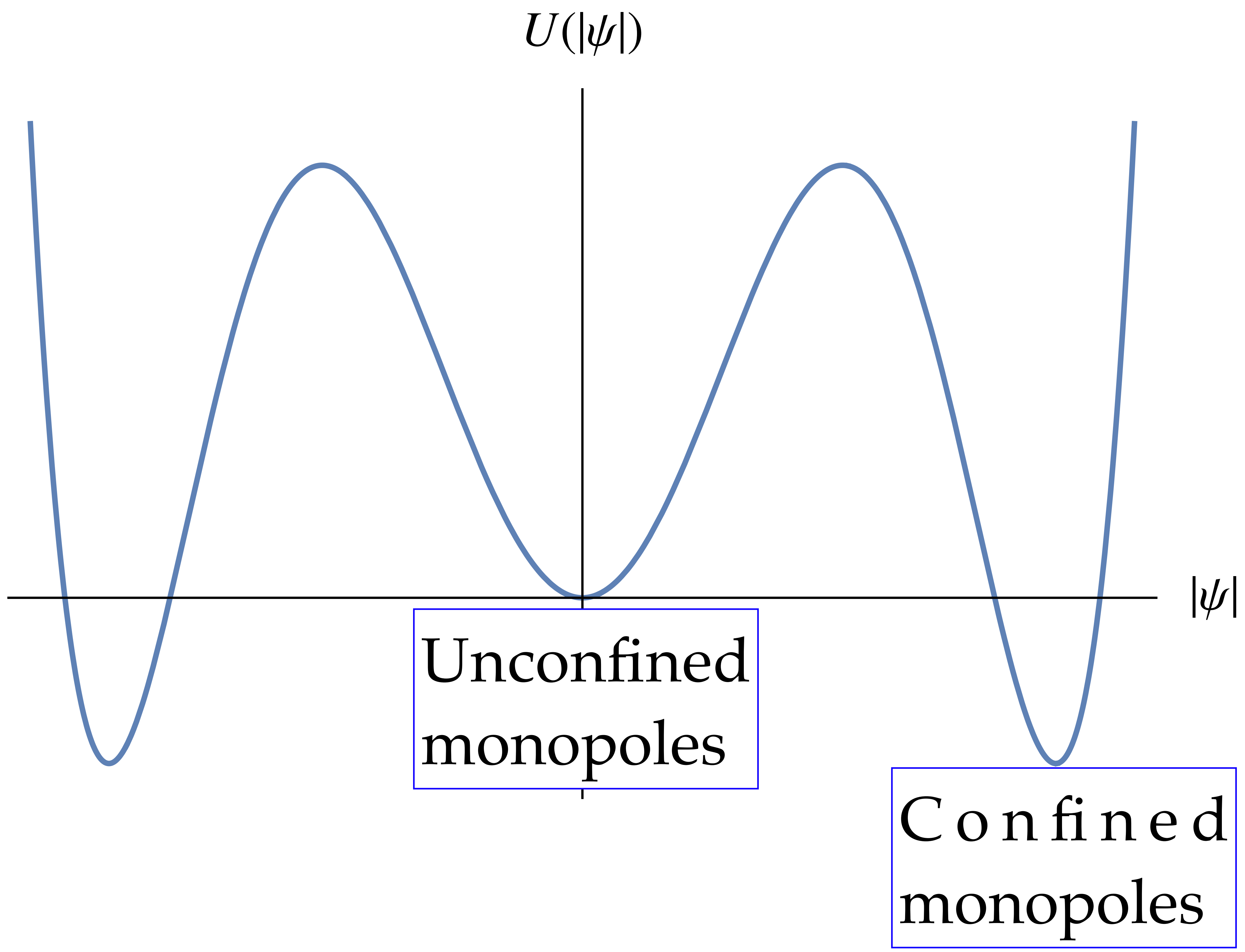
The dynamics is compatible with the one of constantly accelerating relativistic particles with $a = \Lambda^2/m$



Dvali, Bermudez-Valbuena, MZ, *2210.14947*

Confined - unconfined layer

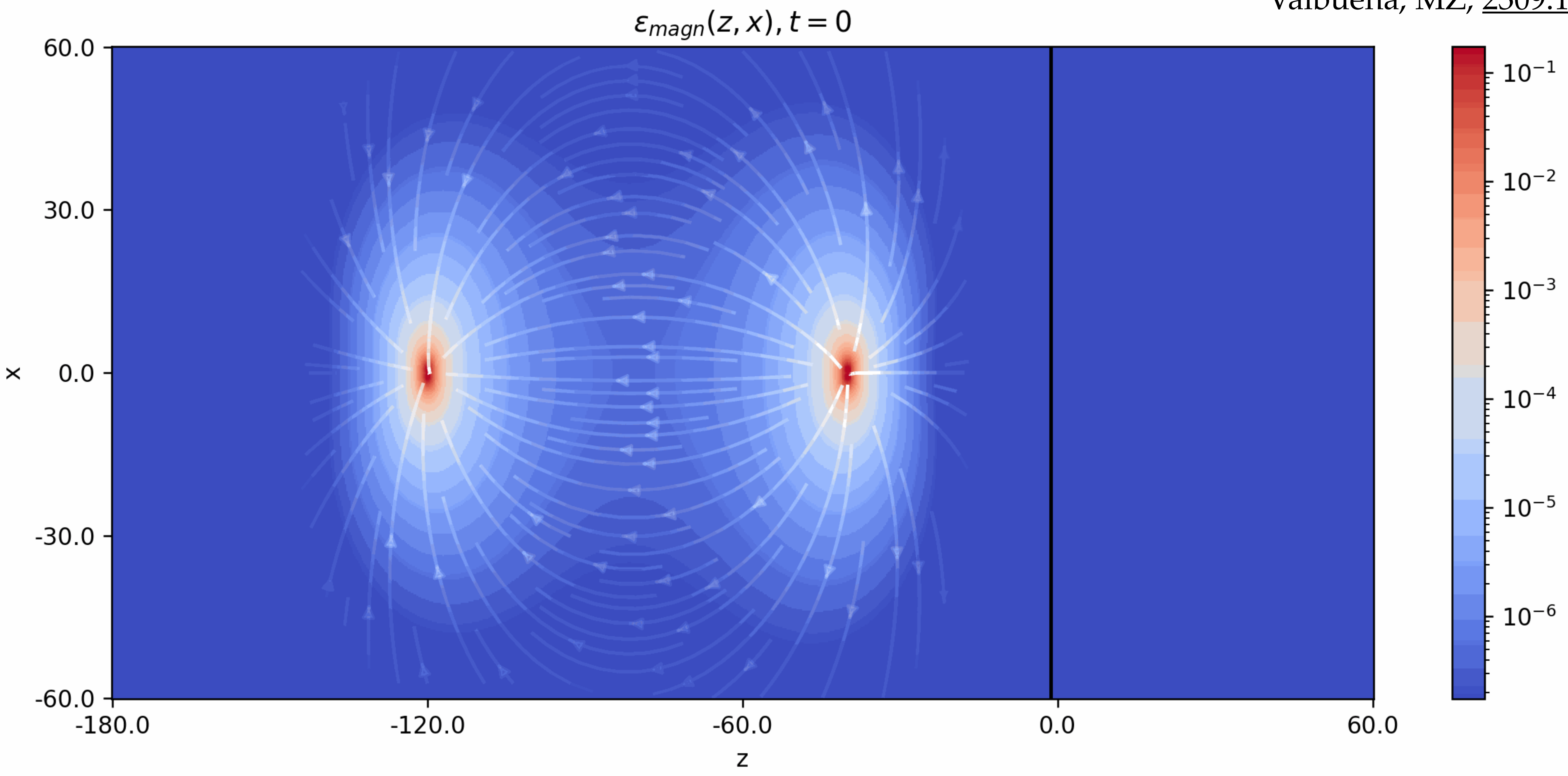
Coexistence of confining and unconfining phase is realised if ψ undergoes a first order phase transition



