Environmental effects and matter systematics for (low-frequency) gravitational astronomy

Enrico Barausse (SISSA, Italy)









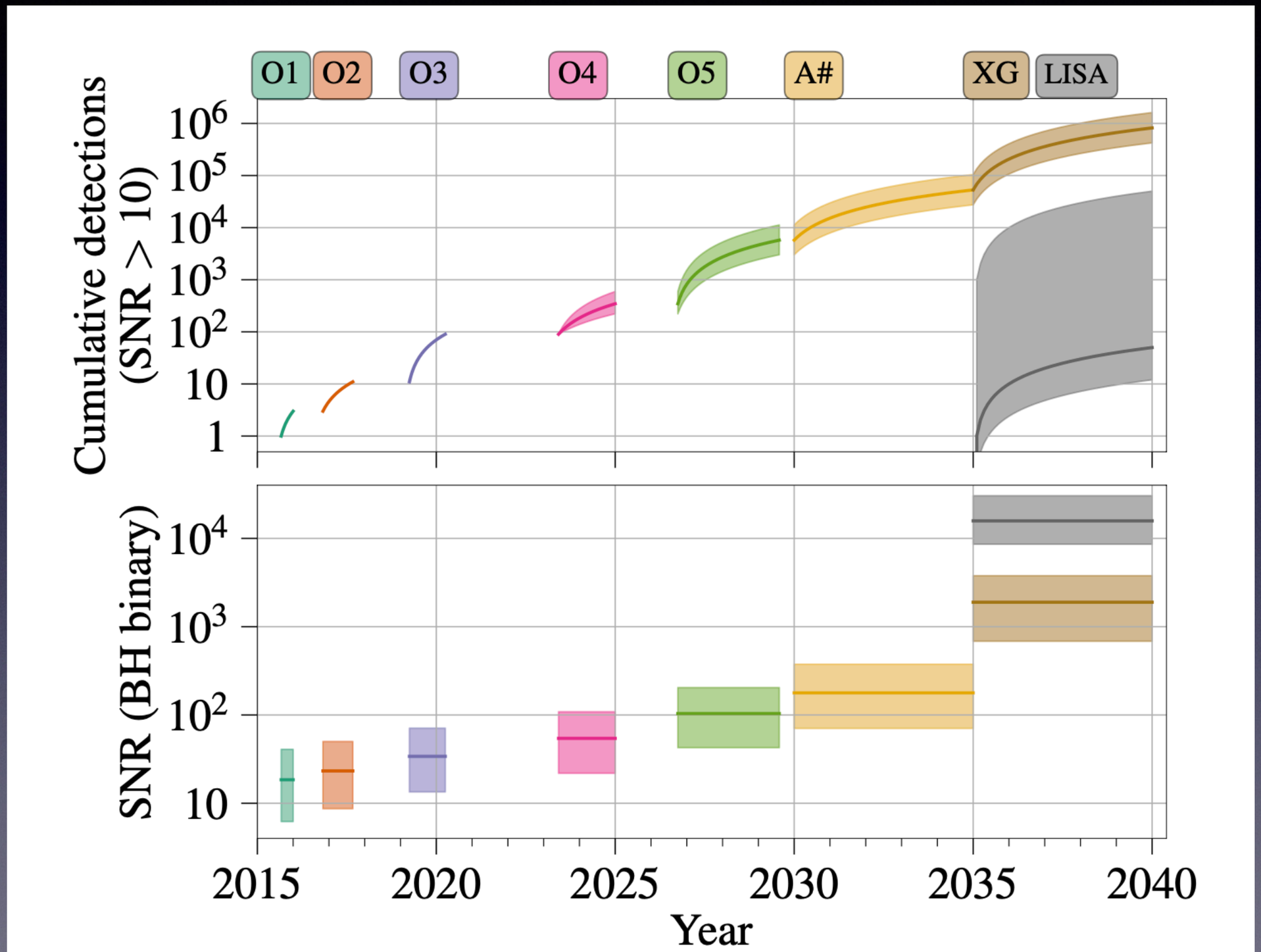




Talk outline

- What sources: SOBHs, MBHs (and their binary versions: SOBHBs, EMRIs, IMRIs, MBBHs)
- What environment? Gas? DM stars? accretion, dynamical friction/migration?
- How we model environment and how we detect it
- Degeneracy with GR tests at single source/population level

The loud future of GW astronomy





At high SNR, we will see deviations from our GR vacuum predictions.

To do physics, need to understand origin of anomalies:

- Waveform systematics?
- Noise artefacts?
- Global fit?
- Astrophysical environment?
- Deviations from GR?



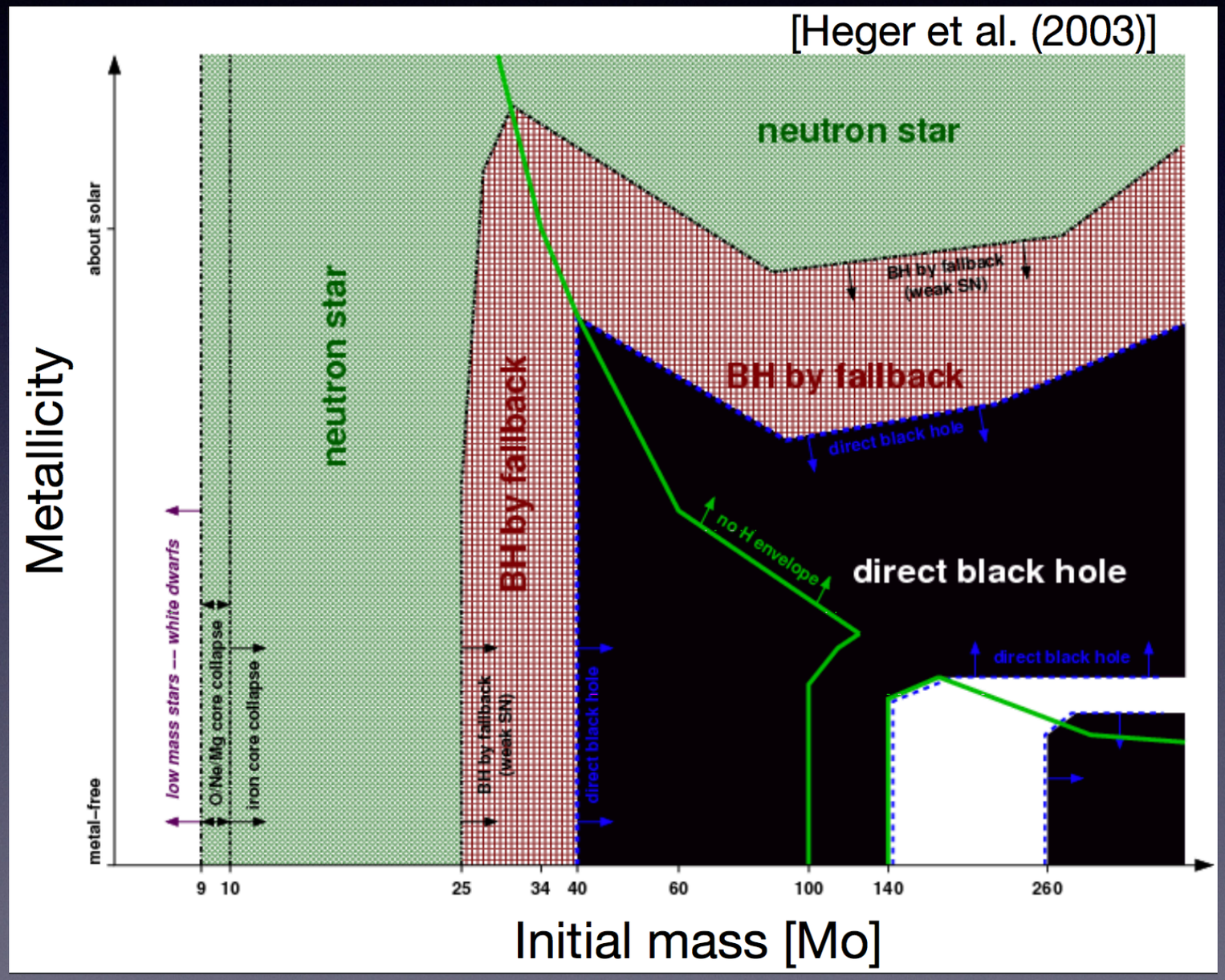
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- **Astrophysical environment**?
- Deviations from GR?

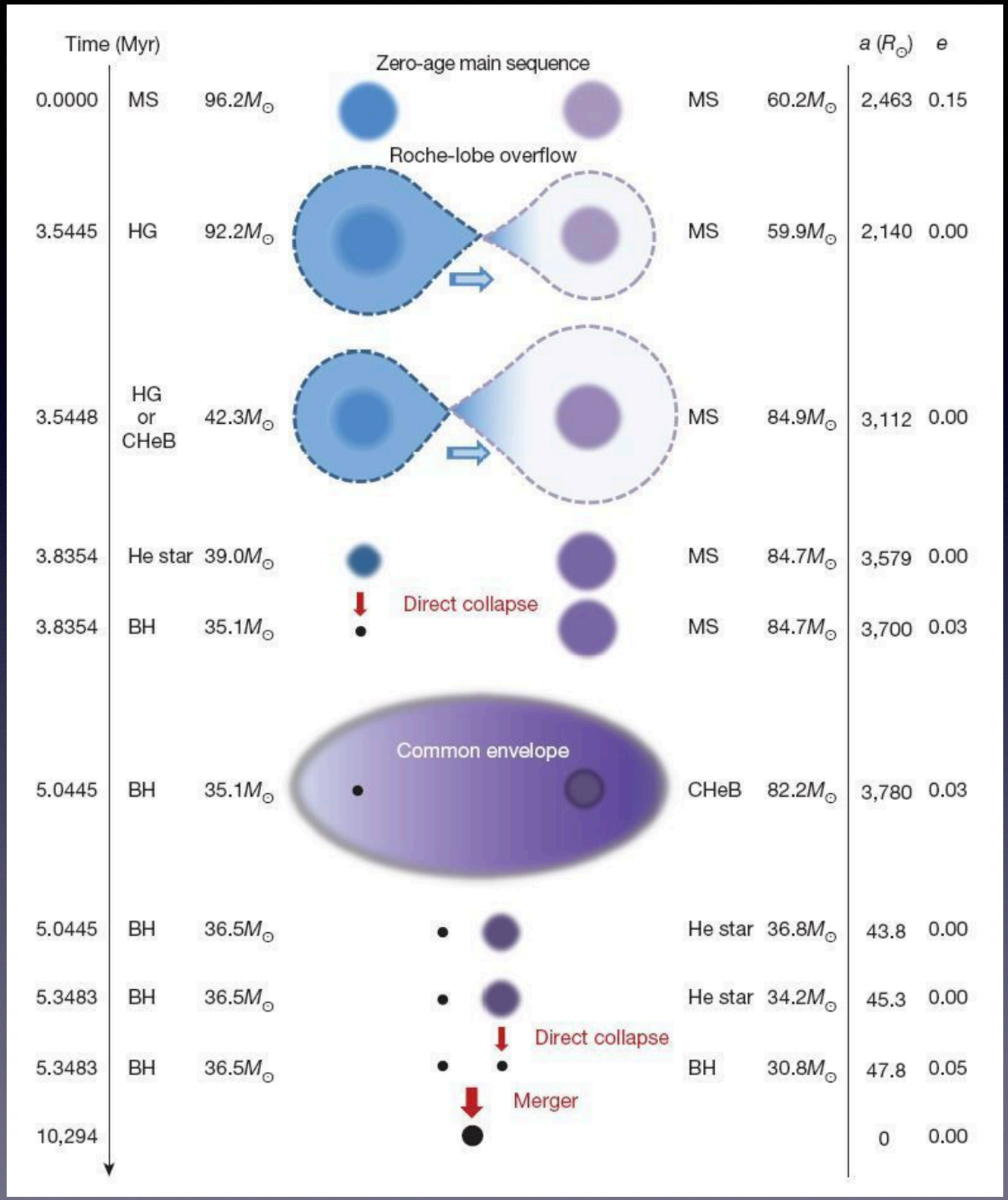
Stellar-mass BH binary formation

Isolated stellar-mass BH are endpoint of stellar evolution



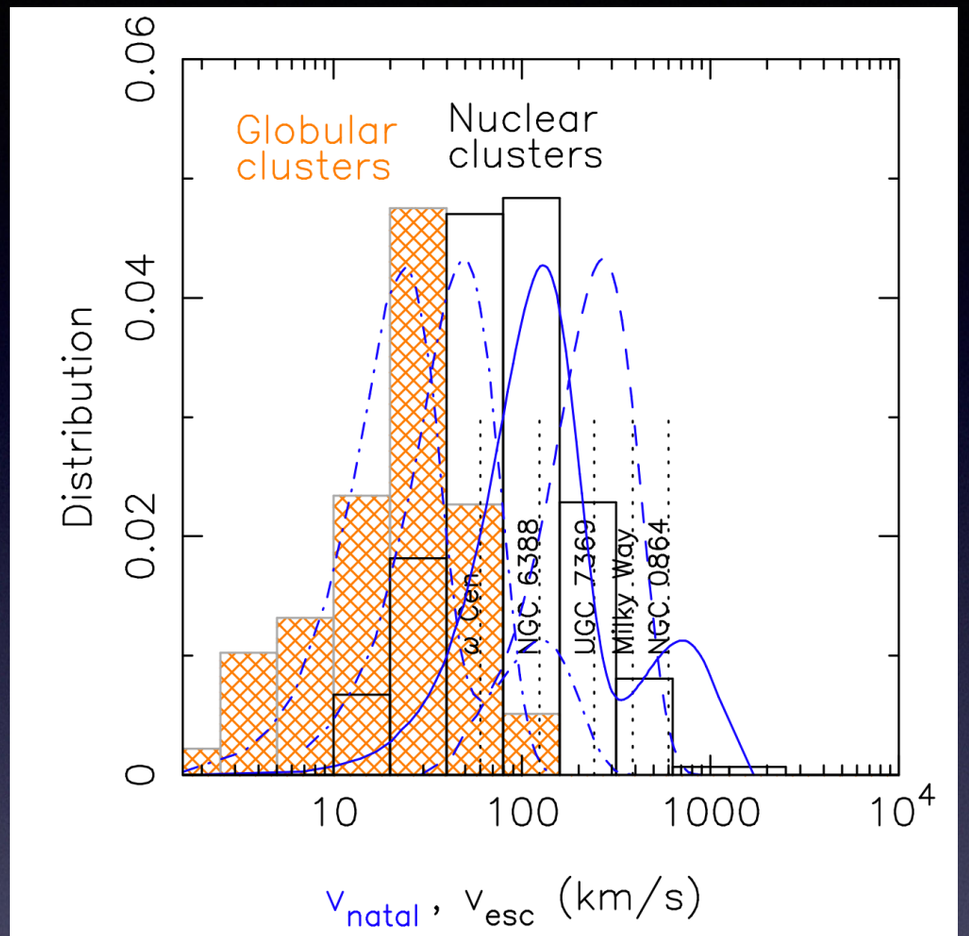
Field SOBHBs

Gas?
Eccentricity?



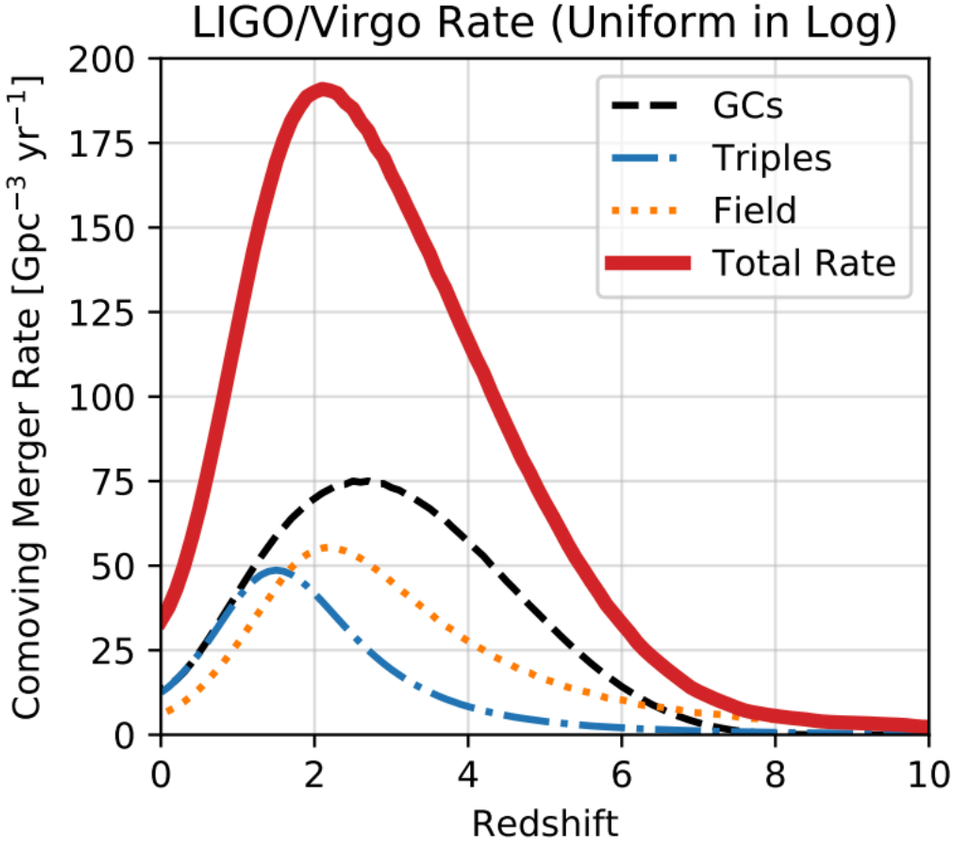
Belczynski et al 2016

Dynamical channel



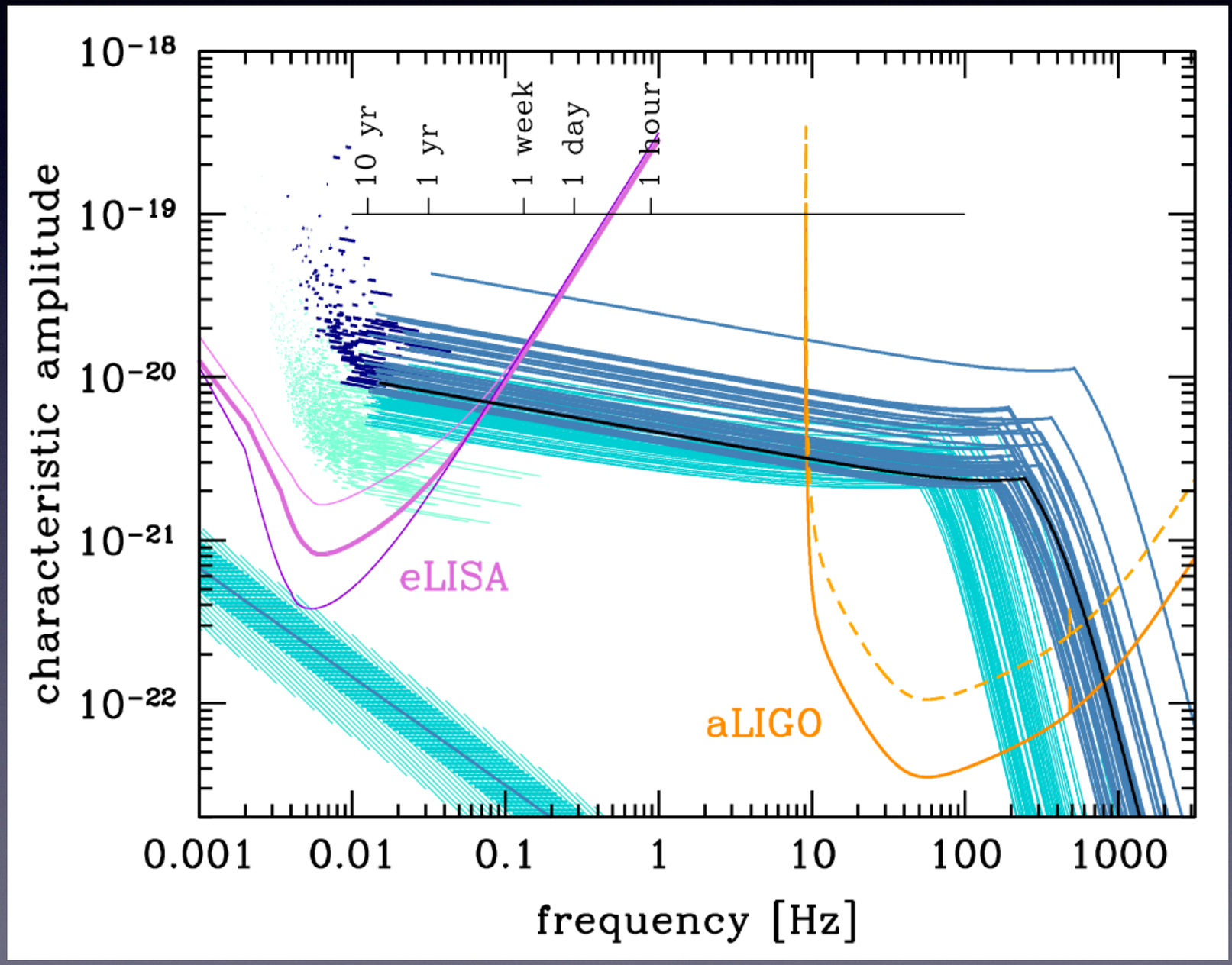
Antonini & Radio 2016

- Possible in dense environments (globular/nuclear clusters, AGNs)
- May be as important as field channel



