Environmental effects and matter systematics for LISA

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Can environmental effects spoil precision gravitational-wave astrophysics?

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(Dated: May 27, 2014)

No, within a broad class of scenarios. Gravitational-wave (GW) astronomy will open a new window on compact objects such as neutron stars and black holes (BHs). It is often stated that large signal-to-noise detections of ringdown or inspiral waveforms can provide estimates of the masses and spins of compact objects to within fractions of a percent, as well as tests of General Relativity. These expectations usually neglect the realistic astrophysical environments in which compact objects live. With the advent of GW astronomy, environmental effects on the GW signal will eventually have to be *quantified*. Here we present a wide survey of the corrections due to these effects in two situations of great interest for GW astronomy: the BH ringdown emission and the inspiral of two compact objects (especially BH binaries). We mainly focus on future space-based detectors such as eLISA, but many of our results are also valid for ground-based detectors such as aLIGO, aVirgo and KAGRA. We take into account various effects such as: electric charges, magnetic fields, cosmological evolution, possible deviations from General Relativity, firewalls, and the effects related to various forms of matter such as accretion disks and dark matter halos.

Our analysis predicts the existence of resonances dictated by the external mass distribution, which dominate the very late-time behavior of merger/ringdown waveforms. The mode structure can drastically differ from the vacuum case, yet the BH response to external perturbations is unchanged at the time scales relevant for detectors. This is because although the vacuum Schwarzschild resonances are no longer quasinormal modes of the system, they still dominate the response at intermediate times. Our results strongly suggest that both parametrized and ringdown searches should use at least two-mode templates.

Our analysis of compact binaries shows that environmental effects are typically negligible for most eLISA sources, with the exception of very few special extreme mass ratio inspirals. We show in particular that accretion and hydrodynamic drag generically dominate over self-force effects for geometrically thin disks, whereas they can be safely neglected for geometrically thick disk environments, which are the most relevant for eLISA. Finally, we discuss how our ignorance of the matter surrounding compact objects implies intrinsic limits on the ability to constrain strong-field deviations from General Relativity.

PACS numbers: 04.30.Db, 04.25.Nx, 04.80.Nn, 04.50.Kd, 04.70.-s, 04.25.Nx, 98.80.Es,

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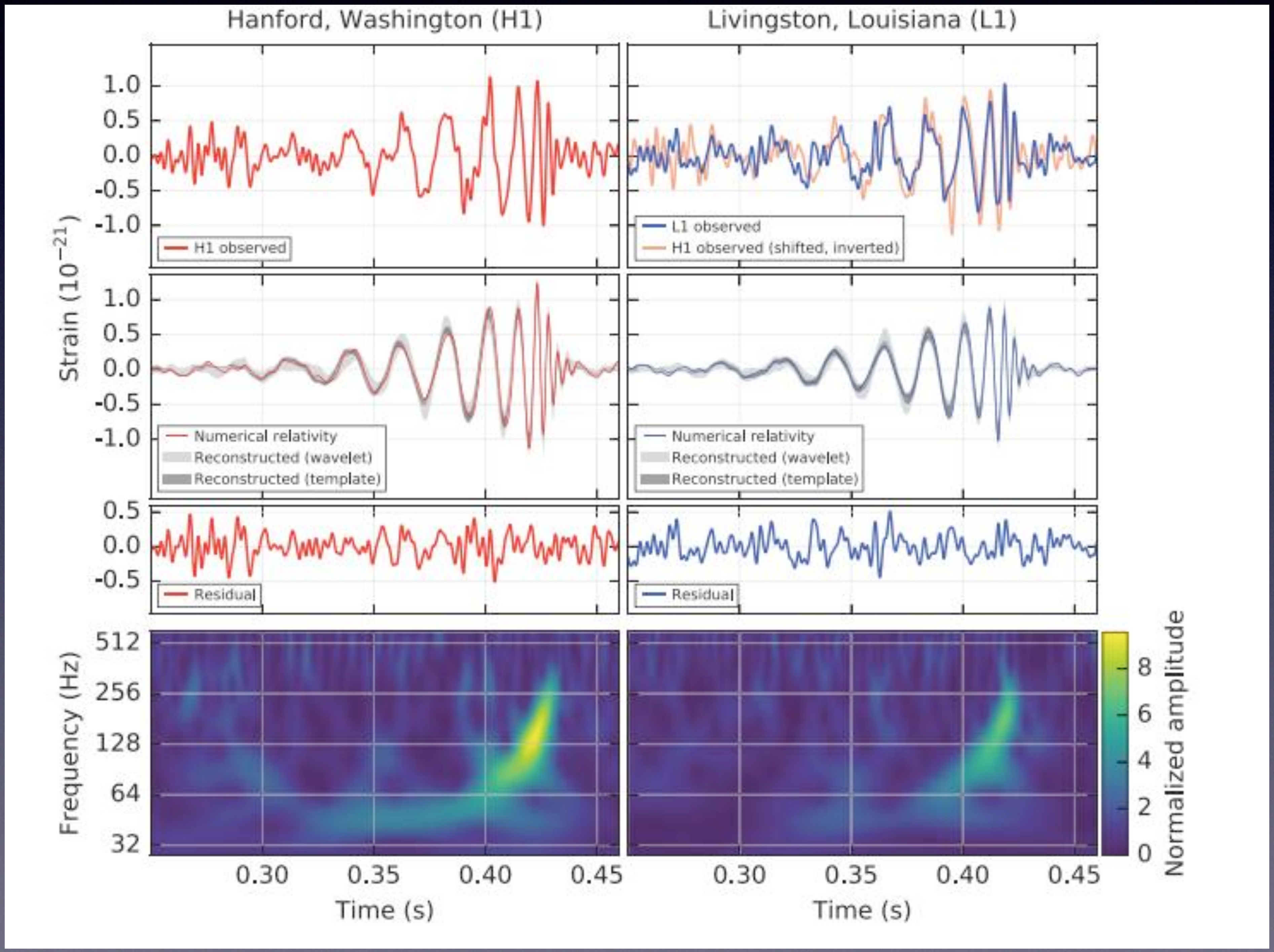
"broad class" =
~90% of EMRIs, ~75% of SOBHBs

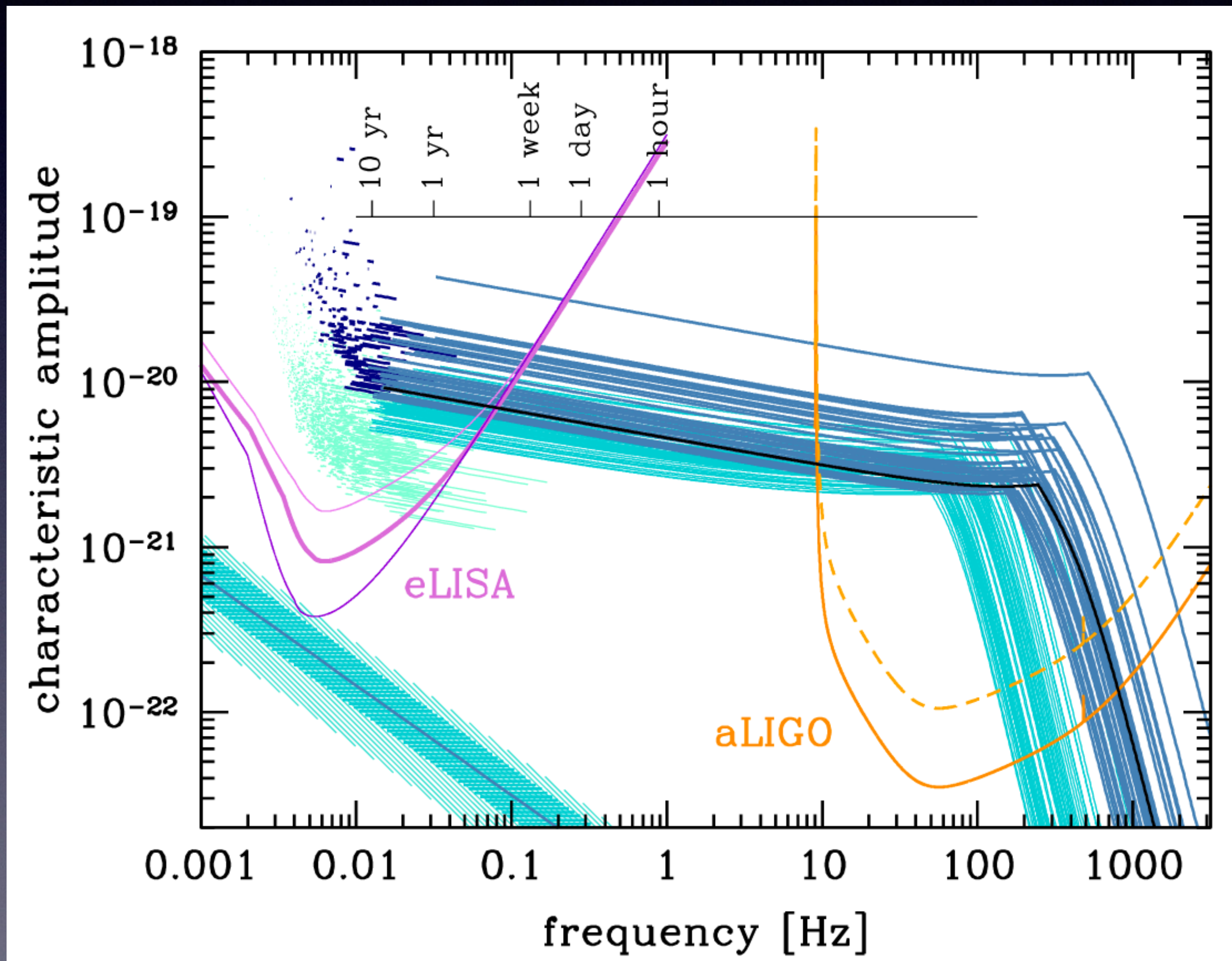
Outline

- The astrophysics of MBHs, AGNs, EMRIs and SOBHBs
- Environmental effects on gravitational waveforms (accretion, planetary migration, dynamical friction, peculiar accelerations/Doppler, Shapiro time delay, Dark Matter, etc)
- Implications for GR tests (and SF calculations)

The first direct observation of GWs and … BHs!

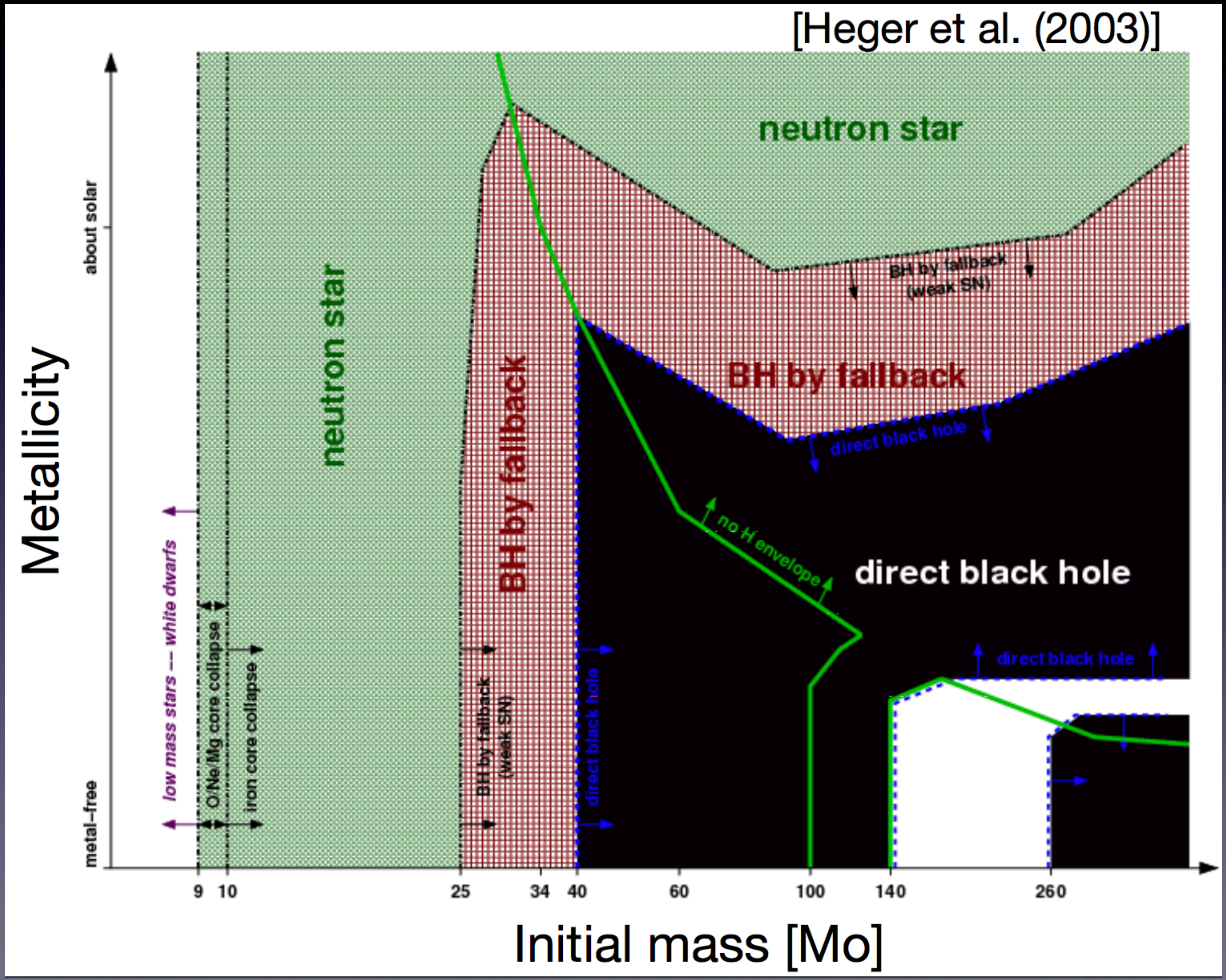


Multi-band gravitational-wave astronomy



Sesana 2016

The formation of stellar-mass BHs

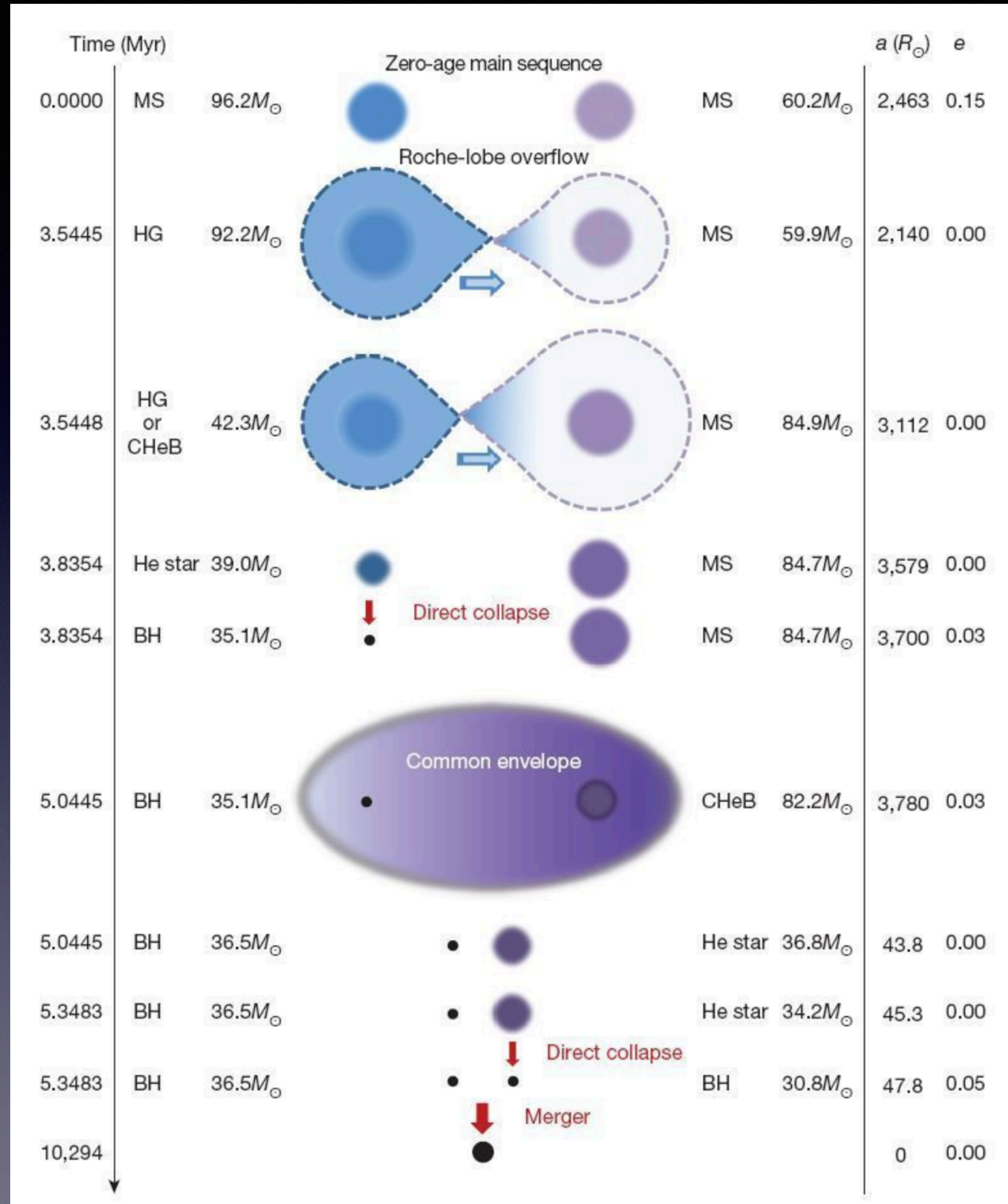


How do stellar-mass BH *binaries* form?

