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eLISA science in the era of first detections

19th Capra meeting, Meudon, June 27 - July 1, 2016

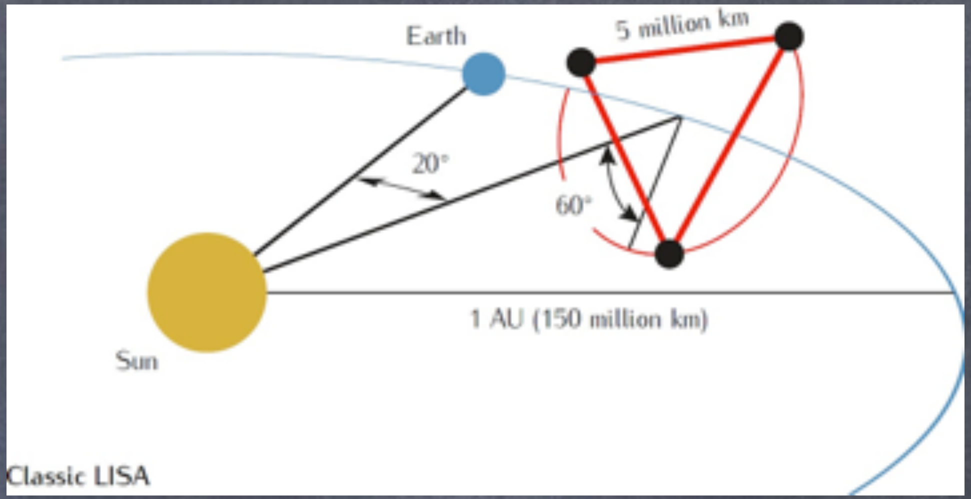
H2020-MSCA-RISE-2015 StronGrHEP-690904
PCIG11-GA-2012-321608

Outline

- The status of eLISA
- eLISA science for competing designs/cost-cutting measures (massive BHs, cosmology, EMRIs, tests of GR, multi-band GW astronomy)
- What can we learn from current GW detectors

The status of eLISA

- ESA selected the "Cosmic Vision" L3 launch slot (2034) for theme "The Gravitational Universe"
- LISA Pathfinder mission a success (surprisingly stable)
- eLISA design/mission not selected yet, options analyzed by Gravitational Wave Advisory Team (GOAT) in collaboration with eLISA consortium

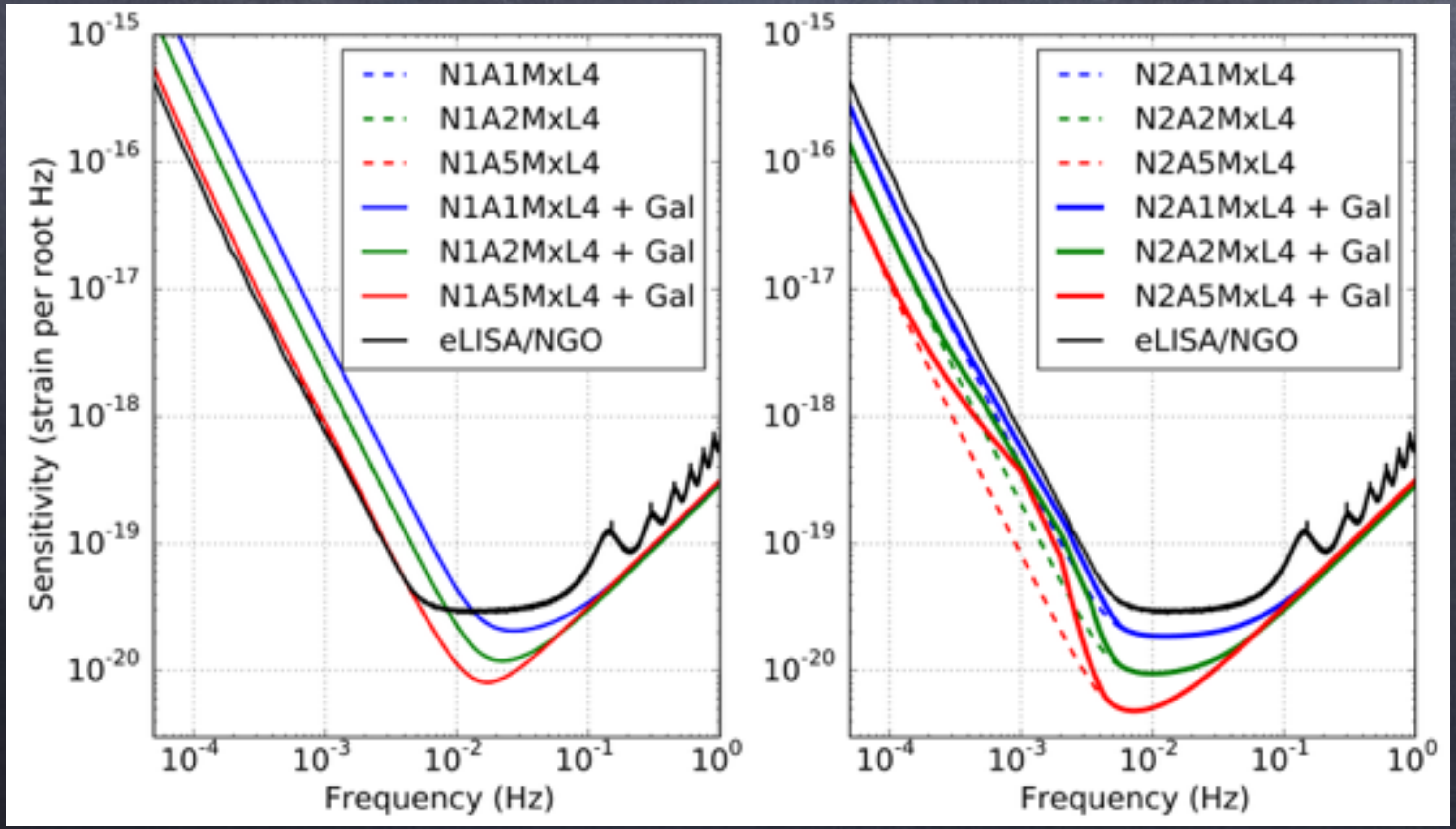


1. Klein, EB, Sesana, Petiteau, Berti, Babak, Gair, Aoudia, Hinder, Ohme, Wardell, PRD 93, 024003 (2016): massive BHs
2. Tamanini, Caprini, EB, Sesana, Klein, Petiteau, JCAP 04 (2016) 002: standard sirens
3. Caprini, Hindmarsh, Huber, Konstandin, Kozaczuk, Nardini, No, Petiteau, Schwaller, Servant, Weir JCAP 04 (2016) 001: stochastic backgrounds
4. Sesana PRL 2016 in press; Nishizawa, Berti, Klein, Sesana, arXiv:1605.01341: multiband
5. EB, Yunes and Chamberlain, PRL 2016 in press: multiband, tests of GR
6. Berti, Sesana, EB, Cardoso, Belczynski: no-hair theorem
7. Gair, Sesana, Babak, Sopuerta, EB, Amaro-Seoane in prep.: EMRIs

- Call will be issued in 2016 to choose design by early 2017, then industrial production (~ 10 yrs) which will make mission possible in ~2030 (?)

Options for the eLISA design

- 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)
- 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

Why massive BH merge

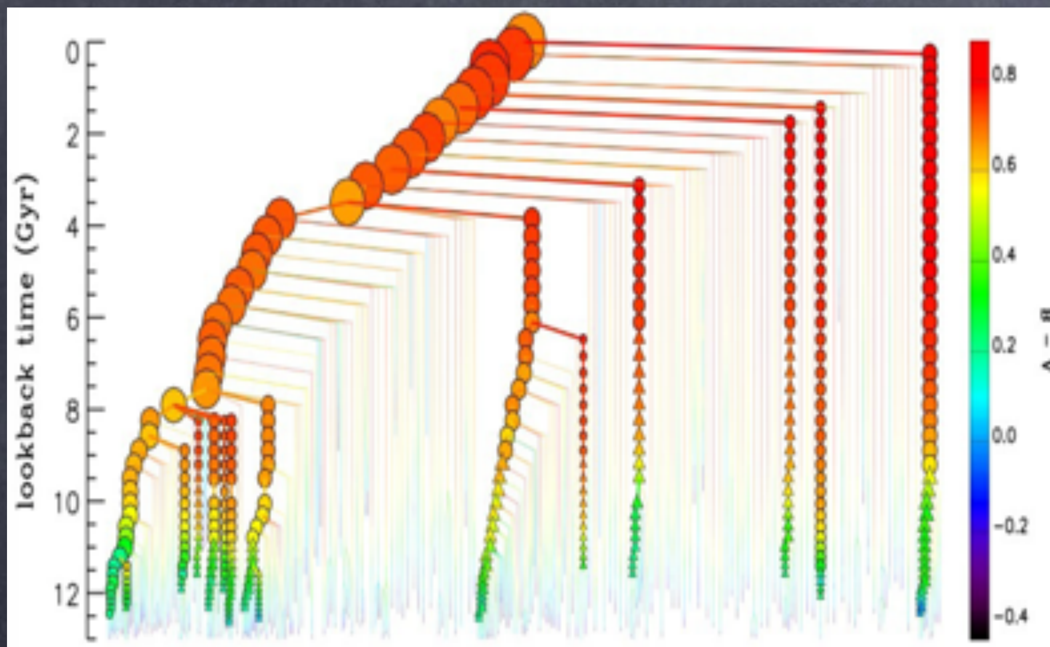


Figure from De Lucia & Blaizot 2007

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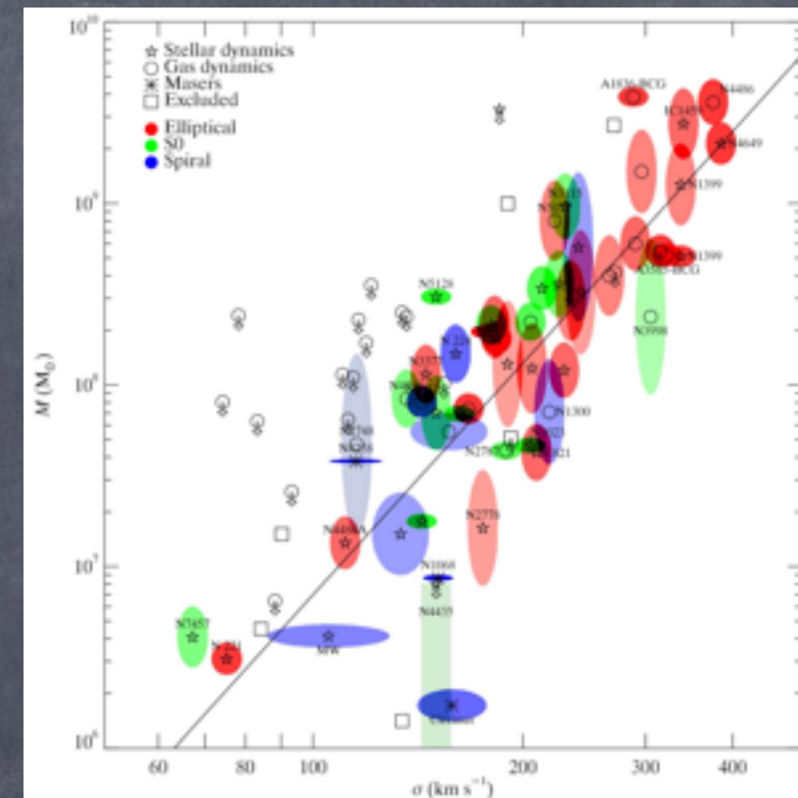

