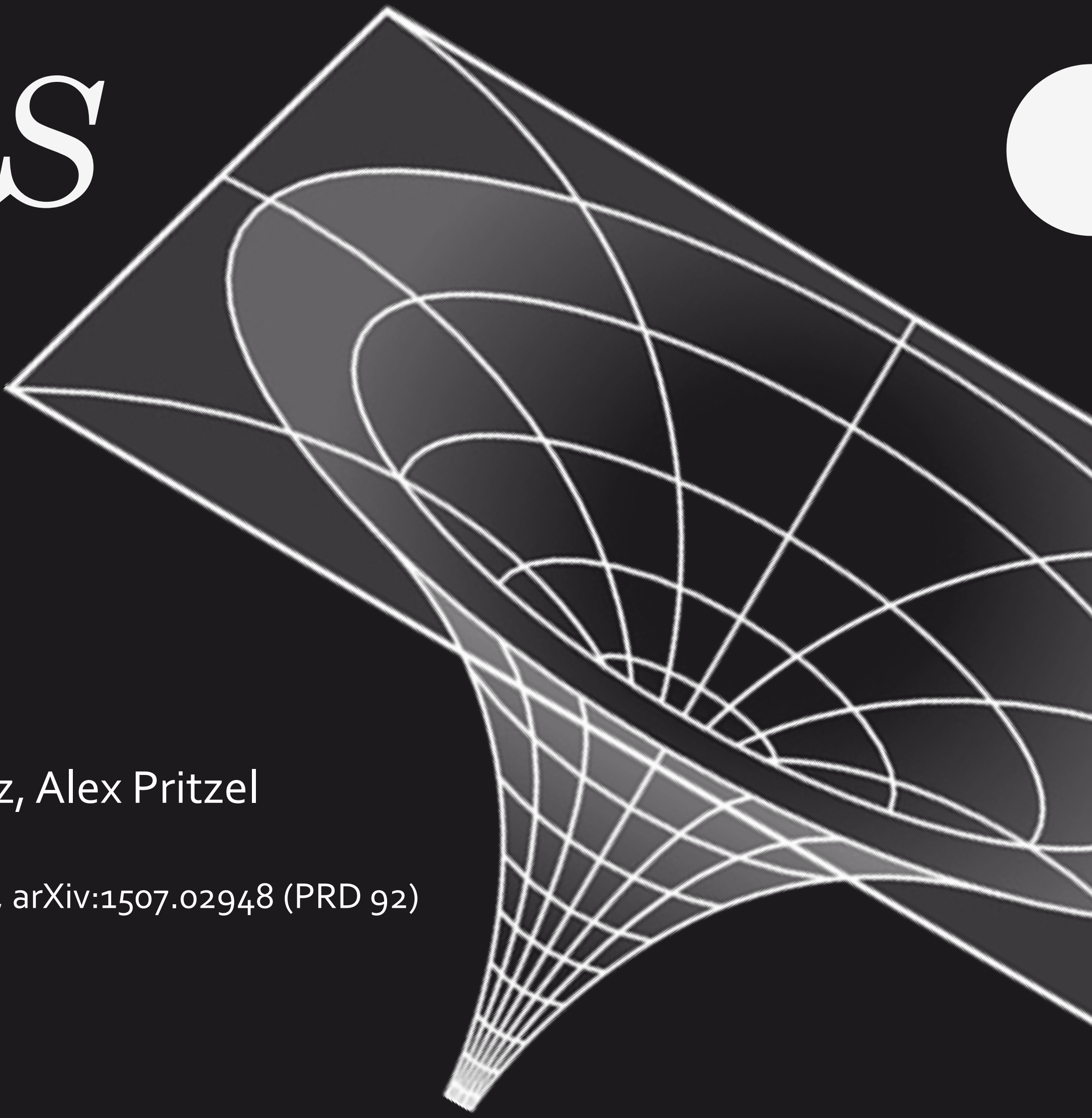
BLACK HOLES IN THE LAB

NICO WINTERGERST
STOCKHOLM UNIVERSITY



Work in collaboration with
Gia Dvali, Daniel Flassig, Tino Foit, Andre Franca, Cesar Gomez, Alex Pritzel

arXiv:1212.3344 (PRD 87), arXiv:1307.3458 (PRD 88), arXiv:1504.04384 (PRD 92), arXiv:1507.02948 (PRD 92)

