Exploring dense matter physics with gravitational wave detections of Neutron Stars

International Symposium on Nuclei in the Cosmos XVIII

Lami Suleiman
Deutsches Elektronen-Synchrotron

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

The detectors of 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 Massimo D'Andrea/EGO

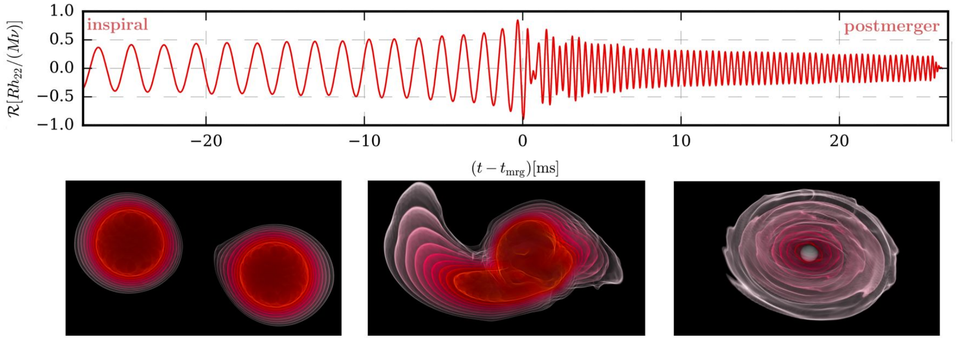
Credits: LIGO Caltech https://www.ligo.caltech.edu/

KAGRA website

The Gravitational Wave signal

The instruments detect ripples in space-time caused by violent and high energy events in the Universe, such as the merger of two compact objects.

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



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Michelson interferometer technology

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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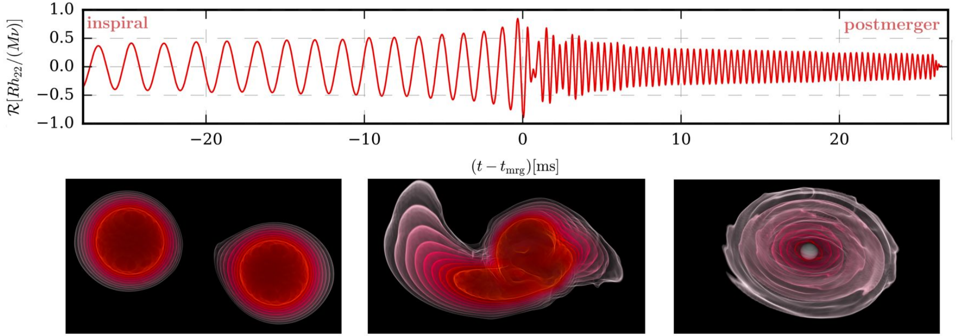
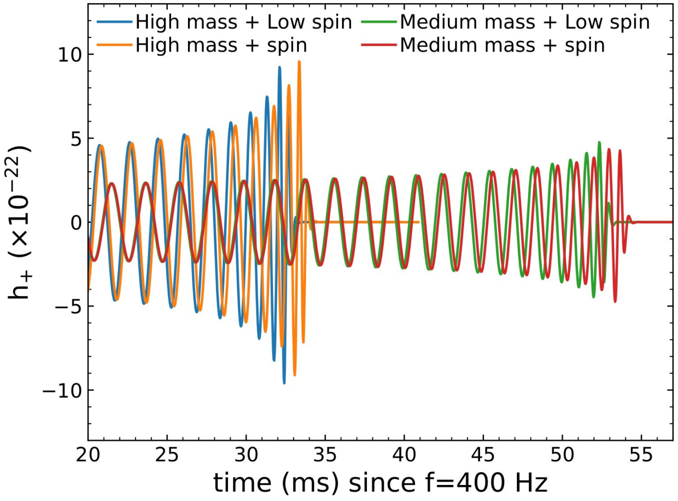
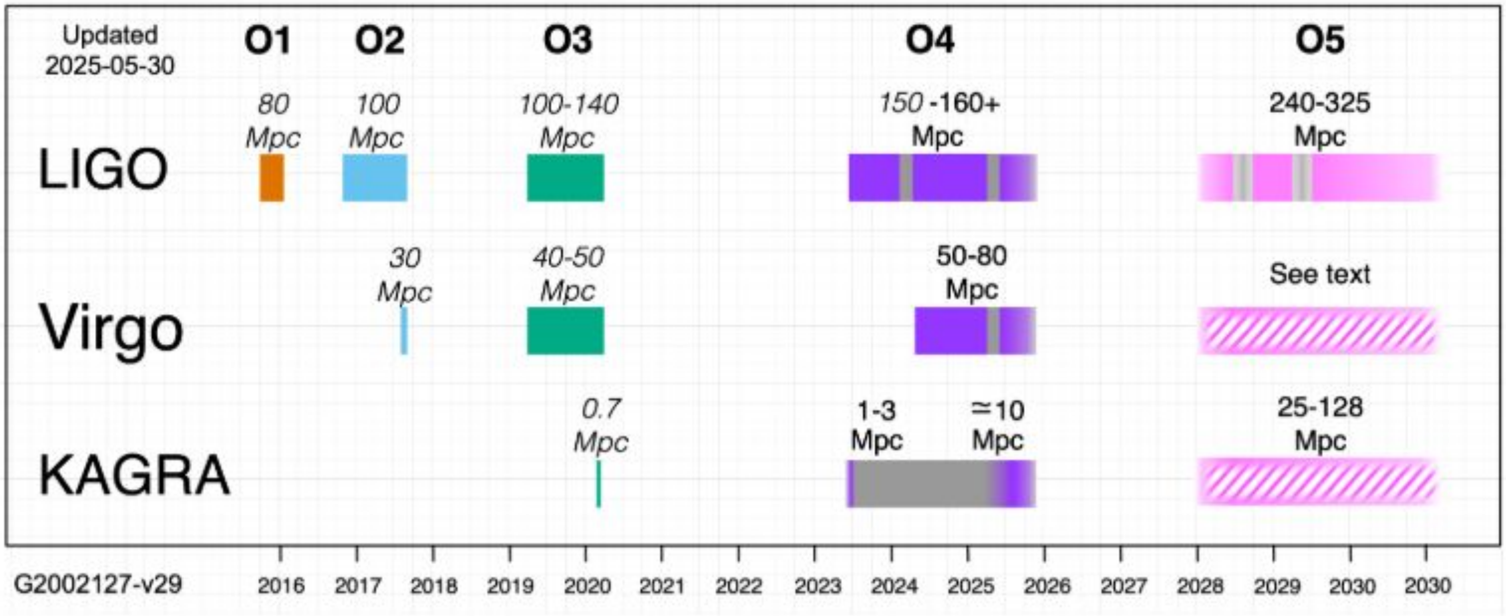




Simulations made with PyCBC: https://doi.org/10.5281/zenodo.10473621

Observing schedule for the LVK collaboration



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

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- Currently at the beginning of the O4c run.
- Detectors are characterized by their Binary Neutron Star (BNS) range.

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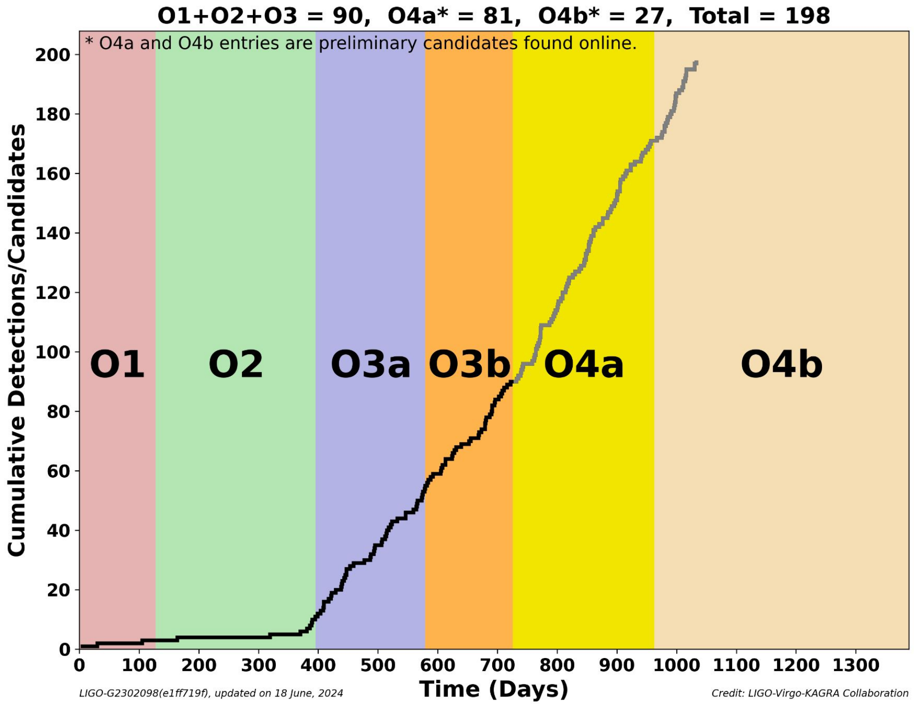