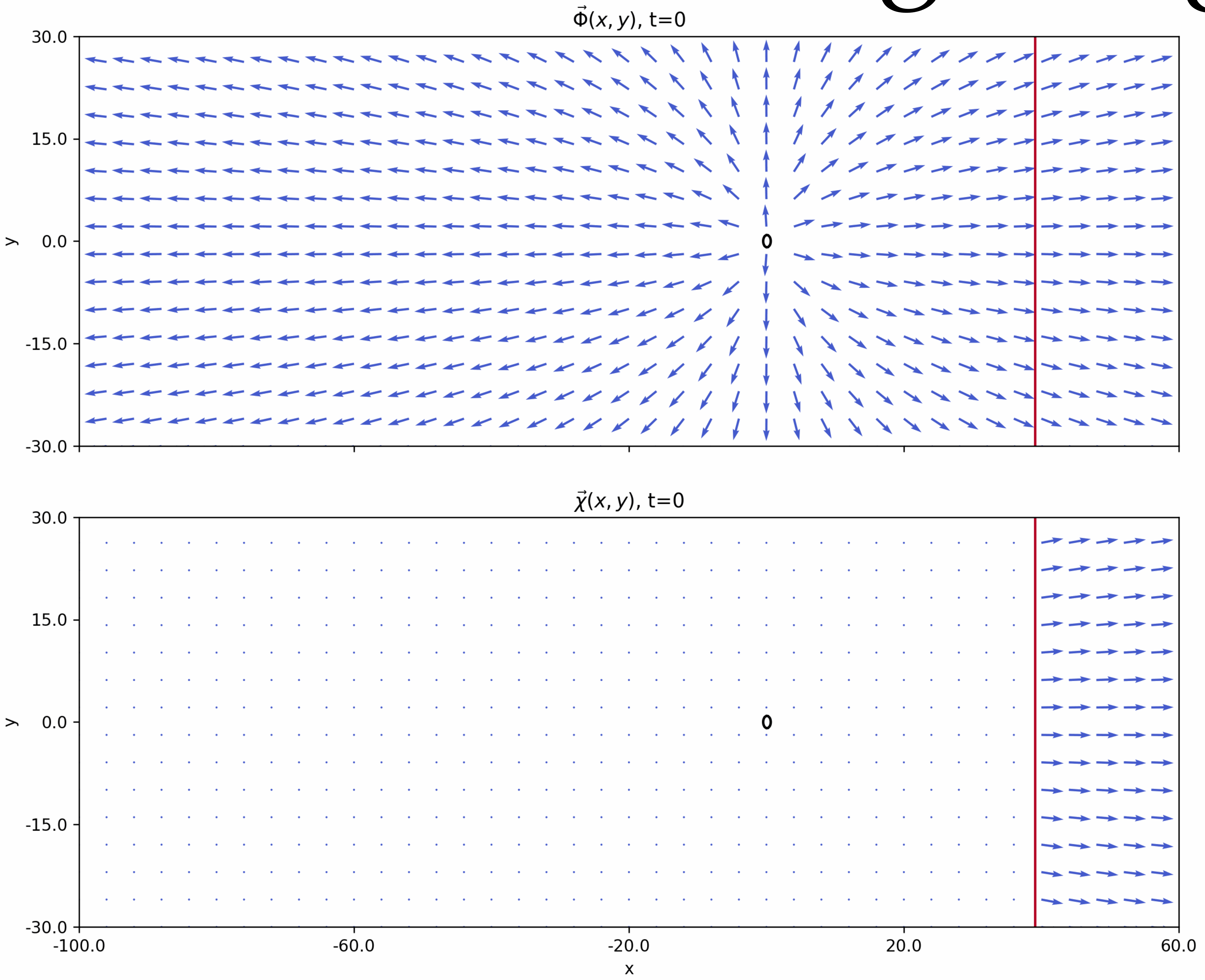
- The potential is typically realised by taking into account thermal corrections in the early Universe
- $\langle \psi \rangle = 0$ corresponds to the unconfined region
- $\langle \psi \rangle = v_\psi$ breaks the U(1) and confines the monopoles
- The system admits (unstable) domain walls (layer) interpolating between the two

Dynamics monopole-antimonopole

Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195



String Slingshot



$$SU(2) \to U(1) \to 1$$

$$U(1) \times Z_2 \to Z_2 \to 1$$

Unconfined region (Z_2 unbroken)

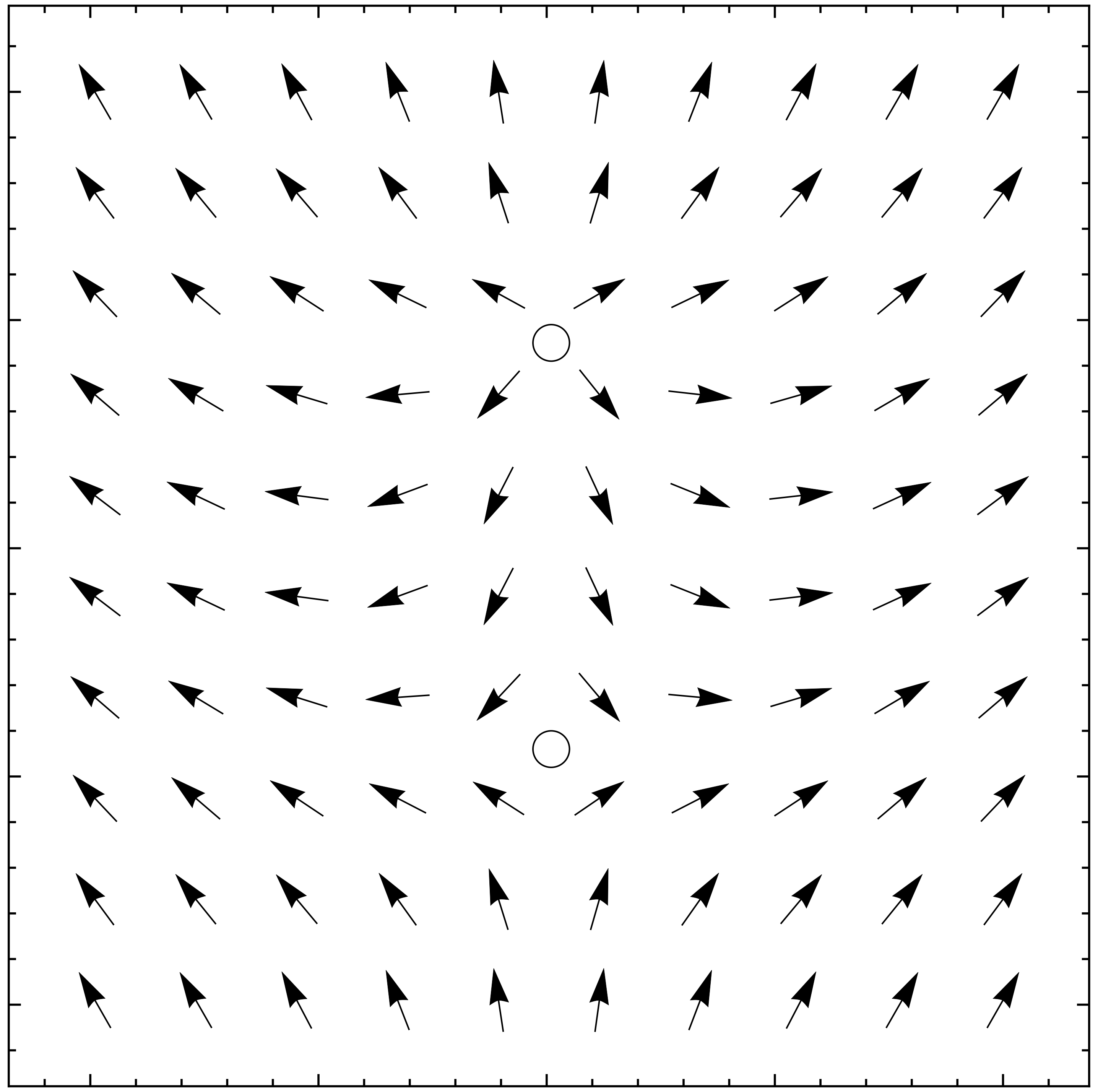
Confined region (Z_2 broken)

String

$$\mathscr{L} \supset \phi^* \chi^2 + \mathrm{h.c.} \propto \cos(\theta_\phi - 2\theta_\chi)$$

