# Confinement slingshot and gravitational waves

Gravitational Wave Probes of Physics Beyond the Standard Model

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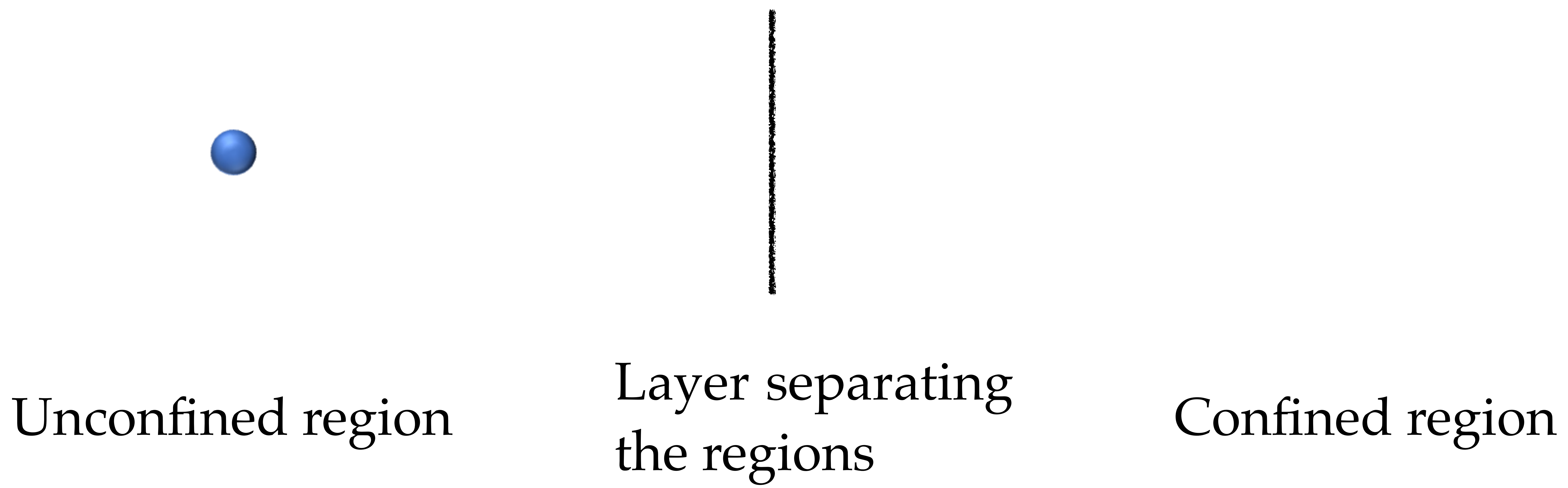
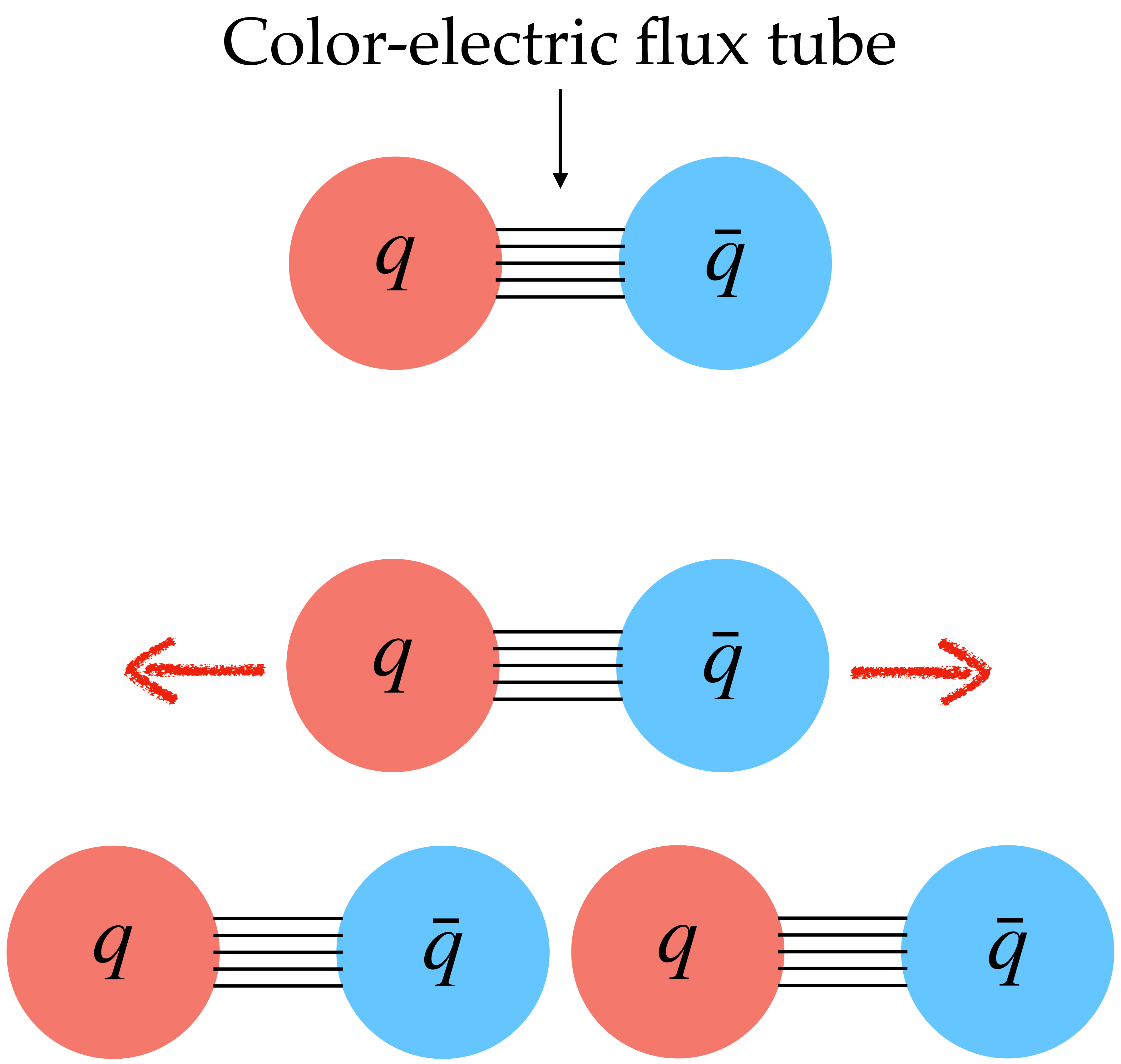
Based on:
Dvali, Kühnel, MZ, 2108.09471
Dvali, Bermudez-Valbuena, MZ, 2210.14947
Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195

# Motivation and Goal

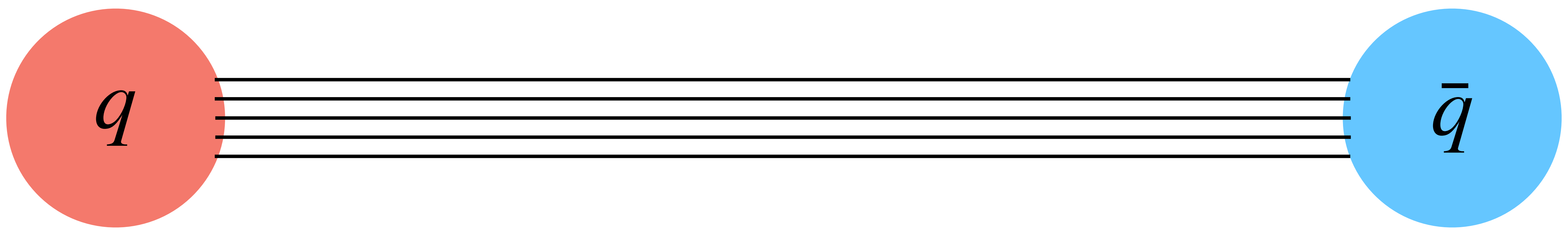
- Understanding the transition between the confining and deconfining regimes of gauge theories in a controllable environment
- The coexistence of confining and unconfining vacua is realised in several beyond Standard Model extensions (e.g., intermediate scales of Grand unified theories, branes).
- Confinement forces a specific dynamics, leading to the production of gravitational waves.



# Confinement

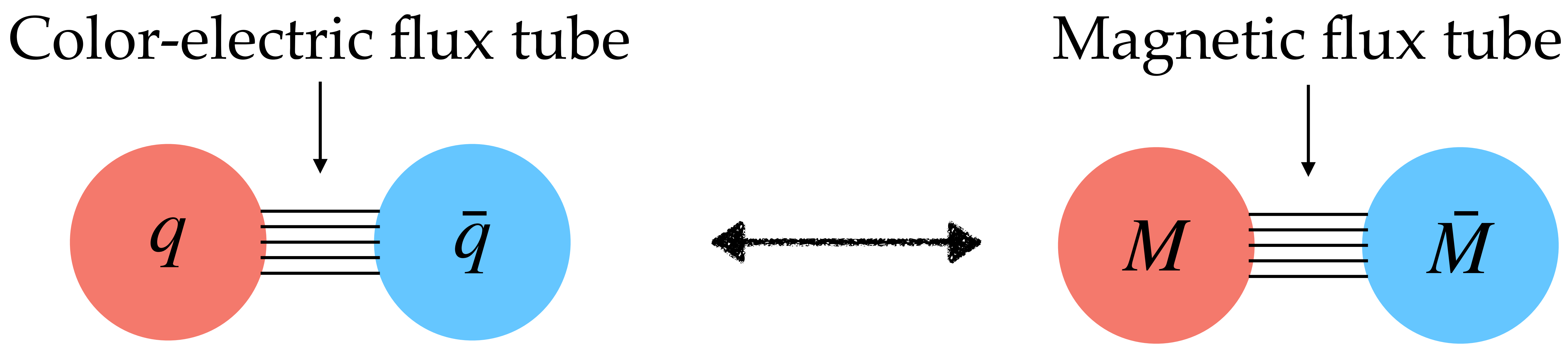



- Colour-charged particles (quarks and gluons) cannot be isolated. States are colourless below the confinement scale $\Lambda_c$
- Flux tubes of colour (strings) connect quarks
- Property of gauge theories (e.g., QCD)
- Separating quarks → nucleation of pairs
- $P_{\text{tunnel}} \propto e^{-\pi\left(M_q/\Lambda_c\right)^2}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



# Confinement

There is a duality between colour electric confinement and magnetic confinement
Dvali, Vilenkin hep-th/0209217

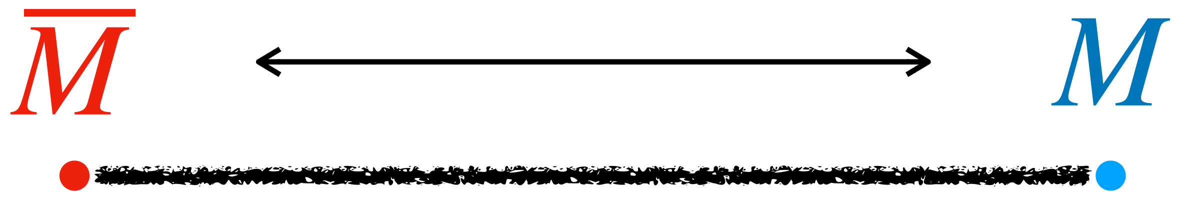



- strongly coupled
- quantum system

- weakly coupled
- admits classical description
- confinement is a realised by Higgsing
- Realisation in terms of confined 't Hooft Polyakov monopoles

