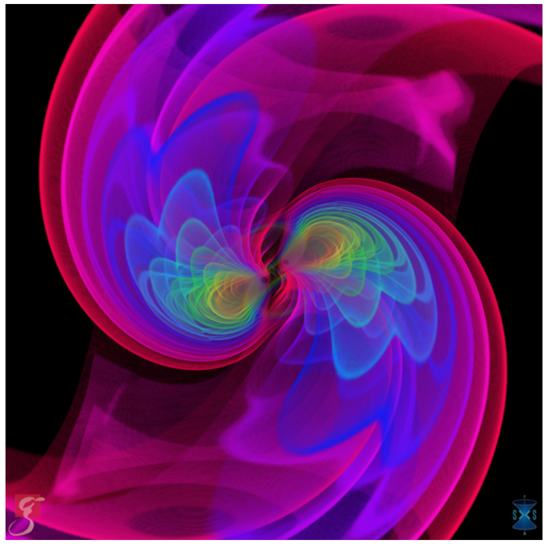
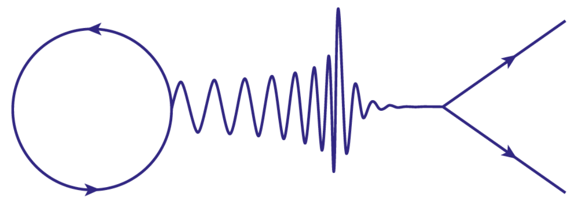
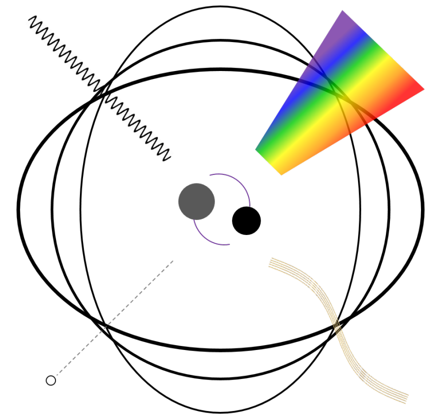
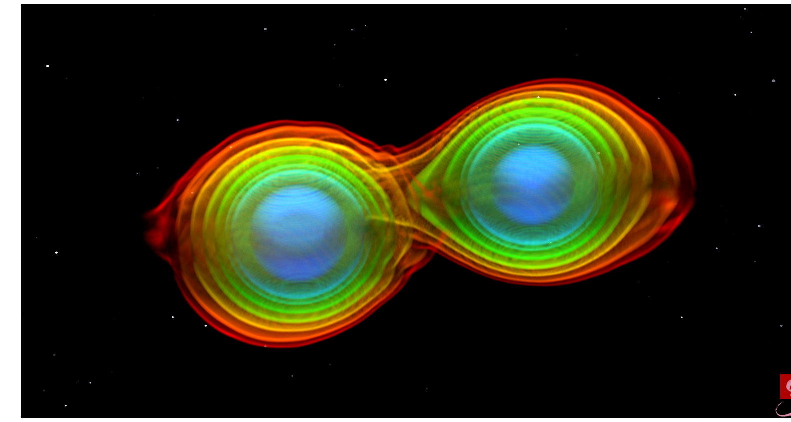





Challenges in Waveform Modeling with 3G Detectors

Alessandra Buonanno

Max Planck Institute for Gravitational Physics

University of Maryland

for "Extreme Gravity & Fundamental Physics/Waveform Models" Working Groups

"3G Science-Case Consortium Meeting" AEI, Potsdam-Golm October 2, 2018

The making of 3G report of XG & Fund. Physics/WM Groups

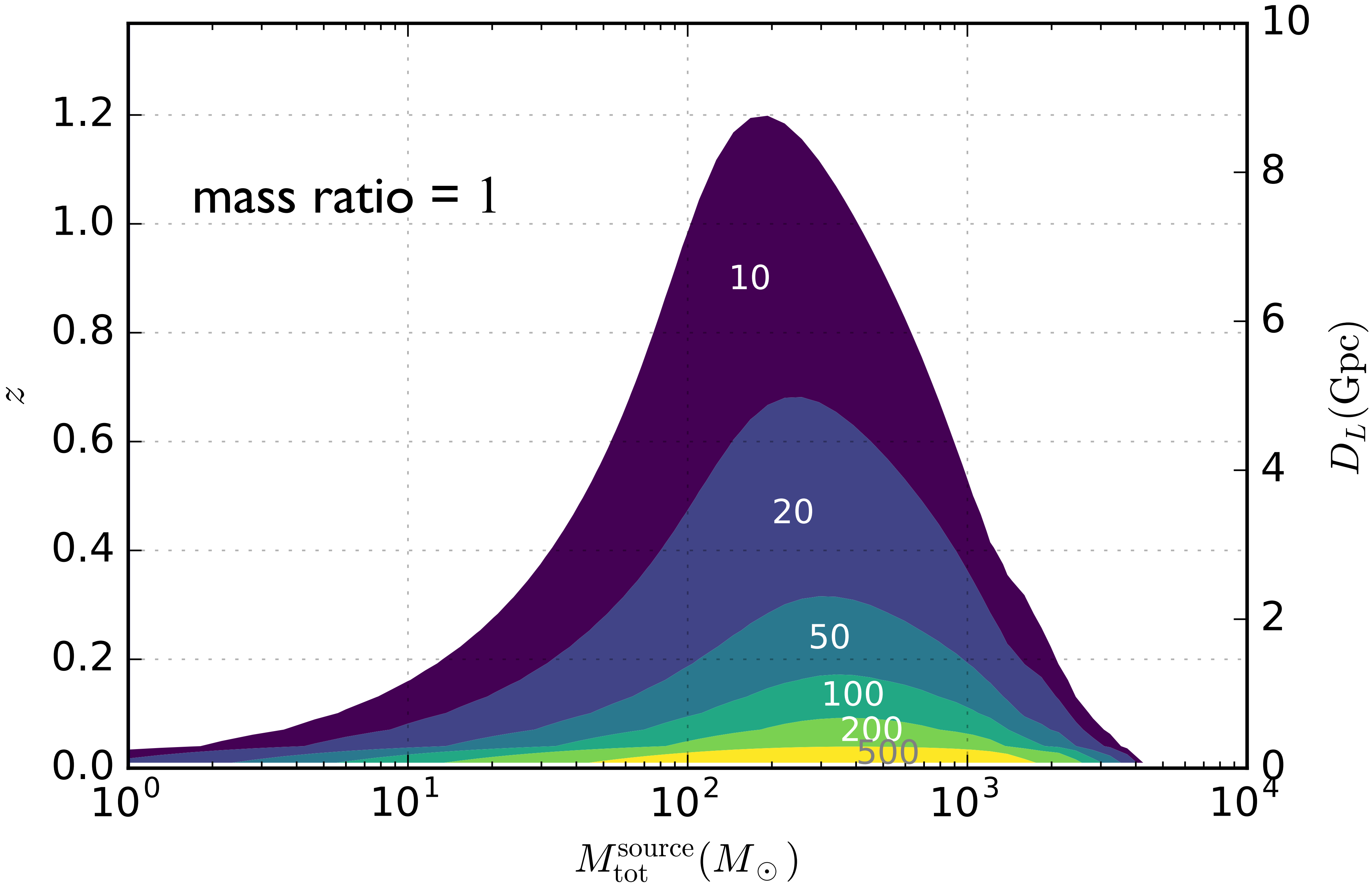
- **Four subgroups** were **formed** with contact persons:
  - Fundamental questions in gravity and particle physics *(Chatziioannou & Sotiriou)*
  - Extreme matter *(Vitale & Yunes)*
  - Exotic objects and phenomena *(Archisman & Pani)*
  - Waveform modeling and data-analysis challenges *(Ajith & Pürrer)*

- **Preliminary draft** produced in late June.

- Co-chairs *Buonanno, Lehner & van den Broeck* worked on preliminary draft and produced **first revised version of 3G report** on Sep 28 [https://github.com/gwic-3g/3g-science-case/blob/master/work-space/xg/XG-WM-report-v1.pdf]

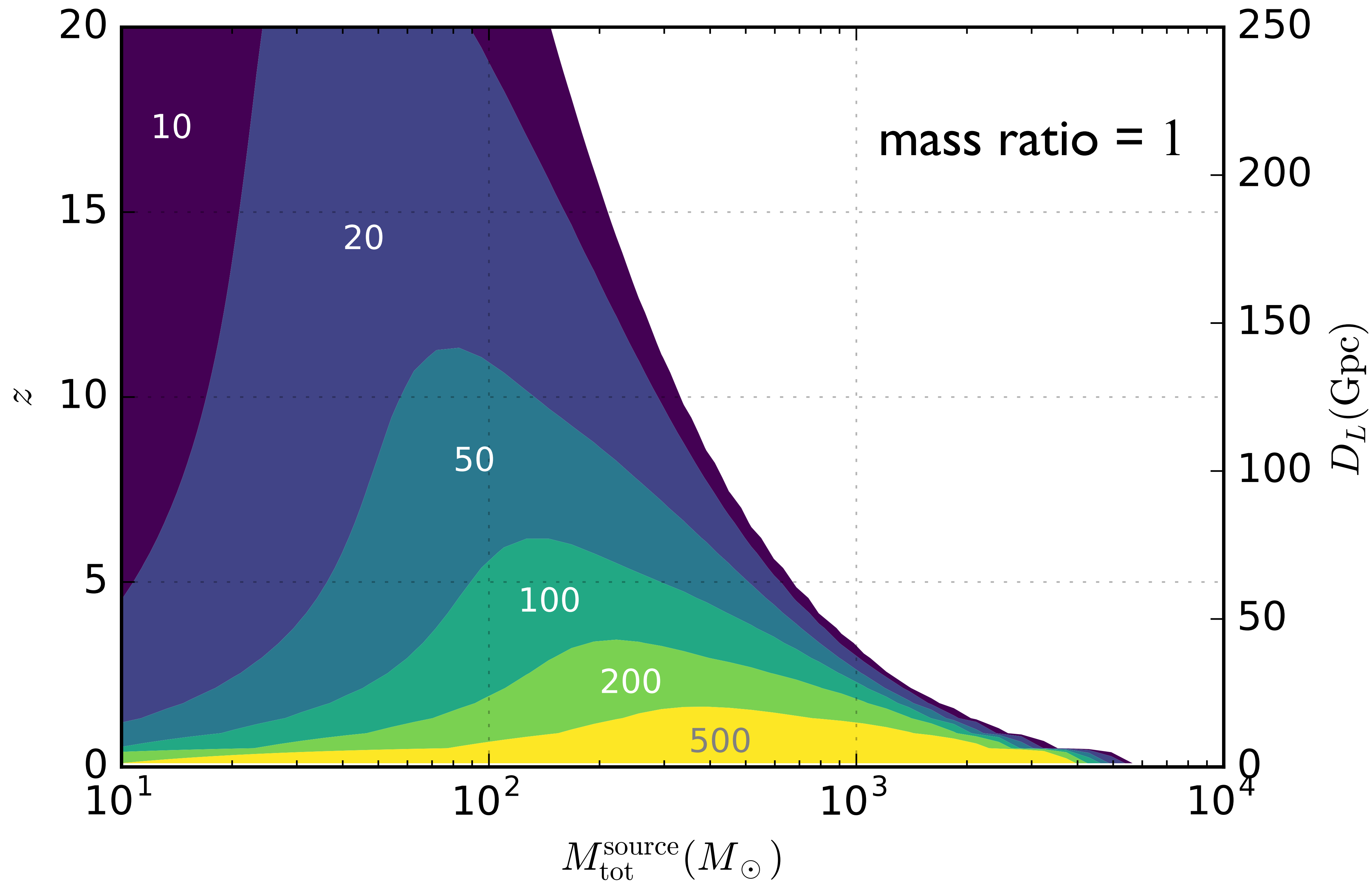
- So far, several **people have contributed to 3G** report, including *Arun, Barausse, Baryakhtar, Brito, Dietrich, East, Gerosa, Harry, Hinderer, Maselli, Pfeiffer, Pratten, Shao, Tamanini, van de Meent, Varma, Vines, Zumalacarregui, Yang, …*

Binary's masses/distance spanned by 2G detectors



- 2G detectors will observe **binary coalescences with SNR** ($\sim$20) **at modest redshift** (z ~ 0.7), and SNR > 100 at z < 0.2.