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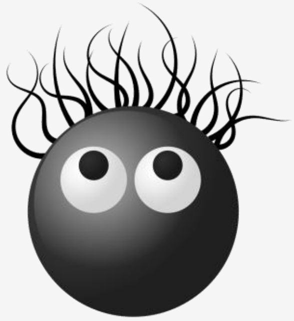
Black holes

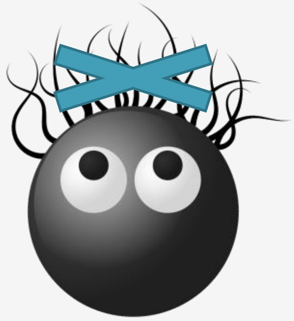


- In stationary state, characterized only by nontrivial asymptotic charges:

$$M,\ J,\ Q$$

- Evaporation: $T = \hbar/4\pi R_s = \hbar/8\pi G_N M$
- Implies entropy $T^{-1} = \frac{\partial S}{\partial M} \Rightarrow S = \frac{R_s^2}{\hbar G_N} = \frac{4A}{\ell_p^2}$
- Mass loss $\frac{dM}{dt} = -\frac{\hbar}{G_N^2 M^2}$, life time $t \sim \frac{G_N^2 M^3}{\hbar}$
- Scrambling: Information entering a black hole scrambled amongst essentially all degrees of freedom in logarithmic time $t_s \sim R_s \log S_{\rm BH}/\hbar$
- Fast entanglement generation. Fastest in nature?

Black holes



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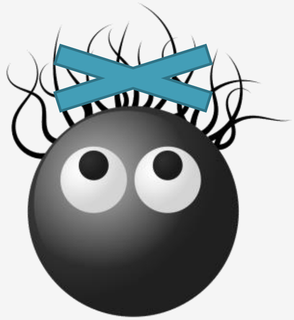

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But not all is great…

Semiclassical limit $G_N \to 0,\ M \to \infty,\ R_s$ fixed. $S \to \infty$

Mass loss for finite M actually implies loss of unitarity. Pure states turned into mixed states.

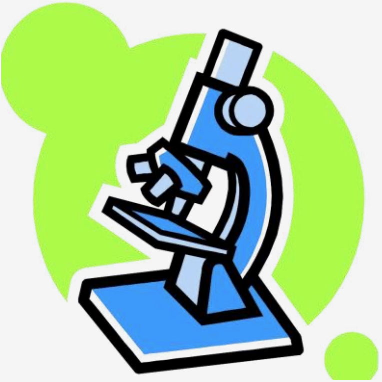
Simple extrapolation from $S = \infty$ to finite S inconsistent.

So how about finite S?

Inspiration from Condensed Matter: Physics of quantum phase transitions

Aspects of black hole information

- Trapping
- Baldness
- Entropy
- Evaporation
- Scrambling
- Quantumness

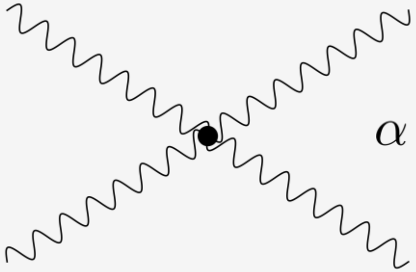


Towards a microscopic description

- Conjectural guideline: Identify light modes with Bogolyubov modes of a quantum critical Bose condensate of (longitudinal) gravitons of wavelength R_s. (Dvali, Gomez)
- N identified with the mean number of gravitons in the condensate.

