Bridging GW and HEP

Next Generation AI
at the Frontier with Science

AI+HEP in East Asia Workshop at IBS
February 27, 2025

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📚 Today's Outline

1. Introduction to GW & KAGRA Experiment

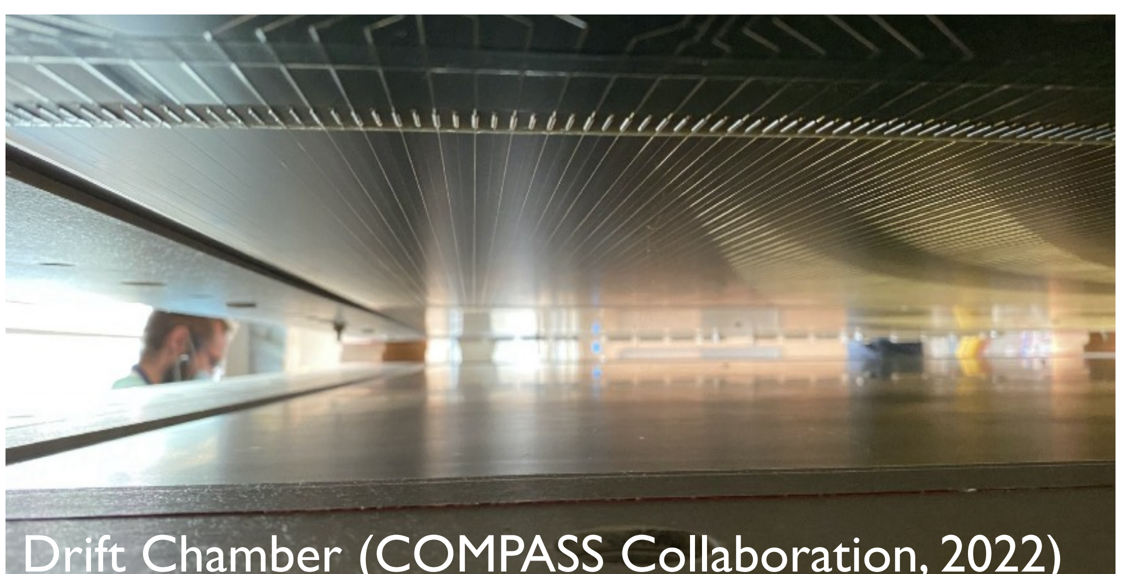
2. Recent developments bridging GW+HEP software

3. Machine Learning applications in Astrophysics
   e.g. Glitch Classification and Visualization

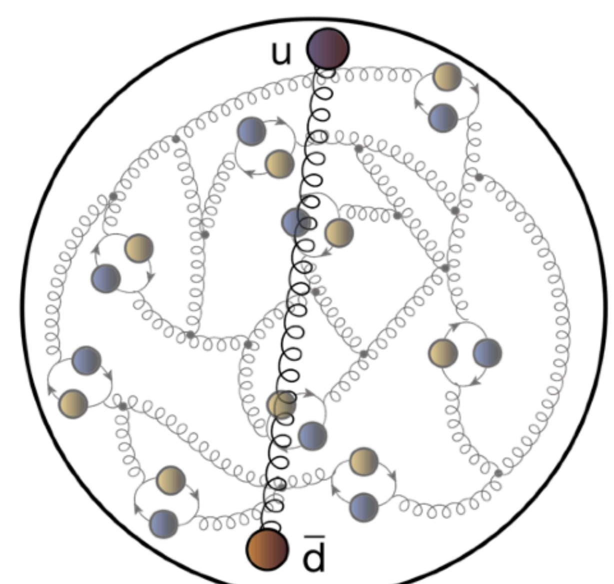
Conclusions

Self Introduction

- Faculty Member at Advanced Research Laboratories in Tokyo City University
  — LIGO-Virgo-KAGRA Gravitational Wave Collaborator
  — Ph.D. Thesis in QCD Physics in France (COMPASS Experiment, SPS, CERN)
- Main research topics:
  — **Astrophysics & Gravitational Waves:** Waveform forecasting & Early-detection
  — **High-Energy-Physics:** detector hardware, study of the meson structure
  — **Signal theory:** Advanced signal processing, digital filter design, etc.

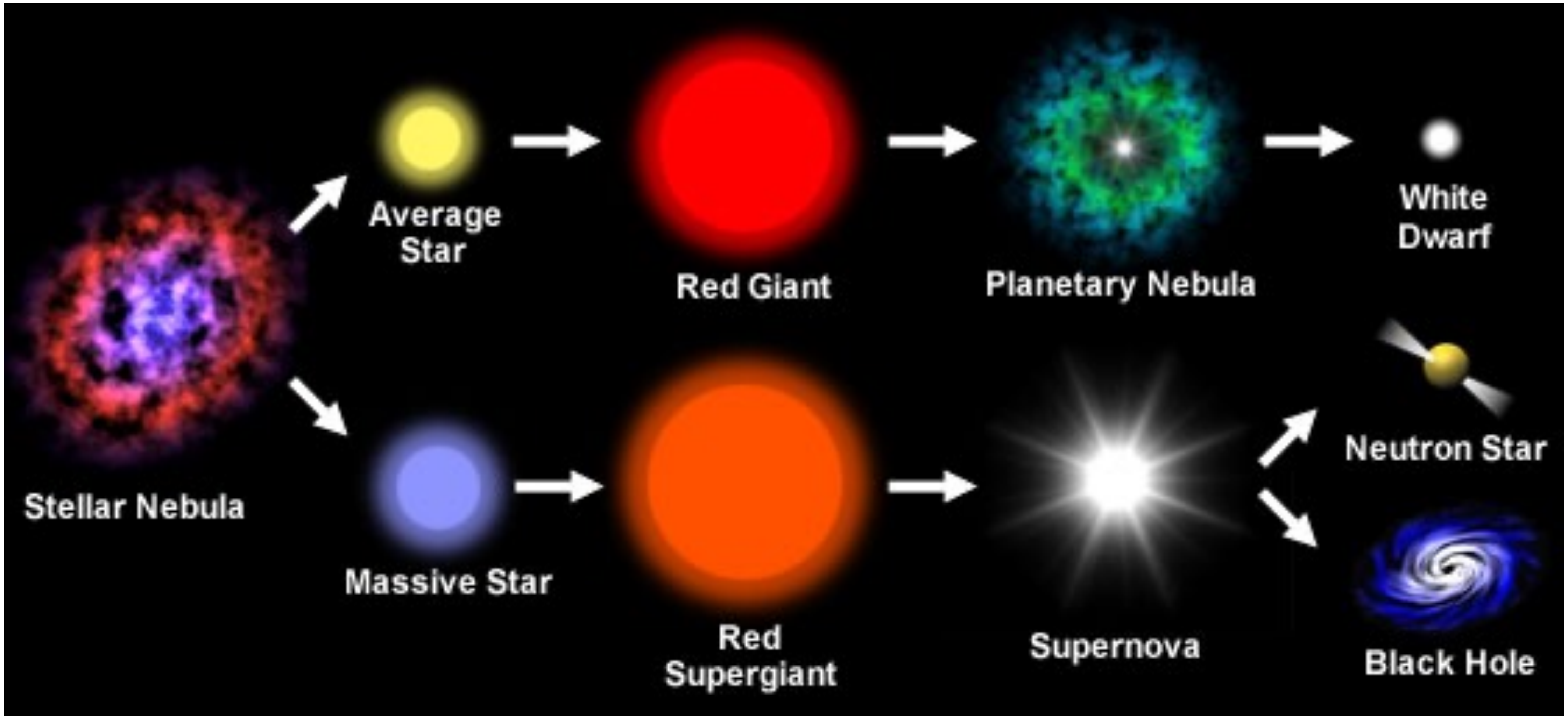


Drift Chamber (COMPASS Collaboration, 2022)



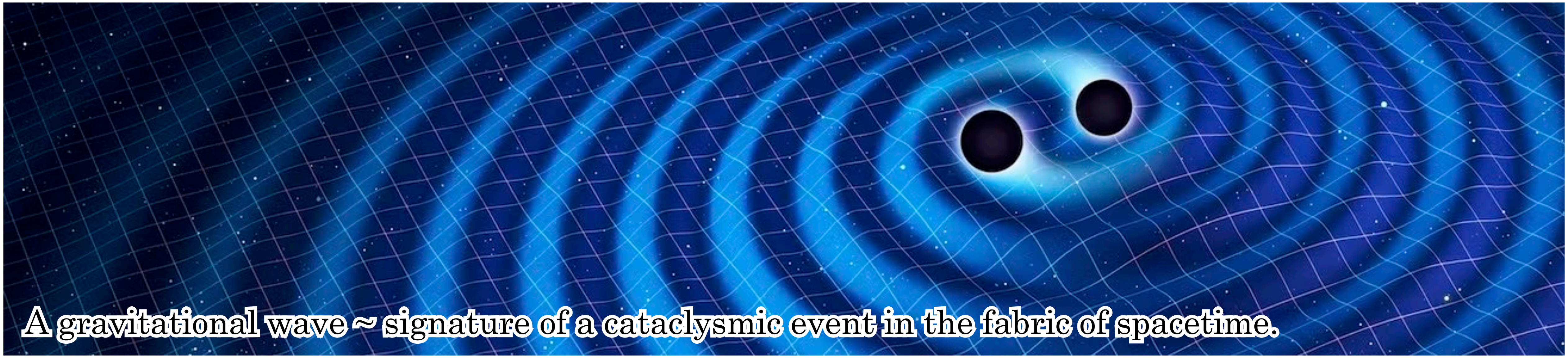
Introduction to GW

💫 Life Cycle of a Star



	Radius (km)	Mass ($M_\odot$)
Neutron star	10-20	1-3
Black hole	30	>3

💫 Gravitation waves (GW) in a nutshell



[*e.g. two black holes (BH) or neutron stars (NS) colliding in space*]

★Key milestones in the History of GW Research:

1916 — Existence prediction by A. Einstein

1974 — First <u>indirect evidence</u>: Hulse-Taylor Pulsar (special type of NS)

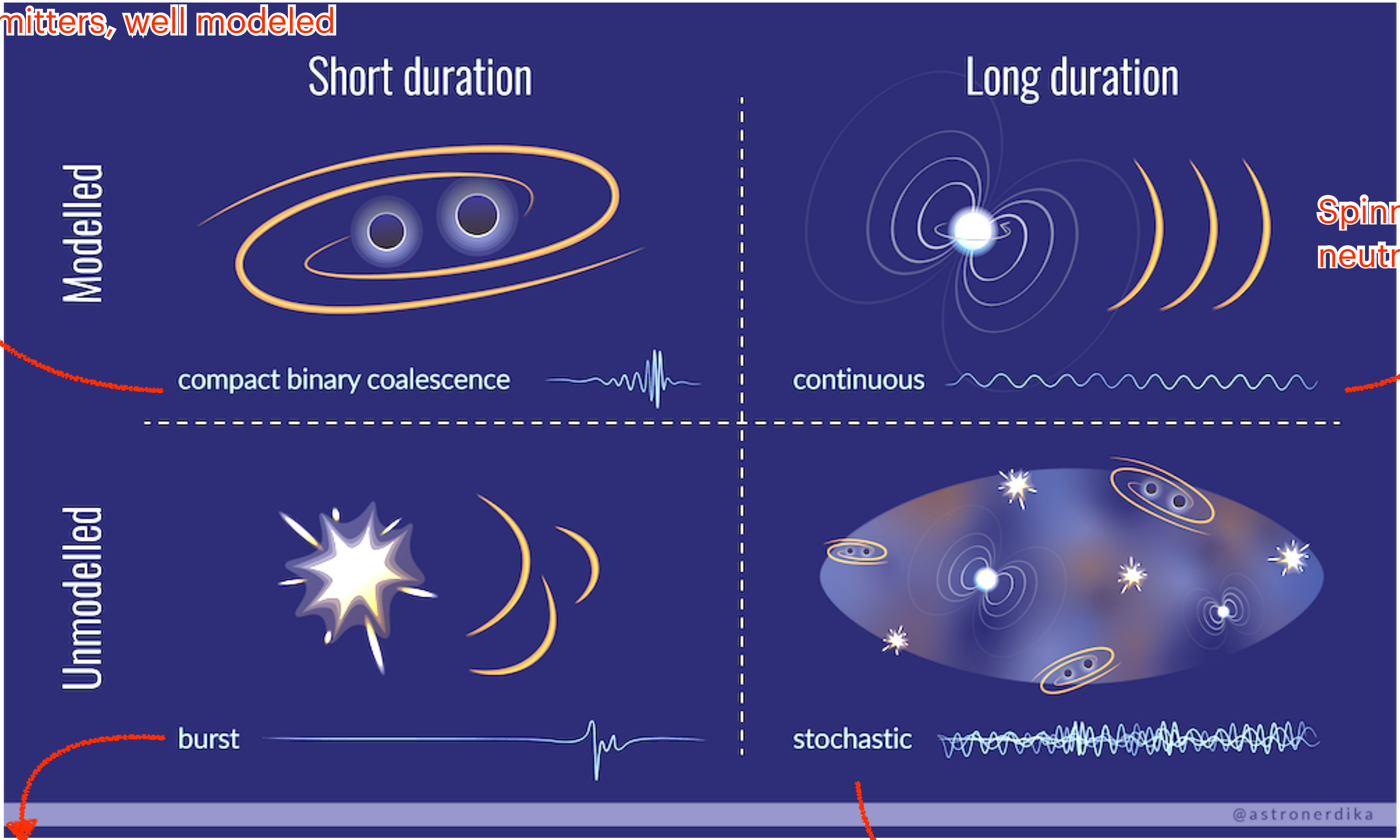
90-00's — LIGO construction (Livingston & Hanford, US)

2015 — First direct BH-BH merger detection: GW150914

2017 — First NS-NS detection merger with <u>Electromagnetic Counterpart</u>
GW170817 / GRB170817A (New Era)

💫 Topology of Gravitational Waves (Modeled)

NS-NS,BH-BH,NS-BH:
Strong emitters, well modeled

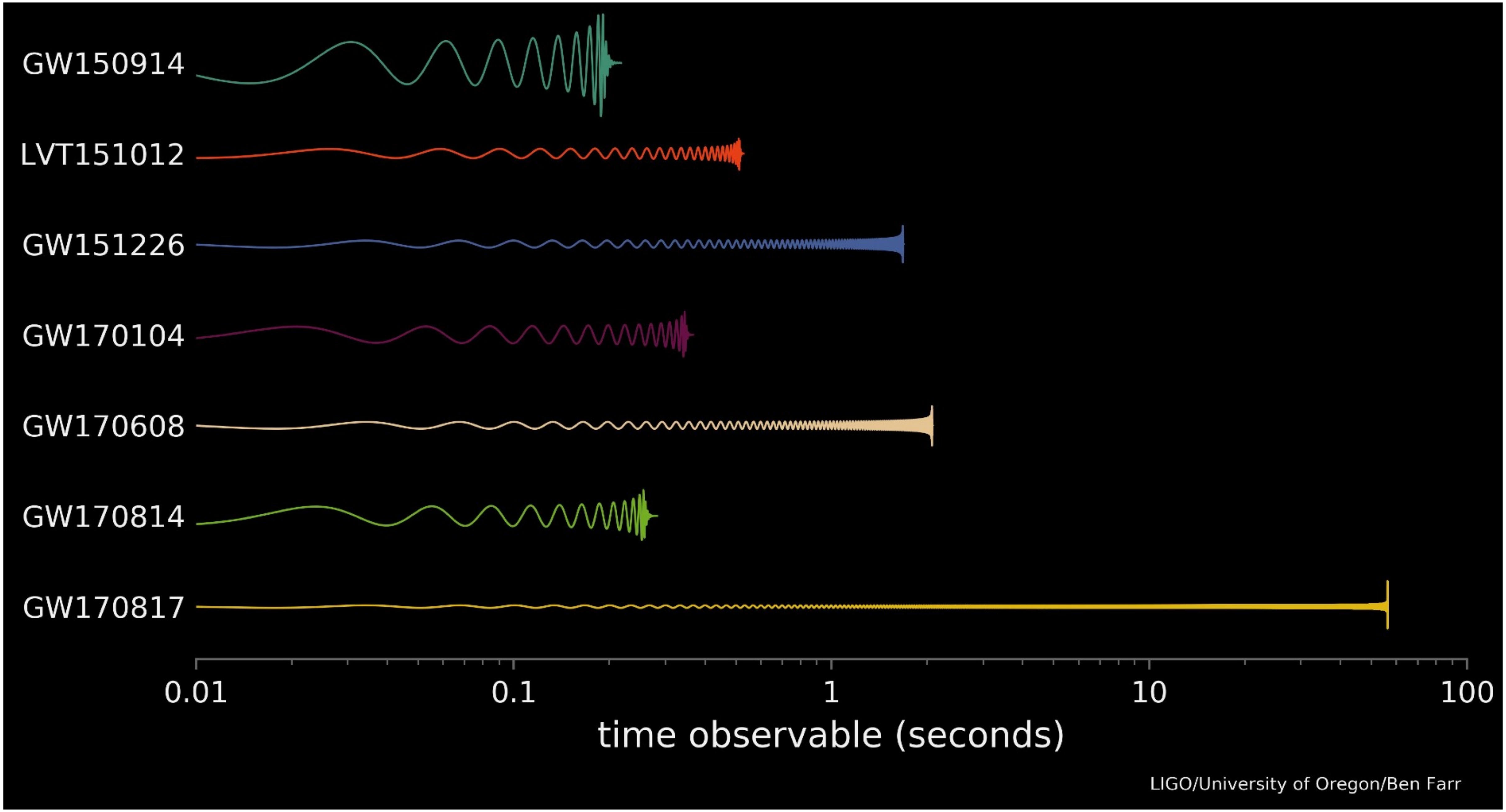


Spinning neutron star

Not well modeled, transients, weak signal, soft gamma-repeater,..

