Title: Gravitational-wave Source Inference with Data-driven Models

Speakers: Bruce Edelman

Series: Strong Gravity

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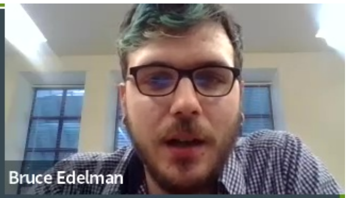
Abstract: With the release of the third gravitational wave transient catalog (GWTC-3), the LIGO and Virgo detectors have reported nearly 100 gravitational waves from colliding black holes and neutron stars. Among these detections there have been numerous surprises, such as the heavy GW190521, the confidently asymmetric GW190412, and the exceptionally small secondary of GW190814. In addition to analyses of each individual sources' properties, such as their masses and spins, one can also summarize the collective properties of the colliding objects as population probability distributions over these parameters. As catalog sizes continue to grow, it enables both finer grained investigations into the population properties of merging compact objects, and robustly testing GR in the strong gravity regime. In this talk I will present data driven statistical models to look for deviations to underlying theoretical expectations, both for individual gravitational waveform models and population models describing the astrophysical distributions of merging compact binaries. I will present the results of an analysis using this novel data-driven model on the 11 compact binary mergers in GWTC-1, then move towards hierarchical models, inferring the binary black hole mass distribution with similar data-driven methods. I will conclude with showing new results from the LVK population analyses of GWTC-3 and motivate the need towards developing more data-driven statistical models for the incoming swath of observations expected in the fourth observing run that, as we have seen, will likely continue to further challenge theoretical expectations.



Gravitational-Wave Source Inference with Data-Driven Models

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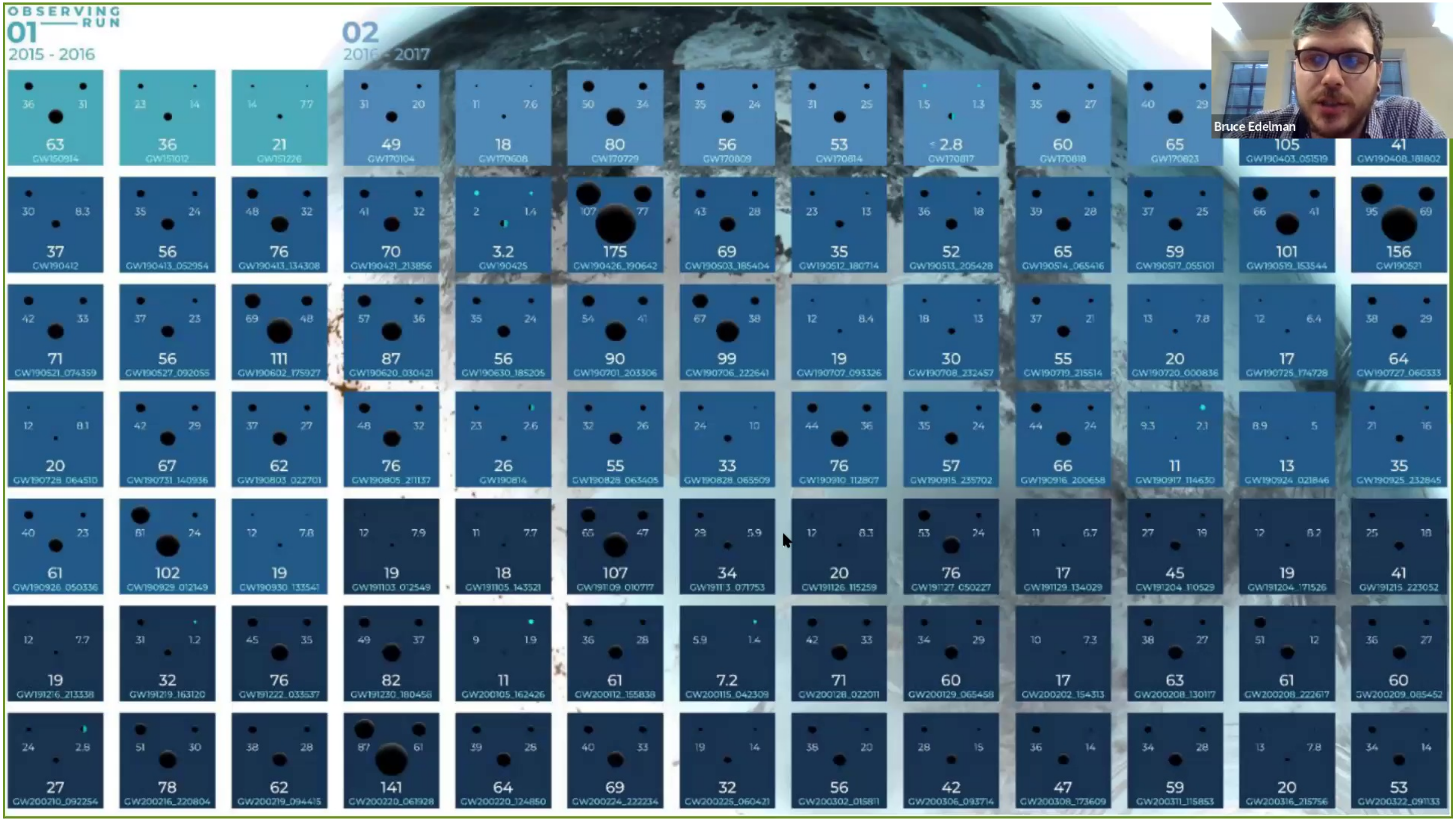
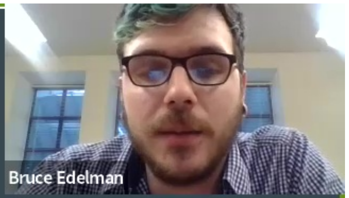
Bruce Edelman, University of Oregon

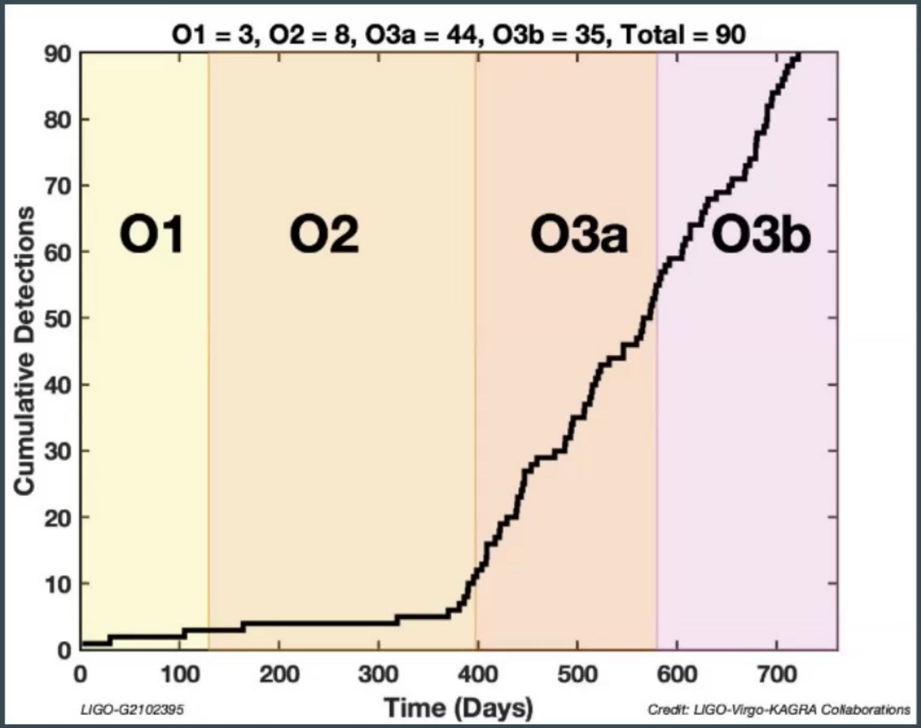
PI Strong Gravity Seminar 01/20/22


OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
Bruce Edelman
63 GW150914
36 GW151012
21 GW151226
49 GW170104
18 GW170608
80 GW170729
56 GW170809
53 GW170814
2.8 GW170817
60 GW170818
65 GW170823
105 GW190403_051519
41 GW190408_181802
37 GW190412
56 GW190413_052954
76 GW190413_134308
70 GW190421_213856
3.2 GW190425
175 GW190426_190642
69 GW190503_185404
35 GW190512_180714
52 GW190513_205428
65 GW190514_065416
59 GW190517_055101
101 GW190519_153544
156 GW190521
71 GW190521_074359
56 GW190527_092055
111 GW190602_175927
87 GW190620_030421
56 GW190630_185205
90 GW190701_203306
99 GW190706_222641
19 GW190707_093326
30 GW190708_232457
55 GW190719_215514
20 GW190720_000836
17 GW190725_174728
64 GW190727_060333
20 GW190728_064510
67 GW190731_140936
62 GW190803_022701
76 GW190805_211137
26 GW190814
55 GW190828_063405
33 GW190828_065509
76 GW190910_112807
57 GW190915_235702
66 GW190916_200658
11 GW190917_114630
13 GW190924_021846
35 GW190925_232845
61 GW190926_050336
102 GW190929_012149
19 GW190930_133541
19 GW191103_012549
18 GW191105_143521
107 GW191109_010717
34 GW191113_071753
20 GW191126_115259
76 GW191127_050227
17 GW191129_134029
45 GW191204_110529
19 GW191204_171526
41 GW191215_223052
19 GW191216_213338
32 GW191219_163120
76 GW191222_033537
82 GW191230_180458
11 GW200105_162426
61 GW200112_155838
7.2 GW200115_042309
71 GW200128_022011
60 GW200129_065458
17 GW200202_154313
63 GW200208_130117
61 GW200208_222617
60 GW200209_085452
27 GW200210_092254
78 GW200216_220804
62 GW200219_094415
141 GW200220_061928
64 GW200220_124850
69 GW200224_222234
32 GW200225_060421
56 GW200302_015811
42 GW200306_093714
47 GW200308_173609
59 GW200311_115853
20 GW200316_215756
53 GW200322_091133

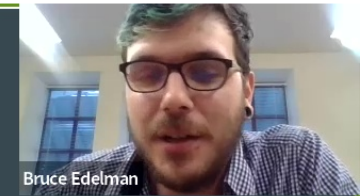
Recent Catalog of Observations – GWTC-3 Papers



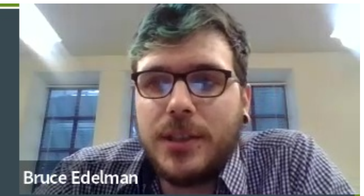
- Catalog [2111.03606]
- Population Analysis [2111.03634]
- Testing GR [2112.06861]
- Cosmology [2111.03604]



Overview

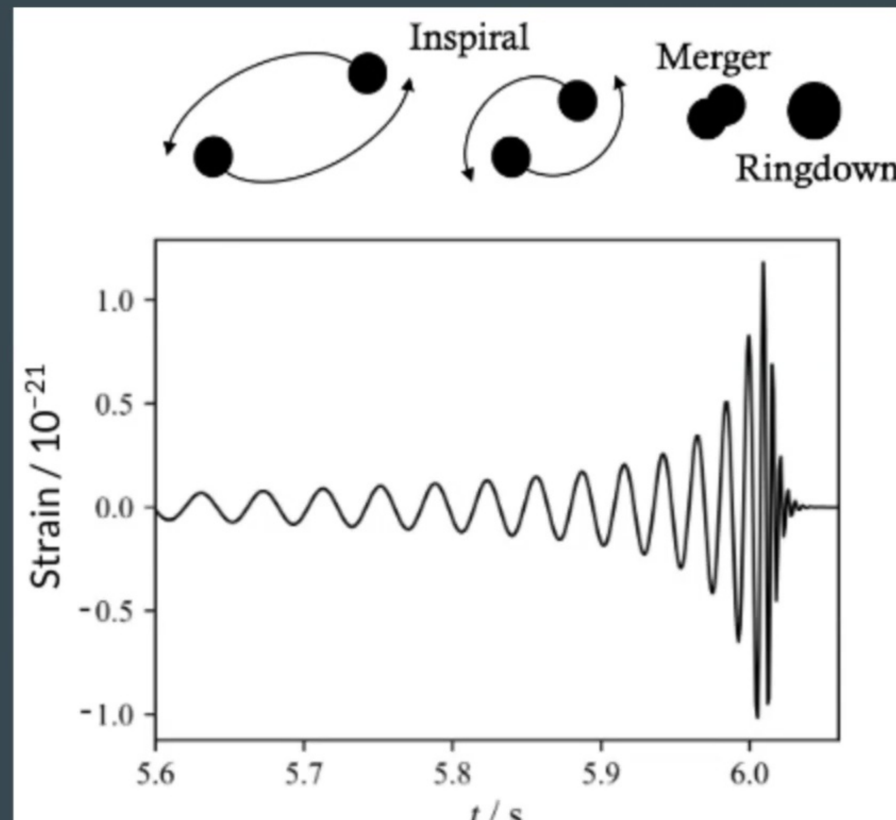


- Single Source Inference and Parameter Estimation
  - Coherent Waveform Deviation Model (Edelman et. al 2021)
- Hierarchical Inference of a Population of Sources
  - Pair-Instability Mass Gap Model (Edelman, Doctor, Farr 2021)
  - Semi-Parametric Modeling of the BBH Mass Distribution (Edelman et al 2022)
- Population Updates from GWTC-3



Parameters Describing a BBH Merger

- Intrinsic (8 parameters)
  - Mass of each BH: m1 >= m2 (2)
  - Spin vector of each BH (6)
- Extrinsic (7 parameters)
  - Luminosity Distance D_L
  - Sky localisation (right ascension, declination), Inclination angle, Arrival Time, Phase, Polarization angles

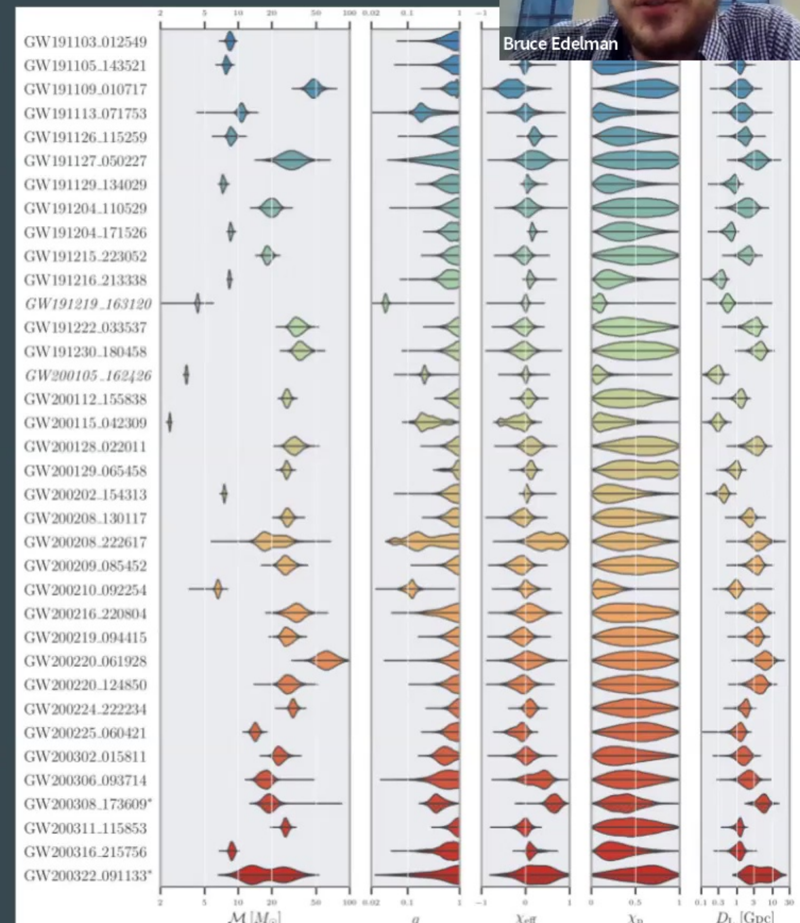


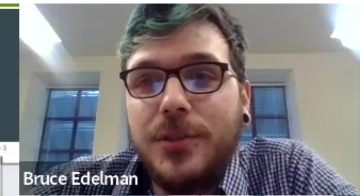
Parameter Estimation – Bayes' Theorem

- Noisy Data Limits our Inferences

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)p(\theta)}{\mathcal{Z}(d)}$$

- Goal: Given a stream of strain data, d, what is the probability distribution over parameters, \theta





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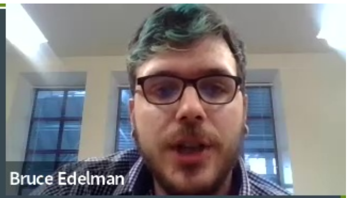
Parameter Estimation – Bayes' Theorem

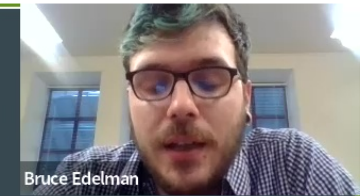


Likelihood — Prior

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)p(\theta)}{\mathcal{Z}(d)}$$

Posterior — Evidence

- Uninformative (Agnostic) Priors



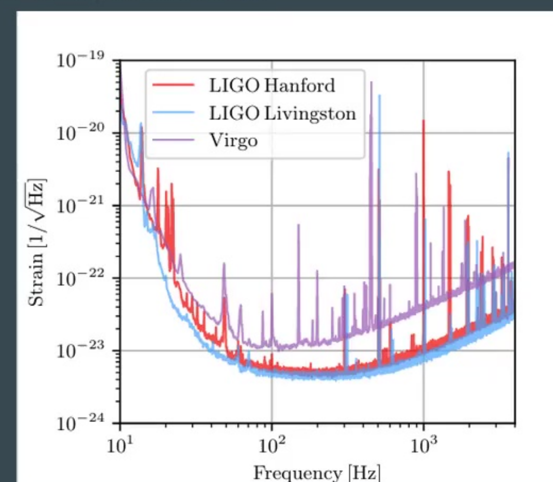
Parameter Estimation – Bayes' Theorem

Likelihood → $\mathcal{L}(d|\theta)$; Prior → $p(\theta)$; Posterior → $p(\theta|d)$; Evidence → $\mathcal{Z}(d)$

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)p(\theta)}{\mathcal{Z}(d)}$$

$$\mathcal{L}(d|\theta) \propto \exp\left(-\frac{1}{2}\sum_k \frac{|d_k - h_k(\theta)|^2}{\sigma_k^2}\right)$$

- Uninformative (Agnostic) Priors
- Under Assumption of Uncorrelated Gaussian Stationary Noise, we use the Whittle Likelihood



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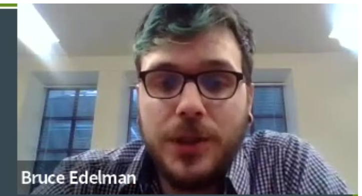
Likelihood and GW Waveform model



- The waveform model h, is different for each detector according to antenna pattern

