Black holes, gravitational waves, and the BEARs

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University of Birmingham

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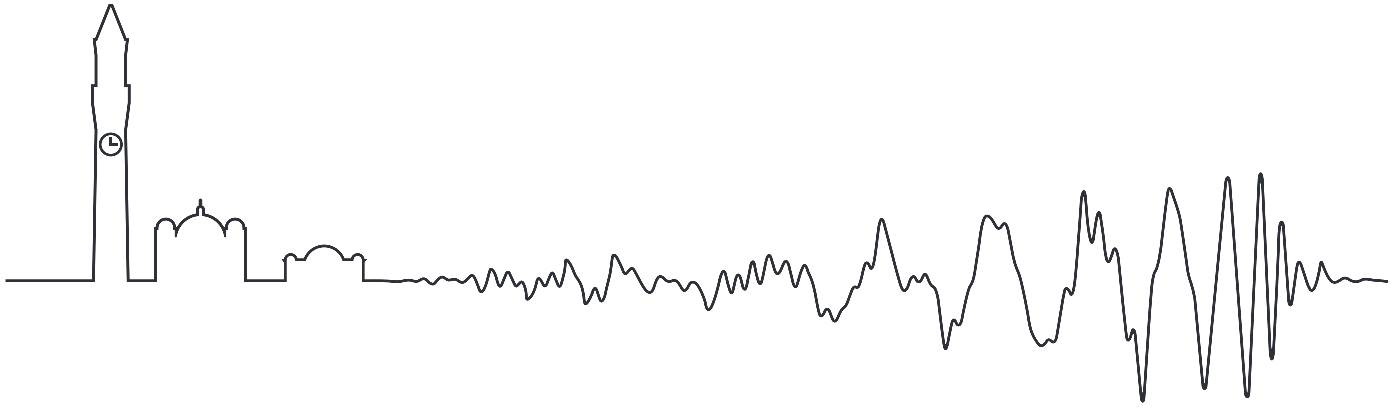
UNIVERSITY OF BIRMINGHAM



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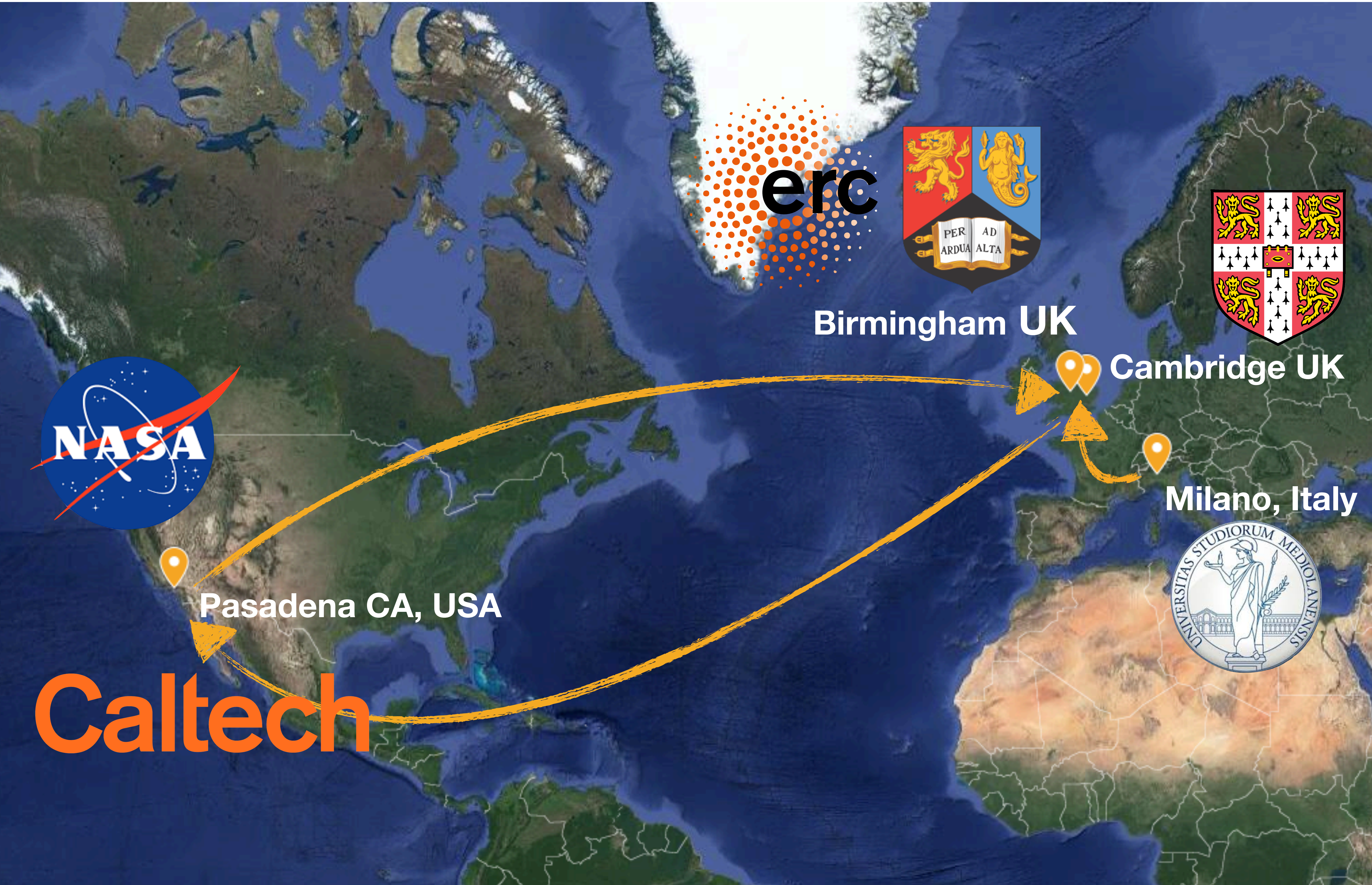
About me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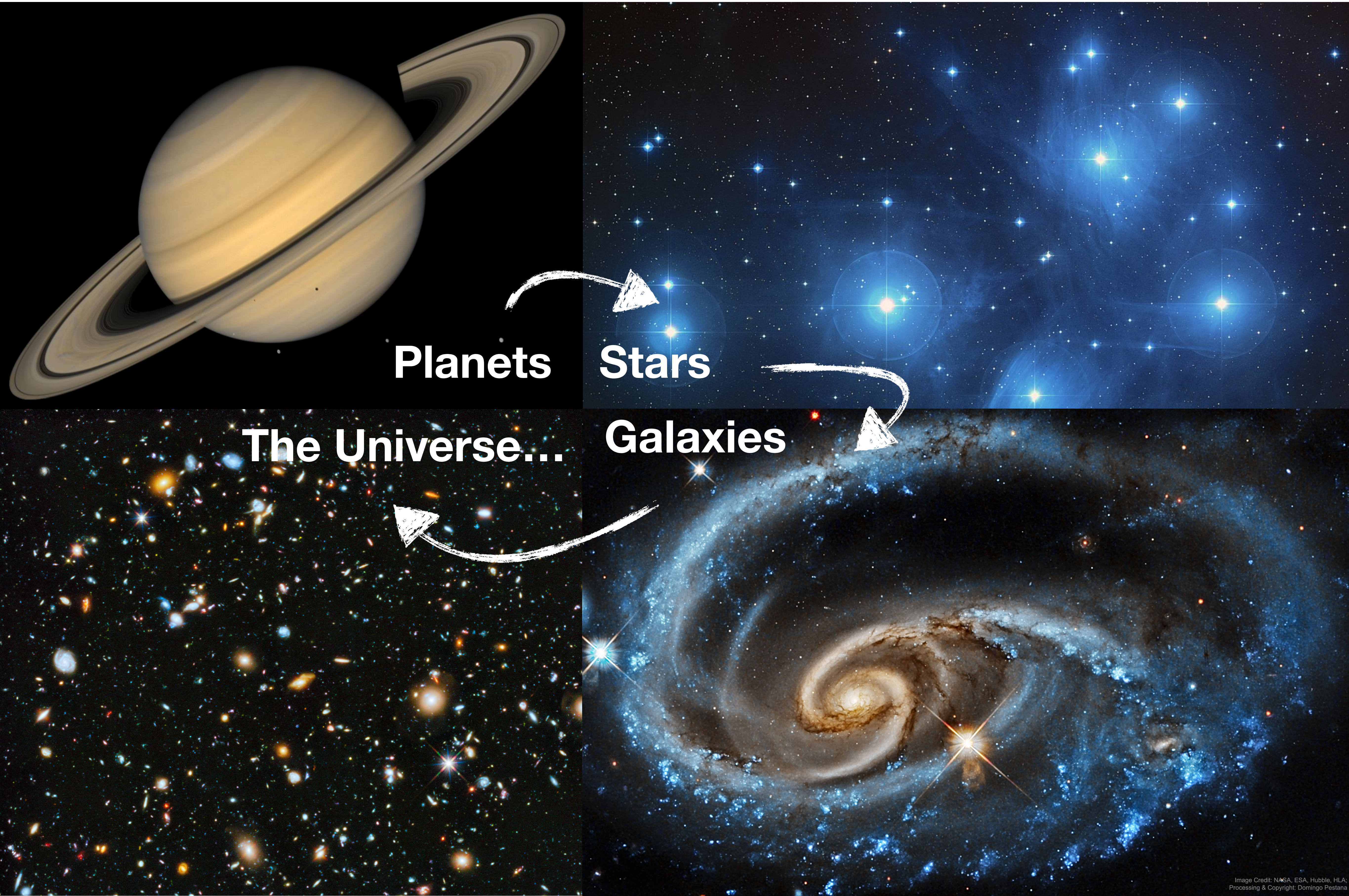
What do we know about the Universe?



What do we actually see?

Can we use gravity?

