Astrophysical sources for LISA

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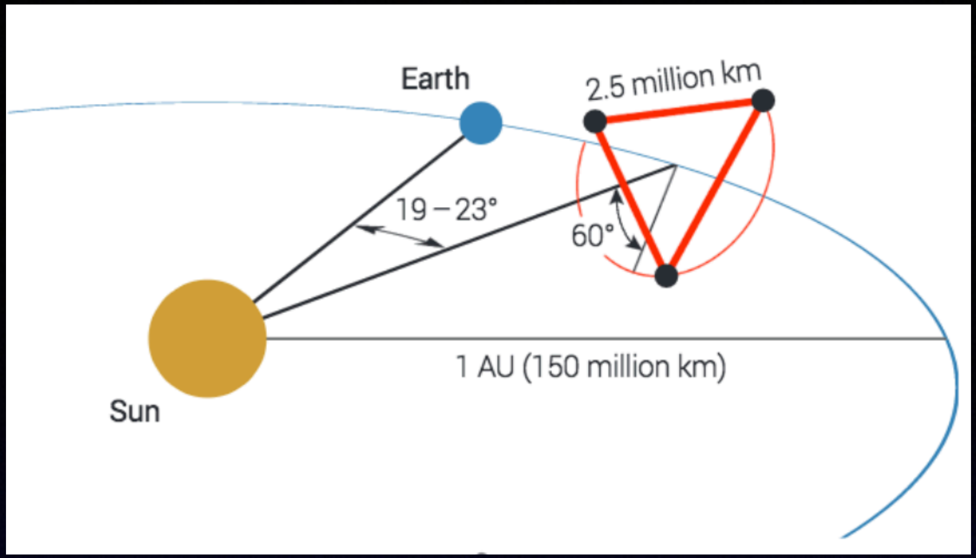
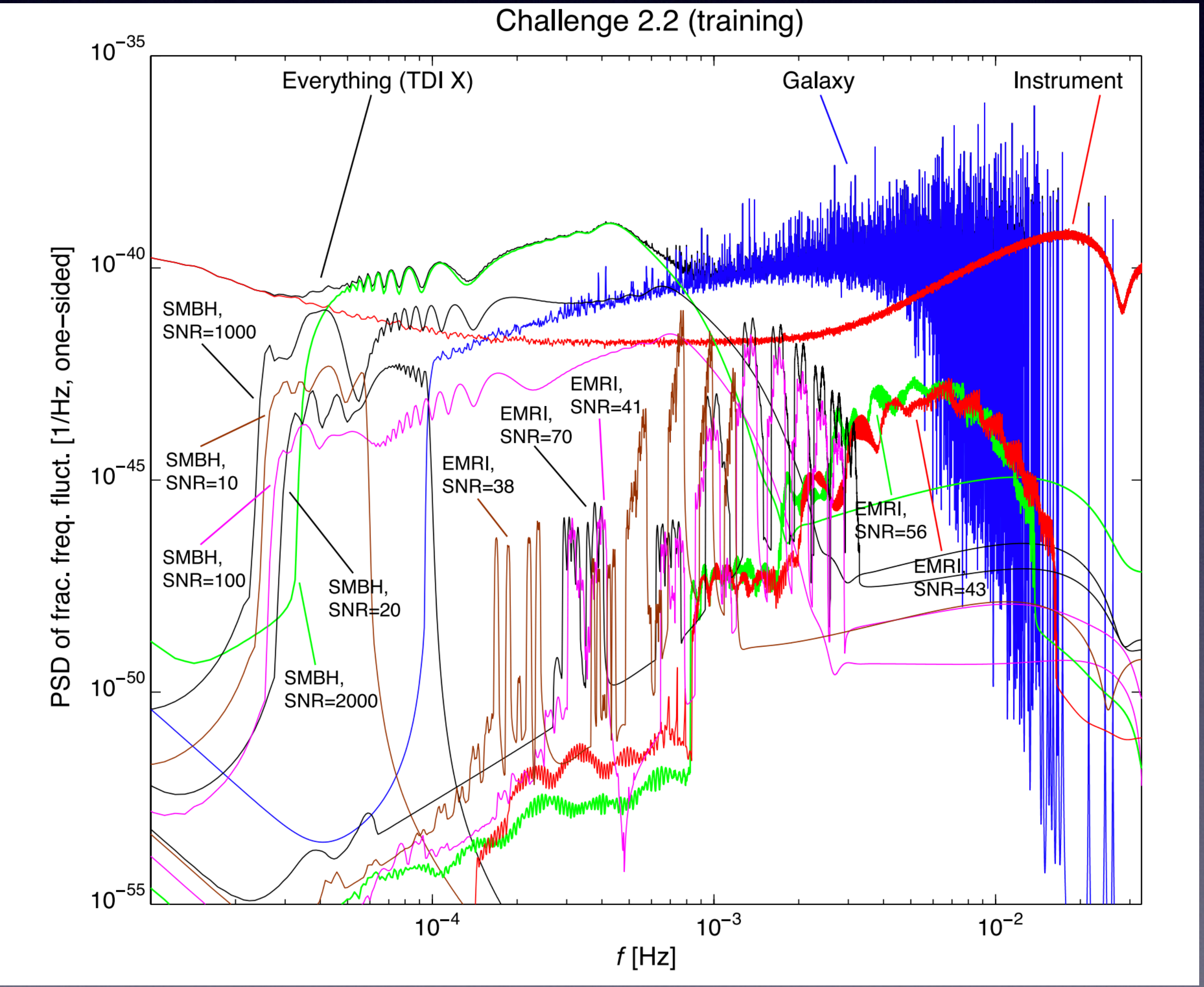
The LISA data





- >~ a few MBHs (Volonteri, Sesana, EB, Bonetti etc)
- From ~1 to thousands of EMRIs (Babak+ 2017)
- Thousands of resolvable Galactic binaries, millions of unresolvable ones (Nelemans, Korol, Lamberts…)
- Resolved and unresolved LVK sources (Sesana 2016)
- Cosmo backgrounds?

In principle, inference problem in several thousand dimensions

Galaxies merge…

… so massive BHs must merge too!

