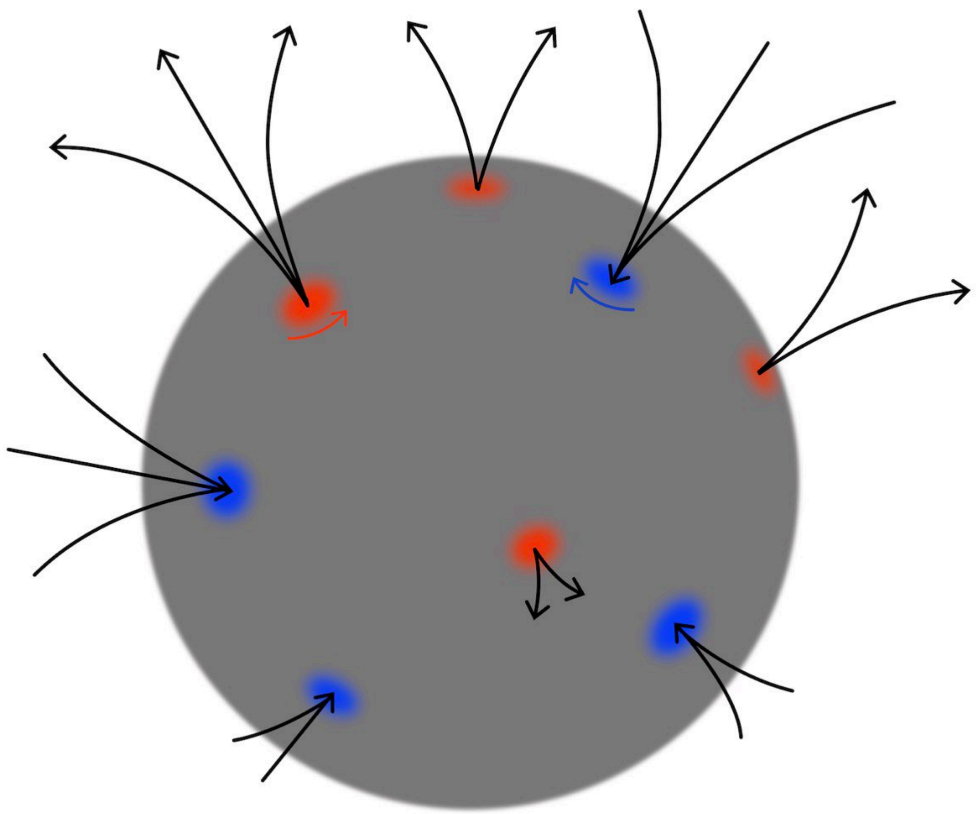
Vortexes and Black Holes

Michael Zantedeschi - LMU MPI
Spontaneous workshop XIV
13th May 2022



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

Main Message:

Properties of black holes are not unique to gravity

There are localized and self-sustained configurations outside of gravity that posses properties analogous to black holes:

1. Entropy-area law $S_{\rm BH} = {\rm Area}/G_{\rm Gold}$

This is maximal entropy compatible with unitarity
Objects saturating this bound will be called ***saturons***

G.Dvali arXiv:2003.05546
arXiv:1907.07332
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2. Hawking thermal emission $T = 1/R$

3. Long time information retrieval (Page time) $t \sim S_{\mathrm{BH}} R \sim R^3/G_{\mathrm{Gold}}$

4. Maximal spin and halt of Hawking emission $J \lesssim S_{\mathrm{BH}}$

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- 2, 3 and 4 are a consequence of 1
- Black holes are saturons under identification $G_{\text{Gold}} = G_{\text{N}}$

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

- Bose-Einstein Condensates
- Gross-Neveu model (Otari Shakelashvili in previous talk)
- Color-glass condensate
- Renormalizable QFTs in 3+1 dim. (example shown in this talk)

Goal: provide a deeper understanding of black holes studying systems easier to control

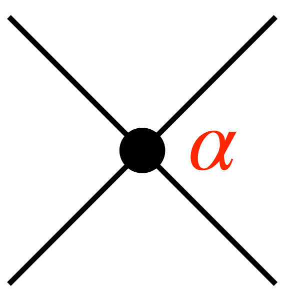
Possible to come up with new predictions?

An example of Saturon

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

$i, j = 1,\ldots,N \rightarrow$ "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 (α) — Goldstone decay constant (f)

Collective coupling is controlled by unitarity

$$\alpha N \lesssim 1$$

NB The model is renormalizable!

