Title: Ergoregion instability: the nonlinear story

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Collection/Series: Charting the Future Symposium

Subject: Cosmology, Particle Physics, Strong Gravity

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Abstract:

Compact, spinning, and horizonless spacetimes can develop an ergoregion, where massless negative-energy states are quasi-trapped and drive the ergoregion instability. I will briefly review the linear mechanism and then describe recent progress in understanding the nonlinear evolution. Nonlinear mode coupling can amplify high-frequency modes through a turbulent direct cascade inside the ergoregion. Gravitational backreaction leads to an enhancement of the unstable process, and ultimately, black hole formation. I will illustrate the relevant dynamics and discuss implications for strongly gravitating horizonless systems.

Charting the Future Symposium

Ergoregion instability: a nonlinear story

Nils Siemonsen
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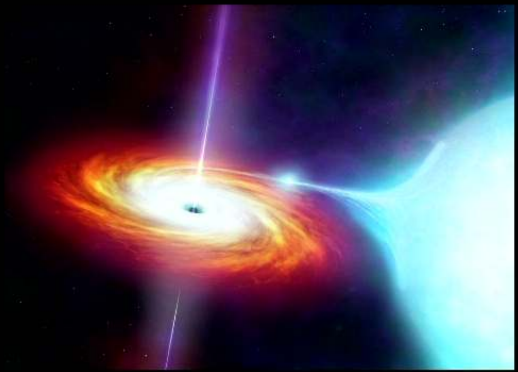
August 28, 2025

Princeton gravity Initiative

Discovery of black holes in 1960s/70s:

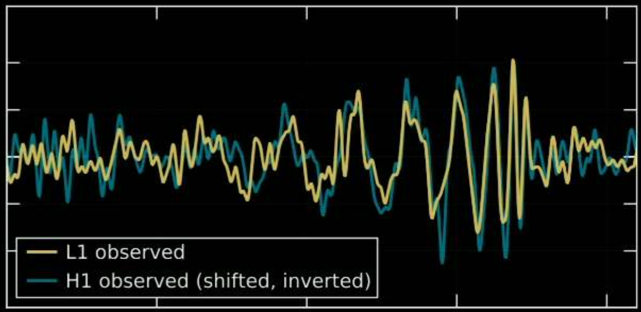
- X-ray sources with companion star
- Extremely luminous and distance objects
- Compact and massive ⇒ black hole



Today:

- Almost every galaxy is believed to host supermassive black hole
- Milky way is estimated to harbor $\sim 10^8$ stellar-mass black holes

[LSC, 2016]



Gravitational waves:

- First detection of gravitational waves
- Theoretical modelling of black hole mergers

⇒ Must be black holes

Observational tests of the black hole paradigm:

- LIGO-Virgo-KAGRA: null tests
- Search for residual power in detector
- Spin-induced quadrupole or tidal effects

Theory:

- How do objects need to look like to be consistent with the data?
- Classify by compactness $C = GM/(c^2 R)$
  - Newtonian object: $C \ll 0.1$
  - Neutron star: $C \sim 0.1$
  - Black hole: $C = 0.5$
  - $\Rightarrow$ Object needs to have $C \lesssim 0.5$

$\Rightarrow$ How do ultra compact objects behave?

Act I:
The Ergoregion Instability

Take massless scalar Φ to explore structure of these objects:

$$\Box_g \Phi = 0.$$

Expand as

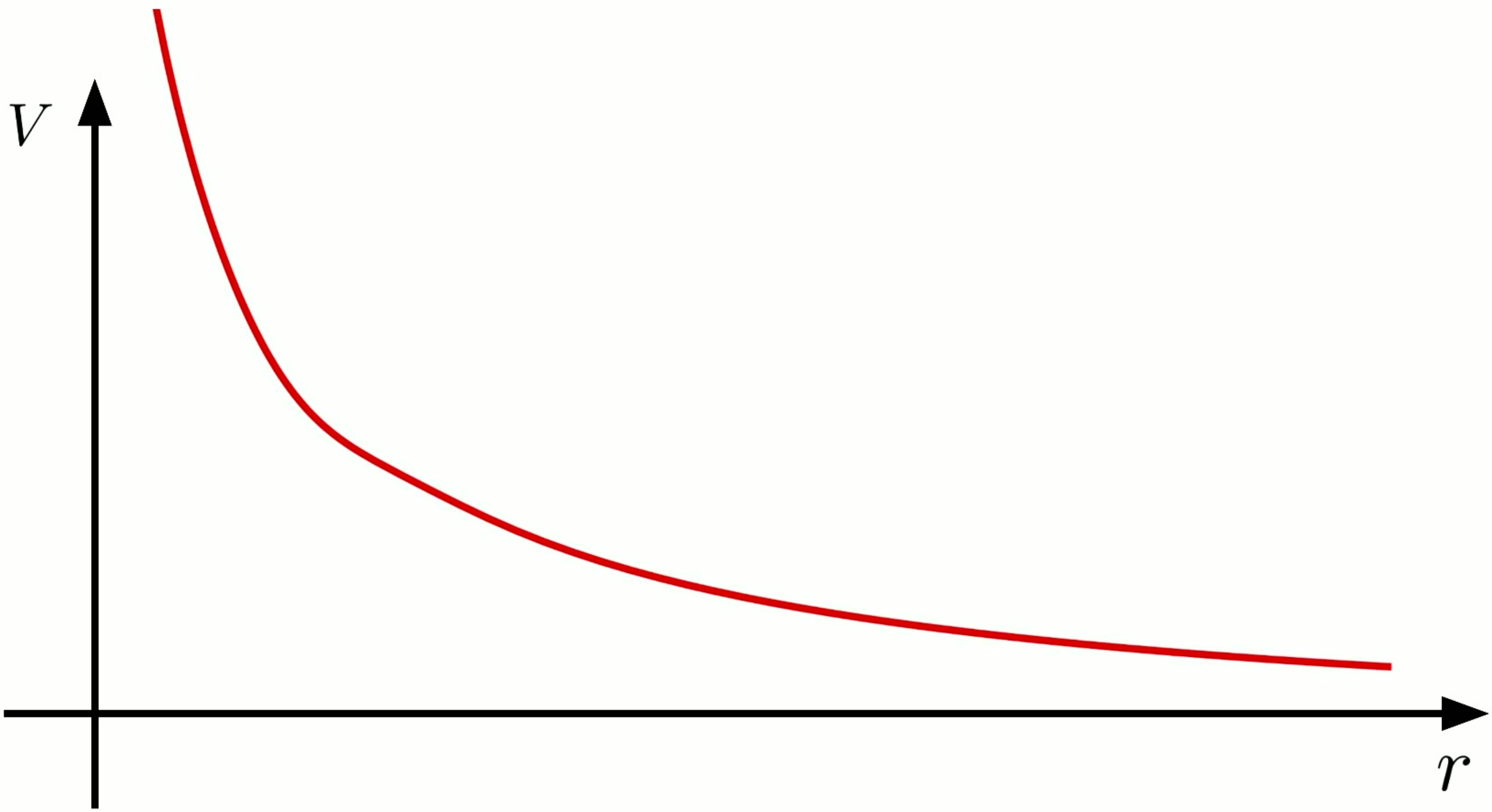
$$\Phi = \frac{1}{r} \sum_{\ell,m} \phi_{\ell m}(t,r) Y_{\ell m}(\theta, \varphi).$$

Then each mode follows:

$$\mathcal{D}\phi_{\ell m} = V_{\ell m} \phi_{\ell m},$$

where

$$V_{\ell m} \sim \frac{\ell(\ell+1)}{r^2} + \text{curvature}.$$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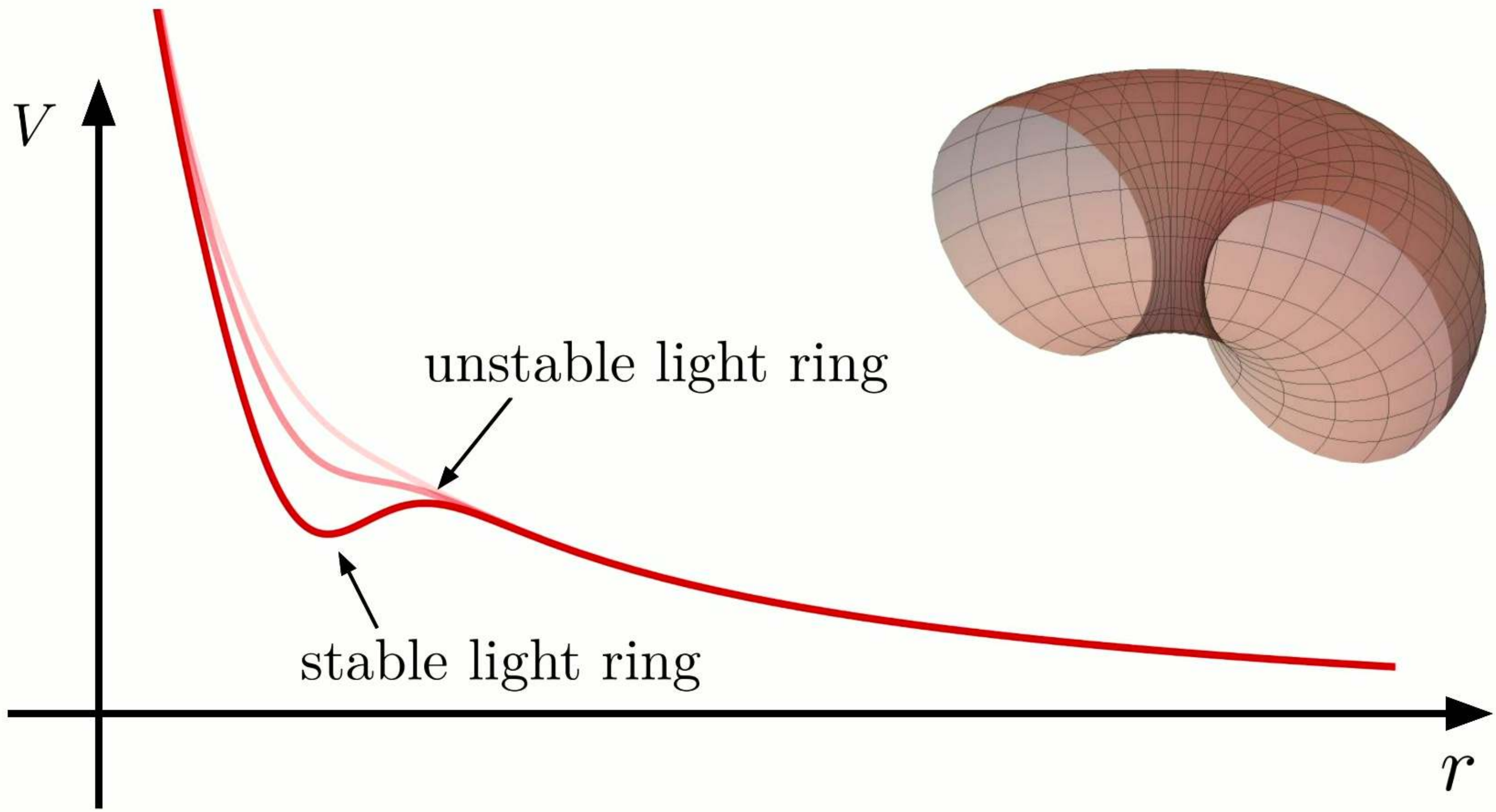
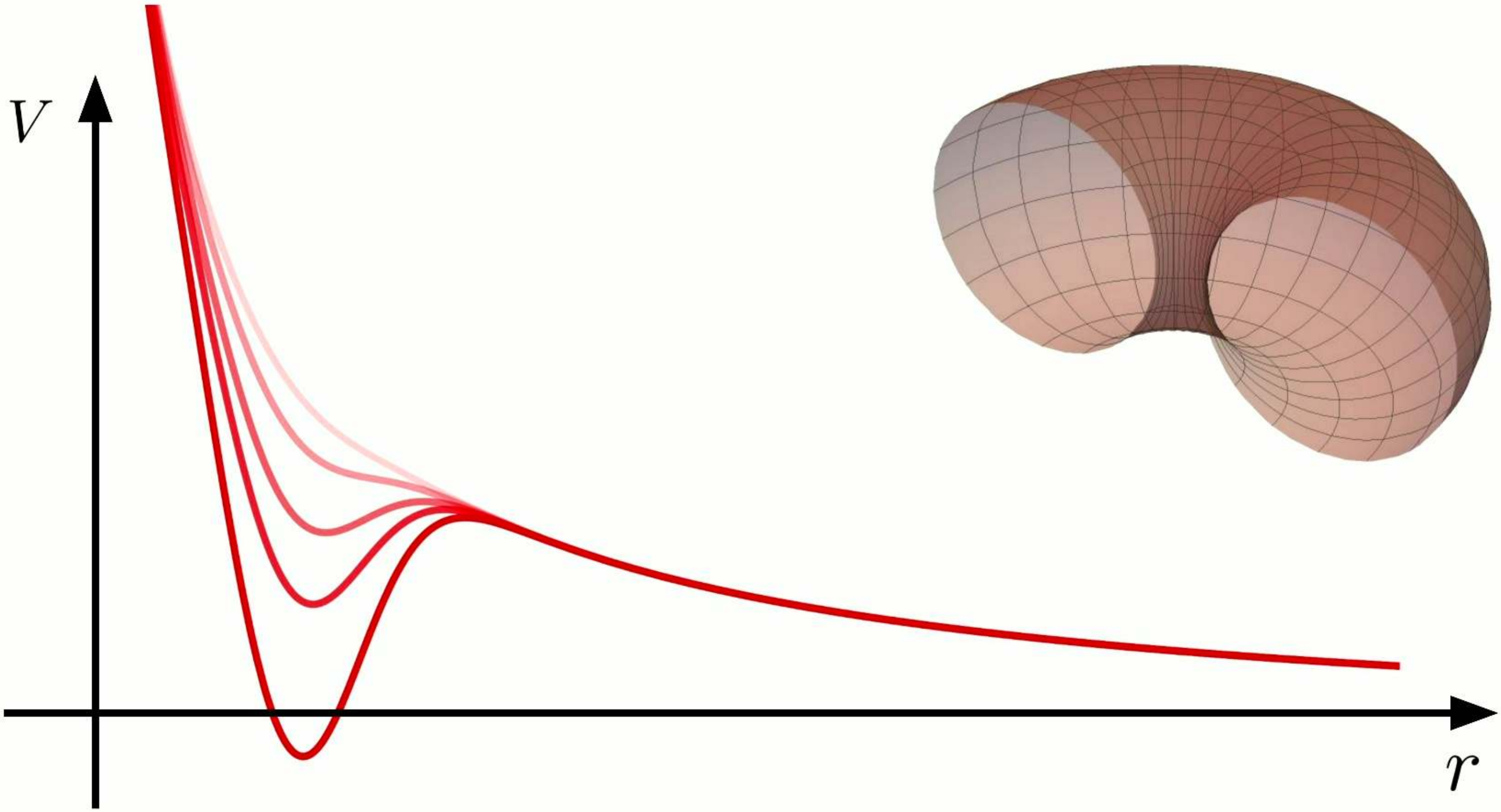
r


