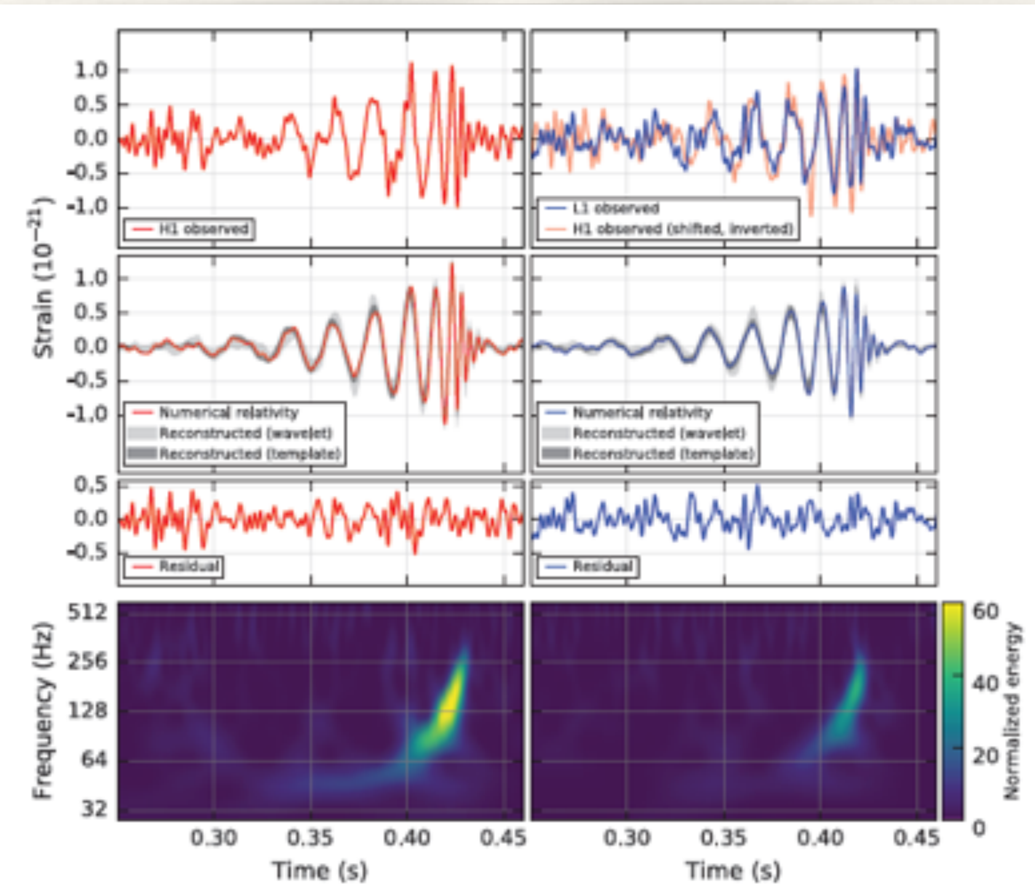
Stas Babak.

Albert Einstein Institute (Potsdam-Golm)

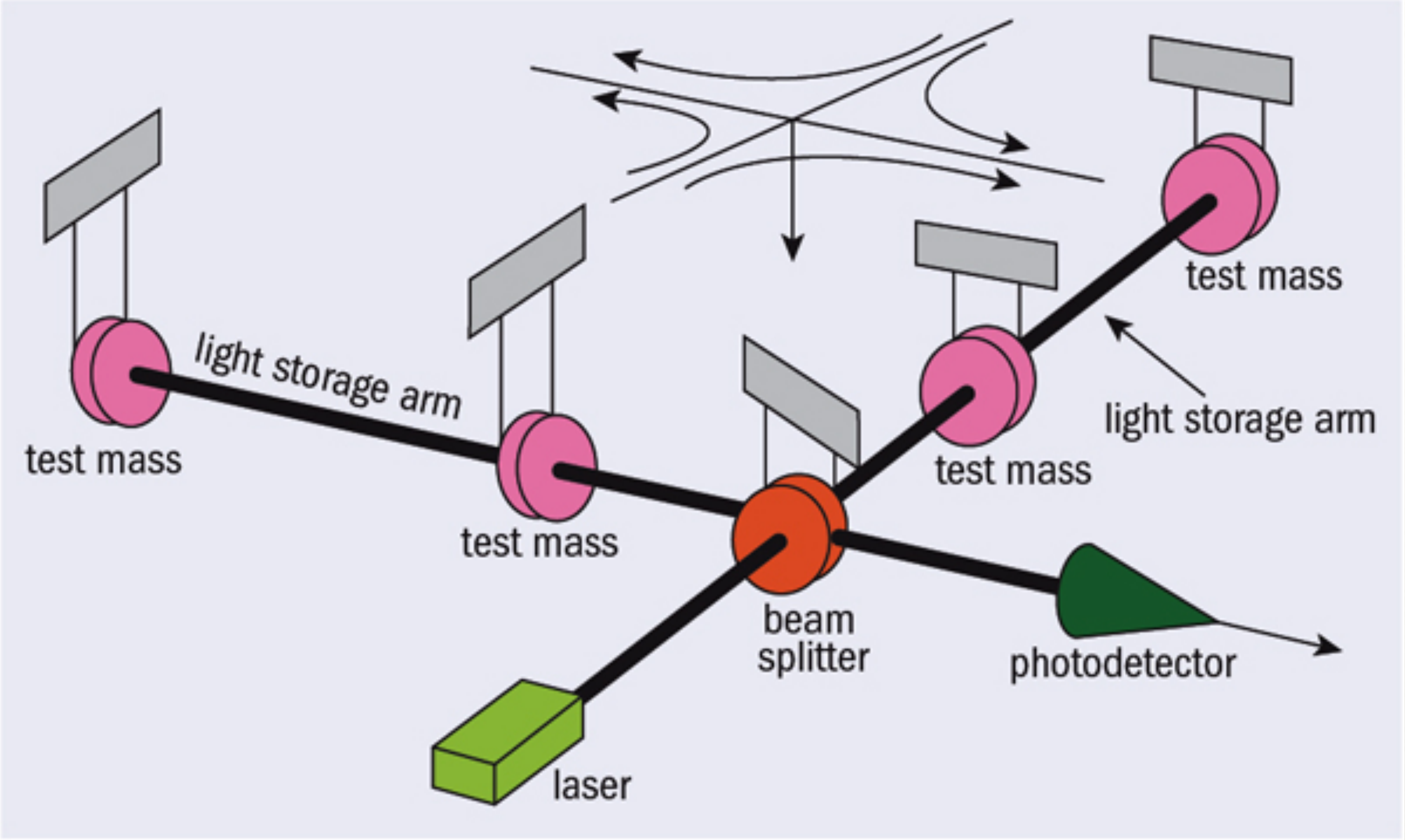
Results from O1 aLIGO run and impact on eLISA science.



Outline

- Overview of GW detections from the first observational run.
    - Overview of the search
    - Signal modeling for BBH
    - Parameters estimation for two GW events
- Multiband observations
- Impact on EMRI observations with eLISA
- Brief overview of GOAT report and eLISA' future

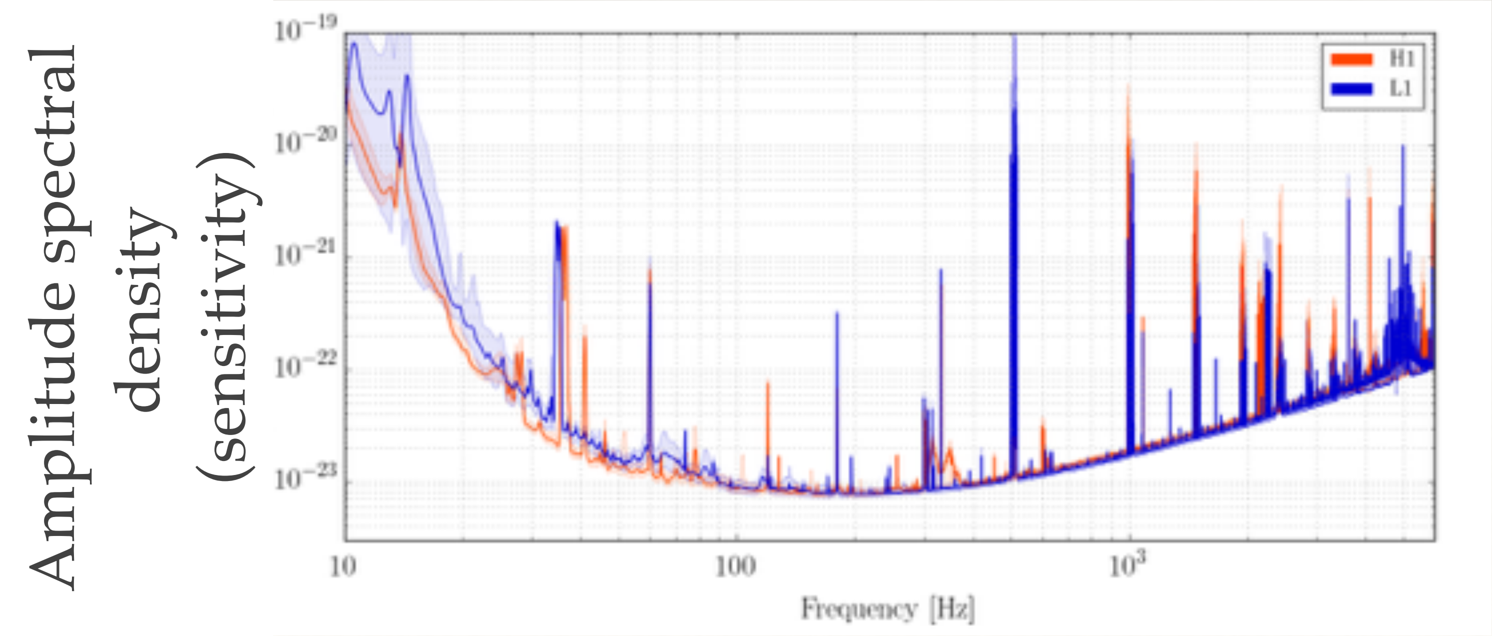
Principles of GW detection



$$\Delta L = \delta L_x - \delta L_y = h(t)L$$

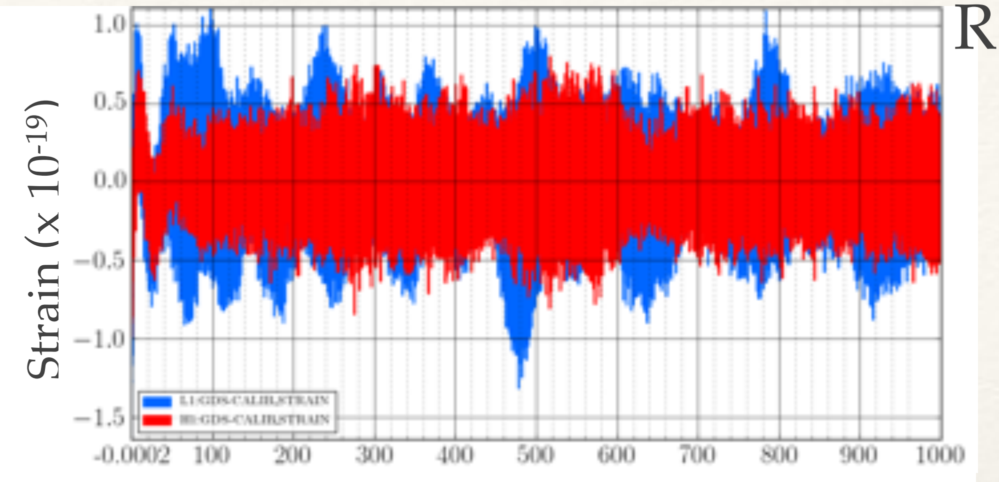
GW strain

We measure difference in the proper distance between beam splitter and end mirrors using laser interferometry



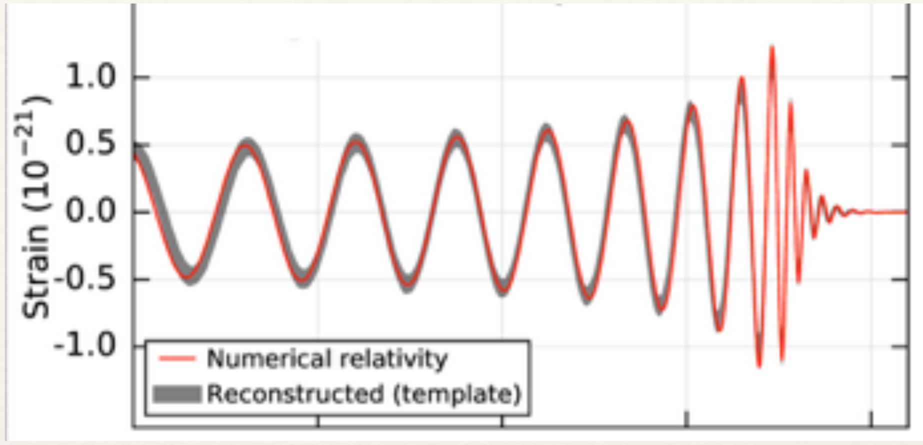
Matched filtering

Raw data



Time (ms) - Event occurs at 390

Signal we are searching



We employ matched filtering: searching the data (deep inside the noise) using template waveform. This implies that we need very accurate model of the signal (to control systematic errors and loss in the detection).

