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Supermassive black-hole binaries as gravitational-wave sources

IGWM2017
Bilbao, May 15th-18th, 2017

H2020-MSCA-RISE-2015 StronGrHEP-690904

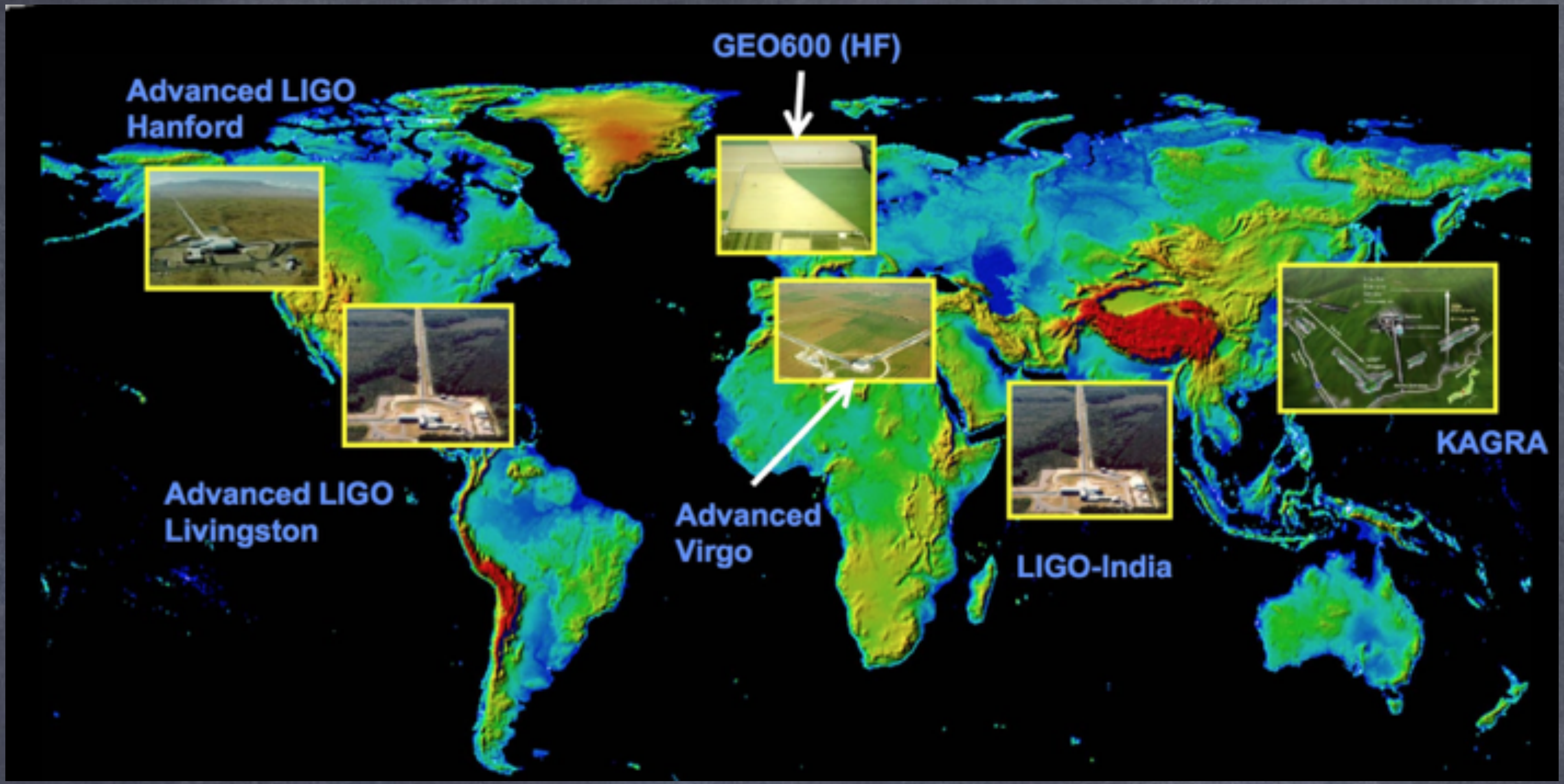
Outline

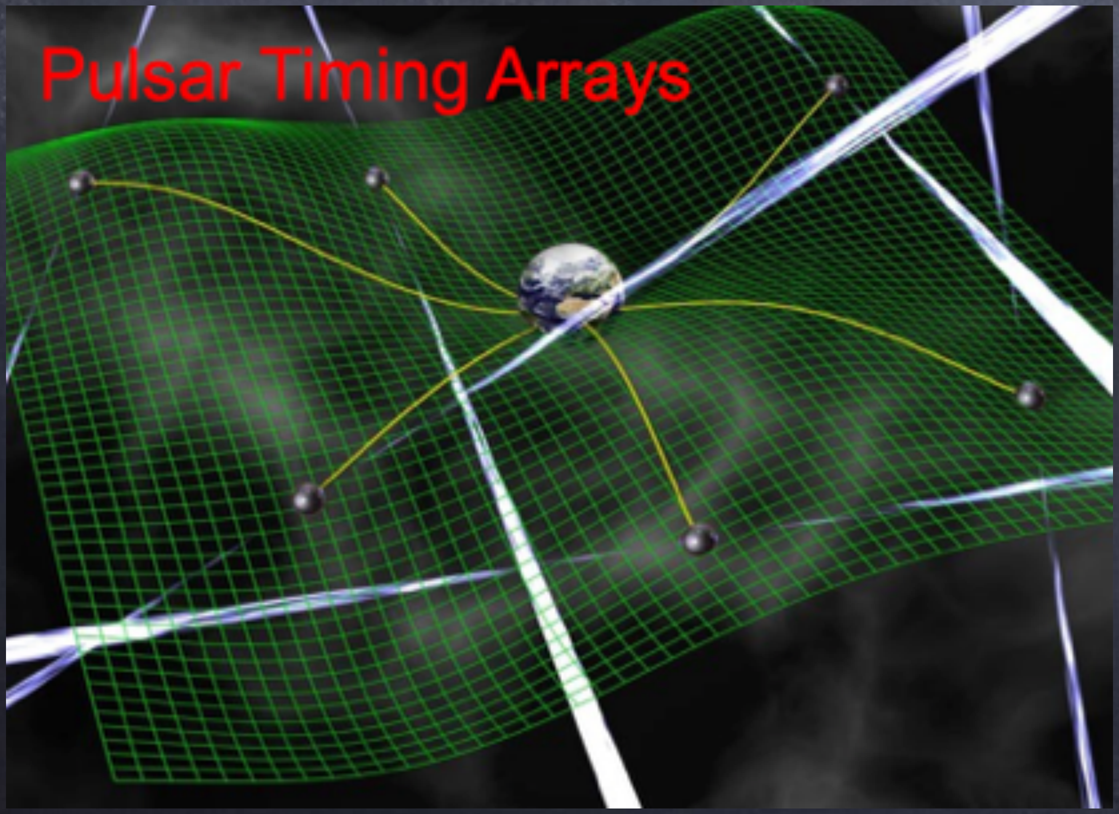
- The status of LISA in the era of the first dections

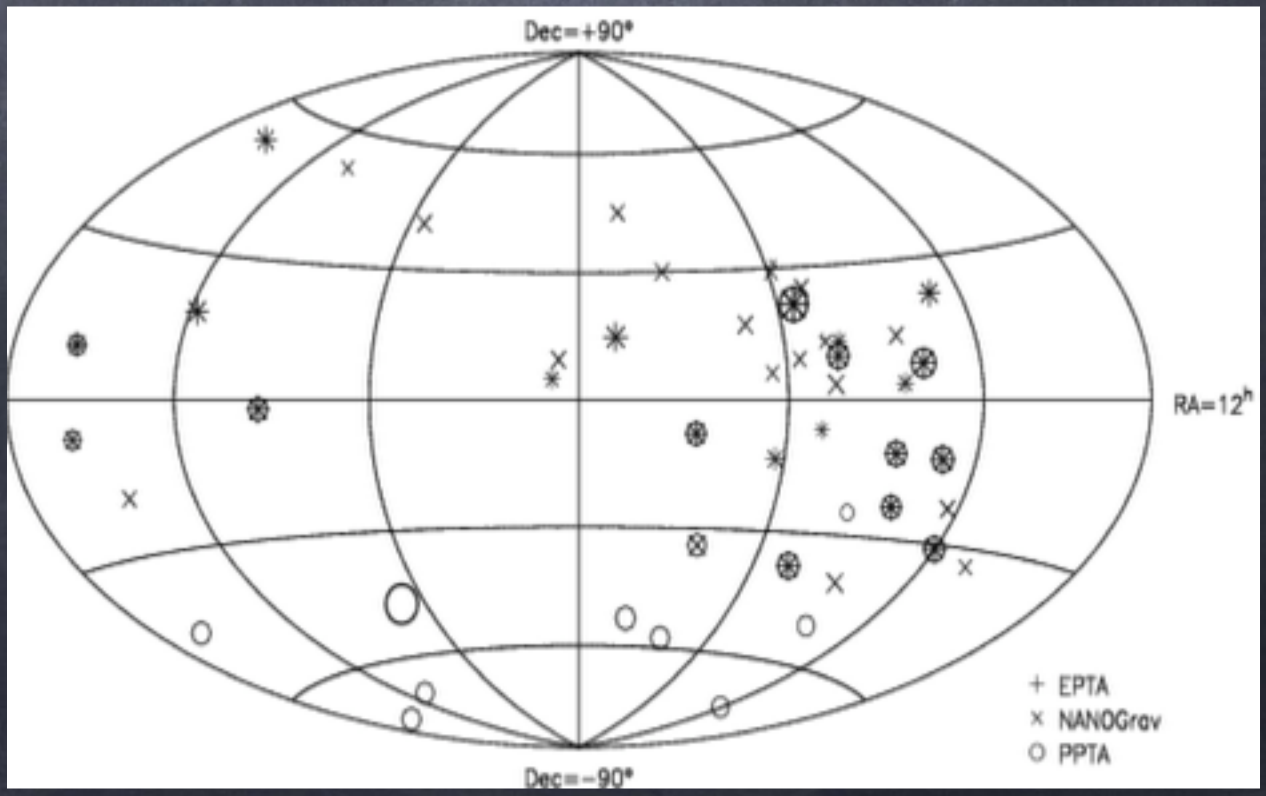
- Massive BH mergers as GW sources for LISA:
  - event rates and parameter estimation
  - standard candles as a tool for cosmology
  - tests of no-hair theorem

- Synergies with PTAs

Existing GW detectors







Frequency windows

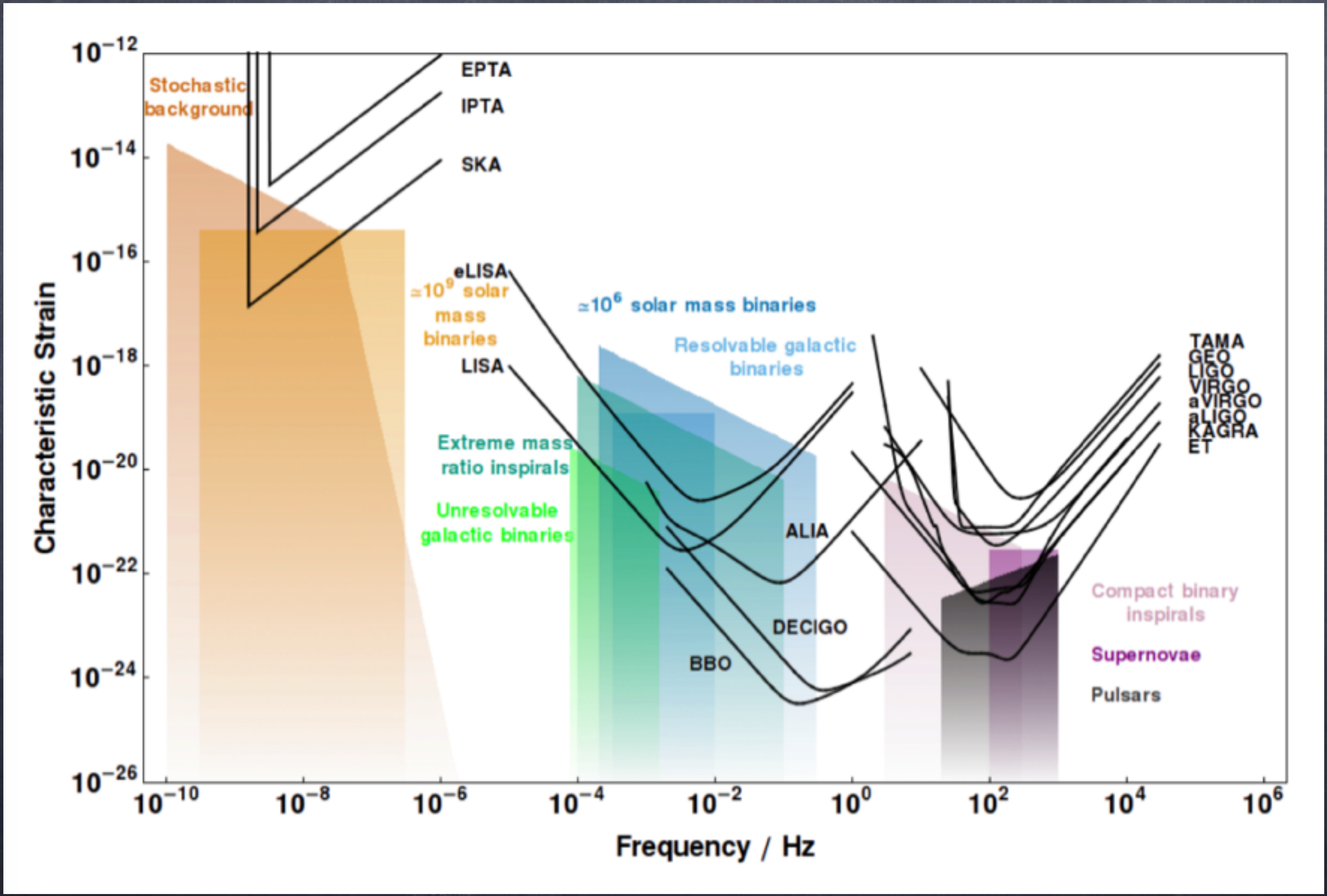
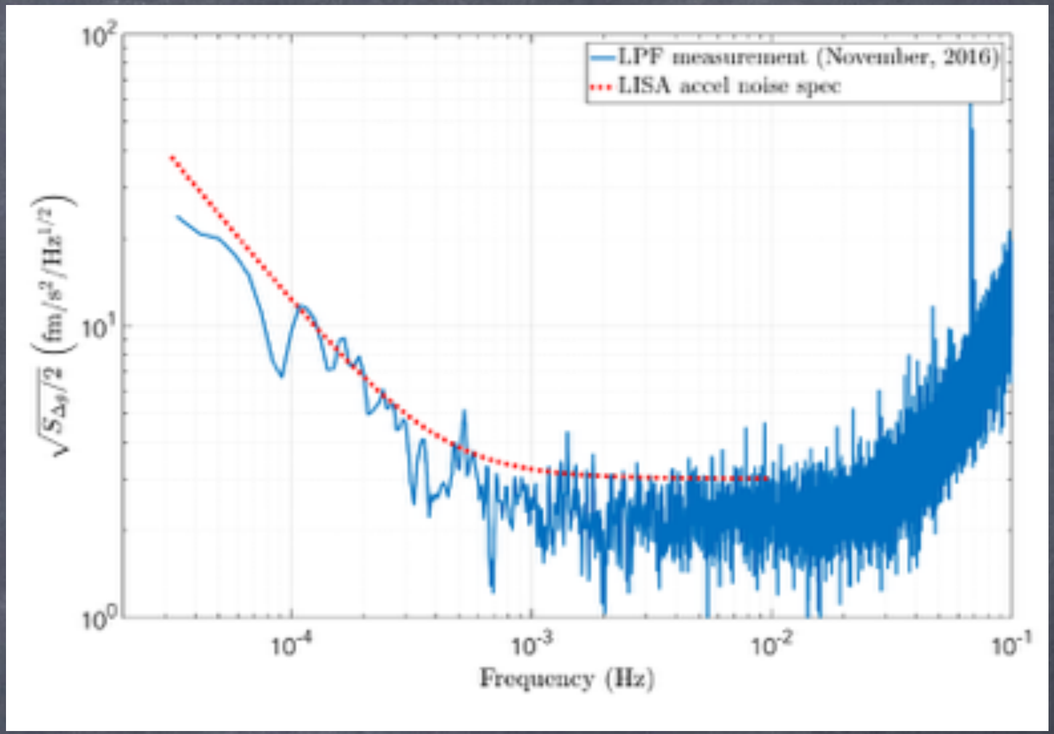


Figure from Moore, Cole and Berry 2015

The status of LISA

- ESA selected the "Cosmic Vision" L3 launch slot (2034) for theme "The Gravitational Universe"

- LISA Pathfinder mission a success (surprisingly stable)



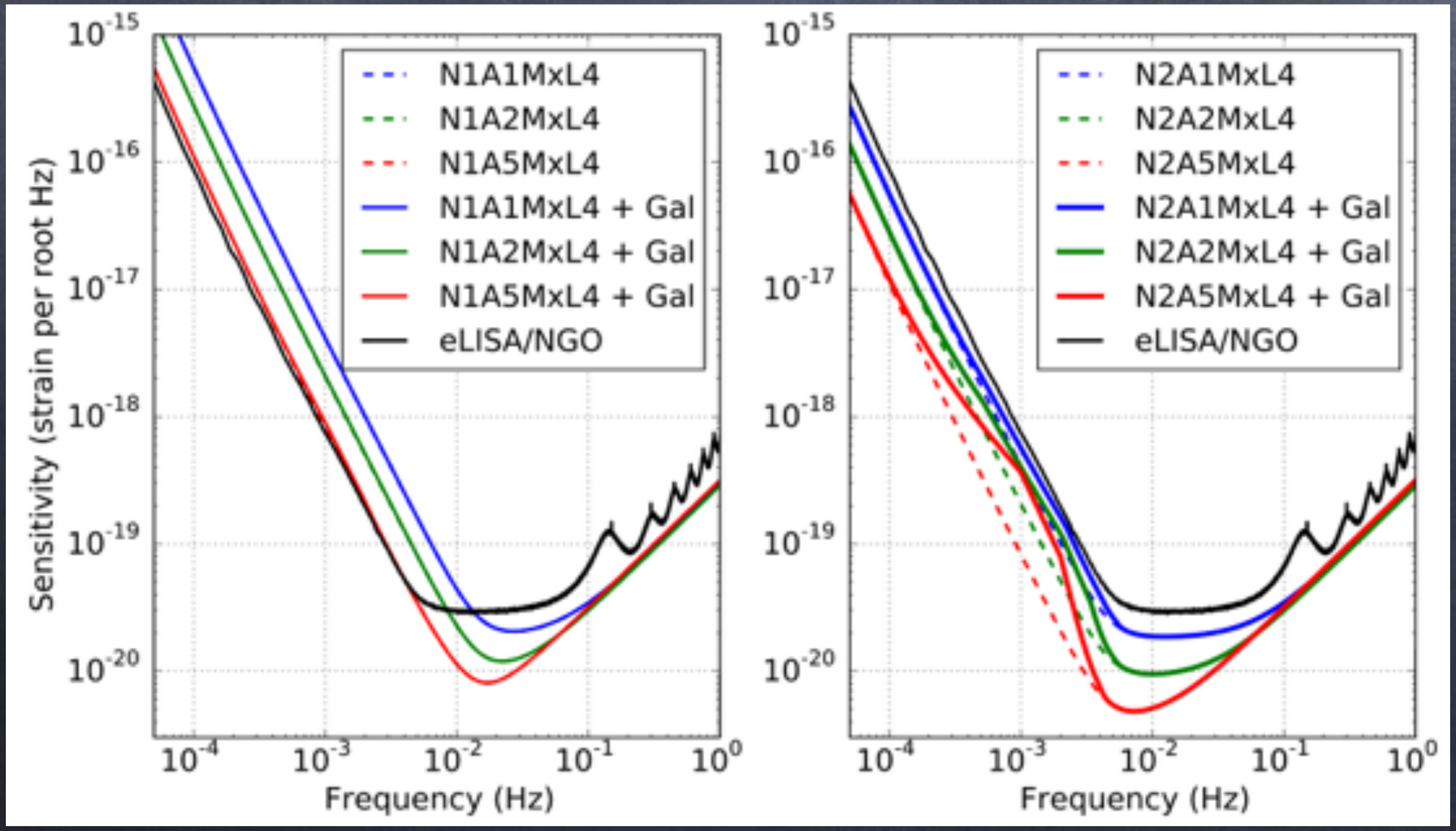
- LISA design/mission not selected yet, options have been analyzed by Gravitational Wave Advisory Team (GOAT) collaboration with LISA consortium

1. Klein, EB, Sesana, Petiteau, et al PRD 93, 024003 (2016): massive BHs
2. Tamanini, Caprini, EB, Sesana, Klein, Petiteau, JCAP 04 (2016) 002: standard sirens
3. Caprini, Hindmarsh, Huber, Konstandin, et al JCAP 04 (2016) 001: stochastic backgrounds
4. Sesana PRL 116, 231102 (2016); Nishizawa, Berti, Klein, Sesana, PRD 94, 064020 (2016): multiband
5. EB, Yunes and Chamberlain, PRL 116, 241104 (2016) : multiband, tests of GR
6. Berti, Sesana, EB, Cardoso, Belczynski, PRL 117, 101102 (2016): no-hair theorem
7. Gair, Sesana, Babak, EB, et al arXiv:1703.09722 : EMRIs

- ESA call for mission adoption in Jan 2017, then industrial production (~ 10 yrs) which will make mission possible in ~2030 (?)

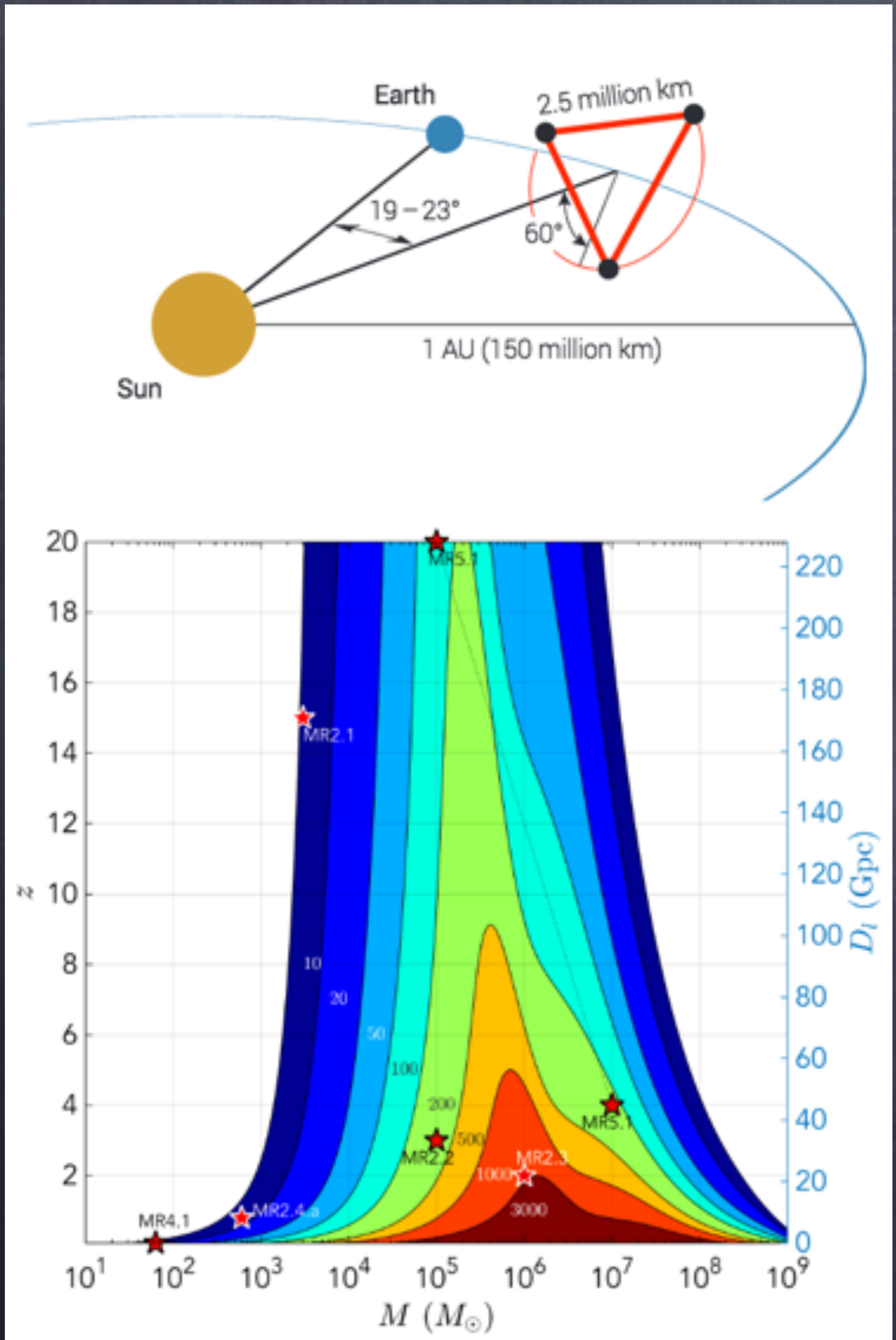
Options for the LISA design considered in GOAT studies (2015-16)