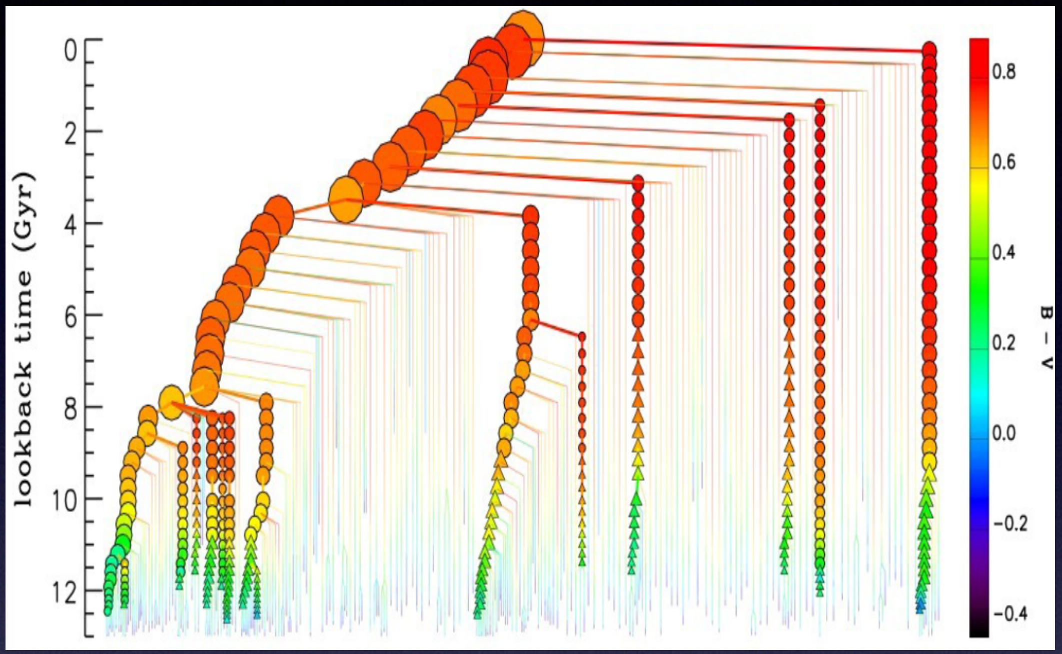


Figure from De Lucia & Blaizot 2007

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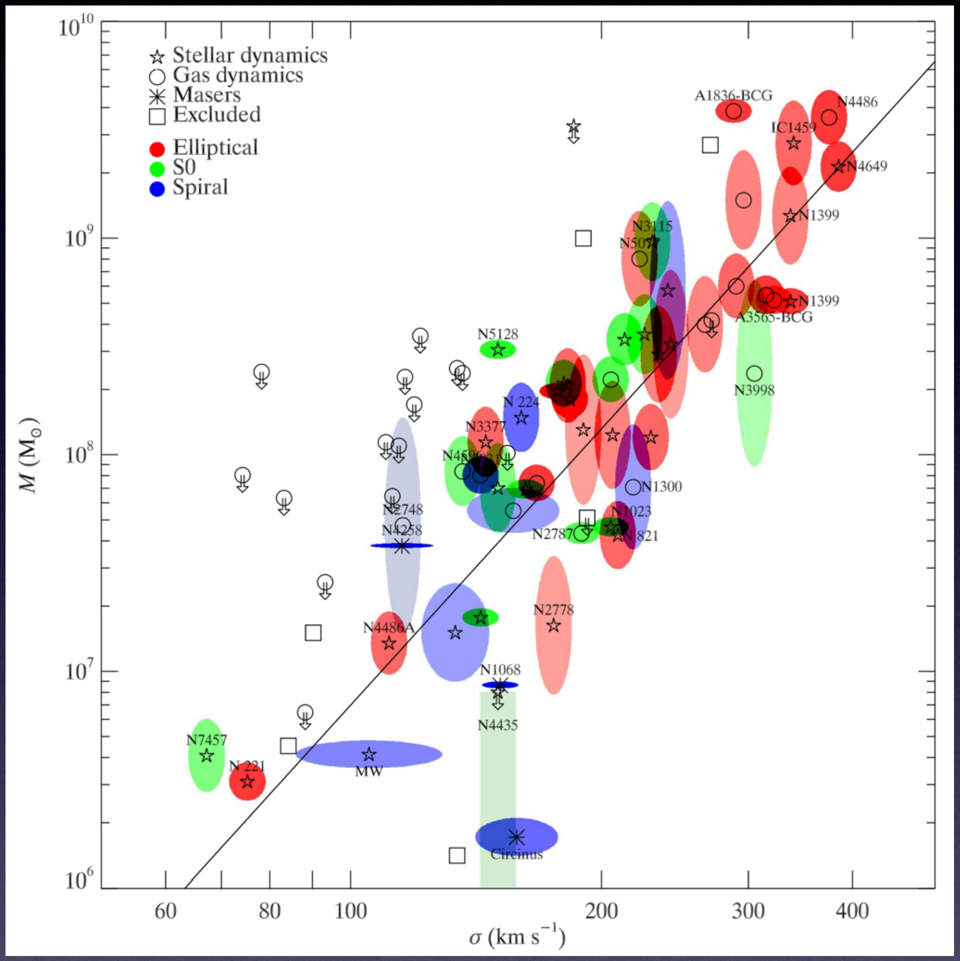

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

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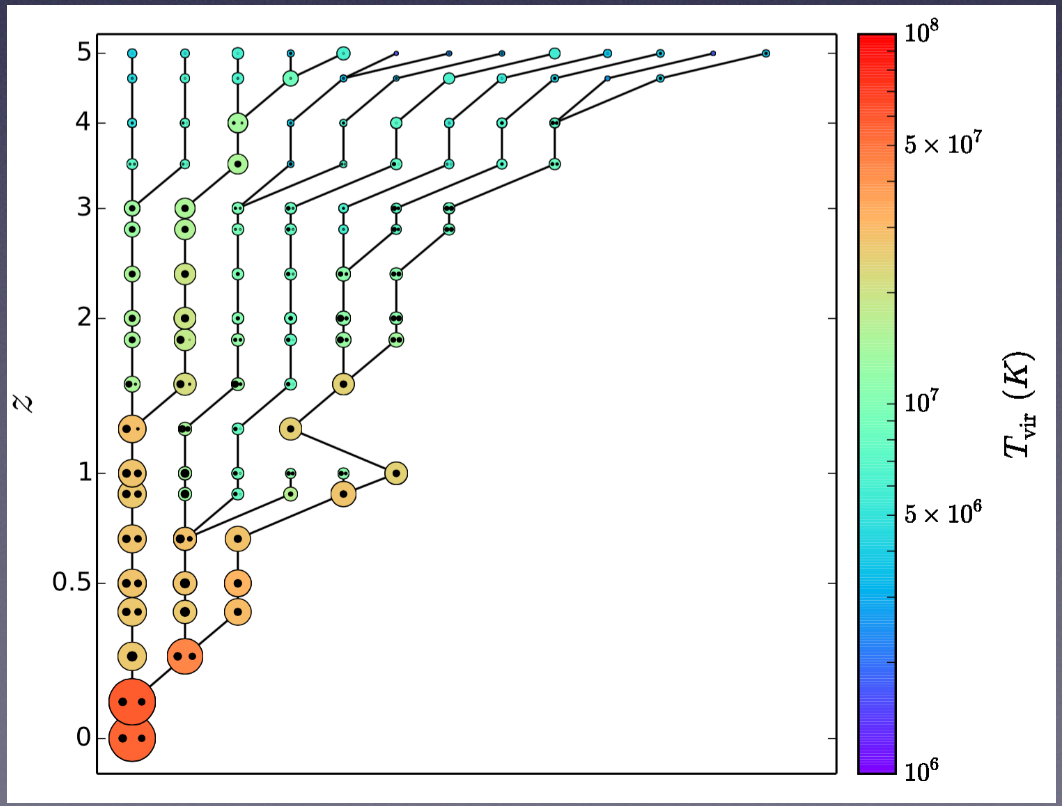
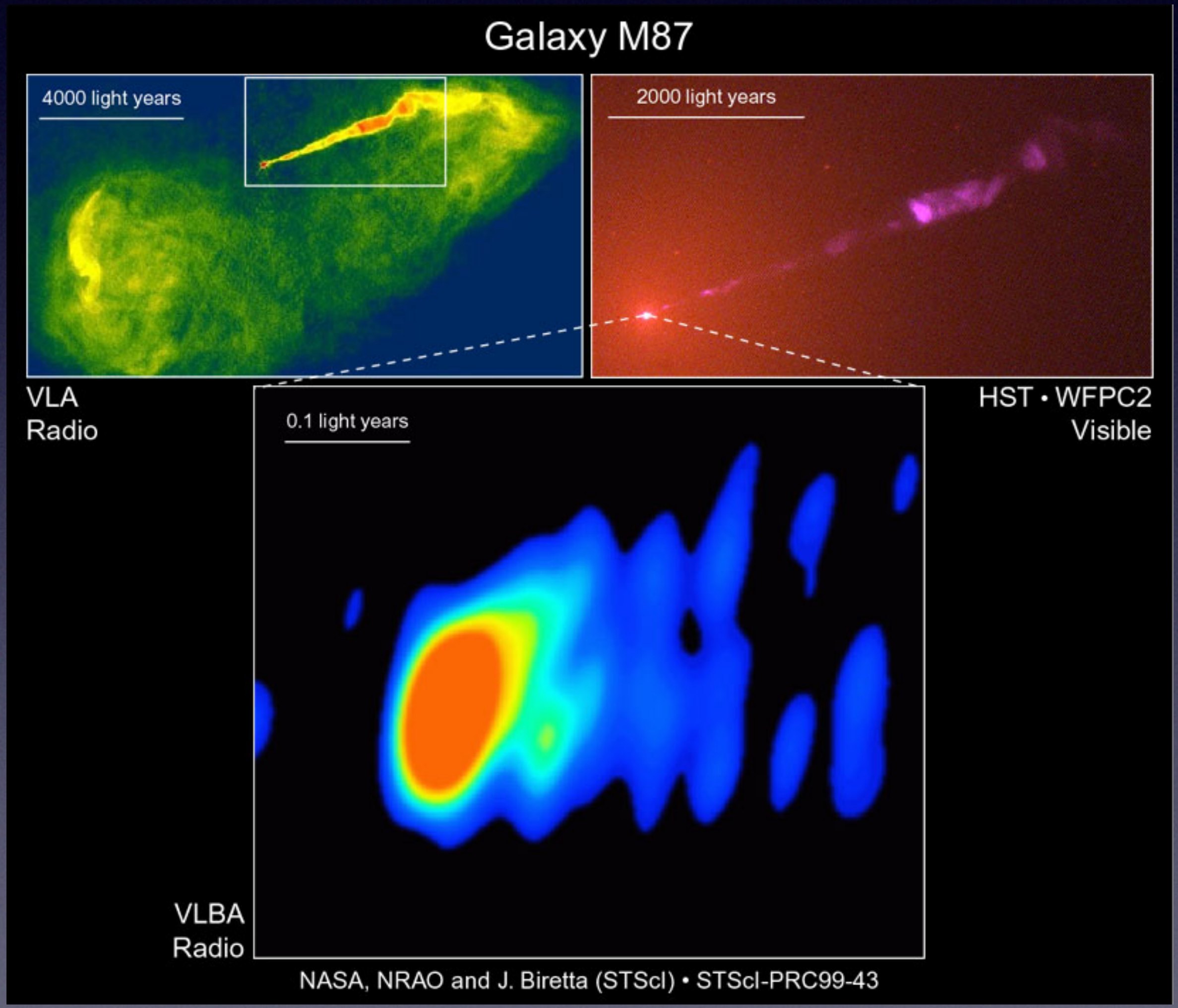
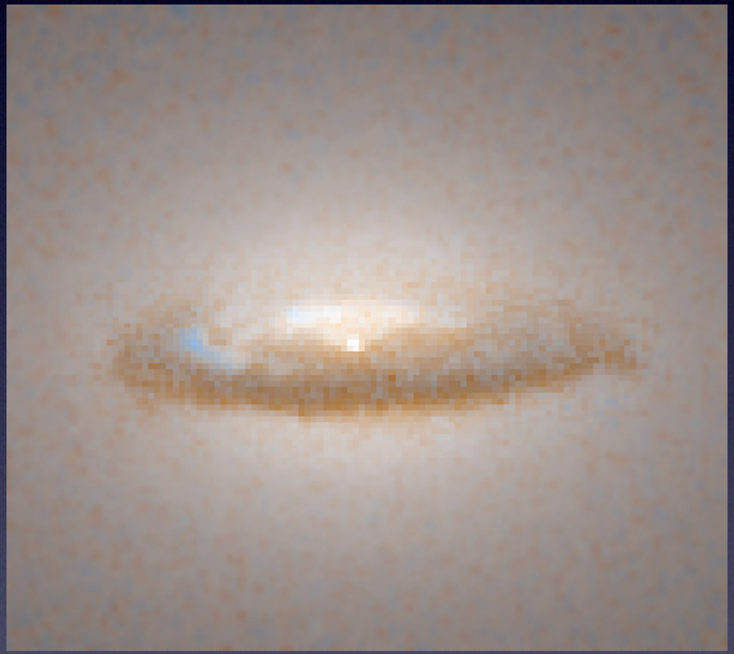