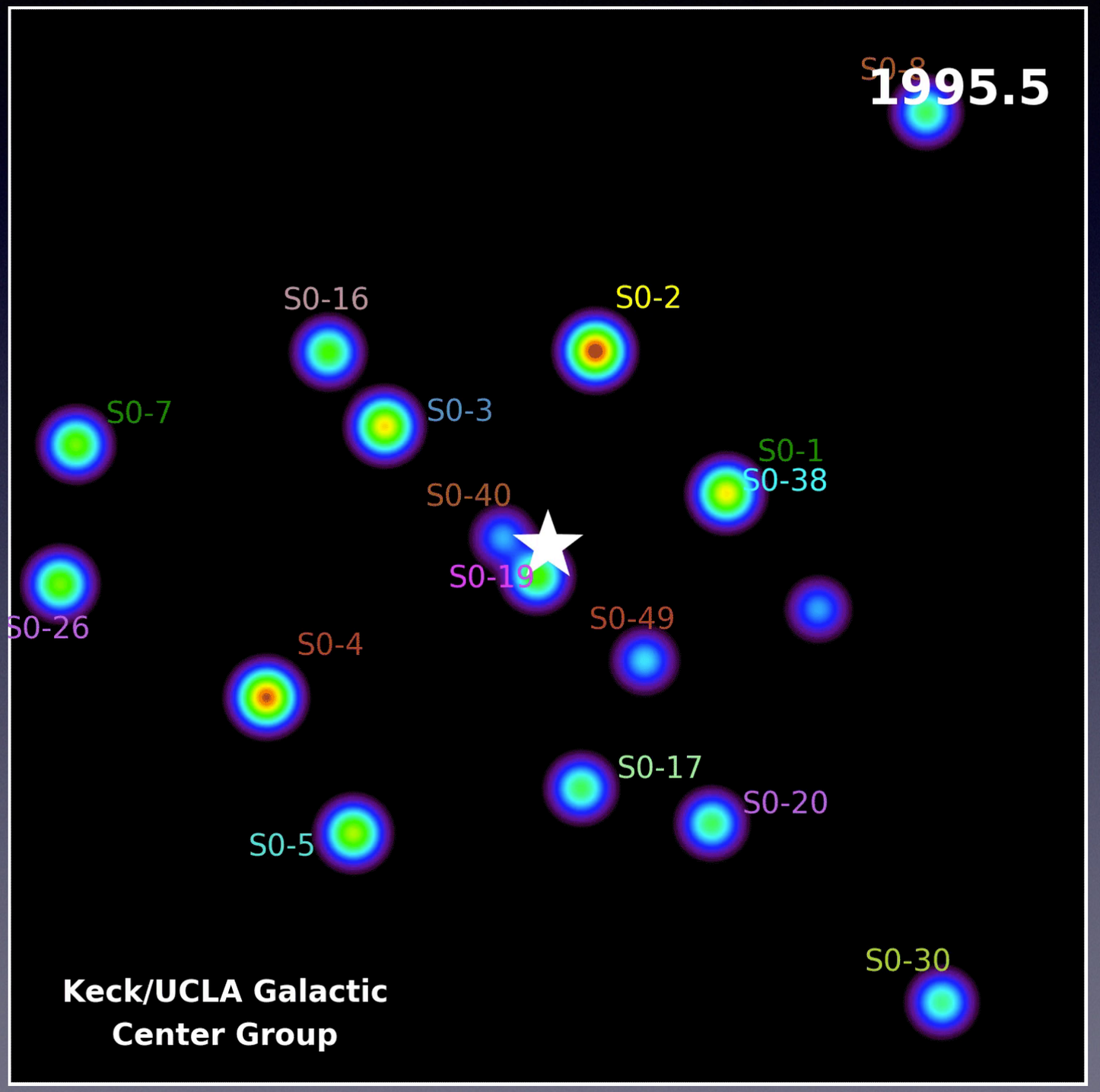
Rodriguez & Loeb 2018

Stellar-mass BH binaries across detectors



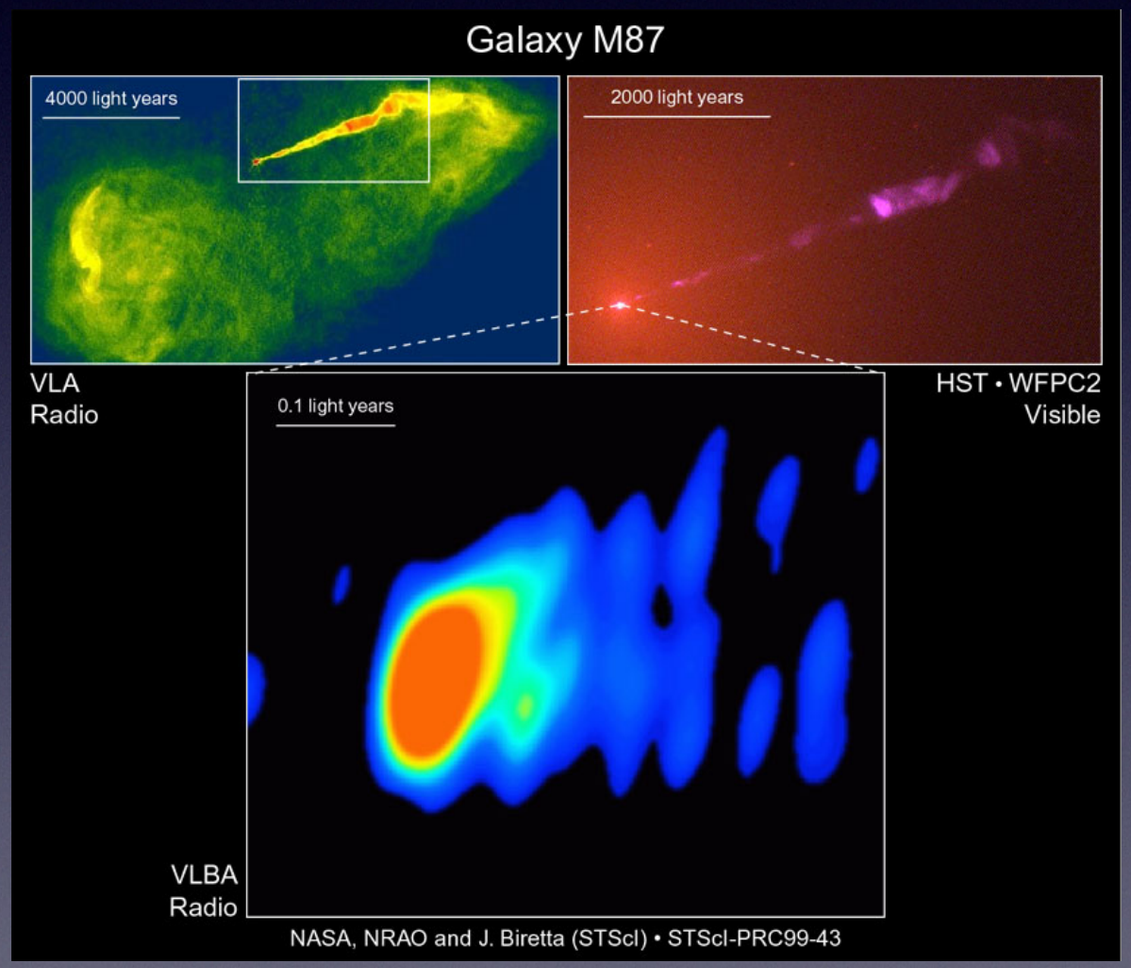
Sesana 2016

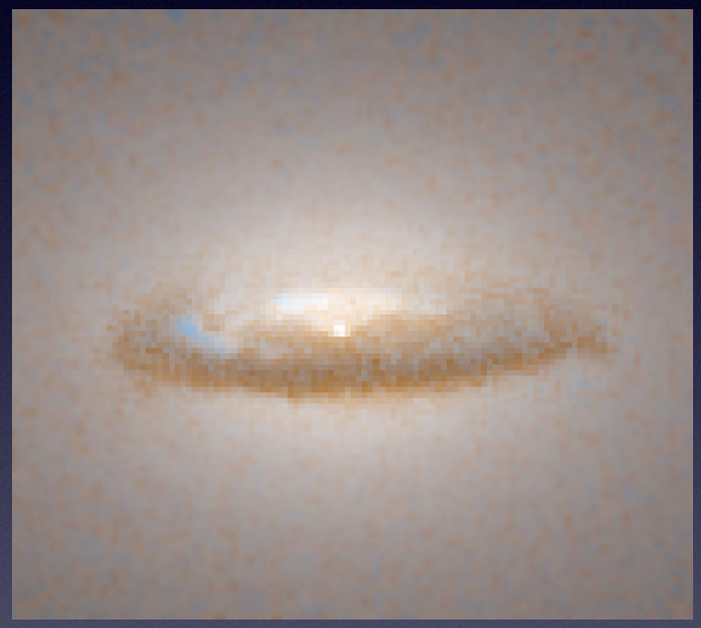
Massive BHs


1995.5
S0-8
S0-16
S0-2
S0-7
S0-3
S0-1
S0-38
S0-40
S0-19
S0-26
S0-49
S0-4
S0-17
S0-20
S0-5
S0-30
Keck/UCLA Galactic
Center Group

MBHs and their milieu

- MBH 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

- Galactic nuclei provide fuel to BHs to grow (”accretion”)

Galaxies merge…

… so massive BHs must merge too!

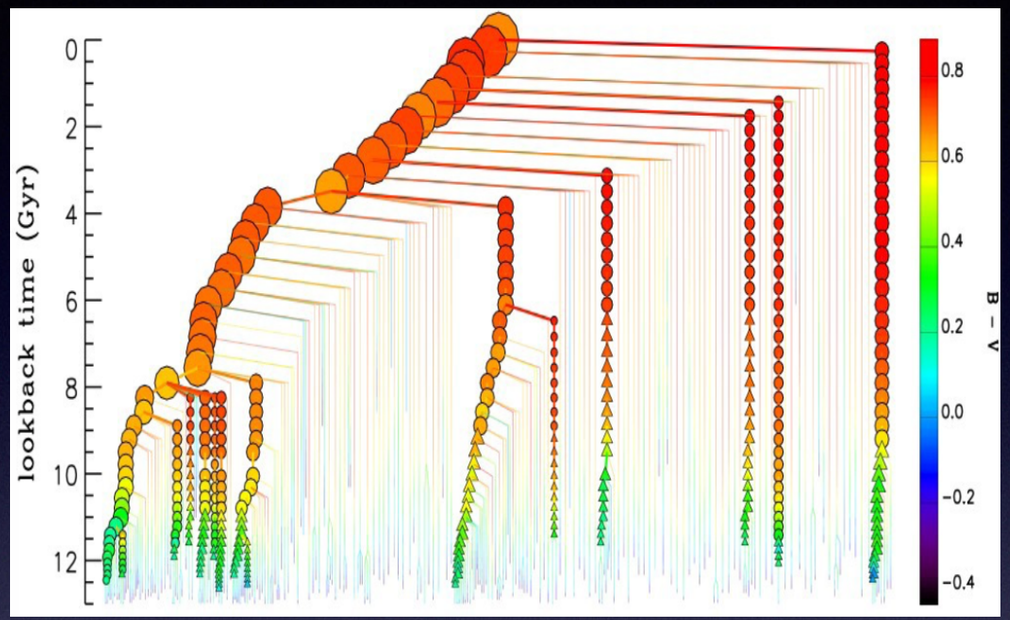
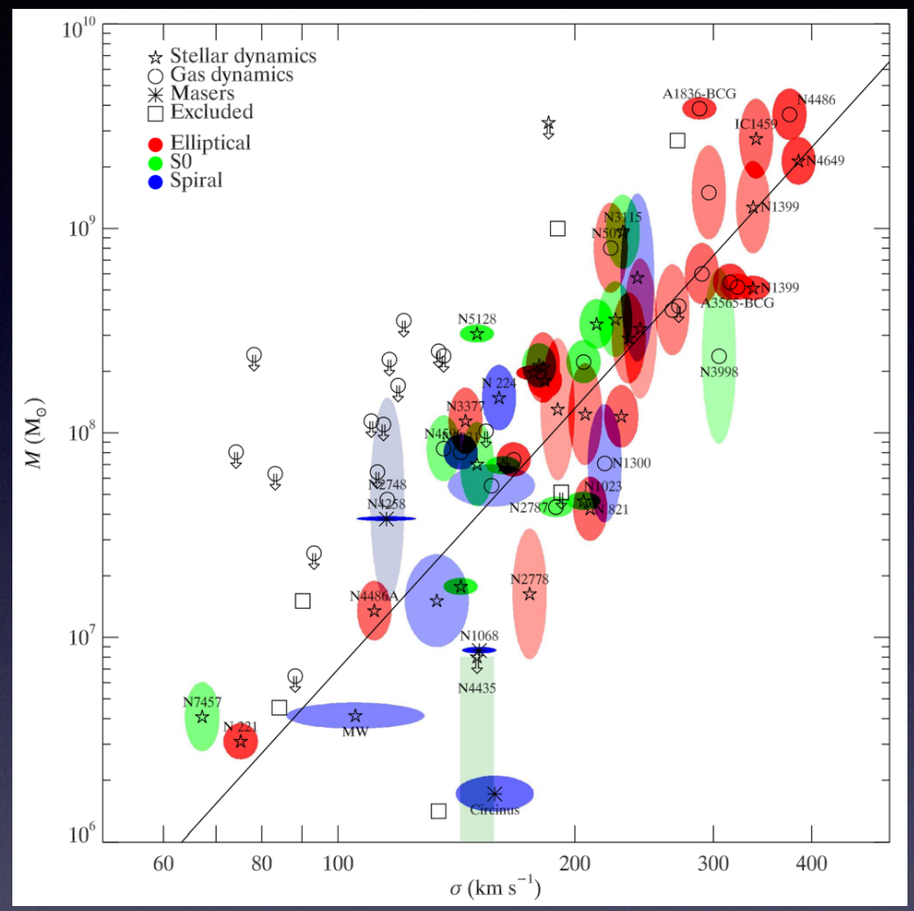


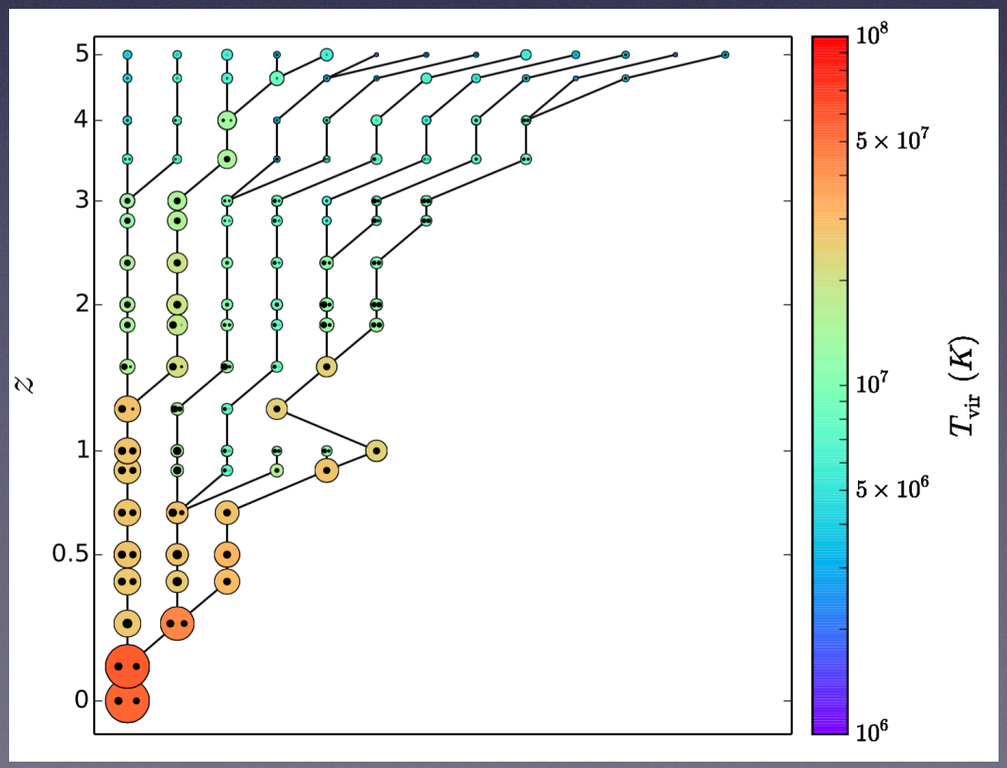
Figure from De Lucia & Blaizot 2007

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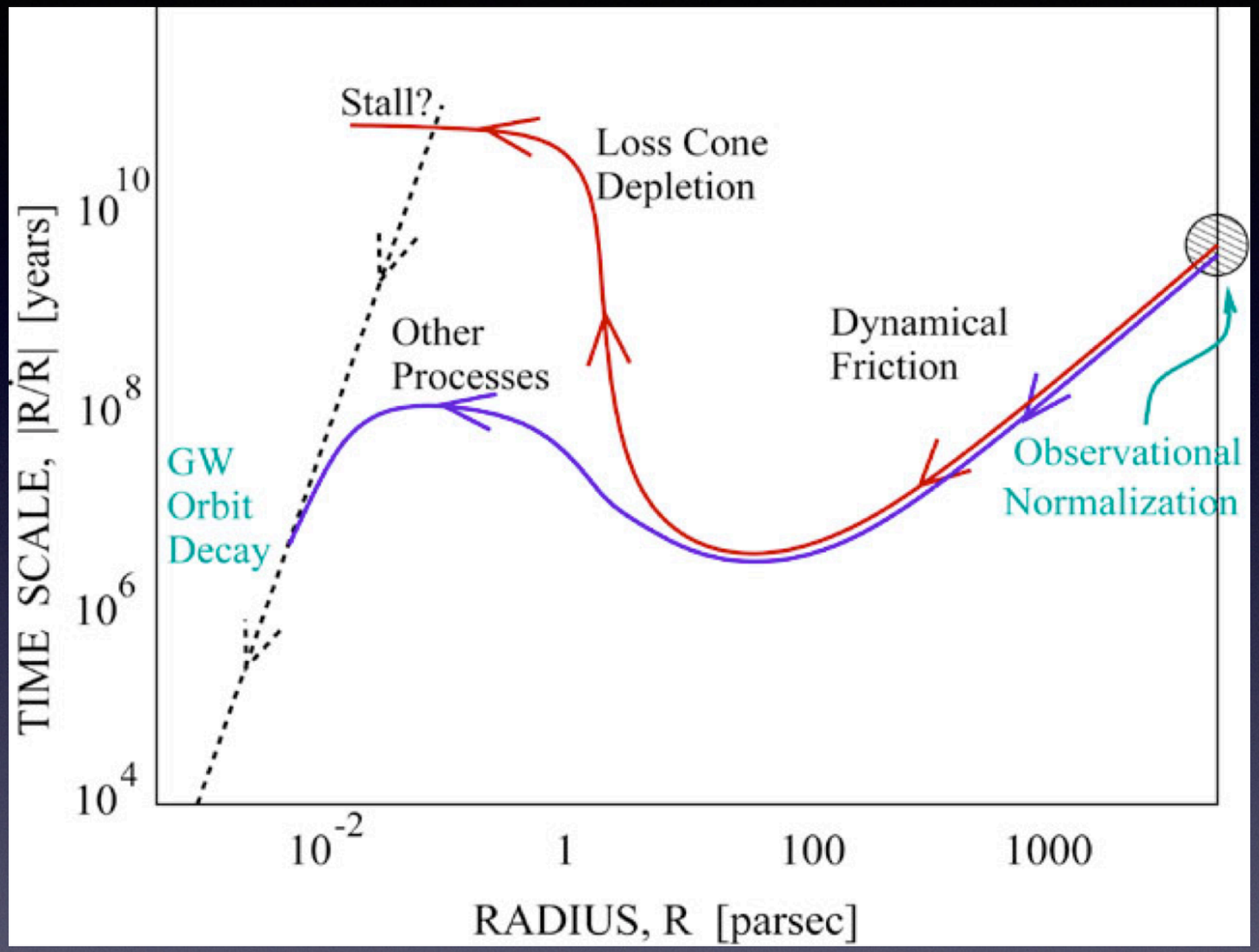
Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

=



EB 2012
Figure credits: Lucy Ward

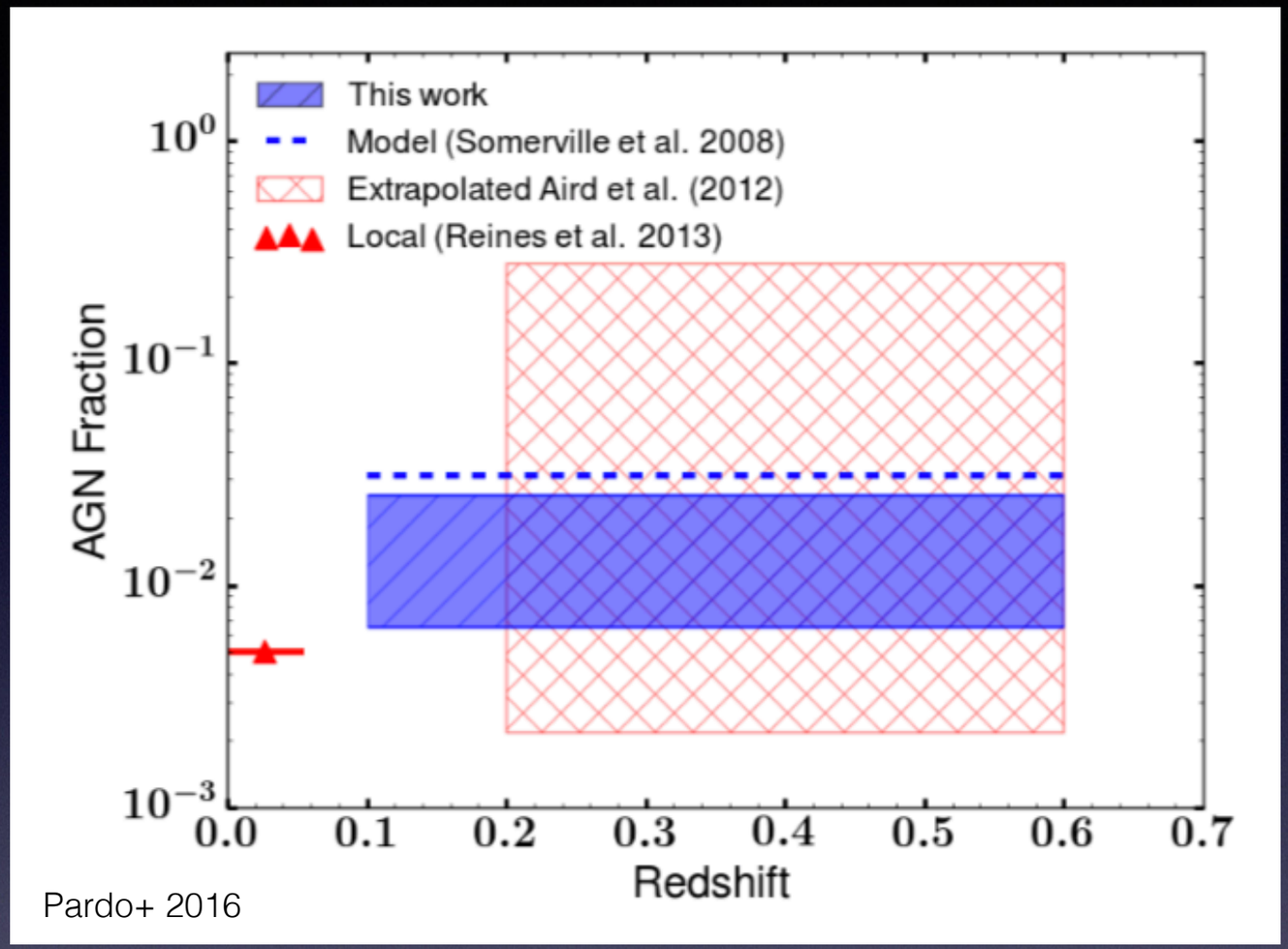
The “final pc problem”



Begelman, Blandford & Rees 1980

Environment is crucial for mergers (dynamical friction, disk migration, stellar hardening, MBH triples, eccentricity…)

How many sources are affected by gas?



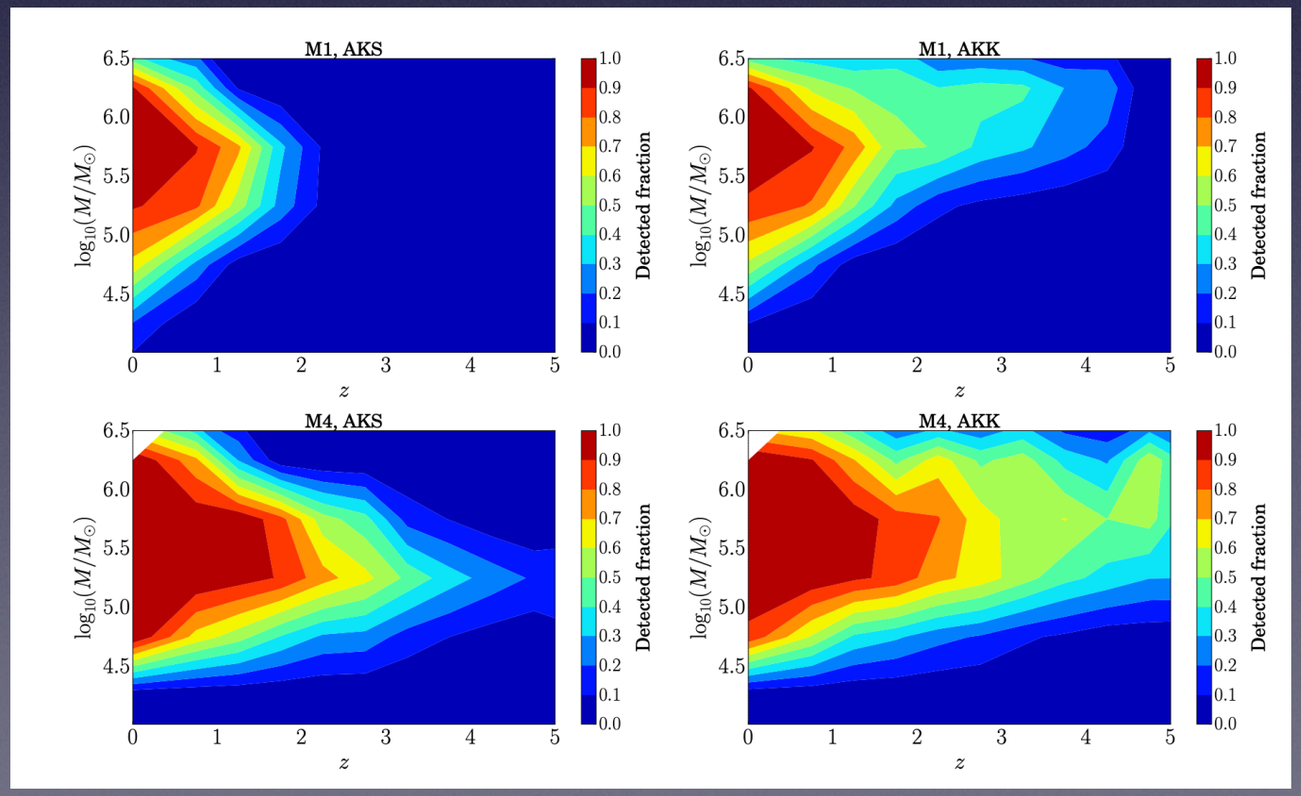
Pardo+ 2016

Several % (at least) of EMRIs/MBHBs/SOBHBs affected by gas/matter:

- Is effect on GW signals measurable?
- Can it bias recovery of source parameters (eg masses) or tests of GR?

