SISSA APG Seminar

# Ergoregion instability: the nonlinear story

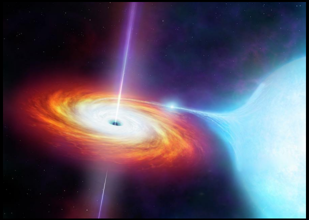
**Nils Siemonsen**
Princeton Gravity Initiative

February 5, 2026

Princeton gravity Initiative

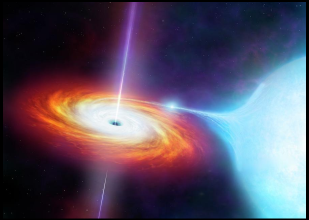
Discovery of black holes in 1960s/70s:

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



Discovery of black holes in 1960s/70s:

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

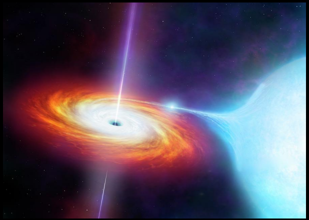


Today:

- Most galaxies are believed to host supermassive black hole
- Milky way is estimated to harbor $\sim 10^8$ stellar-mass black holes

Discovery of black holes in 1960s/70s:

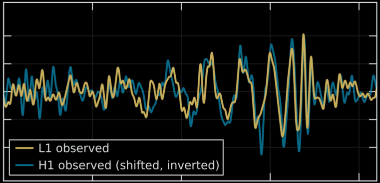
- X-ray sources with companion star
- Extremely luminous and distance objects
- Compact and massive $\Rightarrow$ black hole



Today:

- Most galaxies are 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

$\Rightarrow$ 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

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?

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 $C \lesssim 0.5$

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 $\Phi$ to explore structure of these objects:

$$\Box_g \Phi = 0.$$

Expand as

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

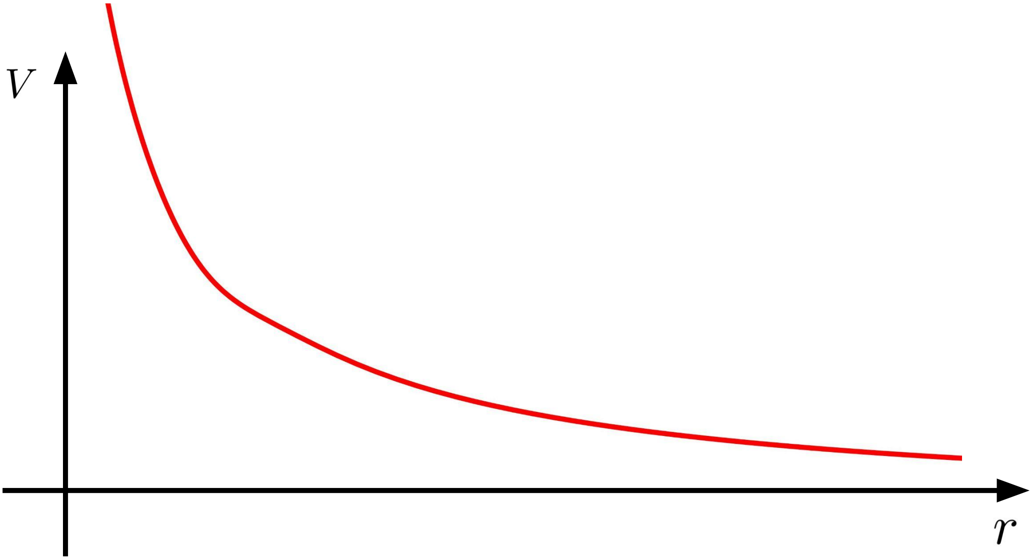
Then each mode follows:

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

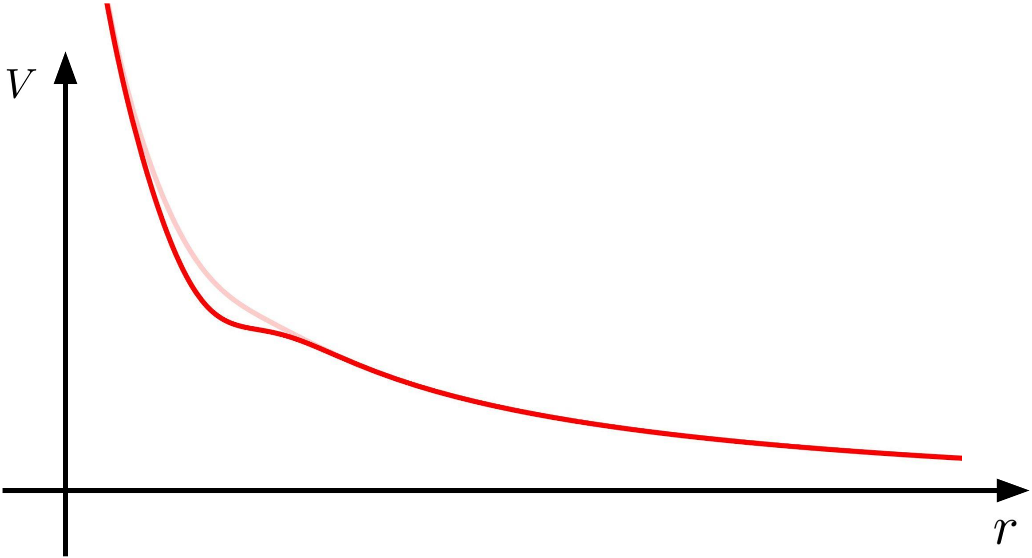
where

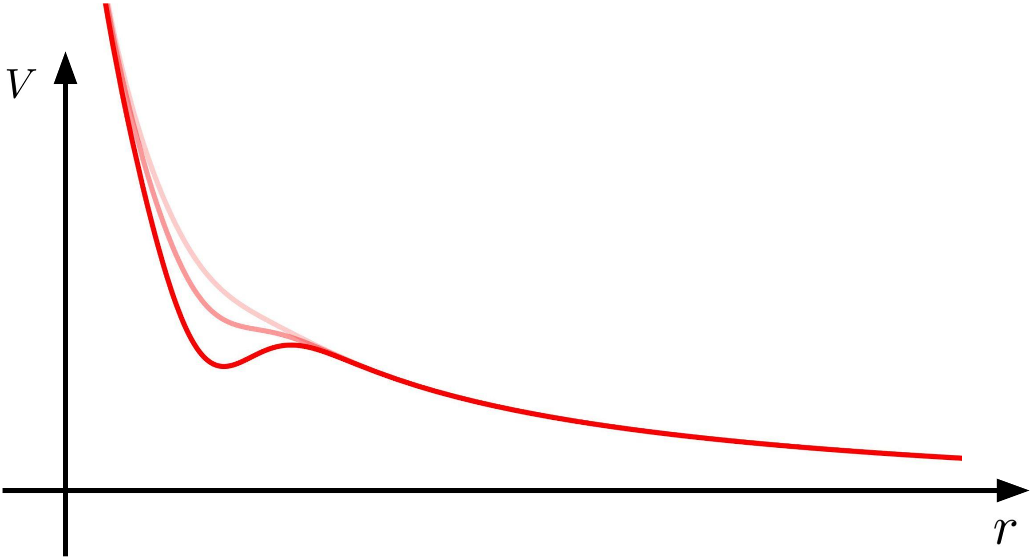
$$V_{\ell m} \sim \frac{\ell(\ell+1)}{r^2} + \text{curvature}.$$

Correspondence between the eikonal limit of the scalar field ($\ell \to \infty$) and null geodesics.