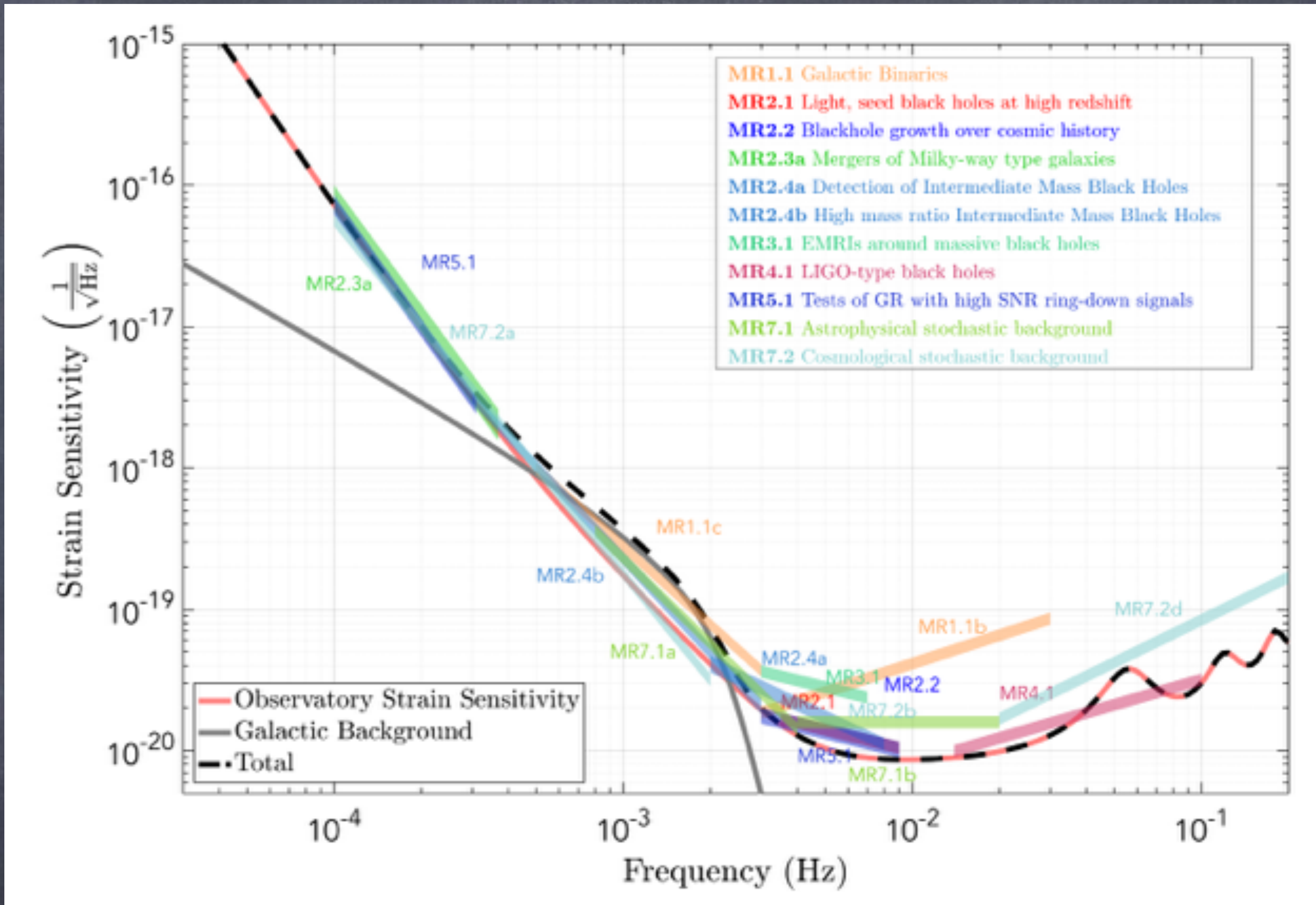
- Armlength L= 1, 2, 5 Gm (A1, A2, A5)
- Low-frequency noise at the LISA requirement level of LISA Pathfinder (N2) or 10 times worse (N1): we know it's N2!
- 4 or 6 links (L4, L6), 2 or 5 year mission (M2, M5)
- Laser power of 0.7 W for A1 and 2 W for A2 and A5; telescope mirror size of 25 cm for A1, 28 cm for A2, 40 cm for A5.
  2W laser and 40 cm telescope improve high-frequency performance



From
Klein EB et al 2015

LISA configuration proposed to ESA, Jan 2017





6 links, 2.5 Gm arms,
nominal 4 yr duration, up to 10 yr

Why massive BH merge

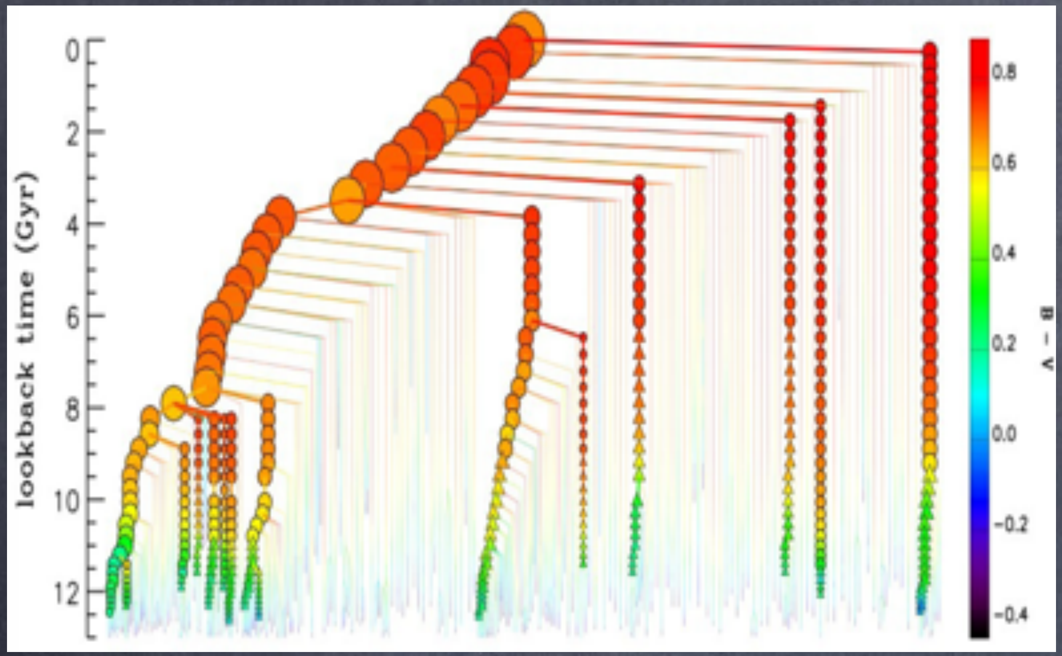


Figure from De Lucia & Blaizot 2007

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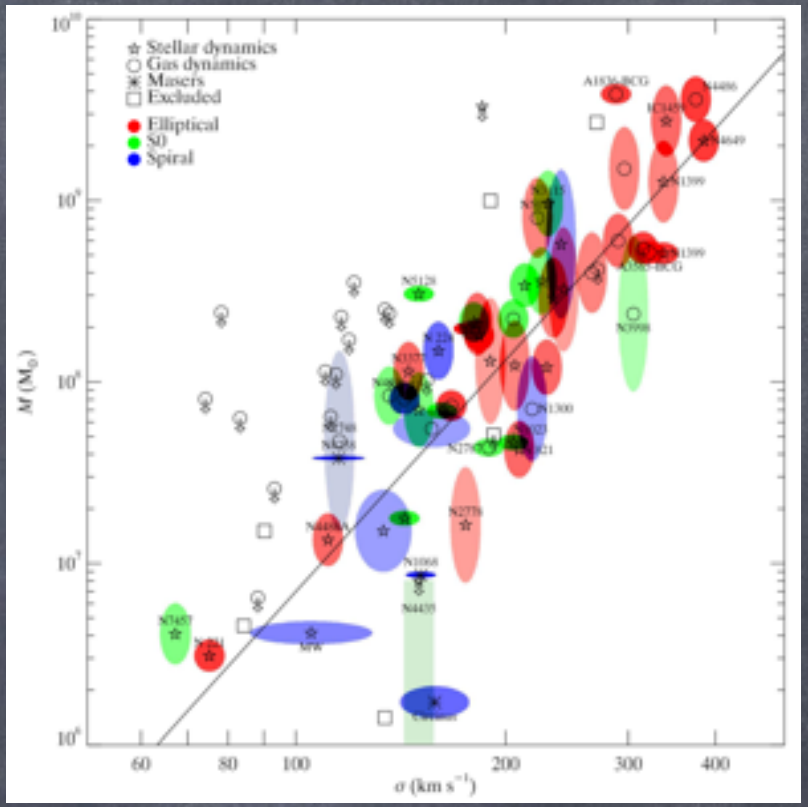
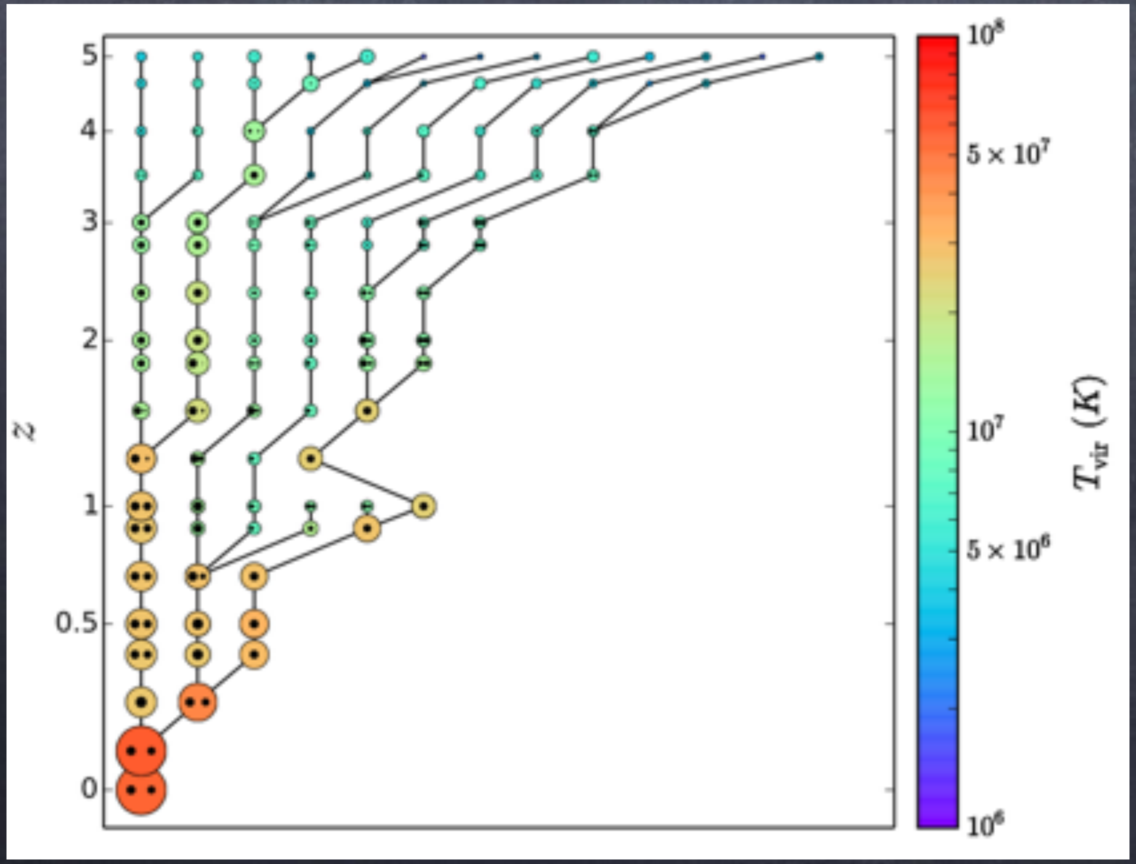


Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

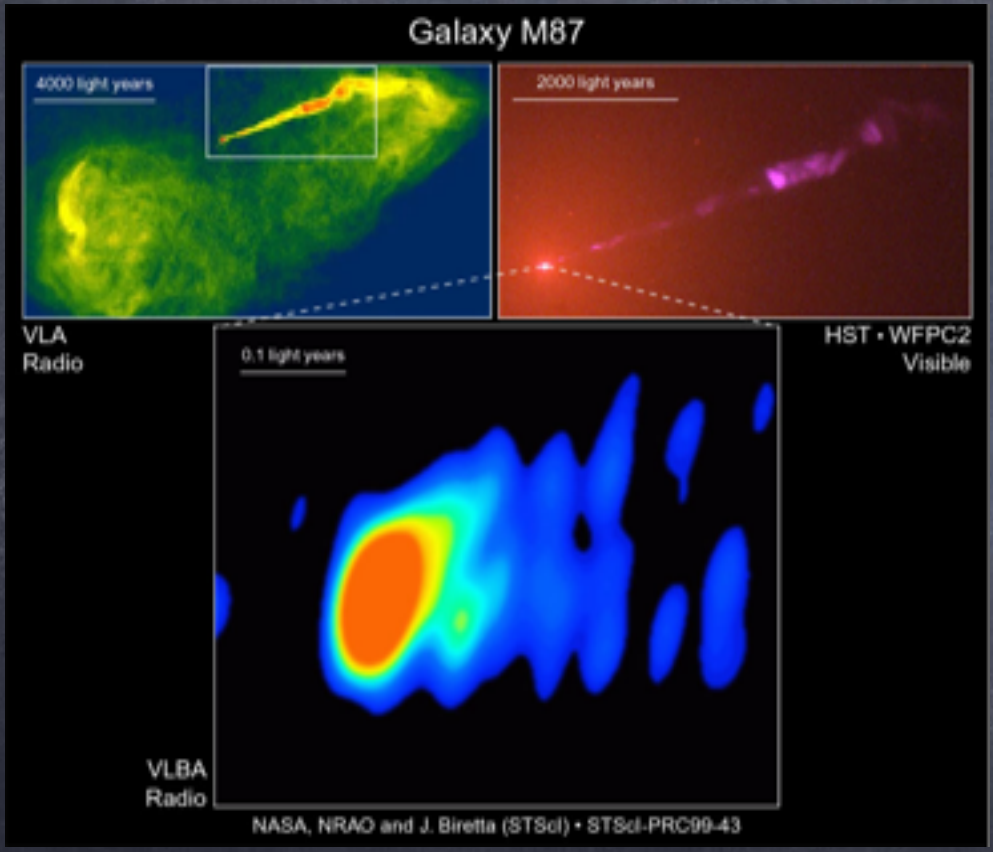
=

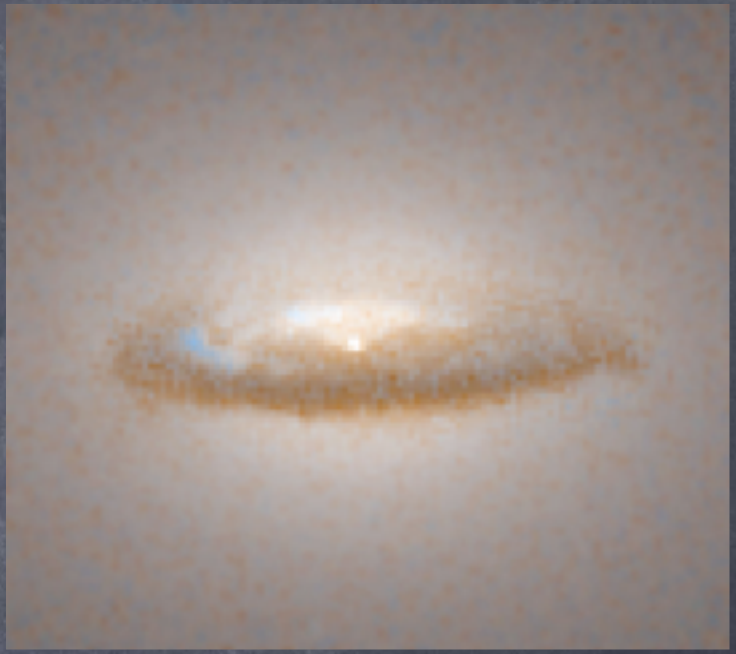


EB 2012
Figure credits: Lucy Ward

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



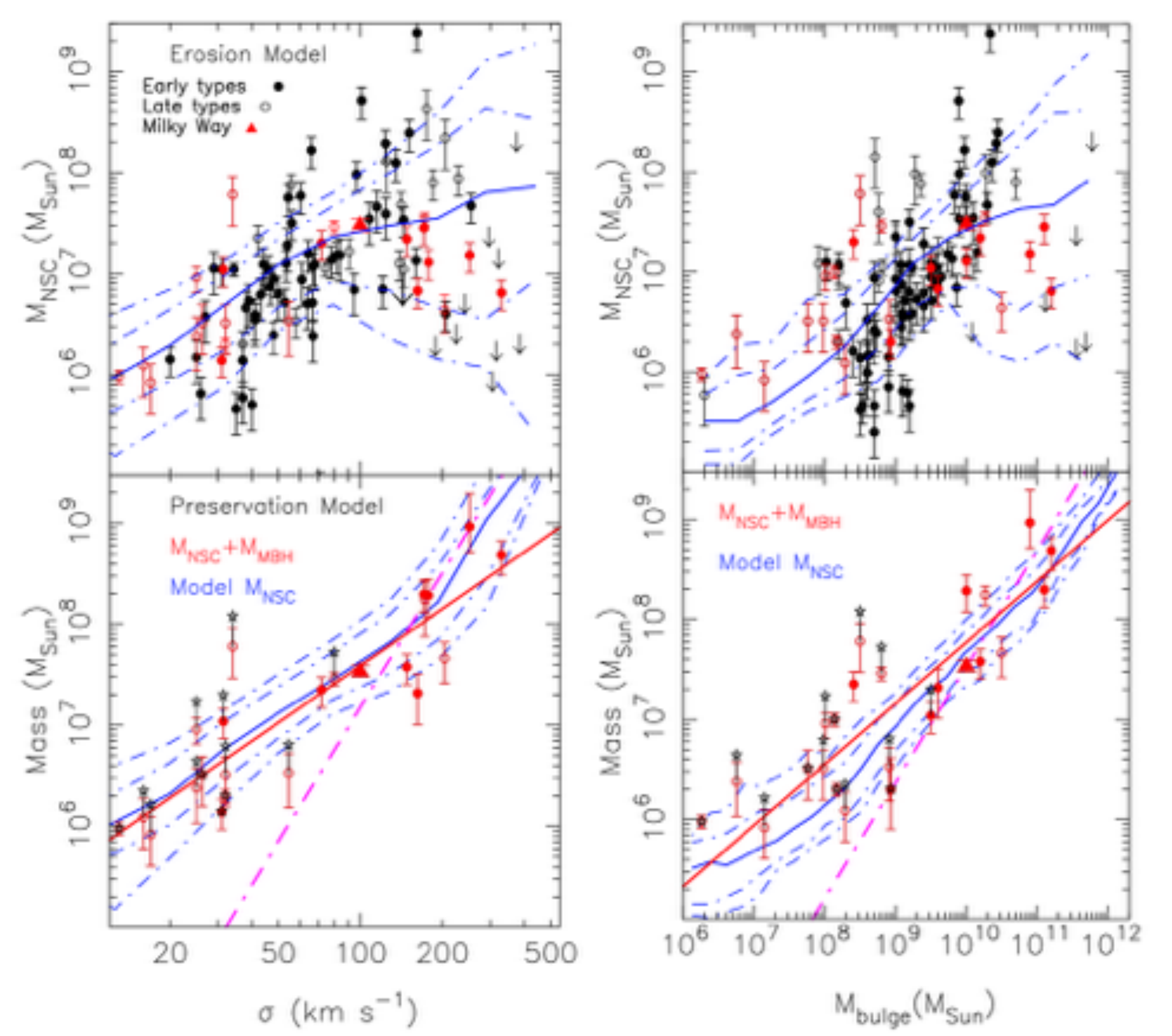


Disk of dust and gas around the massive BH in NGC 7052

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

Evidence for BH mergers from nuclear star cluster observations

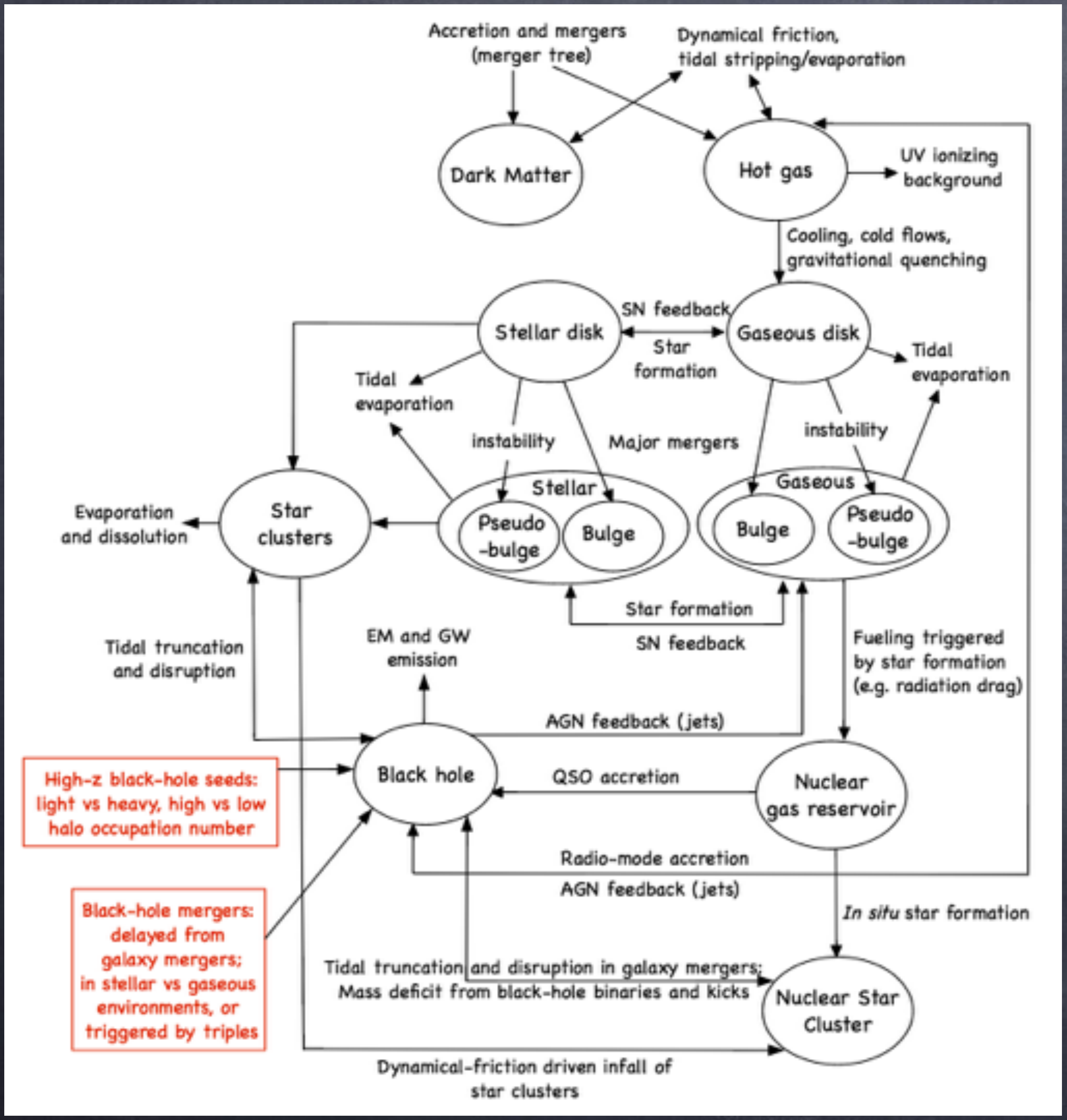
- NSC: masses up to $\sim 10^7$ M_{sun}, $r \sim$ pc
- BH binaries eject stars by slingshot effect and through remnant's recoil ("erosion")
- Erosion by BH binaries crucial to reproduce NSC scaling relations



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

Antonini, EB & Silk (2015)

Science with massive BH binaries



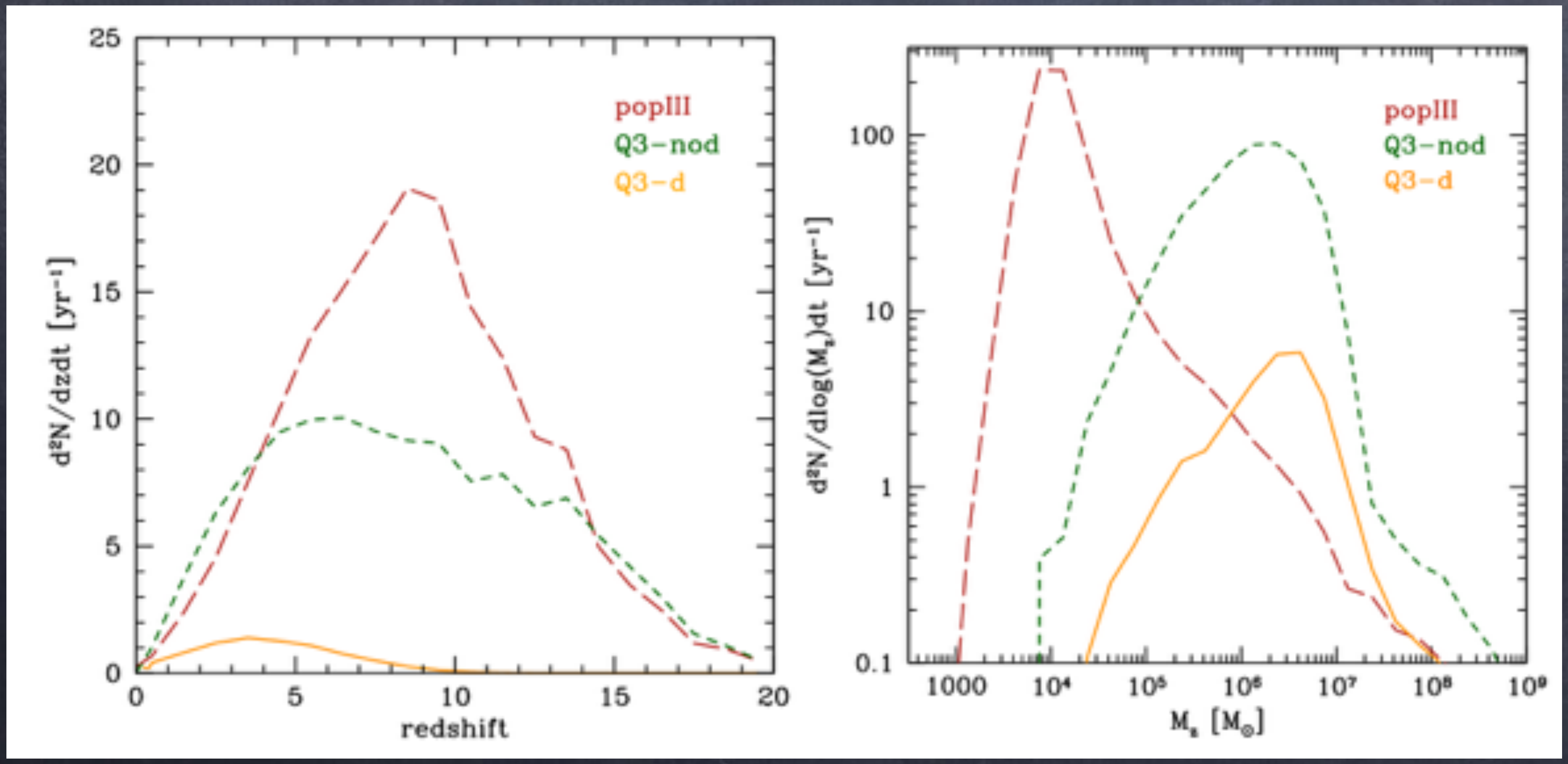
EB 2012

- Evolution of massive BHs difficult to predict because co-evolution with galaxies (c.f. M-σ relation, accretion, jets, feedback, etc)
- Purely numerical simulations impossible due to sheer separation of scales (10^{-6} pc to Mpc) and dissipative/nonlinear processes at sub-grid scales
- Semi-analytical model (EB 2012) with 7 free parameters, calibrated vs data at z = 0 and z > 0 (e.g. BH luminosity & mass function, stellar/baryonic mass function, SF history, M -σ relation, etc)