Initial Conditions

$$\varphi^a = h(r_m)h(\bar{r}_m)\hat{\varphi}^a$$



$$D_\mu \hat{\varphi}\,|_{r\to\infty} = 0$$

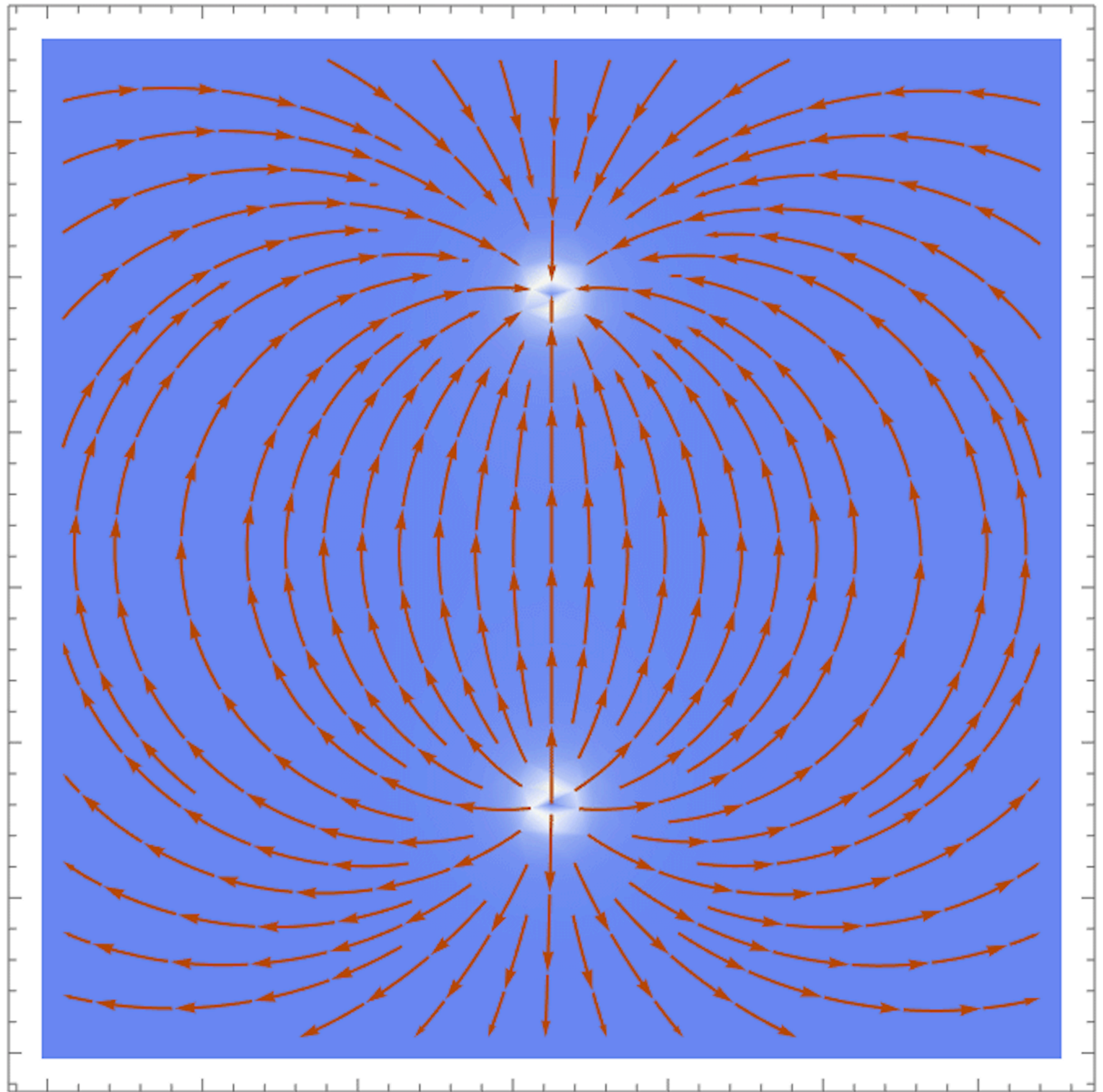
Vachaspati '15

$$\downarrow$$

$$W^a_\mu = -(1-k(r_m))(1-k(\bar{r}_m))\epsilon^{abc}\hat{\varphi}^b\partial_\mu\hat{\varphi}^c$$

$$F_{\mu\nu} = W^a_{\mu\nu}\hat{\varphi}^a - \epsilon^{abc}\hat{\varphi}^a D_\mu\hat{\varphi}^b D_\nu\hat{\varphi}^c$$

Magnetic field lines

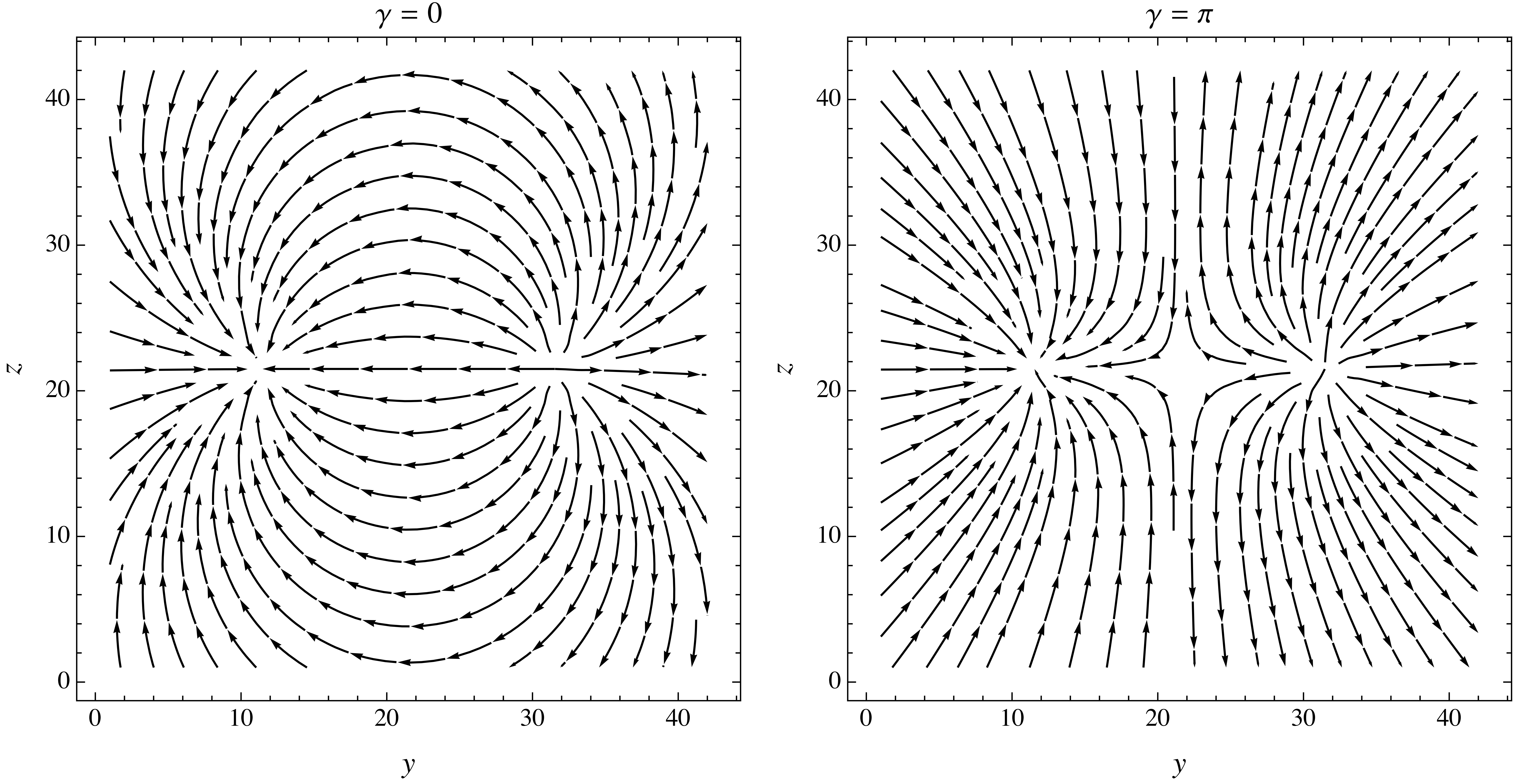


$$\psi = v\, l(r_{xy}, z)\begin{pmatrix} \sin(\theta/2)\sin(\bar{\theta}/2)e^{i\gamma} + \cos(\theta/2)\cos(\bar{\theta}/2) \\ \sin(\theta/2)\cos(\bar{\theta}/2)e^{i\phi} + \cos(\theta/2)\sin(\bar{\theta}/2)e^{i(\phi-\gamma)} \end{pmatrix}$$