EB 2012
Figure credits: Lucy Ward

MBHs link small and large scales

- 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



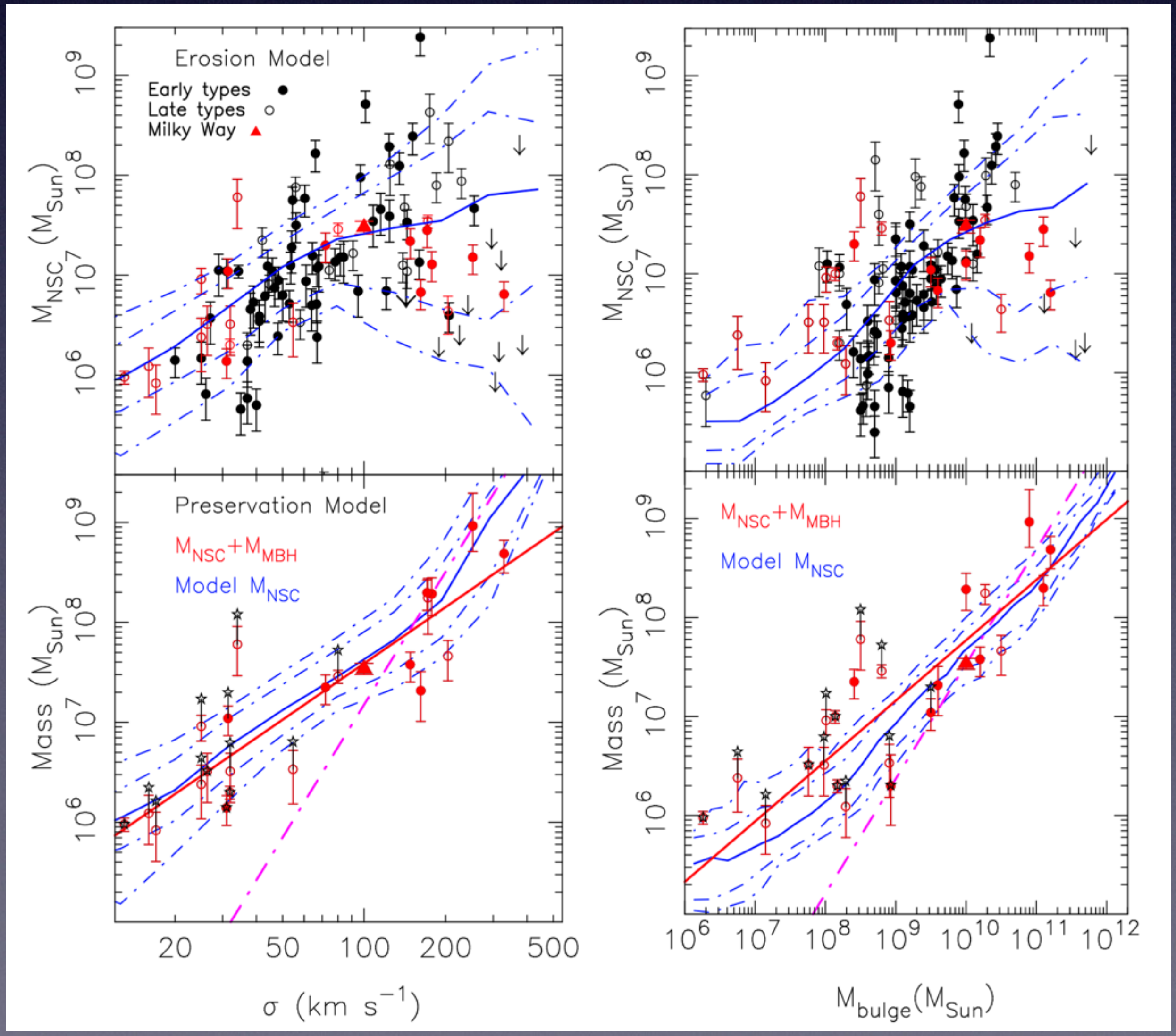


Disk of dust and gas around the massive BH in NGC 7052

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

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



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

Antonini, EB and Silk 2015a,b

How big are baby black holes?

Light seeds from PopIII stars (~100 M_{sun})

vs

Heavy seeds (~10^5 M_{sun})

e.g. direct collapse of gas and dust clouds in protogalaxies (induced by mergers, disk bar instabilities, inflows along filaments…); runaway collisions (favored by mass segregation) of massive stars, etc

Mix between the two? (Toubiana+EB+2022); primordial?

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Favored by JWST (little red dots) and PTAs (with caveats)

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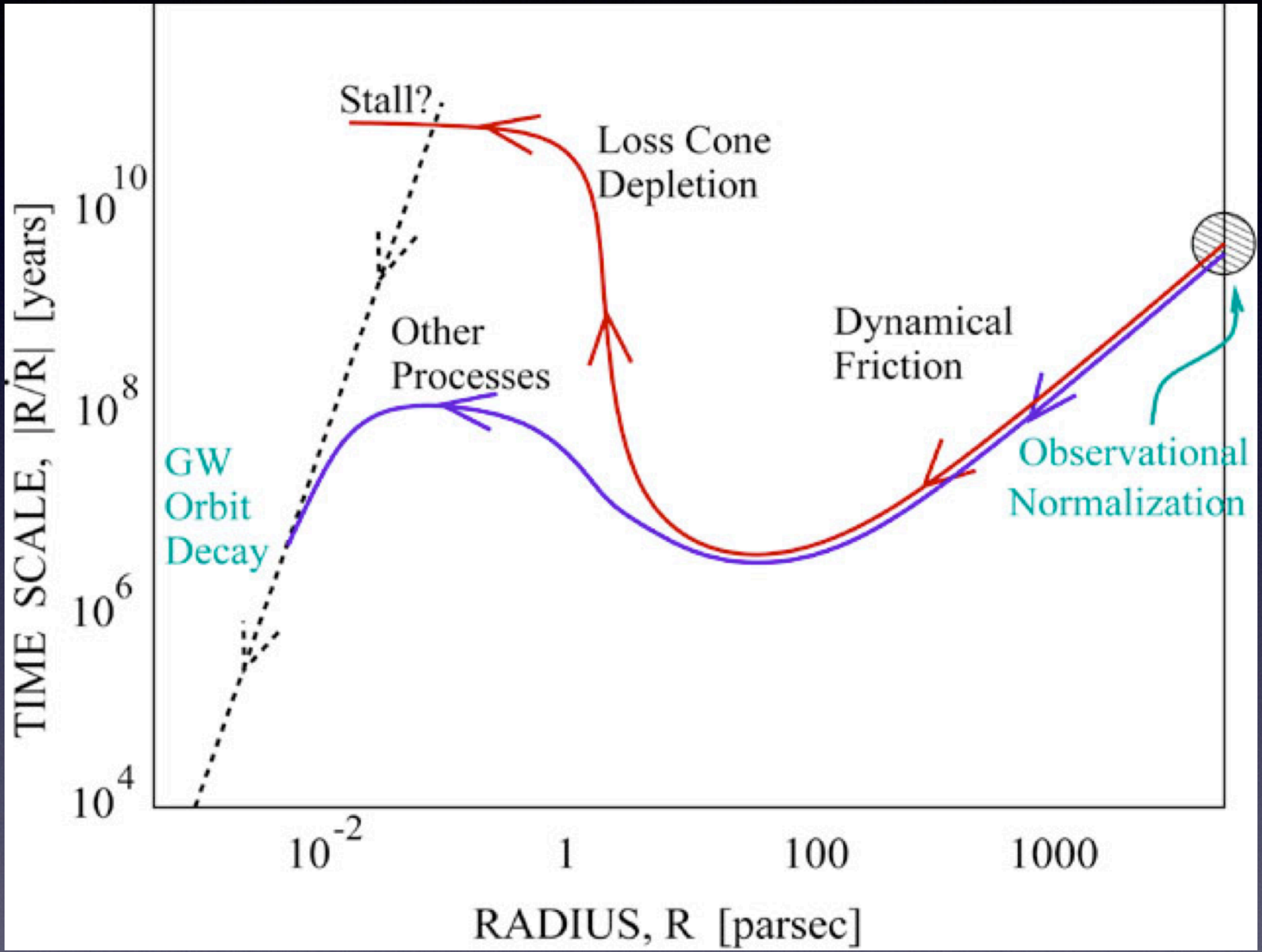
The “final pc problem”



