Searching for transient GW signals

A personal perspective

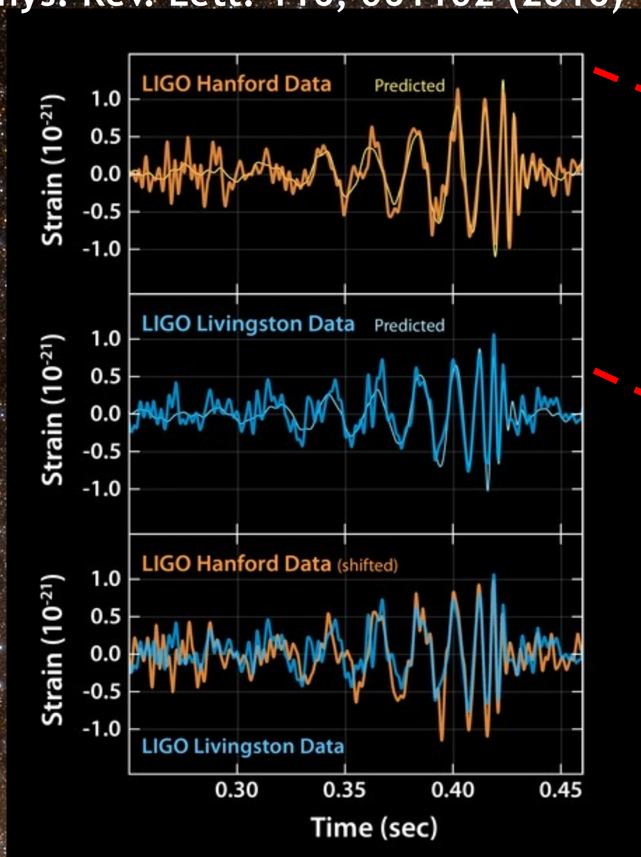
Soumya D. Mohanty

UTRGV

Support: NSF, TACC (Texas Advanced Computing Center), U.S. Dept. of Defense

GRAVITATIONAL WAVE ASTRONOMY: LAUNCH

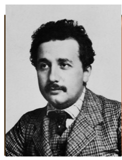
Phys. Rev. Lett. 116, 061102 (2016)

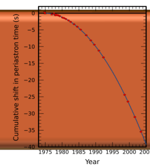


LIGO Hanford, WA

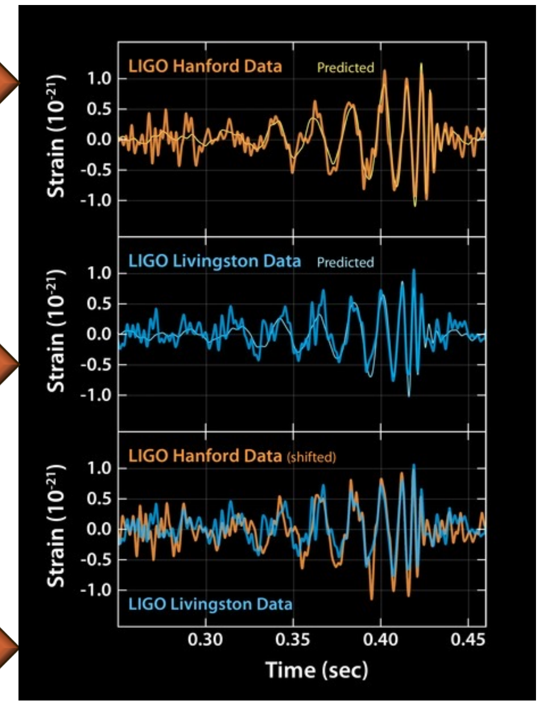
LIGO Livingston, LA

PILLARS: DATA ANALYSIS & COMPUTING





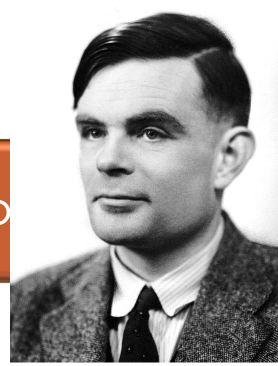
https://arxiv.org/pdf/1610.08803



Gauss/Legendre (1809): Least squares

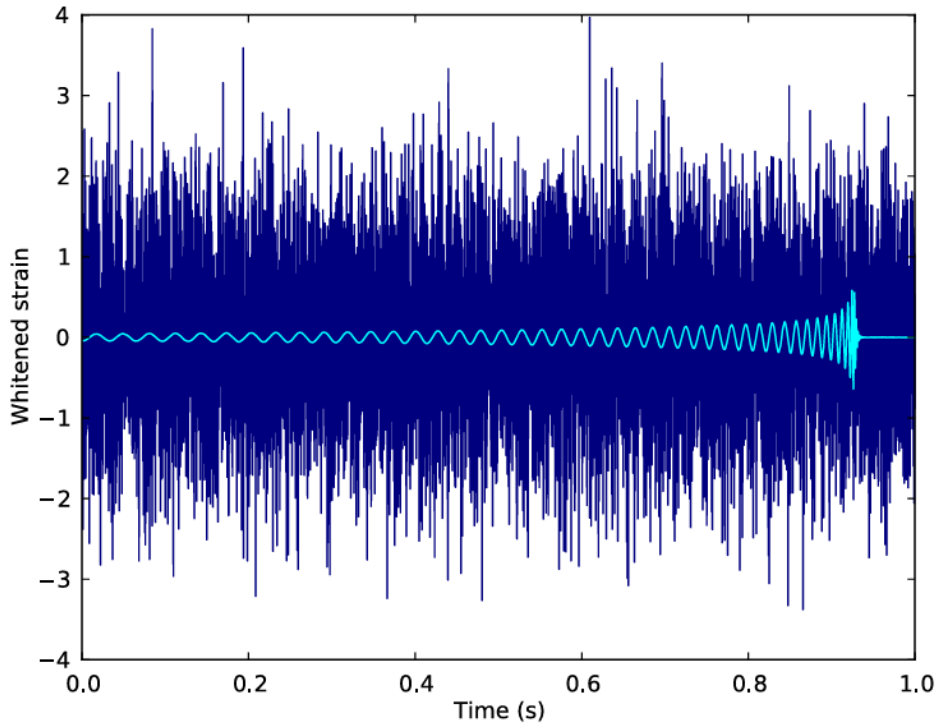
Fisher (1922): Likelihood

D



Turing (1936): Computer Science

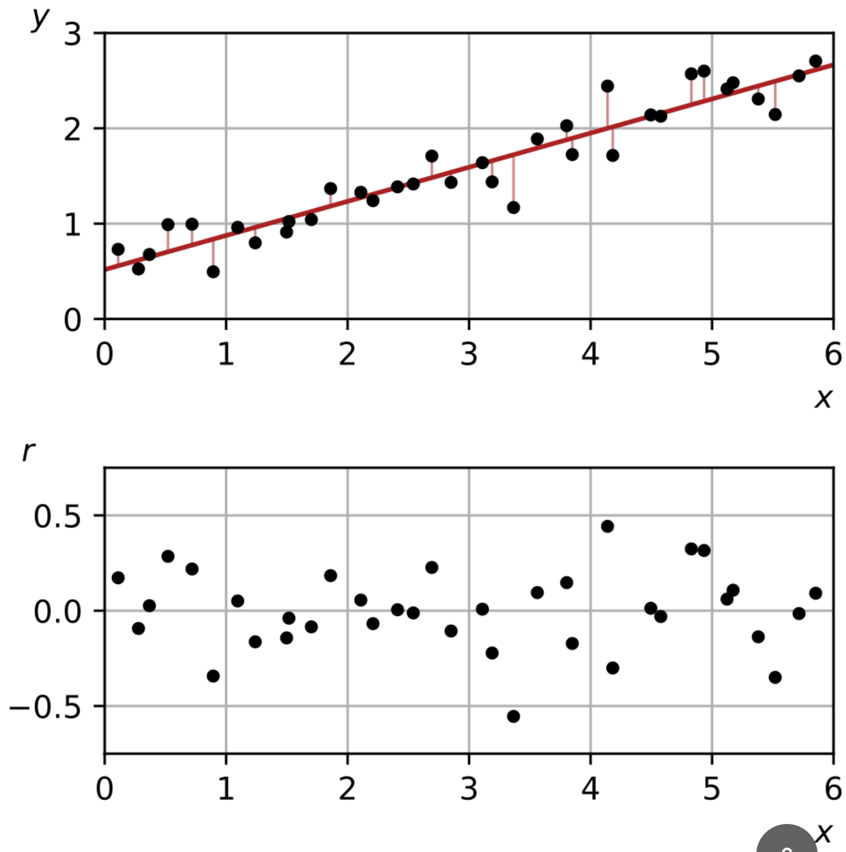
GW DATA: NOISE DOMINATED



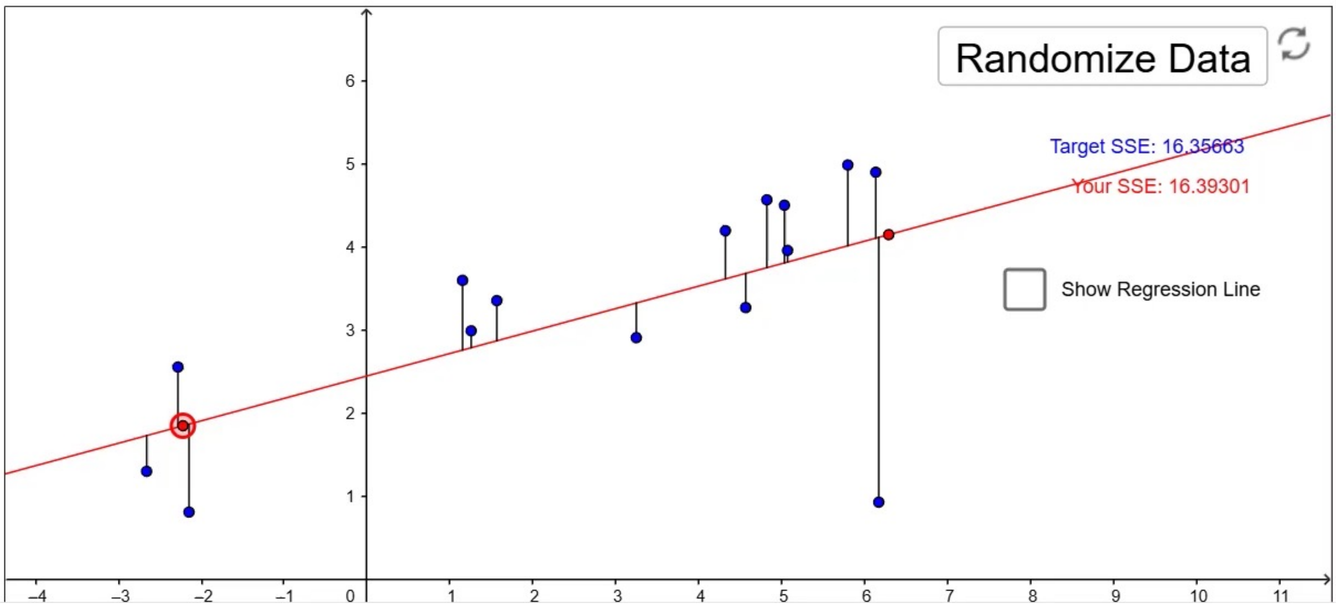
Gabbard et al, PHYSICAL REVIEW LETTERS 120, 141103 (2018)

LEAST SQUARES: LINEAR FUNCTION

- What is the best straight line fit?
- For a given straight line, get the residual
- The best straight line minimizes the spread of the residual points around zero