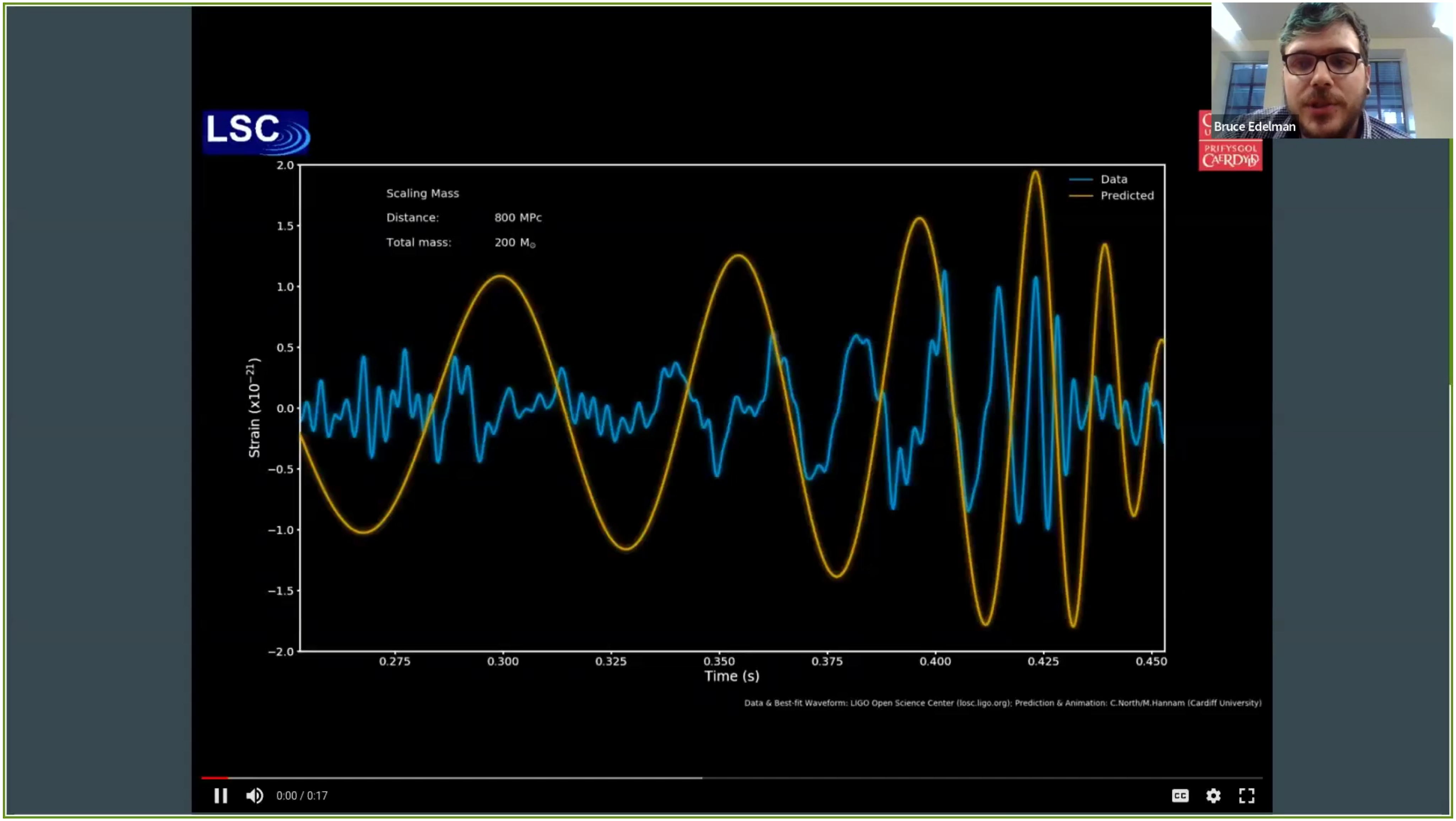
$$\mathcal{L}(d|\theta) \propto \exp\left(-\frac{1}{2} \sum_k \frac{|d_k - h_k(\theta)|^2}{\sigma_k^2} \right)$$

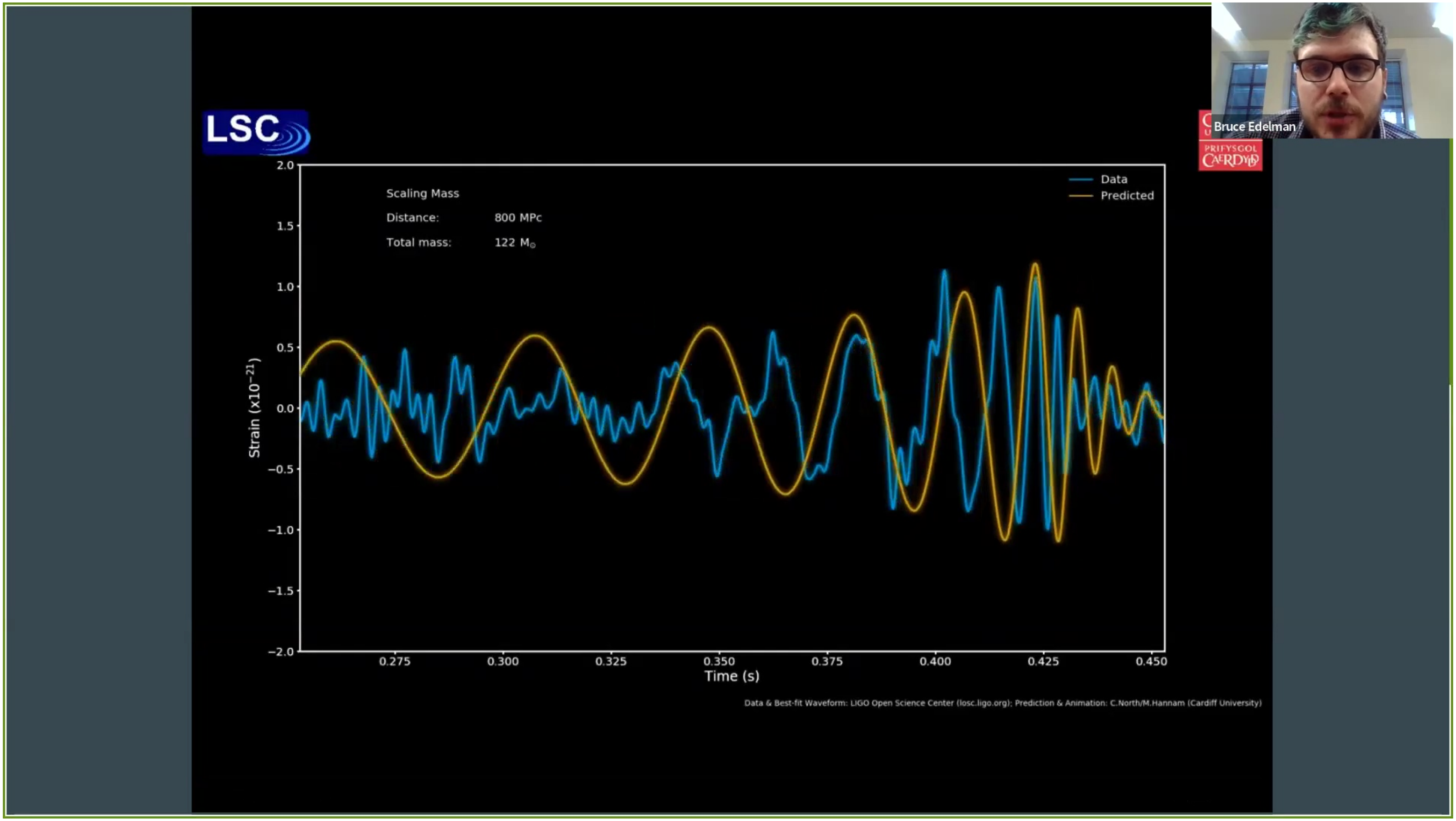
$$d_k(f) = h_{\mathrm{obs},k}(f) + n_k(f)$$

$$h_{\mathrm{obs,k}}(f) = h_+(f) F_{+,k}(f) + h_\times(f) F_{\times,k}(f)$$

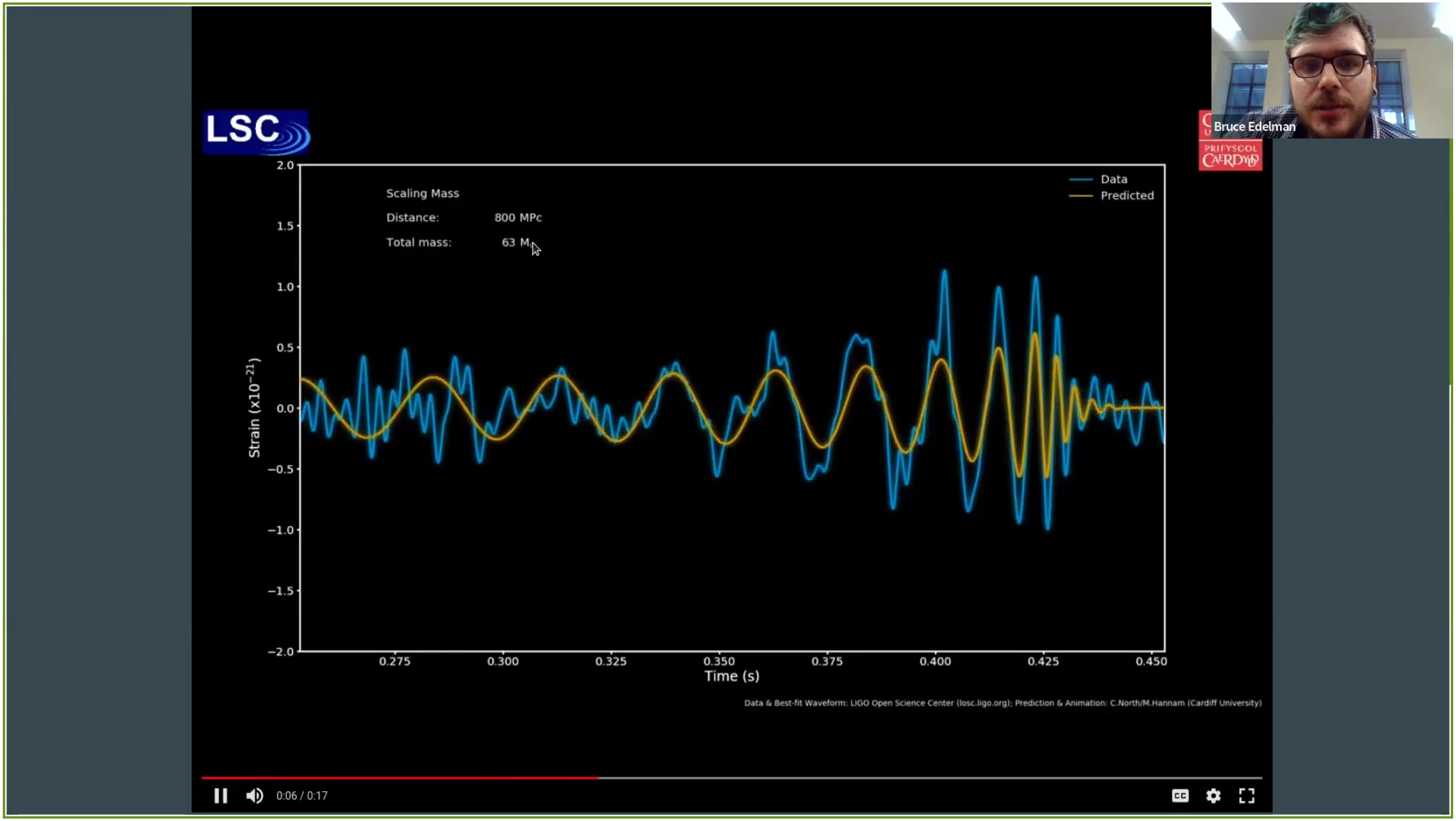
"Observed" signal in detector k

"Intrinsic" or "Coherent" signal across the network

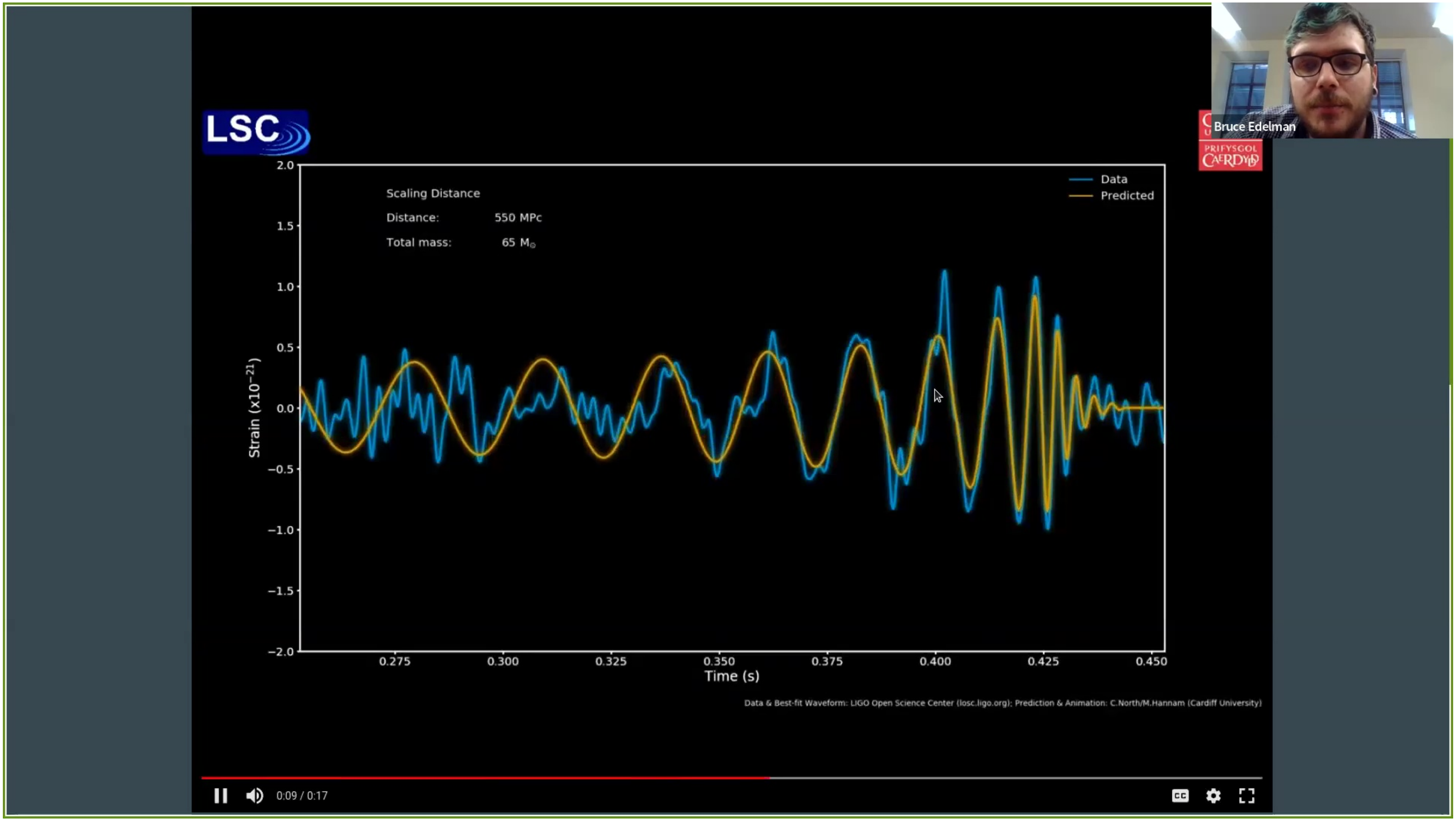

LSC
Scaling Mass
Distance: 800 MPc
Total mass: 200 M⊙
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:00 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD

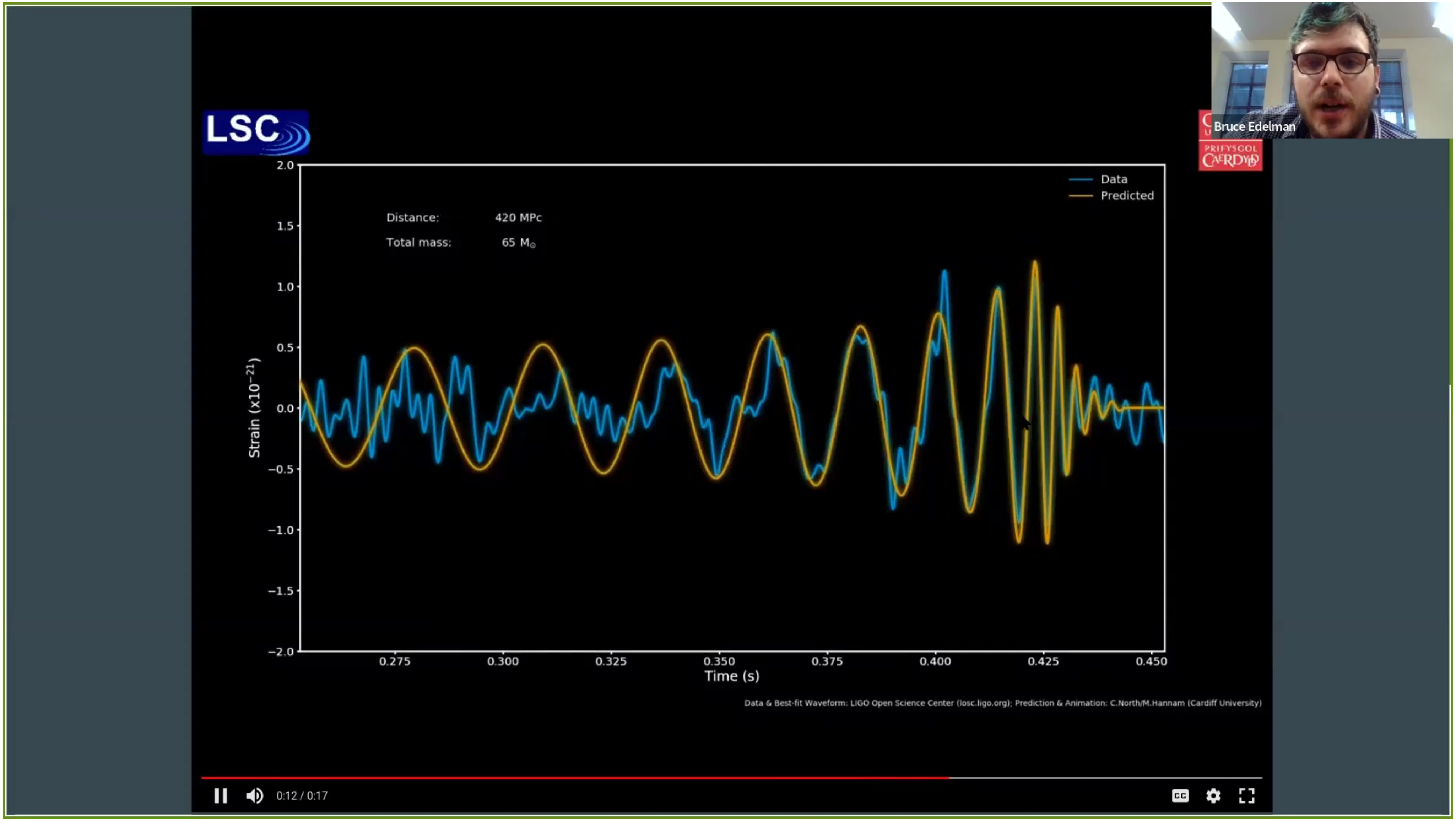


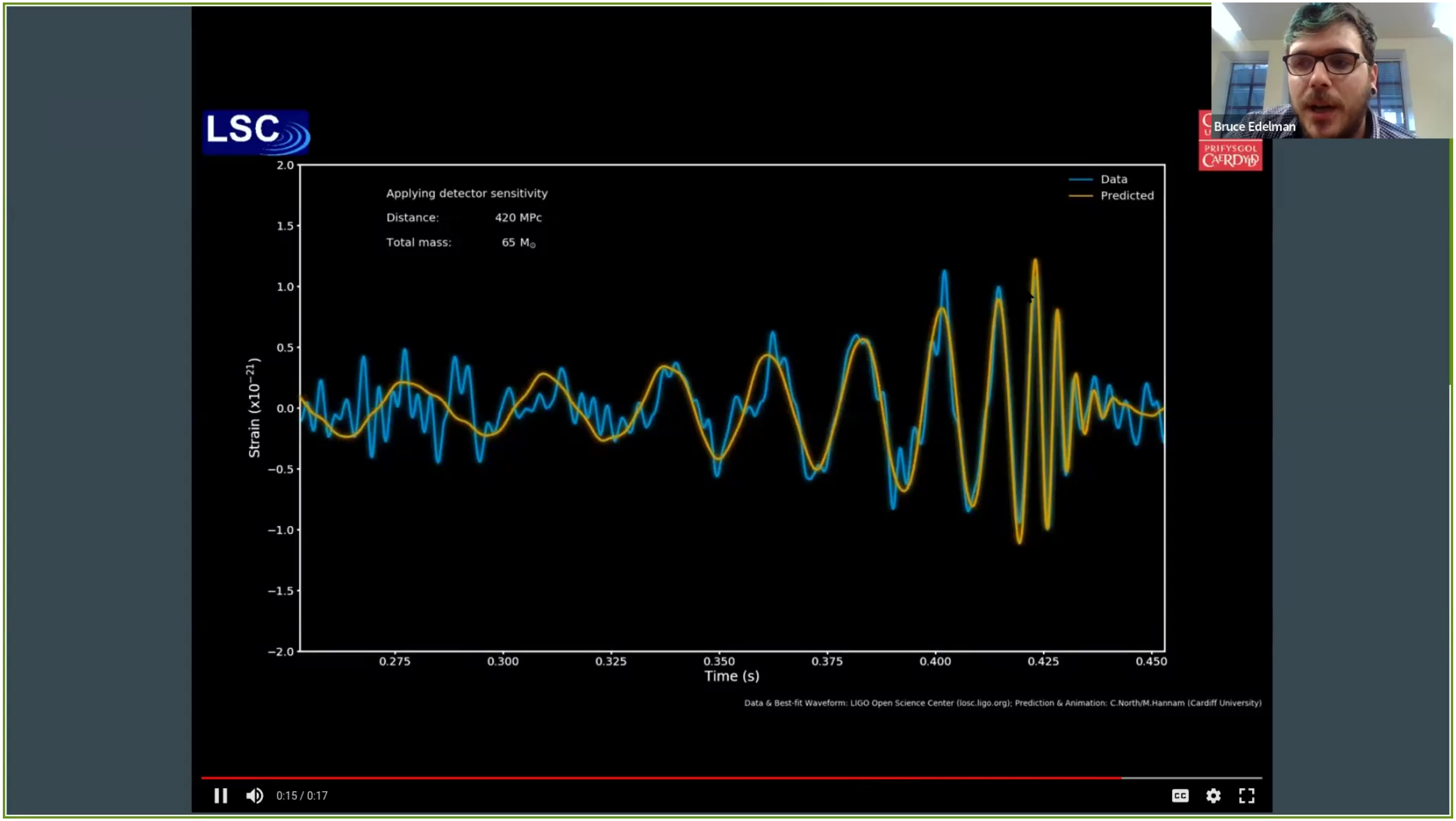
LSC
Scaling Mass
Distance: 800 MPc
Total mass: 122 M☉
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
Bruce Edelman
PRIFYSGOL CAERDYDD