V
unstable light ring
stable light ring
r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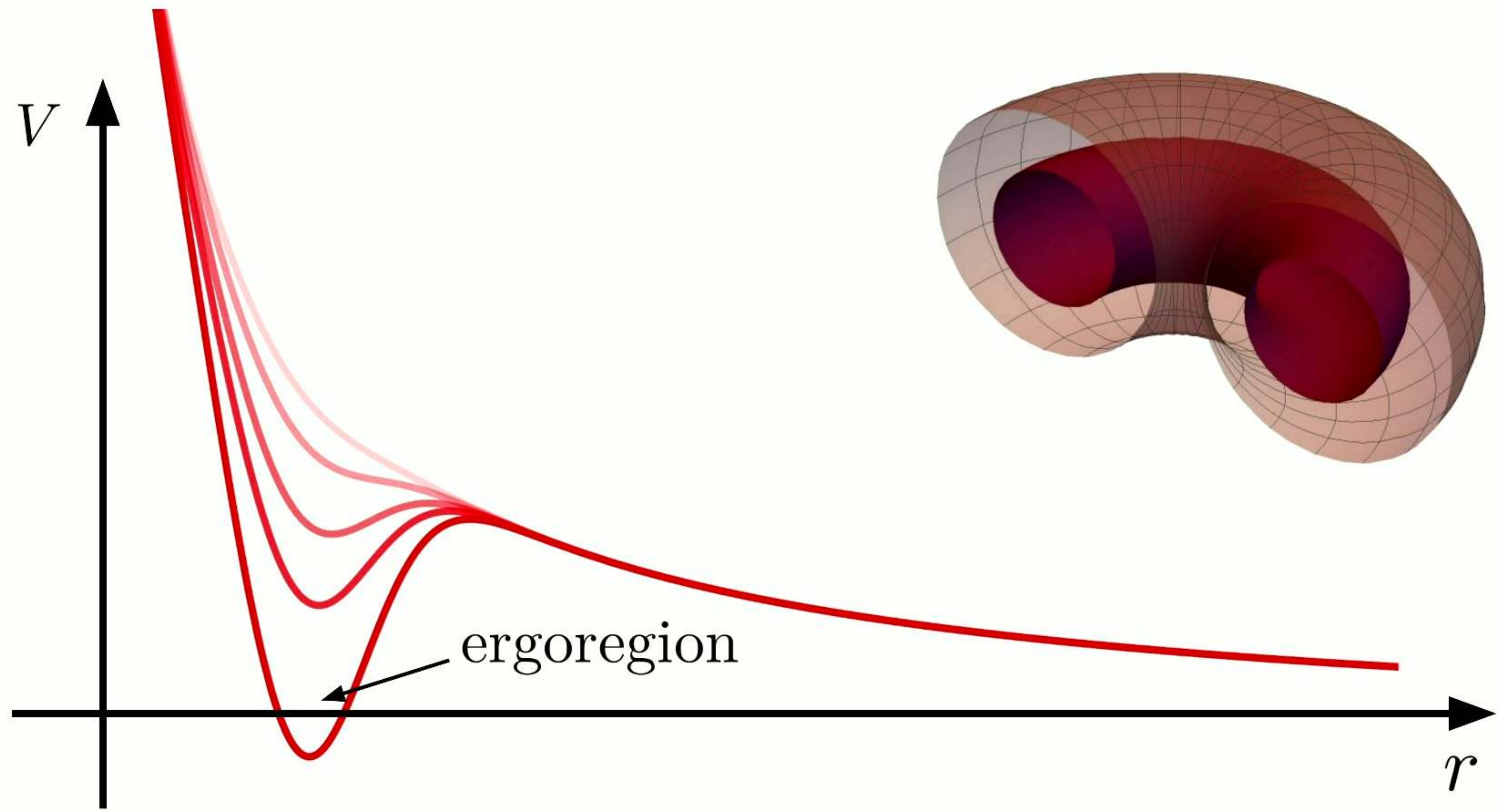
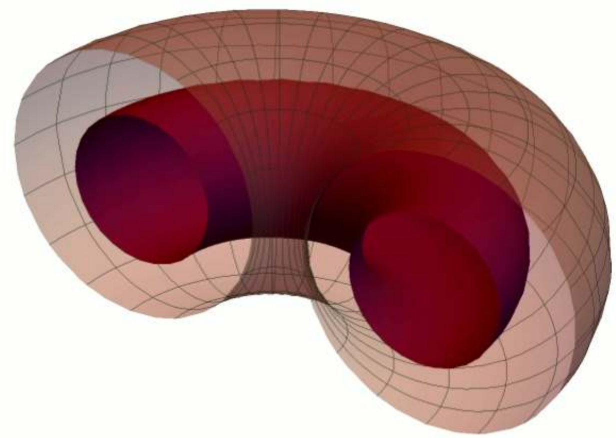