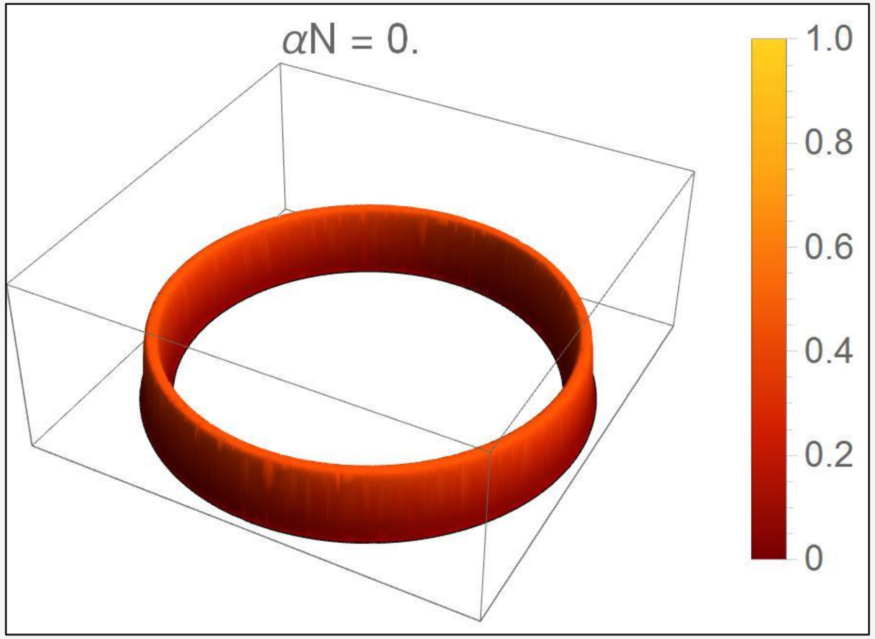
$$N \sim R_s^2/\ell_p^2$$

- Implies that *universally*, for any black hole $\langle \alpha \hat{N} \rangle \sim 1$
- QUANTUM CRITICALITY -- guideline for black hole physics?
- Allows to reproduce properties in much simpler systems, namely atomic Bose condensate.
- These model systems are so simple that they can be, and are being, prepared in labs!



$$\alpha \sim \ell_p^2/R_s^2$$

Lieb-Liniger model



- 1+1d model of nonrelativistic bosons on a ring with attractive interactions.
- Quantum phase transition when varying the strength of the attractive collective coupling αN
- Homogenous ground state for small αN
- At $\alpha N = 1$, homogenous ground state is destabilized. Formation of "bright soliton"
- Hamiltonian in 2nd quantized version:

$$H = \int d\theta\, \psi^\dagger (-\frac{\partial_\theta^2}{2m})\psi - \alpha|\psi|^4 - \mu(|\psi|^2 - N)$$

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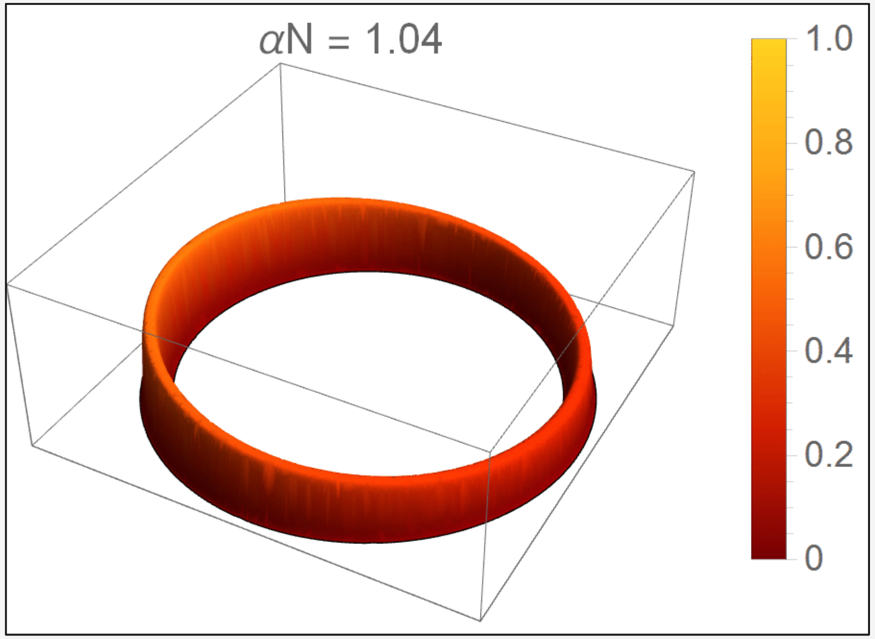

