Georgian-German Science Bridge

"Heath as a Global Challenge: contributions by GGSB and its SMART|Labs“

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LIGO signals from Mirror World

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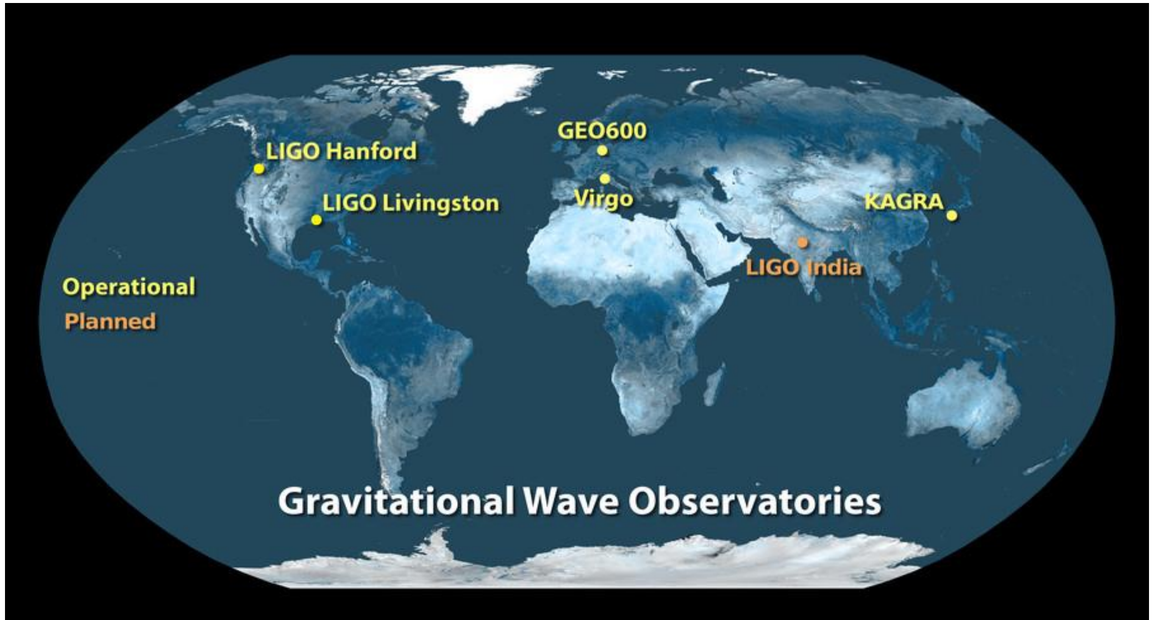
Outline

- A brief review of LIGO & VIRGO data
- Binary compact objects productions and merger rates
- Mirror World Model
- GWs from Mirror World
- Summary

Laser Interferometer Gravitational-Wave Observatory



Source: https: //www.ligo.caltech.edu/image/ligo20160211c

LIGO - gravitational wave detectors in **Hanford** and **Livingston, USA;**

VIRGO - GW detector in **Cascina, Italy;**

KAGRA - Kamioka GW Detector in **Hida, Japan**.

Livingston, LA

New Era of Multi-Messenger Astrophysics!

- „Observation of Gravitational Waves from a **Binary Black Hole** Merger"
  LIGO Scientific Collaboration and Virgo Collaboration
  Phys. Rev. Lett. **116**, 061102 – Published 11 February 2016

- „GW170817: Observation of Gravitational Waves from a **Binary Neutron Star** Inspiral"
  LIGO Scientific Collaboration and Virgo Collaboration
  Phys. Rev. Lett. **119**, 161101 – Published 16 October 2017

Nobel Prize 2017

Events detected so far

After the analysis of first three observing runs

O1, O2, O3a & O3b

there are **90** events with probability of

$$\boldsymbol{P_{astro} > 0.5}$$

being of the astrophysical origin.

