EMRIs in Ultralight Bosonic Environments

Francisco Duque

based on *PRD 105, L061501 (2022), PRL 129, 241103 (2022) + work in prep.*

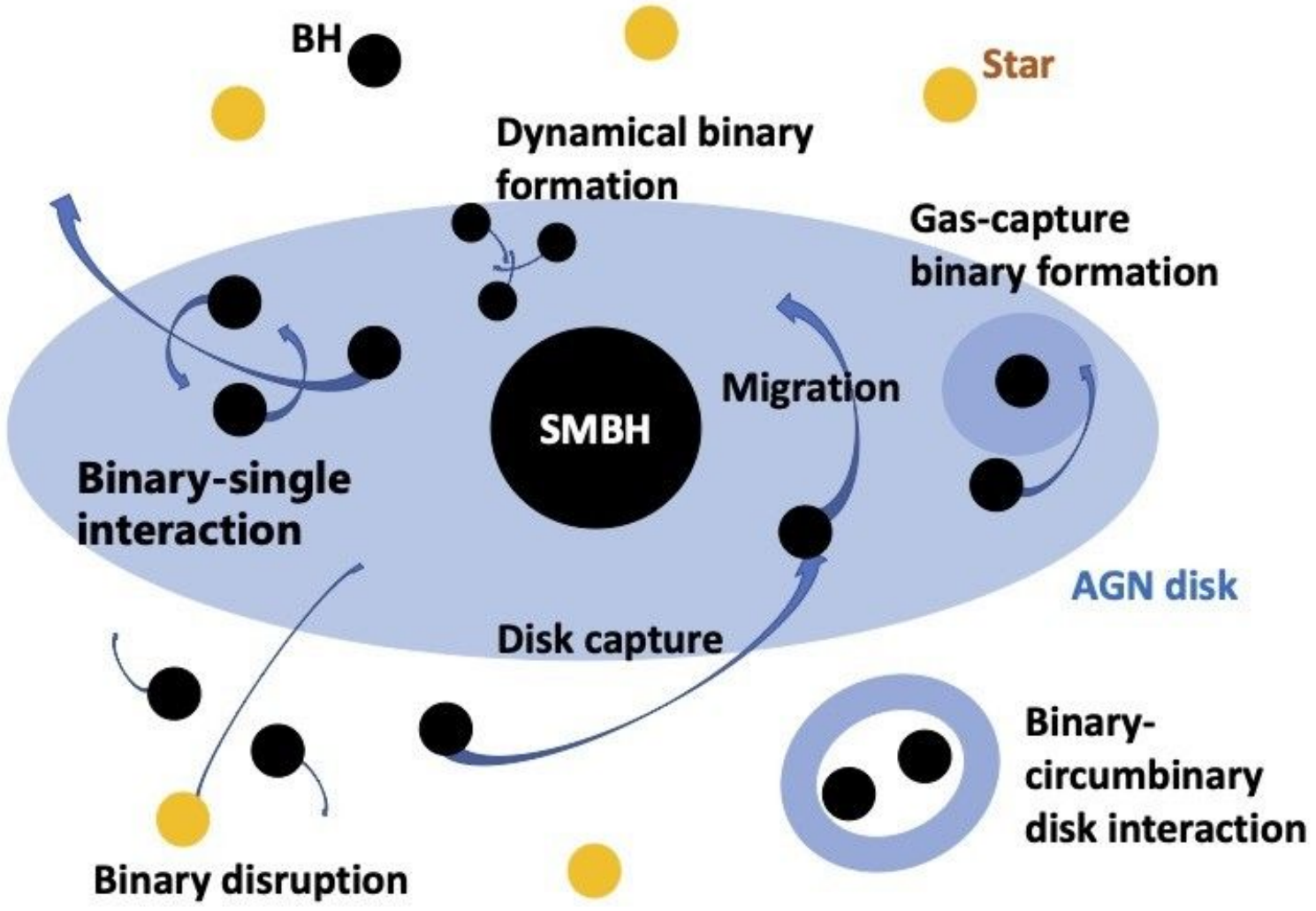
26th Capra Meeting
6th July 2023, Niels Bohr Institute

grit gravitation in técnico

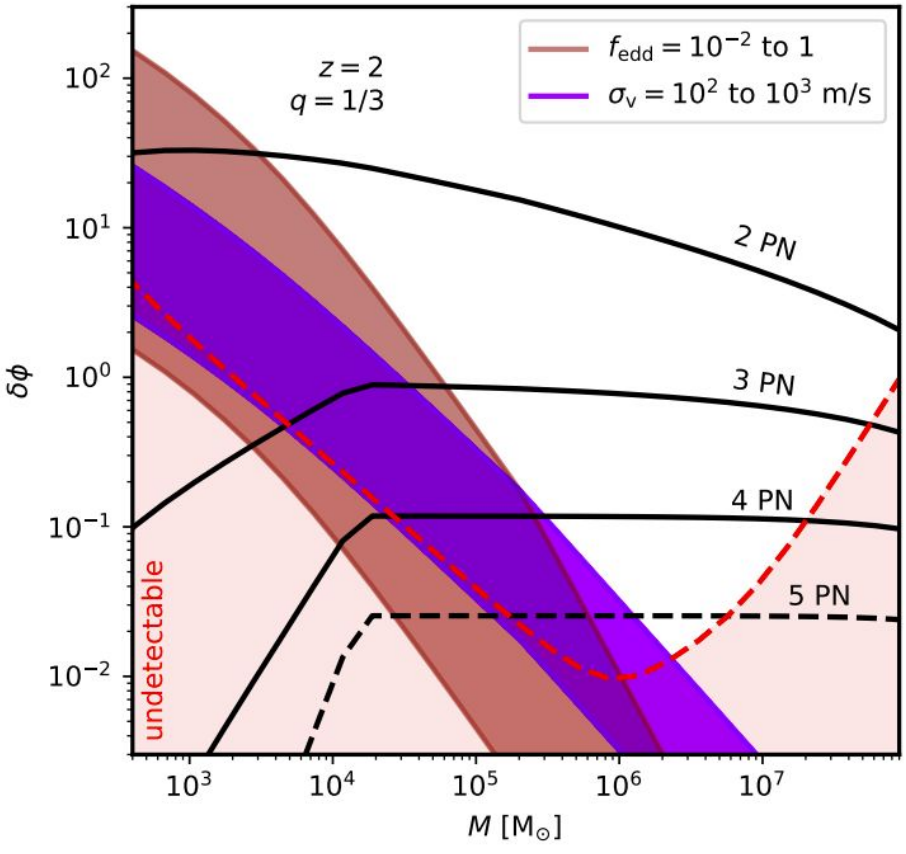
centra

FCT Fundação para a Ciência e a Tecnologia

erc



Tagawa et al. ApJ, 898, 25 (2020)