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

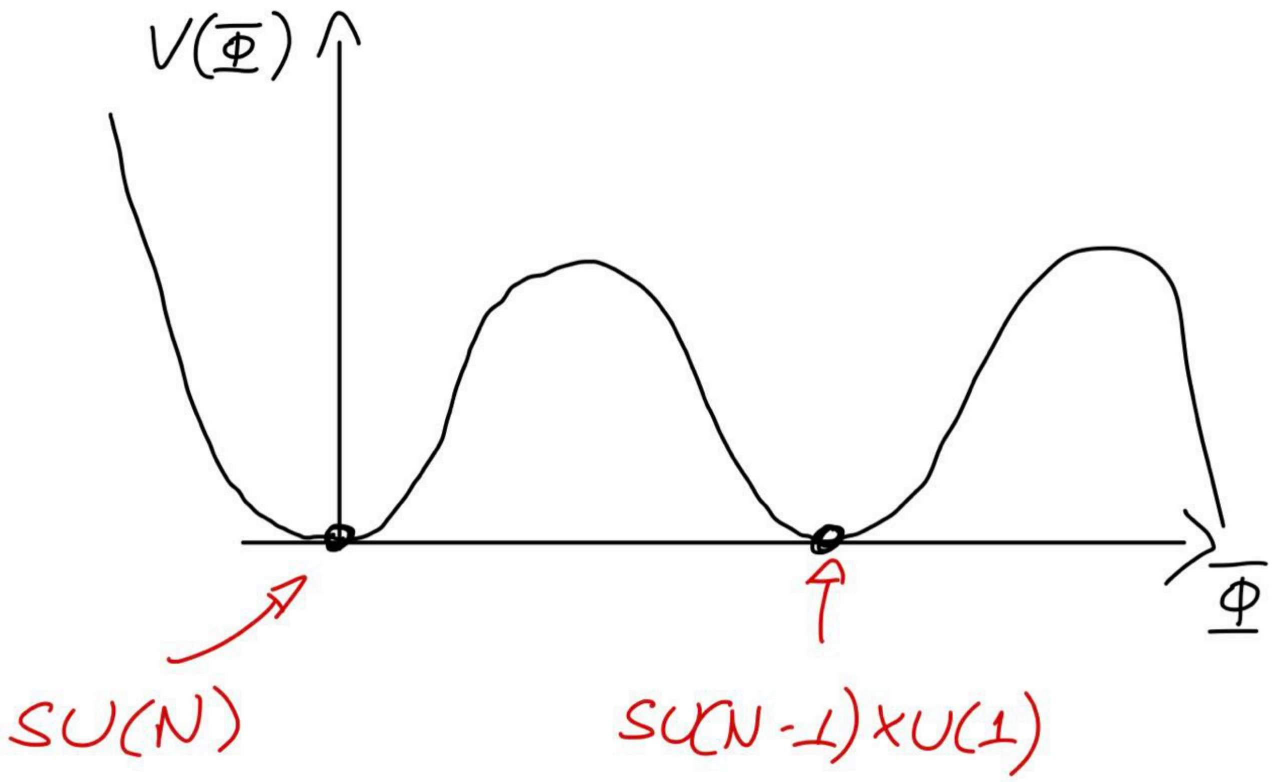
An example of Saturon

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:

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

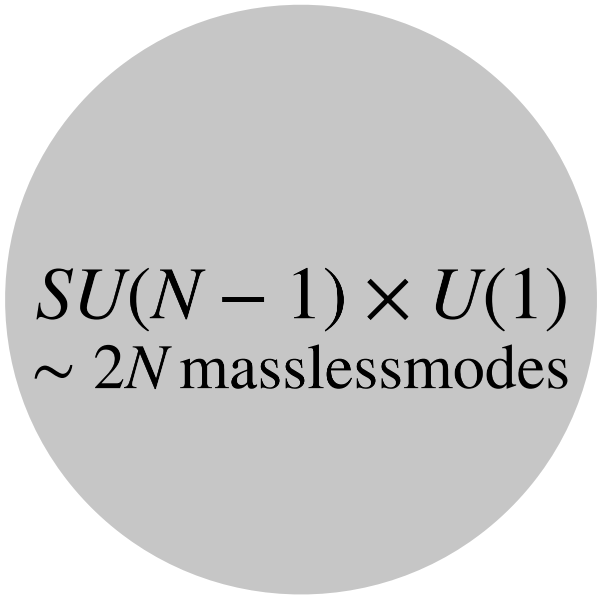
2) SU(N-1)xU(1) symmetric vacuum

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

$\sim 2N$ gapless modes

An example of Saturon

Bubble configuration



$SU(N)$

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

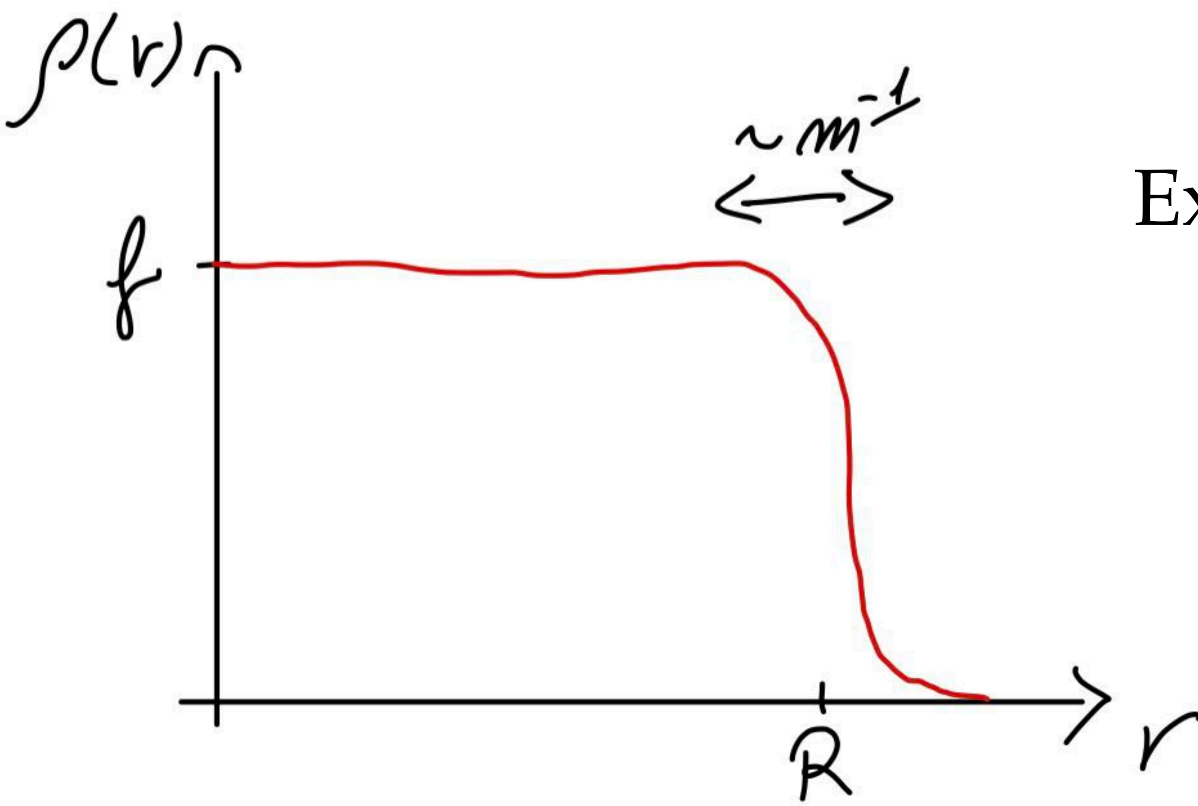
↓

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



An example of Saturon

Configuration saturates unitarity bound i.e., it becomes a saturon when

$$\omega \sim m \sim 1/R \quad \text{and} \quad n_{\rm Gold} \sim N \simeq 1/\alpha$$