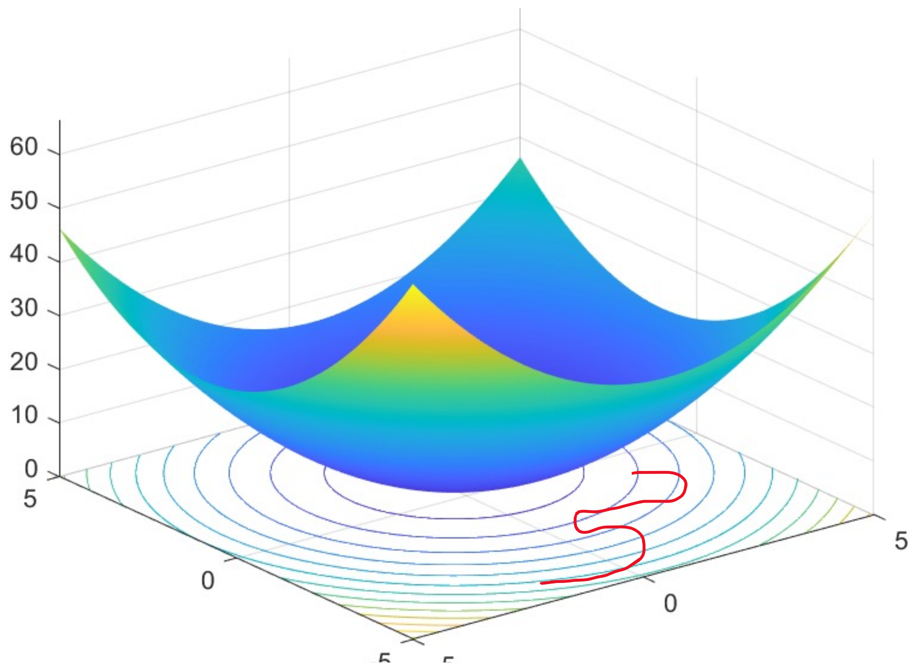


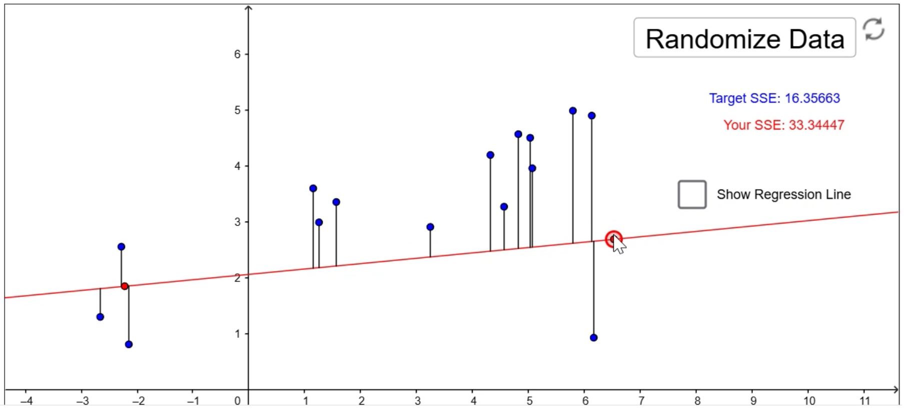
LEAST SQUARES: LINEAR FUNCTION



https://www.geogebra.org/m/xC6zq7Zv

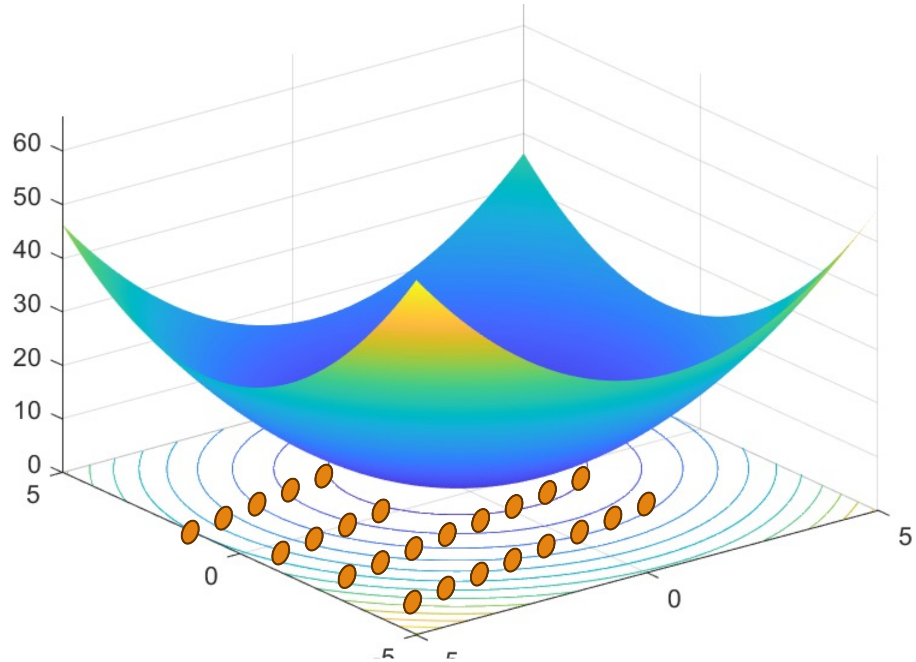
LEAST SQUARES: MODEL FITTING



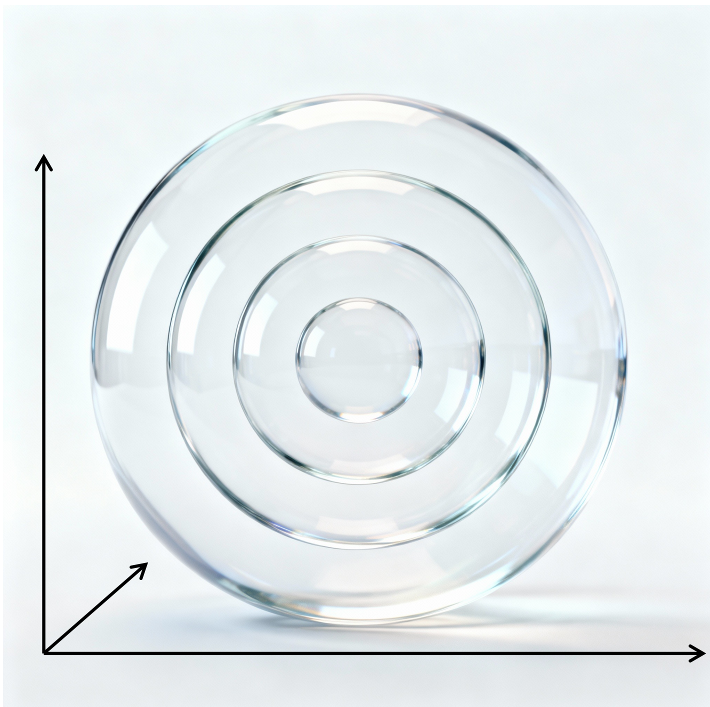


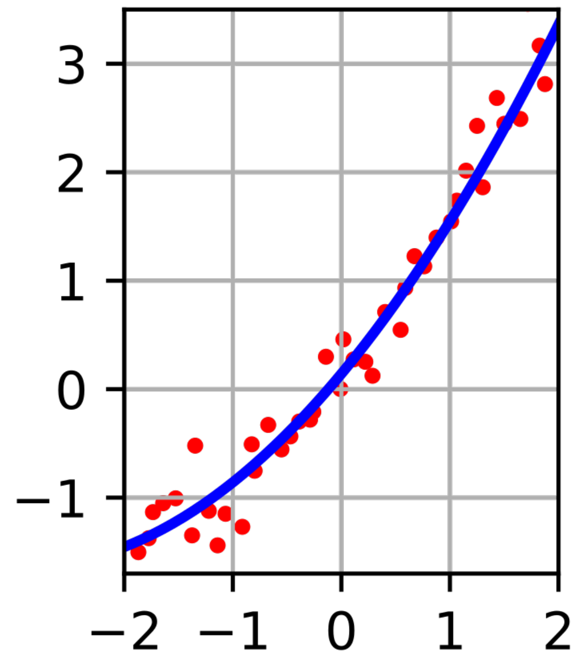
LEAST SQUARES: MODEL FITTING

How to find the minimum?

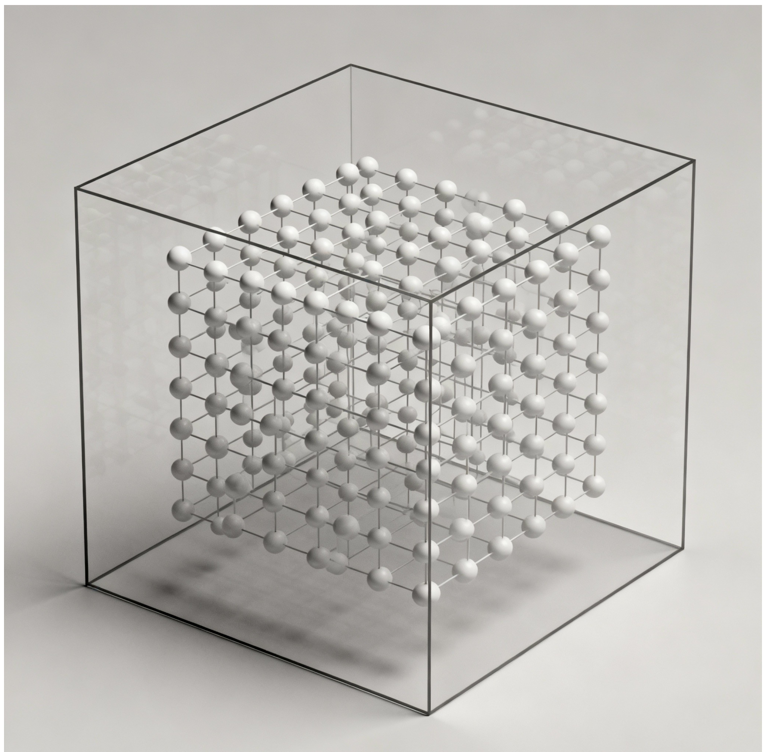


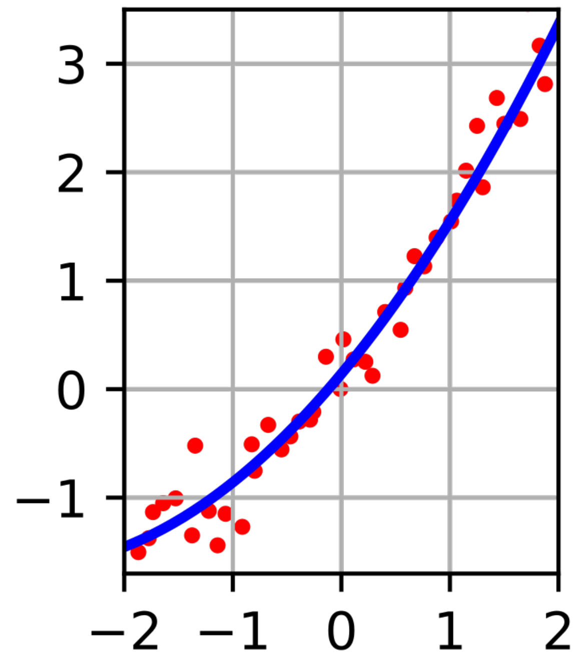
LEAST SQUARES: QUADRATIC FUNCTION



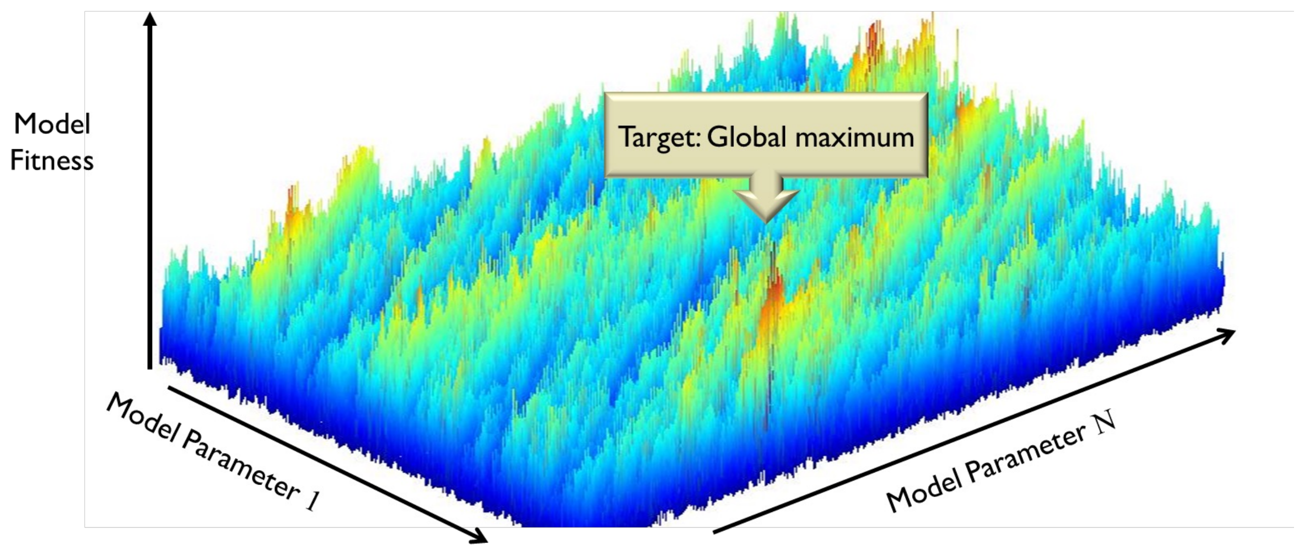


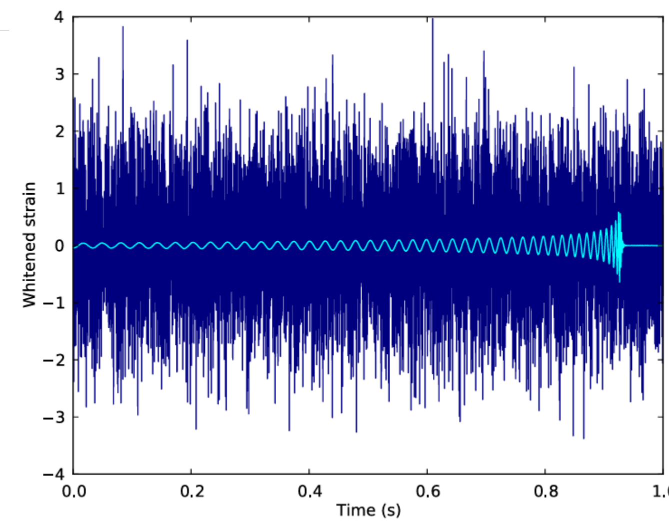
LEAST SQUARES: QUADRATIC FUNCTION





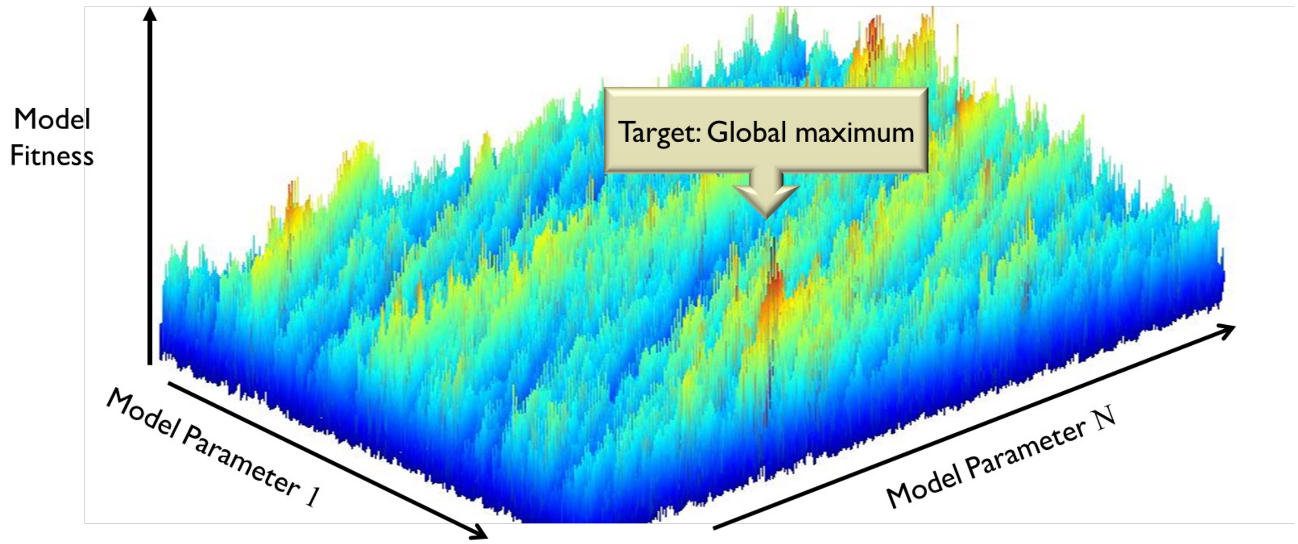
GW DATA ANALYSIS: A FITTING PROBLEM

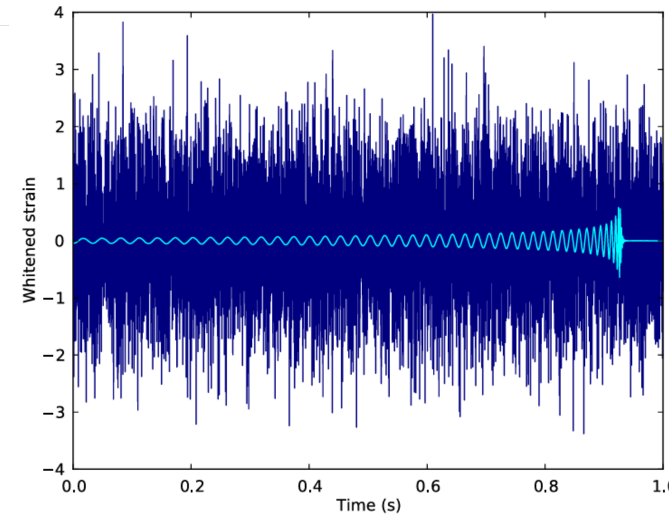




- Extremely rugged fitness landscape
- High dimensional and needle-like global maximum
- Lots of large secondary maxima that need to be avoided