"GW phase shift of a BHB (...) caused by adding higher-order PN terms or environmental effects"

Zwick et al. MNRAS 521, 3(2023)

New Horizons for Fundamental Physics with LISA

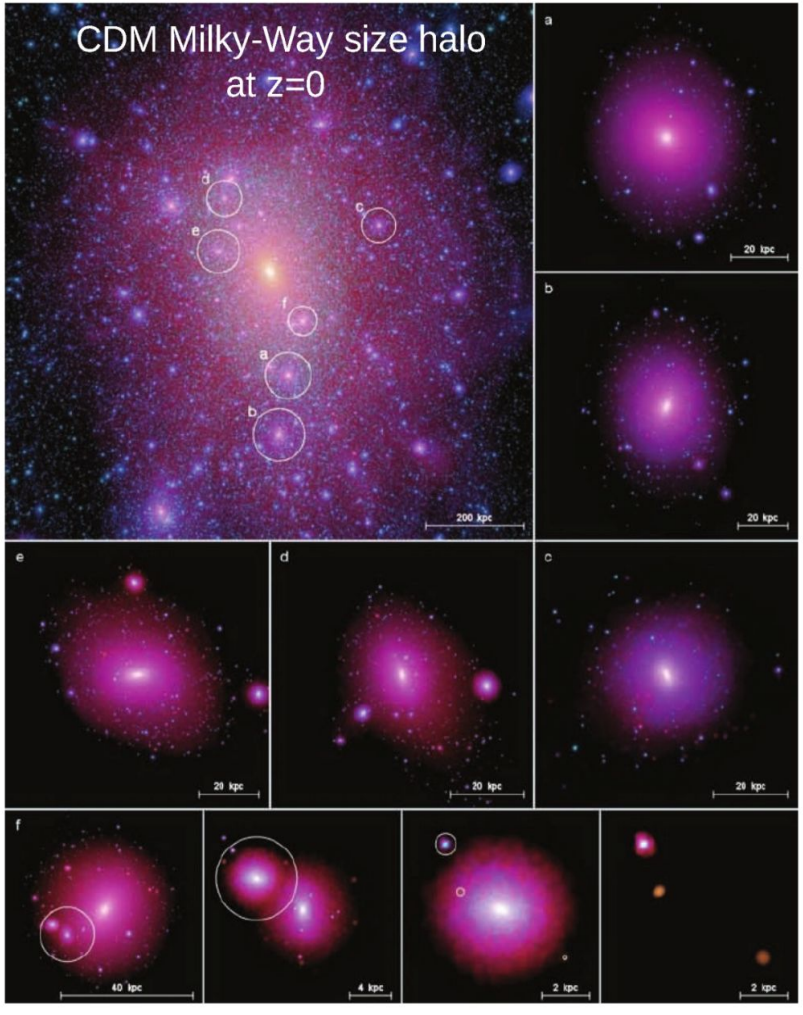
K. G. Arun,[1] Enis Belgacem,[2] Robert Benkel,[3] Laura Bernard,[4] Emanuele Berti,[5] Gianfranco Bertone,[6] Marc Besancon,[7] Diego Blas,[8,9,10] Christian G. Böhmer,[11] Richard Brito,[12] Gianluca Calcagni,[13] Alejandro Cardenas-Avendaño,[14,15,16] Katy Clough,[17] Marco Crisostomi,[18,19] Valerio De Luca,[20] Daniela Doneva,[21,22] Stephanie Escoffier,[23] José María Ezquiaga,[24] Pedro G. Ferreira,[25] Pierre Fleury,[26] Stefano Foffa,[20] Gabriele Franciolini,[20,27] Noemi Frusciante,[28] Juan García-Bellido,[26] Carlos Herdeiro,[29] Thomas Hertog,[30] Tanja Hinderer,[31] Philippe Jetzer,[32] Lucas Lombriser,[20] Elisa Maggio,[27] Michele Maggiore,[20] Michele Mancarella,[20] Andrea Maselli,[33,34] Sourabh Nampalliwar,[35] David Nichols,[6,36] Maria Okounkova,[37] Paolo Pani,[27] Vasileios Paschalidis,[38] Alvise Raccanelli,[39,40,41] Lisa Randall,[42] Sébastien Renaux-Petel,[43] Antonio Riotto,[20] Milton Ruiz,[44] Alexander Saffer,[45] Mairi Sakellariadou,[8] Ippocratis D. Saltas,[46] B. S. Sathyaprakash,[47,48,49] Lijing Shao,[50] Carlos F. Sopuerta,[51,52] Thomas P. Sotiriou,[53] Nikolaos Stergioulas,[54] Nicola Tamanini,[55] Filippo Vernizzi,[56] Helvi Witek,[44] Kinwah Wu,[57] Kent Yagi,[36] Stoytcho Yazadjiev,[21,58,59] Nicolás Yunes,[15] Miguel Zilhão,[60]

“Can accretion, plasma effects or other stellar compact objects in the vicinity of an EMRI induce observable changes in the GW frequency evolution during the inspiral and/or ringdown that can spoil fundamental physics tests?”

“Self-force calculations in vacuum or embedded in a background (e.g. dark matter boson cloud) at second-order are necessary for proper modelling of EMRIs”

“Efforts must be made to include environmental effects (in Phenom and EOB models) such as dynamical friction or interactions with clouds of ultralight fields”

LISA Collaboration, Living Rev. Rel. 25 (2022)



Springel et al, MNRAS, vol 391, p 1685-1711 (2008)

