Massive BH astrophysics with low frequency GWs

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TianQin astronomy workshop (Aug 22-25, 2022)

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ifpU

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Outline

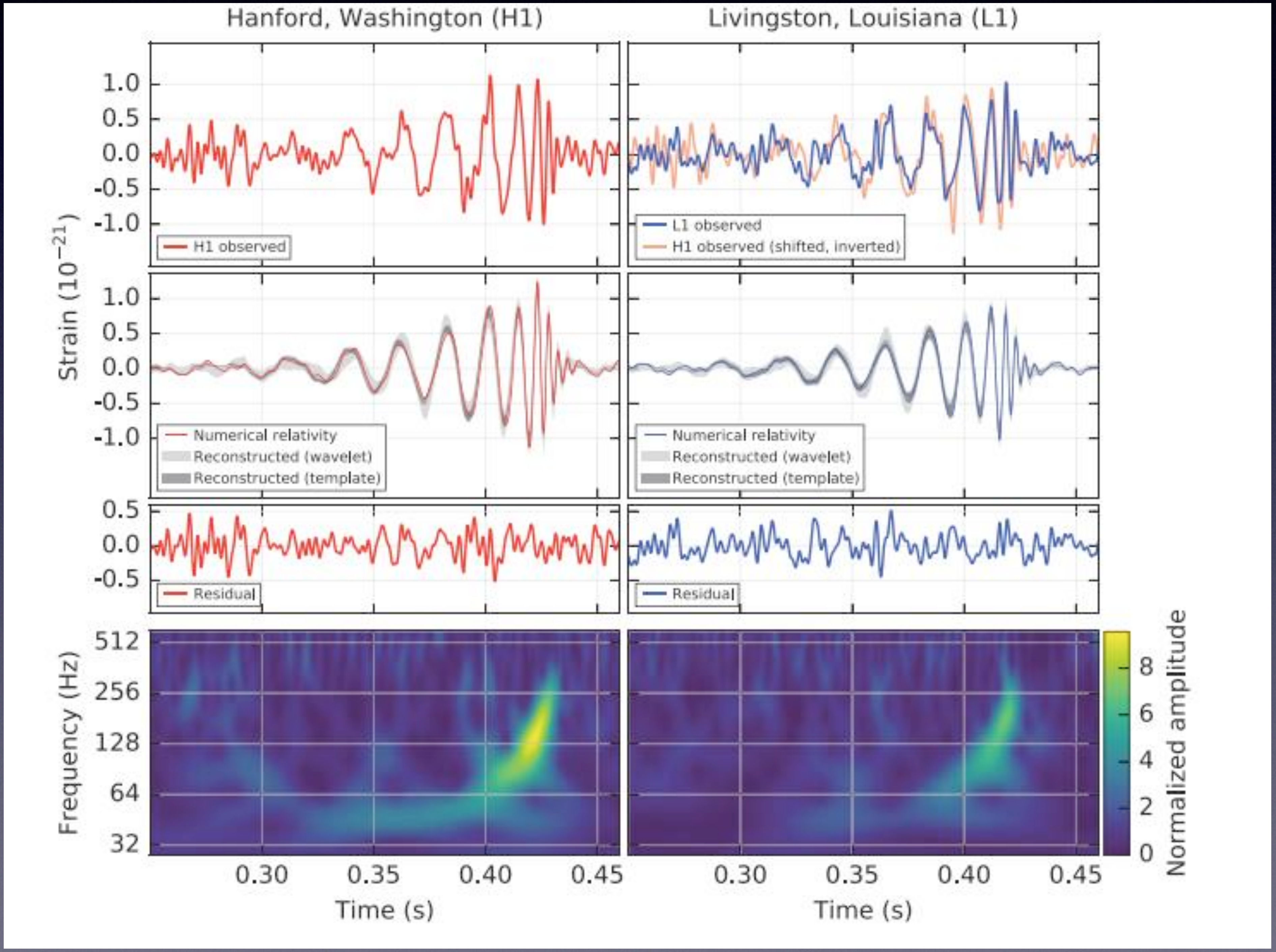
- Why low-frequency GWs? Massive BH mergers!

  - Interferometers (LISA, TianQin…)

  - Pulsar Timing Arrays (PTAs)

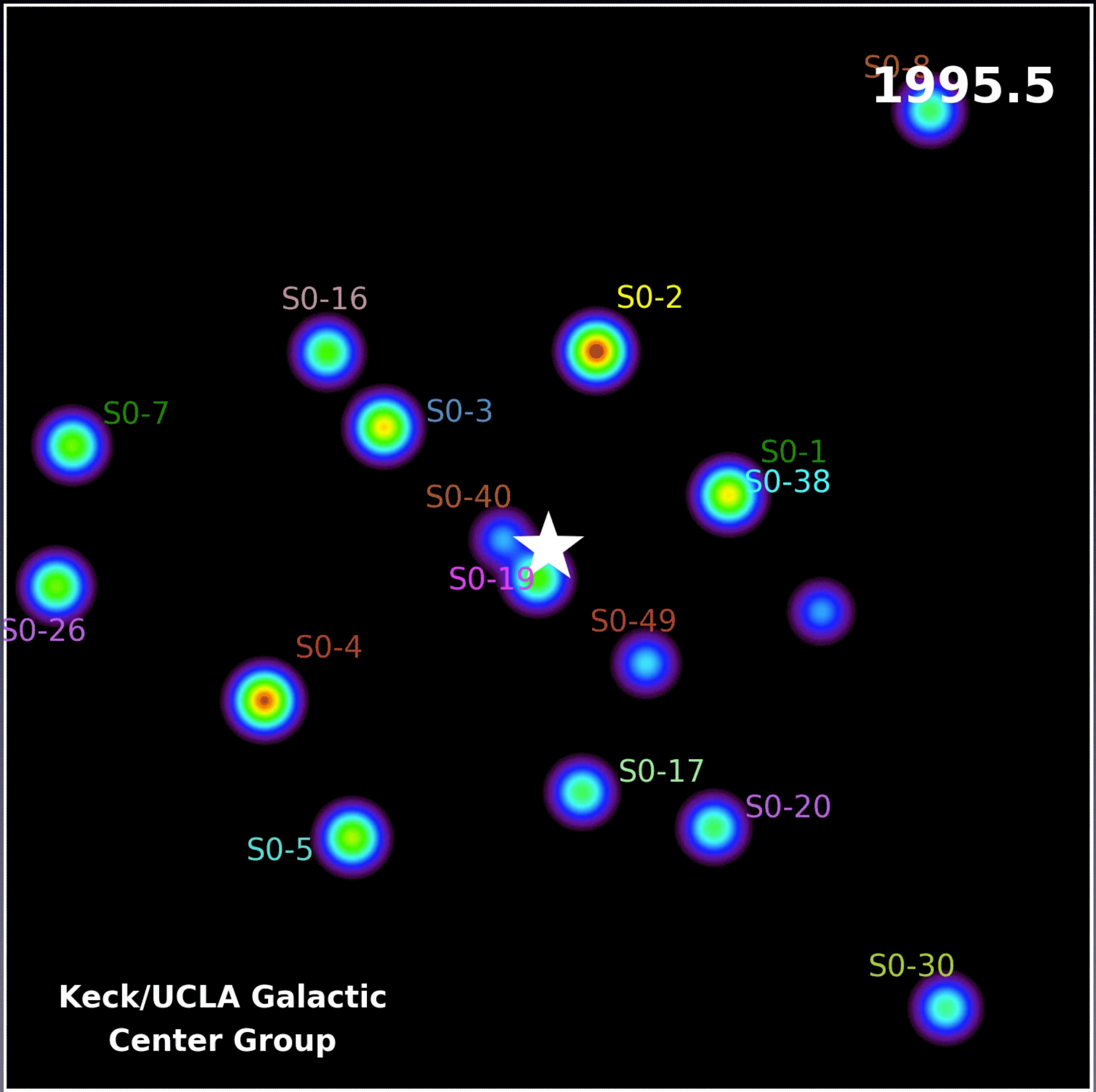
- Other (important) science with low-frequency GWs: ringdown tests, multi-band GW astronomy, tests of GR, white dwarf binaries, cosmography, extreme mass-ratio inspirals, primordial stochastic backgrounds, super-radiance bounds on ultralight bosons/near horizon physics… **Not covered!**

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!



Galaxies merge…

… so massive BHs must merge too!

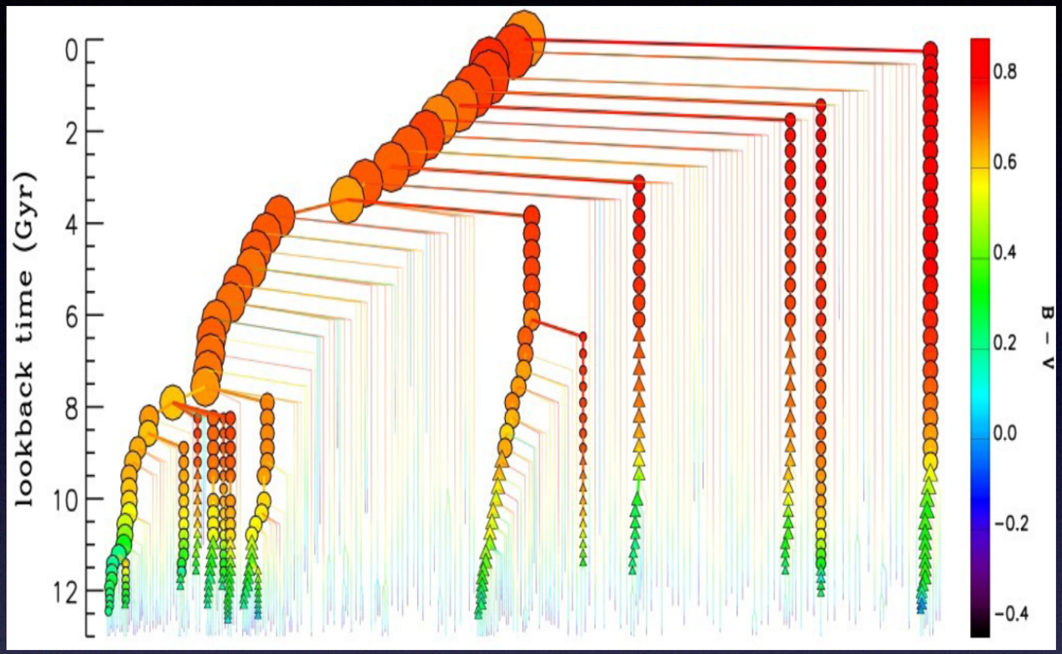


Figure from De Lucia & Blaizot 2007

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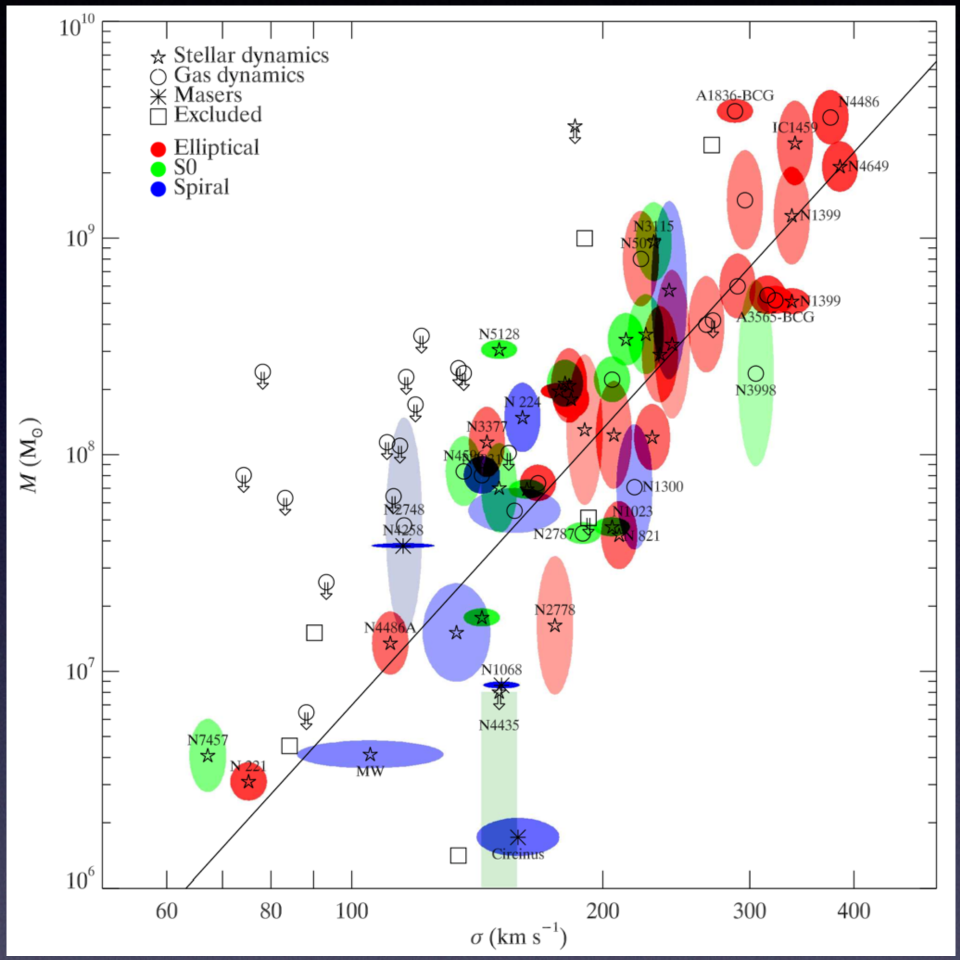
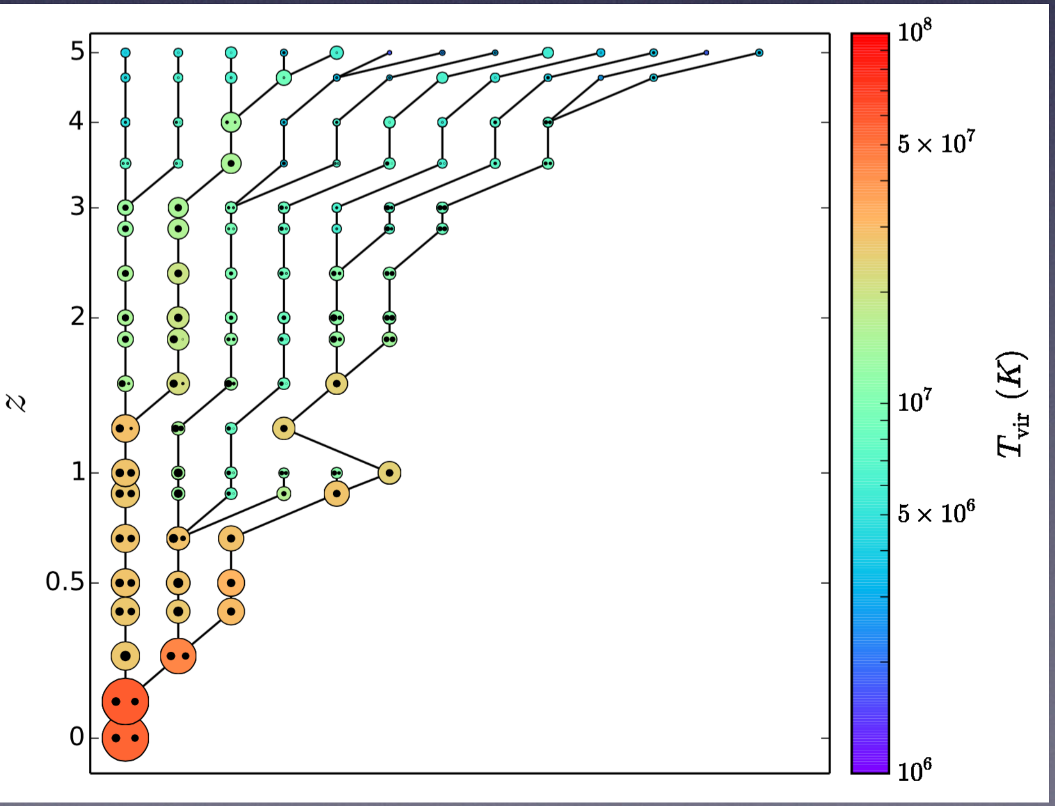


Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

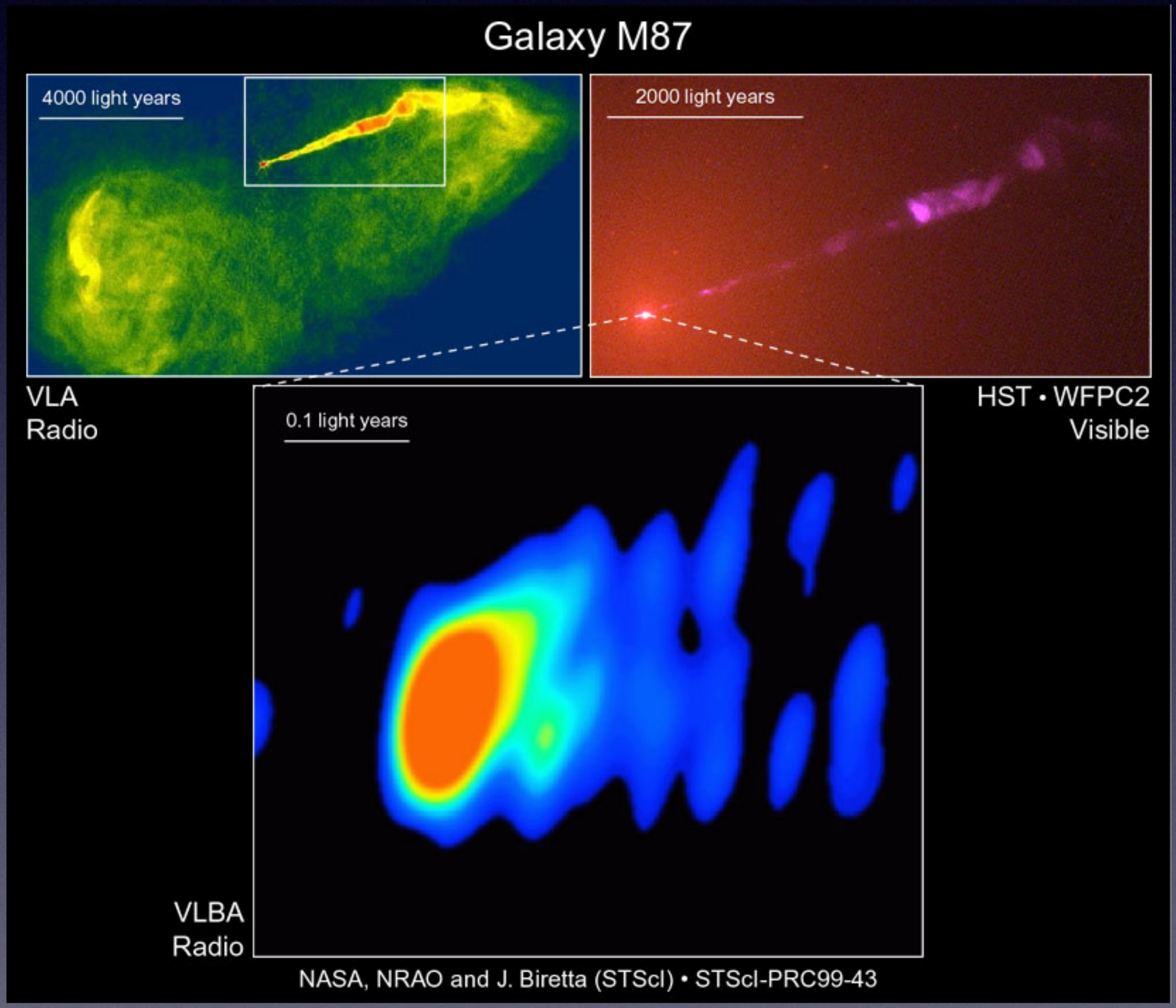
=

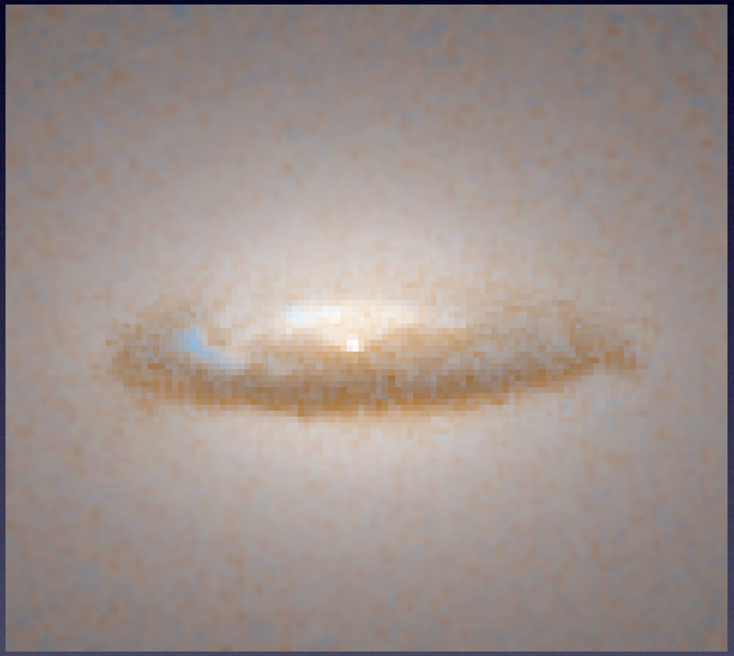


EB 2012
Figure credits: Lucy Ward

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



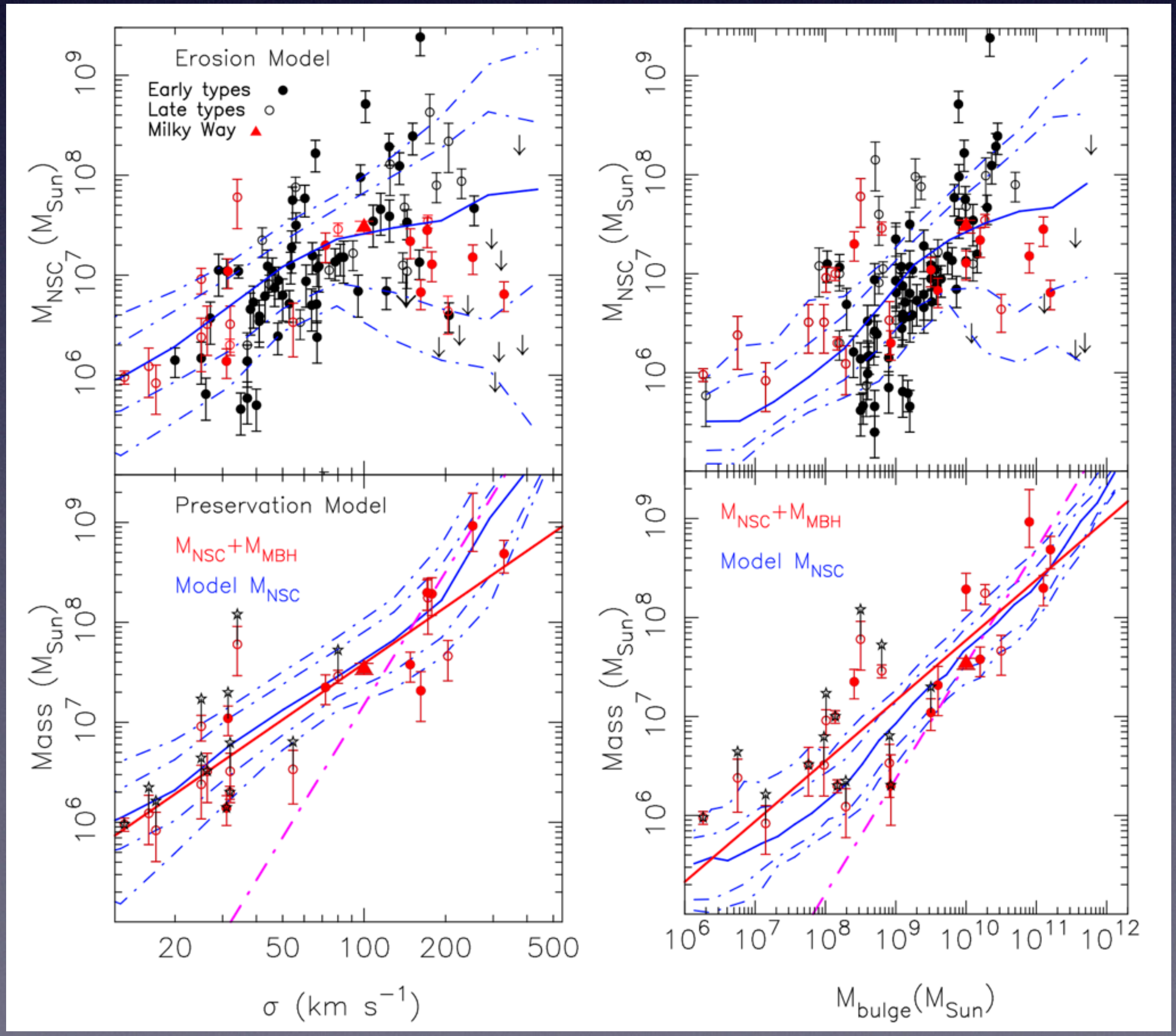


Disk of dust and gas around the massive BH in NGC 7052

- 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

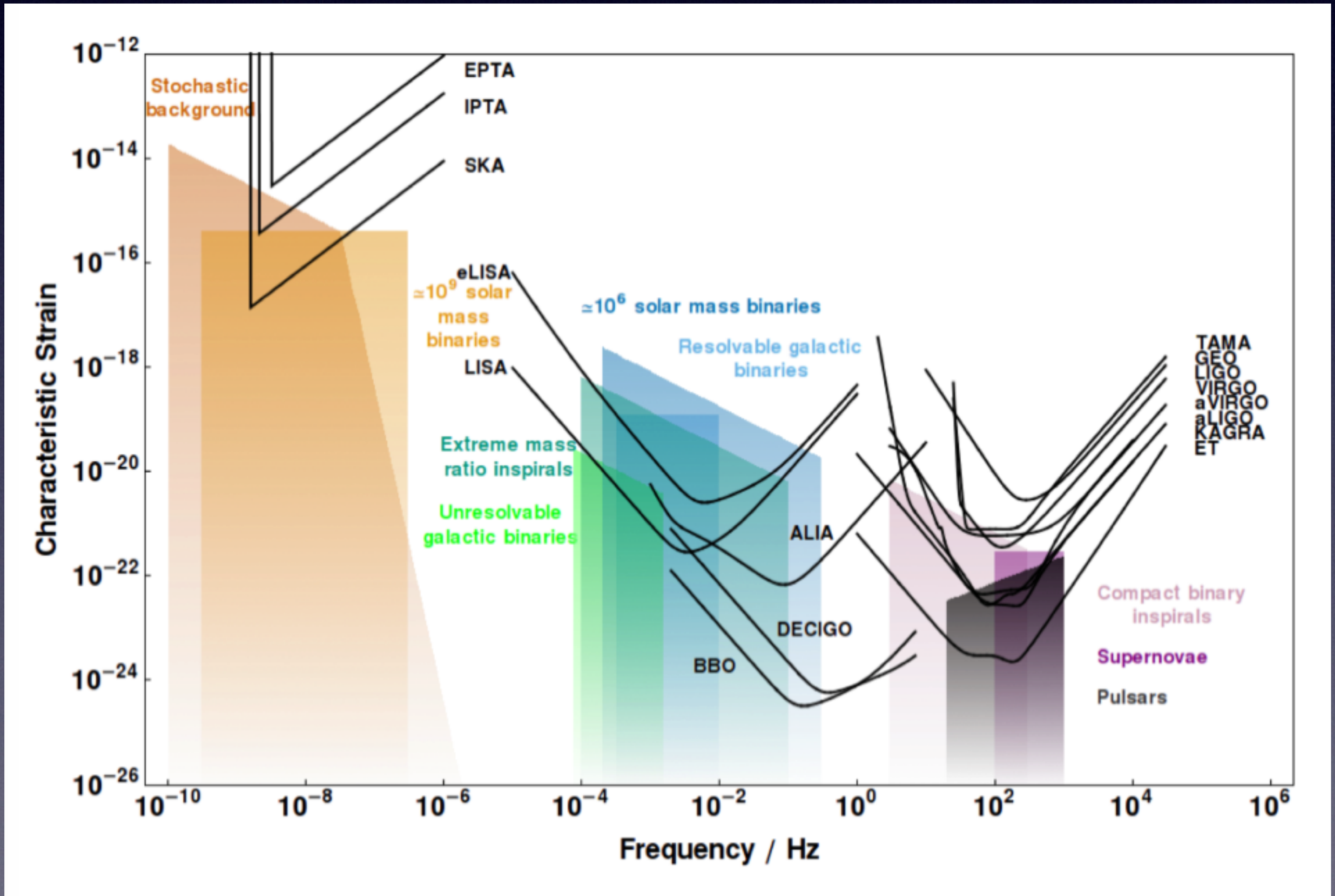


$$M_{\rm ej} \approx 0.7 q^{0.2} M_{\rm bin} + 0.5 M_{\rm bin} \ln\left(\frac{a_{\rm h}}{a_{\rm gr}}\right) + 5 M_{\rm bin} \left(V_{\rm kick}/V_{\rm esc}\right)^{1.75},$$

Antonini, EB and Silk 2015a,b

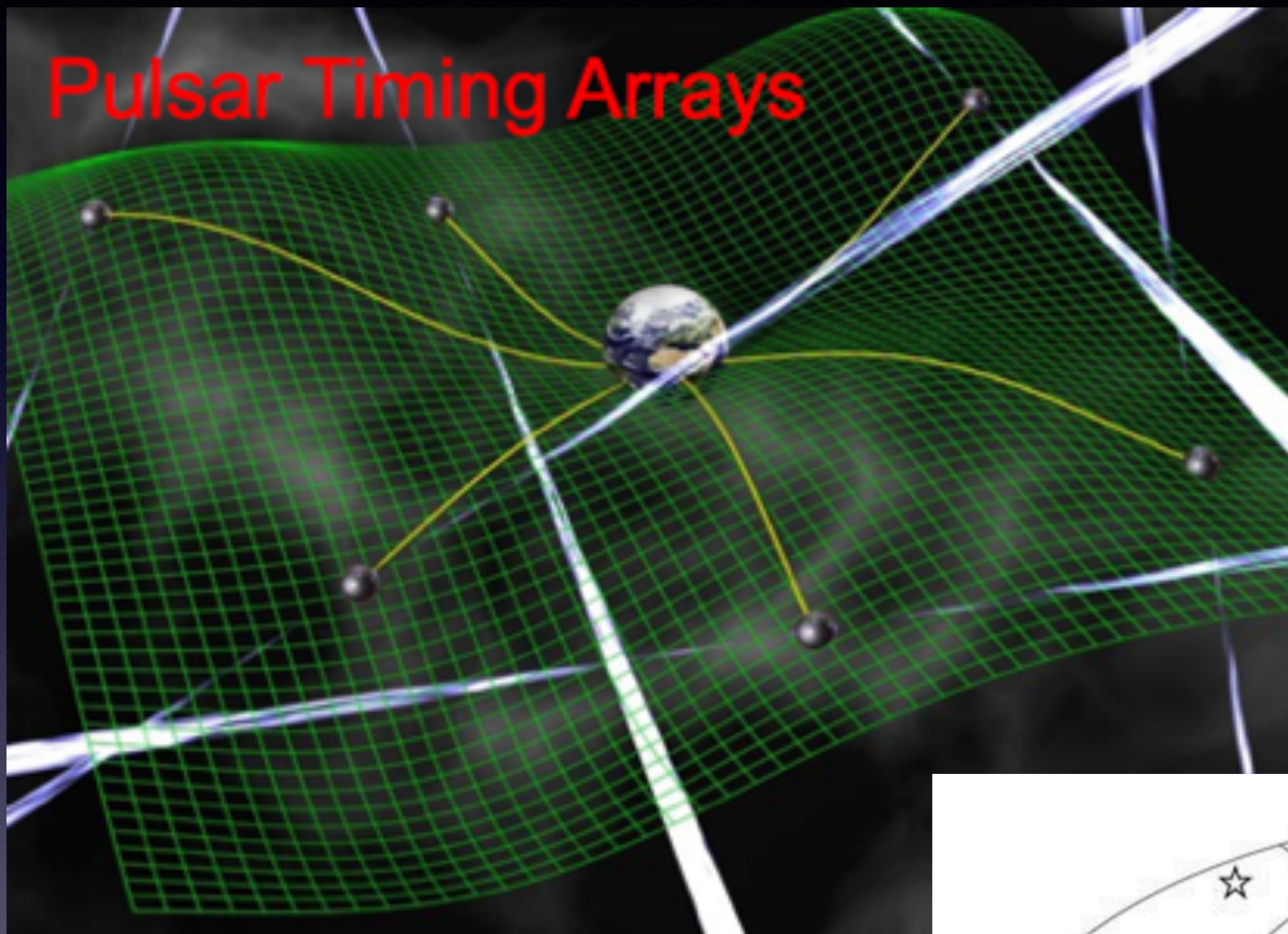
GWs from massive BHs

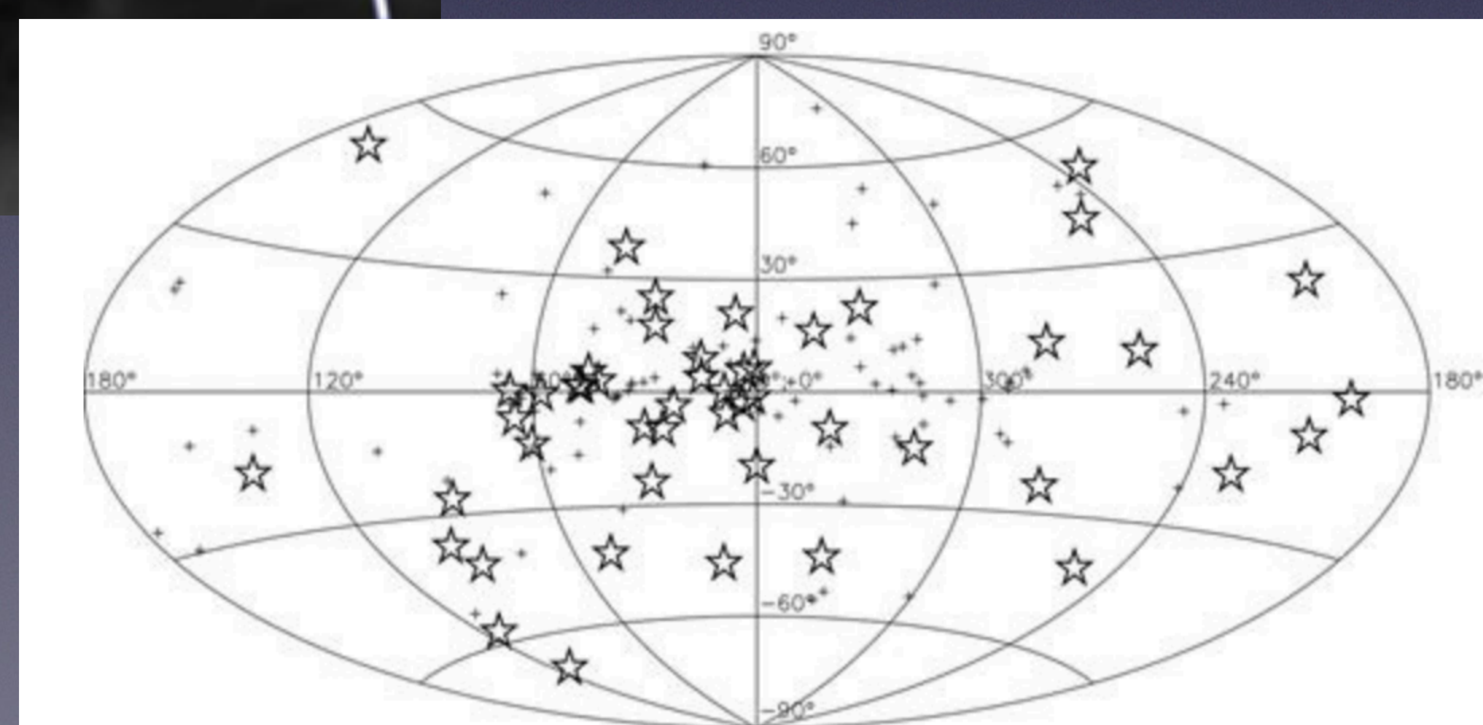
$$f_{\rm GW} = \frac{6 \times 10^4}{\tilde{m}\tilde{R}^{3/2}}\,\mathrm{Hz} \qquad \tilde{R} = R/(Gm/c^2), \quad \tilde{m} = m/M_\odot$$



