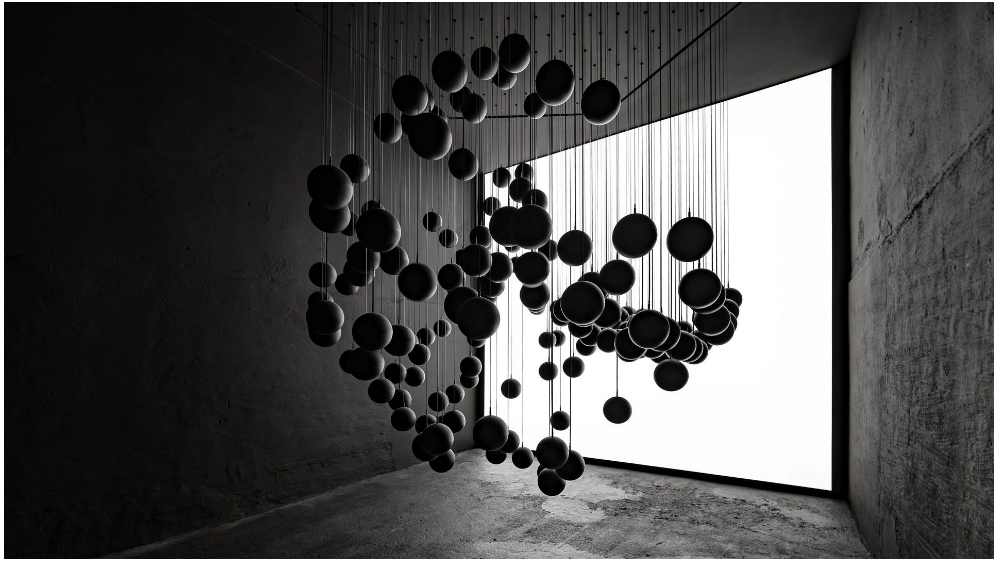
EMRIs: does (Dark) Matter matter?

Francisco Duque



3rd September 2024, *Fundamental Physics meets Waveforms with LISA*

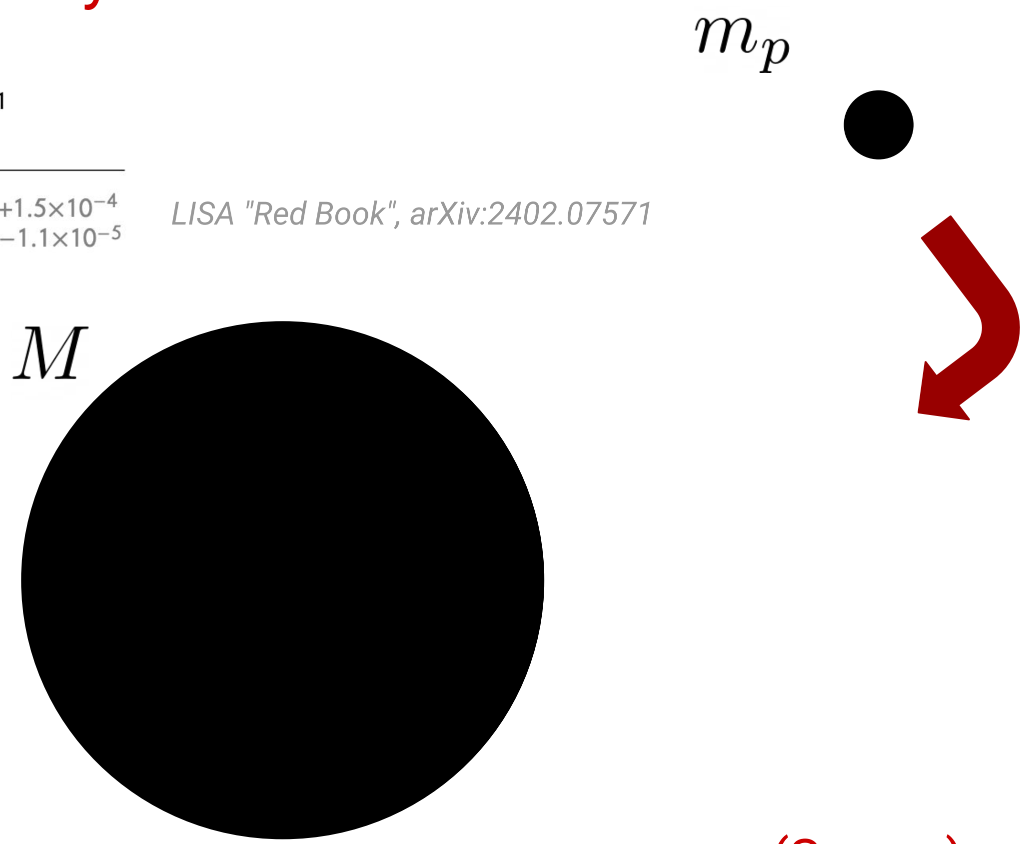
Max-Planck-Institut
für Gravitationsphysik
ALBERT-EINSTEIN-INSTITUT

MAX PLANCK
GESELLSCHAFT

EMRIs: 10^5 orbital cycles in LISA

$\left(\frac{\Delta M}{M}\right)_{\text{obs}}$	$\Delta\chi_1$
$3.5\times10^{-5}{}^{+6\times10^{-5}}_{-1.9\times10^{-5}}$	$3.1\times10^{-5}{}^{+1.5\times10^{-4}}_{-1.1\times10^{-5}}$

LISA "Red Book", arXiv:2402.07571

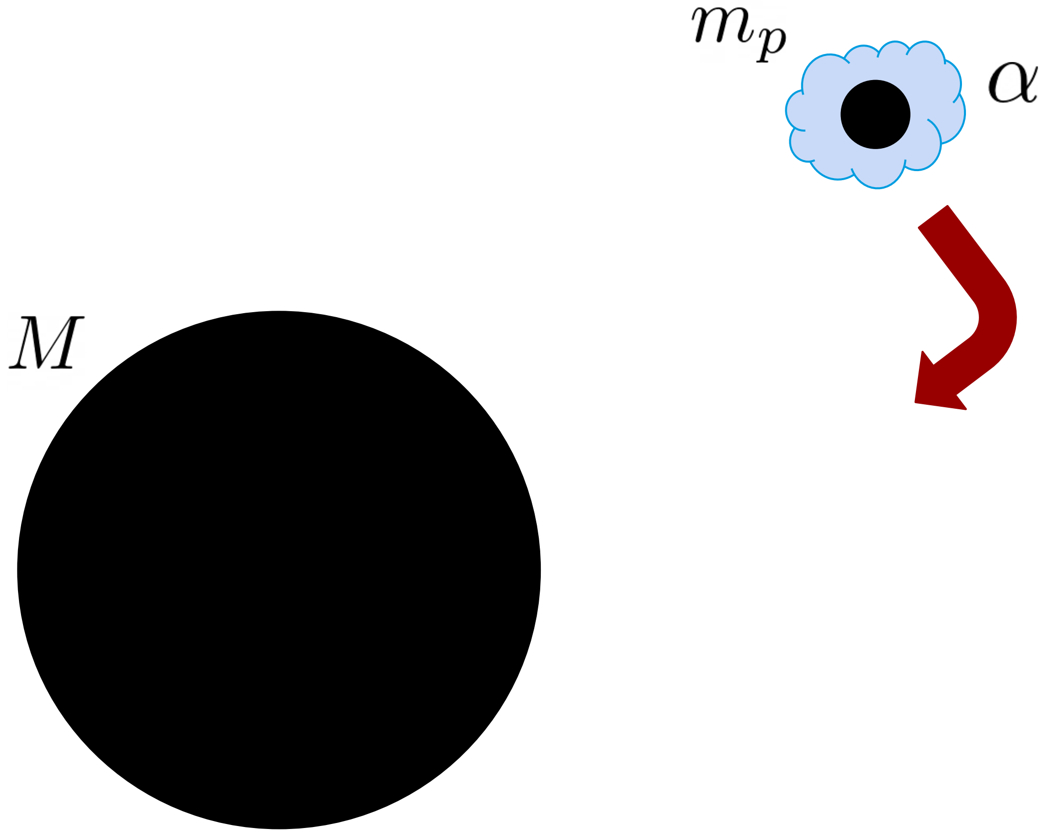


(Sorry...)

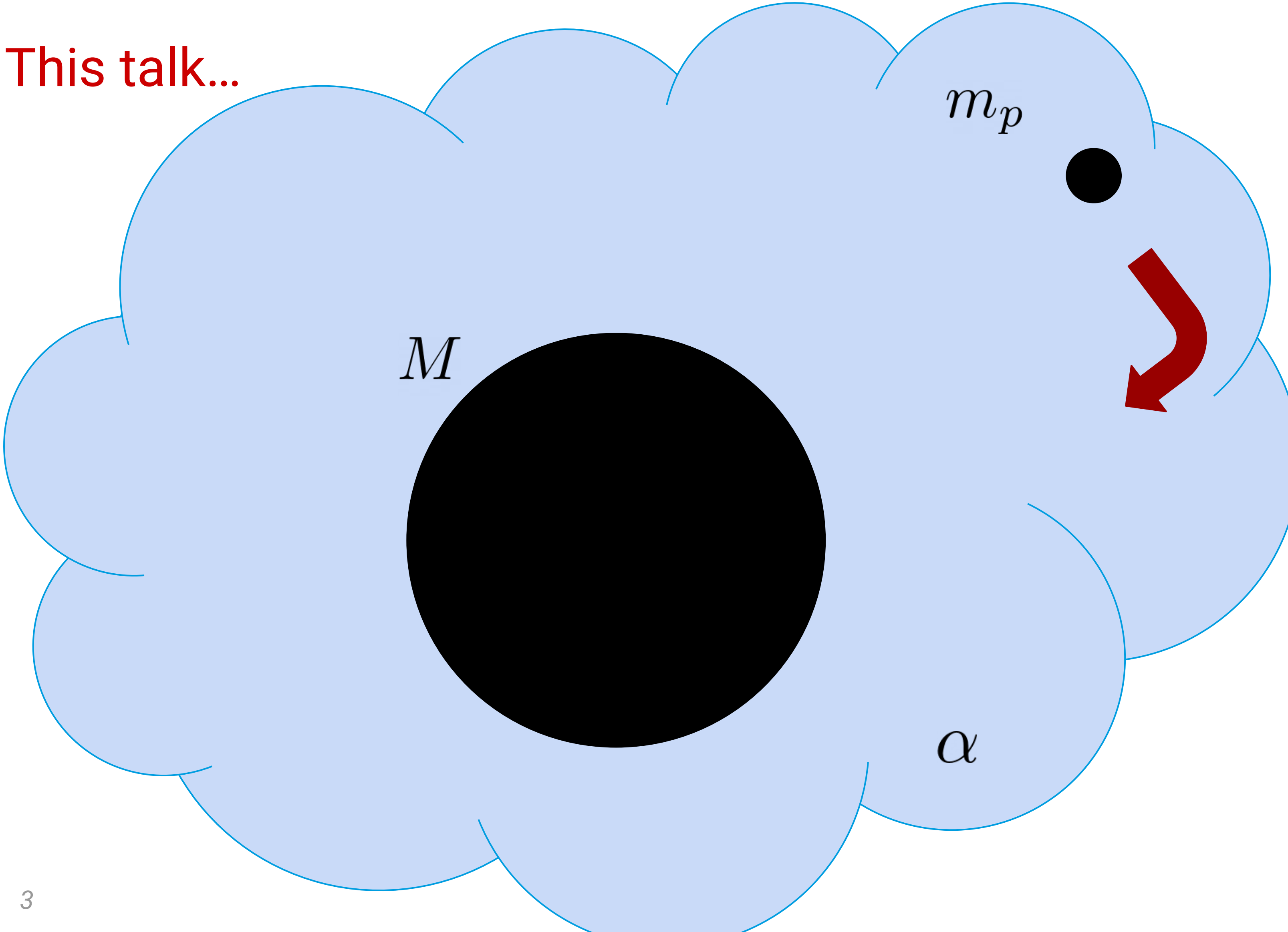
$$g_{\mu\nu}^{\text{exact}} = g_{\mu\nu} + \epsilon h_{\mu\nu}^{(1)} + \epsilon^2 h_{\mu\nu}^{(2)} + \mathcal{O}(\epsilon^3)$$

$$\epsilon = q = m_p/M$$

Susanna's talk...



This talk...