Light vs. gravity

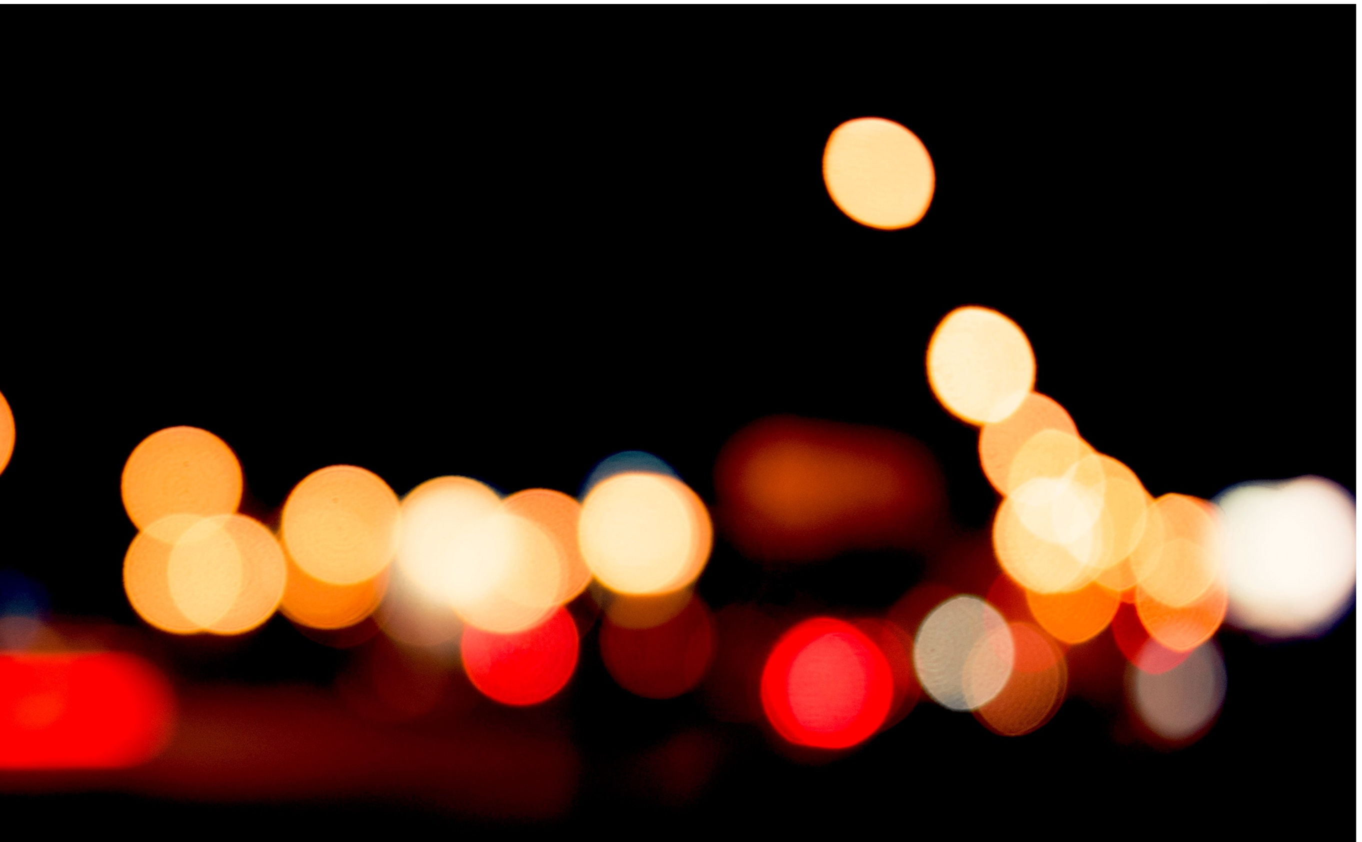
Electromagnetic radiation

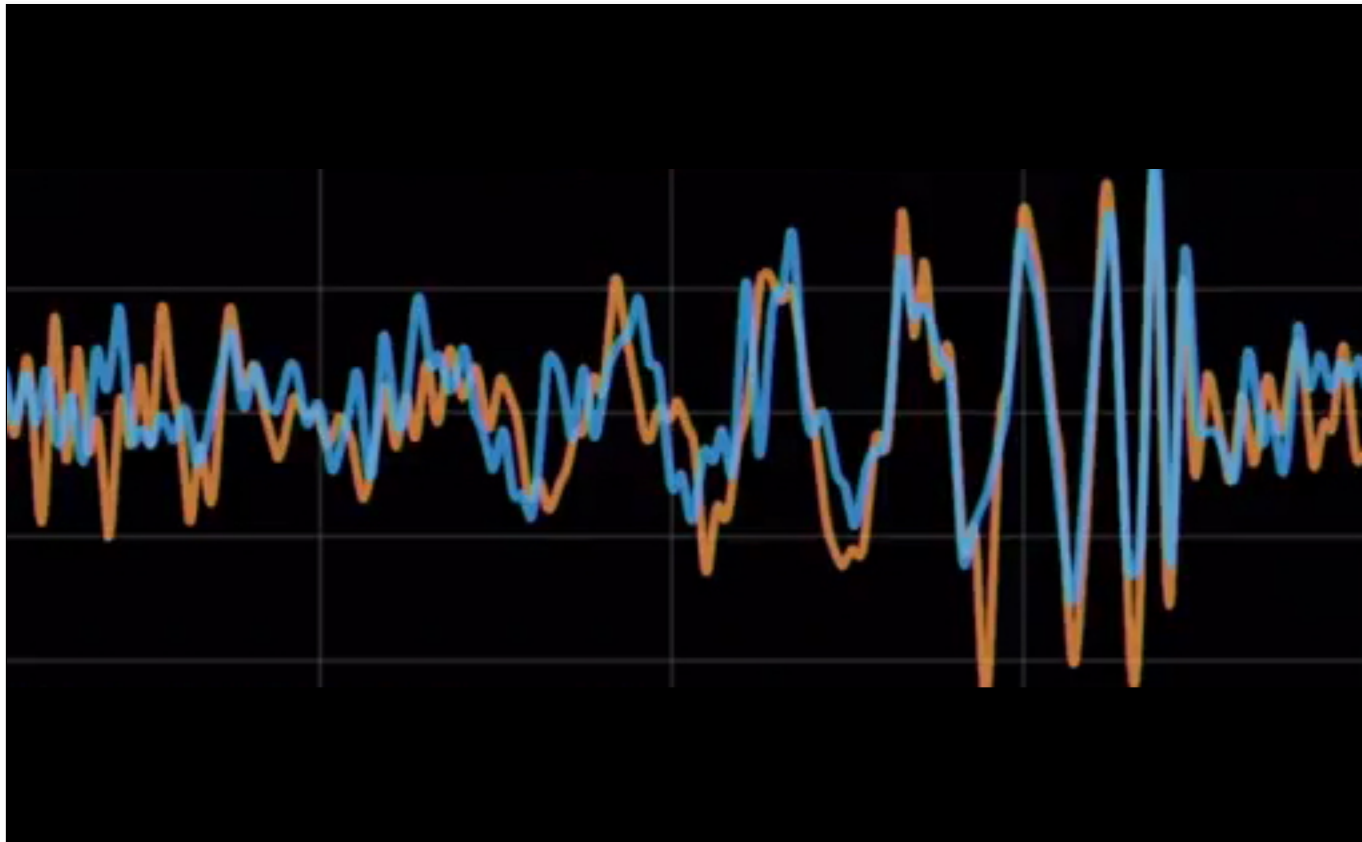
- **Charged** particles, mainly electrons
- **Strongly coupled**: easy to detect, but also easily scattered
- Conservation of charge: no monopole
- **Dipole** radiation

Gravitational radiation

- Cumulative **mass** and momentum distribution
- **Very weakly coupled**: hard to detect, but travel unaffected!
- Conservation of mass and momentum: no monopole, no dipole
- **Quadrupole** radiation

… and cosmology tells us 95% of the mass-energy content of the Universe has no charge!





Ripples in the fabric of spacetime

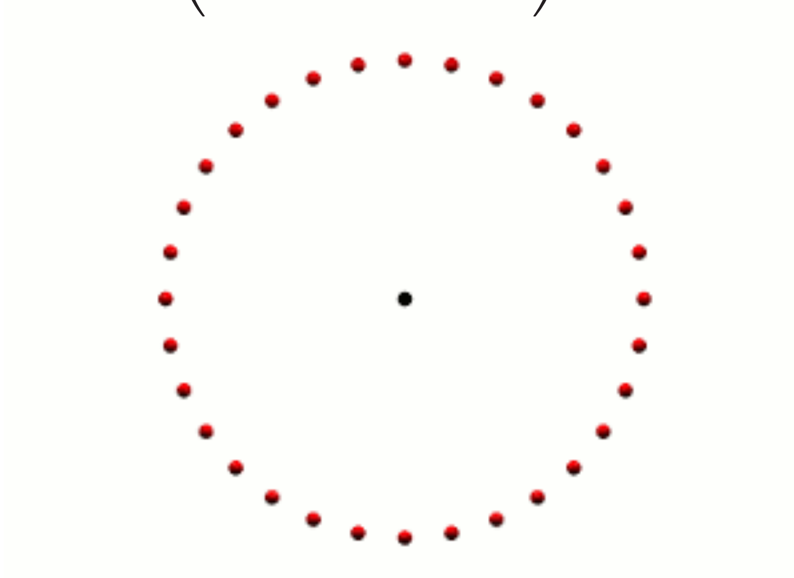
$G_{\mu\nu} = 8\pi T_{\mu\nu}$ Einstein equations

$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ ...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?

