Prospects for O4 of LIGO-Virgo-KAGRA

Max Lalleman on behalf of BelGrav

be.hep meeting Summer Solstice Mons

ULB:

- Eleni Bagui (CBC/SGWB)
- Sébastien Clesse (CBC/SGWB)

UCL:

- Antoine Depasse (CW)
- Matthias Vereecken (CBC)
- Federico De Lillo (SGWB)
- Jishnu Suresh (SGWB)
- Stavros Venikoudis (SGWB)
- Giacomo Bruno (SGWB)
- Ricardo Cabrita (Instrumentation)
- Morgane Zeoli (Instrumentation)
- Joris van Heijningen (Instrumentation)
- Andres Jorge Tanasijczuk (Computing)

ULiège:

- Jean-René Cudell (CBC)
- Vincent Boudart (Burst)
- Maxime Fays (Burst)
- Morgane Zeoli (Instr.)

BelGrav

VUB:

- Simone Blasi (SGWB)
- Hannah Duval (SGWB)
- Aäron Rase (SGWB)
- Alba Romero-Rodríguez (SGWB)
- Kevin Turbang (SGWB)
- Alberto Mariotti (SGWB)
- Alexander Sevrin (SGWB)

UGent:

- Freija Beirnaert (CBC)
- Gergely Dálya (Burst/CBC)
- Cezary Turski (CBC)
- Archisman Ghosh (CBC)
- Daniela Pascucci (Instrumentation)

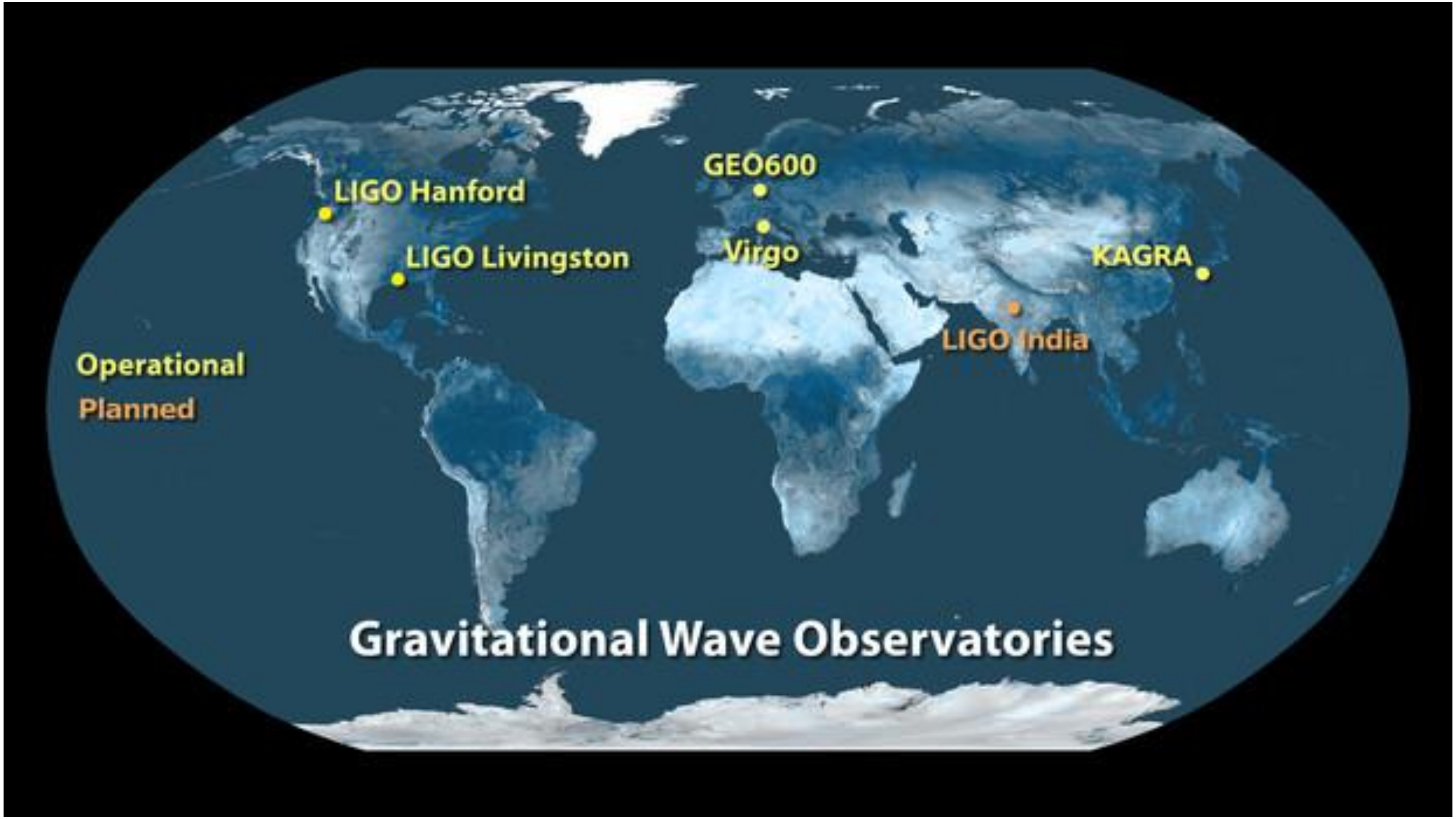
UAntwerpen:

- Guillaume Boileau (SGWB)
- Kamiel Janssens (SGWB)
- Max Lalleman (SGWB)
- Kevin Turbang (SGWB)
- Nick van Remortel (SGWB)
- Anoop Koushik (Instrumentation)
- Kumar Akhil Kukkadapu (Instrumentation)
- Pengbo Li (Instrumentation)
- Hans Van Haevermaet (Instrumentation)

KULeuven in Virgo:

- Alberto Binetti
- Thomas Hertog
- Wei-Fan Hsu
- Tjonnie Li
- Jean-Pierre Locquet
- Simon Maenaut
- Simon Mellaerts
- Arthur Offermans
- Maria Recaman
- Koen Schouteden
- Jin Won Seo
- Milan Wils

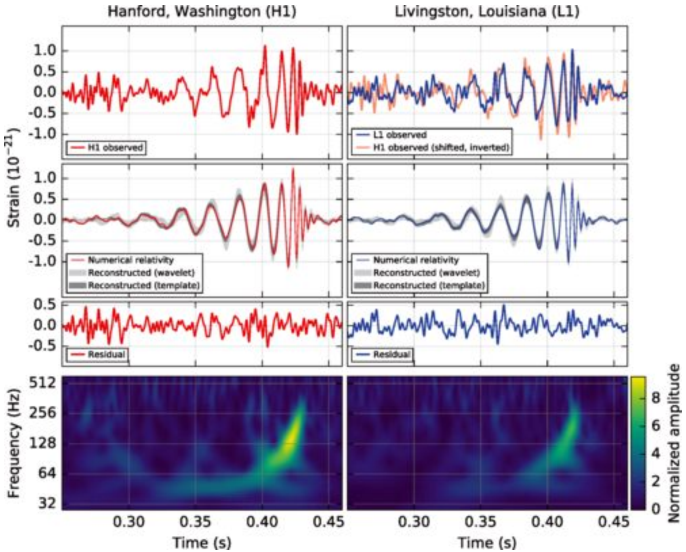
LIGO-Virgo-KAGRA (LVK)



