Environmental effects for gravitational-wave astrophysics

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H2020-MSCA-RISE-2015 StronGrHEP-690904

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Outline

- The astrophysics of MBHs, AGNs and EMRIs (cf also Stas Babak's talk yesterday and Cole Miller's on Thursday)
- Environmental effects on gravitational waveforms (accretion, planetary migration, dynamical friction, peculiar accelerations, etc) in inspiral, merger and ringdown
- "Exotic" environmental effects
- Implications for SF calculations and GR tests

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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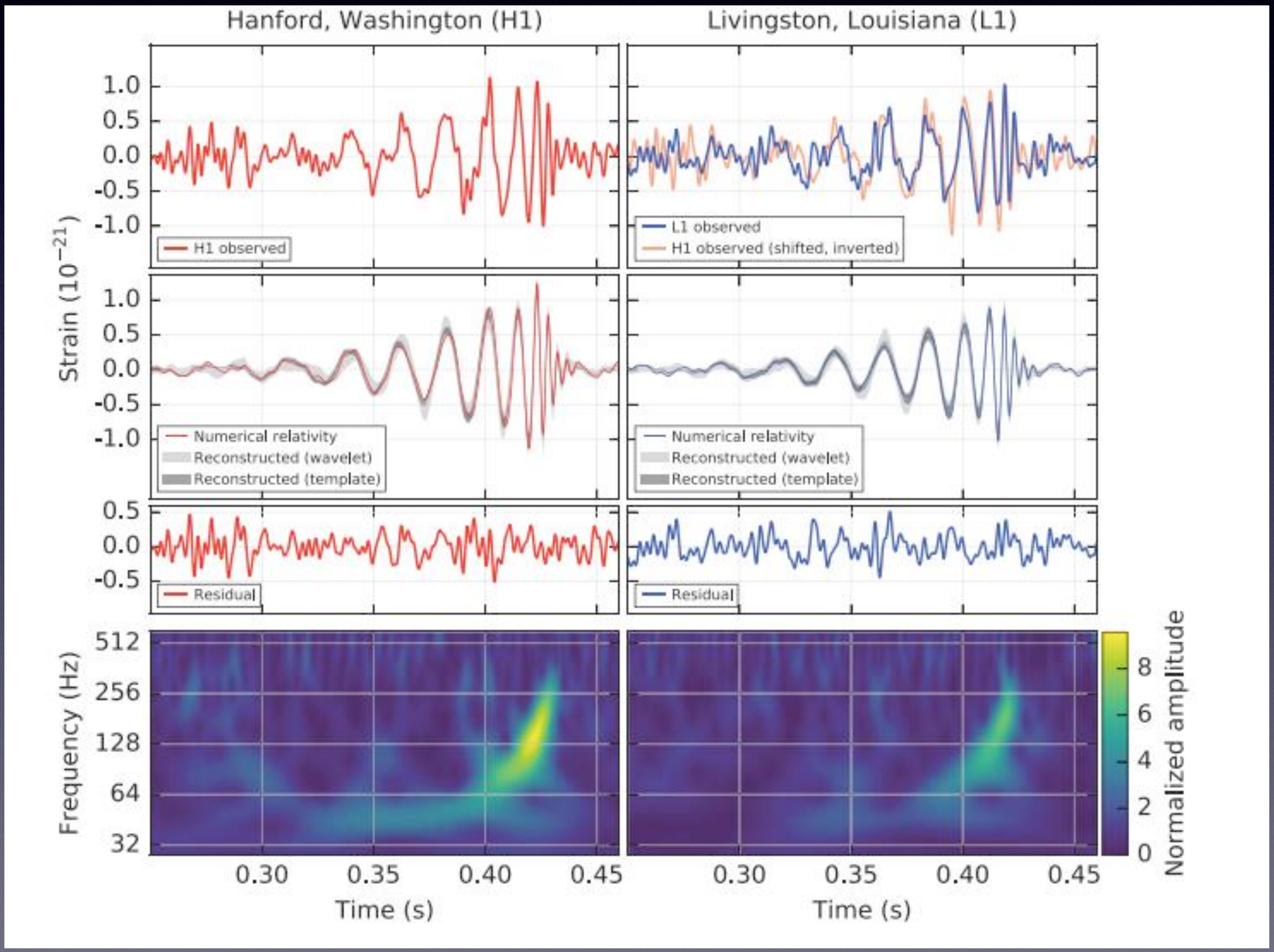
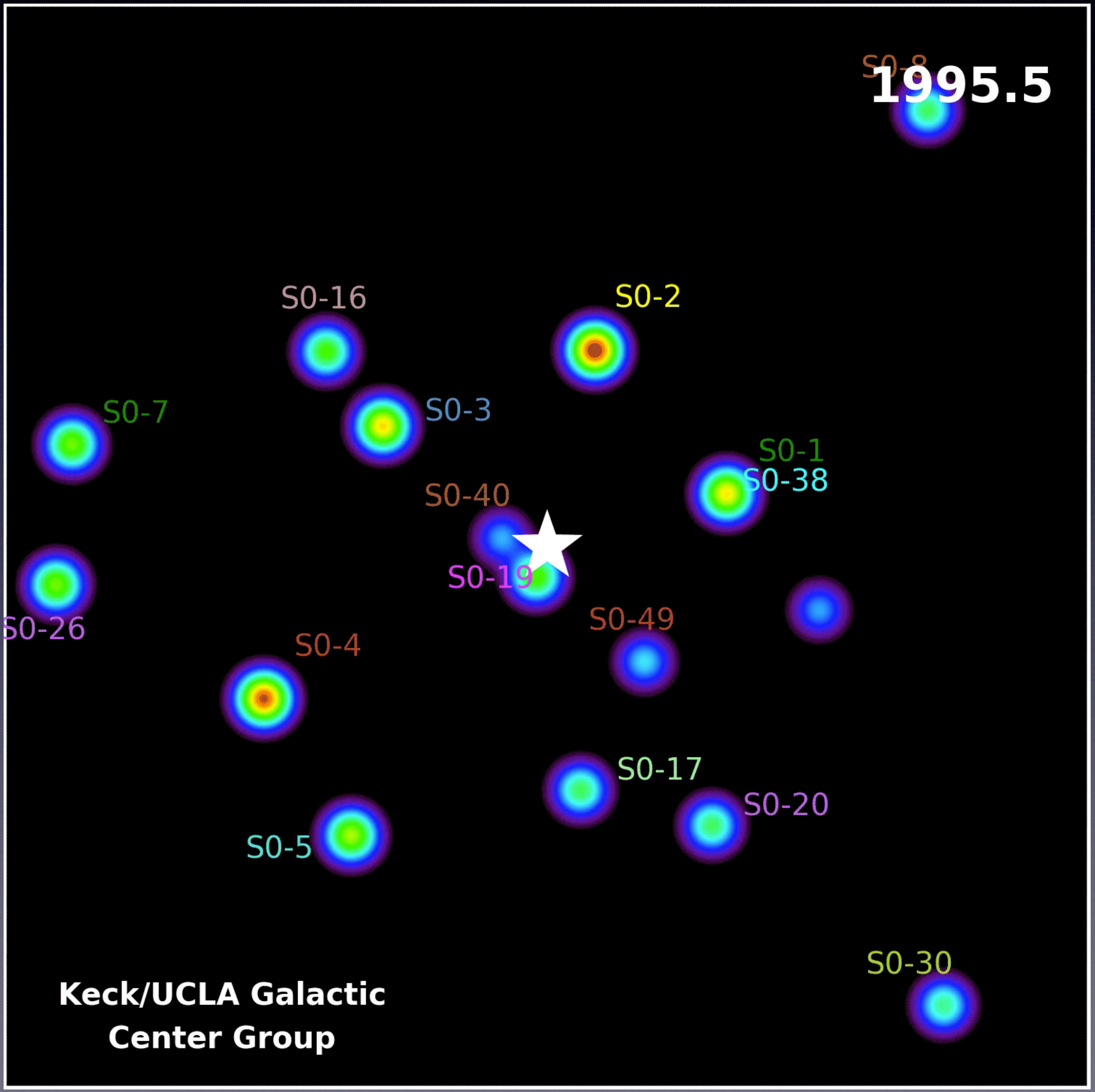
"broad class" = 90-99% of EMRIs

The first direct observation of GWs and … BHs!



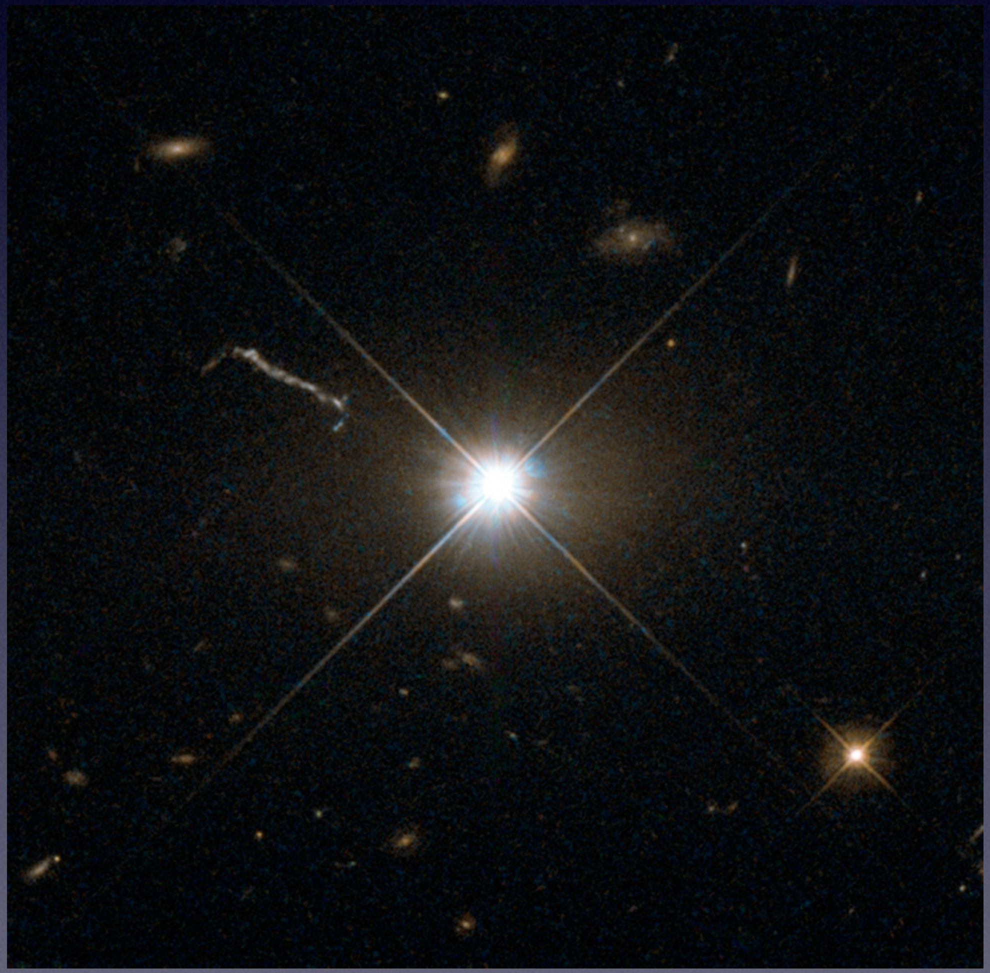
Not the biggest BHs in the Universe!

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

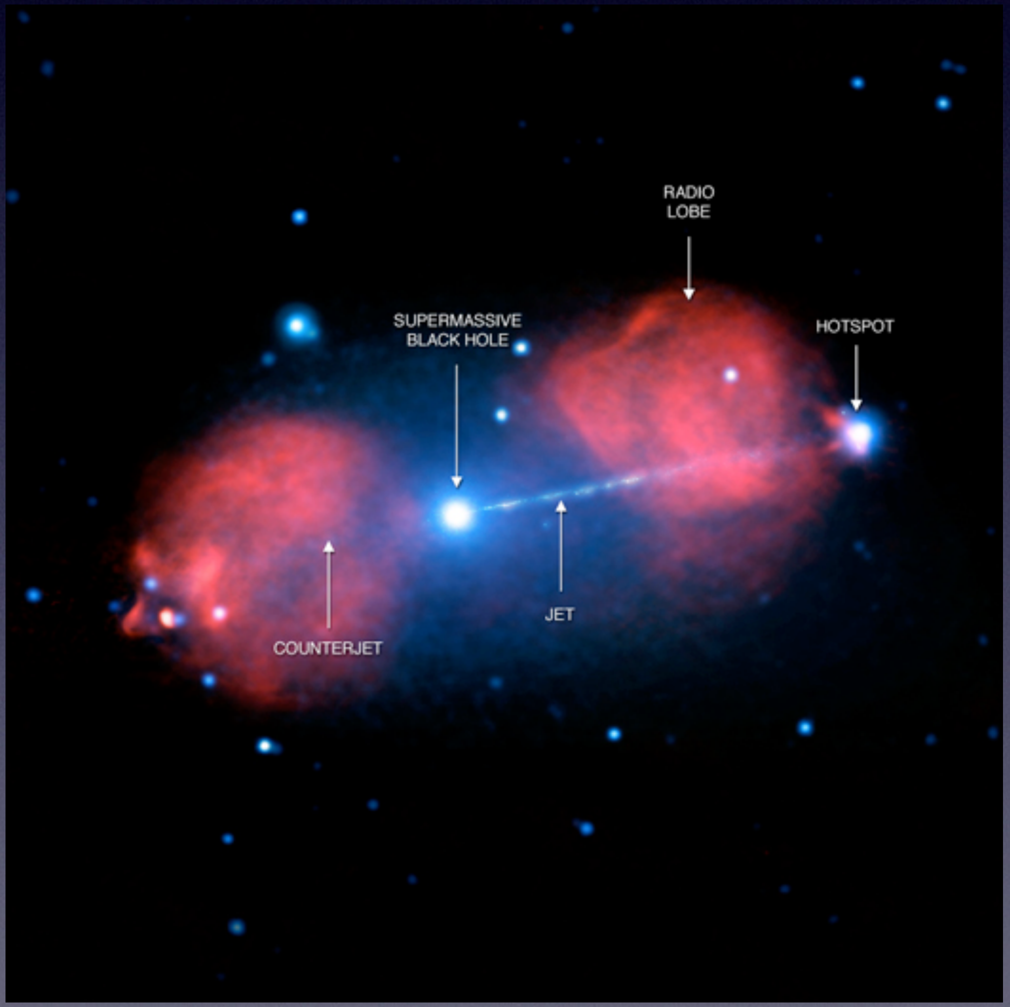


Massive black holes are hosted in (nearly) all galaxies

They power quasars and active galactic nuclei (AGN) that outshine host galaxy



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!