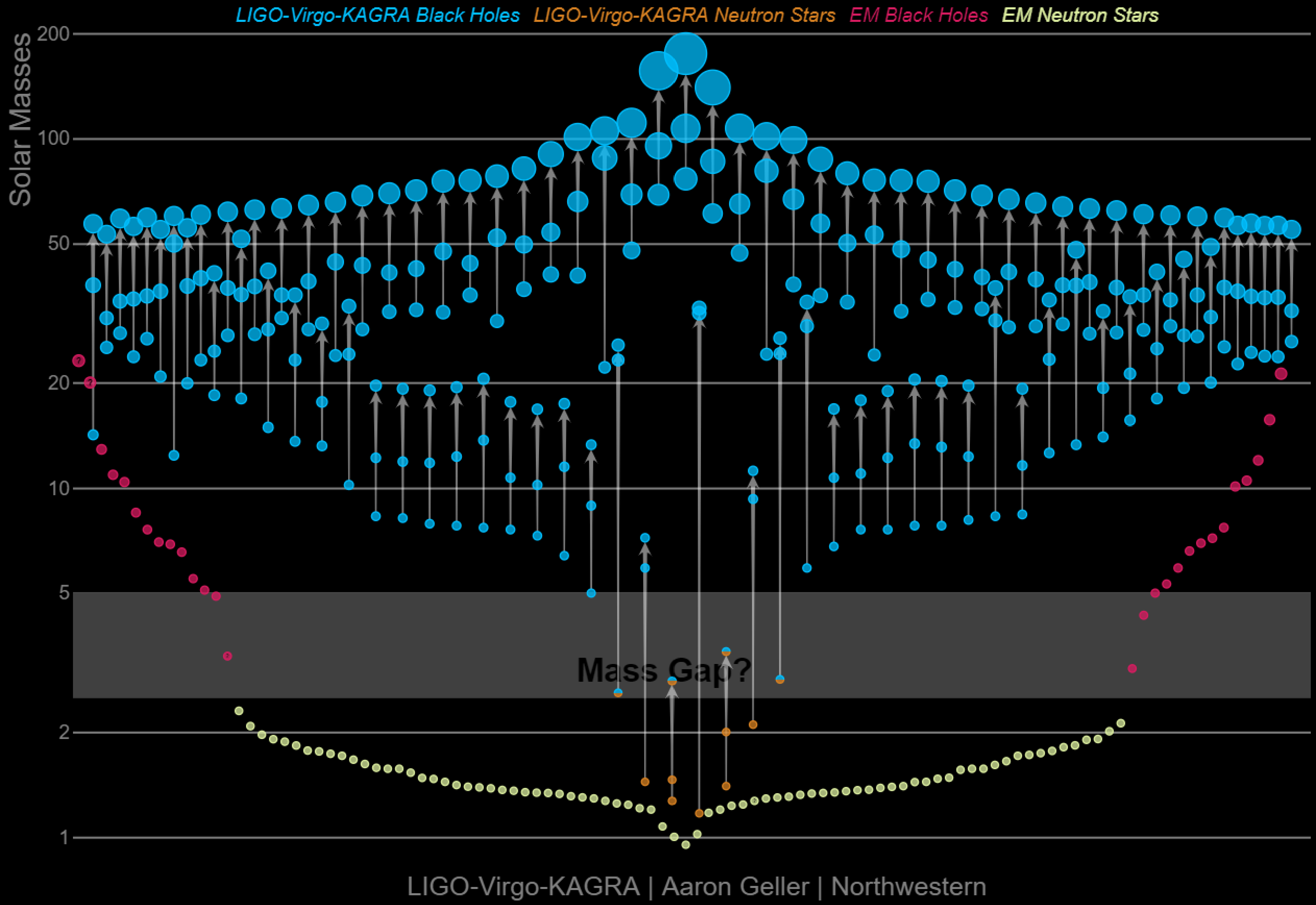
"GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run"

LIGO Scientific and VIRGO and KAGRA Collaborations, R. Abbott et al. arXiv:2111.03606

Merger objects:	BH-BH	NS-NS	BH-NS	BH-Mass gap
Number of events:	84	2	2	2

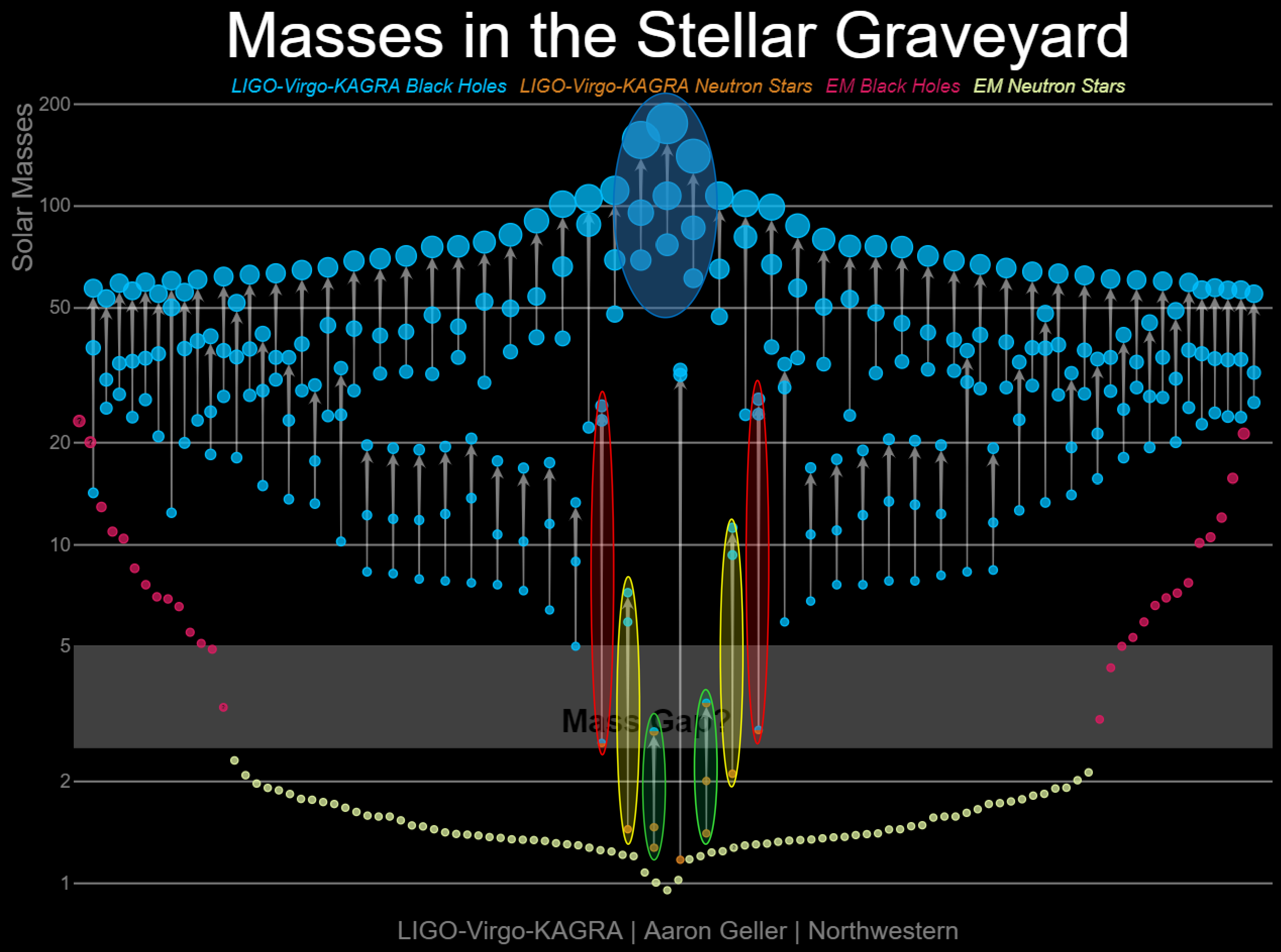
Only one NS-NS merger had accompanying Electromagnetic counterpart!

