Image Credit: NASA/GSFC

GW astronomy at IGFAE

Group members

T. Dent – Research group lead

J. Calderon Bustillo – La Caixa/MSCA Junior Leader

J. Alvarez-Muñiz – USC faculty, Pierre Auger collaboration

J. Sadiq – postdoctoral research fellow (until Oct 2022)

V. Villa-Ortega – FPI PhD candidate (3rd year)

P. Kumar – PhD candidate (starting 2nd year)

Funding

MdM Unit of Excellence (2018–2021 + …)

Research Centre of Galicia (2020–)

Spanish State Research Agency project (2021–)

Ground-based GW network & sources

- Advanced global network

  LIGO / Virgo : O3 2019-20, further runs 2023+

  GEO600 : technology prototyping & cover LIGO breaks

 KAGRA : commissioning / observing 2023+

  LIGO-India : under construction
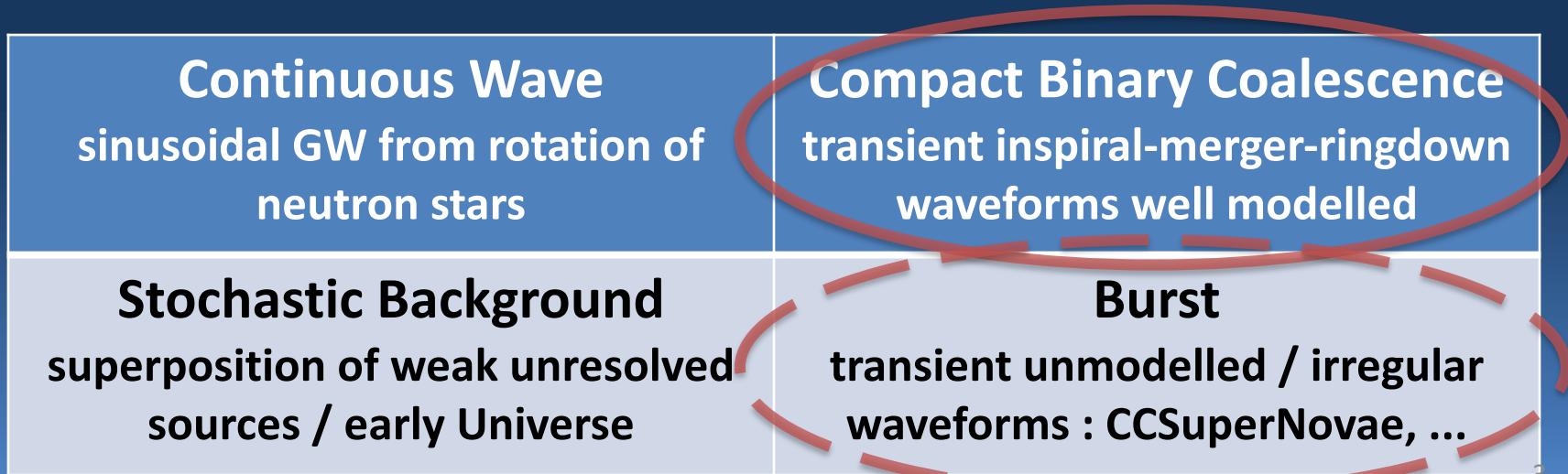
Continuous Wave sinusoidal GW from rotation of neutron stars	Compact Binary Coalescence transient inspiral-merger-ringdown waveforms well modelled
Stochastic Background superposition of weak unresolved sources / early Universe	Burst transient unmodelled / irregular waveforms : CCSuperNovae, ...

Ground-based GW network & sources

- Advanced global network

  LIGO / Virgo : O3 2019-20, further runs 2023+
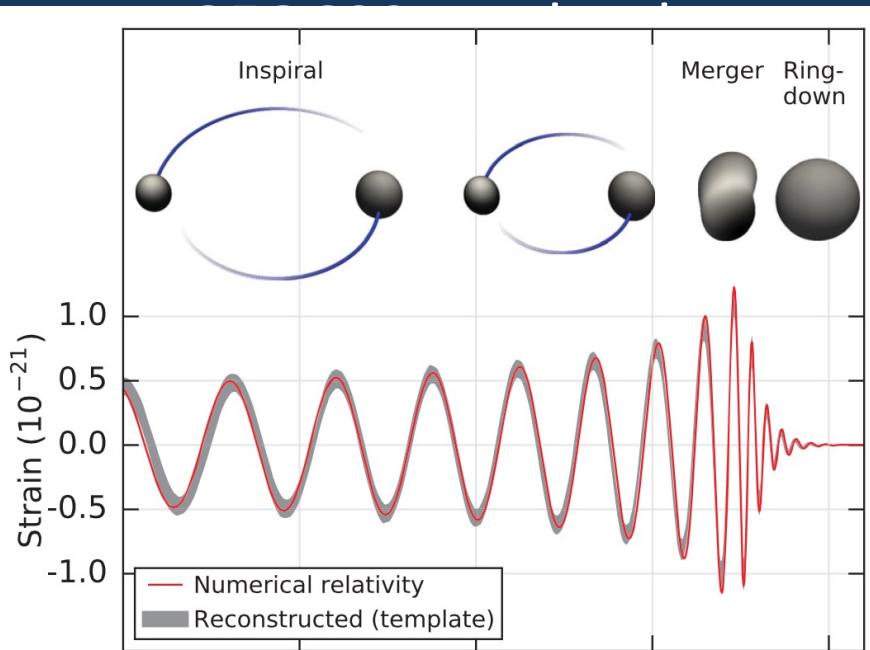
  [...] totyping & cover LIGO breaks

  [...] observing 2023+

  [...] ruction

|	Compact Binary Coalescence transient inspiral-merger-ringdown waveforms well modelled
superposition of weak unresolved sources / early Universe	Burst transient unmodelled / irregular waveforms : CCSuperNovae, ...

