Exploring Neutron Stars with Gravitational waves: current observations and future challenges

Lami Suleiman
On behalf of the **Extreme Matter** group of the LIGO/Virgo/KAGRA collaboration.
https://dcc.ligo.org/G2401607

The LIGO/Virgo/KAGRA collaboration

Network of detectors:

- Laser Interferometer Gravitational-wave Observatory (**LIGO**) in the USA
  - Hanford (Washington)
  - Livingston (Louisiana)
- **Virgo** in Italy
- Kamioka Gravitational Wave Detector (**KAGRA**) in Japan

Credits: LIGO Caltech https://www.ligo.caltech.edu/


Credits Massimo D'Andrea/EGO

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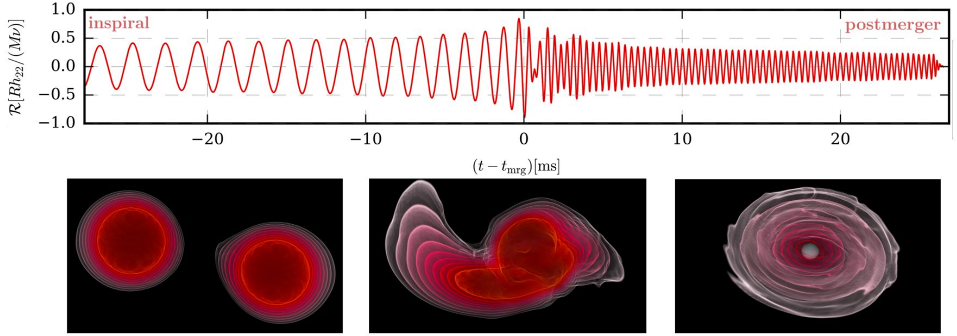
Dietrich,Hinderer & Samajdar, Gen Relativ Gravit 53, 27 (2021)



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The form (phase and amplitude) of the gravitational wave emitted by the event depends on:

- Extrinsic binary parameters: sky localization, luminosity distance etc.
- Intrinsic parameters: object's **mass**, spins, **deformability** etc.

The nature of the compact objects merging is imprinted in the waveform that is detected.

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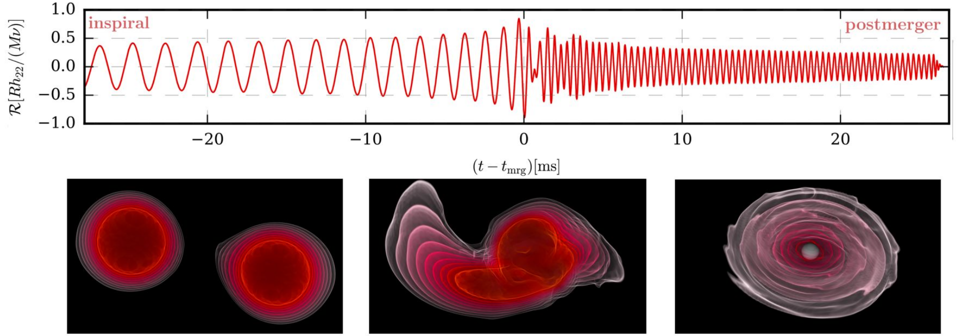
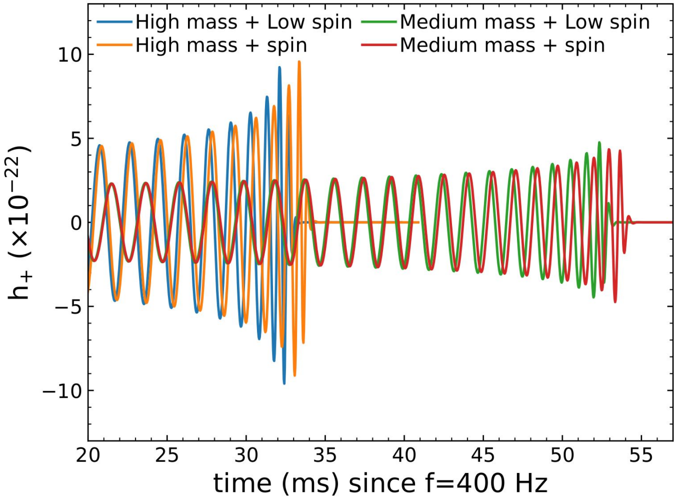
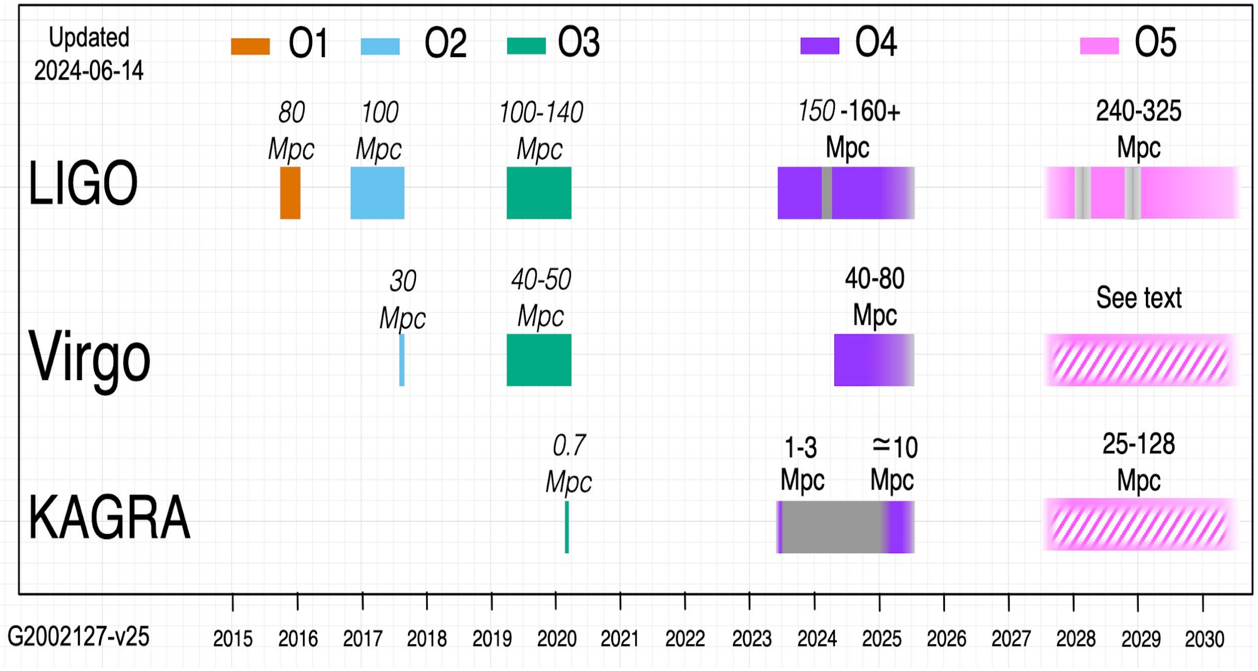




Simulations made with PyCBC: https://doi.org/10.5281/zenodo.10473621

Observing schedule for the LVK collaboration



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

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- Currently in the O4b run.
- Detectors are characterized by their Binary Neutron Star (BNS) range

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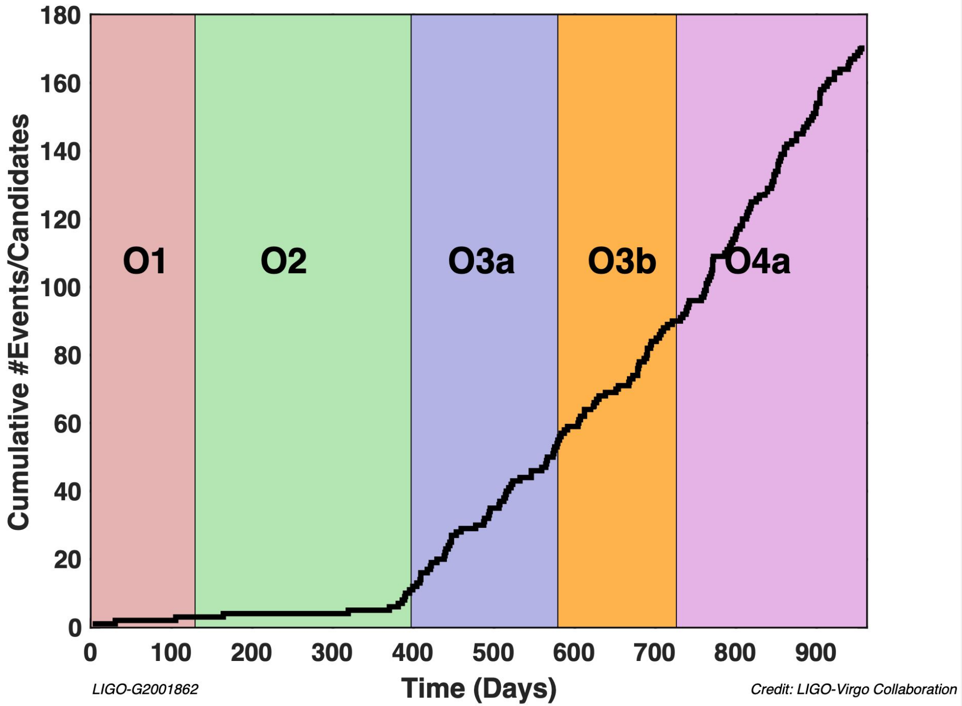