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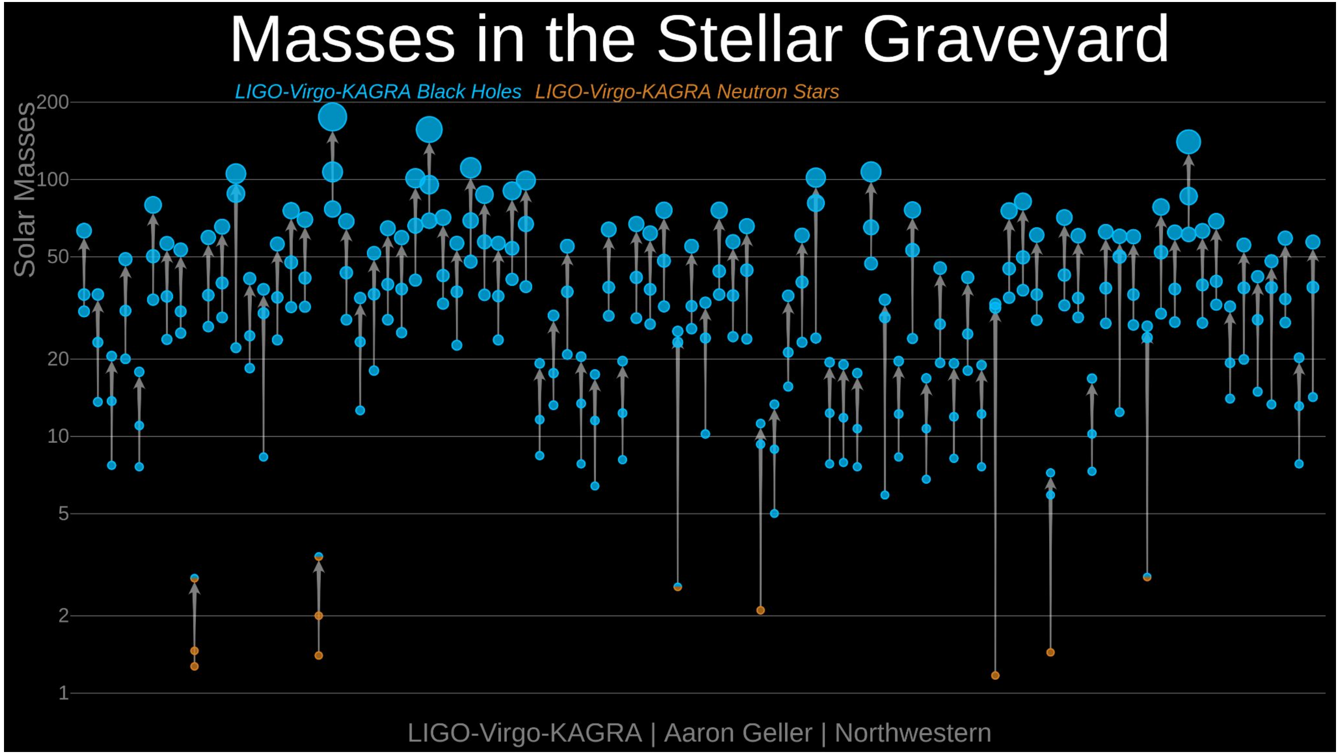
Observations from the first 3 runs of LVK

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



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

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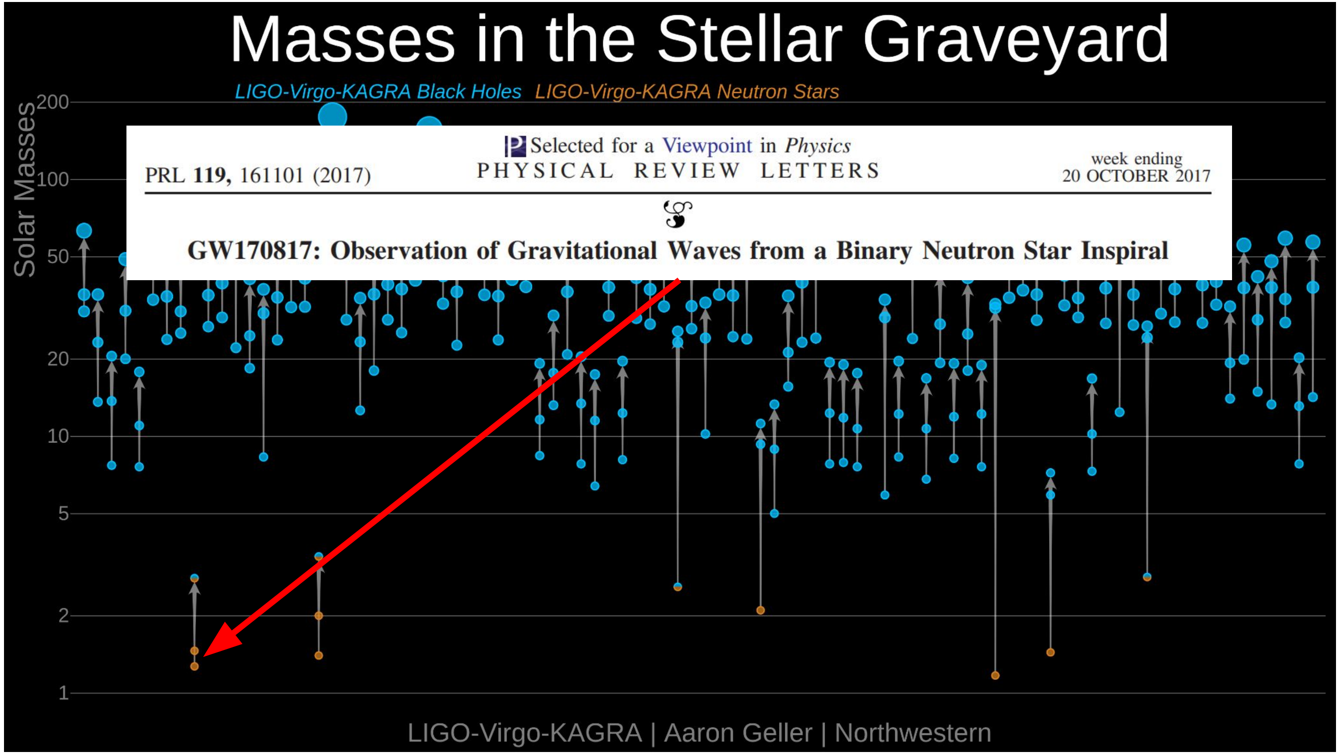

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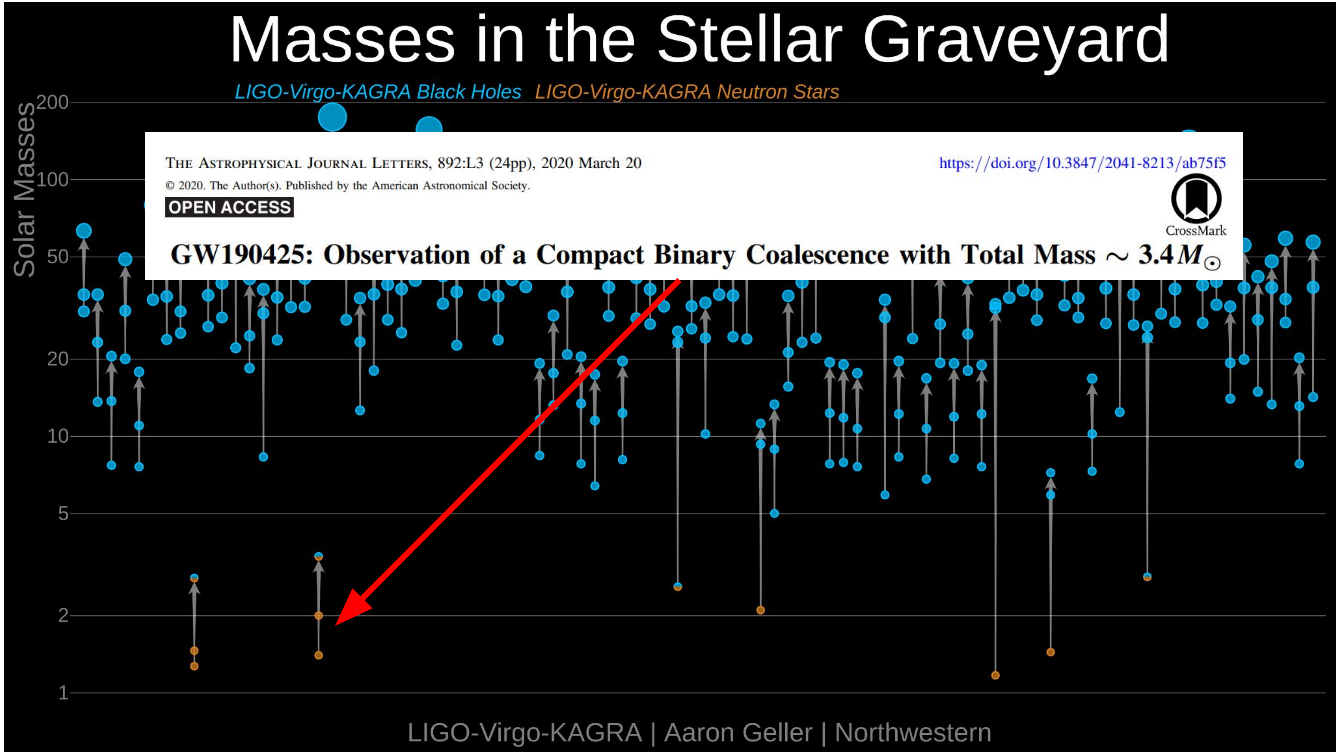