V
ergoregion
r

Ergoregion instability: Friedman (1978)

- Horizonless asymptotically flat spacetime with compact ergoregion
- Time-dependent massless field configurations with negative energy
- Radiating positive energy flux to infinity
- Energy conservation $\Rightarrow$ Unbound growth of negative energy

More precisely:

- $\phi_{\ell m} \sim e^{im\varphi} e^{i\omega t}$
- $\exists m_0 > 0$, such that all $\ell = m \geq m_0$ are unstable
- Field modes grow with e-folding time τ_ℓ^{EI}



Nonlinear evolution:

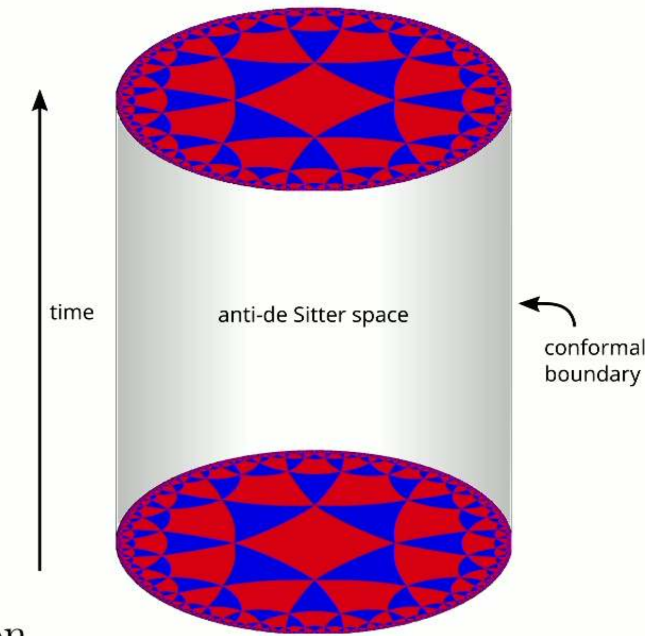
$\Rightarrow$ Essentially unknown except for naive expectations