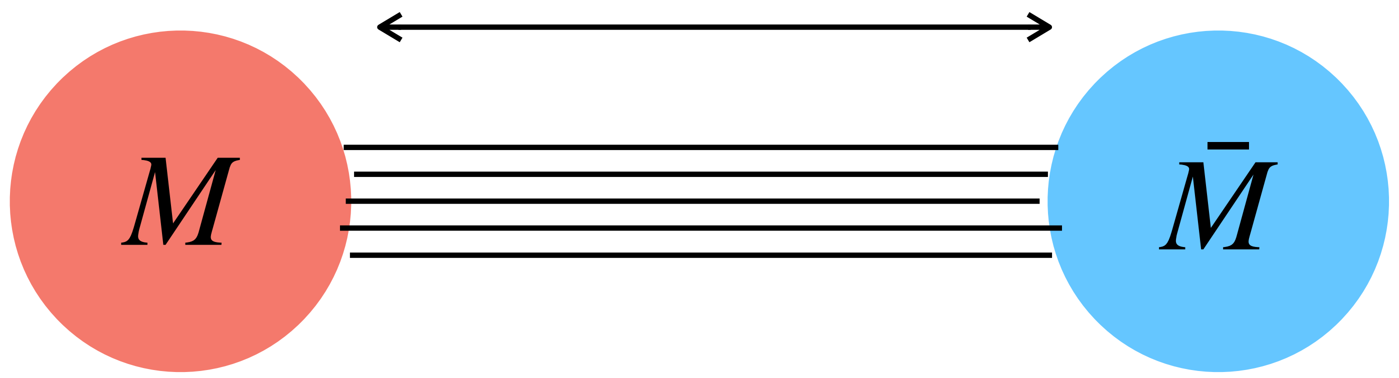
# Confinement

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

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

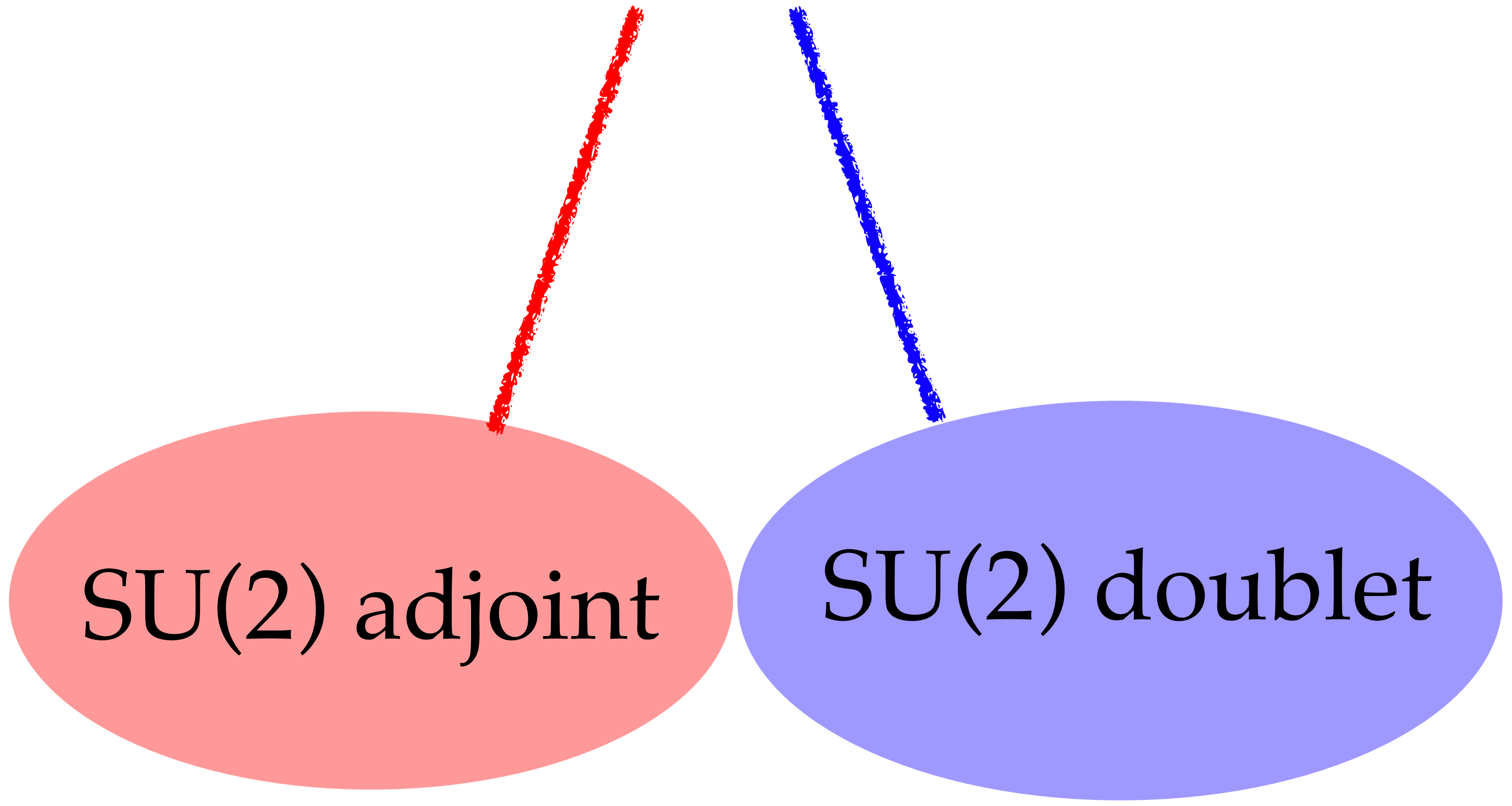
We looked at this in an explicit realisation with 't Hooft Polyakov monopoles