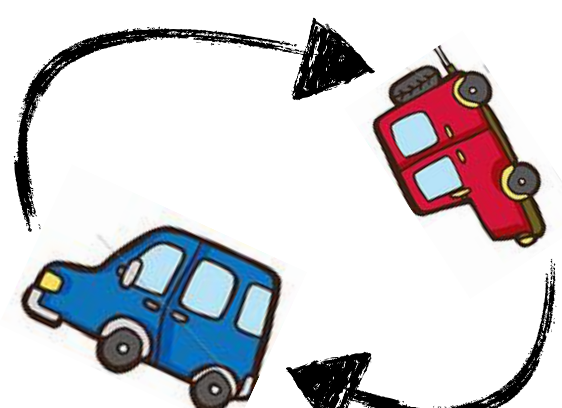
$M \sim 10^3 \mathrm{Kg}$

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

on a 1 km track

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

$h \sim 10^{-42}$



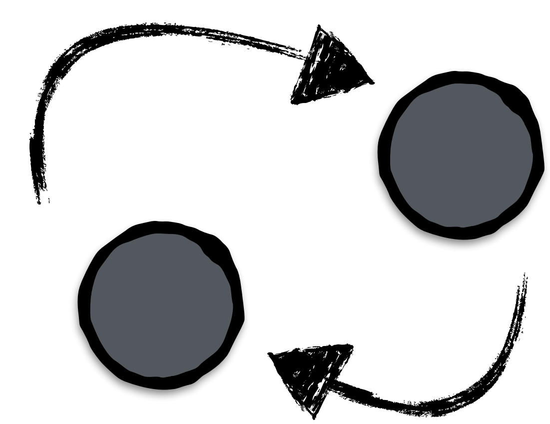
Binary black holes!

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

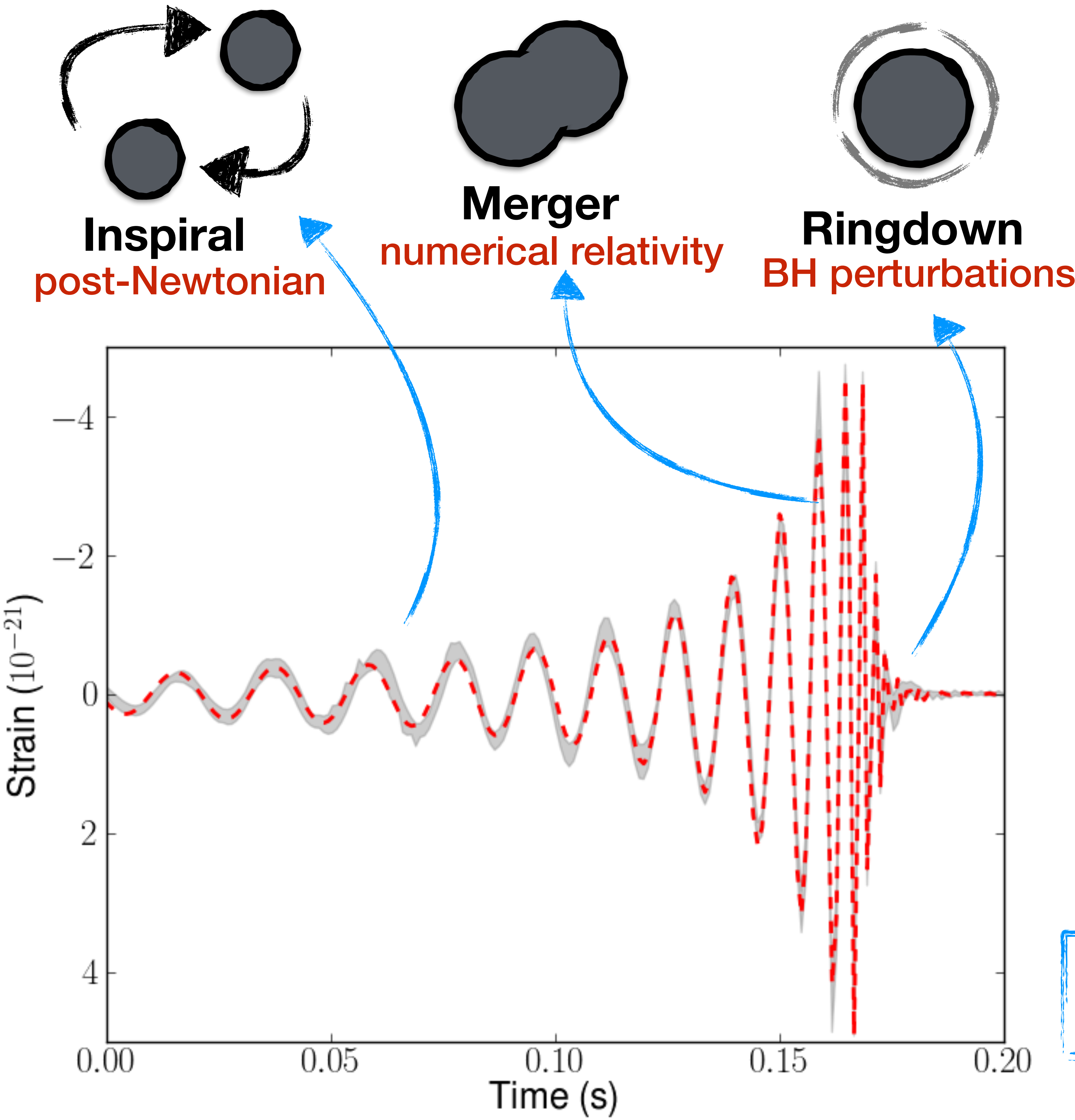
$v \sim 0.1c$

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

$h \sim 10^{-21}$



GW signals from BH mergers



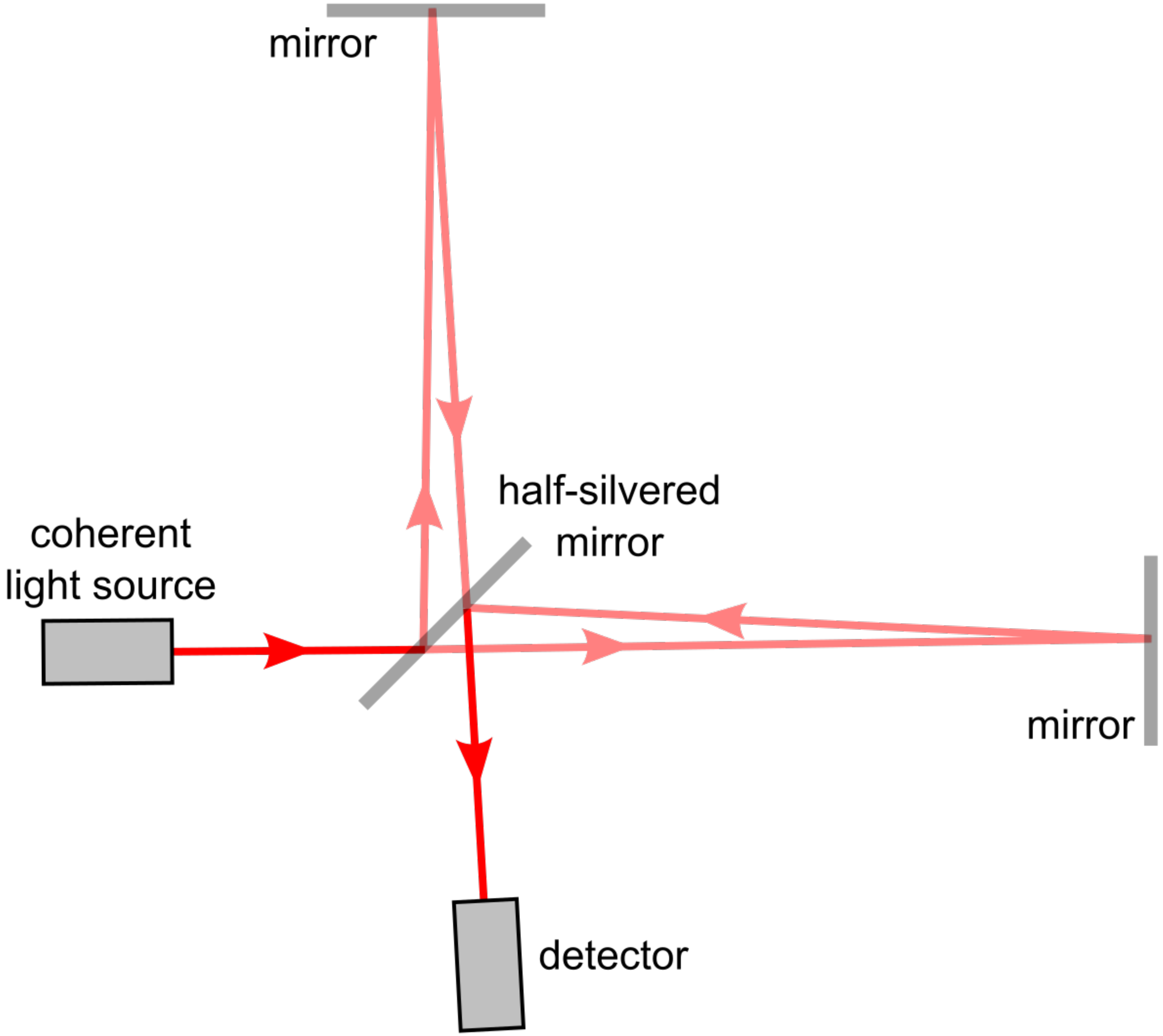
- Frequency gradually increases during the **inspiral**
- **Merger** of two BHs is one of the most energetic events in the Universe
- Direct signal from highly-dynamic strong-field gravity
- *BHs have no hair*: final remnant has to dissipate all properties but mass and spin (**ringdown**)

We need templates!