https://www.ligo.caltech.edu/image/ligo20160211c

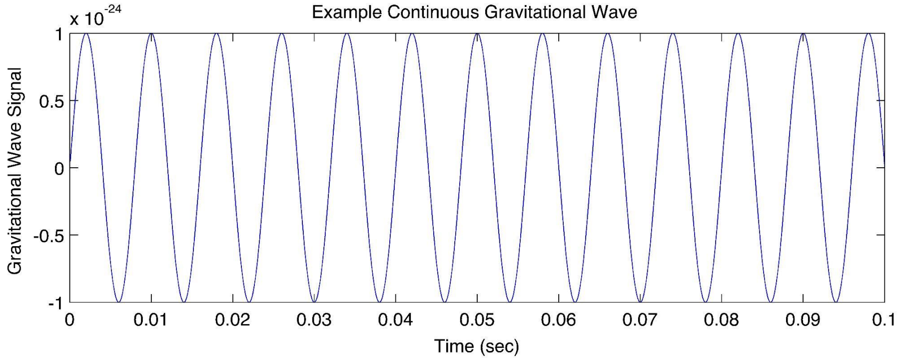
Structure of LVK

Inspiral



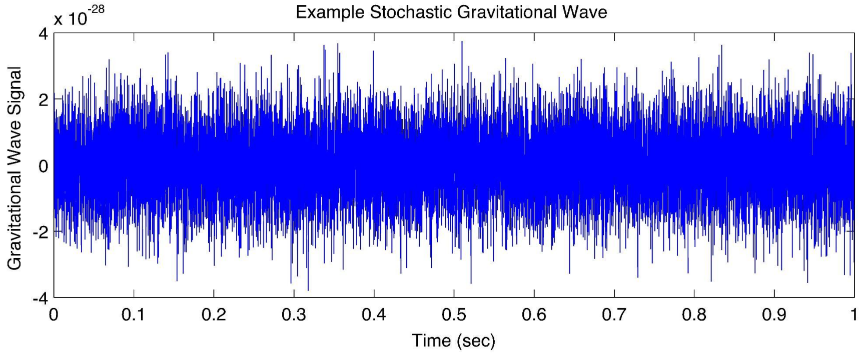
[Phys. Rev. Lett. 116, 061102]

Continuous Waves



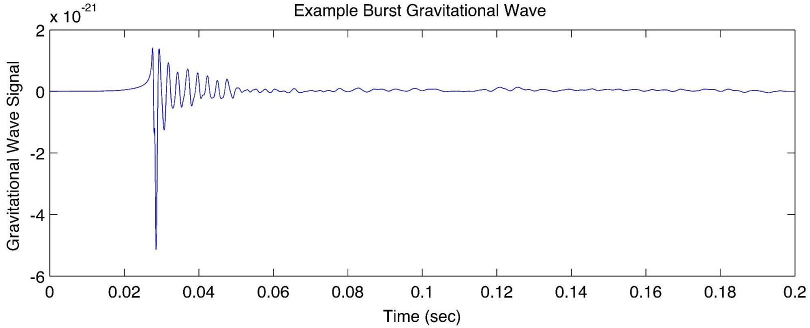
https://www.ligo.org/science/GW-Continuous.php

Stochastic gravitational-wave background



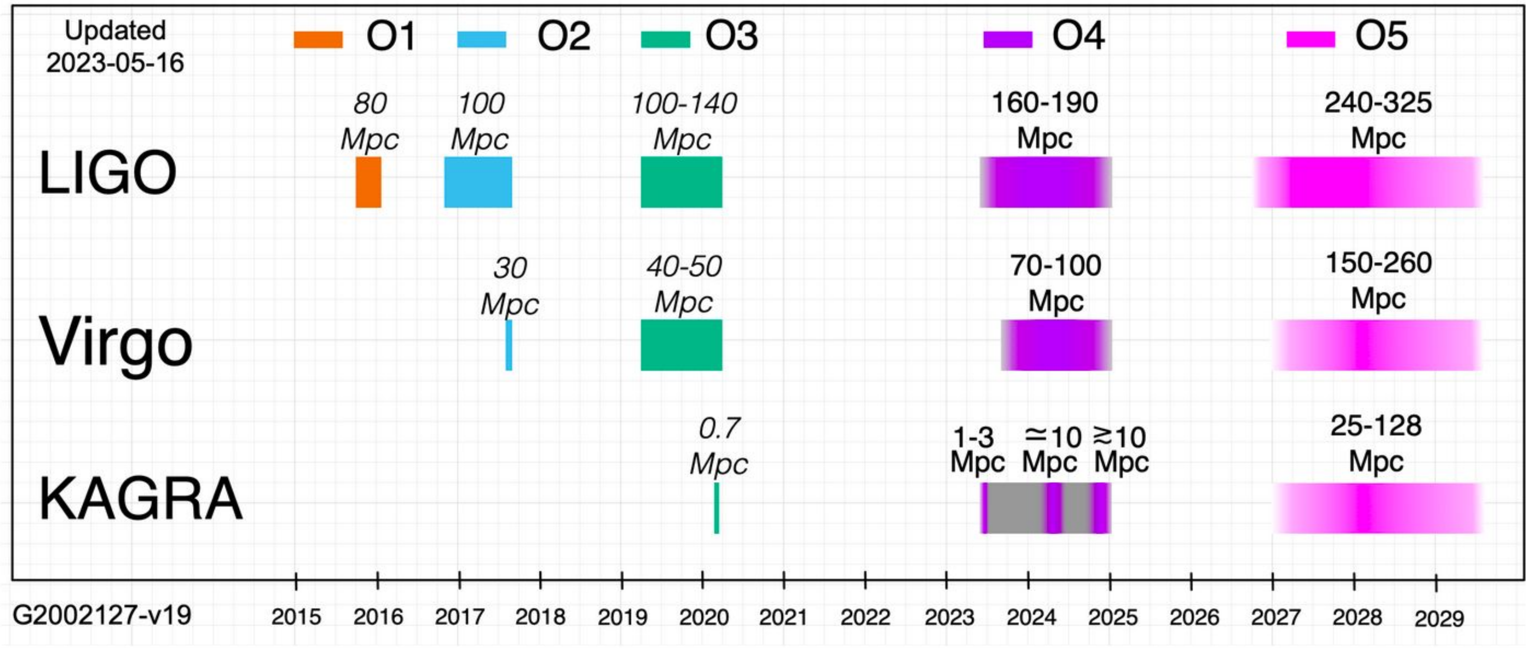
https://www.ligo.org/science/GW-Stochastic.php

Burst



https://www.ligo.org/science/GW-Burst.php

Observing runs, what are they?



https://observing.docs.ligo.org/plan/

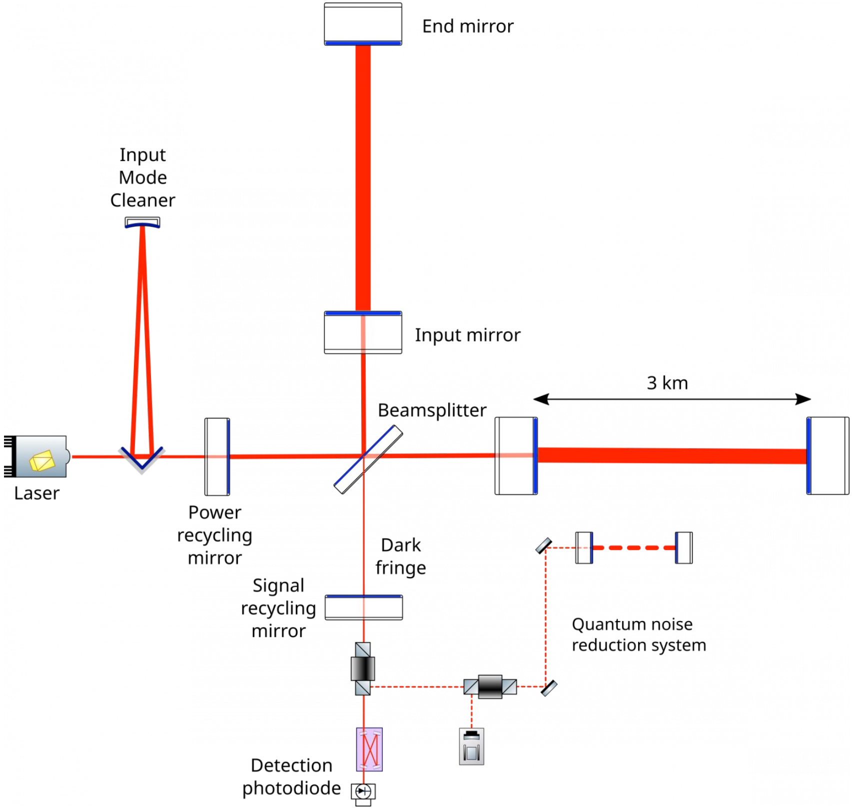
First merger event in O1, now ~ 100 discoveries

Experimental updates in O4

How to achieve these goals?

