The quest for CCSN gravitational waves: the next 10 years

sn2025gw workshop

Marie Anne Bizouard

Outline: the ingredients of the cooking receipt

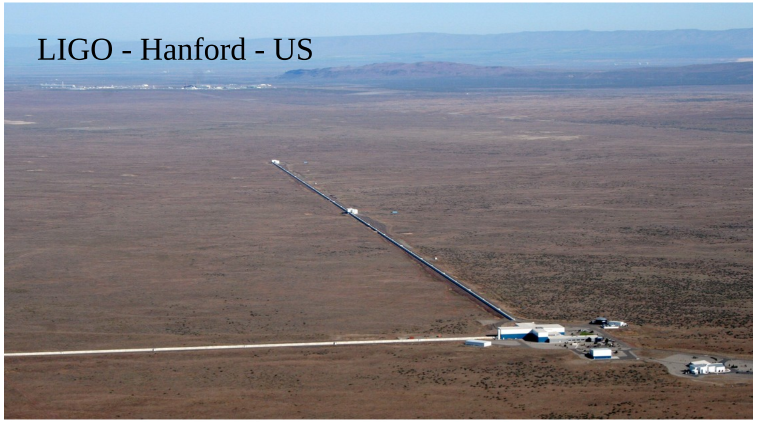
- Some sensitive GW instruments
- Some nearby multi-messenger events
- How many events do we expect?
- Some accurate/robust models → See Toni Mezacappa's presentation
- Some new algorithms: what for?

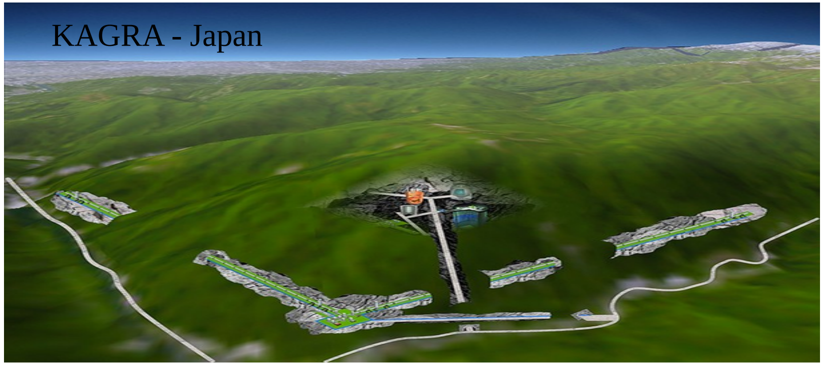
Outline: the ingredients of the cooking receipt

- **Some sensitive GW instruments: the current and the ones in preparation**
- Some multi-messenger events: many telescopes and neutrino detectors available
- How many events do we expect? not a lot!
- ~~Some accurate/robust models → See Toni Mezacappa's presentation~~
- **Some new algorithms: what for?**
  - **Detection & source properties**
  - **The multi-messenger aspects**

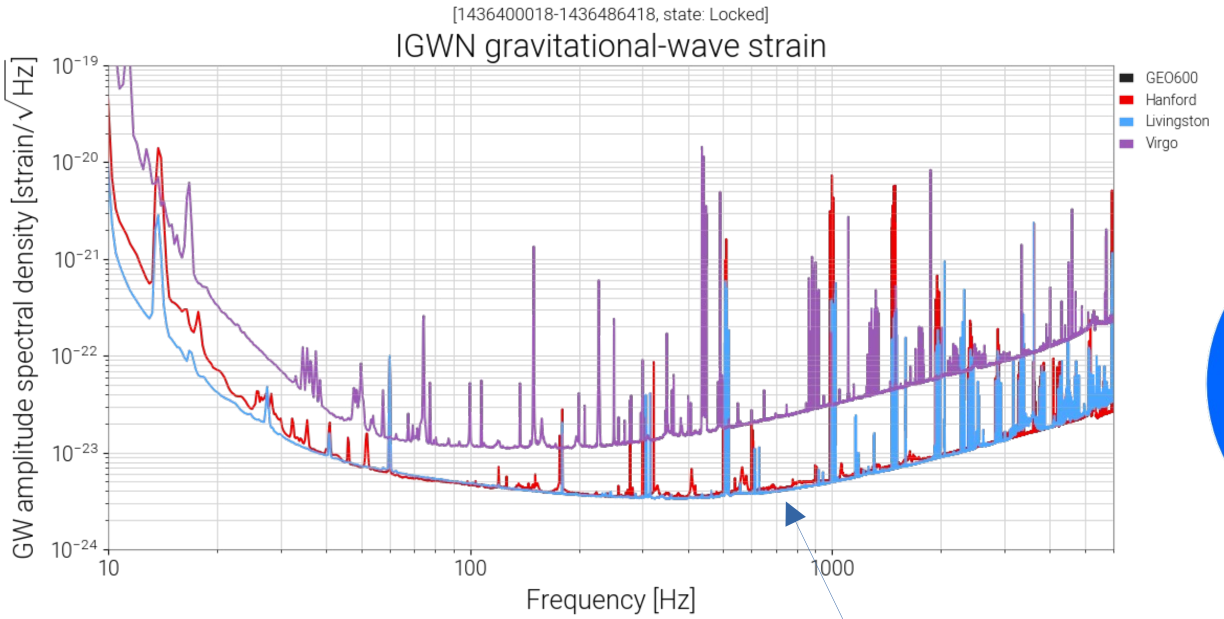
GW detectors current network

CCSN detection prospects with LVK network: see Michele Zanolin lecture

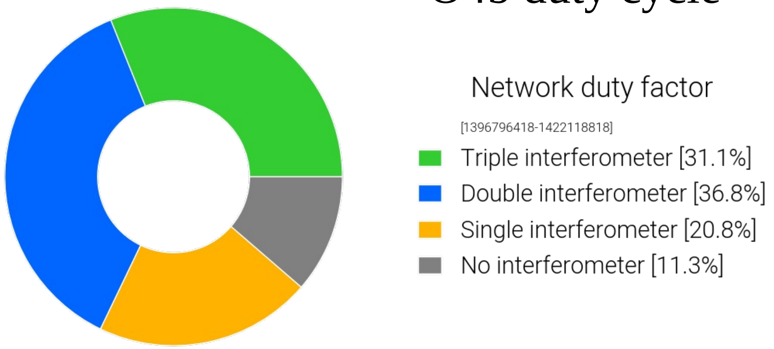




LVK upgrade program : 2025 - 2035



O4b duty cycle



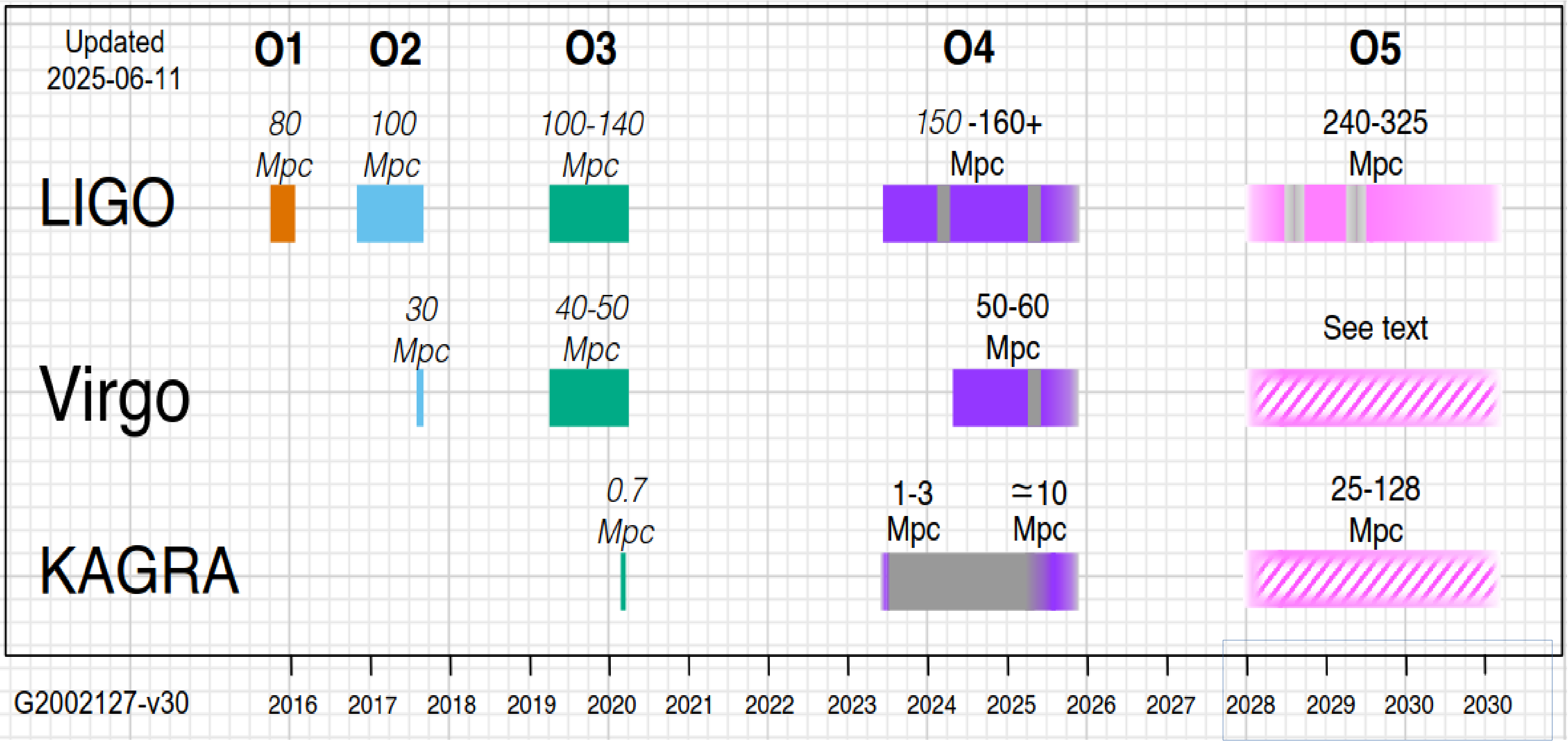
O4c sensitivity (July 2025) :