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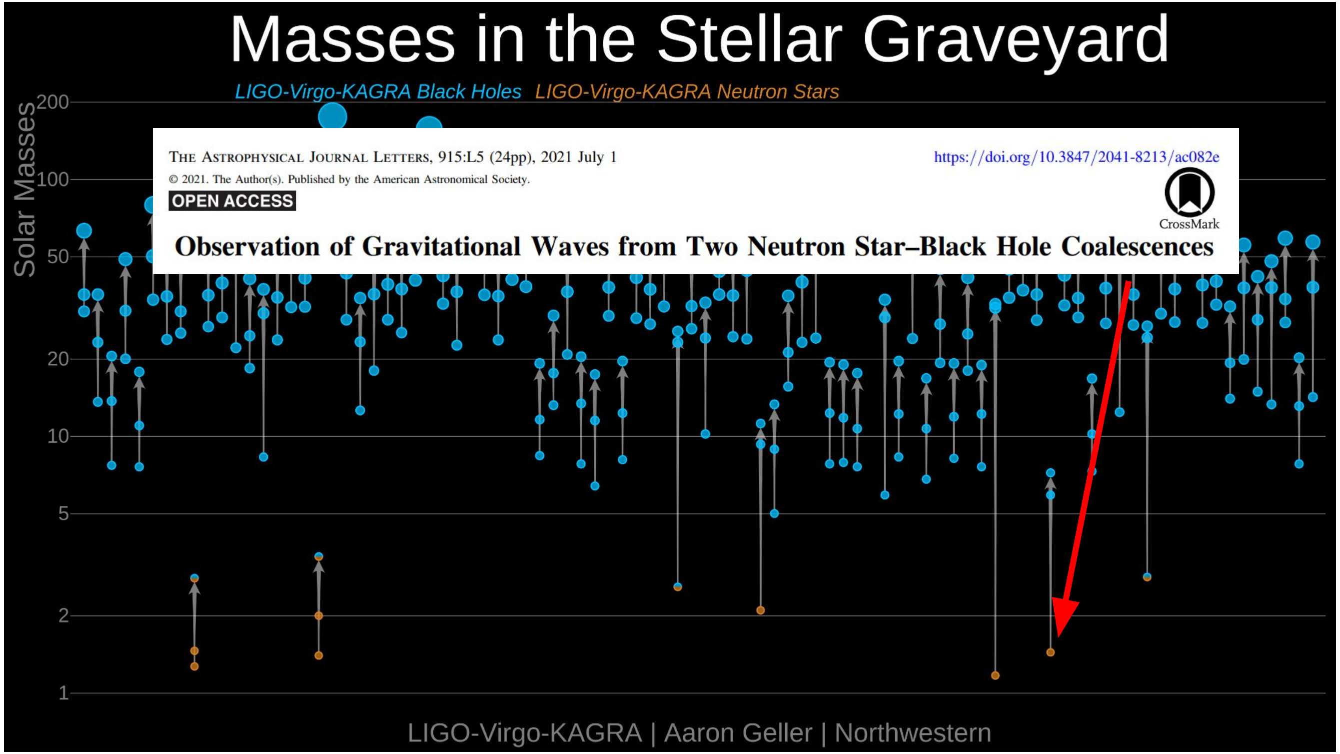

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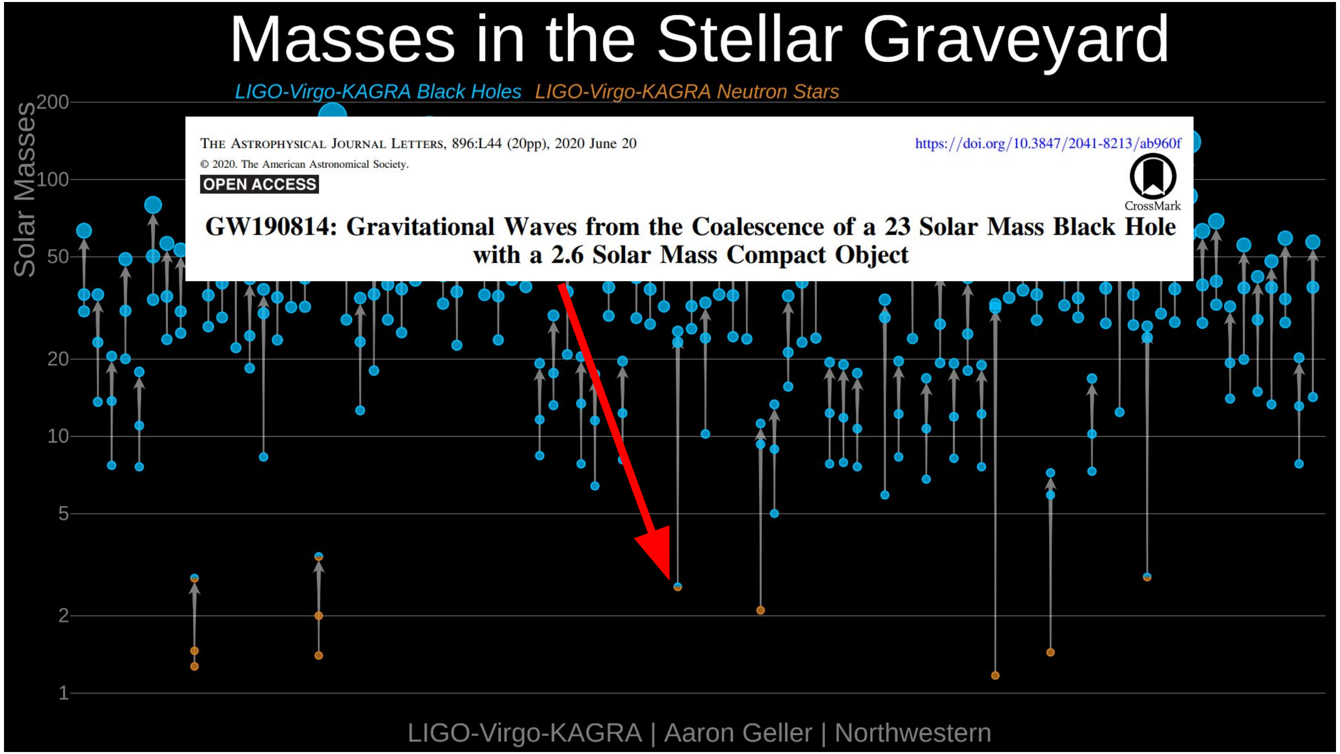

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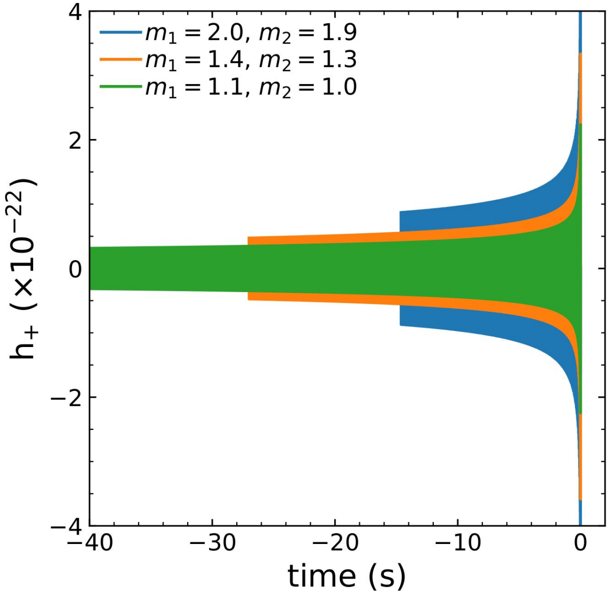
Neutron star observations with Gravitational Waves

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)