Residual of Big-Bang, cosmic GW background, ..

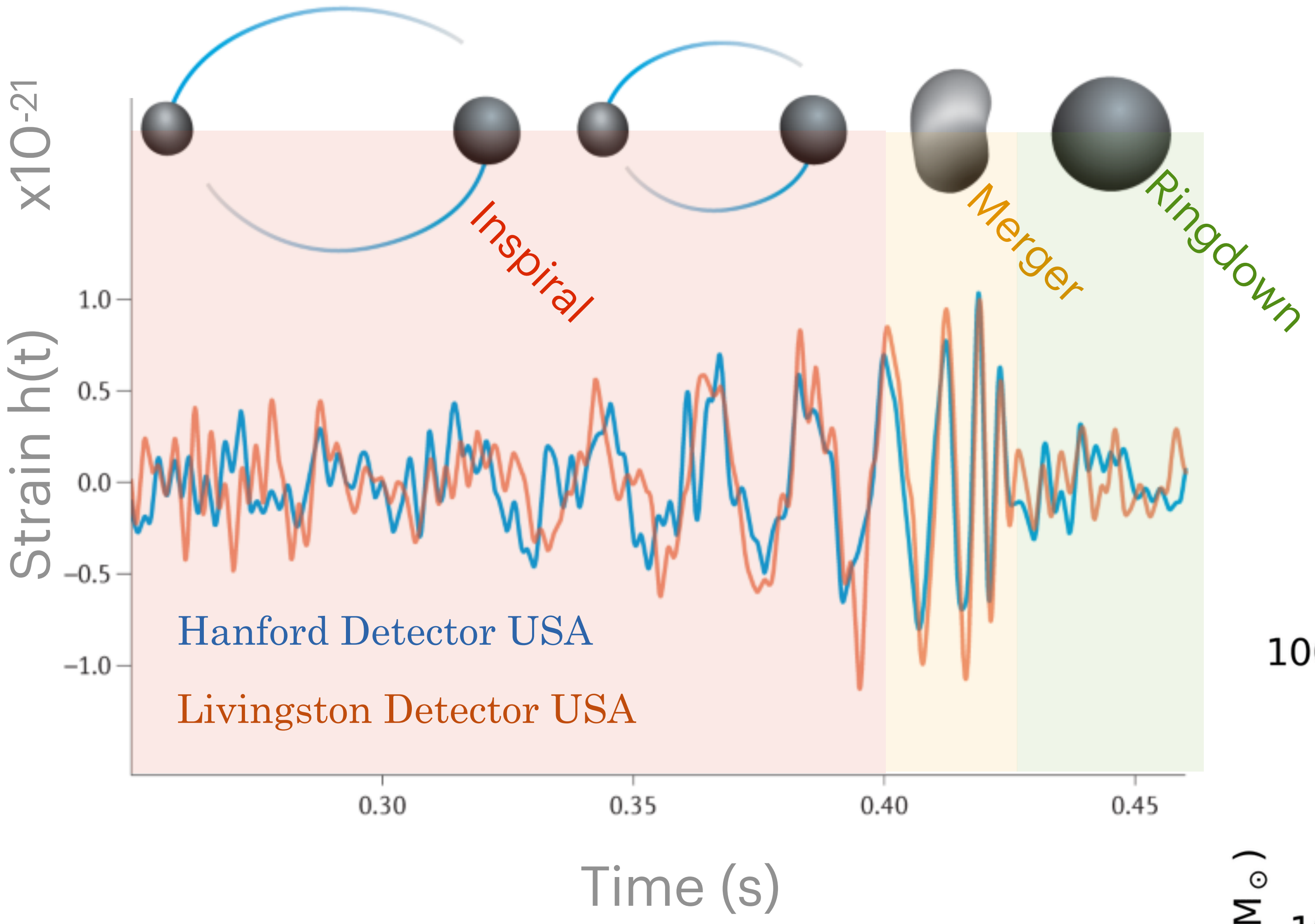
💫 Topology of Gravitational Waves (Modeled)

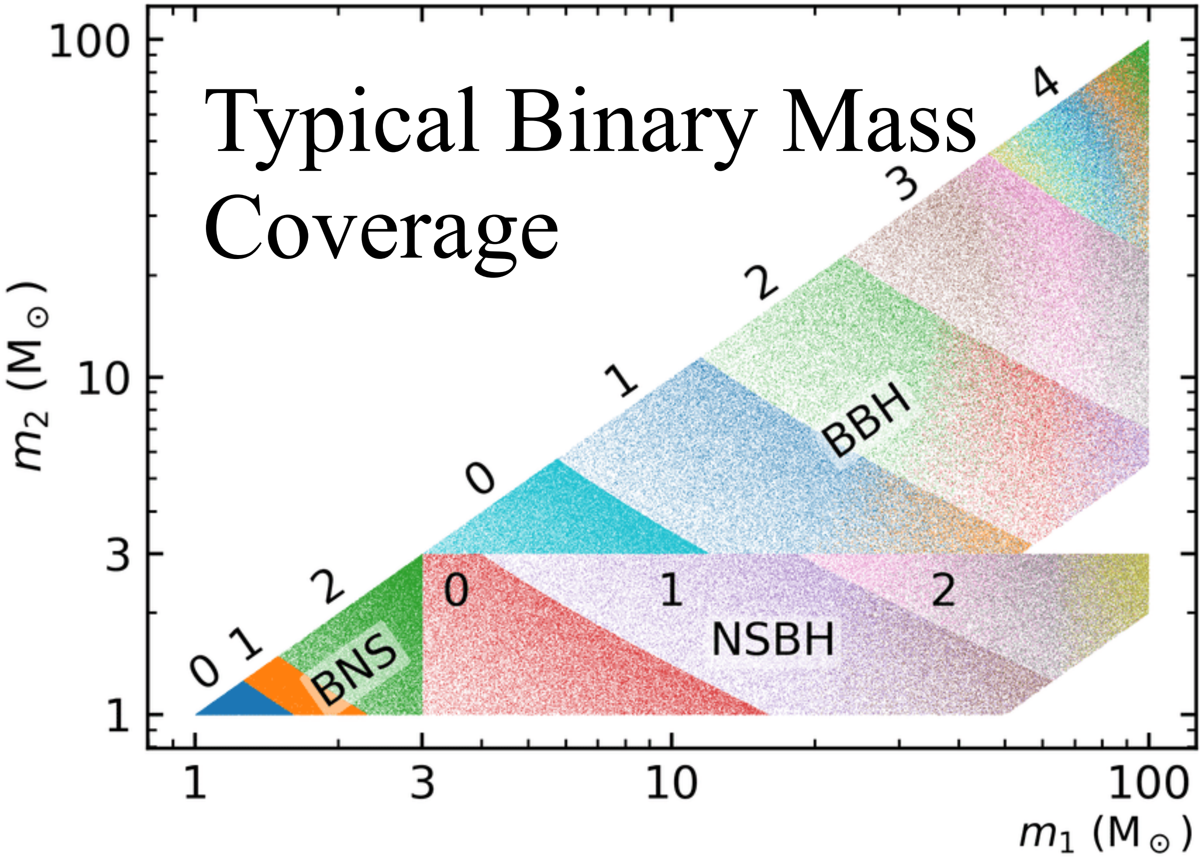


GW150914: First BH-BH merger detect in September 2015
GW170817: First NS-NS merger detected in August 2017

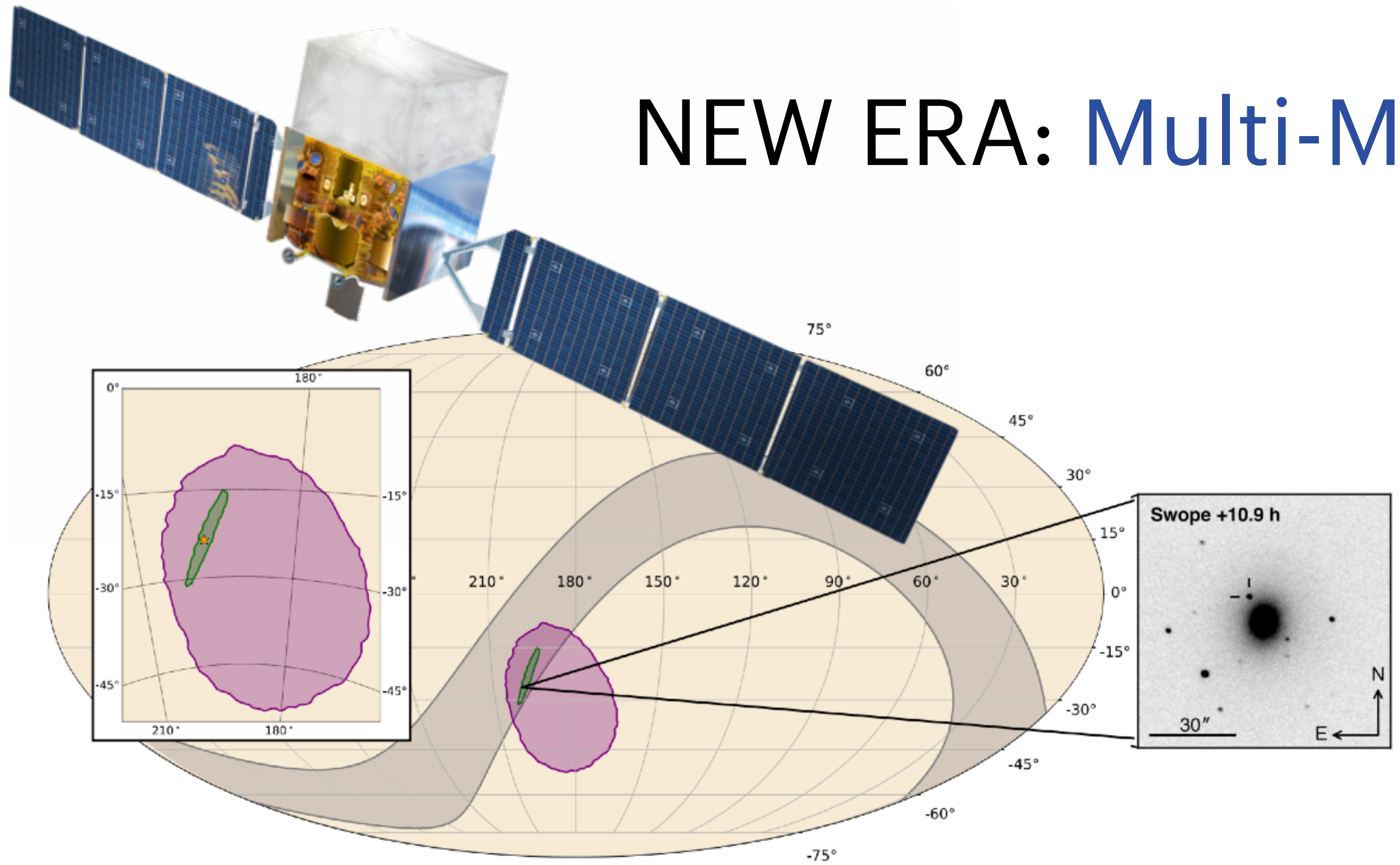
💫 Topology of Gravitational Waves (Modeled)

Focus on modeled short duration signals <u>only</u>





NEW ERA: Multi-Messenger Astronomy

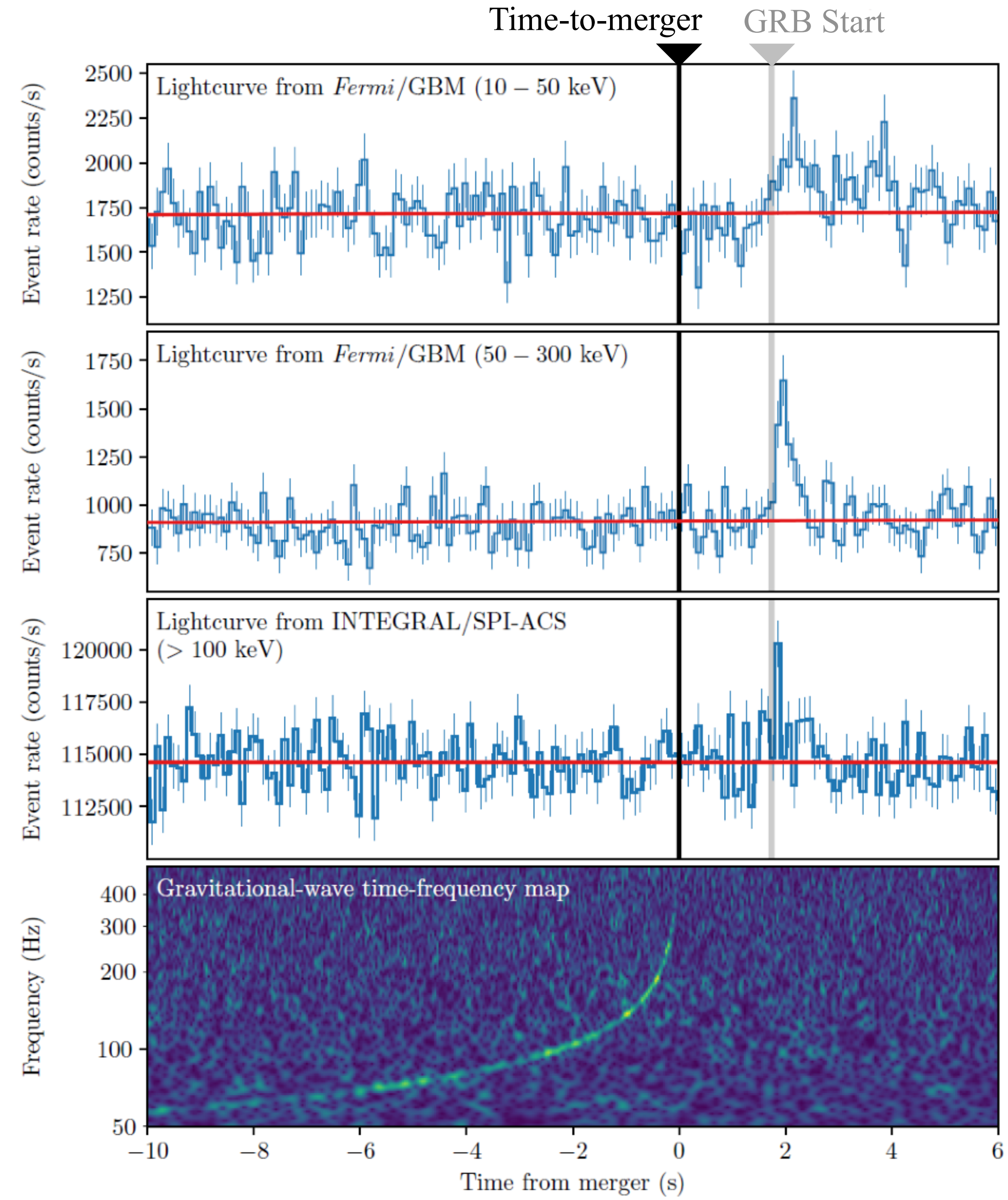


e.g. Sky localization obtained from gravitational wave computing pipeline
(Picture of the EM signal from telescopes after pointing to the right direction)