- In the field (plausible because ~70% of massive stars have companion, c.f. Sana et al 2012)

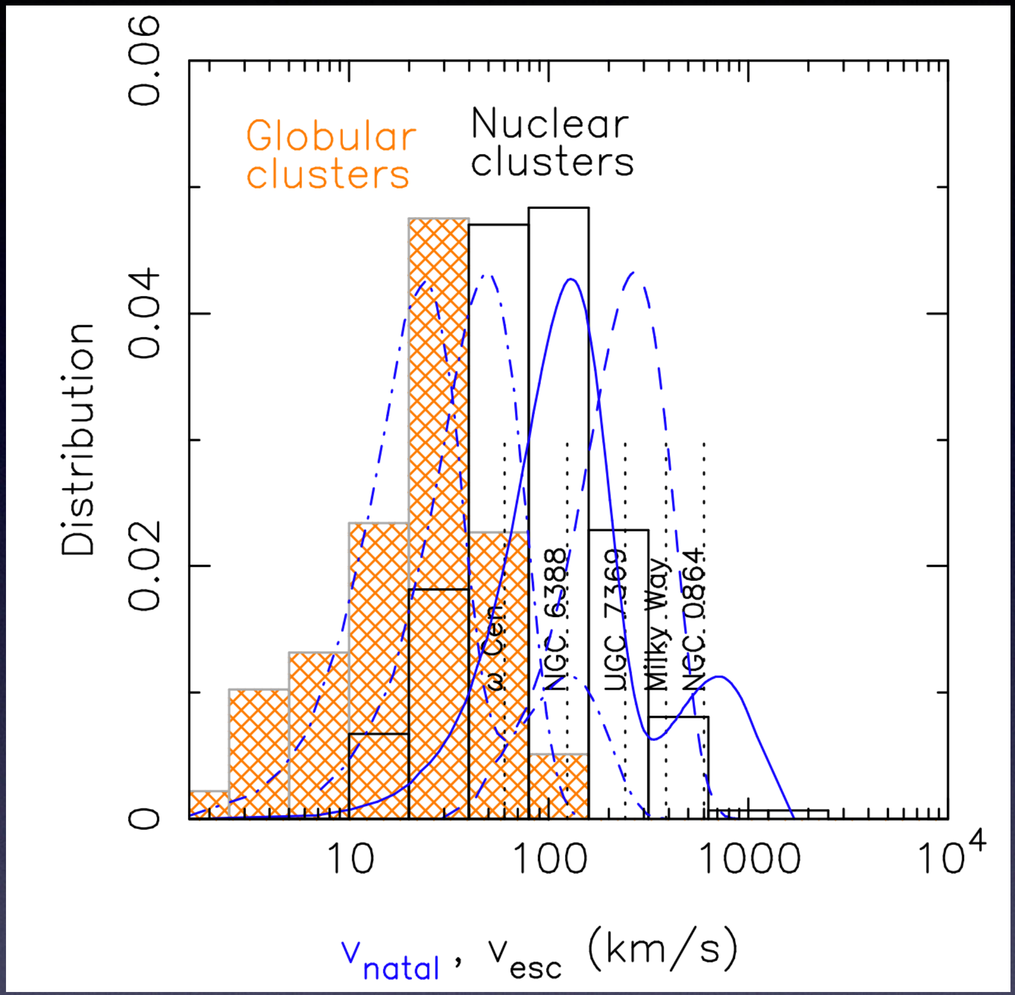
- In dense environments (globular clusters/nuclear star clusters, AGNs) via dynamical mechanisms

Field SOBHBs



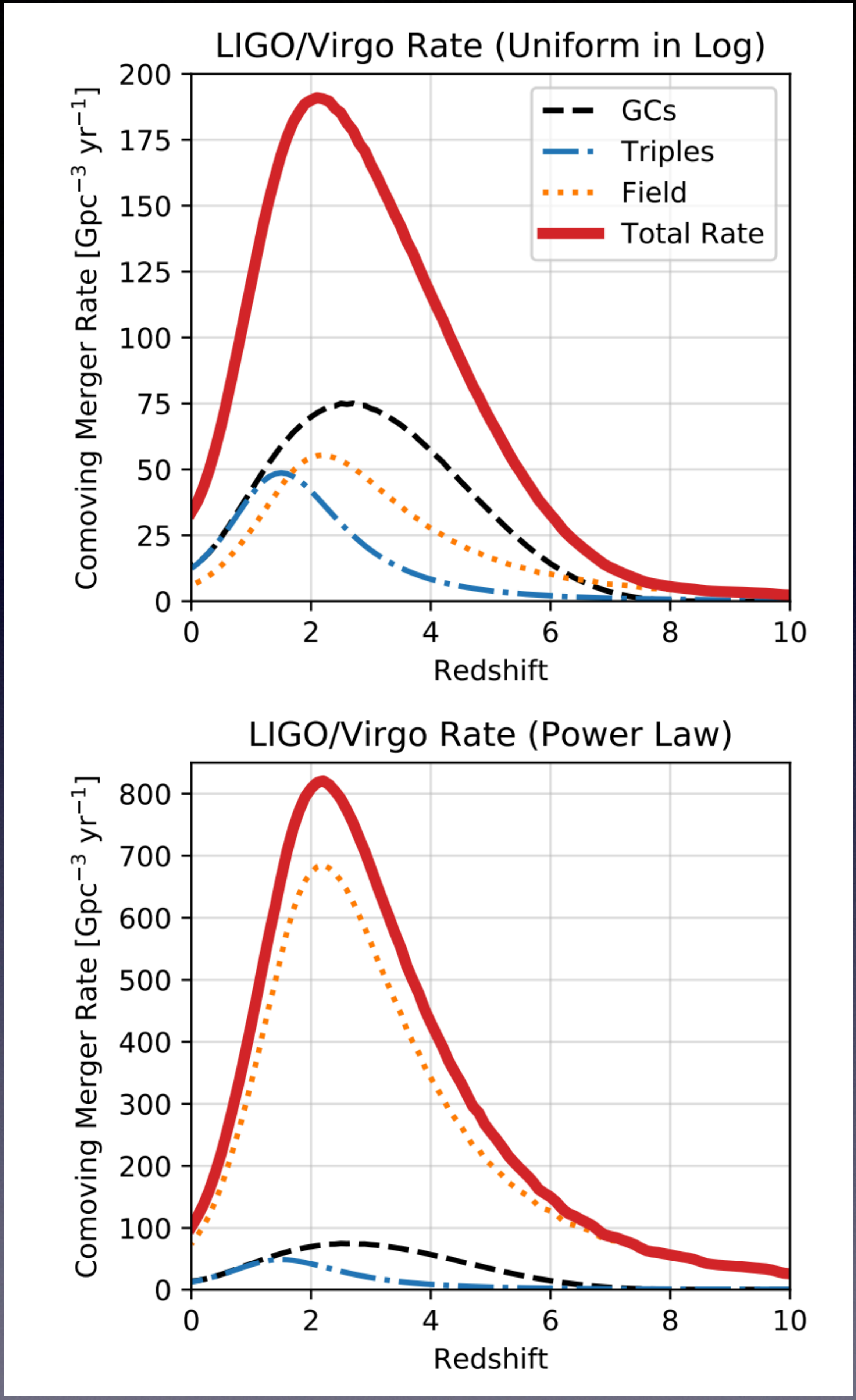
Belczynski et al 2016

Dynamical channel



Antonini & Radio 2016

- Similar uncertainties to field (eg kicks)
- Possible in globular/nuclear clusters, AGNs, or even in the field (field triples)
- May be as important as field channel



Rodriguez & Loeb 2018

SOBHBs in AGNs (GW190521-like)

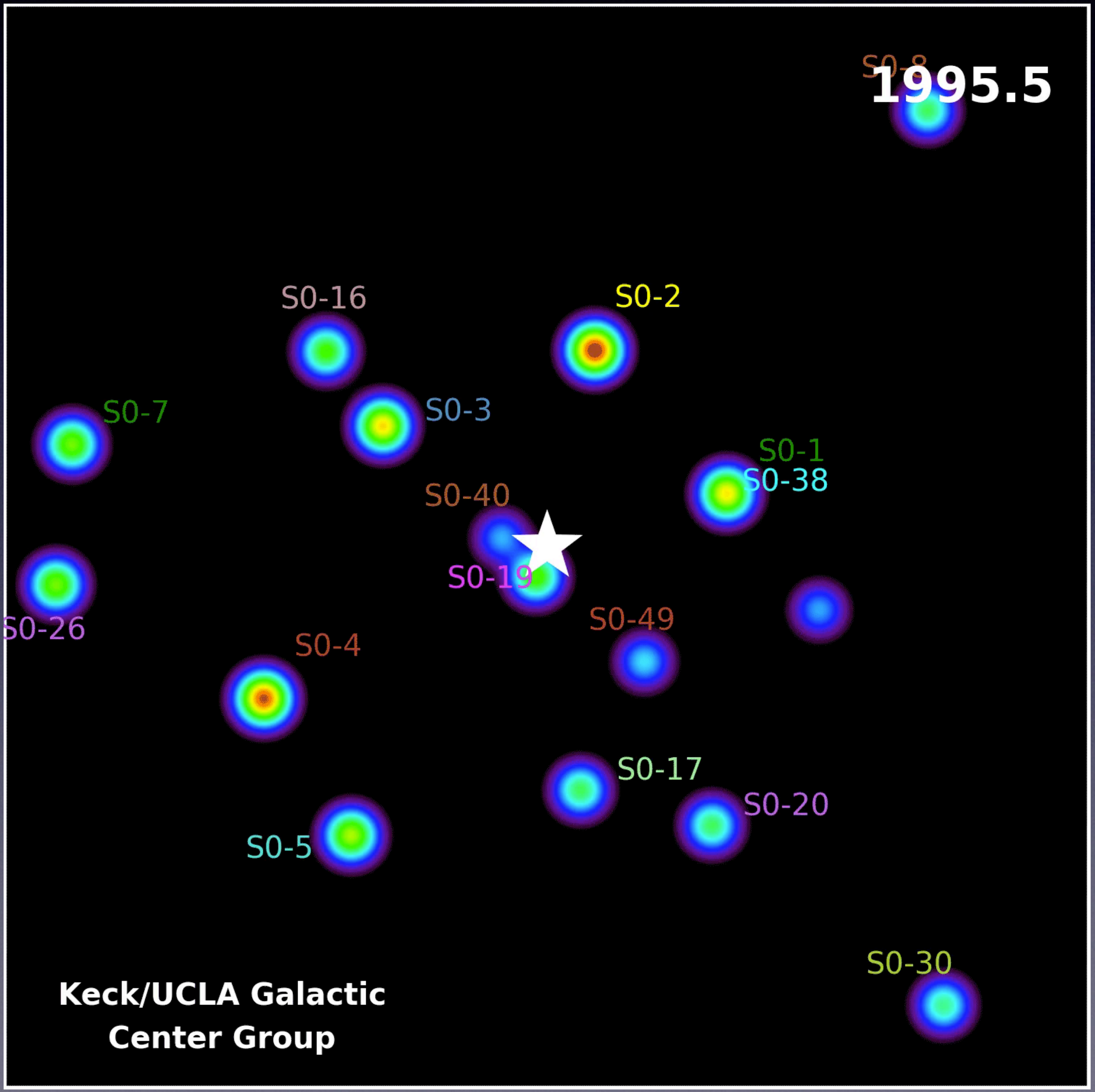
noise, $T_{\rm obs}$, DC	GW190521-like	GWTC-3 massive	GWTC-3
SciRD, 10 yrs, 100%	7^{+24}_{-7}	5^{+45}_{-5}	22^{+44}_{-17}
SciRD, 6 yrs, 100%	4^{+14}_{-4}	2^{+25}_{-2}	10^{+28}_{-8}
SciRD, 6 yrs, 75%	2^{+10}_{-2}	1^{+16}_{-1}	6^{+22}_{-5}
MRD, 10 yrs, 100%	13^{+41}_{-13}	16^{+73}_{-16}	70^{+101}_{-47}
MRD, 10 yrs, 75%	11^{+38}_{-11}	10^{+66}_{-10}	43^{+74}_{-29}
MRD, 6 yrs, 75%	6^{+20}_{-6}	5^{+40}_{-5}	19^{+46}_{-15}

TABLE I. Average number of GW events from (presumed) AGN binaries detectable by LISA, for different detector noise models, mission durations, duty cycles (DC), and population models. We use an SNR threshold of 8.

Toubiana+21, Sberna+ in prep 22

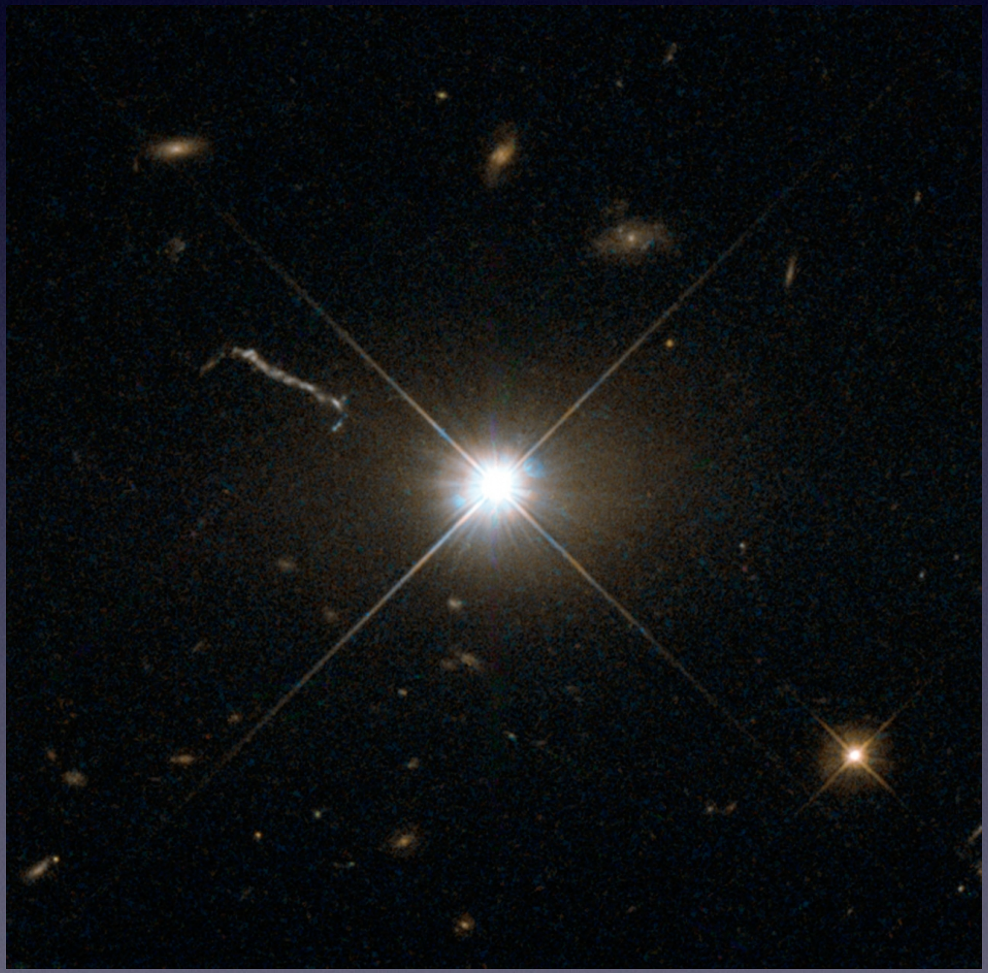
The biggest BHs in the Universe

A monster of
4.5 million solar
masses in the
centre of our Galaxy!

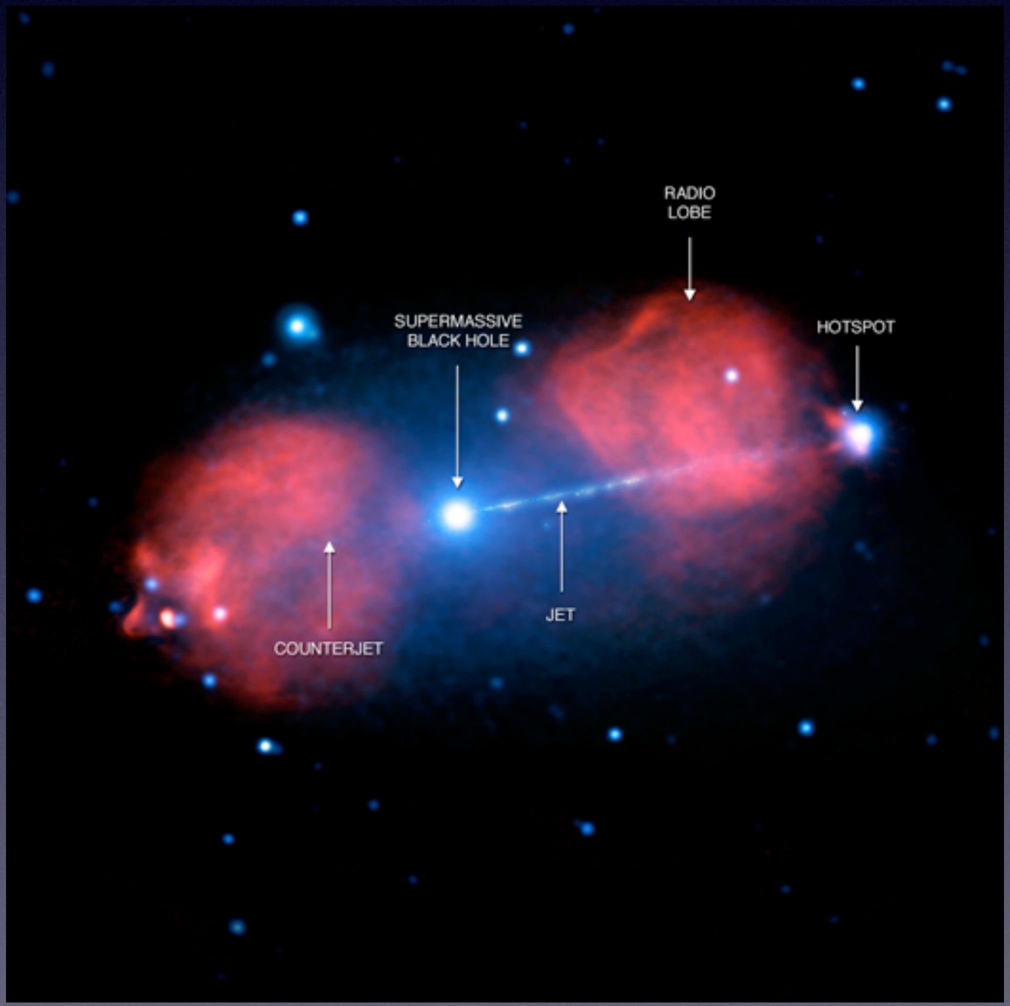


Massive black holes are hosted in (nearly) all galaxies

Accretion powers quasars and active galactic nuclei (AGNs) that outshine host galaxy and feedback on it



3C 273: 2.6 billion light years away, would shine as bright as Sun if at Proxima Centauri distance



Pictor A: giant jet spanning continuously for over 570,000 light years (red=radio, blue=x-ray)

Galaxies merge…

… so massive BHs must merge too!

