From 0 to 50 in 12 years – Development of binary black hole searches in LIGO/Virgo

Commentary on B. Zackay,
'Detecting GW on the open LIGO-Virgo data'

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LIGO Document G2101205-v2

Topics to mention (if time)

1) Recent history : How the (statistical) context has changed since ~2009
2) Present / near future : Continuing and harder statistical challenges
3) A remark on data geometry and GW event ranking

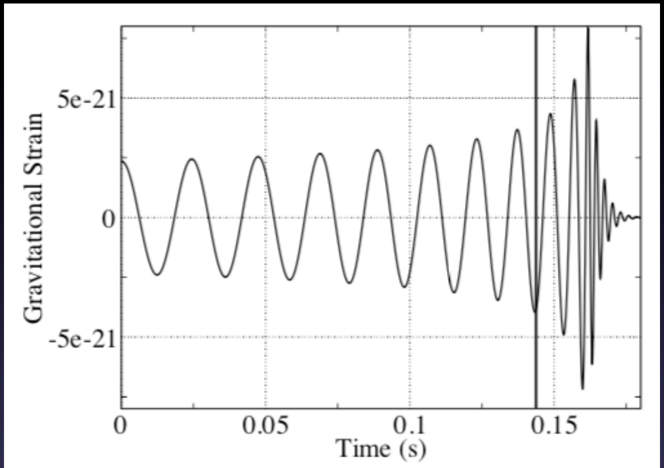
The statistical framework

- ‘The matched filter is the optimal detection statistic’

  … how many ways can that statement be wrong or misleading?

Problems with the signal (historical)

- Initial LIGO (2005-2007) : *no general BBH signal model available*
- EOB / NR
- ***EOBNRv1***
  A. Buonanno et al., Phys. Rev. D 76, 104049 (2007)
- IMRPhenom …
- SEOBNRvN …



LSC/Virgo, Phys. Rev. D 83, 122005 (2011)

Now have quantified model accuracy & effects of (omitting) spin precession, higher multipole emission, …

How to search with ‘the wrong signals’ ?

1. Signal model uncertain in some parameter regions
2. Signal templates do not include all physical parameters / effects (spins, HM, …)

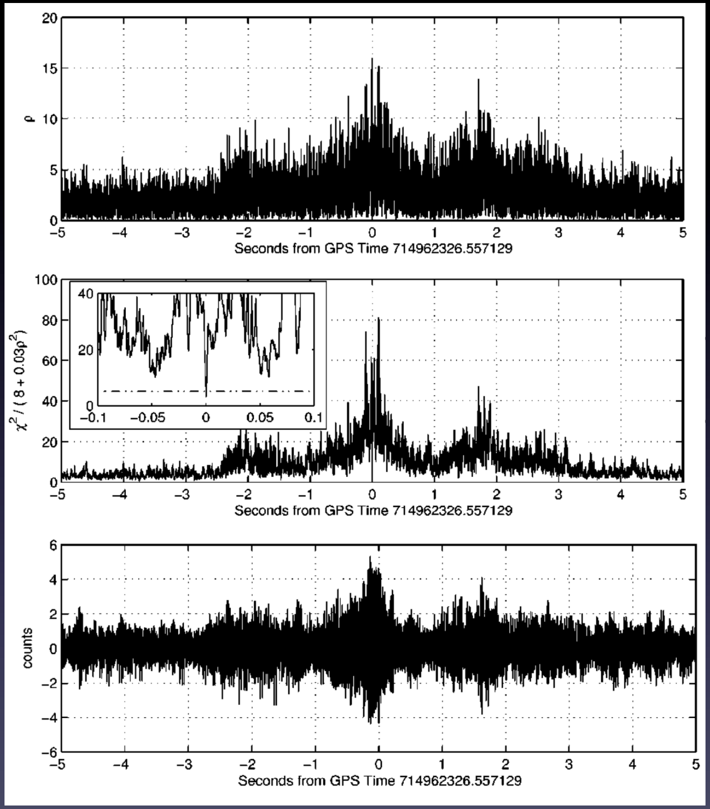
Not aware of formal work on matched filter search with uncertain / incomplete template set

- e.g. expanded search space including parameterised uncertainties ?
- necessarily pick up extra noise ⇒ suboptimal

Problems with the data

LIGO-Virgo data are *in general* non-stationary & non-Gaussian

- Infinite number of ways this could manifest itself
- To make progress need *approx-imately correct* description of detector noise



LSC, PRD **69**, 122001 (2004)

- NB - detector behaviour is different in every run !