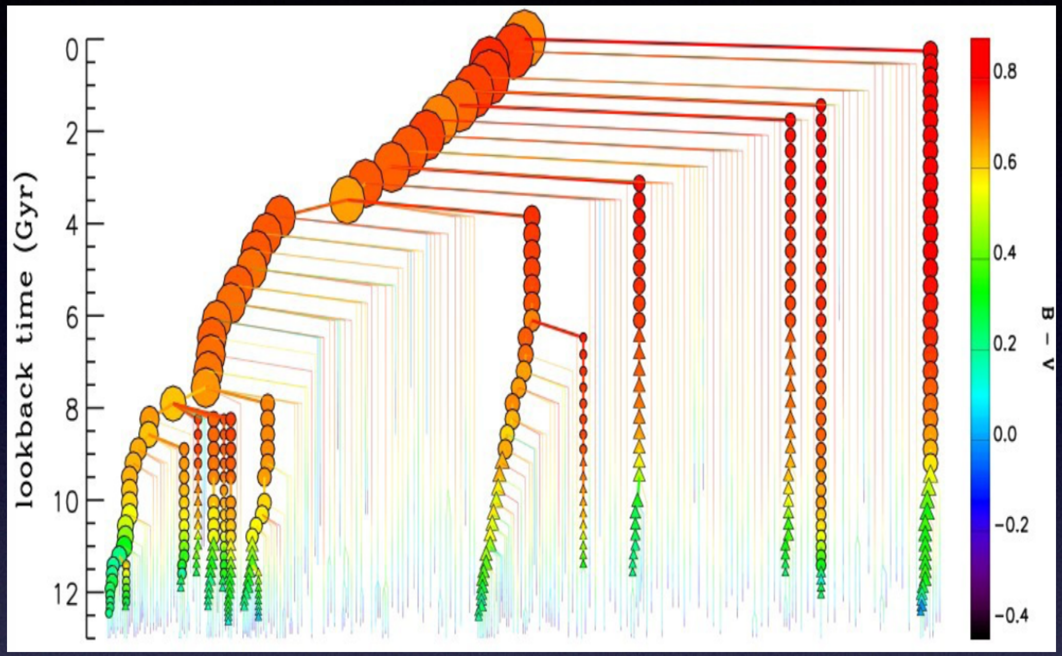


Figure from De Lucia & Blaizot 2007

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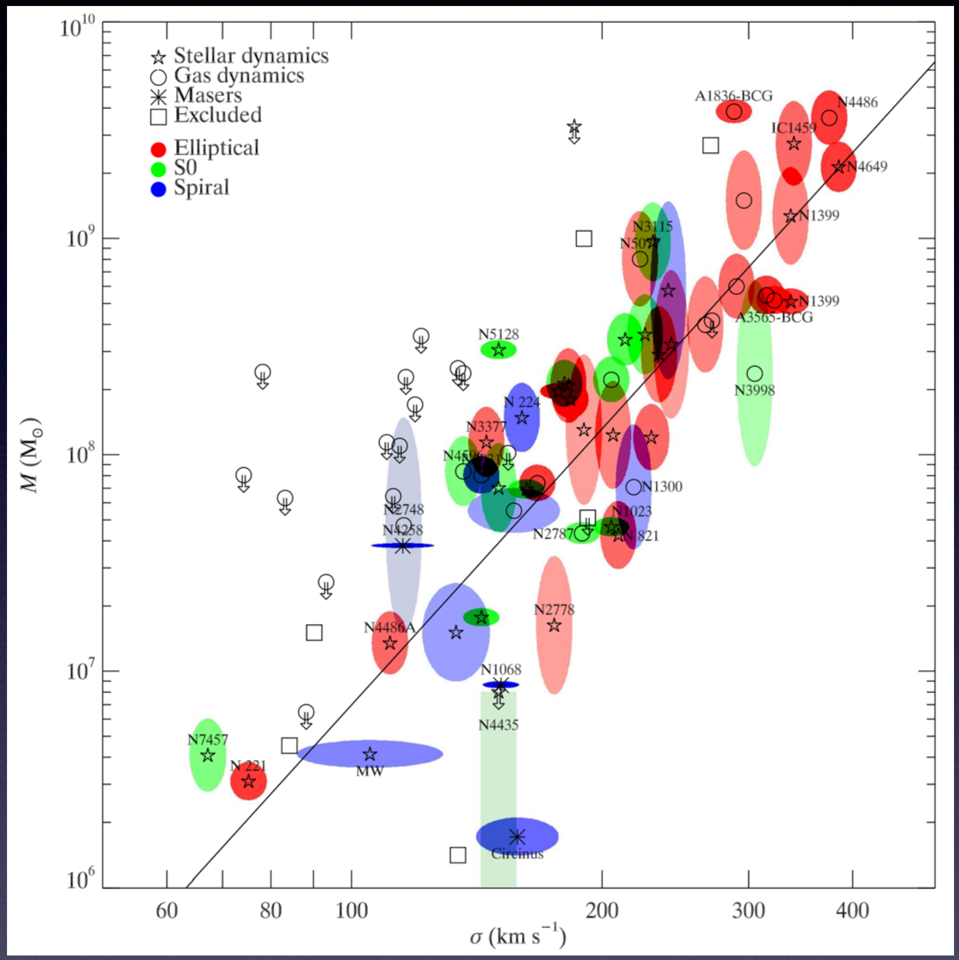

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

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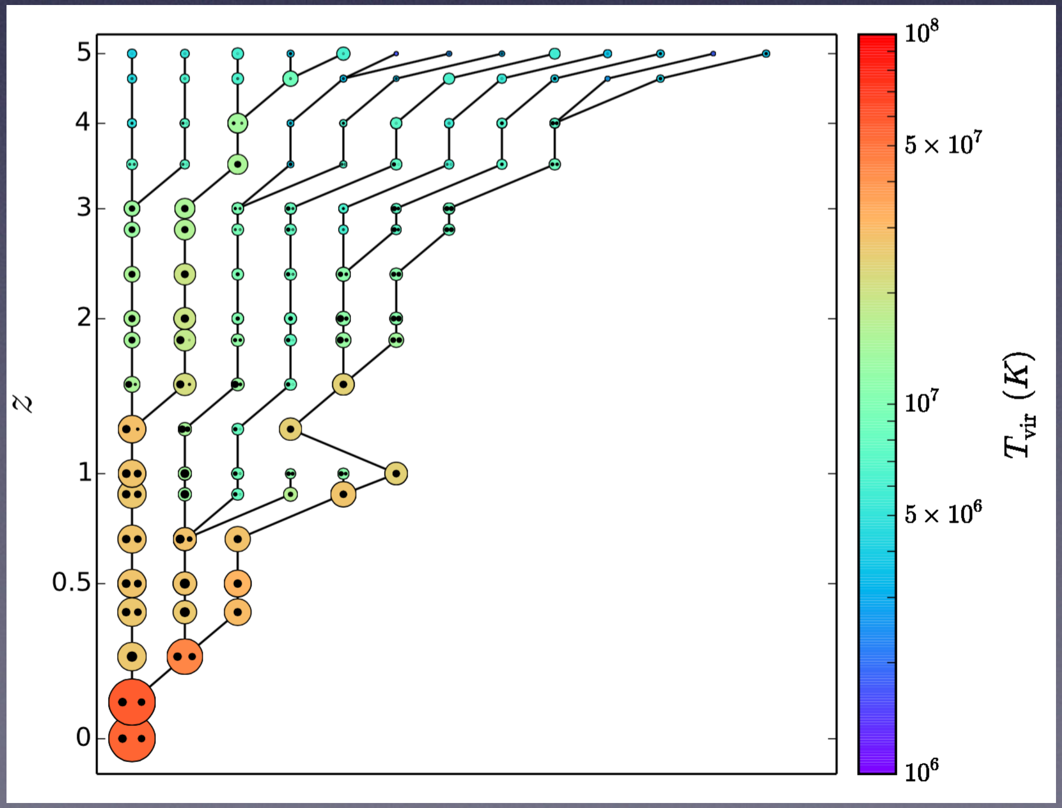
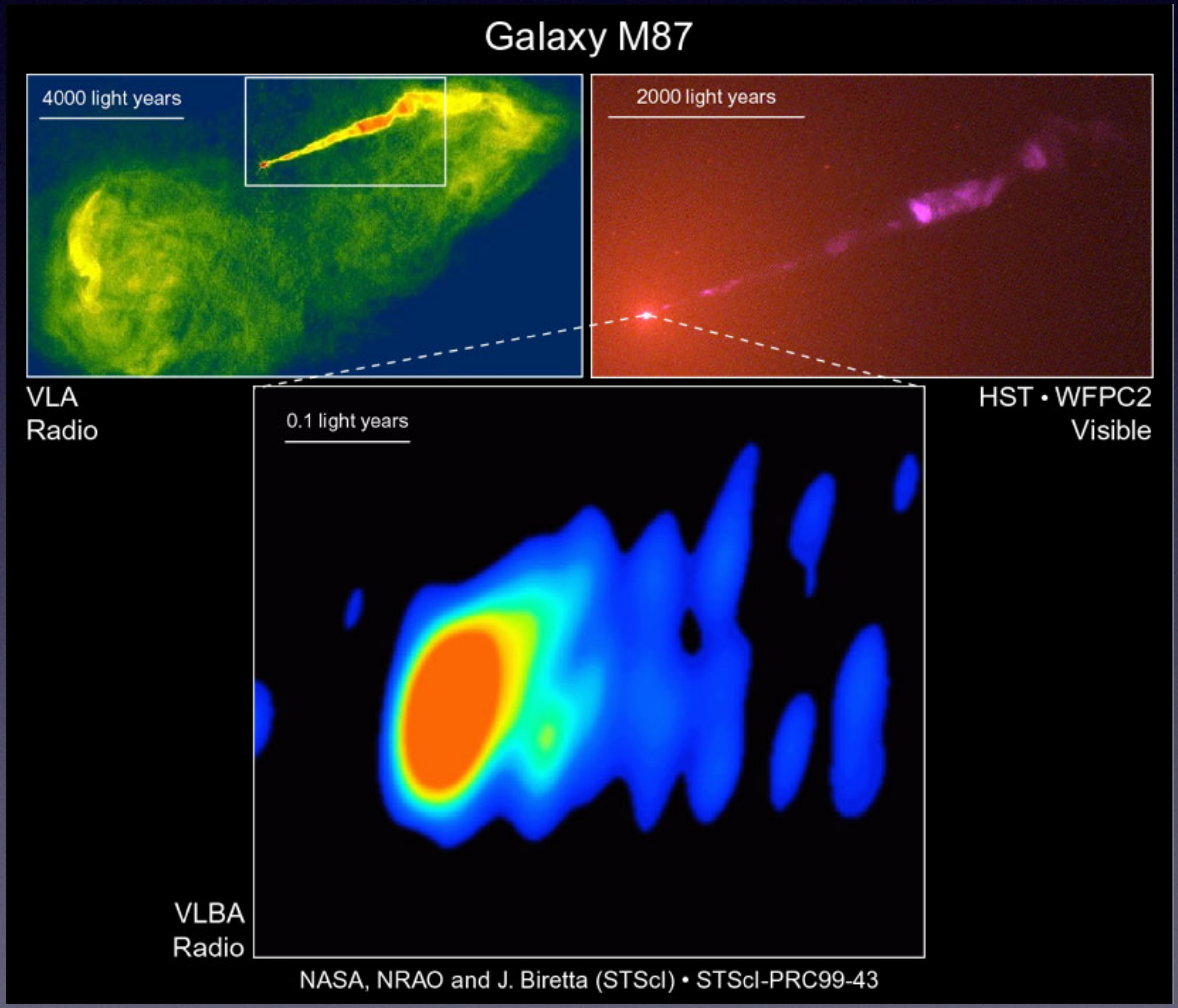
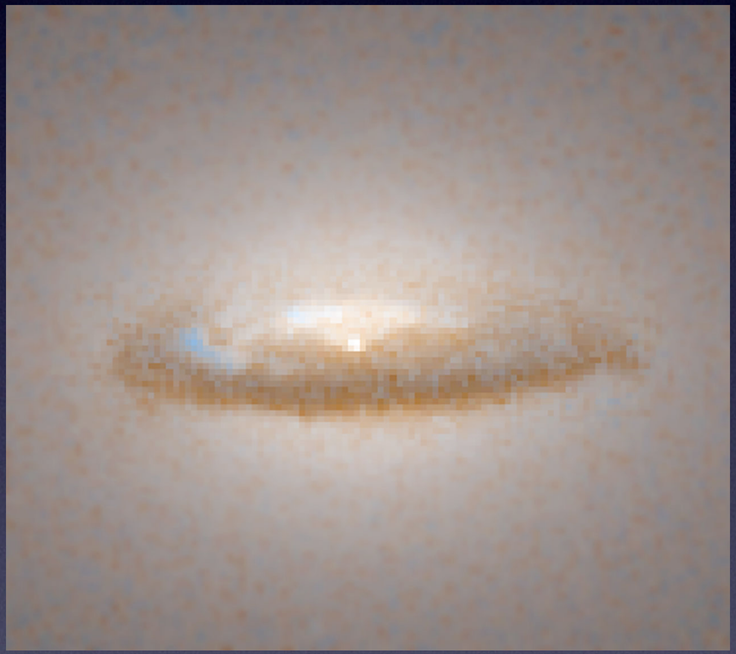


EB 2012
Figure credits: Lucy Ward

What links large and small scale?

- Small to large: BH jets or disk winds transfer kinetic energy to the galaxy and keep it “hot”, quenching star formation (”AGN feedback”). Needed to reconcile ΛCDM bottom-up structure formation with observed “downsizing” of cosmic galaxies