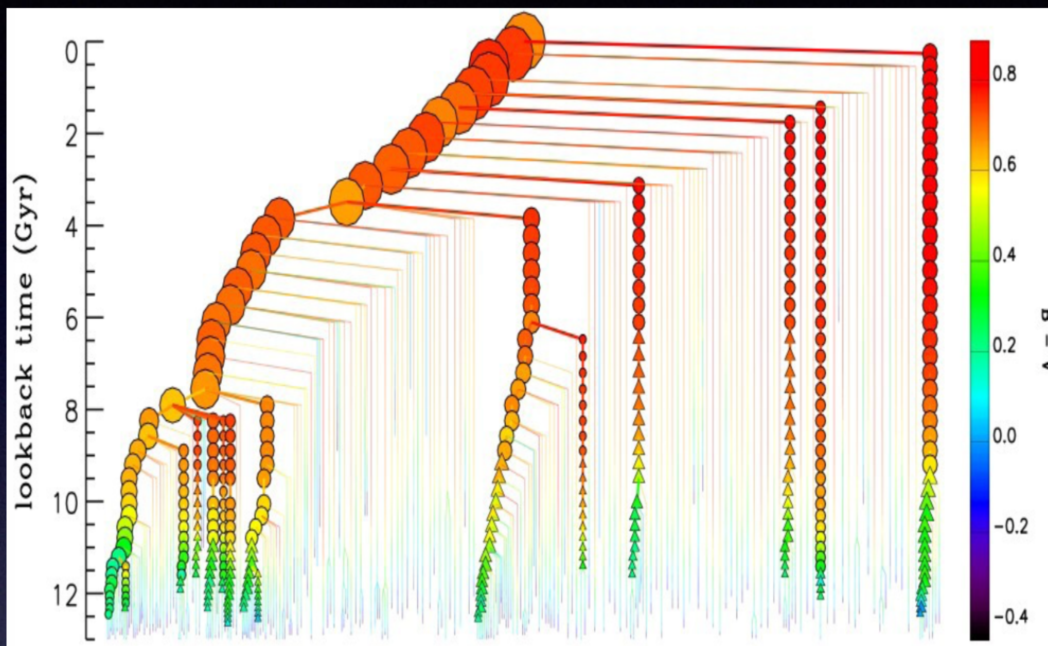


Figure from De Lucia & Blaizot 2007

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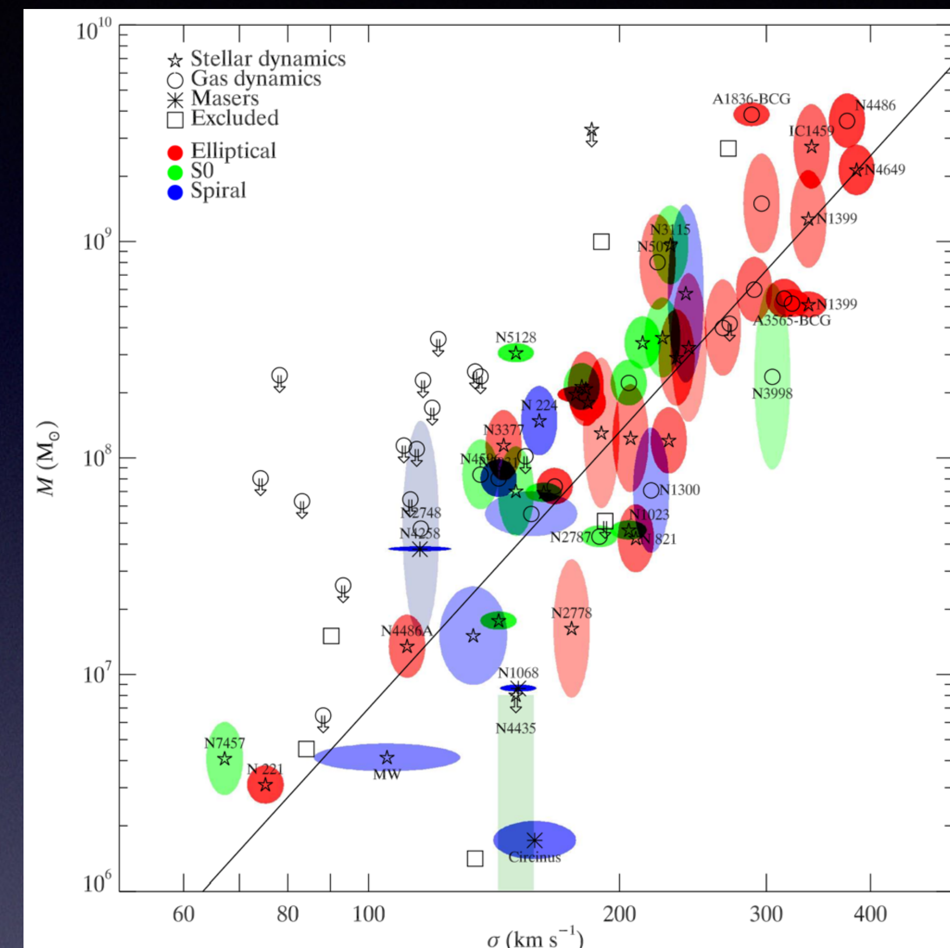
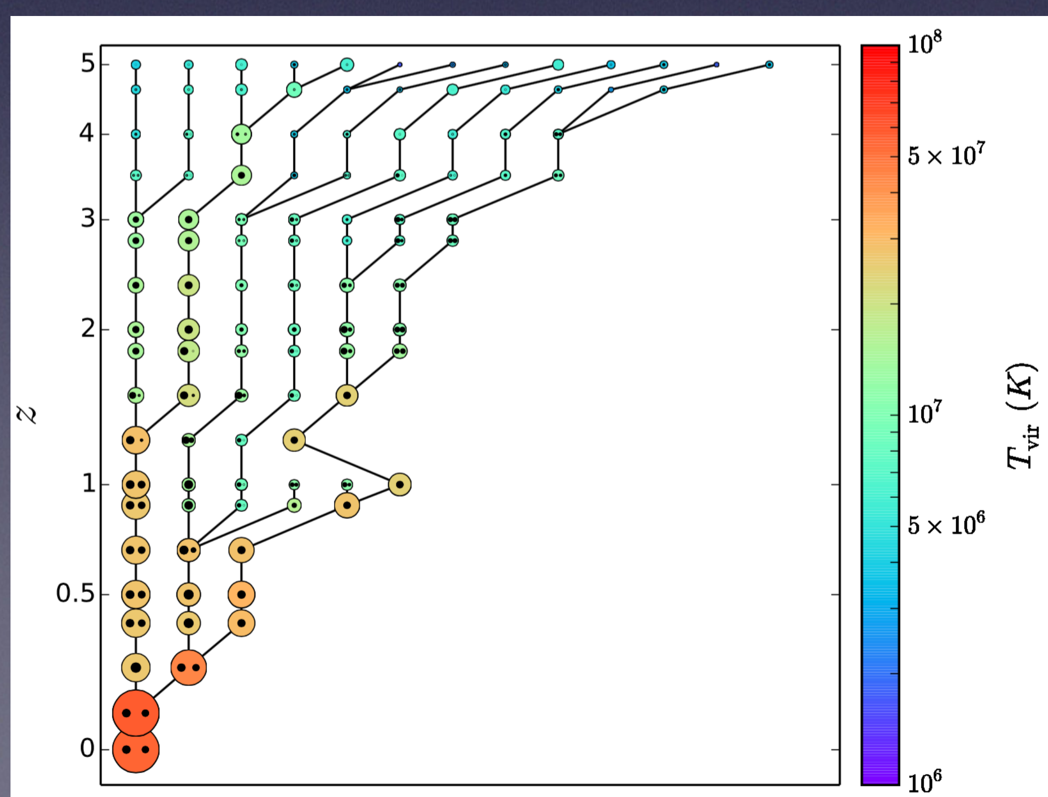


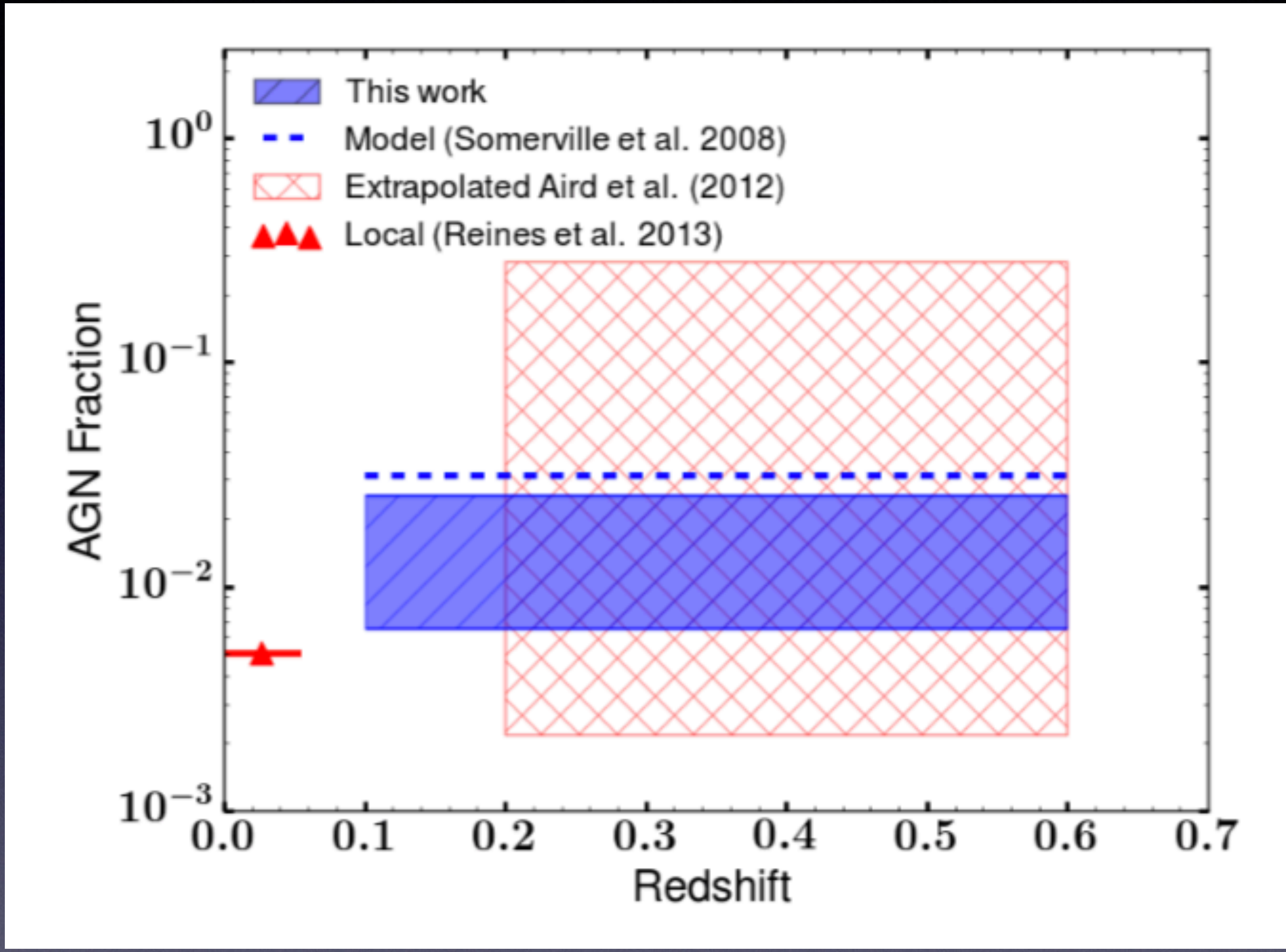
Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

=



EB 2012
Figure credits: Lucy Ward

AGN duty cycle

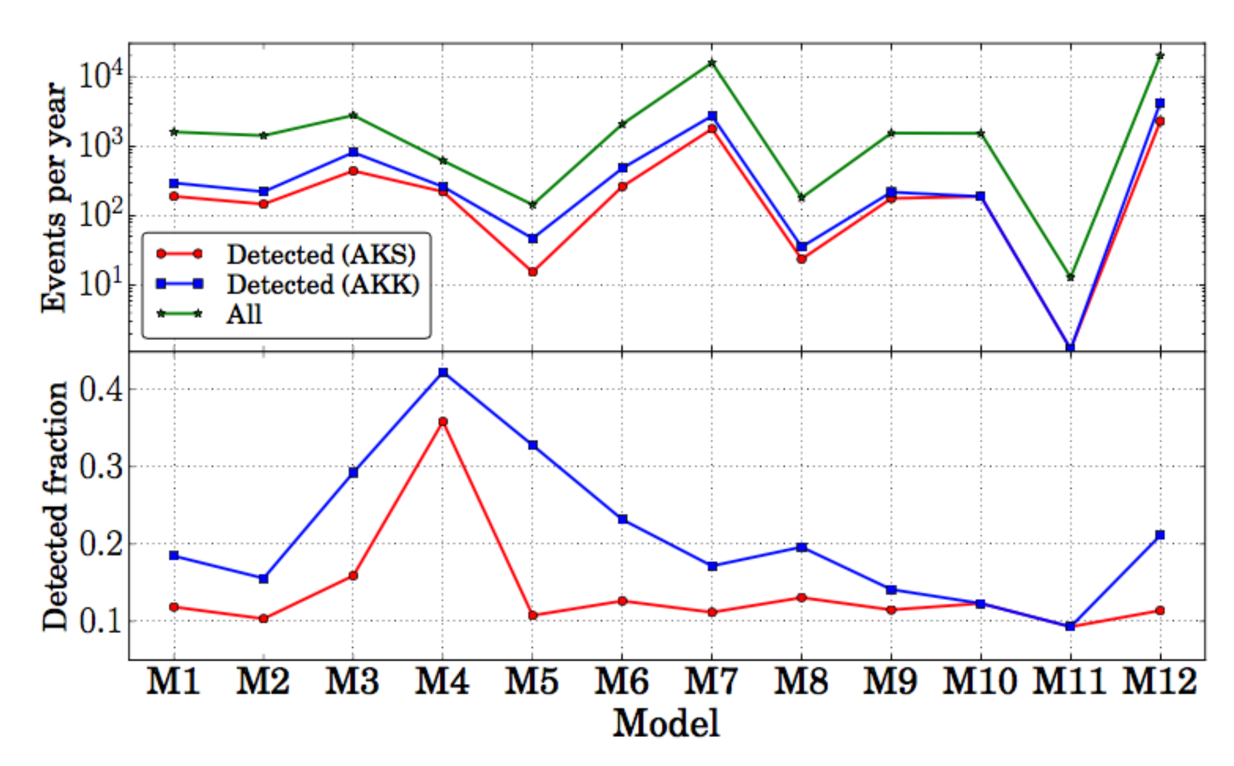


Pardo+ 2016

EMRIs: detectability

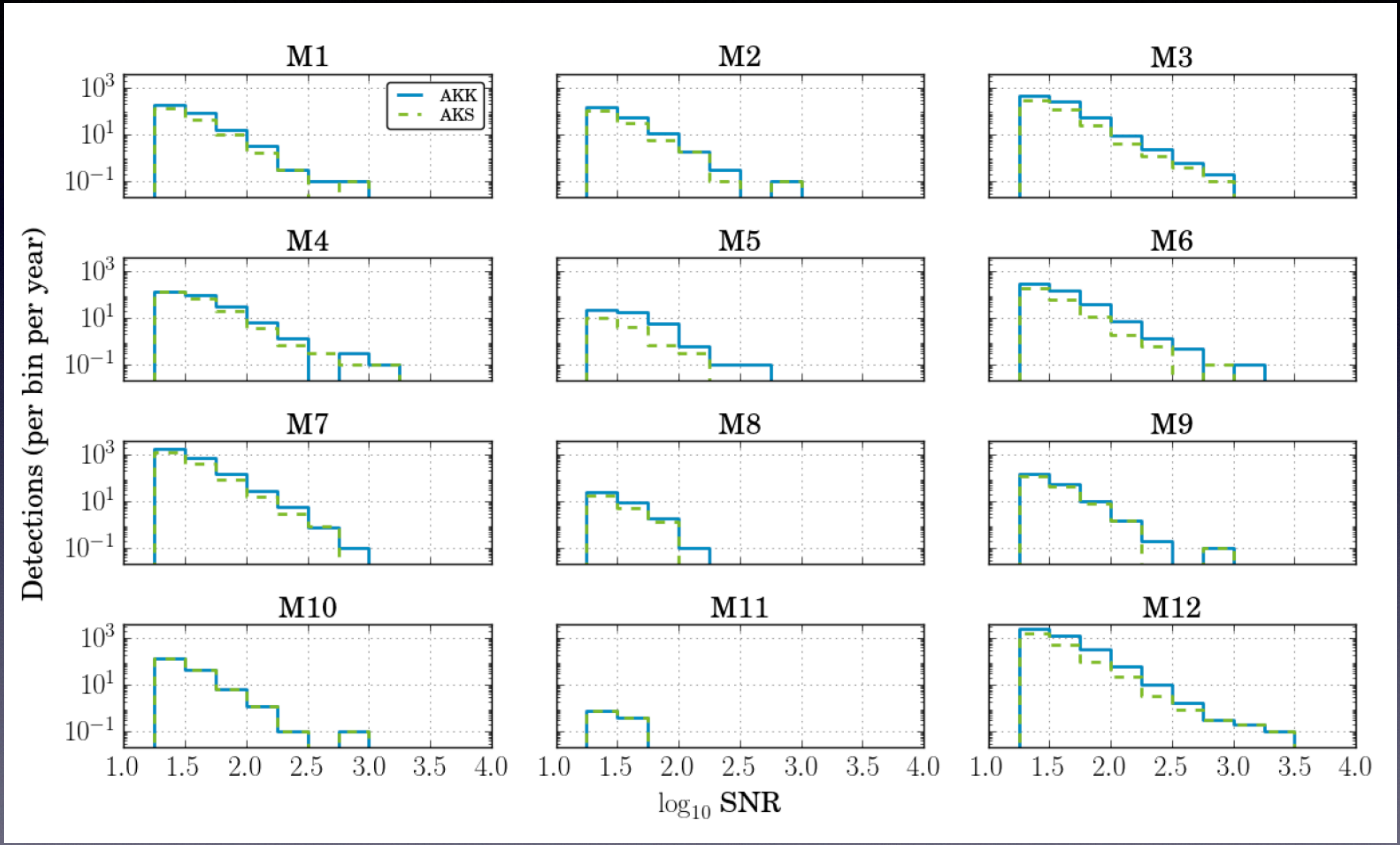
Rates uncertain, depend on low-mass end of BH mass function, presence of core vs cusp, and intrinsic EMRI rate per MBH

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[\mathrm{yr}^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520 (620)	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279



