Where do binary black holes come from? How do we find out?

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January 15th, 2018
Sapienza theory seminars
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Outline

1. A new astronomy
Intro

2. Where do BHs come from?
Review

3. Spins remember formation channels…
DG+ arXiv:1302.4442 (PRD)

4. … and Supernova kicks!
O'Shaughnessy, **DG**+ arXiv:1704.03879 (PRL)

5. … and multiple merger generations!
DG, Berti arXiv:1703.06223 (PRD)

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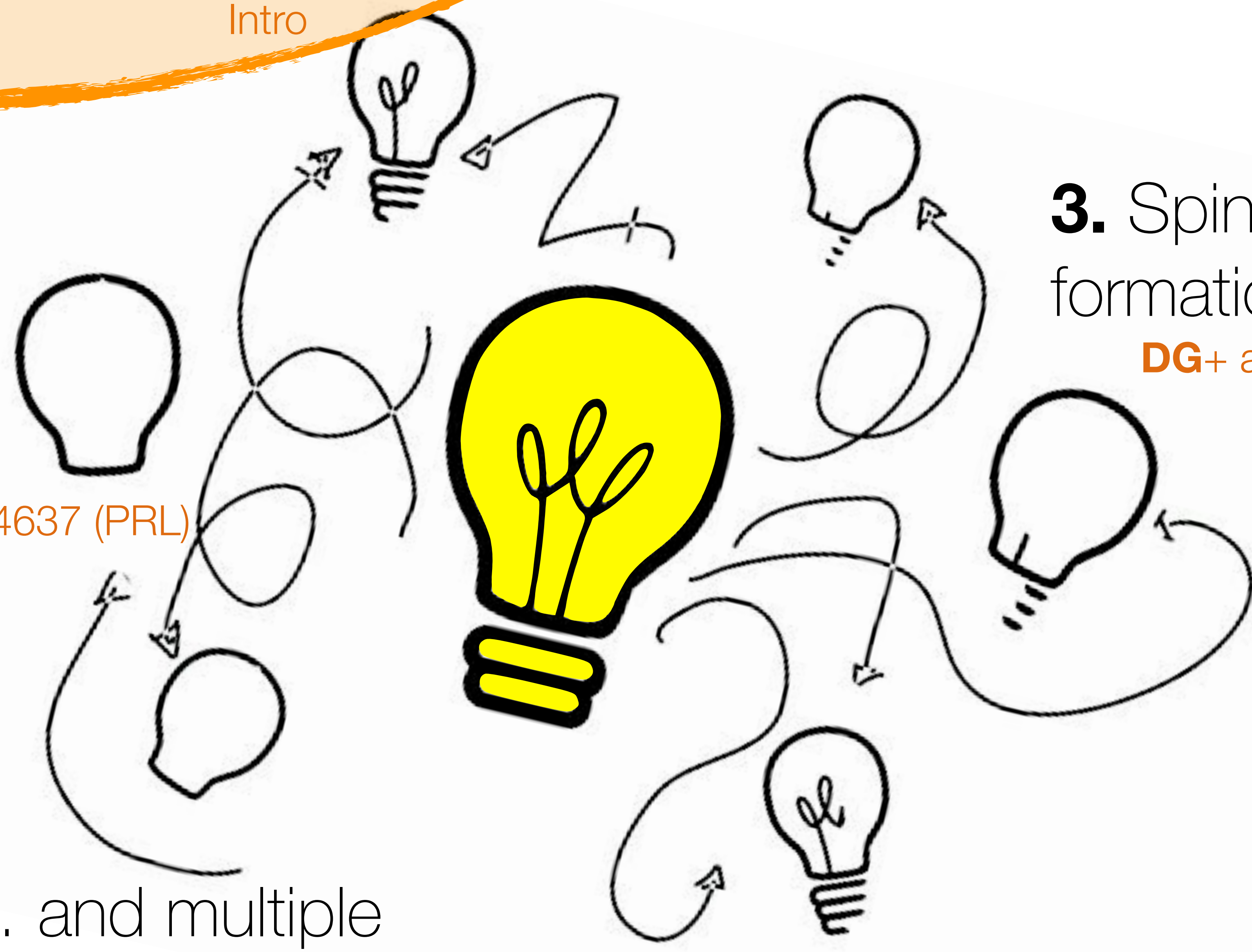

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A new window on the Universe

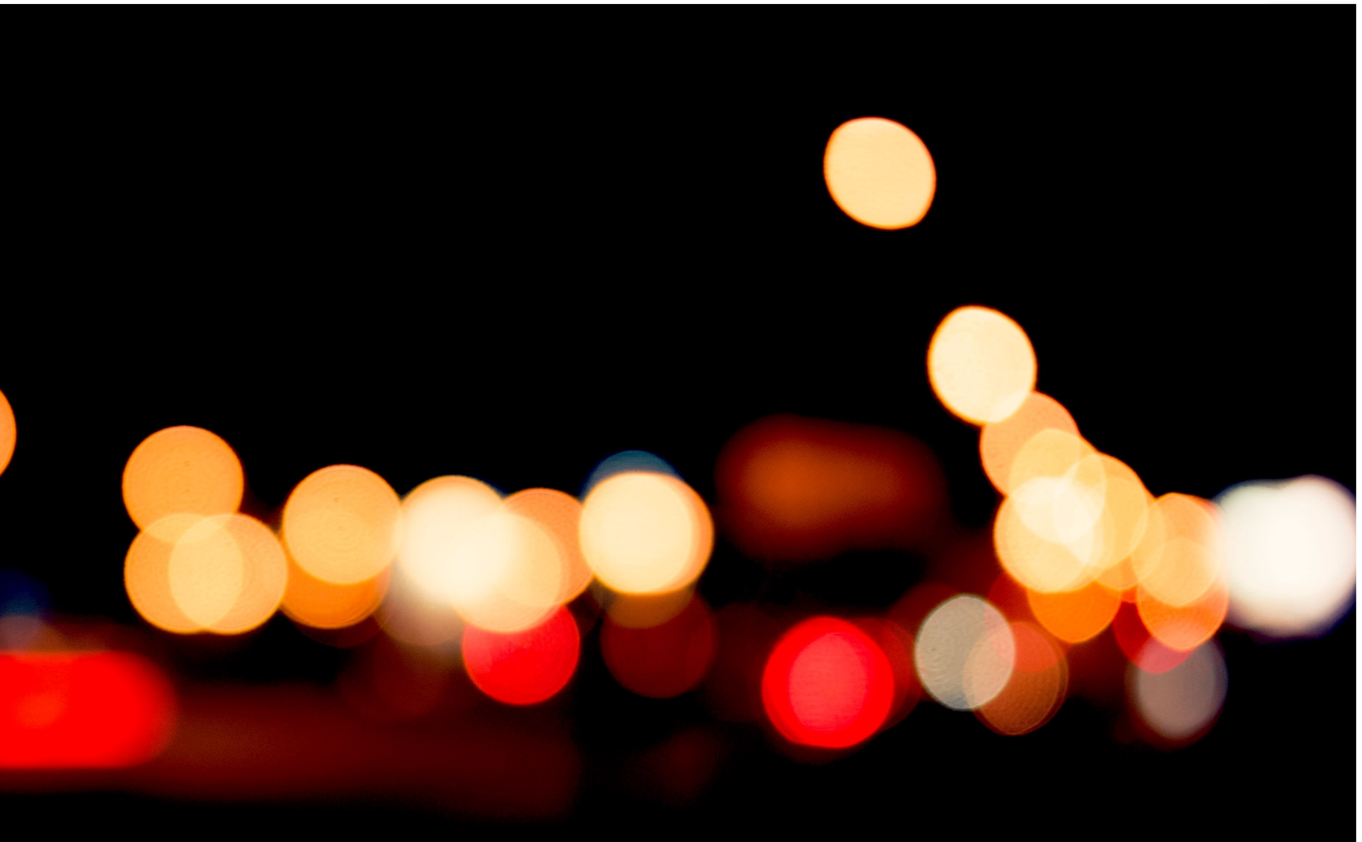
- Almost everything we know about the Universe comes through photons.
- **Gravitational-waves are a fundamentally new way!**
- Serendipitous discoveries came with new electromagnetic bands (X-ray binaries, gamma-ray bursts, pulsars, CMB…)

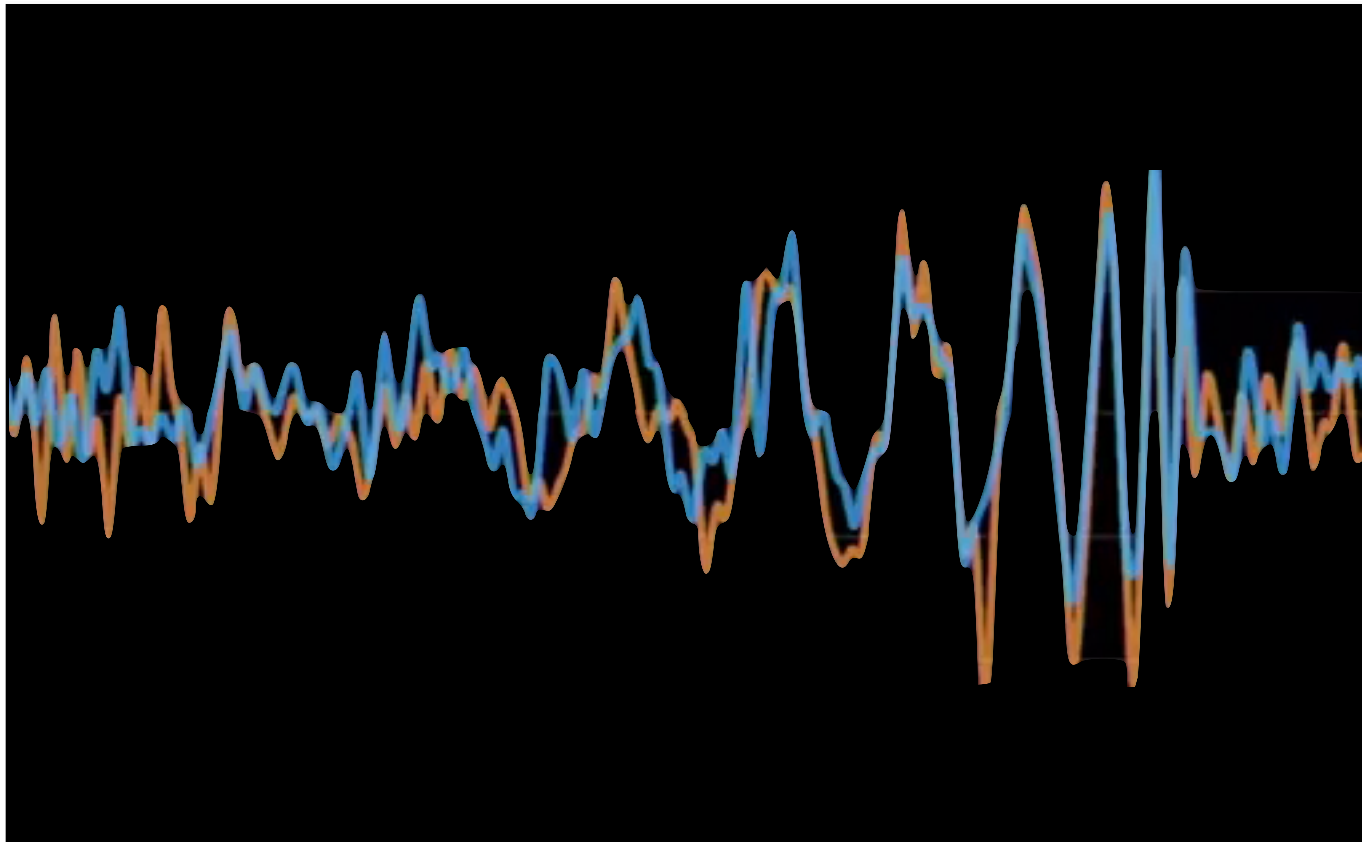
Electromagnetic radiation

- **Charges**
- **Strongly coupled**: easy to detect, but also easily scattered

Gravitational radiation

- Cumulative **mass** and momentum distribution
- **Very weakly coupled**: hard to detect, but travel unaffected!





Ripples in the fabric of spacetime

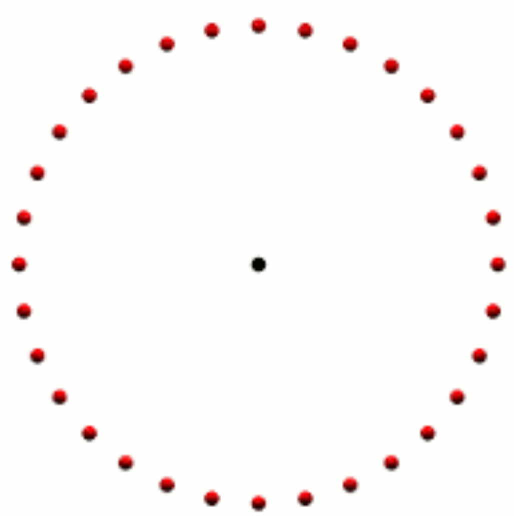
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$ Einstein equations

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$ …linearized

Mass quadrupole $$Q_{jk} = \int \rho x_j x_k \, \mathrm{d}^3 x$$

GW propagation $\Box \bar{h}_{\mu\nu} = 0$

$$h_{ij}^{\mathrm{TT}}(t,z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix} \cos\left[\omega\left(t - \frac{z}{c}\right)\right]$$



Equivalence principle: measure tidal forces

GW emission $h_{jk} = \frac{2}{r}\frac{d^2 Q_{jk}}{dt^2}$

$$h \sim \frac{M v^2}{r} \sim \frac{\Delta L}{L}$$

strain (h), mass (M), velocity (v), distance (r), measurement (ΔL), detector (L)

Binaries are natural emitters

Binary cars?

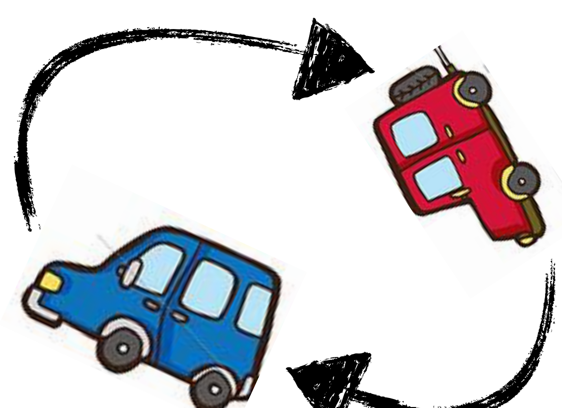
$M \sim 10^3\,\mathrm{Kg}$

$v \sim 1000\,\mathrm{Km/h}$

on a 1 km track

$r \sim \lambda \sim R_{\mathrm{Earth}}$

$h \sim 10^{-42}$



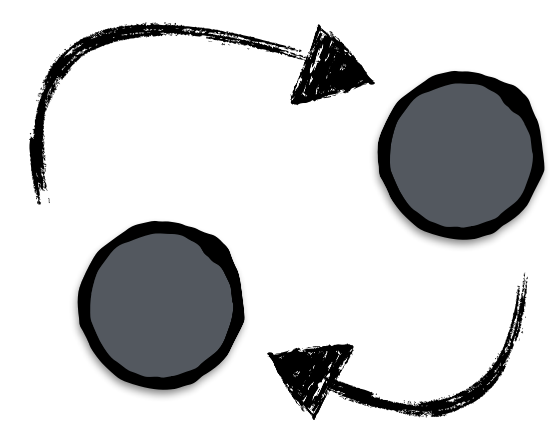
Binary black holes!

$M \sim 10 M_\odot \sim 10^{31}\,\mathrm{Kg}$

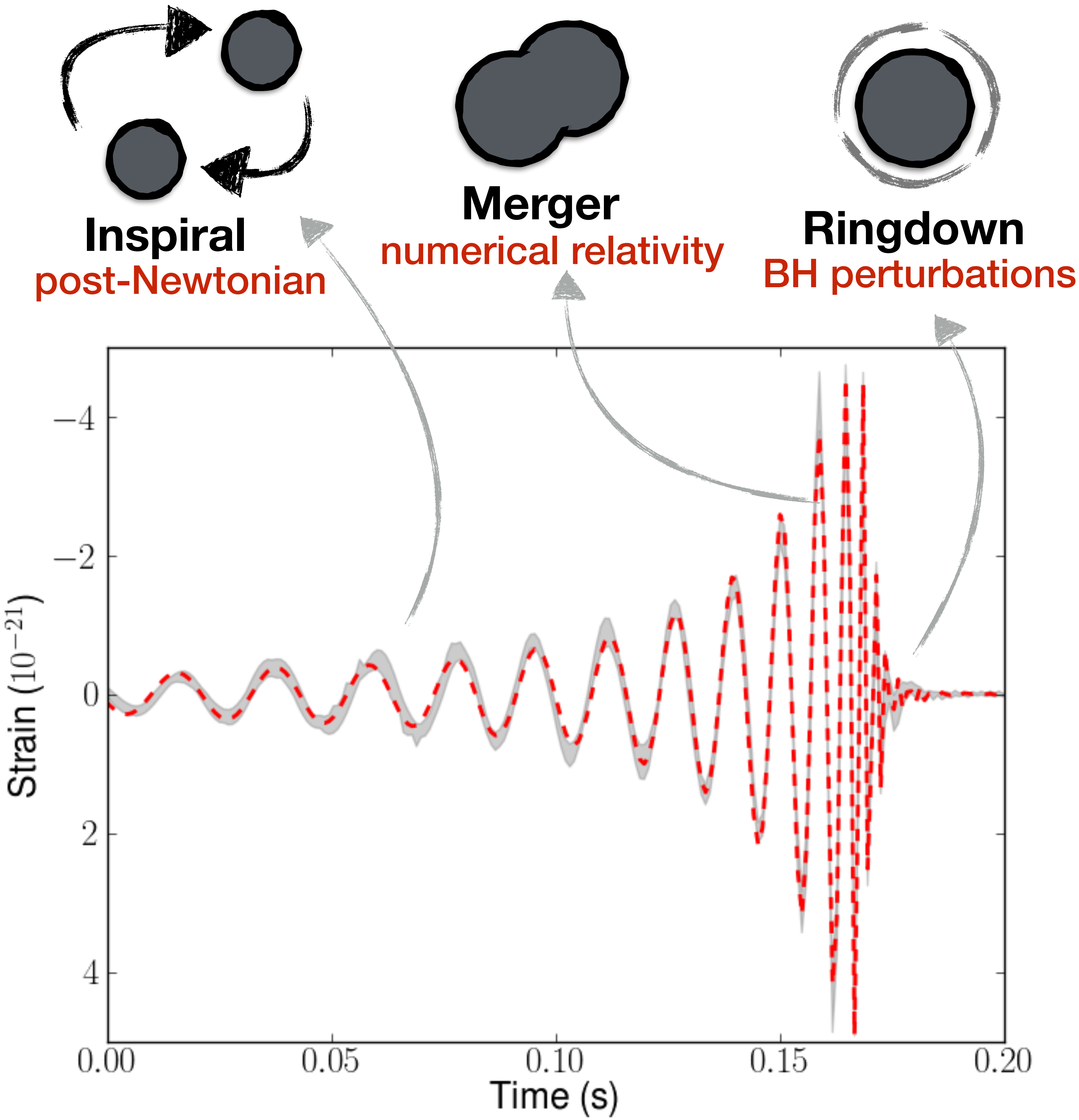
$v \sim 0.1c$

$r \sim 100\,\mathrm{Mpc}$

$h \sim 10^{-21}$

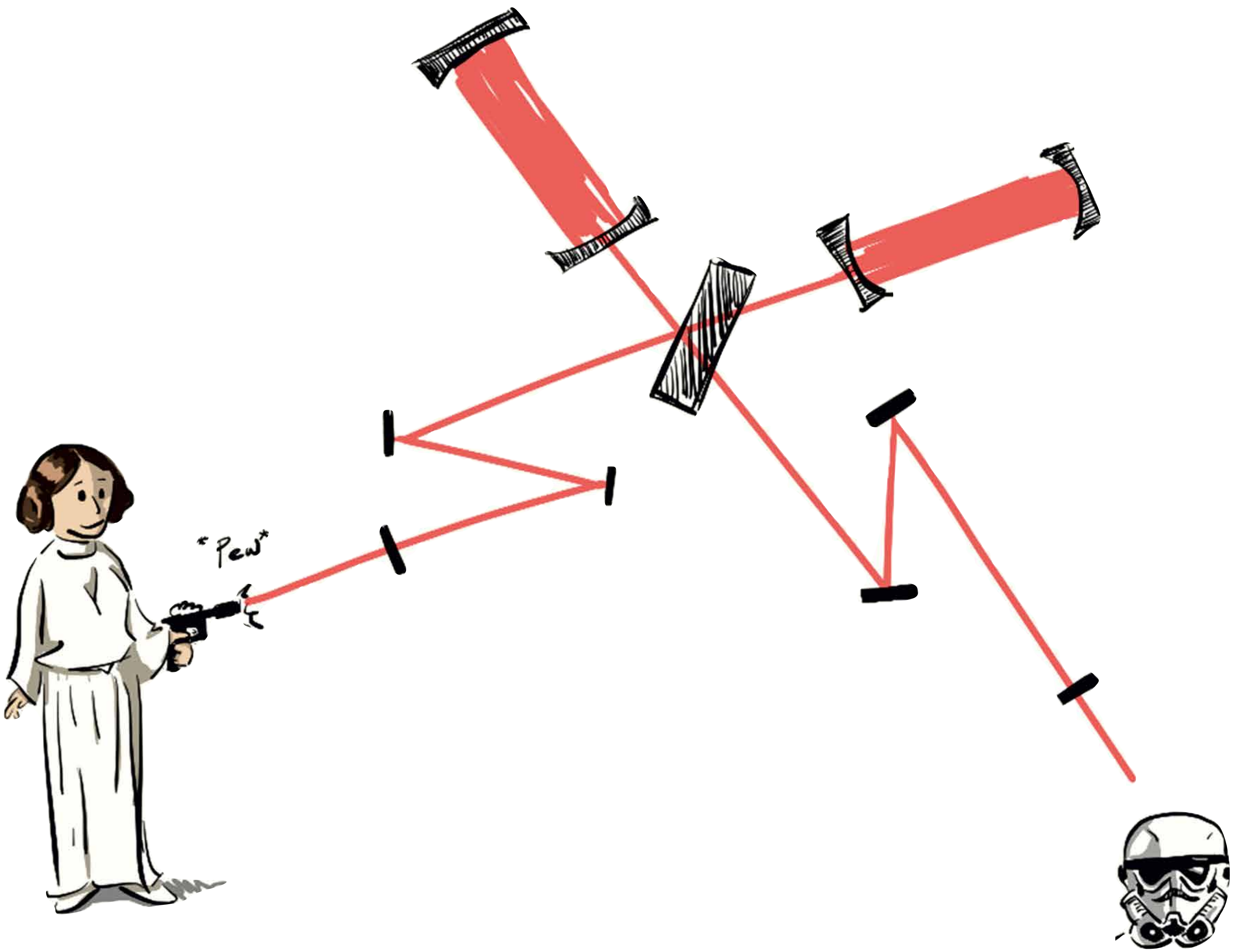


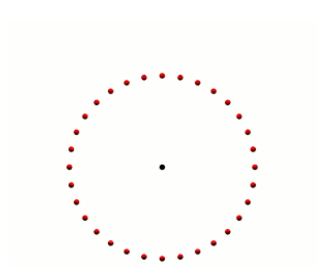
GW signals from BH mergers



- Frequency gradually increases during the **inspiral**
- **Merger** of two BHs is one of the most energetic events in the Universe
- Direct signal from highly-dynamic strong-field gravity
- *BHs have no hair*: final remnant has to dissipate all properties but mass and spin (**ringdown**)