↓

$$S \simeq \frac{\text{Area}}{G_{\rm Gold}} \simeq N \simeq \frac{1}{\alpha}, \qquad M \simeq \frac{1}{R} N$$

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

The saturated bubble also has a thermal spectrum (Hawking) and a notion of information horizon

See Dvali + Dvali, Kaikov, Valbuena '21

An example of Saturon

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

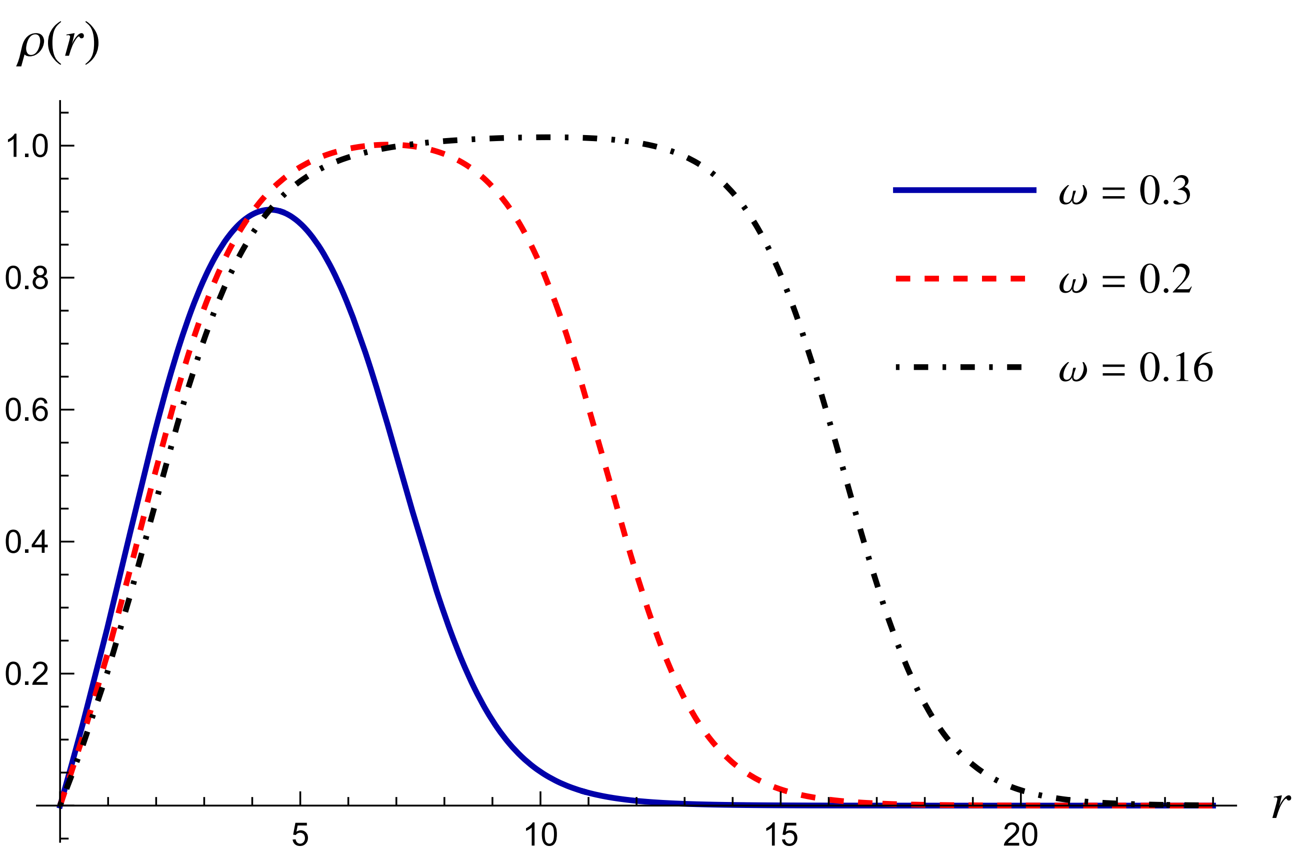
Vorticity

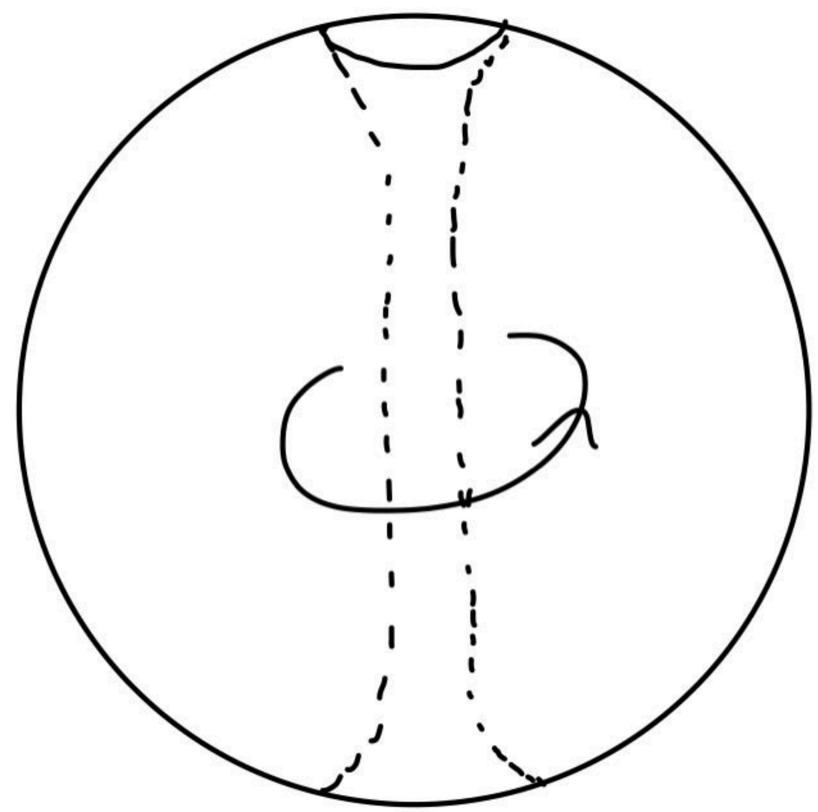
$$\Phi = \frac{\rho(r)}{f} e^{i(\omega t + \kappa\varphi)\hat{T}} \langle \Phi \rangle e^{-i(\omega t + \kappa\varphi)\hat{T}}$$

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

$\varphi =$ polar angle

Angular momentum $J \simeq \kappa\, n_{\rm Gold}$





Multiplicity in broken generators