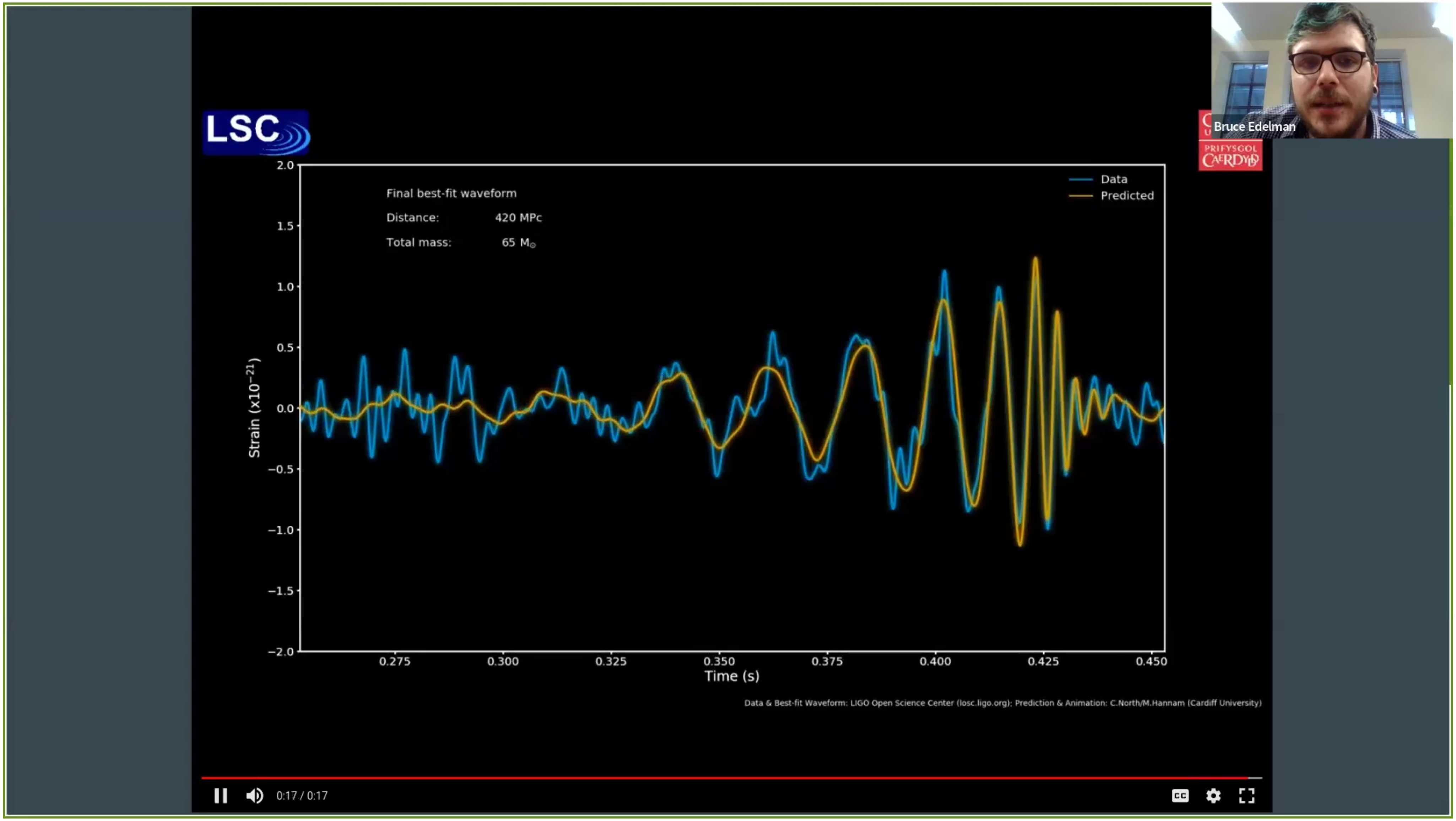
LSC
Scaling Mass
Distance: 800 MPc
Total mass: 63 M
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:06 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD


LSC
Scaling Distance
Distance: 550 MPc
Total mass: 65 $M_\odot$
Data
Predicted
Strain (x10^{-21})
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:09 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD


LSC
Distance: 420 MPc
Total mass: 65 M☉
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:12 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD

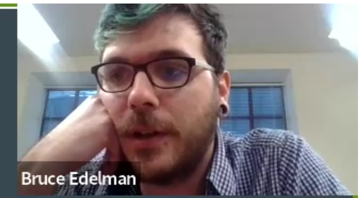


LSC
Applying detector sensitivity
Distance: 420 MPc
Total mass: 65 M☉
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:15 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD



LSC
Final best-fit waveform
Distance: 420 MPc
Total mass: 65 M⊙
Data
Predicted
Strain (x10⁻²¹)
Time (s)
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)
0:17 / 0:17
Bruce Edelman
PRIFYSGOL CAERDYDD

Coherent Waveform Deviations

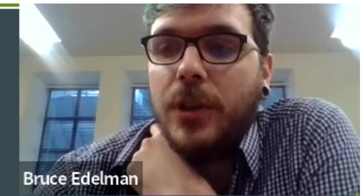


- How do we know our models are correct? Or “good enough”?
- We parametrize deviations to the COHERENT waveform model
- This could be due to:
  - Waveform Model systematic errors
  - Deviations from GR
  - Presence of physics not included in the waveform model

$$h_{+,\times}(f) = h_{\mathrm{model},+,\times}(f)\left[1 + \delta A(f)\right]e^{i\delta\phi(f)}$$

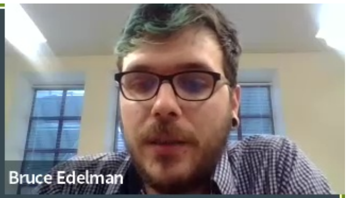
- What Properties do we want in Amp/Phase deviations?
  - Smoothly varying in frequency
  - Flexible enough to fit generic forms without bias
- Let the Data sort it out! (non-parametric models)

Signal Spline Deviation Model



- Use cubic spline functions to model deviations in amplitude/phase
- Construct set of n knot points initialized uniformly across log-frequency space (f_low -> Nyquist)

$$\delta A(f) = \mathcal{I}_3(f; \{f_i, \delta A_i\})$$
$$\delta \phi(f) = \mathcal{I}_3(f; \{f_i, \delta \phi_i\})$$



Signal Spline Deviation Model

- Use cubic spline functions to model deviations in amplitude/phase
- Construct set of n knot points initialized uniformly across log-frequency space (f_low -> Nyquist)
- Add 3n parameters to model
  - n knot locations in freq space
  - n knot heights for amp deviation
  - n knot heights for phase deviation

$$\delta A(f) = \mathcal{I}_3(f; \{f_i, \delta A_i\})$$
$$\delta \phi(f) = \mathcal{I}_3(f; \{f_i, \delta \phi_i\})$$

$$p(\delta\phi_i) = \mathcal{N}(0, \sigma_\phi)$$
$$p(\delta A_i) = \mathcal{N}(0, \sigma_A)$$
$$p(f_i) = \mathrm{U}(f_{\mathrm{low}}, f_{\mathrm{high}})$$

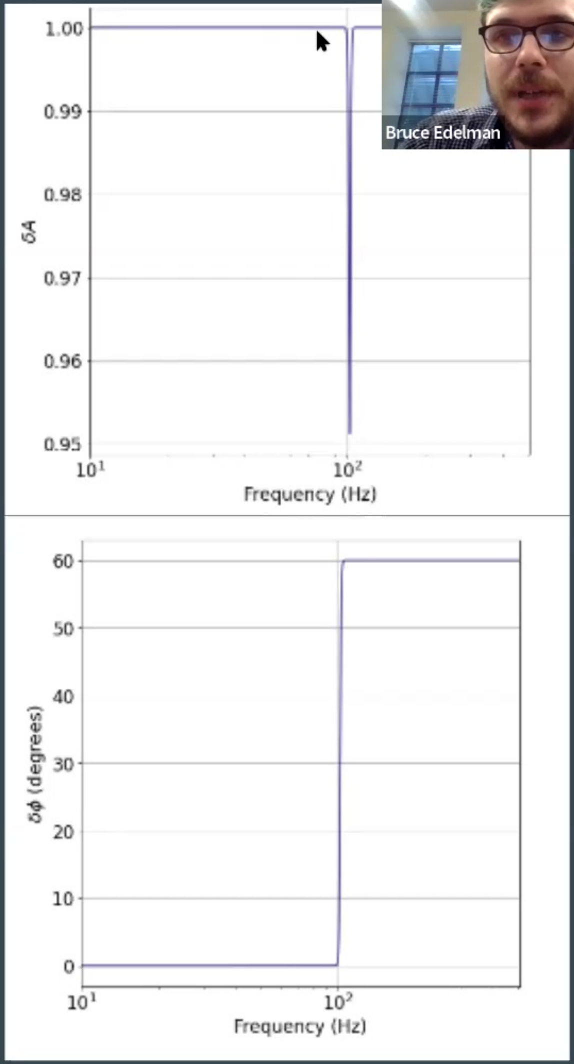
Toy Model of Simulated Deviations

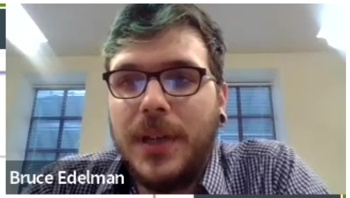
- We construct a toy model deviation based on an extreme spontaneous scalarization
- Rapid jump in phase with temporary amplitude reduction

$$\delta A(f) = \exp(\frac{1}{2} dA \left[\tanh(\frac{f - f_z}{df})^2 - \tanh(\frac{f_{\rm ref} - f_z}{df})^2 \right])$$

$$\delta\phi(f) = \frac{1}{2} d\phi \left[\tanh(\frac{f - f_z}{df}) - \tanh(\frac{f_{\rm ref} - f_z}{df}) \right]$$

Edelman et. al 2021

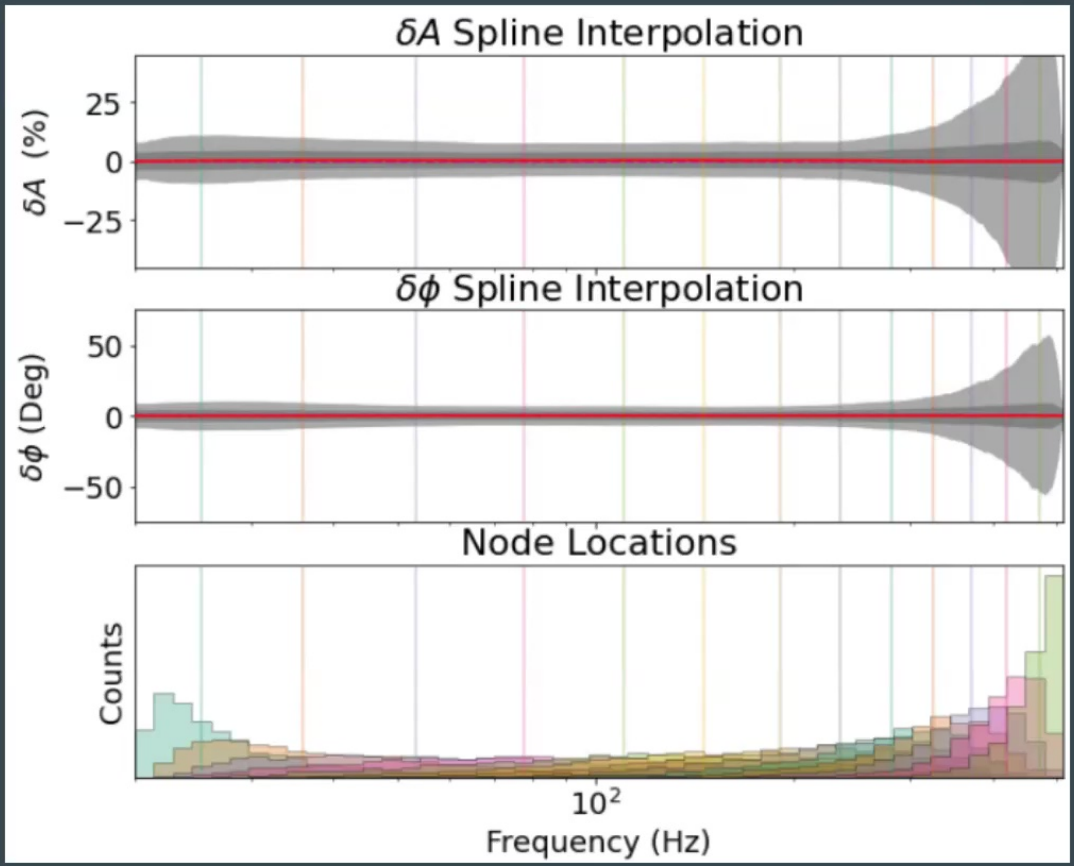




Simulated Deviation Study

- Simulate a GW150914-like signal with IMRPhenomD model with no deviations and fit our deviation model

m_1	$36\ M_\odot$
m_2	$29\ M_\odot$
D_L	450 Mpc
ϕ	2.76 rad
α	1.37 rad
δ	-1.26 rad
$S_{1,z}$	0.0
$S_{2,z}$	0.0



Edelman et. al 2021

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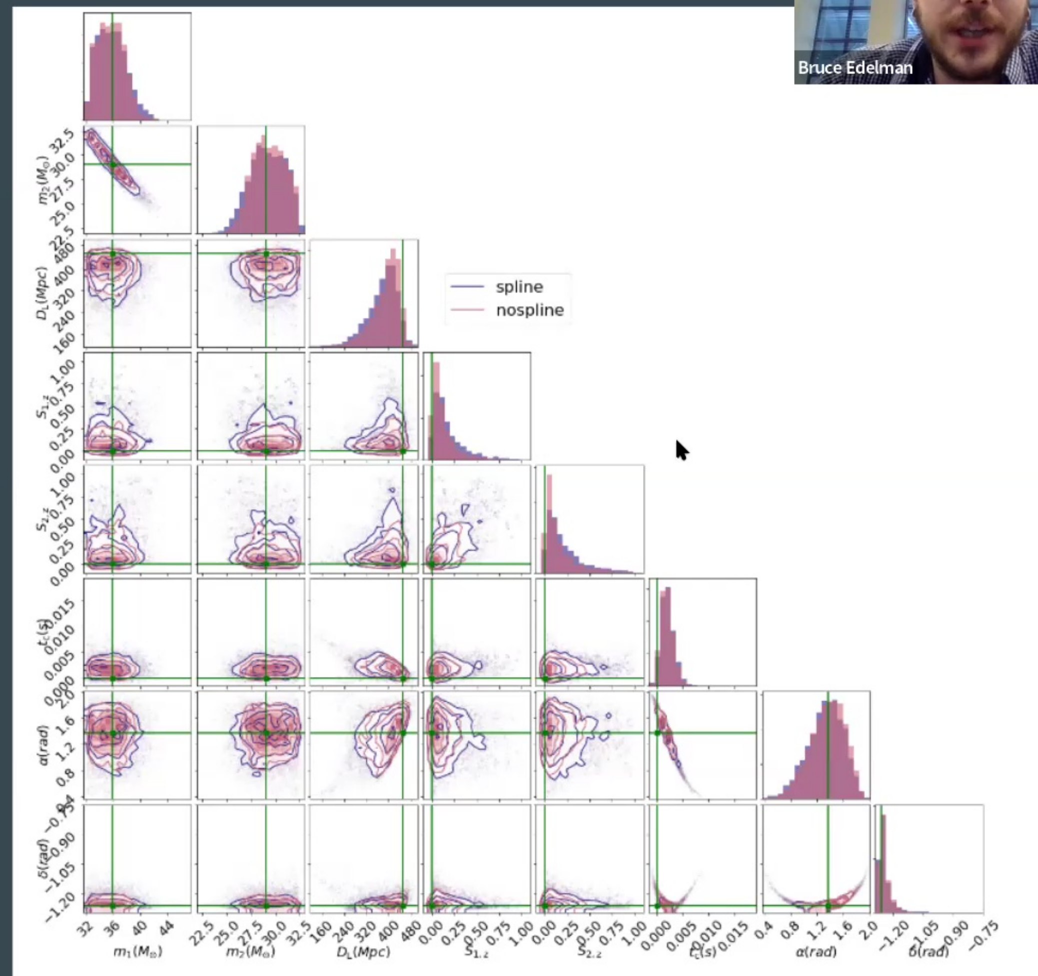