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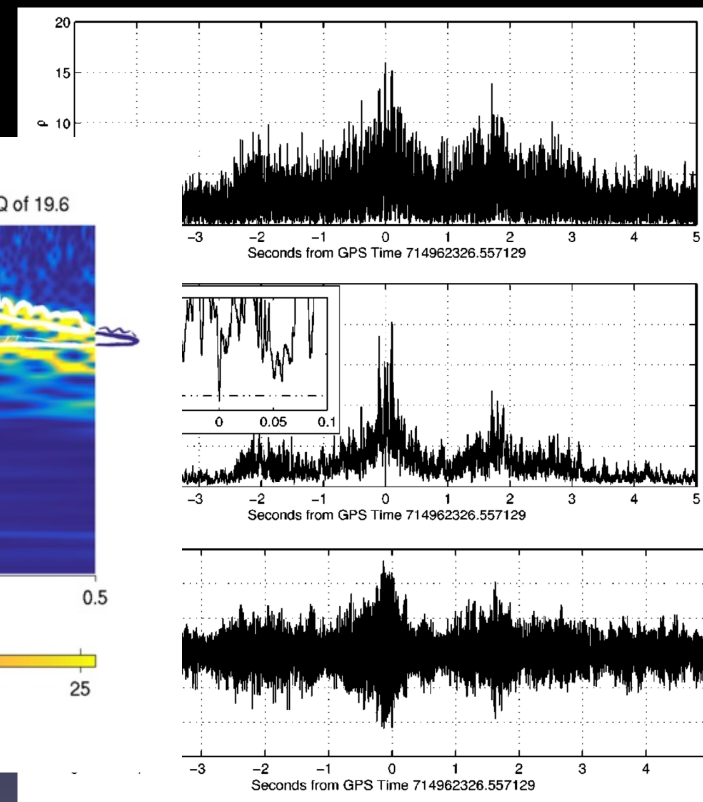
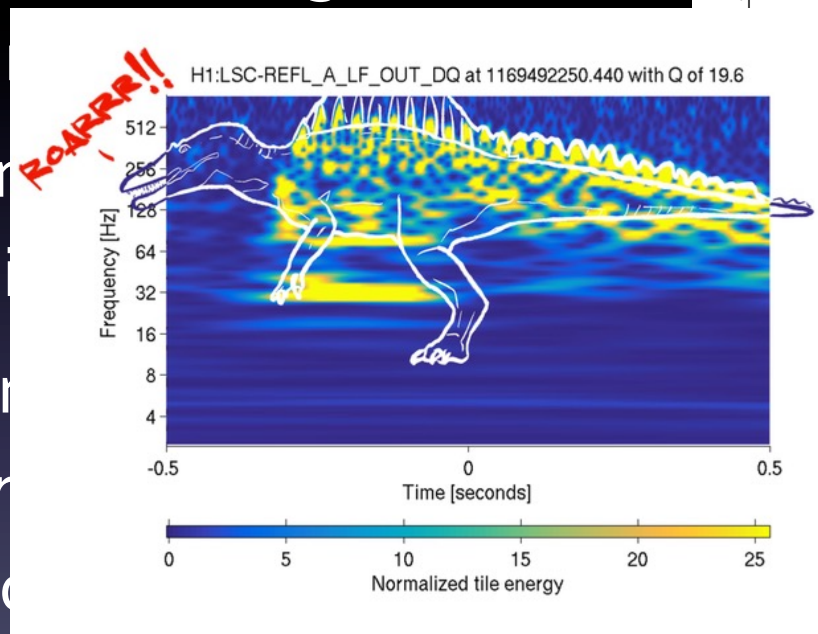




- NB - detector behaviour is different in every run !

‘Usual’ assumptions about noise

- Consider as ‘quasi-stationary’ (approx. stationary over short time periods)
  + isolated ‘bad’ times inconsistent with Gaussian distribution (high amplitude ‘glitches’)
- Measure longer time drifts in noise spectrum
  (Zackay et al. demonstrate *shorter-time* variations & effect on optimal statistic)
- Use generic excess power & signal consistency checks to identify and remove / penalize ‘glitch’ times
  (IAS search uses ‘inpainting’ excision & several novel checks)

Initial LIGO search philosophy

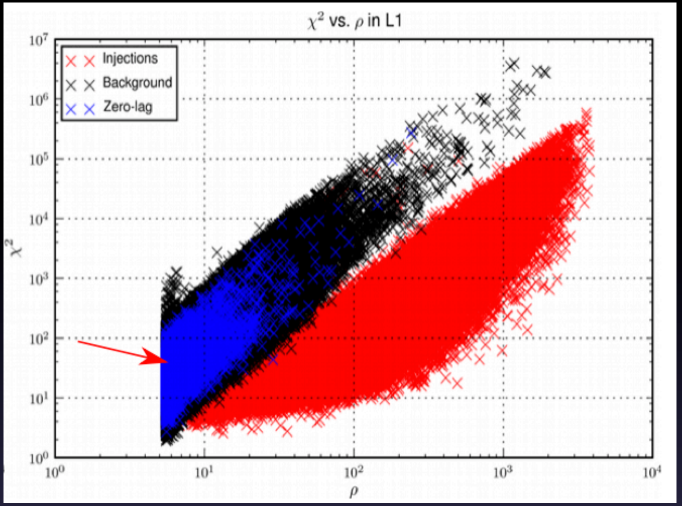


image: LSC-V / K. Cannon

How to impose signal consistency if we don't know the signal accurately?

