Title: Saturons - VIRTUAL

Speakers: Gia Dvali

Series: Particle Physics

Date: February 06, 2024 - 1:00 PM

URL: https://pirsa.org/24020052

Abstract: "Saturons" are macroscopic objects that saturate the field theoretic upper bound on microstate degeneracy. Due to their maximal microstate entropy, from a quantum information perspective, saturons and black holes belong to the same universality class with common key properties. However, as opposed to black holes, saturons do not require gravity and can emerge via ordinary renormalizable interactions, such as QCD, in the form of soliton-like states. Due to this feature, saturons serve as laboratories for understanding certain properties of black holes. After reviewing the general properties of saturons, we discuss their implications for fundamental physics and cosmology. In particular, we explain how saturons can lead to a new form of phase transition.

Zoom link

Saturons

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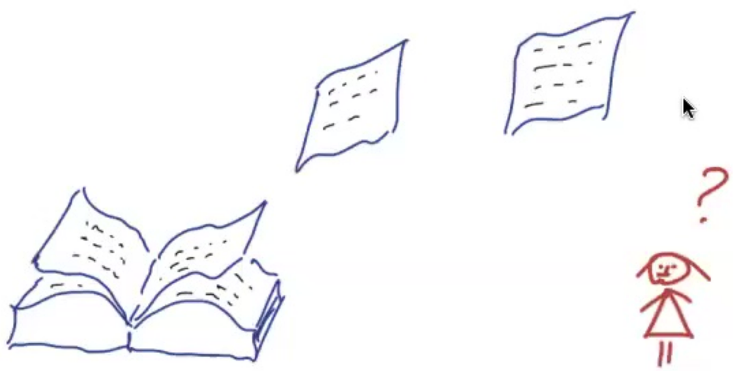
Oleg Kaikov, Otari Sakhelashvili, Michael Zantedeschi

Initial Big goal:

Understanding how black holes work and finding and implementing underlying universal phenomena in generic systems



But then the story changed.

Black hole ``mysteries":

Areal-law entropy of Bekenstein-Hawking:

$$S = \frac{\text{Area}}{G} = \frac{\text{Area}}{M_P^{-2}}$$

Semi-classical information horizon.

Evaporate thermally, via Hawking temperature:

$$T = \frac{1}{R}$$

Information-retrieval time, Page time:

$$t_{min} = SR = R^3 M_P^2$$

How special are black holes?

- G.D., JHEP03(2021) 126, arXiv:2003.05546

In QFT with running coupling α, the miscrostate entropy of the system of radius R is bounded by

$$S \leqslant \frac{1}{\alpha}$$

Equivalently, the upper bound on entropy is:

$$S \leqslant \frac{\text{Area}}{G_{Gold}}$$

where

$$G_{Gold} \equiv f^{-2} = Goldstone\ scale$$

The objects saturating the bound

$$S = \frac{1}{\alpha} = \frac{\text{Area}}{G_{Gold}}$$

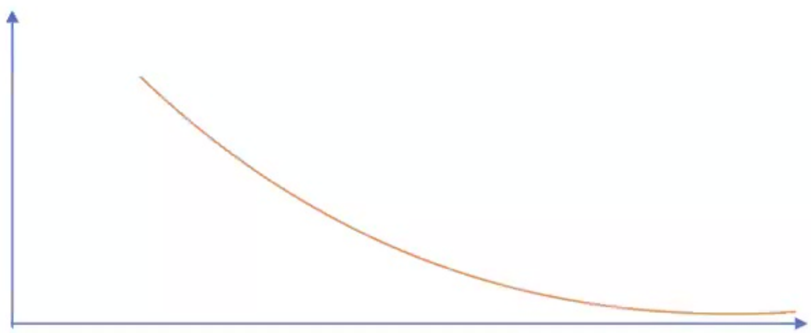
Shall be called: ``saturons”

For many: G.D, JHEP 03, 126 (2021); Fortsch. Phys. 69, no.1, 2000090 (2021);
Fortsch. Phys. 69, no.1, 2000091 (2021)1; Phil. Trans. A. Math. Phys. Eng. Sci. 380, no.2216, 20210071 (2021);
G. D., O. Sakhelashvili, Phys. Rev. D 105, no.6, 065014 (2022);
G. D., O. Kaikov and J. S. V. Berm´udez, Phys. Rev. D 105, no.5, 056013 (2022) ;
G. D., F. K¨uhnel and M. Zantedeschi, Phys. Rev. Lett. 129, no.6, 061302 (2022);

It is easy to see that black hole entropy has the same Poincare Goldstone meaning:

Near horizon:

<GRAVITON > = Planck Mass



Scale of Poincare Goldstone = Planck Mass

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Within validity of QFT saturons also saturate Bekenstein bound on entropy

That is,

$$S = \frac{1}{\alpha} = \frac{Area}{G_{Gold}}$$

implies

$$S = 2\pi E R$$

At the validity boundary of the QFT description the two usually agree.

Saturons share all the ``mysterious" properties with black holes:

- 1. Their entropy satisfies the *area law*:

$$S \sim \frac{Area}{G_{Gold}} \sim \frac{Area}{f^{-2}}$$

2. They exhibit a (semiclassical) *information horizon.*

3. Decay rate is thermal and they have *temperature*

$$T \sim \frac{1}{R}$$

4. Time-scale required for beginning of the *information retrieval* is

$$t_{min} = SR \sim \frac{R^3}{f^{-2}} \sim \frac{Volume}{f^{-2}}$$

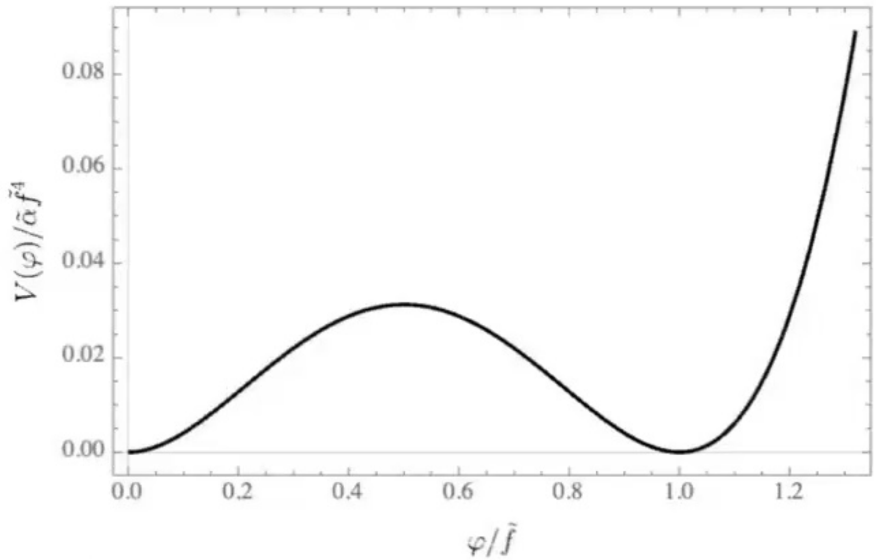
$G_{Gold} \equiv f^{-2}$ Goldstone Coupling