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



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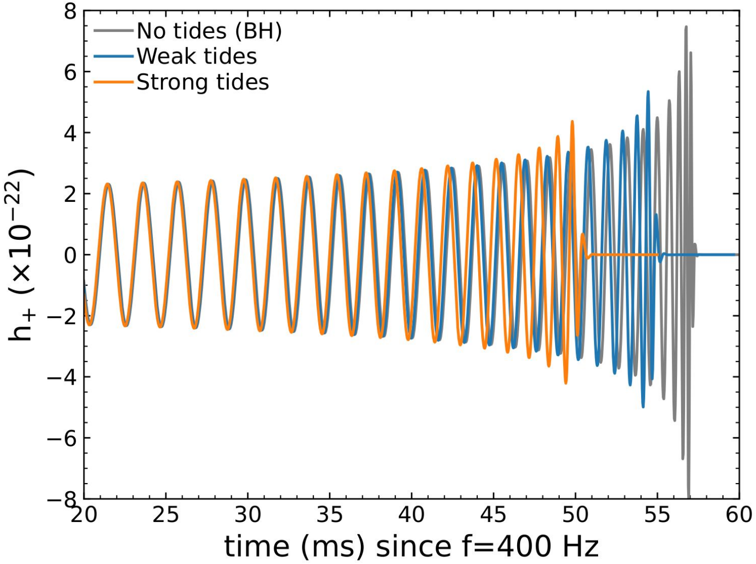
  - measure **chirp mass** ($\mathcal{M}_c$) and **mass ratio** (q)
- the **tidal deformability** of the compact objects impact the waveform
  - neutron stars can be deformed by a neighboring gravitational field: tides imprints on the waveform
  - measure **effective tidals** $\tilde{\Lambda}$ and $\delta\tilde{\Lambda}$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

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

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

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



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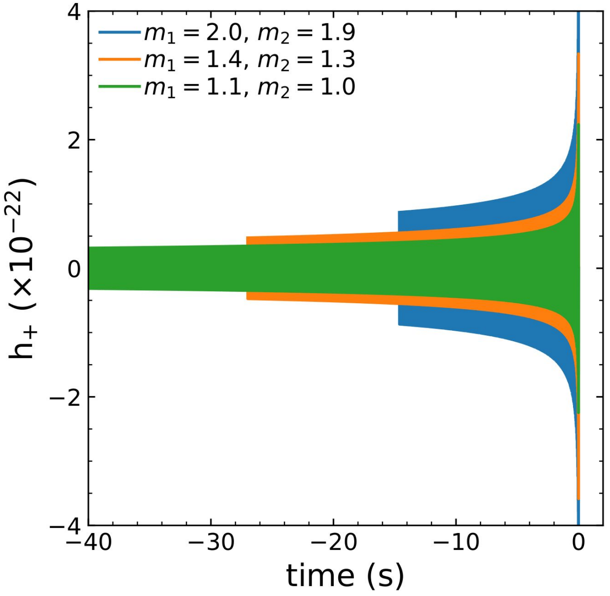
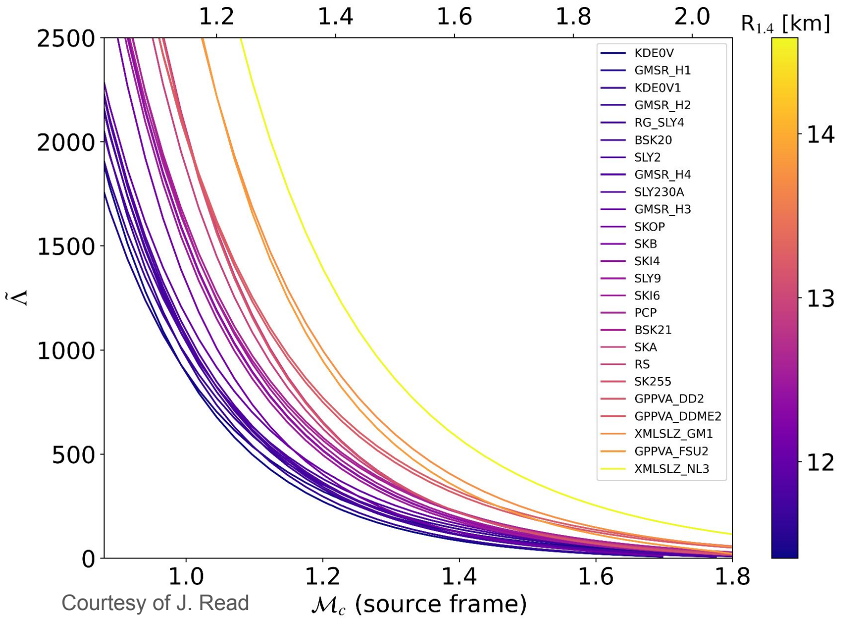


Probing the Equation of State with NS-NS mergers

***Matter** inside NSs (in inspiral) 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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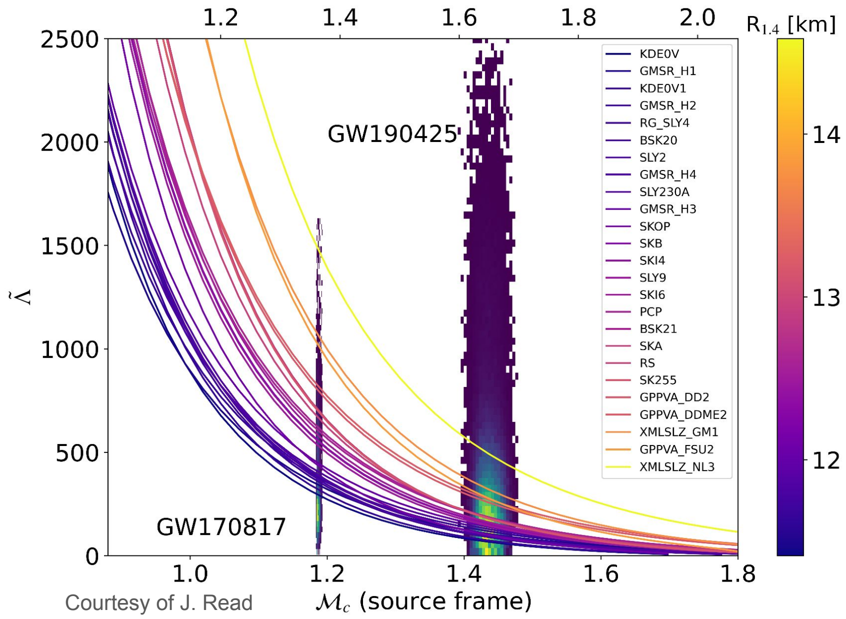

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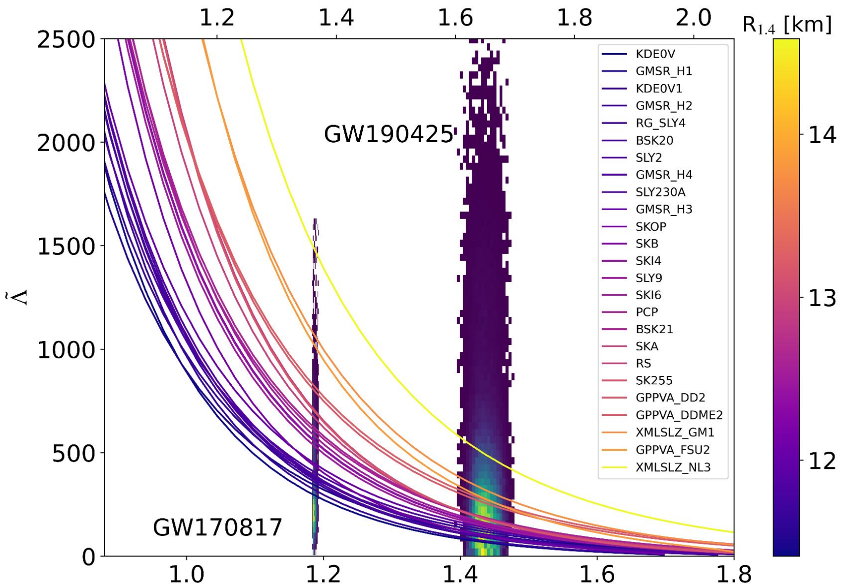