LIGO/Virgo (for a theorist)





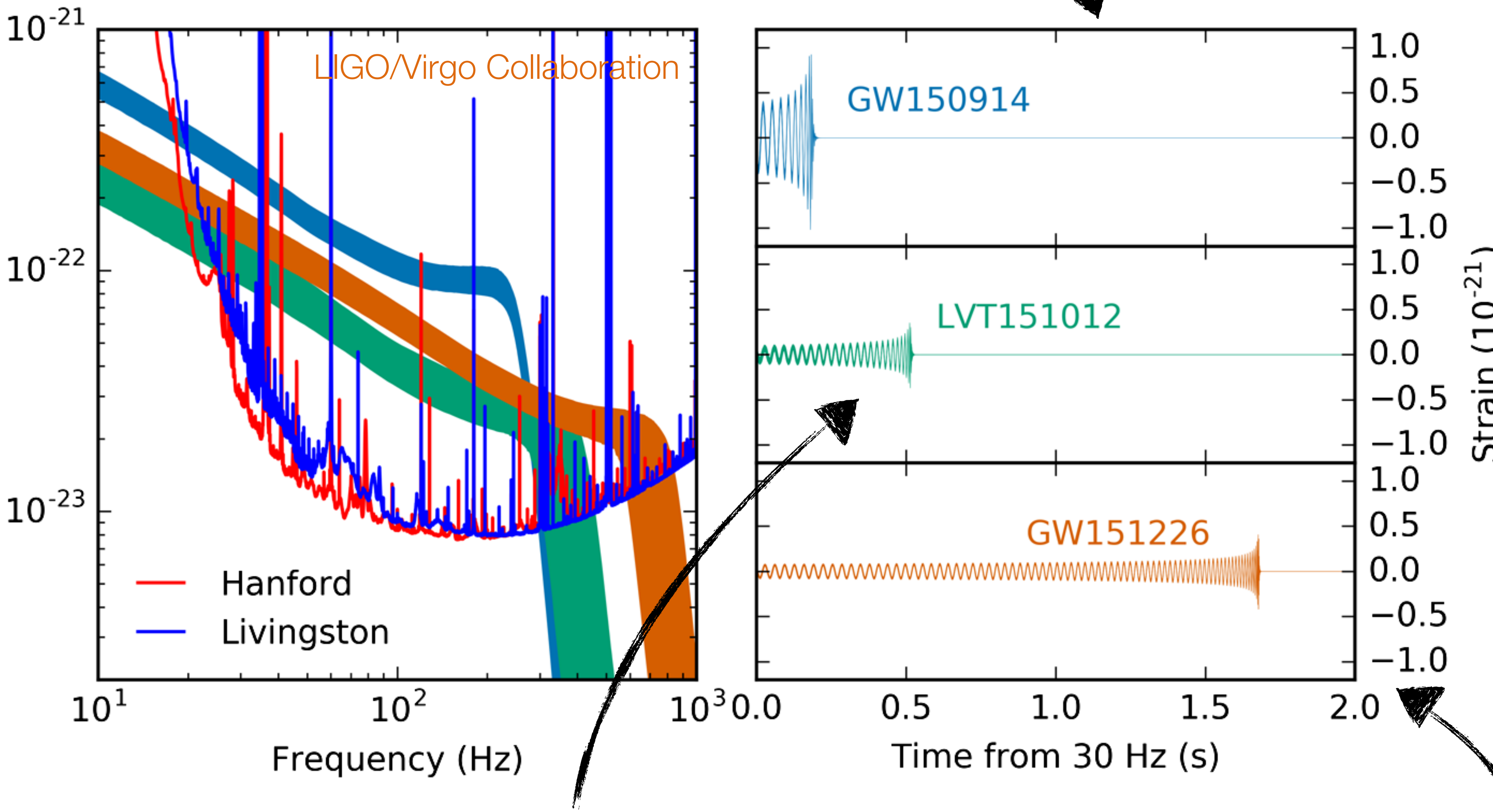
...4 km arms measured with the precision of about 1/1000 the diameter of a proton!

LIGO/Virgo (for real)

LIGO's O1: an incredible story…

GW150914

A few days before starting operations…



LVT151012

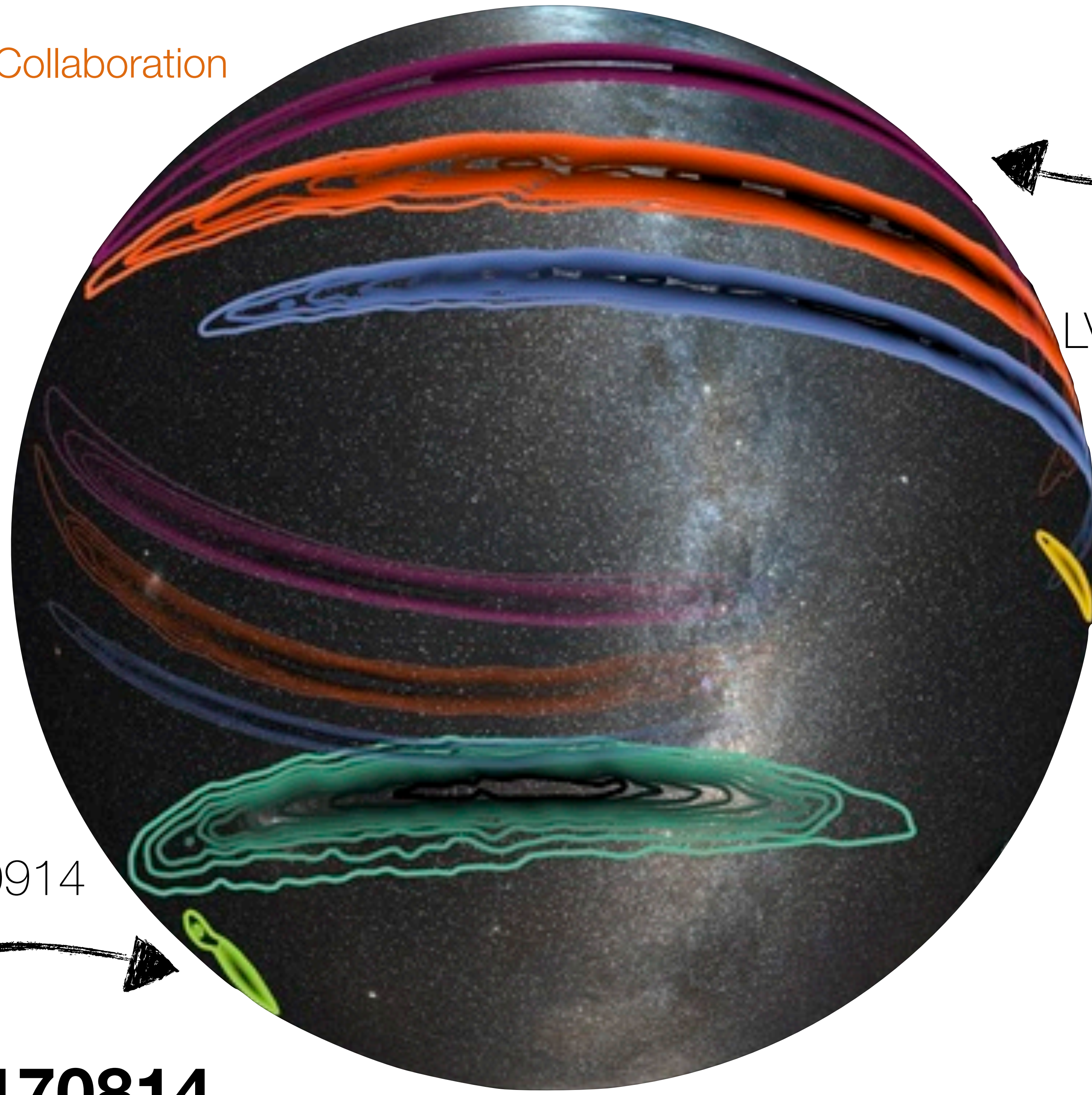
That's 87% of a BH binary…

GW151226

Lower mass, many more cycle and spins!

LIGO/Virgo's O2: a more incredible story…

LIGO/Virgo Collaboration



GW170104

Another big one…

LVT151012

GW151226

GW170817

There's a new kid in town

GW150914

GW170608

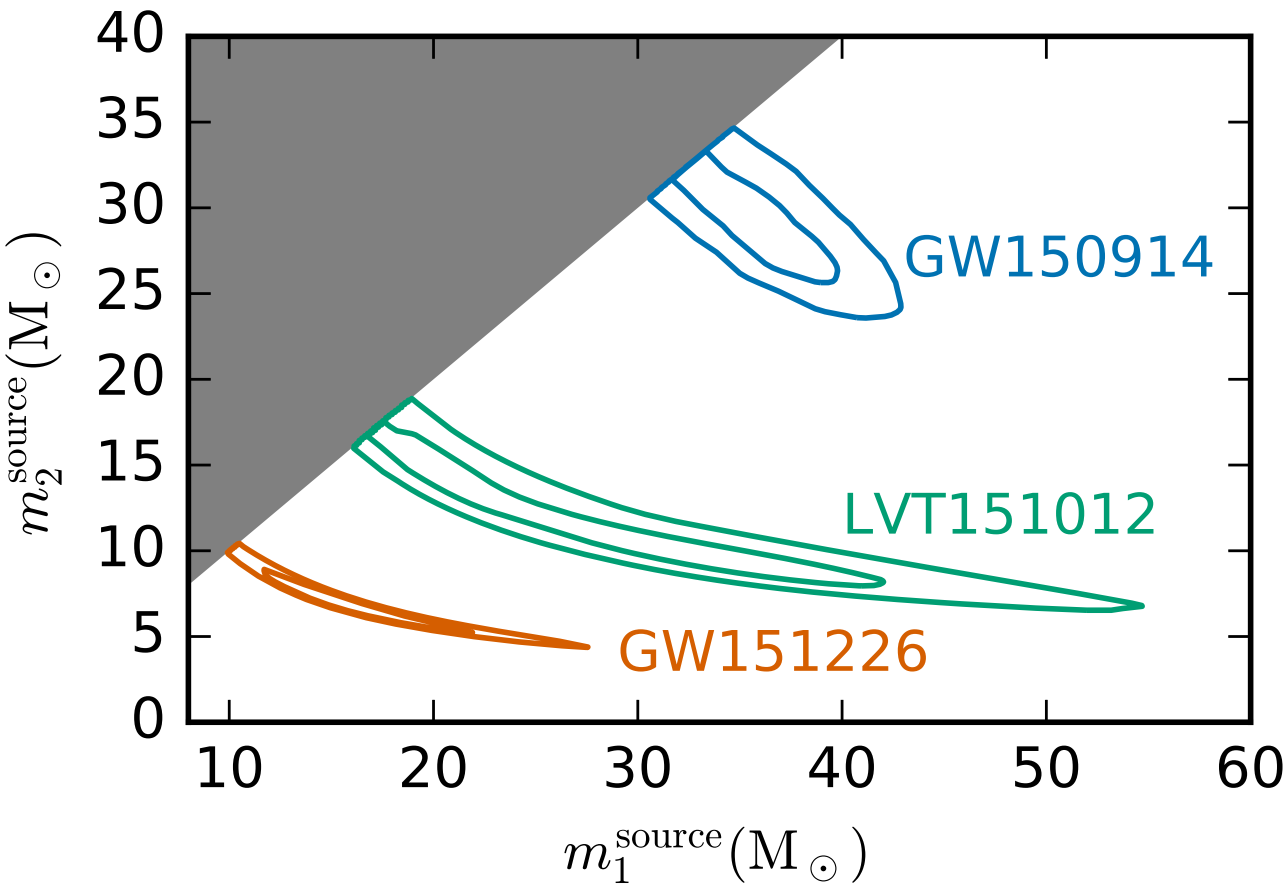
That was too much for a single figure…

GW170814

Neutron stars! Gamma rays, and optical counterpart, and X ray later, radio still on…

…and not all the O2 results are announced!

BH mass measurements



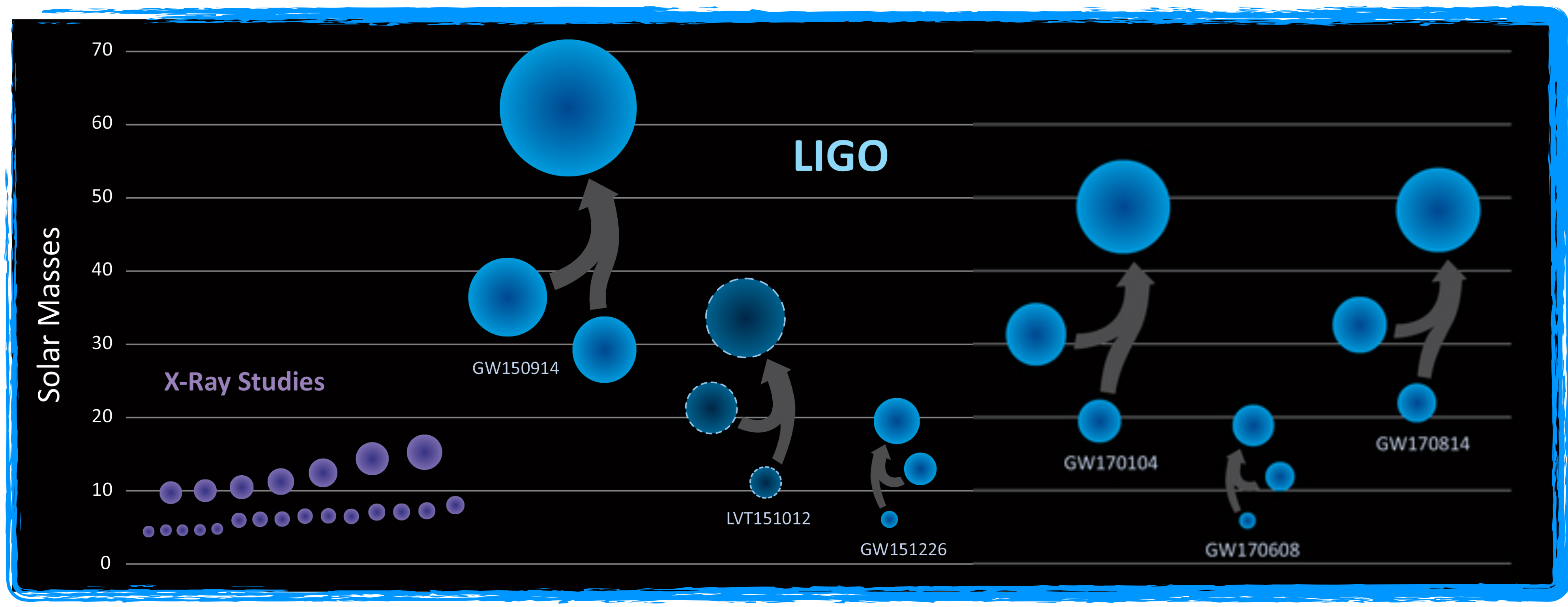
- Low mass: many orbits; chirp mass:

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- High mass: mainly merger; total mass:

$$M_{\rm tot} = m_1 + m_2$$

Another population? Just the tip of the iceberg!

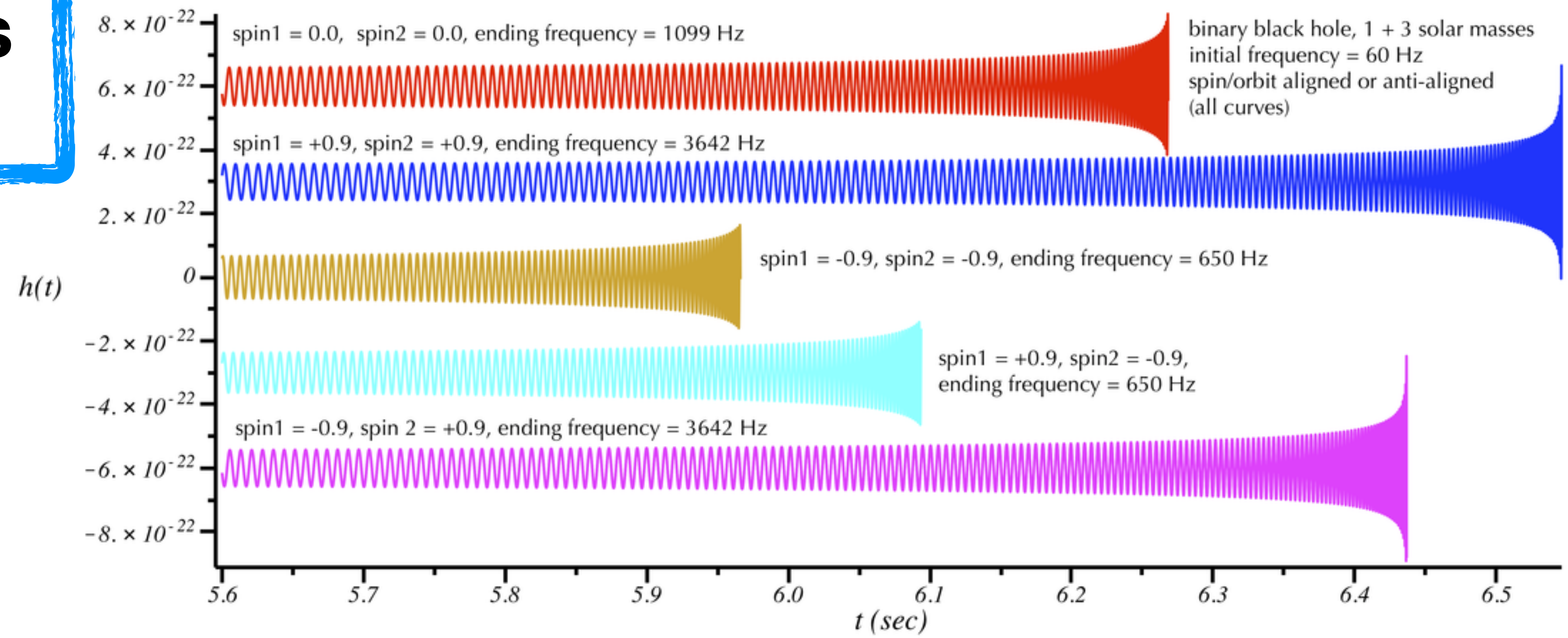


Spin in the waveform

Aligned components of the spins

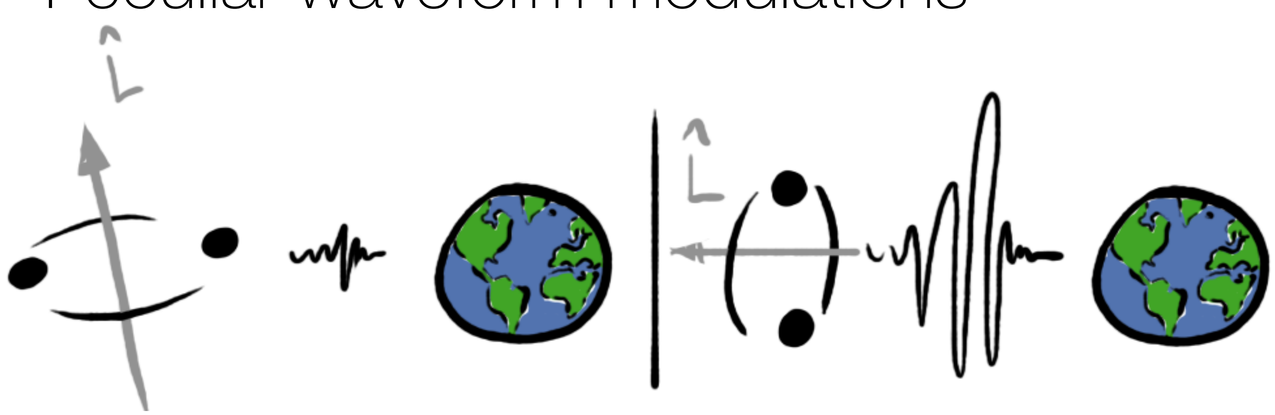
- Different merger frequency (analog of the ISCO)
- Aligned spins take longer to merge