Overview : **L**IGO**V**irgo**K**AGRA observations

➢ LSC member group since 2018 : access to LVK data, commitments to develop/carry out data analysis

➢ Binary search : correlate 10^5–10^6 merger waveforms with network data, low latency alerts, event list, estimate sensitivity **TD, VVO**

➢ Rates/Populations : interpret search results via models of binary merger population **TD co-chair R/P subgroup 2019-2022, JS**

➢ Multi-messenger search : associate GW events with EM/ν/CR events **IGFAE Auger group, JS contributing to GRB triggered search**

➢ Waveform modelling : increased accuracy for binaries with general spins **JS**, non-dominant GW modes **JCB**

➢ Parameter estimation & Beyond-Standard-Model **JCB+** : characterize highest-mass binaries, alternative models (Boson Stars) …

LIGO-Virgo 3rd Observing Run

- Run 2019-04-01 to 2020-04-30, 2×LIGO + Virgo

Binary neutron star inspiral range

Network duty factor
[1238166018-1253977218]

- Triple interferometer [44.5%]
- Double interferometer [37.4%]
- Single interferometer [15.0%]
- No interferometer [3.2%]
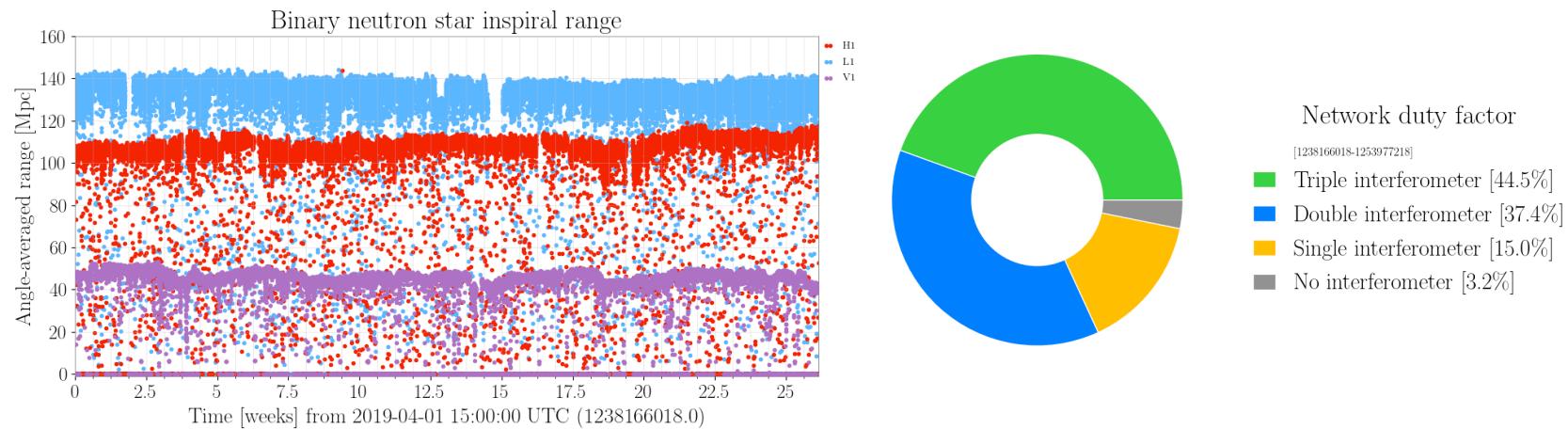
- Vacuum squeezing applied in all ifos
  ~1.4× sensitivity gain over O2 (×2 for Virgo)

- IGFAE-GW : PyCBC online candidate event identification
  & offline analysis for publication

Relevant LVC/-K publications

- GW190521 Detection 2009.01075 / Astro Implications 2009.01190 : first merger with IMBH remnant
- GWTC-2 (O3a catalog update) 2010.14527
- Binary populations from GWTC-2 2010.14533
- O3a GRB triggered search 2010.14550
- O3 IMBH search 2105.15120
- First observations of NS-BH coalescences 2106.15163
- GWTC-2.1 ('deep extended catalog') 2108.01045
- GWTC-3 (O3b catalog update) 2111.03606
- Binary populations from GWTC-3 2111.03634
- O3b GRB triggered search 2111.03608
- …