Masses in the Stellar Graveyard



Interactive figure:

https://ligo.northwestern.edu/media/mass-plot/index.html



NS-NS

BH-NS

BH-lower mass gap

Upper mass gap, intermediate mass BH

Interactive figure:

https://ligo.northwestern.edu/media/mass-plot/index.html

Unexpected Events

- GW190521 & GW190426_190642: First ever observation of Intermediate mass BHs

$$\mathbf{95}M_\odot - \mathbf{69}M_\odot \to \mathbf{156}M_\odot$$
$$\mathbf{107}M_\odot - \mathbf{77}M_\odot \to \mathbf{175}M_\odot$$

- Many models of star evolution predict existence of upper mass gap $65M_\odot - 135M_\odot$ for remnant compact objects

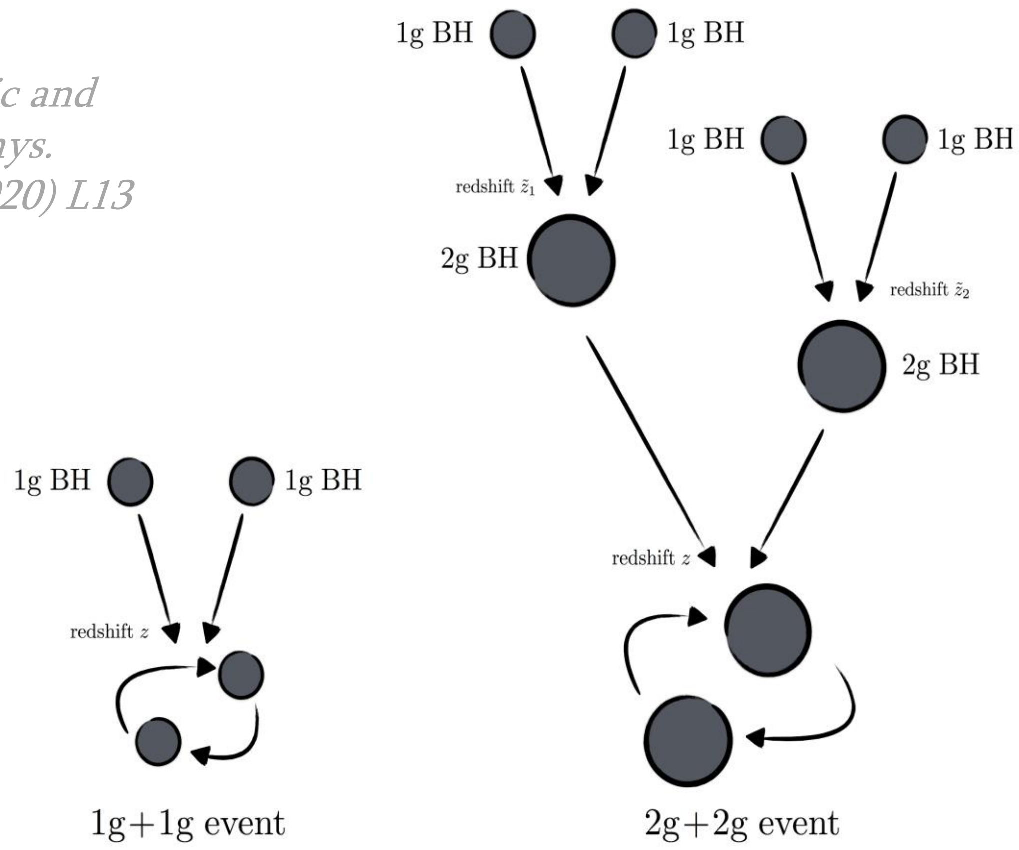
He core mass	Process	Remnant compact object
$32 - 65M_\odot$	Pulsational Pair Instability	$\lesssim 65M_\odot$
$65 - 135\ M_\odot$	Pair Instability	Explodes – no remnant
$\gtrsim 135M_\odot$	Direct collapse into BH	$\gtrsim 135M_\odot$

