TÉCNICO LISBOA

Fundação para a Ciência e a Tecnologia

Dark matter and primordial black holes from the WP perspective

Richard Brito
CENTRA, Instituto Superior Técnico, Lisboa

centra
center for astrophysics and gravitation

grit
gravitation in técnico

Some useful numbers to keep in mind

See e.g. Barausse *et al* 1404.7149 & Cardoso & Maselli, 1909.05870

- Local dark matter density: $\rho_{\rm DM0} \approx 10^{-21}{\rm kg/m^3} \approx 10^{-2} M_\odot/{\rm pc}^3$
- Accretion disks: $\rho_{\rm disks} \approx 10^{-6} - 10^{2}\,{\rm kg/m^3} \approx 10^{13} - 10^{21}\, M_\odot/{\rm pc}^3$

We need ***enhancement* mechanisms** creating large DM overdensities close to BHs in order to see effects on GWs:

$$\rho_{\rm DM\ spikes} \approx 10^{-9} - 10^{2}\,{\rm kg/m^3} \approx 10^{10} - 10^{21}\, M_\odot/{\rm pc}^3$$

$$\rho_{\rm boson\ clouds} \lesssim 10^{3}\,{\rm kg/m^3} \approx 10^{22}\, M_\odot/{\rm pc}^3$$

DM & PBHs in the SIWP: Goals

Adapted from: SIWP documents in LISA wiki

6. Dark Matter

(leads: Diego Blas & Max Isi)

Goals and motivation:

- ❖ Use gravitational-wave signals to detect or constrain dark matter in regimes complementary to other experiments.
- ❖ Probe the large-scale structure and dynamic properties of dark matter; connect this to cosmology.
- ❖ Disentangle potential dark matter signals from confounding factors, like baryonic physics.
- ❖ Determine whether Primordial Black Holes constitute a significant component of dark matter.

7.5. Characterisation of backgrounds

(leads: Irina Dvorkin, Valerie Dock, Marco Peloso, Germano Nardini)

Goals and motivation:

- ❖ The most standard mechanism for PBHs production is from enhanced density perturbations. These perturbations source a SGWB well above the LISA sensitivity
- ❖ (…)

DM & PBHs in the SIWP: Outputs

Adapted from: SIWP documents in LISA wiki

6. Dark Matter

(leads: Diego Blas & Max Isi)

Outputs:

- Hierarchical inference infrastructure for the analysis of populations of compact binary signals within the context of dark matter models.
- Waveforms encoding deviations due to dark matter.
- Framework to translate generic parameterized constraints into dark matter statements.
- Search pipelines dedicated to characteristic dark matter signals.
- Framework to cohesively interpret a variety of measurements into statements about dark matter models

7.5. Characterisation of backgrounds

(leads: Irina Dvorkin, Valerie Dock, Marco Peloso, Germano Nardini)

Outputs:

- Given a null detection, compute constraints on theoretical models (this includes backgrounds generated by primordial black holes)
- (...)

Specific activities: Mission duration document

Amaro Seoane *et al*, arXiv:2107.09665

Report of a study assessing the **impact of mission duration** on the main science objectives of the LISA mission

Different duration/ gap scenarios →

Scenario	T4C	T4G5	T4G1	T5C	T6C	T6G5	T6G1
T_{elapsed}		4 yr		5 yr		6 yr	
$T_{\text{data}} = 0.75 \times T_{\text{elapsed}}$		3 yr		3.75 yr		4.5 yr	
Gaps	one	5 days	1 day	one	one	5 days	1 day
Galactic binaries (SO1 SI1.2) (§3)							
Black hole seeds (SO2 SI2.1) (§2)							
EM counterparts (SO2 SI2.3) (§2, §5)							
EMRIs (SO3 SI3.1) (§4)							
Multiband SOBHs (SO4 SI4.1) (§3)							
SOBH formation (SO4 SI4.2) (§3)							
Kerr tests (SO5 SI5.1&5.2) (§9)							
Tests of GR (SO5 SI5.3&5.4) (§8)							
Ultralight bosons (SO5 SI5.5) (§7)							
H_0 via standard sirens (SO6 SI6.1) (§6)							
Cosmological parameters (SO6 SI6.2) (§6)							