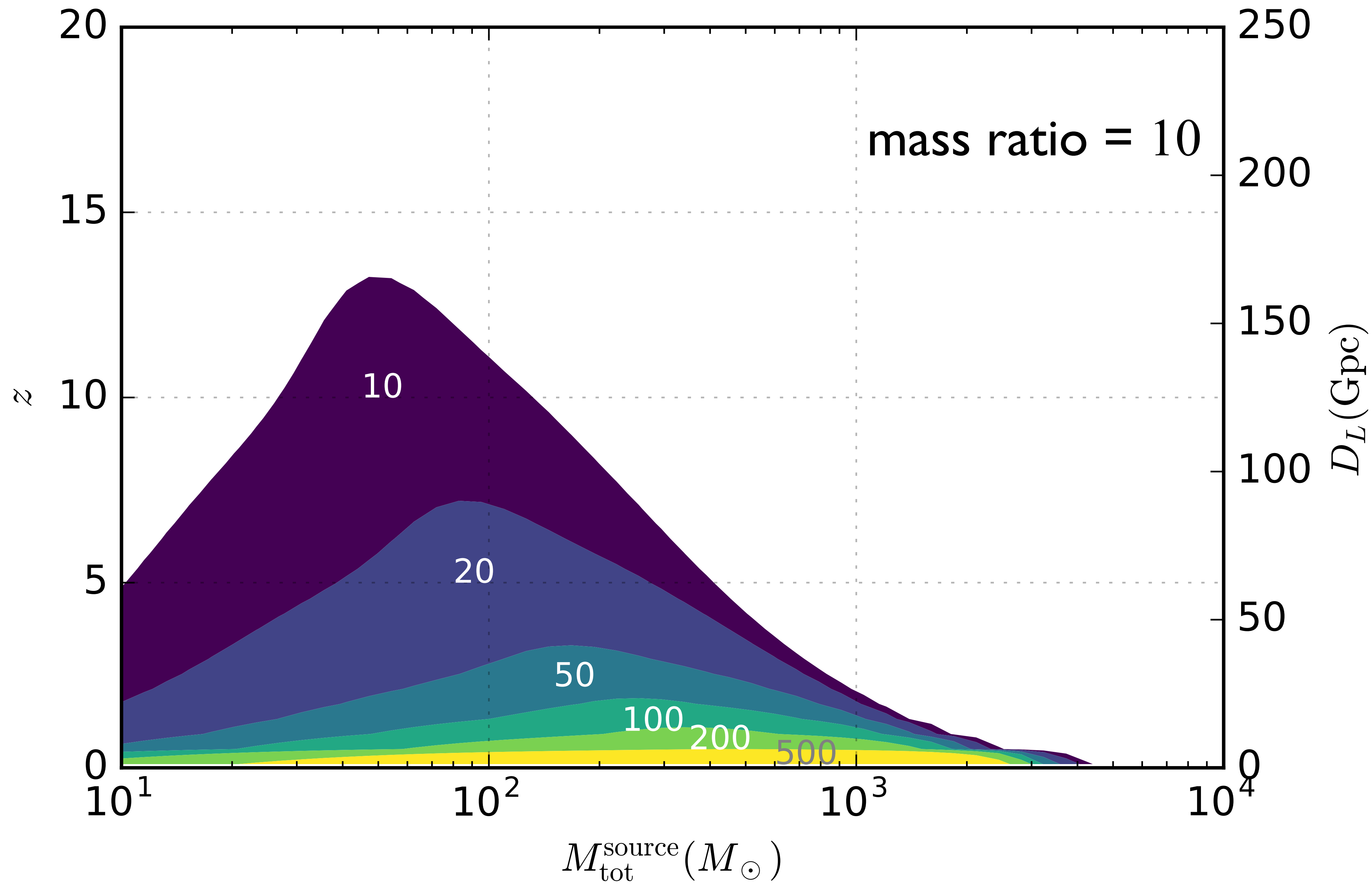
Binary's masses/distance spanned by 3G detectors



- 3G detectors will observe **binary coalescences with SNR** ($\sim$20) even **at high redshift** (z $\sim$10-15), and with **SNR** > 100 at z < 5.

- Demands on waveform **accuracy** are **higher,** modeling is more **challenging.**

Binary's masses/distance spanned by 3G detectors

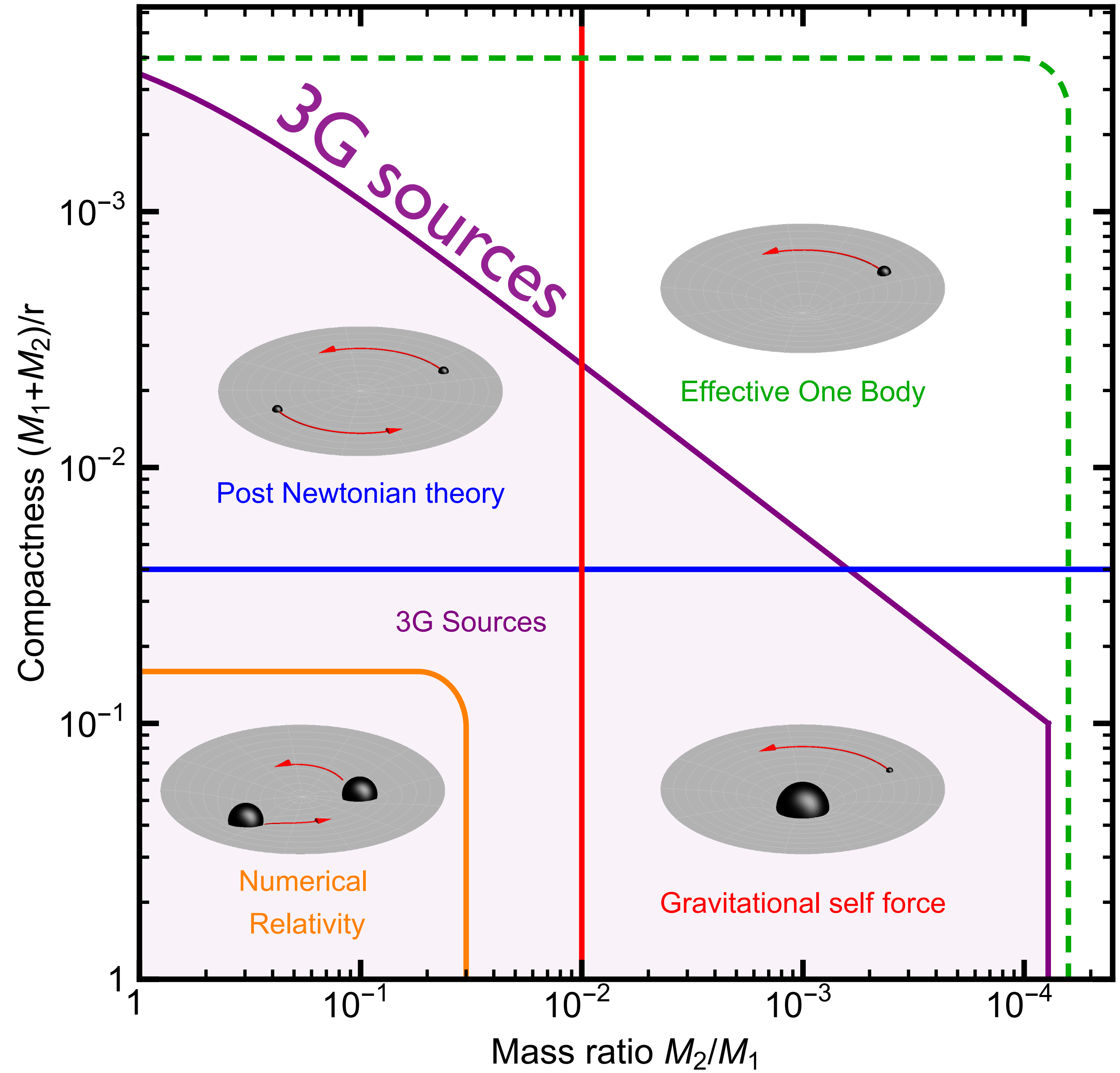


- 3G detectors will observe **binary coalescences with SNR** (~ 10) up to **redshift** (z ~ 12), and with **SNR** > 100 at z < 2.
- Demands on waveform **accuracy** are **higher,** modeling is more **challenging.**

Need to solve 2-body problem in larger region of parameter space with 3G

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- **GR** is **non-linear theory**.
- Einstein's field equations can be solved:
  - **approximately,** but **analytically** (**fast** way)
  - **"exactly"**, but **numerically** on supercomputers (**slow** way)



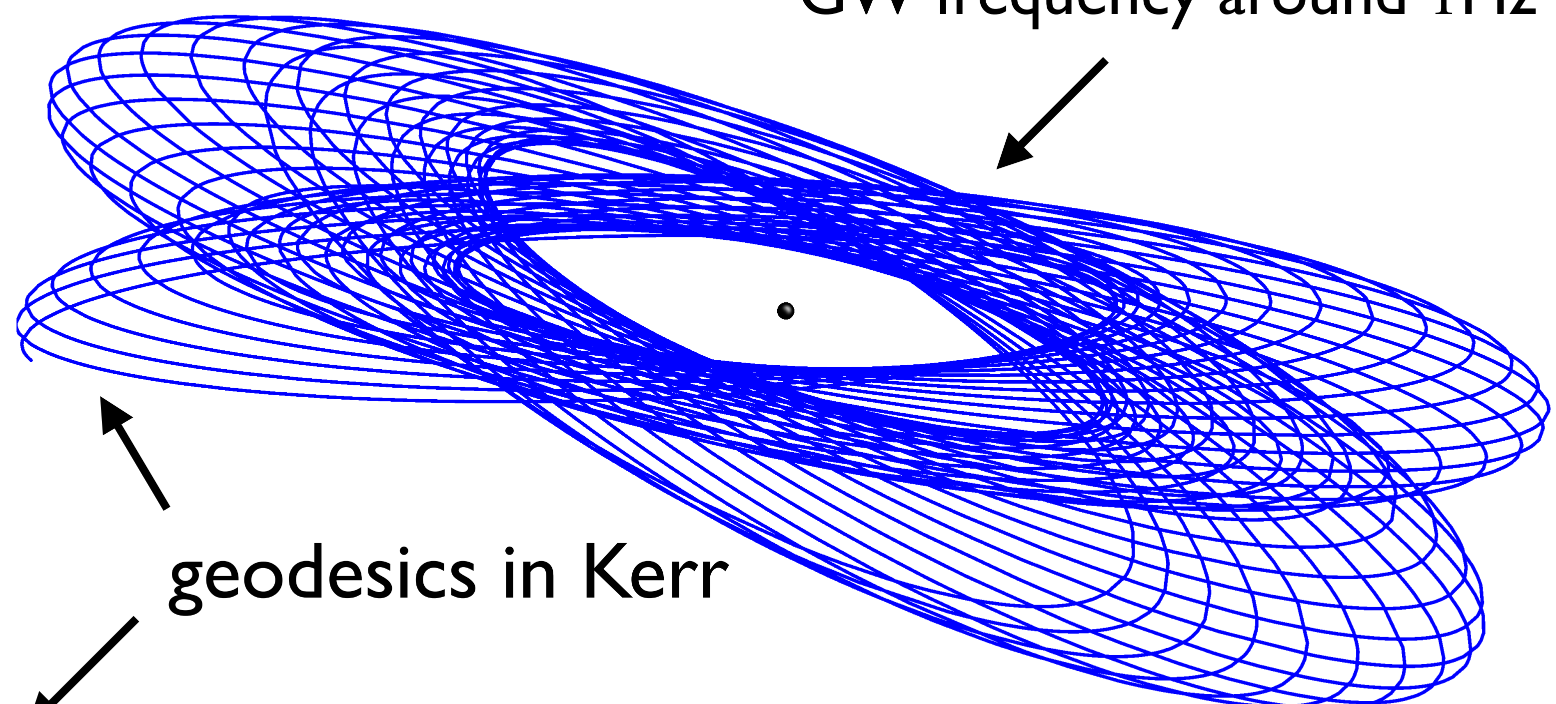
- **Synergy** between **analytical** and **numerical relativity** is **crucial.**