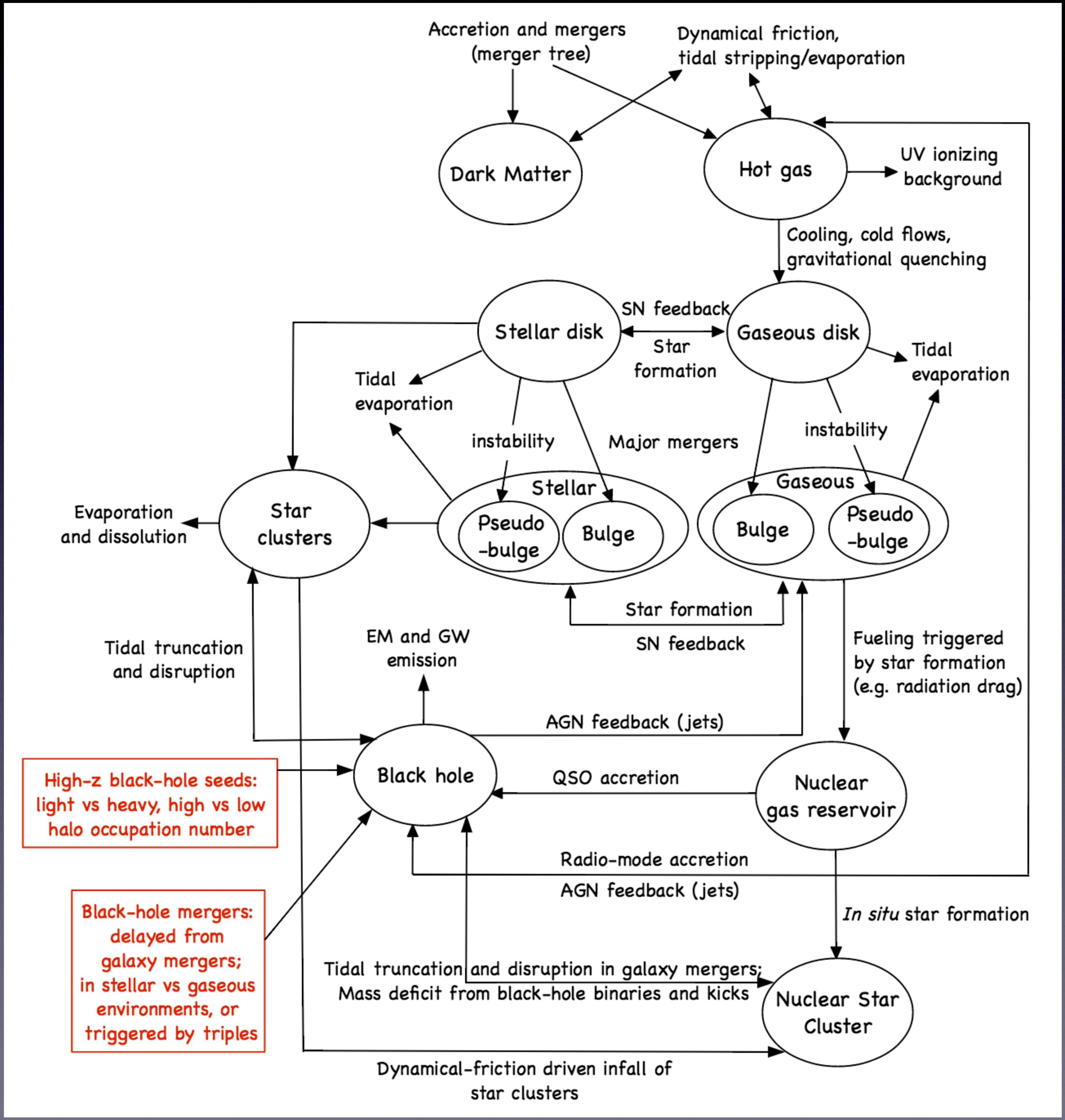




Disk of dust and gas around the massive BH in NGC 7052

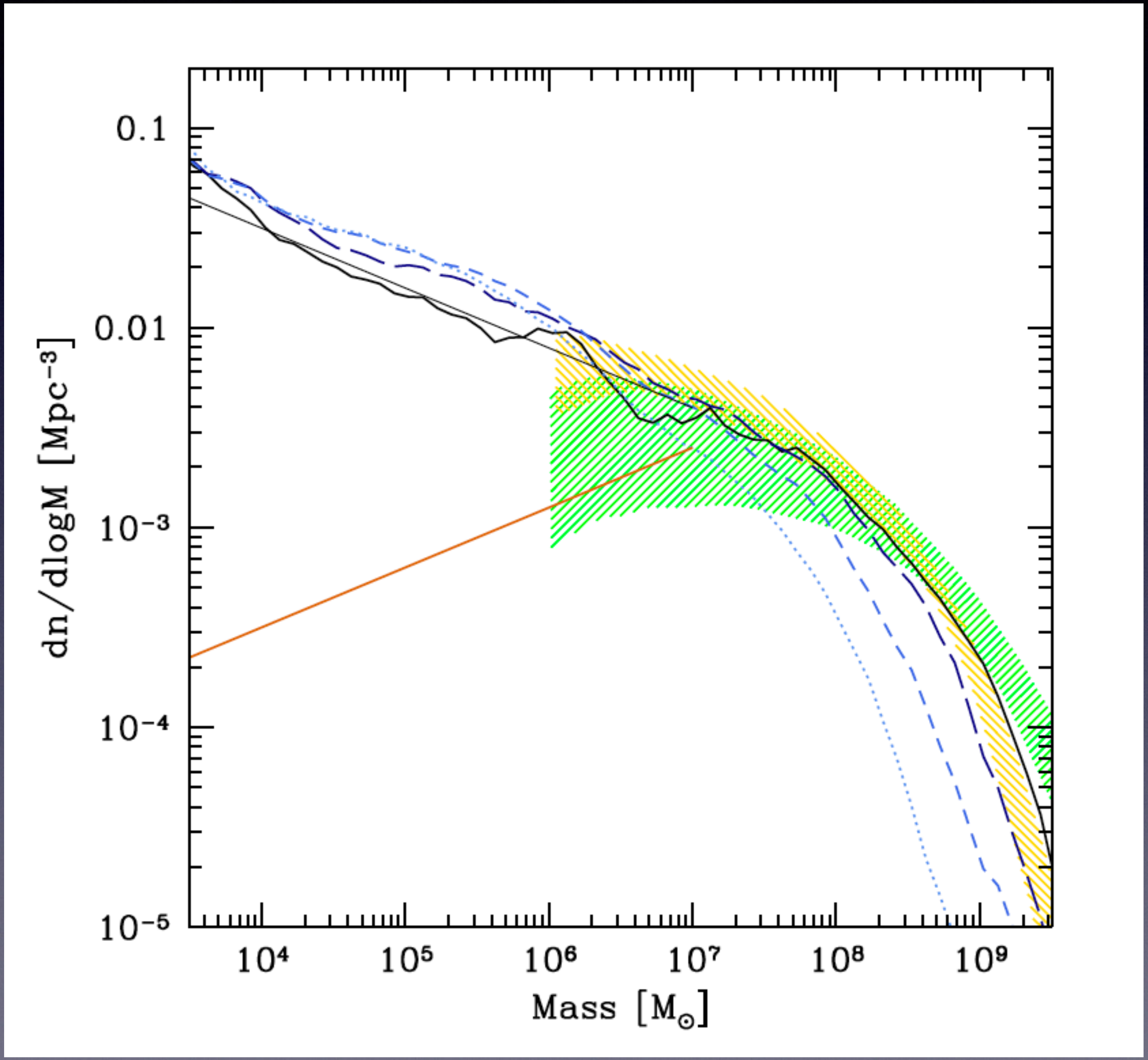
- Large to small: galaxies provide fuel to BHs to grow (”accretion”)

Galaxy/BH co-evolution



EB 2012

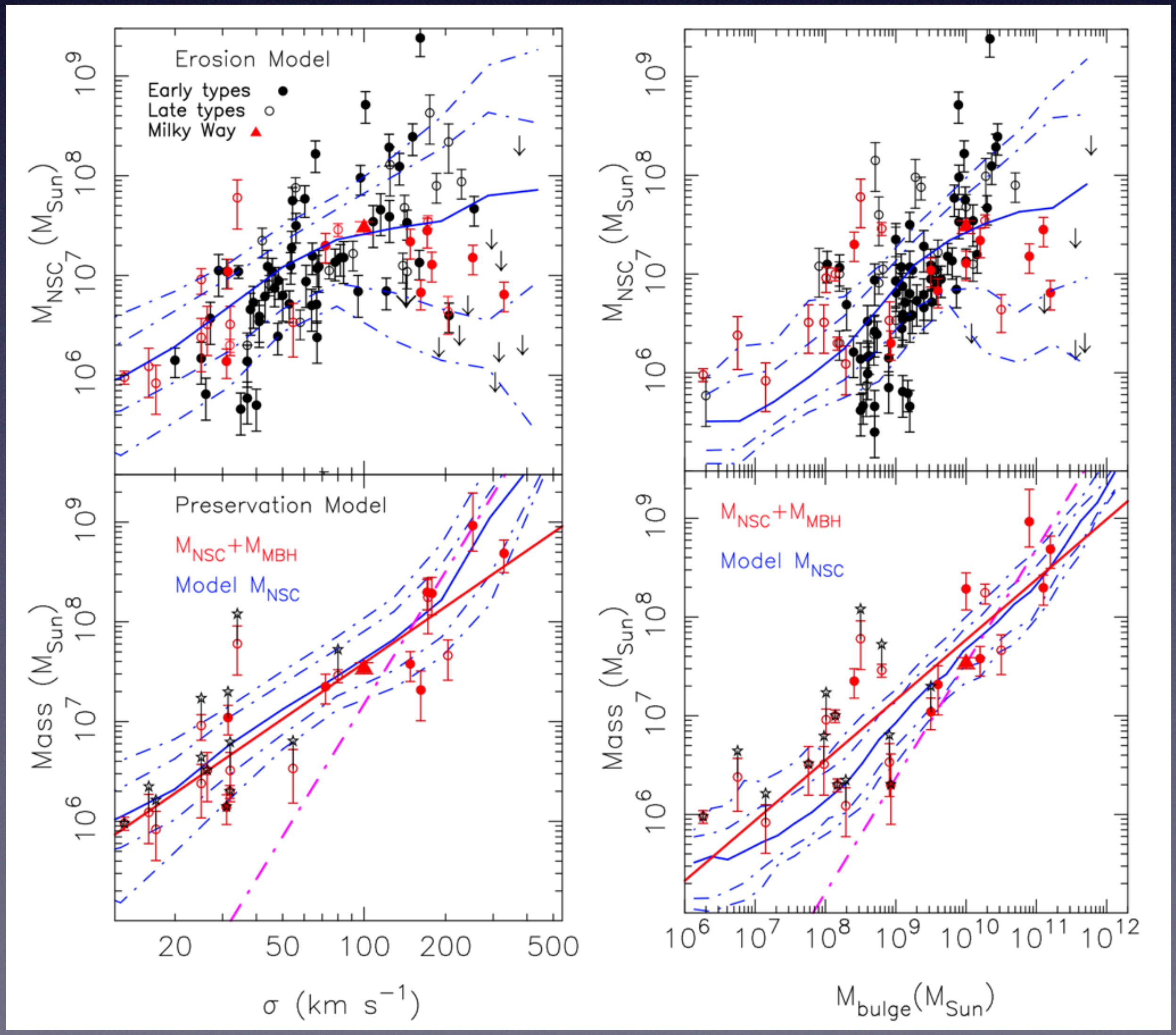
MBH mass function



Fossil evidence for massive BH mergers

- Nuclear Star Clusters: masses up to ~10^7 M_{sun}, r ~ pc
- BH binaries eject stars by slingshot effect and through remnant's recoil ("erosion")
- Erosion by BH binaries crucial to reproduce NSC scaling relations

$$M_{ej} \approx 0.7 q^{0.2} M_{bin} + 0.5 M_{bin} \ln\left(\frac{a_h}{a_{gr}}\right) + 5 M_{bin} \left(V_{kick}/V_{esc}\right)^{1.75} \;,$$

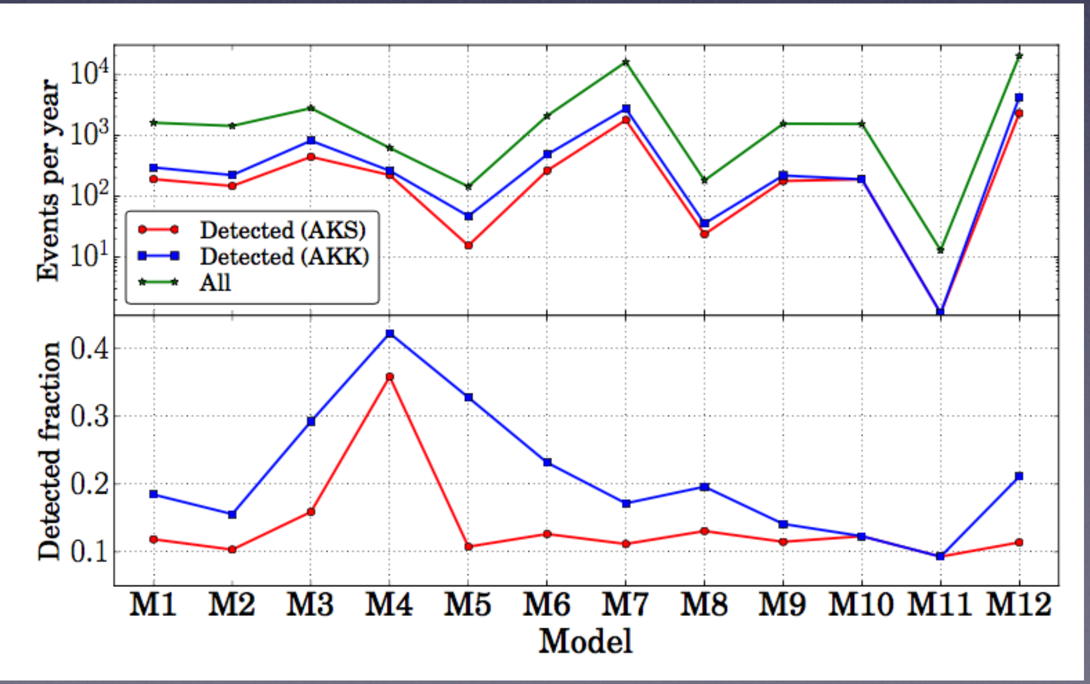


Antonini, EB and Silk 2015a,b

EMRIs: detectability

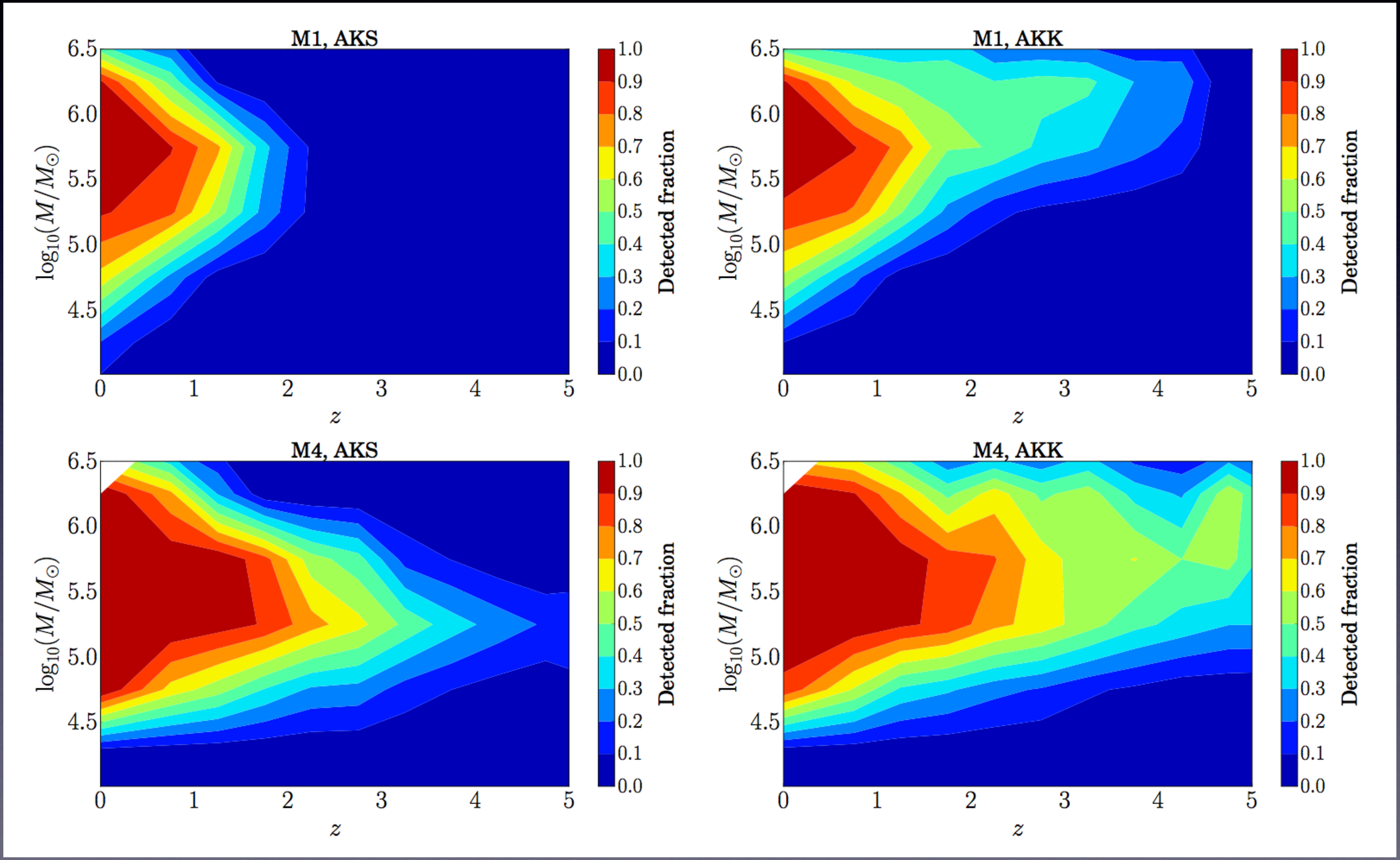
Rates uncertain, depend on low-mass end of BH mass function, presence of core vs cusp, and intrinsic EMRI rate per MBH

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	Total	EMRI rate $[yr^{-1}]$ 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