Highlights: CBC search & populations
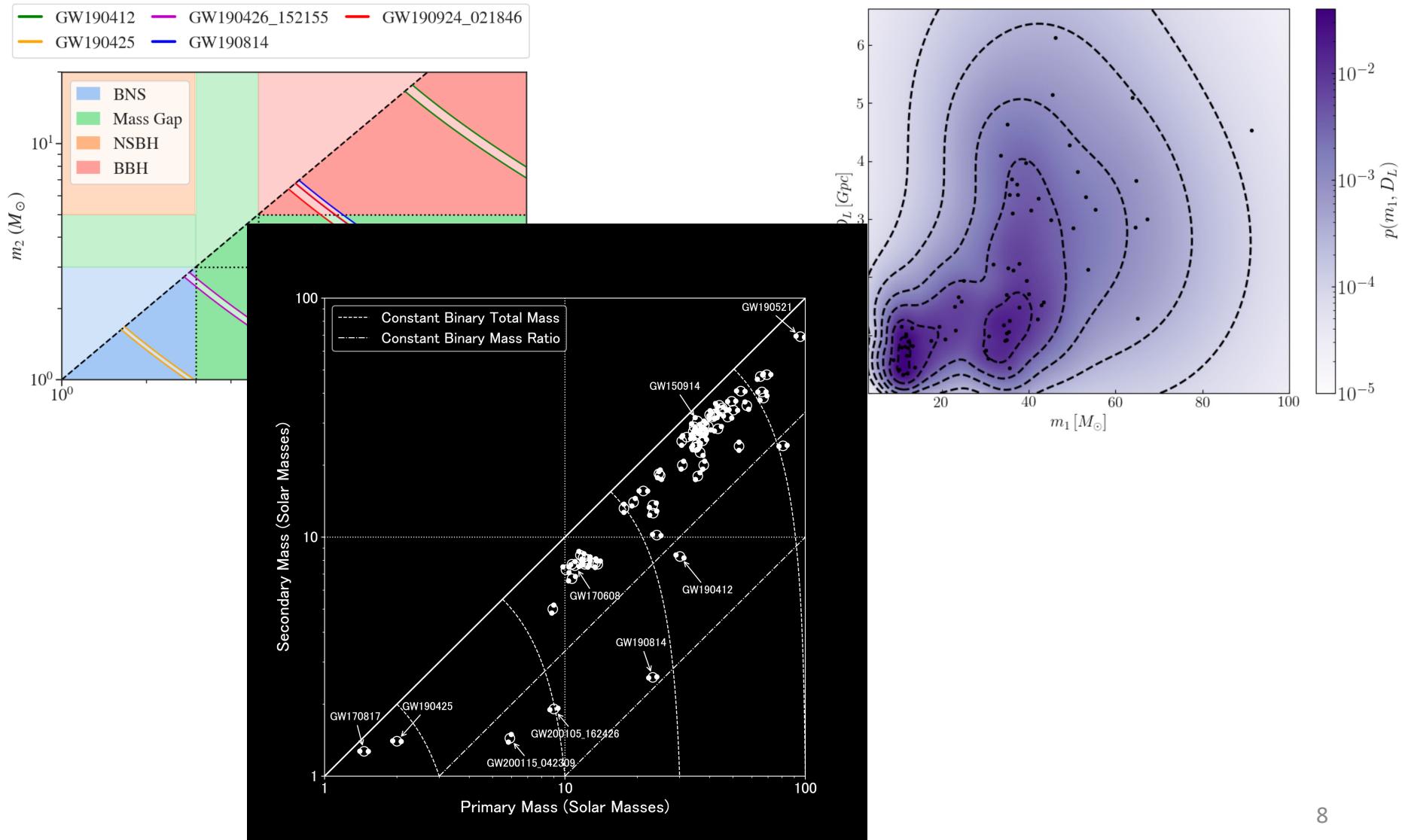
Highlights: CBC search & populations
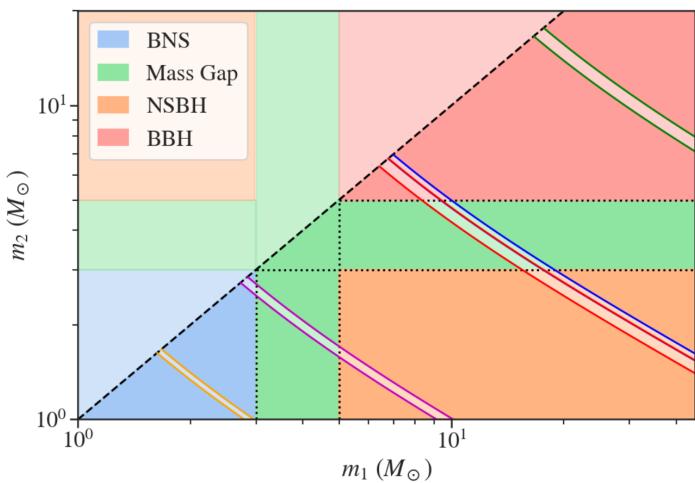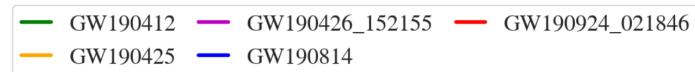
VVO+ 2022
MNRAS