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

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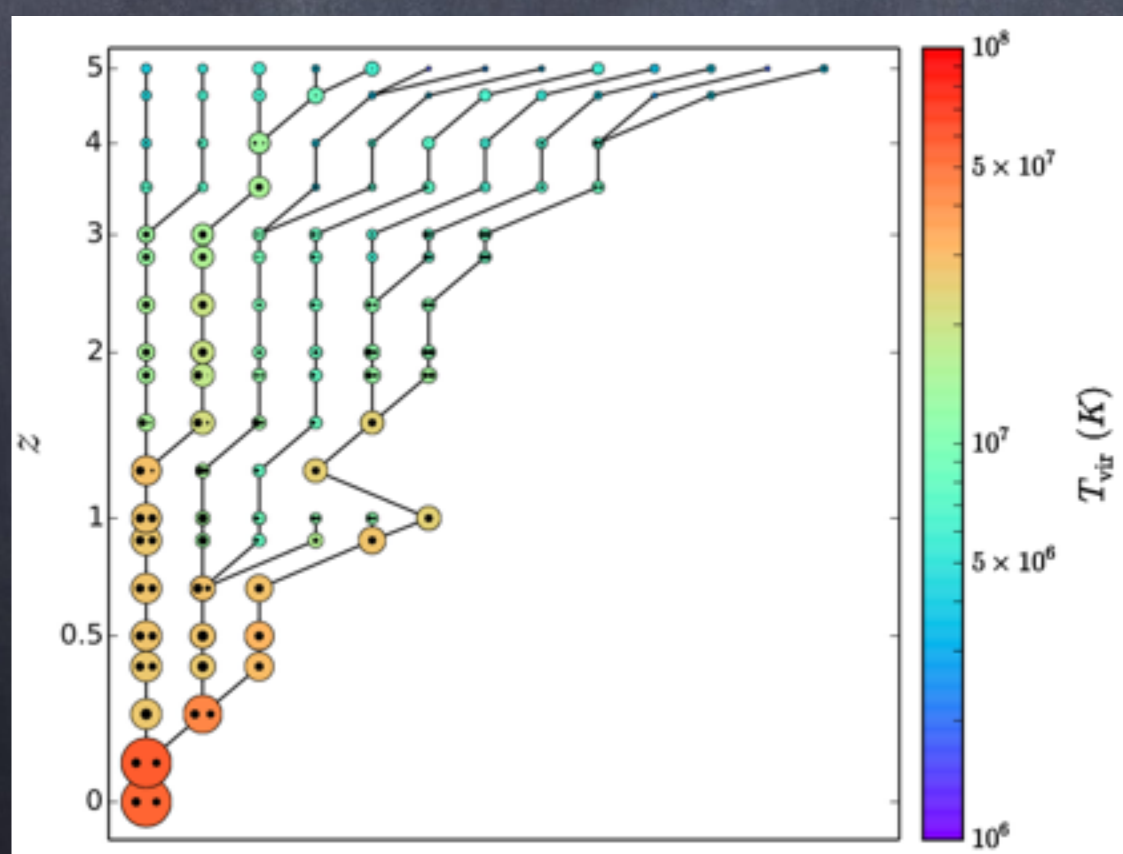
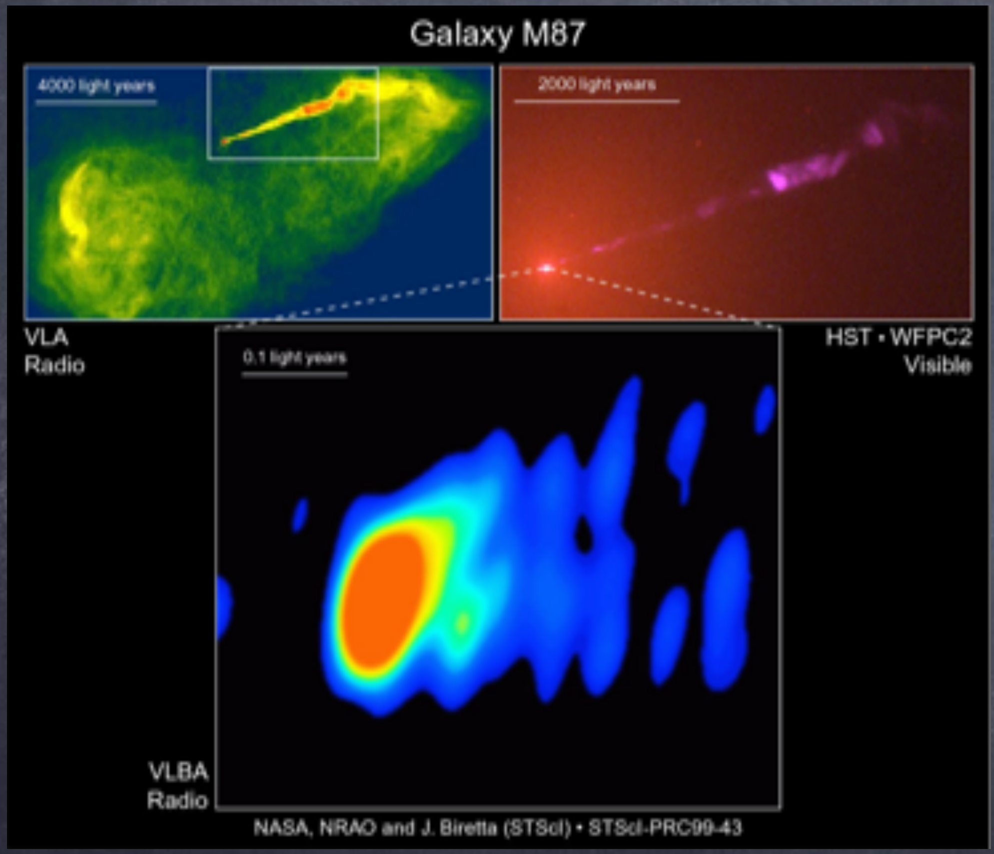
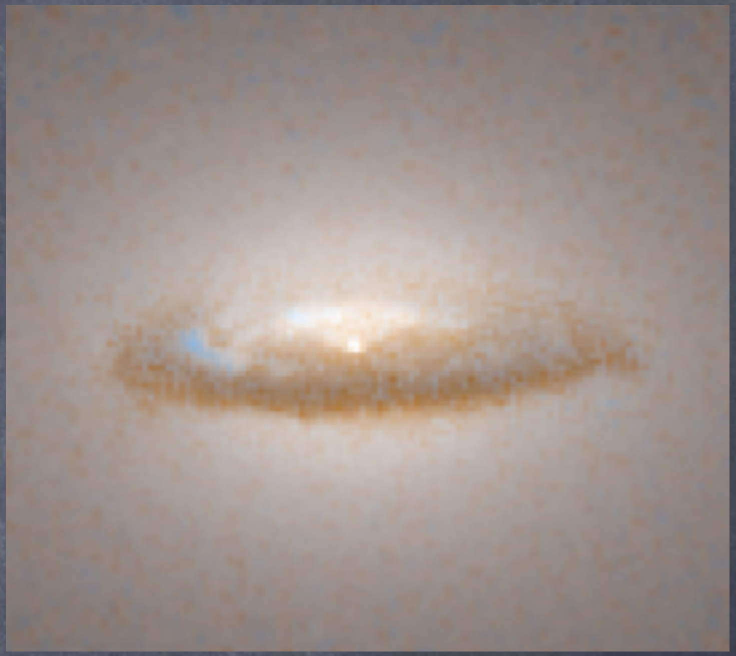


EB 2012
Figure credits: Lucy Ward

What links large and small scale?