EMRI rate: do we know anything?

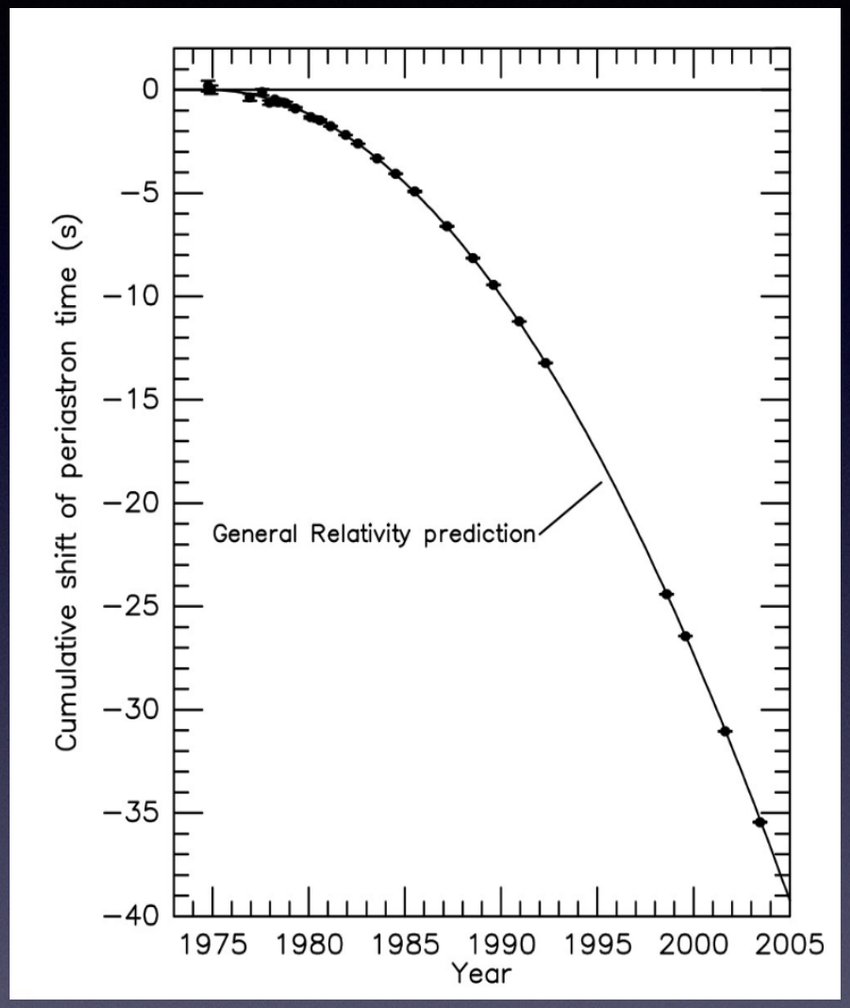
Model	Mass function	MBH spin	Cusp erosion	M–σ relation	$N_{\rm p}$	CO mass [$M_\odot$]	EMRI rate [yr^{-1}] Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
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

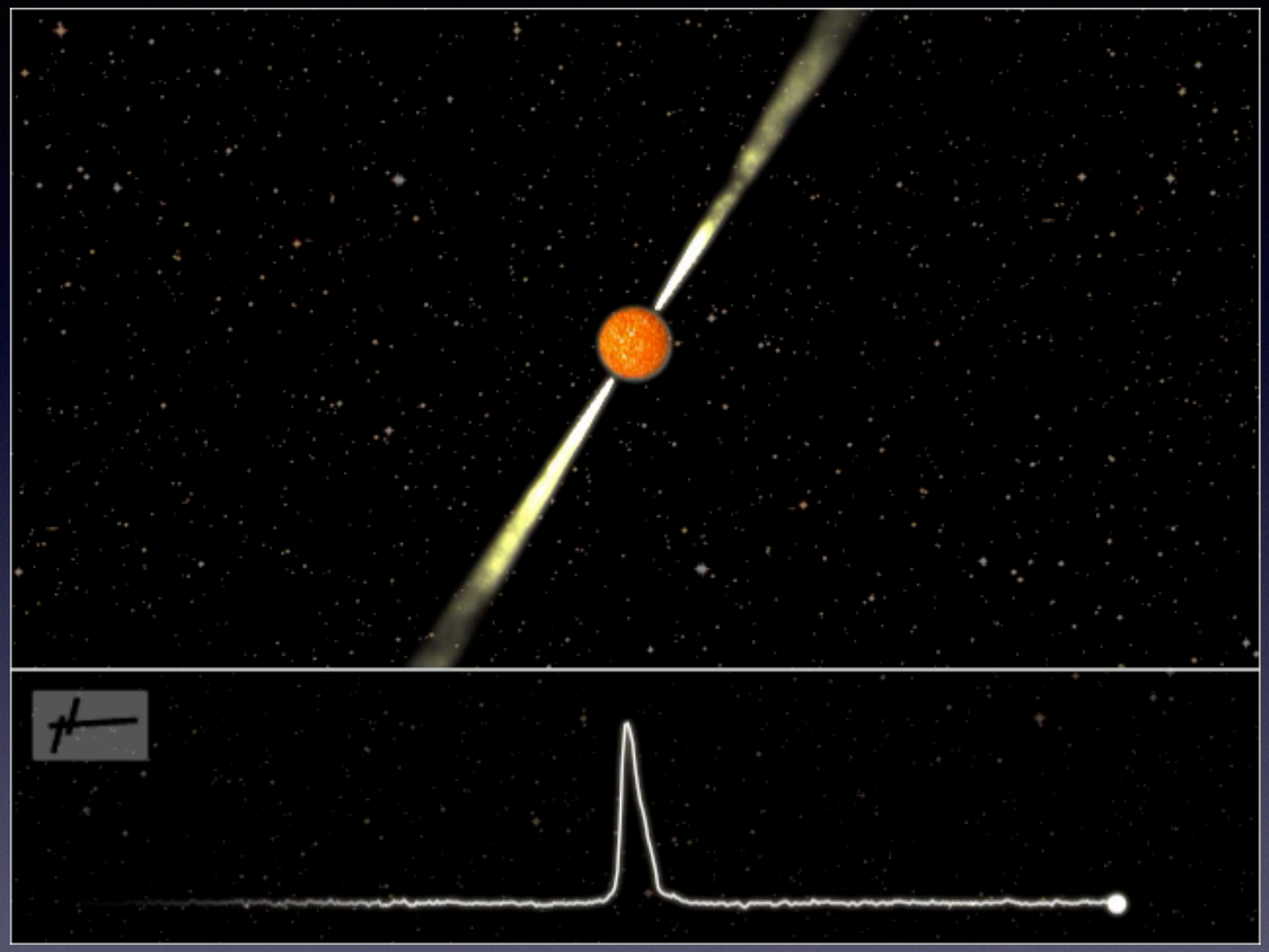


Rates uncertain: depend on low-mass end of BHMF, presence of core vs cusp, and intrinsic EMRI rate per MBH

Babak+2017

Tests of GR and environment



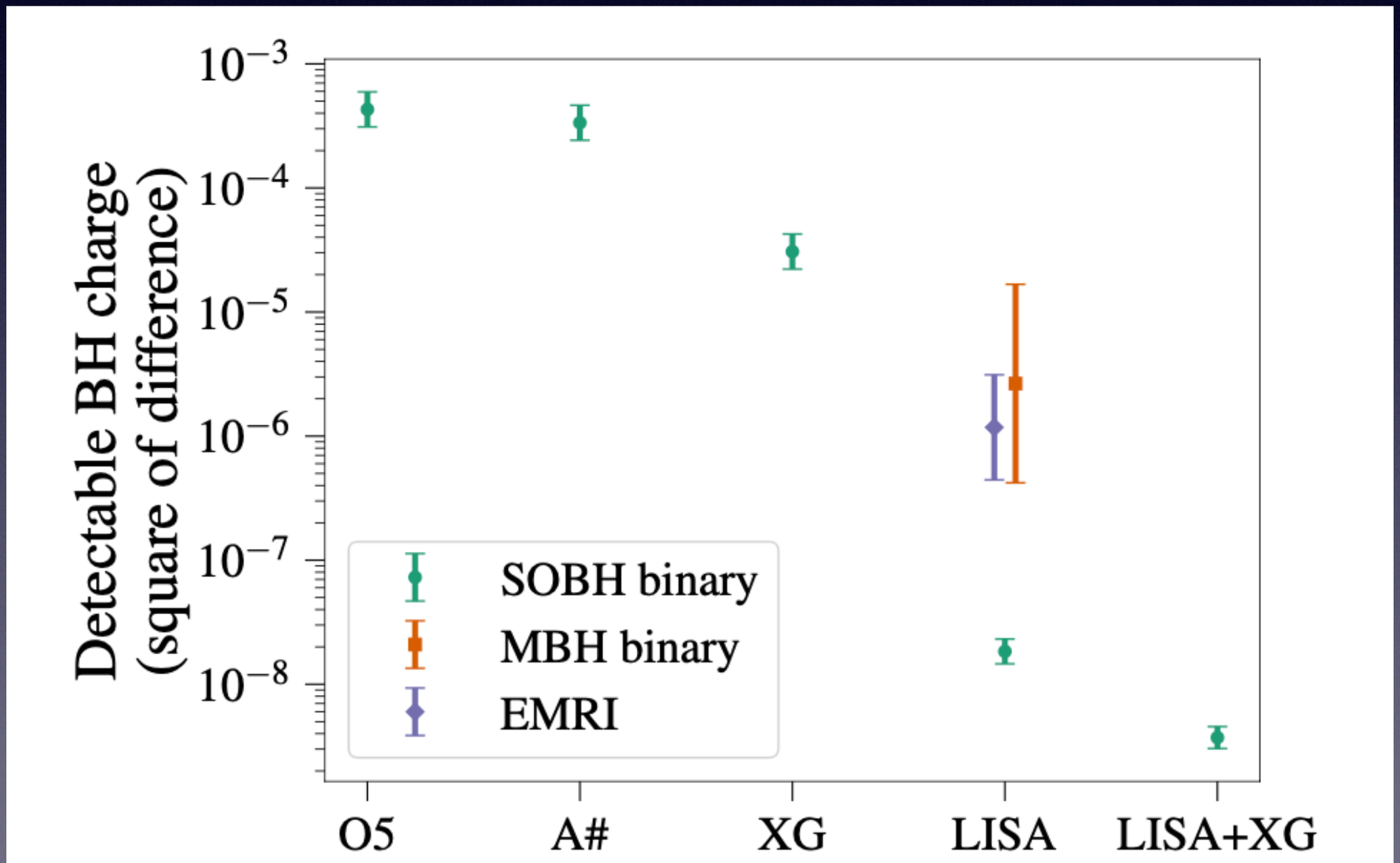


Need to subtract peculiar acceleration (Damour &Taylor 1991)

Acceleration enters fluxes at -4PN like accretion [same effect on M(1+z)]

Tests of GR with BH binaries

Environmental “pollution” of GR tests worrisome as both low frequency effects



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

EB, Yunes & Chamberlain 2016

Environmental effects, orders of magnitude

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

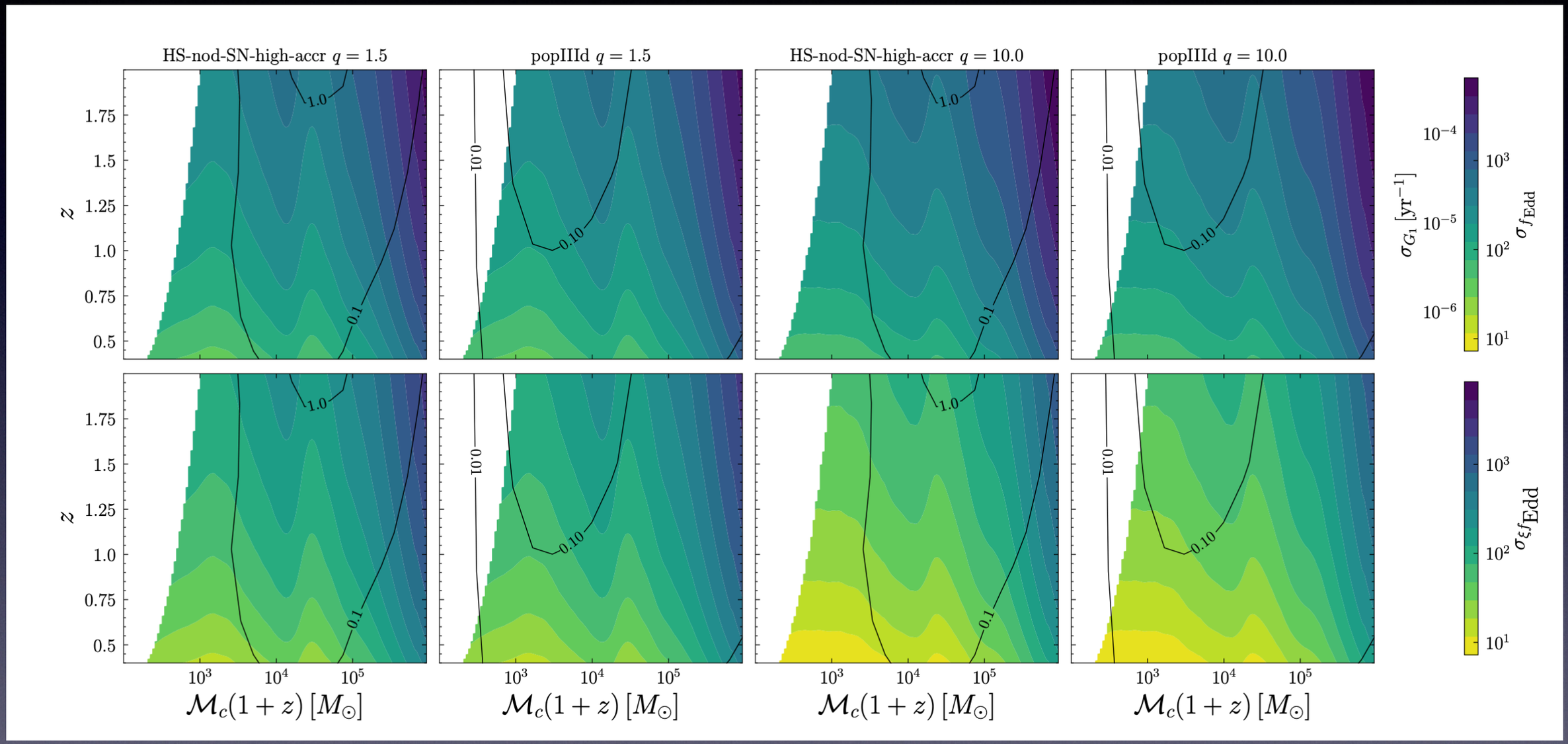
Correction	$\lvert\delta_\varphi\rvert/P$	P
planetary migration	$< 10^{4}$	cf. Refs. [46, 47]
thin accretion disks (DF)	$\lesssim 10^{2}$	$f_{\rm Edd}\left(\frac{0.1}{\alpha}\right)\left(\frac{\nu}{10^{-5}}\right)^{1/2}\left(\frac{M}{10^{6}M_\odot}\right)^{-0.3}$ (cf. Sec. XII J)
thin accretion disks (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

Negligible for MBHBs



Copparoni & EB 2026

EMRIs and SOBHBs are a different story…

Gravitational pull from thin disks

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

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

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

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

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

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

Gravitational pull ~ 2nd order (cons) SF

Dynamical friction/accretion

- Accretion onto BHs (both primary and satellite)/peculiar acceleration

$$\dot{M}_{\rm Edd,cen} \approx 2.2\times10^{-2}\left(\frac{M}{10^6 M_\odot}\right) M_\odot {\rm yr}^{-1}$$

$$\dot{M}_{\rm Edd,sat} \approx 2.2\times10^{-7}\left(\frac{m}{10 M_\odot}\right) M_\odot {\rm yr}^{-1}$$

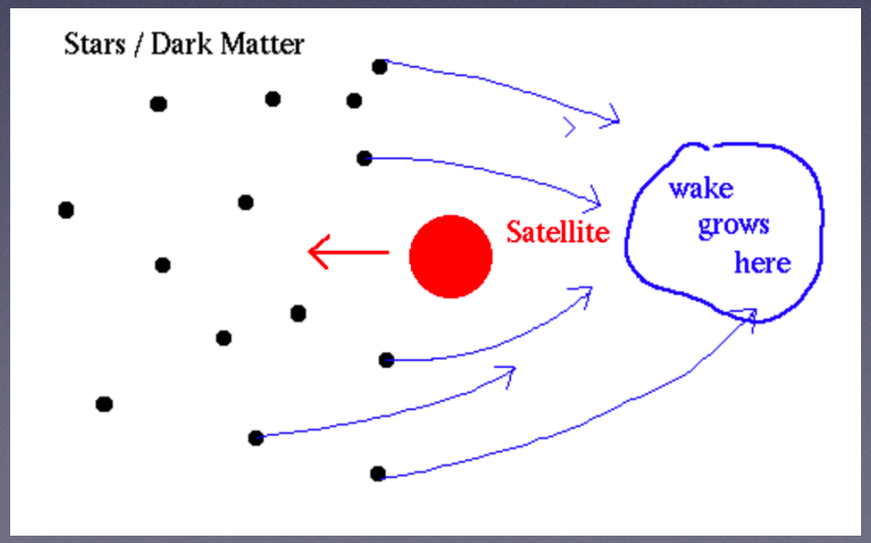
- Hydrodynamic drag/winds due to accretion

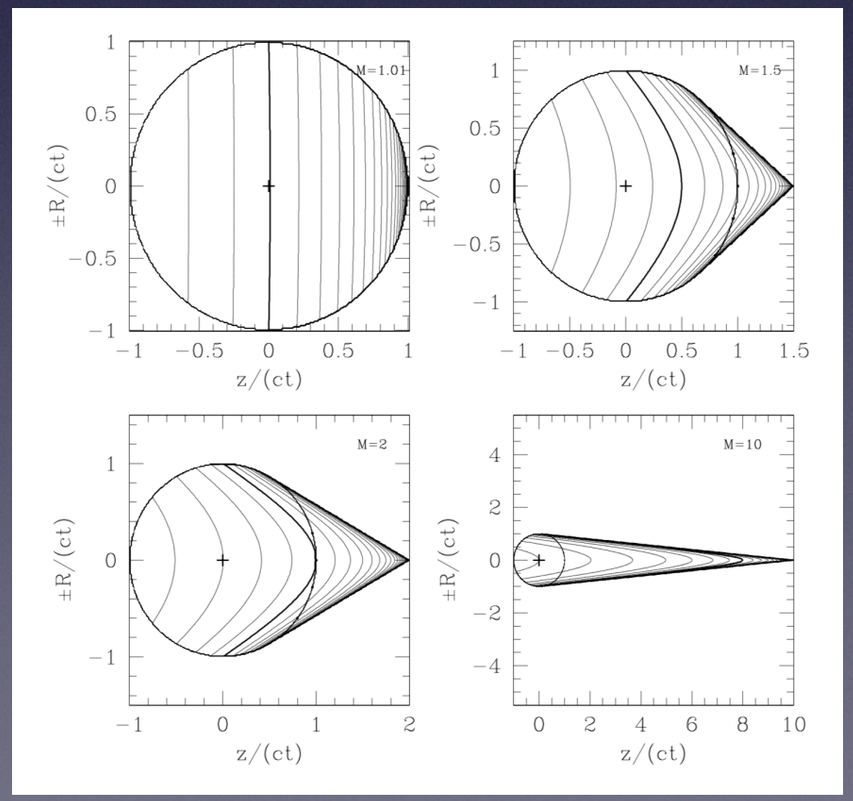
$$\boldsymbol{F}_{\rm accr} = \dot{m}(\boldsymbol{v}_{\rm gas} - \boldsymbol{v}_{\rm sat})\xi$$

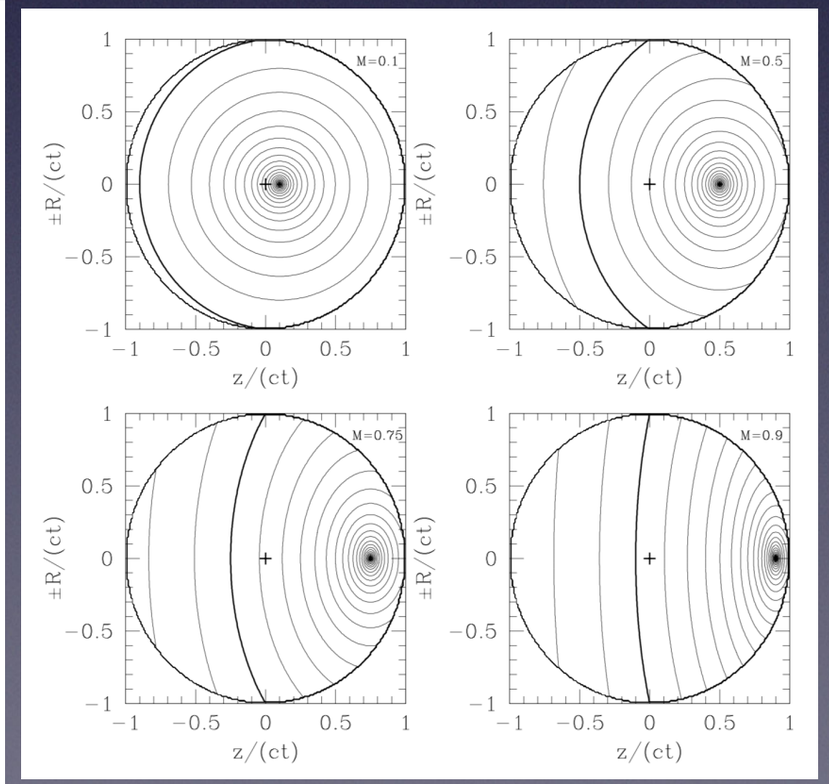
- Dynamical friction (gravitational pull from density waves excited by body): dominant at r > 40 M

