BLACK HOLES AS ENGINES OF DISCORVERY

Vítor Cardoso
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& Técnico Lisboa]

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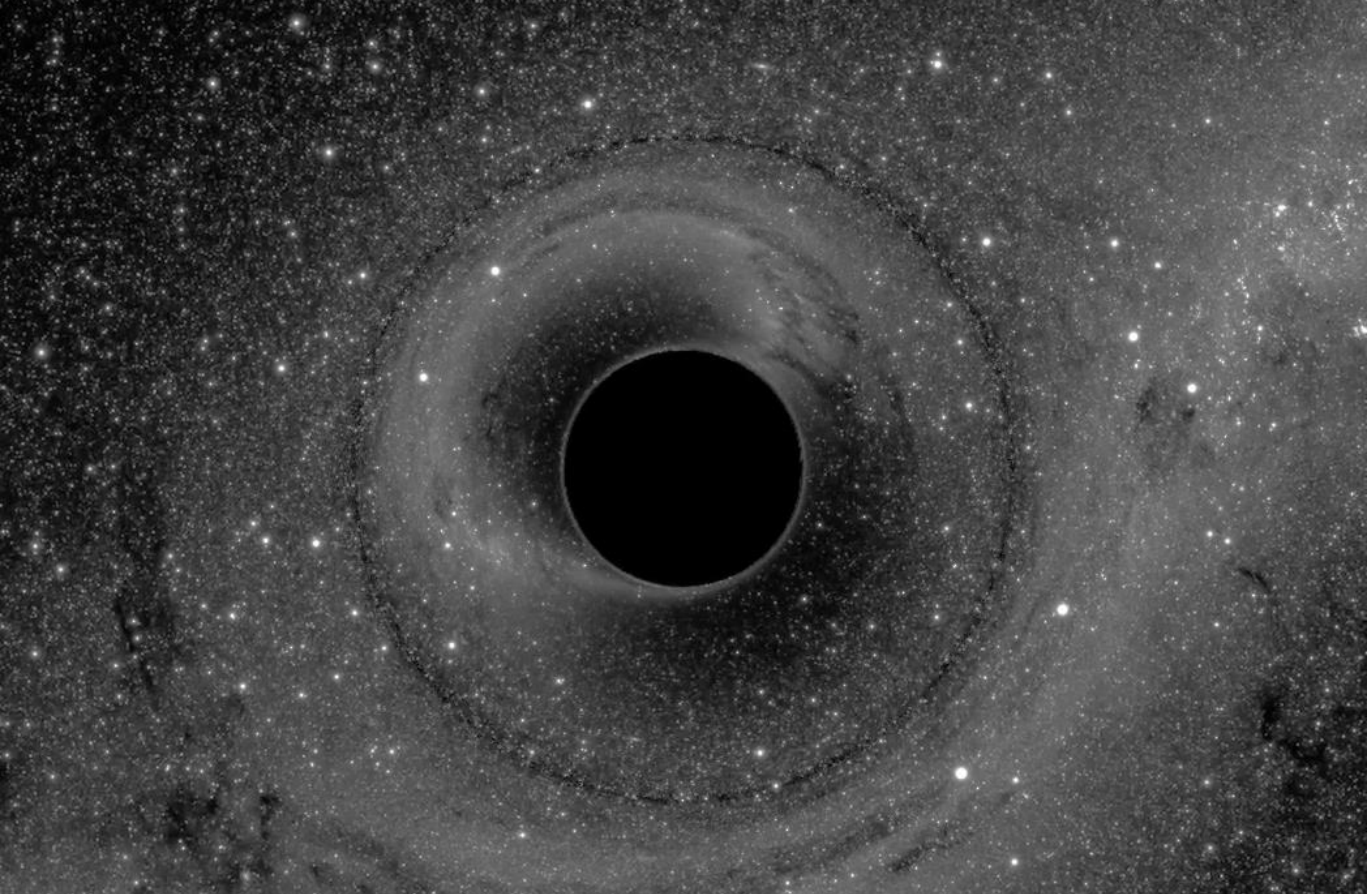
BLACK HOLES
INSIDE AND OUT

NIELS BOHR INSTITUTE
COPENHAGEN
26–30 AUGUST 2024

SOC: Luca Buoninfante, Vitor Cardoso, Astrid Eichorn, Raúl Carballo-Rubio, Francesco Di Filippo. LOC: Vitor Cardoso, Yifan Chen, Julie de Molade, Jose Ezquiaga, Takuya Katagiri, David Pereñiguez, Maarten van de Meent. This meeting is funded by the VILLUM FONDEN, the European Research Council and the Danish National Research Foundation.

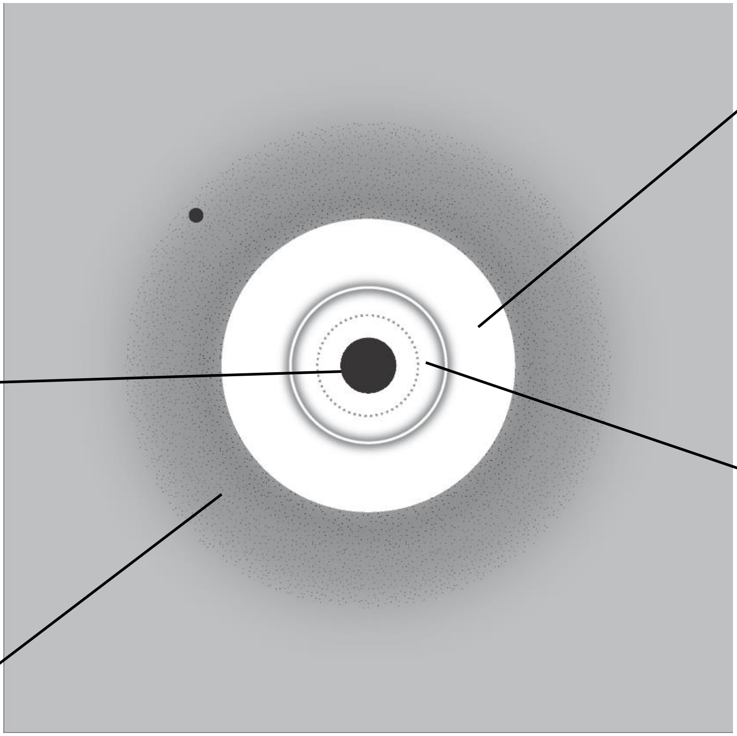
Design by Ana Carvalho

With thanks to Shinji, Naritaka, Kazufumi, Kei-ichi, Masaru and of course, Mrs Yagi



Time stops at black hole horizon.
Hence, they are black and real holes in cosmos.

Black holes are black



Light ring
(defines photosphere)

Horizon

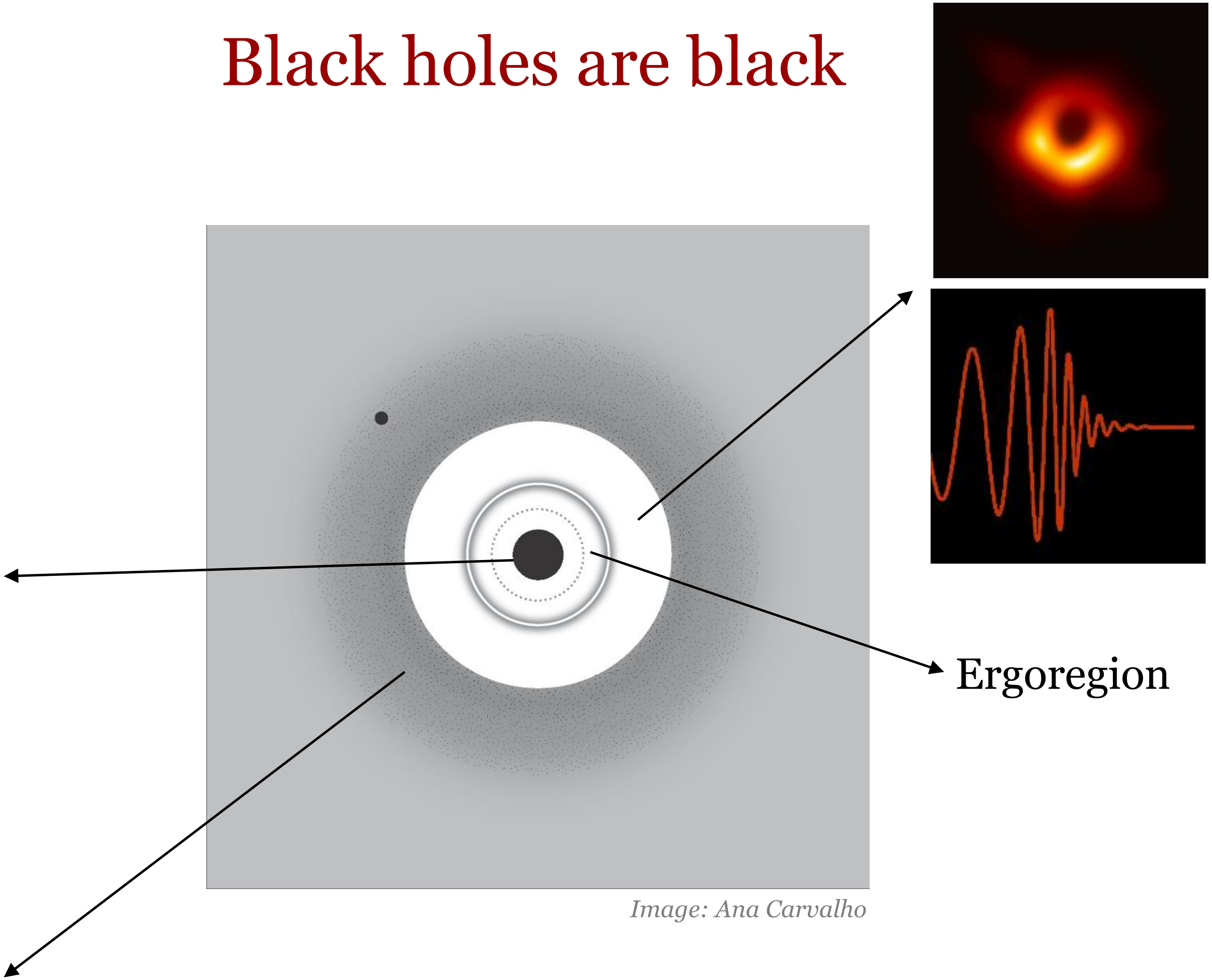
Ergoregion

Innermost Stable Circular Orbit (ISCO)

Image: Ana Carvalho

Cardoso & Pani, Nature Astronomy 1: 586 (2017); Living Reviews in Relativity 22: 1 (2019)

Black holes are black



Horizon

Ergoregion

Innermost Stable Circular Orbit (ISCO)

Image: Ana Carvalho

Cardoso & Pani, Nature Astronomy 1: 586 (2017); Living Reviews in Relativity 22: 1 (2019)

Singularities & Cosmic Censorship

Theorem (Penrose 1965; 1969):

For “reasonable” matter, trapped surface formation results in “singularity,” where at least one of the following holds:

a. Negative local energy occurs.
b. Einstein's equations are violated.
c. The space-time manifold is incomplete.
d. The concept of space-time loses its meaning at very high curvatures – possibly because of quantum phenomena.