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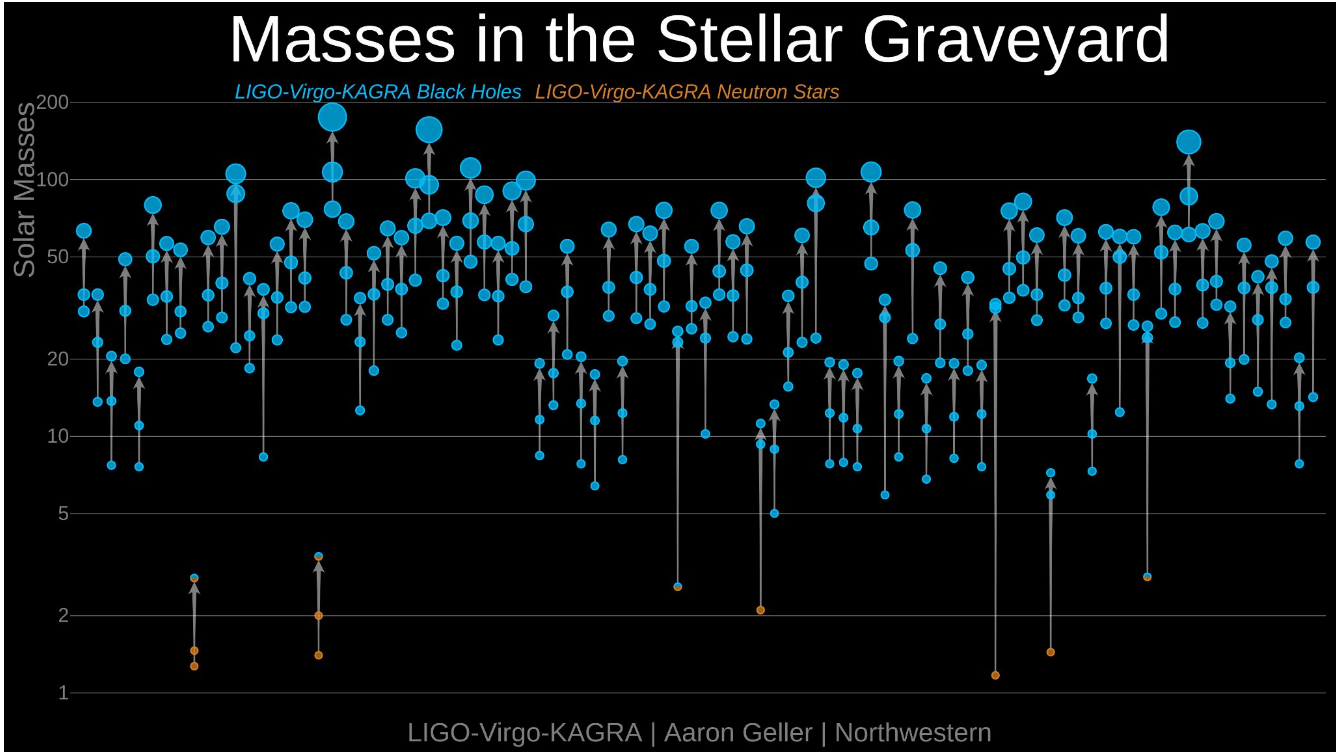
A lot of Black Holes and just a few **Neutron Stars** (NS).



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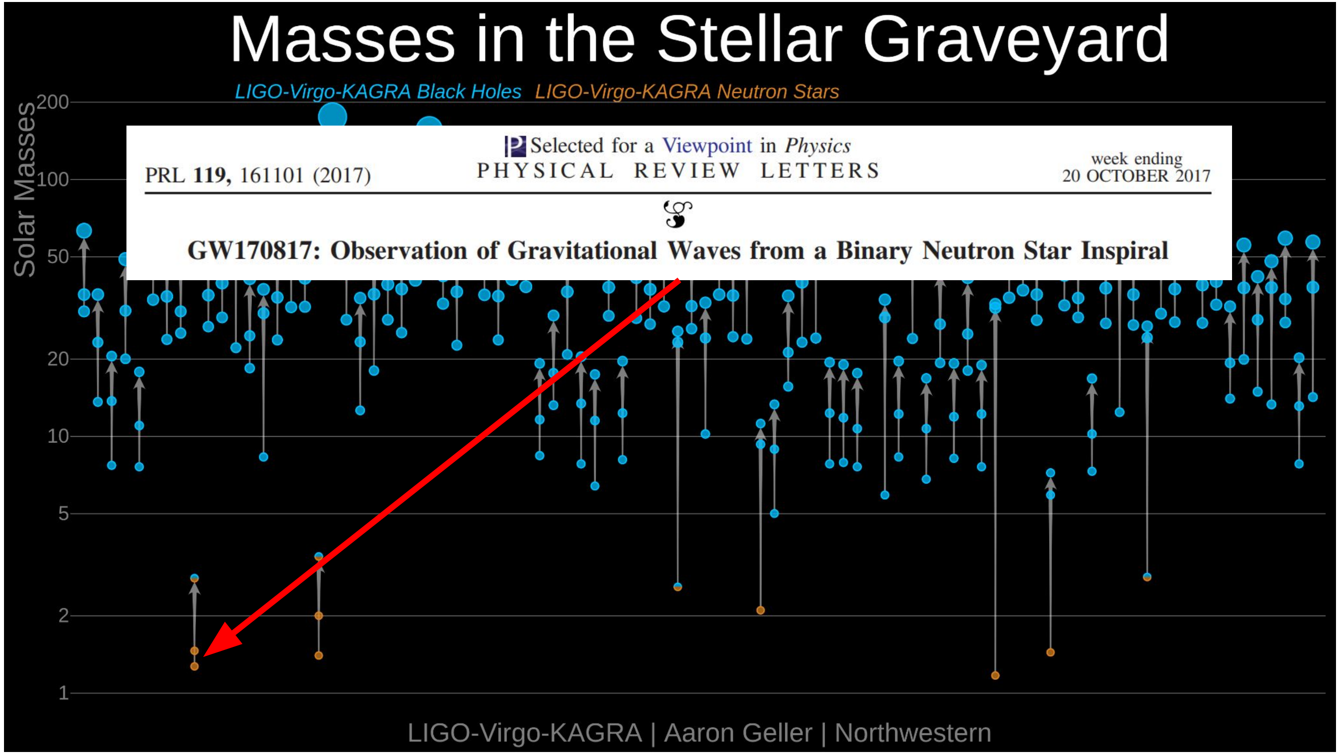

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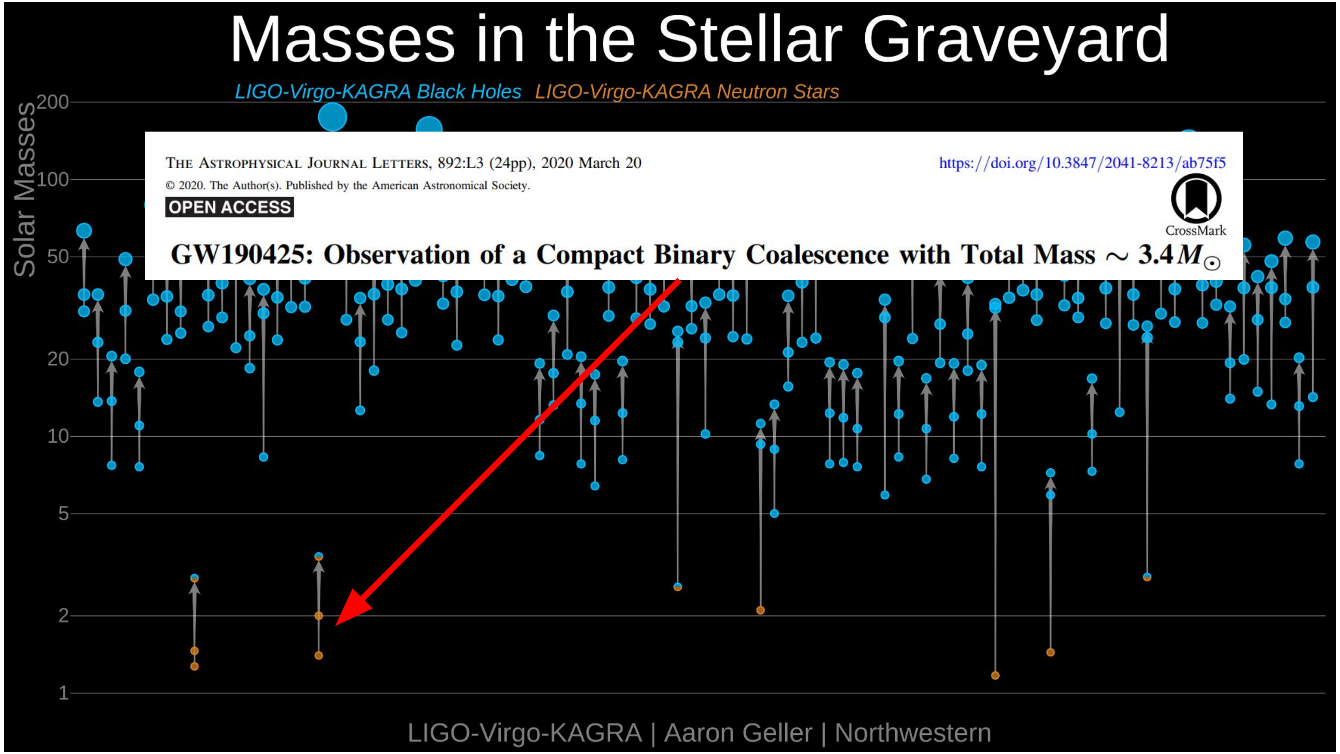