Act II:
Turbulent Times

Conjectured nonlinear instability: Keir (2014)

- Stable light rings quasi-trap massless fields
- Nonlinear effects have time to build up

⇒ May induce nonlinear departure



Nonlinear instability of AdS: Bizon & Rostworowski (2011)

- Perfect trap for massless perturbations
- Massless scalar testfield bounces back and forth
- Weak turbulence building up direct cascade
- Strongly nonlinear effects lead to black hole formation

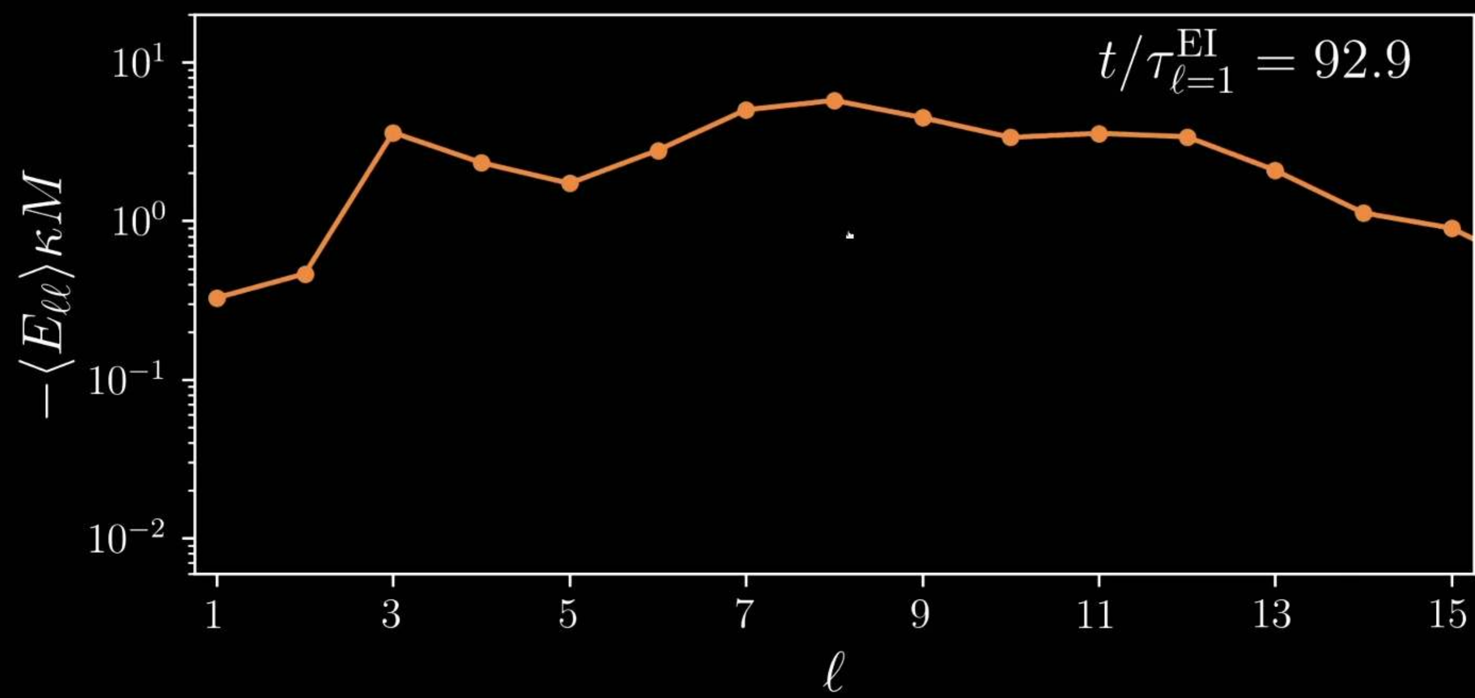
Turbulence in stable light rings: Benomio et al. (2025), Redondo-Yuste et al. (2025)

- Scalar toy model with $\sim \phi^4$ interaction
- Small initial data are laminar
- Large initial data exhibit direct energy cascade

Turbulent saturation of instability

NS in prep.

$$\Box_g \Phi = \kappa \Phi |\Phi|^2$$



Take-aways
NS in prep.

