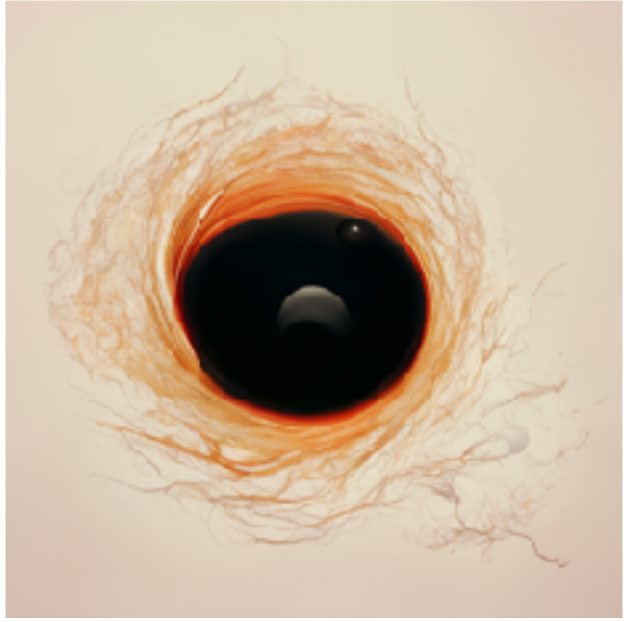
How dirty a black hole can be ?

@ The New Era of Multi-Messenger Astroparticle Physics

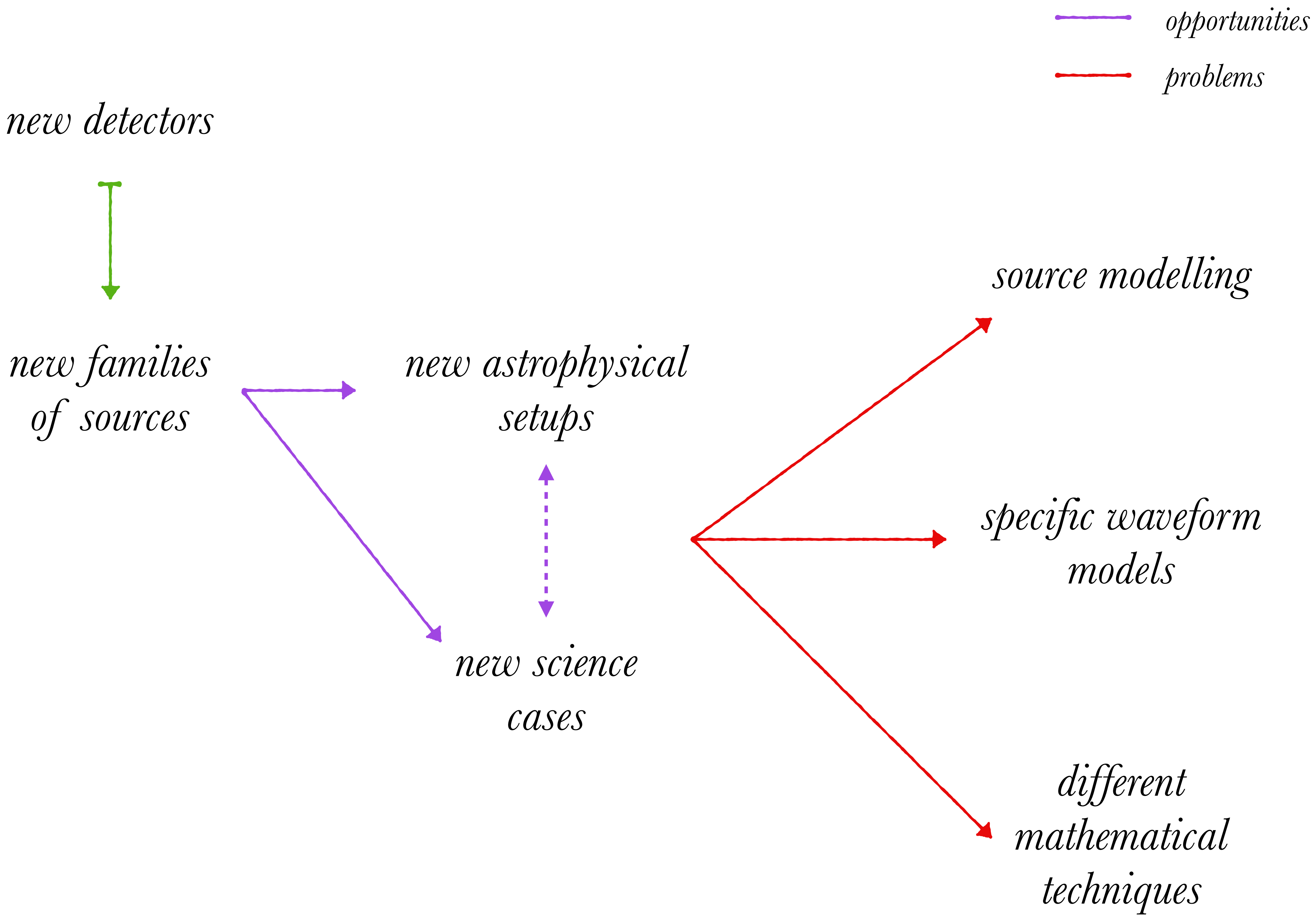
Institute For Fundamental Physics of the Universe
Trieste, 23 Feb 2024