Average density:

$$\sim 0.1\, M_\odot\, \mathrm{pc}^{-3}$$

Dispersion velocity:

$$\sim 100\, \mathrm{km\, s}^{-1}$$

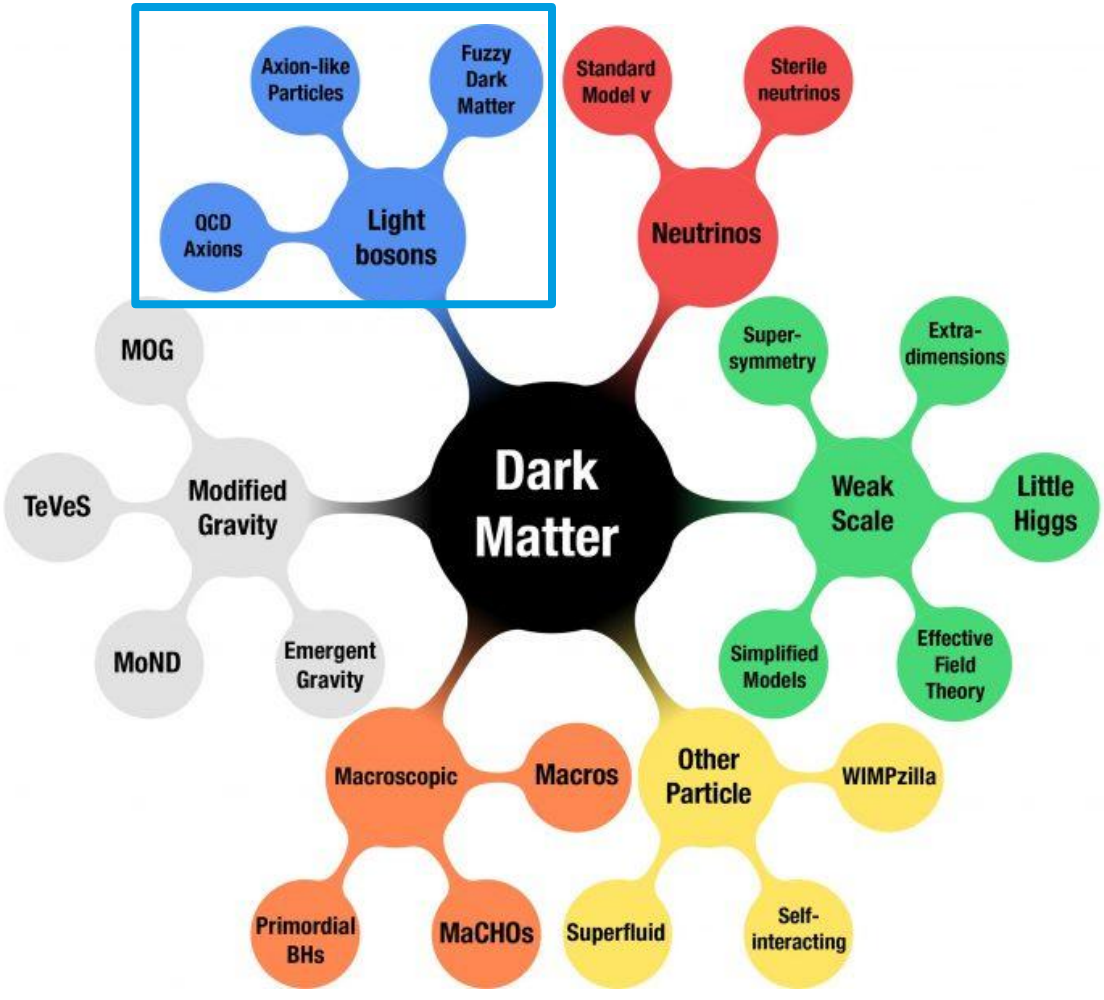
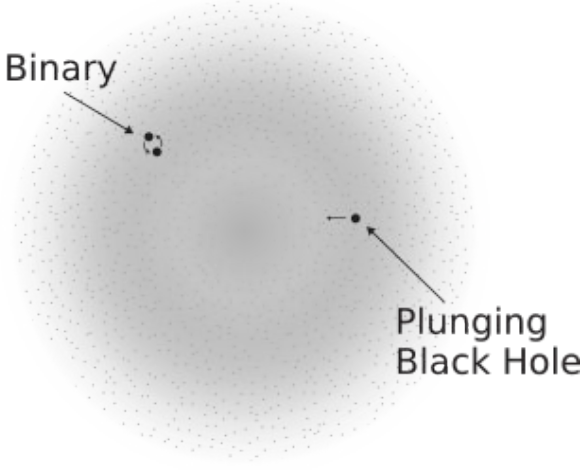
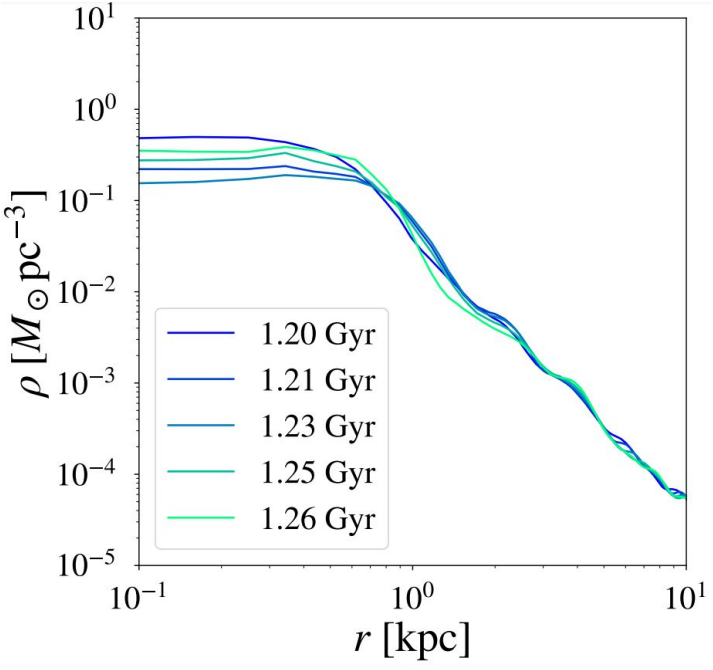


