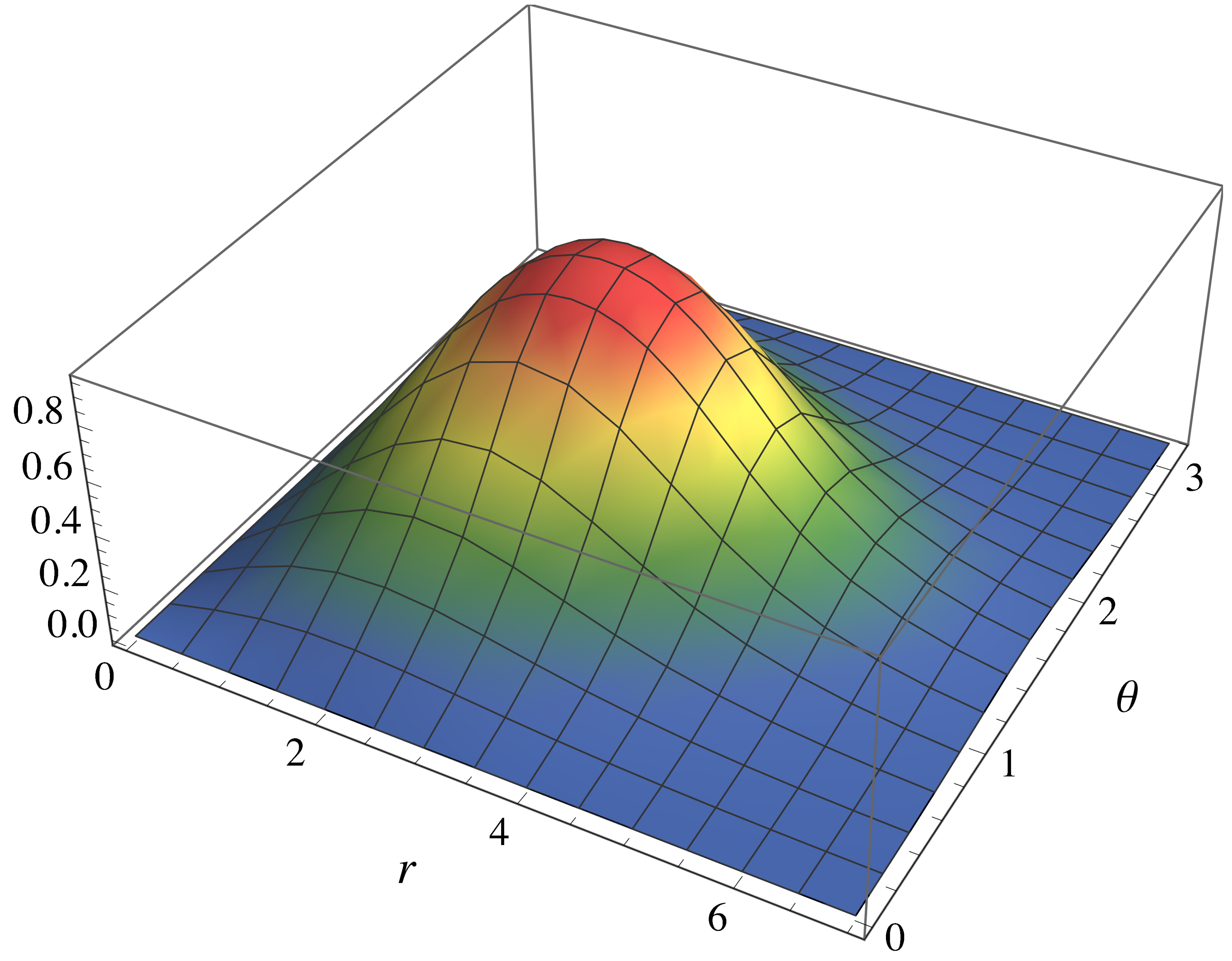
Vortexes and Black Holes

Michael Zantedeschi - LMU and MPP
PASCOS 2022

G. Dvali, F. Kühnel and MZ
arXiv:2112.08354



Saturons

Unitarity puts a bound on entropy $S \leq \frac{\text{Area}}{G_{\text{Gold}}} = \text{Area}\, f^2$ $G_{\text{Gold}} = \text{Goldstone coupling} = f^{-2}$

Dvali arXiv:2003.05546
arXiv:1907.07332
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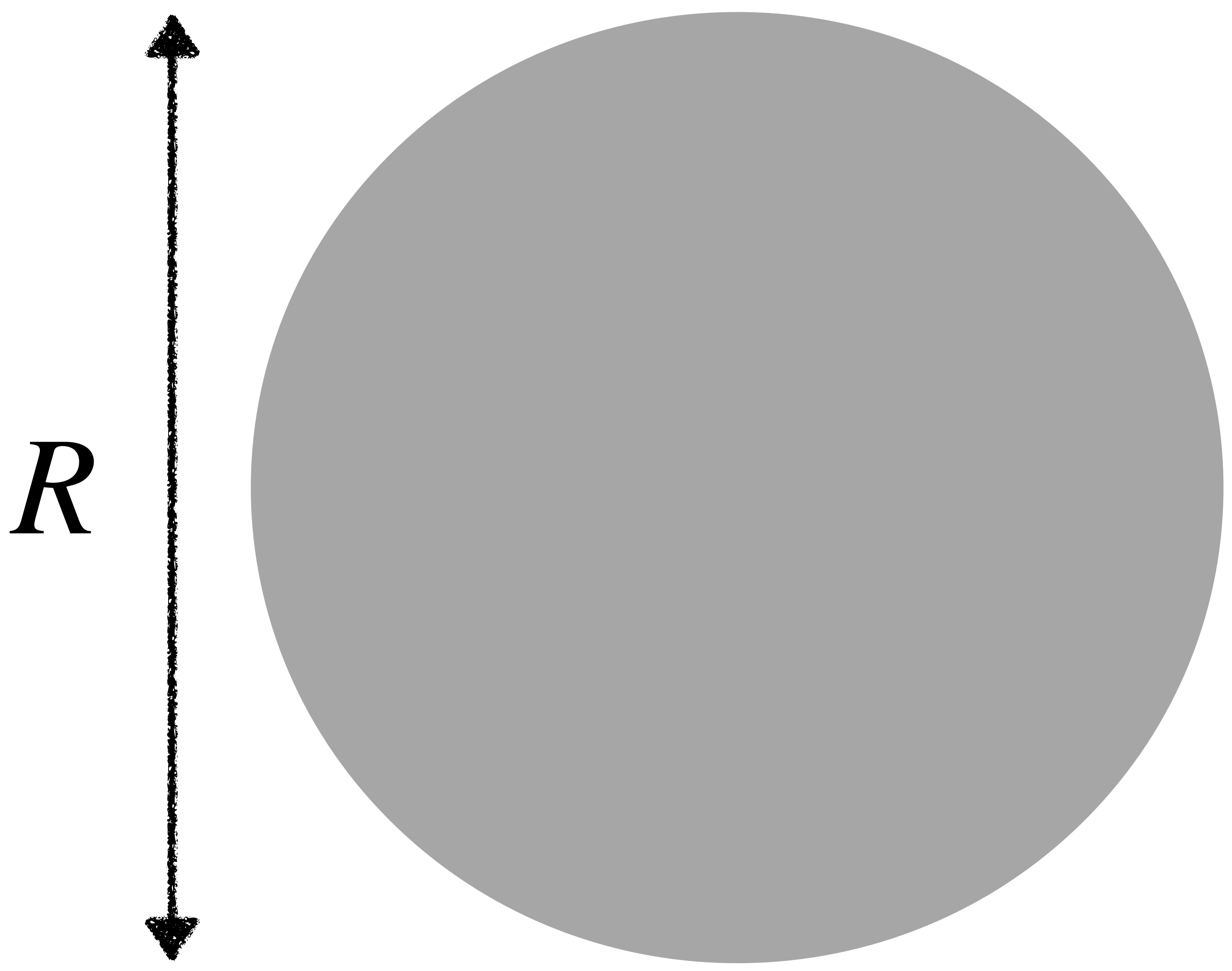