$$\rho = \int_0^\infty \frac{\tilde{d}(f)\tilde{h}^*(f)}{S(f)}$$

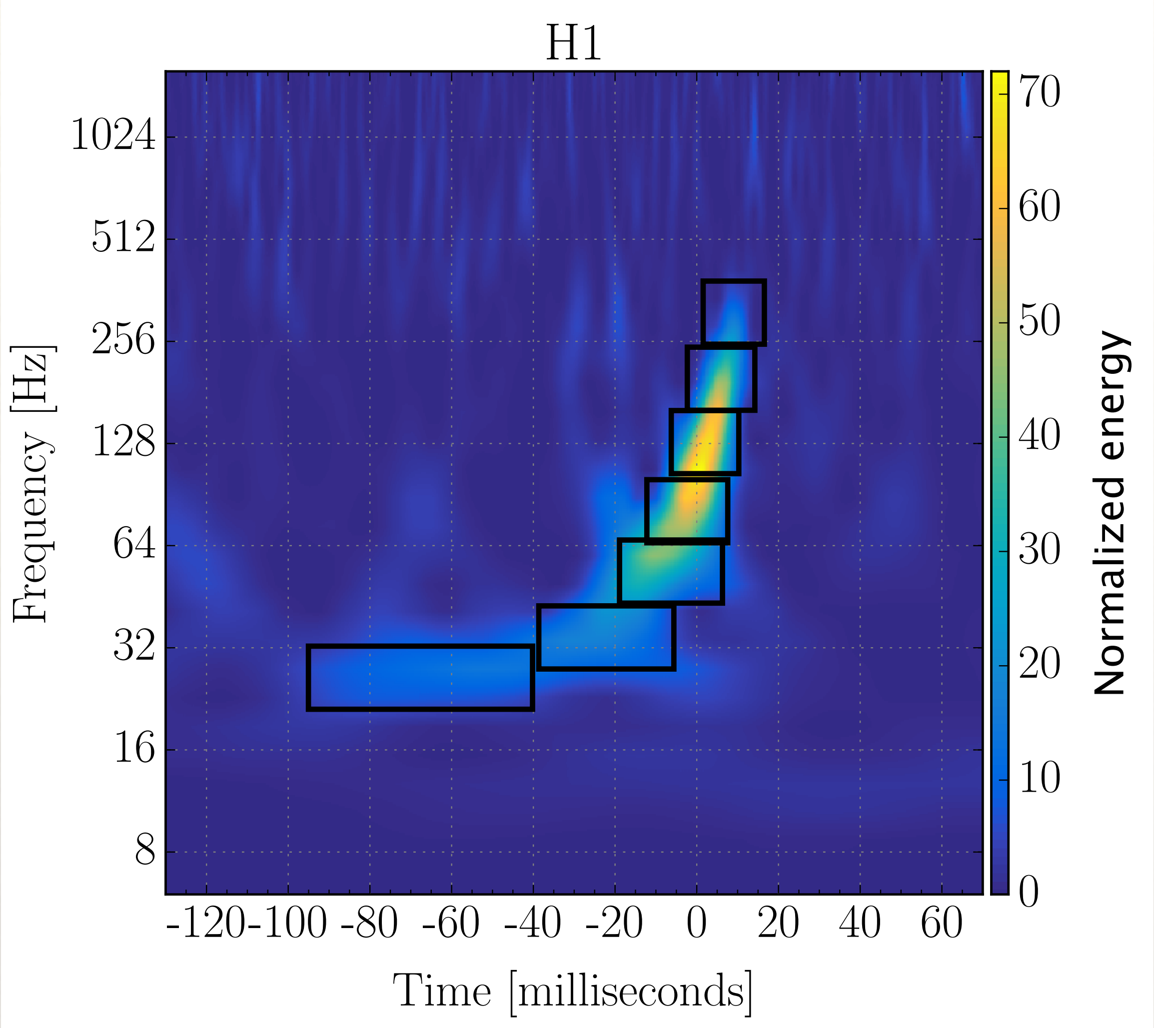
Signal-to-noise ratio

Likelihood

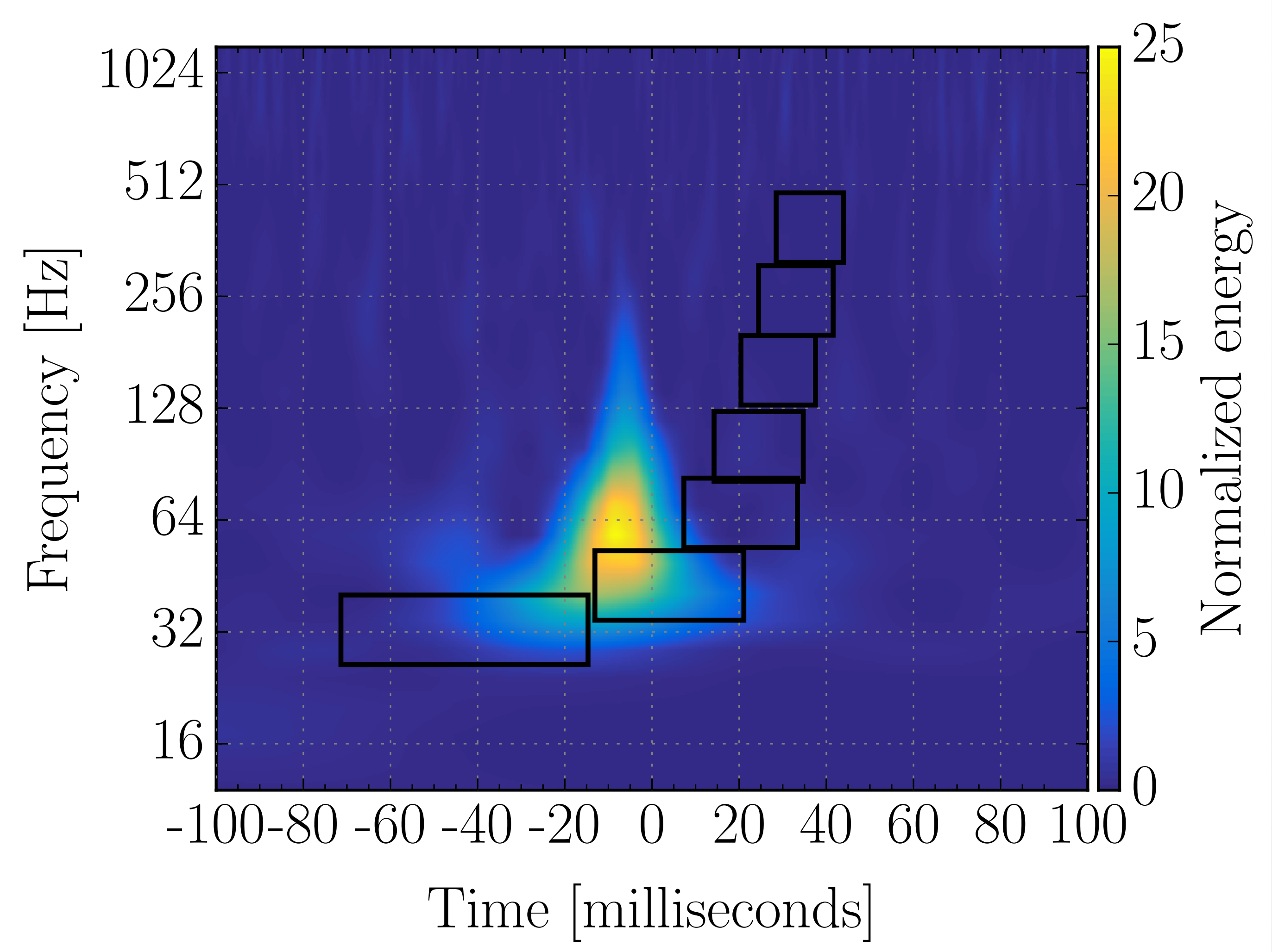
$$\mathcal{L}(\vec{d}|\vec{\vartheta}) \propto \exp\left[\frac{1}{2}\sum_{k=1,2}\left\langle h_k(\vec{\vartheta}) - d_k | h_k(\vec{\vartheta}) - d_k\right\rangle\right]$$

Consistency check

Real signal



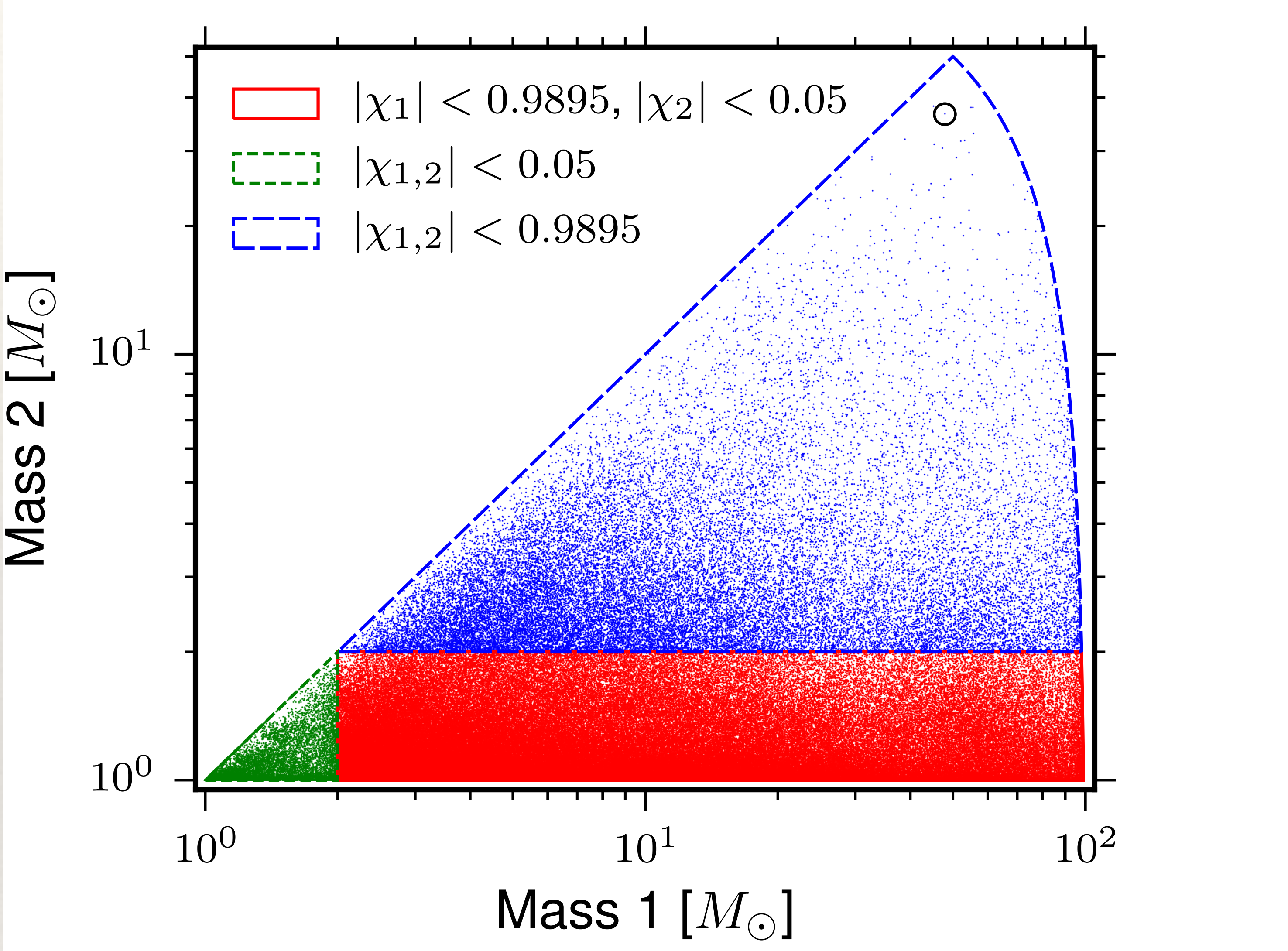
Instrumental artifact



The noise is not Gaussian: need to introduce additional consistency checks into the detection statistic (distribution of power in the signal across the time/frequency).

Allen PRD 71 (2005) 062001
SB, …, IH, SP et al. PRD 87 (2013) 024003

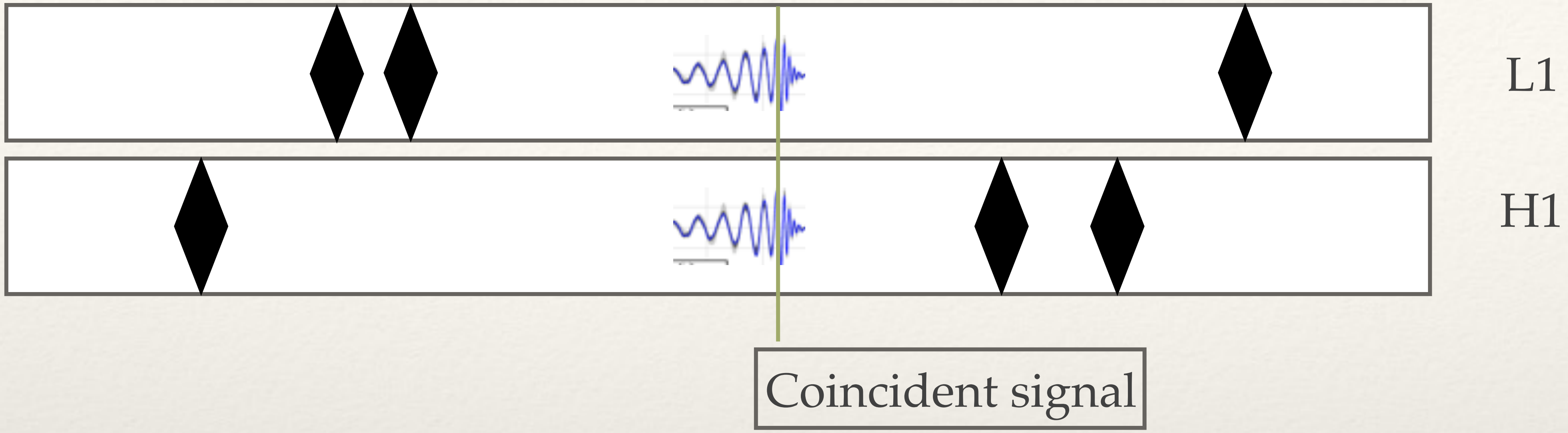
Template bank



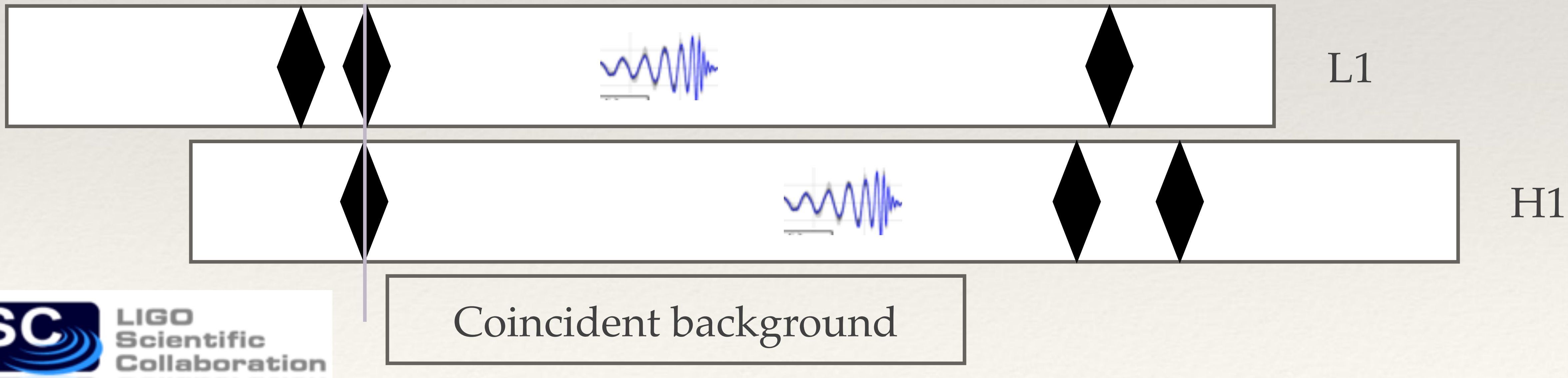
- We don't know apriori parameters of the system
- We construct the bank of templates: we populate the parameter space: uniform taking into accounts the correlation between templates ("volume of each template")
- We filter the data through each template to see which fits the best
- We have used SEOBNR (non-precessing templates)
- Total number of templates used ~250,000

Significance estimation

“Zero lag”

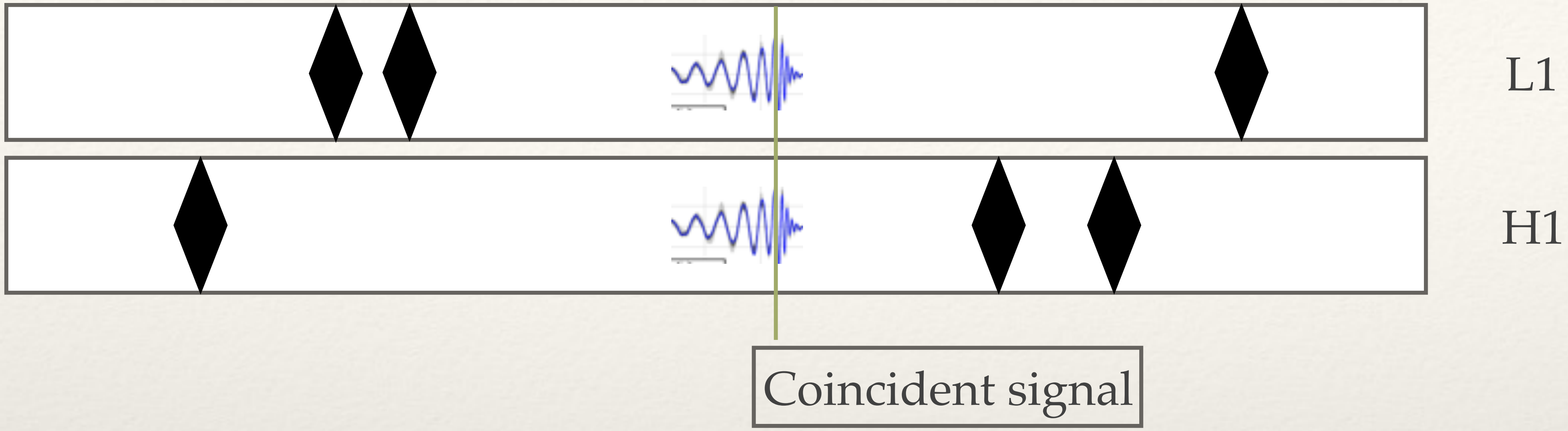


Time shift > light travel time



Significance estimation

“Zero lag”

