BLACK HOLE INSPIRALS IN (WAVE) DARK MATTER HALOS

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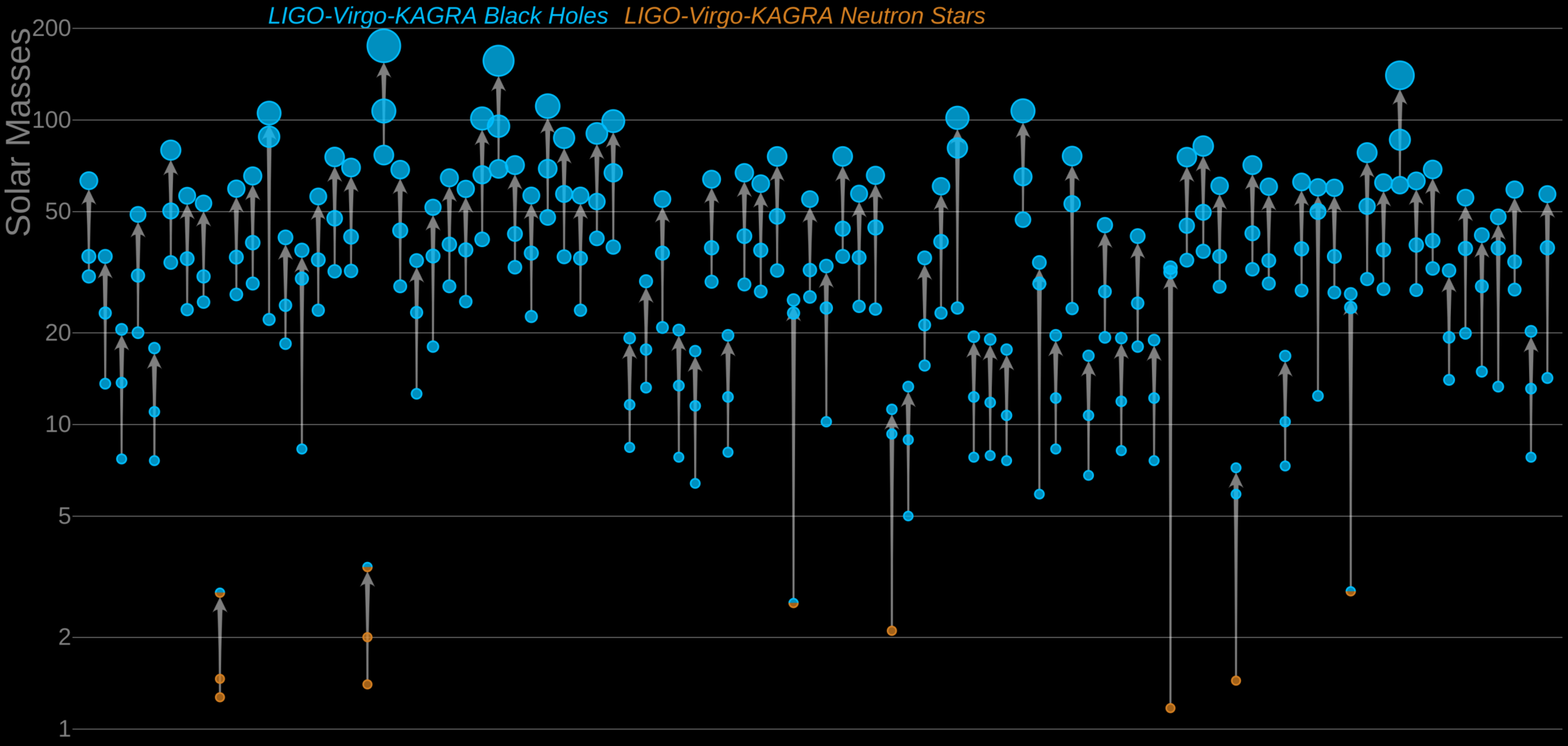
News from the Dark 9 (Marseille)

GW astronomy: Present and Future

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GWs: a new window to Fundamental Physics

GWs are sourced by the strongest gravitational fields in the Universe

GWs interact very weakly with intervening matter

GW detectors sense amplitude strain, most EM detectors sense energy flux

$$A \propto \frac{1}{d_L} \qquad F \propto \frac{1}{d_L^2}$$

"The grand challenges of contemporary fundamental physics—dark matter, dark energy, vacuum energy, inflation and early universe cosmology, singularities and the hierarchy problem—all involve gravity as a key component. And of all gravitational phenomena, black holes stand out in their elegant simplicity (...)"

From "Black holes, gravitational waves, and fundamental physics: a roadmap" [1806.05195] (750+ citations)

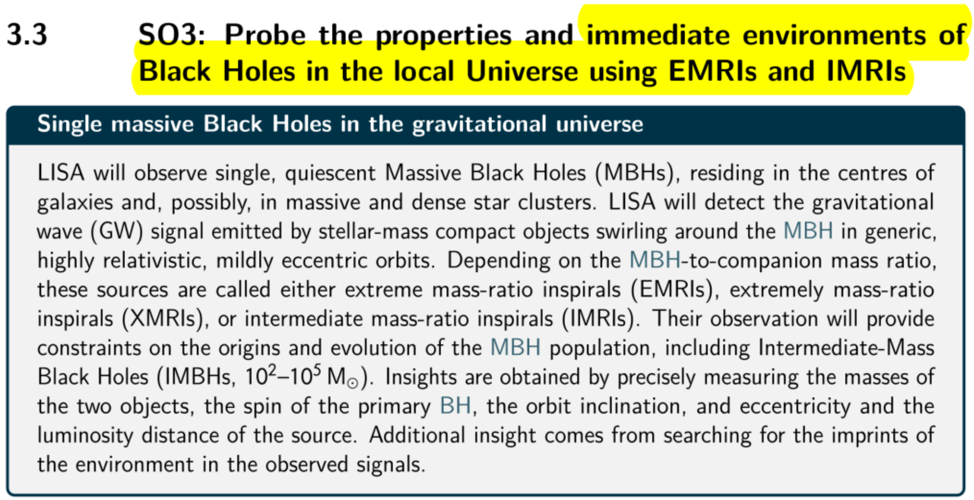
With Power comes Responsibility: better sensitivity asks for better modelling