*Dvali, Bermudez-Valbuena, MZ, 2210.14947*

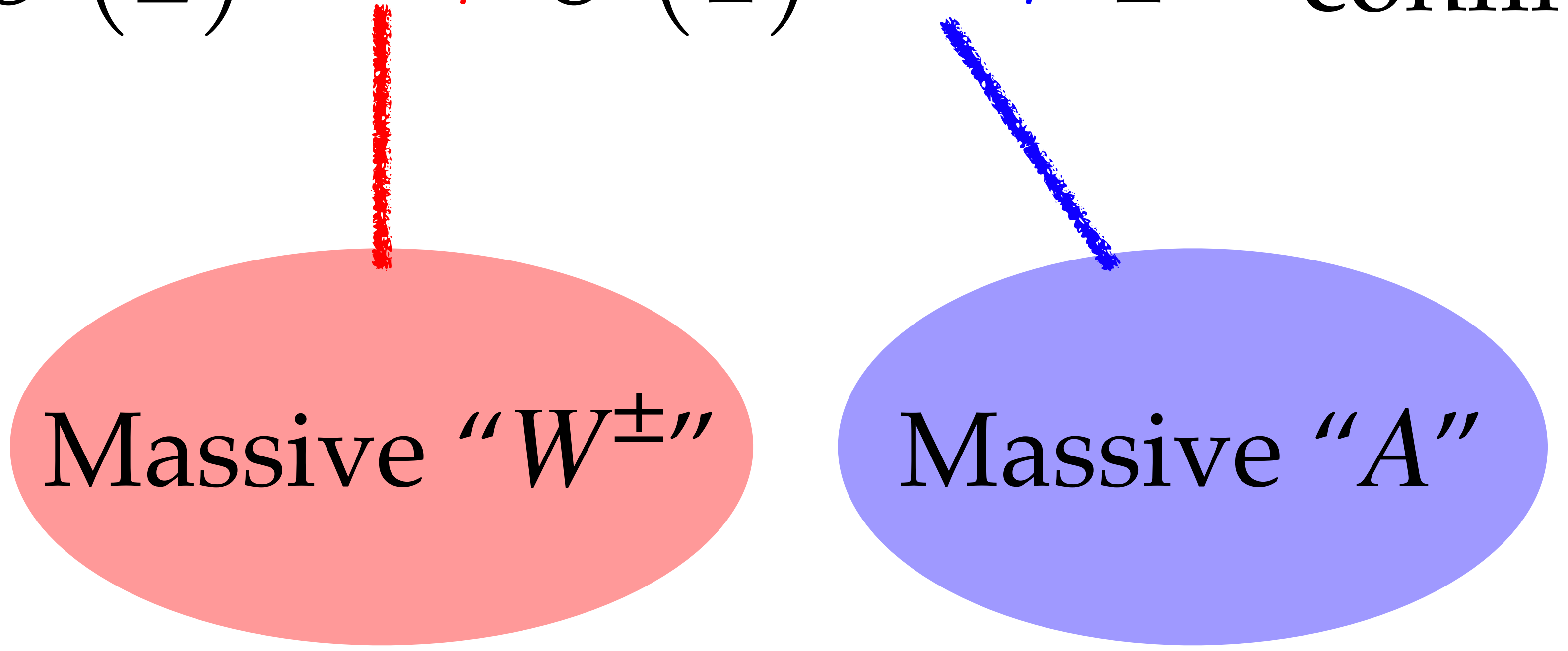
# System

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

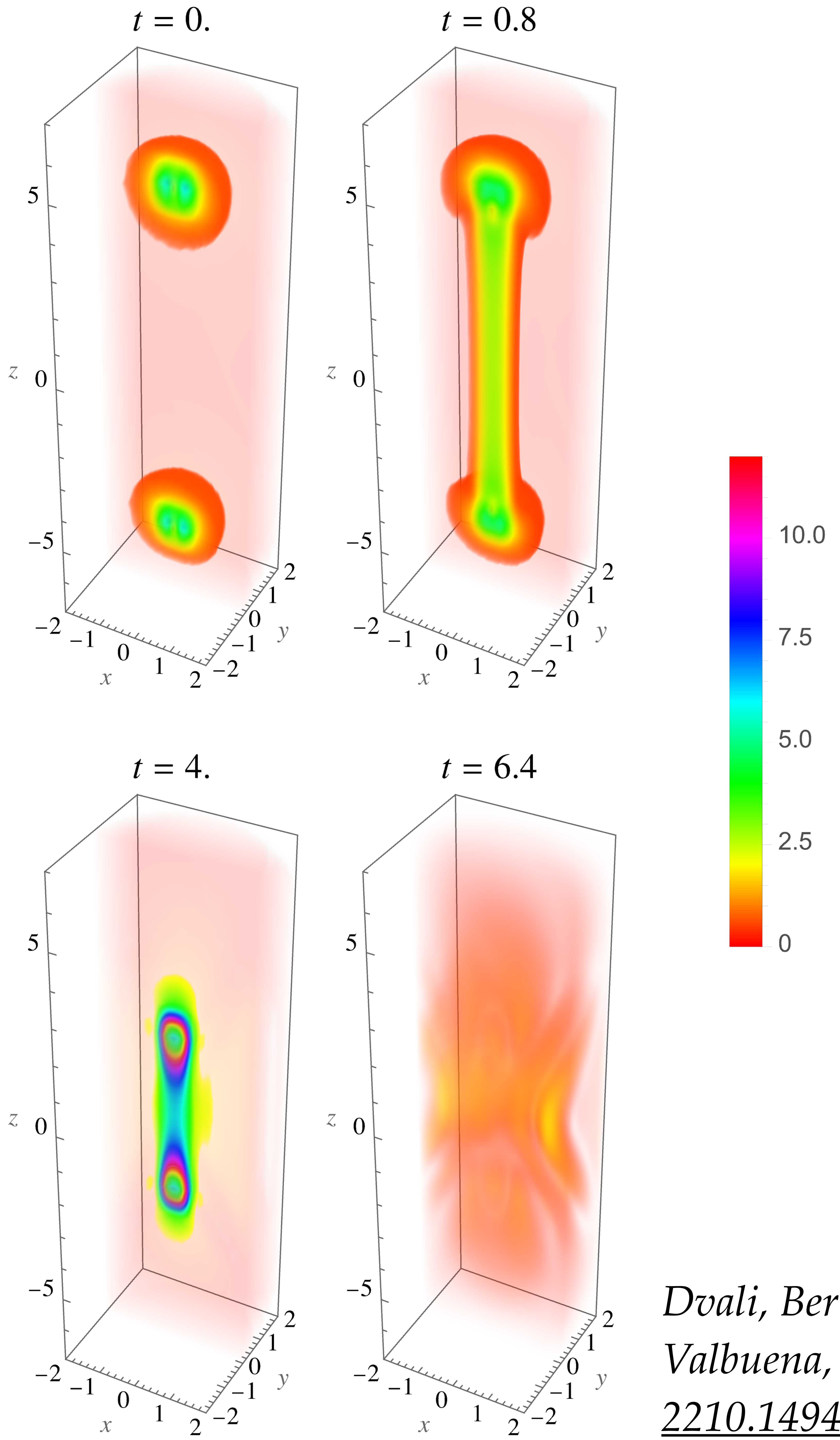
$$U(\phi, \psi) = U(\phi) + U(\psi) + \beta \psi^\dagger \phi \psi$$




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




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

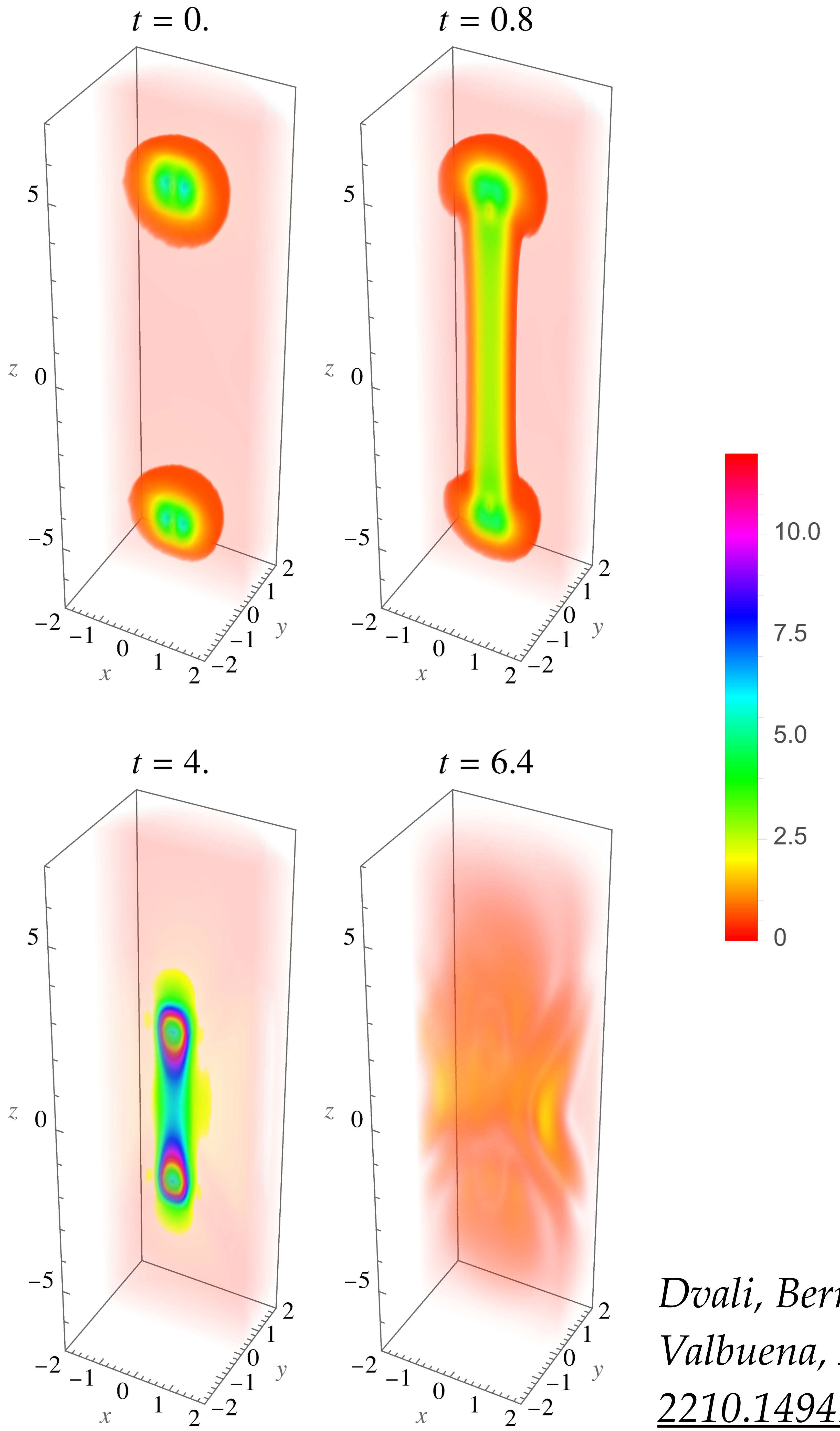



*Dvali, Bermudez-Valbuena, MZ,* *2210.14947*

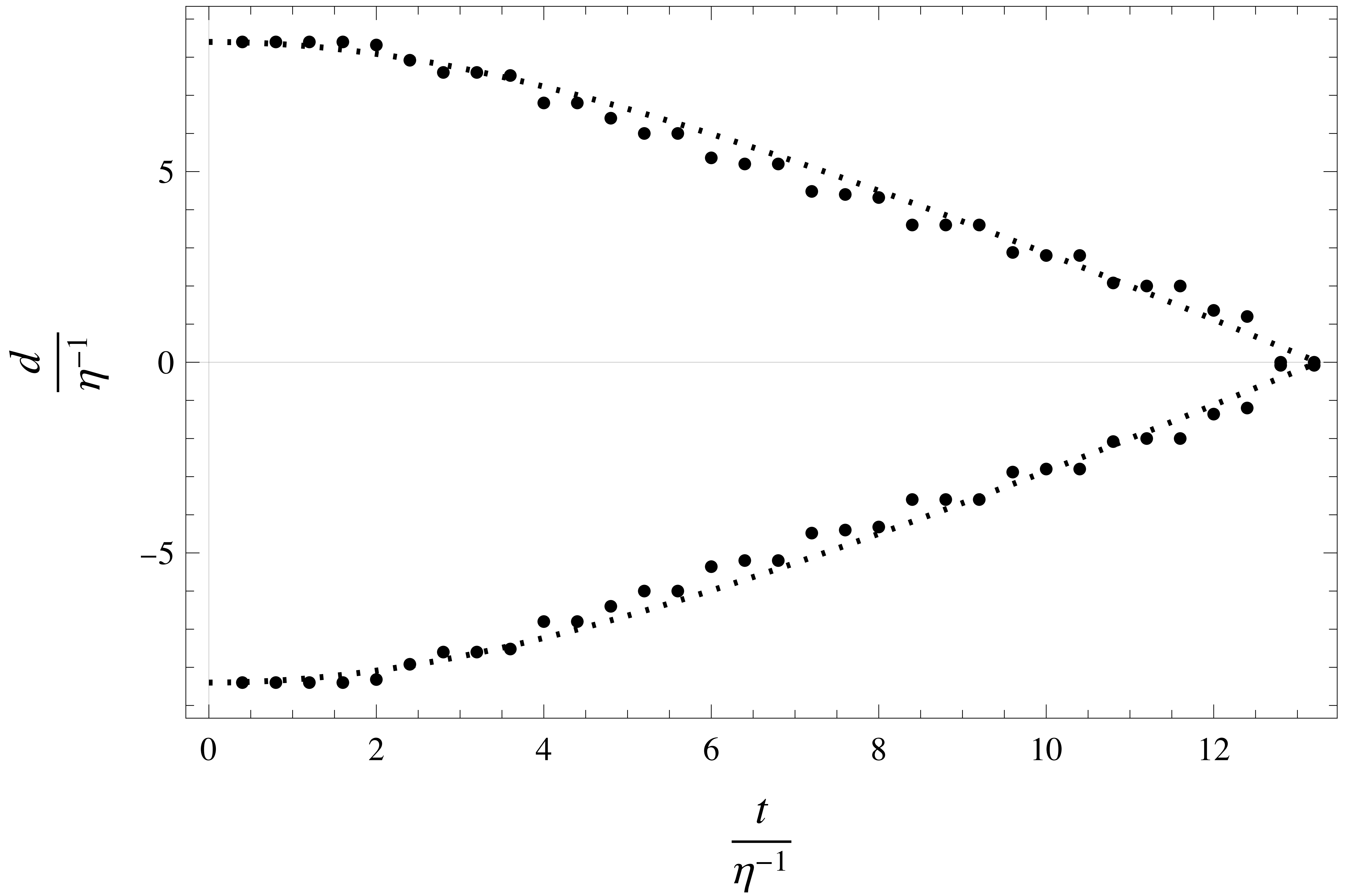
# Dynamics

- Monopole-antimonopole pairs in confined region: their magnetic charge is confined into a string connecting them
- Energy stored in the string, given by $E \sim \Lambda^2 d$, is transferred to the kinetic energy of the monopoles which are constantly accelerated towards each other with $a = \Lambda^2/m$ and eventually annihilates
- System now simply annihilates and does not oscillate as opposed to point-like case
- New possibilities: the monopole can be twisted with respect to the antimonopole. In the maximal 'twist' case, the configuration is a microscopic realization of a sphaleron