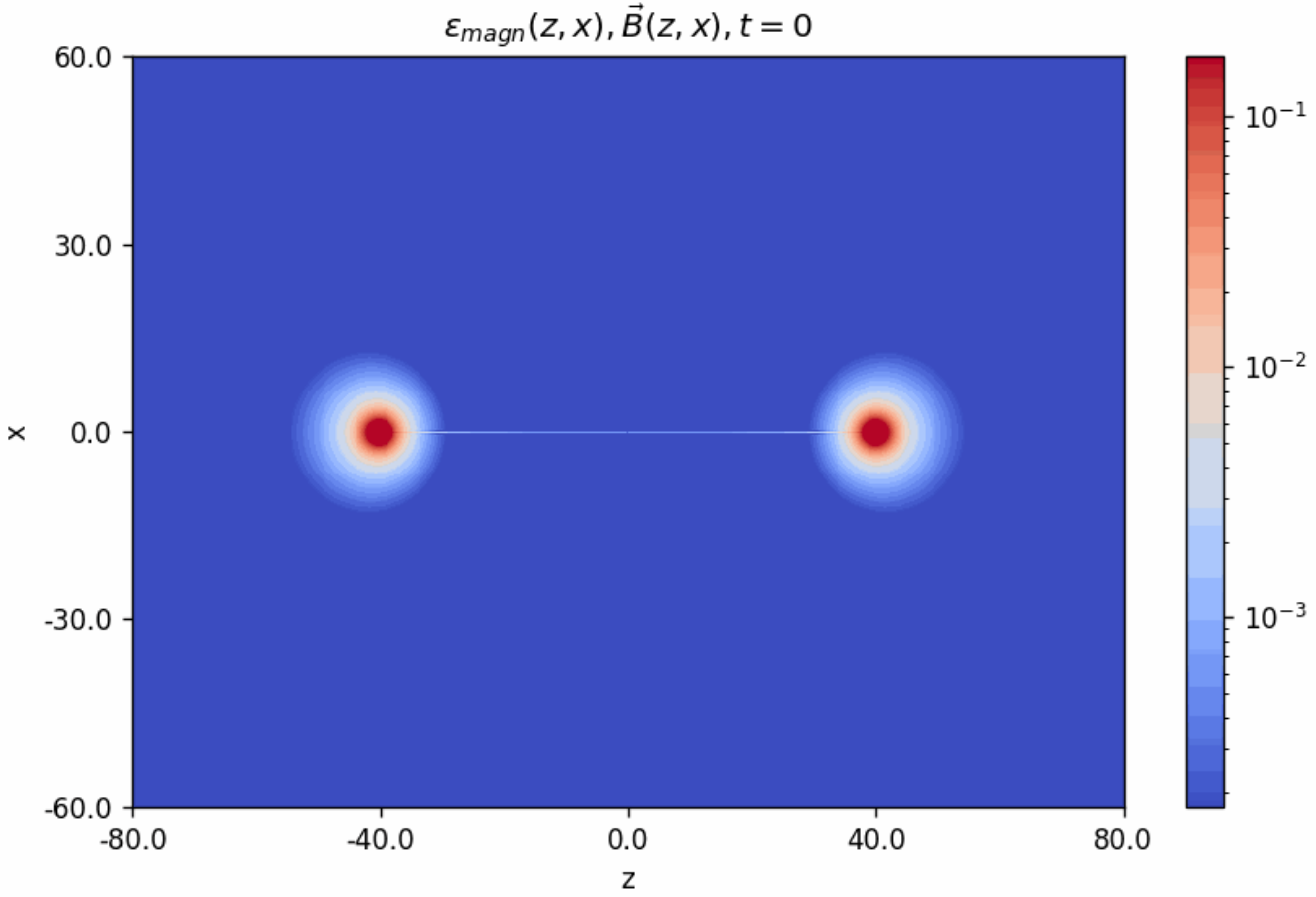
Vachaspati, Field '94

γ = twist angle

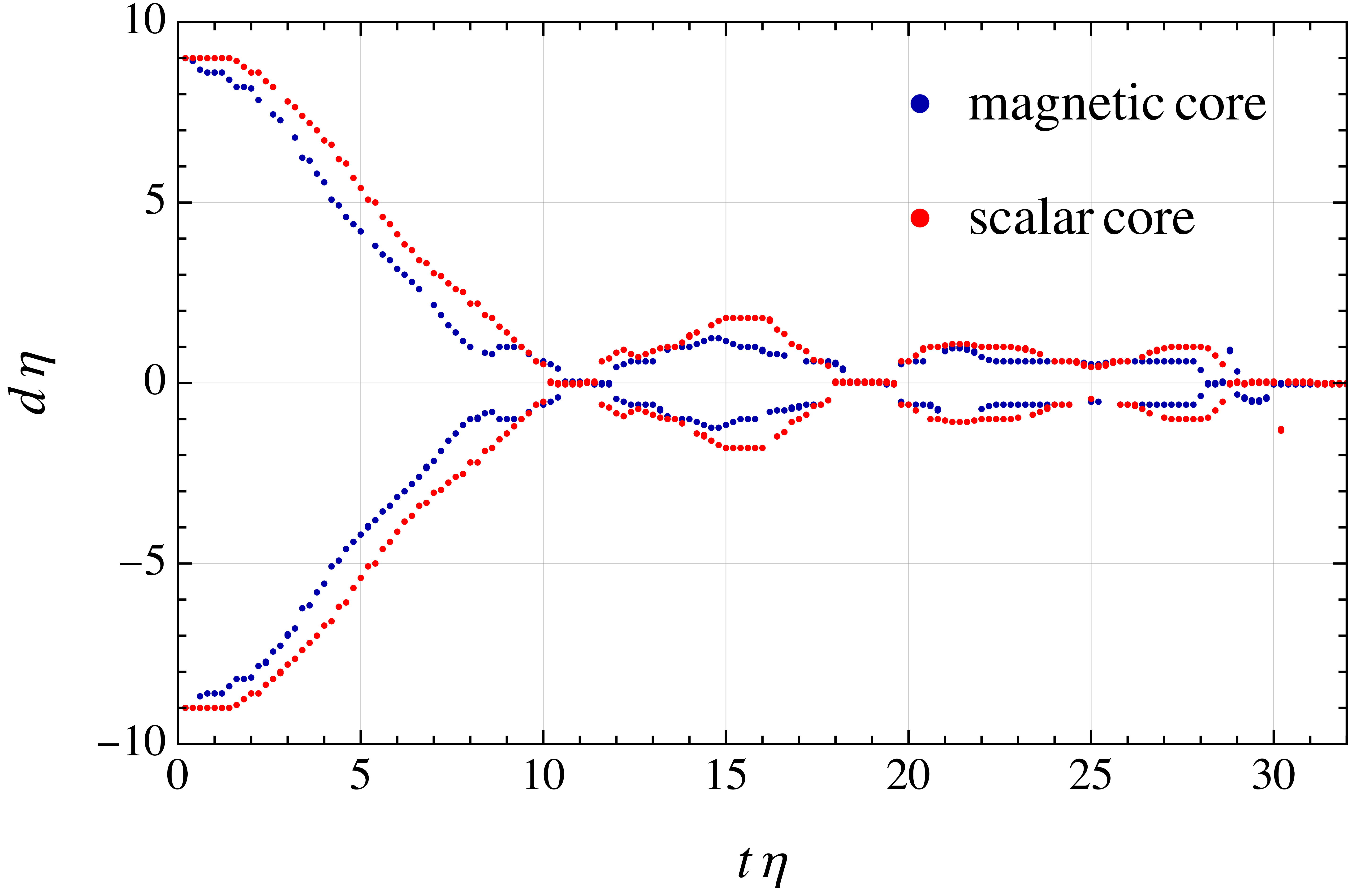
Adding a twist to the story



Adding a twist to the story



Adding a twist to the story



The configuration is metastable. Simply, the monopoles do not know in which direction to untwist to annihilate. Eventually the instability kicks in, the pair untwist, and it annihilates