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

An example of Saturon

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

Requiring vortex energy smaller than bubble energy

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

An example of Saturon

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

Requiring vortex energy smaller than bubble energy

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

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

Non-gravitational Saturon	Black hole
- Entropy Area law	✓
- Thermal spectrum	✓
- Information horizon	✓
- Page time	✓
- Maximal spin bound	✓
- Vorticity	?

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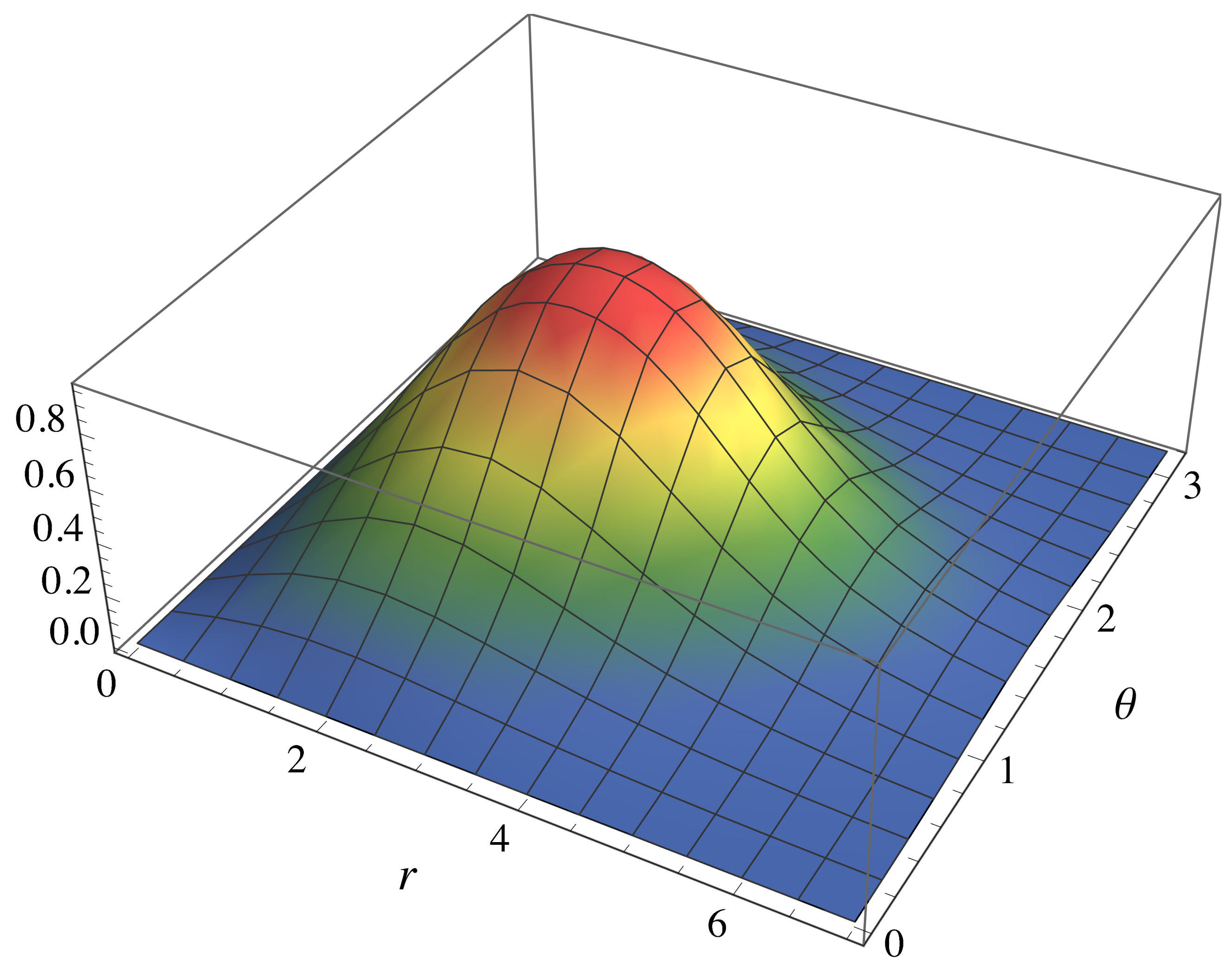
- Maximal spin bound	✓
- Vorticity	?