Objects saturating the above bound are called saturons

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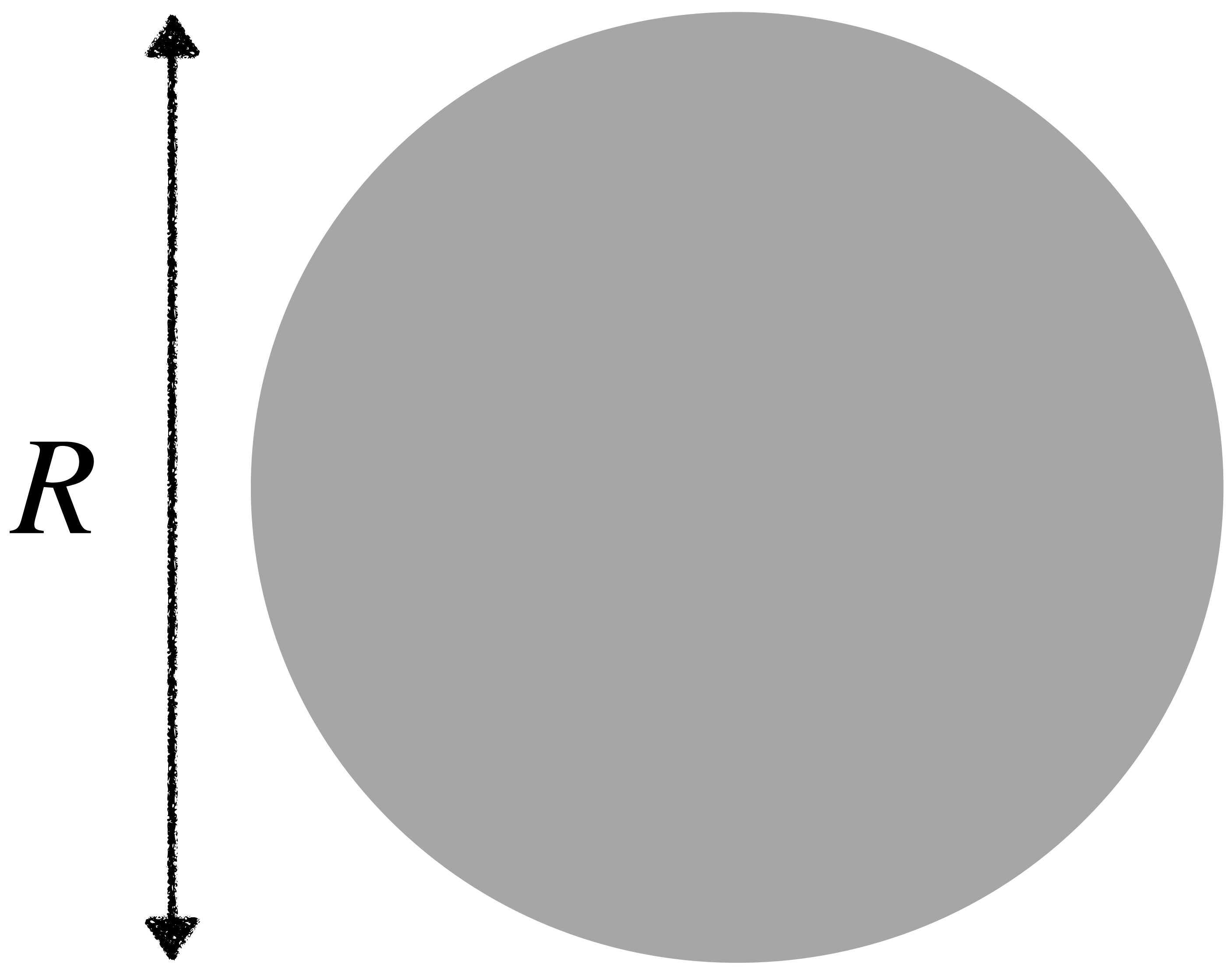

Objects saturating the above bound are called saturons

Black hole = Saturon $\quad G_{\text{Gold}} = G_N$

Saturon configurations can be found also not in gravity, e.g.,

- Bose-Einstein condensates
- Renormalizable QFTs (Valbeuena - previous talk)
- Gross-Neveu model (Shakelashvili)
- Color Glass condensate
- …

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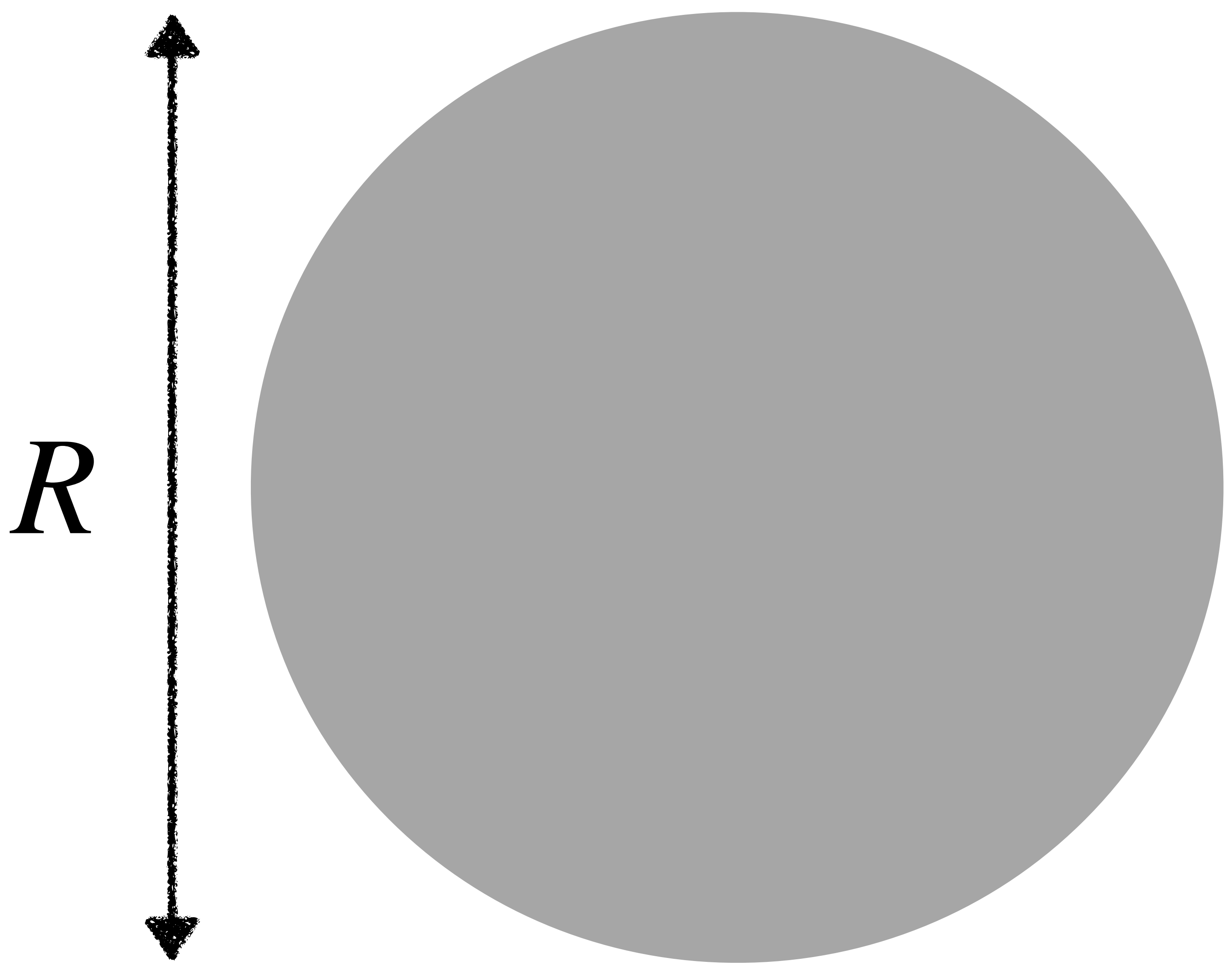

Objects saturating the above bound are called saturons

As a consequence of saturation, the following properties emerge

1. Hawking thermal emission $T \sim 1/R$
2. Notion of information horizon
3. Long time information retrieval (Page time) $t \sim S_{\text{BH}} R \sim R^3/G_{\text{Gold}}$
4. Maximal spin and halt of Hawking emission $J \lesssim S_{\text{BH}}$

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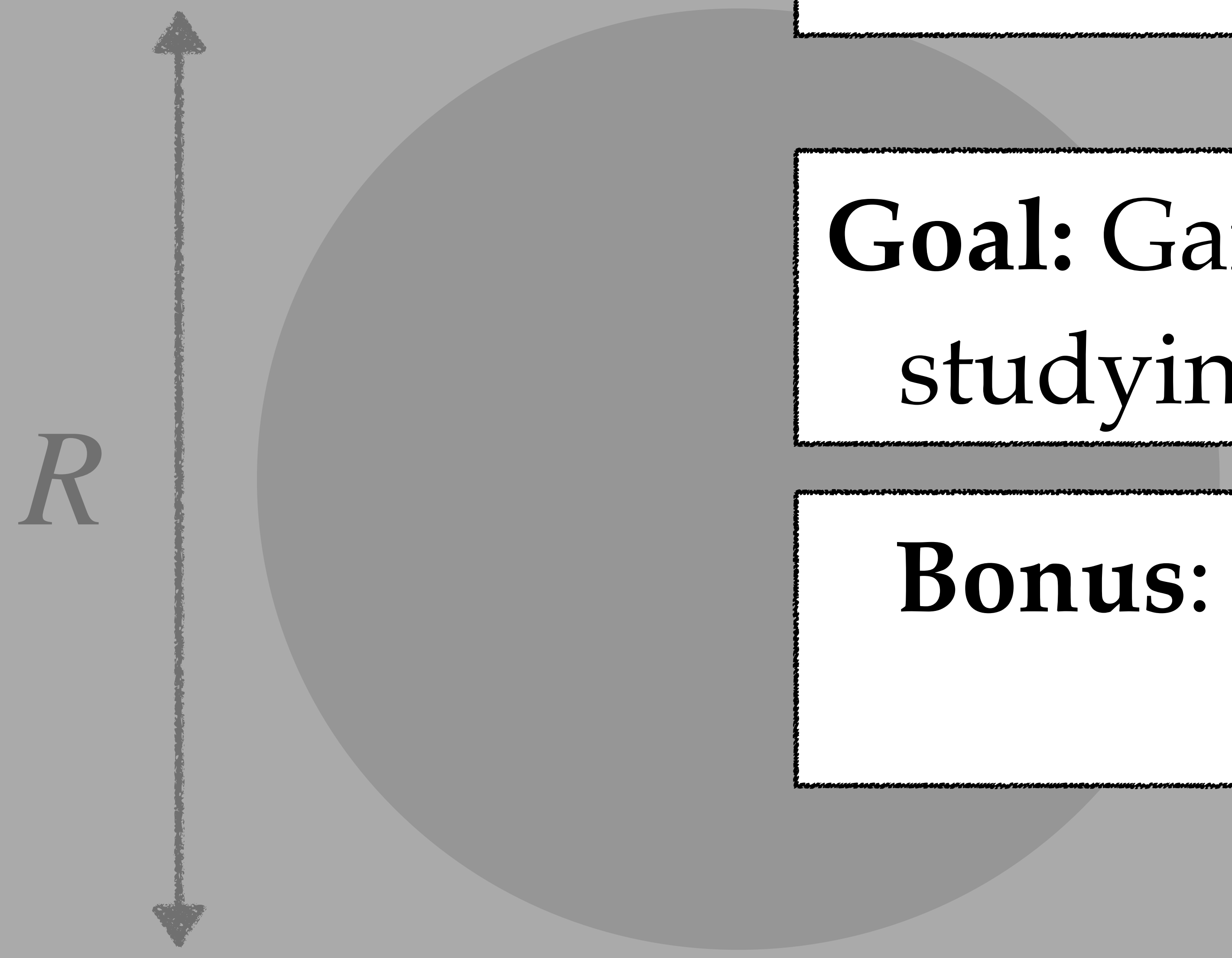
Black hole properties are not unique to gravity