New sources with 3G detectors: intermediate-mass black-hole inspirals

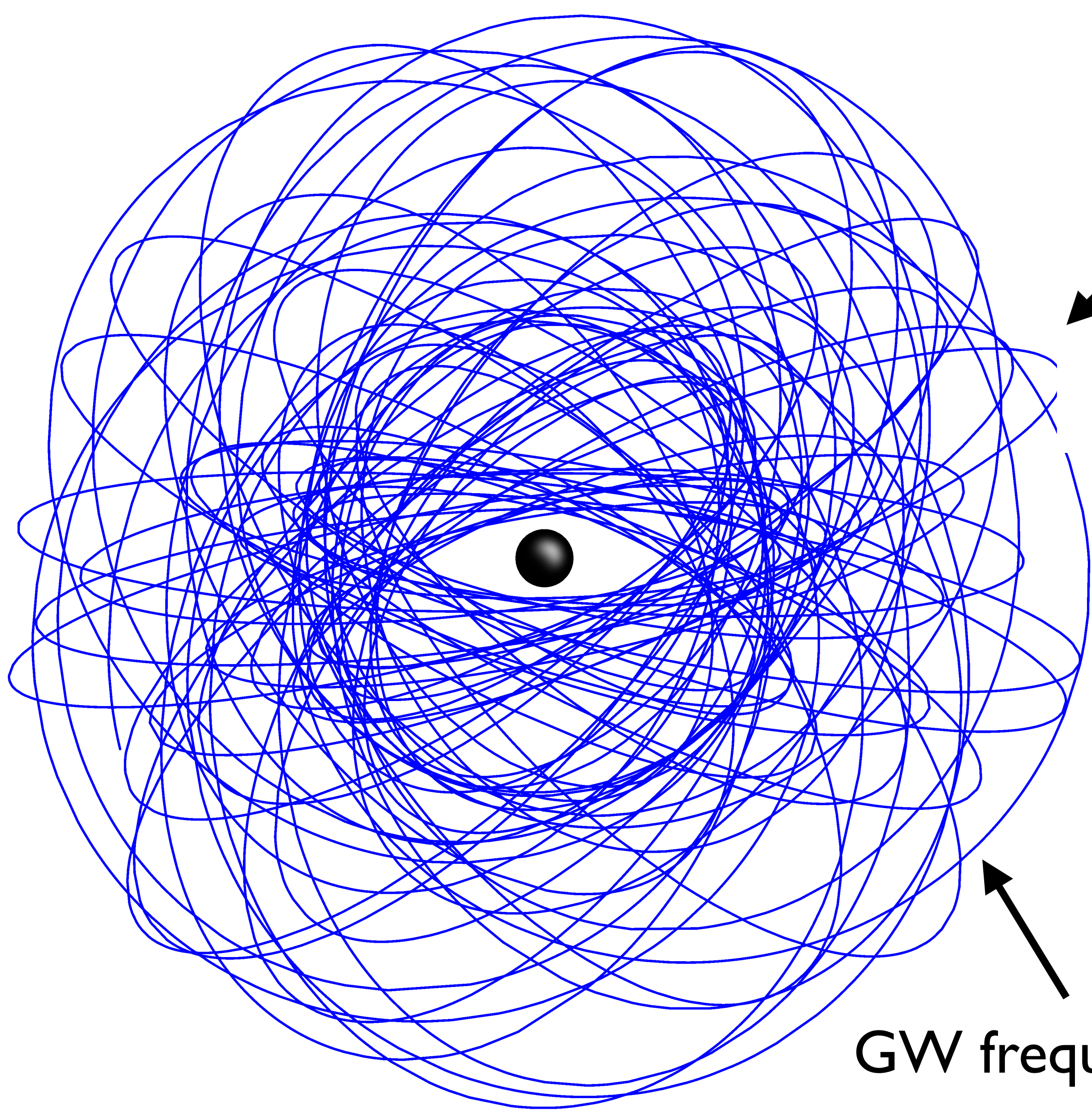
- central BH's spin = 0.9
- eccentricity = 0.5

$$M = 1000 M_\odot$$

GW frequency around 1Hz



geodesics in Kerr



GW frequency around 10 Hz

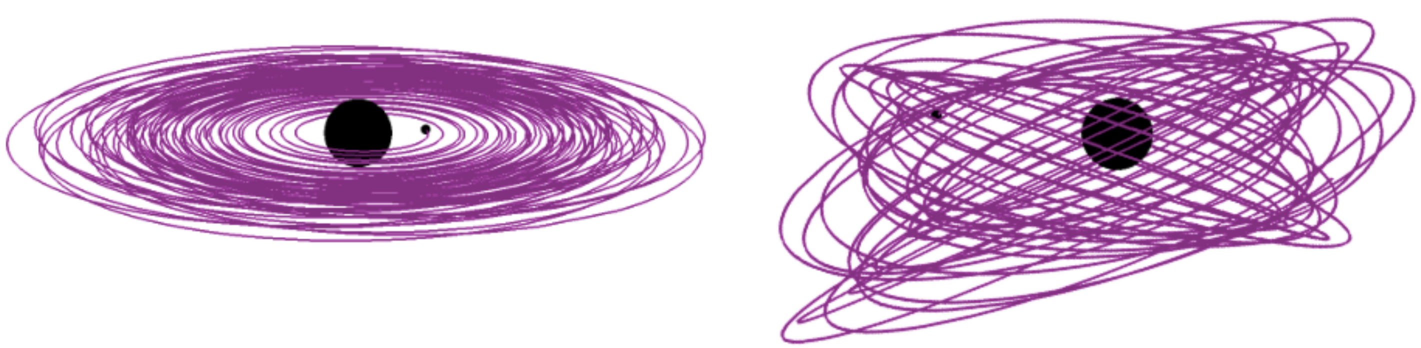
- Sweeping in band for a **few thousand GW cycles,** probing **strong-field** gravity.
- **GSF** is likely to be important, we **need** to develop **accurate waveform models**.

3G science by including missing physical effects: eccentricity

- How to **discriminate** among binary's **formation scenarios**, and **probe astrophysical environment**? **Eccentricity** and **spin-precession can disclose this information.**

- **Eccentric** compact-object **binary:**

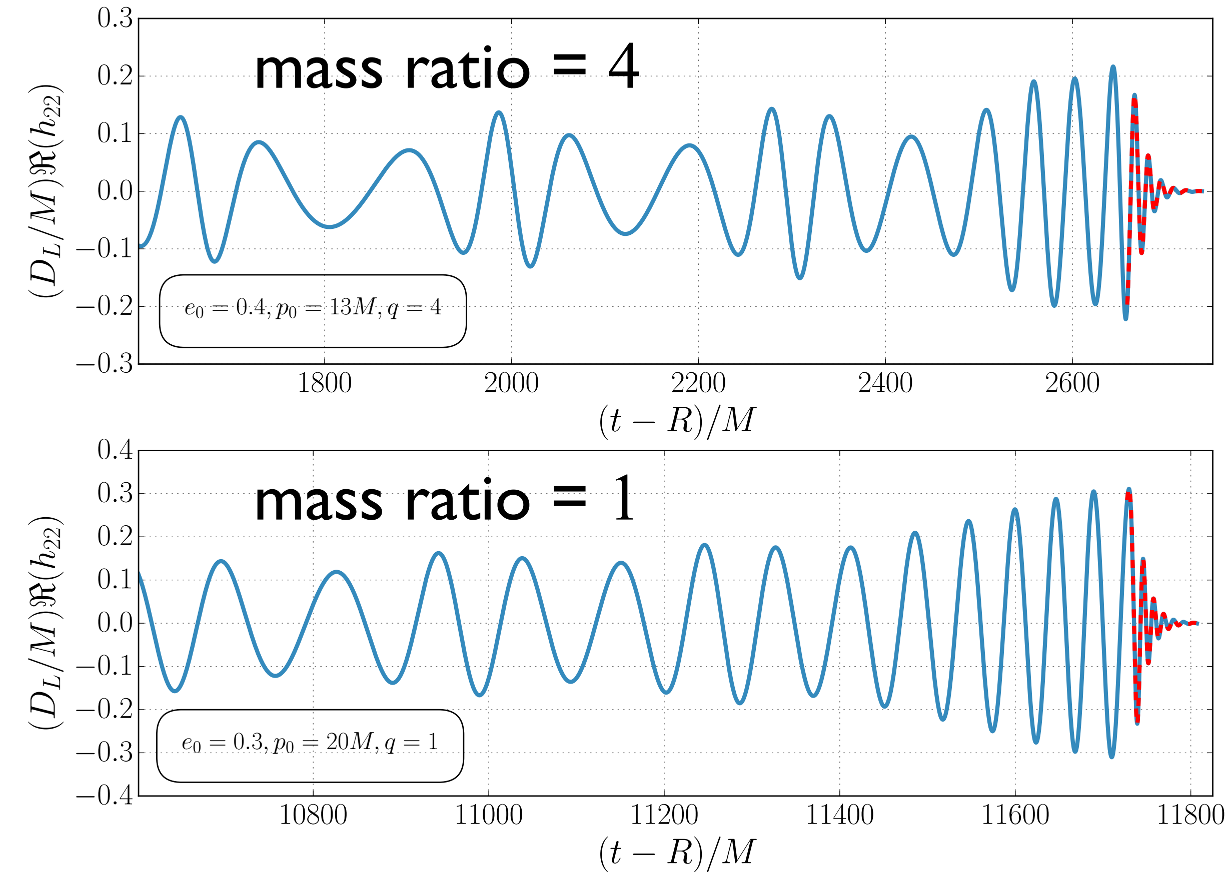
NR simulation



mass ratio = 7

(Lewis et al. 16)

AR waveform model



(Hinderer & Babak 17)

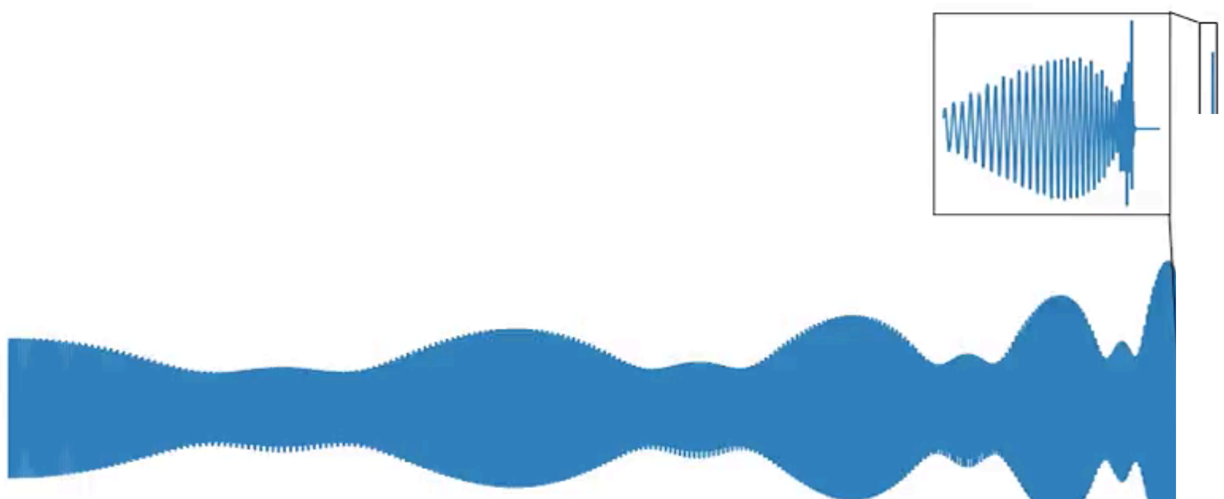
- We **need** accurate **waveform models** with **eccentricity also for stellar mass BBHs.**