LIGO:
- Increasing Arm Power
- Frequency dependent Squeezing + new cavity
- Squeezed light efficacy
- Low frequency noise reduction

Virgo:
- Signal Recycling Cavity
- Increased Input Power
- Input Mode Cleaner Payload
- Frequency Dependent Squeezing
- 3 month delay in joining O4



https://www.virgo-gw.eu/science/detector/optical-layout/

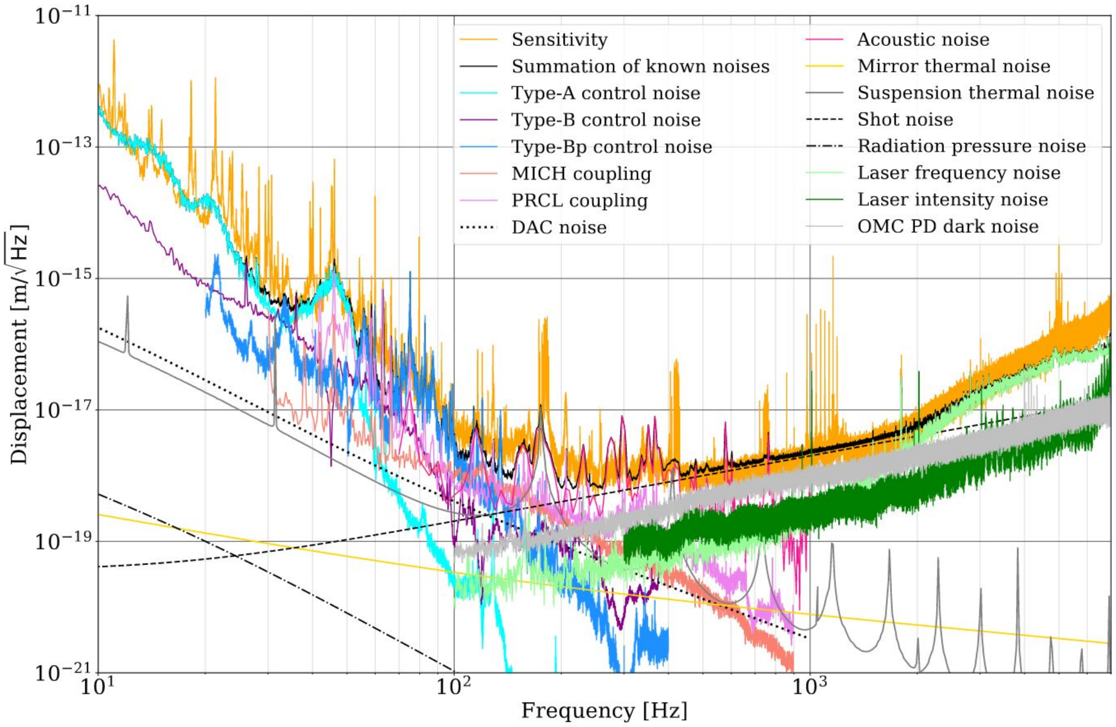
Experimental upgrades O4: KAGRA

What is special about KAGRA?

- Cryogenic to reduce thermal noise
- Underground
- Will ramp up sensitivity quickly next few years
- Did official first run after end of O3 with GEO: O3GK (Prog. of Theor. and Exp. Phys. ptac093)

Added for O4:

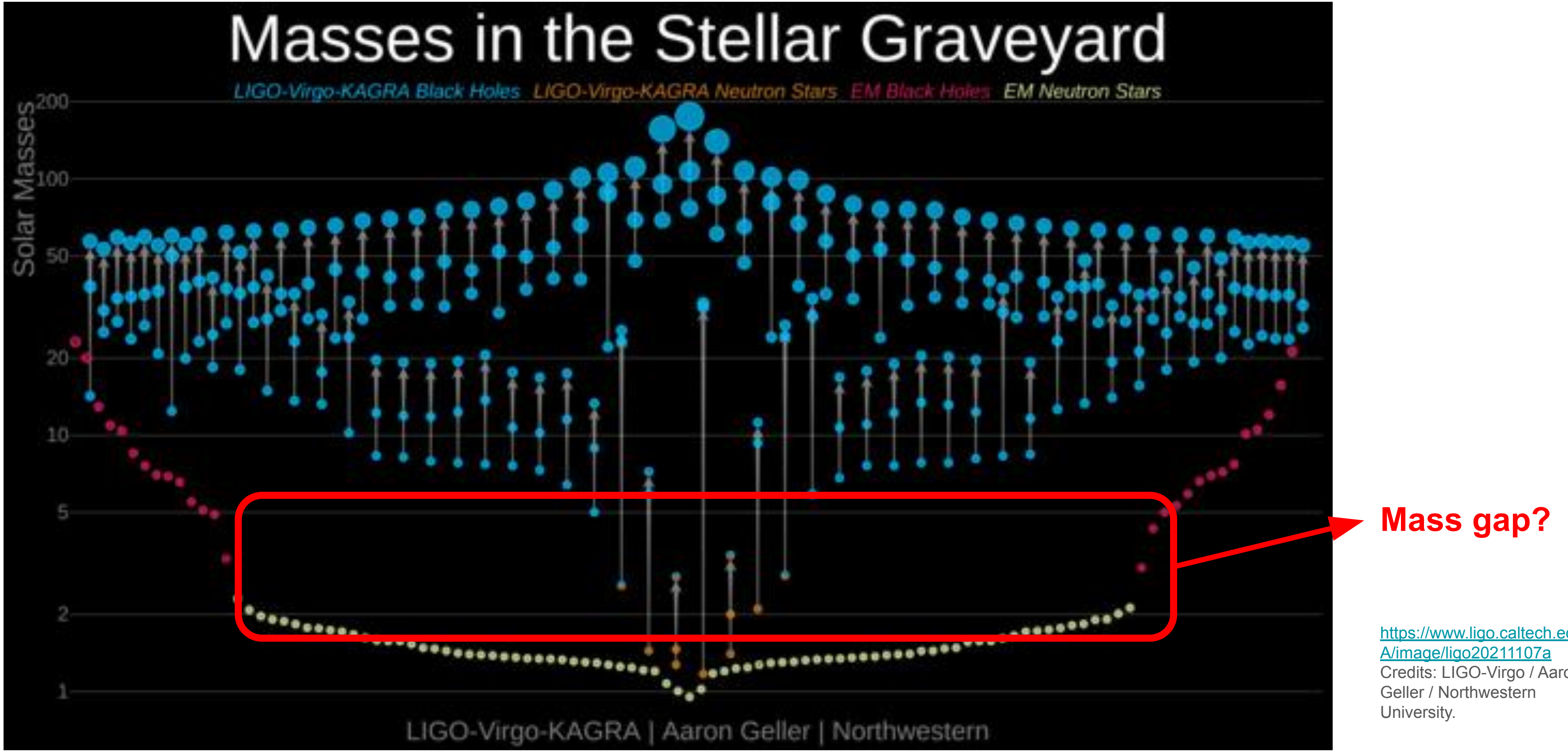
- Increased laser power
- Angular Sensing Control
- Baffles
- Mirrors at cryogenic temperature
- Lock can now be achieved even with disturbance of sea waves.