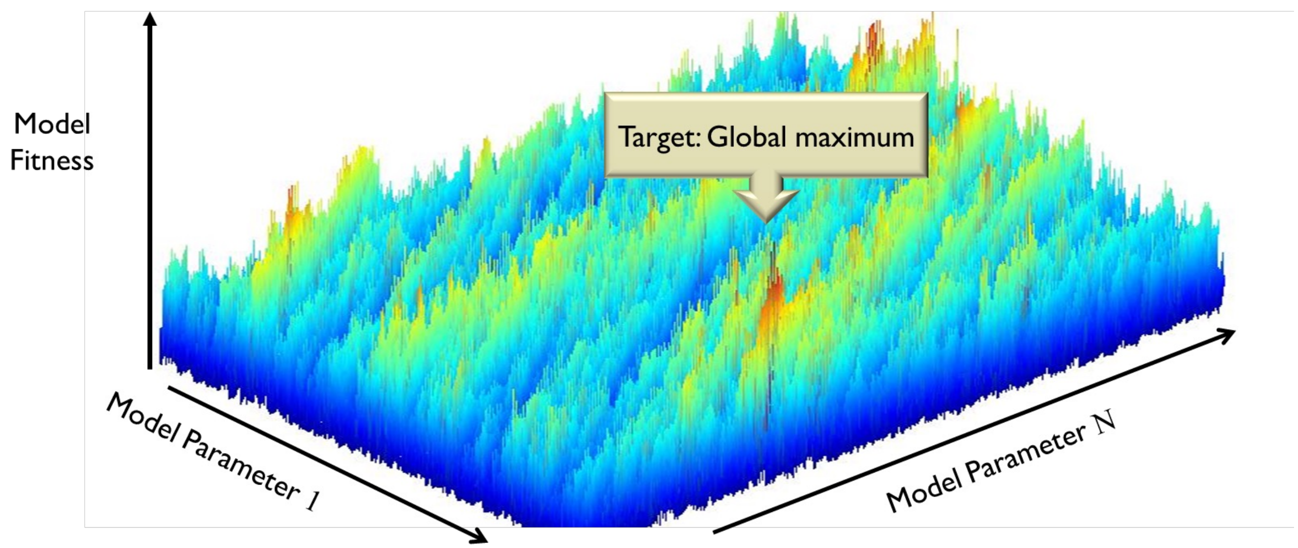
GW DATA ANALYSIS: A FITTING PROBLEM

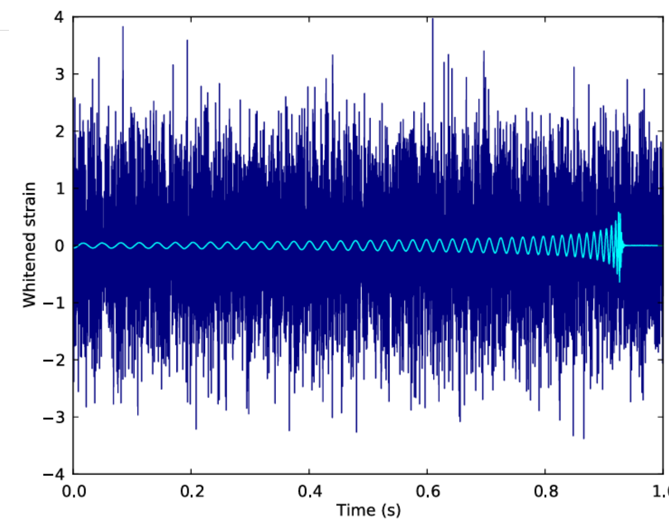




- Large number of grid points needed to locate the maximum reliably
- Search for transient signals: processing must keep pace with incoming data

GW DATA ANALYSIS: A FITTING PROBLEM





- Search for transient signals: processing must keep pace with incoming data
- Multi-messenger astronomy needs fast alerts

COMPUTATIONAL CHALLENGES

- Supercomputing needed
- 1994-1997 PhD problem for SDM: strategy for reducing the number of grid points

BURST SIGNALS: ANOTHER CLASS OF TRANSIENTS

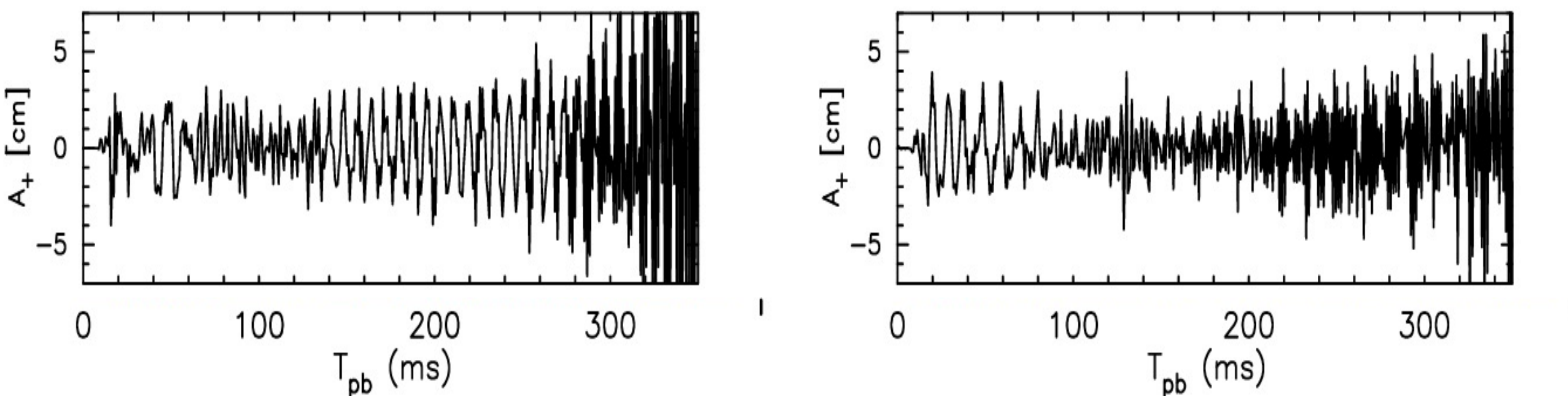
PHYSICAL REVIEW D, VOLUME 60, 121101

Detecting an association between gamma ray and gravitational wave bursts

Lee Samuel Finn* and Soumya D. Mohanty†
Center for Gravitational Physics and Geometry, The Pennsylvania State University, University Park, Pennsylvania 16802

Joseph D. Romano‡
Department of Physical Sciences, The University of Texas, Brownsville, Texas 78520
(Received 30 March 1999; published 29 November 1999)

BURST GRAVITATIONAL WAVE SIGNALS

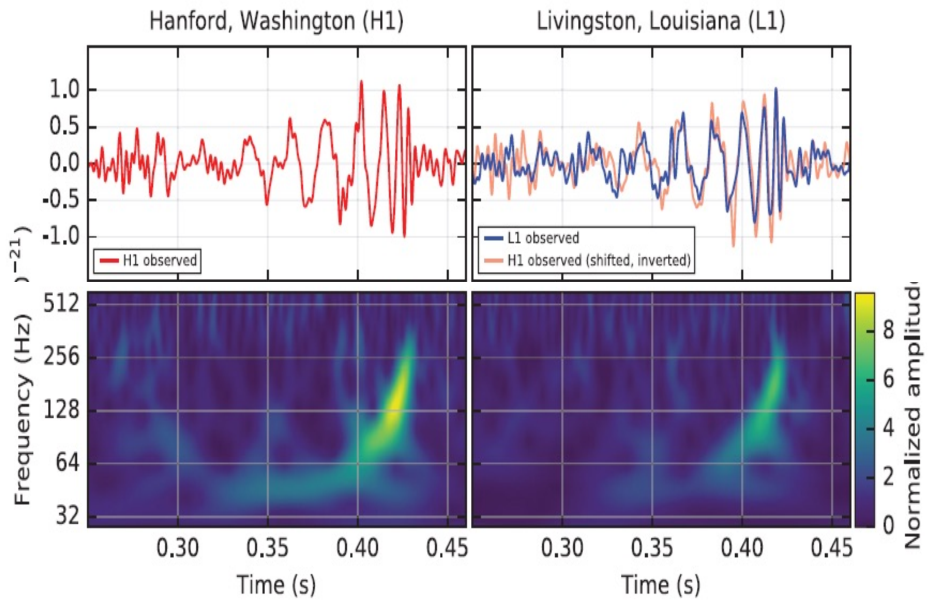


Kuroda et al, ApJL, 2016

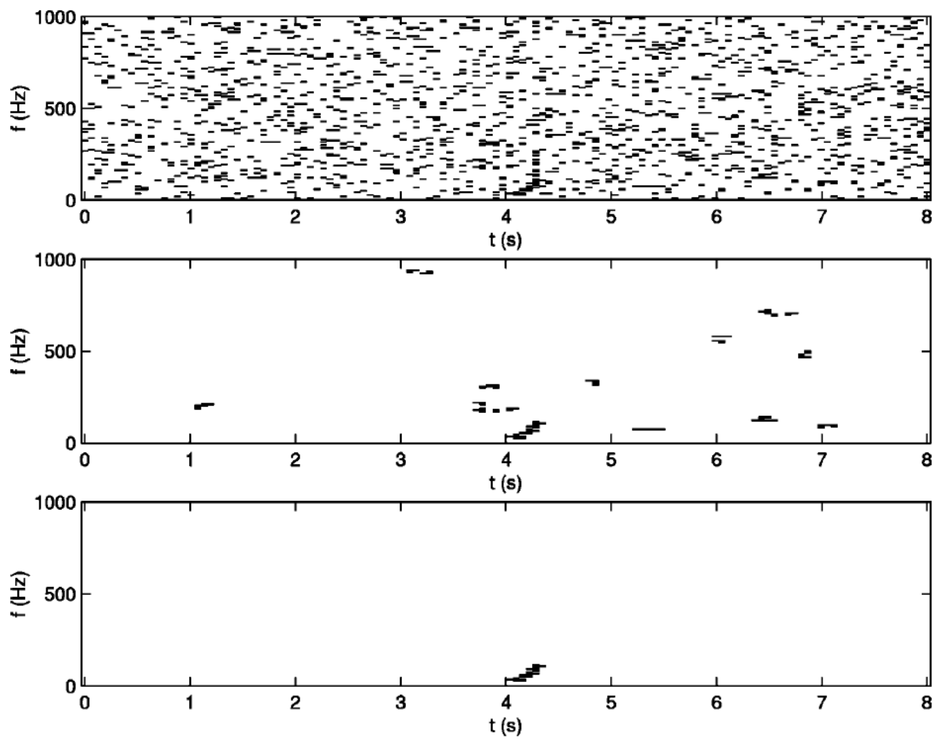
Simulated GW signal from a core-collapse supernova
Nearly stochastic signal: what model should one fit?

BURST SEARCHES (PRE-2003+DISCLAIMER)

- Time-frequency analysis
  - Anderson, Balasubramanian: Wigner-Ville + ridge detection
  - Sylvestre: Time-frequency clustering
  - Chatterjee et al: Q-transform
  - Klimenko et al: Wavelet transform (WaveBurst)
  - Anderson et al: Excess power
- SDM: Change-point detection

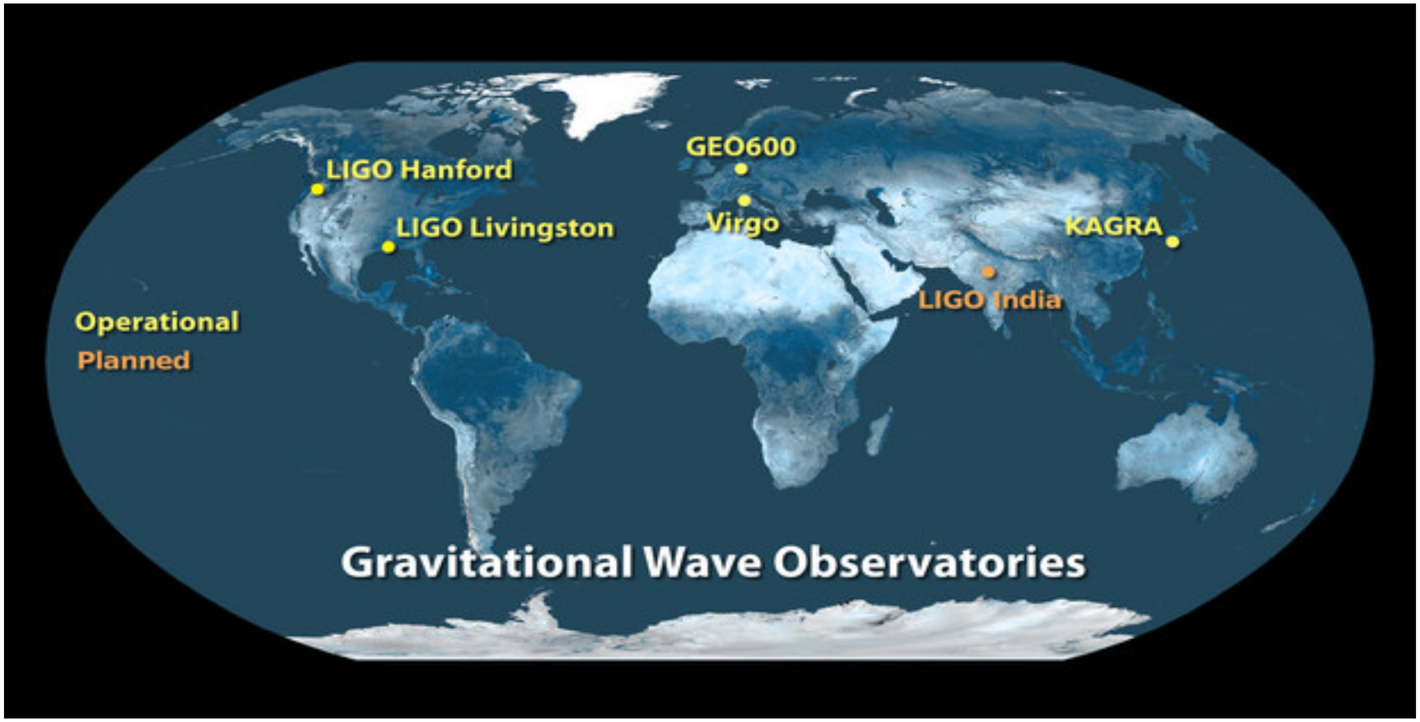


TF CLUSTERING



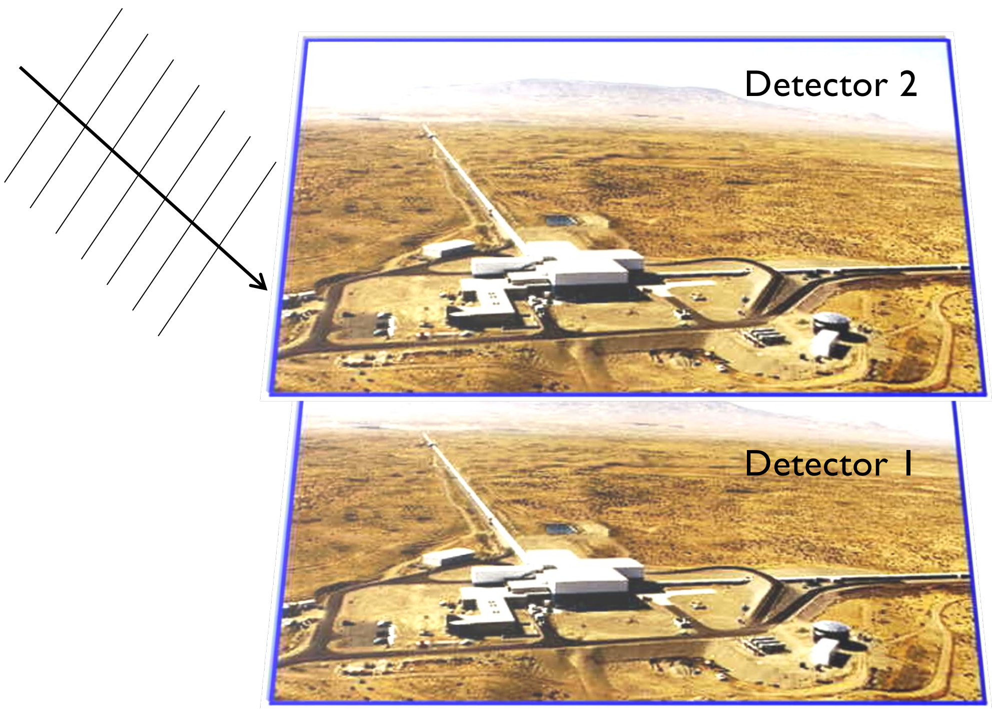
Sylvestre, PHYSICAL REVIEW D **66**, 102004 ~2002!