Problem: terrestrial detectors blind at f ≲ 1-10 Hz (seismic noise)

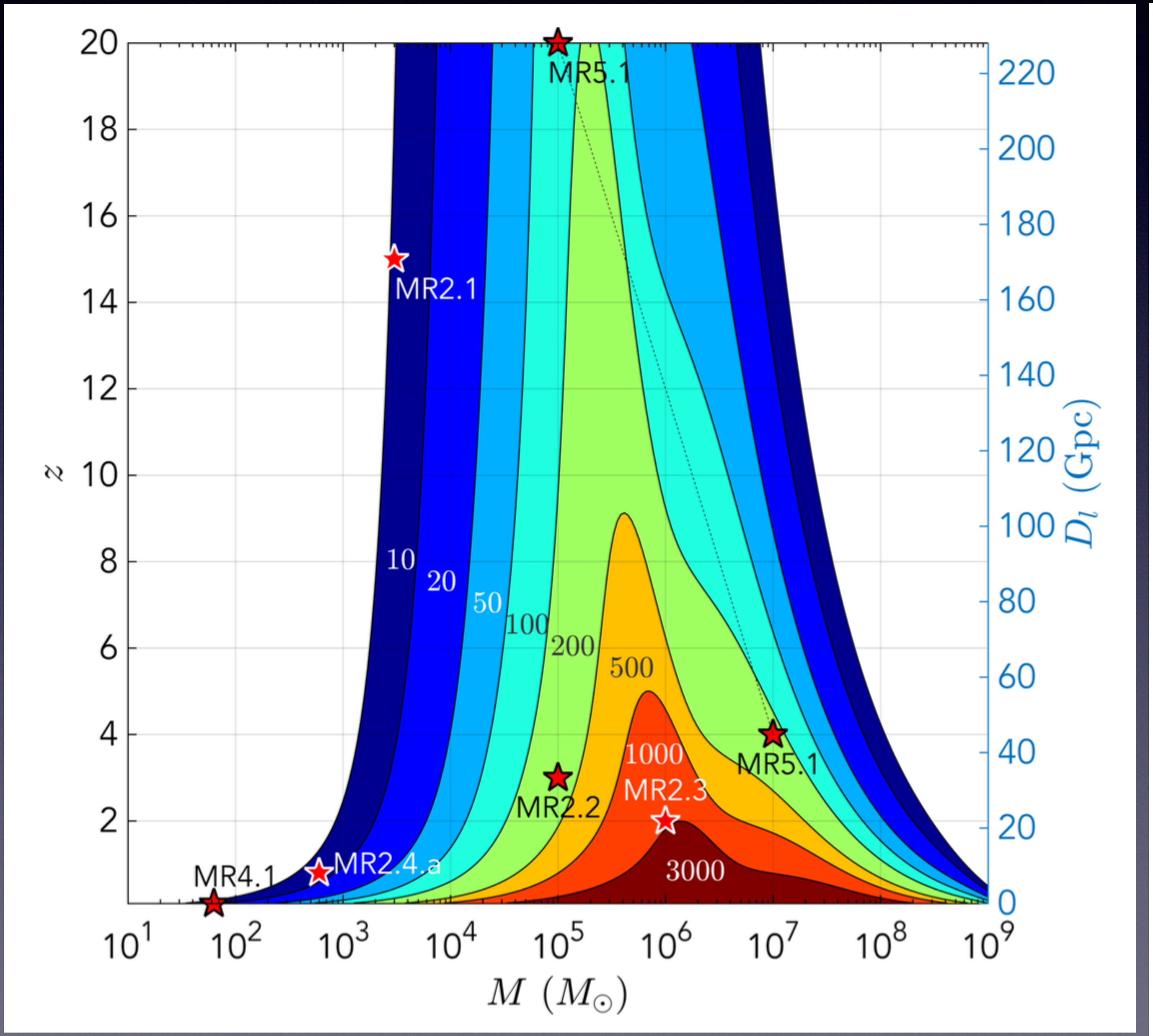
The space race!

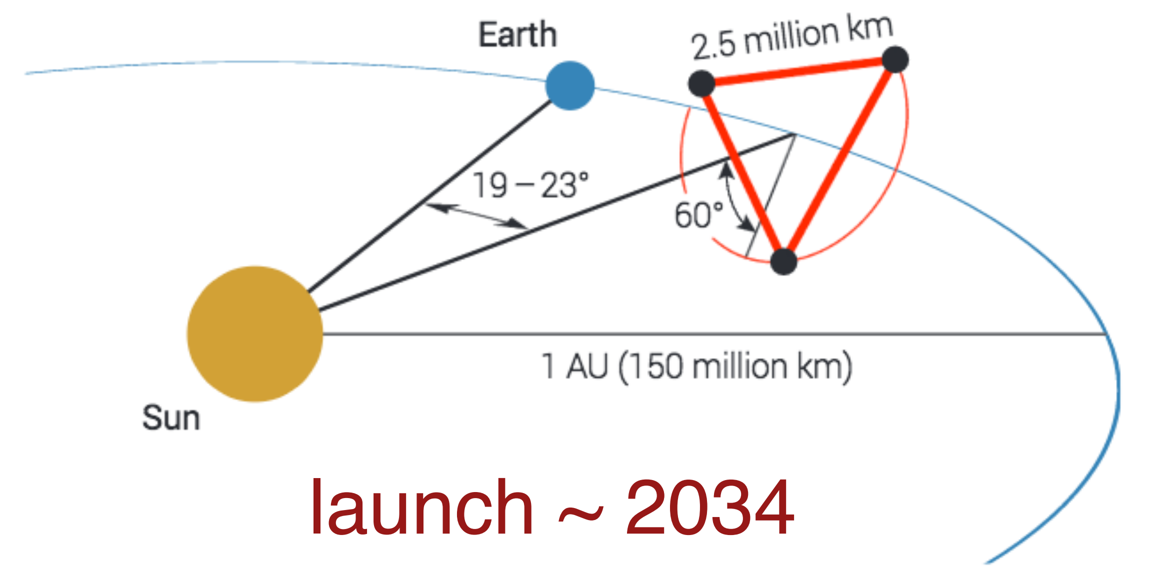




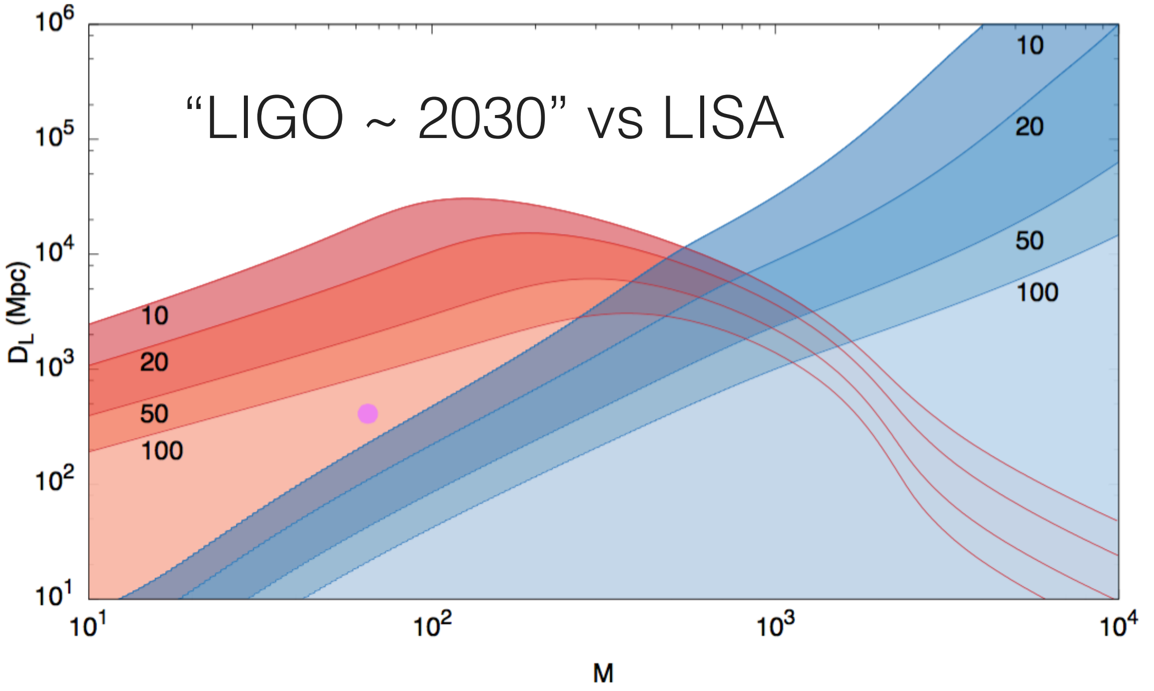
EPTA, Nanograv,
PPTA, GAIA…

Laser Interferometer Space Antenna (LISA)

