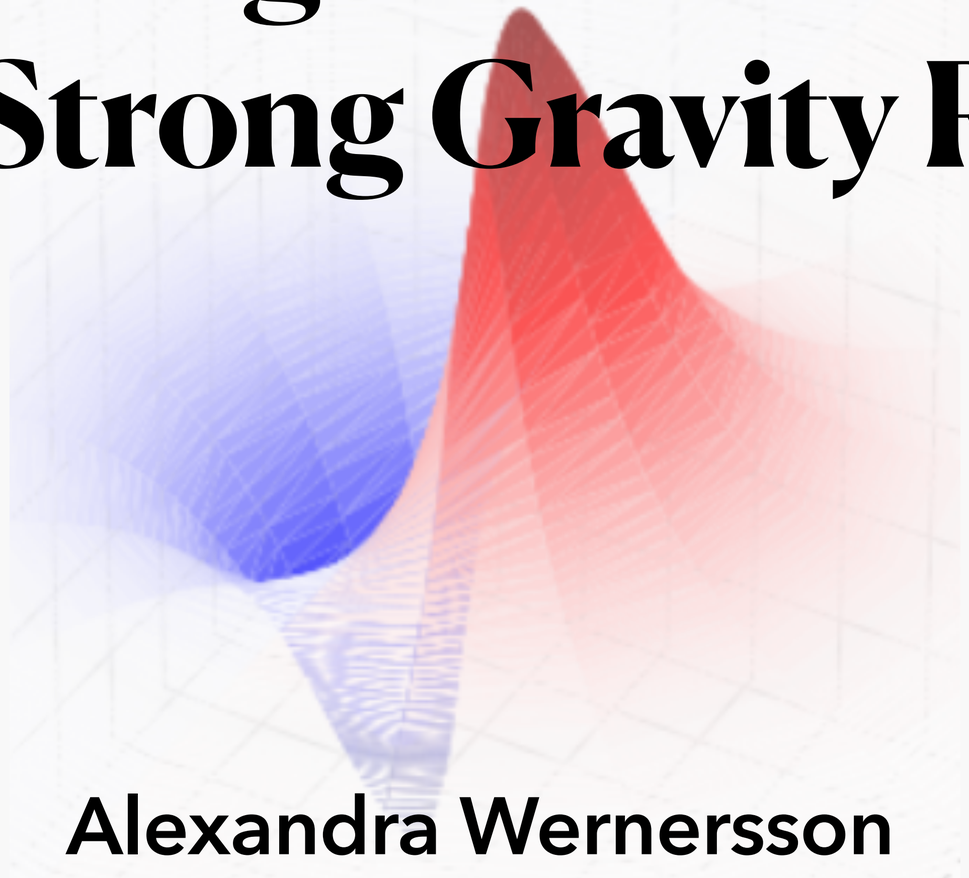
Universiteit van Amsterdam

Self-interacting Gravitational Atoms in the Strong Gravity Regime



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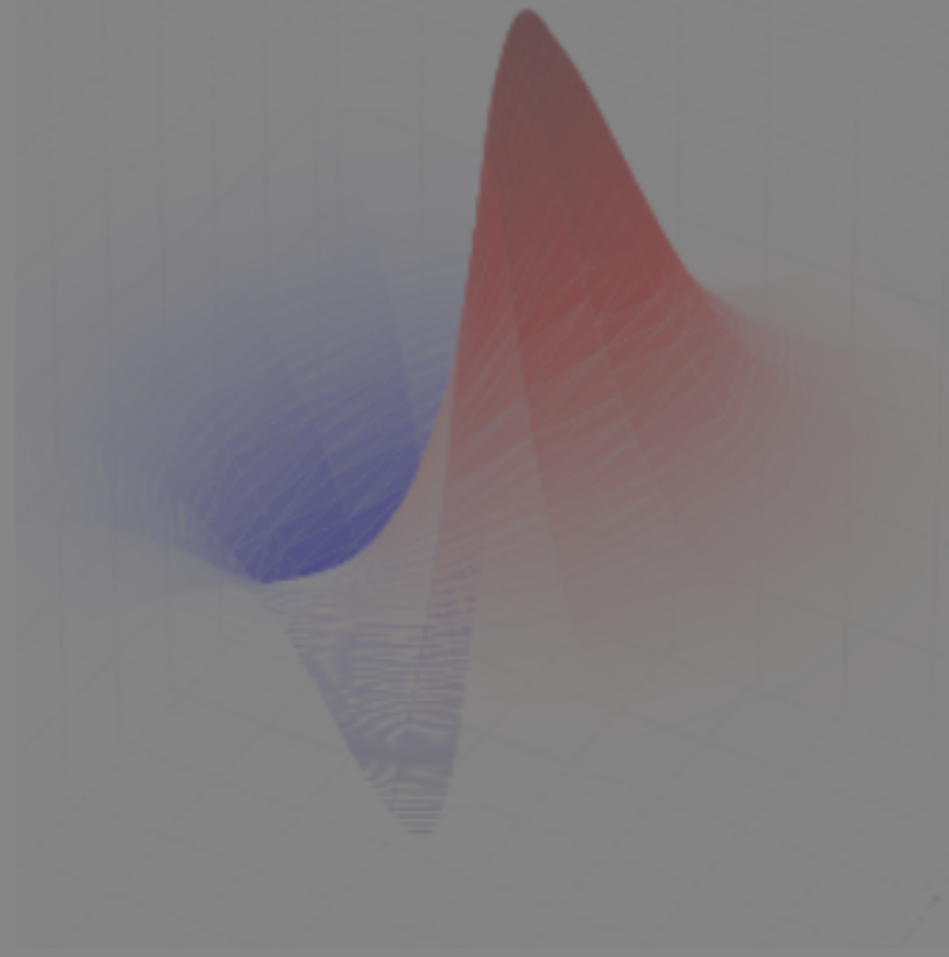
Based on: *JCAP* 04 (2023) 018, arXiv:2212.11948 **[gr-qc]**

Outline

- Motivation:
  - Probe dark matter around black holes
- Goals:
  - Study/Quantify dark matter behavior around black holes
  - Among one of the first fully non-linear exploration with numerical relativity
- Results
  - Bosonic field profile around black hole with self-interactions
- Conclusions & future outlooks