Effect of the signal recycling

LIGO : 160 Mpc
Virgo : 55 Mpc
KAGRA : 10 Mpc

What is the most important ingredients for CCSN physics ?
… the detector's sensitivity
and the duty cycle

LVK upgrade program : 2025 - 2035



Post O5

A#
400-600 Mpc

VirgoNext
400-600 Mpc

KAGRA+

2035 2040

>3 years run

LVK upgrade program : O5 upgrade plans

- LIGO : ~2 years
  - New laser amplifier (150 W)
  - Balanced homodyne detection readout
  - Large aperture beamsplitter
  - New low thermal noise test masses with new Germania/Titania coatings

O5a starts end of 2027

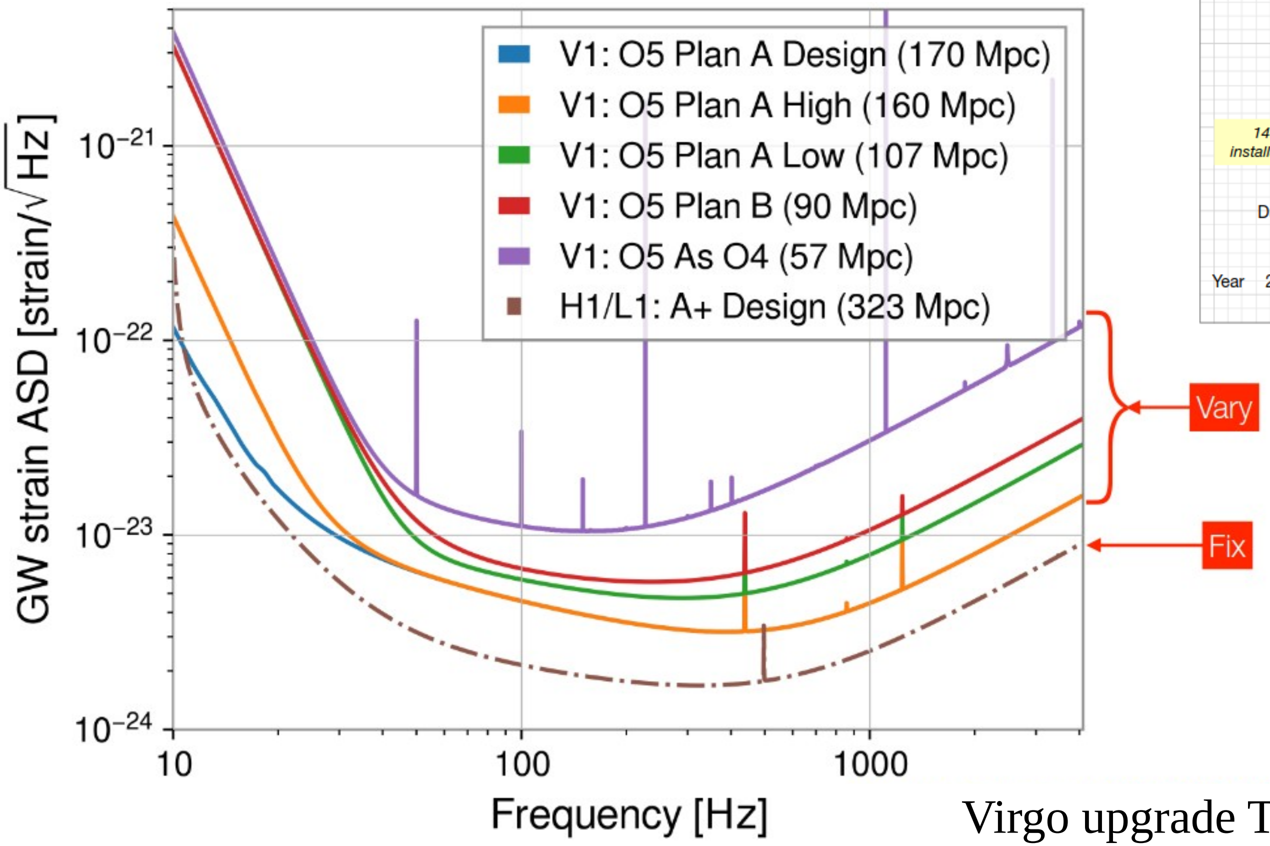
- Virgo: ~4-5 years
  - Install new suspension for stable recycling cavities
  - New test masses with new Germania/Titania coatings
  - Upgrade many parts of the detectors (laser, detection, suspensions, thermal compensation system, ...)

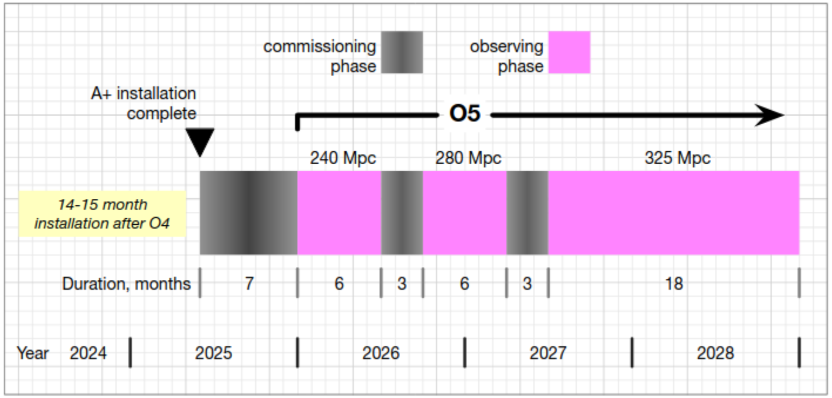
Virgo would join O5c in 2031?

- KAGRA:
  - Implementation of Resonant Sideband Extraction
  - Replacement of Input Mirrors
  - Photodiodes put into vacuum
  - High-power laser: targetting 30 W at the input mode-cleaner output