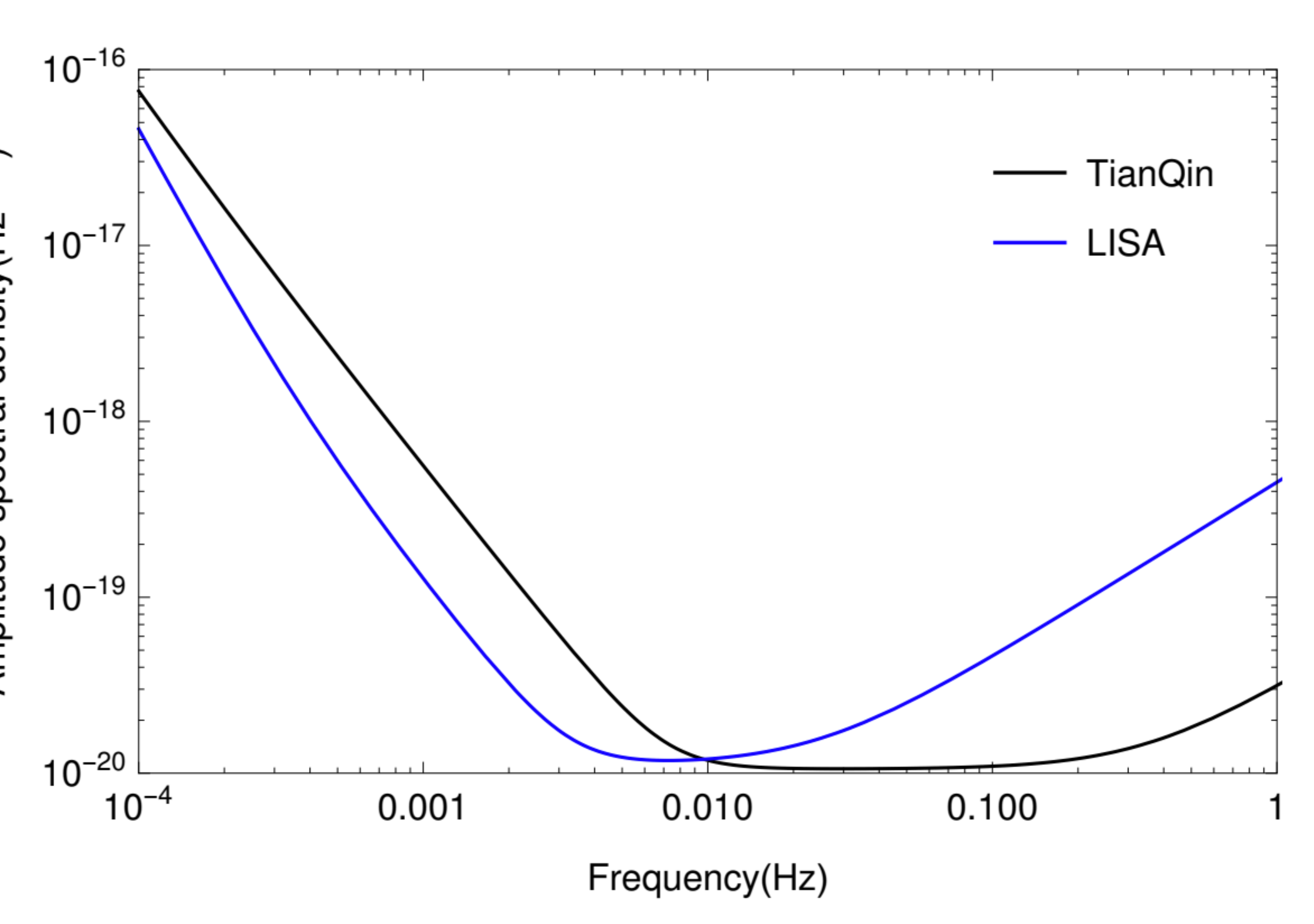


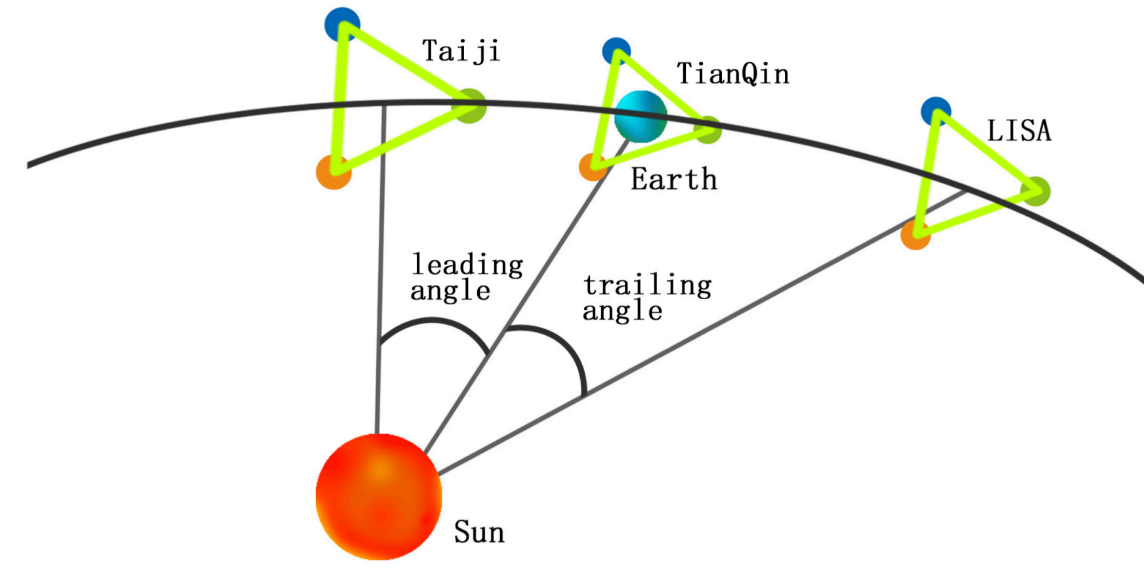


launch ~ 2034



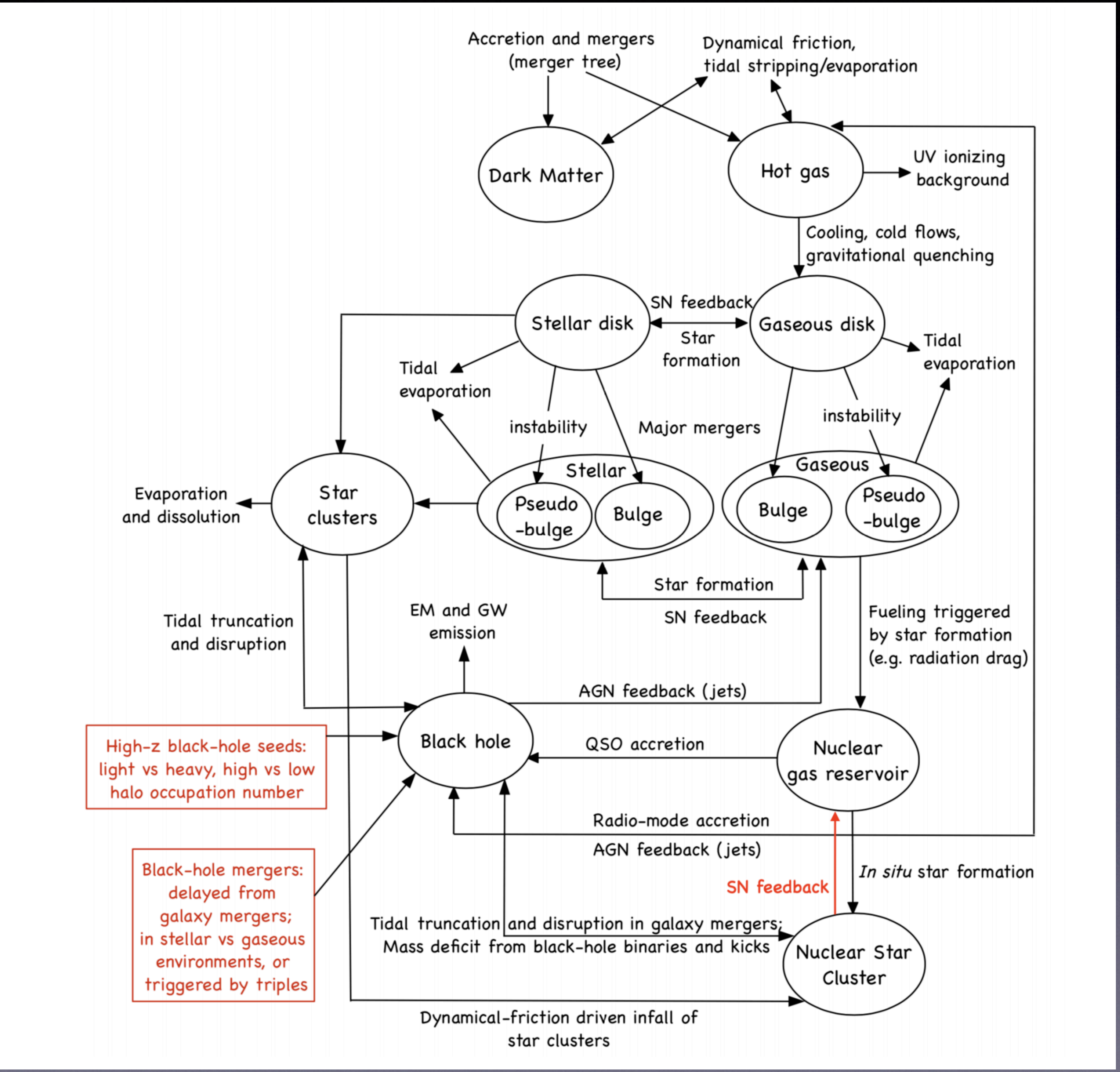
LISA vs TianQin





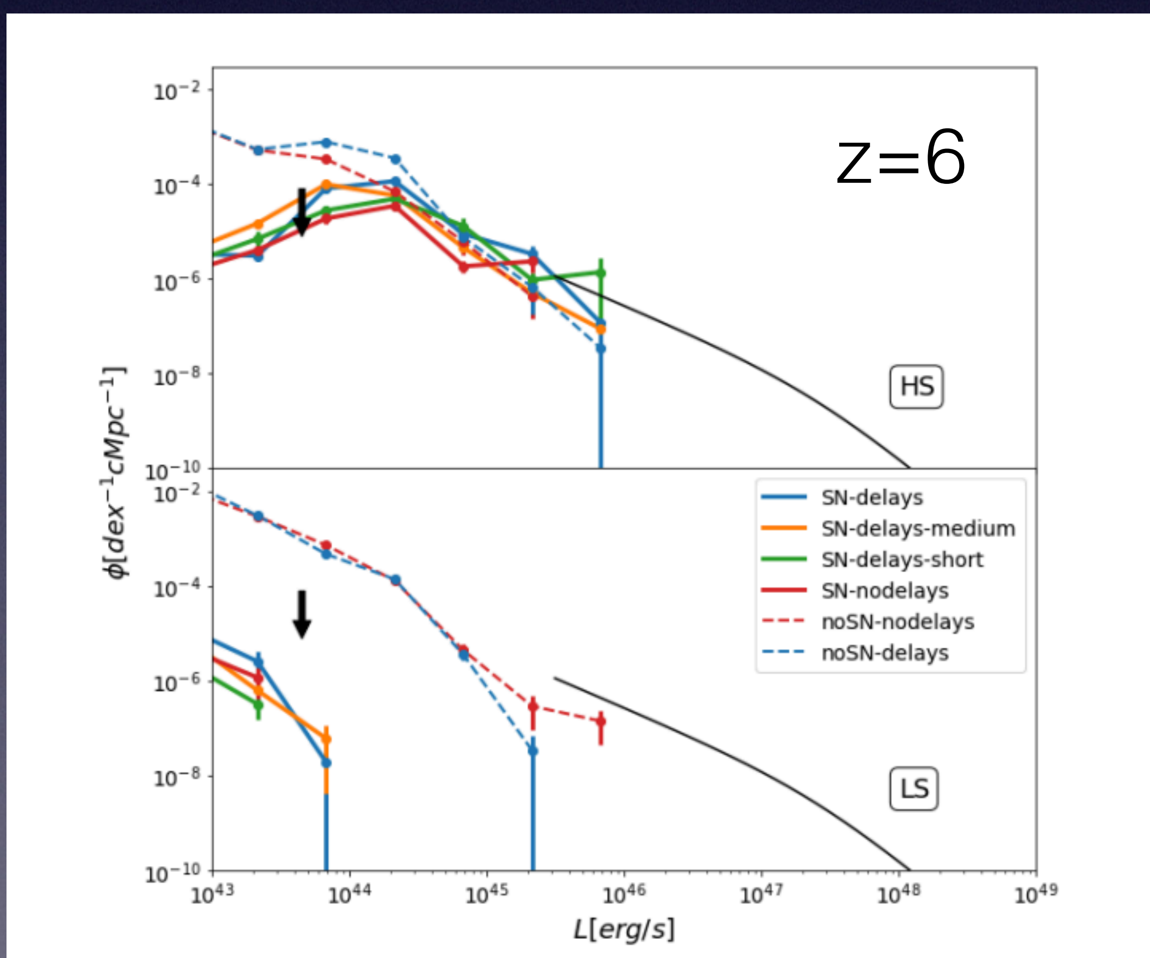
Sensitive to lower masses/IMBHs?
Network with ground based?