Conjecture (Penrose 1969):

No singularity is visible from future null infinity (weak CCC)
General Relativity is deterministic (strong CCC)

Uniqueness: the Kerr solution

Theorem (Carter 1971; Robinson 1975; Chrusciel, Costa & Heusler 2012):
A stationary, asymptotically flat, *vacuum* BH solution must be Kerr

$$
\begin{aligned}
ds^2 \quad &= \quad \frac{\Delta - a^2\sin^2\theta}{\Sigma}dt^2 + \frac{2a(r^2+a^2-\Delta)\sin^2\theta}{\Sigma}dtd\phi \\
&- \frac{(r^2+a^2)^2 - \Delta a^2\sin^2\theta}{\Sigma}\sin^2\theta d\phi^2 - \frac{\Sigma}{\Delta}dr^2 - \Sigma d\theta^2
\end{aligned}
$$

$$
\Sigma = r^2 + a^2\cos^2\theta\,, \quad \Delta = r^2 + a^2 - 2Mr
$$

Describes a rotating BH with mass M and angular momentum J=aM, iff a<M

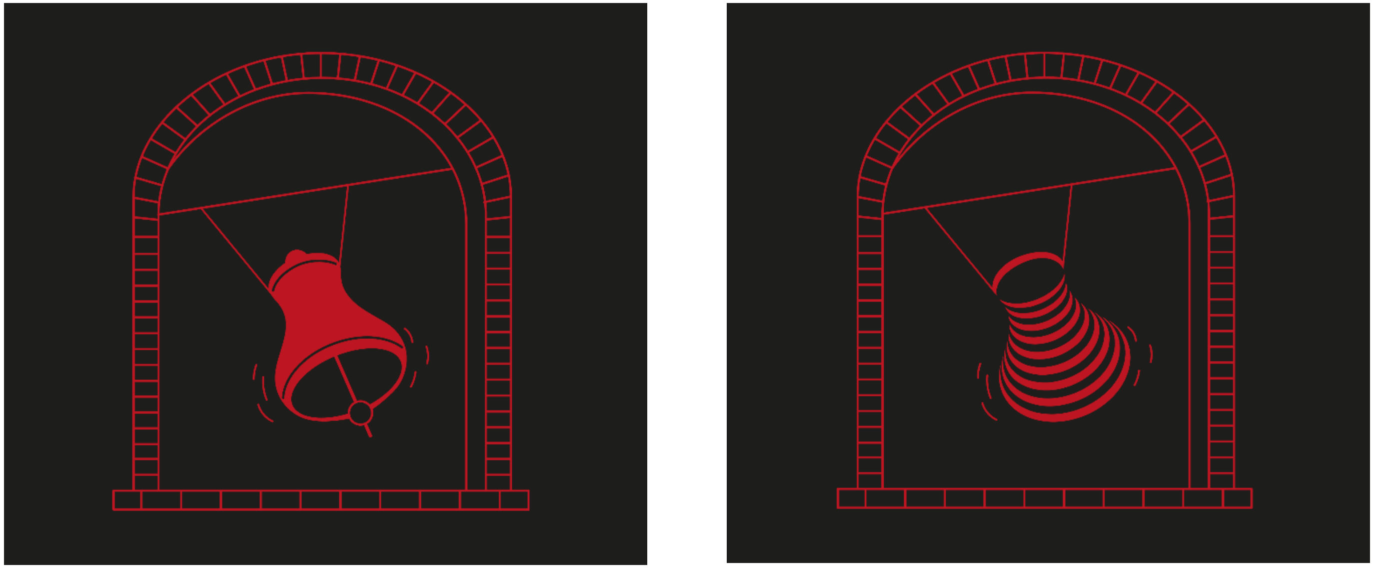
"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe."

S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

Fundamental questions

Are we really looking at black holes?

Is it a Kerr black hole? How can we constrain alternatives?



Answer requires understanding of theoretical framework, PDE analysis, precise modelling, observations, challenging simulations & data analysis techniques

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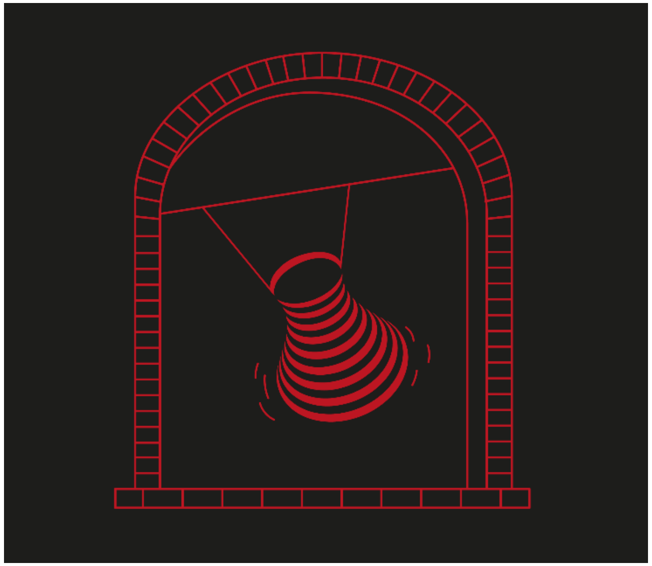

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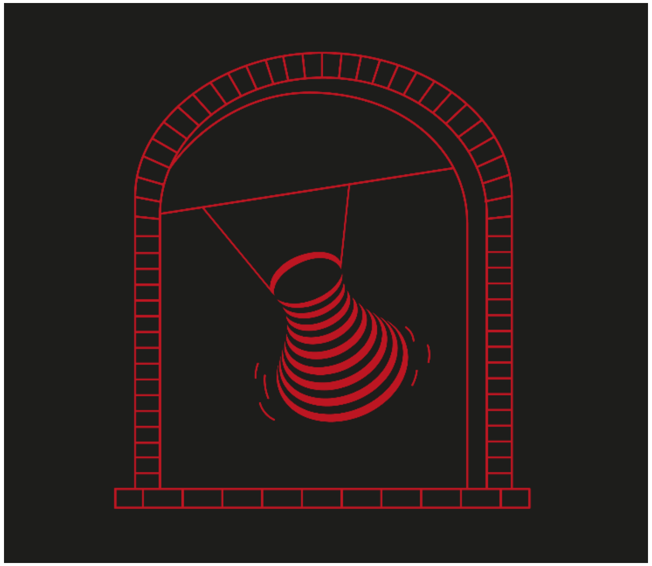
Spectrum is unstable
(Nollert 1996; Barausse+ 2014; Jaramillo+2021; Cheung+ 2022)

Near-horizon structure
(Cardoso+ 2016, 2017, 2018, 2019)

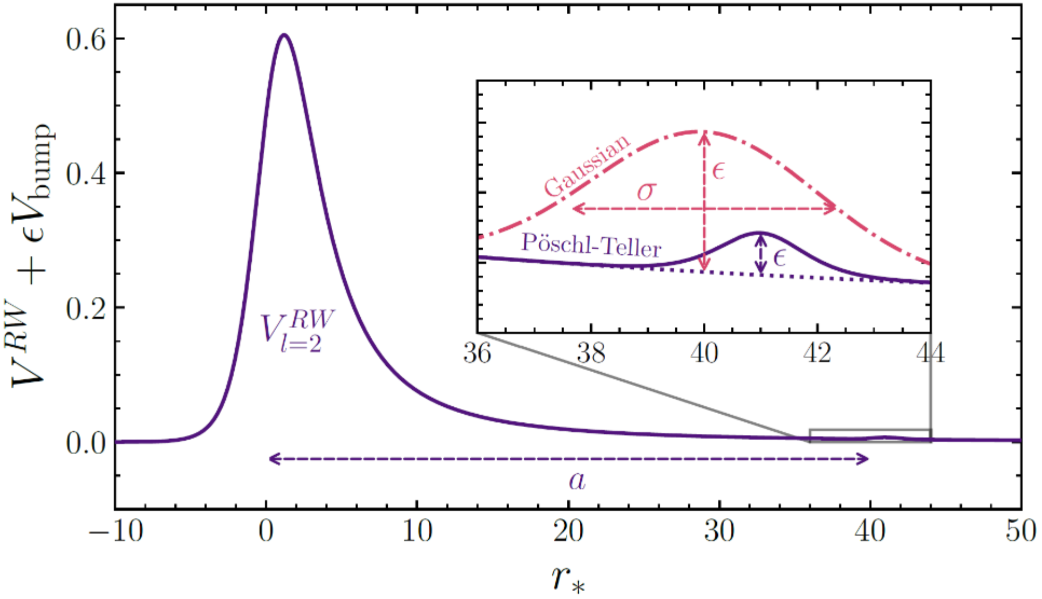
Probes interior if multiple propagation speeds exist
(Cardoso, Mukohyama, Oshita, Takahashi, 2024 in preparation)



Answer requires understanding of theoretical framework, PDE analysis, precise modelling, observations, challenging simulations & data analysis techniques

Spectral stability: the elephant and the flea

Spectrum is unstable: Nollert gr-qc/9602032; Barausse + PRD89:104059 (2014); Jaramillo+ PRX 11: 031003 (2021); Cheung+ PRL128:111103 (2022); PRD106:084011 (2022)