More on the dual electric case

Consider $SU(2)$ theory with scalar adjoint with one heavy fermion

Dvali, Shifman hep-th/9612128

$$\mathscr{L} = -\frac{1}{2}\mathrm{Tr}\left(G^{\mu\nu}G_{\mu\nu}\right) + \mathrm{Tr}\left((D_\mu\phi)^\dagger(D^\mu\phi)\right) - U(\phi) + i\bar{Q}\gamma^\mu D_\mu Q - M_Q\bar{Q}Q$$

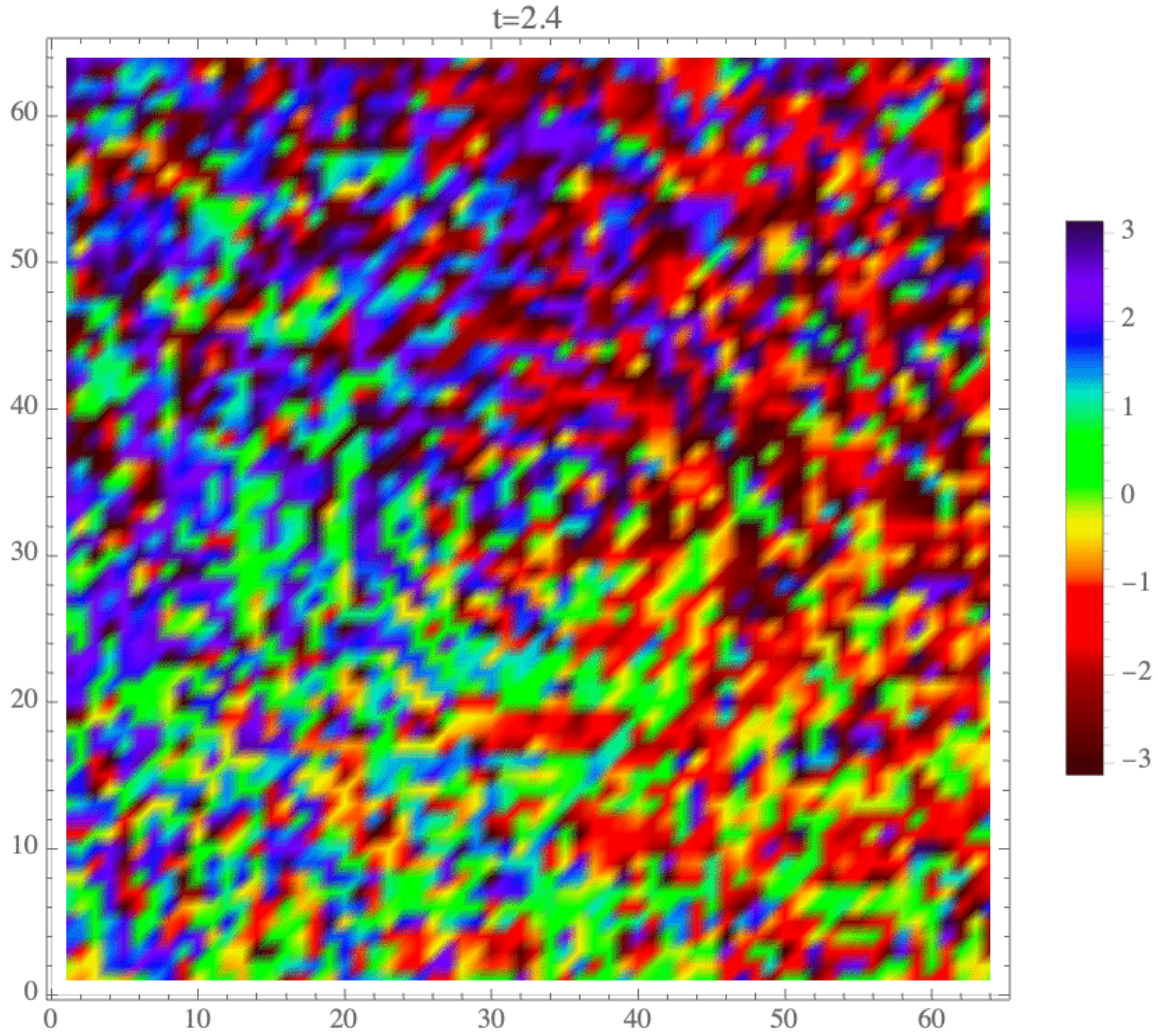
$$U(\phi) = \lambda\,\mathrm{Tr}\left(\phi^2\right)\left(\mathrm{Tr}\left(\phi^2\right) - \frac{v_\phi^2}{2}\right)^2$$

- $\langle\phi\rangle = 0$ theory is in the confined phase - mass gap is generated as in QCD
- $\langle\phi\rangle = v_\phi/\sqrt{2}$ theory is unconfined: there is a residual massless U(1) photon mediating Coulomb interaction

Slingshot expected for $M_Q \gg \Lambda$

Dynamical string formation: phase of confining scalar field - initially randomised