Andrea Maselli

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Summary



opportunities

problems

new detectors

new families of sources

new astrophysical setups

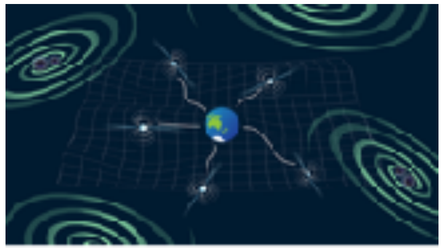
new science cases

source modelling

specific waveform models

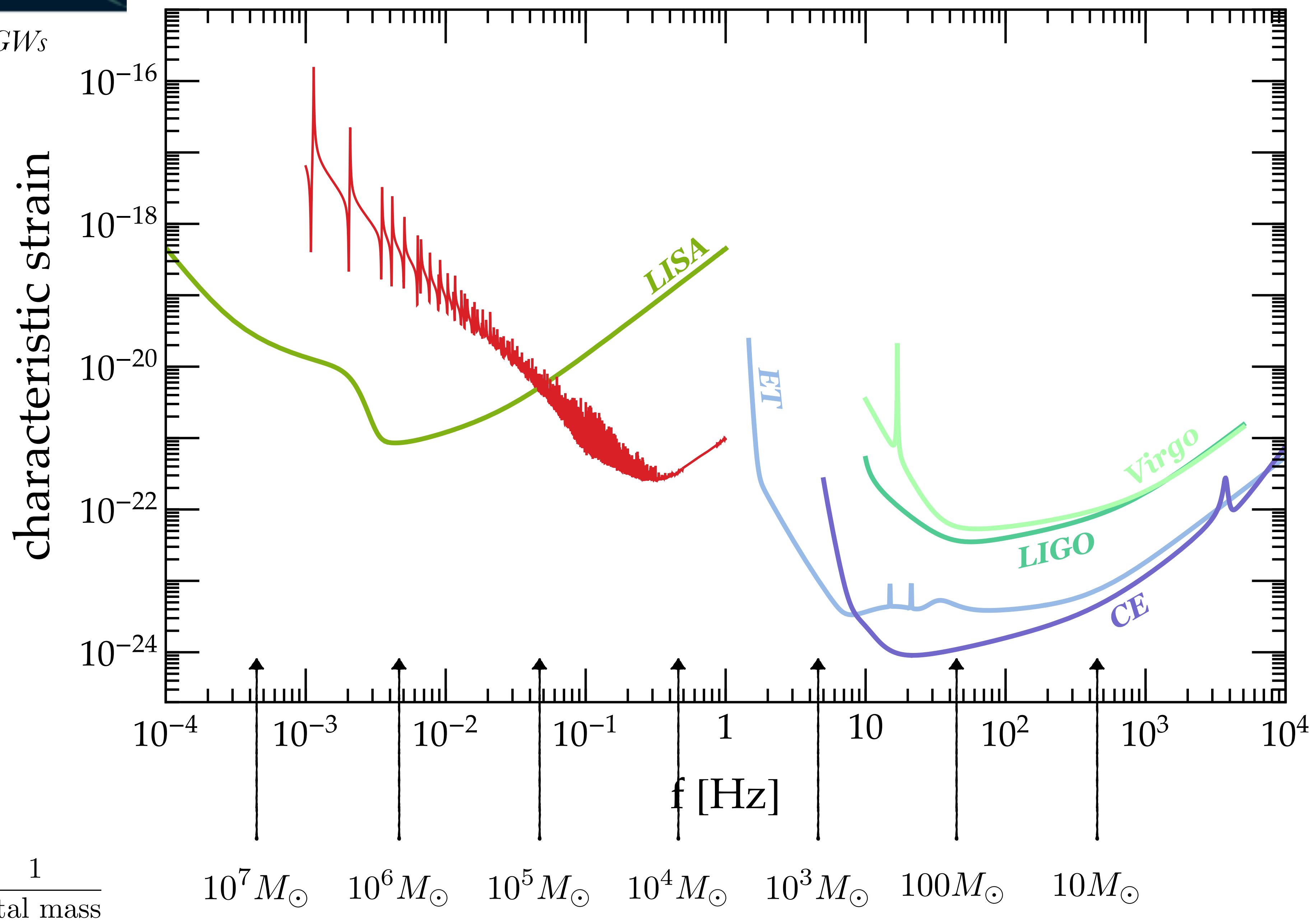
different mathematical techniques

Scales & new families



nanoHz GWs

Binary evolution of compact sources

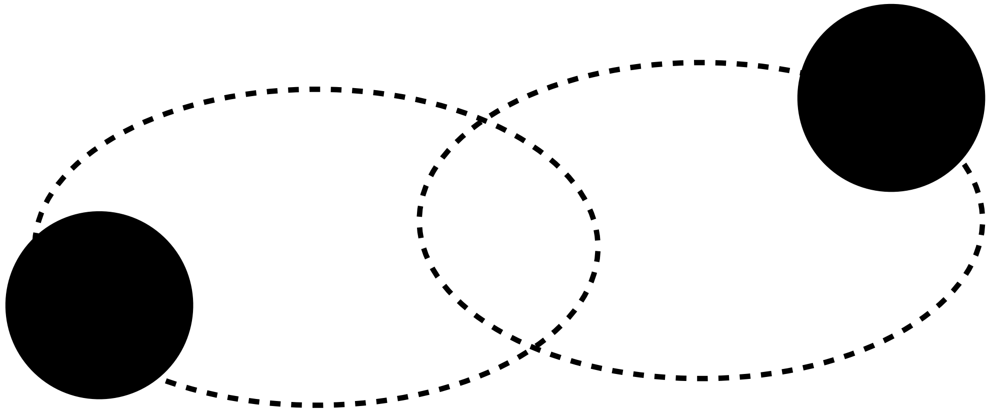


$$f_{\text{merger}} \sim \frac{1}{\text{total mass}}$$

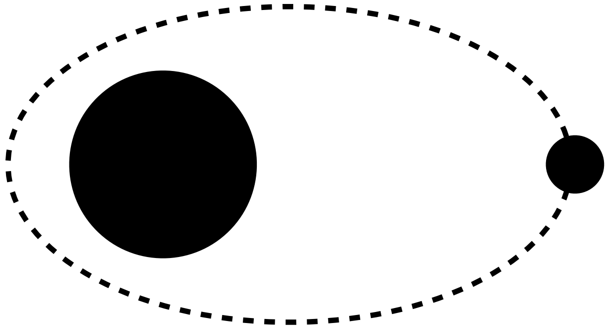
Scales & new families

LISA will observe old-and-new families of binaries

- Huge potential for new science cases and new challenges (problems)



comparable mass binaries



(very) asymmetric binaries, i.e. EMRI, IMRI

- Challenges for waveform modelling of systems on different scales are different
  - different mathematical approaches to model different sources (post-Newtonian, Self Force, ….)
  - astro-physical set up, orbital features, interaction with environment

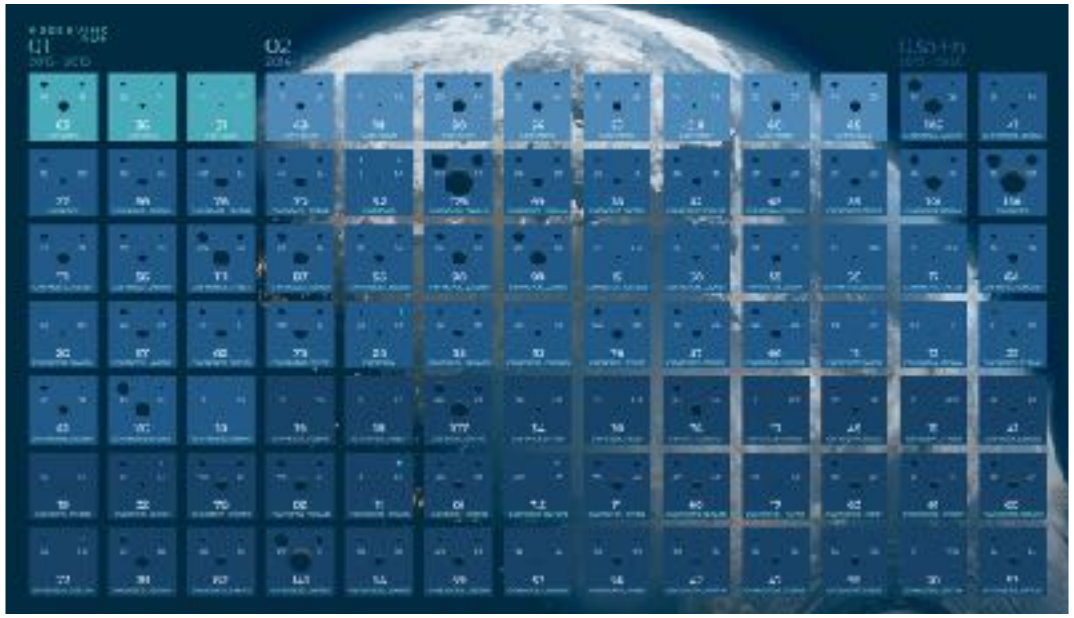
Scales & new families

90+ events observed so far from LVK, spanning a relatively small interval of mass ratios $q \sim 1:30$

- Space detectors expected to beat down such value by several orders of magnitudes

$$q \sim 10^{-6} - 10^{-7}$$

- dynamics dictated by q, with the duration of the inspiral & number of cycles growing as q decreases



LVK, GWTC 3 2111.03605

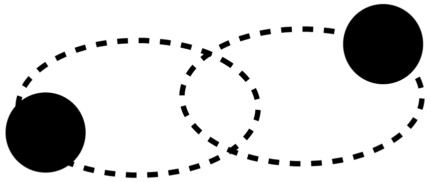
Science potential

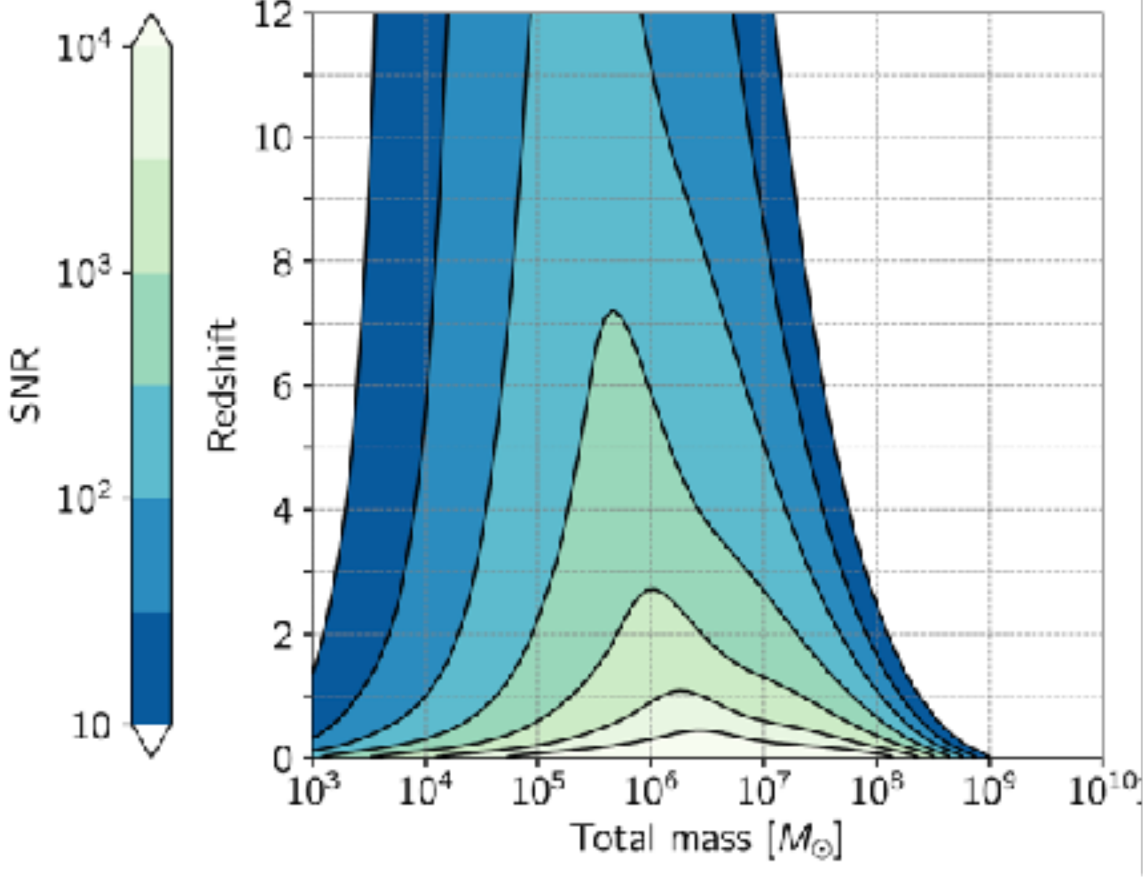
1 Slow inspiral phase which could allow to continuously observe AB for very long periods, from months to years

2 dynamical evolutions with an uncommon richness, with resonances, large eccentricities and off-equatorial orbits, etc.