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

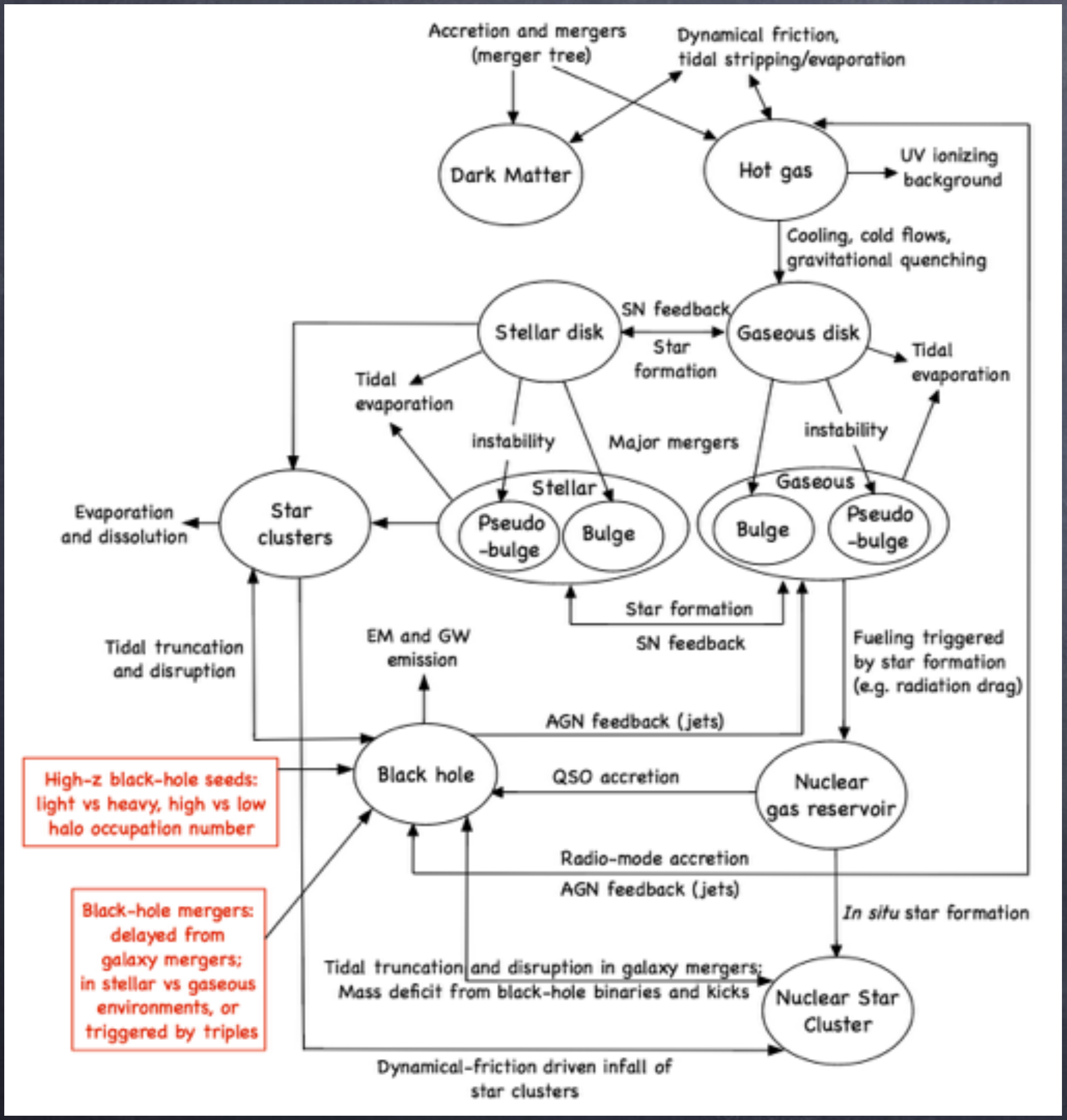




Disk of dust and gas around the massive BH in NGC 7052

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

Science with massive BH binaries

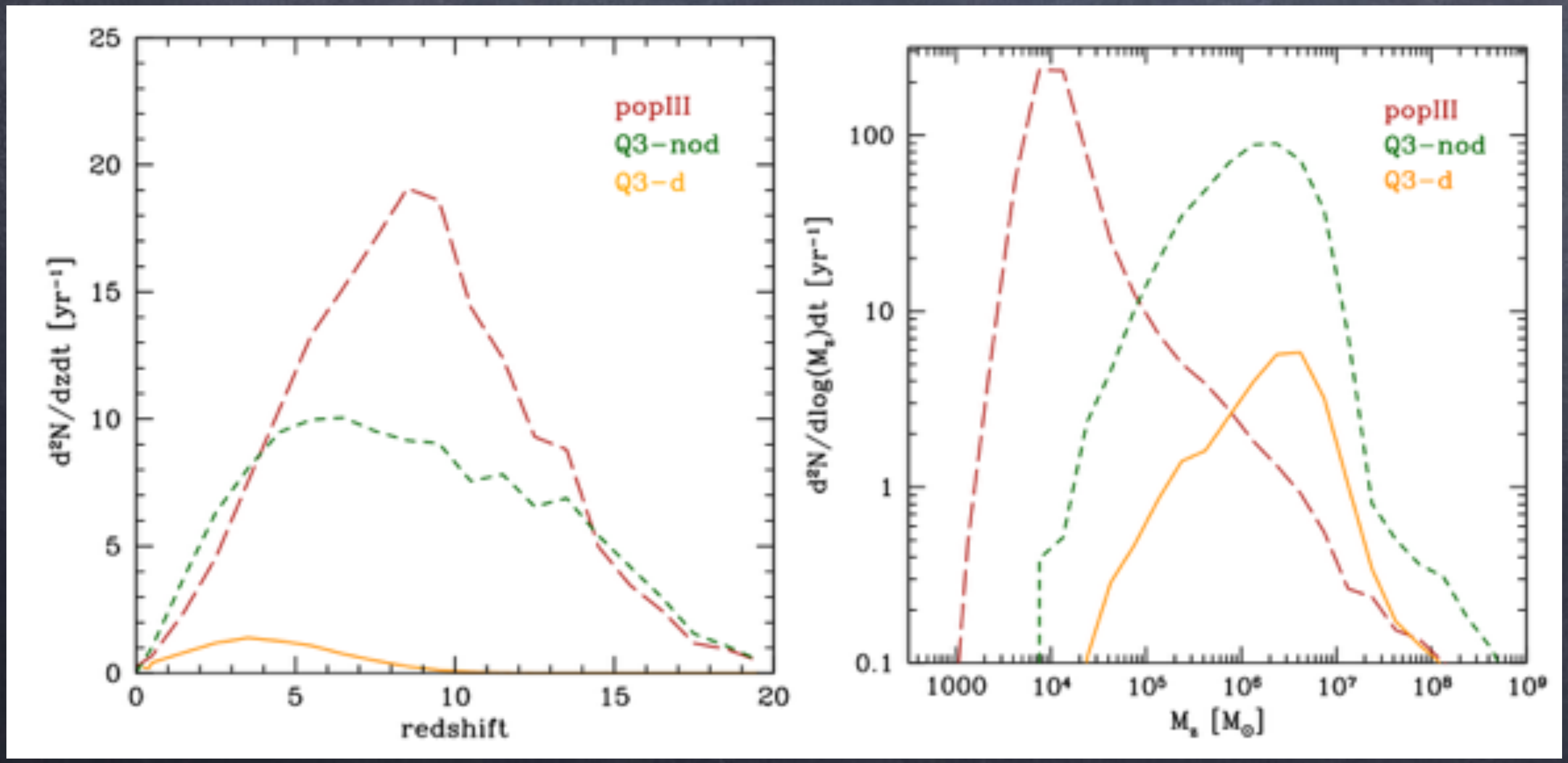


EB 2012

- 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, gas-driven planetary-like migration, triple massive BH systems)

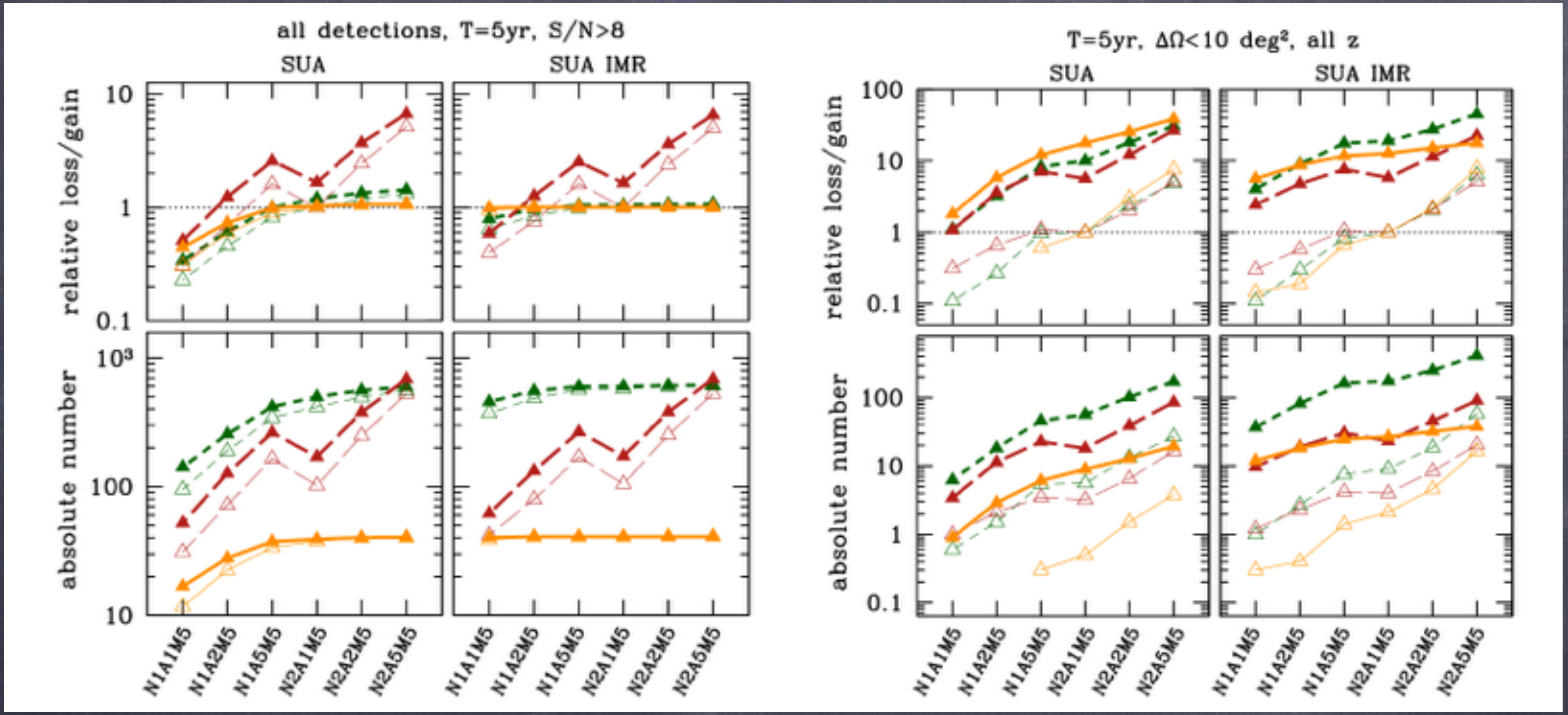


PopIII=light seeds, delays
(but similar results with no delays)

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

From Klein EB et al 2015

Detection rates

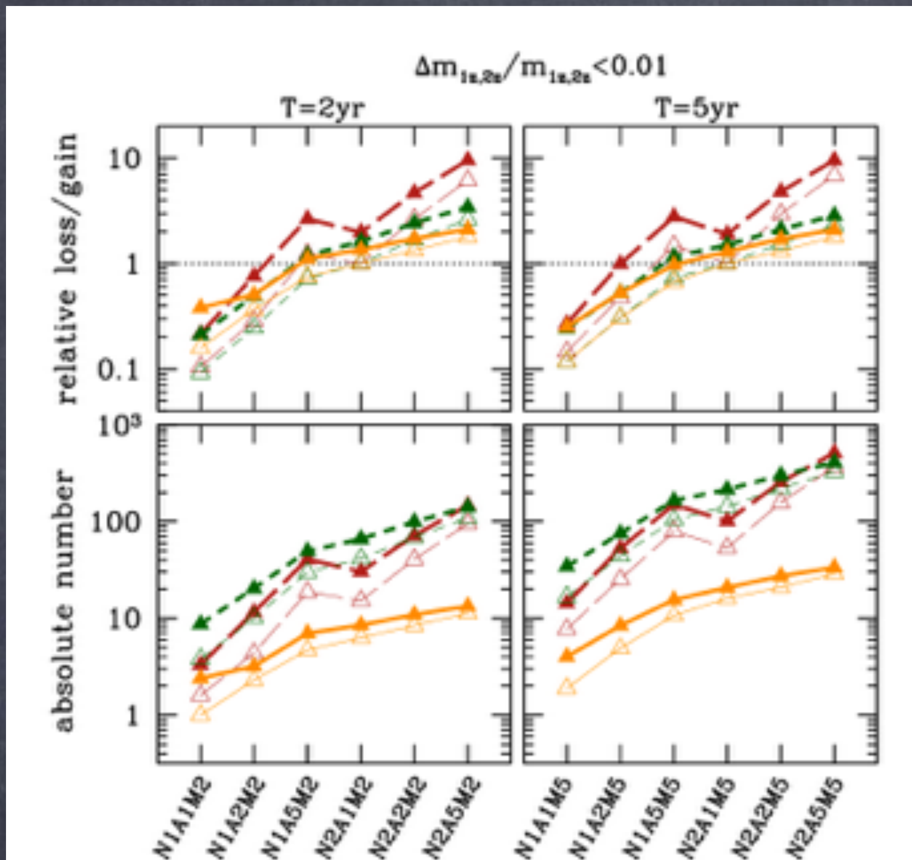


From Klein EB et al 2015

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

Relative loss relative to NGO (N2A1MkL4)