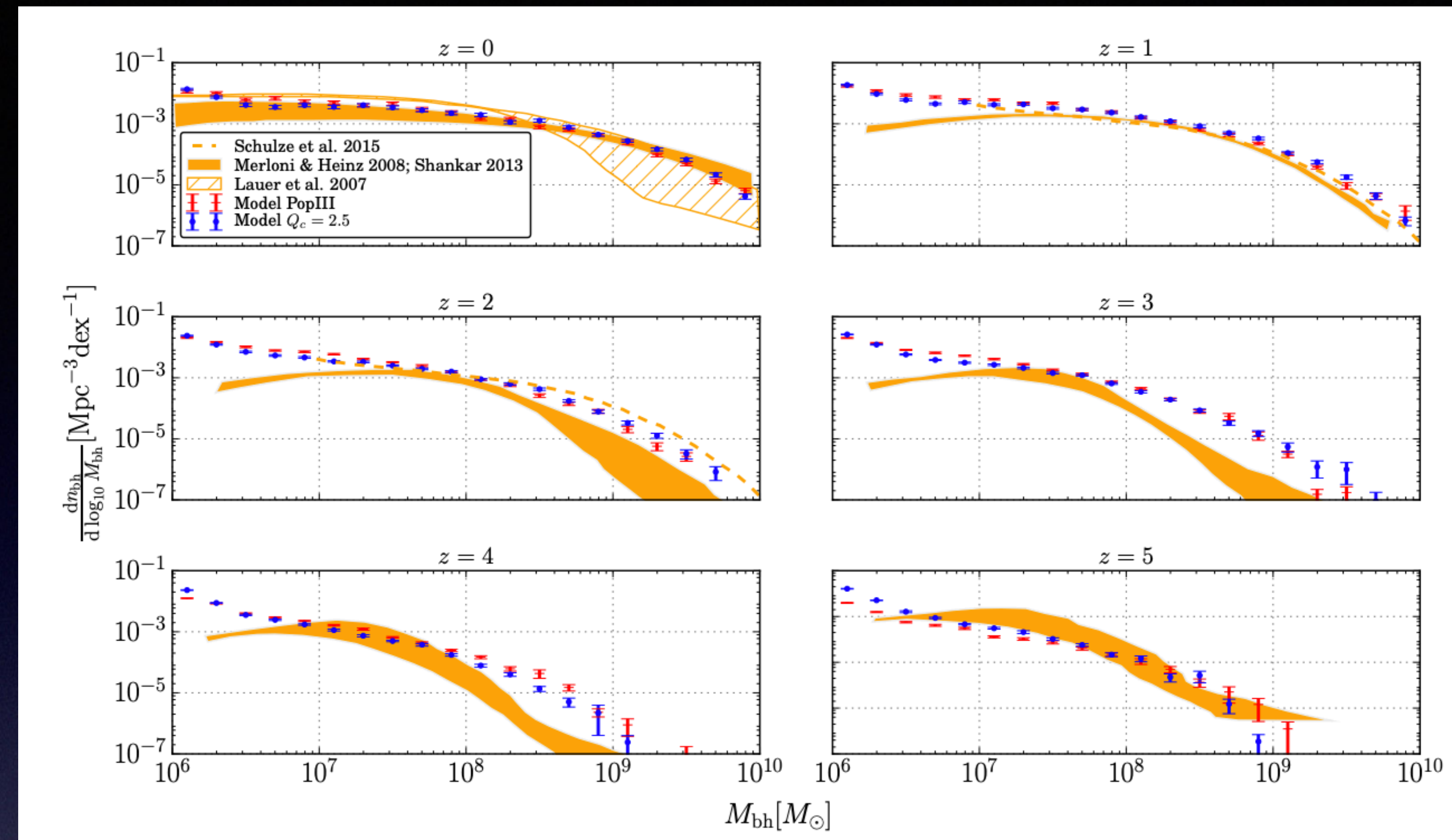
Galaxy/BH co-evolution

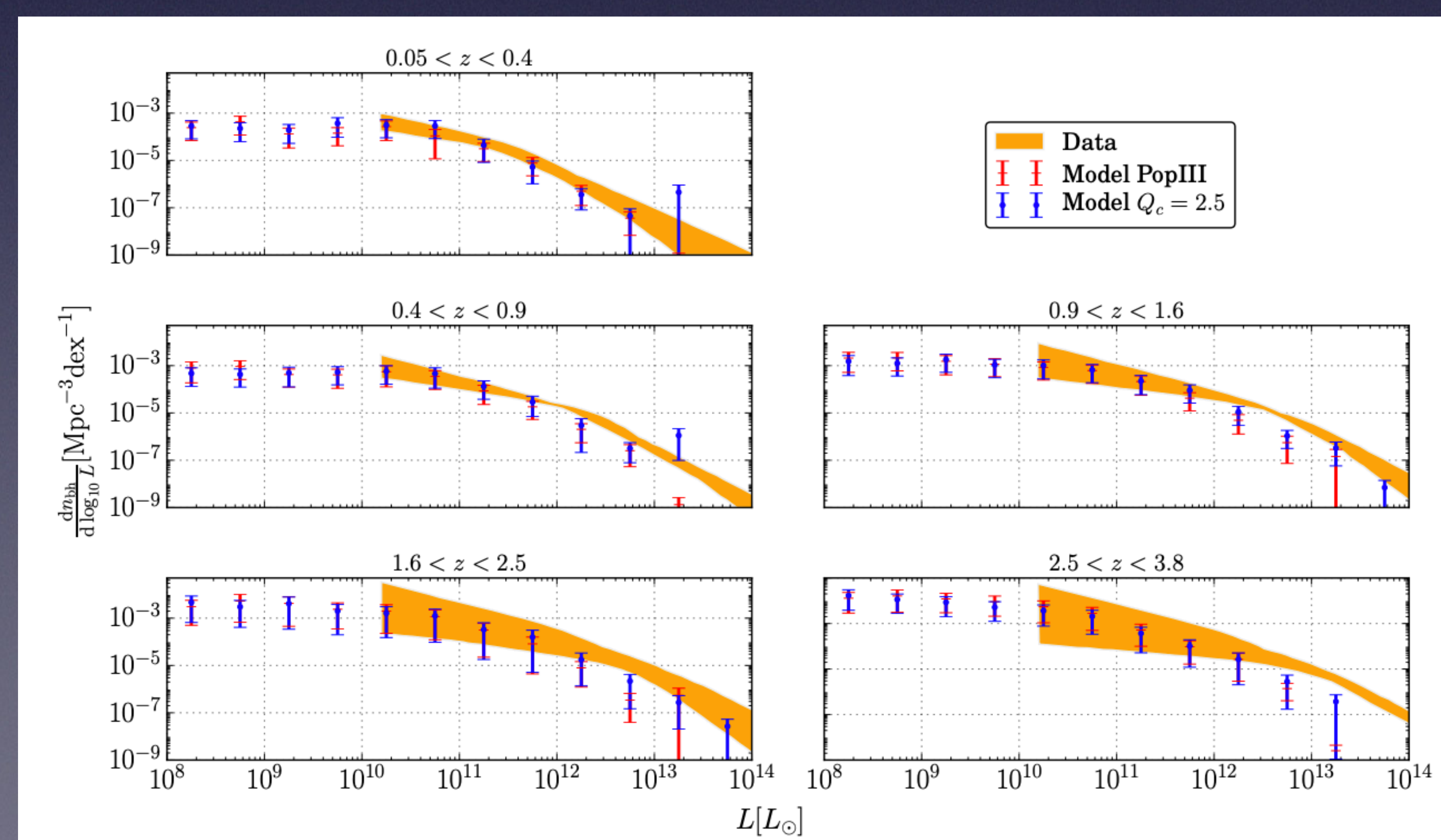


EB 2012, 2014, 2020…

Calibration to EM

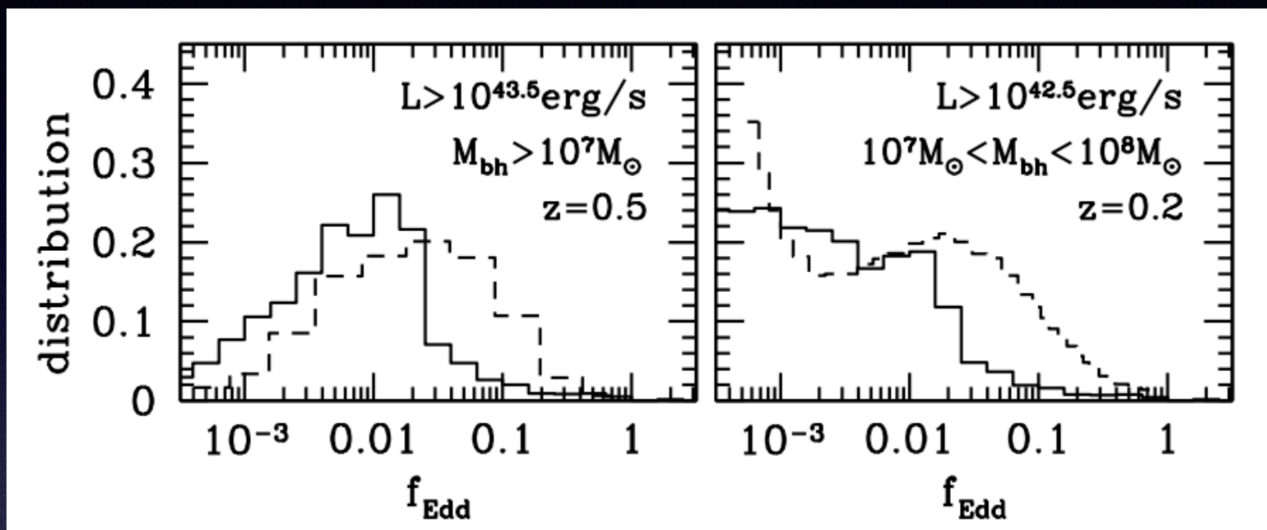


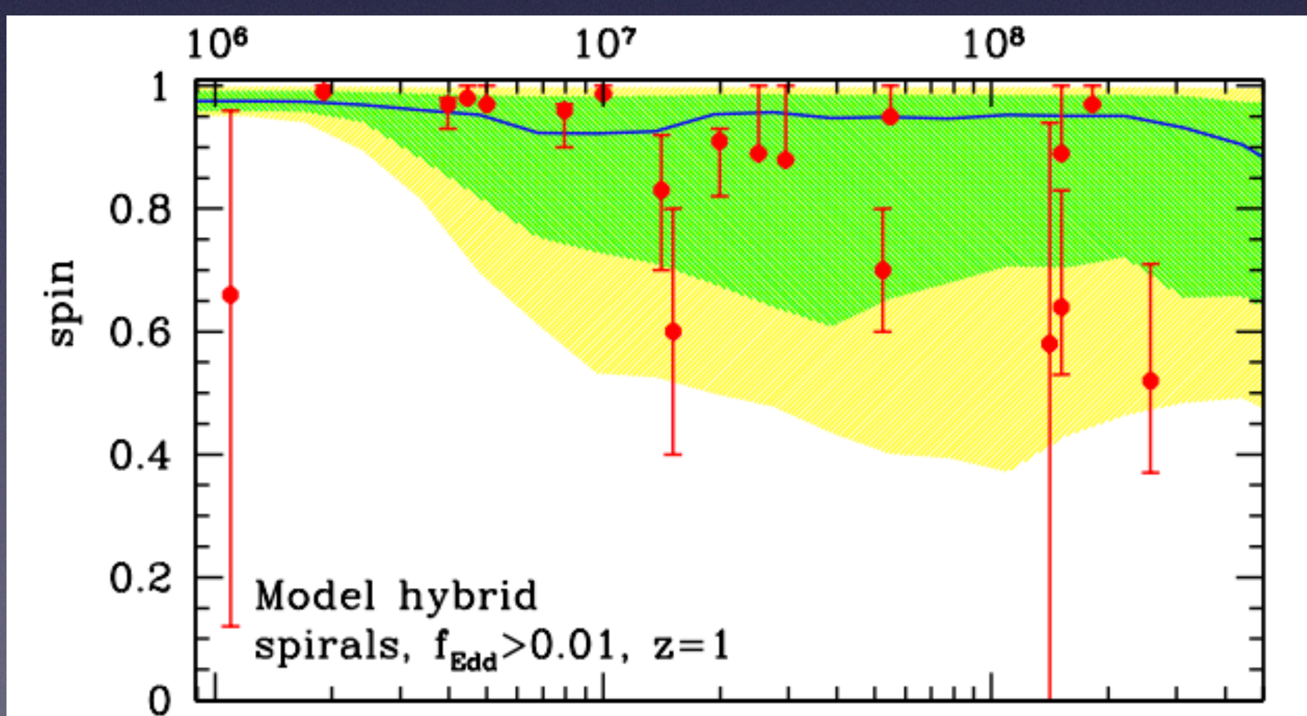


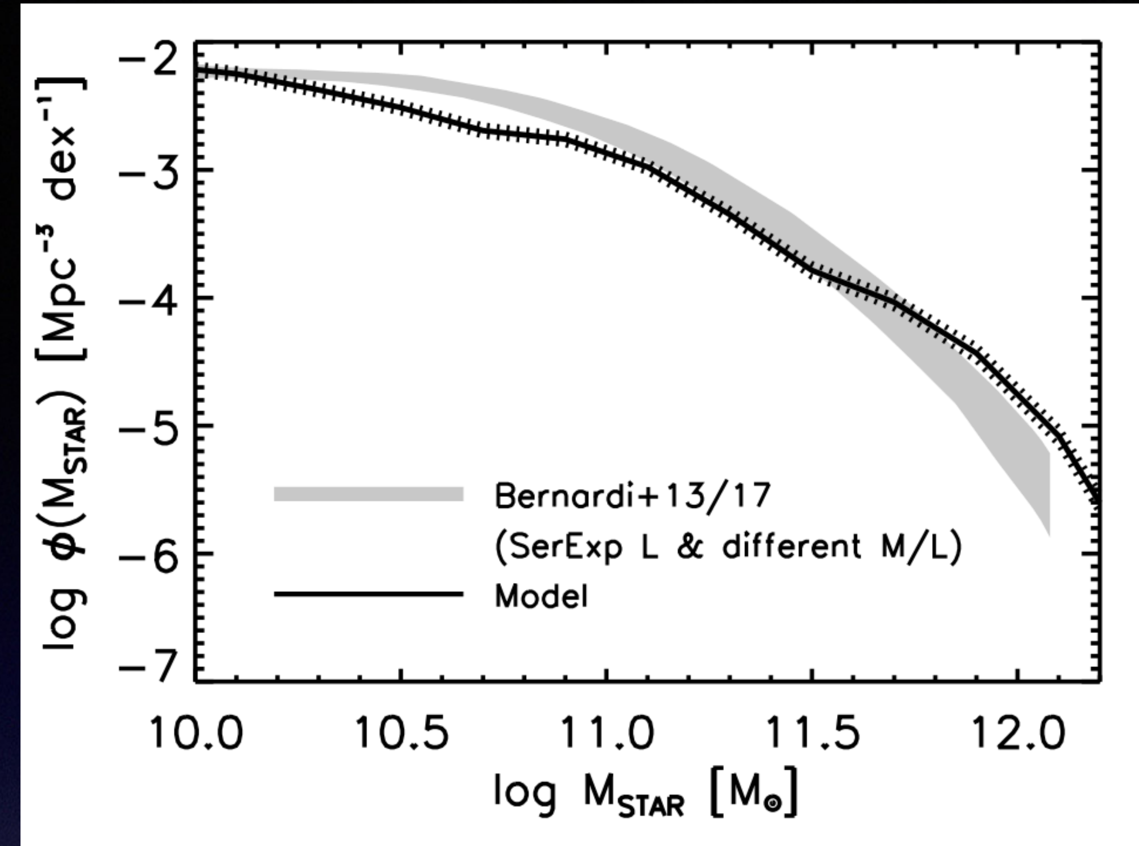


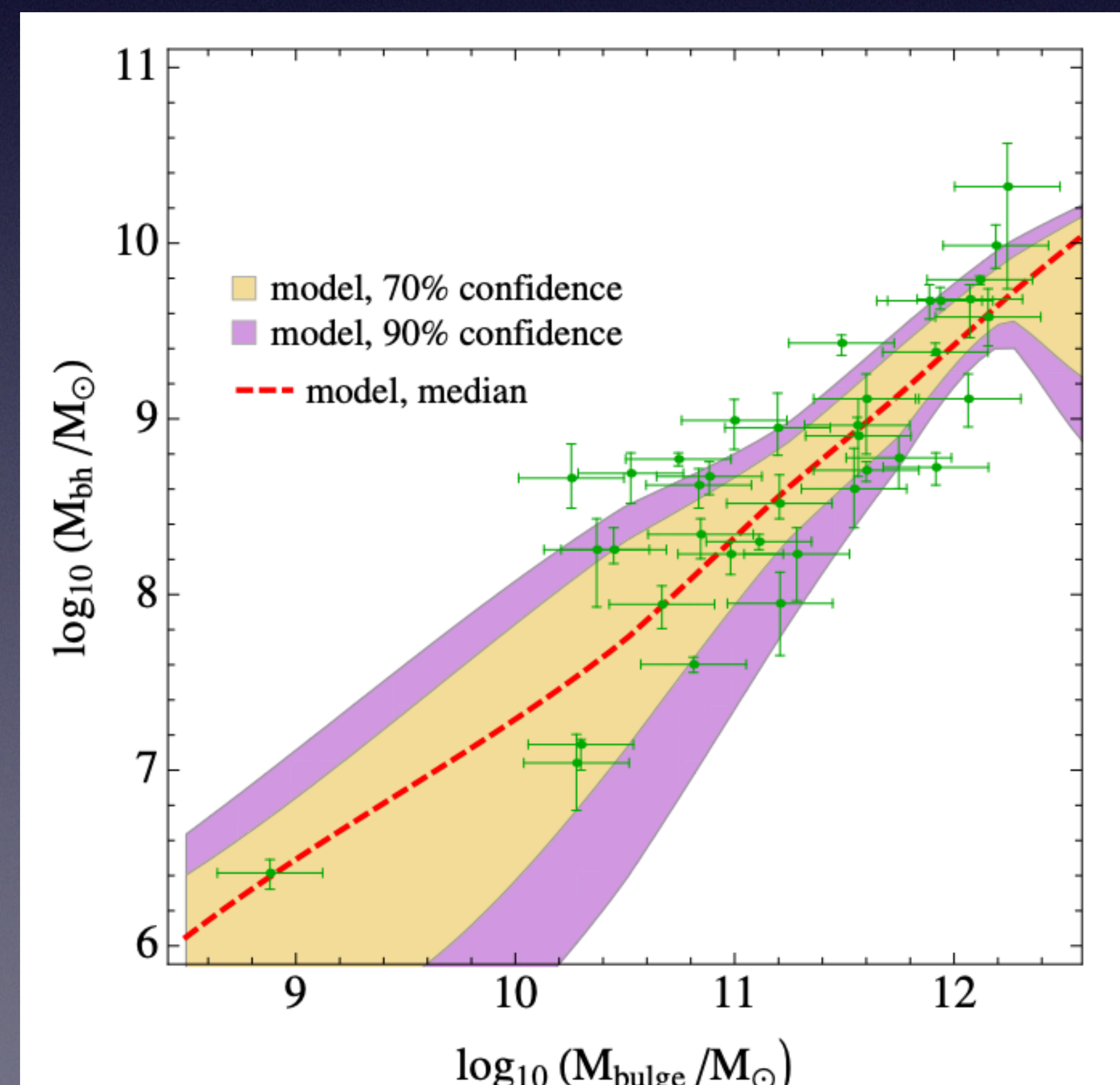
EB+ 2012, 2014, 2020…

Calibration to EM









EB+ 2012, 2014, 2020…

How big are baby black holes?

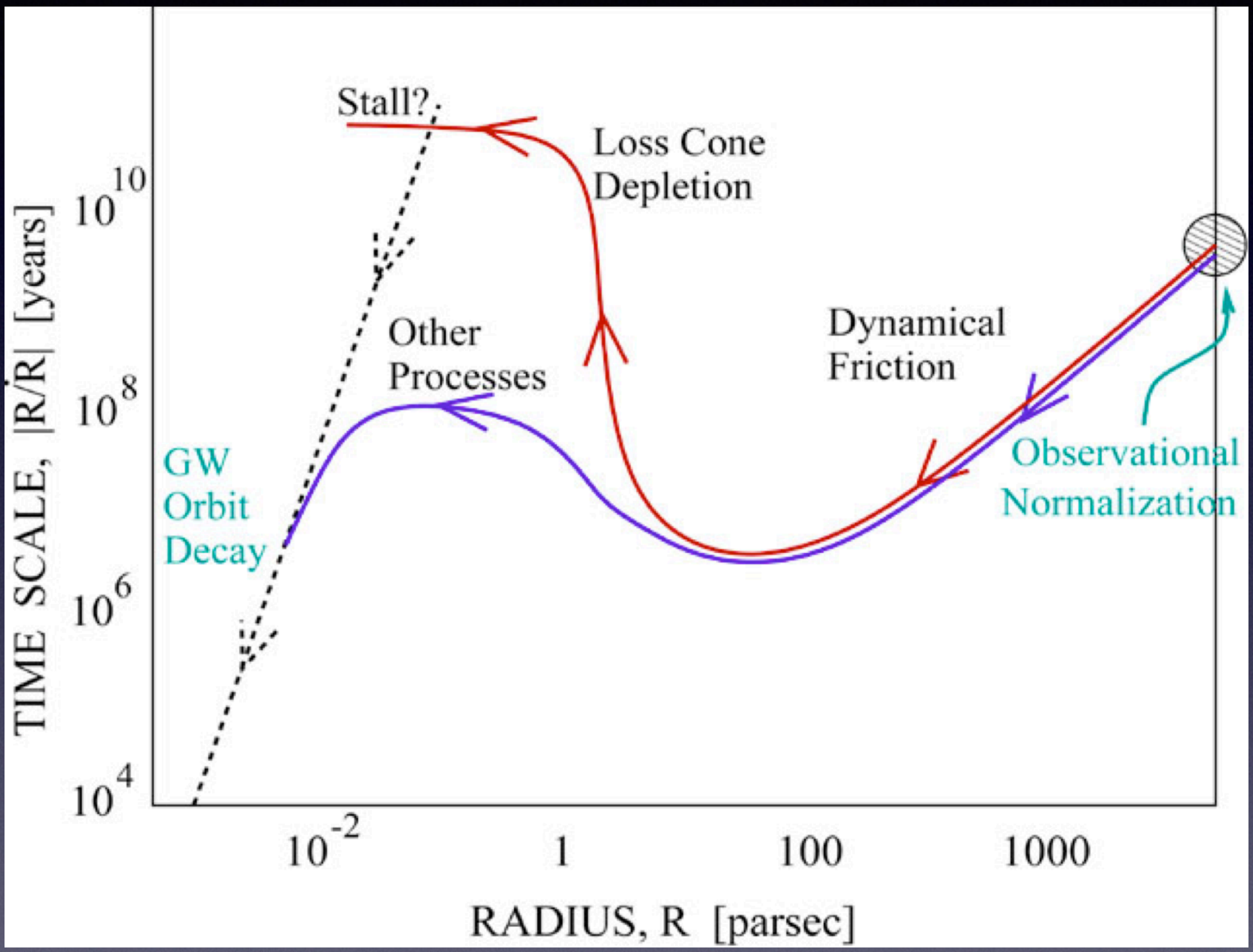
vs

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

Heavy seeds (~10^5 M_{sun}) from 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); IMBHs?

The "final pc problem"



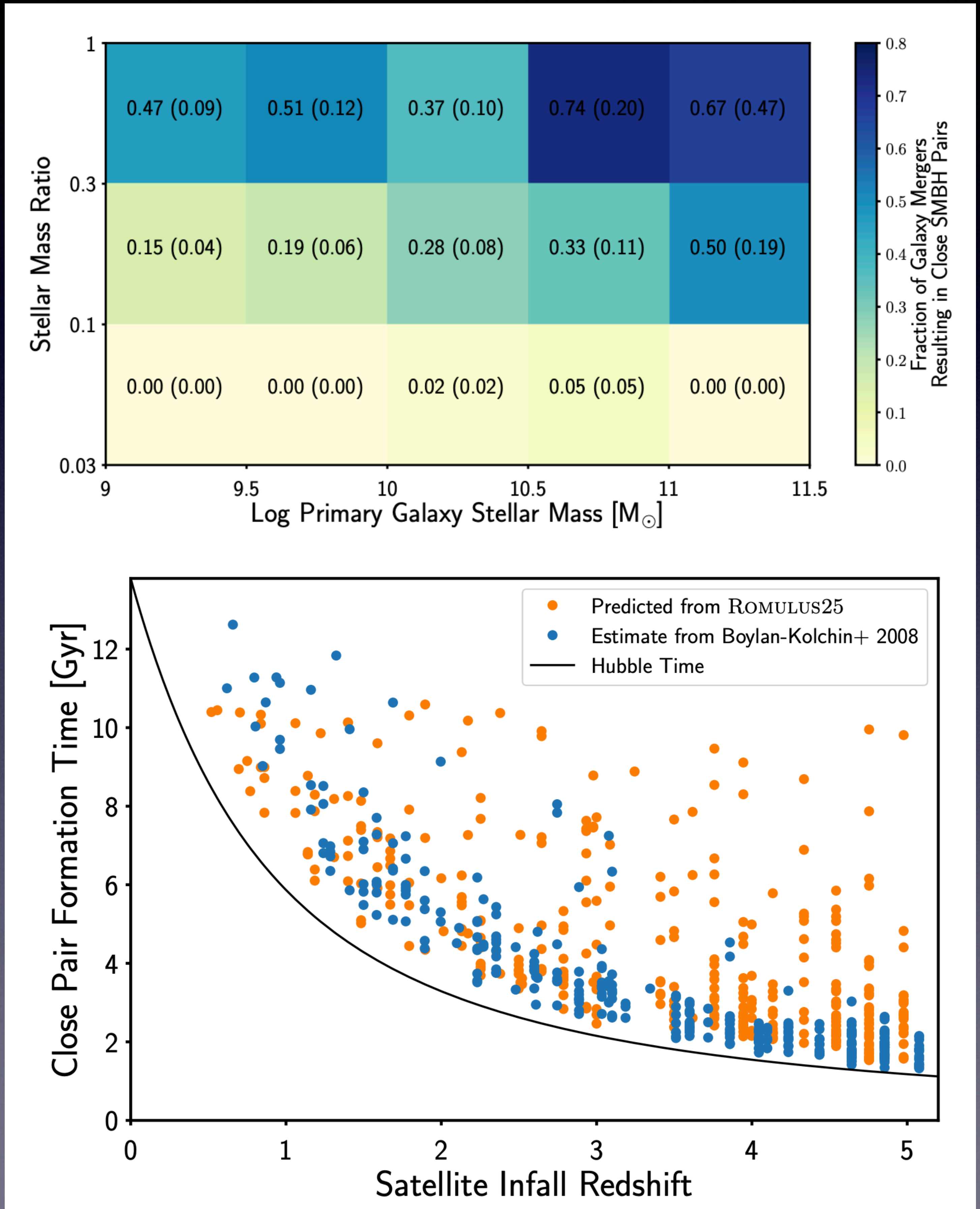
Begelman, Blandford & Rees 1980

Delays between halo and BH mergers

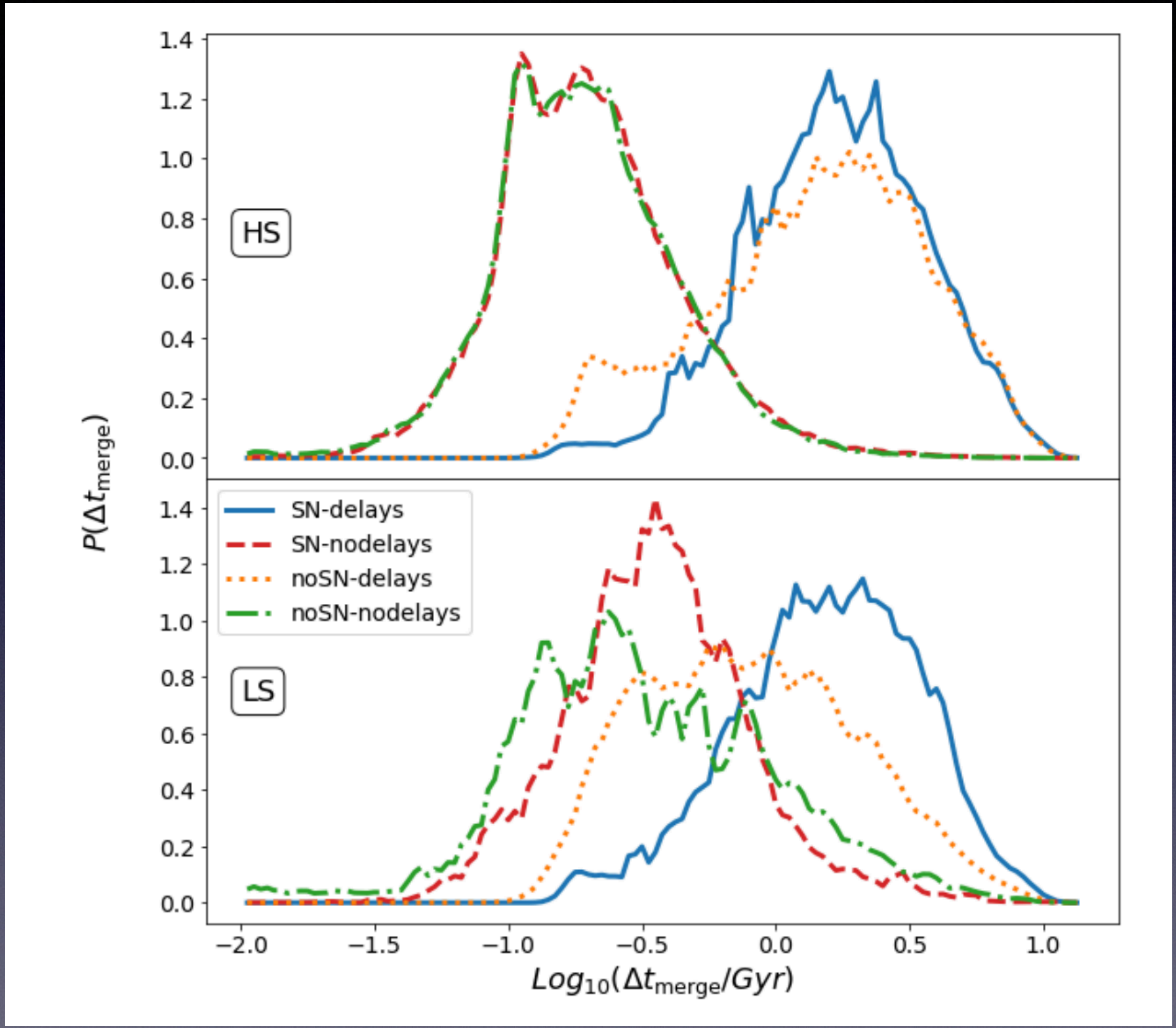
- Halo-halo dynamical friction+tidal disruption/evaporation
- From kpc to tens of pc: galaxy-galaxy dynamical friction/tidal disruption; BH-galaxy dynamical friction
- 3-body interactions with stars on timescales of 1-10 Gyr
- Gas-driven planetary-like migration on timescales ≳ 10 Myr
- Triple massive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

