

Prospettive in Astronomia multimessenger e Onde Gravitazionali

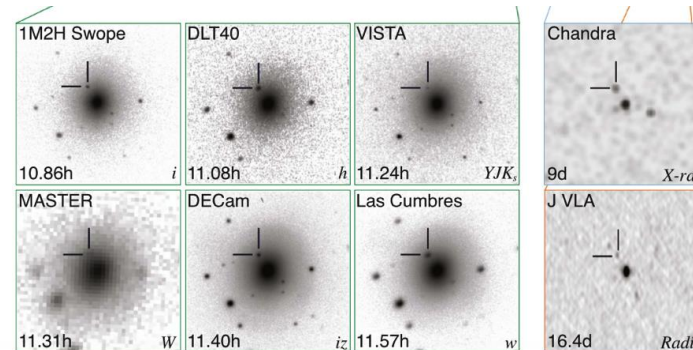
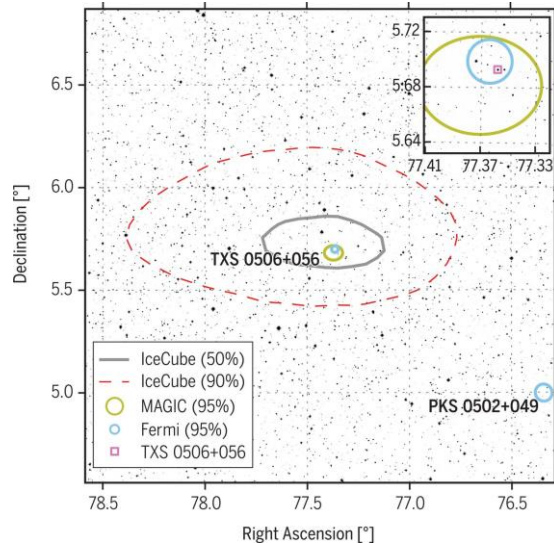
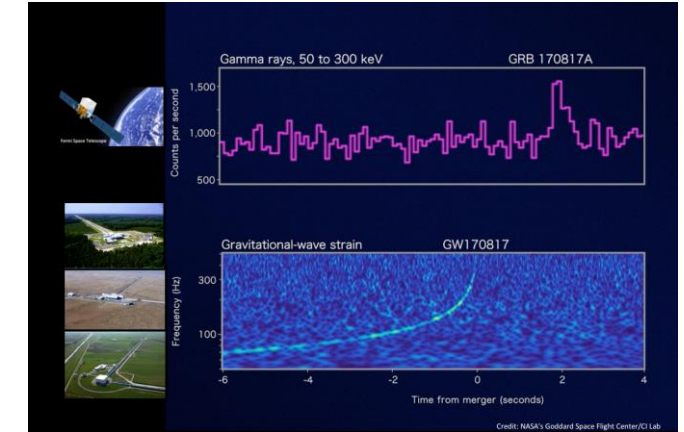
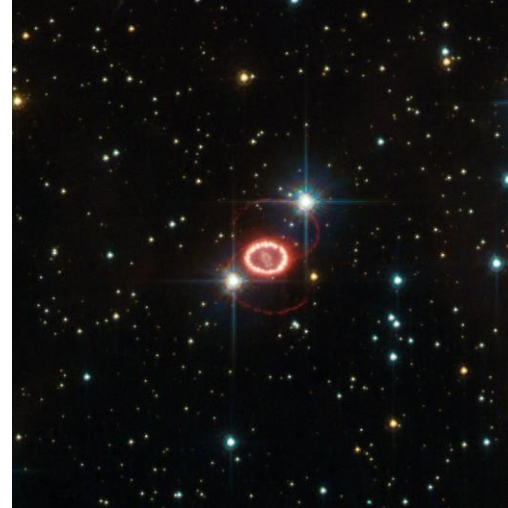
M. Drago

Dipartimento Fisica & INFN

On behalf of the Rome VIRGO group

Multi-Messenger (MM) detections

Sorgente	EM	GW	ν
Sun	✓		✓
Supernova 1987	✓		✓
BNS 170817	✓	✓	
TXS0506+056	✓		✓

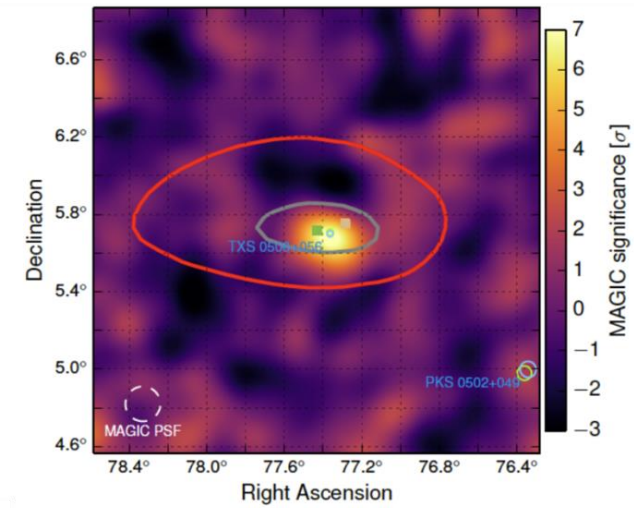
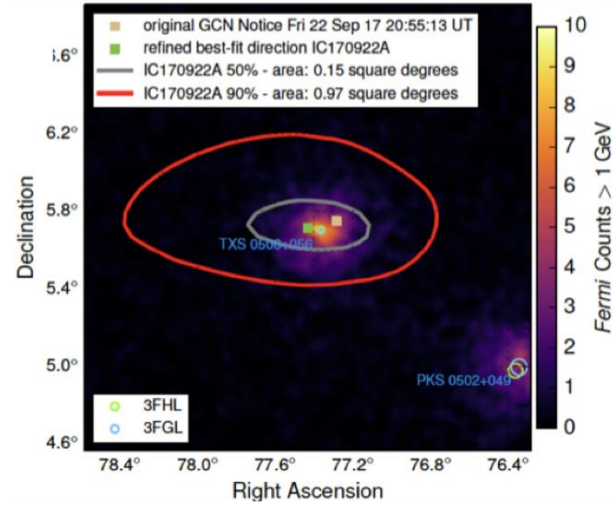


- BNS new discoveries
 - Short GRB produced by BNS
 - GW velocity measurement
 - Heavy element production
 - H_0 measurement

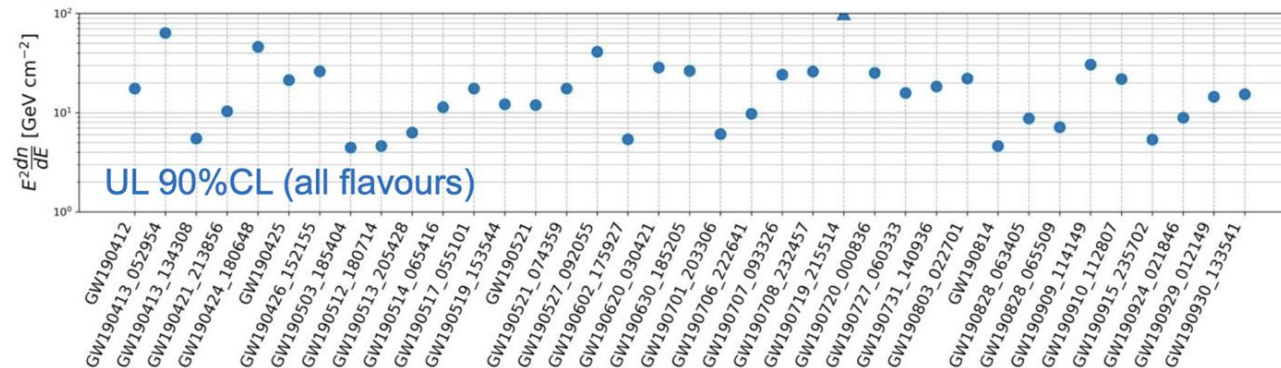
Neutrinos (ν)