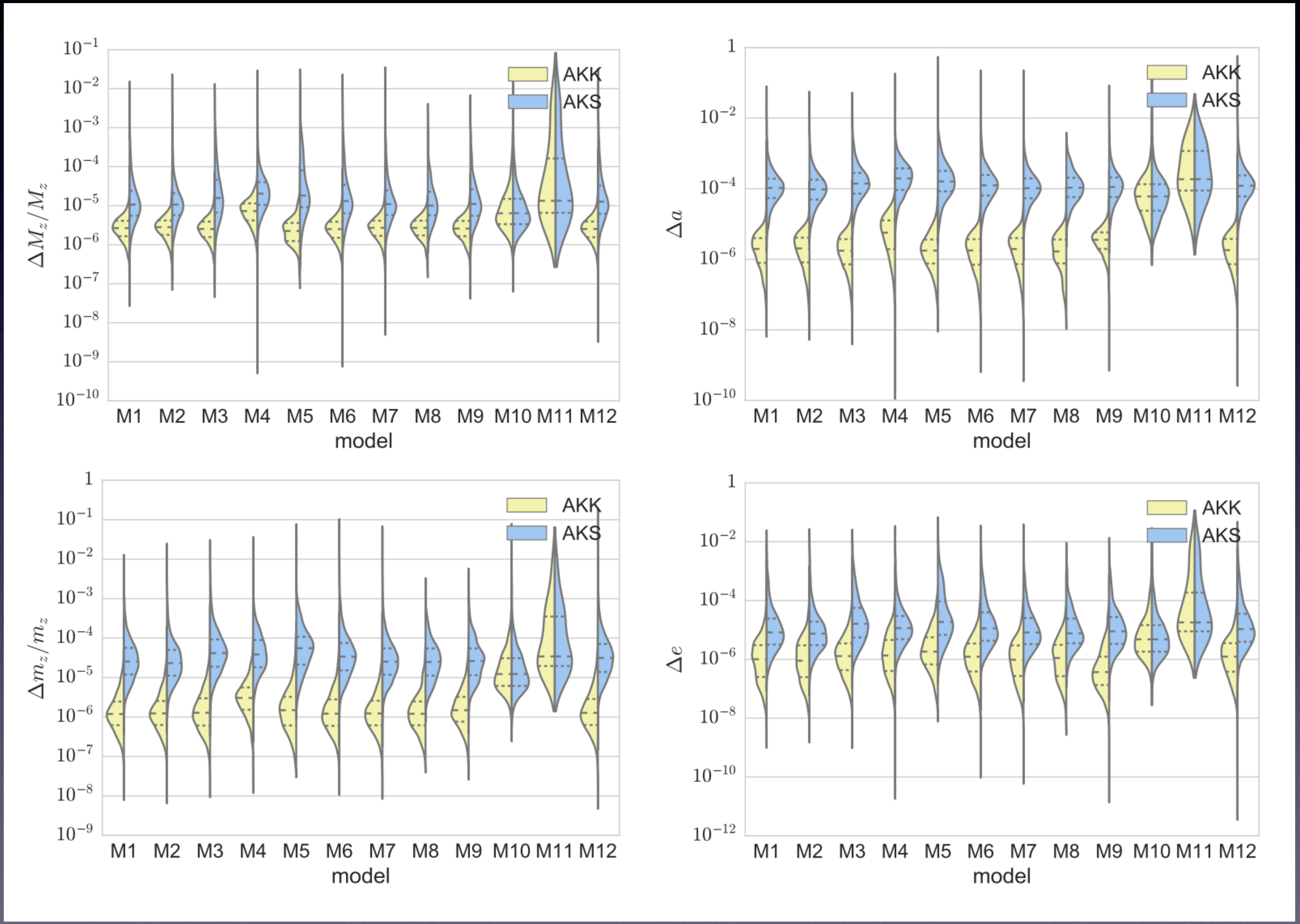
Babak+2017

EMRIs: SNR



Babak+2017

EMRIs: parameter estimation



Babak+2017

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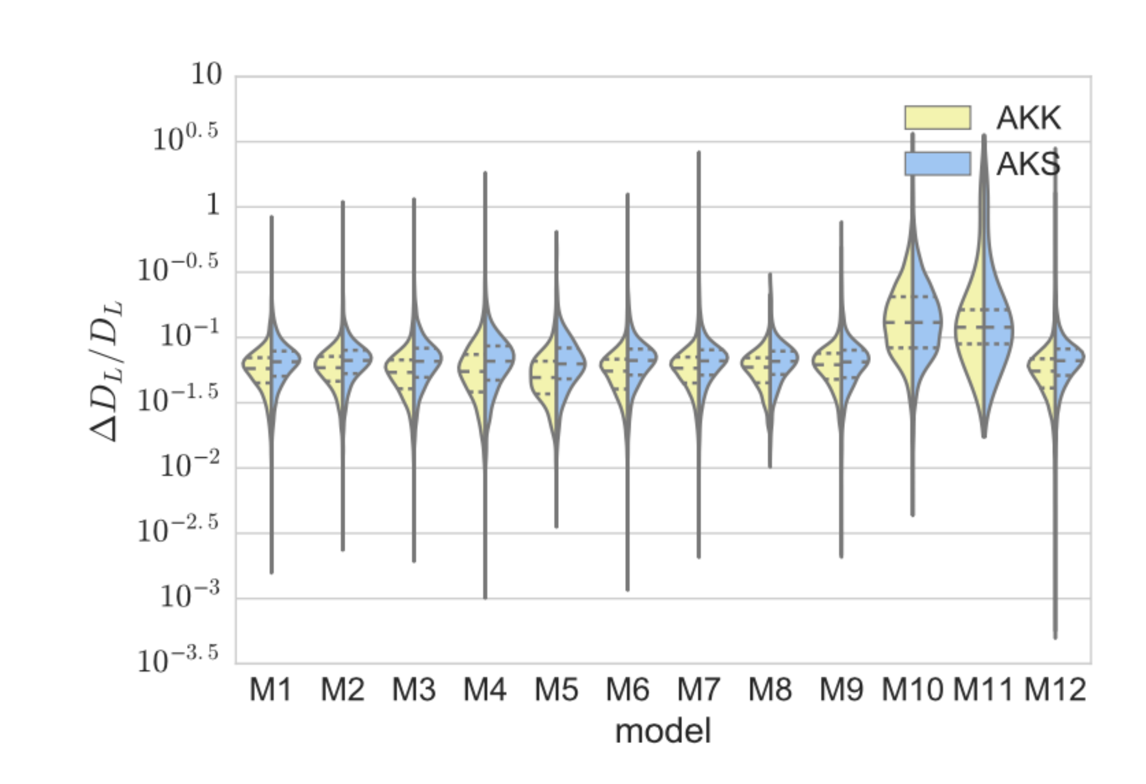
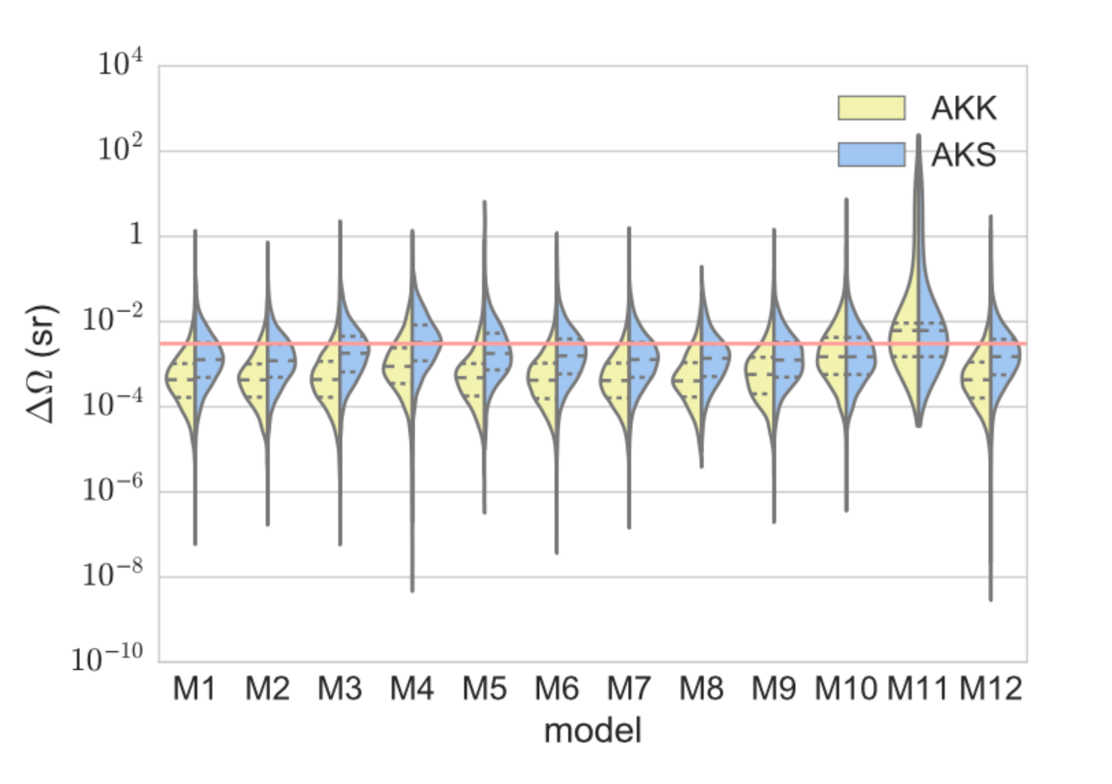
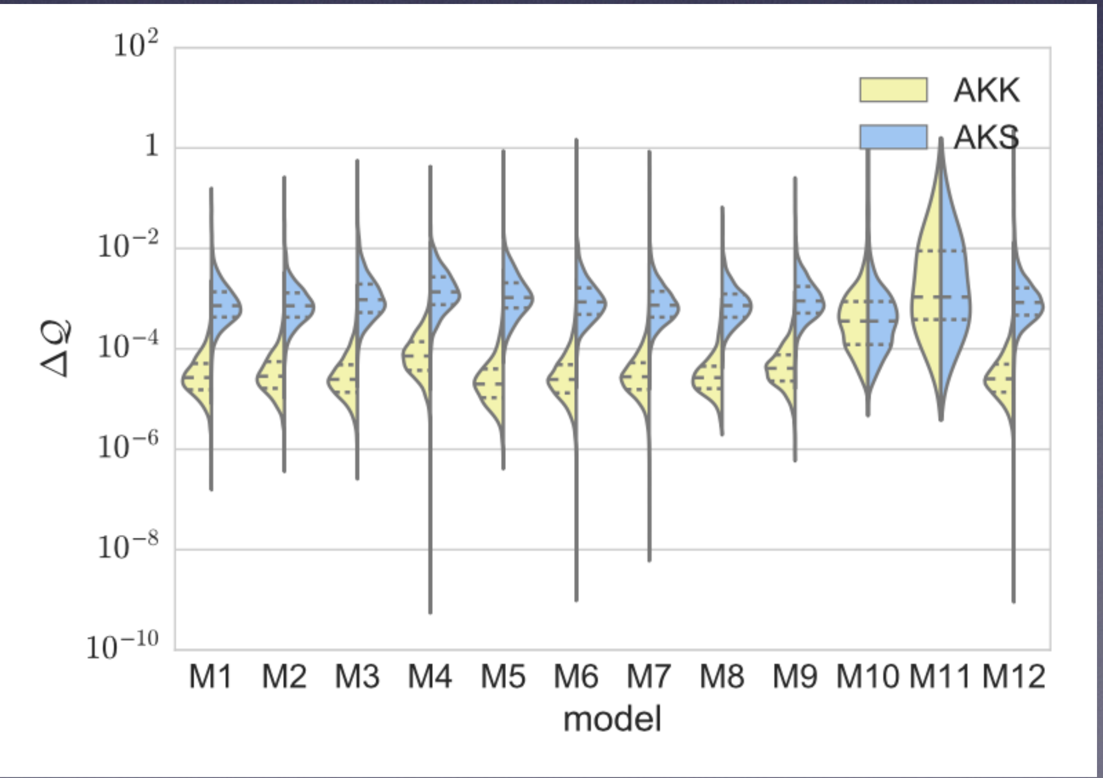






Babak+2017

Environmental pollution of LISA signals
(EB, Cardoso and Pani 2014)

Long possible list of effects

- Direct gravitational pull from matter (accretion disk, halo, stars…)
- Mass changes due to accretion onto BHs (both primary and satellite)

$$\dot{M}_{\rm Edd,cen} \approx 2.2 \times 10^{-2} \left(\frac{M}{10^6 M_\odot}\right) M_\odot {\rm yr}^{-1}$$

$$\dot{M}_{\rm Edd,sat} \approx 2.2 \times 10^{-7} \left(\frac{m}{10 M_\odot}\right) M_\odot {\rm yr}^{-1}$$

- Hydrodynamic drag/winds due to accretion

$$\boldsymbol{F}_{\rm accr} = \dot{m}(\boldsymbol{v}_{\rm gas} - \boldsymbol{v}_{\rm sat})\xi$$

- Dynamical friction (gravitational pull from density waves excited by body)

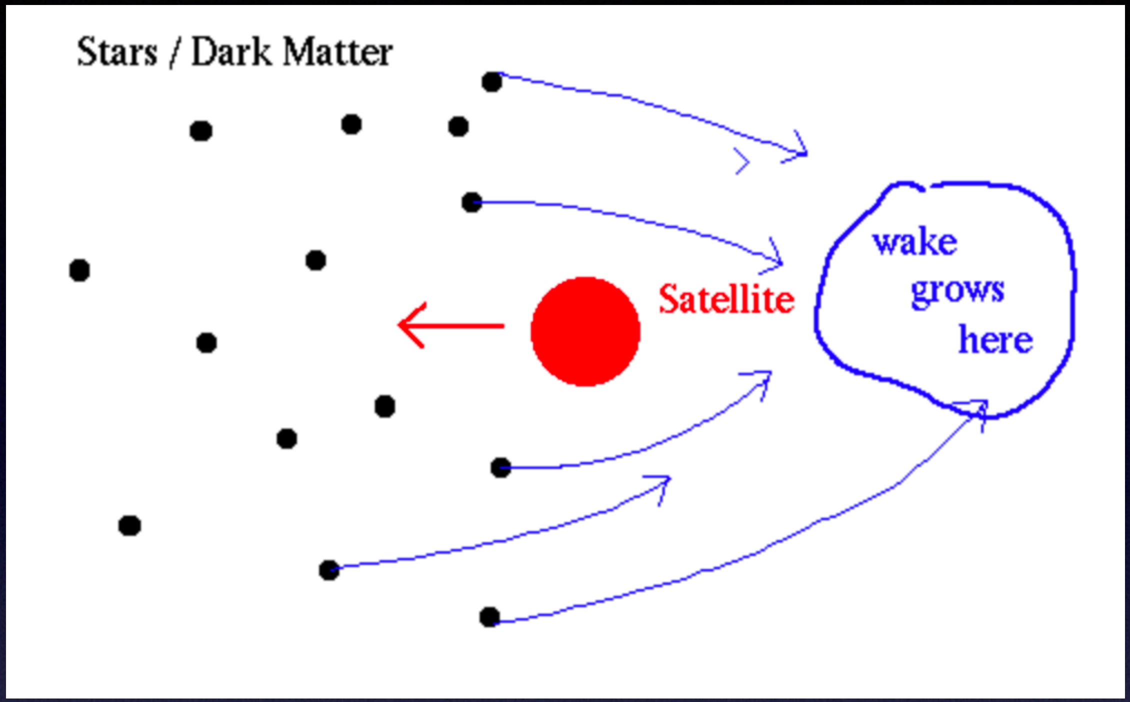
$$\boldsymbol{F}_{\rm df} = \frac{\boldsymbol{v}_{\rm gas} - \boldsymbol{v}_{\rm sat}}{|\boldsymbol{v}_{\rm gas} - \boldsymbol{v}_{\rm sat}|} \frac{4\pi\rho(Gm)^2}{|\boldsymbol{v}_{\rm gas} - \boldsymbol{v}_{\rm sat}|^2} I\xi$$

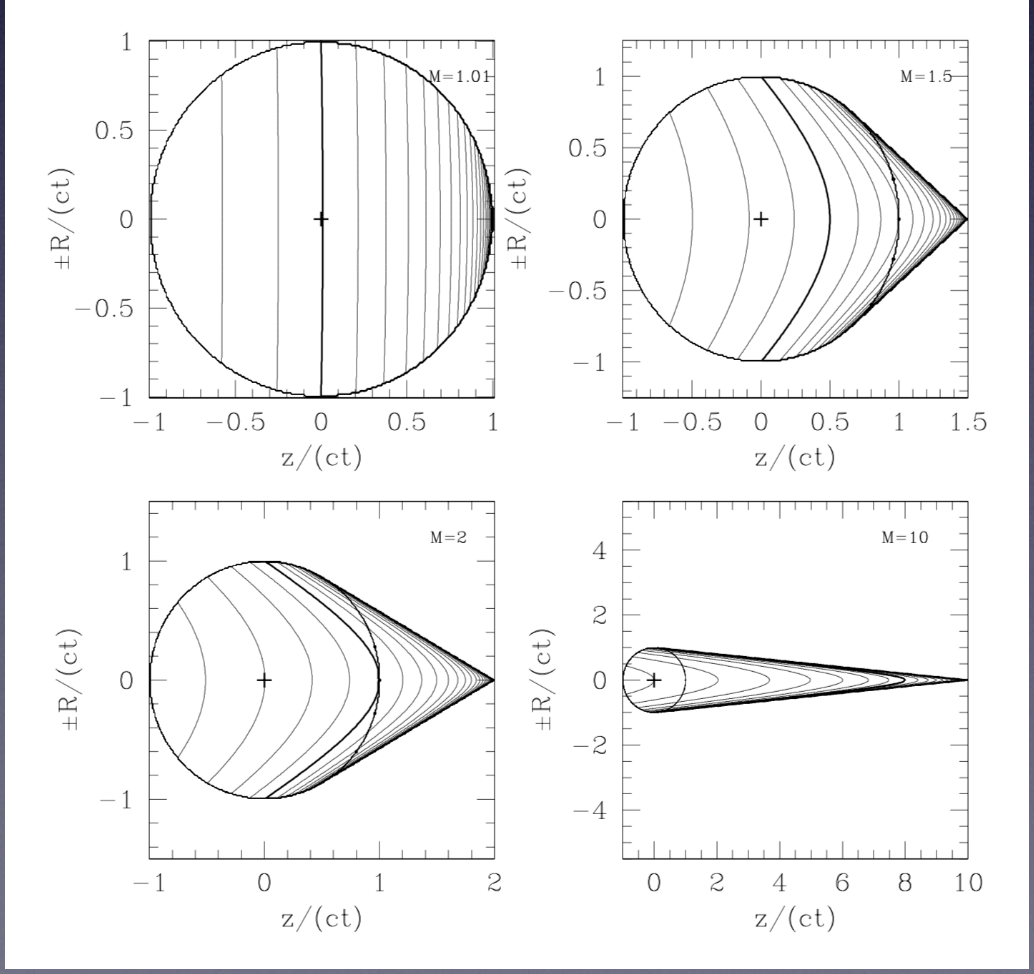
- Planetary migration (exterior wake lags being satellite and thus pulls it, interior wake trails and pushes it); cf also Yunes et al 2011

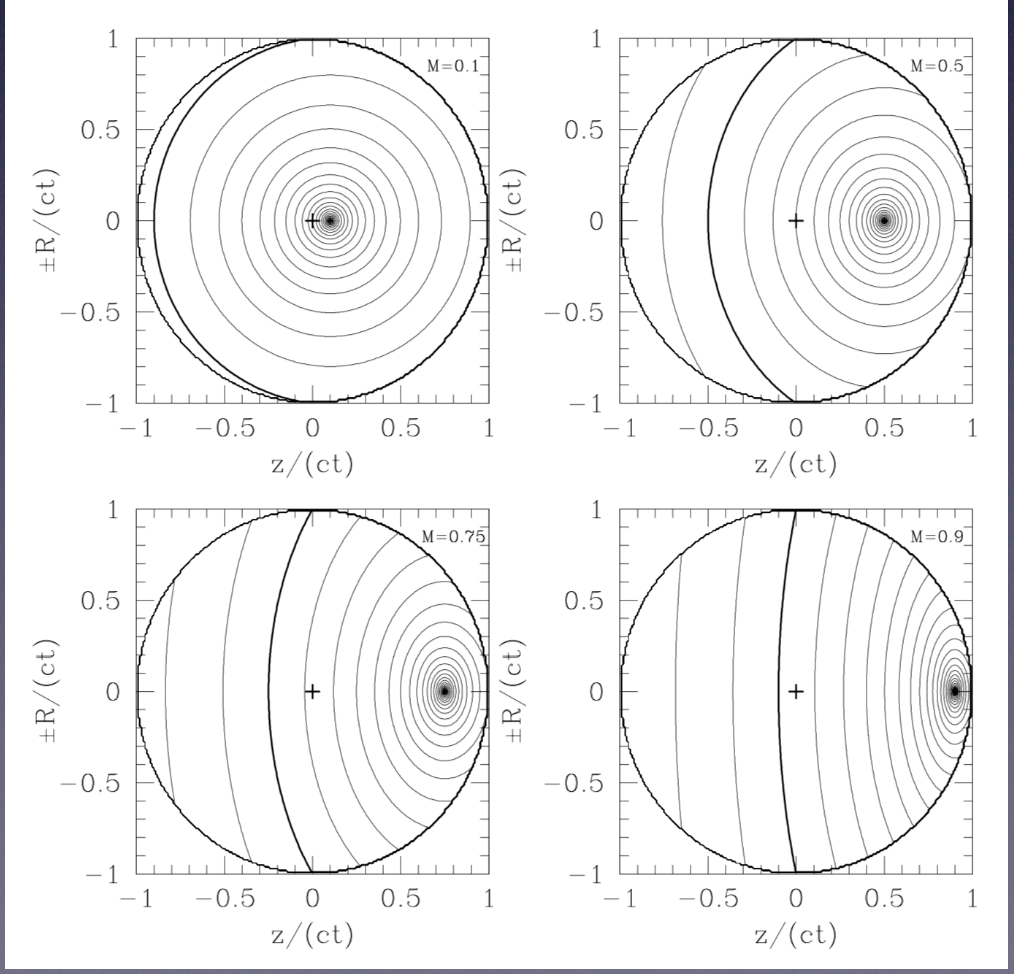
$$\dot{\tilde{L}}_z^{\rm migr} = (\dot{\tilde{L}}_z)_{\rm gw}\left[1 + A(r/M)^B\right]\xi\,,$$
$$\dot{\tilde{E}}^{\rm migr} = \dot{\tilde{L}}_z \frac{M|v_{\rm sat}|}{r}\xi$$

- Electric and magnetic fields, electric charges, etc.