- Heuristic : 'Eyes wide open'
  - Deliberately loose cuts/penalties for events 'somewhat mismatching' templates
  - should also allow for extra physics (spin, HM ...) ?
  - ss a consequence *significantly higher* noise background
- IAS search using opposite heuristic – 'reject anything with significant mismatch to templates'
  - requires confidence in model accuracy
  - what fraction of loud signals are really rejected ?

How do the assumptions fare in O3?

New player : Long-duration, band-limited excess noise

– Caused by scattered light re-entering ifo arms

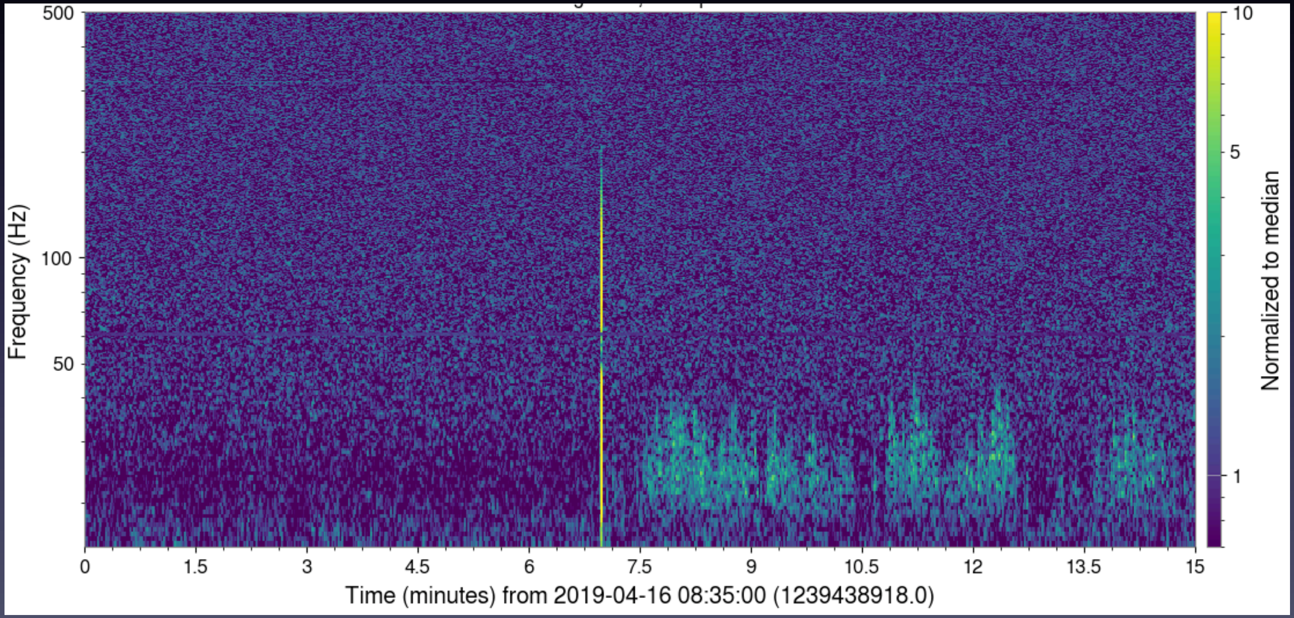


image: LDVW (LIGO open data)

– Does not fit within previous paradigm …

Astrophysics in a time of scattering

- Many O3a events detected *despite* scattering noise

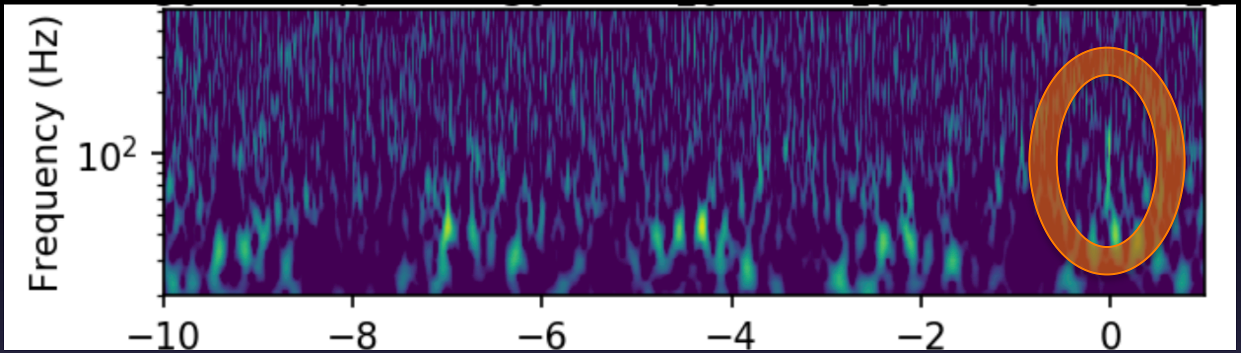


image: PyCBC (LIGO open data)