- Multi-Messenger Astronomy (MMA) Era (started in 2017)
  — IGWN: Ground-based coordination for low-latency alerts
  — NASA: Coordination between space and astronomers.
  — This challenge is about <u>speed</u> (< 60s) not <u>size</u> (~1Mb/s)

- Stereoscopic sky localization to be provided
  — The more data, the better the localization is.
  — Goal: GW signal with <u>negative latency</u>
  (detection prior time-to-merger)

- Interest: connecting GW and HEP fields.
  — Gravitational wave observatories
  — Electromagnetic telescopes *(e.g. Fermi)*

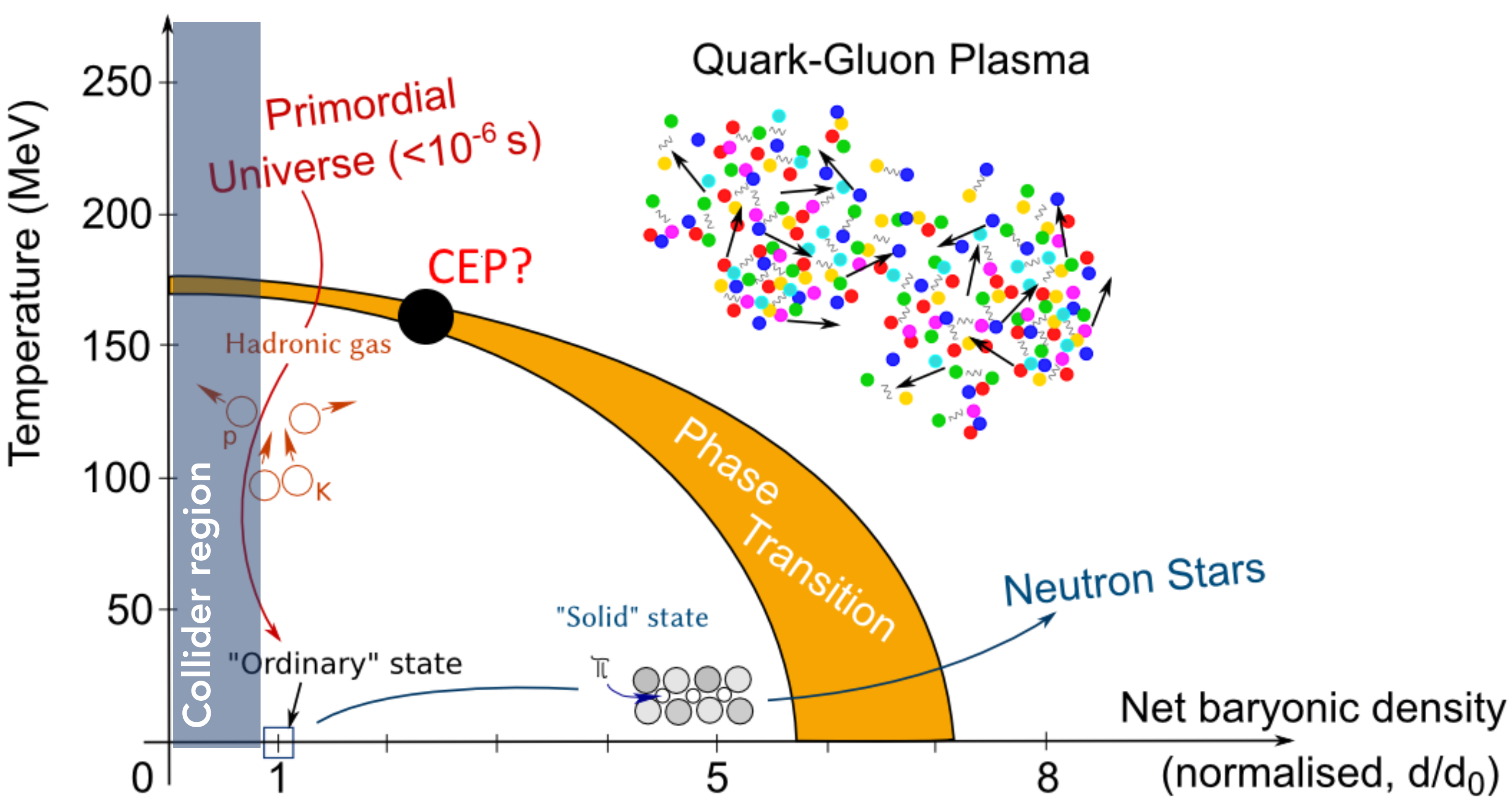


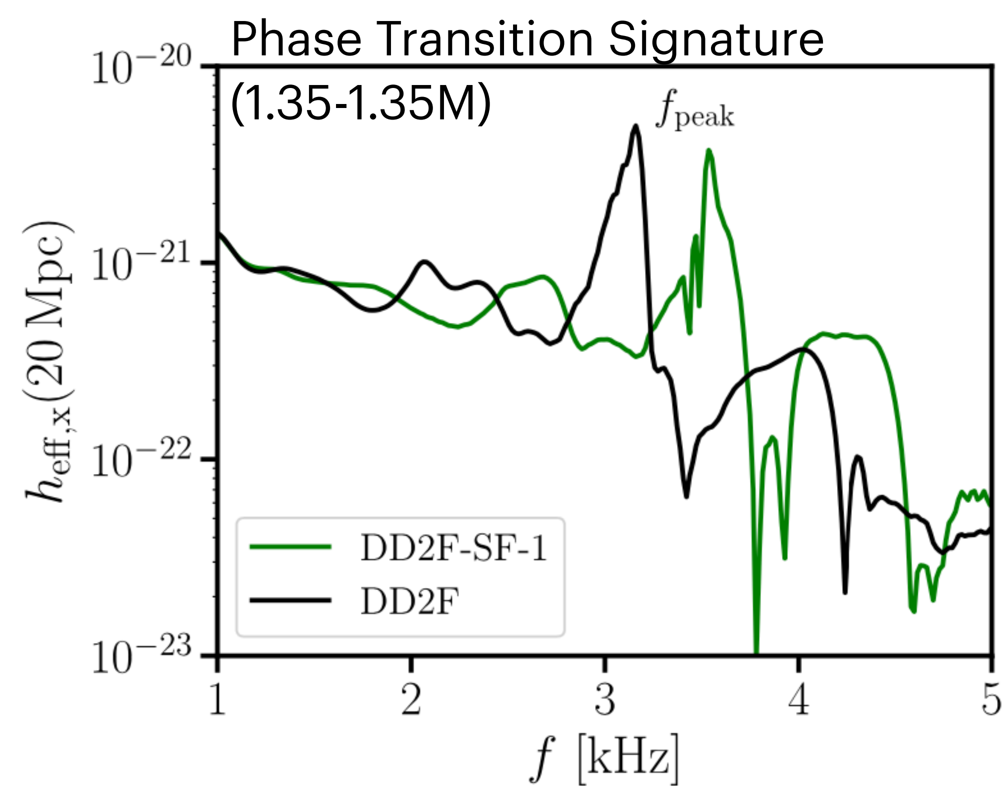
First NS-NS Detection with <u>Electromagnetic Counterpart</u>
(Landmark event: GW170817 / GRB170817A)

Interests in detecting NS-NS mergers

- **Early detection of neutron star merger using GW signal**
  — Localization of merger, measuring EM signal
  — Combining both signals to better constrain EoS.

- **Signature of <u>Phase Transition</u> expected in GW signal**
  — Softening of the Equation-of-State (EoS): Changes in stellar structure, more compact structure
  — Higher oscillations: post-merger signal shifted toward higher frequencies
  — DD2F-SF model: "Density Dependent" Relativistic Model + "Flow Constraint"
  + "Phase Transition (String Flip)" *[arXiv:2006.16183 (2020)]*

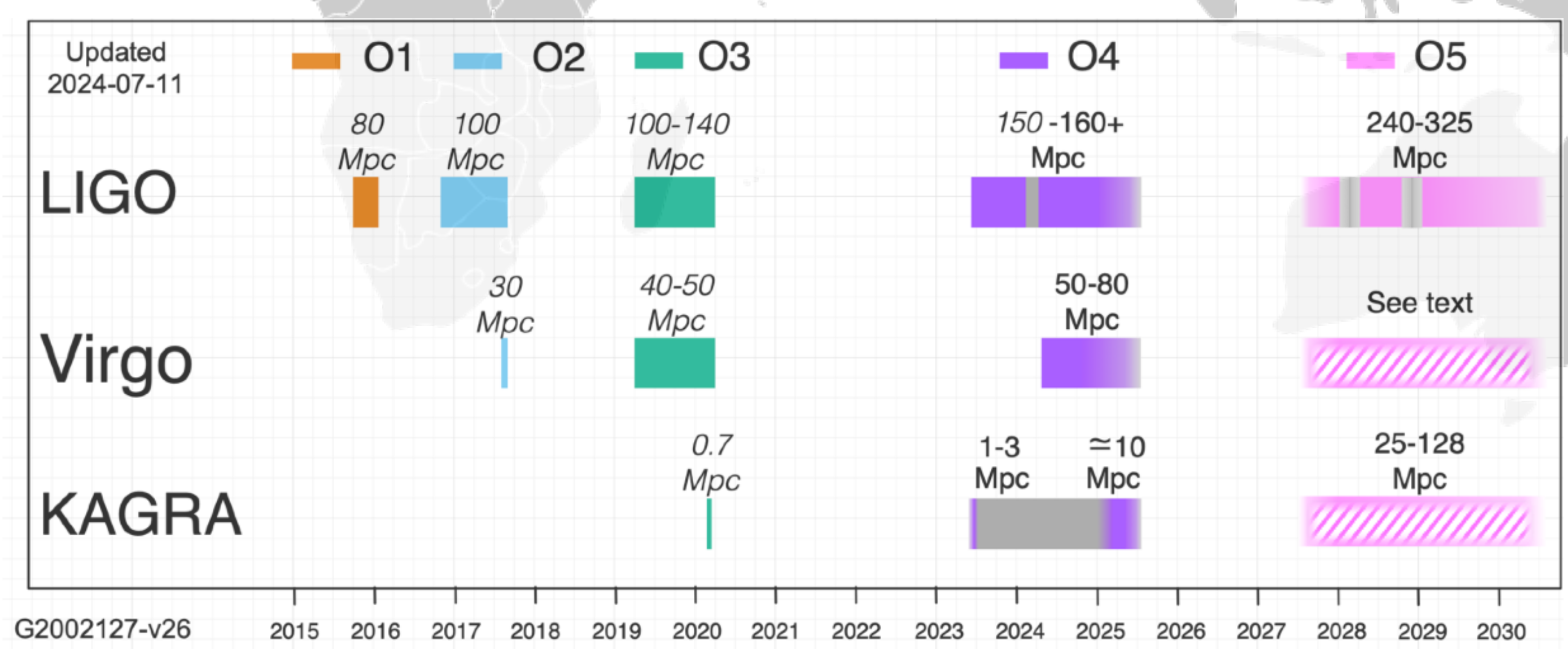




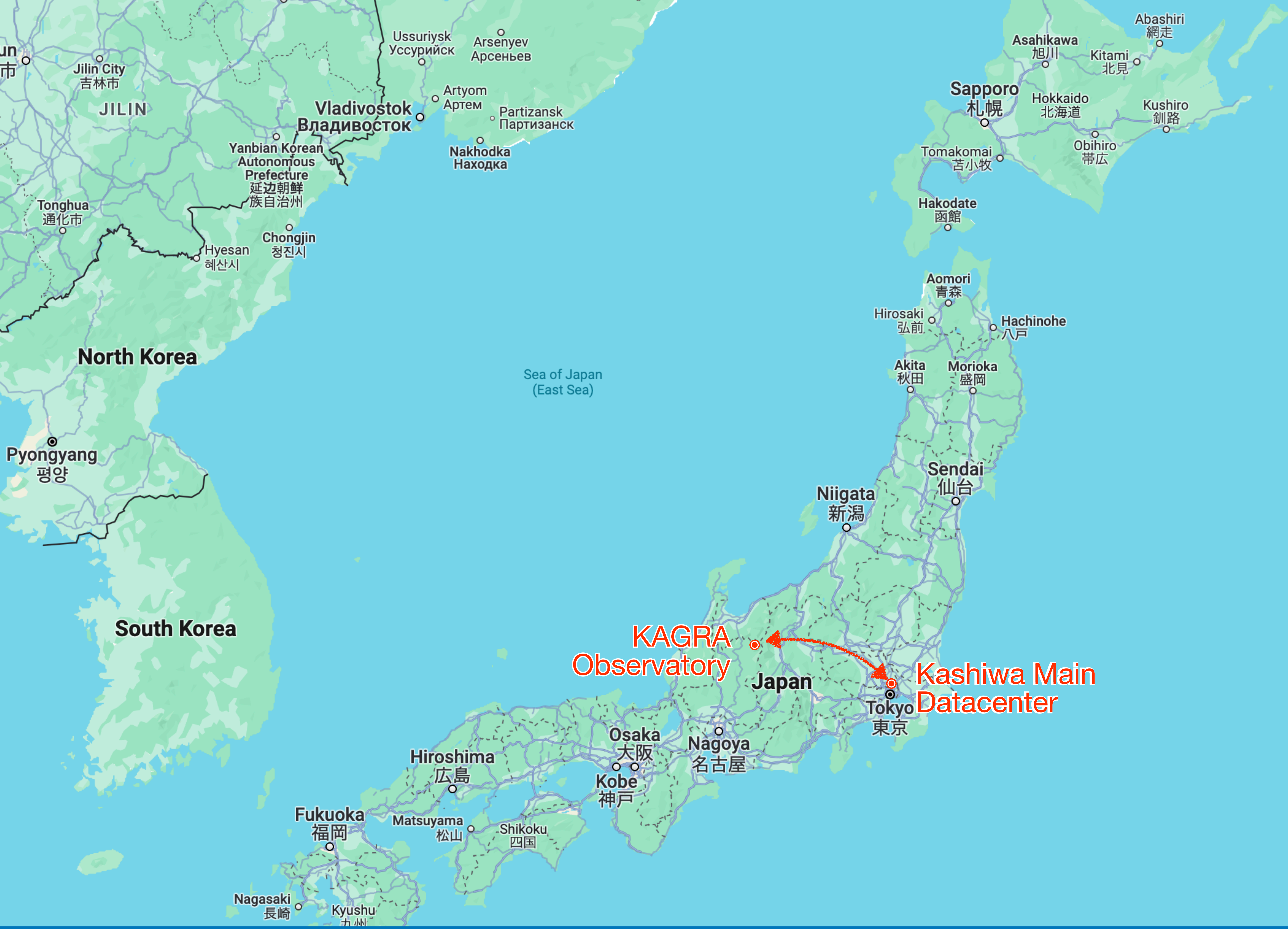
KAGRA Experiment

(PTEP 2023, 10A101, H.Abe et al.)