Reach the design sensitivity:
BNS range of 150 Mpc

LVK upgrade program : 2025 - 2035

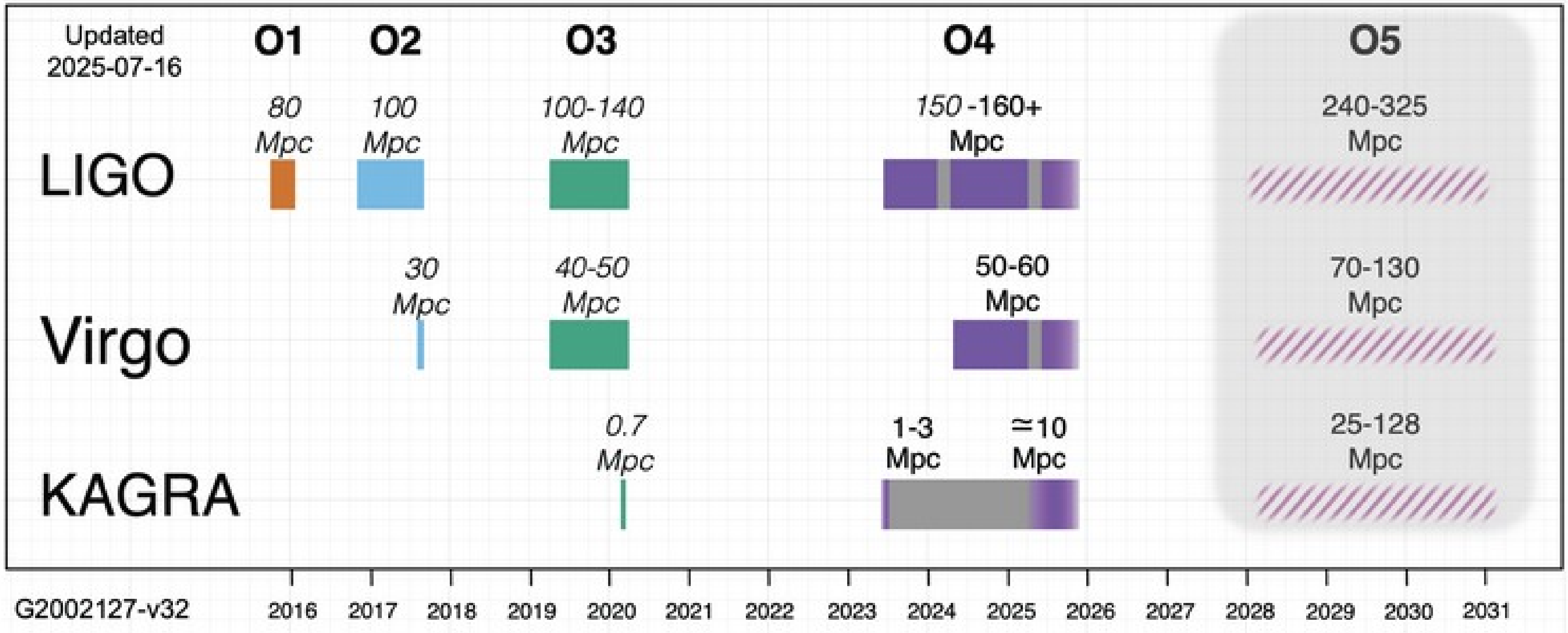




LIGO upgrade Timeline

Virgo upgrade Timeline

LVK upgrade program : some uncertainties



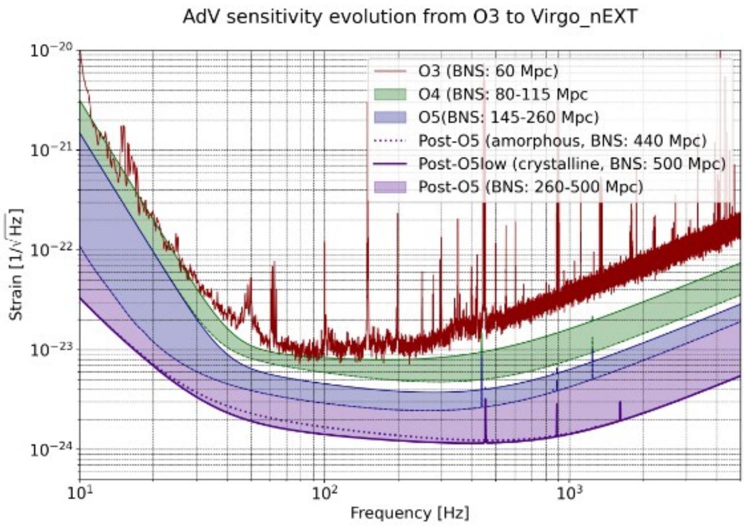
Plans and timeline for the fifth observing run (O5) are being reassessed. Further information will be provided as soon as it becomes available.

LVK upgrade program : after O5 (2030+)

Principle: leverage on successes, using the same infrastructure and push hard on the technology!

- LIGO : A#
  - 100 kg optics on upgraded suspension
  - Reduce thermal noise with better coatings even better than for O5.
  - 1.5 MW power in cavities (O1: 100 kW, O4: 375 kW)
  - 10 dB of squeezing

- Virgo : VirgoNext

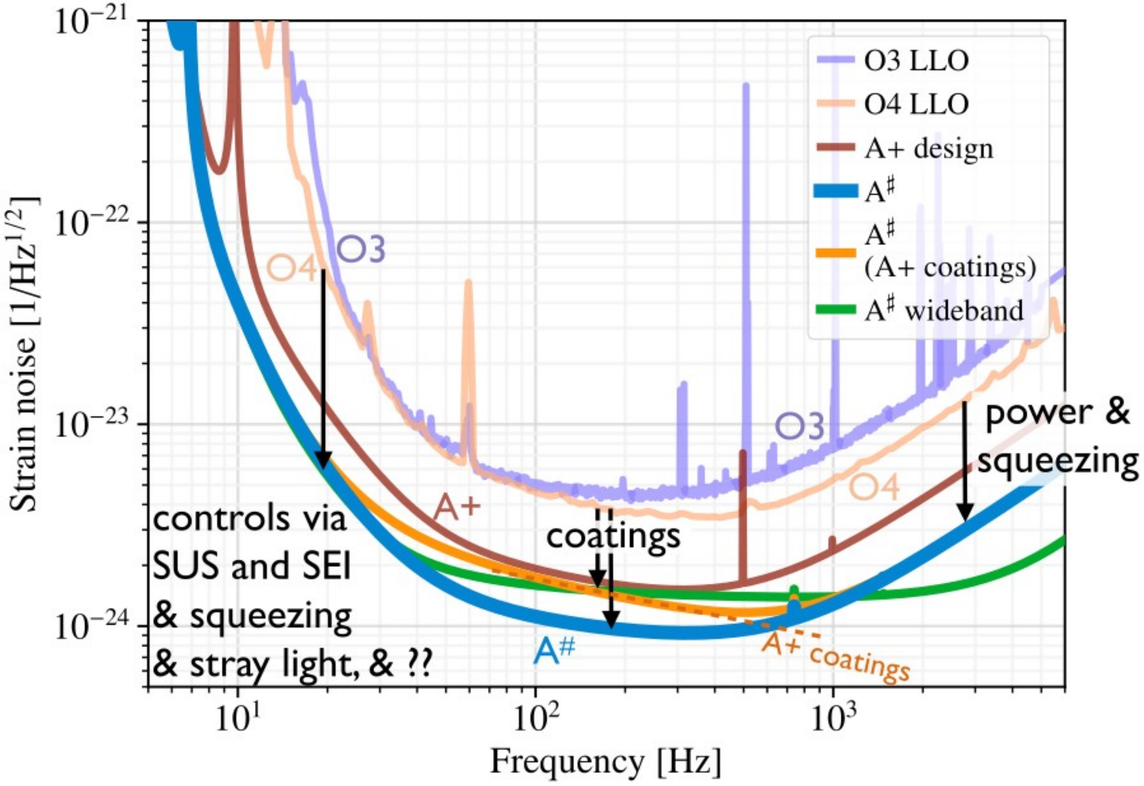


- KAGRA : KAGRA+
  - Leverage on underground (low frequency) and cryogenic (mid frequency) or signal recycling (high frequency)

LVK upgrade program : after O5 (2030+)

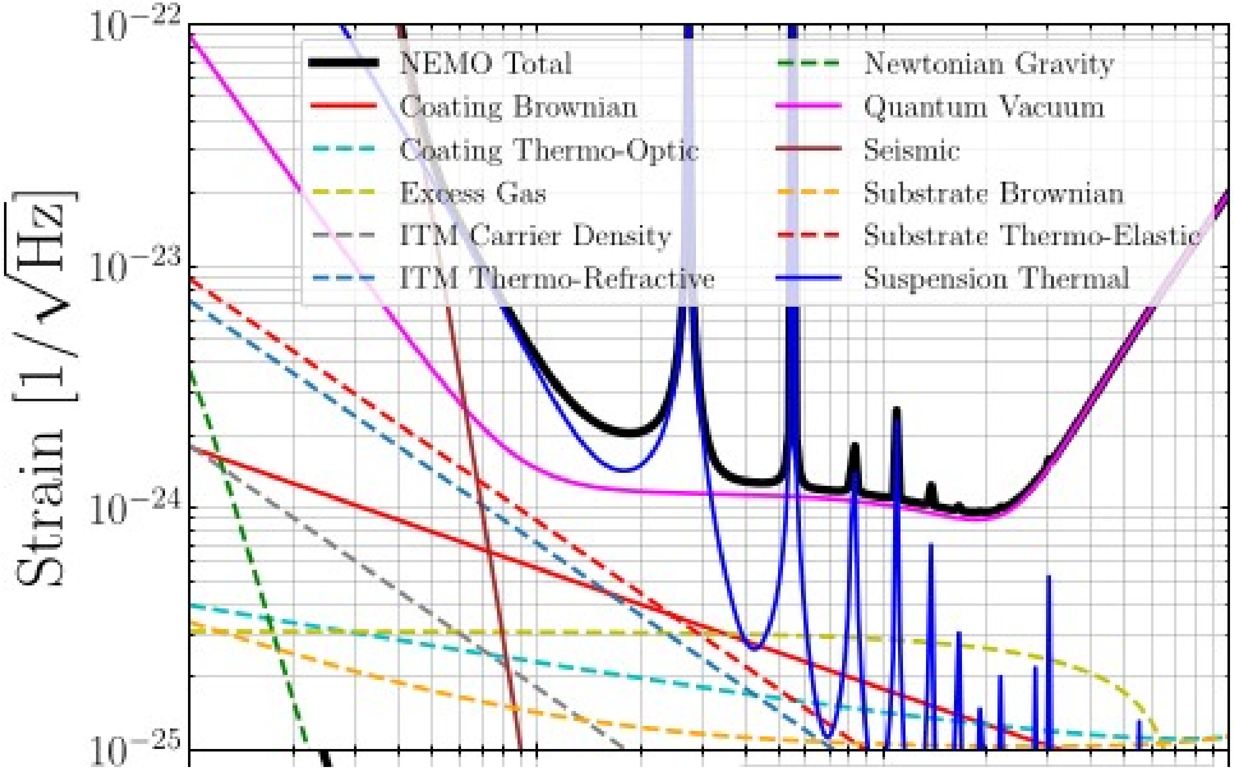
LIGO A# sensitivity: almost a factor 5

https://dcc.ligo.org/LIGO-T2200287/public



Other GW detectors?

