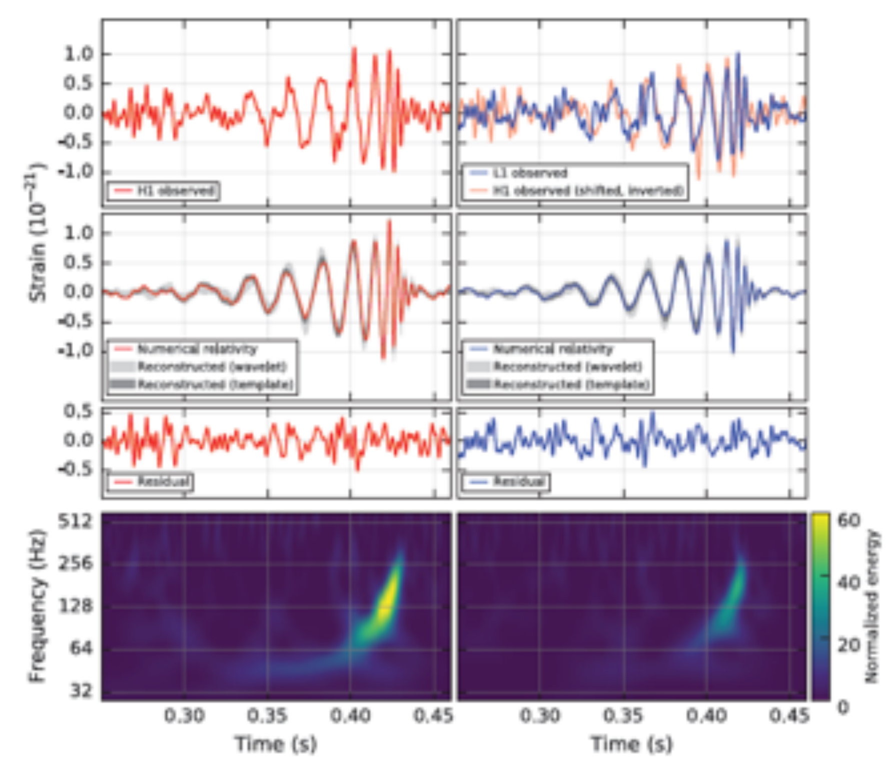
*Stas Babak ( for LIGO and VIRGO collaboration).*
*Albert Einstein Institute (Potsdam-Golm)*

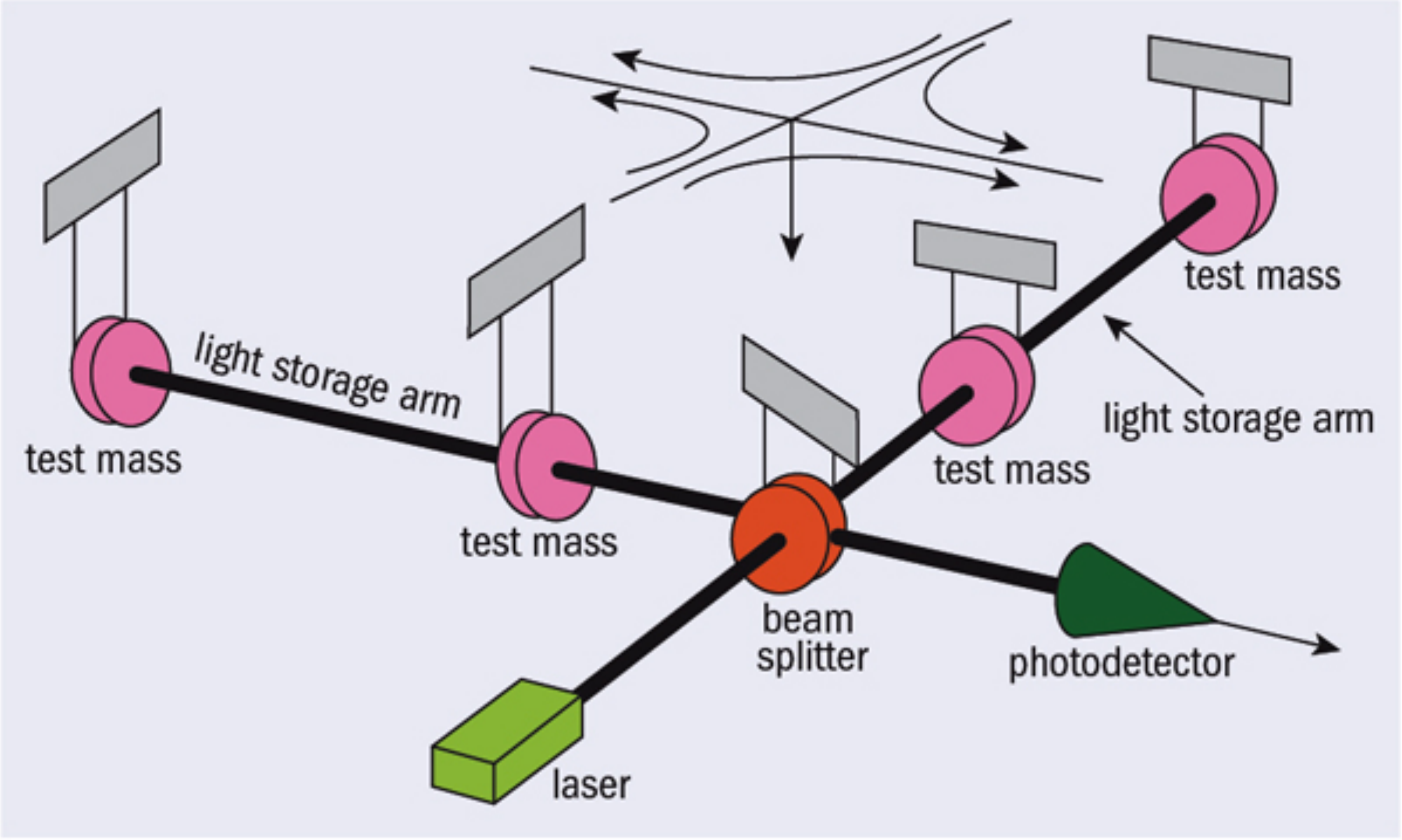
# What have we learned from coalescing Black Hole binary GW150914

LIGO_DCC:G1600346



PRL 116, 061102 (2016)

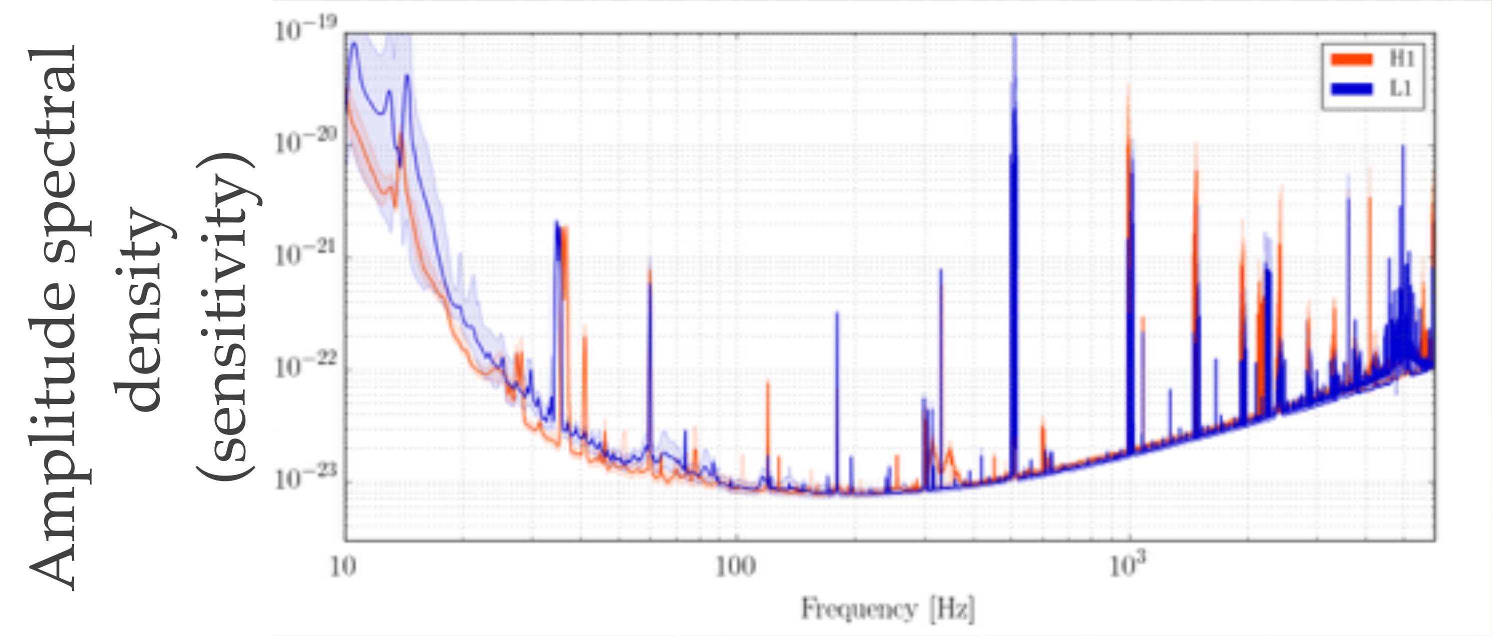
# Principles of GW detection



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

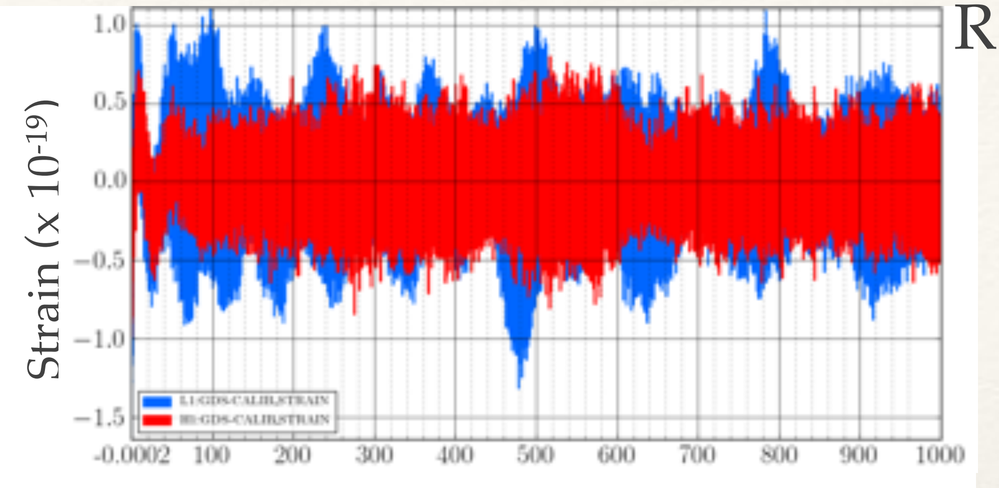
GW strain

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



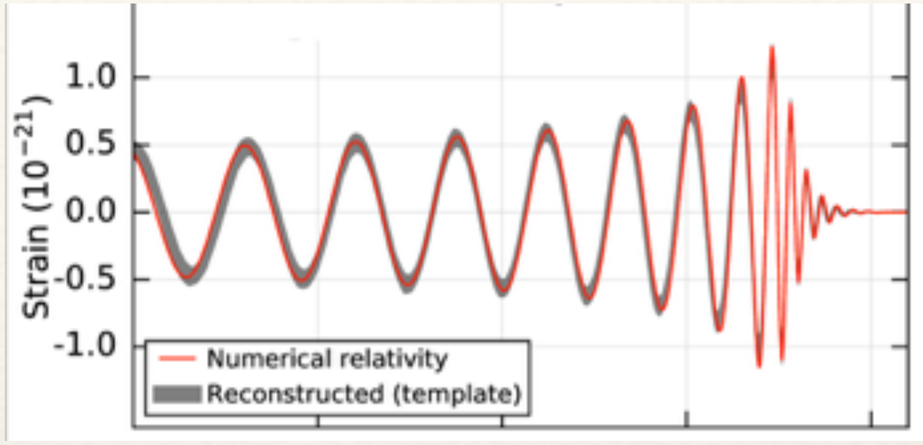
# Matched filtering

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).