x-y plane at z= 0

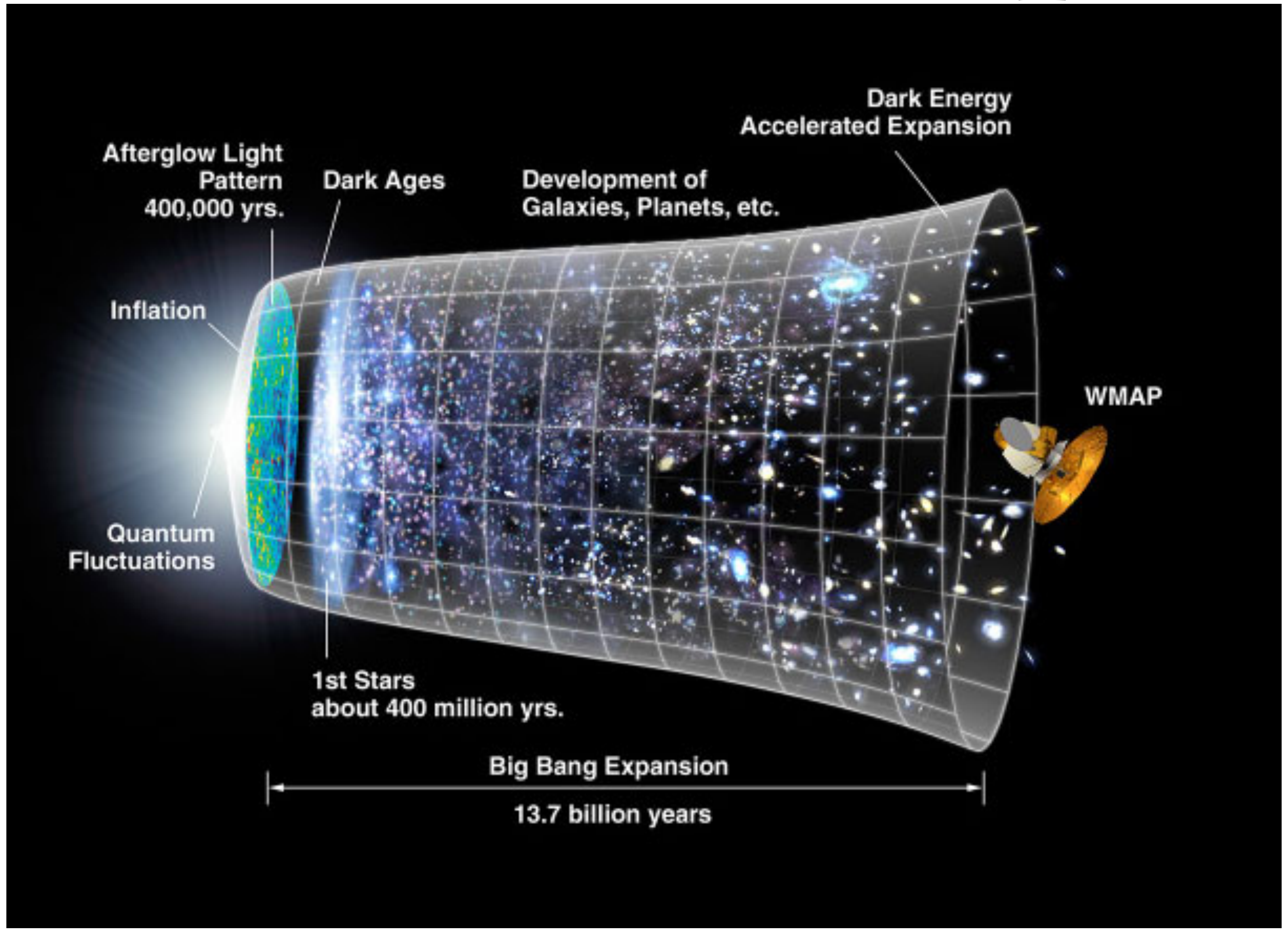


Inflation as source of monopoles

Period of exponential expansion

$$a(t) = a_0\, e^{H_{\rm i}\, t}, \quad H_{\rm i} \approx \text{const}$$

Introduced by Guth to address the flatness, horizon and monopole problem



Credit NASA

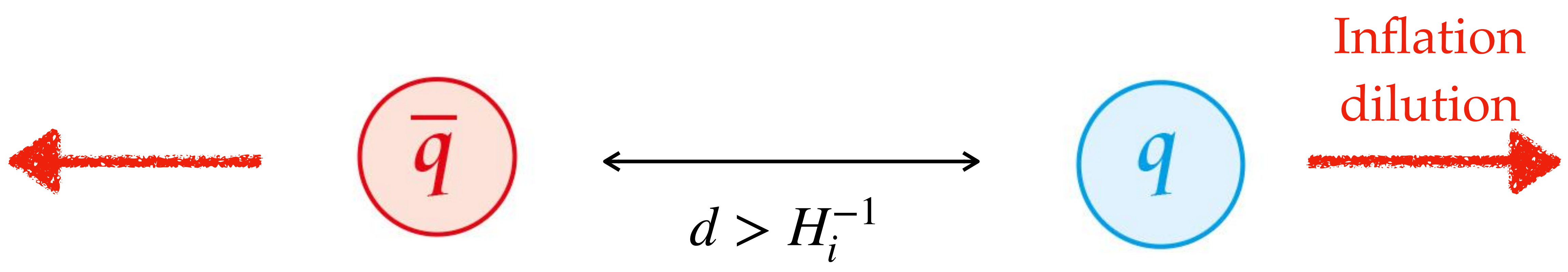
Fields fluctuate due to quasi-de-Sitter spacetime and particles are produced e.g.,

$$P \propto e^{-2\pi \frac{m}{H_{\rm i}}} = e^{-\frac{m}{T_{\rm H}}}, \quad H_{\rm i} < m$$

Basu, Guth, Vilenkin, '91

Formation mechanism

Step 1: de Sitter fluctuations produce quarks during inflation

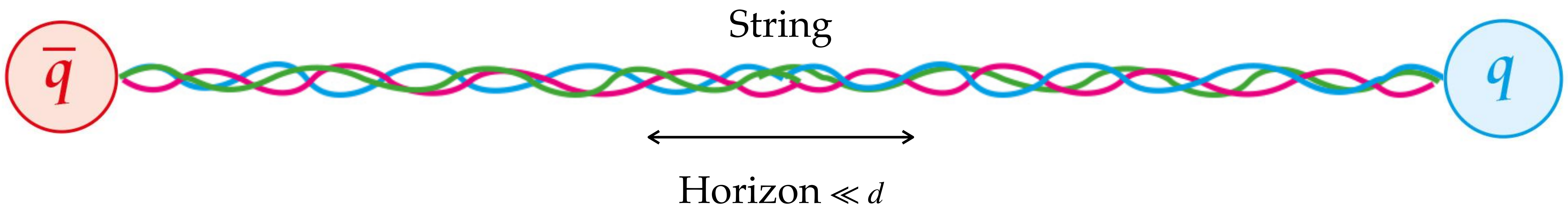


- Focus on a simple pair case (more complicated configurations possible)
- Constant production rate λ
- Depends on the relative mass scales
- Interested in distribution of quarks at super horizon distances
- Distance grows as $d \propto e^{N_e}$

See T Matsuda arXiv:hep-ph/0509061.

Formation mechanism

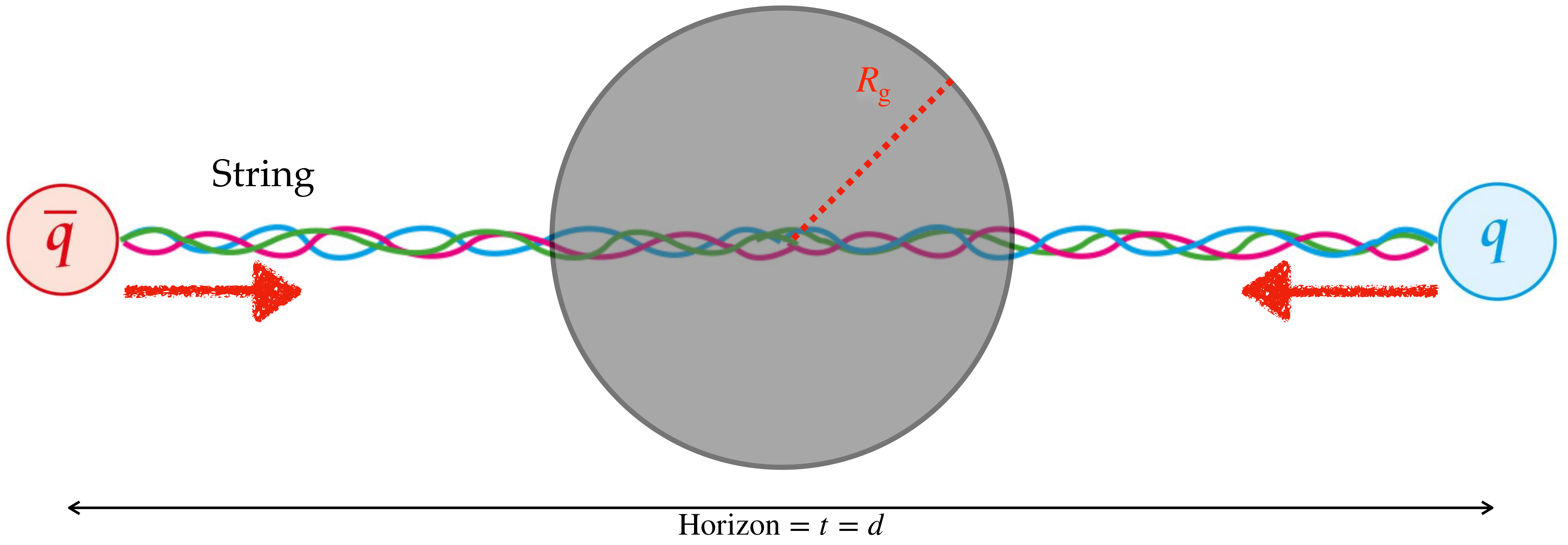
Step 2: Confinement at energy scale Λ_c, $M_q/\Lambda_c \gg 1$



- Flux tubes form connecting quark/anti-quark pairs
- The system cannot collapse as long as $d \gg$ Horizon
- String breaking into quarks pair: $P_{\text{tunnel}} \propto e^{-\pi\left(M_q/\Lambda_c\right)^2}$ suppressed as long as $M_q/\Lambda_c \gg 1$
- This condition should hold for the lightest confined quark
- Confinement can take place during inflationary period or in the late Universe