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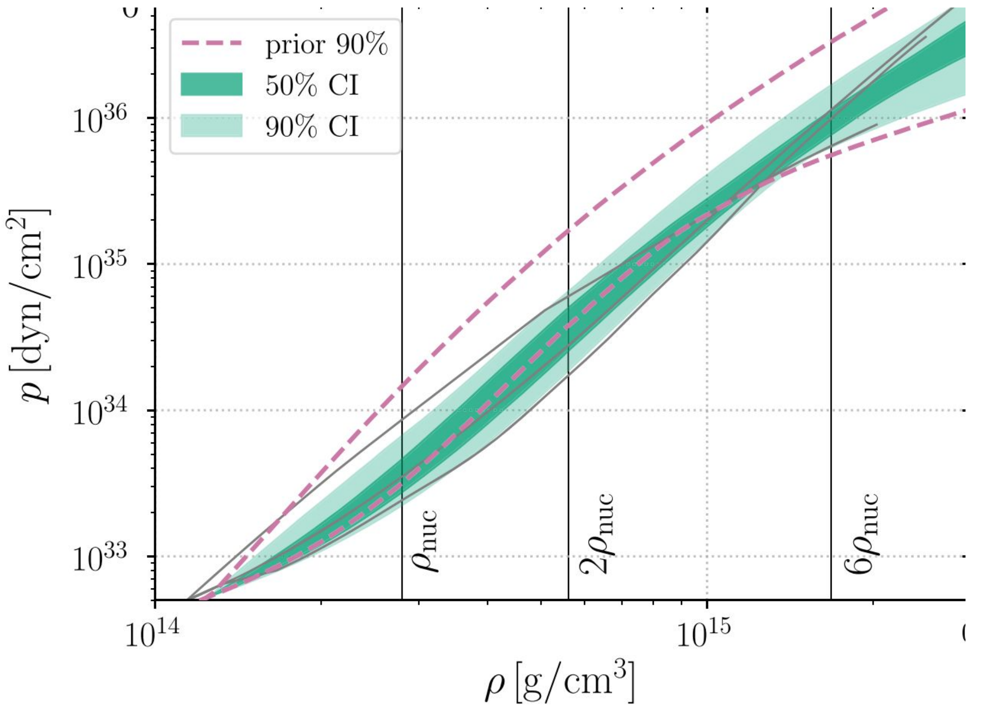
Equation of State Bayesian inference

- GW170817: **softening** of the EoS



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

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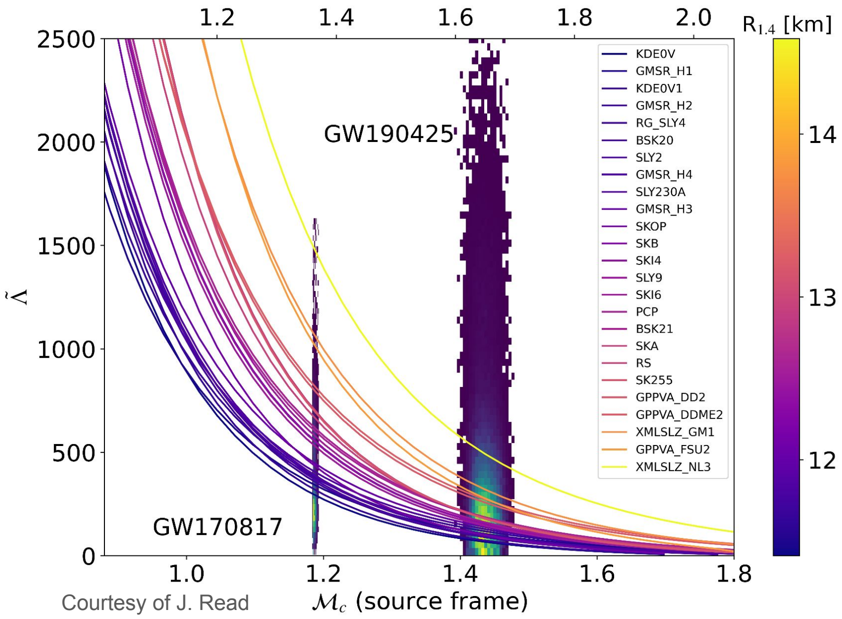

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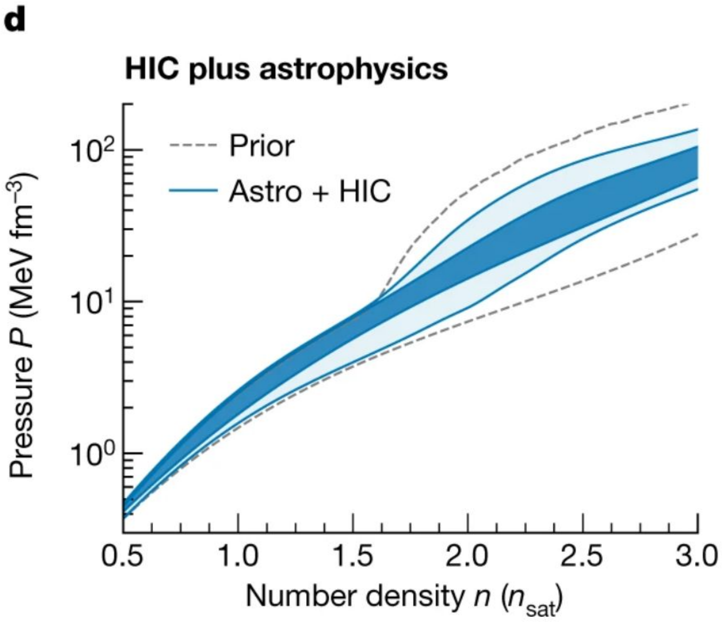
Equation of State Bayesian inference

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



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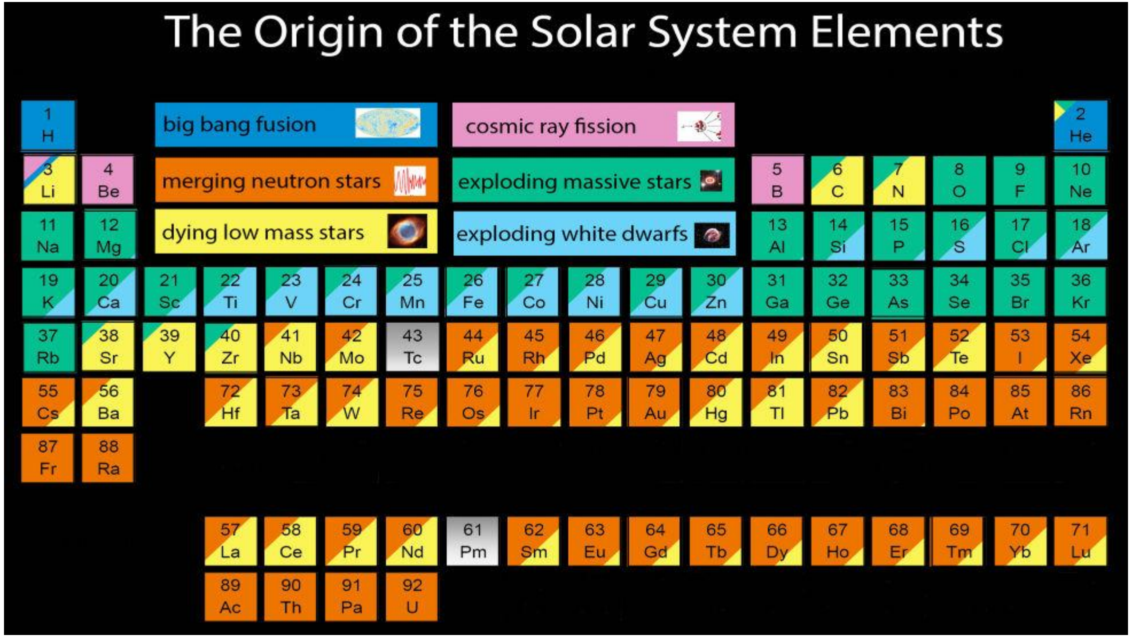
Huth et al. Nature 606, 276–280 (2022)

Post-merger and nucleosynthesis

Electromagnetic counterparts of NS involved mergers.

- **Remnant** matter in the environment
- **r-processes** in the ejecta or remnant matter, source of heavy element production
- **Kilonova**: signature of radioactive decays of heavy nuclei.
    - **We observed it for GW170817 !**



Credits: J. Johnson ESA/NASA/AASNova

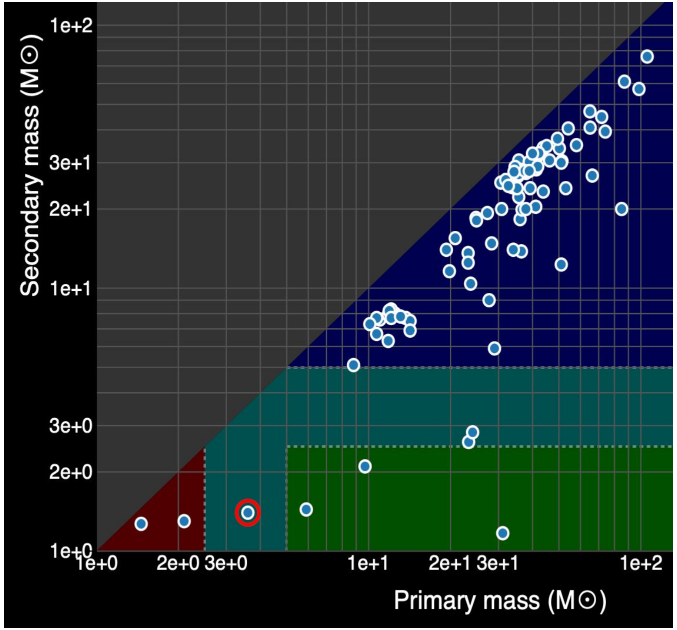
A Neutron Star-Black Hole merger from O4: GW230529

Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 $M_\odot$ Compact Object and a Neutron Star

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration

Primary = large mass m1
Secondary = small mass m2

*Primary is filling the "**mass gap**" between neutron stars and previously-observed BBH*



https://catalog.cardiffgravity.org

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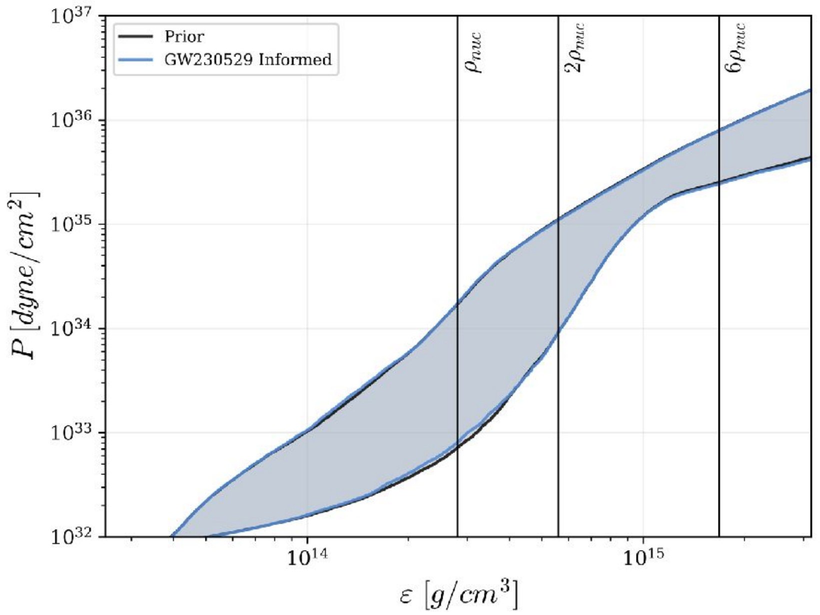

EOS inference using lwp from nonparametric Gaussian Process prior
https://git.ligo.org/reed.essick/lwp
Landry & Essick Phys. Rev. D 99, 084049

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Yet the source has implications for **electromagnetic brightness** and **heavy element production**

- No observed **EM counterpart**…
- 10% **tidal disruption** probability of the NS
- **Remnant baryon mass** $< 0.052 \mathrm{M}_\odot$ (99% credibility)
- **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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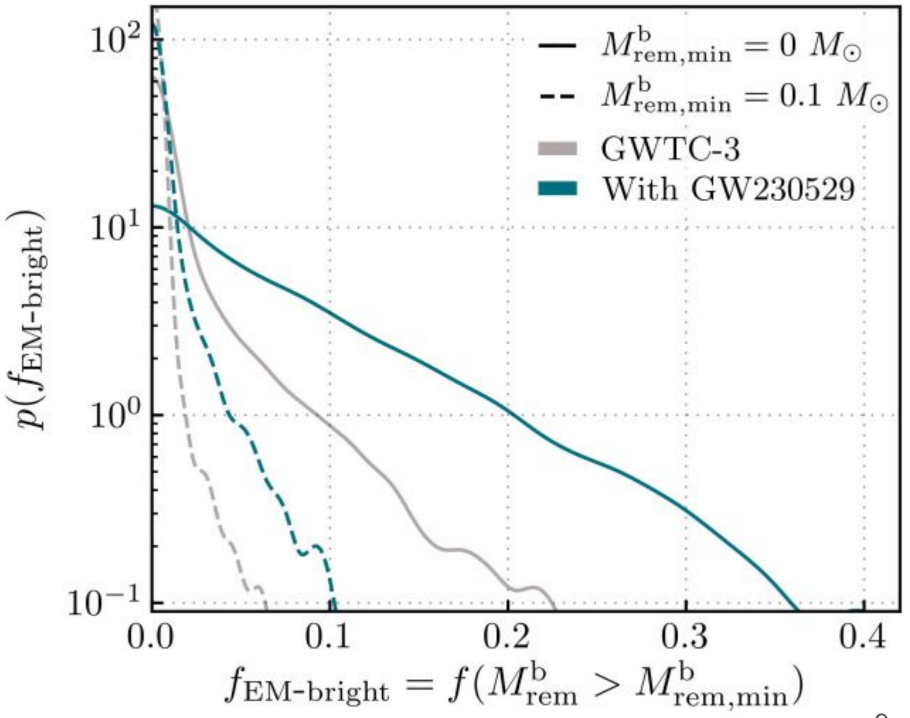

Next generation of detectors: what to expect ?

Project for future detectors:

- **LIGO India**
  - Sky localization enhanced
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Courtesy of D. Chatterjee

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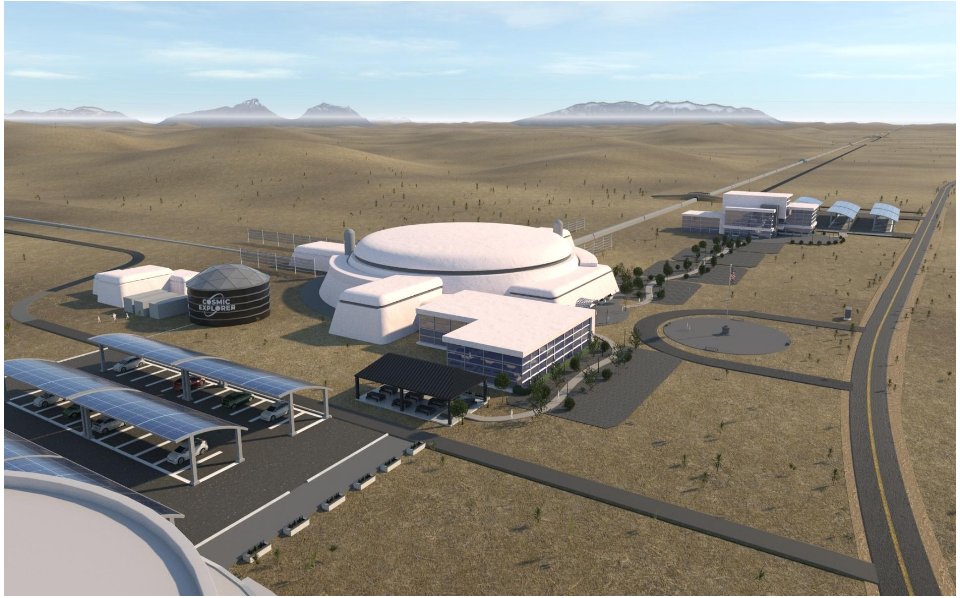
https://dcc.cosmicexplorer.org/CE-G2300014



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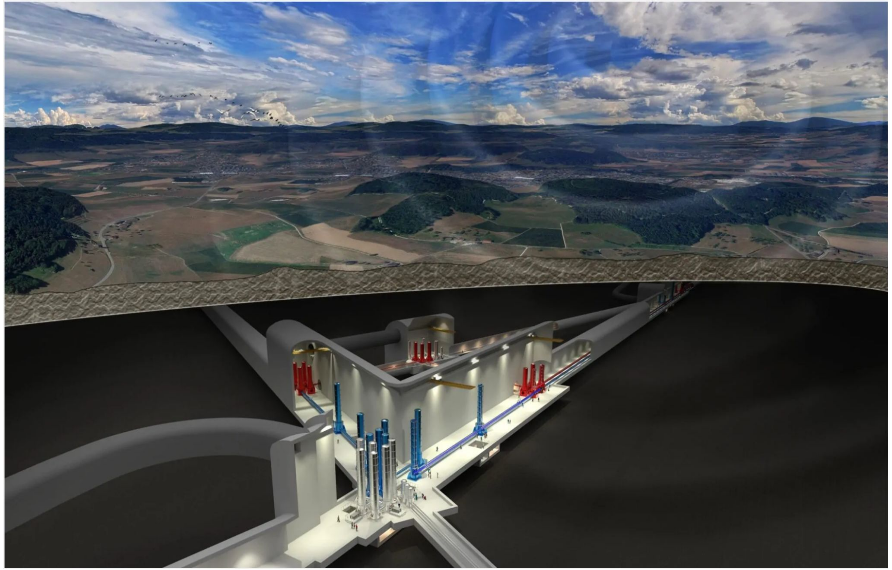