G.D., '19, '20), G.D.,, Sakhelashvili '21, G.D., Kaikov, Valbuena-Bermudez, '21, G.D., Kuhlen, Zantedeschi '21, …

A Model of a Saturon as a Vacuum Bubble

- $d = 4$
- ϕ in the *adjoint rep.* of $SU(N)$
- $N \gg 1$

$$\mathcal{L} = \frac{1}{2}\,\mathrm{tr}\left[(\partial_\mu \phi)(\partial^\mu \phi)\right] - V[\phi]$$
$$V[\phi] = \frac{\alpha}{2}\mathrm{tr}\left[\left(f\phi - \phi^2 + \frac{I}{N}\mathrm{tr}\,[\phi^2]\right)^2\right]$$



- *Unitarity requires:* $\alpha \leq \frac{1}{N}$

Validity domain of QFT description in terms of ϕ

$$\varphi^2 \equiv \mathrm{tr}[\phi^2]$$
$$V(\varphi) \sim \frac{\alpha}{2}\varphi^2(f - \varphi)^2$$

Saturons as Vacuum Bubbles

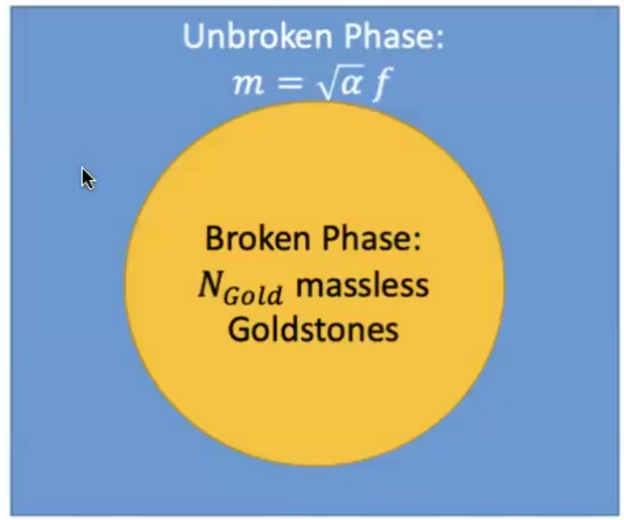
- *Vacuum Bubbles:*

$$\phi = U^{\dagger}\Phi_{\mathrm{D}}U$$

- $U = \exp[-i\theta T]$,
- T corresponds to the broken generators

$$\theta = \omega t$$

$$\Phi_{\mathrm{D}} = \frac{\varphi(r)}{\sqrt{N(N-1)}}\mathrm{diag}\left((N-1), -1, \dots, -1\right)$$



$$SU(N) \rightarrow SU(N-1) \times U(1),$$

G. D., O. Kaikov, J. S. Valbuena-Bermudez (2021)

Vacuum Bubbles Microstates

- $N_G = E_{int}/\omega$ is the total mean *occupation number*.
- $N_{Gold} = 2(N-1)$ Goldstone modes (flavors).
- N_G can be arbitrarily *redistributed* among the N_{Gold} modes.

$$\sum_{a=1}^{N_{Gold}} n^a = N_G$$

- Each sequence represents a *memory pattern*

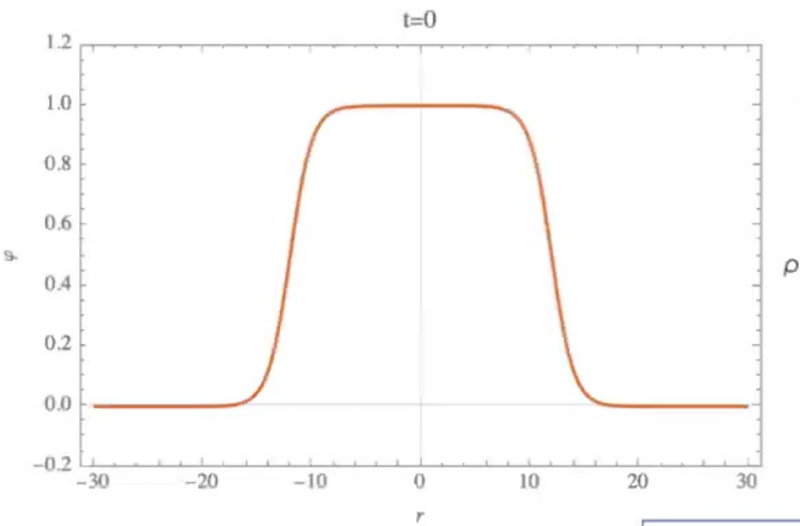
$$|Pattern\rangle = |\, n^1, n^2, \ldots \rangle$$

- The number of degenerate micro-states, n_{st}, is the number of *patterns* satisfying the *constraint* above, and the ***entropy*** is

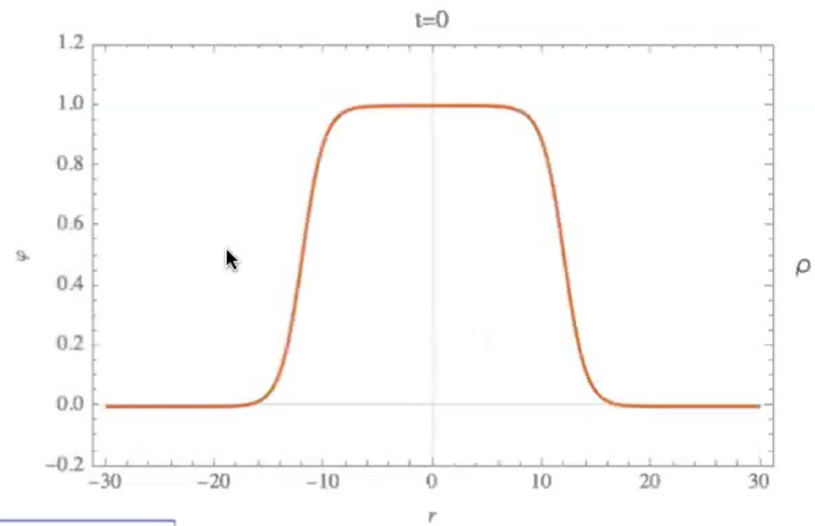
$$S = \ln n_{st} \approx 2N \ln\left[\left(1+\frac{2N}{N_G}\right)^{\frac{N_G}{2N}}\left(1+\frac{N_G}{2N}\right)\right]$$

Vacuum Bubbles Stabilization:

$\dot{\theta} = 0$



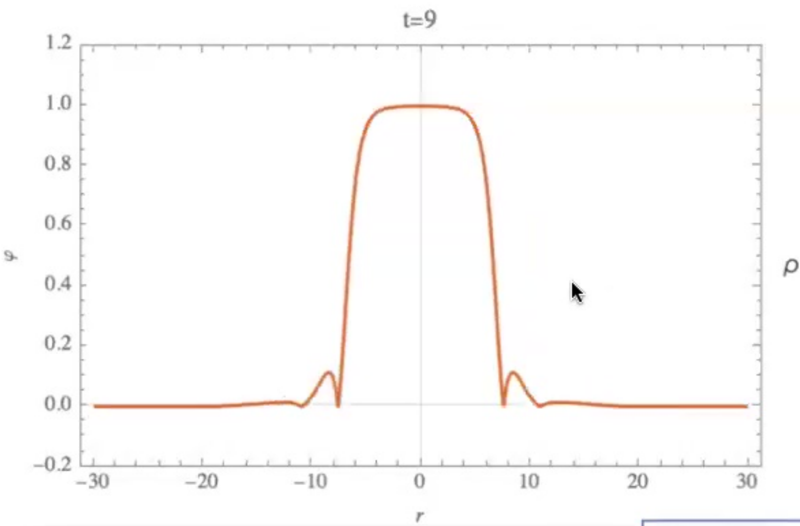
$\dot{\theta} = \omega$



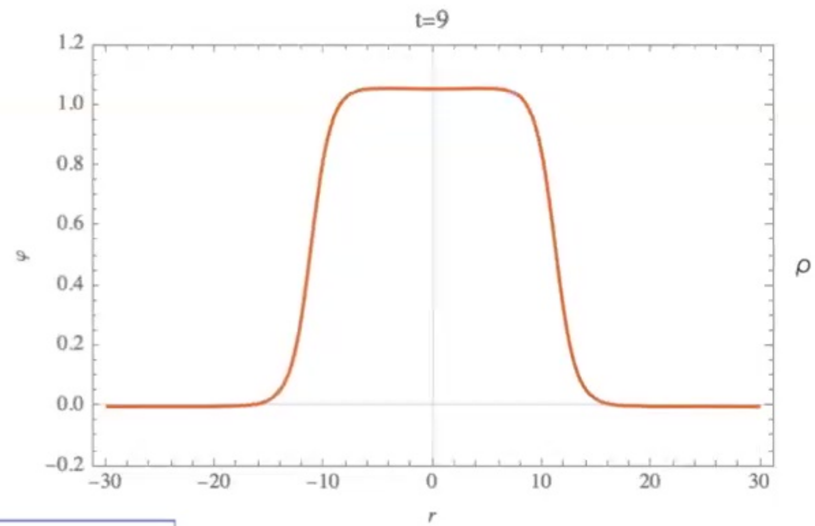
Thin wall approximation for:
$\omega \approx 0.24\, m,$
$R_\omega \sim \frac{m}{\omega^2} \approx \frac{12}{m}$

Vacuum Bubbles Stabilization:

$\dot{\theta} = 0$



$\dot{\theta} = \omega$



Thin wall approximation for:

$\omega \approx 0.24\, m,$

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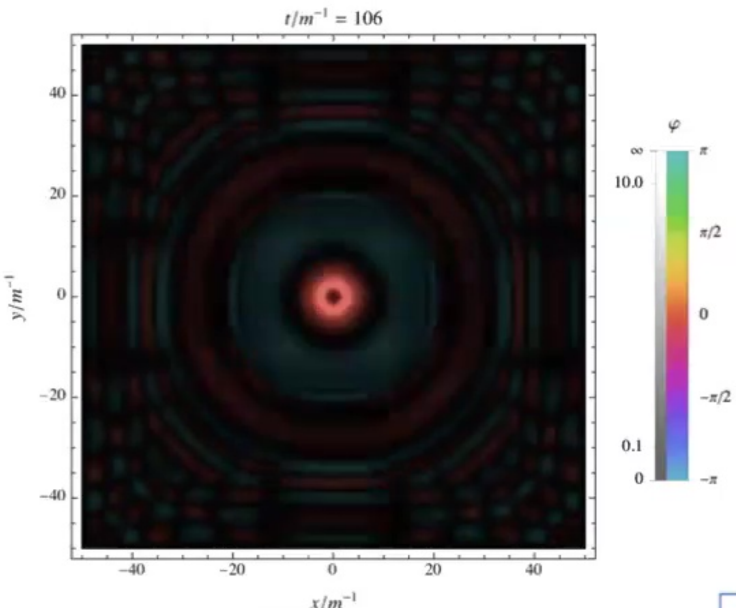
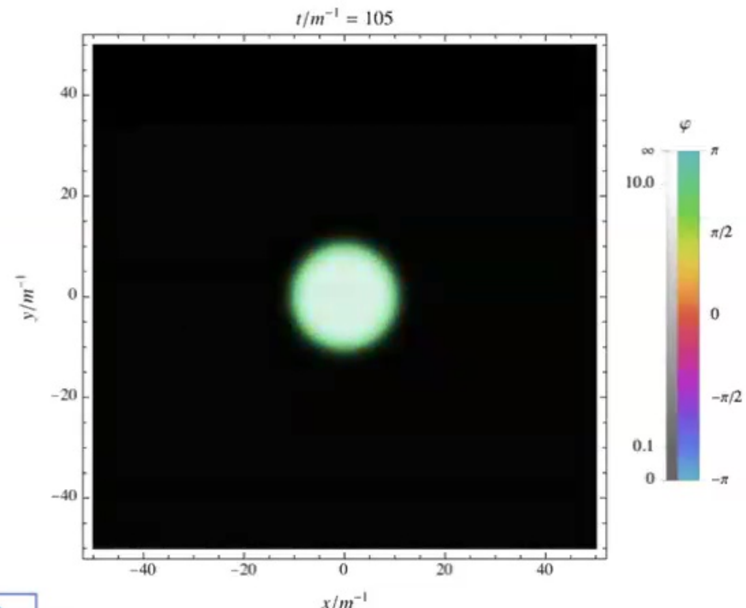
Memory Burden Effect

$\dot{\theta} = 0$



$\dot{\theta} = \omega$



$$R_\omega \sim \frac{m}{\omega^2}$$

G. D., O. Kaikov, J. S. Valbuena-Bermudez (2021), G. D., L. Eisemann, M. Michel, S. Zell (2020)

Information Horizon

Saturons in semiclassical limit

Semi-classical Limit

- The limit in which the classical bubble solution experiences no back reaction from quantum fluctuations

$$\alpha \to 0, \quad R = \text{finite}, \quad \omega = \text{finite}, \quad \alpha N = \text{finite}$$

- Simultaneously

$$f \to \infty, \quad m = \text{finite}, \quad N \to \infty$$

- In this limit, saturons possess a strict *information horizon*.
- Recall: For BH $f \sim M_p$

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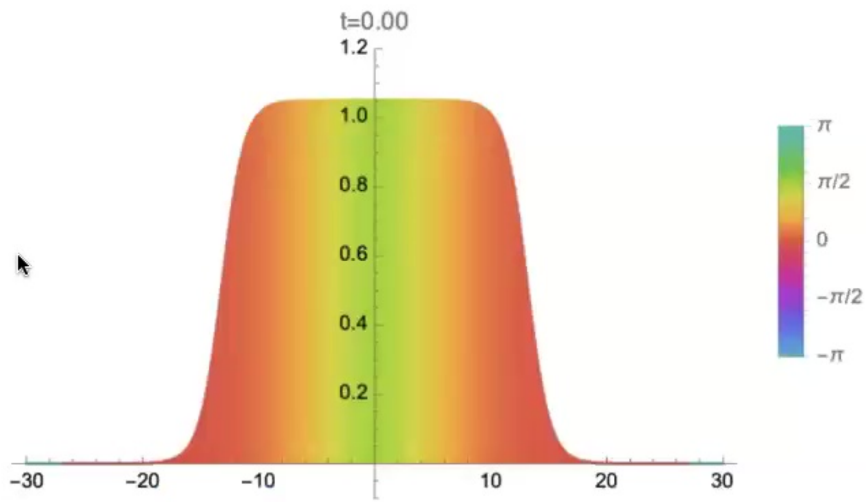
Goldstone Horizon: An Example