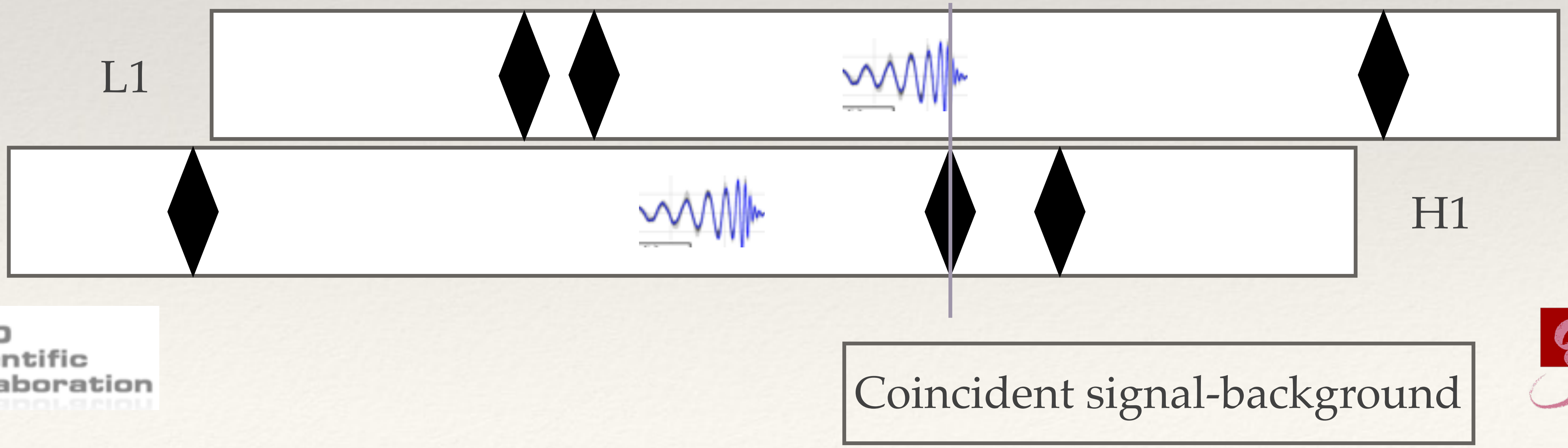


L1

H1

Coincident signal

Time shift > light travel time

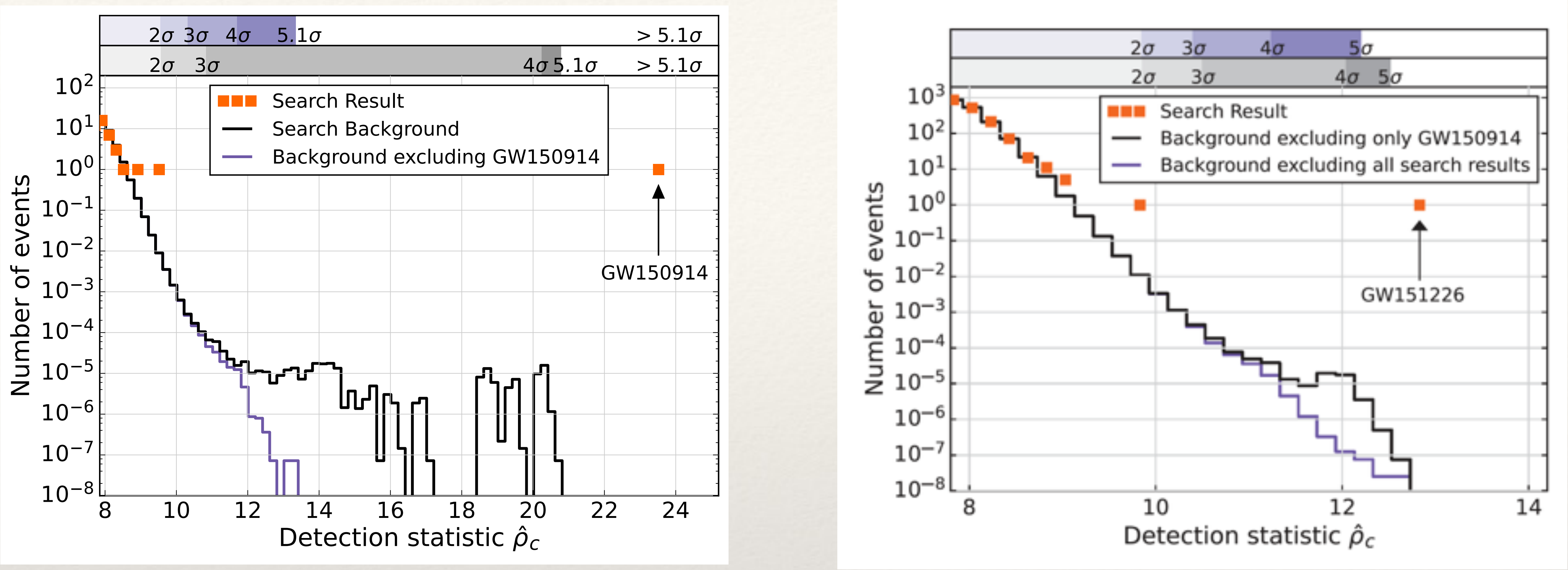


L1

H1

Coincident signal-background

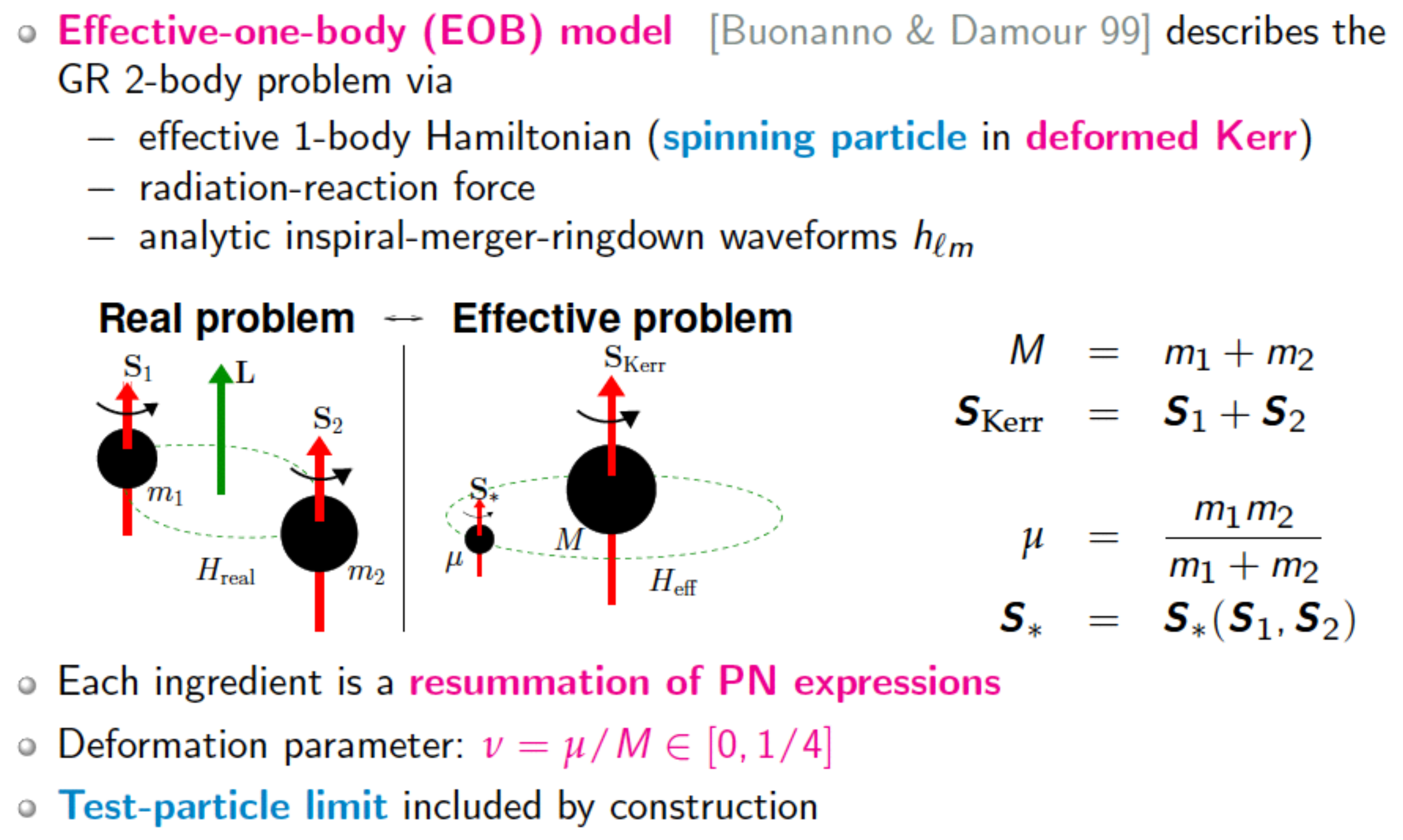
Statistical significance



Background vs detection

LIGO & VIRGO PRL (2016) 116, 061102; PRL. 116, 241103 (2016)

Signal modelling (EOB)



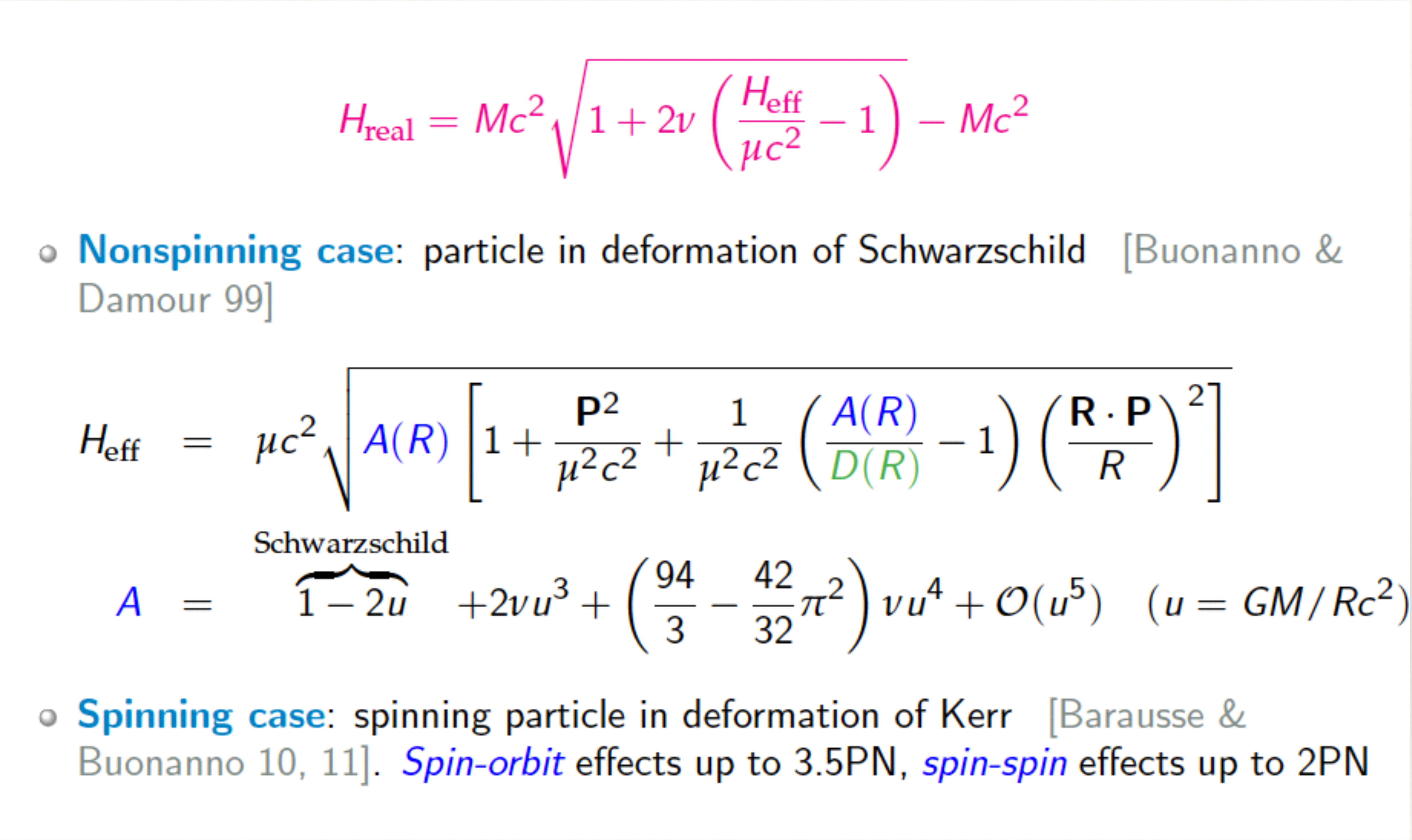
- **Effective-one-body (EOB) model** [Buonanno & Damour 99] describes the GR 2-body problem via
  - effective 1-body Hamiltonian (**spinning particle** in **deformed Kerr**)
  - radiation-reaction force
  - analytic inspiral-merger-ringdown waveforms $h_{\ell m}$

Real problem ↔ Effective problem

$$M = m_1 + m_2$$
$$\boldsymbol{S}_{\rm Kerr} = \boldsymbol{S}_1 + \boldsymbol{S}_2$$
$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$
$$\boldsymbol{S}_* = \boldsymbol{S}_*(\boldsymbol{S}_1, \boldsymbol{S}_2)$$

- Each ingredient is a **resummation of PN expressions**
- Deformation parameter: $\nu = \mu/M \in [0, 1/4]$
- **Test-particle limit** included by construction

Signal Modelling (EOB)



$$H_{\text{real}} = Mc^2\sqrt{1 + 2\nu\left(\frac{H_{\text{eff}}}{\mu c^2} - 1\right)} - Mc^2$$

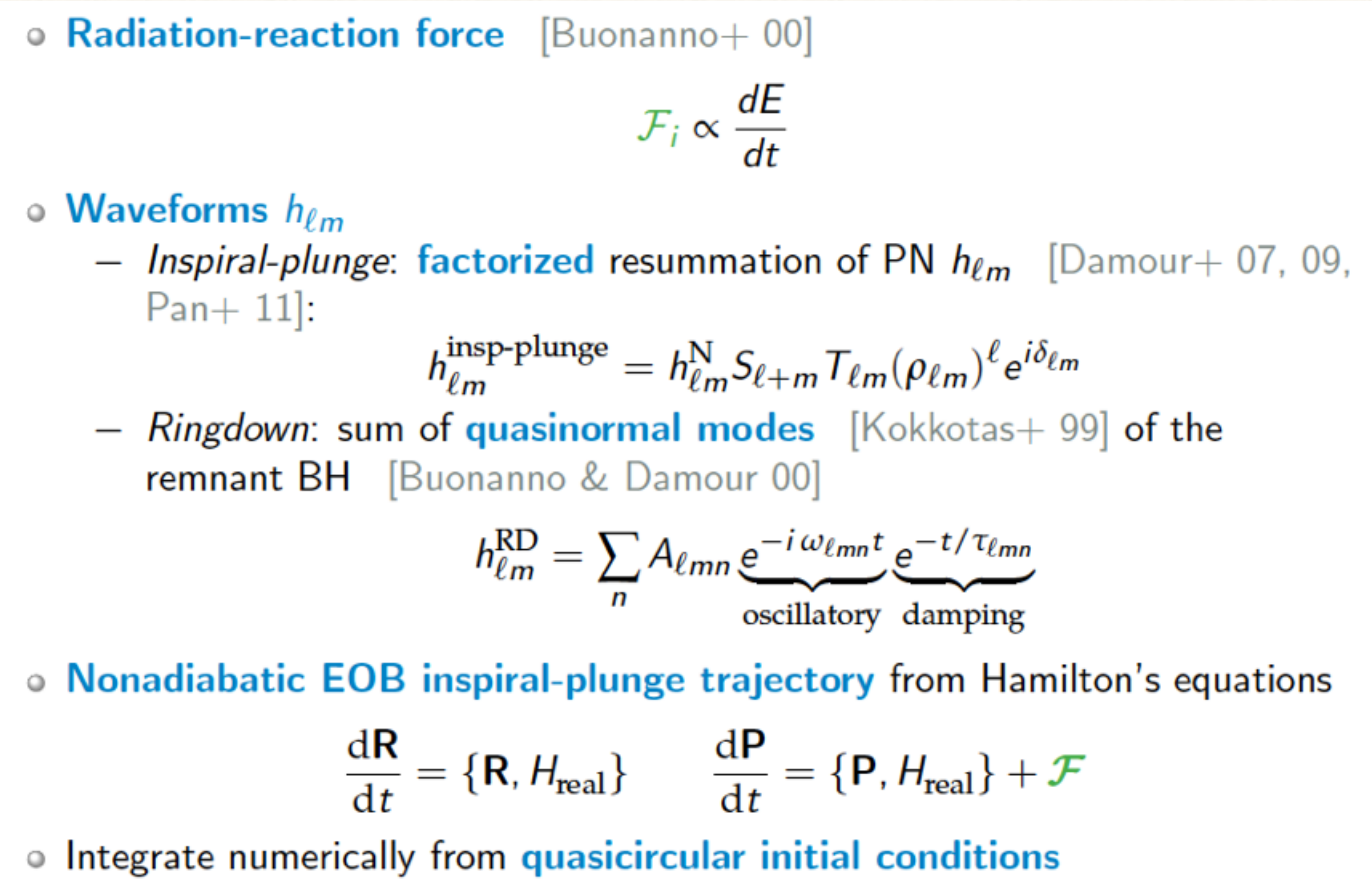
- **Nonspinning case**: particle in deformation of Schwarzschild [Buonanno & Damour 99]

$$H_{\text{eff}} \;=\; \mu c^2\sqrt{A(R)\left[1 + \frac{\mathbf{P}^2}{\mu^2 c^2} + \frac{1}{\mu^2 c^2}\left(\frac{A(R)}{D(R)} - 1\right)\left(\frac{\mathbf{R}\cdot\mathbf{P}}{R}\right)^2\right]}$$

$$A \;=\; \overbrace{1 - 2u}^{\text{Schwarzschild}} \; + 2\nu u^3 + \left(\frac{94}{3} - \frac{42}{32}\pi^2\right)\nu u^4 + \mathcal{O}(u^5) \quad (u = GM/Rc^2)$$

- **Spinning case**: spinning particle in deformation of Kerr [Barausse & Buonanno 10, 11]. *Spin-orbit* effects up to 3.5PN, *spin-spin* effects up to 2PN

Signal modelling (EOB)



- **Radiation-reaction force** [Buonanno+ 00]

$$\mathcal{F}_i \propto \frac{dE}{dt}$$

- **Waveforms** $h_{\ell m}$
  - *Inspiral-plunge*: **factorized** resummation of PN $h_{\ell m}$ [Damour+ 07, 09, Pan+ 11]:

$$h_{\ell m}^{\text{insp-plunge}} = h_{\ell m}^{\text{N}} S_{\ell+m} T_{\ell m} (\rho_{\ell m})^{\ell} e^{i\delta_{\ell m}}$$

  - *Ringdown*: sum of **quasinormal modes** [Kokkotas+ 99] of the remnant BH [Buonanno & Damour 00]

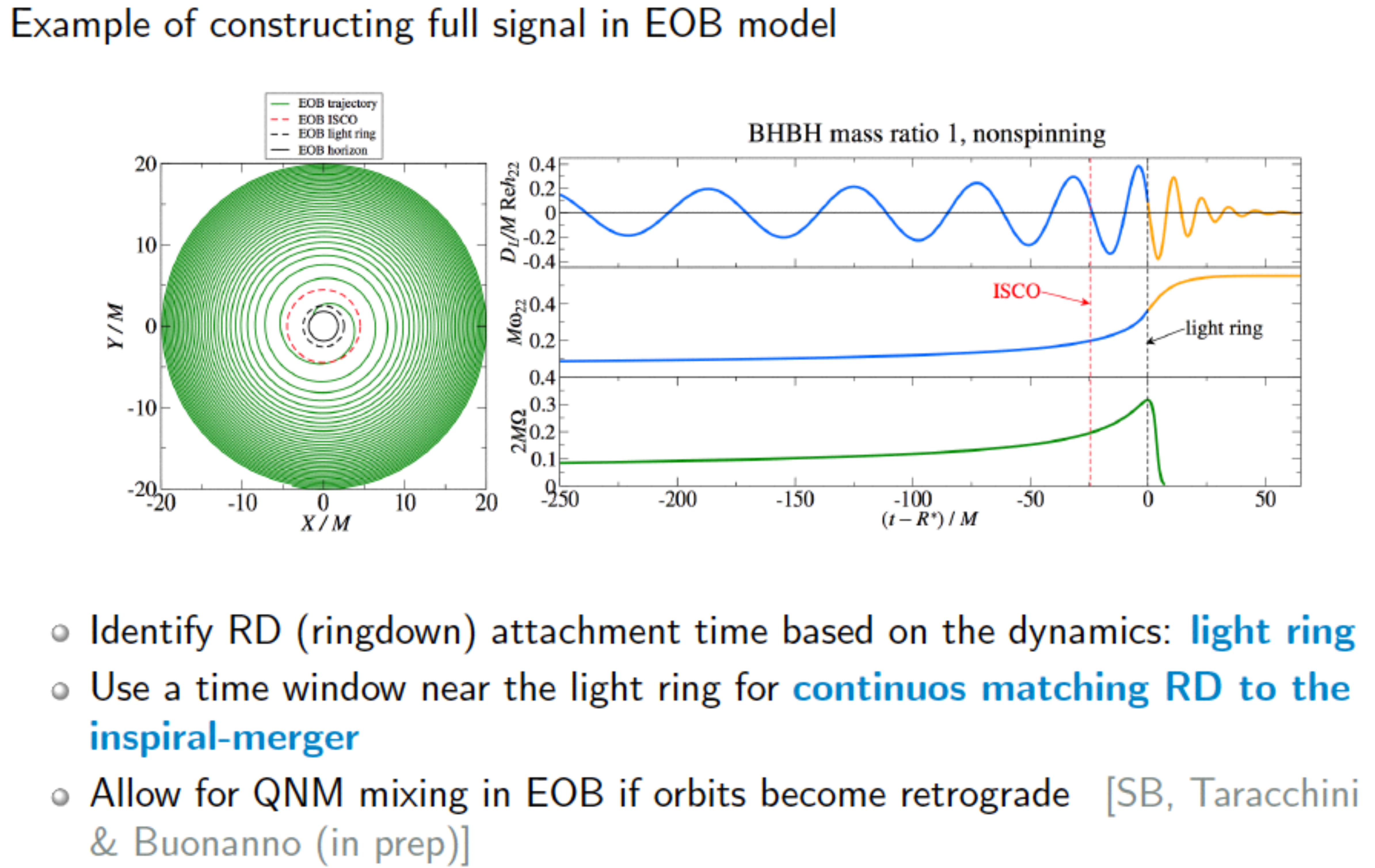
$$h_{\ell m}^{\text{RD}} = \sum_n A_{\ell m n} \underbrace{e^{-i\,\omega_{\ell m n} t}}_{\text{oscillatory}} \underbrace{e^{-t/\tau_{\ell m n}}}_{\text{damping}}$$