# Dynamics



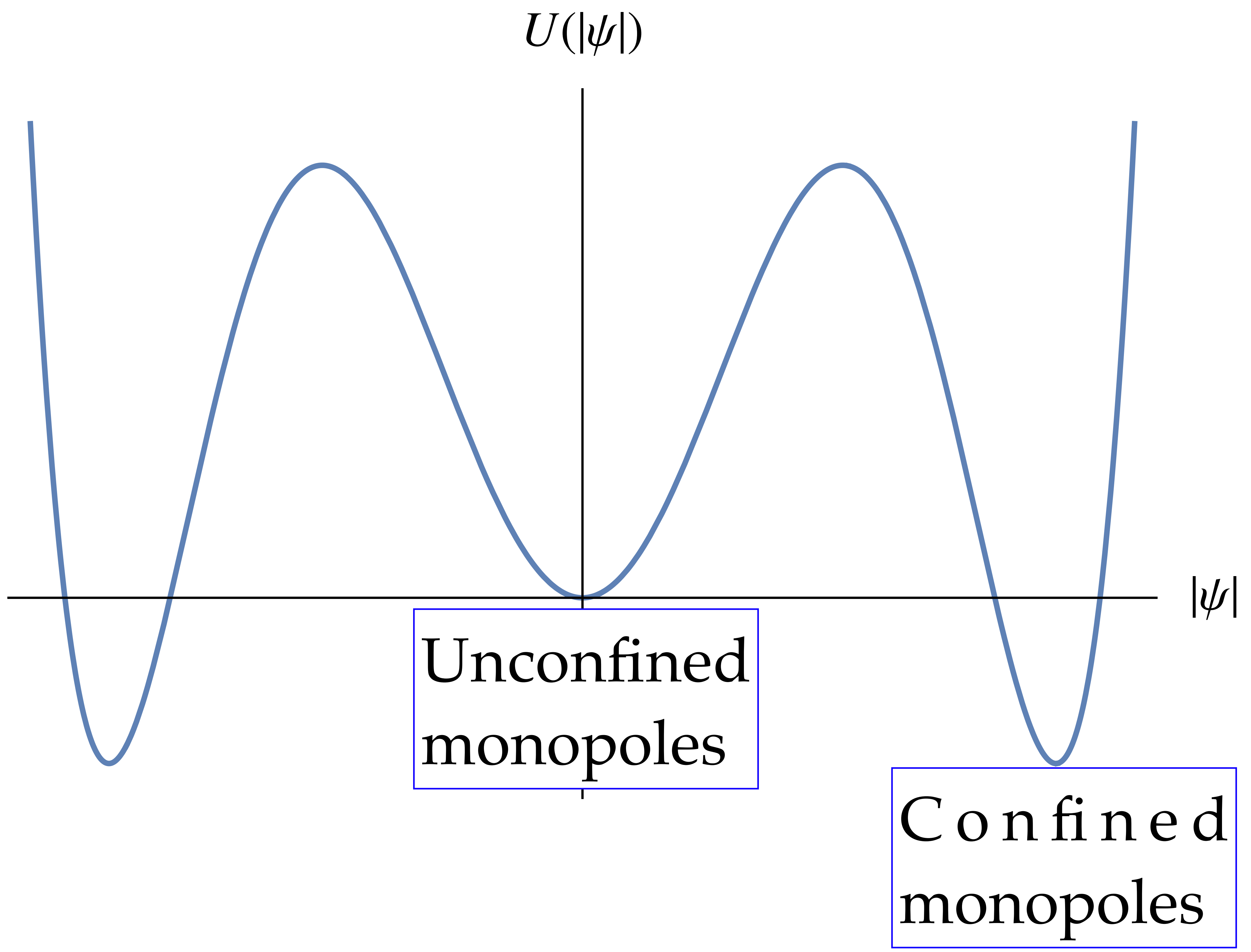

The dynamics is compatible with the one of constantly accelerating relativistic particles with $a = \Lambda^2/m$




*Dvali, Bermudez-Valbuena, MZ,* 2210.14947

# Confined - unconfined layer

Coexistence of confining and unconfining phase is realised if $\psi$ undergoes a first order phase transition

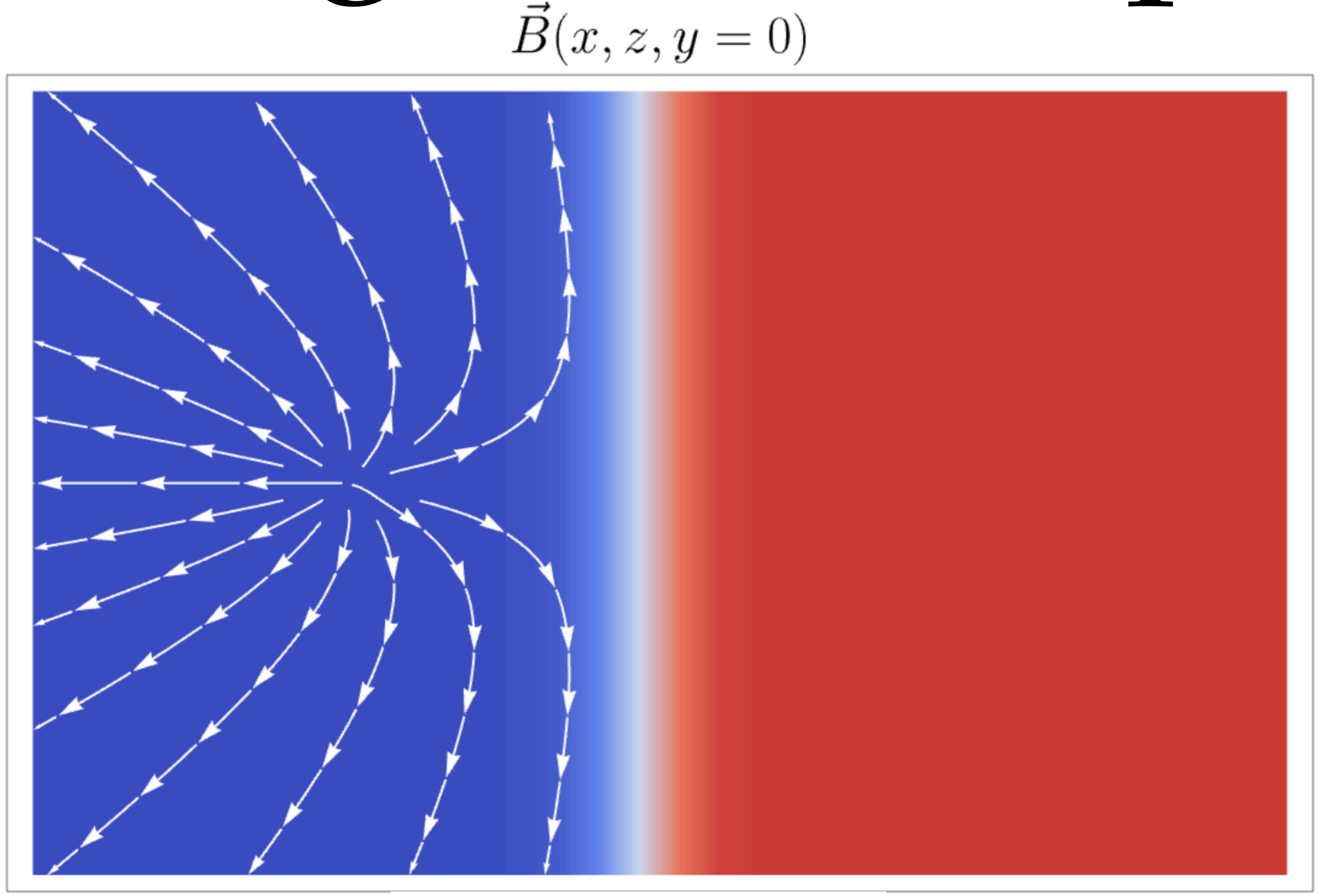



- The potential is typically realised by taking into account thermal corrections in the early Universe
- $\langle \psi \rangle = 0$ corresponds to the unconfined region
- $\langle \psi \rangle = v_\psi$ breaks the U(1) and confines the monopoles
- The system admits (unstable) domain walls (layer) interpolating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