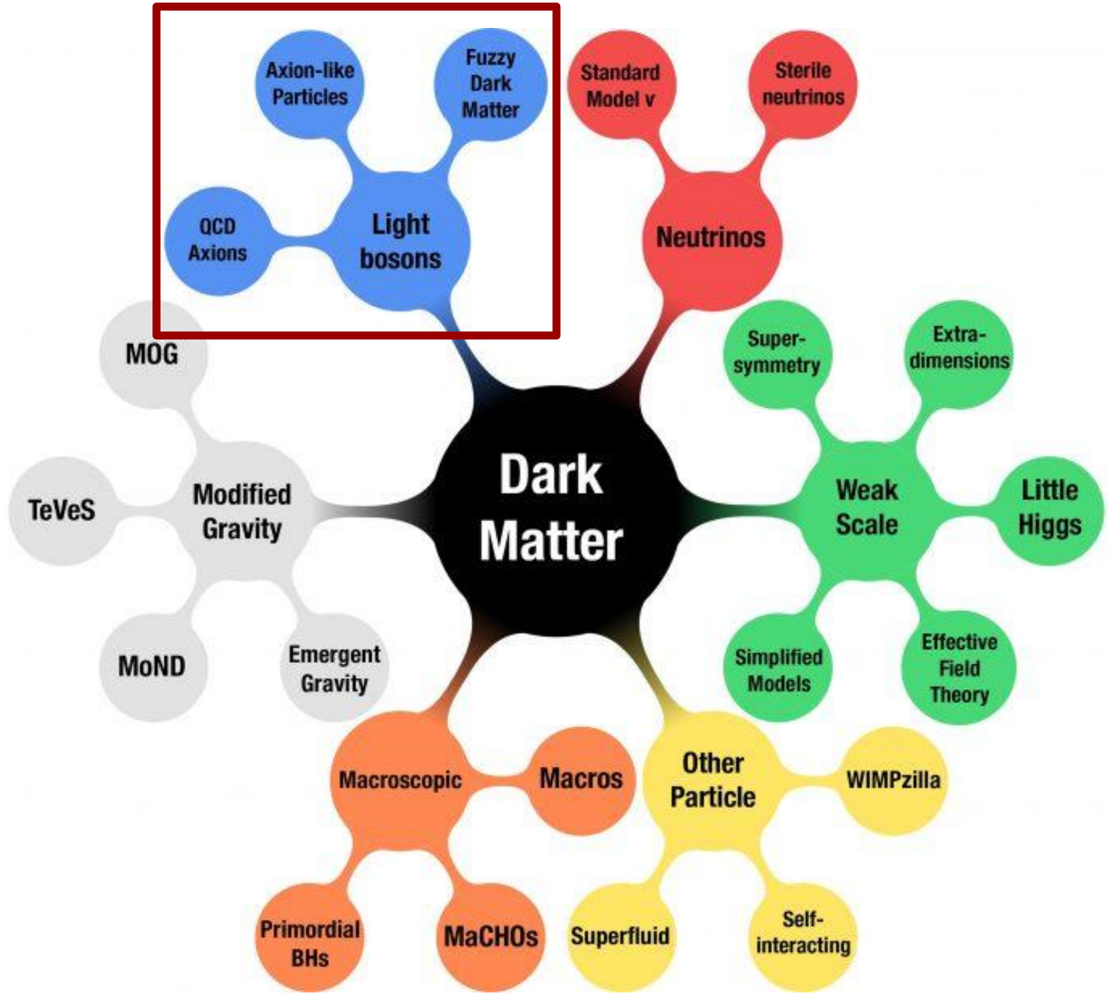


Image Credit: G. Bertone and T. M. P. Tait

de Broglie wavelength

$$\lambda_{\mathrm{dB}} = \frac{2\pi}{m_\Phi v} = 0.48\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m_\Phi}\right)\left(\frac{250\mathrm{km/s}}{v}\right)$$

No. particles in *de Broglie* volume λ_{dB}^3

$$N_{\mathrm{dB}} \sim \left(\frac{34\,\mathrm{eV}}{m_\Phi}\right)^4 \left(\frac{250\,\mathrm{m/s}}{v}\right)^3$$

$m_\Phi \lesssim 10\,\mathrm{eV}$ → *Classical* Waves

Hui ARAA 59, 247-289 (2021)

$$r \gtrsim 1\,\mathrm{kpc}$$

Particle

$$r \lesssim 1\,\mathrm{kpc}$$

Wave

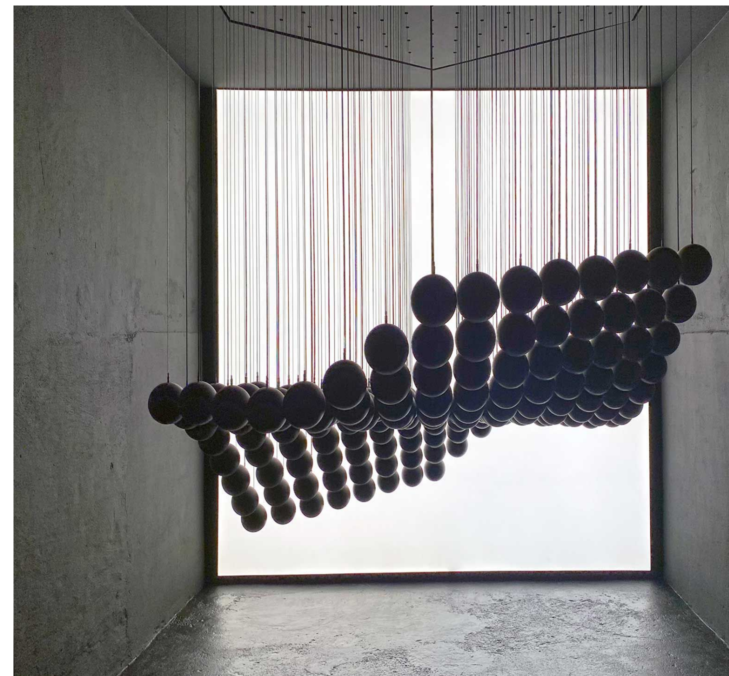
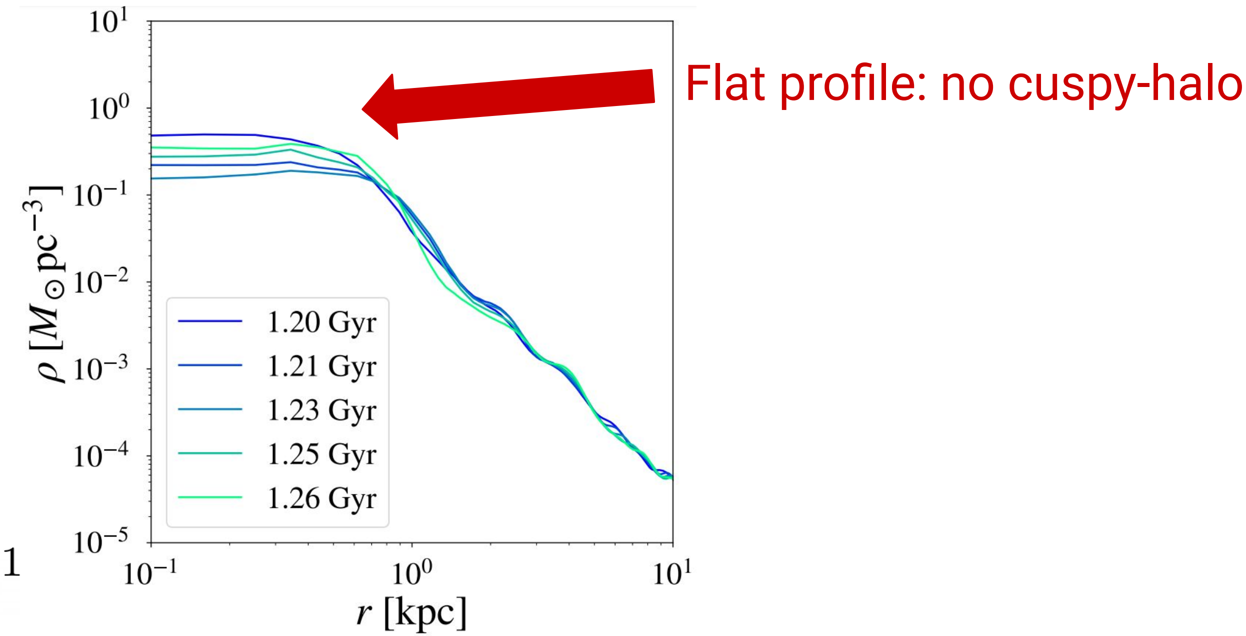


Image Credit: DARK MATTER Berlin

Boson Stars: self-gravitating (compact) objects



$$\mu = m_\Phi c/\hbar = \lambda_c^{-1}$$

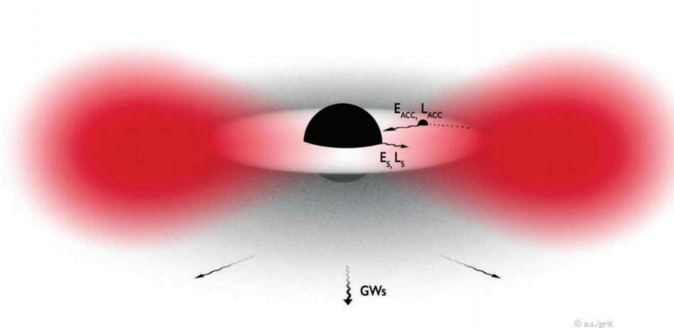
$$\frac{M_{\rm BS}}{10^9 M_\odot} \sim \frac{1\,\rm kpc}{R_{\rm BS}} \left(\frac{10^{-22}\,\rm eV}{\mu}\right)^2$$

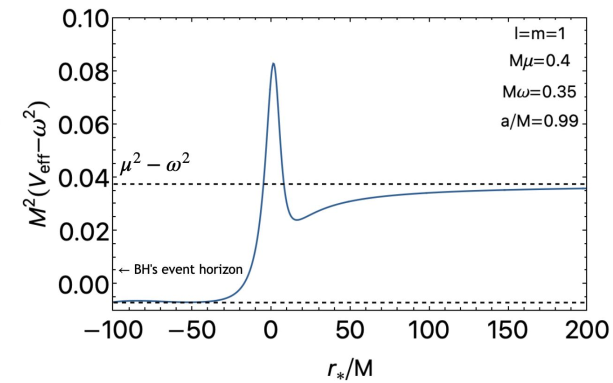
$$\tau_{\rm accr} \sim 30{\rm Gyr}\, f(\nu_0) \left(\frac{10^{10} M_\odot}{M_{\rm BS,0}}\right)^5 \left(\frac{10^{-22}\rm eV}{\mu}\right)^6$$

Superradiant clouds: dominated by BH gravity

$$\omega < m\Omega_H$$

$$\alpha = M\mu \sim \mathcal{O}(1)$$

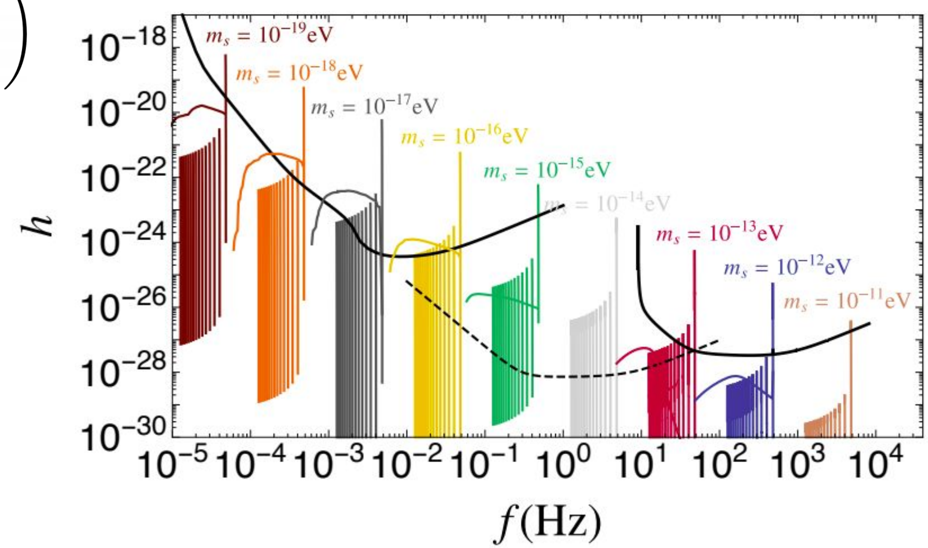




$$\tau^{s}_{\rm inst} \approx 30\,{\rm days}\left(\frac{M}{10M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{J/M^2}\right)$$

$$\tau^{\rm vec}_{\rm inst} \approx 280\,{\rm s}\left(\frac{M}{10M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{J/M^2}\right)$$

$$\tau^{s}_{\rm GW} \approx 10^5{\rm yr}\left(\frac{M}{10M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\Delta\left(J/M\right)^2}\right)$$