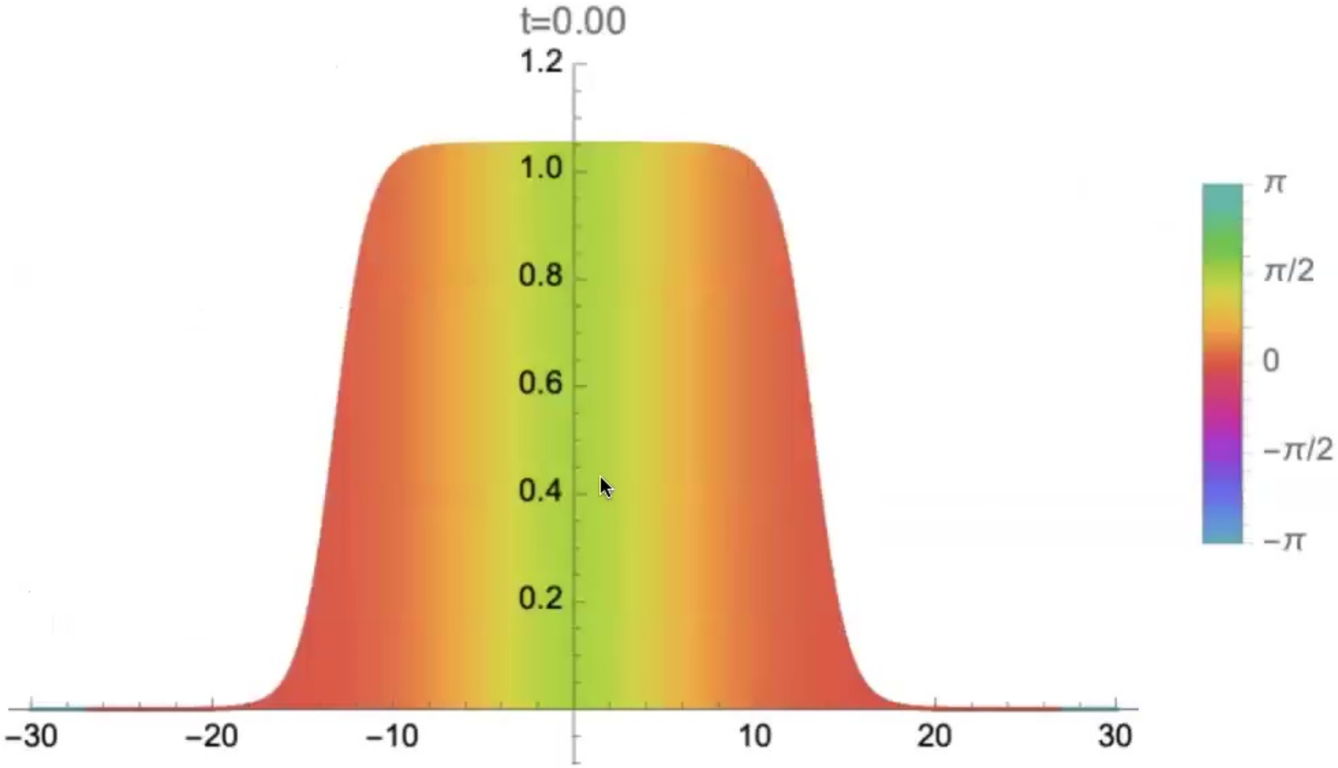
- • Lets consider a perturbation on a stable vacuum bubble, ϕ_{VB},

$$\phi\Big|_{t=0} = P^{\dagger}(r)\phi_{VB}(r)P(r)$$

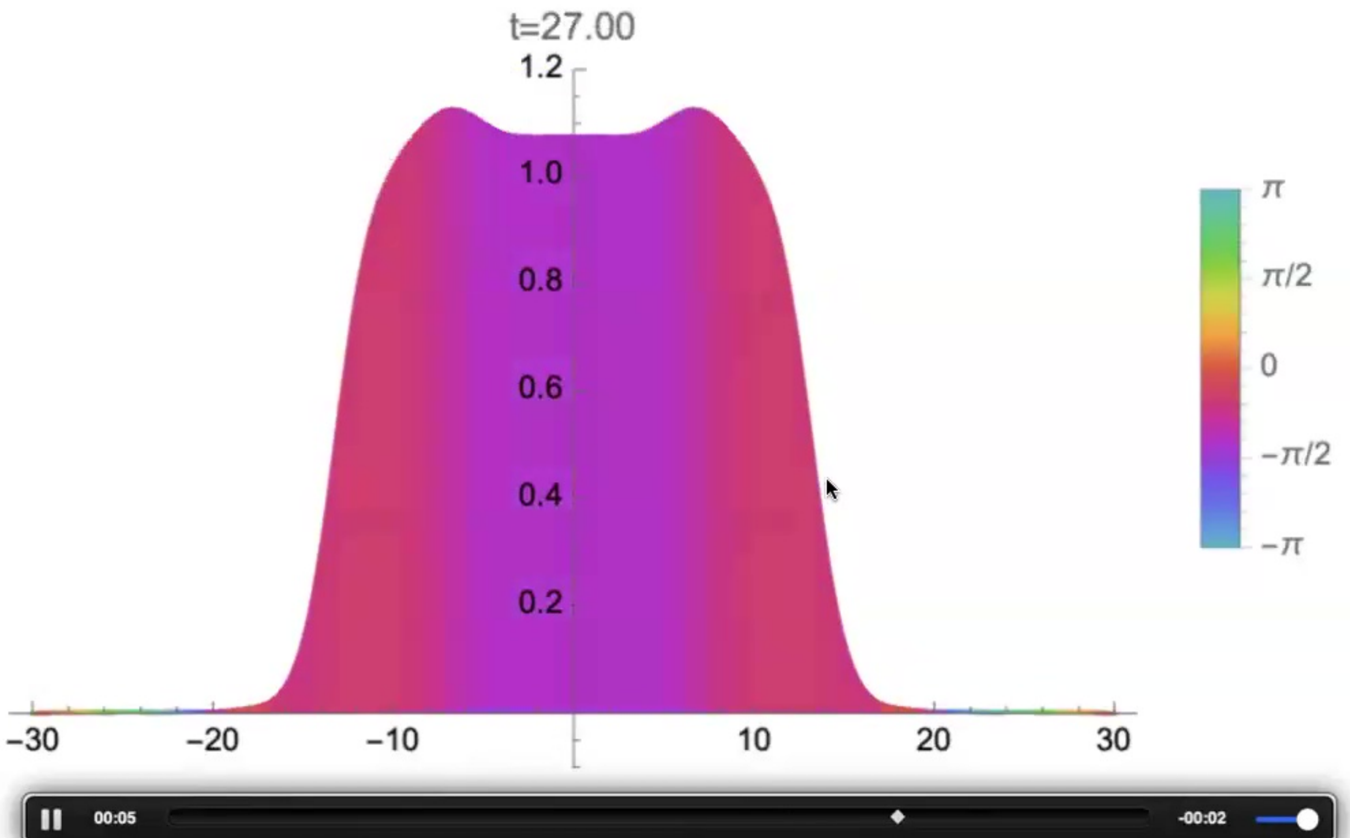
$$P(r) = \exp\left[\frac{i\pi}{2} e^{-\frac{r^2}{2r_0^2}T}\right]$$