Systematics from different waveform models can impact astrophysical inference with future detectors.
Up to 20% of sources with SNR>100 could have significant systematic bias.
Kapil *et al.* [2404.00090], and many others

Systematic biases from waveform mismodelling will lead to false deviations of GR!!
Chandramouli *et al.* [2410.06254], Garg *et al.* [2410.02910], Roy & Vicente [2410.16388] , and many others

The environments of massive BHs: Opportunities and Challenges

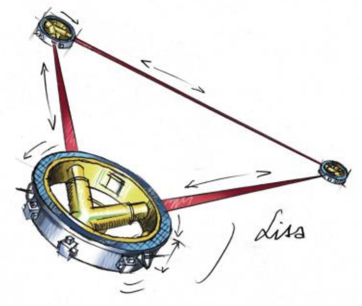
Future (2030s) GW observations will probe the environments of MBHs!! (A bless or a curse?)



3.3 SO3: Probe the properties and immediate environments of Black Holes in the local Universe using EMRIs and IMRIs

Single massive Black Holes in the gravitational universe

LISA will observe single, quiescent Massive Black Holes (MBHs), residing in the centres of galaxies and, possibly, in massive and dense star clusters. LISA will detect the gravitational wave (GW) signal emitted by stellar-mass compact objects swirling around the MBH in generic, highly relativistic, mildly eccentric orbits. Depending on the MBH-to-companion mass ratio, these sources are called either extreme mass-ratio inspirals (EMRIs), extremely mass-ratio inspirals (XMRIs), or intermediate mass-ratio inspirals (IMRIs). Their observation will provide constraints on the origins and evolution of the MBH population, including Intermediate-Mass Black Holes (IMBHs, 10^2–10^5 $M_\odot$). Insights are obtained by precisely measuring the masses of the two objects, the spin of the primary BH, the orbit inclination, and eccentricity and the luminosity distance of the source. Additional insight comes from searching for the imprints of the environment in the observed signals.



"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."

From LISA's red book [2402.07571]

"If the goal is to maximise the science yield of future missions, the community could be better served by shifting the focus from the source of GWs to its surroundings"

Zwick, Capelo, and Mayer [2209.04060]

What densities can EMRIs probe? A back-of-the-envelope calculation

$$\#_{\rm cycles} \sim f_{\rm gw} T_{\rm obs} \left(\frac{\dot{E}_{\rm DF} T_{\rm obs}}{E} \right) \gtrsim 1$$

$$\text{w/} \qquad E = -\frac{1}{2} m_2 v^2 \quad \text{and} \quad \dot{E}_{\rm DF} \approx -4\pi G^2 \frac{\rho m_2^2}{v} \Lambda(v, \cdot)$$

$$\boxed{\rho \gtrsim \frac{10^{-5}\,{\rm g/cm^3}}{\Lambda} \left(\frac{10^{-5}}{\epsilon} \right) \left(\frac{4\,{\rm yr}}{T_{\rm obs}} \right)^2}$$

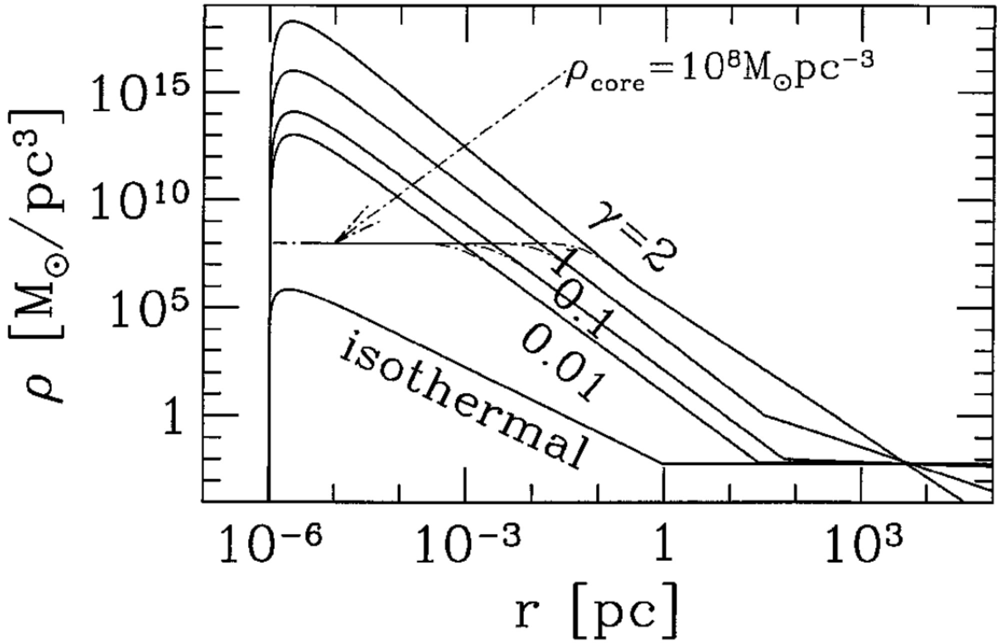
$$10^{-5}\,{\rm g/cm^3} \sim 10^{17}\,M_\odot/{\rm pc^3} \quad \Longrightarrow \quad \rho \gtrsim 10^{20} \rho_\odot^{\rm DM}$$

