The quest for low-frequency gravitational waves

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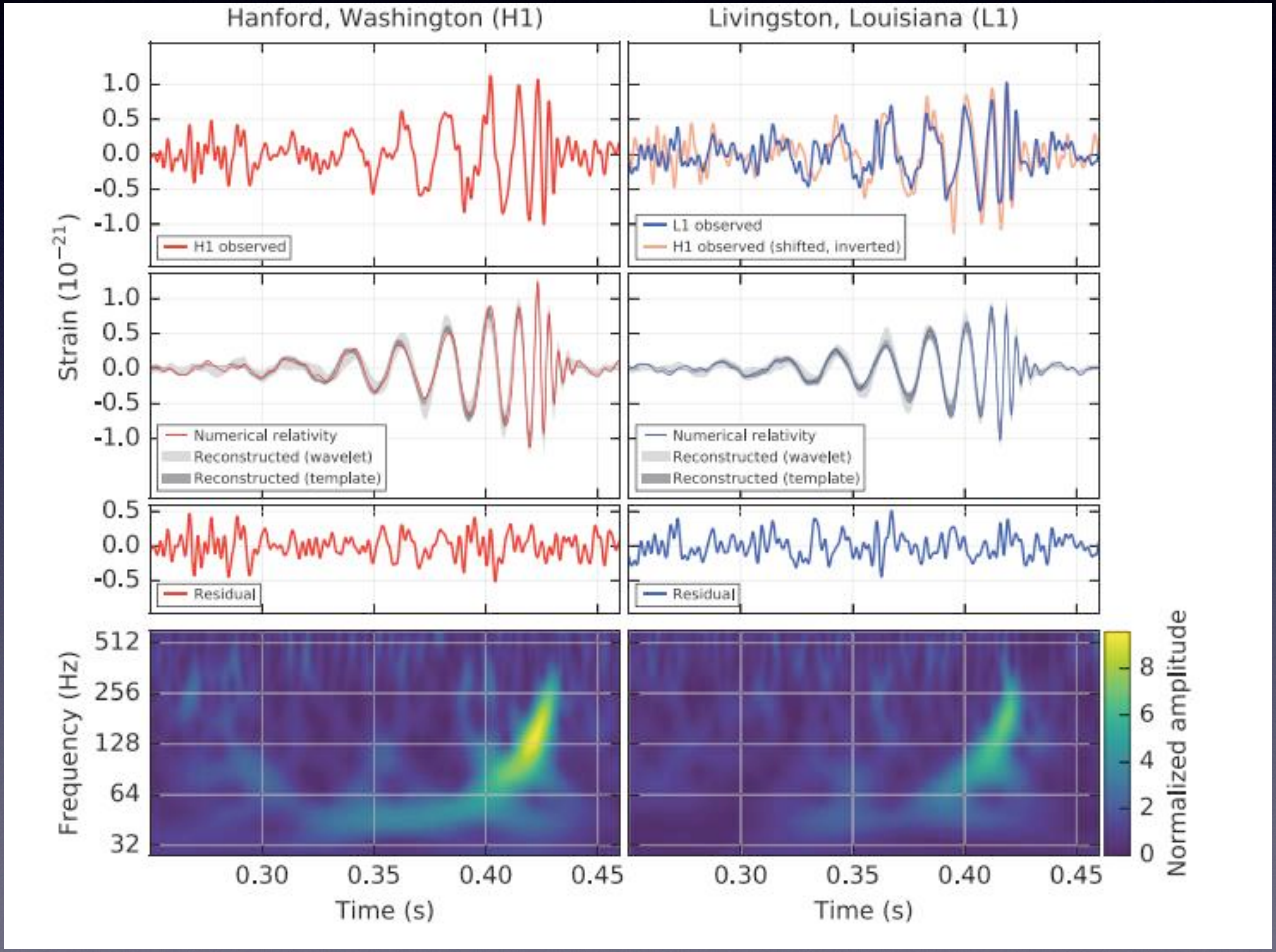
Outline

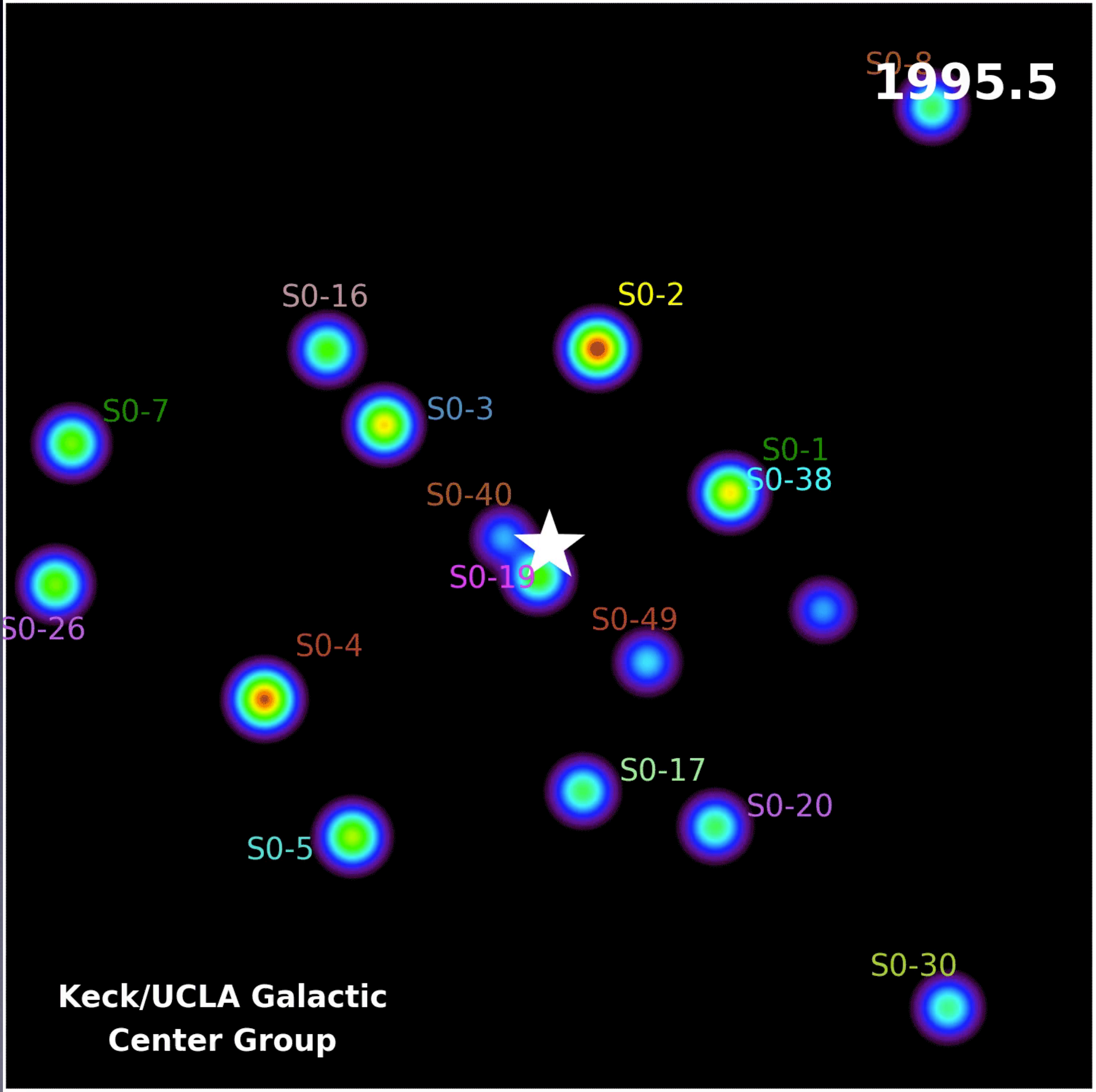
- Why low-frequency GWs?
- The Laser Interferometer Space Antenna (LISA)
  - Massive BH mergers
  - Tests of GR & implications for particle physics/Dark Matter
  - **Not covered/covered briefly:** other LISA sources (Extreme mass-ratio inspirals, white-dwarf binaries, stellar-mass/intermediate-mass BHs, stochastic backgrounds) and implications for cosmology
- Pulsar Timing Arrays (PTAs)

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!

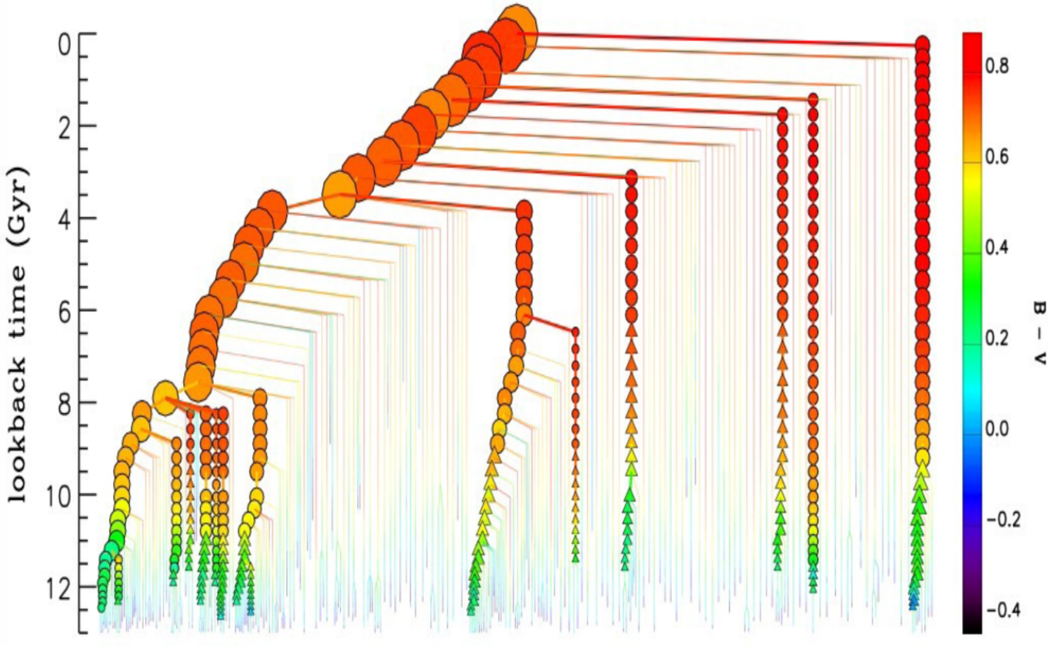


Figure from De Lucia & Blaizot 2007

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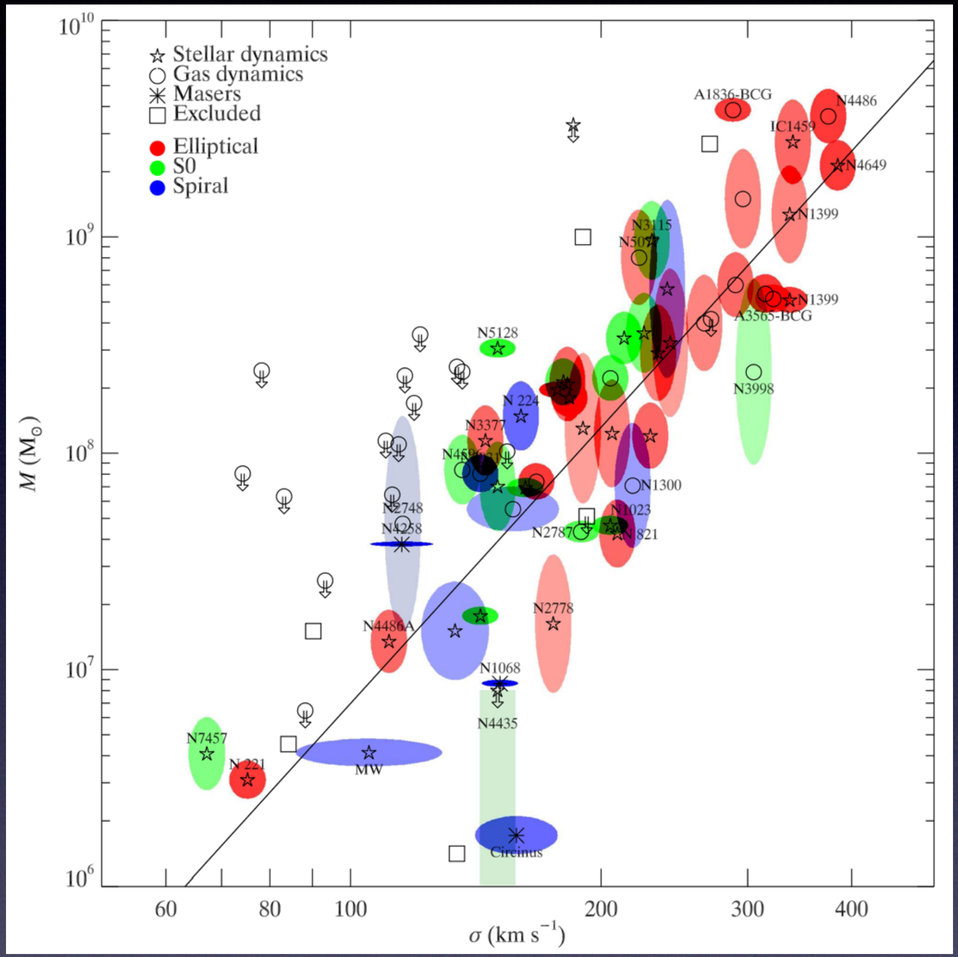

Ferrarese & Merritt 2000
Gebhardt et al. 2000,
Gültekin et al (2009)

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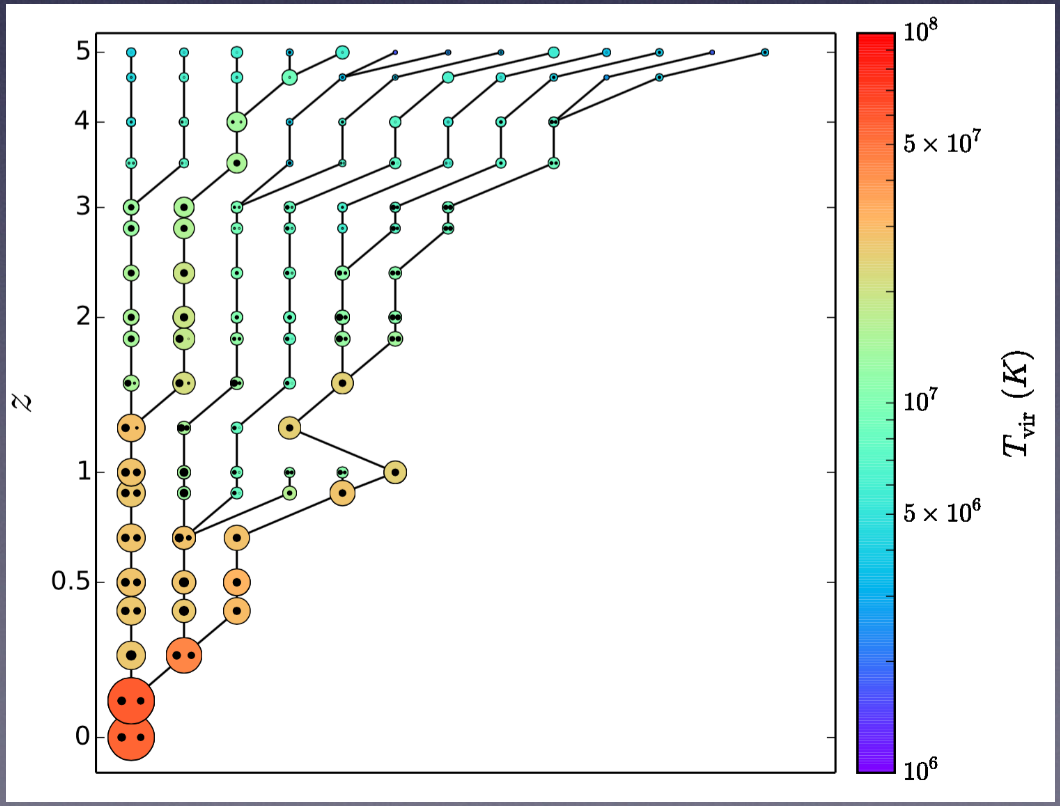
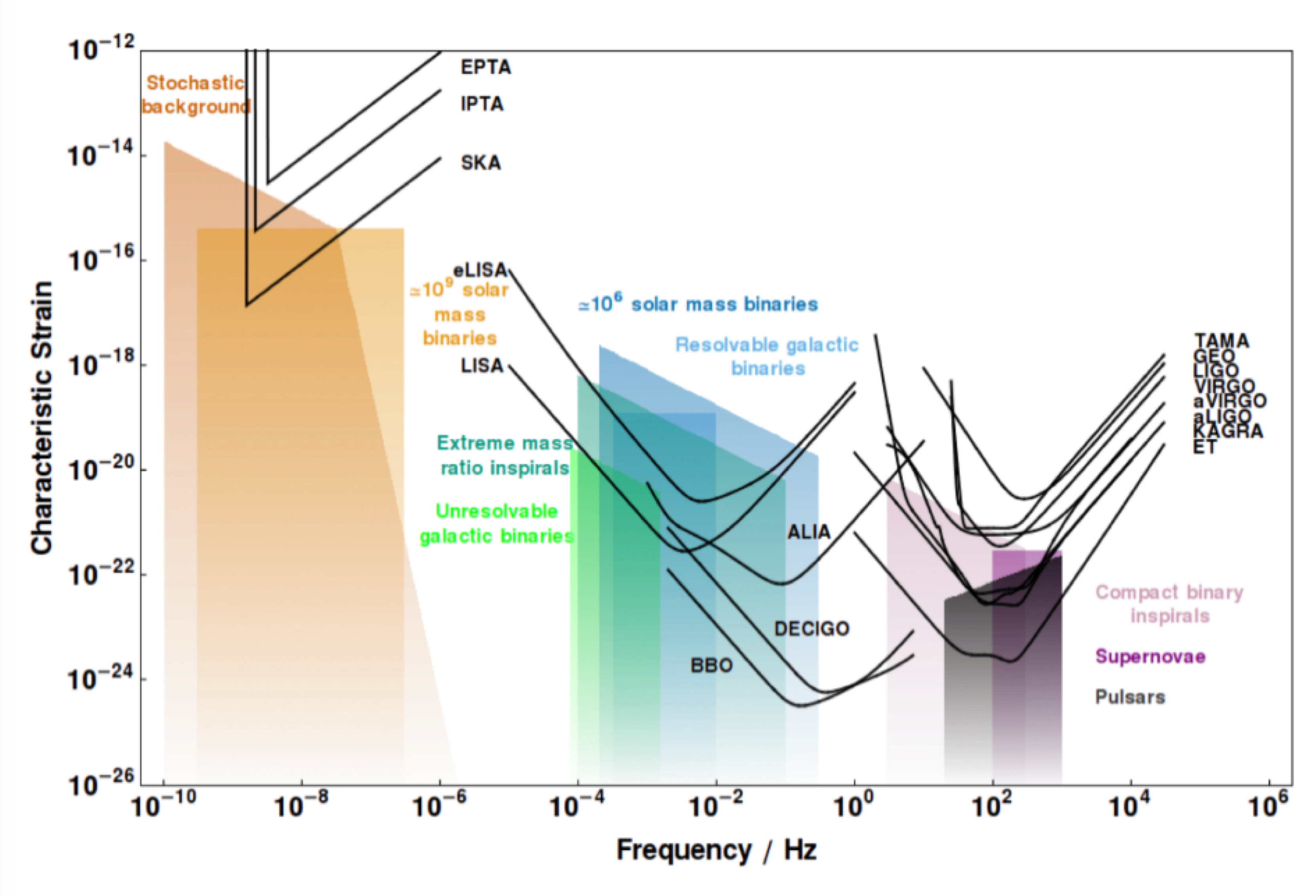