Hierarchical Mergers

Merger rate of **GW190521**-like events:

$$\mathcal{R}_{\rm exp} = 0.13^{+0.30}_{-0.11}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

LIGO Scientific and Virgo, Astrophys. J. Lett. ***900*** *(2020) L13*



source: Gerosa D. & Berti E. (2017)

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LIGO Scientific and Virgo, Astrophys. J. Lett. ***900*** *(2020) L13*

Theoretical estimate:

Liu B. & Lai D. arXiv: 2009.10068

$$\mathcal{R} = \mathcal{R}_{\rm 1G} \times f_{\rm triple} \times f_{\rm survival} \times f_{\rm merger}$$

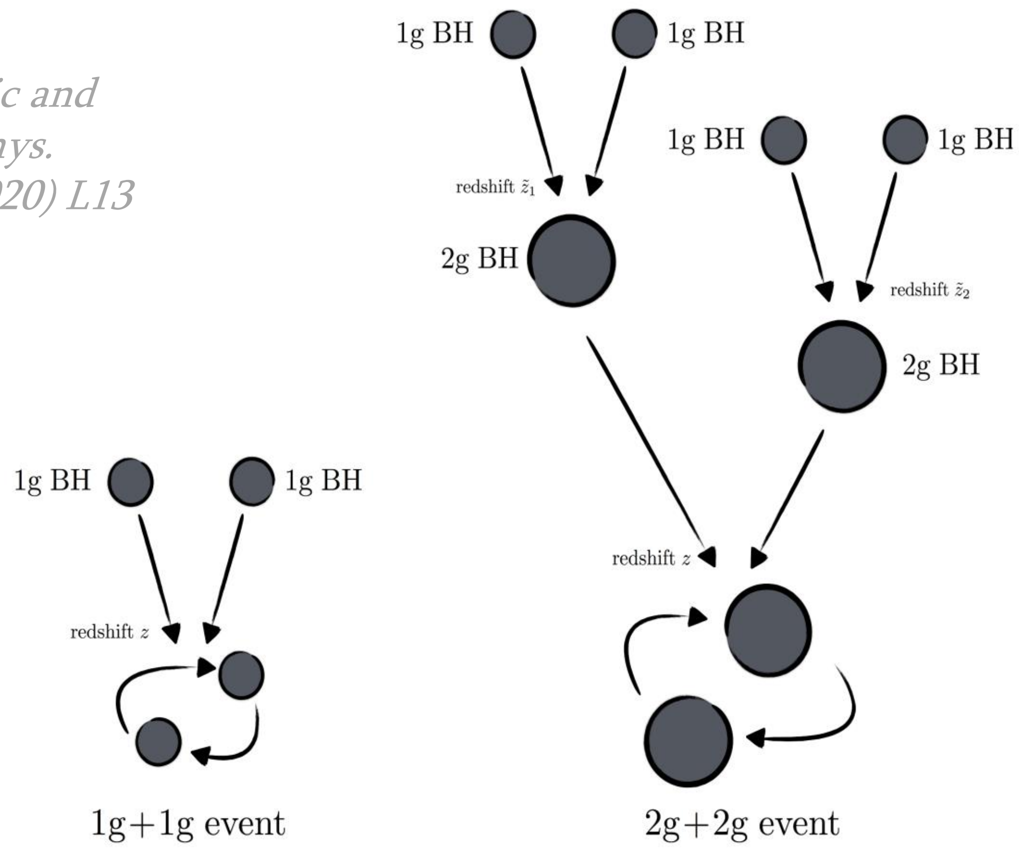
$$\mathcal{R}_{\rm 1G} \sim (10 - 100)\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

LIGO Scientific and Virgo, Phys. Rev. X ***9*** *(2019) 031040*

$$f_{\rm triple} \simeq 50\% \qquad f_{\rm merger} \simeq 20\%$$

$$f_{\rm survival} \simeq 60\%$$

$$\mathcal{R}_{\rm theo} = 0.6 - 6\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