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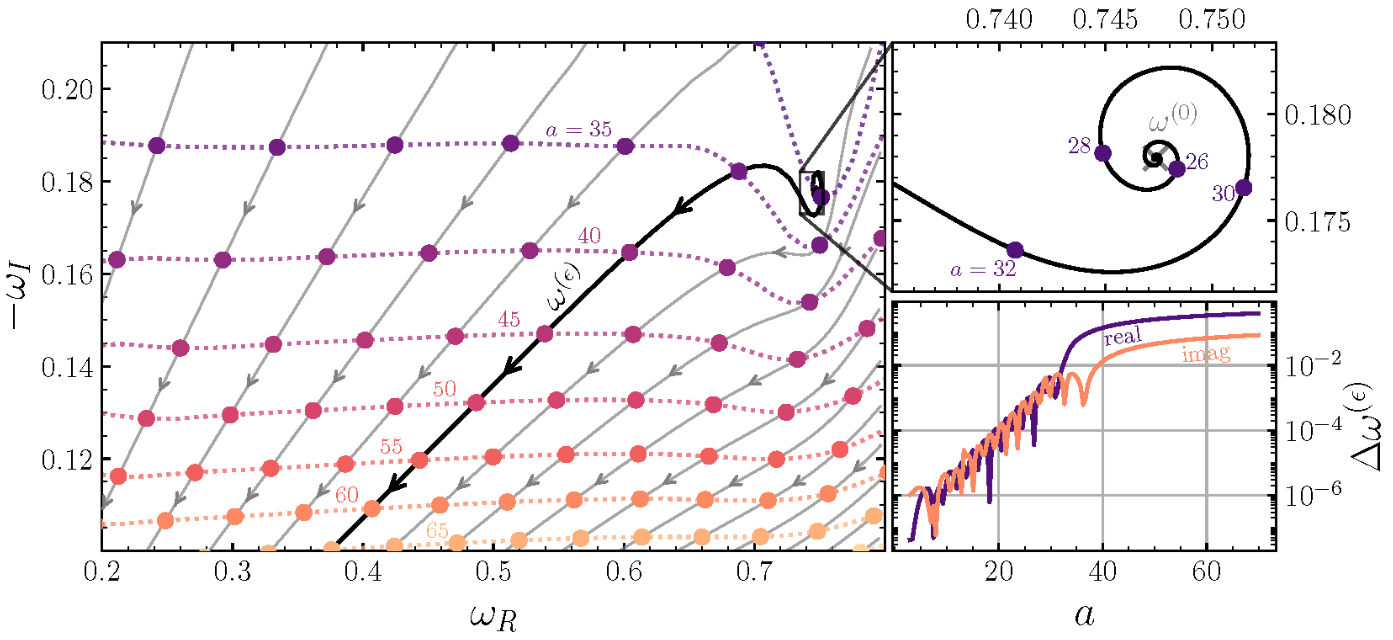
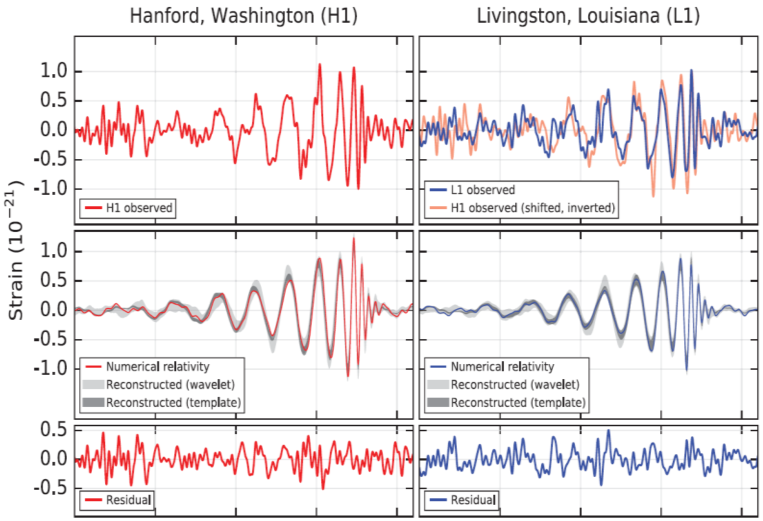
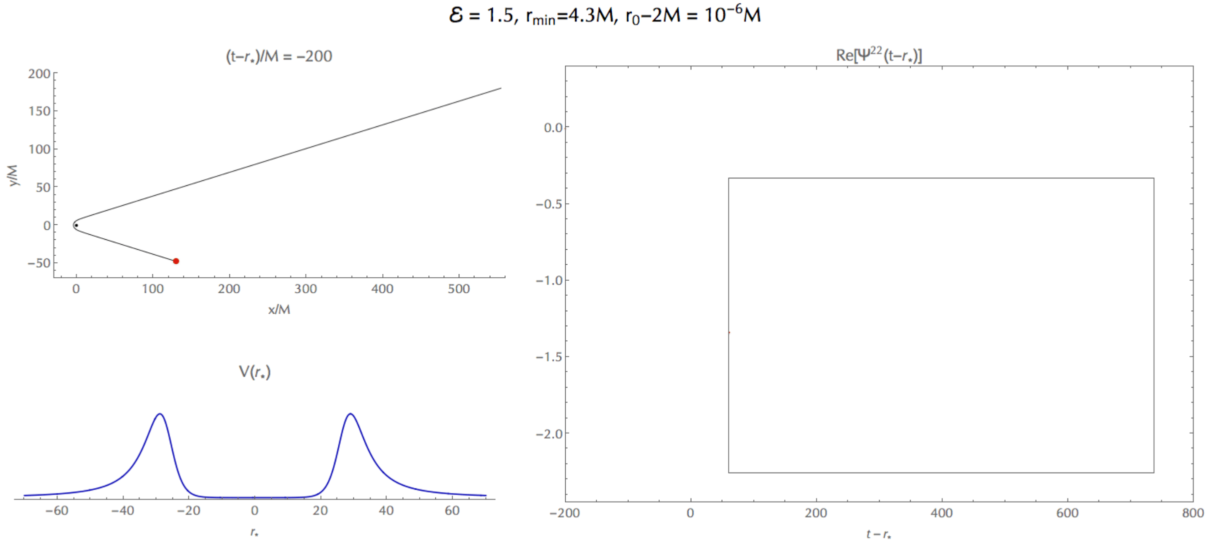


$\varepsilon=10^{-6}$

Bumps on the horizon: post-merger echoes





Cardoso + PRL116:171101 (2016); Nature Astronomy 1: (2017); Living Reviews in Relativity 22:1 (2019)
LVK arXiv:2010:14529; arXiv:2112.06861

Fundamental questions

Are we really looking at black holes?

Is it a Kerr black hole? How can we constrain alternatives?

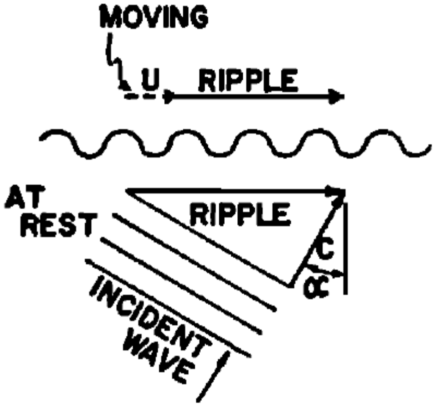
Can black holes be used as particle detectors?

Can black holes be used as tools to understand environment?

Answer requires understanding of theoretical framework, PDE analysis, precise modelling, observations, challenging simulations & data analysis techniques

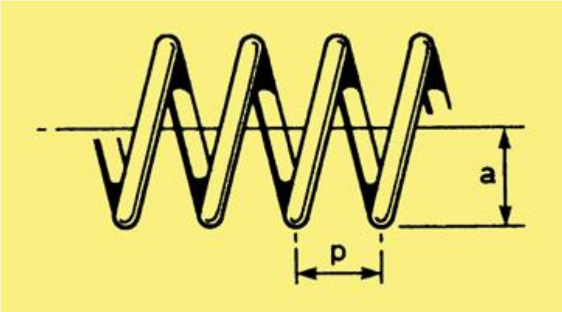
Superradiance: something from nothing

Zel'dovich JETP Lett. 14:180 (1971); Brito+ Lect. Notes Phys.971 (2020)

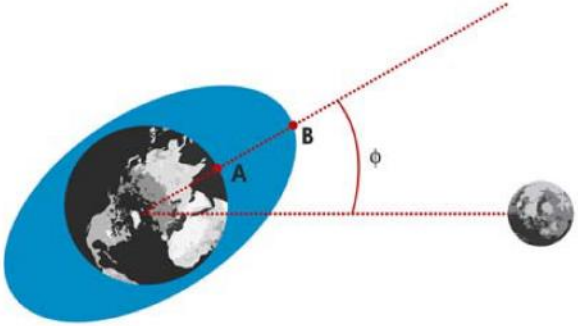


Ribner, J. Acous. Soc. Amer. 29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

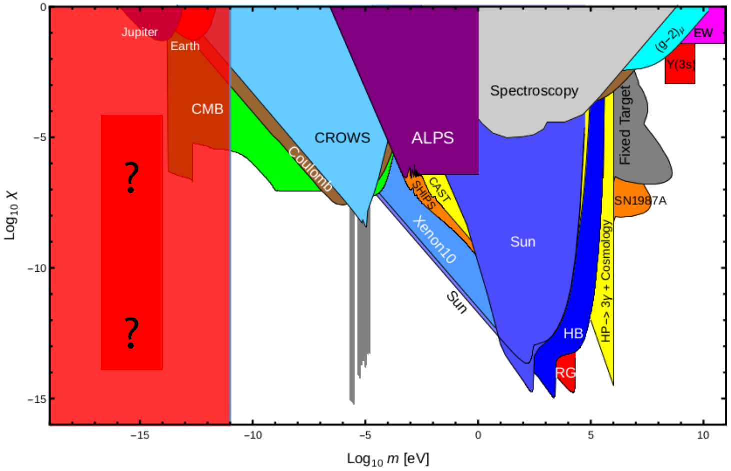


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



G. H. Darwin, Philos. Trans.
R. Soc. London 171 (1880)

Light fields



Interesting as effective description; bosons exist (Higgs) & lighter versions may too

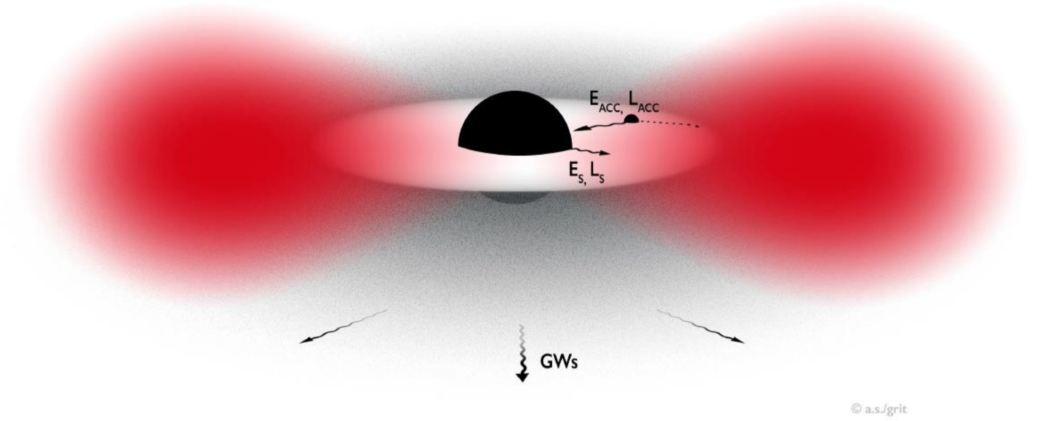
Peccei-Quinn (interesting because not suggested to solve dark matter issue),
Axiverse (moduli and coupling constants in string-theory, Arvanitaki+2010)