EB 2012
Figure credits: Lucy Ward

GWs from massive BHs

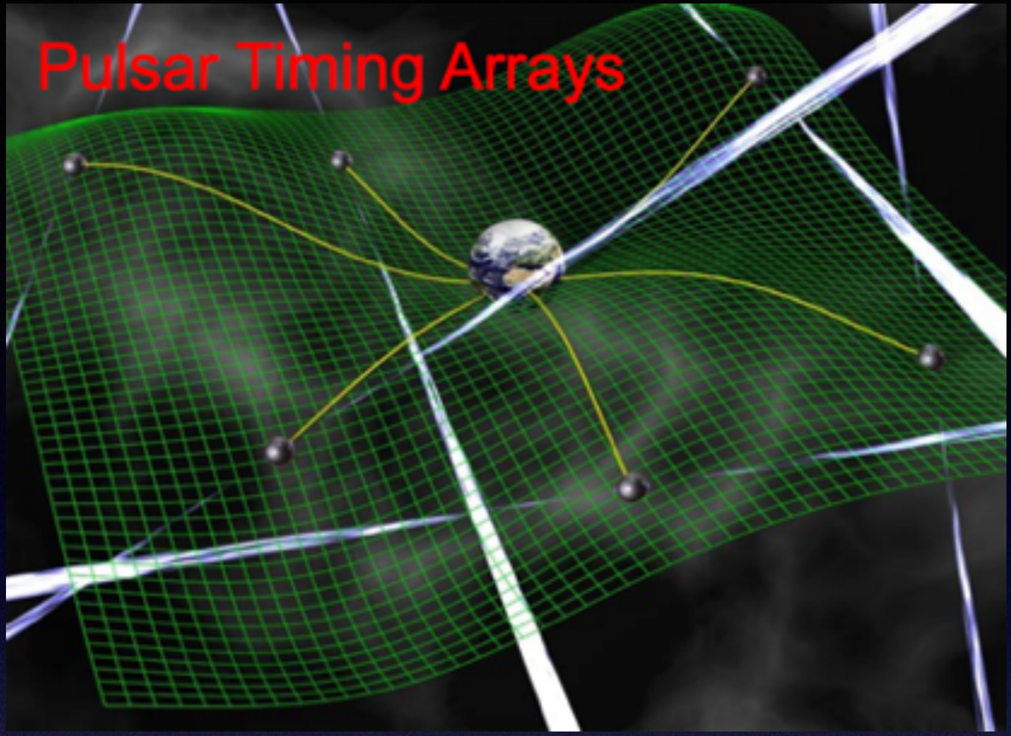
$$f_{\rm GW} = \frac{6 \times 10^4}{\tilde{m}\tilde{R}^{3/2}}\,{\rm Hz} \qquad \tilde{R} = R/(Gm/c^2)$$

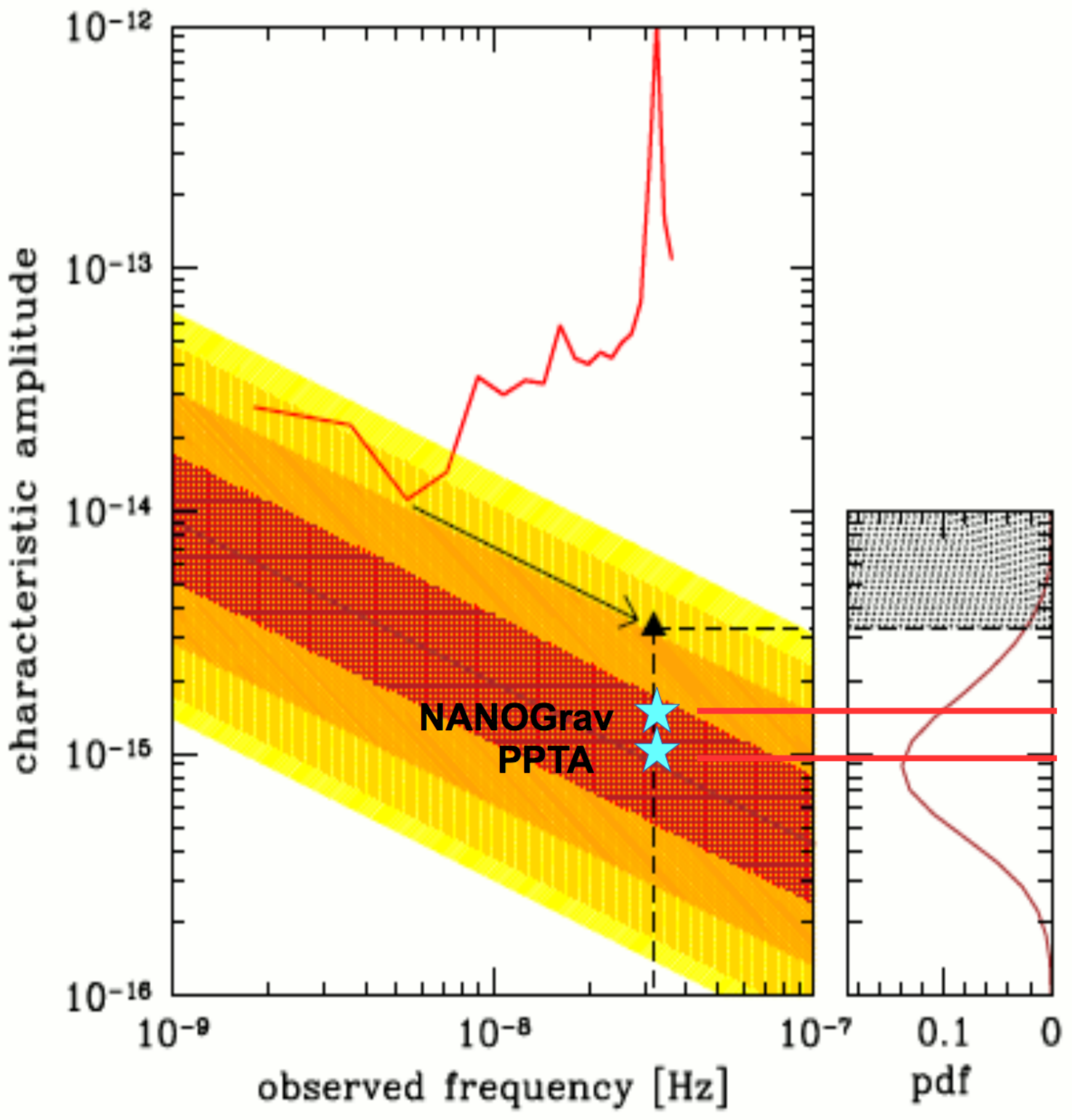
$$\tilde{m} = m/M_\odot$$

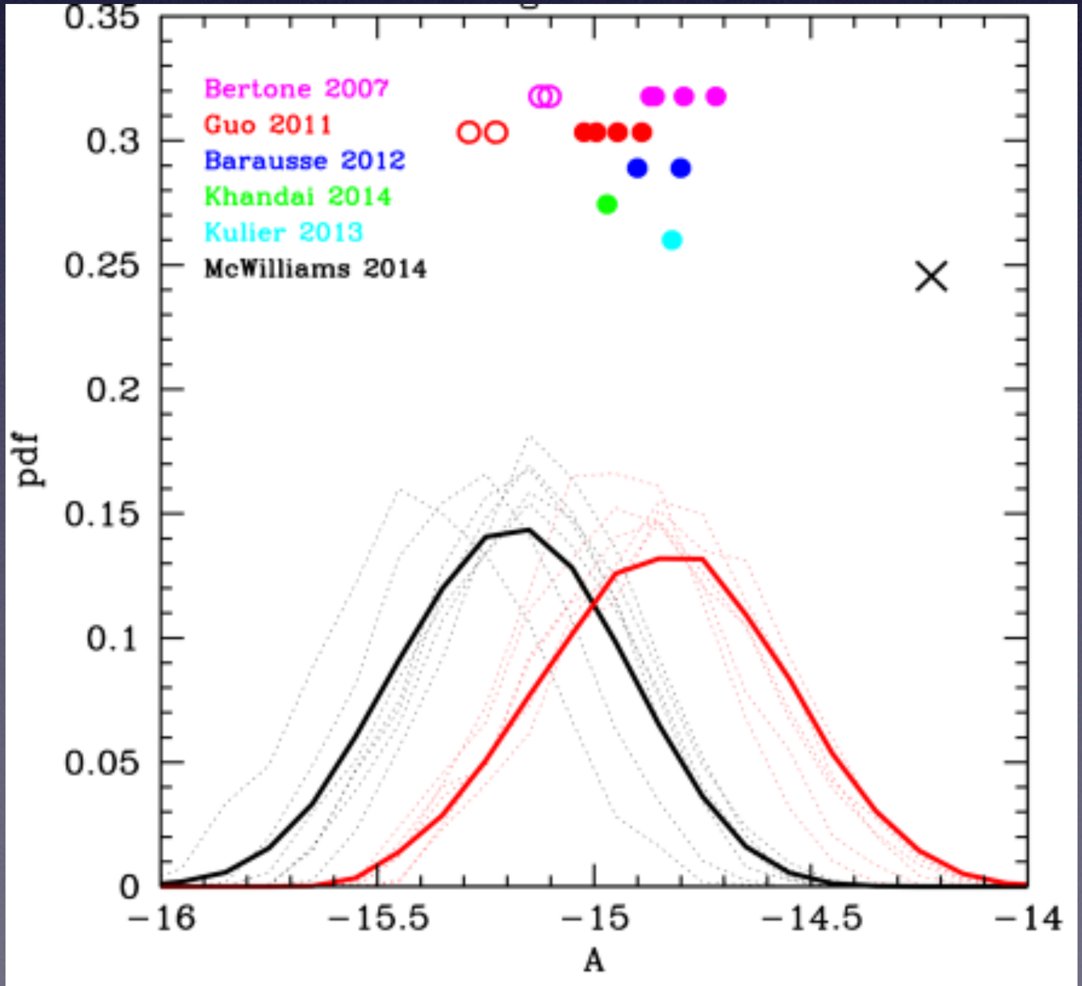


Problem: terrestrial detectors blind at f ≲ 1-10 Hz (seismic noise)

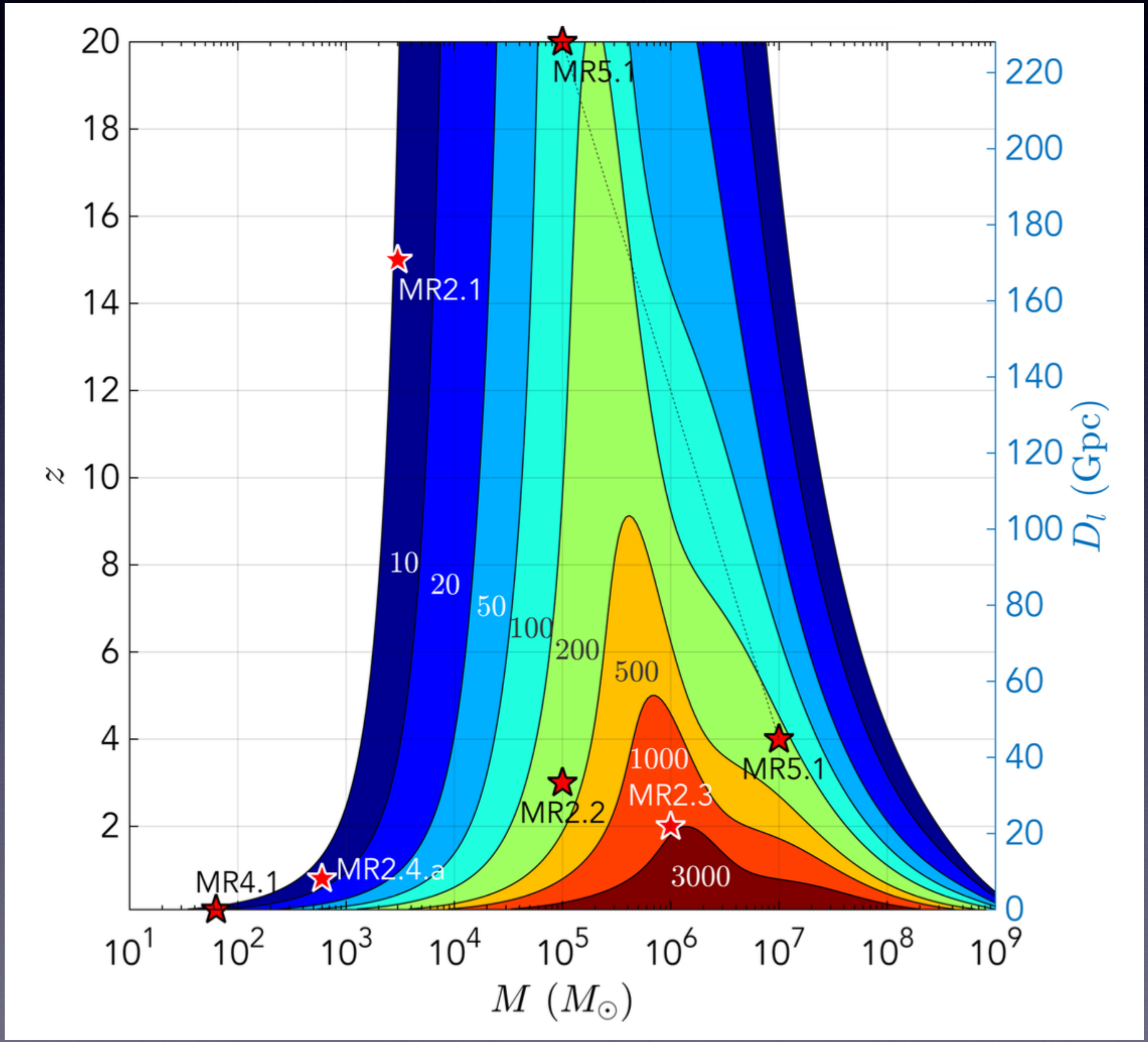
The space race!

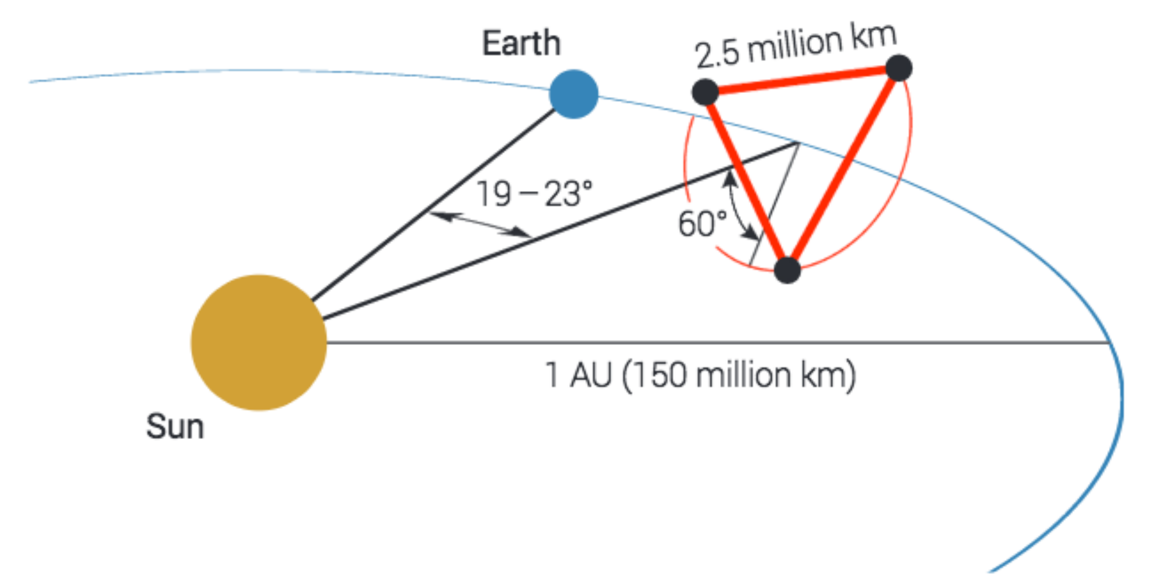


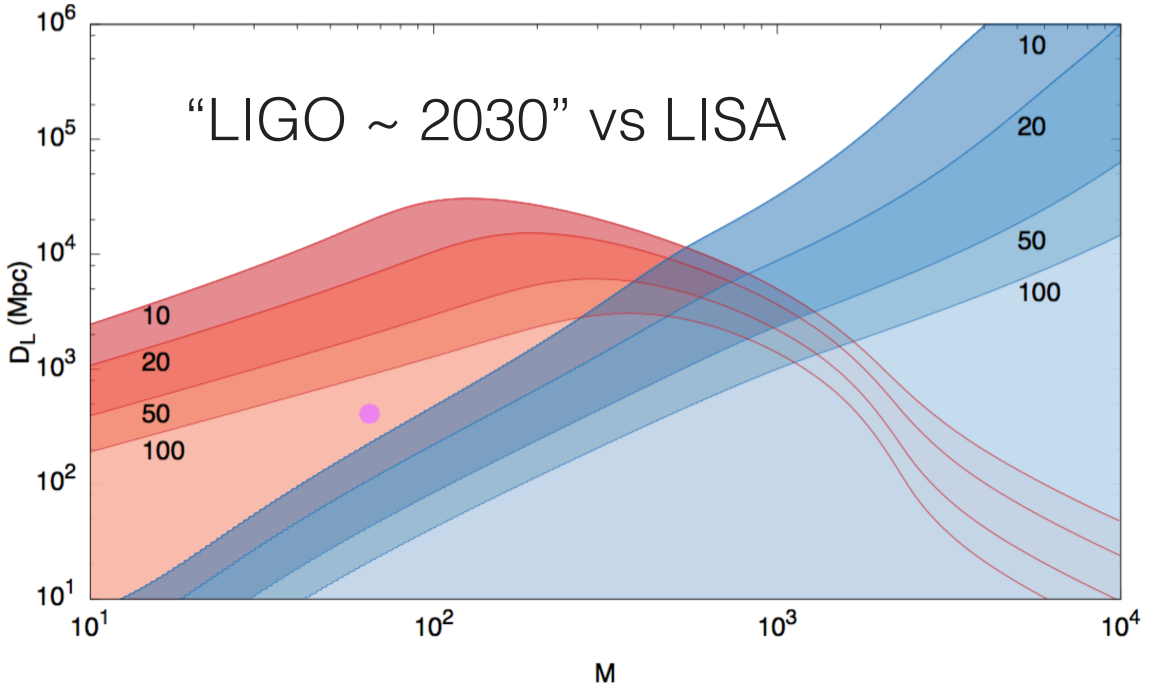




Laser Interferometer Space Antenna (LISA)