Relevant for DM/PBHS → Tests of GR, Ultralight bosons, Cosmological parameters

Objective exceeded

Objective achieved

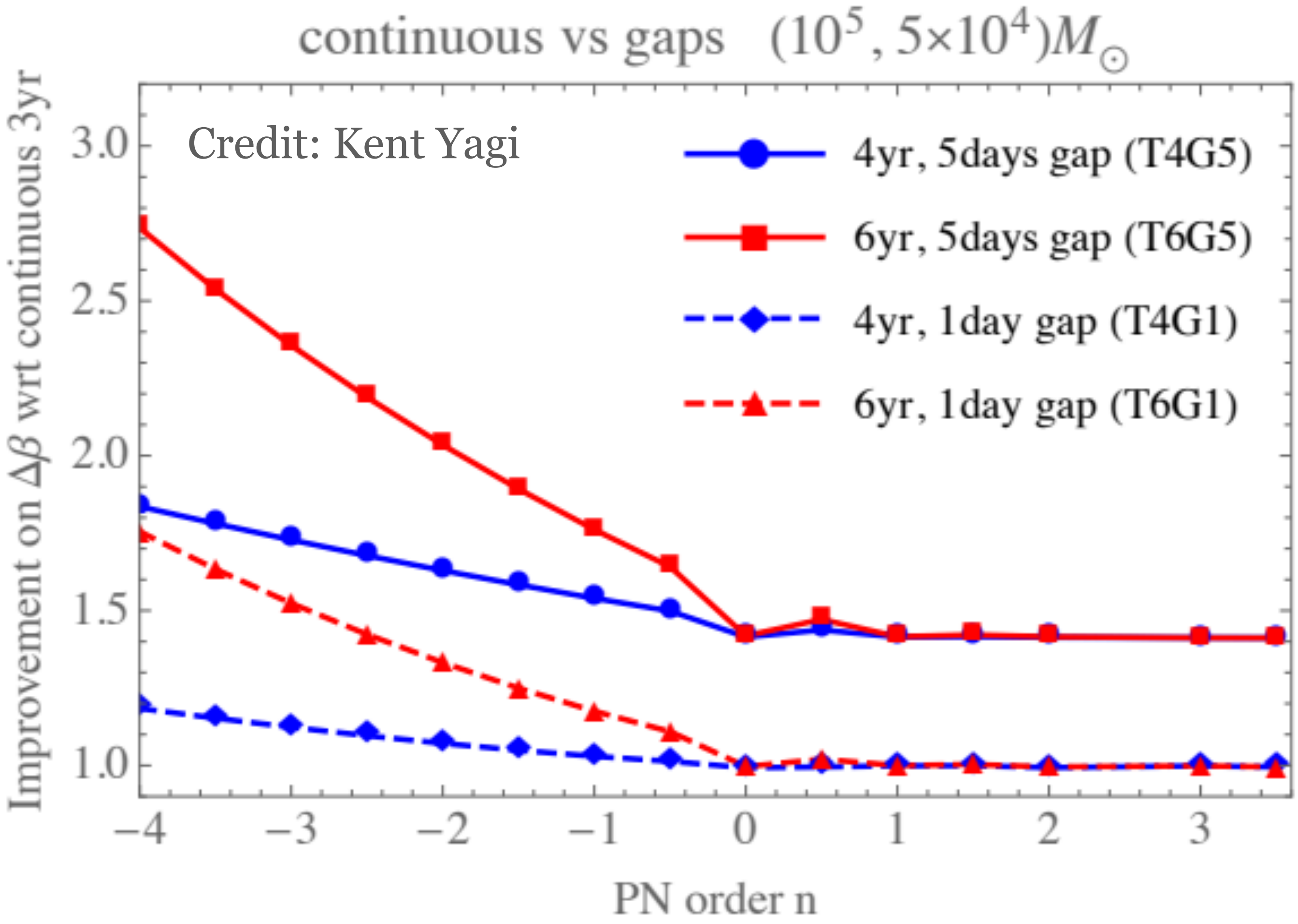
Objective degraded

Objective likely failed

Specific activities: Mission duration document

Amaro Seoane *et al*, arXiv:2107.09665

A specific example: impact on **ppE tests**



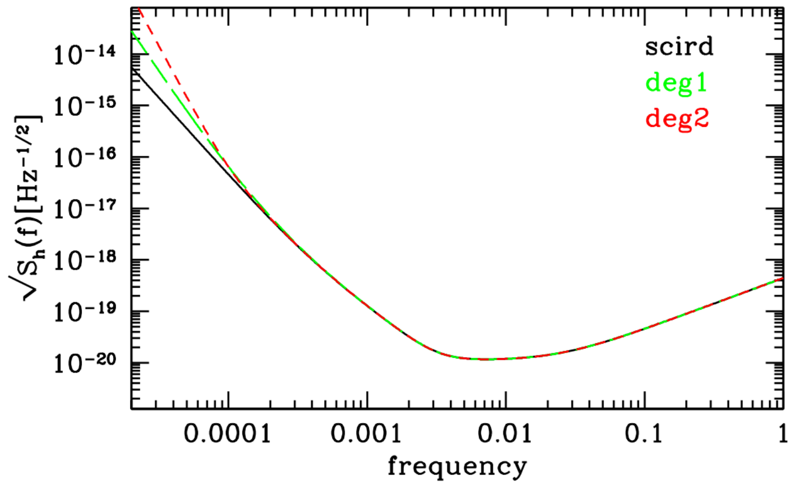
Note: duty cycle always kept fixed to 0.75, so continuous observation segments longer for 5-day gaps

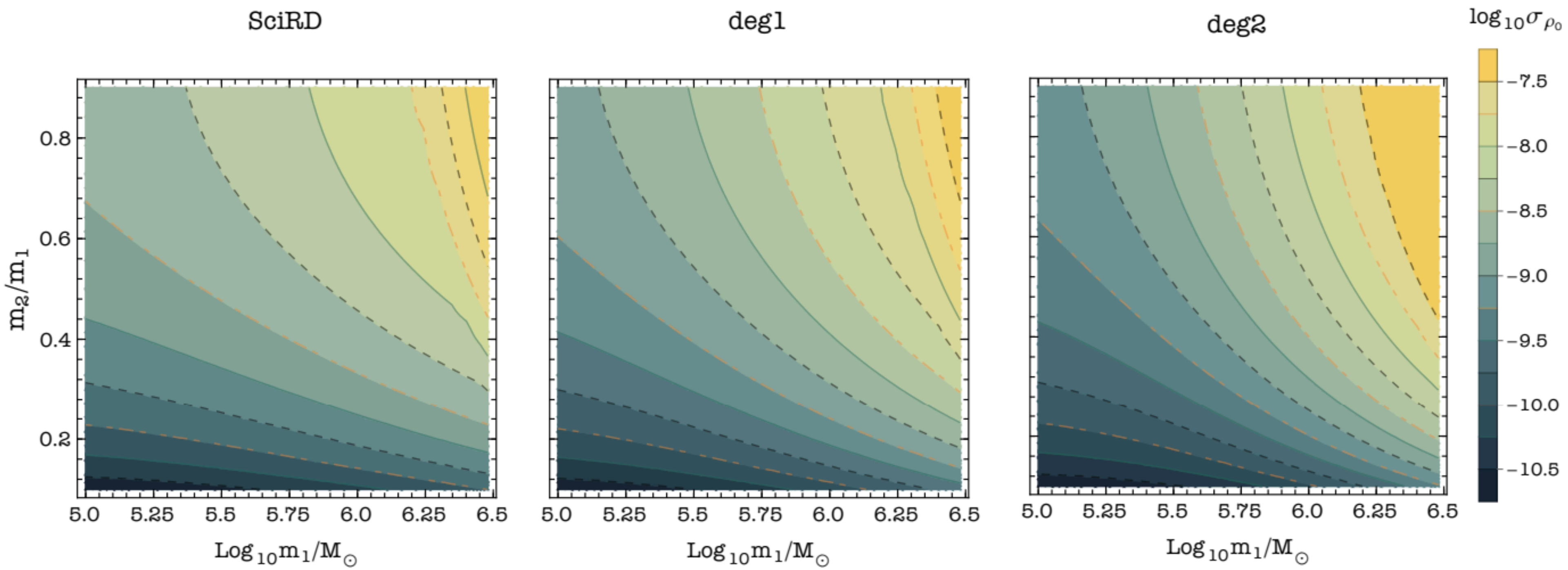
Negative PN corrections relevant for dark matter tests (e.g. dynamical friction and accretion)

Specific activities: Low-frequency document

(Amaro Seoane *et al*, unpublished)

- Impact of **low-frequency degradations** also studied within SIWP
- Scenarios studied relevant for DM&PBHs:
  - SGWB from superradiant scalar clouds **(minimal impact)**
  - SGWB from primordial perturbations giving rise to sub-lunar PBHs **(minimal impact)**
  - (negative PN) ppE tests