Dynamical friction in stars and gas

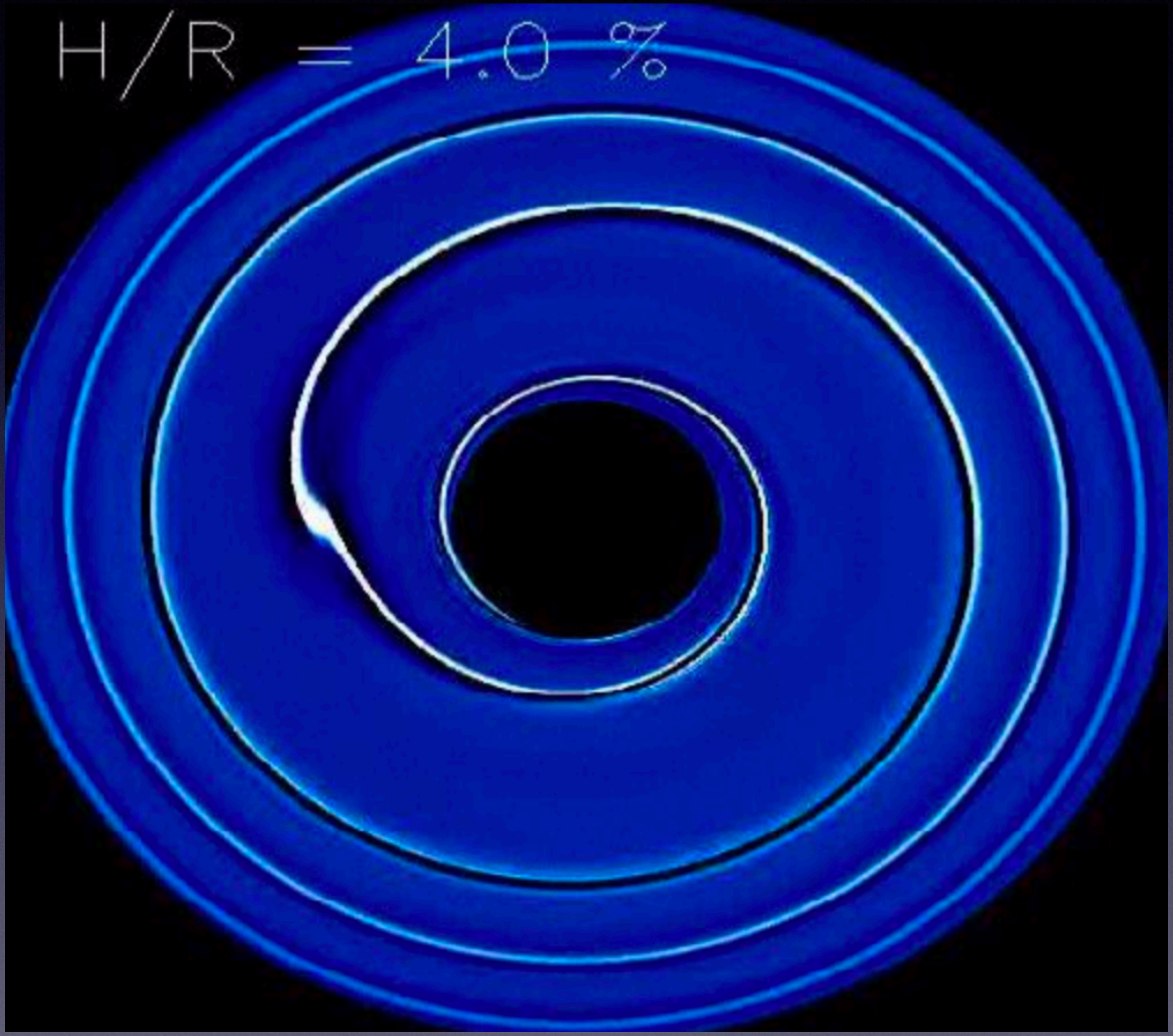






E. C. Ostriker
1998

Planetary migration



Simulation by F. S. Masset

Satellite can open gap if

$$\left(\frac{m_{\rm sat}}{3M}\right)^{1/3} r \gtrsim H$$

Type I (no gap) or Type II (gap) migration

Gravitational pull from thin disks

Assume steady state thin accretion disk
(a la Shakura Sunyaev)

$$\dot{M} = 2\pi r H \rho v_r$$

$$v_r \sim \frac{\alpha v_s H}{r}$$

$$H \sim \frac{v_s r}{v_K}$$

$$\rho \approx 169 \frac{f_{\rm Edd}^{11/20}}{\tilde{r}^{15/8}} \left(1 - \sqrt{\frac{\tilde{r}_{\rm in}}{\tilde{r}}}\right)^{11/20} \left(\frac{0.1}{\alpha}\right)^{7/10} \left(\frac{10^6 M_\odot}{M}\right)^{7/10} \mathrm{kg/m^3}$$

$$\frac{\Delta M}{M} \sim \frac{2\pi \rho r H \Delta r}{M} \sim 5 \times 10^{-9} \left(\frac{0.1}{\alpha}\right)^{4/5} \left(\frac{M}{10^6 M_\odot}\right)^{6/5} f_{\rm Edd}^{7/10} \left(1 - \sqrt{\frac{\tilde{r}_{\rm in}}{\tilde{r}}}\right)^{7/10} \tilde{r}^{1/4} \Delta\tilde{r}$$

Gravitational pull ~ 2nd order SF

Accretion/dynamical friction

Accretion

$$\frac{\Delta M}{M} = \frac{\dot{M}\Delta t}{M} = 2.2\, f_{\rm Edd} \times 10^{-8}$$

Larger than 2nd order SF!

Dynamical friction

$$\dot{E}_{\rm DF} = F_{\rm DF} v_K \sim 4\pi\rho \frac{(G m_{\rm sat})^2}{v_K} I \bar{K}$$

$$\frac{\dot{E}_{\rm DF}}{\dot{E}_{\rm GW}} \sim 5 \times 10^{-7} f_{\rm Edd}^{11/20} \left(\frac{M}{10^6 M_\odot}\right)^{13/10} \left(1 - \sqrt{\frac{\tilde{r}_{\rm in}}{\tilde{r}}}\right)^{11/20} \left(\frac{0.1}{\alpha}\right)^{7/10} \tilde{r}^{29/8} I \bar{K}$$

Dominant at r > 40 M;

~ 2nd order SF at small separations

Planetary-like migration

$$\left(\frac{\dot{L}_{\mathrm{migr\,I}}}{\dot{L}_{\mathrm{GW}}}\right)_{\mathrm{thin}} = 10^{-5} f_{\mathrm{Edd}}^{2/5} \left(\frac{M}{10^6 M_\odot}\right)^{7/5} \left(1-\sqrt{\frac{\tilde{r}_{\mathrm{in}}}{\tilde{r}}}\right)^{2/5} \left(\frac{\alpha}{0.1}\right)^{-3/5} \tilde{r}^{7/2},$$

$$\left(\frac{\dot{L}_{\mathrm{migr\,II}}}{\dot{L}_{\mathrm{GW}}}\right)_{\mathrm{thin}} = 2\times 10^{-4} f_{\mathrm{Edd}}^{9/16} \left(\frac{M}{10^6 M_\odot}\right)^{1/4} \left(1-\sqrt{\frac{\tilde{r}_{\mathrm{in}}}{\tilde{r}}}\right)^{-7/16} \left(\frac{\alpha}{0.1}\right)^{1/2} \left(\frac{\nu}{10^{-5}}\right)^{-11/8} \tilde{r}^{103/32}$$

Dominates over GW fluxes at r>20-30 M, larger than 2nd SF at all separations

Dark matter

Gravitational pull

$$\frac{\Delta M}{M_T} \sim 5\times 10^{-19}\left(\frac{M_T}{10^6 M_\odot}\right)^2\left(\frac{\tilde{r}}{100}\right)^3\left(\frac{\rho_{\rm DM}}{10^3 M_\odot {\rm pc}^{-3}}\right)$$

(Collisionless) accretion (because BH size >> MFP)

$$\frac{\Delta M}{M} \sim 5\times 10^{-14}\left(\frac{M}{10^6 M_\odot}\right)\left(\frac{\rho_{\rm DM}}{10^3 M_\odot {\rm pc}^{-3}}\right)\left(\frac{T}{1\,{\rm yr}}\right)\left(\frac{\sigma_v}{220\,{\rm km/s}}\right)^{-1}$$

Dynamical friction

$$\frac{\dot{E}_{\rm DF}}{\dot{E}_{\rm GW}} \sim 2\times 10^{-14}\left(\frac{M_T}{10^6 M_\odot}\right)^2\left(\frac{\rho_{\rm DM}}{10^3 M_\odot {\rm pc}^{-3}}\right)\left(\frac{\tilde{r}}{100}\right)^{11/2}\ln\left(\frac{r}{r_{\rm min}}\right)$$

Neglibigle unless HUGE cusps near the BH (Silk & Gondolo 1999); for comparison, local DM density is ~ 10^{-2} Msun/pc^3

More effects…

BH electric charge:

- Discharged by Schwinger pair-production and/or by vacuum breakdown triggering electron positron cascade
- Intergalactic or accretion disk plasma sufficient to neutralize any charged BH, because electrons have a huge charge-to-mass ratio (accretion of ~ 10^{-21} M sufficient to neutralize even an extremely charged BH)
- But charge can be induced by external B (Wald 1974)

$$q \lesssim 1.7 \times 10^{-6} \frac{M}{10^6 M_\odot} \frac{B}{10^8 \mathrm{Gauss}} \quad \longrightarrow \quad q \ll 10^{-3}$$

More effects…

- Stellar perturbers: probably unlikely because

1. binary separation << interstellar distance (even in dense nuclei)

1. Two-body scattering timescale ~ Gyr >> radiation reaction time

BUT if we’re lucky this may be observable! (Amaro-Seone+ 2011)

- Other possibility: 2nd SMBH at ~ 0.1 pc distance (Yunes, Miller & Thornburg 2011)

Environmental effects, orders of magnitude

EMRI, 1y inspiral; EB, Cardoso and Pani 2014

Correction	$\lvert\delta_\varphi\rvert/P$	P
planetary migration	$< 10^4$	cf. Refs. [46, 47]
thin accretion disks (DF)	$\lesssim 10^2$	$f_{\rm Edd}\left(\frac{0.1}{\alpha}\right)\left(\frac{\nu}{10^{-5}}\right)^{1/2}\left(\frac{M}{10^6 M_\odot}\right)^{-0.3}$ (cf. Sec. XII J)
thin accretion disks (GP)	$\lesssim 10^{-3}$	cf. Fig. 16
magnetic field	10^{-4}	$\left(\frac{B}{10^8\,{\rm Gauss}}\right)^2\left(\frac{r_f}{6M}\right)^{9/2}\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{c_B(\chi)}{2538}$
charge	10^{-2}	$\left(\frac{q}{10^{-3}}\right)^2\left(\frac{r_f}{6M}\right)^{3/2}\frac{10^{-5}}{\nu}\frac{c_q(\chi)}{-0.08}$
gas accretion onto the central BH	10^{-2}	$f_{\rm Edd}\left(\frac{M}{10^6 M_\odot}\right)^{-5/8}\left(\frac{\nu}{10^{-5}}\right)^{-3/8}\left(\frac{\tau}{1{\rm yr}}\right)^{5/8}$
thick accretion disks (DF)	10^{-9}	$\frac{f_{\rm Edd}}{10^{-4}}\left(\frac{0.1}{\alpha}\right)\left(\frac{\nu}{10^{-5}}\right)^{0.48}\left(\frac{M}{10^6 M_\odot}\right)^{-0.58}$ (cf. Sec. XII J)
DM accretion onto central BH	10^{-8}	$\left(\frac{M}{10^6 M_\odot}\right)\left(\frac{\langle\rho_{\rm DM}\rangle}{10^3 M_\odot {\rm pc}^{-3}}\right)\left(\frac{T}{1\,{\rm yr}}\right)\left(\frac{\sigma_v}{220\,{\rm km/s}}\right)^{-1}$
thick accretion disks (GP)	10^{-11}	$\frac{f_{\rm Edd}}{10^{-4}}\left(\frac{r_f}{6M}\right)^4\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{0.1}{\alpha}\frac{c_{\hat\alpha=3/2}(\chi)}{0.3}$
DM distribution (DF)	10^{-14}	$\left(\frac{\langle\rho_{\rm DM}\rangle}{10^3 M_\odot/{\rm pc}^3}\right)\left(\frac{\nu}{10^{-5}}\right)^{0.65}\left(\frac{M}{10^6 M_\odot}\right)^{0.17}$
DM distribution $\rho\sim r^{-\hat\alpha}$ (GP)	10^{-16}	$\left(\frac{R}{7\times10^6 M}\right)^{\hat\alpha}\frac{\langle\rho_{\rm DM}\rangle}{10^3 M_\odot/{\rm pc}^3}\left(\frac{r_f}{6M}\right)^{11/2-\hat\alpha}\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{c_{\hat\alpha}(\chi)}{0.15}$
galactic DM halos	10^{-16}	$\frac{\langle\rho_{\rm DM}\rangle}{10^3 M_\odot/{\rm pc}^3}\left(\frac{r_f}{6M}\right)^{11/2}\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{c_\Lambda(\chi)}{68}$
cosmological constant	10^{-26}	$\frac{\Lambda}{10^{-52}{\rm m}^{-2}}\left(\frac{r_f}{6M}\right)^{11/2}\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{c_\Lambda(\chi)}{68}$

$$\varphi = \varphi_{\rm GR} + \delta_\varphi$$

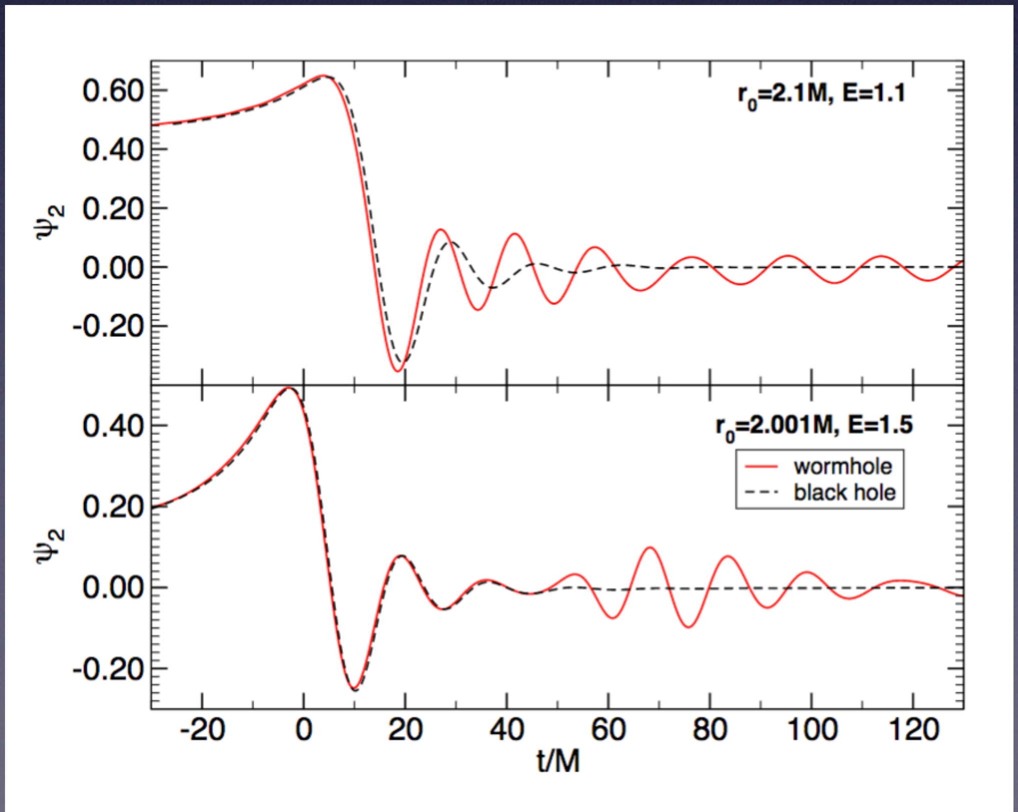
EMRIs: ~10^4-10^5 cycles in band

Extrapolation to q ~ 1 shows all effects are negligible at least at r < 60-70 M for MBH binaries