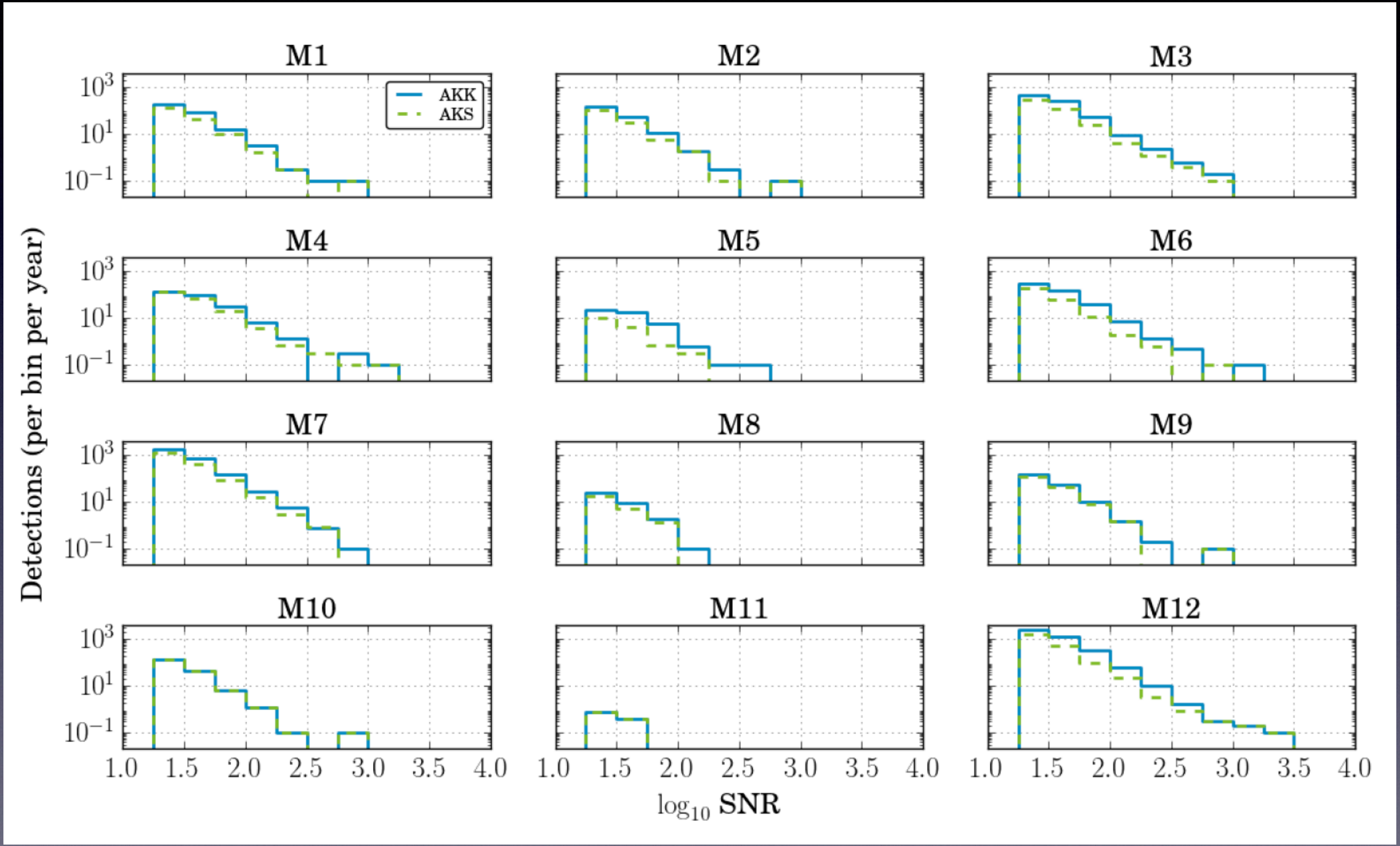
Babak et al (incl. EB) 2017

EMRIs: detectability



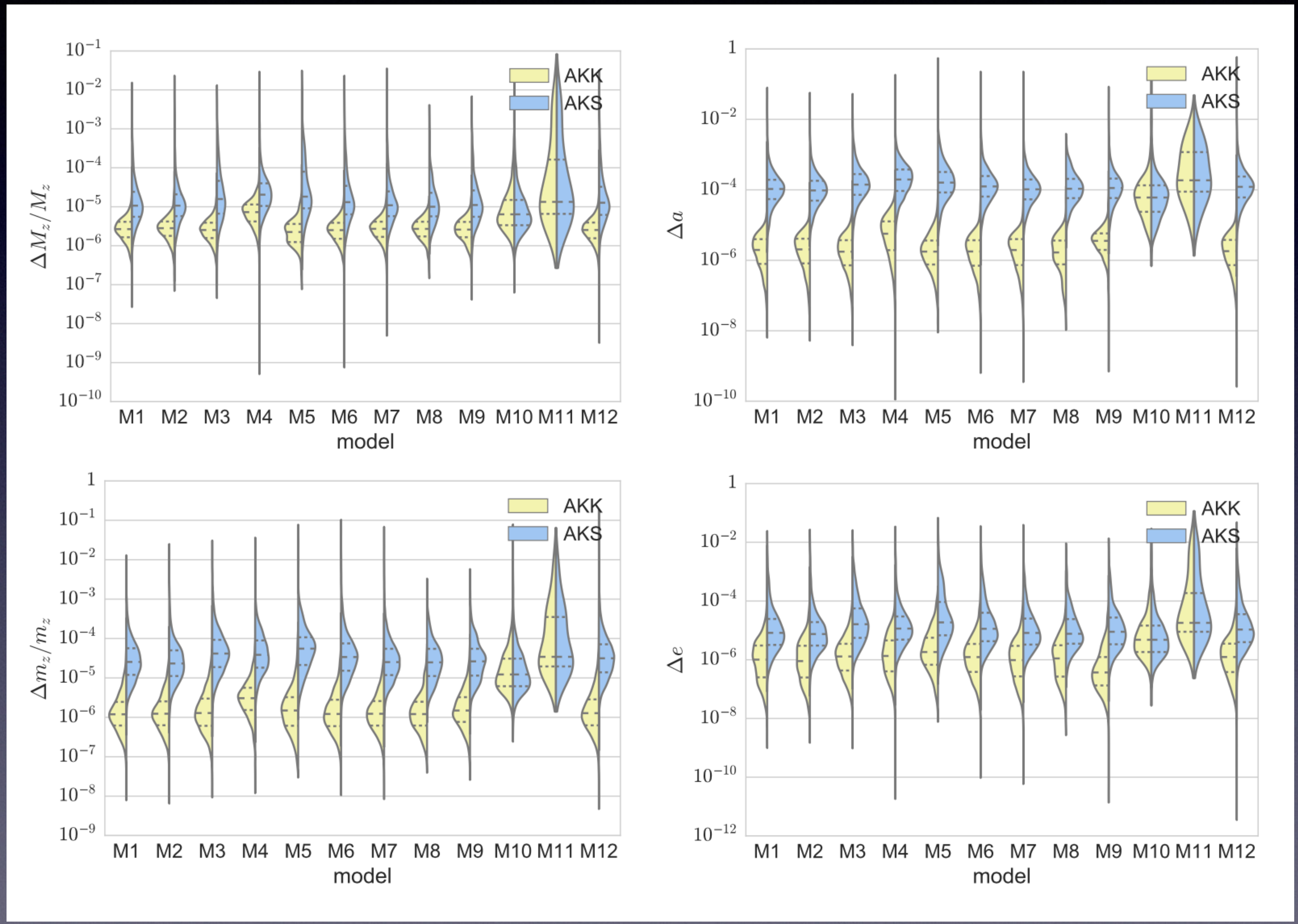
Babak et al (incl. EB) 2017

EMRIs: SNR



Babak et al (incl. EB) 2017

EMRIs: parameter estimation



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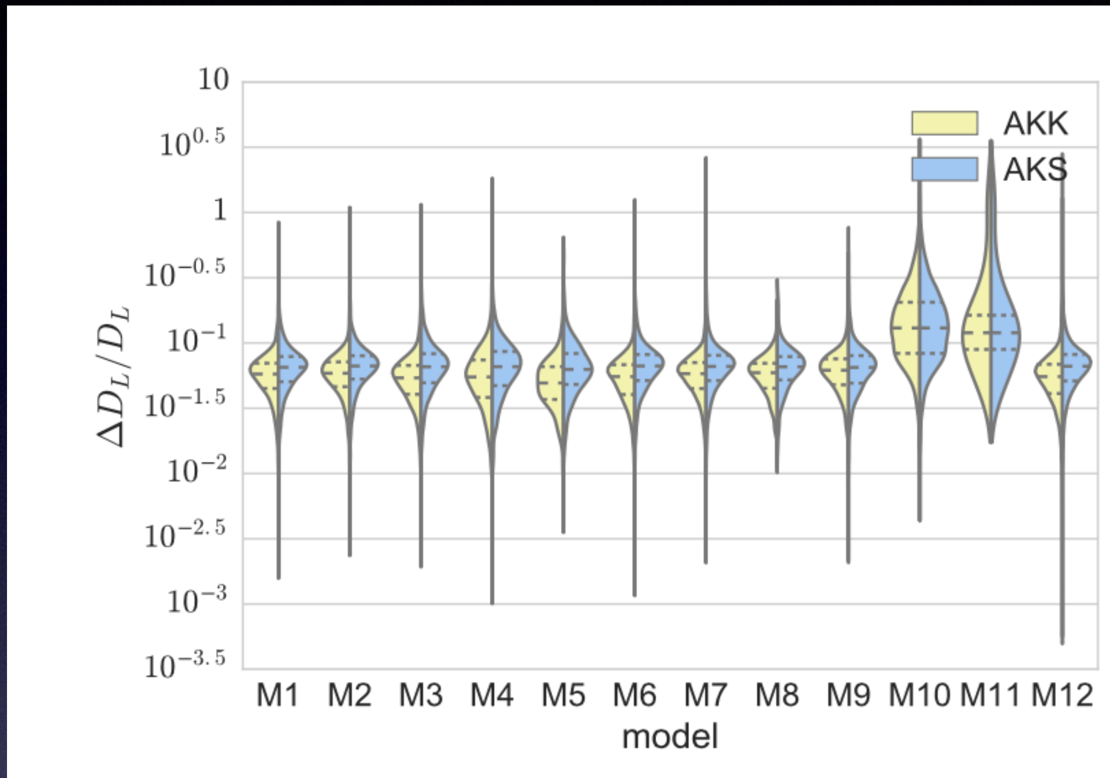
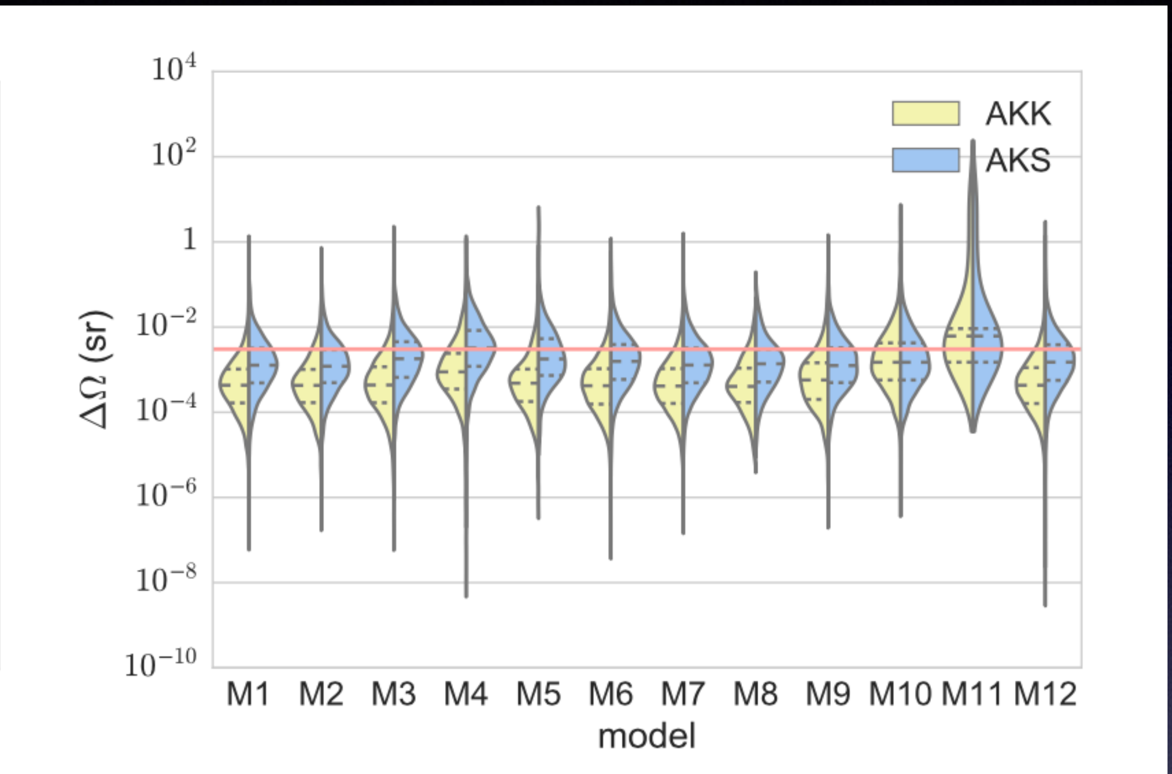
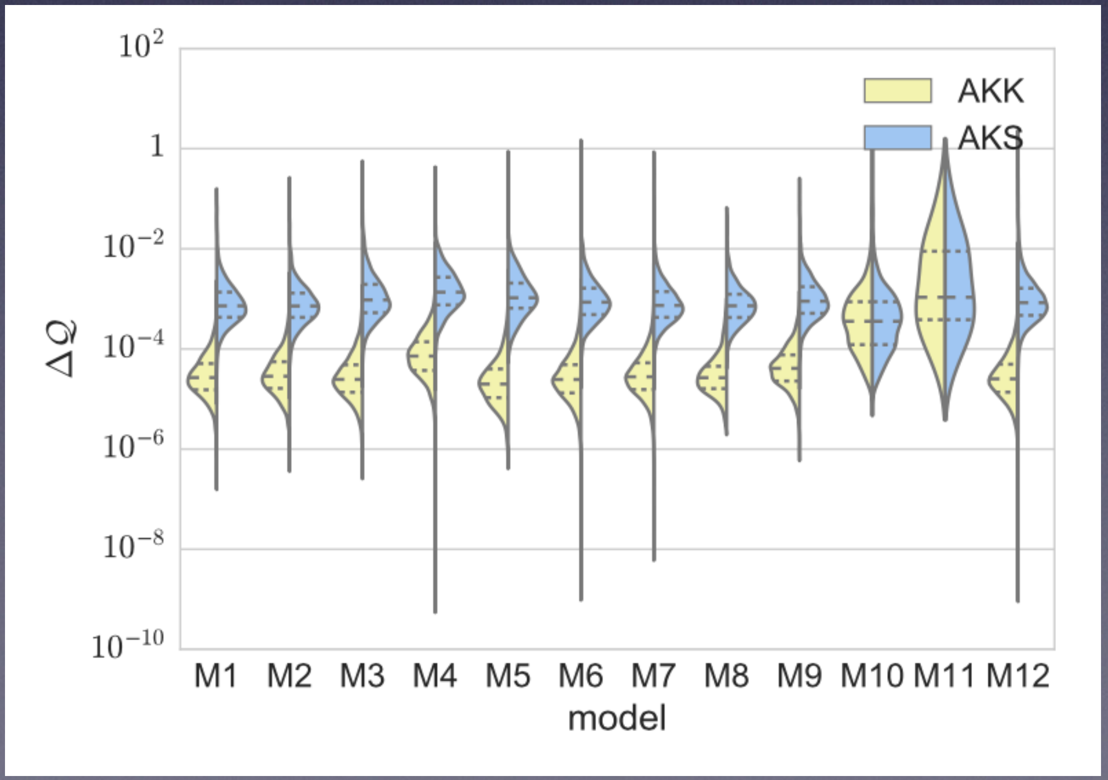
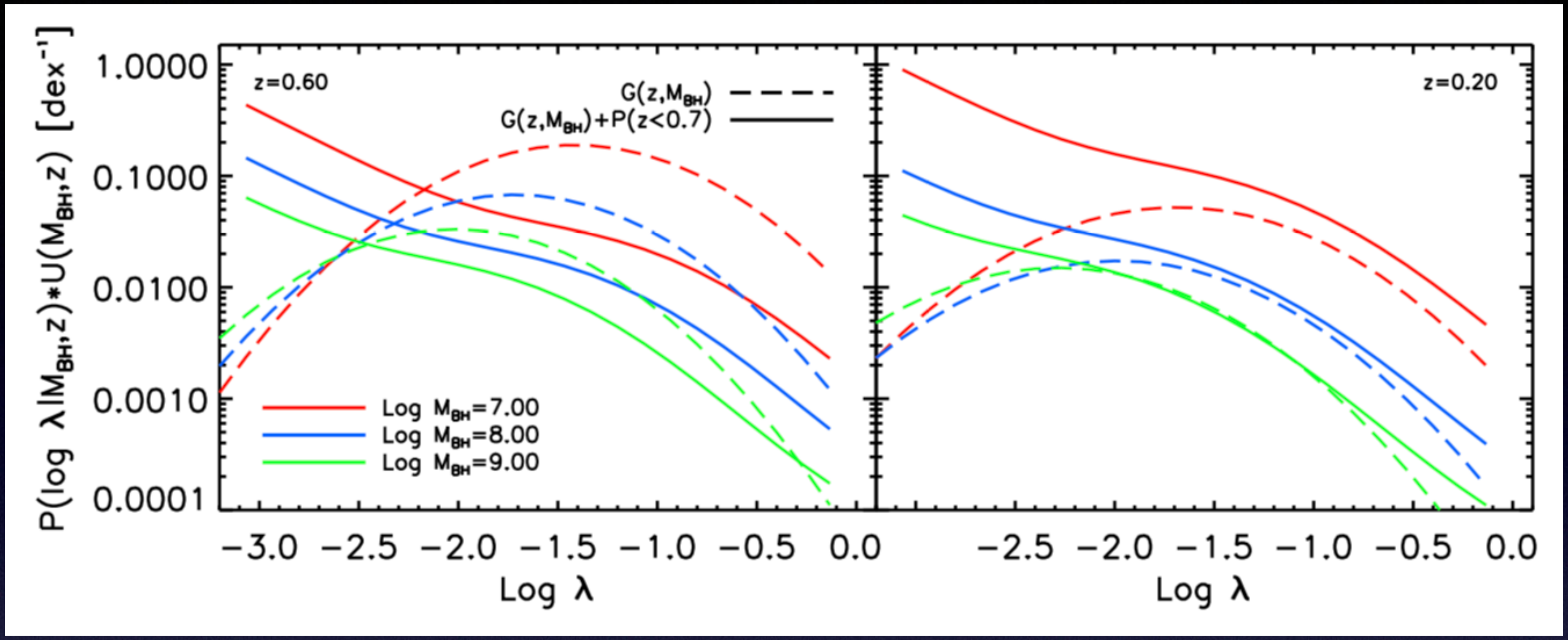