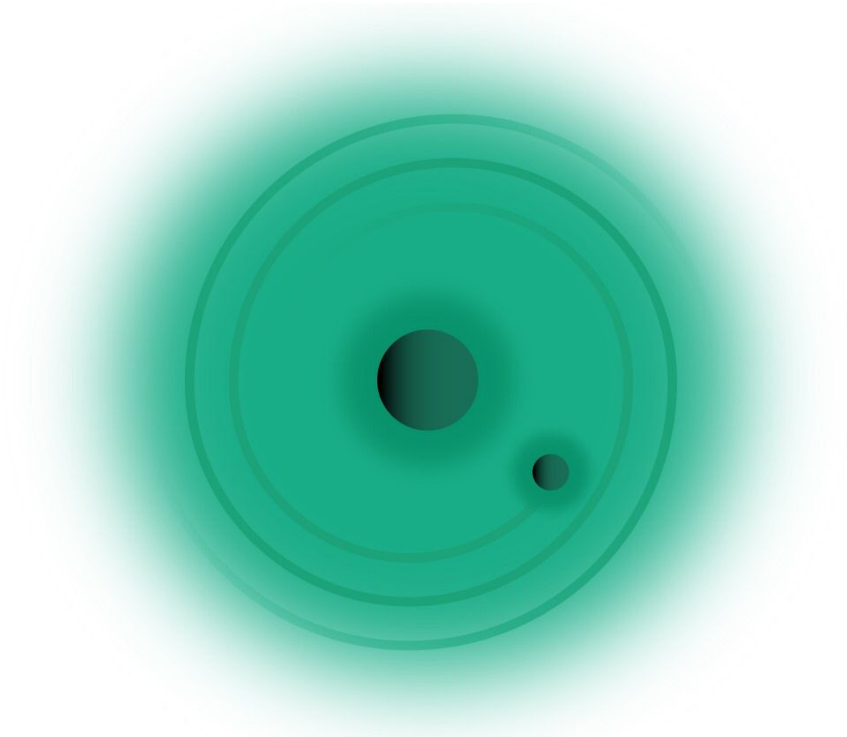


Image Credit: Beatriz Oliveira

EMRI surrounded by bosonic environment

↓

Binary interacts w/ matter

↓

Trajectory changes w.r.t. vacuum

↓

GW signature changes

↓

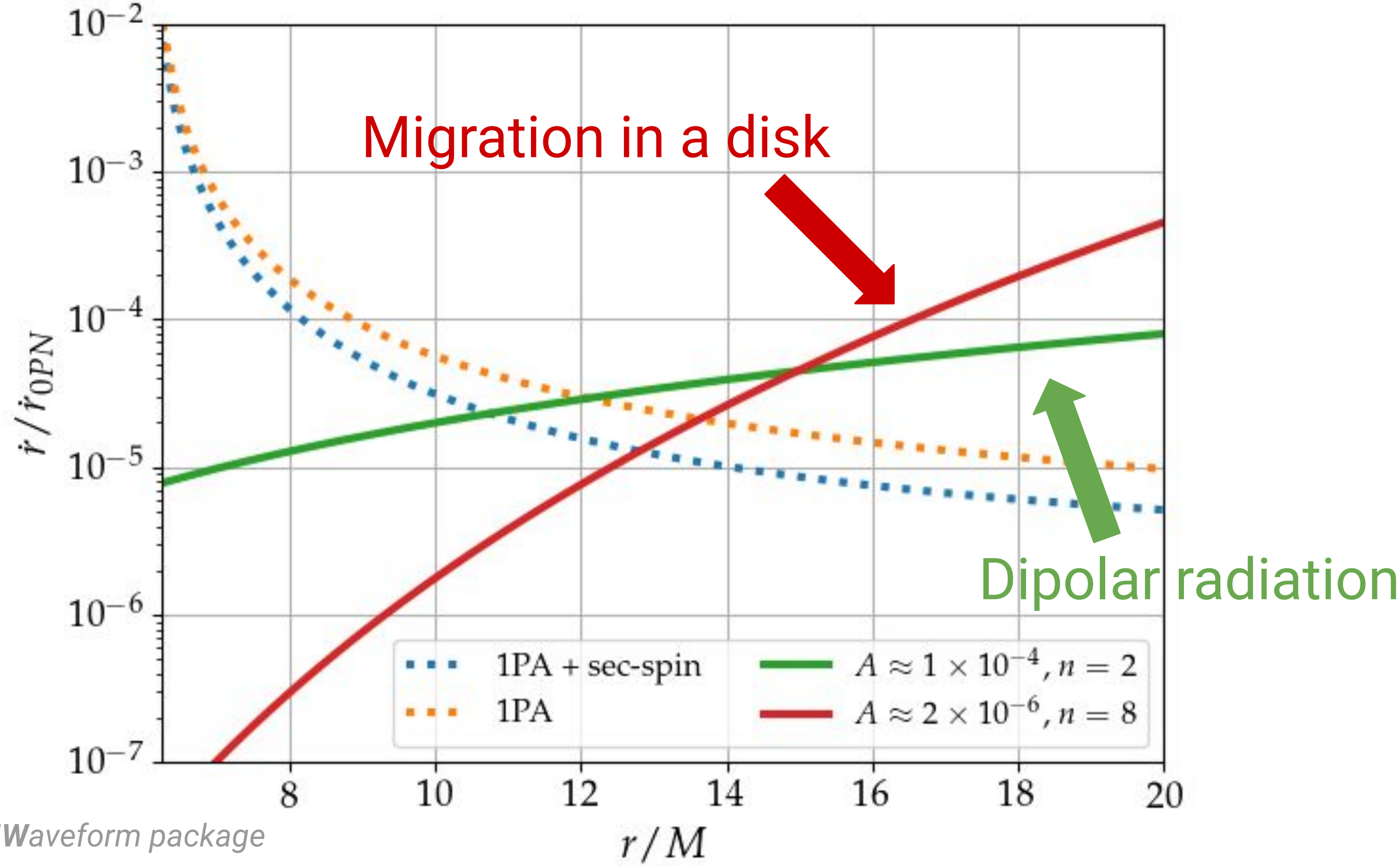
What can we (not) learn?

EMRIs are a novel probe of stellar populations in the close vicinity of MBHs. A typical EMRI observation will provide a measurement of the sBH mass to ~1 % and the eccentricity and inclination of the sBH orbit to 10^{-5} and 10^{-4} respectively. The emerging picture is that environmental effects will be detectable in a variety of realistic astrophysical scenarios. Even a single successful measurement would provide invaluable information on the presence of matter in the form of stars, gas or dark matter, only a few Schwarzschild radii from the MBH horizon.

LISA "Red Book", arXiv:2402.07571

$$\dot{L} = \dot{L}_{\rm GW} + \dot{L}_{\rm BGR}$$

$$\dot{L}_{\rm BGR}/\dot{L}^{(0)}_{\rm GW} = A\left(\frac{r}{10M}\right)^n$$



*Uses the **F**ast**E**MRI**W**aveform package*

Beyond-vacuum GR effects compete with 2nd-order SF

Tackle the problem with BH perturbation theory

Duque et al., arXiv:2312.06767 (accepted @ PRL) + Brito & Shah, Phys. Rev. D 108, 084019 (2023)

$$S=\int \mathrm{d}^4x\sqrt{-g}\left(\frac{R}{16\pi}-\frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi^*-\frac{1}{2}V(\Phi^*\Phi)+\mathcal{L}^{\mathrm{m}}\right)$$

U(1) symmetry

$$J^\mu_Q=2g^{\mu\nu}\mathrm{Im}\left[\Phi^*\partial_\nu\Phi\right]$$

$$Q=\int \mathrm{d}^3x\sqrt{-g}J^t_Q$$

Einstein-Klein-Gordon

$$G_{\mu\nu}=T^\Phi_{\mu\nu}+T^{\mathrm{m}}_{\mu\nu}$$

$$\Box_g\Phi=\frac{\partial V}{\partial\Phi^*}\approx\mu^2\Phi$$

$\mathcal{L}^{\mathrm{m}}$ models the point-particle → perturbative scheme

$$g^{\mathrm{exact}}_{\mu\nu}=g_{\mu\nu}+\epsilon h_{\mu\nu}+\mathcal{O}(\epsilon^2)$$

$$\Phi^{\mathrm{exact}}=\Phi+\epsilon\delta\Phi+\mathcal{O}\left(\epsilon^2\right)$$

Susanna's talk *vs* Now

Susanna's talk

$$G_{\mu\nu} = T^{\rm m}_{\mu\nu}$$

$$\Box_g \Phi = \alpha\, T^{\rm m}_{\mu\nu}$$

Vacuum GR background

No scalar background

$$\Phi^{\rm exact} = \text{✖} + \epsilon\delta\Phi + \mathcal{O}\left(\epsilon^2\right)$$

Now

$$G_{\mu\nu} = T^{\Phi}_{\mu\nu} + T^{\rm m}_{\mu\nu}$$

$$\Box_g \Phi = \frac{\partial V}{\partial \Phi^*} \approx \mu^2 \Phi$$

No vacuum background

No direct coupling of particle to scalar

Exploit spherical symmetry to expand perturbations in spherical harmonics

Group in polar vs axial depending on how they transform under parity transformations

Massage perturbation equations to get (in some *gauge*) a coupled set of evolution equations for metric + scalar

Pick the bosonic environment + particle motion

Solve E.O.M. ("hard") and obtain GW/Scalar flux + waveform

Motion of the point particle

$\mathcal{O}(\epsilon^0)$: geodesics on background spacetime

Two-timescale expansion

Hinderer & Flanagan, PRD 78.064028 (2008)

Orbital Timescale $\ll$ Inspiral Timescale

$T_o \sim M$ ⬇ $T_i \sim M^2/m_p$

Orbital energy evolves much slower than the orbital phase

⬇

$\mathcal{O}(\epsilon^1)$: adiabatic flow over a succession of geodesics

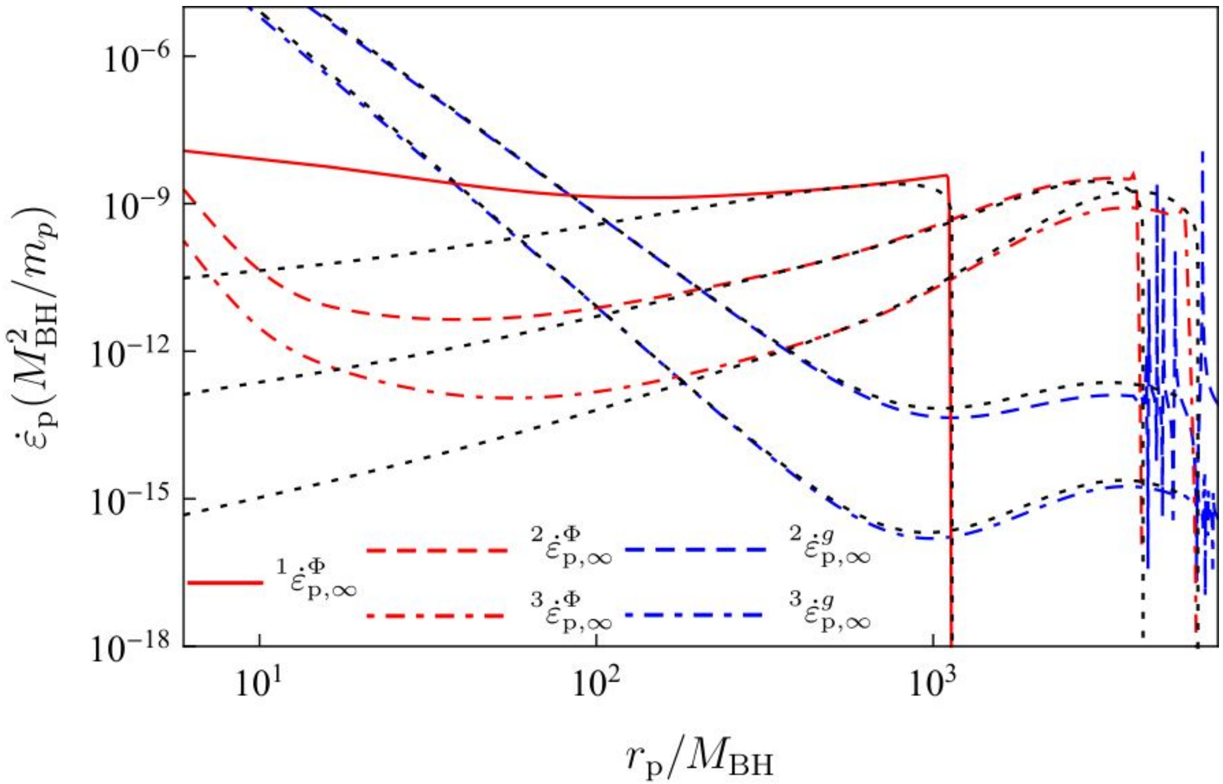
$$\frac{dE_p}{dt} = -\dot{E}^g_\infty - \dot{E}^g_H \boxed{- (\dot{E}^\Phi_\infty - \omega \dot{Q}_\infty) - (\dot{E}^\Phi_H - \omega \dot{Q}_H)}$$

Boson stars: circular orbits

Duque et al., arXiv:2312.06767 (accepted @ PRL) + Annulli, Vicente & Cardoso PRD 102, 063022 (2020)

Self-gravity of the scalar configuration is not negligible

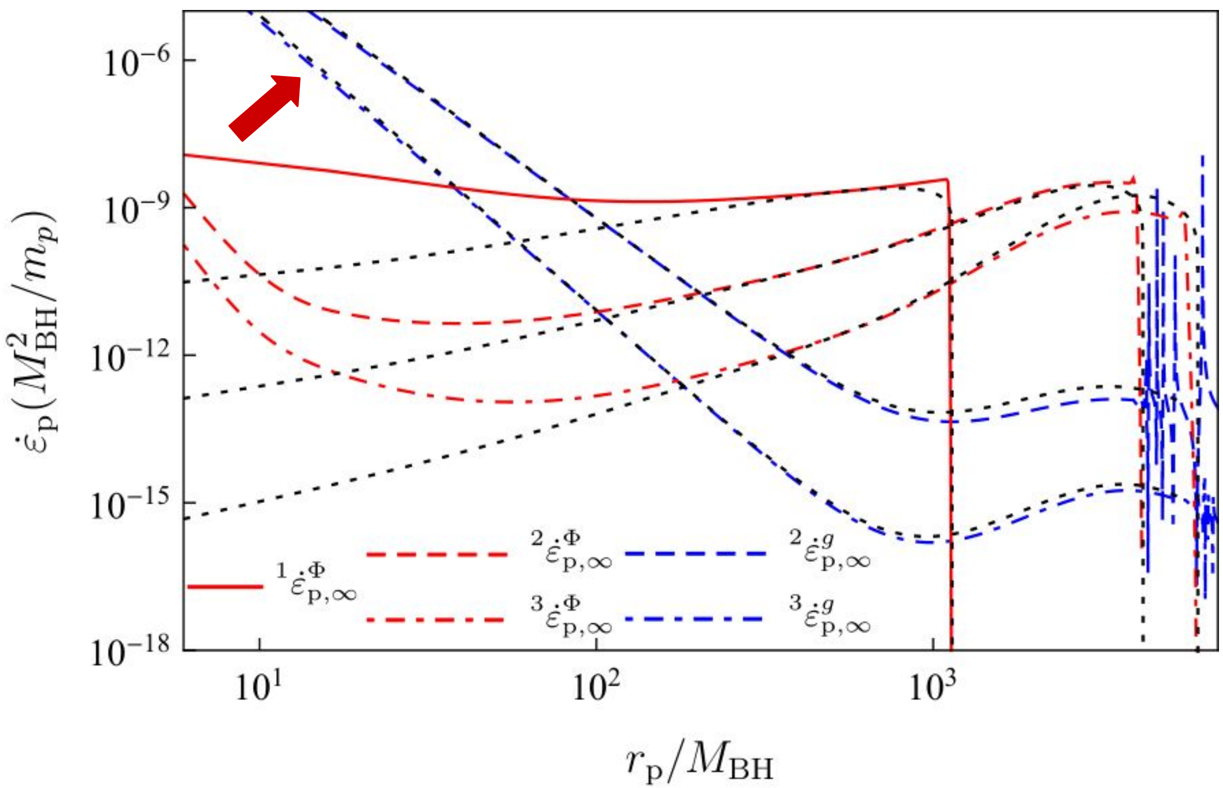
Must solve coupled scalar + gravity sector @ same time



Boson stars: circular orbits

Duque et al., arXiv:2312.06767 (accepted @ PRL)