3G science by including missing physical effects: spin-precession

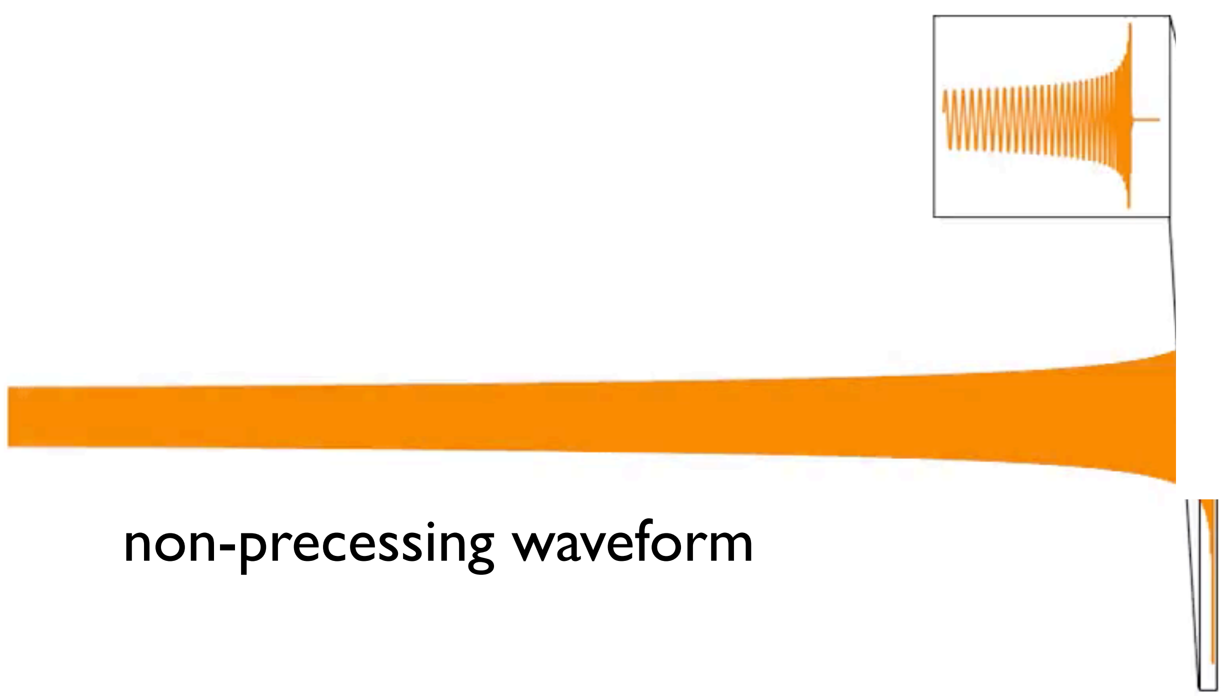
(credit: *Ossokine*)

total mass = $29 M_\odot$
mass ratio = 5

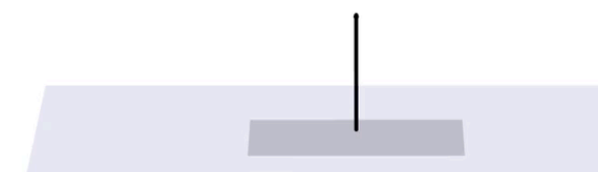
574 GW cycles, from 10 Hz
5 precessional cycles
40 sec duration



precessing waveform



non-precessing waveform

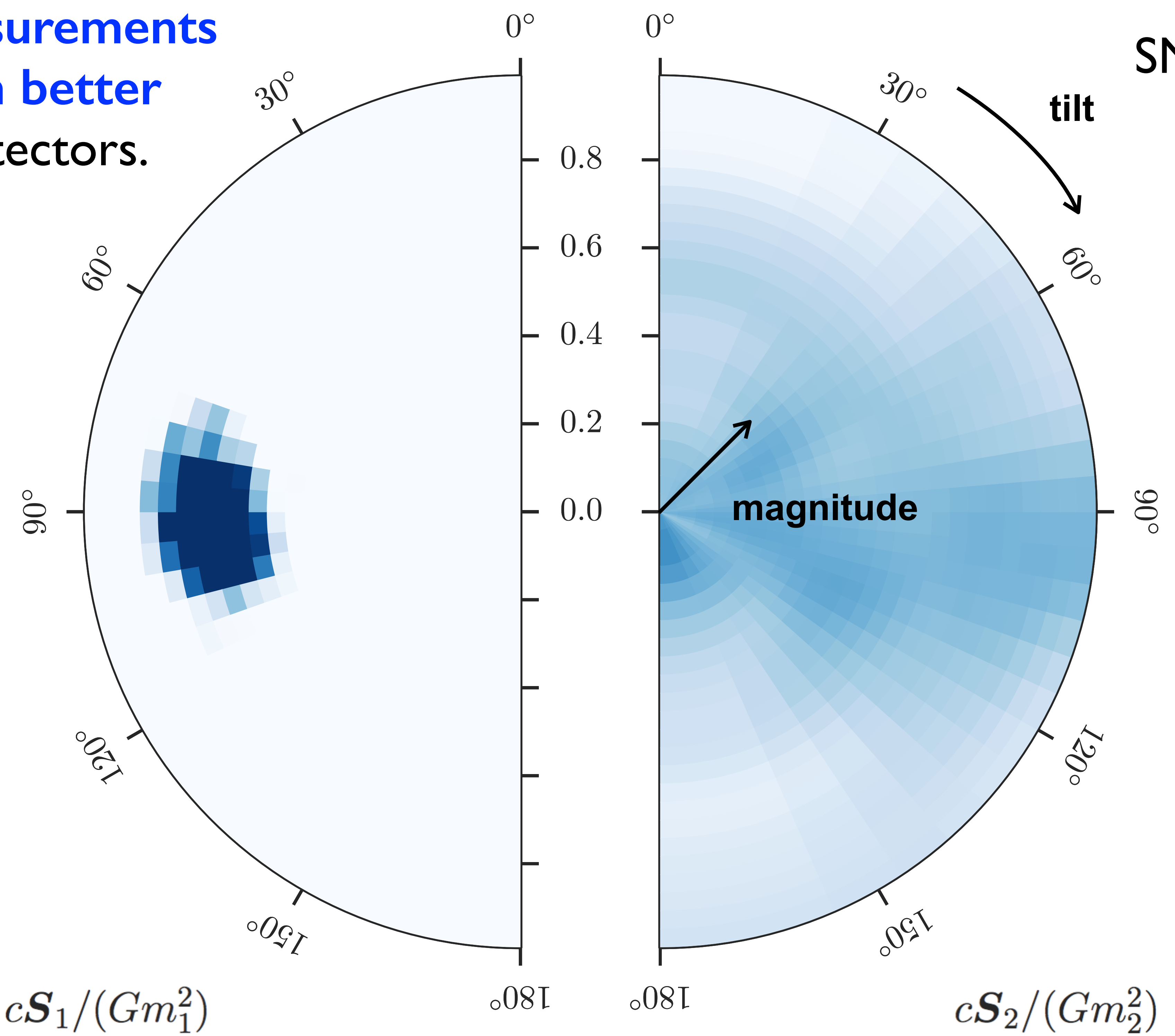


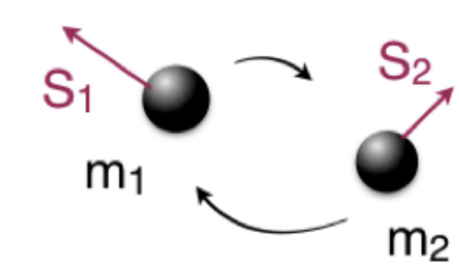
binary orbital plane

- **3G detectors** will observe **10^2-10^4 events** per year. We will observe **unusual events.**

Measuring spin-precession with 2G detectors

- Spin meausurements will be even better with 3G detectors.

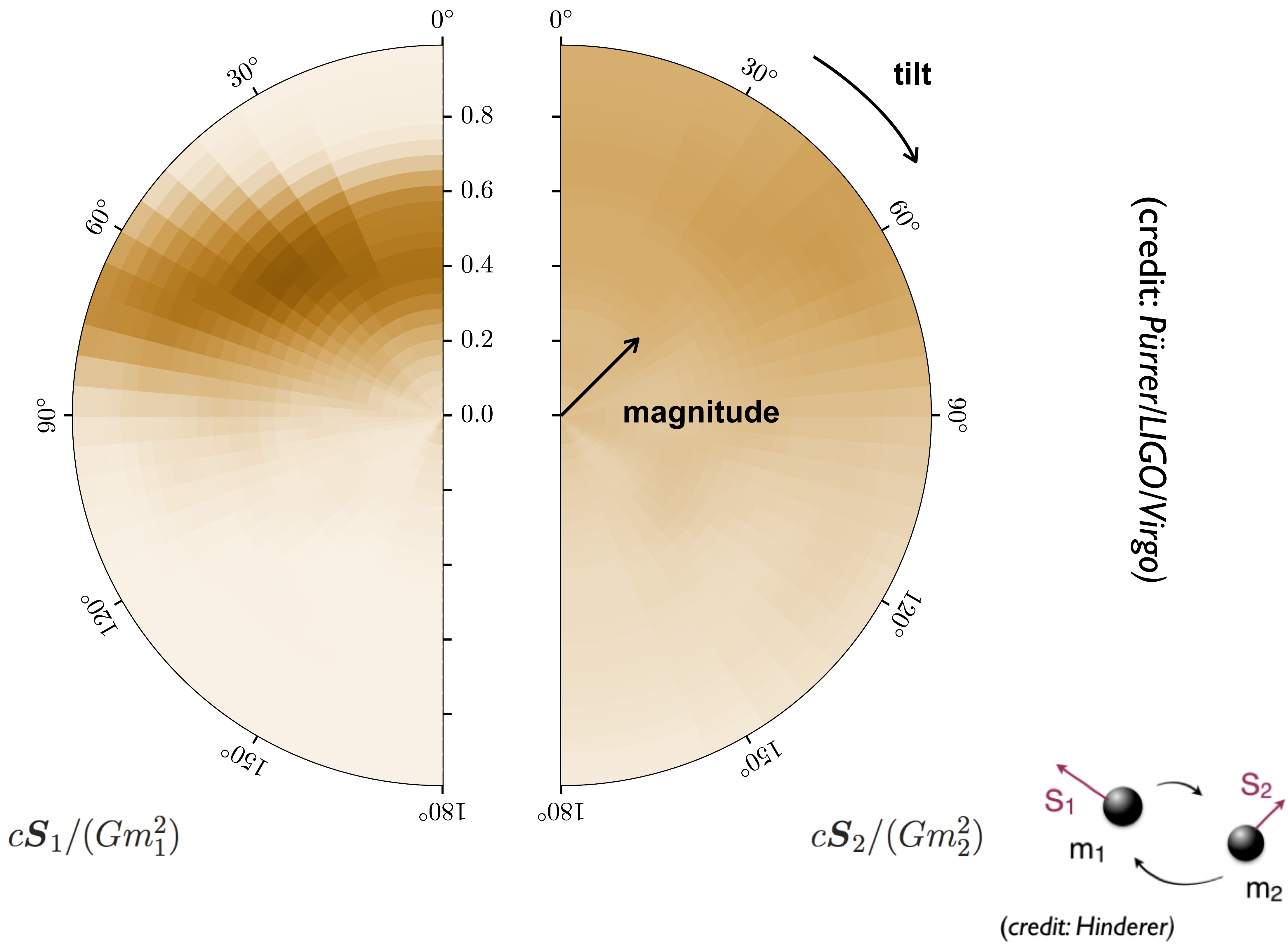




(credit: Hinderer)

Measuring spin-precession with GW151226

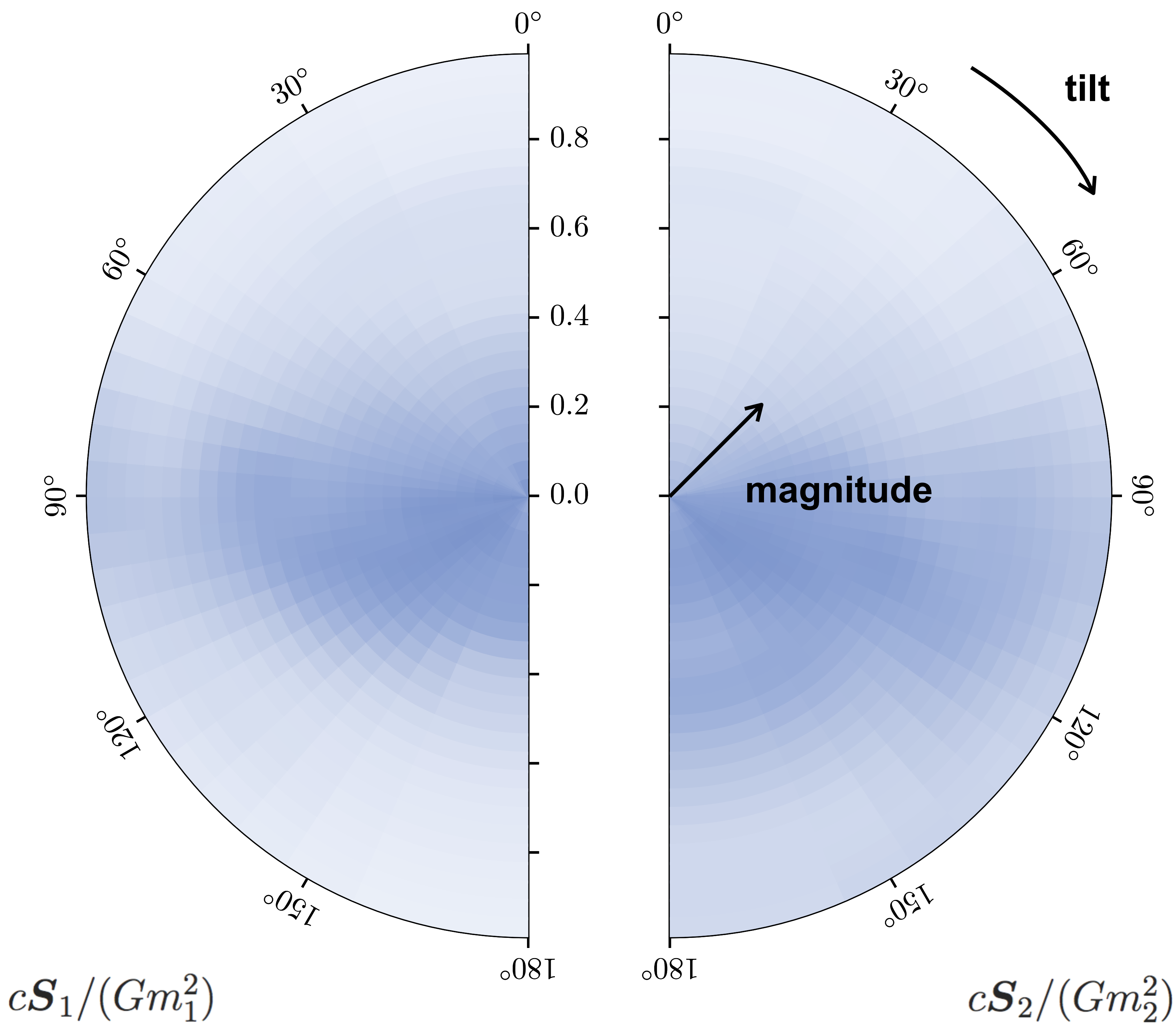
(Abbott et al. PRL 116 (2016) 241103)