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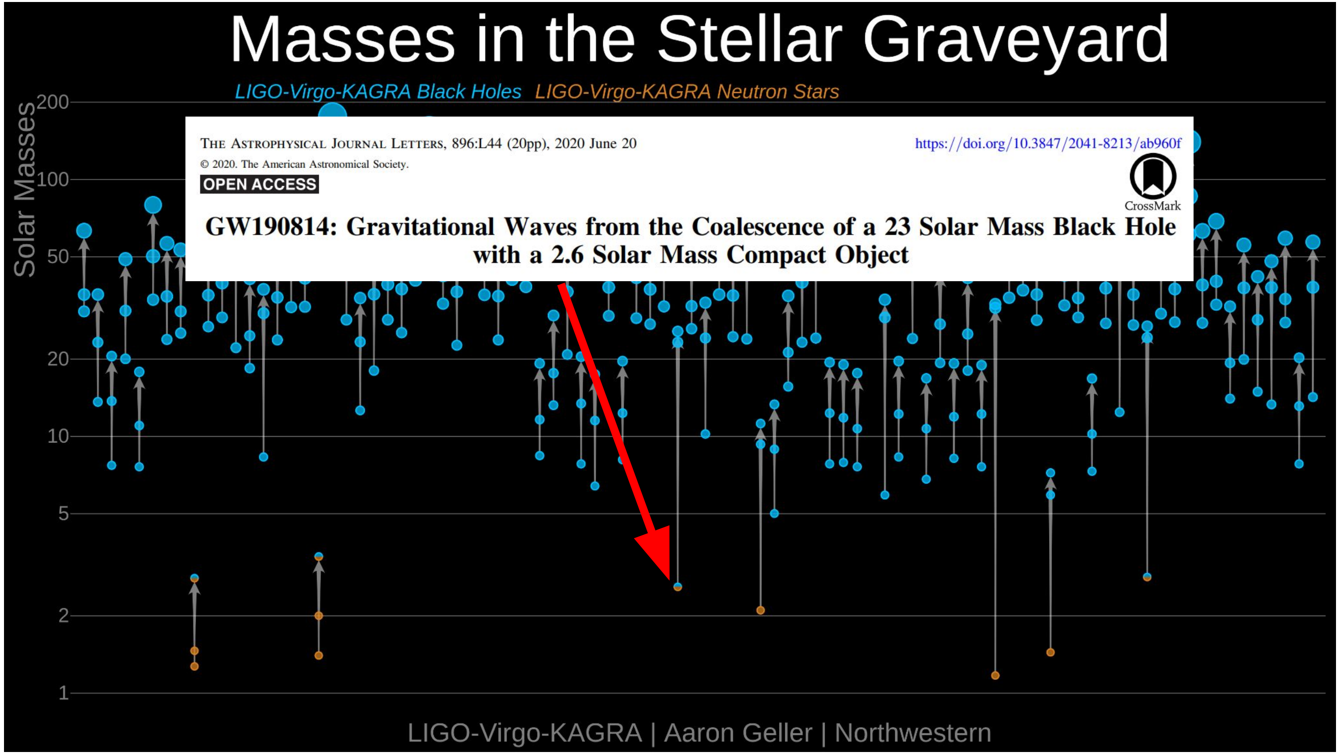

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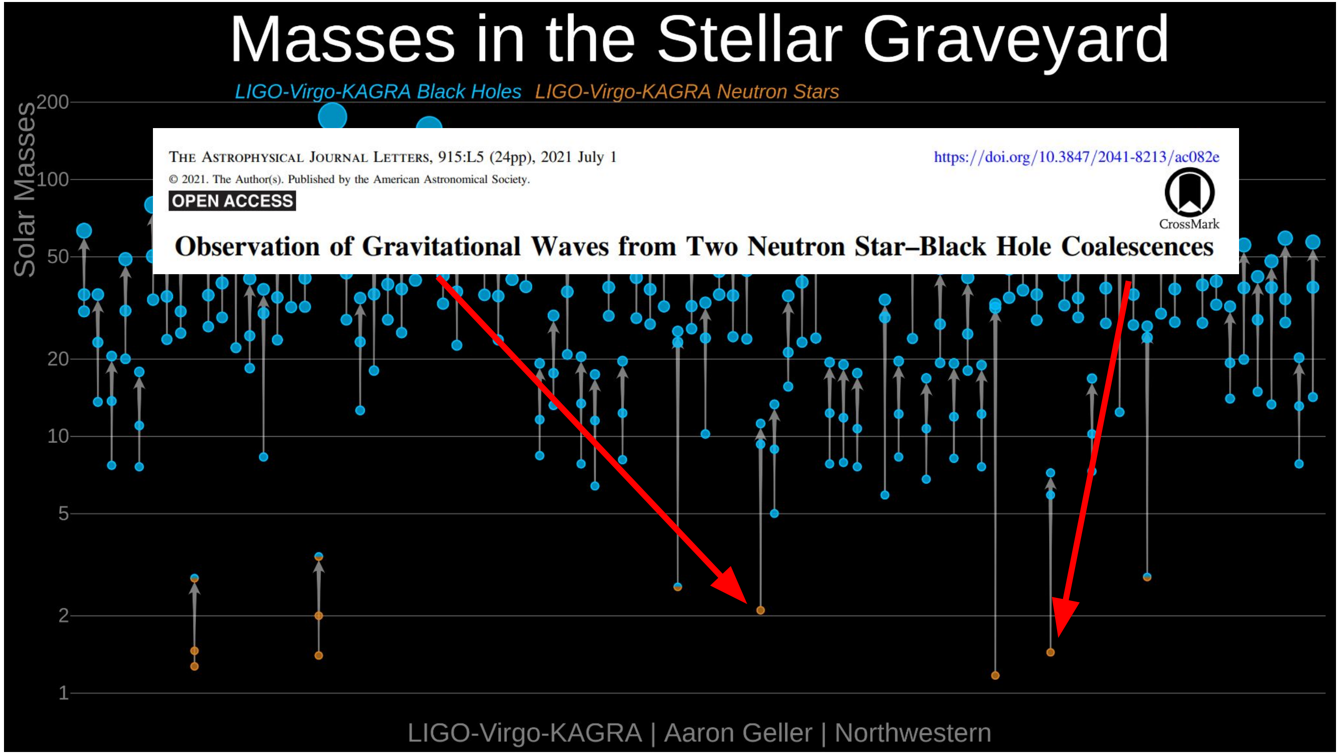

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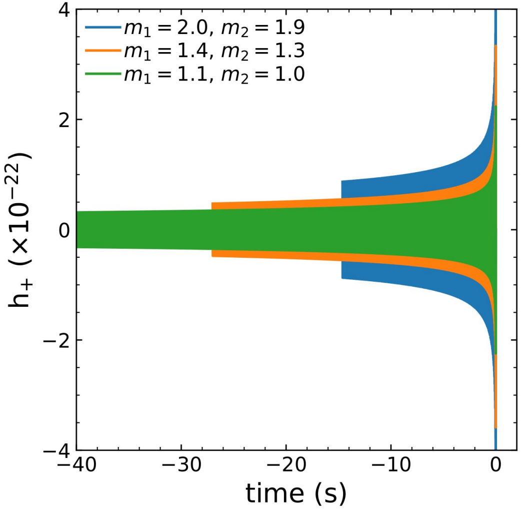
Neutron star observations with Gravitational Waves

NS features revealed by the **waveform** of a NS merger:

- the **masses** of the compact objects impact the waveform
  - measure **chirp mass** ($\mathcal{M}_c$) and **mass ratio** (q)
  - extract individual masses m_1 and m_2