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_{\mathrm{S}}^2}{2}\Psi\Psi - \frac{k_{\mathrm{axion}}}{2}\Psi\ {}^*F^{\mu\nu}F_{\mu\nu}$$

...and one one more could be a component of dark matter. New scale:

$$L = 2000\left(\frac{10^{-10}\mathrm{eV}}{\mu_S}\right)\ \text{meters}$$

Fundamental fields: bounding the boson mass



$$\nabla_\gamma \nabla^\gamma \Psi = \mu^2 \Psi\,, \quad \nabla_\gamma F^{\gamma\nu} = \mu^2 A^\nu\,, \quad \nabla_\gamma \nabla^\gamma h_{\mu\nu} = \mu^2 h_{\mu\nu}$$

$$\Psi \sim e^{-i\omega t} Y_{lm}$$

$$\omega \sim \mu + i(m\Omega_H - \mu)(M\mu)^{4l+5+S}$$

$$S = -s, -s+1 ..., s-1, s$$

lot of work here!

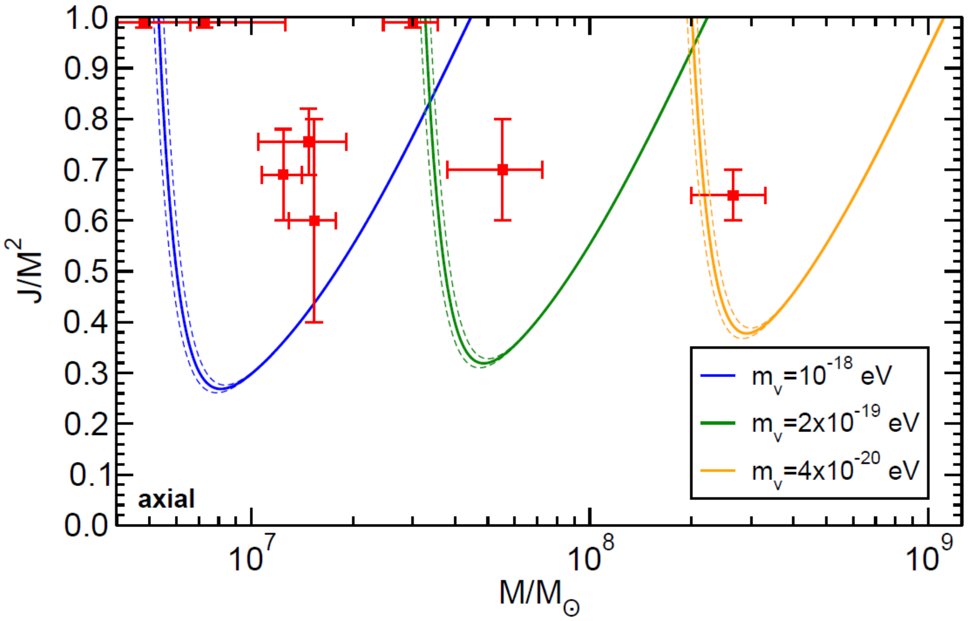
$$\tau \sim 100a \left(\frac{10^6 M_\odot}{M}\right)^8 \left(\frac{10^{-16}\,\mathrm{eV}}{\mu}\right)^9 \mathrm{sec}$$

Wonderful sources of GWs & BH spindown

Arvanitaki & Dubovsky PRD83:0441026 (2011); Yoshino & Kodama PTP 128:153 (2012); Brito+ CQG32:134001 (2015); Brito+ Lecture Notes Physics 971 (2020)

Bounding the boson mass with EM observations

Pani + PRL109, 131102 (2012)



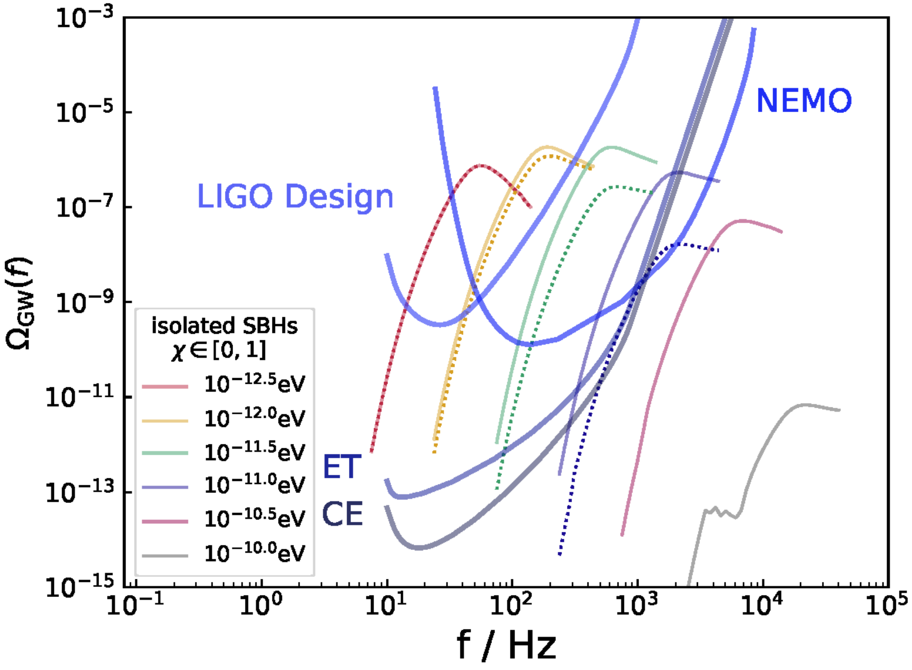
Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important… but gravitons interact very weakly!

$$m_g < 5 \times 10^{-23}\,\mathrm{eV}$$

Brito + PRD88:023514 (2013); Review of Particle Physics 2014

Wonderful sources for different GW-detectors

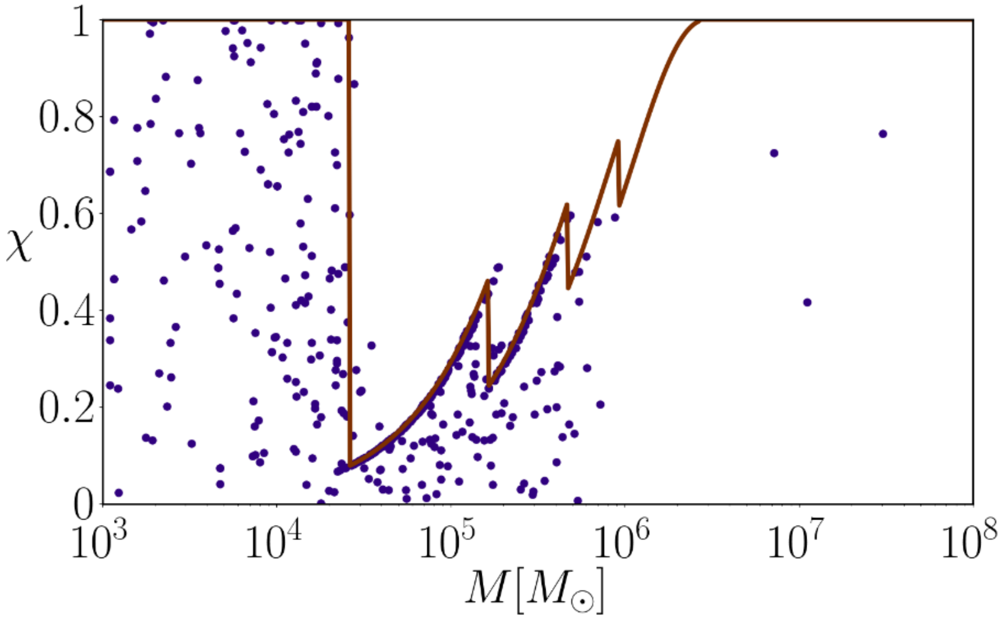
Arvanitaki+ PRD91: 084011 (2015); Brito + PRL119: 131101 (2017); Yuan + PRD104:044011 (2021)



Dotted lines only include m = 1 mode, solid lines include all modes. Plot also shows power-law integrated sensitivity curves. Assume four-year-detection and two co-aligned and co-located identical detectors for NEMO/CE/ET.

Yuan + PRD104:044011 (2021)
The LIGO Scientific Collaboration arXiv:2111.15507;
For LISA see Brito + PRL119: 131101 (2017); PRD96:064050 (2017)

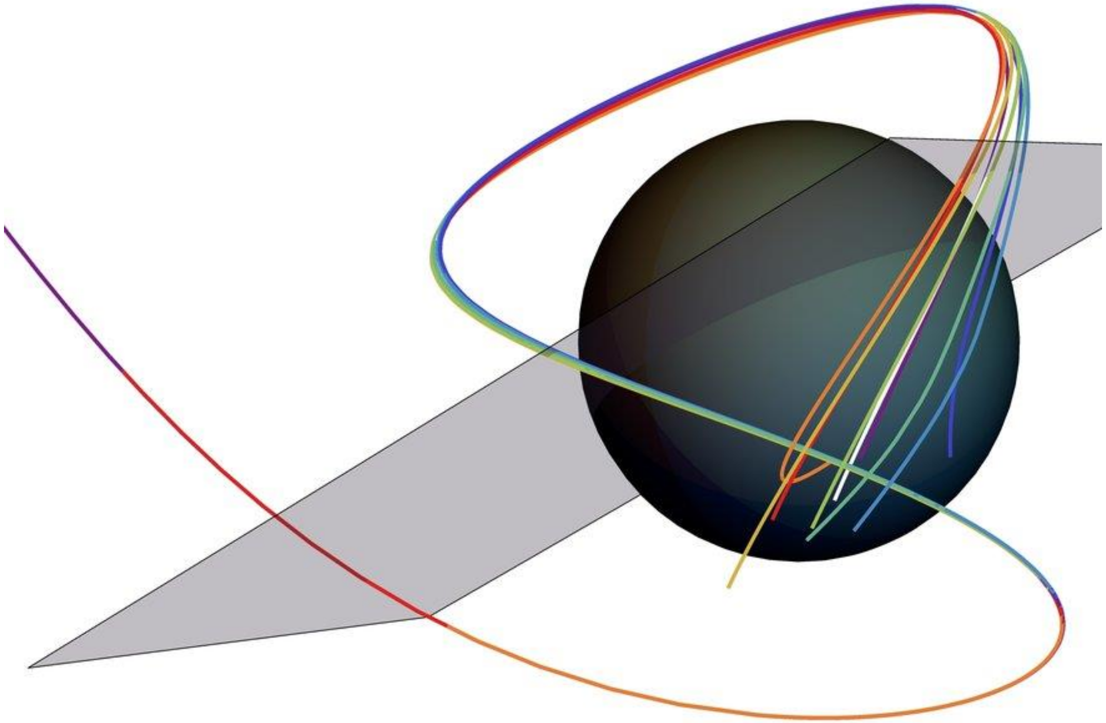
Signatures in Regge plane



Two-year simulation for LISA and a boson with $10^{-16}\,\mathrm{eV}$. Saw-tooth due to different m harmonics. Final estimate from LISA: $(0.88 - 1.35) \times 10^{-16}\,\mathrm{eV}$