# Slingshot setup

Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195

Unconfined region
(Coulomb region)
"Photon" is massless



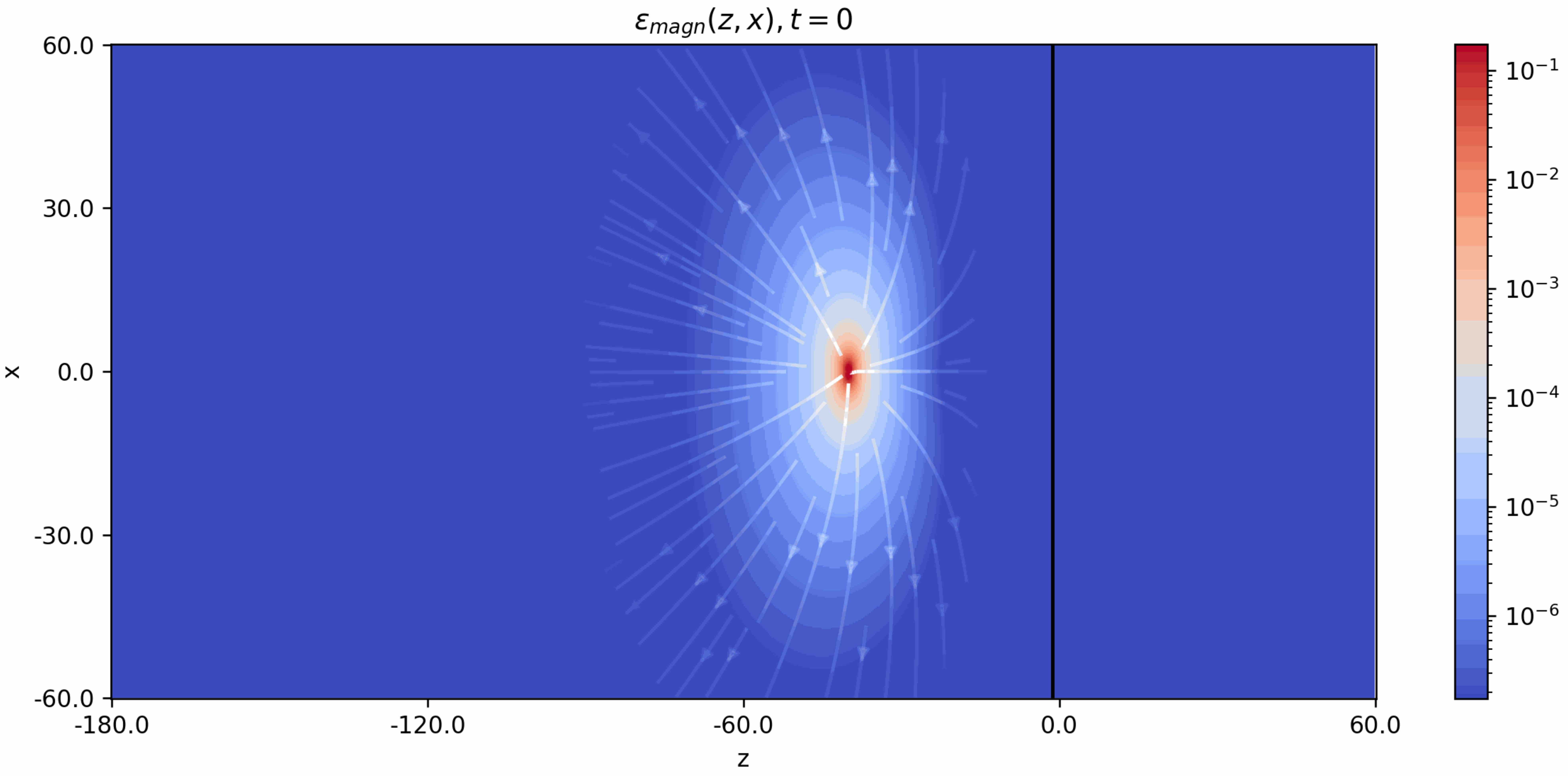

Confined region
(Higgsed region)
"Photon" is massive

Layer separating the regions

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



# Dynamics monopole-antimonopole

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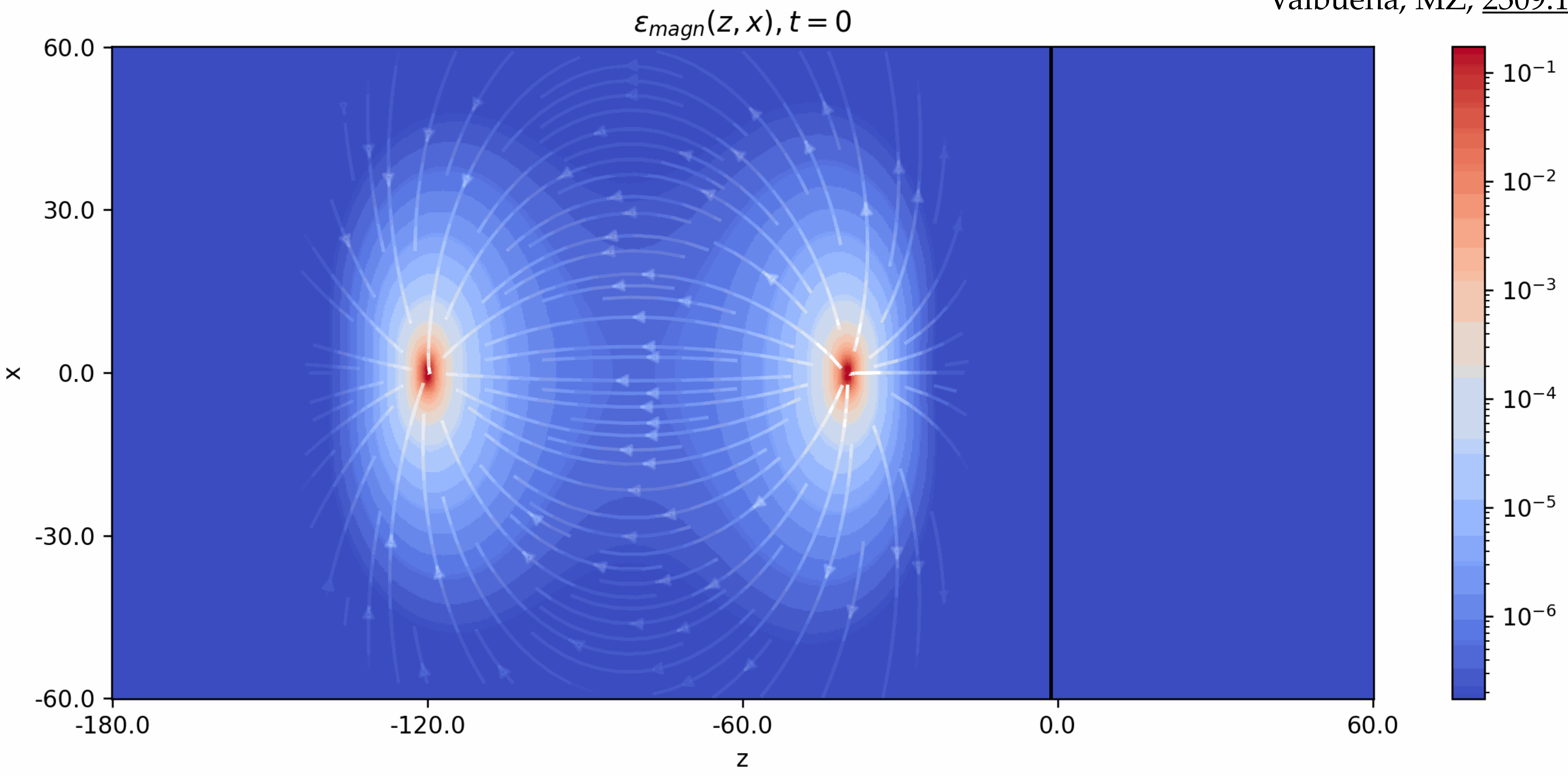

# Gravitational Waves from Slingshot

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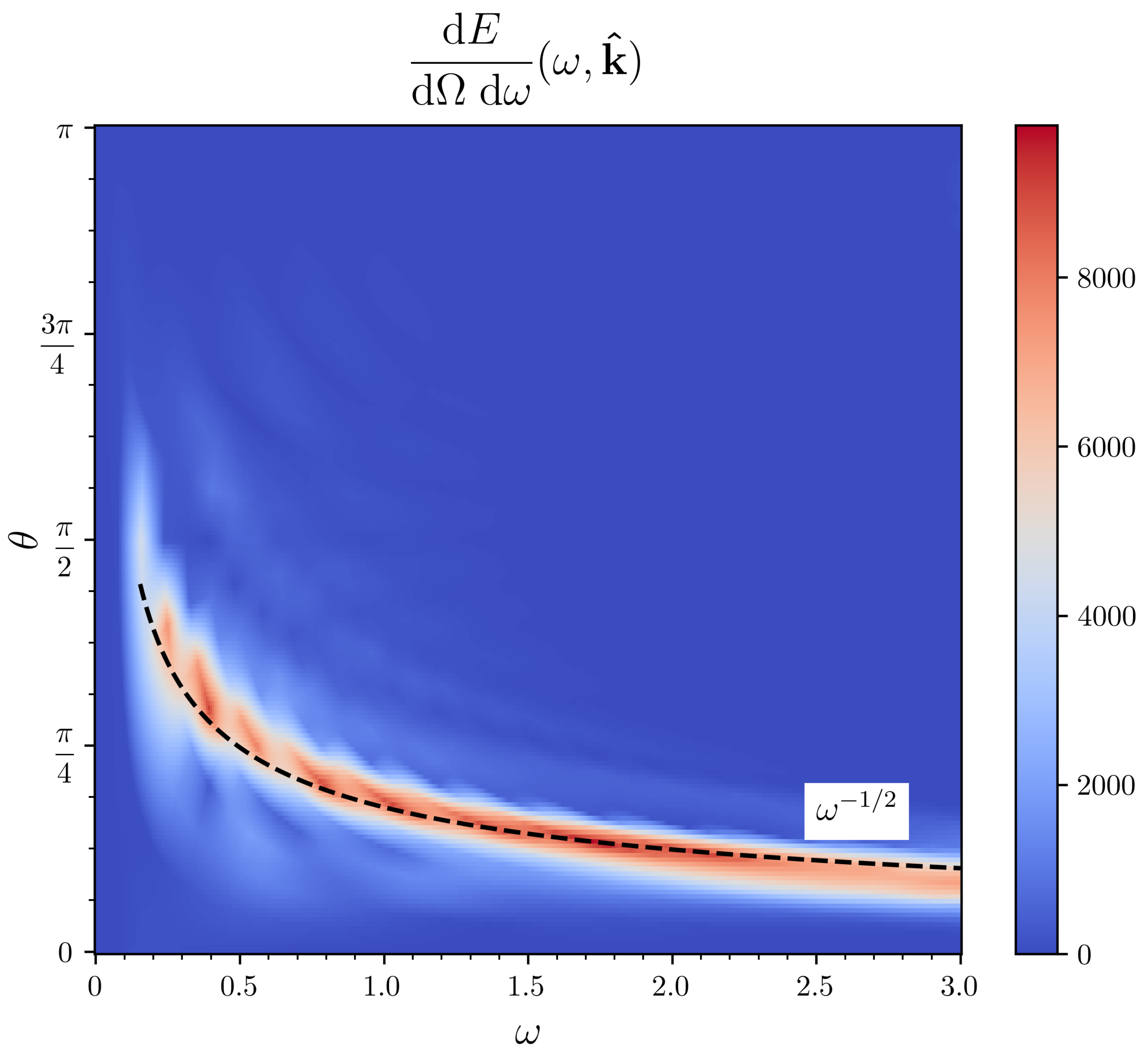


$$\frac{dE_n}{d\Omega\, d\omega} = \frac{G\,\omega_n^2}{\pi}\left(T^*_{\mu\nu}(\omega_n, \mathbf{k})T^{\mu\nu}(\omega_n, \mathbf{k}) - \frac{1}{2}\,|\,T^{\mu}_{\mu}(\omega_n, \mathbf{k})\,|^2\right)$$