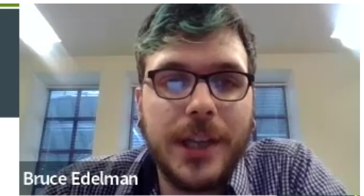

Edelman et. al 2021

Simulated Deviation Study

- Simulate a GW150914-like signal with IMRPhenomD model and Modify it according to our toy model

m_1	$36\ M_\odot$
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ϕ	2.76 rad
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δ	-1.26 rad
$S_{1,z}$	0.0
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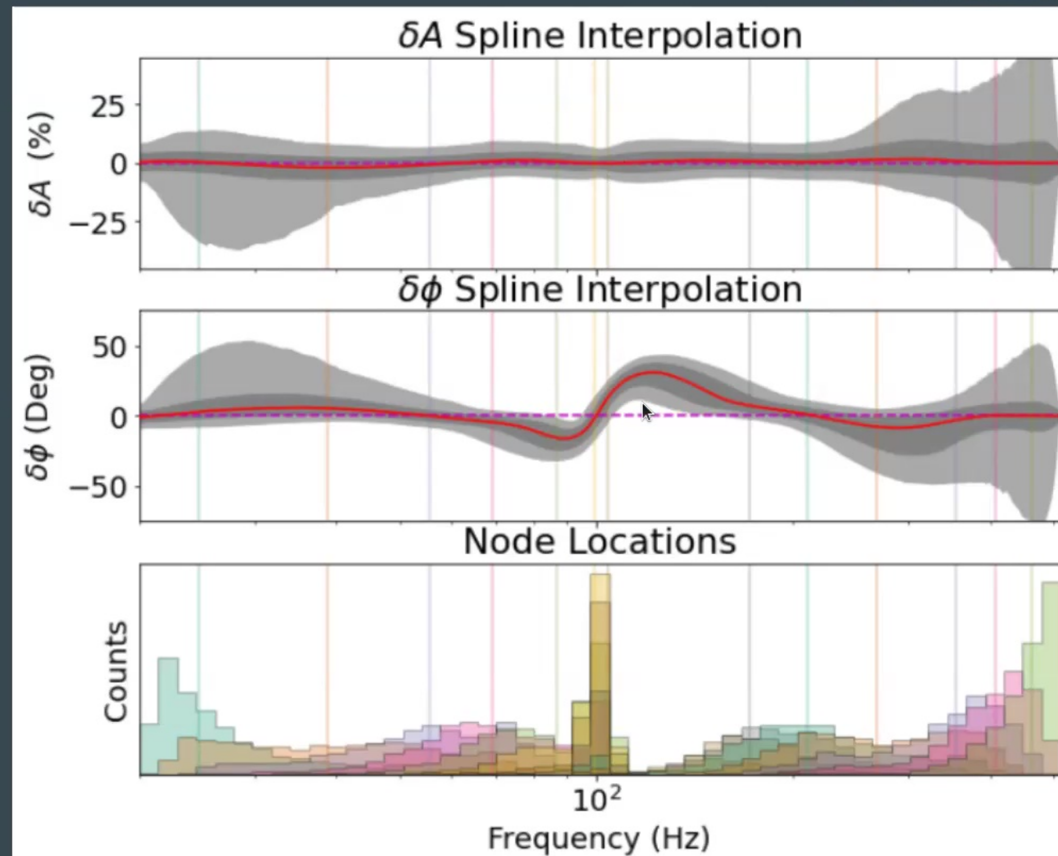

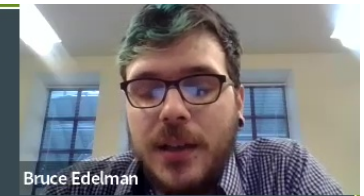

Edelman et. al 2021

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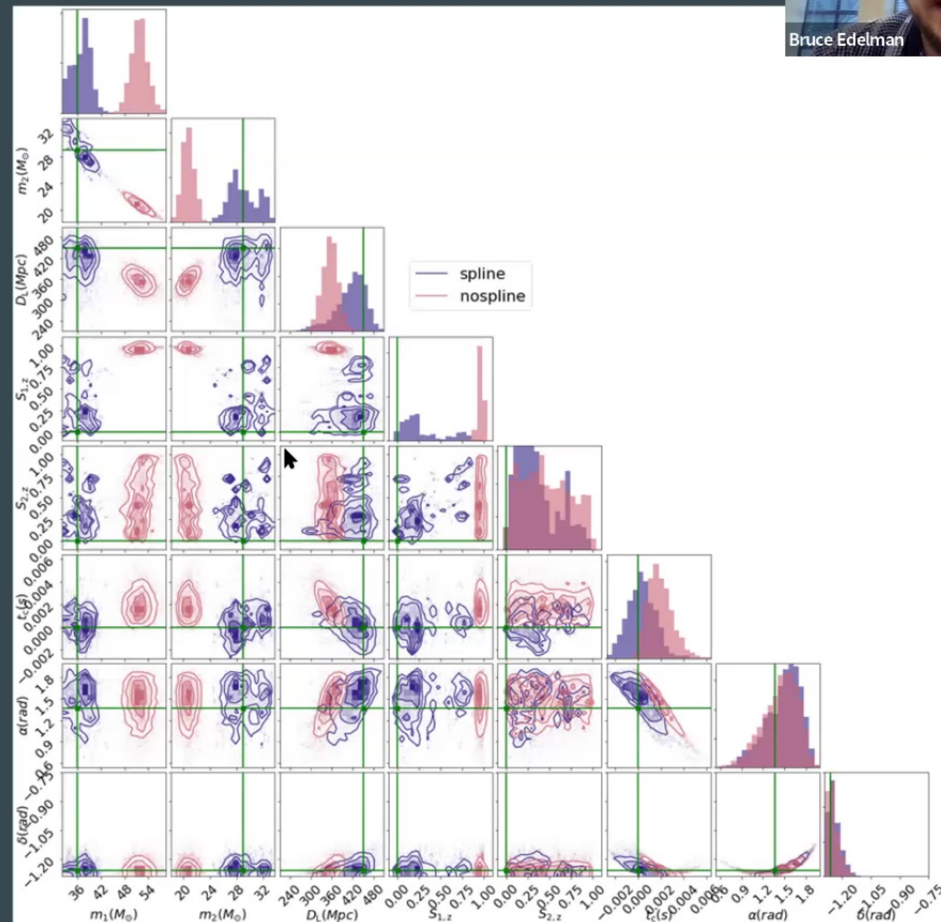
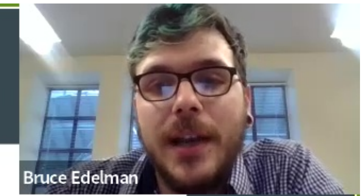
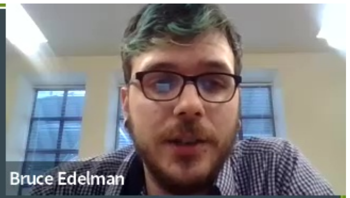


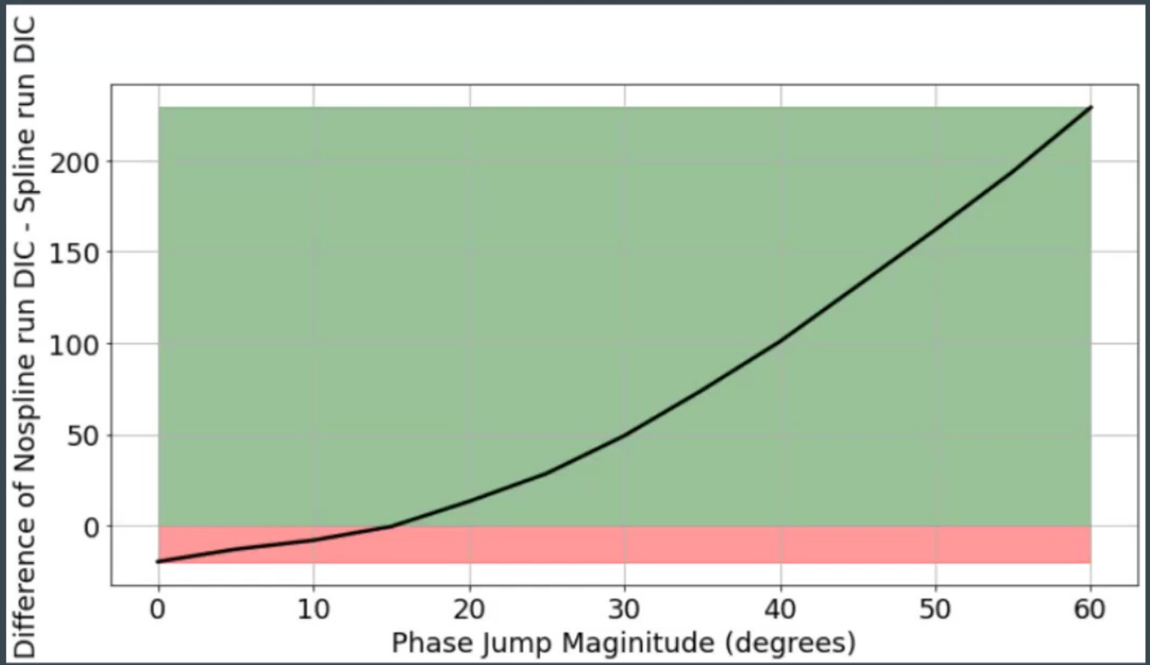


Edelman et. al 2021

Simulated Deviation Study

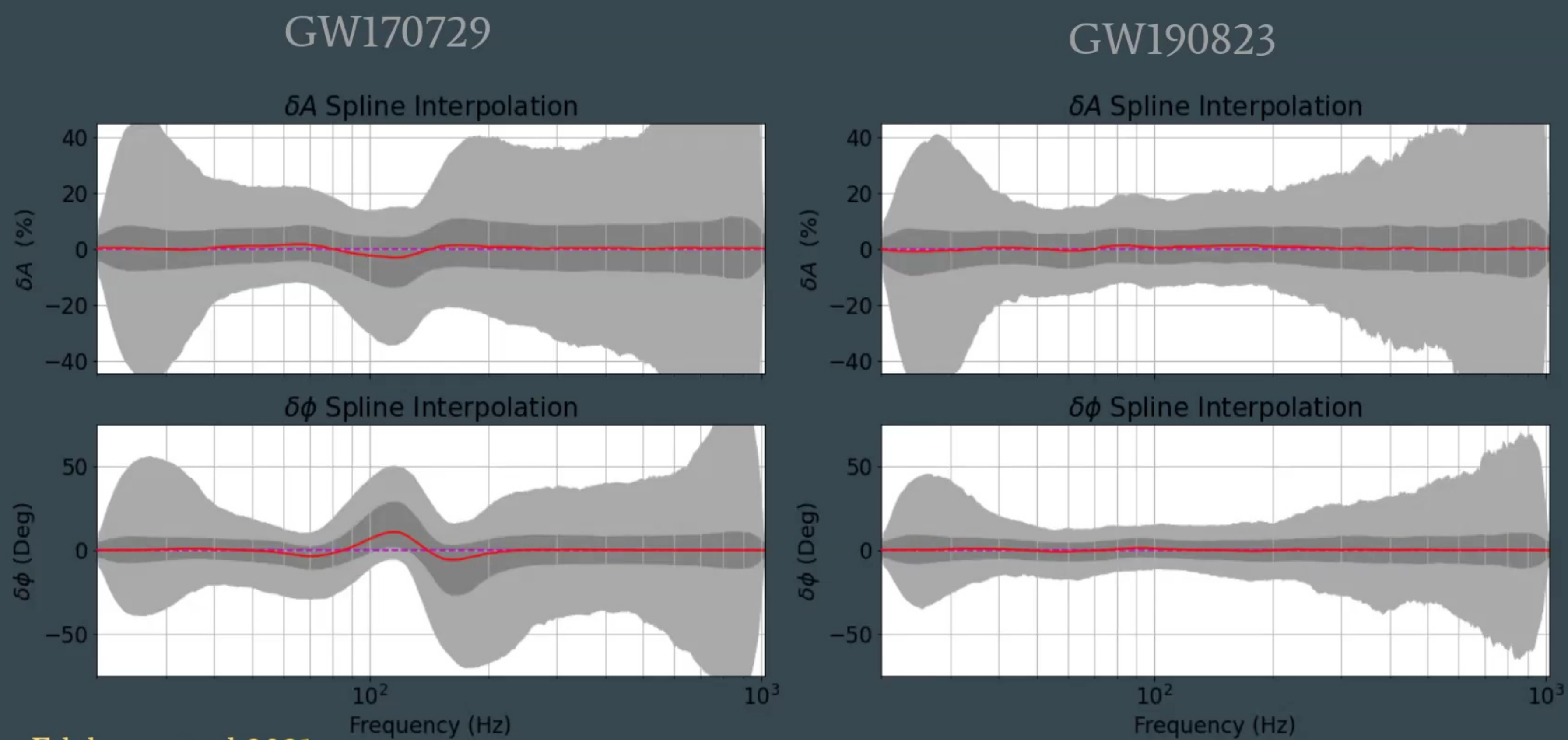


- Do same procedure with varying phase jump from 0 -> 60 degrees (increments of 5)
- Use DIC metric to compare using the signal deviation model vs. not



Edelman et. al 2021

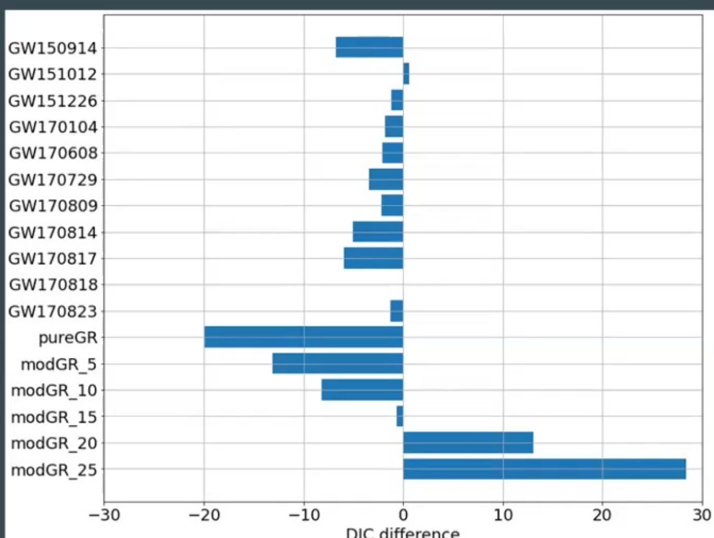
Looking for Deviations in the 11 CBCs of GWTC-1 (2-3)



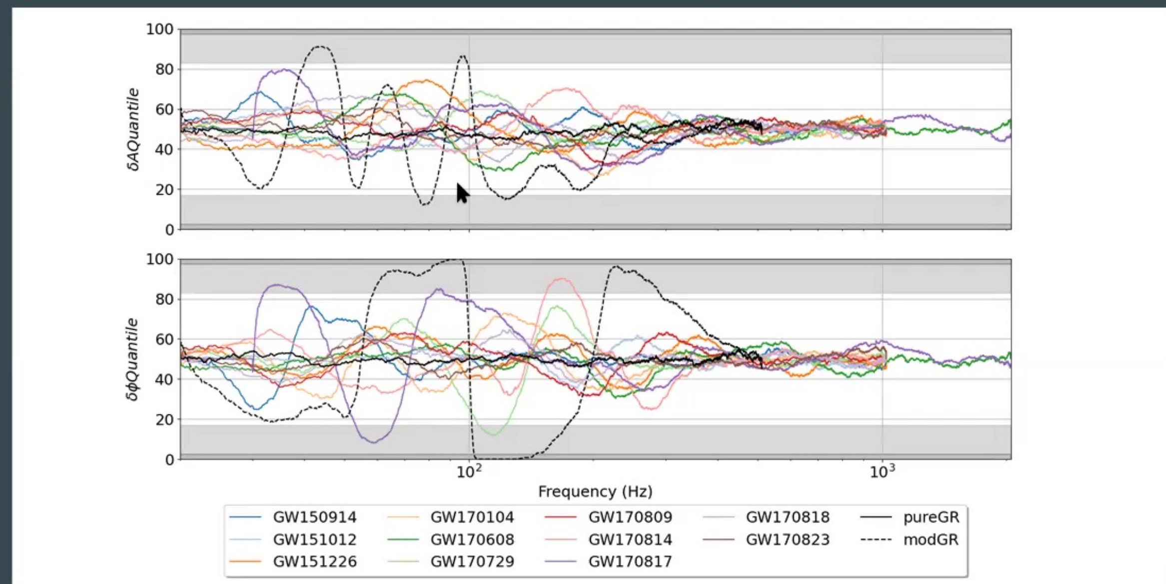
Edelman et. al 2021

Looking for Deviations in the 11 CBCs of GWTC-1 (2-3)

- no significant deviation from IMR family of waveform models

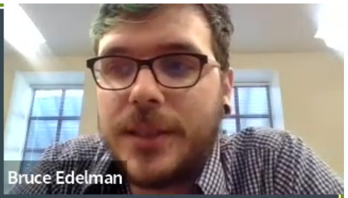


Edelman et. al 2021



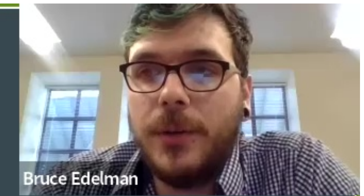
- Model comparisons show no preference or slight disfavoring of spline mode in all GWTC-1 events

Overview

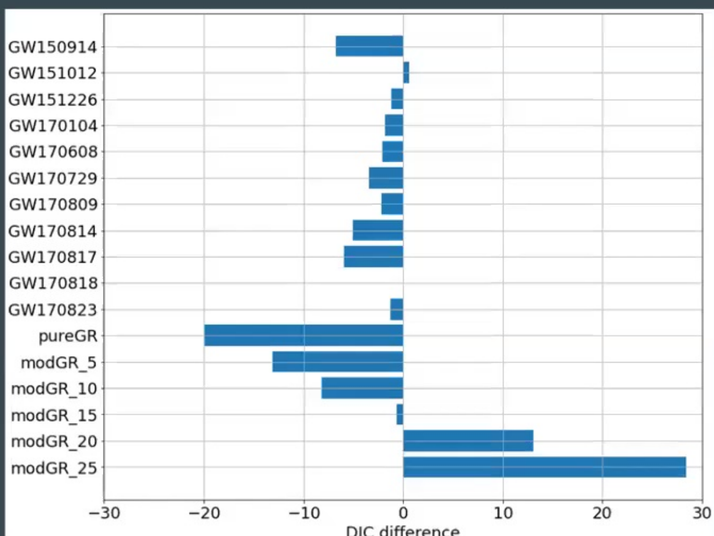


- Single Source Inference and Parameter Estimation
  - Coherent Waveform Deviation Model (Edelman et. al 2021)
- **Hierarchical Inference of a Population of Sources**
  - Pair-Instability Mass Gap Model (Edelman, Doctor, Farr 2021)
  - Semi-Parametric Modeling of the BBH Mass Distribution (Edelman et al 2022)
- Population Updates from GWTC-3

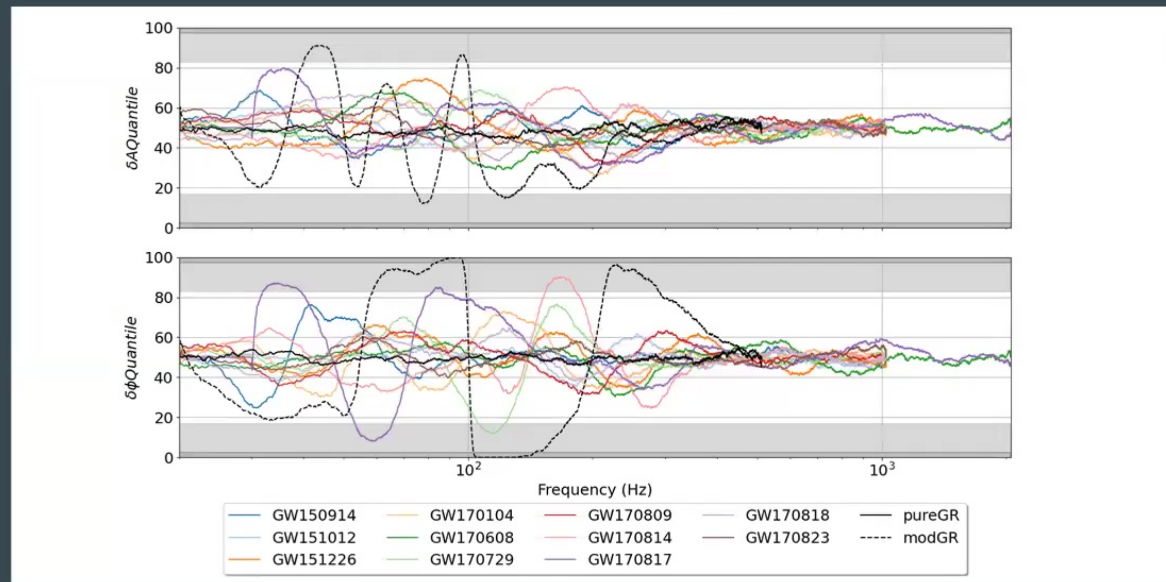
Looking for Deviations in the 11 CBCs of GWTC-1 (2-3)