- require 'mitigation' to extract event properties
  – detailed modelling & subtraction of extended excess noise

Name	Mitigation
GW190413_134308	L1 glitch subtraction, glitch-only model
GW190424_180648	L1 glitch subtraction, glitch-only model
GW190425	L1 glitch subtraction, glitch-only model
GW190503_185404	L1 glitch subtraction, glitch-only model
GW190513_205428	L1 glitch subtraction, glitch-only model
GW190514_065416	L1 glitch subtraction, glitch-only model
GW190701_203306	L1 glitch subtraction, glitch+signal model
GW190727_060333	L1 f_{min}: 50 Hz
GW190814	L1 f_{min}: 30 Hz; H1 non-observing data used
GW190924_021846	L1 glitch subtraction, glitch-only model

LVC, GWTC-2 (arXiv:2010.14527)

Problems with the signal population

- Before (late) 2015 : ~zero idea of the actual BBH population
- Rate 'predictions' cover many orders of magnitude & ~no idea about masses, spins, …

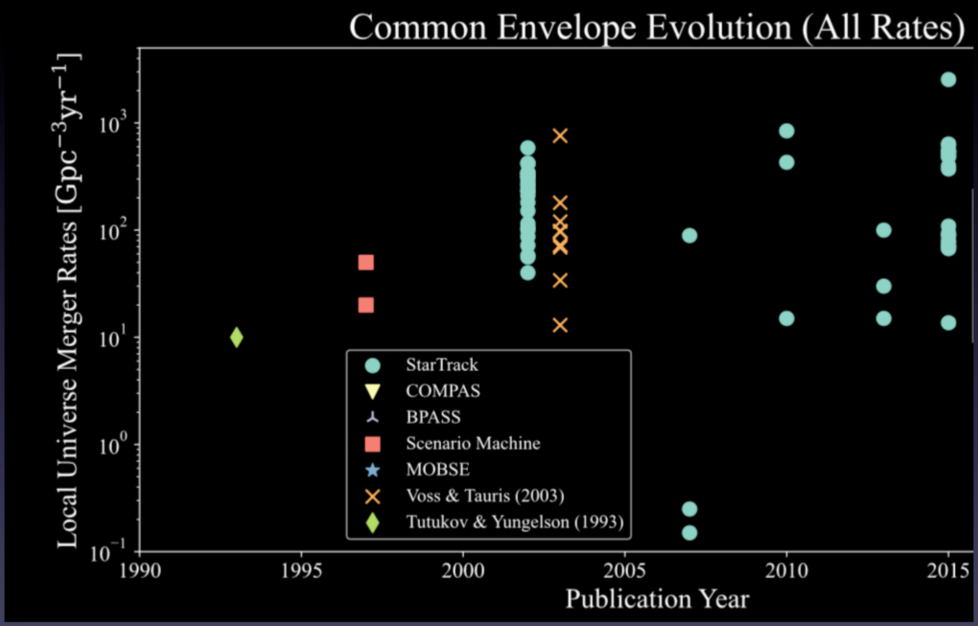


image: C. Rodriguez, CMU

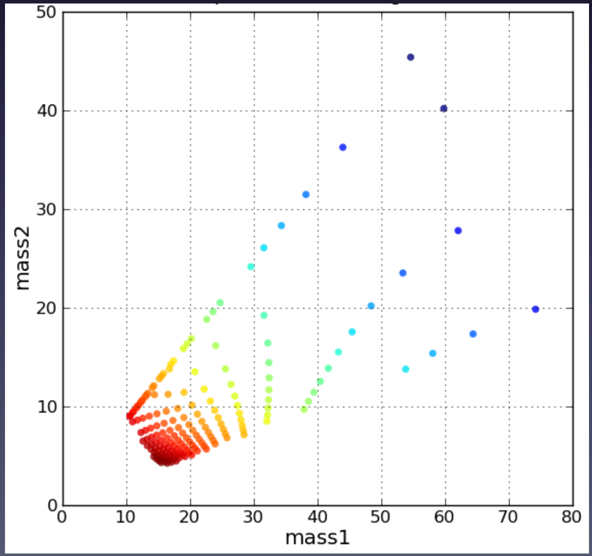
- No overall search *figure of merit* (… for what source population ?)
- Initial LIGO optimized *de facto* weighting each template equally (goal: rate upper limit over a wide range of binaries)

A (historical) alternative approach

- 2011 : 'Focused highmass' proposal (unpublished) motivated by Belczynski et al. 2010 ApJL

> Our results indicate that BH–BH binaries are 25–times more likely sources than NS–NS systems and that we are on the cusp of GW detection.