Goldstone Horizon: An Example

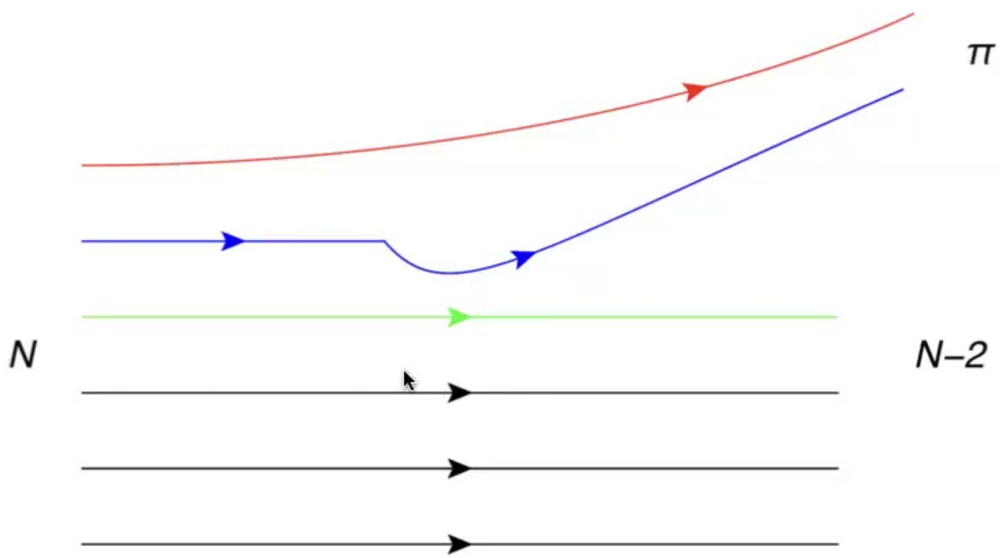


Goldstone Horizon: An Example



``Hawking" evaporation: Information leaks as 1/N (=1/S).

Therefore, the information retrieval time is t = SR



G.D., Otari Sakhelashvili, Phys. Rev. D 105, no.6, 065014 (2022);'

Correspondence to Black Holes

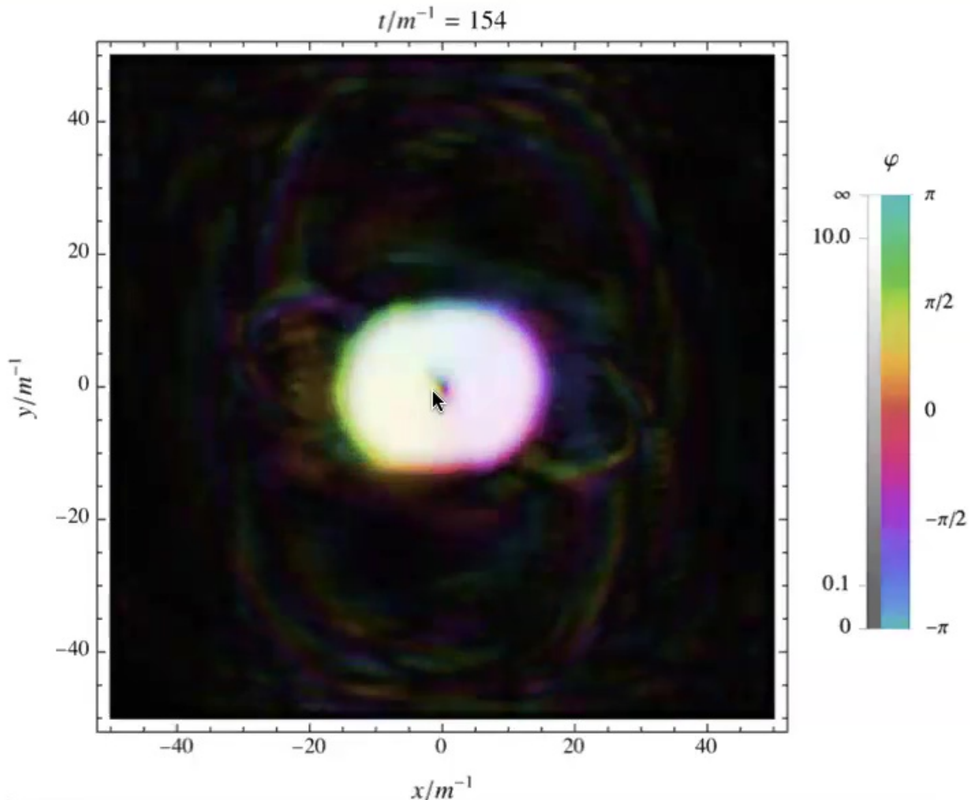
Saturons

- $S = (fR)^2 = \alpha^{-1}$
- $T = R^{-1}$
- $t_{\min} = R^3 f^2 = SR$
- Information/Goldstone Horizon

Black Holes

- $S = (M_P R)^2$
- $T = R^{-1}$
- $t_{\min} = R^3 M_P^2 = SR$
- Information Horizon

Vortices in Saturons (and Black Holes?): Dynamical creation



G. D.i, F. Kühnel, M. Zantedeschi (2021)
G. D.,, O. Kaikov, F. Kühnel, J. S. Valbue

Just as for black holes, the maximal spin of a saturon is set by entropy

$$J_{max} = S_{sat}$$

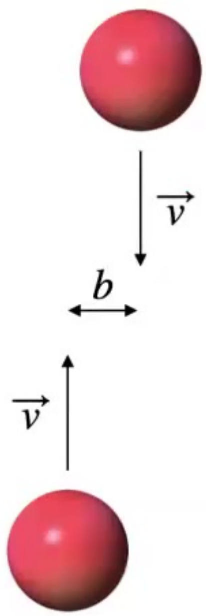
For saturons, the reason is vorticity: Spin implies vorticity and there is a limit to it.

Can the same be true for black holes?