Project in Australia : NEMO targetting high frequency band → NS physics

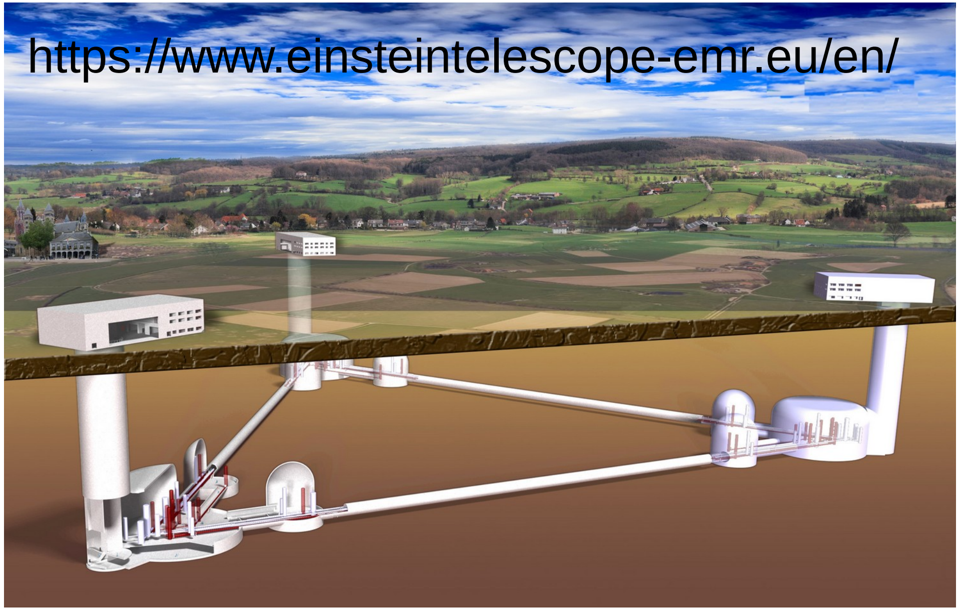


Ackley et al,PASA (2020) 37

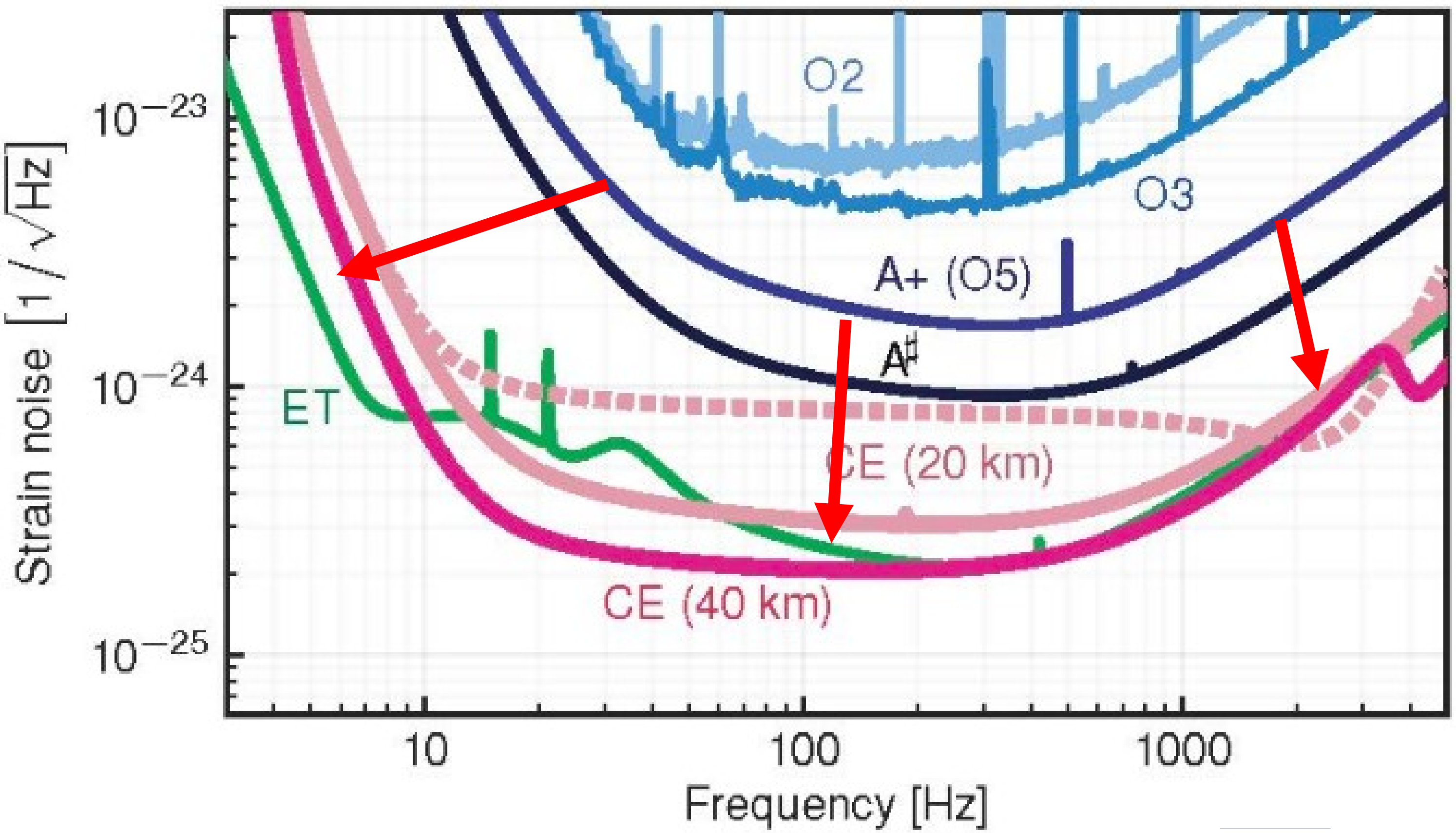
Einstein Telescope and Cosmic Explorer

Goal: a network of interferometers to observe the Universe and carry out fundamental physics program with detectors 10x more sensitive than today's observatories.

- Einstein Telescope: 10km triangular underground and cryogenic (or two 15 km L-shaped) in Europe
- Cosmic Explorer: 40 km and 20 km L-shaped in the USA: 1064 nm @ room temperature