MM searches with neutrinos

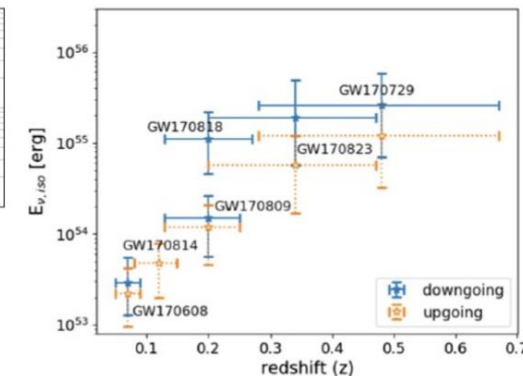
1. Realtime ν trigger to EM follow-up



2. ν -follow up of GW alerts

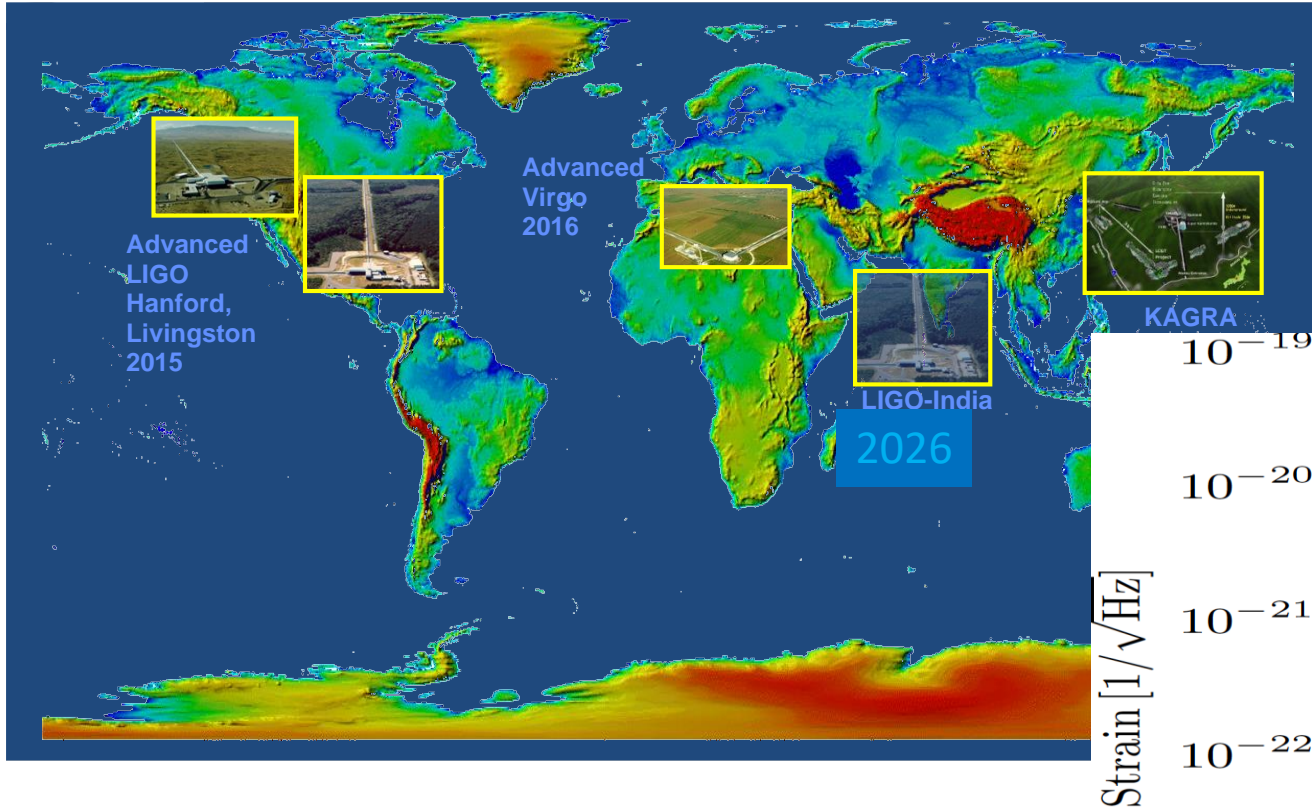


Talk di Silvia Celli

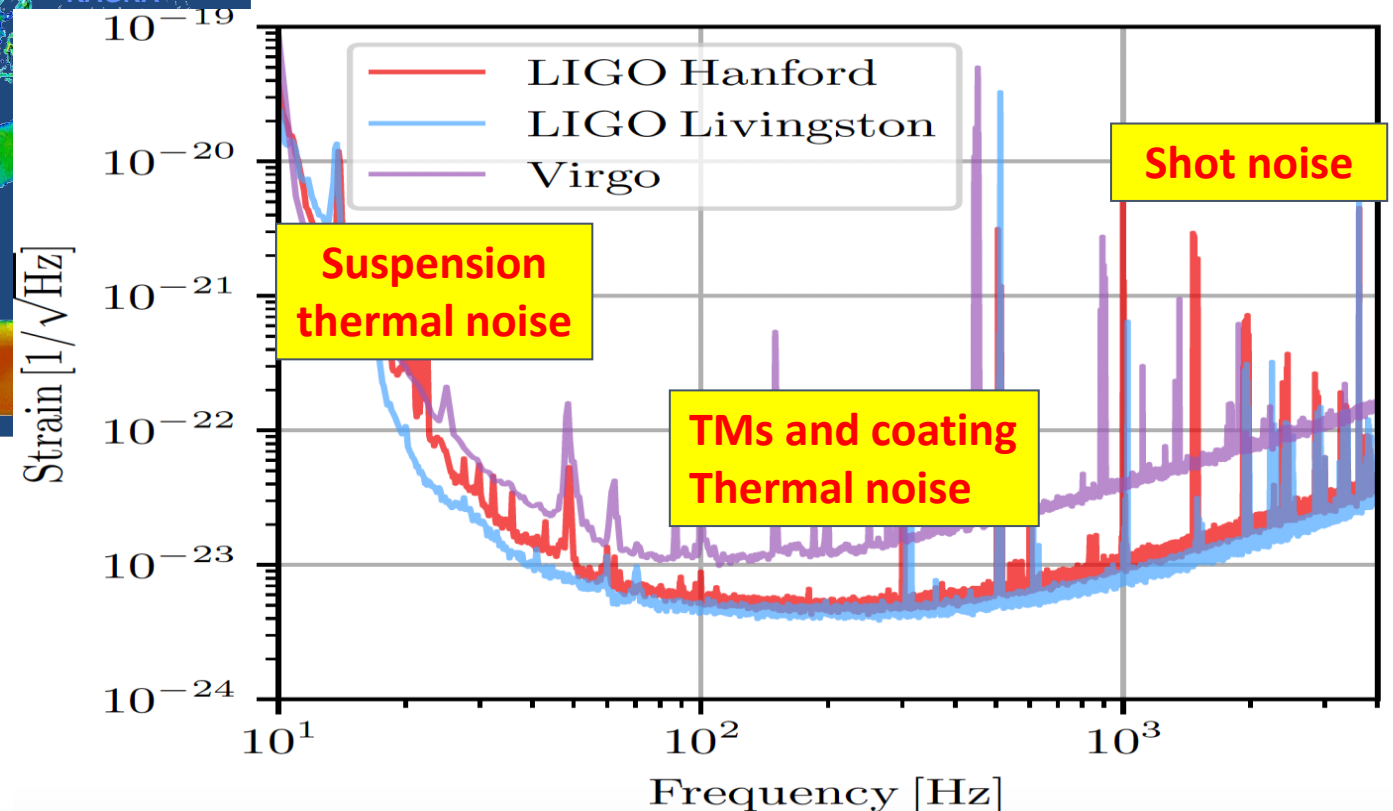


Gravitational waves (GW)

Second generation Detectors

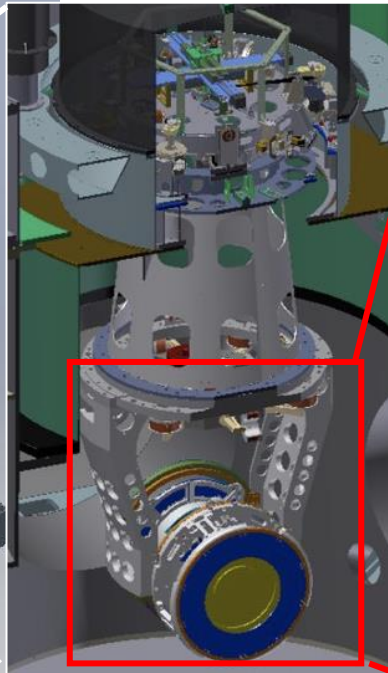
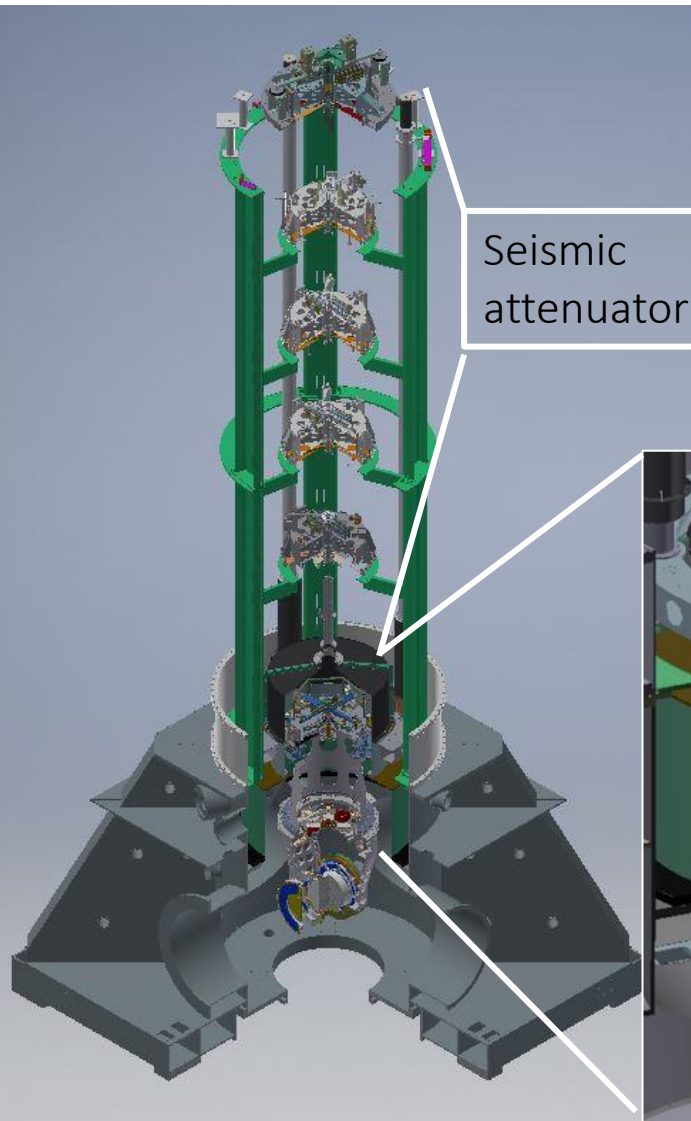


Last run sensitivity (O3)



Test mass suspensions and seismic isolator in Virgo: overall system

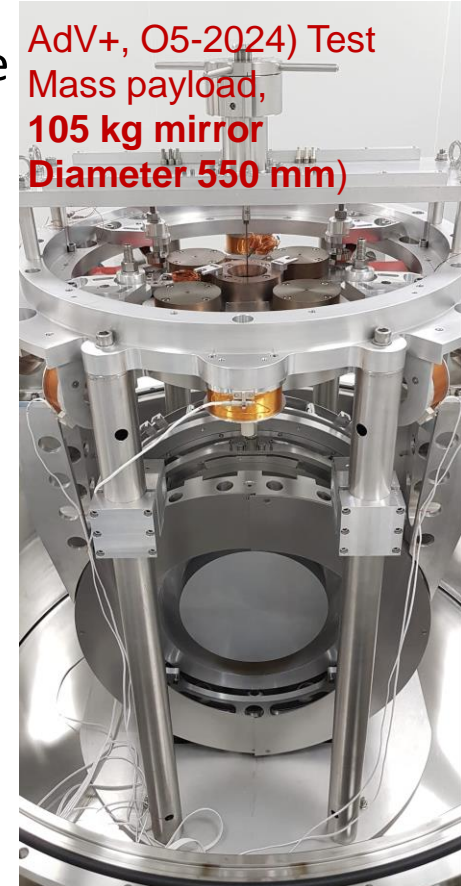
- ROMA group in charge of thermal noise modelling and payload design, development, production, integration in the detector and local control
- Our tasks concern last stage of suspension of the test masses (FP cavity mirrors) and main suspended optics (beamsplitter, power recycling and signal recycling mirrors).
- O4 The Signal recycling payload has been deployed and in use
- O5 A *Large Mass* payload has been designed for O5



AdV Test Mass payload, 42 kg mirror Dia 350 mm)



AdV+ Signal Recycling payload, 21 kg mirror Dia 350 mm)



AdV+, O5-2024) Test Mass payload, 105 kg mirror Diameter 550 mm)

Towards broadband quantum noise reduction: from FIS to FDS squeezing

- VIRGO ROMA group engaged in the application of SQUEEZED LIGHT in the detector dark port as well as in the R&D on new techniques for frequency dependent squeezing (FDS)

Quantum noise: **radiation pressure noise (RPN)** + **shot noise (SN)** one of the main limit to the detector sensitivity.