- **Nonadiabatic EOB inspiral-plunge trajectory** from Hamilton's equations

$$\frac{\mathrm{d}\mathbf{R}}{\mathrm{d}t} = \{\mathbf{R}, H_{\text{real}}\} \qquad \frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \{\mathbf{P}, H_{\text{real}}\} + \mathcal{F}$$

- Integrate numerically from **quasicircular initial conditions**

Signal Modelling (EOB)

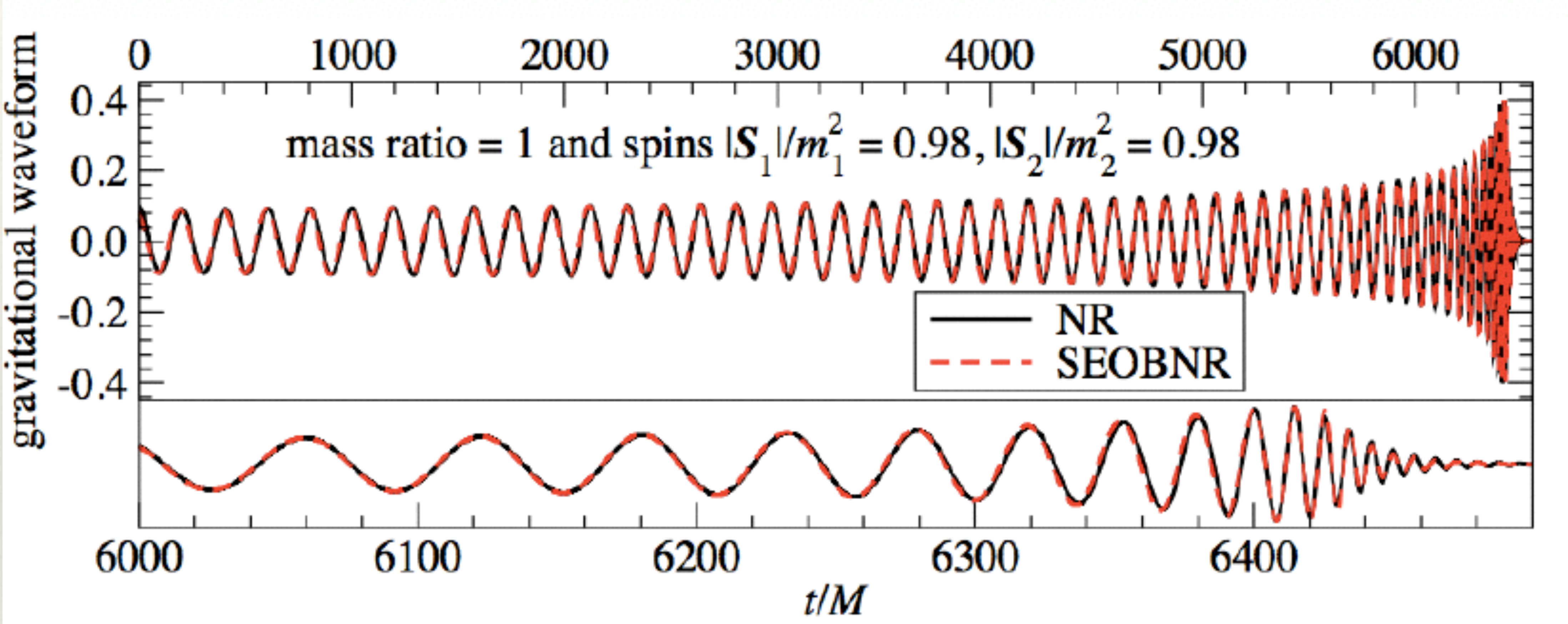


Example of constructing full signal in EOB model

- Identify RD (ringdown) attachment time based on the dynamics: **light ring**
- Use a time window near the light ring for **continuos matching RD to the inspiral-merger**
- Allow for QNM mixing in EOB if orbits become retrograde [SB, Taracchini & Buonanno (in prep)]

EOB - NR comparison

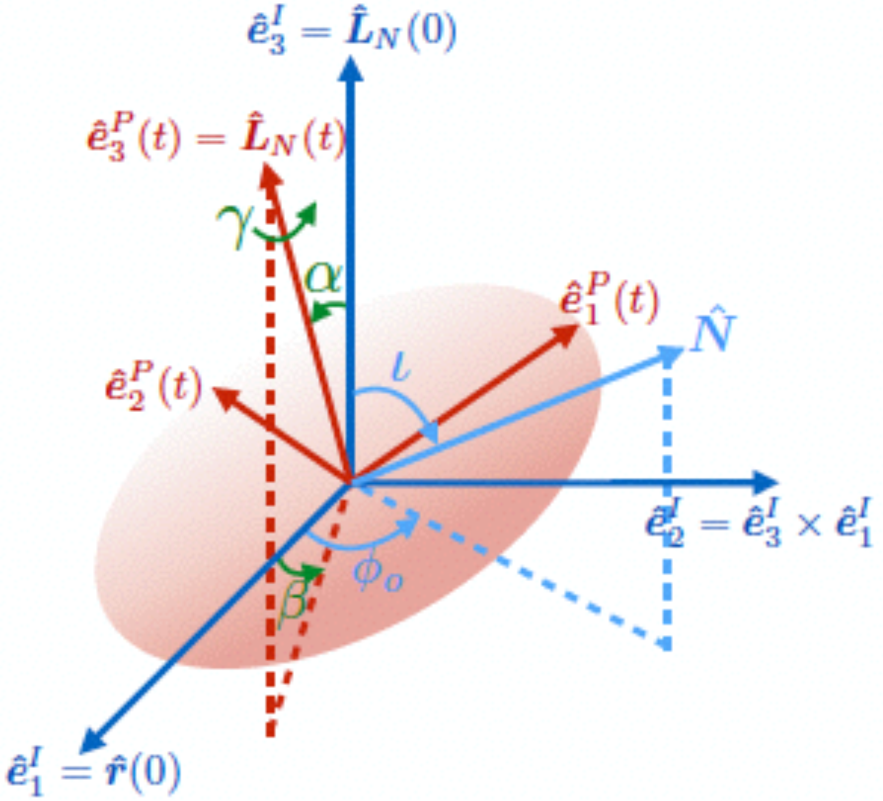
EOB waveform, spins are aligned with the orbital momentum

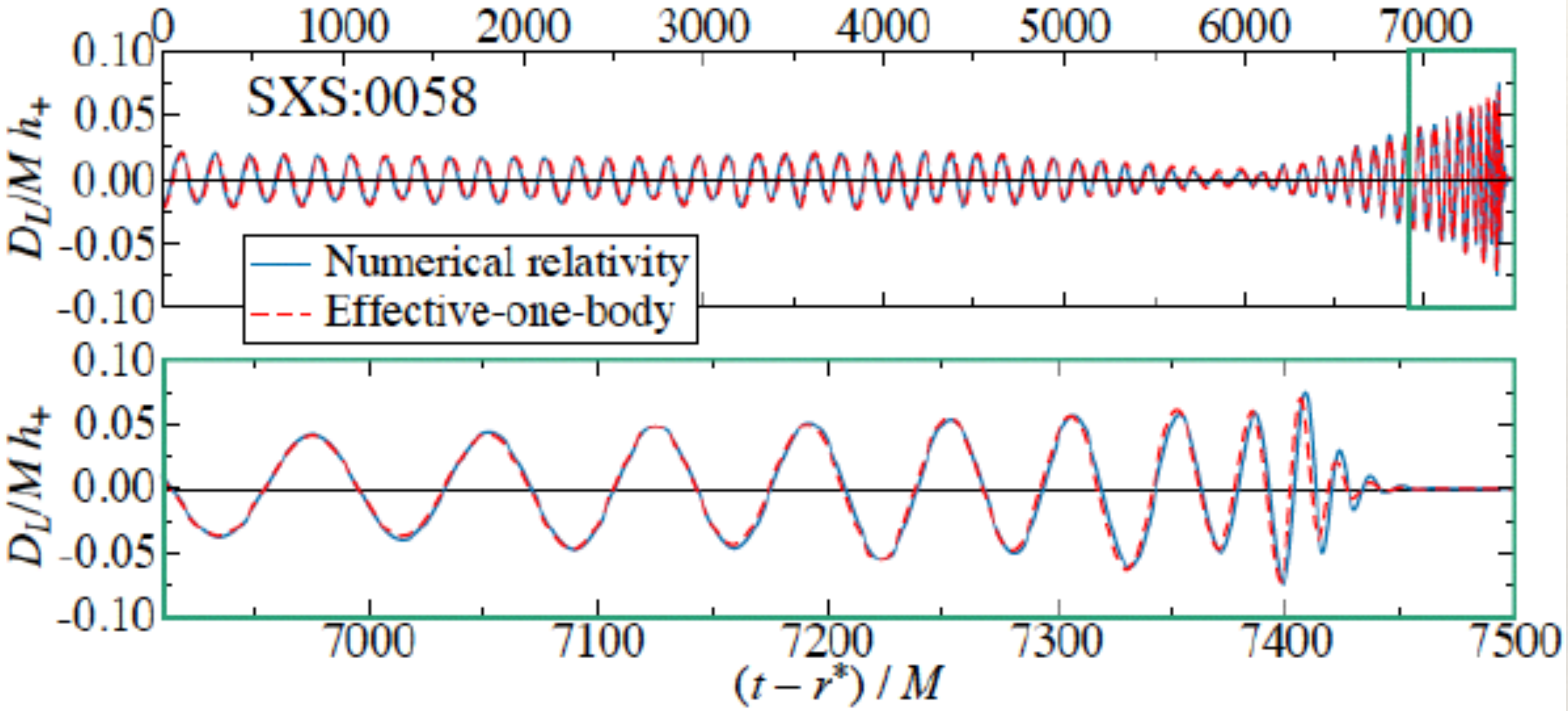


Taracchini et. al. 2013

Precessing BH binary (EOB)

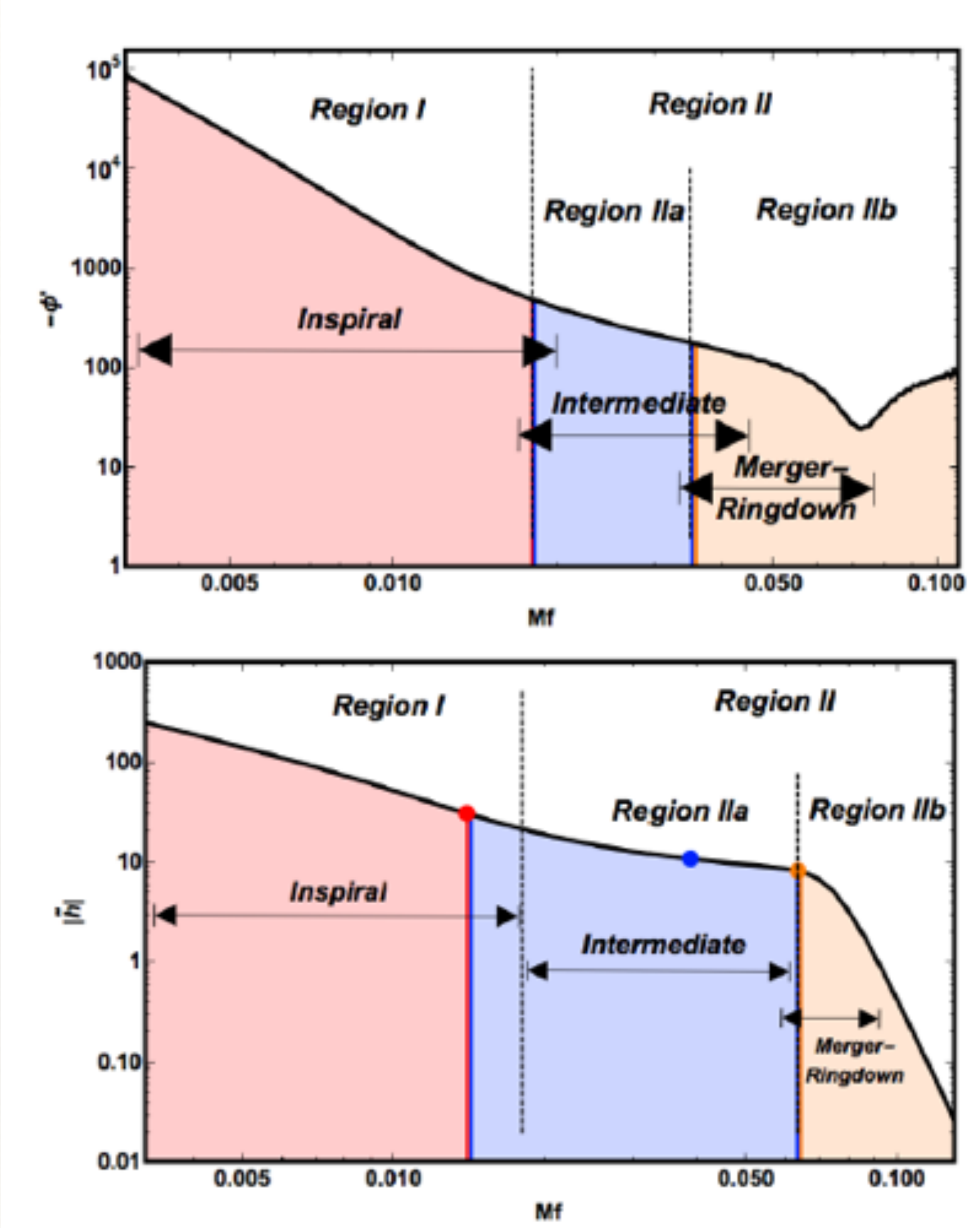
- Model precessing-frame waveforms with **calibrated IMR nonprecessing models**. **No recalibration** of inspiral of underlying nonprecessing models [Pan+13, Babak+(in prep)]



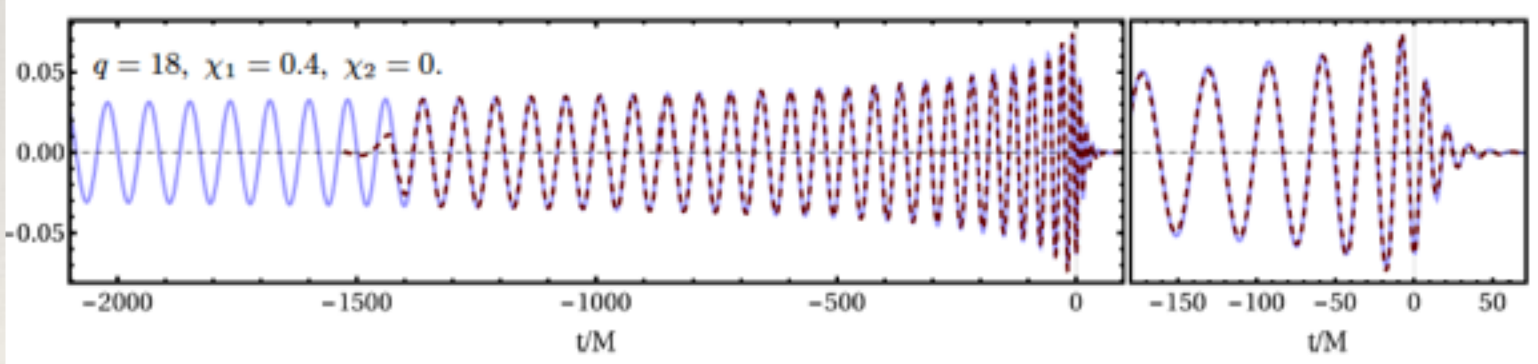


- **70 NR simulations** [SXS13] w/ mass ratios b/w 1 and 5, spins magnitudes up to 0.5, generic orientations [Babak+(in prep)]

IMRPhenomP



- Waveform constructed in the frequency domain
- Uses Post-Newtonian results for the early evolution (inspiral) of a binary
- For merger-ringdown part: there is an analytical expression with free parameters which are calibrated to fit the NR data
- Precession is added by rotation taken from the Post-Newtonian evolution
- Very fast to generate