G.D., Kuhnel, Zantedeschi, PRL 129, 2022, 061302

Setup

Merger of black-hole prototypes (solitons with global charge - aka Q-balls)



For certain range of parameters, a vortex can form in the final state

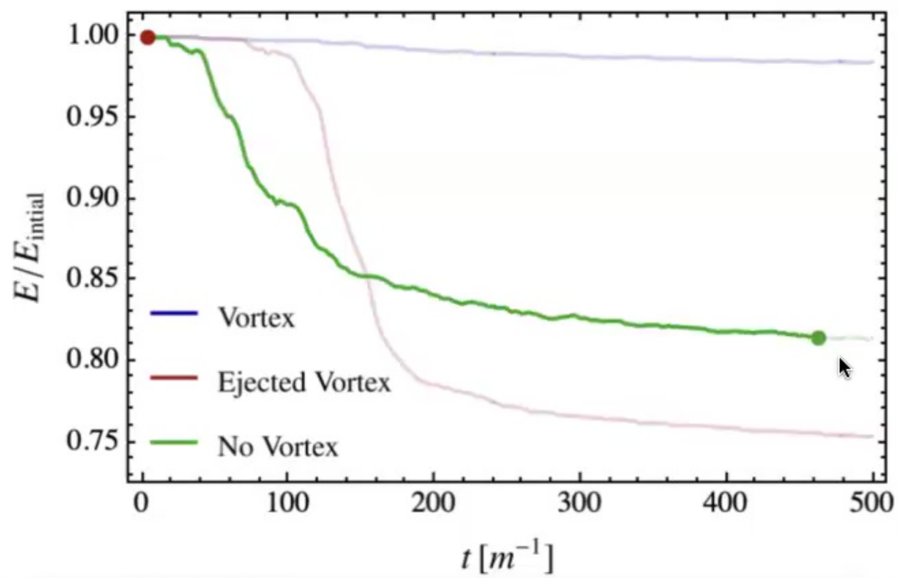
We show three cases

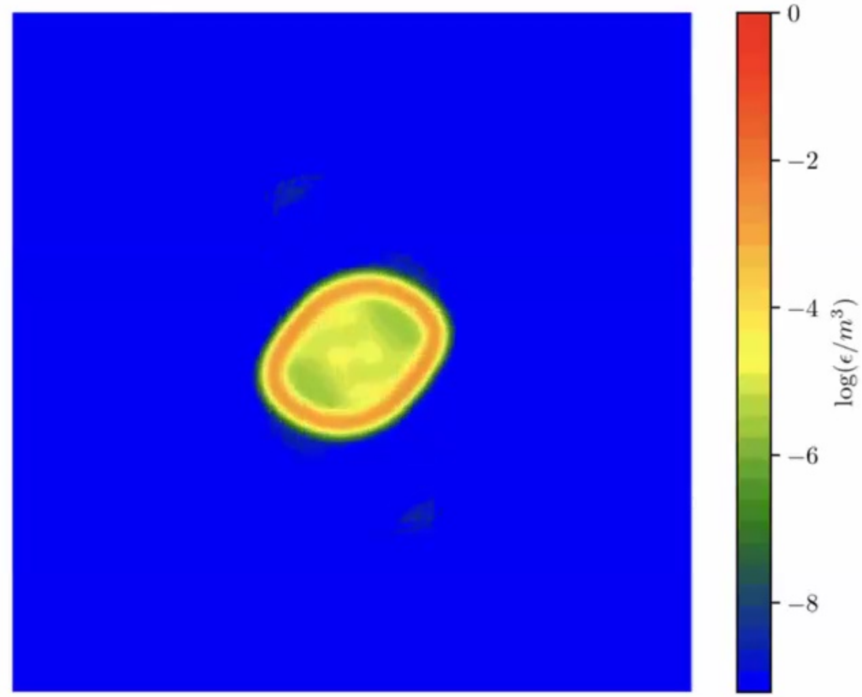
- No Vortex: the solitons simply merge
- Ejected vortex: the final soliton is near the threshold for vortex formation
- Vortex: the final soliton attains vorticity

G. Dvali, O. Kaikov, F. Kühnel, J. S. Valbuena Bermúdez and M. Zantedeschi

2+1D perspective

No-Vortex Case





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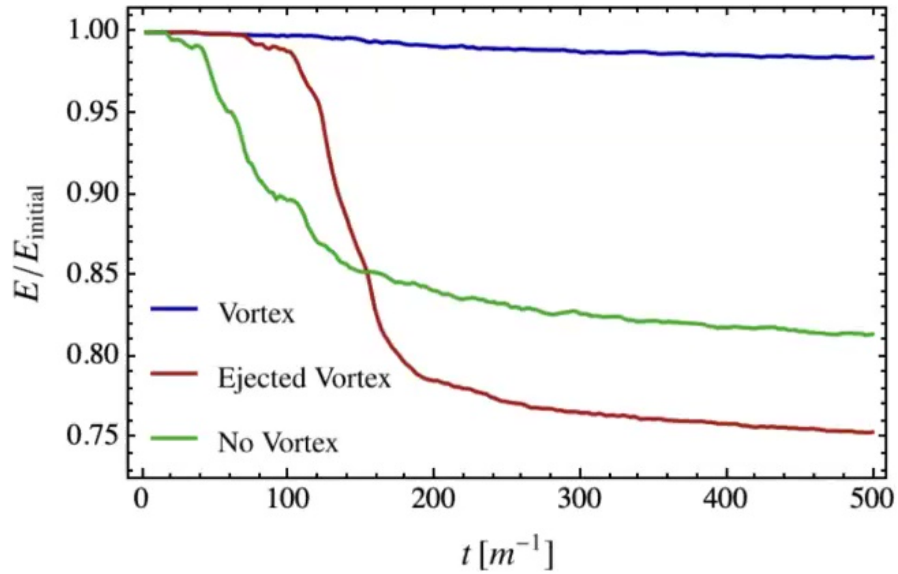
2+1D perspective

Energy and Spin evolve in a similar manner



- No Vortex: the solitons simply merge
- Ejected Vortex: the resulting soliton possesses a vortex for a while. Eventually it is ejected resulting in a close-to-zero spin configuration
- Vortex: almost no emission takes place in this case. The energy and angular momentum are invested in vortex formation

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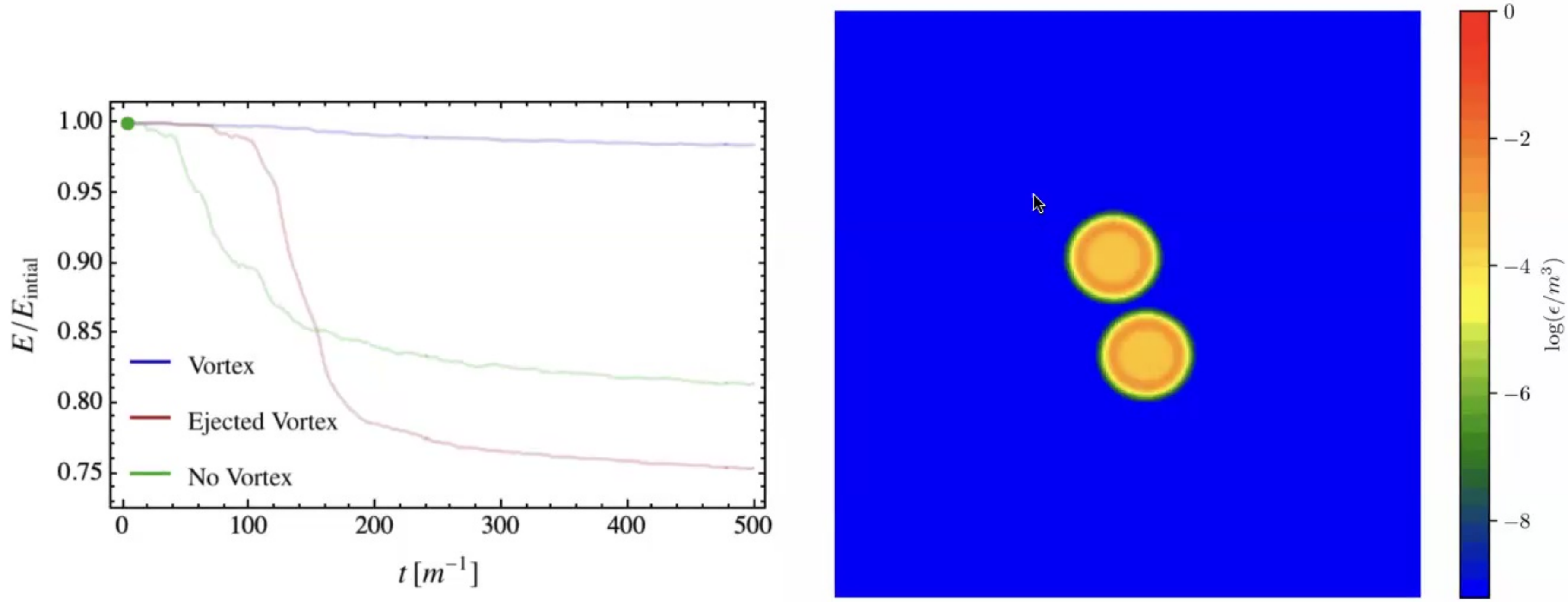
2+1D perspective

