Regional Doctoral Program in Theoretical and Experimental Particle Physics

PhD School & Workshop, 08-12 November, 2021

“Aspects of Symmetry“

LIGO signals from Mirror World

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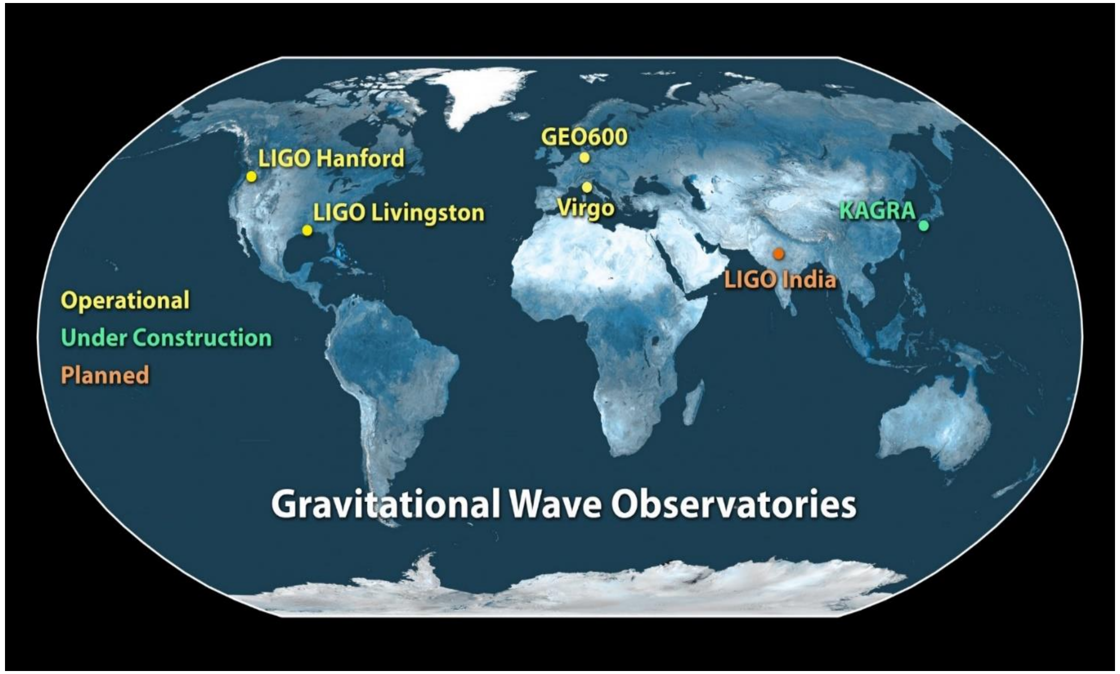
Outline

- 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



LIGO - gravitational wave detectors in **Hanford** and **Livingston**, **4 km** tunnels separated by **3000 km.**

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

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.