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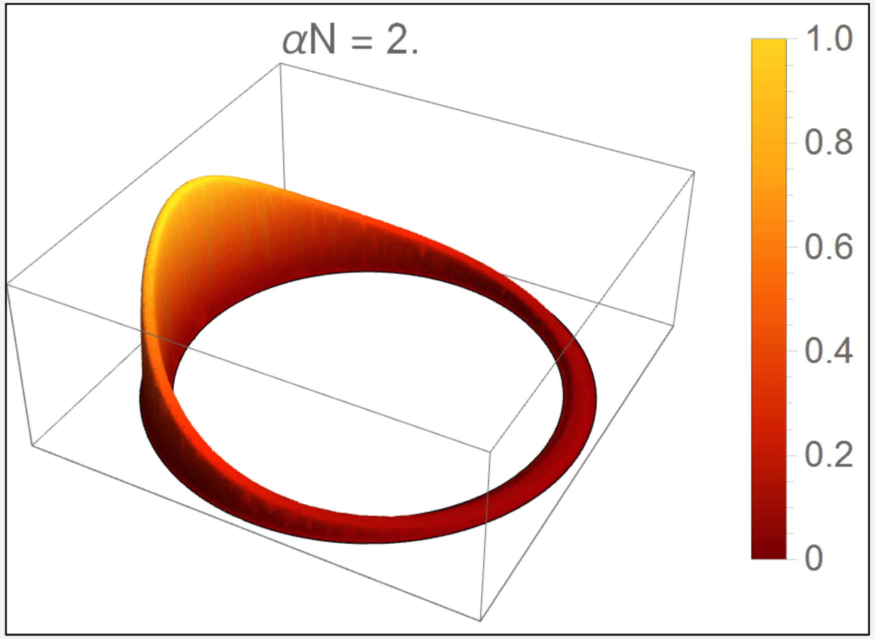

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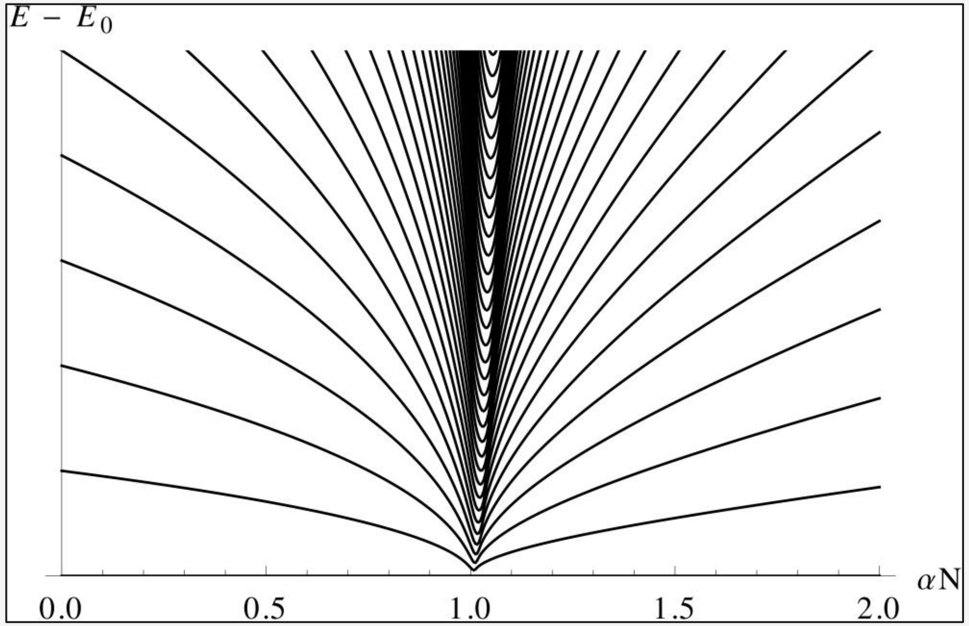
Goldstone modes



- LL Hamiltonian of lowest modes can be written as SU(3) invariant Hamiltonian with explicit breaking

$$H = H_{SU(3)} + H_{br}$$

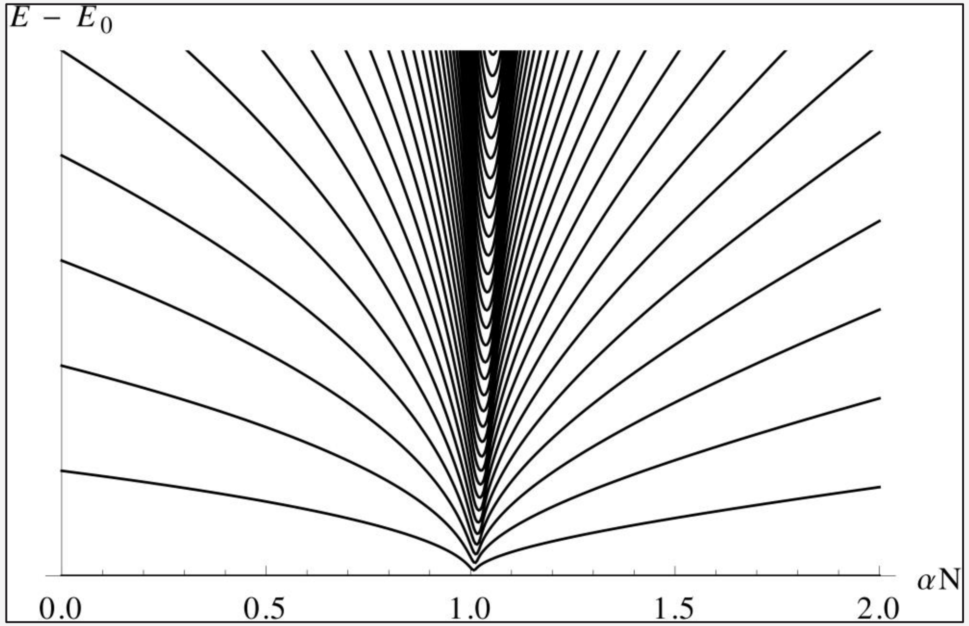
- Particle number breaks SU(3) symmetry down to U(1) → pseudo-Goldstone doublet due to explicit breaking
- For $\alpha N = 1,\ H_{br} = 0$. Light mode becomes massless.
- Effective Hamiltonian around critical point