Prog. of Theor. and Exp. Phys. ptac093

Inspiral/CBC

What have we seen already?



https://www.ligo.caltech.edu/LA/image/ligo20211107a
Credits: LIGO-Virgo / Aaron Geller / Northwestern University.

CBC

Expected amount of events:

- ~ 100s of binary black holes
- ~ 10 events with neutron stars
- ~ O(1) multimessenger event
- Unknown exceptional events

Keep an eye on our public alert database: https://gracedb.ligo.org/ or check out

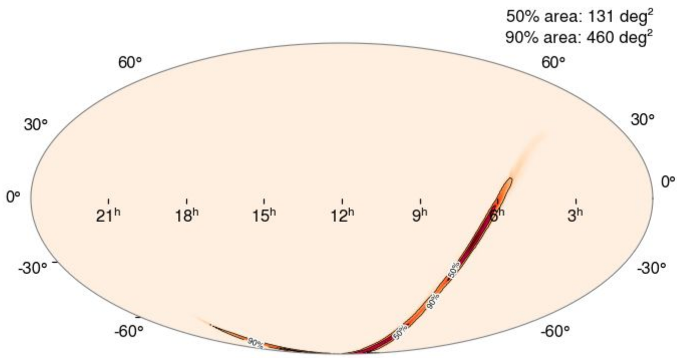
https://emfollow.docs.ligo.org/userguide/, https://wiki.gw-astronomy.org/OpenLVEM

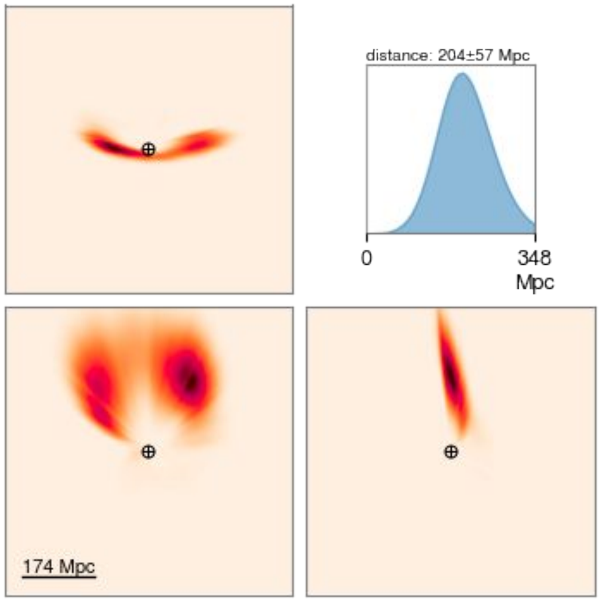
Some alerts have already been pushed out (https://gcn.nasa.gov/circulars?query=LIGO%2FVirgo)

S230518h -> FAR: 1 per 98.463 years

https://gcn.nasa.gov/circulars/33813: NSBH candidate

GraceDB: https://gracedb.ligo.org/superevents/S230518h/view/





CBC

Looking at released O3 papers:

KULeuven in Virgo

- ➔ Catalog paper https://arxiv.org/abs/2111.03606
- ➔ Tests of GR https://journals.aps.org/prd/accepted/17075Qf4Z7b11729787e85f1c18faca230d51e013, https://arxiv.org/abs/2112.06861
- ➔ Fast Radio Bursts GW Follow-up https://arxiv.org/abs/2203.12038
- ➔ Lensing of O3 BBH https://arxiv.org/abs/2304.08393

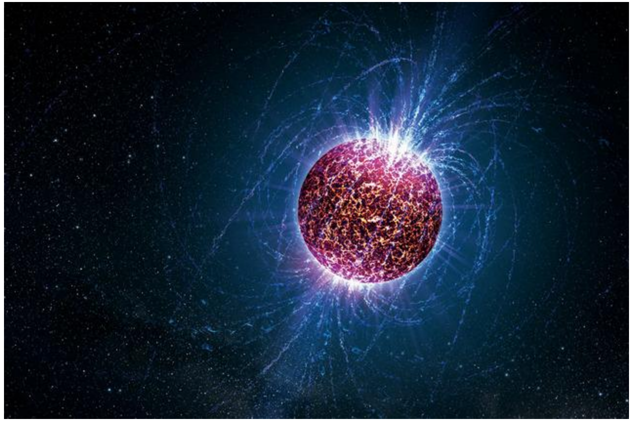
KULeuven in Virgo

BelGrav

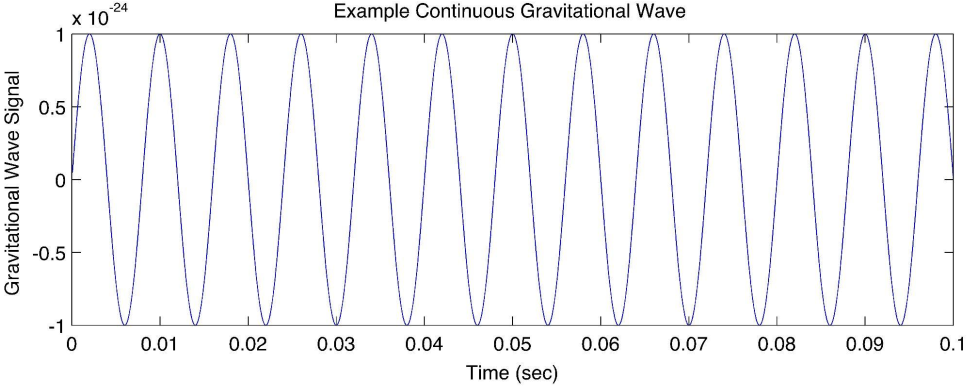
- ➔ Neutrinos and GWs from CBCs (in AGN accretion disk)
- ➔ Subsolar mass CBCs (Monthly Notices of the RAS, stad588, https://arxiv.org/abs/2301.11619)

Continuous Waves

- Search for continuous GW signals, e.g. spinning neutron stars
- Monochromatic, but weak signal



https://cw.docs.ligo.org/public/



https://www.ligo.org/science/GW-Continuous.php

- We are ready to make the first CW detection
- Collaboration with stochastic group on dark photon as DM
- Spin-down limit has been reached.

CW: Searches

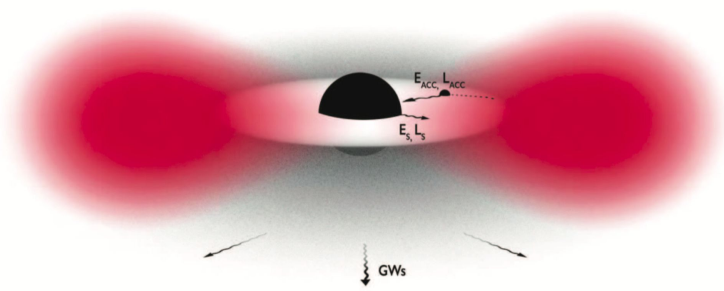
Multiple types of searches:

- Targeted searches -> Known pulsars
- Directed searches -> Known non-pulsar sources
- All-sky searches -> Blind search for e.g. non-EM pulsars
- Also probing for exotic physics, like DM interaction and Boson clouds.

BelGrav

Ultra-light boson cloud GW creation.