S. Khan et.al. 2015

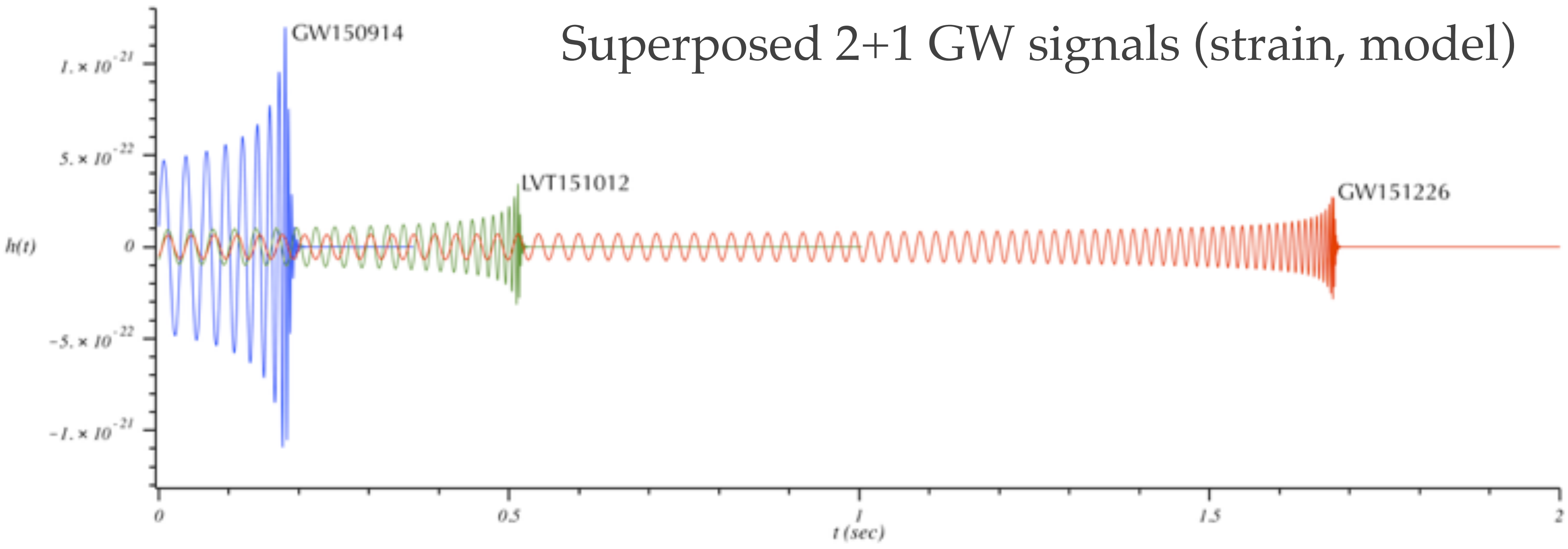
Basic parameters

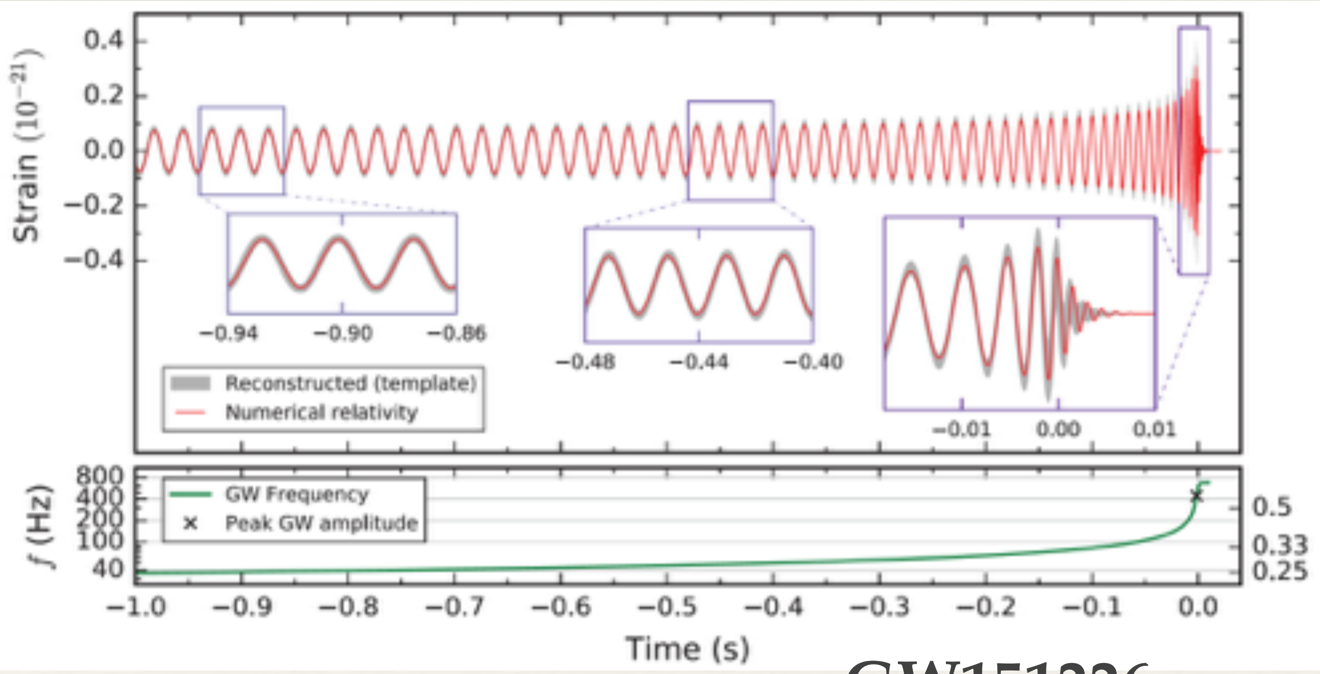
- GW150914
  - Distance: 440 Mpc (z=0.9)
  - m1=39, m2=30
  - Inclination: face-off, 600 sq.d
  - Duration (from 30Hz), ~200ms, ~10 cycles
  - QNM: 250Hz, τ = 4ms
  - Peak luminosity: 3.6 x 10^{56} erg s^{-1}

- GW151226
  - Distance: 250-620 Mpc (z=0.05 - 0.13)
  - m1=[11-23], m2=[5,10]
  - Inclination: (poor)
  - Duration (from 35 Hz), ~ 1s, ~55 cycles
  - QNM: 750Hz, τ = 1.3ms
  - Peak luminosity: 2-4 x 10^{56} erg s^{-1}

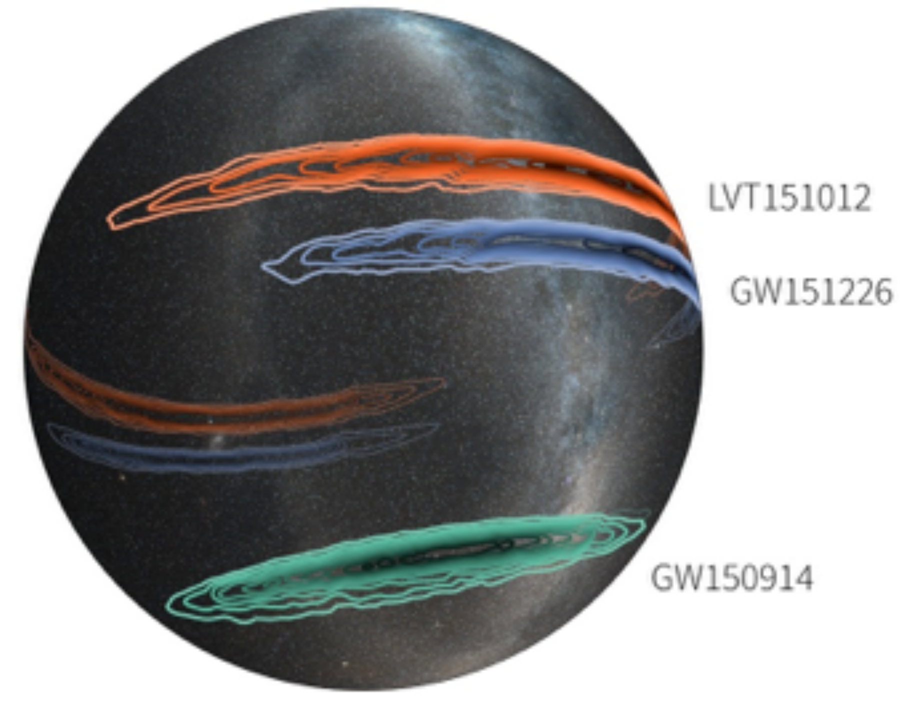
LIGO & VIRGO PRL (2016) 116, 061102; PRL. 116, 241103 (2016)

Comparison of GW events


Superposed 2+1 GW signals (strain, model)



GW151226

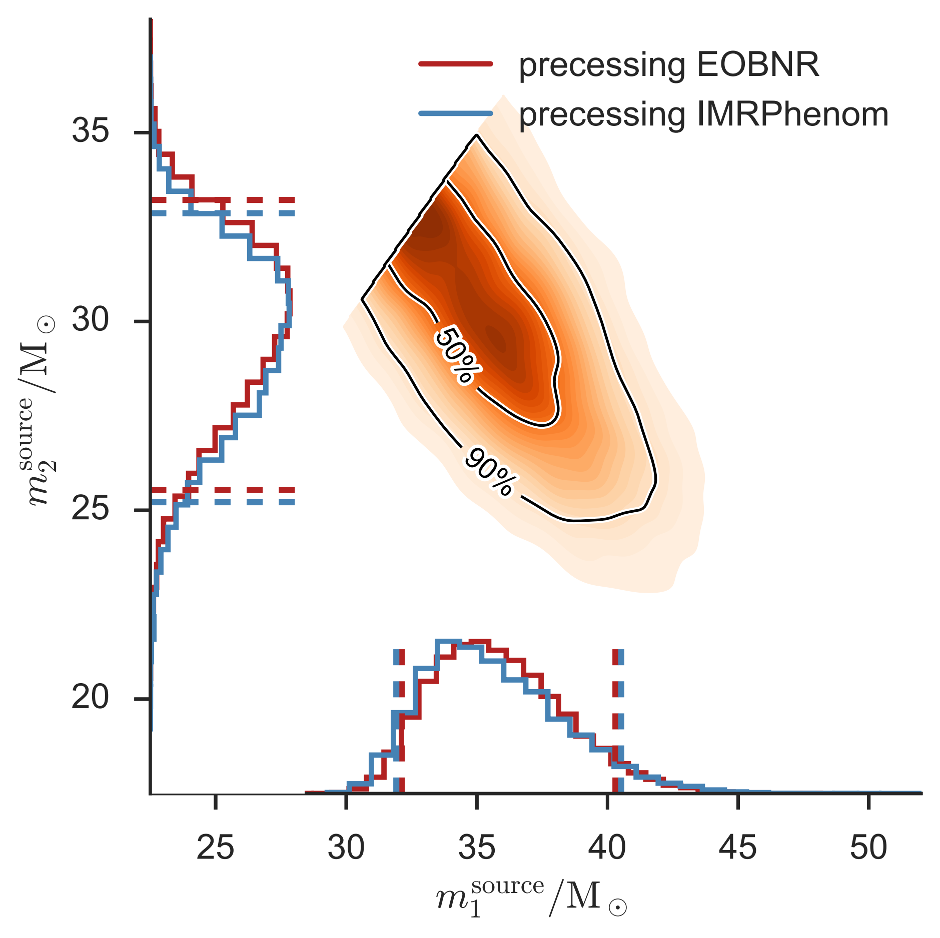


Sky localisation

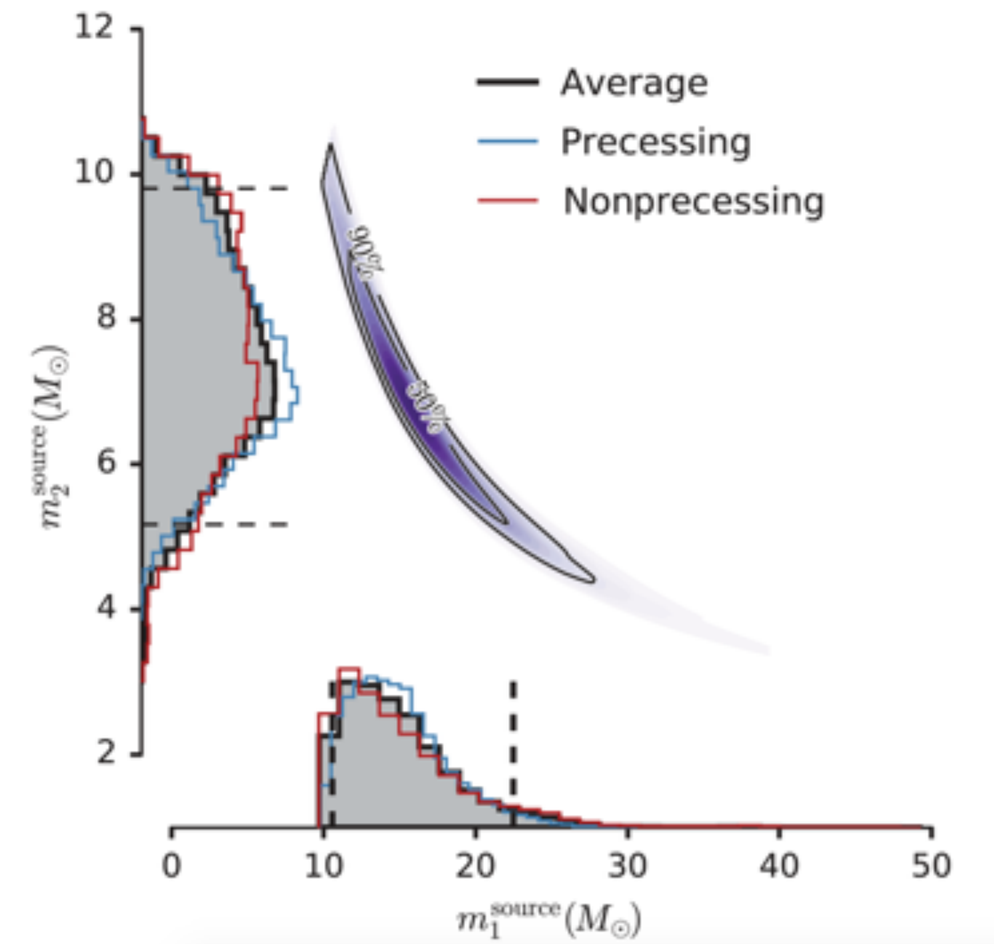
LIGO Scientific Collaboration

Parameter estimation: masses and spins

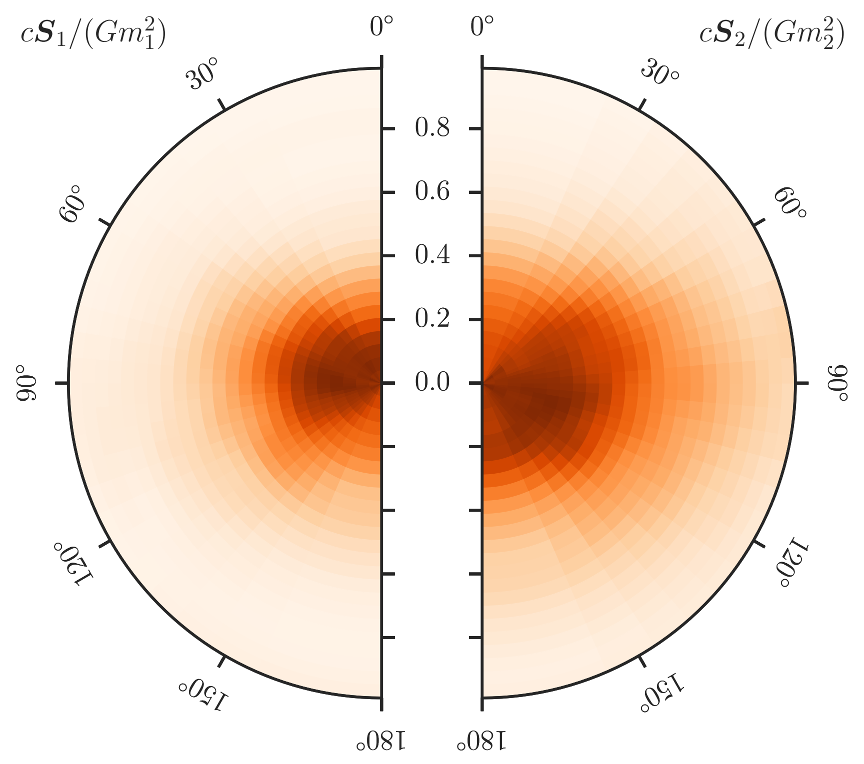
- We ha arkov ch neters of each G
- We ha on-prec a strong precess

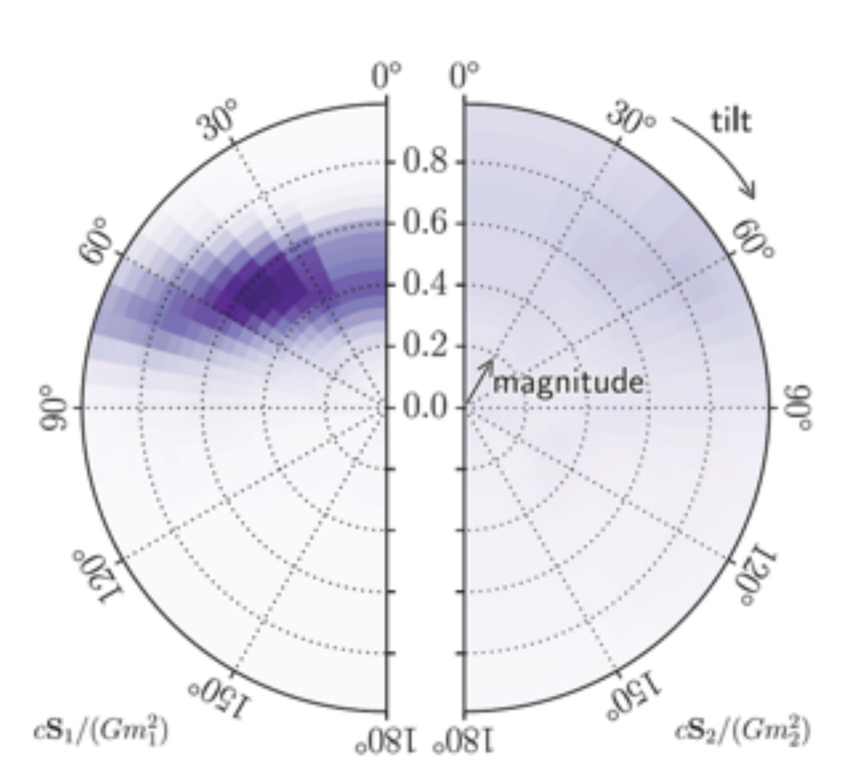


LIGO & VIRGO arXiv:1606.01210



LIGO & VIRGO PRL. 116, 241103 (2016)