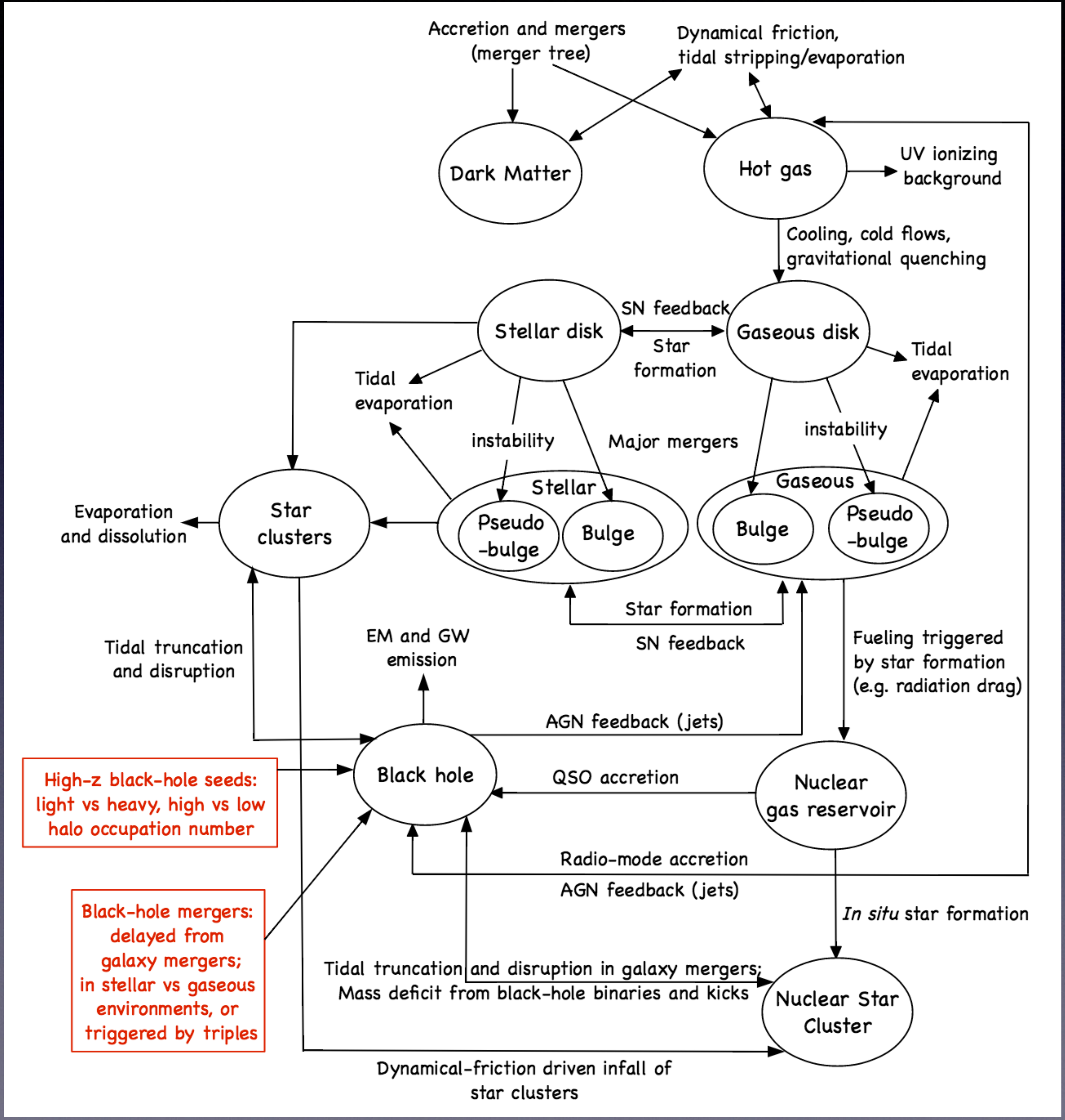


LISA status and timeline

- LISA Pathfinder mission a success (surprisingly stable)
- LISA is now a mission (June 2017)
- Phase 0 to end this year, Phase A in 2018-19, then ~ 10 yrs of industrial production, with launch ~ 2030-34
- Phase 0/A: finalization of mission design (options analyzed by ESA's Gravitational Wave Advisory Team in collaboration with industry & LISA Consortium) + consortium re-organization
- Design options used in the following:

Armlength L= 1, 2, 5 Gm (A1, A2, A5); 4 or 6 links (L4, L6); 2 or 5 year mission (M2, M5)

Galaxy/BH co-evolution



Accretion and mergers
(merger tree)

Dynamical friction,
tidal stripping/evaporation

Dark Matter

Hot gas

UV ionizing
background

Cooling, cold flows,
gravitational quenching

Stellar disk

SN feedback

Star
formation

Gaseous disk

Tidal
evaporation

Tidal
evaporation

instability

Major mergers

instability

Stellar

Pseudo
-bulge

Bulge

Gaseous

Bulge

Pseudo
-bulge

Evaporation
and dissolution

Star
clusters

Star formation

SN feedback

Tidal truncation
and disruption

EM and GW
emission

Fueling triggered
by star formation
(e.g. radiation drag)

AGN feedback (jets)

High-z black-hole seeds:
light vs heavy, high vs low
halo occupation number

Black hole

QSO accretion

Nuclear
gas reservoir

Radio-mode accretion

AGN feedback (jets)

In situ star formation

Black-hole mergers:
delayed from
galaxy mergers;
in stellar vs gaseous
environments, or
triggered by triples

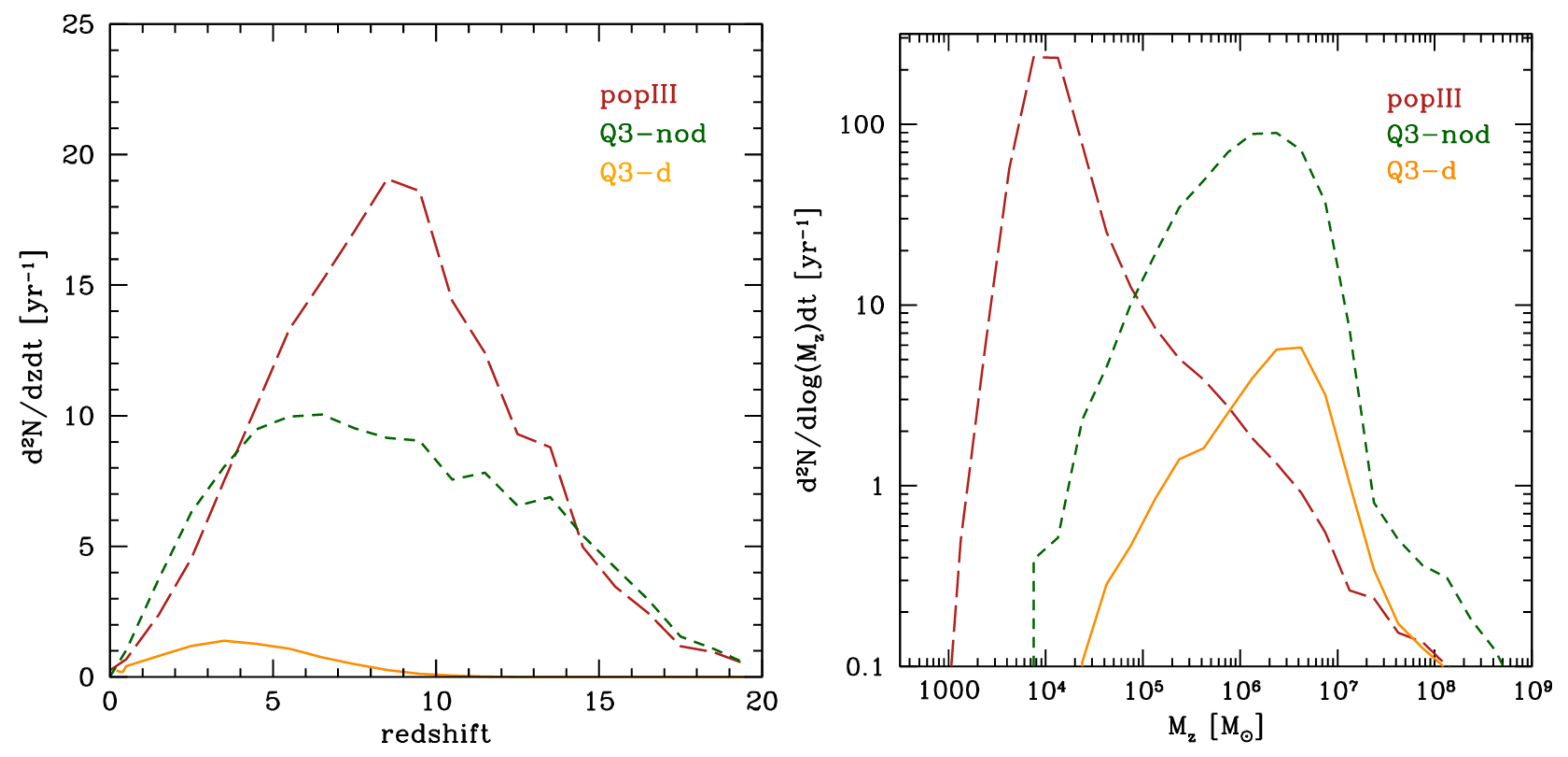
Tidal truncation and disruption in galaxy mergers;
Mass deficit from black-hole binaries and kicks

Nuclear Star
Cluster

Dynamical-friction driven infall of
star clusters

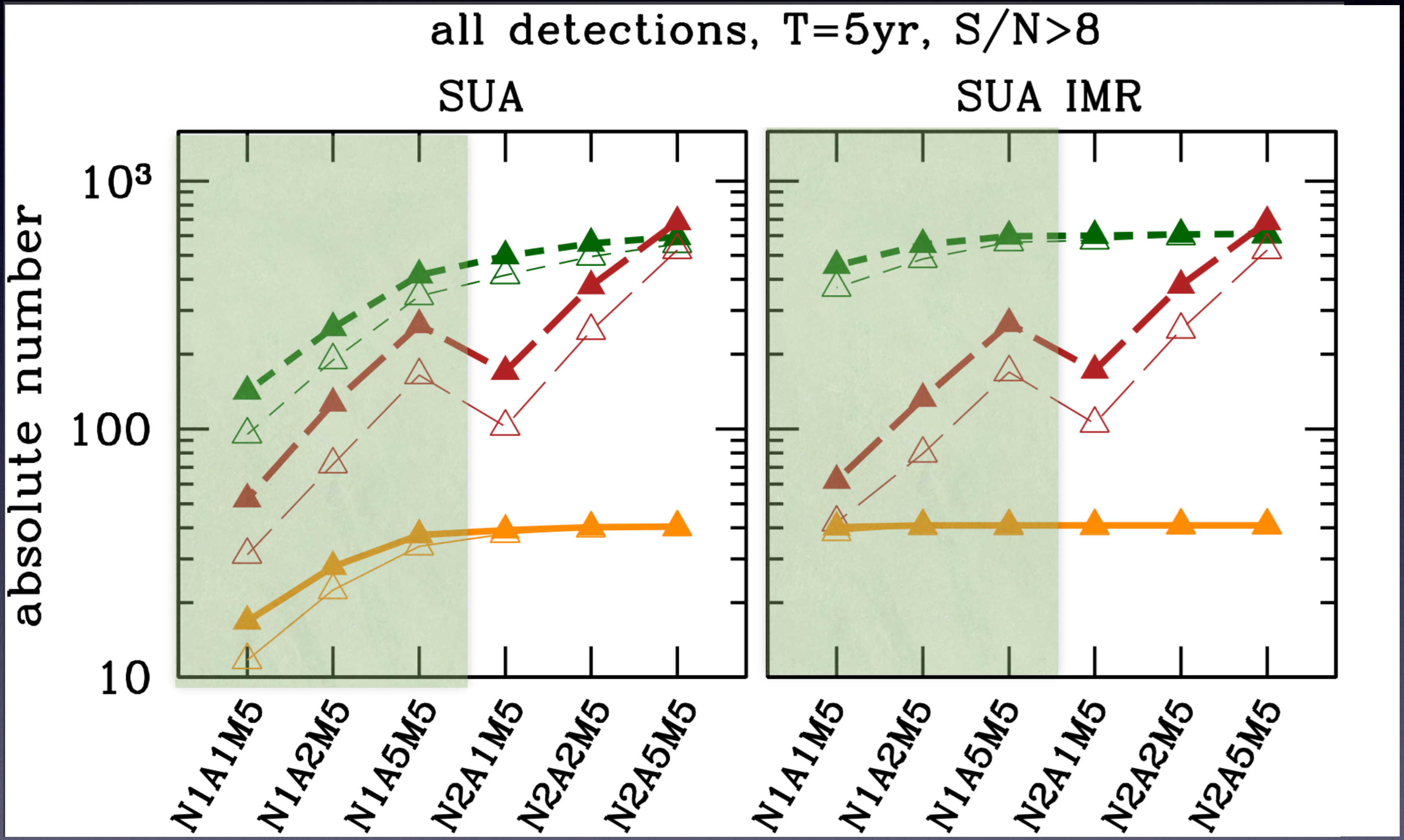
EB 2012

Semianalytic galaxy/BH evolution



Light ("popIII") vs heavy ("Q3") seeds
No delays ("nod") vs realistic delays ("d")

Detection rates

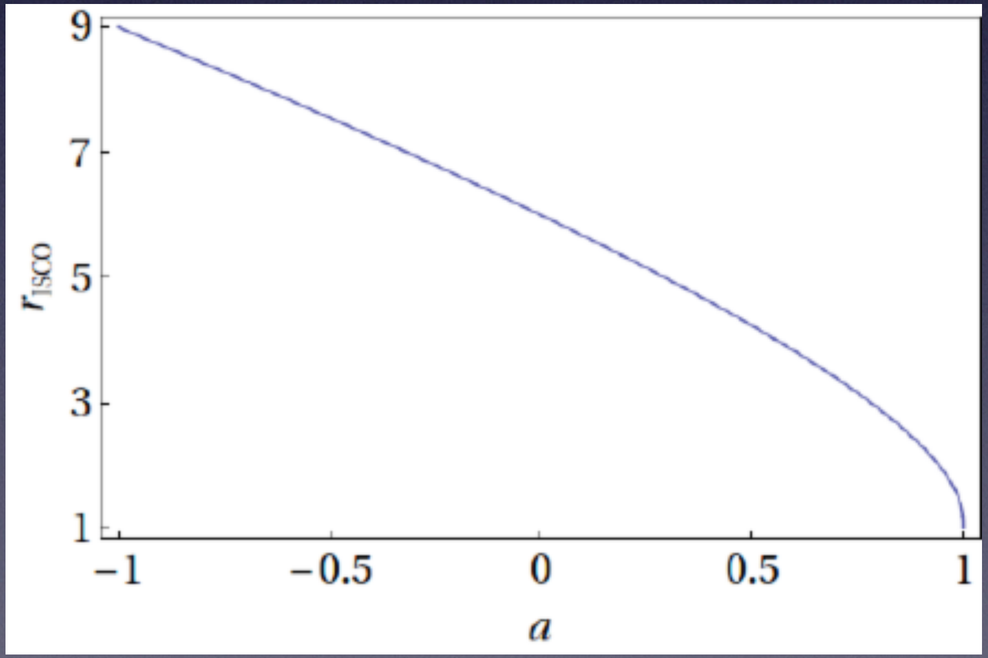


Red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

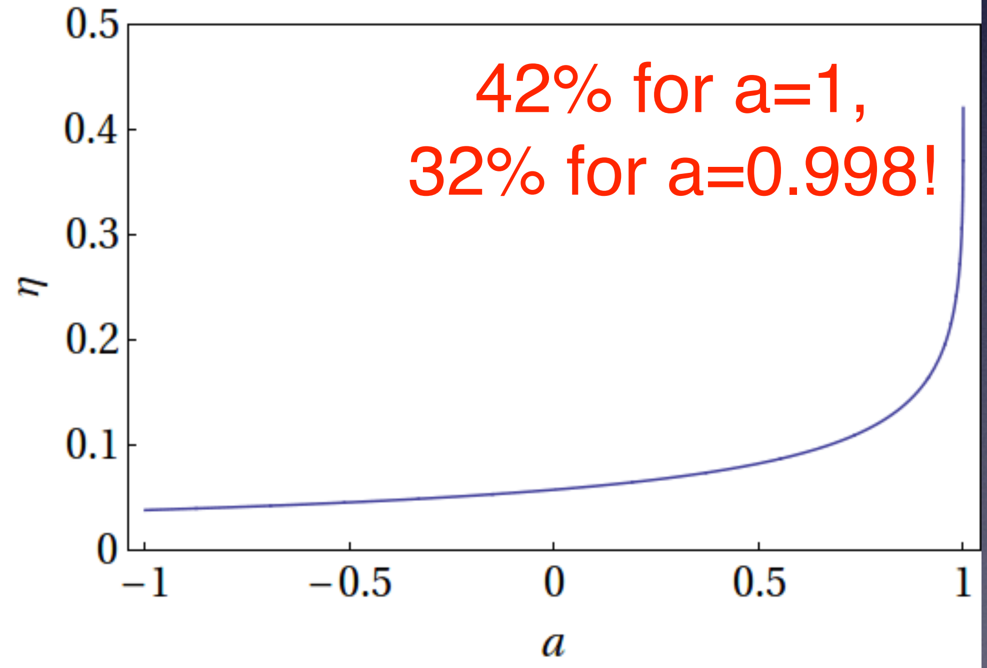
From Klein EB et al 2015

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)



42% for a=1,
32% for a=0.998!

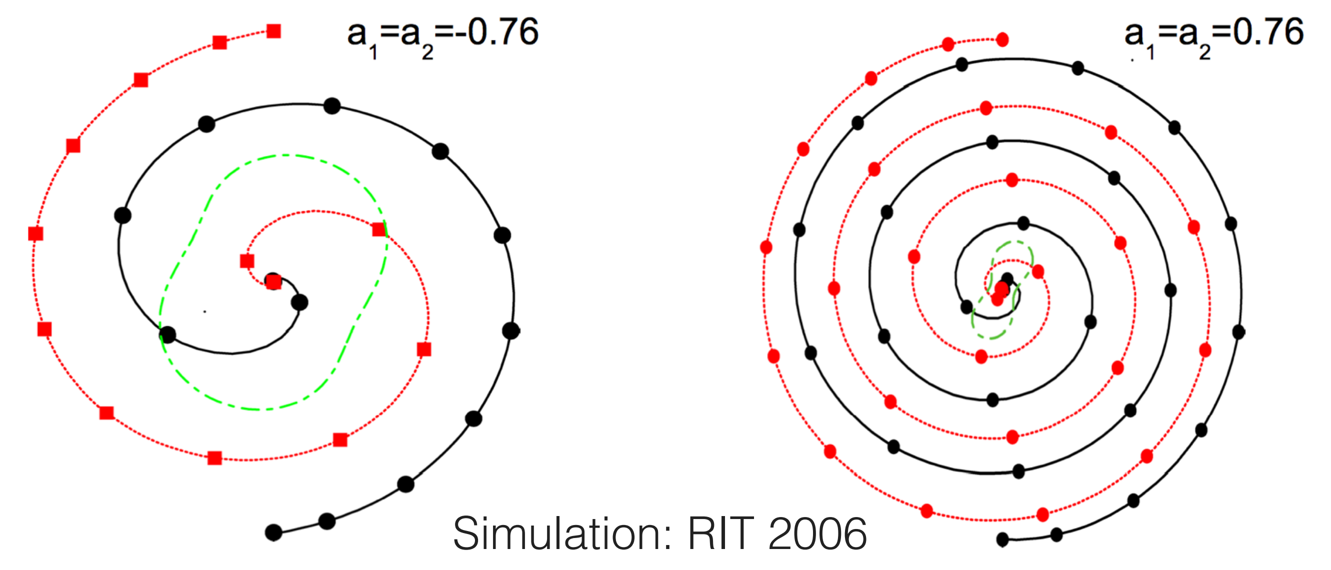
Efficiency of EM
emission from thin disks