3 astro-fundamental physics setups

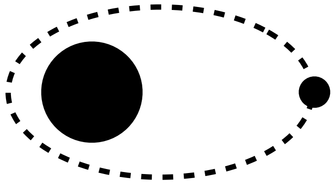
Every family has problems

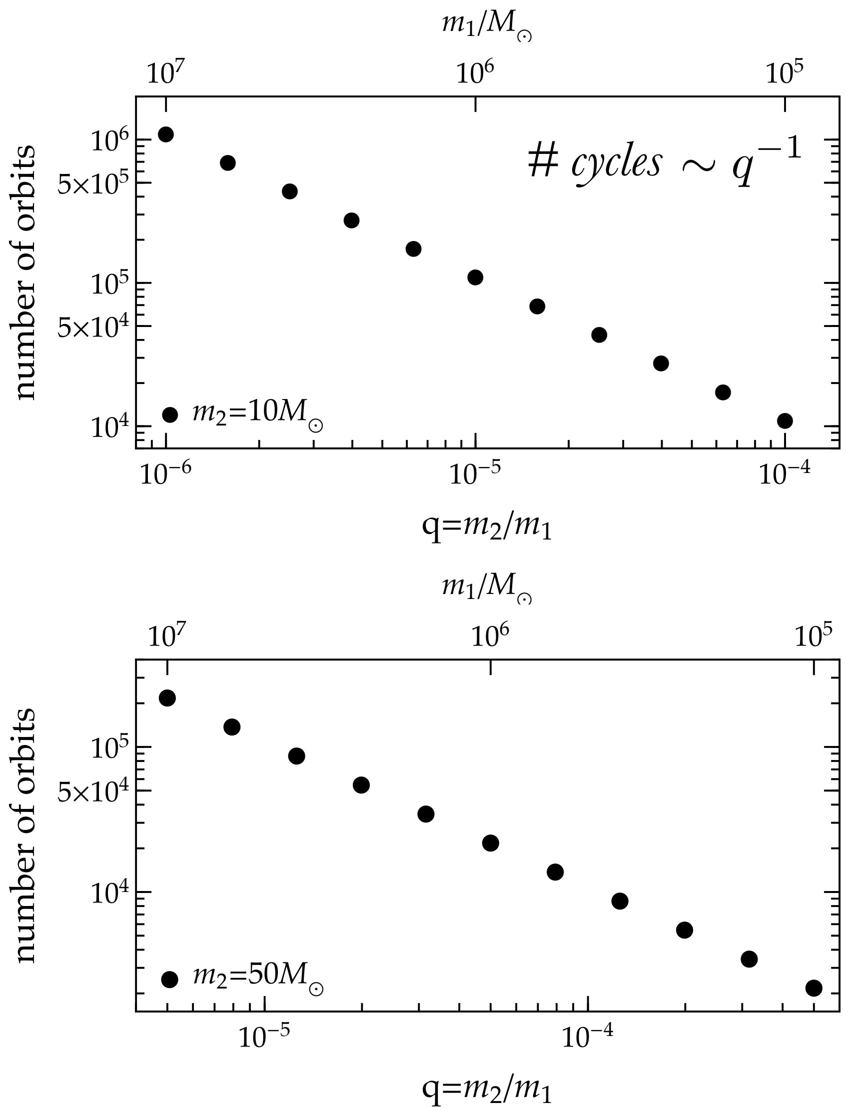




M. Colpi + 2402.07571 (2024)

loudest events in the universe



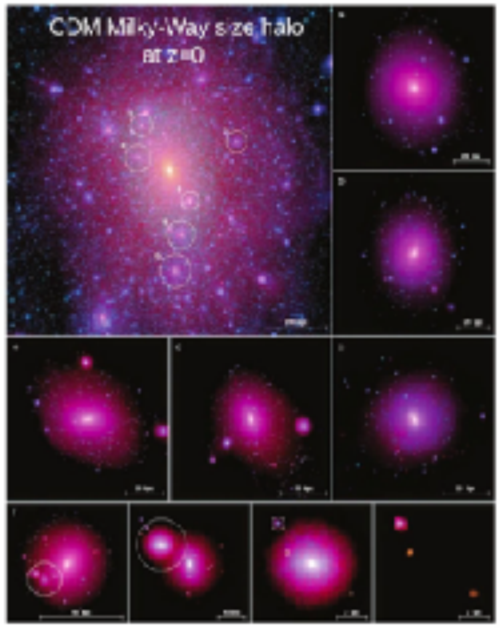


dynamics dictated by the mass ratio $q = \dfrac{m_2}{m_1} \ll 1$

Why so dirty?

GW sources evolve in a variety of gas/matter contents/fields, which may leave detectable imprints on GW → *changes in generation and propagation of GWs*

- Can we infer properties on the environment in which binaries evolve?
- Are vacuum templates safe against (astrophysical) systematics?



V. Springel et al., Mon. Not. Roy. Astron. 391 (2008)

G. Bertone et al., Nature 562, 7725 (2008)

massive BH evolve in DM-rich environment, within galaxies

binaries can assemble and evolve in accretion disks

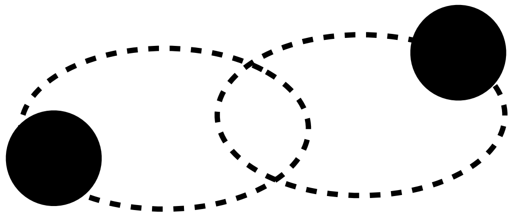
⟷

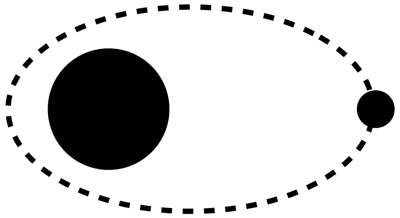
particle physics laboratories

How do we describe dirty BHw?

Different approaches to compute GW signals

$\tilde{h}(f) = Ae^{i\psi_{\rm GW}}$





post-Newtonian theory

speed of light expansion $\frac{v}{c}$

$$\psi_{\rm GW} \propto (m\pi f)^{-5/3}\Big[1 + \frac{(m\pi f)^{2/3}}{c^2} + \frac{\cdots}{c^3} + \cdots$$

- ○ breaks before the merger
- ○ good for comparable mass binaries
- ○ bad for asymmetric binaries

(some) dirty BH models

Self-Force theory

mass ratio expansion $q = \frac{m_2}{m_1} \ll 1$

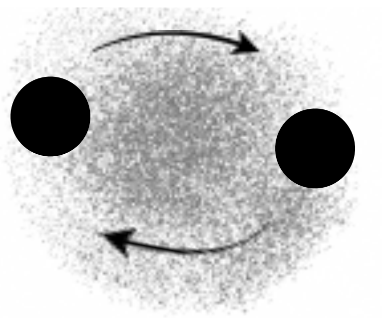
$$\psi_{\rm GW} \propto \underset{\mathcal{O}(1/q)}{\underset{\downarrow}{\psi_{\rm 0PA}}} + \underset{\mathcal{O}(1)}{\underset{\downarrow}{\psi_{\rm 1PA}}} + \dots$$

- ○ fully relativistic
- ○ good for asymmetric binaries
- ○ bad for comparable mass binaries (but)

(almost) no dirty BH model

Which family?

The environment affects the binary orbital motion



→ *changes generation and propagation of GWs*

- ○ different effects can be included adding specific corrections the post-Newtonian waveforms $h = Ae^{i\psi_{\rm GW}}$

Cardoso & Maselli AA 644, A147 (2020)

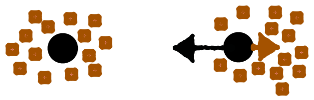
$$\psi_{\rm GW} \propto (m\pi f)^{-5/3}\left[vacuum + \delta\psi_{\rm env}\right]$$

- ○ generic correction due to the binary environment

$$\delta\psi_{\rm env} \propto \rho_{\rm env}(\pi m f)^{-\gamma}$$

density of the medium

$\gamma = 11/3$ | $\gamma = 3$ | $\gamma = 2$



gravitational drag | *accretion* | *gravitational pull*

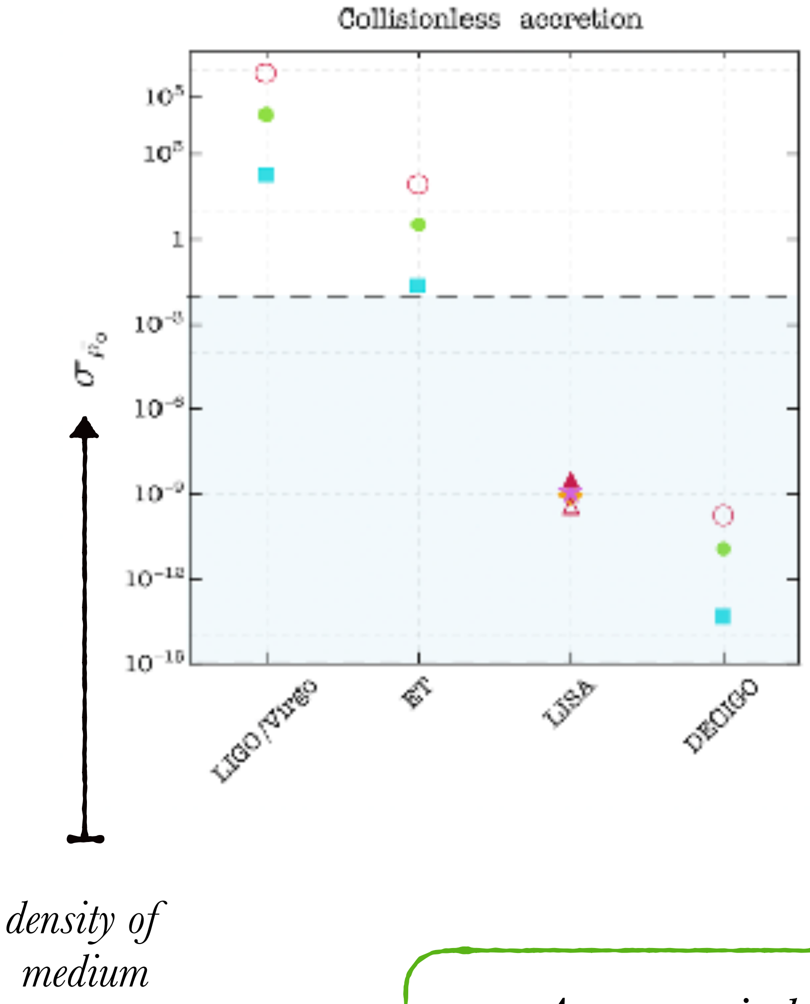
- ○ GW can be used to bound the density of the matter distribution in which binary evolve