Goal: Gain a better understanding of black holes studying their non gravitational counterparts

Bonus: Maybe new black hole features can be obtained?



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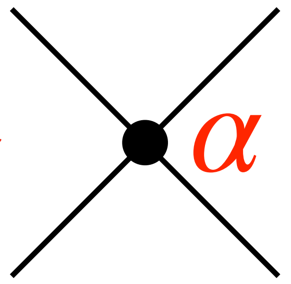
An example of Saturon

Consider theory with large N symmetry (renormalizable!) - e.g., $SU(N)$ scalar adjoint

Coupling

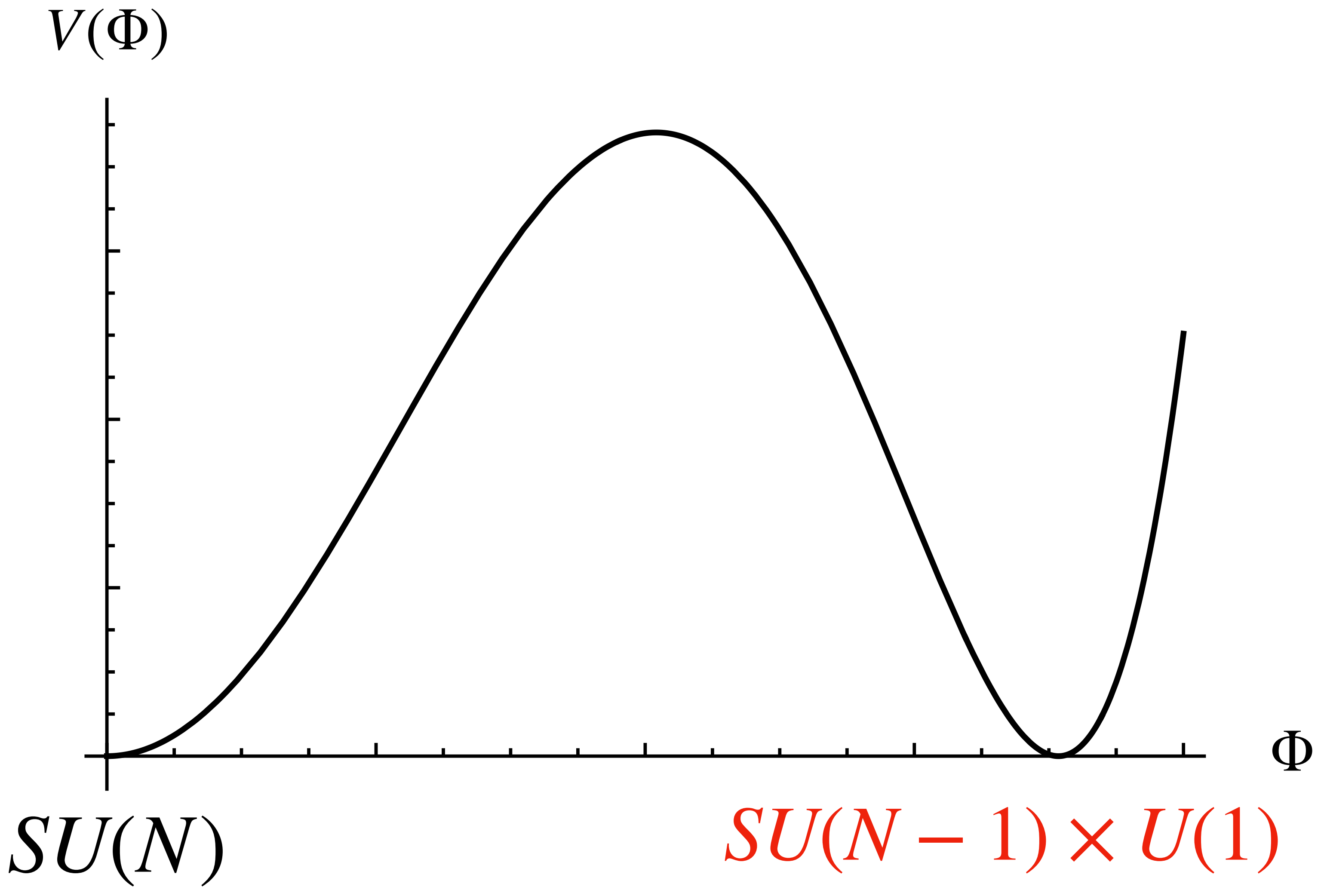


Dimensionful scale f

Build a localised configuration — bubble

An example of Saturon

Mass gap
$m = \sqrt{\alpha} f$



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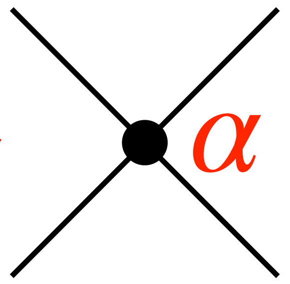
Coupling 

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Entropy = microstate degeneracy of Goldstone mode occupation

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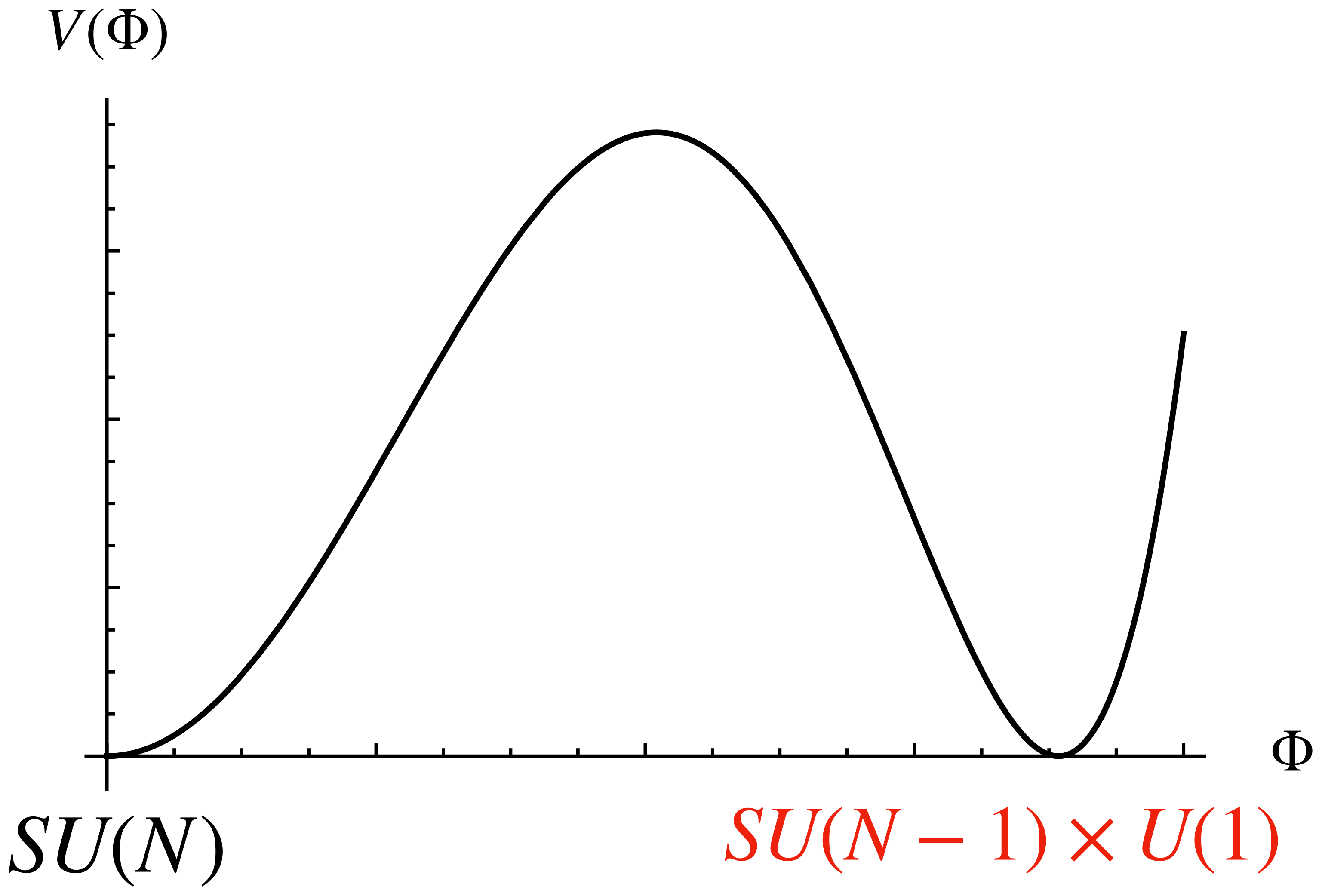