- no significant deviation from IMR family of waveform models

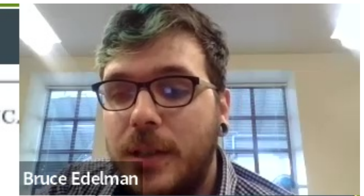


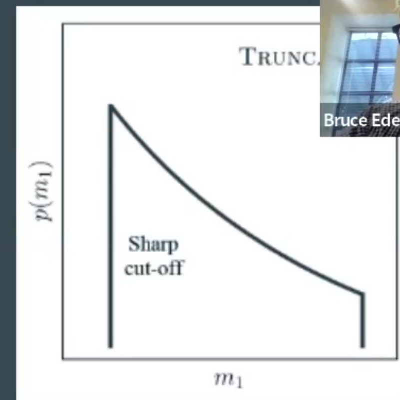
Edelman et. al 2021



- Model comparisons show no preference or slight disfavoring of spline mode in all GWTC-1 events

Hierarchical Bayesian Inference





- How many BBH mergers are there in the Universe?
- How often do they merge?
- How are their event properties distributed?

$$p(\theta|\Lambda)$$

Hyper-Prior

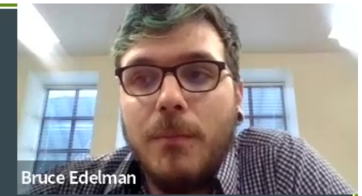
$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)p(\theta)}{\mathcal{Z}(d)}$$

$$p(\Lambda|d) = \frac{p(\Lambda)\int d\theta \mathcal{L}(d|\theta)p(\theta|\Lambda)}{\mathcal{Z}(d)}$$

$$p(\Lambda|\{d_i\}) = \frac{p(\Lambda)\prod_i \left[\int d\theta_i \mathcal{L}(d_i|\theta_i)p(\theta_i|\Lambda)\right]}{\mathcal{Z}(\{d_i\})}$$

https://iopscience.iop.org/article/10.3847/1538-4357/ac3667

GW Selection Effects



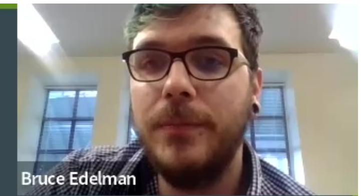
- GW Detection efficiency depends on parameters
  - Distance (Malmquist Bias)
  - Mass (Heavier mass BBHs merge at lower frequencies)
- Number of observed BBHs should be dependent on region of parameter space (Inhomogeneous Poisson Process)
- Use Importance sampling to compute monte carlo Integrals

$$p(\Lambda, N|\{d_i\}) \propto \left[\prod_{i=1}^{N_{\rm obs}} \int d\theta_i \mathcal{L}(d_i|\theta_i) p(\theta_i|\Lambda)\right] N^{N_{\rm obs}} e^{-N p_{\rm det}(\Lambda)} p(\Lambda) p(N)$$

$$p_{\rm det}(\Lambda) = \int_{\{d_i\}>threshold} d\{d_i\} d\theta \mathcal{L}(\{d_i\}|\theta) p(\theta|\Lambda)$$

https://iopscience.iop.org/article/10.3847/1538-4357/ac3667

GW Selection Effects



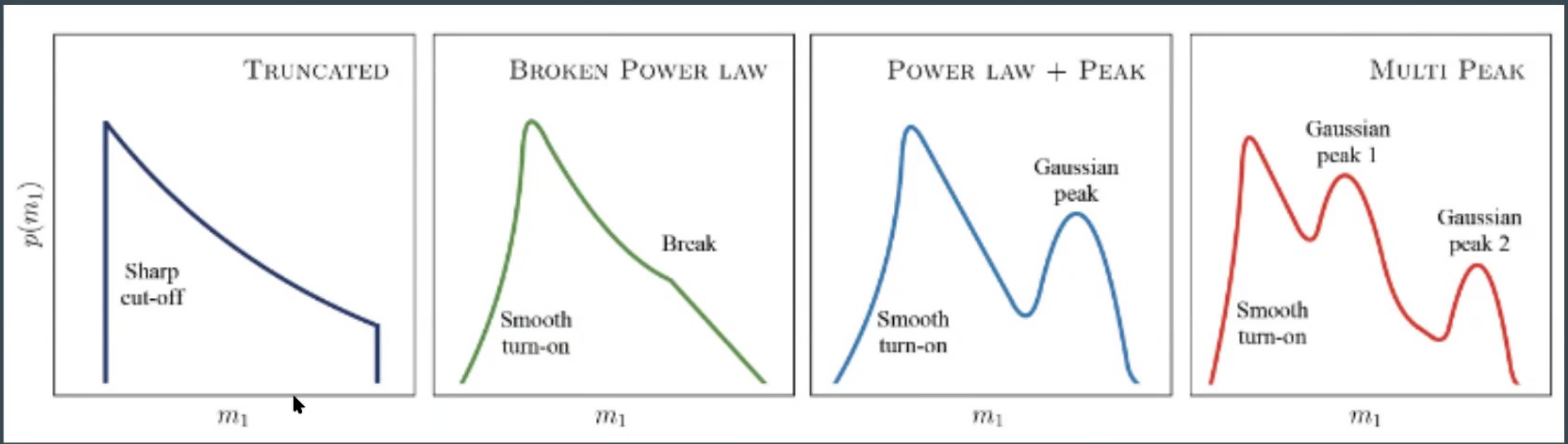
- Use catalog Posterior samples to access the Likelihood
- Use a set of Software "Injections" ran through search pipelines to estimate p_{det}

$$p(\Lambda, N|\{d_i\}) \propto p(\Lambda)p(N)\prod_i \left[\frac{1}{K_i}\sum_j^{K_i}\frac{p(\theta_i^j|\Lambda)}{p_{PE}(\theta_i^k)}\right] N^{N_{\rm obs}} e^{-Np_{\rm det}(\Lambda)}$$

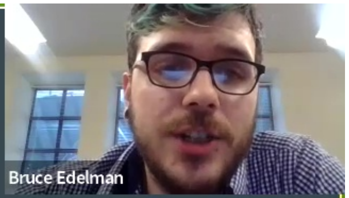
$$p_{\rm det}(\Lambda) = \frac{1}{N_{\rm draw}}\sum_i^{N_{\rm found}}\frac{p(\theta_i|\Lambda)}{p_{\rm draw}(\theta_i)}$$

https://iopscience.iop.org/article/10.3847/1538-4357/ac3667

BBH Mass Population Models



R. Abbott *et al* 2021 *ApJL* **913** L7



BBH Mass Population Models

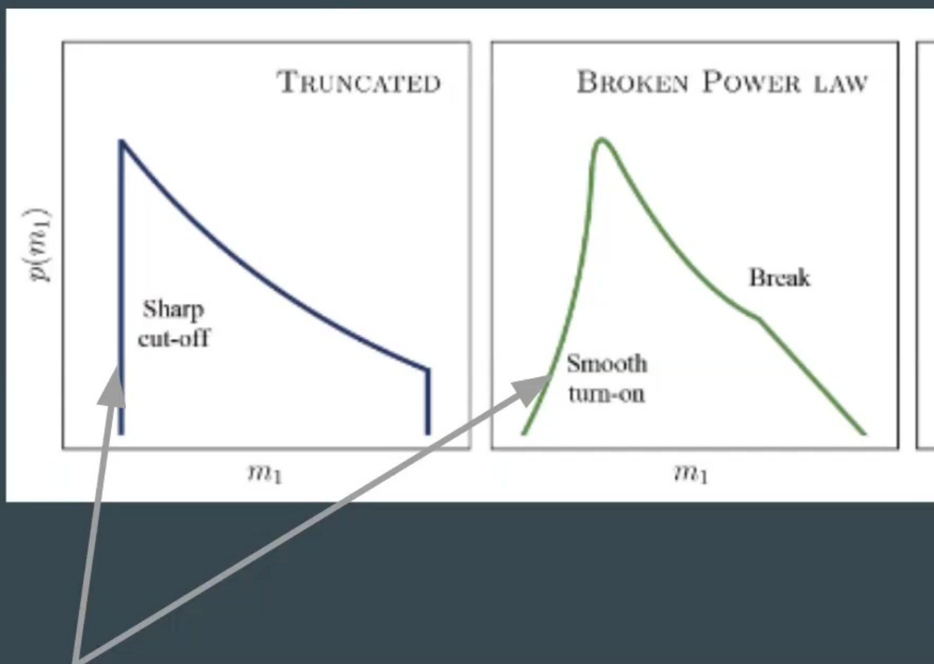
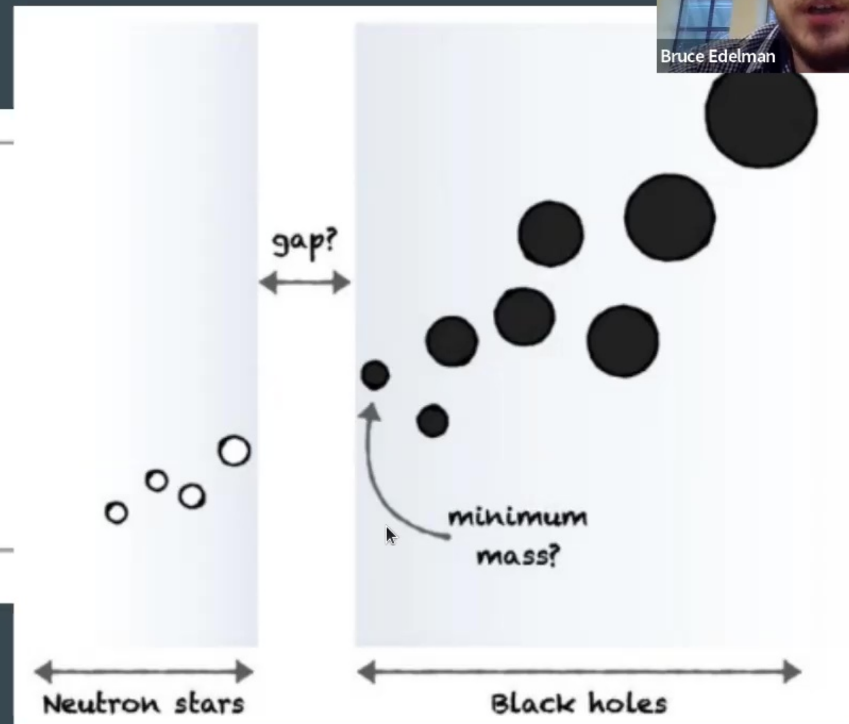
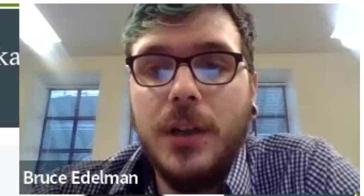


Illustration: Shanika





Low-Mass End: Lower mass gap? What's the minimum BH mass? Is the NS-BH gap populated?

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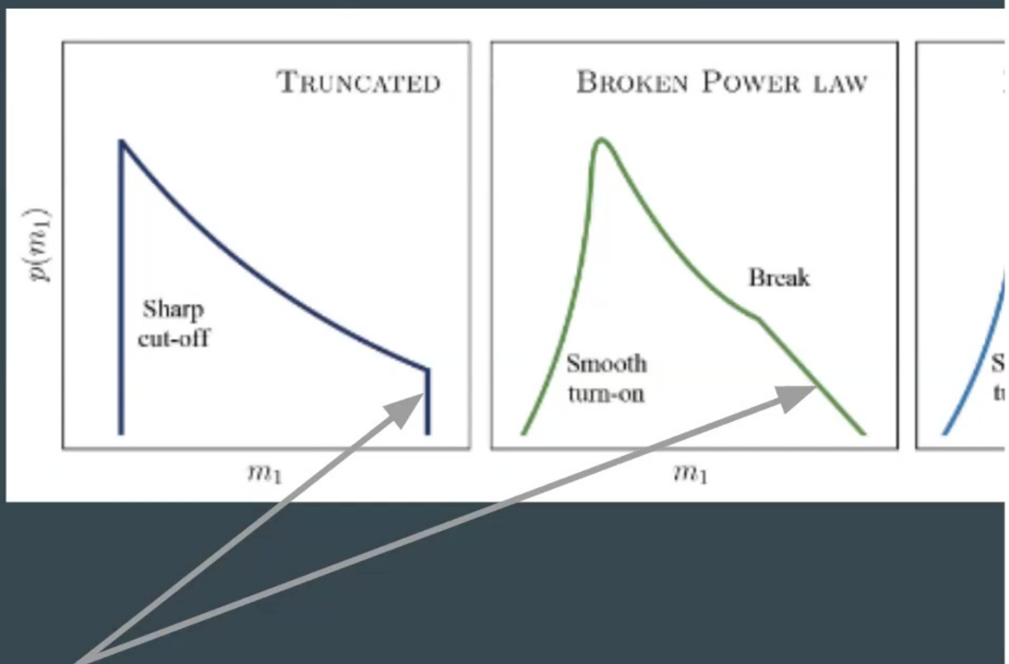
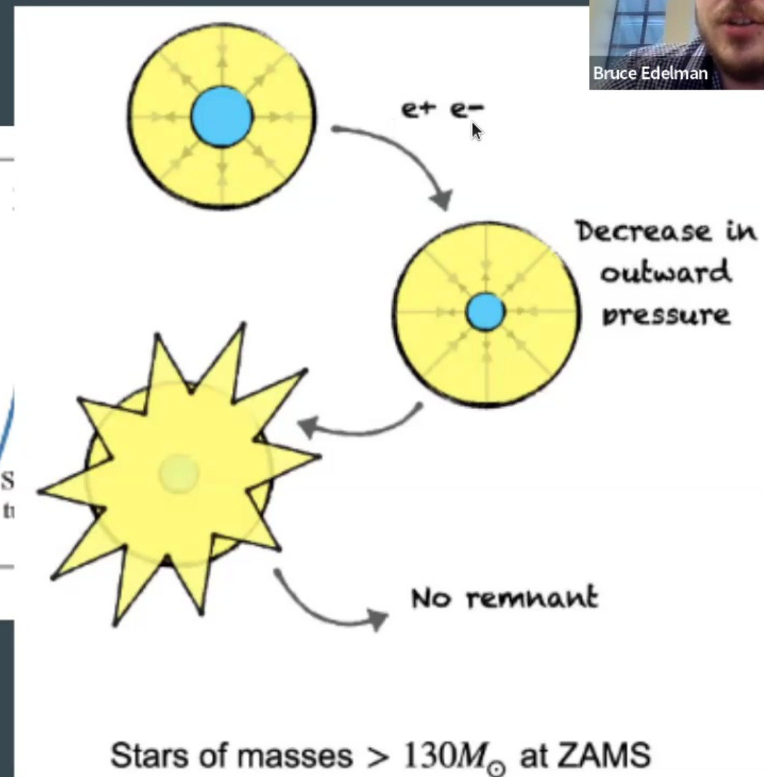
BBH Mass Population Models

Illustration: Shanika





High Mass end: Sharp Cutoff or slow taper? PISN mass gap?

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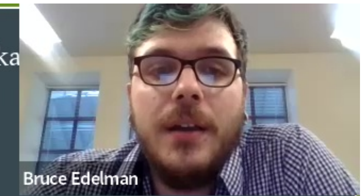
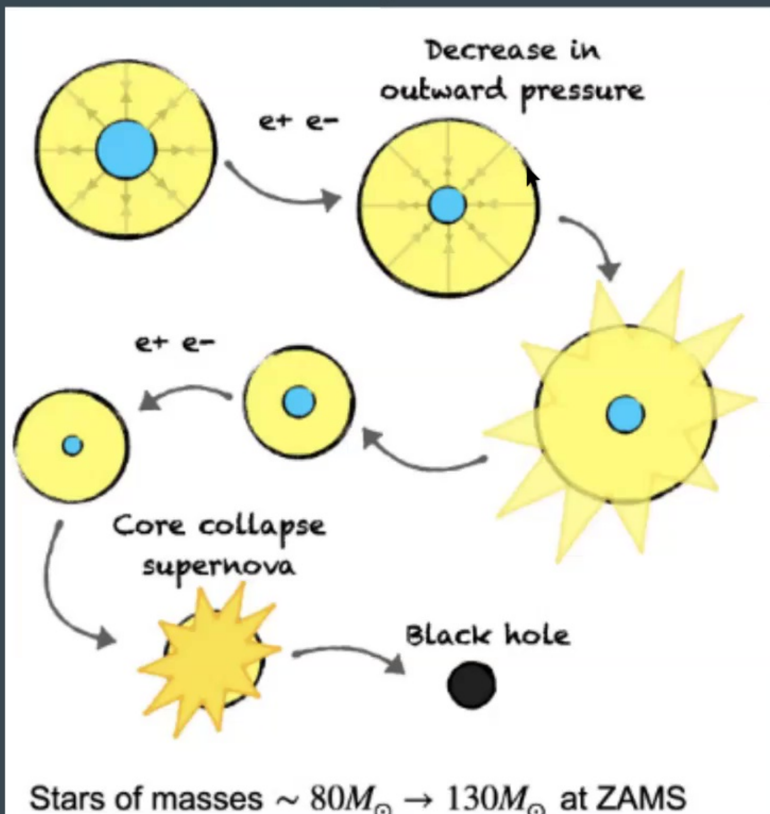
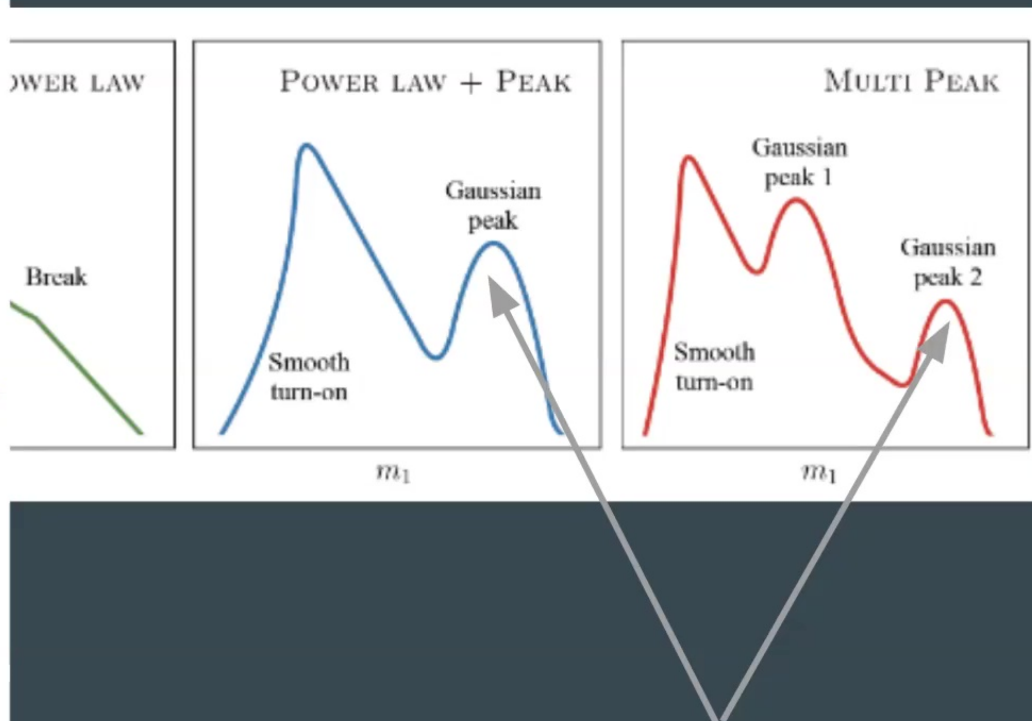
Illustration: Shanika



BBH Mass Population Models





Is there a “pileup” of BBHs from PPISNe? Second peak from hierarchical mergers?