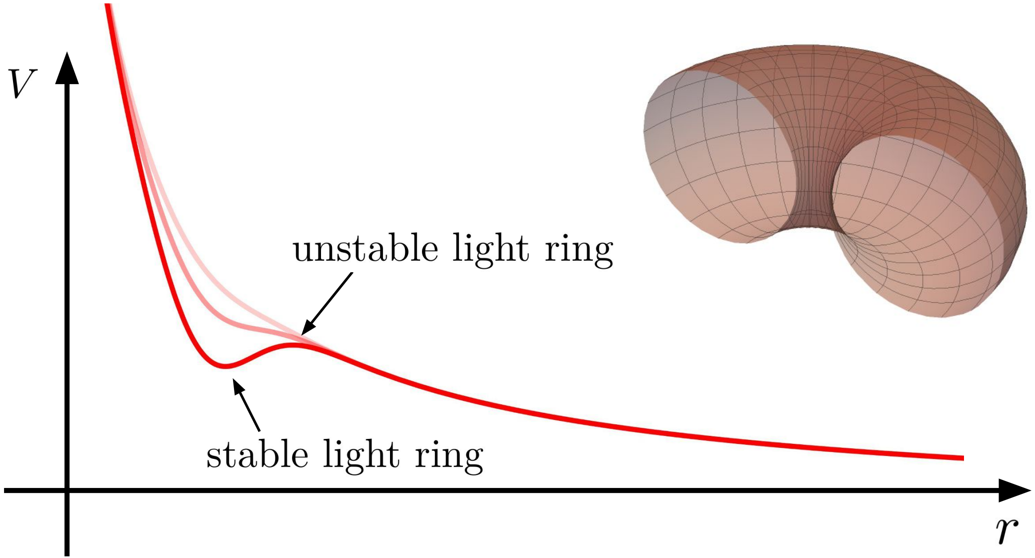


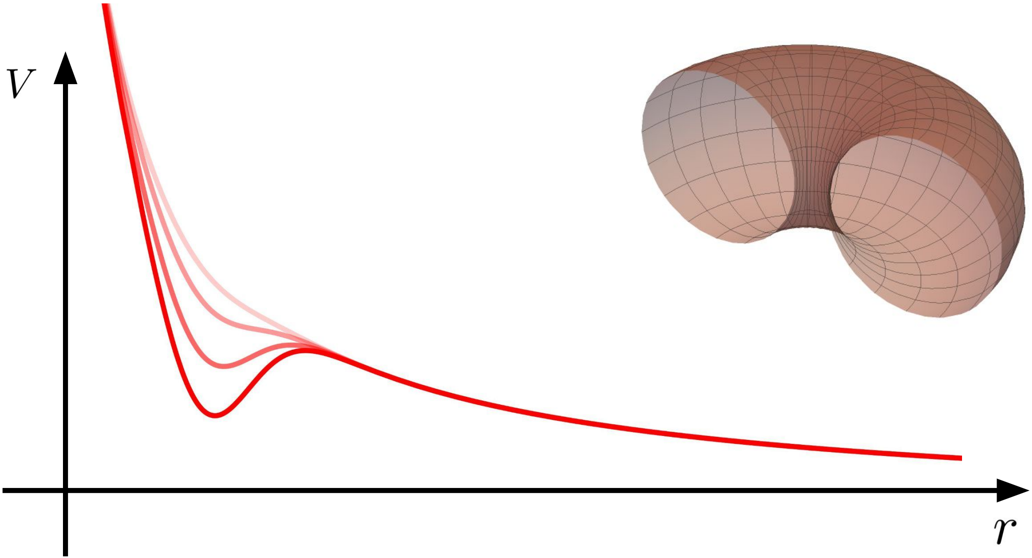
V
r


V
r

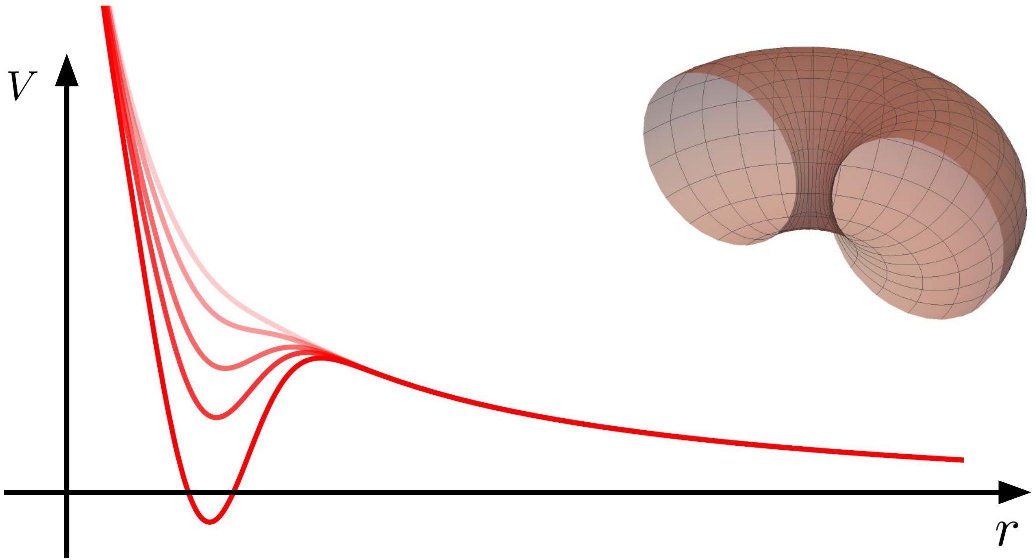


V
r

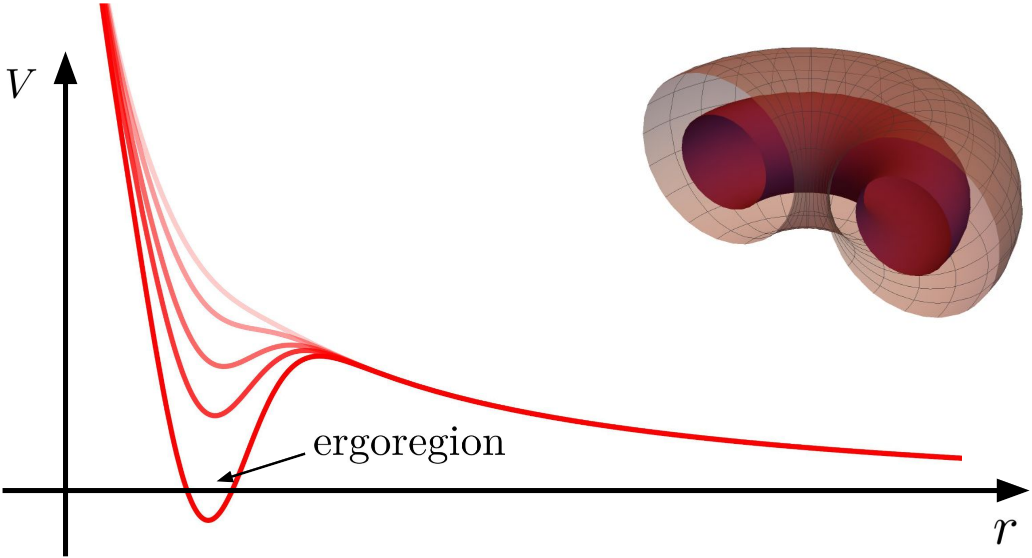

V
unstable light ring
stable light ring
r



V
r



$V$
$r$



$V$
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

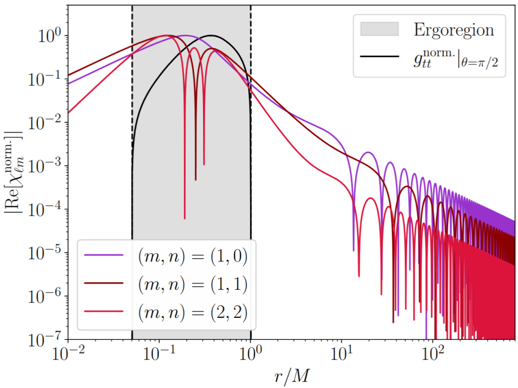
Ergoregion instability: Friedman (1978)

- 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

NS (2025)

More precisely:

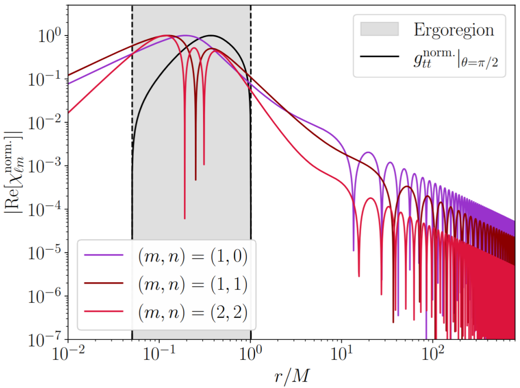
- $\phi_{\ell m} \sim \chi_{\ell m}(r) e^{im\varphi} e^{i\omega t}$
- $\exists m_0 > 0$, s.t. all $\ell = m \geq m_0$ are unstable
- Field modes grow with e-folding time $\tau_\ell^{\text{EI}}$