No-Vortex Case



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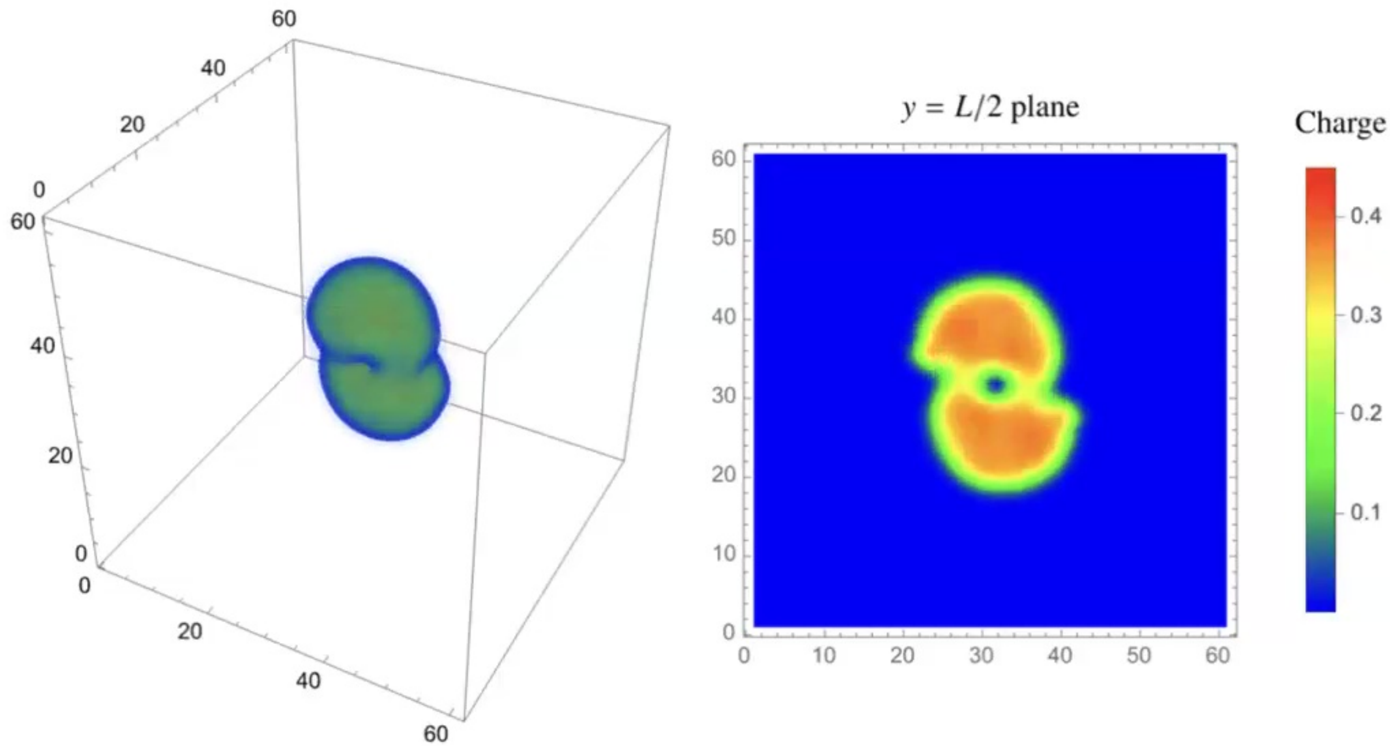
3+1D perspective

Vortex Case: Charge Evolution



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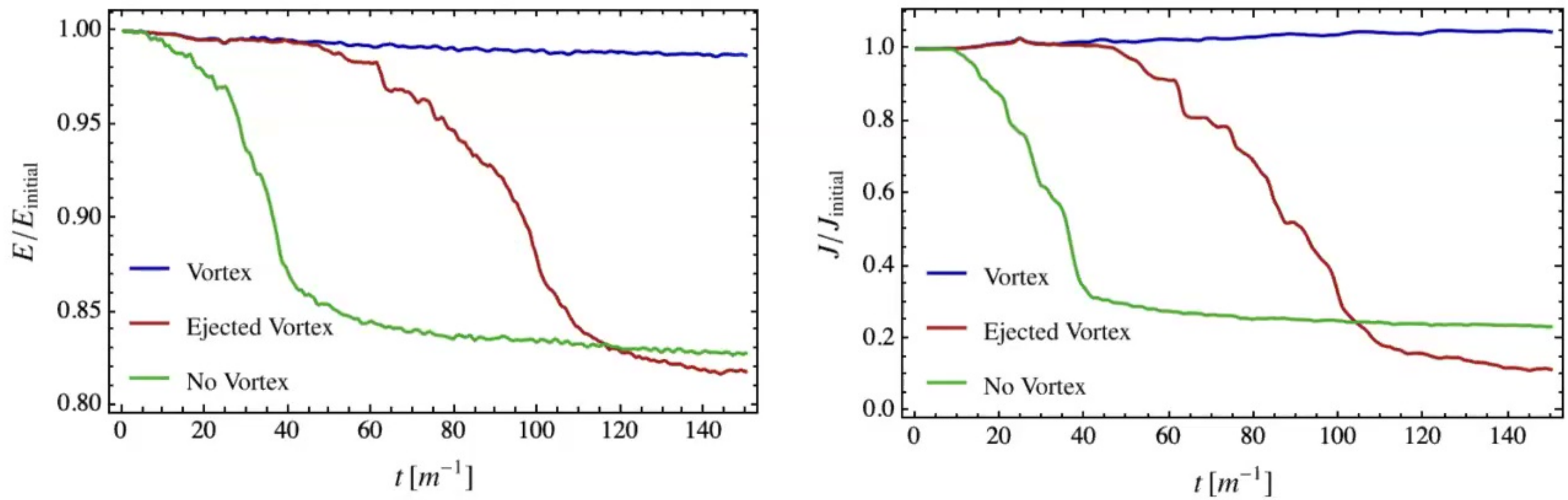
3+1D perspective

Energy and angular momentum evolve analogously to the 2+1D case



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Saturon cosmology

- Creation of ordinary macroscopic objects (e.g., solitons) from a homogeneous thermal bath is exponentially suppressed.
- For example, the bubble nucleation rate in ordinary first order phase transition (Linde, Nucl. Phys. B216, 421 (1983)):

$$\Gamma(T) \sim \exp\left(-\frac{E_{Bub}}{T}\right)$$

- Due to this, the bubbles are rare and by the time they meet each other, they are essentially classical.
- Saturon story is fundamentally different.