GWs are shifted w.r.t. to vacuum prediction



Boson stars: circular orbits

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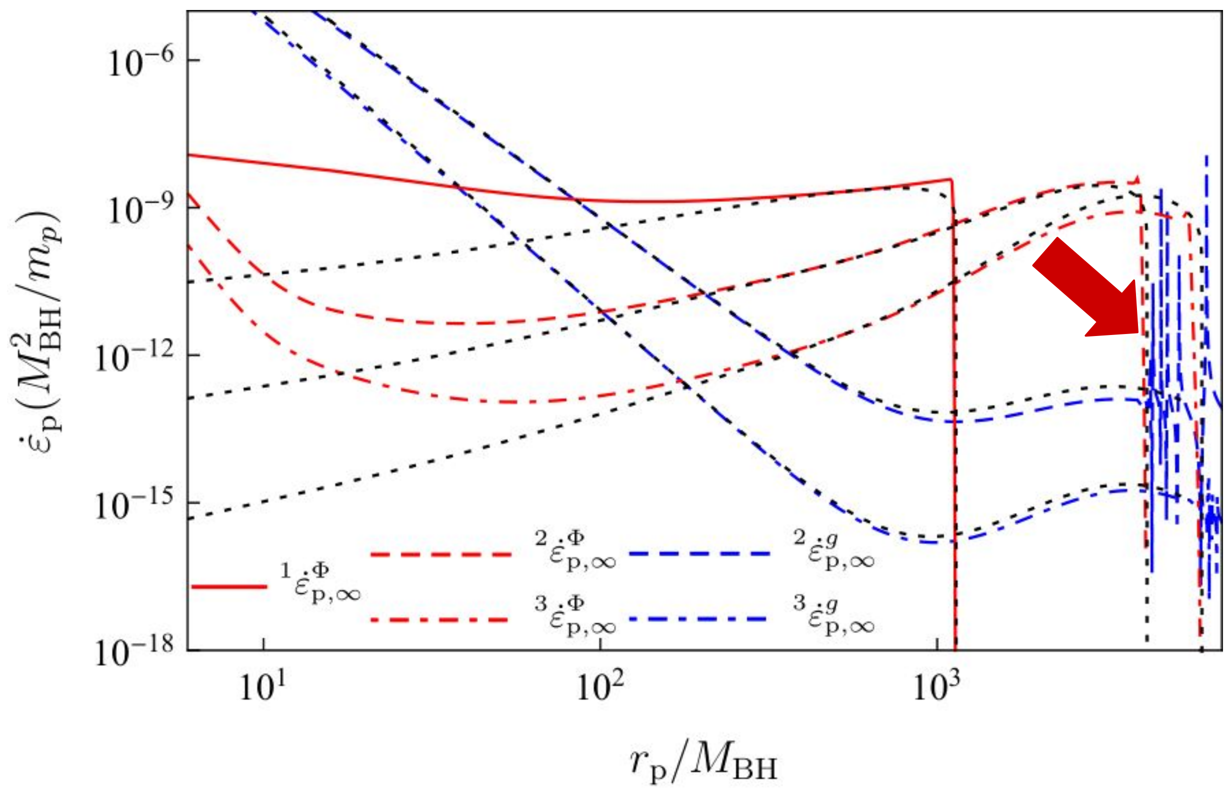
GWs are shifted w.r.t. to vacuum prediction

Resonances at low frequencies in the gravitational sector

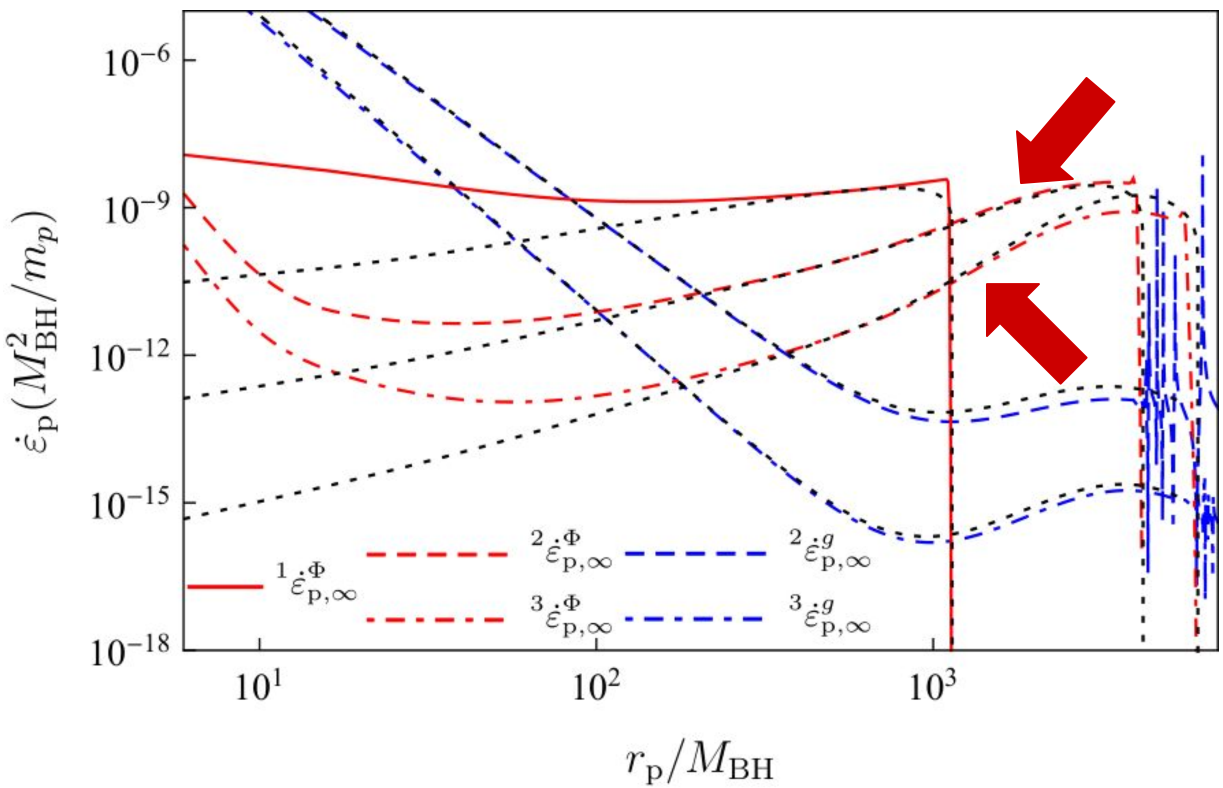


Boson stars: circular orbits

Duque et al., arXiv:2312.06767 (accepted @ PRL)

Scalar flux agrees with Newtonian, analytic predictions @ $\Omega_p \ll \mu$

Annulli, Vicente & Cardoso PRD 102, 063022 (2020)

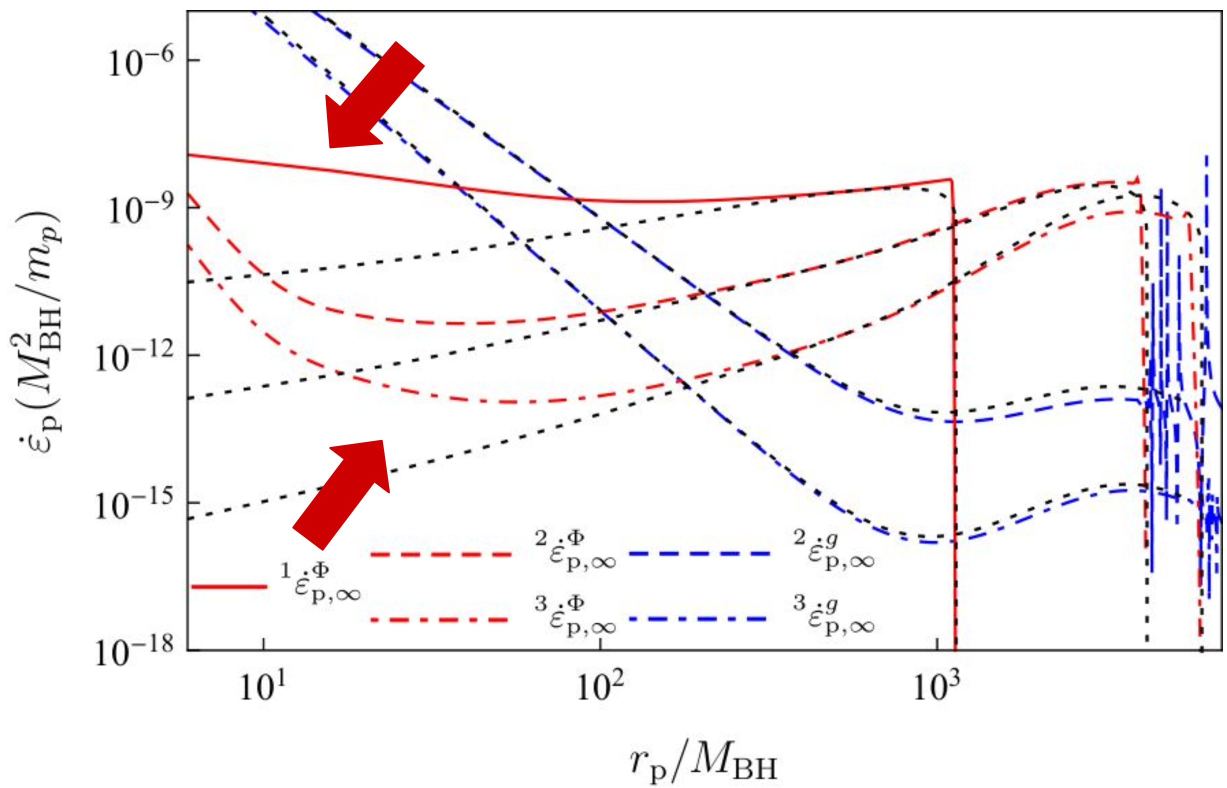


Boson stars: circular orbits

Duque et al., arXiv:2312.06767 (accepted @ PRL)

Scalar flux agrees with Newtonian, analytic predictions @ $\Omega_p \ll \mu$

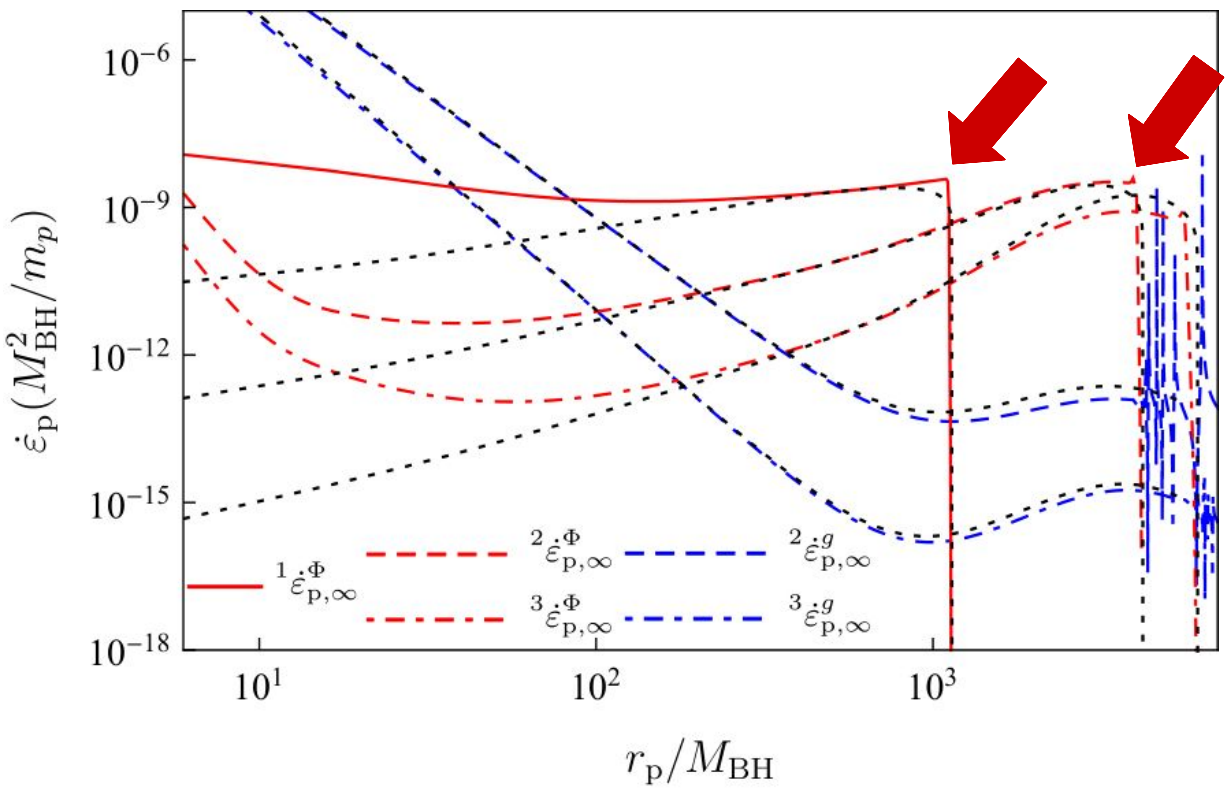
But fails completely @ $\Omega_p \gg \mu$