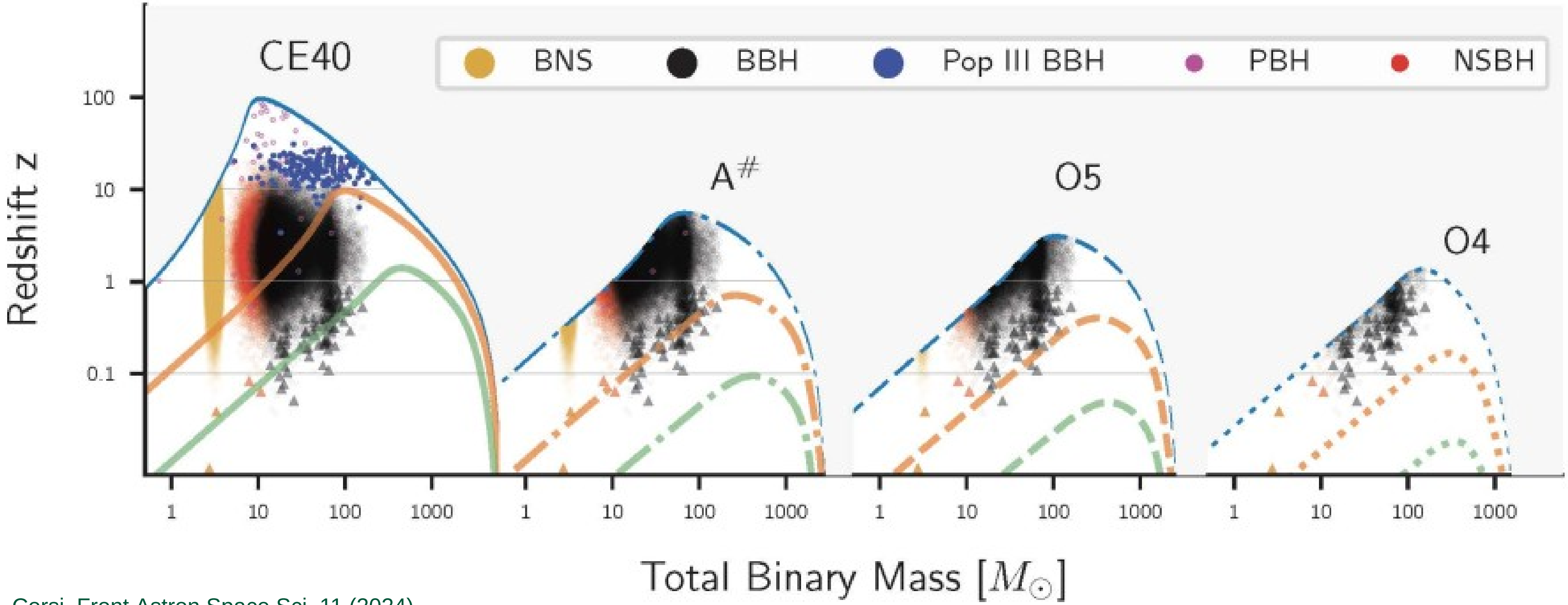
Einstein Telescope and Cosmic Explorer



- 3G detectors are designed for low and high frequency: perfect for CCSN
- Is a factor x10 in sensitivity enough to detect a CCSN in a few years ?

Einstein Telescope and Cosmic Explorer

Technical challenges, huge cost but science impact will be huge.



Corsi, Front.Astron.Space Sci. 11 (2024)

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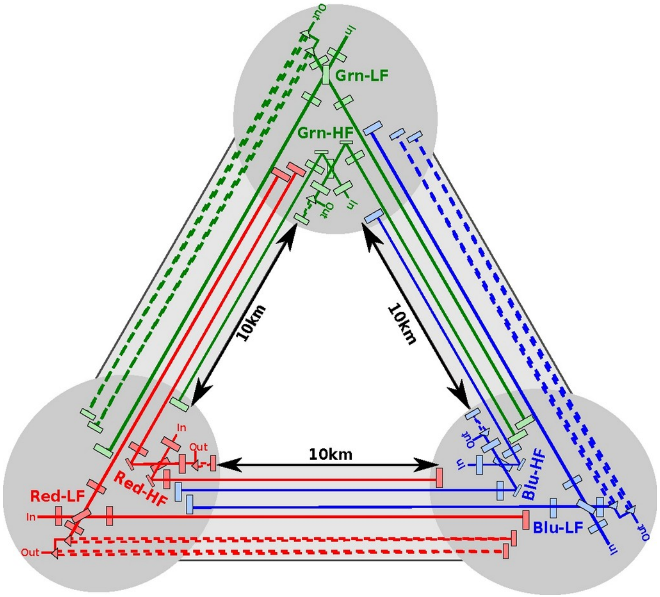
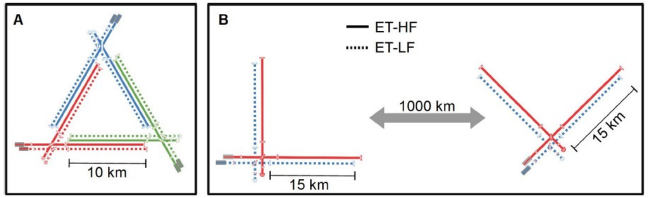
  - Einstein Telescope: 10km triangular underground and cryogenic vs two 15 km L-shaped in Europe
  - Cosmic Explorer: 40 km and 20 km L-shaped in the USA: 1064 nm @ room temperature
- Timeline: both @conceptual design stage
- Challenges:
  - Technological challenges: some breakthroughs are needed (thermal noise, cryogenics, intracavity high power etc ...)
  - Cost: not yet established but the order of magnitude is several billions each detector/infrastructure.

Einstein Telescope timeline

- ET entered the ESFRI roadmap in 2023.
- 3 sites have been proposed in Europe : Meuse-Rhin region, Sardinia and Saxonny. Choice in the next years.
- Einstein Telescope design revisited ? Triangular (6 IFOs) vs 2 L-shaped IFO

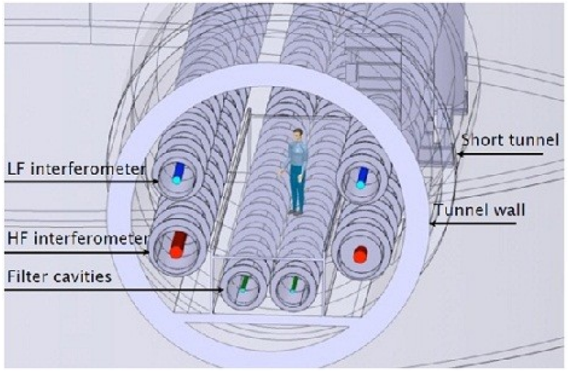




Science with the Einstein Telescope: a comparison of different designs

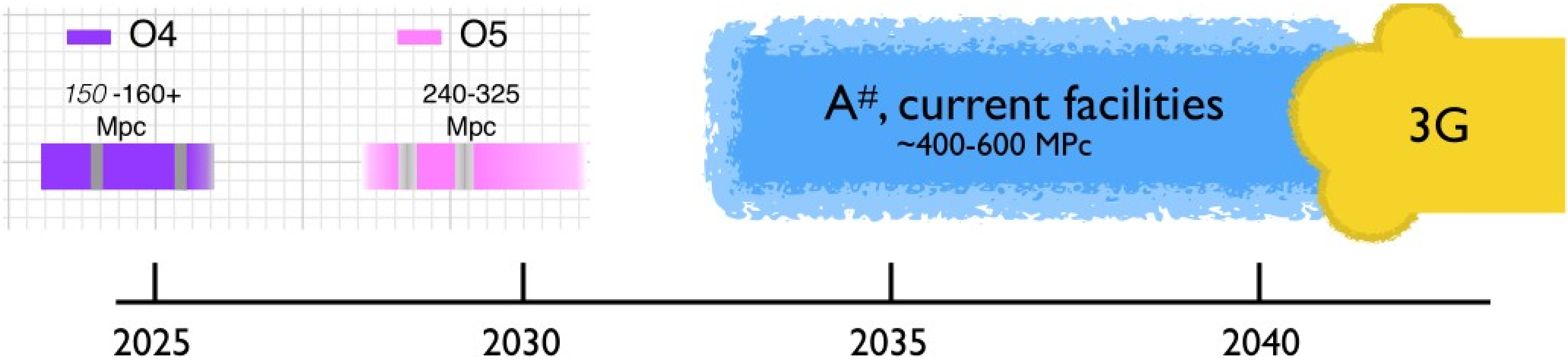
Marica Branchesi,[1,2] Michele Maggiore,[3,4] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Enis Belgacem,[3,4] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19]

Branchesi et al, JCAP 07 (2023) 068



How to deal with correlated noise ?

GW detectors upgrade timeline



How many CCSN can we detect ?

1. Observations in the local Universe (PTF, Pan_STARRS, ASASSN, LOSS, ZTF, ...)

	10 Mpc		50 Mpc		100 Mpc	
	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})
LOSS		0.3±0.04		37.0±6		295±46
Kennicutt et al.	87±4	0.40±0.02				
Lee et al.	123±8	0.6±0.04				
Bothwell et al.	75±5	0.4±0.02	9420±602	45±3	75360±4814	362±23
Hopkins & Beacom	65	0.3	8836	42	76121	365
Madau & Dickinson	63	0.3	8059	39	66568	319
Observations		$1.1^{+1.7}_{-0.6}$		38.0±3		153±5

Table 7.2: Our estimates of the expected CCSNe per year within 10 Mpc, 50 Mpc and 100 Mpc, respectively. These estimates are derived from the volumetric rate measured by LOSS, several measurements of the total SFR in the same volumes, and our estimates of the observed number of CCSNe per year based on discovery reports and archives.

Abac et al, The science of Einstein Telescope

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- Some CCSN missed because they too faint.
- ~20 % are missed because of dust extinction.
- Failed CCSN (BH collapse) : estimation ~ 1 in 300-1000 yrs in the MW and its satelites.
- Rate (under-)estimated with SFR : 0.3 yr^{-1} with 10Mpc

Abac et al, The science of Einstein Telescope

How many CCSN can we detect ?