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

E. C. Ostriker 1998



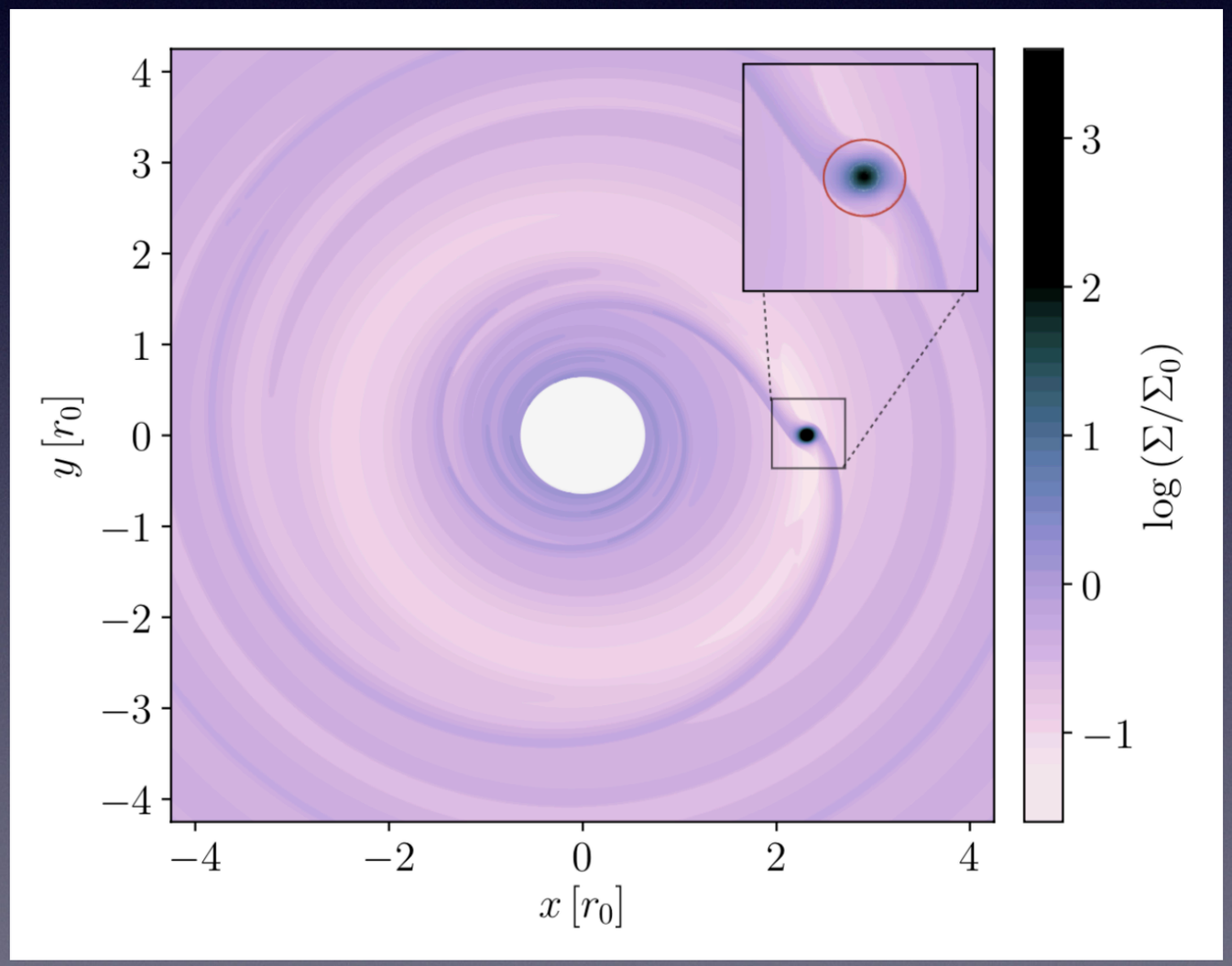




Planetary migration

- Exterior wake lags being satellite and thus pulls it, interior wake trails and pushes it (cf Yunes+11, Derdzinski+20): dominates over GW fluxes at r>20-30 M, larger than 2nd SF at all separations

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



Derdzinski+20

- 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

- Sign can change (migration traps)
- Can have stochastic contributions (Derdzinski+20, Copparoni+EB+25)

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 >> mean free path)

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

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 overdensities 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)

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



$q < 10^{-3}$

More effects…

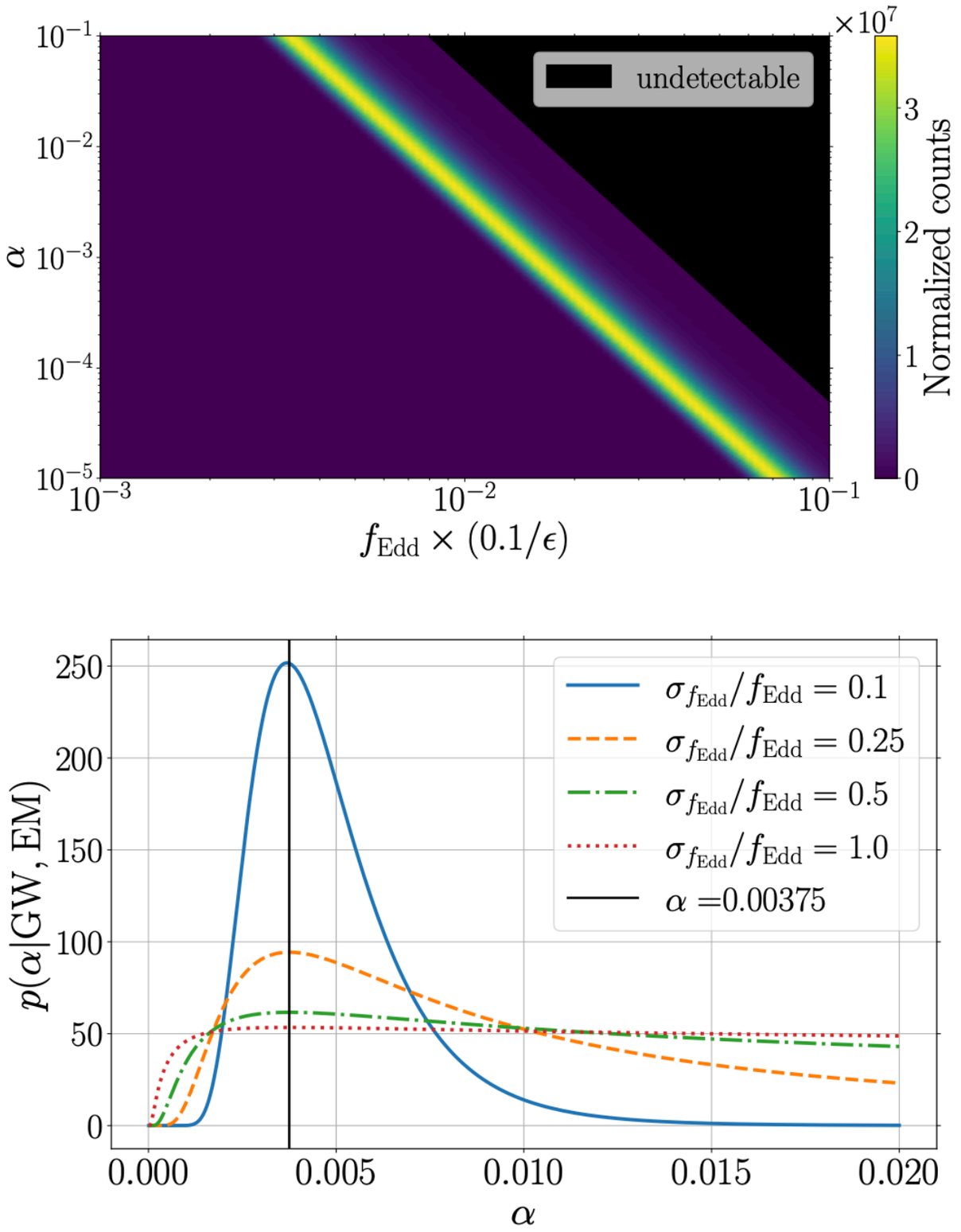
- Stellar perturbers: probably unlikely because

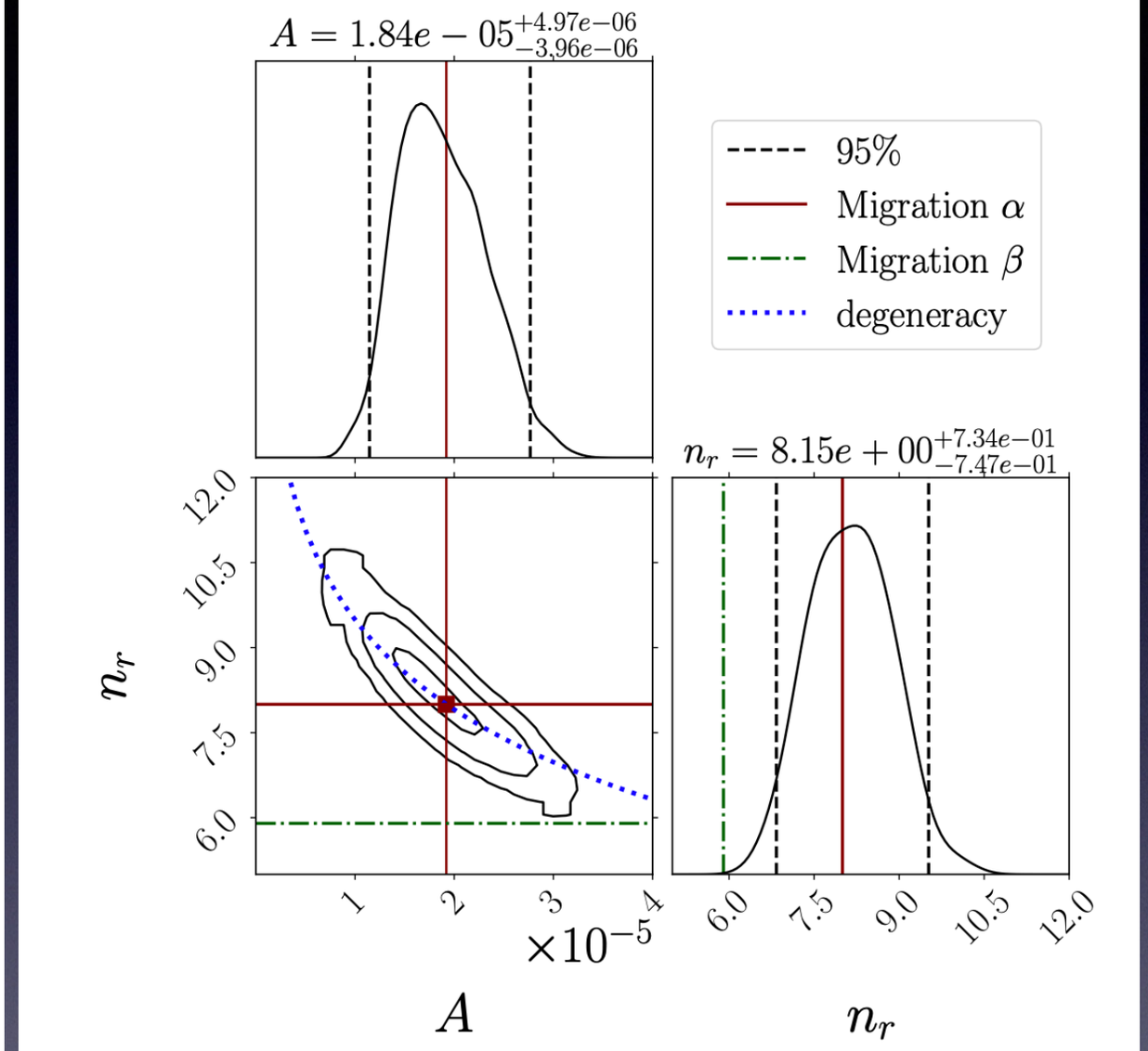
- binary separation << interstellar distance (even in dense nuclei)
- Two-body relaxation timescale ~ Gyr >> radiation reaction time

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

- Other possibilities: 2nd SMBH at ~ 0.1 pc distance (Yunes, Miller & Thornburg 2011), b-EMRIs (SOBHB+MBH)

EMRIs as probes of AGNs

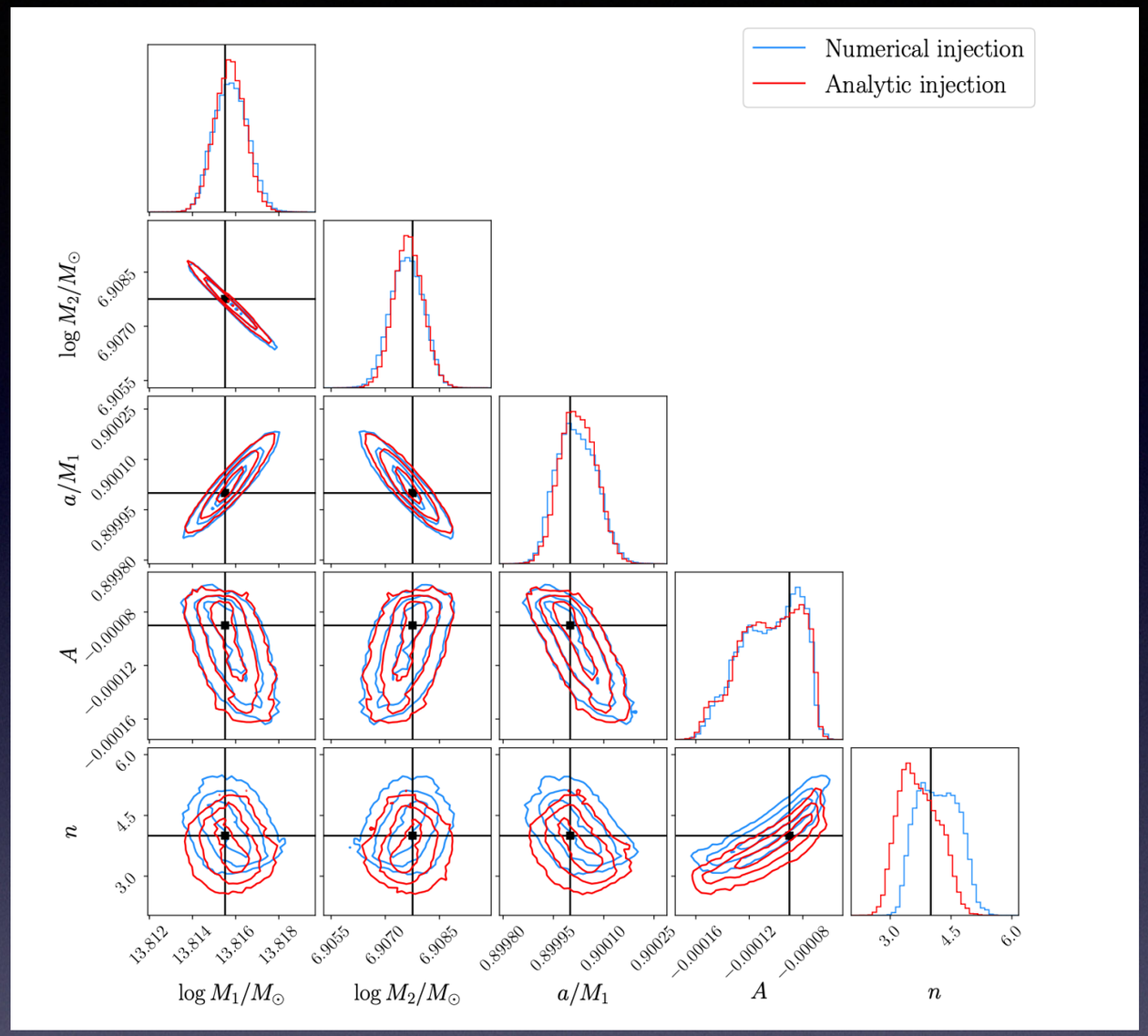




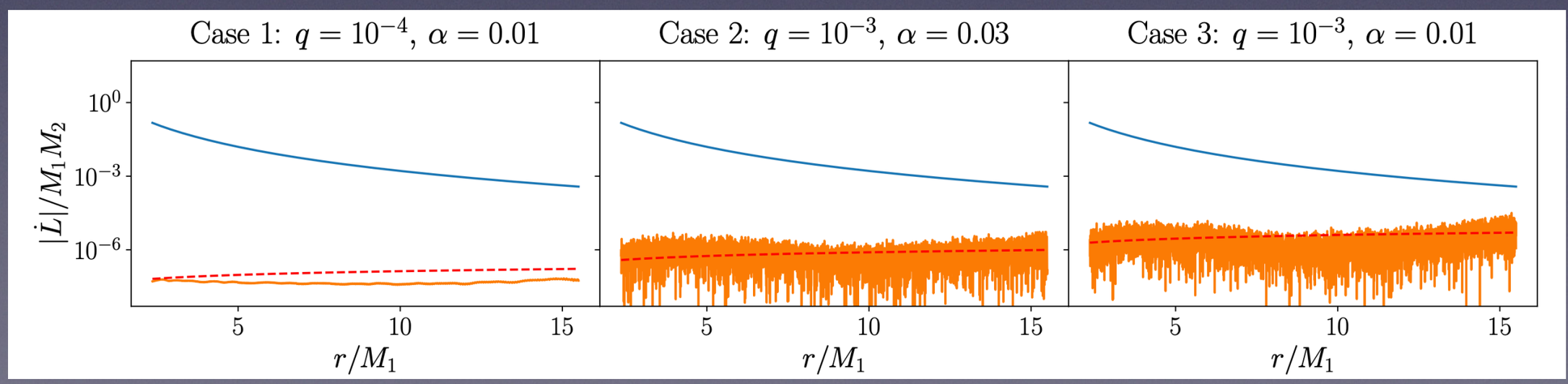
$$\dot{L}_{\rm disk} = A \left(\frac{r}{10M_1}\right)^{n_r} \dot{L}^{(0)}_{\rm GW}$$