Image Credit: G. Bertone and T. M. P. Tait

$$G_{\mu\nu} = 8\pi T^{\Phi}_{\mu\nu} \qquad \Box\Phi = \mu^2\Phi$$

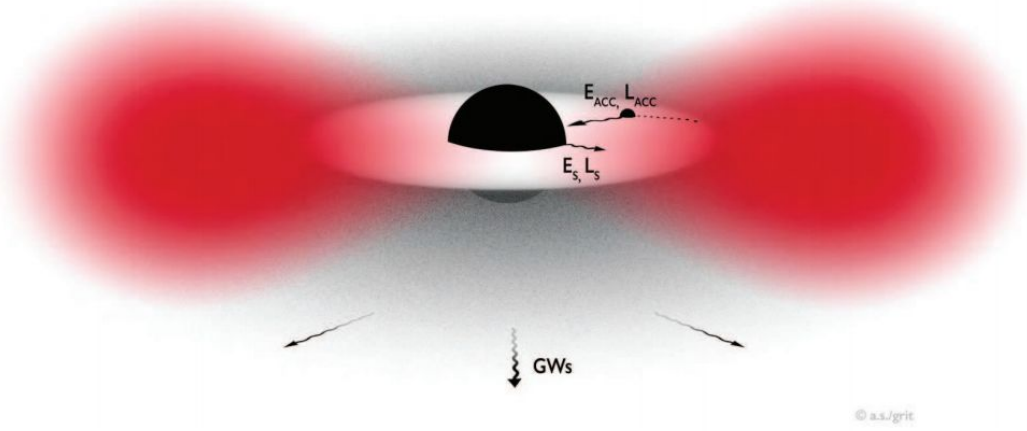




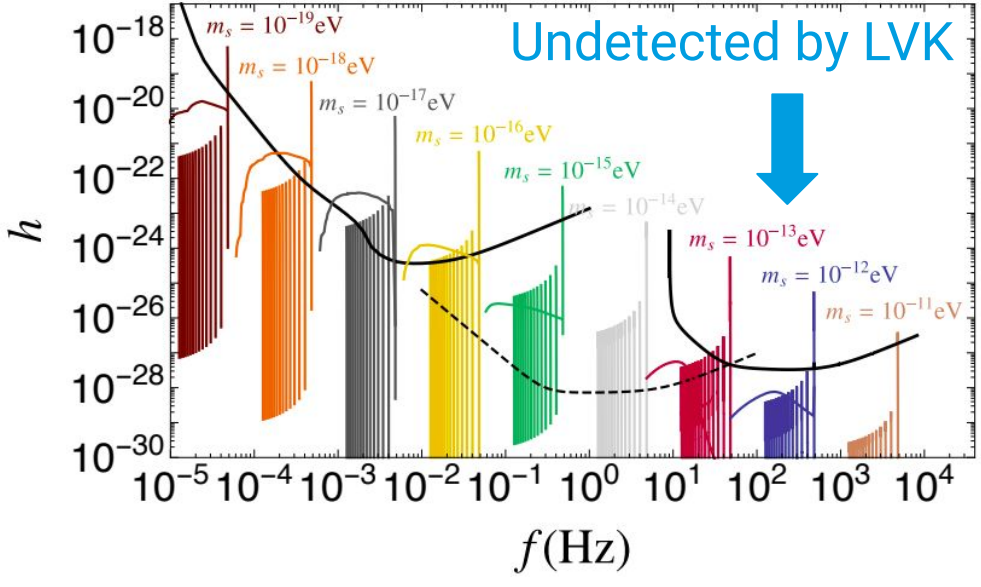
$$\frac{M_{\rm BS}}{10^9 M_\odot} \sim \frac{1\,{\rm kpc}}{R_{\rm BS}} \left(\frac{10^{-22}\,{\rm eV}}{\mu}\right)^2 \qquad \tau_{\rm accr} \sim 30{\rm Gyr}\, f(\nu_0) \left(\frac{10^{10} M_\odot}{M_{\rm BS,0}}\right)^5 \left(\frac{10^{-22}{\rm eV}}{\mu}\right)^6$$

Cardoso et al. PRD 12, L121302 (2022) + Annulli, Vicente & Cardoso PRD 102, 063022 (2020) + Hui ARAA 59, 247-289 (2021)

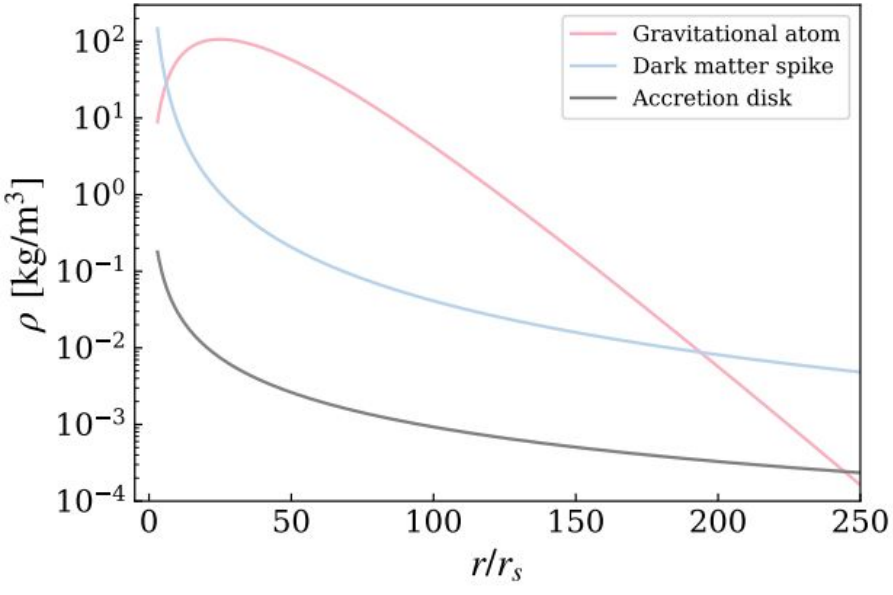
$$\omega < m\Omega_H$$

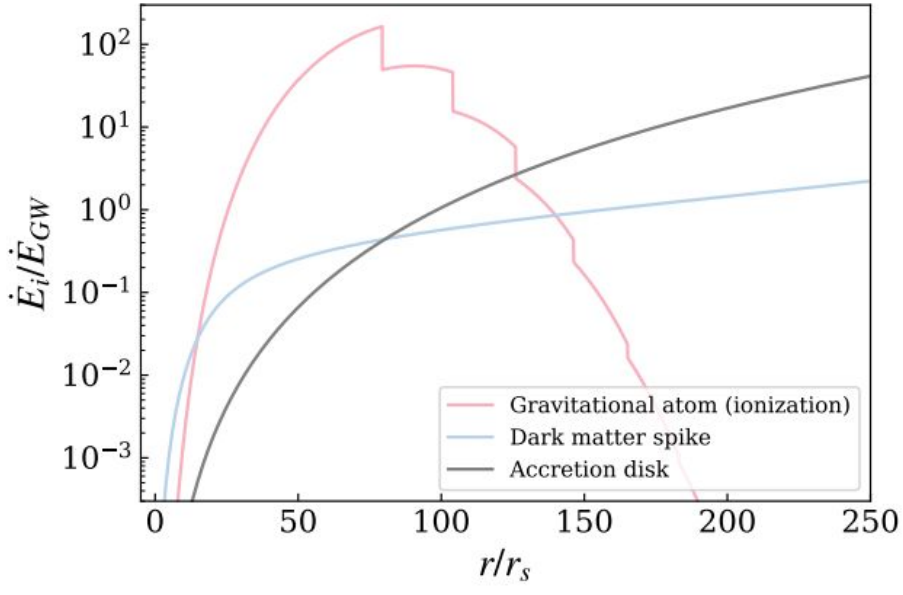


$$\mu \sim M^{-1} \sim 10^{-17} \left(\frac{10^6 M_\odot}{M}\right) \text{eV}$$



Brito, Cardoso & Pani Lect. Notes Phys. 971, Springer (2020) + Brito et al., PRL, 119.131101 (2017)