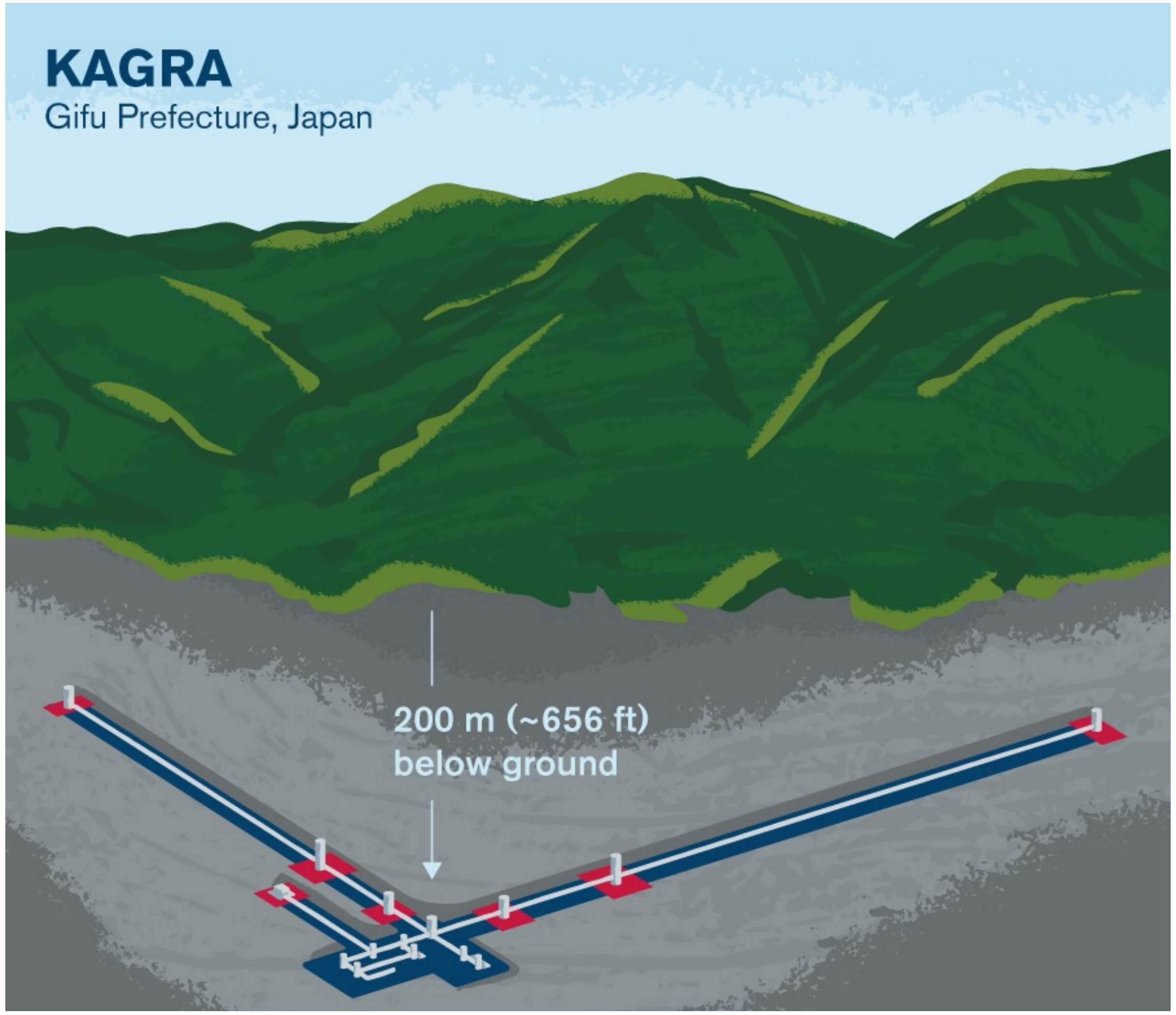
International Gravitation Wave Network



e.g. Future projects: Einstein telescope, LISA interferometer, etc.


KAGRA
Observatory
Kashiwa Main
Datacenter
Japan
Tokyo
東京
Sea of Japan
(East Sea)
North Korea
South Korea
Pyongyang
평양
Jilin City
吉林市
JILIN
Vladivostok
Владивосток
Ussuriysk
Уссурийск
Arsenyev
Арсеньев
Artyom
Артем
Partizansk
Партизанск
Nakhodka
Находка
Yanbian Korean
Autonomous
Prefecture
延边朝鲜
族自治州
Tonghua
通化市
Hyesan
혜산시
Chongjin
청진시
Sapporo
札幌
Asahikawa
旭川
Abashiri
網走
Kitami
北見
Hokkaido
北海道
Kushiro
釧路
Obihiro
帯広
Tomakomai
苫小牧
Hakodate
函館
Aomori
青森
Hirosaki
弘前
Hachinohe
八戸
Akita
秋田
Morioka
盛岡
Sendai
仙台
Niigata
新潟
Osaka
大阪
Nagoya
名古屋
Kobe
神戸
Hiroshima
広島
Matsuyama
松山
Shikoku
四国
Fukuoka
福岡
Nagasaki
長崎
Kyushu

🇯🇵 KAGRA Experiment in Japan

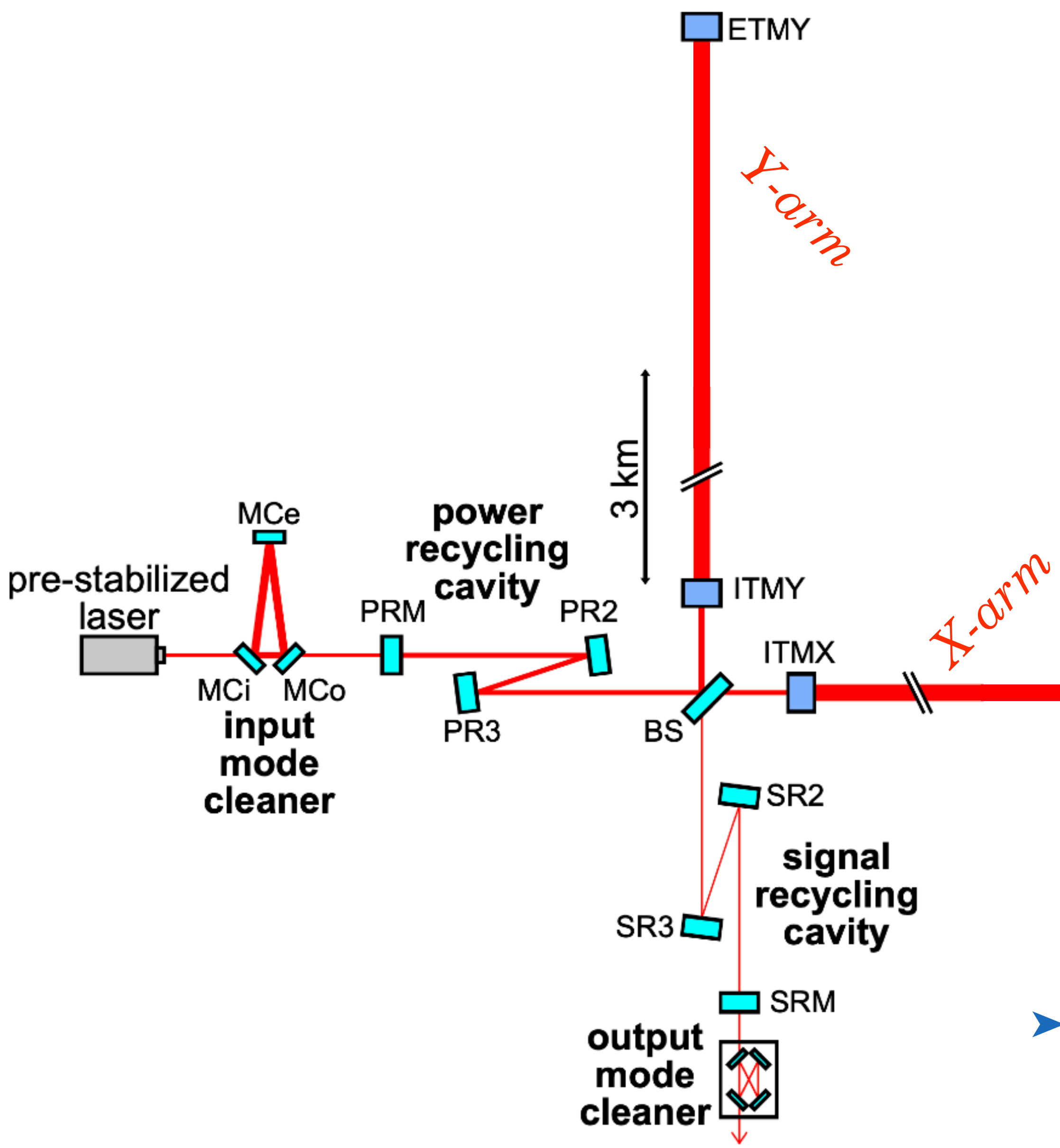


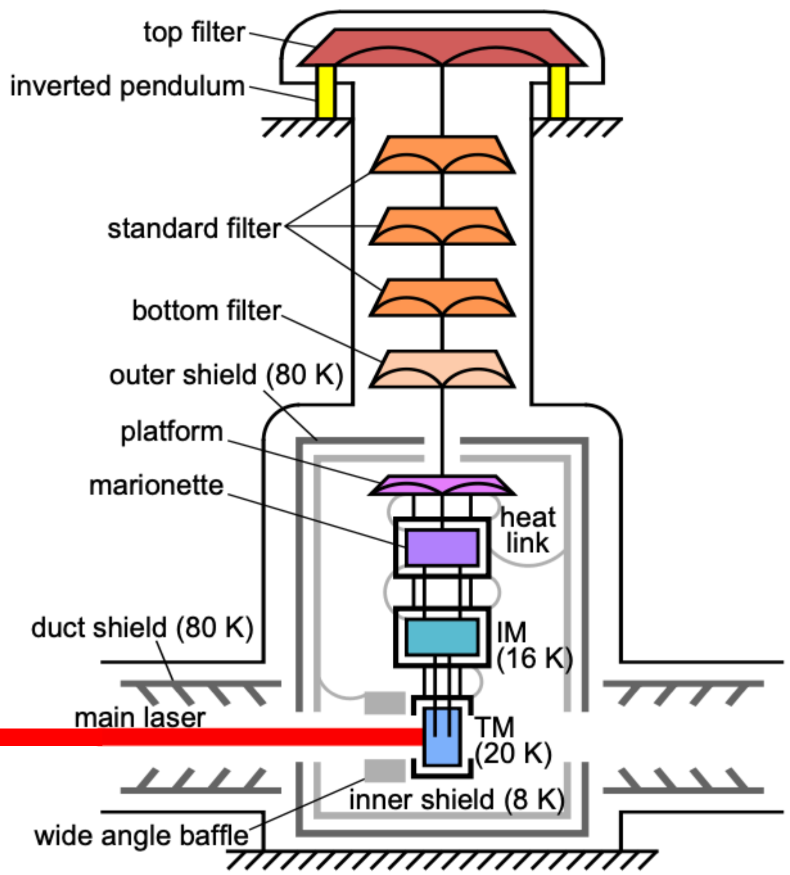
KAGRA Observatory has been established in 2016 in Kamioka, Gifu prefecture
(same place as Kamiokande neutrino experiment)

The telescope is a 3 km Fabry-Perot interferometer
with 20K Cryogenic Sapphire Mirrors in Mt. Ikenoyama.

🇯🇵 On-site Data Acquisition at KAGRA

Prog. Theor. Exp. Phys. 2023 10A101(35 pages)
DOI: 10.1093/ptep/ptac093





cryogenic suspension system for sapphire test masses

- Fabry-Perot Interferometer (power recycling)
  - — Laser 180W continuous source at $\lambda = 1064$ nm
  - — XY-arms, 20K-cryogenic cooled suspended mirrors
- On-site infrastructure actions
  - — Data acquisition, pre-processing, environmental monitor.
  - — Feedback control to actuators on ETMX,ETMY

On-site Data Acquisition at KAGRA

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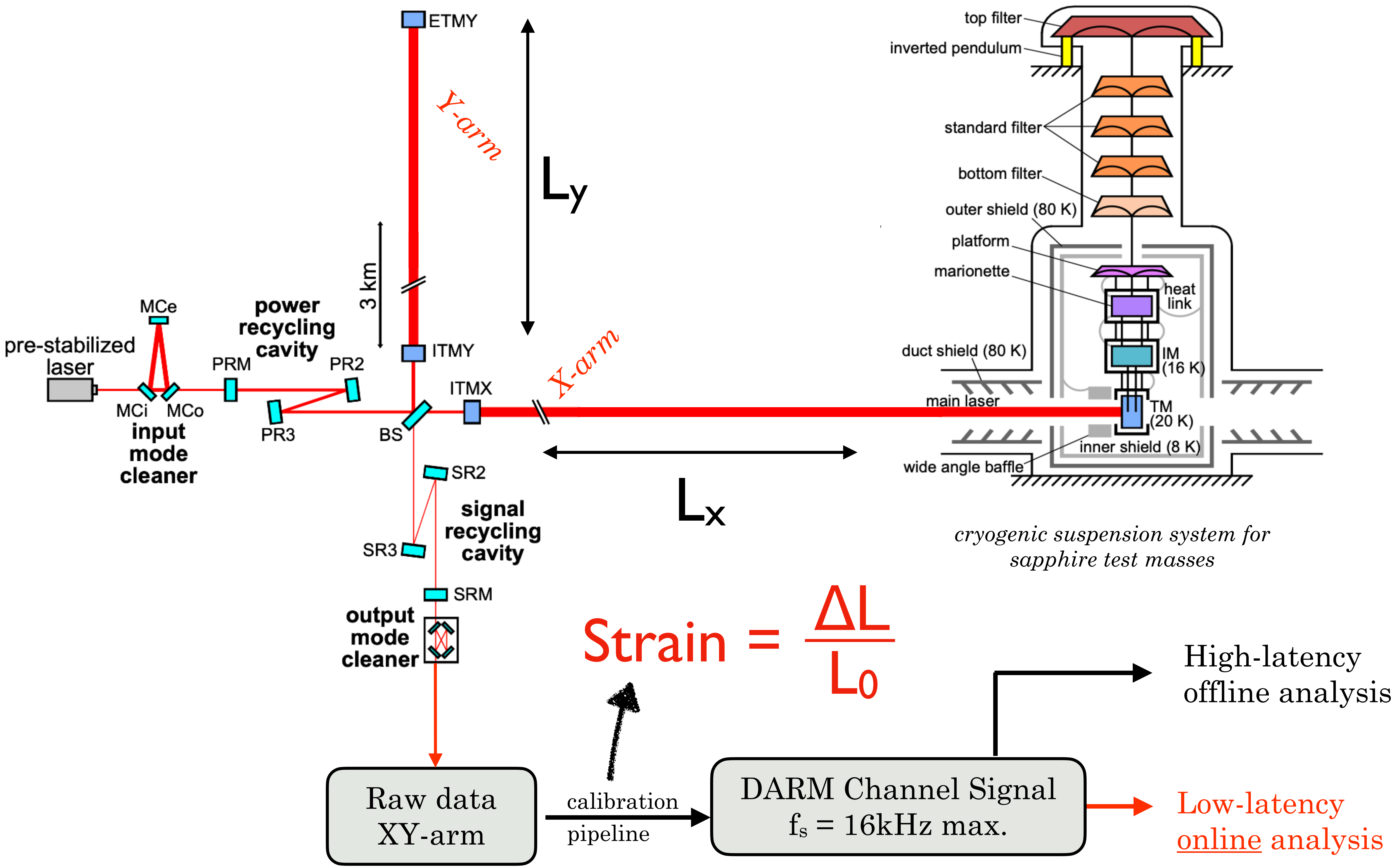
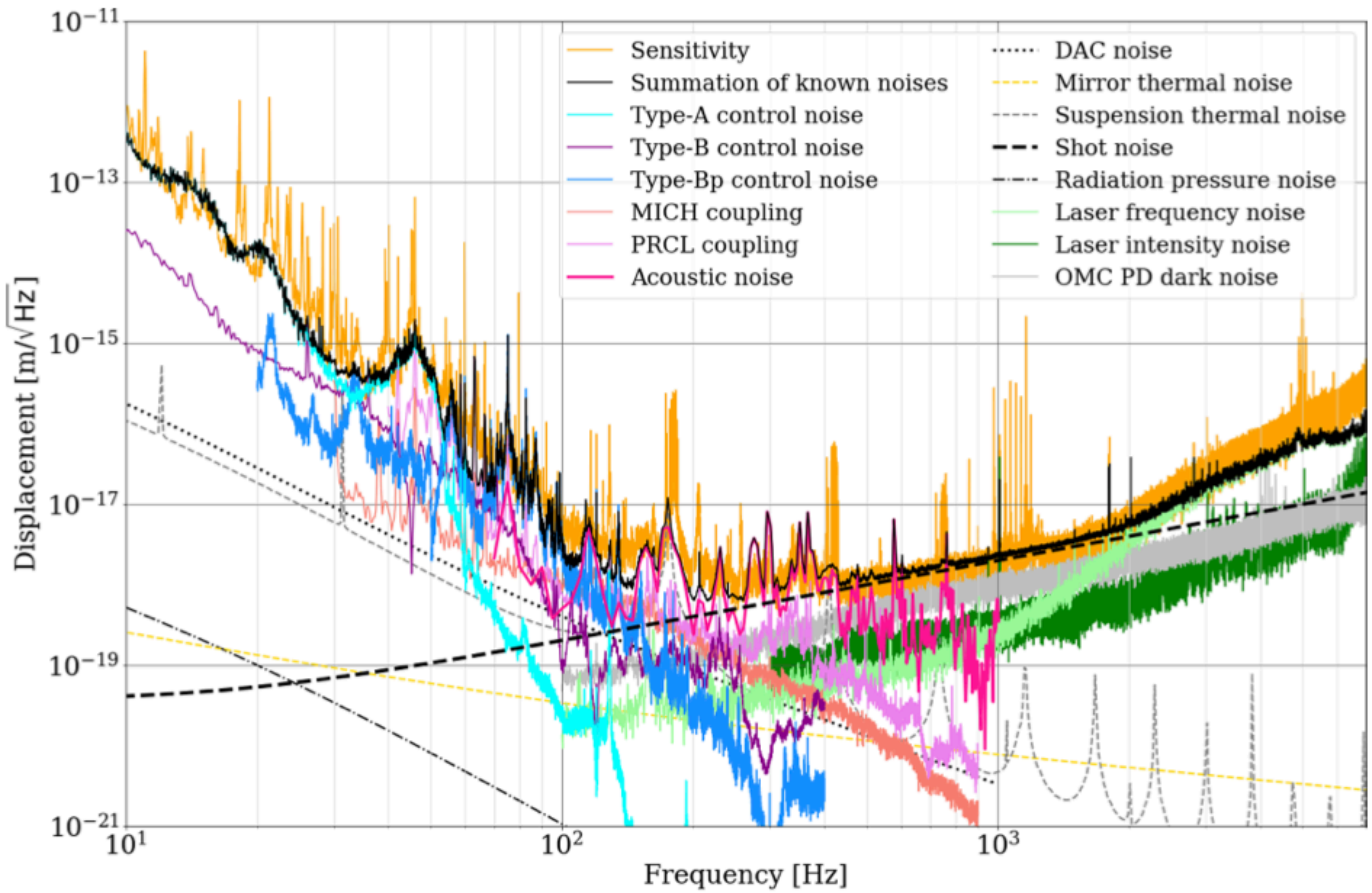