No worries we “just” need a precision of

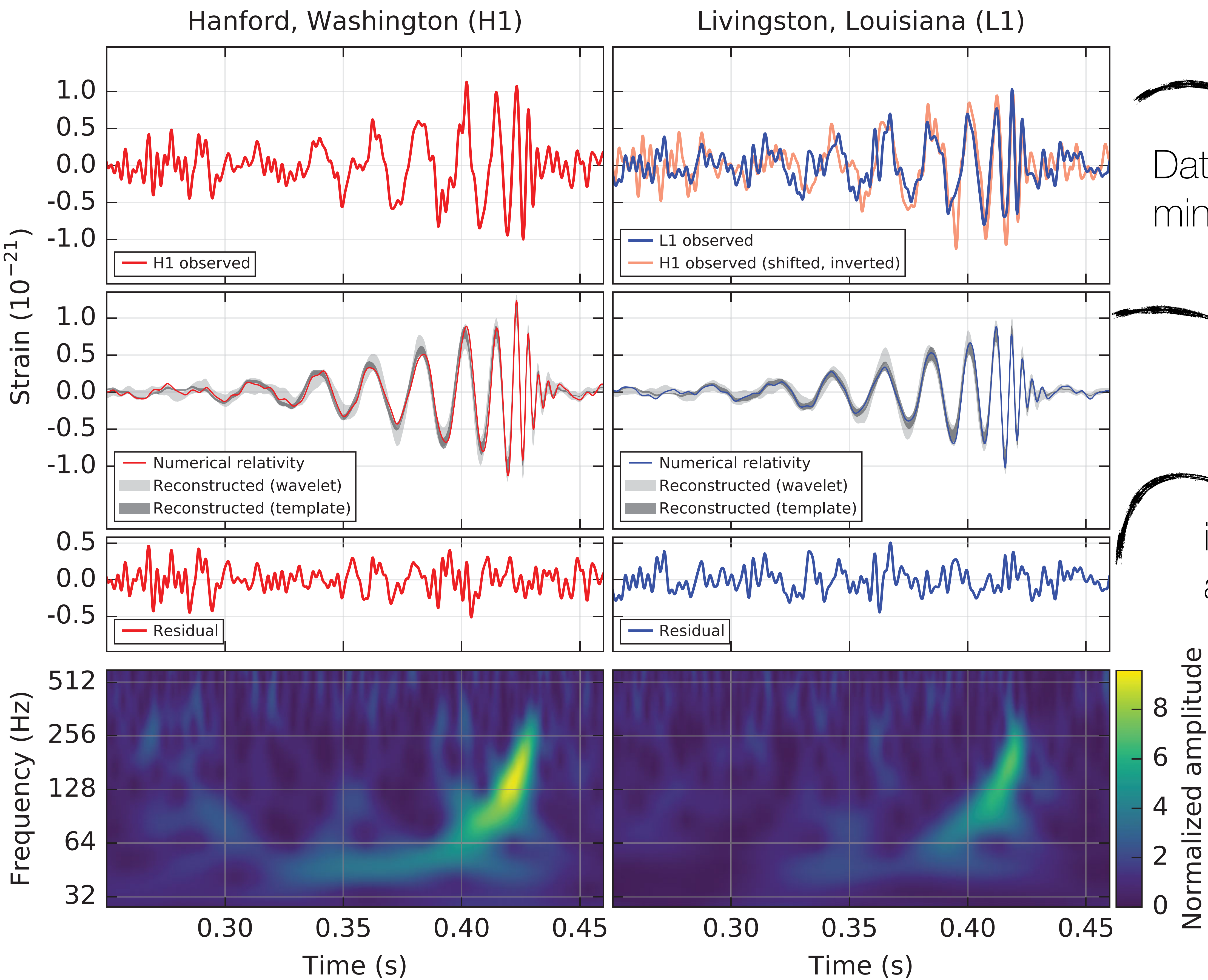
0.00000000000000000000001

Lasers to detect gravity



LIGO and Virgo on Google Maps

It all begun with GW150914



Data streams with minimal filtering

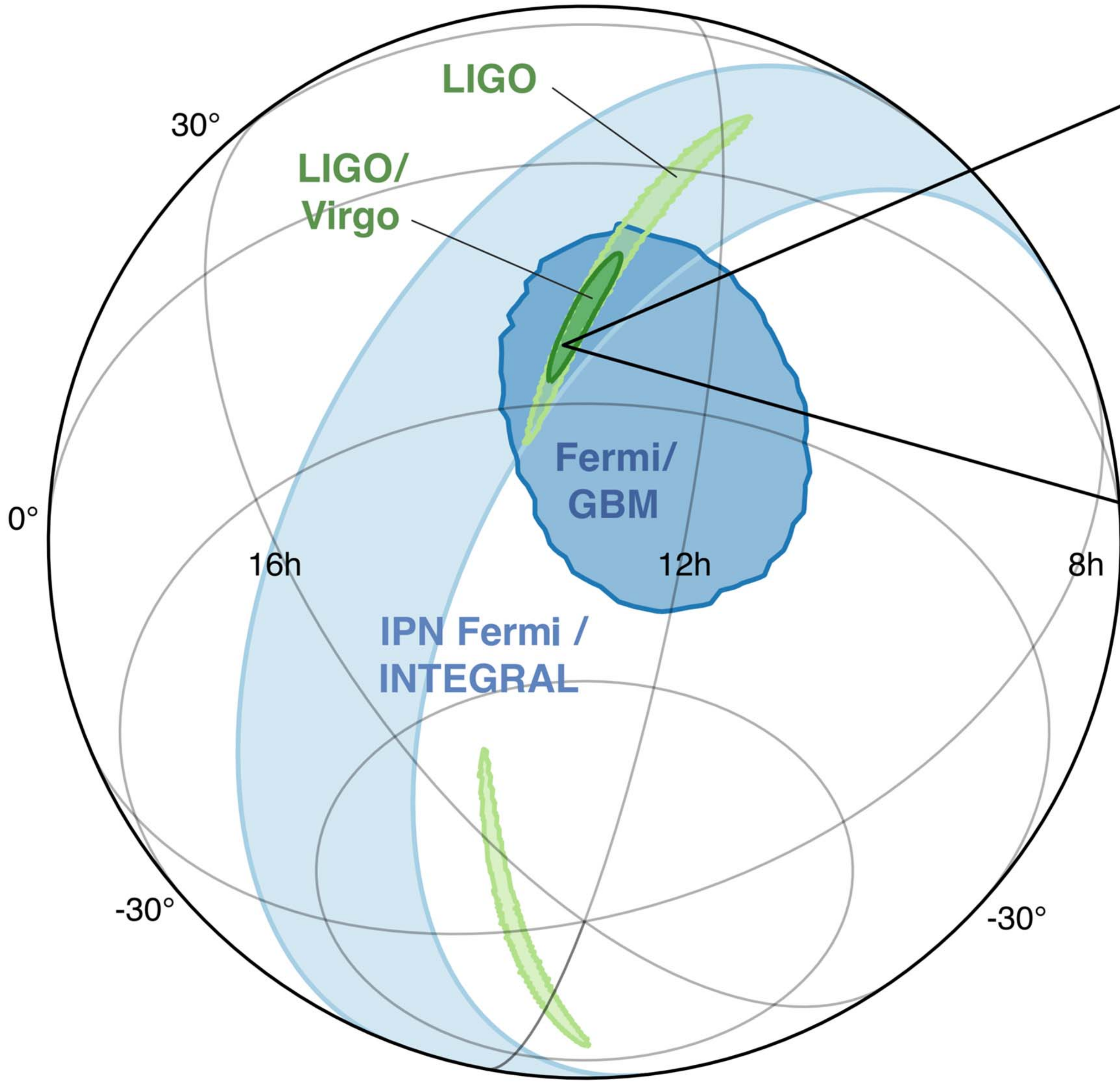
A numerical model…

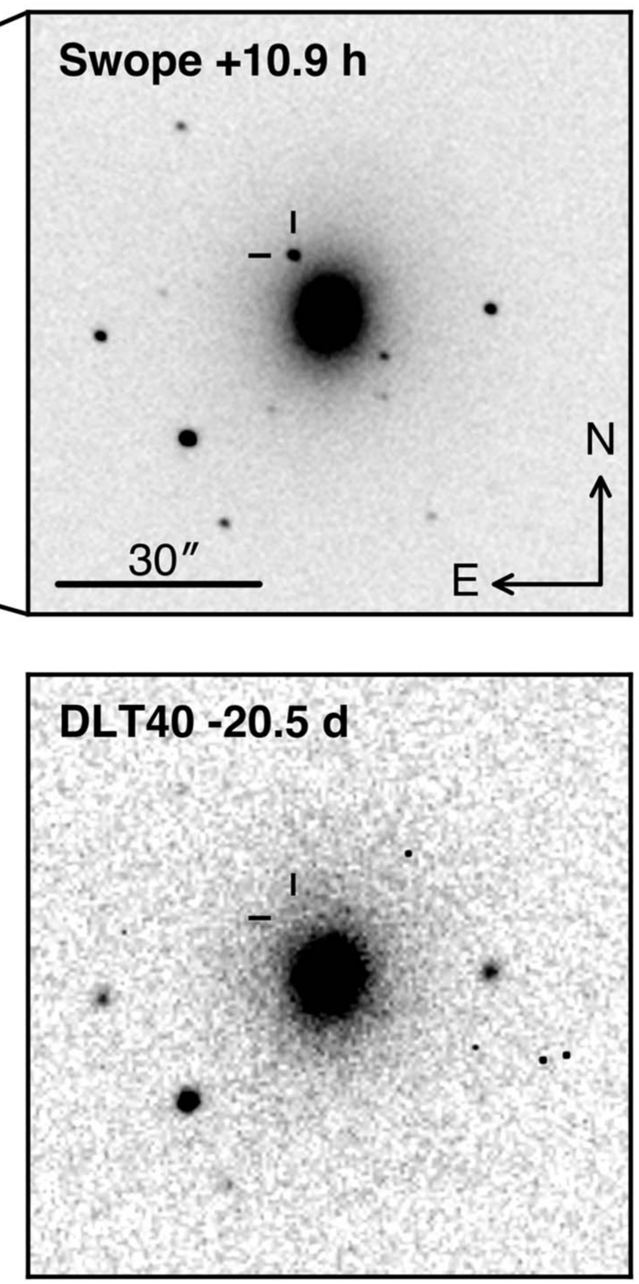
in spectacular agreement

$f \sim t^{8/3}$

The gold rush

- A third GW detector is the only reasonable way to do this
- Time coincidence with gamma rays and fast communication
- Still some 50 galaxies…