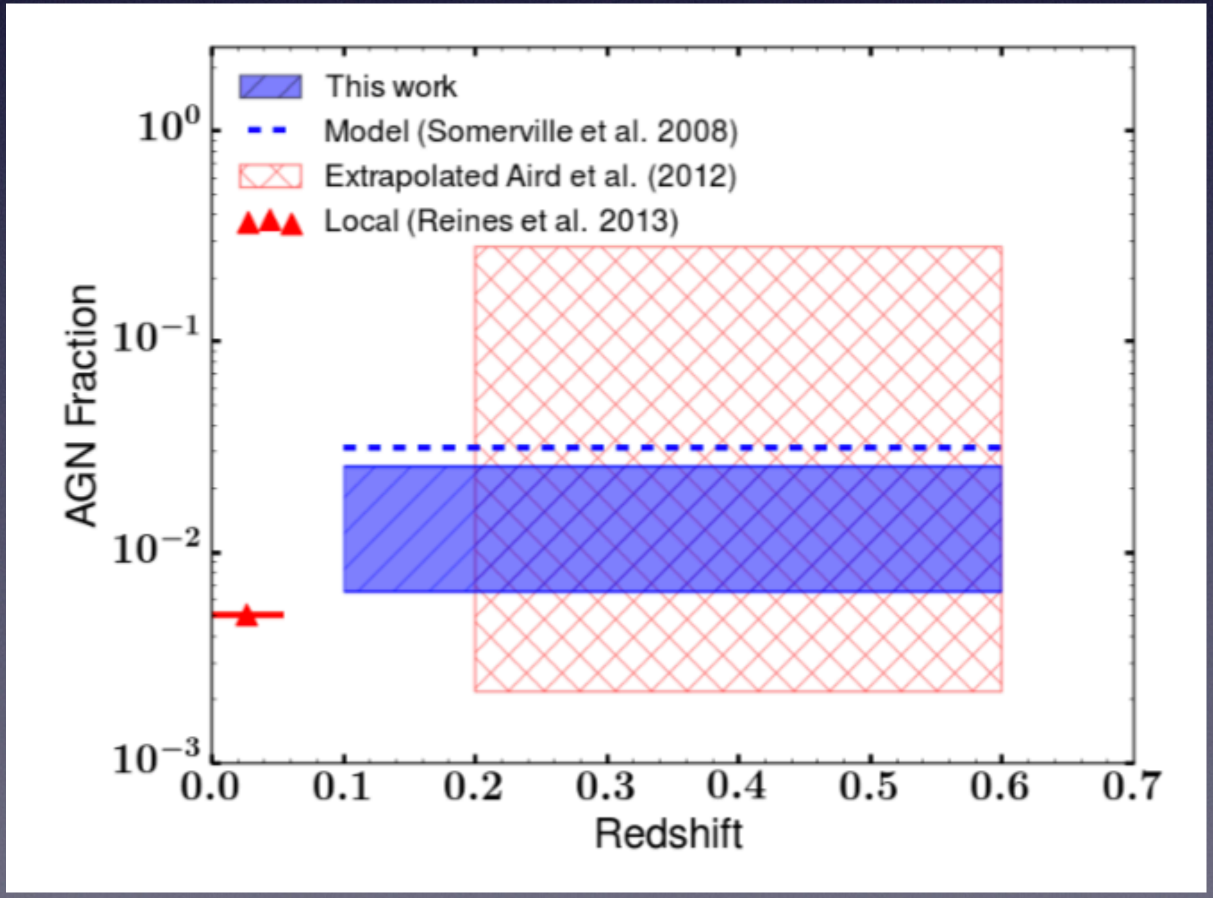


Babak et al
(incl. EB) 2017

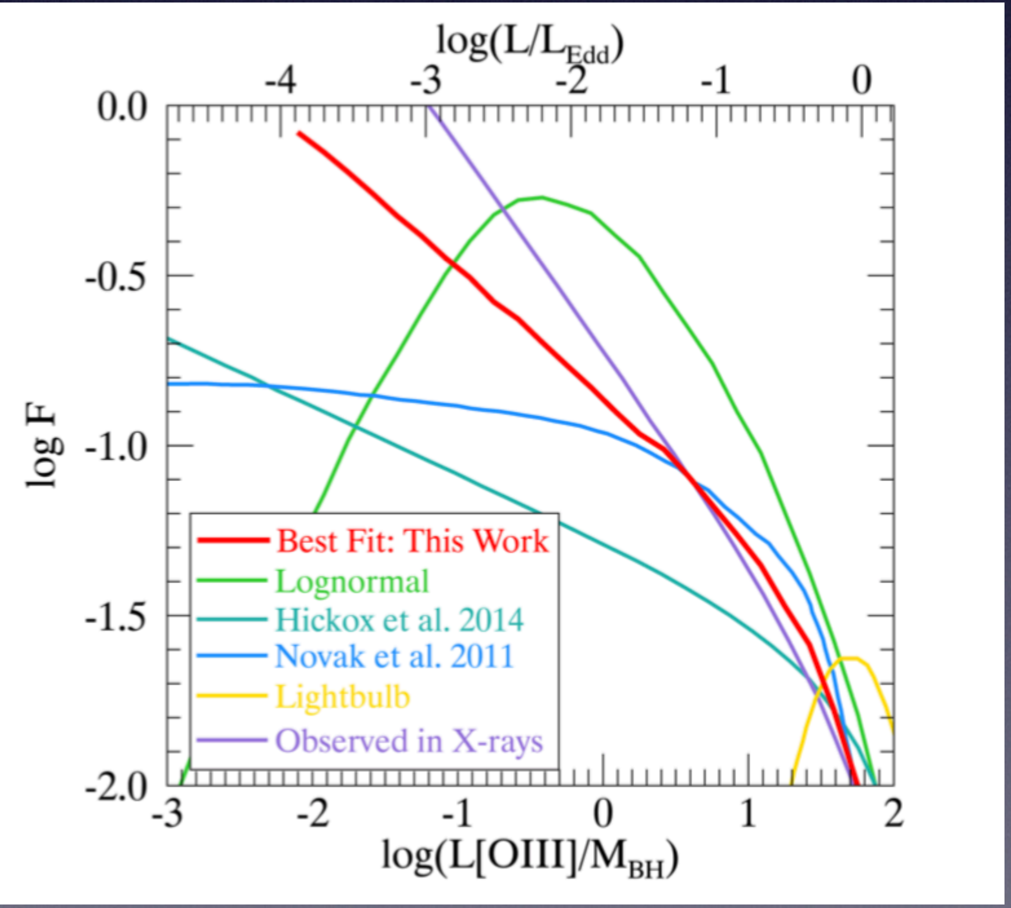
AGN duty cycle



Shankar+ 2011



Pardo+ 2016



Jones+ 2016

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 due to accretion (from conservation of linear momentum)

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

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

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

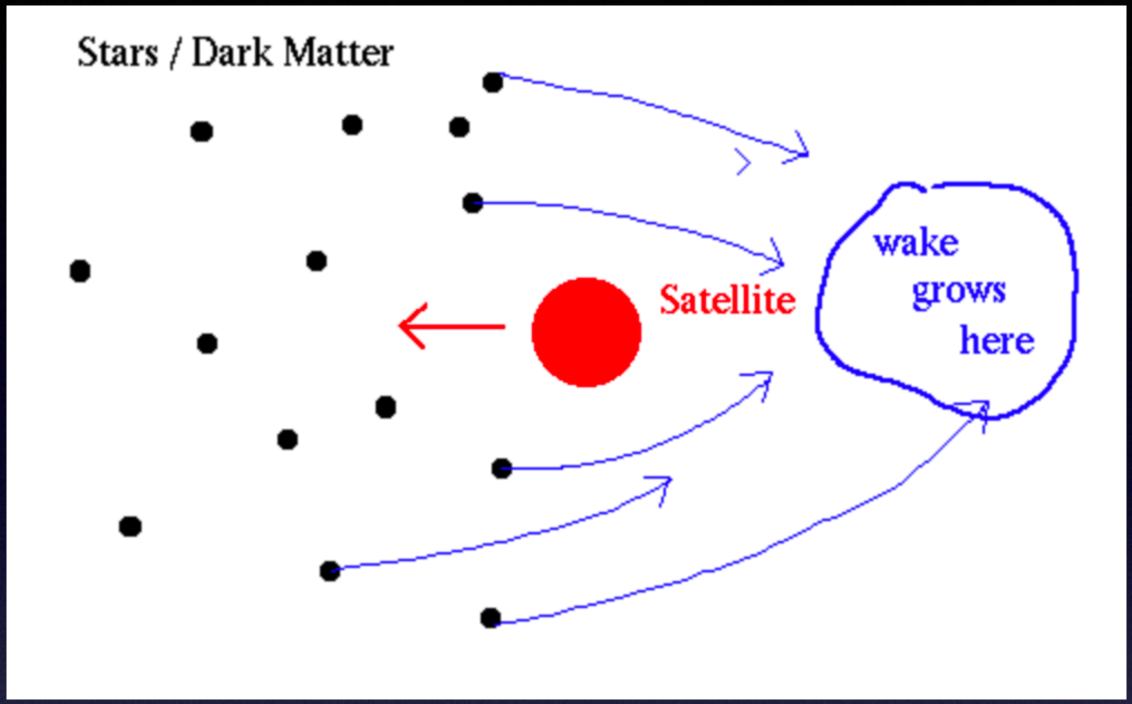
- Planetary migration (exterior wake lags being satellite and thus pulls it, interior wake trails and pushes it); cf also Yunes et al 2011

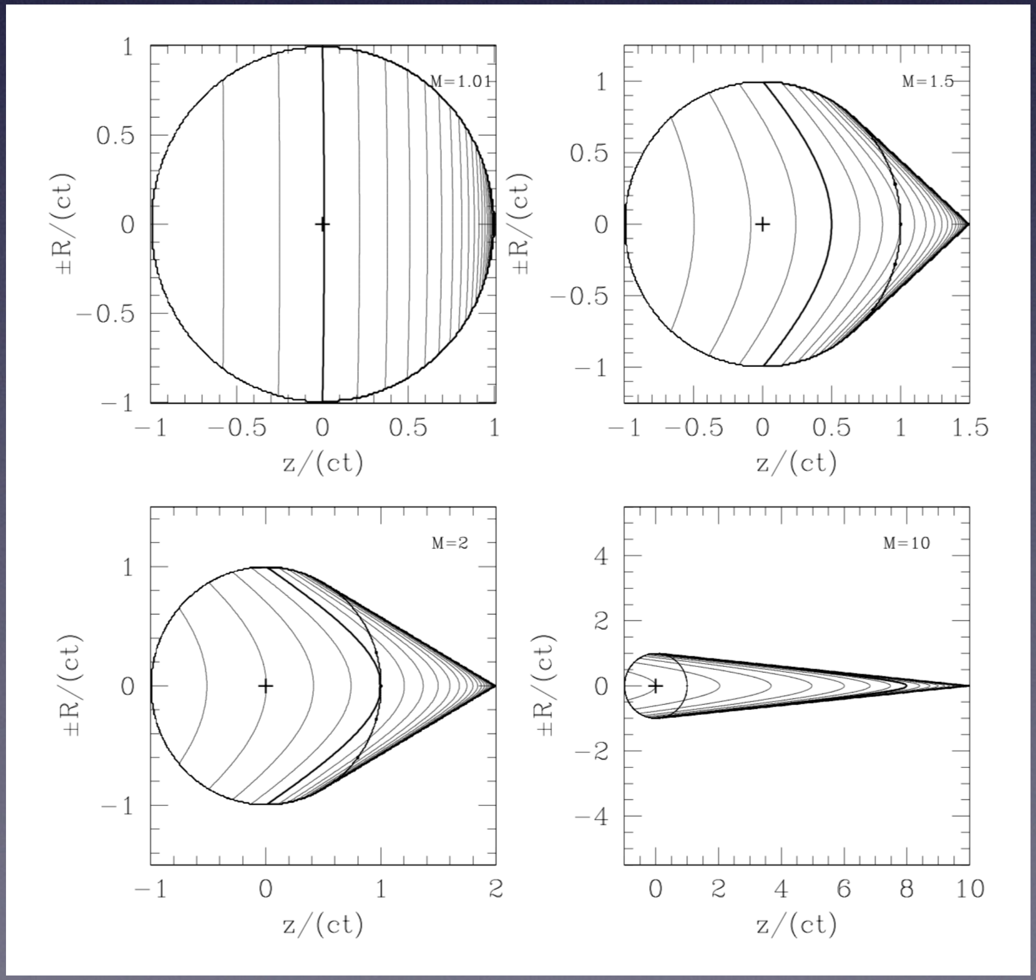
$$\dot{\tilde{L}}_z^{\rm migr} = (\dot{\tilde{L}}_z)_{\rm gw} \left[1 + A(r/M)^B\right] \xi\,,$$

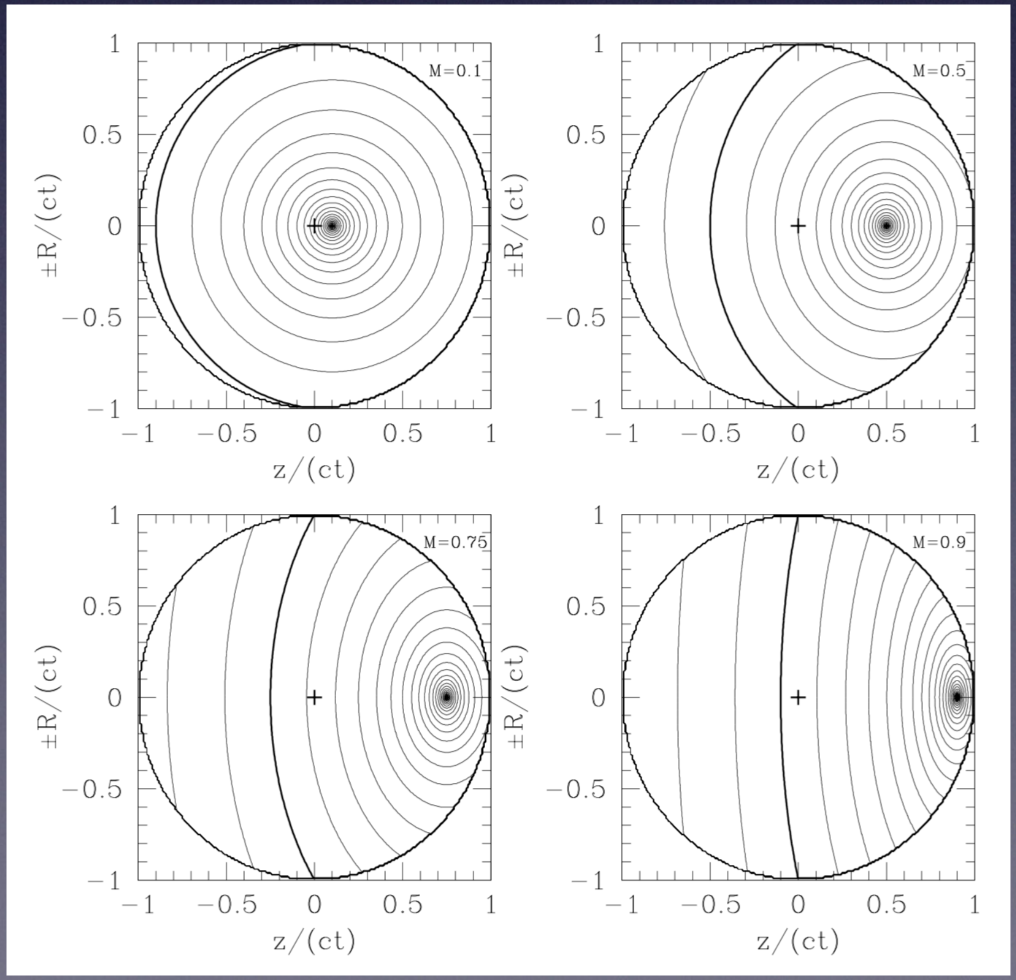
$$\dot{\tilde{E}}^{\rm migr} = \dot{\tilde{L}}_z \frac{M|v_{\rm sat}|}{r} \xi$$

- Electric and magnetic fields, electric charges, etc.