JS+ 2022
PRD

9

Waveforms & parameter estimation

$$h(t) = \sum_{\ell,m} Y_{\ell,m}^{-2}(\iota, \varphi) h_{\ell,m}(t)$$

Face-on: Only Quadrupole
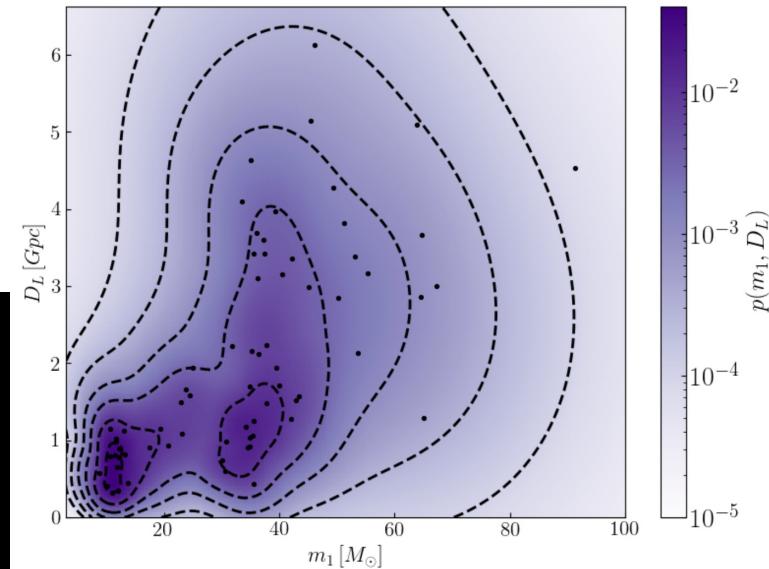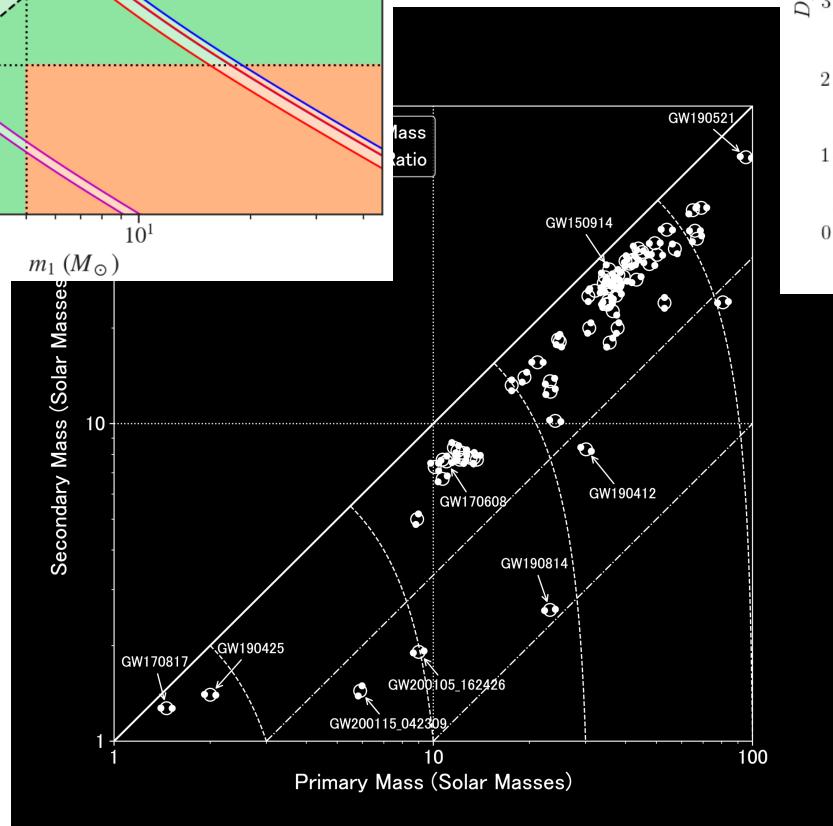
Edge-on: Full mode collection
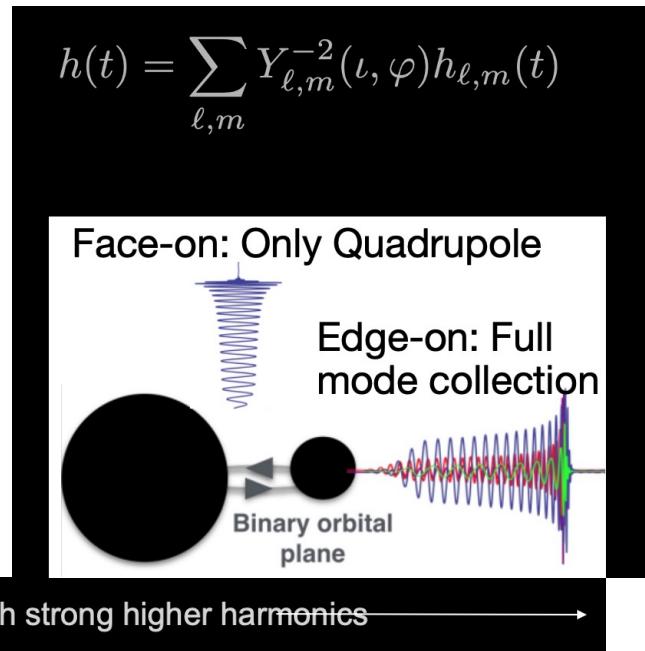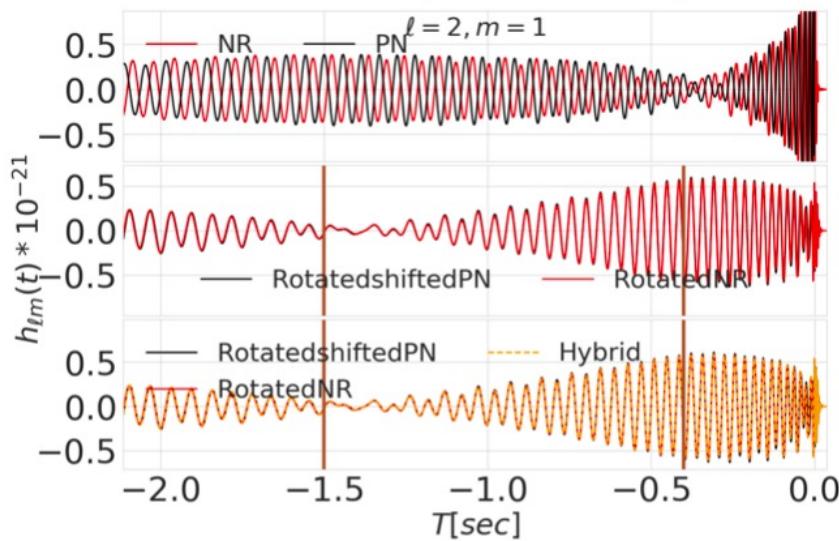
Typical LIGO-Virgo chirp ← ——————————— → Signals with strong higher harmonics