The effect of BH spins: frame-dragging in binaries

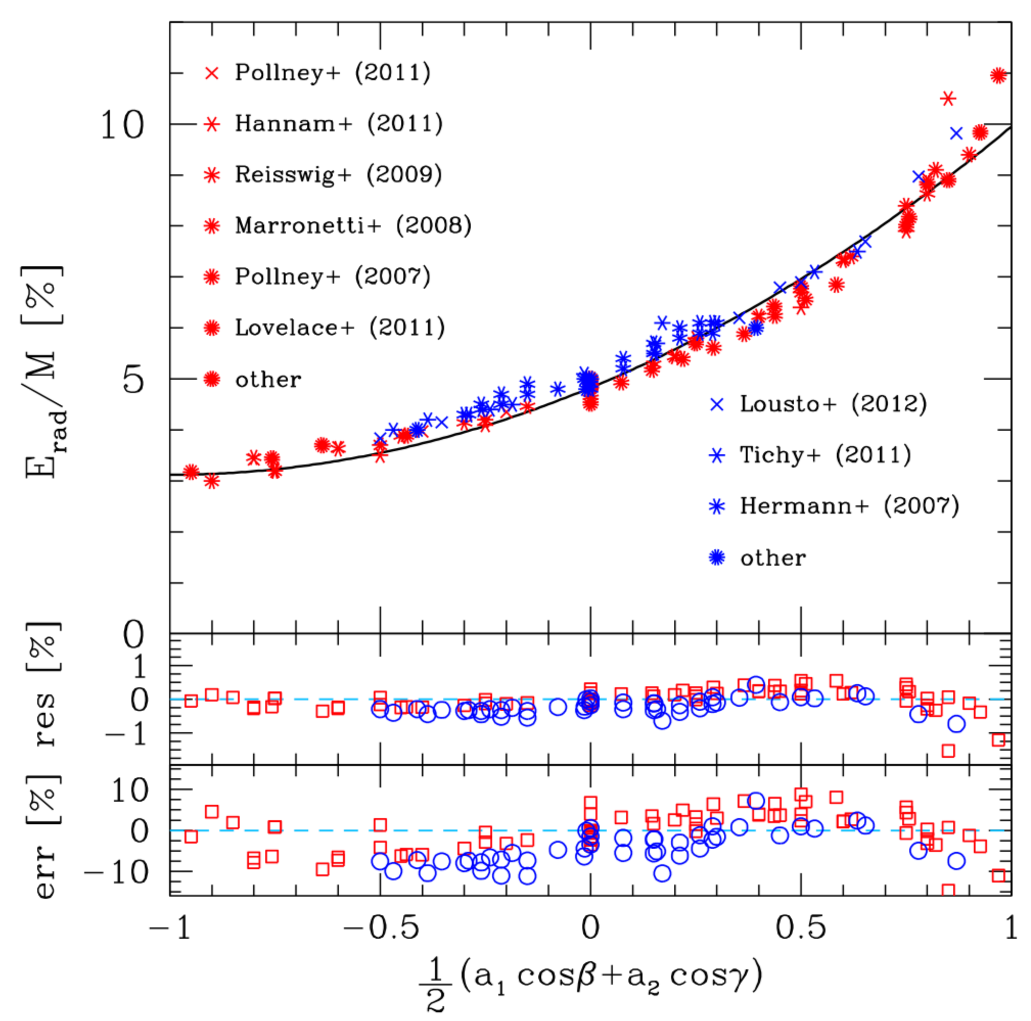
- For large spins aligned with L, effective ISCO moves inward …

- ... and GW “efficiency” gets larger

Spins increase GW amplitudes



Simulation: RIT 2006



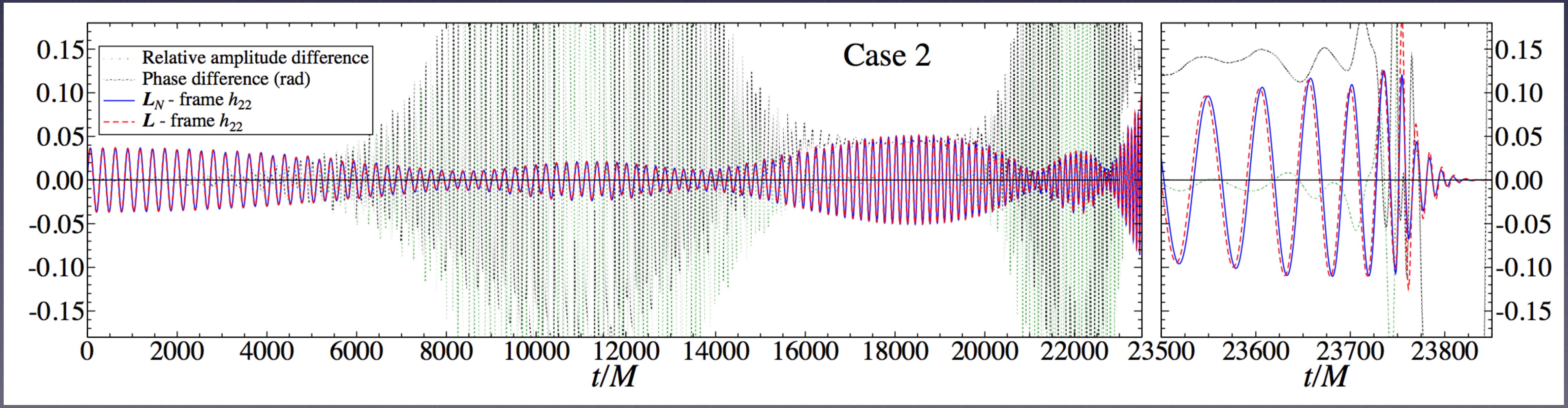
EB, Morozova & Rezzolla (2012)

The effect of BH spins on the waveforms

- Spin precesses around total angular momentum $J=L+S_1+S_2$
- Precession-induced modulations observable with GW detectors:

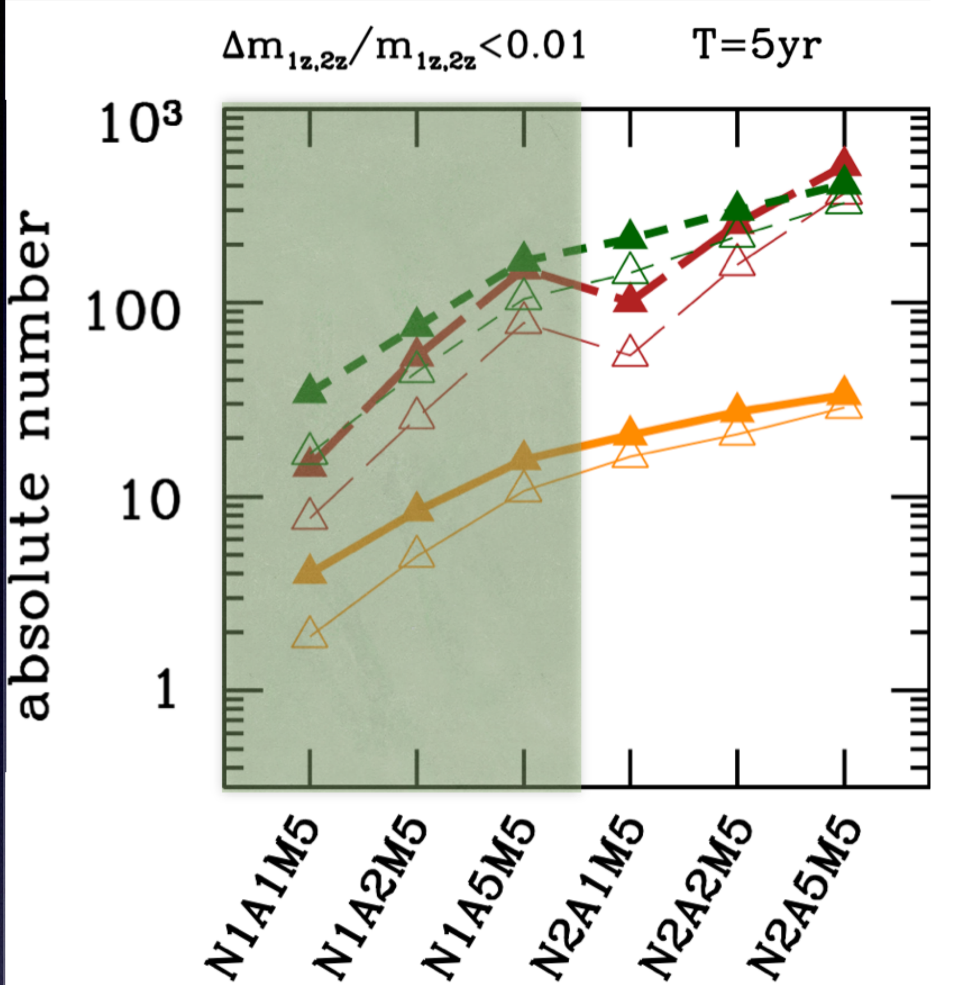
  - Increase SNR and improve measurements of binary parameters (e.g. luminosity distance and sky localization)

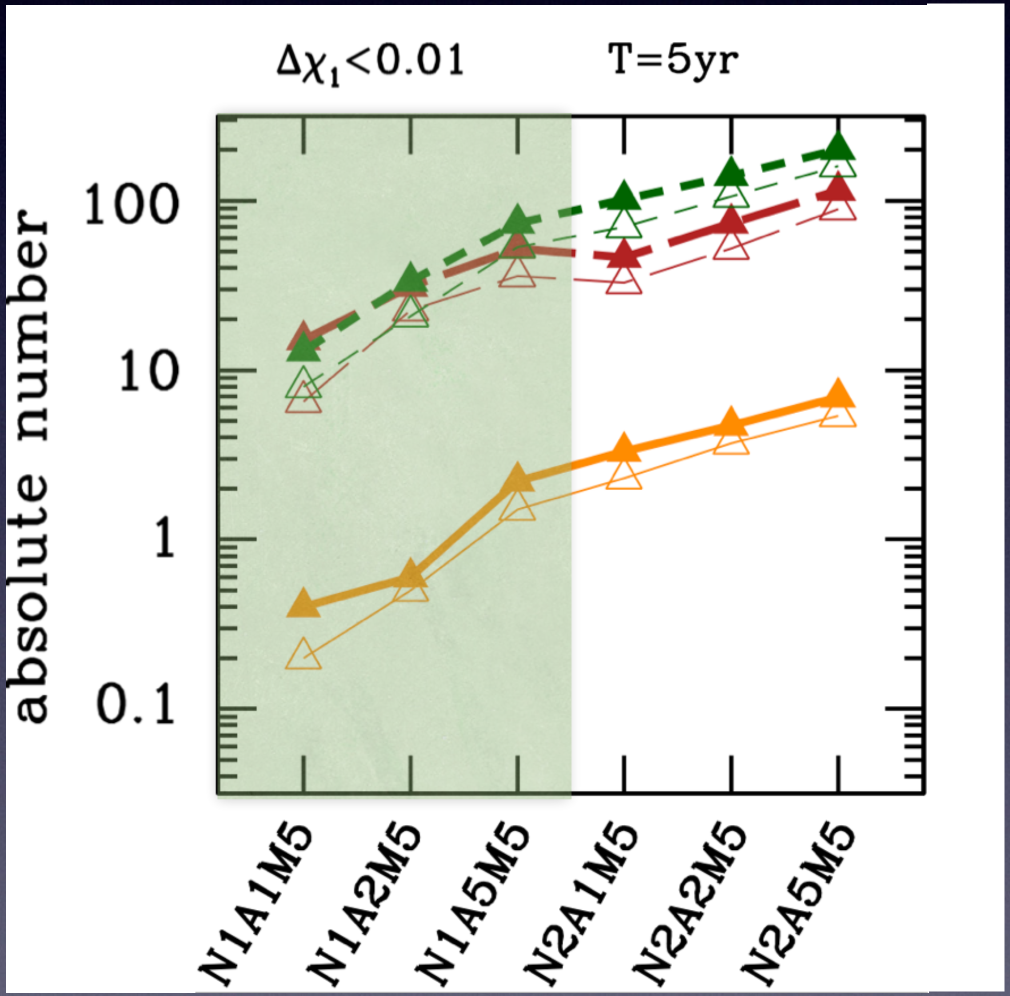
  - Allow measurements of angle between spins

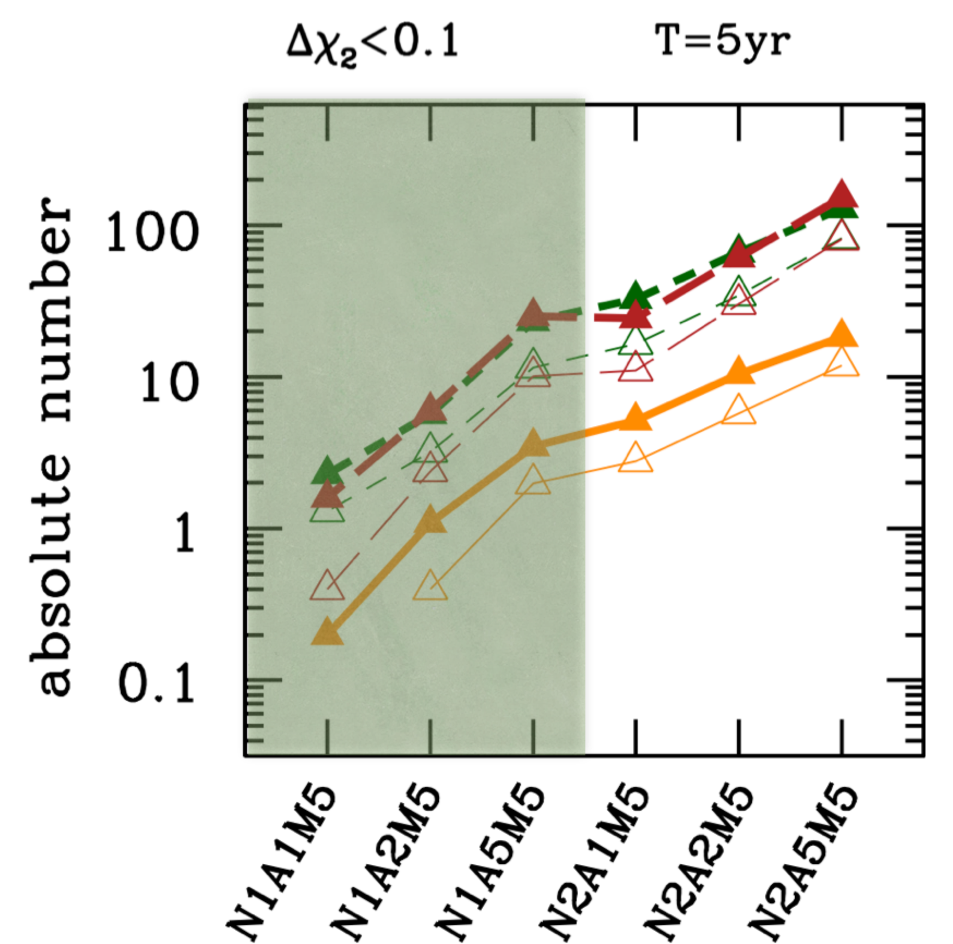


EOB waveforms for BH binary with mass ratio 1:6 and spins 0.6 and 0.8, from Pan et al (2013) [using spin-EOB model of EB & Buonanno 2010, 2011]