Errors on individual masses/spins



brown = popIII, orange = Q3-d, green = Q3-nod
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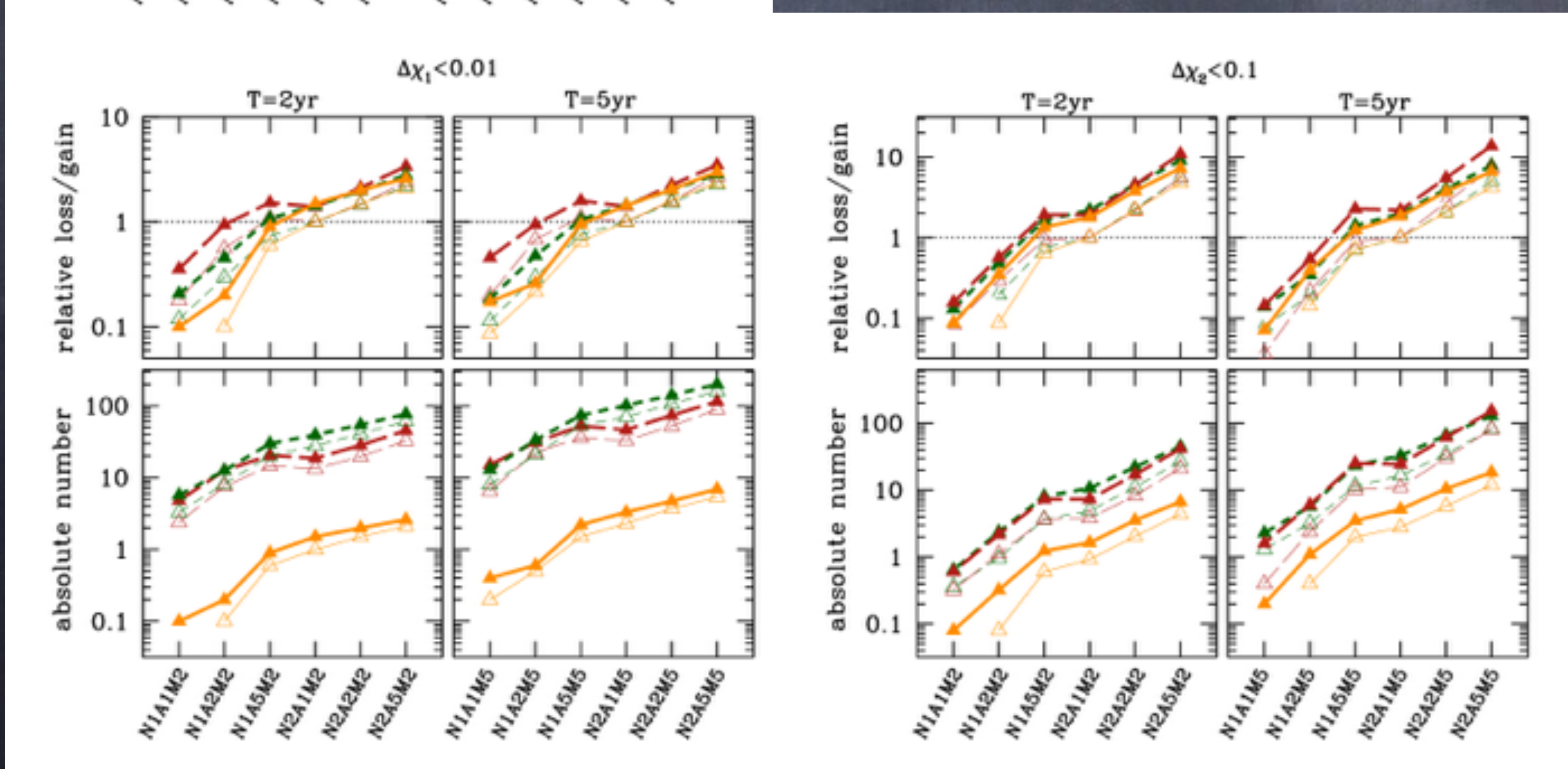
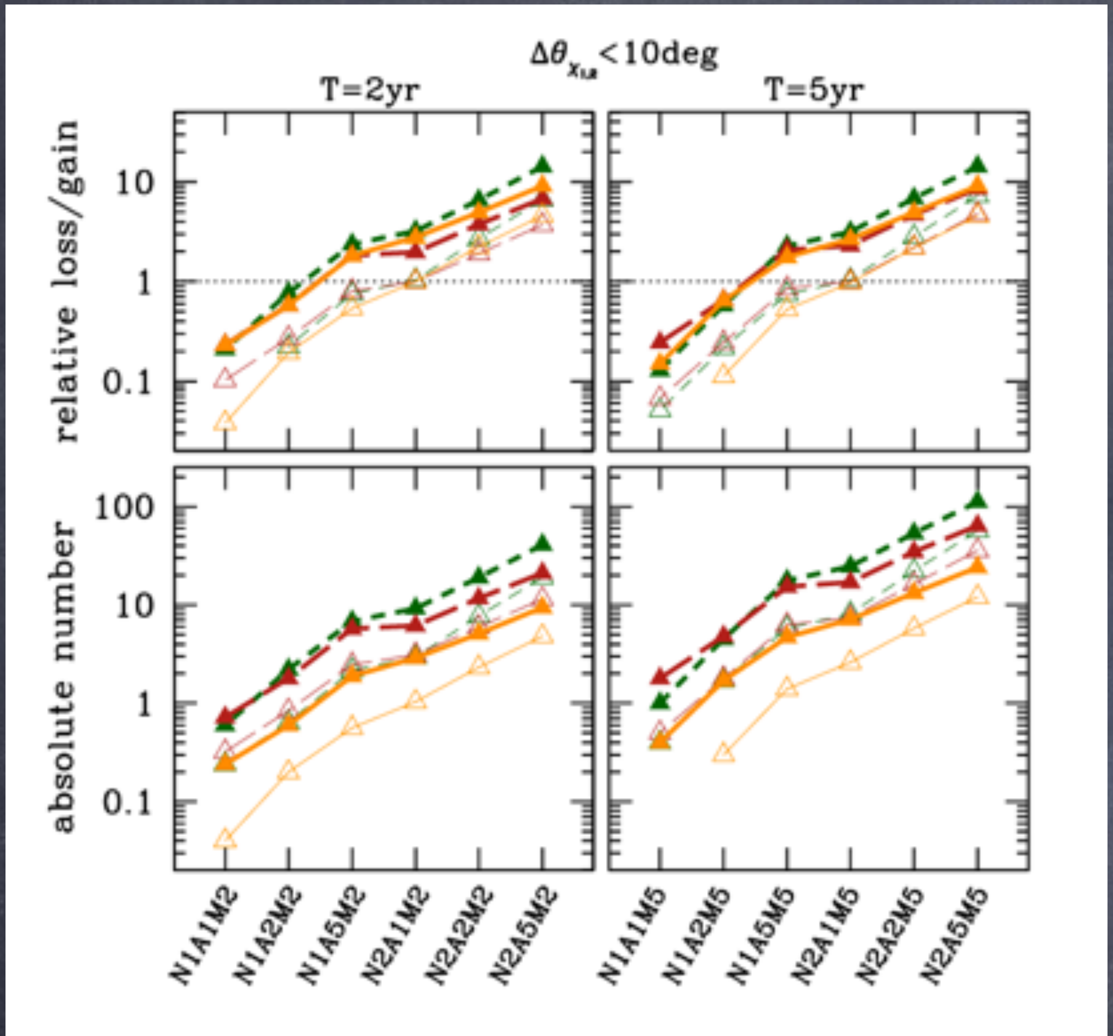
Relative loss relative to NGO (N2A1MkL4)

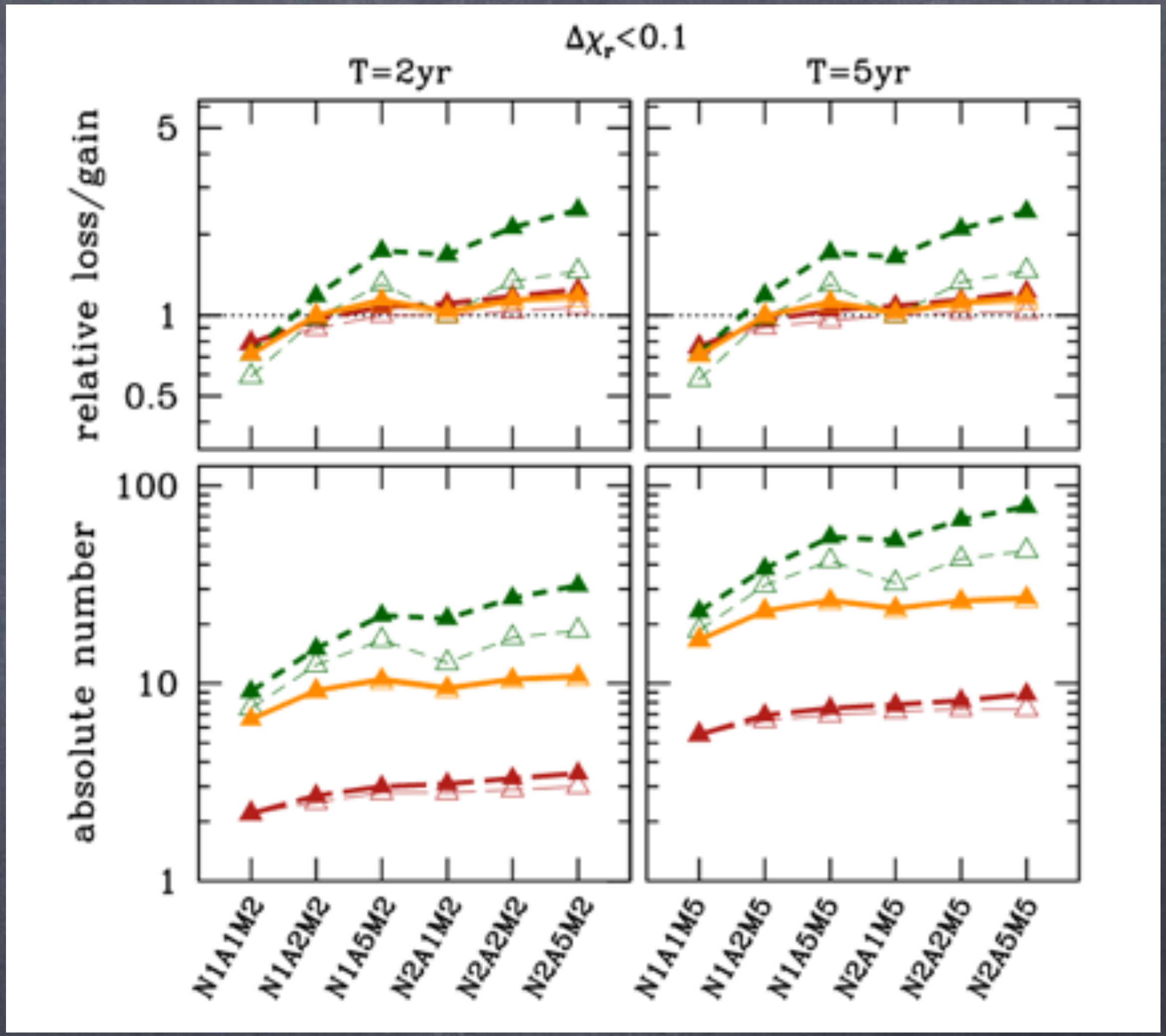
Provides information about properties of BH accretion and BH mass history



From
Klein EB et al
2015

Errors on spin inclinations and final spin





From Klein EB et al 2015

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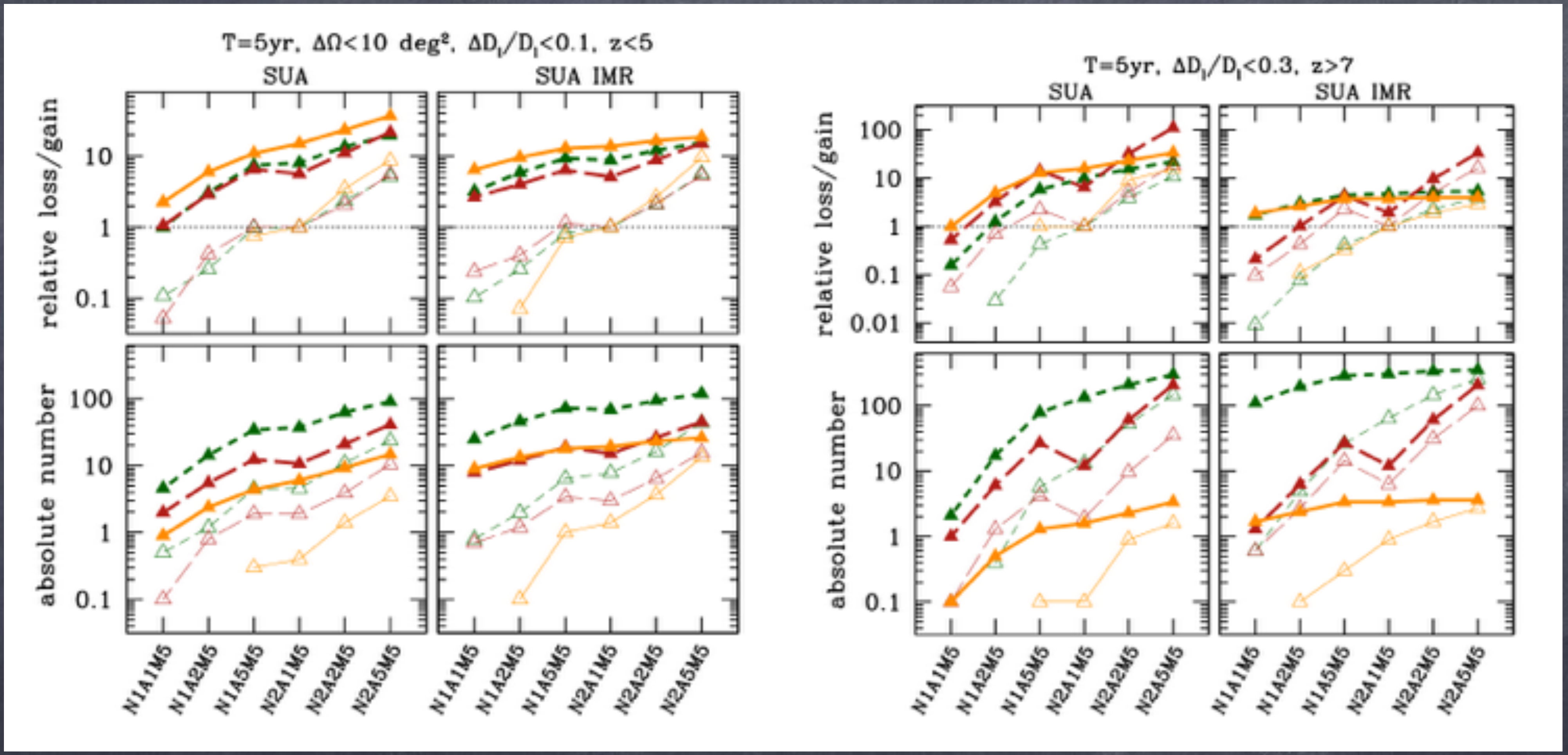
Relative loss relative to NGO (N2A1MkL4)