In O3 frequency independent squeezing (FIS):

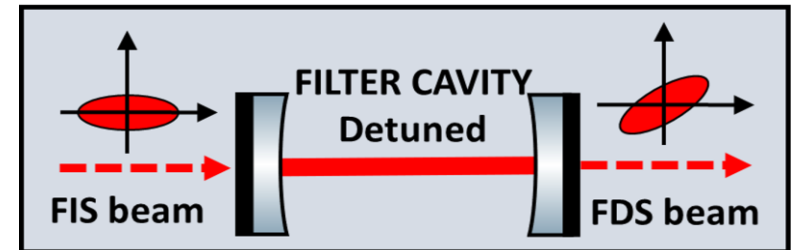
Injection of phase squeezed vacuum field from the dark port of the ITF → **Shot Noise** improved!



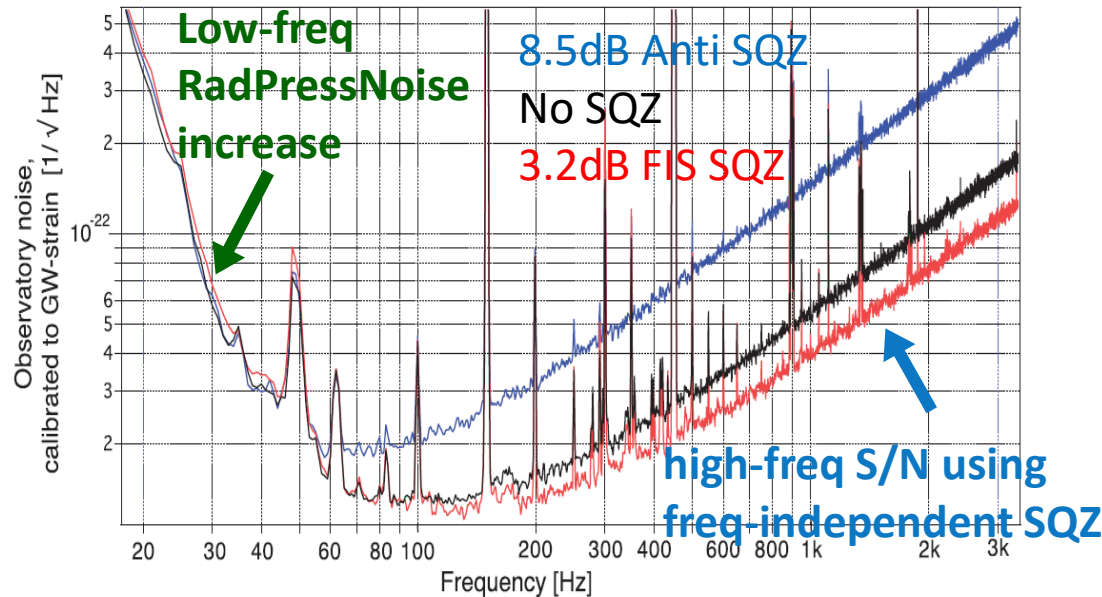
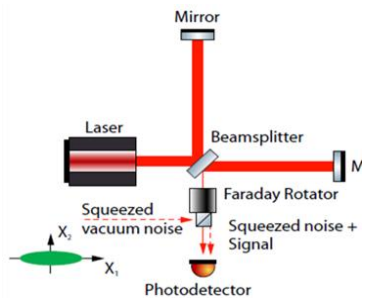
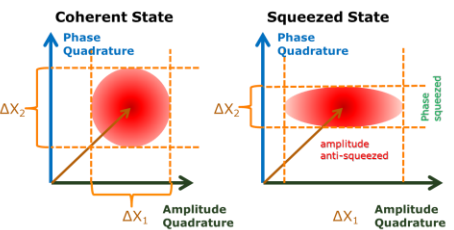
In O4 frequency dependent squeezing (FDS) is needed:

rotation of the squeezing ellipse in function of the frequency.

Technique adopted: FIS setup coupled with a detuned Filter Cavity



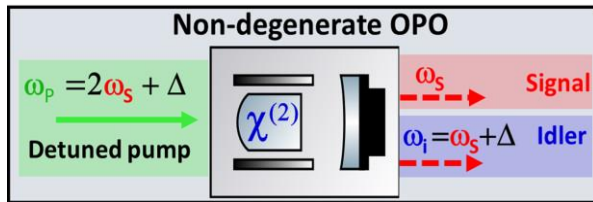
(285 m for Virgo, 300 m FC for LIGO)



[Acernese et al. Phys. Rev. Lett. 123, 231108 \(2019\)](#)

- VIRGO ROMA group engaged in the development of new techniques for frequency dependent squeezing (FDS): more compact setups wrt filter cavity**

Einstein Podolsky Rosen (EPR) squeezing (quantum entanglement)

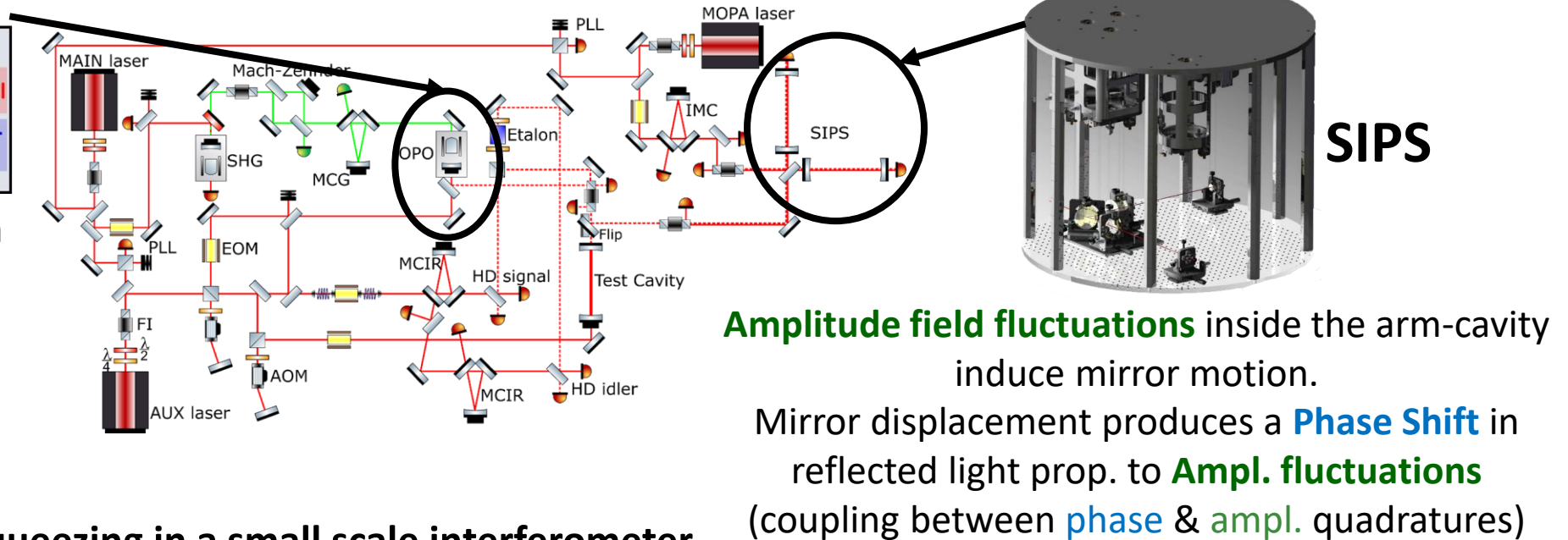


a detuned green pump beam into a non-degenerate OPO cavity produces 2 entangled squeezed beams:
signal & idler
(EPR induced rotation angle)

Novelty: Test EPR squeezing in a small scale interferometer
EPR + SIPS integration at the R&D squeezing LAB at EGO (Virgo)

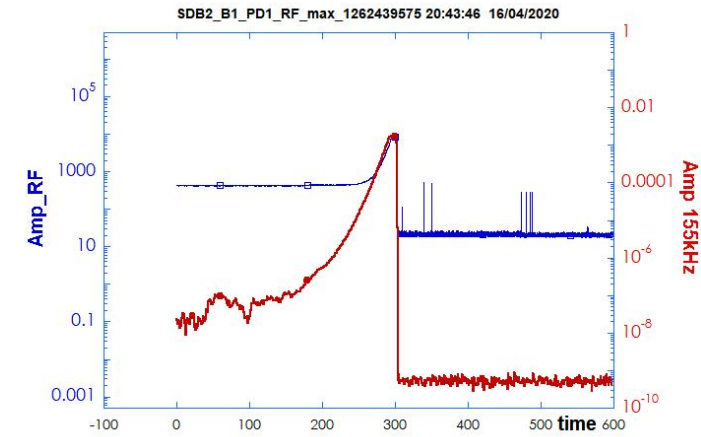
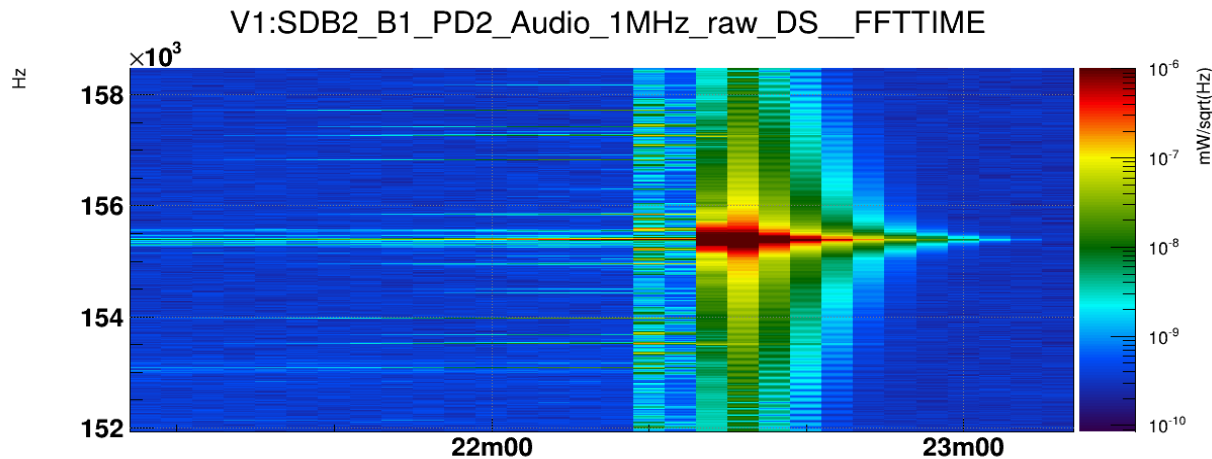


Suspended Interferometer for Ponderomotive Squeezing (SIPS) (optical spring principle)