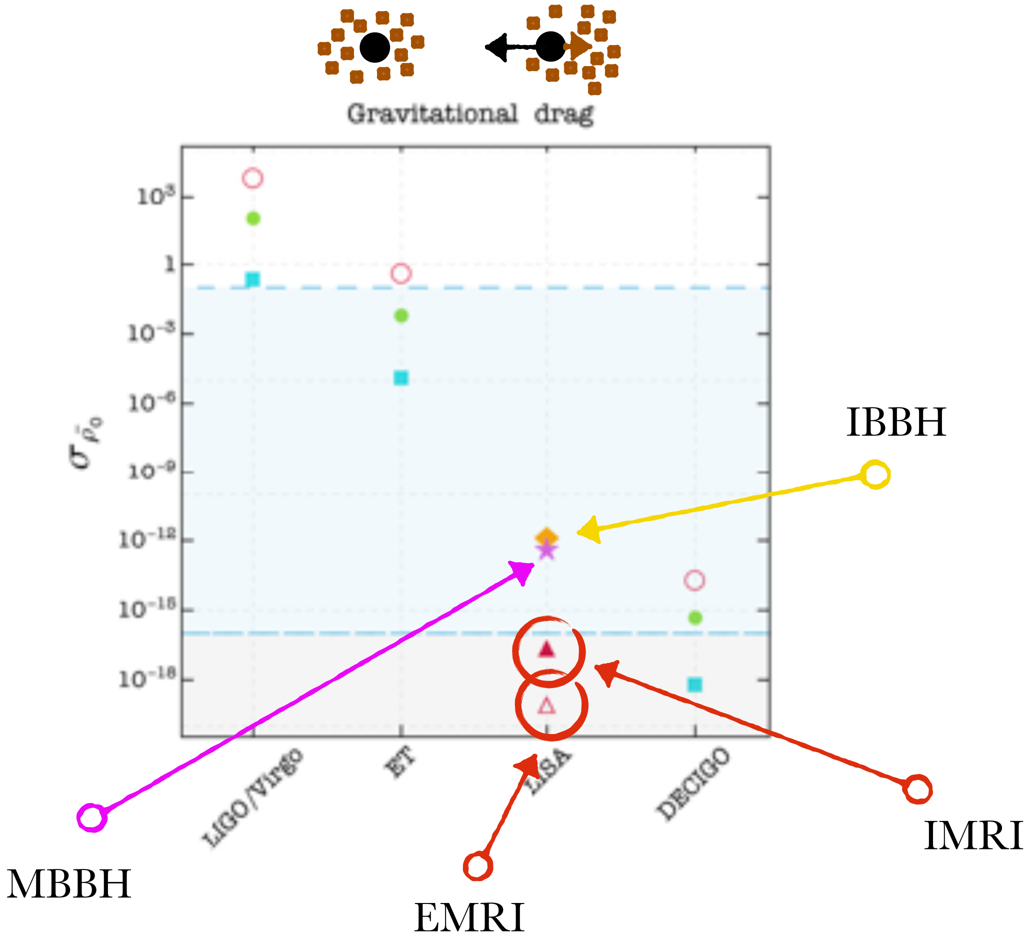
Which family?

Constraints on the environment’s density from different effects & sources & detectors

V. Cardoso & A. M., A&A 644, A147 (2020)

- environmental effects typically contribute at low frequencies
- astrophysical setups matter! (overdensities)





Asymmetric binaries work (really) well

EMRIs in nuce

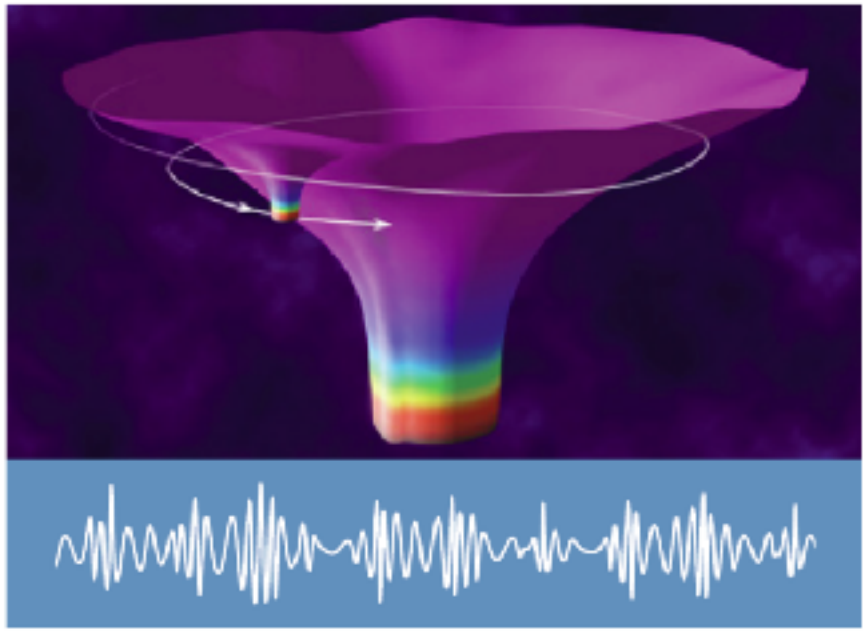
Binary systems with a stellar-mass body inspiralling into a massive BH

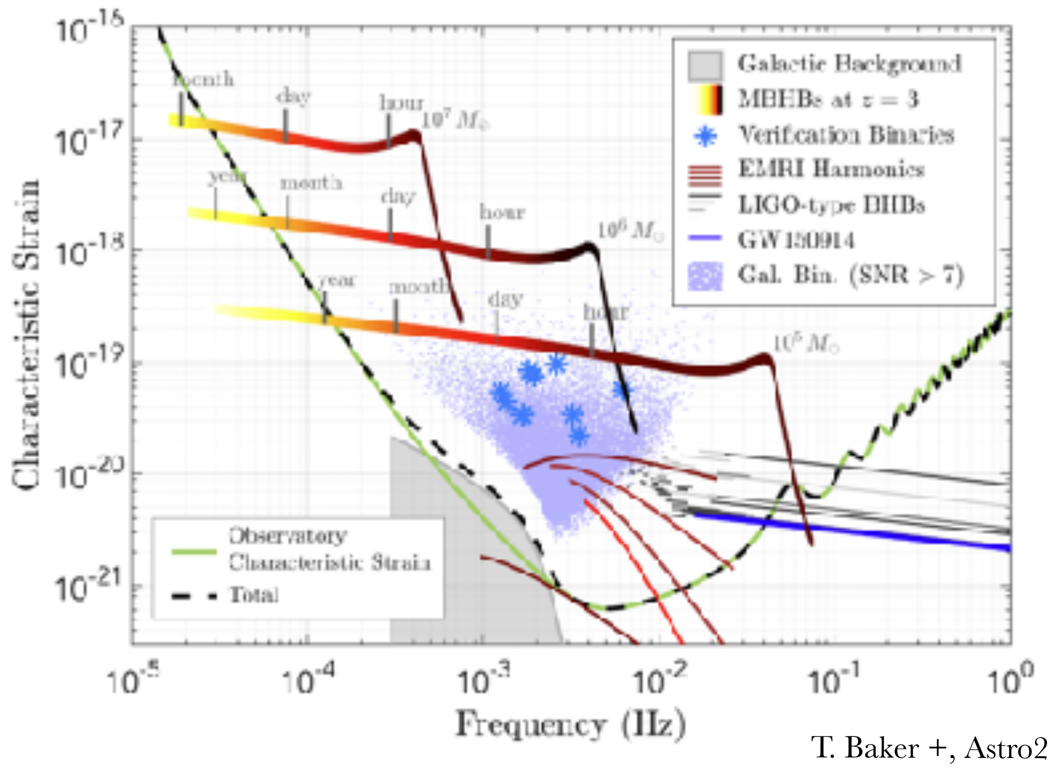
- Primary with $M \sim (10^4 - 10^8) M_\odot$

- Secondary such that the mass ratio

$$q = m_p/M \sim (10^{-6} - 10^{-3})$$

Key point of theoretical description



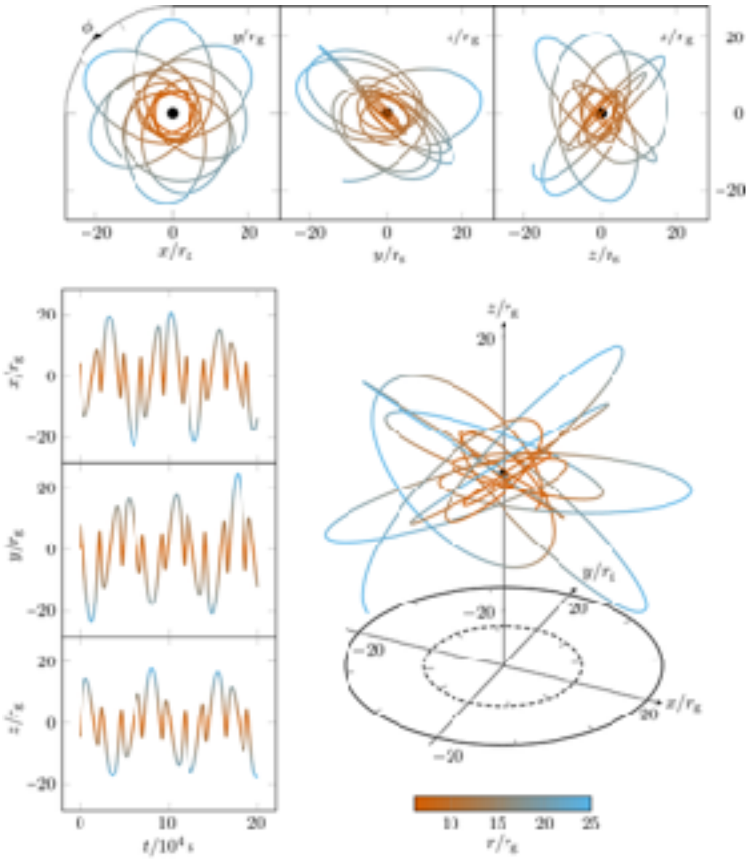


T. Baker +, Astro2020 1907.06482 (2019)

- Emit GWs in the mHz band, golden targets for LISA

EMRIs in nuce

EMRIs provide a rich phenomenology, due to their orbital features



Berry +, Astro2020 1903.03686 (2019)