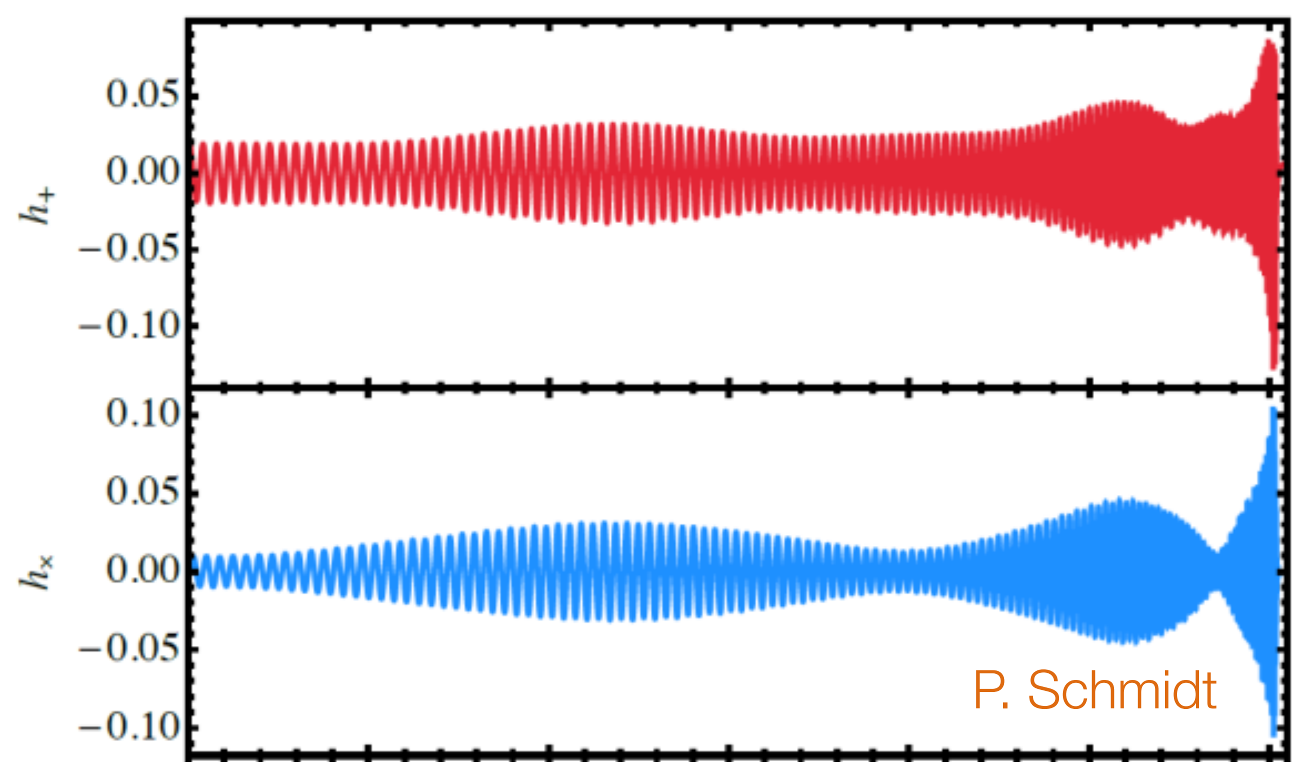
M. Favata



Orbital-plane components of the spins

- spin precession; orbital plane precession
- Peculiar waveform modulations



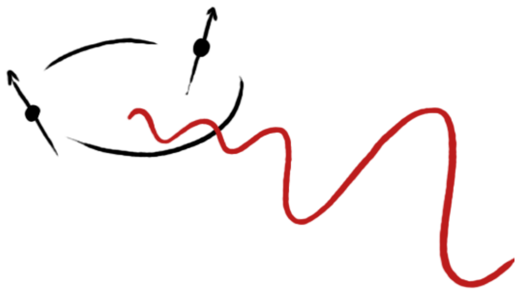


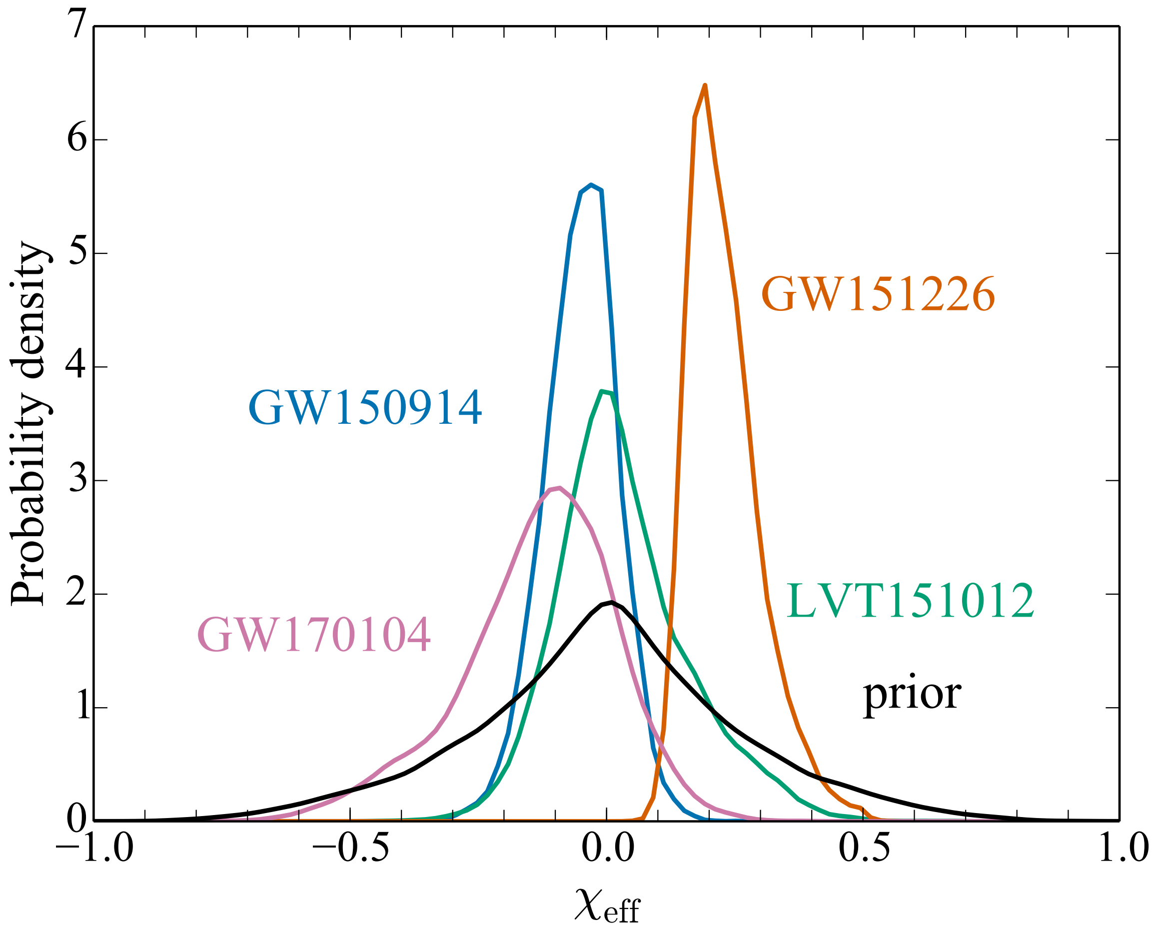
Spin measurements

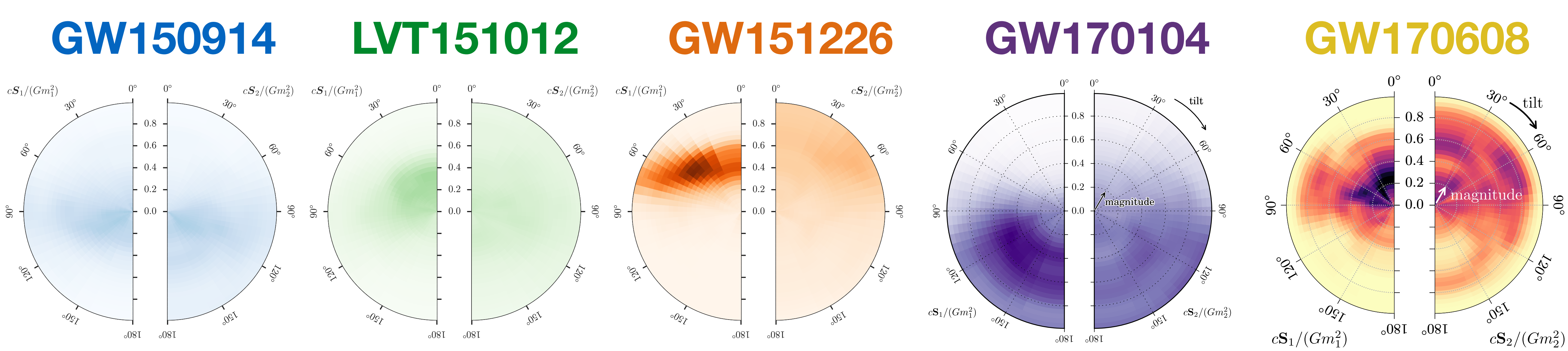
- Best measured quantity: effective spin

$$\chi_{\rm eff} = \left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\frac{\hat{\mathbf{L}}}{M}$$

- Constant of motion at 2PN Racine 2008; **DG**+ 2015
- Careful with that prior… Vitale. **DG**+ 2017







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Can BHs really make it?

Peters and Mathews 1963
Peters 1964

At lowest order, **GW emission** causes the orbit to shrink:

separation $$\frac{da}{dt} = -\frac{64}{5}\frac{G^3M^3}{c^5a^3}\frac{q}{(1+q)^2}(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

eccentricity $$\frac{de}{dt} = -\frac{304}{15}e\frac{G^3M^3}{c^5a^4}\frac{q}{(1+q)^2}(1-e^2)^{-5/2}\left(1+\frac{121}{304}e^2\right)$$

Circularization

$$\frac{da}{de} \sim \frac{12}{19}\frac{a}{e} \longrightarrow a \sim e^{12/19}$$

GW-driven inspiral timescale

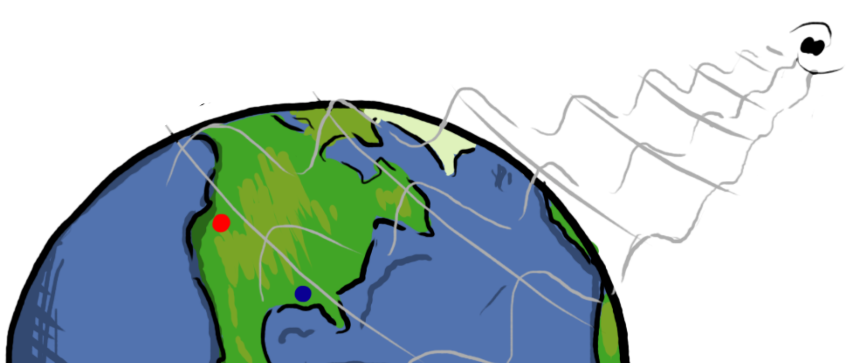
$$t_{\rm GW} \sim a\frac{dt}{da} \sim a^4$$

Gravitational waves are efficient below

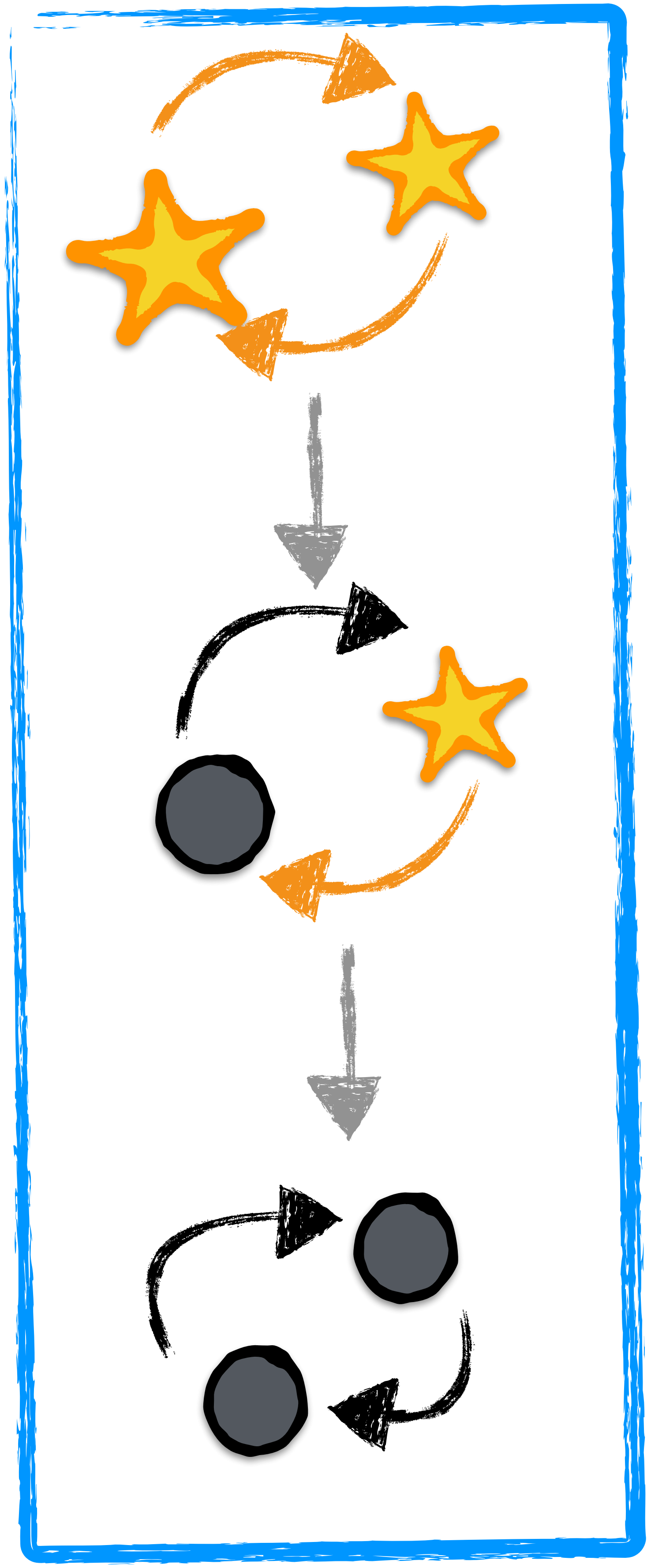
$$a_{\rm GW} = 1.2\times10^{11}\left(\frac{t_{\rm GW}}{1.4\times10^{10}{\rm yr}}\right)^{1/4}\left(\frac{M}{M_\odot}\right)^{3/4}{\rm cm}$$

$\sim 10R_\odot$ stellar-mass BHs

~ 0.01 pc supermassive BHs

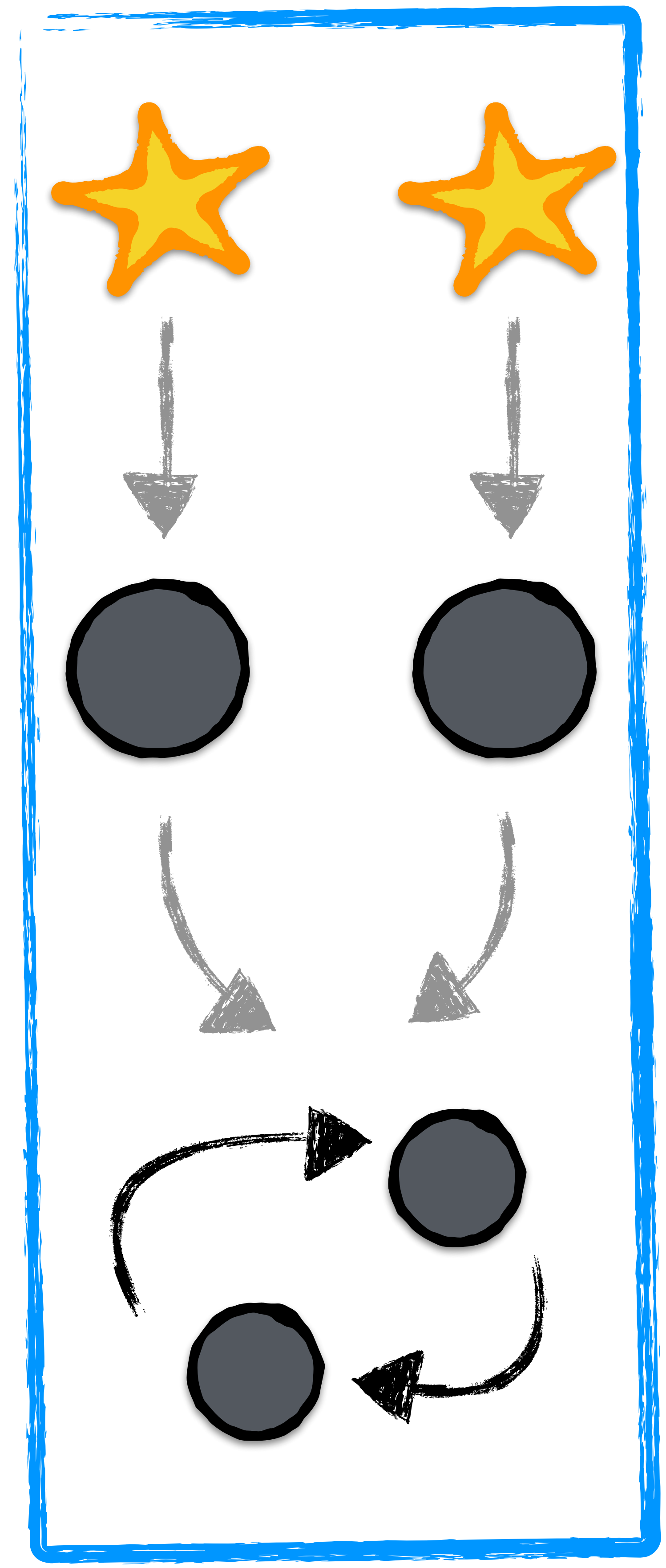


Have we been together for so long?



Yes! I’ve known you since you were a star

Don’t you remember? We just met in cluster



Massive stars to BHs: *field* evolution

1. **Main-sequence** binary star

2. First evolves to supergiant:
Roche-lobe overflow, **mass transfer**

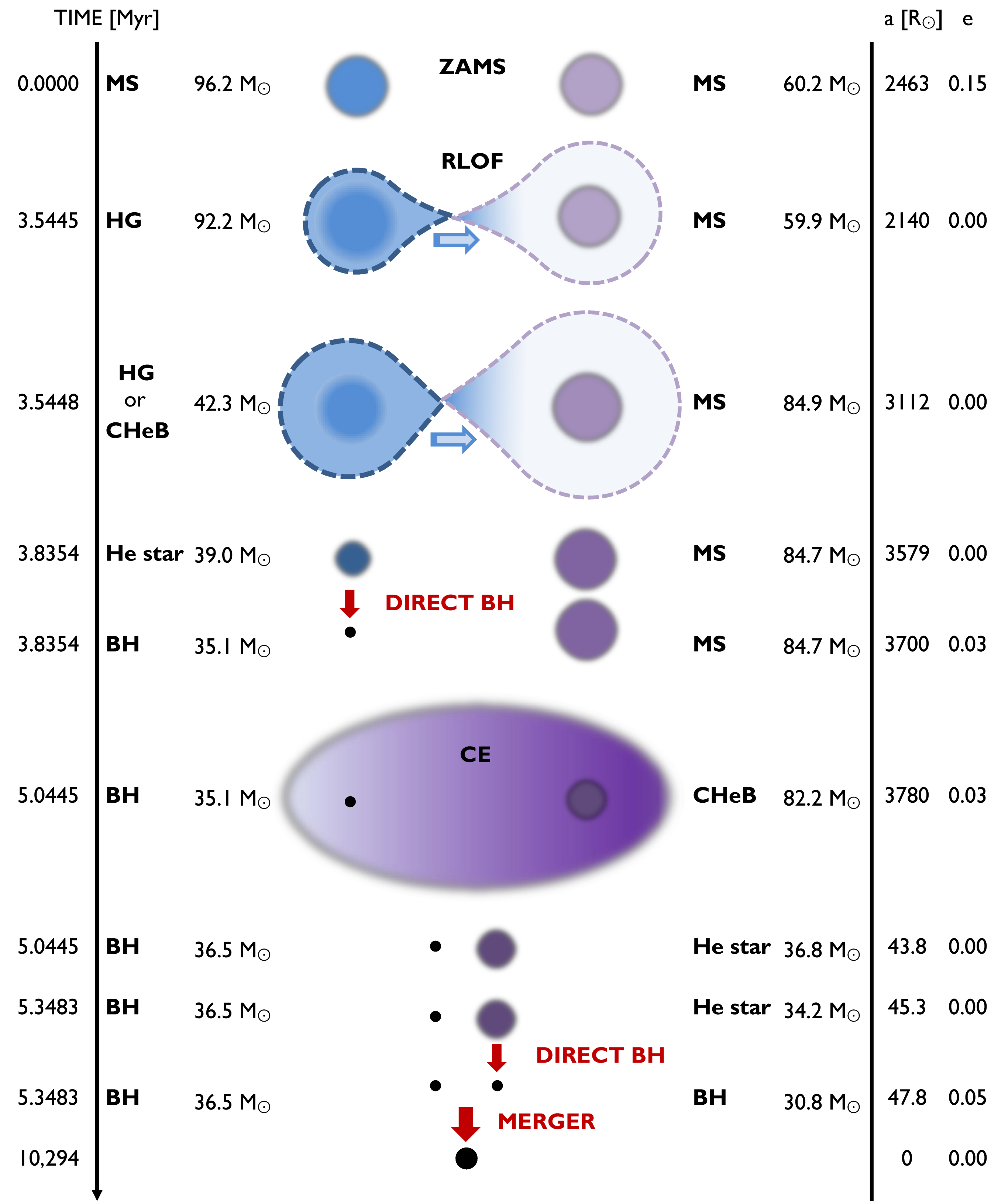
3. First goes **supernova** and forms a BH
Is it still a binary?