Waveforms & parameter estimation

$$h(t) = \sum_{\ell,m} Y_{\ell,m}^{-2}(\iota, \varphi) h_{\ell,m}(t)$$

Face-on: Only Quadrupole

Edge-on: Full
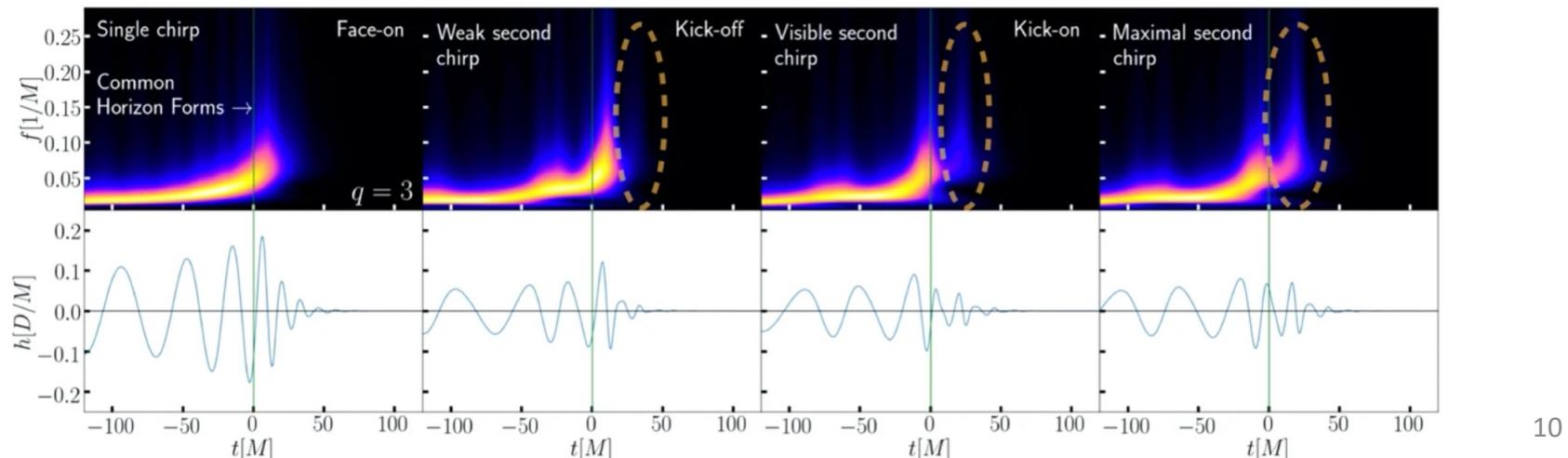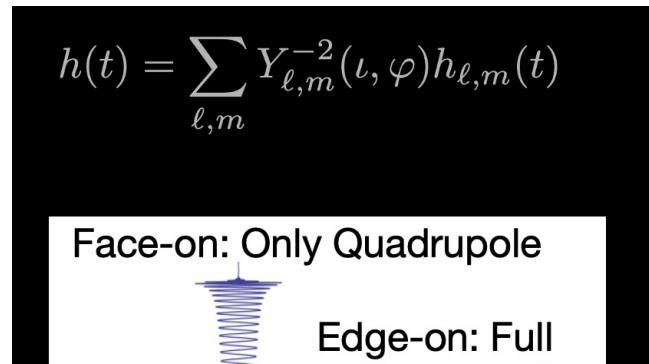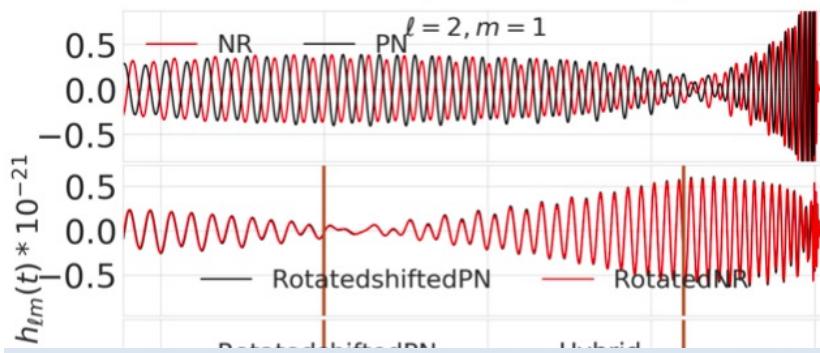
- Search for merger signals with higher harmonics   Chandra+ JCB 2022
- Use of higher harmonics for Hubble constant estimates with BNSs
  JCB+ ApJL 912 1 (2021)
- New framework : analyze Newman-Penrose scalar instead of strain
  JCB+ 2205.15029
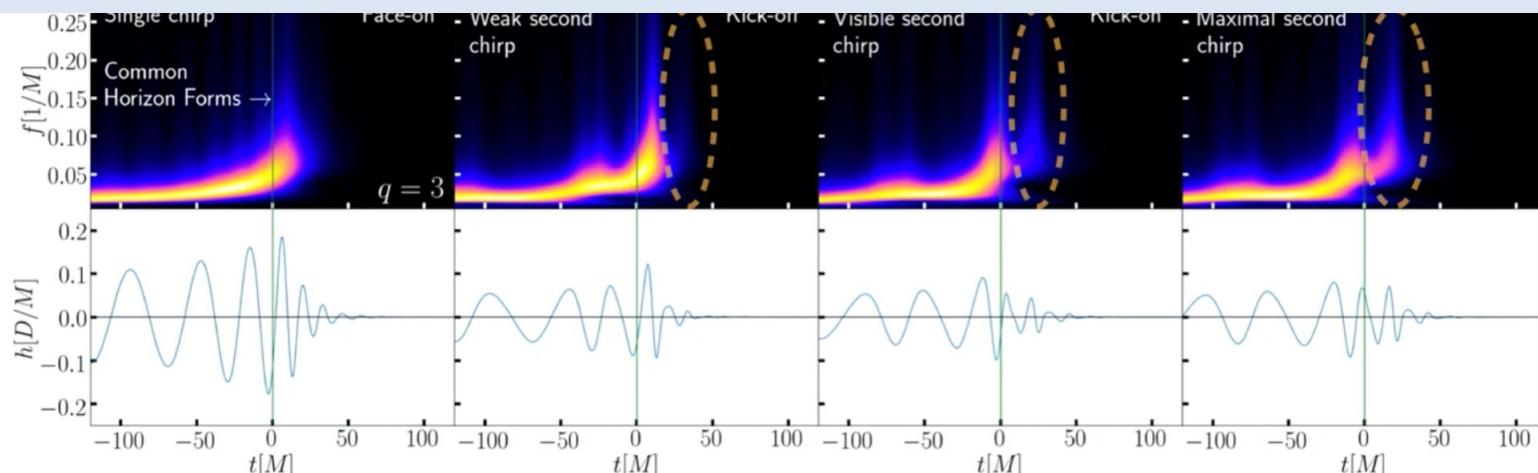
Interpreting high mass mergers

➤ 'BSM' = Beyond Standard Model / Boson Star Merger ?

Comparison of four LIGO-Virgo events to boson-star mergers JCB+ arXiv:2206.02551
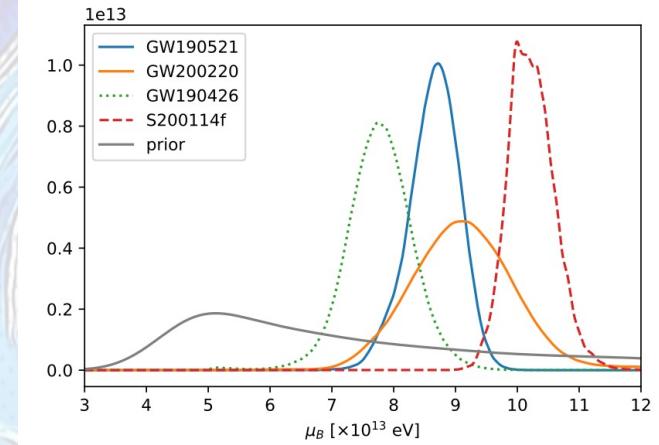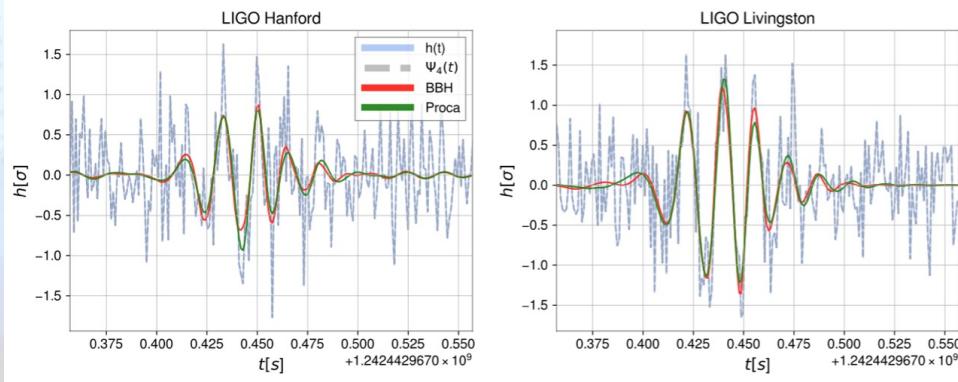