$$H_{Gold} \sim (n_{gold})^2 \alpha_{gold} + n_{gold} m_{gold}^2$$

→ gap $\Delta \sim \frac{1}{N} \left(\frac{\hbar^2}{2R^2 m} \right)$

- LL only one light mode, but simple extensions can supply $\mathcal{O}(N)$ modes with gap $1/N$
- Entropy $S \sim N$
- Decoupling as $1/N$→ "no hair"

Goldstone modes
Entropy and no hair



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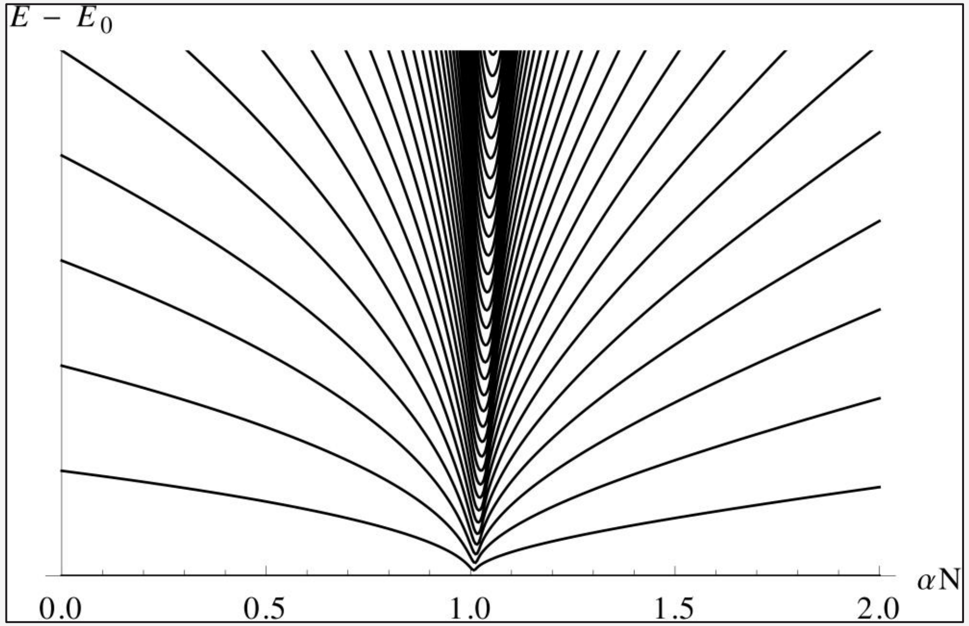

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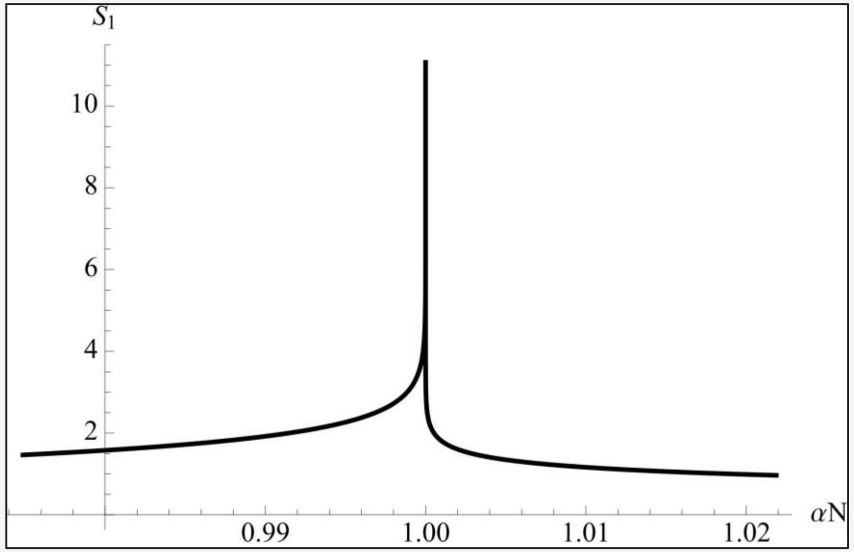
Quantumness