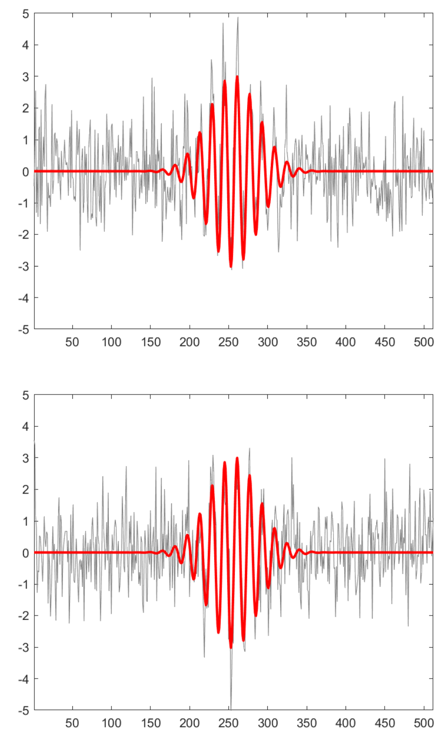
BURST SEARCH: GW DETECTOR NETWORK



- GW Detector network essential for localizing a GW source on the sky
- Guersel and Tinto, PRD, 1989: Null stream method for networks of 3+ detectors

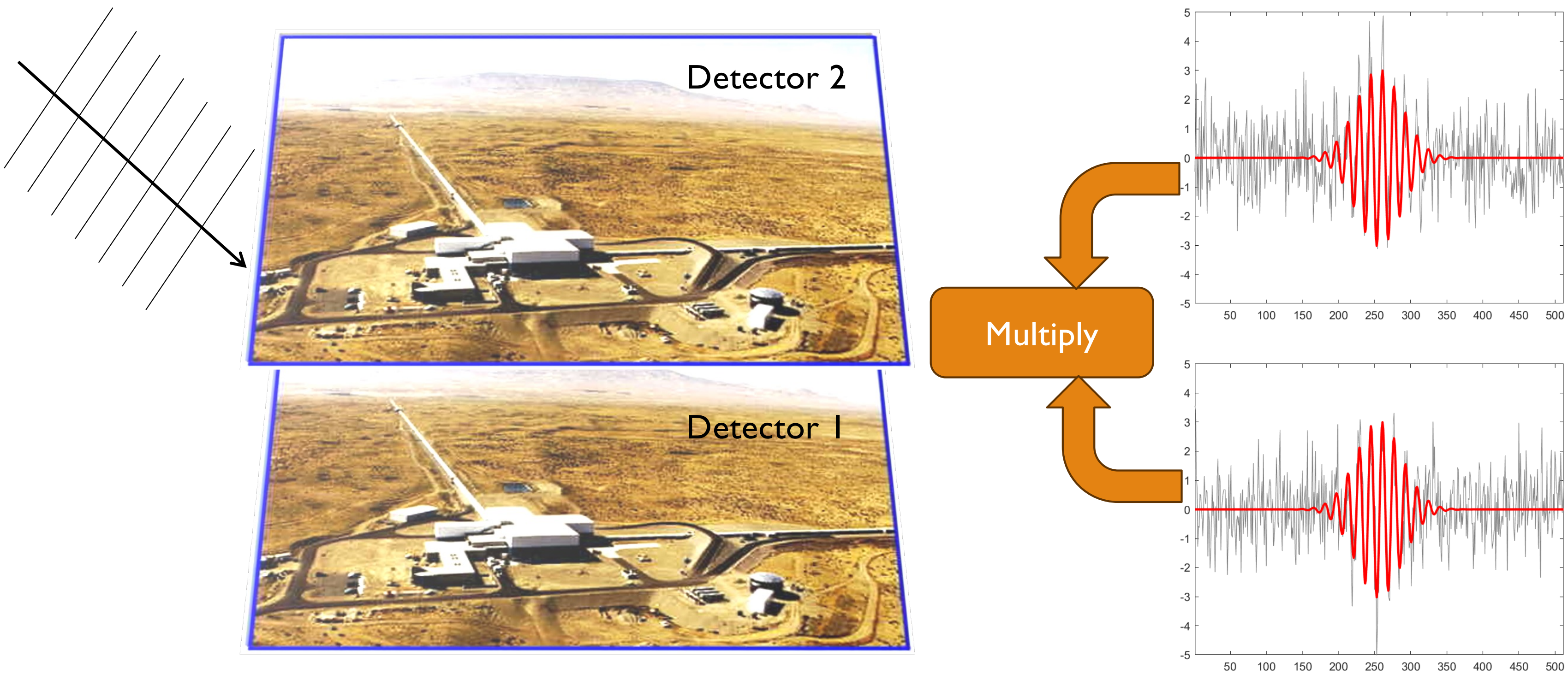
MULTIPLE DETECTORS: CROSS-CORRELATION



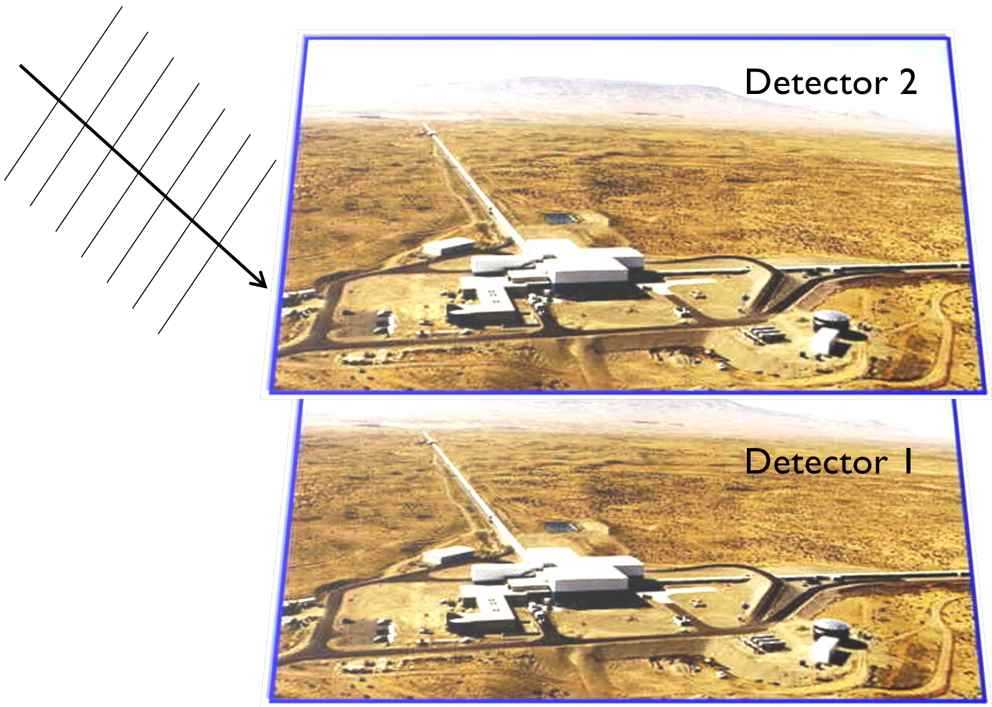


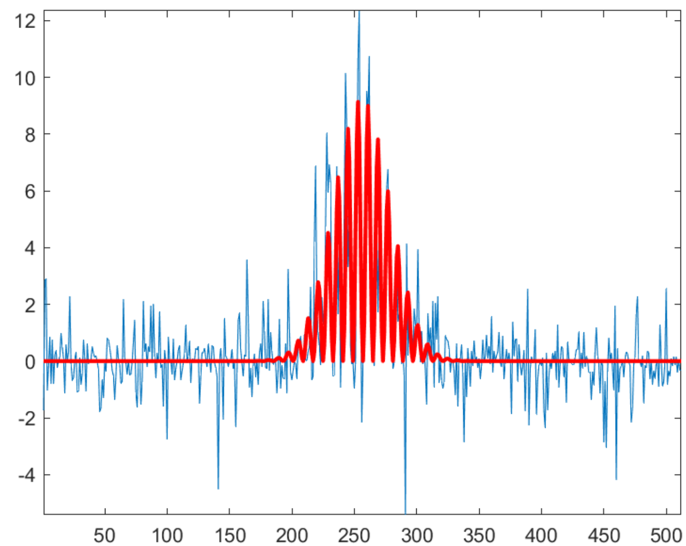
Identical signals but different noise

IDENTICAL DETECTORS: CROSS-CORRELATION



IDENTICAL DETECTORS: CROSS-CORRELATION





BURST SEARCHES: LEAST SQUARES FRAMEWORK

- Treat each sample of the GW signal as an independent parameter in least squares
- **Cross-correlation appears naturally**
- Flanagan, Hughes, PRD, 1998 (Part 1 and 2)
- Appendix, part 2: Focus on Estimation
- Derived independently in:

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY
Class. Quantum Grav. **21** (2004) S1831–S1837 PII: S0264-9381(04)79347-8

Search algorithm for a gravitational wave signal in association with gamma ray burst GRB030329 using the LIGO detectors

S D Mohanty[1], Sz Márka[2], R Rahkola[3], S Mukherjee[1], I Leonor[3], R Frey[3], J Cannizzo[4] and J Camp[4]

POST-UTB: TWO-DETECTOR PARADOX

- William R. Johnston (M.S.) assigned the "simple" task of extending the formalism to a network of misaligned detectors
- Two-detector paradox: the cross-correlation term vanishes for even an **infinitesimal** misalignment!
- The problem arises because the "parameters" are unconstrained: the GW signals in a pair of misaligned detectors can be arbitrary and not identical
- The least squares solution must be constrained: **Regularization**

SOLVING THE TWO-DETECTOR PARADOX

PHYSICAL REVIEW D **72,** 122002 (2005)

Constraint likelihood analysis for a network of gravitational wave detectors

S. Klimenko,[1] S. Mohanty,[2] M. Rakhmanov,[1] and G. Mitselmakher[1]

PHYSICAL REVIEW D **72,** 122002 (2005)

[21] Wm. R. Johnston, Master's thesis, The University of Texas at Brownsville, 2004.

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **23** (2006) 4799–4809 doi:10.1088/0264-9381/23/15/001

Variability of signal-to-noise ratio and the network analysis of gravitational wave burst signals

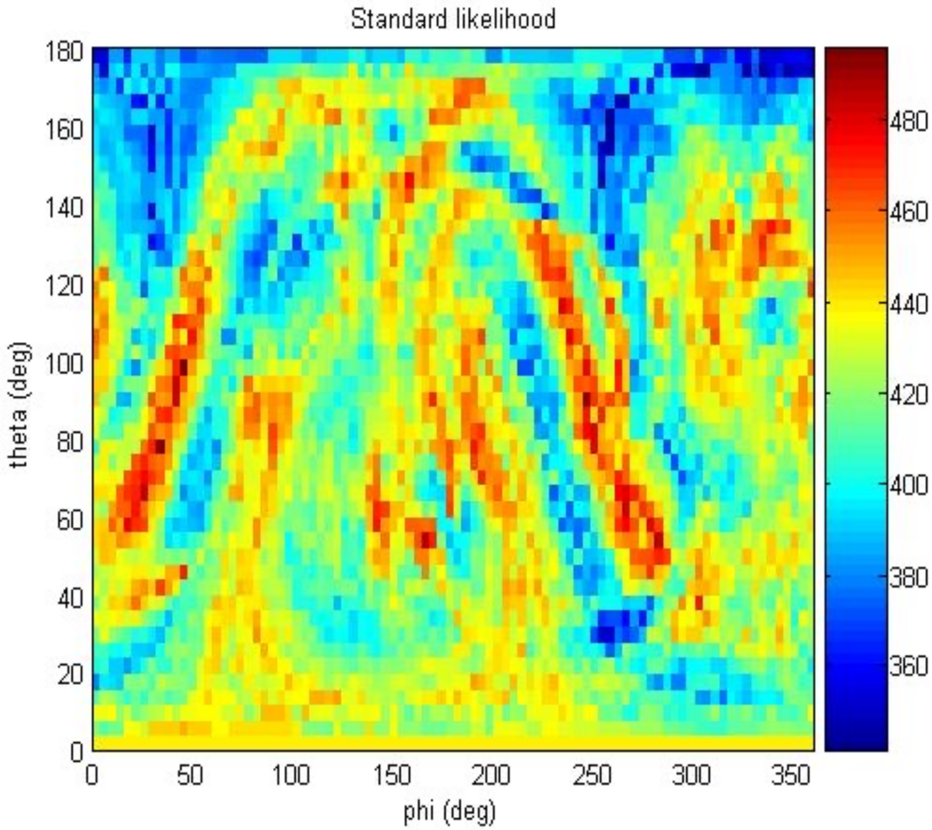
S D Mohanty[1], M Rakhmanov[2], S Klimenko[3] and G Mitselmakher[3]

Rank deficiency and Tikhonov regularization in the inverse problem for gravitational-wave bursts

To cite this article: M Rakhmanov 2006 *Class. Quantum Grav.* **23** S673

REGULARIZATION: SIGNIFICANT EFFECT

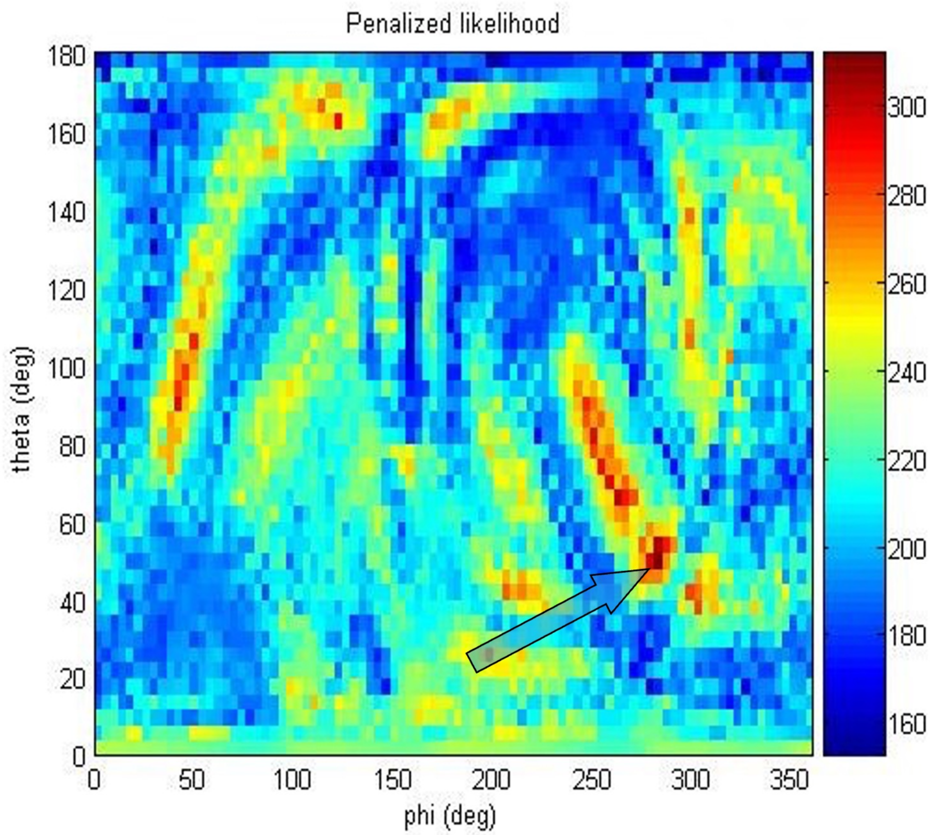
Constraints OFF



L1, H1, GEO network

REGULARIZATION: SIGNIFICANT EFFECT

Constraints ON



L1, H1, GEO network

COHERENT WAVEBURST

- Regularized network analysis + WaveBurst: **Coherent** WaveBurst (CWb)
- Current flagship LVK pipeline for burst searches
- First pipeline to see GW150914