DM **dense** halos around BHs

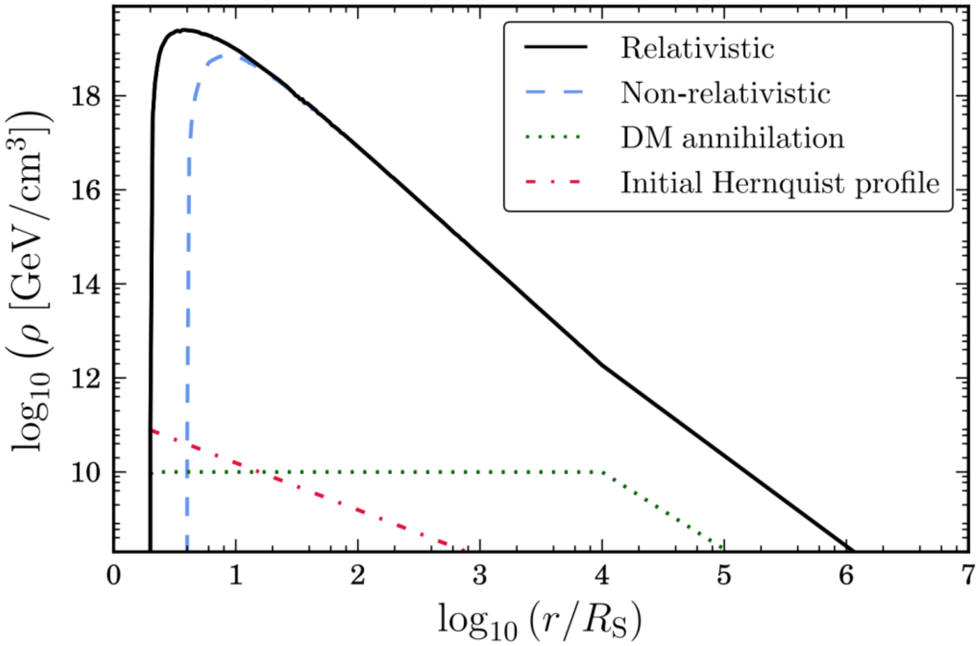
Particle DM spikes

Kinetically supported, model-dependent [initial DF, contraction dynamics, baryon feedback, ...]

DM density vanishes at $2R_S$. GR corrections lead to considerable enhancement of peak density!



Gondolo & Silk [9906.391]



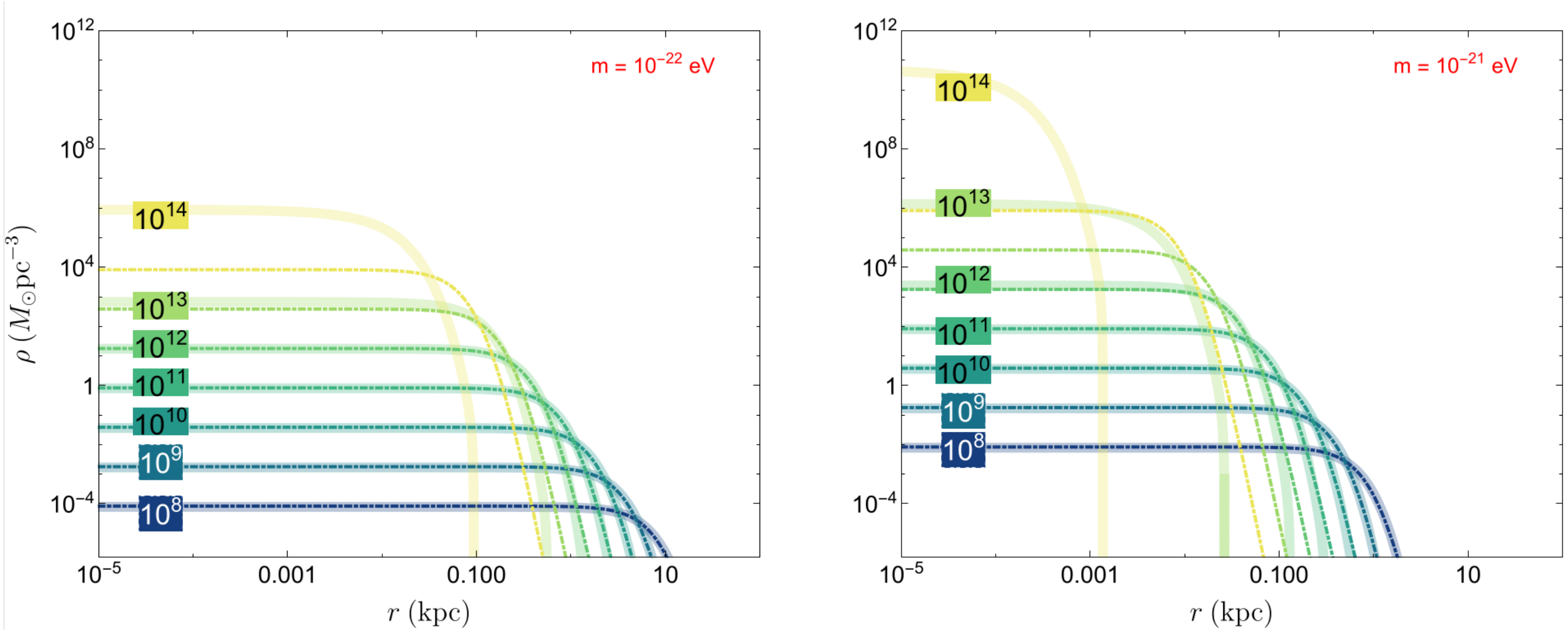
Sadeghian, Ferrer, Will [1305.2619]