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

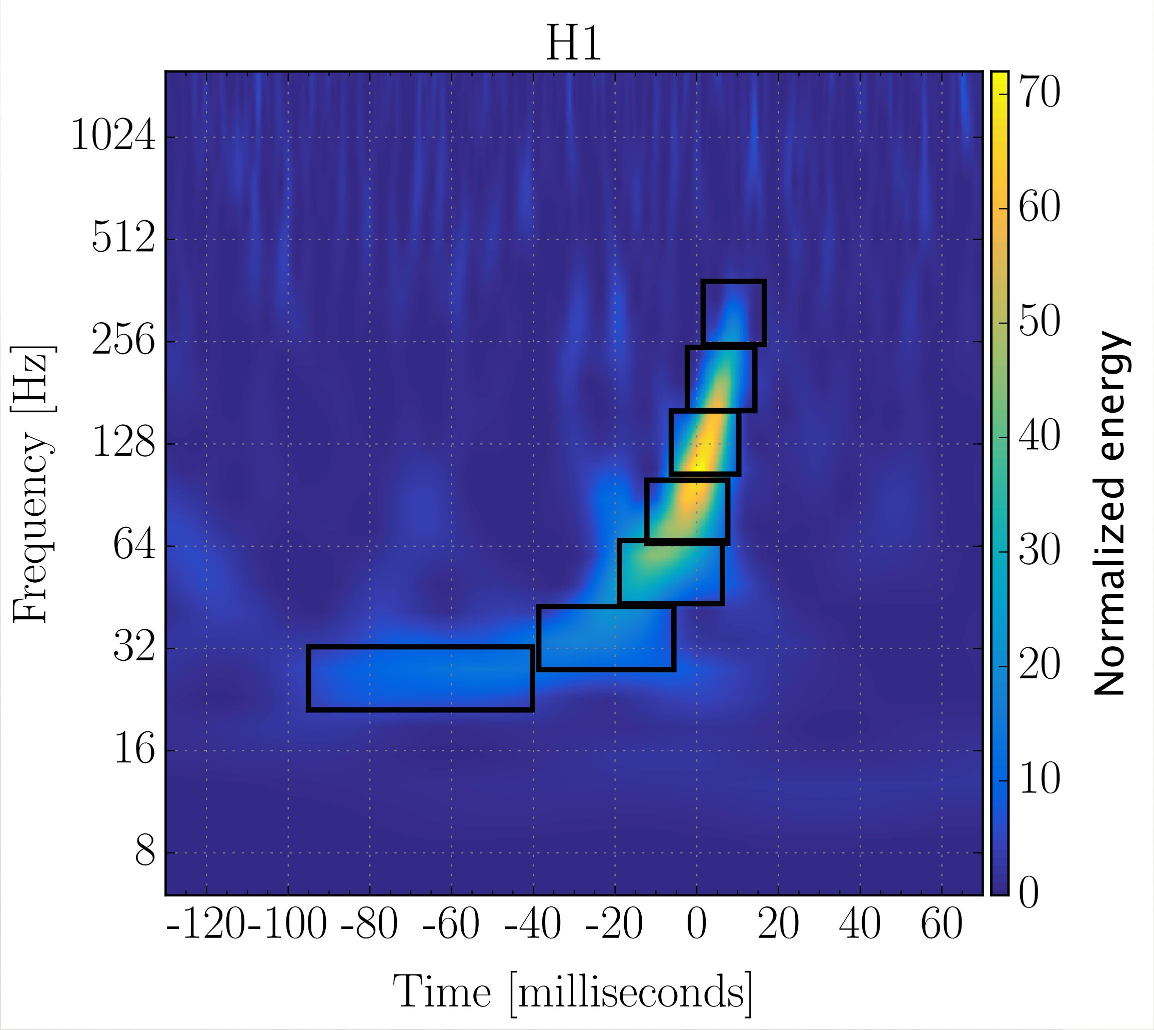
Signal-to-noise ratio

Likelihood

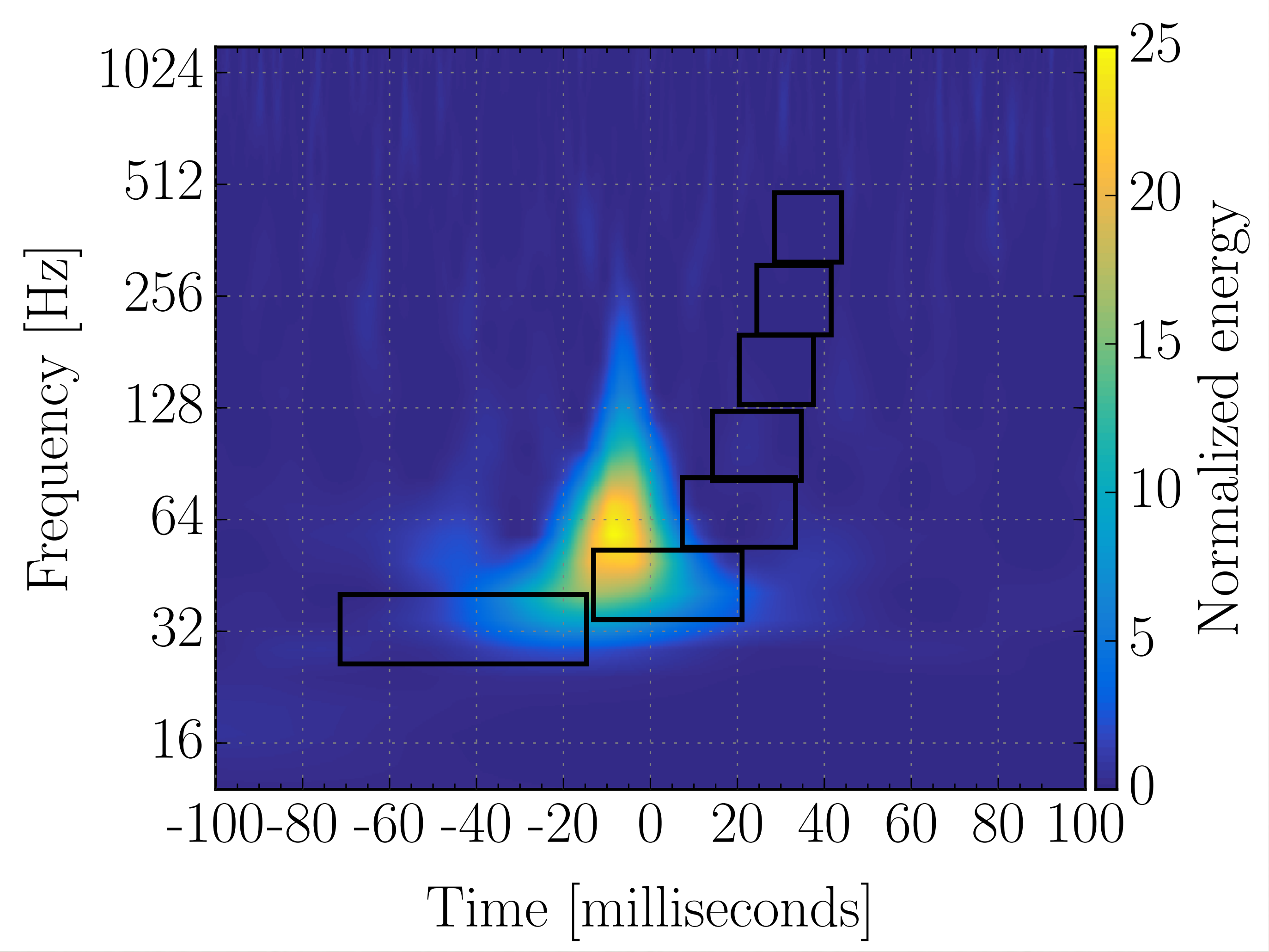
$$\mathcal{L}(\vec{d}|\vec{\vartheta}) \propto \exp\left[\frac{1}{2}\sum_{k=1,2}\left\langle h_k(\vec{\vartheta}) - d_k | h_k(\vec{\vartheta}) - d_k\right\rangle\right]$$

# Consistency check

Real signal



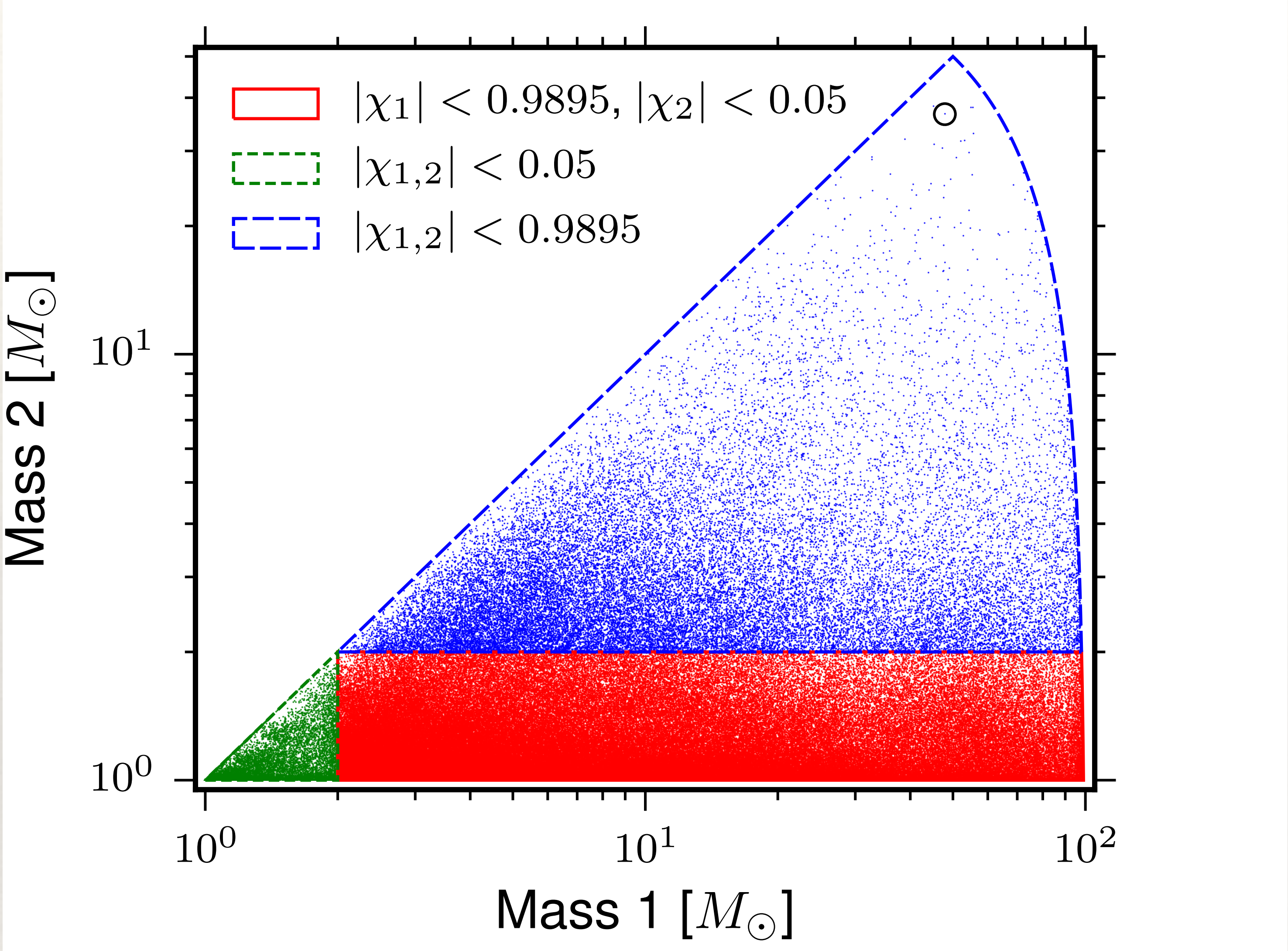
Instrumental artifact



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

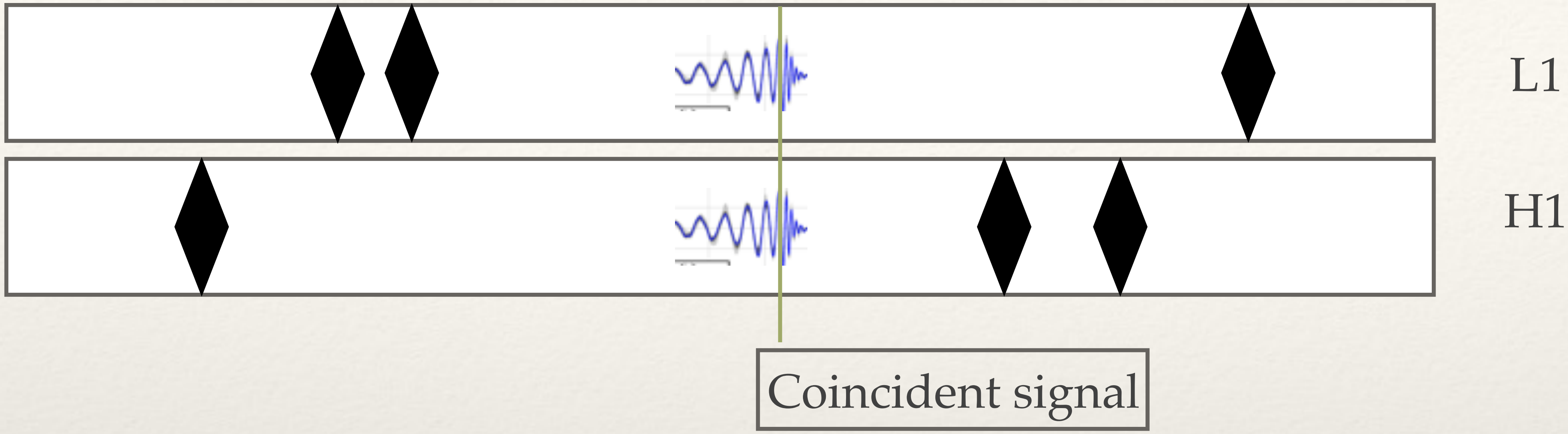


- We don't know apriori parameters of the system
- We construct the bank of templates: we populate the parameter space: uniform taking into accounts the correlation between templates ("volume of each template")
- We filter the data through each template to see which fits the best
- We have used SEOBNR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