PHYSICAL REVIEW D **93,** 122004 (2016)

Observing gravitational-wave transient GW150914 with minimal assumptions

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

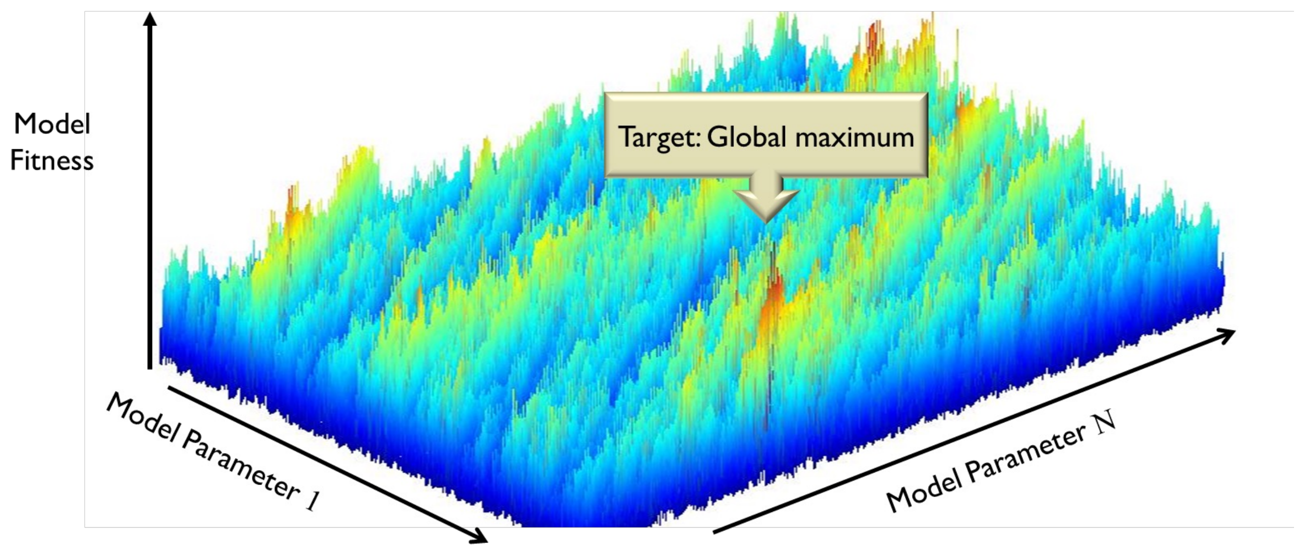
(Received 25 February 2016; published 7 June 2016; corrected 20 September 2016)

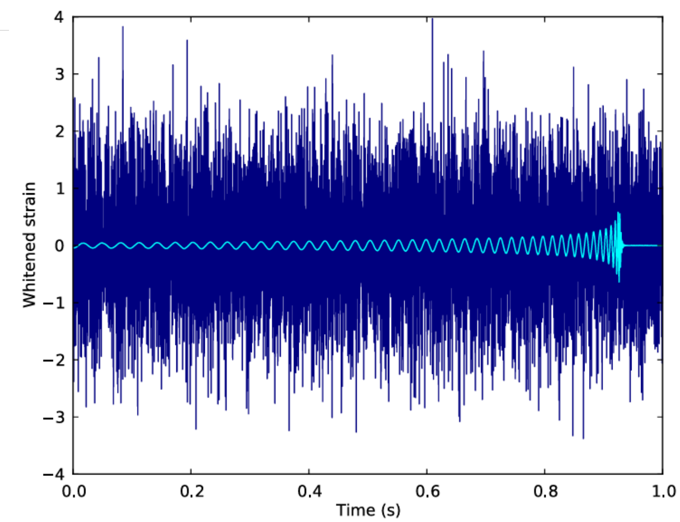
On September 14, 2015, an online burst search [25] reported a transient that clearly stood above the expected background from detector noise [26]. The alert came only 3 min after the event's time stamp of 09:50:45UTC. A second online burst search independently identified the event with a latency of a few hours, providing a rapid confirmation of the signal [23]. The initial waveform

- Research at UTB integral to CWb

[35] S. Klimenko, S. Mohanty, M. Rakhmanov, and G. Mitselmakher, Constraint likelihood analysis for a network of gravitational wave detectors, Phys. Rev. D **72**, 122002 (2005).

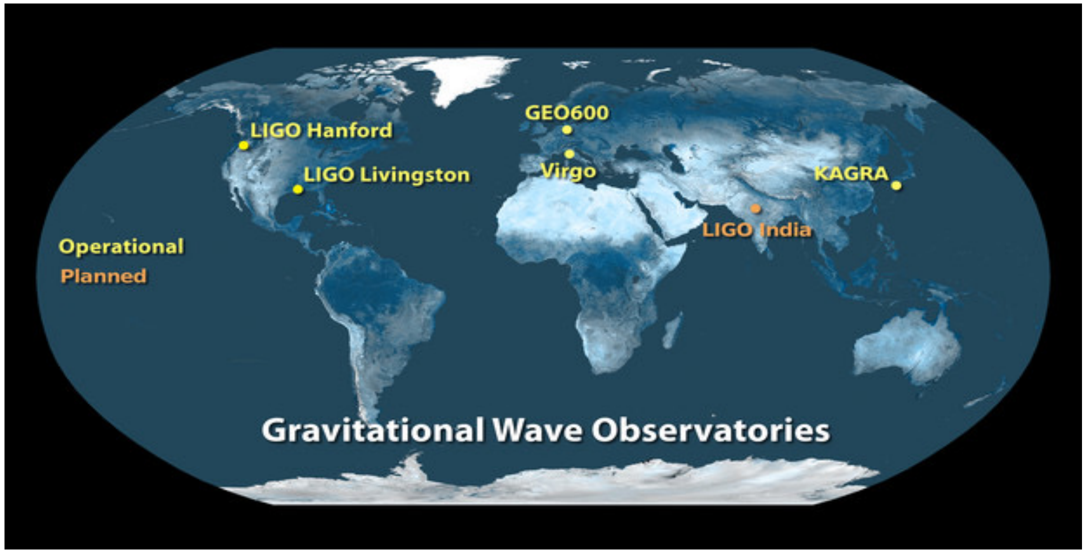
GW DATA ANALYSIS: A FITTING PROBLEM

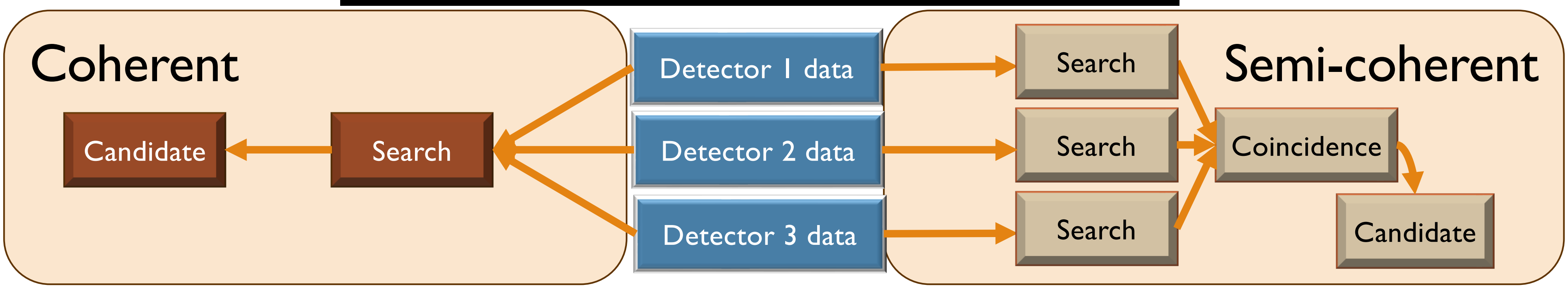




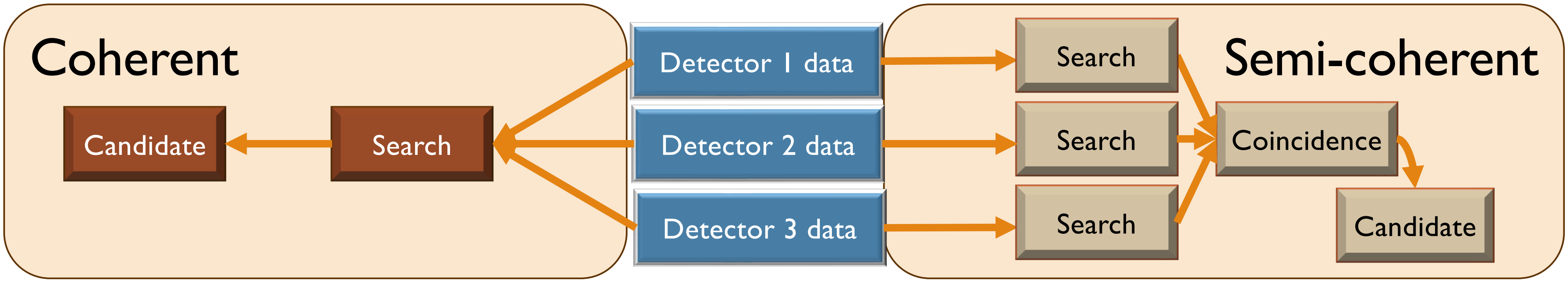
- Search for transient signals: processing must keep pace with incoming data
- Multi-messenger astronomy needs fast alerts
- **Computational efficiency is of critical importance in GW data analysis**

FULLY-COHERENT ALL-SKY SEARCH





FULLY-COHERENT ALL-SKY SEARCH



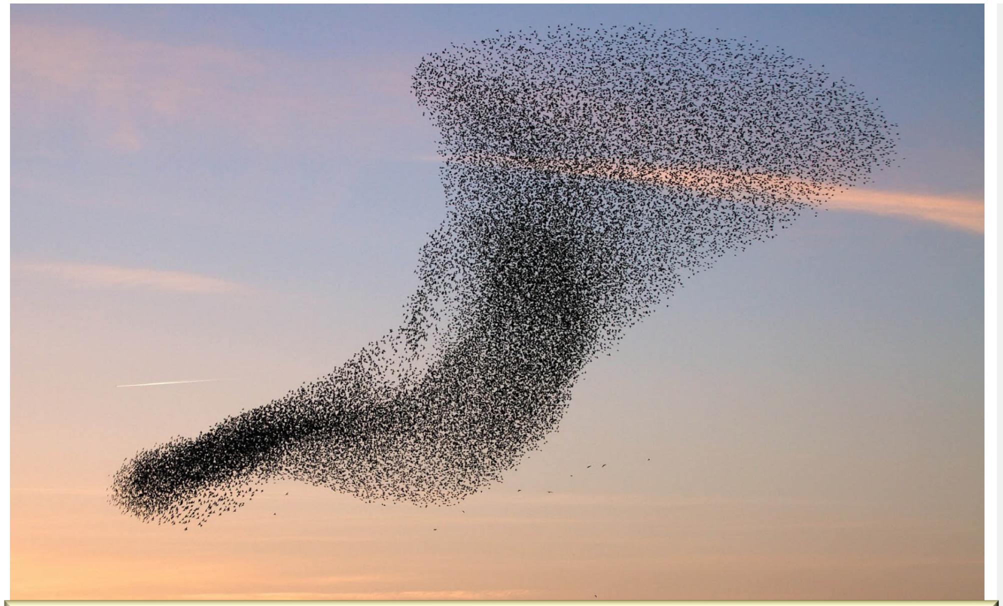
Coherent search

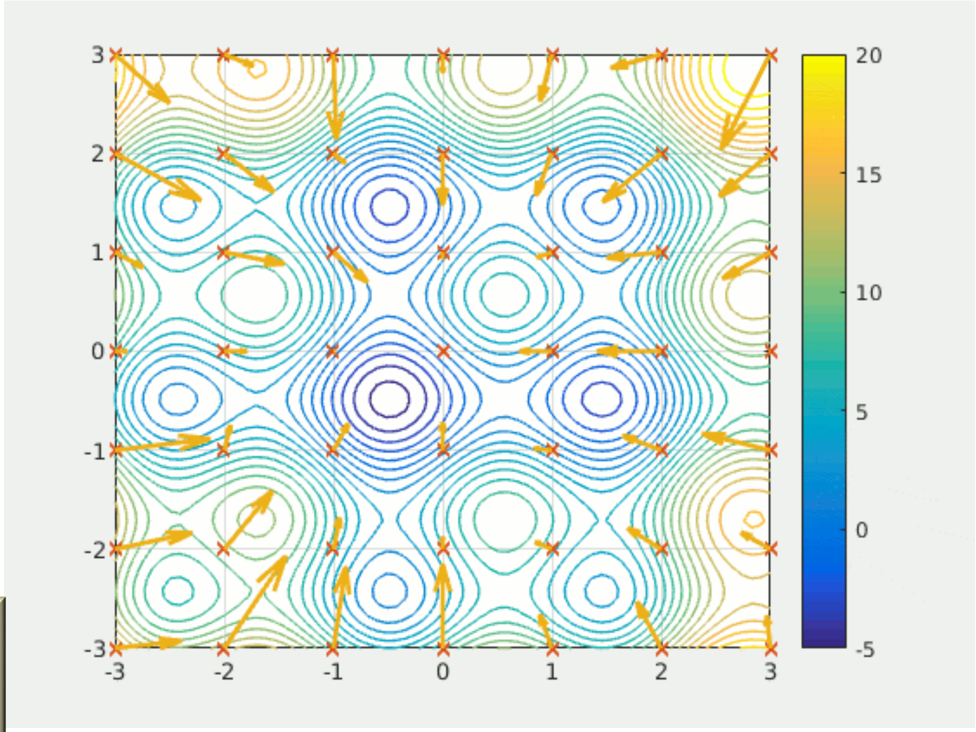
- Multiple data, single model fit
- Binary merger: ≥4D parameter space
  - Direct grid-based optimization: **2000X** semi-coherent grid size
- Not implemented on all GW data

Semi-coherent search

- Multiple data, multiple model fits
- Binary merger: ≥2D parameter space
- All current searches are semi-coherent
- Incurs a **25% drop** in sensitive volume
- MacLeod et al, Physical Review D, 2016

PARTICLE SWARM OPTIMIZATION





- Multi-agent optimization algorithm
- Agents explore independently but also communicate
- **Agent fitness evaluations are parallelizable**

BINARIES PIPELINE

BINARY INSPIRAL NETWORK ANALYSIS RAPID IMPLEMENTATION ENABLED BY SWARM-INTELLIGENCE

Global Optimization acceleration

- Stochastic optimization
- **Particle Swarm Optimization** (PSO)