Doped Boson Stars (aka ULDM solitons)

Wave-pressure supported. If it's to be the halo core, it's too dilute to be probed via EMRIs!

$$\rho(M_\phi \gg M) \sim 10\, M_\odot/\mathrm{pc}^3 \left(\frac{m_\phi}{10^{-22}\,\mathrm{eV}}\right)^6 \left(\frac{M_\phi}{10^9 M_\odot}\right)^4$$

$$\rho(M_\phi \lesssim 2M) \sim 10^{12}\, M_\odot/\mathrm{pc}^3 \left(\frac{\epsilon_\phi}{0.1}\right) \left(\frac{m_\phi}{10^{-21}\,\mathrm{eV}}\right)^6 \left(\frac{M}{10^{10} M_\odot}\right)^4 \qquad \tau_{\mathrm{accr}} \sim 10^3 \mathrm{yr} \left(\frac{10^{10} M_\odot}{M}\right)^5 \left(\frac{10^{-21}\,\mathrm{eV}}{m_\phi}\right)^6$$



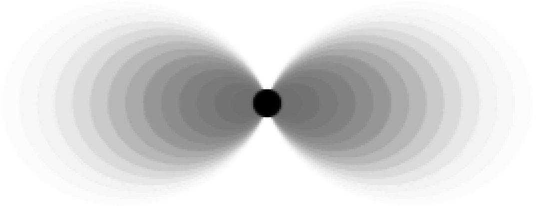
Davies & Mocz [1908.04790]

Superradiant Boson Clouds (aka gravitational atom states)

Wave-pressure supported, powered by the BH spin. Doesn't rely on the ultralight boson being DM.

BH superradiance powers the growth of gravitational atom states:

$$\phi_{n\ell m}(r \gg R_S) \approx C_{n\ell m} e^{-i(m_\phi + E_{n\ell m})t} Y_\ell^m(\theta, \varphi) \left(\frac{r}{r_B}\right)^\ell e^{-\frac{r}{2r_B}} L_{n-\ell-1}^{2\ell+1}\left(\frac{r}{r_B}\right) \quad + \quad \text{c.c.}$$



where

$$r_B \equiv \frac{n}{2Mm_\phi^2} \qquad \text{and} \qquad C_{n\ell m} \equiv \sqrt{\frac{\epsilon_{n\ell m} M}{r_B^3} \frac{(n-\ell-1)!}{2n(n+\ell)!}}$$

$$\bar{\rho} \sim 10^{19} M_\odot/\text{pc}^3 \left(\frac{\epsilon_\phi}{0.1}\right) \left(\frac{m_\phi M}{0.05}\right)^6 \left(\frac{10^6 M_\odot}{M}\right)^2$$

Environmental Effects on Waveforms

Adiabatic orbital evolution (two timescale expansion)

Stationarity + axisymmetry: geodesic $\gamma(\tau)$ w/ $\mathbf{u} \equiv d\gamma/d\tau$ has const of motion

$$\varepsilon \equiv -\mathbf{u} \cdot \boldsymbol{\partial}_t \qquad\qquad l_z \equiv \mathbf{u} \cdot \boldsymbol{\partial}_\varphi$$

Radiation reaction + environmental effects lead to $\mathbf{a} \equiv D\mathbf{u}/d\tau$,

$$\frac{d\varepsilon}{d\tau} = -\mathbf{a} \cdot \boldsymbol{\partial}_t \qquad\qquad \frac{dl_z}{d\tau} = \mathbf{a} \cdot \boldsymbol{\partial}_\varphi$$

If environmental effects are subleading, $\mathbf{a}_{\mathrm{env}}$ is all we need to get the waveform!

DF and Accretion in particle DM halos

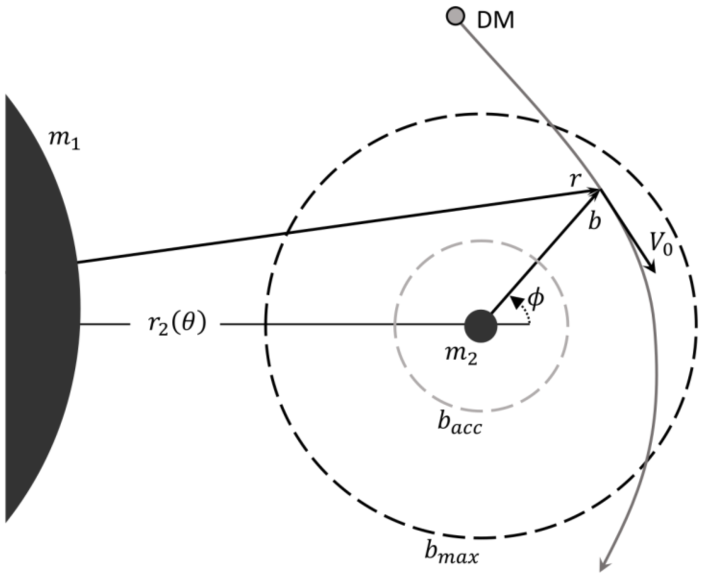
The 4-force in the small object's (free-falling) rest frame is

$$\frac{D(m\vec{u})}{d\tau} = m\vec{a} = \pi\mu \int b_{cr}^2(k)\vec{k} f(\vec{k}) d^3\vec{k} + 2\mu \int_{b>b_{cr}(k)} \cos^2[\phi_\infty(b,k)]\vec{k} d\nu$$

w/ differential collision rate $d\nu \equiv \nu(2\pi b\, db)(f(\vec{k})d^3\vec{k})$.