Speri+EB+2022

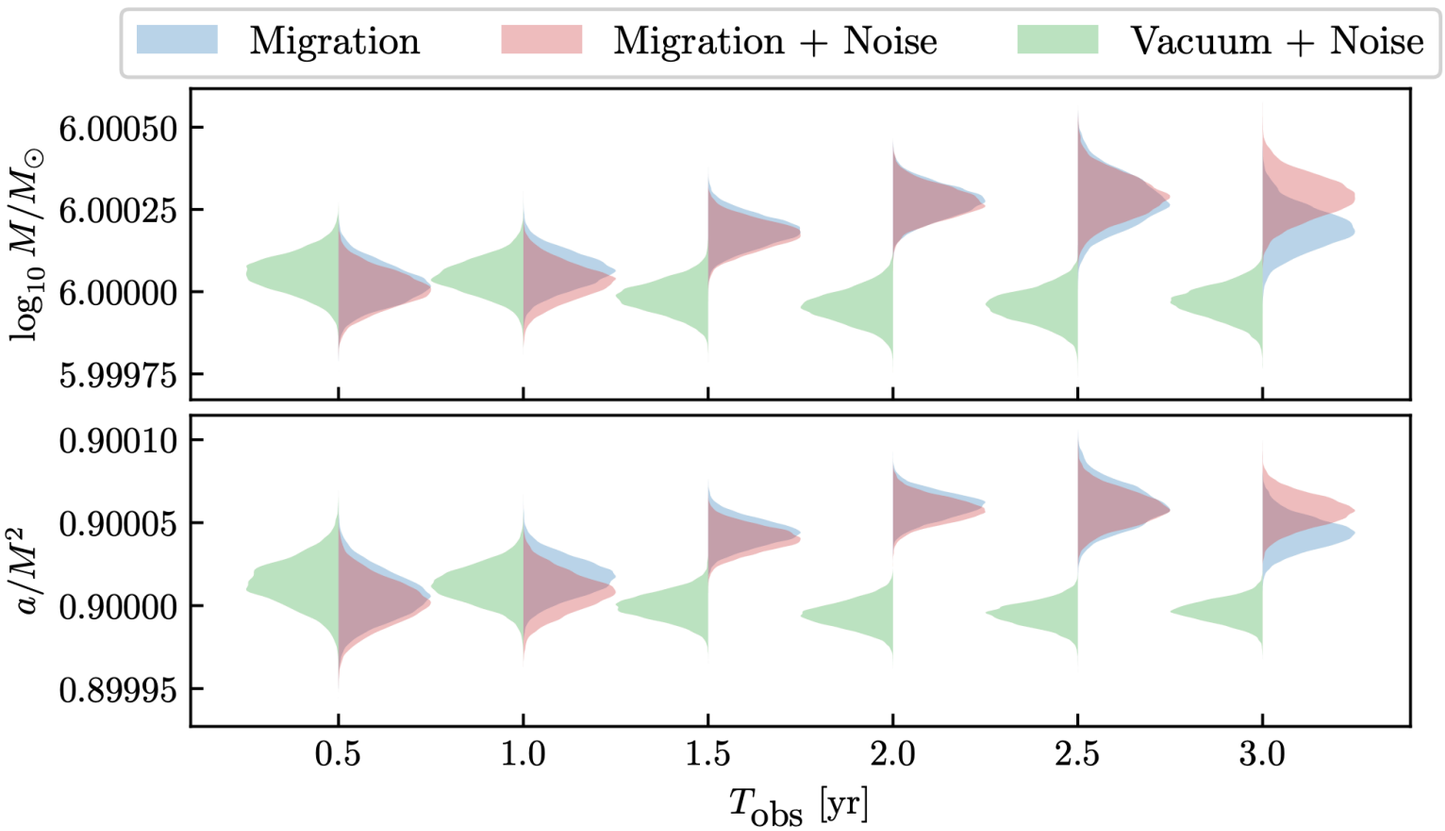
Results robust despite simple models…

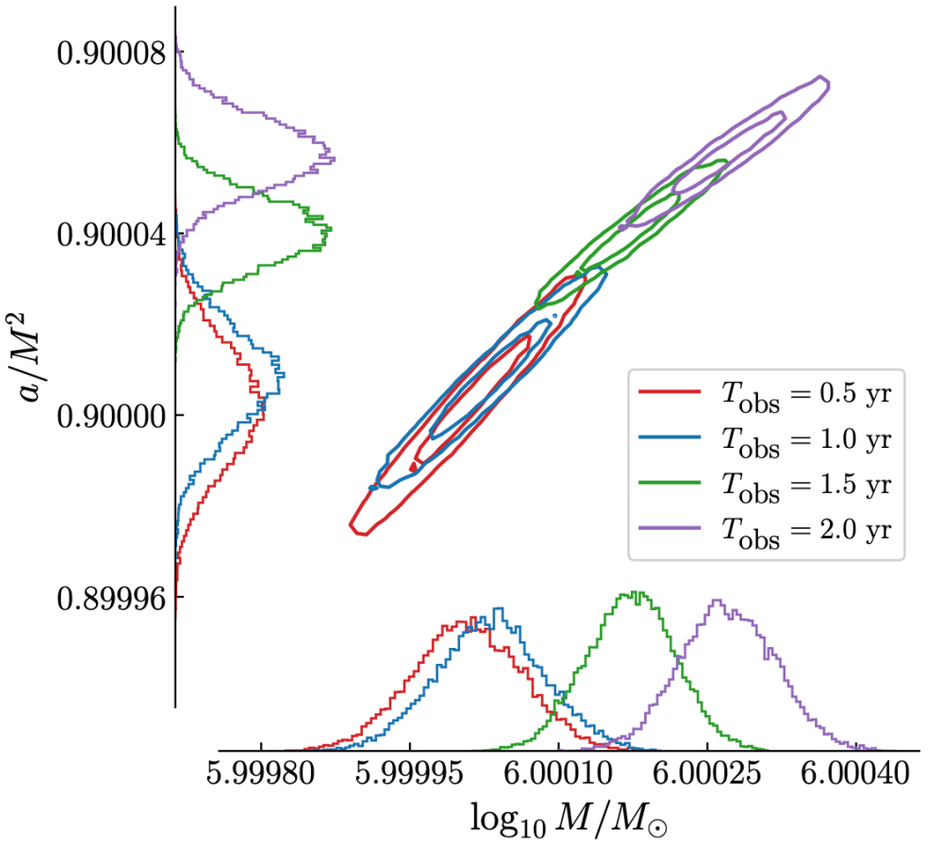


Copparoni+EB+2025
Also Copparoni & Duque in prep



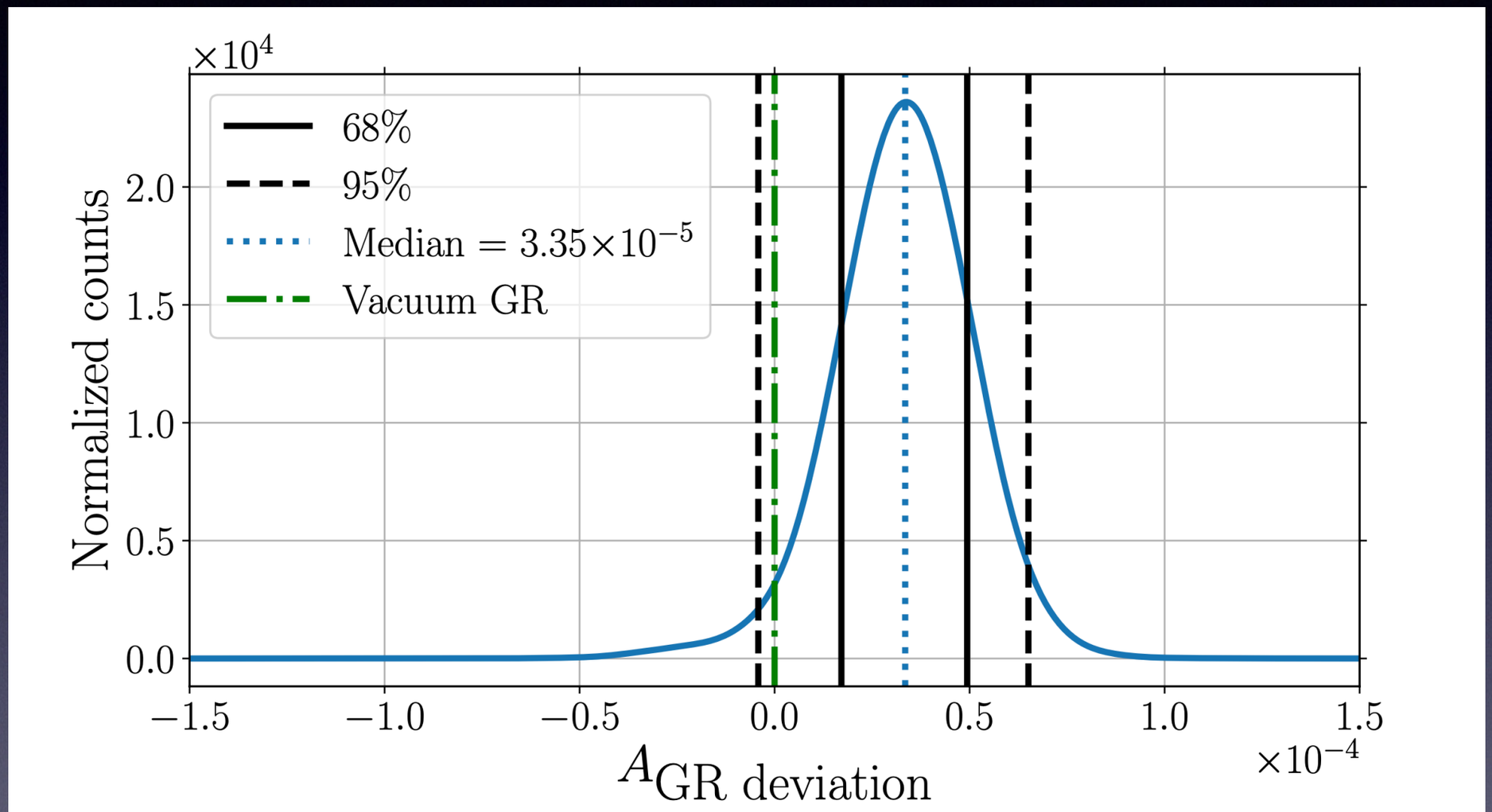
Environment can be discovered via consistency tests





Copparoni, Chandromouli & EB 2025

Environment as foreground for tests of GR

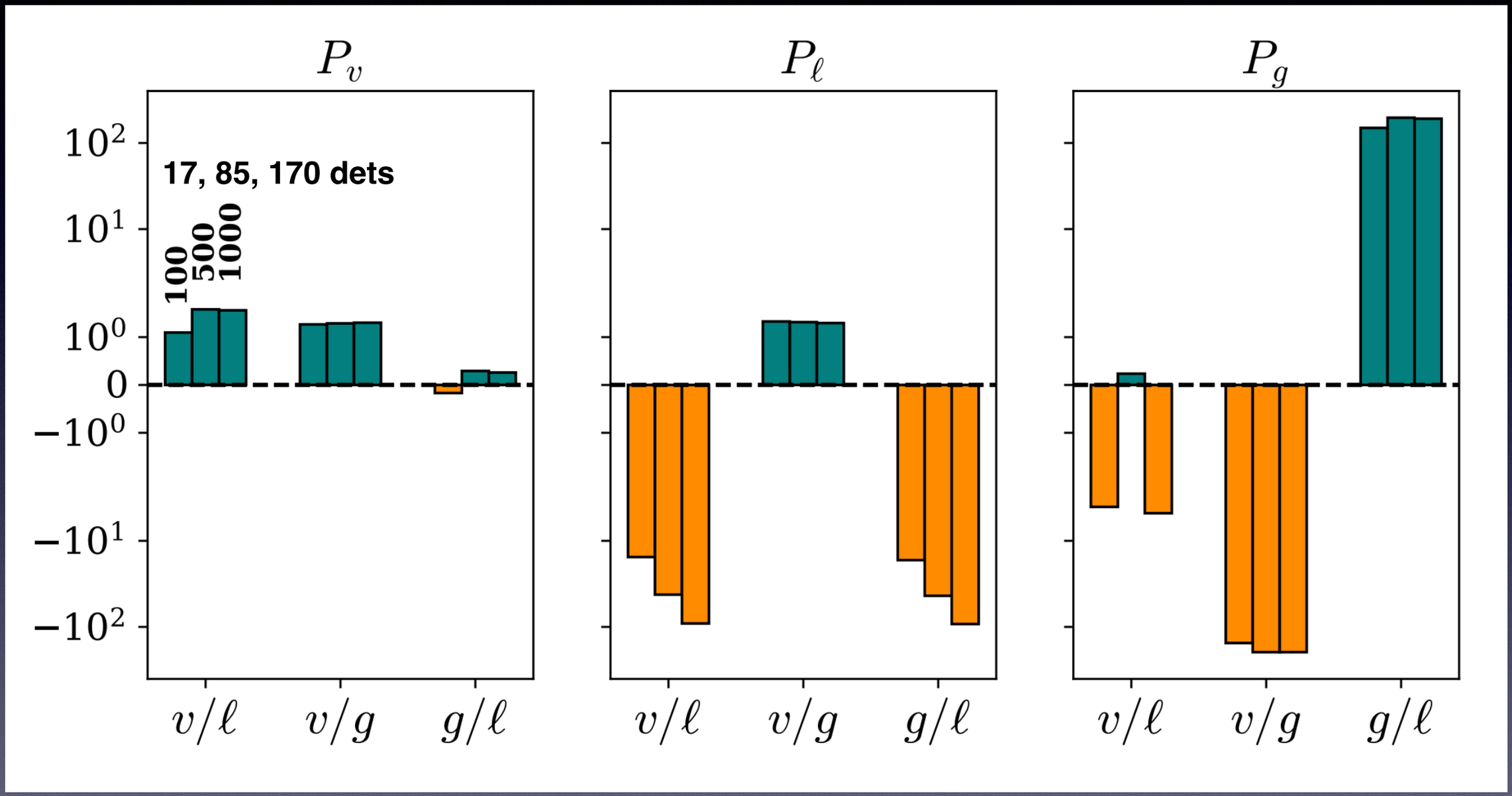


Speri+EB+2022

Injected: disk migration

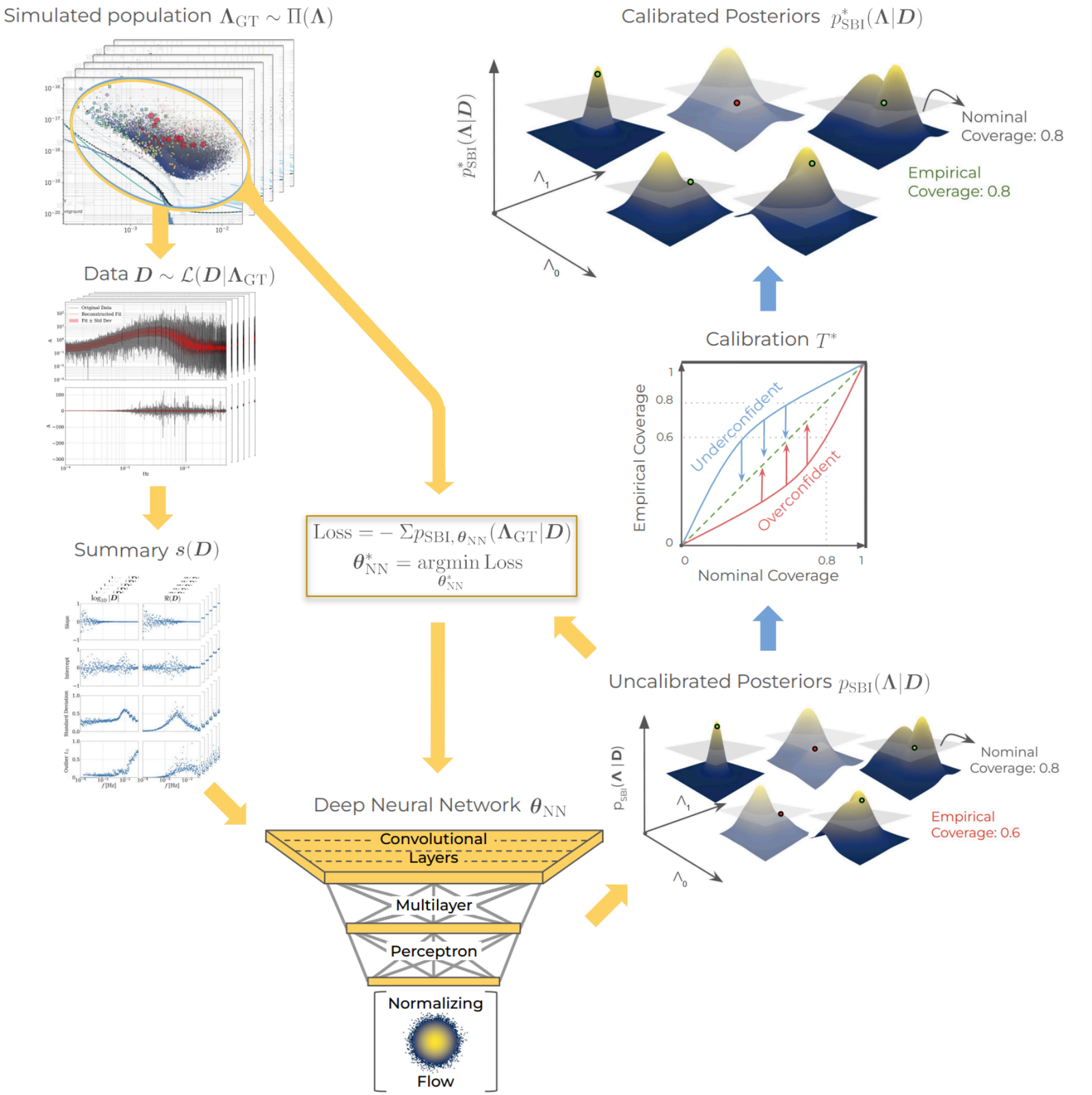
Recovered: Gdot~ G $A_{\mathrm{GR\ deviation}}$/yr

Degeneracy broken at population level



Modified gravity is global, while environment is local
Kejriwal+EB+2025, Copparoni & EB 2026

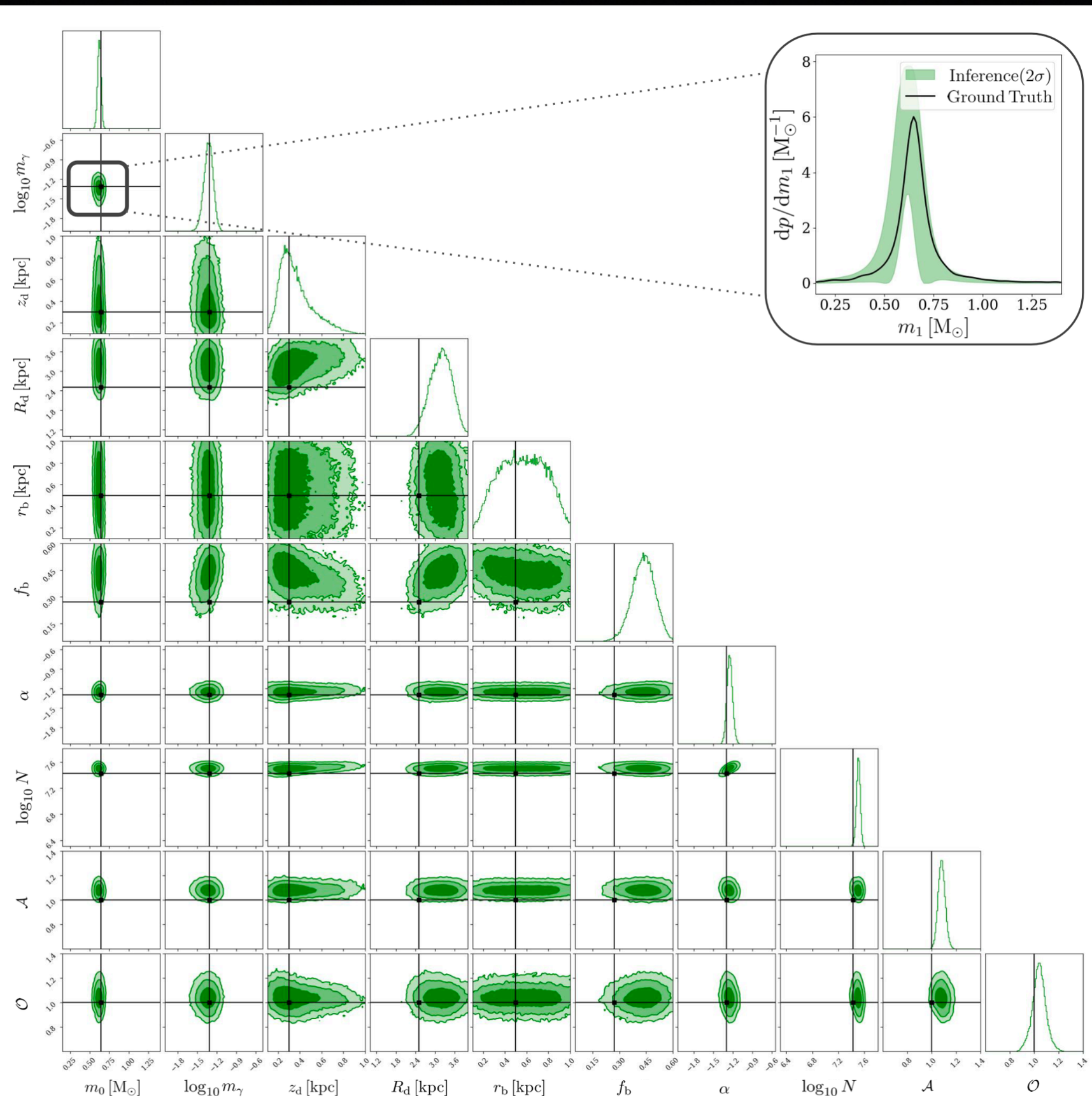
Population inference without the global fit



Λ	Description	Prior	Fiducial
m_0	Primary-mass peak [$M_\odot$]	$\mathcal{U}(0.15, 1.4)$	0.649
$\log_{10} m_\gamma$	Primary-mass log-half width half maximum	$\mathcal{U}[-2.0, 0.5]$	2.686
$R_{\rm d}$	Disk scale radius [kpc]	$\mathcal{U}(1.0, 4.0)$	2.5
$z_{\rm d}$	Disk scale height [kpc]	$\mathcal{U}(0.1, 1.0)$	0.3
$r_{\rm b}$	Bulge scale radius [kpc]	$\mathcal{U}(0.1, 1.0)$	0.5
$f_{\rm b}$	Bulge fraction	$\mathcal{U}(0.05, 0.6)$	0.27
α	DWD separation index	$\mathcal{U}(-2.05, -0.55)$	-1.3
$\log_{10} N$	DWD log-number	$\mathcal{U}(6.3, 7.8)$	6.8
$\mathcal{A}$	Acceleration noise factor	$\mathcal{N}(1, 0.2)$	1.0
$\mathcal{O}$	Optical noise factor	$\mathcal{N}(1, 0.2)$	1.0

Srinivasan+EB+25

Population inference without the global fit



Srinivasan+EB+25

arXiv > gr-qc > arXiv:2009.01075
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General Relativity and Quantum Cosmology

[Submitted on 2 Sep 2020]

GW190521: A Binary Black Hole Merger with a Total Mass of $150\,M_\odot$

The LIGO Scientific Collaboration, the Virgo Collaboration: R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, A. Aich, L. Aiello, A. Ain, P. Ajith, S. Akcay, G. Allen, A. Allocca, P. A. Altin, A. Amato, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Ansoldi, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, S. M. Aronson, K. G. Arun, Y. Asali, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P. Aufmuth, K. Au M. K. M. Bader, S. Bae, A. M. Baer, J. Baird, F. Baldaccini, G. Ballardin, S. W. Ballmer, A. Bals, A. Barayoga, C. Barbieri, B. C. Barish, D. Barker, K. Barkett, P. Barneo, F. Barone, B. Barr, L. Barsot Bawaj, J. C. Bayley, M. Bazzan, B. Bécsy, M. Bejger, I. Belahcene, A. S. Bell, D. Beniwal, M. G. Be Bernuzzi, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, R. Bhandare, A. V. Bhandari e

On May 21, 2019 at 03:02:29 UTC Advanced LIGO and Advanced Virgo observed a short duration gravitati noise ratio of 14.7, and an estimated false-alarm rate of 1 in 4900 yr using a search sensitive to generic tr detected signal is consistent with the merger of two black holes with masses of $85^{+21}_{-14}M_\odot$ and $66^{+17}_{-18}M_\odot$ (9 within the gap produced by (pulsational) pair-instability supernova processes, and has only a 0.32 % proba $142^{+28}_{-16}M_\odot$, which can be considered an intermediate mass black hole (IMBH). The luminosity distance of th inferred rate of mergers similar to GW190521 is $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.

GW231123: a Binary Black Hole Merger with Total Mass 190–265 $M_\odot$

The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, A. G. Abac, I. Abouelfettouh, F. Acernese, K. Ackley, C. Adamcewicz, S. Adhicary, D. Adhikari, N. Adhikari, R. X. Adhikari, V. K. Adkins, S. Afroz, A. Agapito, D. Agarwal, M. Agathos, N. Aggarwal, S. Aggarwal, O. D. Aguiar, I.-L. Ahrend, L. Aiello, A. Ain, P. Ajith, T. Akutsu, S. Albanesi, W. Ali, S. Al-Kershi, C. Alléné, A. Allocca, S. Al-Shammari, P. A. Altin, S. Alvarez-Lopez, W. Amar, O. Amarasinghe, A. Amato, F. Amicucci, C. Amra, A. Ananyeva, S. B. Anderson, W. G. Anderson, M. Andia, M. Ando, M. Andrés-Carcasona, T. Andrić, J. Anglin, S. Ansoldi, J. M. Antelis, S. Antier, M. Aoumi, E. Z. Appavuravther, S. Appert, S. K. Apple, K. Arai, C. Araujo Alvarez, A. Araya, M. C. Araya, M. Arca Sedda, J. S. Areeda, N. Aritomi, F. Armato, S. Armstrong, N. Arnaud, M. Arogeti, S. M. Aronson, K. G. Arun, G. Ashton, Y. Aso, L. Asprea, M. Assiduo, S. Assis de Souza Melo, S. M. Aston, P. Astone, F. Attadio, F. Aubin, K. AultONeal, G. Avallone, E. A. Avila, S. Babak, C. Badger, S. Bae, S. Bagnasco, L. Baiotti, R. Bajpai, T. Baka, A. M. Baker, K. A. Baker, T. Baker, G. Baldi, N. Baldicchi, M. Ball, G. Ballardin, S. W. Ballmer, S. Banagiri, B. Banerjee, D. Bankar, T. M. Baptiste, P. Baral, M. Baratti, J. C. Barayoga et al. (1674 additional authors not shown)

On 2023 November 23 the two LIGO observatories both detected GW231123, a gravitational-wave signal consistent with the merger of two black holes with masses $137^{+23}_{-18}\,\mathrm{M}_\odot$ and $101^{+22}_{-50}\,\mathrm{M}_\odot$ (90\% credible intervals), at luminosity distance 0.7-4.1 Gpc and redshift of $0.40^{+0.27}_{-0.25}$, and a network signal-to-noise ratio of ~20.7. Both black holes exhibit high spins, $0.9^{+0.10}_{-0.19}$ and $0.80^{+0.20}_{-0.52}$ respectively. A massive black hole remnant is supported by an independent ringdown analysis. Some properties of GW231123 are subject to large systematic uncertainties, as indicated by differences in inferred parameters between signal models. The primary black hole lies within or above the theorized mass gap where black holes between 60-130 $\mathrm{M}_\odot$ should be rare due to pair instability mechanisms, while the secondary spans the gap. The observation of GW231123 therefore suggests the formation of black holes from channels beyond standard stellar collapse, and that intermediate-mass black holes of mass ~200 $\mathrm{M}_\odot$ form through gravitational-wave driven mergers.

arXiv > astro-ph > arXiv:2006.14122

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 25 Jun 2020]

Candidate Electromagnetic Counterpart to the Binary Black Hole Merger Gravitational Wave Event S190521g

M. J. Graham, K. E. S. Ford, B. McKernan, N. P. Ross, D. Stern, K. Burdge, M. Coughlin, S. G. Djorgovski, A. J. Drake, D. Duev, M. Kasliwal, A. A. Mahabal, S. van Velzen, J. Belicki, E. C. Bellm, R. Burruss, S. B. Cenko, V. Cunningham, G. Helou, S. R. Kulkarni, F. J. Masci, T. Prince, D. Reiley, H. Rodriguez, B. Rusholme, R. M. Smith, M. T. Soumagnac

We report the first plausible optical electromagnetic (EM) counterpart to a (candidat consistent with expectations for a kicked BBH merger in the accretion disk of an act source. The lack of color evolution implies that it is not a supernovae and instead is microlensing or a tidal disruption event, are ruled out or constrained to be $< O(0.1$ $M_{\rm BBH} \sim 100 M_\odot$, kick velocity $v_k \sim 200\,\mathrm{km\,s^{-1}}$ at $\theta \sim 60^\circ$ in a disk with aspect rat could have occurred at a disk migration trap ($a \sim 700\,r_g$; $r_g \equiv GM_{\rm SMBH}/c^2$, where implies a significant spin for at least one of the black holes in S190521g. The timing flare. We predict a repeat flare in this source due to a re-encountering with the disk

arXiv > gr-qc > arXiv:2310.16025
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General Relativity and Quantum Cosmology

[Submitted on 24 Oct 2023]

GW190521: a binary black hole merger inside an active galactic nucleus?