4. Second evolves to supergiant:
common envelope
<u>Must be efficient… Critical stage to bring the separation down!</u>
… but not too much: is it still a binary?

5. Second goes **supernova** and forms a BH
Is it still a binary?

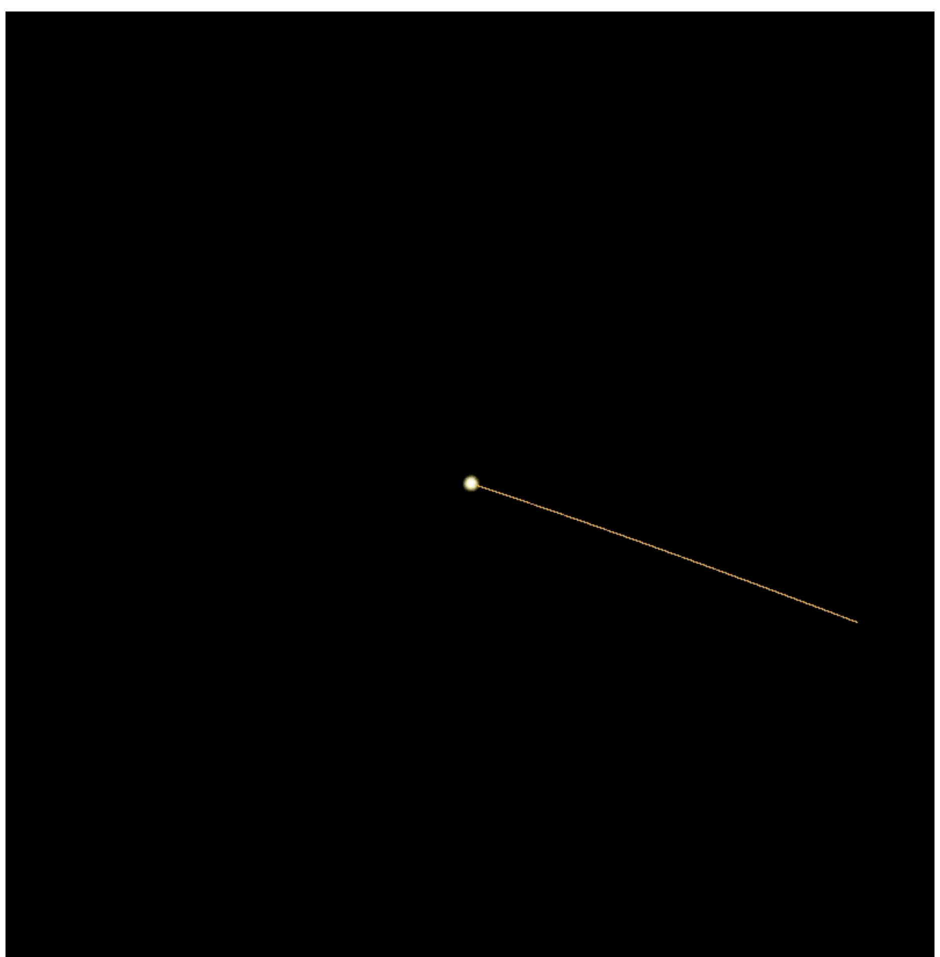
6. Inspiral, merger, ringdown and LIGO

Belczynski+2016



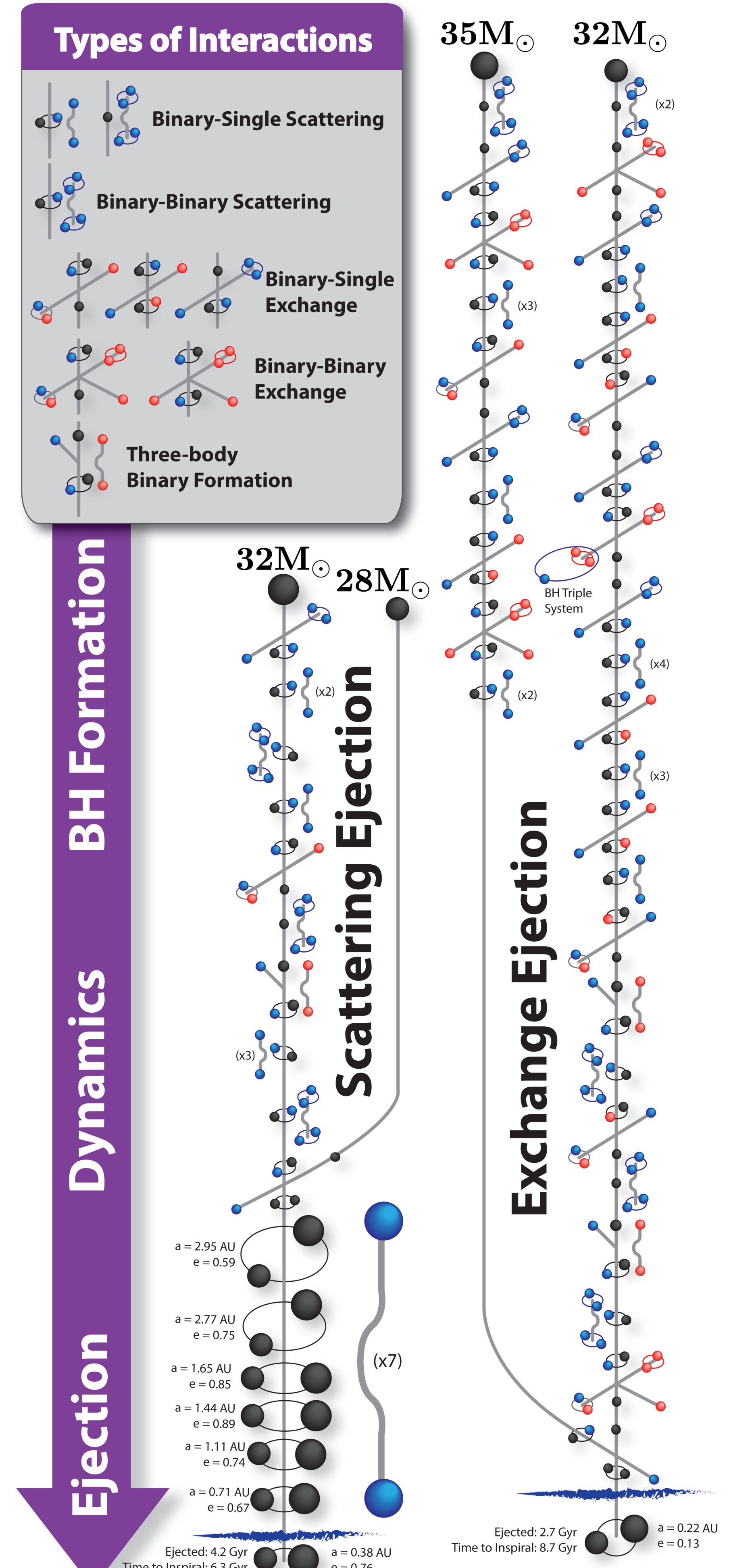
Dynamical assembling: *cluster* evolution

1. **Dense stellar clusters, many three body interactions**
2. Dynamical friction: heavy objects sink towards the center
3. Soft binaries become softer, hard binaries become harder



A. Geller

Key point: stellar evolution is separate! They meet, swap, meet again, etc…

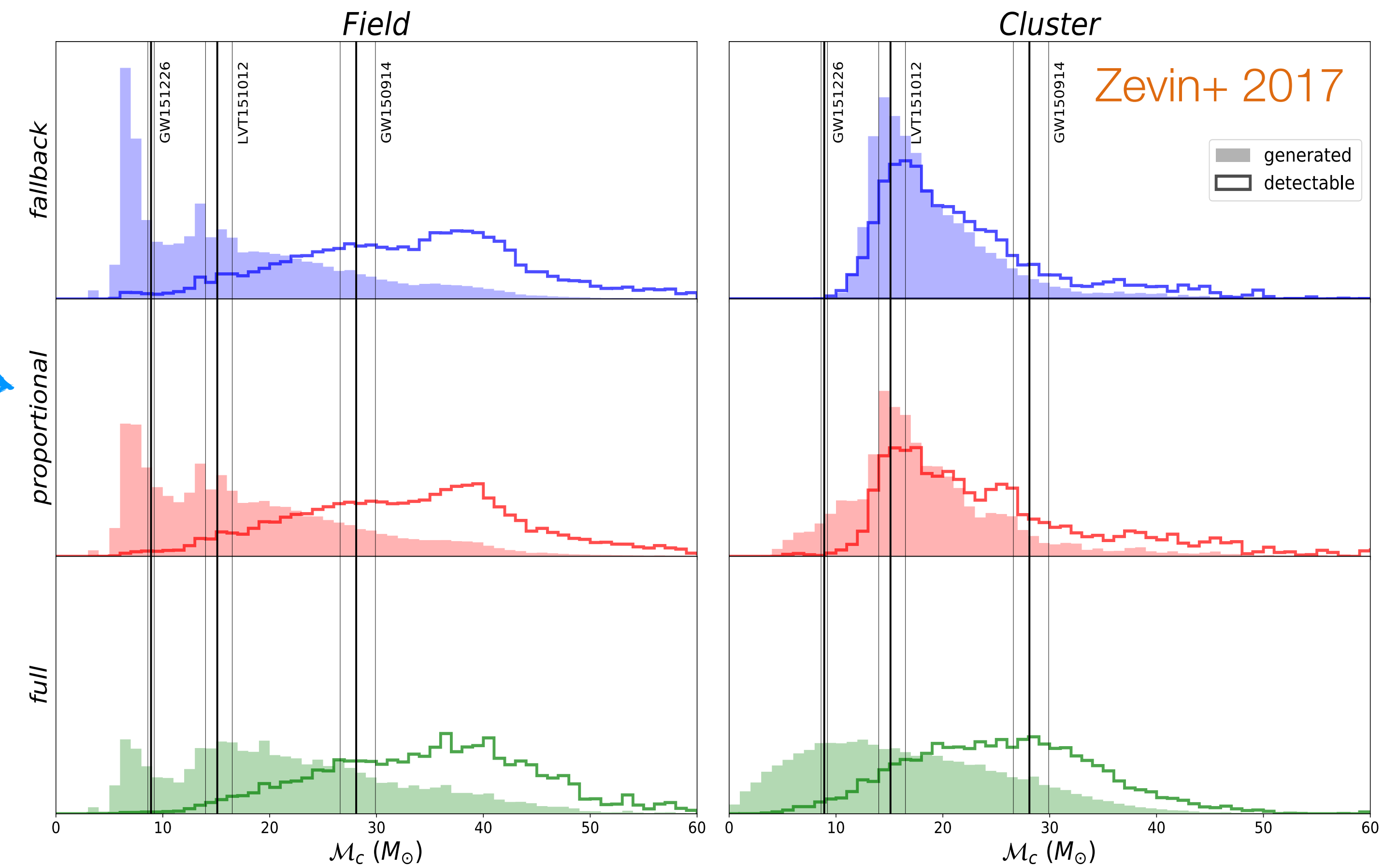


Rodriguez+2016

Can we tell them apart?

Masses and rates

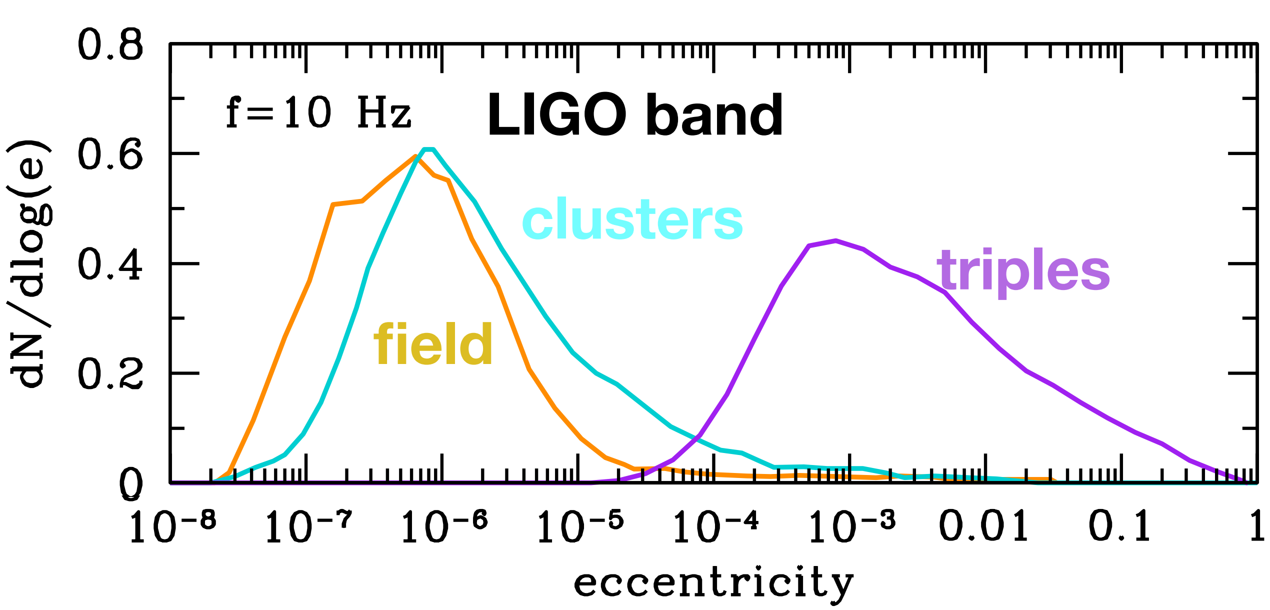
>100 events needed to distinguish these populations with masses and rates…
Stevenson+ 2015, Zevin+ 2017



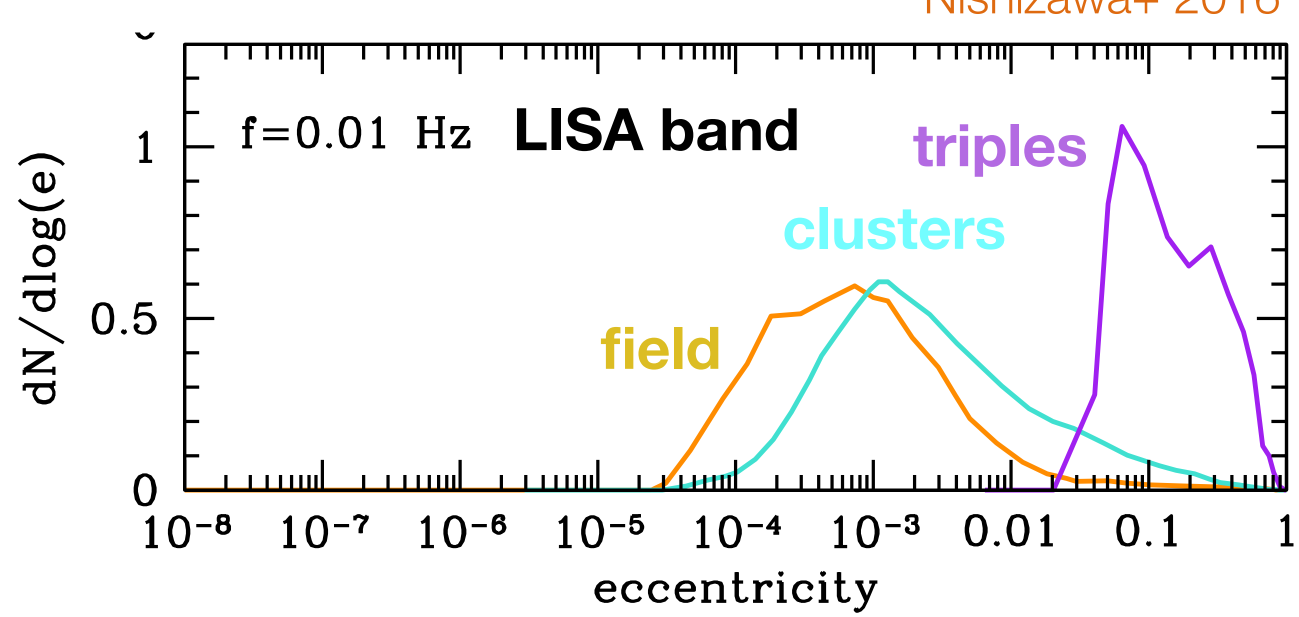
Eccentricities

Promising! Especially for specific scenarios, e.g. Antonini Perets 2012

Multiband GW astronomy:
O(10) LISA observations Nishizawa+ 2016



Nishizawa+ 2016



Spins have secrets!

Field binaries: evolve together. Tidal interactions and accretion tend to align the spins?

Cluster binaries: evolve separately and then meet. Isotropic spin distribution, more precession?

What information is encoded in the spins for the events we have?
And from many more detections?

My two cents. The good news first…

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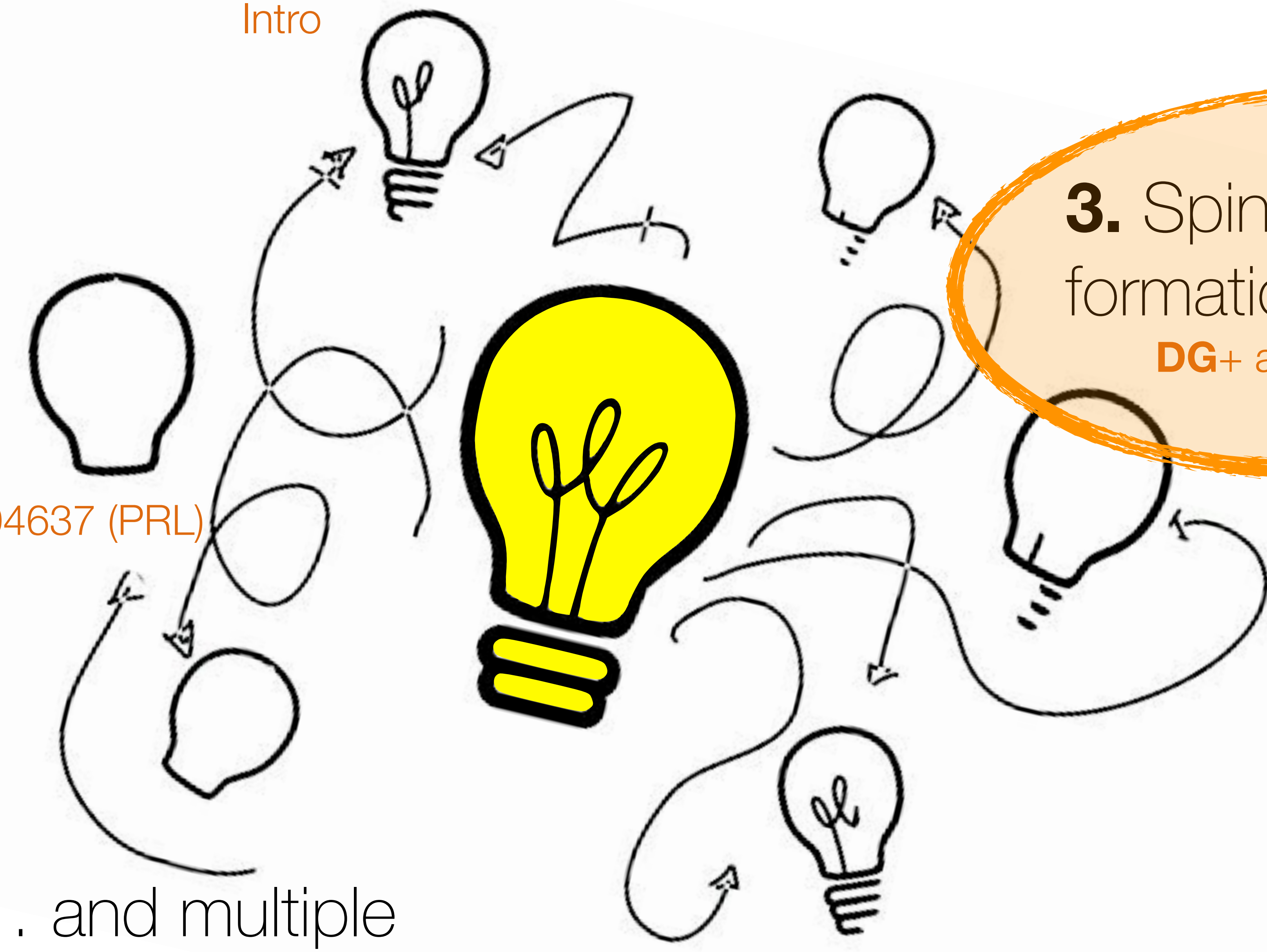

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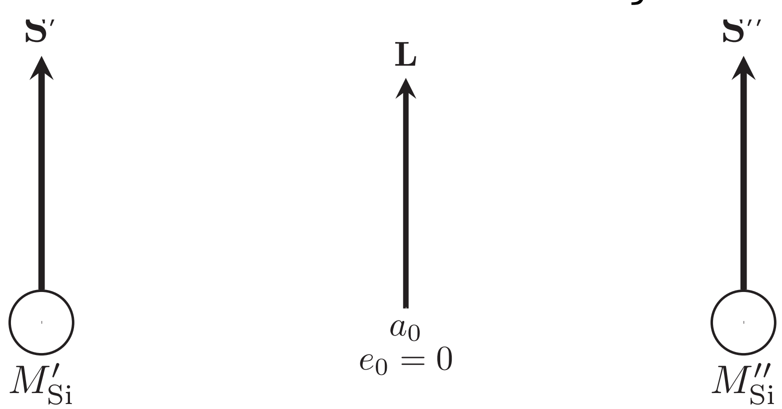
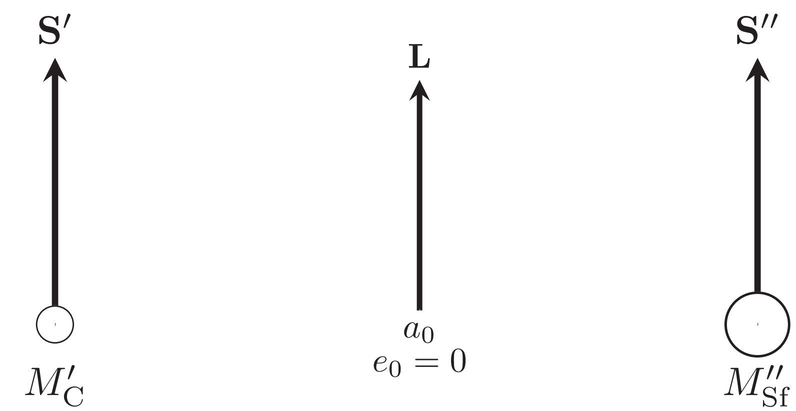
Field binaries, spin tracking