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \qquad q = \frac{m_2}{m_1}$$



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  - measure **chirp mass** ($\mathcal{M}_c$) and **mass ratio** (q)
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- the **tidal deformability** of the compact objects impact the waveform
  - neutron stars can be deformed by a neighboring gravitational field: tides imprints on the waveform
  - measure **effective tidals** $\tilde{\Lambda}$ and $\delta\tilde{\Lambda}$ from the late inspiral
  - extract individual tidal deformabilities λ_1 and λ_2

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \qquad q = \frac{m_2}{m_1}$$

$$\tilde{\Lambda} = f(m_1, m_2, \lambda_1, \lambda_2)$$

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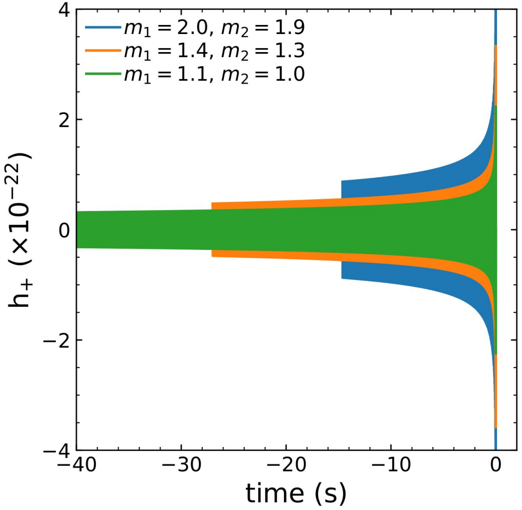

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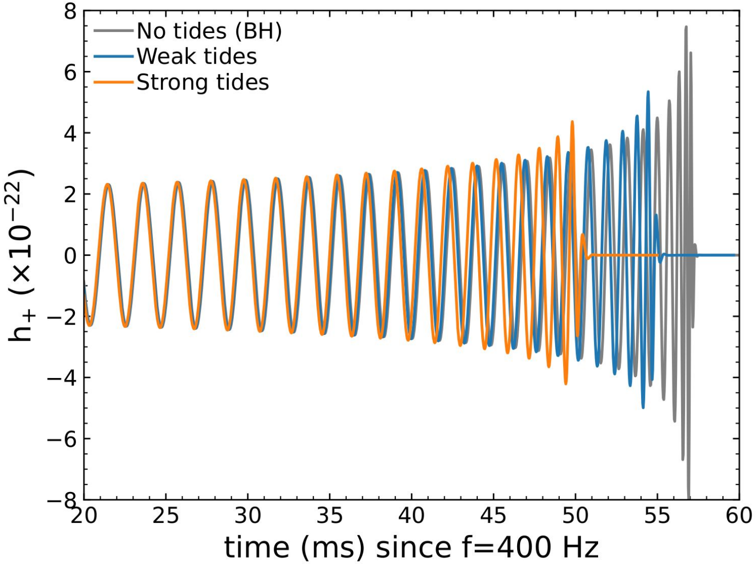

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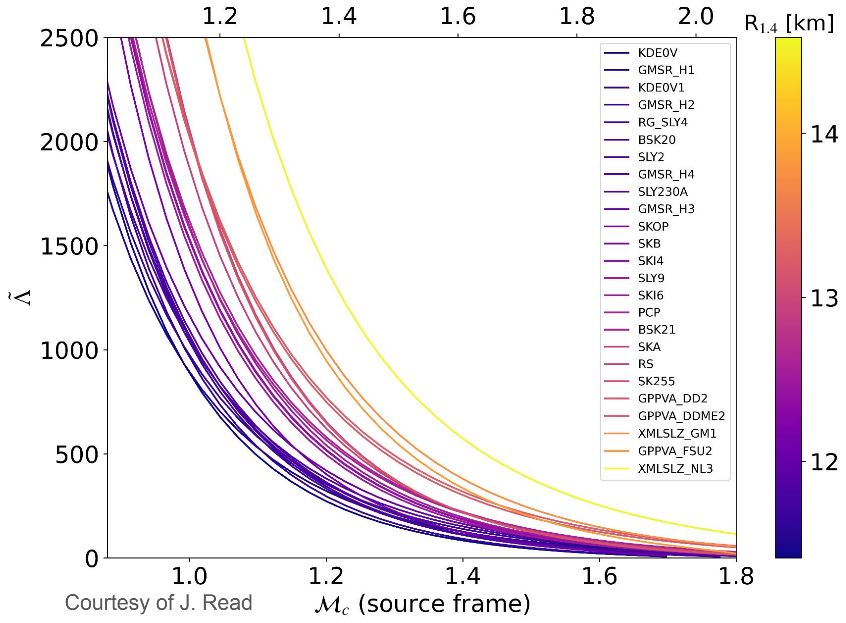
Probing the Equation of State with NS-NS mergers

Matter *inside NSs is described by the beta-equilibrated and dense matter* ***Equation of State*** *(EoS).*

- 1 EoS model = 1 $\Lambda(M)$sequence = 1 $\tilde{\Lambda}(\mathcal{M}_c, q)$



Courtesy of J. Read

GWTC-1 Phys. Rev. X9, 031040 (2019) and GWTC-2 Phys. Rev. X11, 021053 (2021)
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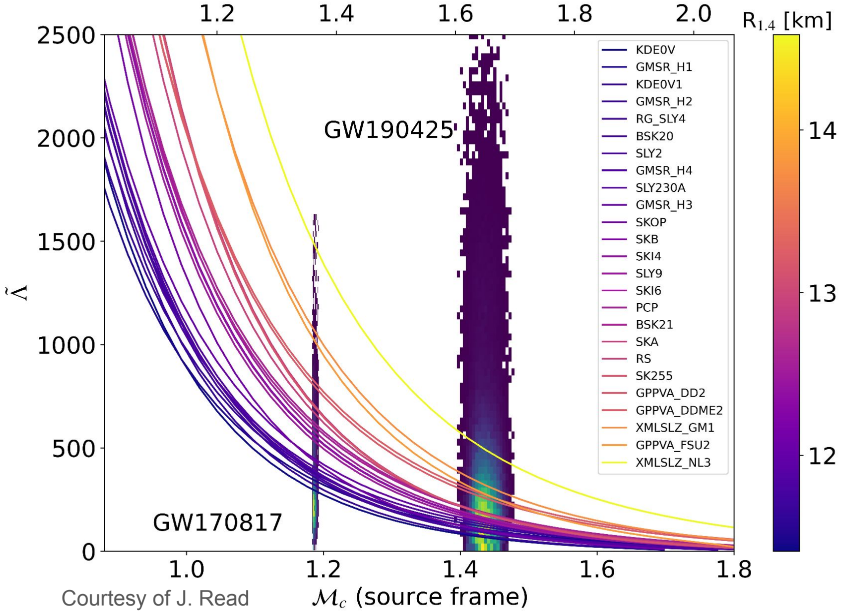

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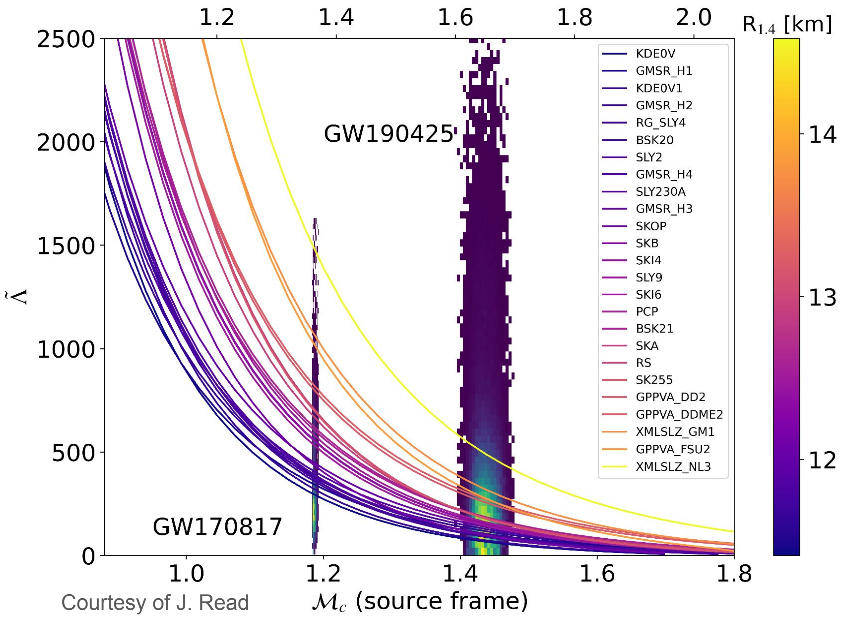