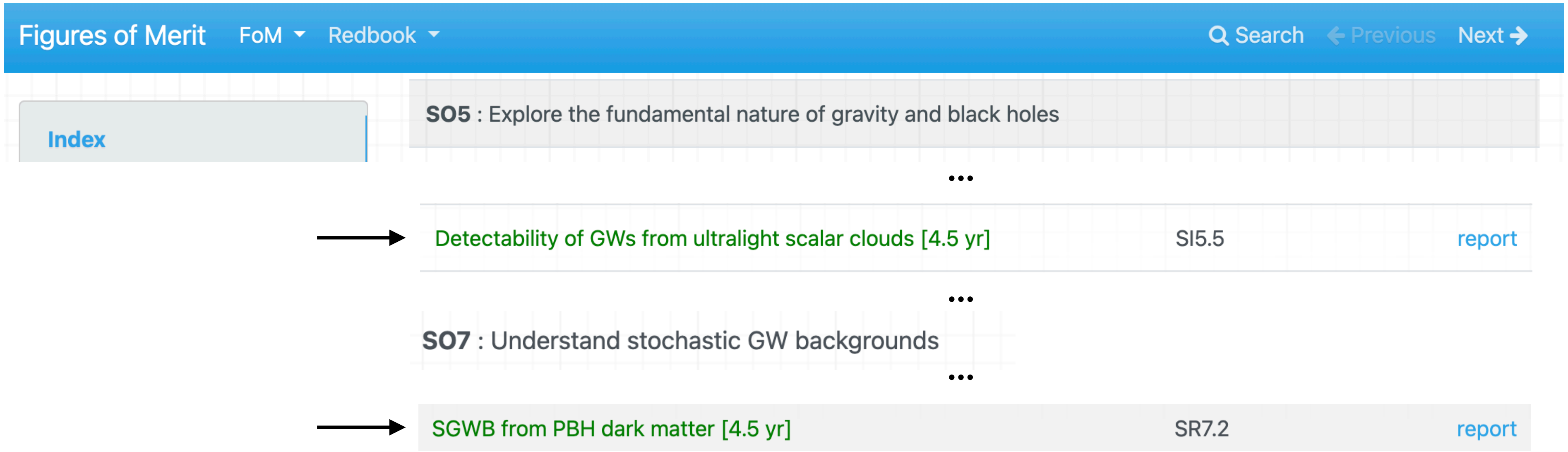


$d = 1\,\mathrm{Gpc}\,, \chi_1 = 0.9\,, \chi_2 = 0.8$

Credit: Andrea Maselli

Specific activities: Figures of Merit

Adapted from FoM webpage: https://apc.u-paris.fr/~sartirana/LISA/FOM/dc_82/site/
(Credit: Maude Le Jeune, Stas Babak and many more…)



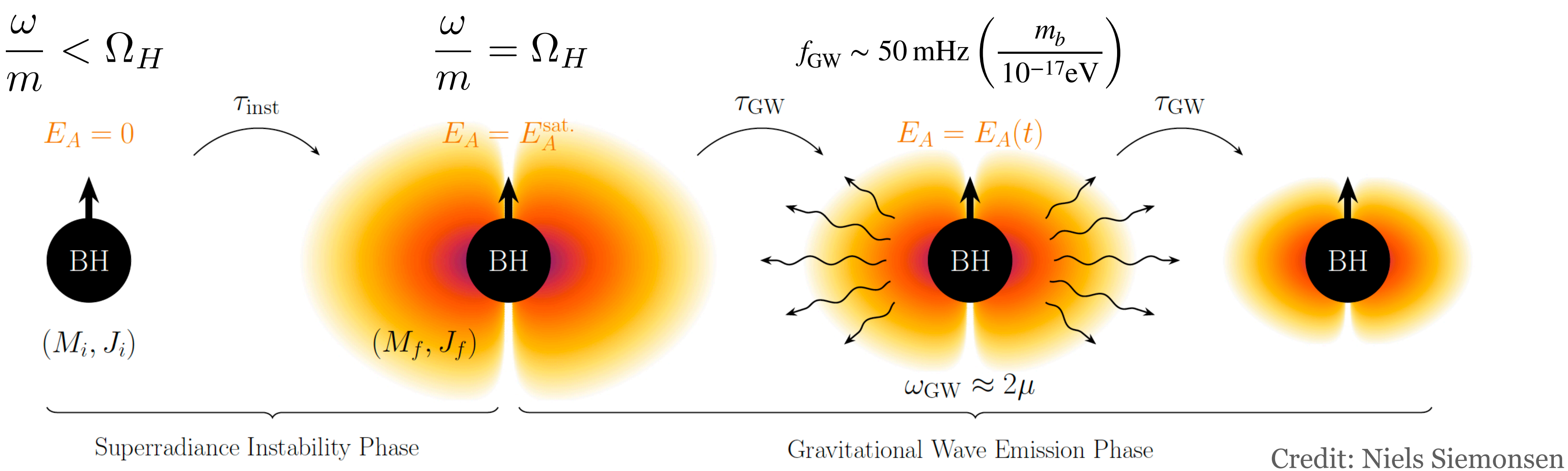
Objective exceeded
Objective achieved
Objective degraded
Objective likely failed

- Some time ago, some of us were asked to come up with **Figures of Merit** (FoM) for different Science Objectives.
- Document written, that included several **FoM for fundamental physics**
- Some of these FoM for fundamental physics were implemented in FoM pipeline
- Main problem, at the time, with (most) of fundamental physics FoM: implemented in **Mathematica codes**, not always straightforward to translate to **Python**. Not sure where things stand now…

FoM example: GWs from boson clouds

Damour '76; Zouros & Eardley '79; Detweiler '80; Dolan '07; Arvanitaki+ '10, Rosa & Dolan '12; Pani+ '12; RB, Cardoso & Pani '13; Baryakthar+ '17; East '17; Cardoso+ '18; Frolov+ '18; Dolan '18; Baumann+ '19; RB, Grillo & Pani '20; Dias+ 23,...