Different environments → Different inspirals

Cole et al. arXiv:2211.01362 (2020)

Relativistic framework for GW emission in generic environments

Duque et al. PRD 105, L061501 (2022) + Duque et al. PRL 129, 241103 (2022)

Idea: apply BH perturbation theory to extended distributions of matter surrounding a central BH (inspired in studies of relativistic stars)

Allen et al., PRD 58, 124012 (1998) + Macedo, PRD 88, 064046 (2013)

Axial: 1 master wave equation

Polar: coupled wave equations for the gravitational + matter perturbations

Outcome: energy/angular momentum carried by GWs + matter waves

Dynamical Friction/Accretion + Feedback on the environment

Parasitic BH inside a Boson Star

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

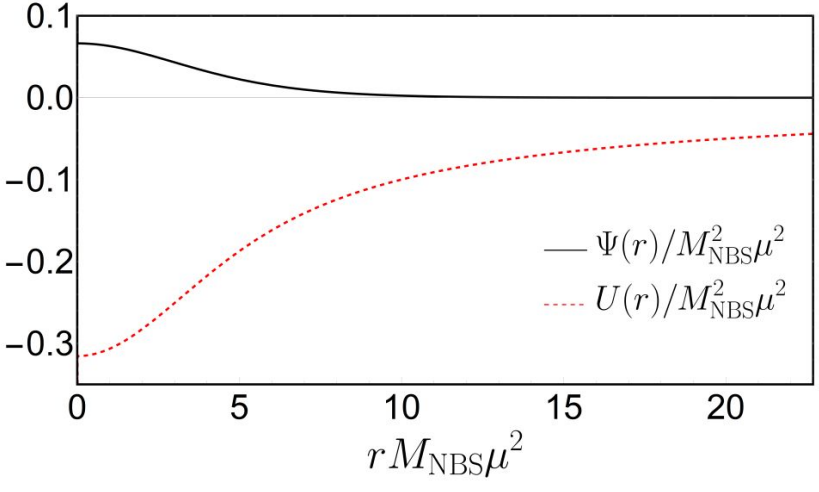
$$f = \left(1 - \frac{2M_{\rm BH}}{r}\right) e^{2\mathcal{U}_{\rm NBS}(r)}$$

$$e^{2\mathcal{U}_{\rm NBS}(r)} \underset{r\to 2M_{\rm BH}}{\sim} 1 - M_{\rm NBS}/R_{\rm NBS}$$

Redshift

$$m(r) = M_{\rm BH} + 4\pi\mu^2 \int_{2M}^{r} dr' r'^2 |\Phi_{\rm NBS}(r')|^2$$

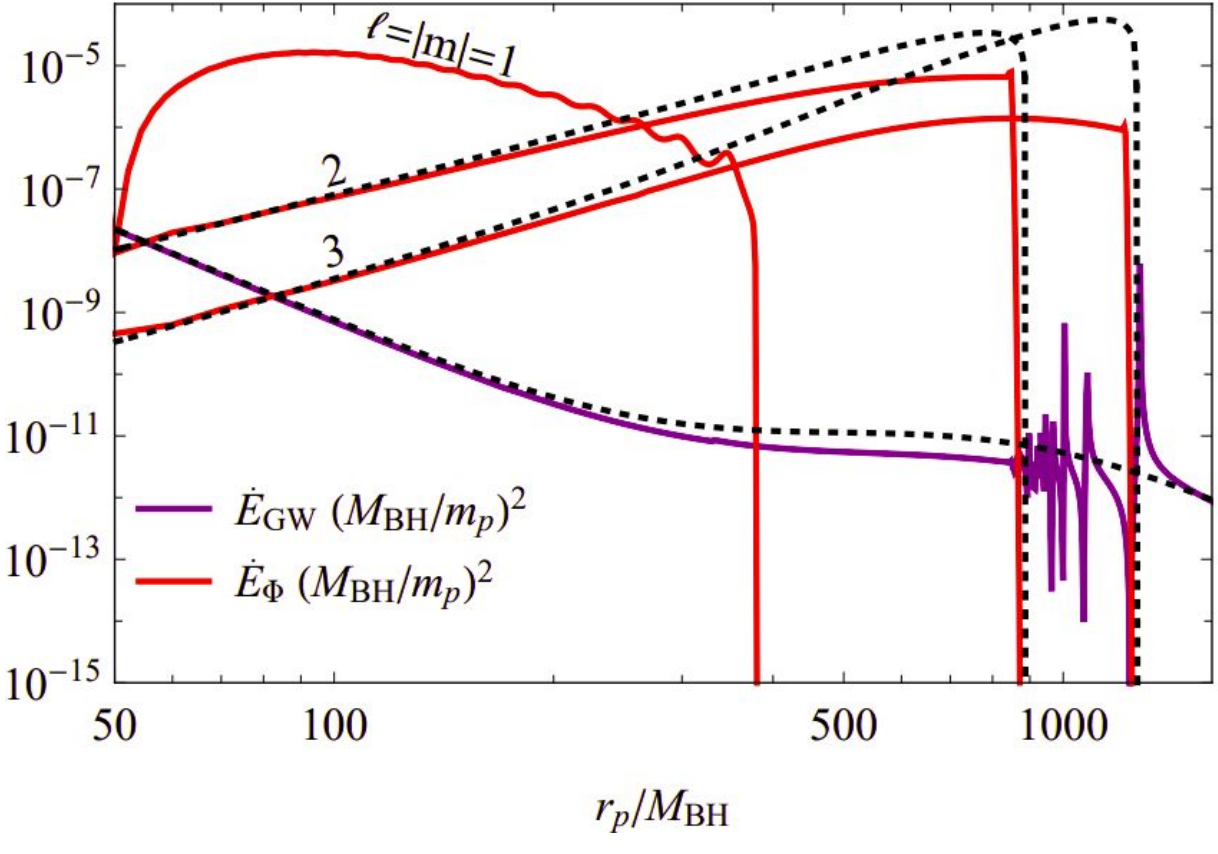
$$\Phi(r) = \Phi_{\rm NBS}(r) \left(1 - \frac{2M_{\rm BH}}{r}\right)^{-2i\mu M_{\rm BH}}$$