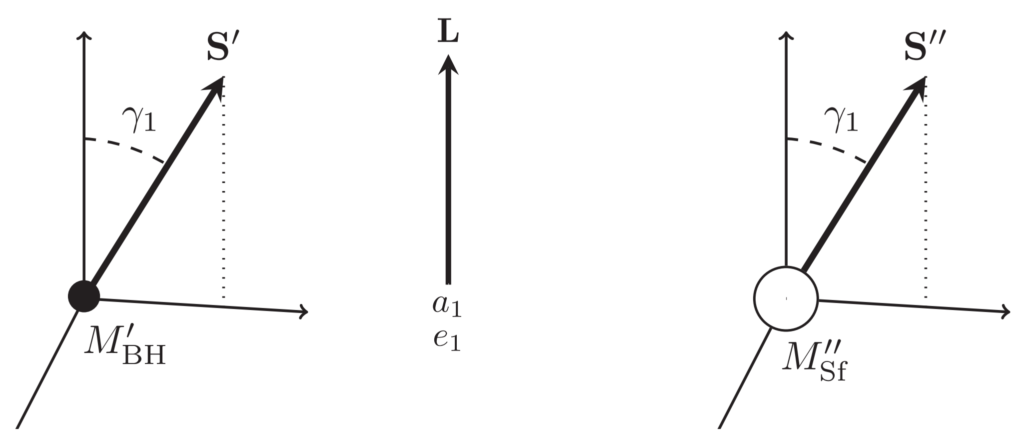
1. Massive binary stars



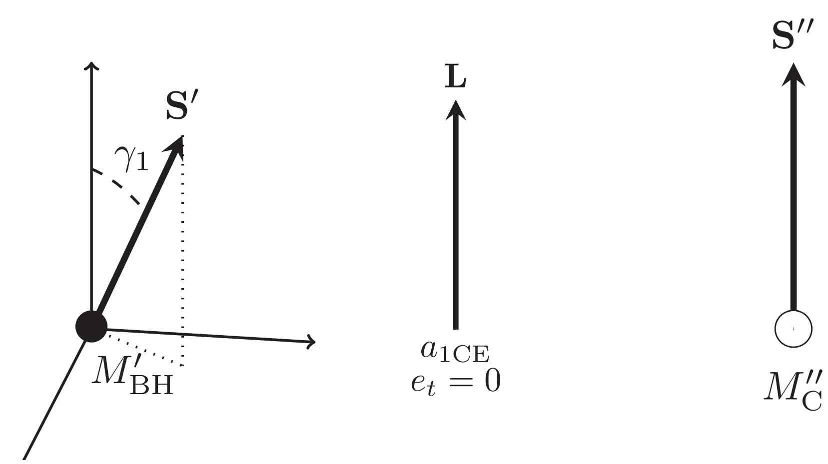
2. Mass transfer



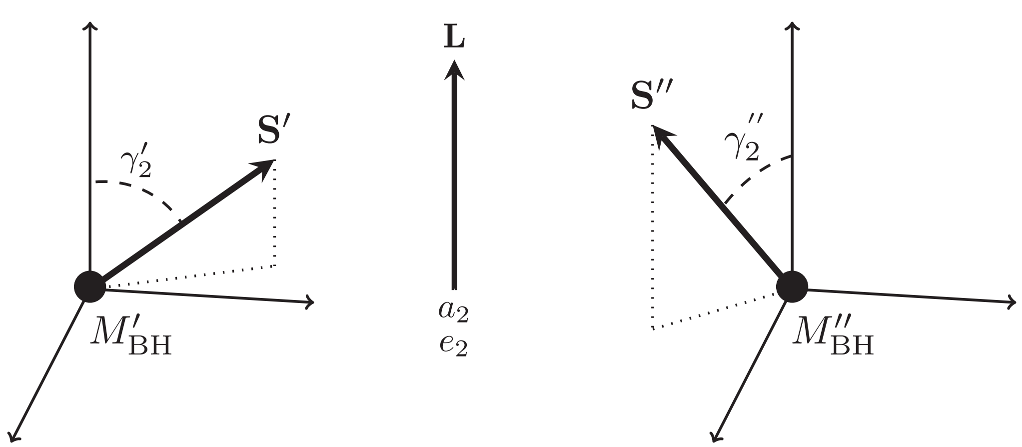
3. 1st Supernova explosion



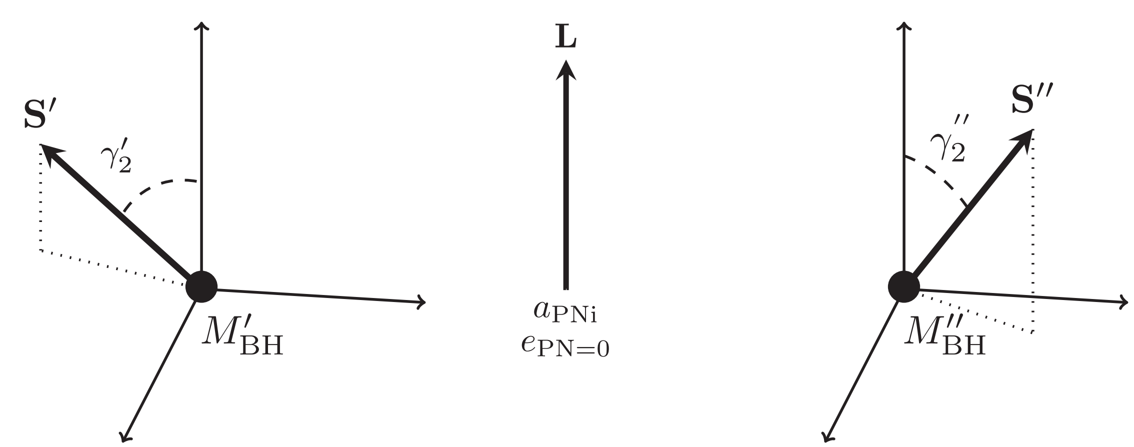
4. Tides, common envelope



5. 2nd Supernova explosion



5. Inspiral, merger, LIGO



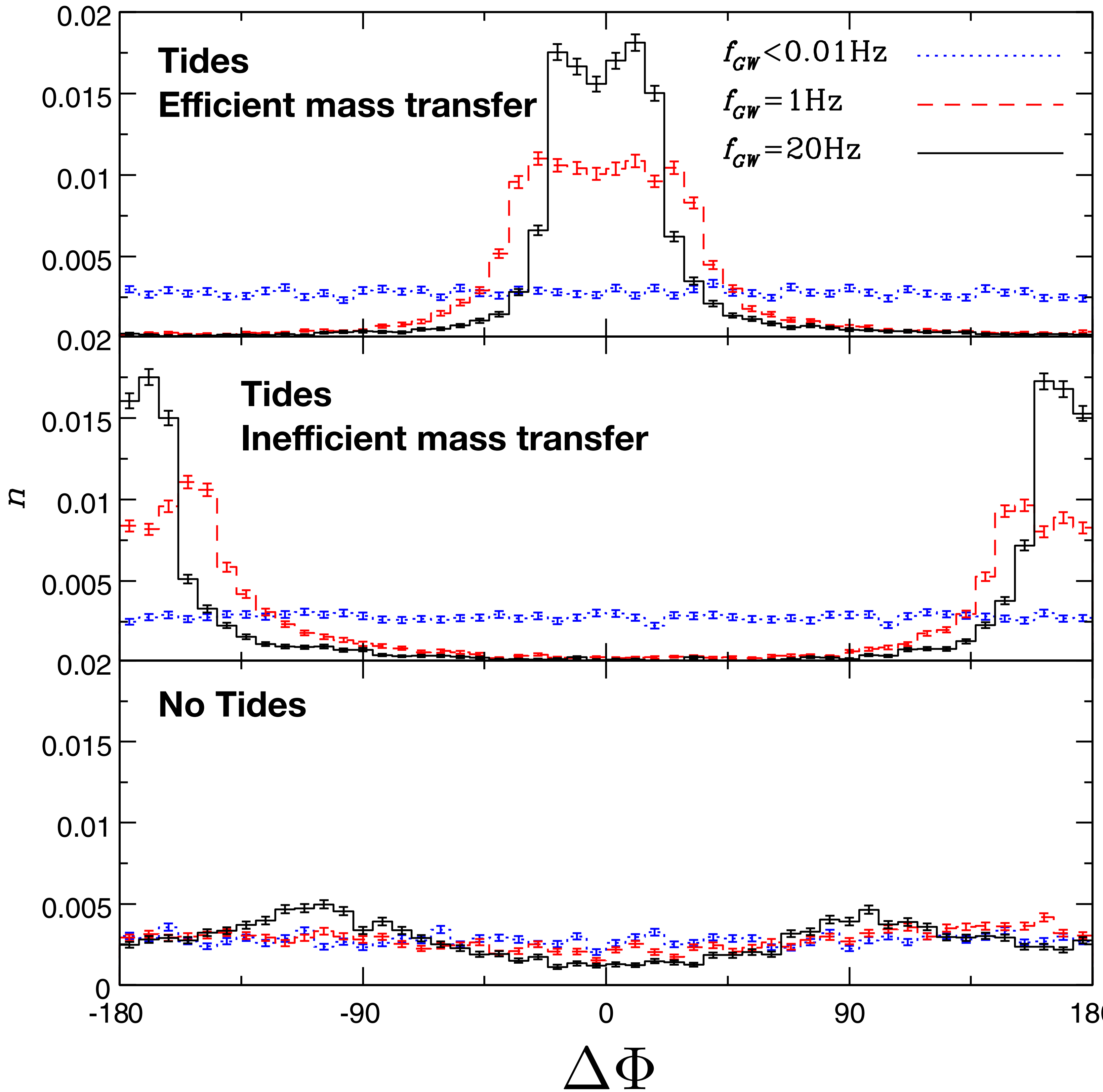
A diagnostic of BH binary formation

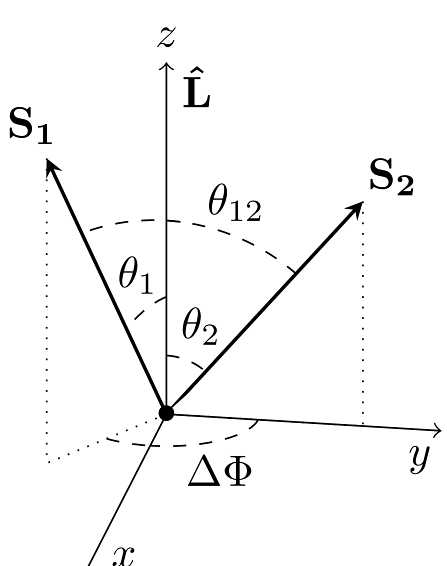
DG+2013

Two main knobs:

- **Tides**: when the system is formed of a BH and a star, can tidal interactions align the star's spin?
- **Mass transfer**: is mass transfer efficient enough to reverse the mass ratio?

Spin dynamics remembers *precise* formation steps!





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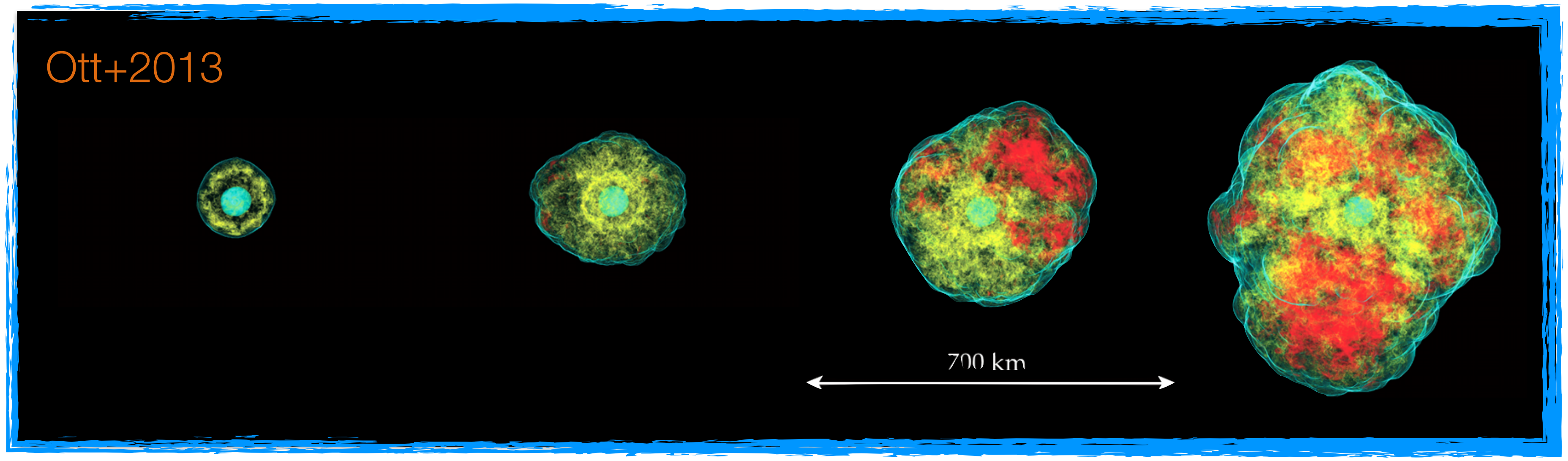
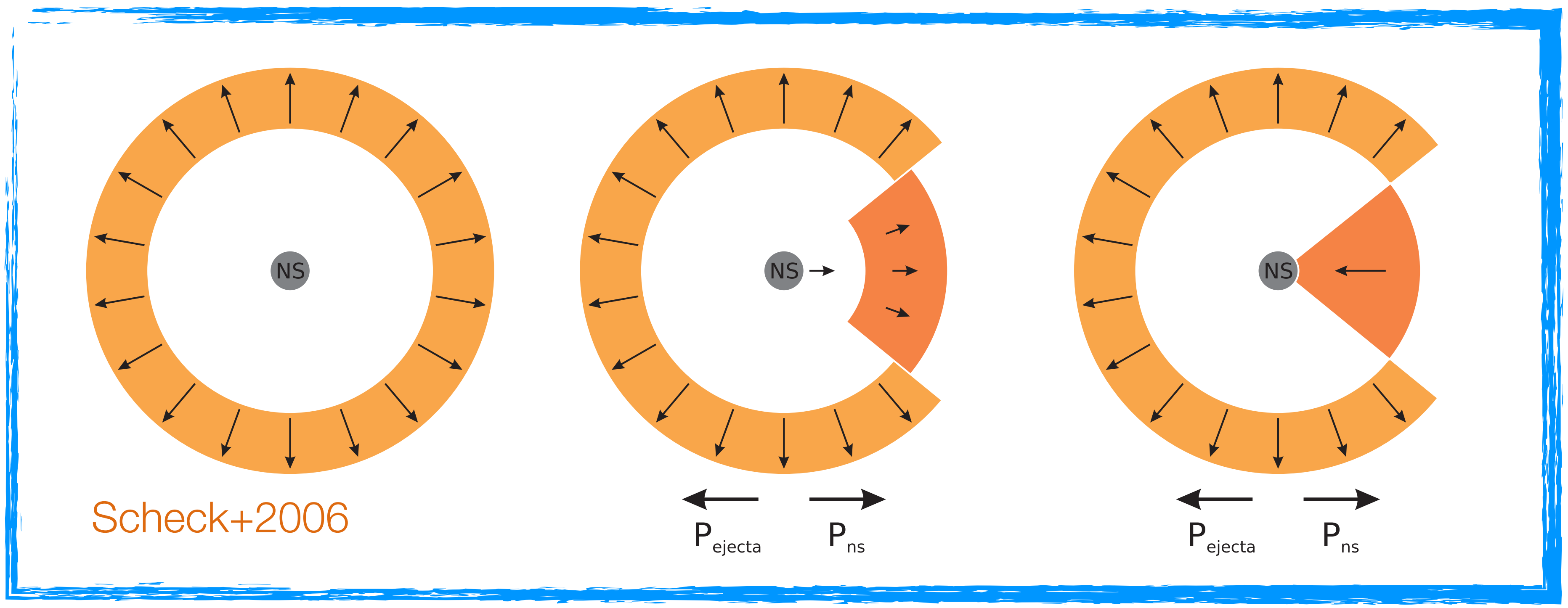
Supernova asymmetries and kicks

Scheck+2006; Repetto+2013,2015; Janka 2013



Asymmetric Supernova: multiD simulations shows strong mass/neutrino asymmetric emission



Gravitational tugboat mechanism

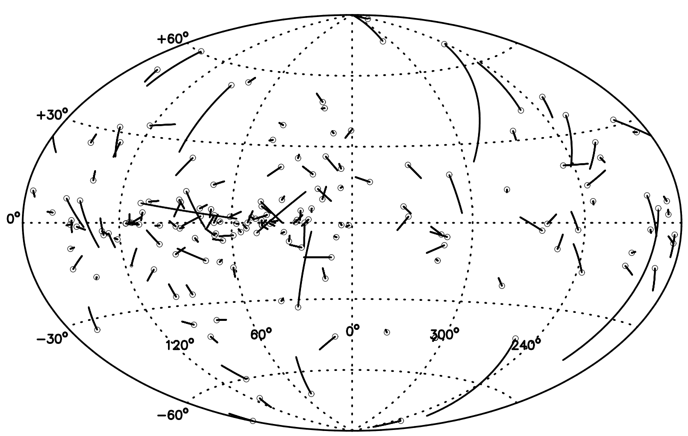
- Emission concentrated close to the shock
- Remnant starts recoiling towards the slow ejecta
- Gravitational attraction and fallback material

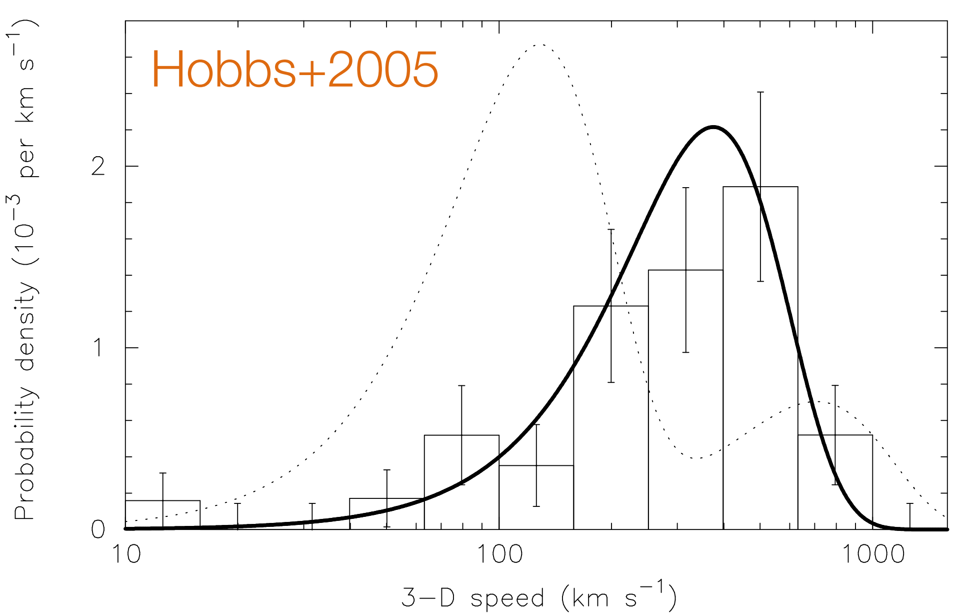
How big is the kick?