- Ground state at critical point characterized by large quantum fluctuations
- Fluctuations δa_k for low k strongly entangled in GS
- Breakdown of mean field theory despite large N, large macroscopic quantumness!
- Superposition of classical field configurations
- Testable through engineering appropriate coupling to external modes, e.g. magnetic field, …

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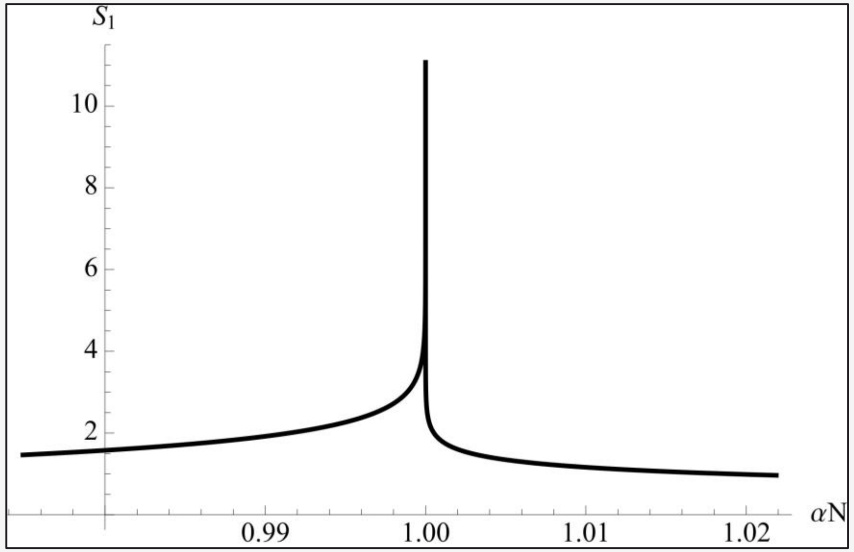

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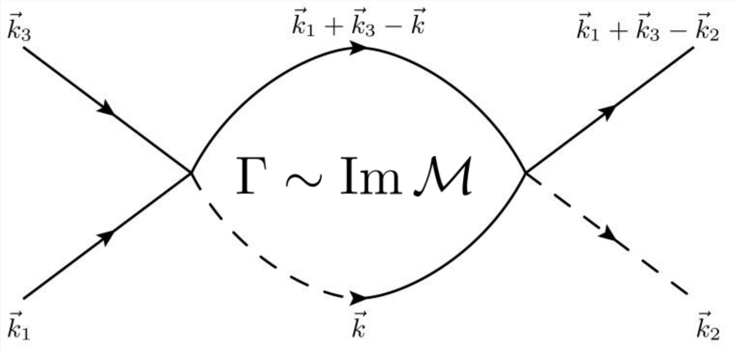
Particle loss and collapse



$$\dot{N} = -\int \Gamma(\mathbf{k}_1, \mathbf{k}_2)\phi^\dagger_{\mathbf{k}_1}\phi_{\mathbf{k}_2}$$

- Physical picture for condensate evaporation: Condensate modes scatter, eject on-shell particle
- Scaling solutions $R_c(N) \sim \Lambda^{-1}\sqrt{a_0 N} \Rightarrow \alpha N \sim 1$
- Time dependence corresponds to Hawking loss law:

$$\dot{R}_c \sim -\frac{1}{\Lambda^2 R_c^2}$$

- Process of course unitary. Backreaction included. ☺
- Emission of other degrees of freedom suppressed by N'/N Trapping.
- Can in principle be tested in labs (Bosenova, ...)
- <u>Use Feshbach resonance to tune self-interaction to maintain criticality.</u>