- Modes are peaked around stable light ring



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

NS (2025)




More precisely:

- $\phi_{\ell m} \sim \chi_{\ell m}(r) e^{im\varphi} e^{i\omega t}$
- $\exists m_0 > 0$, s.t. all $\ell = m \geq m_0$ are unstable
- Field modes grow with e-folding time $\tau_\ell^{\text{EI}}$
- Modes are peaked around stable light ring

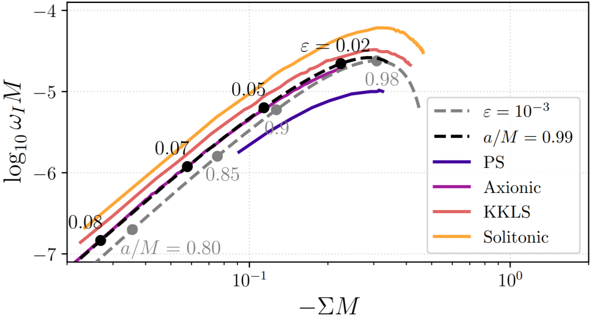
Nonlinear evolution:

$\Rightarrow$ Unknown up to naive expectations

# Linear instability

$\Sigma = \omega_R / m$

**NS** (2025)



# Linear instability

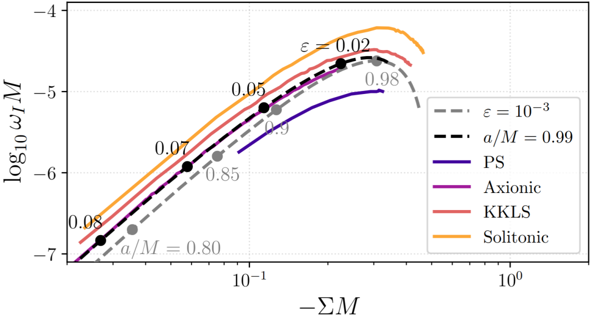
"Kerr-like" objects: Vilenkin (1978), Zhong (2022)