Question: *Is vorticity an inherent property of (close-to-)extremal black holes?*

If so, these structures offer a natural support for magnetic field, and can bear pheno consequences

Thank you!



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

- Motivated also by the black hole N-portrait
- Degeneracy of Goldstone vacuum, responsible for maximal entropy, is in one to one correspondence with the degeneracy of vortex configurations (share same generators)
- This would give a microscopic rationale for the maximal spin bound of black holes
- There can exists non-stationary non-axisymmetric configurations with zero net vorticity but multiple vortices
- Phenomenological consequences possible

Indeed it can be that BHs are very special objects!

Magnetic trapping

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

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

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

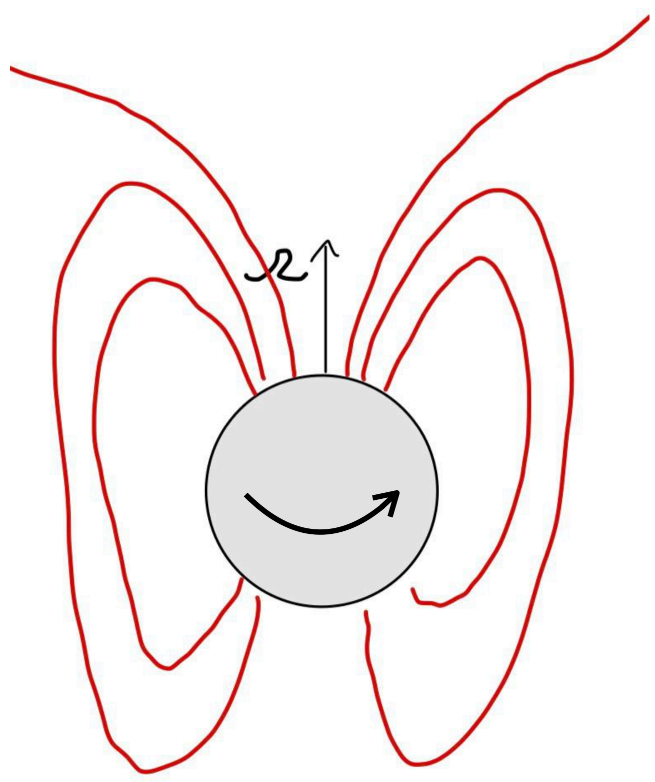
E.g., charged components of neutral plasma or charged dark matter

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)



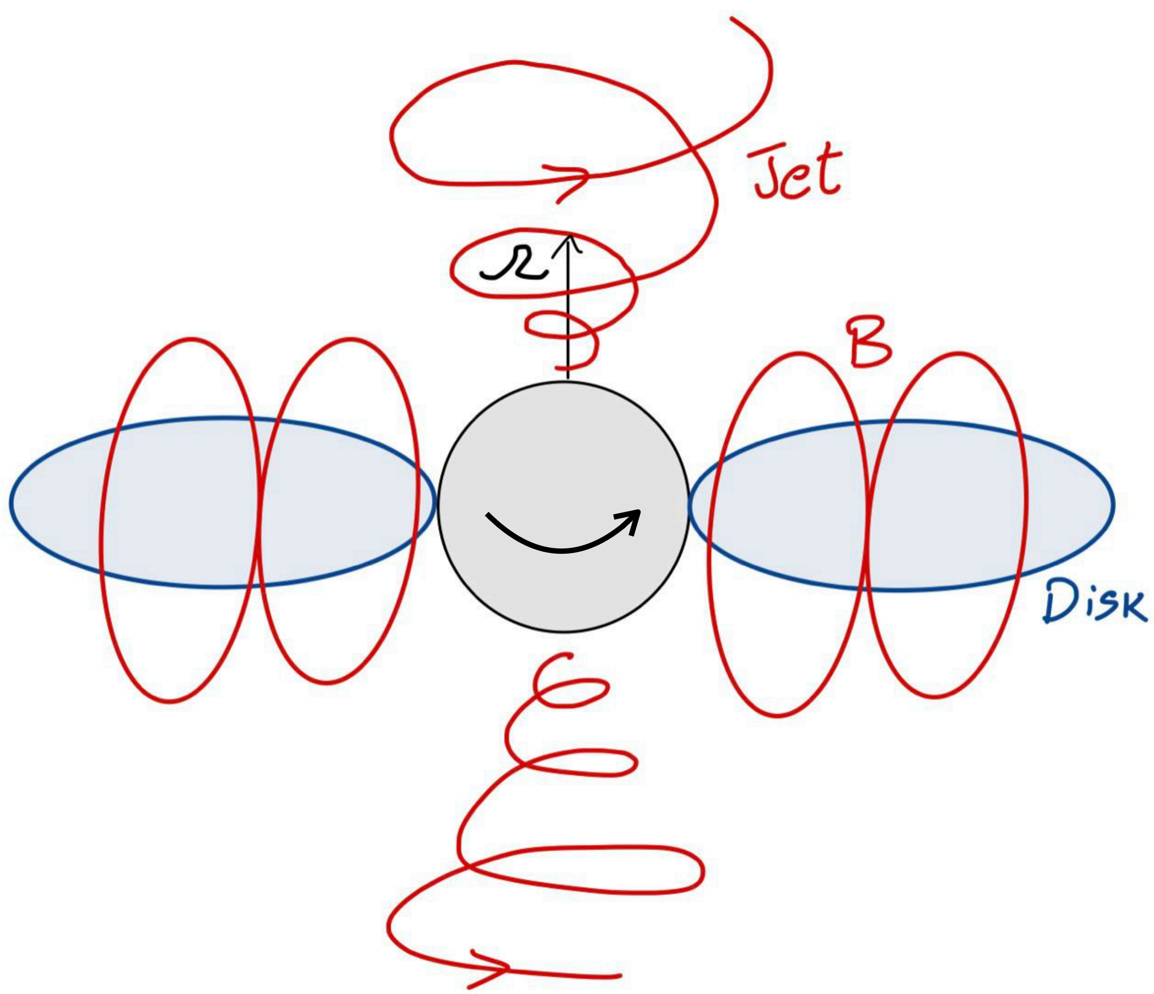
$$P_{BZ} \sim \text{Flux}^2\Omega^2$$

Classically, a BH cannot have magnetic hairs. The mechanism providing magnetic field remains to present day a mystery (although BZ-like emissions are observed).