Brito + PRL119: 131101 (2017); PRD96:064050 (2017)

Light ring measurements



Oscillating axions or scalars induce varying spacetime geometry, and light ring structure is exponentially sensitive to it. Photon autocorrelation provides important bounds on such structures.

Chen+ Phys. Rev. Lett. 130: 111401 (2023)

Constraints on fundamental fields via superradiance

Review in Brito+ Lect. Notes Phys.971 (2020)

	excluded region (in eV)	source
*	$5.2 \times 10^{-13} < m_S < 6.5 \times 10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.
*	$1.1 \times 10^{-13} < m_V < 8.2 \times 10^{-12}$	
*	$2.9 \times 10^{-13} < m_T < 9.8 \times 10^{-12}$	
	$6 \times 10^{-13} < m_S < 2 \times 10^{-11}$	Indirect bounds from BH mass-spin measurements.
	$7 \times 10^{-20} < m_S < 1 \times 10^{-16}$	
*	$2 \times 10^{-14} < m_V < 1 \times 10^{-11}$	
*	$1 \times 10^{-20} < m_V < 9 \times 10^{-17}$	
*	$6 \times 10^{-14} < m_T < 1 \times 10^{-11}$	
*	$3 \times 10^{-20} < m_T < 9 \times 10^{-17}$	
	$1.2 \times 10^{-13} < m_S < 1.8 \times 10^{-13}$	Null results from blind all-sky searches for continuous GW signals.
	$2.0 \times 10^{-13} < m_S < 2.5 \times 10^{-12}$	
	m_V: NA	
	m_T: NA	
	$5.8 \times 10^{-13} < m_S < 8.6 \times 10^{-13}$	Null results from searches for continuous GW signals from Cygnus X-1.
	m_V: NA	
	m_T: NA	
	$2.0 \times 10^{-13} < m_S < 3.8 \times 10^{-13}$	Negative searches for a GW background.
	m_V: NA	
	m_T: NA	
	$5 \times 10^{-13} < m_S < 3 \times 10^{-12}$	Bounds from pulsar timing.
	$m_V \sim 10^{-12}$	
	m_T: NA	
	$2.9 \times 10^{-21} < m_S < 4.6 \times 10^{-21}$	Bounds from mass and spin measurement of M87 with EHT.
	$8.5 \times 10^{-22} < m_V < 4.6 \times 10^{-21}$	
*	$1.0 \times 10^{-21} < m_T < 8.2 \times 10^{-21}$	

Couplings to Standard Model

Thomas Spieksma's talk

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_S^2}{2}\Psi\Psi - \frac{k_{\text{axion}}}{2}\Psi\ {}^*F^{\mu\nu}F_{\mu\nu}$$

Boskovic+ PRD99:035006 (2019); Ikeda+ PRL122:081101 (2019); Spieksma+PRD108:063013 (2023)

$$k_{\text{axion}} < \left(\frac{M_{BH}}{M_S}\right)^{1/2} (\mu\, M)^{-1}$$

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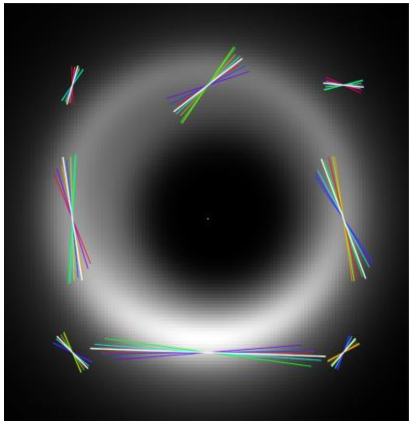
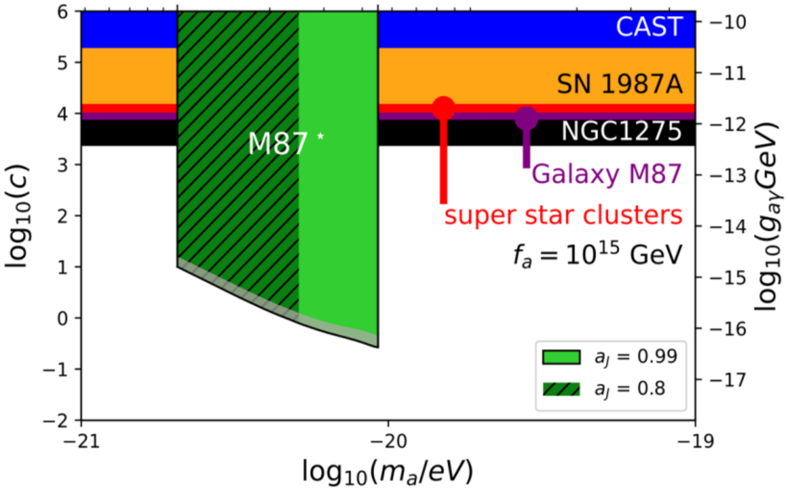


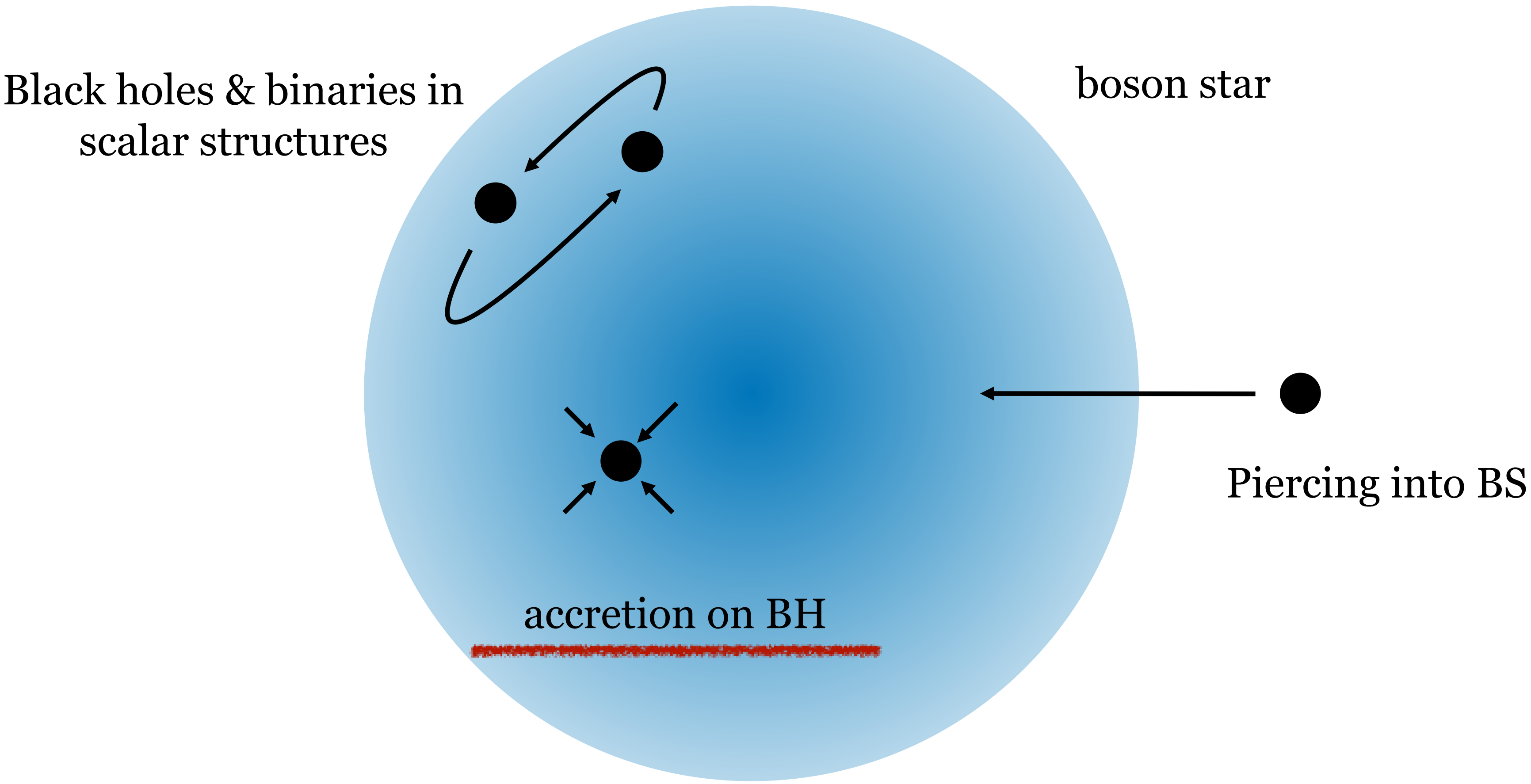


Oscillating axion fields induce electric vector polarization angle oscillation (5-20 days for M87*) achromatically. 4 days EHT 21' polarimetric observations excludes axion-photon coupling to previous unexplored region (BH spin is assumed to be 0.99 or 0.8).