- Consider scalar field on Kerr exterior
- Place boundary conditions at $r_{\rm obj}$
- Radius: $r_{\rm obj} = r_+(1+\varepsilon)$

$\Rightarrow$ Ergoregion instability

$\Sigma = \omega_R/m$

NS (2025)



# Linear instability

"Kerr-like" objects: Vilenkin (1978), Zhong (2022)

- Consider scalar field on Kerr exterior
- Place boundary conditions at $r_{\rm obj}$
- Radius: $r_{\rm obj} = r_+(1+\varepsilon)$

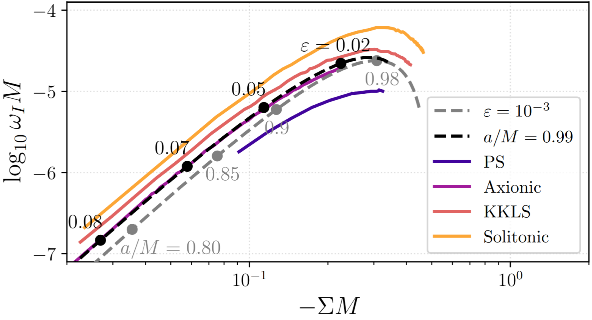
$\Rightarrow$ Ergoregion instability

Near-universality: NS (2025)

- Instability in "Kerr-like" objects
- Different ultra compact bosonic stars
- Vary self-interactions

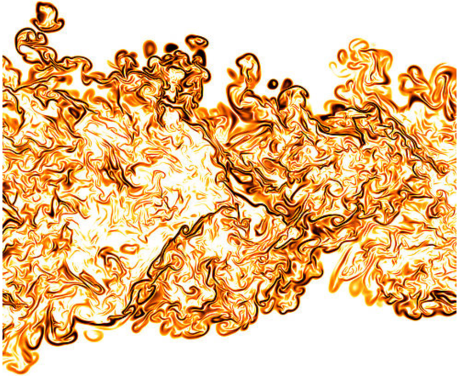
$\Rightarrow$ Near-universal behavior

$\Sigma = \omega_R/m$ NS (2025)

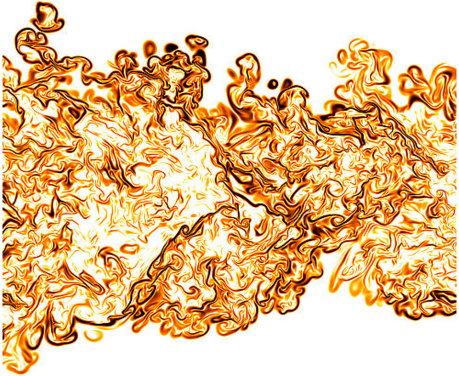


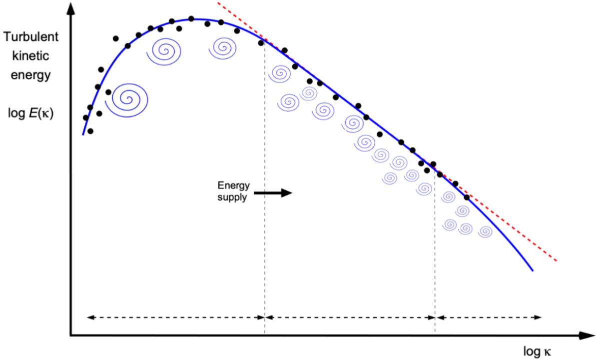
# Act II:
# Turbulent Times

# What is turbulence?



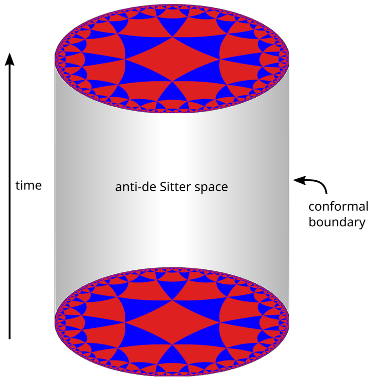
# What is turbulence?