Massive BH model's uncertainties

- Seed model: light seeds from PopIII stars (~100 M_{sun}) vs heavy seeds from instabilities of protogalactic disks (~10^5 M_{sun})

- No delays between galaxy and BH mergers, or delays depending on environment/presence of gas:
  - 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



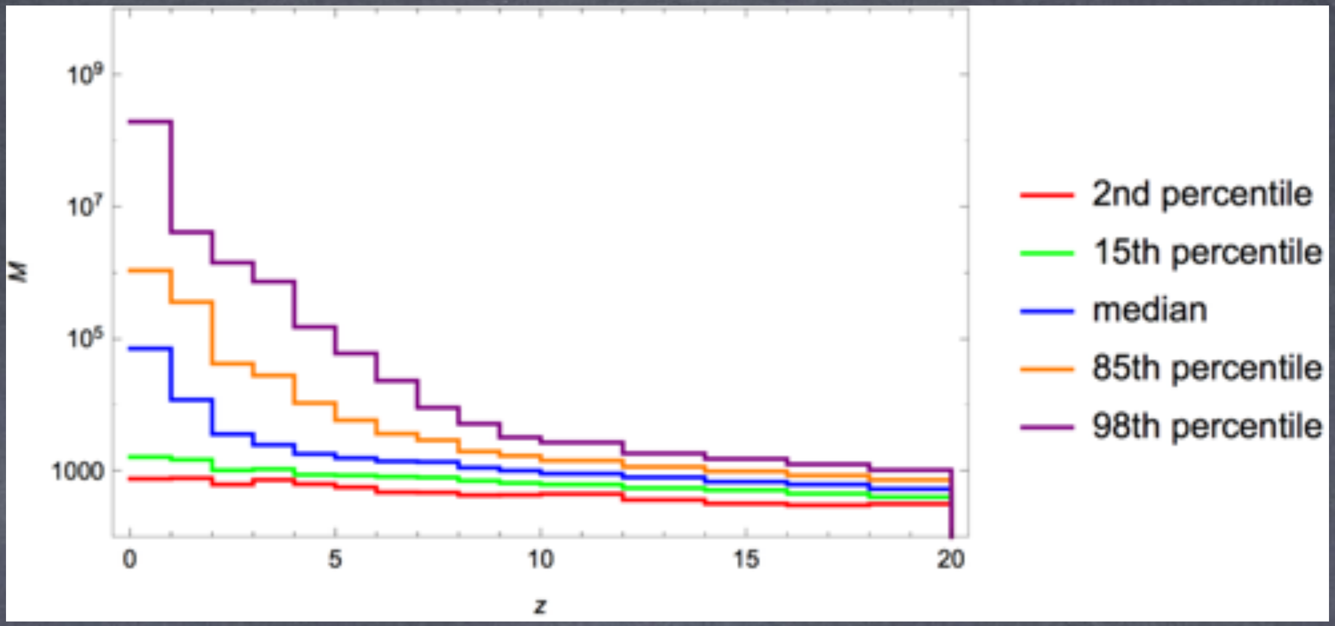
PopIII=light seeds, delays
(but similar results with no delays)

Q3-d= heavy seeds, delays
Q3-nod= heavy seeds, no delays

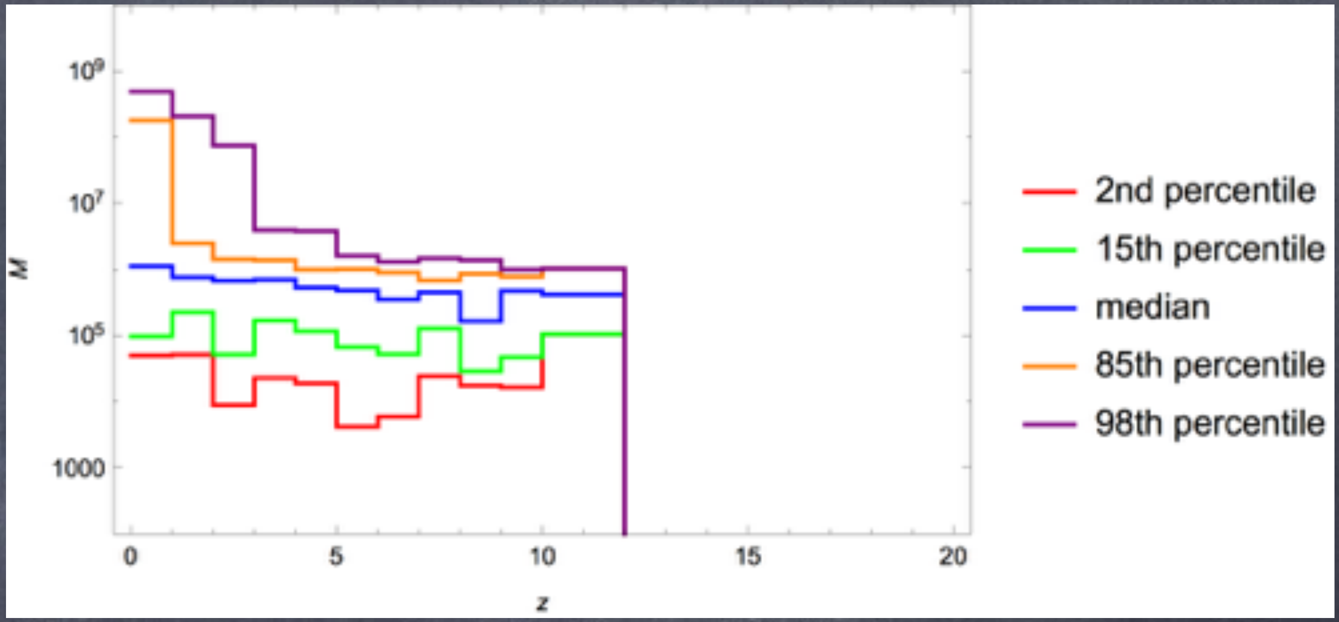
From Klein EB et al 2015

Model predictions

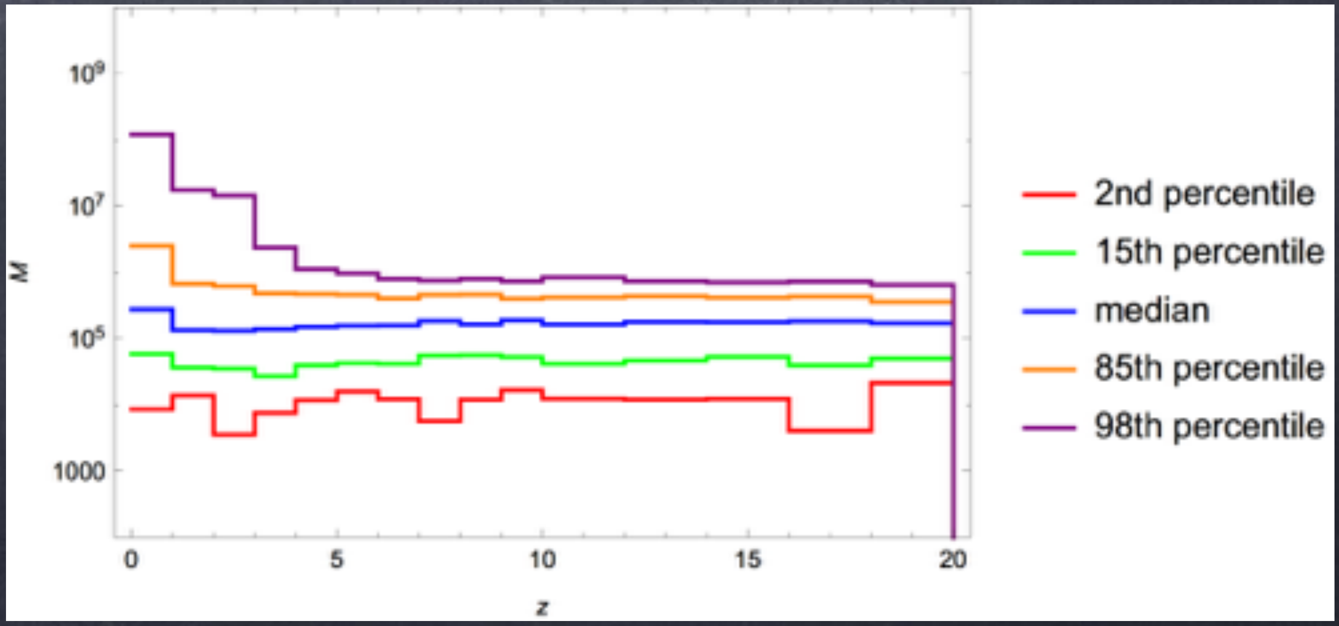
PopIII = light seeds, delays



Q3-d = heavy seeds, delays



Q3-nod = heavy seeds, no delays



Model predictions

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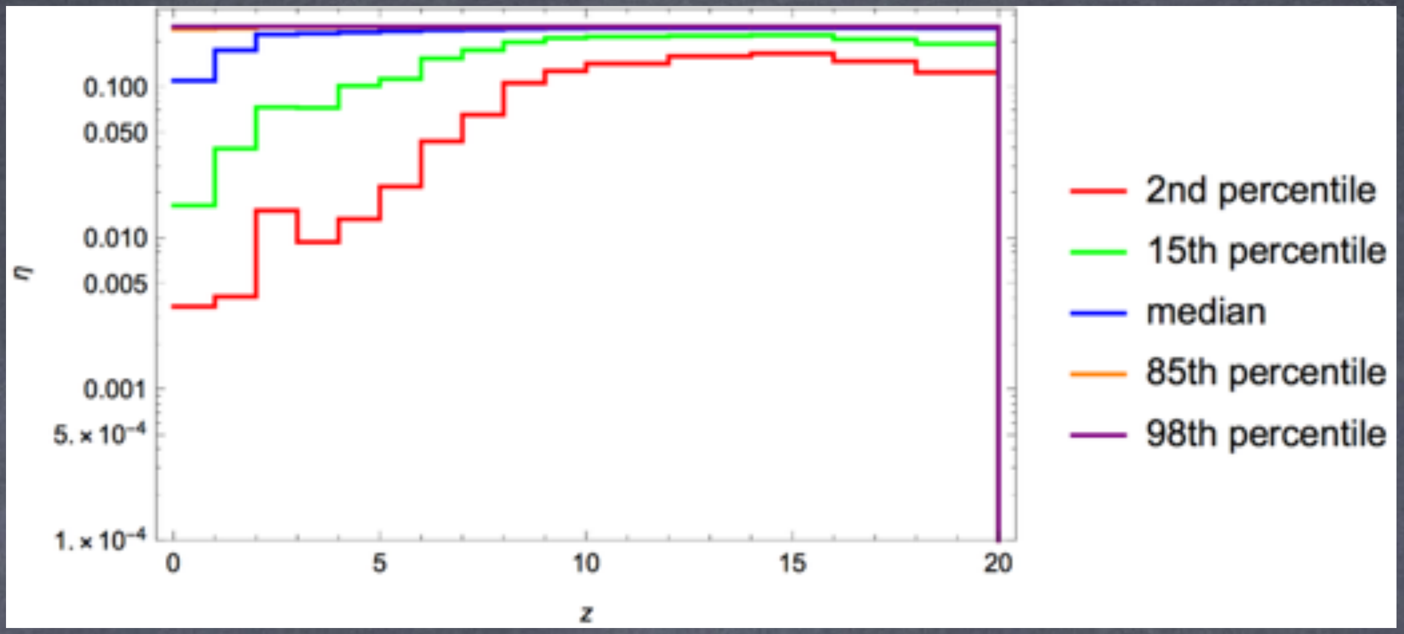

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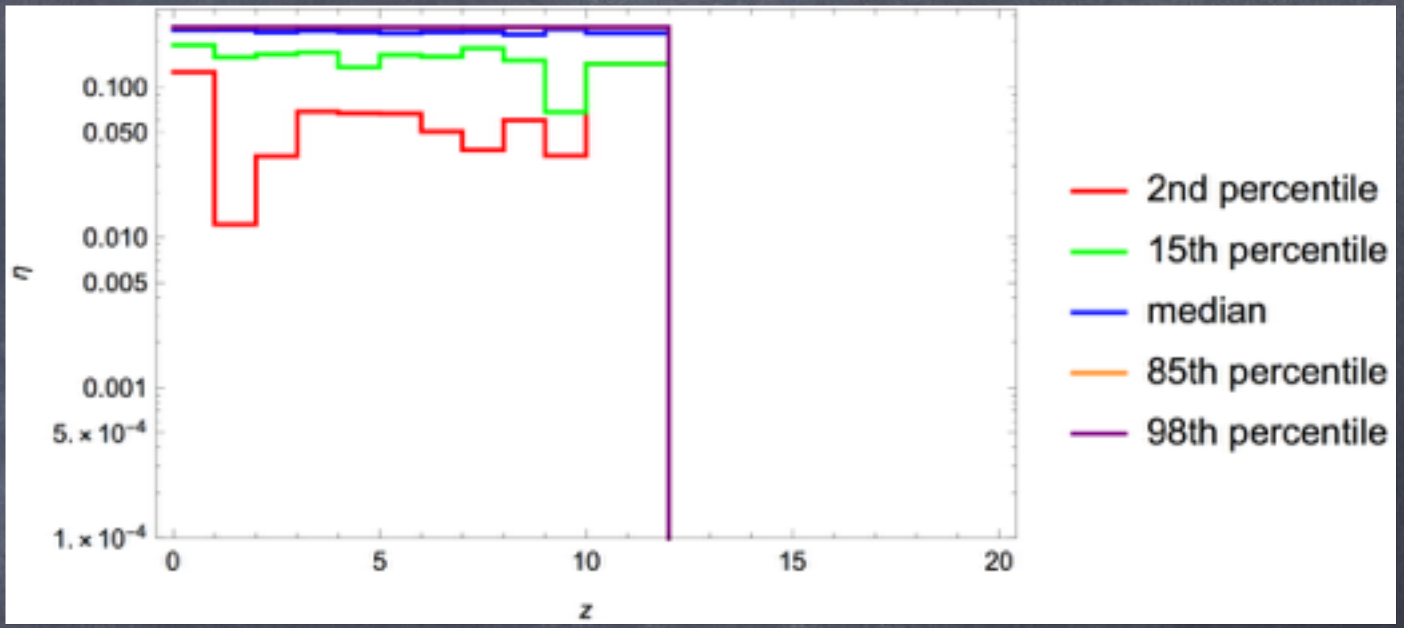
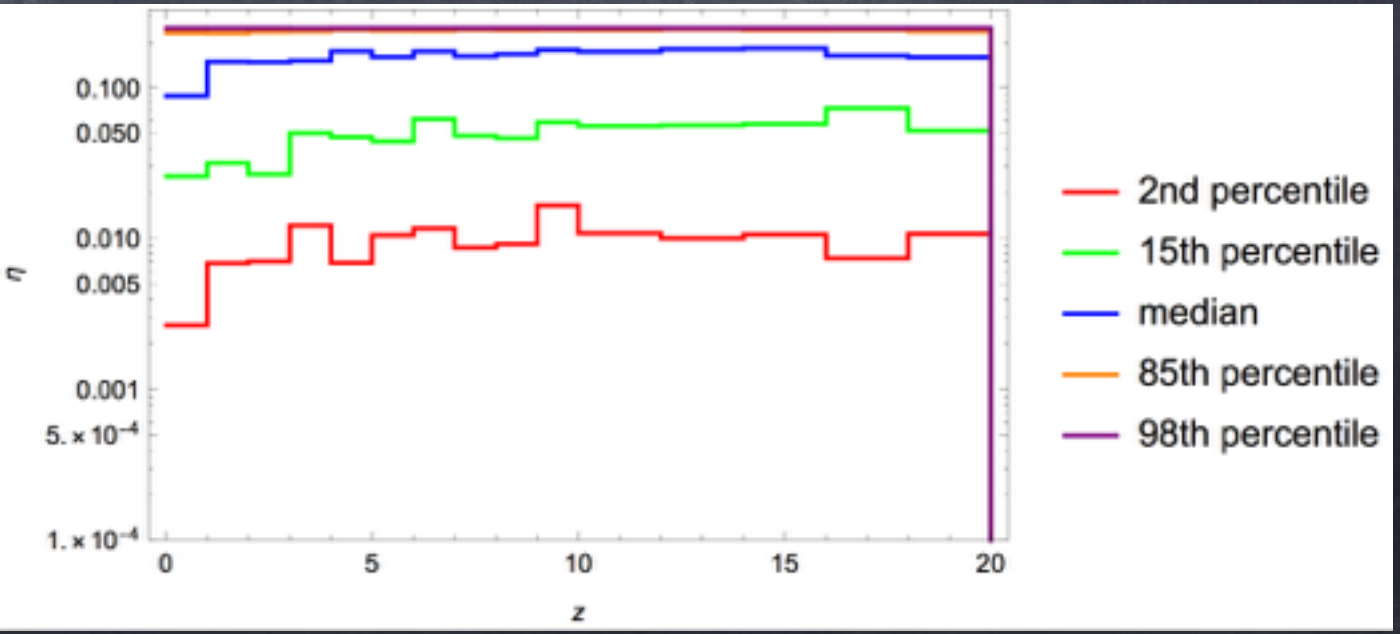
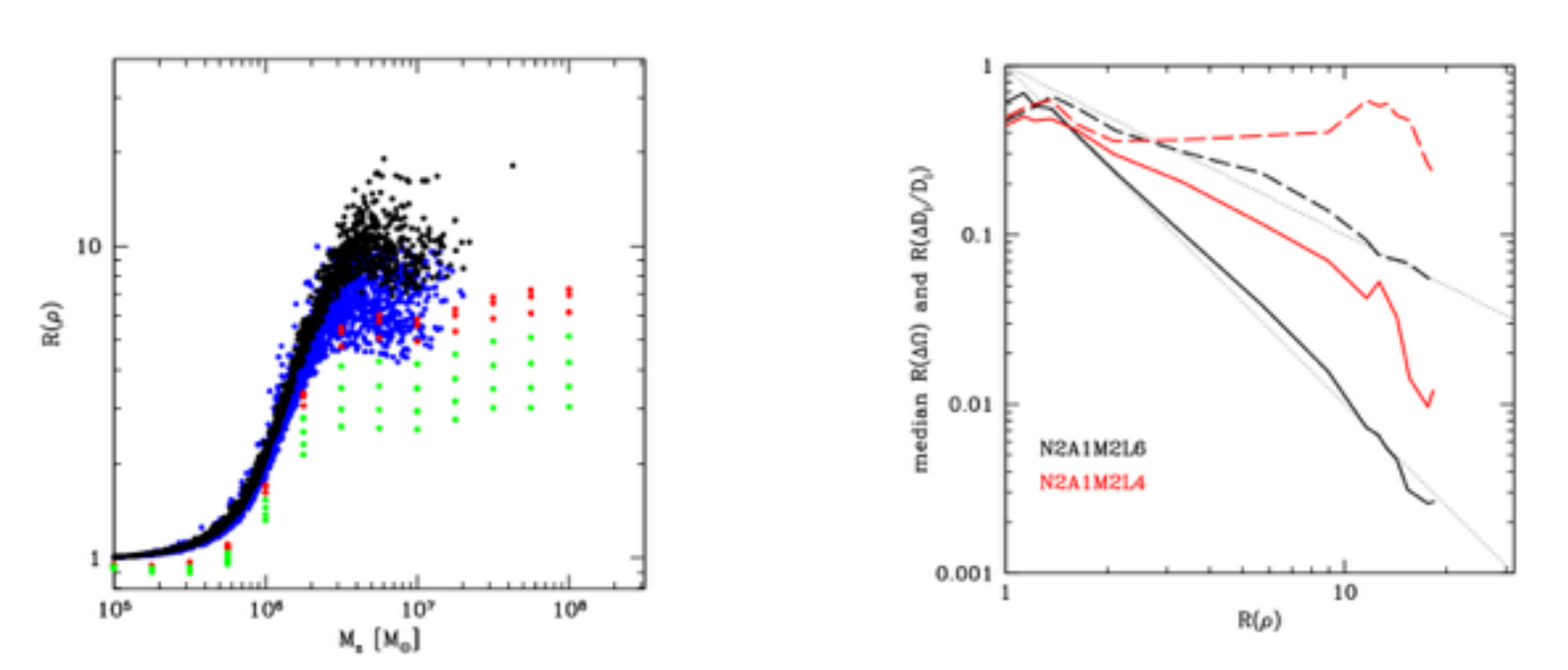


Q3-nod = heavy seeds, no delays



Detection and parameter estimation

- Detection threshold: SNR>8; parameter estimation: Fisher analysis
- Generic precessing inspiral-only gravitational waveform (shifted uniform asymptotics, SUA), includes leading and next-to-leading SO and leading SS coupling, no sky/orientation average
- Checked robustness of SNR/detection by using restricted 2PN waveforms
- Merger/ringdown important at high masses. Rescaled SNR and distance/sky-location errors based on dedicated precessing IMR hybrid waveforms and on SNR gain $R=SNR_{IMR}/SNR_{insp}$, computed with spin-aligned PhenomC waveforms. Contribution of merger ringdown on final spin error accounted for via analytic approximation