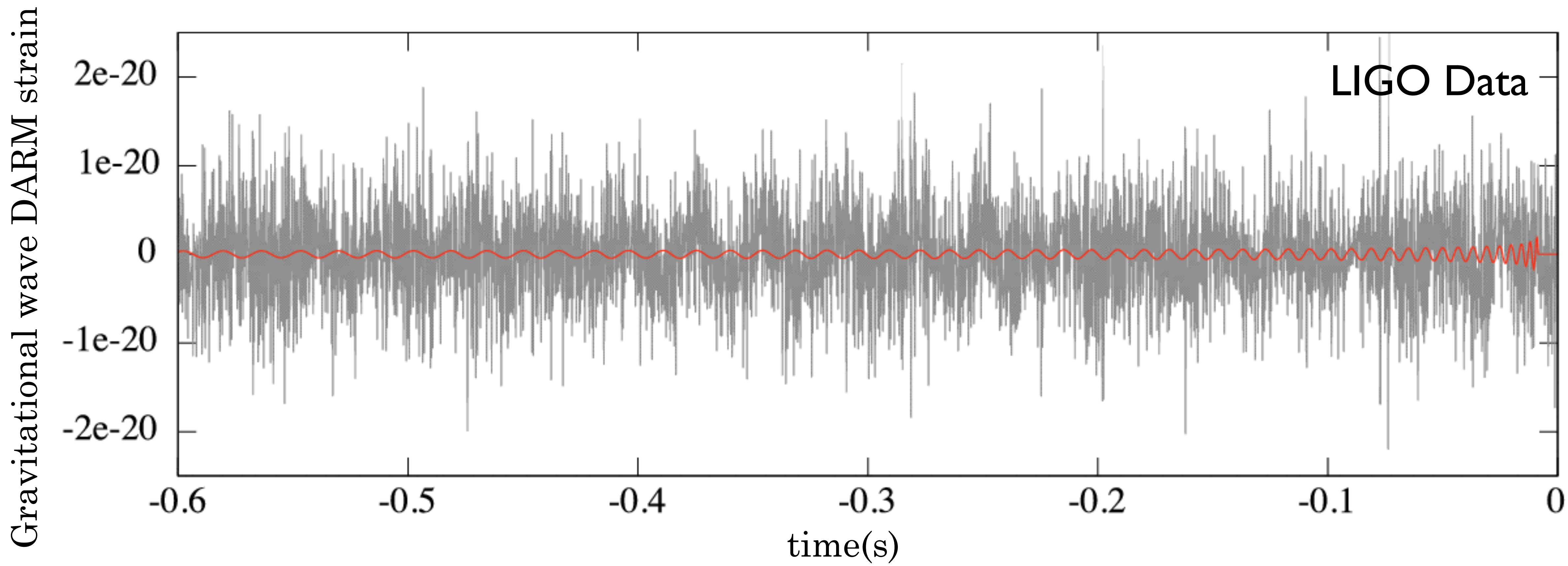
Detector Sensitivity @ KAGRA (O3GK)

- **Power Spectrum Density:** Average distribution of stationary noise in the detector
- Strain signal preprocessing in FFT domain. : $H(f) = H_0(f)$ / PSD(Sentitivity)



PTEP 2023: Various noise sources in the KAGRA detector during the O3GK run (12 April 2020)

🇯🇵 On-site Data Acquisition at KAGRA



- Gravitation wave signal (here is LIGO experiment data); typical GW signal injection is in red
- Data transfer via Apache Kafka (Message Broker): Low-latency reliable sustained data-stream
- Typical latencies at Kashiwa Data center for "1 second" files:

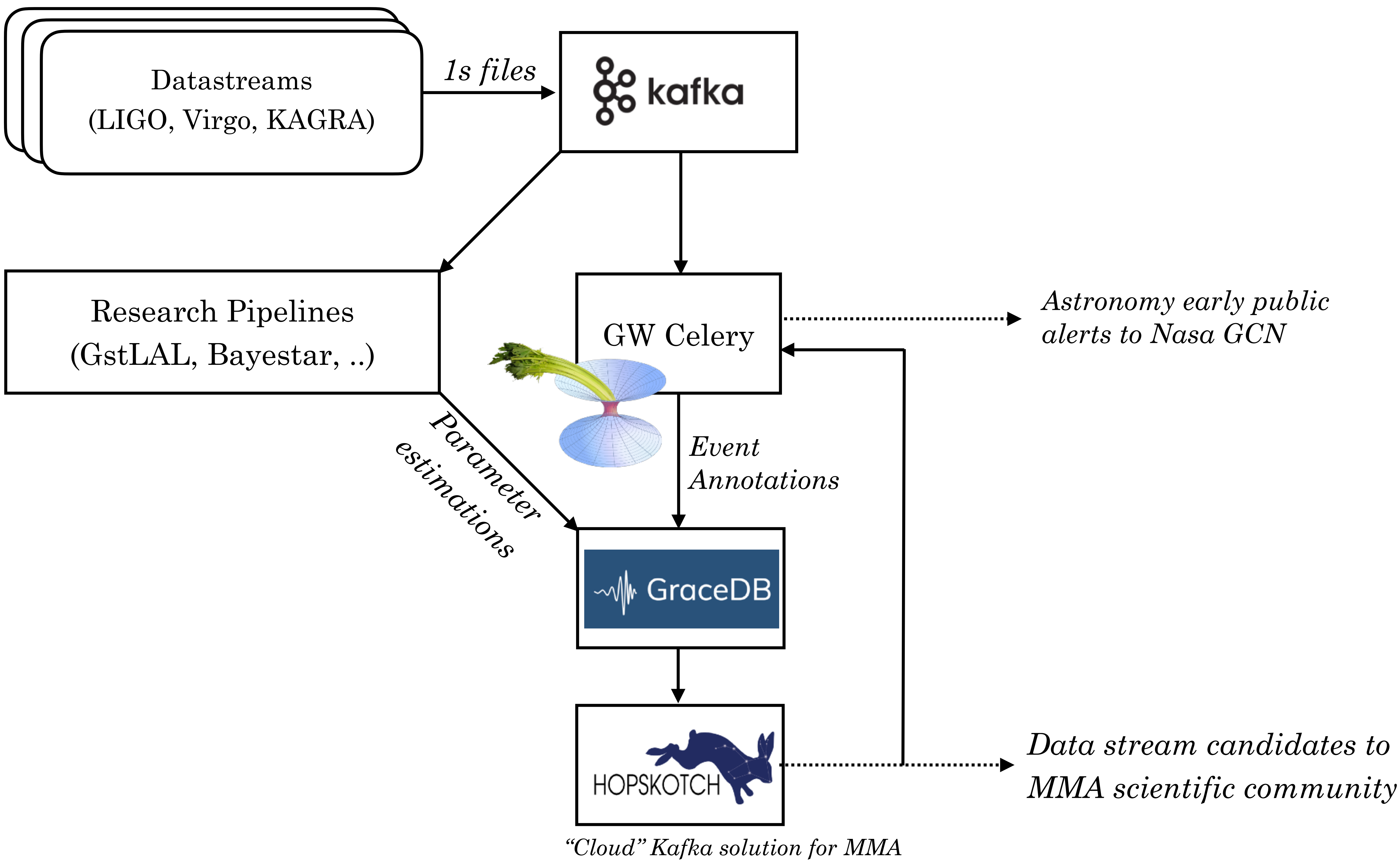
LIGO to Kashiwa	6-8s latency
VIRGO to Kashiwa	10s latency
KAGRA to Kashiwa	2.5s latency

(Latency = transfer from ADC to on-site servers + FIR filtering + transfer from On-Site (L1,H1,V1,K1) to Kashiwa)

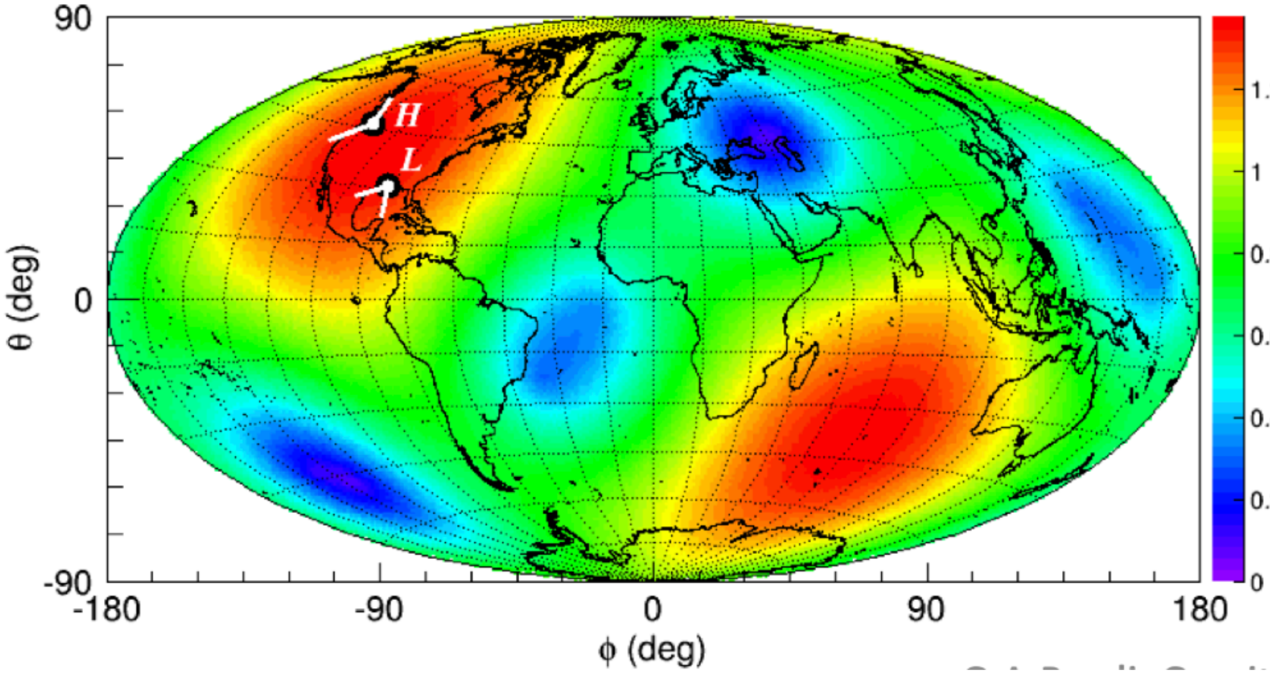
Strain $h(t) = \frac{\Delta L}{L_0}$

Apache kafka

LOW-LATENCY ORCHESTRATION

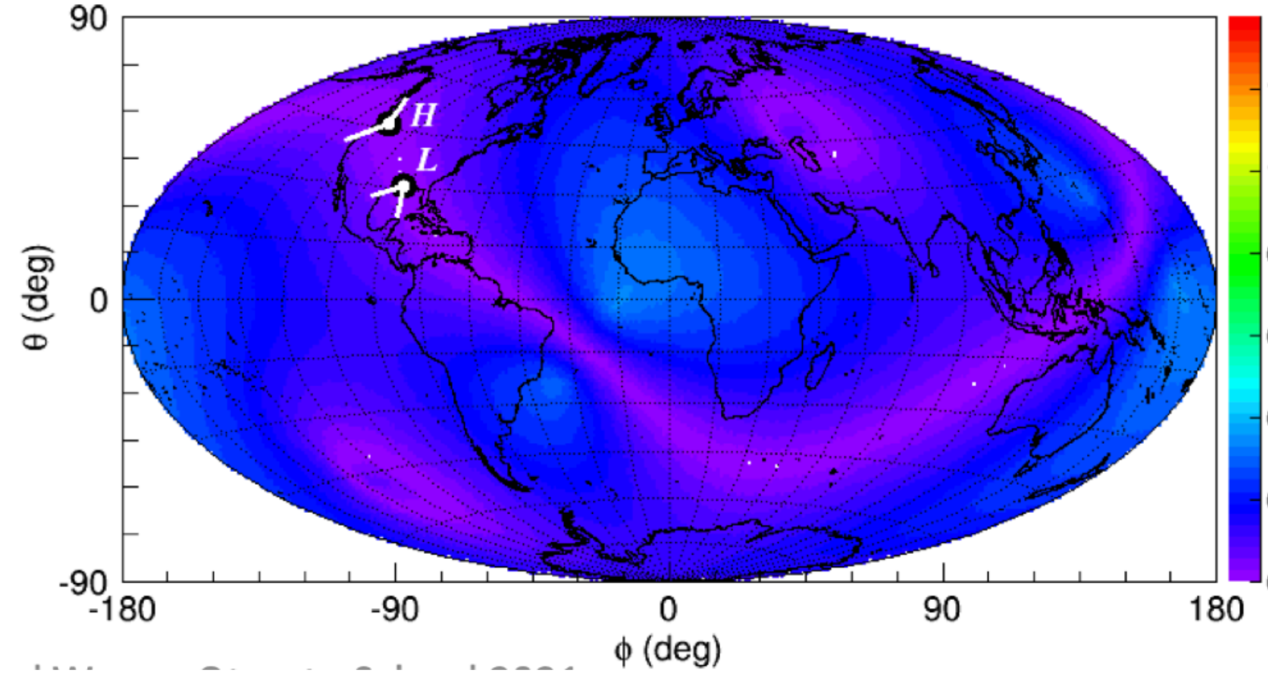


Yesterday public alert: S250226dl



$F_\times$ antenna pattern amplitude response

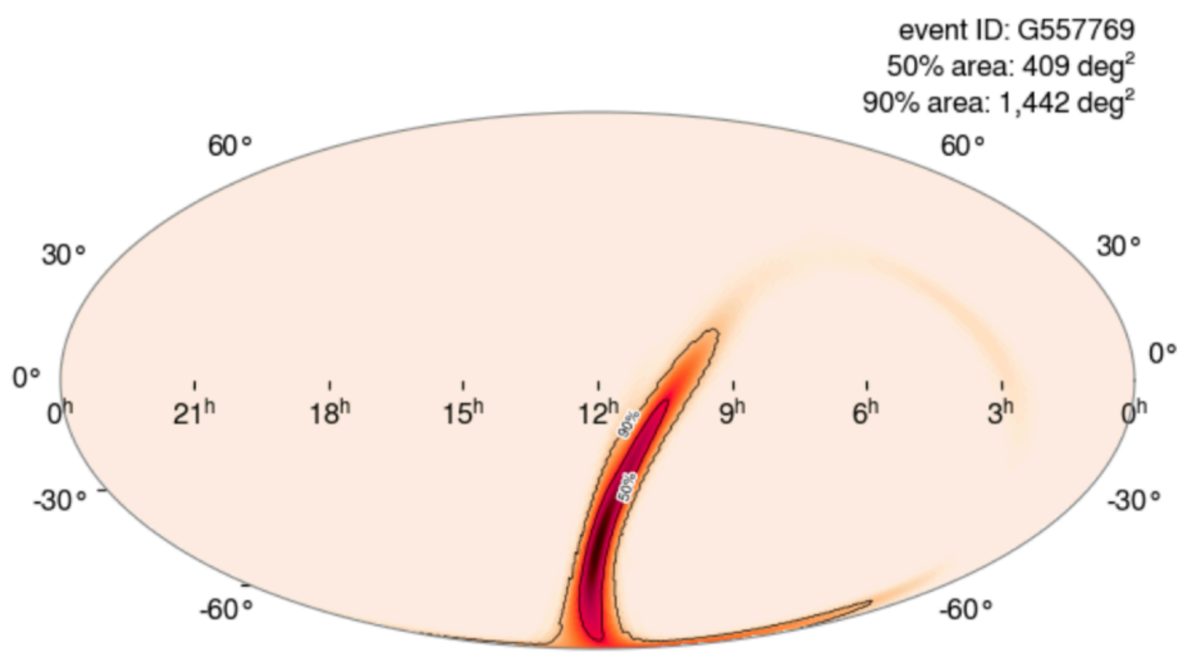
(G.A.Prodi, Gravitational Waves, Otranto School 2021)



F_+ antenna pattern amplitude response

(G.A.Prodi, Gravitational Waves, Otranto School 2021)

$$h(t) = F_+(\theta,\phi)h_+ + F_\times(\theta,\phi)h_\times$$



Superevent Information	
Superevent ID	S250226dl
Category	Production
FAR (Hz)	1.169e-12
FAR (yr^{-1})	1 per 27103 years
t_0 (GPS time)	1424645336.70
t_{end} (GPS time)	1424645337.70
Submitted ▾	2025-02-26 22:48:53 UTC
Links	Data

Software bridging HEP-GW

(IOPScience, ACAT2024 conference, Invited Talk)
https://inspirehep.net/conferences/2756906

ACAT 2024
Stony Brook

GW vs. HEP Requirements / Ecosystems

- Goal: Get the best of the two world; <u>Speed vs. Scale</u> in data processing + better signal processing

- In Gravitational Wave Physics:
  — Sensitivity ↗ ; Detection range ↗ ; Smaller noise ↗ ; Signal-to-Noise-Ratio (SNR) ↗

  — Raw data is not increasing much over years

  — Computing pipelines are heterogeneous and complex, but <u>no common framework</u>

  — Main scientific package in GW physics : <u>LVK Algorithm Library Suite</u> (LALSuite; C/C++)

ROOT
Data Analysis Framework

ROOT has already been used in GW community (mainly people in Europe, originating from HEP).