- ○ Non equatorial orbits
- ○ Eccentric motion
- ○ Resonances
- ○ Complete $\sim (10^4 - 10^5)$ cycles before the plunge

blessing & **disguise**

Tracking EMRIs for O(year) requires accurate templates

Very appealing to test fundamental & astro-physics

Precise space-time map and accurate binary parameters

Accretion disks

Accretion disks induce torques that can affect EMRI trajectories

L. Speri + PRX 143, 021035 (2023)

- radiatively efficient, Newtonian, thin accretion-disk models

surface density

$$\Sigma_\alpha \sim \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{f_{\rm Edd}}{0.1}\frac{0.1}{\epsilon}\right)^{-1} \left(\frac{r}{10 m_1}\right)^{3/2}$$

$$\Sigma_\beta \sim \left(\frac{\alpha}{0.1}\right)^{-4/5} \left(\frac{f_{\rm Edd}}{0.1}\frac{0.1}{\epsilon}\right)^{3/5} \left(\frac{m_1}{10^6 M_\odot}\right)^{1/5} \left(\frac{r}{10 m_1}\right)^{-3/5}$$

$\alpha \sim (0.01, 0.1)$

viscosity

height

$$H \sim \left(\frac{f_{\rm Edd}}{0.1}\frac{0.1}{\epsilon}\right) m_1$$

- Subdominant compared to GW emission but potentially observable

amplitude

slope

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

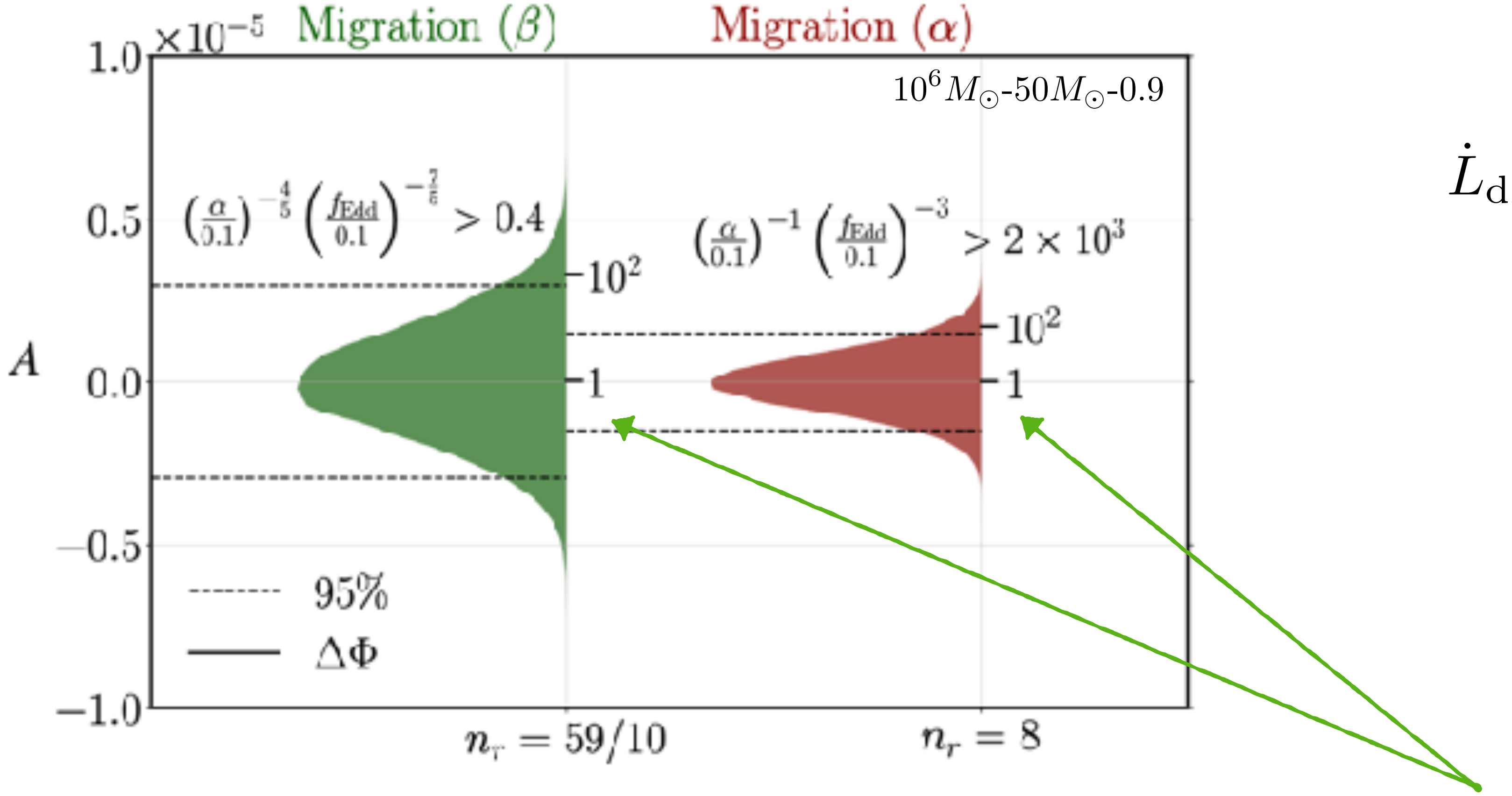
$$\dot{L}_{\rm disk} = A \left(\frac{r}{10 M_1}\right)^{n_r} \dot{L}^{(0)}_{\rm GW}$$

type I migration

Accretion disks

vacuum injection v.s. recovery + agnostic

Are agnostic templates useful?



posterior on the amplitude for agnostic search
(vacuum injection v.s. recovery + accretion)

agnostic model

$$\dot{L}_{\rm disk} = A \left(\frac{r}{10 M_1} \right)^{n_r} \dot{L}_{\rm GW}^{(0)}$$

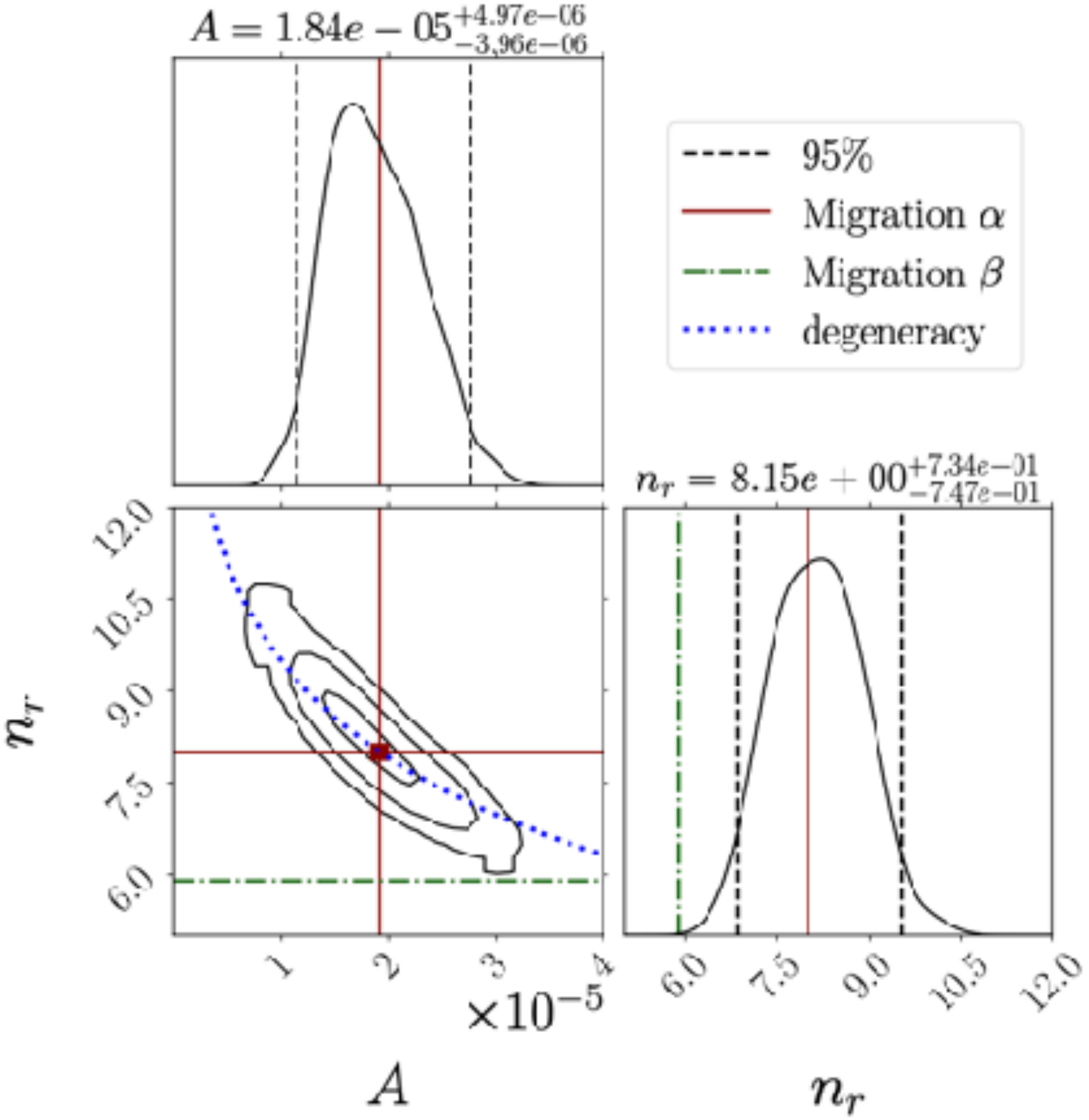
amplitude such that the dephasing
vacuum injection v.s. recovery + accretion
$\Delta\Phi \gtrsim 1$