The importance of kpc-100pc delays

- Normally assumed to be small compared to halo-halo dynamical friction
- Large scale simulations (Tremmel+2018) suggest that “the formation of a close SMBH pair is not a common result of galaxy mergers”



Delays between galaxy and MBH mergers

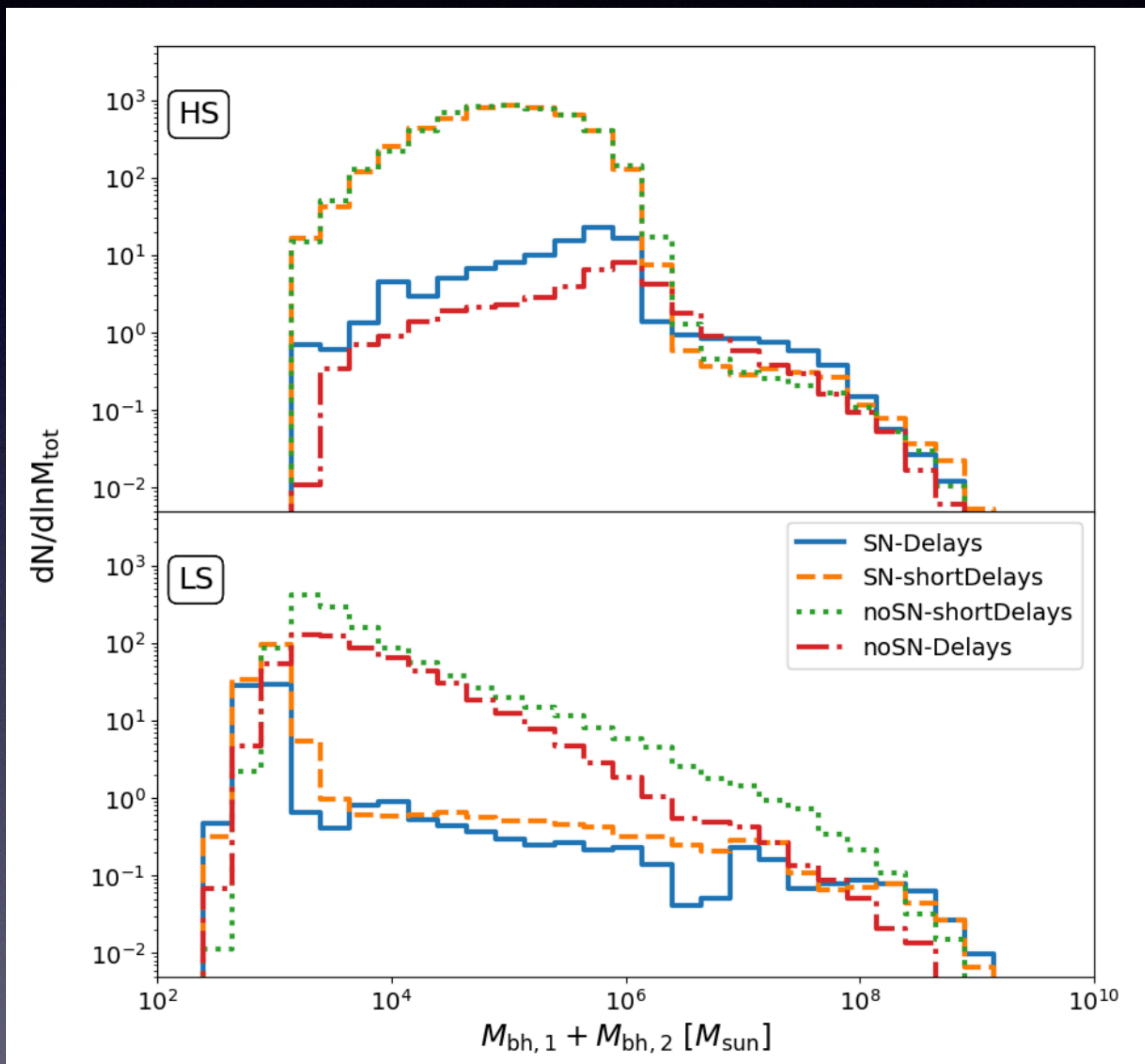


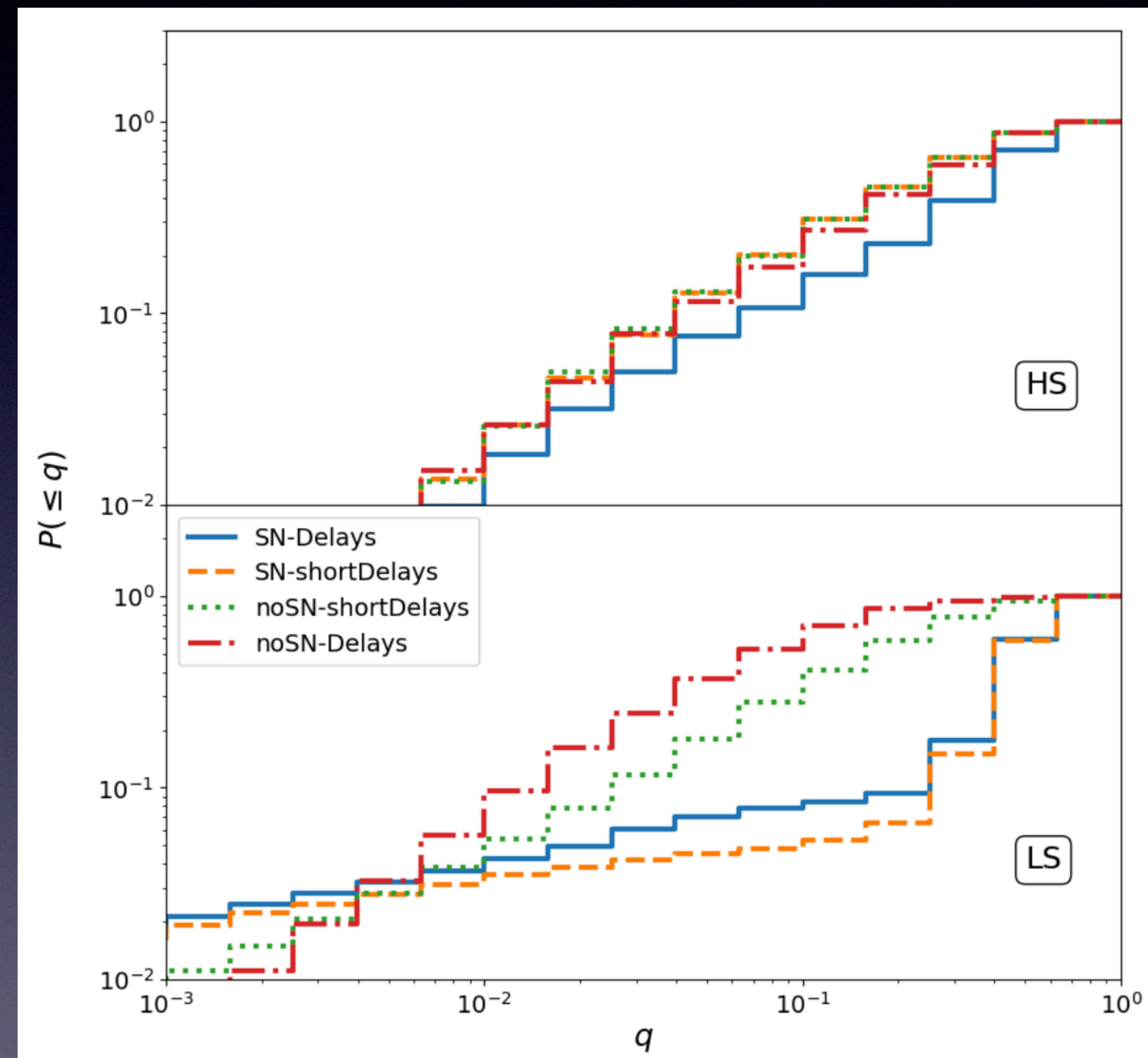
For detected systems only (LISA)

SN winds

- SN feedback may stunt MBH growth in low-mass galaxies, where velocity of SN winds (~200-300 km/s) exceeds escape velocity
- Evidence from hydro simulations (Habouzit+2017), but effect depends on feedback sub grid physics/ implementation

Effect of SN winds/more realistic delays

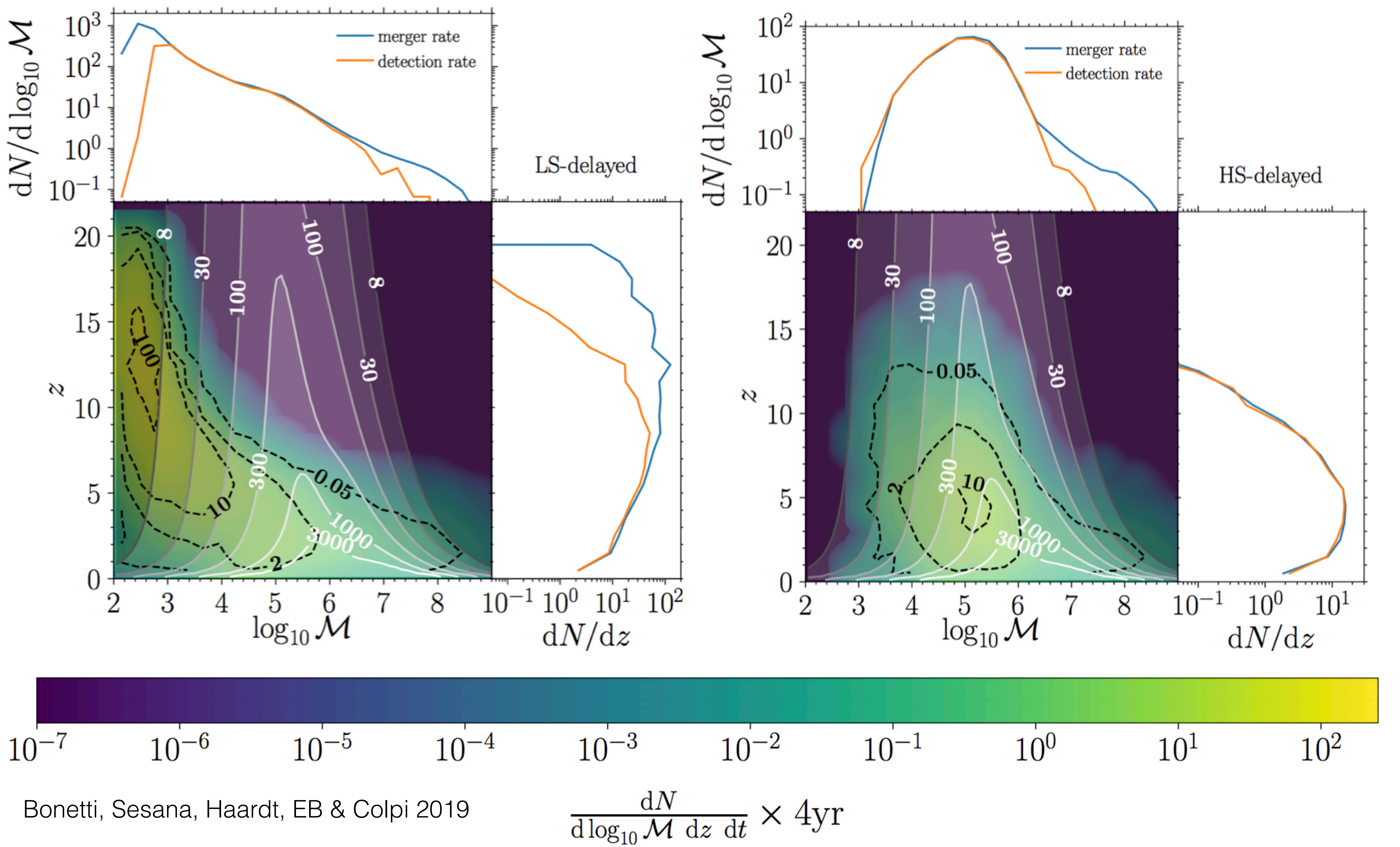




EB+2020

For detected systems only (LISA)

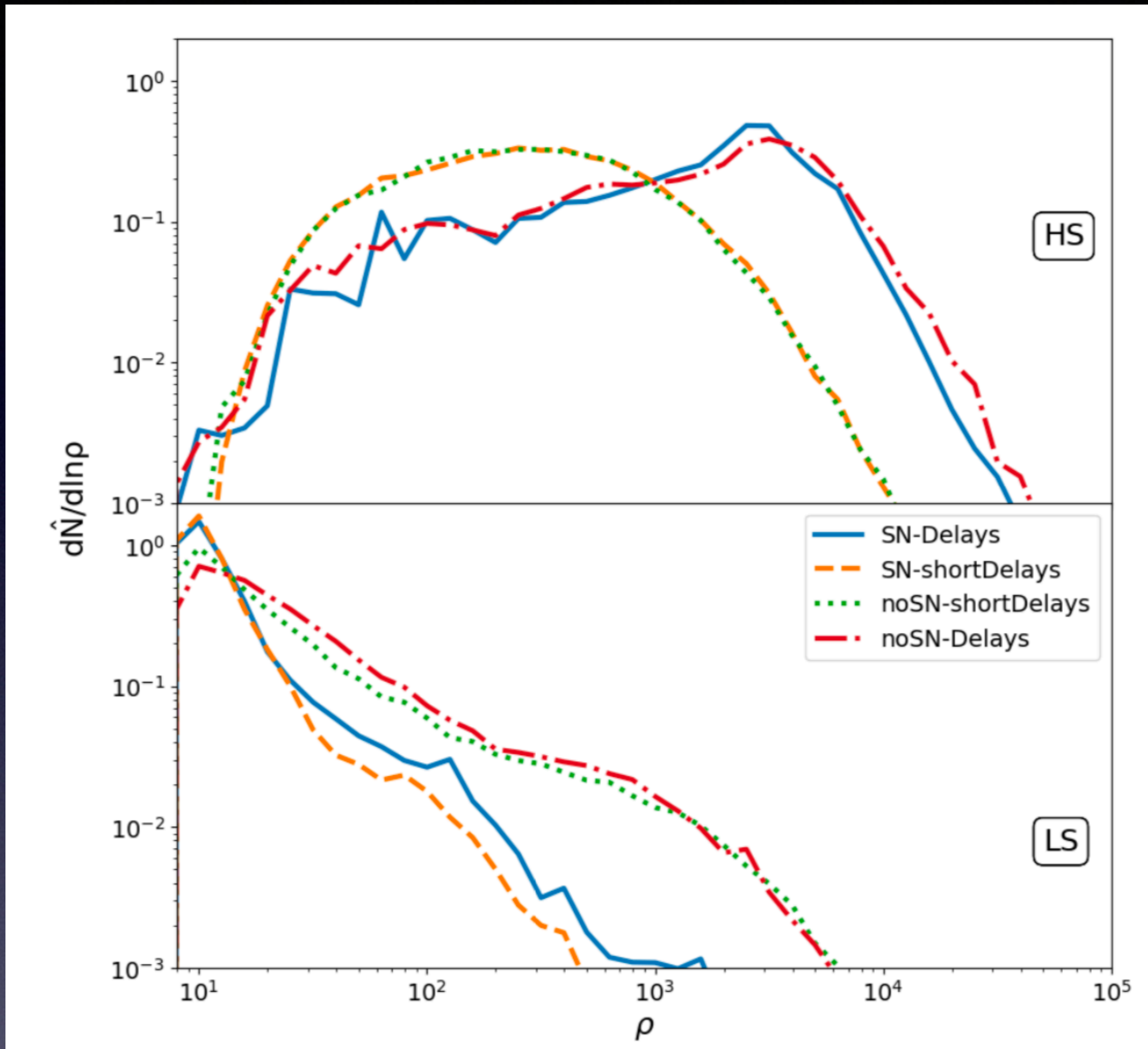
Detection rates (LISA)