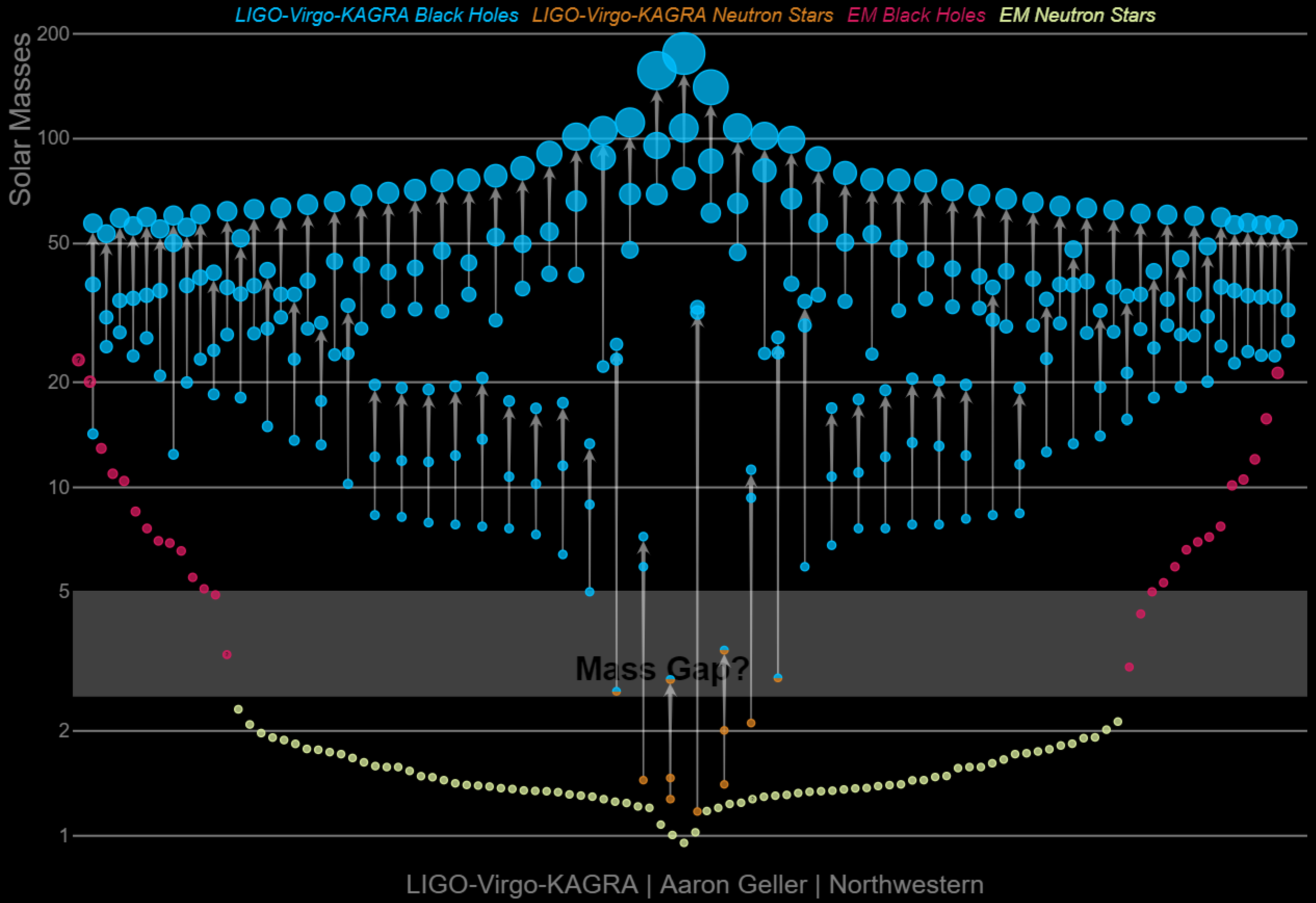
"GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run"

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

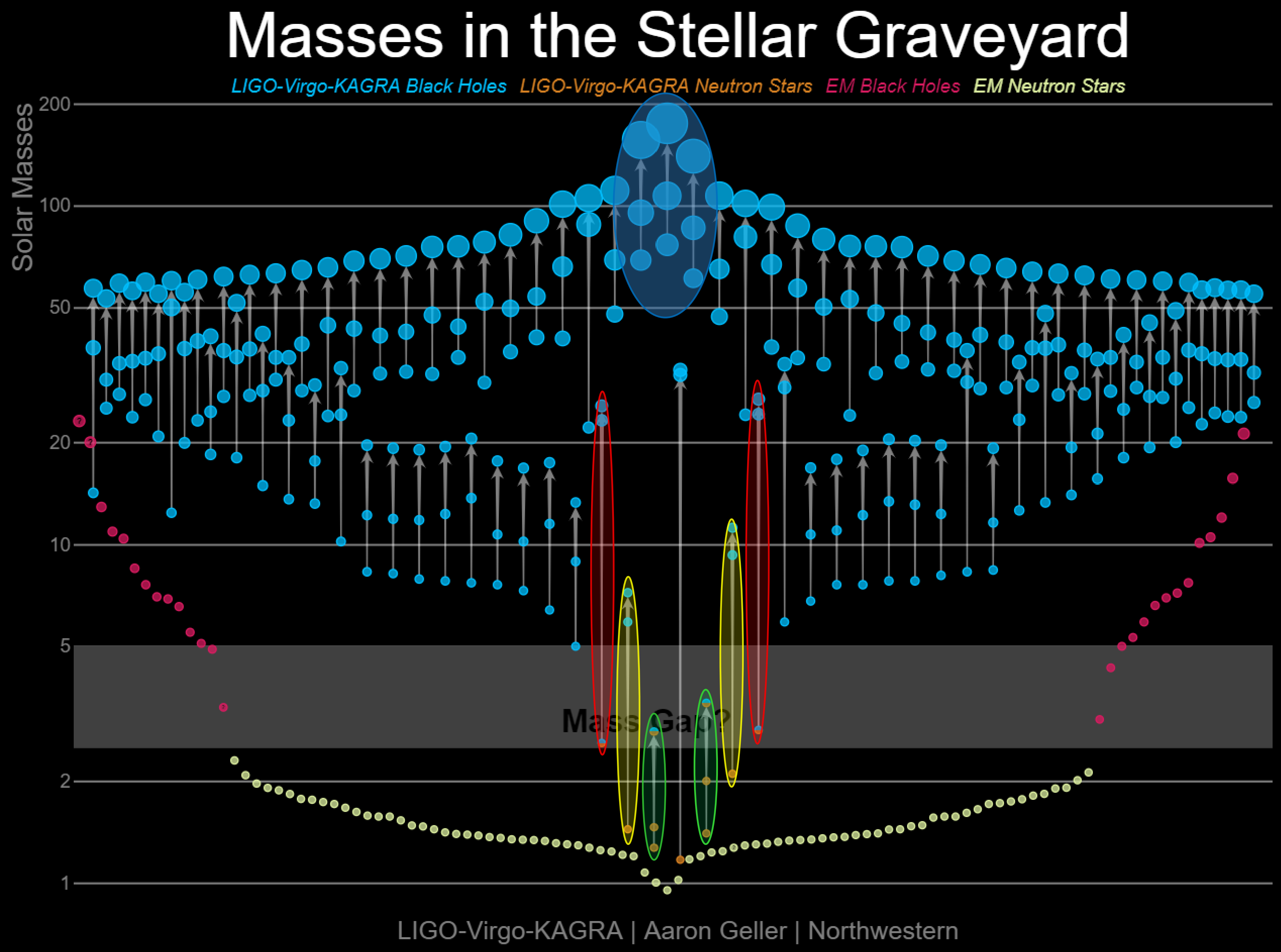
Only one NS-NS merger had accompanying Electromagnetic counterpart!