2. Observations in the Milky Way (historical records, galaxy models, NS birthrate, ...)

Method	CCSNR $(100\ \mathrm{yr})^{-1}$	Reference	
Galaxy models	2.1	[3507]	
	$3.2^{+7.3}_{-2.6}$	[3474]	
	$1.4^{+1.6}_{-0.9}$	[3508]	
CCSNR measurements	1.7 $\pm$1.1	[3509]	
	2.4-2.7$\pm$ 0.9	[3510]	SN1054, SN1181, Cas A, G1.9+0.3 from the MW. Include other galaxies
	2.30 $\pm$0.48	[3014]	
Counts of massive stars	1 - 2	[3511]	Sample of 420 O3-B2 stars within 1.5kpc of the sun. Not precise
NSs	7.2	[3016]	NS birthrate in the Galaxy seems too high
SN remnants	0.43	[3512]	~300 SN remnants found in radio. Missing information lead to uncertainties
^{26}Al distribution	1.9 $\pm$ 1.1	[3513]	Assuming Al is produced by CCSN. INTEGRAL measurement.
Combination of different methods	$\boxed{1.63 \pm 0.46}$	[3016]	

Table 7.3: The expected CCSNR per century in the Milky Way estimated with different proxies.

Abac et al, The science of Einstein Telescope

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Table 7.3: The expected CCSNR per century in the Milky Way estimated with different proxies.

- The MW rate is low. Last CCSN ~200 yrs ago.
- The neighborhood of the MW contains ~50 dwarf galaxies (including the magelanic clouds). Gaining any factor in sensitivity to the GW horizon is important.

Abac et al, The science of Einstein Telescope

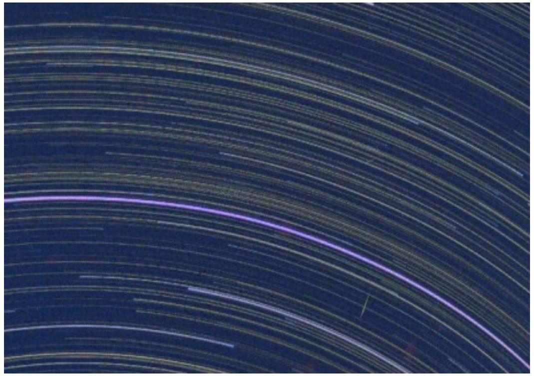
CCSN : what is the GW strategy ?

What do we know ?

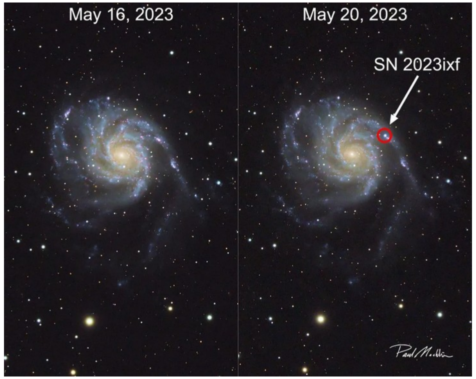
1) GW signal will be rare and faint
2) GW should be accompanied with neutrino and anti-neutrino emission
3) EM emission might be absent (failed SN and dust obscuration)

→ Two approaches :

All-sky/all-time search



Targeted search (ex : SN2023ixf)

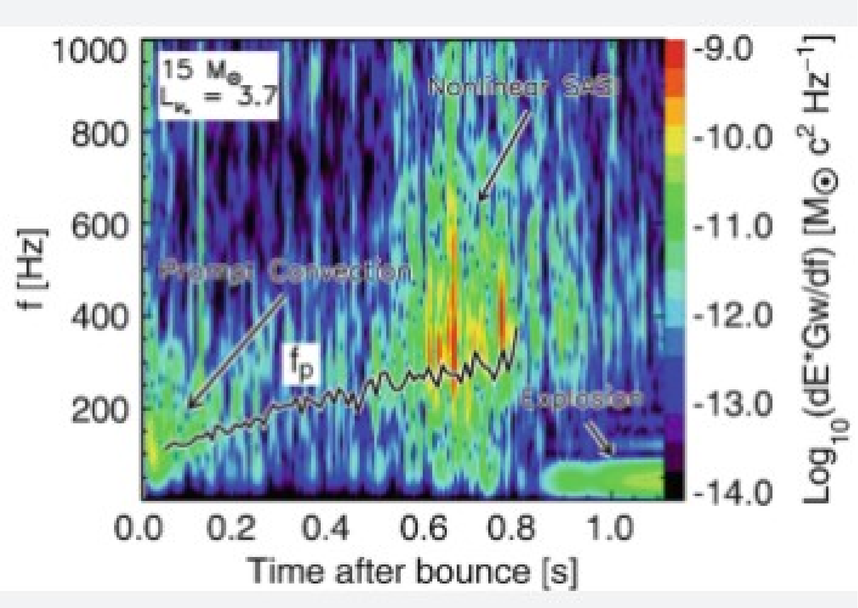


All-sky/all-time search

What do CCSN pipelines do ? search for an excess of GW energy in the time-frequency space

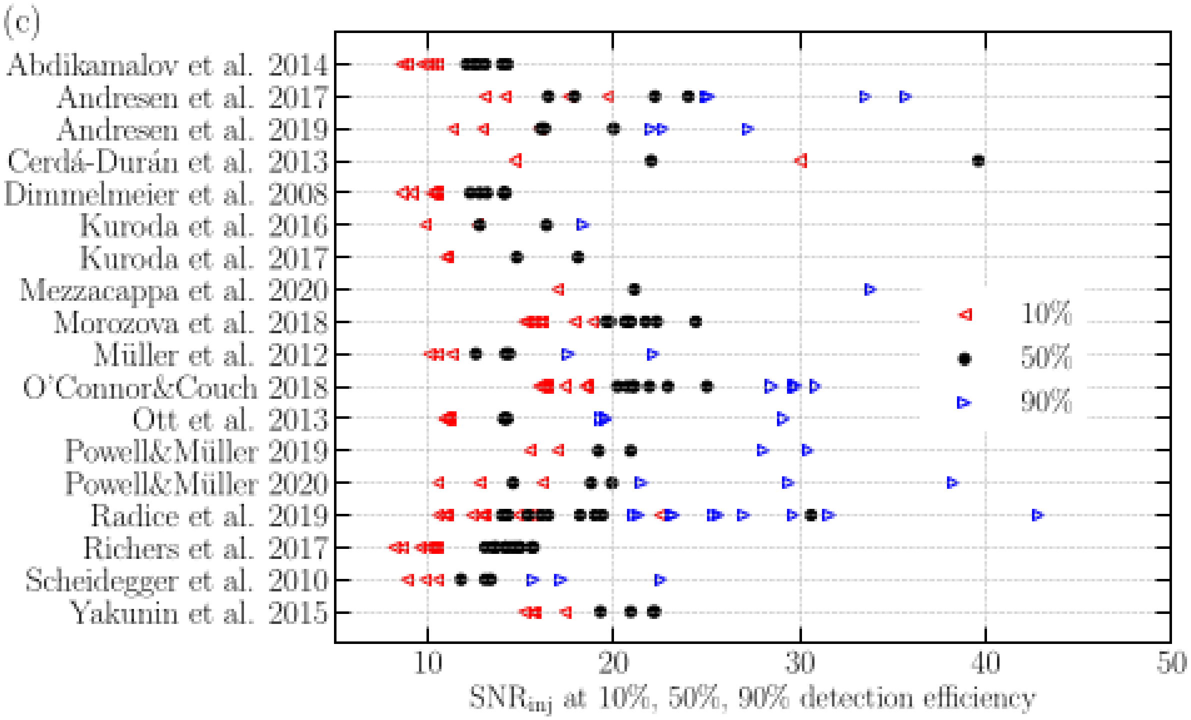
→ clustering problem !

→ usual assumption : the GW signal is localized in the time-frequency plane : incorrect !



All-sky/all-time search

Current CCSN pipeline (cWB) sensibility



Szczepanczyk et al, Phys.Rev.D 104 (2021)

- Detection requires SNR ~20
- Long GW signal are badly reconstrcuted.
- Not a background free search
- Room for improvement !

All-sky/all-time search : improvements?

- Include robust features of expected CCSN signals in the search (cf Sergey Klimenko, Adrian Paquis talks)
- Use machine learning techniques to reduce the glitch contamination : trained on bank of glitches or not and CCSN models ?
- Reduce the frequency band (cf Christine Lee talk)
- Search any strecht of data, including single interferometer data (cf Marco Drago)
- …

→ Information from CCSN models will play a bigger role in the coming years

Targeted search : multi-messy aspects !

- Reduce the time window using EM (up to 5 days) or neutrinos (<1s) and the sky position

➡ allow to dig into the noise ?

  - Yes, but 5 days on-source window (EM) is way too much ! Gain wrt all-sky/all-time is moderate
  - 1s on-source window (neutrinos) : no more a discovery search, but a source properties problem !

➡ models role will be crucial to test and infer the presence/absence of all predicted components

  - Bounce
  - Convections
  - SASI
  - PNS modes
  - Memory
  - ...

Cf the very many talks and posters on the subject !