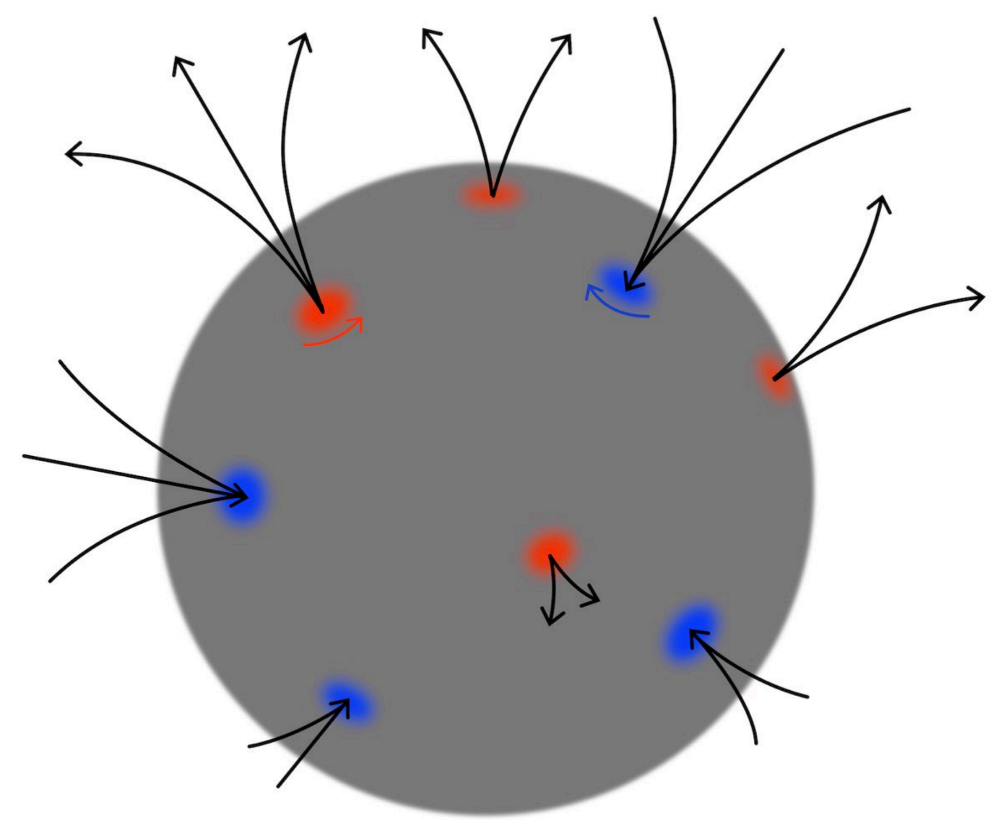
Intermezzo: Blandford Znajek emission

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 $eq \sim 10^{-39}$

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

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

Maximal flux

Maximal magnetic field for BH is restricted by $E_{\text{magnetic}} < M_{\text{BH}}$

$$B \sim \text{Flux}/R_{\text{BH}}^2 \lesssim M_{\text{pl}}/R_{\text{BH}} \sim M_{\text{pl}}^2/\sqrt{S}$$

Which in turn implies a bound on maximal flux

$$\text{Flux} \sim \frac{1}{eq} \lesssim \sqrt{S}$$

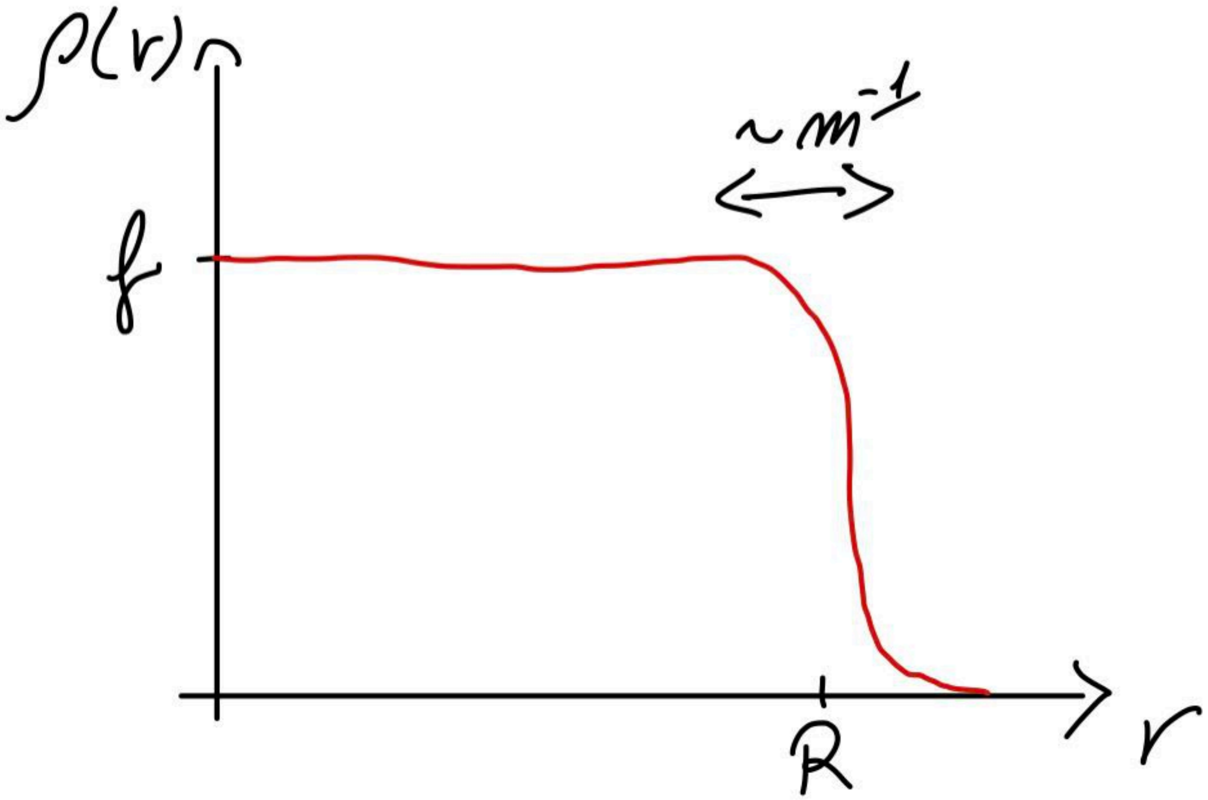
For M87 case $\sqrt{S} \sim 10^{47}$ (we used $eq \sim 10^{-39}$)