➔ Extracting energy from BH
➔ Bosons annihilate and GWs are emitted
➔ Focus on signals from known binary systems



https://cga.anu.edu.au/research/projects/gravitational-waves-ultralight-boson-clouds-around-black-holes

Burst

Low latency pipelines are vetted and tested for O4

Supernovae research

-> Short duration follow-up on interesting supernovae

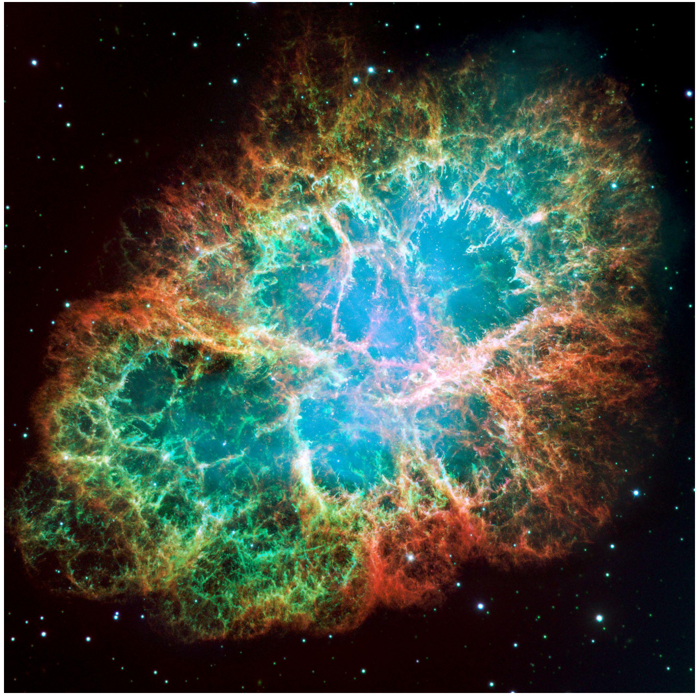
Long duration: final tests for pipelines

Using O3 data, Burst waveform models were injected

-> Challenge to test search pipelines

They worked with CBC on O3 FRB paper

Also preparing for burst detections in O4

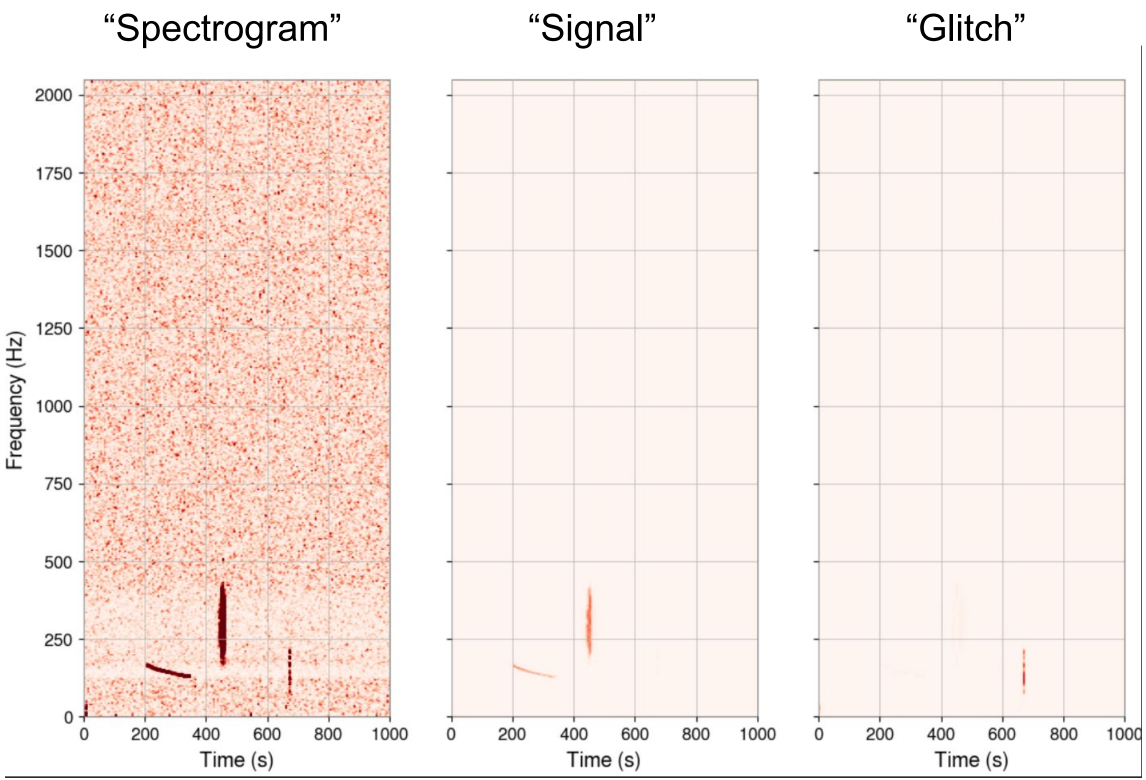


https://airandspace.si.edu/exhibitions/outside-the-spacecraft/online/image-detail.cfm?id=3117, Credit: NASA, ESA, J. Hester (Arizona State University)

Burst: new tool

Developing machine learning pipeline for long duration GWpyxel:

- Classify the “anomaly” of a pixel.
- Train on background using time slides.
- Train with random injected chirp signals
- Capability added to discriminate glitches from signals



Credits: V. Boudart and M. Fays

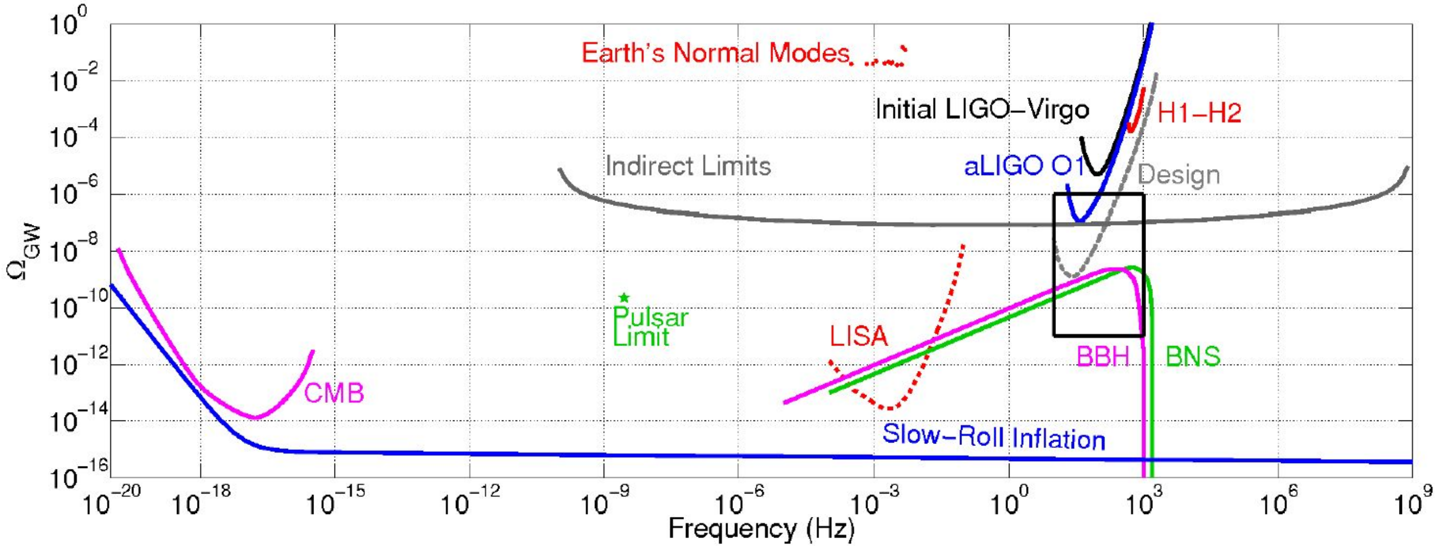
Stochastic background of GW's

Stochastic background is superposition of weak sources.