Chen+ Nature Astronomy 6: 592 (2022)

Vacuum is an illusion: black hole aerodynamics

see also Conor Dyson's talk



Black holes & binaries in scalar structures

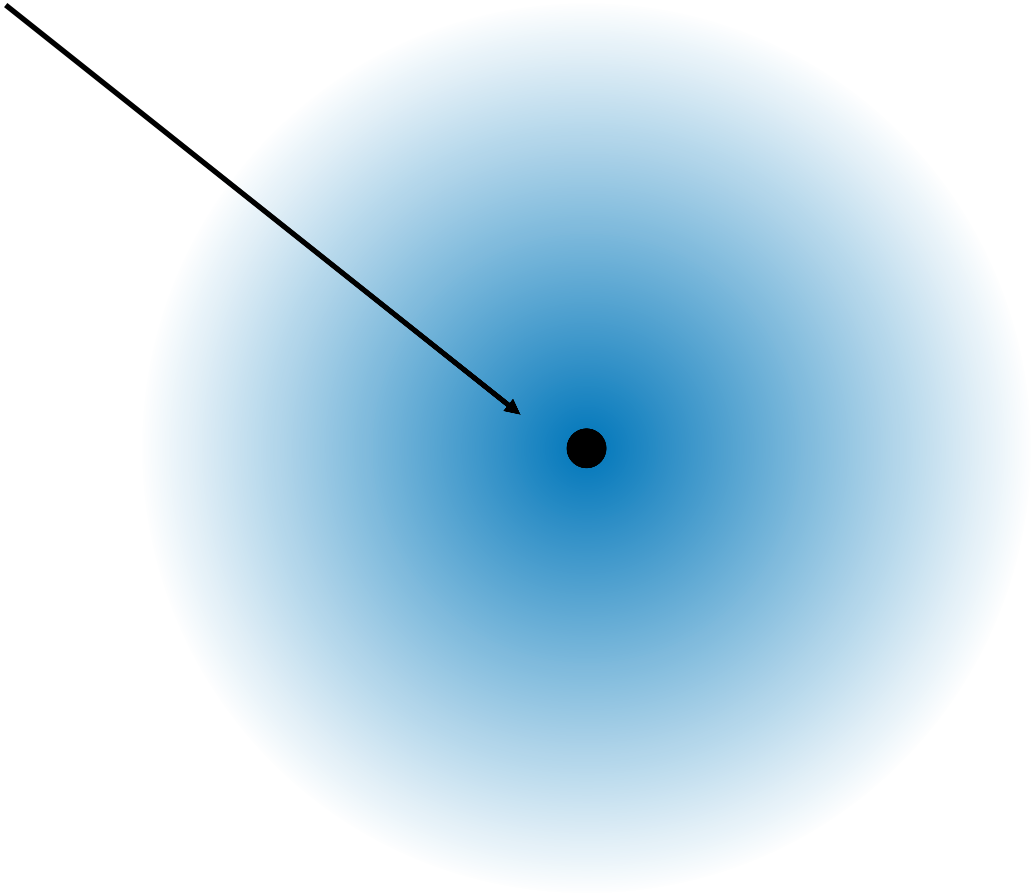
boson star

Piercing into BS

accretion on BH

Details of dynamics, time scales?

Accretion of a boson star onto a BH



Black hole, M_0

boson star (ground state)

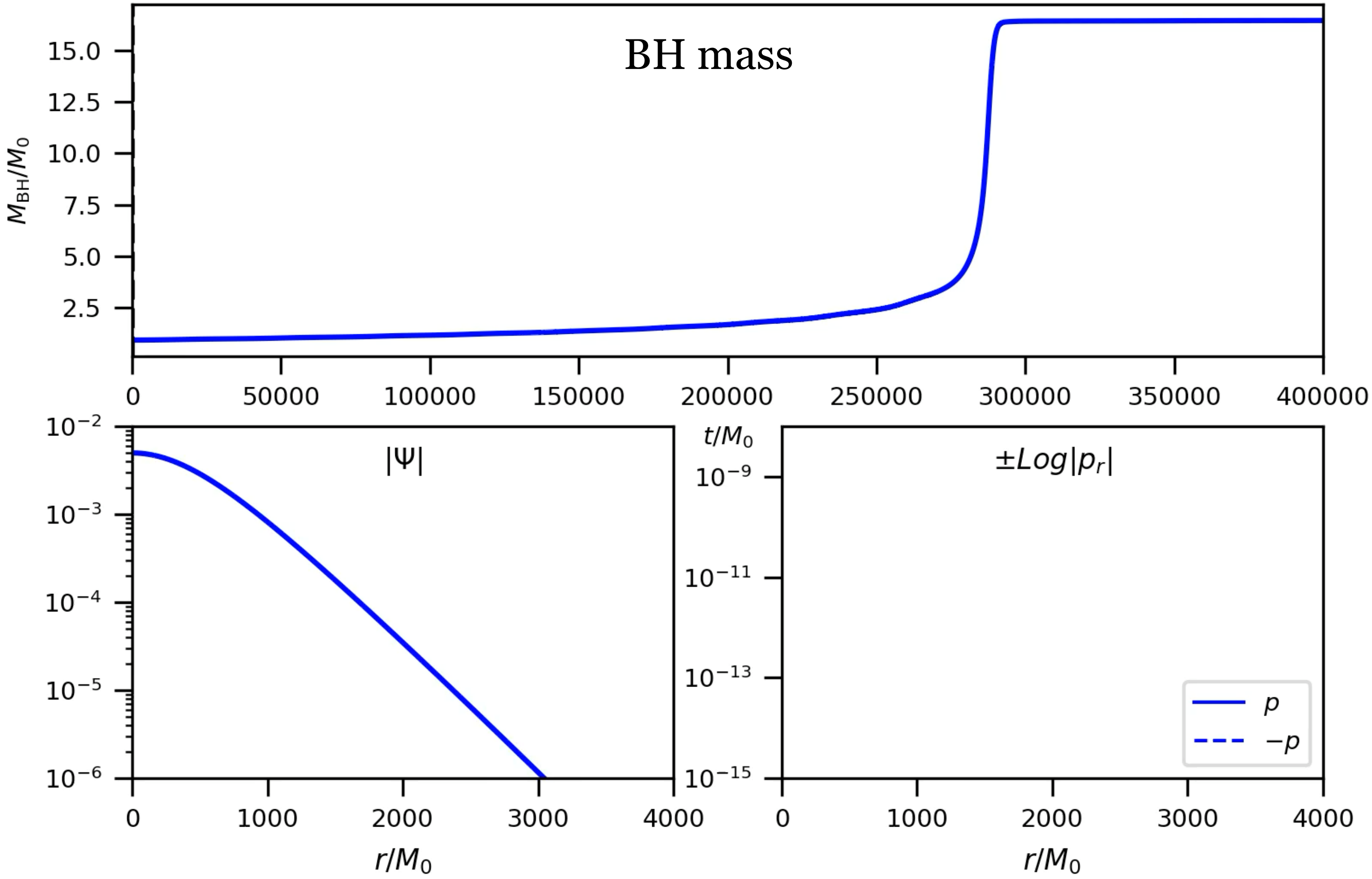
Parameters

$(M_{\mathrm{BS}}/M_0, R_{\mathrm{BS}}/M_0)$

Initial Data

Numerical results

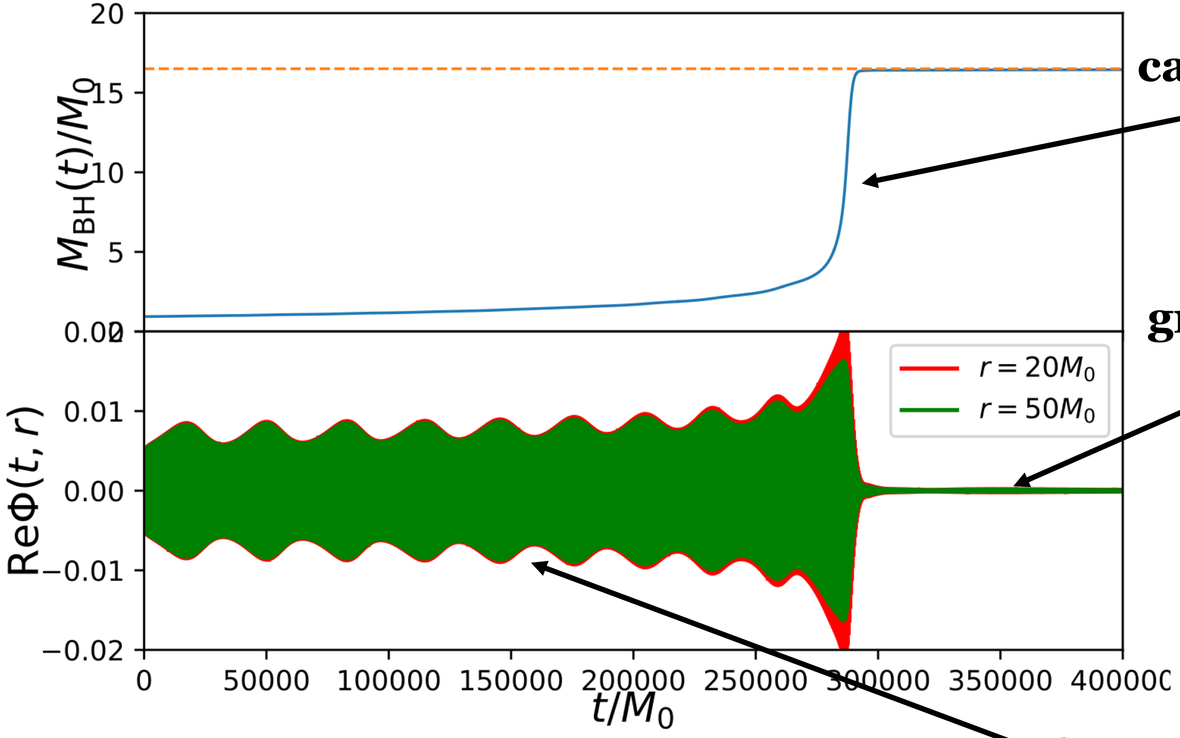
$R_{\mathrm{BS}} = 1360 M_{\mathrm{BH,0}}$ $M_{\mathrm{BS}} = 15.5 M_{\mathrm{BH,0}}$



Scalar field Energy flux

Numerical results

No potential barrier for large BHs $M_{\rm BH,crit} = 0.25\mu^{-1}$



catastrophic stage

gravitational atom

boson-quake stage
(BS modes)

$$\frac{t_{10\%}}{10\ \mathrm{Gyr}} \simeq 4\,\frac{M_{\rm BS,0}}{M_{\rm BH,0}}\left(\frac{10^{10}M_{\rm sun}}{M_{\rm BS,0}}\right)^5\left(\frac{10^{-22}\mathrm{eV}}{\mu}\right)^6$$