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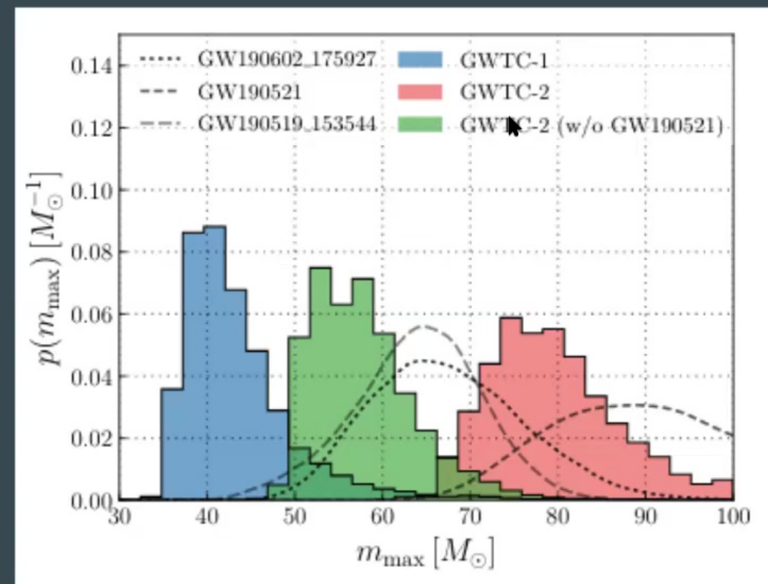
Astrophysical Lessons from GWTC-2

- Truncated Powerlaw is **no longer consistent** with the data
- We are seeing more heavy BBHs



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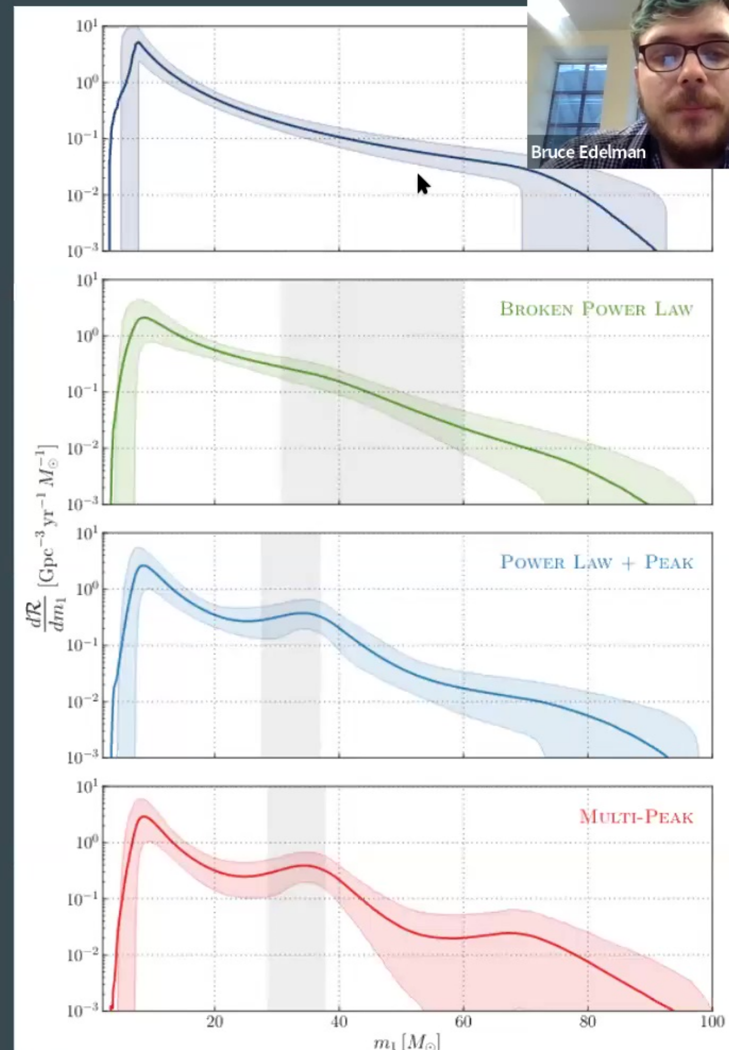
Astrophysical Lessons from GWTC-2

- Truncated Powerlaw is **no longer consistent** with the data
- We are seeing more heavy BBHs
- There is a feature at 35-40 solar masses that could be described by a **peak** or a **break** in the Powerlaw
- Appears to be a dearth of Low-mass black holes <6 solar masses

Mass model	$\mathcal{B}$	$\log_{10} \mathcal{B}$
Power Law + Peak	1.0	0.0
Multi Peak	0.5	−0.3
Broken Power Law	0.12	−0.92
Truncated	0.01	−1.91



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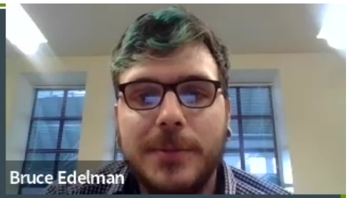
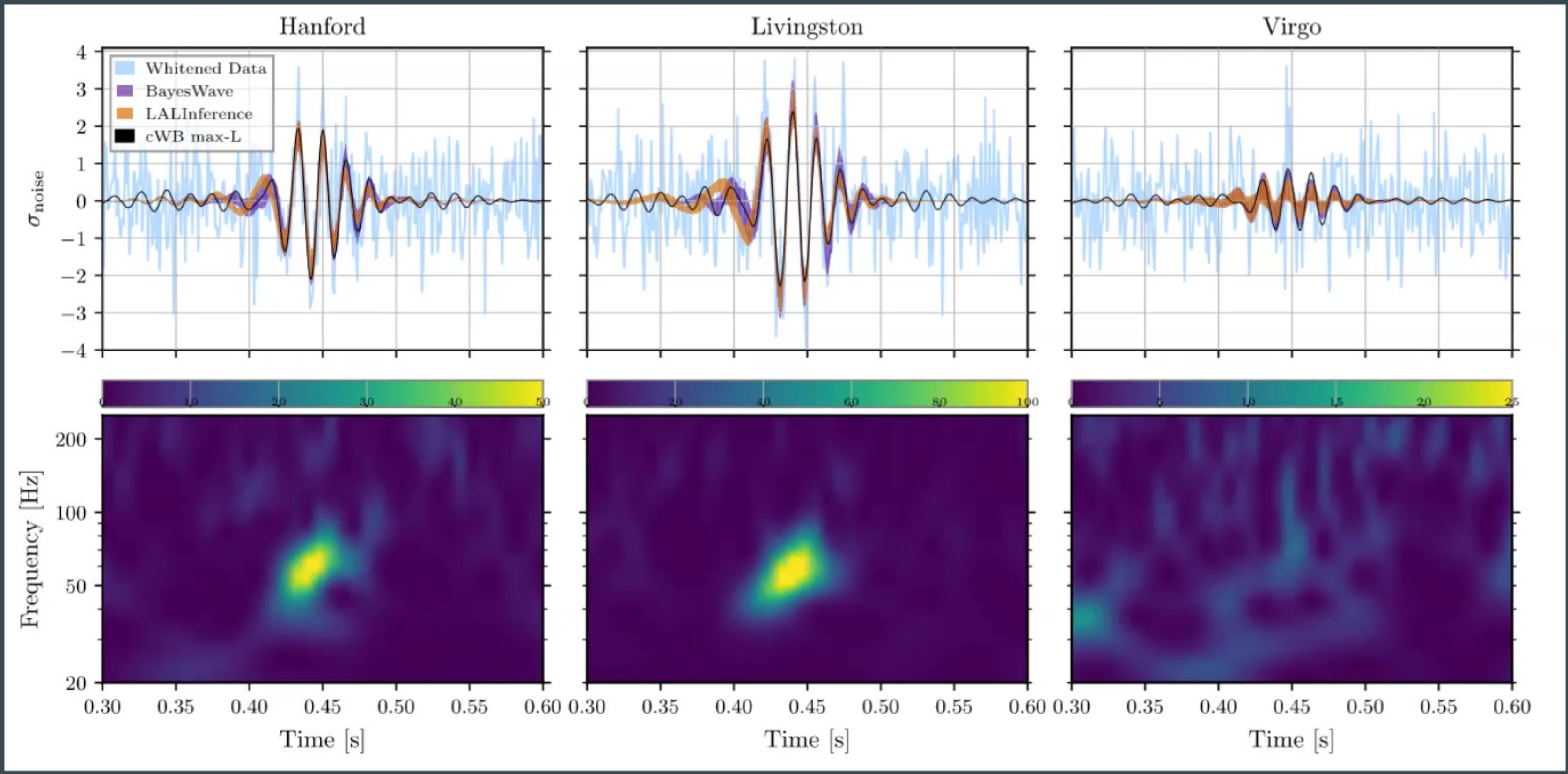
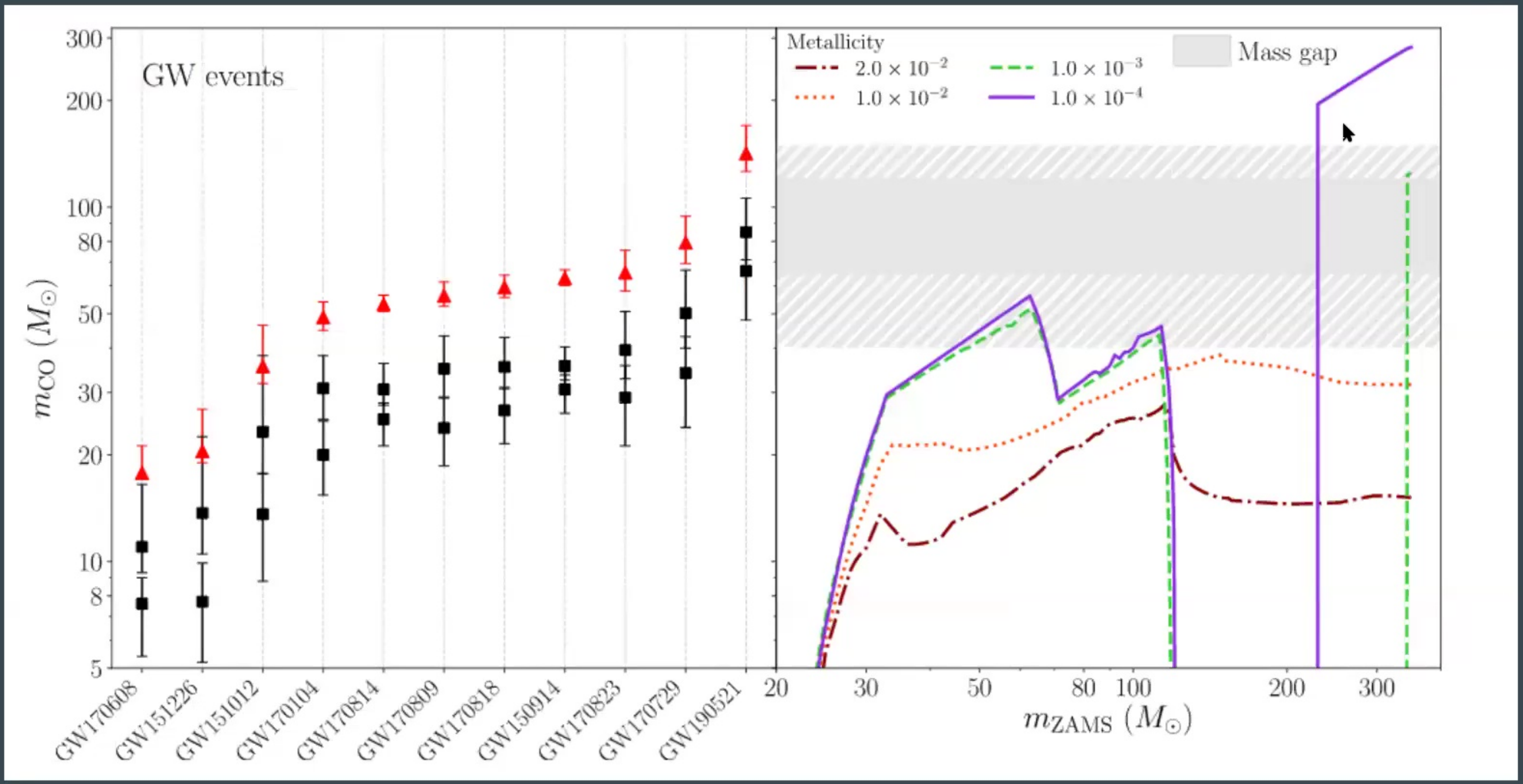
GW190521 – A Challenge for Pair-Instability

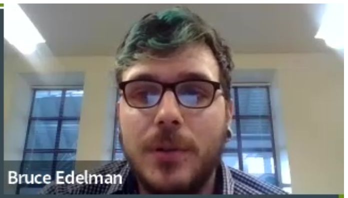




Phys. Rev. Lett. 125, 101102

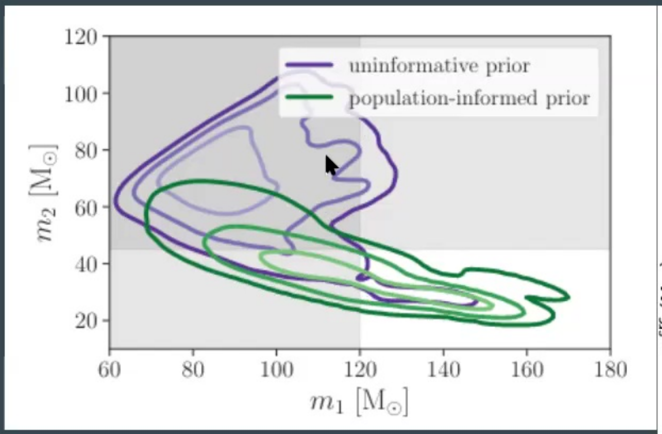
GW190521 – A Challenge for Pair-Instability

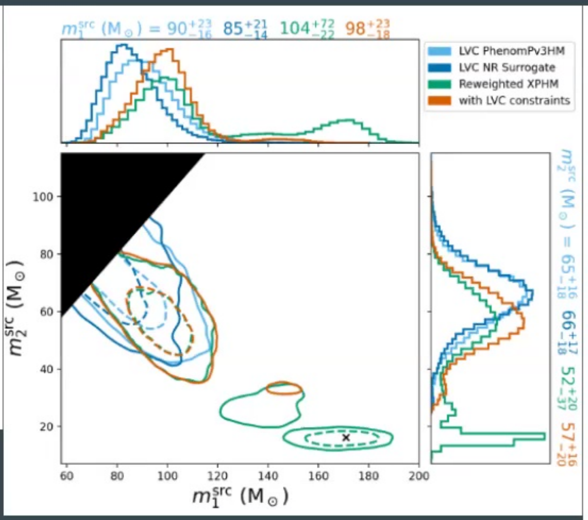


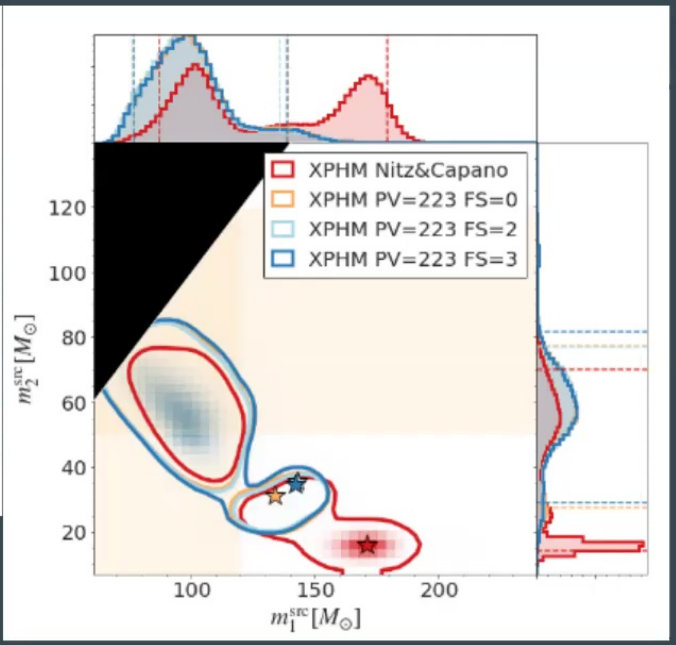


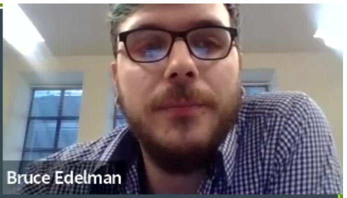
R. Abbott *et al* 2020 *ApJL* **900** L13

GW190521 – A Challenge for Pair-Instability









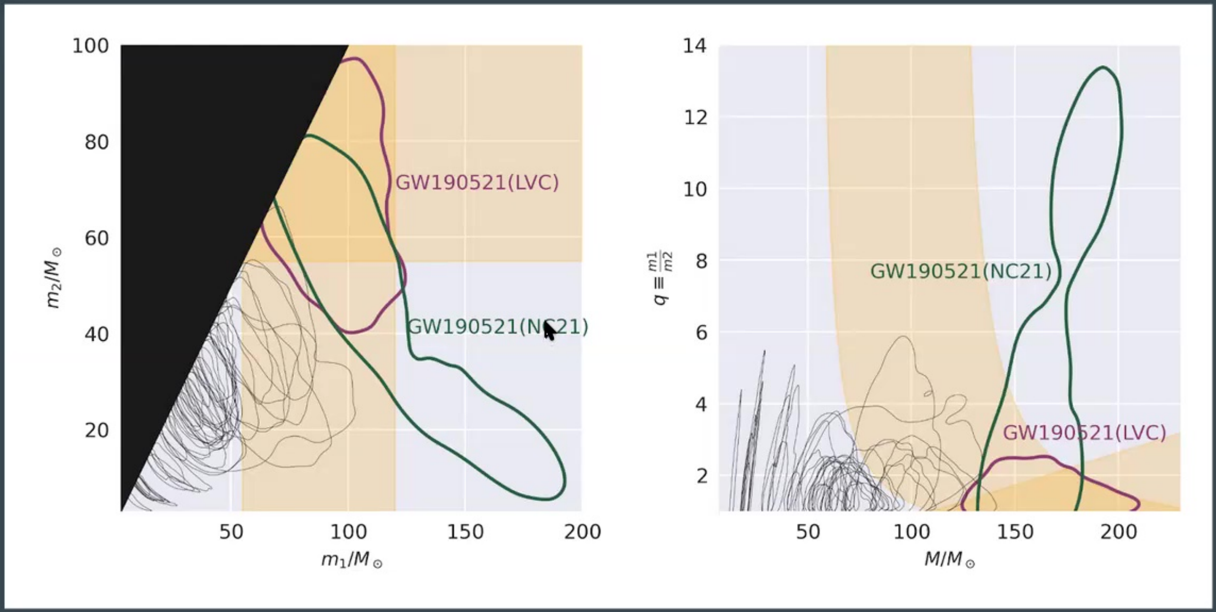
Maya Fishbach and Daniel E. Holz 2020 *ApJL* **904** L26