Rely on cross-correlation data analysis methods.

Two types:

- Astrophysical
- Cosmological



Nelson Christensen 2019 *Rep. Prog. Phys.* **82** 016903

Astrophysical background

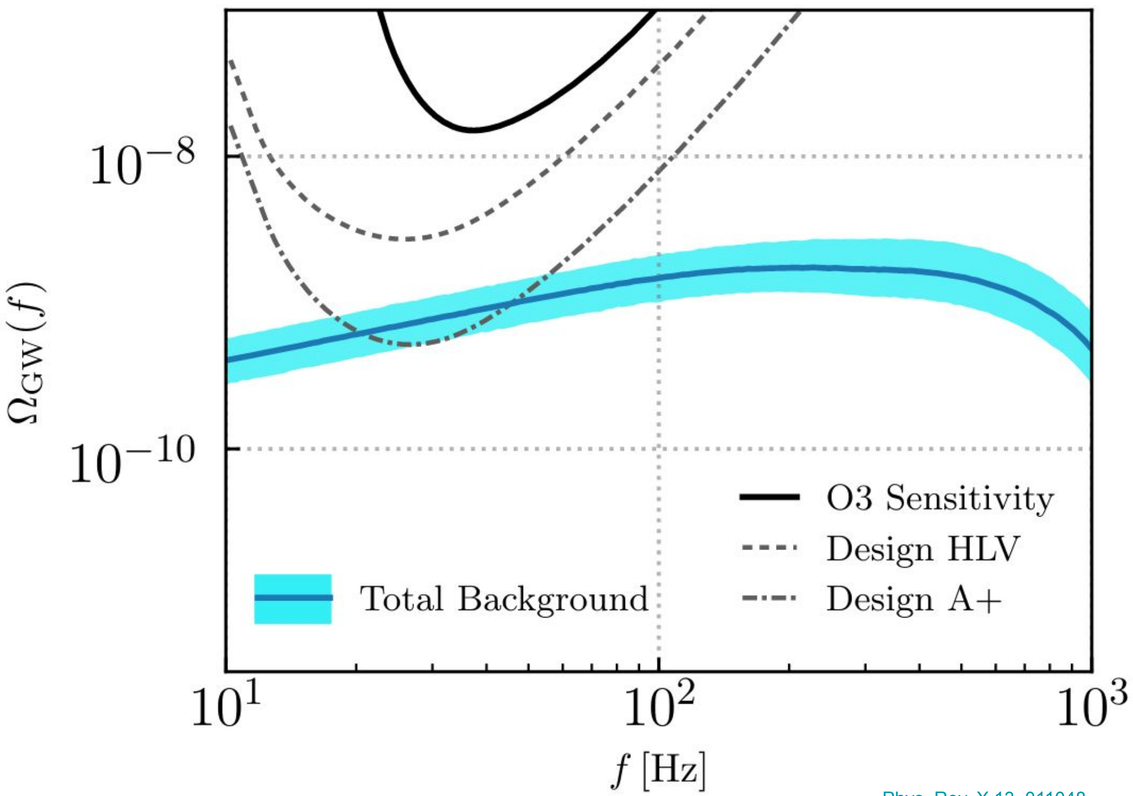
Prospects of discovering the astrophysical background