→ **One of the main uncertainties in all population synthesis models**

Neutron stars:
solid measurement from pulsar proper motion distribution

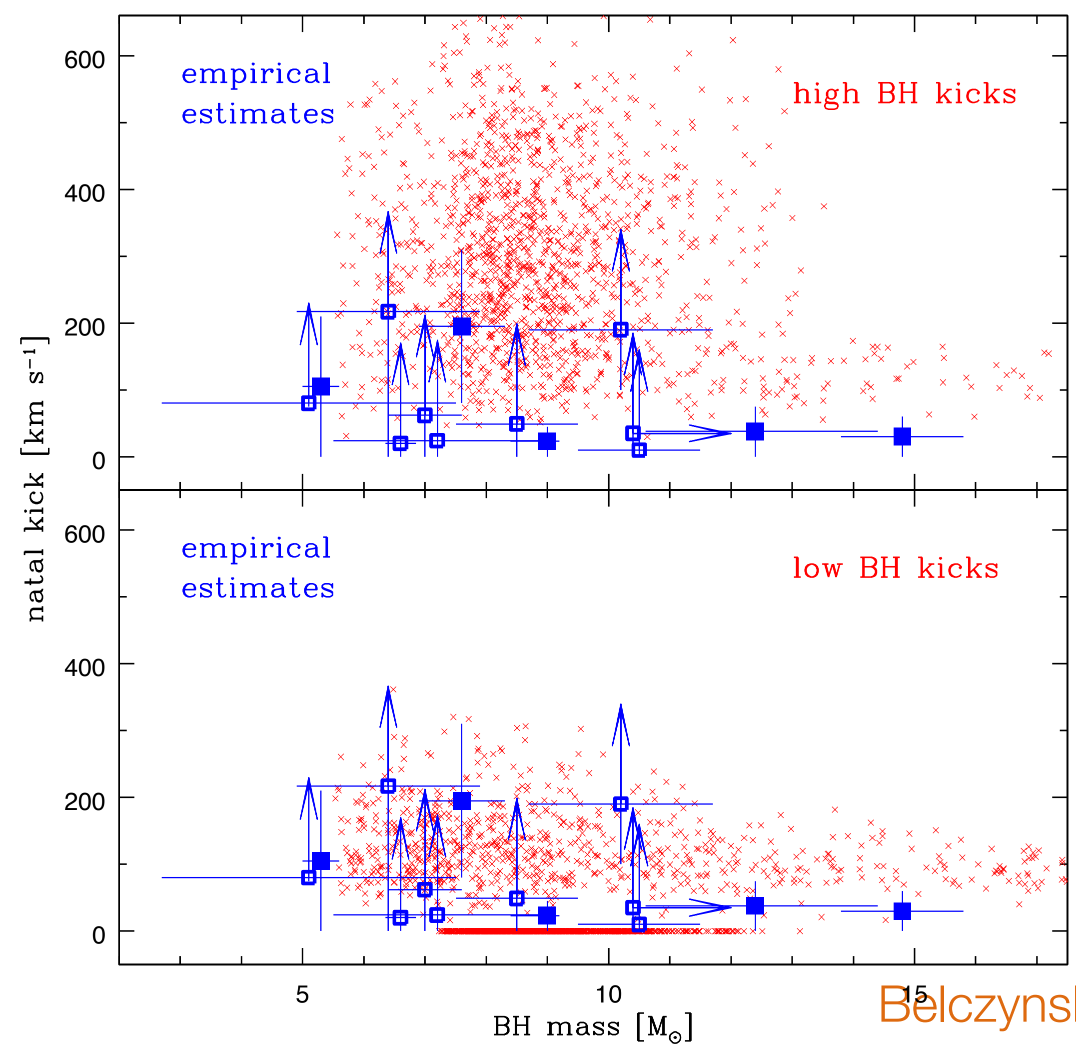
$v_k \sim 450 \mathrm{km/s}$





Black holes? We don't know much…

- Fallback prevents kicks entirely, especially for high masses? Fryer+2001,2012; Janka 2013
- Kicks as large as those imparted to NS? Repetto+2013,2015

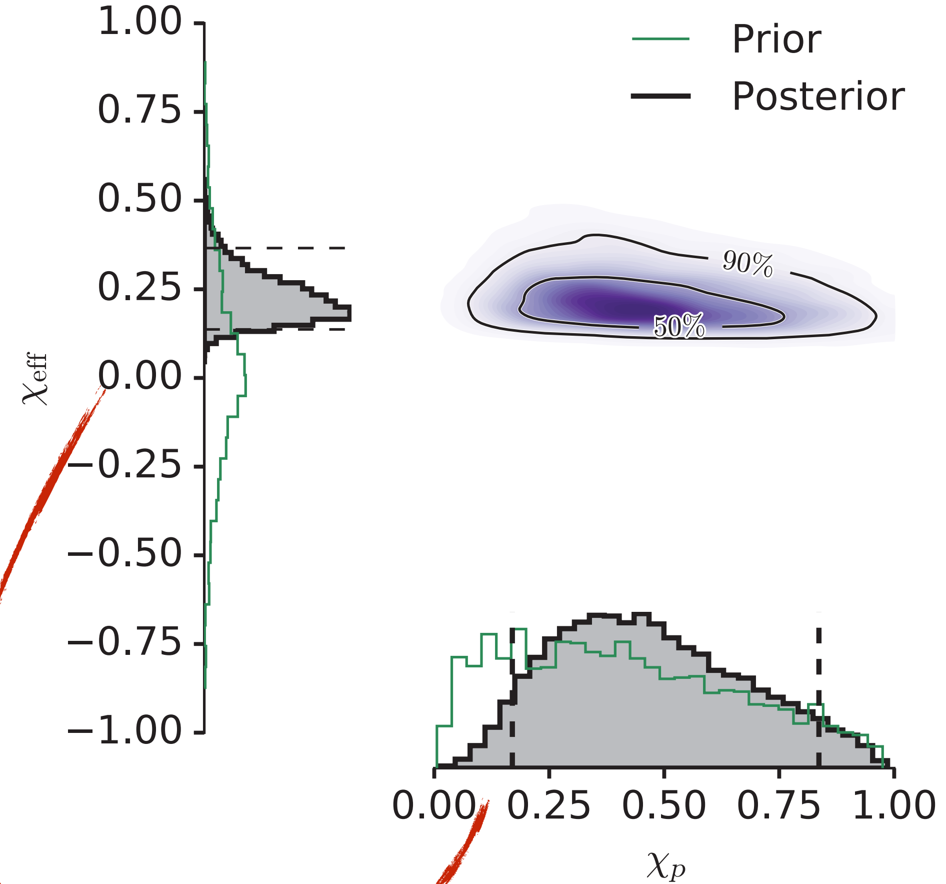


Belczynski+2015

Boxing day event (GW151226)

A light event…

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$

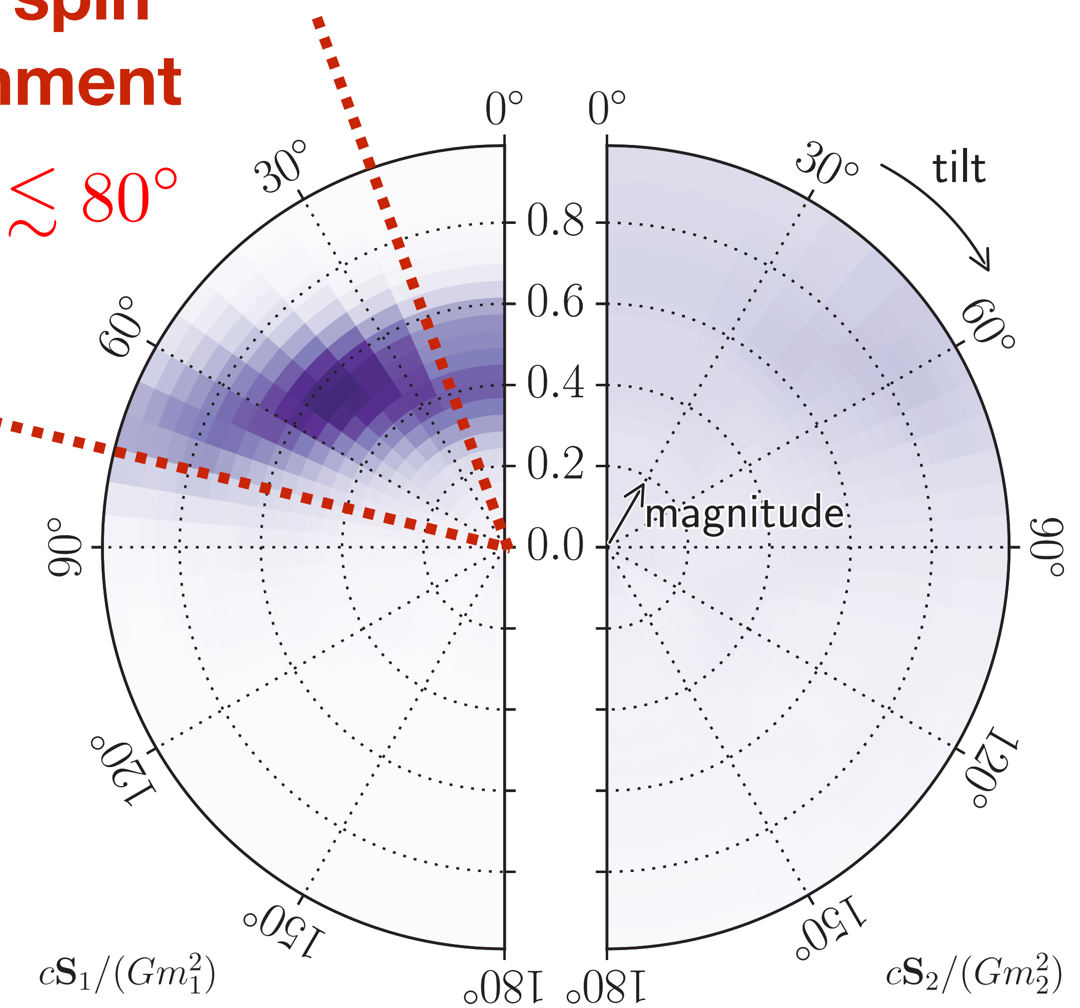


Spins not consistent with zero

LIGO/Virgo Collaboration

Primary spin misalignment

$25^\circ \lesssim \gamma \lesssim 80^\circ$

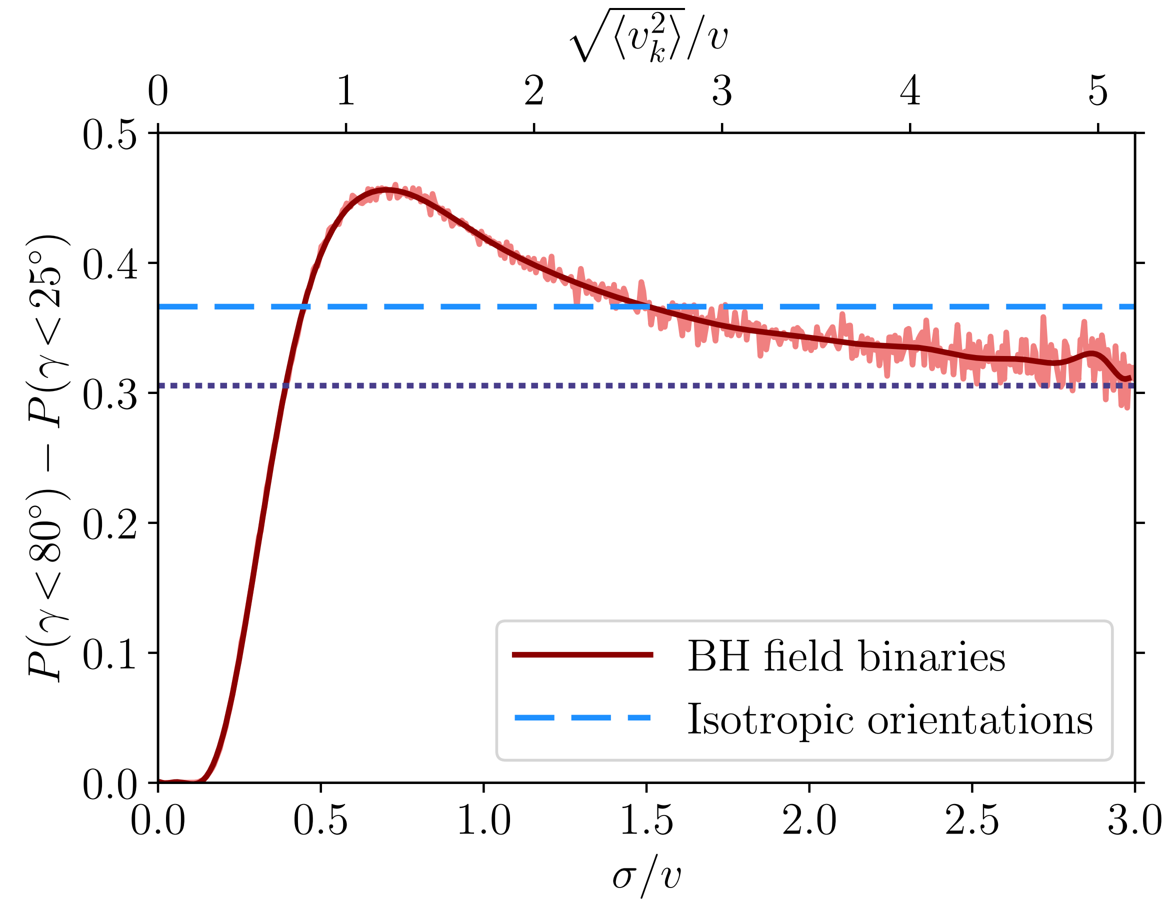


First GW kick *measurement*!

O'Shaugnessy, **DG**+2017

Newtonian kinematics:

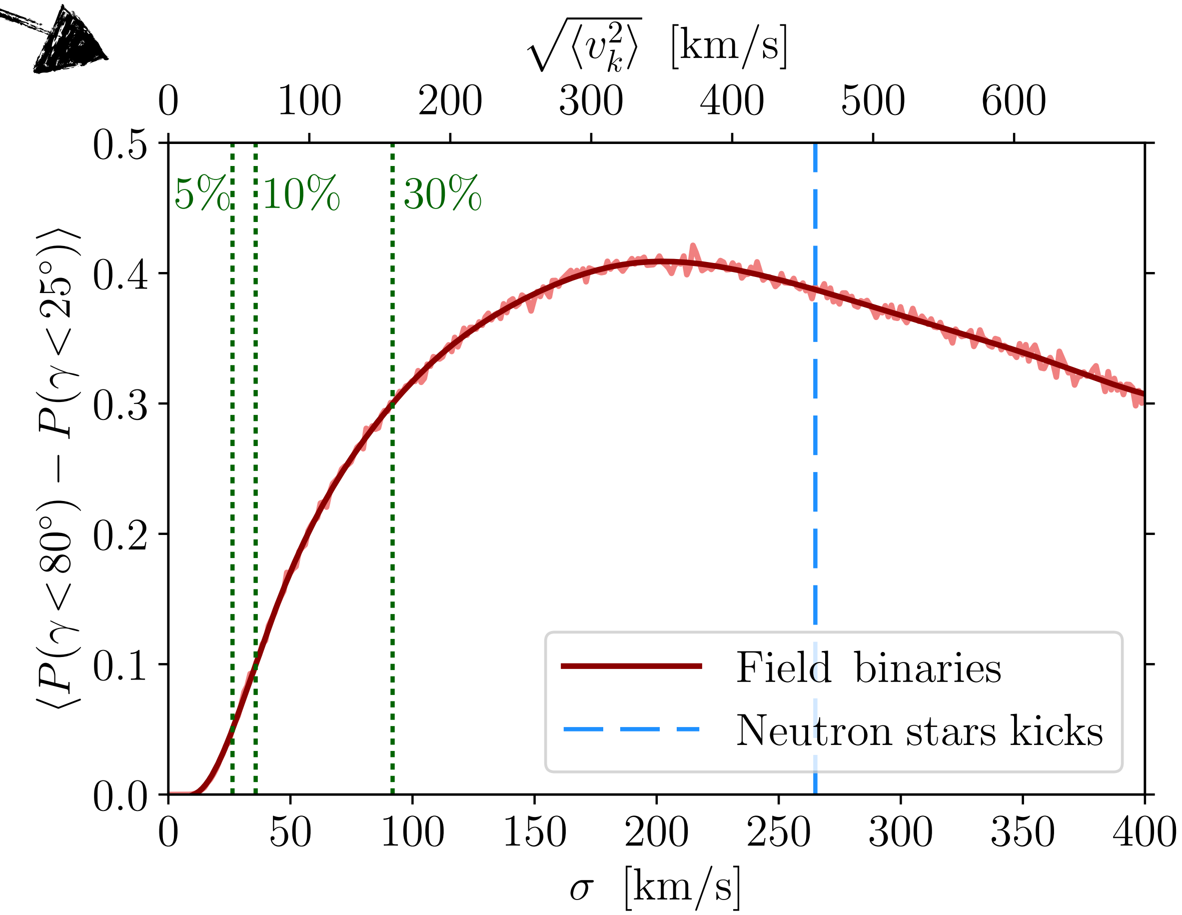
- kick: $\mathbf{v} \to \mathbf{v} + \mathbf{v_k}$
- mass loss: $M \to M_f = \beta M$
- Orbital plant tilt $\cos\gamma = \hat{\mathbf{L}} \cdot \hat{\mathbf{L}}_f$
- Kick distribution 1d RMS σ



Probability of obtaining boxing day as a function of BH natal kick

Average over stellar population

Belczynski+2016



GW151226 consistent only with a natal kick of at least

$$v_k \sim 50\mathrm{km/s}$$

- Towards those X-ray measurements?
- Such high kicks are challenging for SN theorists!

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DG+ arXiv:1302.4442 (PRD)

5. But careful with the prior!
Vitale, **DG**+ arxiv:1707.04637 (PRL)

5. … and multiple merger generations!
DG, Berti arXiv:1703.06223 (PRD)

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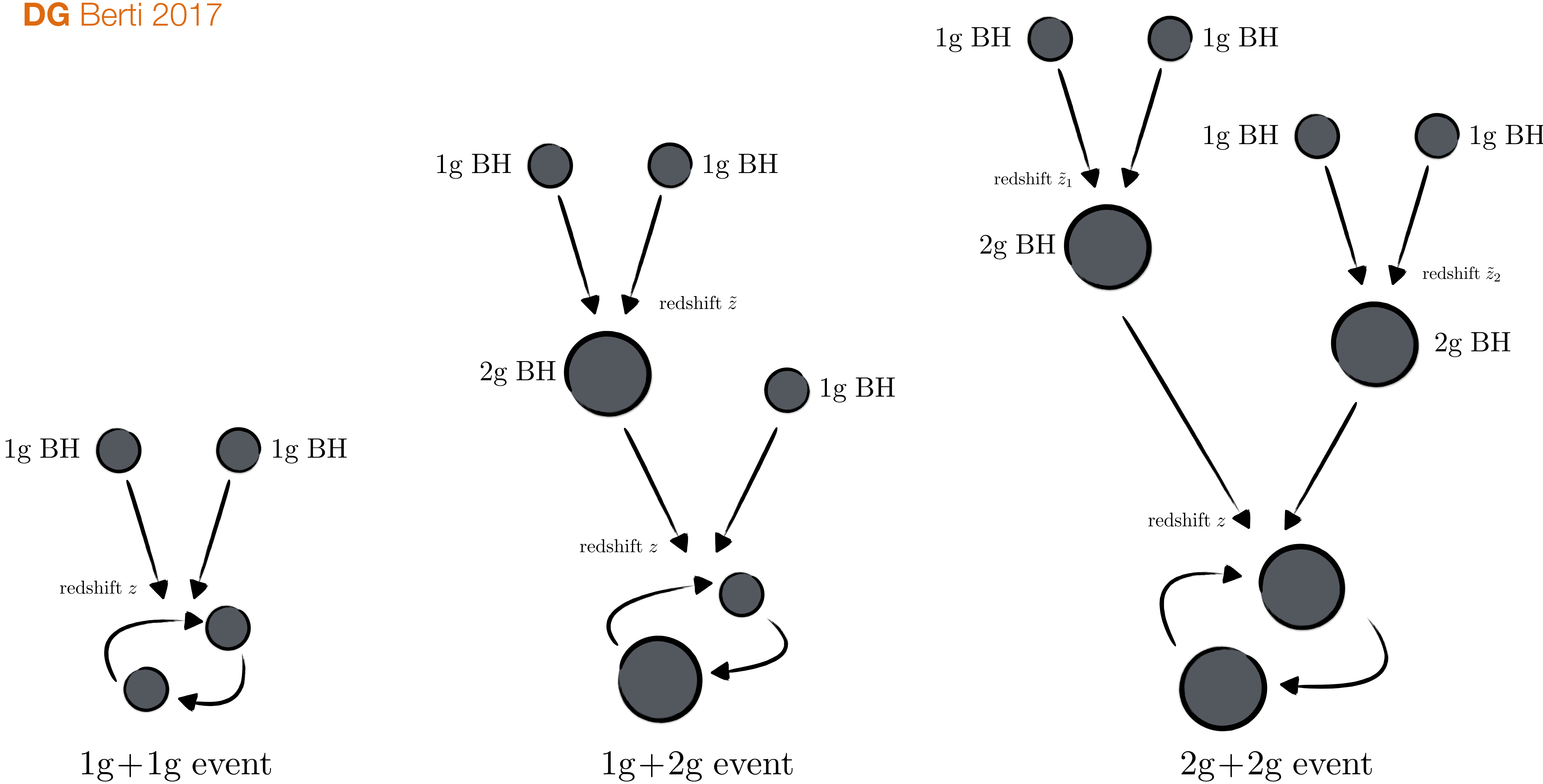
O'Shaughnessy, **DG**+ arXiv:1704.03879 (PRL)