Dynamical friction in stars and gas

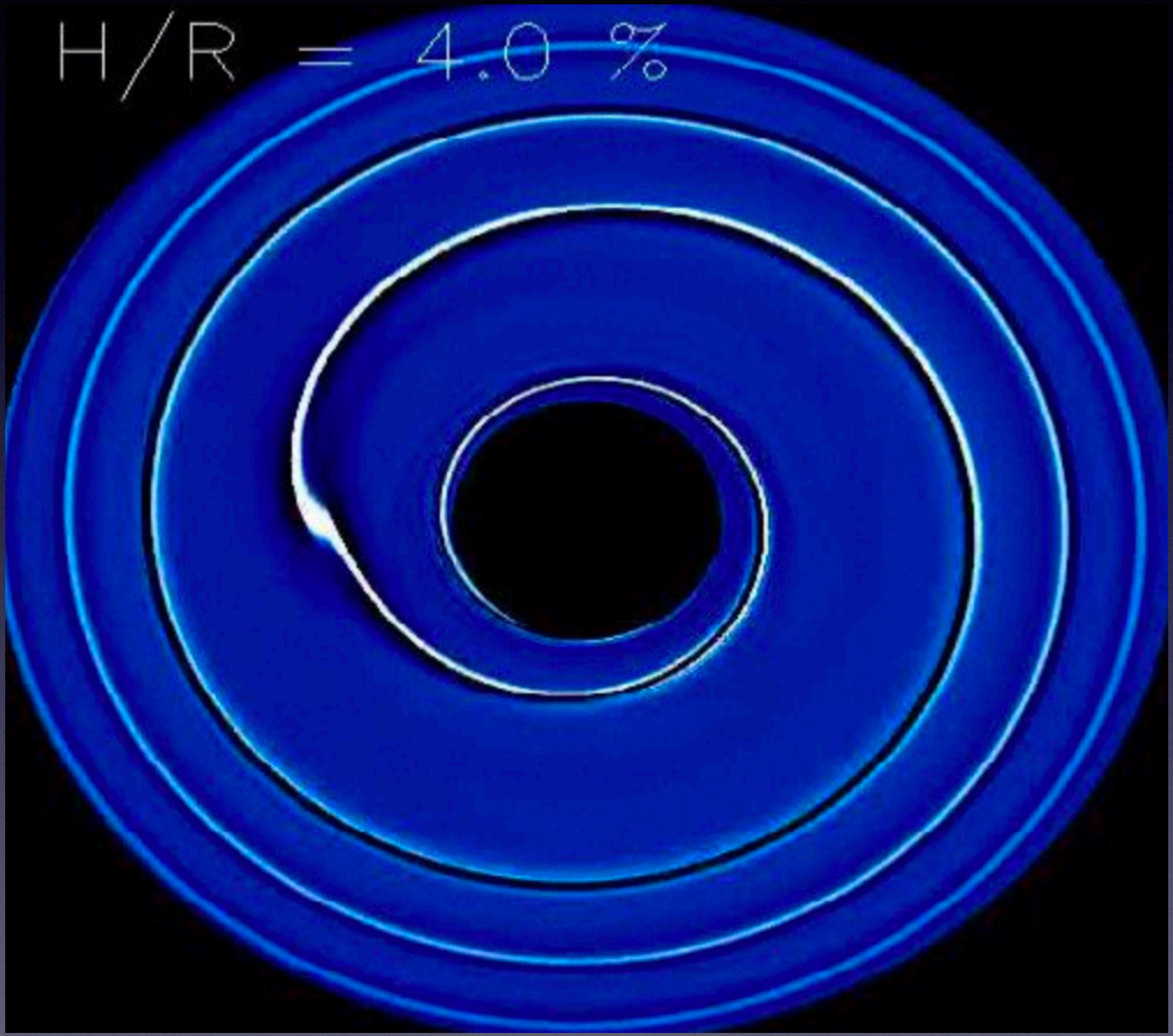






E. C. Ostriker
1998

Planetary migration



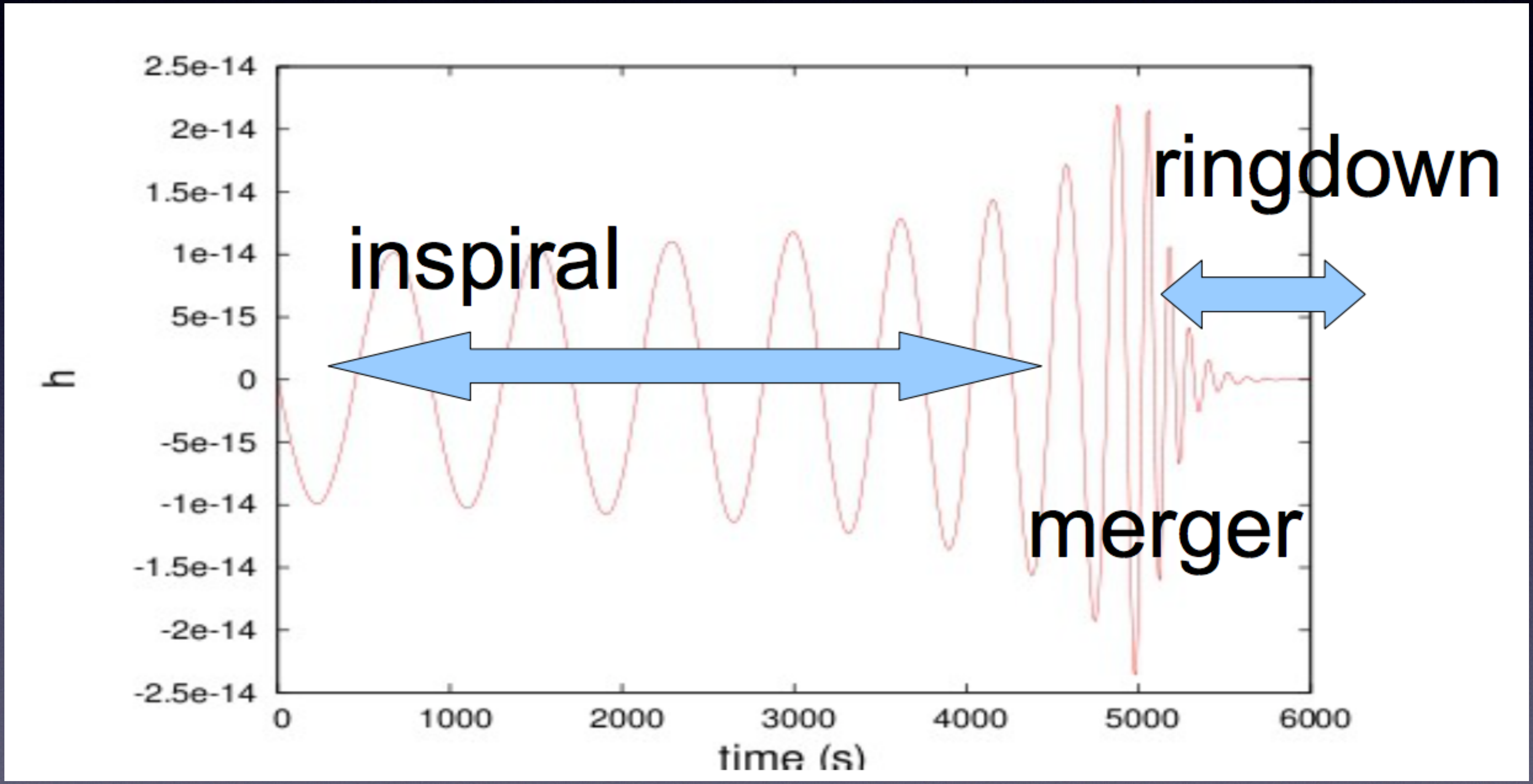
Simulation by F. S. Masset

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

Environmental effects, where?



Inspiral, dissipative dynamics

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

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

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

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

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

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

Gravitational pull ~ 2nd order SF

Inspiral, dissipative dynamics

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

Inspiral, dissipative dynamics

Planetary 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

Inspiral, dissipative dynamics

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

Inspiral, dissipative dynamics

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)

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

Inspiral, dissipative dynamics

- Stellar perturbers: probably unlikely because

- binary separation << interstellar distance (even in dense nuclei)

- 2-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)

Inspiral, dissipative dynamics

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

Correction	$\vert\delta_\varphi\vert/P$	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}	$\left(\frac{R}{7\times 10^6 M}\right)^{\hat\alpha}\frac{\langle\rho_{\rm DM}\rangle}{10^3 M_\odot/{\rm pc}^3}\left(\frac{r_f}{6M}\right)^{11/2-\hat\alpha}\left(\frac{M}{10^6 M_\odot}\right)^2\frac{10^{-5}}{\nu}\frac{c_{\hat\alpha}(\chi)}{0.15}$
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

- Results checked with direct orbital integrations, SPA
- Extrapolation to q ~ 1 shows all effects are negligible at least at r < 60-70 M for MBH binaries

Inspiral, conservative dynamics

Correction	$\delta_{\rm per}/P$	P
Cosmological constant	10^{-31}	$\frac{\Lambda}{10^{-52}\,{\rm m}^{-2}}\left(\frac{M}{10^6\,M_\odot}\right)^2(\tilde{r}_c/10)^4$
Galactic DM halos	10^{-21}	$\left(\frac{M}{10^6\,M_\odot}\right)^2\frac{\rho_{\rm DM}}{10^3\,M_\odot/{\rm pc}^3}(\tilde{r}_c/10)^4$
Thick accretion disk	10^{-16}	$\frac{f_{\rm Edd}}{10^{-4}}\frac{M}{10^6\,M_\odot}\frac{0.1}{\alpha}(\tilde{r}_c/10)^{5/2}$
Accretion	10^{-8}	$f_{\rm Edd}$
Thin disk (assuming Eq. (95) and $\tilde{r}_c = 10$)	10^{-8}	${f_{\rm Edd}}^{7/10}\left(\frac{M}{10^6\,M_\odot}\right)^{6/5}\left(\frac{\alpha}{0.1}\right)^{-4/5}$
Charge	10^{-7}	$(q/10^{-3})^2$
DM distribution $\rho\sim r^{-\hat{\alpha}}$	10^{-21}	$\left(\frac{M}{10^6\,M_\odot}\right)^2\frac{\rho_{\rm DM}}{10^3\,M_\odot/{\rm pc}^3}(\tilde{r}_c/10)^{4-\hat{\alpha}}\left(\frac{R}{7\times10^6\,M}\right)^{\hat{\alpha}}$
Magnetic field	10^{-8}	$\left(\frac{B}{10^8\,{\rm Gauss}}\right)^2\left(\frac{M}{10^6\,M_\odot}\right)^2(\tilde{r}_c/10)^4$

$$\delta\phi = 2\pi\left(\frac{\Omega_\phi}{\Omega_r}-1\right)$$

$$\delta\phi = \frac{6\pi M}{r_c}(1+\delta_{\rm per}) + \mathcal{O}\left(\frac{M}{r_c}\right)^2$$

$$\delta_{\rm per}^{\rm SF} \sim a_1\nu + a_2\nu^2$$

EB, Cardoso and Pani 2014

Merger ringdown

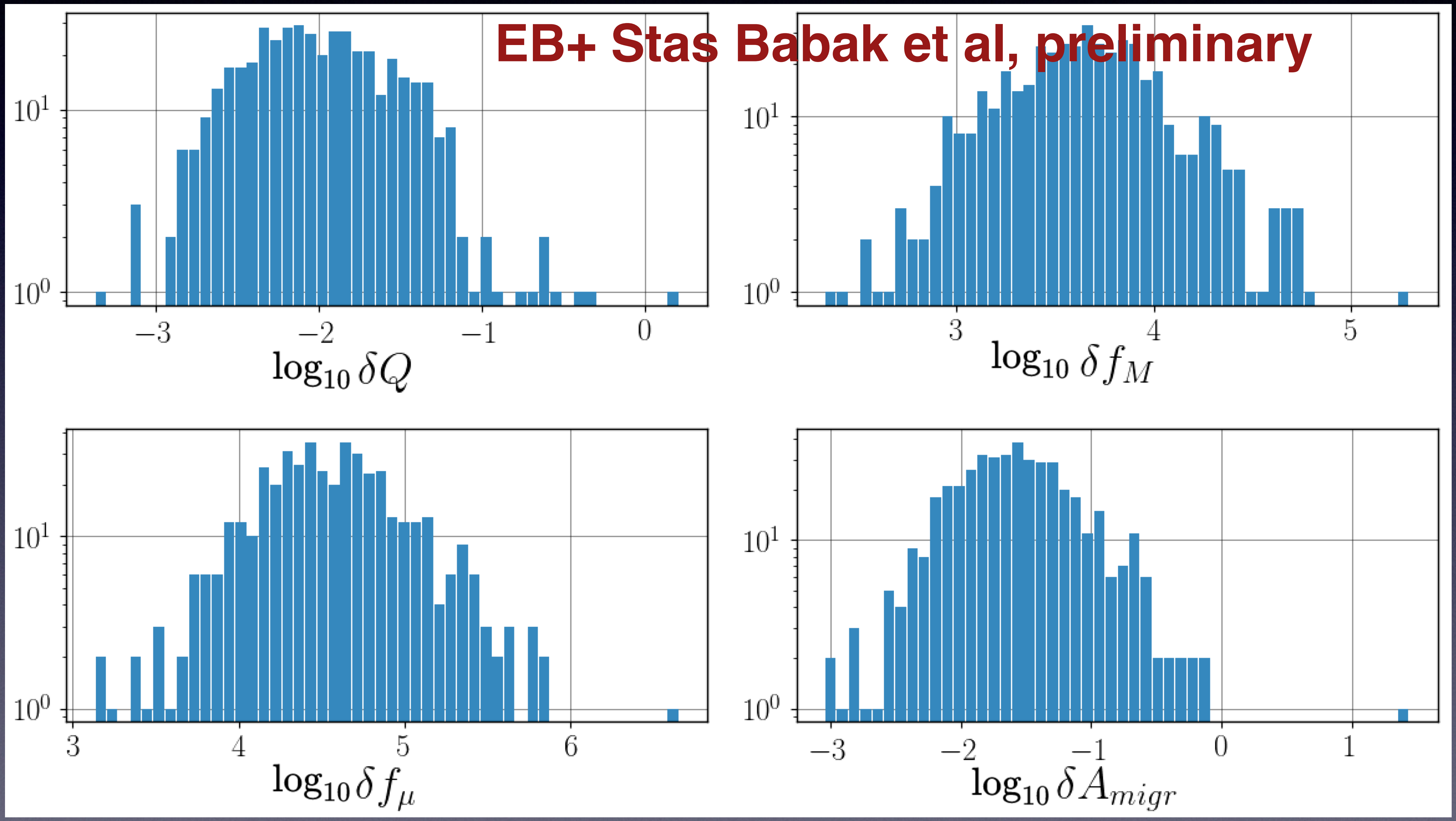
Correction	$\lvert\delta_R\rvert[\%]$	$\lvert\delta_I\rvert[\%]$
spherical near-horizon distribution	0.05	0.03
ring at ISCO	0.01	0.01
electric charge	10^{-5}	10^{-6}
magnetic field	10^{-8}	10^{-7}
gas accretion	10^{-11}	10^{-11}
DM halos	$10^{-21}\rho_3^{\mathrm{DM}}$	$10^{-21}\rho_3^{\mathrm{DM}}$
cosmological effects	10^{-32}	10^{-32}