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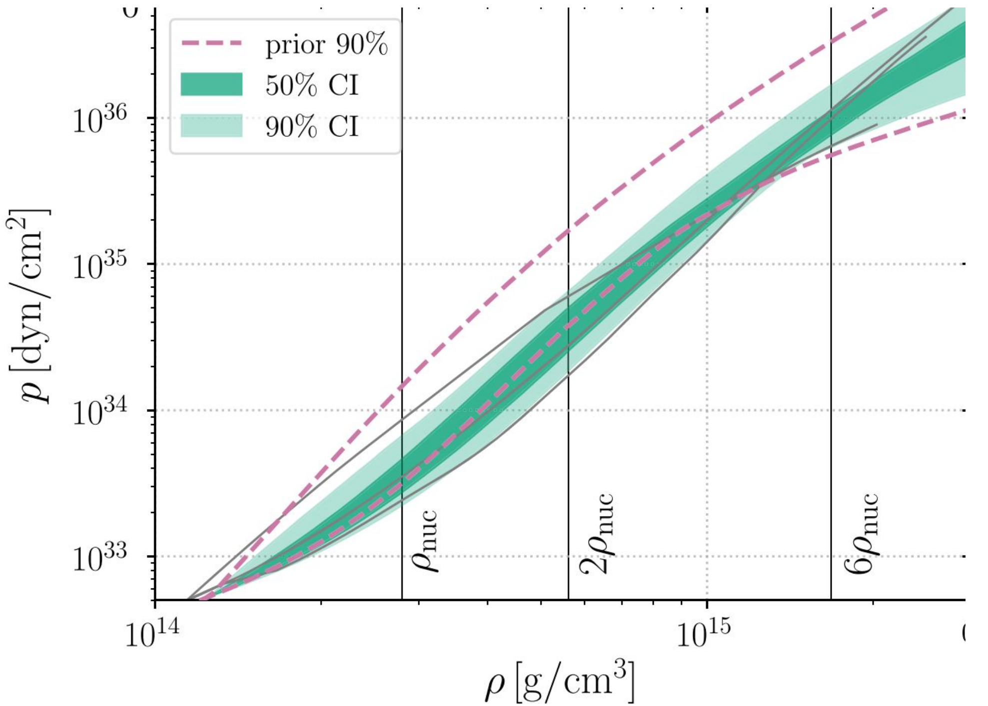
Equation of State Bayesian inference

- GW170817: **softening** of the EoS



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Spectral representation GW170817 posteriors Phys. Rev. L121 161101 (2018)

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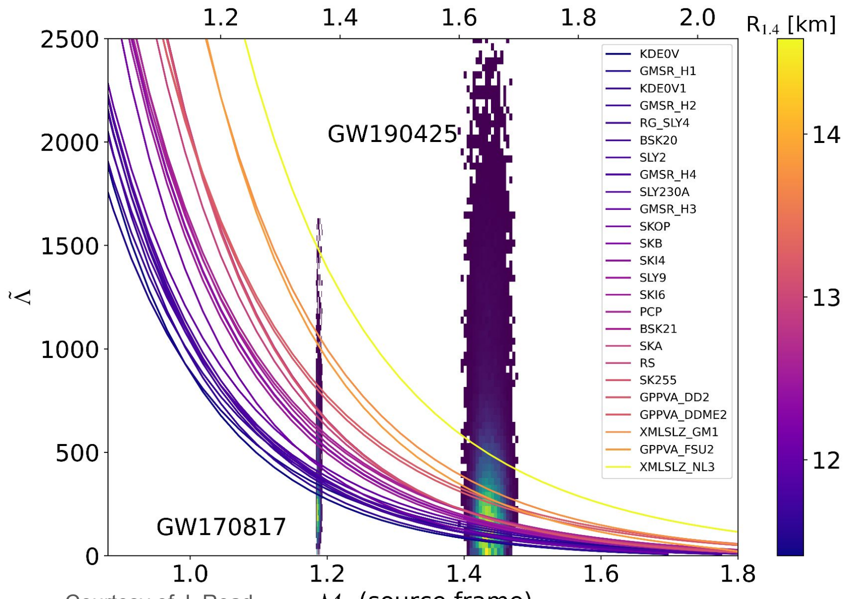

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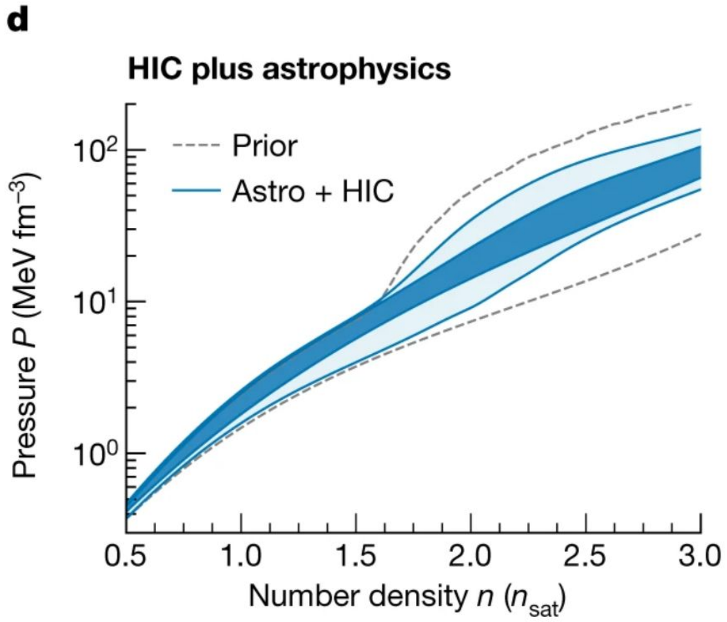
Equation of State Bayesian inference

- GW170817: **softening** of the EoS
- Combining **multi-messenger** constraints
  - astronomy: Xray, radio…
  - nuclear physics experiments



Huth et al. Nature 606, 276–280 (2022)

A Neutron Star-Black Hole merger from O4: GW230529

Electromagnetic counterparts of NS involved mergers.

- **Kilonova**: signature of radioactive decays of heavy nuclei,
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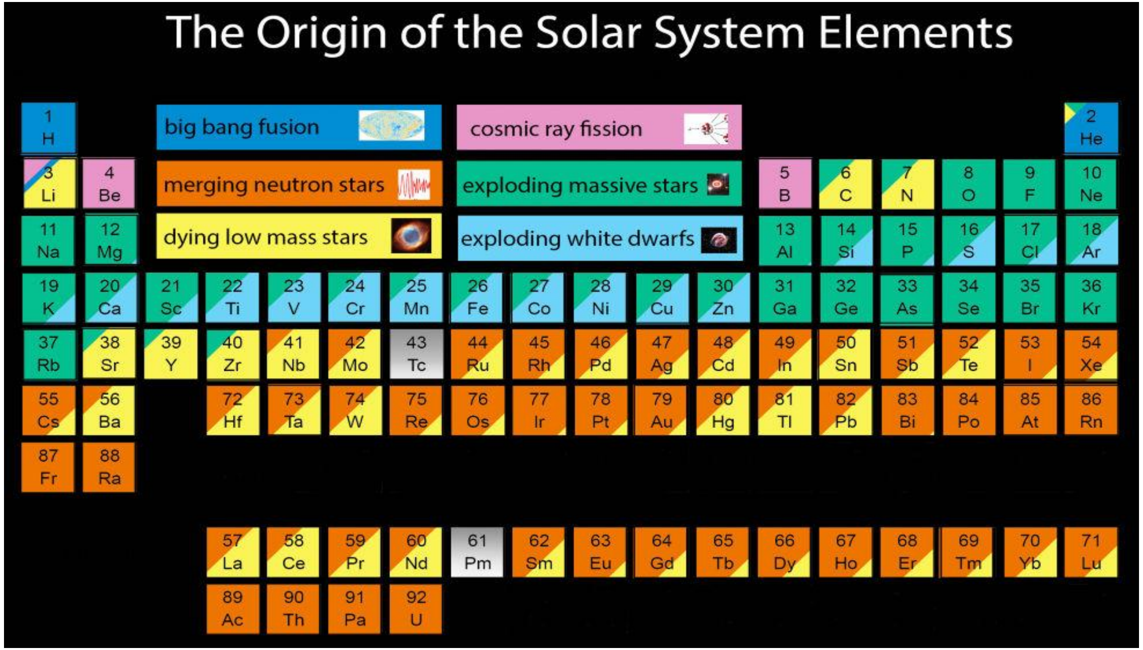