Errors on individual masses/spins

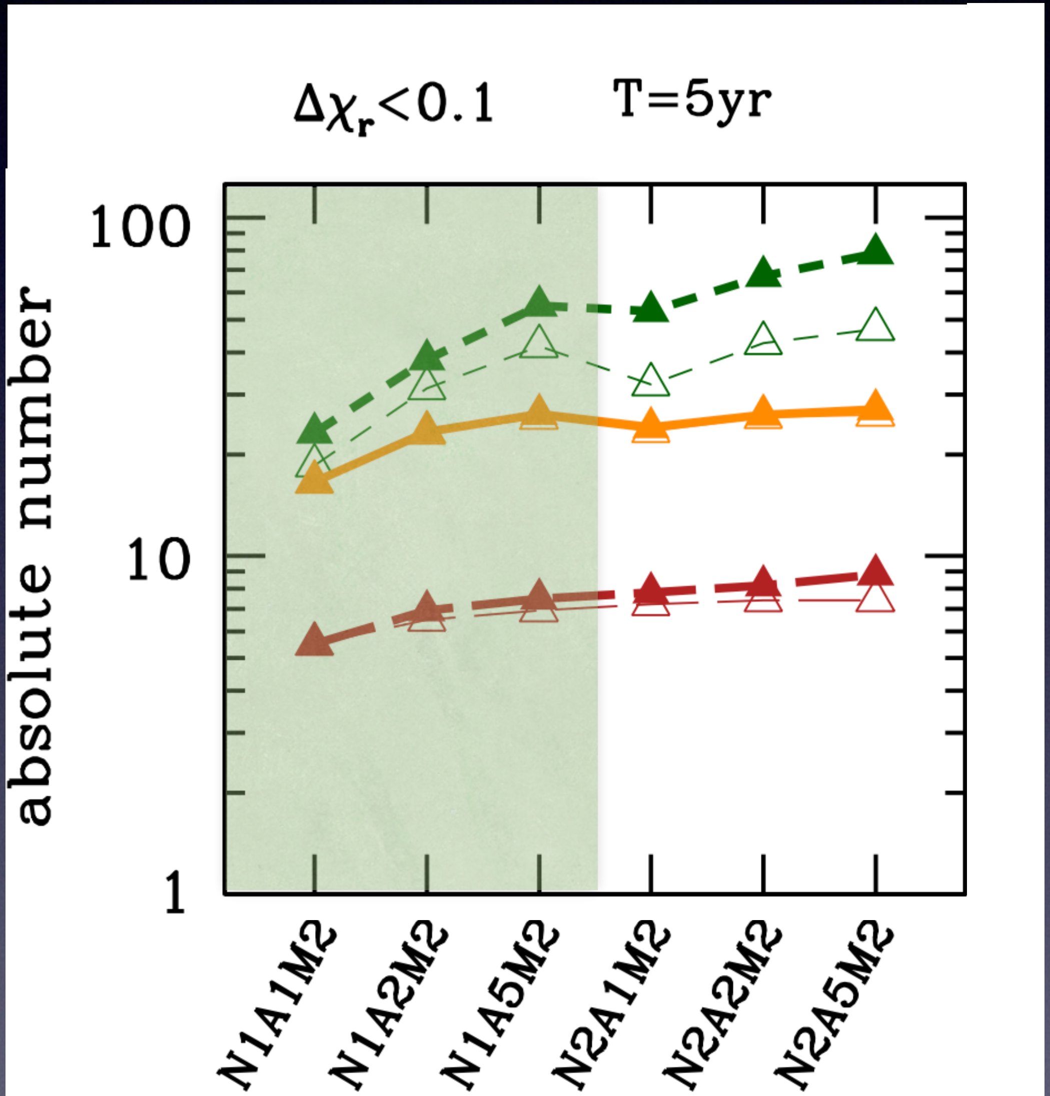


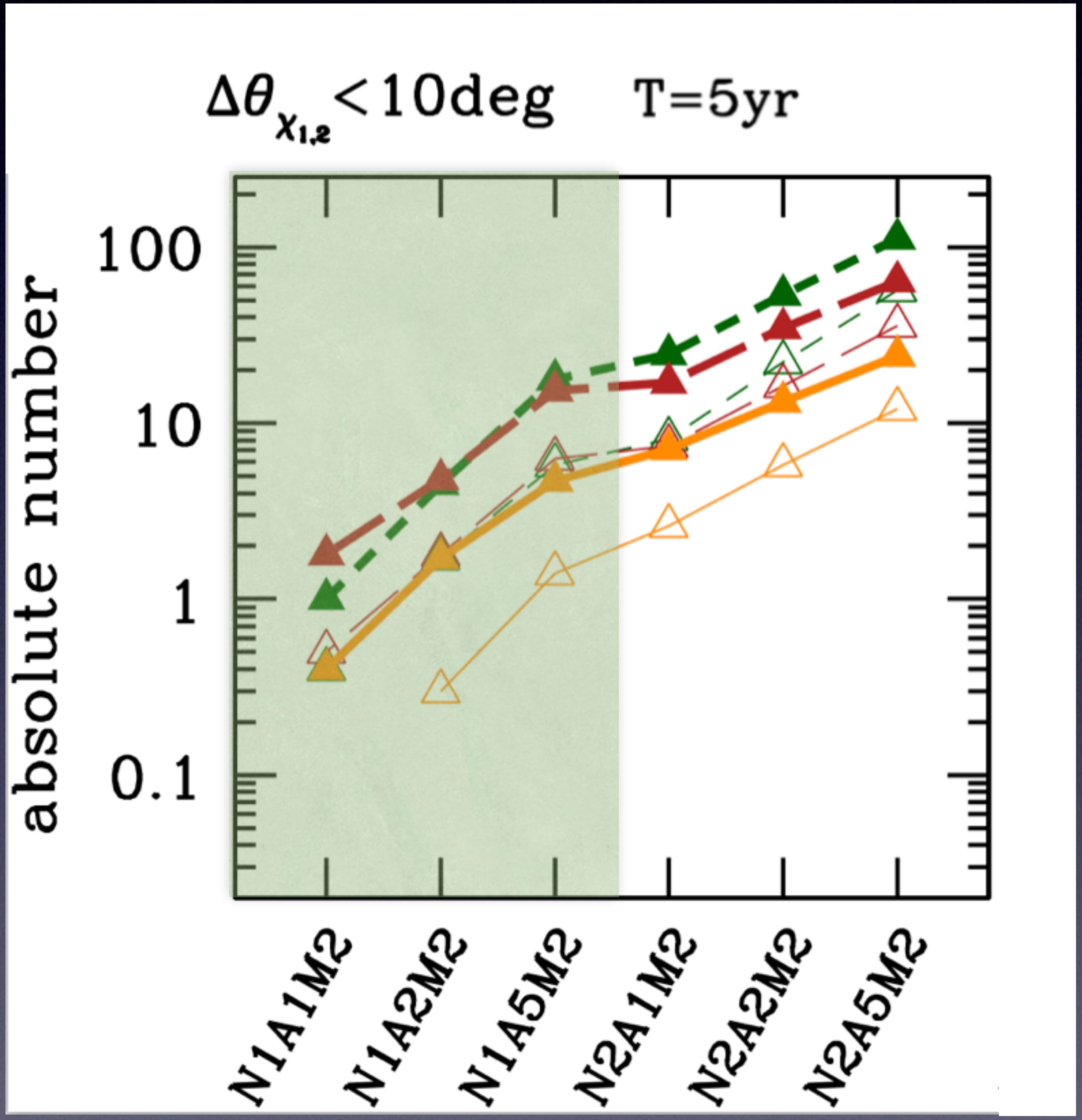




Red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

Errors on spin inclinations and final spin



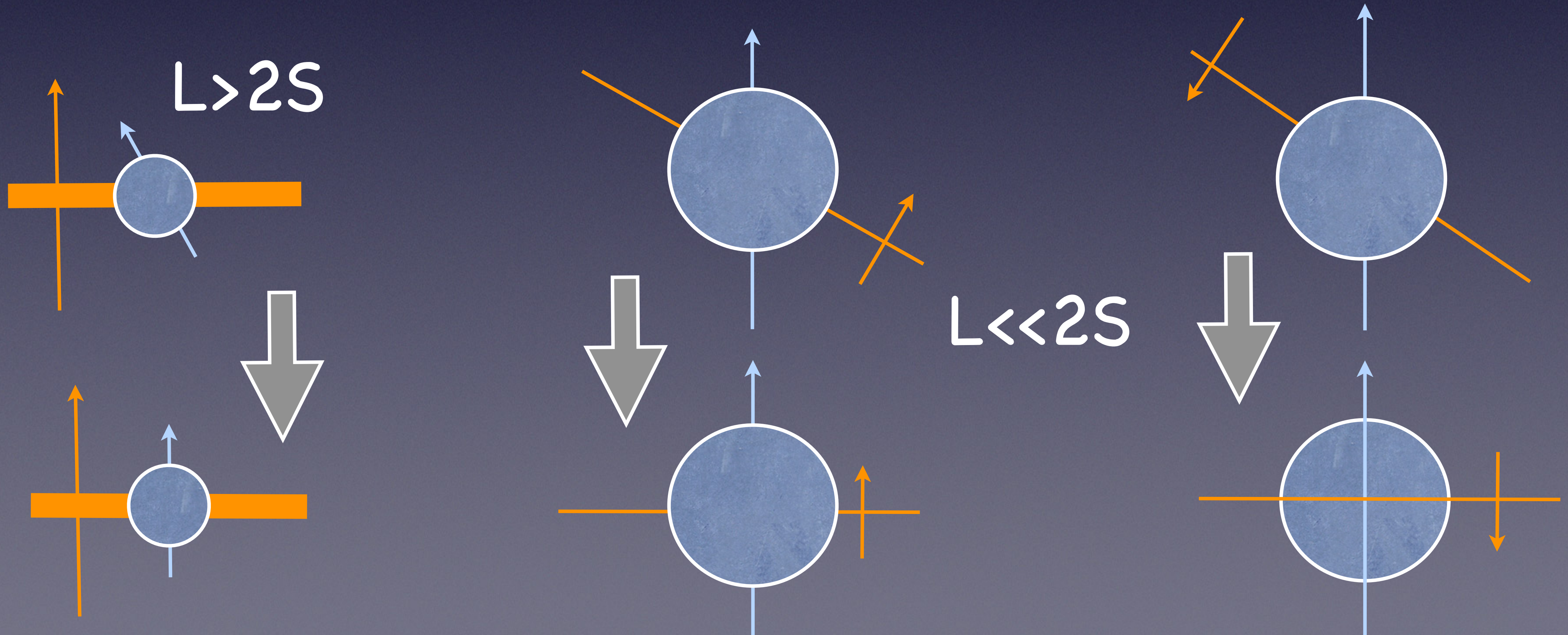


Red = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

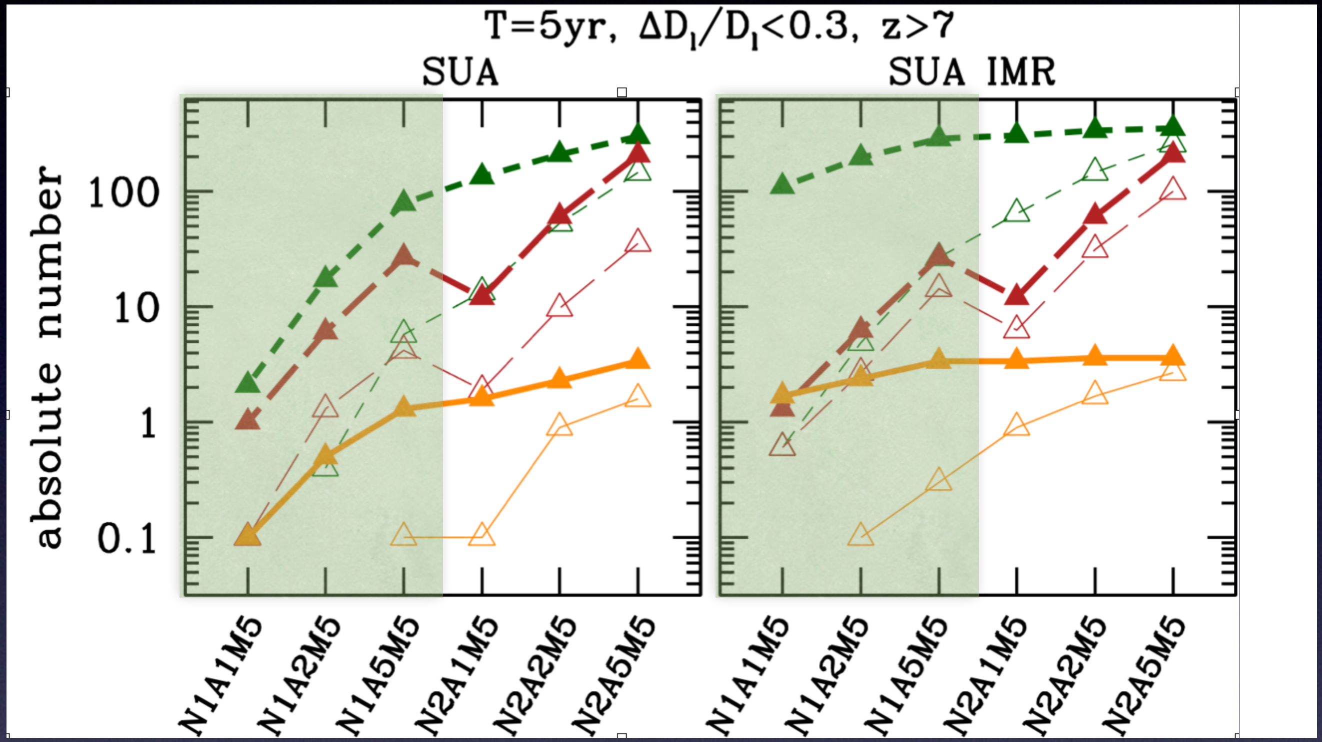
Provides information about interactions with gas (Bardeen-Petterson effect) and ringdown tests of GR

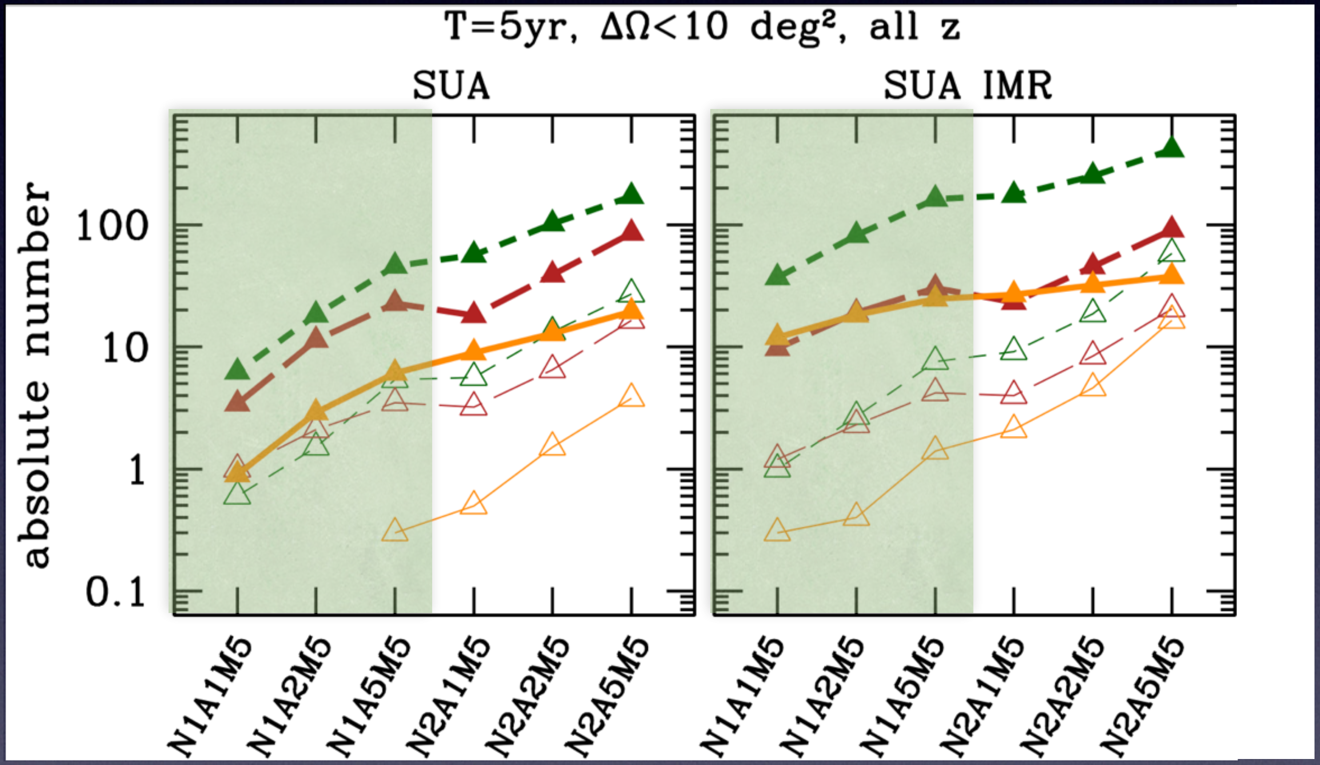
The Bardeen Petterson effect

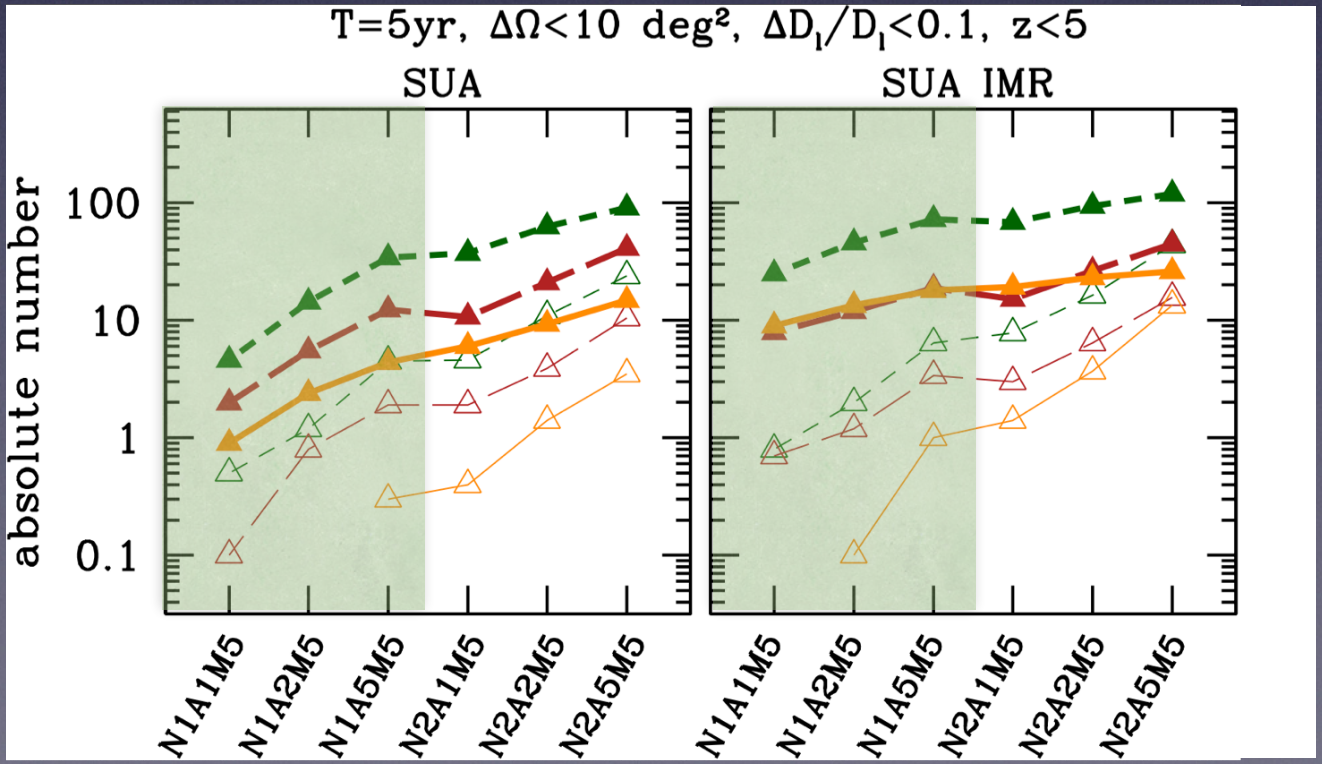
- Coupling between BH spin S and angular momentum L of misaligned accretion disk + dissipation
- Either aligns or anti-aligns S and L in ~10^5 yrs (for MBHs) << accretion timescale
- Anti-alignment only if disk carries little angular momentum ($L < 2S$) and is initially counterrotating



Cosmography (“standard sirens”) and probes of massive BH formation



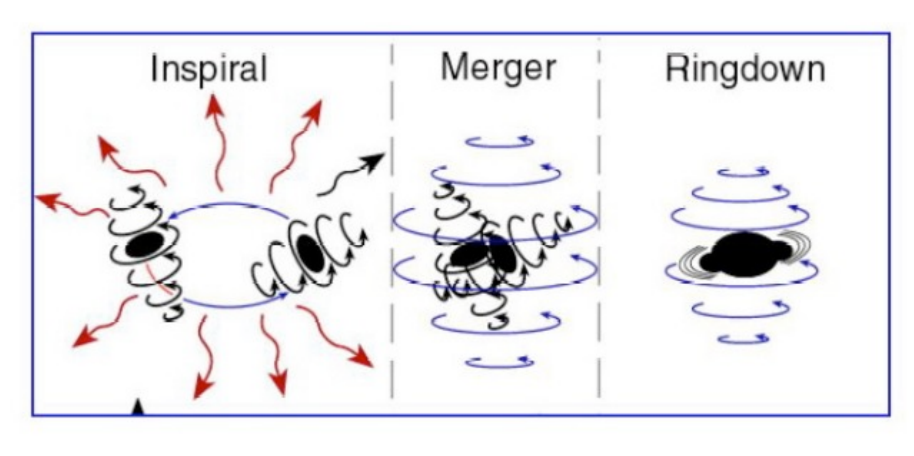




brown = popIII, orange = Q3-d, green = Q3-nod
thick = six links (L6), thin = four links (L4)

From Klein EB et al 2015; see also Tamanini EB et al 2016

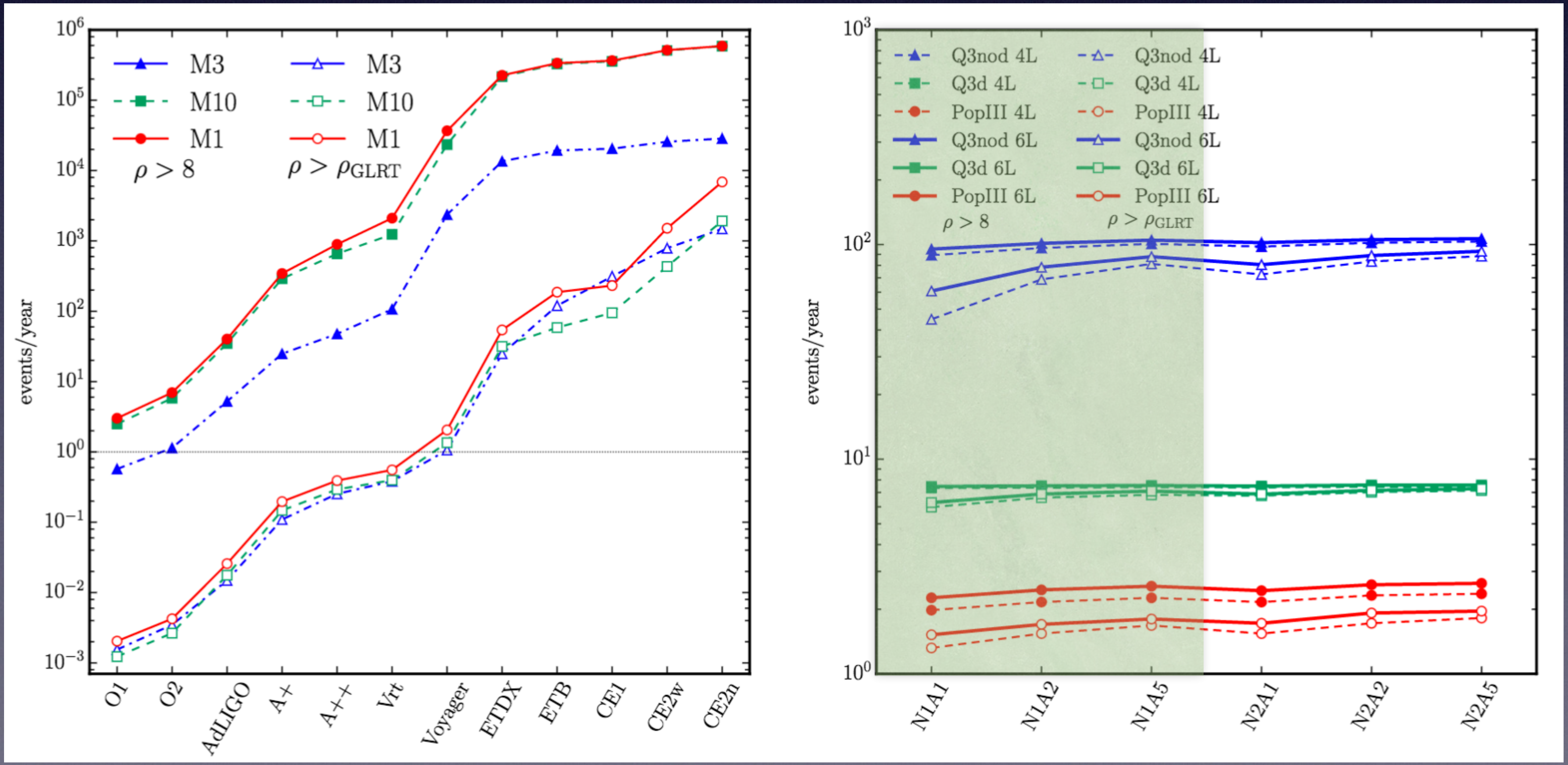
Ringdown tests of the no-hair theorem



In GR, BHs have two hairs (mass and spin)