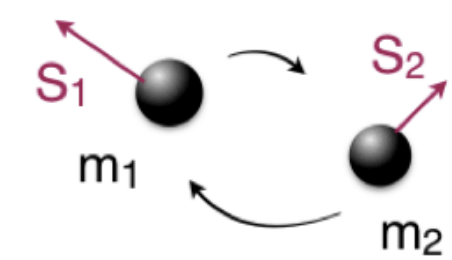
(credit: *Pürrer/LIGO/Virgo*)

Measuring spin-precession with GW150914

(Abbott *et al.* PRL 116 (2016) 061102)

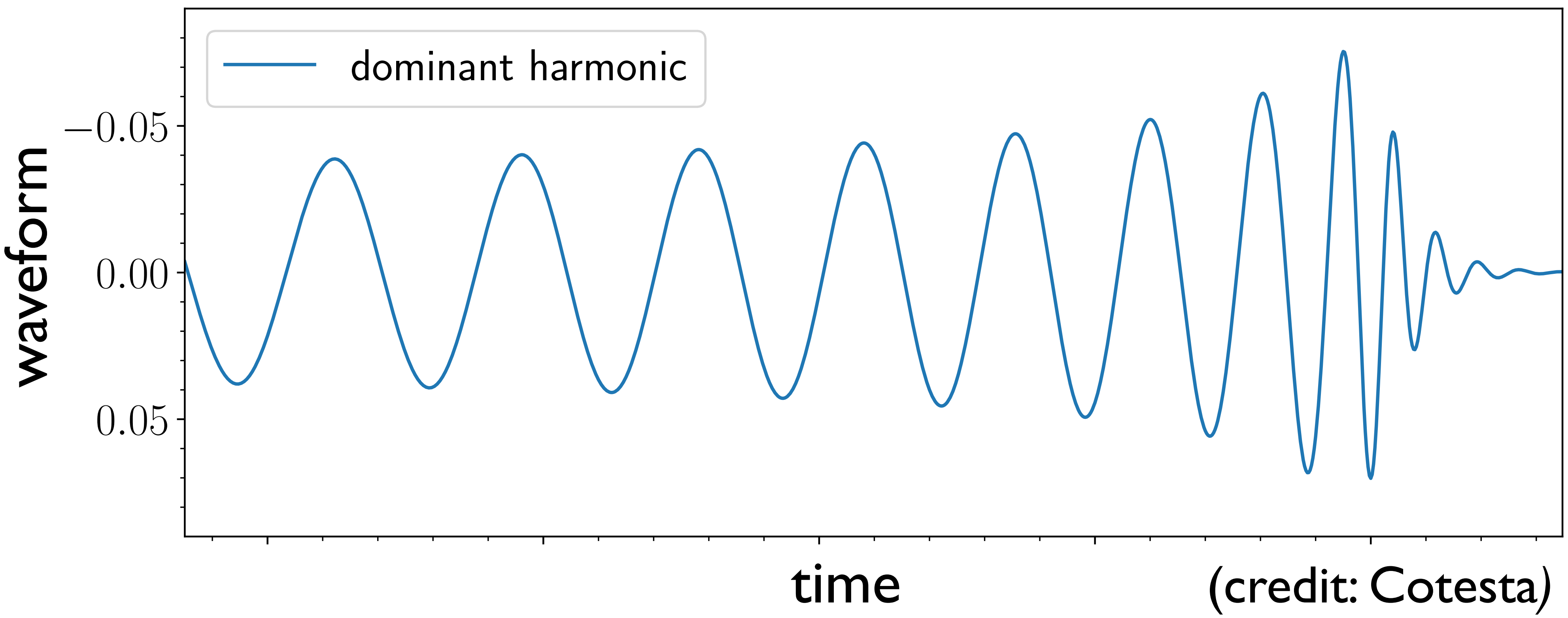


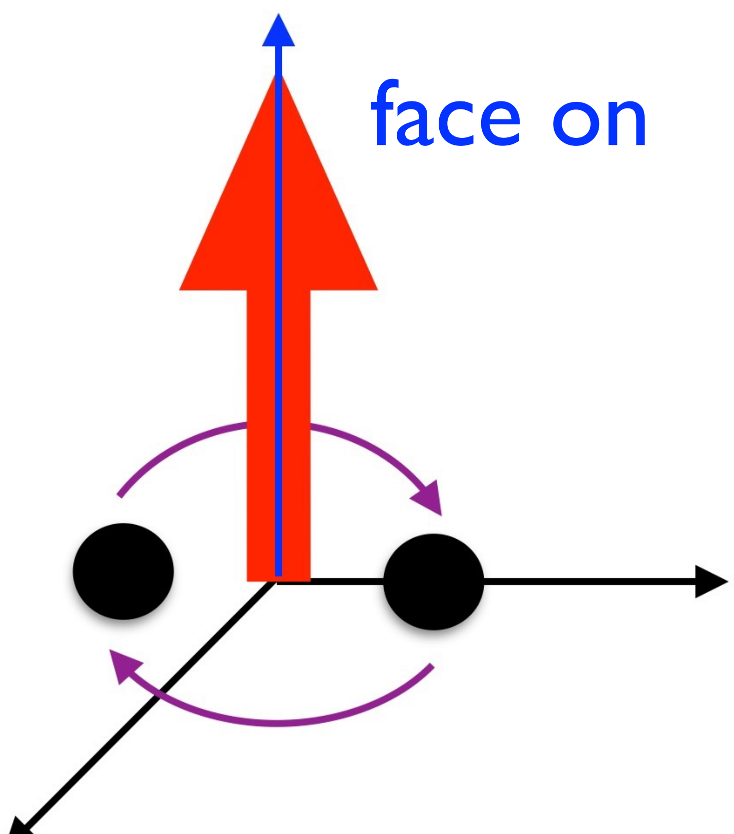
(credit: *Pürrer/LIGO/Virgo*)



(credit: Hinderer)

3G science by including missing physical effects: higher harmonics



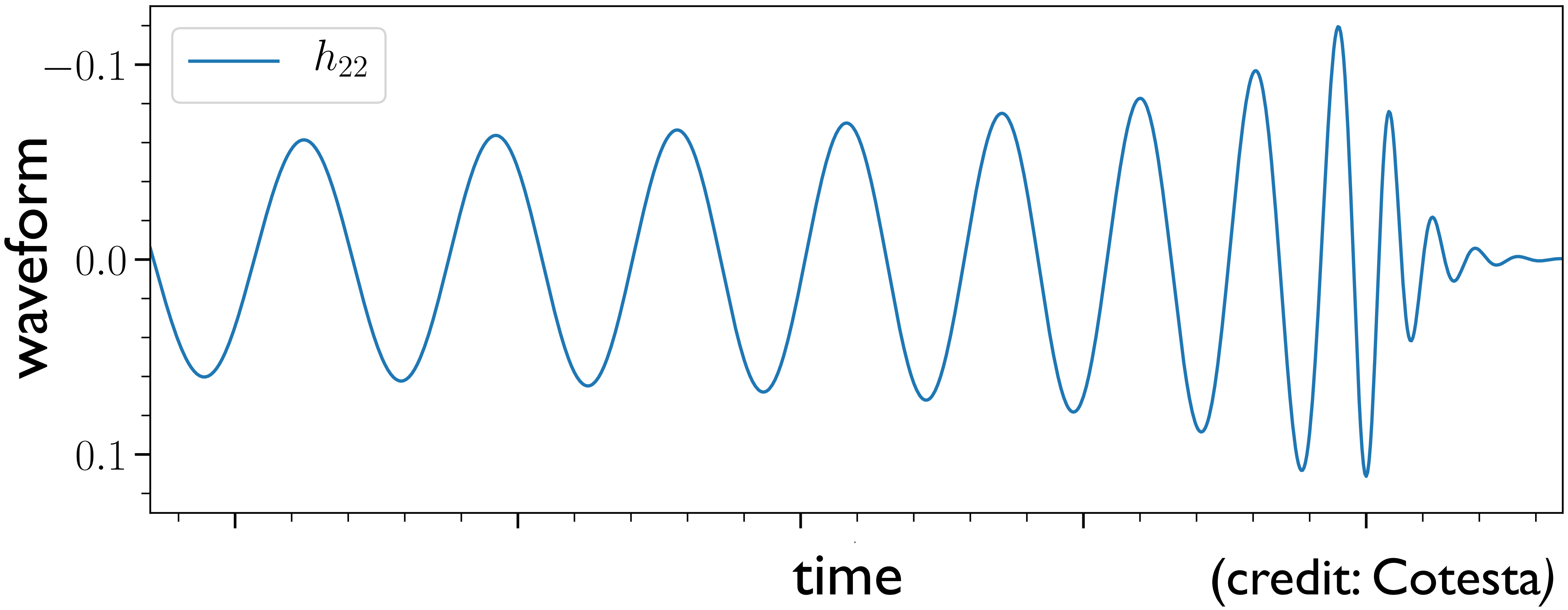


- So far, 2G detectors **observed** GW **events mostly face-on/face-off.**

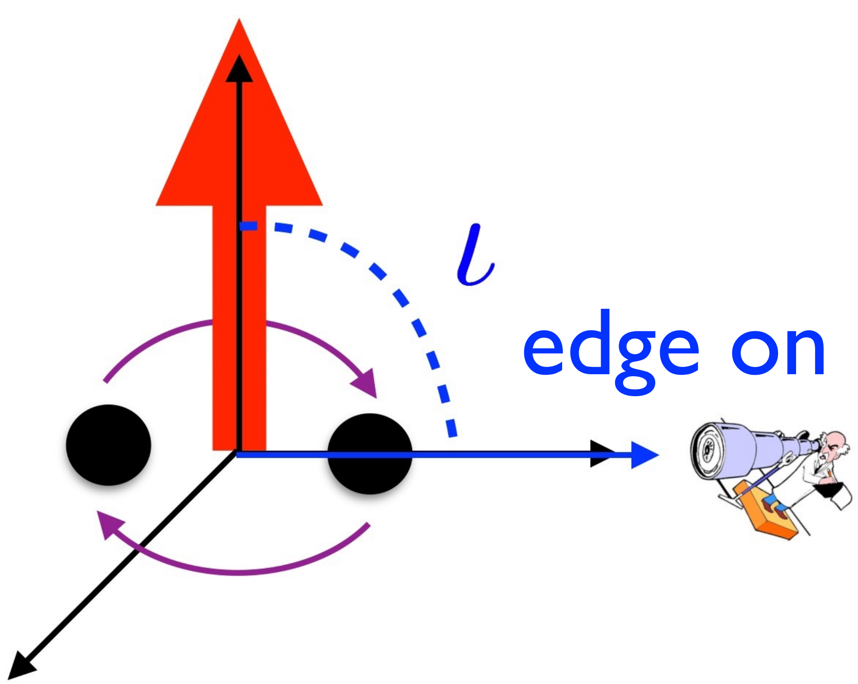
- **Face-on/face-off orientation** suppress **higher harmonics, spin-precessional effects,** making **harder to infer** source's **properties.**