Low-Energy BHB within Boson Star $\Omega_p \ll \mu$

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

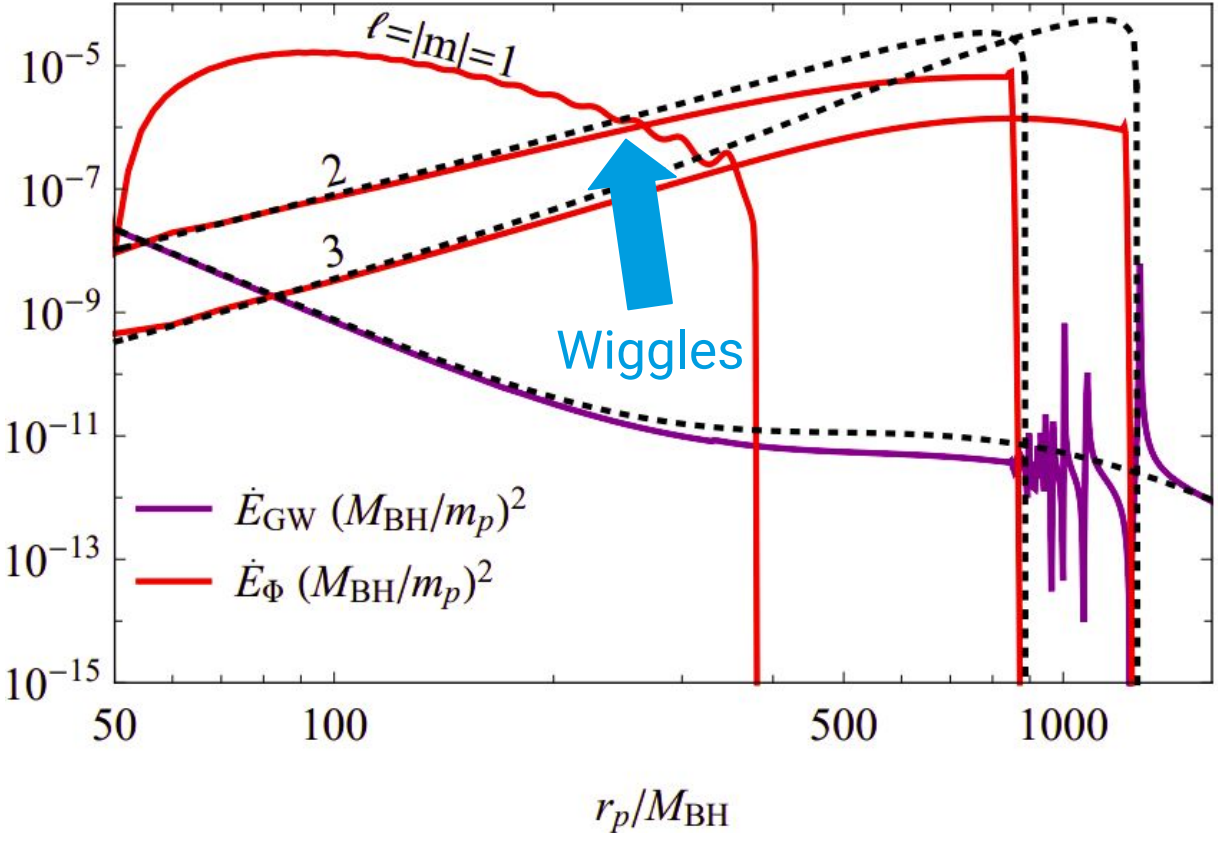
$$\mu \sim 10^{-22}\,\mathrm{eV} \sim 1\,\mathrm{kpc} \sim 1\,\mathrm{year}$$



Low-Energy BHB within Boson Star $\Omega_p \ll \mu$

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

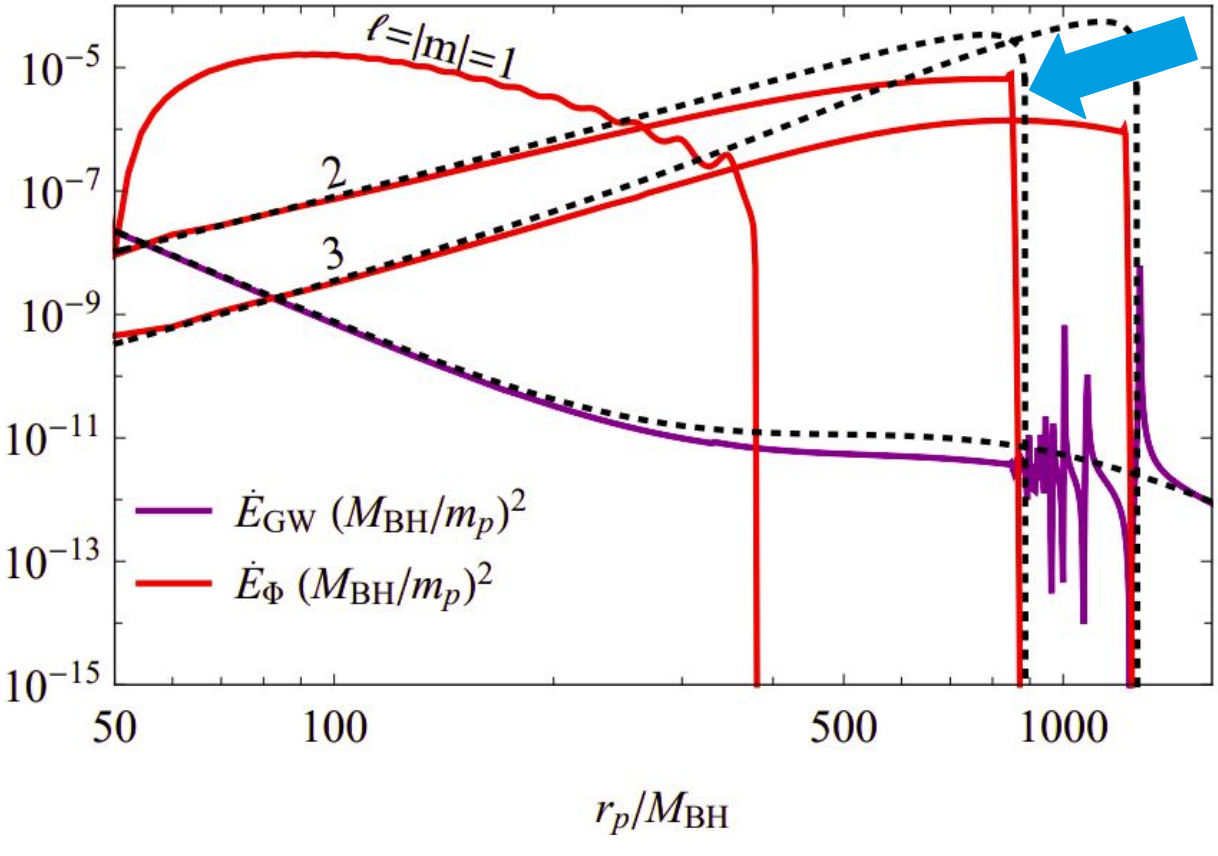
$$\mu \sim 10^{-22}\,\mathrm{eV} \sim 1\,\mathrm{kpc} \sim 1\,\mathrm{year}$$