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

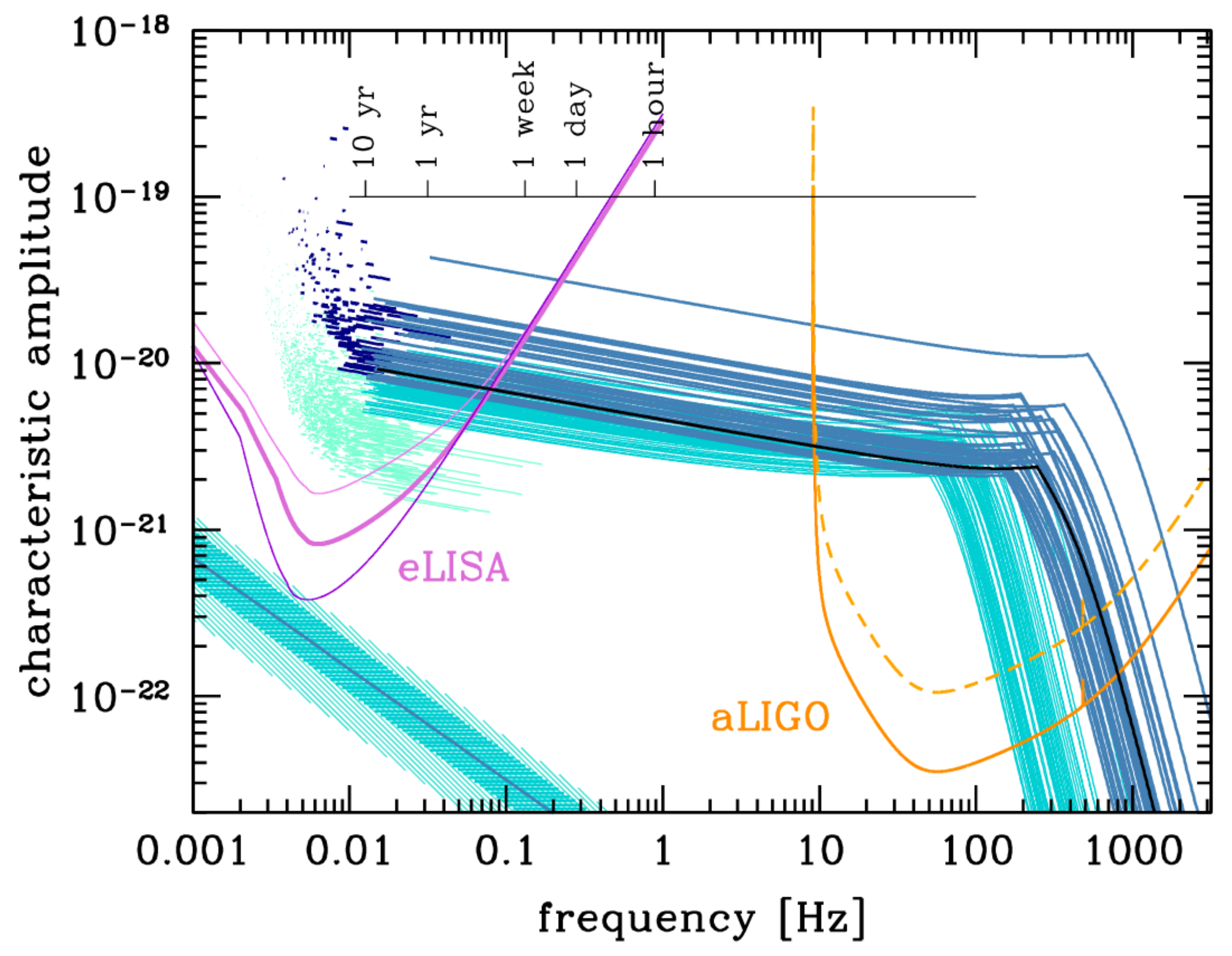
Tests impossible in ground-based detectors because little SNR in ringdown



Berti, Sesana, EB, Cardoso, Belczynski, 2016

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

Multi-band gravitational-wave astronomy



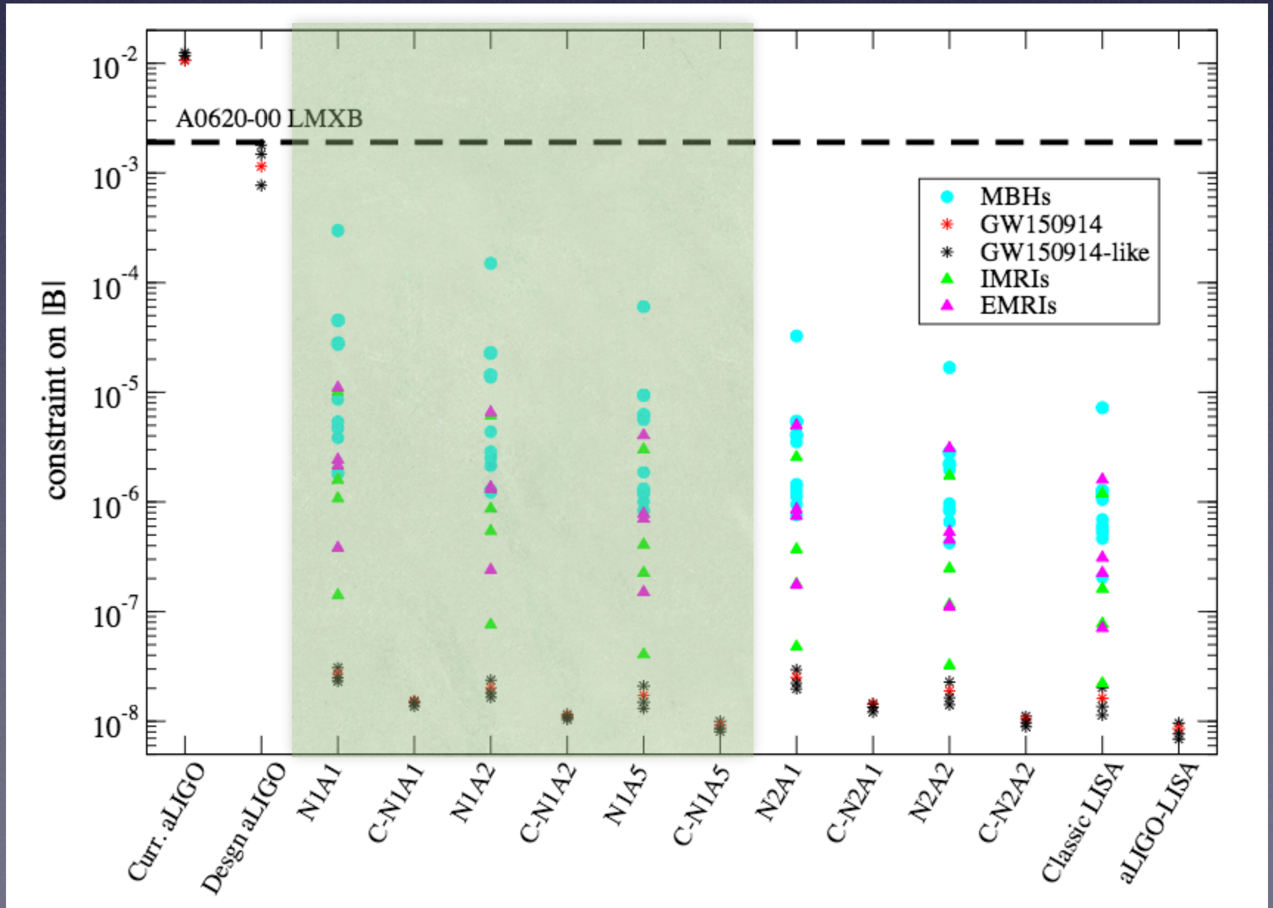
Sesana 2016

Tests of the equivalence principle with multi-band observations

- Smoking-gun sign of deviation from GR/BH “hairs” would be 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

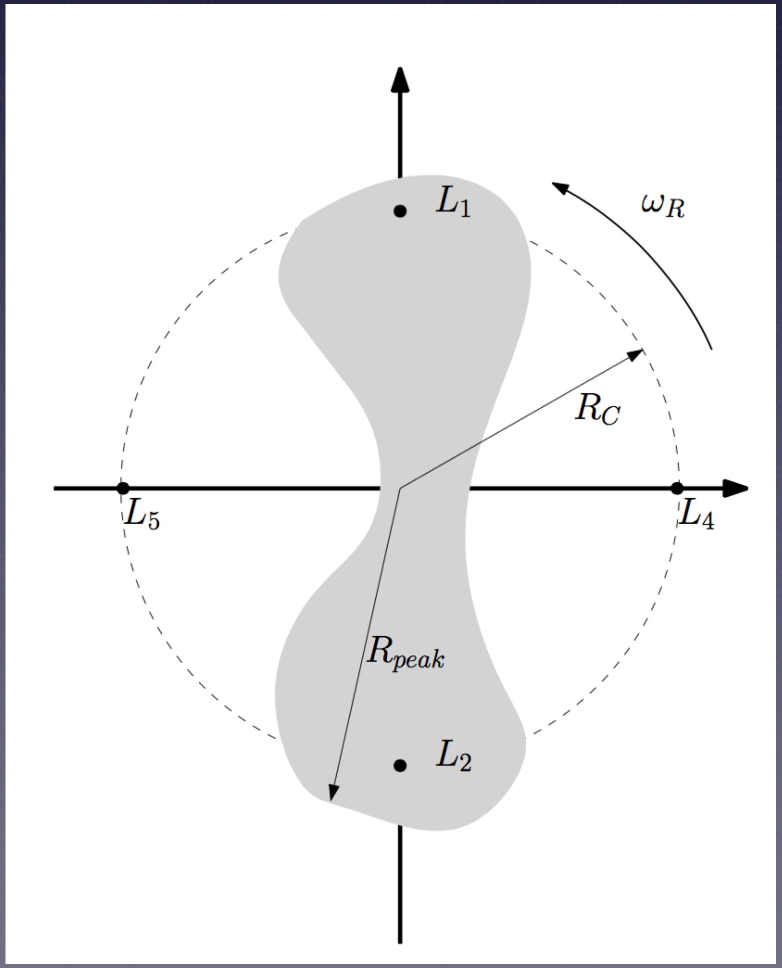
Constraints on axions/fuzzy DM

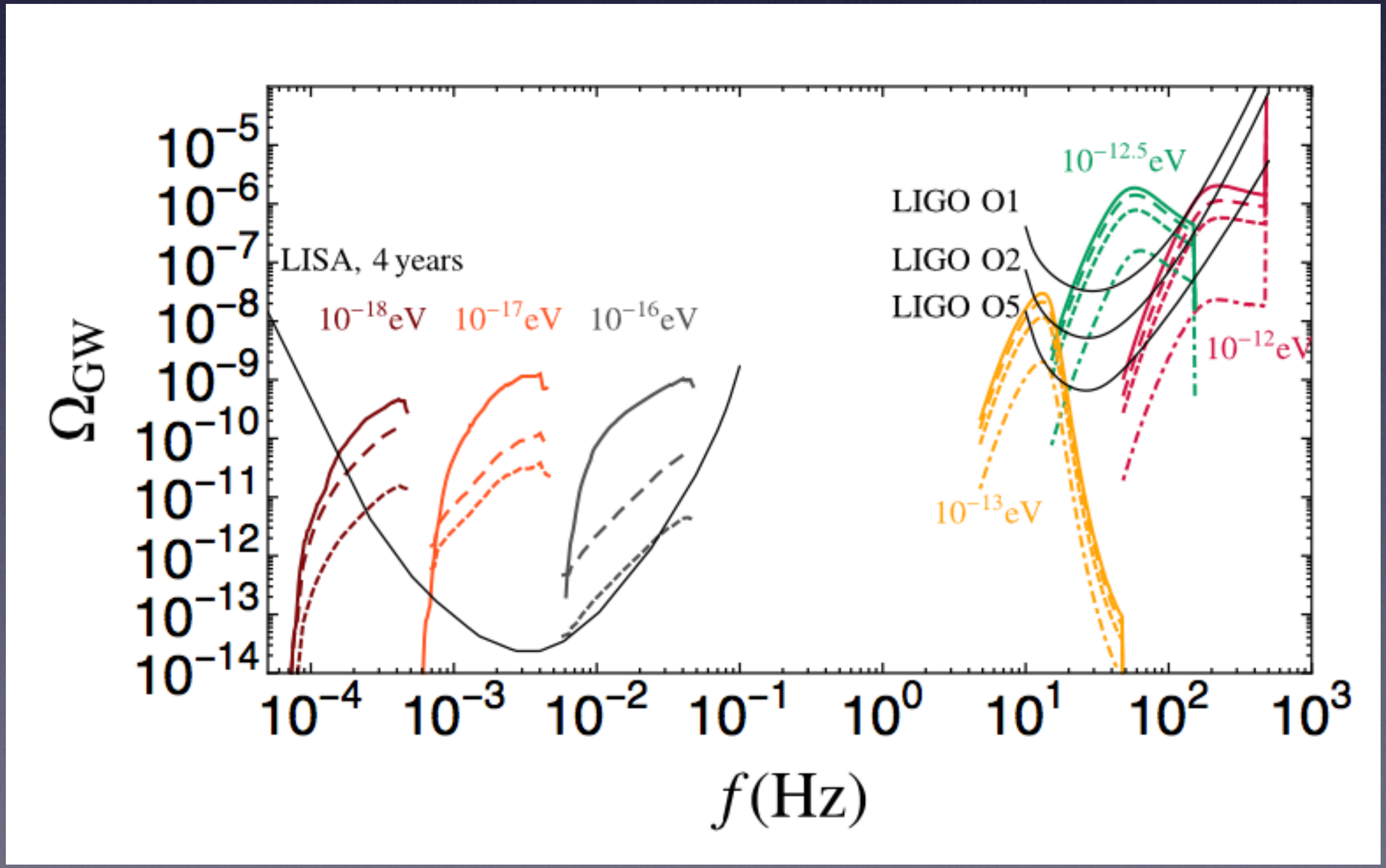
- Isolated spinning BH + massive scalar fields with Compton wavelength comparable to event horizon radius are unstable under super-radiance

- 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

$$\tau_{\rm inst} \sim 0.07\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{9}\,{\rm yr}\,,\quad \tau_{\rm GW} \sim 6\times10^{4}\,\chi^{-1}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\,{\rm yr}\,.$$

- Observable by LIGO/LISA as stochastic background and resolved sources

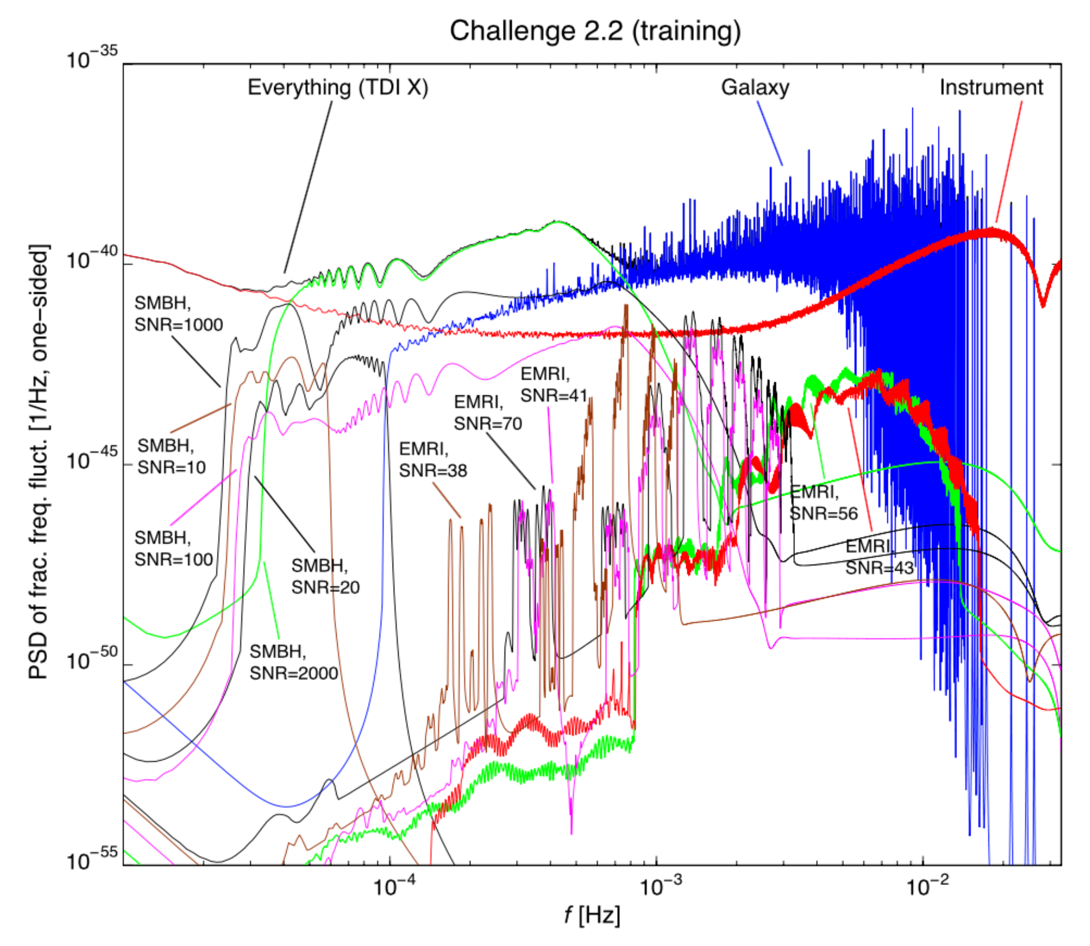




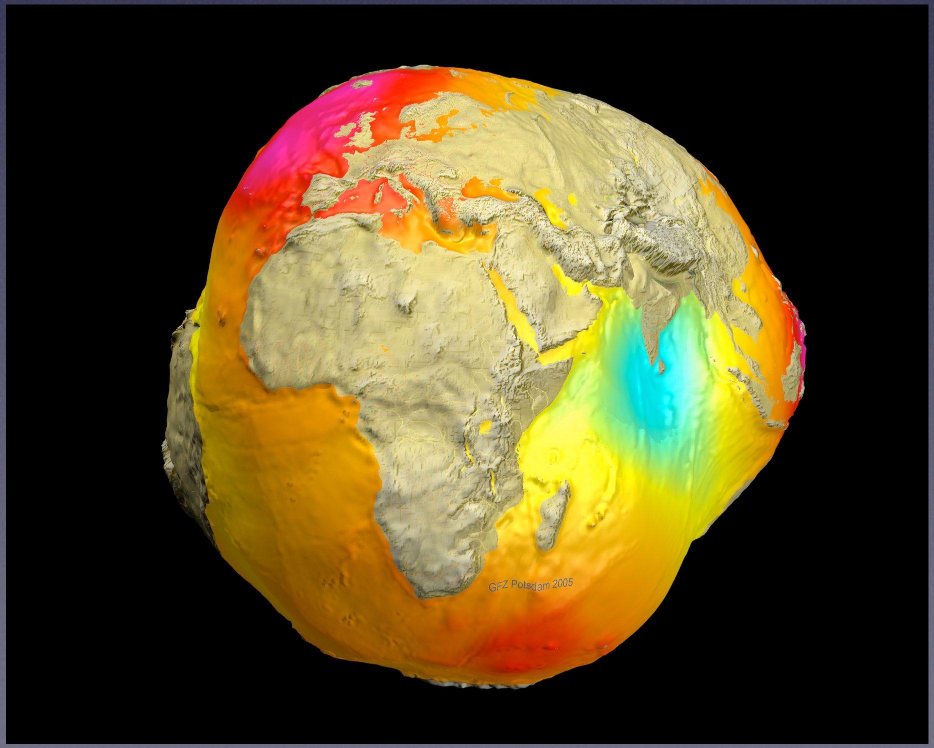
Brito, Ghosh, EB et al, PRL+PRD 2017, in press

More science with LISA...