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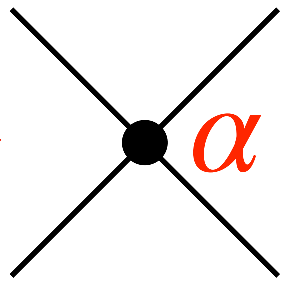
Coupling 

Dimensionful scale f

Build a localised configuration — bubble

Entropy = microstate degeneracy of Goldstone mode occupation

Saturation of unitarity — $\alpha N \sim 1$

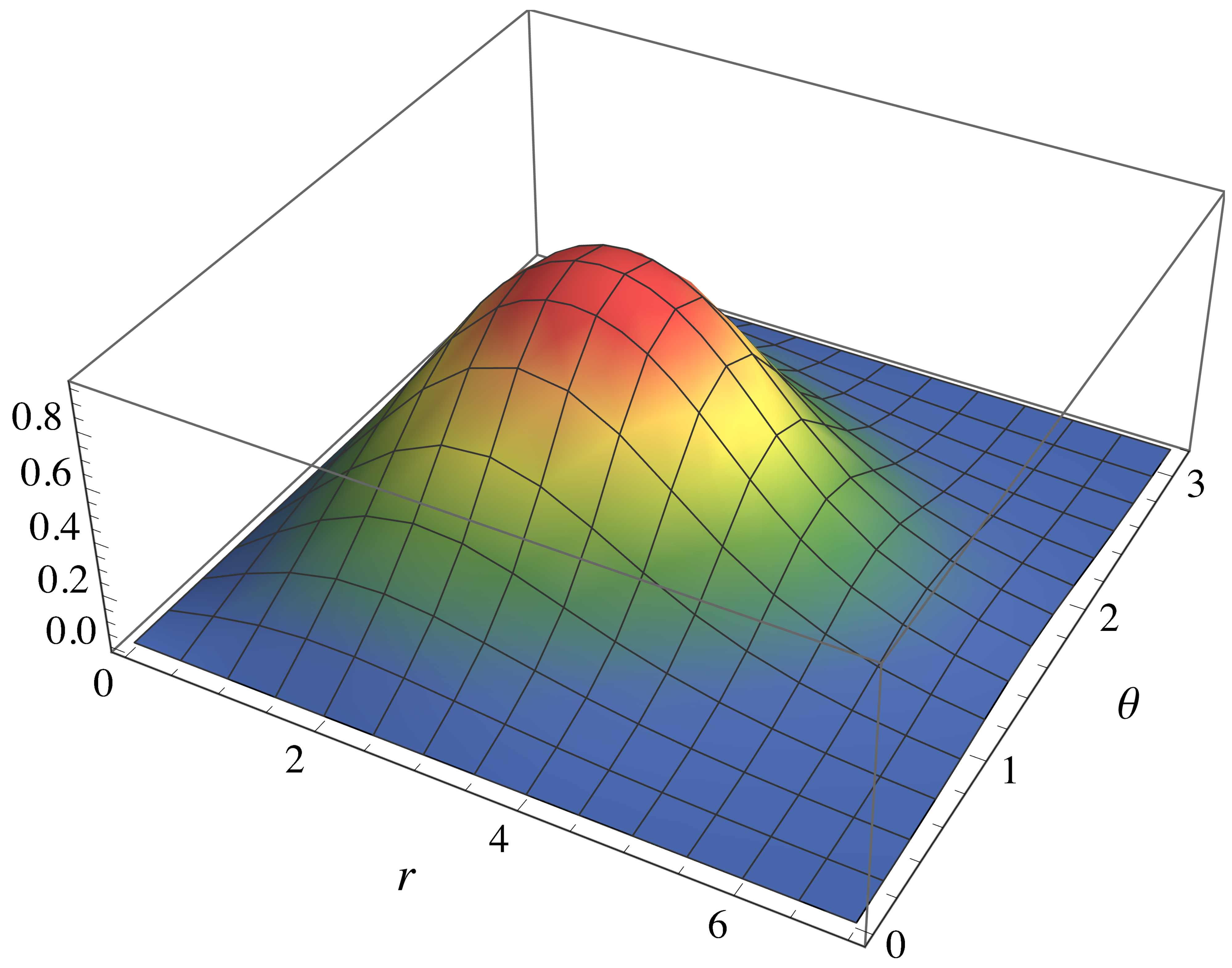
↓

$$S \simeq \text{Area} f^2 \simeq N \simeq \frac{1}{\alpha}, \qquad M \simeq \frac{1}{R} N \simeq R f^2$$

Valbuena, previous talk

Analogy with black holes ⟶ $G_{\text{Gold}} = G_{\text{N}} \quad \left(f = M_{\text{pl}}\right)$

Spin



An example of Saturon

There is a way to spin a saturon bubble in an axial-symmetric way:

Vorticity

$$\Phi = e^{i\kappa\varphi\hat{T}}\,\Phi_{Bubble}\,e^{i\kappa\varphi\hat{T}}$$

winding number $= \kappa = 0, \pm 1, \pm 2, \ldots$

$\varphi =$ polar angle, $\hat{T} =$ broken generator inside bubble

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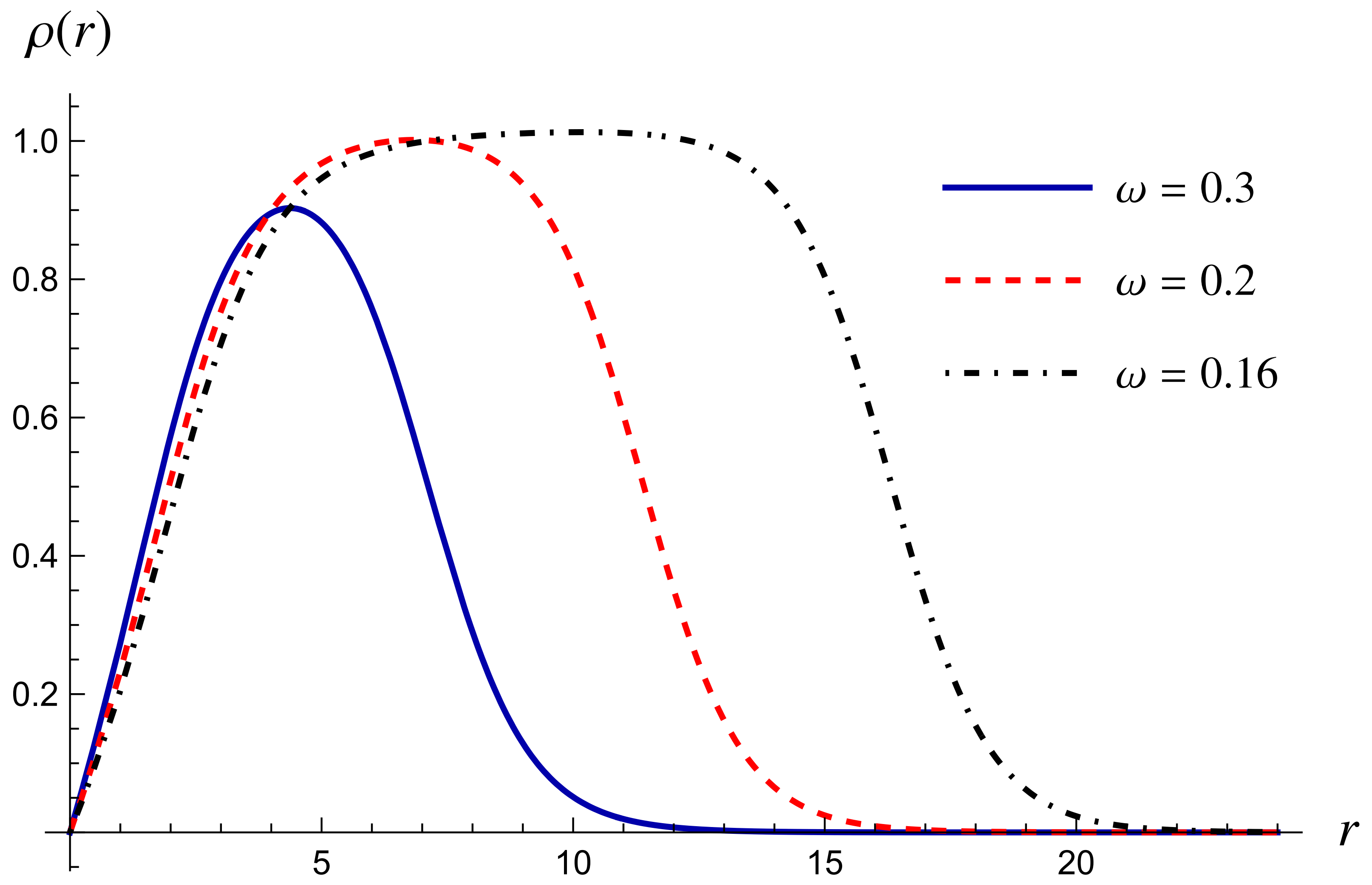
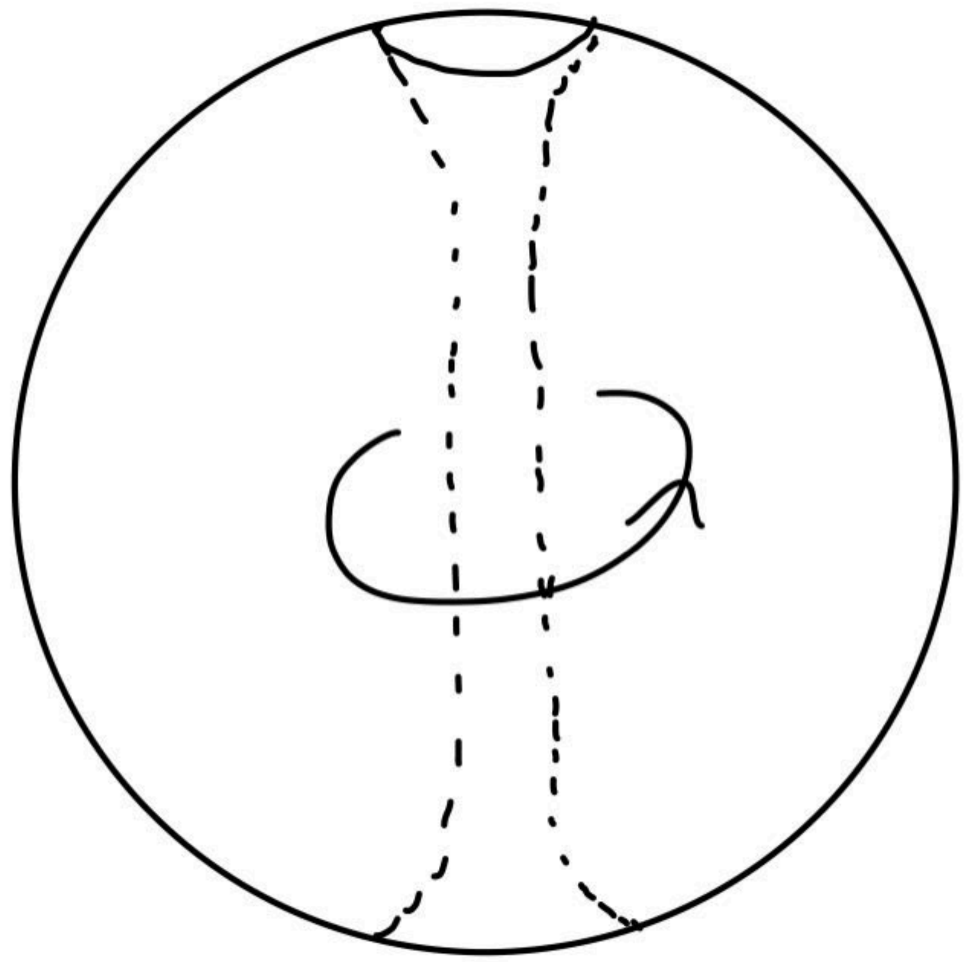
Angular momentum $J = \int_V T_{0\varphi} \simeq \kappa\, S$





Similar study for Q-ball see Volkov, Wohnert '02

An example of Saturon

Angular momentum $J \simeq \kappa S$

Requiring vortex energy smaller than bubble energy

$$E_{\text{spin}} \lesssim M_{\text{bubble}} \to \kappa \sim \mathcal{O}(1)$$

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Saturon bubble

$$J_{saturon} \underset{\kappa \sim \mathcal{O}(1)}{\lesssim} M^2 G_{\text{Gold}}$$

Black hole

$$J_{black\,hole} \lesssim M^2 G_{\text{N}}$$

- Saturon and black hole obey the same bound on spin
- For maximally spin, topology prevents Hawking-like emission

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- Can novel properties be extrapolated to the substructure of black holes?
- Example: beyond semiclassicality in the N-portrait

Dvali, Gomez '11

An example of Saturon

Angular momentum $J \simeq \kappa \, n_{\rm Gold} \sim \kappa \, S$ @ saturation

Requiring vortex energy smaller than bubble energy

Conjecture: *highly rotating black holes correspond to graviton condensates endowed with vorticity.*

Saturon bubble	Black hole
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Saturon bubble | Black hole

Caveat: black hole might just be special

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Are there observable consequences?

- Satu
- For maximally spin, topology prevents Hawking-like emission

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Dvali, Gomez '11

Magnetic trapping

Global vortex, when interacting with charged matter under arbitrary $U(1)_{\text{gauge}}$, traps the associated magnetic field

Dvali, Senjanovic '93

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Global vortex, when interacting with charged matter under arbitrary $U(1)_{\text{gauge}}$, traps the associated magnetic field

Dvali, Senjanovic '93

Consider two oppositely $U(1)_{\text{gauge}}$ charged field

$$\chi_+ = \rho_+ e^{i\theta_+}, \quad \chi_- = \rho_- e^{i\theta_-}$$

Effectively coupled to the vortex order parameter $\psi = \rho e^{i\theta}$ as

$$\psi\chi_+\chi_- + \text{h.c.} = 2\,\rho\,\rho_+\,\rho_- \cos\left(\theta + \theta_+ + \theta_-\right)$$

Asymptotically for the gauge field

$$A_\mu = \frac{1}{eq}\frac{\langle\rho_+\rangle^2\partial_\mu\theta_+ - \langle\rho_-\rangle^2\partial_\mu\theta_-}{\langle\rho_-\rangle^2 + \langle\rho_+\rangle^2}$$

Magnetic trapping

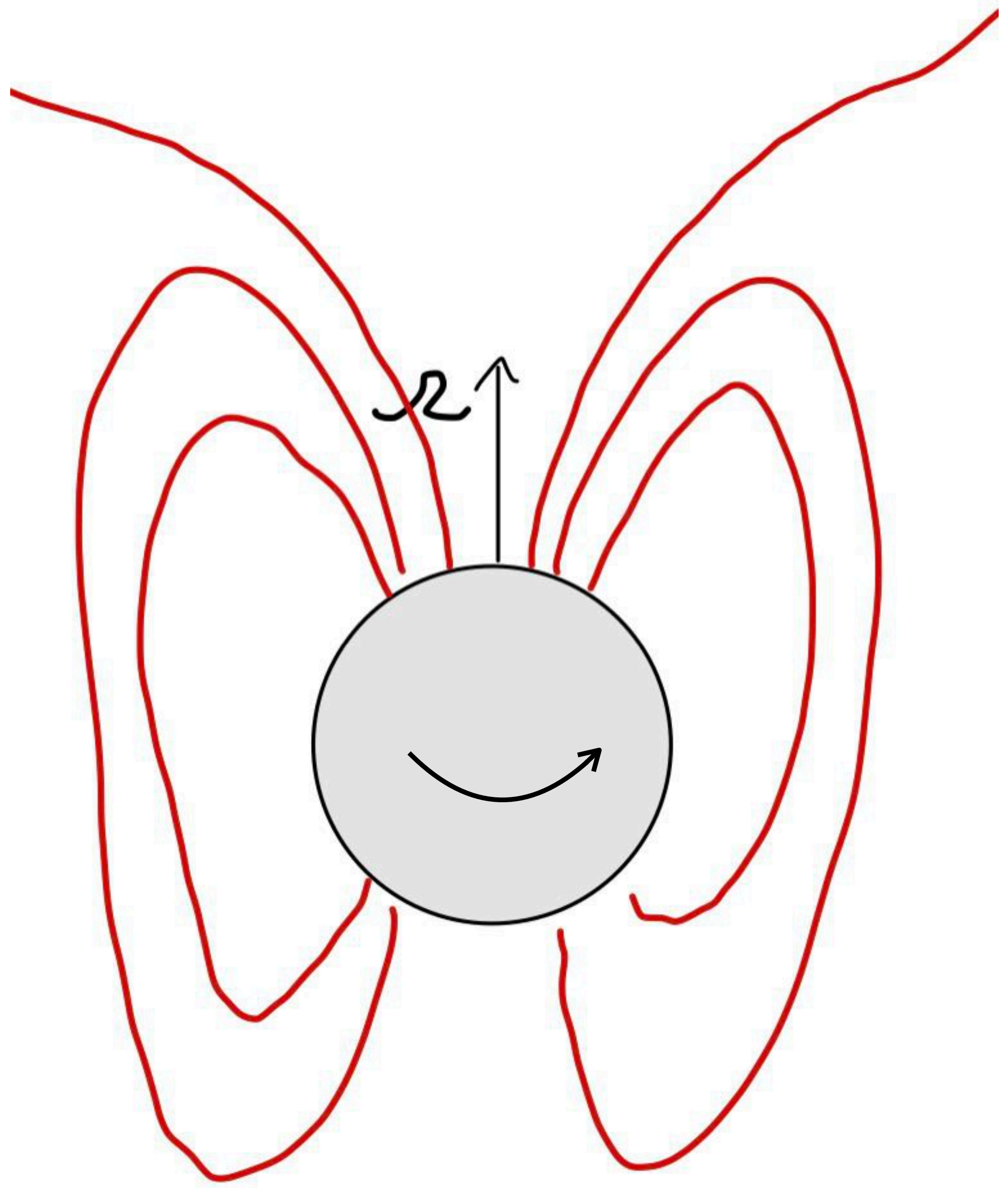
$$\text{Flux} = \int \mathrm{d}x^\mu A_\mu = \frac{2\pi}{eq}\left[\kappa_+ + \kappa \frac{\langle\rho_-\rangle^2}{\langle\rho_-\rangle^2 + \langle\rho_+\rangle^2}\right]$$