Part I: Dark Matter around Black Holes

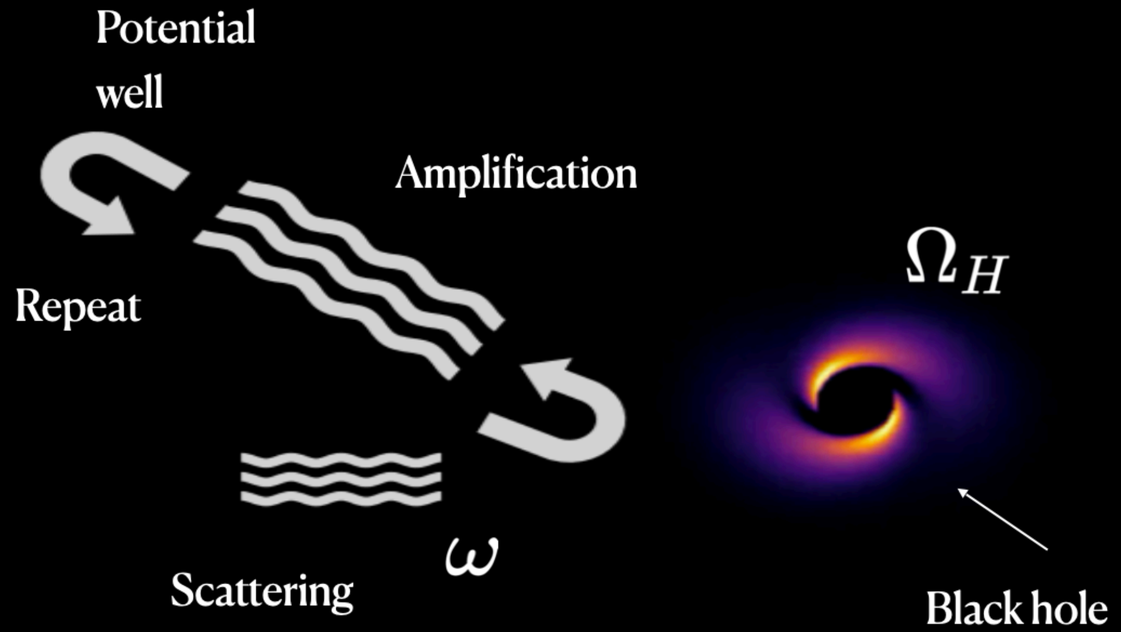


Superradiance

Ultralight bosons, $\mu \in [10^{-20}, 10^{-10}]$ eV, may form clouds around Black holes through the *superradiance process*:

Instability criteria (for cloud growth):

$$\frac{\omega}{m} < \Omega_H$$



Credit: Katy Clough, Thomas Helfer

Gravitational atoms

- Compare to a hydrogen atom

(see M. Baryakhtar, R.Lasenby,

X. Huang et. al.)

$$\phi_{nlm}(t,\mathbf{r}) = R_{nl}(r)Y_{lm}(\theta,\phi)e^{-i(\omega_{nlm}-\mu)t}$$

$$|nlm\rangle = |211\rangle \text{ } (2p \text{ state})$$

Fundamental mode for the scalar case

- Fine-structure like constant:

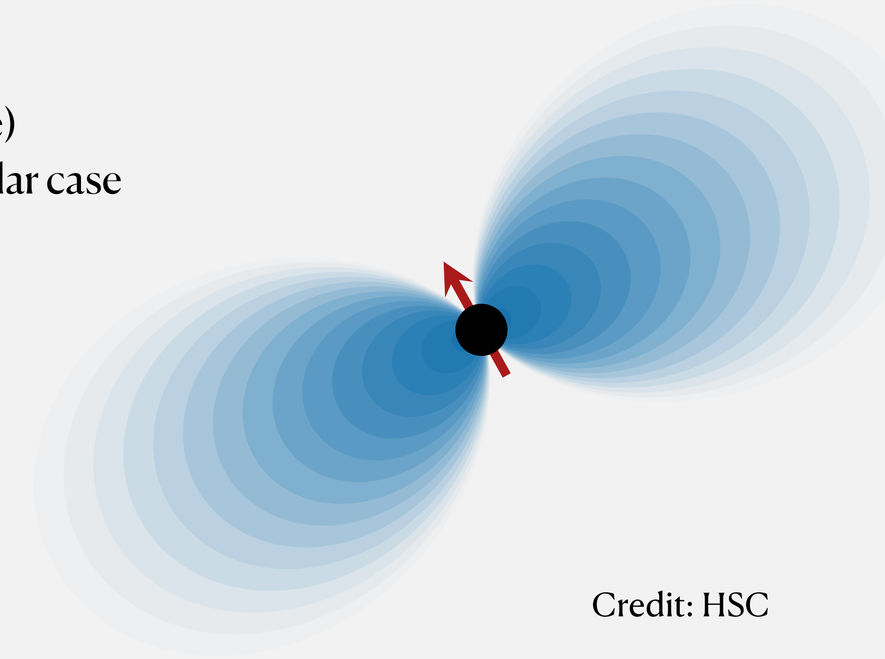
Black hole mass

Boson mass

$$\alpha = \frac{GM\mu}{\hbar c} = \frac{r_g}{\lambda_c}$$

Black hole radius

Compton wavelength



Credit: HSC

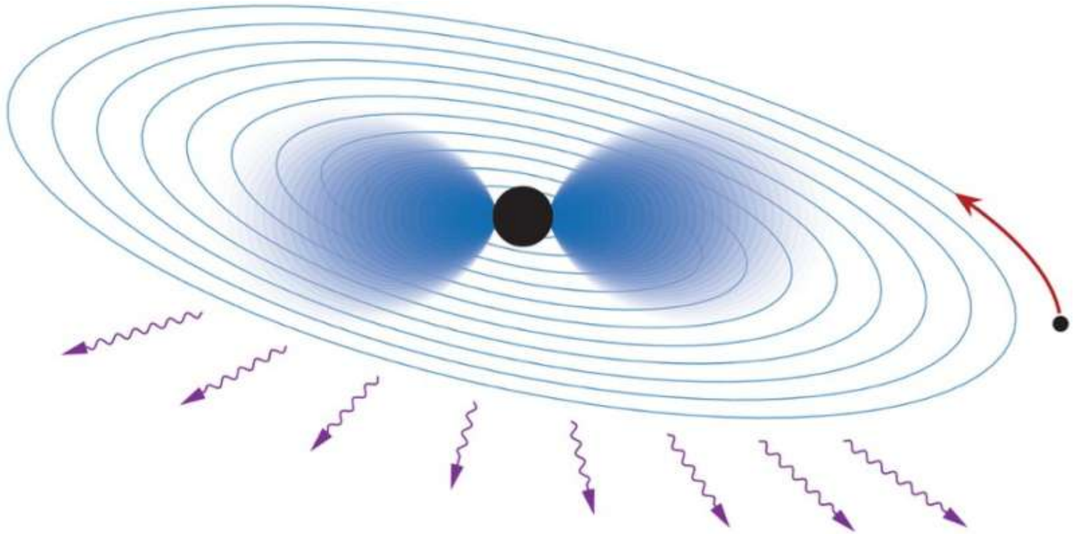
Gravitational Wave signatures

- Resonant & "Ionization" signals
  (see work by H.S. Chia et. al.)

- Continuous Gravitational Waves

(see KKY. Ng, C. Yuan, et al.)

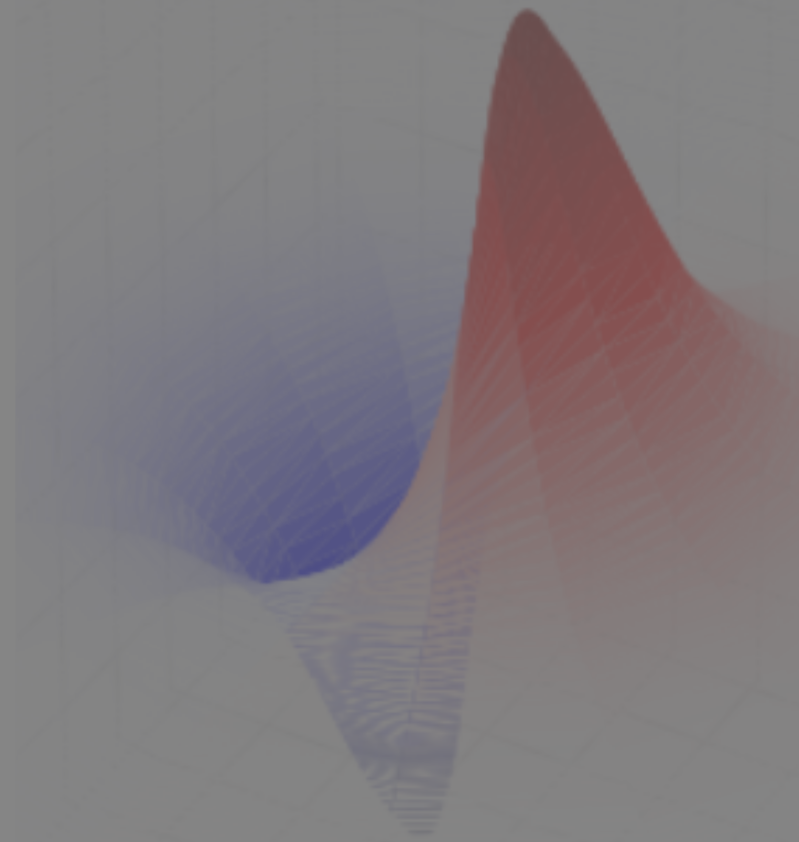
  - Monochromatic signal due to annihilation



Credit: HSC

- Environmental effects
  - Dephasing of GW waveform (see work by P. Cole et. al.)

Part I I: Numerical Boson Clouds



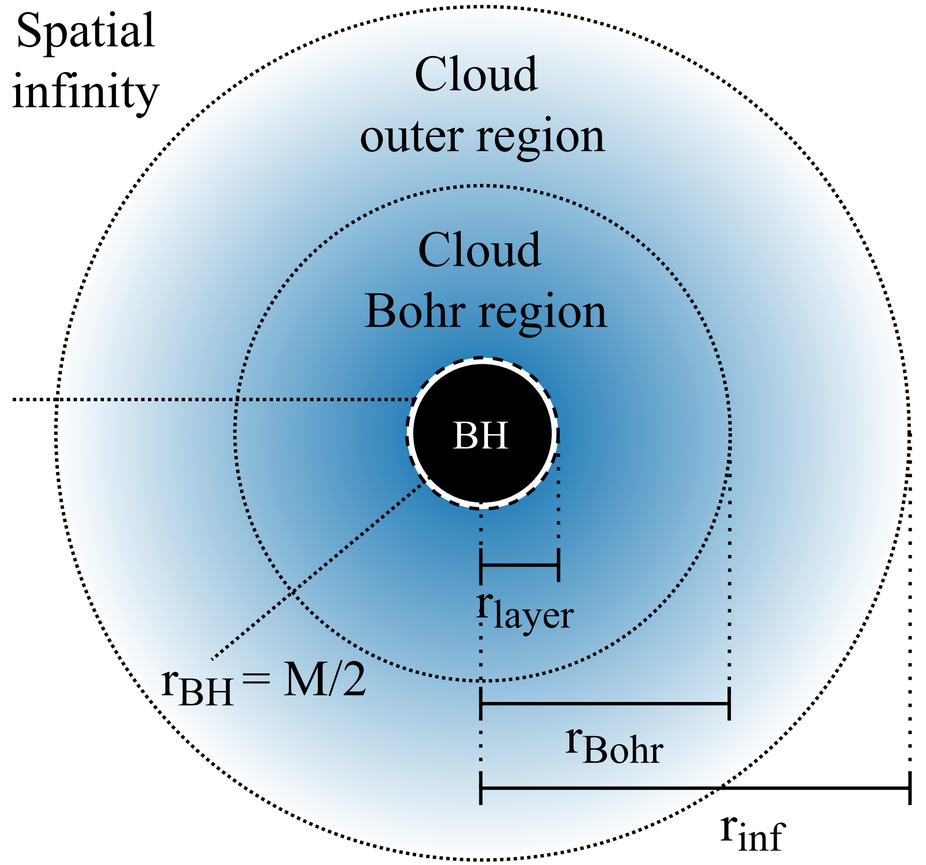
Numerical boson clouds

- Spectral solver KADATH (P. Grandclement)