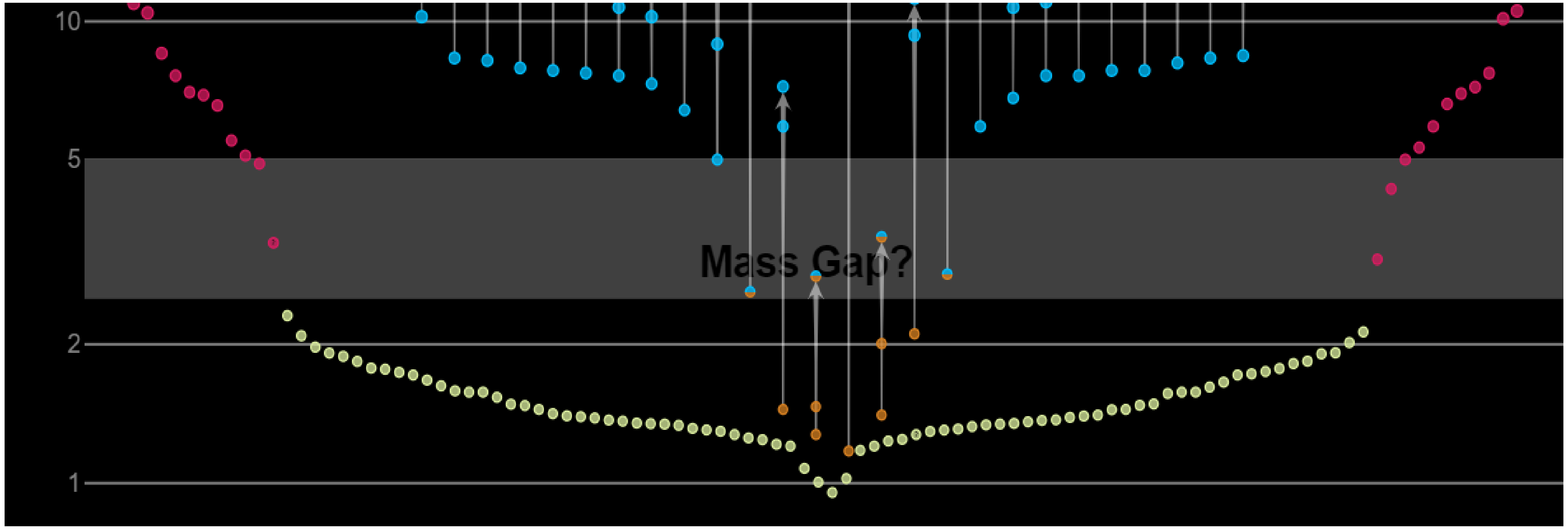


source: Gerosa D. & Berti E. (2017)

In price of extremal assumptions!

GW190425: Most massive binary NS system $3.4^{+0.3}_{-0.1}\ M_{\odot}$

X-ray binaries give the lower mass gap!