$$\kappa_\pm = \frac{1}{2\pi}\int \mathrm{d}x^\mu \partial_\mu \theta_\pm \qquad \kappa_+ + \kappa_- = -\kappa$$

E.g., charged components of neutral plasma or charged dark matter

Fractional flux has further stabilising properties

If $U(1)_{\text{gauge}} = U(1)_{\text{em}}$ natural support for magnetic field
Black hole pierced by magnetic field lines



Intermezzo: Blandford Znajek emission

Highly rotating BHs endowed with a magnetosphere produce extremely powerful jets (BZ)

$$P_{\rm BZ} \sim {\rm Flux}^2 \Omega^2$$

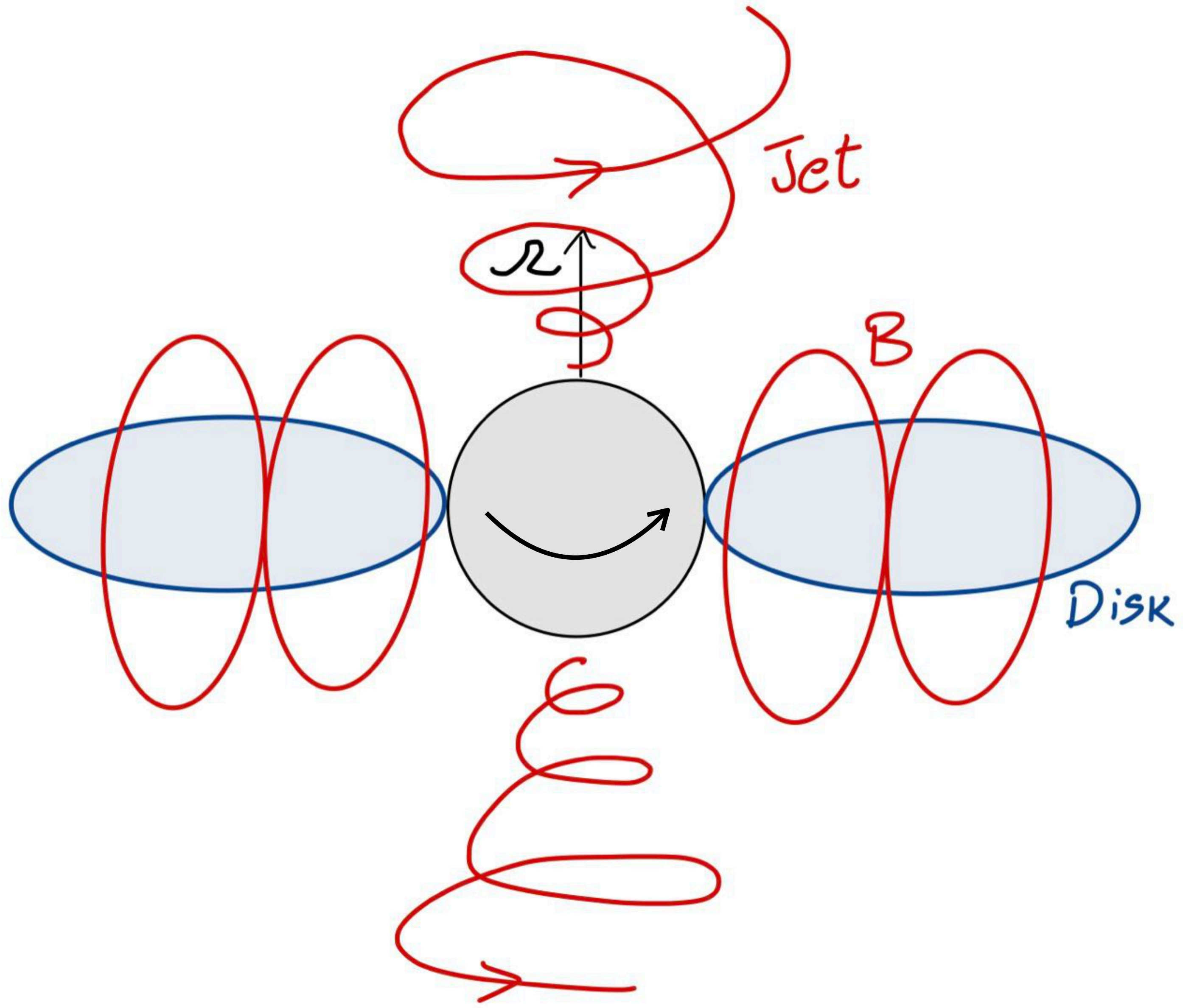
Classically, a BH cannot have magnetic hairs.

The mechanism providing magnetic field remains to present day a mystery (although BZ-like emissions are observed)

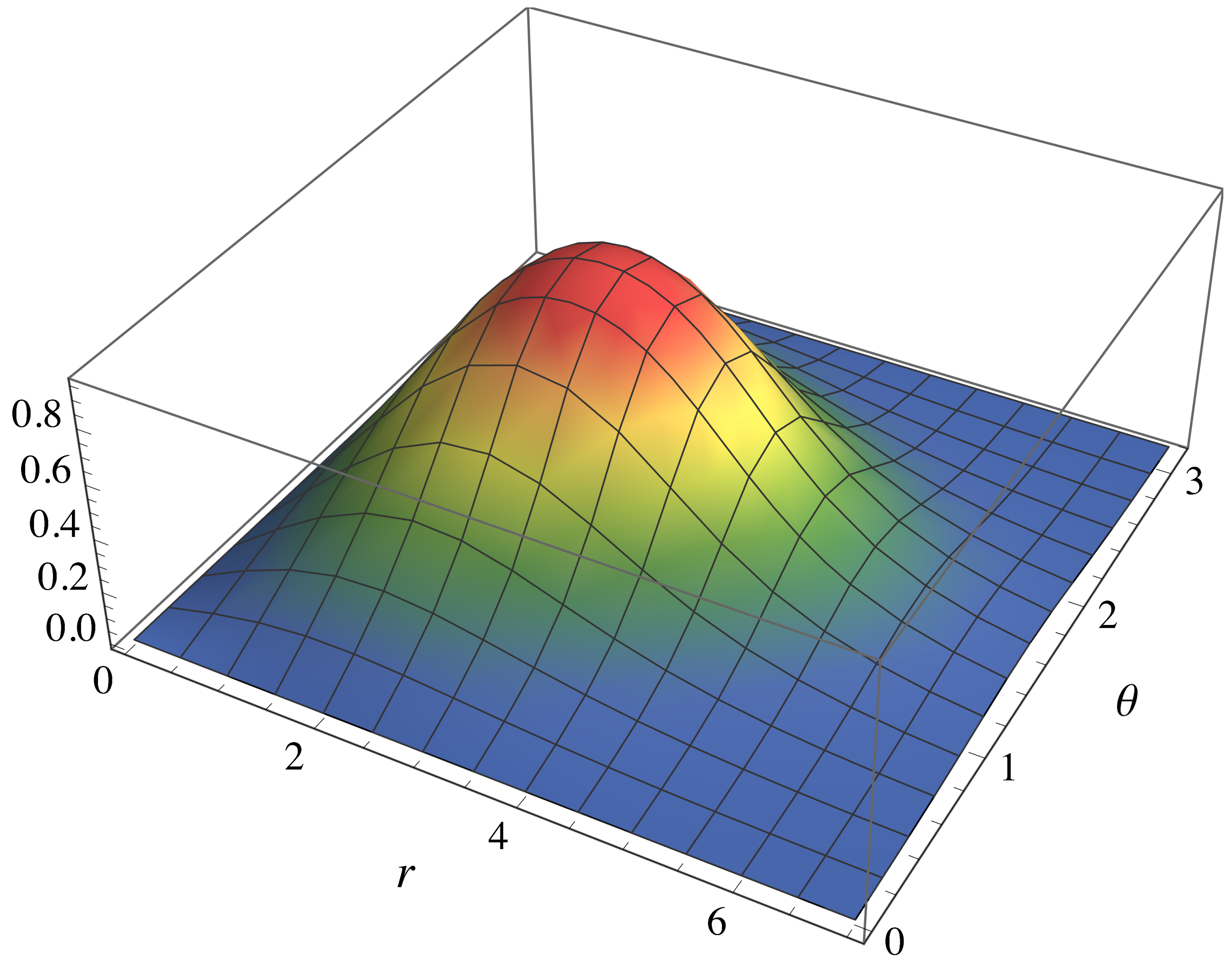
Intermezzo: Blandford Znajek emission

Highly rotating BHs endowed with a magnetosphere produce extremely powerful jets (BZ)