(Solve Initial Data for Einstein-Klein-Gordon system)

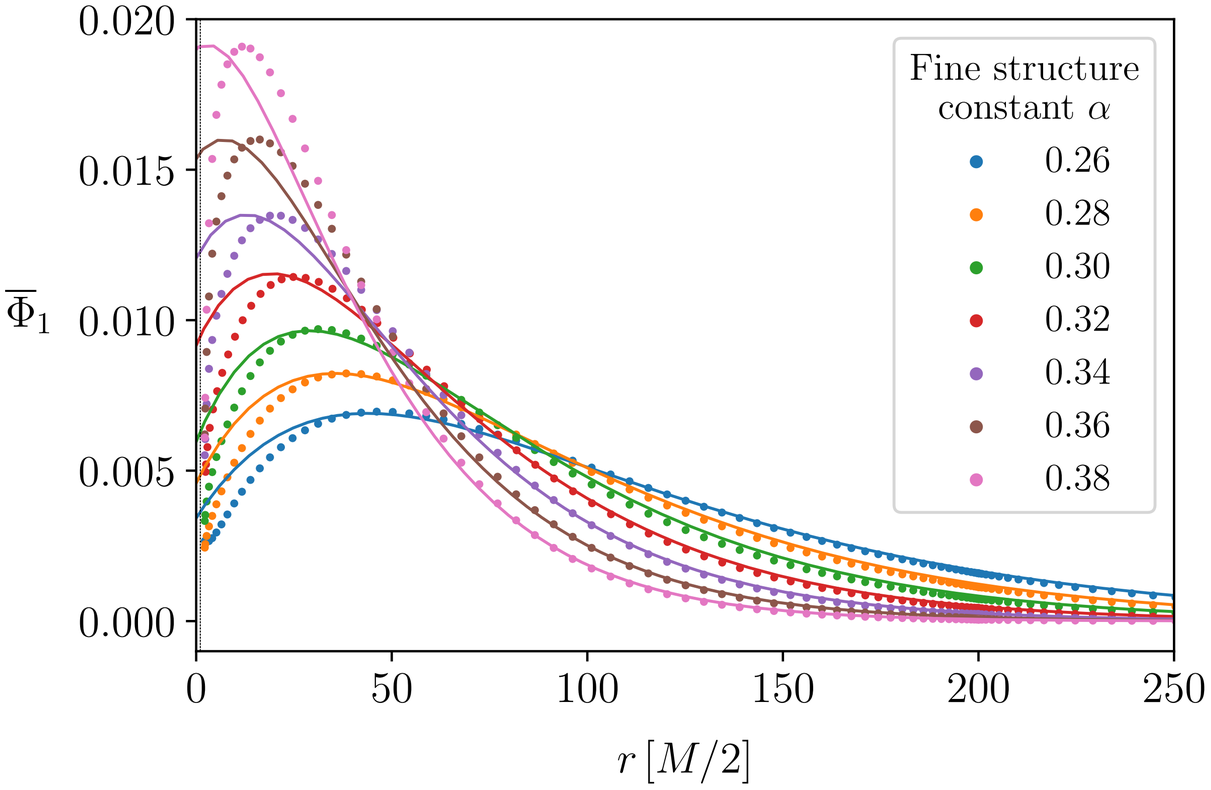
1. Solve for metric quantities Ψ, N

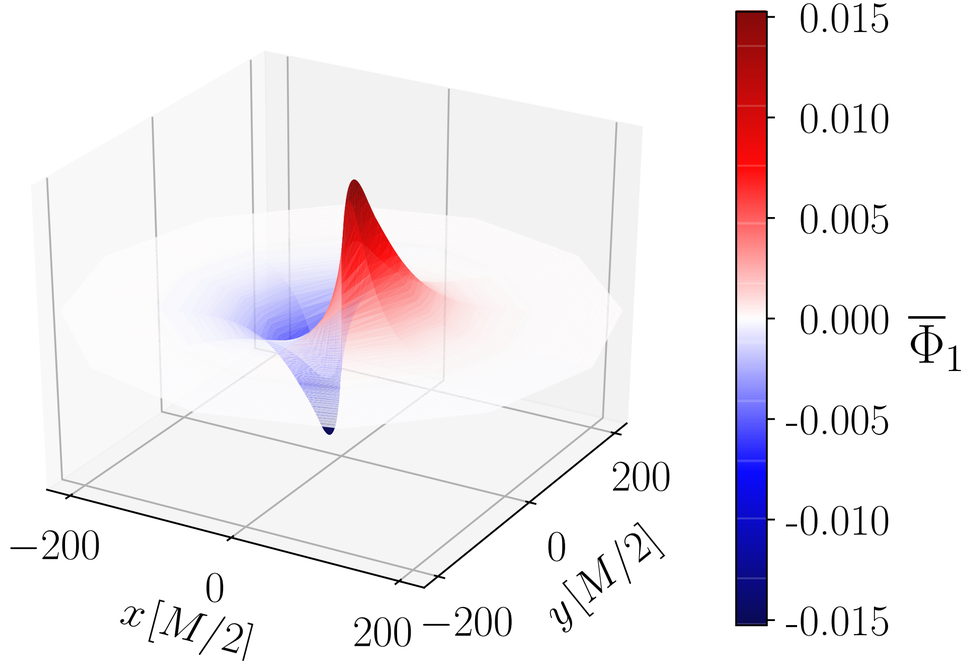
2. Solve for scalar field Φ



Credit: C. Doormann

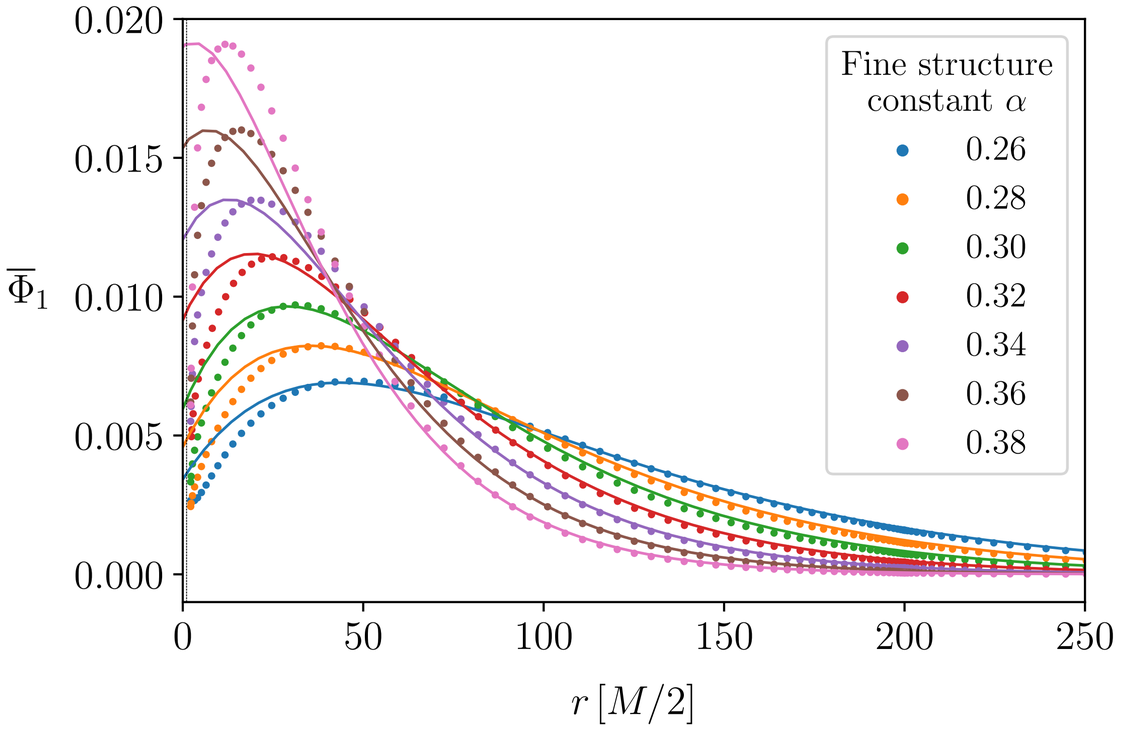
Free field profile

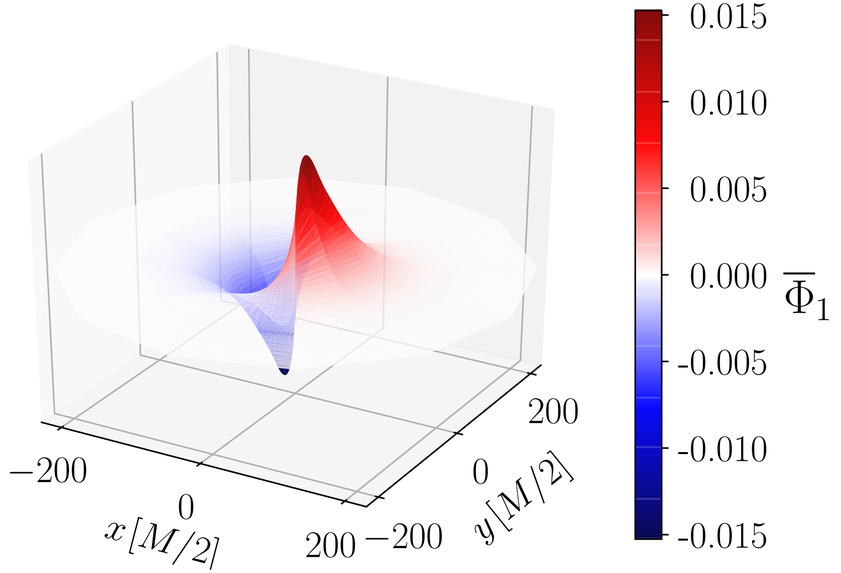