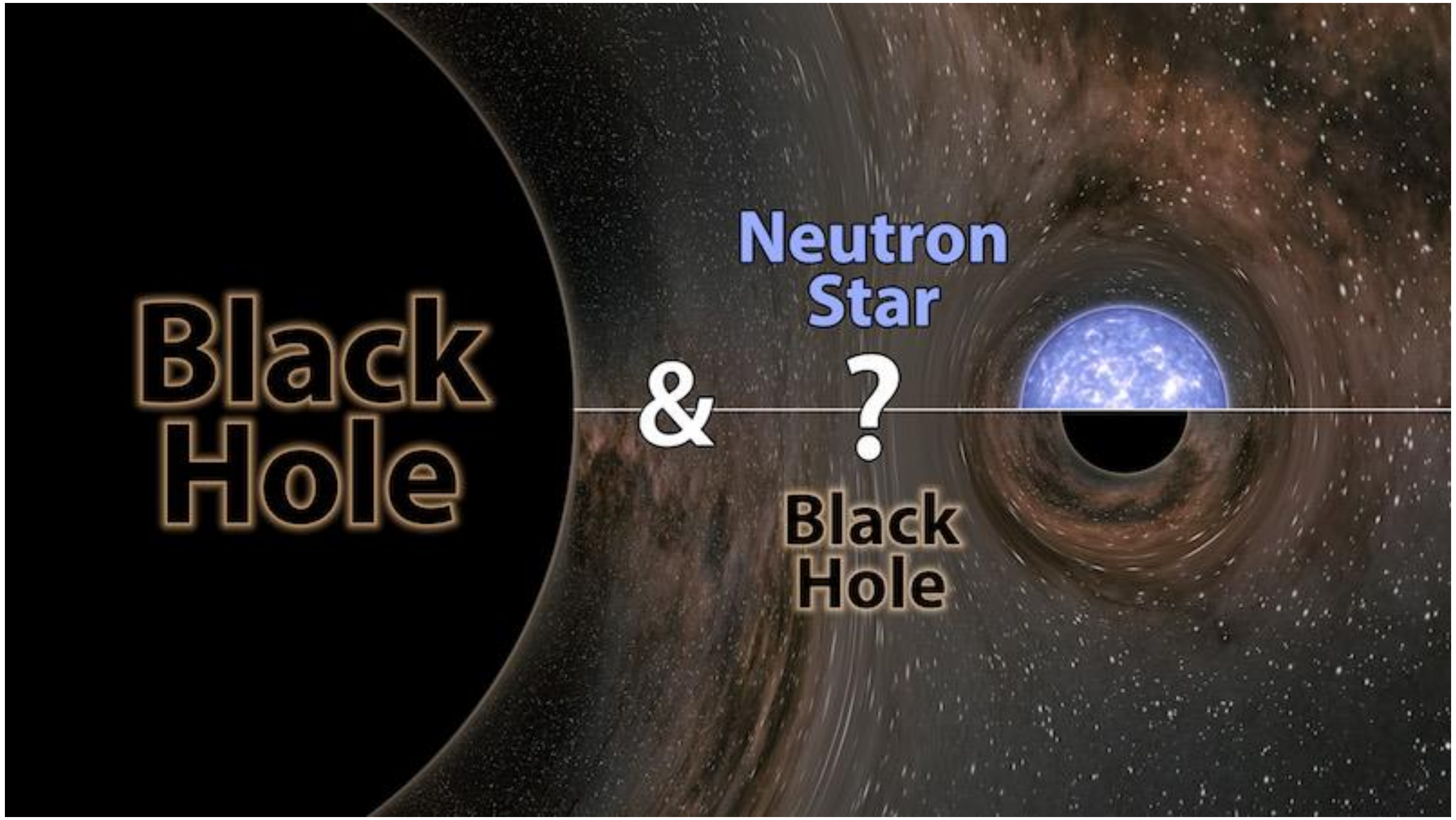


- **GW190525**-like systems could be obtained as a result of evolution of ultra-tight binary **He-star – NS** systems;

*LIGO Scientific and Virgo, Astrophys. J. Lett. **892** (2020) L3*

- phase of mass transfer from post-helium main-sequence star on to NS is required.

GW190814 & GW200210_092254: BH-mass gap systems



- First components are clearly BHs
- Origins of second components with masses $2.59^{+0.08}_{-0.09} M_\odot$ & $2.83^{+0.48}_{-0.43} M_\odot$ are controversial.

They are heavier than any known pulsars, and lighter than any known BHs so far

Binary Compact Objects creation mechanisms

- Primordial Black Holes; *(Sasaki, Suyama, Tanaka & Yokoyama 2018)*

  PBH abundance is constrained by microlensing, CMB spectral distortion and wide binaries.

- Astrophysical binary systems:

  - Common Envelope Evolution; *(Giacobbo & Mapelli 2018)*
  - Chemically homogenous evolution; *(Mandel & de Mink 2016)*
  - Dynamical processes in dense stellar clusters. *(Askar, et al. 2017)*

$$\mathcal{R}^{\rm BBH}_{\rm theor} \sim 5 - 10 \ {\rm Gpc}^{-3} \ {\rm yr}^{-1} \quad < \quad \mathcal{R}^{\rm BBH}_{\rm LIGO} = 17.3 - 45 \ {\rm Gpc}^{-3} {\rm yr}^{-1}$$

LIGO Scientific and VIRGO and KAGRA Scientific Collaborations arXiv:2111.03634

Theoretical BBH merger rate

$$\mathcal{R} = \frac{1}{2}\,\epsilon P(\tau) N_{\rm BH}$$

$\epsilon \simeq 0.01 - 0.001$ - dimensionless efficiency coefficient

$P(\tau)$ - delay time distribution

Number of Black Holes: *(Elbert, Bullock & Kapling-hat 2018)*

$$N_{\rm BH} = \mathrm{SFR(z)} \times \int \phi(m)\; N(m) \int f(Z,m) \int \xi(M)\; dM\; dZ\; dm$$

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$$N(m) = \frac{m}{\int M\; \xi(M)\; dM}$$ - Number of stars in galaxy of m mass;

$\xi(M)$ - Initial mass function (IMF);

$\phi(m)$ - Galactic mass function;

$f(Z,m)$ - Metallicity distribution function;

Star formation rate: *(Madau & Dickinson 2014)*

$$\mathrm{SFR(z)} = 0.015\frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}}\;\mathrm{M_\odot\;Mpc^{-3}\;yr^{-1}}$$

Peaks at:

$z \sim 2 \;\approx\; t_{\rm lookback} \sim 10.3$ Gyr

Problems

- Observed Merger Rates are higher than theoretical predictions

- Only 1 out of 90 events had EM counterpart, while
  - BNS merger must always be accompanied by Gamma-Ray Bursts;
  - BH-NS mergers in many configurations should emit EM-radiation;
  - If BHs accrete matter they can also emit EM-radiation;
- Mass gap events

Suggestion

- GWs detected by LIGO may be emitted by Mirror World binaries

Mirror World model

- Each Standard Model (SM) particle has its Mirror partner with opposite chirality;
- Ordinary and Mirror particles interact only by gravity;
- Mirror world, along with Ordinary world, was created by **Big Bang**, but with low reheating temperature;
- Constrain from **Big Bang Nucleosynthesis**: $x \equiv \frac{T'}{T} < 0.64$
- Certain **leptogenesis** mechanism gives: $1 \leq \frac{n'_b}{n_b} \lesssim 10$
- Mirror world can explain all Dark Matter: $\frac{\Omega'_b}{\Omega_b} \approx 5$

For the review of mirror world see ***Berezhiani 2005***

In Mirror World:

- Helium abundance is higher: He - 75-80 %

- Stars are composed mostly of Helium, they are more **massive** and evolve **faster**.