Black hole generations

DG Berti 2017

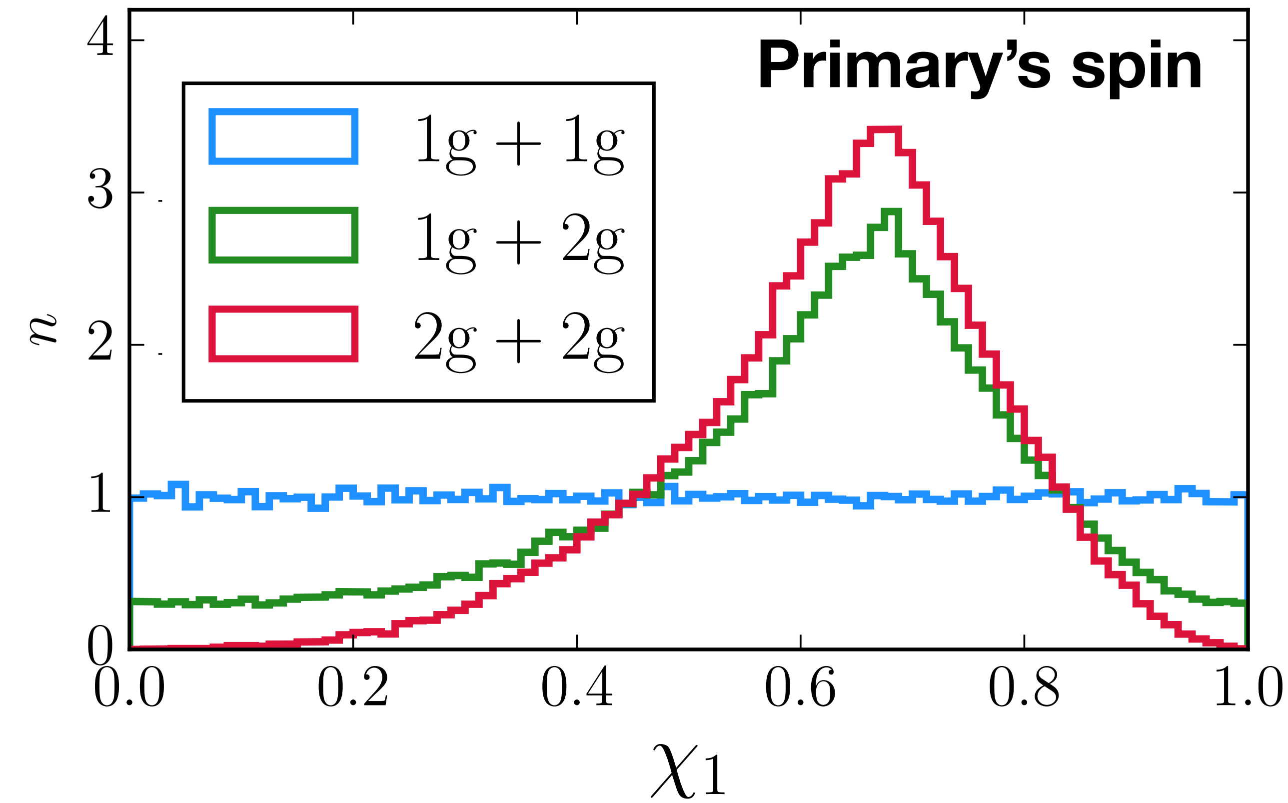


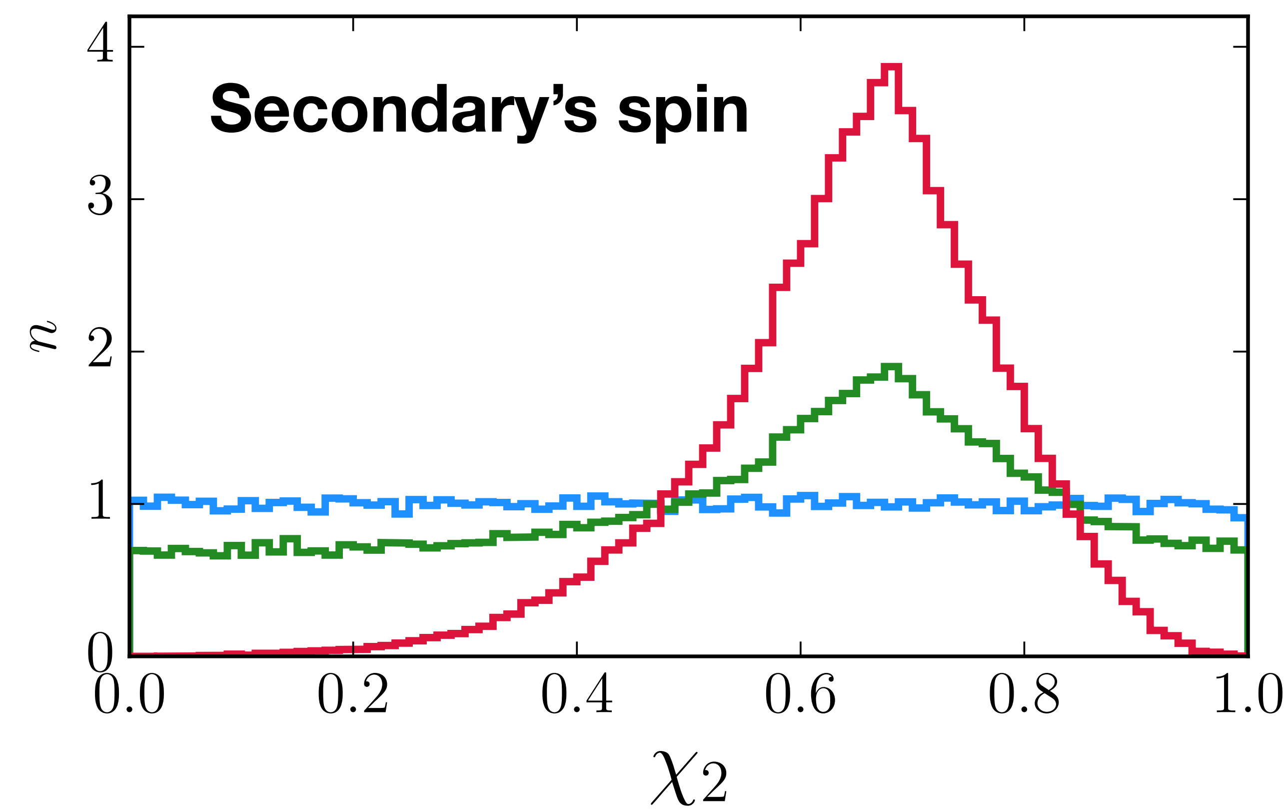
Orthogonal, but complementary, direction to the usual field vs. cluster debate

Spins, 1st and 2nd generations

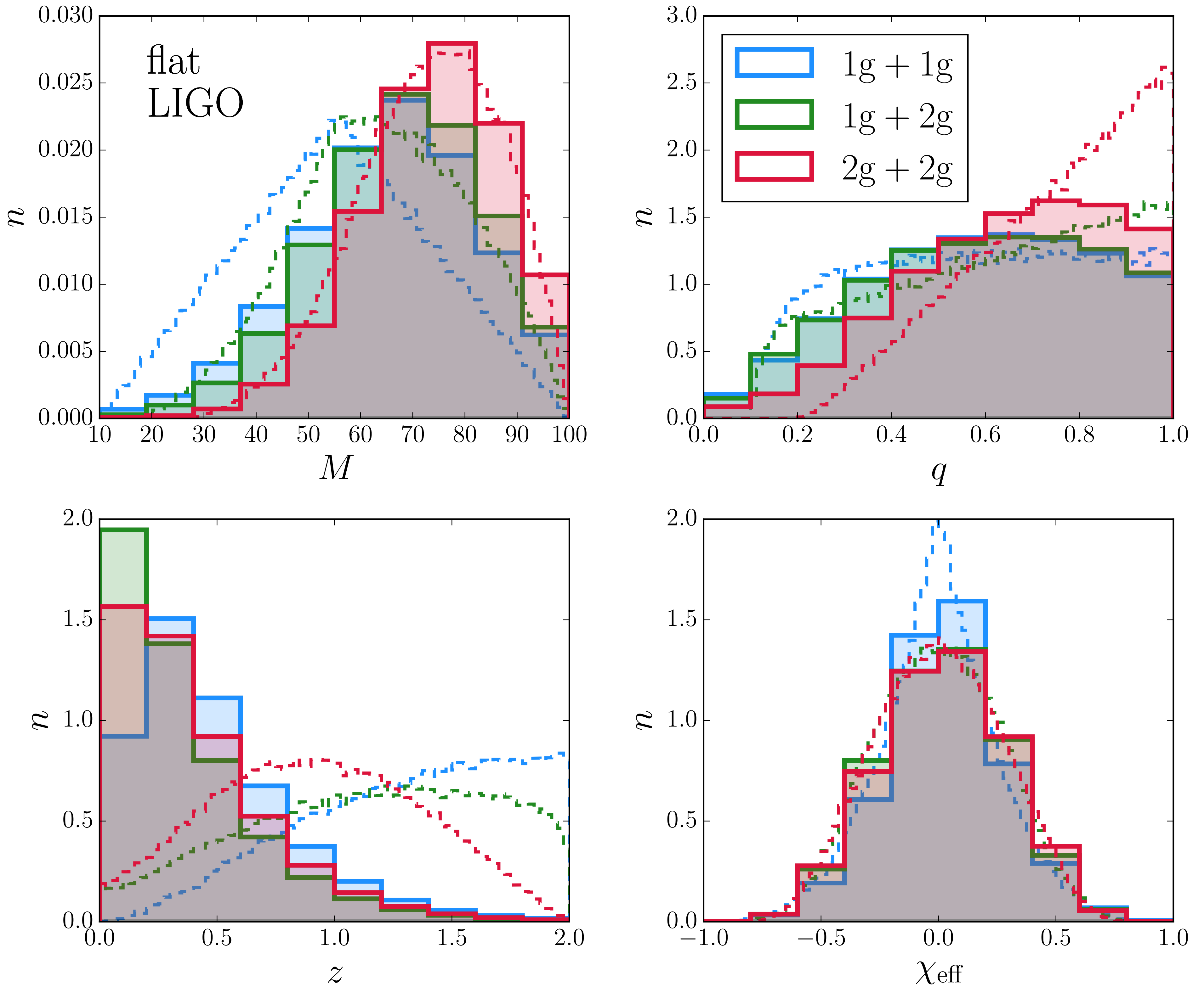
- At merger, the binary's orbital angular momentum has to be converted into spin
- More or less whatever you do when you merge two BHs, you get ~0.7!

Spins remember previous mergers!





More mergers means…



Mergers means:

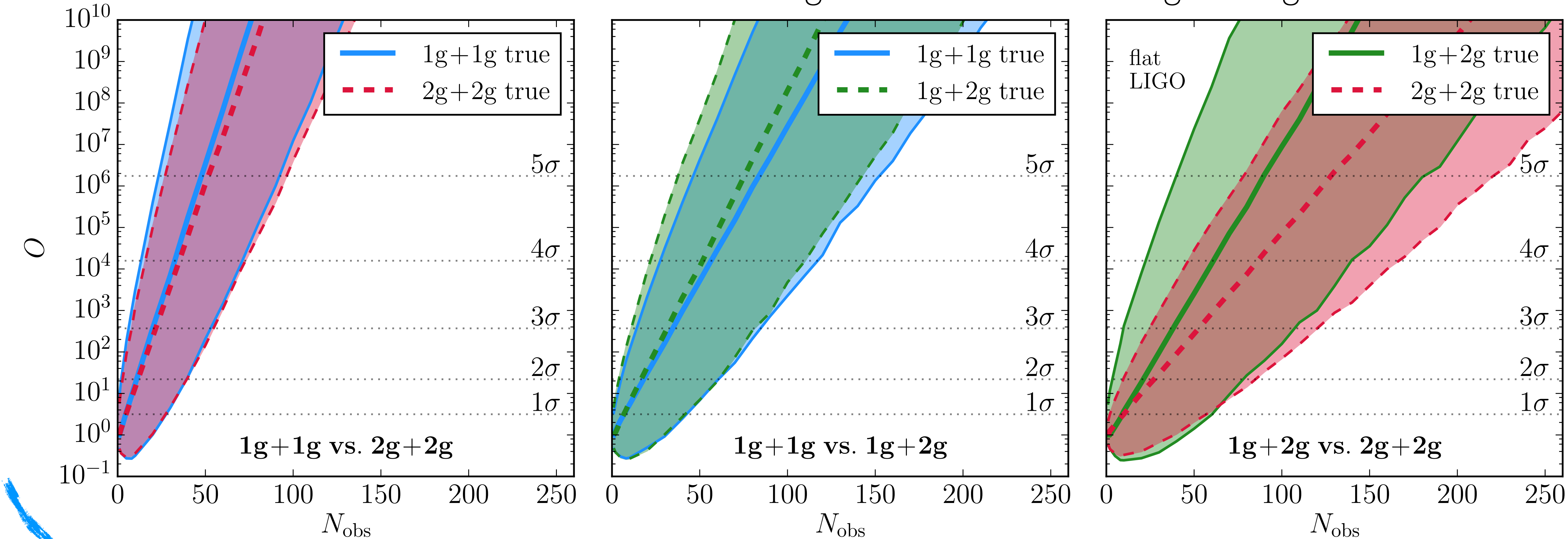
- more massive
- equal mass
- closer
- higher spins

Analysis:

- filter SNR
- measurement errors, spread over multiple bins
- Bayesian model comparison

Can we infer previous mergers happened?

Number of observations needed to distinguish two models at a given significance



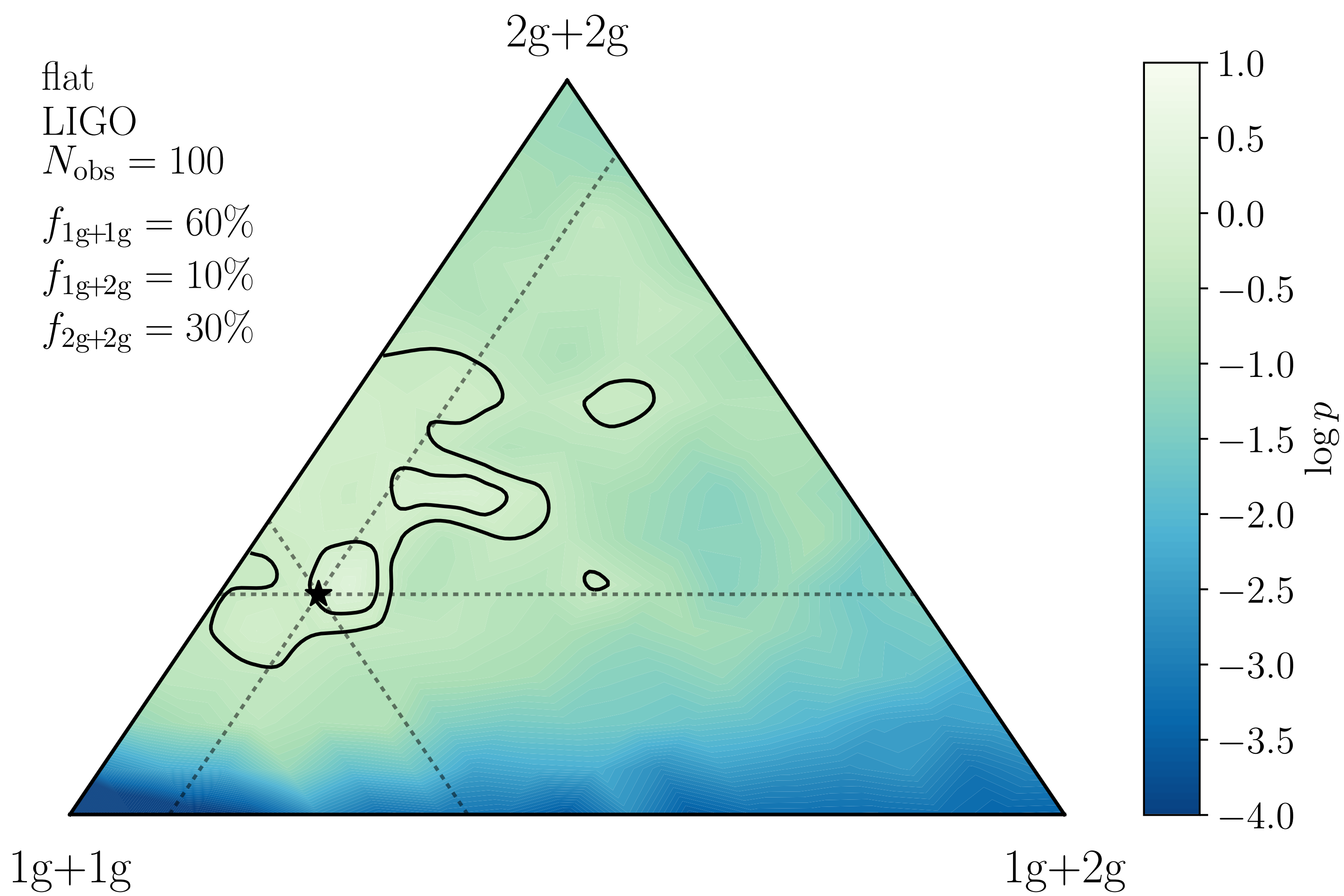
Need only 10-60 observations to distinguish 1g+1g vs 2g+2g at 5σ!

Already! Using O1 events only:

1g1g vs. 2g2g. Odds: 12
1g1g vs. 1g2g. Odds: 2
1g2g vs. 2g2g. Odds: 6

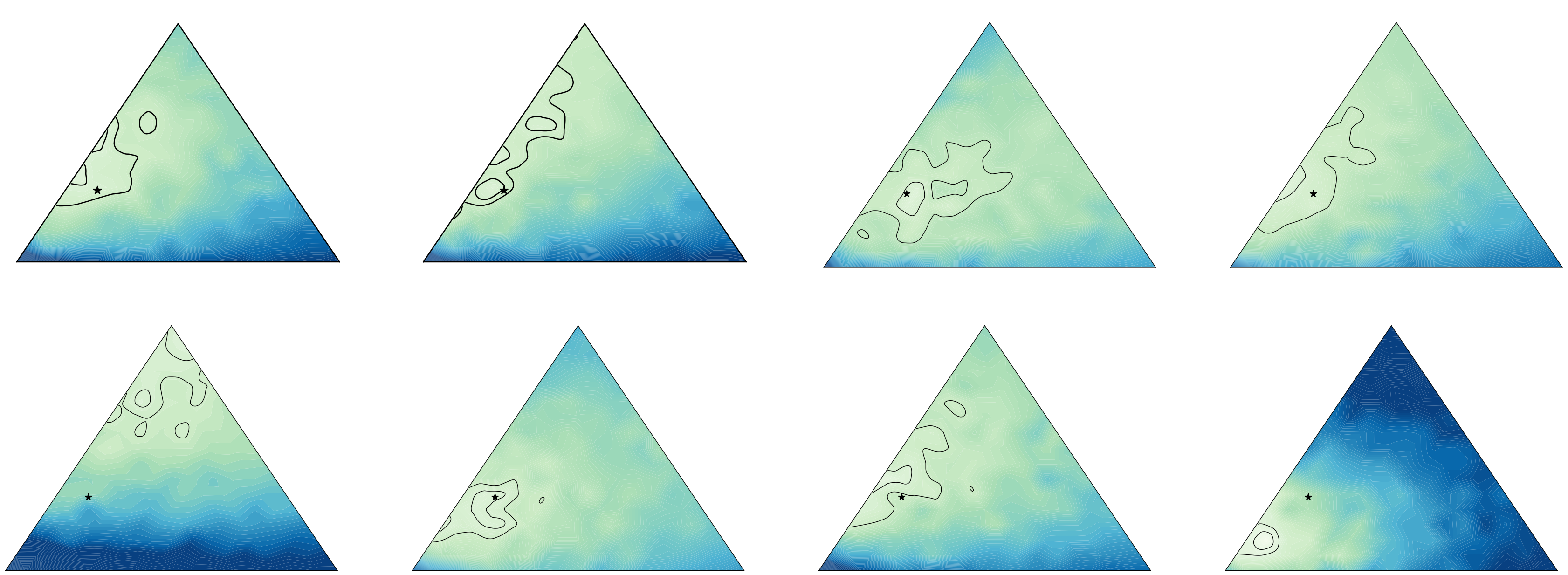
2σ statement our BHs are not 2g+2g!

Can we infer previous mergers happened?



Three models mixed,
can we measure their mixing fraction?

- each pure model is on a corner
- assuming 100 BBH
- 90% and 50% confidence intervals



Yes, but that's harder.
Need O(100) observations and/or a better detector!

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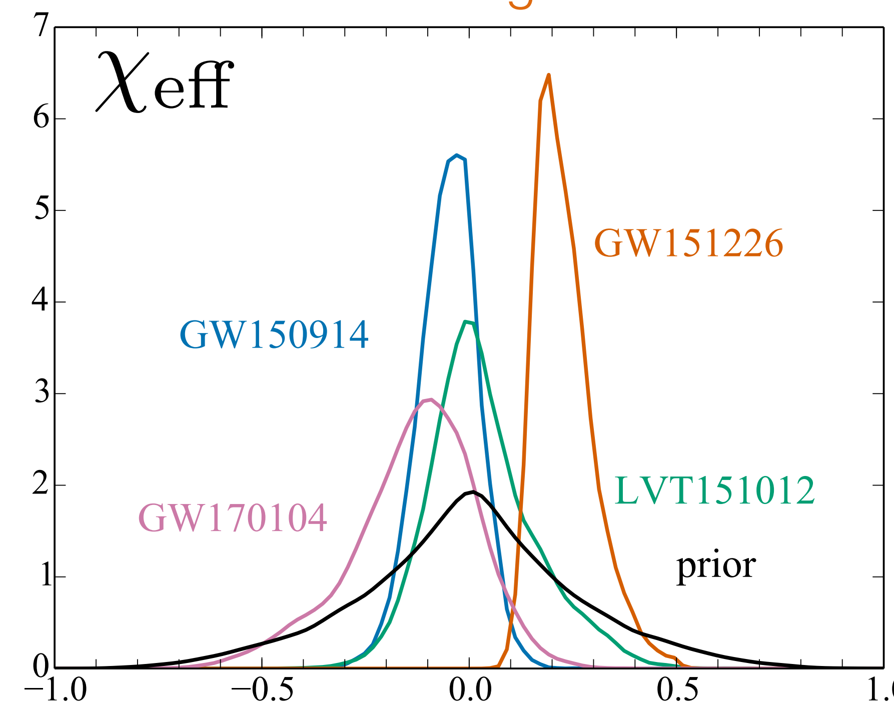
Hold on… How about the prior?