$$\Lambda \approx \xi_{<\nu} \ln \sqrt{\frac{b_{max}^2 + b_{90}^2}{b_{min}^2 + b_{90}^2}}$$

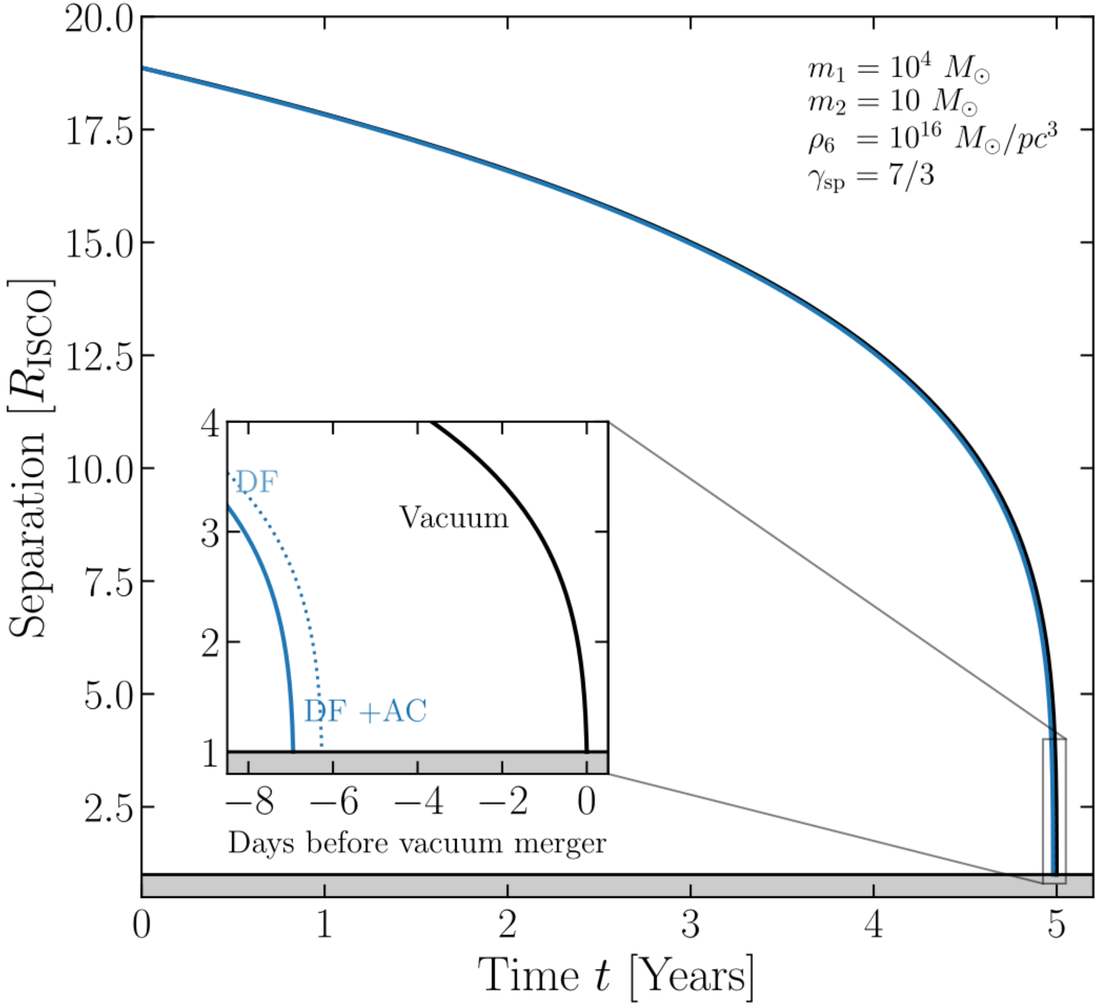
GR computation of the force in Traykova, Vicente, *et al.* [2305.10492]



Karydas, Kavanagh, Bertone [2402.13053]

Fully GR approach to EMRIs in DM spike
(in progress with T. Karydas and G. Bertone)

(Newtonian) de-phasing of IMRIs in particle DM halos



Karydas, Kavanagh, Bertone [2402.13053]

Tidal torques in wave DM halos

DF (from Hill sphere) and accretion onto the small BH are suppressed (due to the hierarchy of scales)