An example of Saturon

$$d_r^2\rho + \frac{2}{r}d_r\rho + \rho\left[\omega^2 - \alpha(\rho - f)(2\rho - f)\right] = 0$$

$$Q = n_{\text{Gold}} \sim \frac{1}{\alpha}\left(\frac{m}{\omega}\right)^5 \qquad R \sim \frac{m}{\omega^2} \qquad E \sim \omega\, n_{\text{Gold}}$$

$$n_{\text{states}} \simeq \left(1 + \frac{2N}{n_{\text{Gold}}}\right)^{n_{\text{Gold}}}\left(1 + \frac{n_{\text{Gold}}}{2N}\right)^N \qquad S = \log n_{\text{states}}$$



Where the number of states is counted as number of configurations of form

$$|\,\text{Pattern}\rangle = |\,n_\omega^1, n_\omega^2, \ldots, n_\omega^{2N}\rangle$$

under the constraint

$$\Sigma_a^{2N}\, n_\omega^a = n_{\text{Gold}}$$

An example of Saturon

Properties

$$n_{\rm Gold} \sim \omega f^2 R^3 \sim \frac{1}{\alpha}\left(\frac{m}{\omega}\right)^5 \qquad R \sim \frac{m}{\omega^2} \qquad E \sim \omega\, n_{\rm Gold}$$

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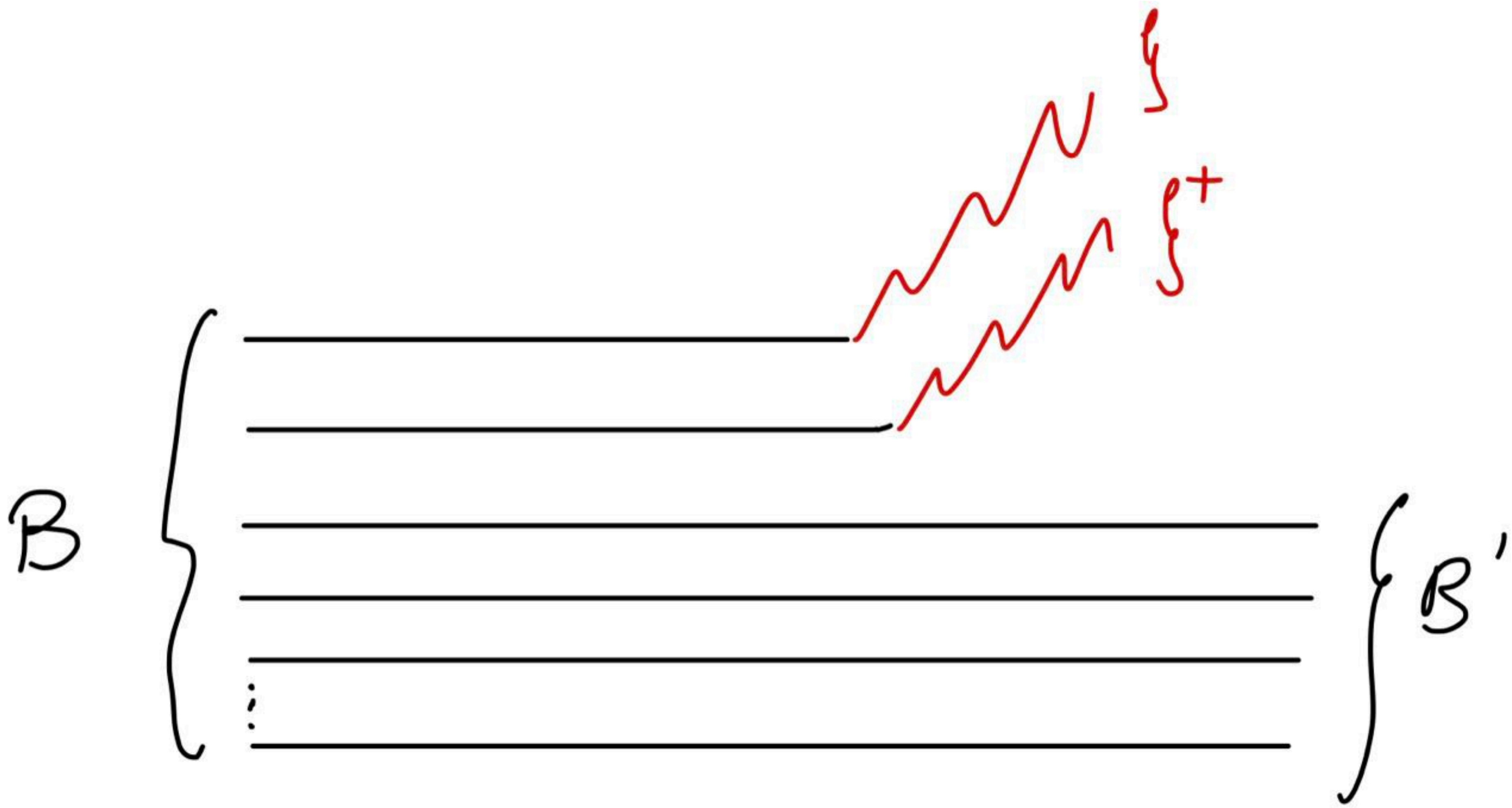
Remember: At saturation