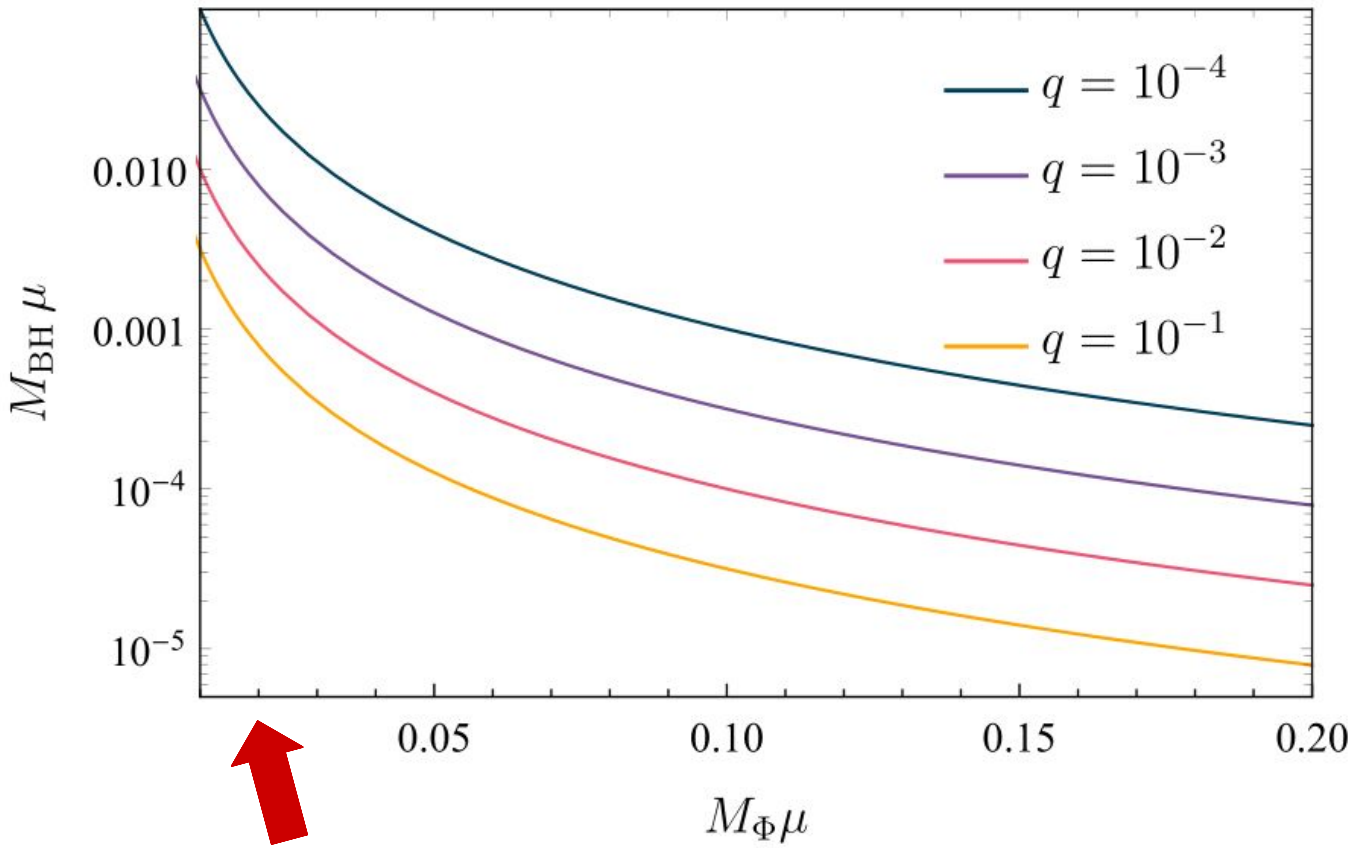
Boson stars: circular orbits

Duque et al., arXiv:2312.06767 (accepted @ PRL)

Ionization: scalar emission only activated for $m\Omega_p \geq \mu - \omega$



Dephasing with 4 years of observation close to merger



Astrophysical Halos

Duque et al., arXiv:2312.06767 (accepted @ PRL)

Bosonic Clouds

Test-Field: $G_{\mu\nu} = \cancel{T^{\Phi}_{\mu\nu}} + T^{\mathrm{m}}_{\mu\nu}$ $\qquad \Box_g \Phi = \mu^2 \Phi$

"Vacuum" background + cloud w/ hydrogen atom structure

$\alpha = M\mu$ is the "gravitational fine-structure" constant

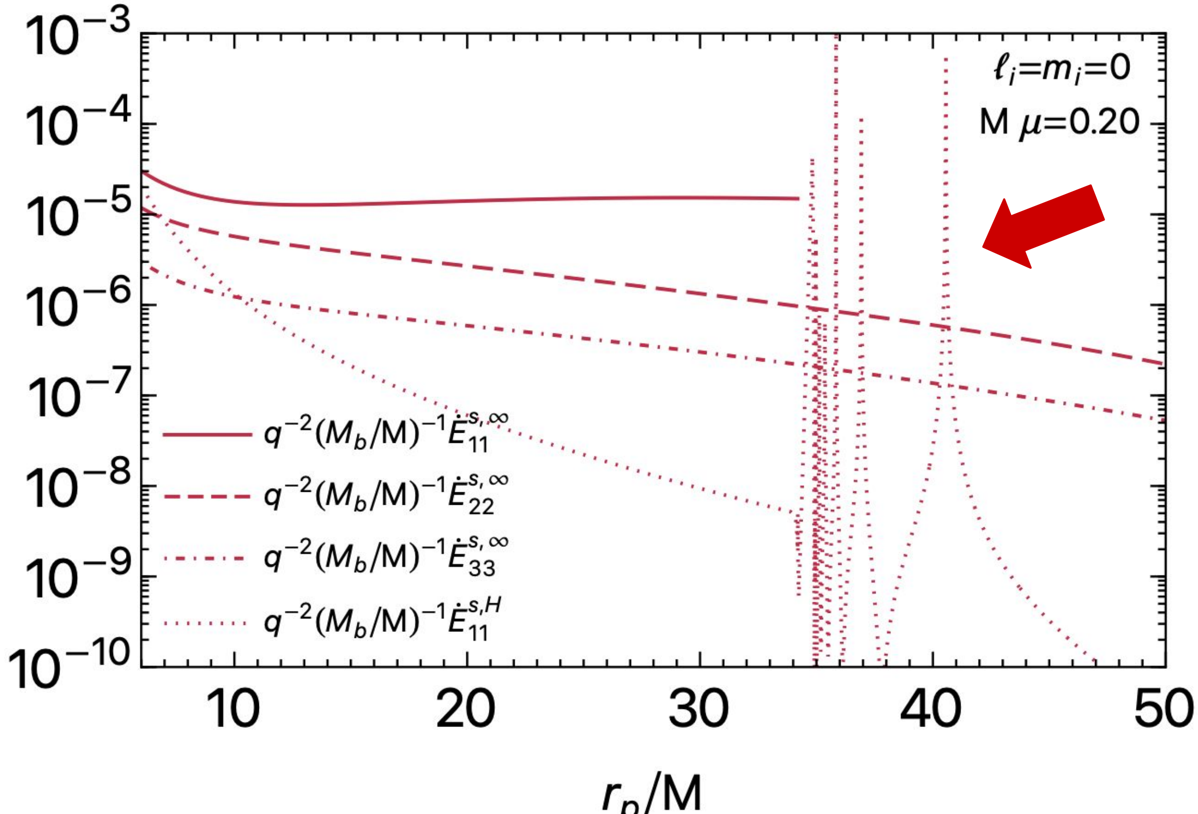
For $M\mu \ll 1$, solutions in Laguerre polynomials

$$\Phi(r) \approx \sqrt{\frac{M_\Phi}{\pi M_{\mathrm{BH}}}}(M_{\mathrm{BH}}\mu)^2 \left(1 - \frac{2M_{\mathrm{BH}}}{r}\right)^{-2i\mu M_{\mathrm{BH}}} e^{-M_{\mathrm{BH}}\mu^2 r}$$

$$\omega = \mu\left[1 - \frac{1}{2}(M\mu)^2\right]$$

Bosonic Clouds: circular orbits

Resonances at low frequencies in the scalar flux @ BH horizon



Brito & Shah, Phys. Rev. D 108, 084019 (2023)

The Gravitational Atom

Baumann et al., JCAP 12.006 (2019) + Tomaselli et al., arXiv:2403.03147 (2024)

Emission only for $m\Omega_p > \mu - \omega$ Photoelectric effect

For our system $\Omega_p = \sqrt{M/r_p^3} \approx 4 \times 10^{-3}$ vs $\mu - \omega = 4 \times 10^{-3}$

Cloud is in the fundamental $\ell = m = 0$ state

But there are overtones/states w/ different ℓ m

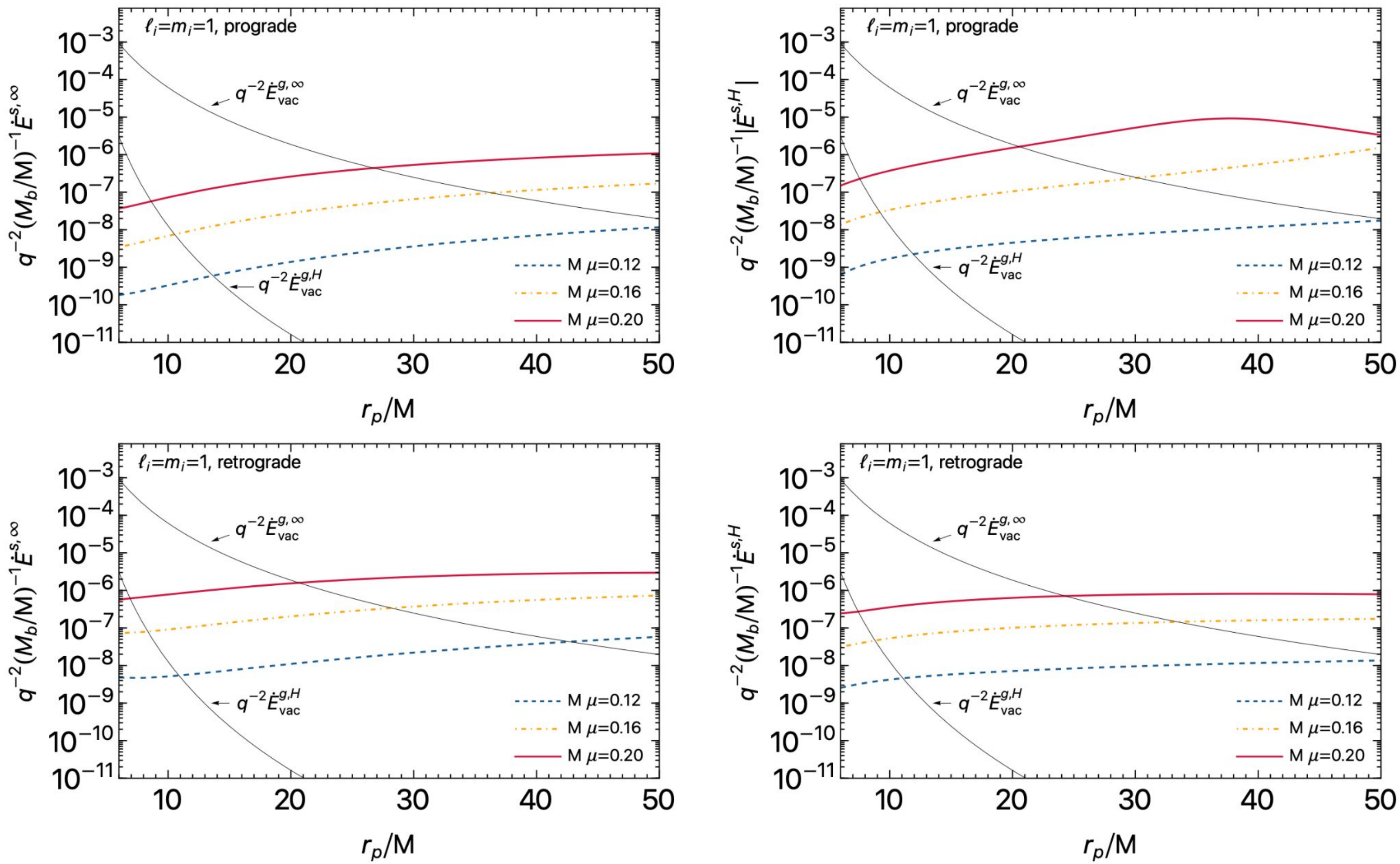
$$\omega_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - \frac{\alpha^4}{8n^4} - \frac{(3n - 2\ell_i - 1)\,\alpha^4}{n^4(\ell_i + 1/2)} + \frac{2(a/M)m_i\alpha^5}{n^3\ell_i(\ell_i+1)(\ell_i+1/2)} + \mathcal{O}(\alpha^6)\right)$$

If $m\Omega_p = \Delta\omega$ binary induces resonant transitions

Non-Spherical Clouds

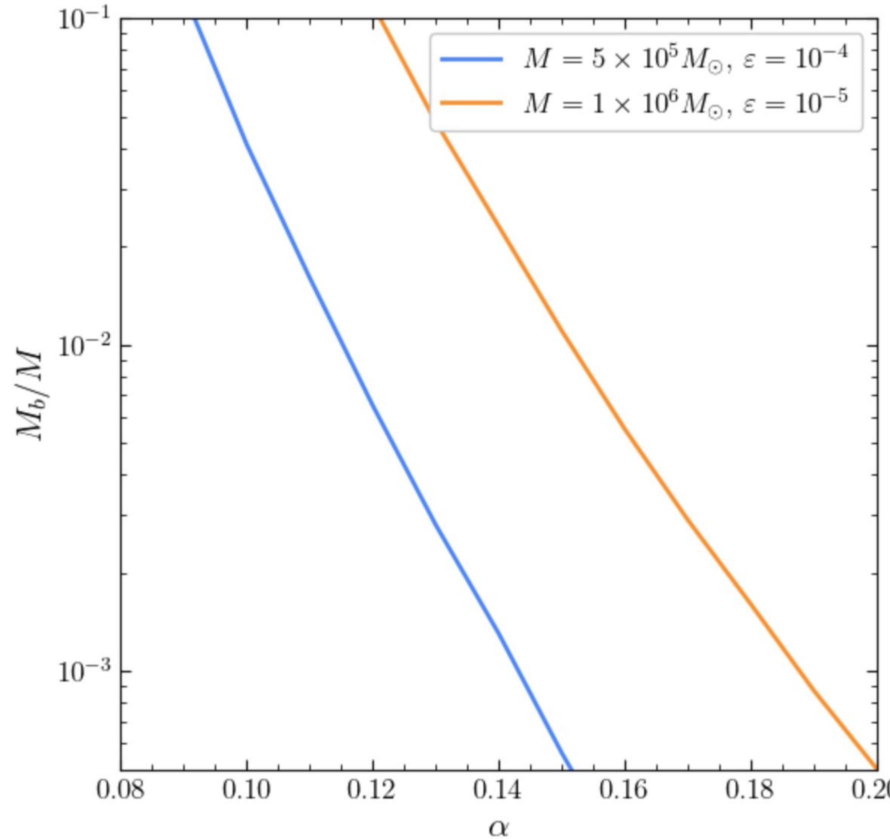
Brito & Shah, Phys. Rev. D 108, 084019 (2023)

$$M_b = M_\Phi$$



Dephasing with 4 years of observation before merger

$$M_b = M_\Phi$$



Khalvati + Santini et al., in prep

$M_\Phi/M \lesssim 0.1$ → $M\mu \gg 0.1$ could be probed

For the details...