https://www.einsteintelescope-emr.eu/en/

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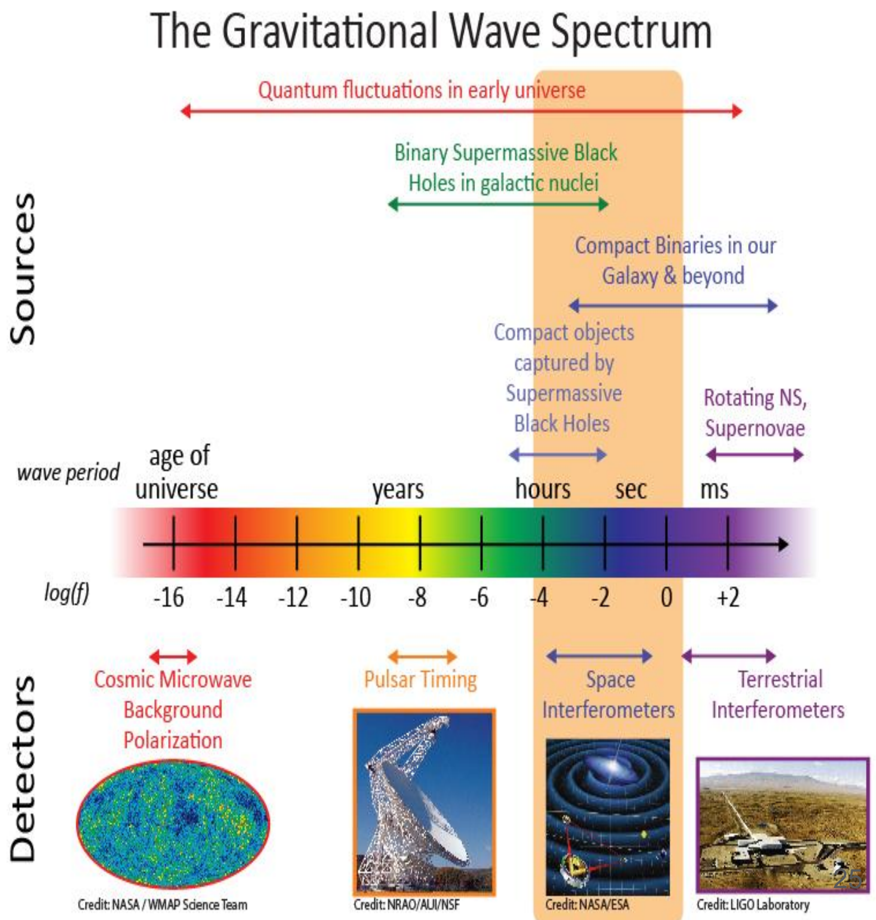
https://lisa.nasa.gov/



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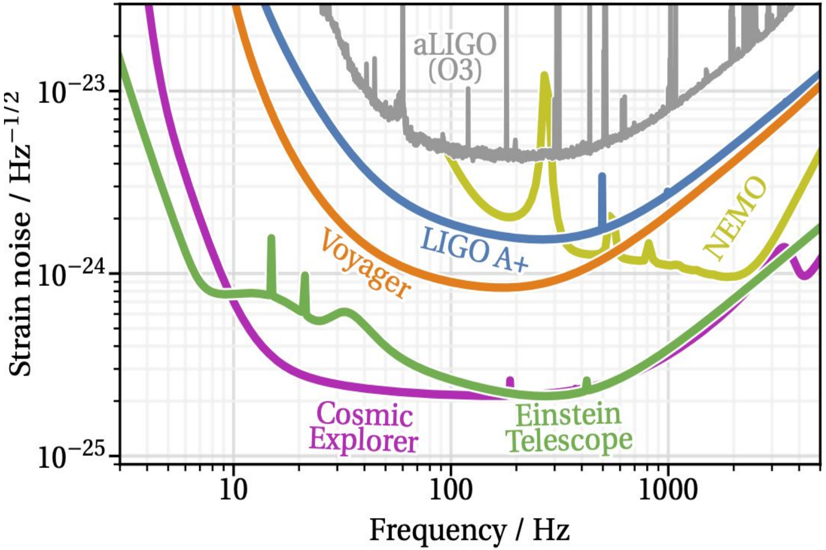
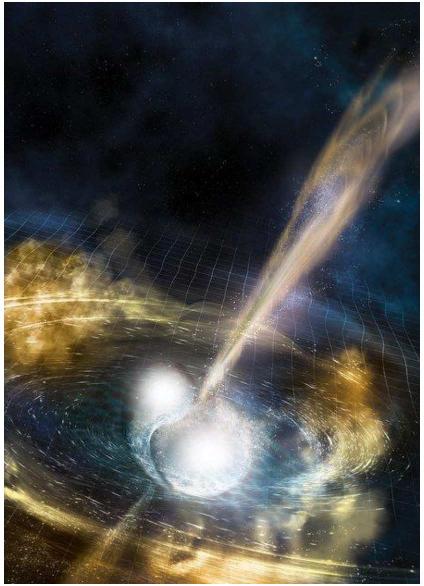