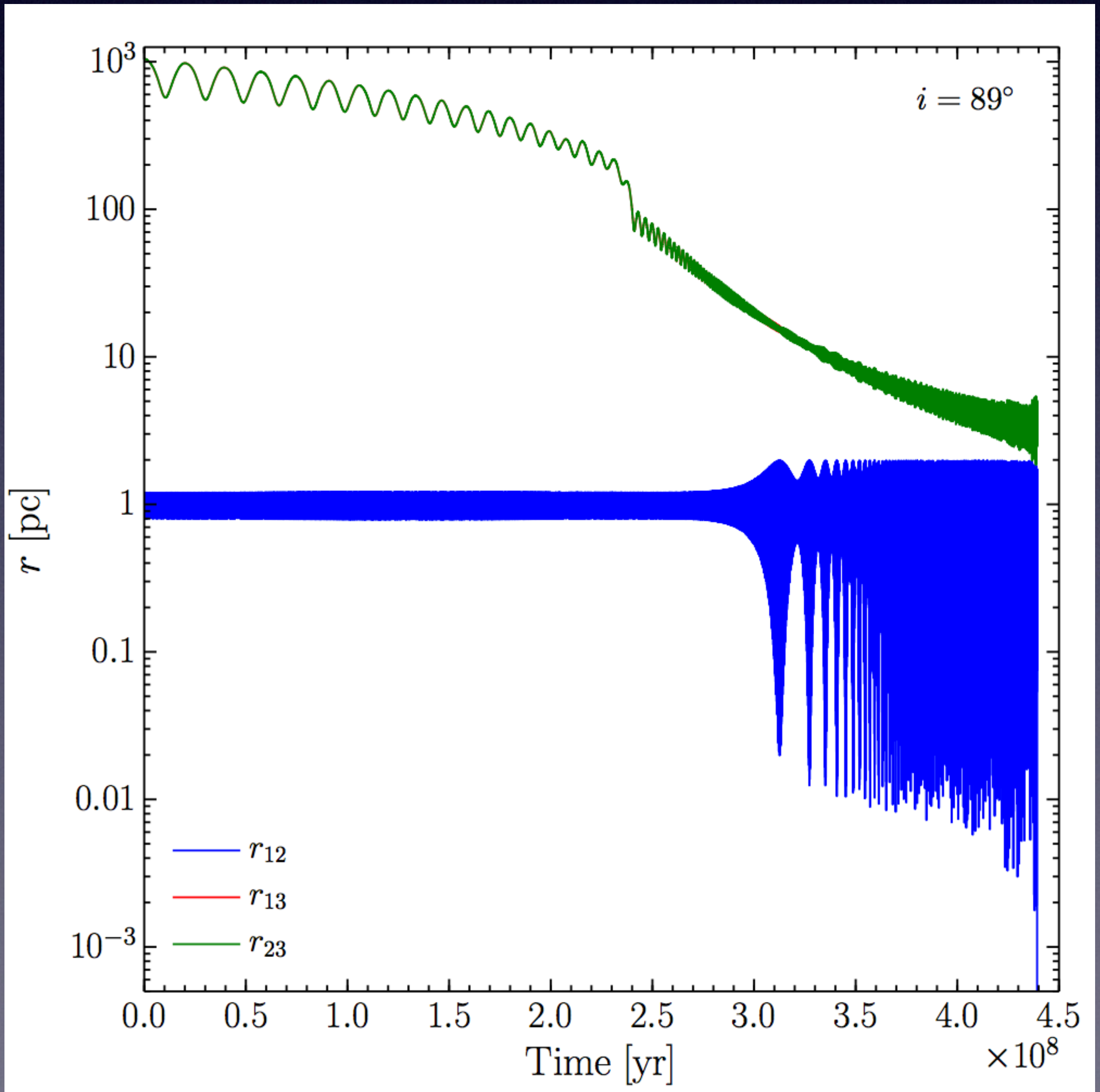
Begelman, Blandford & Rees 1980

Delays between halo and BH mergers

- Halo-halo dynamical friction+tidal disruption/evaporation
- From kpc to tens of pc: galaxy-galaxy dynamical friction/tidal disruption; BH-galaxy dynamical friction
- 3-body interactions with stars on timescales of 1-10 Gyr
- Gas-driven planetary-like migration on timescales ≳ 10 Myr
- Triple massive BH systems on timescales of 0.1-1 Gyr

What if MBHs do not merge?

- If BH binaries stall and do not 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)



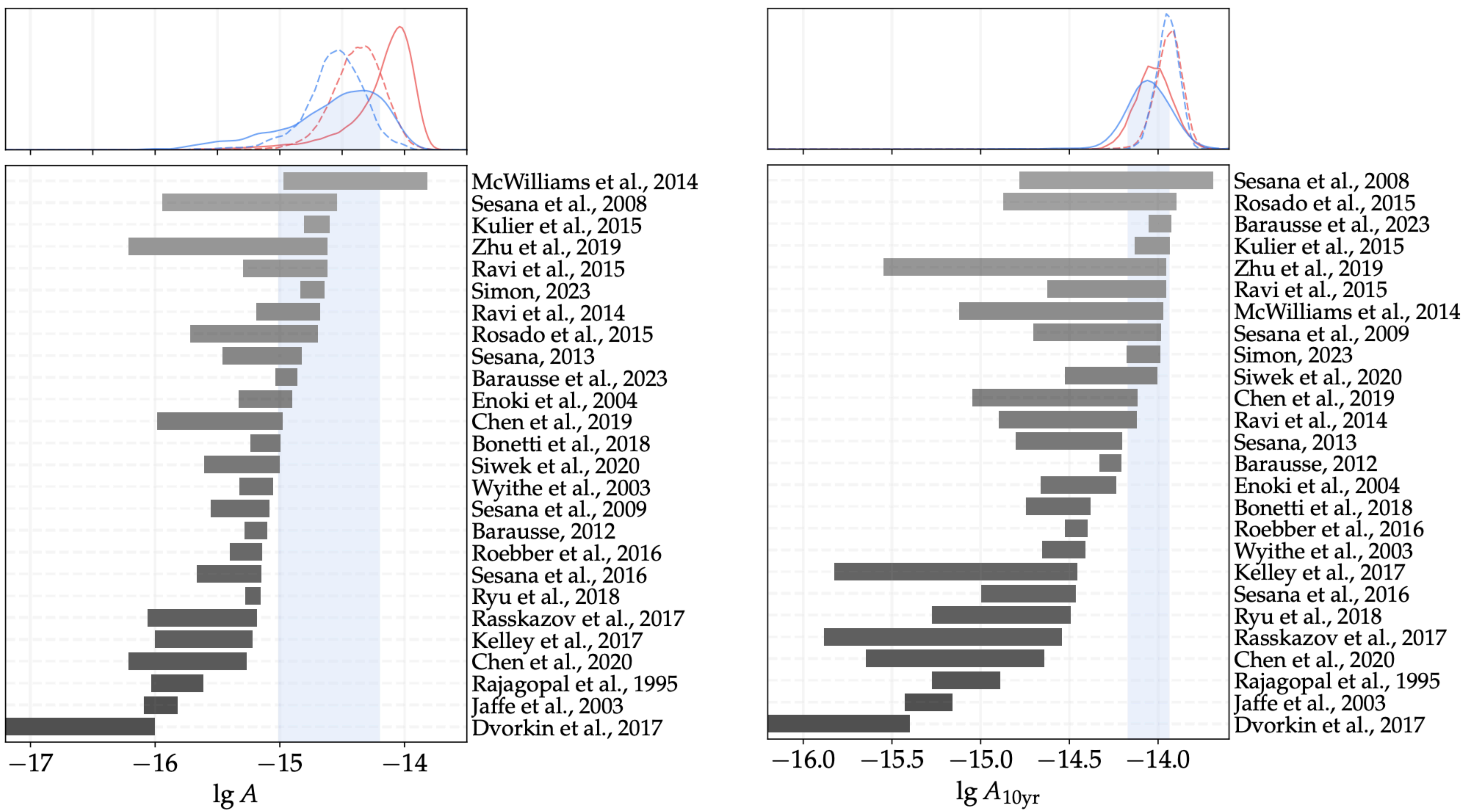
$$t_{\rm KL} \sim \frac{a_{\rm out}^3 (1 - e_{\rm out}^2)^{3/2} \sqrt{m_1 + m_2}}{G^{1/2} a_{\rm in}^{3/2} m_3} \simeq 2 \times 10^6 \ \ {\rm yrs},$$

$m_1 = m_2 = m_3 = 10^8\ {\rm M}_\odot$, $a_{\rm in} = 1$ 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)

Triple driven systems can display eccentricities >0.99 (at band entrance)!