- Torques may not be detectable even if dephasing larger than $\Delta\Phi \gtrsim 1$
- Torques may not be detectable for typical value of the disk viscosity α

Accretion disks

injection + *accretion v.s. recovery* + *accretion*

Detectability of torques

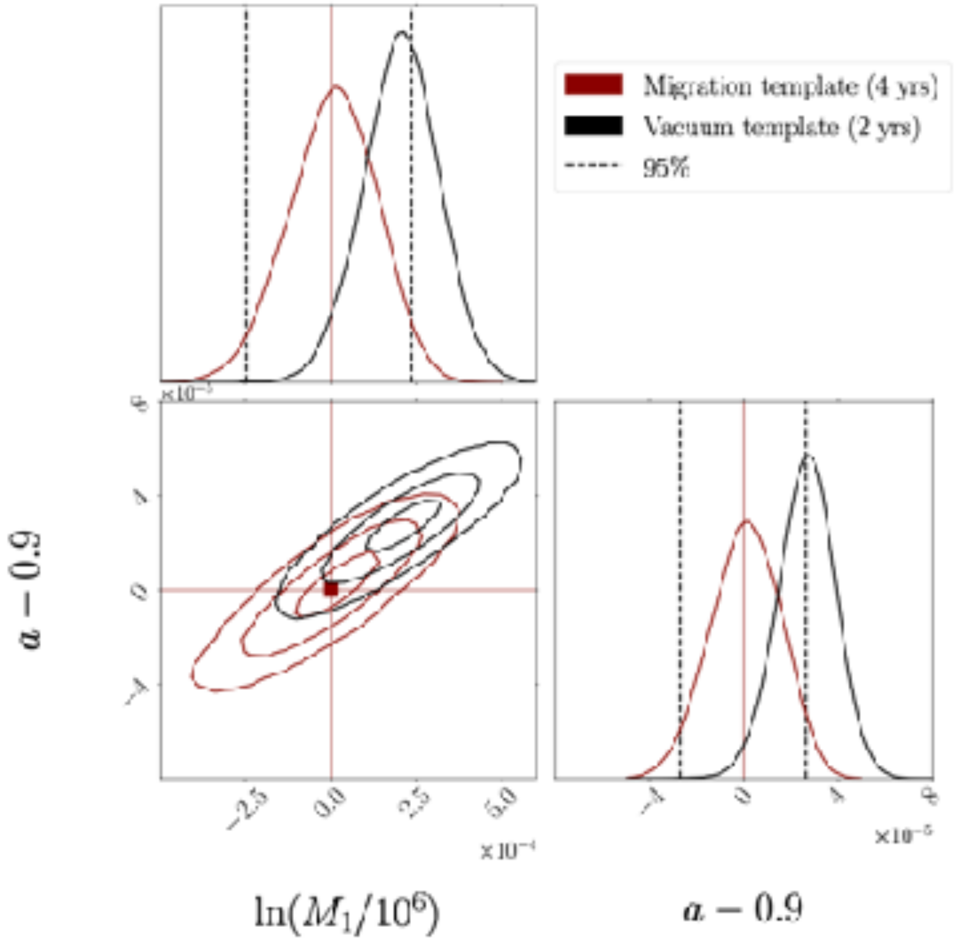


- Strong correlation between amplitude and slope
- Posterior inconsistent with *A=0* at more than 3σ
- Torque can be detected by agnostic template with a power-law in the radius

- If we have a physical model, (A,n_r) can be mapped to viscosity & efficiency of the disk

Accretion disks

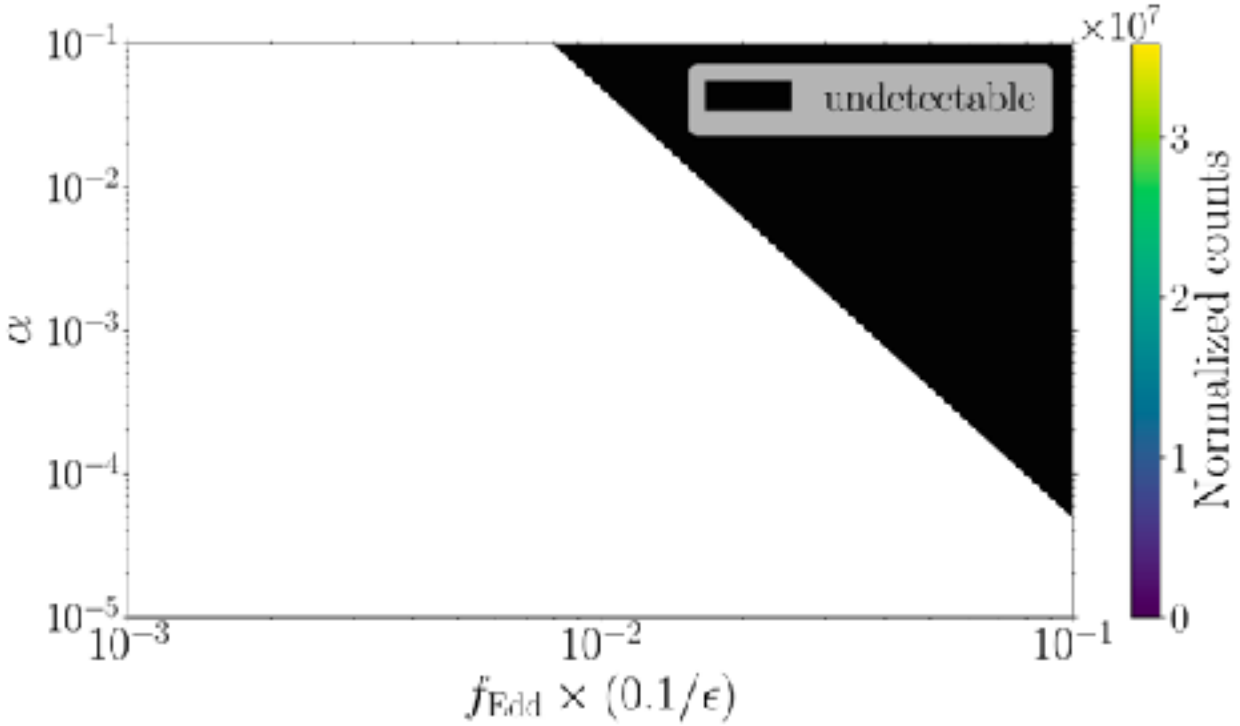
Parameter's bias due to mismodeling of the 'true' signal



- Good match only on a shorter portion of the signal
- Bias in the source intrinsic parameter is small → *won't affect astro-conclusions*
- problematic for 'small' deviations, like beyond GR corrections

Accretion disks: multi-messenger

Map to fundamental parameters of the disk

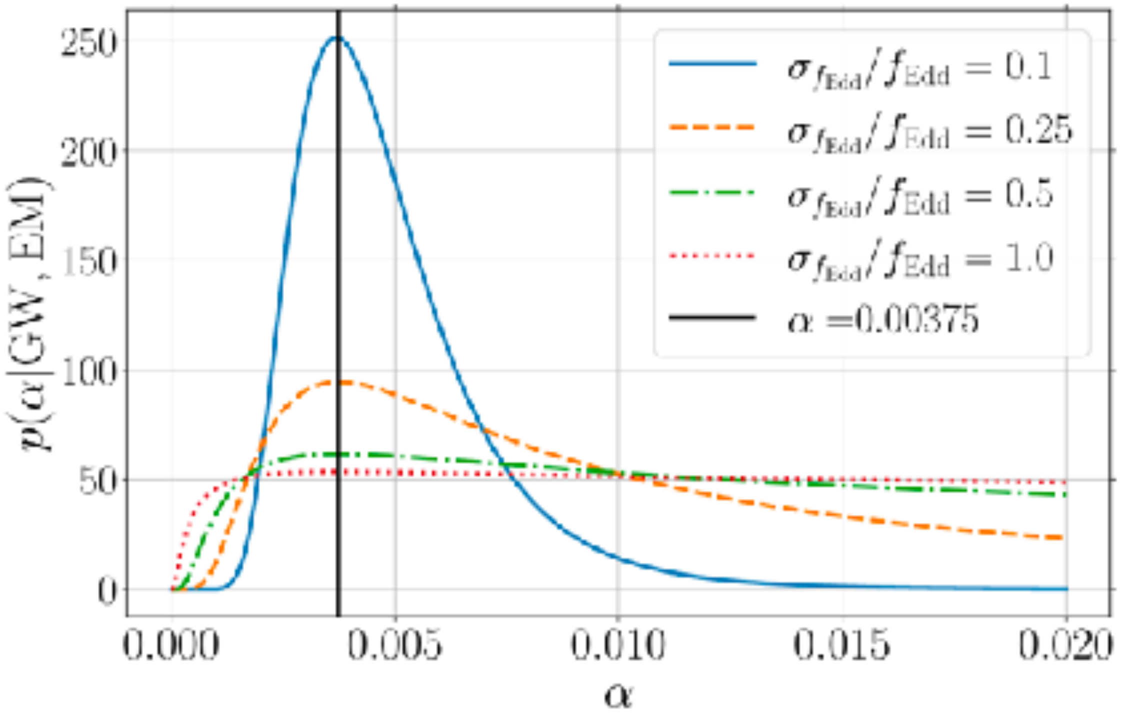


$$A = \mathcal{C}\left(\frac{\alpha}{0.1}\right)^{n_\alpha}\left(\frac{f_{\rm Edd}}{0.1}\frac{0.1}{\epsilon}\right)^{n_{f_{\rm Edd}}}\left(\frac{M_1}{10^6 M_\odot}\right)^{n_{M_1}}$$