NEW HORIZONS FOR PSI

About Venue Speakers Program Participants Registration

Day 2 (school), Tuesday, July 2nd

Chair: Valentin Boyanov

09:00-10:00 Eugen Radu: BH uniqueness and dirty BHs
10:00-10:30 Coffee break
10:30-11:30 Maria Alessandra Papa: GWs from monochromatic sources: data analysis_Lec1
11:30-12:30 Francisco Duque: **EMRIs or evolution of binaries in fundamental fields** lecture note_EMRIEMRI_BosonCloud

grit
gravitation in técnico

About Team News Publications Files Outreach Baltasar Grittings Centra

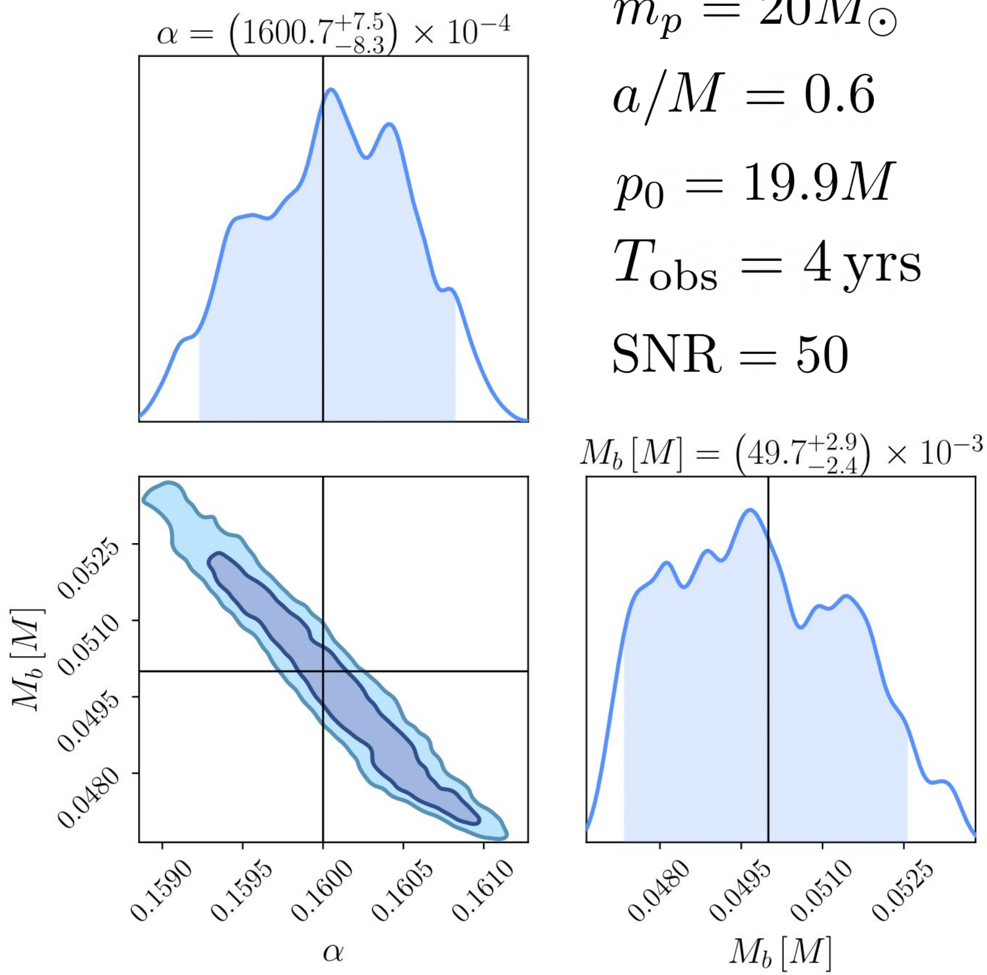
Here you can find routines that can be used to compute the flux in gravitational waves emitted by a scalar cloud around a Kerr black hole. Some computations make use of the Black Hole Perturbation toolkit (https://bhptoolkit.org/). We also use results from arXiv:gr-qc/0306120 , arXiv:0705.2880 and arXiv:1312.2326. The data generated by this routine served as input for the python package gwaxion (https://pypi.org/project/gwaxion/).

Gravitational waves from boson clouds

Description	References	Download
Computation of gravitational-wave flux from a scalar cloud	Brito et al. [arXiv:1706.06311] and [arXiv:1706.05097]	Notebook
Scalar and gravitational fluxes from EMRIs in scalar environments	Duque et al. [arXiv:2312.06767]	File

P.E. w/ FastEMRIWaveforms

Katz et al., PRD 104.064047 (2021)



$M \sim 4 \times 10^5 M_\odot$

$m_p = 20 M_\odot$

$a/M = 0.6$

$p_0 = 19.9M$

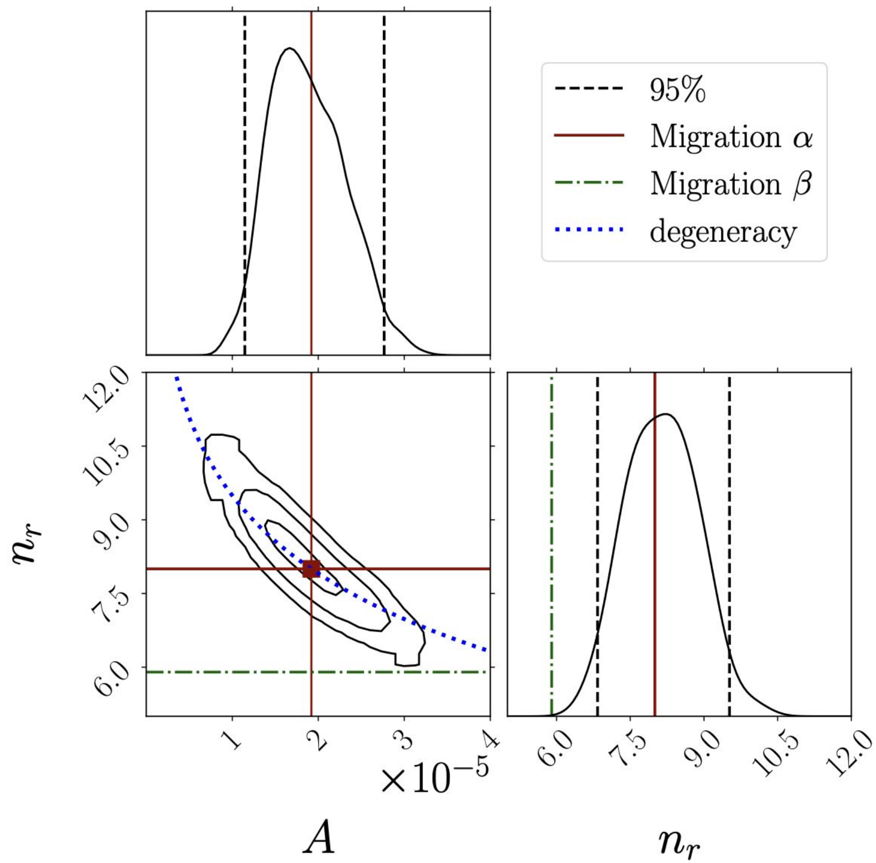
$T_{\rm obs} = 4\,{\rm yrs}$

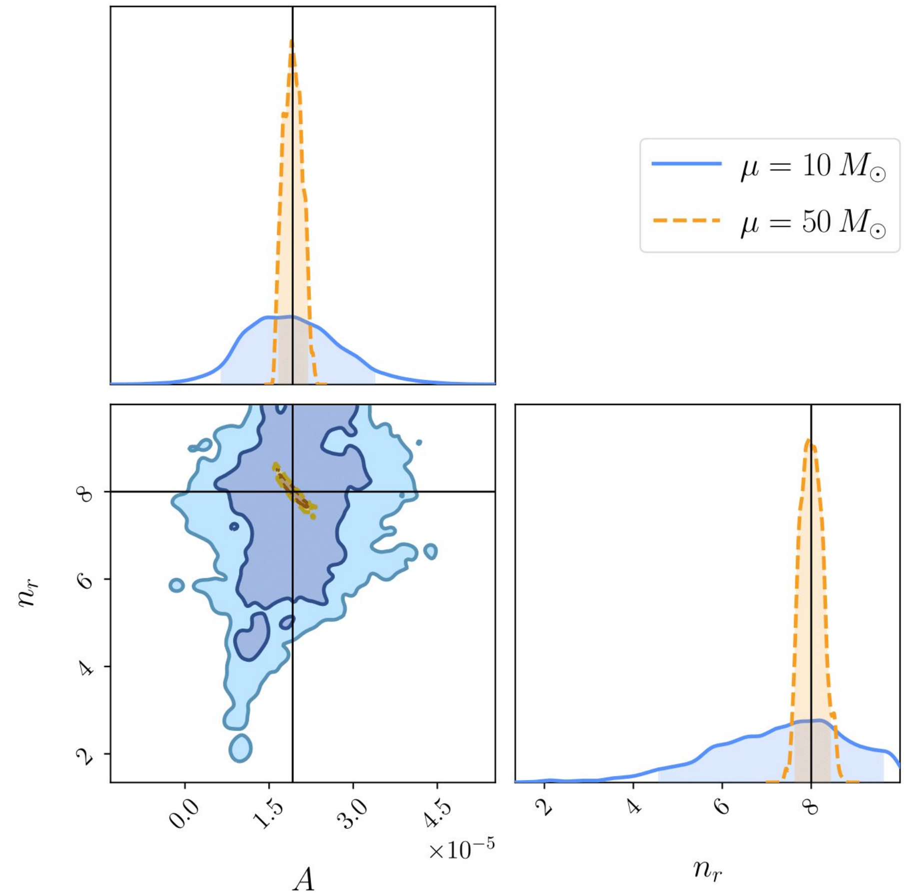
$\mathrm{SNR} = 50$

Khalvati + Santini et al., in prep
+
Cole et al. Nature Astron. 7 (2023) 8, 943-950

$$\dot{L}_{\mathrm{BGR}}/\dot{L}_{\mathrm{GW}}^{(0)} = A\left(\frac{r}{10M}\right)^{n_r}$$

AAK waveforms *vs* Relativistic waveforms



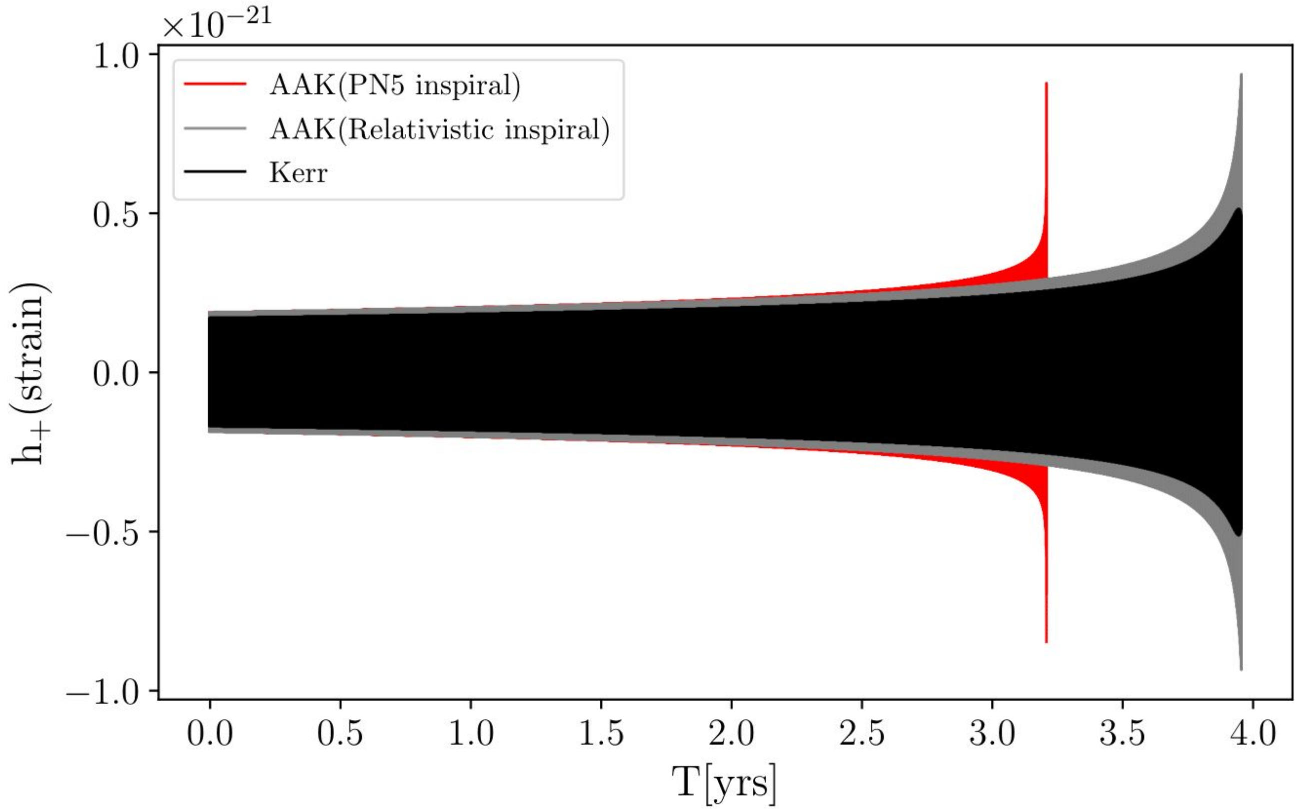


Speri et al. PRX 13, 021035 (2023)

Khalvati + Santini et al., in prep

Same EMRI system for $a/M = 0.99$

Khalvati + Santini et al., in prep



AAK underestimates relative power on early inspiral

Where environmental effects are more important!