- **Massive bosons** can form (oscillating) **bound-states** around black holes
- Around spinning black-holes, bound-states can **grow exponentially** by extracting energy and angular momentum through to black-hole superradiance



Credit: Niels Siemonsen

Most efficient when:

$$2M\mu \equiv \frac{2Mm_b}{M_{\text{Pl}}^2} = R_G/\lambda_C \sim \mathcal{O}(1)$$

$$\alpha \equiv M\mu \sim 0.1\left(\frac{M}{10^6 M_\odot}\right)\left(\frac{m_b c^2}{10^{-17}\text{eV}}\right)$$

$$\tau_{\text{inst}}^{\text{spin}-0} \approx 10^4\,\text{yrs}\left(\frac{M_i}{10^6\,M_\odot}\right)\left(\frac{0.1}{M_i\mu}\right)^9\left(\frac{0.9}{J_i/M_i^2}\right)$$

$$\tau_{\text{GW}}^{\text{spin}-0} \approx 10^{10}\,\text{yrs}\left(\frac{M_i}{10^6\,M_\odot}\right)\left(\frac{0.1}{M_i\mu}\right)^{15}\left(\frac{0.5}{\Delta(J/M^2)}\right)$$

FoM example: GWs from boson clouds

Detectability of GWs from ultralight scalar clouds [4.5 yr]

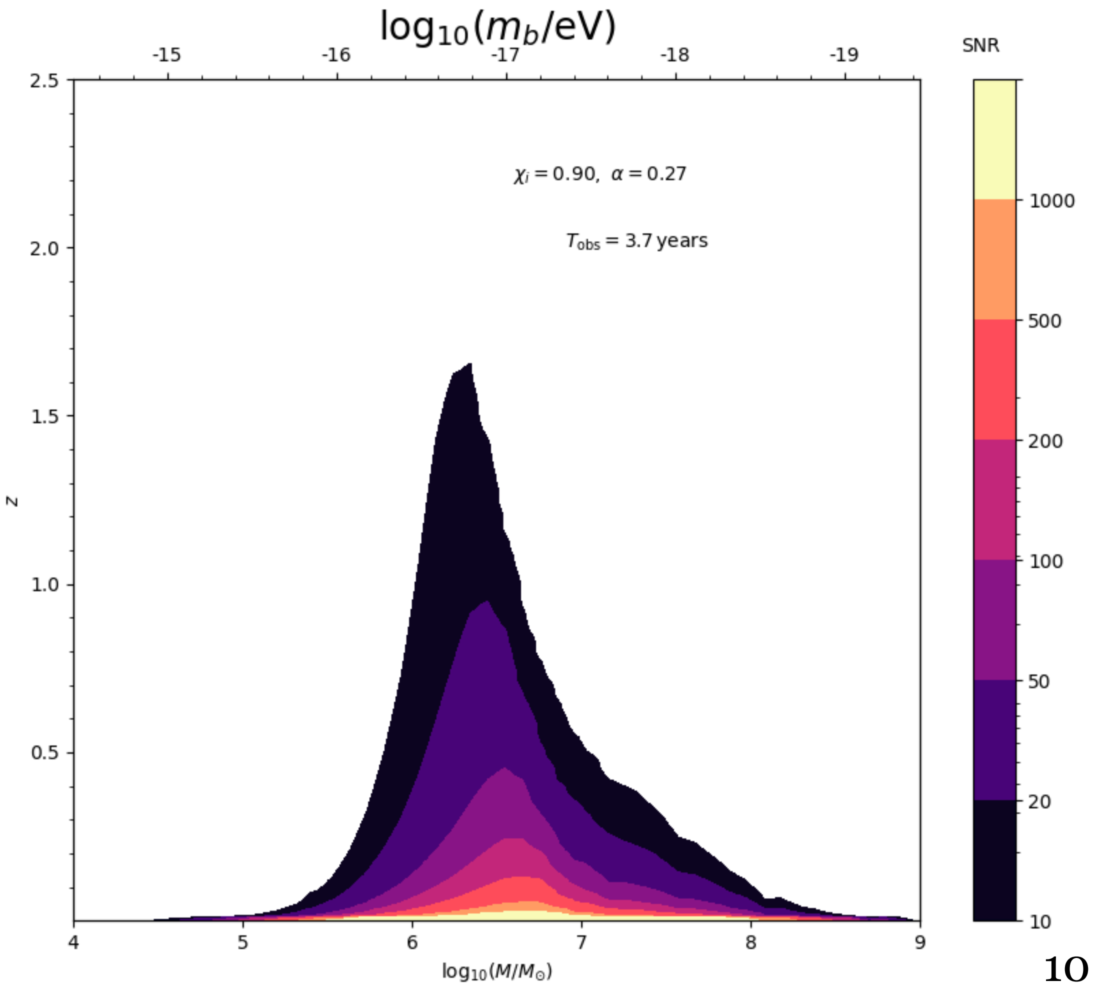
Detectability of GWs from ultralight scalar clouds [4.5 yr]

FoM

Science investigation and Observational requirement: SI5.5 from Science requirement document.

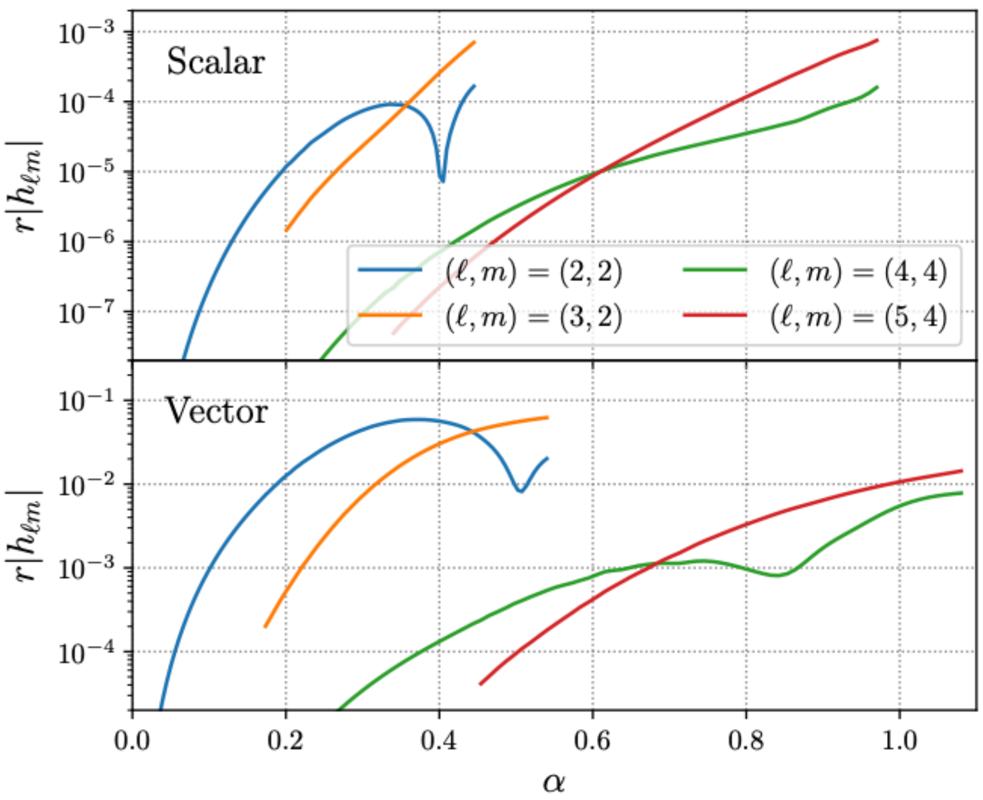
Compute the range of detectable ($SNR > 10$) boson masses for a reference BH with initial mass $M = 4 * 10^6 M_\odot$ (i.e. SgrA*-like) and spin $a/M = 0.9$ at $z = 0.5$}