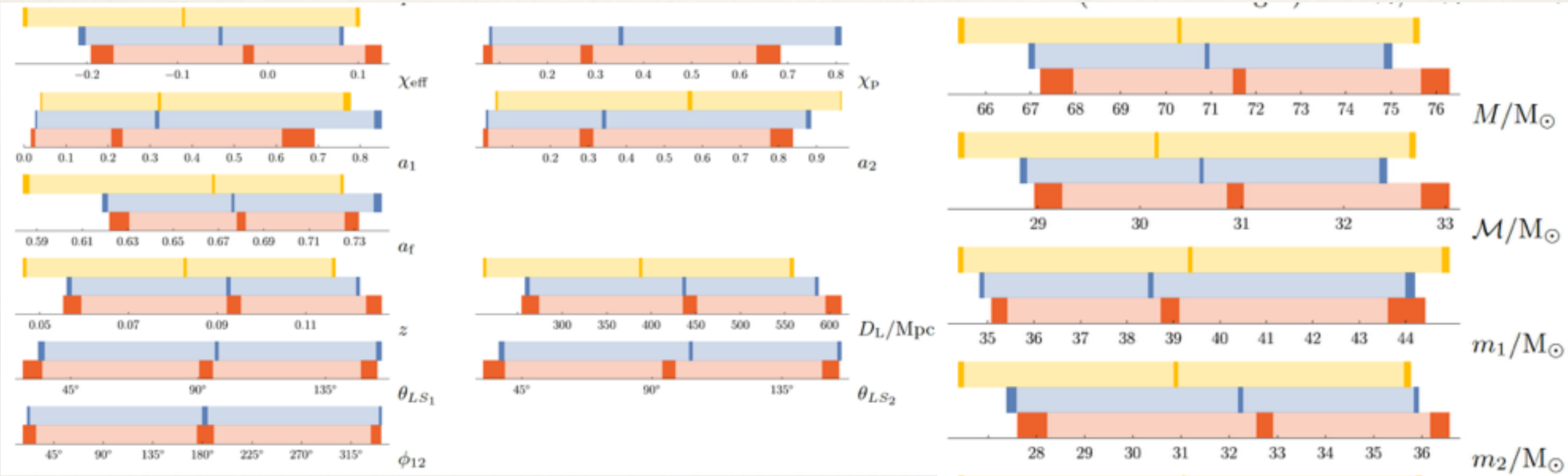




Uncertainties in the parameter estimation

- We expect some uncertainties in the parameter estimation coming from the finite size of the posterior points, two precession models have their own constrains and "faithfulness"

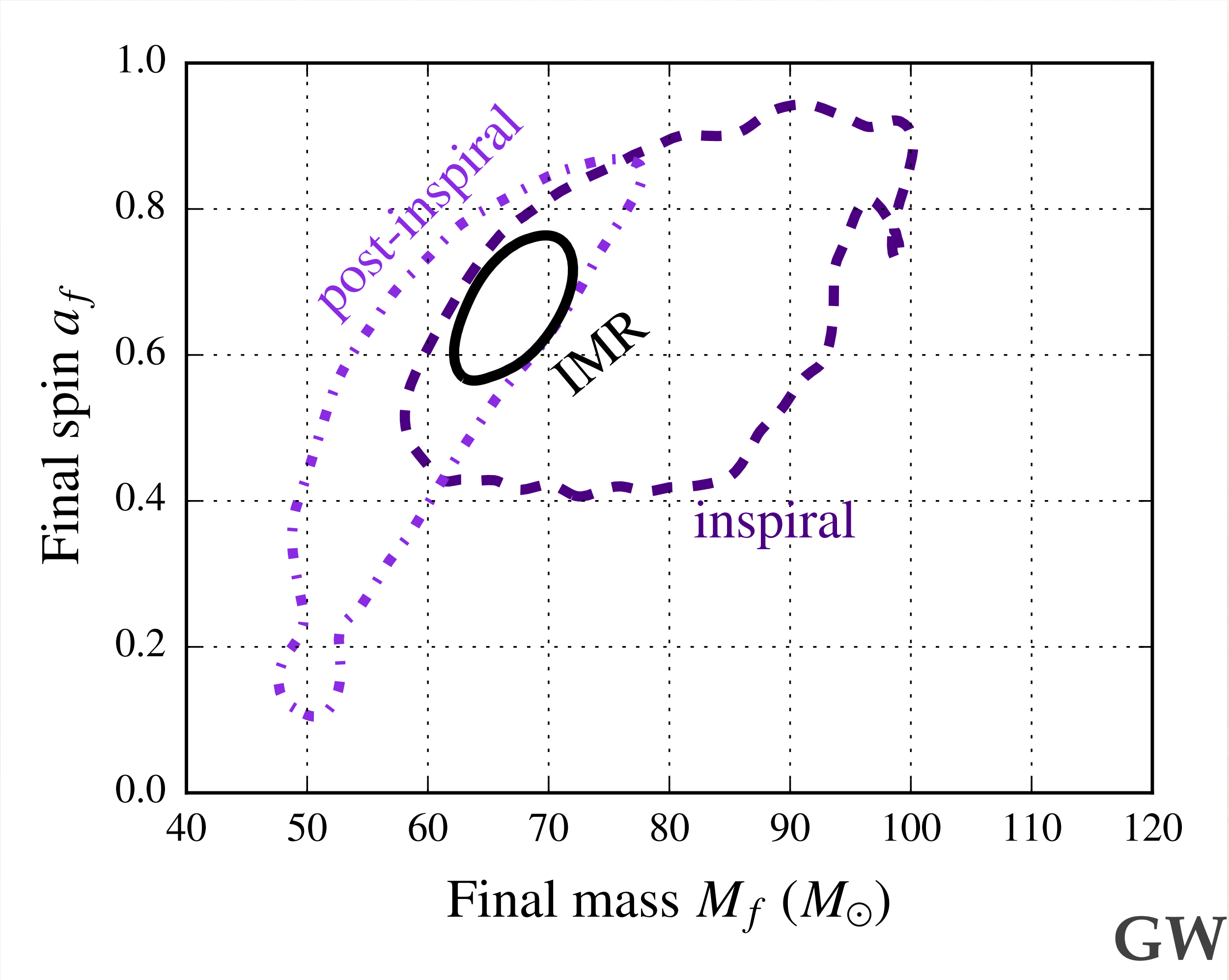
LIGO & VIRGO arXiv:1606.01210



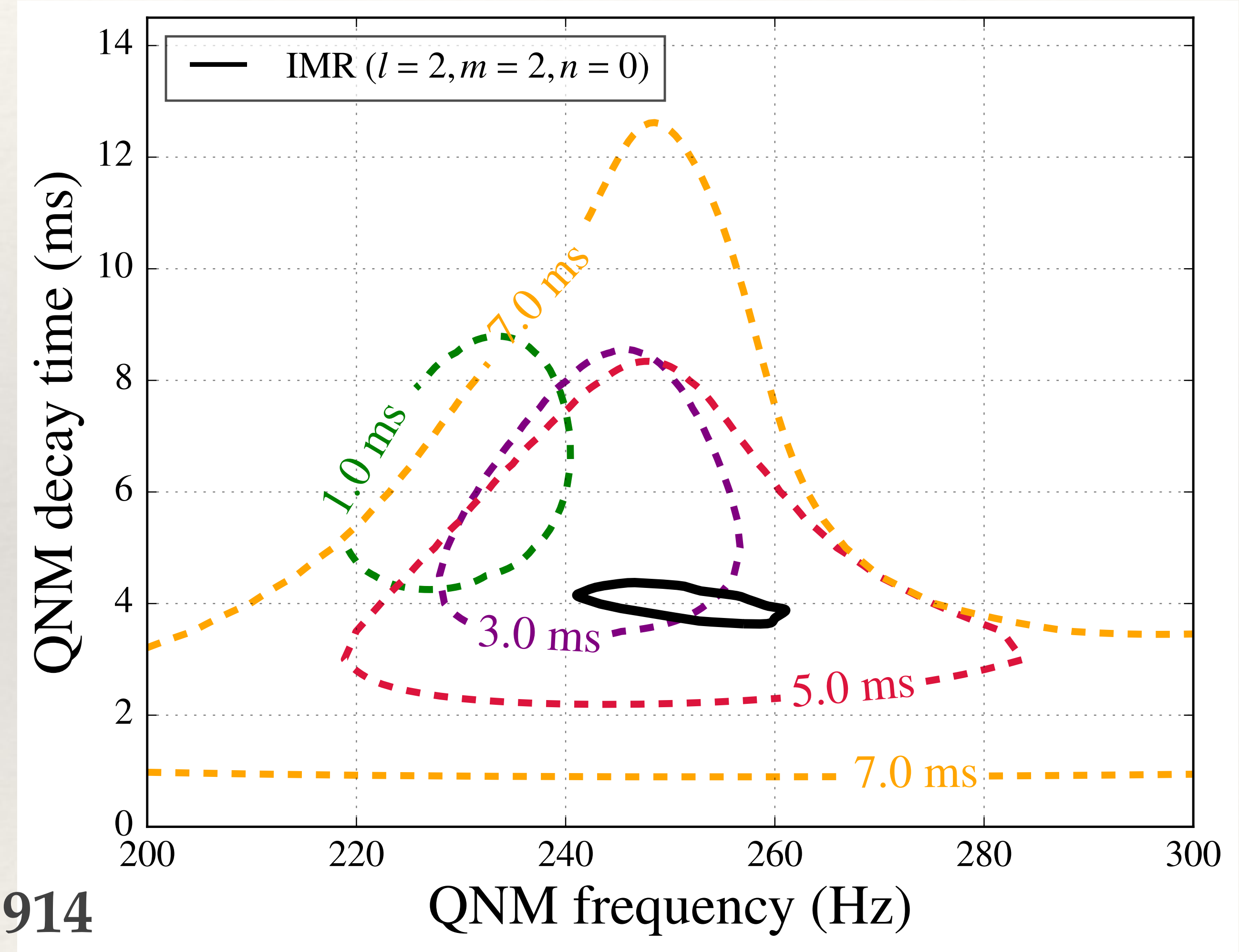
Red - precessing SEOBNR model
Blue - precessing PhenomP model
Yellow - non-precessing SEOBNRmodel

Consistency with GR predictions

- Study of consistency of inspiral (early orbital evolution) and merger parts of the signal: they show consistent estimation of the final mass and final spin of the remnant BH
- Quasi-normal modes produced during formation and relaxation of a remnant BH: superposition of the exponentially damped eigen modes of a BH. We attempt to identify the n=0 overtone (the longest lived mode) as a function of "post-merger" time



GW150914



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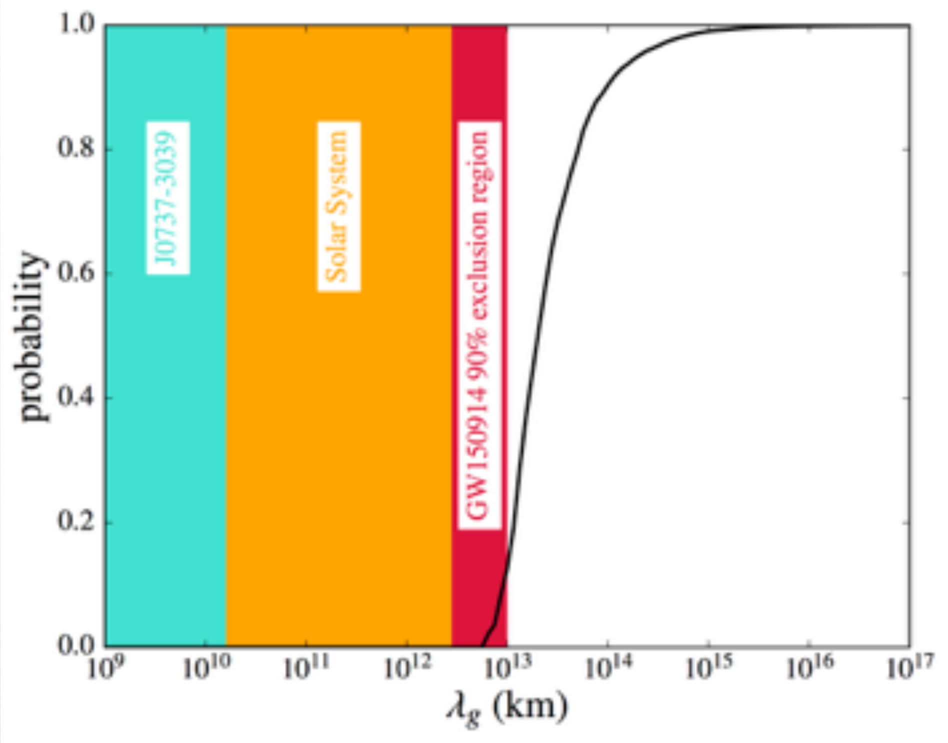
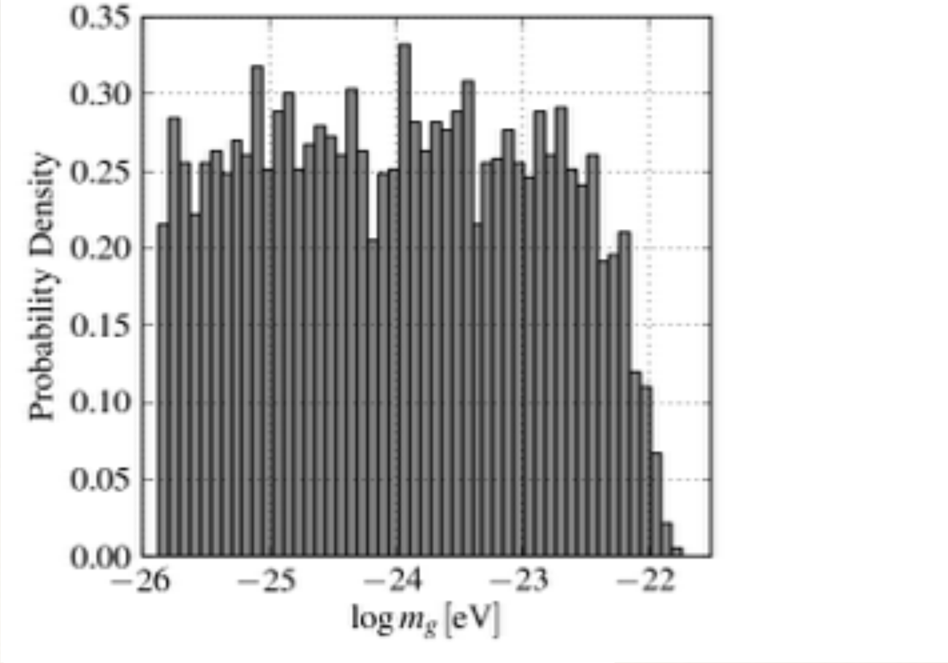
LIGO & VIRGO arXiv:1606.01210

Constraining dispersion in the GW signal



GW150914



$$\Delta t_a = (1+z)\left[\Delta t_e + \frac{D}{2\lambda_g^2}\left(\frac{1}{f_e^2} - \frac{1}{f_e'^2}\right)\right]$$

$$\Delta t_e = t_e - t'_e$$

time of emission f′$_e$

time of emission f$_e$

GR part

$$\tilde{h}(f) = \boxed{A(f)e^{i\Psi(f)}} \times \boxed{e^{-i\beta_g(\pi\mathcal{M}_c f)^{-1}}}$$