Low-Energy BHB within Boson Star $\Omega_p \ll \mu$

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

$$\mu \sim 10^{-22}\,\mathrm{eV} \sim 1\,\mathrm{kpc} \sim 1\,\mathrm{year}$$

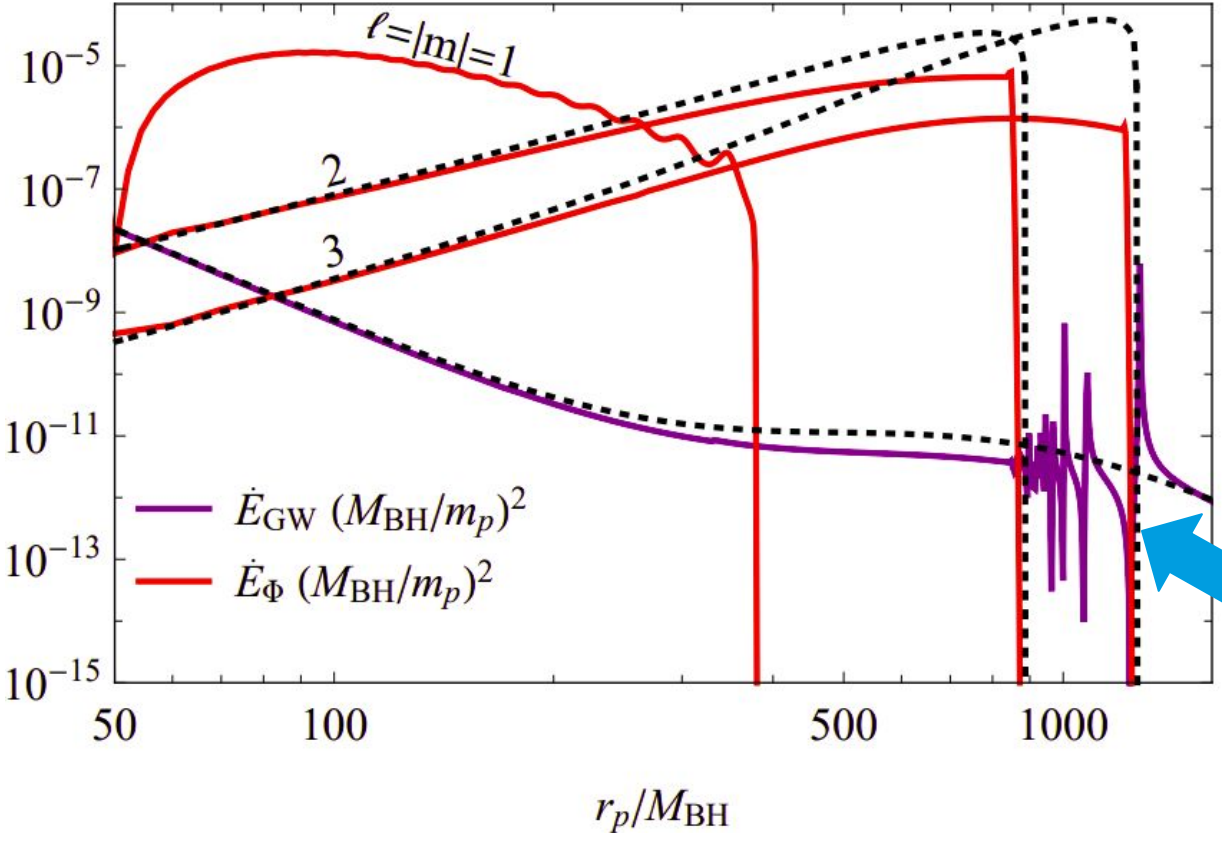


Discontinuities

Low-Energy BHB within Boson Star $\Omega_p \ll \mu$

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

$$\mu \sim 10^{-22}\,\mathrm{eV} \sim 1\,\mathrm{kpc} \sim 1\,\mathrm{year}$$



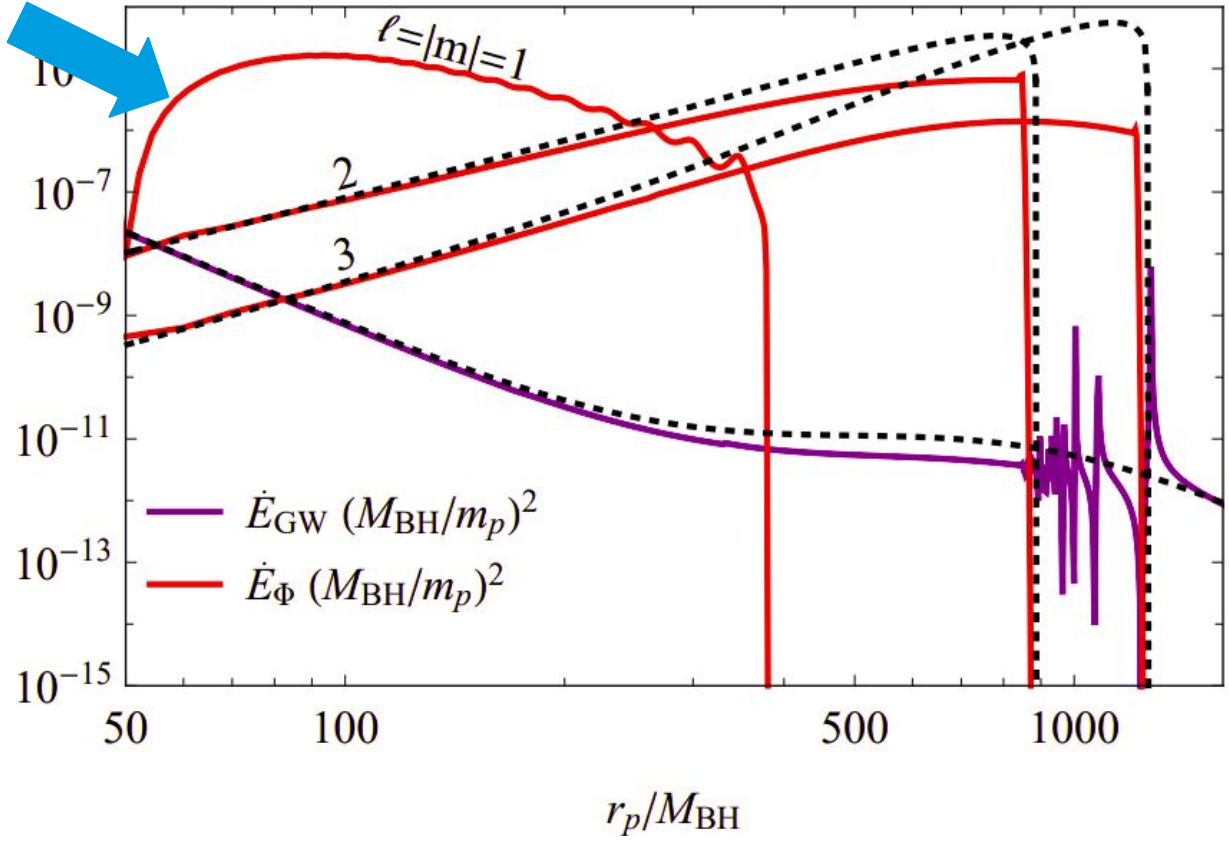
Resonances

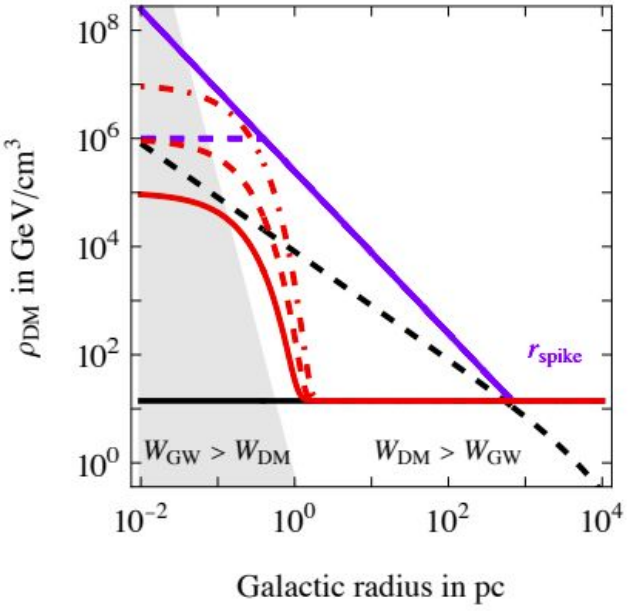
Low-Energy BHB within Boson Star $\Omega_p \ll \mu$

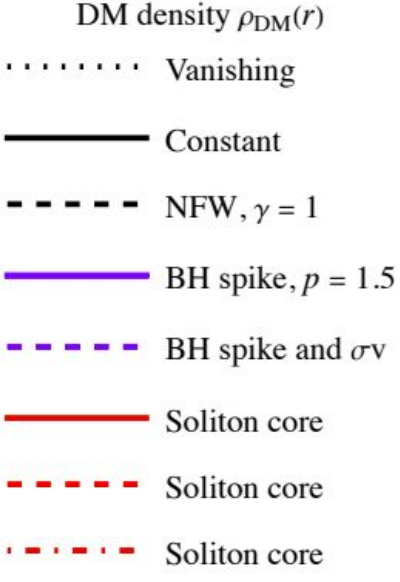