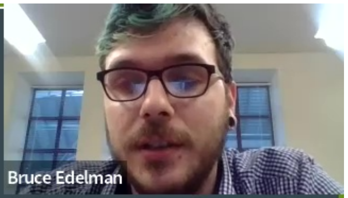
Alexander H. Nitz and Collin D. Capano 2021 *ApJL* **907** L9

Héctor Estellés *et al* 2022 *ApJ* **924** 79

Parameterized PISN Mass Gap Model

- GW190521's component masses could straddle the PISN mass gap
- Parameterize mass gap with start, mg, (Msun) and width, wg (Msun)
- Use Truncated and Powerlaw+Peak model and explicitly enforce zero rate within the gap



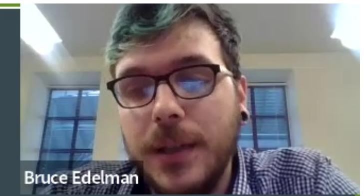


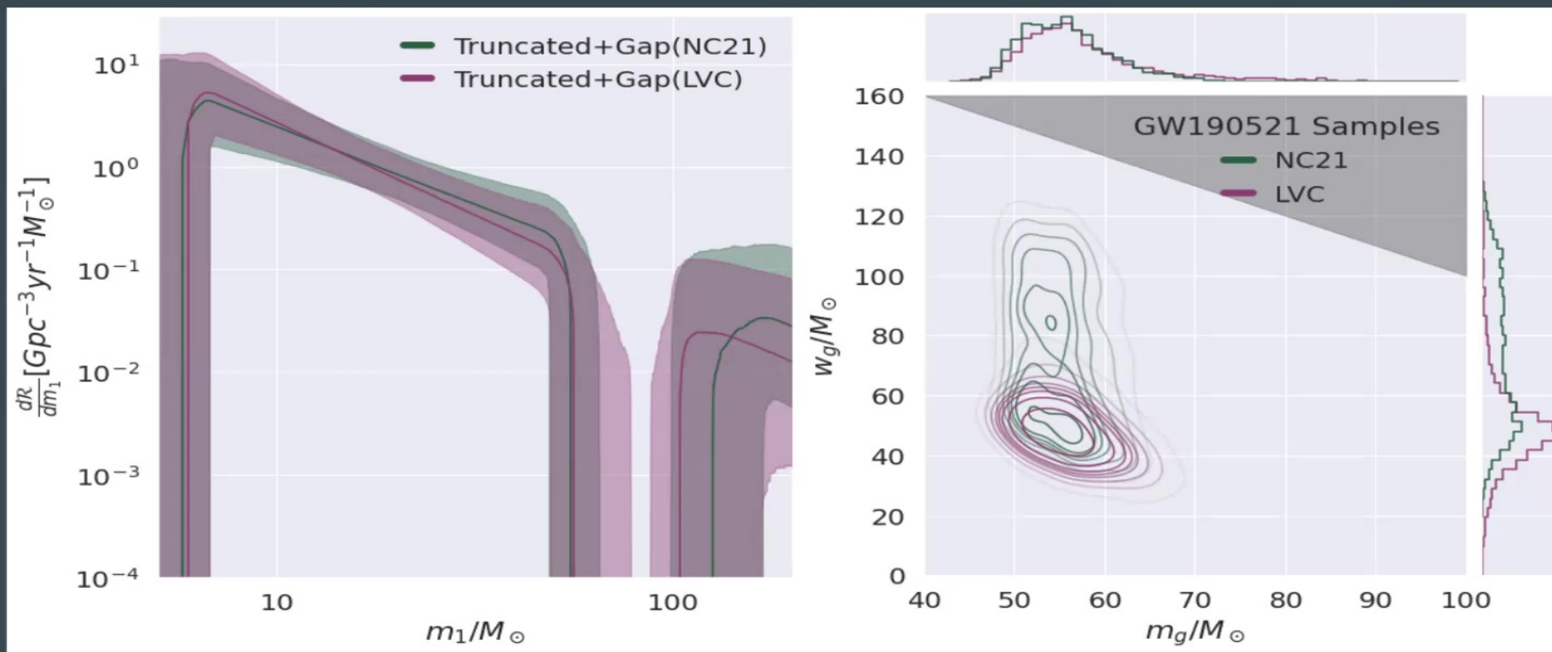
$$p(m_1|\Lambda, m_g, w_g) = \begin{cases} 0 & \text{for } m_g \leq m_1 \leq m_g + w_g \\ p(m_1|\Lambda) & \text{otherwise} \end{cases}$$

$$p(q|\Lambda, m_1, m_g, w_g) = \begin{cases} 0 & \text{for } m_g \leq m_1 * q \leq m_g + w_g \\ p(q|\Lambda) & \text{otherwise} \end{cases}$$

Edelman, Doctor, Farr 2021

Evidence for an Upper Mass gap in GWTC-2





log-BF for a gap: 2.7

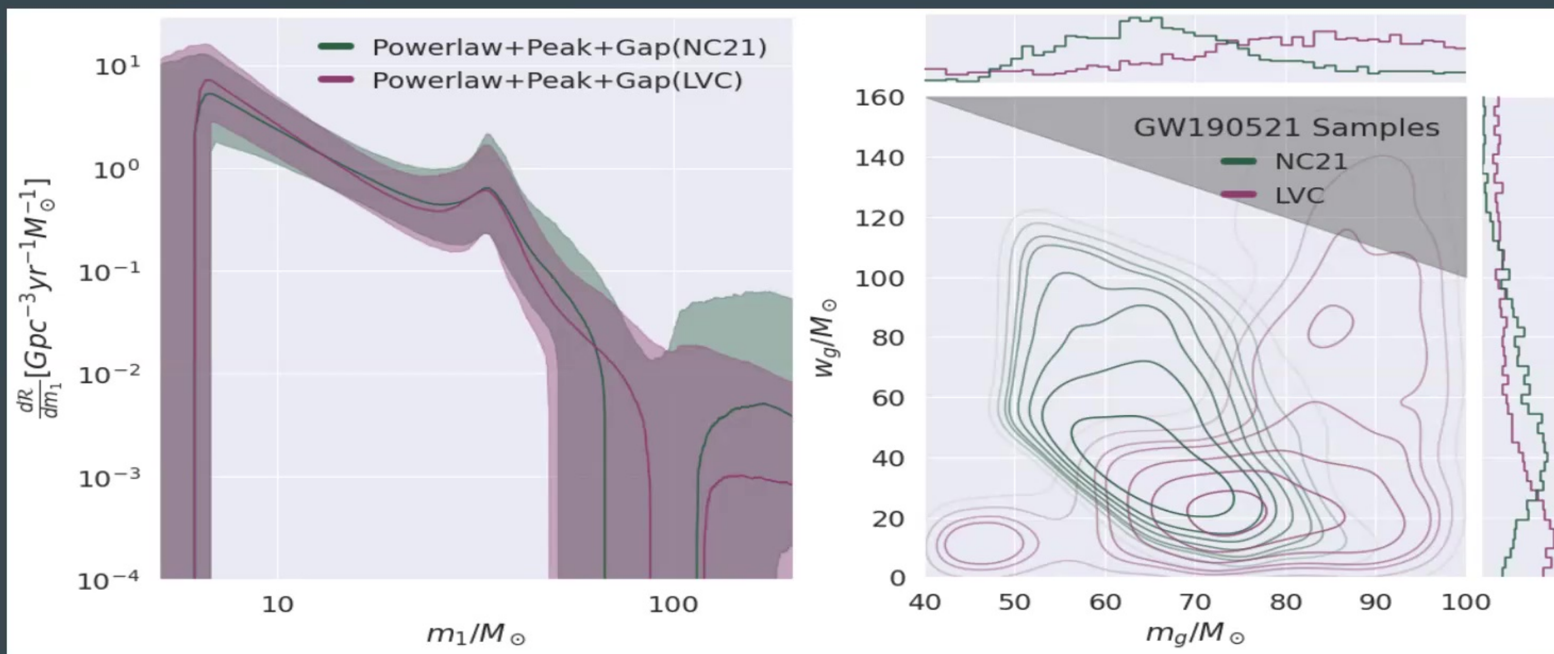
Gap bounds: $55.12^{+7.54}_{-4.38}$ ---> $103.74^{+17.01}_{-6.32}$

log-BF for a gap: 6.5

Gap bounds: $55.33^{+5.21}_{-4.21}$ ---> $126.03^{+30.25}_{-22.65}$

Edelman, Doctor, Farr 2021

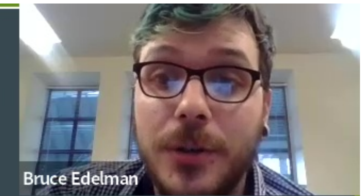
Evidence for an Upper Mass gap in GWTC-2



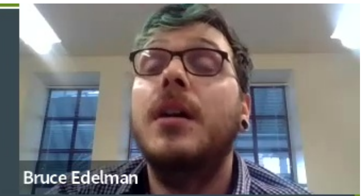
log-BF for a gap: -0.5
(Inconclusive)

log-BF for a gap: 0.5
(Inconclusive)

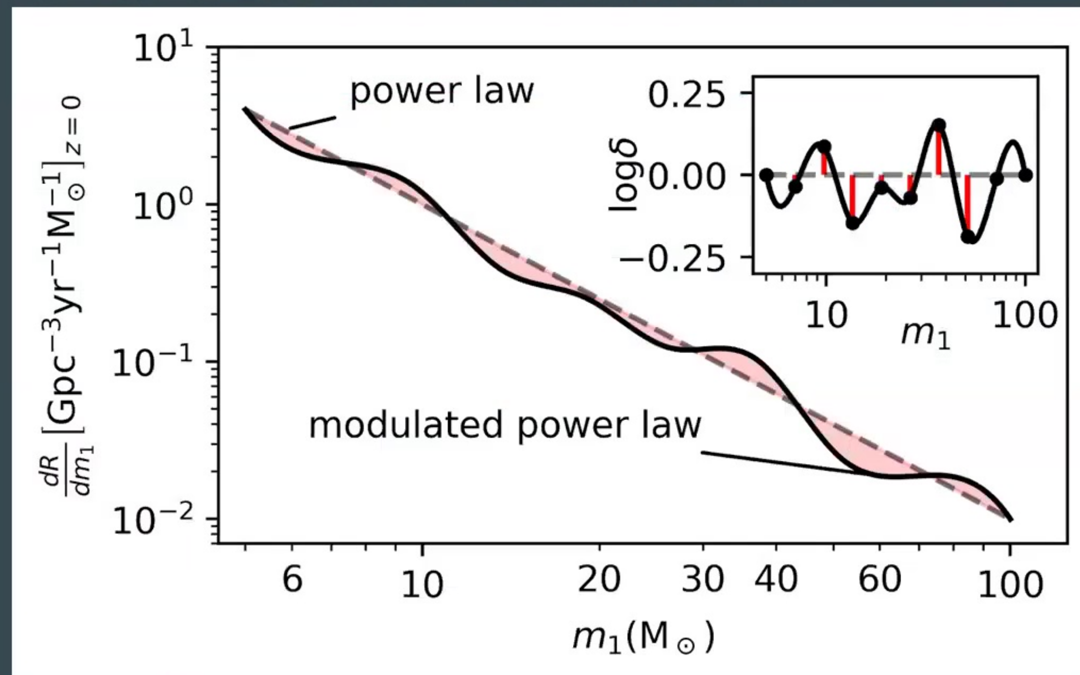
Edelman, Doctor, Farr 2021



Semi-Parametric Modeling of the BBH Mass Distribution



- Introduce a multiplicative perturbation factor to the simple Truncated mass model
- We choose to model the perturbation with cubic splines interpolated from n knots

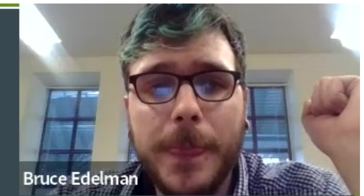


$$p_{\text{spline}}(m_1|\Lambda, \{f_i\}) \propto p(m_1|\Lambda)\exp(f(m_1|\{f_i\}))$$

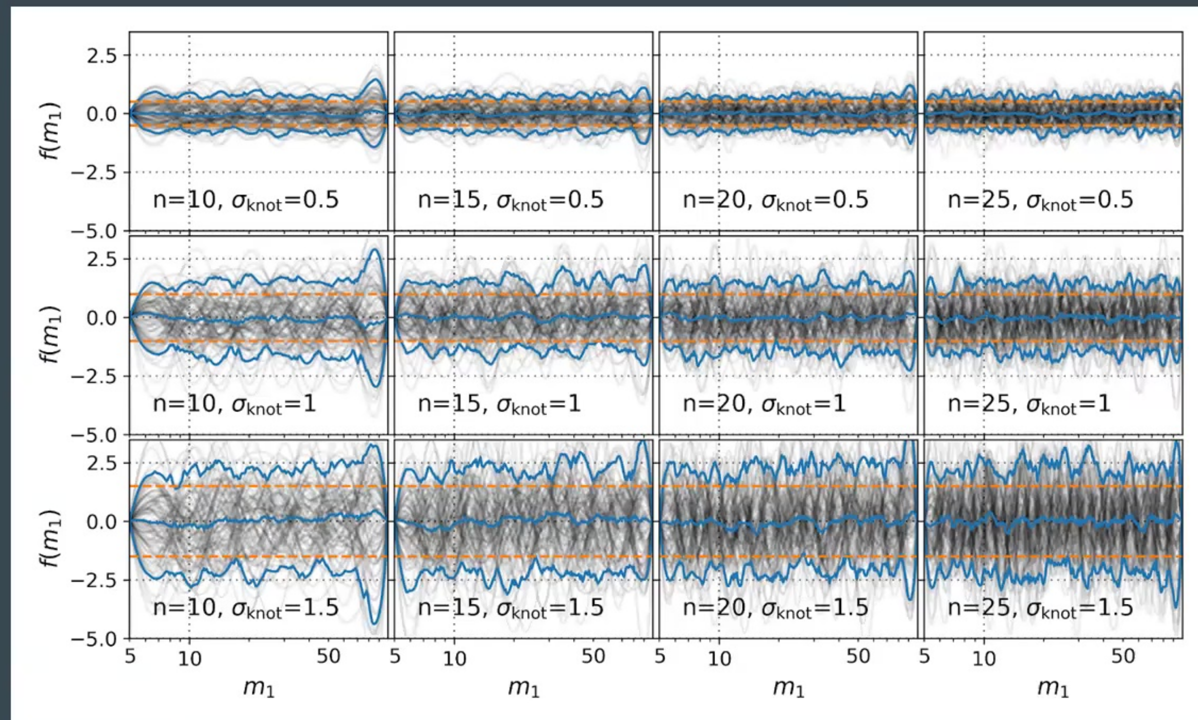
Edelman et al 2022

$$f(m_1) = \mathcal{I}_3(m_1; \{m_n, f_n\})$$

Semi-Parametric Modeling of the BBH Mass Distribution



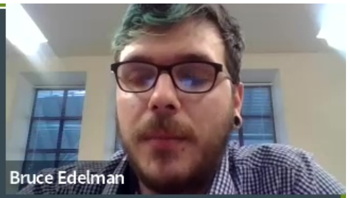
- knots linearly spaced in log-m1 space,
- Gaussian Priors on knot heights centered on zero
- Model Specifications
  - n, the number of knots, sets the resolution of perturbations
  - Width of the gaussian priors sets the a priori magnitude of perturbations



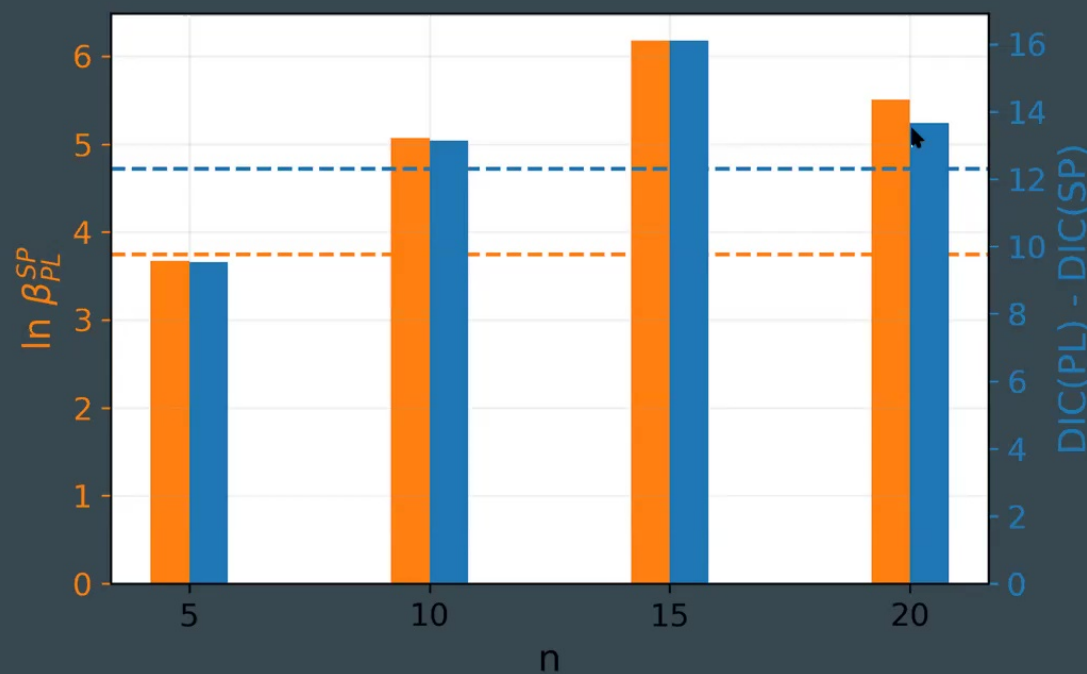
$$p(\{f_i\}) = \mathcal{N}(\mu = 0, \sigma = \sigma_{\text{knot}})$$

Edelman et al 2022

Semi-Parametric Modeling of the BBH Mass Distribution

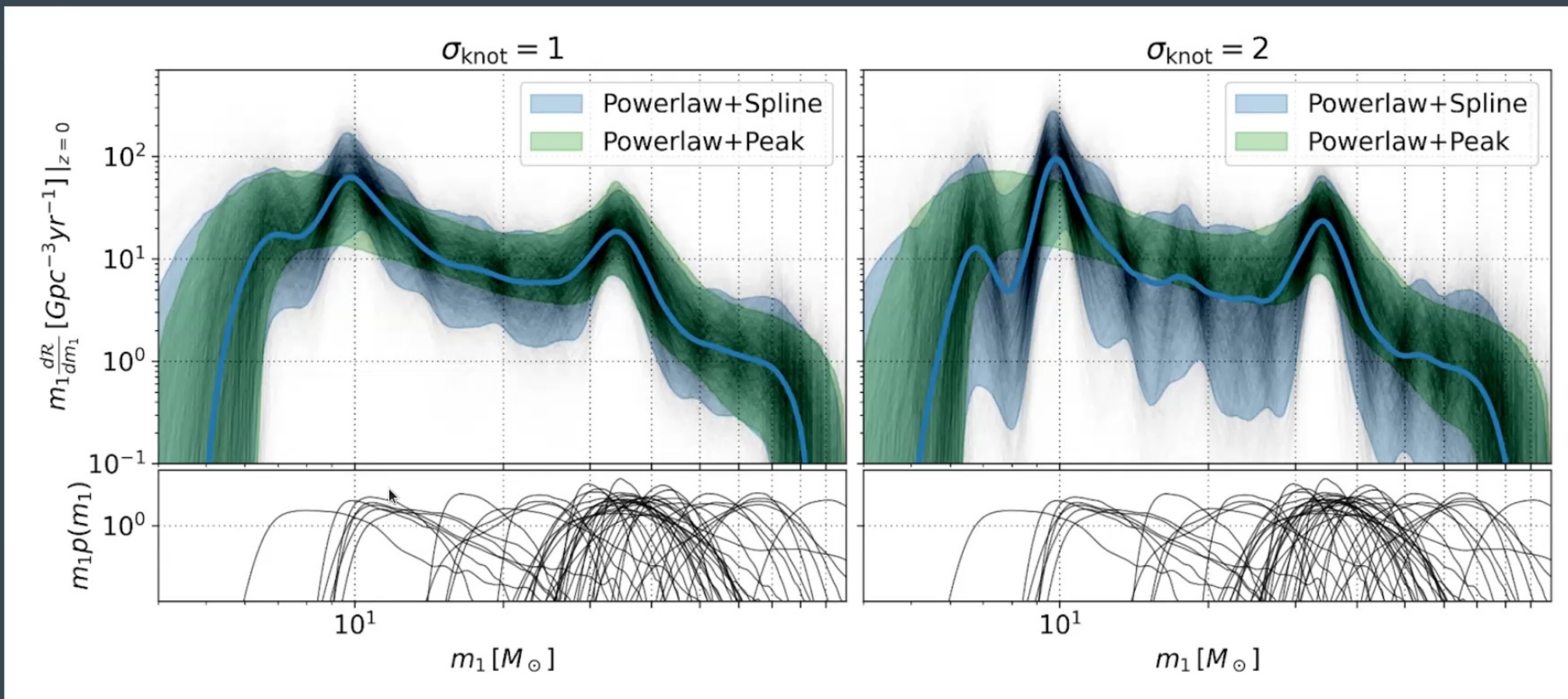


- Run multiple models with variable number of knots
- Use Model Comparison Metrics to evaluate
- Combine posterior samples from each model variant according each BF