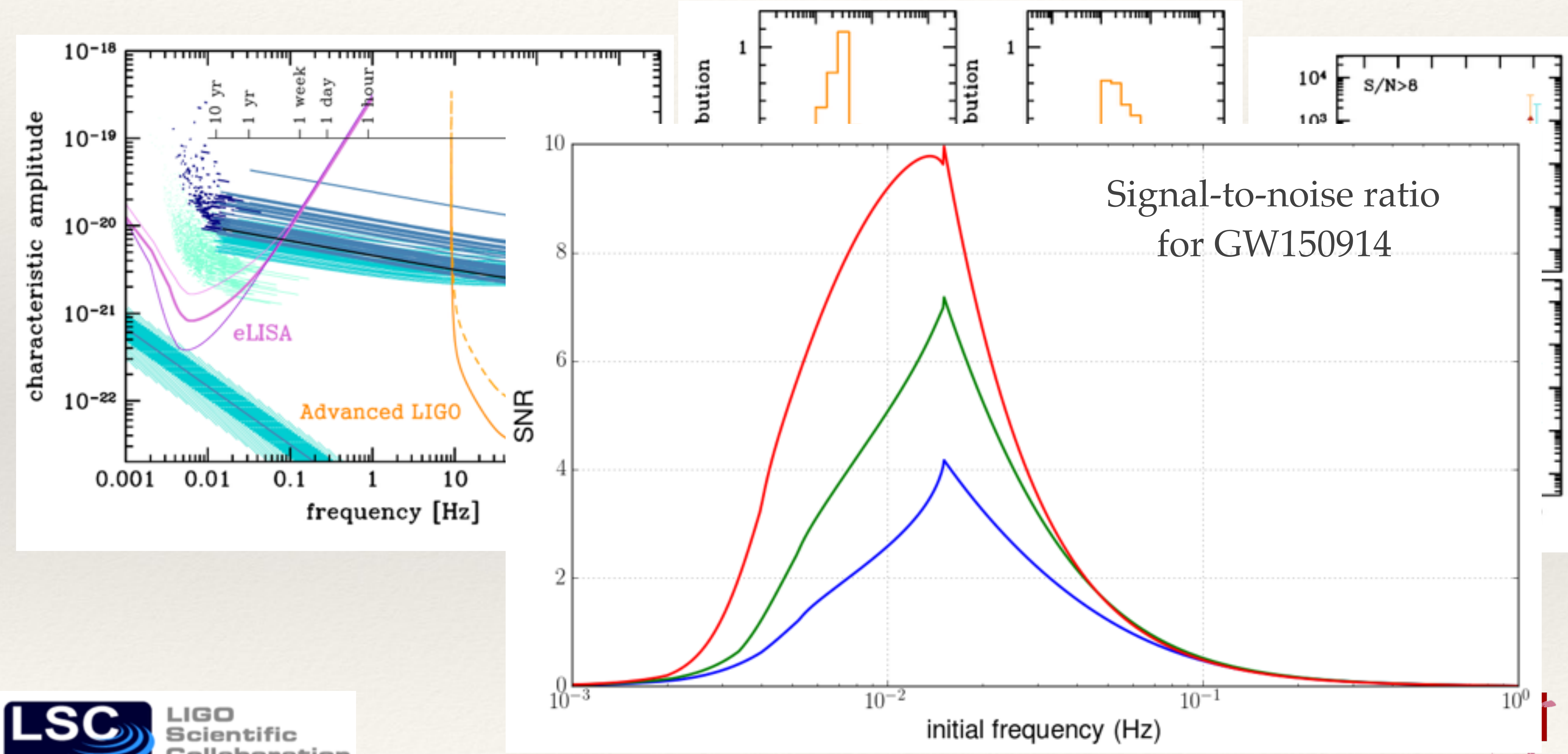
dispersion term

$$\beta \equiv \frac{\pi^2 D\mathcal{M}_c}{\lambda_g^2(1+z)} \qquad \lambda_g = h/(m_g c)$$

$$\lambda_g > 10^{13}\text{km}; \quad \mathrm{m_g} < 1.2 \times 10^{-22}\text{eV}$$

Multi-band astronomy

- The observed GW events should be also visible in eLISA band (A. Sesana PRL, 2016)
- See also talk by E. Barausse

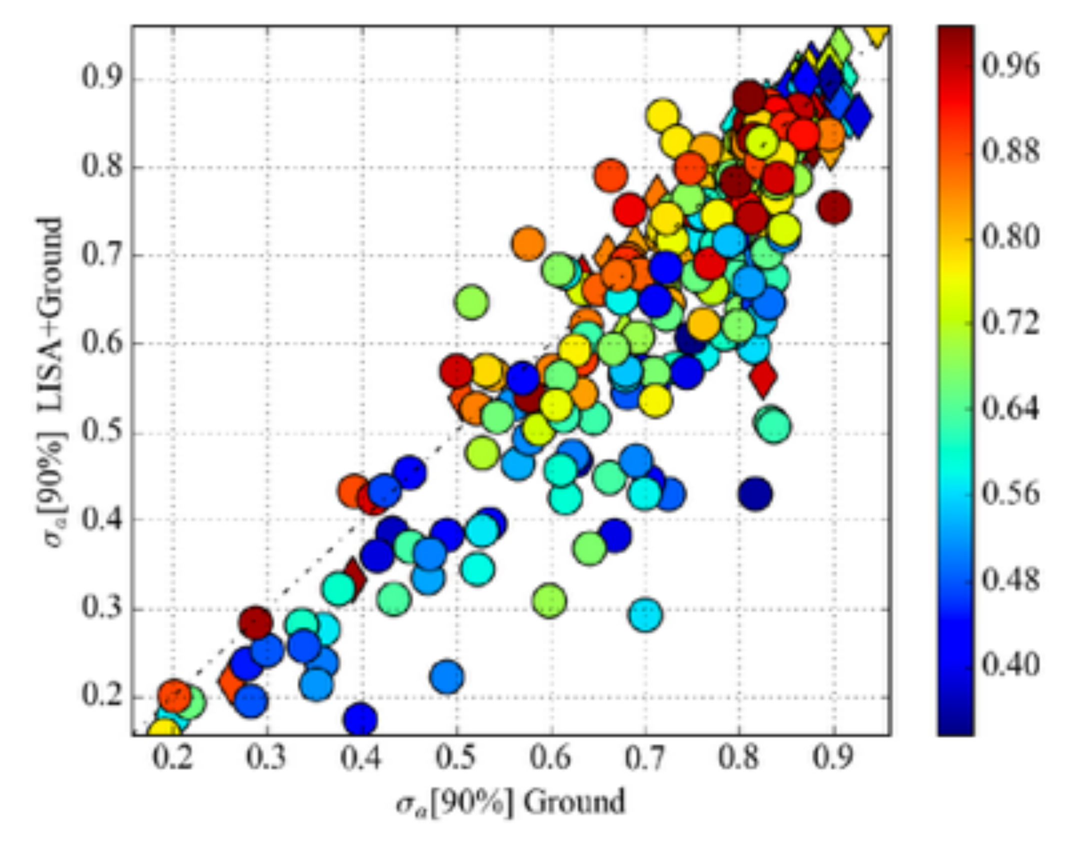


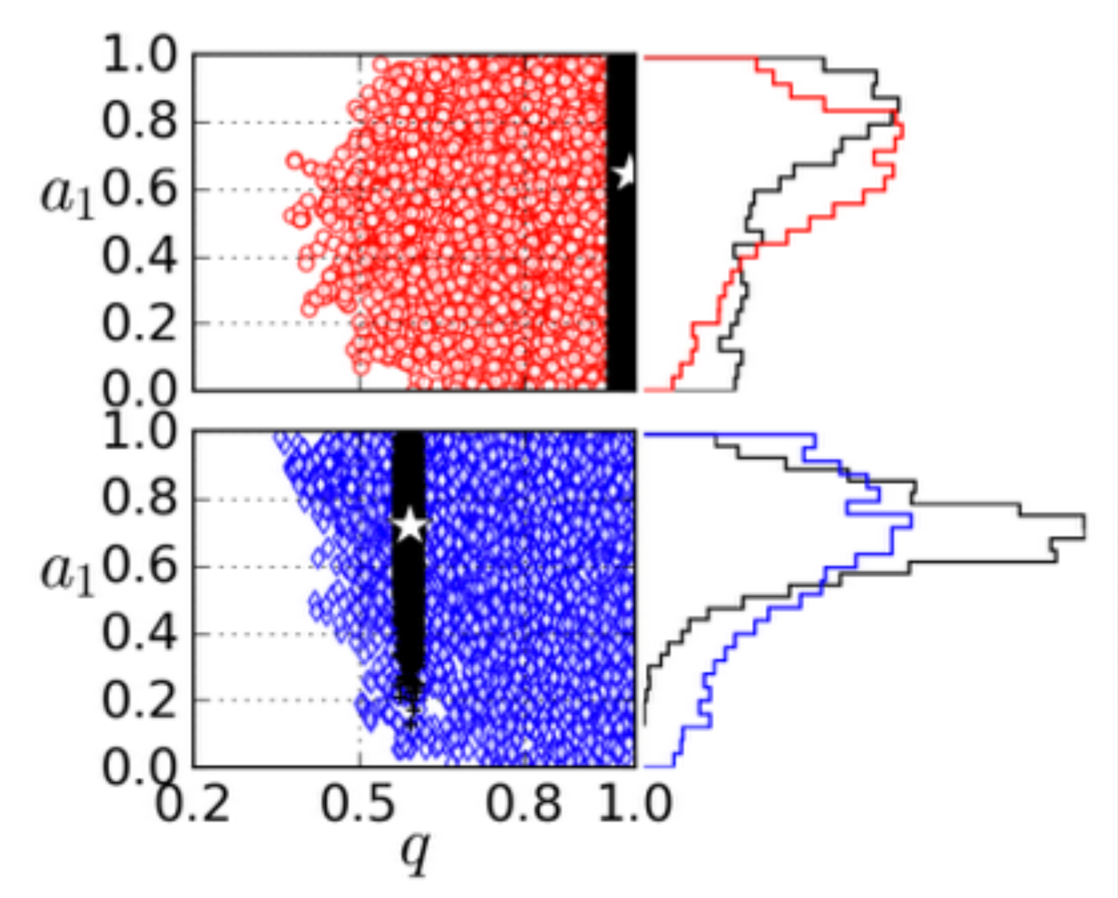
Signal-to-noise ratio
for GW150914

arXiv:1605.01037

Multi-band astronomy

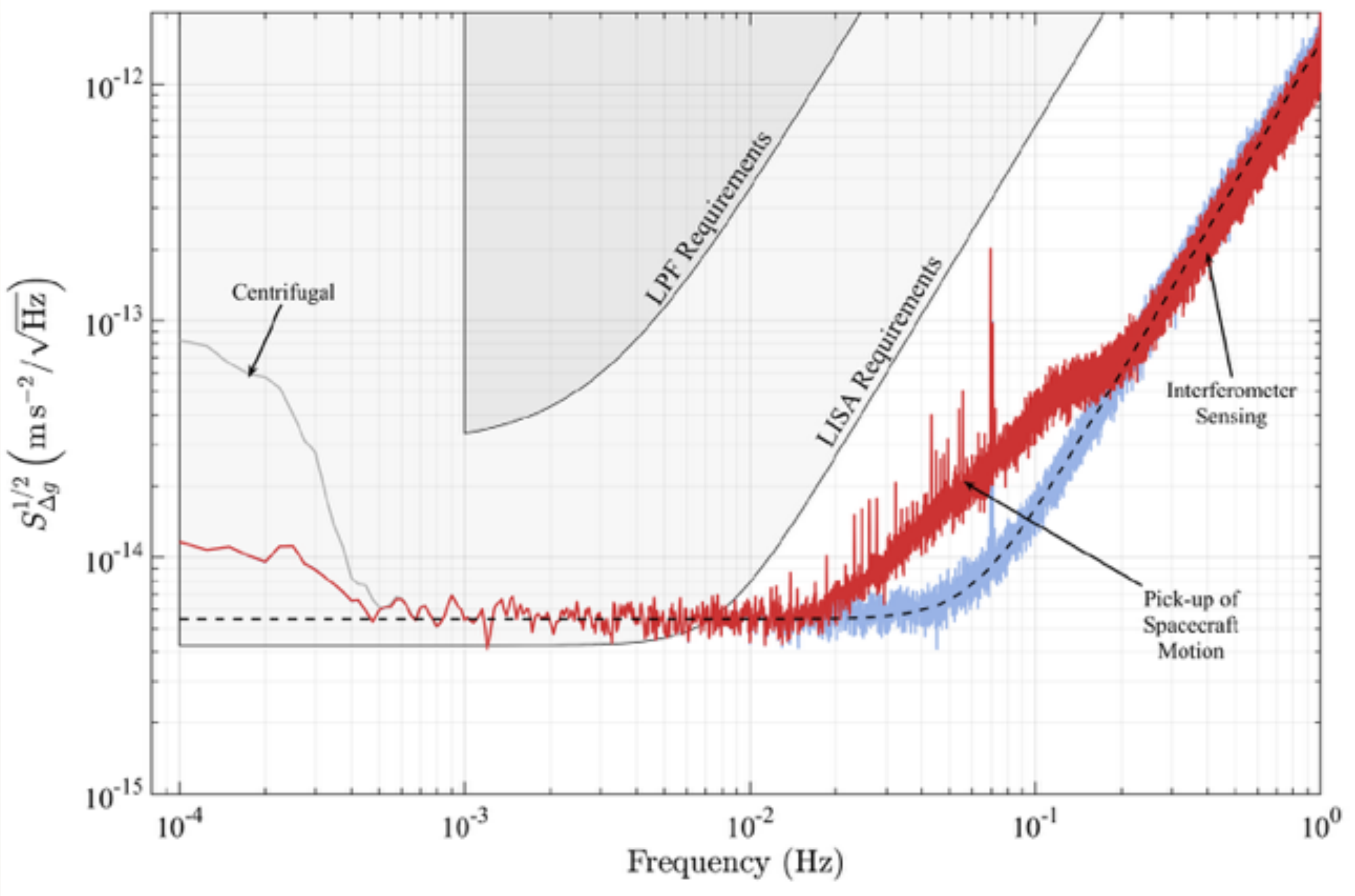
The follow-up work suggested that we could use eLISA observations as ‘prior’ for aLIGO (or whatever will be there) in order to improve estimation of spins (S. Vitale arXiv:1605.01037)





arXiv:1605.01037

LISA PathFinder results



This implies that we could have for eLISA better (lower) acceleration noise than we have anticipated.

More measurements at low frequency will be done during the extended mission time.

LPF Team: PRL 116, 231101 (2016)

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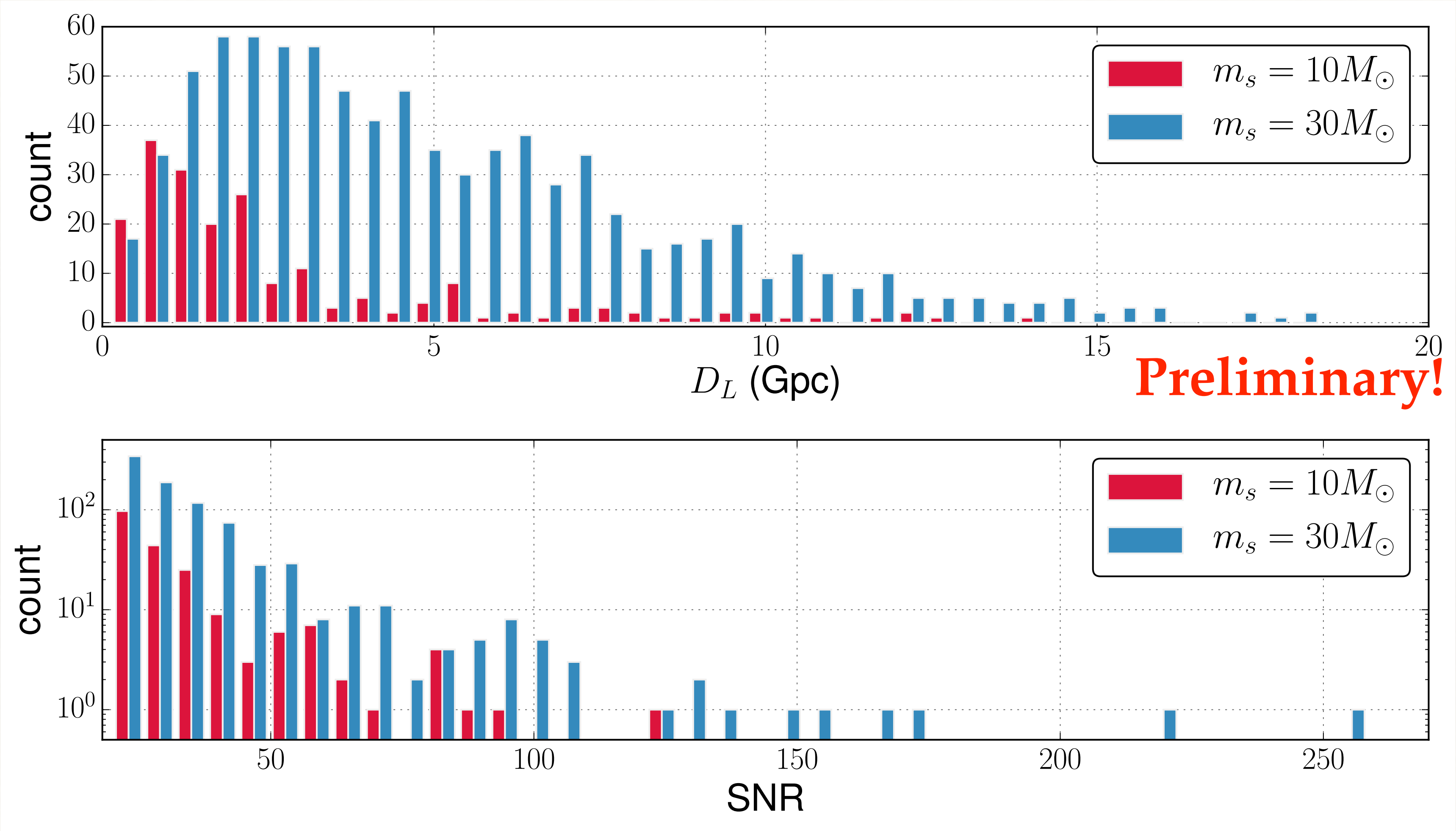
Impact on EMRIs