GW190521 well described as boson-star merger JCB+ PRL 126.081181 (2021)

➤ Impact of assumptions on astro interpretation

GW190521 possible coincidence with EM counterpart
arXiv:2112.12481

Possibility of mistaking eccentricity as precession
JCB+ PRL 126.201101 (2021)
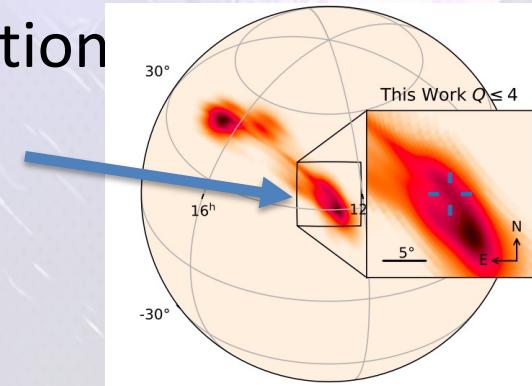
IGFAE-GW events etc.

- Joint organization of Neutron Star physics & astronomy [research lecture series](#) with invited speakers (Nov 2021)

- Masters lectures on GW (Advanced Gravitation course)

- Many visitors: Tjonnie Li (KU Leuven), Nicolas Sanchis, Alejandro Torres (Valencia), Angela Borchers (AEI), Ornella Piccinni (UAB), Jorge Delgado (Aveiro), those of NS course...

- 12 seminars (and counting ..)

- IGNITE Project: Development of exotic-star models for waveform template generation – student visiting U. Aveiro and U. Valencia

Computing acquisition

- CPU purchases funded from Xunta de Galicia
  - ~2000 CPU cores
- Installed in CESGA
- Priority use for LVK (offline) analysis via OSG/IGWN Grid
- Light use up to now, expect heavier in O4 (next run)

THE FUTURE . . .

Upcoming science runs

LIGO

Virgo

KAGRA

LVK, Living Rev. Relativity (2019)
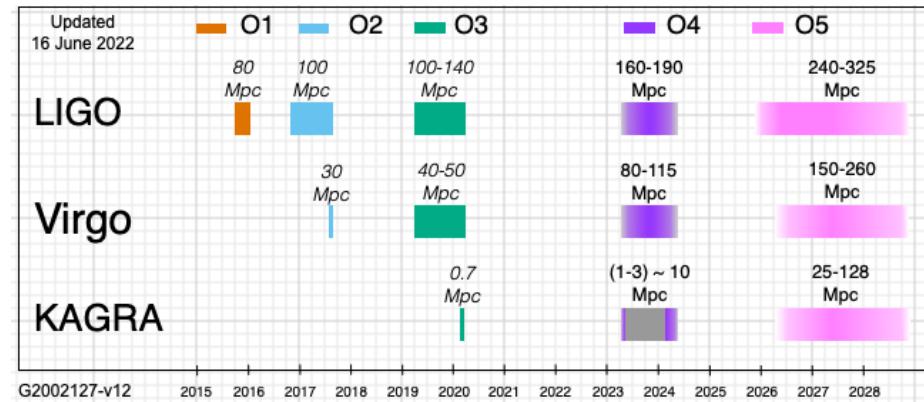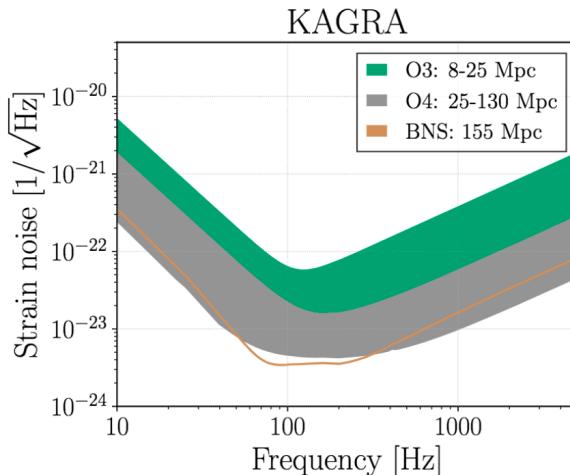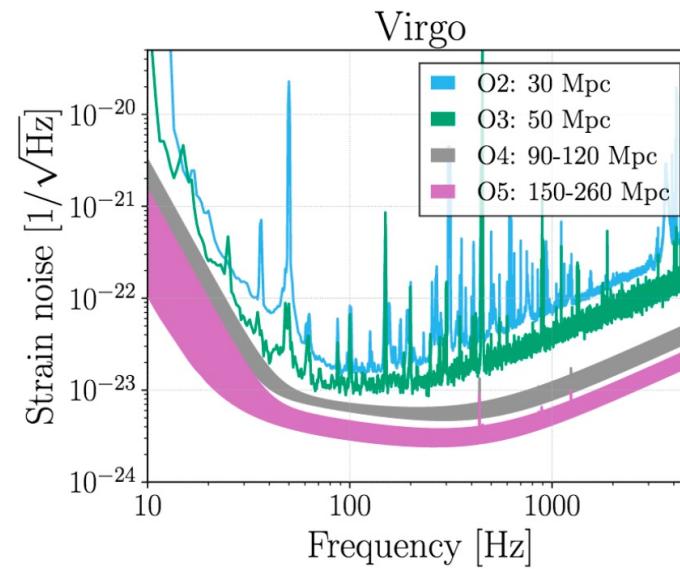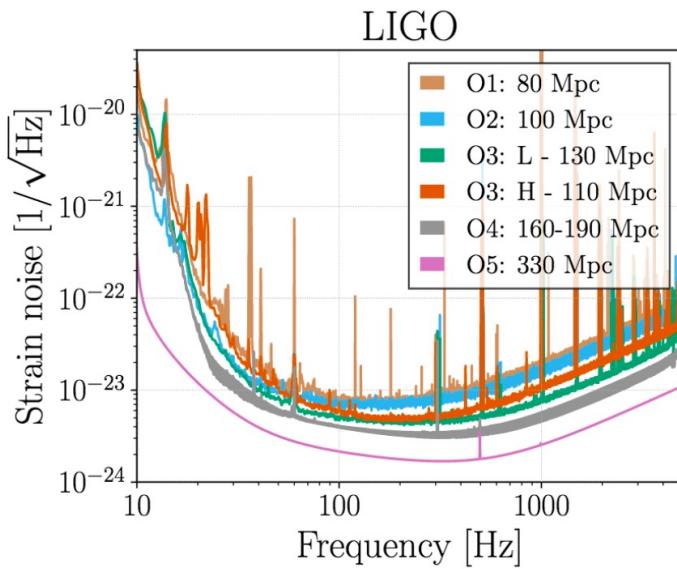
- Advanced LIGO/Virgo design sensitivity by 2023-4