Possible Extensions

1. Numerical Relativity *Katy Clough's talk tomorrow*
2. Eccentric/Inclined orbits *Tomaselli et al., arXiv:2403.03147 (2024)*
3. Vector fields
4. Spinning BHs *(someone is doing it…)*
5. Real fields

Possible Extensions

1. Numerical Relativity *Katy Clough's talk tomorrow*

2. *Eccentric/Inclined orbits* *Tomaselli et al., arXiv:2403.03147 (2024)*

3. Vector fields

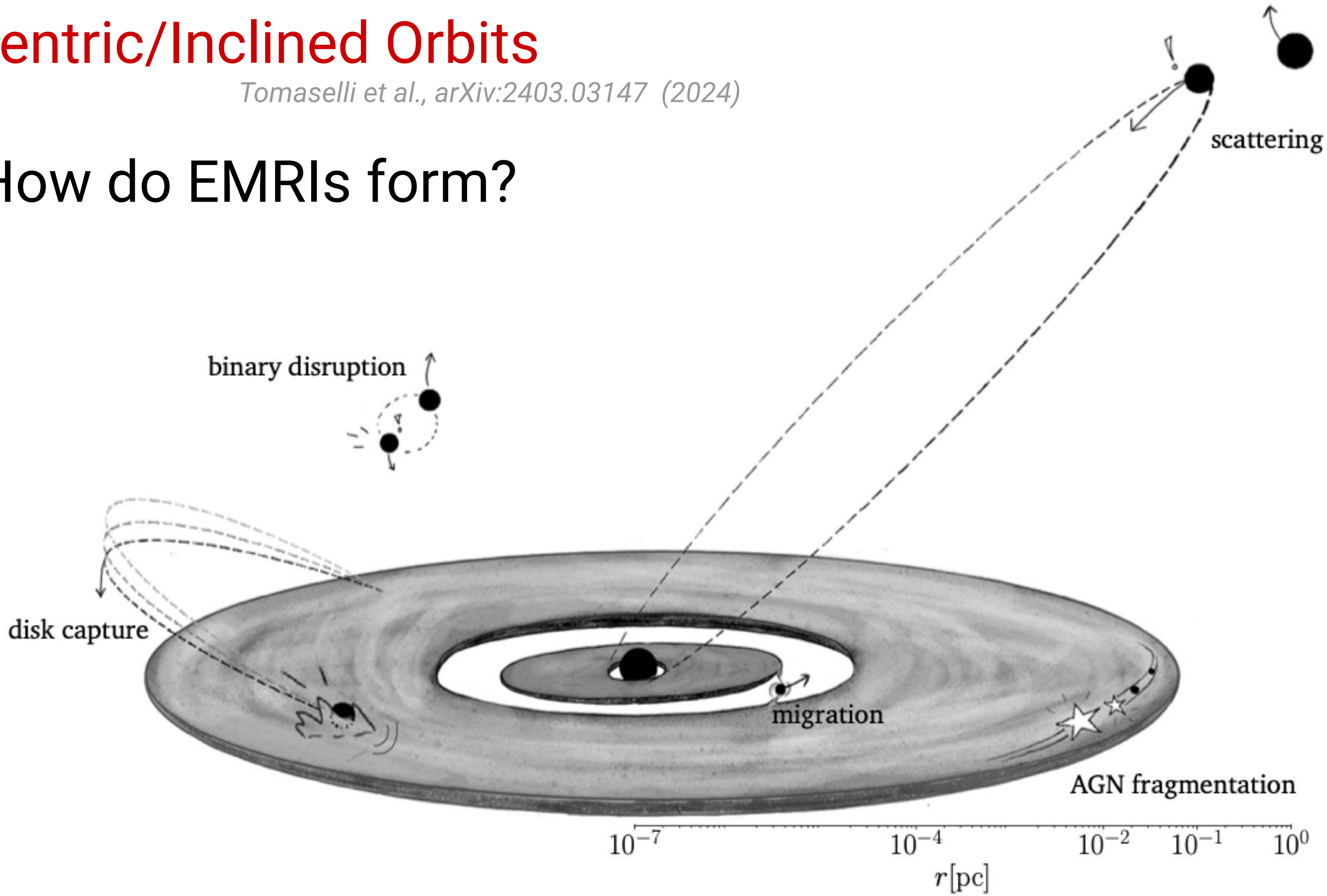
4. Spinning BHs *(someone is doing it…)*

5. *Real fields*

Eccentric/Inclined Orbits

Tomaselli et al., arXiv:2403.03147 (2024)

Q: How do EMRIs form?



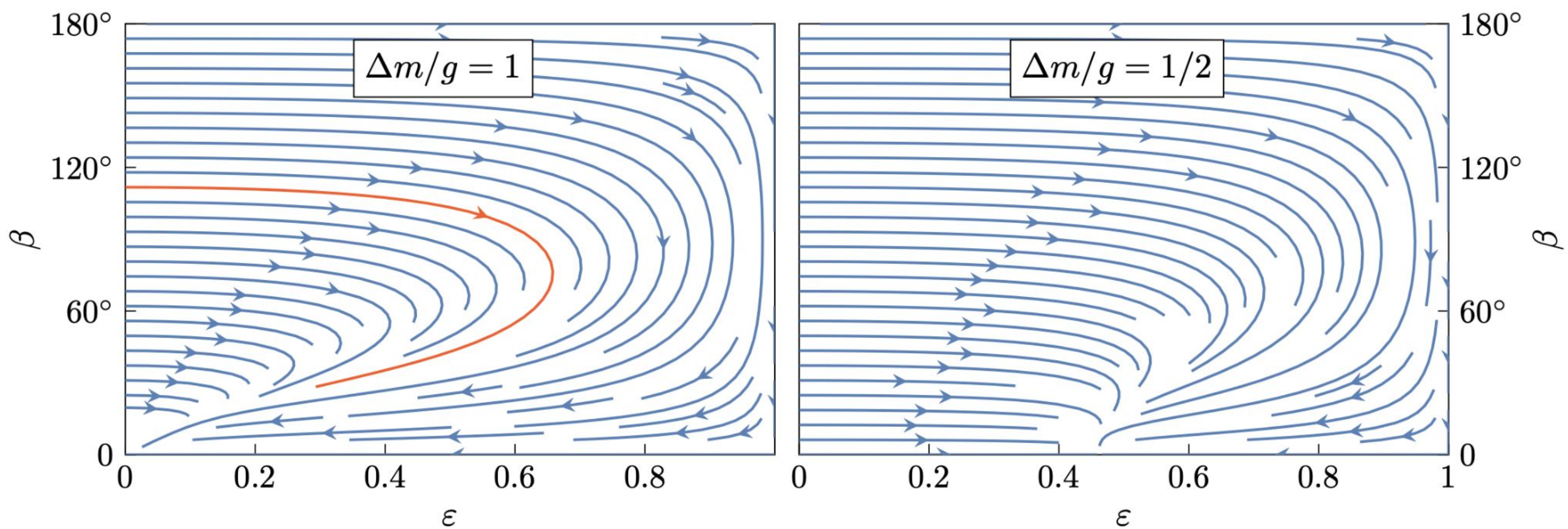
Derdzinski & Zwick arXiv:2310.16900 (2023)

Eccentric/Inclined Orbits

Tomaselli et al., arXiv:2403.03147 (2024)

Q: Does the cloud survive when binary enters in band?

A: More chance for retrograde orbits



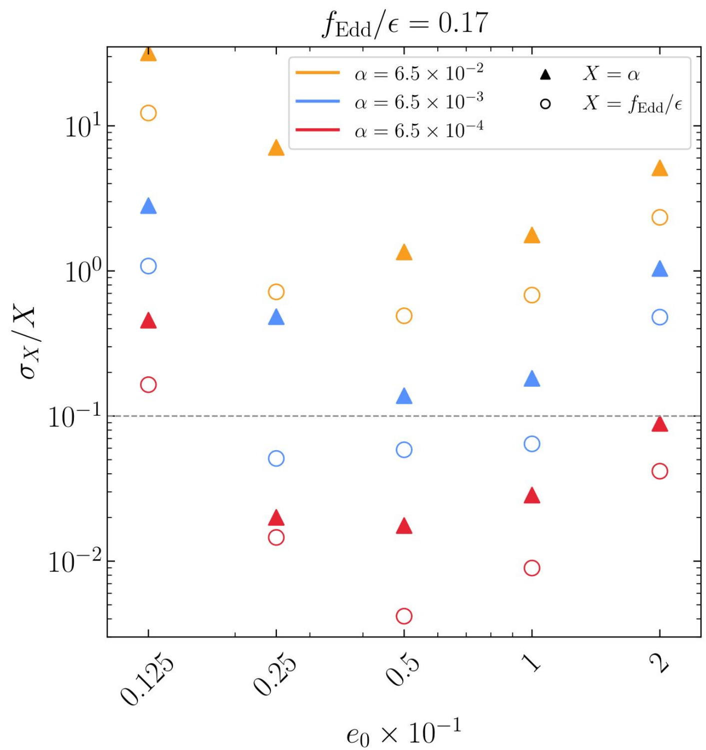
Resonances lead to fixed points in eccentricity and inclination

Fixed points also observed for Accretion Disks

Ishibashi & Gröbner, MNRAS 529, Issue 2, April (2024)

Breaking degeneracies: more detailed/better models should help

Example: eccentric EMRI in accretion disk *Duque, Kejriwal et al., in prep*



$$M = 10^6 M_\odot$$

$$m_p = 50 M_\odot$$

$$p_0 = 16.83 M$$

$$\mathrm{SNR} = 50$$

$$T_{\rm obs} = 4\,\mathrm{yrs}$$

Can constrain accretion rate **and** viscosity **simultaneously**

Not possible for circular motion w/ migration torques

Real Fields: $T^{\Phi}_{\mu\nu}$ is no longer time independent ➡ Q

Cloud emits GWs ➡ Different Energy-Balance law

Environment introduces new timescales: T_{relax} , $T_{\mathrm{Env\ Reac}}$

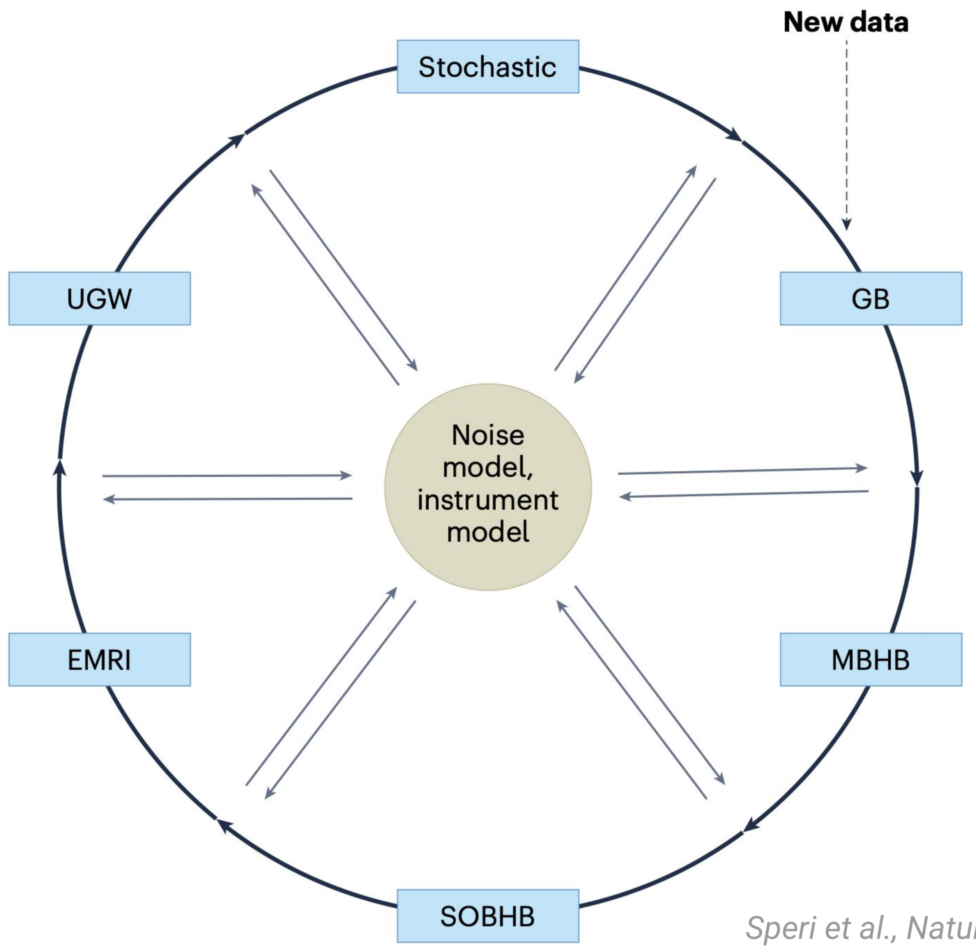
Q: How to integrate this in the (Post-)Adiabatic way?

Warburton: "Give us a force and we (SF comm.) know how to do it"

Environmental self-force ⟷ Multi-timescale expansion (?)

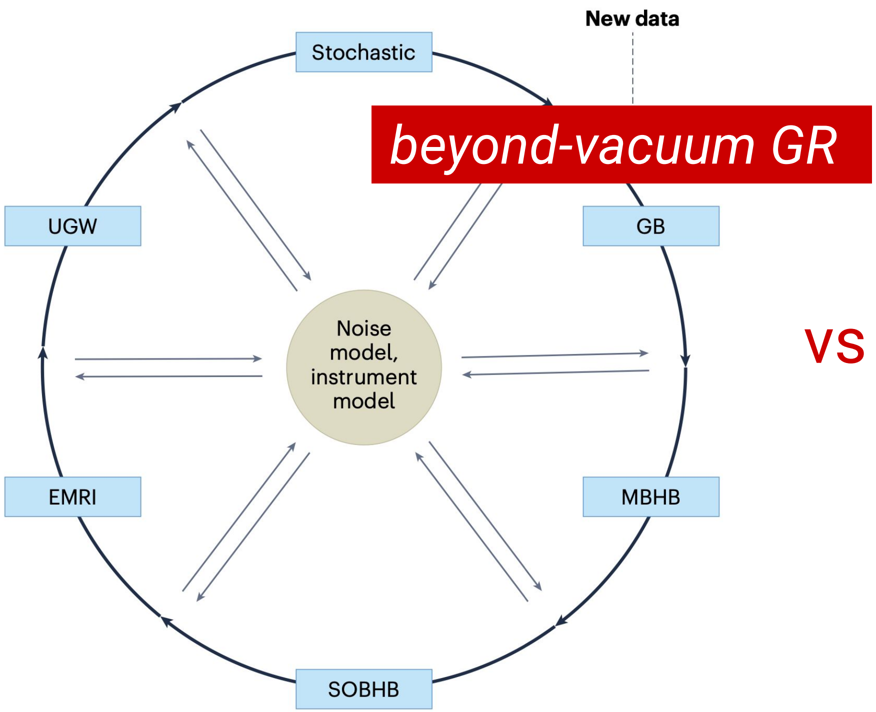
e.g. : $T_{\mathrm{orb}} \ll T_{\mathrm{relax}} \ll T_{\mathrm{Rad\ Reac}} \ll T_{\mathrm{Env\ Reac}}$

Global Fit: how to study beyond-vacuum GR physics w/ LISA?