- For example, $10M_{\odot}$ mass star with 75% He abundance evolves ~ 10 times faster than normal star (He-24%).

- Number of **stars**: $N'(m) \sim 5 \times N(m)$

- Due to the lower temperature in Mirror World, important cosmological processes occur earlier, star formation should also begin in earlier epoch.

LIGO signals from Mirror world

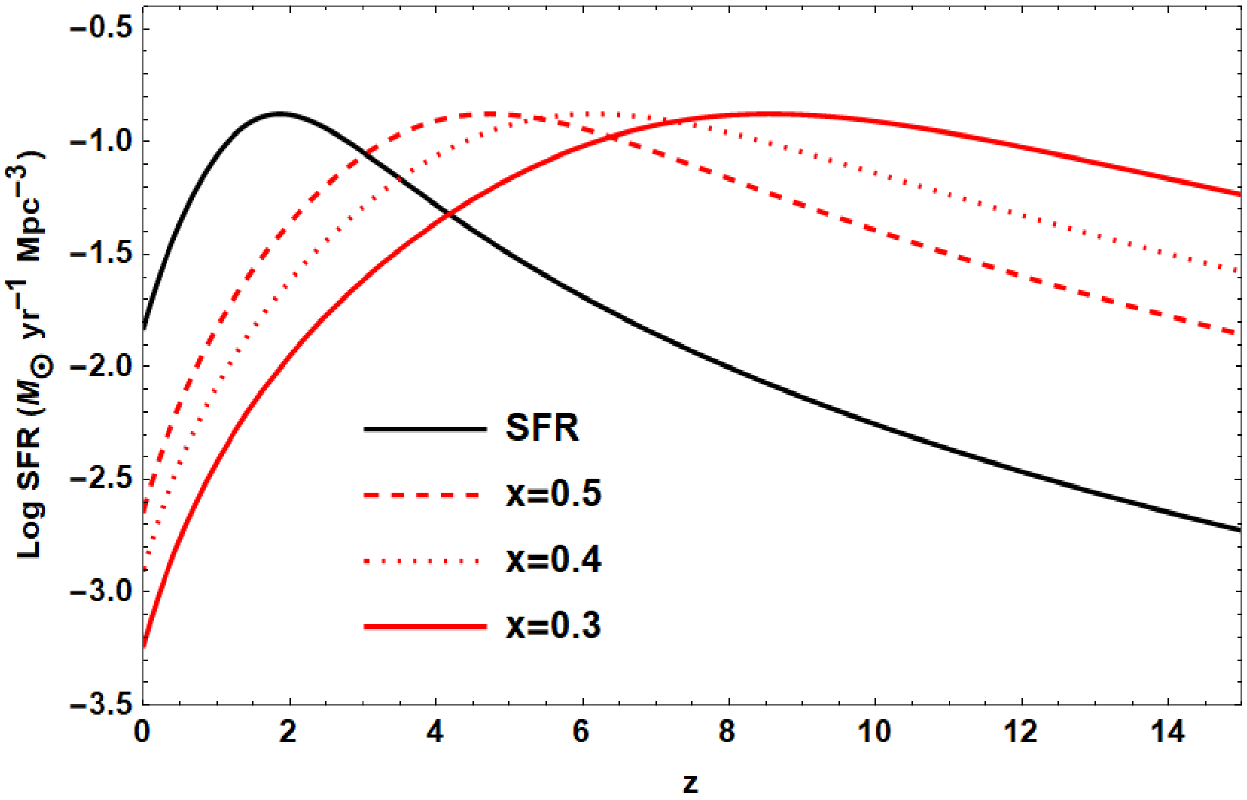
- In the period $0 < z < 14$ more stars are formed in Mirror sector relative to our:

$$\frac{\int_0^{14} \mathrm{SFR}' \; dz}{\int_0^{14} \mathrm{SFR} \; dz} = 2.3$$

- Combining, the number of black holes in mirror world can be

$$N'_{BH} \sim 10 \; N_{BH}$$

- Even though if mirror matter does not make up all dark matter, or if formation of binary systems is not so efficient, the amplification factor still can be $\sim$ **5**



The plot for SFR in the interval $0 < z < 14$ is built up by experimental results (Madau & Dickinson 2014)

In red, the star formation rate (SFR') is shown for mirror world for different temperatures ($x = T'/T$).

LIGO signals from Mirror world

- Combining these factors,

$$\mathcal{R}'_{\rm BBH} \sim 5 \times \mathcal{R}^{\rm theor}_{\rm BBH} \sim 25 - 50 \ {\rm Gpc}^{-3} \ {\rm yr}^{-1}$$

and coincides with LIGO's bounds even if some assumptions of binary formation are relaxed.