CONDA®

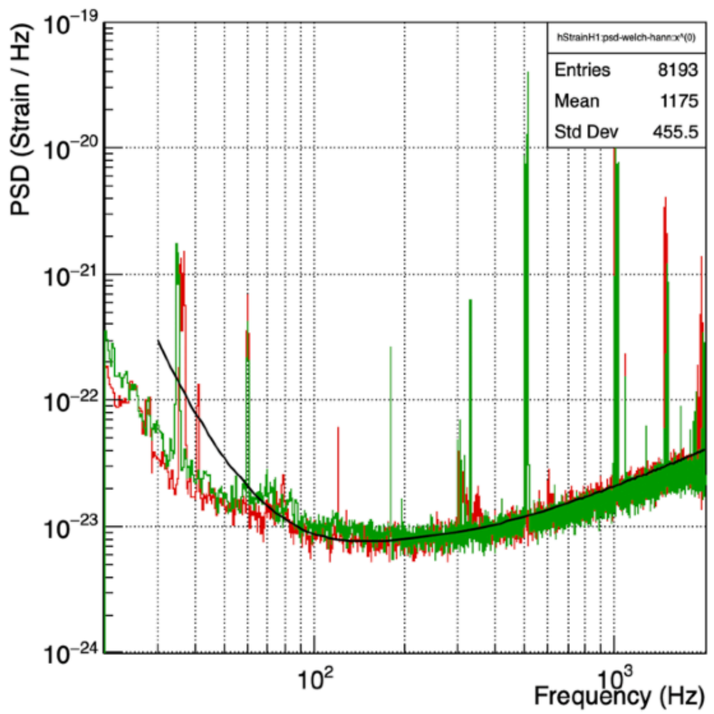
- Requirements to make use of ROOT in GW community
  — (1) Handling typical I/O files used in the community: GWF files and HDF5 files
  — (2) Advanced digital signal processing and (3) complex digital filtering (4) complex tensors + AI

- Ecosystems: Rapid software deployment using Conda: Python/C++ pre-compiled software
  — Anaconda: New HEP-Forge channel available: <u>https://github.com/hep-forge</u> / <u>http://anaconda.org/hep-forge</u>
  — Docker: HEPDock containers available: <u>https://hub.docker.com/repository/docker/hepdock/root/tags</u>

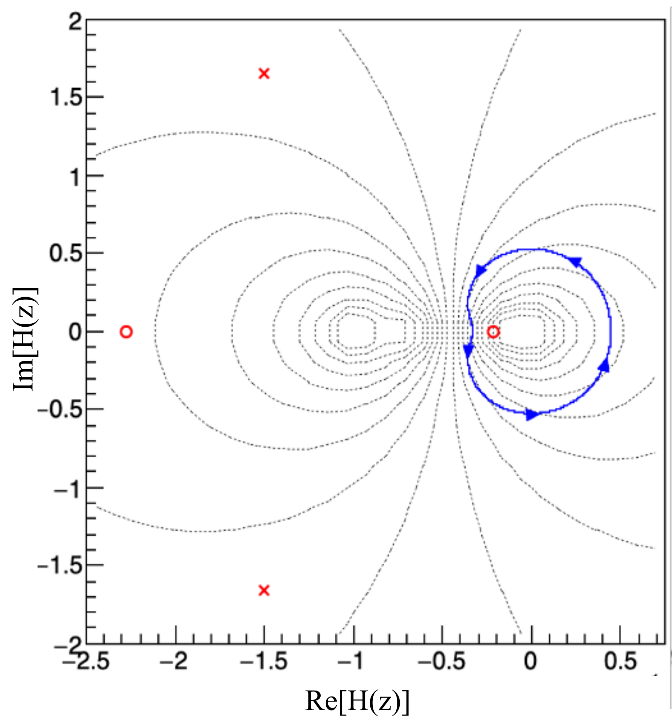
(A) Advanced Signal library & (B) ROOT+ library

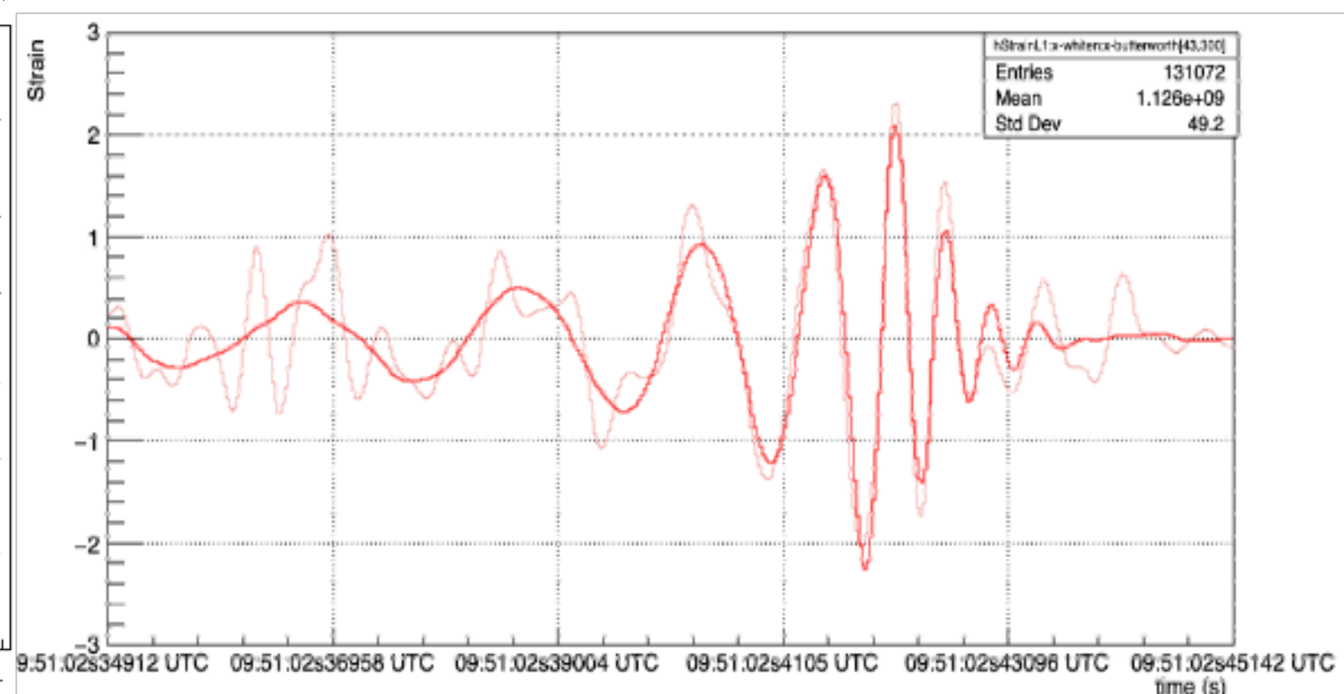
- Signal processing in particular FFT computing is involving different backends:
  - — For CPU computation: KFR as a FFTW replacement.
  - — For GPU calculations are performed using libTorch with generic tensor implementations
- Analog and digital filter H = B/A implementations. (ZPK, BA, SOS, SS representations)
  - — Finite/Infinite Impulse Response filtering + Chebychev, Butterworth, Elliptical filters
- Implementation of libTorch: a TTensor class for complex matrix calculation
  - — Next Generation AI: any model available with Torch and ONNX compatible is compatible.
  - — CPU/GPU computation seamlessly available thanks to libTorch.

Power Spectrum Density calculation using GW150914 OpenScience data



Example of digital filter implementation
$H(z)=(5.0+3.0z+1.0z^2)/(1.0+5.0z+2.0z^2)$





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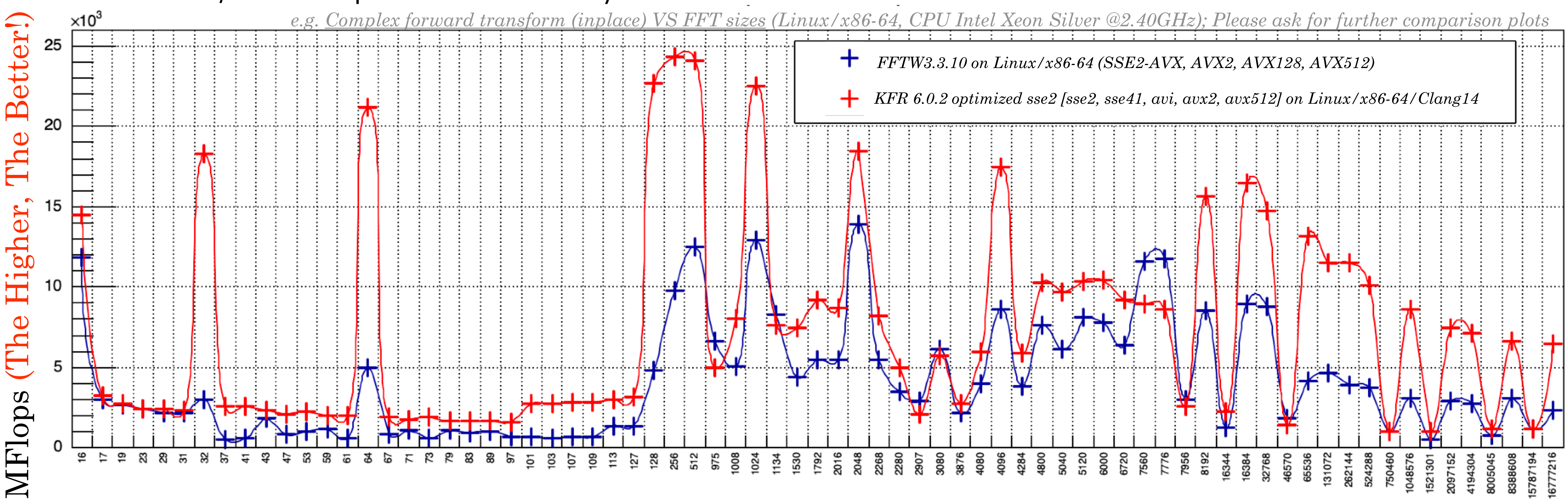
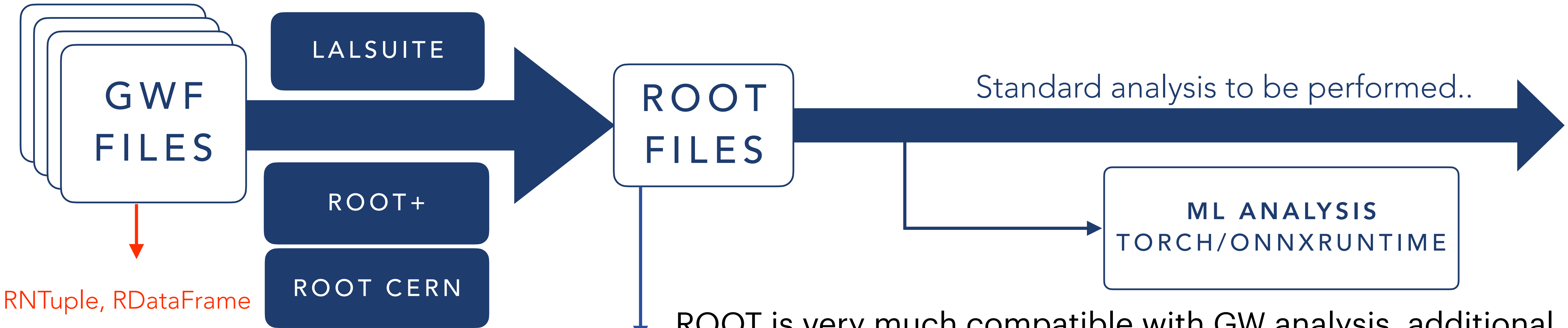
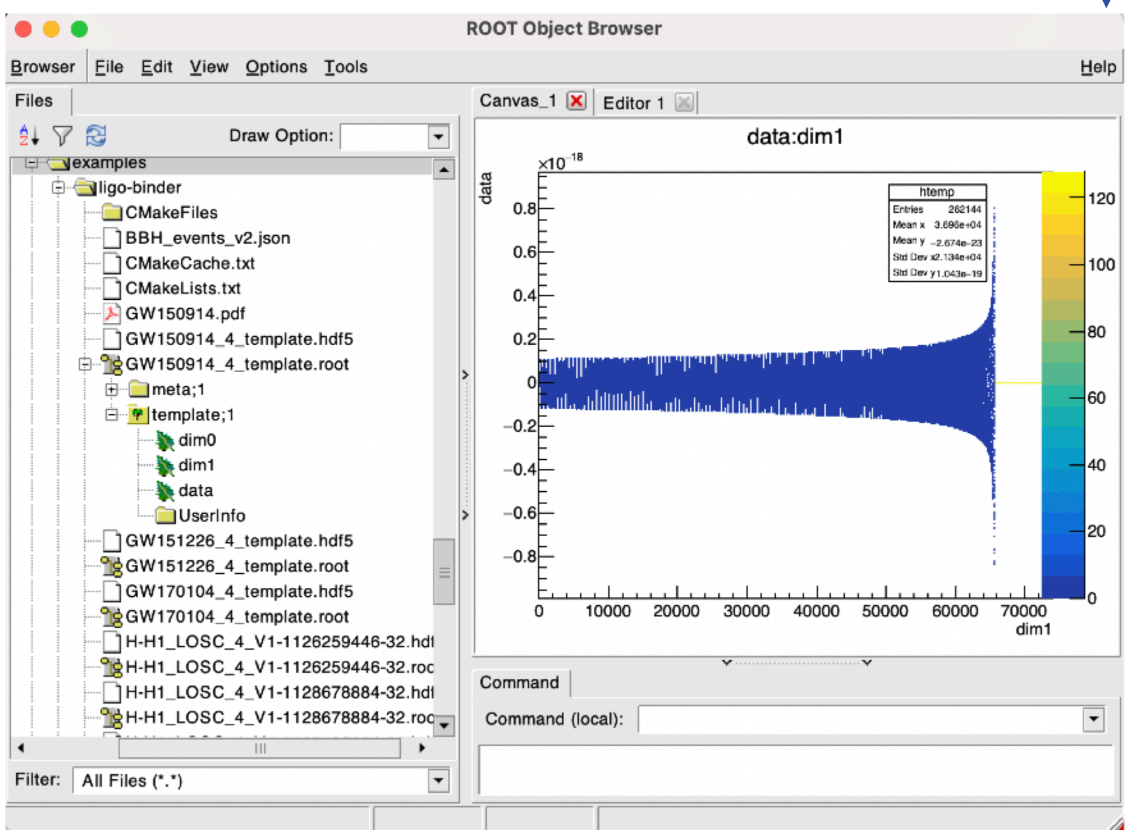