Sophia Morton, Stefano Rinaldi, Alejandro Torres-Orjuela, Andrea Derdzinski, Maria Paola Vaccaro, Walter Del Pozzo

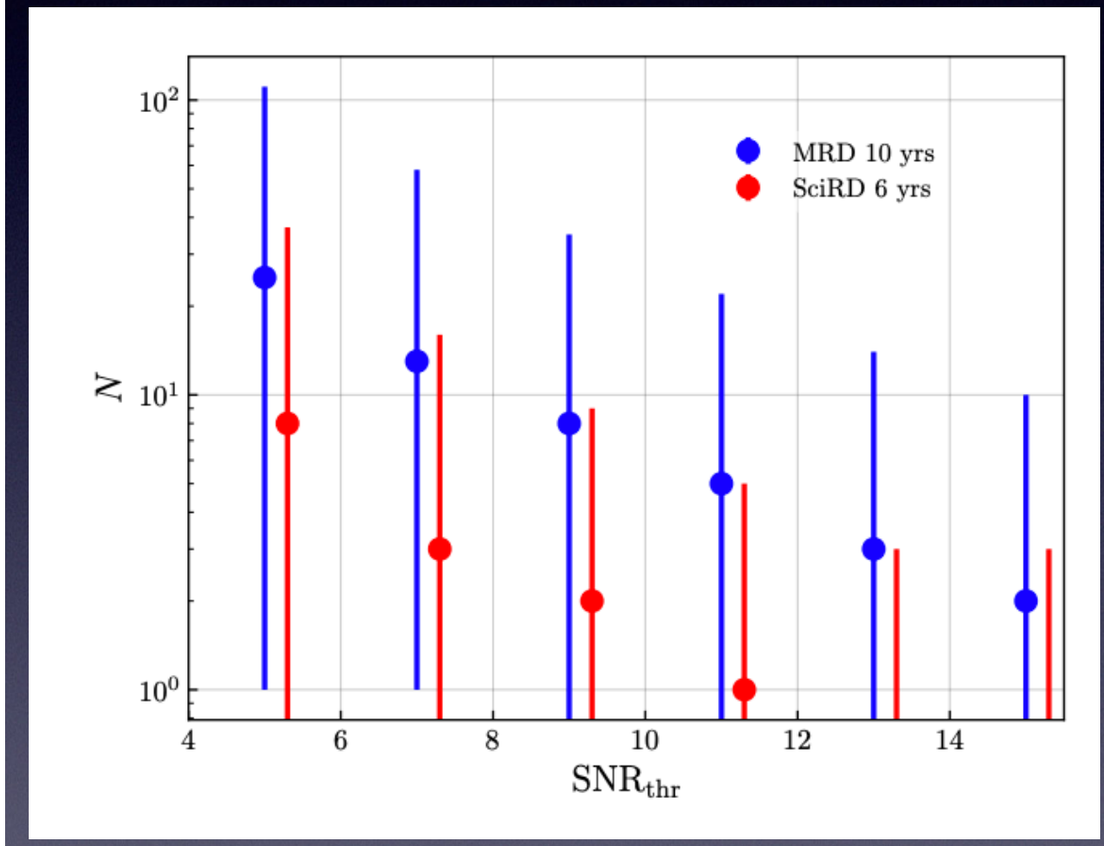
GW190521, the most massive binary black hole merger confidently detected by the LIGO-Virgo-KAGRA collaboration, is the first gravitational-wave observation of an intermediate-mass black hole. The signal was followed approximately 34 days later by flare ZTF19abanrhr, detected in AGN J124942.3+344929 by the Zwicky Transient Facility at the 78\% spatial contour for GW190521s sky localization. Using the GWTC-2.1 data release, we find that the association between GW190521 and flare ZTF19abanrhr as its electromagnetic counterpart is preferred over a random coincidence of the two transients with a log Bayes factor of 8.6, corresponding to an odds ratio of ~ 5400 to 1 for equal prior odds and ~ 400 to 1 assuming an astrophysical prior odds of 1/13. Given the association, the multi-messenger signal allows for an estimation of the Hubble constant, finding $\mathrm{H}_0 = 102^{+27}_{-25}\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ when solely analyzing GW190521 and $79.2^{+17.6}_{-9.6}\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ assuming prior information from the binary neutron star merger GW170817, both consistent with the existing literature.

Comments: 10 pages, 5 figures
Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: arXiv:2310.16025 [gr-qc]
(or arXiv:2310.16025v1 [gr-qc] for this version)
https://doi.org/10.48550/arXiv.2310.16025

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}

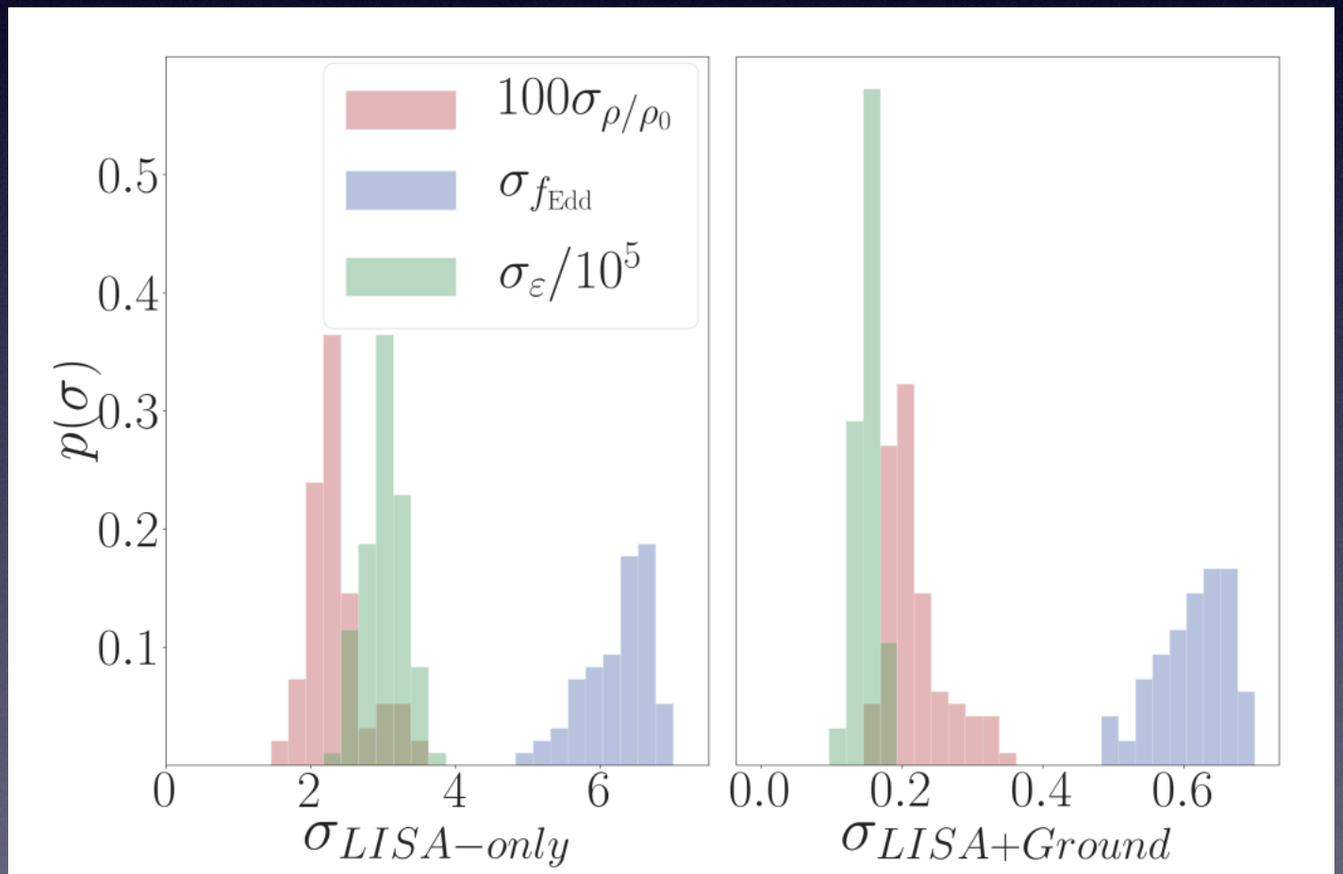
TABLE I. Average number of GW events from (presumed) AGN binaries detectable by LISA, for different detector noise models, mission durations, duty cycles (DC), and population models. We use an SNR threshold of 8.



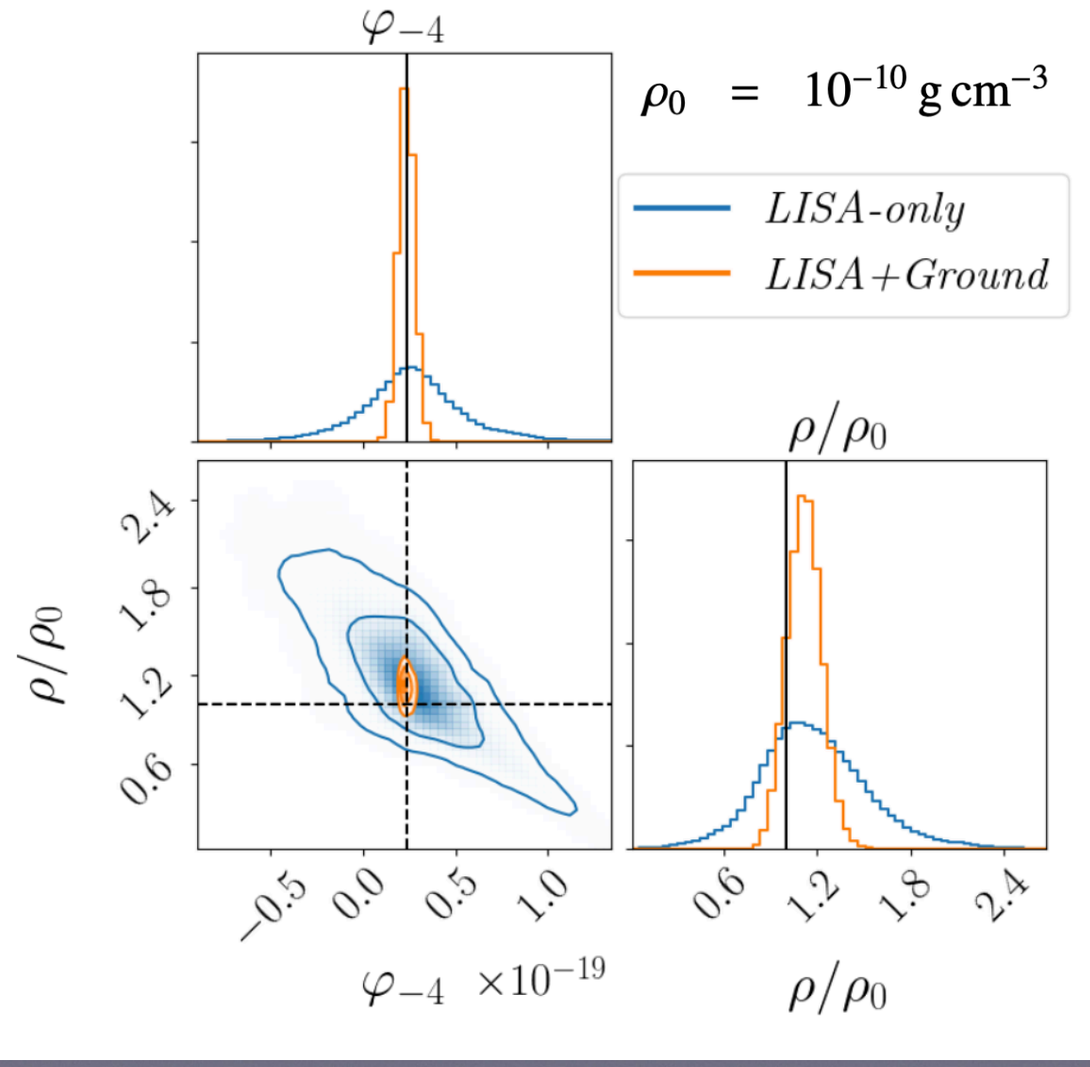
Toubiana+EB+21, Sberna+EB+22

GW190521-like systems as probes of AGNs

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



$$\epsilon = \left(\frac{v_{\rm orb}}{100\,{\rm km/s}}\right)^2 \frac{10\,{\rm kpc}}{a}\cos\psi$$



SOBHBs as probes of AGNs

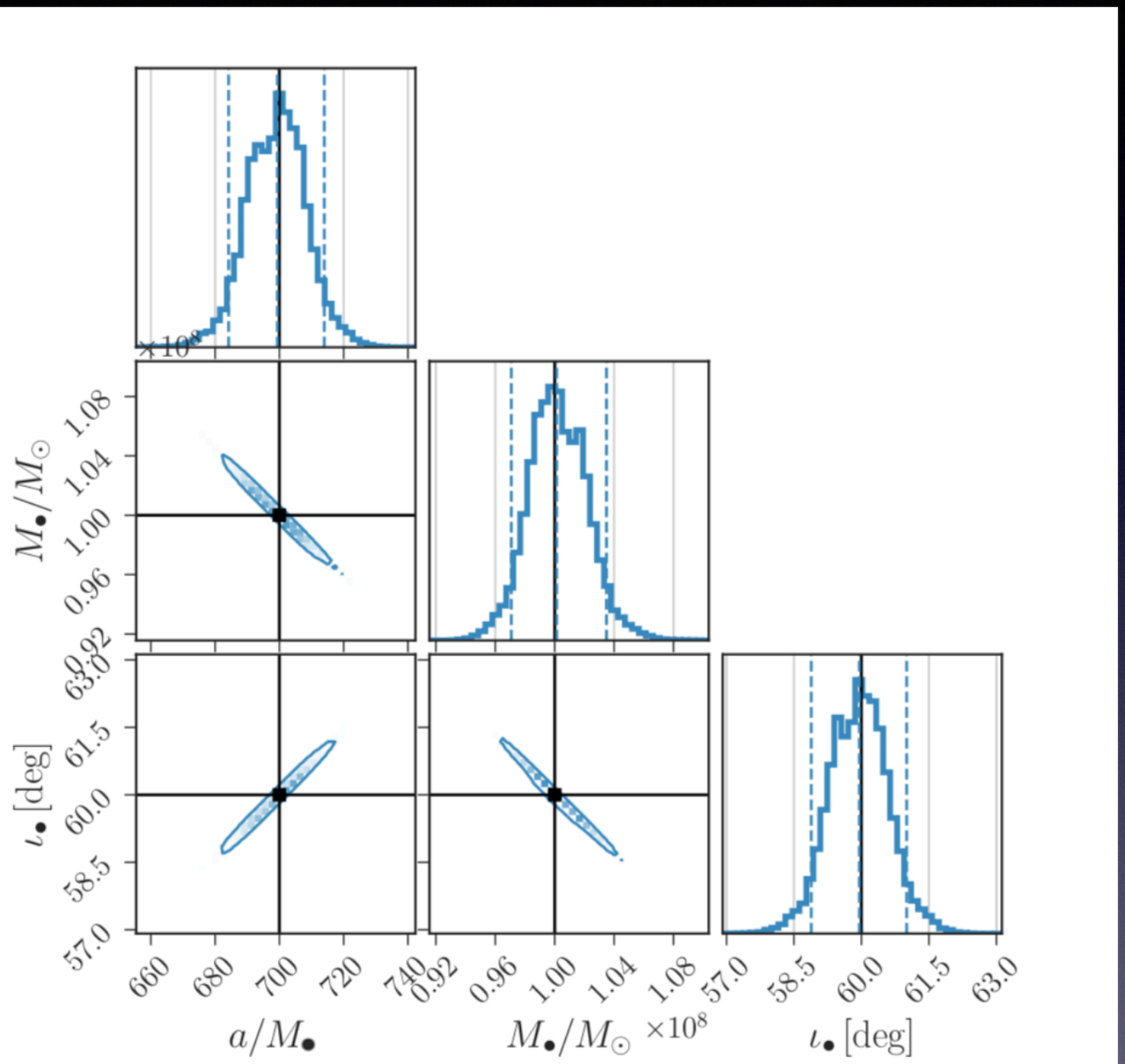
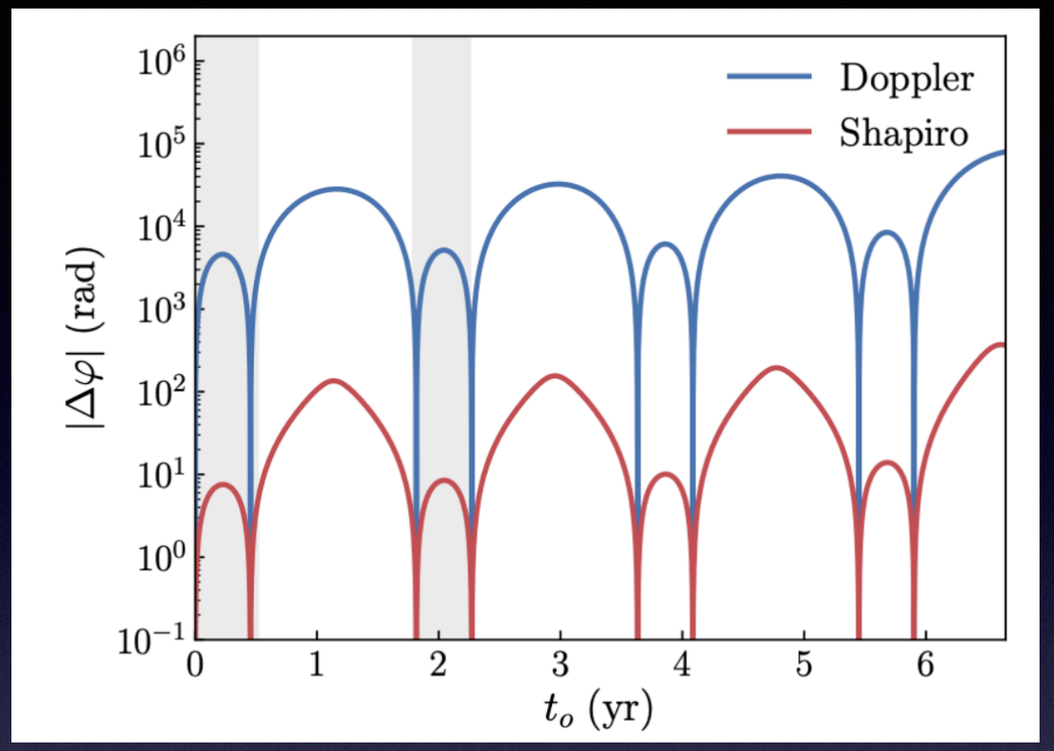
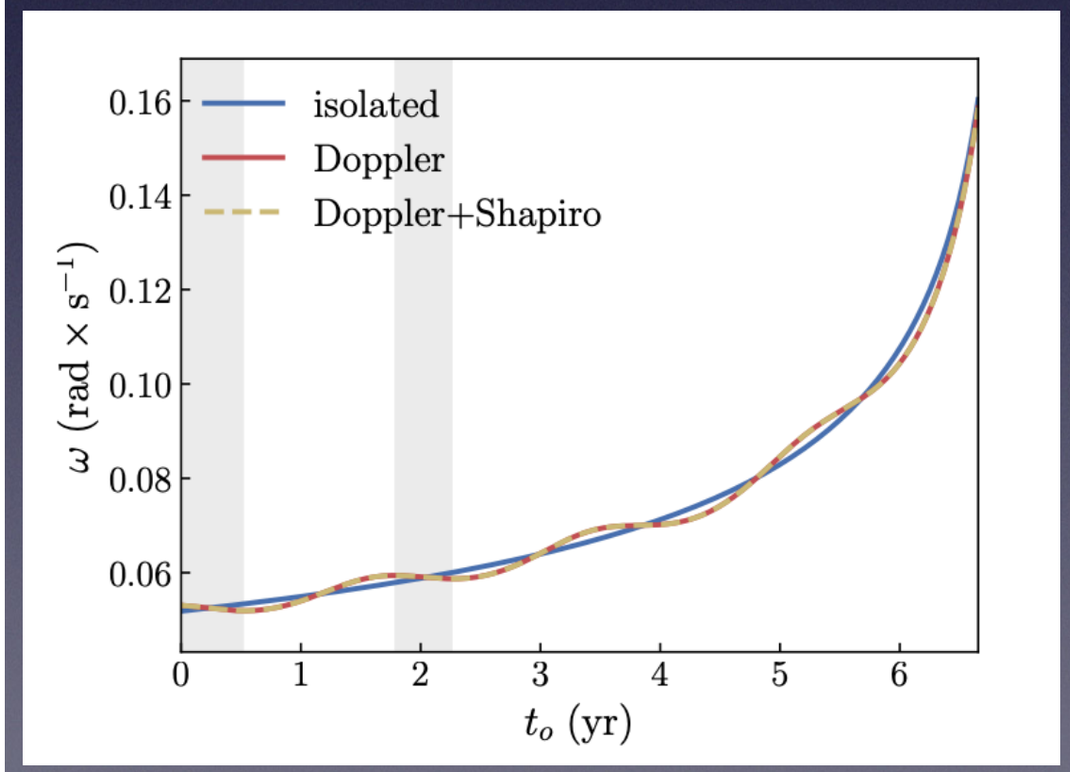


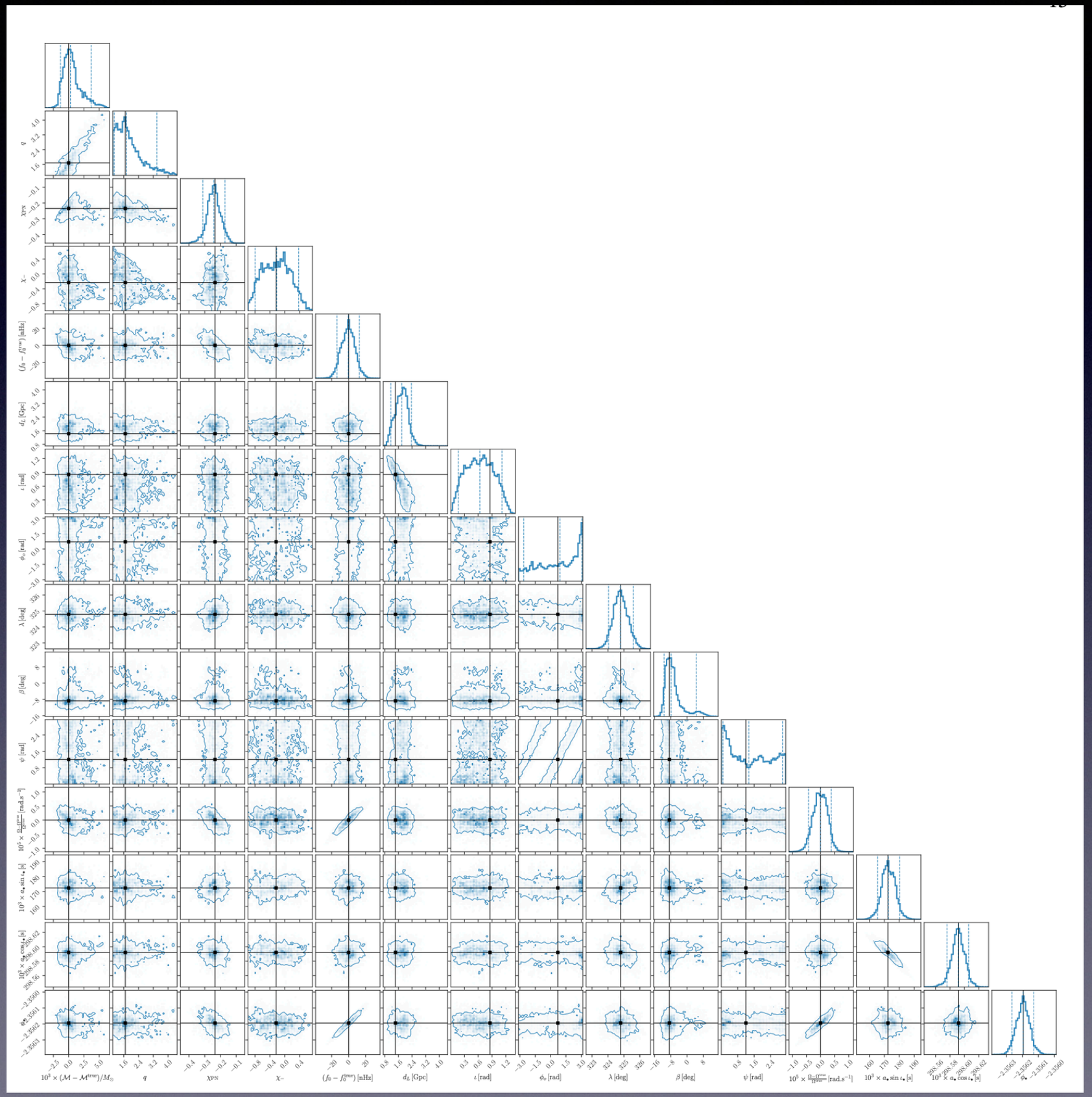
FIG. 5. Inference of the SMBH mass ($M_\bullet$) and the parameters of the outer orbit: inclination $\iota_\bullet$ and orbital radius a. The true (redshifted) parameters are marked by black lines.