LVC: arXiv:1602.03839

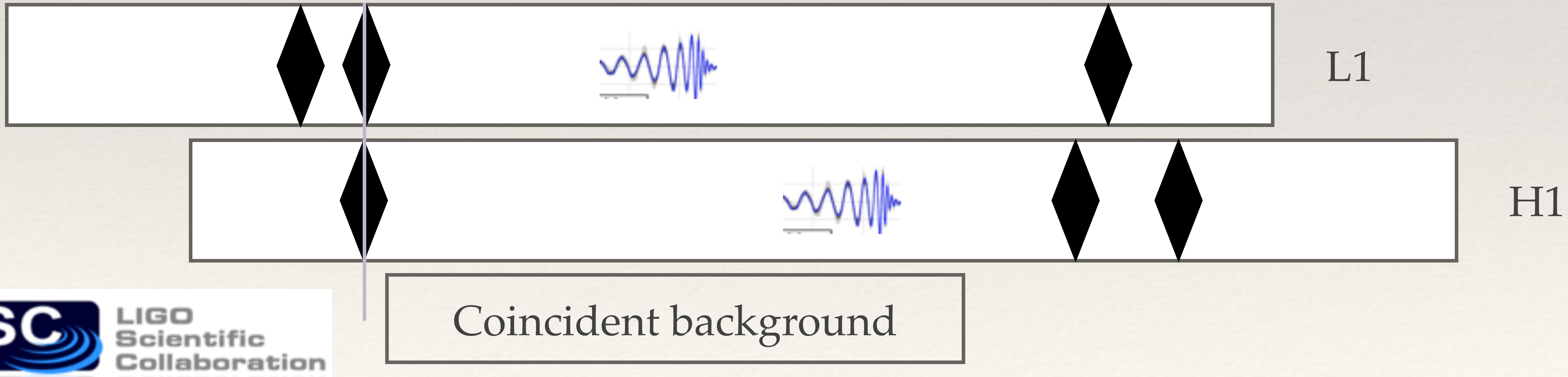
# Significance estimation

**“Zero lag”**



Coincident signal

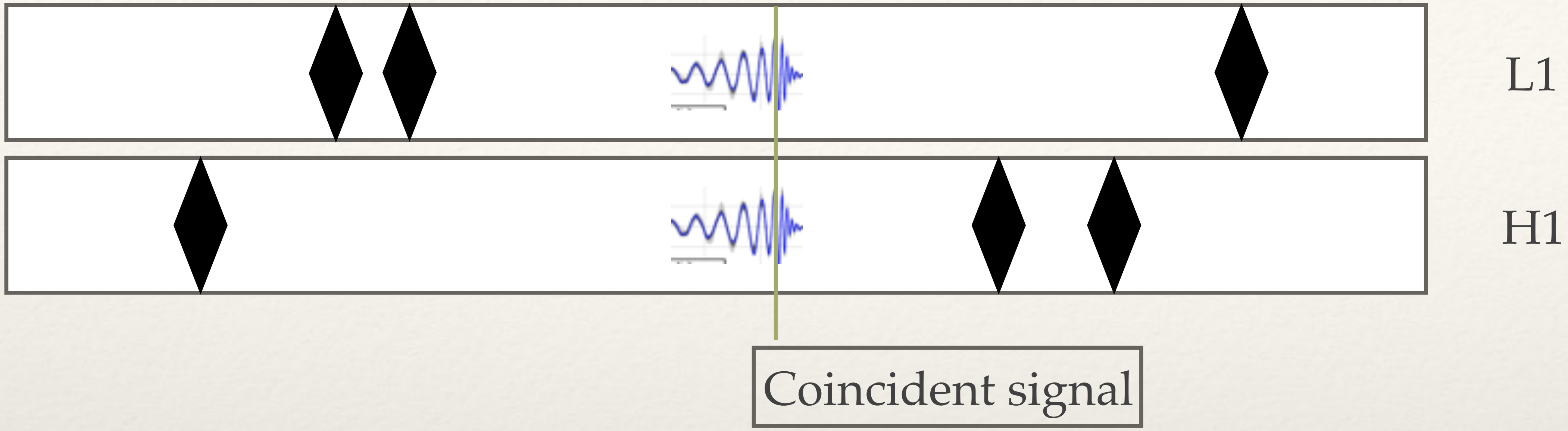
**Time shift > light travel time**



Coincident background

# Significance estimation

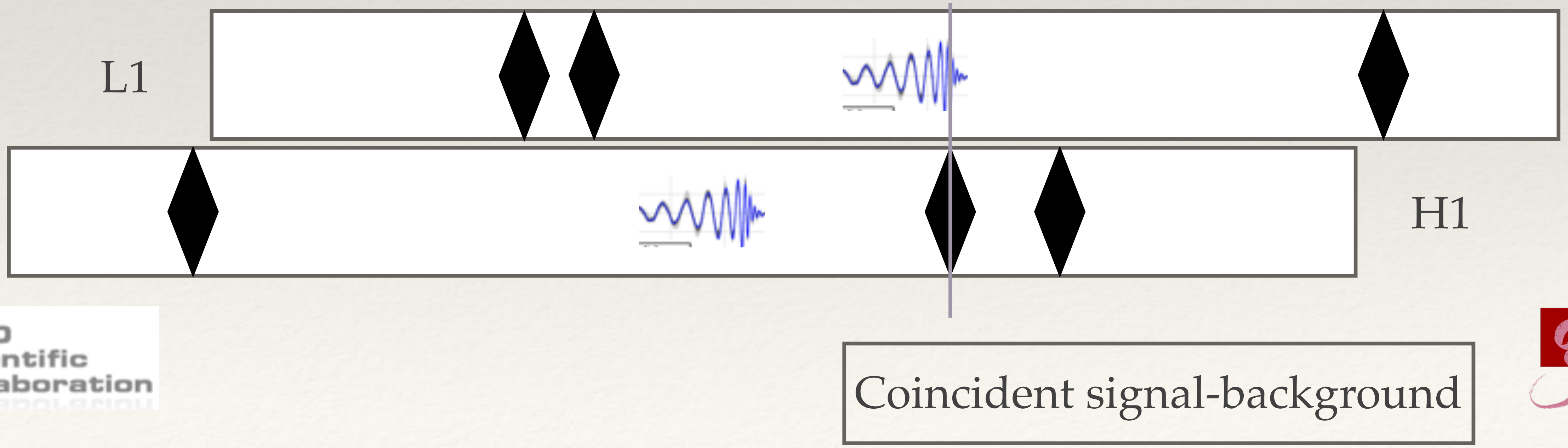
**“Zero lag”**


L1

H1

Coincident signal

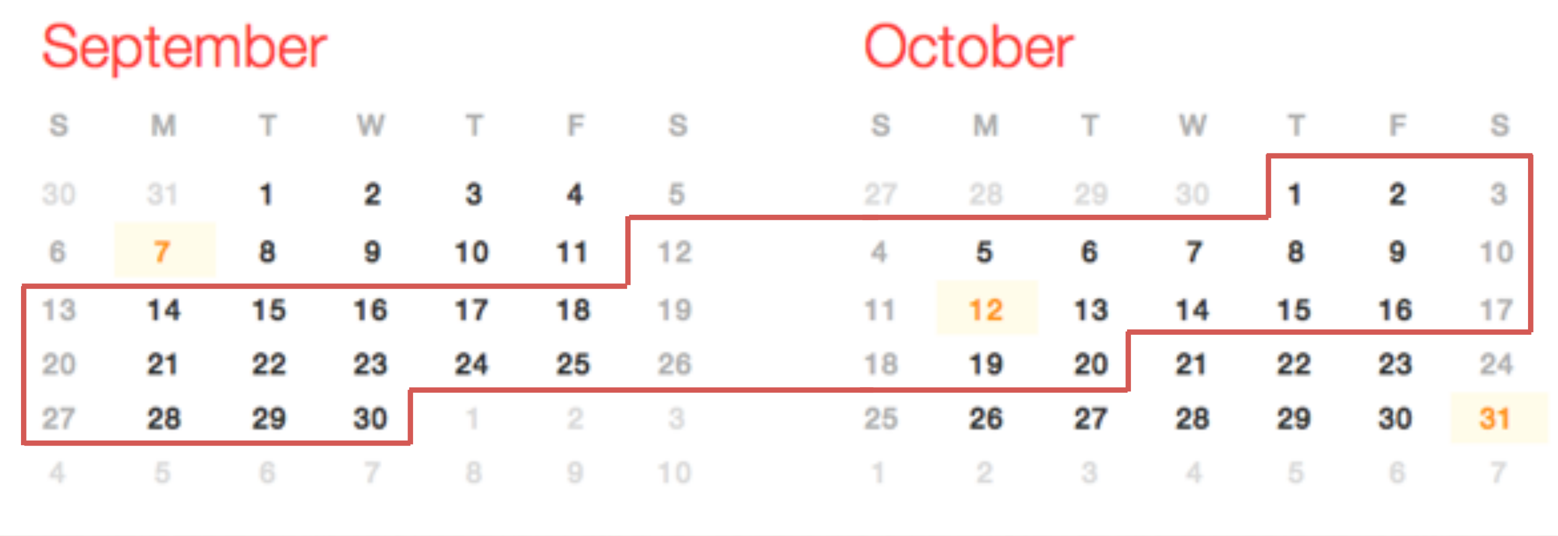
**Time shift > light travel time**


L1

H1

Coincident signal-background

# Observation



September

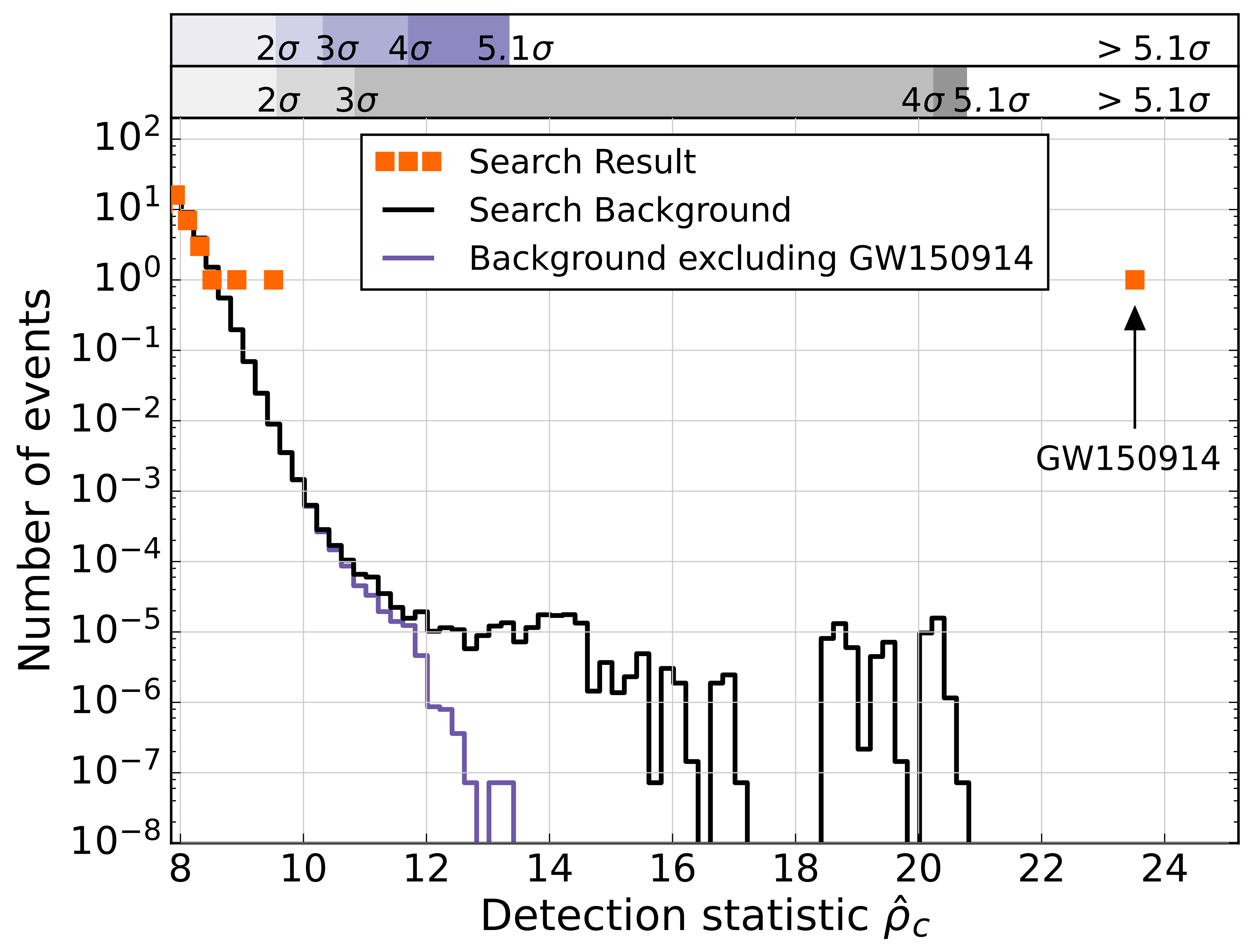
| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| 30 | 31 | 1 | 2 | 3 | 4 | 5 |
| 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| 27 | 28 | 29 | 30 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |

October

| S | M | T | W | T | F | S |
|---|---|---|---|---|---|---|
| 27 | 28 | 29 | 30 | 1 | 2 | 3 |
| 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

- Used 38.6 days of calendar data, which gives 18.4 days of coincident data (coincident lifetime ~48%)
- 20.7 hours of this data were contaminated by known instrumental issues - left 17.5 days of data

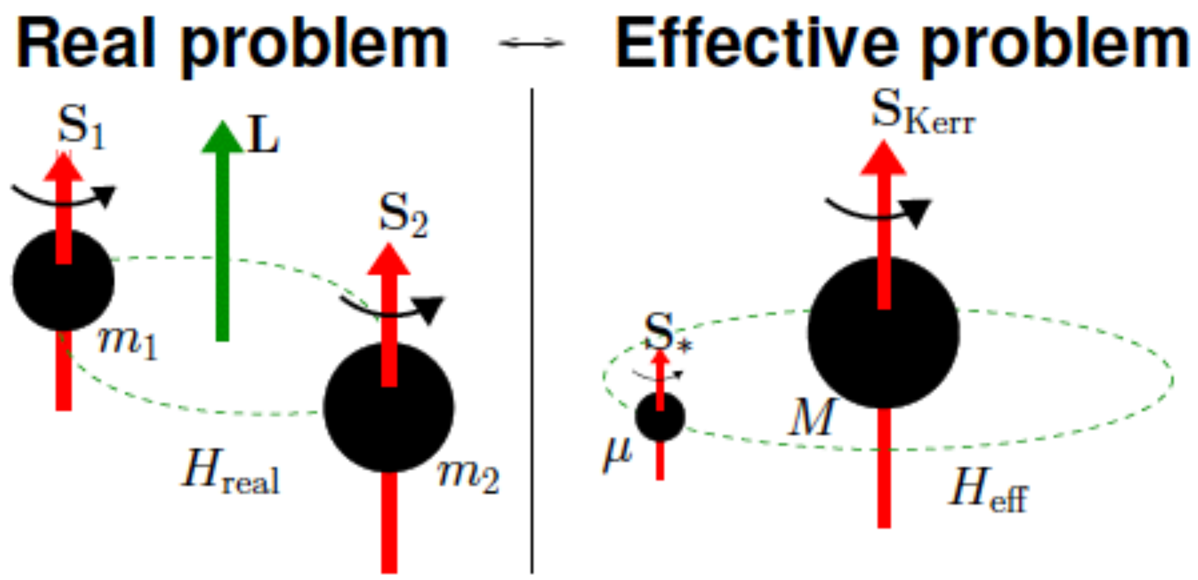
# Statistical significance



LVC: arXiv:1602.03839

# Signal modelling (EOB)

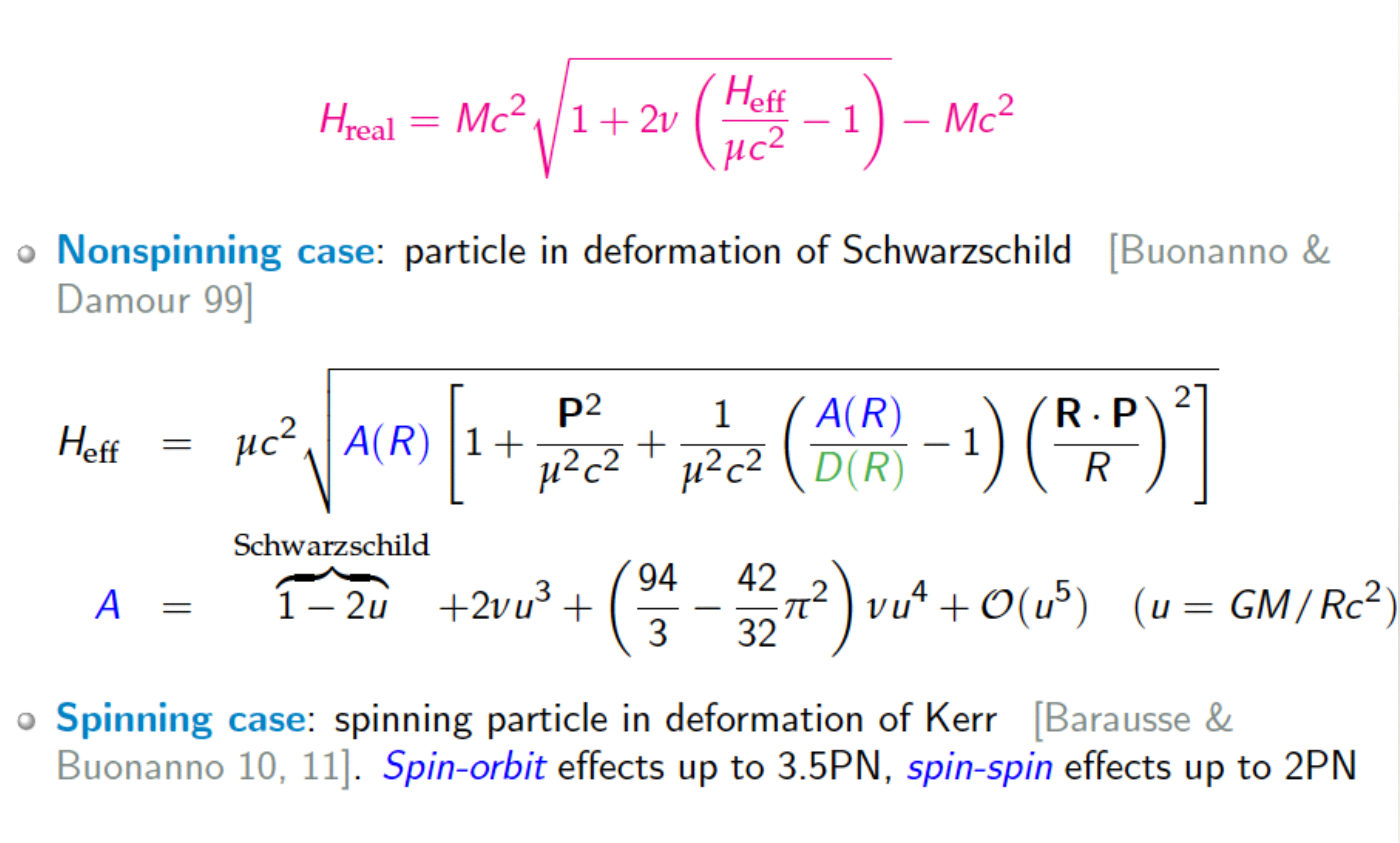
- **Effective-one-body (EOB) model** [Buonanno & Damour 99] describes the GR 2-body problem via
  - effective 1-body Hamiltonian (**spinning particle** in **deformed Kerr**)
  - radiation-reaction force
  - analytic inspiral-merger-ringdown waveforms $h_{\ell m}$



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

- 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)