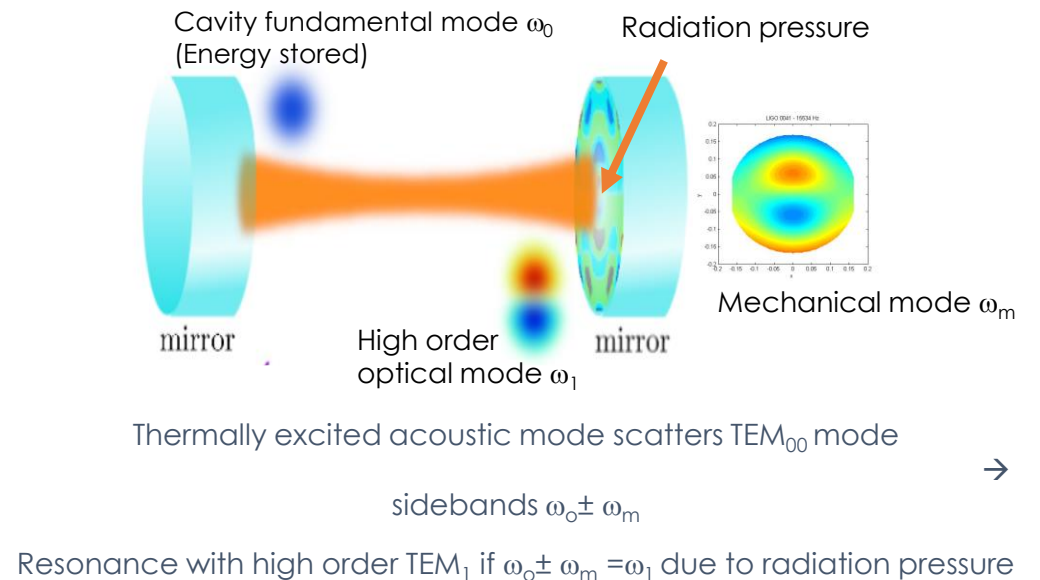


Parametric instabilities

- Optical cavity modes interact with the acoustic modes of the mirrors leading to exponential growth of the acoustic vibration.
- Already observed in O3
- Mitigation for interferometers with increasing power
- **Coordination activity in Rome**

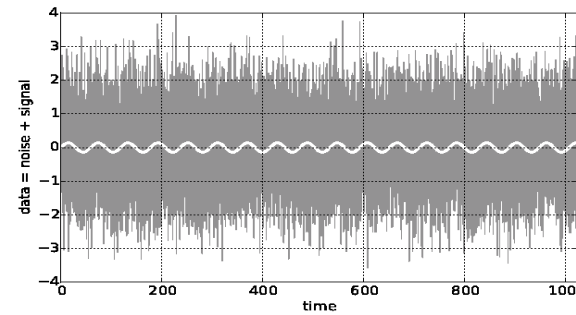
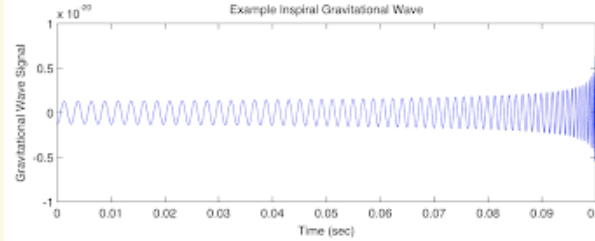
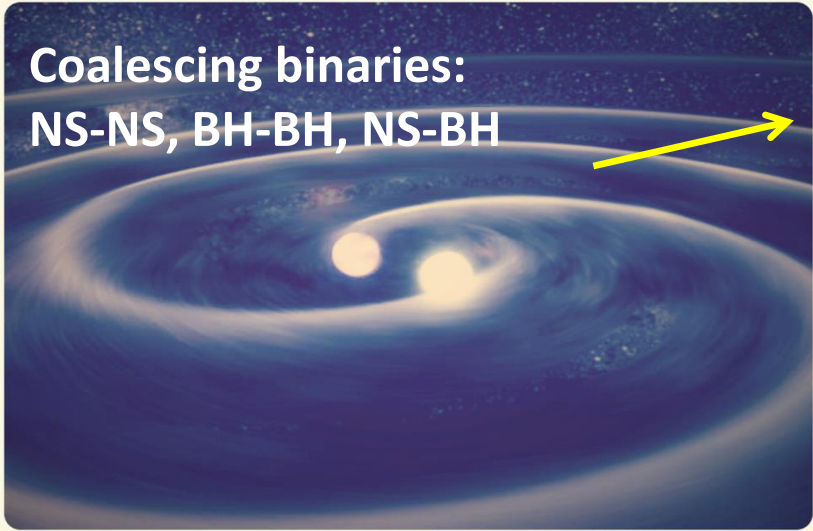


Parametric Instability : 3 modes interaction

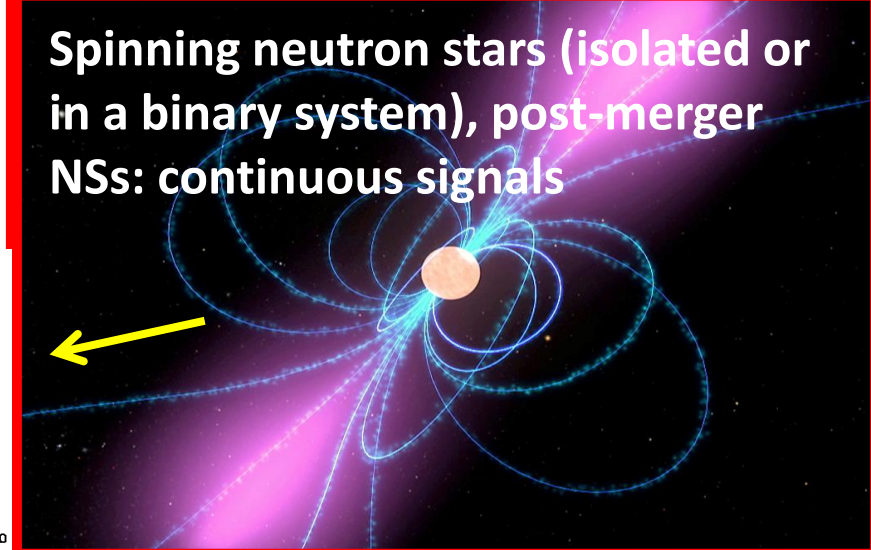


Resonance condition:
 $\omega_0 - \omega_1 = \omega_m$, high spatial overlap

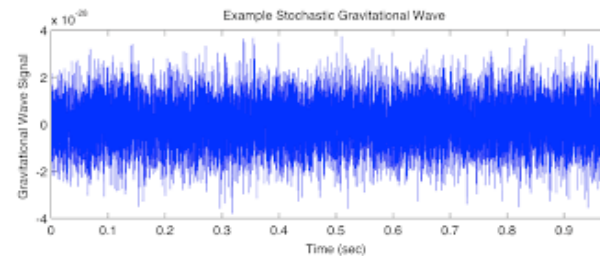
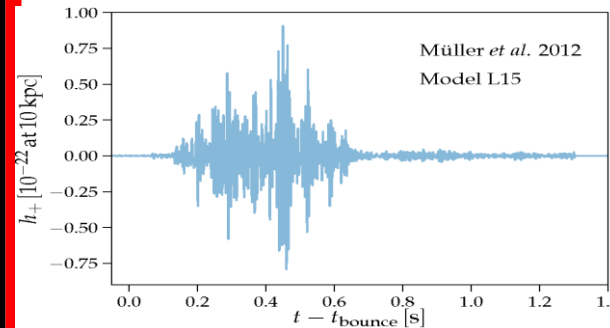
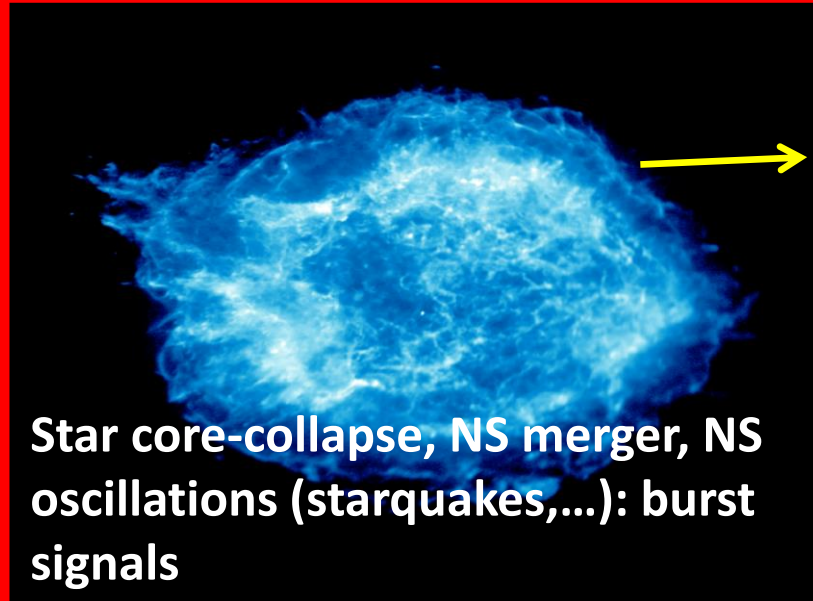
Coalescing binaries:
NS-NS, BH-BH, NS-BH



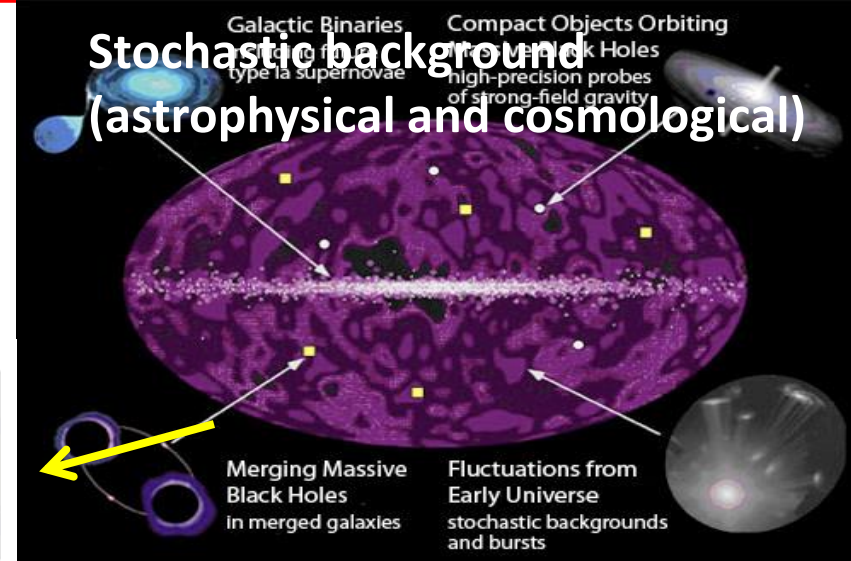
Spinning neutron stars (isolated or in a binary system), post-merger NSs: continuous signals