https://cosmicexplorer.org/

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

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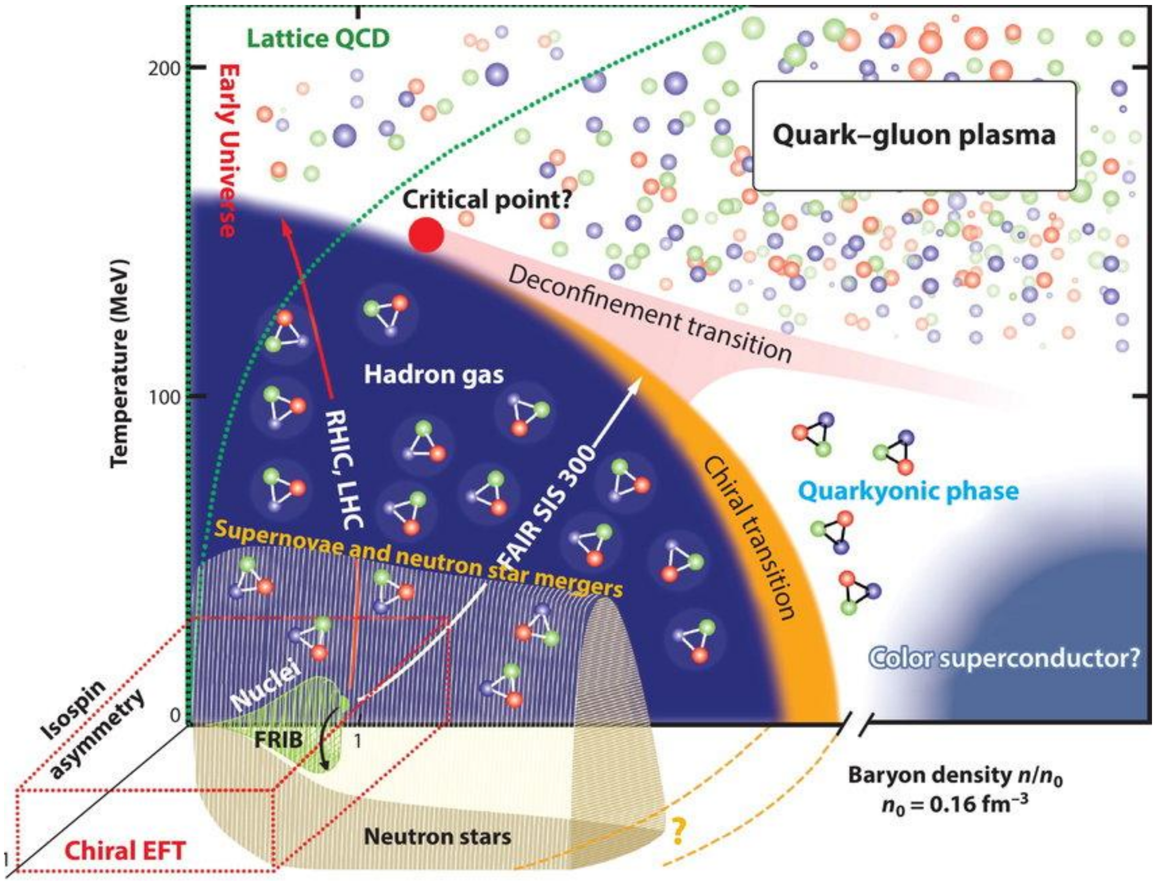
Lattice QCD
Early Universe
Quark–gluon plasma
Critical point?
Deconfinement transition
Hadron gas
RHIC, LHC
FAIR SIS 300
Chiral transition
Quarkyonic phase
Supernovae and neutron star mergers
Nuclei
FRIB
Color superconductor?
Temperature (MeV)
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100
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Isospin asymmetry
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Chiral EFT
Neutron stars
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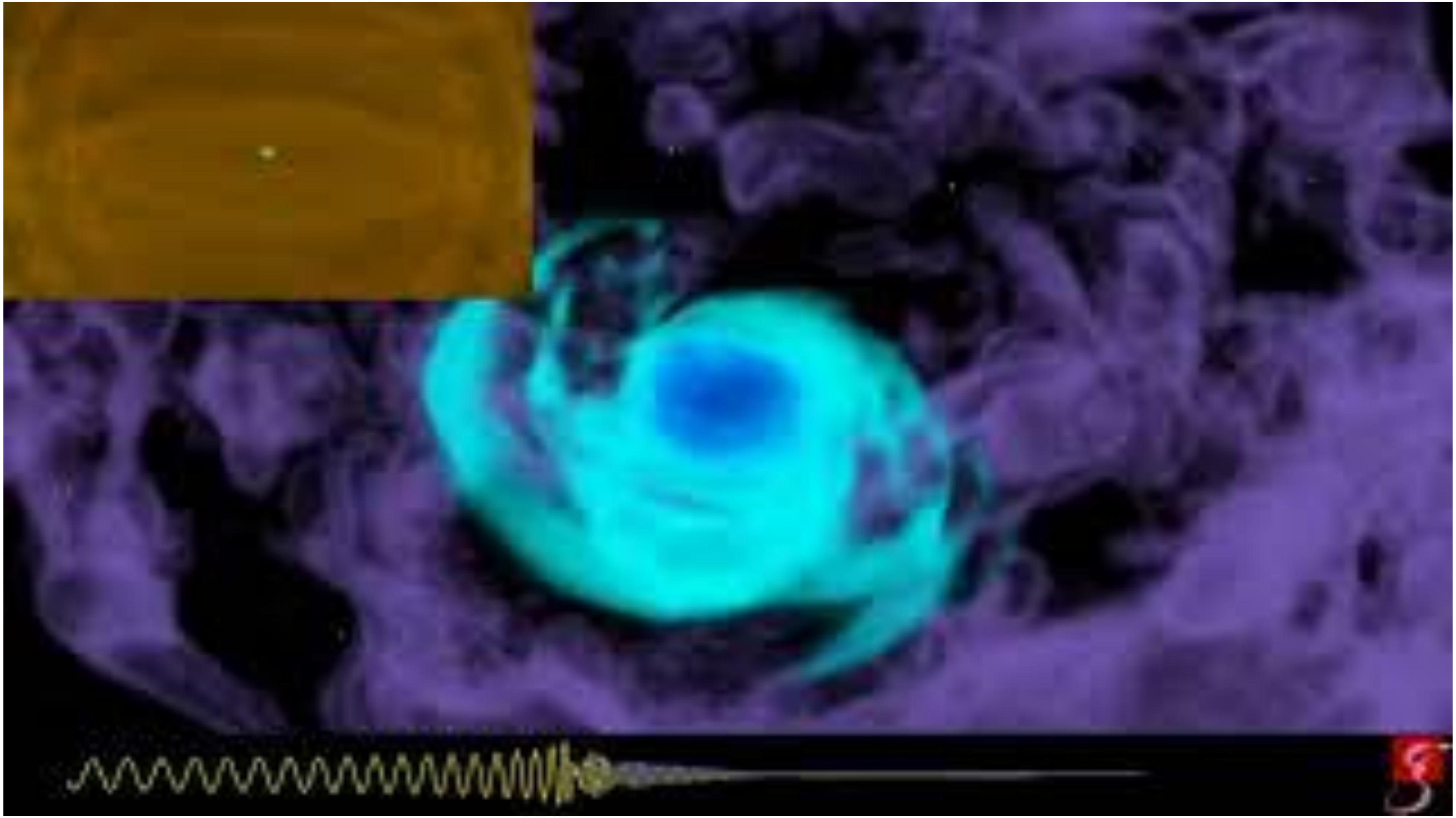
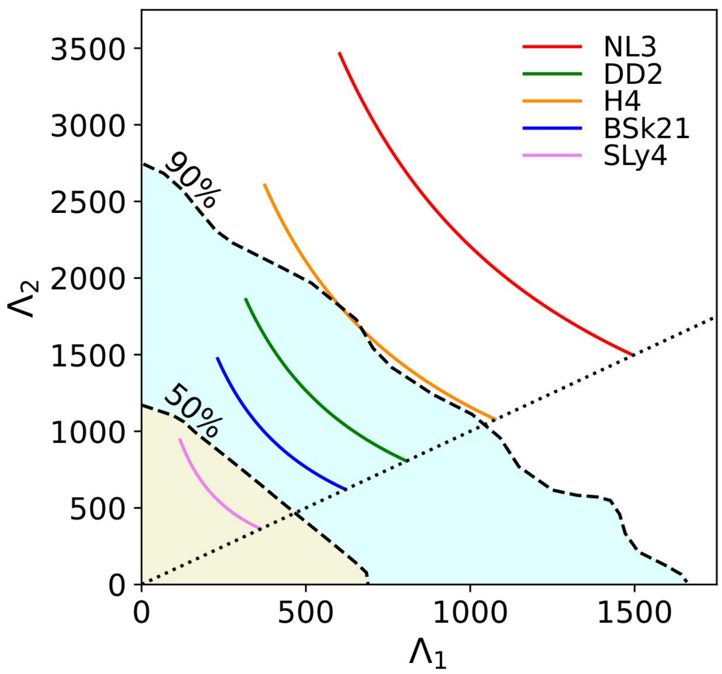
Baryon density n/n_0
$n_0 = 0.16\ \mathrm{fm}^{-3}$





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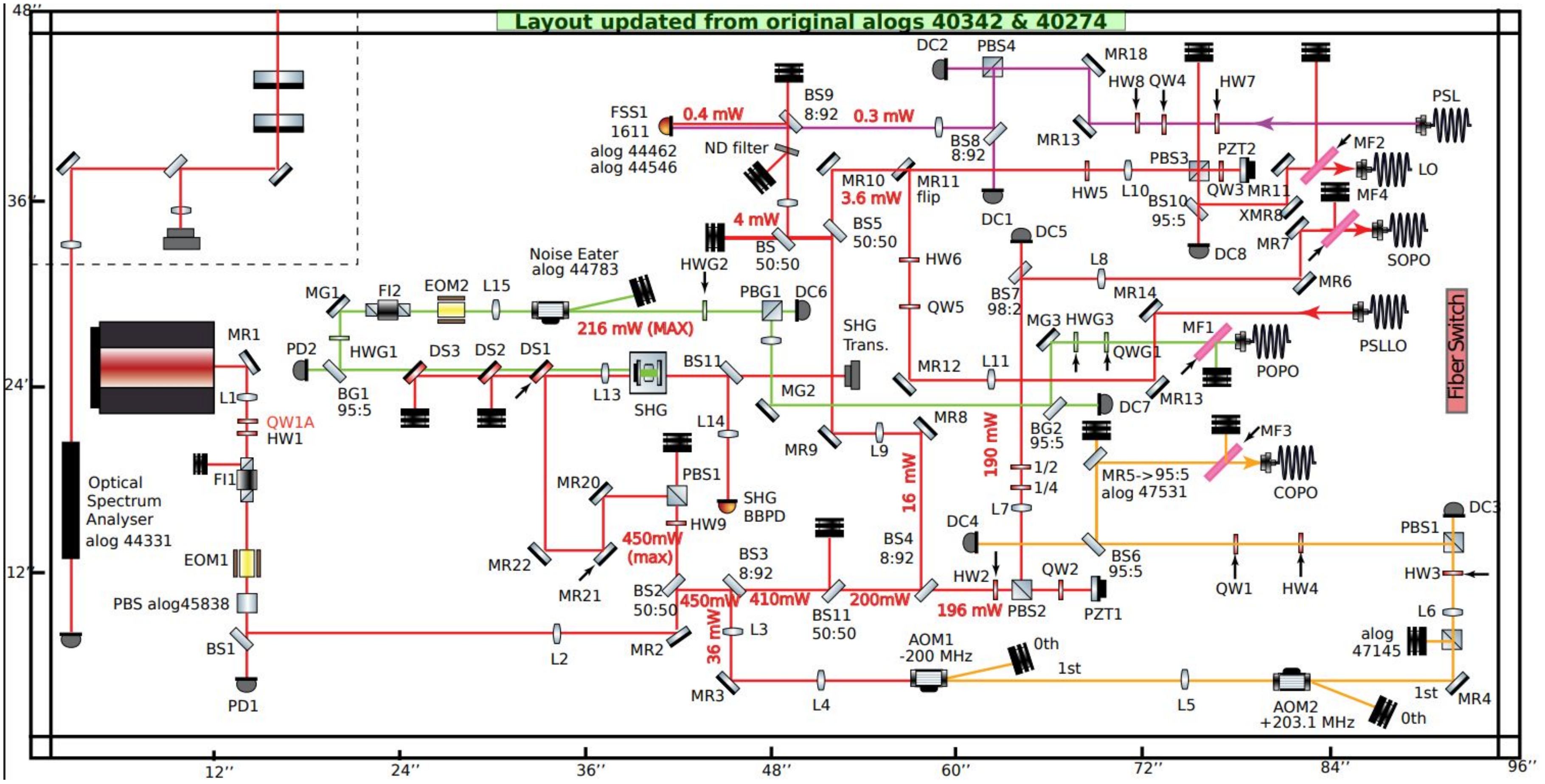
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