3G science by including missing physical effects: higher harmonics

fundamental harmonic

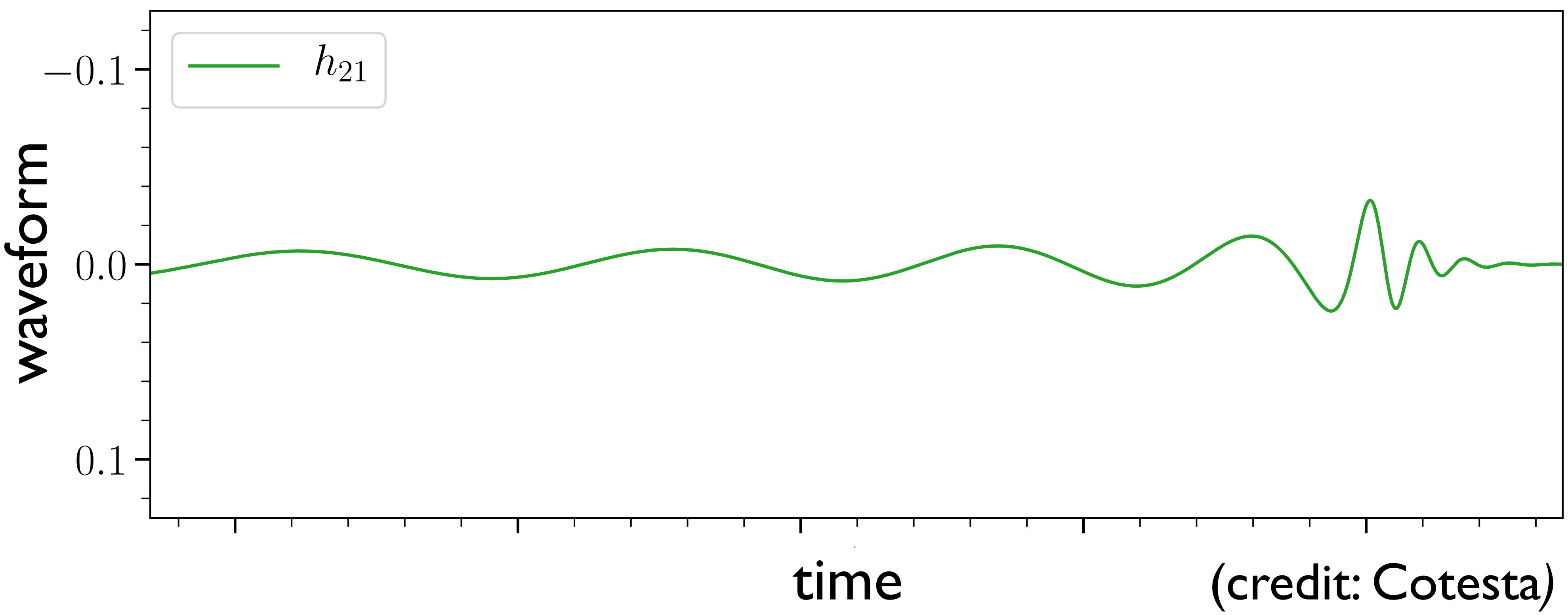


(credit: Cotesta)

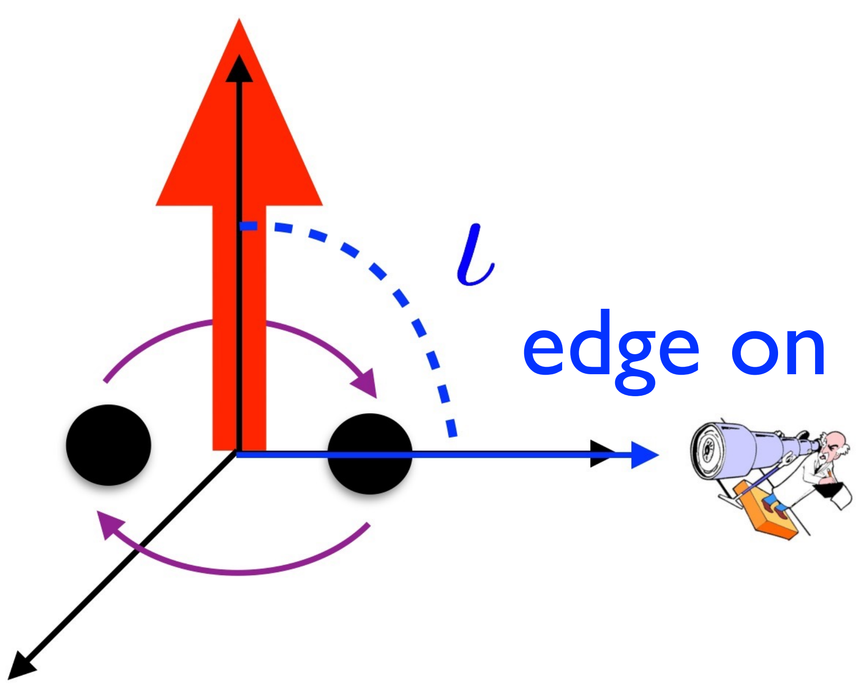


3G science by including missing physical effects: higher harmonics

first harmonic

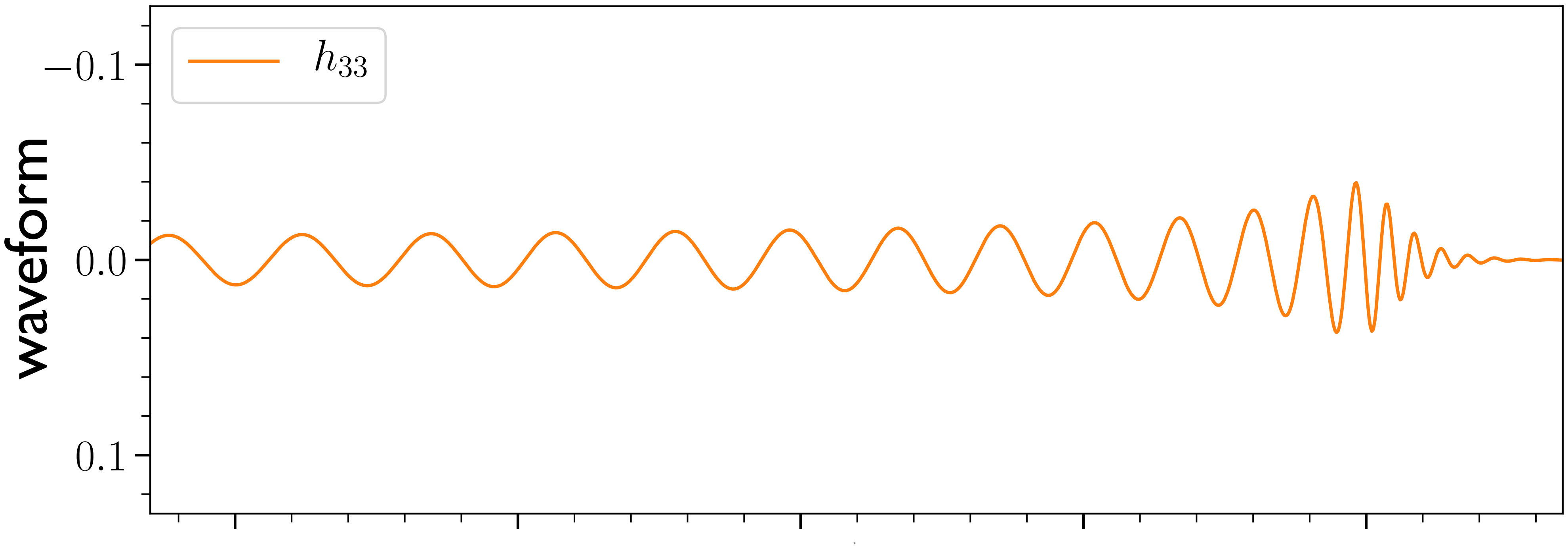


(credit: Cotesta)

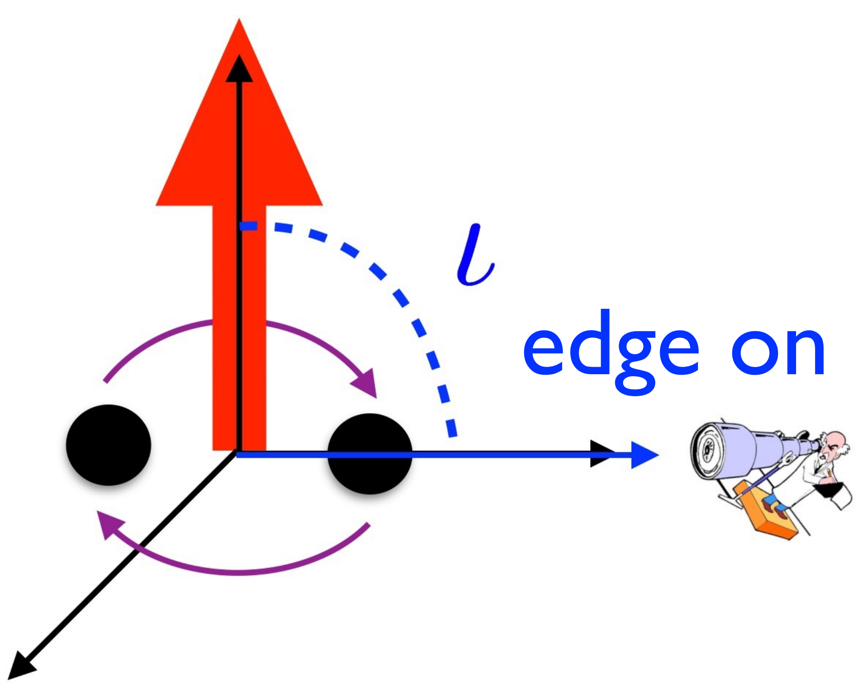


3G science by including missing physical effects: higher harmonics

third harmonic

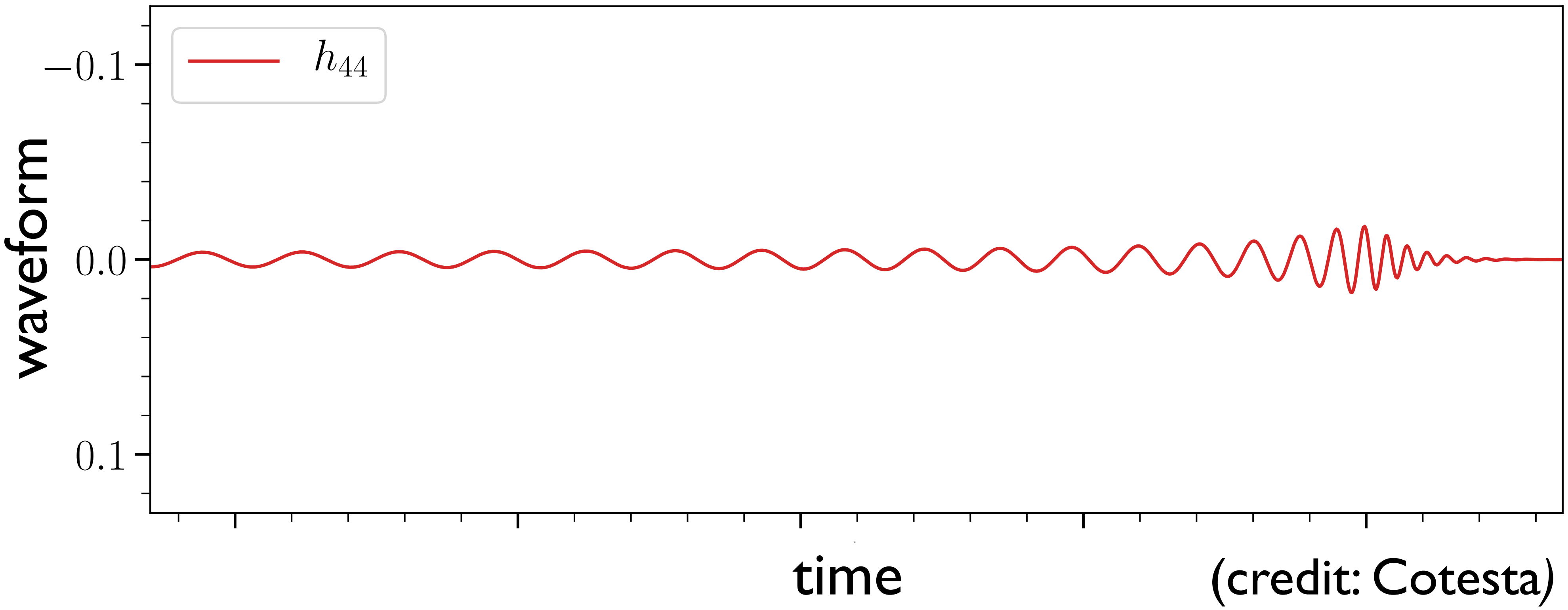


(credit: Cotesta)