- Numerical solution
- Analytical solution (derived for small α)

Free field profile



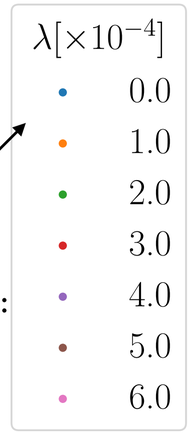


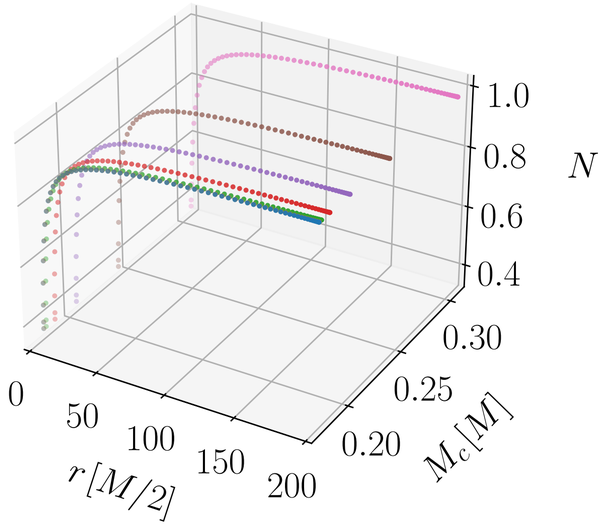
Now include a self-interacting term; $V(\Phi) \propto \lambda\Phi^4$

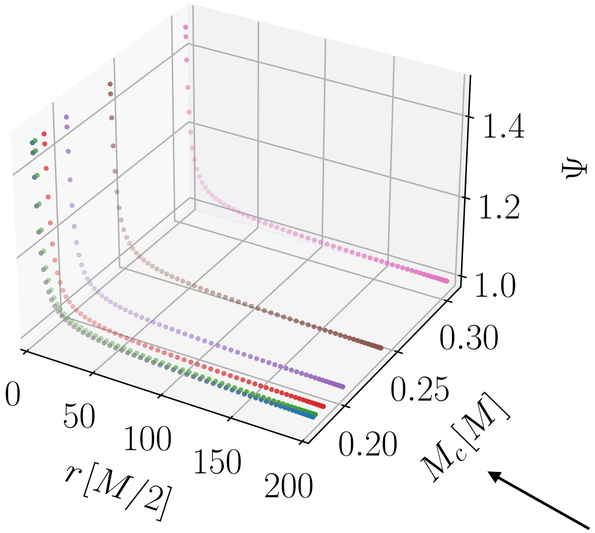
Backreaction & Self-interactions effects On Metric Quantities