- Most likely first detection scenario : near equal mass BBH ($q = m_2/m_1 > 1/4$)
- Much smaller template bank
- Full use of signal consistency
- **Factor of 2.5 – 3 improved sensitive volume over 'standard' LIGO search**



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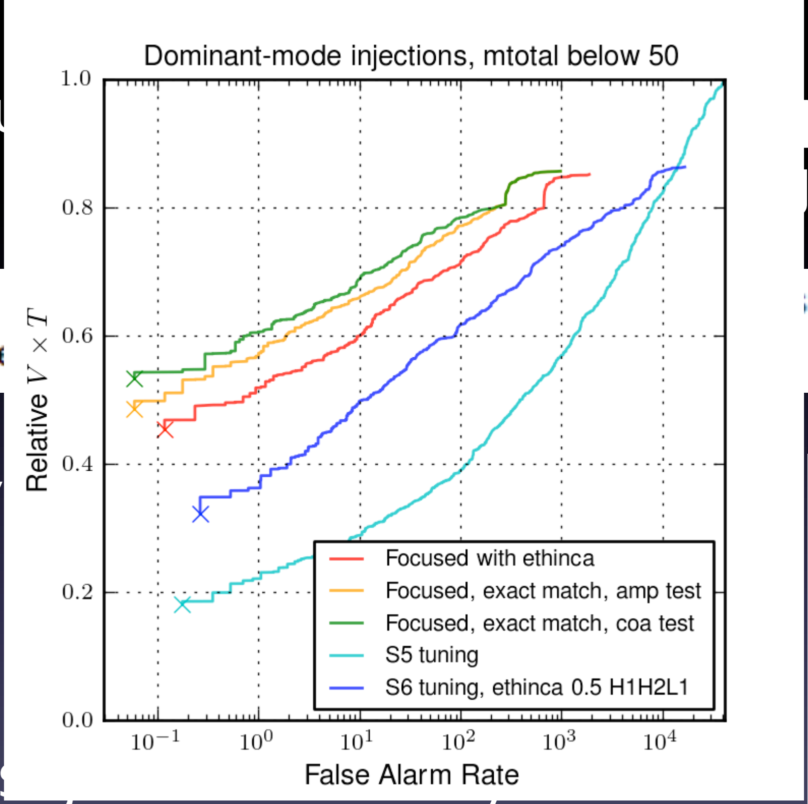