Saturon cosmology (G.D., [arXiv:2302.08353 [hep-ph]])

Notice that the standard suppression can be understood as the entropy suppression:

$$\Gamma(T) \sim \exp\left(-\frac{3\pi}{4} S_{rad}\right)$$

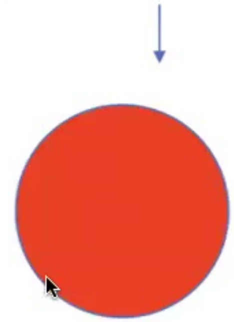
Saturon rate is enhanced by the saturon entropy which is much higher than the thermal entropy:

$$S_{sat} = S_{rad}\frac{3\pi}{2}(TR) \gg S_{rad}$$

The saturon rate saturates the unitarity of the process:

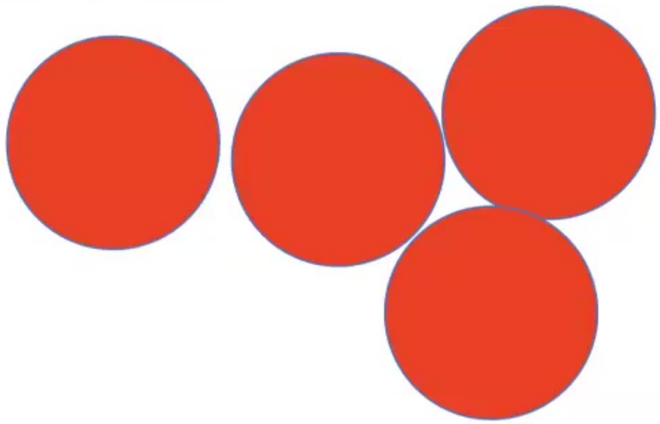
$$\Gamma(T)_{sat} = \Gamma(T)\exp\left(S_{sat}\right)$$

Saturon bubble of radius R



in thermal bath at temperature T

Due to saturation of unitarity, unlike ordinary first order phase transition, the saturon matter grows regardless of the bubble expansion due to vacuum energy difference.



The growth is due to a high creation rate thanks to maximal entropy of saturons.

The saturon transition is:

entropy-assisted

Notice that the theory is at arbitrarily weak coupling (the weaker the better!):

$$S_{sat} = \frac{1}{\alpha} \gg 1$$

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Optimal temperature for saturon nucleation:

$$T_* \sim \frac{1}{R}(S_{sat})^{\frac{1}{4}}$$

At this temperature the energy of the saturon of radius R matches the energy of the same-radius radiation bubble. At the same time, the saturon entropy is (much) higher.

$$E_{sat} = E_{rad}, \qquad S_{sat} \gg S_{rad}$$

The factor $\mathrm{e}^{S_{sat}}$ kills the suppression.

Saturons have several cosmological implications:

- Long lived saturons can offer a new type of macroscopic dark matter;
- They have advantage with respect to black holes which cannot be produced via quantum transition from the thermal bath;
- Saturons can assist in creation of primordial black holes;
- Saturons can be a new source of gravitational waves;
- Saturons make transitions with creation of solitons and topological defects more efficient.

QFT implications of saturons

They saturate unitarity in processes of the type:

$$few \rightarrow many$$

For example, a process $2 \rightarrow N$ at the point of optimal truncation $N = \dfrac{1}{\alpha}$

goes as: $\Gamma_{2\rightarrow N} \sim \mathrm{e}^{-\frac{1}{\alpha}}$

However, for saturon, $S_{sat} = \dfrac{1}{\alpha}$ the rate is enhanced as:

$$\Gamma_{few\rightarrow Saturon} \sim \mathrm{e}^{-\frac{1}{\alpha}}\mathrm{e}^{S_{sat}} \sim 1$$

Suppression of processes few-to-many

$$\Gamma_{few \to many} \sim e^{-\frac{1}{\alpha}}$$

explains why most of the macroscopic classical objects (e.g., solitons), despite of available energy, are produced with exponentially suppressed rates in collision processes.

This is because such objects represent coherent states with undersaturated microstate entropies:

$$S \ll \frac{1}{\alpha}$$

This has many important implications. We consider one example:

The erasure of defects.

Black hole as critical BEC:

G.Dvali, C.Gomez, '11, '12

$$H = \int dx\, \psi^{+} \frac{\hbar^2 \Delta}{2m} \psi - g^2 \psi^{+} \psi^{+} \psi \psi$$

Where

$$\psi = \int dk\, e^{-ikx} \hat{a}_k$$

Hamiltonian in terms of creation operators:

$$H = \sum_k k^2\, \hat{a}_k^\dagger \hat{a}^\dagger - \frac{\alpha}{4} \sum_{k_1+k_2-k_3-k_4=0} \hat{a}_{k_1}^\dagger \hat{a}_{k_2}^\dagger \hat{a}_{k_3} \hat{a}_{k_4}$$

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Bogoliubov approximation:

$$\langle \hat{a}_0^\dagger, \hat{a}_0 \rangle = N$$

$$\hat{a}_0^\dagger, \hat{a}_0 \rightarrow \sqrt{N}$$

Hamiltonian of Bogoliubov modes:

$$\hat{H}_B = \epsilon \sum_j \hat{b}_j^\dagger \hat{b}_j$$

Energy gaps:

$$\epsilon = \sqrt{1 - \alpha N}$$

Emergence of gapless modes at criticality:

$$N = 1/\alpha$$

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The overcritical BEC is a fast scrambler:

G. Dvali, D. Flassig, C. Gomez, A. Pritzel and N. Wintergerst, Phys. Rev. D 88, no. 12, 124041 (2013) [arXiv:1307.3458 [hep-th]]

The system develops Lyapunov exponent, L,
and scrambles (quantum breaks via maximal entanglement)
over time:

$$t_{scr} = L \ln(N)$$

Exactly as conjectured for black holes by Hayden and Preskill

P. Hayden and J. Preskill, JHEP 0709 (2007) 120, arXiv:0708.4025 [hep-th]

OUTLOOK

1. Black hole information properties are not specific to gravity: they are universal characteristics of the phenomenon of saturation: A maximal microstate degeneracy within the validity of the QFT description.

2. This universality allows us to understand the microscopic mechanism of quantum information storage and processing in black holes.

3. In addition, the objects saturating the bound on degeneracy, saturons, have various implications in particle physics and cosmology.

4. They allow to shed new light on known phenomena such as confinement in QCD.

5. They also predict new phenomena in QFT and cosmology.

6. Also, several effects such as erasure of defects can be understood in the light of undersaturation.