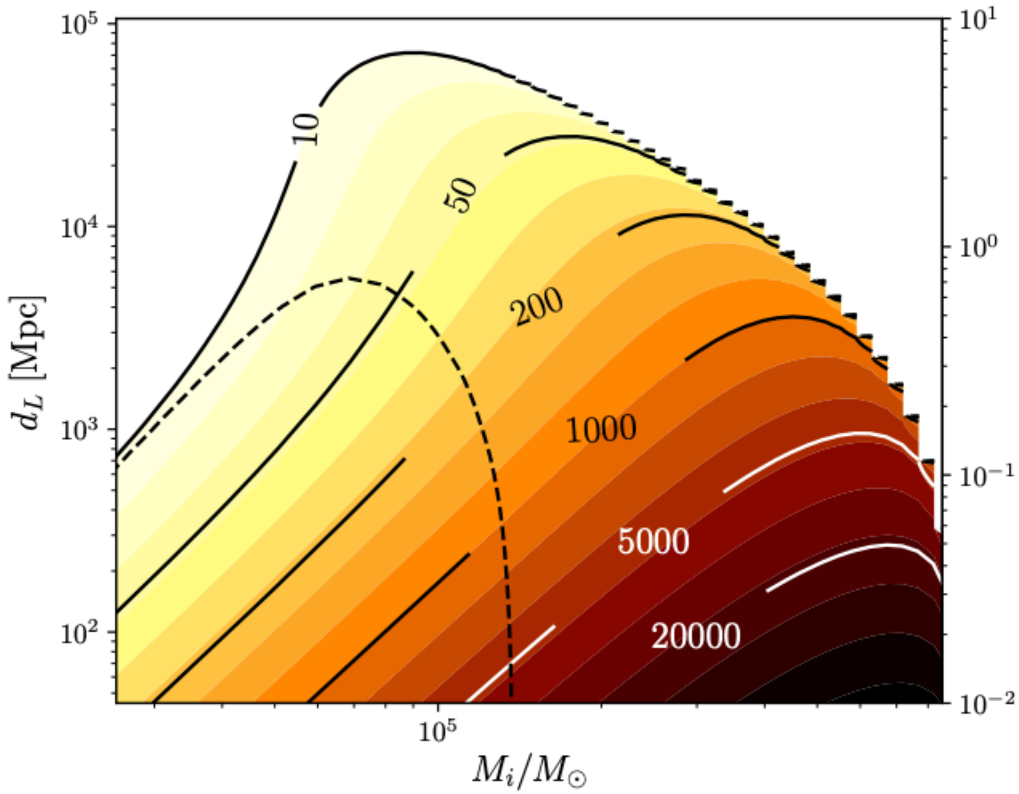
- Used a **publicly available python code** that computes GW strain amplitude of the signal (gwaxion, main dev: Max Isi) + various LISA tools implemented within FoM pipeline



GWs from boson clouds: SuperRad

- Another python code recently publicly released: SuperRad (developers: Nils Siemonsen, Taillte May & Will East, arXiv:2211.03845)
- Includes waveforms for **vector clouds**: stronger signals, good potential for follow-ups on supermassive black-hole mergers with LISA

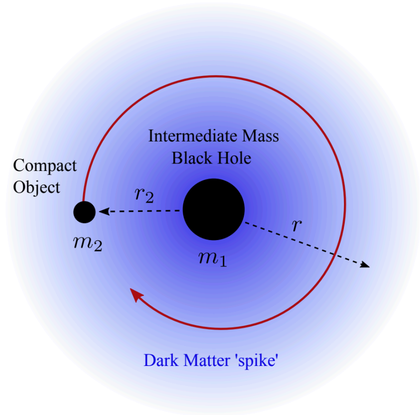




From: Siemonsen, May & East, Phys.Rev. D107, 104003

I/EMRIs in dark matter environments

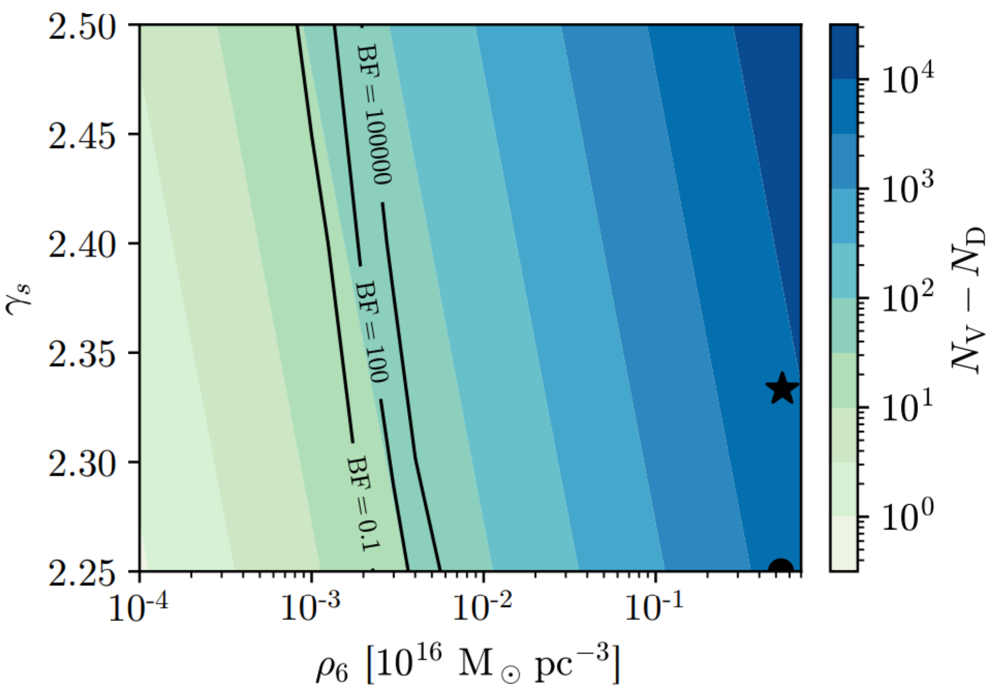
Figures from: Kavanagh *et al.*, arXiv:2002.12811; Coogan *et al*, arXiv:2108.04154