O5 -> Medium probability

O4 -> Probably not

Still the best known path to first stochastic discovery of LVK

Mock data challenge to prepare for O5 sensitivity

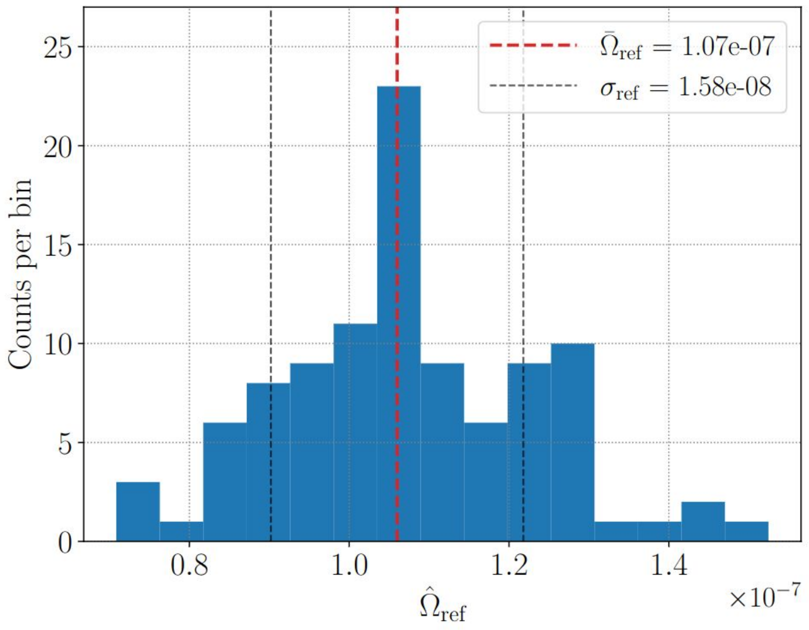


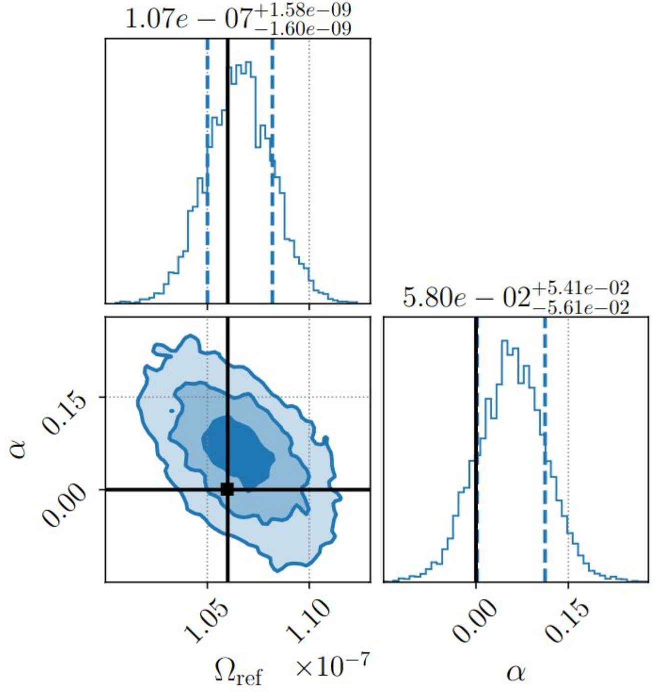
Phys. Rev. X 13, 011048

Isotropic stochastic search

Introduced new pipeline: pygwb, replacing older MATLAB code

- Better performance
- Tested on simulated and real O3 data



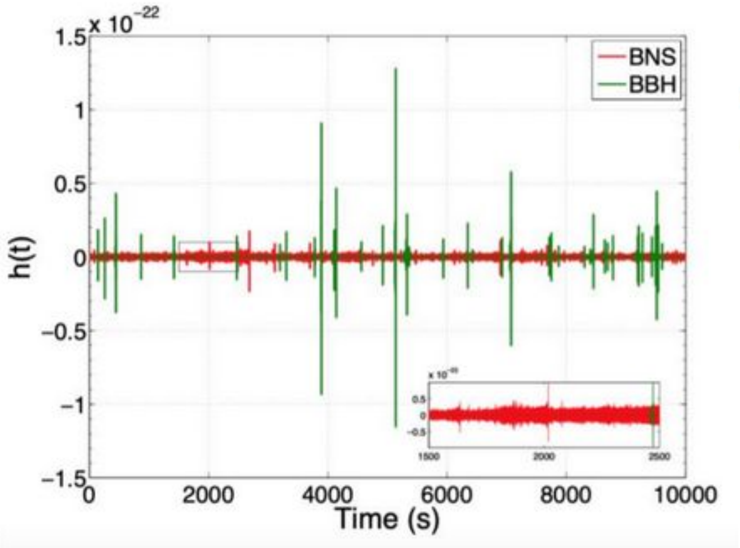


Both from: https://arxiv.org/abs/2303.15696

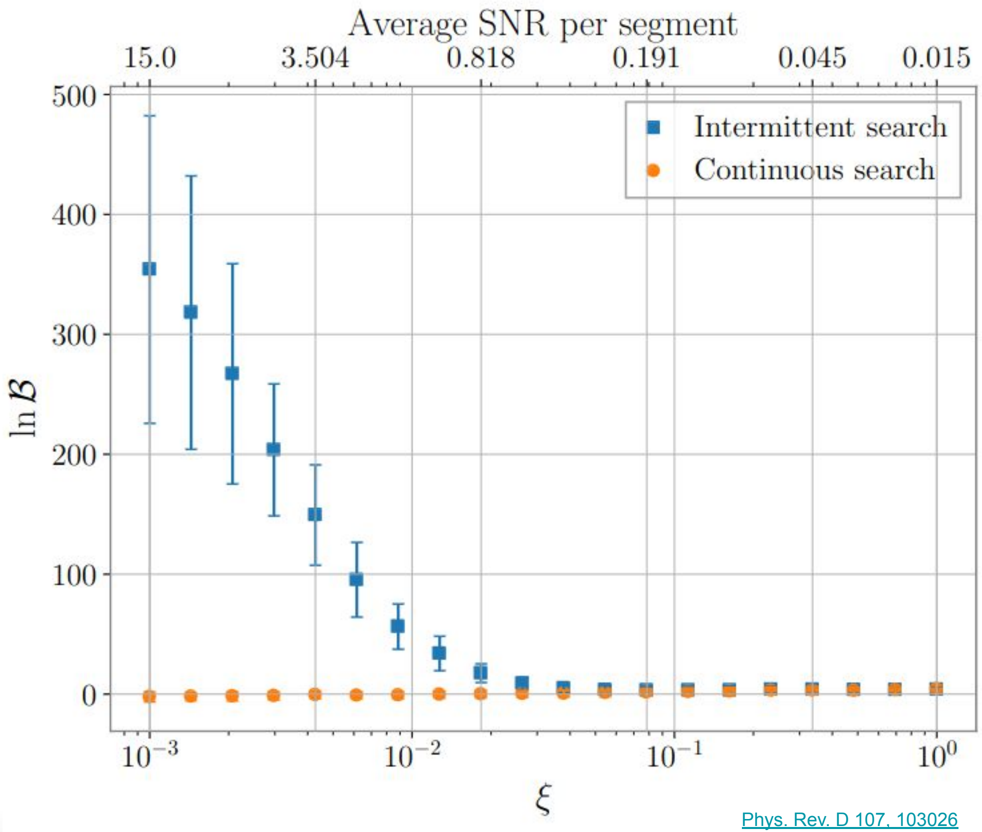
Isotropic search: SSI

SSI or stochastic search for intermittent backgrounds

Step by step getting closer to real data analysis, maybe after O4?



Phys. Rev. Lett. 120, 091101



Phys. Rev. D 107, 103026

Anisotropic stochastic search

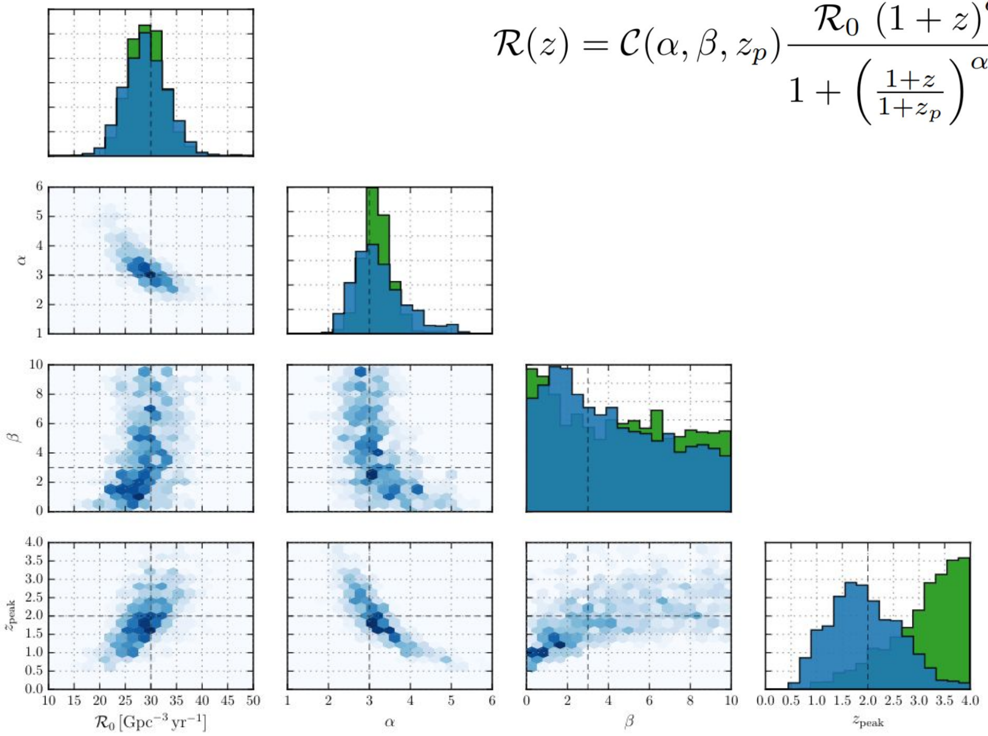
Isotropic averages over directions, what if we do not?

Same pipeline as in O3: PyStoch (Phys. Rev. D 98, 024001)

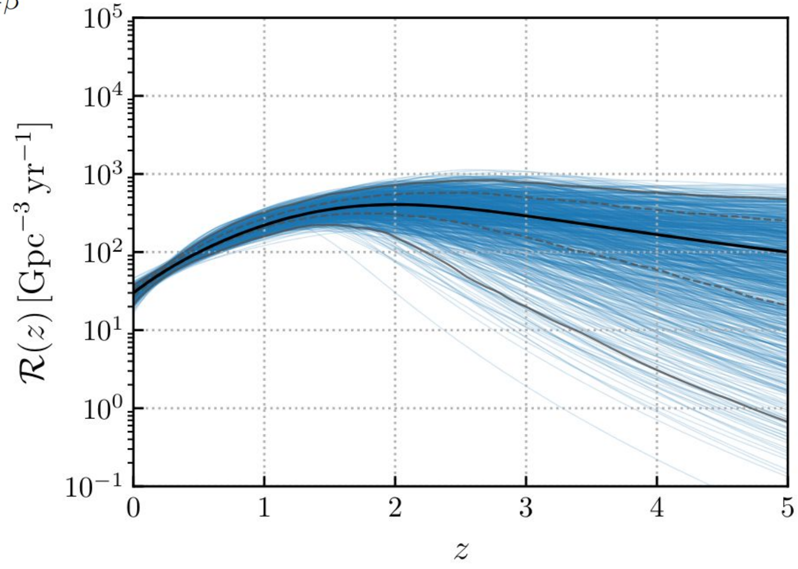
All sky all frequency (ASAF) model-independent analysis as basis

➔ Folded data will be used
➔ Derive narrowband and broadband from it
➔ Spherical harmonics
➔ In case of outliers -> frequency info given to CW and DQ

Astrophysical Implications and PE



$$\mathcal{R}(z) = \mathcal{C}(\alpha, \beta, z_p)\frac{\mathcal{R}_0\,(1+z)^{\alpha}}{1+\left(\frac{1+z}{1+z_p}\right)^{\alpha+\beta}}$$

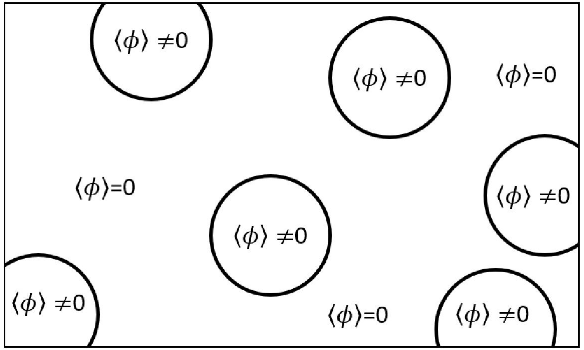


Both from: Tom Callister *et al* 2020 *ApJL* **896** L32

Cosmological Implications and PE

Multiple exotic models exist.