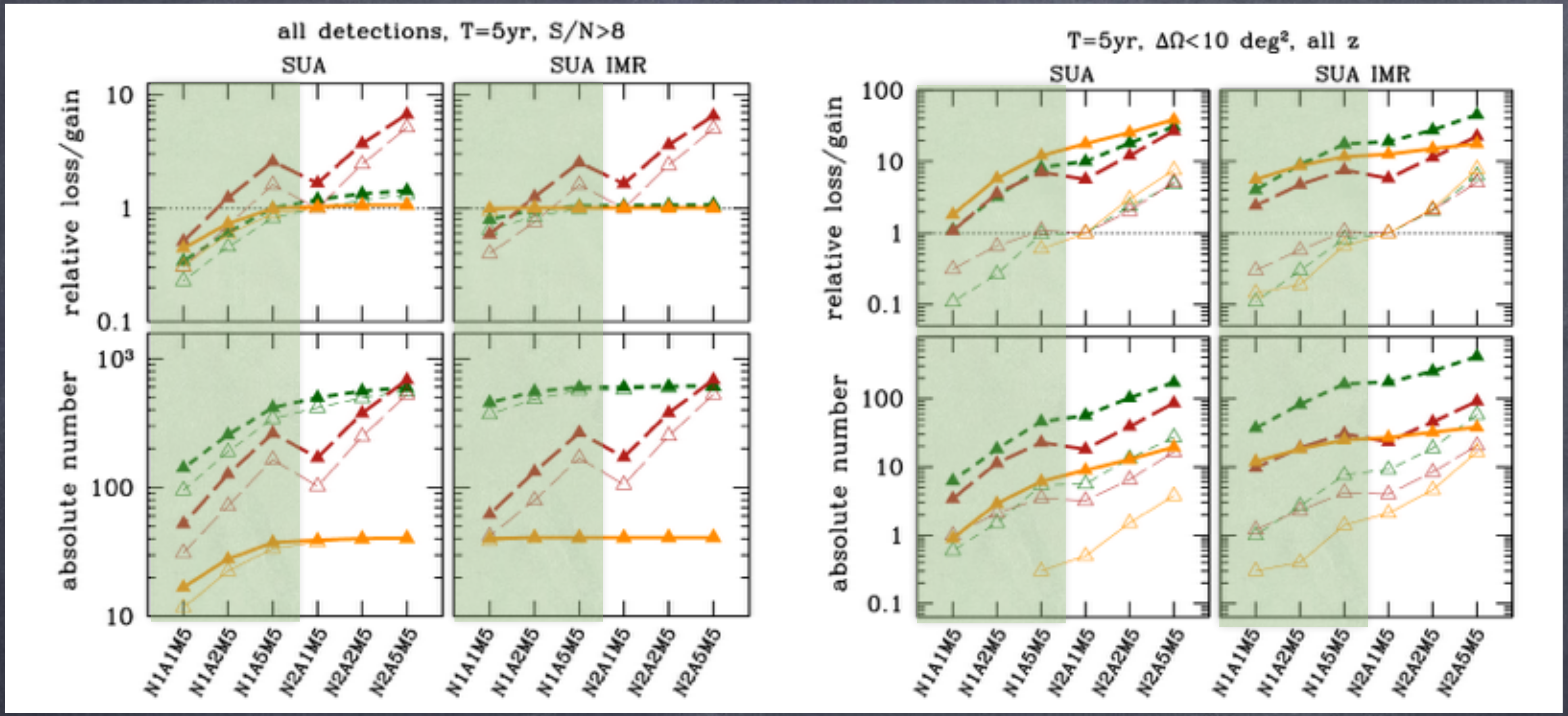
solid = sky localization

dashed = luminosity distance

dotted = linear and quadratic scaling

From Klein EB et al 2015

Detection rates



From Klein EB et al 2015

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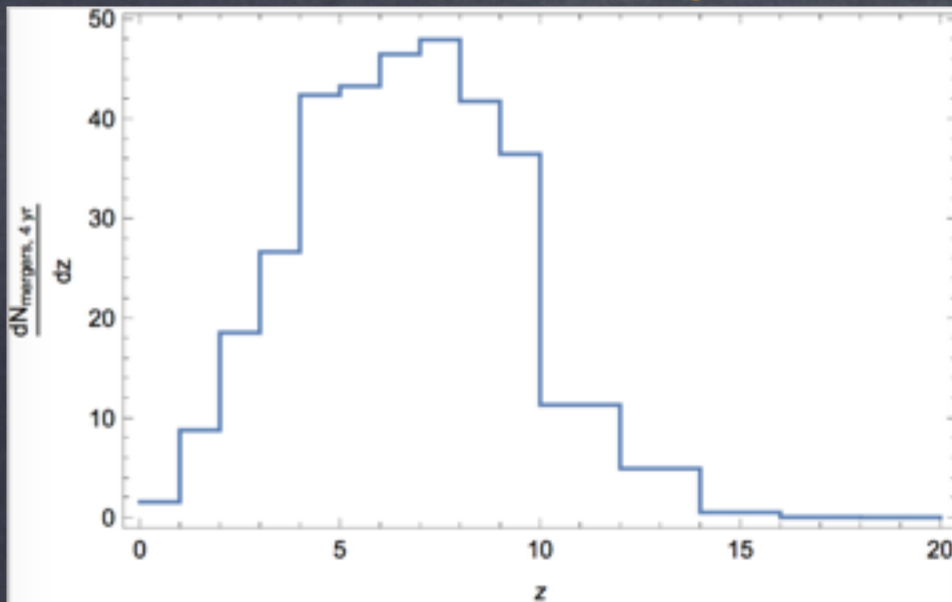
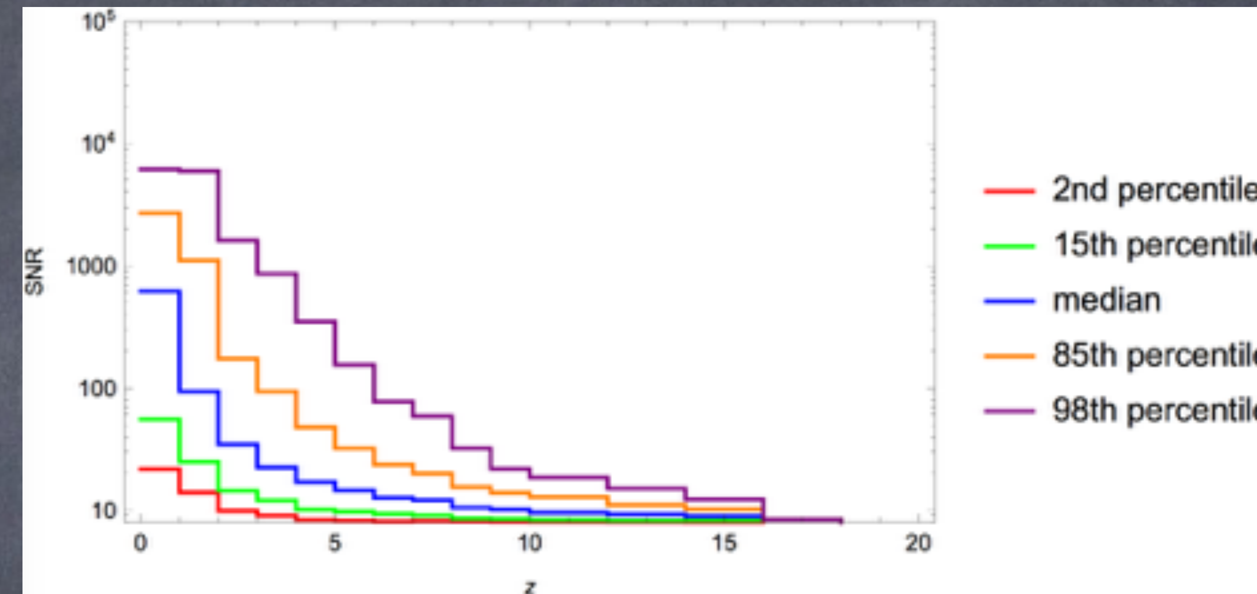
thick = six links (L6), thin = four links (L4)

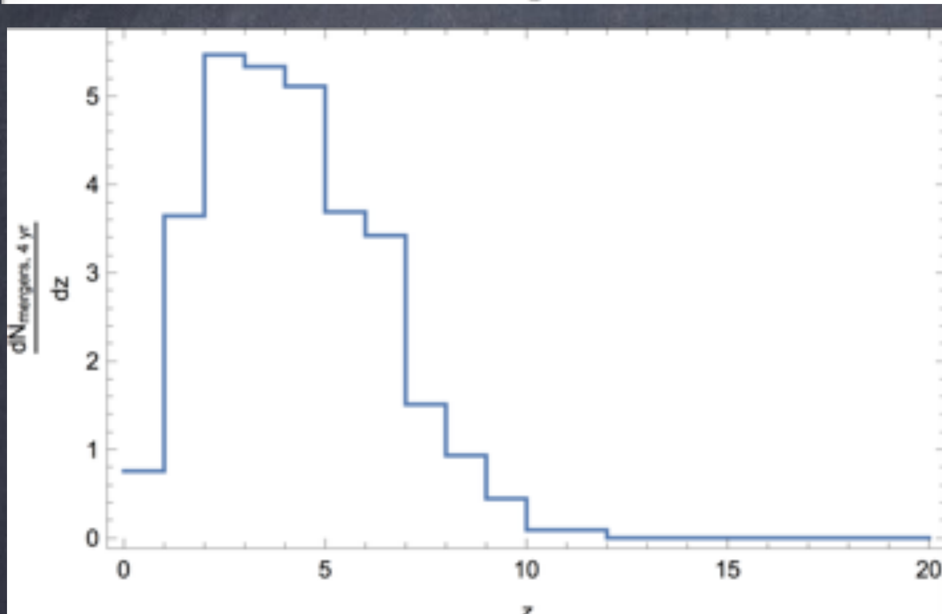
Relative loss relative to NGO (N2A1MkL4)

LISA configuration proposed to ESA, Jan 2017

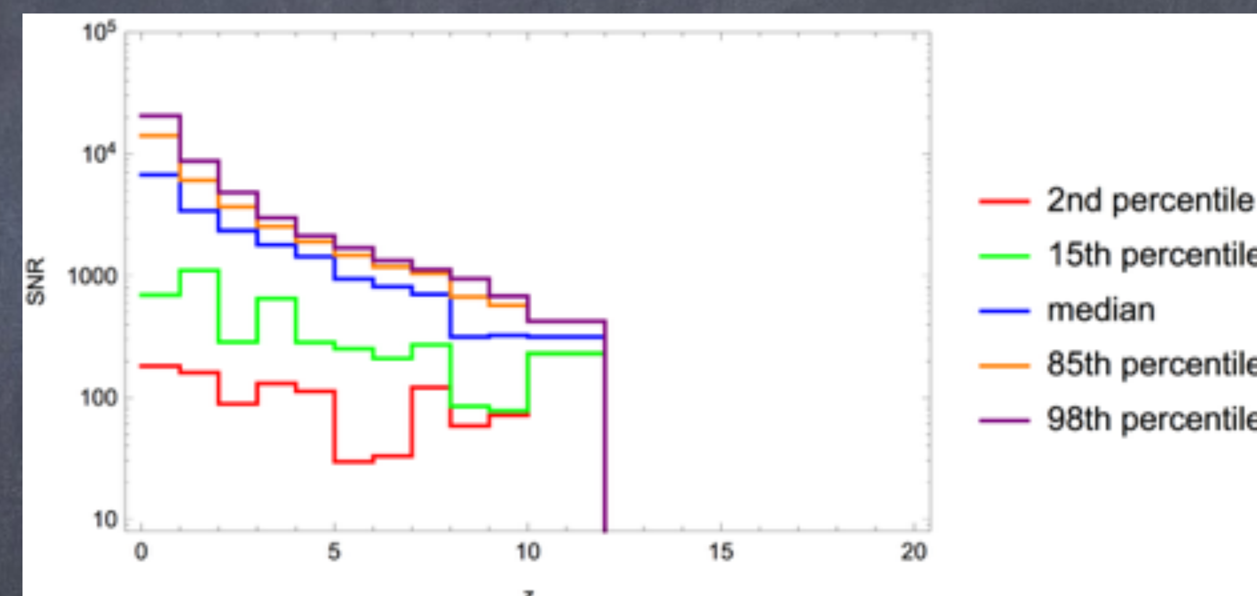


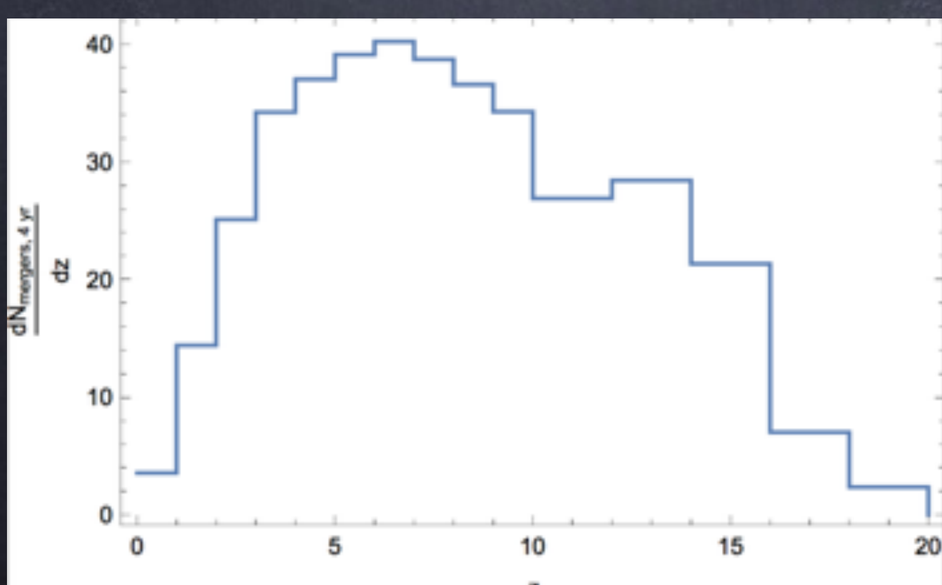
PopIII



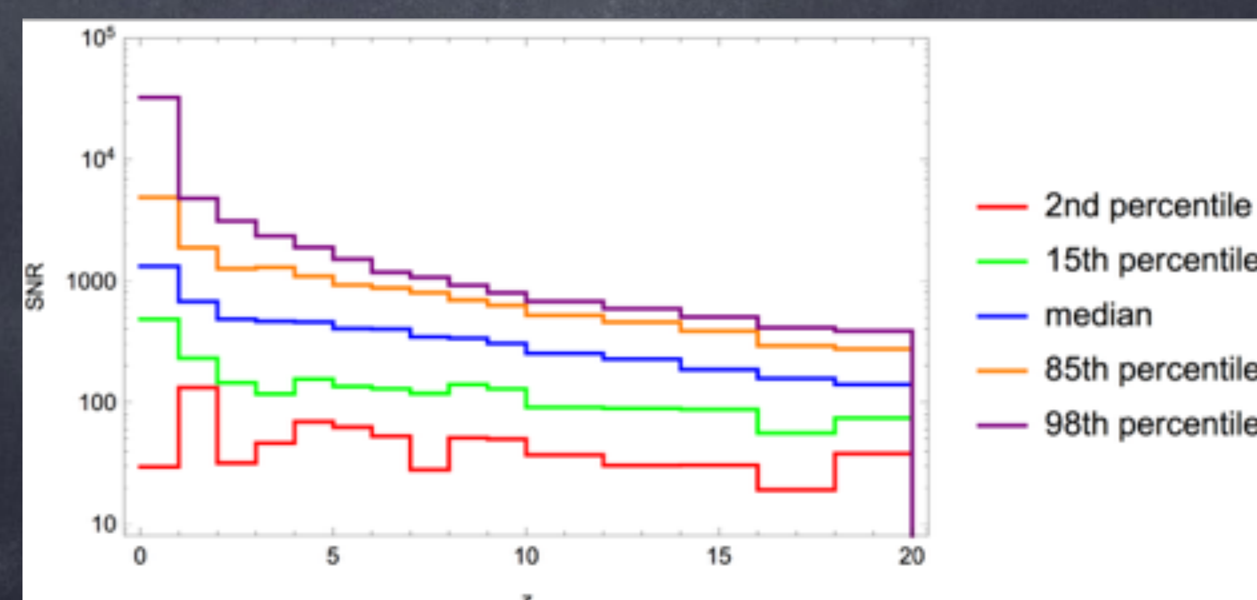


Q3-d



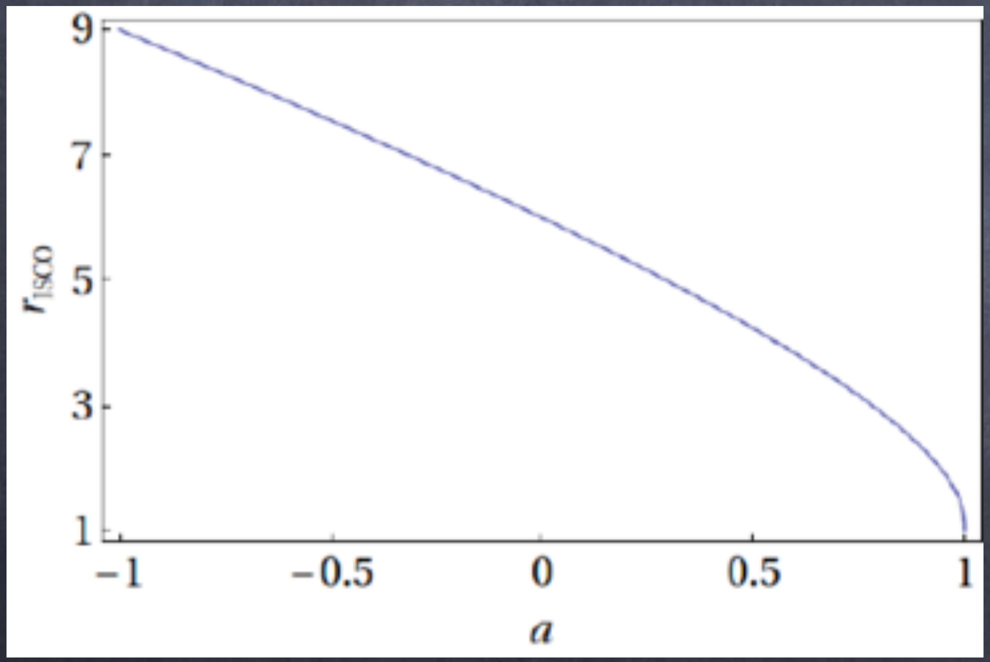


Q3-nod

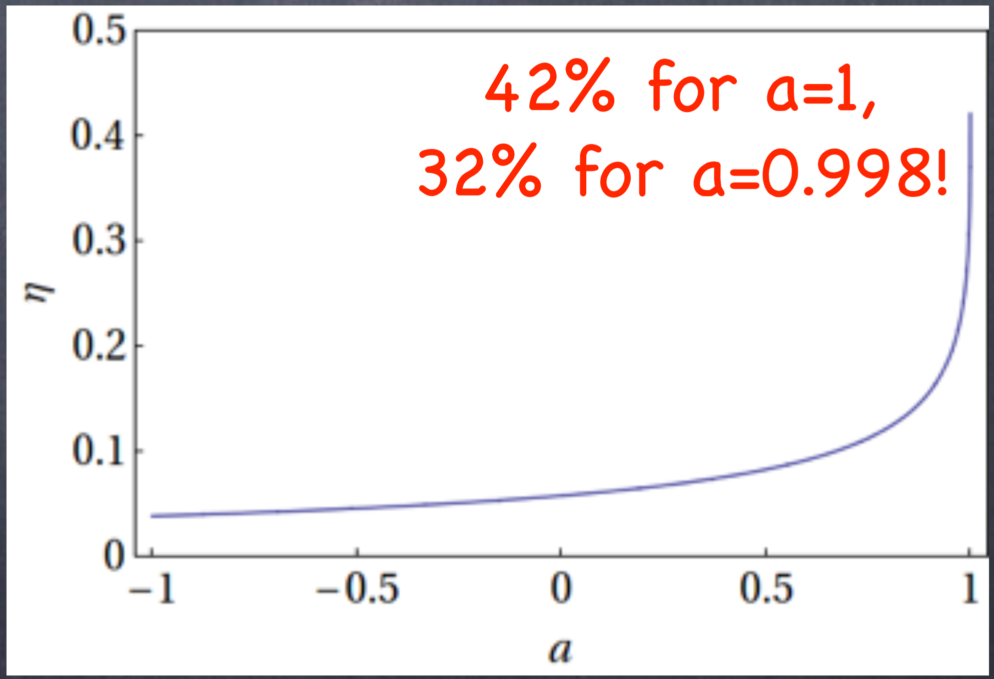


The effect of BH spins: frame-dragging in isolated BHs

- Mass behaves qualitatively like in Newtonian gravity
- Spin affects motion around BHs ("frame dragging"):



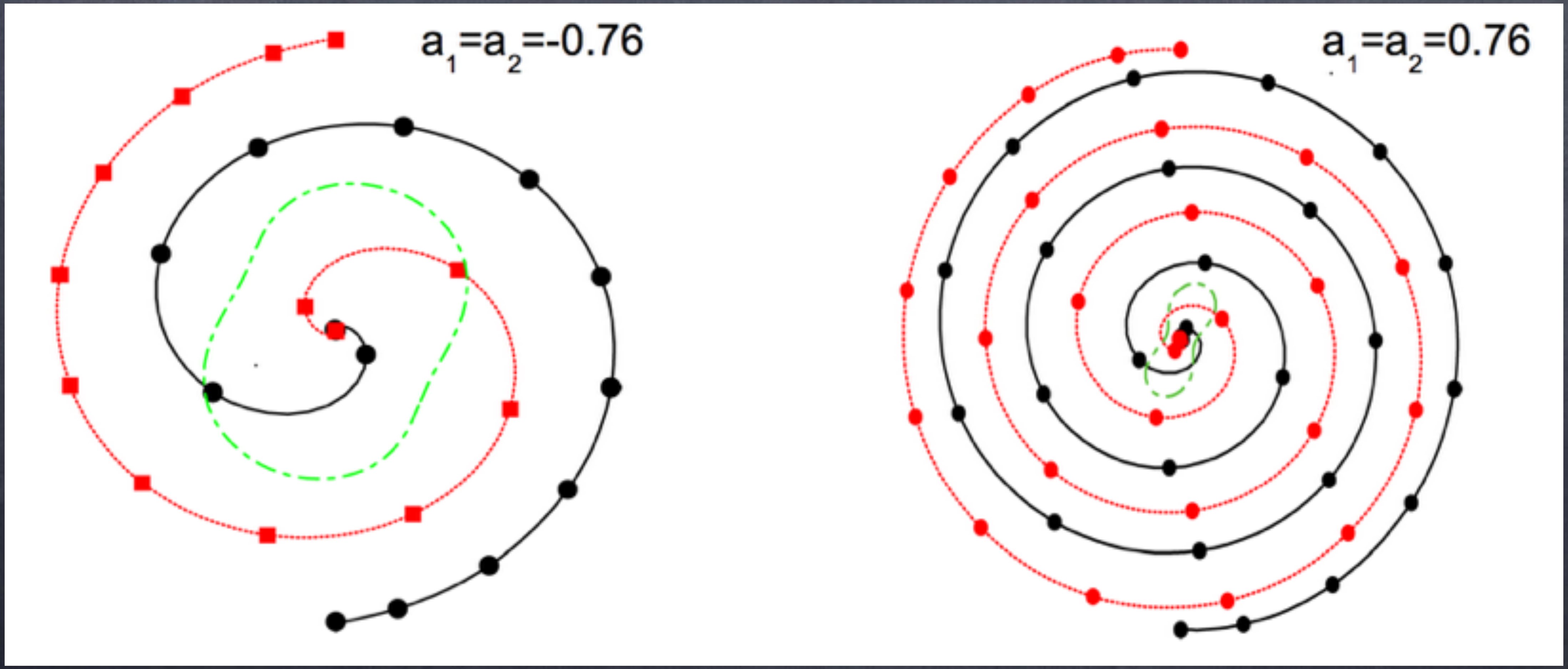
Innermost Stable Circular Orbit
(i.e. inner edge of thin disks)



Efficiency of EM
emission from thin disks

The effect of BH spins: frame-dragging in binaries

- Spin-orbit coupling or "hang-up" effect: for large spins aligned with L, effective ISCO moves inward ...



Figures from Lousto, Campanelli & Zlochower (2006)

The effect of BH spins: frame-dragging in binaries

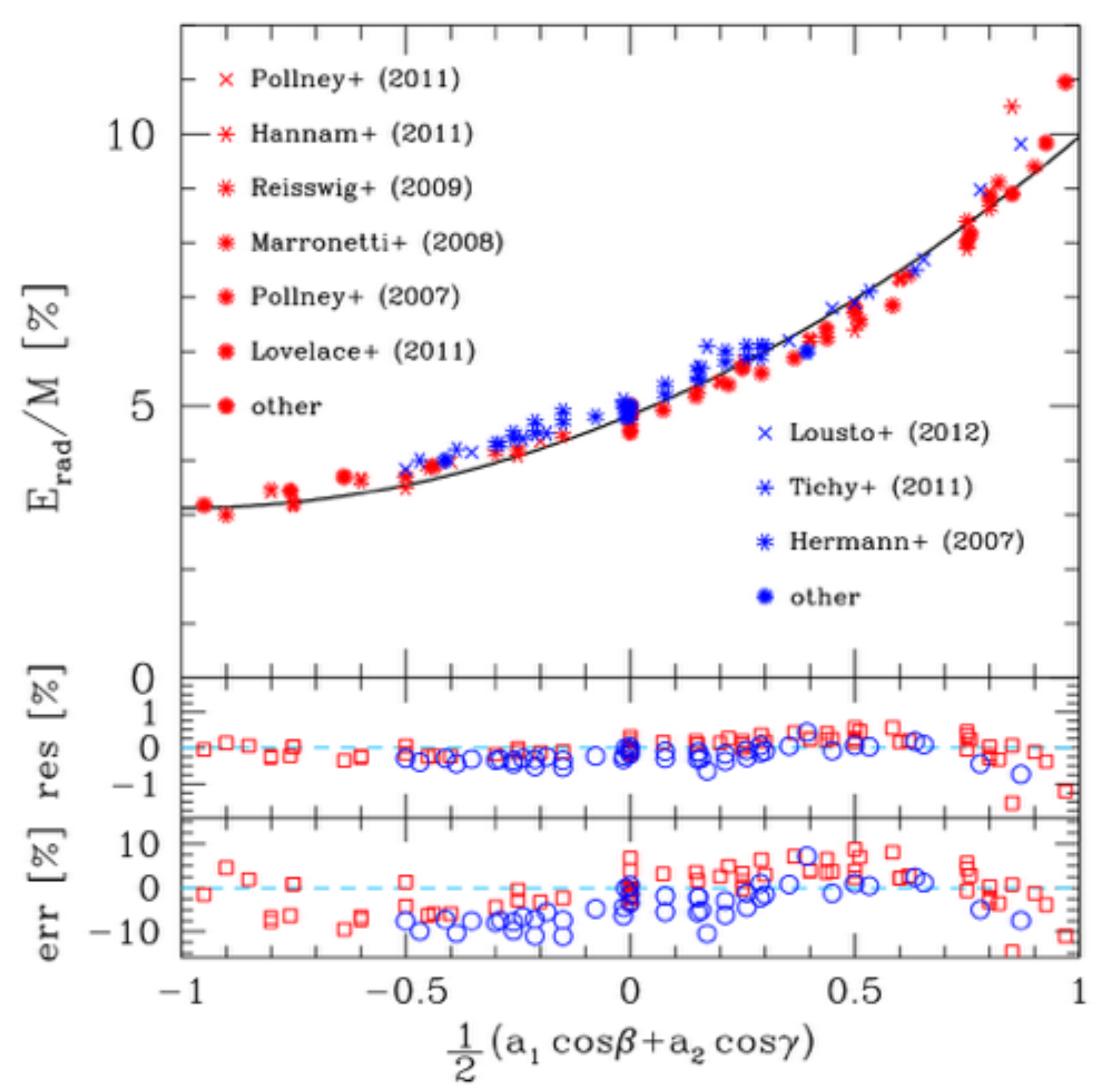


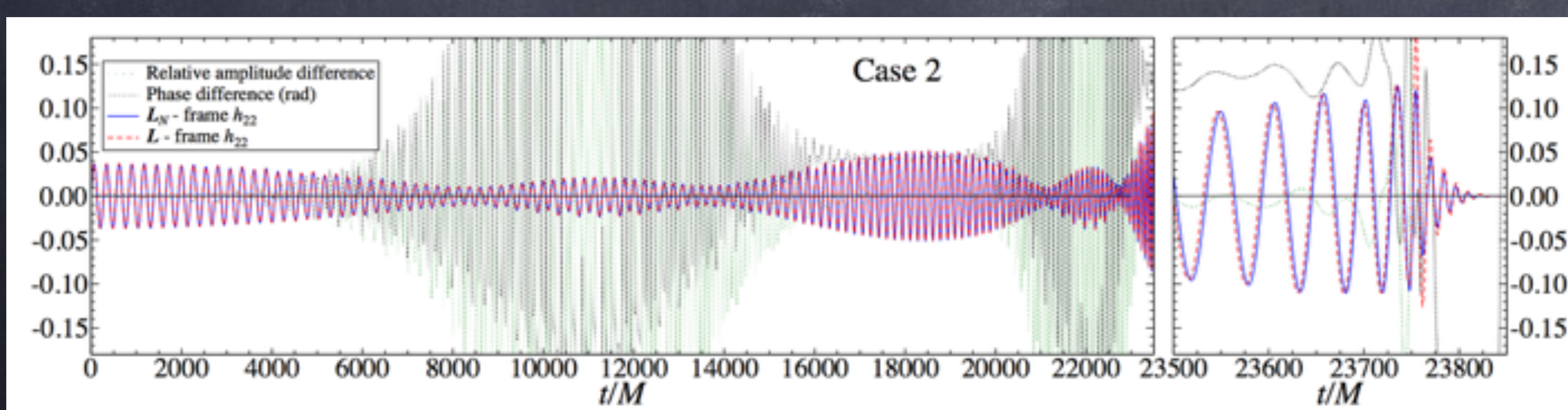
Figure from EB, Morozova & Rezzolla (2012)

... and GW "efficiency" gets larger

Spins strongly affect GW signals!