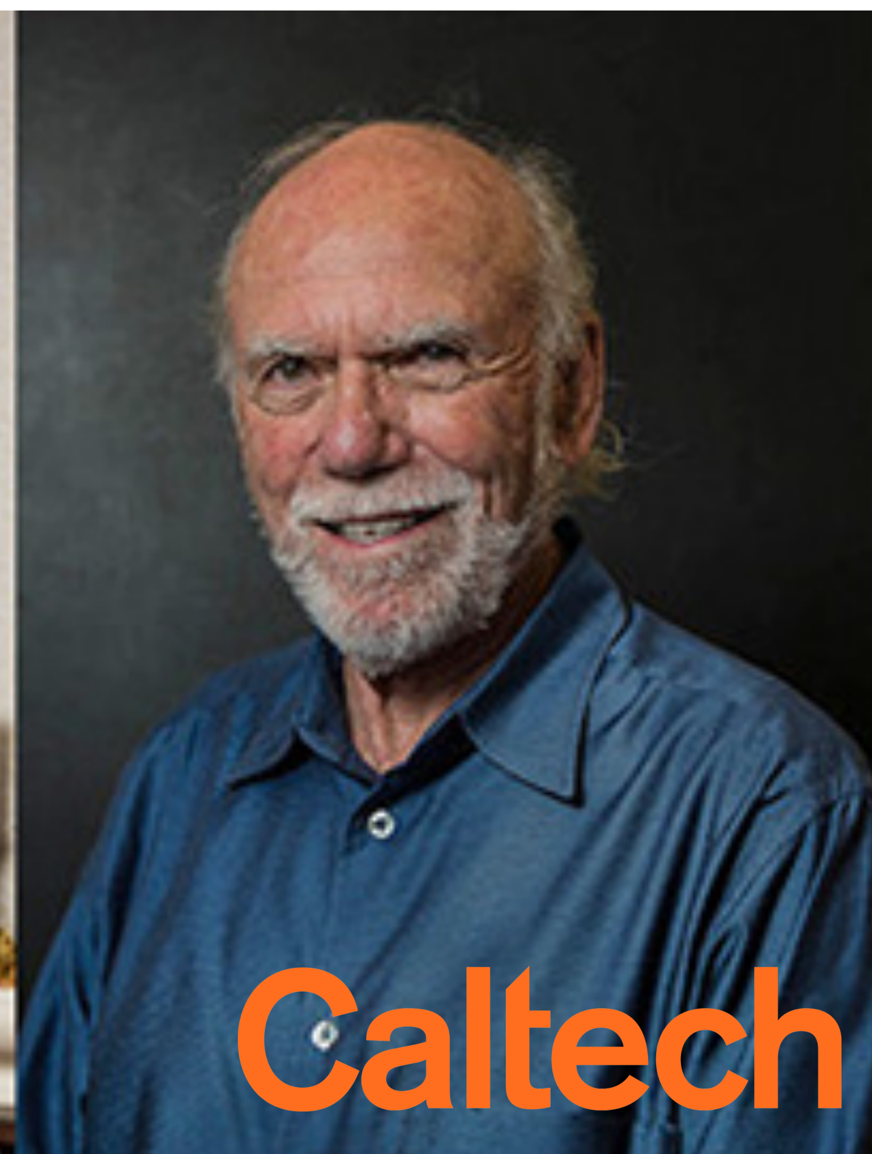




2017 Nobel Prize

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

R. Weiss **B. Barish** **K. Thorne**



Just passing by…

Can BHs really make it?

Peters and Mathews 1963
Peters 1964

Power emitted in gravitational waves:

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3 M^3}{c^5 a^3}\frac{q}{(1+q)^2}$$

GW-driven inspiral timescale

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

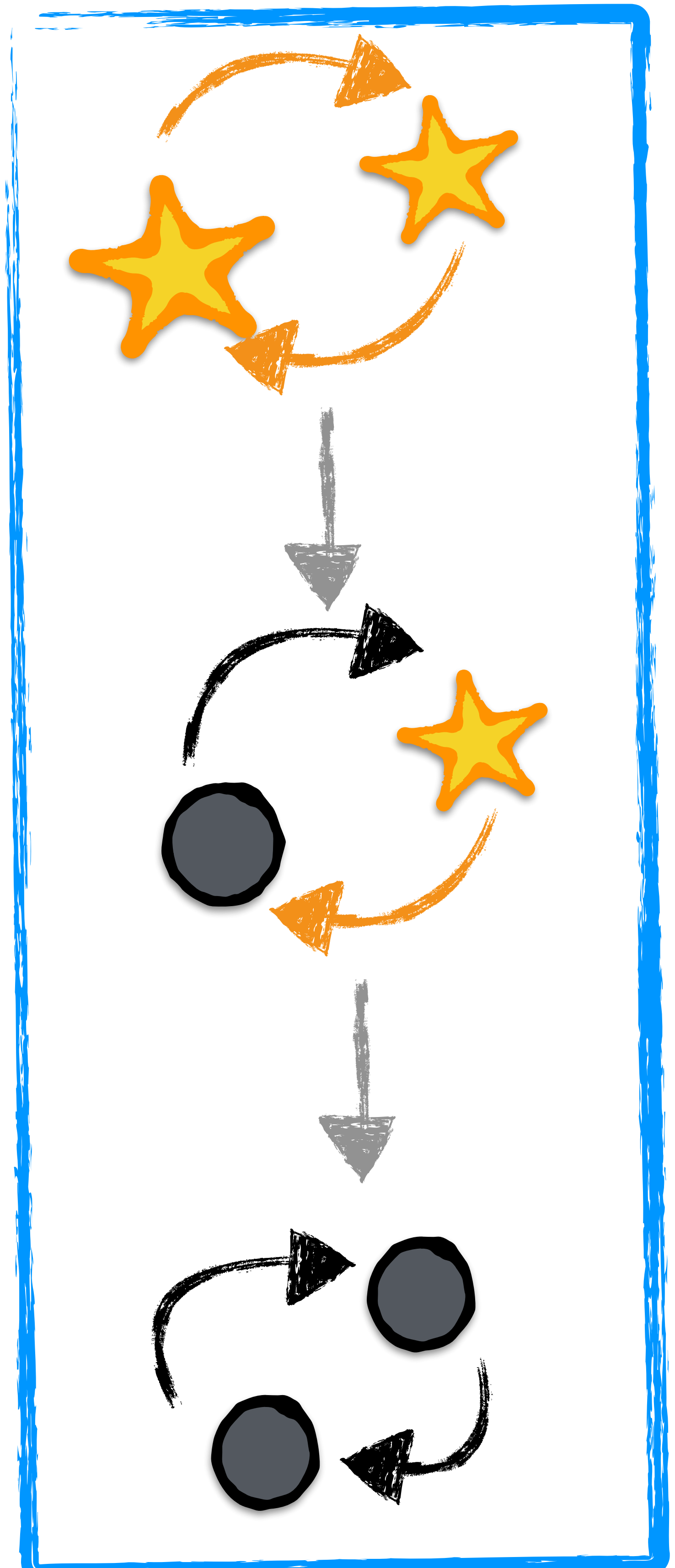
Gravitational waves are efficient below

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

stellar-mass BHs

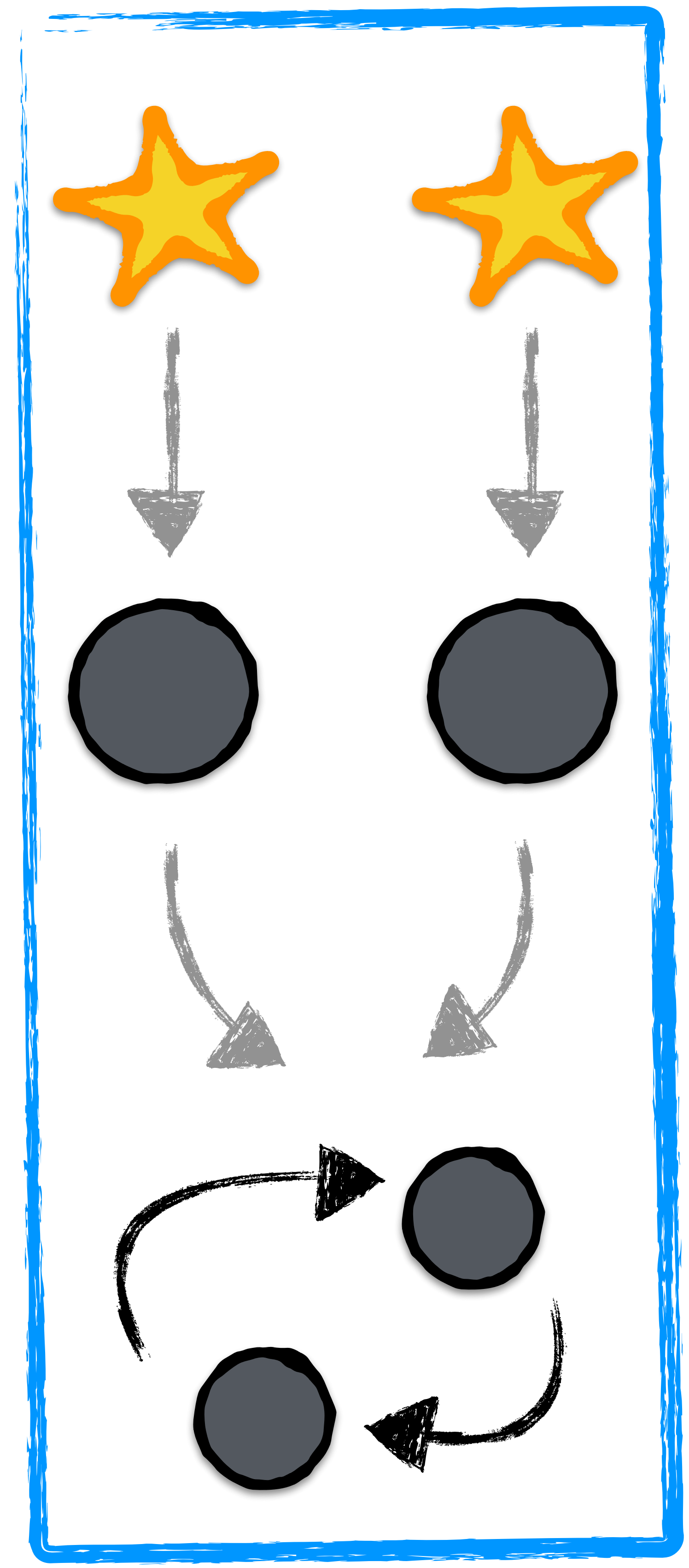
Relativity alone cannot explain the LIGO events!
We need some **astrophysics!**

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



Bayes: the man

$$P(\theta|d) = \frac{P(d|\theta)\; p(\theta)}{\int P(d|\theta)\; p(\theta)} \rightarrow P(\theta|d,\beta) = \frac{P(d|\theta)\; p(\theta|\beta)}{\int P(d|\theta)\; p(\theta|\beta)}$$

θ

Parameters: describe single events.