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

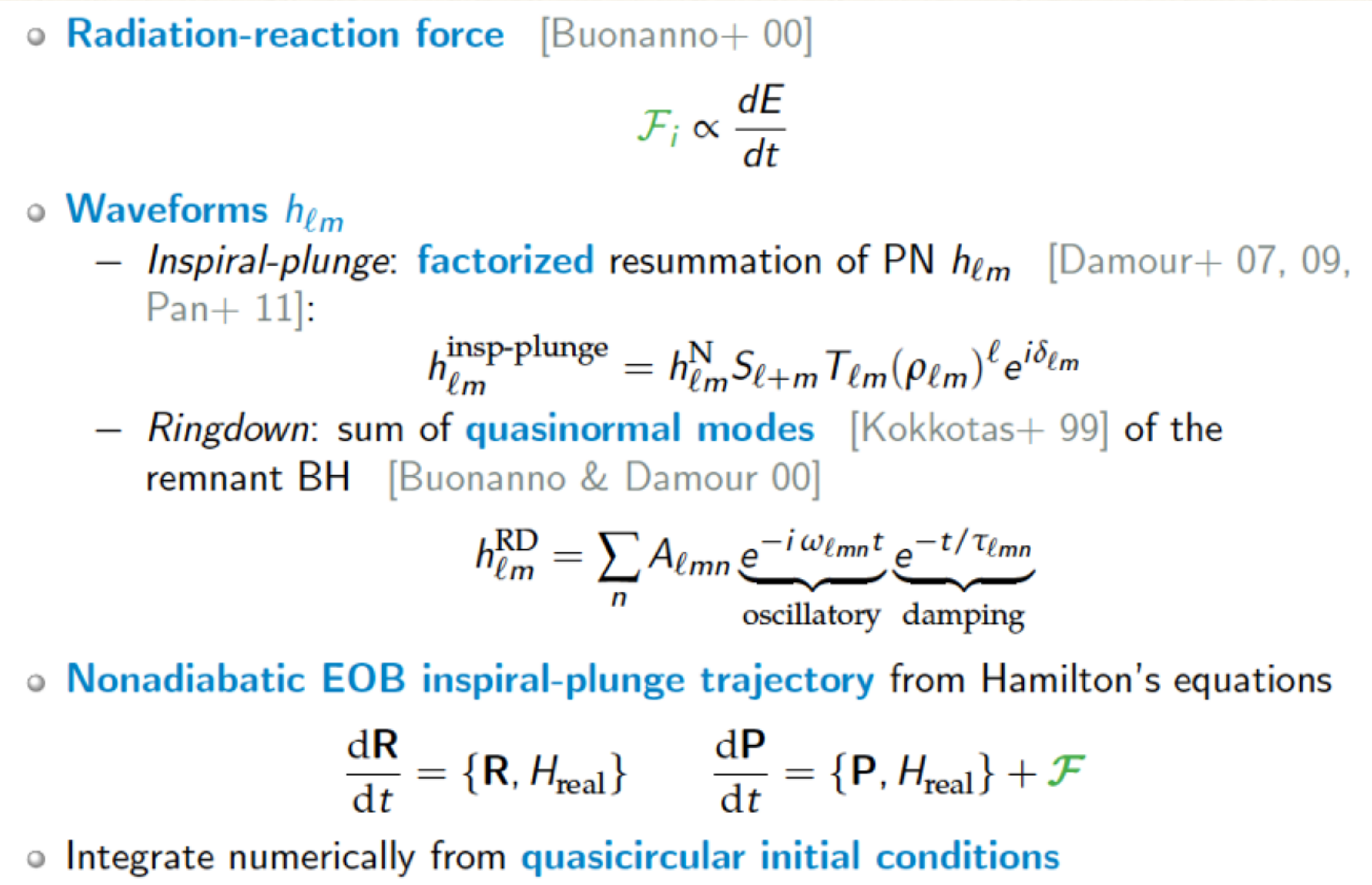
- **Nonspinning case**: particle in deformation of Schwarzschild [Buonanno & Damour 99]

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

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

- **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]

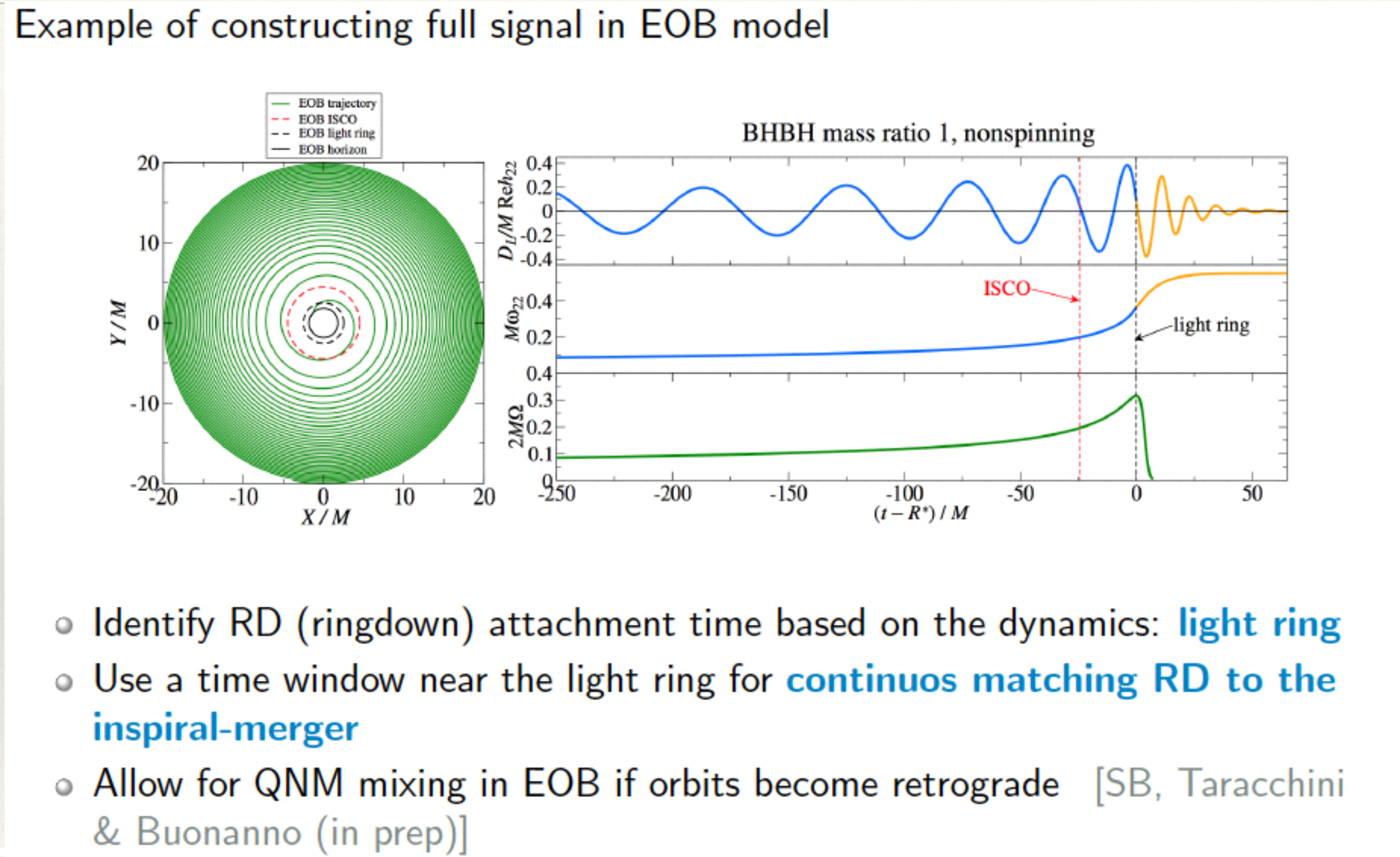
$$h_{\ell m}^{\text{RD}} = \sum_n A_{\ell mn} \underbrace{e^{-i\,\omega_{\ell mn} t}}_{\text{oscillatory}} \underbrace{e^{-t/\tau_{\ell mn}}}_{\text{damping}}$$

- **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)

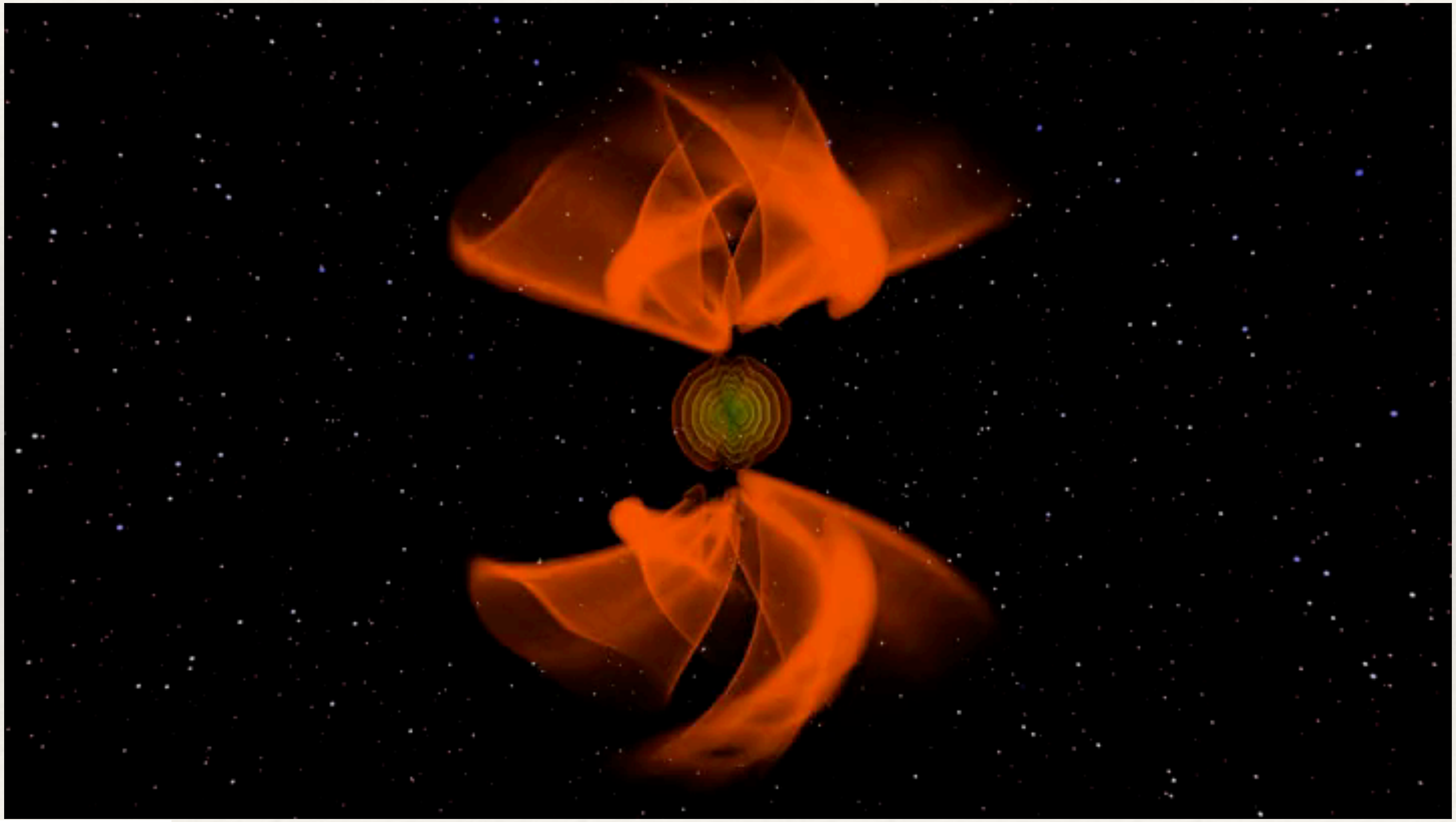


Example of constructing full signal in EOB model

- 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)]

# Numerical Relativity

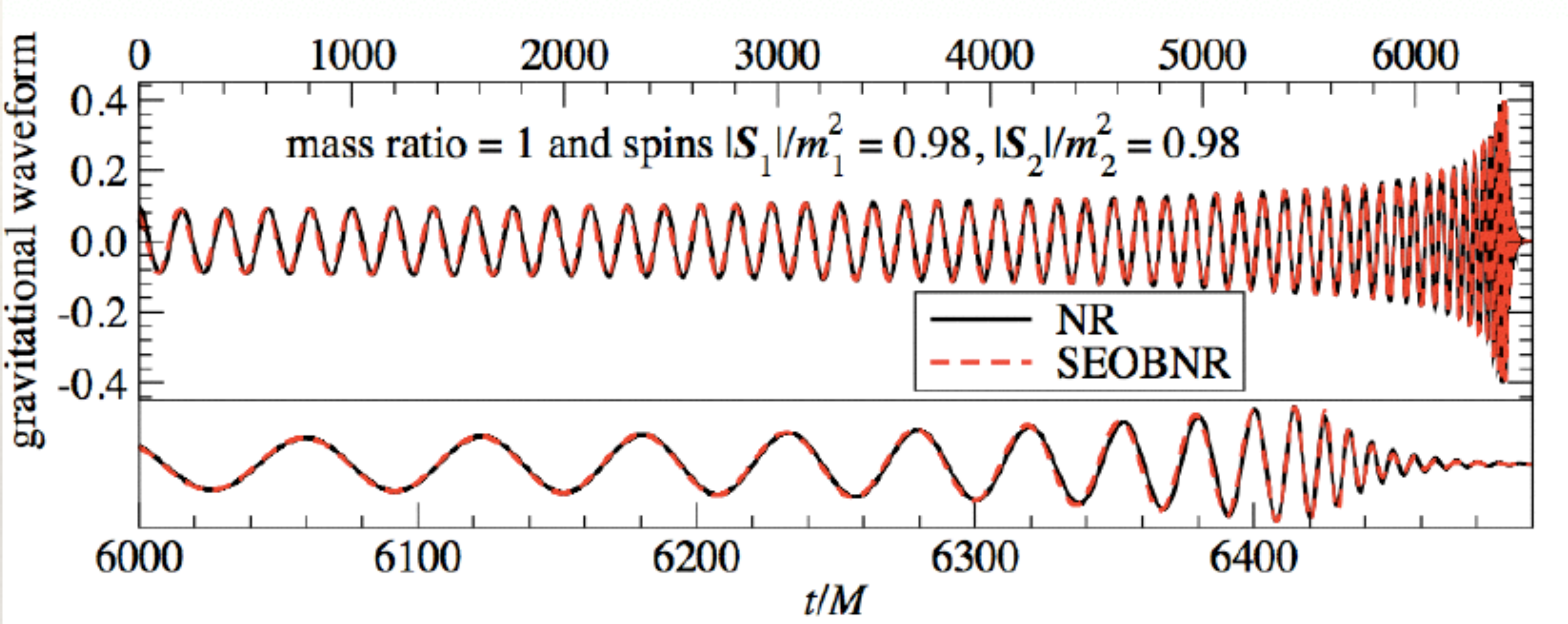
Solving Einstein equations "exactly" numerically: computationally very demanding
rather limited number of waveforms can be generated and they are short



NR simulations (AEI/SXS)