GPU acceleration

- Implemented on UTRGV GPU Cluster
- 64 NVIDIA A100

Foundational papers used TACC

- Weerathunga, Mohanty, Physical Review D, 2017
- Normandin, Mohanty, Weerathunga, PRD, 2018
- Normandin, Mohanty, PRD, 2020

UTRGV GPU Cluster (CRADLE)

96 A100, 12 A30, 12 L40s

BINARIES PIPELINE PERFORMANCE

≈50x faster than real-time

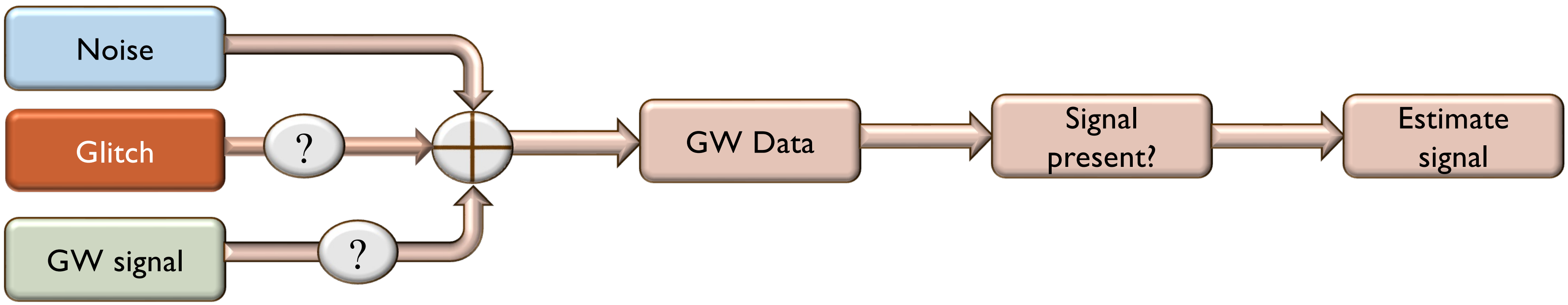
- Data from all four operational detectors

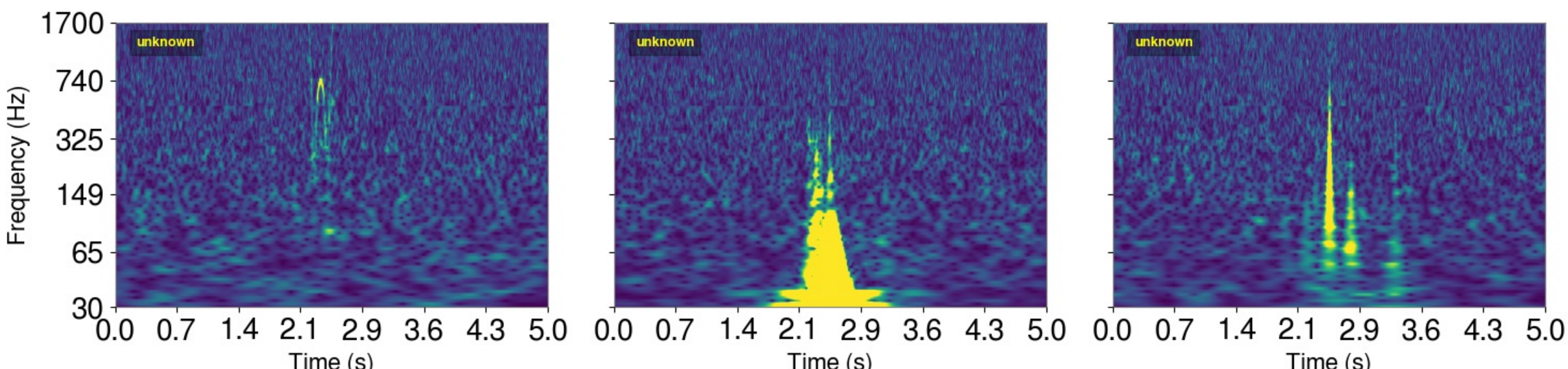
⇒Low latency

From signal termination to recording detection

- ≈ 5 sec for double neutron star searches
- ≈ half of median semi-coherent search latencies

THE CHALLENGE OF GLITCHES





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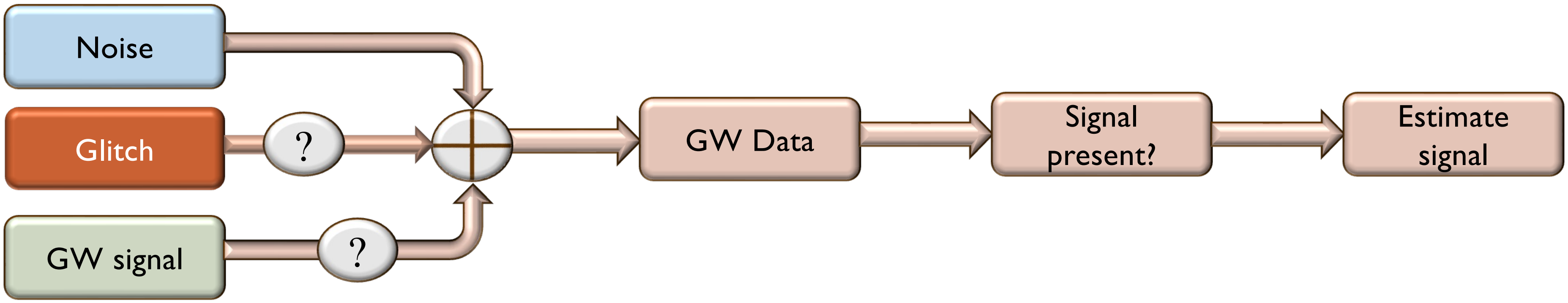

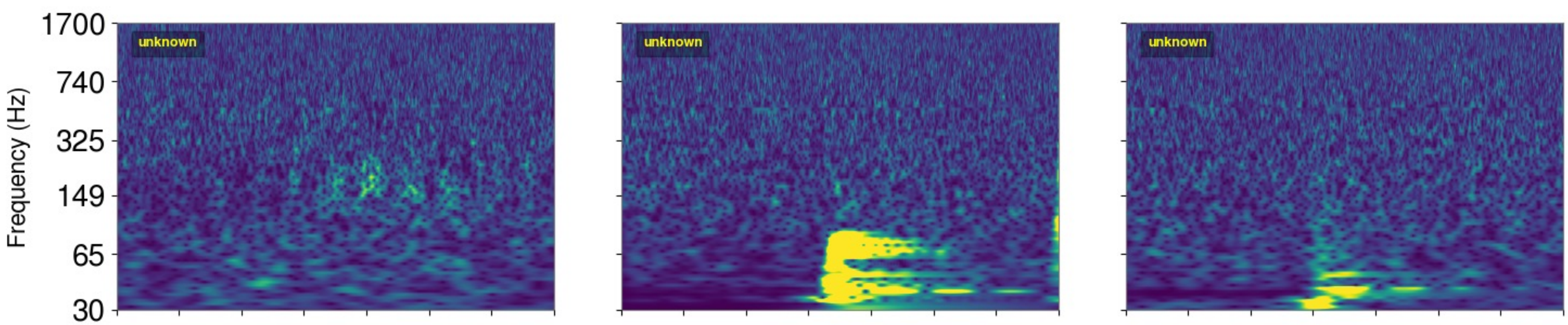

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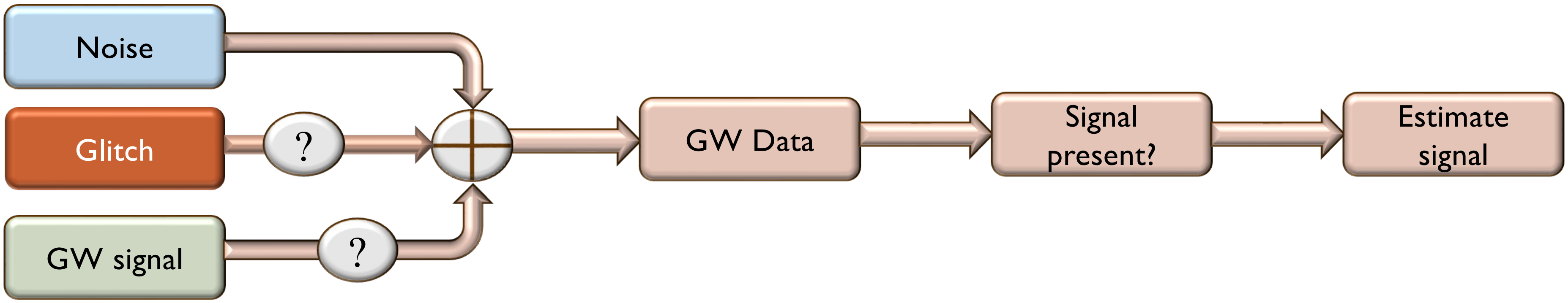

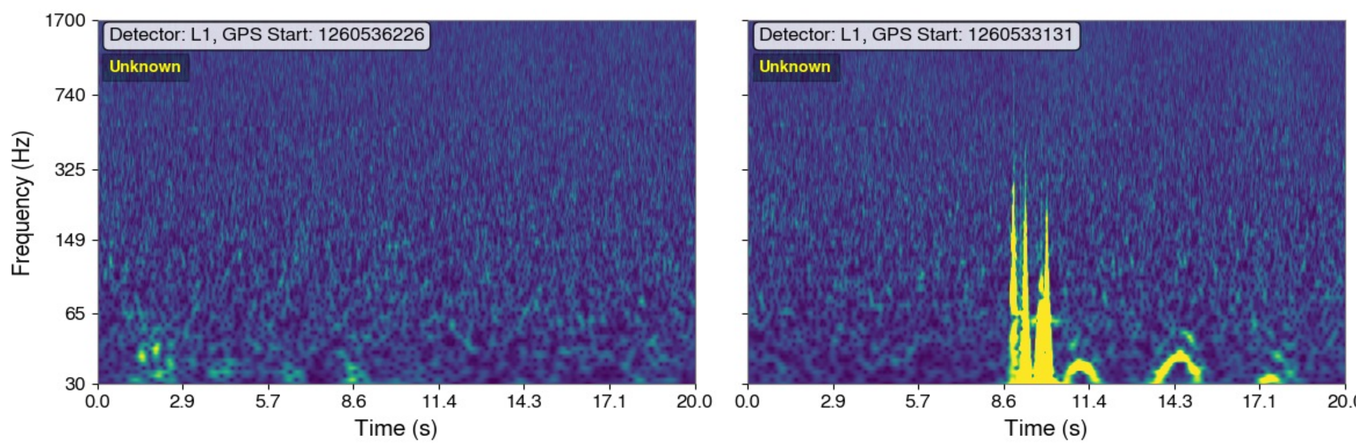

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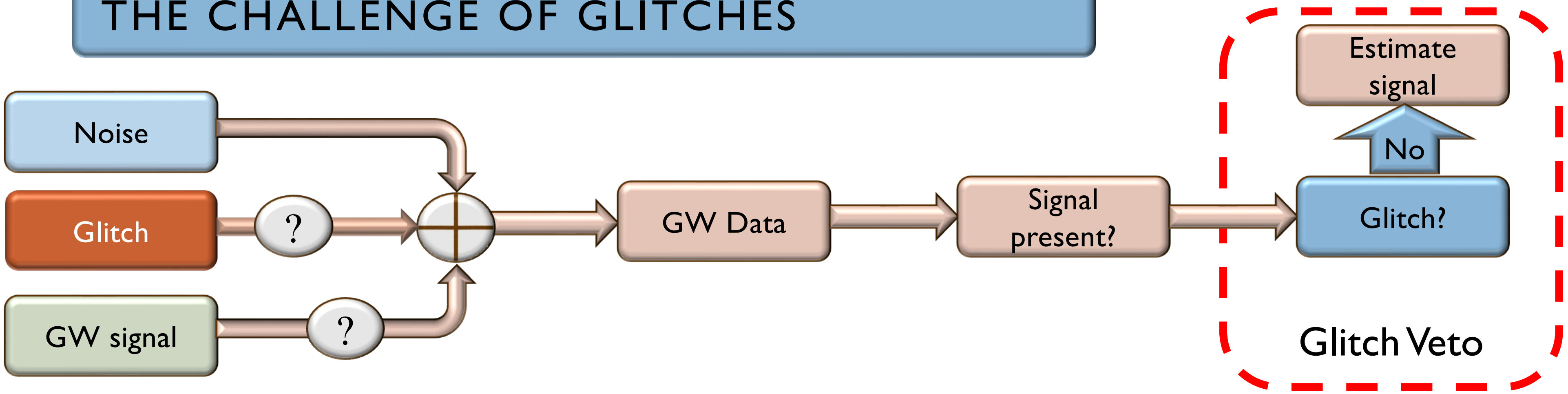
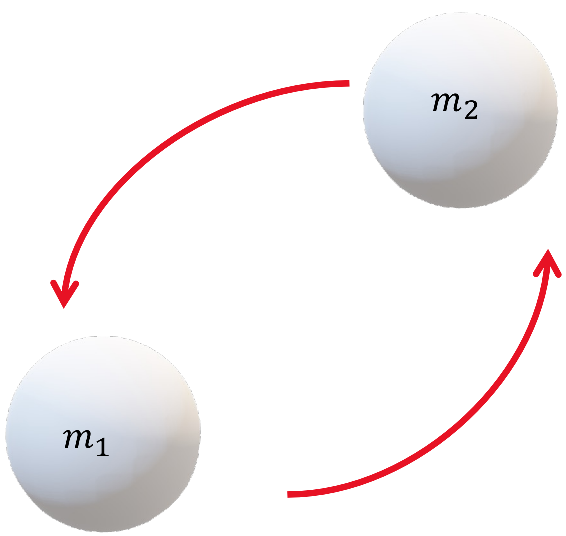
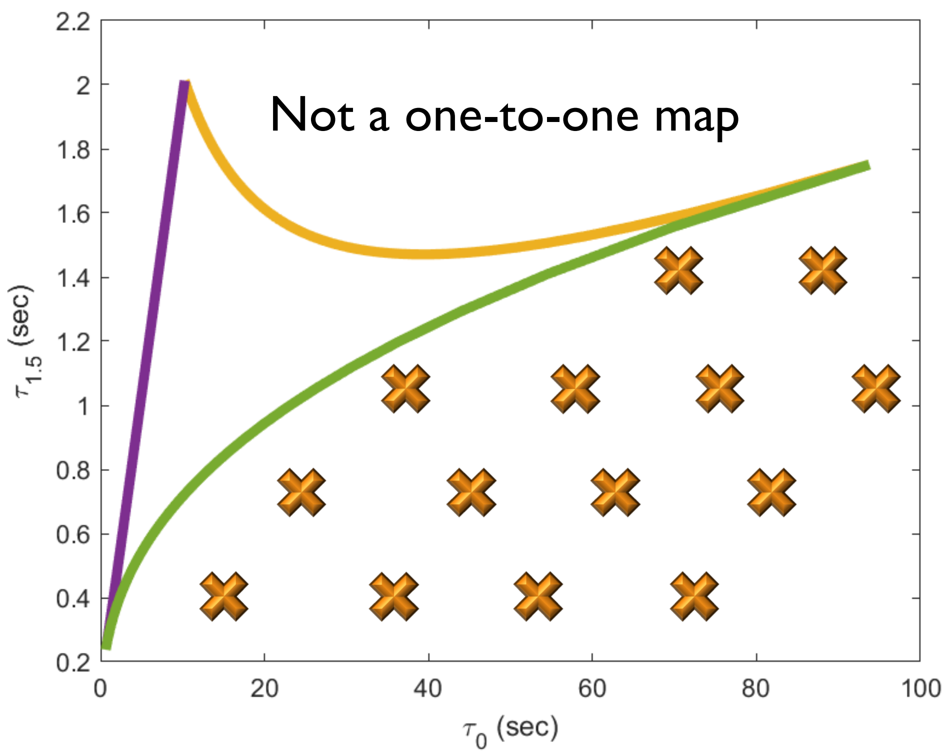