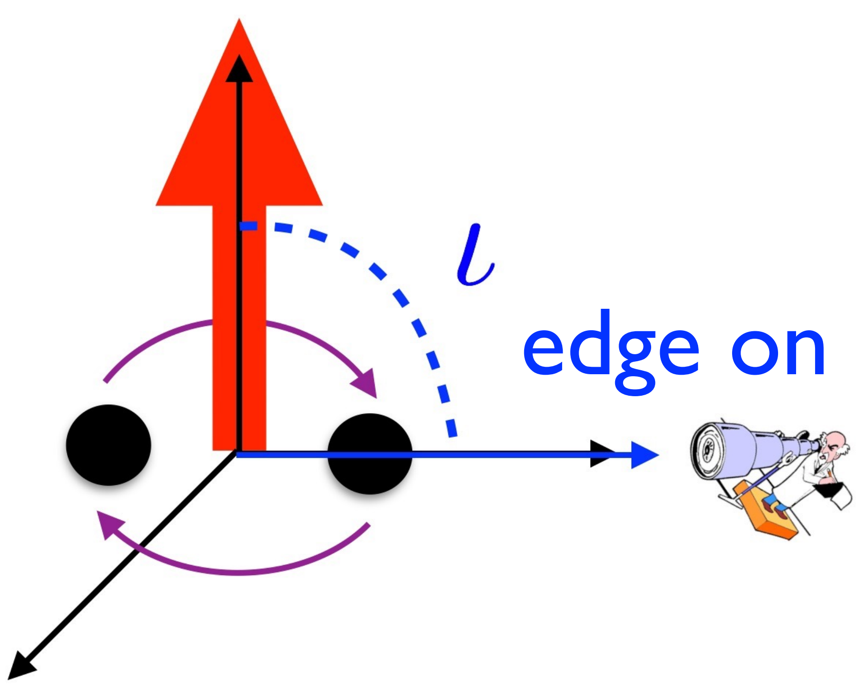


3G science by including missing physical effects: higher harmonics

fourth harmonic

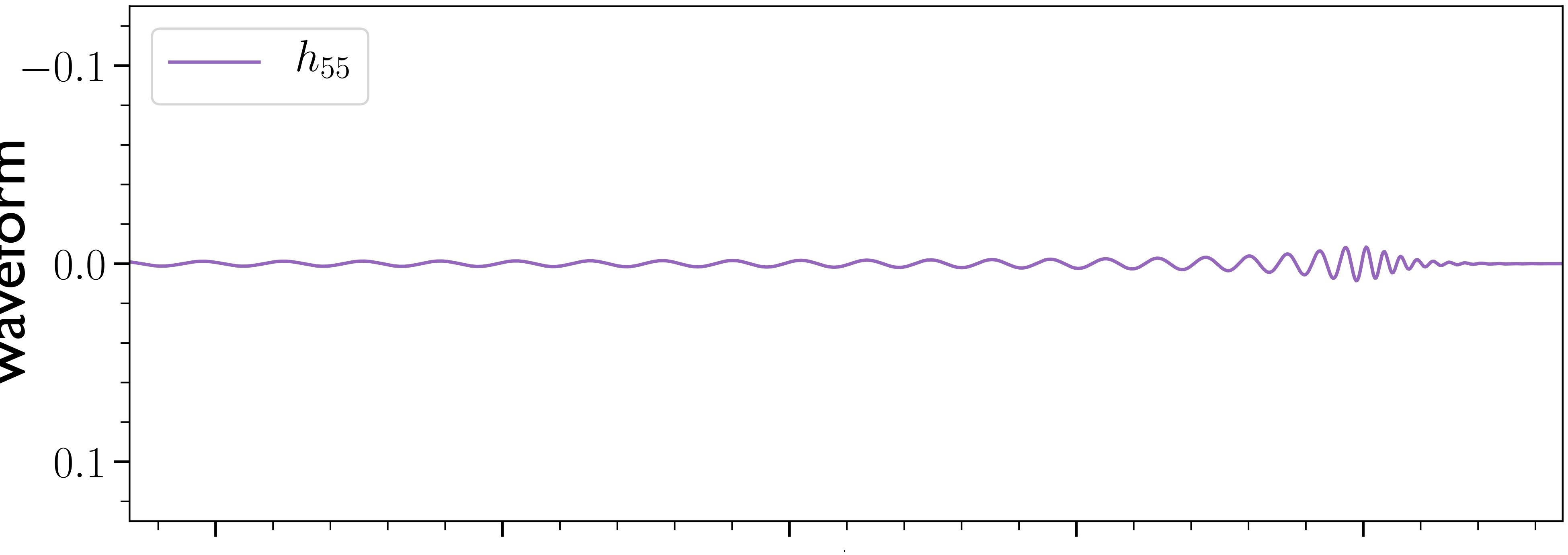


(credit: Cotesta)

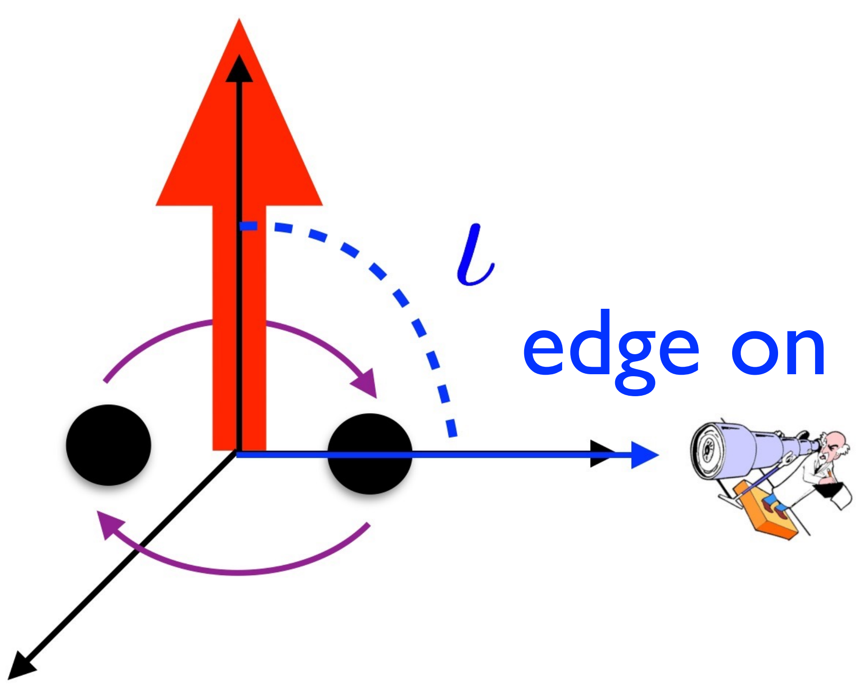


3G science by including missing physical effects: higher harmonics

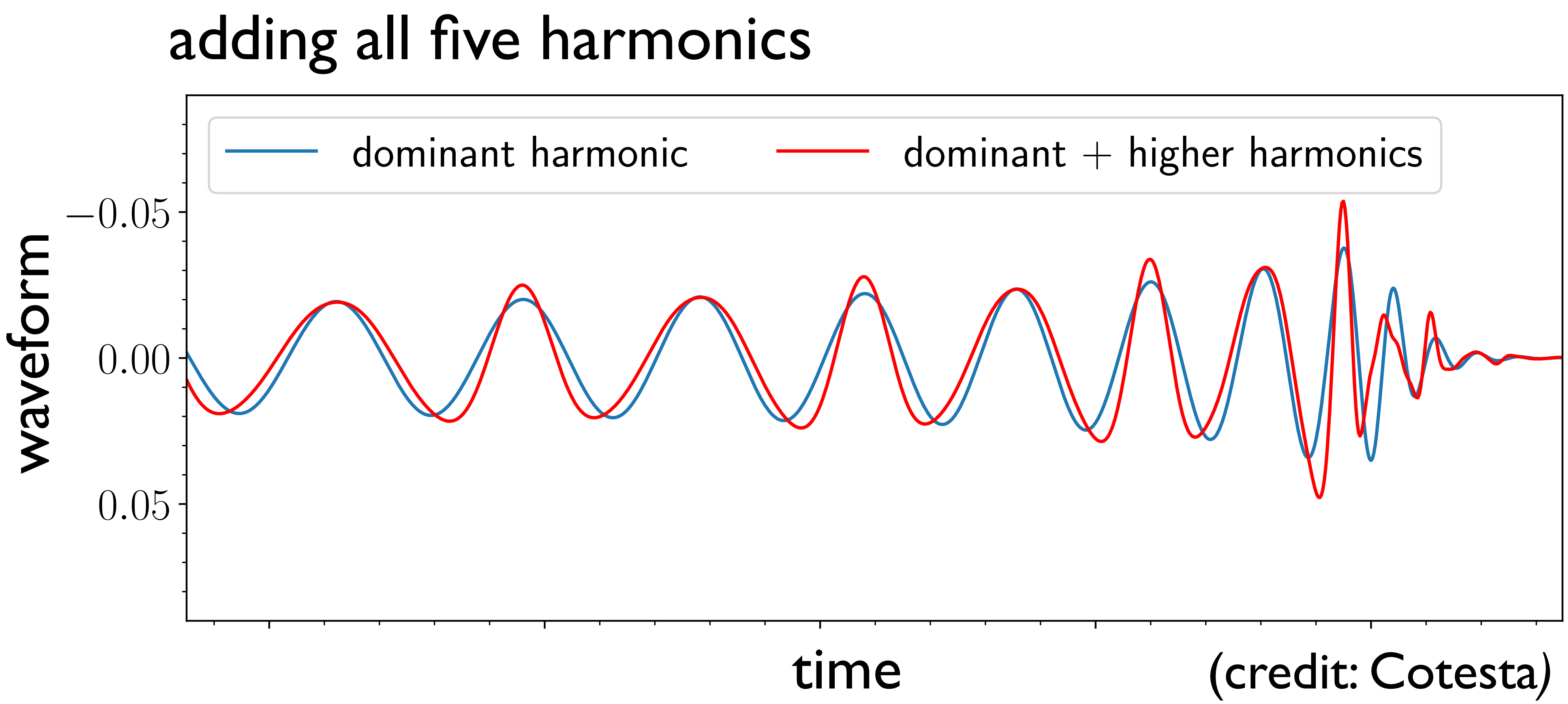
fifth harmonic

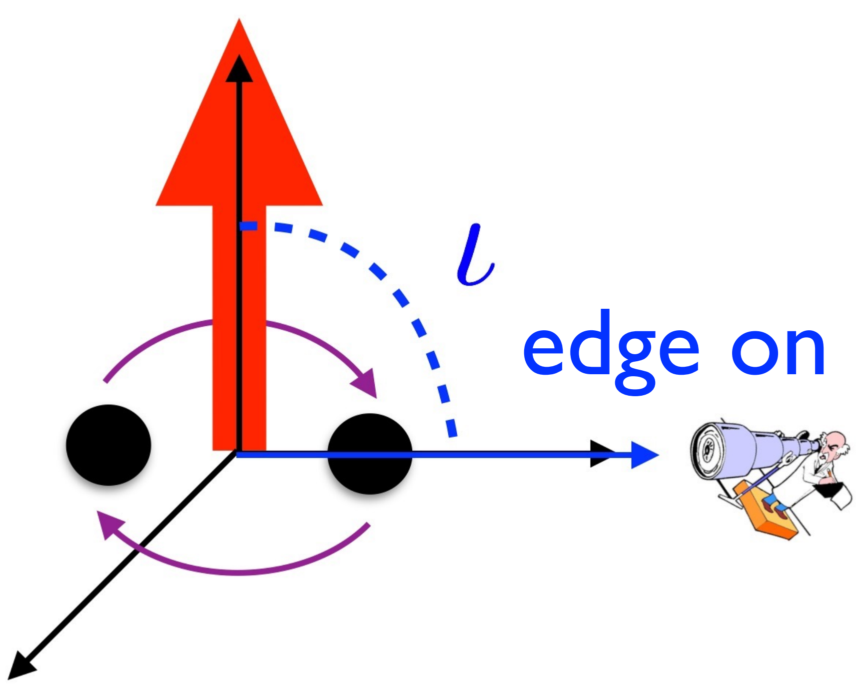


(credit: Cotesta)