1. First nonlinear evolution of the ergoregion instability
2. Turbulent direct energy cascade
3. Nonlinear transfer time $\tau_\ell^{\mathrm{NL}} \gtrsim \tau_{\ell=1}^{\mathrm{EI}}$
4. Toy model for gravity

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Act III:
An Unexpected Ending

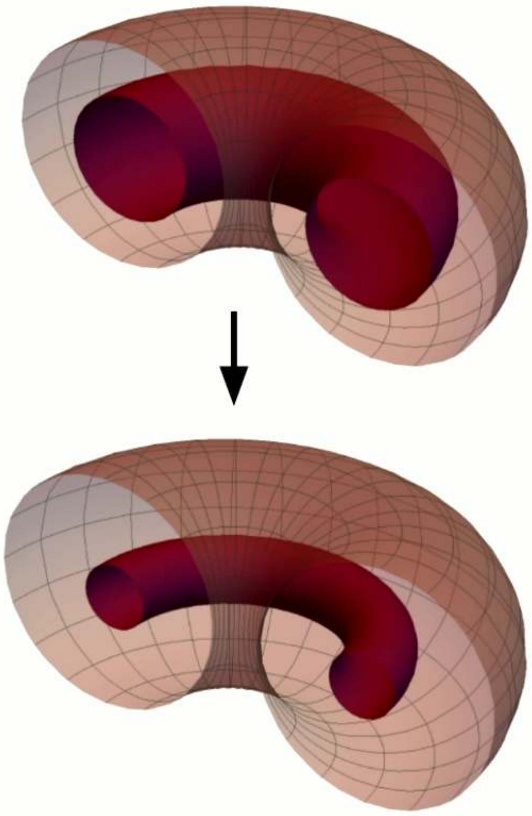
Expectation

Adiabatic nonlinear evolution:

- Emission of energy and angular momentum
- Slow spin-down of object
- Terminate spin-down, when ergoregion is small

Observational inferences:

- Observation of highly spinning objects
- Absence of gravitational wave background

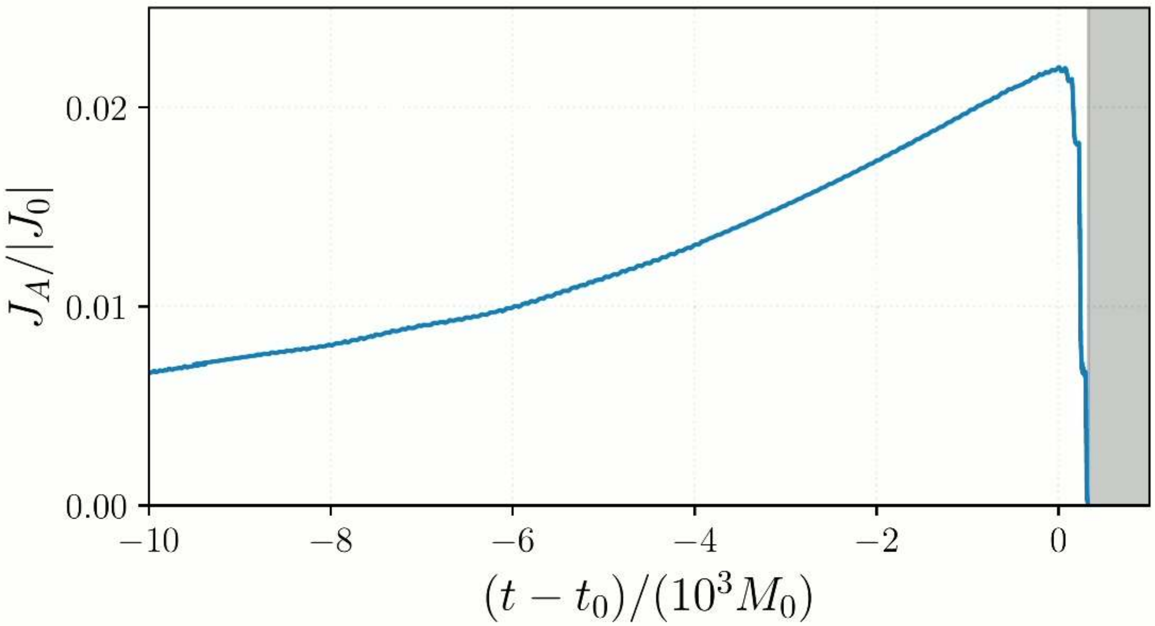


Nonlinear gravitational saturation

NS & East, in prep.