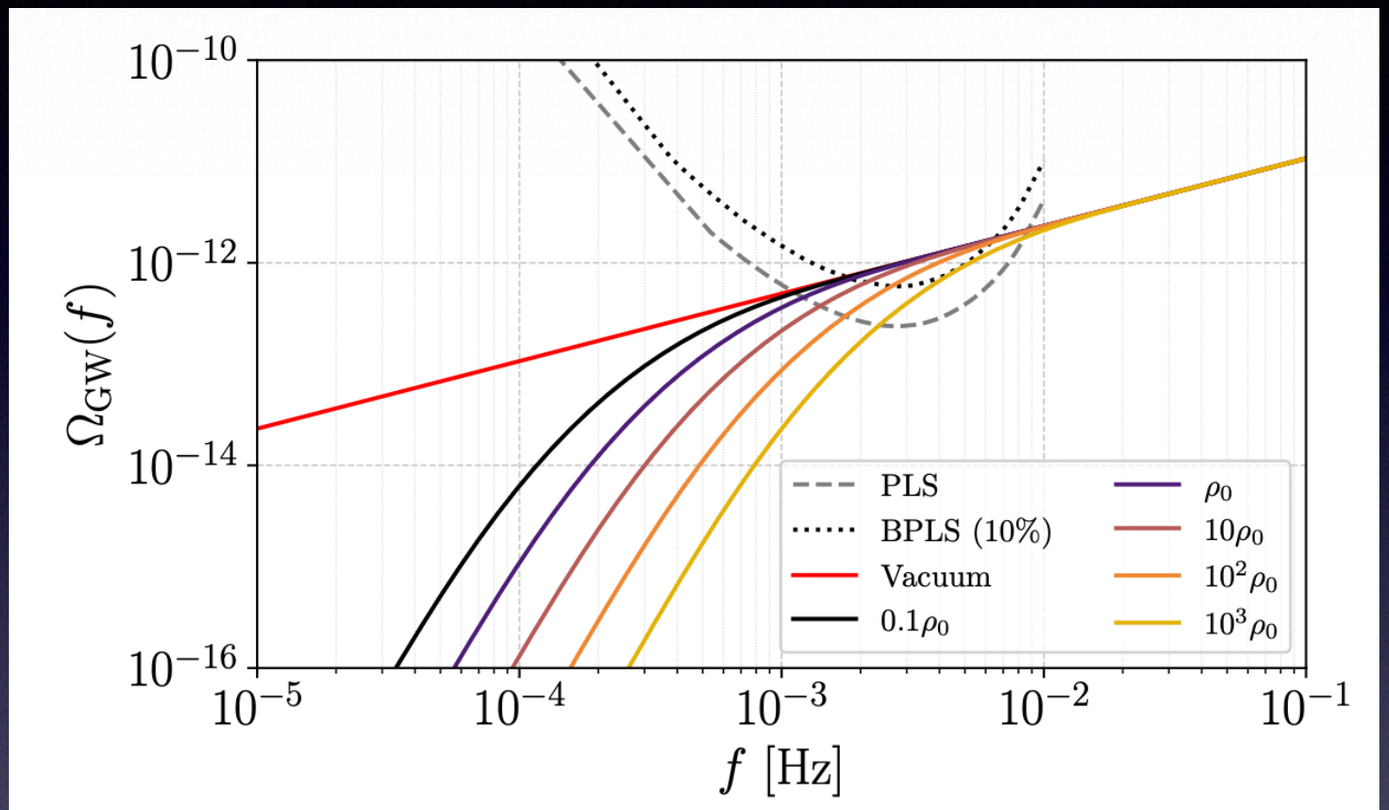


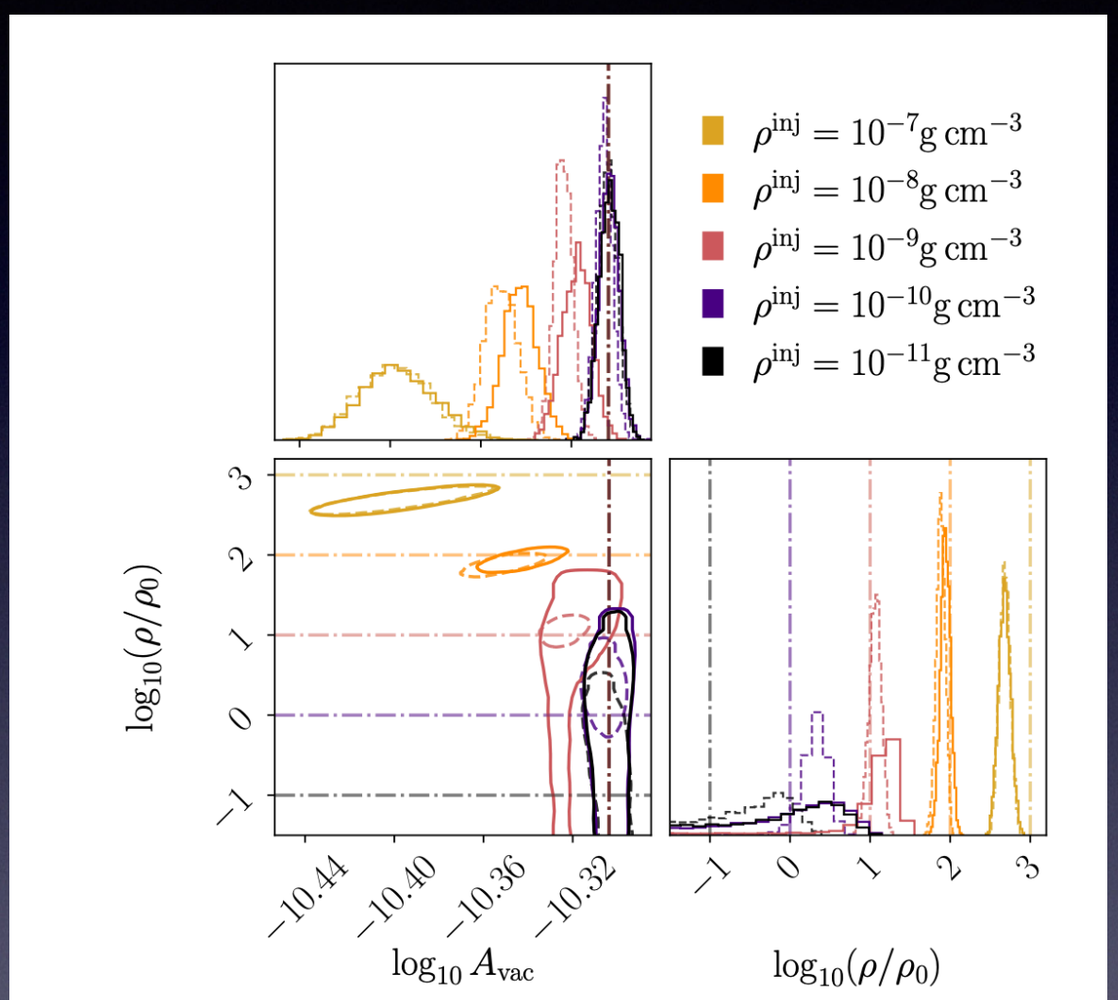
Doppler+Shapiro; Sberna+EB+22

Full posteriors…



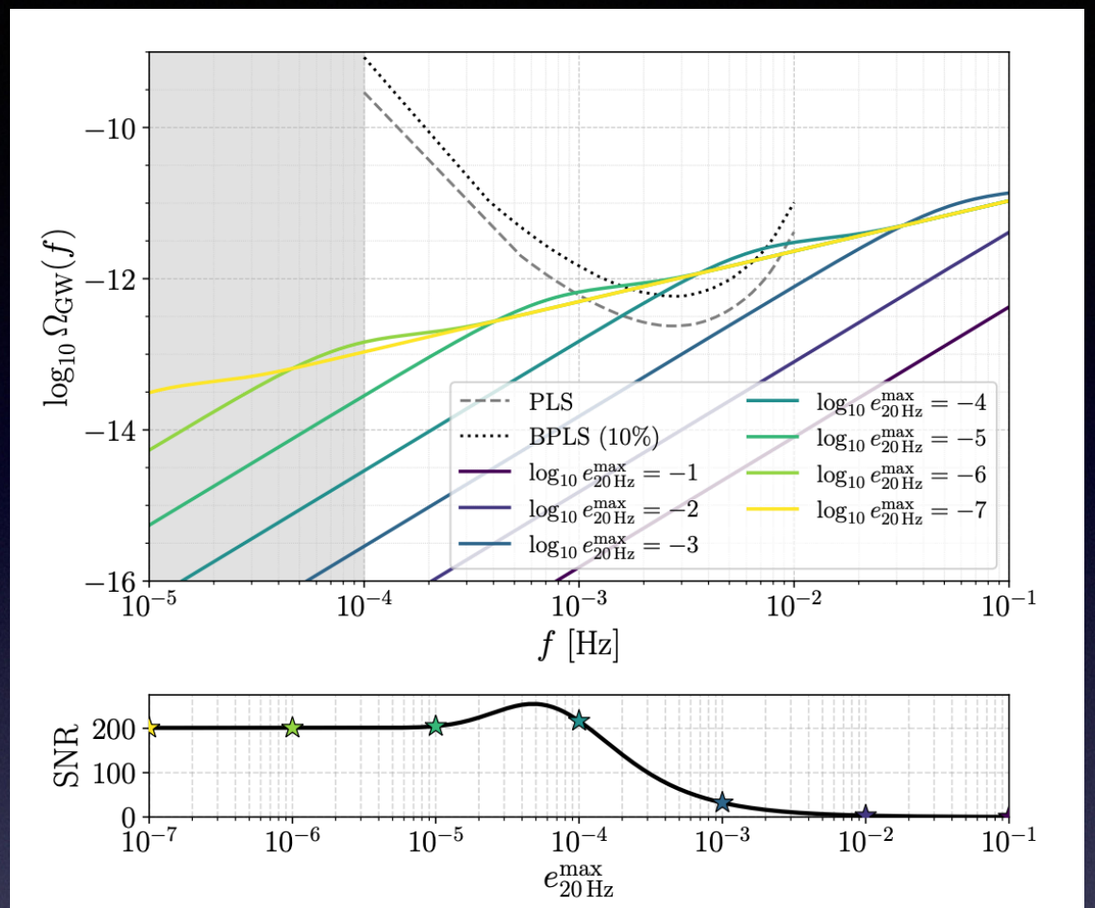
Environmental effects on SOBHB background