Star core-collapse, NS merger, NS oscillations (starquakes,...): burst signals



Stochastic background
(astrophysical and cosmological)



Targeted & narrowband searches

All-sky searches (isolated and binary NSs)

Directed searches from young SN remnants and from the GC

Long transient searches (magnetars)

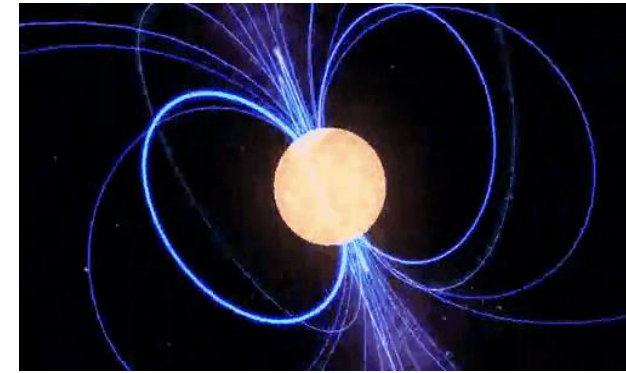
Ultra light dark matter searches (boson clouds around BHs, dark photons)

Joint searches with Stochastic Background

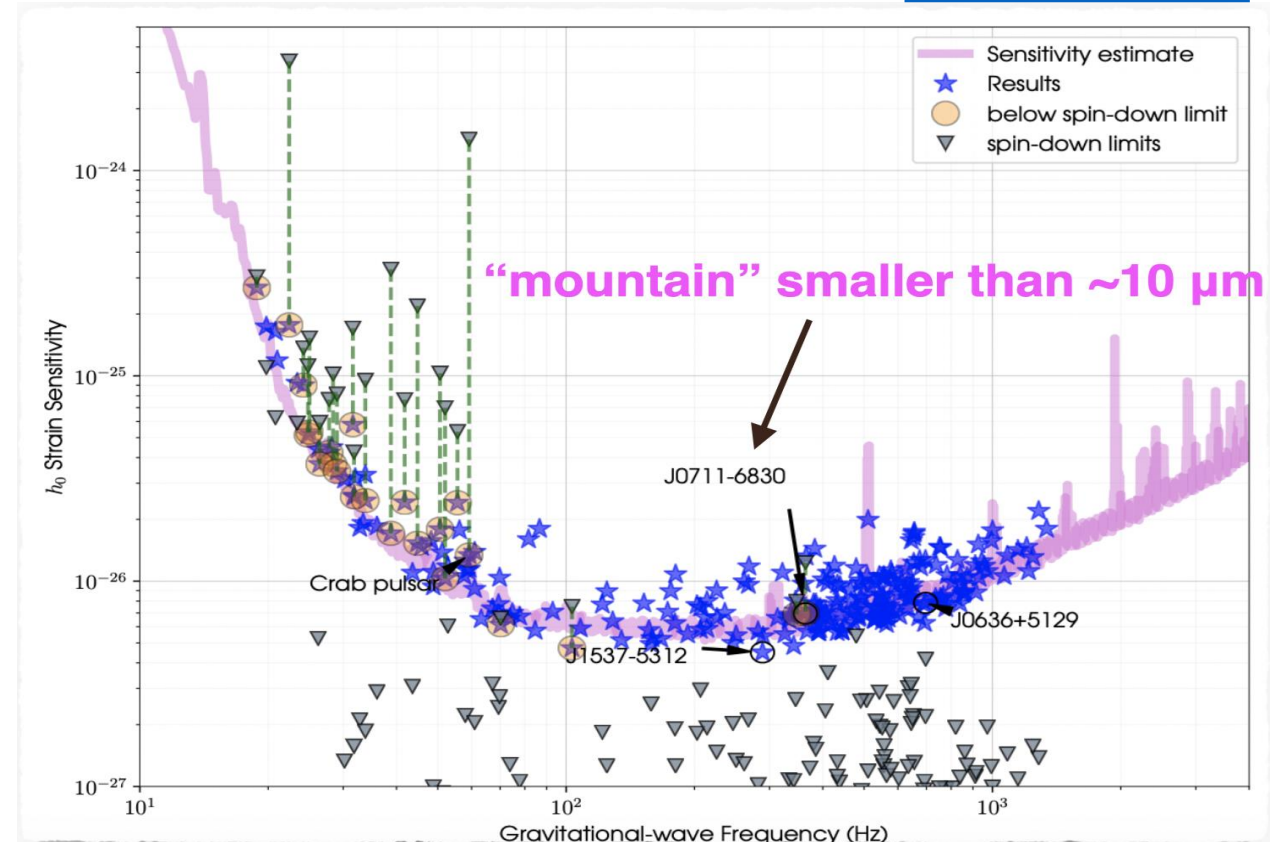
GPUs and exploration of machine learning techniques

Expected sources:

Asymmetric neutron stars with respect to the axis of rotation, magnetar. Bosonic clouds around BHs. Direct interaction of dark matter and gravitational wave detectors



[ArXiv:2111.13106](https://arxiv.org/abs/2111.13106)



Neutron star binary mergers: pipeline development and searches for mergers in coincidence with GRBs or FRBs in LIGO/Virgo data

NS-NS and NS-BH waveform modelling

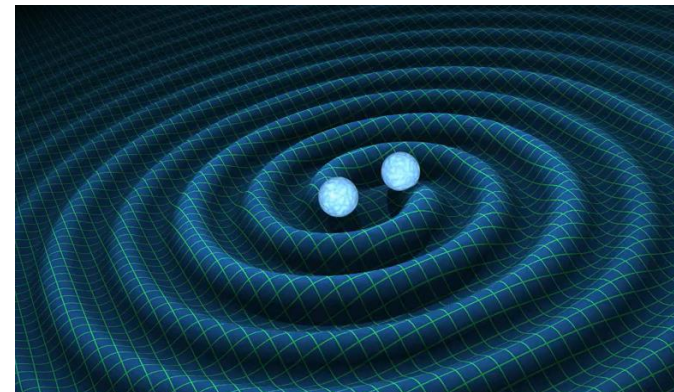
Study of equilibrium properties of NSs containing mirror dark matter

Assessing a fundamental test of General Relativity via the inference of the polarization content of transient GWs (*con.Sienze 2020 prize*)

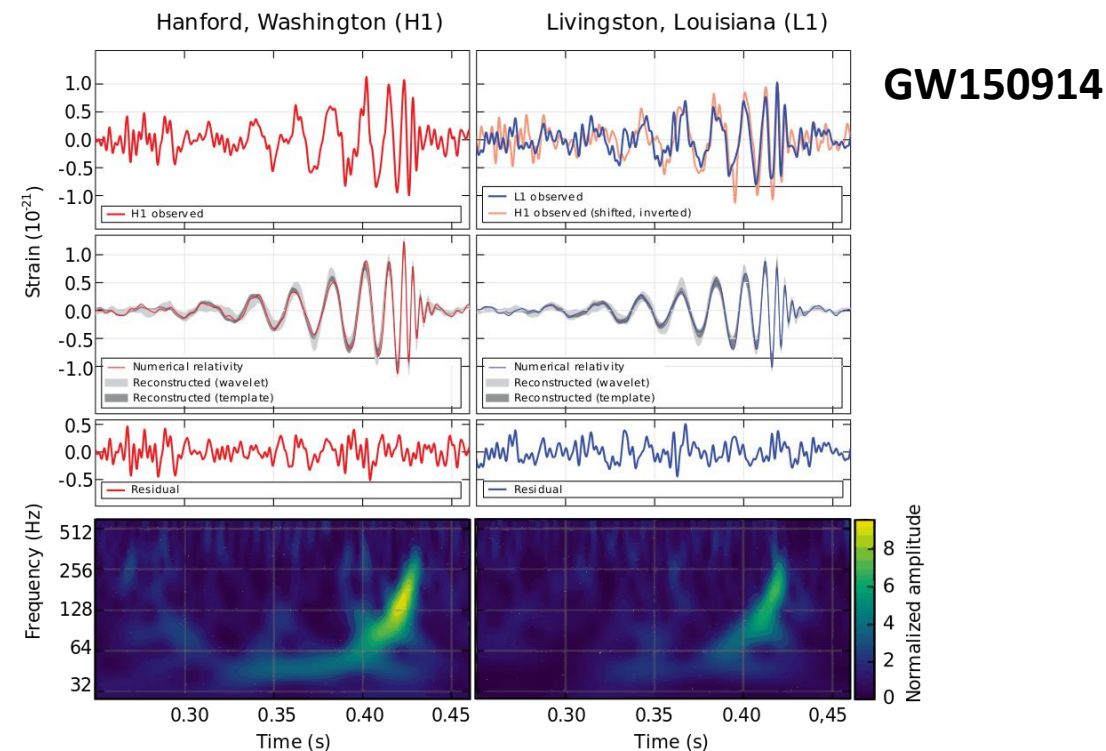
Machine learning applications to low-latency classification of compact binary source properties

Expected sources:

Compact objects coalescing: BH-BH ; NS-BH ; NS-NS



[*Phys. Rev. Lett. 116, 061102 \(2016\)*](#)



Burst (un-modeled transients)