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

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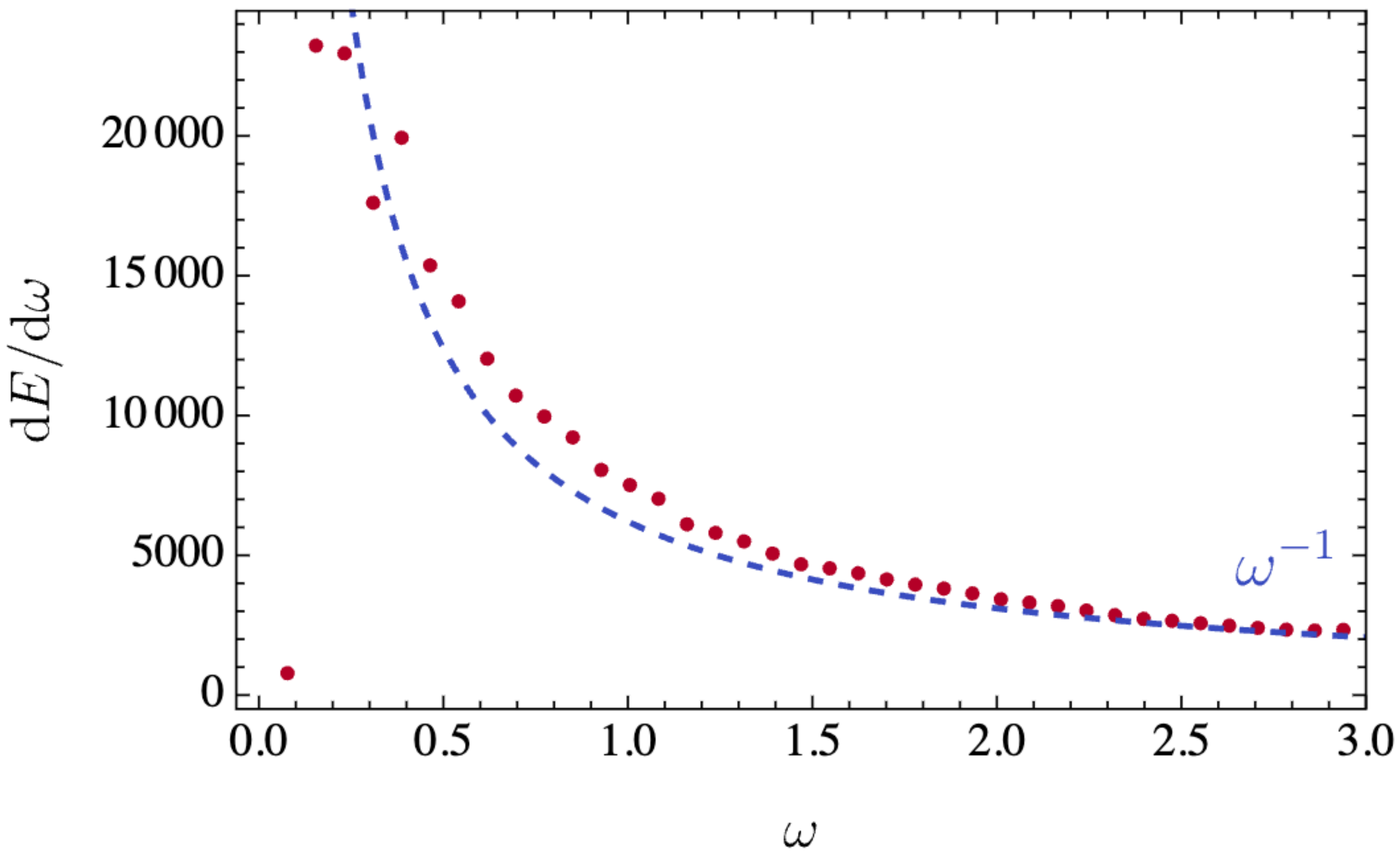



Angularly integrated spectrum scales approximately as

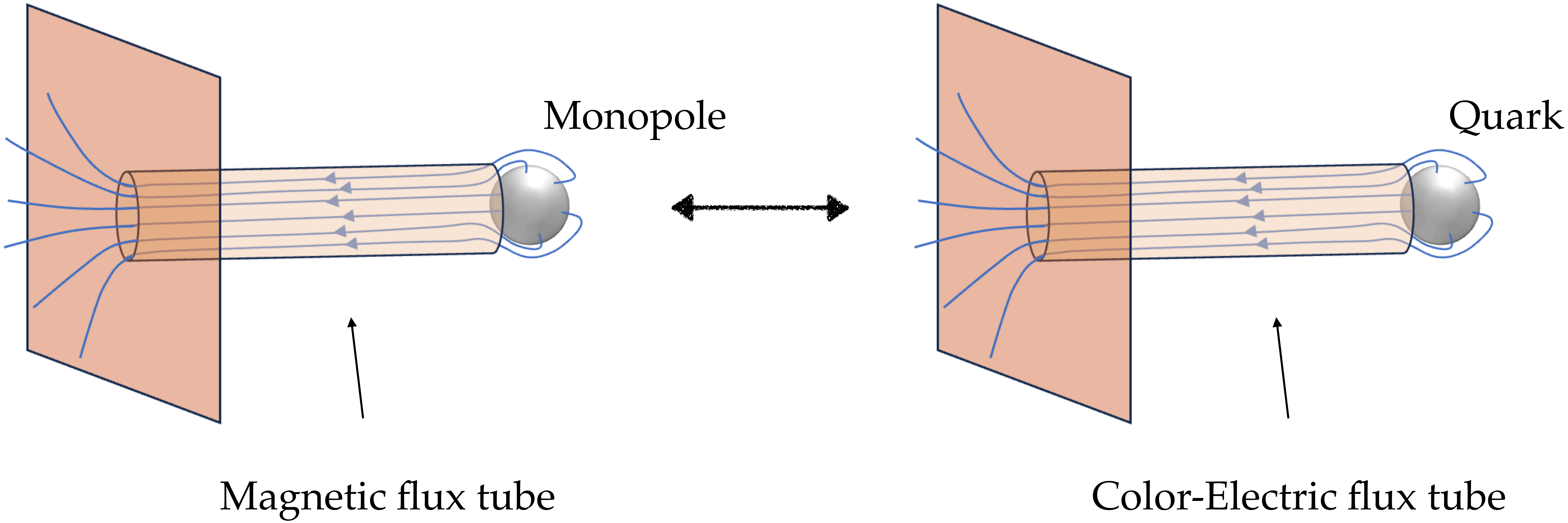
$$\frac{\mathrm{d}E}{\mathrm{d}\omega} \propto \omega^{-1}$$

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

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

# Dual picture

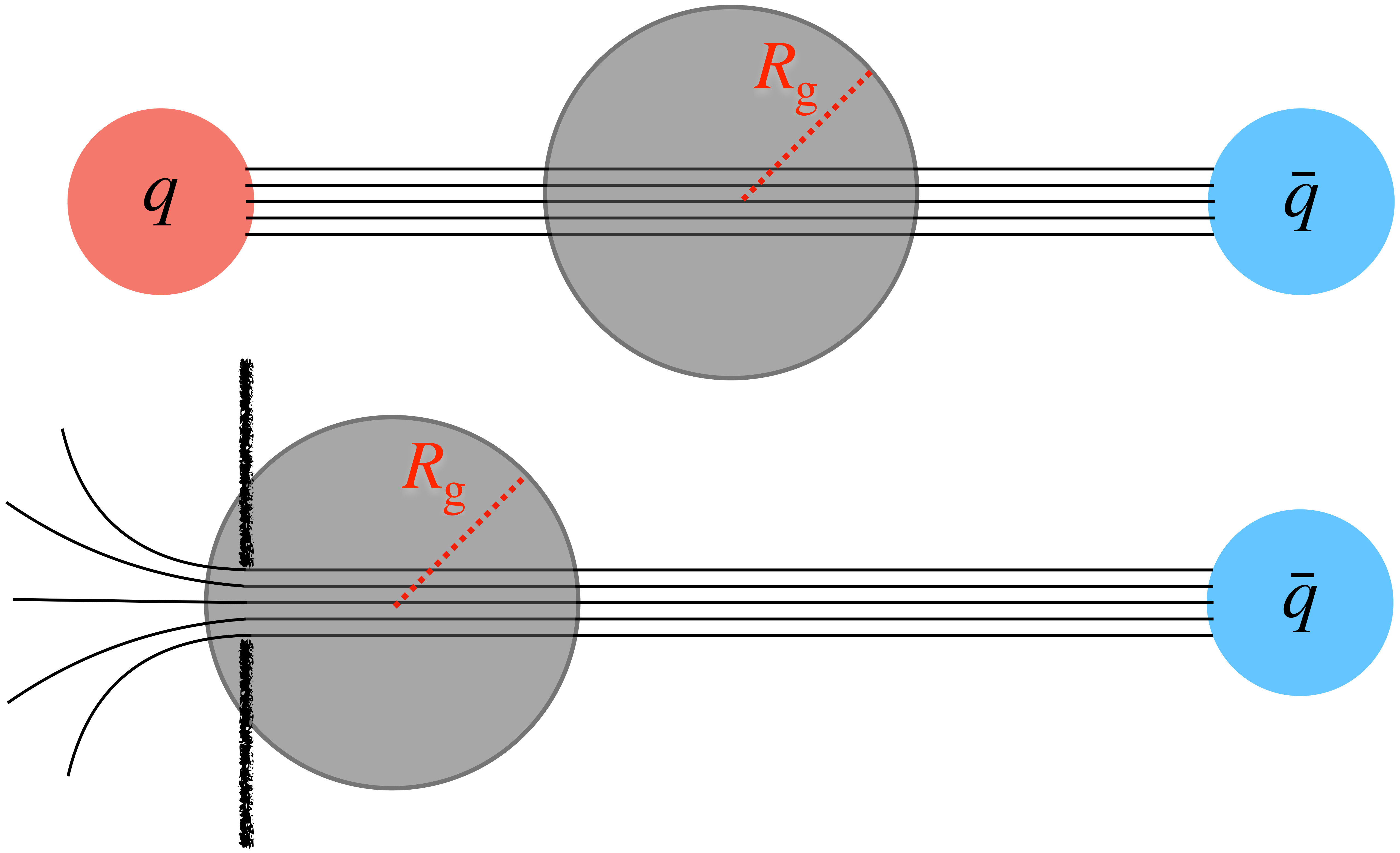
The similar slingshot effect is expected in the “dual” picture when a heavy quark crosses into a confined vacuum of QCD




Field theoretic analogue realisation of a D-brane

# 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

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

- Eventually, system might find itself within its own Schwarzschild radius, leading to black hole formation. This dynamics could lead to production of primordial black holes in the early Universe