Formation mechanism

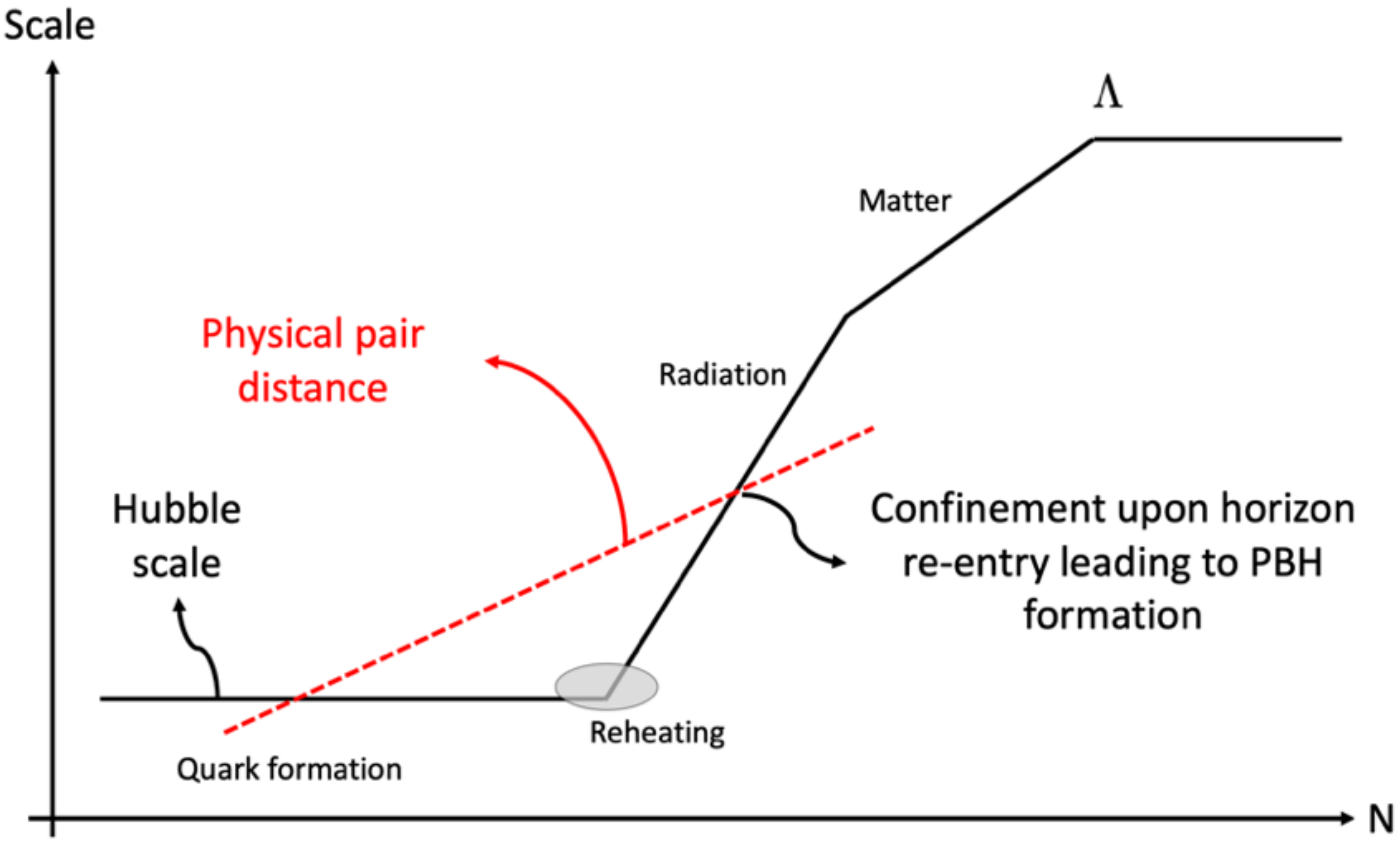
Step 3: As they re-enter horizon, collapse leads to BH formation



- Quarks accelerate towards each other $a = \Lambda_c^2/m_q$ and become relativistic

$$E \simeq \Lambda_c^2 t \simeq M_{\rm PBH}, \quad R_g \gg \Lambda_c^{-1}$$

- The connecting string is not *exactly straight*
- Primordial BHs due to overdensities are heavier $M_{\rm PBH}^{\rm over} \sim t$

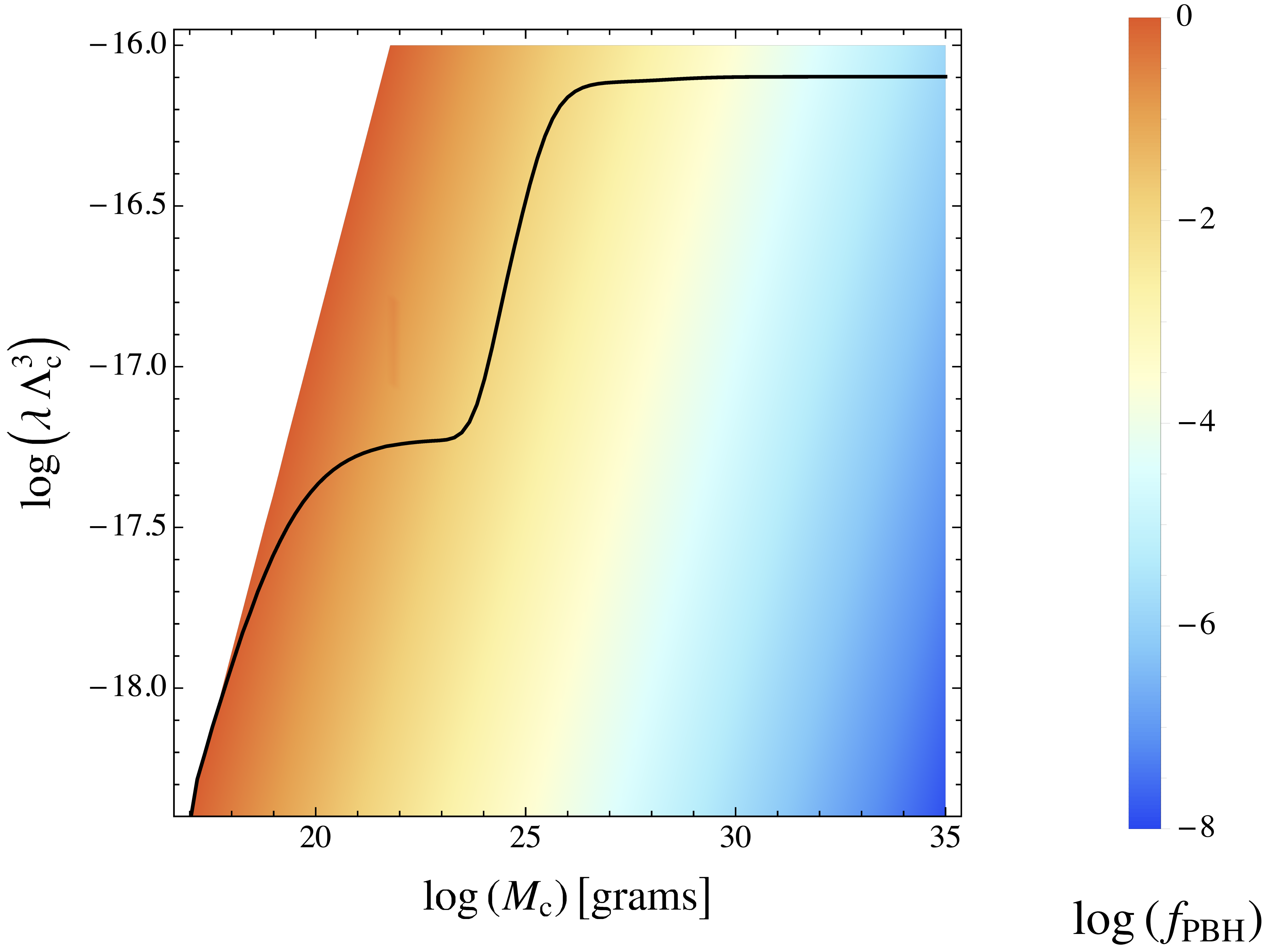


Scale
Λ
Matter
Physical pair
distance
Radiation
Hubble
scale
Confinement upon horizon
re-entry leading to PBH
formation
Reheating
Quark formation
N

Dark matter

Extended spectrum $\displaystyle \int_{M_1}^{M_2} \mathrm{d}\ln M_{\mathrm{PBH}} \, \frac{\mathrm{d} f_{\mathrm{PBH}}(M_{\mathrm{PBH}})}{\mathrm{d}\ln M_{\mathrm{PBH}}} \frac{1}{f_{\max}(M_{\mathrm{PBH}})} \overset{!}{\leq} 1$