Analysis and code optimizations
for a wide class of transient signals

LIGO/Virgo low-latency searches

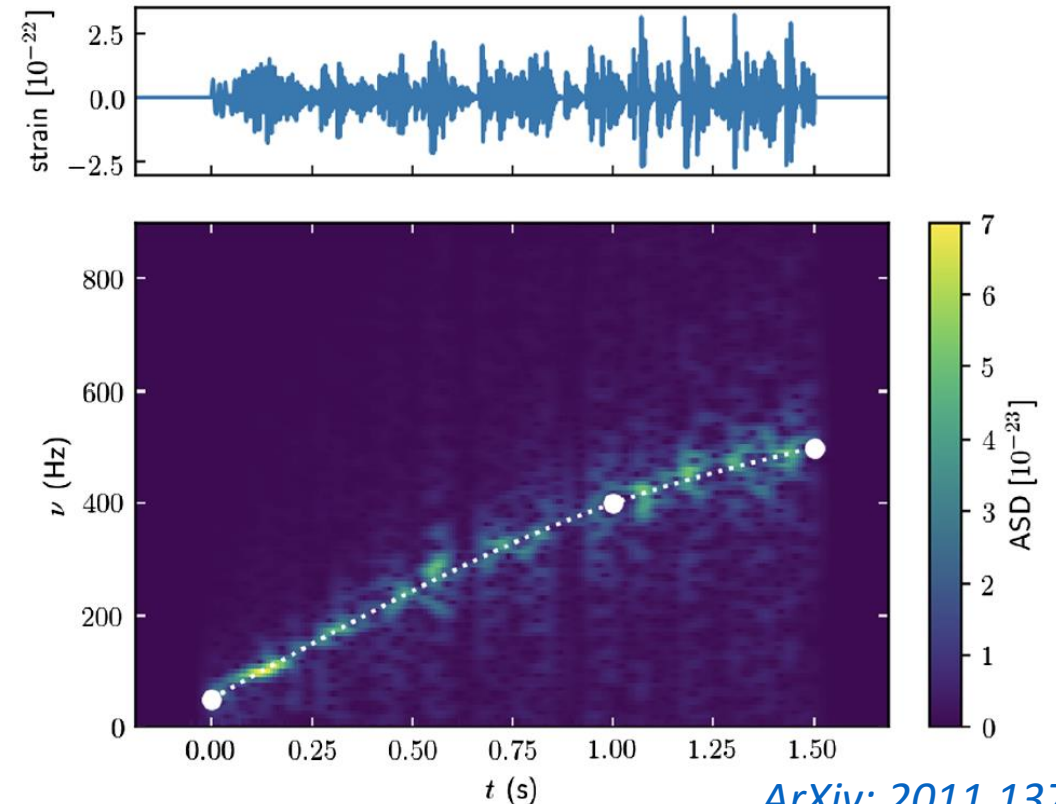
Waveform parameter estimation
for unmodeled signals

Analysis procedures for the science case of MMA
with neutrinos and GWs for Supernova searches

Machine learning algorithms for Core Collapse
Supernovae

Expected sources:

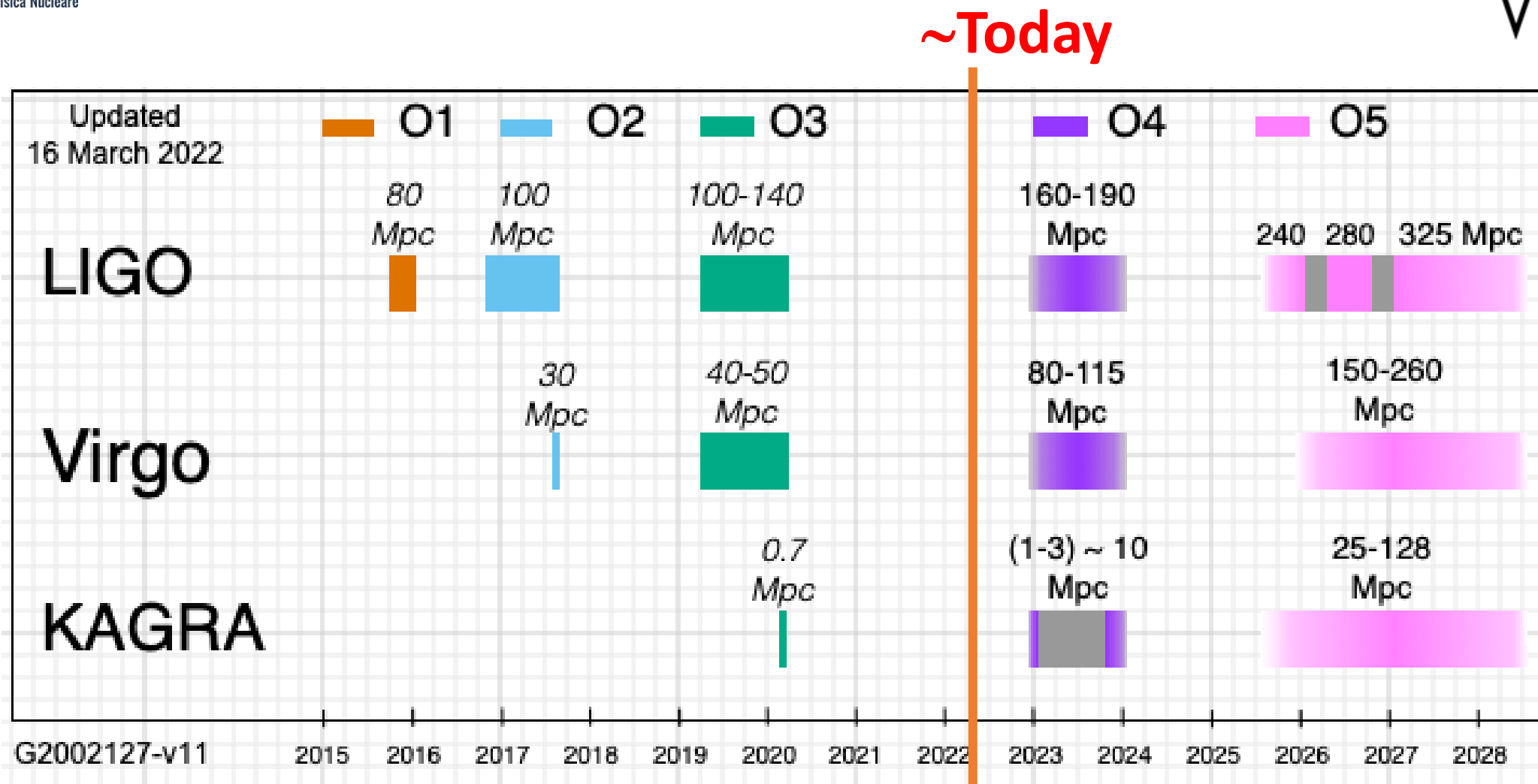
Core collapse supernovae, CBC, GRB, Soft Gamma Repeater, FRB, whatever-we-do-not-know-is-in-the-universe



[ArXiv: 2011.13733](https://arxiv.org/abs/2011.13733)

Future perspectives

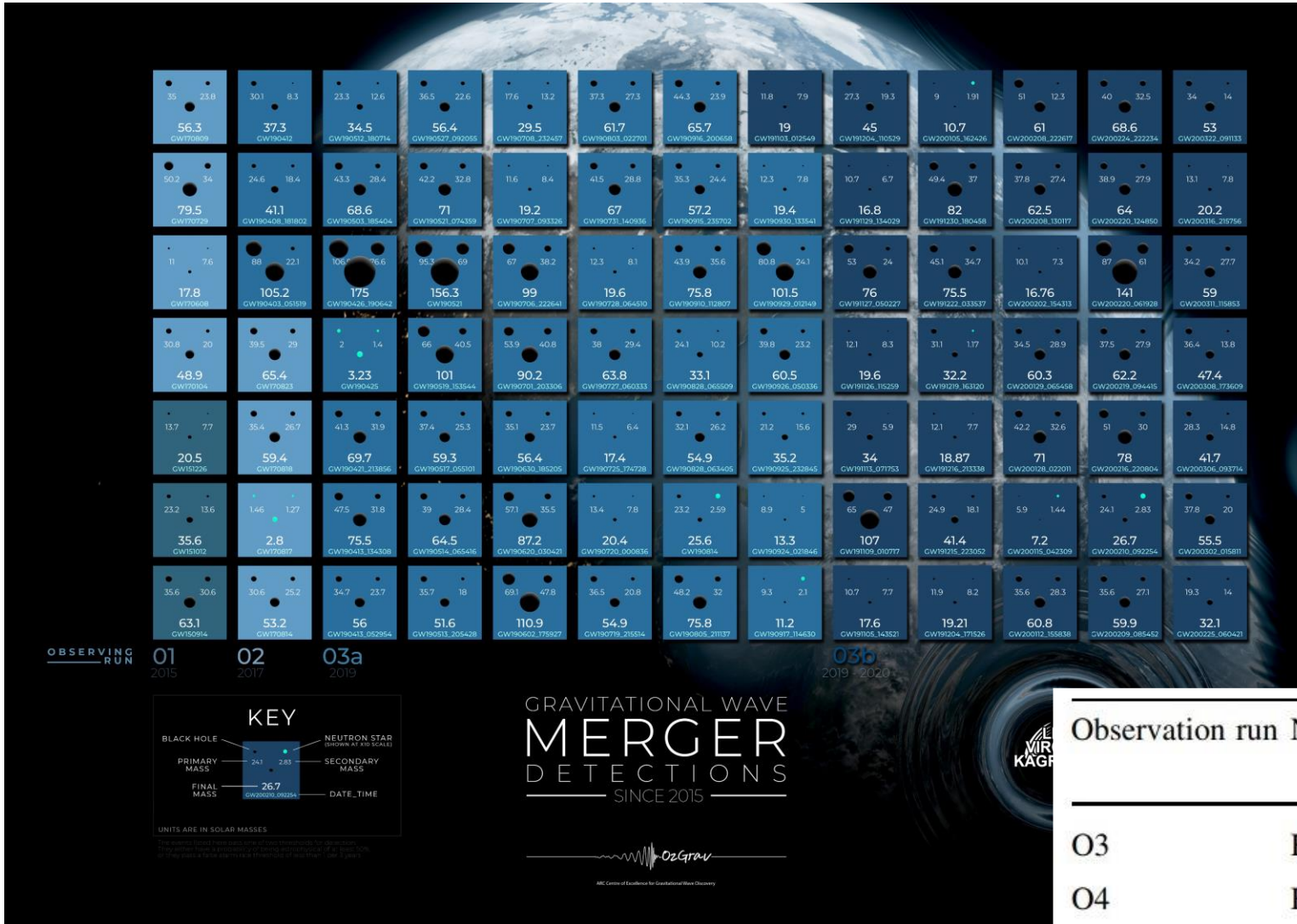
GW: when?



[LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS](#)

GW: how many?