Masses, spins, redshifts, eccentricity, etc

Enter the likelihood

β

Hyperparameters: describe the population

Common envelope efficiency, cluster hardening, SN kicks, etc

Enter the prior

Odds ratio

$$\mathcal{O}_{12} = \frac{P(\theta|d,\beta_1)\; p(\beta_1)}{P(\theta|d,\beta_2)\; p(\beta_2)}$$

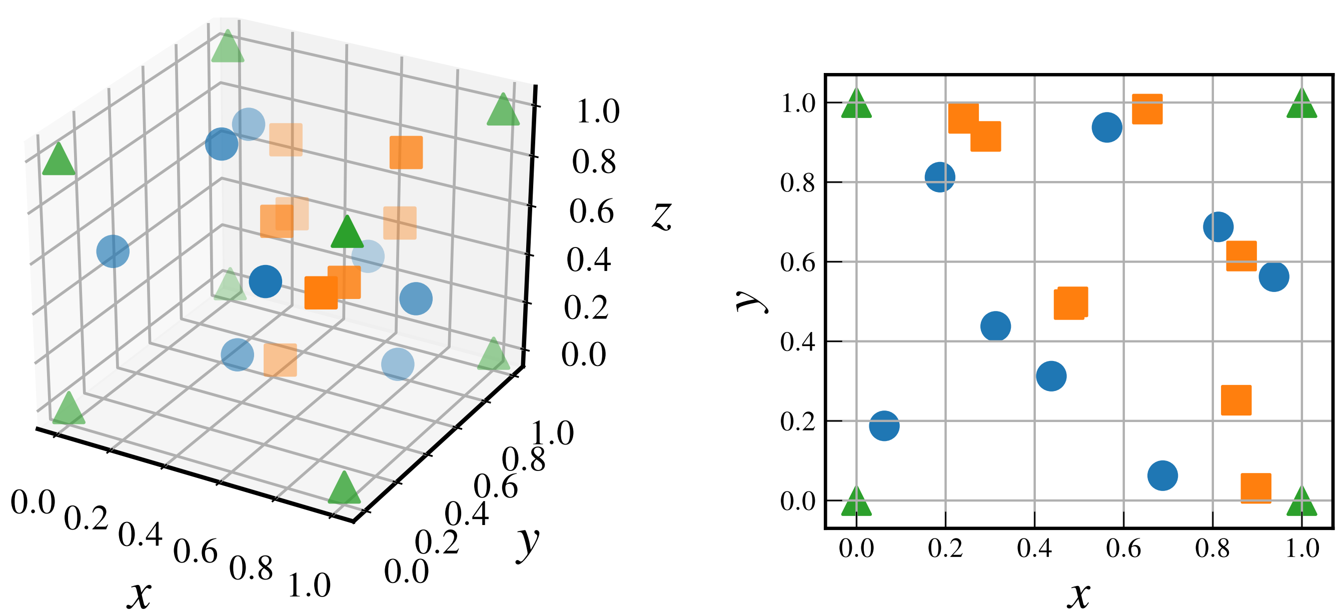
Hierarchical framework:

$$P(\beta|\theta,d) = \frac{P(\theta|d,\beta)p(\beta)}{\int \dots}$$

Do it for real: ingredients

1. A population synthesis code

2. Design a training bank. Space filling algorithms



Latin hypercubes

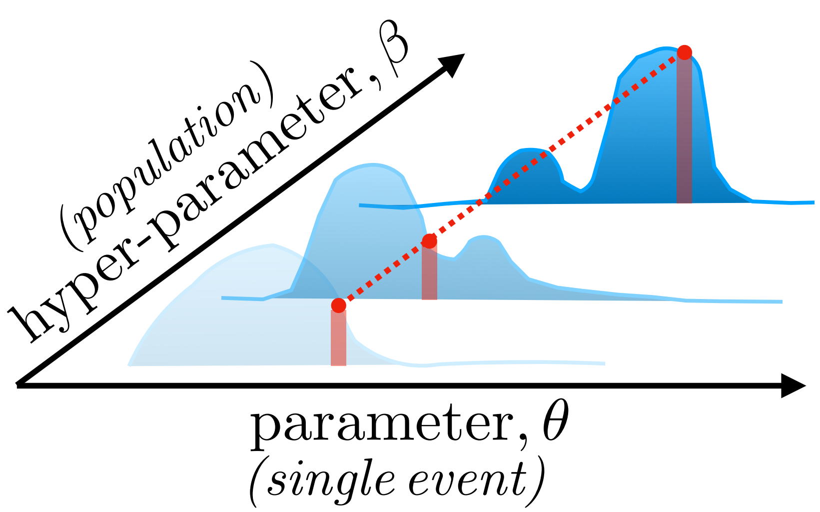
3. Some form of data compression

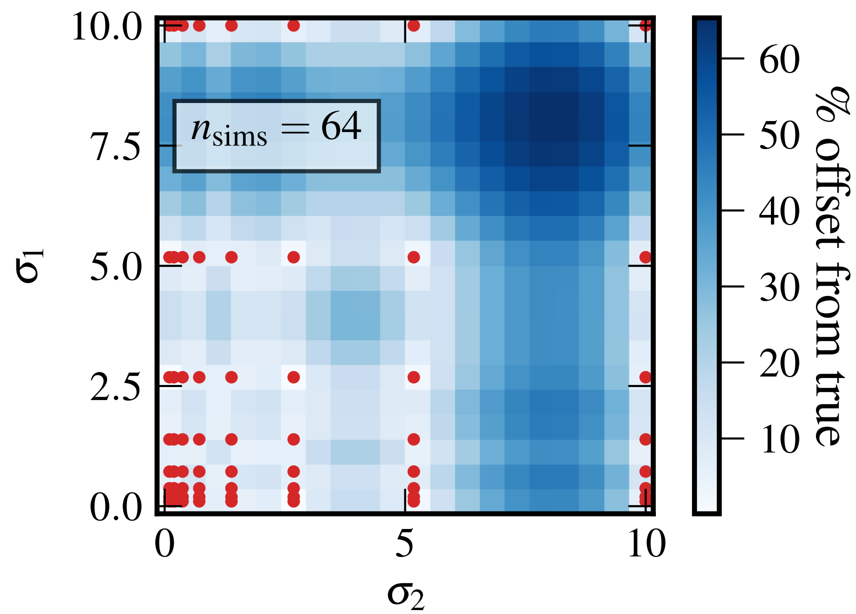
Principal component analysis

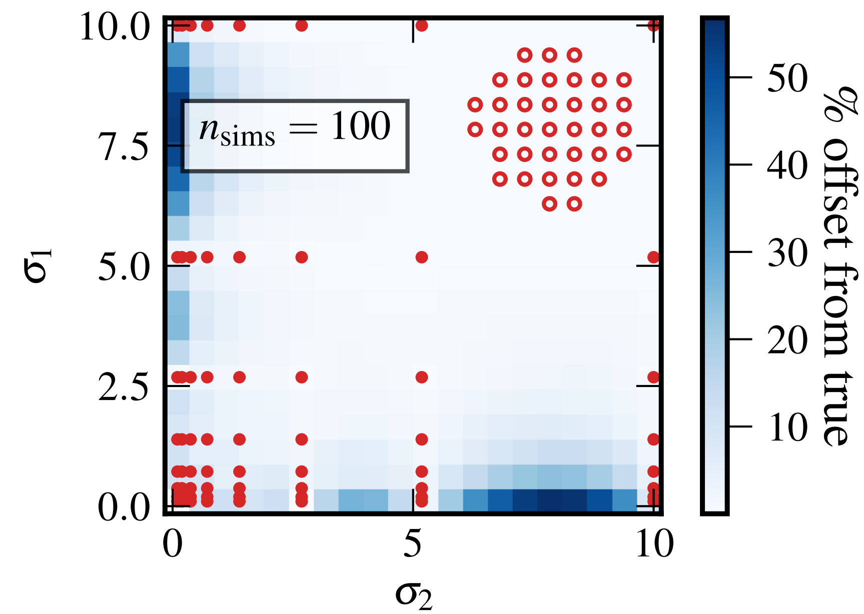
Do it for real: ingredients

4. A powerful interpolation scheme

Gaussian Process Regression







5. Likelihood with selection effects, measurements errors

Loredo 2004, Mandel+ 2019

$$p(\lambda, N|d) \propto \pi(\lambda) N(\lambda)^{N_{\rm obs}} \exp\left[-N(\lambda)\int \mathrm{d}\theta\, p_{\rm det}(\theta) p_{\rm pop}(\theta|\lambda)\right] \prod_{i=1}^{N_{\rm obs}} \int \mathrm{d}\theta\, p_i(\theta|d) \frac{p_{\rm pop}(\theta|\lambda)}{\pi(\theta)}$$