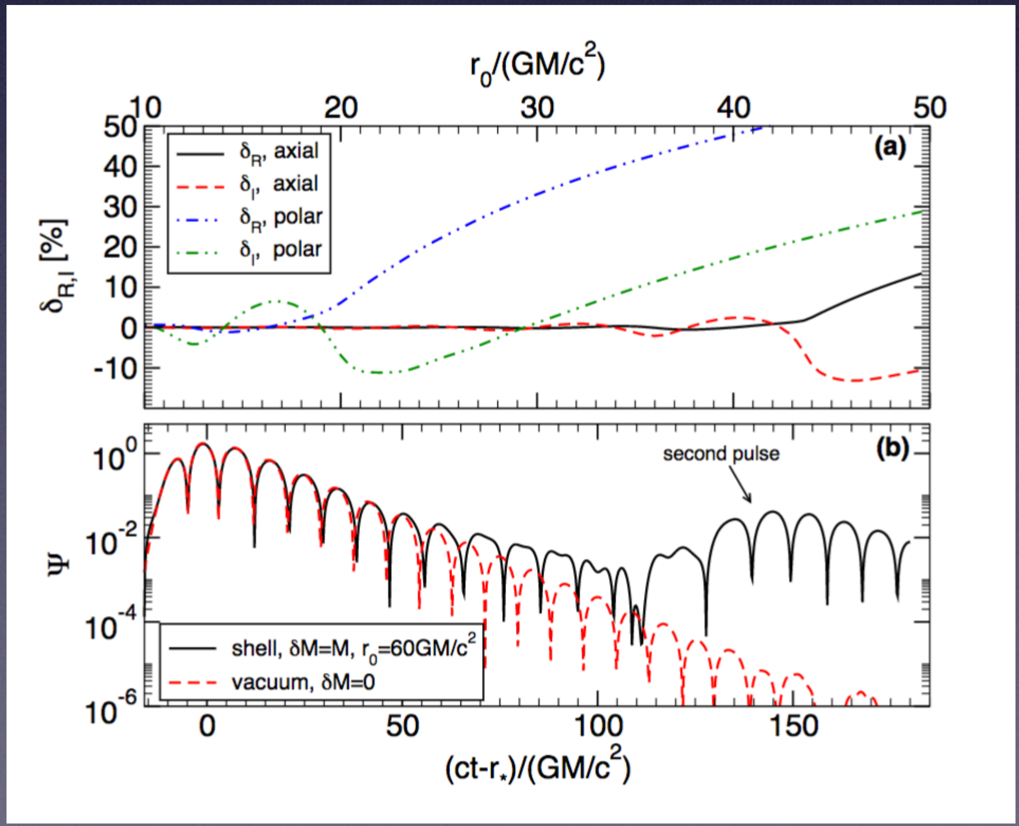
RD's sensitivity to near horizon/far away physics

- Deviations away from Kerr geometry near horizon (e.g. firewalls, gravastars, wormholes, etc) can produce significant changes in QNM spectrum
- Deviations take $\Delta t \sim \log[r_0/(2M) - 1]$ to show up in time-domain signal because QNMs generated at the circular null orbit (Damour & Solodukhin 2007, EB, Cardoso & Pani 2014, Cardoso, Franzin & Pani 2016) and coordinate time diverges on horizon
- Same effect with "bumps" in the potential far from the BH

Schwarzschild BH of mass M+thin shell of 0.01 M at r_0



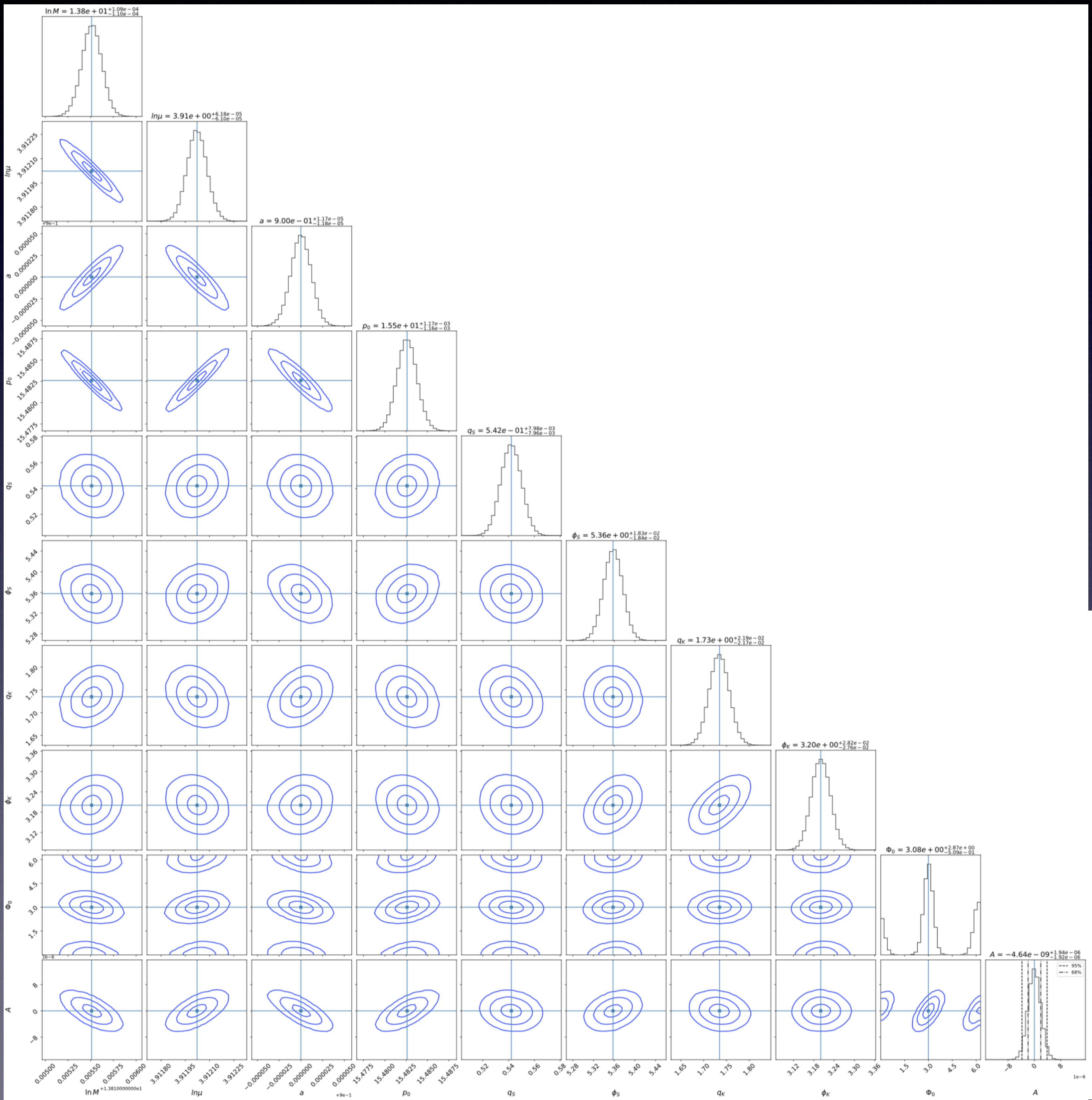
Cardoso, Franzin & Pani 2016



EB, Cardoso & Pani 2014

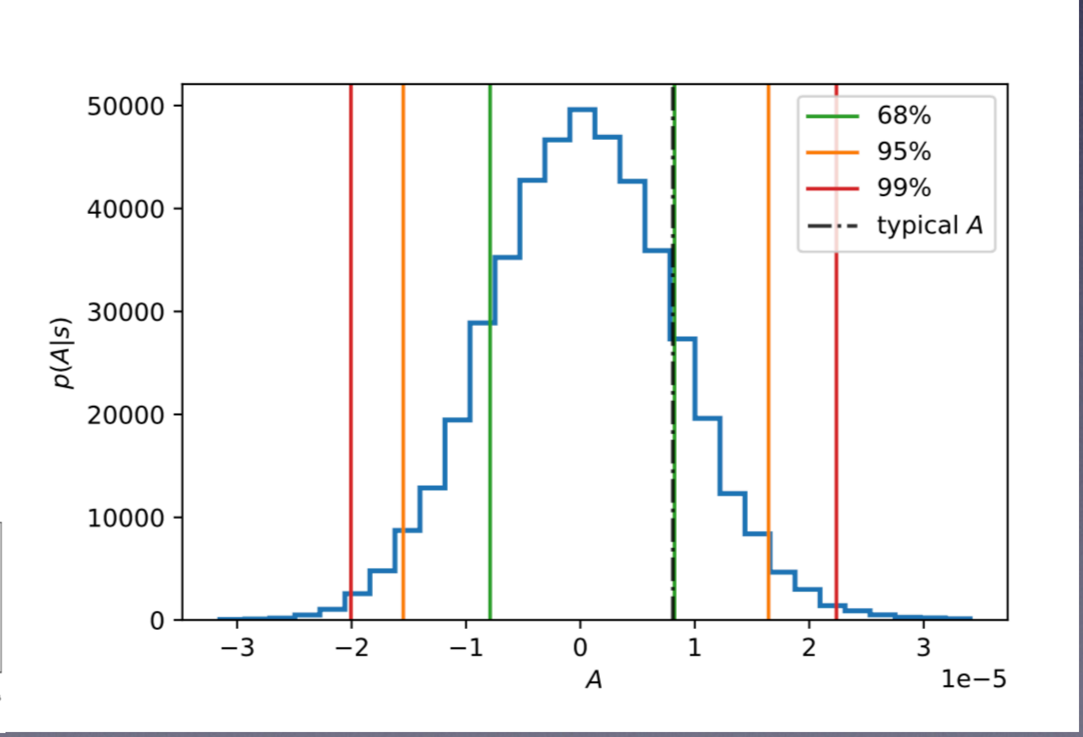
r_0 =60 M, shell of mass M,
Gaussian wavepacket initially at ISCO

Preliminary PE EMRI results

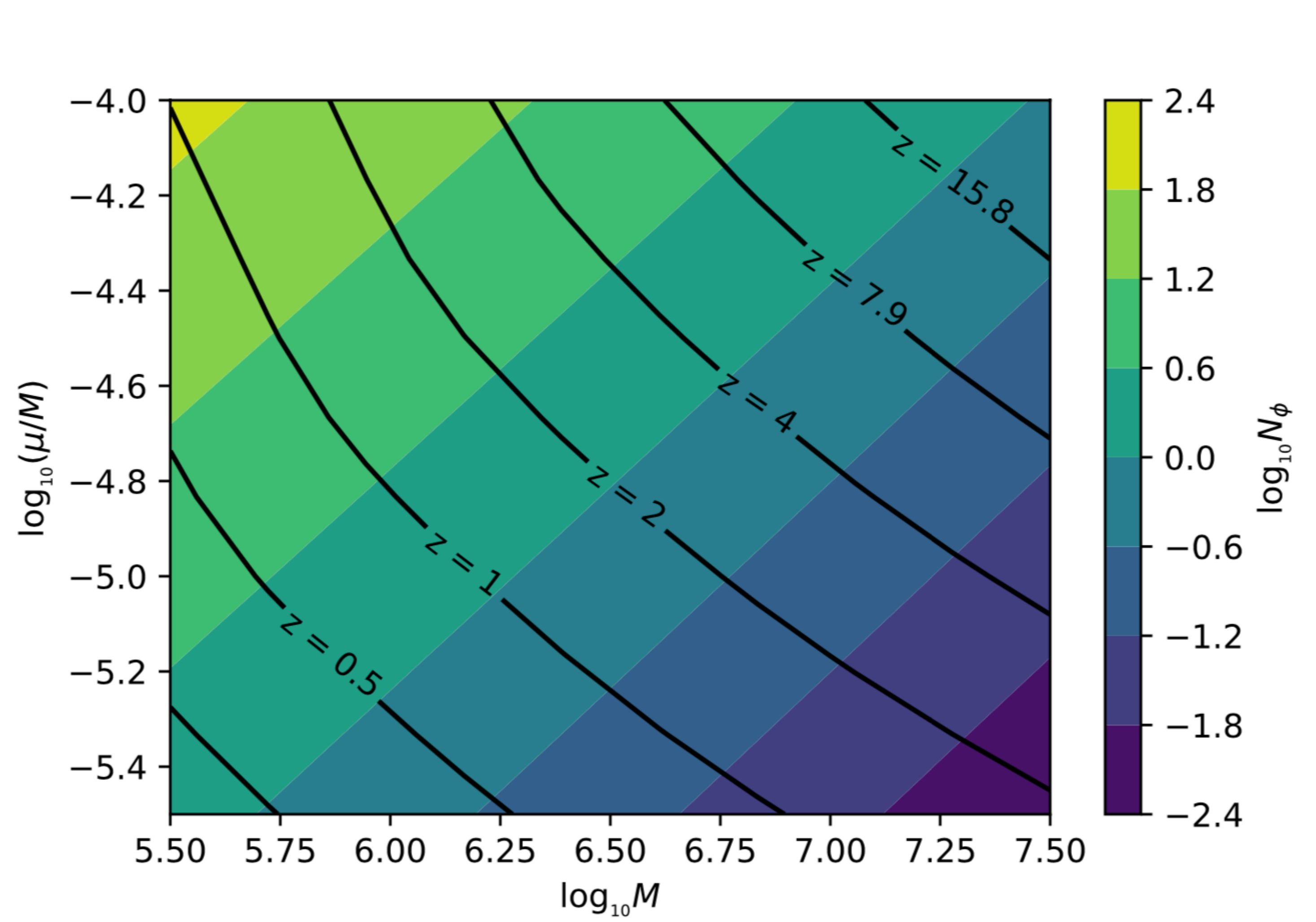


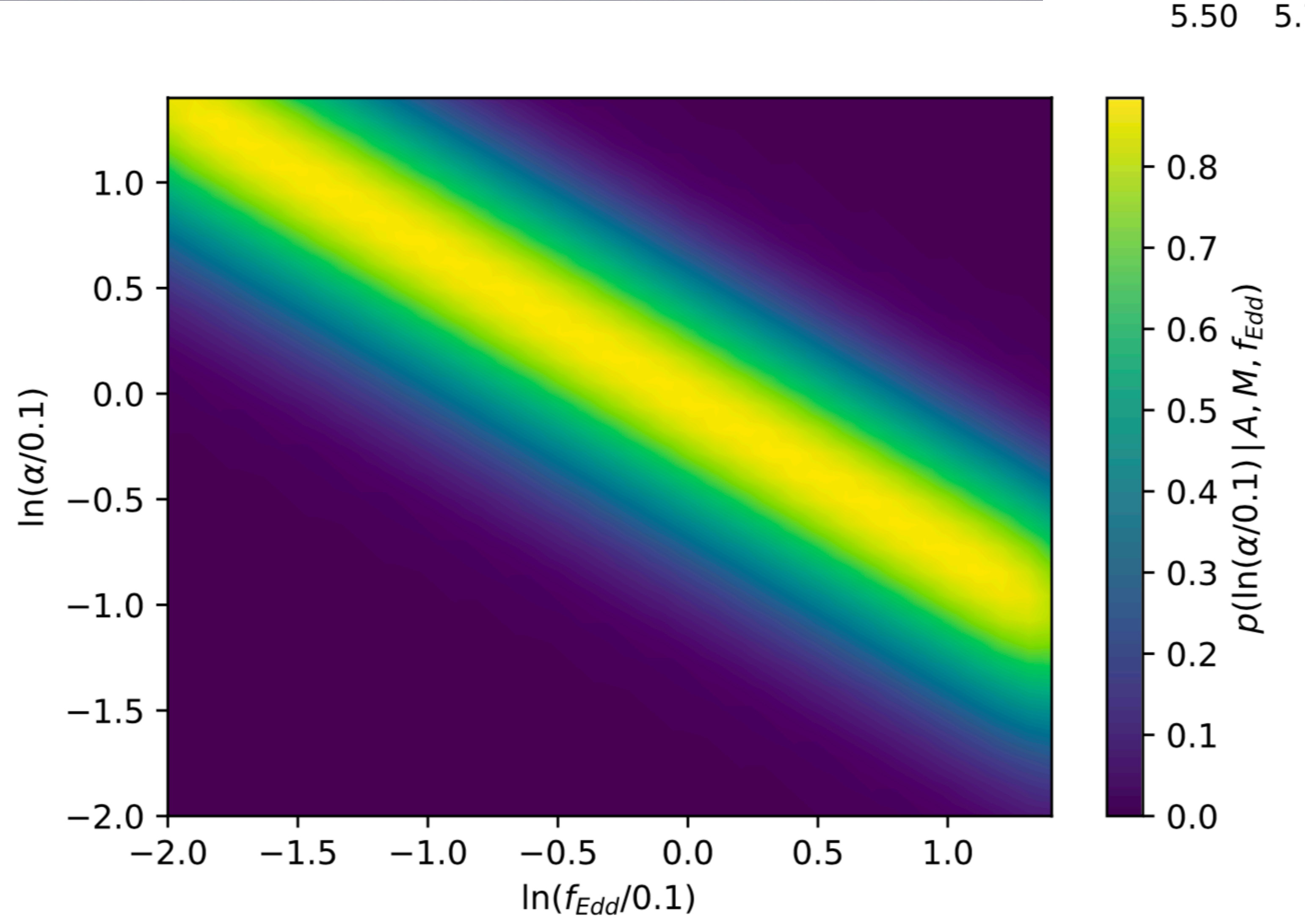
$$A \sim \dot{L}_{\rm migr}/\dot{L}_{\rm gw}$$