- Galactic white-dwarf binaries

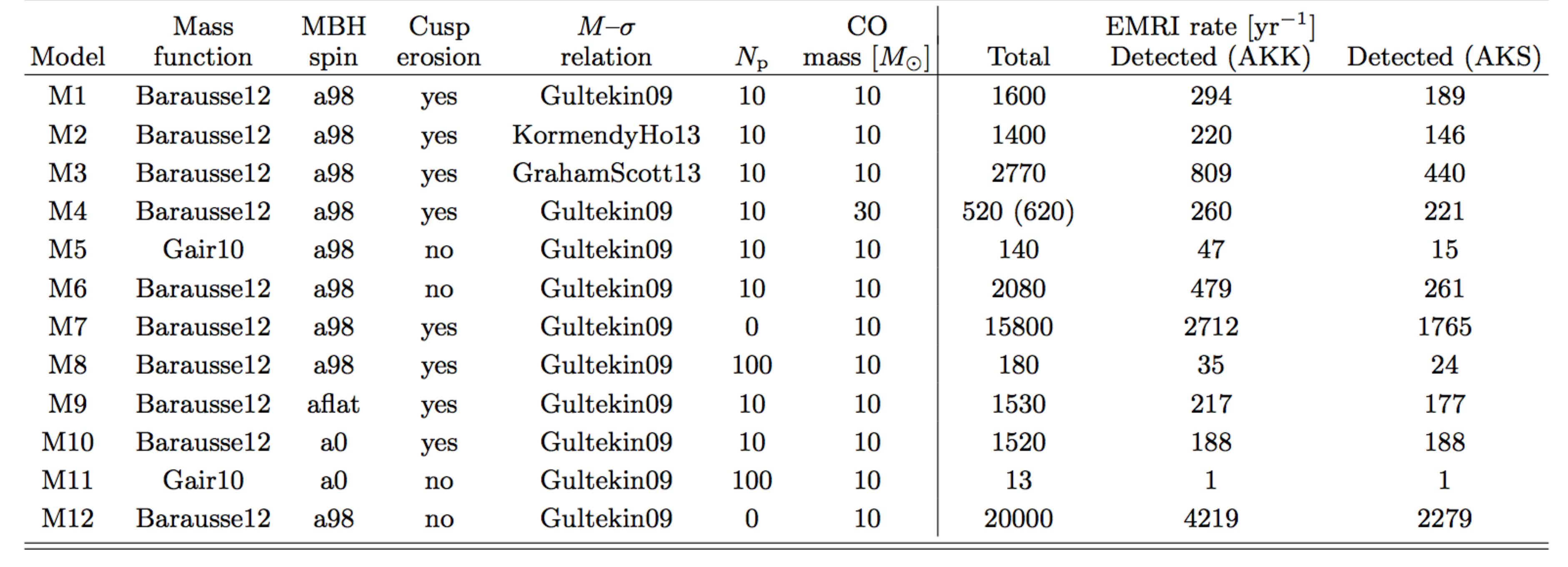


- Extreme mass ratio inspirals: neutron star or “LIGO” BH + a massive BH
- Will test the “no hair” theorem
- Akin to mapping Earth’s gravitational field with artificial satellites

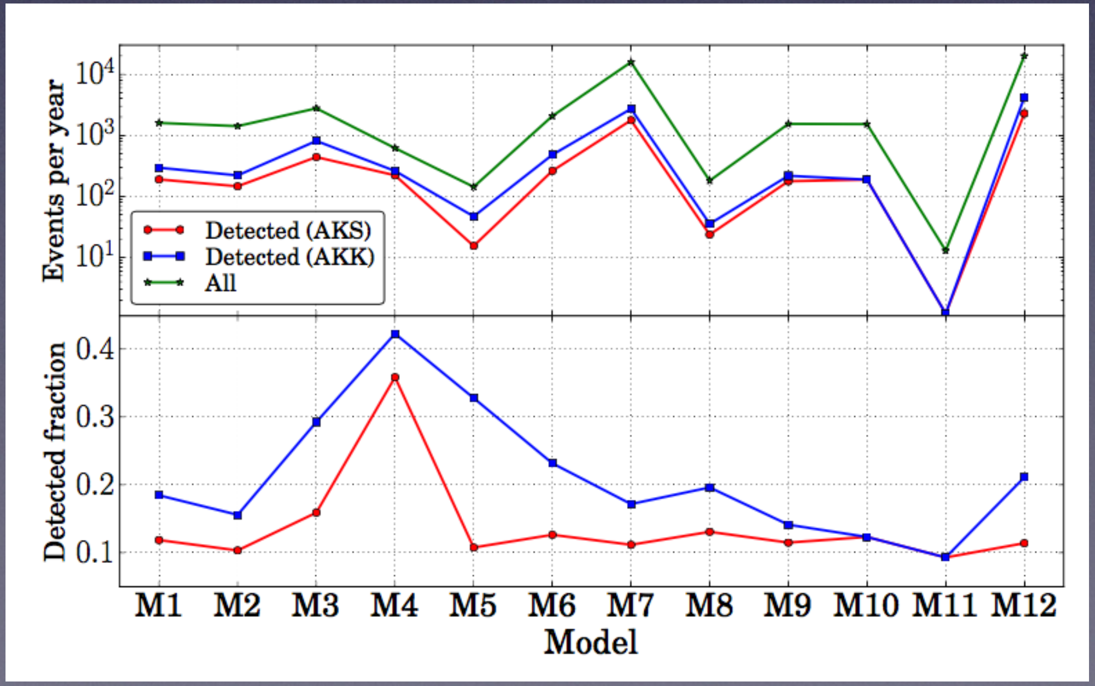


EMRIs: detectability

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

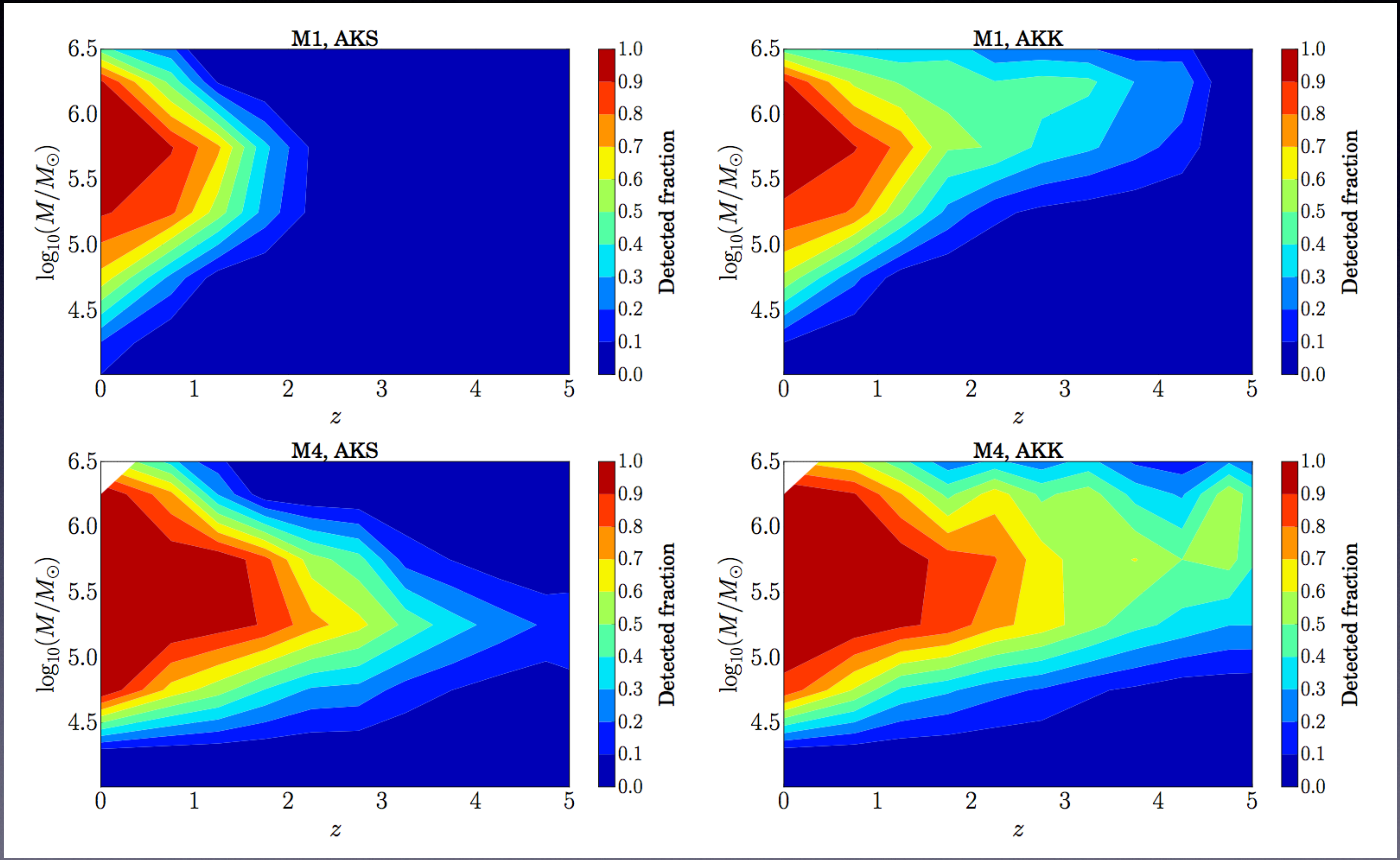


Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass $[M_\odot]$	EMRI rate $[\mathrm{yr}^{-1}]$ Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809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