— One of the benchmark test result (Mflops) comparing KFR 6.0.2 with FFTW3.3.10 / The Higher the Better! —

ROOT+ & Advanced Signal libraries





ROOT is very much compatible with GW analysis, additional features (not mentioned today, but available in the link below)

✅ TKafka consumer/broker client prototype

✅ TConfigParser (YAML,JSON,TOML,XML,.. run-time files) prototype

✅ TCurlFile / TArchive prototype (download/cache files and archive handling)

✅ THDF5 parser prototype

✅ TTensorT for complex tensor calculation on the fly (using libTorch for tensor calculation on CPU/GPU)

⏳ ML training/inference via libTorch (being interfaced)

Amazon Simple Storage S3 being finalized for sharing models on the fly with S3 compatible volume

🤗 http://git.ligo.org/kagra/libraries-addons/root/ (+ some on conda hep-channel)

Machine Learning Applications

A Rationale-Augmented CNN for Glitch Classification

(https://iopscience.iop.org/article/10.1088/2632-2153/ad6391/pdf)

Additional Machine Learning Applications we can discuss after the talk:

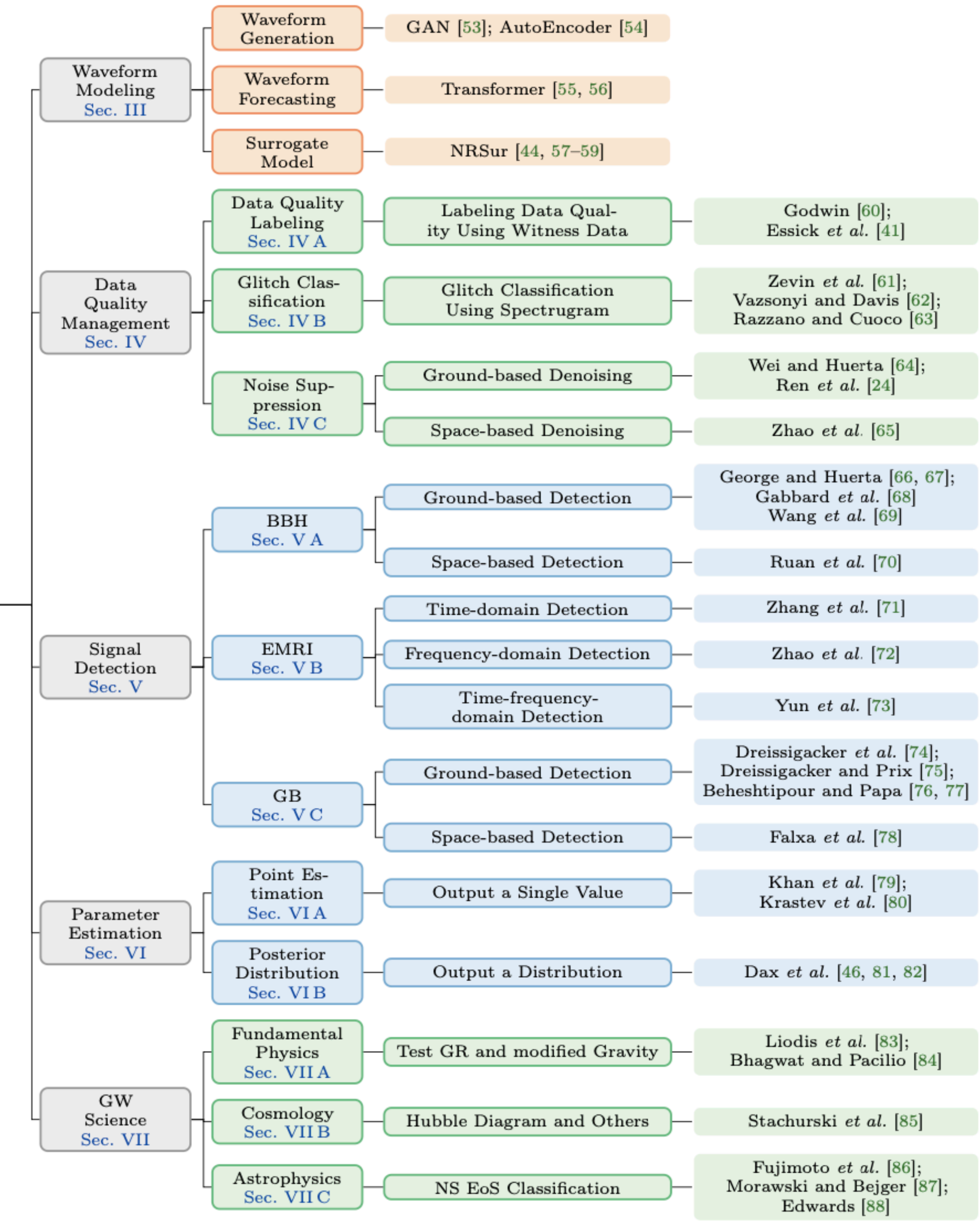
Noise subtraction using SciNet TimeSeries Network: Suspension Thermal Noise Reduction @ KAGRA

SimCRL Contrastive Learning: Core-Collapse Supernovae (CCSNe) Classification

Transformer Model: Waveform Forecasting for Binary Neutron Star detection

🤖📚 "Dawning of a New Era in GW Data Analysis"

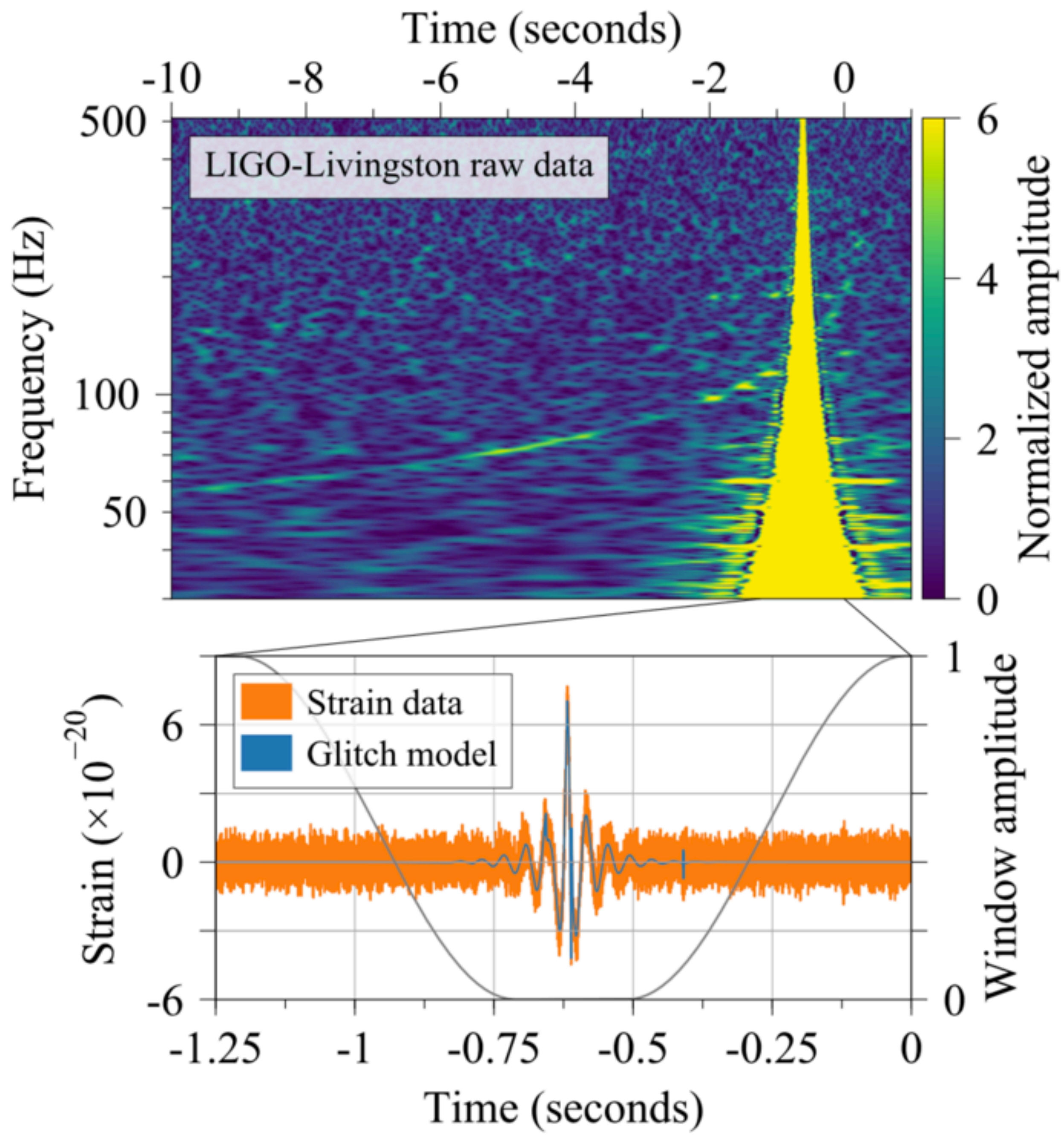
(Zhao et al., arXiv:2311.15585v1)



- A great systematic review paper: "Dawning of a New Era in GW Data Analysis", arXiv:2311.15585v1 *(Zhao et al., 2023)*
- Reference paper in GW: First CNN in Astrophysics "Deep neural networks to enable real-time multi-messenger astrophysics", [*PhysRevD.97.044039*] *(George and Huerta, 2018)*
- Research focus on Waveform forecasting — in collaboration with D3 in Osaka University (with Prof. Nagahara and Prof. Nakashima)

Glitch Classification: Detection of system anomalies

- **What is a glitch in GW signal ?**
  — GW170817: “Very loud” Glitch in Livingstone L1
  — Signal anomaly in the detection system
- **How to catch ?** Q-Transform calculation
  — Highlight transient signal (GW) and glitches
  — Glitch visible in the time series
  — Trigger: Excess of power

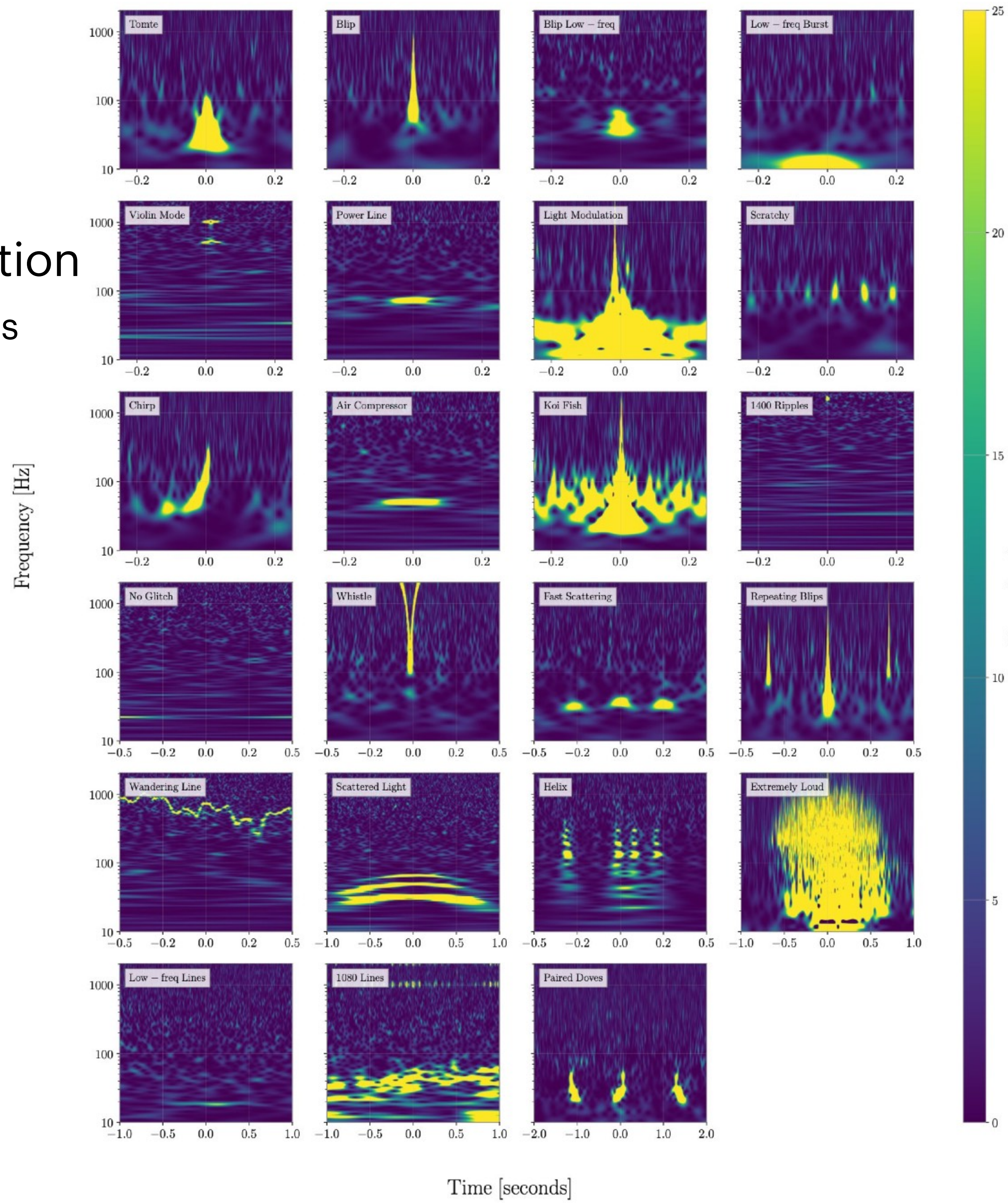


Gravity Spy Database: Publicly available list of known glitches

- **What is a glitch in GW signal ?**
- **How to catch ?** Q-Transform calculation
  - — Highlight transient signal (GW) and glitches
  - — Glitch visible in the time series
  - — Trigger: Excess of power

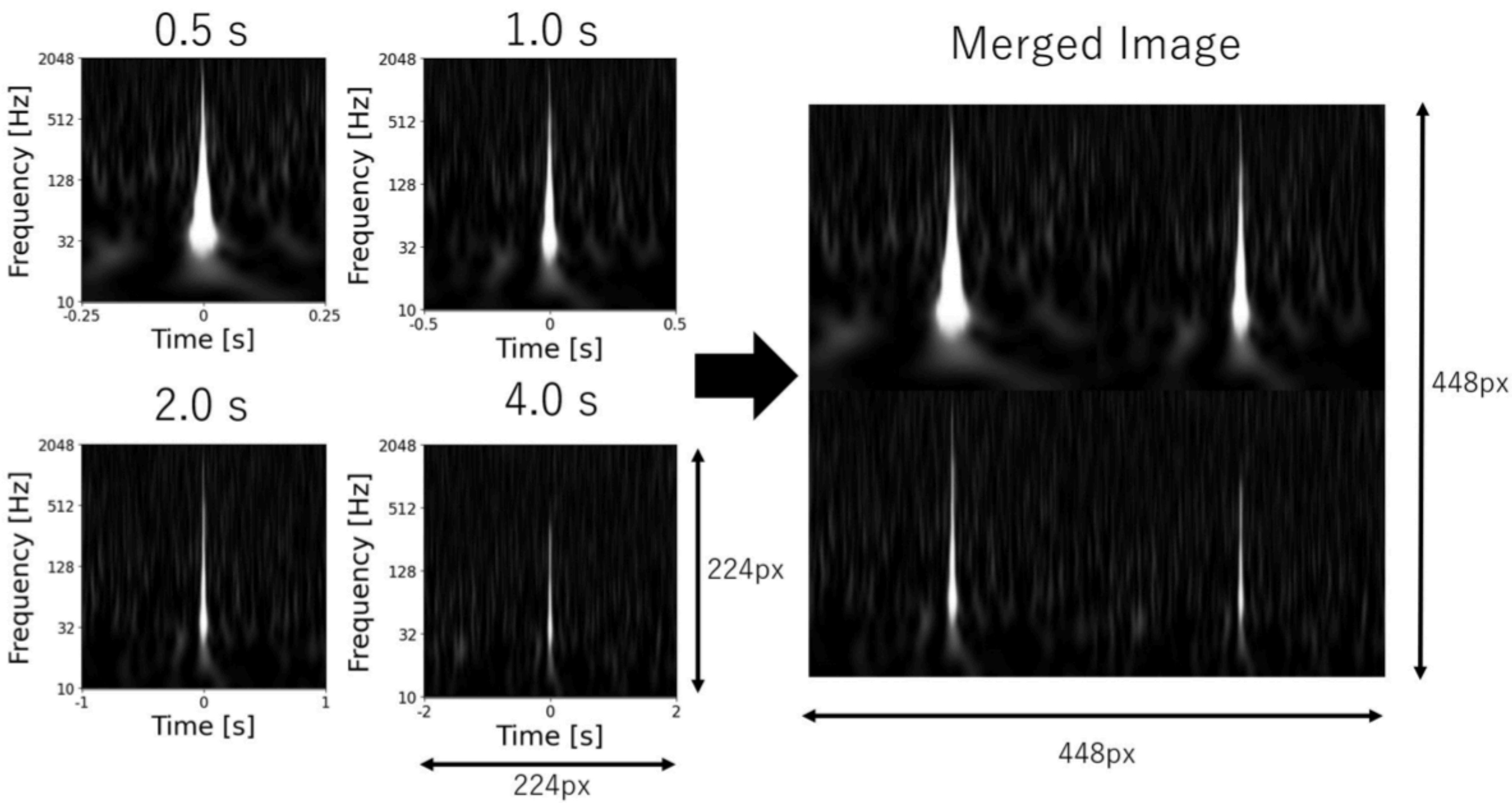
- **Glitch Characterizations**
  - — Around 26 glitches found since O1
  - — Glitches have various shapes
  - — Classify to detect system failure (air cooling, malfunctions)