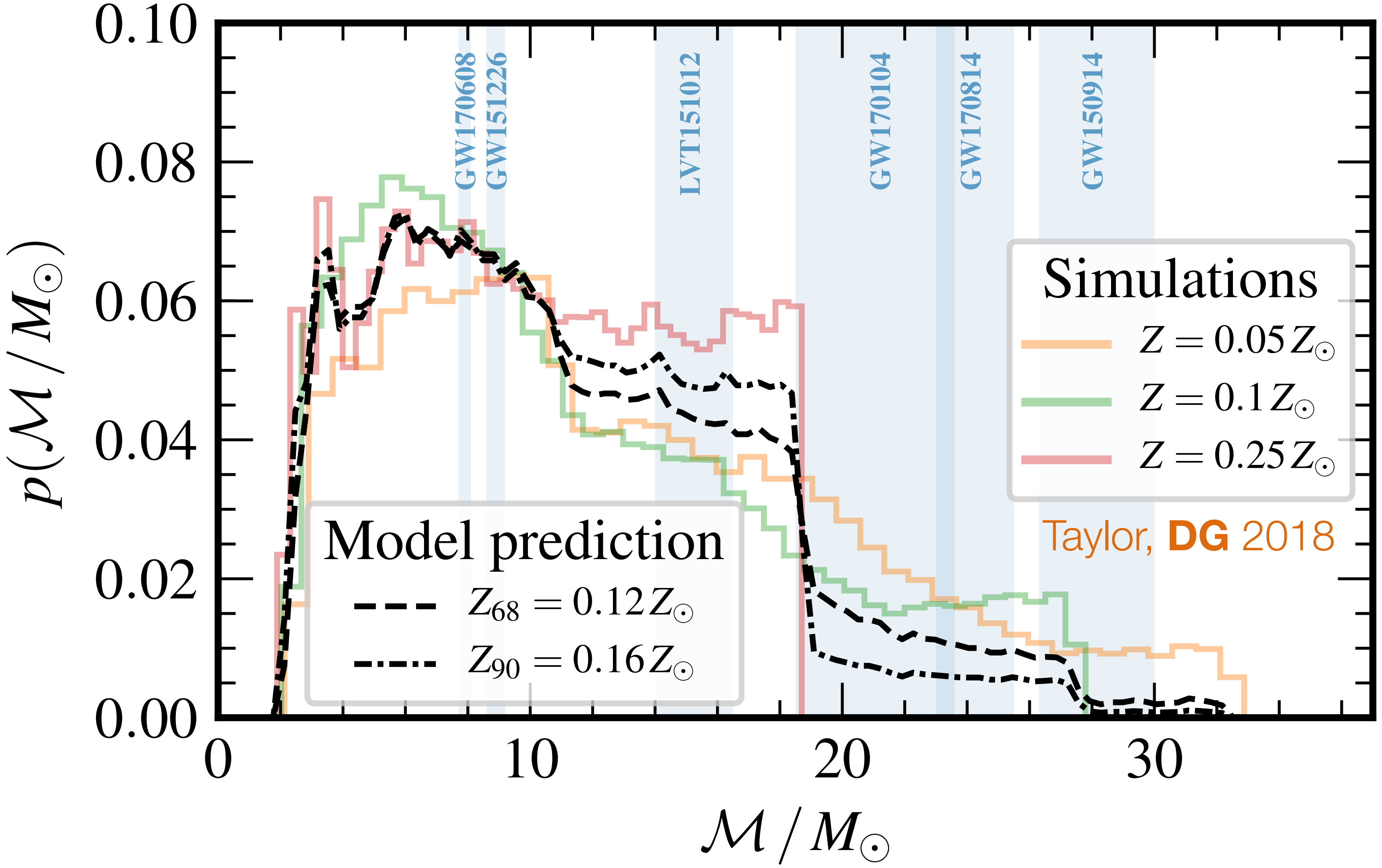
marginalize over N: $$p(\lambda|d) \propto \pi(\lambda) \prod_{i=1}^{N_{\rm obs}} \frac{\int \mathrm{d}\theta\, p_{\rm pop}(\theta|\lambda) p_i(\theta|d)/\pi(\theta)}{\int \mathrm{d}\theta\, p_{\rm pop}(\theta|\lambda) p_{\rm det}(\theta)}$$

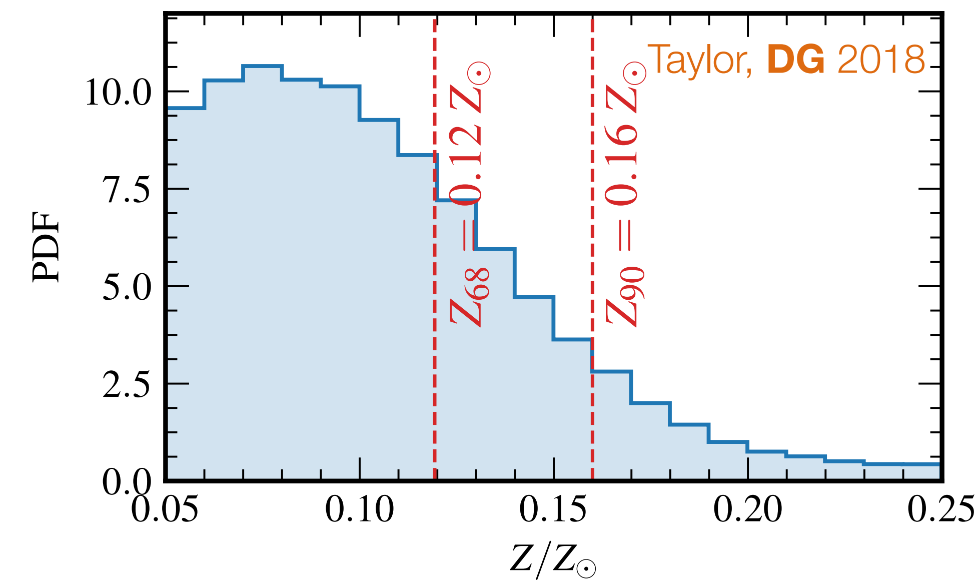
Proof of principle

Interpolating predictions by Stevenson+2017 along metallicity

Predict what a pop-synth simulation would look like. GPR interpolator works great!

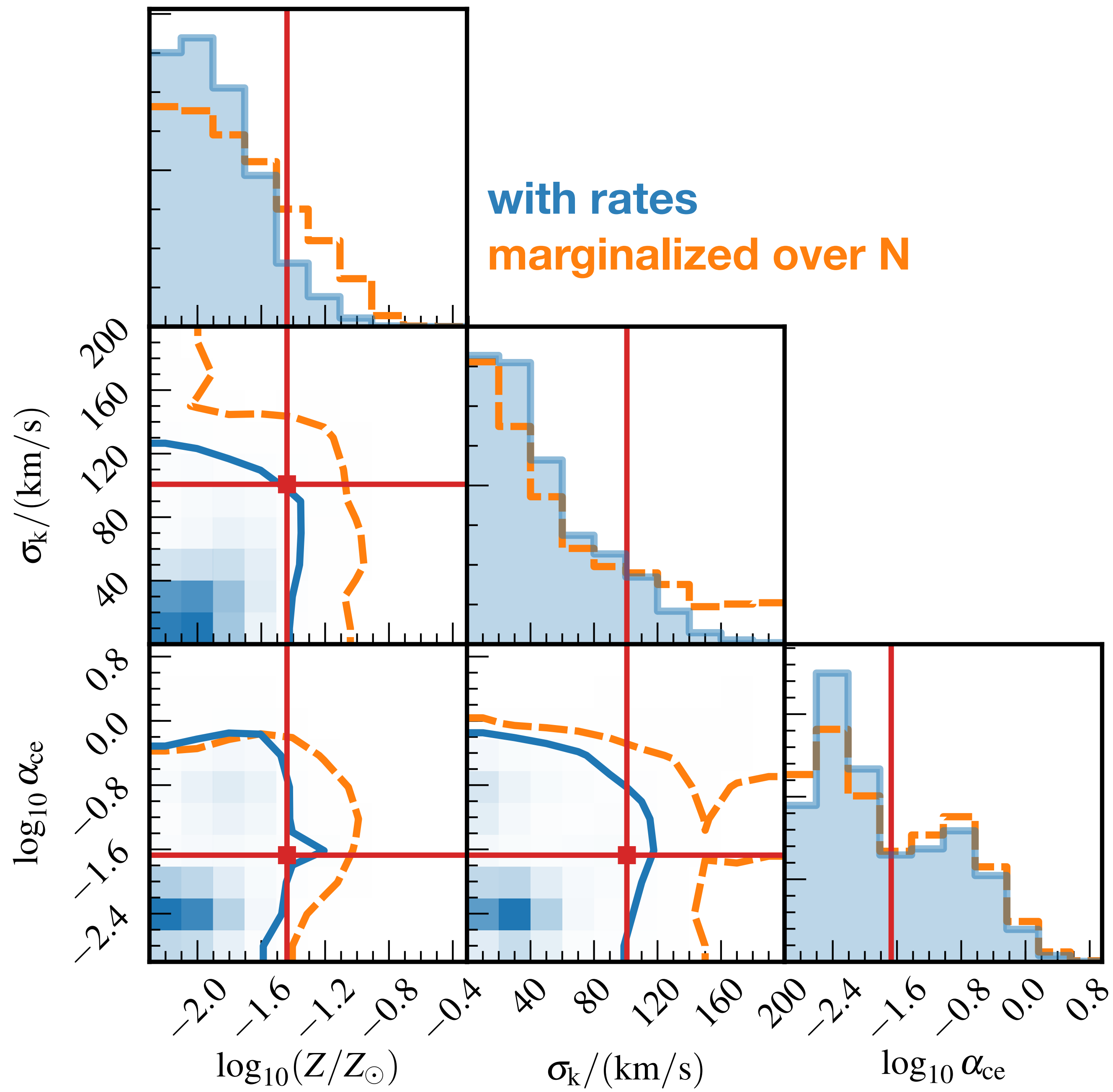
Posterior distribution of the hyperparameter! Not just odds ratios!