Antonelli, Sberna, Speri
et al in prep



Preliminary PE EMRI results

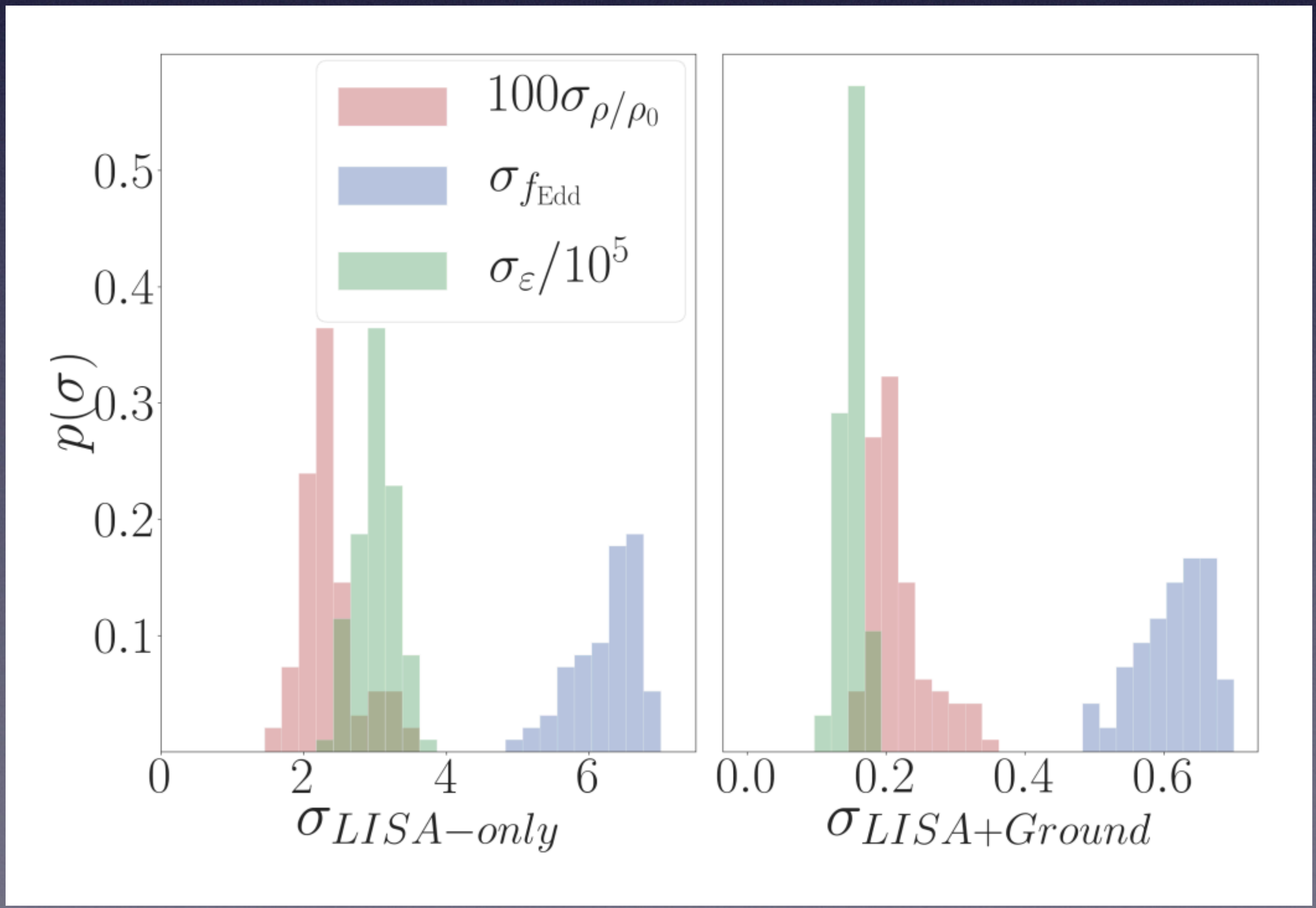


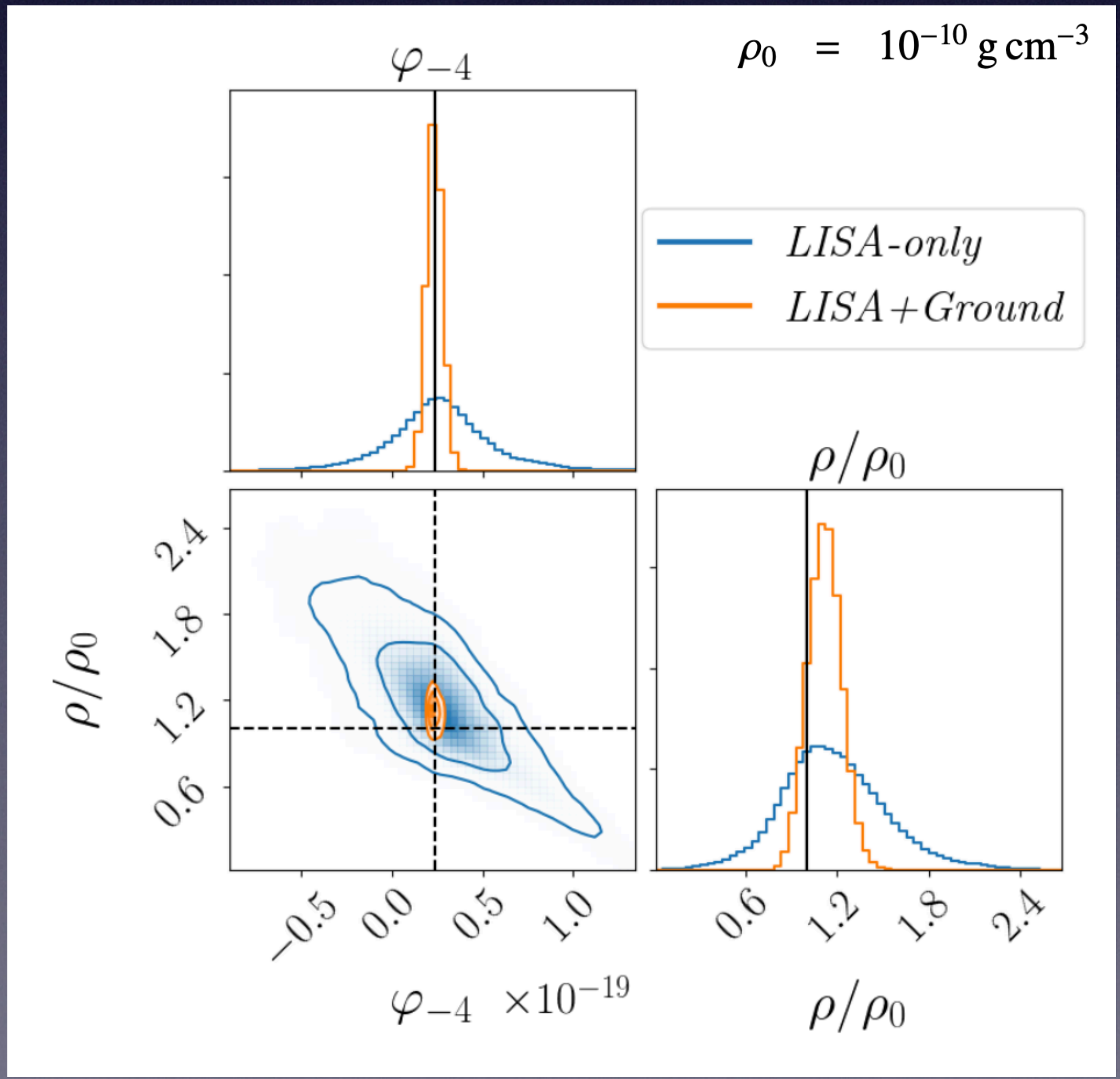


Antonelli, Sberna, Speri
et al in prep

Matter effects in SOBHBs

- Possibly detectable in SOBHBs formed near AGNs (GW190521), see Toubiana+21
- Gas accretion, dynamical friction, and orbital motion around the AGN's massive black hole (acceleration/Doppler, strong lensing and Shapiro time delay, precession)





SOBHBs as probes of AGN physics

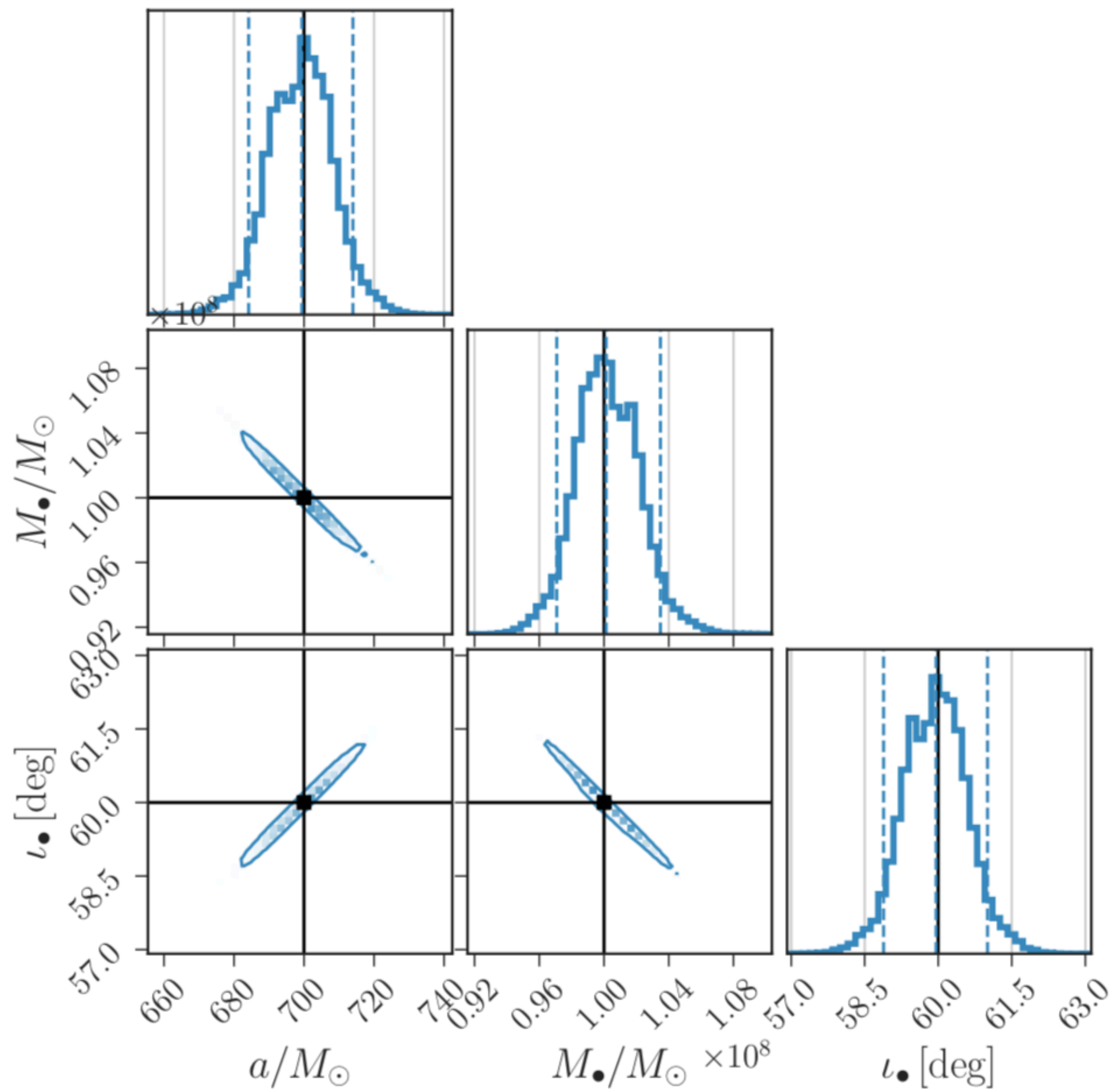
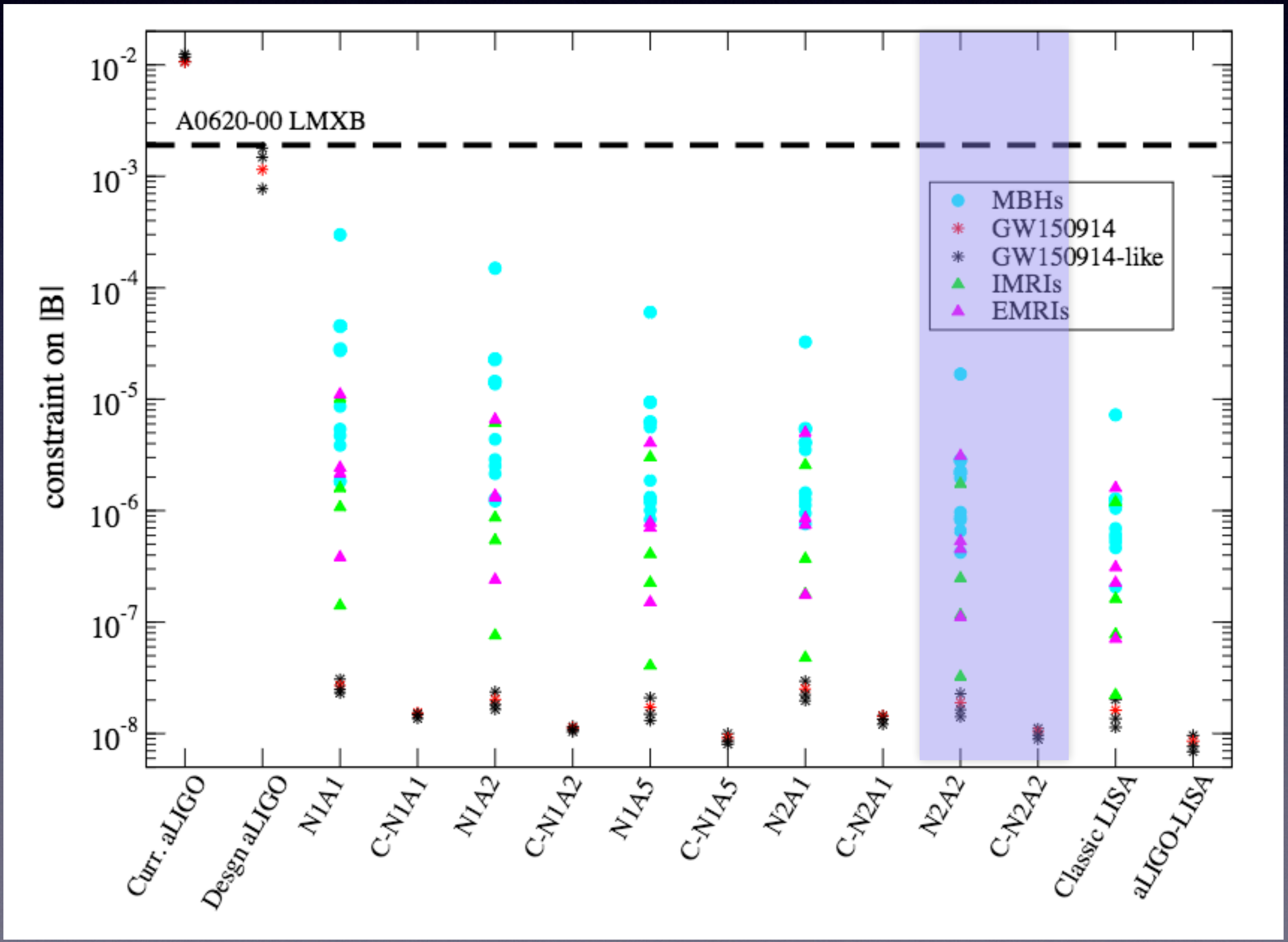


FIG. 5. Inference of the SMBH mass ($M_\bullet$) and the parameters of the outer orbit: inclination $\iota_\bullet$ and orbital radius a. The true (redshifted) parameters are marked by black lines.

Doppler+Shapiro only;
Sberna+ in prep 22

Systematics in GR tests

Environmental pollution of GR tests worrisome as both low frequency effects



$$\dot{E}_{\mathrm{GW}} = \dot{E}_{\mathrm{GR}} \left[1 + B \left(\frac{Gm}{r_{12}c^2} \right)^{-1} \right]$$

From EB, Yunes & Chamberlain 2016

Systematics in GR tests

$$S = \frac{c^4}{16\pi\mathcal{G}}\int dx^4\sqrt{-g}\left[R+\partial^2\boldsymbol{\Psi}+\sum_i a_i U_i(\boldsymbol{\Psi},\boldsymbol{g},\partial\boldsymbol{\Psi},\partial\boldsymbol{g},...)\right]$$
$$+ \quad S_m^{(0)}[\boldsymbol{\Psi}_m, g_{\mu\nu}] + \sum_i b_i S_{m,i}^{(1)}[\boldsymbol{\Psi}_m,\boldsymbol{\Psi},\boldsymbol{g},...]\,,$$

	Intrinsic lower bound				
Theory	magnetic fields	Pull of DM profile $\rho\sim\rho_0(R/r)^{3/2}$	Pull of disk profile $\rho\sim\rho_0(R/r)^{\hat{\alpha}}$	electric charge	coefficient $\mathcal{T}$
BD	$\omega_{\rm BD}^{-1}\gtrsim 10^{-6}\mathcal{P}\mathcal{T}$	$\omega_{\rm BD}^{-1}\gtrsim 10^{-19}\mathcal{P}\mathcal{T}$	$\omega_{\rm BD}^{-1}\gtrsim 10^{-1-5\hat{\alpha}}\mathcal{P}\mathcal{T}$	$\omega_{\rm BD}^{-1}\gtrsim 10^{-15}\mathcal{P}\mathcal{T}$	$\left[\frac{0.1}{S}\right]^2$
EDGB	$\zeta_3\gtrsim 10^{-12}\mathcal{P}\mathcal{T}$	$\zeta_3\gtrsim 10^{-25}\mathcal{P}\mathcal{T}$	$\zeta_3\gtrsim 10^{-7-5\hat{\alpha}}\mathcal{P}\mathcal{T}$	$\zeta_3\gtrsim 10^{-21}\mathcal{P}\mathcal{T}$	$\left[\frac{\nu}{0.1}\right]^4\left[\frac{1}{\delta_m}\right]^2$
DCS	$\zeta_4\gtrsim 10^{6}\mathcal{P}\mathcal{T}$	$\zeta_4\gtrsim 10^{-7}\mathcal{P}\mathcal{T}$	$\zeta_4\gtrsim 10^{-7-5\hat{\alpha}}\mathcal{P}\mathcal{T}$	$\zeta_4\gtrsim 10^{-3}\mathcal{P}\mathcal{T}$	$\left[\frac{\nu}{0.1}\right]^2 v_3^{-6}\left[\frac{1}{\beta_{\rm dCS}}\right]$
Æ/Hořava	$\mathcal{F}\gtrsim 10^{-9}\mathcal{P}\mathcal{T}$	$\mathcal{F}\gtrsim 10^{-22}\mathcal{P}\mathcal{T}$	$\mathcal{F}\gtrsim 10^{-4-5\hat{\alpha}}\mathcal{P}\mathcal{T}$	$\mathcal{F}\gtrsim 10^{-18}\mathcal{P}\mathcal{T}$	1
coefficient $\mathcal{P}$	$B_8^2 M_{10}^2 v_3^{-4}$	$\rho_3^{\rm DM} M_{10}^2 v_3^{-1} R_{\rm DM}^{3/2}$	$\gamma_{\hat{\alpha}}\rho_2^{\rm disk} M_{10}^2 v_3^{2\hat{\alpha}-4} R_{10}^{\hat{\alpha}}$	$q_3^2 v_3^4$	