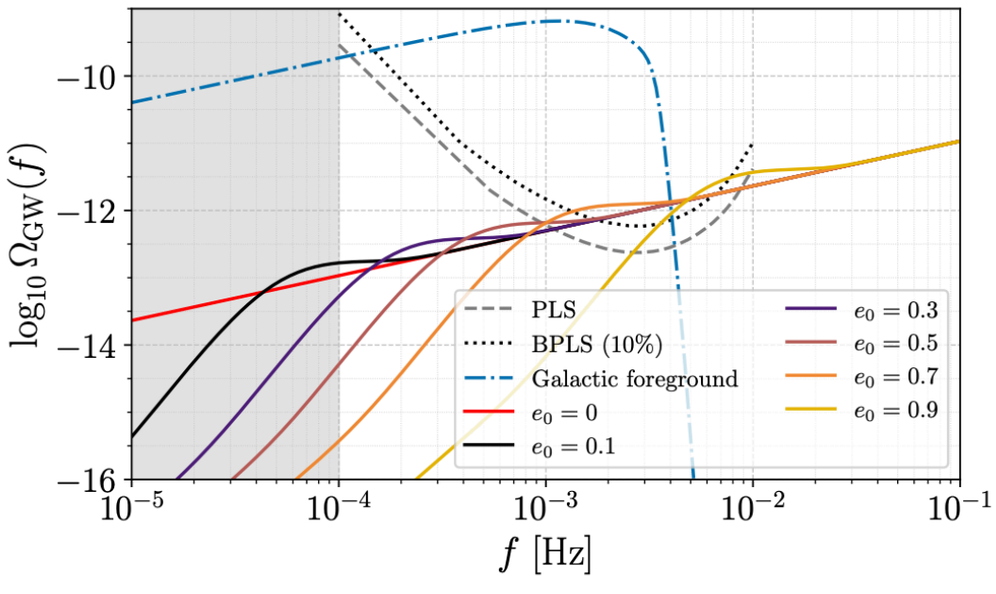


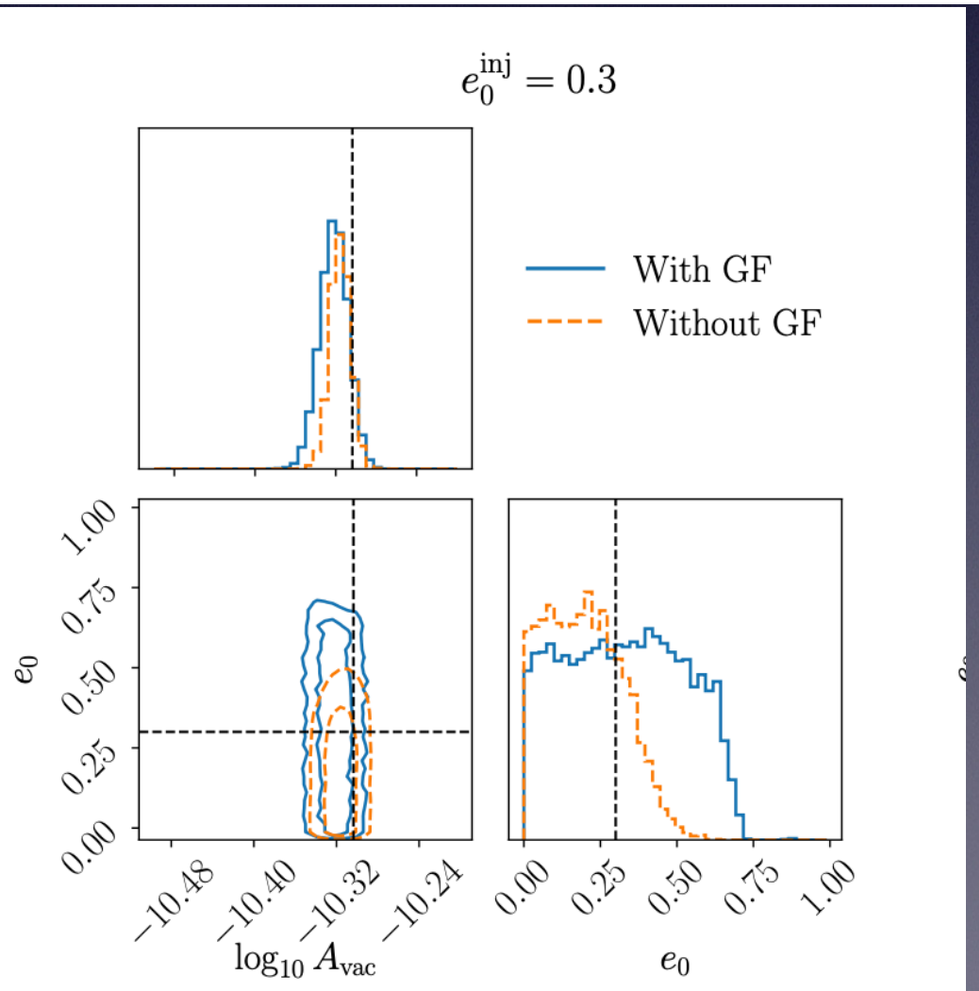


Chen+EB+2025

Eccentric SOBHB background

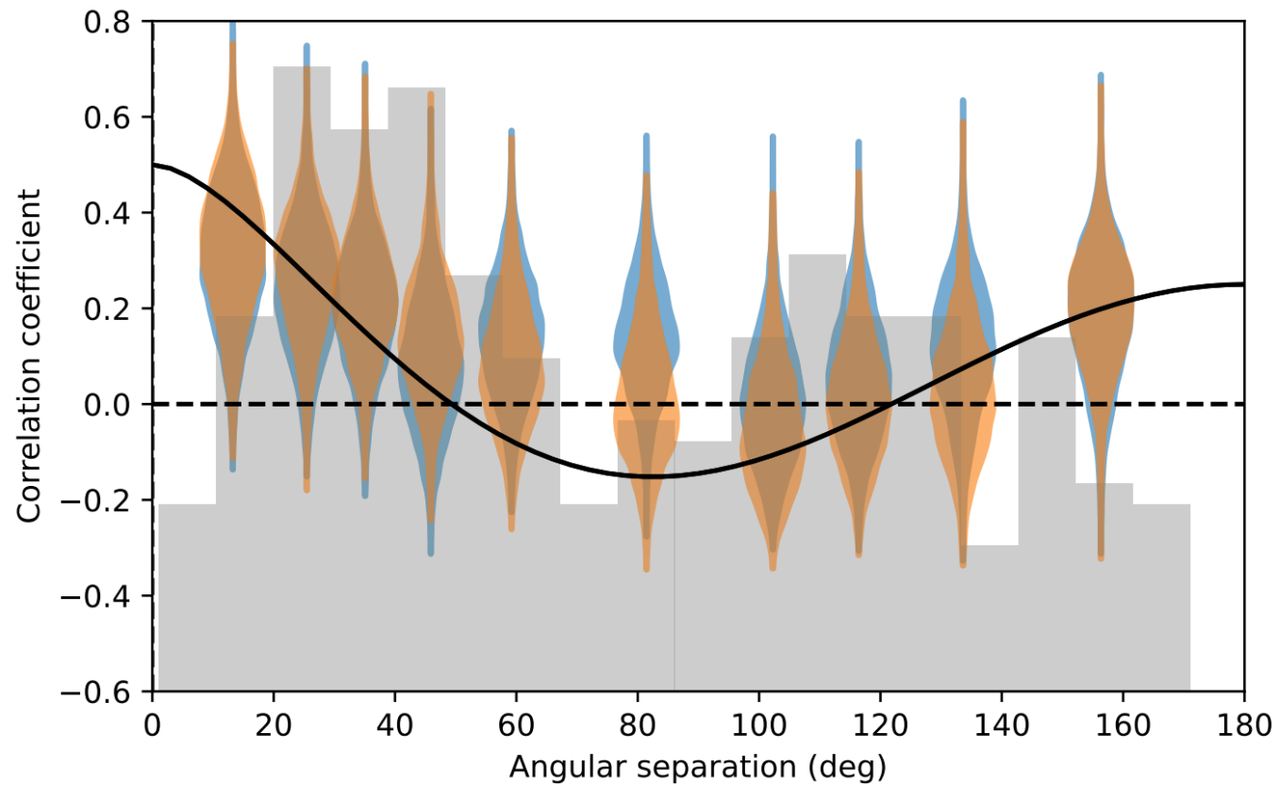


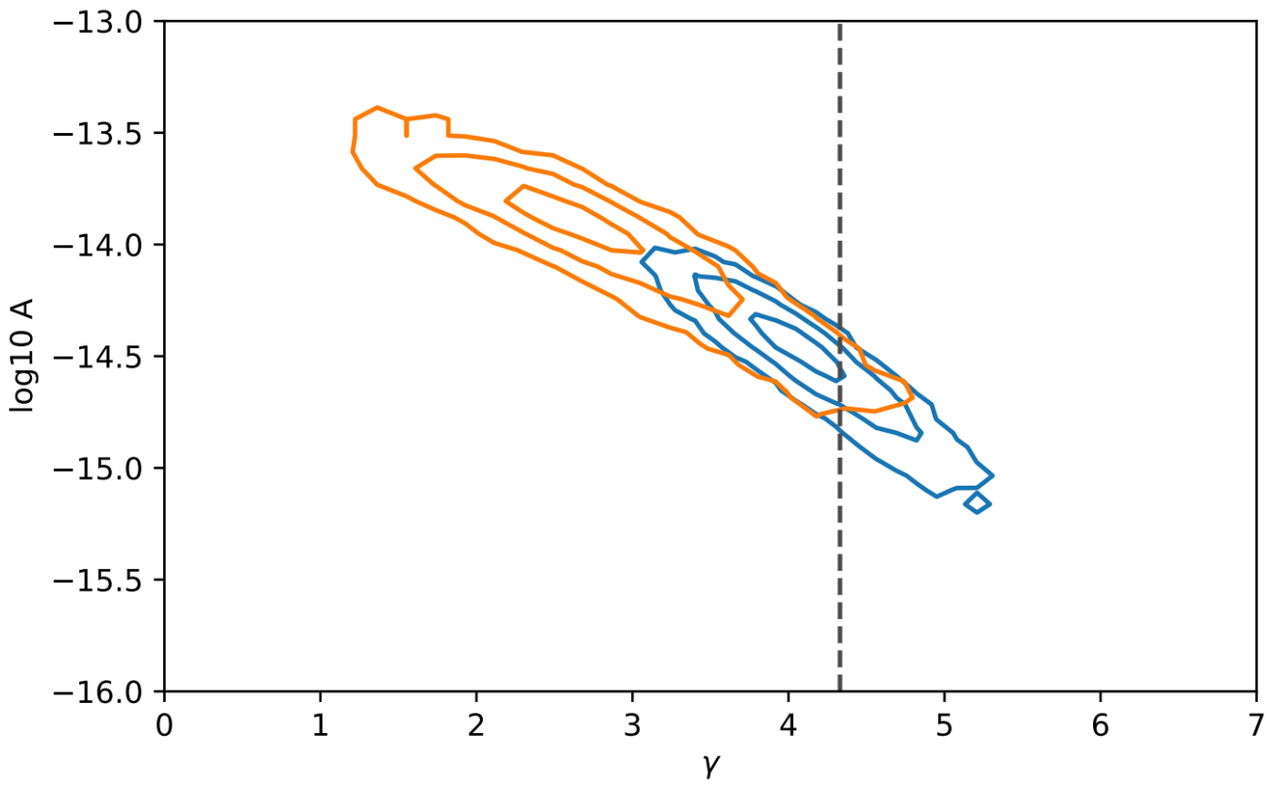




Chen+EB+2026

A nHz stochastic background of GWs

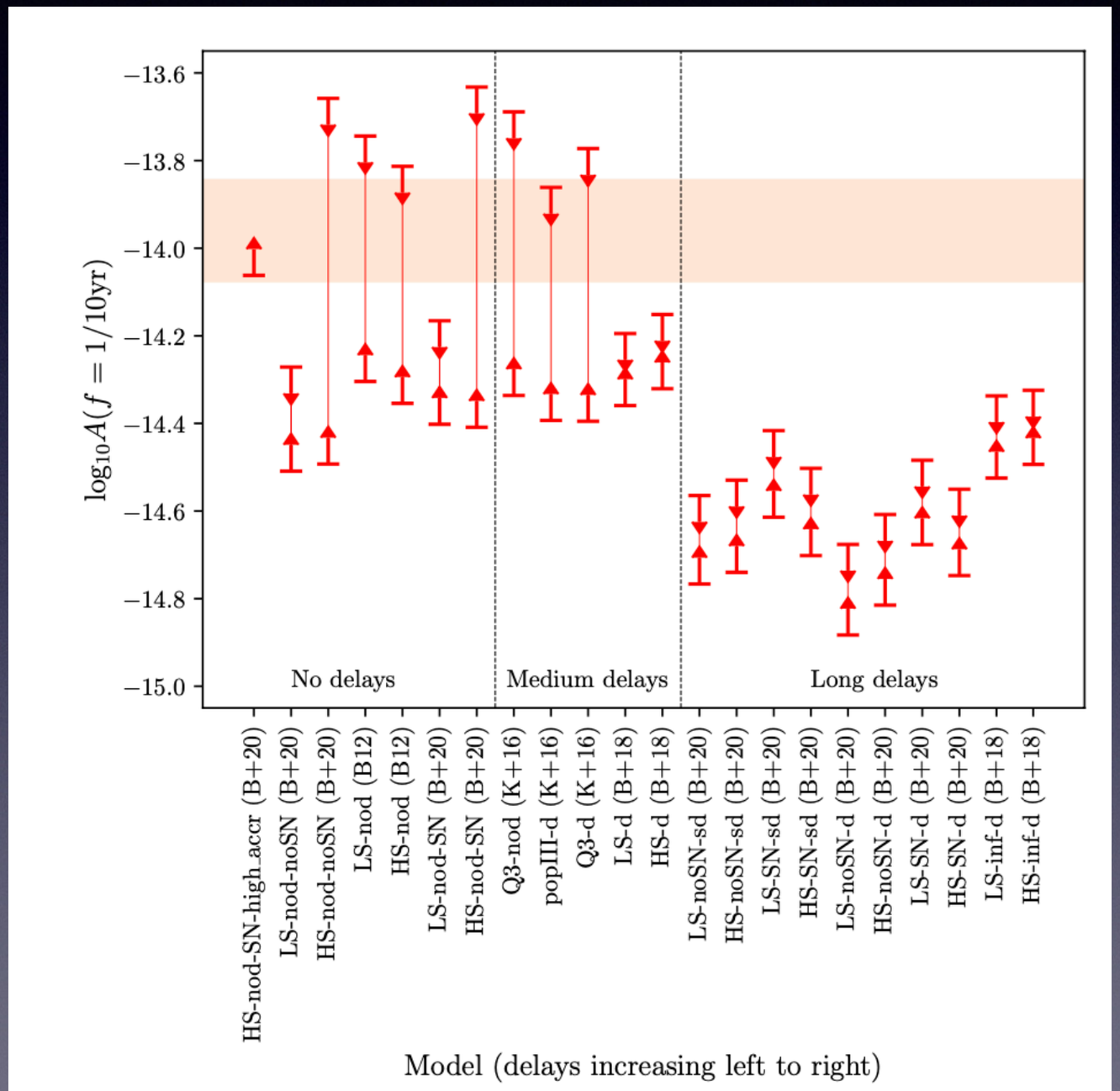


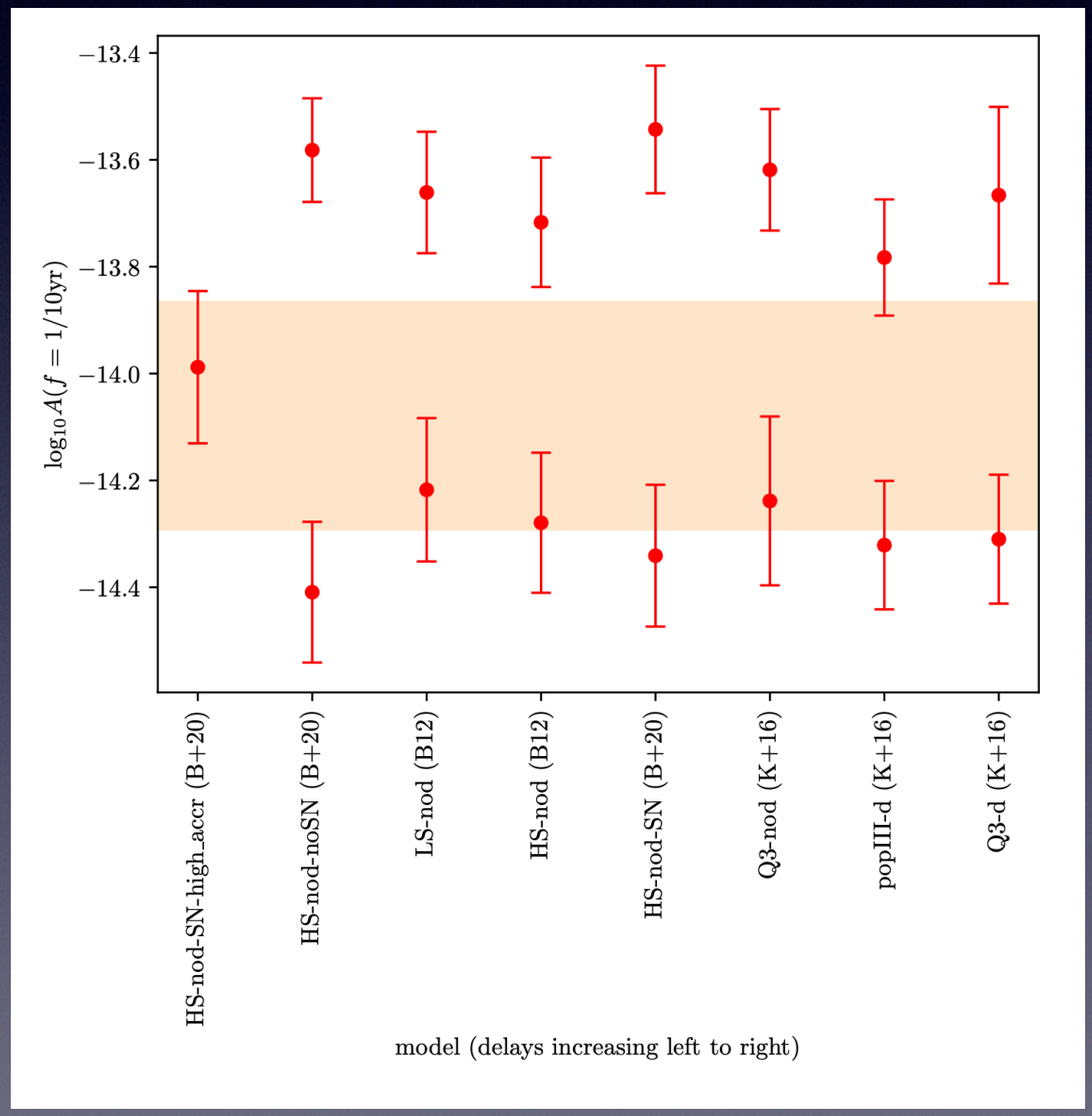


DR2full Binned ORF DR2new Binned ORF

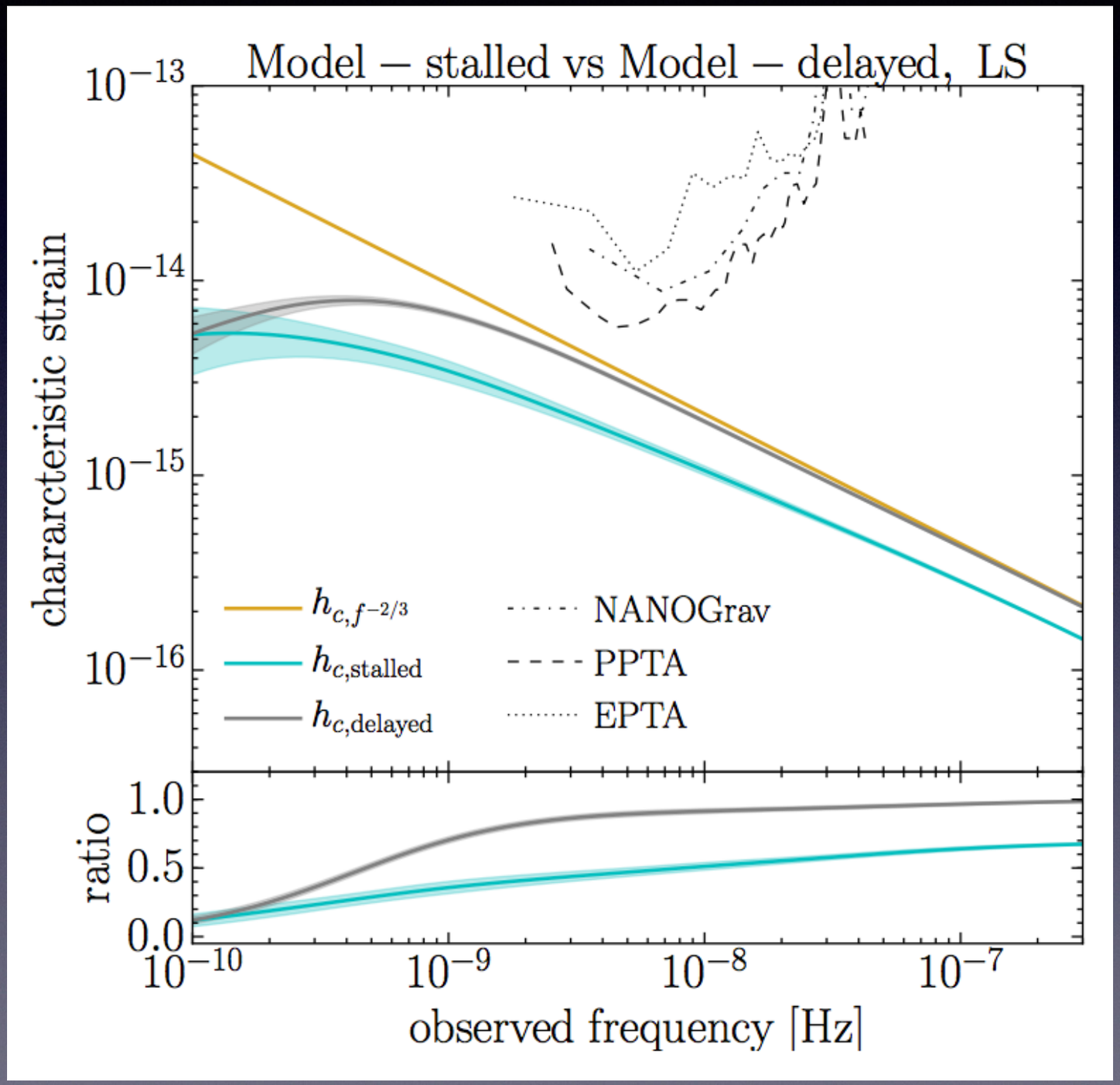
EPTA 2023, also other PTAs…

The PTA signal vs MBHB predictions





Environmental effects and eccentricity change spectral slope

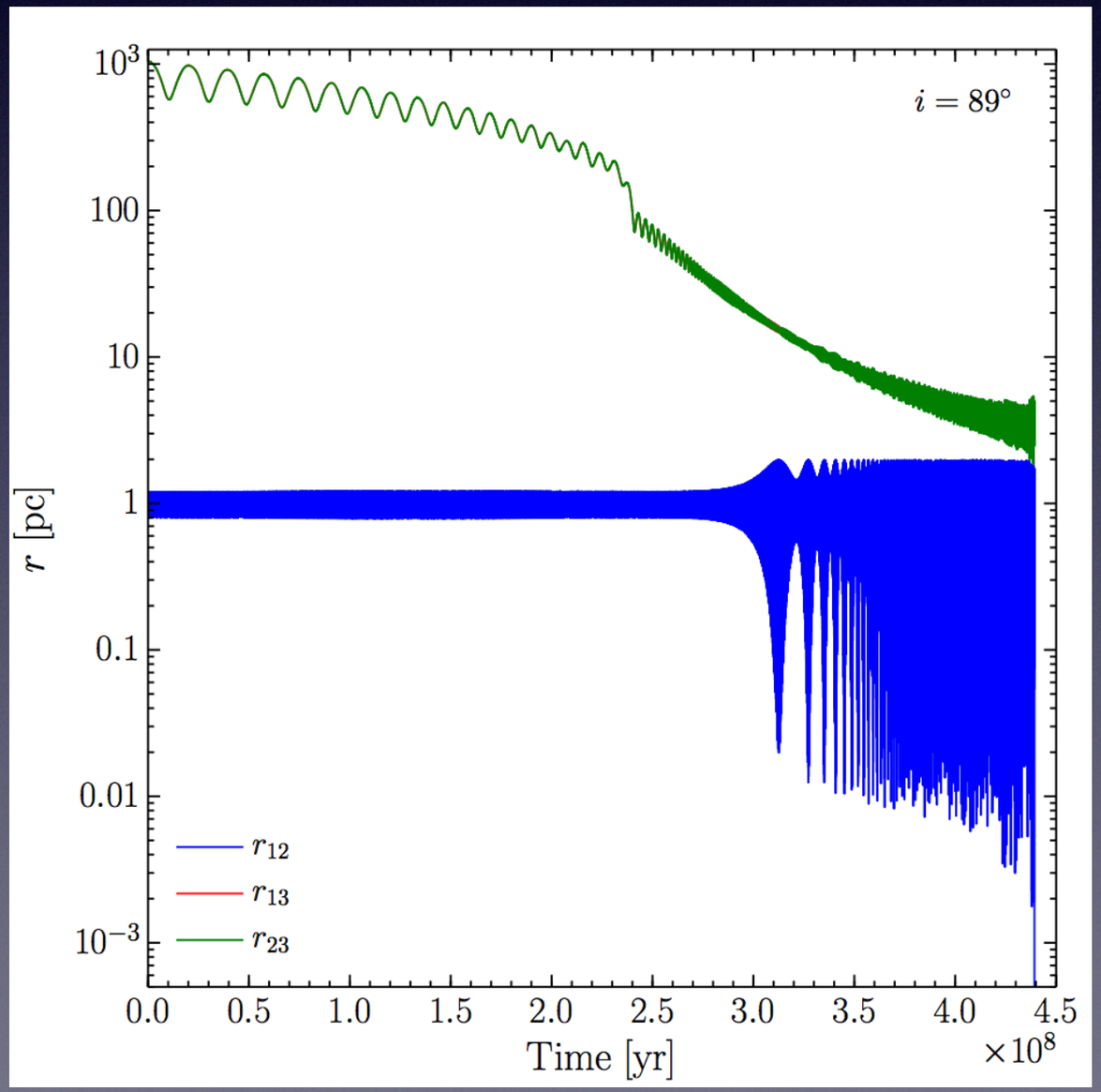


Bonetti, Sesana, EB, Haardt 2018

Dynamical friction, hardening, gas migration, MBH triples…
cf last parsec problem

MBHB eccentricity from triples

- If BH binaries take long to merge, triple systems naturally form as a result of later galaxy mergers
- Merger induced by Kozai-Lidov mechanism (secular exchange between eccentricity and orbital inclination)



$$t_{\rm KL} \sim \frac{a_{\rm out}^3(1-e_{\rm out}^2)^{3/2}\sqrt{m_1+m_2}}{G^{1/2}a_{\rm in}^{3/2}m_3} \simeq 2\times 10^6 \ \ {\rm yrs},$$

$m_1 = m_2 = m_3 = 10^8\ {\rm M}_\odot$, $a_{\rm in} = 1$ pc, $a_{\rm out} = 10$ pc, and $e_{\rm out} = 0$.

PN 3-body simulation in a stellar environment, with m_1=10^8 M_{sun}, m_2=3 x 10^7 M_{sun}, m_3=5 x 10^7 M_{sun} (Bonetti, Haardt, Sesana & EB 2016)

Eccentricities >0.99 (at LISA band entrance) and ~0.1 at merger

Exotica: axions/fuzzy DM

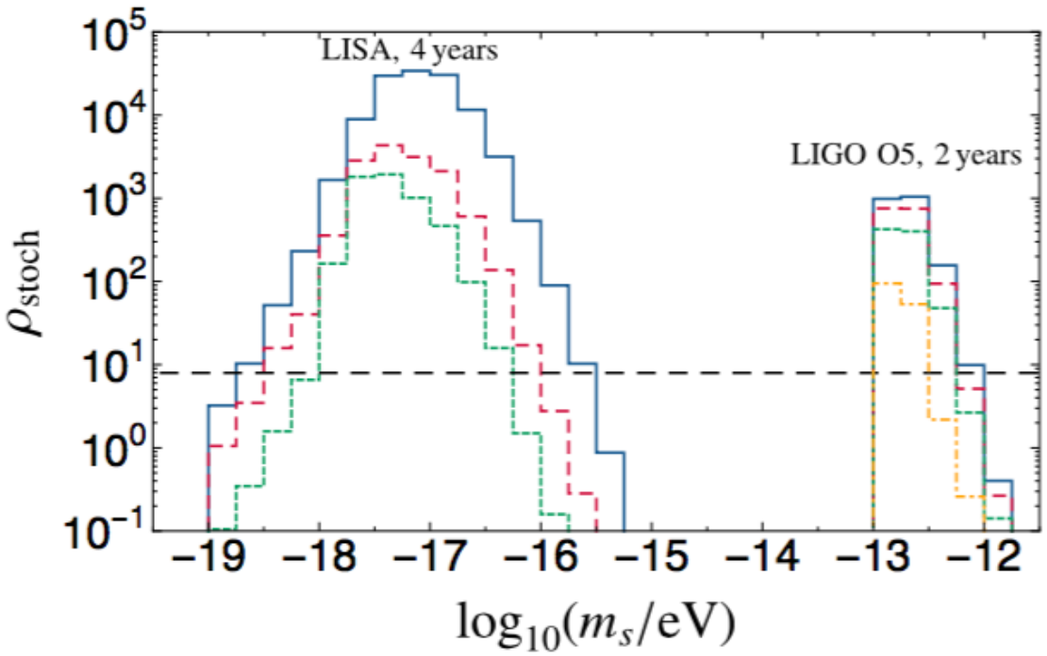
- Isolated spinning BH + massive scalar fields with Compton wavelength comparable to event horizon radius are unstable under super-radiance

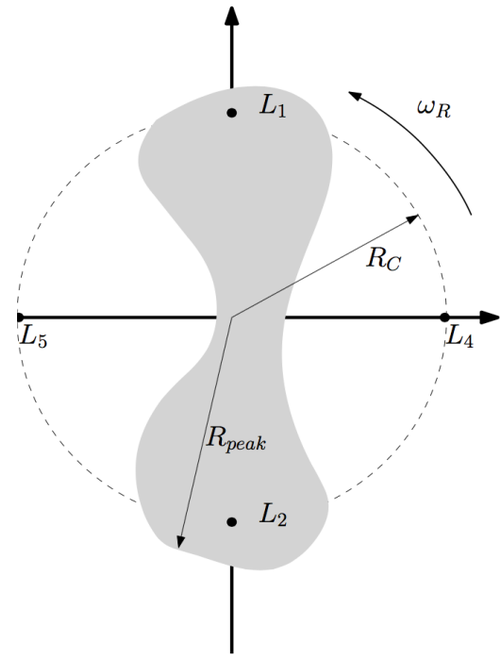
- Mass and (mostly) angular momentum are transferred from BH to scalar condensate surrounding BH on instability timescale; condensate then emits almost monochromatic waves on timescale

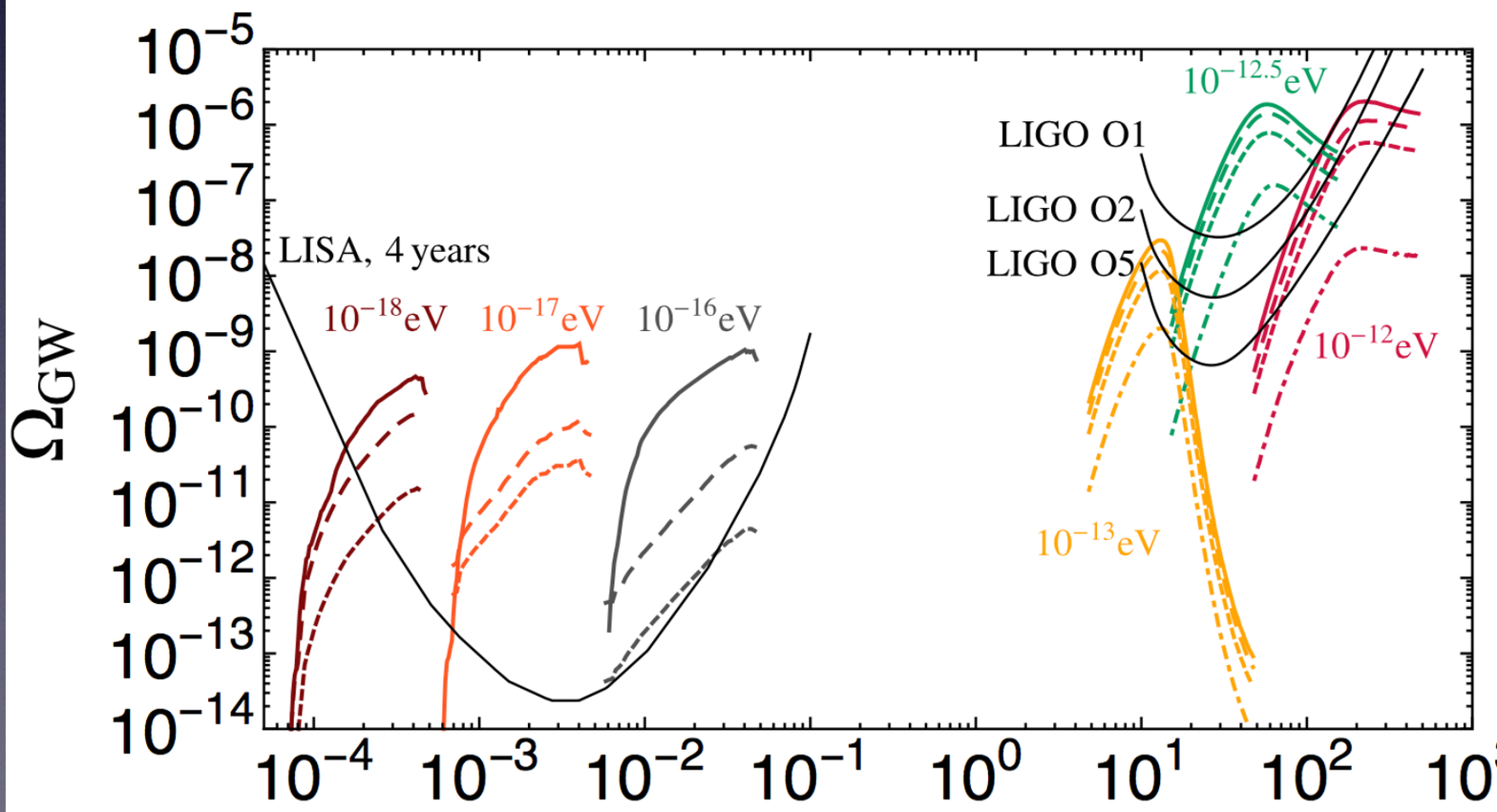
- Observable by LIGO/LISA as stochastic background and resolved sources; effect on EMRIs, etc

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

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







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

Conclusions

- In EMRIs moving in AGN accretion disks, environmental effects (especially planetary migration, dynamical friction and accretion) are significant
- Overall, majority of EMRIs **should** still 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 (but possibly not IMRIs) are **probably** quite safe from these effects, at least at $r < 60$-$70\ M$
- Unmodeled environmental effects could bias tests of GR, especially at low PN orders, but populations come to the rescue
- More exotic environmental effects (DM)?

Open questions

- Can we model environmental effects accurately? Agnostic waveform model for matter effects?
- 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/ bias?
- How to tell matter from non-GR effects? hierarchical analysis?
- Implications for waveform modeling (eg SF)?