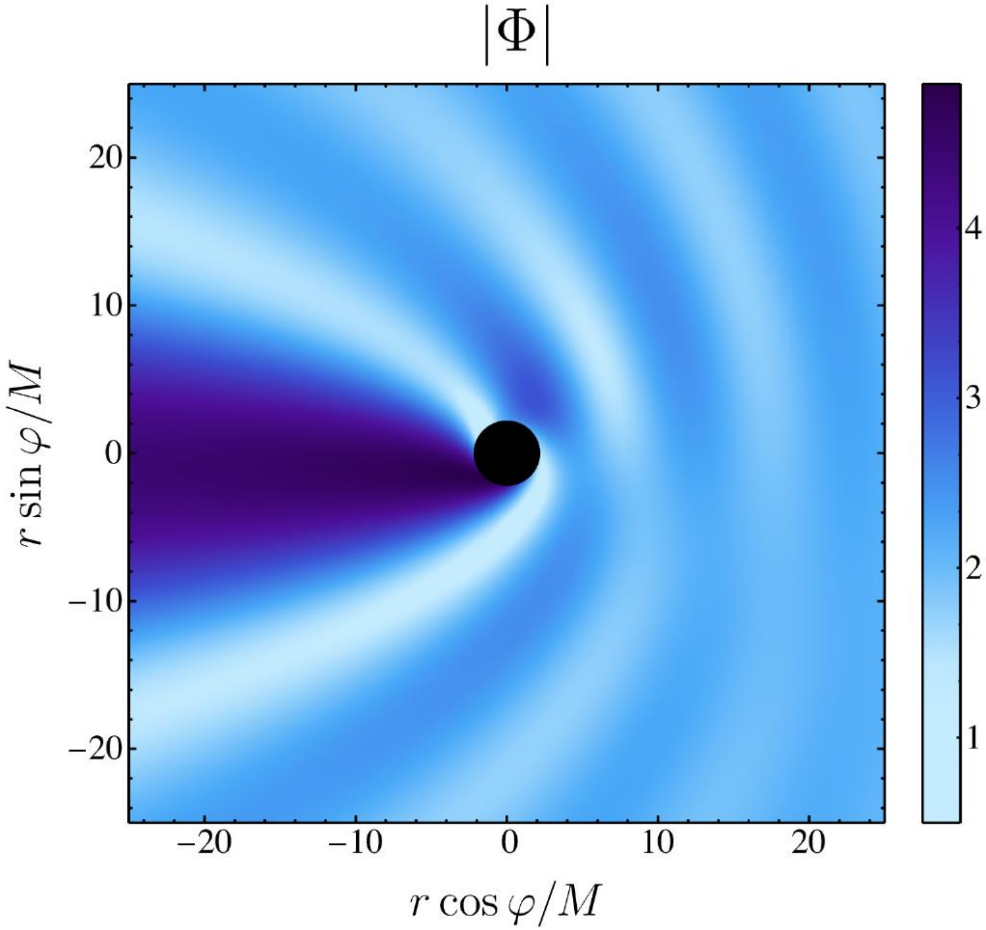
Vacuum is an illusion: black hole aerodynamics

Accretion

Cardoso + PRDLetters 106:121302 (2022)

Dynamical friction

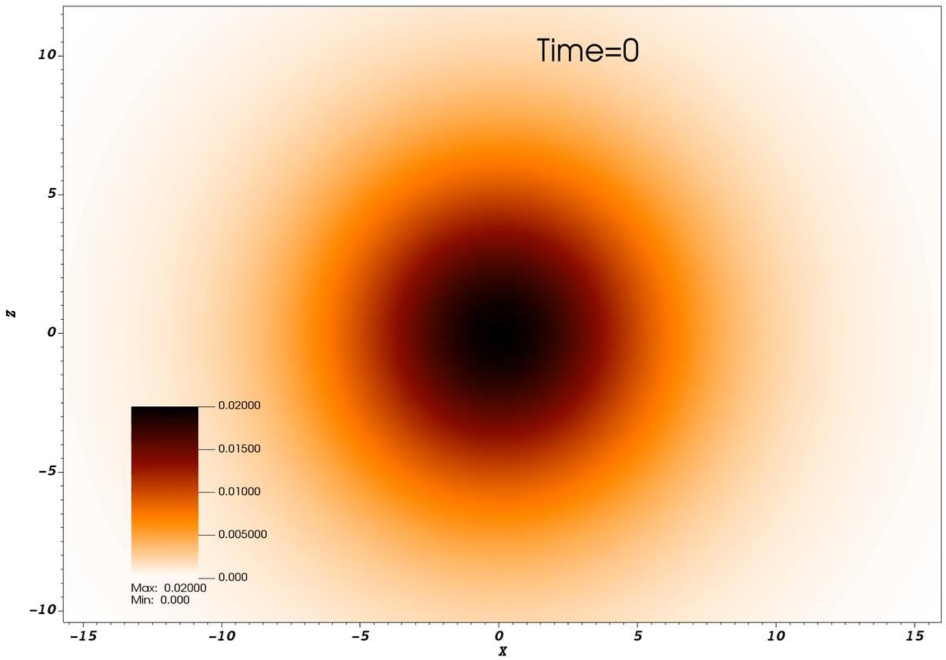
Chandrasekhar 1943; Ostriker 1999;
Annulli+ PRD102:063022 (2020);
Traykova+ PRD104:103014 (2021);
Cardoso + PRD106:044030 (2022);
Vicente + PRD105:083008 (2022)



Challenges

Dynamical friction understood well in Newtonian setups…

Annulli+ PRD102:063022 (2020); Traykova+ PRD104:103014 (2021);
Vicente + PRD105:083008 (2022); Buehler & Desjacques arXiv:2207.13740;
Dyson+ 2402.07981; Wang+ arXiv:2402.07977



Cardoso + PRD106:044030 (2022)

Vacuum is an illusion: black hole aerodynamics

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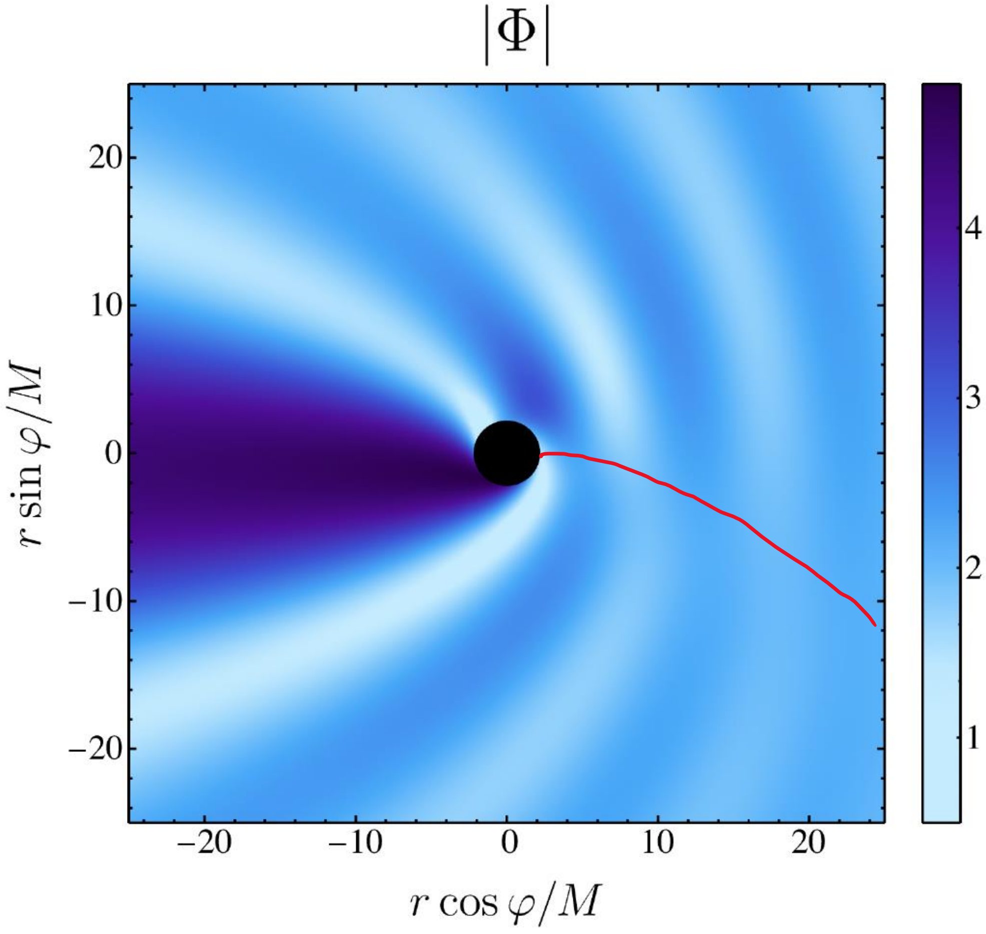
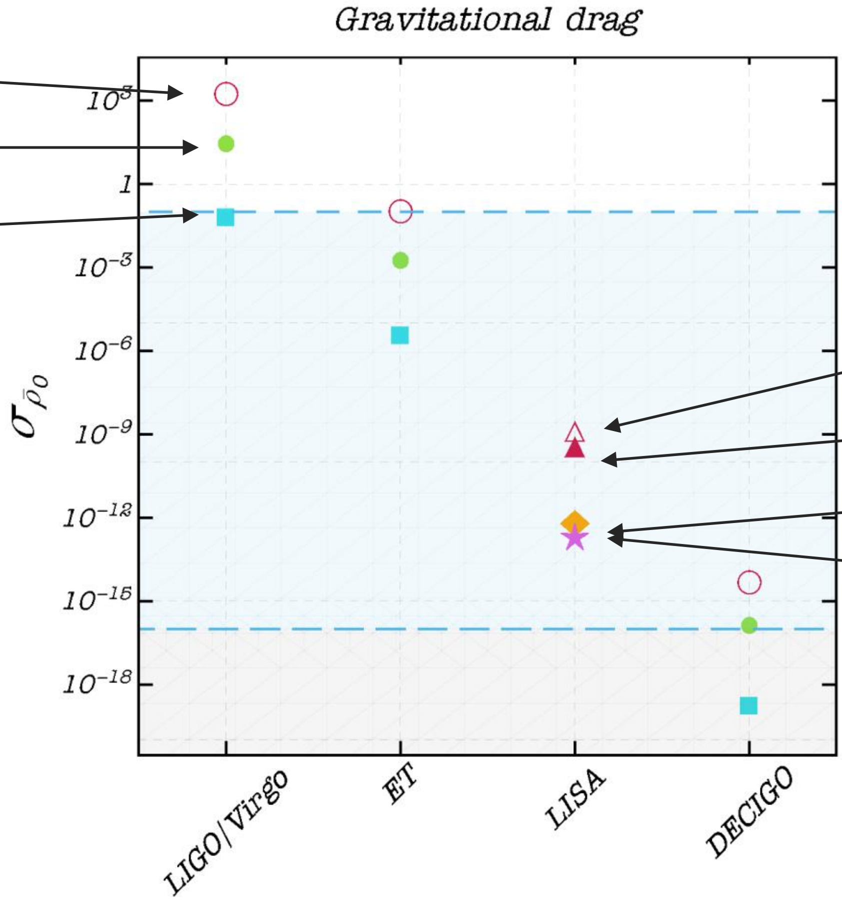
Magnus & lift forces

Costa + PRD98:024026 (2018);
C. Dyson + arXiv:2402.07981;
Wang+ arXiv:2402.07977



Binaries: first constraints on environment



GW150914

GW170608

GW170817

IMRI

EMRI

MBBH high spin

IMBBH low spin

Effect is -5.5 PN on GW phase

Cardoso & Maselli AA644: A147 (2020); Santoro + arXiv:2309.05061
Also Eda + PRL 110 (2013) 221101; Macedo+ApJ774 (2013) 48; Annulli+ PRD102;063022 (2020)

Galaxy tomography?