$$\phi = \phi^{(0)} + \epsilon\phi^{(1)} + \dots$$

$$\mathbf{g} = \mathbf{g}^{(0)} + \epsilon\mathbf{h} + \dots$$

$$\downarrow$$

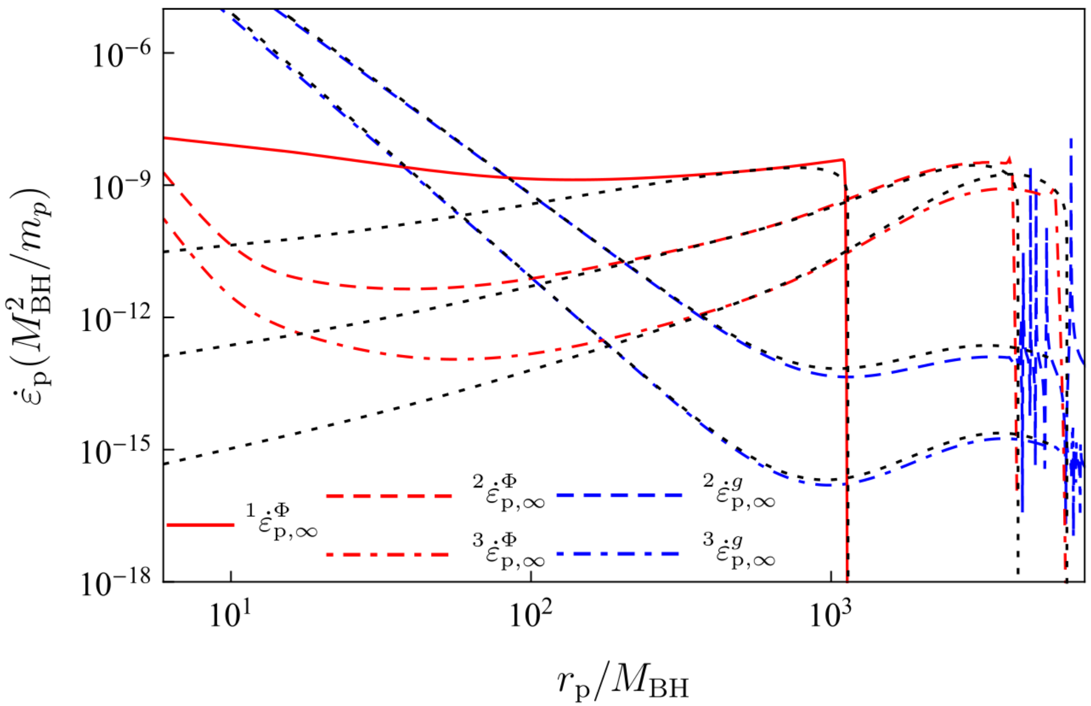
$$G_{\mu\nu}[\mathbf{g}^{(0)}] = 8\pi T^{\phi}_{\mu\nu}[\phi^{(0)}, \mathbf{g}^{(0)}]$$

$$(\Box_{\mathbf{g}^{(0)}} - m_\phi^2)\phi^{(0)} = 0$$

$$\downarrow$$

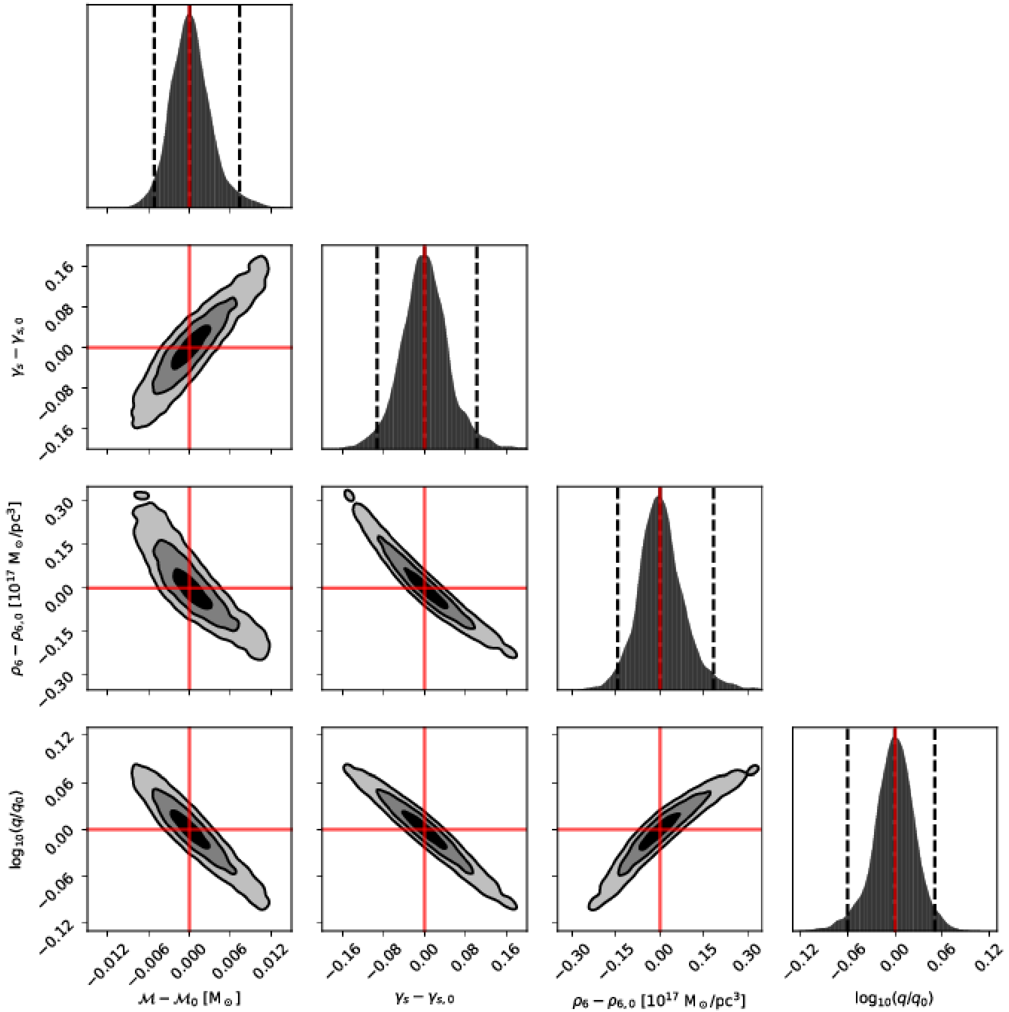
$$\delta G_{\mu\nu}[\mathbf{h}] = 8\pi T^{p}_{\mu\nu}[\mathbf{g}^{(0)}]$$

$$(\Box_{\mathbf{g}^{(0)}} - m_\phi^2)\phi^{(1)} = q\mathcal{S}[\Phi^{(0)}, \mathbf{h}]$$