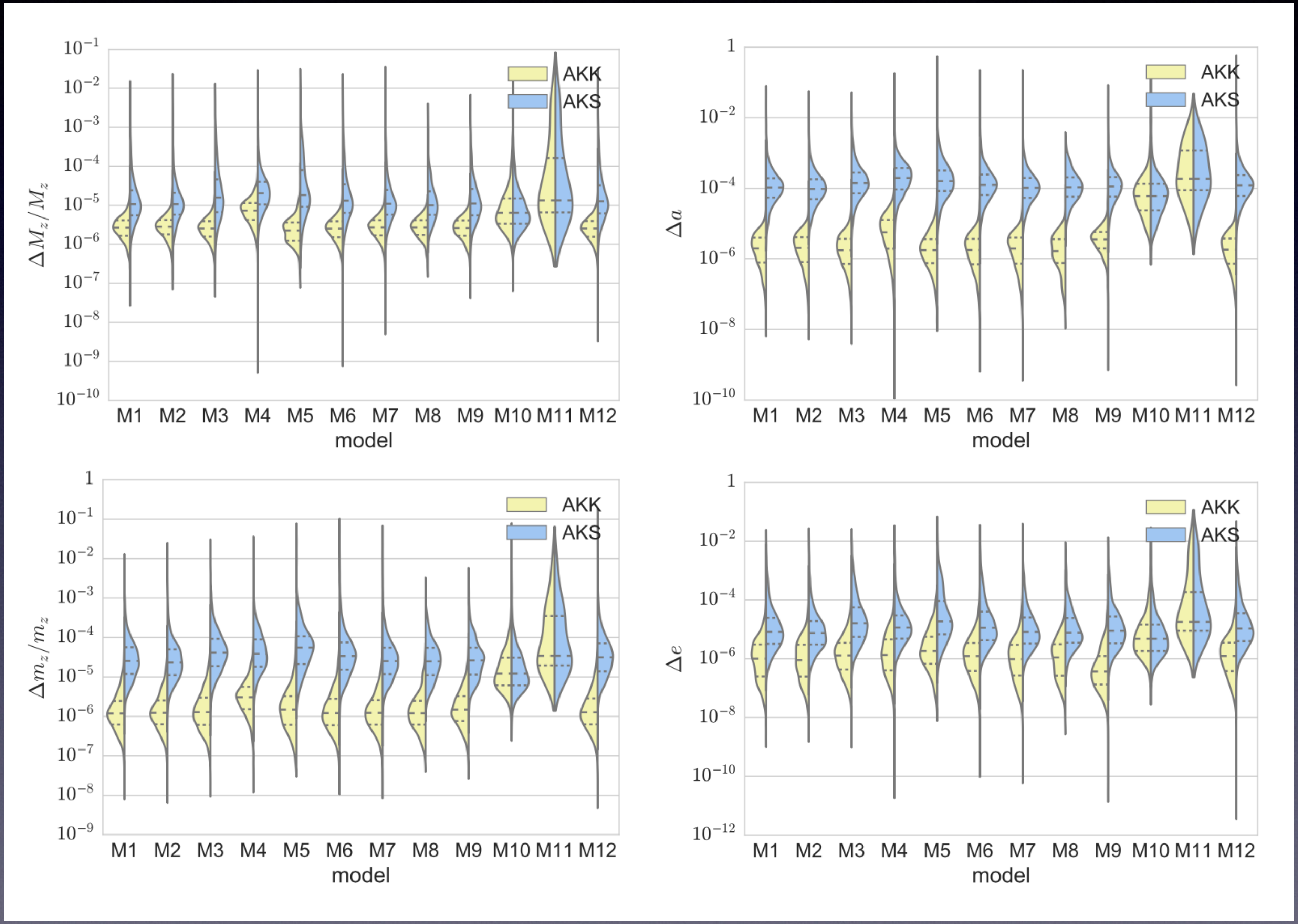
Babak et al
(incl. EB) 2017

EMRIs: detectability



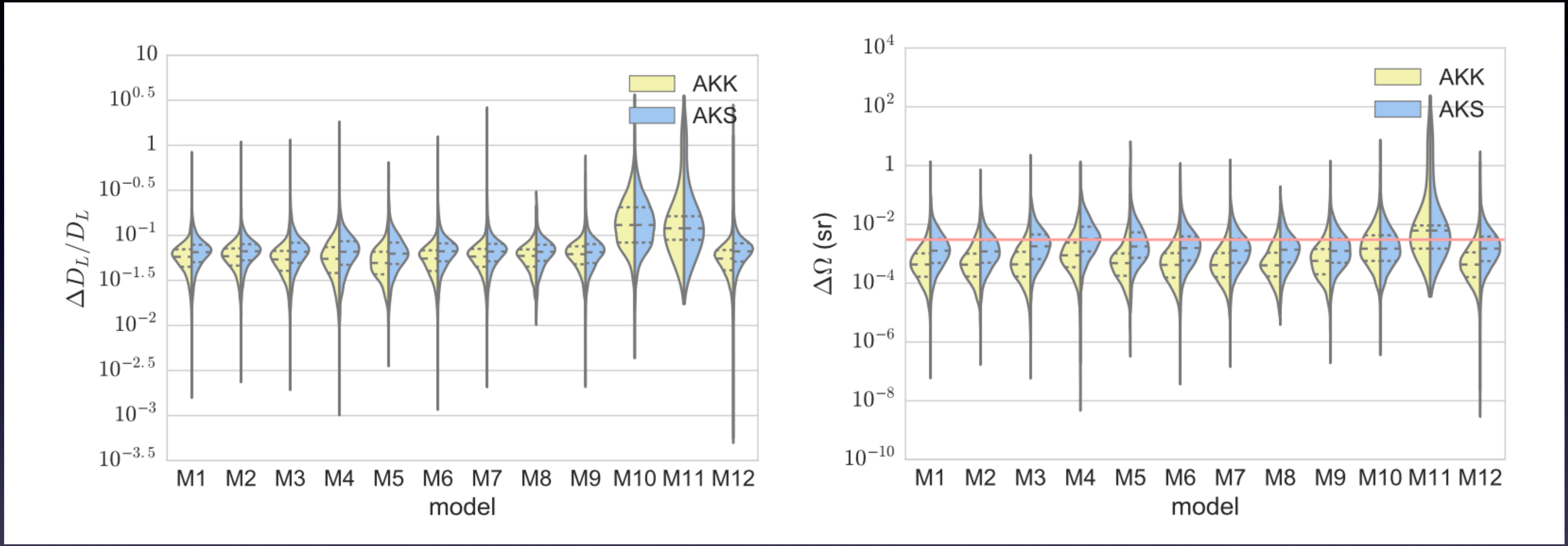
Babak et al (incl. EB) 2017

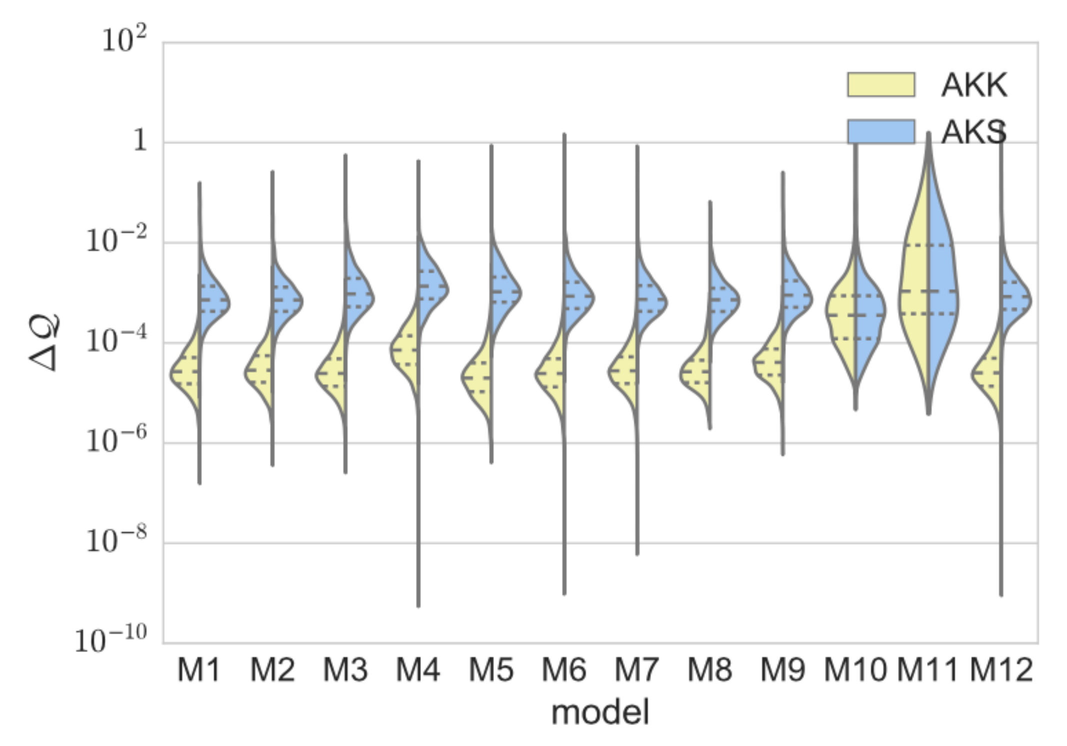
EMRIs: parameter estimation



Babak et al (incl. EB) 2017

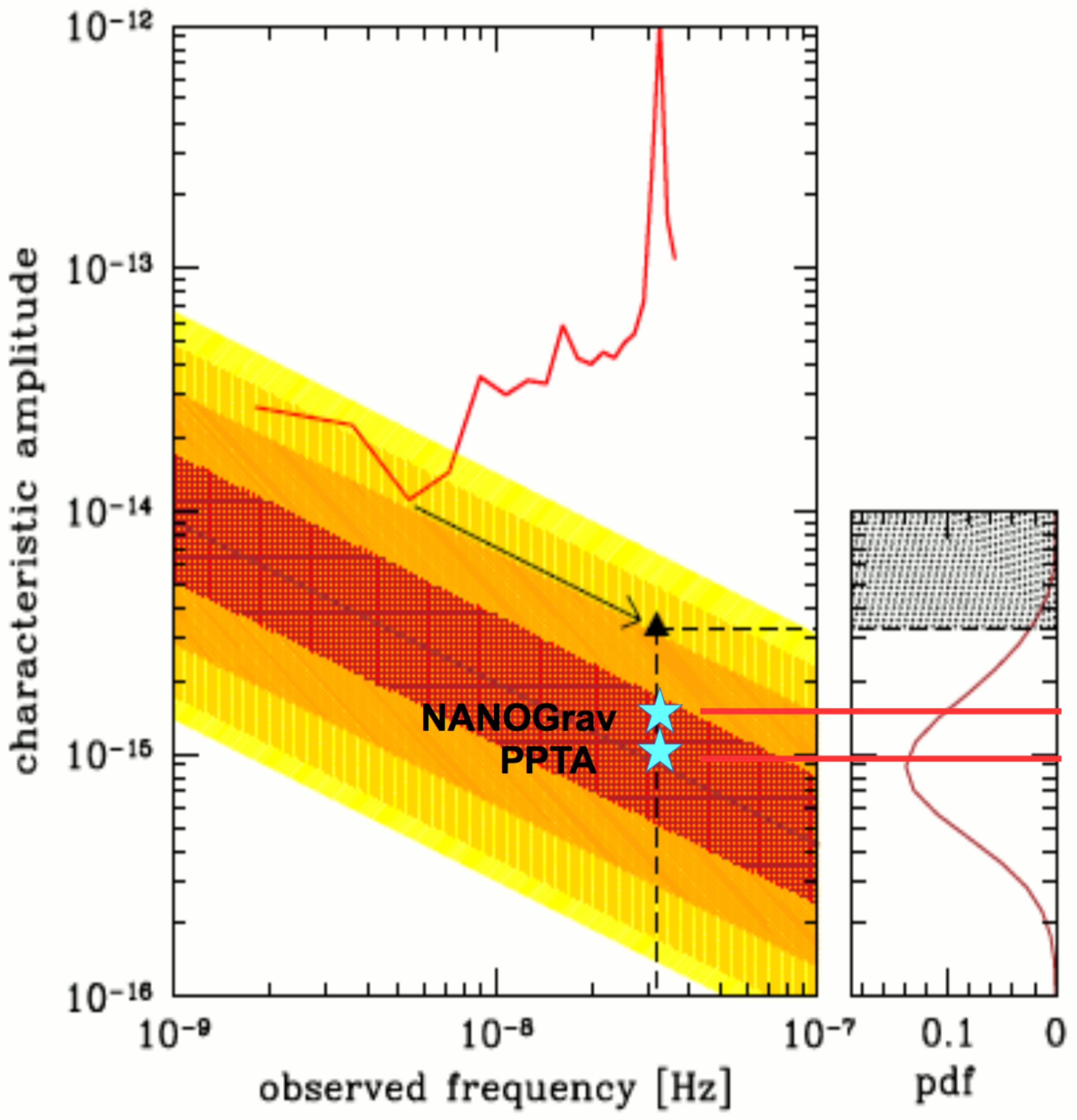
EMRIs: parameter estimation





Babak et al
(incl. EB) 2017

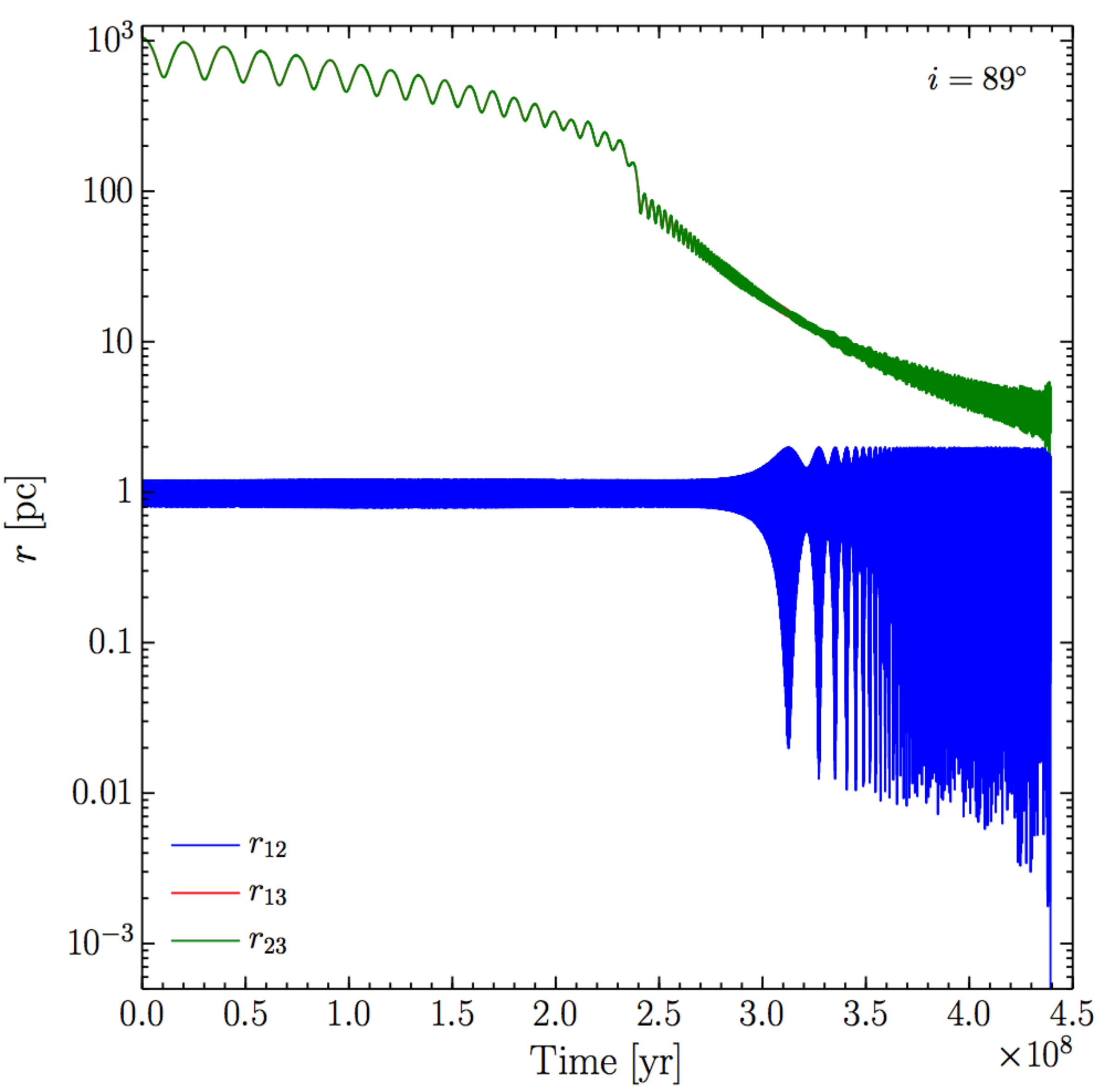
What can we learn from PTA limits?

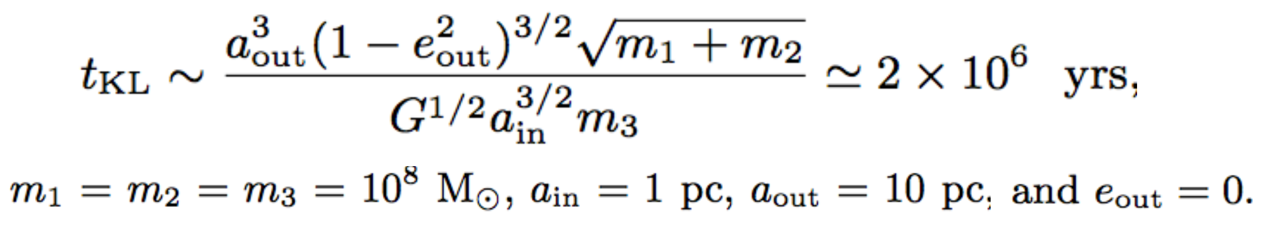


Is this evidence for last-parsec stalling of massive BH binaries?

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 resonances (secular exchange between eccentricity and orbital inclination)



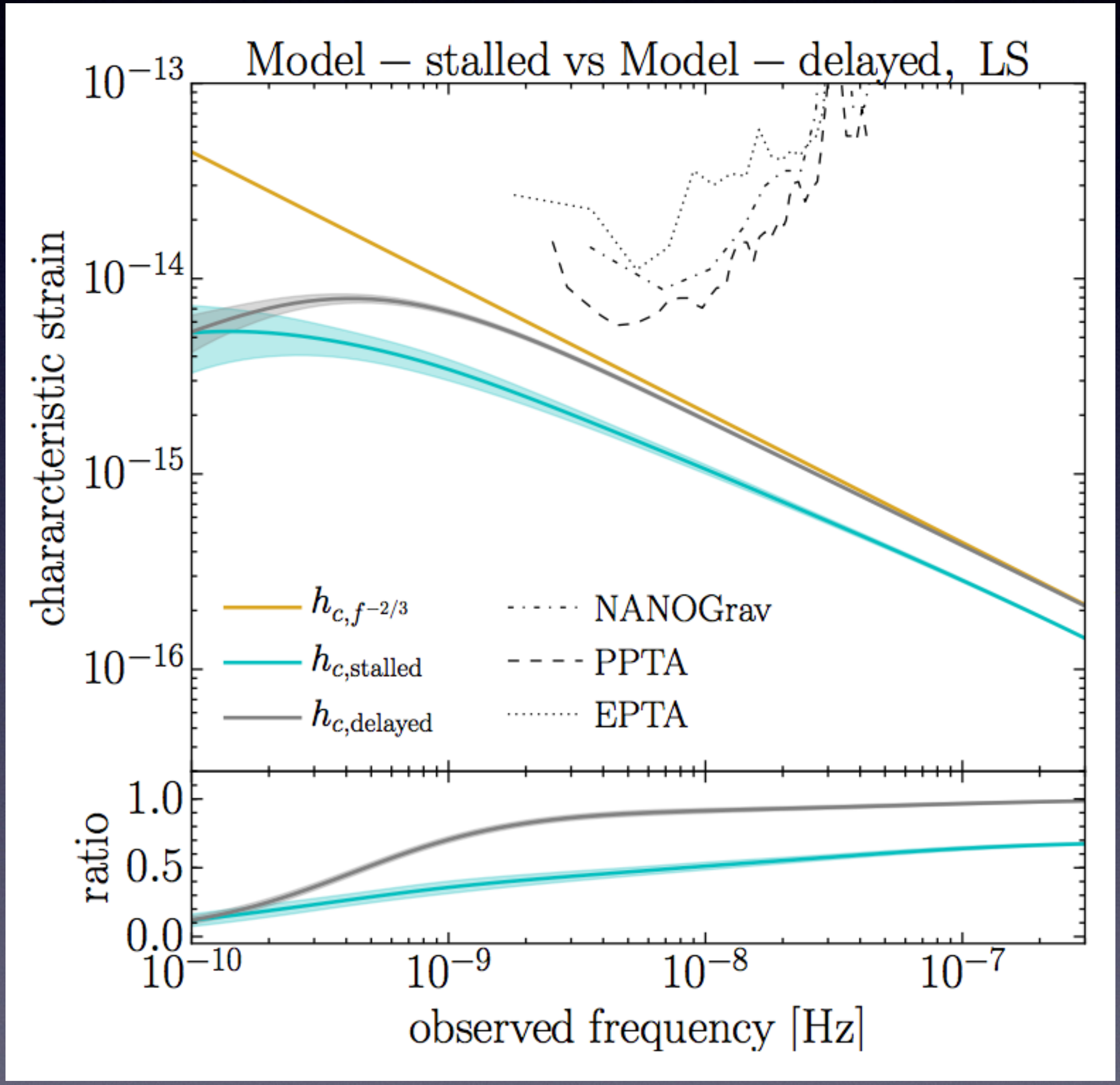


$$t_{\rm KL} \sim \frac{a_{\rm out}^3 (1 - e_{\rm out}^2)^{3/2} \sqrt{m_1 + m_2}}{G^{1/2} a_{\rm in}^{3/2} m_3} \simeq 2 \times 10^6 \quad \text{yrs},$$

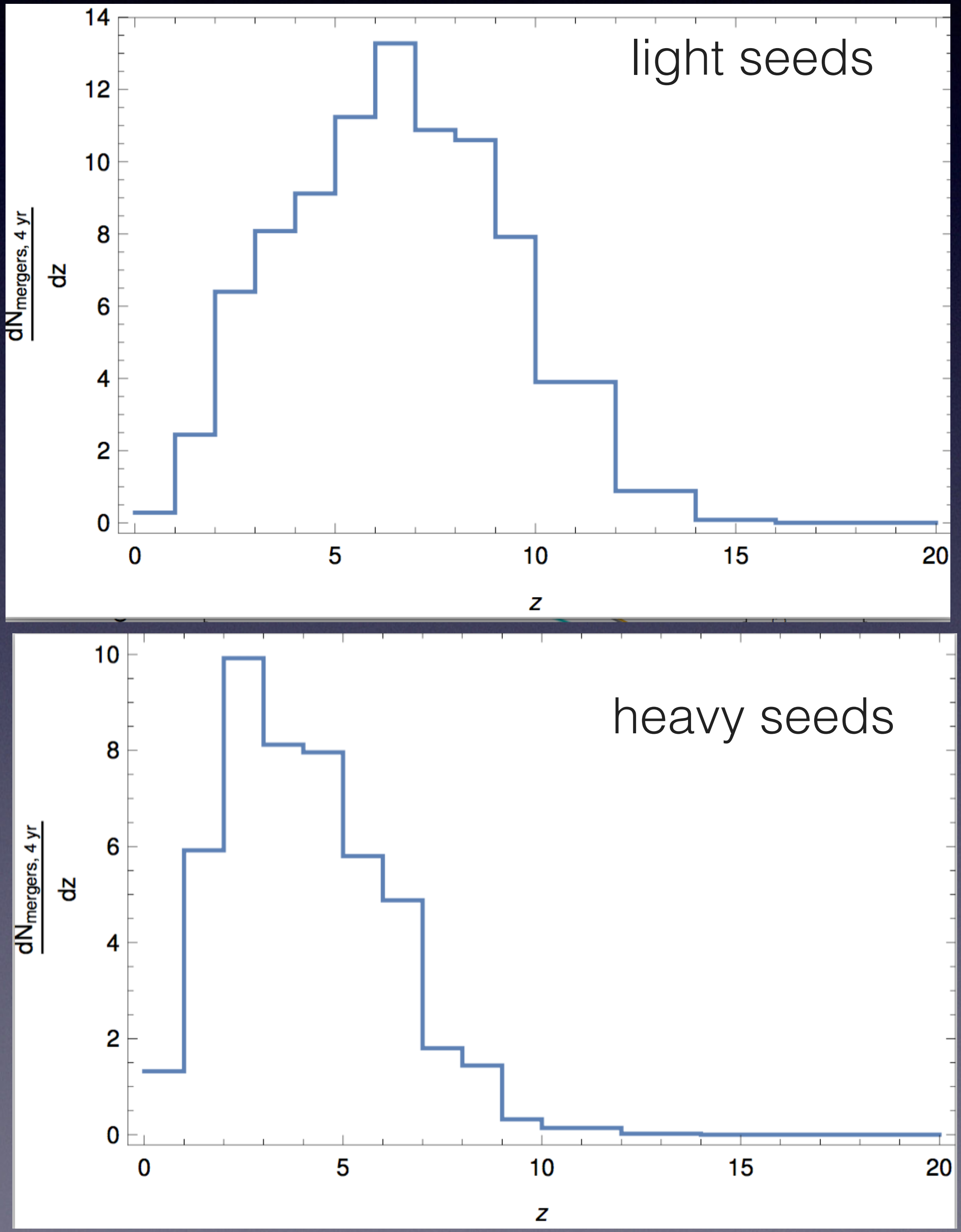
$m_1 = m_2 = m_3 = 10^8\ \mathrm{M}_\odot$, $a_{\rm in} = 1$ pc, $a_{\rm out} = 10$ pc, and $e_{\rm out} = 0$.

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

Triple-induced BH mergers: PTA and LISA

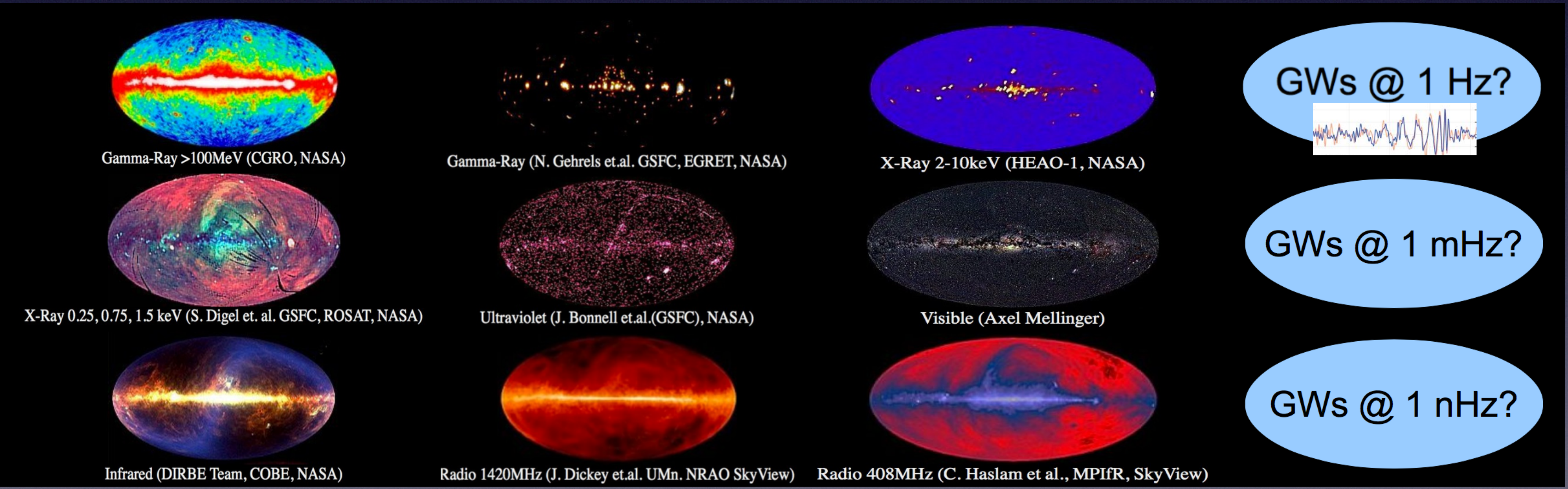


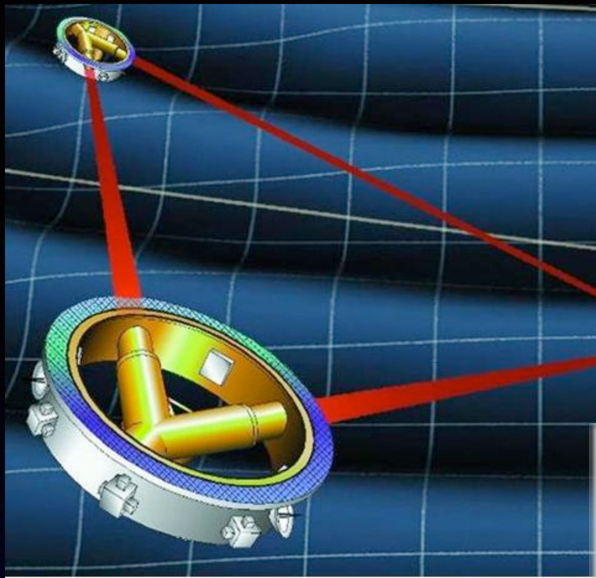
Bonetti, Sesana, EB, Haardt 2017



Conclusion

Gravitational waves have opened a new window on the Universe, and the LIGO detection is just the beginning…





STAY TUNED!


Green Bank Telescope, WV, US
Arecibo Observatory, PR, US
LOFAR, Exloo, Netherlands
Parkes Observatory, Parkes, Australia
GMRT, Pune, India
WSRT, Westerbork, Netherlands
Effelsberg 100-m Radio Telescope, Effelsberg, Germany