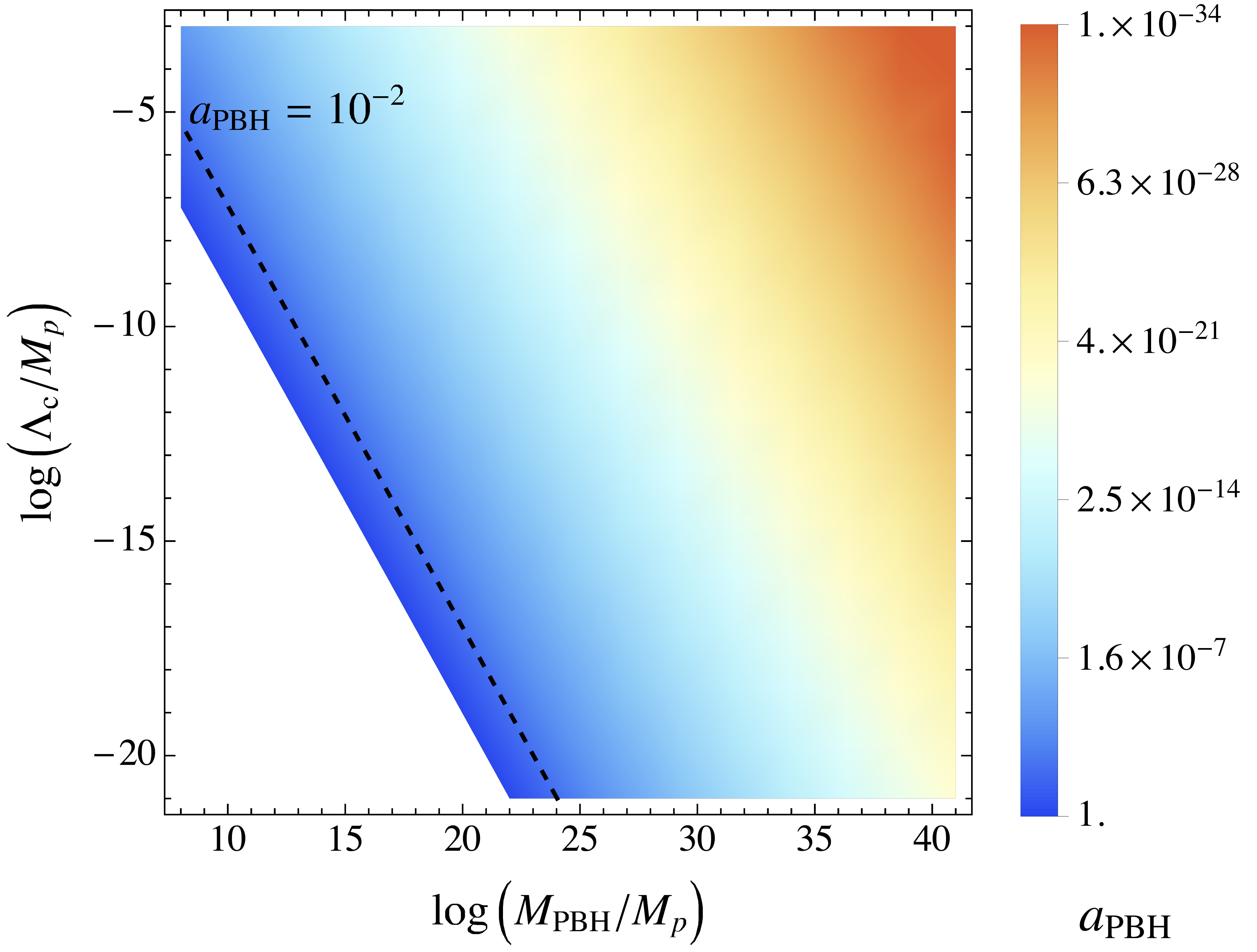
Carr, Raidal, Tenkanen, Vaskonen, Veermäe '17

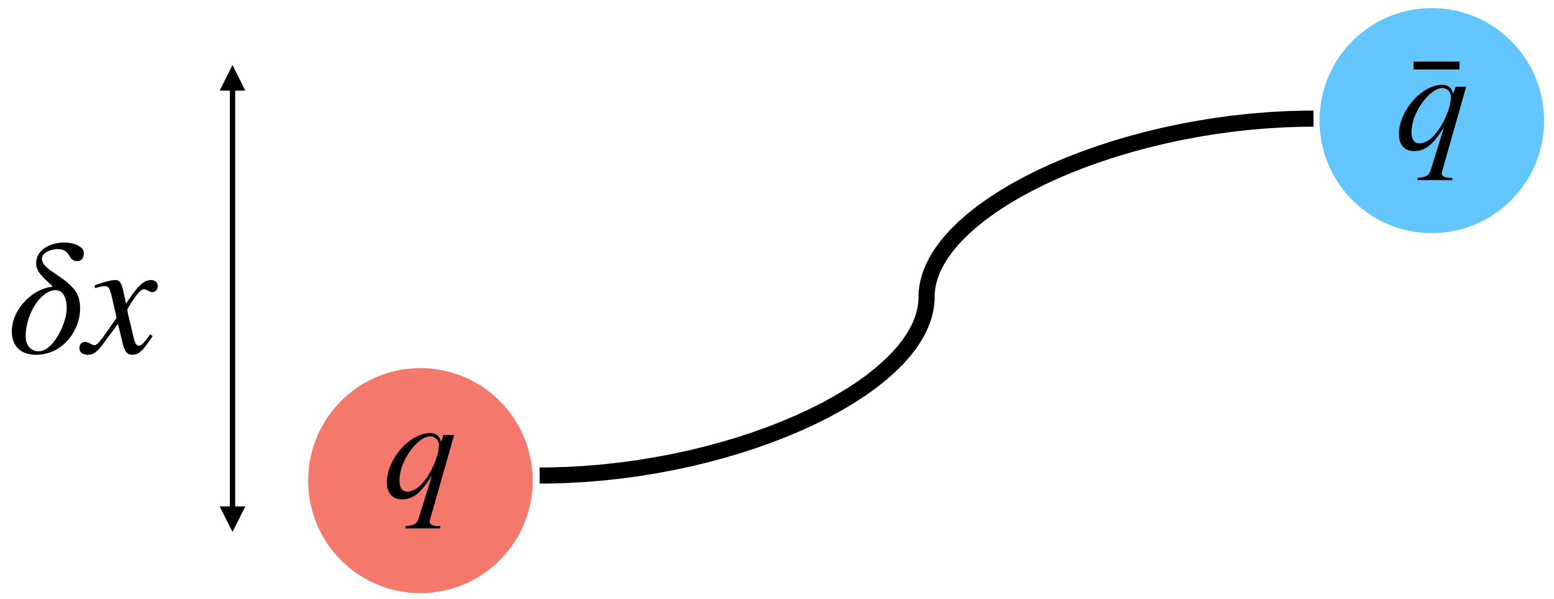


Compatibility with observations below the black line

100% of dark matter

Highly spinning sub-solar mass PBH





$$\delta x \simeq \sqrt{N_e}\, H_i^{-1}$$

$$a_{\rm PBH} \simeq \frac{\delta x}{R_g} \simeq \frac{1}{H_i M_{\rm PBH}} \log\left(\frac{H_i M_{\rm PBH}}{\Lambda_c^2}\right)^{1/2}$$

N.B. Overdensity PBHs do not rotate (in radiation)

→This source of spin matters for lighter black holes

Possible embedding with QCD

- Assumption required:

$\Lambda_c < M_q$ from nucleation to collapse

- At $T = 0$ QCD does exactly the opposite $\Lambda_c > M_q$, however,…

- It is natural for the confining and mass scales to change in the Early Universe

Dvali '95

- This is the case if couplings are expectation values of fields (moduli) with flat potentials

- For example, couplings between inflaton and standard model can achieve that

Possible embedding with QCD

$$g_y \bar{\psi}_L \psi_R \phi \qquad \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu}$$

Couplings are expectation values of fields and can be very different in the early Universe

$$g_y = f_y \left(S_y / M_* \right), \quad \frac{1}{g^2} = f_F \left(S_F / M_* \right)$$

Expectation values of fields ϕ, S_y and S_F change at non-zero temperature

Requirement: Low temperature expectation value should set the right coupling values

This should happen before BBN→ large room for PBH production

Supermassive black holes

- These are black holes in the galactic centres which might be too heavy to be explained by accretion of stellar black holes

- They have masses $\geq 10^9 M_\odot$

- Primordial BHs of masses $M_{\rm PBH} \geq 10^4 M_\odot$ can explain them due to accretion

- $f_{\rm PBH}^{constain}(M \gtrsim 10^4\, M_\odot) \lesssim 10^{-9}$, which is satisfied

$$f_{\rm PBH}^{\rm heavy} \equiv \int_{10^4\, M_\odot} {\rm d}\ln M_{\rm PBH}\, \frac{{\rm d} f_{\rm PBH}(M_{\rm PBH})}{{\rm d}\ln M_{\rm PBH}} \approx 10^{-10}$$

Correct value to obtain SMBHs via accretion *Serpico, Poulin, Inman, Kohri '20*