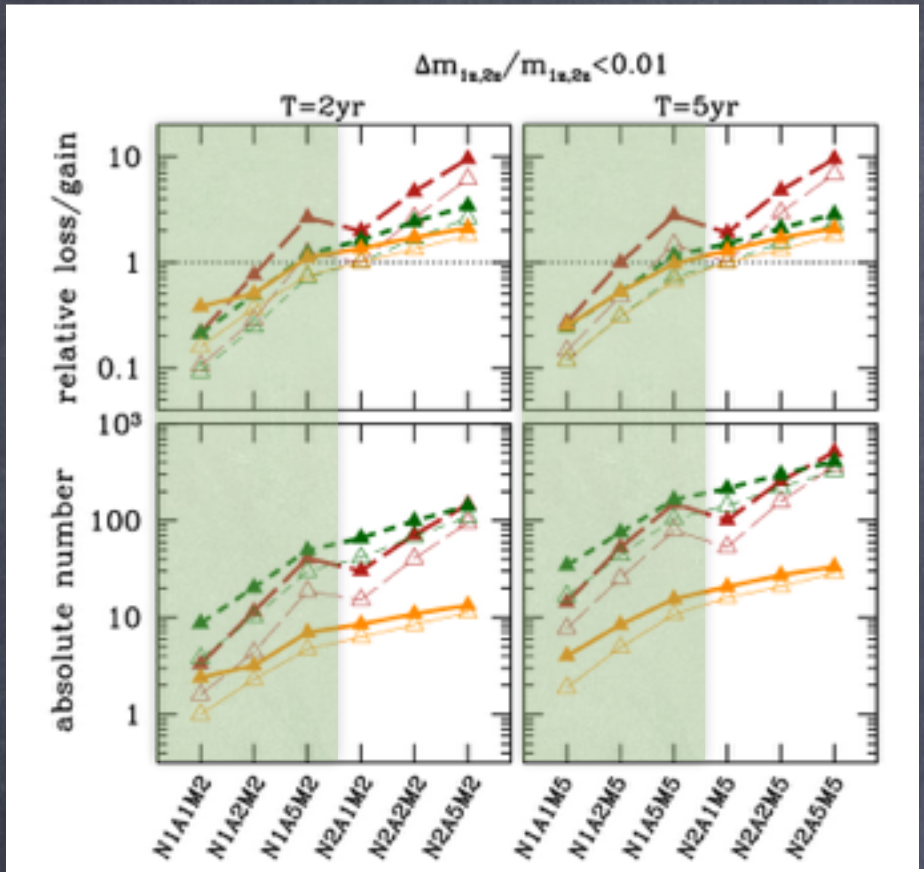
The effect of BH spins on the waveforms

- GW amplitude at merger increases with spins (because ISCO moves inward for larger spins)
- Spin precesses around total angular momentum $J=L+S_1+S_2$
- Precession-induced modulations observable with GW detectors:
  - increase SNR and improve measurements of binary parameters (e.g. luminosity distance and sky localization)
  - Allow measurements of angle between spins



EOB waveforms for BH binary with mass ratio 1:6 and spins 0.6 and 0.8, from Pan et al (2013)

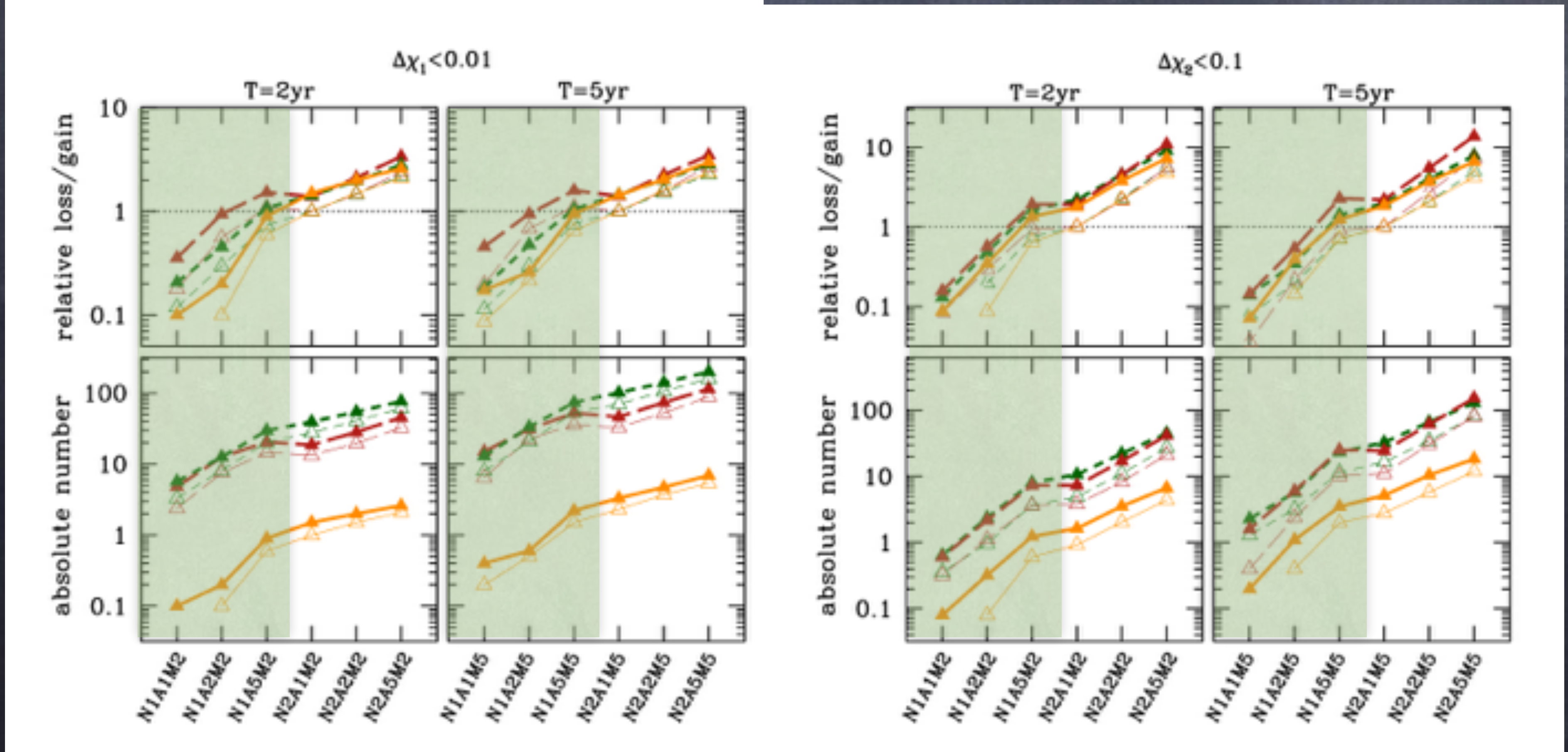
Errors on individual masses/spins



brown = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

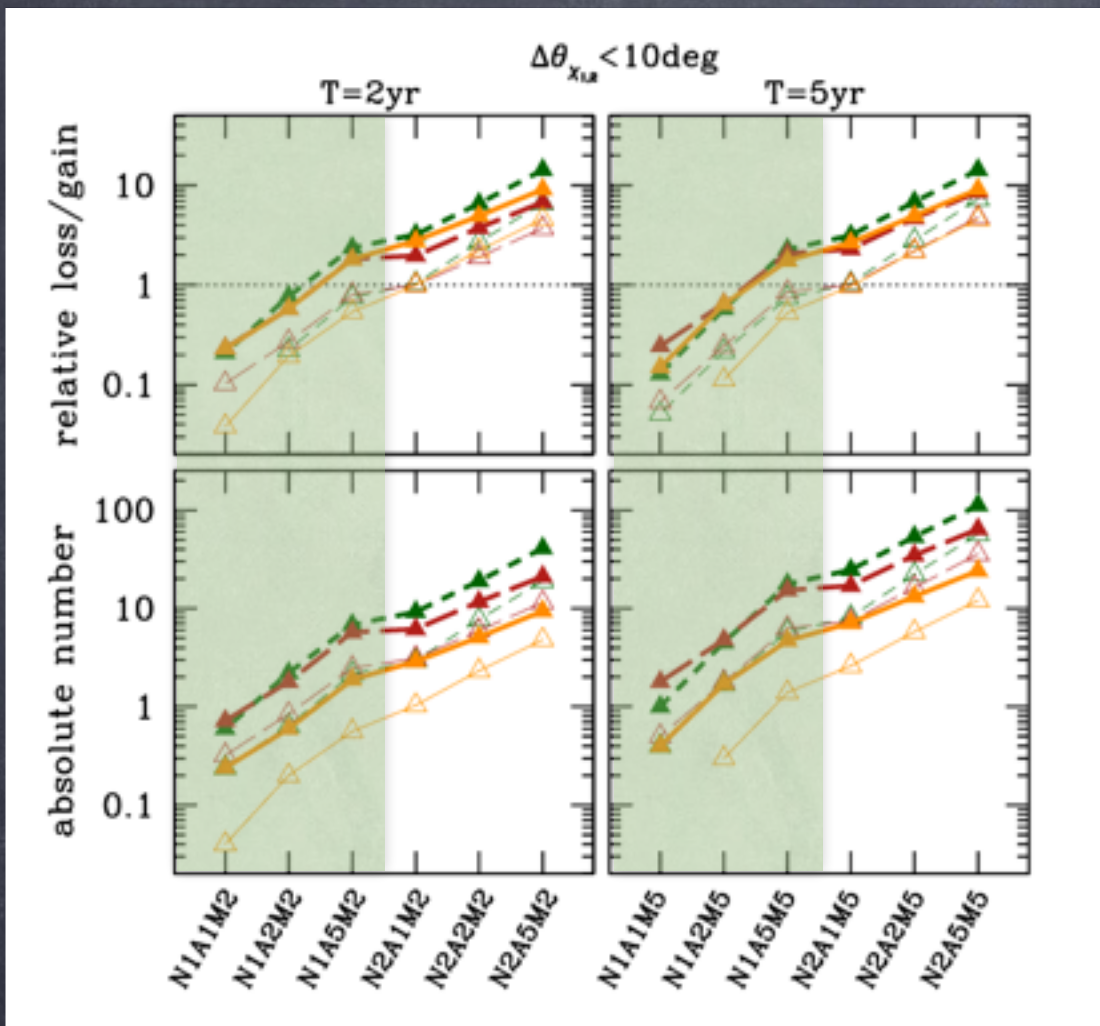
Relative loss relative to NGO (N2A1MkL4)

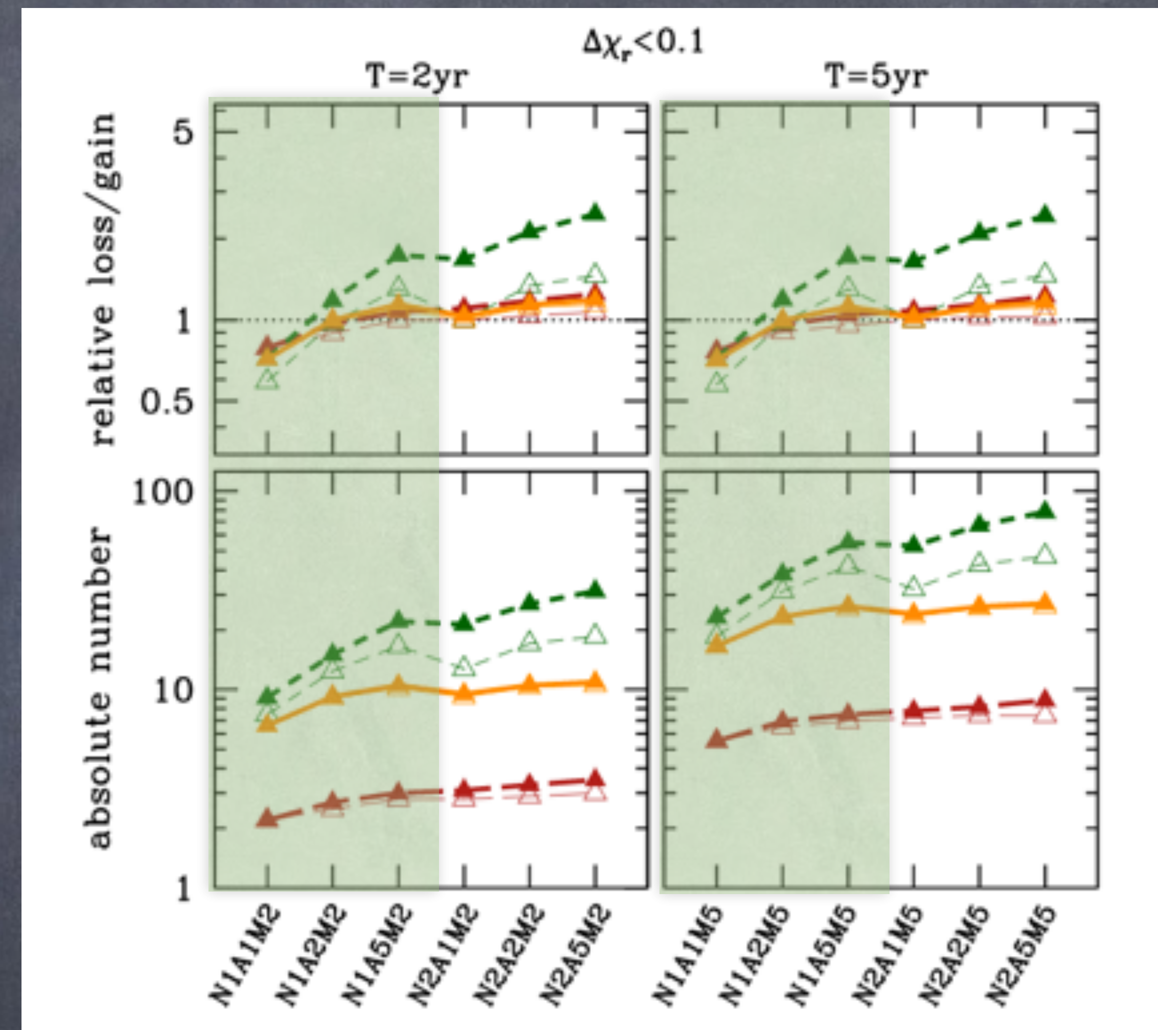
Provides information about properties of BH accretion and BH mass history



From
Klein EB et al
2015

Errors on spin inclinations and final spin





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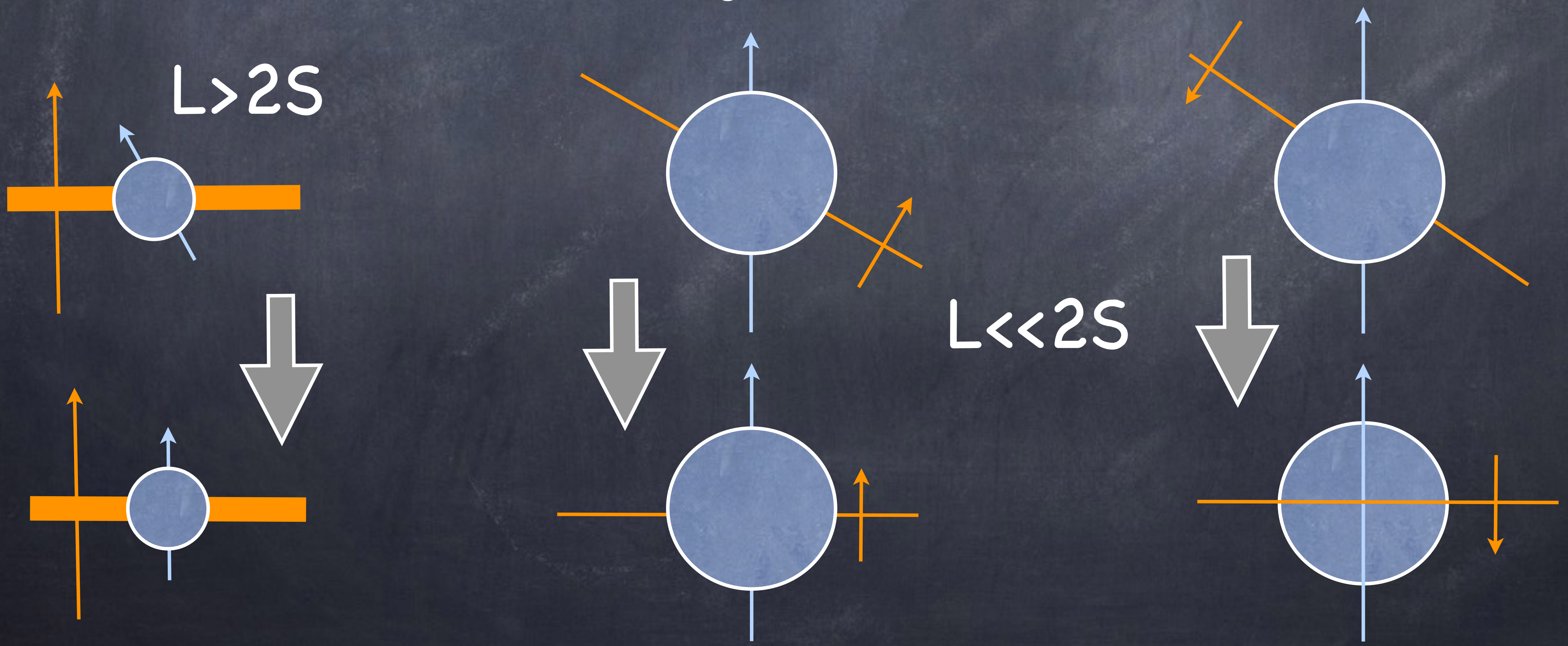
Relative loss relative to NGO (N2A1MkL4)

Provides information about interactions with gas (Bardeen-Petterson effect) and ringdown tests of GR

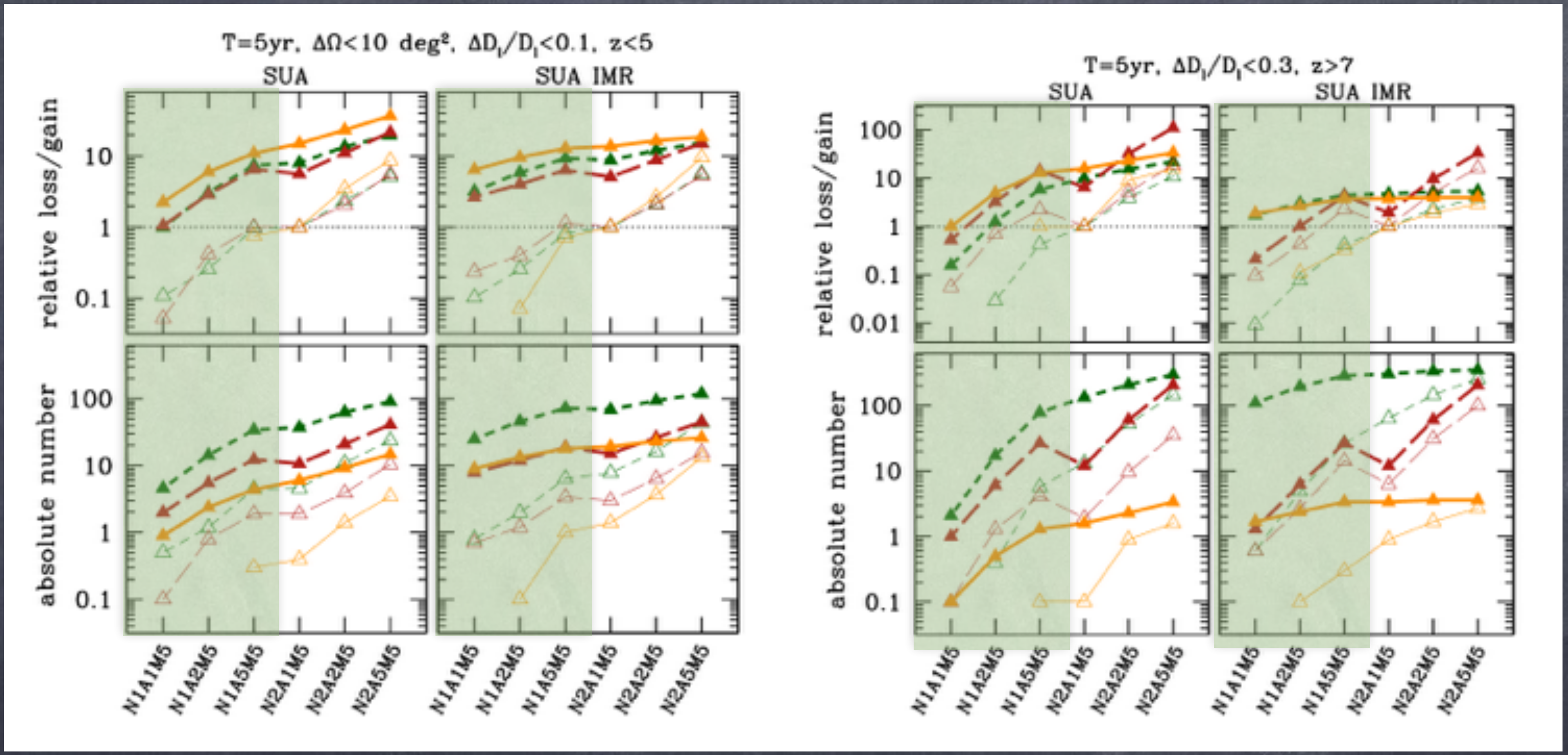
The Bardeen Petterson effect

(see also King, Pringle, Dotti, Volonteri, Perego, Colpi, ...)