Duque, Macedo, Vicente and Cardoso [*PRL*, 2312.06767]

Degeneracies and Distinguishability of Environments



Log$_{10}$ Bayes comparison

	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	—

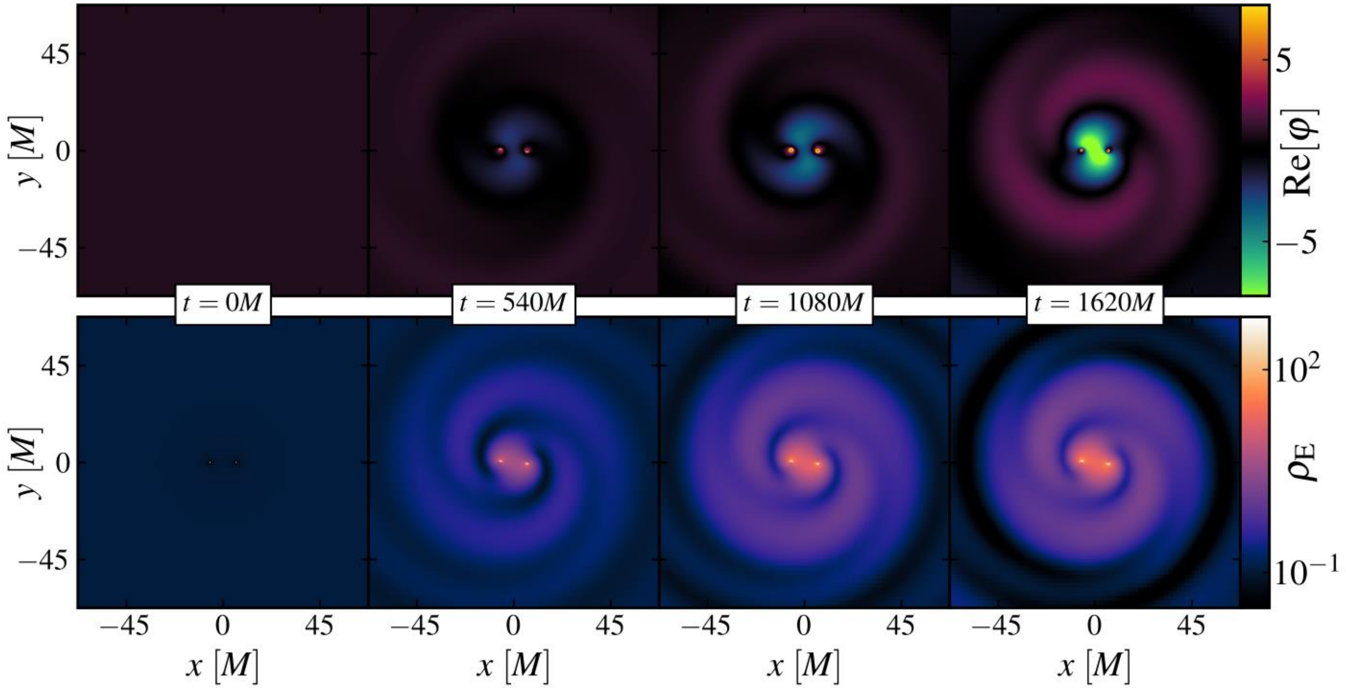
Cole *et al.* [*Nature Astron.*, 2211.01362]

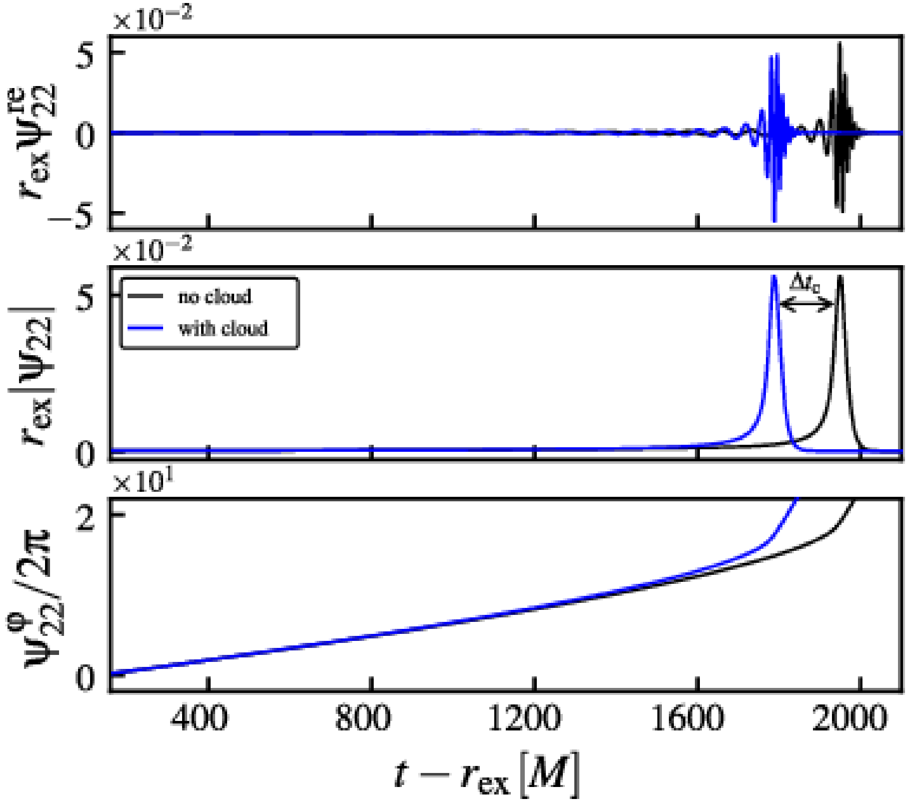
Constraints on scalar field environments from current observations