- ➔ Domain walls
- ➔ First Order Phase Transitions
- ➔ Stiff Equation / Kination
- ➔ Parity Violation
- ➔ Inflation
- ➔ Primordial Black Holes



Bubbles after FOPT

Credits: K. Turbang

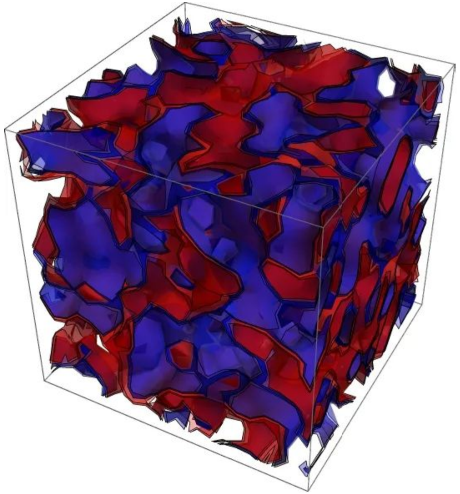


Illustration of domain walls

Credits: A. Rase made with CosmoLattice

Exciting times ahead!

- Many more CBCs to be discovered
  - Able to perform population analysis
- Multimessenger event possible (neutrinos?)
- CW updating pipelines and hoping for first detection
- Bursts pipelines are tested and ready for O4
- Stochastic background searches updated and refined
- O4 and O5 usher in new age of GW: statistics of events

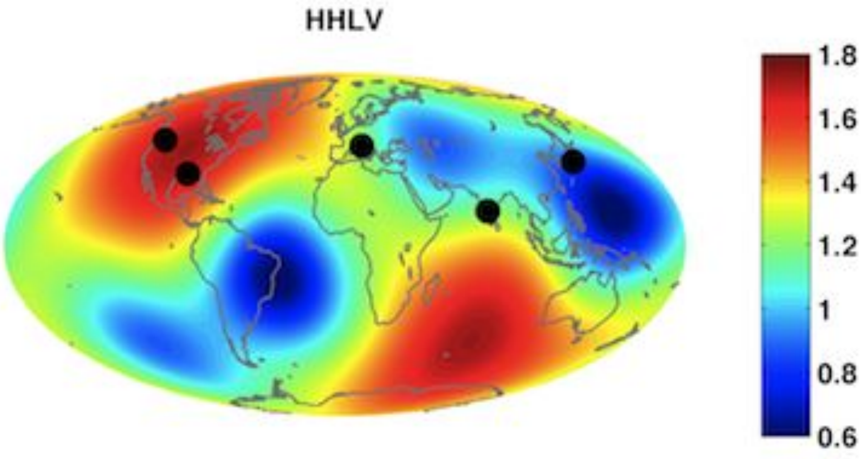
Thanks to everybody who helped me make these slides!

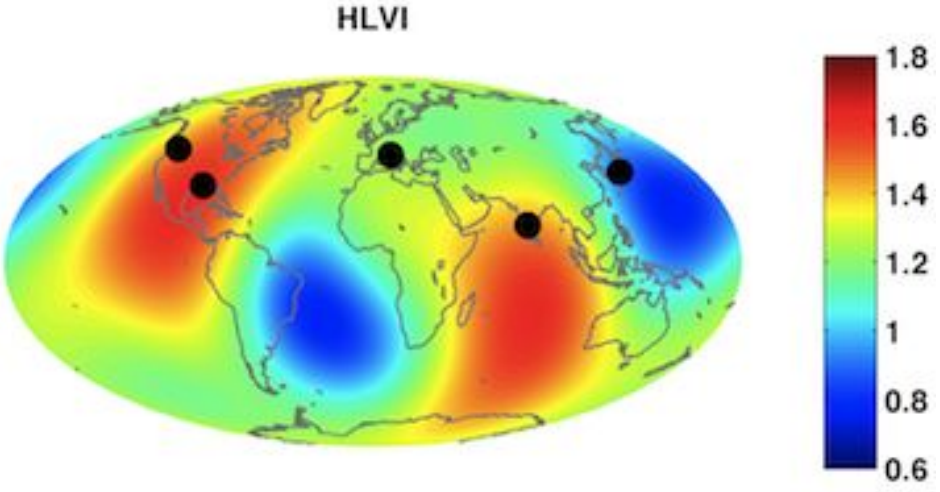
Back-up slides

Structure of O4

- ➔ Started on 24th of May
- ➔ Will last for 20 months
- ➔ Two months of commissioning included
- ➔ Virgo joins later
- ➔ KAGRA joins, goes down, and joins back at the end
- ➔ Approx. 30% more sensitive
- ➔ A merger event every 2 or 3 days

Antenna patterns LVK and benefit of LIGO-India





- + Duty cycle
- + Better localisation

http://www.gw-indigo.org/tiki-index.php?page=Scientific+Benefits+of+LIGO-India

Stochastic detchar

In O3, most work was performed at the end of the run.

Now: more proactive approach

- ➔ Weekly DQ issues follow-up, lines in StochDQShifts.
- ➔ Producing notch lists (bi-)monthly.
- ➔ Workload is spread over more time + more people involved.

Tools:

- ➔ Stochmon: Daily run over data
- ➔ pygwb: (bi-)monthly run
- ➔ Line/comb detection tools: STAMP-PEM, Witspec, Fscan
- ➔ Injections: magnetic, correlated magnetic, hardware

Acronyms

- **LVK**: LIGO-Virgo-KAGRA Collaboration
- **CW**: Continuous Waves
- **SGWB:** Stochastic Gravitational-Wave Background
- **O1-5**: Observing Run 1-5 from LVK
- **CBC**: Compact Binary Coalescences
- **FAR**: False Alarm Rate
- **GW**: Gravitational Wave
- **AGN**: Active Galactic Nuclei
- **MSP**: Milli-Second Pulsars
- **EM**: Electromagnetic
- **DM**: Dark Matter
- **PBH**: Primordial Black Hole
- **DQ**: Data Quality (group)
- **FRB:** Fast Radio Burst

References for figures

[1] Image | Gravitational-Wave Observatories Across the Globe | LIGO Lab | Caltech
[2] Abbott, Benjamin P.; et al. (LIGO Scientific Collaboration and Virgo Collaboration) (2016) “Observation of Gravitational Waves from a Binary Black Hole Merger”. Physical Review Letters. **116** (6): 061102. https://arxiv.org/abs/1602.03837 https://doi.org/10.1103/PhysRevLett.116.061102
[3] https://www.ligo.org/science/GW-Burst.php
[4] https://www.ligo.org/science/GW-Continuous.php
[5] https://www.ligo.org/science/GW-Stochastic.php
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[13] https://airandspace.si.edu/exhibitions/outside-the-spacecraft/online/image-detail.cfm?id=3117
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[20] Turbang, K. The Strong CP Problem and Gravitational Waves