Traditionally it is assumed the presence of an accreting disk with very specific coherent magnetization which can temporary source a magnetic field on the BH



A possible source could also be vorticity



Magnetic trapping

$$\text{Flux} = \int \mathrm{d}x^\mu A_\mu = \frac{2\pi}{eq}\left[\kappa_+ + \kappa \frac{\langle\rho_-\rangle^2}{\langle\rho_-\rangle^2 + \langle\rho_+\rangle^2}\right]$$

Jet emission (e.g., à la Blandford Znajek) can take place without the need of an accreting magnetized disk providing a smoking gun for the scenario

Example: milli-charged dark matter

Consider the axial-symmetric solution found before and $eq \sim 10^{-39}$

$$P_{\mathrm{BZ}} \sim \mathrm{Flux}^2\Omega^2 \sim P_{\mathrm{M}_{87}} \sim 10^{44}\mathrm{erg\,s}^{-1} \quad \text{for maximally rotating BH}$$

Reminder: $\kappa_+ + \kappa_- = -\kappa \sim \mathcal{O}(1)$

Outlook

- Can we have saturons with multiple vortexes? What about their dynamics?

- How does the emission change in the presence of a magnetized accretion disk?

- Electromagnetic counter part in mergers

- Early Universe relevance for primordial black holes

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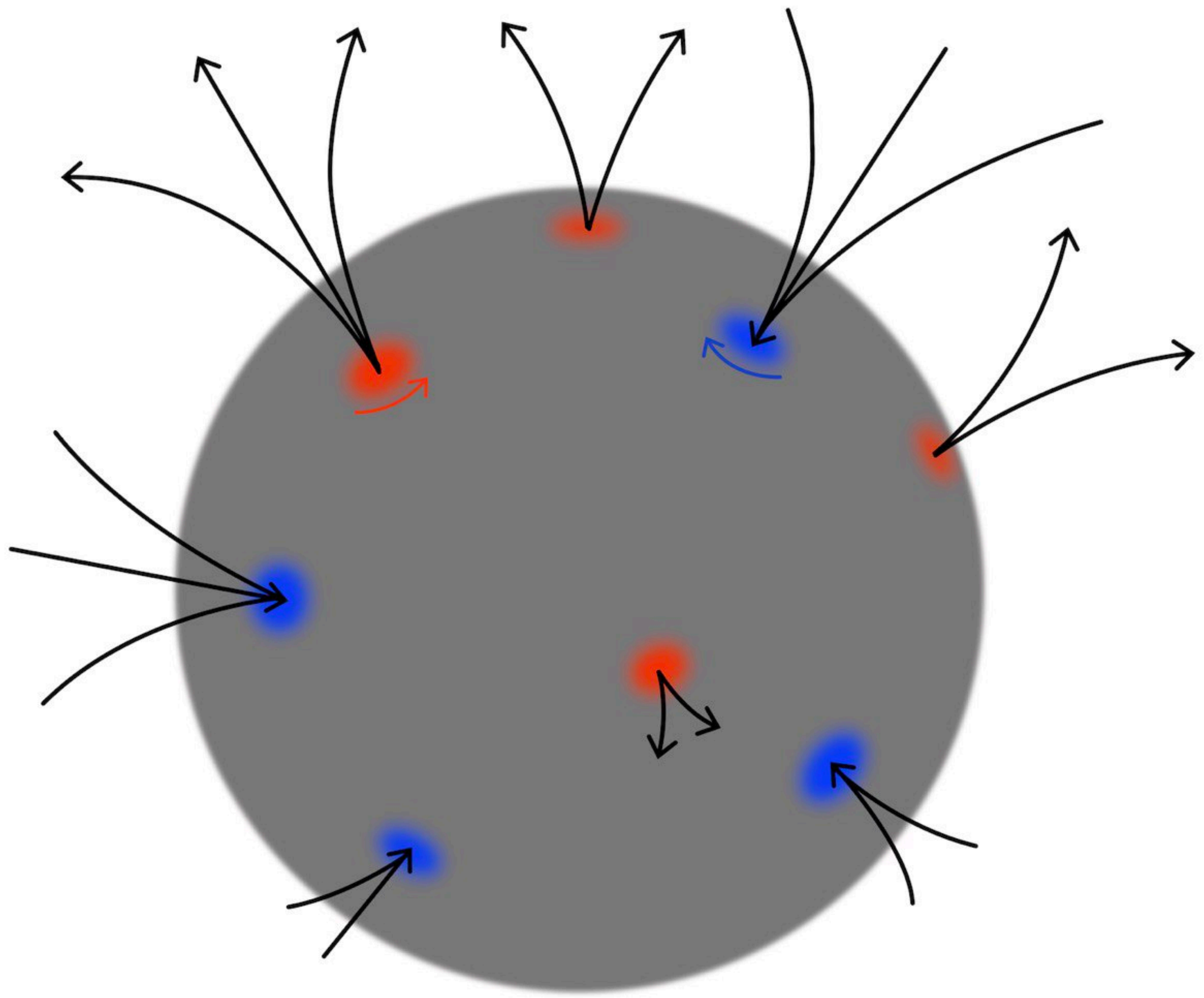


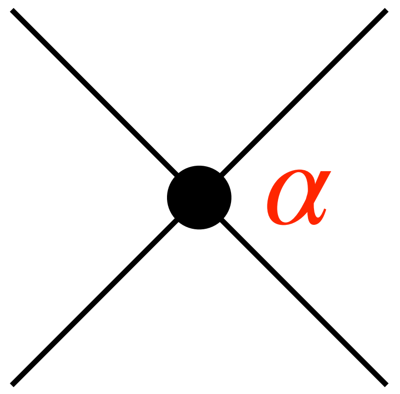
Thank you

Explicit model

Consider scalar field Φ_i^j in the adjoint representation of $SU(N)$ theory

$i, j = 1,...,N \rightarrow$ "flavour" indices, $\quad \mathrm{Tr}\,\Phi = 0, \quad \Phi = \Phi^\dagger$

$$\mathscr{L} = \mathrm{Tr}\,\partial_\mu \Phi \partial^\mu \Phi - \alpha\,\mathrm{Tr}\left(f\,\Phi - \Phi^2 + \frac{1}{N}\mathrm{Tr}\Phi^2 \right)^2$$



Coupling

Goldstone decay constant

Collective coupling is controlled by unitarity

$$\alpha N \lesssim 1$$

NB The model is renormalizable!