- Coupling between BH spin S and angular momentum L of misaligned accretion disk + dissipation
- Either aligns or anti-aligns S and L in ~10^5 yrs (for MBHs) << accretion timescale
- Anti-alignment only if disk carries little angular momentum (L < 2S) and is initially counterrotating



Cosmography ("standard sirens") and probes of massive BH formation



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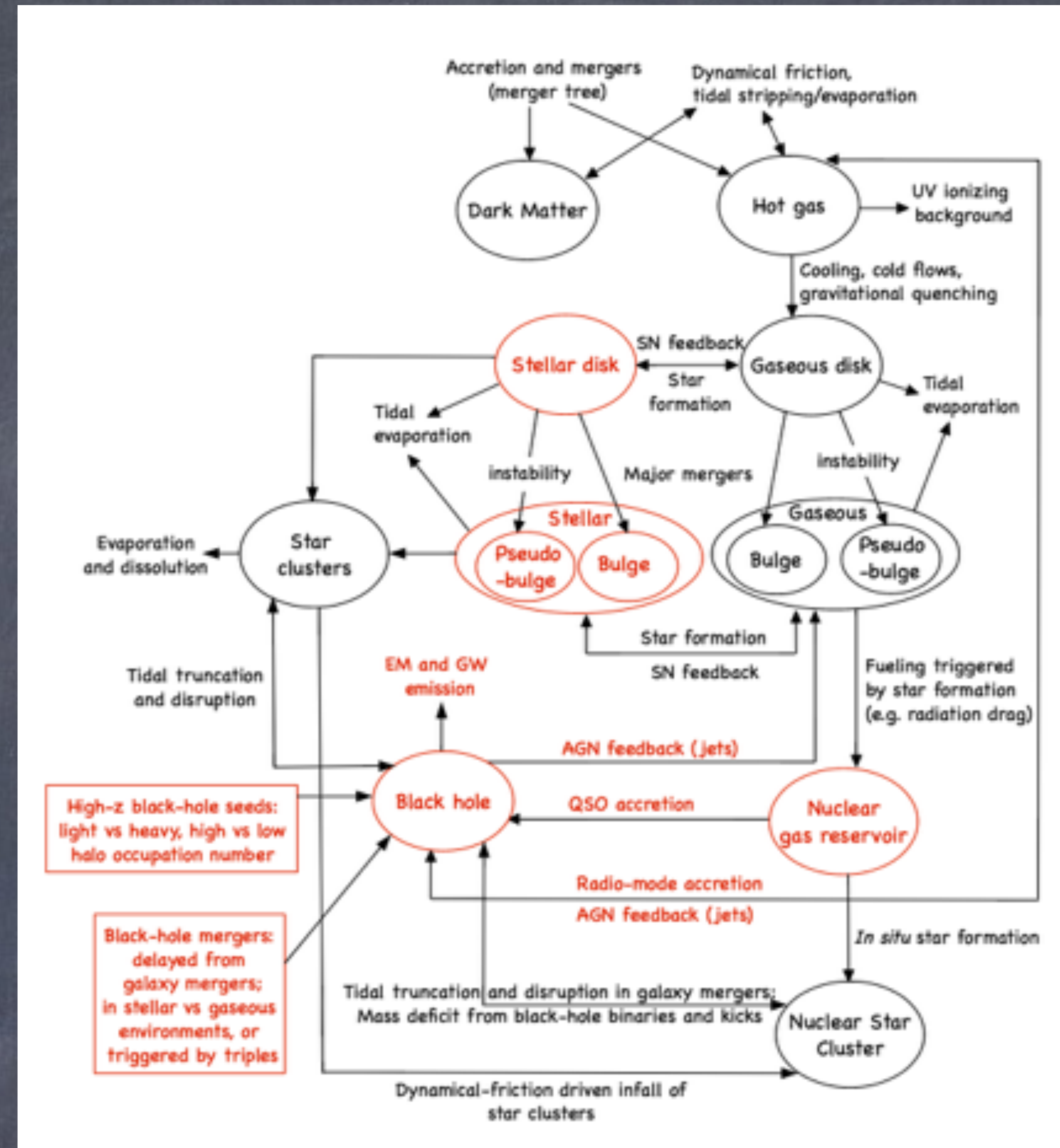
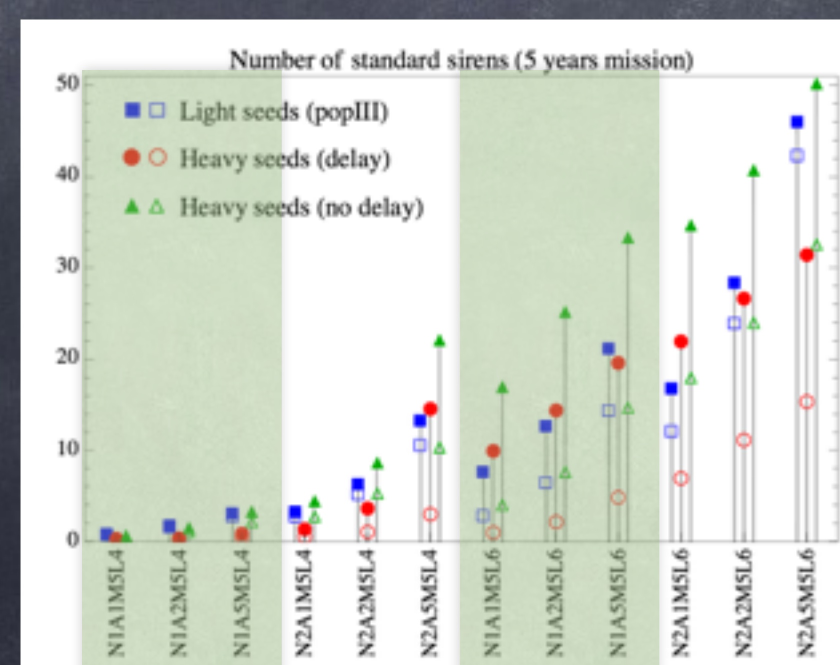
Relative loss relative to NGO (N2A1MkL4)

Electromagnetic counterparts

- GWs provide measurement of luminosity distance (though degraded by weak lensing) but not redshift
- In order to do cosmography in a non-statistical way, we need redshift
- Electromagnetic (spectroscopic or photometric) redshift measurement needs presence of gas, e.g. radio jet+ follow-up optical emission





From Tamanini et al 2016

Electromagnetic counterparts and cosmography

Model	N2A5M5L6						N2A2M5L4					
	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a
5 param.	100	4.31	7.16	1.58	13.2	92.3	67.8	320	799	47.7	344	5530
	100	18.0	24.9	9.95	88.6	392	2.54	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$
	100	2.80	5.15	0.681	4.66	55.7	68.6	138	306	13.3	127	2400
ΛCDM + curv.	100	0.0819	0.281	0.0521			91.5	0.471	2.66	0.429		
	100	0.220	0.541	0.136			12.7	$\gg 10^4$	$\gg 10^4$	$\gg 10^4$		
	100	0.0473	0.207	0.0316			90.7	0.174	1.26	0.145		
ΛCDM	100	0.0473	0.0473	0.0210			97.5	0.275	0.275	0.0910		
	100	0.0917	0.0917	0.0480			32.2	0.543	0.543	0.220		
	100	0.0371	0.0371	0.0146			99.2	0.126	0.126	0.0400		
DDE	100				0.253	1.32	97.5				1.03	6.36
	100				0.584	2.78	37.3				4.96	26.1
	100				0.176	1.00	95.8				0.427	2.87
Accel. & curv. test	100	0.0190	0.0735				99.2	0.211	0.396			
	100	0.0280	0.105				37.3	0.977	1.30			
	100	0.0213	0.0631				94.1	0.116	0.202			
Error on Ω_M	100	0.0173					100	0.0670				
	100	0.0238					53.4	0.0755				
	100	0.0172					100	0.0437				
Error on h	100			0.00712			100			0.0146		
	100			0.00996			53.4			0.0175		
	100			0.00531			100			0.00853		
Error on w_0	100				0.0590		100				0.121	
	100				0.0786		53.4				0.146	
	100				0.0467		100				0.0734	

sky-location by inspiral only

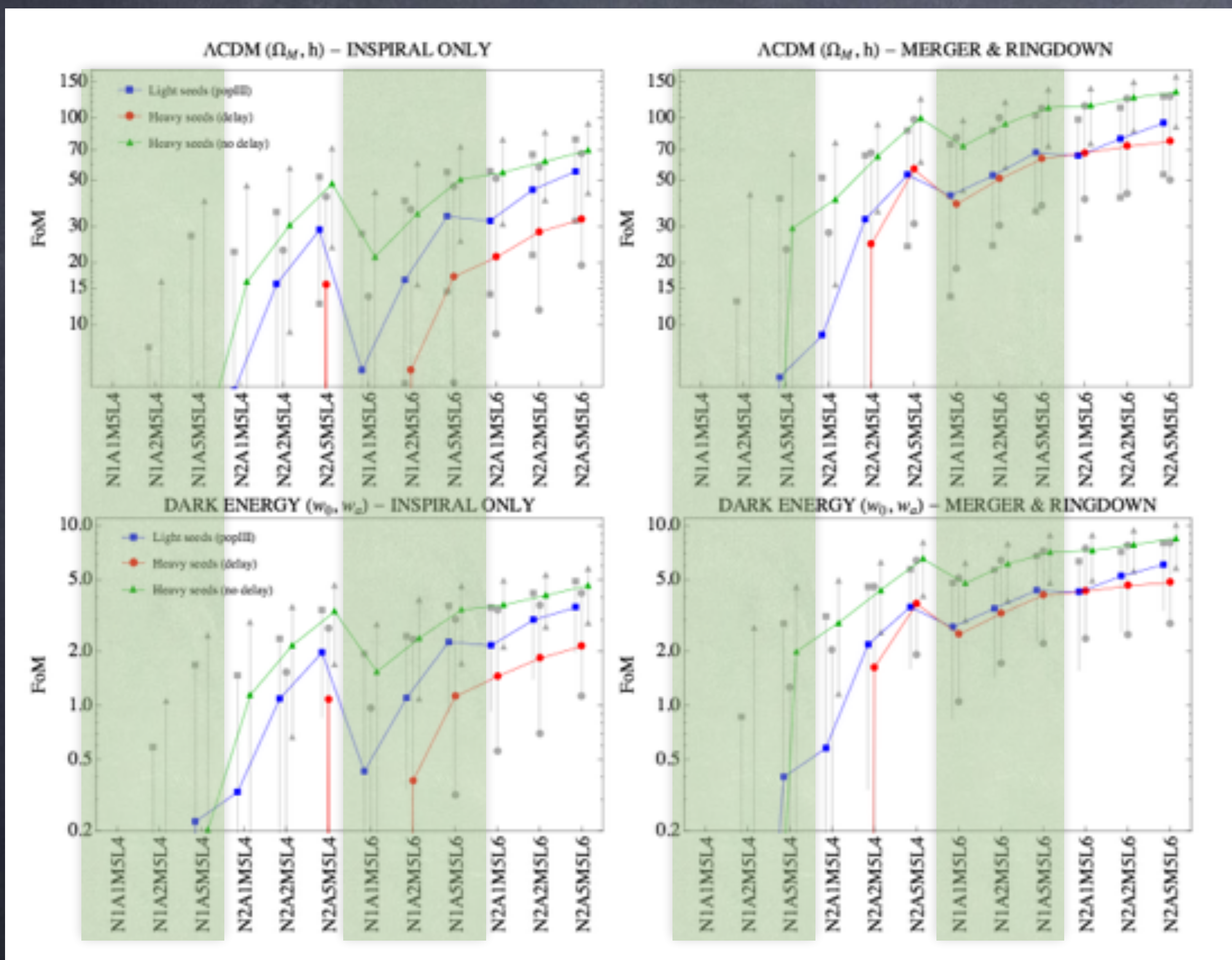
Model	N2A5M5L6						N2A2M5L4					
	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a
5 param.	100	2.51	4.40	0.951	8.01	55.2	80.5	120	253	24.8	177	2230
	100	4.64	6.90	2.58	22.4	103	44.1	1480	3250	371	2350	$\gg 10^4$
	100	1.05	1.97	0.265	2.07	21.2	93.2	12.6	27.8	2.08	15.9	227
ΛCDM + curv.	100	0.0467	0.155	0.0299			96.6	0.315	1.51	0.228		
	100	0.0875	0.209	0.0527			77.1	0.396	1.61	0.306		
	100	0.0265	0.0914	0.0161			99.2	0.0610	0.342	0.0520		
ΛCDM	100	0.0267	0.0267	0.0121			99.2	0.121	0.121	0.0445		
	100	0.0368	0.0368	0.0199			90.7	0.151	0.151	0.0681		
	100	0.0186	0.0186	0.00803			100	0.0464	0.0464	0.0159		
DDE	100				0.149	0.798	98.3				0.507	3.09
	100				0.241	1.14	89.0				0.777	4.06
	100				0.101	0.544	99.2				0.201	1.20
Accel. & curv. test	100	0.0105	0.0412				99.2	0.0660	0.174			
	100	0.00972	0.0429				84.7	0.0544	0.161			
	100	0.00887	0.0310				99.2	0.0381	0.0804			
Error on Ω_M	100	0.00966					100	0.0319				
	100	0.00935					94.1	0.0283				
	100	0.00788					100	0.0199				
Error on h	100			0.00412			100			0.00850		
	100			0.00446			94.1			0.00937		
	100			0.00307			100			0.00485		
Error on w_0	100				0.0342		100				0.0678	
	100				0.0368		94.1				0.0729	
	100				0.0254		100				0.0416	

From Tamanini et al 2016

sky-location by IMR

- Better LISA configurations provide measurements of h under different systematics than present probes
- Measurement of Ω_m slightly better than SNIa with best designs
- Measurement of combination of Ω_m and Ω_Λ different from SNIa/CMB (i.e. potential to break degeneracy)
- Discovery space: LISA sensitive to cosmological evolution at z ~ 1 - 8

Cosmography with different designs



N2A5M5L6 N2A2M5L6 N2A1M5L6 N1A5M5L6 N2A5M5L4	Constraints comparable to or slightly worse than N2A5M5L6
N1A2M5L6	Constraints worse than N2A5M5L6, but better than N2A2M5L4.
N1A1M5L6 N2A2M5L4	Constraints comparable to or slightly better than N2A2M5L4
N2A1M5L4 N1A5M5L4 N1A2M5L4 N1A1M5L4	Constraints worse than N2A2M5L4 or no constraints at all.

FoM ~ 1/error

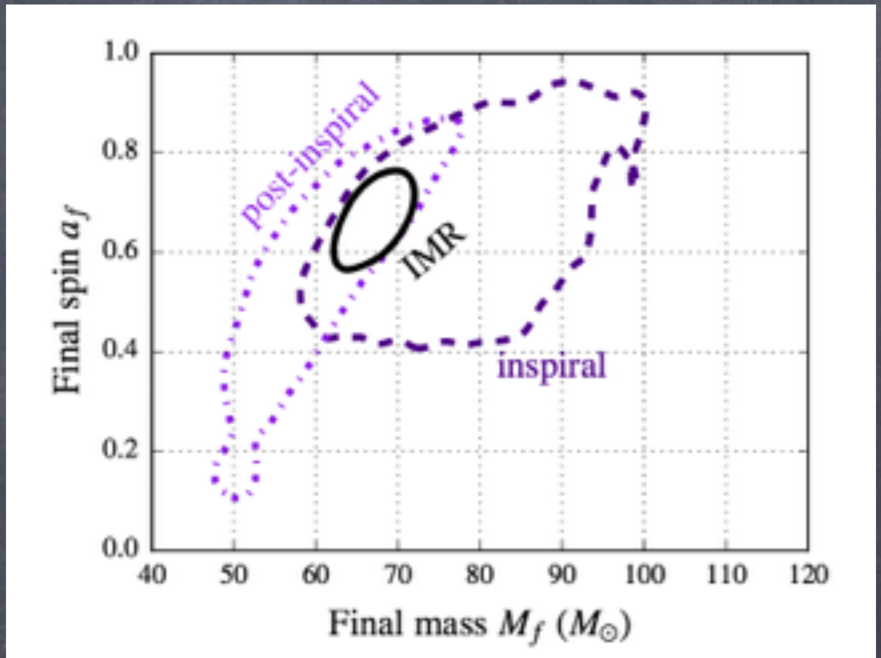
From Tamanini et al 2016

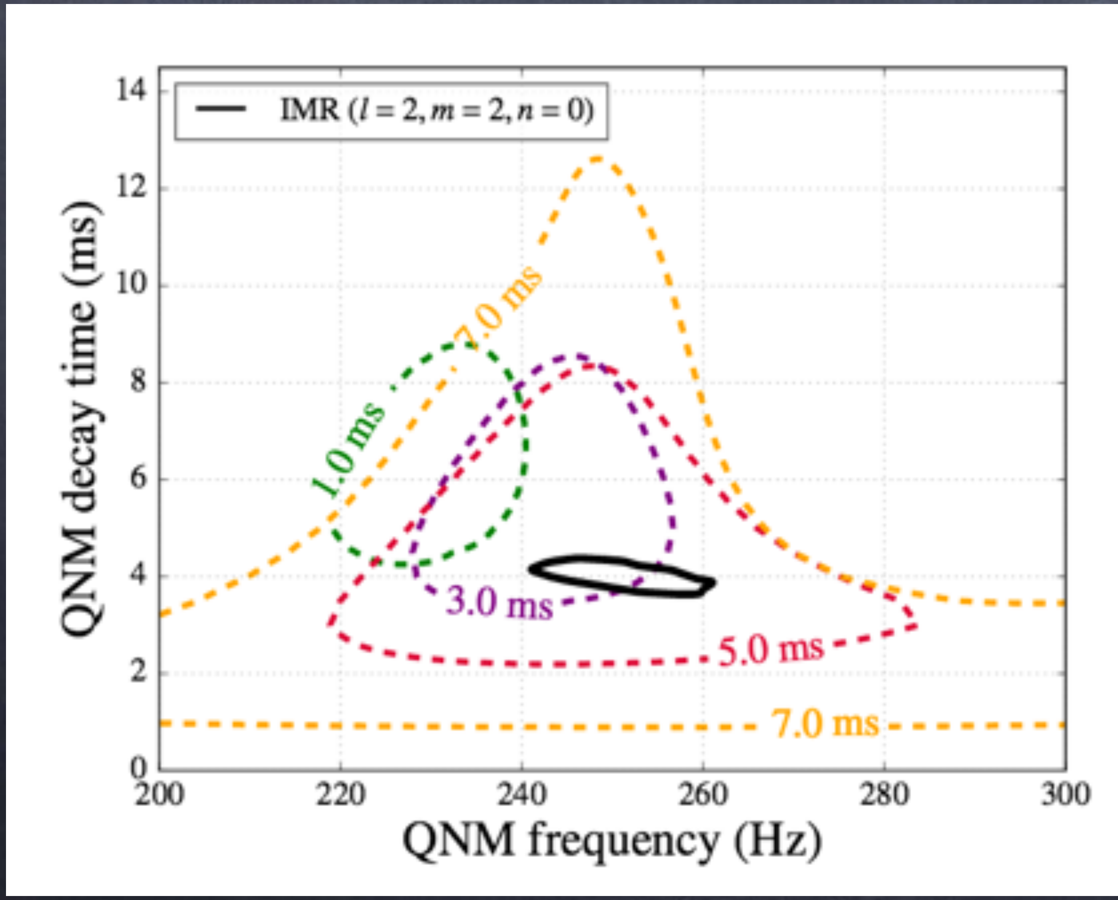
(Future) ringdown tests

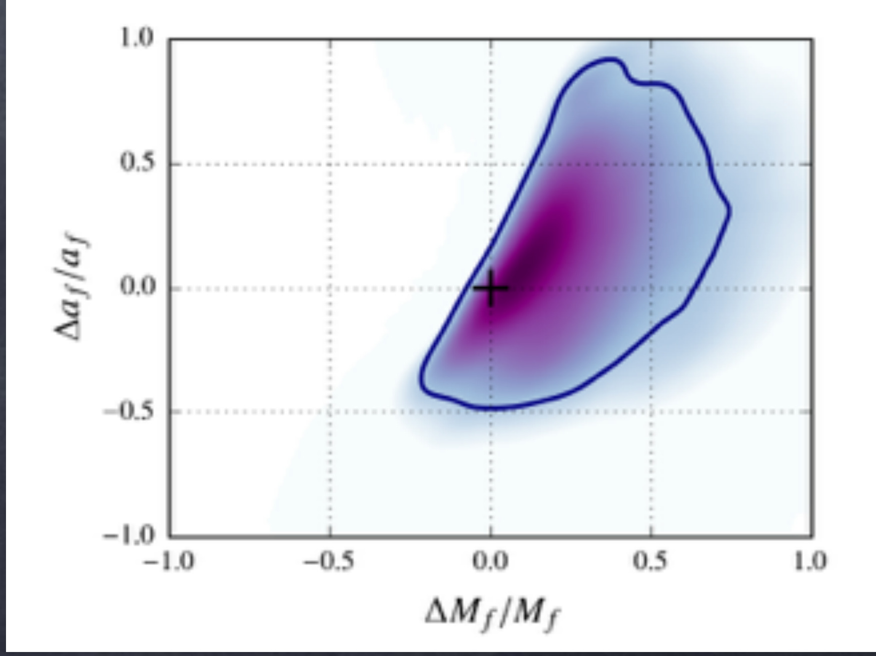
Tests of the no-hair theorem:

$$\omega_{\ell m} = \omega_{\ell m}^{GR}(M,J)(1+\delta\omega_{\ell m}) \qquad \tau_{\ell m} = \tau_{\ell m}^{GR}(M,J)(1+\delta\tau_{\ell m})$$

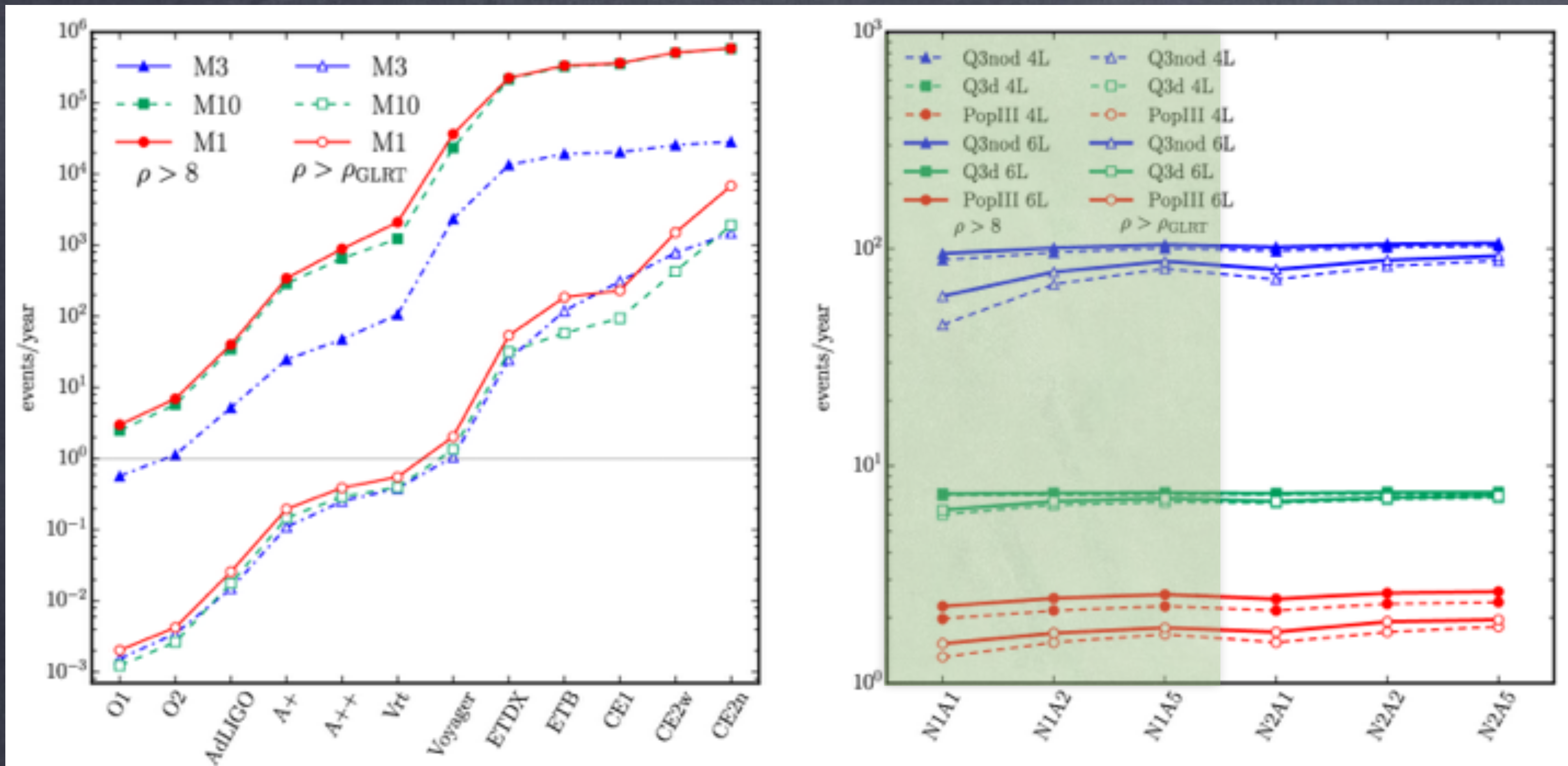
Difficult with advanced detectors because little SNR in ringdown







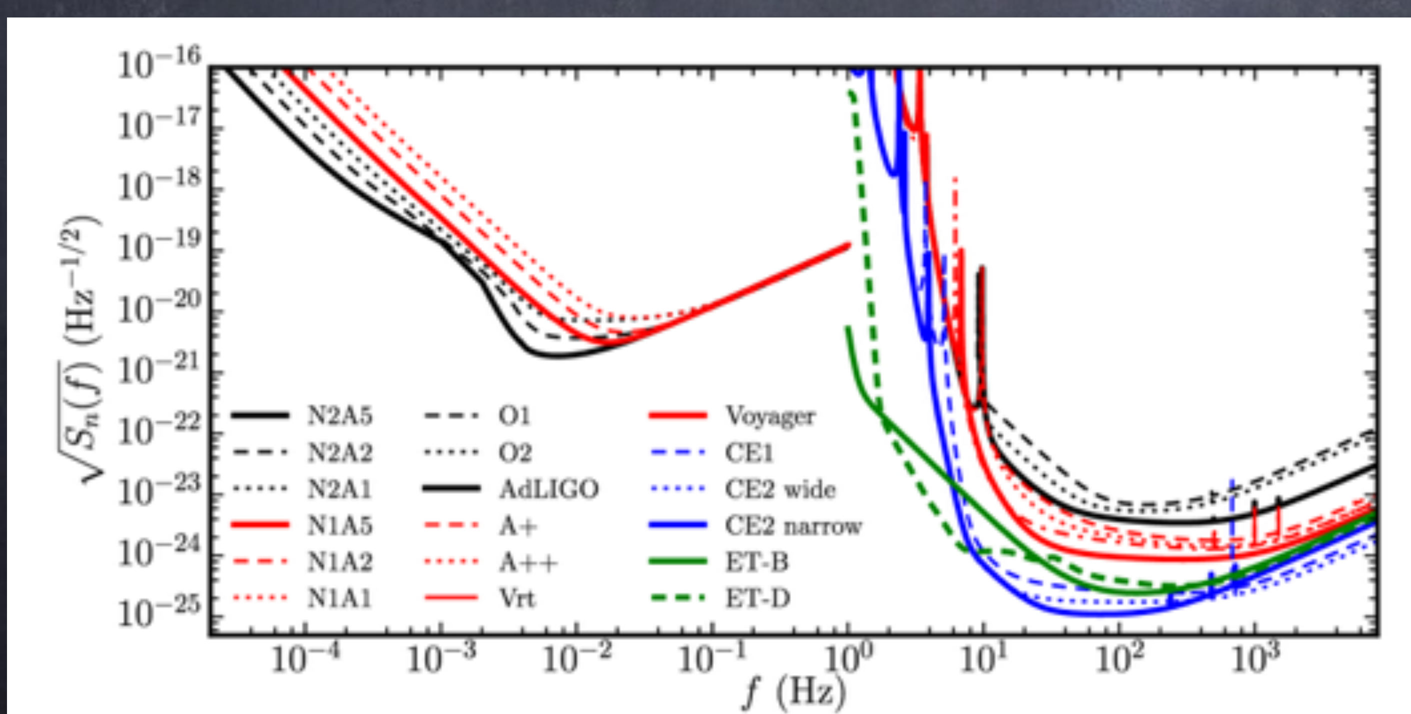
Tests of no-hair theorem by BH ringdown

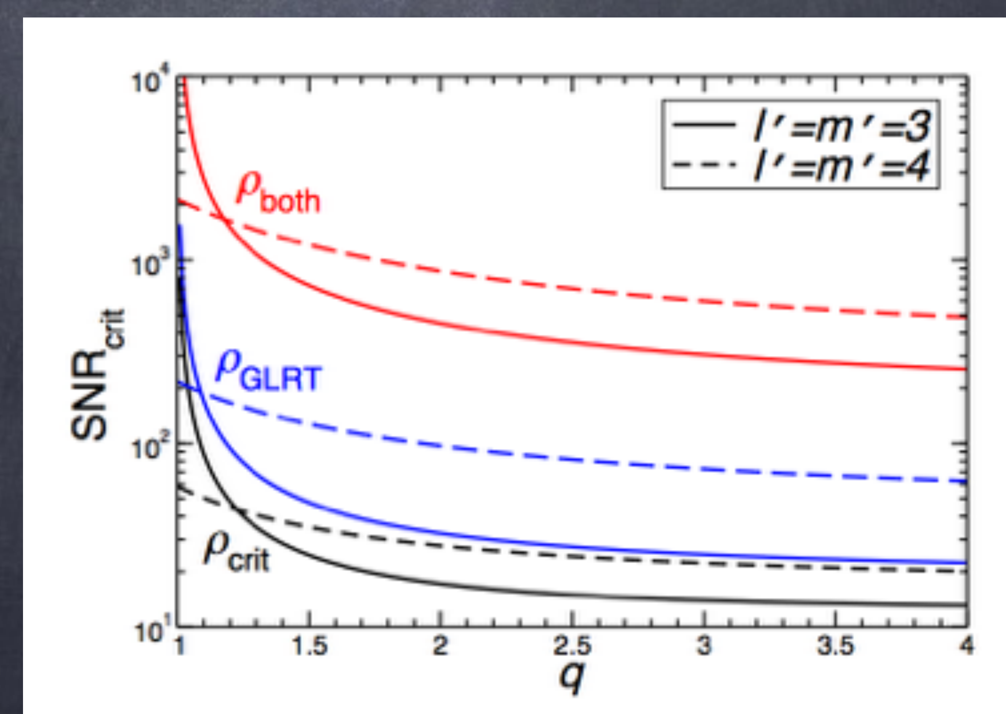


Berti, Sesana, EB, Cardoso, Belczynski, 2016

$$\rho_{\rm GLRT} \equiv \min(\rho^{2,3}_{\rm GLRT}, \rho^{2,4}_{\rm GLRT})$$

Berti et al 2007





What can we learn from PTA limits?