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

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



From Klein EB et al 2015

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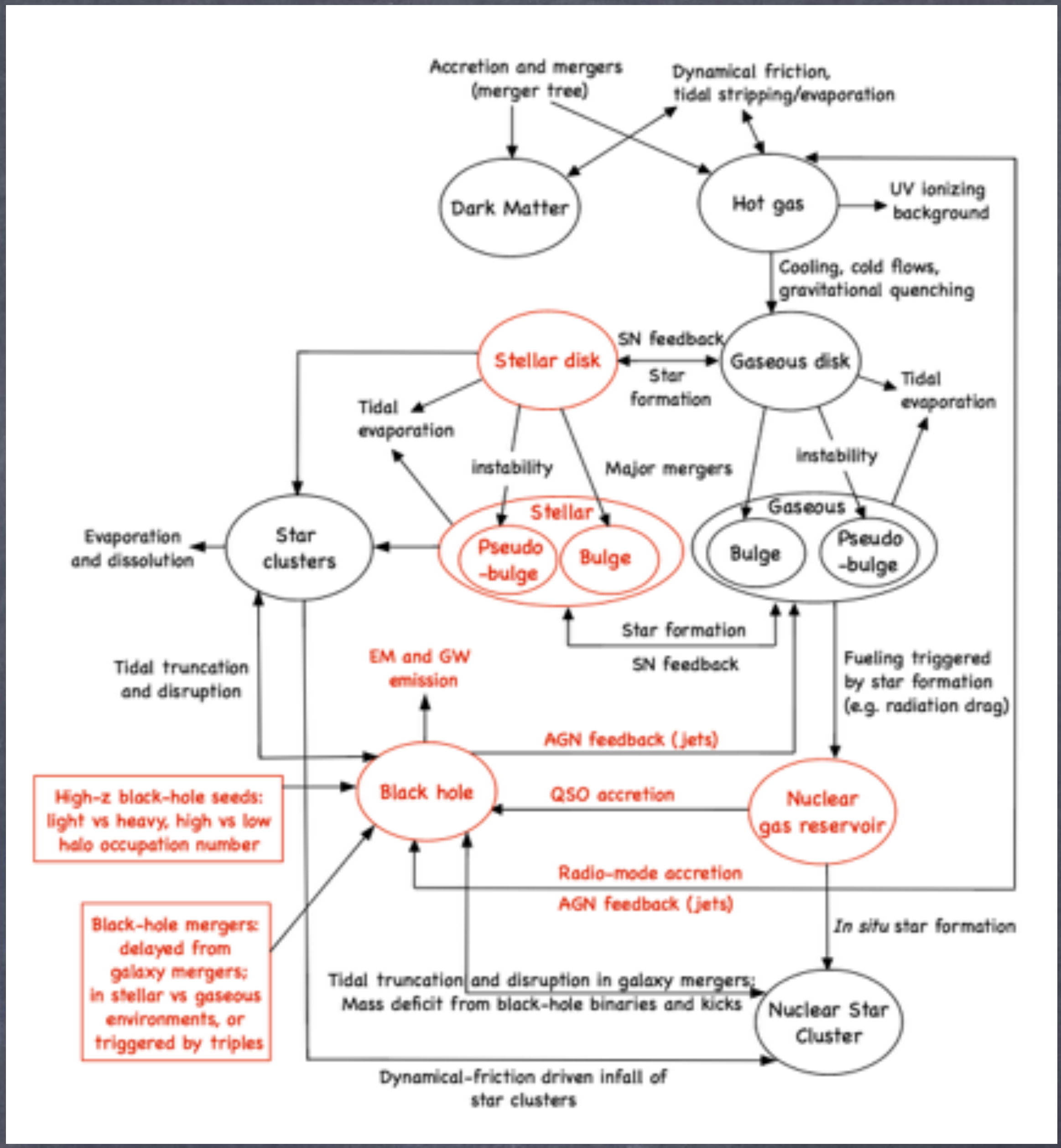
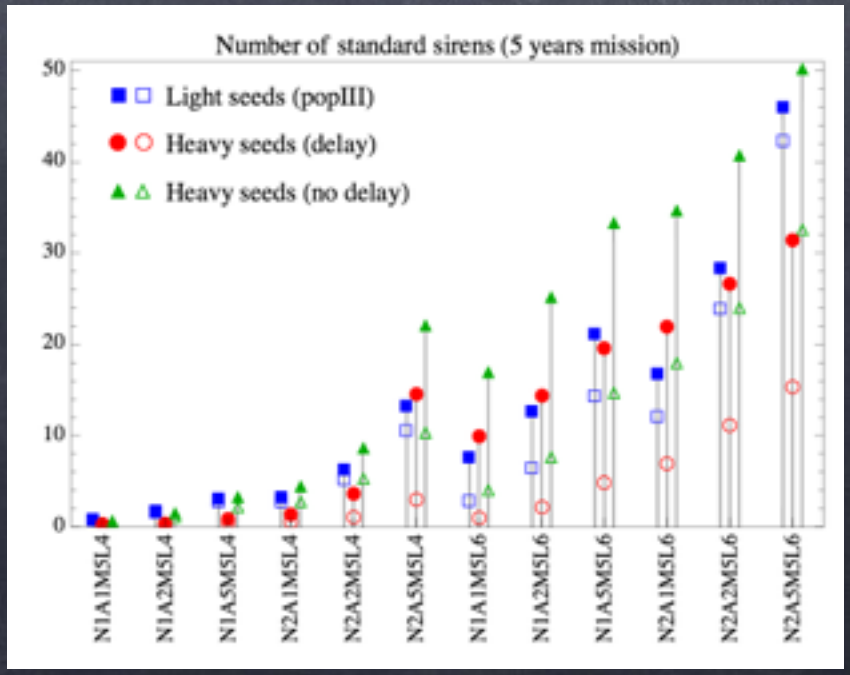
thick = six links (L6), thin = four links (L4)

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

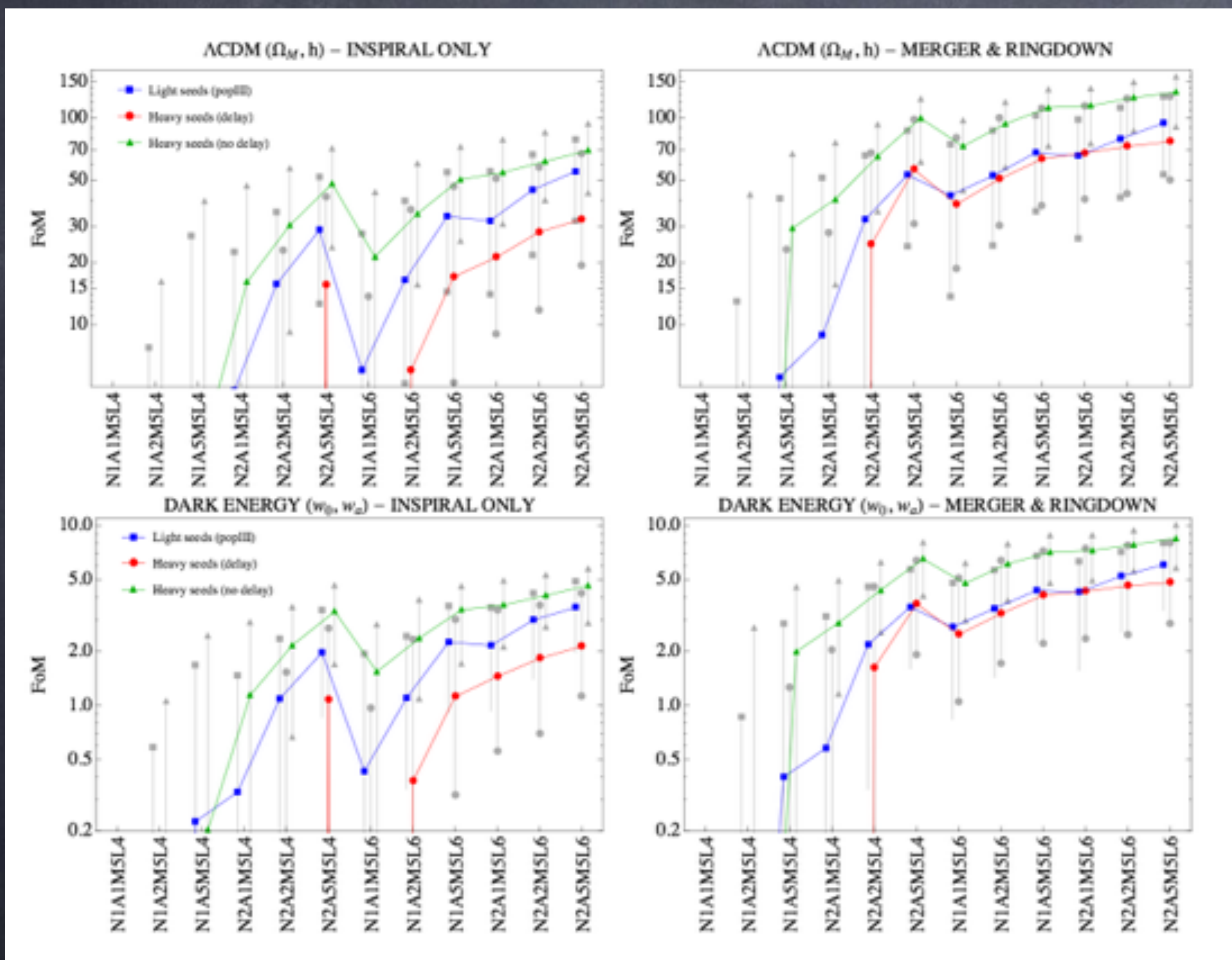
Model	N2A5M5L6						N2A2M5L4					
	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a	$P(\%)$	$\Delta\Omega_M$	$\Delta\Omega_\Lambda$	Δh	Δw_0	Δw_a
5 param.	100	2.51	4.40	0.951	8.01	55.2	80.5	120	253	24.8	177	2230
	100	4.64	6.90	2.58	22.4	103	44.1	1480	3250	371	2350	$\gg 10^4$
	100	1.05	1.97	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 eLISA 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: eLISA sensitive to cosmological evolution at z ~ 1 - 8

Cosmography with different designs



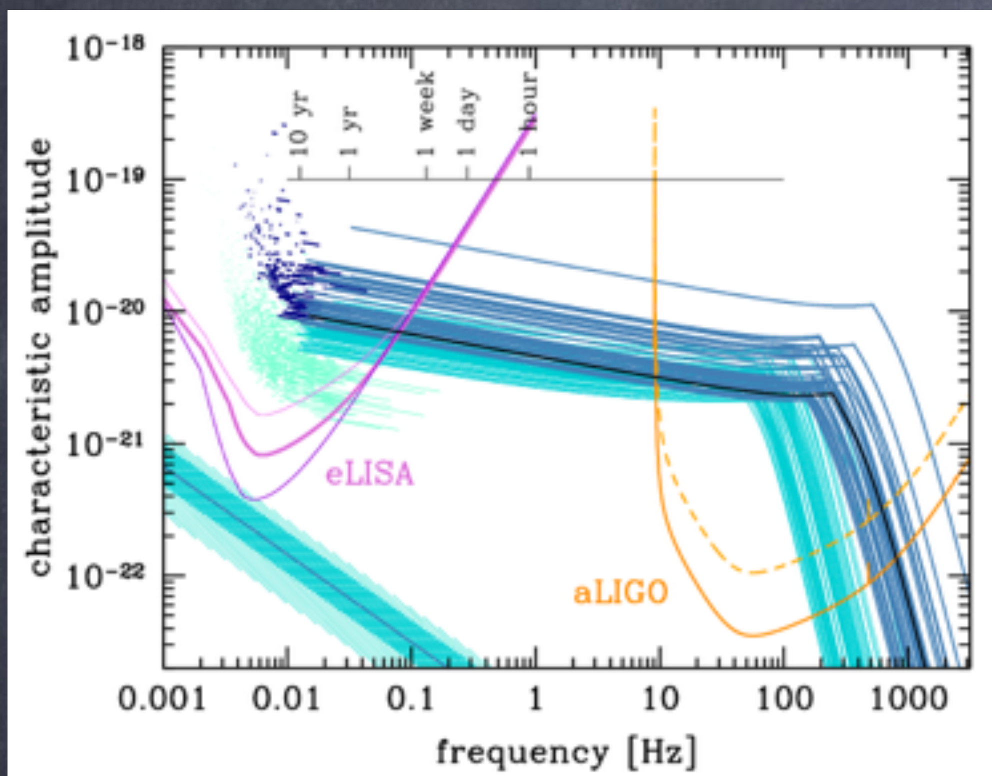
N2A5M5L6 N2A2M5L6 N2A1M5L6 N1A5M5L6 N2A5M5L4	Constraints comparable to or slightly worse than N2A5M5L6
N1A2M5L6	Constraints worse than N2A5M5L6, but better than N2A2M5L4.
N1A1M5L6 N2A2M5L4	Constraints comparable to or slightly better than N2A2M5L4
N2A1M5L4 N1A5M5L4 N1A2M5L4 N1A1M5L4	Constraints worse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