Extending the network

~ 2017+
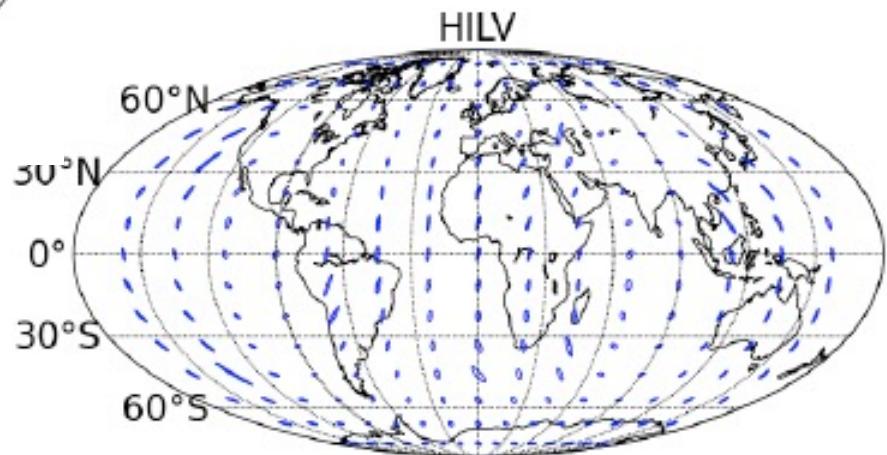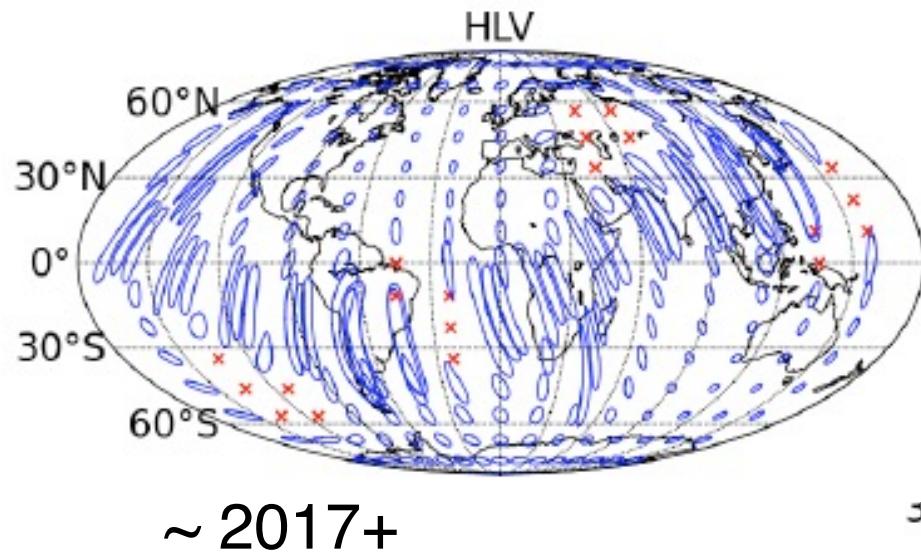
2026+ ?
with LIGO-India

'A+' Advanced LIGO Mid-scale Upgrade

- Upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk

- Target: average 1.7x increase in range over aLIGO

→ ***~ 5x greater event rate than Advanced LIGO***

  ~ 40 times greater than current Advanced LIGO sensitivity

- Stepping stone to future detector technologies

A+ Strain Projection (Comoving Ranges: NSNS 1.4/1.4 $M_\odot$ and BHBH 20/20 $M_\odot$)

Strain noise h [1/√ Hz] vs Frequency (Hz)