(in progress w/ S. Roy, J. Aurrekoetxea, K. Clough, and P. Ferreira)

Numerical Relativity waveforms (~ 10 cycles)

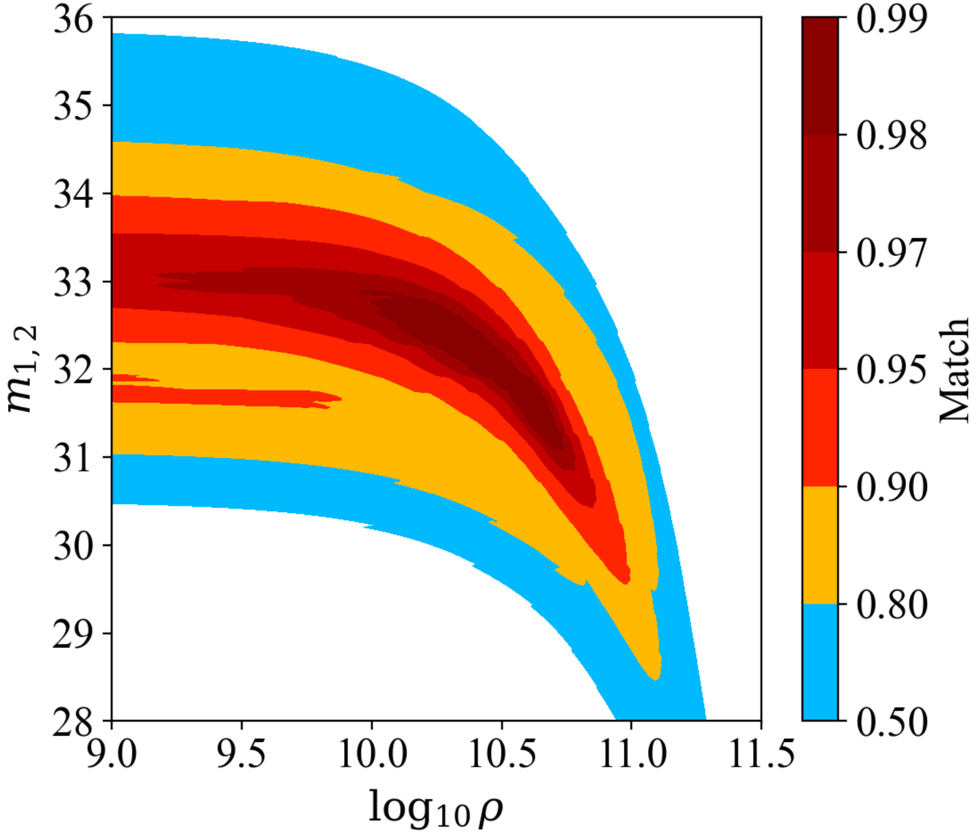
$$\rho M_t^2 \sim 10^{-9} \implies \rho \sim 6\times 10^6 \mathrm{g/cm^3} \left(\frac{10 M_\odot}{M_t}\right)^2$$





Bamber, Aurrekoetxea, Clough, and Ferreira [2210.09254]
Aurrekoetxea, Clough, Bamber, and Ferreira [*PRL*, 2311.18156]

(Newtonian) Analytic vs Numerical Relativity waveforms



Bayesian MCMC analysis (some contraints)

$$\mathrm{GW150914}\ [M_1 \sim 36M_\odot,\ M_2 \sim 29M_\odot,\ M_f \sim 62M_\odot,\ \mathrm{SNR} = 24] \implies \log_{10}\rho[\mathrm{g/cm}^3] \approx 6.6$$

$$\mathrm{GW151226}\ [M_1 \sim 14M_\odot,\ M_2 \sim 7.5M_\odot,\ M_f \sim 21M_\odot,\ \mathrm{SNR} = 13] \implies \log_{10}\rho[\mathrm{g/cm}^3] \approx 4.6$$

$$\mathrm{GW170608}\ [M_1 \sim 12M_\odot,\ M_2 \sim 7M_\odot,\ M_f \sim 18M_\odot,\ \mathrm{SNR} = 12] \implies \log_{10}\rho[\mathrm{g/cm}^3] \approx 4.3$$

$$\bar{\rho} \sim 10^6 \mathrm{g/cm}^3 \left(\frac{\epsilon_\phi}{0.1}\right)\left(\frac{m_\phi M}{0.05}\right)^6\left(\frac{10M_\odot}{M}\right)^2$$

Take away

2030s GW observations will probe the environments of massive BHs (including dense DM halos)

Preliminary results point to no degeneracy and distinguishability of different (DM) environments

Exquisite sensitivity demands same level of modeling (relativistic corrections most probably needed)

Many technical challenges on modelling and the analysis (e.g., LISA global fit) will need to be overcome in the next few years to realize the full potential of GW astronomy