Future search R&D : ideas for the next years

- Template search ?
  - Maybe for some components of the expected GW signal. Ex : bounce signal.
  - Needs : AI based waveform generator ?
  - Pb : one recovers only a (small) fraction of the signal ? Gain wrt agnostic search ?
- Joint GW-neutrino search / parameter estimation
  - Time and spatial coincident search already exist (offline and online RAVEN with IceCube triggers)
  - Ideas to use SASI neutrino emissions
  - Goal : increase the significance of a faint GW signal and extract source parameters.

Availability of bank of models (including neutrino information) is important to develop these methods

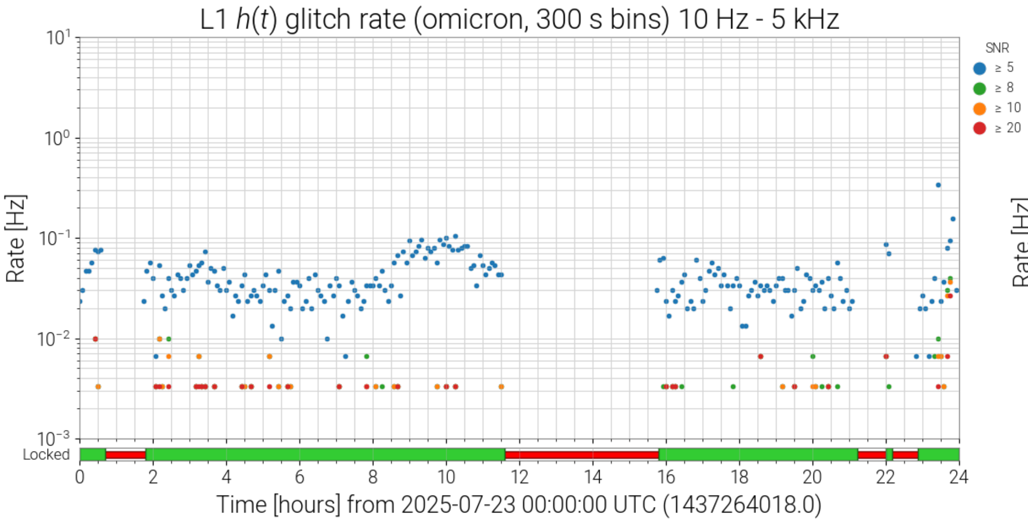
CCSN source properties with the one event!

- Extract features: bounce, convection, PNS modes, SASI, memory, … from the data.
- Classification (rotation, bounce, convection, neutrino driven/MHD, glitch), etc …
- Progenitor nature with GW information ? That will be hard!
- Include more information in our GraceDB GW alerts? (cf Marek S. talk)

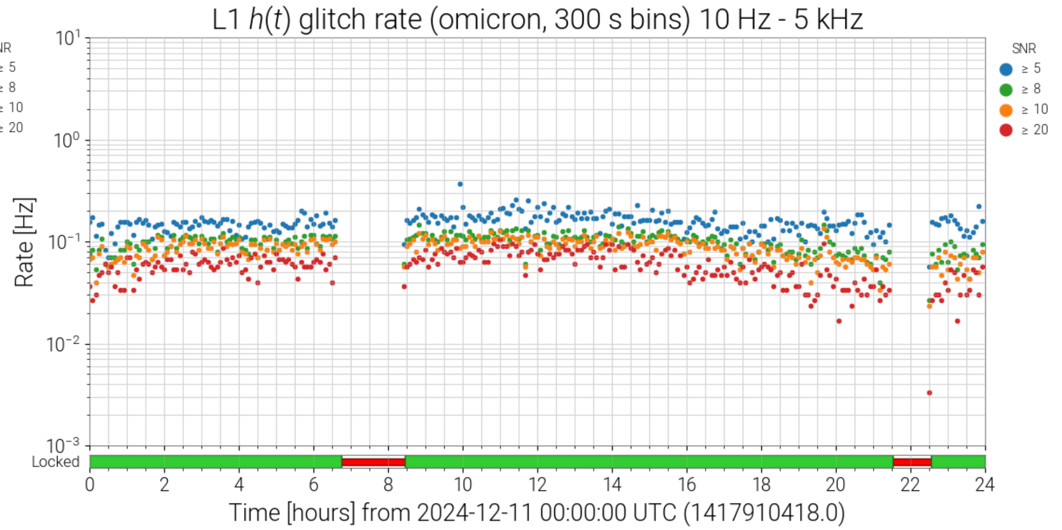
➡ We need robust/accurate prediction from modelers

➡ Waveforms and waveform generations : Use of ML techniques to build waveform generators

Quality of the data

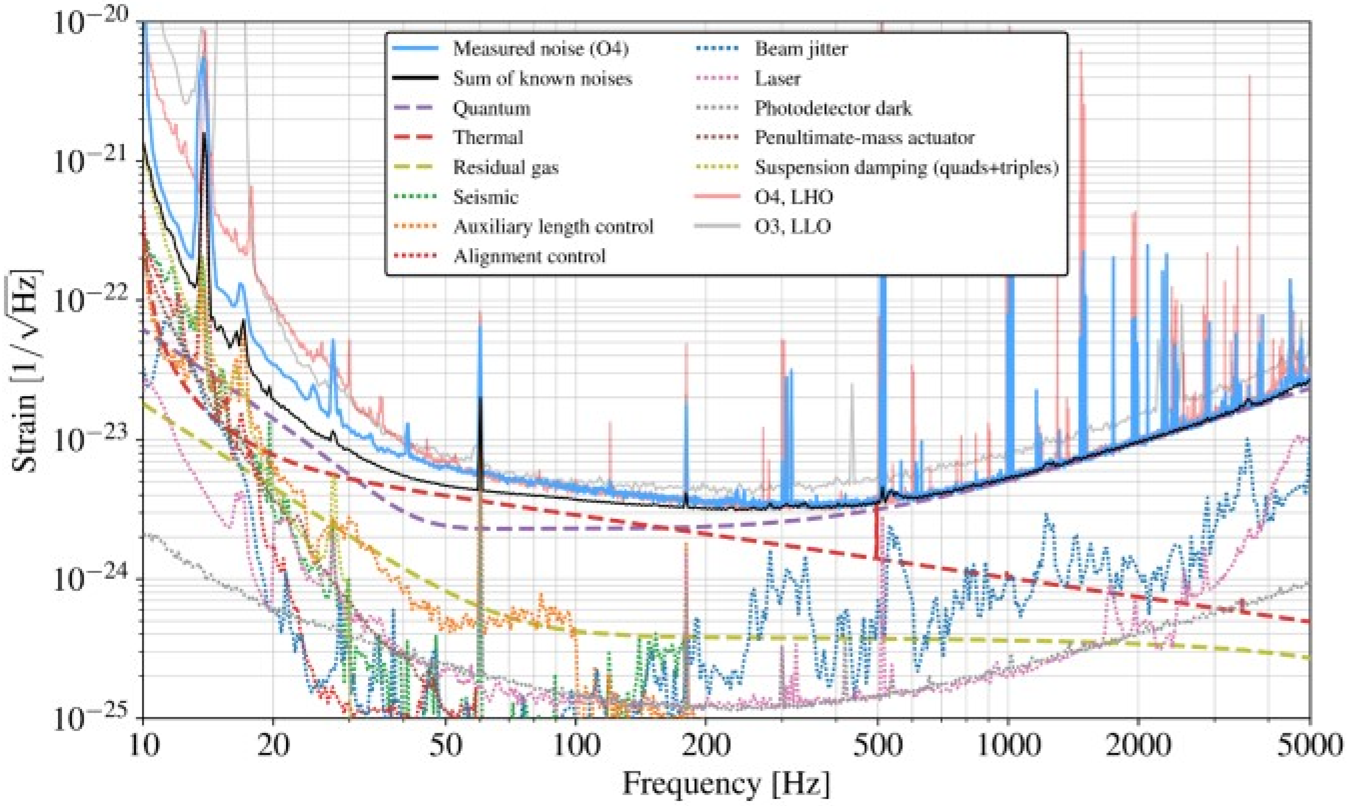


Quiet day (July 2025)



Noisy day (July 2025)