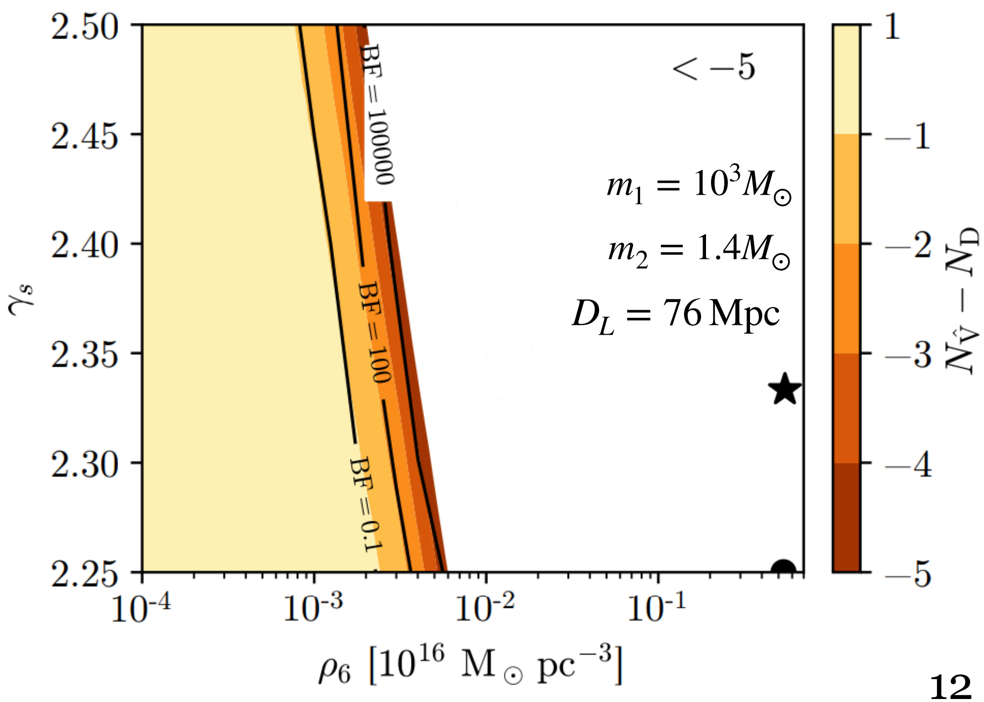


$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$

- Waveform for **quasi-circular, "Newtonian" inspiral** implemented in pydd code (developers: Adam Coogan, Bradley J. Kavanagh)
- Takes into account **halo feedback**, which may reduce instantaneous density

$$\rho_{\rm DM}(r, t=0) = \begin{cases} \rho_6 \left(\frac{r_6}{r}\right)^{\gamma_{\rm sp}} & r_{\rm in} \leq r \leq r_{\rm sp} \\ 0. & r < r_{\rm in} \end{cases}$$

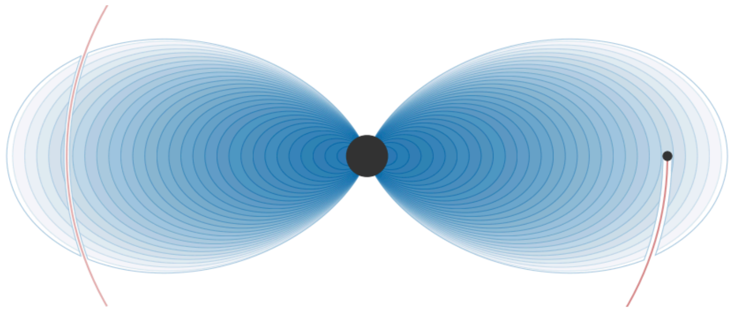




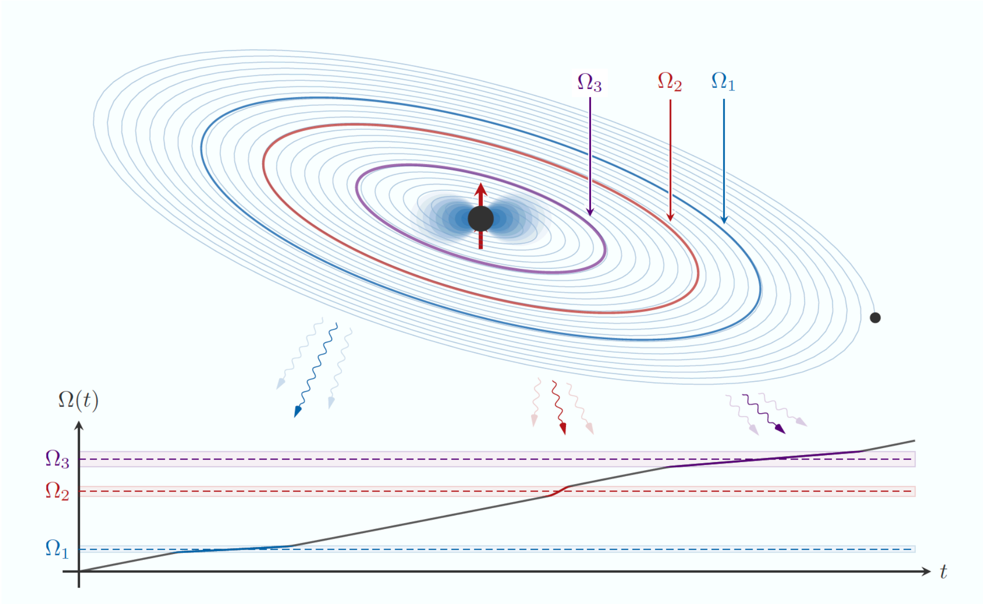
I/EMRIs in boson clouds

Baumann+'18, '19, '21; Hannuksela+ '19; Tomaselli+'23; RB & S. Shah '23...