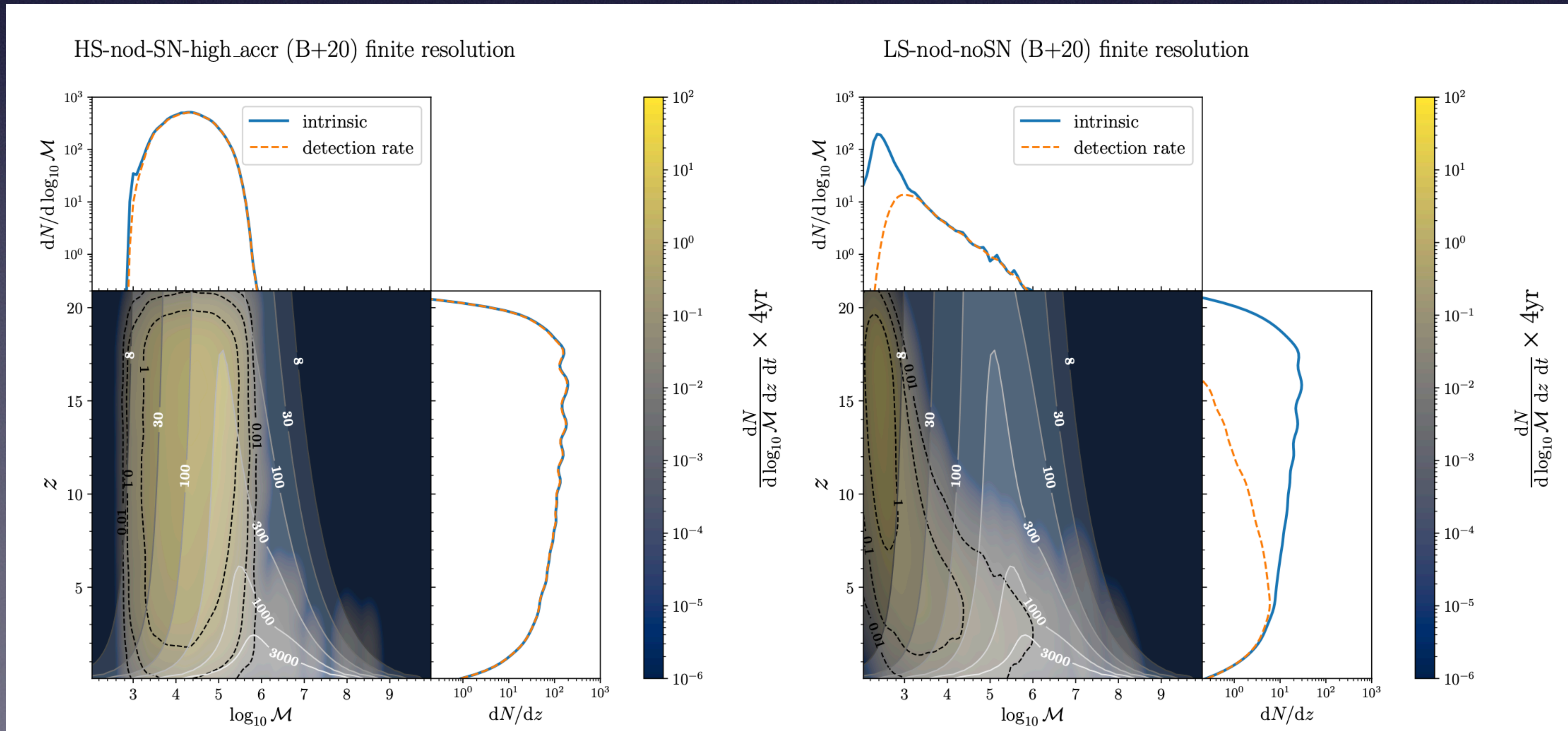
The PTA signal vs MBHB predictions



Goncharov+24

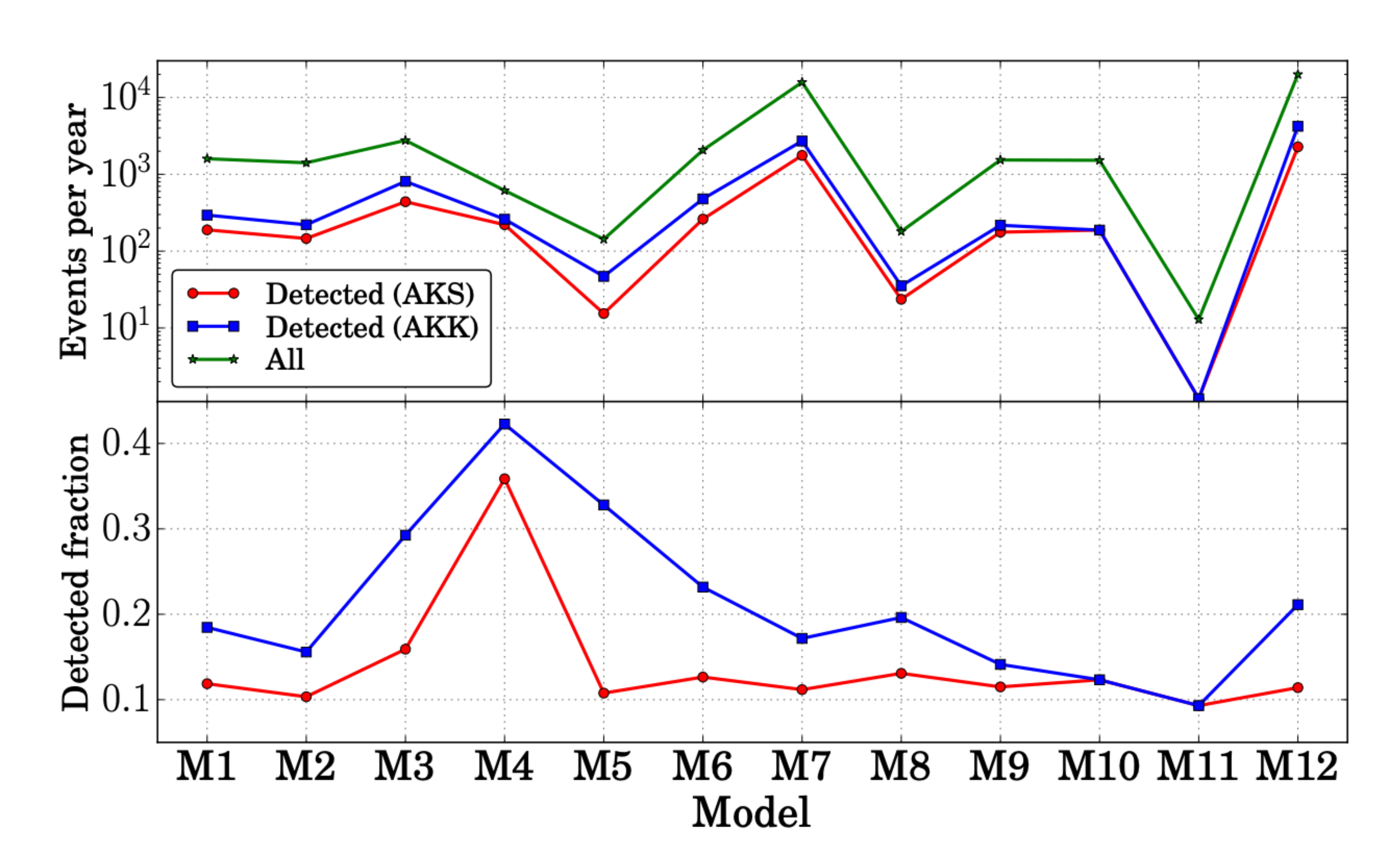
Merger rates for LISA after PTAs

Model	$N_{\rm det}(4\ {\rm yr})$ *finite res.*	$N_{\rm det}(4\ {\rm yr})$ *inf. res.*
HS-nod-SN-high-accr (B+20)	8901	-
LS-nod-noSN (B+20)	203	250
HS-nod-noSN (B+20)	15821	38712
LS-nod (B12)	432	570
HS-nod (B12)	6154	7184
LS-nod-SN (B+20)	11	12
HS-nod-SN (B+20)	16133	36090
Q3-nod (K+16)	468	656
popIII-d (K+16)	183	339
Q3-d (K+16)	33	74