Credits: J. Johnson ESA/NASA/AASNova

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Primary = large mass m1
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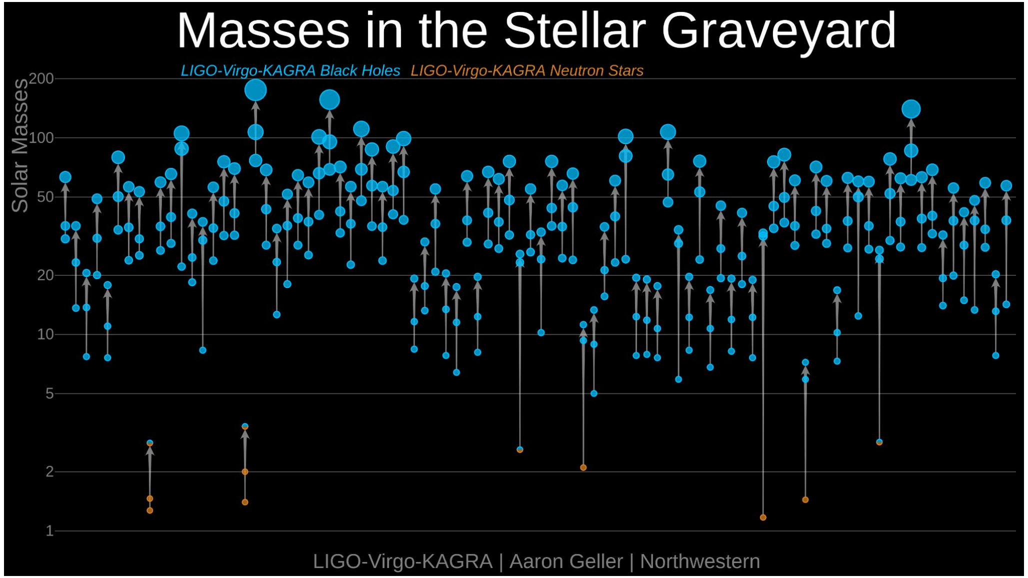

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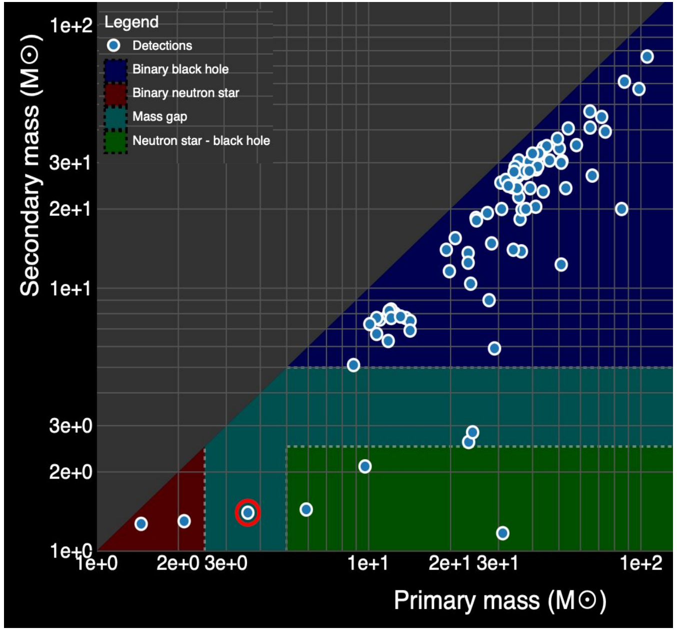

https://catalog.cardiffgravity.org

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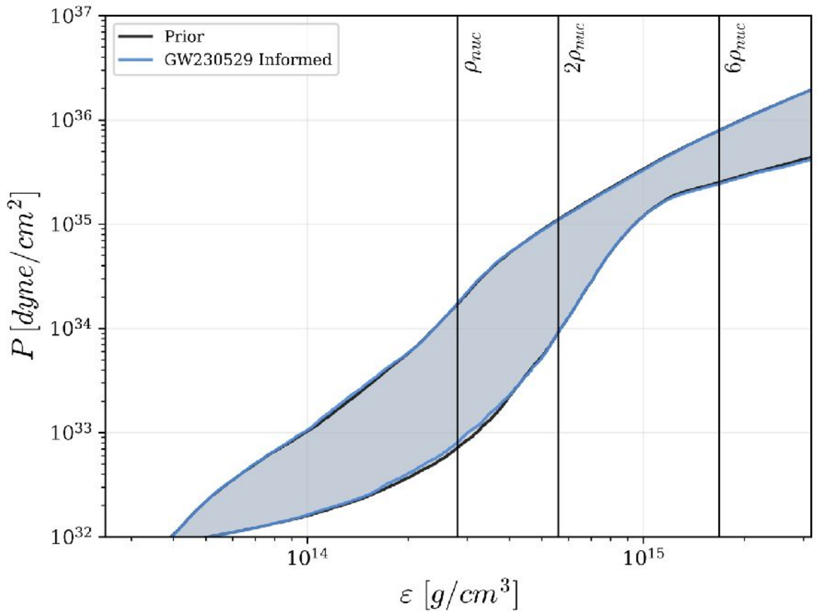

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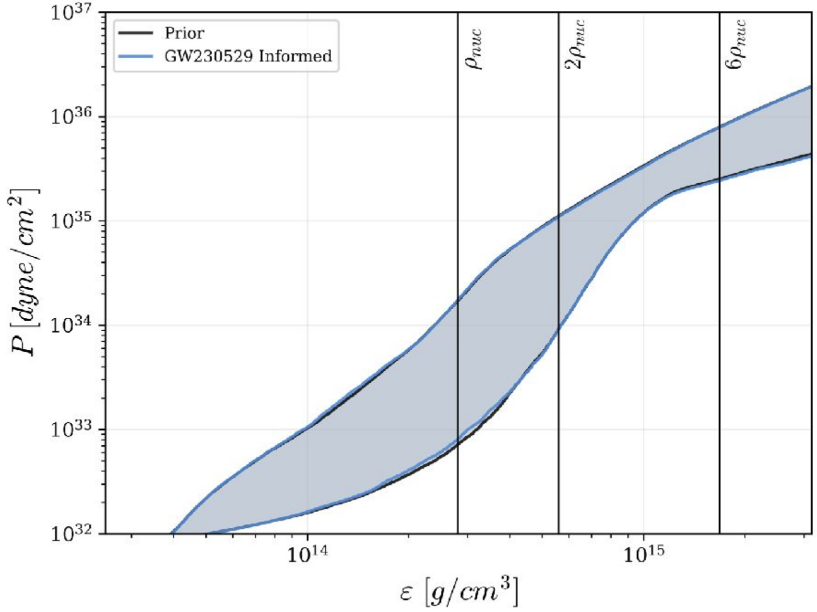

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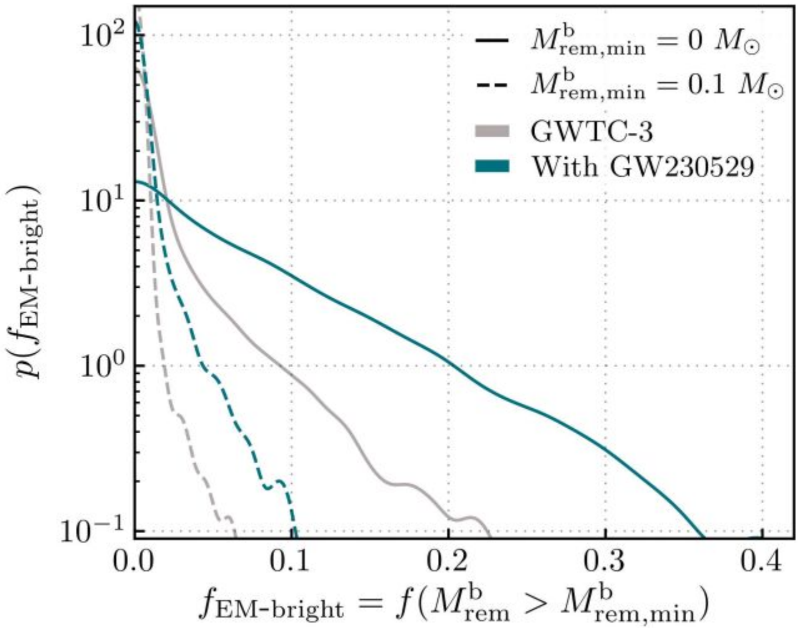

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- **Fraction of NSBH** mergers with remnant matter
  - ≤ 0.18 (with ***X-Ray*** data $0.13^{0.19}_{-0.11}$).
- NSBH contribution to:
  - **heavy element production**: at most $1.1\mathrm{M}_\odot/\mathrm{Gpc}^3/\mathrm{yr}$
  - **GRB**: small $< 23/\mathrm{Gpc}^3/\mathrm{yr}$

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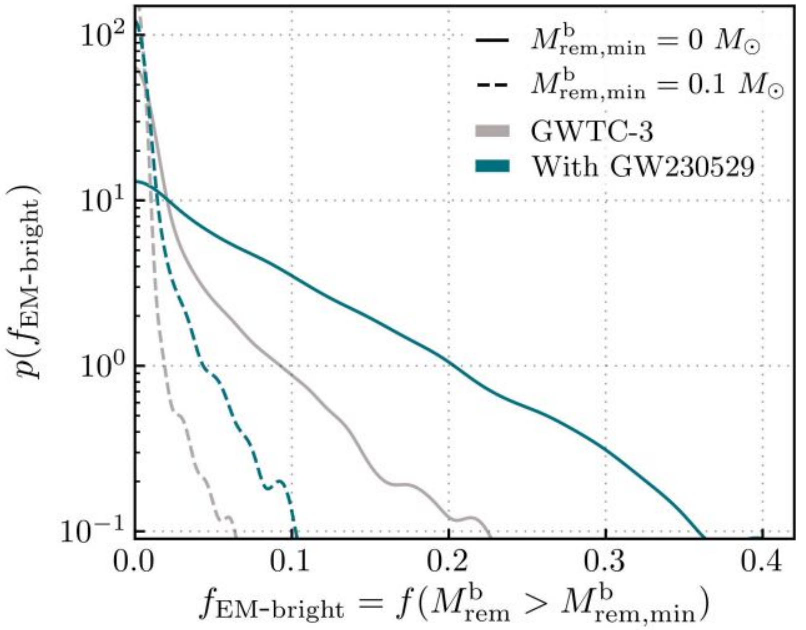

Next generation of detectors: what to expect ?