GRITCLEAN VETO

GLITCH REJECTION USING ILLEGAL TEMPLATES AND CROSS-LINKING OF EVENT ATTRIBUTE NUMBERS



$$(m_1, m_2) \rightarrow (\tau_0, \tau_{1.5})$$



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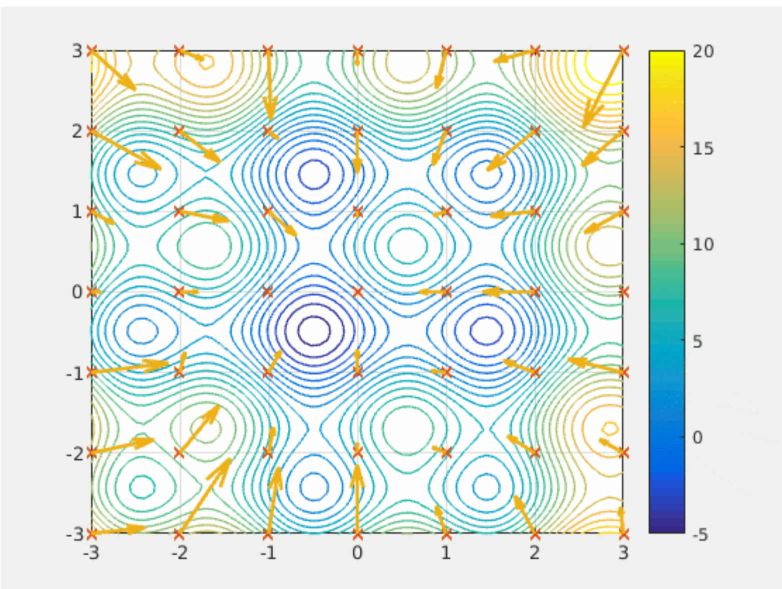

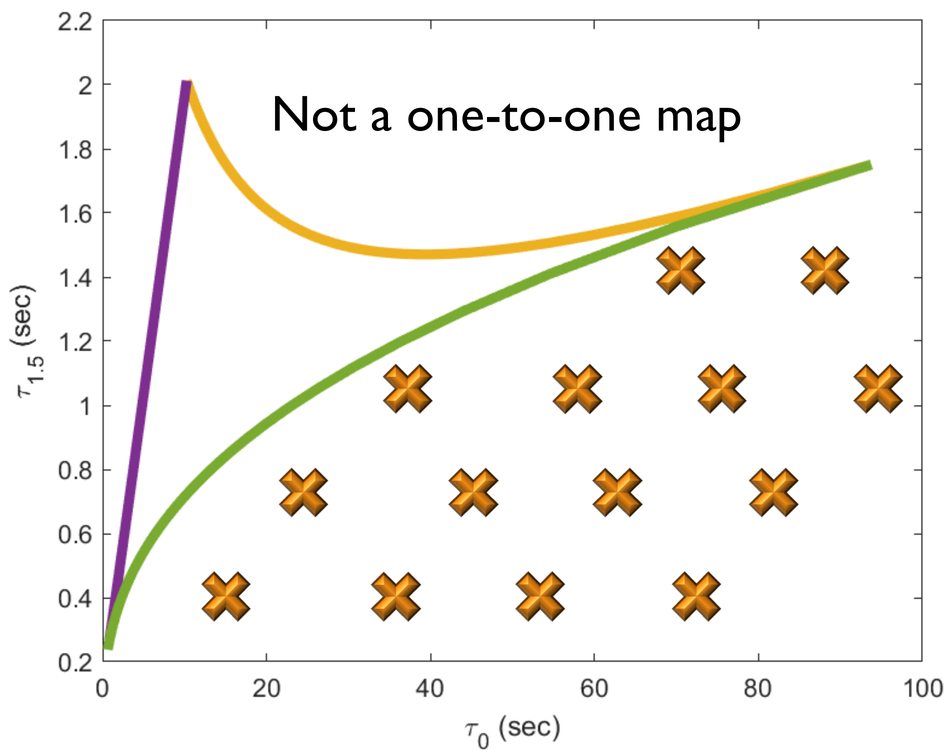

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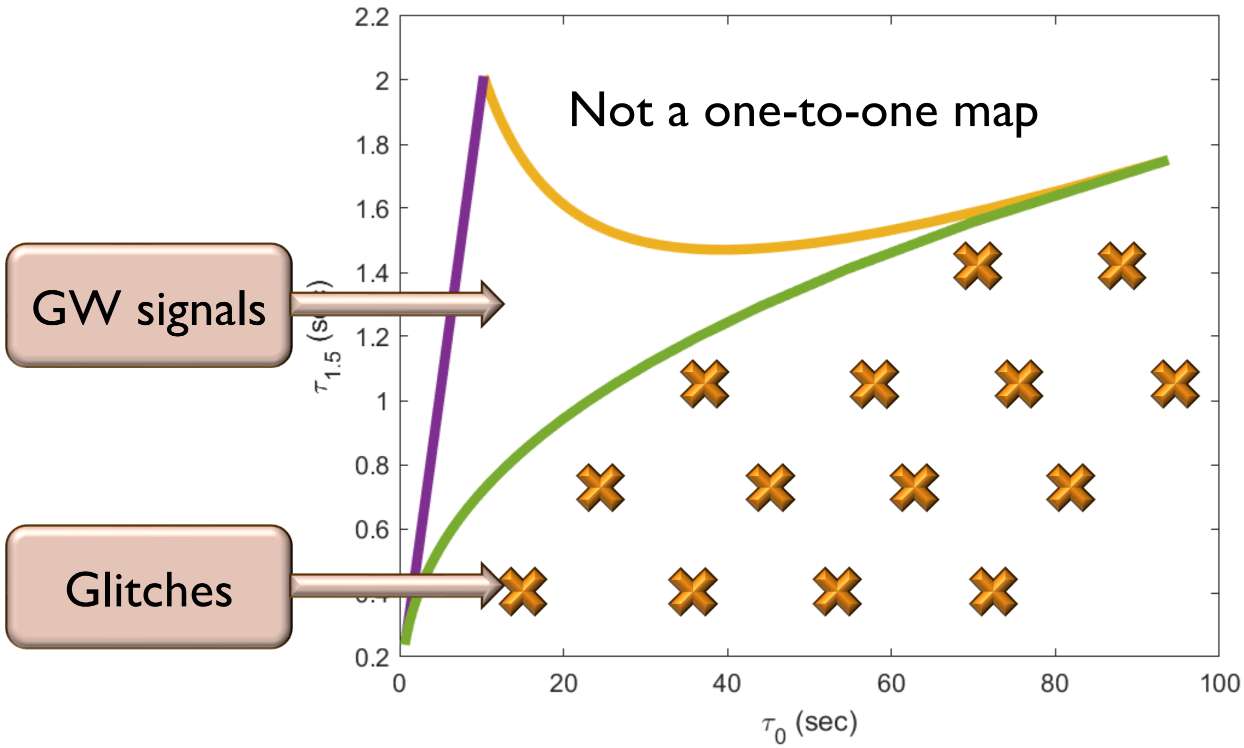

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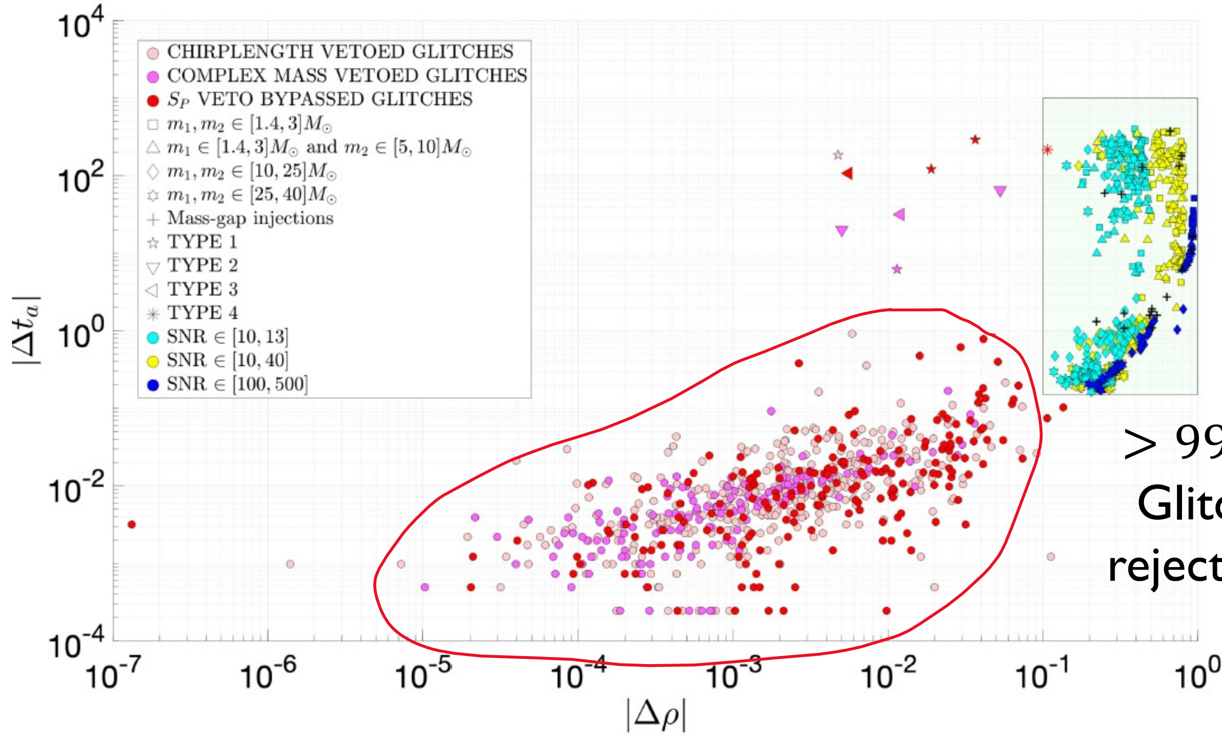
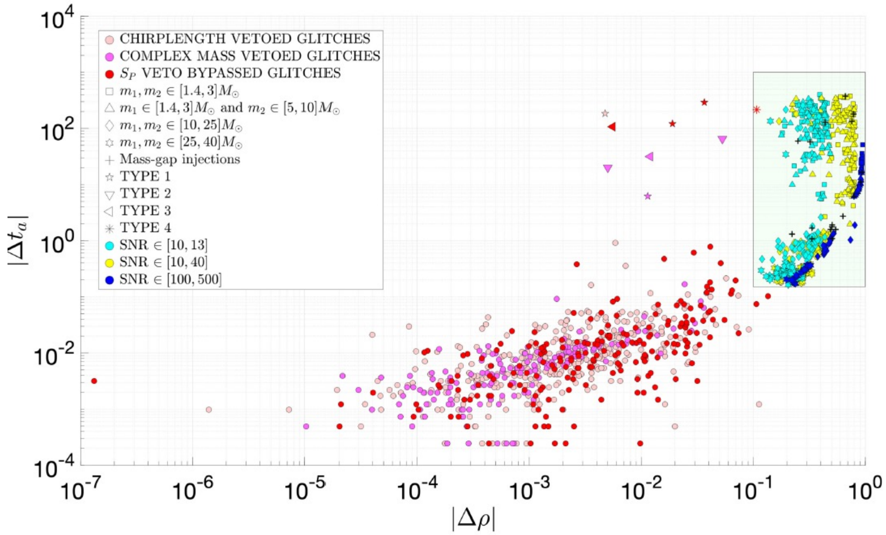