FoM ~ 1/error

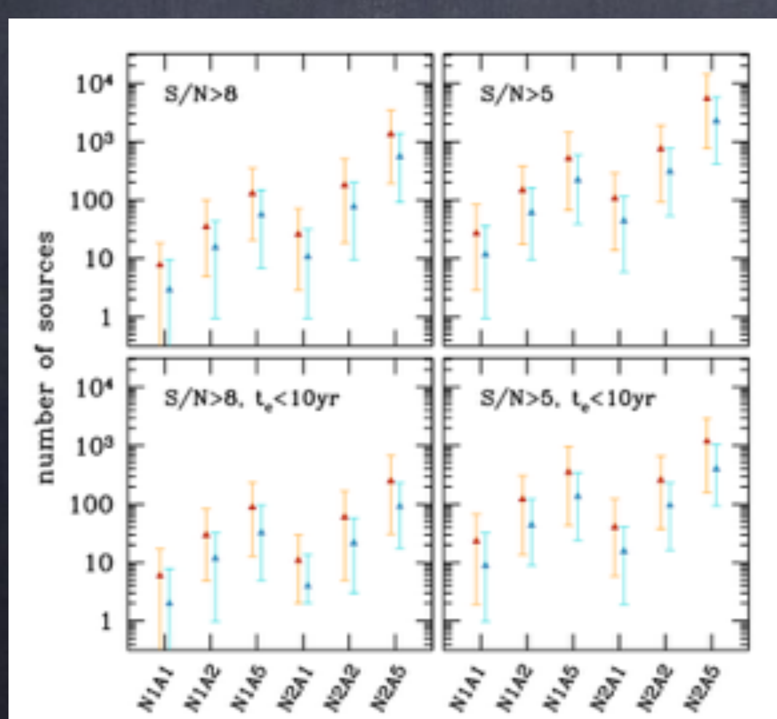
From Tamanini et al 2016

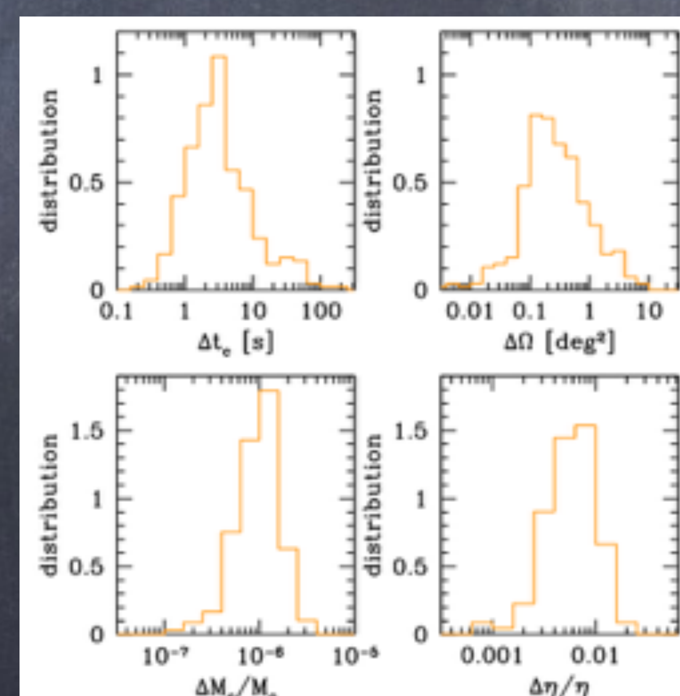
GW150914-like/intermediate-mass binary BHs

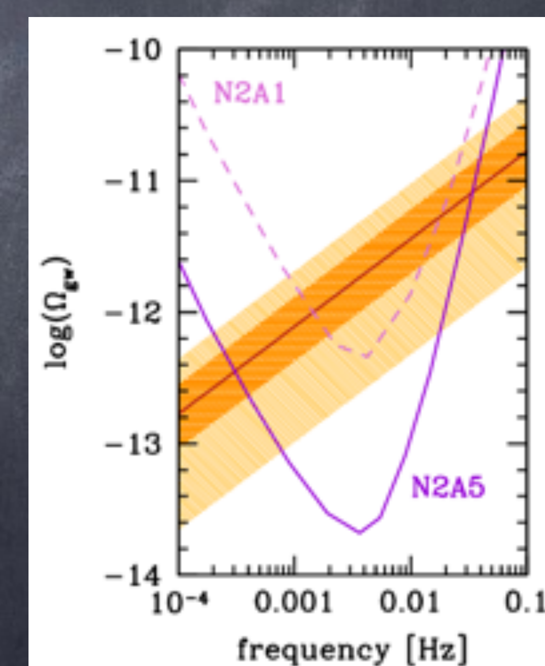
Also visible by eLISA if 6 links and 5 year mission!
(Sesana 2016,Amaro-Seoane & Santamaria 2009)



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





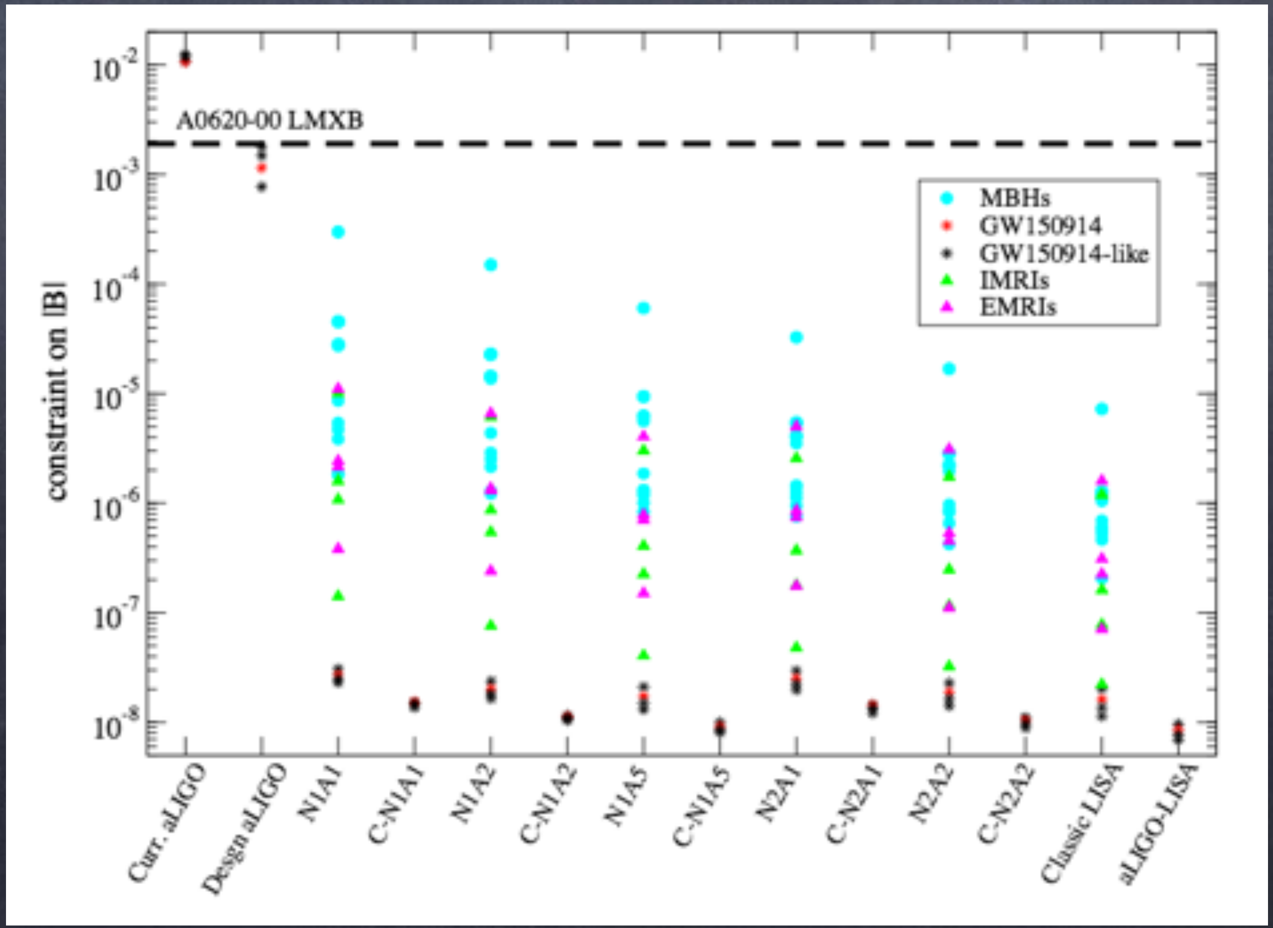


Tests of GR with multi band observations

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

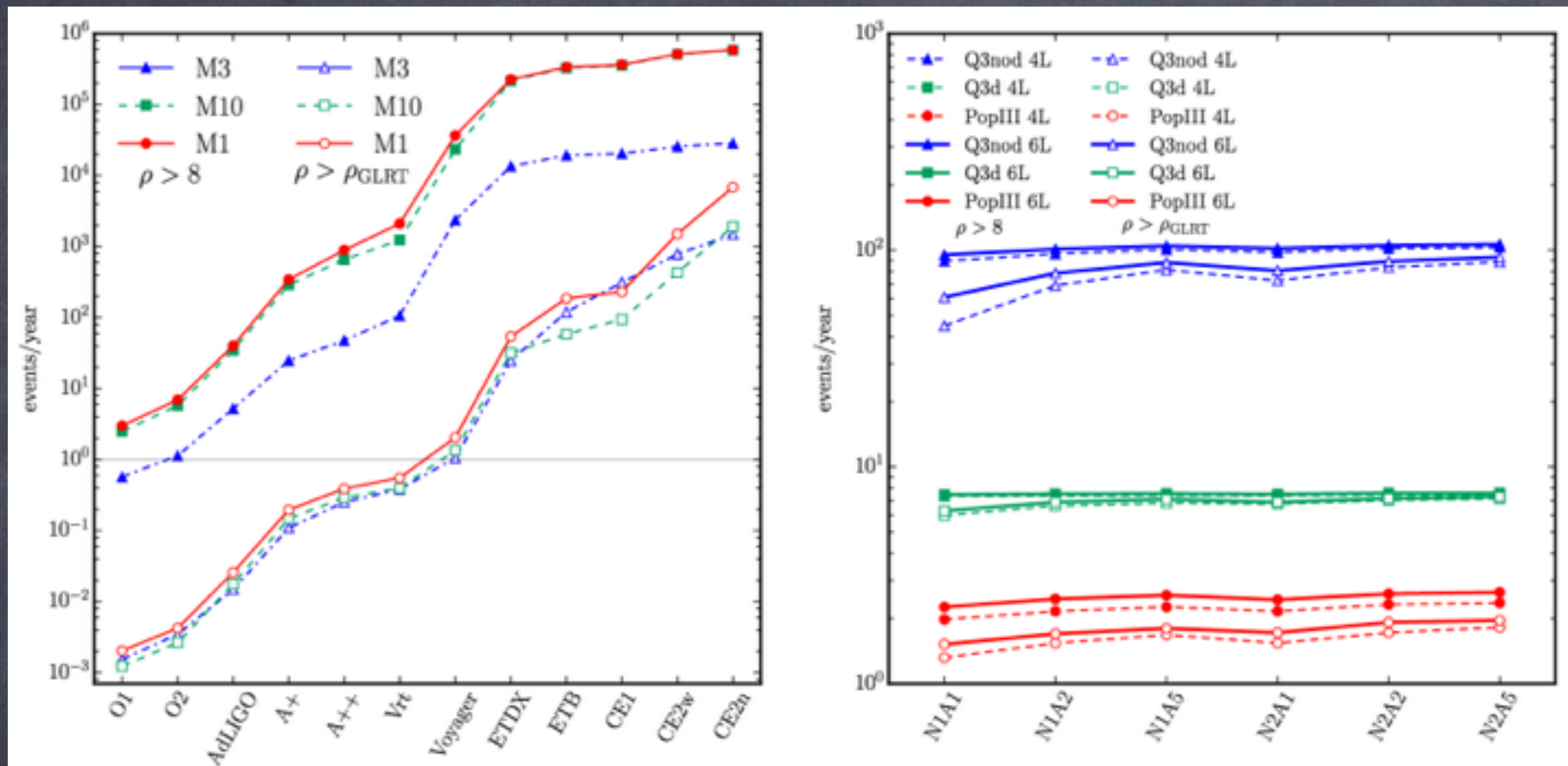
$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$