[ArXiv:2111.03606](https://arxiv.org/abs/2111.03606)



Three scientific runs:

- O1: 3 GW
- O2: 8 GW
- O3: 79 GW

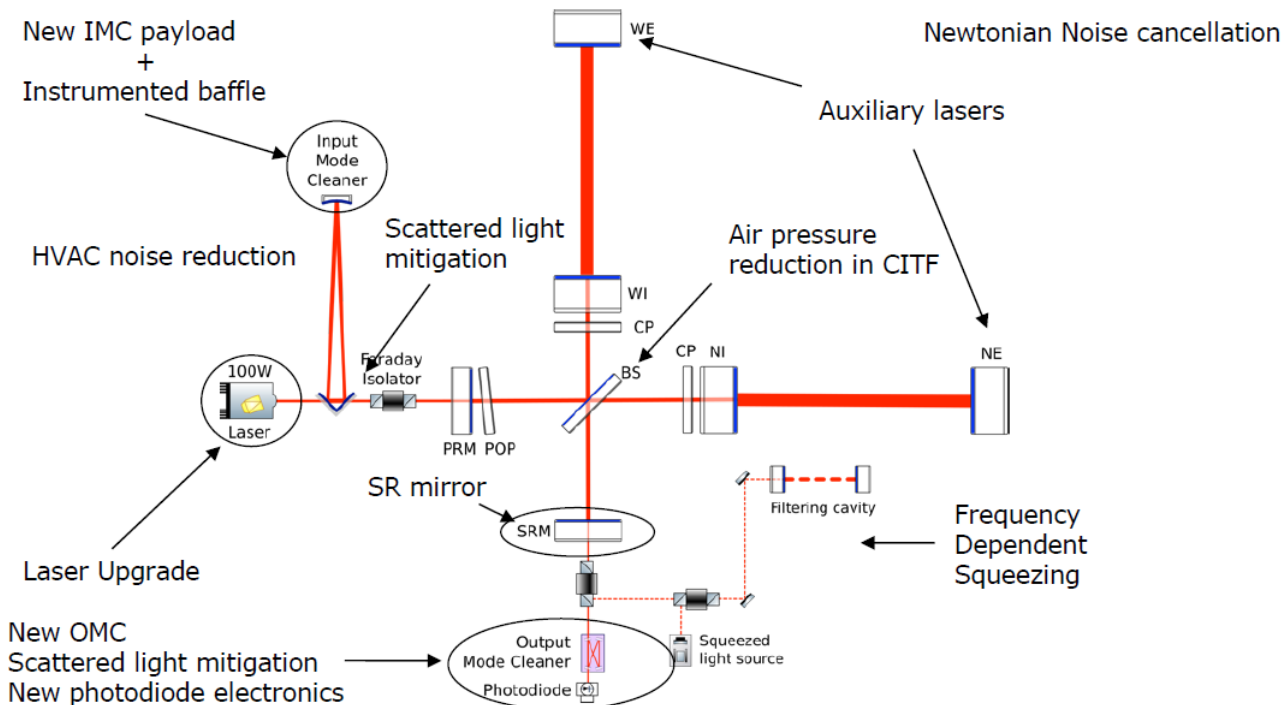
90 detections

Expected rate:

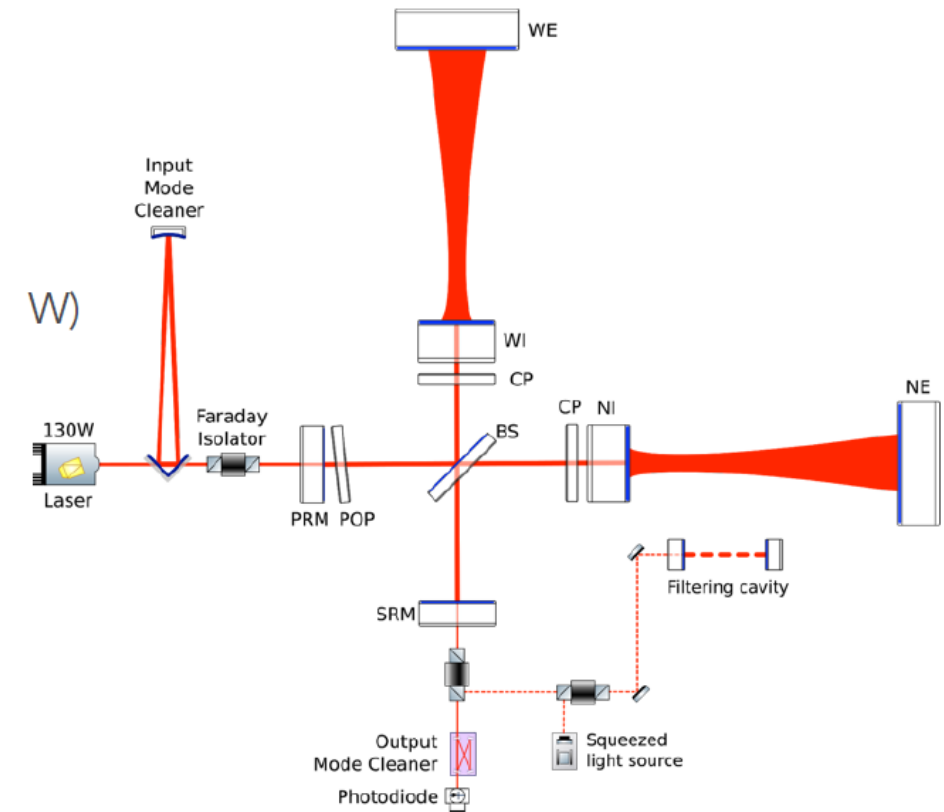
[ArXiv:1304.0670](https://arxiv.org/abs/1304.0670)

Observation run	Network	Expected BNS detections	Expected NSBH detections	Expected BBH detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

- Phase I → O4
reduce quantum noise, hit
against thermal noise



- Phase II → O5
lower the thermal noise wall



INFN Futura generazione: ET

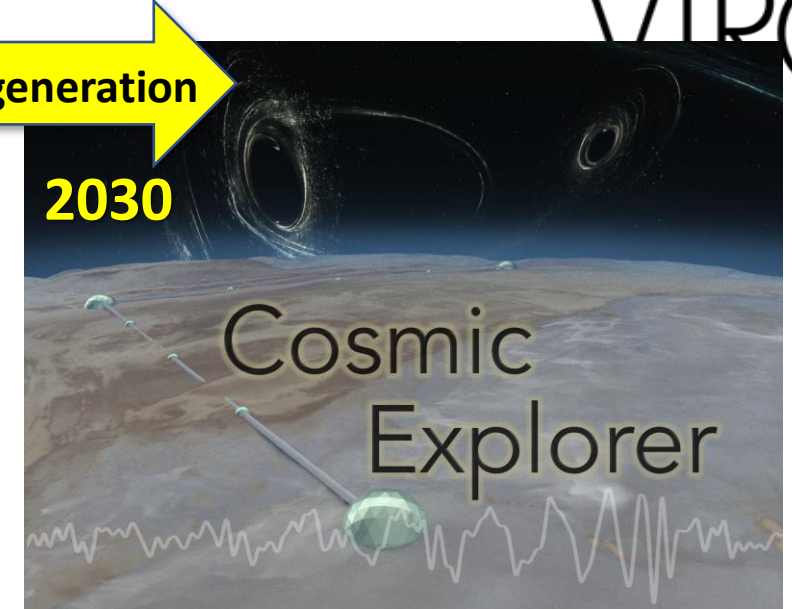


2nd generation

2015

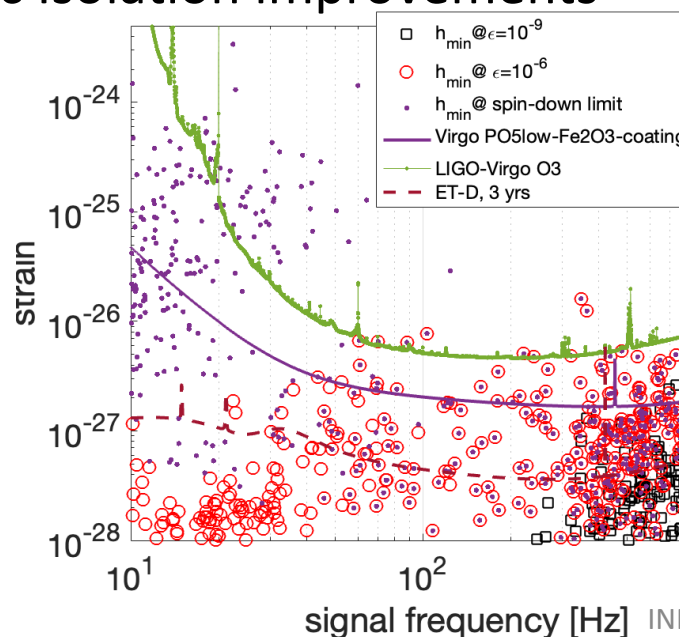
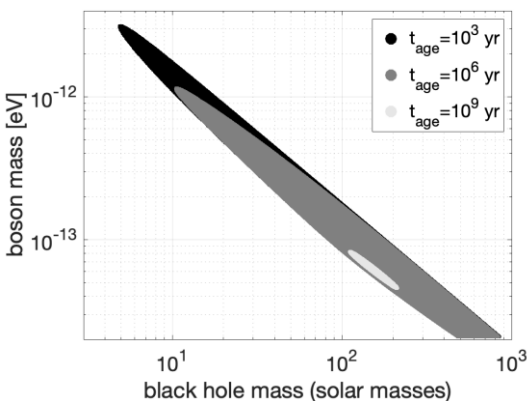
2.5 generation

3rd generation

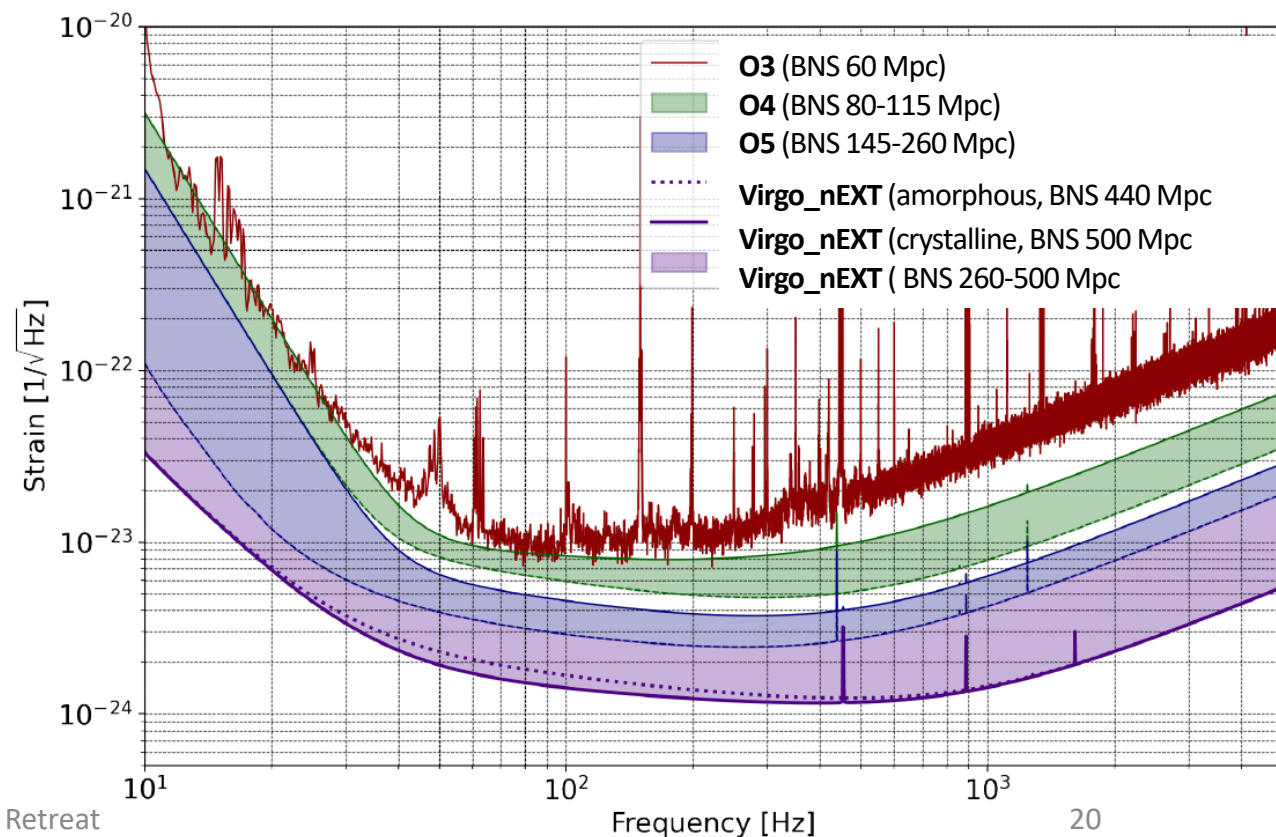


Source	O5 low	Virgo_nEXTlow
BNS range (Mpc)	258	500
BBH range ($30 + 30 M_{\odot}$) (Mpc)	590	3320