Dvali, Kühnel, MZ, 2108.09471

# Overlook

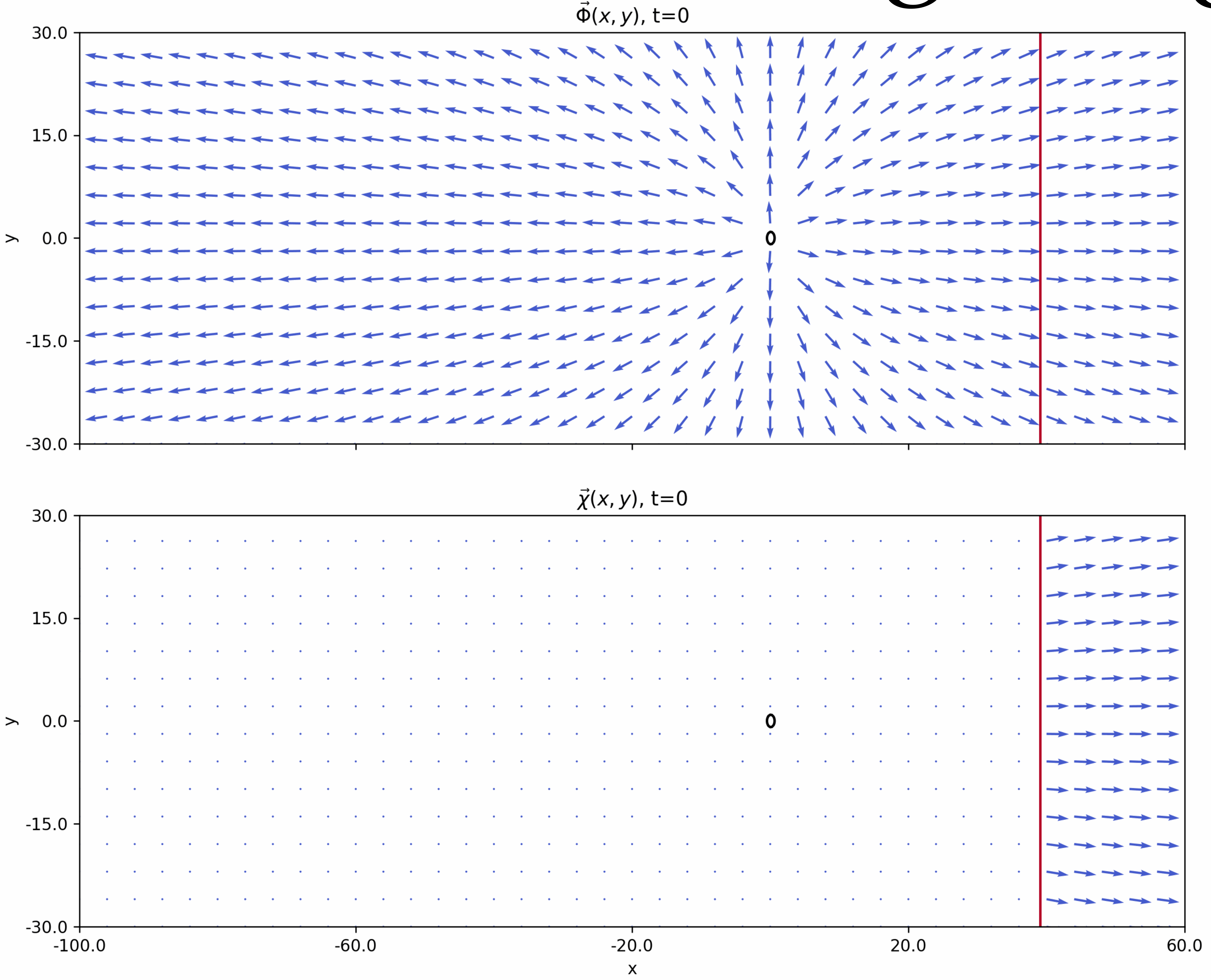
So far we have discussed the case of a monopole slingshot. Can the same effect take place with topological defects of different co-dimension? (YES - Dvali, Bachmaier, Bermudez-Valbuena, MZ, 2309.14195)

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).

Cosmological embedding

# Backup

# String Slingshot




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

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

Unconfined region ($Z_2$ unbroken)

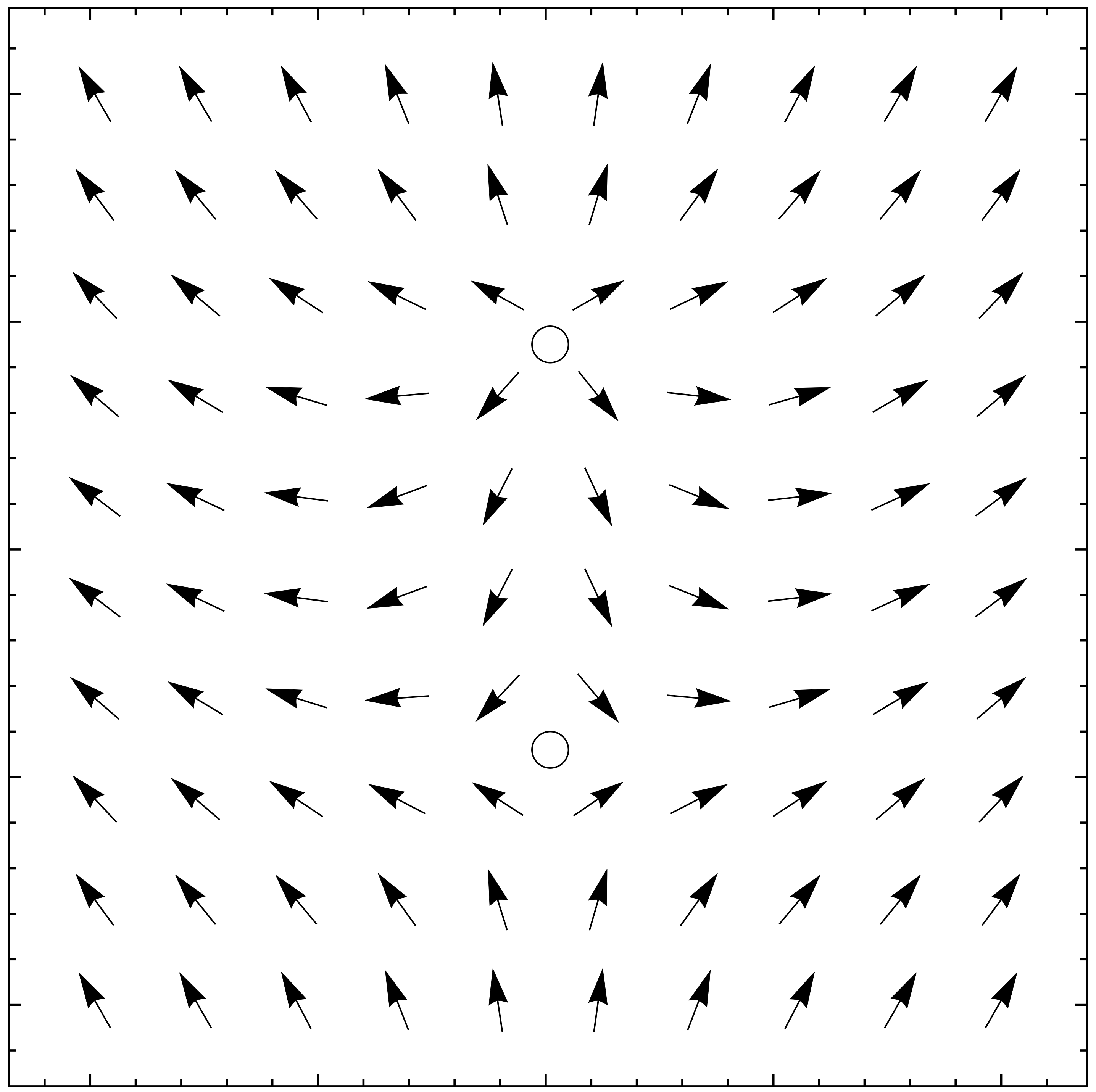
Confined region ($Z_2$ broken)