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

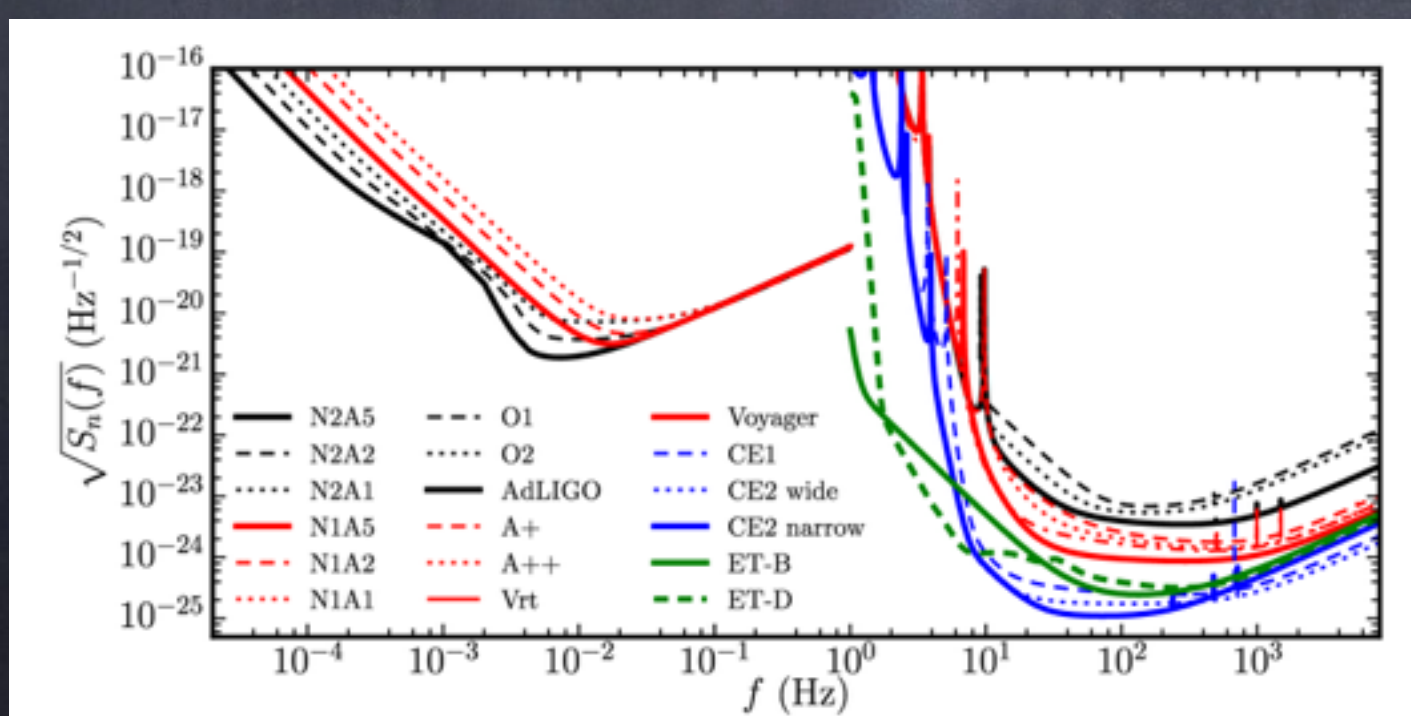


From EB, Yunes & Chamberlain 2016

Tests of no-hair theorem by BH ringdown



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



Berti, Sesana, EB,
Cardoso, Belczynski, 2016

EMRIs

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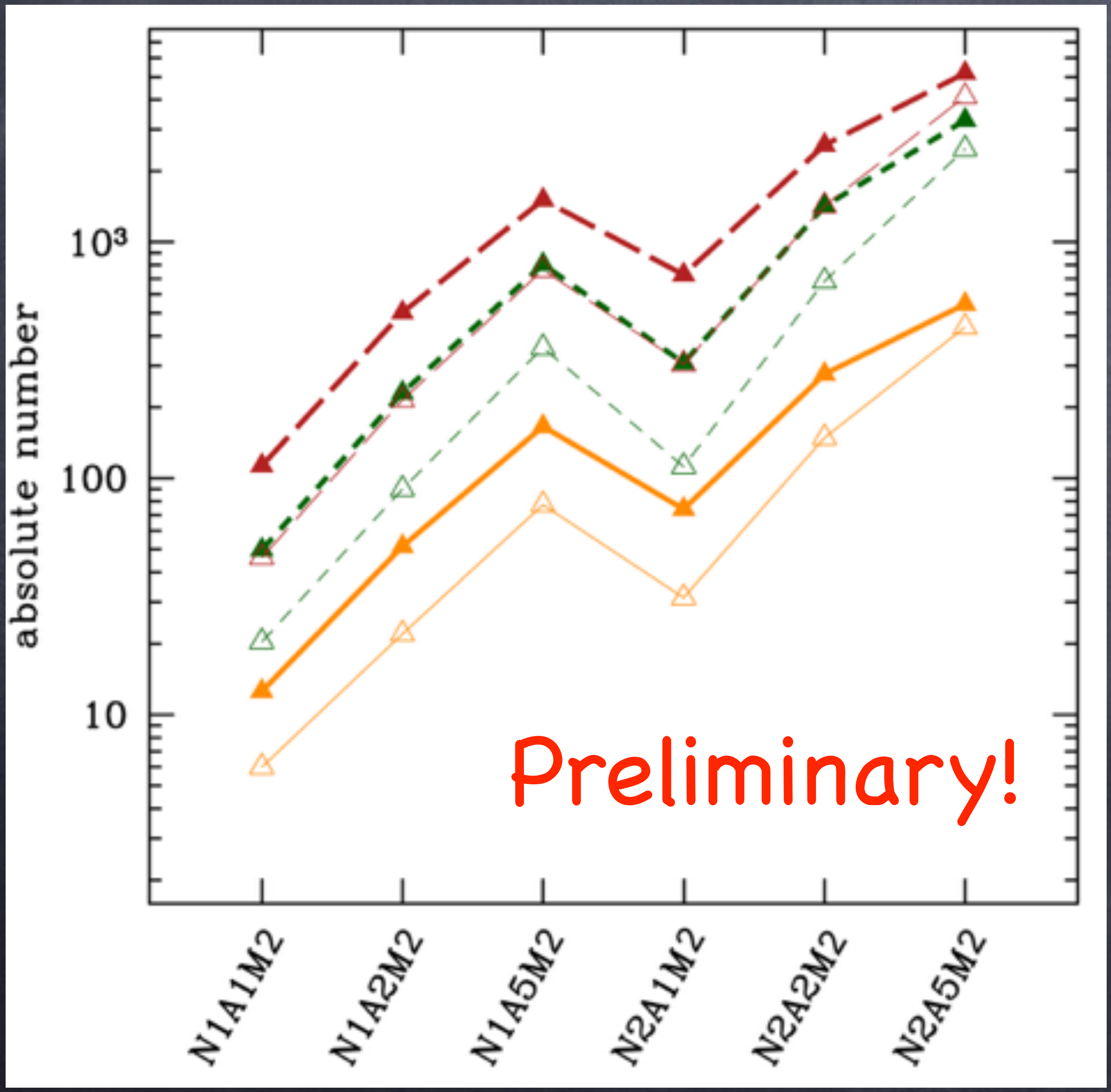
thick = six links (L6), thin = four links (L4)



- Rates shown are "optimistic" as they assume negative slope for low-mass end of massive BH mass function
- There might be unresolvable background (c.f. galactic binaries)
- "Pessimistic" rates (i.e. positive slope) ~10 times lower
- Account for presence of core vs cusp in stellar density profile
- No "Schwarzschild barrier" (cf Bar-Or & Alexander 2015, Brem, Amaro-Seoane & Sopuerta 2014)

What can we learn from PTA limits?