EB+23

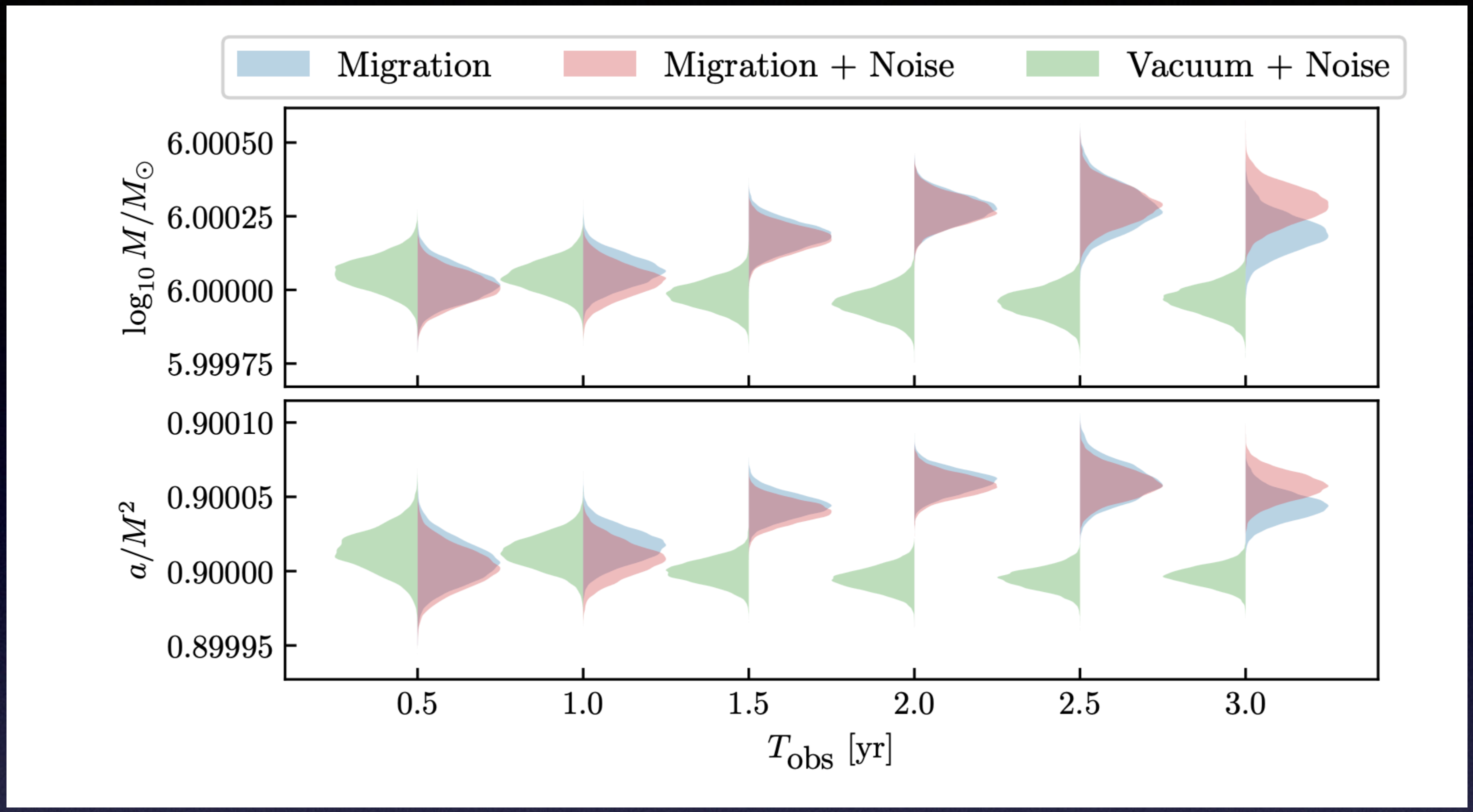
EMRI rates



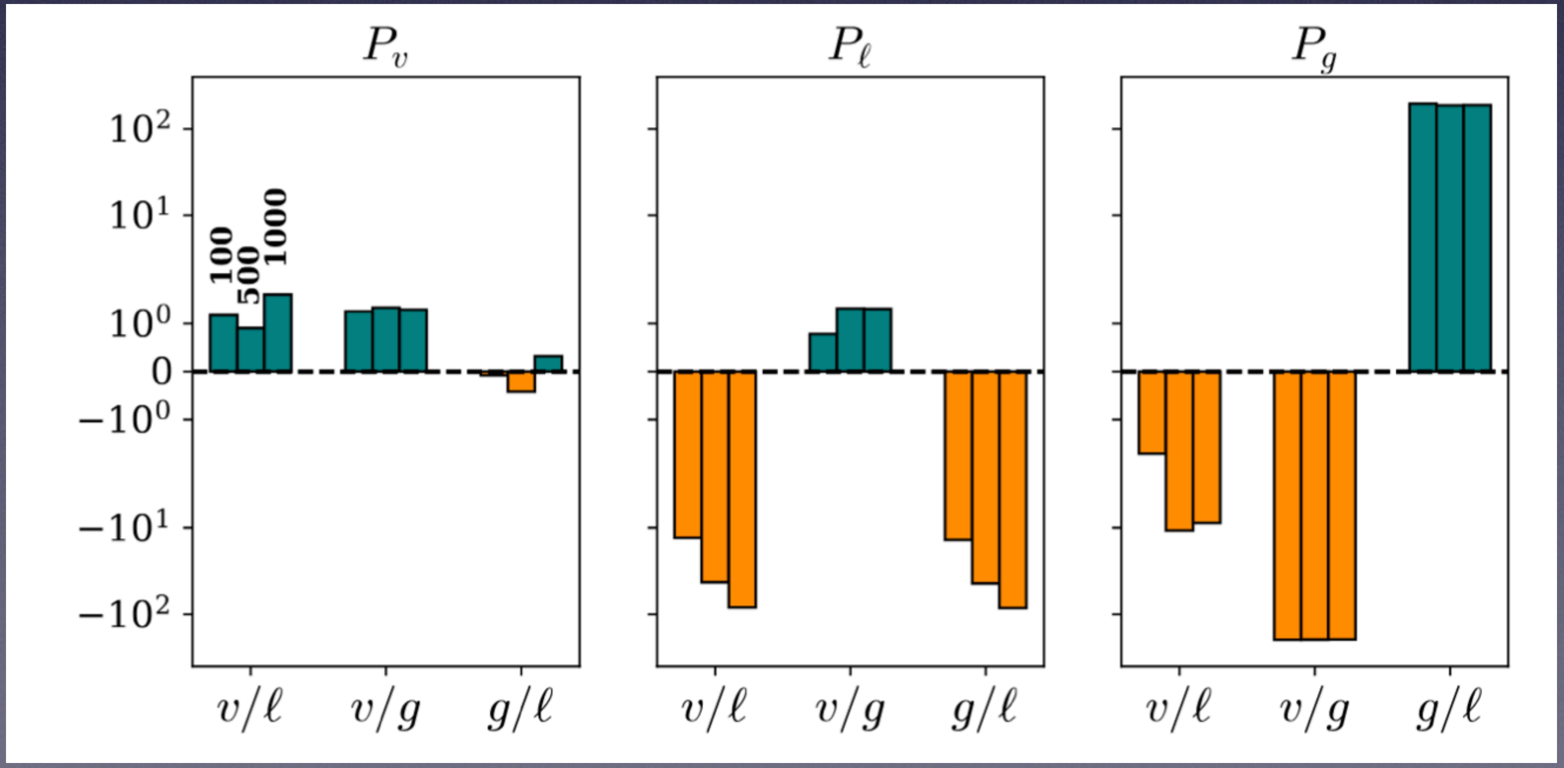
Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[yr^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	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