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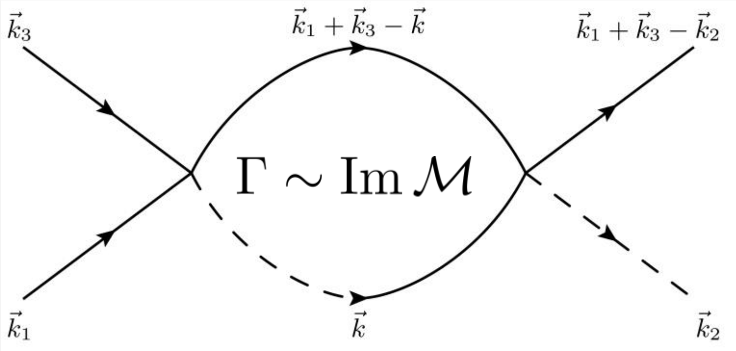

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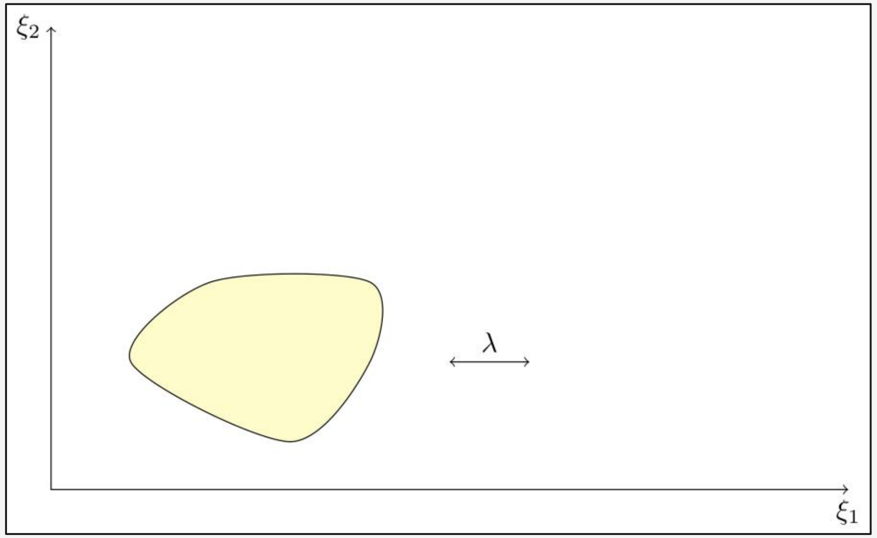
Scrambling BECs

Instability implies Entanglement

- Phase space instability with positive Lyapunov coefficient λ
- In QM, no compression beyond $\hbar$ -> quantum breaking after

$$t_{\rm br} \sim \lambda^{-1} \log S/\hbar$$

- For critical BEC analogous mechanism, with $S \sim \hbar N$
- LL after quantum quench to $\alpha N > 1$, monitor entanglement entropy
- In 3+1d $\lambda = R$
- Agrees with scrambling time!
- Again testable by quenching through Feshbach resonance



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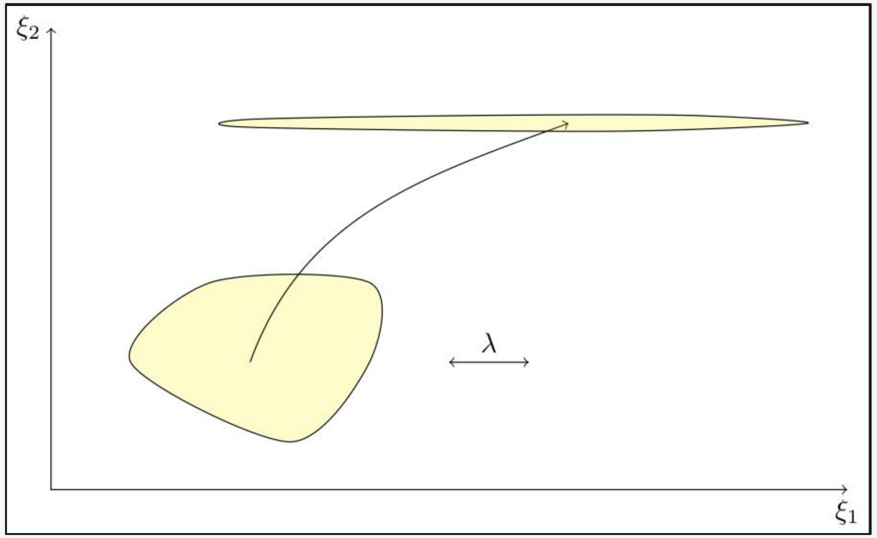