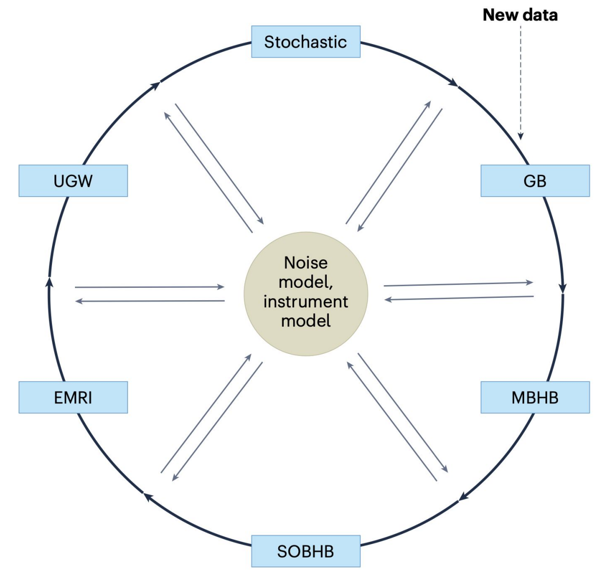


Speri et al., Nature Astr. 6, p. 1356–1363 (2022)

Global Fit: how to study beyond-vacuum GR physics w/ LISA?



VS



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Post-processing

Take-home message

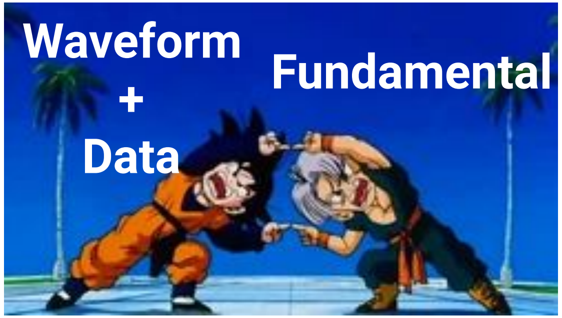
EMRIs in relativistic environments is still quite unexplored *but so far…*

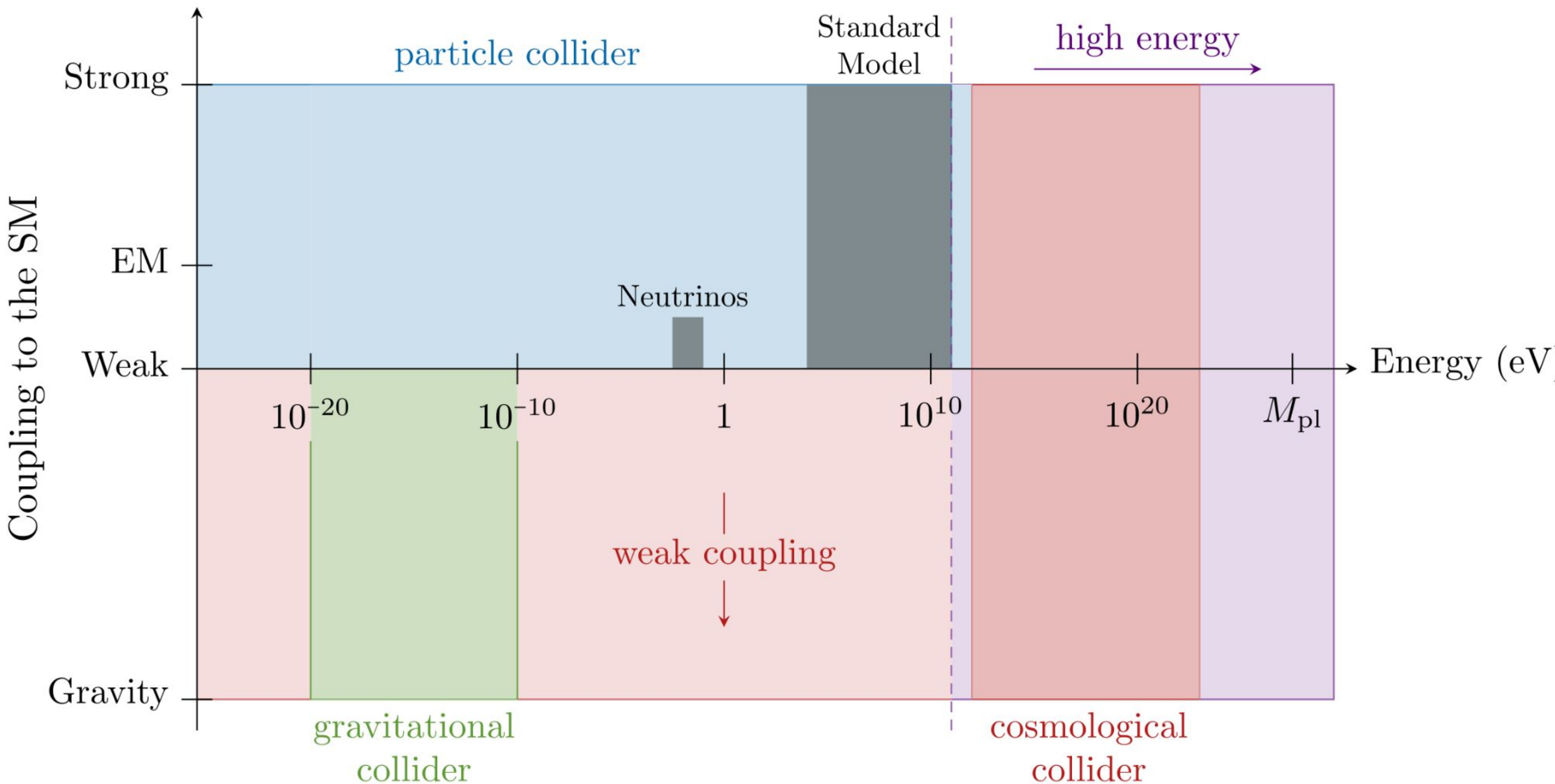
Matter does seem to matter

+ models ➡ **+** phenomenology ➡ **+** distinguishability (**?**)

But how to do it for LISA?

But how to do it for LISA?





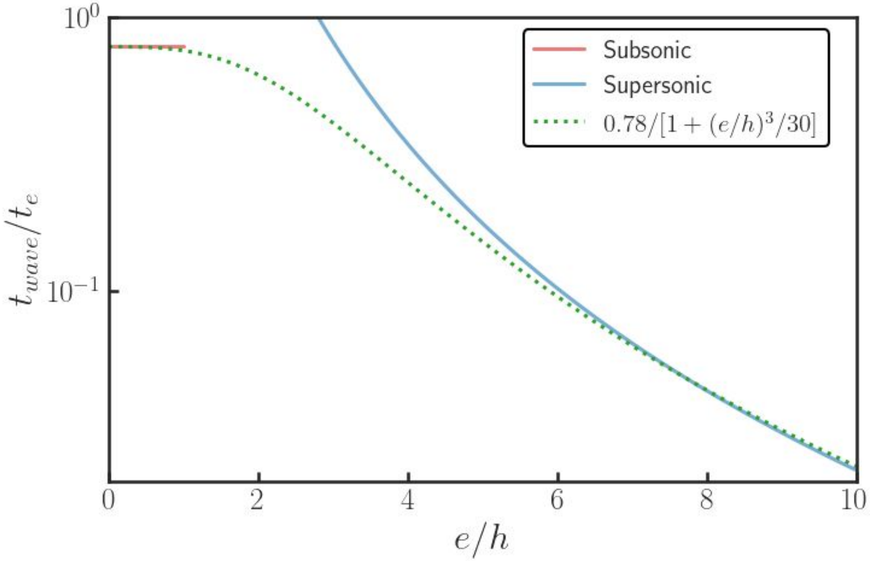
Baumann et al. PRD 101, 083019 (2020)

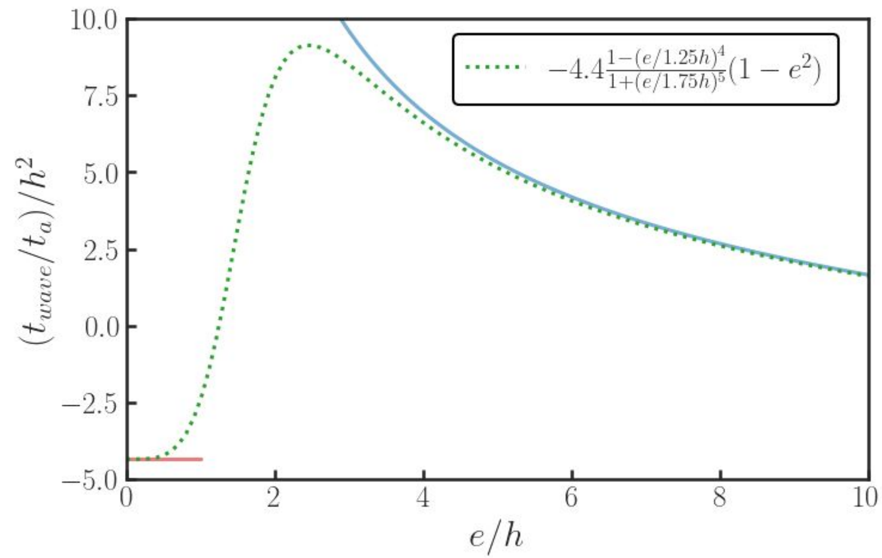
Inner region α - disk: $\Sigma(r) = \Sigma_0 \left(\frac{r}{10M}\right)^{3/2}$ $h(r) = h_0 \left(\frac{10M}{r}\right)$

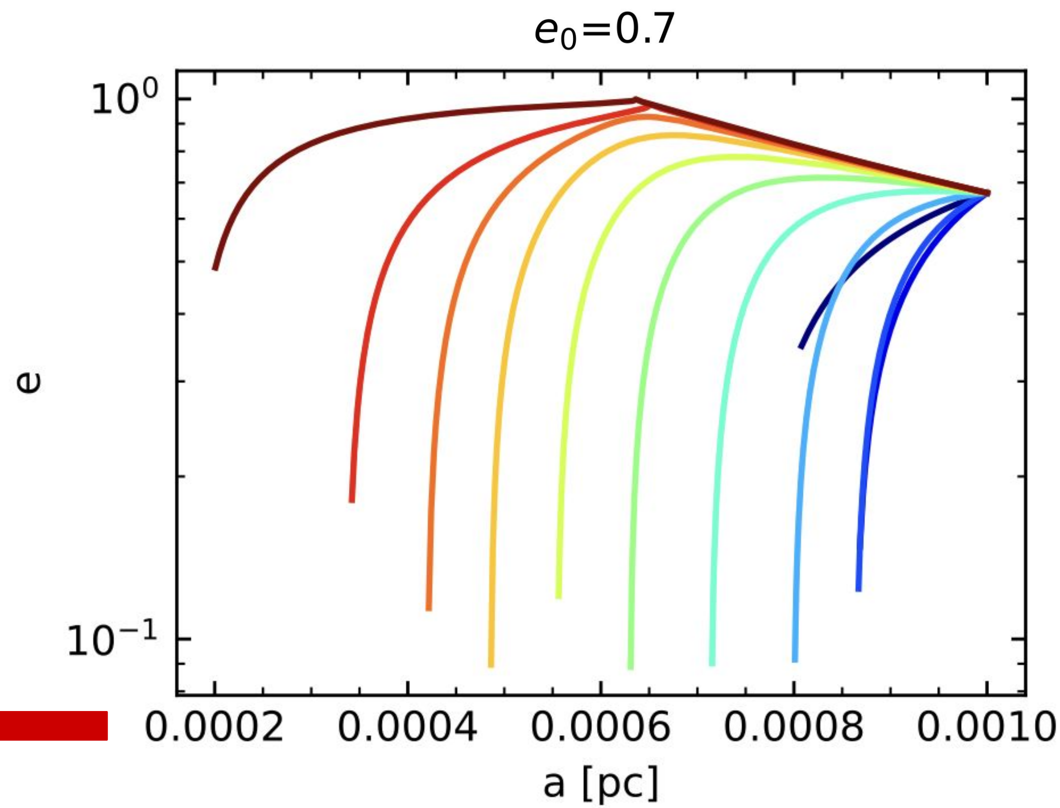
$e < h$	$e > h$
Subsonic	Supersonic
(Global) Migration Torques	(Local) Dynamical Friction
$\langle \dot{a} \rangle \propto -(\Sigma_0/h_0^2)a^5$	$\langle \dot{a} \rangle \propto (\Sigma_0/h_0)\, a^4/e$
$\langle \dot{e} \rangle \propto -(\Sigma_0/h_0^4)a^6 e$	$\langle \dot{e} \rangle \propto -(\Sigma_0/h_0)a^3/e^{7/4}$
$t_X = X/\langle \dot{X} \rangle$ $t_e/t_a \sim h^2 \ll 1$	$t_e/t_a \sim (e/h)^2 \gg 1$

For supersonic motion, migration timescale << damping of eccentricity

$$t_{\rm wave}^{-1} = \varepsilon \left(\frac{\Sigma r^2}{M}\right) \frac{\Omega_K}{h^4}$$







40 *M*

Since the eccentricity damping may not be as efficient as inclination damping, there might be some eccentricity residual on captured BHs

Wang et al., arXiv:2308.09129