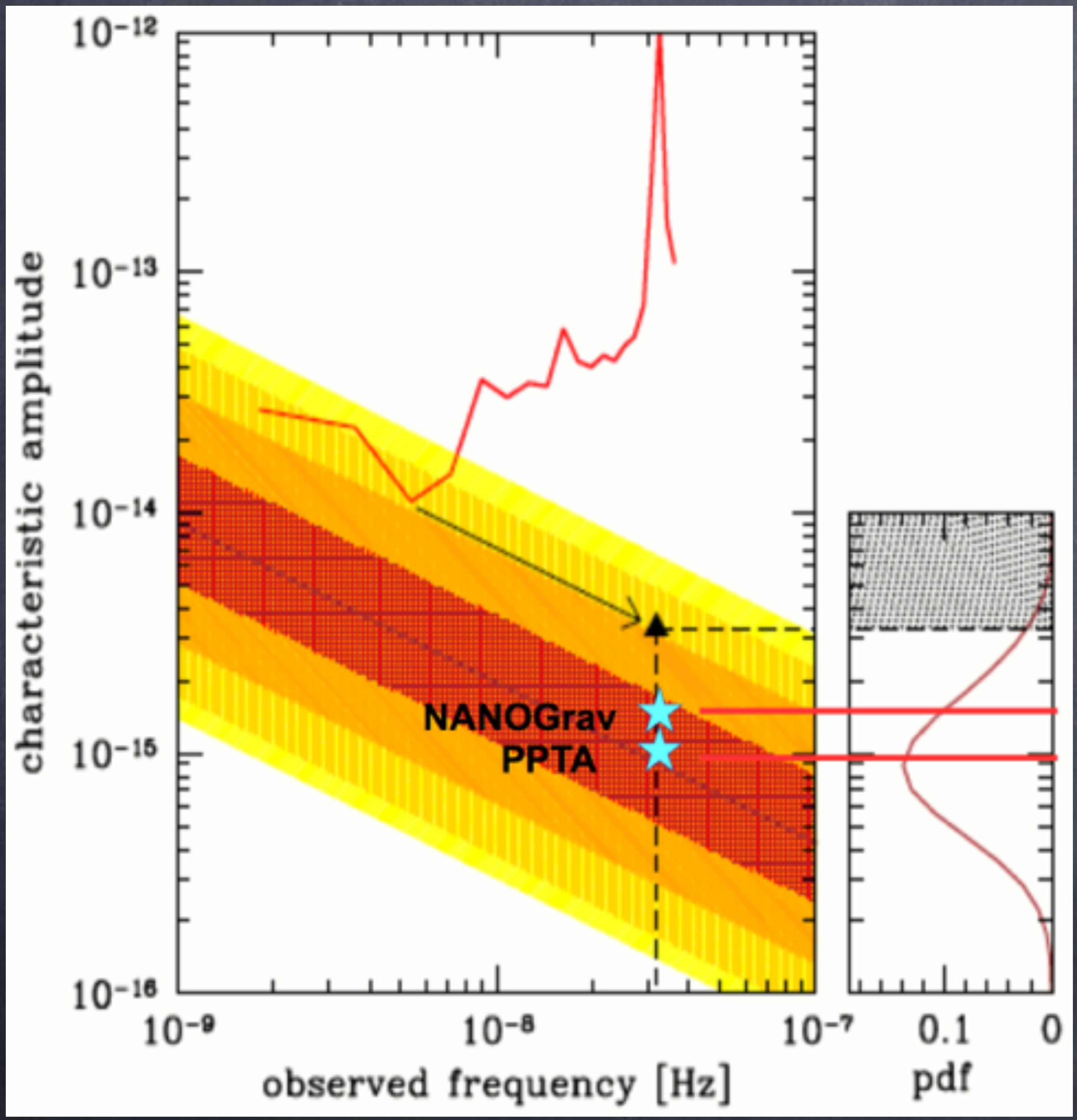


Figure courtesy of A. Sesana

Why are we seeing nothing?

Predictions assume:

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

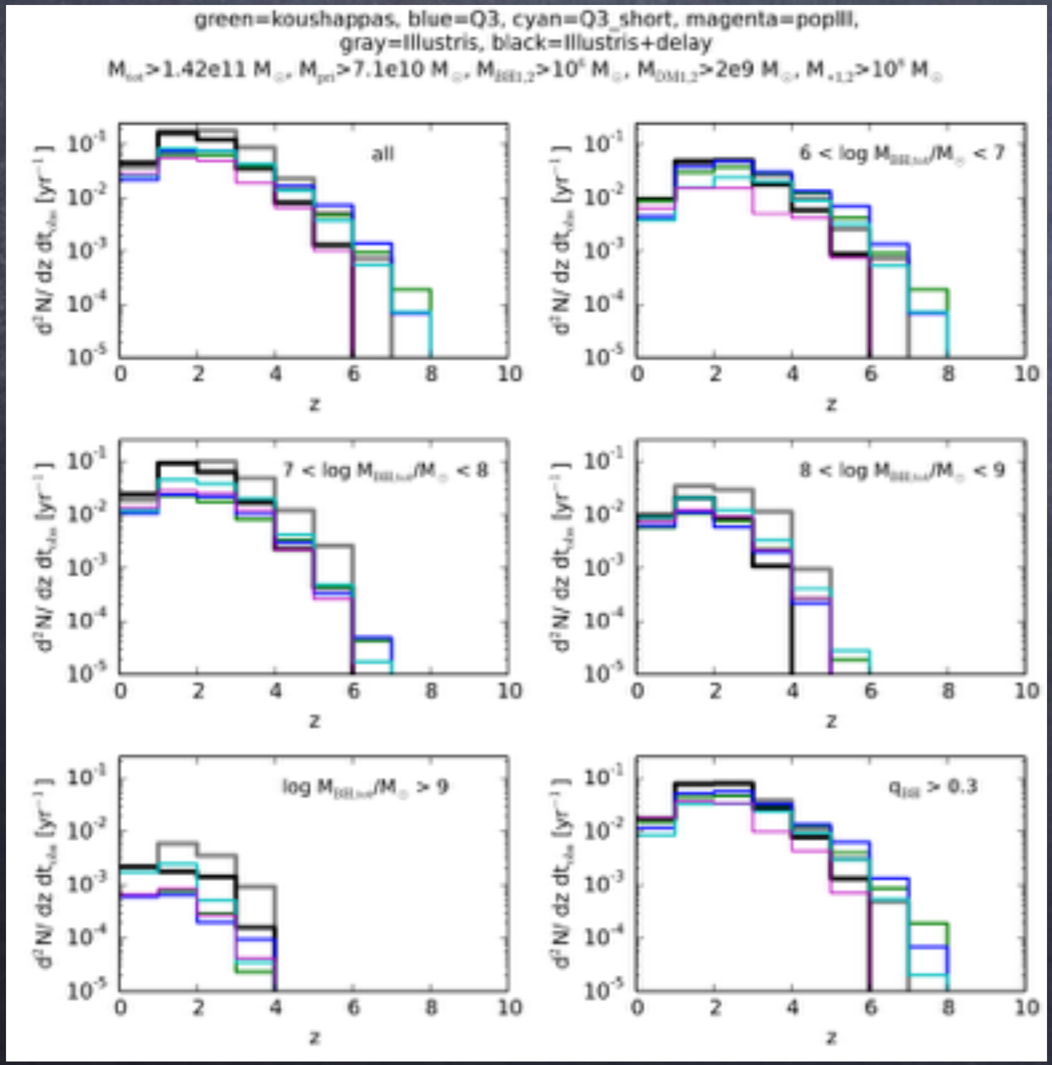
Loopholes:

- 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

What can we learn from PTA limits?

- PTAs sensitive to massive BH mergers like LISA, but larger masses
- Agreement among theoretical models of target massive BH population

EB 2012 vs Illustris



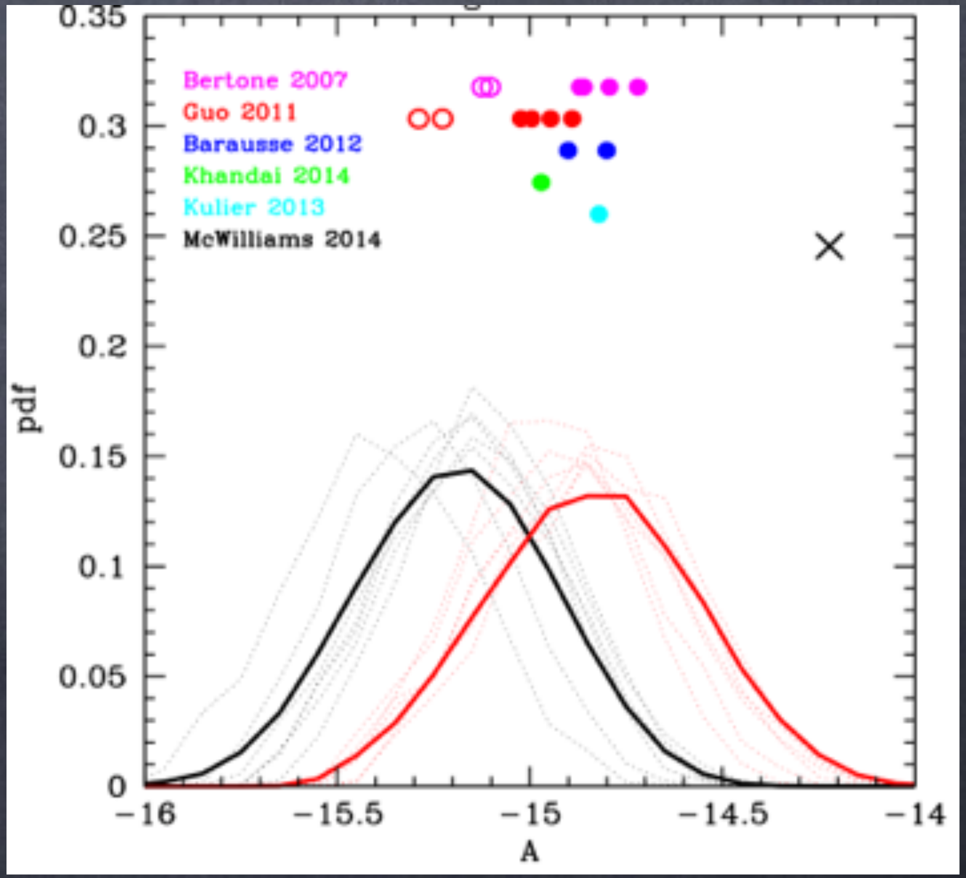
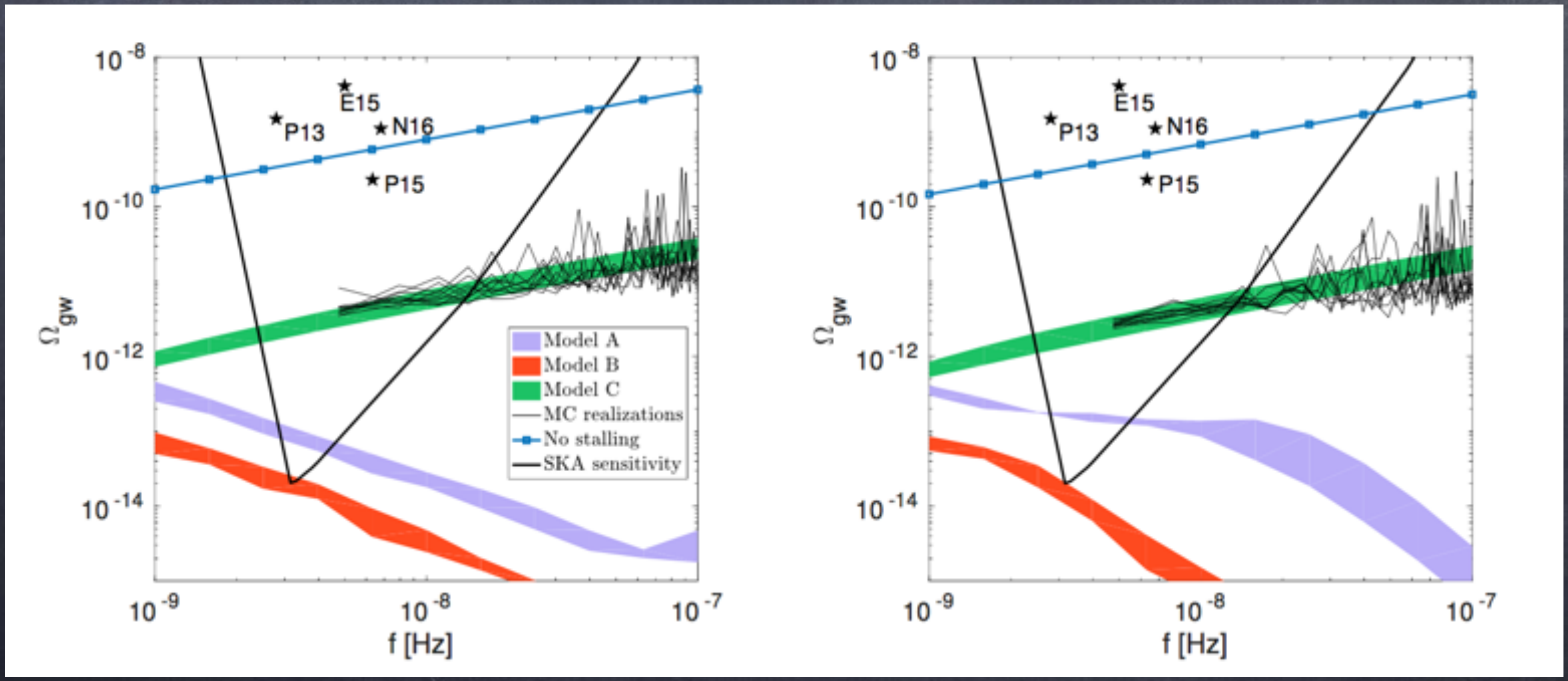


Figure courtesy A. Sesana

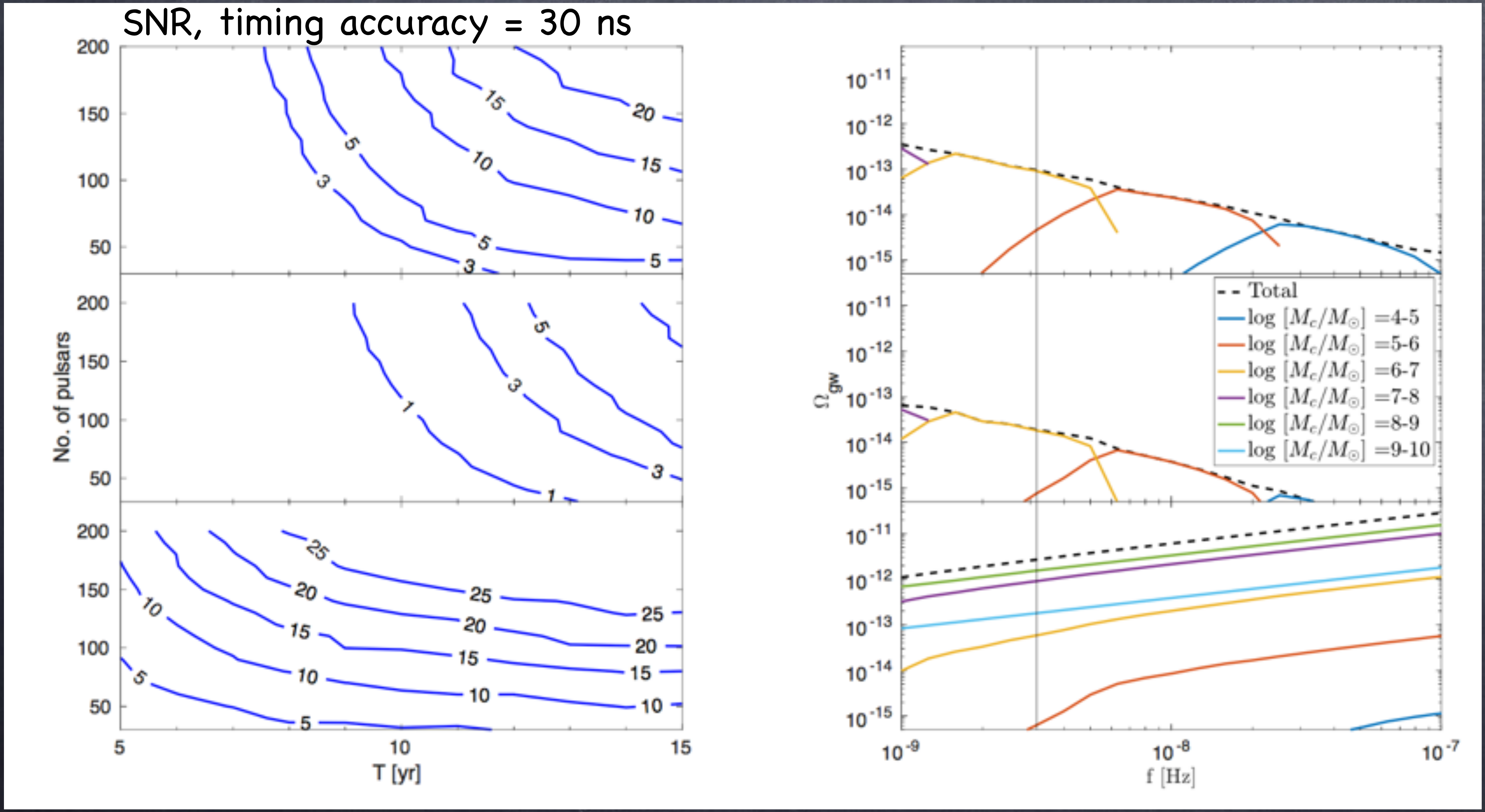
The nightmare scenario, aka the final-pc problem

- What if binaries stall at separations ≳ hardening radius? (i.e. no loss cone replenishment and 3-body interactions with stars become inefficient)
- Model A: all binaries stall 13 Gyr before merger ($a = a_{GW}$)
  Model B: all binaries stall at $a = \max(a_h, a_{GW})$
  Model C: all binaries stall at $a = a_h$
- In model C, binaries with $q \lesssim$ 1.e-3 merge in a Hubble time because $a_h < a_{GW}$



Assumed 50 pulsars with timing accuracy of 30 ns and 10 yrs observation time (Dvorkin & EB 2017)

The nightmare scenario, aka the final-pc problem



Model A

Model B

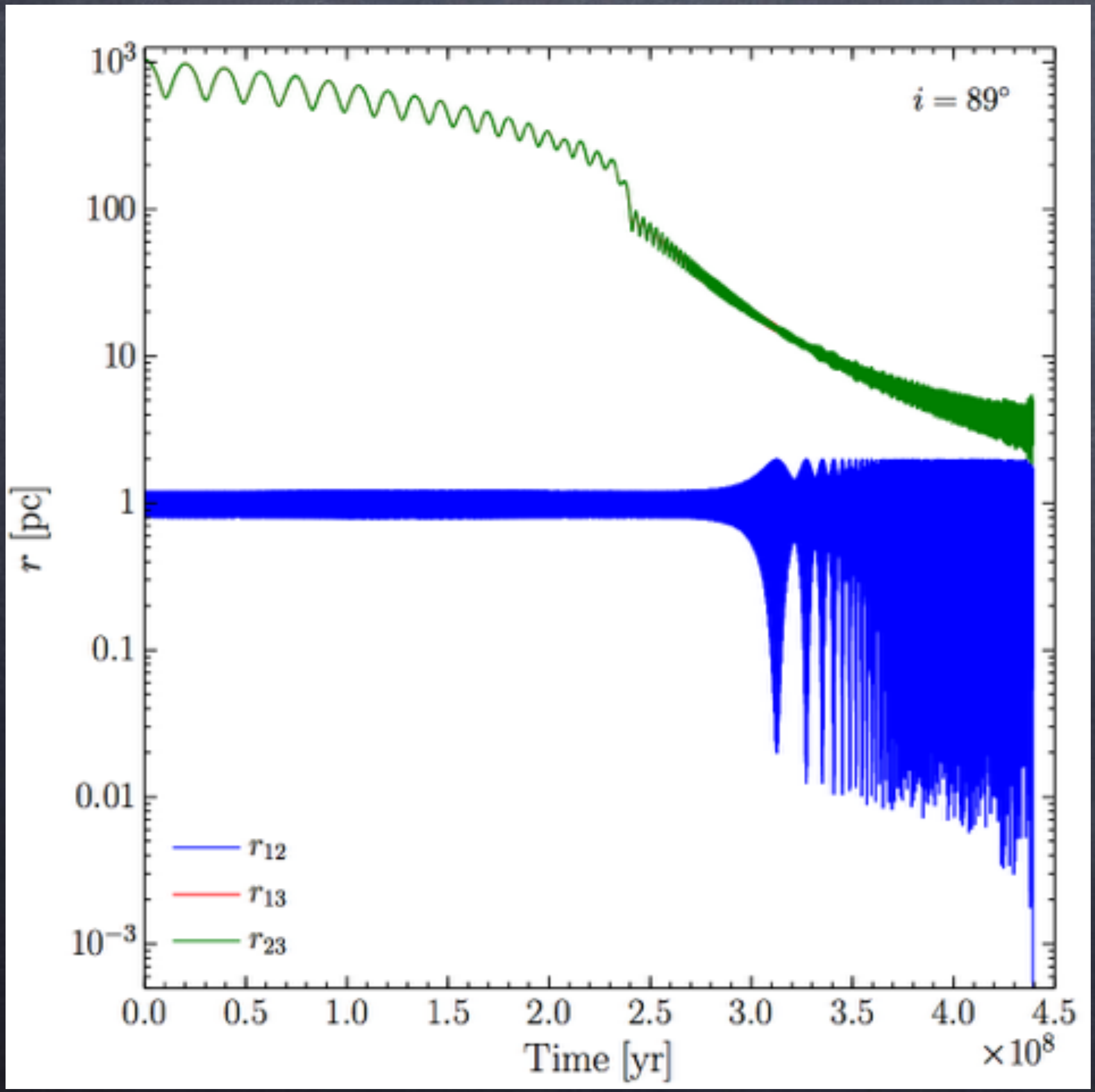
Model C

The nightmare scenario, aka the final-pc problem

If long delays, triple systems will naturally form as a result of later galaxy mergers, which will favour mergers via Kozai-Lidov resonances (periodic exchange between eccentricity and orbital inclination)

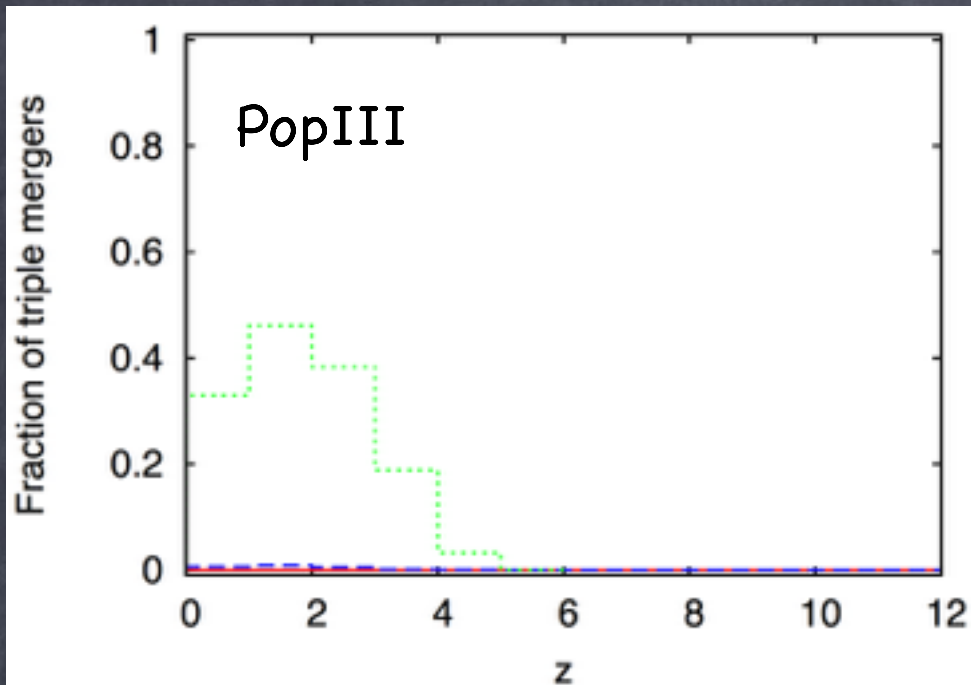
$$t_{\rm KL} \sim \frac{a_{\rm out}^3 (1-e_{\rm out}^2)^{3/2}\sqrt{m_1+m_2}}{G^{1/2} a_{\rm in}^{3/2} m_3} \simeq 2\times 10^6 \ \ {\rm yrs},$$

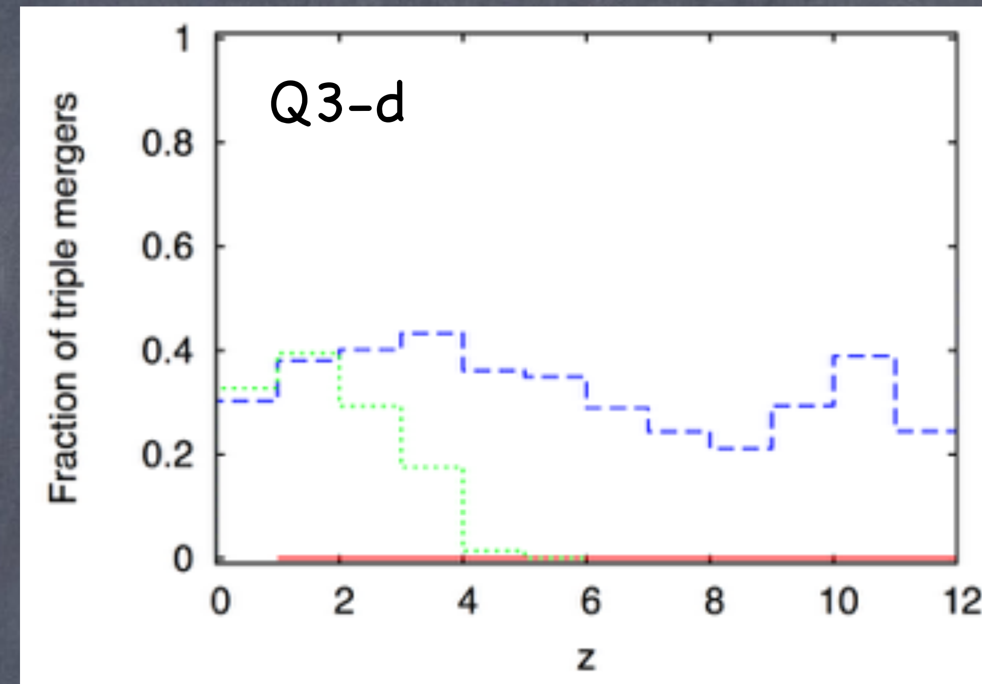
$m_1 = m_2 = m_3 = 10^8$ M$_\odot$, $a_{\rm in} = 1$ pc, $a_{\rm out} = 10$ pc and $e_{\rm out} = 0$.