# EOB - NR comparison

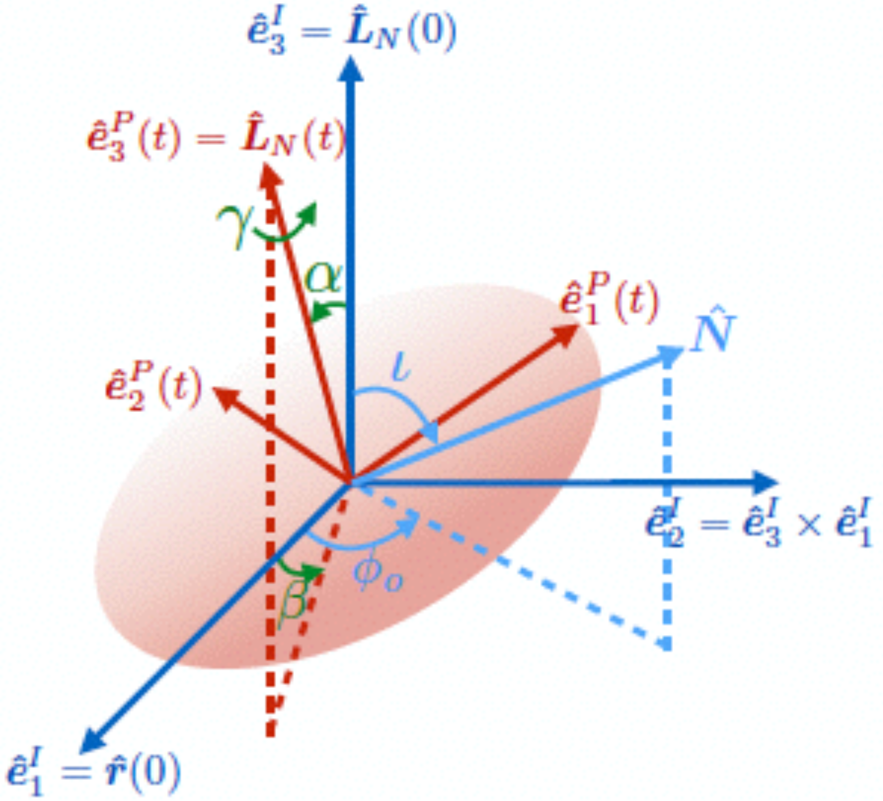
EOB waveform, spins are aligned with the orbital momentum

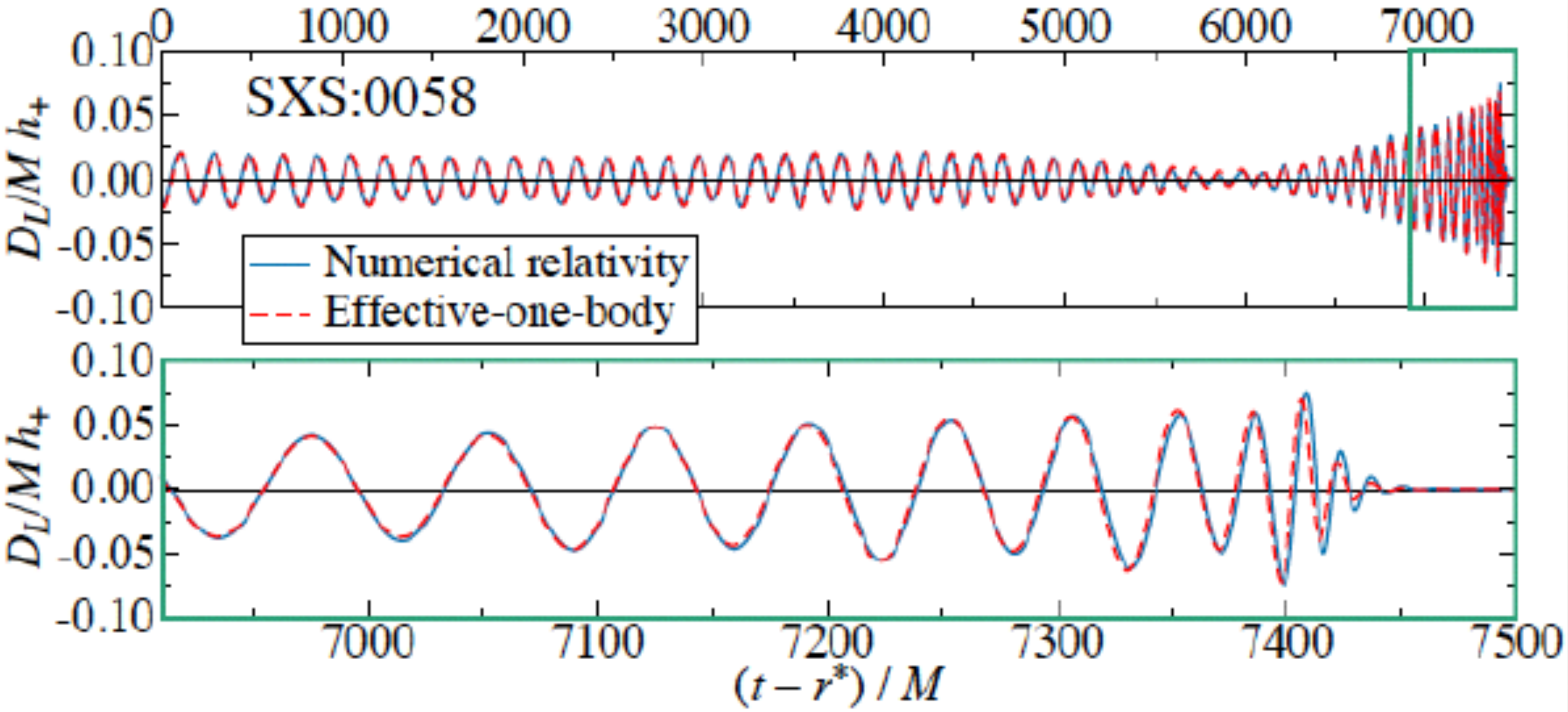


Taracchini et. al. 2013

# Precessing BH binary (EOB)

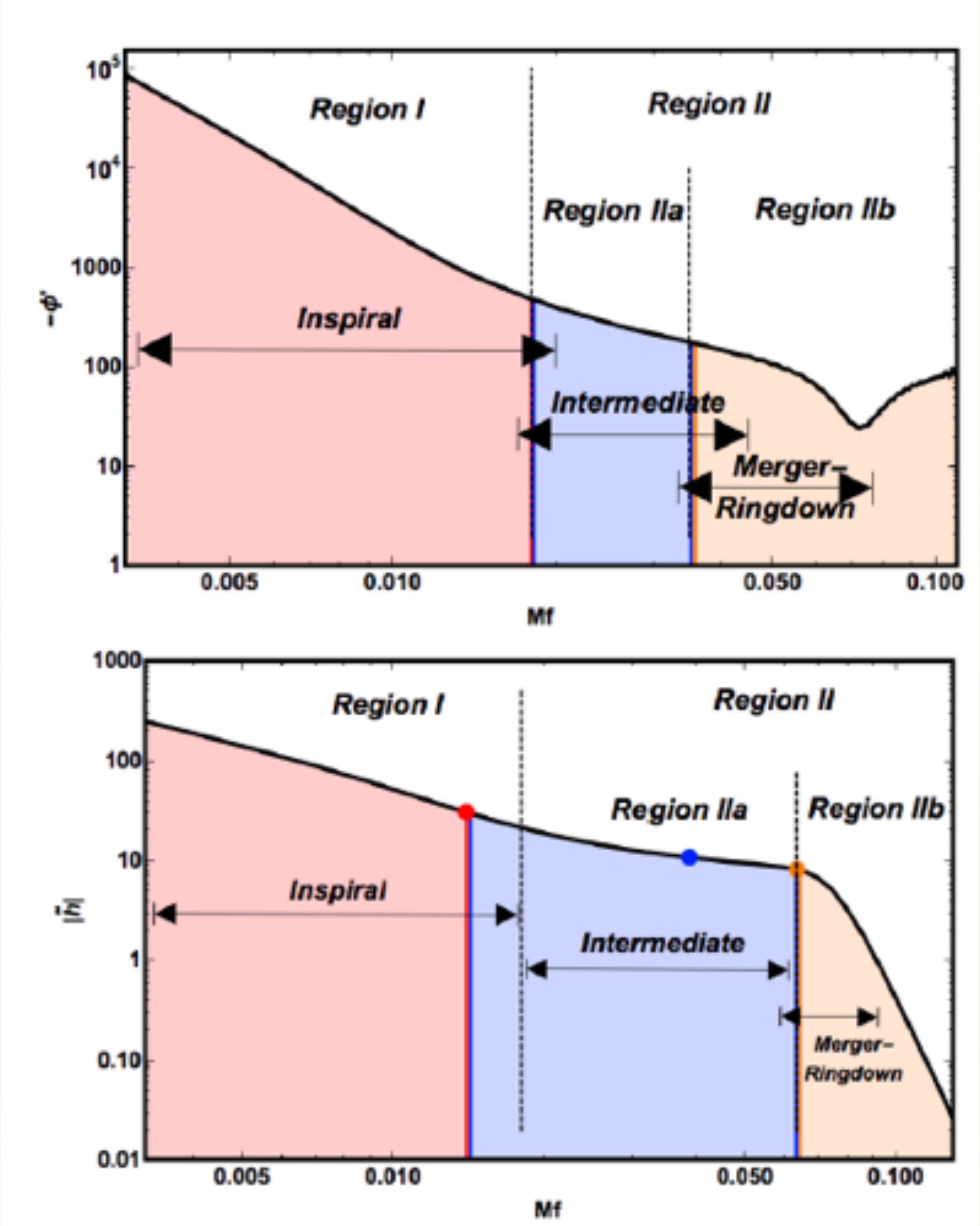
- Model precessing-frame waveforms with **calibrated IMR nonprecessing models**. **No recalibration** of inspiral of underlying nonprecessing models [Pan+13, Babak+(in prep)]



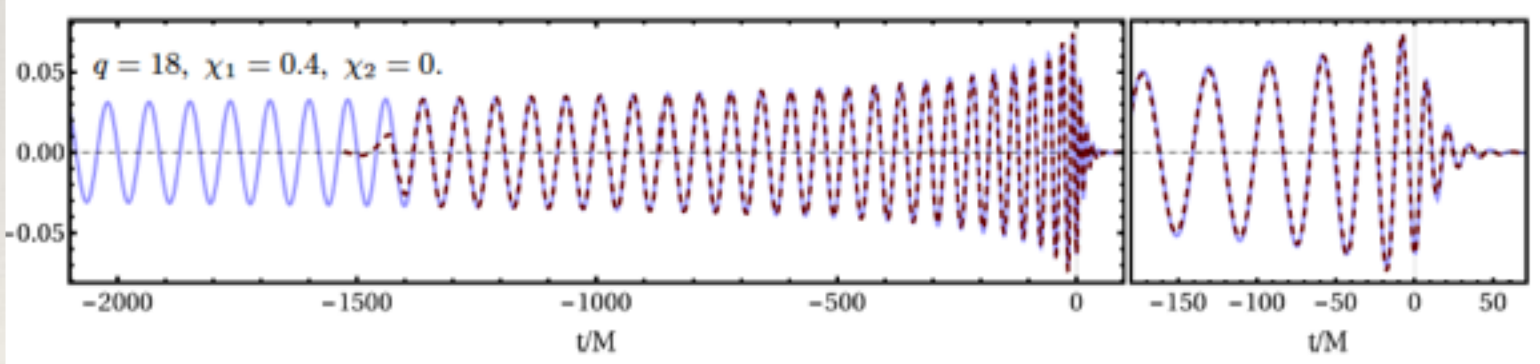


- **70 NR simulations** [SXS13] w/ mass ratios b/w 1 and 5, spins magnitudes up to 0.5, generic orientations [Babak+(in prep)]

# IMRPhenomP



- Waveform constructed in the frequency domain
- Uses Post-Newtonian results for the early evolution (inspiral) of a binary (EOB)
- 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



Khan et.al. 2015

# Basic parameters of the BH binary

Distance: 440 Mpc (z=0.09)

m1 = 39, m2 = 30 , remnant mass = 67 mass ratio ~ 0.8

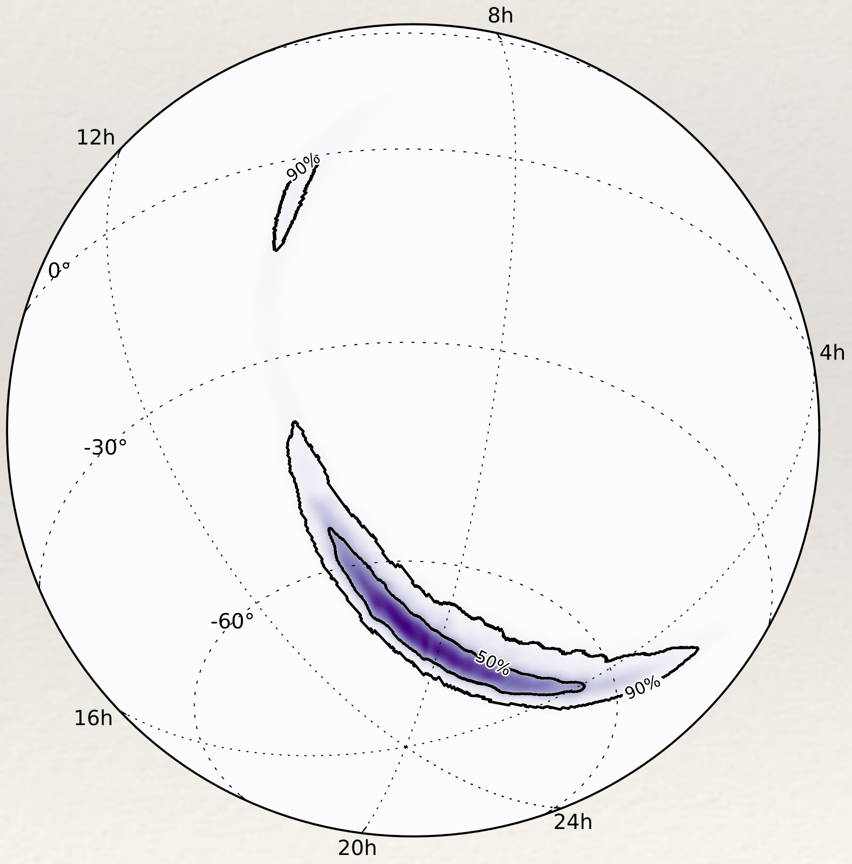
Position: face-off, south hemisphere , 600 sq.deg.