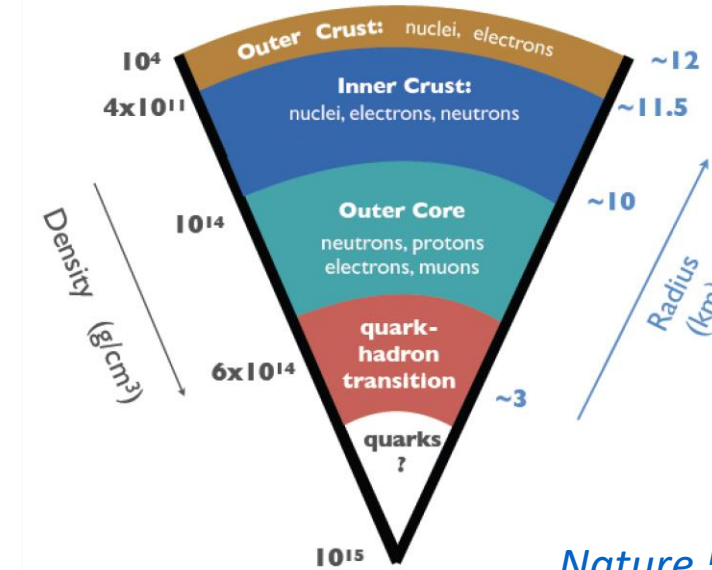
- Higher power: 1.5 MW in the arms (doubling from A+)
- Lasers, thermal compensation, parametric instability mitigation
- Higher levels of squeezing: 10 dB
- Reduced optical losses, improved mode-matching
- Larger Test Masses: 100 kg
- Test Mass Suspension Upgrades
- Coatings, Seismic Isolation improvements



AdV sensitivity evolution from O3 to Virgo_nEXT

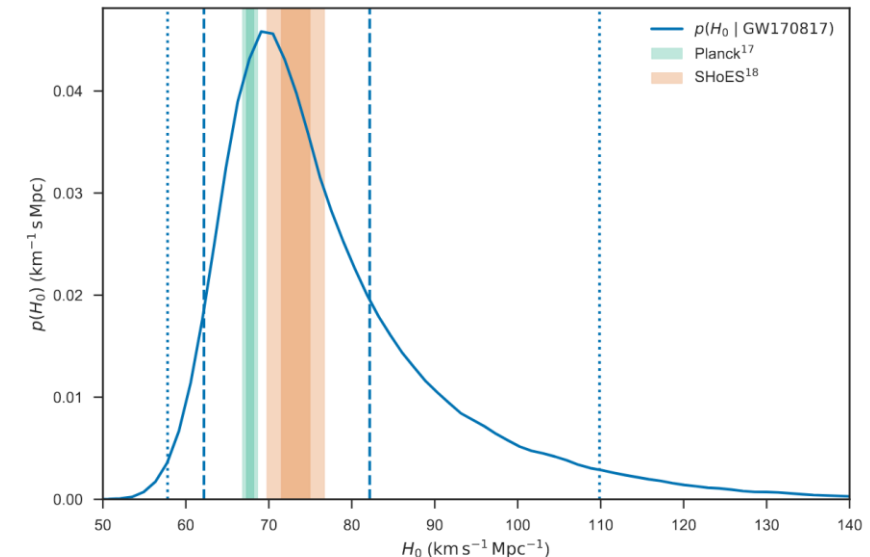
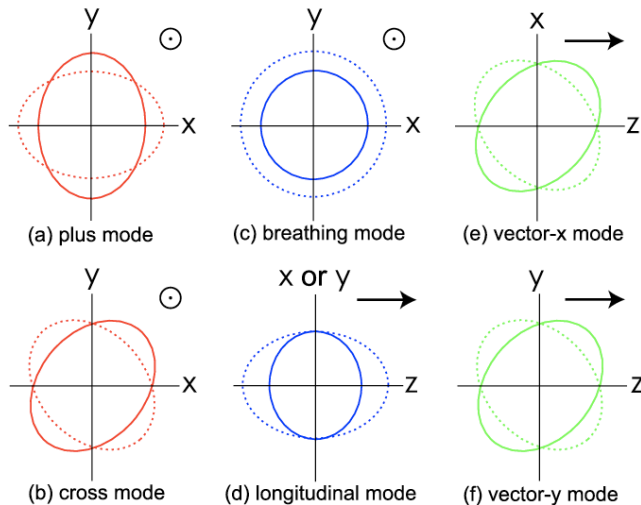


- Binaries population and BH physics
- GR Constraints
- NS equation of state
- GRB formation/process mechanism
- Cosmology
- CCSN process study (when detected)



[Nature 551, pages 85–88 \(2017\)](#)

[Phys. Rev. D 79, 082002 \(2009\)](#)



- We search for weak signals buried in the detector noise
- Challenges inspire synergy between different groups
 - Noise reduction and detection efficiency increase
 - Binaries templates definition
 - Parameter estimation (source direction, waveform shape)
 - Reconstruction of astrophysical process
 - Computational efficiency (GPU, ML techniques).
 - Algorithm development for Quantum Computing

Conclusions

INFN GW a ROMA

P. Astone, S. Dall'Osso, S. Di Pace, I. Di Palma, M. Drago



P. Leaci, E. Maiorana, L. Naticchioni, C. Palomba



F. Pannarale, E. Placidi, P. Puppo, P. Rapagnani, M. Serra



14/06/2022

INFN Retreat



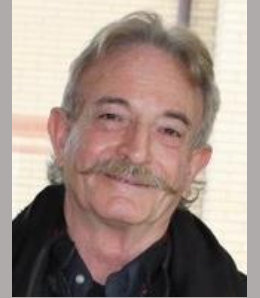
S. Frasca,



F. Ricci,



M. Perciballi



Retired friends

V. Mangano,



F. Muciaccia,

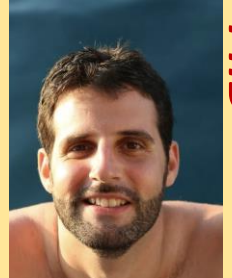
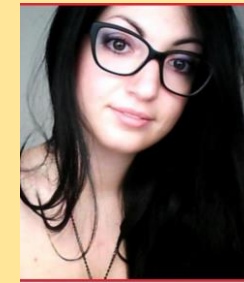


A. S. Rezaei



PostDoc

M. Boldrini, L. Giacoppo, I La Rosa, L. Pierini



PhD

Thesis projects

- Master

- **S. Bez Baruah**: characterization of SN reconstruction with unmodeled search
- **F. De Marco**: "Optical design of the laser injection line into a small scale suspended interferometer for Quantum noise reduction in Gravitational Wave detectors"
- **M. Emma** (coll. Postdam); numerical relativity with dark matter
- **R. Felicetti**: "Searching for persistent GW emission from ultra-light boson clouds in globular clusters"
- **N. Mancini**: machine learning
- **A. F. Mascioli**: Bayesian Parameter Estimation
- **G. Palloni**: Criogenia
- **L. Piccari**: Virgo searches
- **E. Velcani**: "Data analysis methods for the search of GWs from sub-solar mass primordial BH binaries"

- PhD

- **M. Boldrini**: Angular sensing, degree of freedom, modelization of radiation pressure
- **L. D'Onofrio** (Napoli): "New methods for the search of continuous GWs from an ensemble of known pulsars"
- **L. Giacoppo**: "Control system for an optomechanical demonstrator of Quantum Noise Reduction in Gravitational Waves interferometers"
- **I. La Rosa** (coll LAPP): "Fast Identification of continuous gravitational-wave signals"
- **G. Giarfagna** (coll Roma Tor Vergata): multimessenger astronomy
- **L. Pierini**: "Boosting the sensitivity of continuous gravitational waves all-skysearches using advanced filtering techniques"

The detection effect

Number of institutes/groups in the Virgo collaboration before and after the announcement

Stato	31/01/16 (link)	Oggi (link)
Francia	16	30
Italia	25	58
Olanda	4	11
Polonia	7	10
Ungheria	2	2
Spagna	-	9
Belgio	-	7
Grecia	-	2
Cina, Repubblica Ceca, Danimarca, Irlanda, Giappone, Monaco	-	1

Molti nuovi gruppi (anche di formazione non gravitazionale)

The detection effect

Number of institutes/groups in the Virgo collaboration before and after the announcement

Stato	31/01/16 (link)	Oggi (link)
Francia	16	30
Italia	<ul style="list-style-type: none"> • Gravitational wave astronomy is just at the beginning! • LIGO-Virgo-Kagra starting next scientific run starting on end 2002/beginning 2023 <ul style="list-style-type: none"> • Potential for master these, PhD, post-doc projects, etc... 	
Olanda		
Polonia		
Ungheria		
Spagna		
Belgio	-	7
Grecia	-	2
Cina, Repubblica Ceca, Danimarca, Irlanda, Giappone, Monaco	-	1

Molti nuovi gruppi (anche di formazione non gravitazionale)

- A lot of **interesting sources** for MM astronomy
 - GRB, Core-collapse SN, BNS, ...
- **MM searches** already performed
 - GRB, SN -> EM Triggering GW
 - Antares/IceCube triggering GW
 - GW triggering EM/ ν
- More exploration is possible, **synergies** with different groups can be promising
 - You are welcome to collaborate!