Annulli, Vicente and Cardoso PRD 102, 063022 (2020)

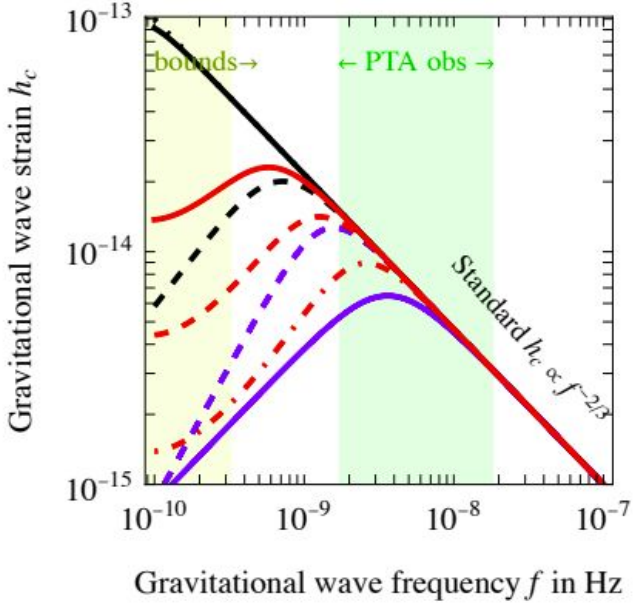
l=1 different?

$$\mu \sim 10^{-22}\,\mathrm{eV} \sim 1\,\mathrm{kpc} \sim 1\,\mathrm{year}$$









Goshal and Strumia arXiv:2306.17158 (2023)

High-Energy BHB within Boson Star $\Omega_p \gg \mu$

Capra 2024...

Future plans

1. Improve modelling

- More environments: AGN disks…
- Rotation + Eccentricity

2. Waveform implementation

3. Detectability/Parameter Estimation Survey

- Can the environment spoil tests of GR?
- Can we infer properties of the environment?
- Modified gravity vs Environmental effects