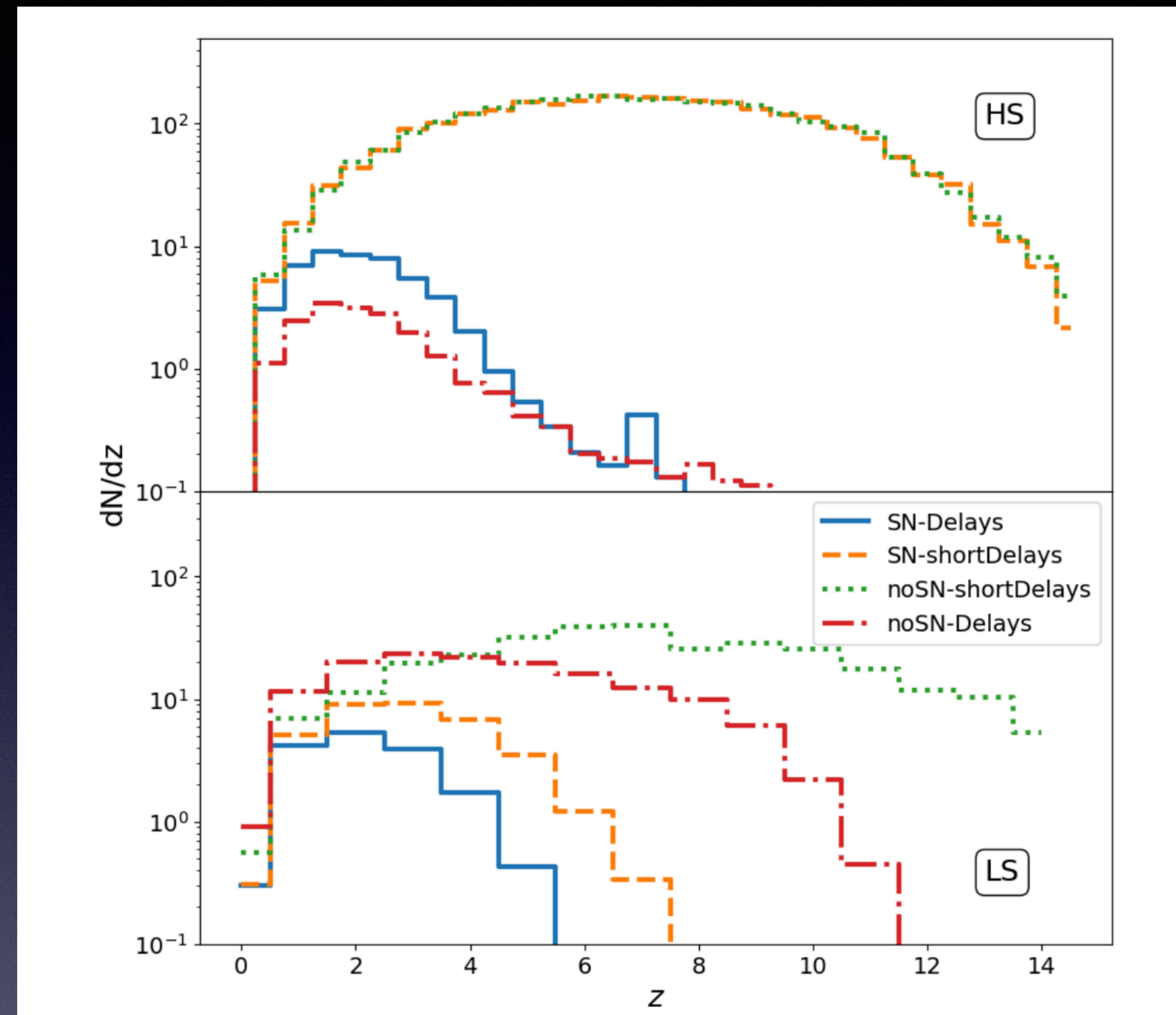


Bonetti, Sesana, Haardt, EB & Colpi 2019

“short delays” (no kpc-to-100 pc delays), no SN winds

Detectability (LISA) with SN winds & delays





EB+2020

Model	LS		HS	
	Total	Detected	Total	Detected
SN feedback				
SN-Delays	48	16	25	25
SN-shortDelays	178	36	1269	1269
No SN feedback				
noSN-Delays	192	146	10	10
noSN-shortDelays	1159	307	1288	1288

LISA vs TianQin

Need to compare apples to apples (ie same astro model)

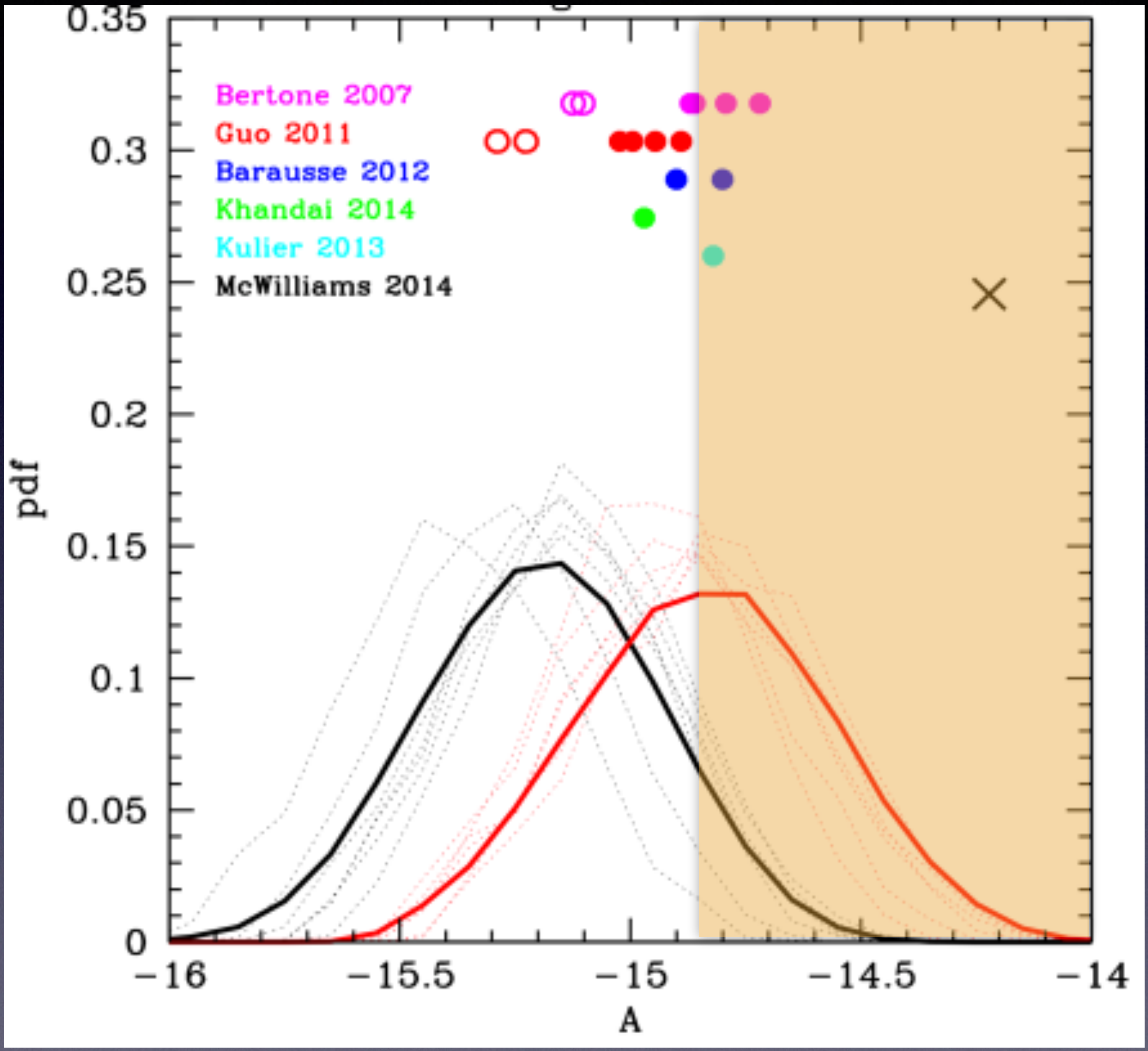
Klein+16

Config ID	SUA (IMR)						restricted 2PN					
	popIII		Q3-nod		Q3-d		popIII		Q3-nod		Q3-d	
	all	$z>7$	all	$z>7$	all	$z>7$	all	$z>7$	all	$z>7$	all	$z>7$
N2A5M5L6	659.7(660.4)	401.1(401.1)	595.6(611.8)	342.6(358.0)	40.4(40.8)	3.6(3.6)	665.8	402.7	610.2	357.0	40.4	3.6
N2A5M5L4	510.7(511.8)	277.5(277.5)	555.6(608.7)	306.4(355.0)	40.2(40.8)	3.4(3.6)	507.6	278.5	602.4	349.8	40.4	3.6
N2A2M5L6	356.8(357.9)	160.1(160.1)	558.8(609.4)	307.6(355.9)	40.2(40.8)	3.6(3.6)	359.3	162.6	593.8	341.8	40.4	3.6
N2A2M5L4	233.1(235.0)	78.8(78.8)	495.9(598.1)	253.2(346.1)	39.8(40.8)	3.4(3.6)	223.4	76.8	557.5	309.6	39.9	3.6
N2A1M5L6	157.6(159.5)	34.9(34.9)	498.1(602.9)	251.6(350.0)	39.1(40.8)	3.1(3.6)	152.4	34.6	570.5	320.0	40.4	3.6
N2A1M5L4	97.2(99.9)	16.4(16.4)	417.9(574.1)	186.8(327.5)	37.9(40.6)	2.8(3.4)	96.3	14.9	519.1	278.2	39.1	3.3
N1A5M5L6	246.6(249.3)	86.8(86.8)	416.2(598.3)	177.5(345.5)	37.5(40.8)	2.5(3.6)	245.9	87.0	533.0	283.9	39.9	3.6
N1A5M5L4	153.9(158.7)	36.1(36.1)	342.9(565.4)	125.6(317.7)	33.7(40.7)	2.0(3.5)	149.1	35.6	470.8	231.6	38.7	3.4
N1A2M5L6	118.7(122.1)	22.5(22.5)	255.7(554.2)	66.5(305.0)	27.8(40.8)	1.1(3.6)	120.3	21.9	398.2	167.5	36.8	2.4
N1A2M5L4	70.6(78.0)	8.0(8.1)	189.7(484.1)	37.3(249.0)	22.4(40.6)	0.7(3.4)	69.5	7.8	316.7	113.4	31.1	1.8
N1A1M5L6	48.8(58.6)	3.9(4.1)	142.1(456.4)	17.0(223.0)	16.8(40.1)	0.5(3.4)	56.1	4.1	262.0	69.6	29.2	1.1
N1A1M5L4	28.4(38.2)	1.3(1.5)	95.3(371.4)	6.1(161.5)	11.7(38.5)	0.3(2.9)	35.4	1.4	193.5	39.3	24.0	0.7

Wang+19

Model	Event rate(yr^{-1})	TianQin		Twin constellations	
		Detection rate(yr^{-1})	Detection percentage	Detection rate(yr^{-1})	Detection percentage
L − seed	2.57	0.08	3.1%	0.162	6.3%
H − seed	2.57	1.055	41.1%	1.642	63.9%
popIII	174.70	10.58	6.1%	22.60	12.9%
Q3_d	8.18	4.42	54.0%	8.06	98.5%
Q3_nod	122.44	58.96	48.2%	118.12	96.5%

What can we learn from PTA limits?



Background characteristic strain at f=1/yr is $A<1.45 \times 10^{-15}$ (Nanograv 2018)

A possible detection?

arXiv.org > astro-ph > arXiv:2009.04496

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Astrophysics > High Energy Astrophysical Phenomena

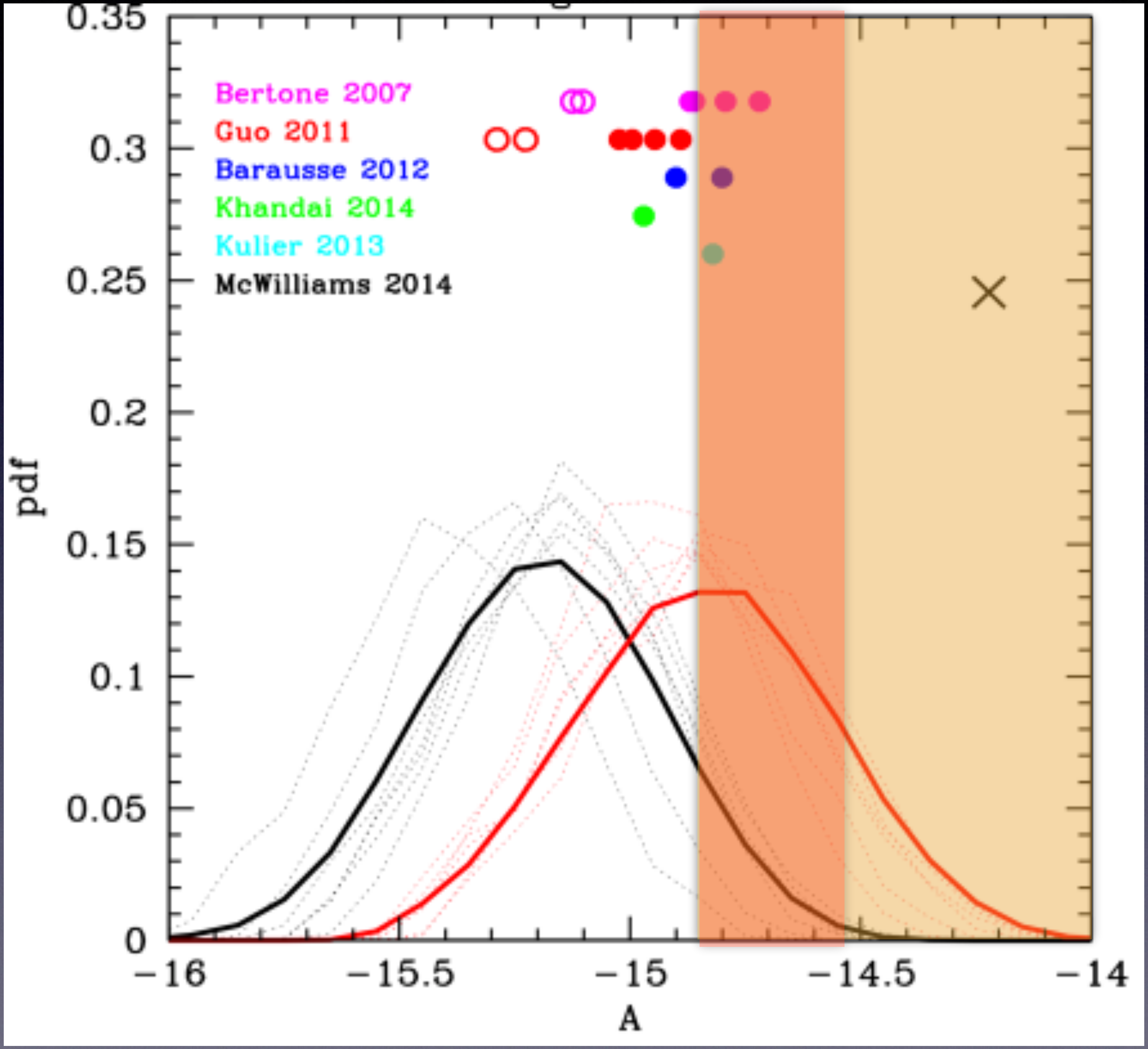
[Submitted on 9 Sep 2020 (v1), last revised 8 Jan 2021 (this version, v2)]

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background

Zaven Arzoumanian, Paul T. Baker, Harsha Blumer, Bence Becsy, Adam Brazier, Paul R. Brook, Sarah Burke-Spolaor, Shami Chatterjee, Siyuan Chen, James M. Cordes, Neil J. Cornish, Fronefield Crawford, H. Thankful Cromartie, Megan E. DeCesar, Paul B. Demorest, Timothy Dolch, Justin A. Ellis, Elizabeth C. Ferrara, William Fiore, Emmanuel Fonseca, Nathan Garver-Daniels, Peter A. Gentile, Deborah C. Good, Jeffrey S. Hazboun, A. Miguel Holgado, Kristina Islo, Ross J. Jennings, Megan L. Jones, Andrew R. Kaiser, David L. Kaplan, Luke Zoltan Kelley, Joey Shapiro Key, Nima Laal, Michael T. Lam, T. Joseph W. Lazio, Duncan R. Lorimer, Jing Luo, Ryan S. Lynch, Dustin R. Madison, Maura A. McLaughlin, Chiara M. F. Mingarelli, Cherry Ng, David J. Nice, Timothy T. Pennucci, Nihan S. Pol, Scott M. Ransom, Paul S. Ray, Brent J. Shapiro-Albert, Xavier Siemens, Joseph Simon, Renee Spiewak, Ingrid H. Stairs, Daniel R. Stinebring, Kevin Stovall, Jerry P. Sun, Joseph K. Swiggum, Stephen R. Taylor, Jacob E. Turner, Michele Vallisneri, Sarah J. Vigeland, Caitlin A. Witt (for the NANOGrav Collaboration)

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. The Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%--95% quantiles of 1.37--2.67×10^{-15} at a reference frequency of $f_{\rm yr} = 1~{\rm yr}^{-1}$. The Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

Tension with upper limit due to priors?