Quartic self-interaction:

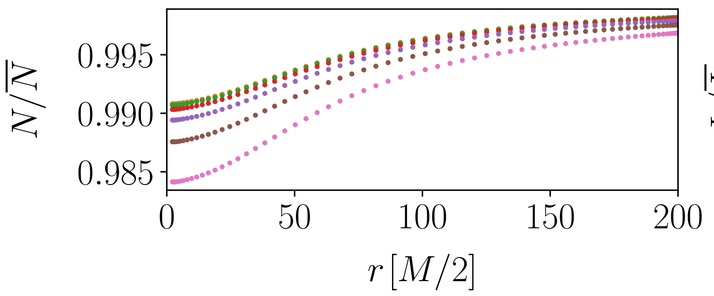
$V(\Phi) \propto \lambda\Phi^4$

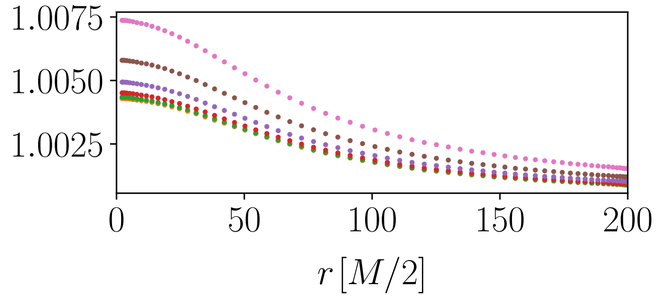






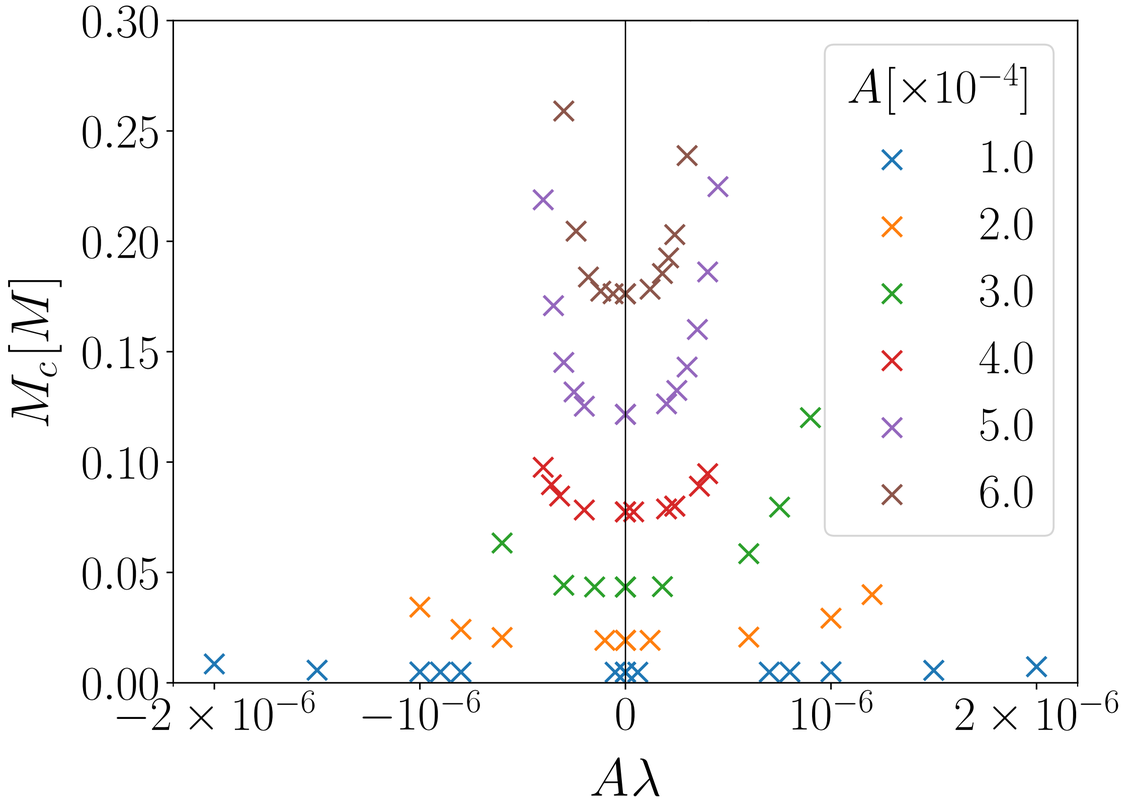
Cloud mass

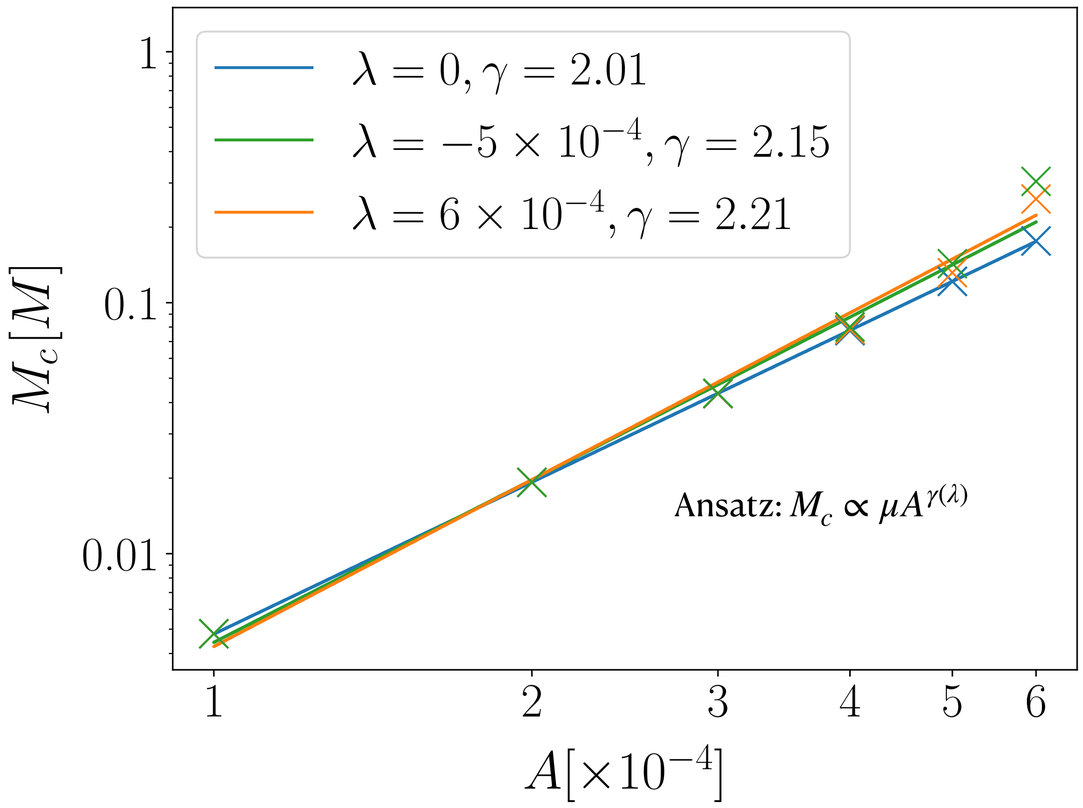




Marginal effect on the metric quantities even for large cloud mass, M_c, 1.5% and 0.7% for N and Ψ respectively.