$$\delta_{R,I} = 1 - \omega_{R,I}/\omega_{R,I}^{(0)}$$

$$\delta M \sim 10^{-3} M$$

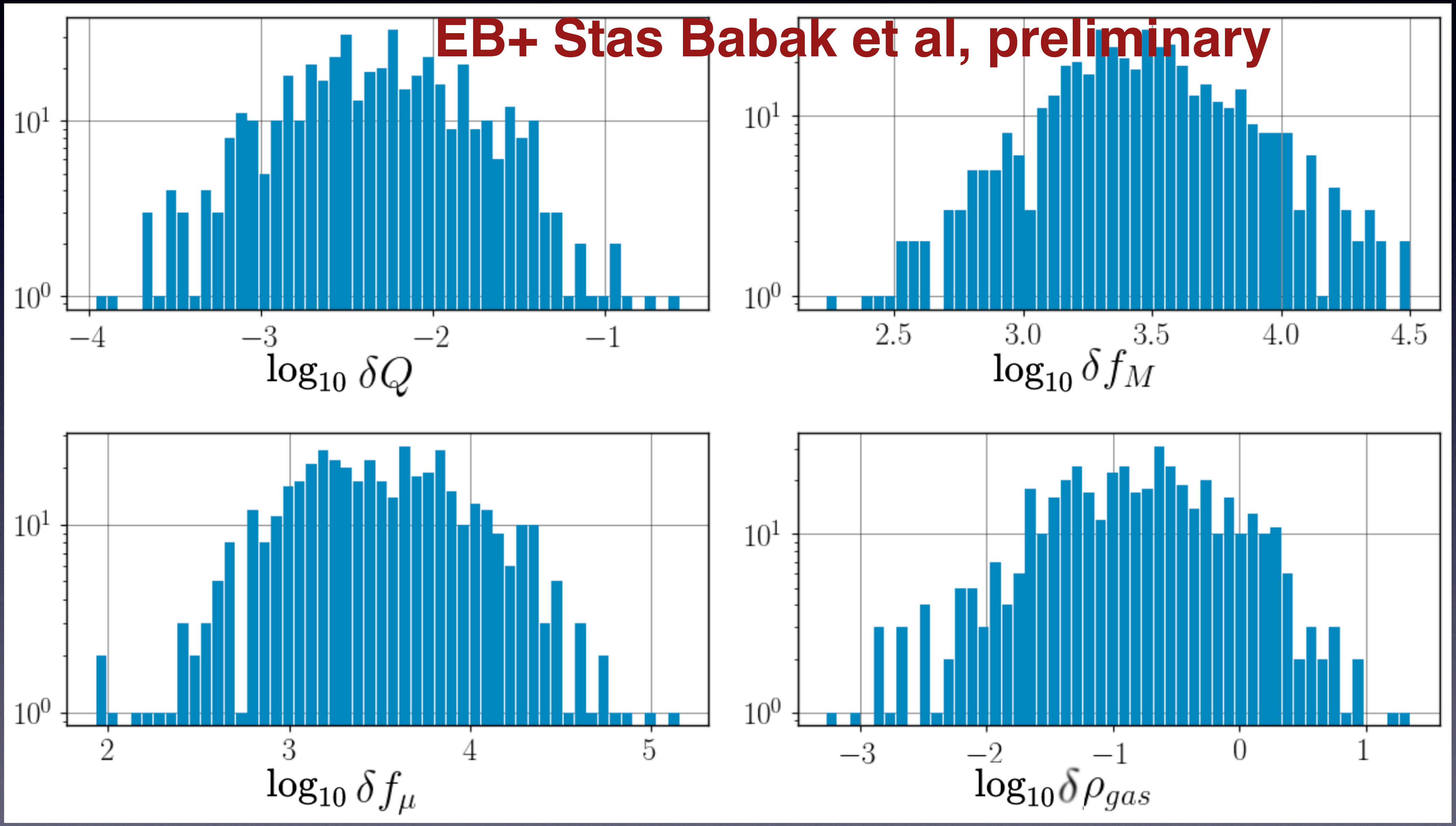
EB, Cardoso and Pani 2014

FIM PE of environmental effects in EMRIs



A_{migr} ~1 for thin accretion disk; prograde orbits

FIM PE of environmental effects in EMRIs

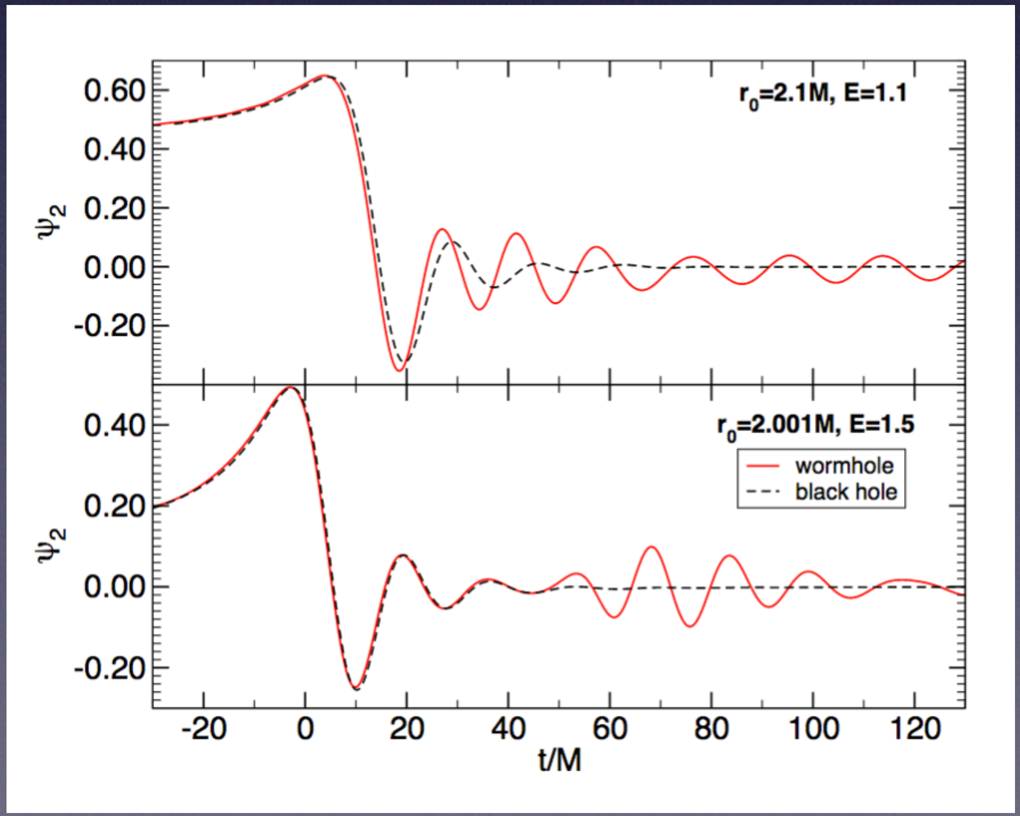


Gas density normalized to 169 $f_{Edd}^{11/20}$ kg/m^3 (thin accretion disk); retrograde orbits

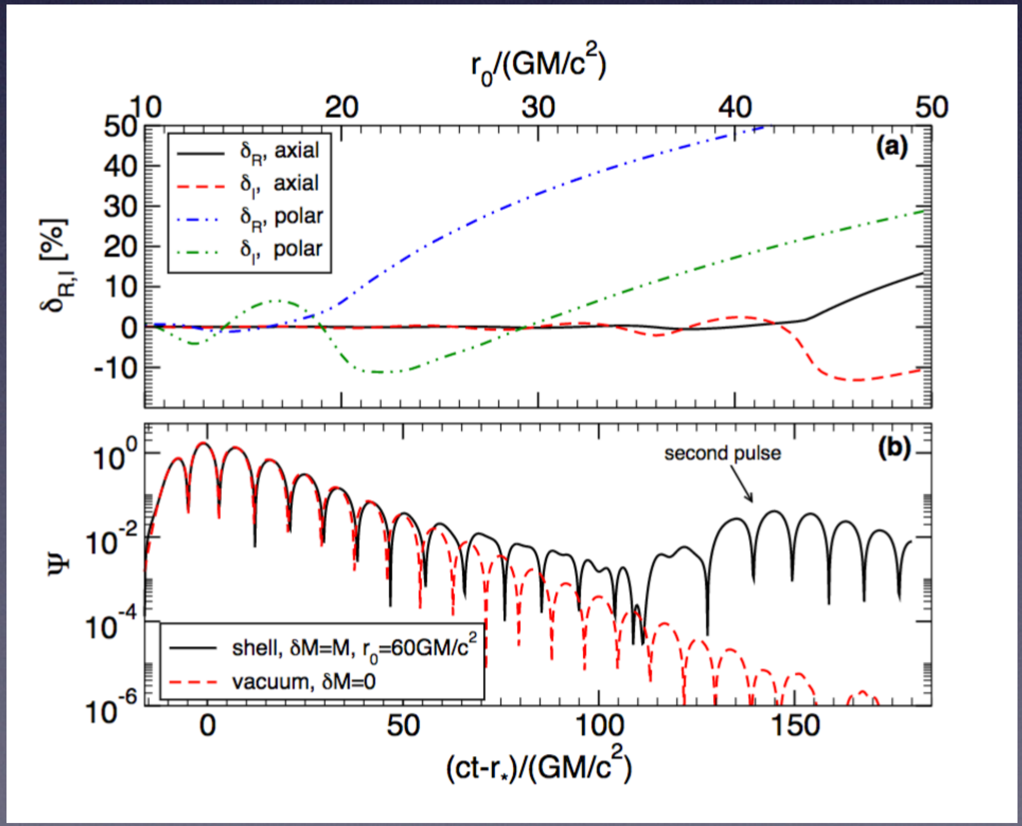
Ringdown's sensitivity to near horizon physics

- 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
- Need "matter" with high viscosity to explain absence of hydrodynamic modes; possible with NS matter+large B, but not with boson stars (Yunes, Yagi & Pretorius 2016);

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



Cardoso, Franzin & Pani 2016



EB, Cardoso & Pani 2014

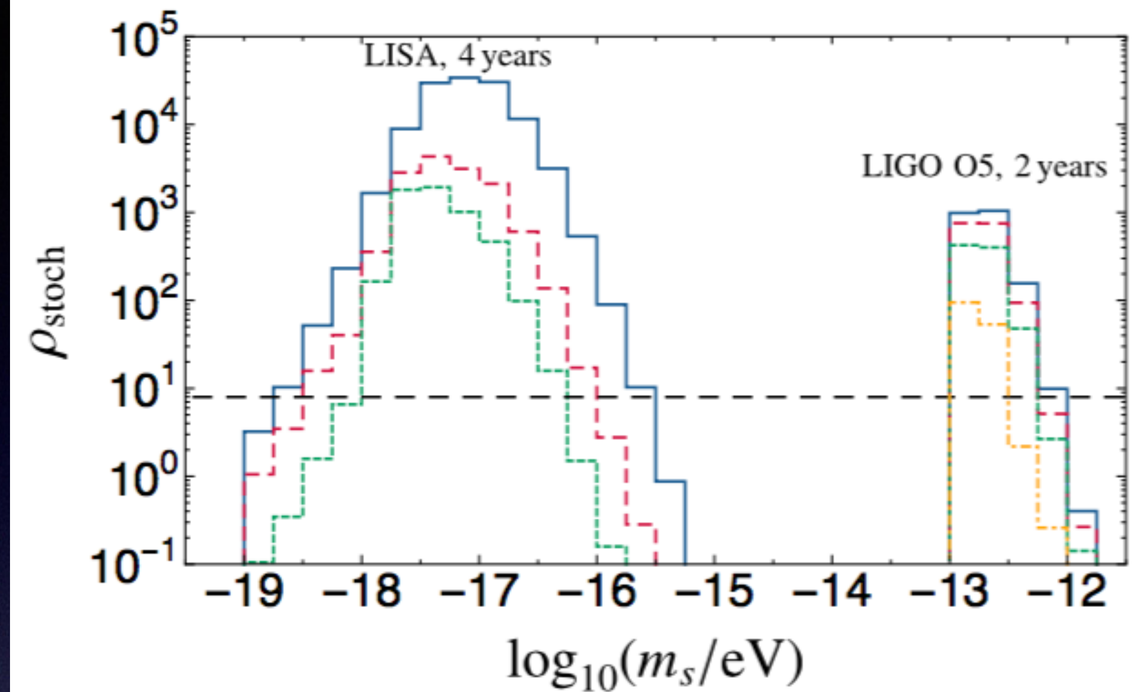
r_0 =60 M, shell of mass M,
Gaussian wavepacket initially at ISCO

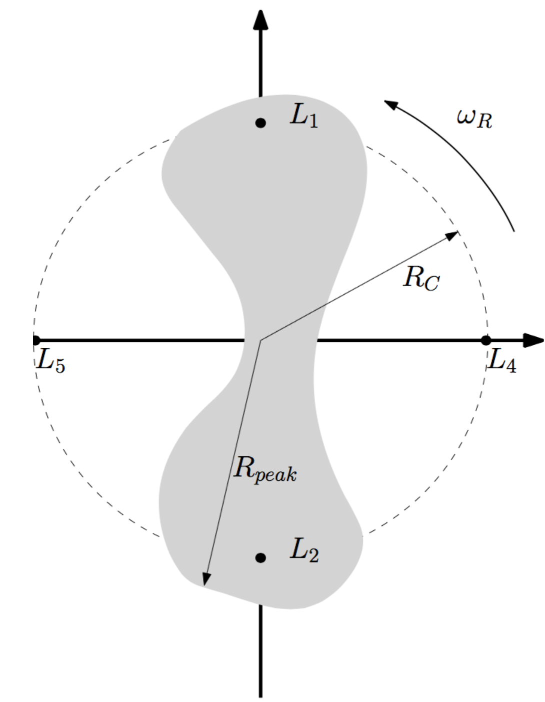
Constraints on axions/fuzzy DM

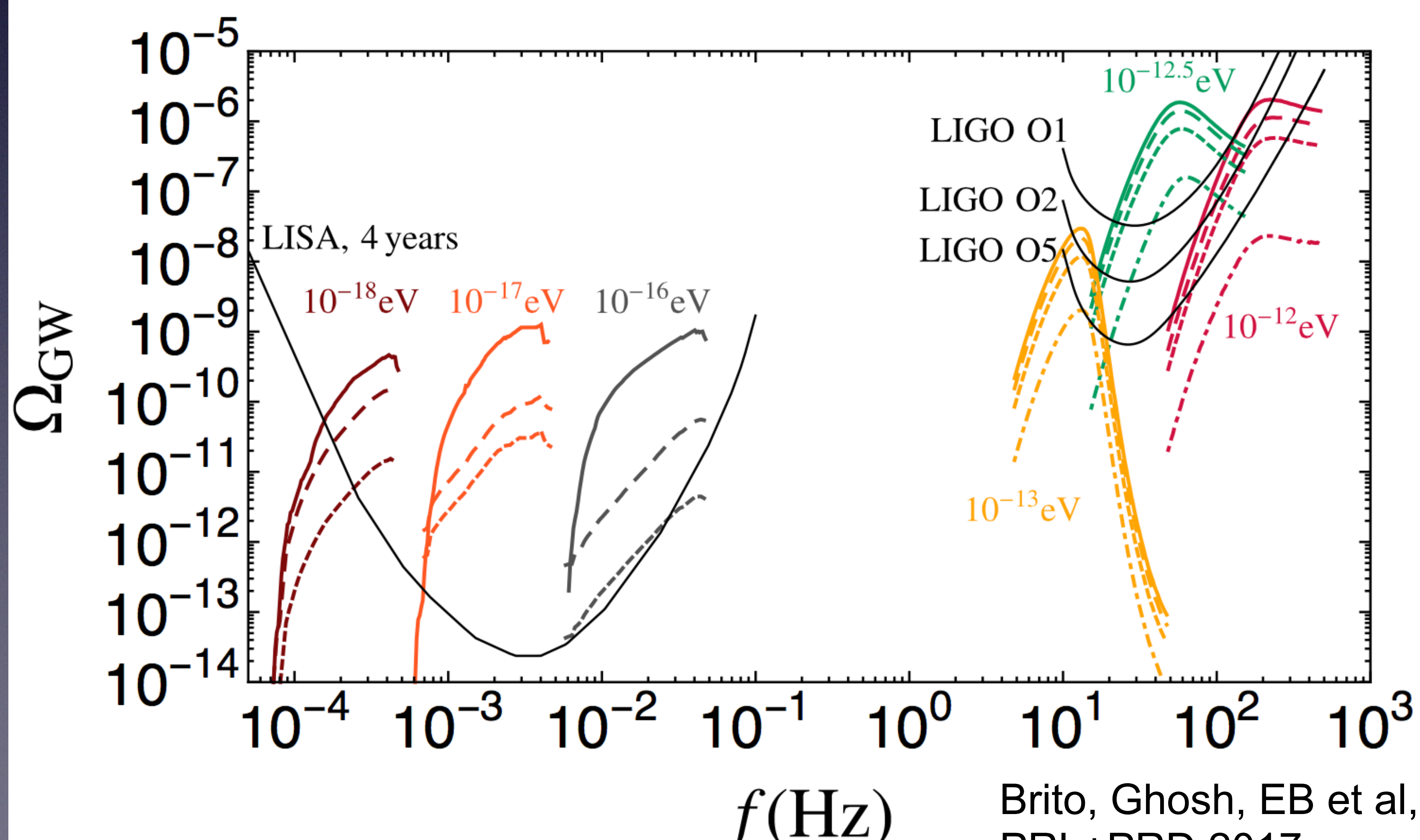
- Isolated spinning BH + massive scalar fields with Compton wavelength comparable to event horizon radius are unstable under super-radiance
- Mass and (mostly) angular momentum are transferred from BH to scalar condensate surrounding BH on instability timescale; condensate then emits almost monochromatic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