Nightmare scenario: what if MBHs do not merge

PTA predictions assume:

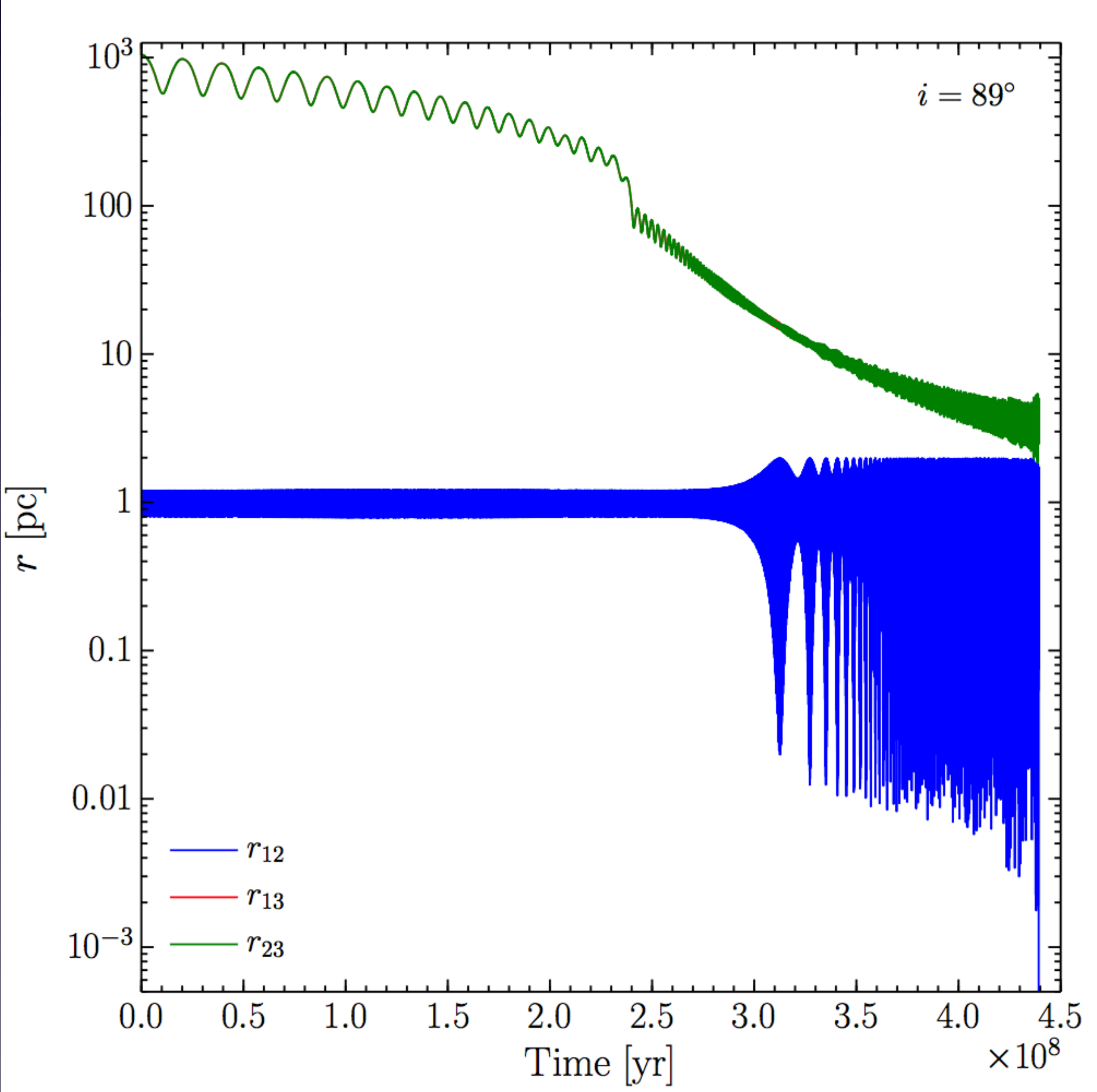
- GW driven binaries
- Circular orbits
- Efficient formation of bound massive BH binaries after galaxy mergers
- M-σ relation

Loopholes:

- Binaries may merge faster than expected based on GW emission alone (hence less time in band)
- Eccentric binaries (more power at high frequencies) due e.g. to strong environmental effects/triple systems
- Last pc problem (binaries stall)
- M-σ relation may be biased

The final parsec “problem”

- 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)

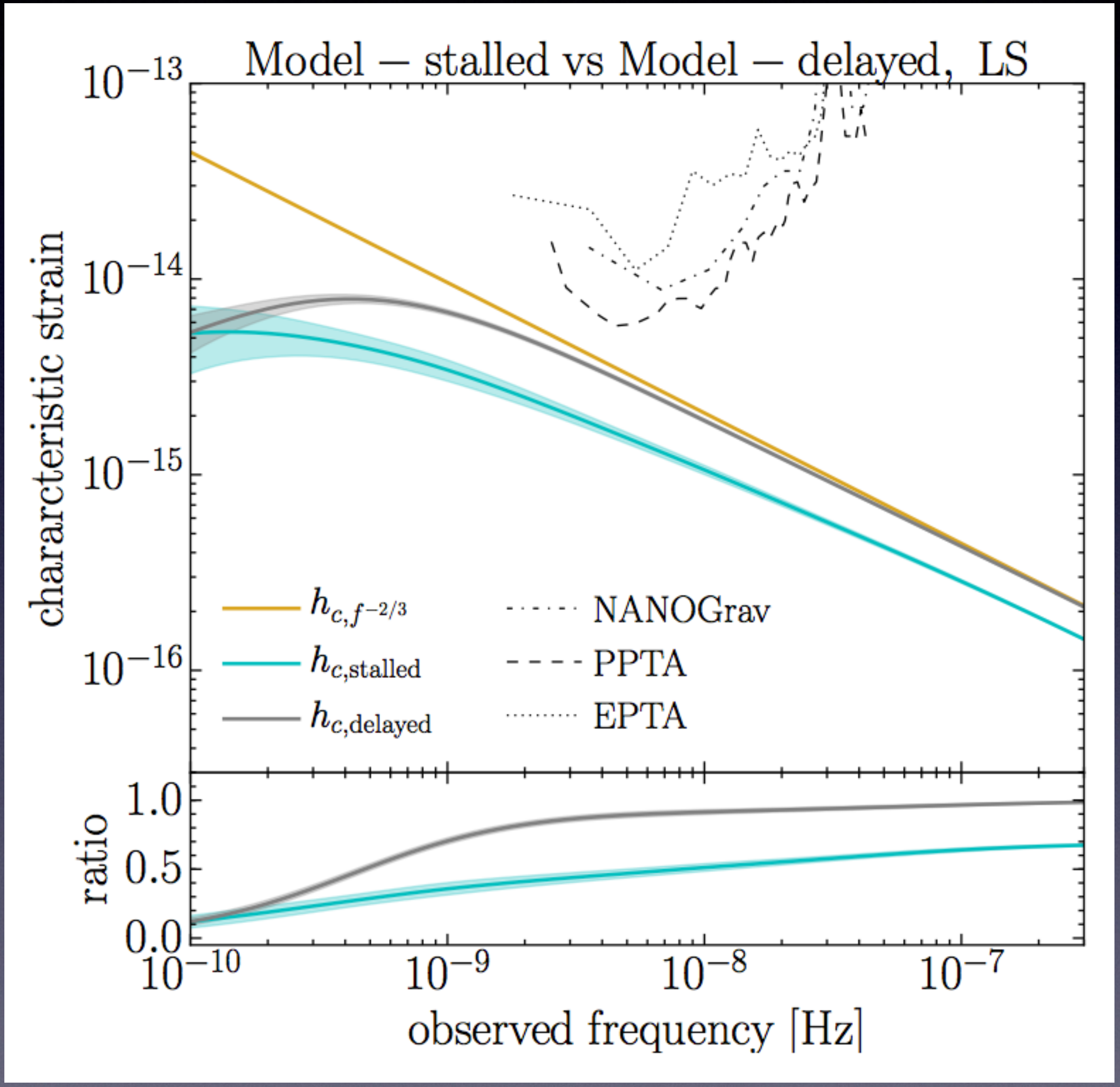


$$t_{\rm KL} \sim \frac{a_{\rm out}^3 (1 - e_{\rm out}^2)^{3/2} \sqrt{m_1 + m_2}}{G^{1/2} a_{\rm in}^{3/2} m_3} \simeq 2 \times 10^6 \ \ \text{yrs},$$

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

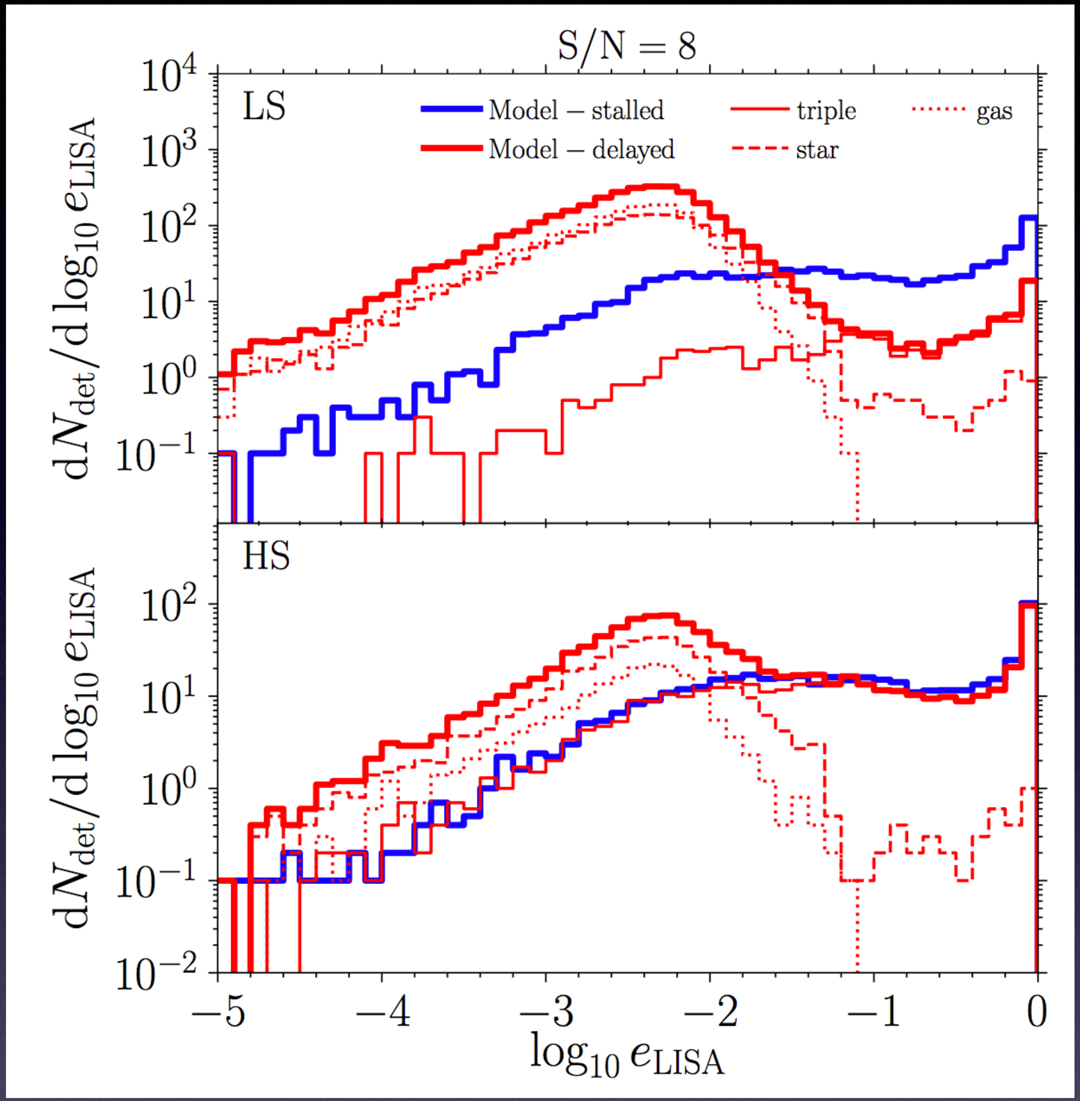
PN 3-body simulation in a stellar environment, with $m_1=10^8$ M_{sun}, $m_2=3 \times 10^7$ M_{sun}, $m_3=5 \times 10^7$ M_{sun} (Bonetti, Haardt, Sesana & EB 2016)

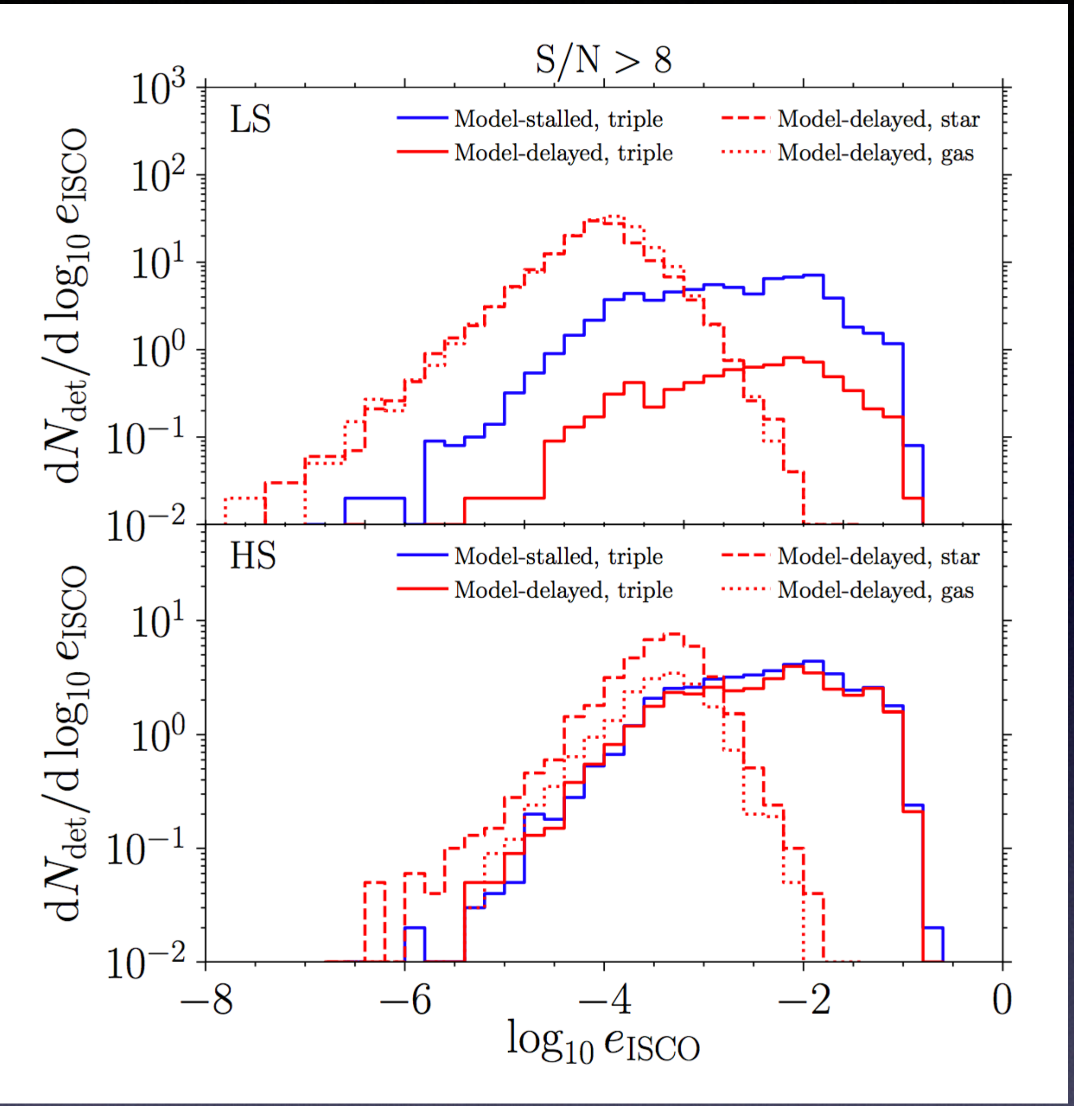
Triple-induced MBH mergers



Bonetti, Sesana, EB, Haardt 2018

LISA: eccentric inspirals and bursts?





- Standard hardening channels (gas, stars) produce small eccentricities by the time MBHBs get into band
- Triple driven systems can display eccentricities >0.99 (at band entrance)!
- Possibility to see eccentric non-merging sources (bursts)
- Possibility of an unresolved signal?

Model	$N_{det}(e_{LISA} > 0.1)$	$N_{det,triple}$	$N_{det,total}$
LS-*stalled*	35.4	77.8	77.8
LS-*delayed*	4.6	7.9	310.9
HS-*stalled*	22.5	49.4	49.4
HS-*delayed*	19.8	41.7	96.7

Conclusions

- Astrophysics of massive BH mergers and their interactions with baryons (host galaxy) is main scientific motivation of LISA and pulsar timing arrays

- Detection rate by LISA is highly uncertain (final pc problem) but will be >~ a few, with huge SNR ~ 100-1000 (enough for tests of GR/ringdown etc)

- TianQin detection rate smaller but potentially sensitive to IMBHs/seeds

- Eccentricity can be substantial

- If Nanograv's detection is confirmed, much shorter delays between galaxy and MBH mergers may be favoured

Open questions

- Can we decrease the uncertainty on the predicted MBH merger rate? Use EM observations to constrain astro models?
- Synergies with PTA/ground based?
- How well can the MBHB eccentricity be constrained? Can we develop sufficiently accurate eccentric waveforms?
- Can we discriminate between MBHB astro models?