Babak+EB+17

EMRIs and environment



Copparoni, Chandramouli & EB 25

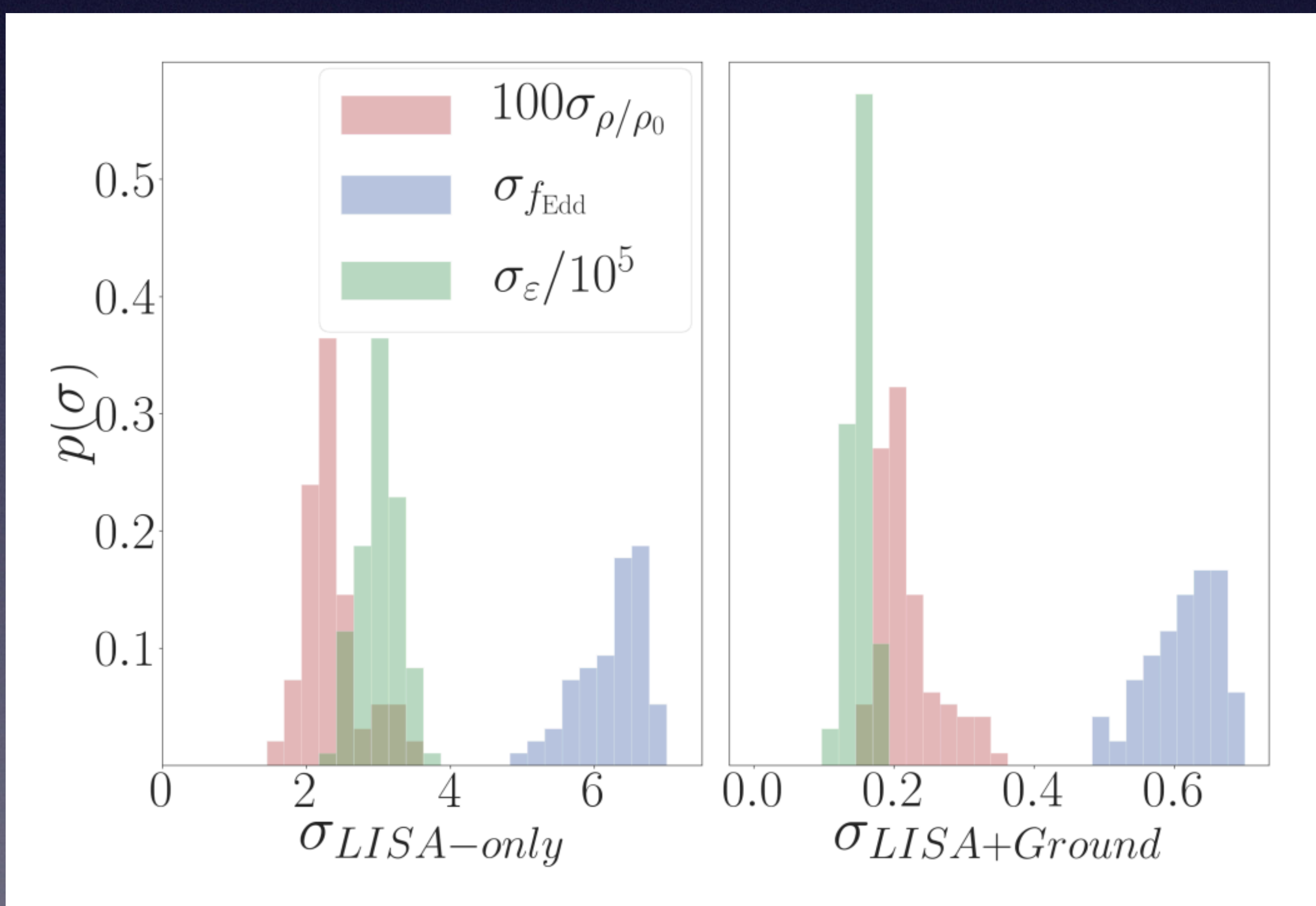


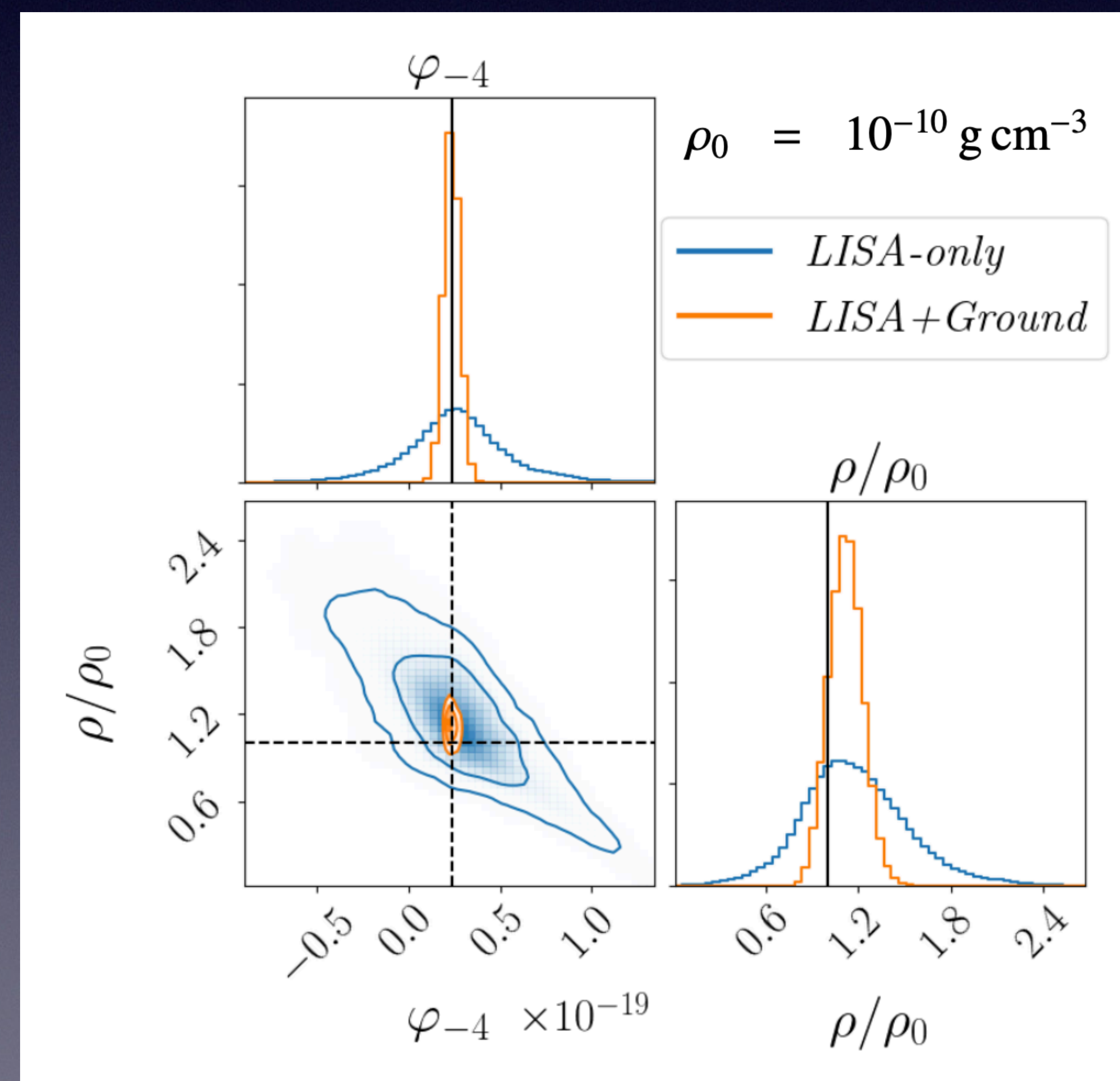
Kejriwal, Chua & EB 25

- AGN disks likely to affect > 10% EMRIs through migration torques
- Effect visibile with and without suitable templates
- Degeneracy with modified gravity for a single source but not for population

GW190521-like systems as probes of AGNs

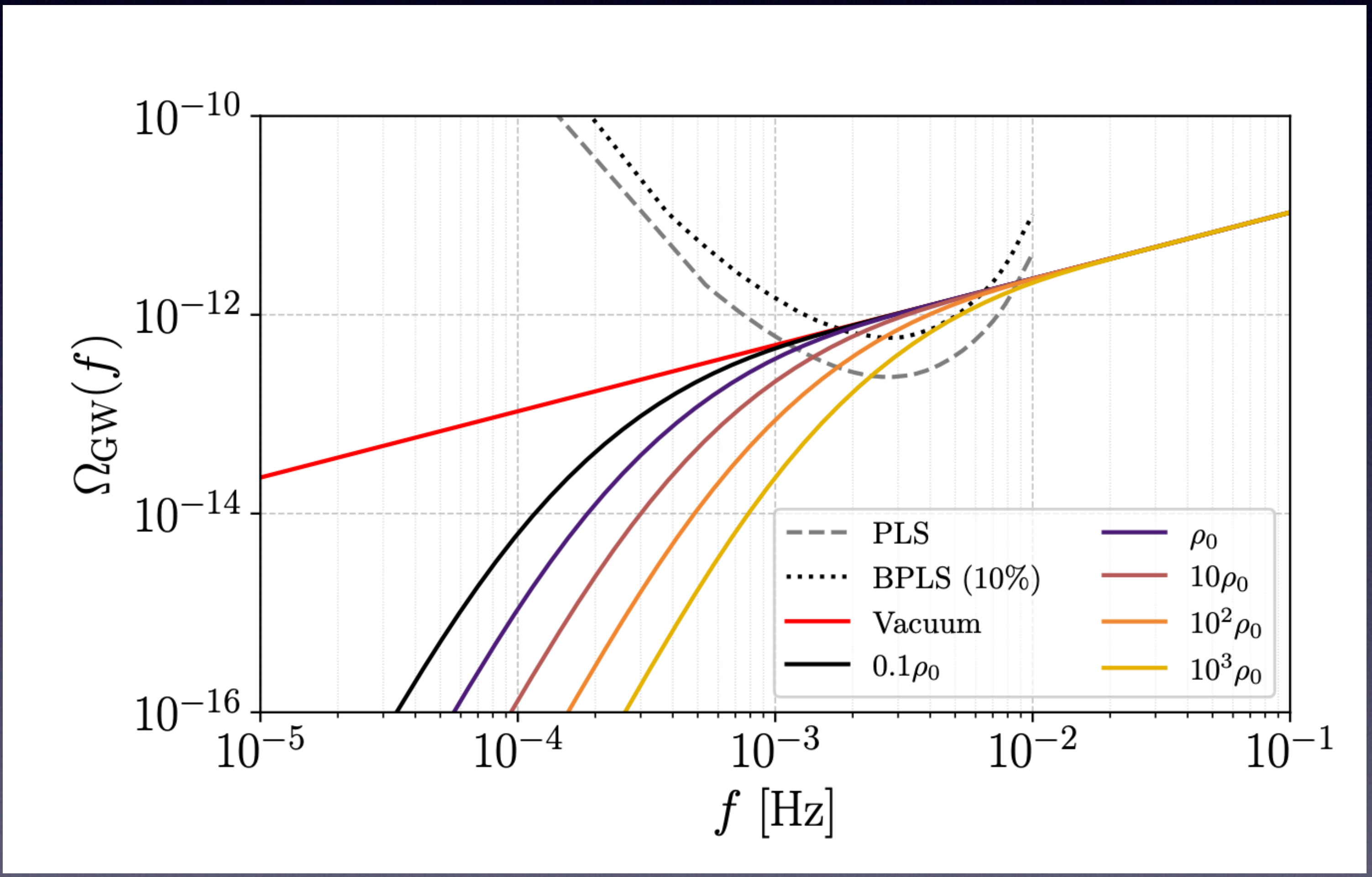
Gas accretion, dynamical friction, and orbital motion around the AGN's massive black hole (acceleration/Doppler, strong lensing and Shapiro time delay, precession) detectable in SOBHBs formed near AGNs, cf Toubiana et al (incl EB) 21

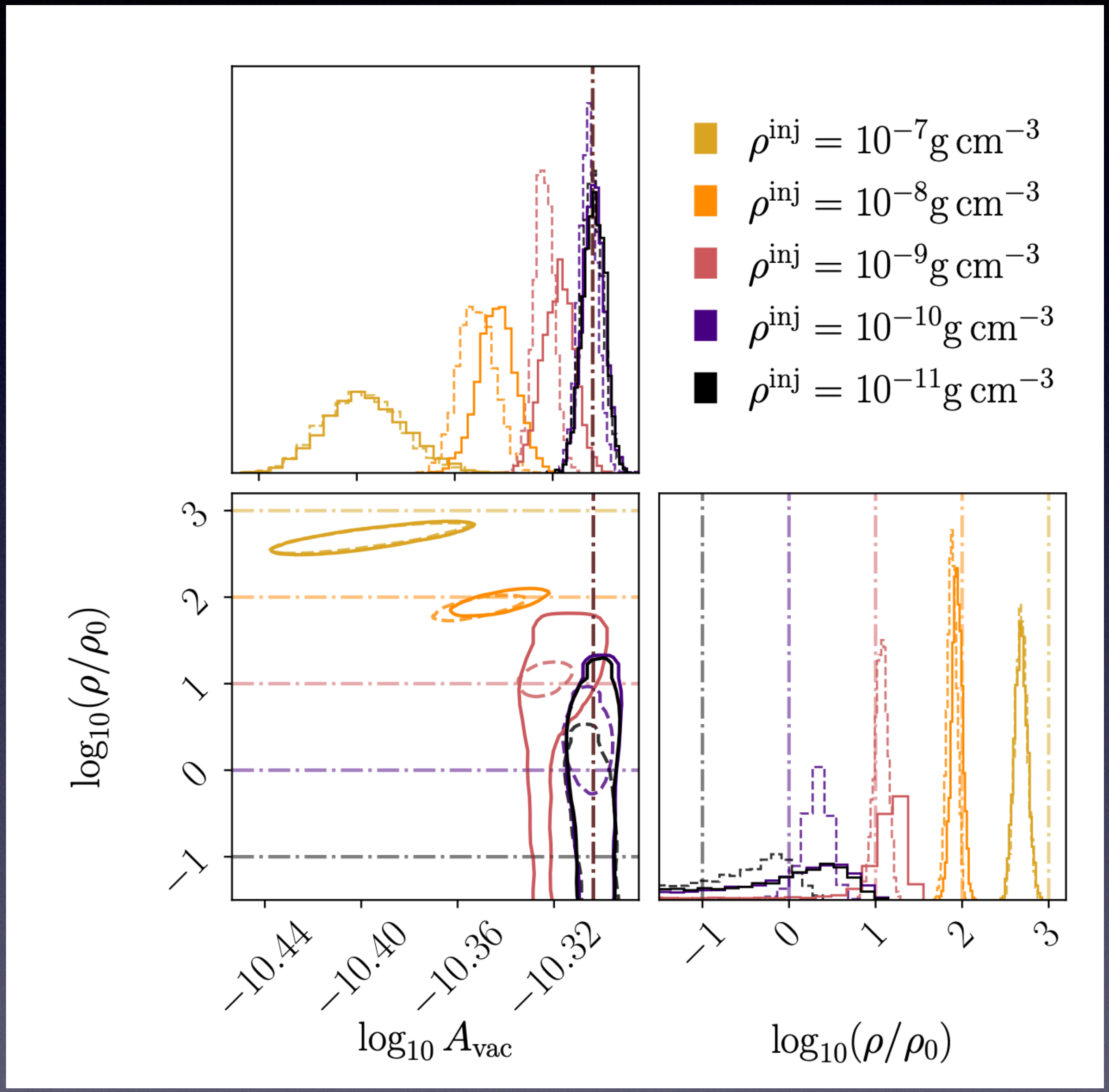




$$\epsilon = \left(\frac{v_{\rm orb}}{100\,{\rm km/s}}\right)^2 \frac{10\,{\rm kpc}}{a} \cos\psi$$