NNB Double scaling limit $N \rightarrow \infty$, $\alpha \rightarrow 0$

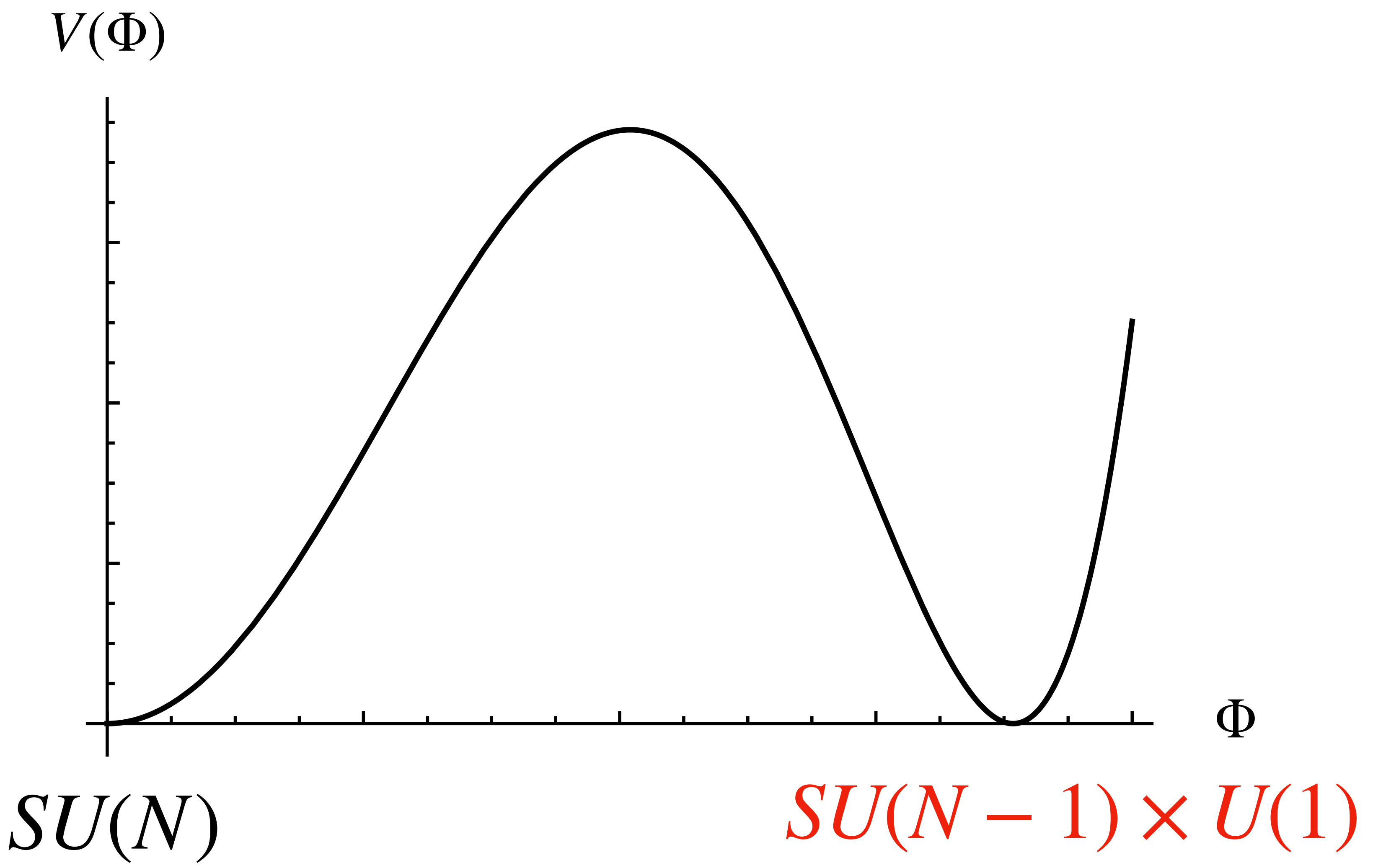
An example of Saturon

Vacuum structure - many degenerate vacua

$$V(\Phi) = 0$$

$$\downarrow$$

$$f\Phi - \Phi^2 + \frac{1}{N}\mathrm{Tr}\,\Phi^2 = 0$$



1) SU(N) symmetric vacuum:

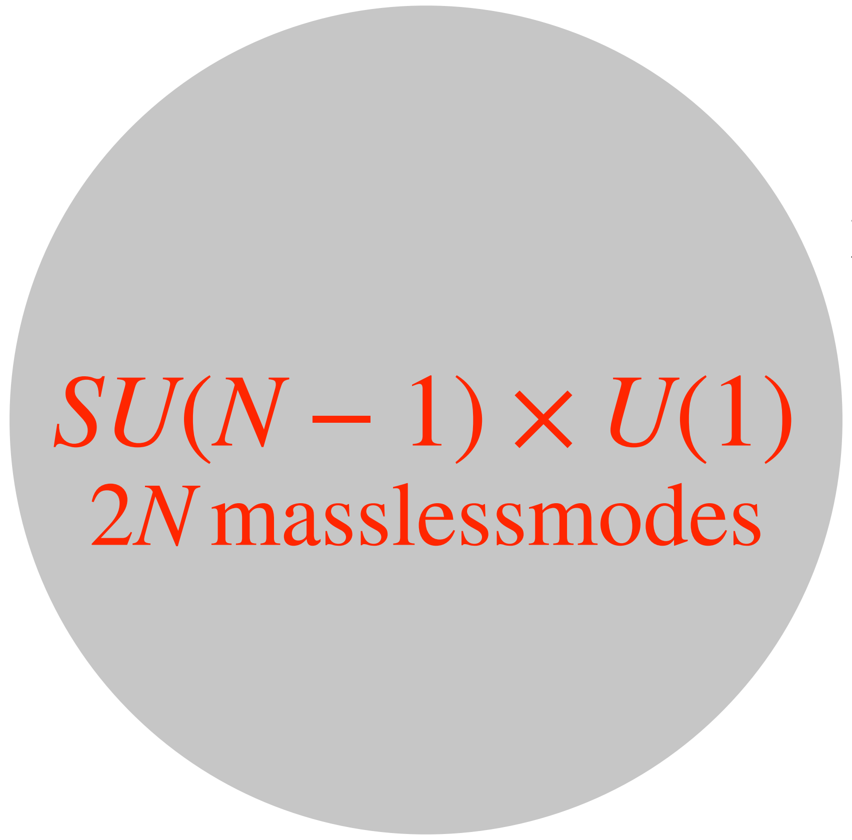
$$\langle \Phi \rangle = 0, \quad \text{mass gap } m = \sqrt{\alpha} f$$

2) SU(N-1)xU(1) symmetric vacuum

$$\langle \Phi \rangle = \frac{f}{N}\mathrm{diag}\,(N-1, -1, \ldots, -1)$$

$\sim 2N$ gapless modes

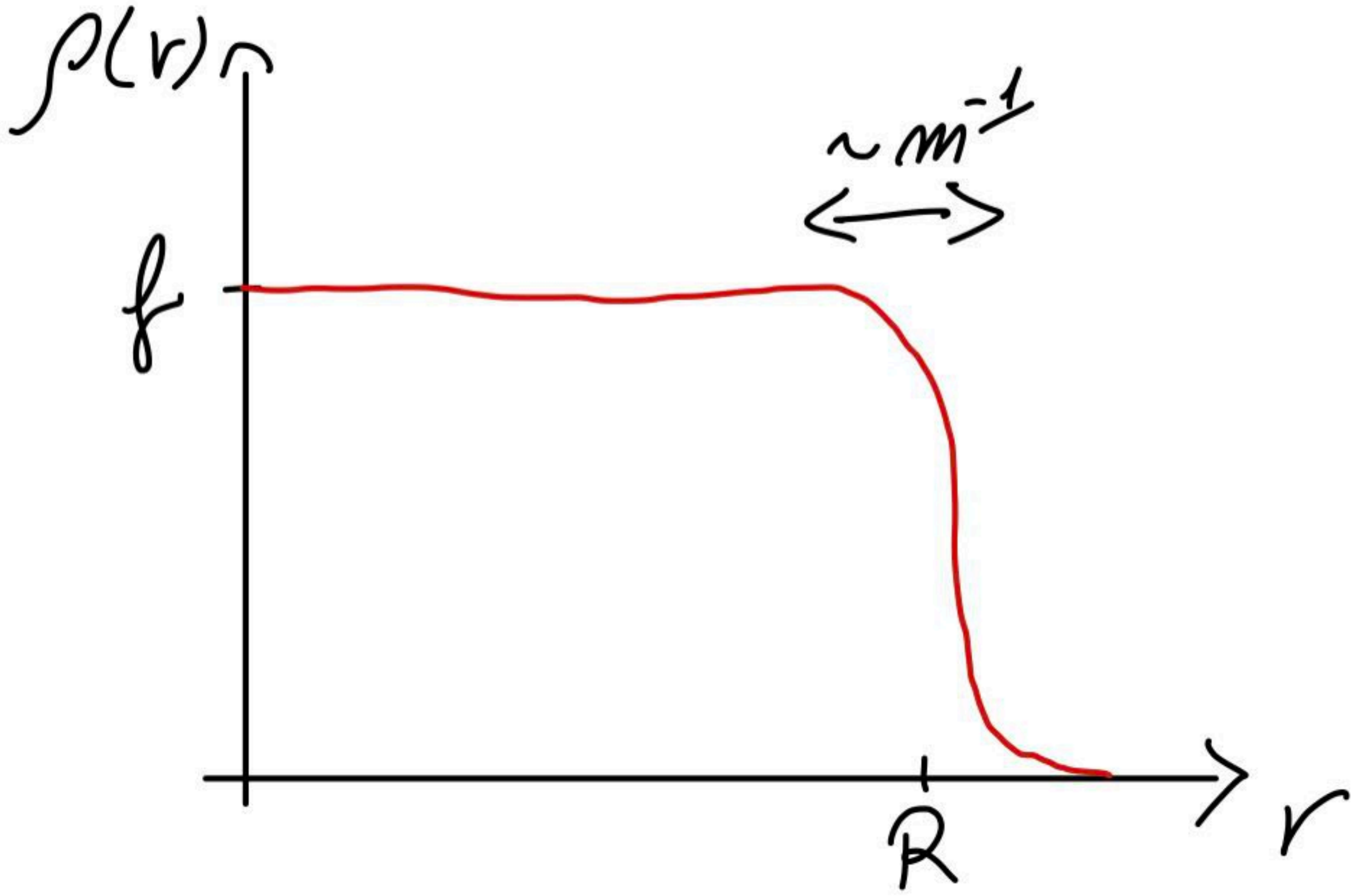
An example of Saturon



$SU(N)$
mass gap $m=\sqrt{\alpha}f$

$$\Phi = \frac{\rho(r)}{f}\langle\Phi\rangle$$

Bubble is highly degenerate and can store information in Goldstone modes



Exciting Goldstones stationarizes the bubble (adding information)

$$\Phi \to U^\dagger \Phi\, U = \frac{\rho(r)}{f} e^{i\omega t\,\hat{T}}\langle\Phi\rangle e^{-i\omega t\,\hat{T}}$$

$\hat{T}$ being one of the broken generators

Similar construction in non-topological solitons