Cloud mass and self-interactions

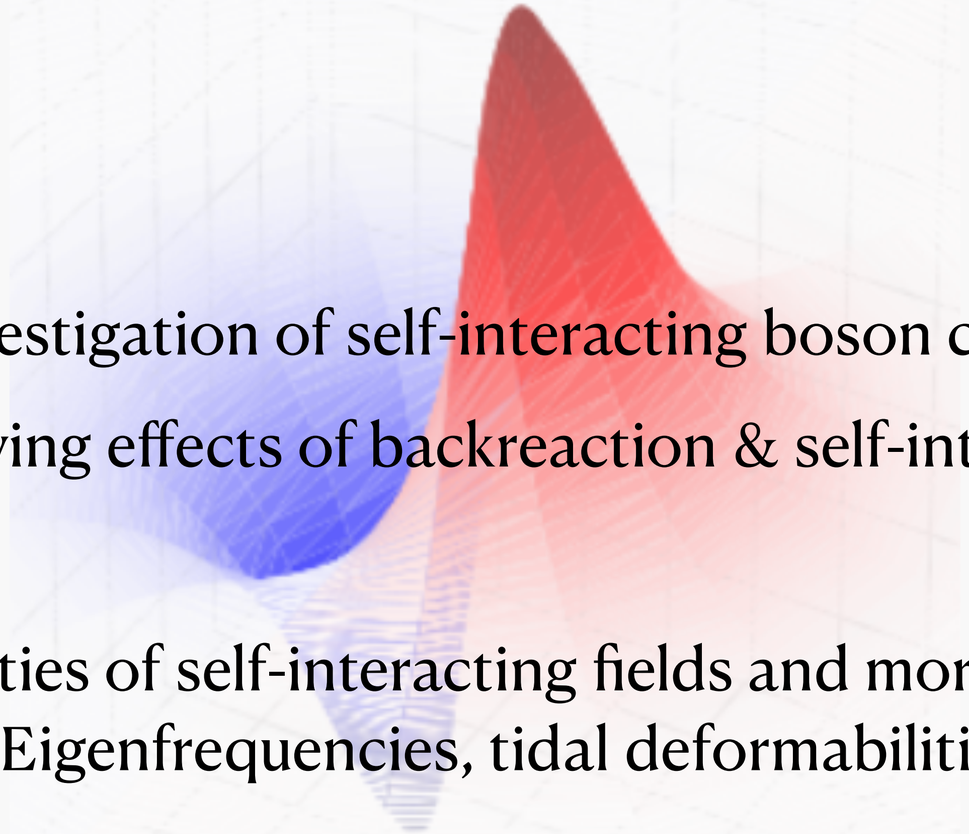




For the free field approximately; $M_c \sim A^2$

Find a non-trivial, approximately quadratic scaling $M_c \sim (A\lambda)^2$

Conclusions and outlook

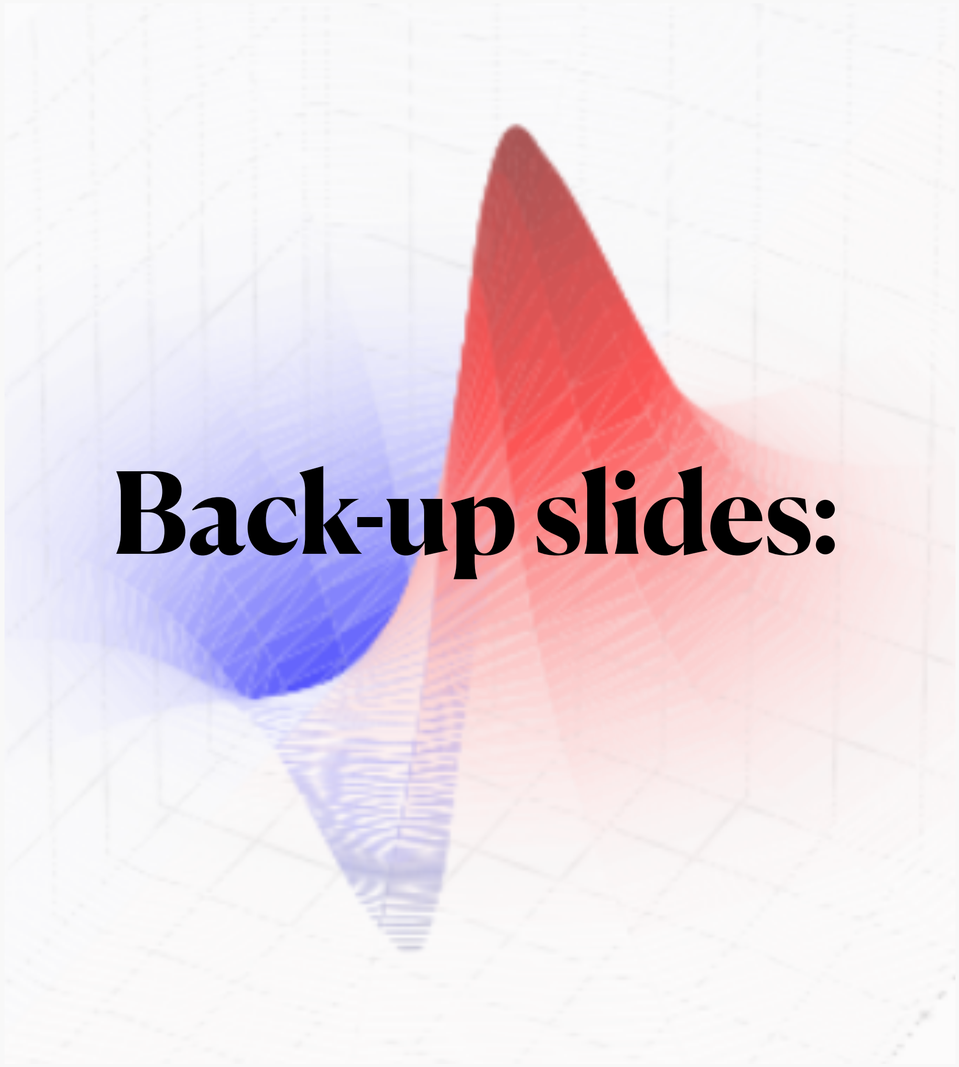


- Numerical investigation of self-interacting boson clouds; including

  Quantifying effects of backreaction & self-interaction

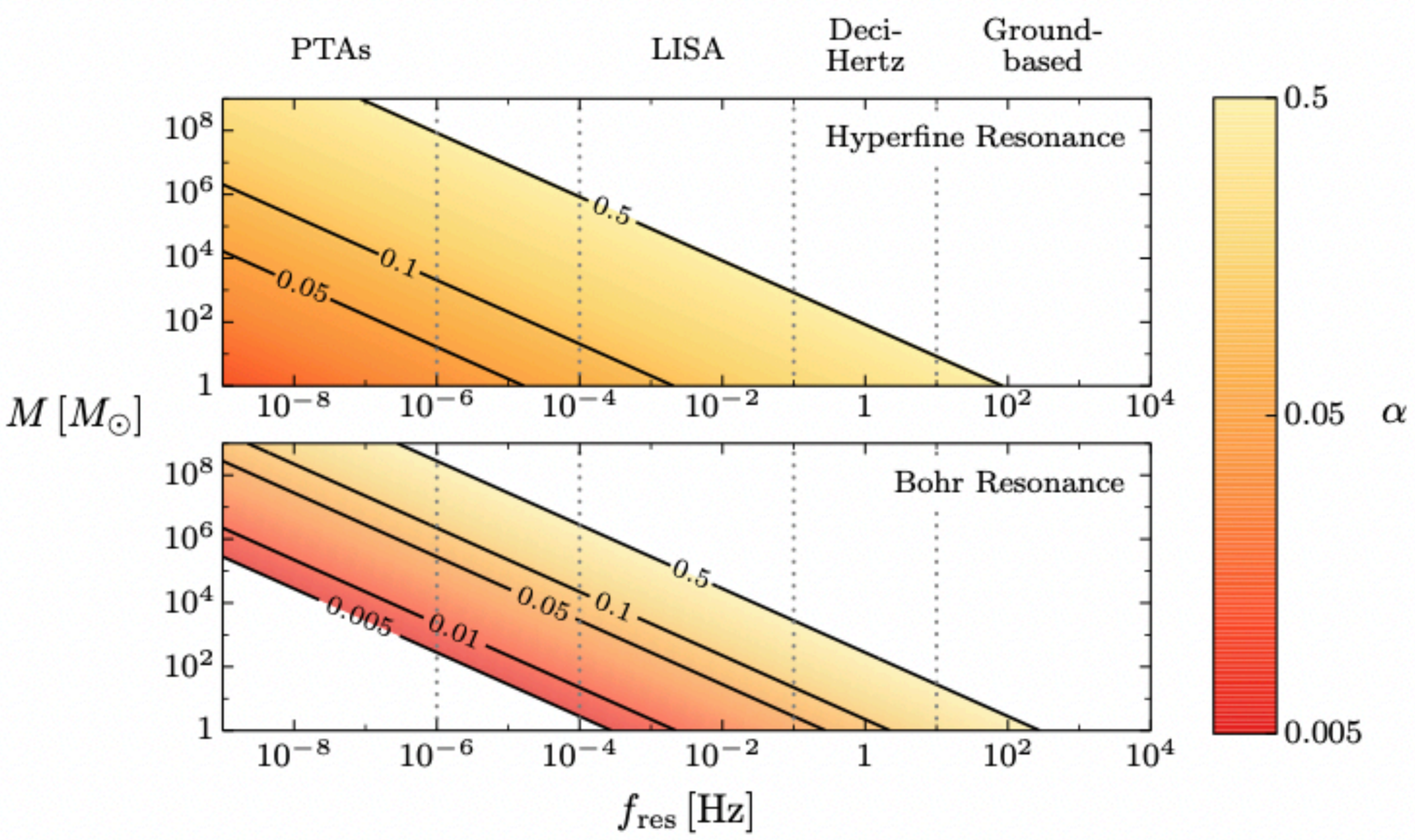
- Interesting properties of self-interacting fields and more directions to go in!
  (Eigenfrequencies, tidal deformabilities)

- Use results as initial data for dynamical evolution



Back-up slides:

Resonance Frequencies



Credit: HSC, arXiv:1804.03208

Numerical boson clouds

- Einstein equation's ⟶ Set of evolution equations

$$g_{\mu\nu} = -N^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

- Spacetime is characterized by:
  - N - Lapse function
  - Ψ - Conformal factor
  - β - Shift vector