Cardoso+ PRDL061501 (2022); PRL129:241103 (2022); Figueiredo + PRD107:104033 (2023); Speeney 2024

Black holes in galaxies: an Einstein Cluster prescription (Einstein 1939)

Assume averaged stress-tensor

$$\langle T^{\mu\nu}\rangle = \frac{n}{m_p}\langle P^\mu P^\nu\rangle \Leftrightarrow T^\mu_\nu = \mathrm{diag}(-\rho, 0, P_t, P_t)$$

Impose spherical symmetry

$$ds^2 = -f dt^2 + \frac{dr^2}{1-2m(r)/r} + r^2 d\Omega^2$$

Assign mass function

Hernquist ApJ356:359 (1990)

$$m(r) = M_{\rm BH} + \frac{Mr^2}{(a_0+r)^2}\left(1-\frac{2M_{\rm BH}}{r}\right)^2$$

Solve field equations

$$f = \left(1-\frac{2M_{\rm BH}}{r}\right)e^\Upsilon$$

$$\Upsilon = -\pi\sqrt{\frac{M}{\xi}} + 2\sqrt{\frac{M}{\xi}}\arctan\frac{r+a_0-M}{\sqrt{M\xi}}$$

$$\xi = 2a_0 - M + 4M_{\rm BH}$$

Generalization to other profiles is straightforward.
see Figueiredo + arXiv:2303.08183; Speeney + 2401.00932

Galaxy tomography?

Cardoso+ PRDL061501 (2022); PRL129:241103 (2022); Figueiredo + PRD107:104033 (2023); Speeney 2024

Two ingredients play a role:

1. Compactness of distribution $\frac{M}{a_0}$, which dictates geometry & wave generation effects. For typical galaxies $\frac{M}{a_0}$=10^{-4}- 10^{-6}. For dark matter spikes one can pump up to 10^{-3}.

2. Density ρ which governs matter effects (dynamical friction etc)

Galaxy tomography?

Cardoso+ PRDL061501 (2022); PRL129:241103 (2022); Figueiredo + PRD107:104033 (2023); Speeney 2024

$$b_{\rm crit} = 3\sqrt{3}M_{\rm BH}\left(1+\frac{M}{a_0}+\frac{M(5M-18M_{\rm BH})}{6a_0^2}\right)$$

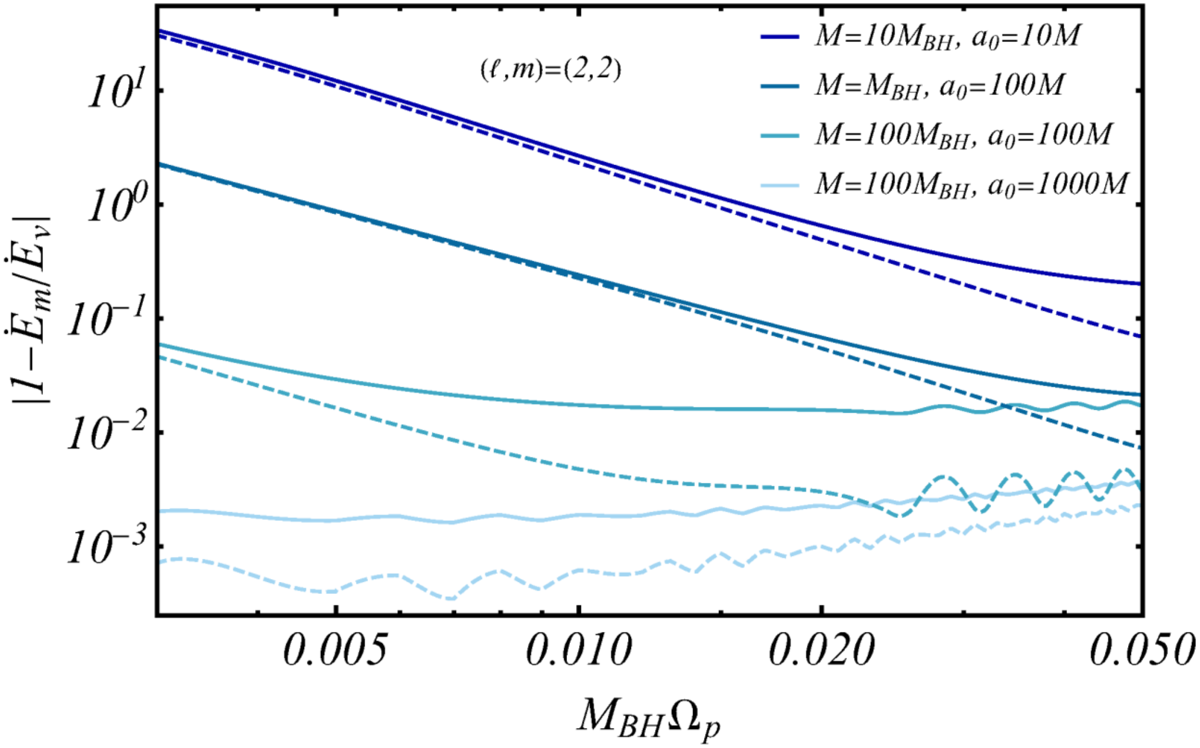
Thus EHT physics affected to levels of 10^{-8} only, *for expected parameters* (tests on nature of compact objects can be done to very good precision)

Light-ring corrections:

$$M_{\rm BH}\Omega_{\rm LR}\sim\frac{1}{3\sqrt{3}}\left(1-\frac{M}{a_0}-\frac{M^2}{6a_0^2}\right)\sim M_{\rm BH}\Omega_{\rm LR}^{\rm Schw}\left(1-\frac{M}{a_0}-0.17\frac{M^2}{a_0^2}\right)$$

Environments: a fully relativistic analysis

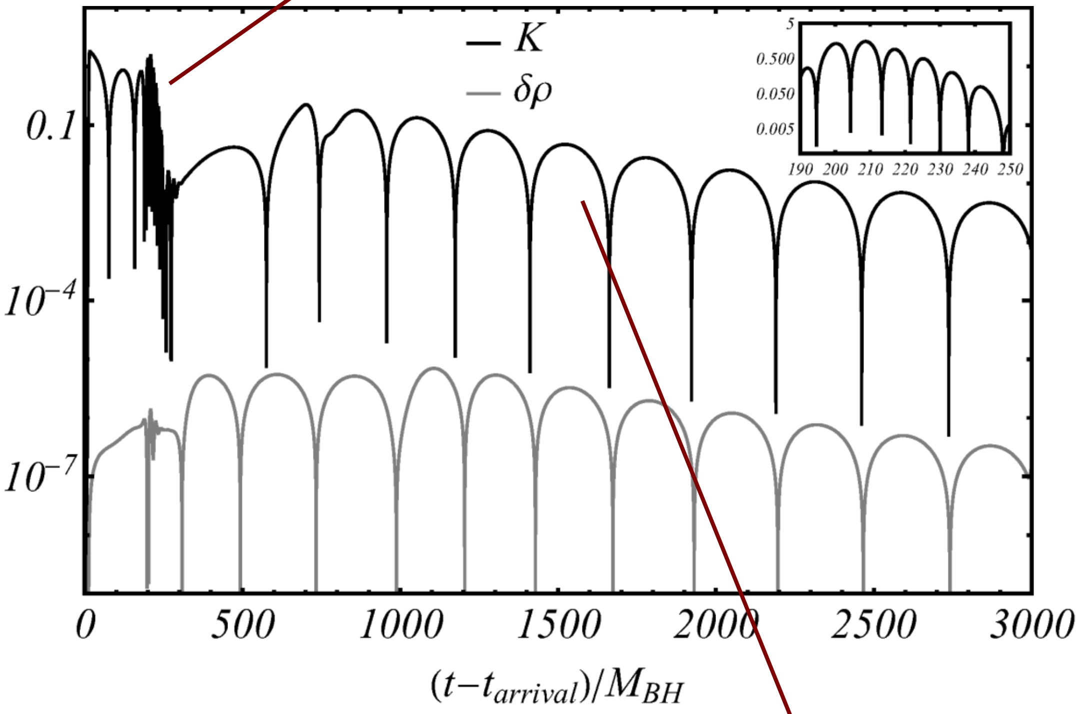
Cardoso+ PRL129:241103 (2022)



Extension to arbitrary profiles: Figueiredo+ PRD107:104033 (2023); Speeney+ arXiv:2401.00932

Spectral instability in action

Cardoso+ PRL129:241103 (2022)



Light ring modes
(BH ringdown)

Fluid modes

Conclusions: exciting times!

Gravitational wave astronomy *will* become a precision discipline, mapping compact objects throughout the entire visible universe.

Strong field gravity is a fascinating topic. From precise maps of Universe to tests of Cosmic Censorship or constraints on dark matter, possibilities are endless & exciting. Black holes respond in simple way to external perturbations, and may serve as detectors for nontrivial environments.

Black holes remain the most outstanding object in the universe.
Spectroscopy will allow to test GR and provide strong evidence for the presence of horizons… improved sensitivity pushes putative surface closer to horizon, like probing short-distance structure with accelerators.

Thank you