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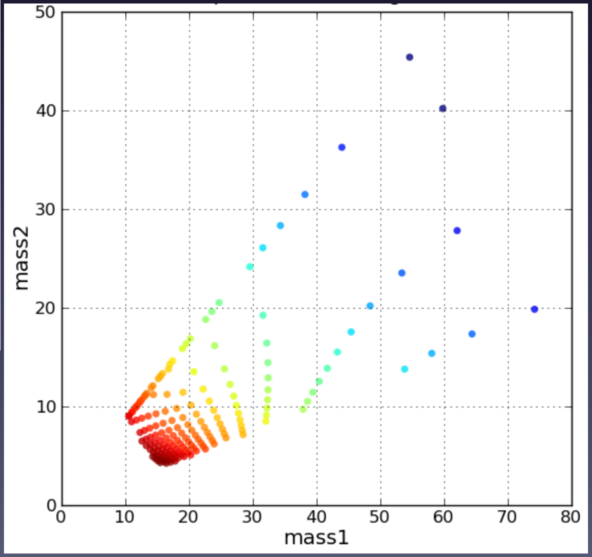
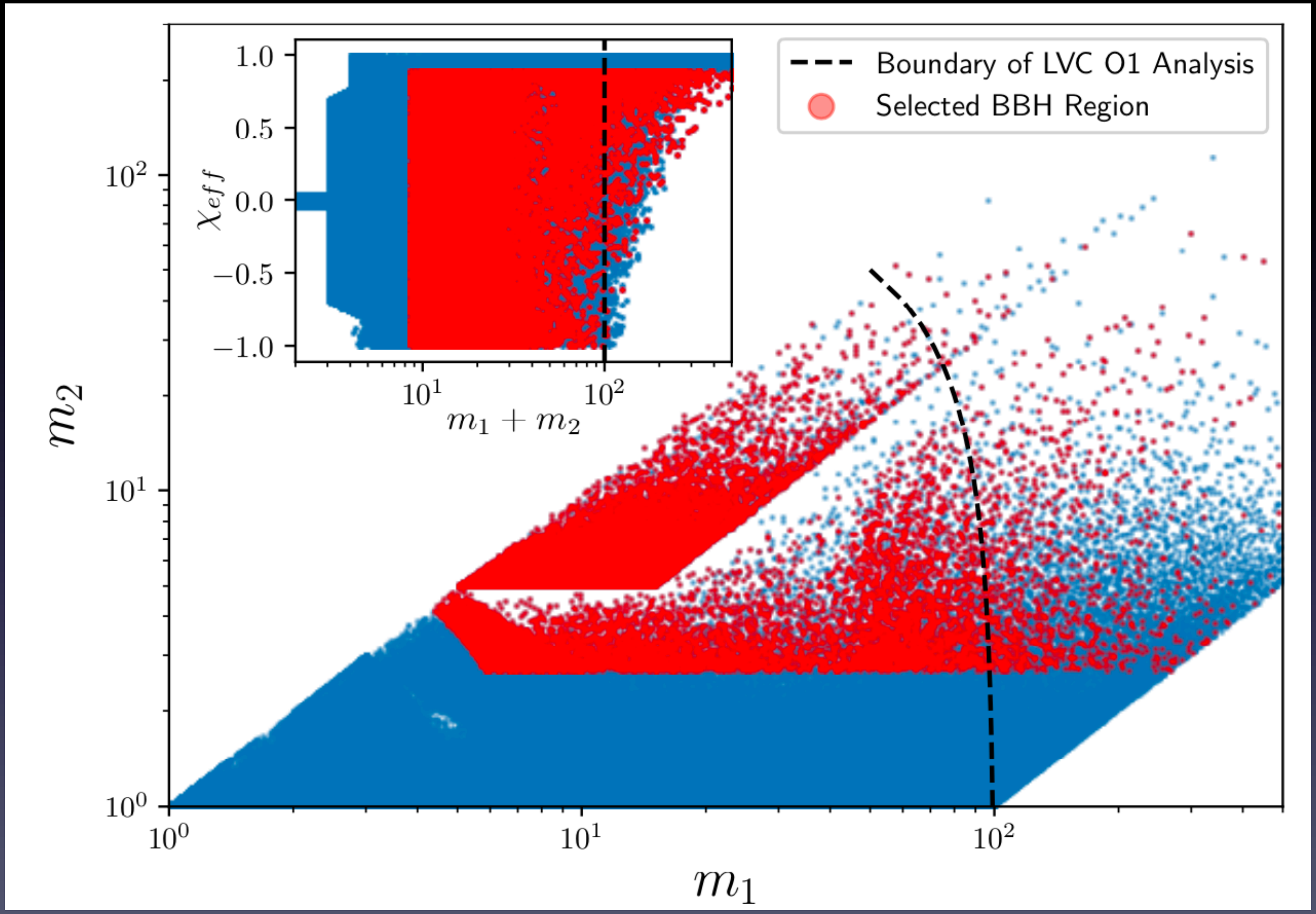
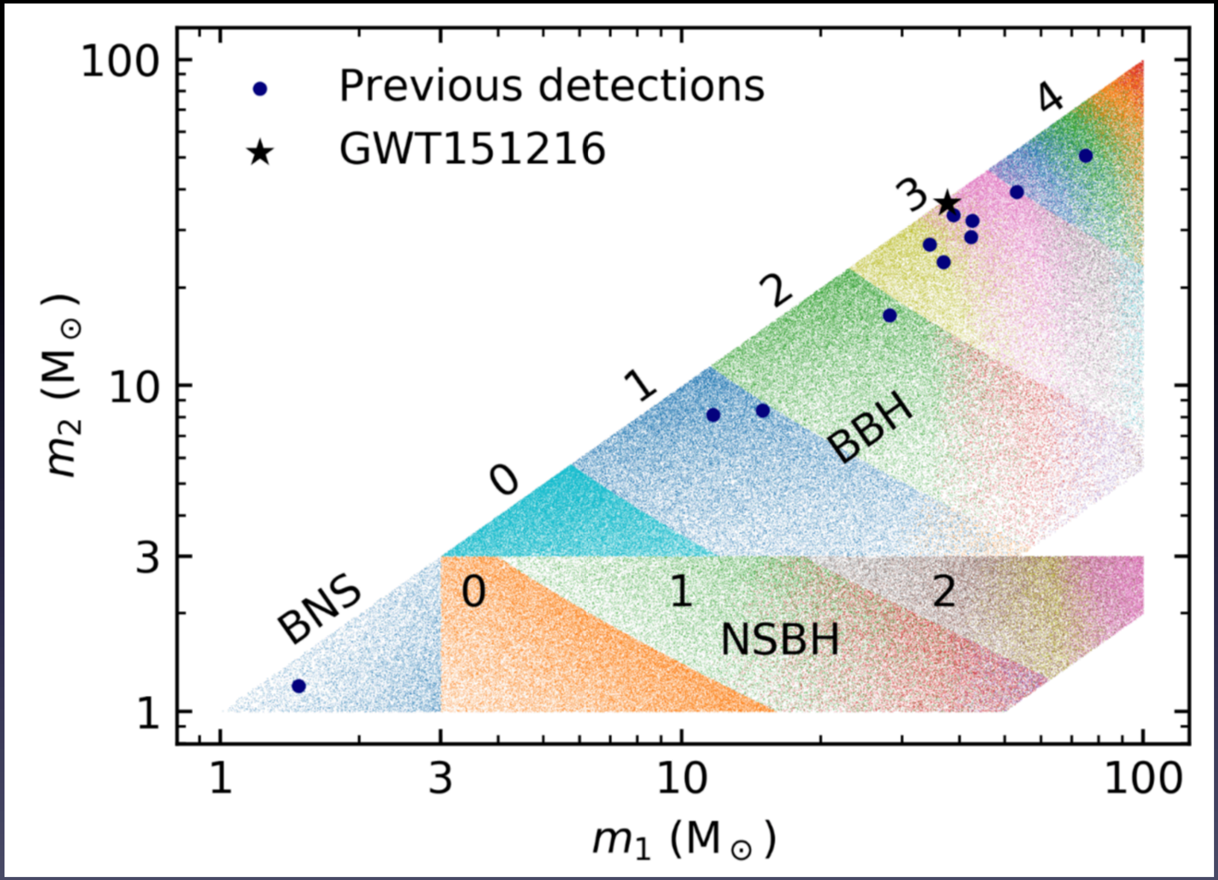