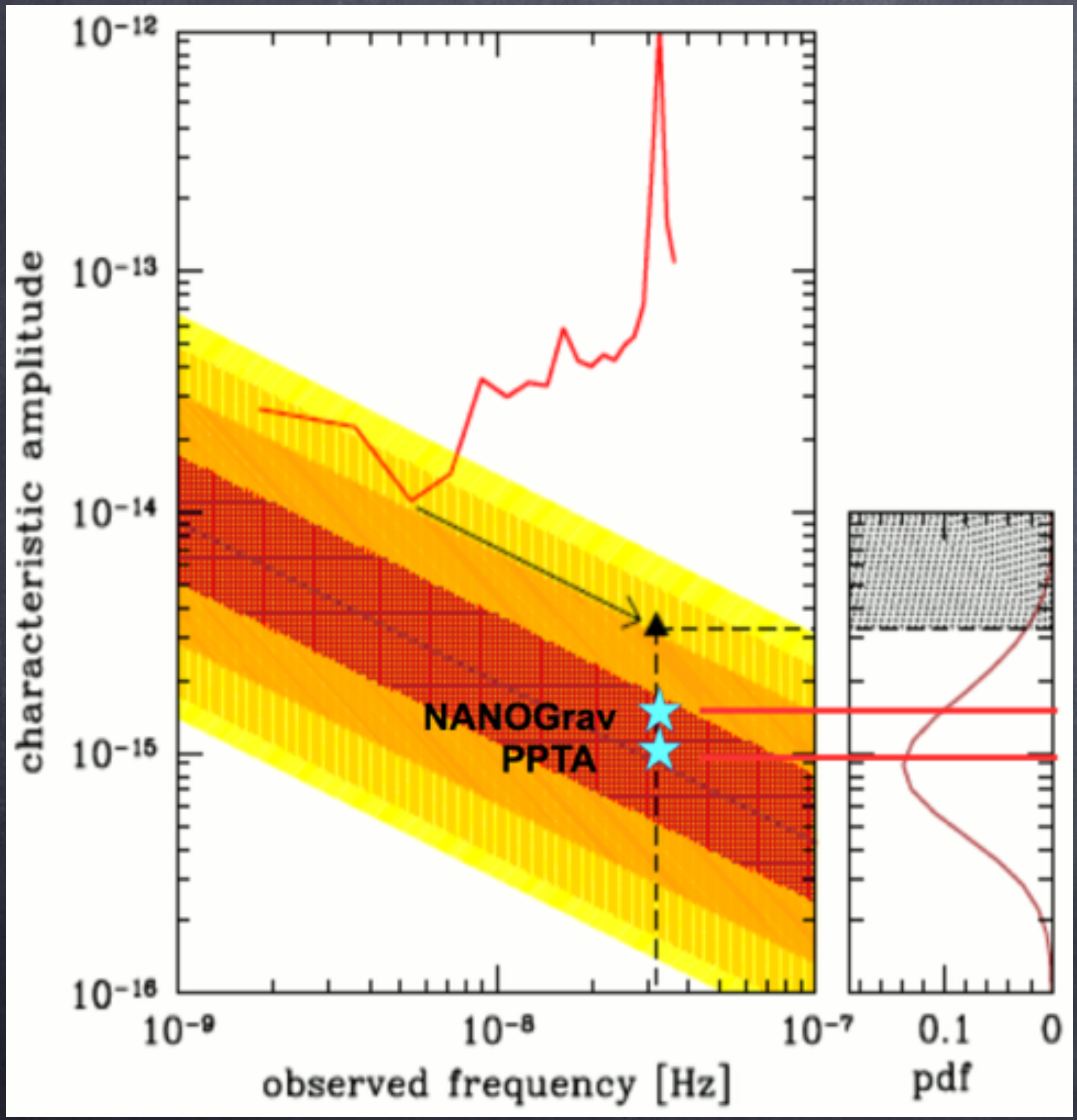


Figure courtesy of A. Sesana

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

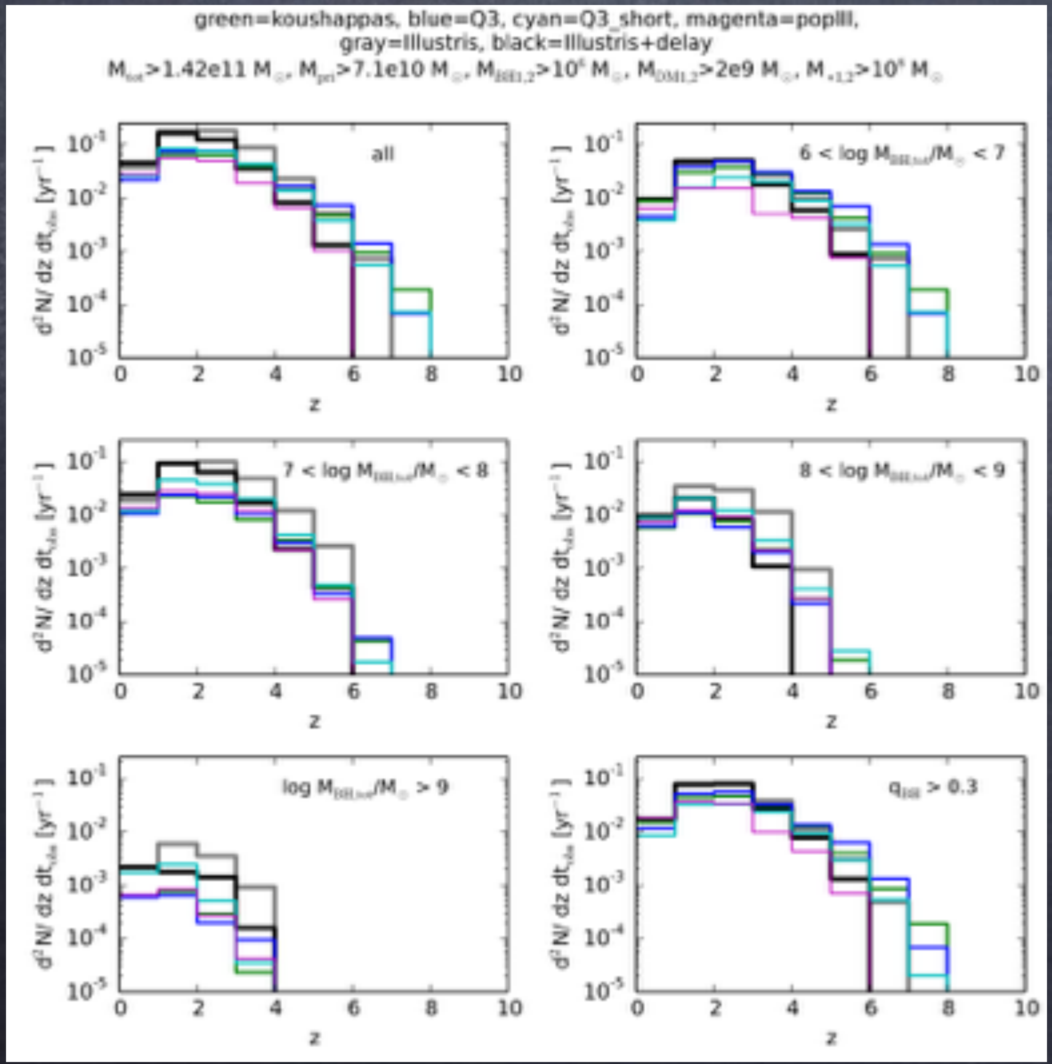
Loopholes:

- 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 eLISA, but larger masses
- Agreement among theoretical models of target massive BH population

EB 2012 vs Illustris



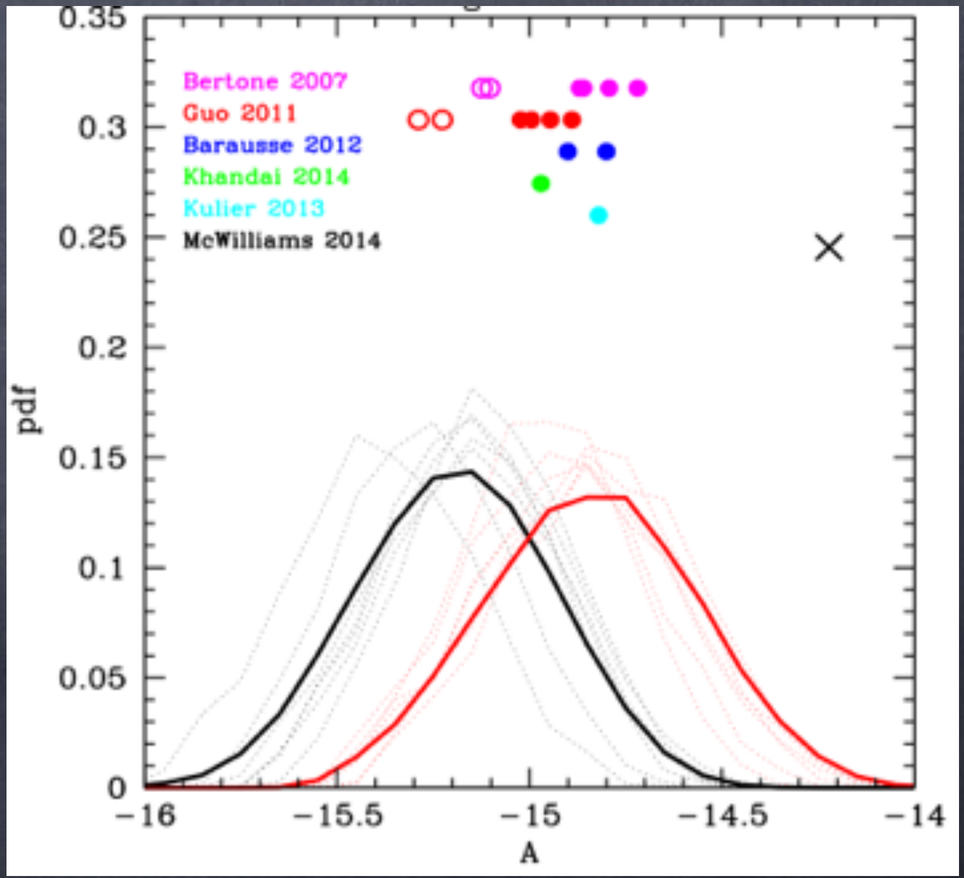
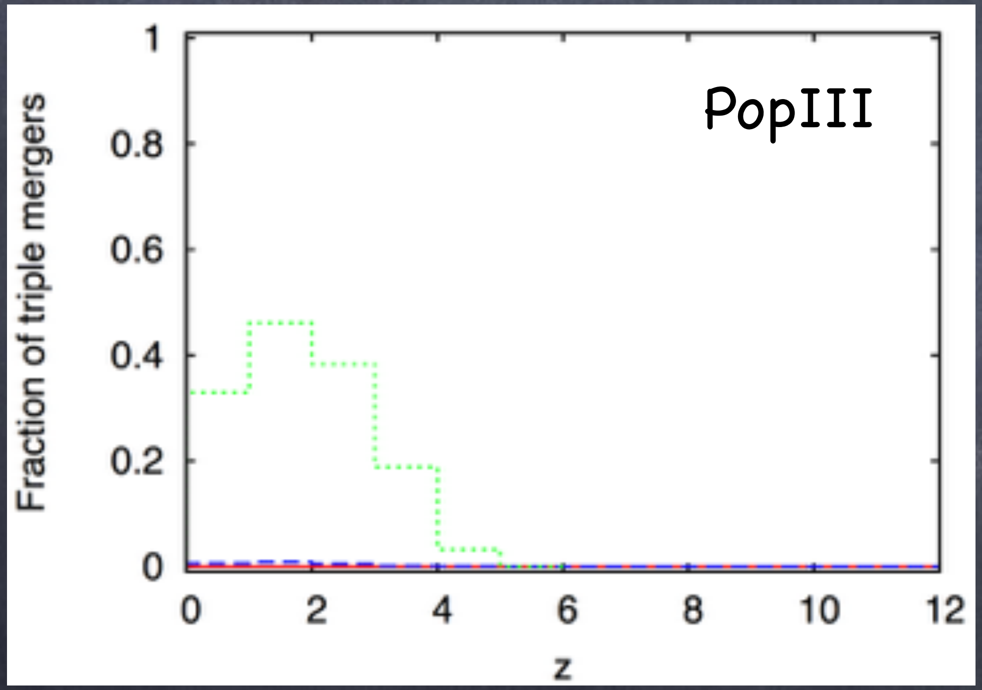
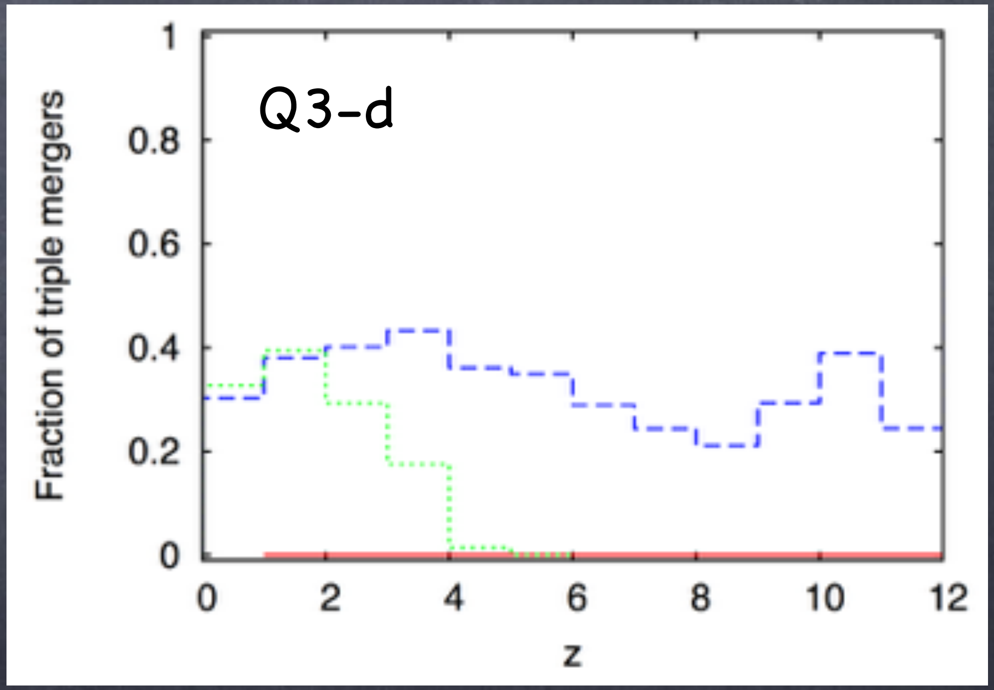


Figure courtesy A. Sesana

The nightmare scenario, aka the final-pc problem

- Binary stalls when all stars in its "loss-cone" are ejected
- Loss cone replenishment may happen due to triaxial potentials/galaxy mergers/galaxy rotation (merger times ~ 1-10 Gyr)
- Gas drives mergers in ~ 10 Myr
- If the above processes are inefficient, triple massive BH systems form





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

In progress: implications of eccentricity/triples for eLISA (M. Bonetti)

Conclusions

- aLIGO/aVirgo detection probes for the first time not only the existence of GWs but also that of black holes
- eLISA targets mergers of black holes with a variety of masses and mass ratios, e.g. massive BH mergers, EMRIs, IMRIs, GW150914-like systems
- Cosmological implications from standard sirens/stochastic background
- Synergies with other detectors (aLIGO/aVirgo, PTAs)
- eLISA's science goal best achievable with not-too-descoped configurations (6 links), so ESA has decided to go for Classic LISA!
- ESA's decision on final design by 2017 so as to allow launch in ~2030 (thanks to NASA involvement?)

Thank you!