Duration (from 30Hz), ~200ms, ~10 cycles Peak amplitude freq.: 150 Hz

QNM frequency: 250 Hz, damping time: 4 ms

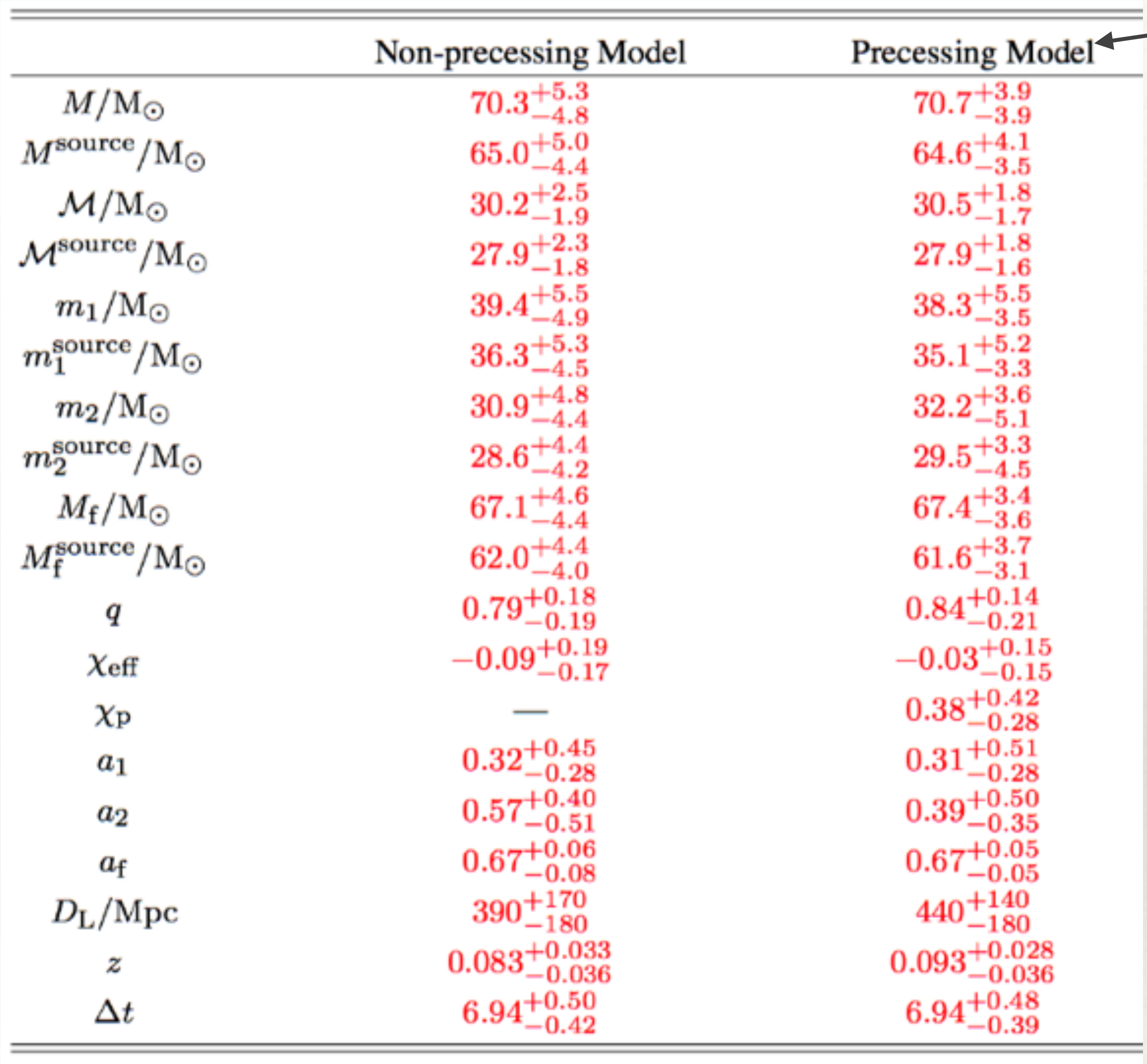
Radiated energy: 2.25 M (between 30 and 240 Hz)

Peak luminosity: 3.6 x $10^{56}$ erg $s^{-1}$



LIGO Scientific Collaboration

# Recovered parameters of the binary



| | Non-precessing Model | Precessing Model |
|---|---|---|
| $M/\mathrm{M}_\odot$ | $70.3^{+5.3}_{-4.8}$ | $70.7^{+3.9}_{-3.9}$ |
| $M^{\mathrm{source}}/\mathrm{M}_\odot$ | $65.0^{+5.0}_{-4.4}$ | $64.6^{+4.1}_{-3.5}$ |
| $\mathcal{M}/\mathrm{M}_\odot$ | $30.2^{+2.5}_{-1.9}$ | $30.5^{+1.8}_{-1.7}$ |
| $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$ | $27.9^{+2.3}_{-1.8}$ | $27.9^{+1.8}_{-1.6}$ |
| $m_1/\mathrm{M}_\odot$ | $39.4^{+5.5}_{-4.9}$ | $38.3^{+5.5}_{-3.5}$ |
| $m_1^{\mathrm{source}}/\mathrm{M}_\odot$ | $36.3^{+5.3}_{-4.5}$ | $35.1^{+5.2}_{-3.3}$ |
| $m_2/\mathrm{M}_\odot$ | $30.9^{+4.8}_{-4.4}$ | $32.2^{+3.6}_{-5.1}$ |
| $m_2^{\mathrm{source}}/\mathrm{M}_\odot$ | $28.6^{+4.4}_{-4.2}$ | $29.5^{+3.3}_{-4.5}$ |
| $M_{\mathrm{f}}/\mathrm{M}_\odot$ | $67.1^{+4.6}_{-4.4}$ | $67.4^{+3.4}_{-3.6}$ |
| $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$ | $62.0^{+4.4}_{-4.0}$ | $61.6^{+3.7}_{-3.1}$ |
| $q$ | $0.79^{+0.18}_{-0.19}$ | $0.84^{+0.14}_{-0.21}$ |
| $\chi_{\mathrm{eff}}$ | $-0.09^{+0.19}_{-0.17}$ | $-0.03^{+0.15}_{-0.15}$ |
| $\chi_{\mathrm{p}}$ | — | $0.38^{+0.42}_{-0.28}$ |
| $a_1$ | $0.32^{+0.45}_{-0.28}$ | $0.31^{+0.51}_{-0.28}$ |
| $a_2$ | $0.57^{+0.40}_{-0.51}$ | $0.39^{+0.50}_{-0.35}$ |
| $a_{\mathrm{f}}$ | $0.67^{+0.06}_{-0.08}$ | $0.67^{+0.05}_{-0.05}$ |
| $D_{\mathrm{L}}/\mathrm{Mpc}$ | $390^{+170}_{-180}$ | $440^{+140}_{-180}$ |
| $z$ | $0.083^{+0.033}_{-0.036}$ | $0.093^{+0.028}_{-0.036}$ |
| $\Delta t$ | $6.94^{+0.50}_{-0.42}$ | $6.94^{+0.48}_{-0.39}$ |

IMRPhenom

"Combined" spin along orbital angular momentum

$$\chi_{eff} = \left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2}\right)\frac{\hat{\mathbf{L}}}{M}$$

"Combined" spin components in the orbital plane

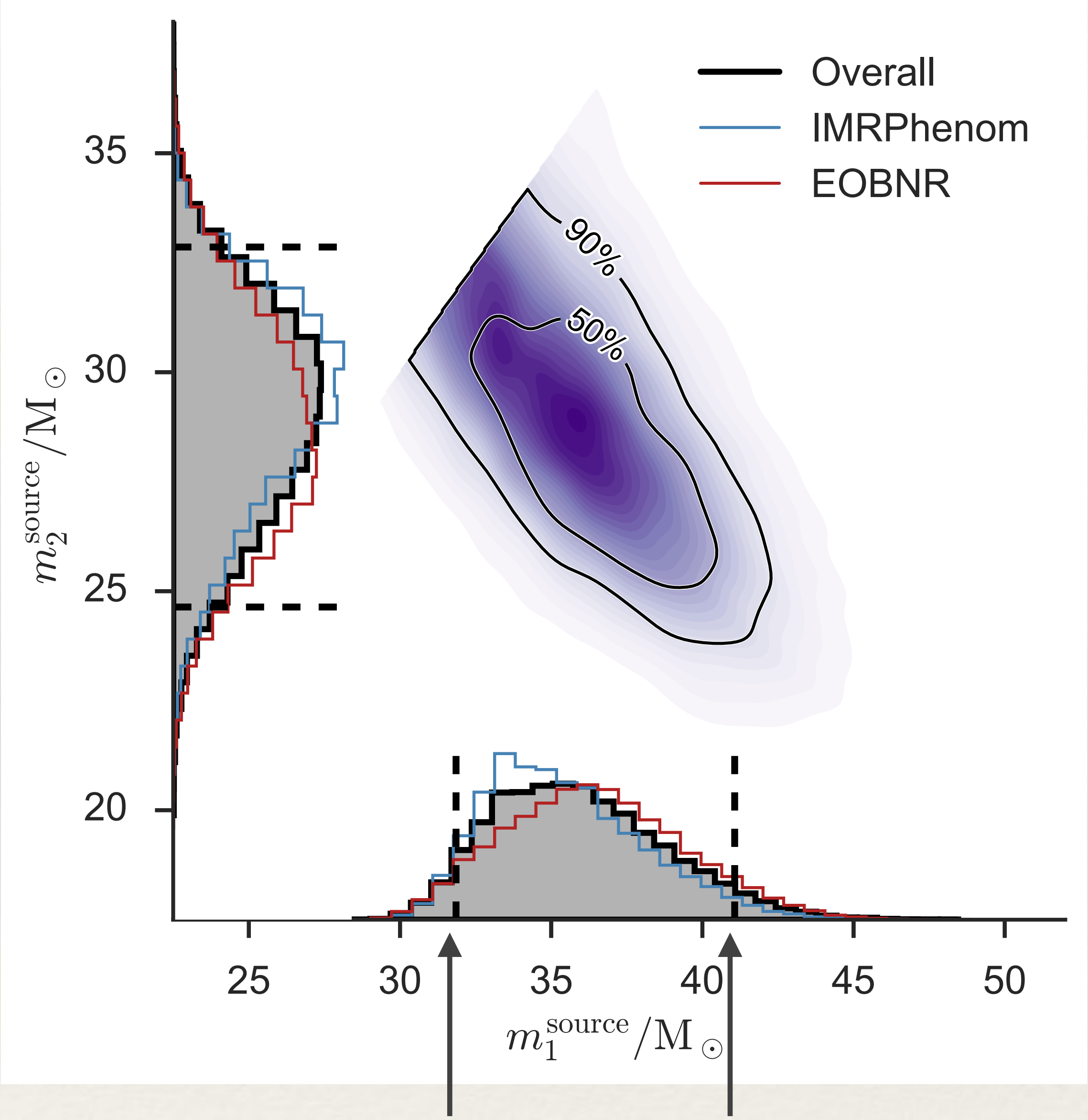
$$\chi_p = \frac{1}{B_1 m_1^2}\max\left(B_1 S_{1\perp}, B_2 S_{2\perp}\right)$$

$$B_1 = 2 + \frac{3m_2}{2m_1}, \quad B_2 = 2 + \frac{3m_1}{2m_2}$$

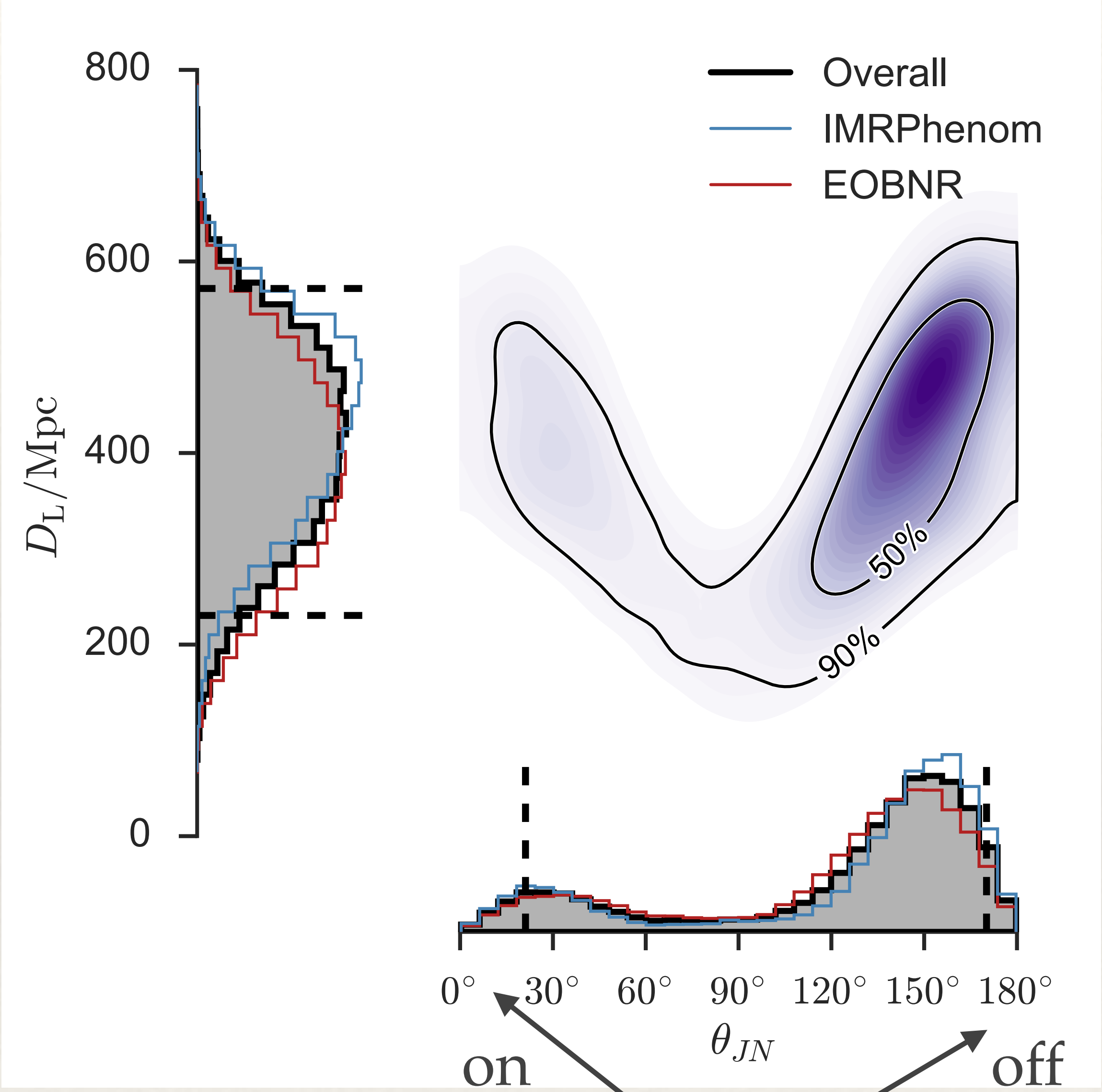
LVC arXiv:1602.03840

# Masses, distance, inclination

Posterior distribution function for masses, distance and orbital inclination: recovered in post-processing analysis using Bayesian techniques.