PN 3-body simulation in a stellar environment, with m1=1.e8 Msun, m2=3.e7 Msun, m3=5.e7 Msun (Bonetti, Haardt, Sesana & EB 2016)

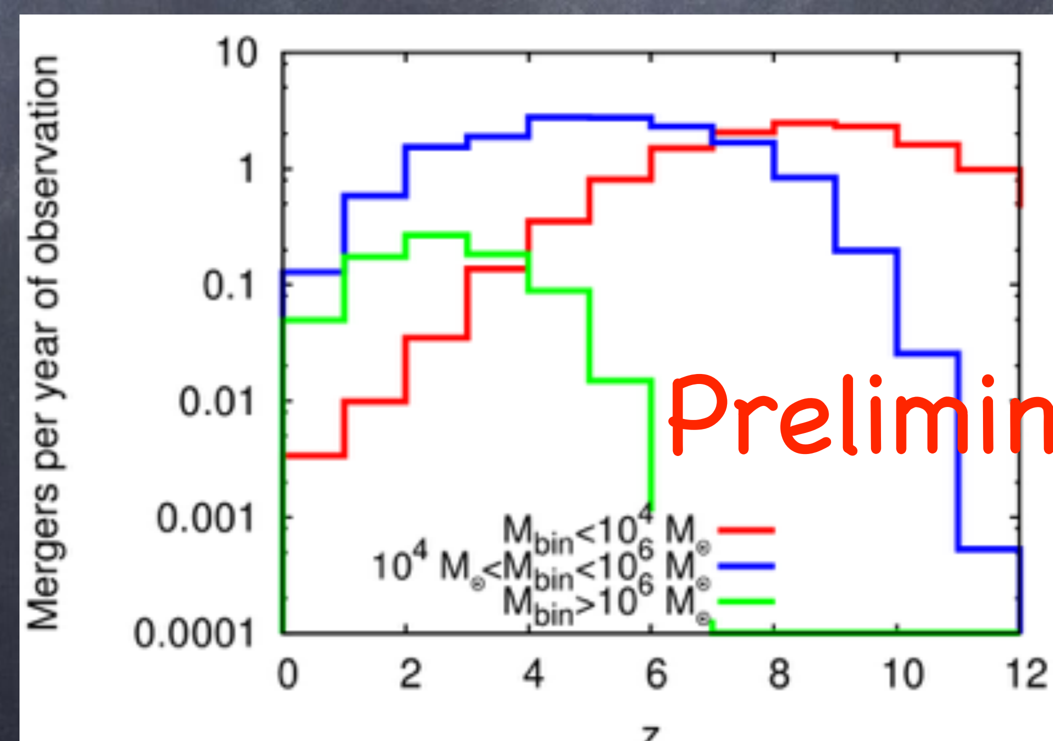
How many triple-induced mergers?





red: $M_{tot} < 10^4\ M_{sun}$; blue: $10^4 < M_{tot} < 10^8\ M_{sun}$; green: $M_{tot} > 10^8\ M_{sun}$

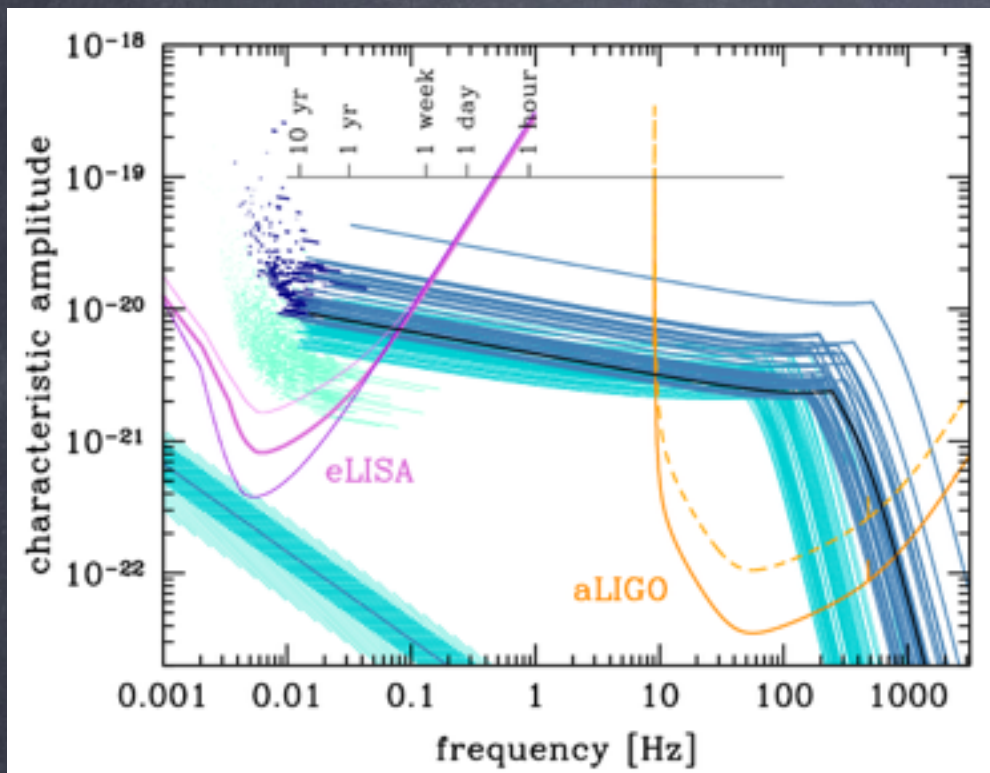
What if delays are infinite (nightmare scenario)?



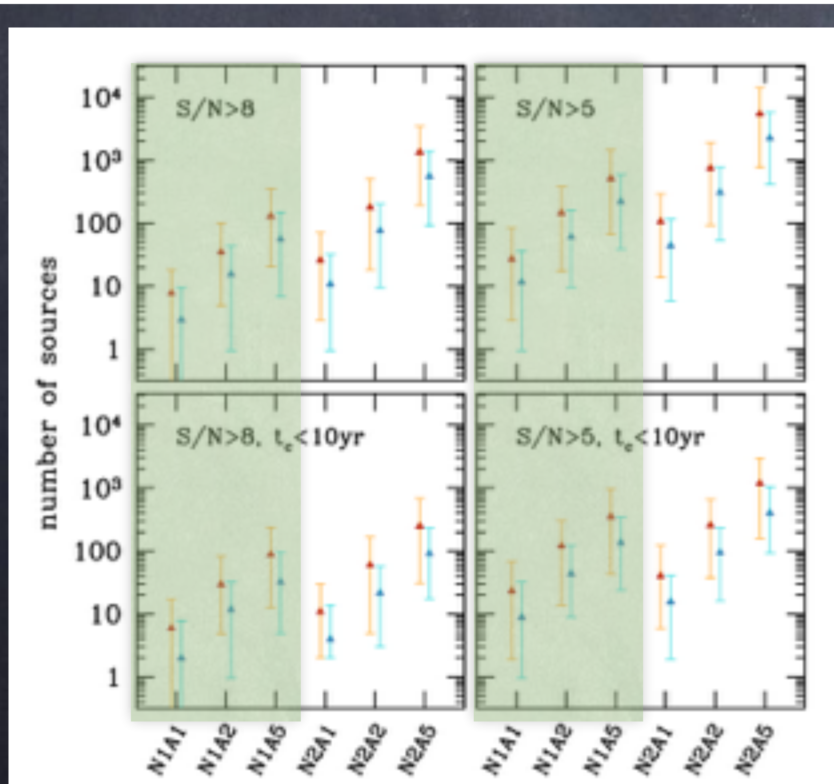
Preliminary!

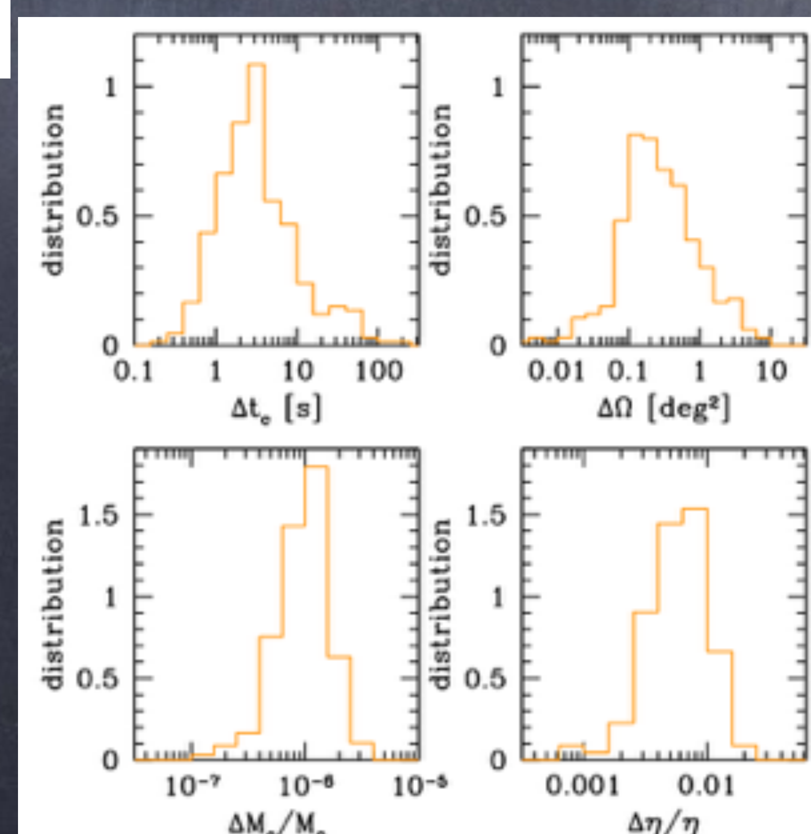
GW150914-like/intermediate-mass binary BHs

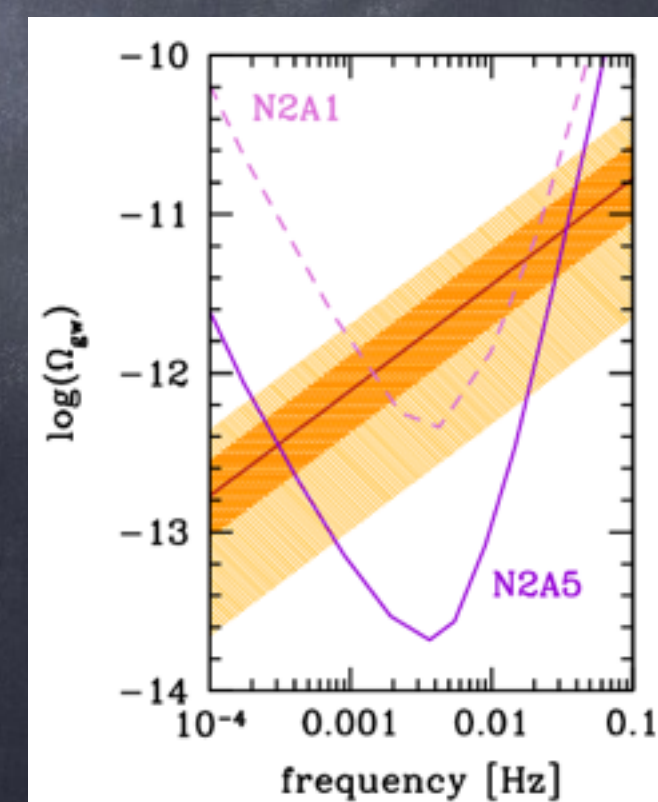
Also visible by LISA if 6 links and 5 year mission!
(Sesana 2016,Amaro-Seoane & Santamaria 2009)



- High-frequency noise is crucial!
- Astrophysical stochastic background may screen primordial ones



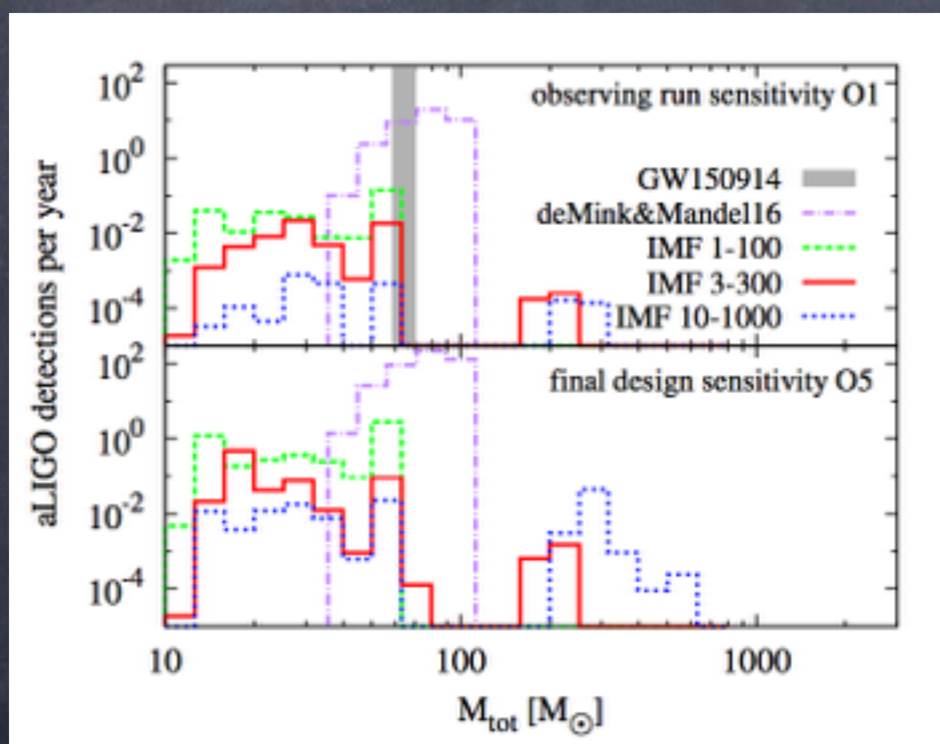




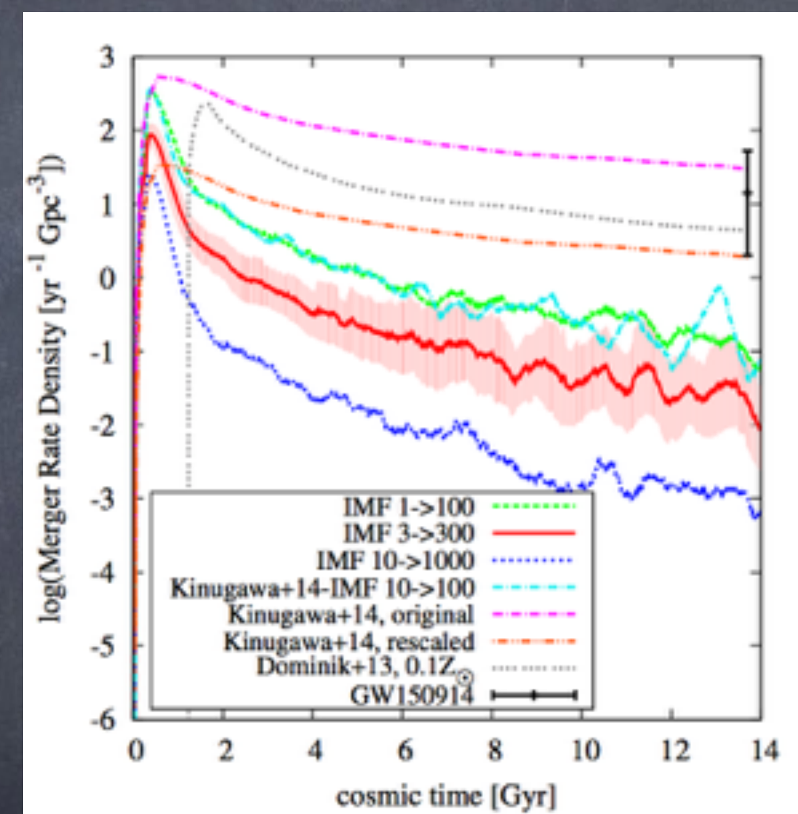
Astrophysics with LISA's observation of GW150914-like/intermediate-mass binary BHs

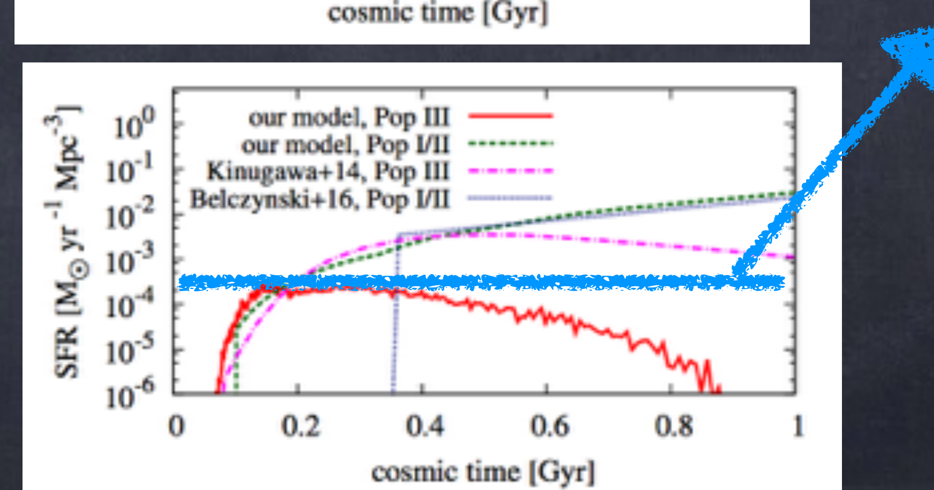
- More accurate measurements of parameters (e.g. spins, sky position, residual eccentricity, etc) may shed light on formation mechanism (field vs globular clusters) or help find counterpart

- Detection of BH binary with total mass > 200 M_{sun} fingerprint of primordial (i.e. popIII) origin



	BH-BH	BH-NS	NS-NS	$m_1 > M_{PI}$
1-100	5.3	1.4×10^{-2}	7.2×10^{-3}	0
1σ	0.07 dex	0.19 dex	0.04 dex	–
3-300	0.48	2.1×10^{-3}	8.1×10^{-4}	0.011
1σ	0.08 dex	0.19 dex	0.05 dex	0.18 dex
10-1000	0.12	2.4×10^{-4}	1.1×10^{-5}	0.089
1σ	0.18 dex	0.22 dex	0.43 dex	0.24 dex





Planck reionization limit

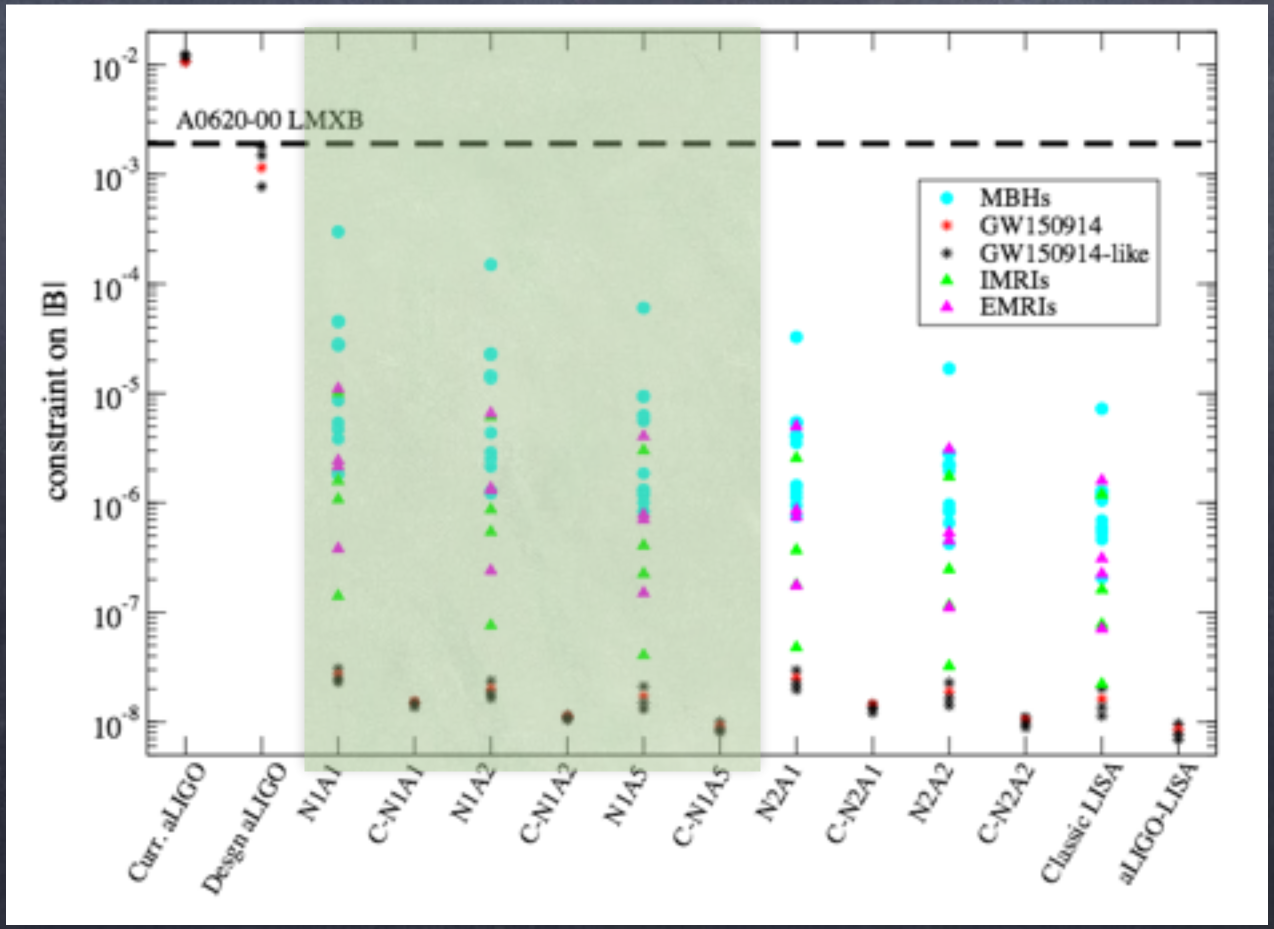
Hartwig, Volonteri, Bromm, Klessen, EB, Magg & Stacy 2016

Tests of GR with multi band observations

- Smoking-gun effect would be deviation from GR, e.g. BH-BH dipole emission (-1PN term in phase/flux)

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

- Pulsar constrain $|B| \lesssim 2 \times 10^{-9}$, GW150914-like systems + LISA will constrain same dipole term in BH-BH systems to comparable accuracy



From EB, Yunes & Chamberlain 2016

Conclusions

- LISA main science goal is to reconstruct cosmological merger history of massive BHs
- Uncertainties about seed model and delays (final-parsec problem) but we expect tens to hundreds of detections
- Synergies with PTA experiments and LIGO/Virgo
- LISA science goal best achievable with not-too-descoped configurations (6 links, 2.5 Gm arms, >4 yrs mission)
- ESA decision on final design by 2017 so as to allow launch in ~2034 or even before

Thank you!