First appearance of 'focused BBH'



Reanalysis of O1 open data : '1-OGC', Nitz et al. ApJ **872** 195 (2019)

GW events vs. IAS template bank



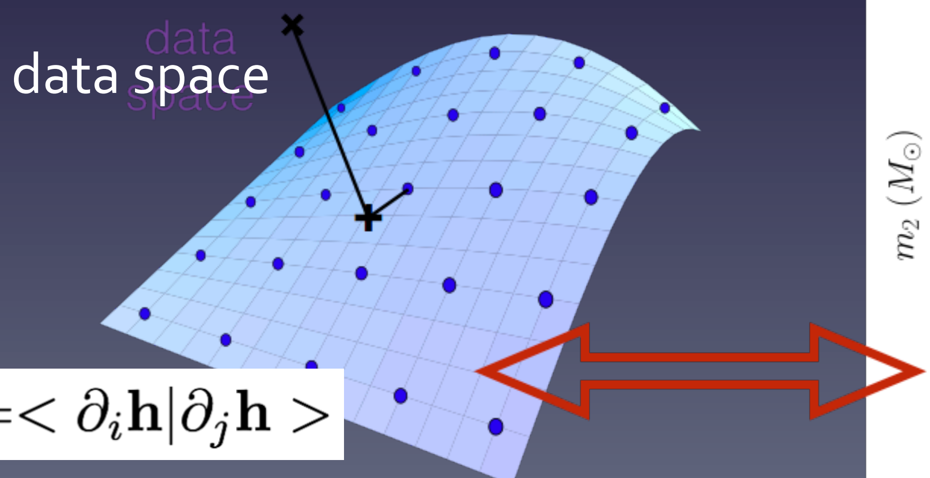
(from B. Zackay's talk)

- Odds for signal vs. noise ∝ density of signal events / density of noise events

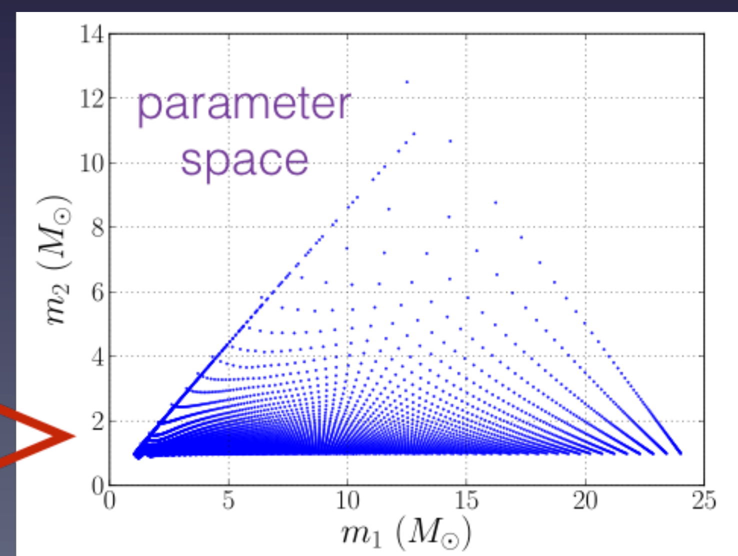
Optimal search for a known population

GW detection is a *composite hypothesis* problem

- Formally: marginalize $\mathcal{L}$ over signal parameters (time, phase, masses, spins …)
- Approximate $\mathcal{L}$ as quadratic near peak : get Fisher matrix
- Also get *metric over binary parameter space*