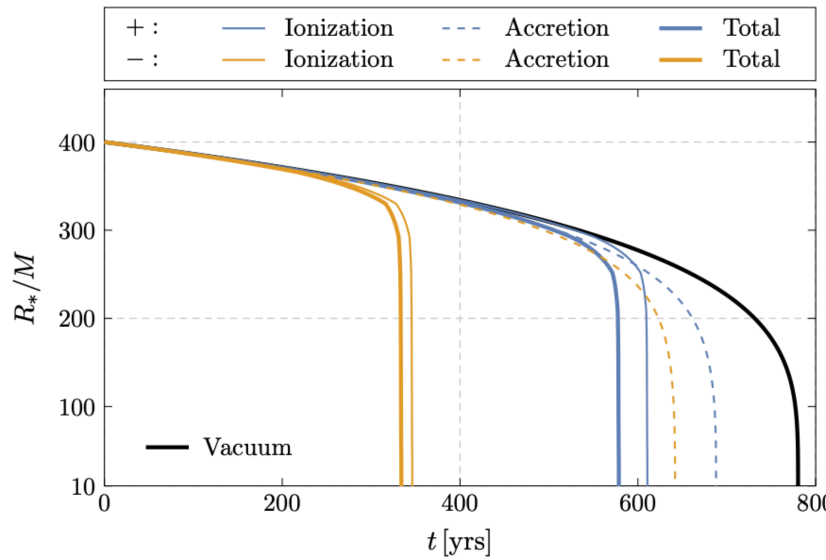
- Several effects induced by the presence of a boson cloud studied within **Newtonian approximations**:
  - **Floating/Sicking orbits** at specific orbital frequencies due to excitation of **resonances**
  - Different orbital evolution due to **dynamical friction** ("ionization"), **accretion** and **self-gravity** of the cloud



From: Baumann *et al*, PRD105, 115036 (2022)



From: Baumann *et al*, PRD101, 083019 (2020)



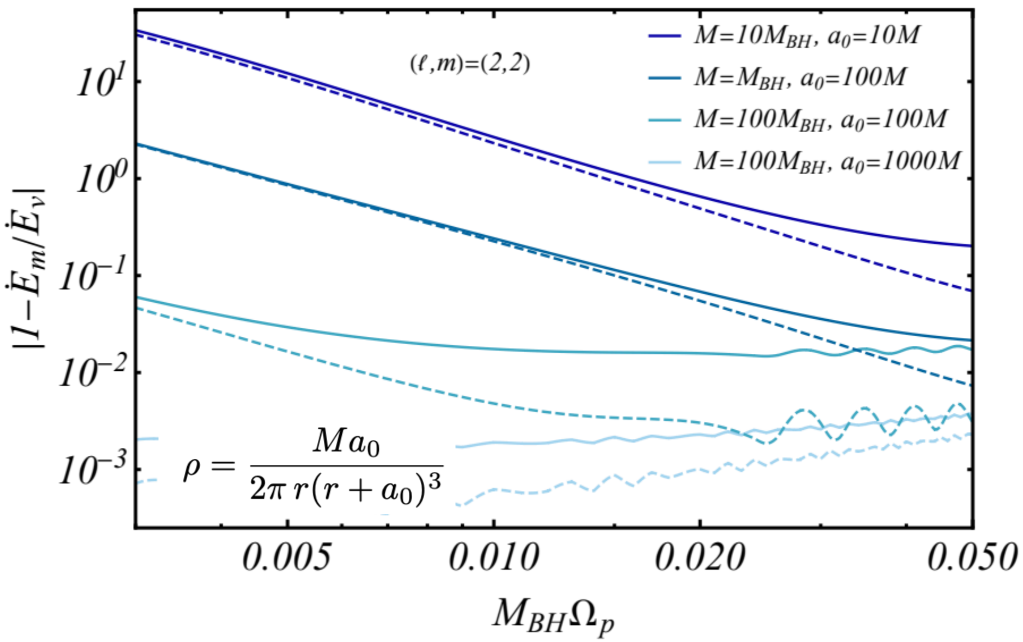
From: Baumann *et al*, PRD105, 115036 (2022)

I/EMRIs in DM environments: relativistic calculations

- Are (post)-Newtonian approximations enough? Probably not (?) for IMRIs/EMRIs
- Recent work made the first steps towards considering such systems in a **relativistic setup**: Cardoso *et al* '21-22; Figueiredo, Maselli & Cardoso '23

$$g^{(0)}_{\mu\nu}dx^{\mu}dx^{\nu} = a(r)dt^2 + b(r)^{-1}dr^2 + r^2 d\Omega^2\,, \qquad T^{\rm env(0)}_{\mu\nu} = \rho u_\mu u_\nu + p_r k_\mu k_\nu + p_t \Pi_{\mu\nu}$$

$$q = m_2/m_1 \ll 1 : \qquad g_{\mu\nu} = g^{(0)}_{\mu\nu} + q h_{\mu\nu}\,, \qquad T^{\rm env(0)}_{\mu\nu} = T^{\rm env(0)}_{\mu\nu} + q T^{\rm env(1)}_{\mu\nu}$$



From: Cardoso+, PRL129, 241103 (2022)

Time (C code) and frequency-domain (Mathematica) codes publicly available:

https://centra.tecnico.ulisboa.pt/network/grit/files/

https://github.com/masellia/SGREP/

(developers: Vitor Cardoso, Kyriakos Destounis, Francisco Duque, Rodrigo P. Macedo, Andrea Maselli)

I/EMRIs in boson clouds: relativistic calculations

RB & S. Shah, arXiv:2307.16093

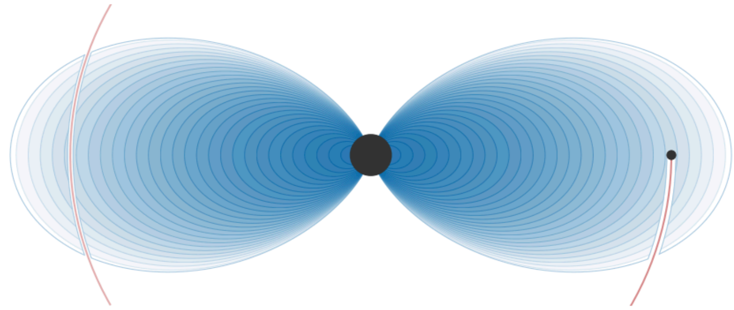
$$G_{\mu\nu} = 8\pi(T^{\Phi}_{\mu\nu} + T^{p}_{\mu\nu})\,, \qquad \Box\,\Phi - \mu^2\Phi = 0$$