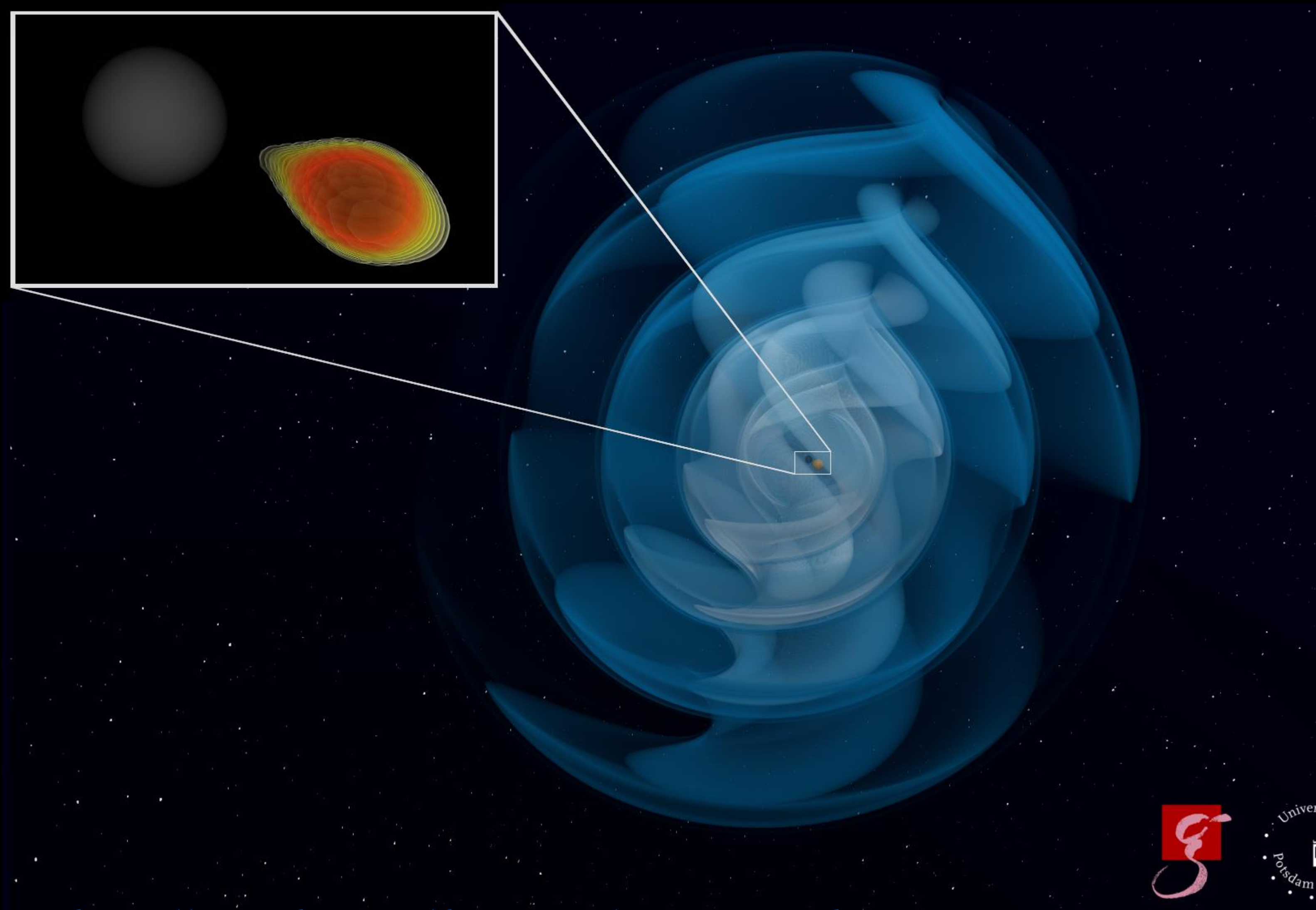
- Hierarchical mergers are more probable in Mirror World and merger rates of upper mass gap systems **(GW190521 & GW190426_190642)** would agree better even with less strict assumptions.

- Production of 'heavy NSs' **(GW190525)** or lower mass gap objects **(GW190814 & GW200210_092254)** are easier in Mirror World, as it is dominated by **He**.

Summary

- In the Mirror world scenario:
  - Number of binary systems is higher;
  - So BBH merger rate is amplified, coinciding better with LIGO estimations;
  - Mass gap events can be better explained;
  - Non-detection of EM-radiation is natural, since Mirror photons **DO NOT** interact with Ordinary particles;
- Prediction:
  - Binary compact objects' merger rates are order of 5 higher than expected and only 1 of 10 NS-NS events discovered by GW detectors may have EM-counterpart.

Thank you for your attention!



- R. Beradze and M. Gogberashvili, MNRAS 487 (2019) 650.
- R. Beradze, M. Gogberashvili and A. S. Sakharov, Phys. Lett. B 804 (2020) 135402.
- R. Beradze and M. Gogberashvili, MNRAS 503 (2021) 2882

Image source: https://www.ligo.org/detections/NSBH2020.php