## Nonlinear instability of AdS: Bizon & Rostworowski (2011)

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



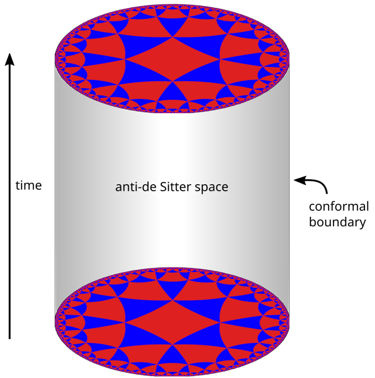
Nonlinear instability of AdS: Bizon & Rostworowski (2011)

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

Conjectured nonlinear instability: Keir (2014)

- Stable light rings quasi-trap massless fields
- Nonlinear effects may cause instability
- Instability was claimed to exist Cunha et al. (2022)

⇒ We cannot reproduce their result Evstafyeva, **NS**, East (2025)



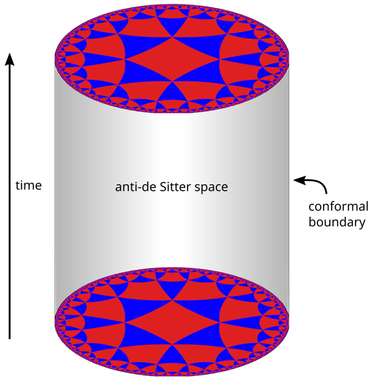
Nonlinear instability of AdS: Bizon & Rostworowski (2011)

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

Conjectured nonlinear instability: Keir (2014)

- Stable light rings quasi-trap massless fields
- Nonlinear effects may cause instability
- Instability was claimed to exist Cunha et al. (2022)

$\Rightarrow$ We cannot reproduce their result Evstafyeva, **NS**, East (2025)




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

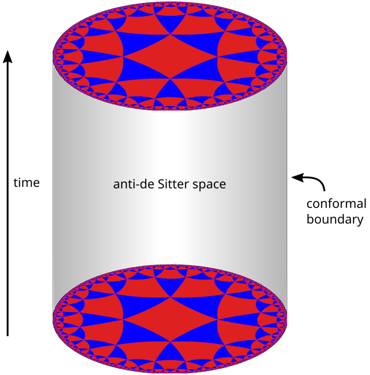
Nonlinear instability of AdS: Bizon & Rostworowski (2011)

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

Conjectured nonlinear instability: Keir (2014)

- Stable light rings quasi-trap massless fields
- Nonlinear effects may cause instability
- Instability was claimed to exist Cunha et al. (2022)

$\Rightarrow$ We cannot reproduce their result Evstafyeva, **NS**, East (2025)




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

$\Rightarrow$ Is turbulence relevant for the ergoregion instability?

# Turbulent saturation of instability
**NS** (2025)

Einstein equations: $\partial^2 g \sim g(\partial g)^2$

$\Phi = r^{-1} \sum_{\ell,m} \phi_{\ell m} Y_{\ell m}$

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

$\Box_g \Phi = \alpha \Phi^* g^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi$

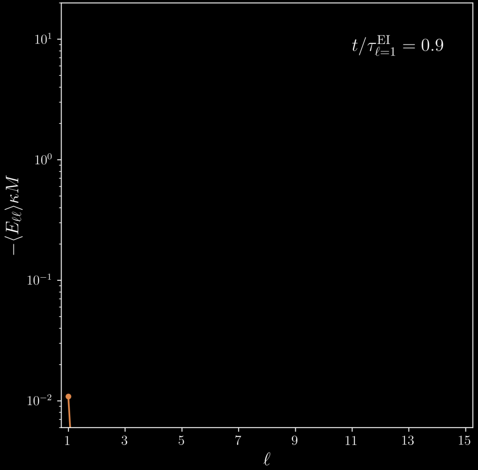
# Turbulent saturation of instability
**NS** (2025)

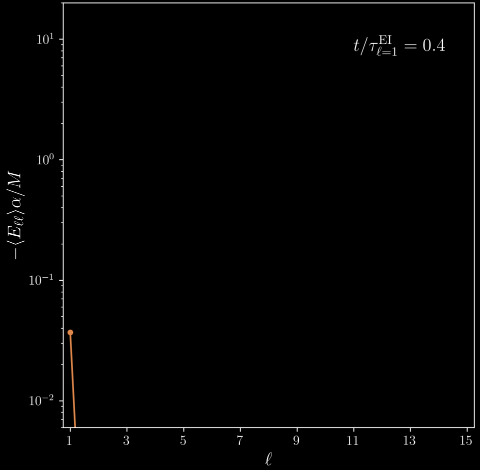
Einstein equations: $\partial^2 g \sim g(\partial g)^2$

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

$\Phi = r^{-1} \sum_{\ell,m} \phi_{\ell m} Y_{\ell m}$

$\Box_g \Phi = \alpha \Phi^* g^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi$