Current detector noise budget



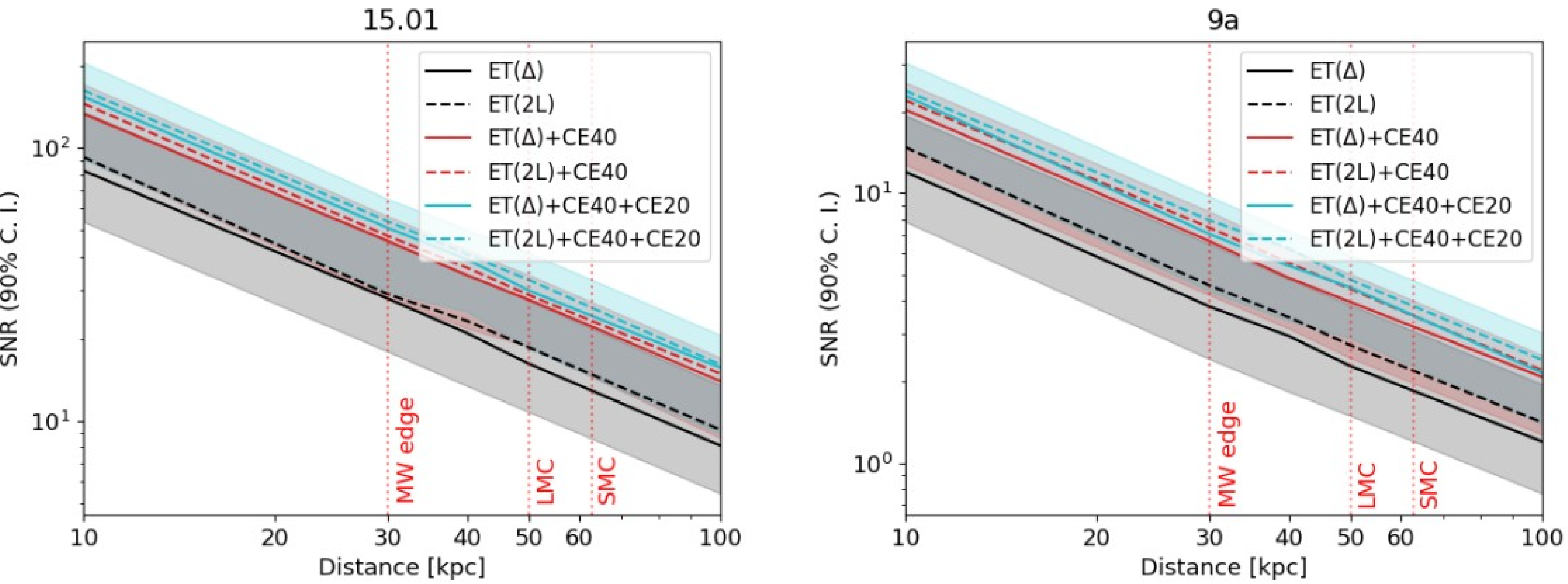
Reference:

Phys. Rev. D 111, 062002 (2025)

Future directions

- Detector wise:
  - The GW ground detector community will continue to push the sensitivity limits. There is now a long term goal: the 3G detectors.
  - This means we will continue to have interlaced R&D and observation period as long as fundings do exist!
  - Remember: these GW detectors are functioning at the limit of their sensitivity. Operation is a critical activity to make them reliable and increase their duty cycle.
- Analysis wise:
  - Despite the low number of expected source, it is still attracting attention
  - Models including neutrino information will play an important role in the coming years
- The LVK MOU ends at the end of O4 (end of 2026?)
  - A new consortium is getting set up: IGWN (International GW Network)

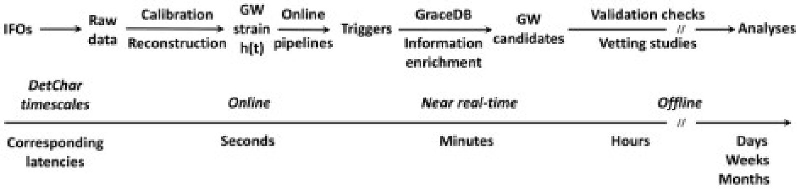
Current algorithms detection sensitivity : 3G case

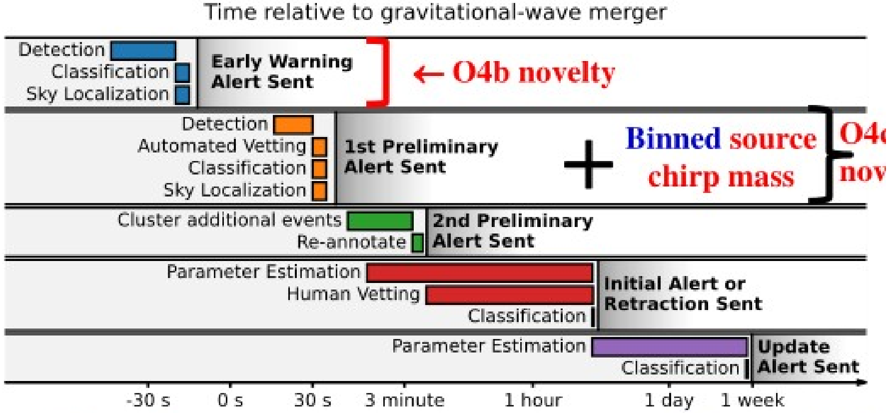


Low latency alerts

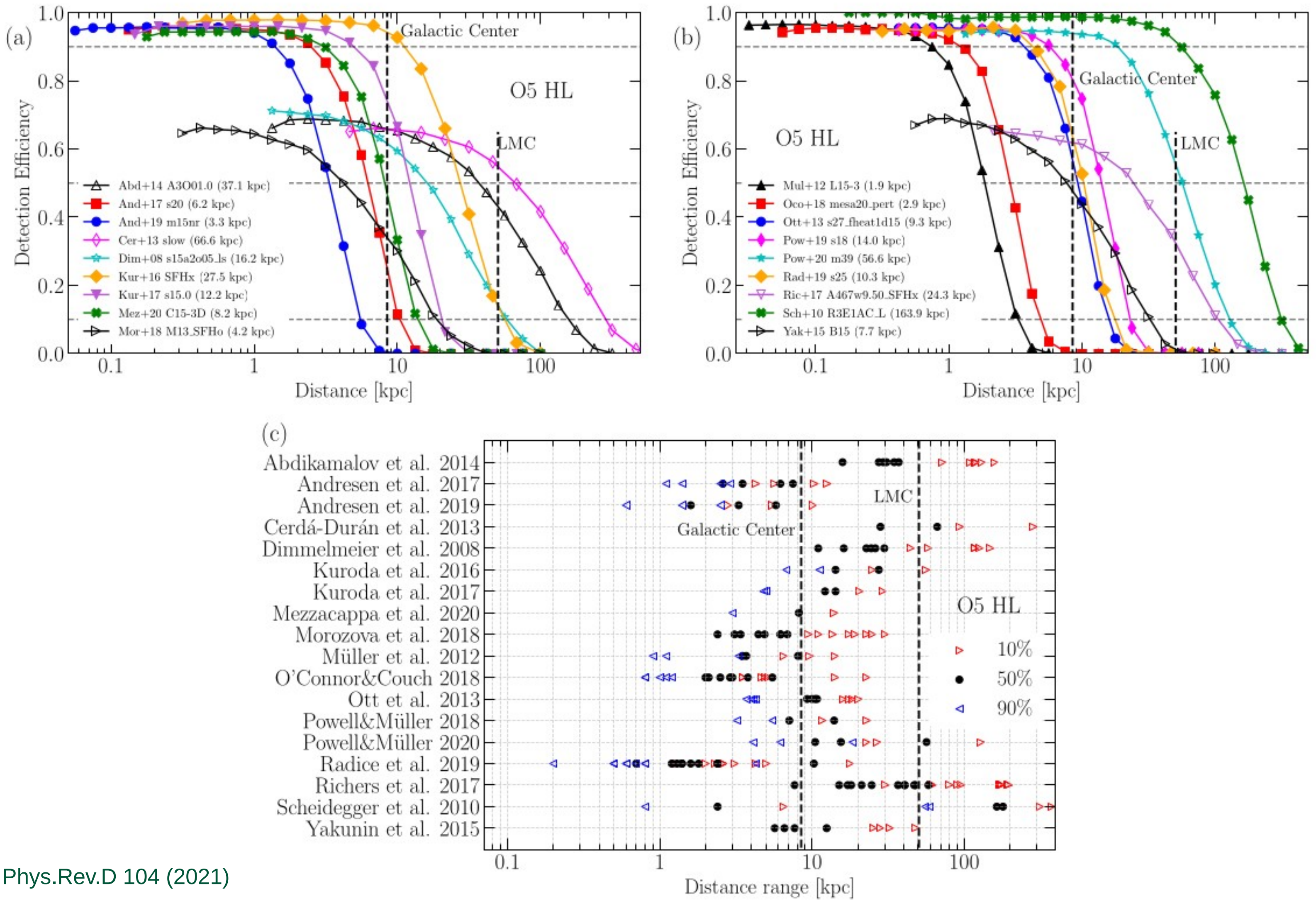
- General Coordinates Network (GCN)
  - https://gcn.nasa.gov
- Real-time processing of LVK data
  - Dedicated data analysis pipelines searching for transient GW events
- Latency is the main challenge for the public alert
  - The lower, the better
- An alert must be informative for the astronomy community
- Automated alerts later found not to originate from the cosmos are retracted
- Central database: GraceDB
  - Gravitational wave candidate event DataBase

  → Public portal: https://gracedb.ligo.org/superevents/public/O4





[O4a] [O4b]
[O4c]



Szczepanczyk et al, Phys.Rev.D 104 (2021)