Project for future detectors:

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Courtesy of D. Chatterjee

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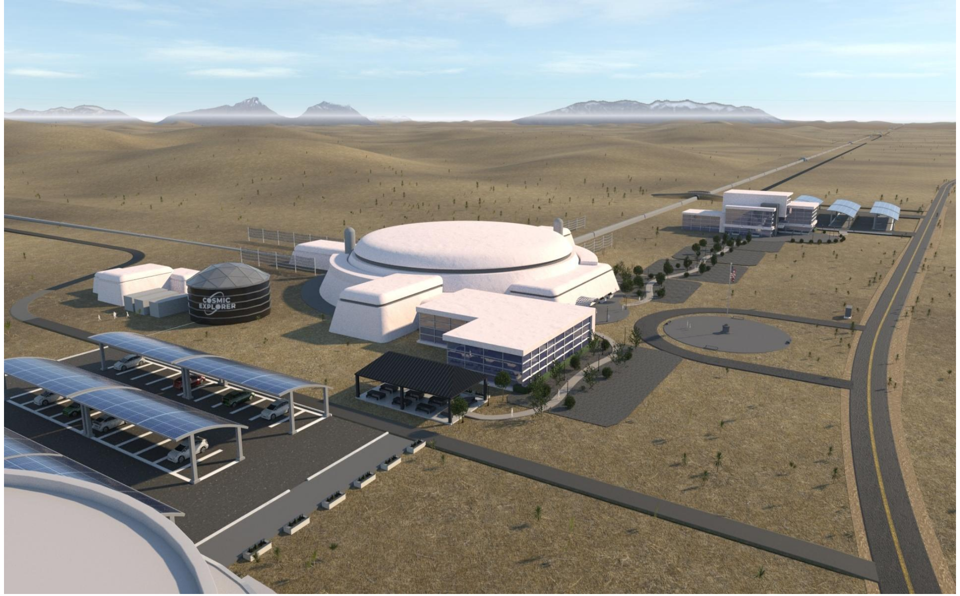
https://dcc.cosmicexplorer.org/CE-G2300014



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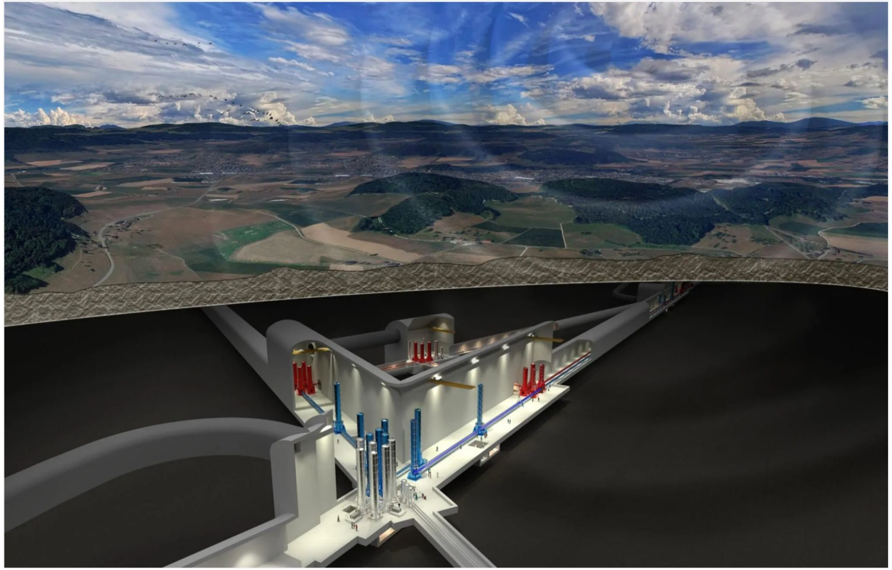

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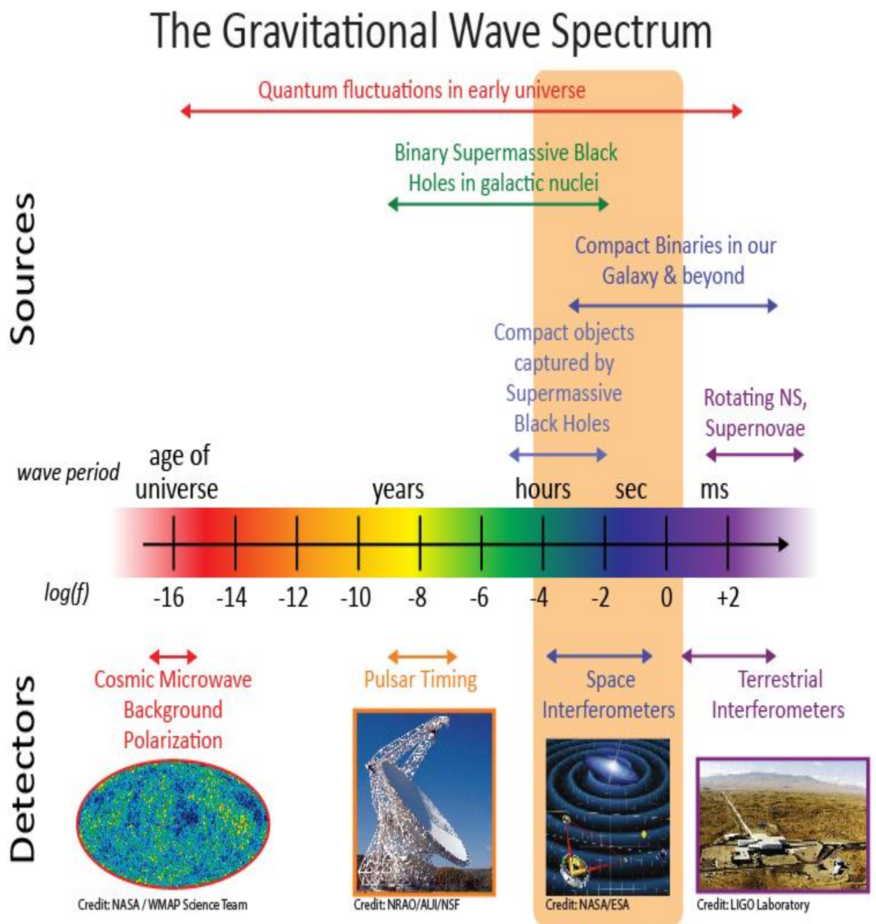
  - Triangular space base detector
  - ESA + NASA collaboration
  - Launch mid 2030s

https://lisa.nasa.gov/



Challenges in an era of high precision detections

Systematics vs statistics

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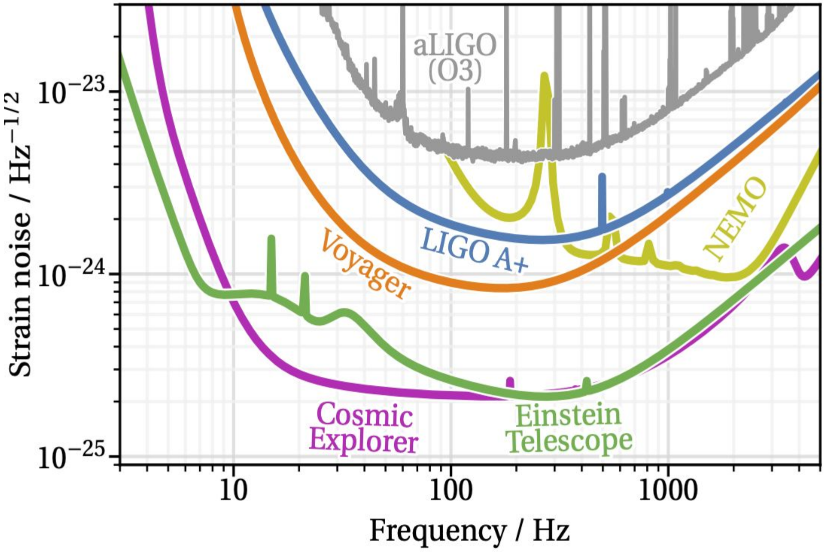