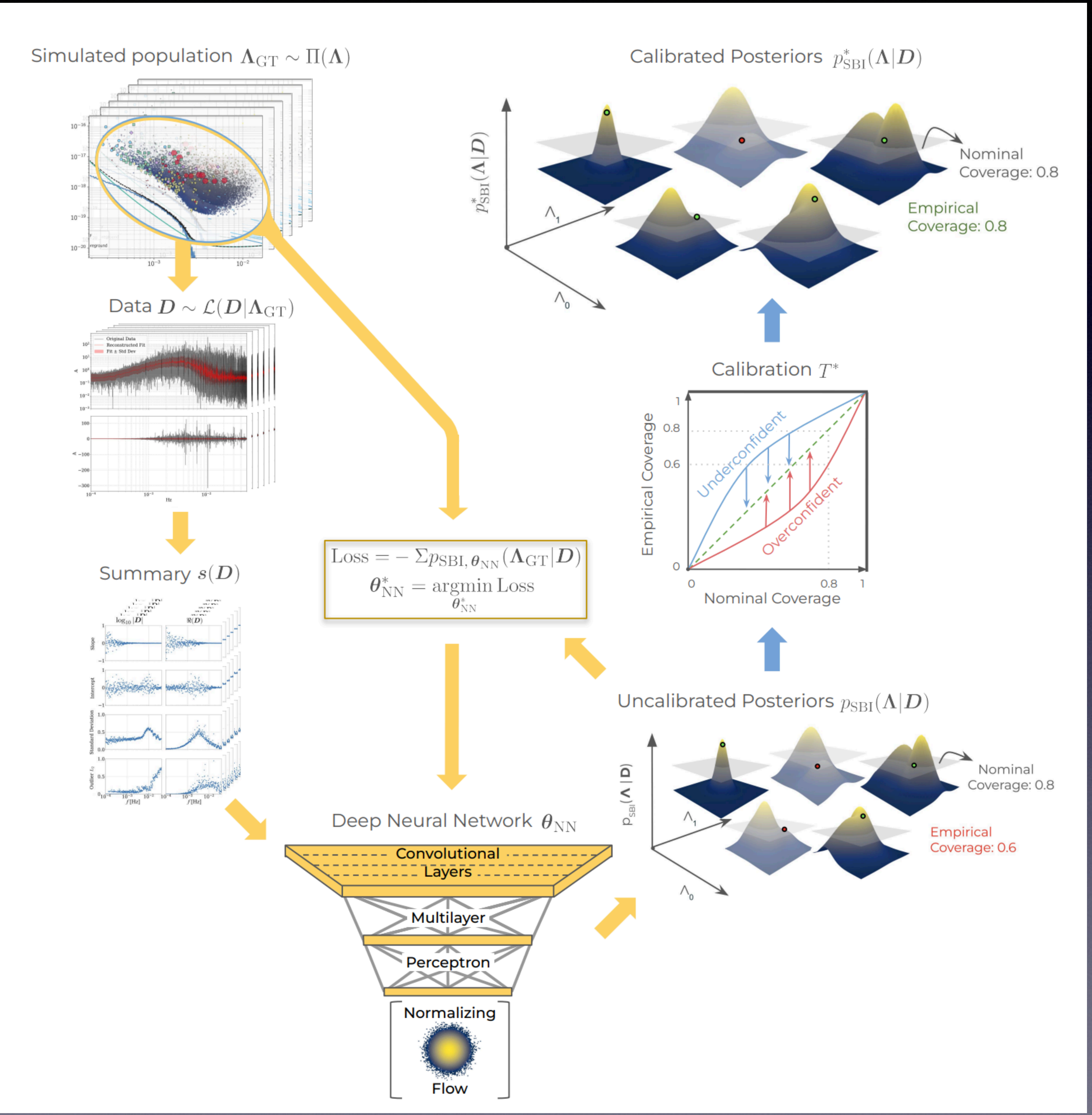
Environment may also affect SOBHB background's shape





Chen+EB+25

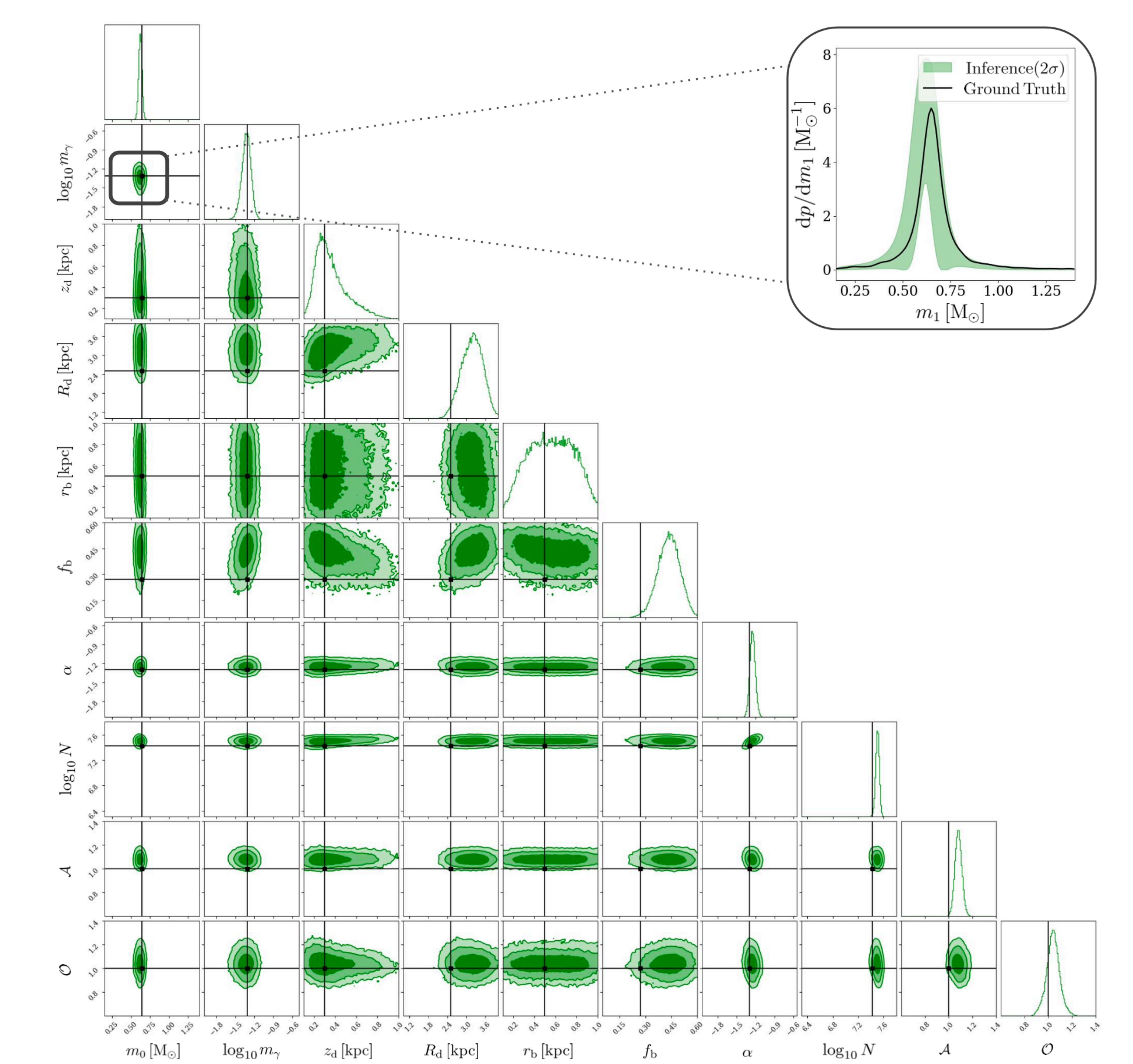
Population inference without the global fit



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

Conclusions

LISA astrophysics uncertain but:

- > a few MBHs (cf PTAs, JWST)
- From ~1 to thousands of EMRIs
- ~1.e3 resolvable Galactic binaries, millions of unresolvable ones
- Resolved and unresolved LVK sources
- Environment may be important for EMRIs and LVK sources: beware of biases (eg false detections of GR)
- Important to perform hierarchical analysis (eg vacuum vs environment, environment vs non-GR): SBI may complement global fit