$$\omega \sim m \sim 1/R \quad \text{and} \quad n_{\rm Gold} \sim N$$

Hawking emission

Following Hawking couple massless field ξ

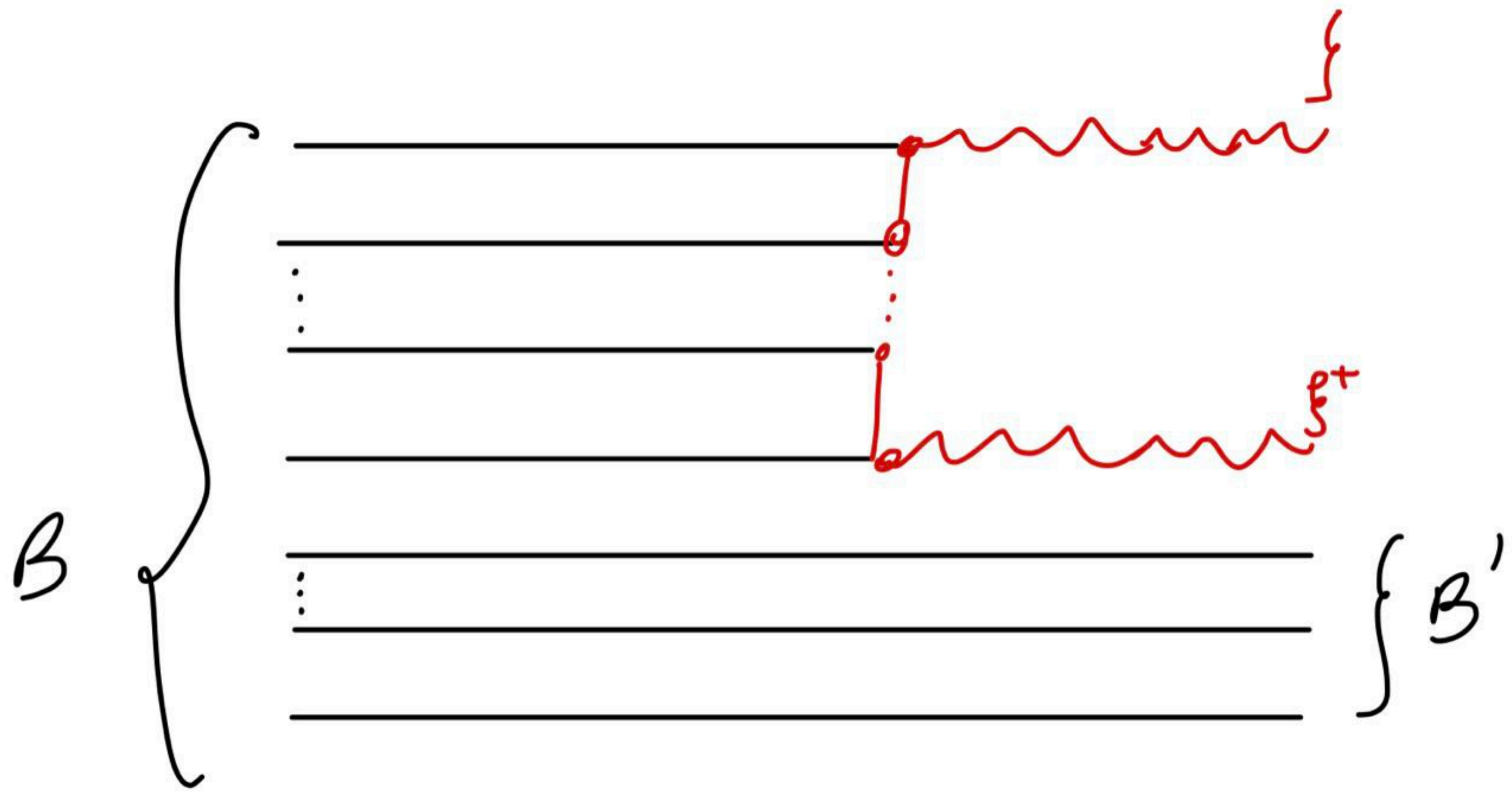


$$\Gamma \sim (\alpha N)^2 \frac{1}{R} \sim \frac{1}{R}$$

$\alpha N \simeq 1$ at saturation

Hawking emission

Temperature emerge as rescattering of multiple constituents



$$E_\xi \gg 1/R$$

$\Gamma \propto e^{-E_\xi/T}$ Boltzmann suppression

More on millicharged DM

Charged cold dark matter generate photon mass

$$m_\gamma = eq\sqrt{\rho_{\rm local}}/m_{\rm DM}$$

On galactic scales photon mass is constrained by galaxy magnetic field

$$m_\gamma < \sqrt{eqB_{\rm galaxy}}$$

Example from before ($eq \sim 10^{-39}$):

$$m_\gamma \sim m_{\rm DM} \sim 10^{-18}{\rm eV}, \quad \rho_{\rm local} \sim 10^4{\rm eV}^4$$

Close to fuzzy-like DM

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