Edelman et al 2022

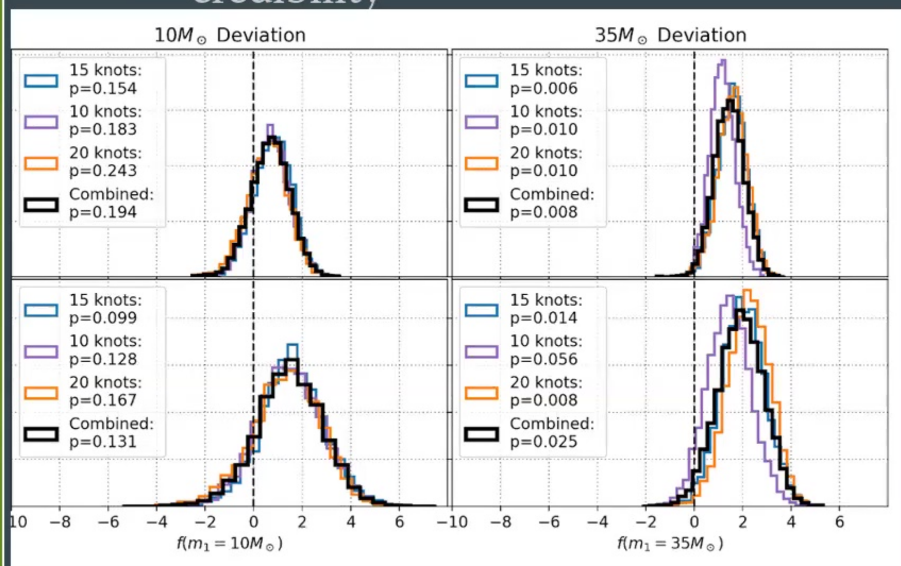
Signs of Structure in the BBH Mass Distribution

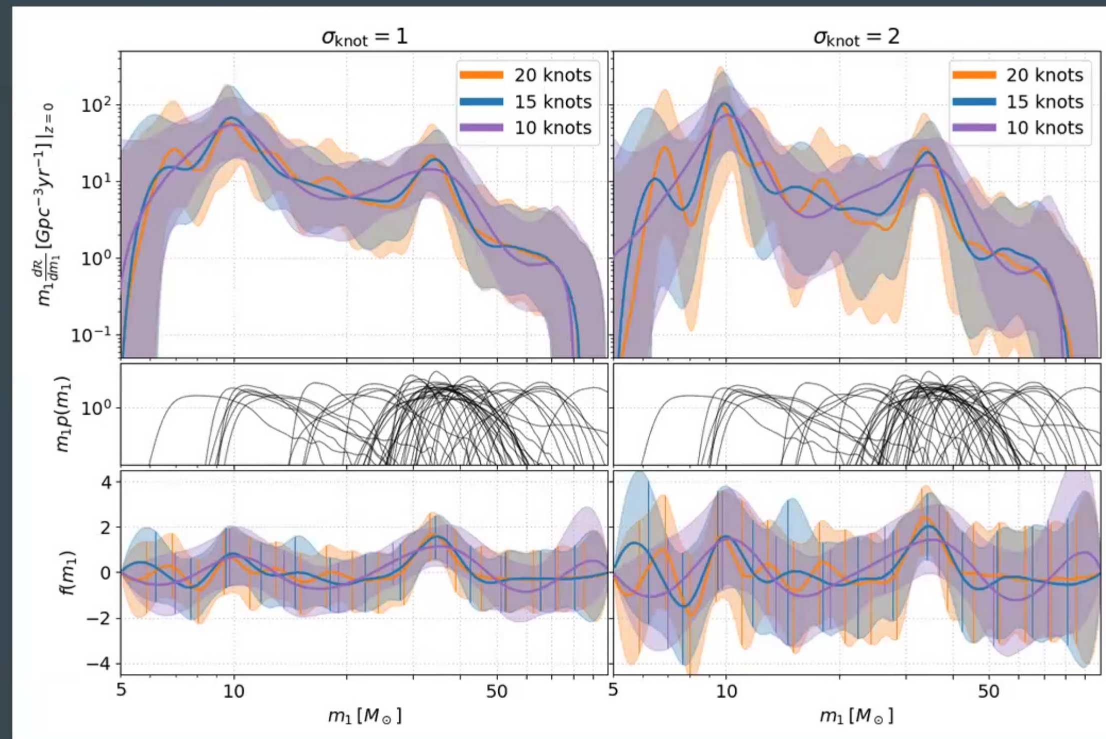


Edelman et al 2022

Signs of Structure in the BBH Mass Distribution

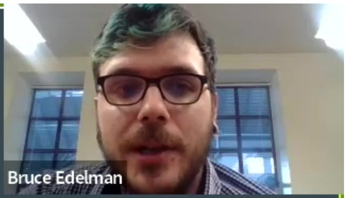
- 10 Solar mass excess at 80-87% credibility
- 35 Solar mass excess at 97-99% credibility





[Edelman et al 2022]

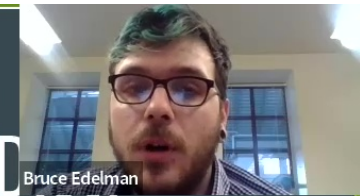
- Less certain about low-mass end where there are less observations and sensitivity



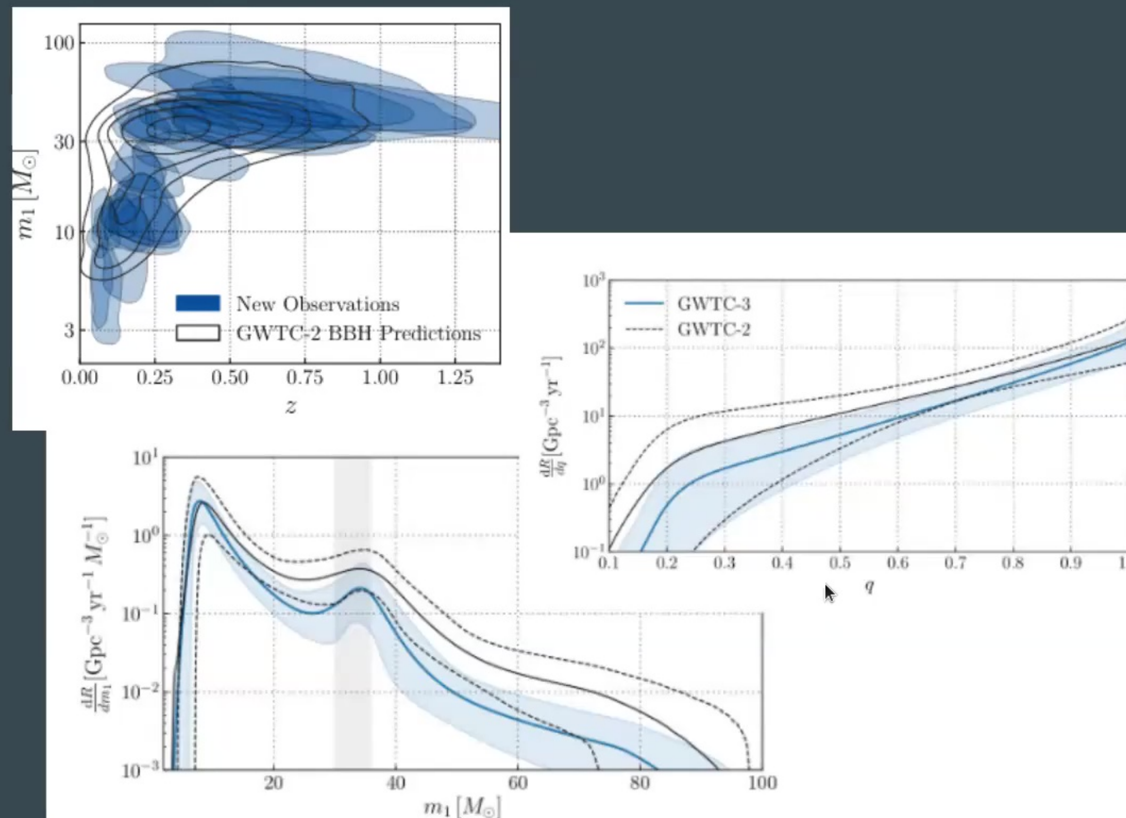
Overview

- Single Source Inference and Parameter Estimation
  - Coherent Waveform Deviation Model (Edelman et. al 2021)
- Hierarchical Inference of a Population of Sources
  - Pair-Instability Mass Gap Model (Edelman, Doctor, Farr 2021)
  - Semi-Parametric Modeling of the BBH Mass Distribution (Edelman et al 2022)
- **Population Updates from GWTC-3**

What is new in the population with GWTC-3? (BBH Mass D



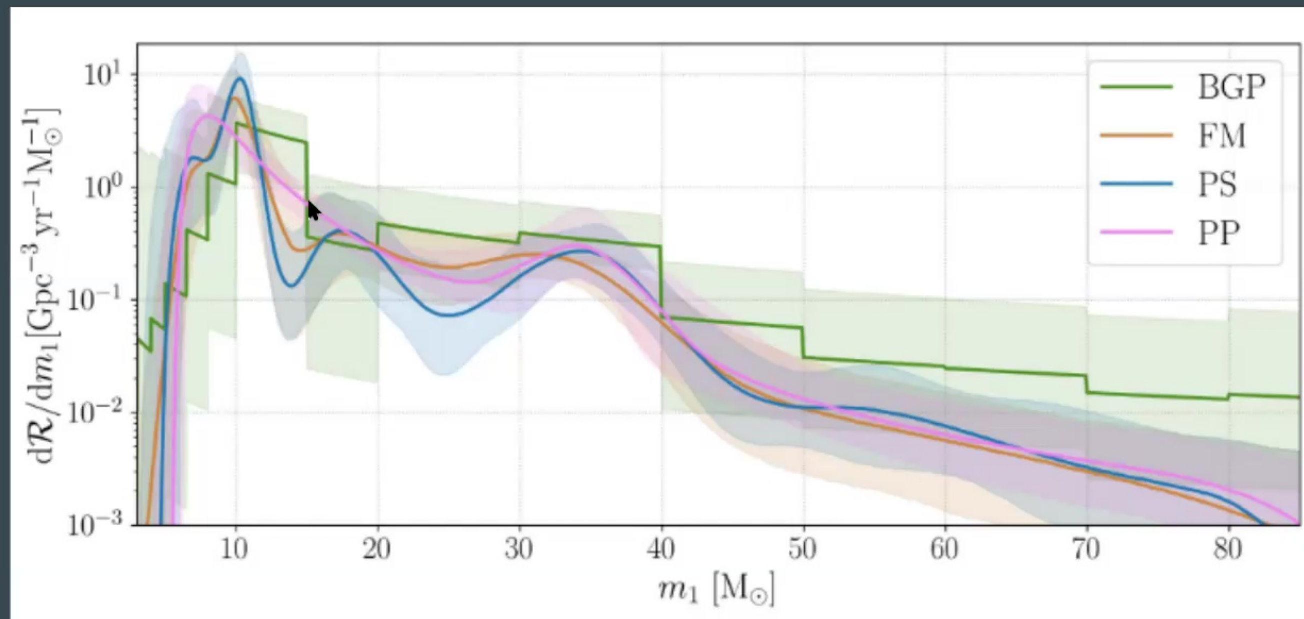
- New events broadly consistent with previous predictions
- PL+Peak model still "favorite"
- Steeper primary mass power law
- Shallower mass ratio power law



2111.03634

What is new in the population with GWTC-3? (BBH Mass D

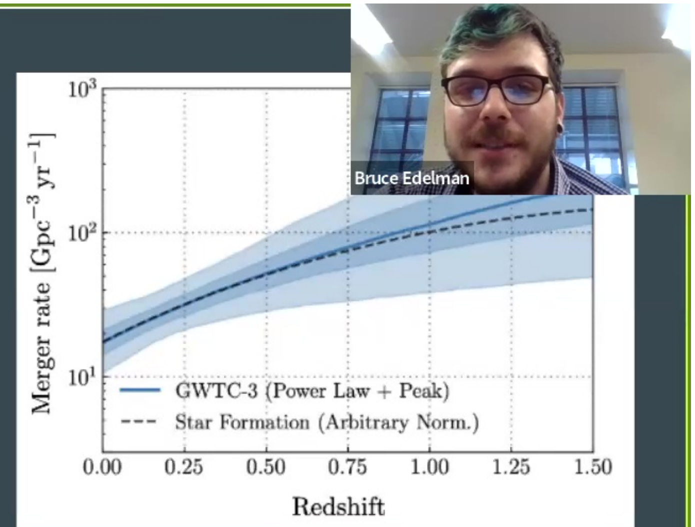
- First application of more "flexible" models
- Three different Non or semi parametric approaches broadly agree
- Signs of Structure in the mass distribution (peaks/dips/etc) are now stronger than in GWTC-2
- Repeat of PISN mass gap model with LVK GW190521 samples in GWTC-3 shows inconclusive evidence

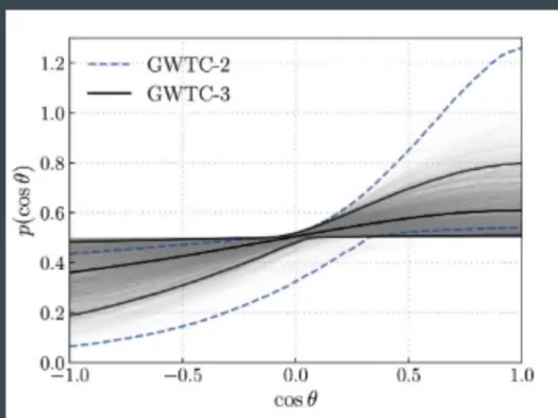


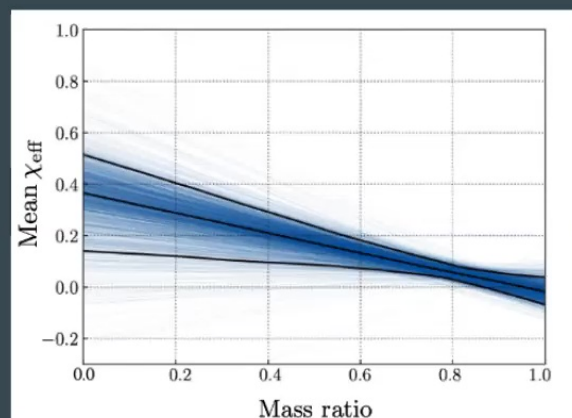
2111.03634

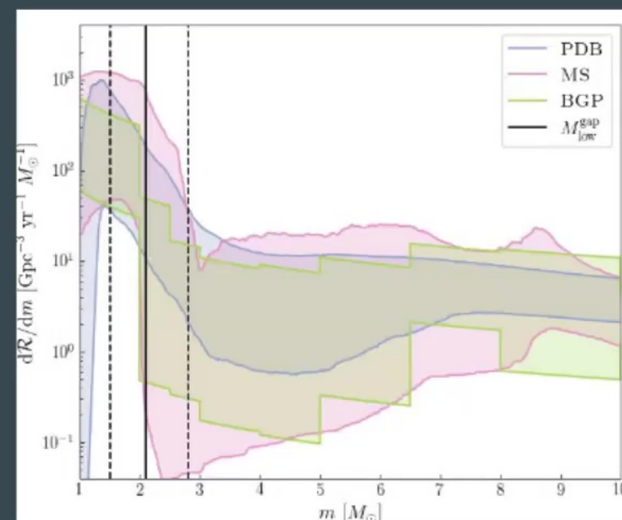
GWTC-3 Population - Other Lessons Learned

- NS Mass distribution broader than galactic
- First self-consistent measurement of merger rate across all compact object masses
- Merger rate confidently increases with redshift
- Misaligned Spins are present in the population
- Correlation between spin and mass ratio



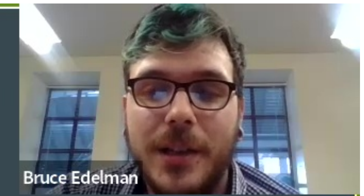




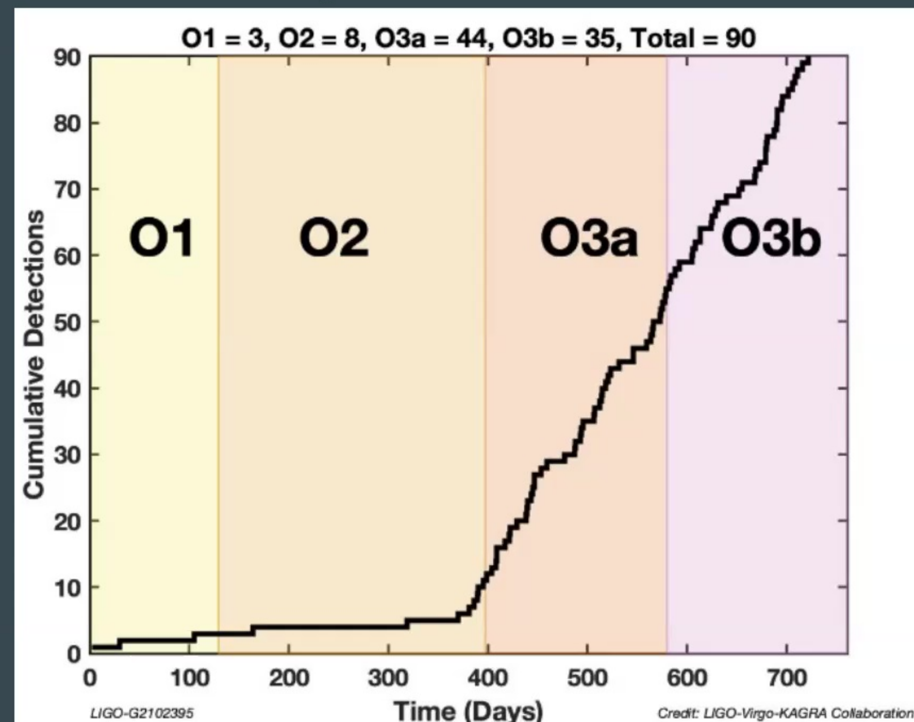


2111.03634

Conclusions



- Data-Driven Models provide a useful method for testing where our observations agree or disagree with expectations
- The population of compact objects is proving to be a treasure trove of astrophysical information
- O4 coming soon will only increase the fidelity we can probe these properties with
- Semi-parametric population modeling will only become more necessary as we further develop our understanding



Thanks!

bedelman@uoregon.edu