- **Goal:** Improve GW Data Quality



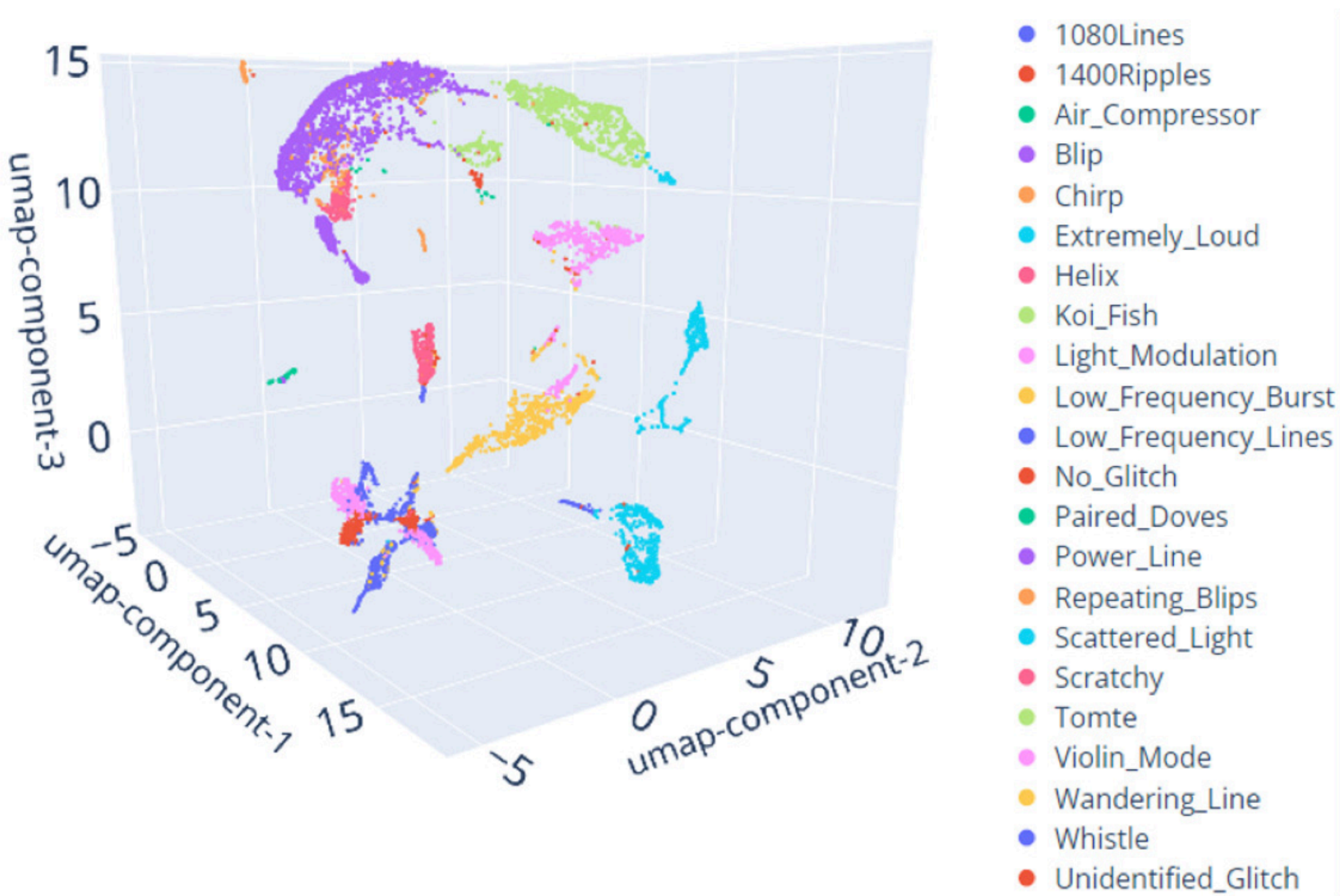
A Rationale-Augmented CNN for Glitch Classification 🐛

(https://iopscience.iop.org/article/10.1088/2632-2153/ad6391/pdf)



A Rationale-Augmented CNN for Glitch Classification 🐛

- **Visualization using UMAP:**
  — Uniform Manifold Approximation and Projection for Dimension Reduction
  — Dimension reduction, find clusters depending on shapes
  — ML label comparisons before/after tagging
- **Find cluster for pre-tagging, find features in embedded space**



A Rationale-Augmented CNN for Glitch Classification 🐛

Input Image

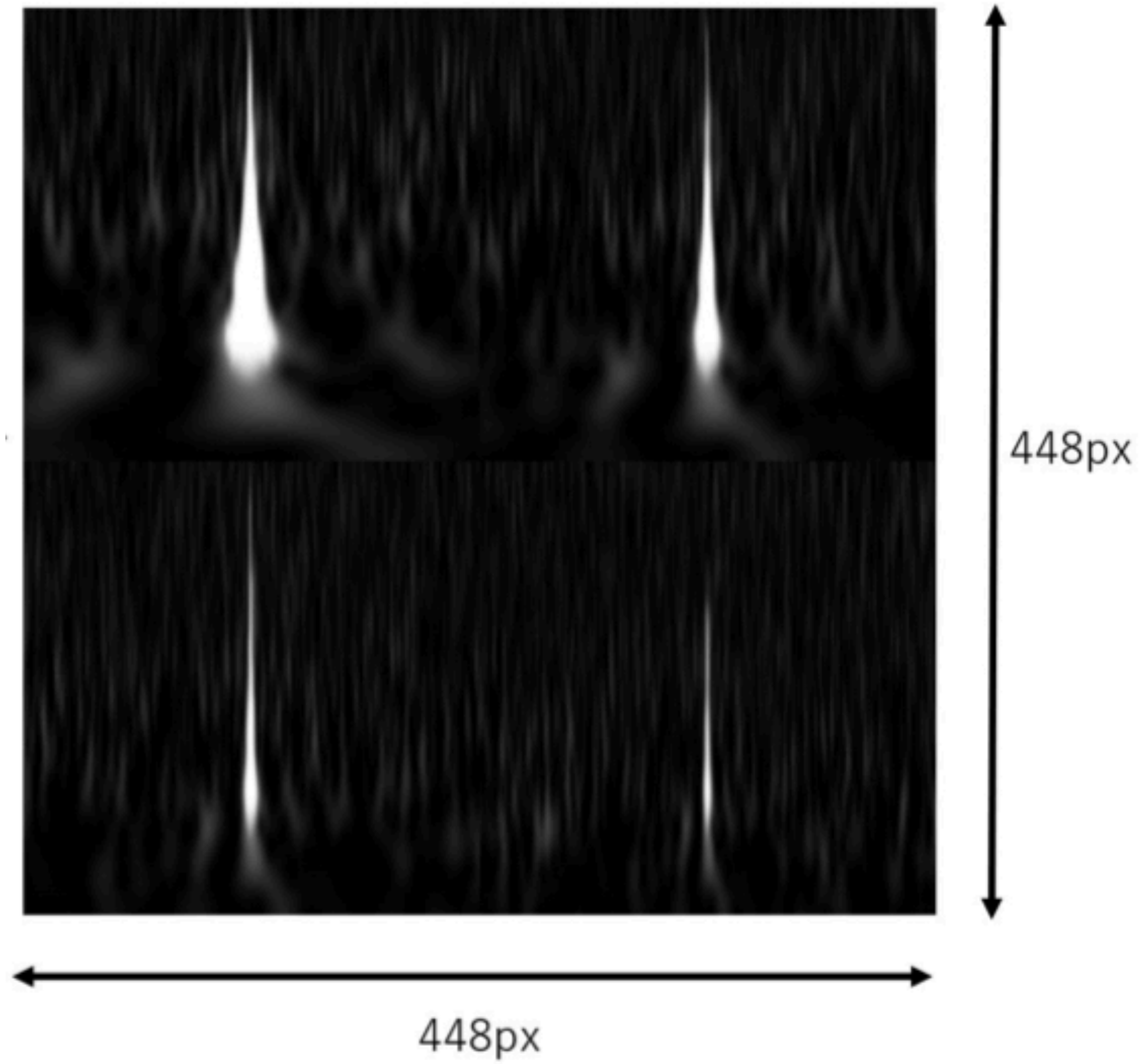
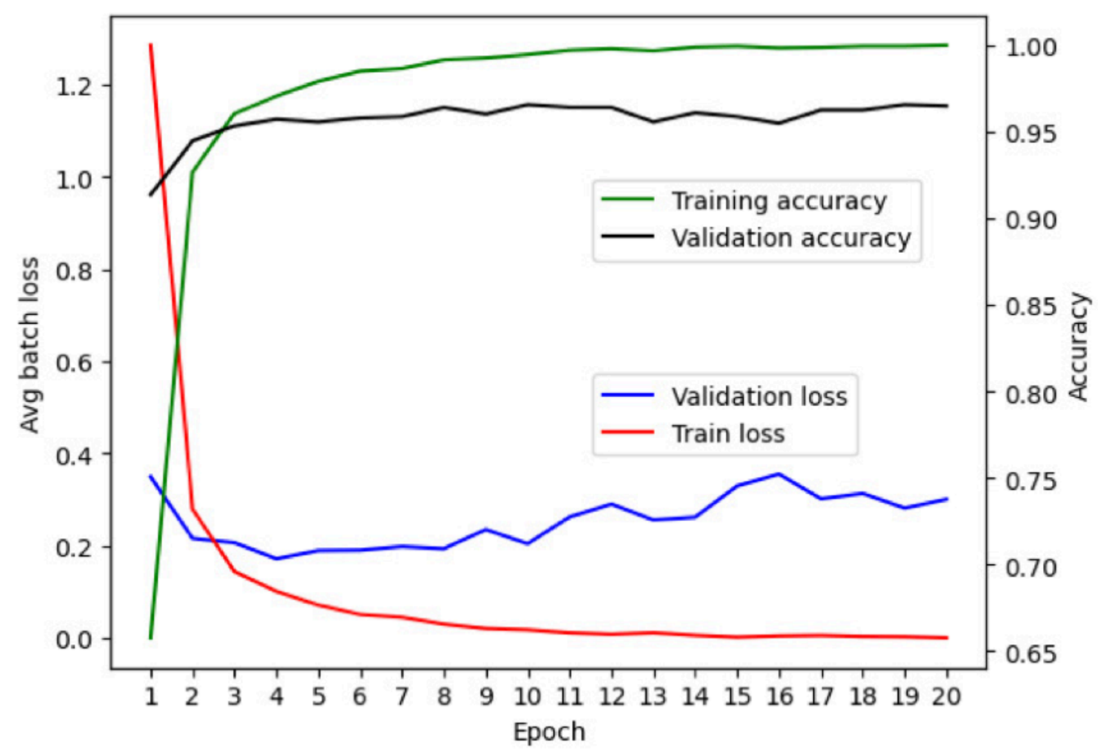


Table 2. CNN architectures for glitch classification.

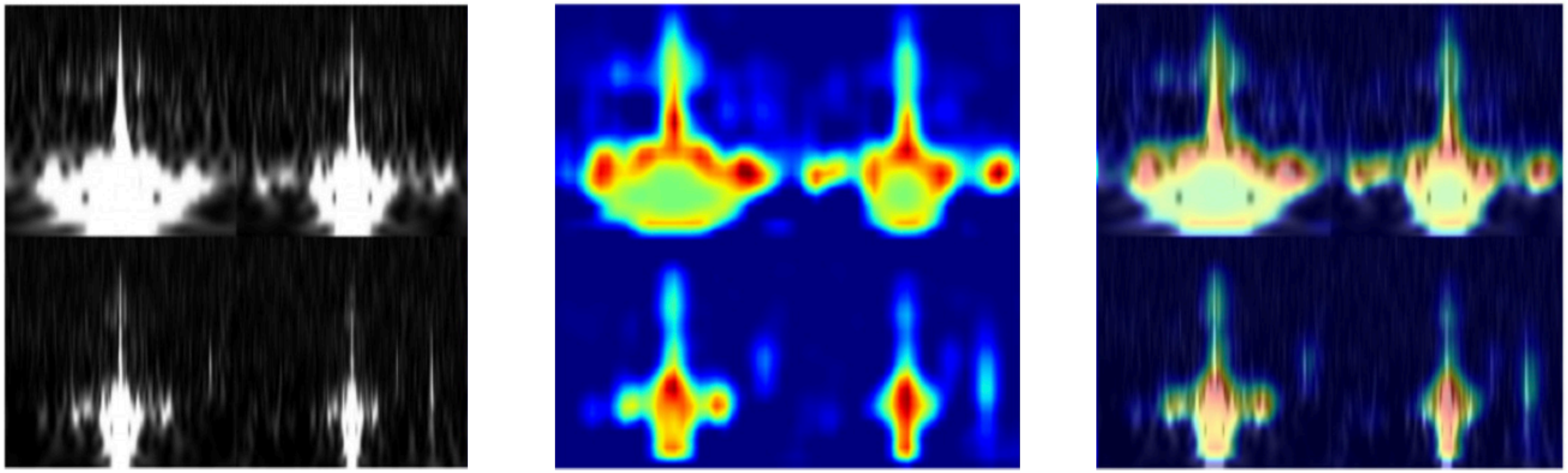
Bahaadini *et al.* [22]	In this study
Input 94 × 114	Input 448 × 448
5 × 5 Convolutional layer (128)	5 × 5 Convolutional layer (32) with ReLU
2 × 2 Max-pooling layer	2 × 2 Max-pooling layer
ReLU	
5 × 5 Convolutional layer (128)	5 × 5 Convolutional layer (32) with ReLU
2 × 2 Max-pooling layer	2 × 2 Max-pooling layer
ReLU	
	5 × 5 Convolutional layer (64) with ReLU
	2 × 2 Max-pooling layer
	5 × 5 Convolutional layer (64) with ReLU
	2 × 2 Max-pooling layer
	5 × 5 Convolutional layer (128) with ReLU
Fully connected layer (256)	Fully connected layer (100352)
Softmax (20)	Softmax (22)

CNN + FC layers



A Rationale-Augmented CNN for Glitch Classification 🐛

- **Koi Fish**



Input *Heatmap* *(Score-CAM)* *Superposition*

- Confirmation of the glitch shape using Score-CAM heat map.
- Score-CAM provide additional interpretability to ensure we are triggering on true features.

Summary

- **A Rationale-Augmented CNN for Glitch Classification**
  — Classification of glitches, visualization using UMAP
  — Score-CAM improve rationale

  N.Koyama, Y.Sakai, S.Sasaoka, D.Dominguez, K.Somiya, Y.Omae, Y. Terada, M.Meyer-Conde and H.Takahashi, Mach. Learn.: Sci. Technol. 5 035028 (2024)

- **Software bridging HEP-GW**
  — Modernization of our analysis tools
  (download on-the-fly, configuration file reading & writing, Amazon Cloud S3 storage)
  — Software deployment and containerization using docker.

  — Implementation of complex filtering (also useful in HEP signal processing analysis)
  — Complex Tensor calculation (using Torch CPU/GPU acceleration)
  — Machine learning inference (and ultimately training) is upcoming.

Thank you for your attention!