- O1 typical: NSNS 74 Mpc, BHBH 581 Mpc
- aLIGO full power: NSNS 191 Mpc, BHBH 1366 Mpc
- A+: NSNS 354 Mpc, BHBH 2240 Mpc
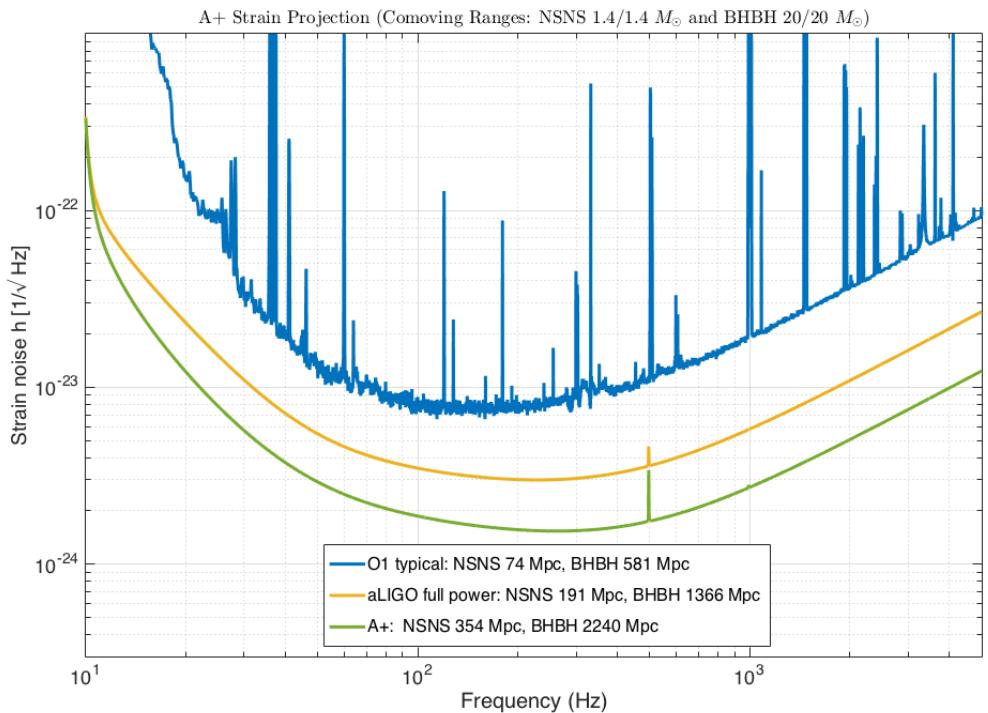
A+ key parameters

12 dB injected squeezing
15% readout loss
100 m filter cavity (FC)
**20 ppm round trip FC loss**
Coating Thermal Noise half of aLIGO

Instrumentation for Advanced(+) / 3G interferometers

- Opportunity for IGFAE to engage in GW detector hardware development

- Contribute to reaching & surpassing Advanced design sensitivities /
develop technology for next-gen terrestrial facilities (Einstein Telescope, Cosmic Explorer ..)

- Expertise in microelectronics, silicon radiation detectors and readout, sensor photodiodes, monitoring and control systems (eg LHCb instrumentation)

- Requires significant impetus to set up lab

Further on: Voyager, Einstein Telescope, Cosmic Explorer

LIGO Voyager – exploiting the LIGO Observatory facility limits

Laser $\lambda = 2\ \mu m$

Φ_m

$P_{in} = 150\ W$

$T_{PRM} = 2\%$

$P_{BS} = 15\ kW$

BS

$T_{SRM} = 10\%$

$T_{ITM} = 1\%$

$T_{ETM} = 5\ ppm$

Silicon
m = 140 kg
T = 123 K

$P_{cav} = 3\ MW$
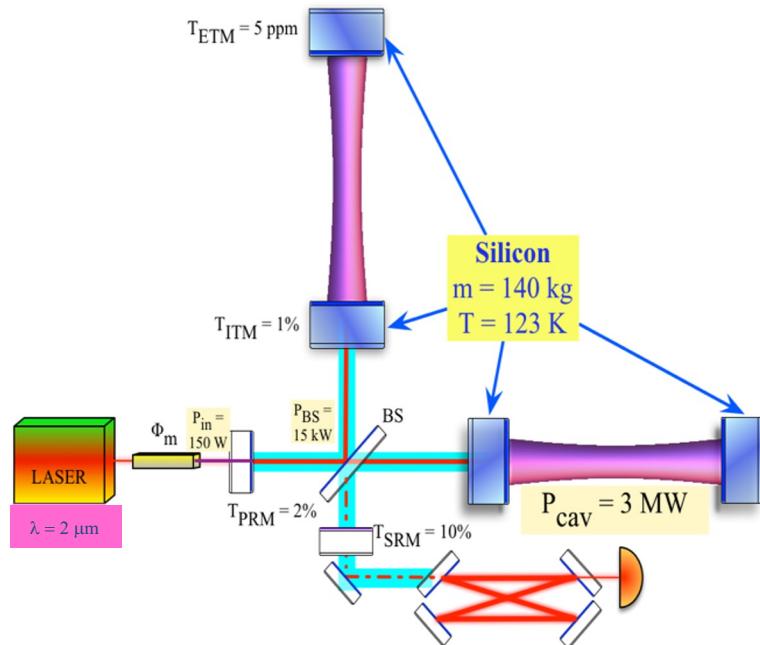
Longer Arm Length Interferometers

Einstein Telescope

A future GW observatory in the EU
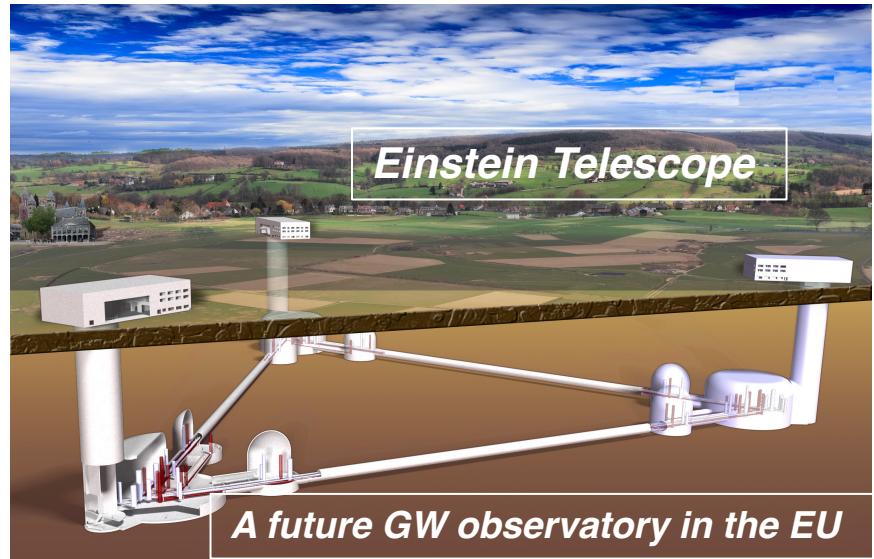
Cosmic Explorer – A future GW observatory in the US

DAWN III

Credit:
R. Ward
S. Ballmer