$$g_{ij} =< \partial_i \mathbf{h} | \partial_j \mathbf{h} >$$



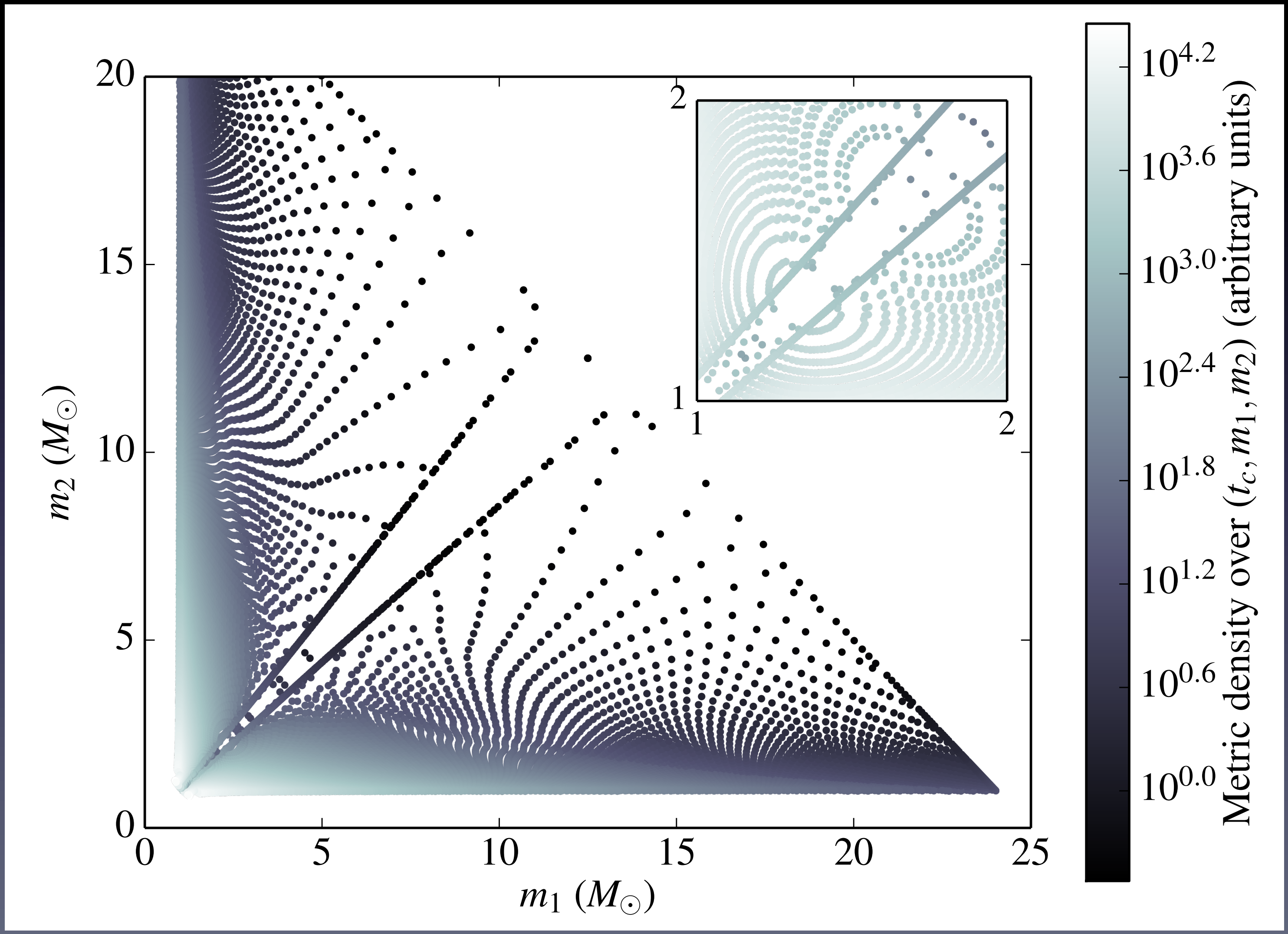
Fisher metric ⇒ noise event density

Marginalize over masses & spins ⇒
get factors $\exp\left(-\frac{\rho_{\max}^2}{2}\right)$ $\sqrt{\frac{(2\pi)^{n+1}}{\det\gamma(\vec{\theta}^{\mathrm{ML}})}}$

- Matched filter likelihood effectively corrected by 1/(Fisher metric density) – cf. $dV \propto \sqrt{\det g_{ij}}$
- Similar to *template placement metric* (describing density of independent templates)
- Interpretation:
  likelihood ratio ∝ 1/(density of noise events)

T. Dent & J. Veitch, Phys. Rev. D 89, 062002 (2014)

‘Information’ density is not source population density!



Takeaways

- Always necessary to understand data (noise !)
  - New noise description for every observing run ?
  - No 'silver bullet' (... deep learning ?!)
- Matched filter search is easier to optimize if you know your signal model is accurate
  - still not solved for precessing spins, HM, eccentricity ...
- Matched filter search is easier to optimize if you know what your signal *population* is
  - so far not applied for precessing spins, HM, eccentricity ...
- What does 'optimize' mean anyway ?
  - do we always want to maximize total signal count ??