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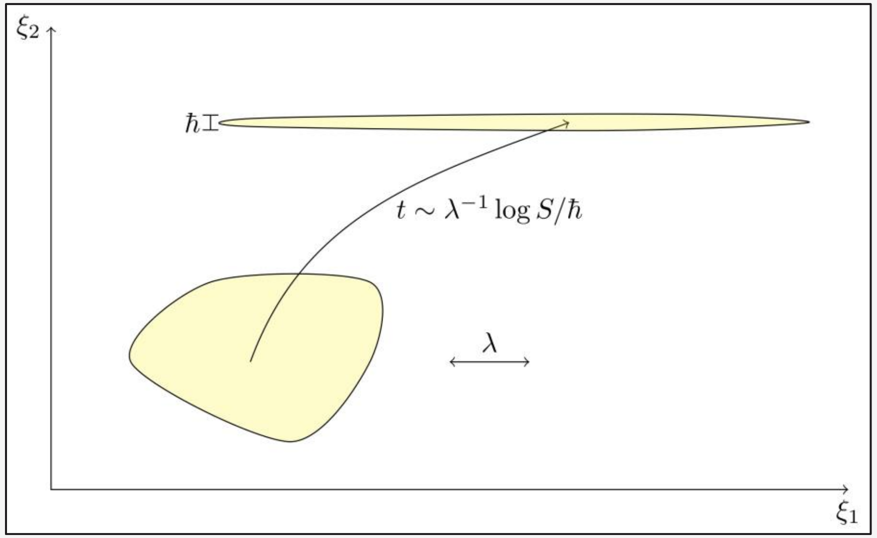

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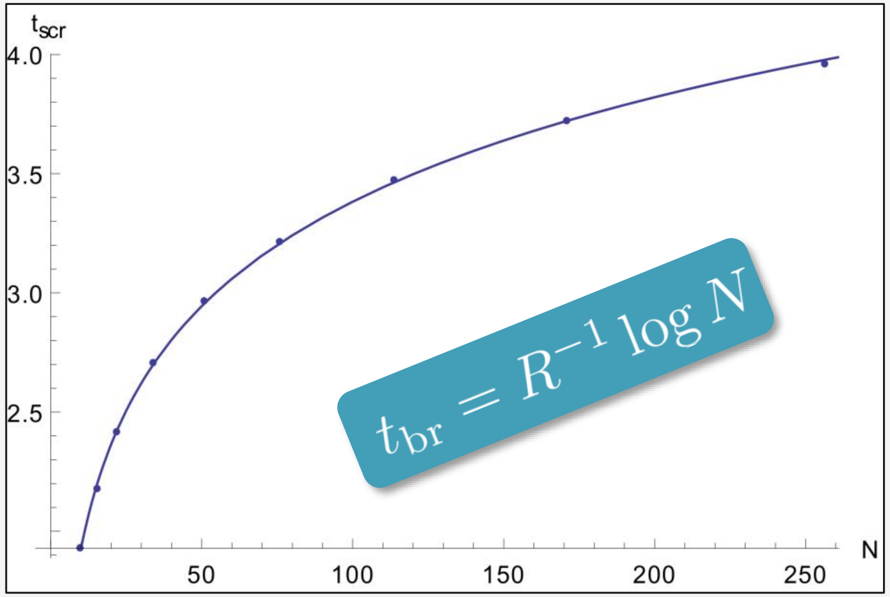

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Conclusions

- Quantum criticality responsible for many BH properties in lab systems:
  - Trapping
  - Baldness and decoupling
  - Entropy
  - Temperature and evaporation
  - Quantumness
  - Scrambling
- Many of these properties can be experimentally tested with current technology.

Many other results and open questions

- What to learn about gravity? Useful description of BH as BECs?
- Black hole formation both through collapse and high energy scattering. Model as condensate formation?
  (Dvali, Gomez, Lüst, Stieberger, Isermann; Kühnel, Sundborg)
- Nonperturbative understanding of black holes as bound states. (Hofmann, Rug, Gründing, Müller)
- Global charges.
  (Dvali, Gomez; Gußmann; Kühnel, Sandstad)
- Goldstone modes and broken gauge symmetries
  (Averin, Dvali, Gomez, Lüst, Zell)
- Observation!
- Construct thermalizing Bose condensates and measure them!