String

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

# Initial Conditions

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



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

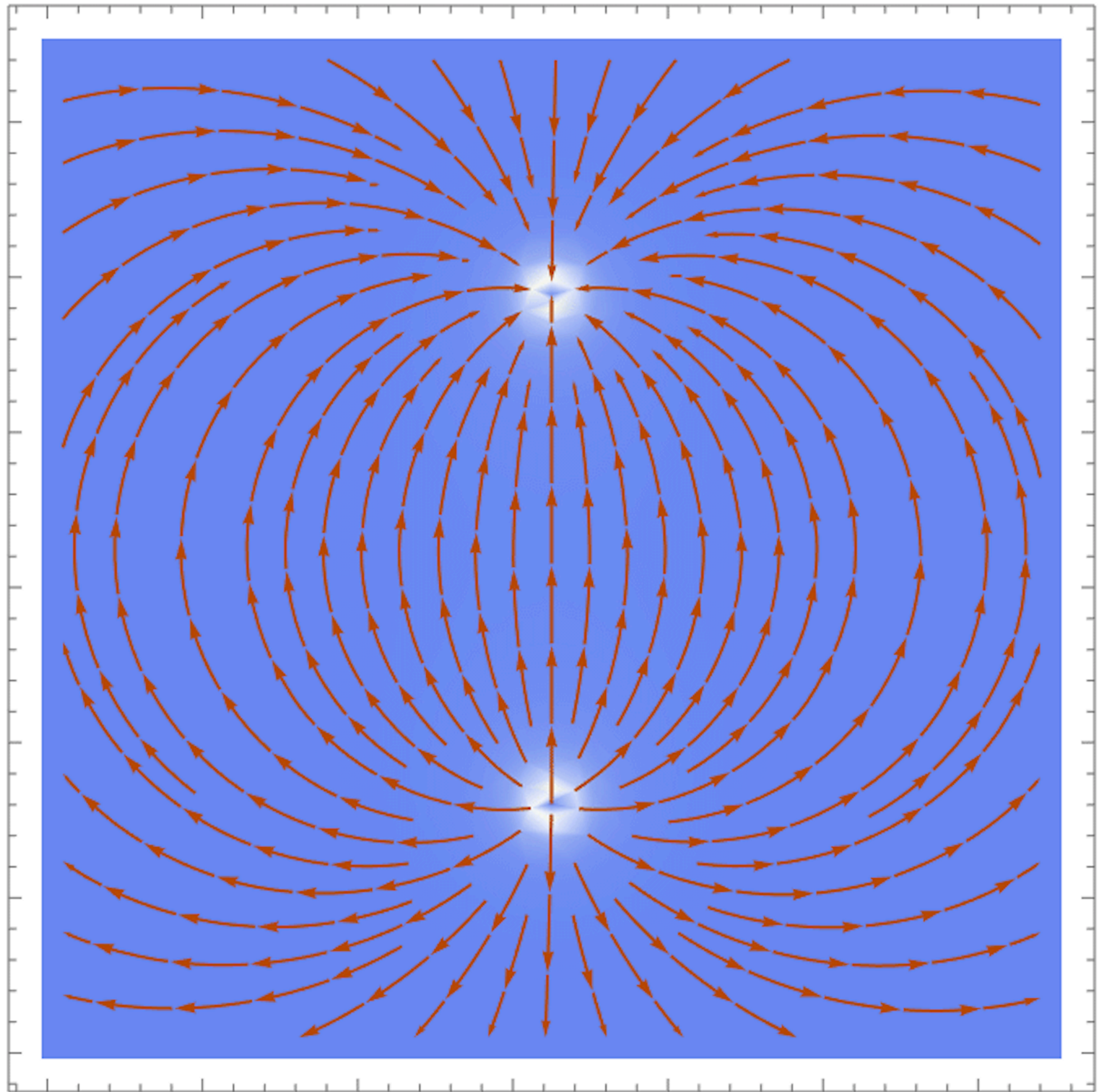
$$\downarrow$$

Vachaspati '15

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

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

Magnetic field lines

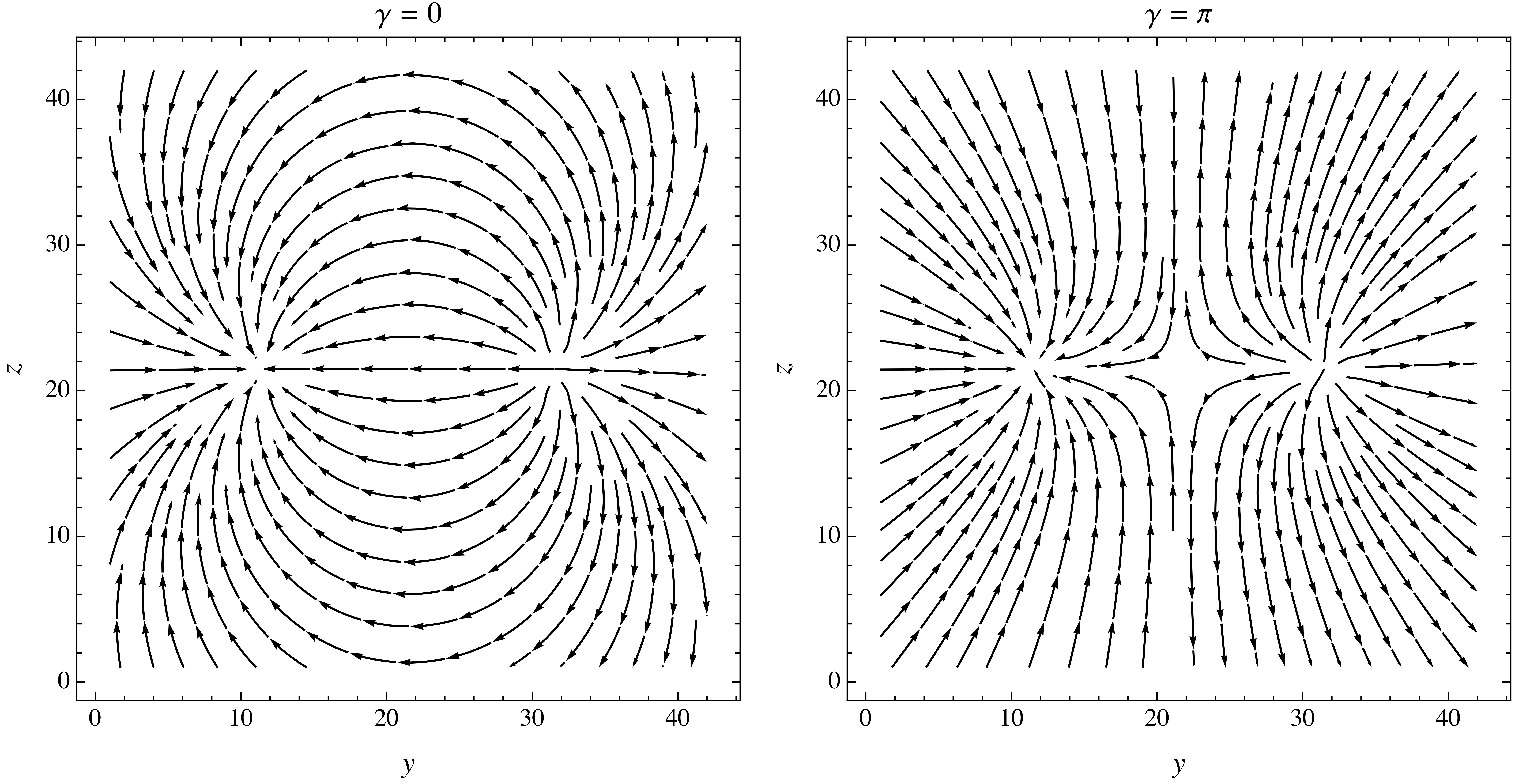


$$\psi = v\,l(r_{xy}, z)\begin{pmatrix} \sin(\theta/2)\sin(\bar{\theta}/2)e^{i\gamma} + \cos(\theta/2)\cos(\bar{\theta}/2) \\ \sin(\theta/2)\cos(\bar{\theta}/2)e^{i\phi} + \cos(\theta/2)\sin(\bar{\theta}/2)e^{i(\phi-\gamma)} \end{pmatrix}$$

Vachaspati, Field '94

$\gamma$ = twist angle

# Adding a twist to the story



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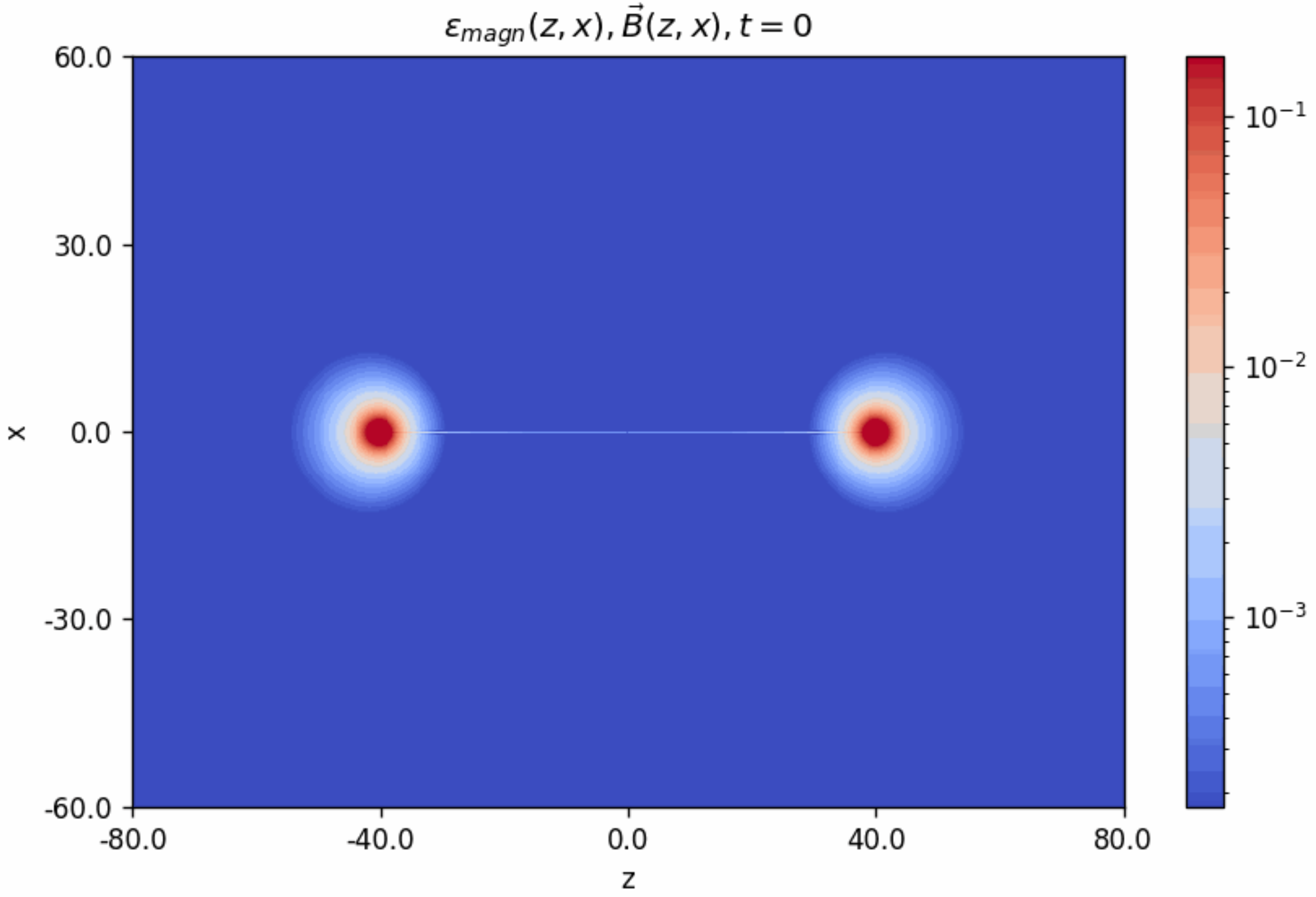
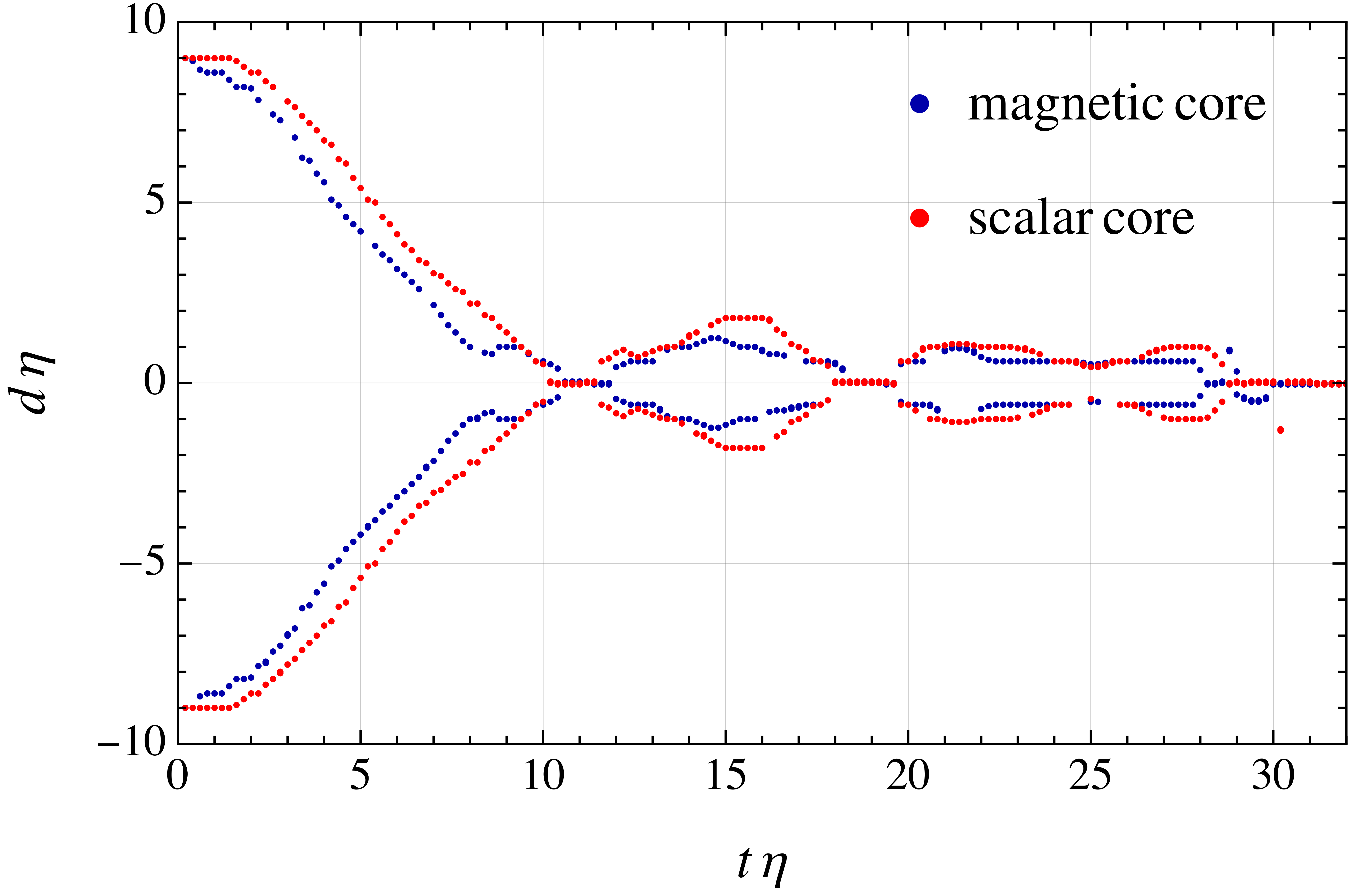


# Adding a twist to the story




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