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + q h_{\mu\nu} + \epsilon^2 g^{(2)}_{\mu\nu} + \ldots$$

$$\Phi = \epsilon(\Phi^{(1)} + q\Phi^{(q)}) + \ldots$$

$\epsilon \ll 1$

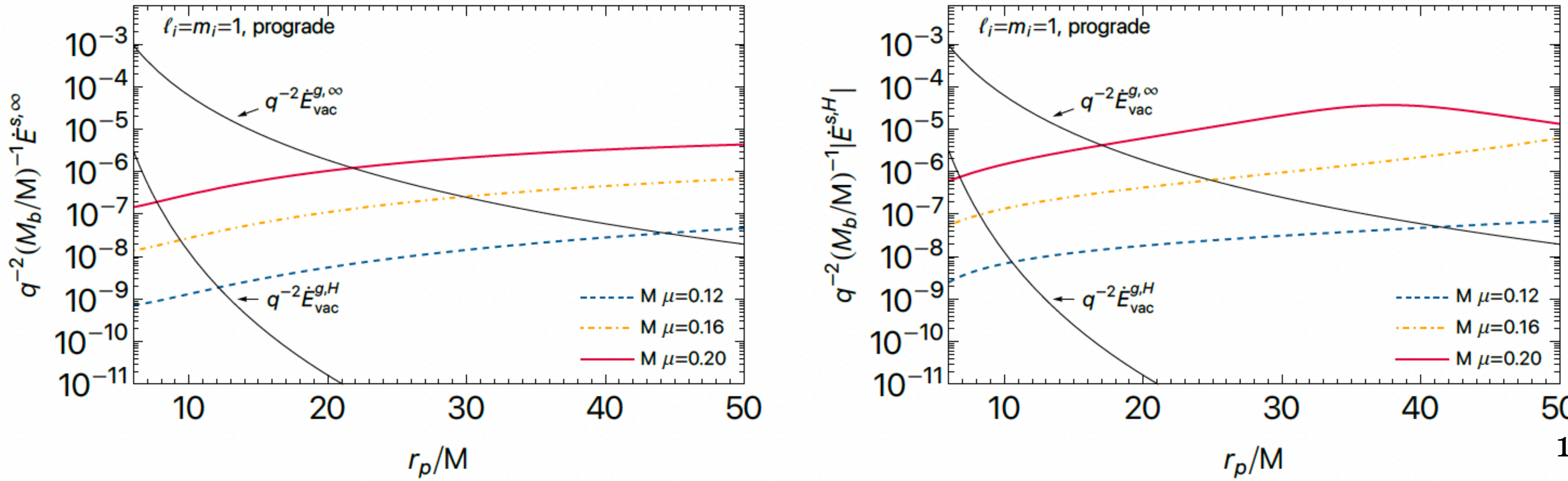
$q \ll 1$



From: Baumann *et al*, PRD105, 115036 (2022)

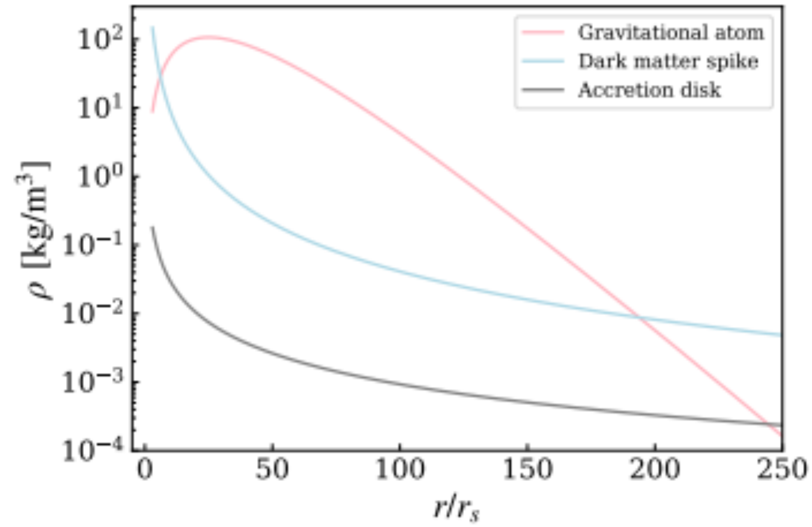
$$\mathcal{O}(q^0, \epsilon^0):\quad G_{\mu\nu}[g^{(0)}] = 0 \qquad\qquad \mathcal{O}(q^0, \epsilon^1):\quad \Box^{(0)}\,\Phi^{(1)} - \mu^2\Phi^{(1)} = 0$$

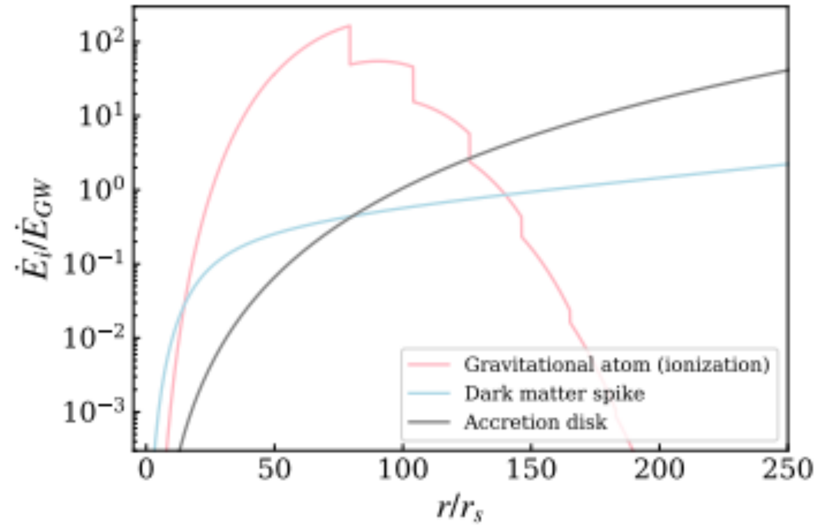
$$\mathcal{O}(q^1, \epsilon^0):\quad \delta G^{(0)}_{\mu\nu}[h] = 8\pi T^{p}_{\mu\nu}[g^{(0)}] \qquad\qquad \mathcal{O}(q^1, \epsilon^1):\quad \left(\Box^{(0)} - \mu^2\right)\Phi^{(q)} = S^{\Phi}[h, \Phi^{(1)}]$$



Possible WG/WP activity: model comparisons

- An activity we can start doing as a group: mock data challenges, model comparisons (also with beyond GR signals)
- Can we **distinguish** different dark matter models? How **accurately** do we need to model dark matter effects?





	Dark dress signal	Accretion disk signal	Gravitational atom signal
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

$m_1 = 10^5 M_\odot$

$m_2 = 10 M_\odot$

$d_L = 3.3\text{Gpc}$

SNR = 15

TABLE II. Logarithm of the Bayes factors, $\log_{10} \mathcal{B}$, comparing the evidence for the correct template that fits the signal, with an incorrect template.

From: P. S. Cole *et al*, arXiv: 2211.01362

Closing remarks

- The possibility to detect dark matter and/or primordial black holes with gravitational waves is exciting
- Subject requires large spectrum of expertise, from particle physics to cosmology and (of course) GW modelling
- A lot of development in the last few years, but still not at the level of providing accurate generic waveforms in some cases
- How accurately do we need to model DM effects in gravitational waveforms?
- What else should we be focusing on? Are our models too simplistic (e.g. interactions of DM with matter typically neglected)?

Thank you!