joint constraints on density & accretion ratio

measurement of the bolometric luminosity can help breaking the degeneracy

$f_{\rm bol} = f_{\rm bol}(\alpha, \epsilon)$

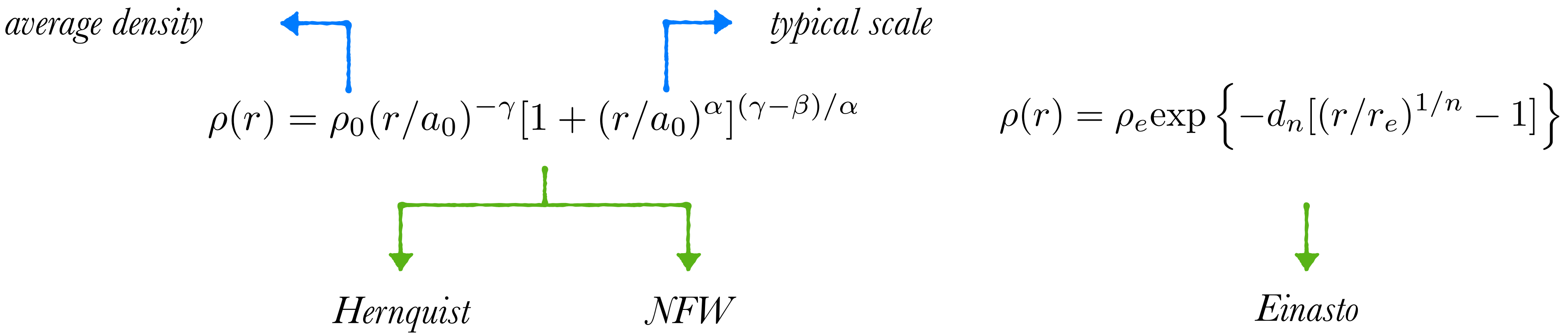


The curious case of a rigorous spacetime

How do we make a BH (relativistically) dirty?

V. Cardoso+, PRD Lett. 105, L061501, (2022)
V. Cardoso +, PRL 129, 241103, (2022)
E. Figueiredo +, PRD 107, 104033, (2023)
N. Speeney +, 2401.00932 (2024)

- Numerical solution for BHs in DM rich environments



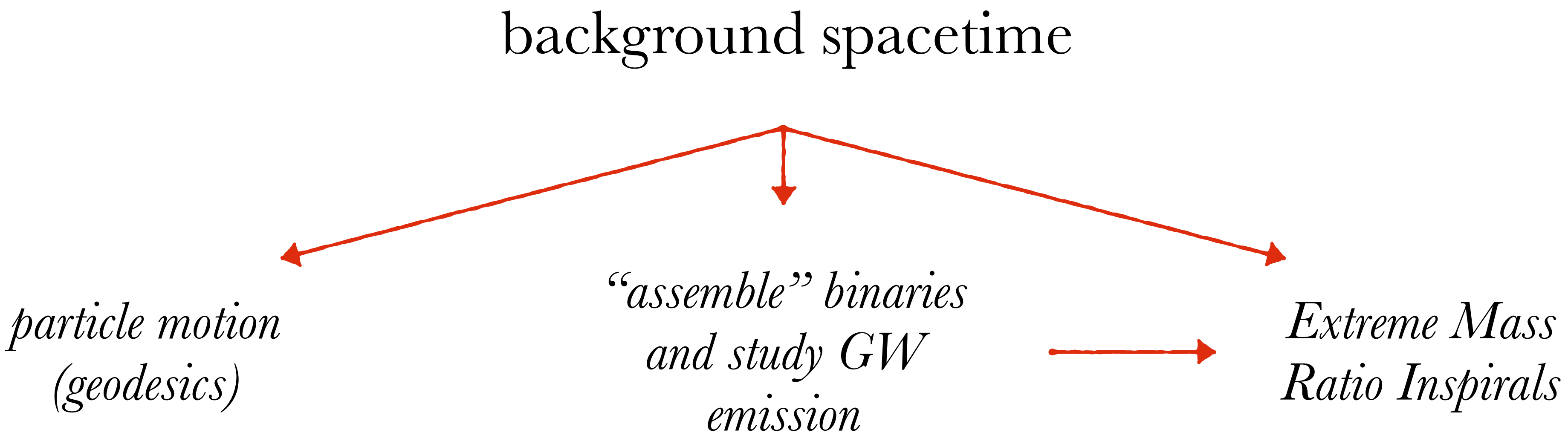
average density *typical scale*

$$\rho(r) = \rho_0 (r/a_0)^{-\gamma} [1 + (r/a_0)^{\alpha}]^{(\gamma-\beta)/\alpha}$$

$$\rho(r) = \rho_e \mathrm{exp} \left\{ -d_n [(r/r_e)^{1/n} - 1] \right\}$$

Hernquist *NFW* *Einasto*

- Model characterised by $M_{\rm halo}, a_0$



background spacetime

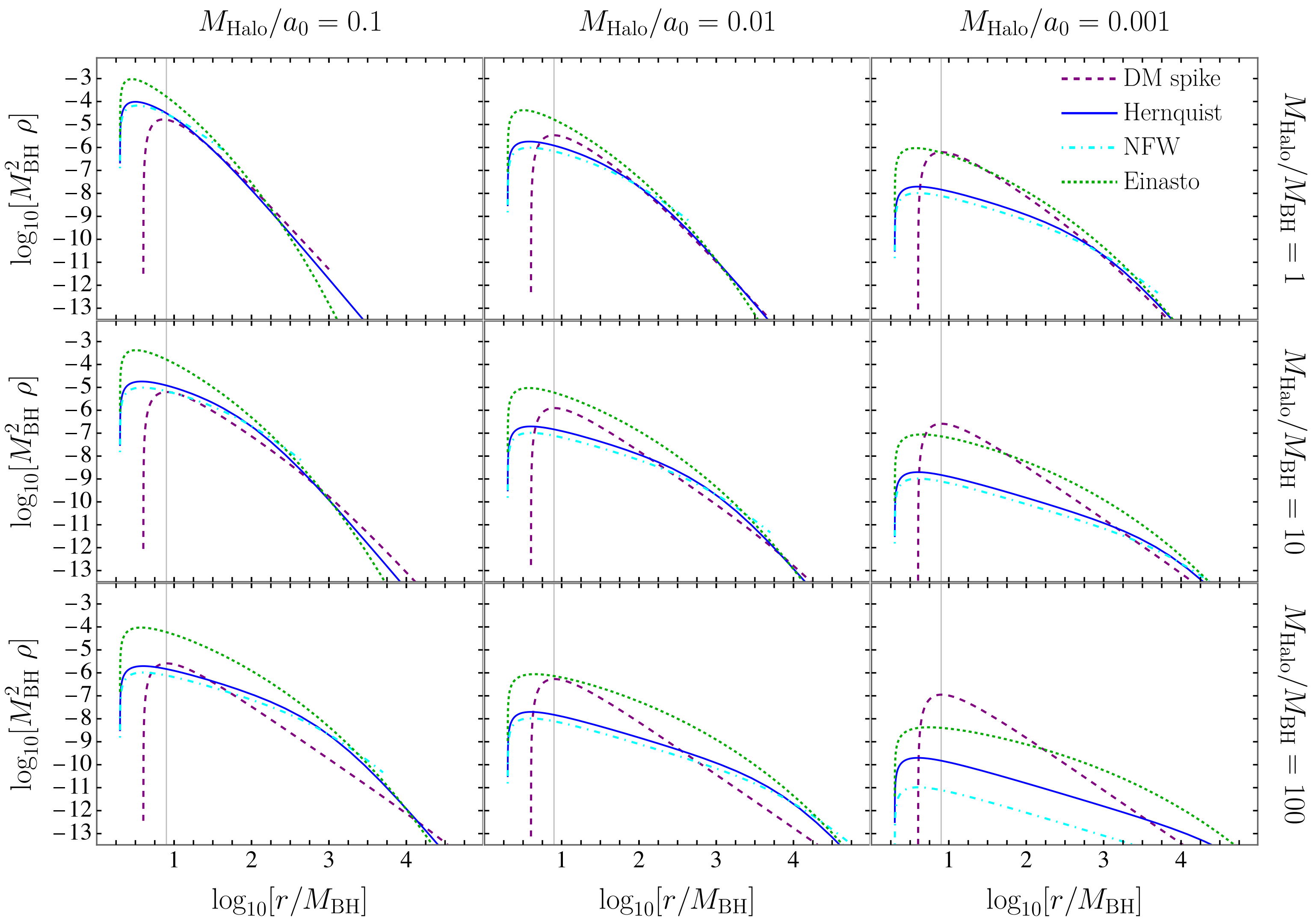
particle motion (geodesics)