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

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





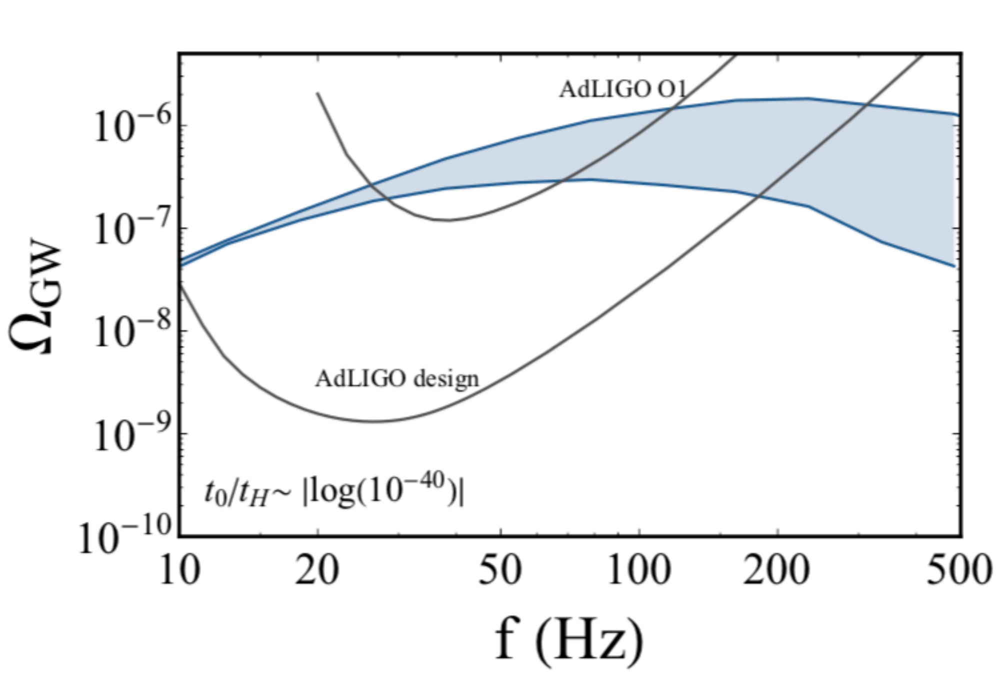


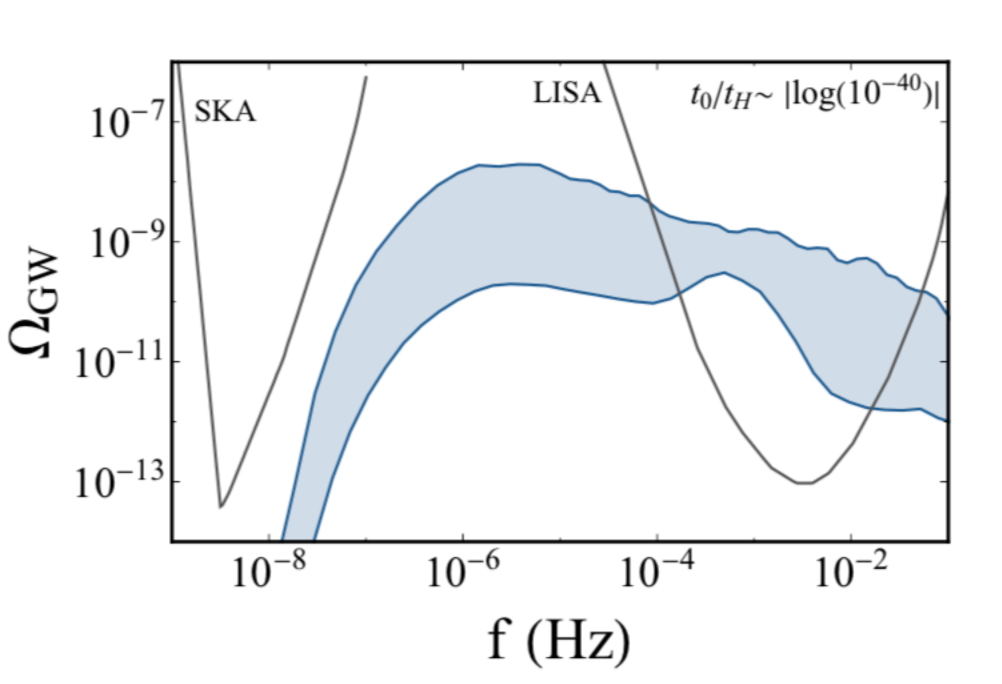
Brito, Ghosh, EB et al, PRL+PRD 2017

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





Systematics in GR tests

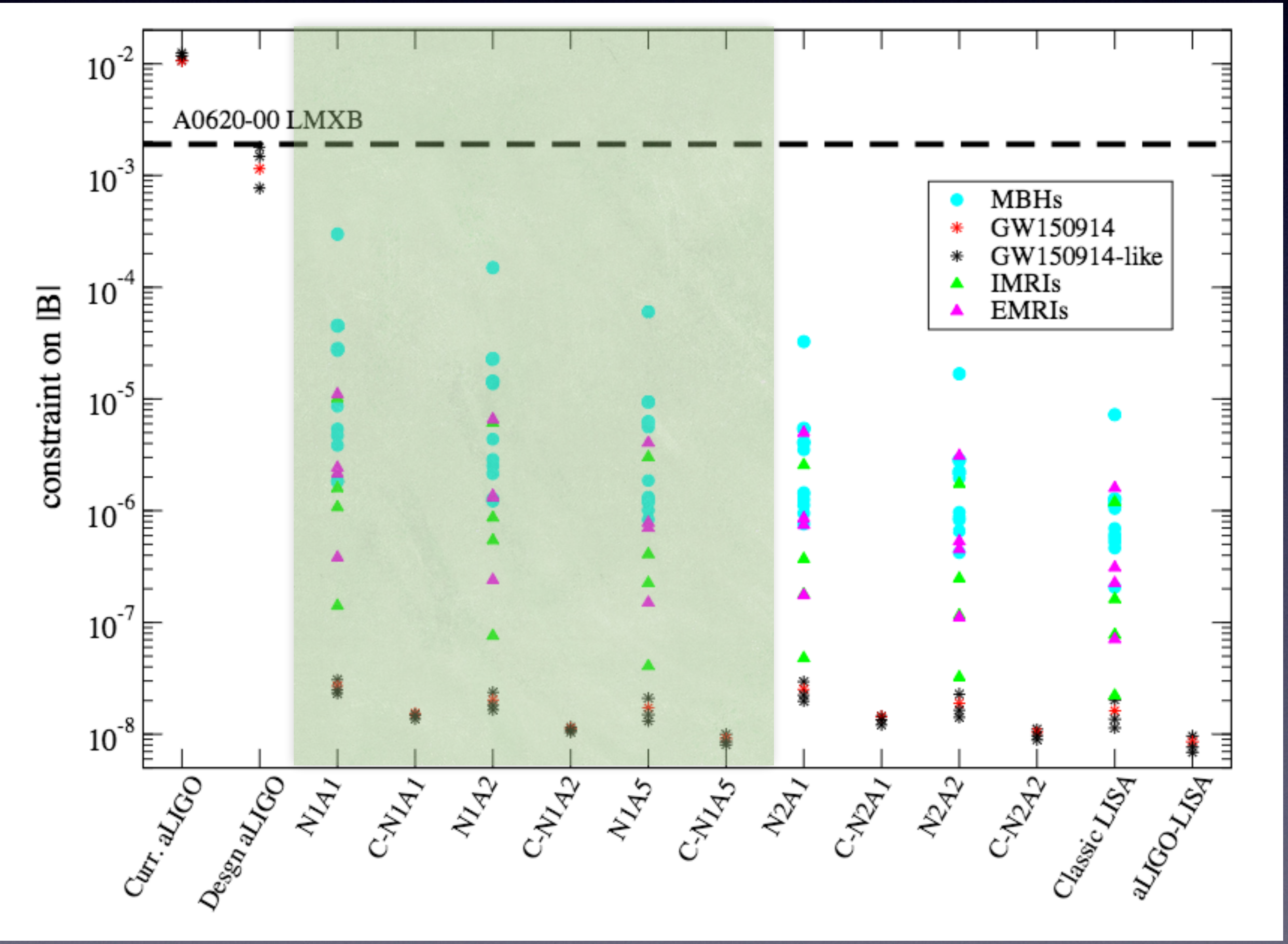
$$S = \frac{c^4}{16\pi\mathcal{G}}\int dx^4\sqrt{-g}\left[R+\partial^2\boldsymbol{\Psi}+\sum_i a_i U_i(\boldsymbol{\Psi},\boldsymbol{g},\partial\boldsymbol{\Psi},\partial\boldsymbol{g},...)\right]$$
$$+ \quad S_m^{(0)}[\boldsymbol{\Psi}_m, g_{\mu\nu}] + \sum_i b_i S_{m,i}^{(1)}[\boldsymbol{\Psi}_m, \boldsymbol{\Psi},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

	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

Systematics in GR tests

Environmental pollution of tests of GR violations is especially relevant because both are expected to be mainly low frequency effects



From EB, Yunes & Chamberlain 2016

Peculiar acceleration

- Constant velocity gives Doppler shift (re-absorbed in re-normalization of chirp mass and distance)

- Acceleration of binary's center of mass formally gives -4PN term in waveforms, but that term has small coefficient proportional to acceleration

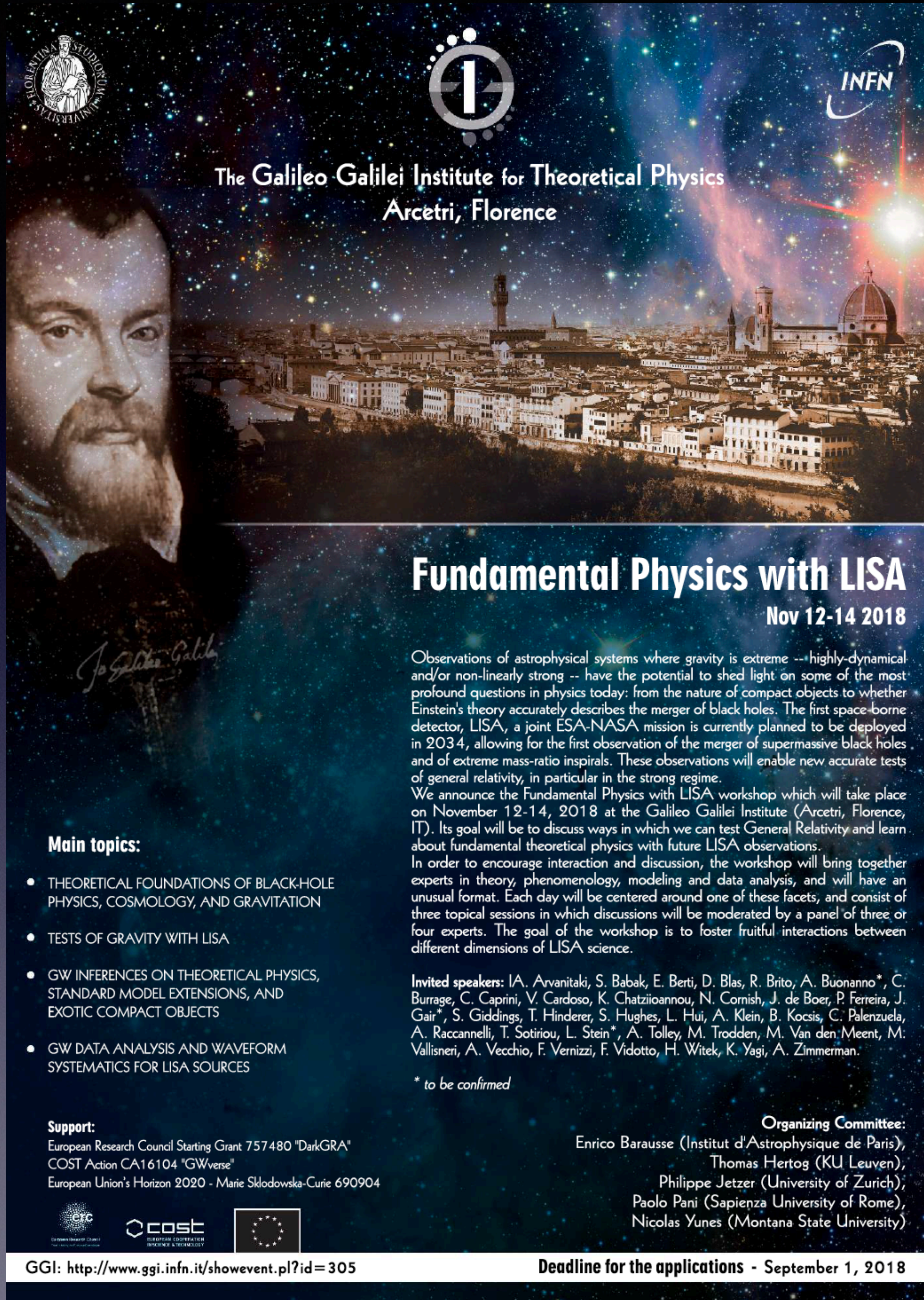
- Detectability explored in stellar-mass BH binaries in LISA for binaries forming in dense clusters or AGN disks

LISA mission duration	Acceleration scenario	LISA only					LISA+LIGO ($t_c < 10$y)				
		Total	100%	50%	30%	10%	Total	100%	50%	30%	10%
4 years	4	406.5	0.	0.	0.	0.	250.	0.	0.	0.	0.
		292.5	0.	0.	0.	0.	172.5	0.	0.	0.	0.
	5	406.5	1.	0.	0.	0.	240.	3.5	0.5	0.	0.
		288.	0.	0.	0.	0.	174.5	1.	0.	0.	0.
10 years	4	554.5	1.	0.	0.	0.	310.5	6.5	2.	0.	0
		394.	0.	0.	0.	0.	205.	5.	1.	0.	0.
	5	547.	69.	27.	12.5	0.	300.5	106.5	67.	38.5	7.5
		388.5	49.	20.	9.5	0.	200.5	72.	44.5	26.5	5.5

- EMRIs to be investigated, but probably difficult to accelerate COM significantly due to MBH mass

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)
- MBHs are probably safe from these effects, at least at $r < 60$-70 M
- Environmental effects could “blur” tests of GR, especially at low PN orders
- Overall, majority of EMRIs should be “matter-free” (for practical purposes) due to 1-10% AGN duty cycle
- More exotic environmental effects can be due to axionic DM or near-horizon structure (fuzzballs, firewalls)



http://www.ggi.infn.it/showevent.pl?id=305

https://signup.lisamission.org/