90% credible interval



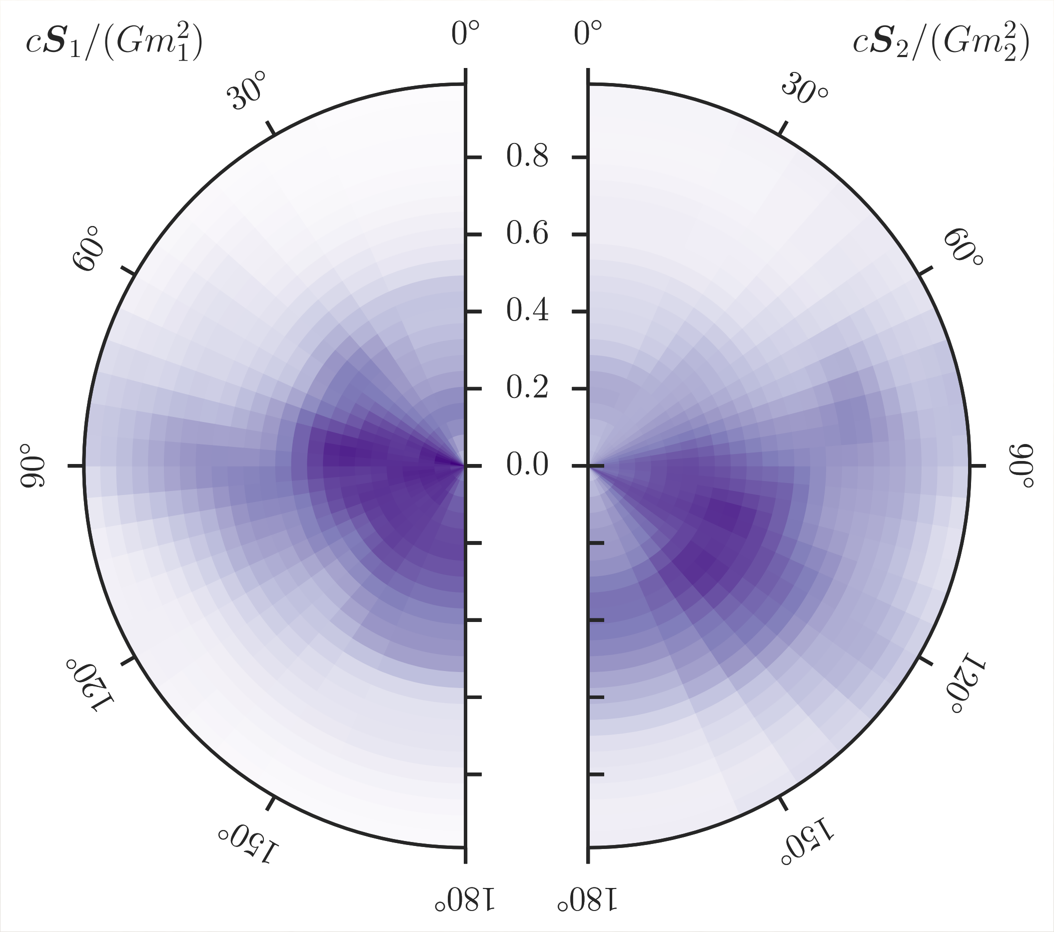
on

off

face

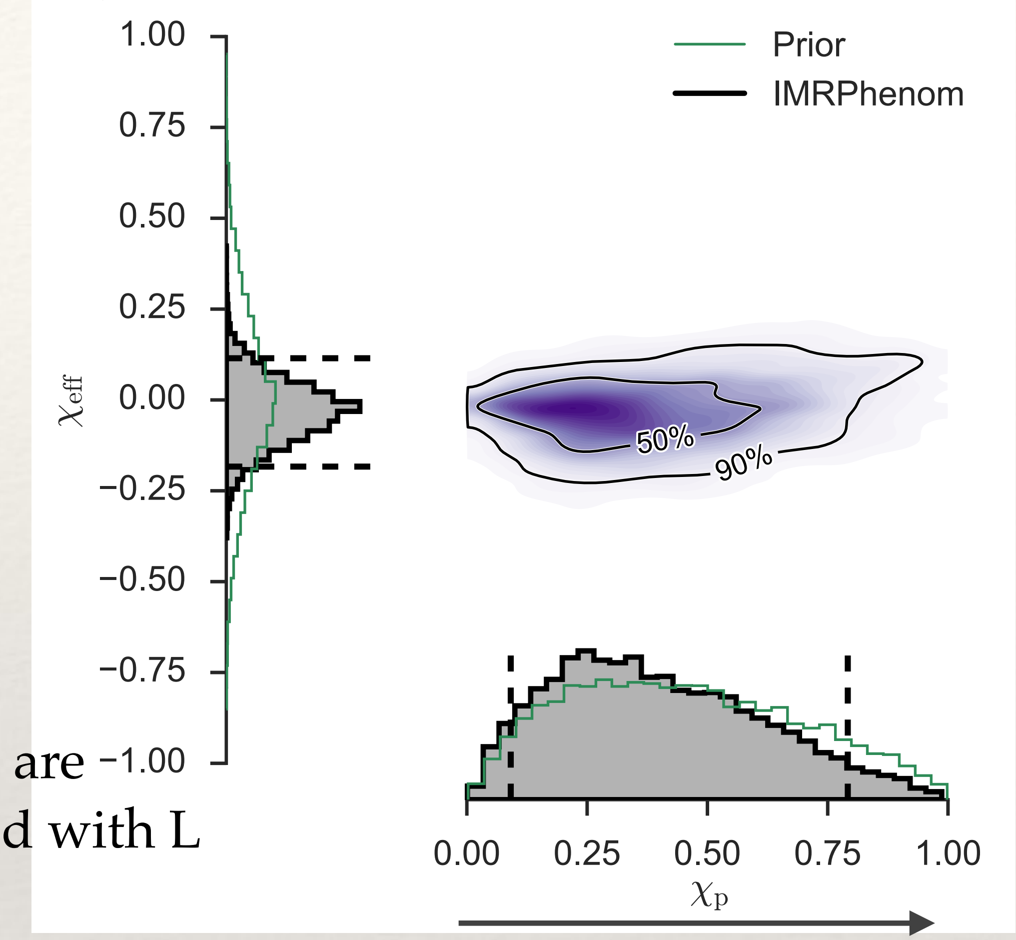
LVC arXiv:1602.03840

# Spins (IMRPhenomP)



Slice orthogonal to the orbital plane

S1, S2 are
aligned with L



S1, S2 are
anti-aligned with L

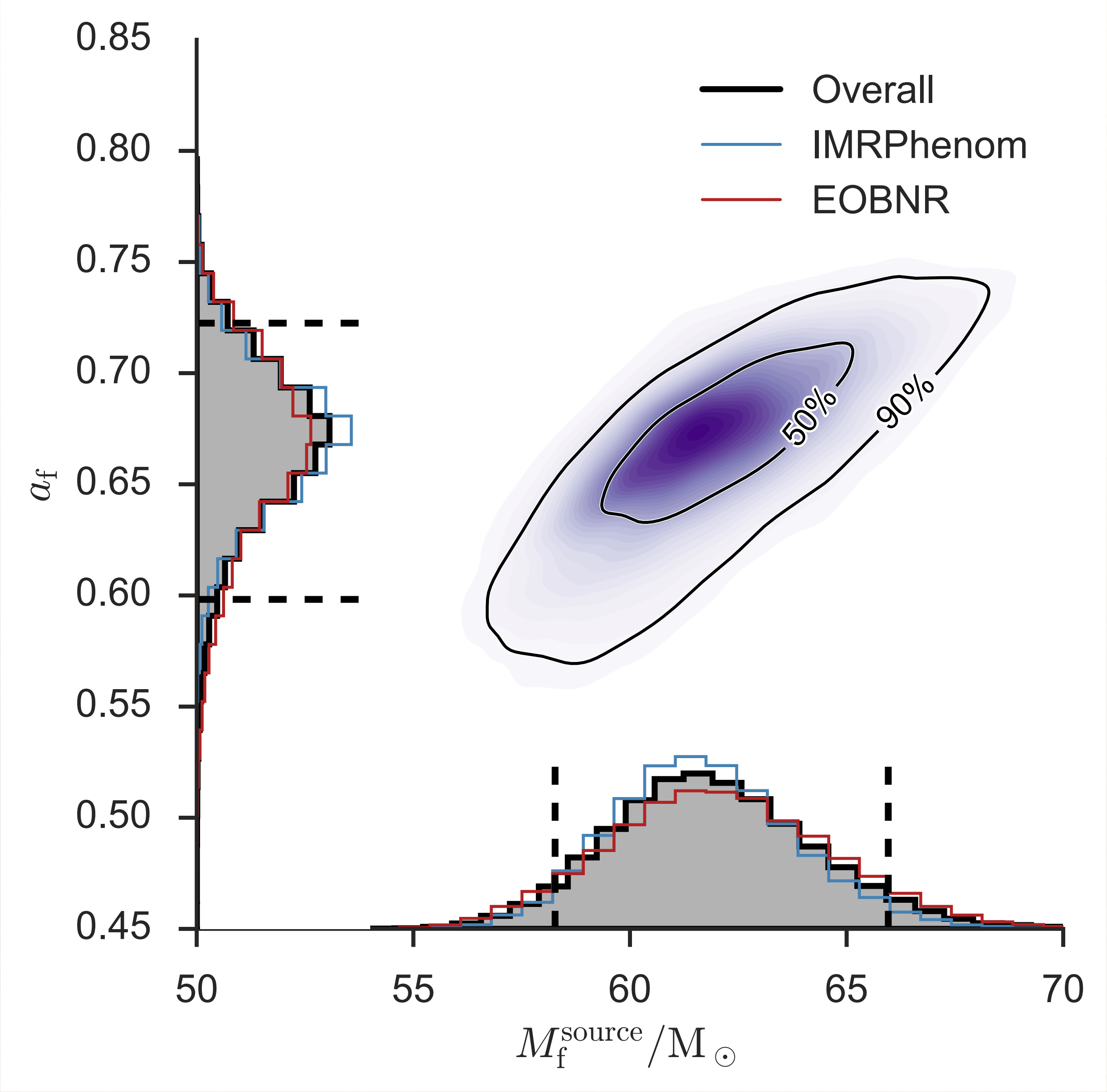
No precession

Strong precession

Posterior distribution as reported by running data analysis with IMRPhenomP waveforms

LVC arXiv:1602.03840

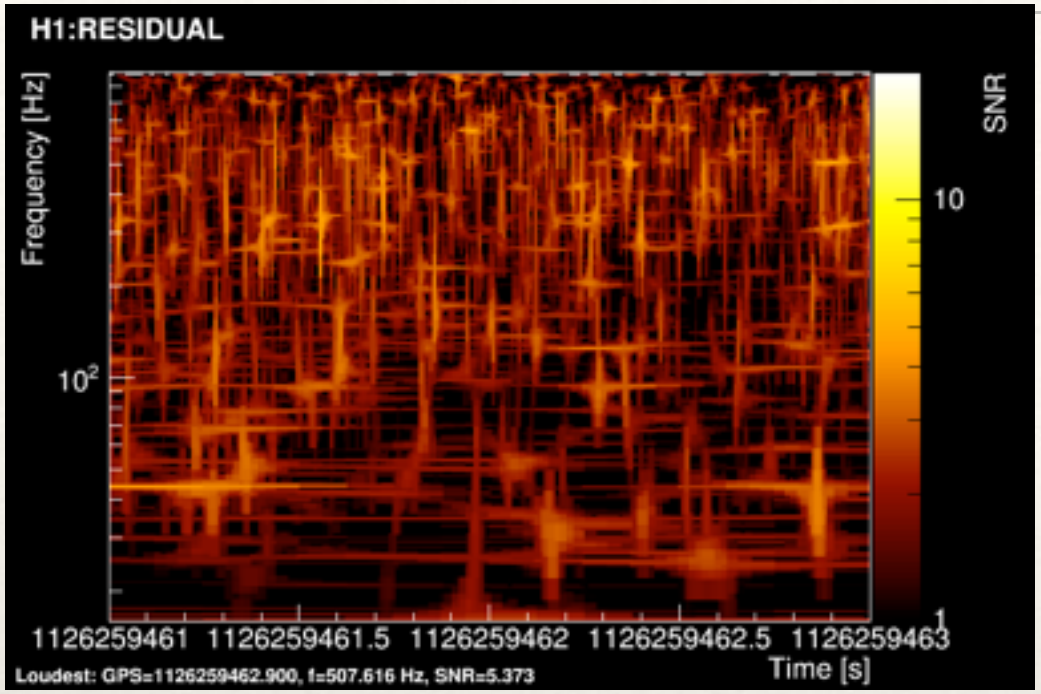
# Remnant BH



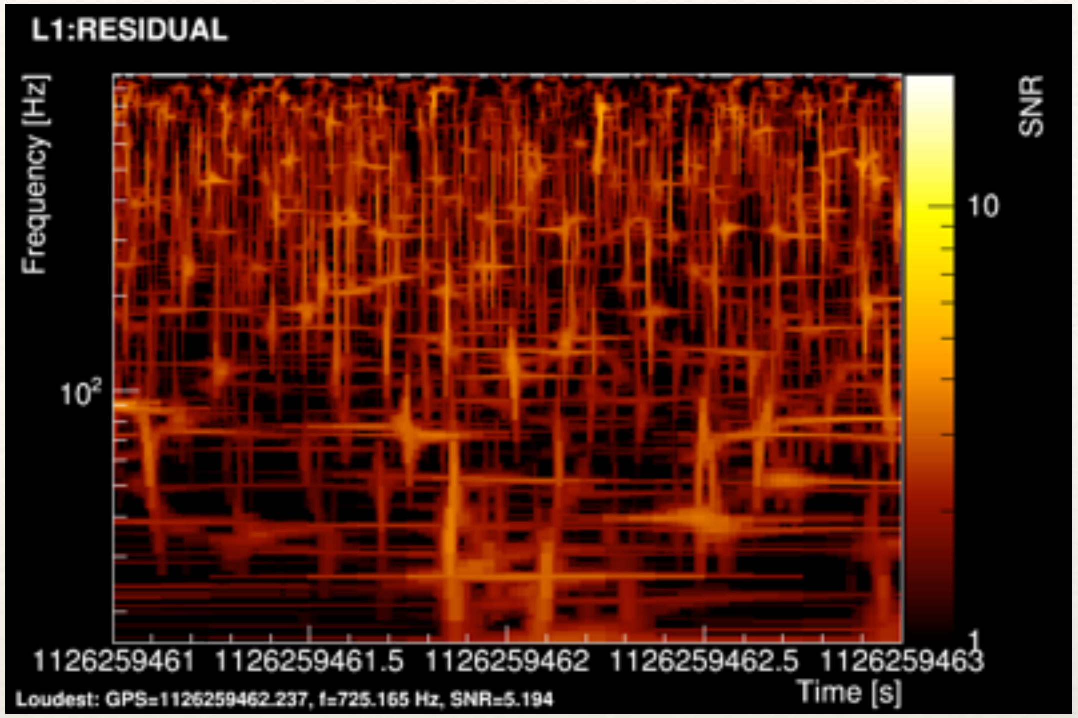
- Parameters of the remnant BH: final spin and mass
- Obtained using the fitting expression calibrated using NR data(Healy et.al. 2014)
- Mass deficit: Radiated energy: 2.25 M between 30 and 240 Hz

LVC arXiv:1602.03840
Healy et al 2014.

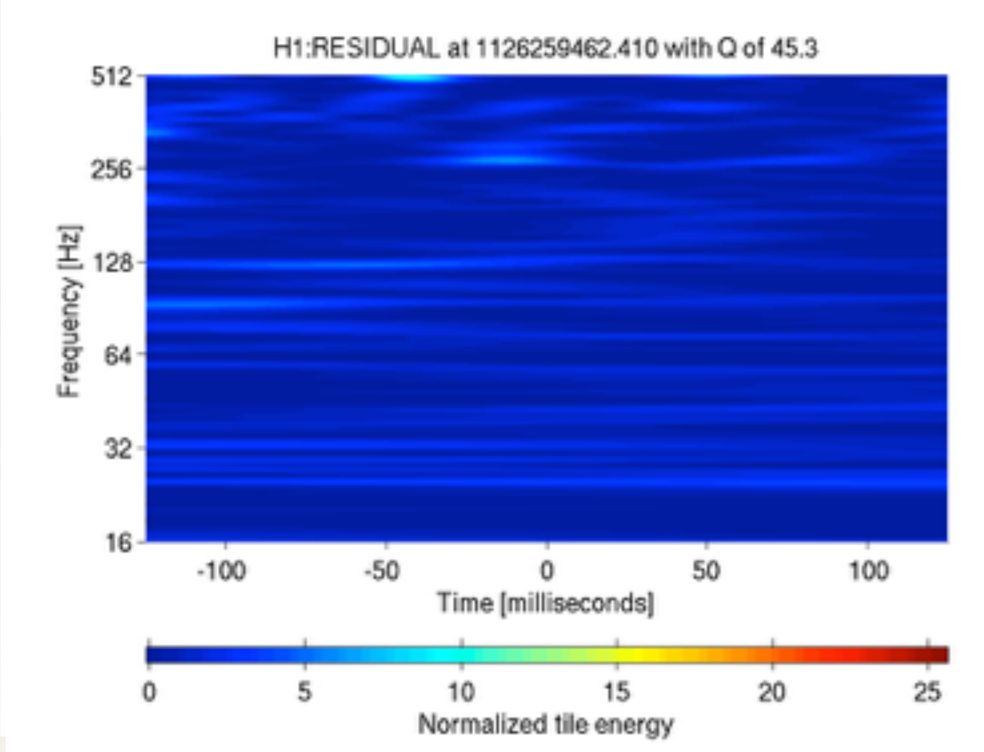
# Consistency with GR (residuals study)