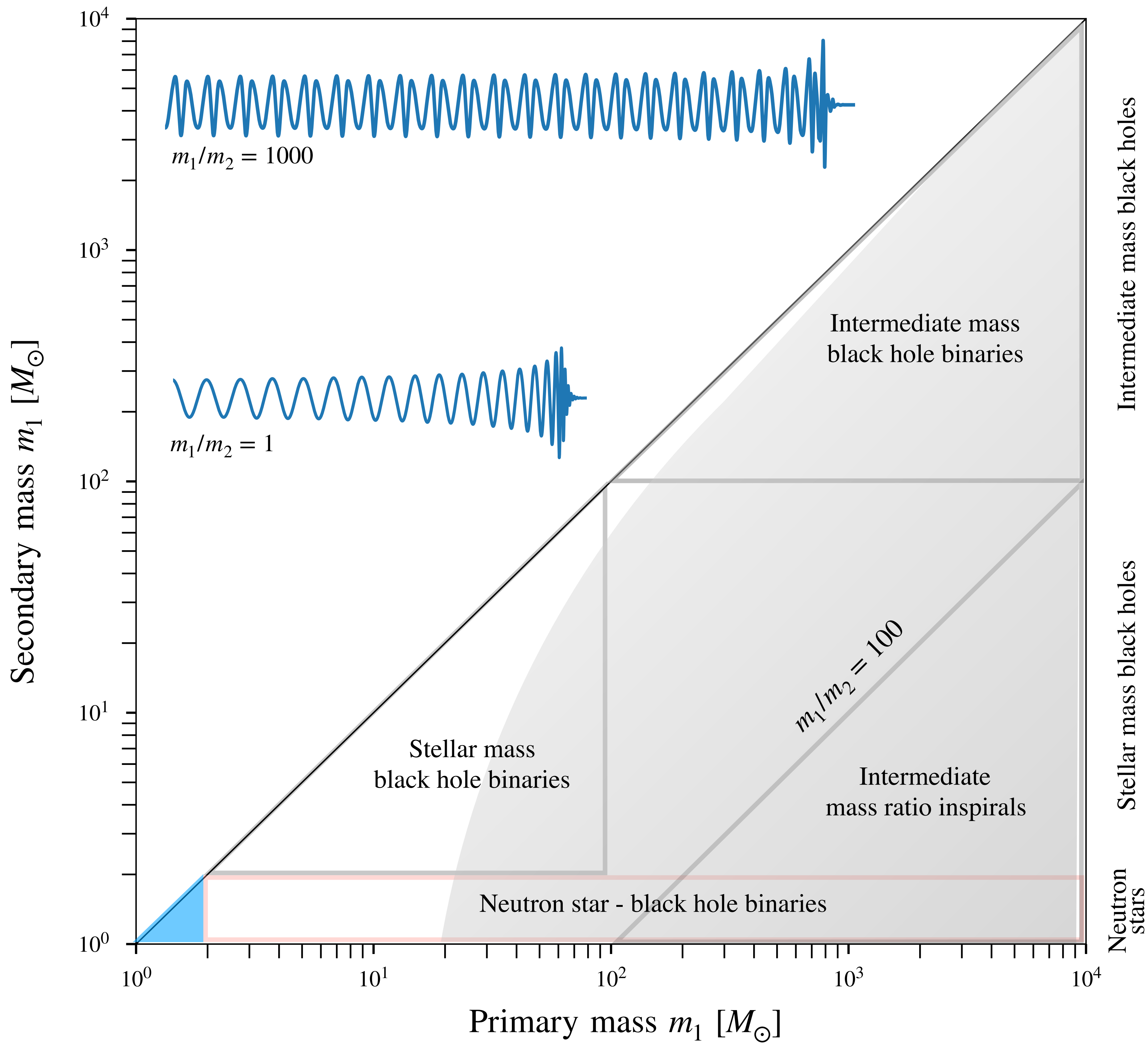
3G science by including missing physical effects: higher harmonics





- We will **detect unusual** GW events with 3G detectors.
- We need accurate waveform models with **higher harmonics, spin precession & eccentricity.**

Relevance of higher harmonics for 3G detectors



Gray region: more than **10% loss** in detection rate, thus **impacting parameters inference** and **science**.

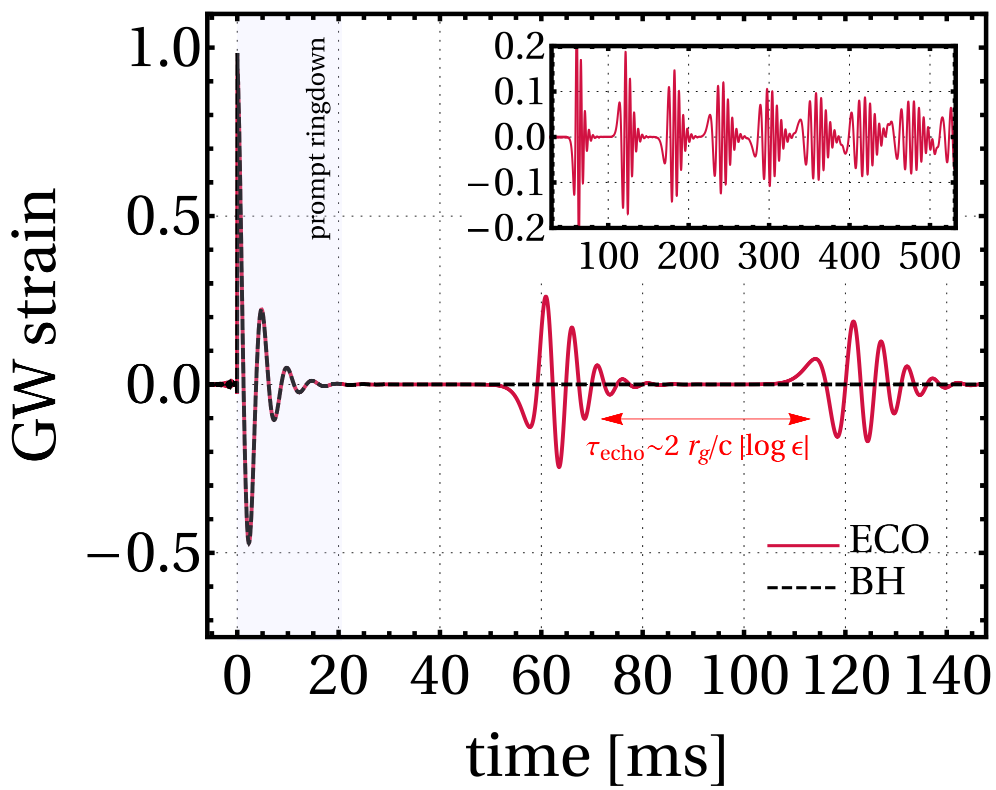
2G placeholder to be replaced by 3G results.

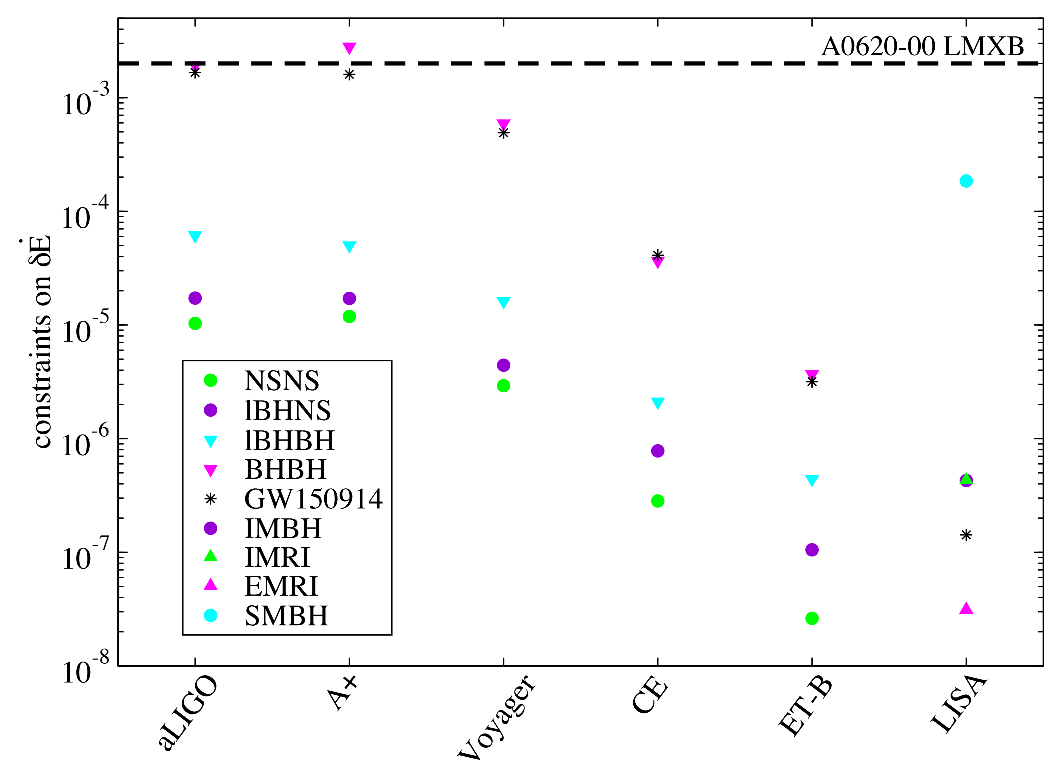
Need waveforms to test GR and probe nature of compact objects

- Need **AR & NR waveforms** in **modified theories of GR**: scalar-tensor theories, Einstein-Aether theory, dynamical Chern-Simons, Einstein-dilaton Gauss-Bonnet theory, massive gravity theories, etc.

- Need **AR & NR waveforms** of binaries composed of **exotic compact objects** (BH & NS mimickers), such as boson stars, gravastar, etc.

- Can we **disprove** the **presence** of BH "**horizon**" in binary mergers? **QNMs not consistent** with GR. **Echoes. Need modeling.**





Need novel and efficient methods to solve 2-body problem

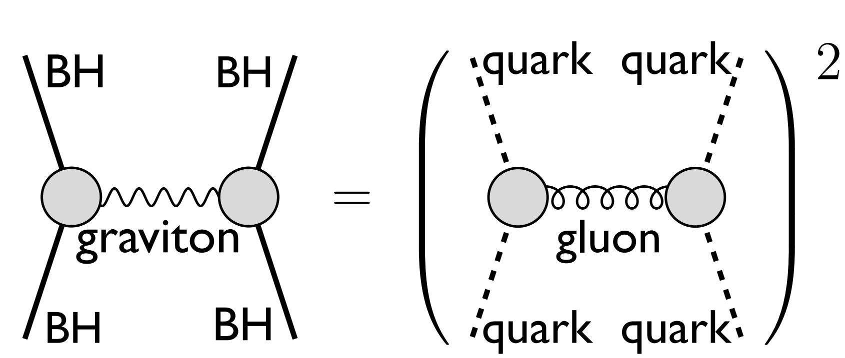
- Finite difference/spectral NR codes cannot be simply adapted to achieve **higher accuracy** over **longer evolutions** of compact objects with **large spins** and **mass ratios**. **Novel algorithms** are needed for **3G** detectors.

- Genuine **computations of PN/PM/GSF** corrections at **higher order** are **needed** but **will not solve accuracy** problem by themselves.

(credit: Justin Vines)

		0PN	1PN	2PN	3PN	4PN	5PN	...
0PM:	1	v^2	v^4	v^6	v^8	v^{10}	v^{12}	
1PM:		$1/r$	v^2/r	v^4/r	v^6/r	v^8/r	v^{10}/r	
2PM:‡			$1/r^2$	v^2/r^2	v^4/r^2	v^6/r^2‡	v^8/r^2‡	
3PM:				$1/r^3$	v^2/r^3	v^4/r^3	v^6/r^3	
4PM:					$1/r^4$	v^2/r^4	v^4/r^4	
...						...	...	

- **Modern scattering amplitude** methods of particles **applied to 2-body problem in GR**?



- **EOB** may combine efficiently PN/PM/GSF & NR, but it is likely that it **would need to be enhanced, tested and improved for 3G era.**

- **3G detectors** offer a challenging but exciting **opportunity** to build new **methods** (universal method?) to **solve 2-body problem** in entire parameter space.

Question

Is there anything else we should be high-lighting in the report about challenges in waveform modeling that would need to be addressed and solved to achieve 3G-detector science?