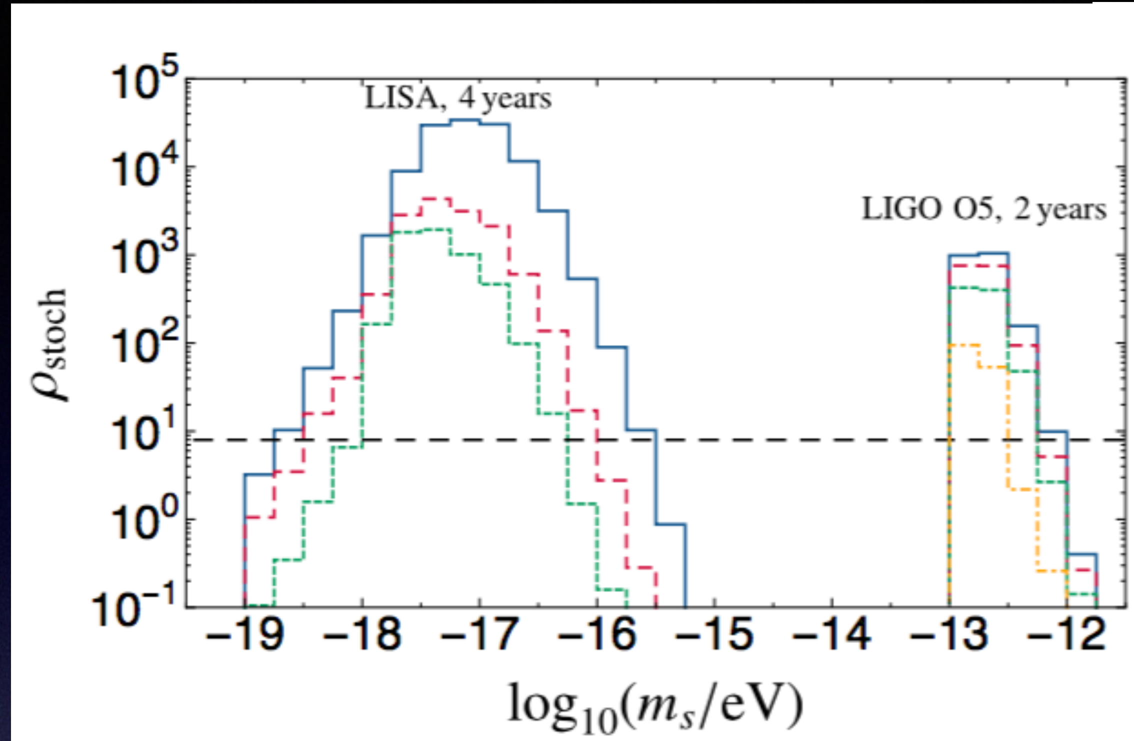
EB, Cardoso and Pani 2014

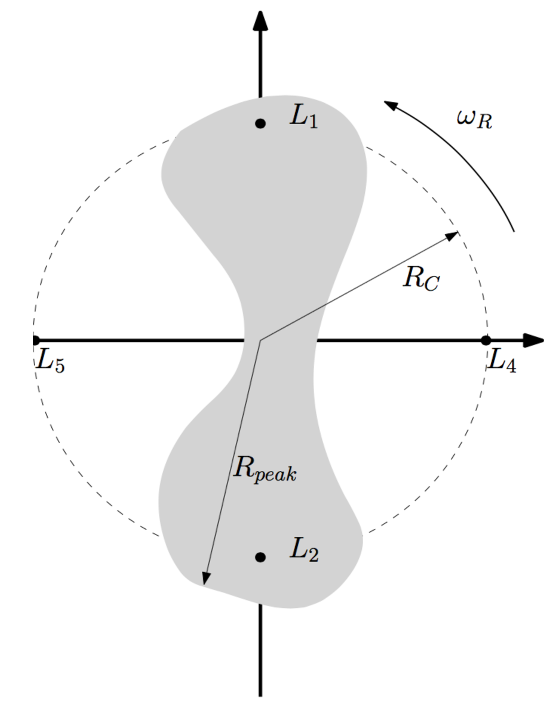
Constraints on axions/fuzzy DM

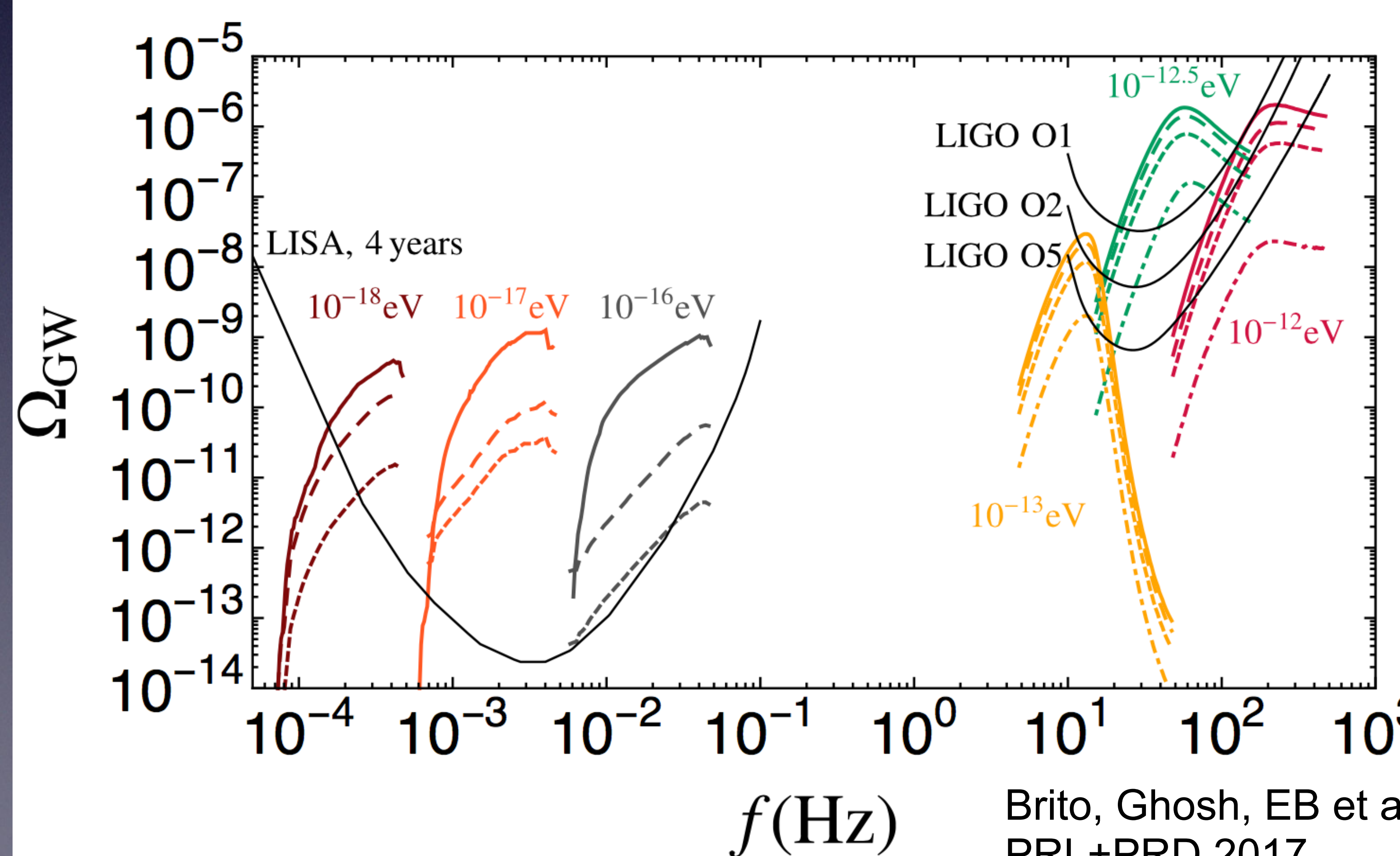
- Isolated spinning BH + massive scalar fields with Compton wavelength comparable to event horizon radius are unstable under super-radiance
- Mass and (mostly) angular momentum are transferred from BH to scalar condensate surrounding BH on instability timescale; condensate then emits almost monochromatic waves on timescale
- Observable by LIGO/LISA as stochastic background and resolved sources

$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9 {\rm yr}\,,$$

$$\tau_{\rm GW} \sim 6\times 10^4\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15} {\rm yr}\,.$$



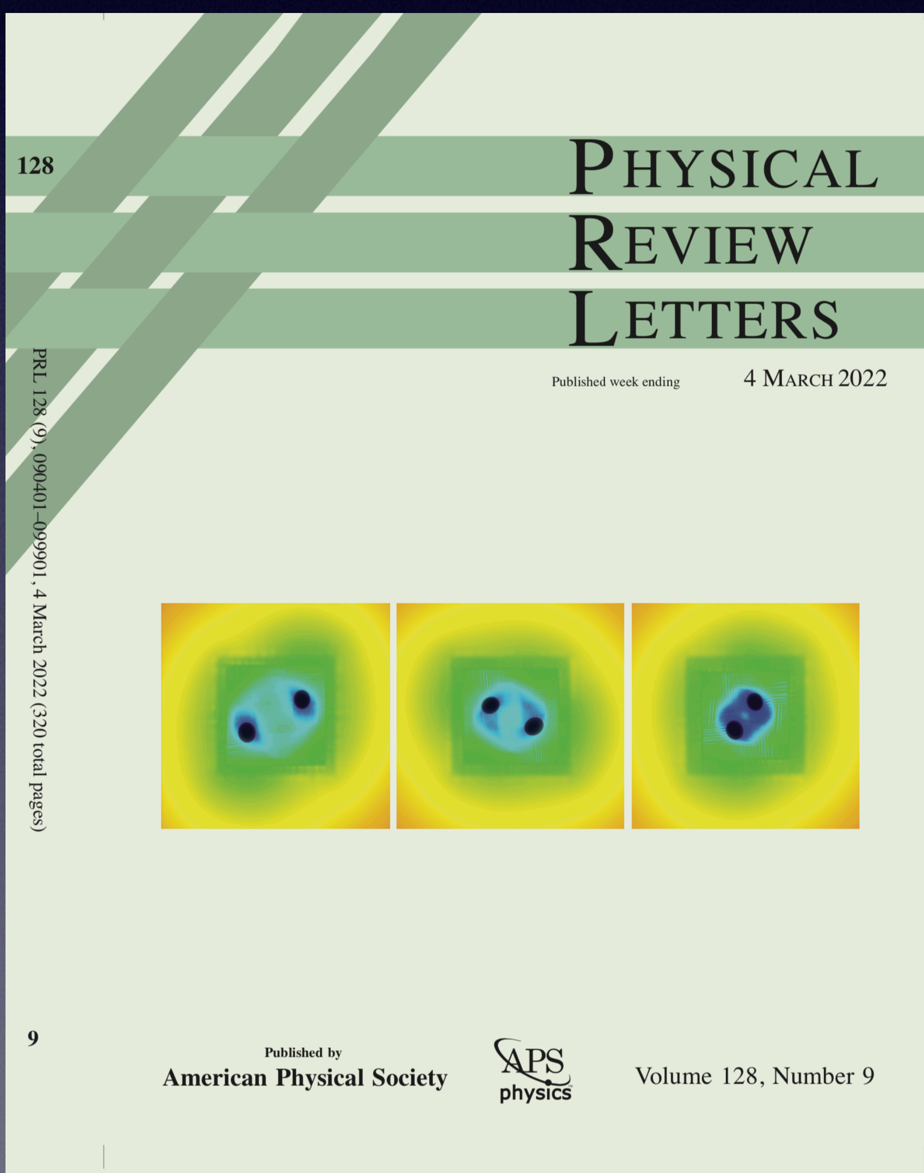


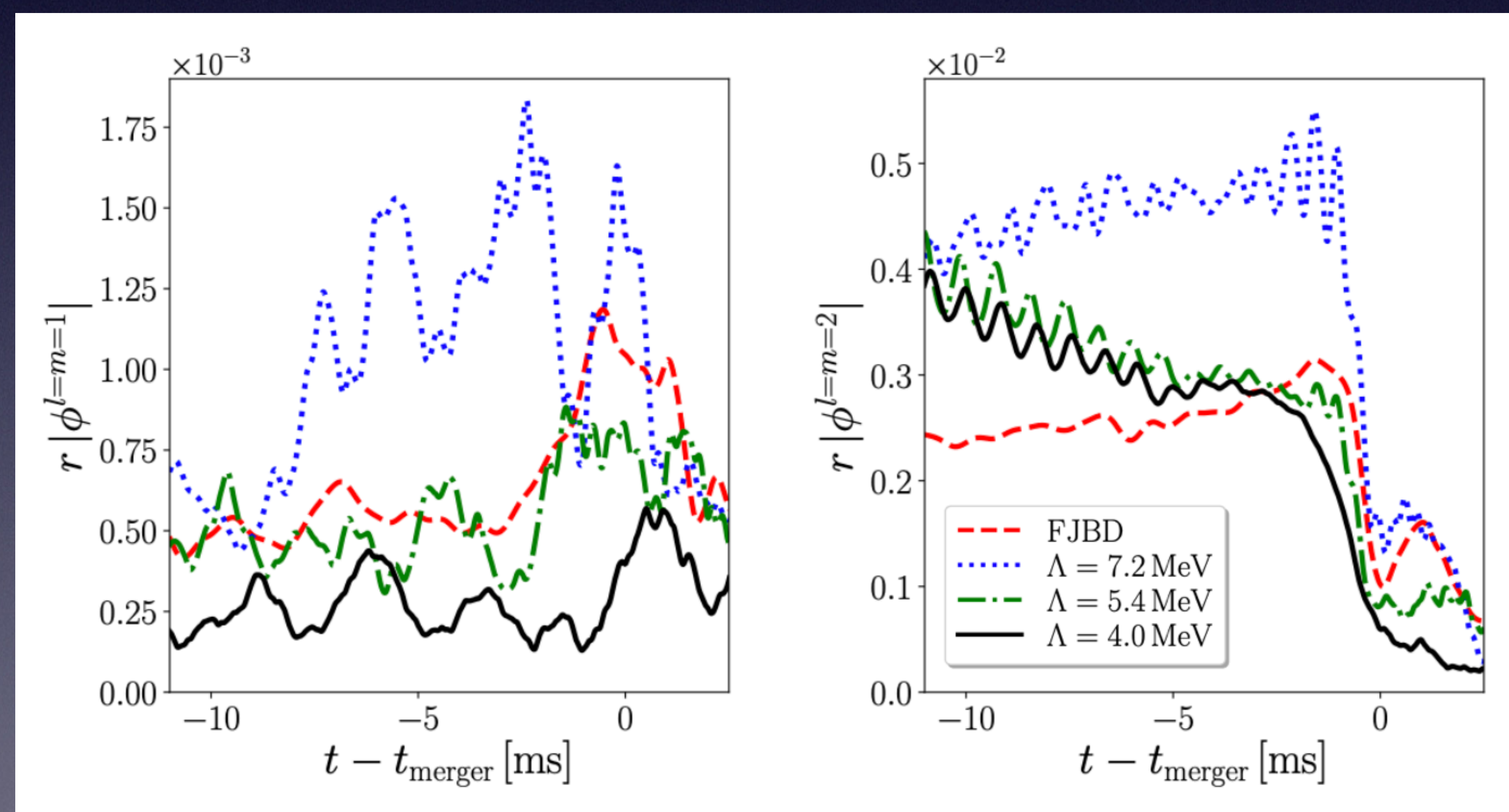


Brito, Ghosh, EB et al,
PRL+PRD 2017

GW emission in EFTs of Dark Energy

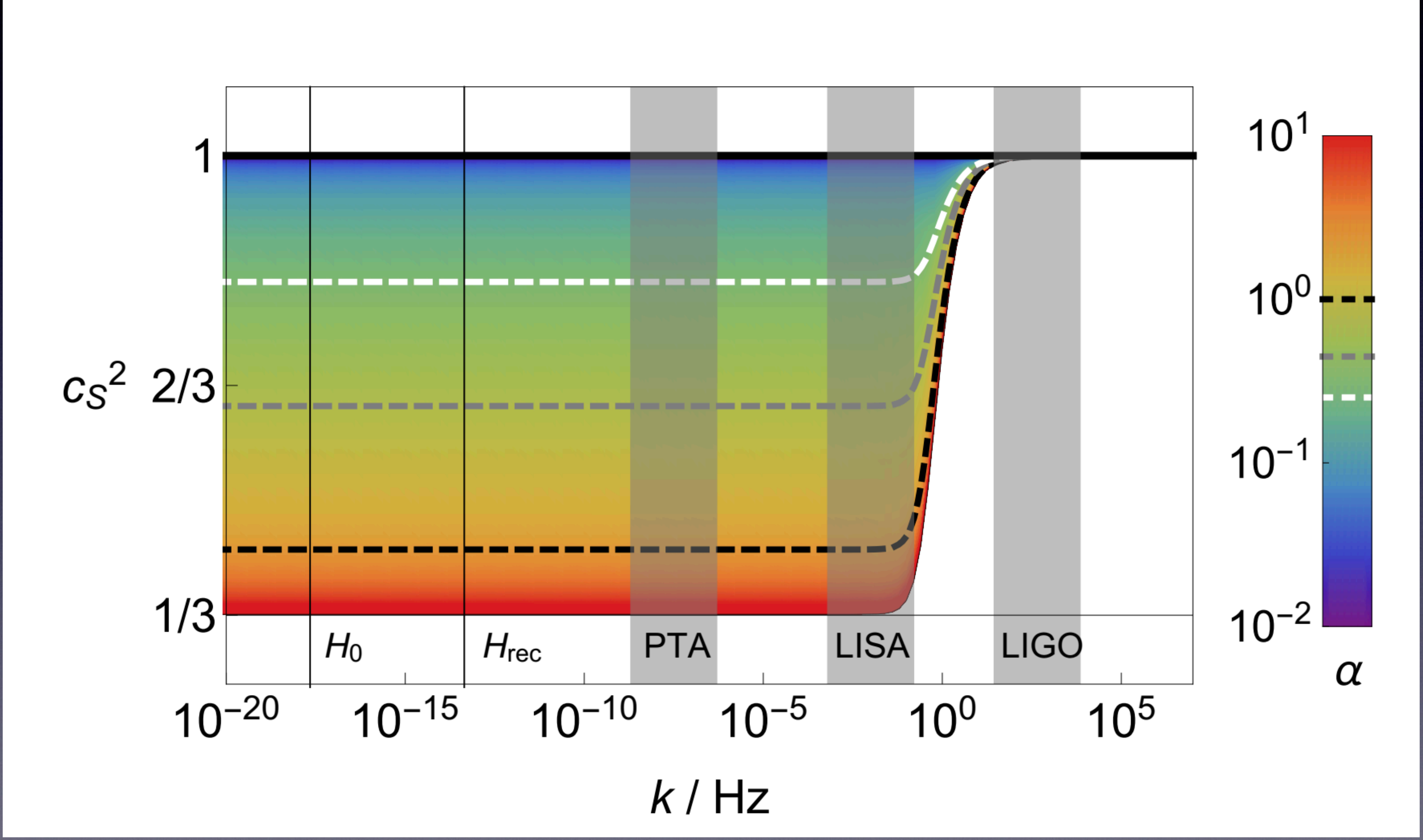
Dipole is suppressed but quadrupole deviations from GR are not, effects appear to grow at low frequencies (ET, binary pulsars, LISA)





Bezares,Aguilera-Miret, ter Haar, Crisostomi, Palenzuela and Barausse,PRL 128 091103 (2022)

GW propagation in EFTs of Dark Energy



De Rham & Melville 2018

Conclusions

- In EMRIs moving in AGN accretion disks, environmental effects (especially planetary migration, dynamical friction and accretion) are comparable to 2nd order SF, and possibly to 1st order SF (in extreme cases)
- Overall, majority of EMRIs should be "matter-free" (for practical purposes) due to 1-10% AGN duty cycle
- SOBHBs may show detectable environmental effects if formed dynamically in AGNs disks (like GW190521?)
- MBHs are probably safe from these effects, at least at $r < 60\text{-}70\ M$
- Environmental effects could "blur" tests of GR, especially at low PN orders
- More exotic environmental effects can be due to axionic DM or near-horizon structure (fuzzballs, firewalls)

Questions

- Surprises? Matter effects we did not think about? On sources we don't not think will be affected?
- What if matter effects are too large? Missed detections?
- How to tell matter from non-GR effects? Stacking/ hierarchical analysis?
- Implications for waveform modeling (eg SF)?
- Agnostic waveform model for matter effects?

Bounds on BH mimickers

- Spinning objects (eg BHs) possess ergoregion, i.e. region where free falling observers cannot be static and need to coronate with BH due to frame dragging
- In ergoregion, negative energy modes can be produced but are confined within ergoregion (only positive energy modes can travel to infinity)
- By energy conservation, more negative energy modes can be produced, which would cause instability save for the existence of BH horizon (which acts as sink)
- BH mimickers with no horizon are unstable (ergoregion or super-radiance instability)
- Constraints on models of “echos” in LIGO signal

EB, Brito, Cardoso, Dvorkin, Pani 2018