$> 99\%$ Glitch rejection

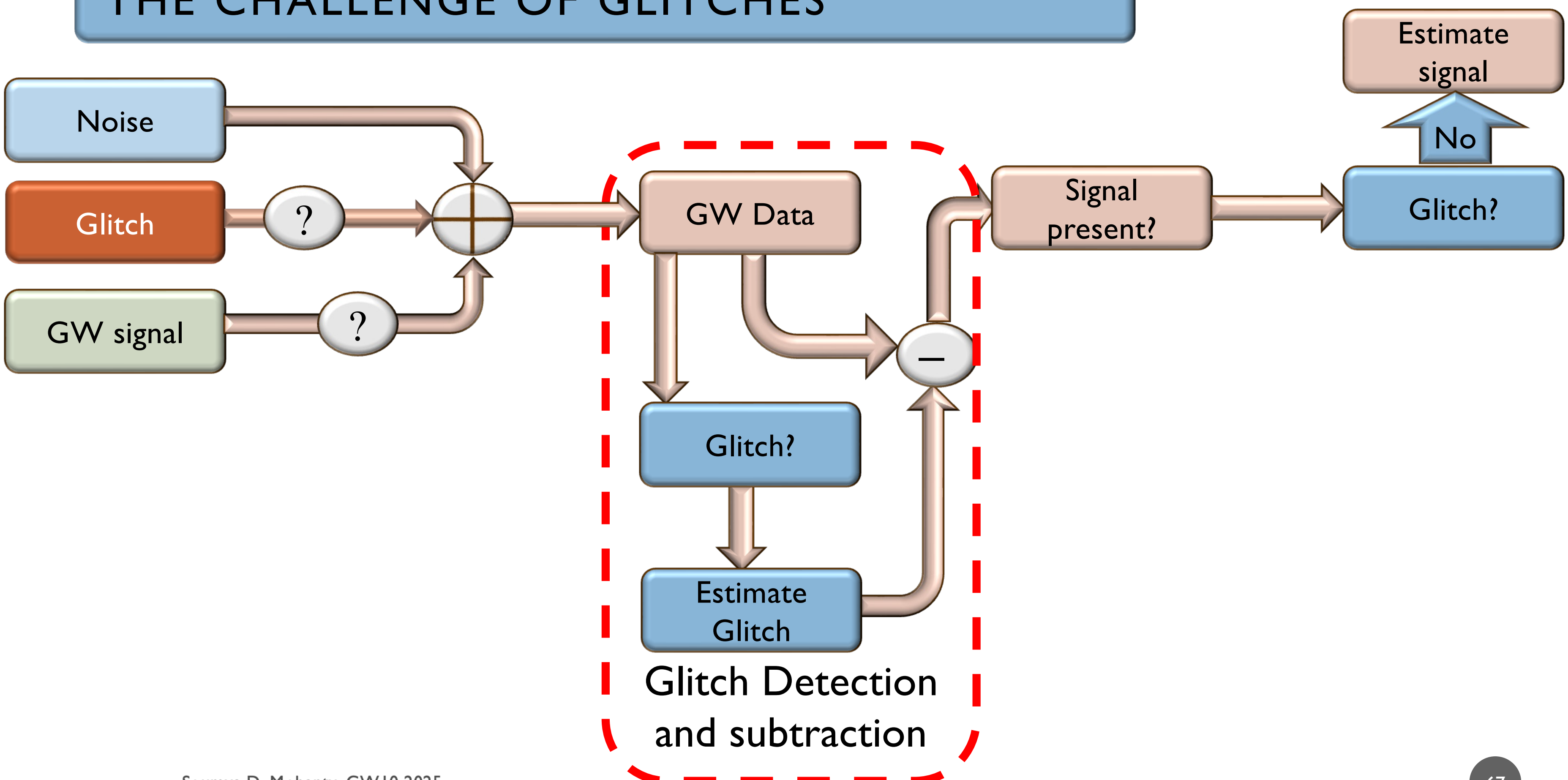
GRITCLEAN VETO

GLITCH REJECTION USING ILLEGAL TEMPLATES AND CROSS-LINKING OF EVENT ATTRIBUTE NUMBERS



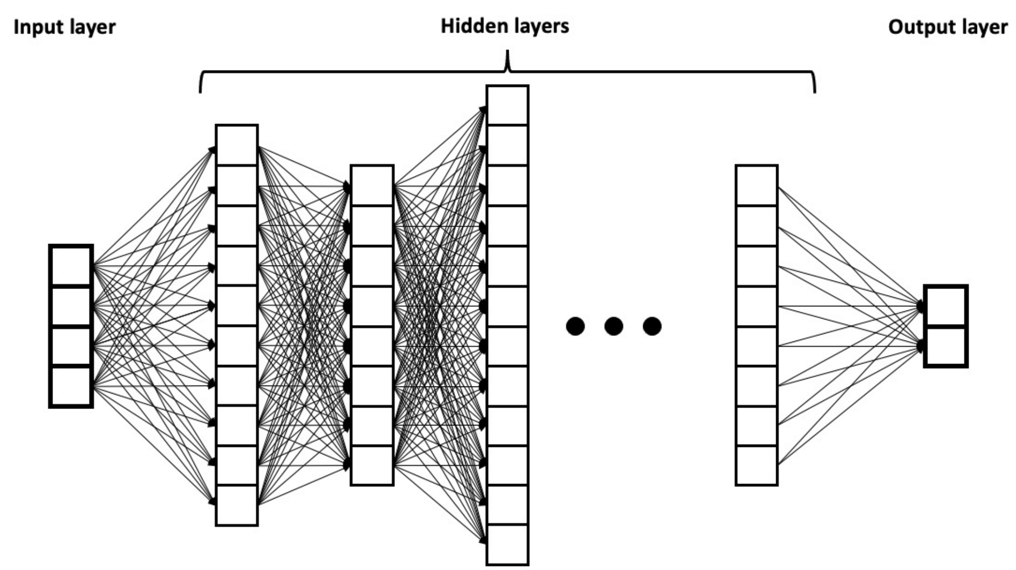
- R. Girgaonkar: Platform talk, TACCSTER'23
- Girgaonkar, Mohanty, PHYS. REV. D 110, 023037 (2024)

THE CHALLENGE OF GLITCHES



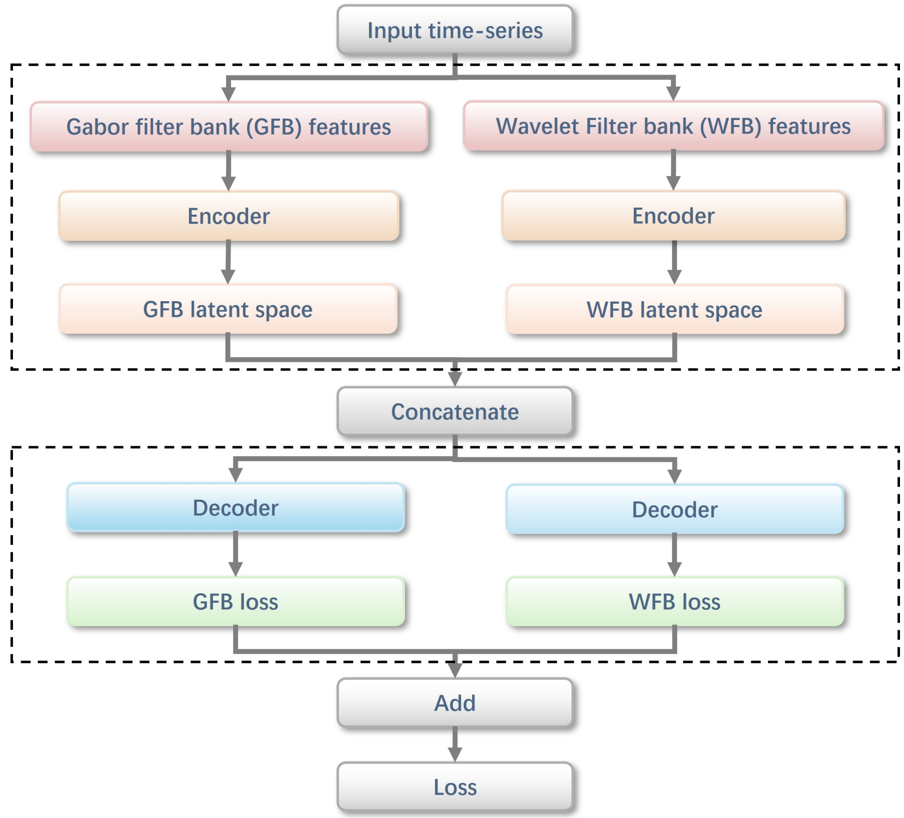
AI MODELS FOR GLITCH DETECTION

- Diversity of glitch waveforms and timescales: Challenge for traditional ML
- **Deep Learning using ANNs**: An active research area in GW data analysis



ABNORMAL: SEMI-SUPERVISED GLITCH DETECTOR
AI BASED NONSTATIONARITY OBSERVER FOR RESECTIONING AND MARKING ANOMALIES

- Autoencoder architecture: Model learns to reconstruct its input
- Anomaly detection: out-of-distribution data → poor reconstruction (high loss)
- ABNORMAL is trained exclusively on Normal data (noise)
- Guo et al, arXiv:2508.19772



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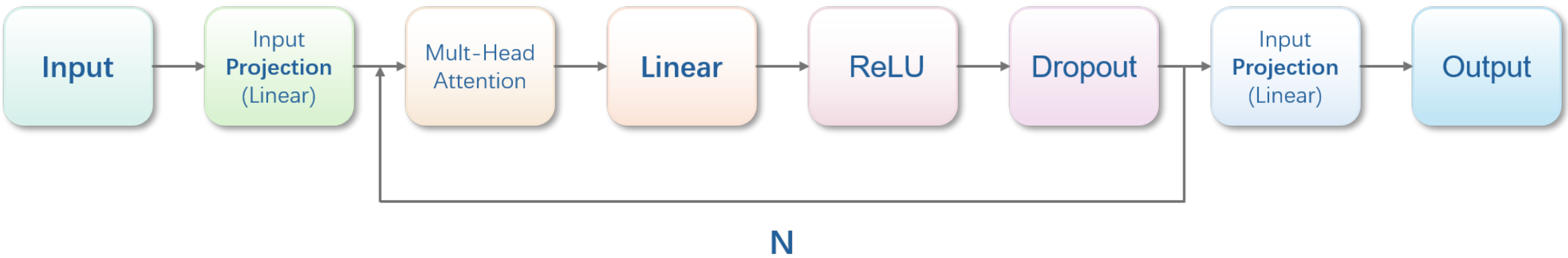
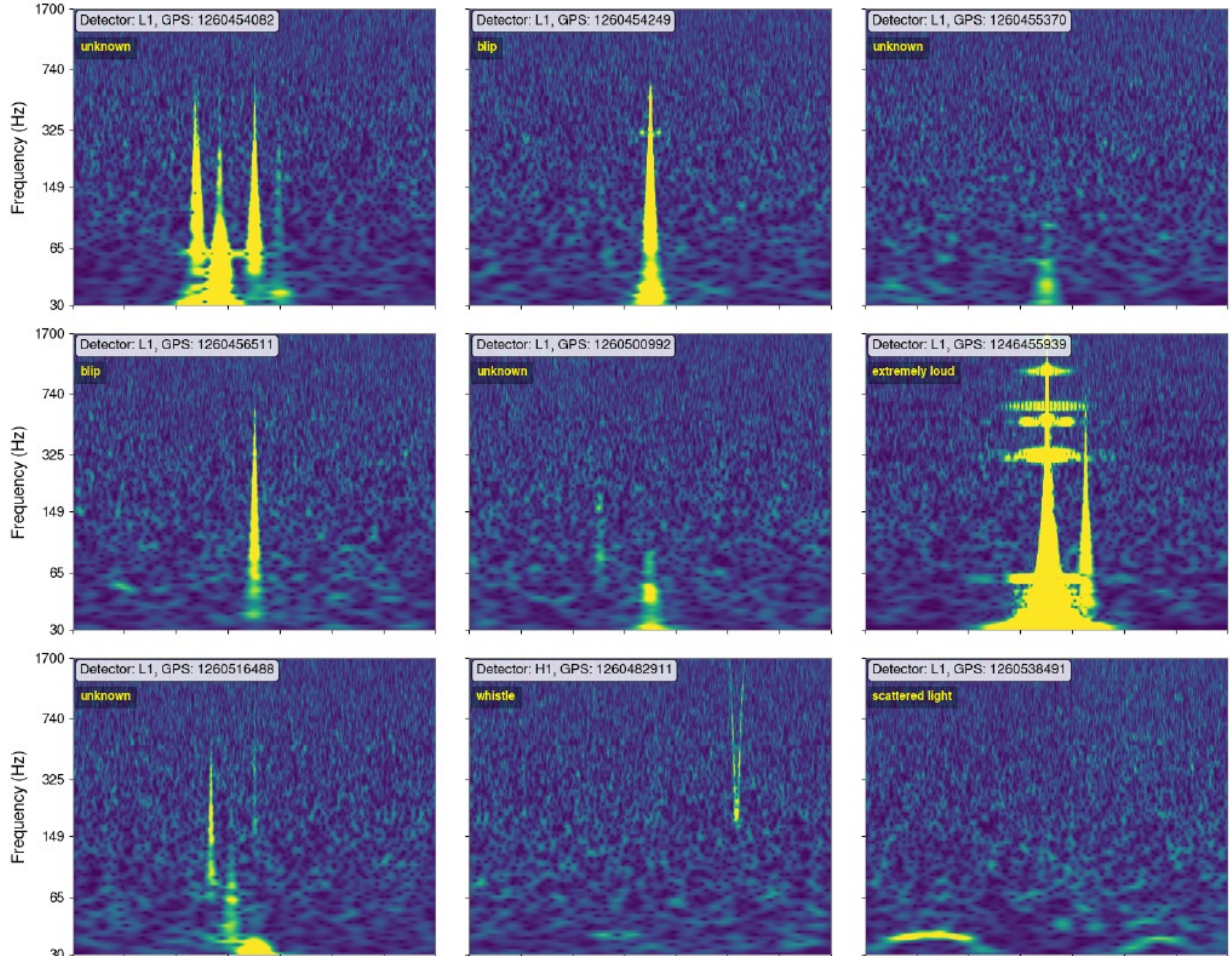


- Encoder/decoders based on Transformer architecture
  - Chat Generative Pre-trained Transformer (GPT)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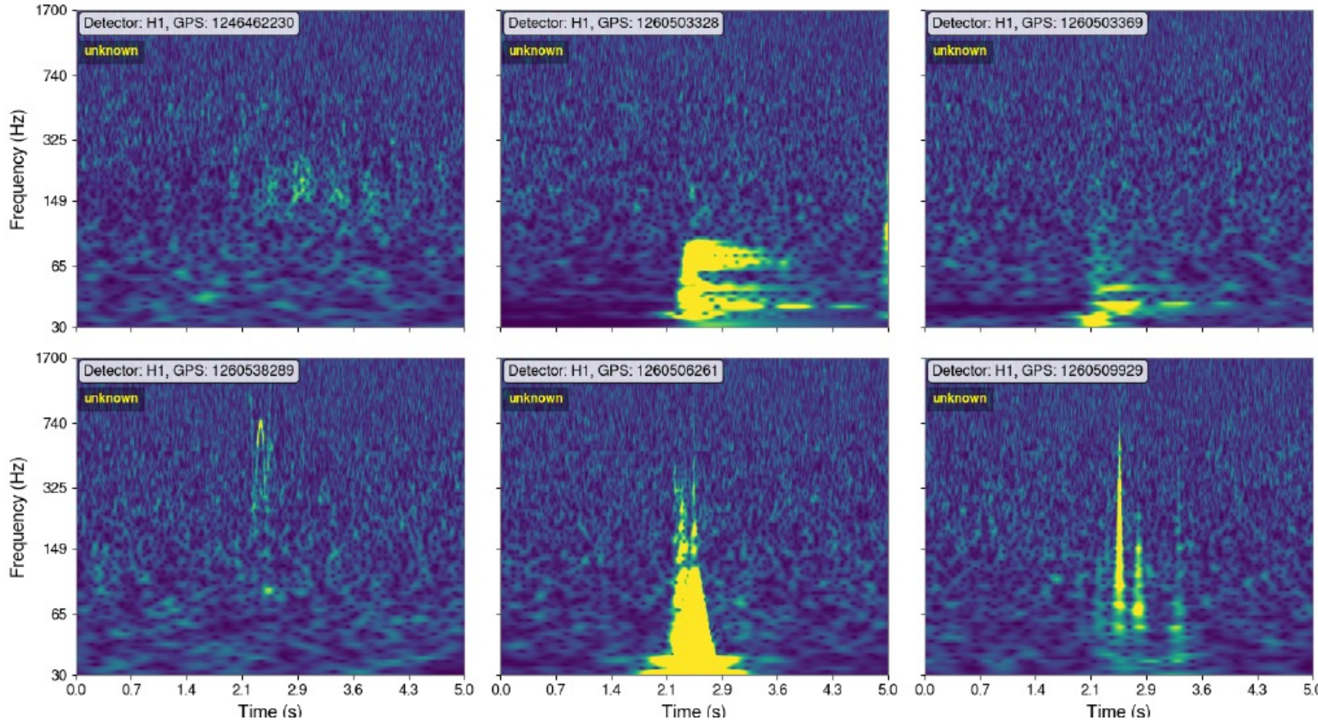
unknown
Detector: L1, GPS: 1260454249
blip
Detector: L1, GPS: 1260455370
unknown
Detector: L1, GPS: 1260456511
blip
Detector: L1, GPS: 1260500992
unknown
Detector: L1, GPS: 1246455939
extremely loud
Detector: L1, GPS: 1260516488
unknown
Detector: H1, GPS: 1260482911
whistle
Detector: L1, GPS: 1260538491
scattered light
Frequency (Hz)
1700
740
325
149
65
30



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Detector: H1, GPS: 1260503369
unknown
Detector: H1, GPS: 1260538289
unknown
Detector: H1, GPS: 1260506261
unknown
Detector: H1, GPS: 1260509929
unknown
Frequency (Hz)
1700
740
325
149
65
30
Time (s)
0.0
0.7
1.4
2.1
2.9
3.6
4.3
5.0

SUMMARY

- GW Astronomy depends critically on advances in data analysis
- Future detectors (ground, space, PTA) will only have more challenging problems
  - Resolving overlapping GW signals, resolving signals from glitches, Computational cost, …
- Covered only selected challenges for ground-based interferometer data
- GW data analysis imparts skills to students: HPC, Statistics, Machine learning, AI
  - Marc Normandin, PhD: Senior scientist, Neuroscience, University of Iowa
  - Thilina Weerathunga, PhD: Quant Analyst (Capital markets, banking, fintech), Citi group
  - Raghav Girgaonkar, (last of 13 MS): PhD Physics at UW Milwaukee