"assemble" binaries and study GW emission

Extreme Mass Ratio Inspirals

Spikes

The halo mass function



numerical simulations of BH accretion growth predict spikes with overdensities

P. Gondolo & J. Silk, PRL 83, (1999)

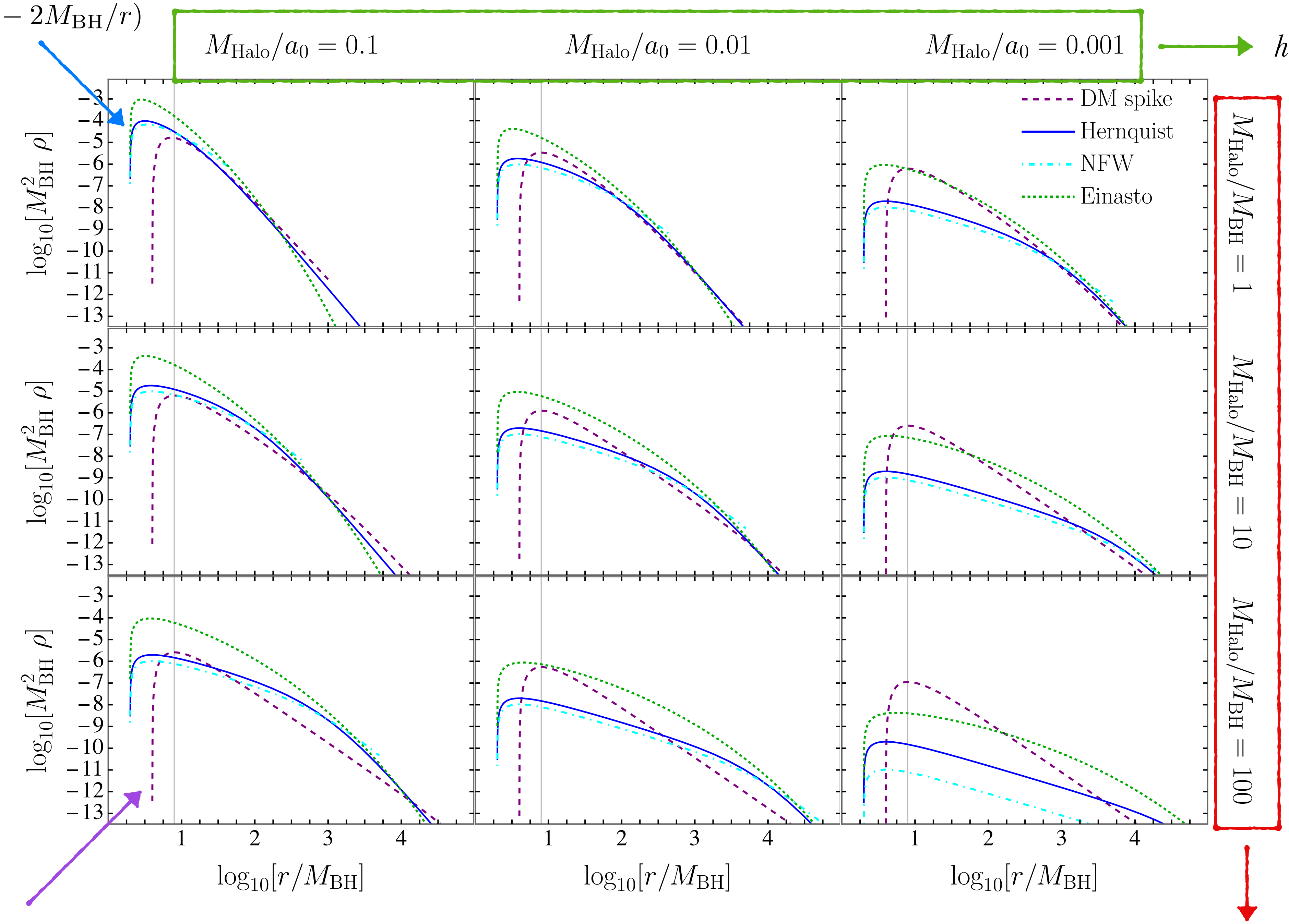
- lengthscale dependent on the BH mass
- spike vanishing between $(2-4)M_{\rm BH}$

- Spikes are relevant to enhance GW emission for close binaries and hence environment detectability

Spikes

The halo mass function

$\rho_{\rm DM}(1-2M_{\rm BH}/r)$



halo compactness

halo mass

adiabatic growth

Orbital properties

Properties of test particles: orbital frequencies

- To mimic galaxy observations $a_0 \gtrsim 10^4 M_{\rm halo}$ $\longrightarrow$ $M_{\rm BH} \ll M_{\rm halo} \ll a_0$

Innermost Stable
Circular Orbit

Light Ring

$$M_{\rm BH}\Omega_{\rm ISCO} \simeq \frac{1}{6\sqrt{6}}$$

vacuum

$$M_{\rm BH}\Omega_{\rm LR} \simeq \frac{1}{3\sqrt{3}}$$

$$M_{\rm BH}\Omega_{\rm ISCO} \simeq \frac{1}{6\sqrt{6}}\left(1 - \underbrace{\frac{M_{\rm halo}}{a_0}}_{\textit{redshift factor}} + \underbrace{\frac{M_{\rm halo}(M_{\rm halo} + 396 M_{\rm BH})}{6a_0^2}}_{\textit{non-linear corrections}}\right)$$

$$M_{\rm BH}\Omega_{\rm LR} \simeq \frac{1}{3\sqrt{3}}\left(1 - \underbrace{\frac{M_{\rm halo}}{a_0}}_{\textit{redshift factor}} + \underbrace{\frac{M_{\rm halo}(M_{\rm halo} + 18 M_{\rm BH})}{6a_0^2}}_{\textit{non-linear corrections}}\right)$$

- At the leading order the halo only redshifts the dynamics

GW emission from EMRI

How do we evolve a dirty binary?

background $\longrightarrow$ perturbations $\longrightarrow$ GW fluxes

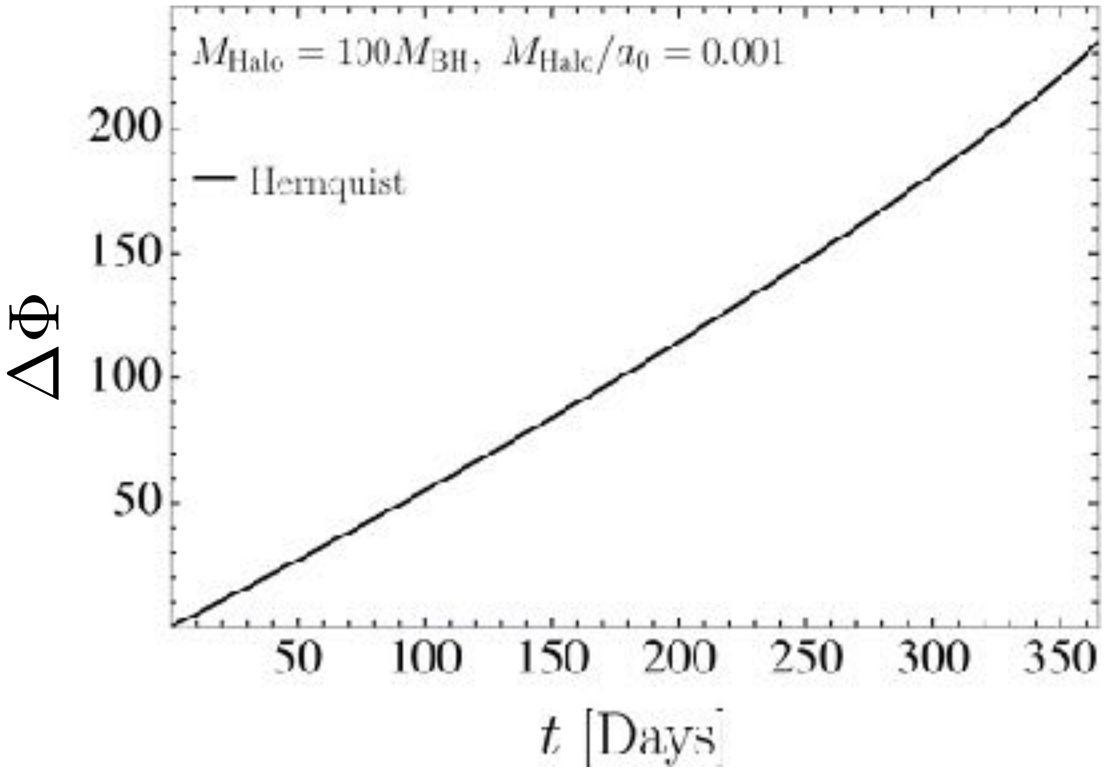
$g^{(0)}_{\mu\nu}$ $\qquad$ $g^{(0)}_{\mu\nu} + h_{\mu\nu}$ $\qquad$ $\dot{E}_{\rm GW} \sim |h_{\mu\nu}|^2$

orbital elements $\longrightarrow$ waveform $\longrightarrow$ $h_+[r(t),\Phi(t)]$

$h_\times[r(t),\Phi(t)]$

$$\frac{dr}{dt} = -\dot{E}_{\rm GW}\frac{dr}{dE_{\rm orb}} \qquad \frac{d\Phi}{dt} = \sqrt{\frac{M}{r^3}}$$

S. Glorio +, in preparation



GW dephasing

$$\Delta\Phi = \Phi_{\rm vacuum} - \Phi_{\rm halo}$$

$\Delta\Phi \gtrsim 1$ $\longrightarrow$ *signals <u>may</u> be distinguishable*

Summary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REALE MUTUA
REALE MUTUA
MM
TRIATHLON MM T3
234
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