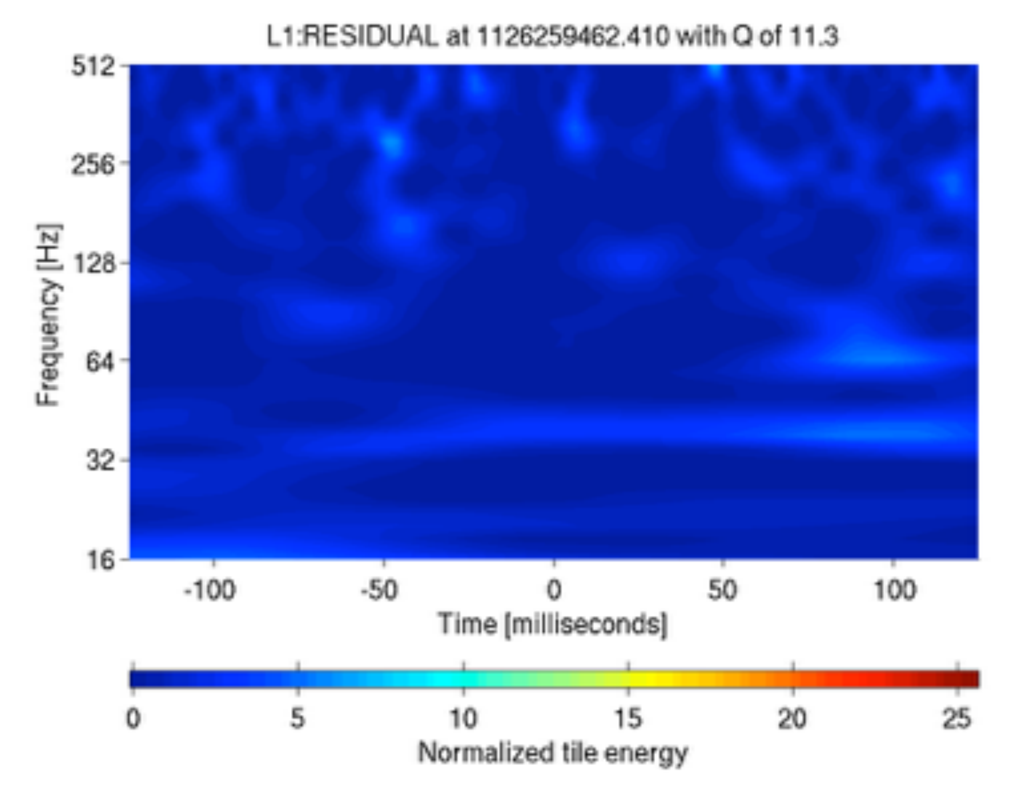

H1:RESIDUAL

Loudest: GPS=1126259462.900, f=507.616 Hz, SNR=5.373


L1:RESIDUAL

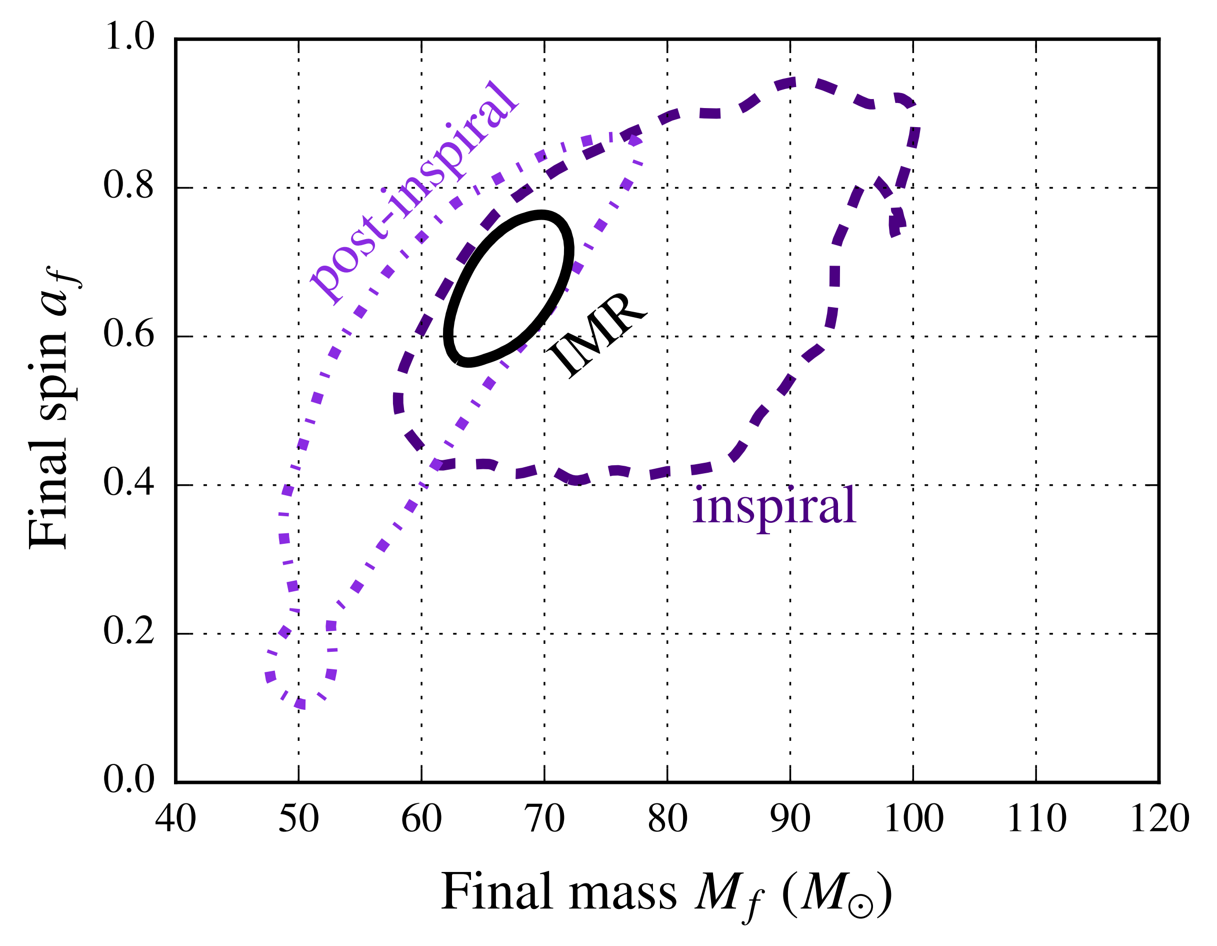
Loudest: GPS=1126259462.237, f=725.165 Hz, SNR=5.194

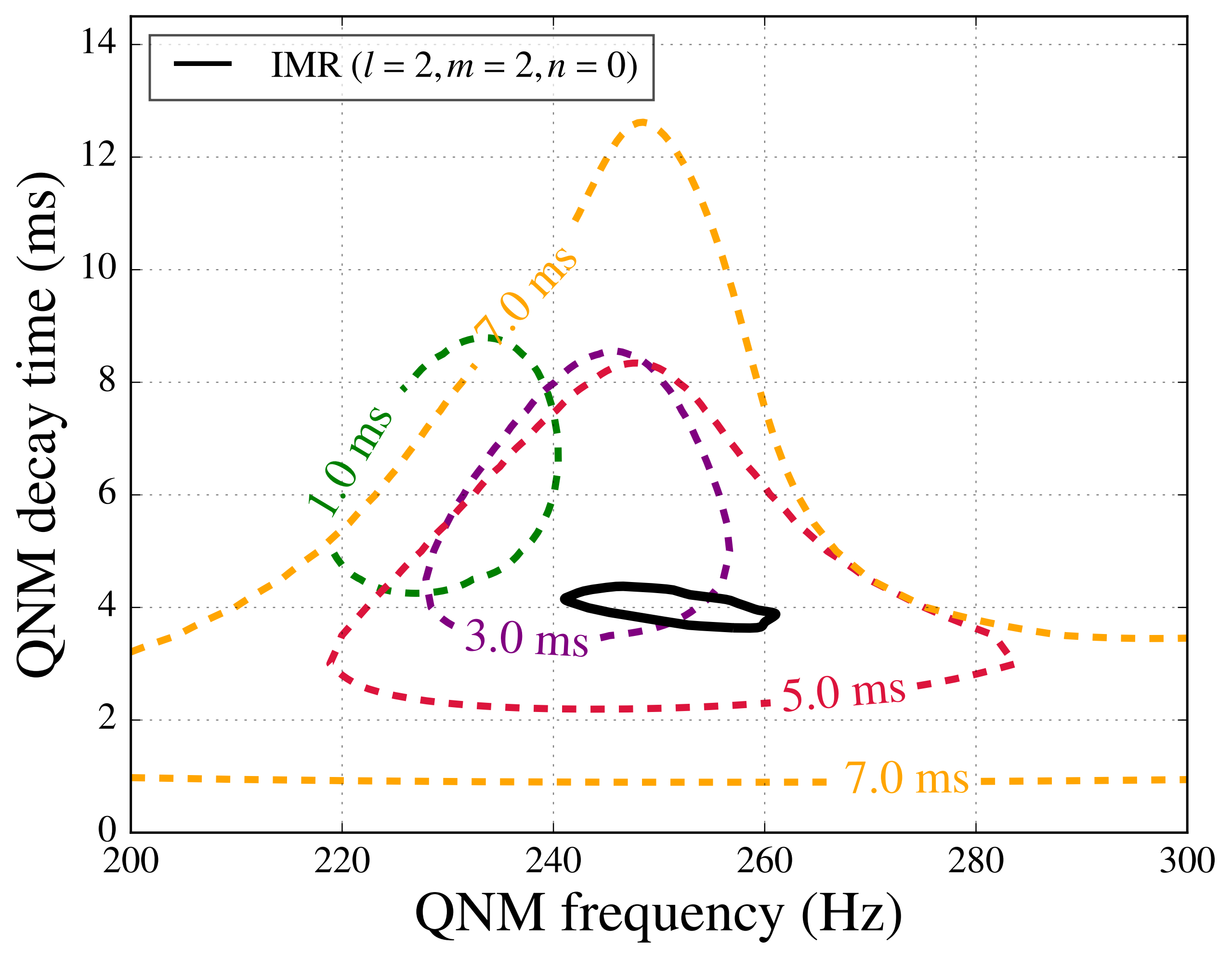

H1:RESIDUAL at 1126259462.410 with Q of 45.3


L1:RESIDUAL at 1126259462.410 with Q of 11.3

# Consistency with GR predictions

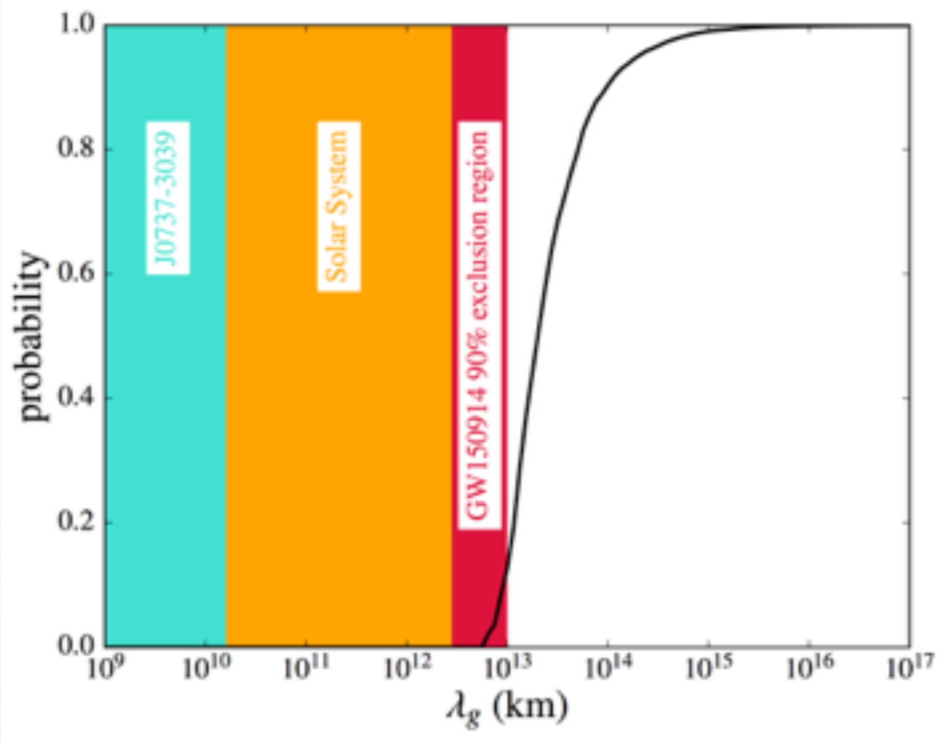
- Study of consistency of inspiral (early orbital evolution) and merger parts of the signal: they show consistent estimation of the final mass and final spin of the remnant BH
- Quasi-normal modes produced during formation and relaxation of a remnant BH: superposition of the exponentially damped eigen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

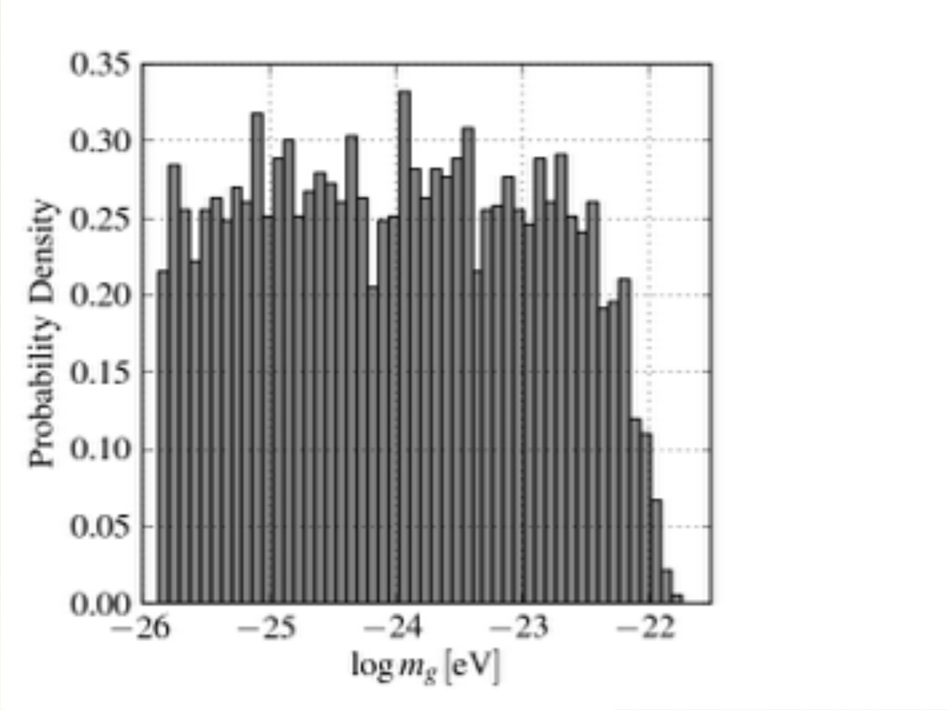




LVC arXiv:1602.03841

# Constraining dispersion in the GW signal





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

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

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

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

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

LVC arXiv:1602.03841

# Conclusion

- The gravitational wave event GW150914:
  - First detection of gravitational wave signal
  - First detection of Black Hole binary system
  - First detection of the heaviest stellar-mass black hole
- We have accurate waveforms (theoretical models ) to reliably detect GW signals and estimate their parameters
- The observational bias (selection) prefers BH systems face-on/off, which in turn makes it hard to estimate well the spins and their orientation
- All consistency checks performed on the GW signal show no indication of any deviation from General Relativity and binary Black Hole system