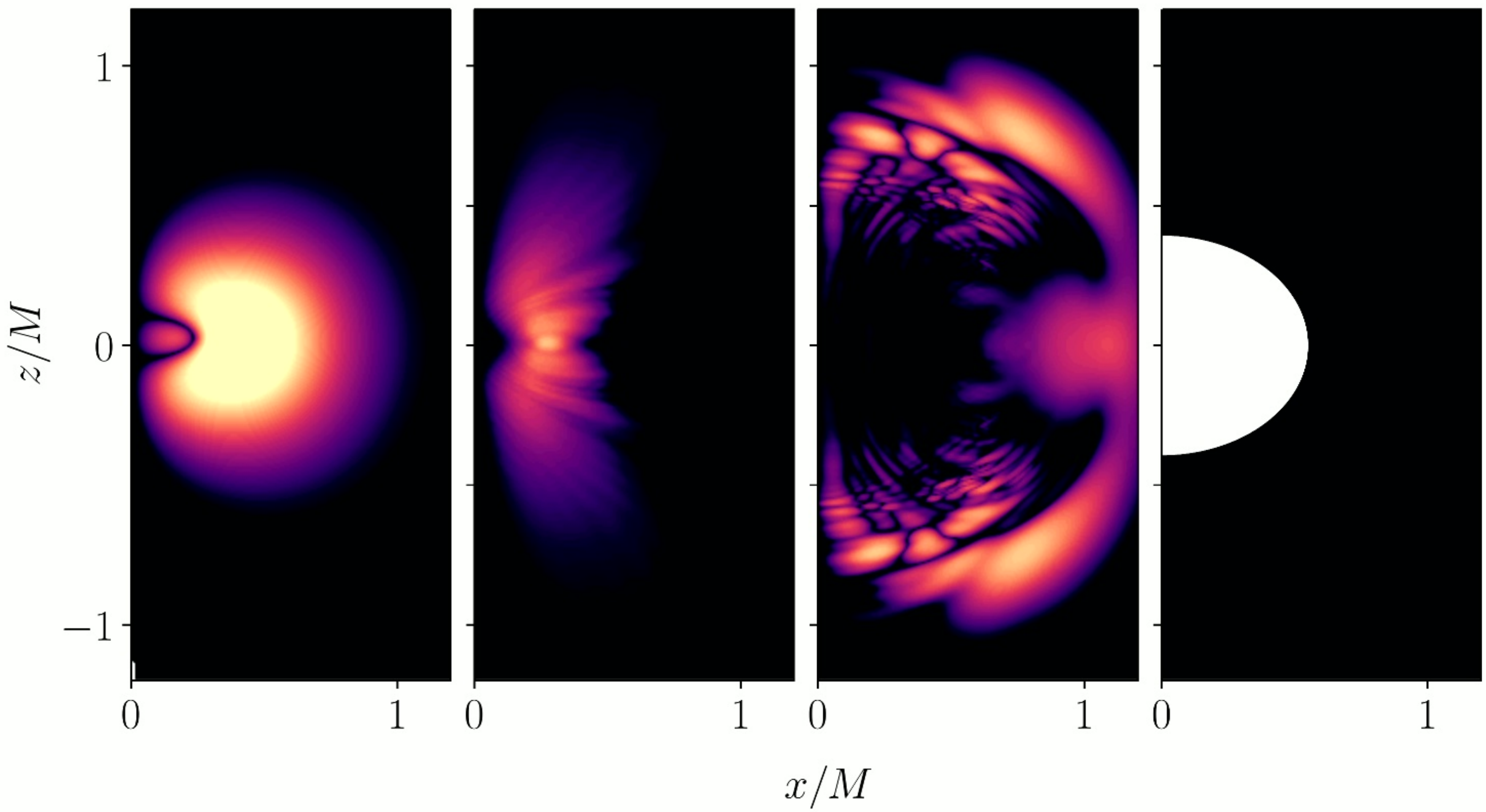
Ingredients:

- Ergostar + Numerical Relativity ⇒ Boson stars
- Massless vector unstable probe field A_μ
- Initialize A_μ in linear regime



Gravitational turbulence

NS & East, in prep.



Summary

1. Ergoregion instability major player in ultra compact objects
2. Weakly turbulent saturation of scalar ergoregion instability
3. Hints for gravitational turbulence during instability saturation
4. Gravitational backreaction leads to black hole formation