Custom simulation design

- 125 sims: custom-made BSE pop-synth runs for training
  Hurley, Tout, Pols 2002. Lamberts+ 2016
- 2 parameters: chirp mass and redshift
- 3 hyperparameters: metallicity, common envelope, SN kicks



Taylor, **DG** 2018

Pipeline prototyped on BlueBEAR and Athena. Stay tuned!

Mould, **DG**+, in prep
Wong, **DG**+, in prep

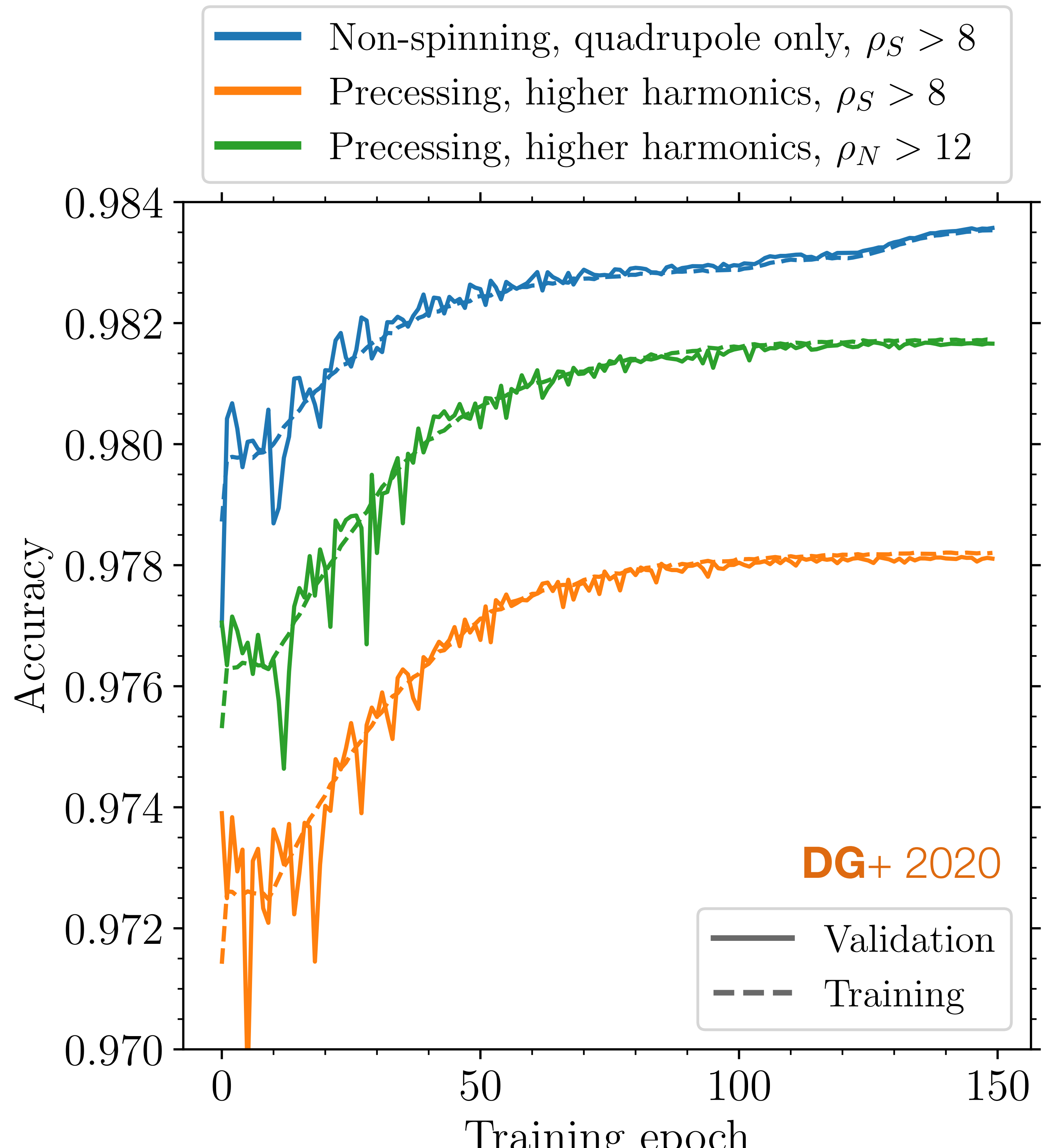
Need to know what we are missing

DG+ 2020

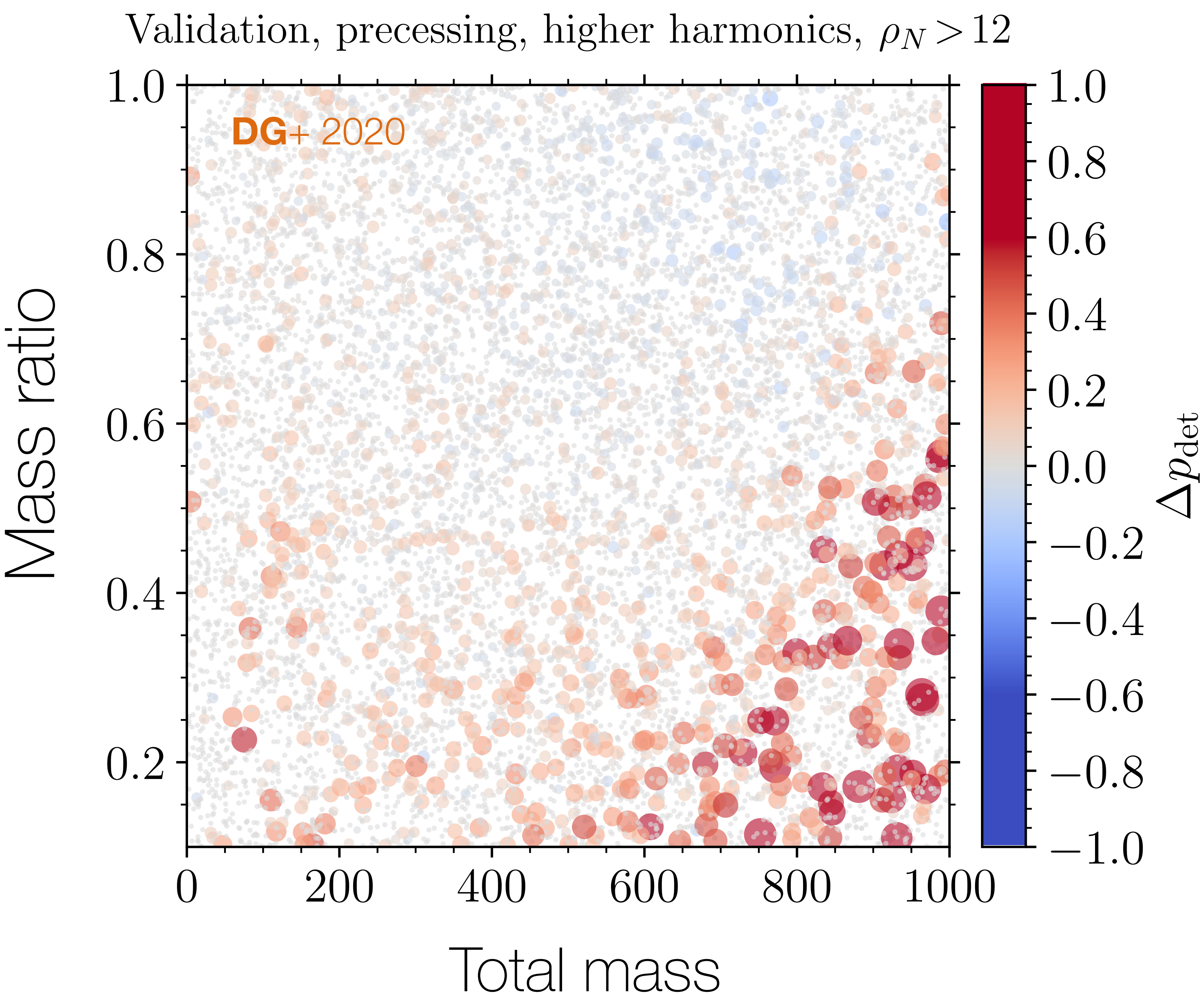
Unbiassed inference requires accurate modelling of selection effects

Very first AI model was developed on BlueBEAR!

Goes beyond common single-detector approximation and fully consider the network response

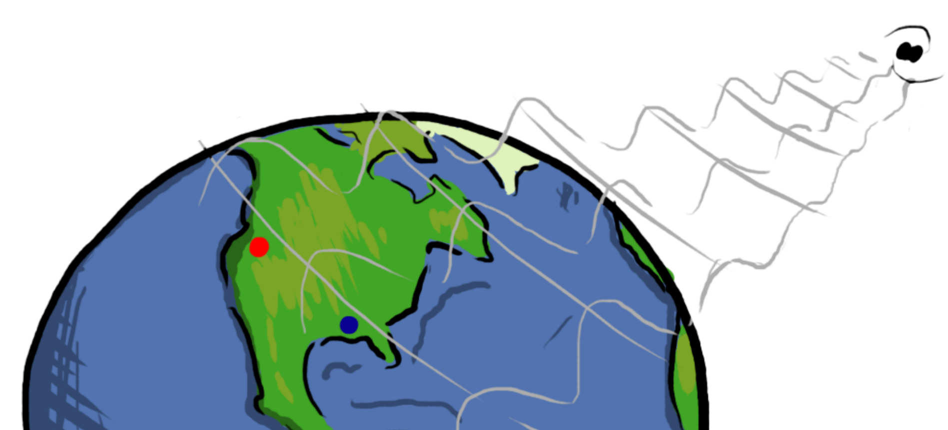


Need to know what we are missing



Current inference biassed in specific region of the parameter space.

If future events are there…



Listening to the Universe

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