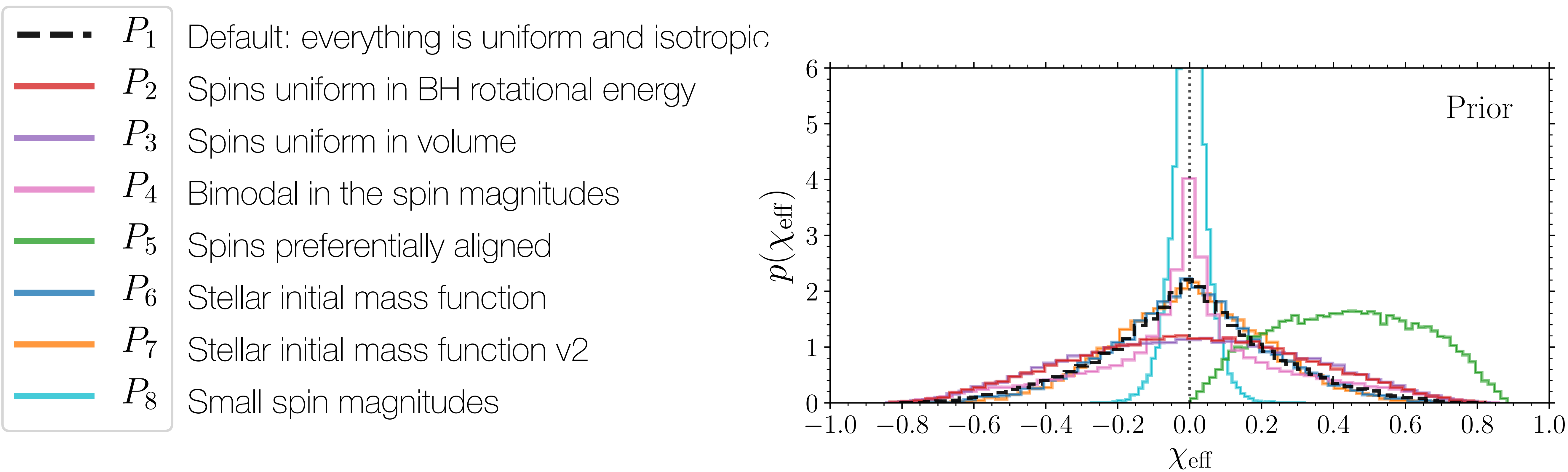
- Everything derived using priors with isotropic spins!
- **Risky situation**: our prior is one of the models we are trying to discriminate!

LIGO/Virgo Collaboration

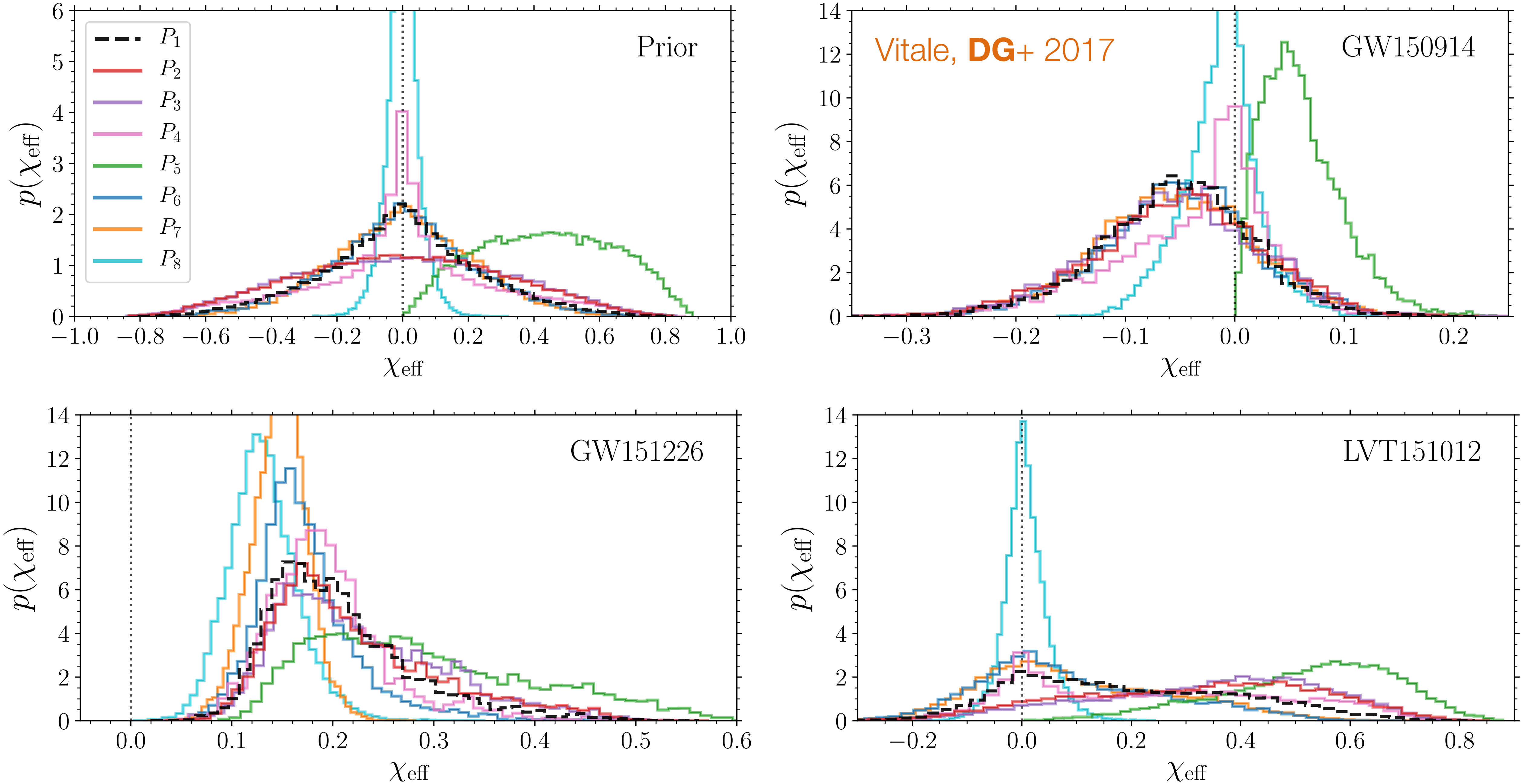


First independent reanalysis of the LIGO data

Vitale, **DG+** 2017



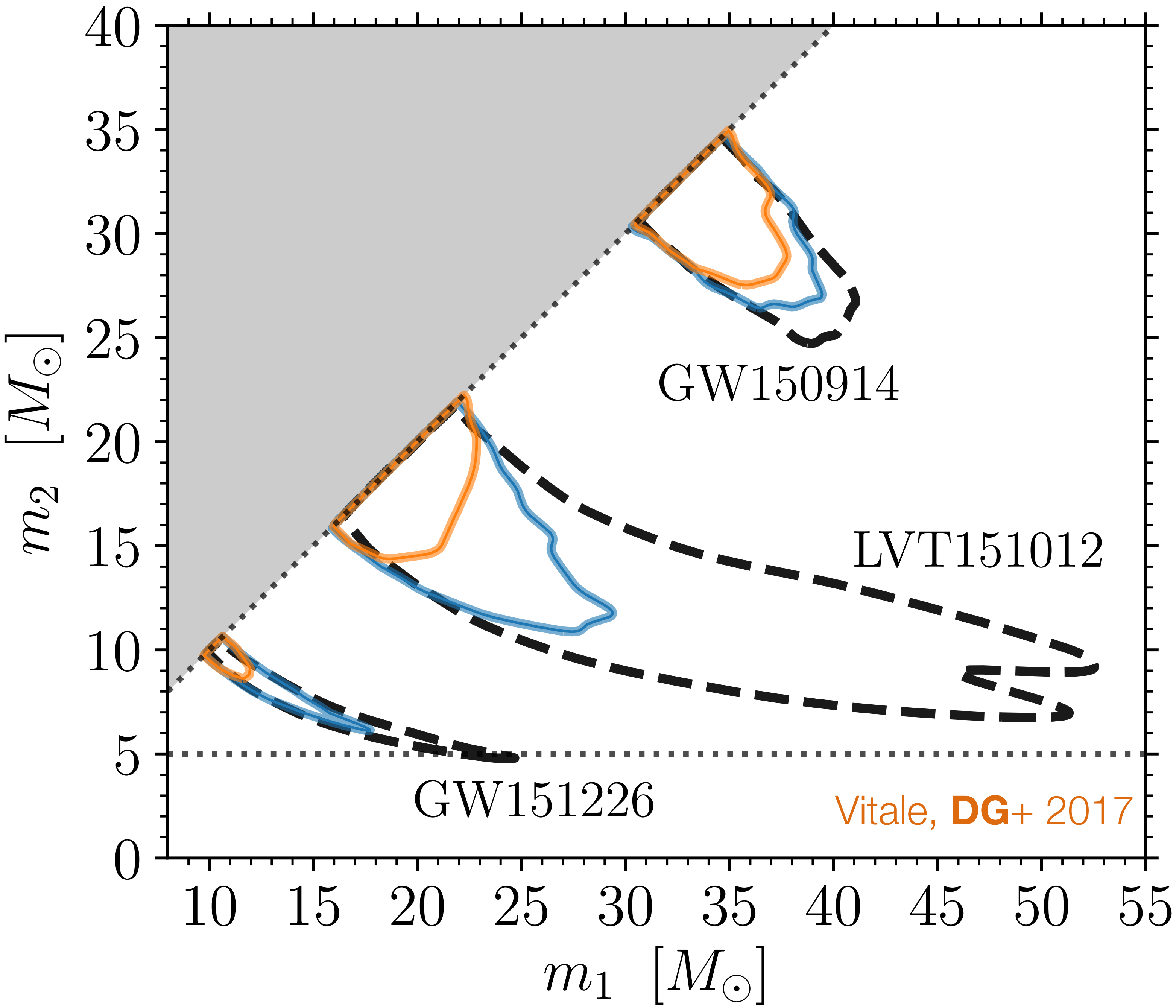
Impact on inferred BH spins



- GW151226 not consistent with zero spins (robust!)
- The bimodal spin prior choses the high spin mode. Support misalignment.
- All others fully consistent with zero spins (robust!)
- More severe issues for low SNR like LVT

Variations in the 90% confidence interval up to ~20%!

Impact on inferred BH masses



- Chirp mass (GW151226 and LVT151012), total mass (GW150914) are **very solid**.
- Median change of $\sim 0.1 M_\odot$
- But component masses are not

If you insert the analysis the information that BH should come from stars:…

- **Data tends to favor more equal mass systems**
- **…especially if info from dynamical interactions are in**

P_1 Default: everything is uniform and isotropic

P_6 Stellar IMF, uniform mass ratio Sana+ 2012

P_7 Stellar IMF, logistic mass ratio Rodriguez+ 2016

Is there a mass gap between BHs and NSs?

Miller & Miller 2015; Kreidberg 2012

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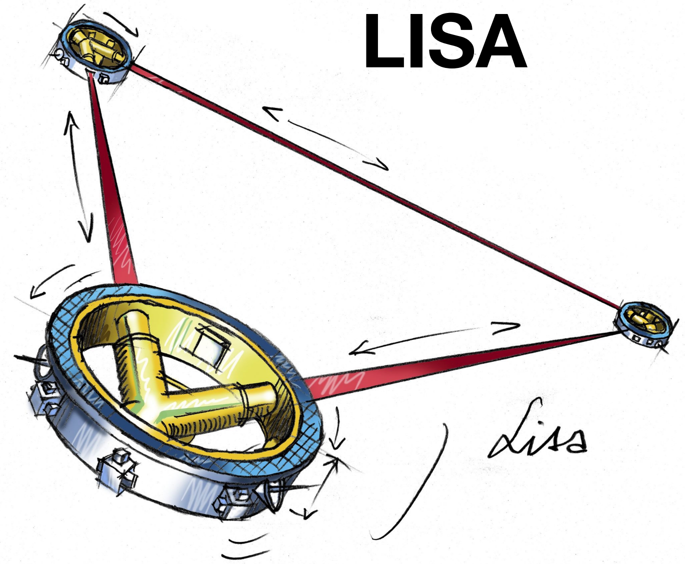
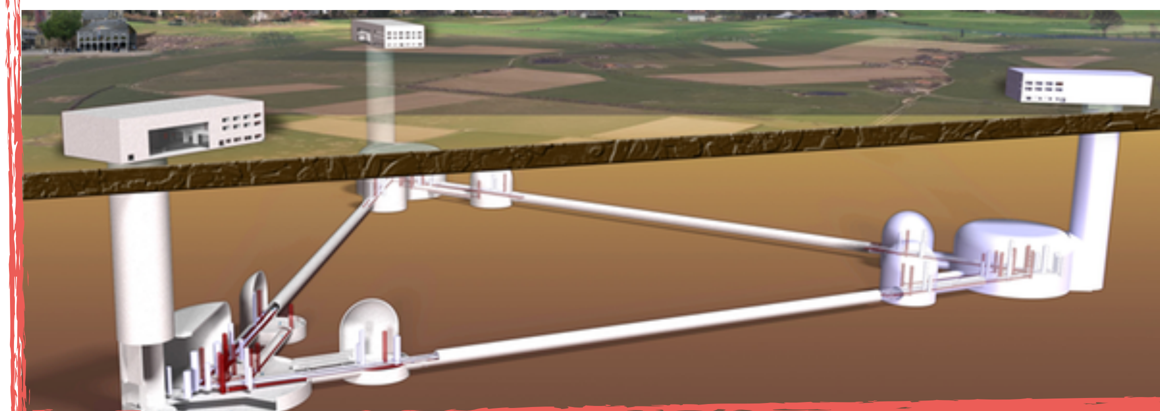
The future is bright and loud

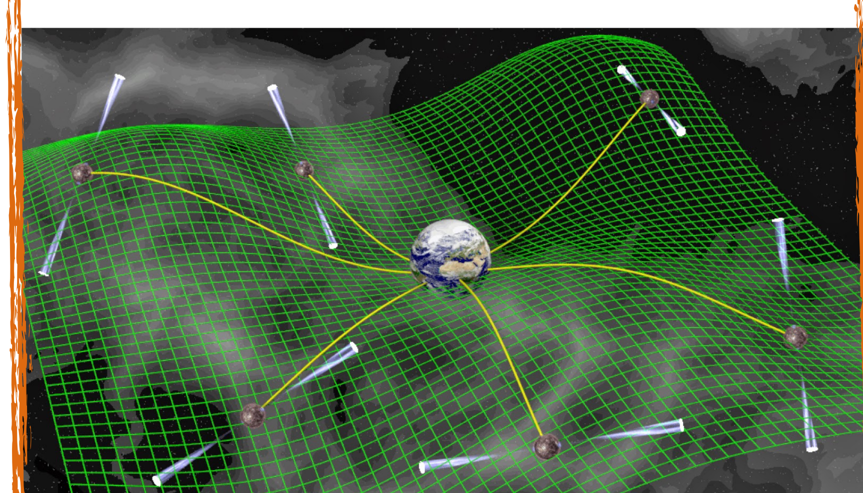
LISA

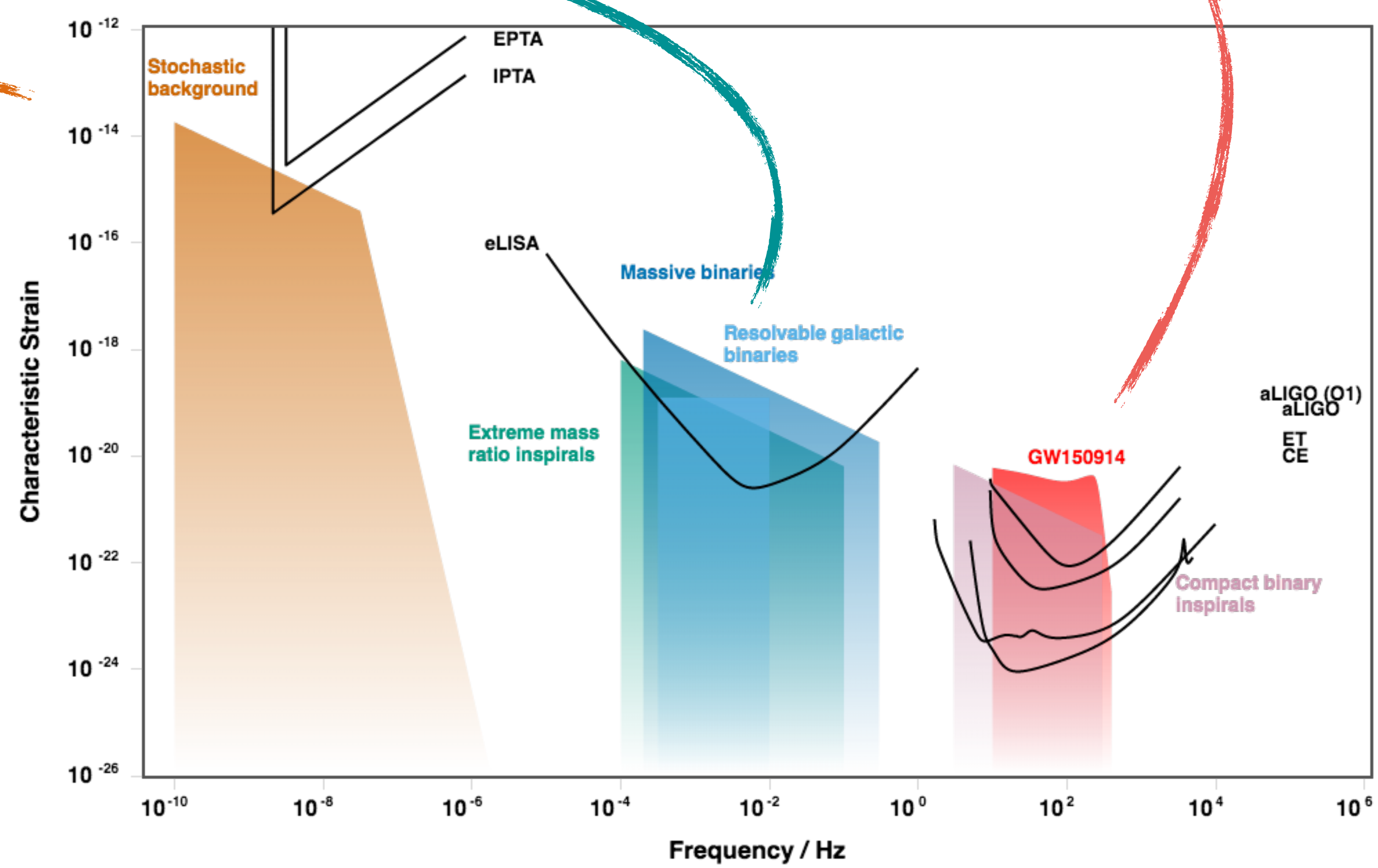


Einstein Telescope, Cosmic Explorer

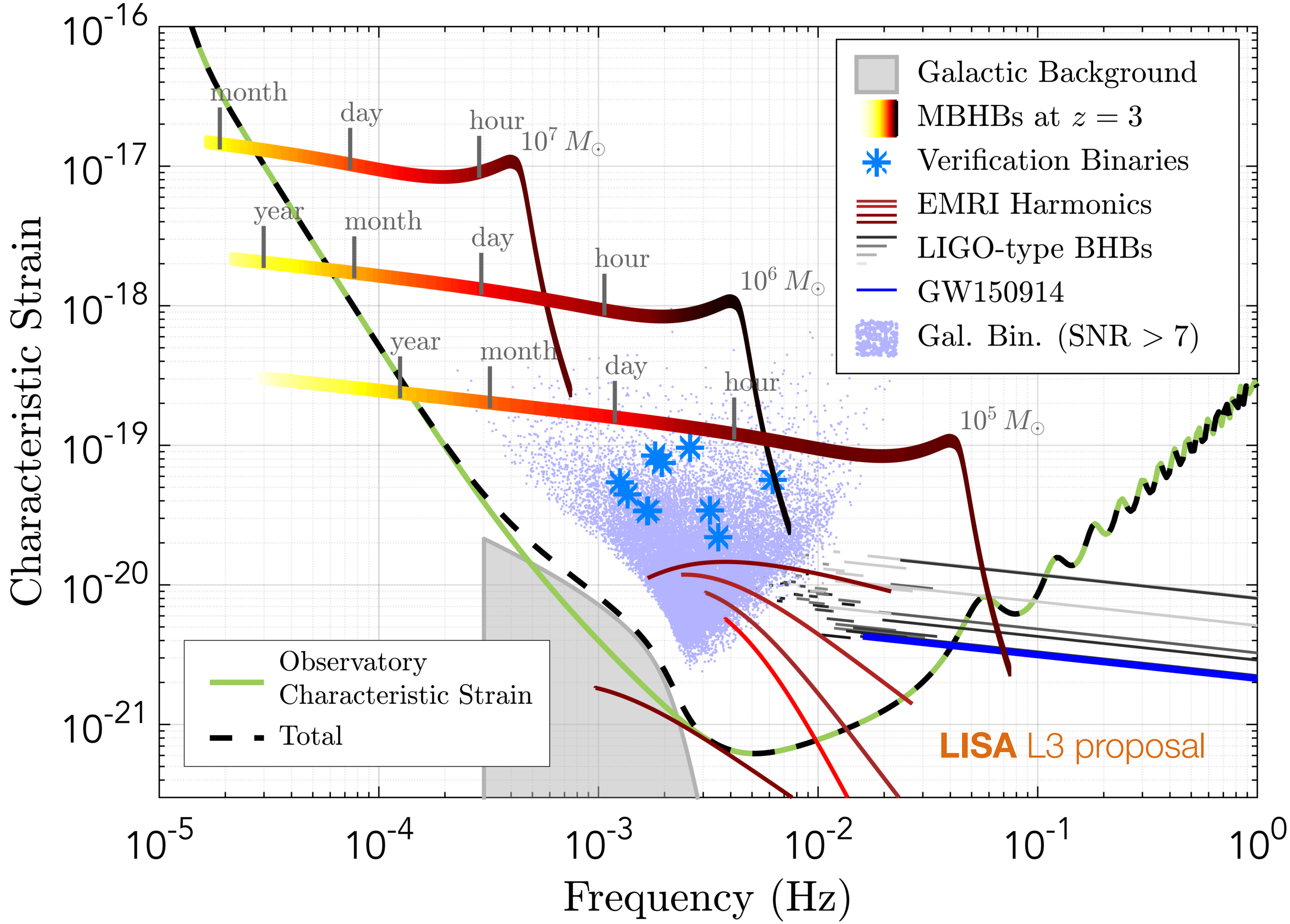


Pulsar timing arrays (**PTA**)





LISA: the next revolution



- **Fully approved** by ESA. Now being commissioned. NASA expressed interests
- Amazing LISA pathfinder performance
- **The next big thing** in GW astronomy

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