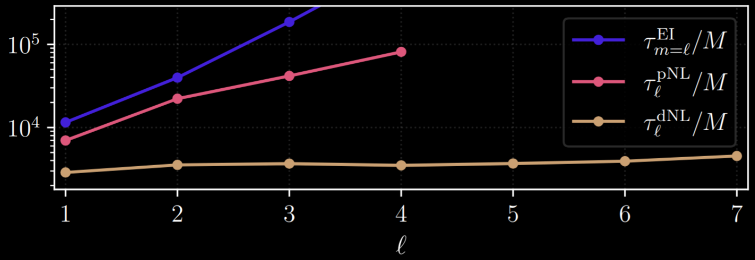



# Nonlinear timescales

**NS** (2025)

Timescales:

- Ergoregion instability e-folding times: $\tau_m^{\mathrm{EI}}$
- Nonlinear timescales are amplitude-dependent: $\tau_\ell^{\mathrm{NL}} \sim A^{-p}, p > 0$
- Define $\tau_\ell^{\mathrm{NL}}$ to be time between peaks of energy
- Nonlinear timescales depend on types of self-interactions



# Act III:
# An Unexpected Ending

# Expectation

Adiabatic nonlinear evolution:

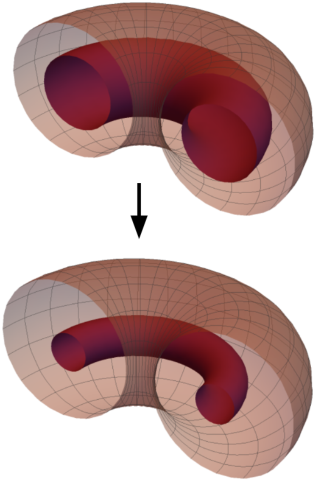
- Emission of energy and angular momentum
- Slow spin-down of object
- Terminate spin-down, when ergoregion is small

$\Rightarrow$ Analogy to black hole superradiance instability

Observational inferences:

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

$\Rightarrow$ Implications for existence of black hole mimickers



# Nonlinear gravitational saturation

**NS** & East 2025

Ingredients for full treatment:

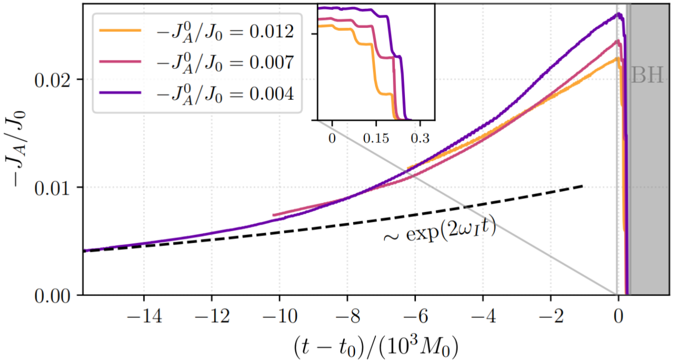
- Ergostar + Numerical Relativity $\Rightarrow$ Boson stars
- Massless vector unstable probe field $A_\mu$ (initialize in linear regime)
- Assume axisymmetry (keeping $A_\mu$ in $m = 1$ state)

# Nonlinear gravitational saturation

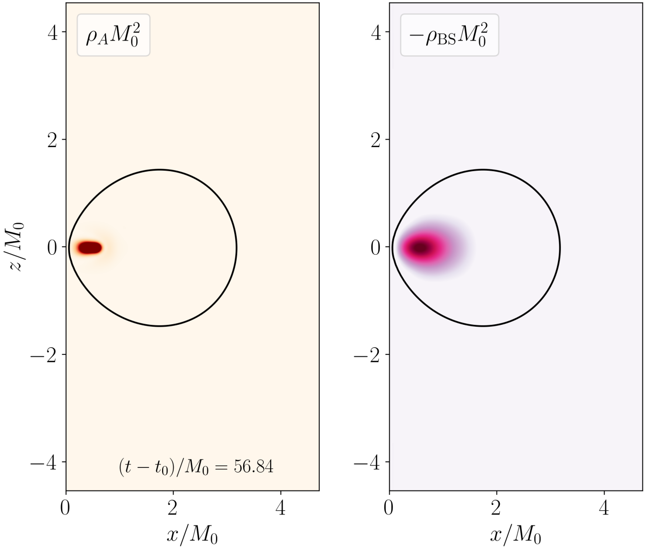
## **NS** & East 2025

Ingredients for full treatment:

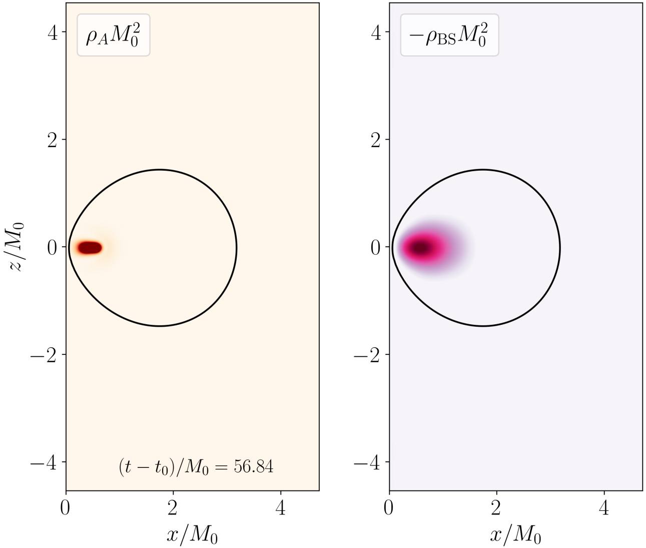
- Ergostar + Numerical Relativity ⇒ Boson stars
- Massless vector unstable probe field $A_\mu$ (initialize in linear regime)
- Assume axisymmetry (keeping $A_\mu$ in $m = 1$ state)



# Black hole formation
**NS** & East 2025



# Black hole formation
**NS** & East 2025




Final state intuition:

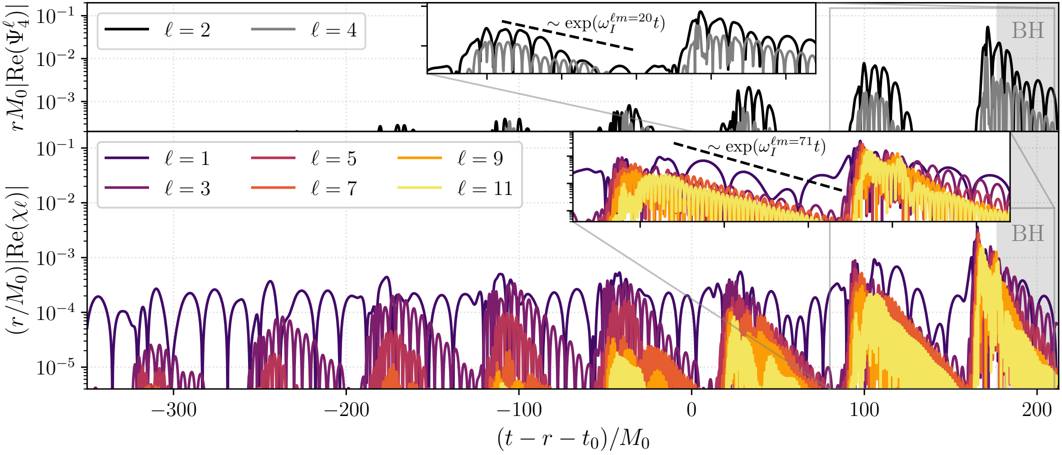
- No net angular momentum emission
- Approximately conserved U(1)-charge
- Nonlinearities enhance growth rate
- Instability taps binding energy

$\Rightarrow$ Dynamics drives compactness

# Gravitational waveform

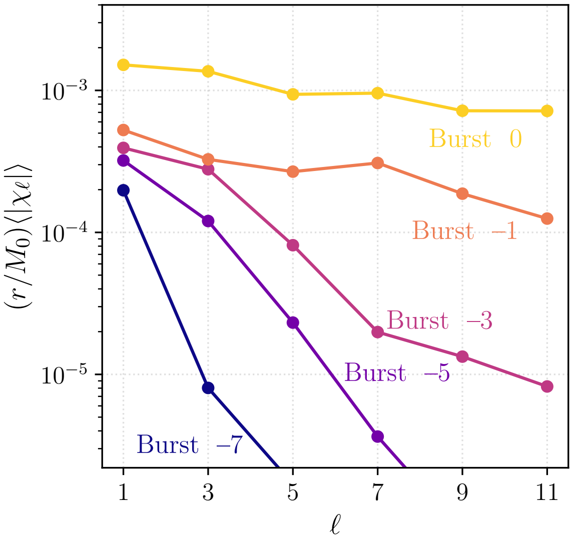
**NS** & East (2025)

$\chi = -n_\mu A^\mu$ $\Psi_4$ is Weyl-Newman-Penrose scalar



# Turbulence

**NS** & East (2025)



# Summary

Take aways:

1. Ergoregion instability major player in ultra compact objects
2. Weak turbulent relevant in nonlinear evolution of ergoregion instability
3. Perturbations become more localized on stable light ring
4. Weakly nonlinear effects increase the instability rate
5. Gravitational backreaction leads to black hole formation, not spin-down
6. Gravitational wave signal is a series of "inverse-echo"

Open questions:

⇒ Gravitationally driven instability? Generalization of conclusions? Observational relevance?