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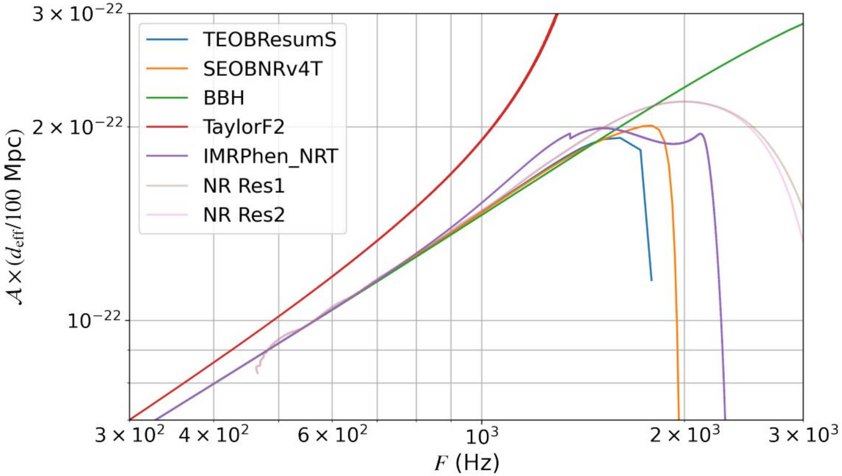
- **Waveform approximant** uncertainty
- **Quasi**-universal relations
- Temperature effects and **post merger**
- Crust breaking under **resonant modes** (GRBs)
- etc…

Read 2023, Class. Quantum Grav. 40 135002



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Resonant shattering flares as multimessenger probes of the nuclear symmetry energy FREE

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Monthly Notices of the Royal Astronomical Society, Volume 504, Issue 1, June 2021, Pages 1129–1143, https://doi.org/10.1093/mnras/stab764

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And constantly **developing software** for dense matter analysis with gravitational waves.

- LIGO Algorithm Library (LALSuite)
- Bilby with GW applications
- Likelihood Weighing Protocol (LWP)
- CUTER, Reprimand, RIFT etc.

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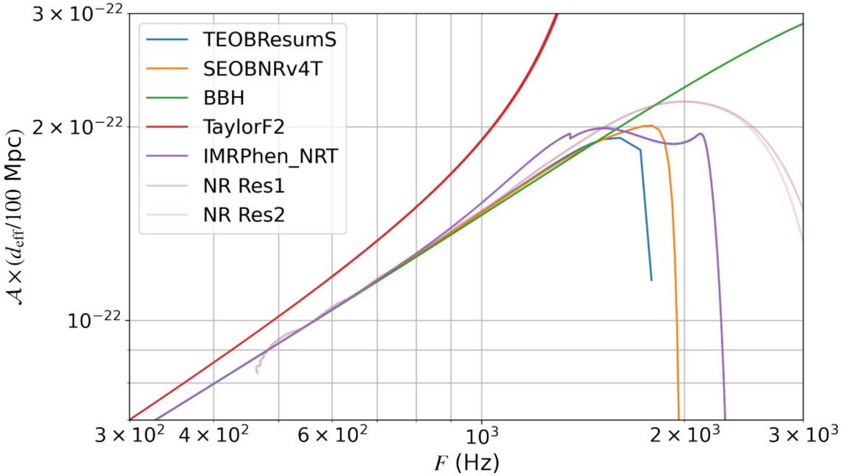

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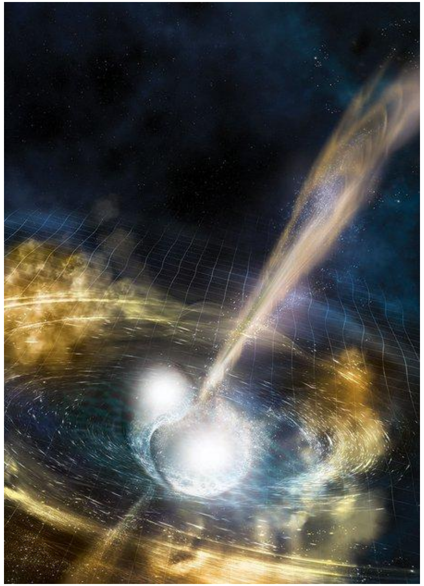
Monthly Notices of the Royal Astronomical Society, Volume 504, Issue 1, June 2021, Pages 1129–1143, https://doi.org/10.1093/mnras/stab764

and many others !

Conclusion

- Gravitational wave detections expanded the field of **multi-messenger** Astronomy.
- Currently on the **4th run** of the LIGO/Virgo/KAGRA collaboration.
- A few mergers involving NSs have taught us about **neutron rich** and **dense matter behavior**.
- **Kilonova** detections signal **heavy element production** in NS involved mergers.
- **Next-generation of detectors** will see **further** (more sources) and with **higher precision** (better constraints).
- Continuously working towards a better analysis of NSs.



Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Acknowledgements

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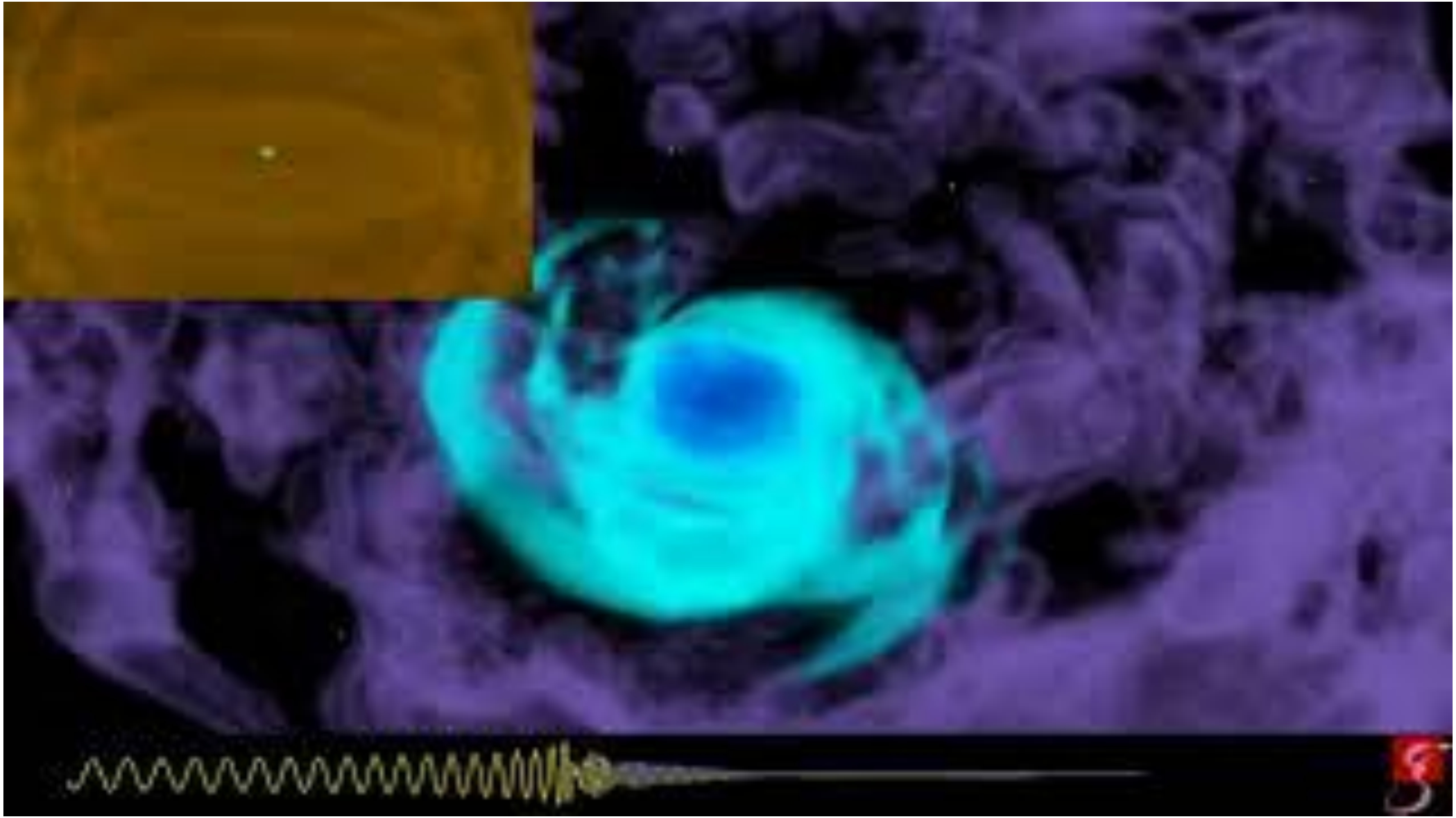
"This material is in part based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation."



Credits: Max Planck Institute for Gravitational Physics (Albert Einstein Institute)/Milde Marketing/exozet effects