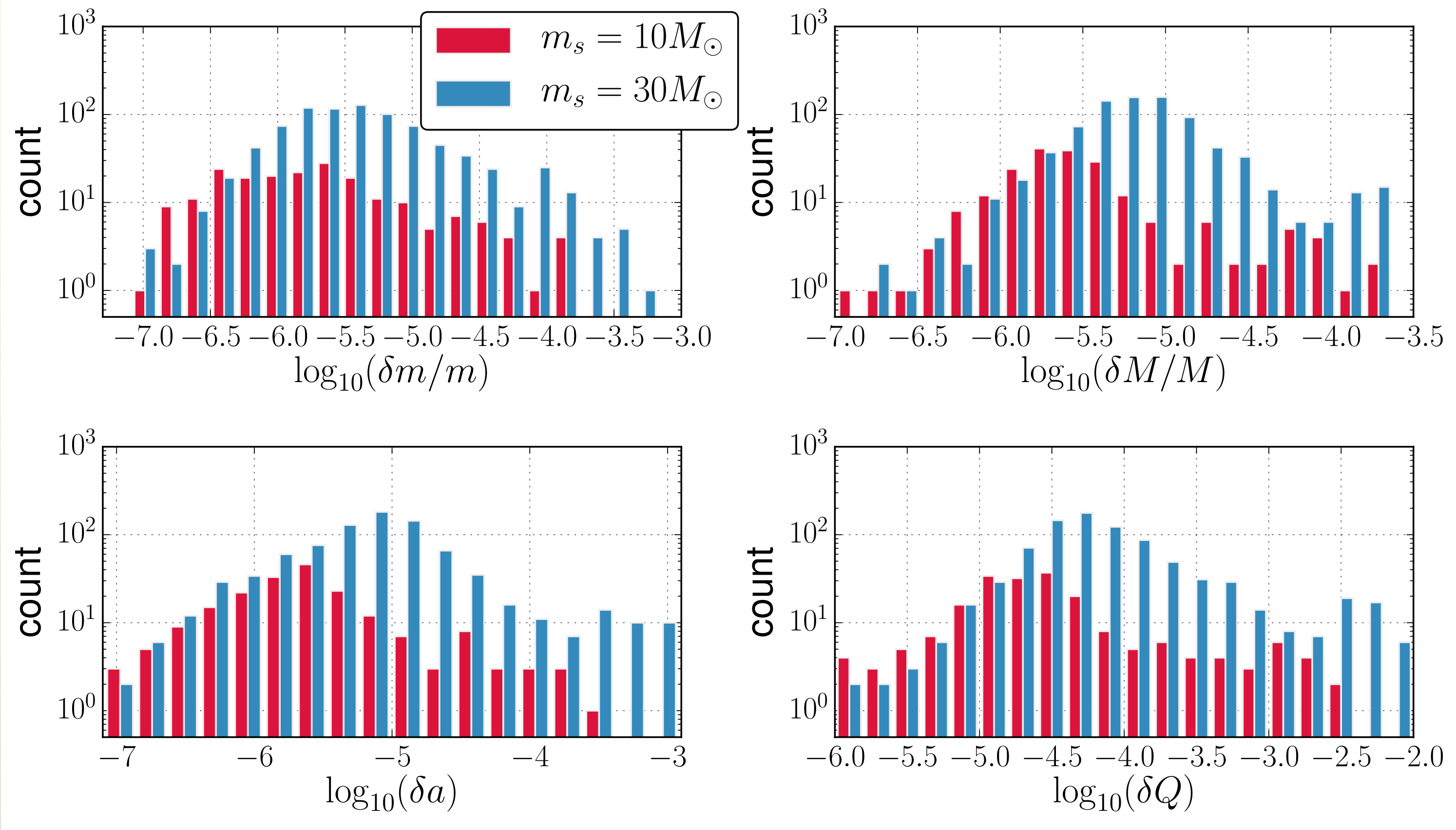
- We know now that BHs with mass > 30 solar mass exist. Dynamical friction is most efficient for heavier masses, which implies that "canonical EMRI" could be 30-10^6 solar mass binary (instead of 10-10^6)
- We have used population of massive BHs (see talk by E. Barausse) to investigate EMRIs event rate and parameter estimation with eLISA

SNR>20
1 min. km arm
6 links



Preliminary!

EMRIs parameter estimation



m - mass of small BH

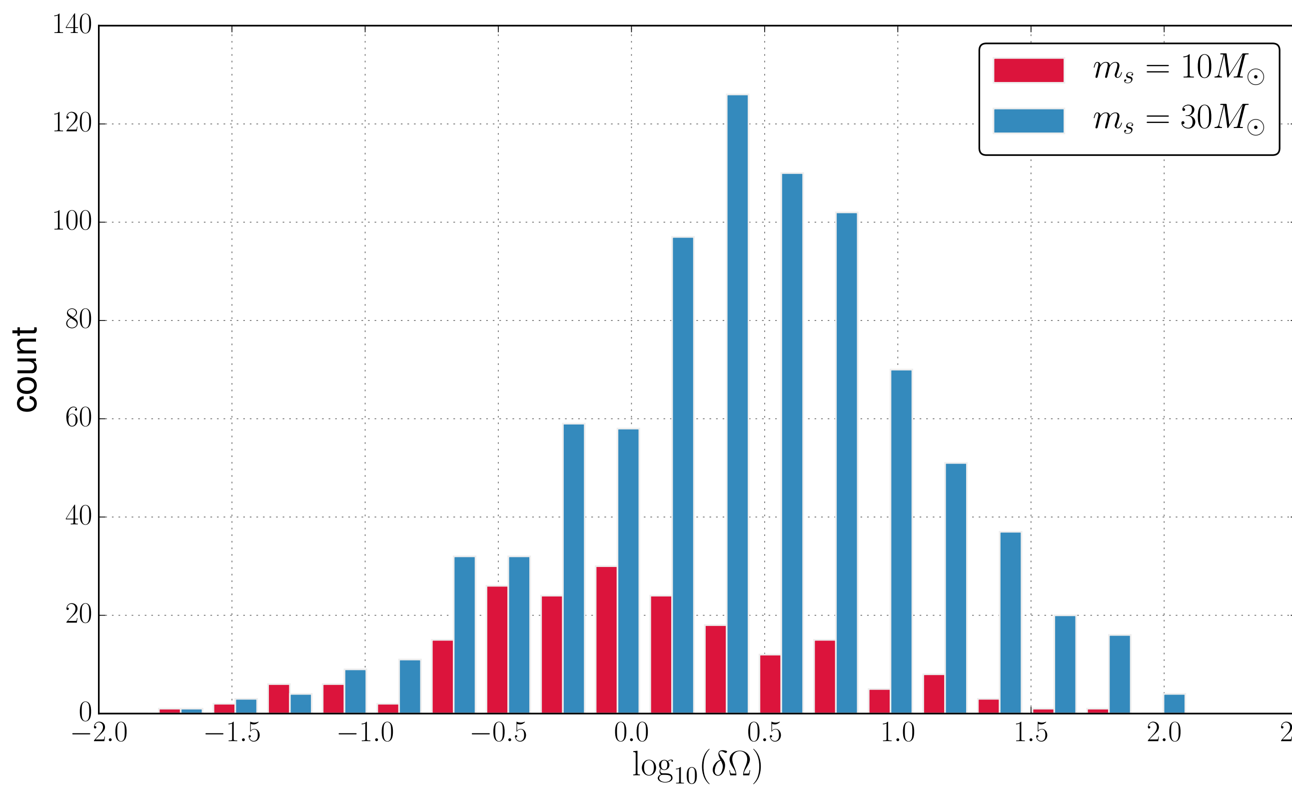
M - mass of massive BH

a - spin of massive BH

Q - deviation from Kerr quadrupole moment

Using analytic kludge model:
Barack & Cutler (2004)

Preliminary



We might have sufficient number of sources with good sky localisation to estimate Hubble constant

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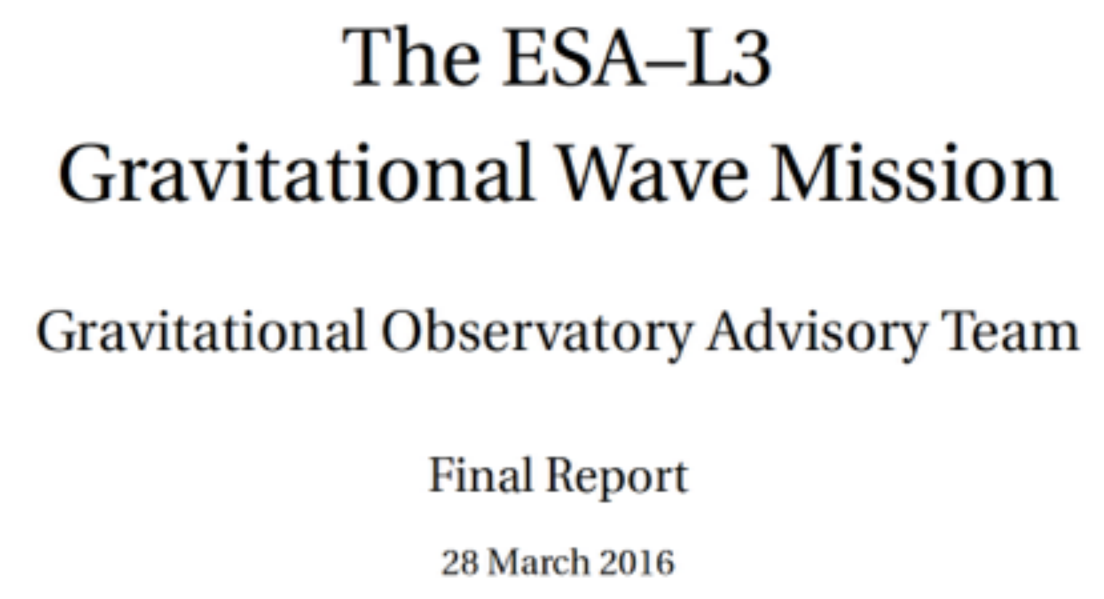
Brief summary from GOAT report



The ESA–L3
Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016

Committee members:

Pierre Binétruy	AstroParticule et Cosmologie (APC), Paris (F)
Philippe Bouyer	Laboratoire Photonique, Numérique et Nanosciences (LP2N), Bordeaux (F)
Mike Cruise	University of Birmingham, Emeritus (UK)
Reinhard Genzel	Max-Planck-Institut für extraterrestrische Physik (MPE), Munich (D)
Mark Kasevich	Stanford University (USA)
Bill Klipstein	JPL, Pasadena (USA)
Guido Müller	University of Florida, Gainesville (USA)
Michael Perryman	University College Dublin (IRL, adjunct), Chair
Bernard Schutz	Albert Einstein Institute, Golm (D) and University of Cardiff (UK)
Stefano Vitale	Università degli Studi di Trento (I)

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Brief summary from GOAT report

- Accordingly, in late 2014, ESA’s Director of Science and Robotic Exploration appointed an external committee, the Gravitational Observatory Advisory Team, to advise on the scientific and technical implementation of L3.
- Main objectives:
  - is the mission technically feasible?
  - is laser interferometry still the best approach to the measurement of gravitational waves from space?
  - how can the technical development of L3 be organised to minimize cost and schedule overruns?

It has concluded that laser interferometry both fully responds to the science goals set out in the 2013 Senior Science Committee report, and is also sufficiently well advanced to offer a highly realistic prospect of implementation according to the L3 schedule.

LSC LIGO Scientific Collaboration

GOAT report

Committee has re-evaluated the scientific capabilities of a gravitational wave observatory, quantifying and presenting the expected performance as a function of:

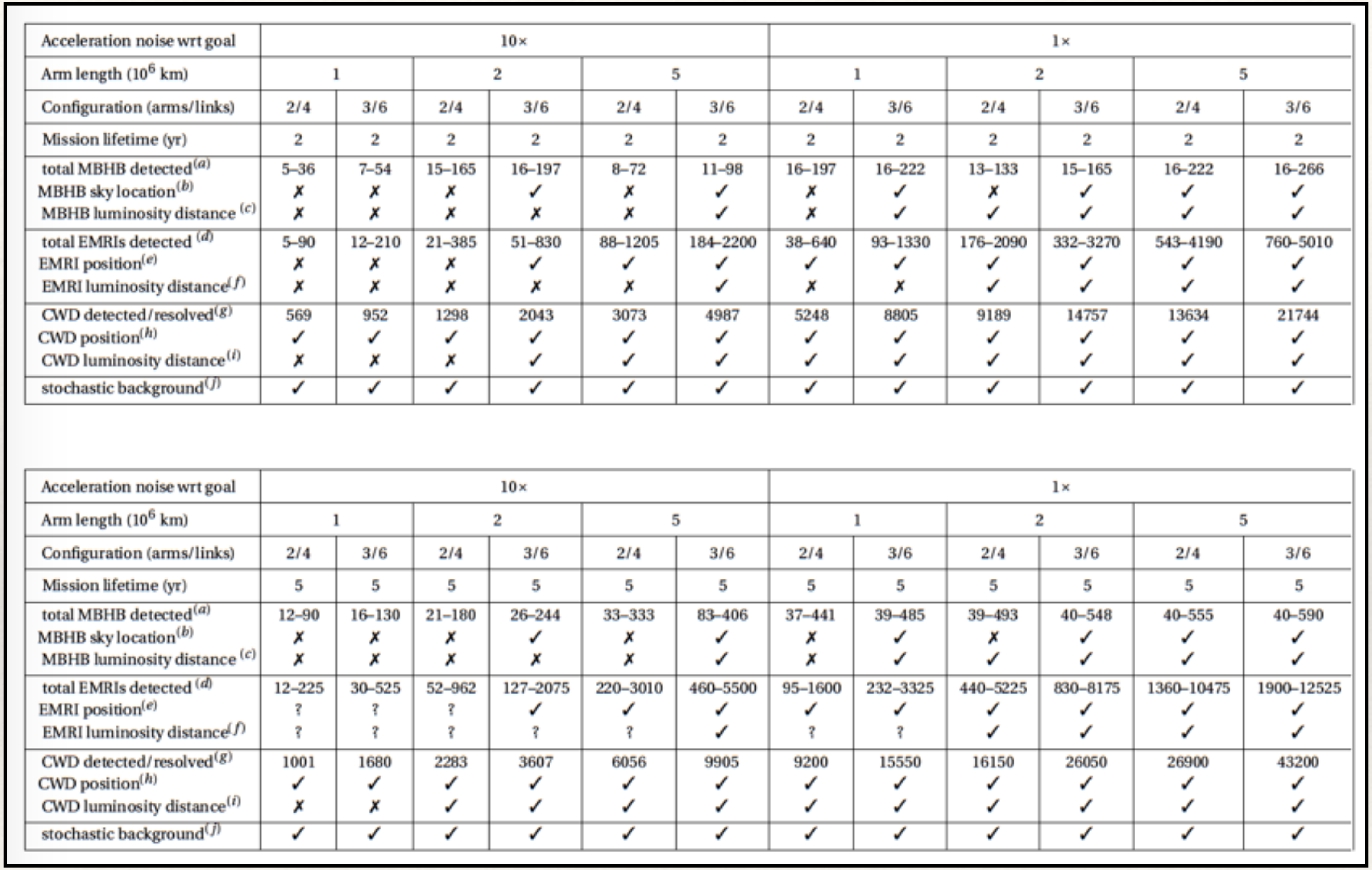
- the number of interferometric baselines (2 or 3 arms, i.e. with 4 or 6 links);
- the interferometric arm-length (between $1\mathrm{x}10^6$ km and $5\mathrm{x}10^6$ km);
- the mission duration (2 years or 5 years);
- test mass 'acceleration noise'.

Committee finds that the minimum architectural configurations studied may be considered as scientifically viable. However, the improved reliability and science performance offered by <u>three identical spacecraft</u>, and the enhanced scientific return of a <u>longer duration mission</u>, with <u>at least intermediate armlength</u>, provides much greater impact;

GOAT report

The momentum that had built up in the LISA/eLISA/NGO community has somewhat dissipated, with national funding generally no longer forthcoming, presumably due to the distant launch date. The Committee considers that this is a risk situation, and that it would be advantageous for certain data analysis activities to be resumed promptly, not least since some will impact on, and will guide, the technical design

GOAT assessment table



Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	2	2	2	2	2	2	2	2	2	2	2	2
total MBHB detected$^{(a)}$	5–36	7–54	15–165	16–197	8–72	11–98	16–197	16–222	13–133	15–165	16–222	16–266
MBHB sky location$^{(b)}$	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance $^{(c)}$	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected $^{(d)}$	5–90	12–210	21–385	51–830	88–1205	184–2200	38–640	93–1330	176–2090	332–3270	543–4190	760–5010
EMRI position$^{(e)}$	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI luminosity distance$^{(f)}$	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓
CWD detected/resolved$^{(g)}$	569	952	1298	2043	3073	4987	5248	8805	9189	14757	13634	21744
CWD position$^{(h)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CWD luminosity distance$^{(i)}$	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
stochastic background$^{(j)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Acceleration noise wrt goal	10×						1×					
Arm length (10^6 km)	1		2		5		1		2		5	
Configuration (arms/links)	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6	2/4	3/6
Mission lifetime (yr)	5	5	5	5	5	5	5	5	5	5	5	5
total MBHB detected$^{(a)}$	12–90	16–130	21–180	26–244	33–333	83–406	37–441	39–485	39–493	40–548	40–555	40–590
MBHB sky location$^{(b)}$	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✓	✓
MBHB luminosity distance $^{(c)}$	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓
total EMRIs detected $^{(d)}$	12–225	30–525	52–962	127–2075	220–3010	460–5500	95–1600	232–3325	440–5225	830–8175	1360–10475	1900–12525
EMRI position$^{(e)}$	?	?	?	✓	✓	✓	✓	✓	✓	✓	✓	✓
EMRI luminosity distance$^{(f)}$	?	?	?	?	?	✓	?	?	✓	✓	✓	✓
CWD detected/resolved$^{(g)}$	1001	1680	2283	3607	6056	9905	9200	15550	16150	26050	26900	43200
CWD position$^{(h)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CWD luminosity distance$^{(i)}$	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
stochastic background$^{(j)}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Conclusion

- Finally… we have detecting the GW signal, even 2.5
- GW detection together with unbelievably successful LISA Pathfinder mission brings credibility of GW community to extremely high level: time to go to space
- It is possible to have multi-band astronomy
- The sensitivity of eLISA might be better than what we are currently use in the study. The new astrophysical models predict more sources: very challenging, very interesting!
- Need to bring back LISA community: data analysis + theoretical GW signal modelling + astrophysics. Still a lot of work to be done and we do not have not that much time.