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

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

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

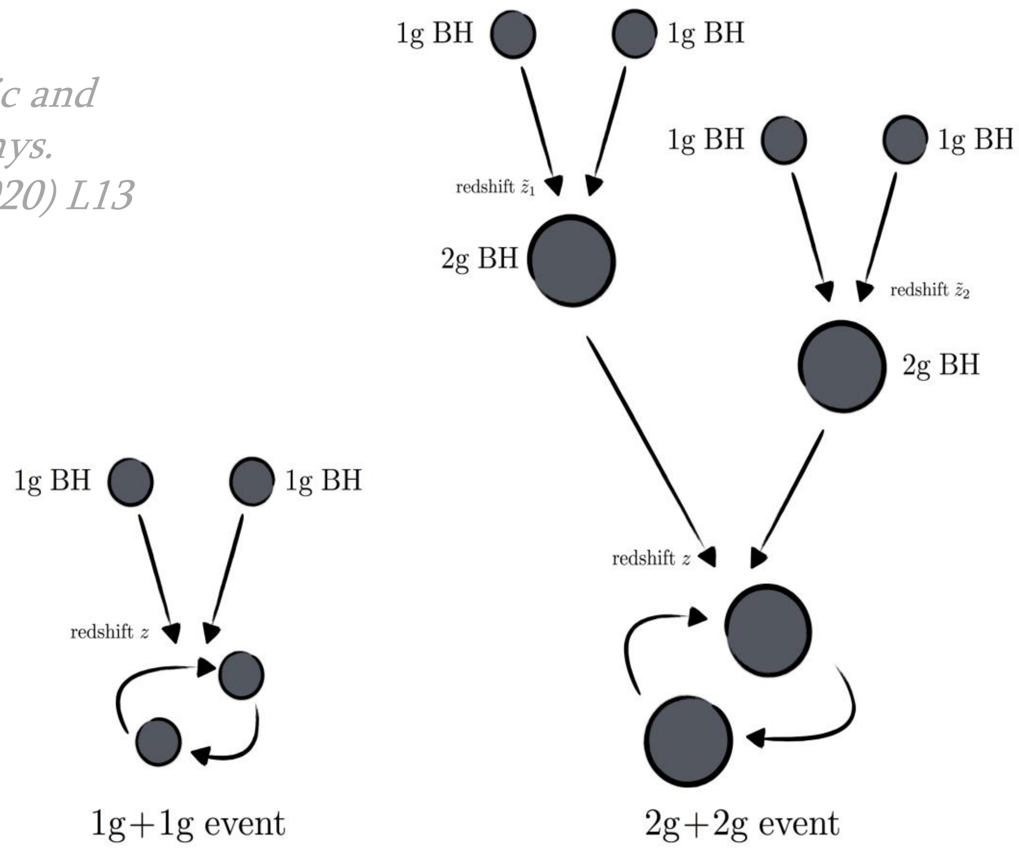
He core mass	Process	Remnant compact object
$32-65M_{\odot}$	Pulsational Pair Instability	$\lesssim 65M_{\odot}$
$65-135\ M_{\odot}$	Pair Instability	Explodes – no remnant
$\gtrsim 135M_{\odot}$	Direct collapse into BH	$\gtrsim 135M_{\odot}$

Hierarchical Mergers

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

$$f_{\rm exp} = 0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

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



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

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Theoretical estimate:

Liu B. & Lai D. arXiv: 2009.10068

$$f = f_{\rm 1G} \times f_{\rm triple} \times f_{\rm survival} \times f_{\rm merger}$$

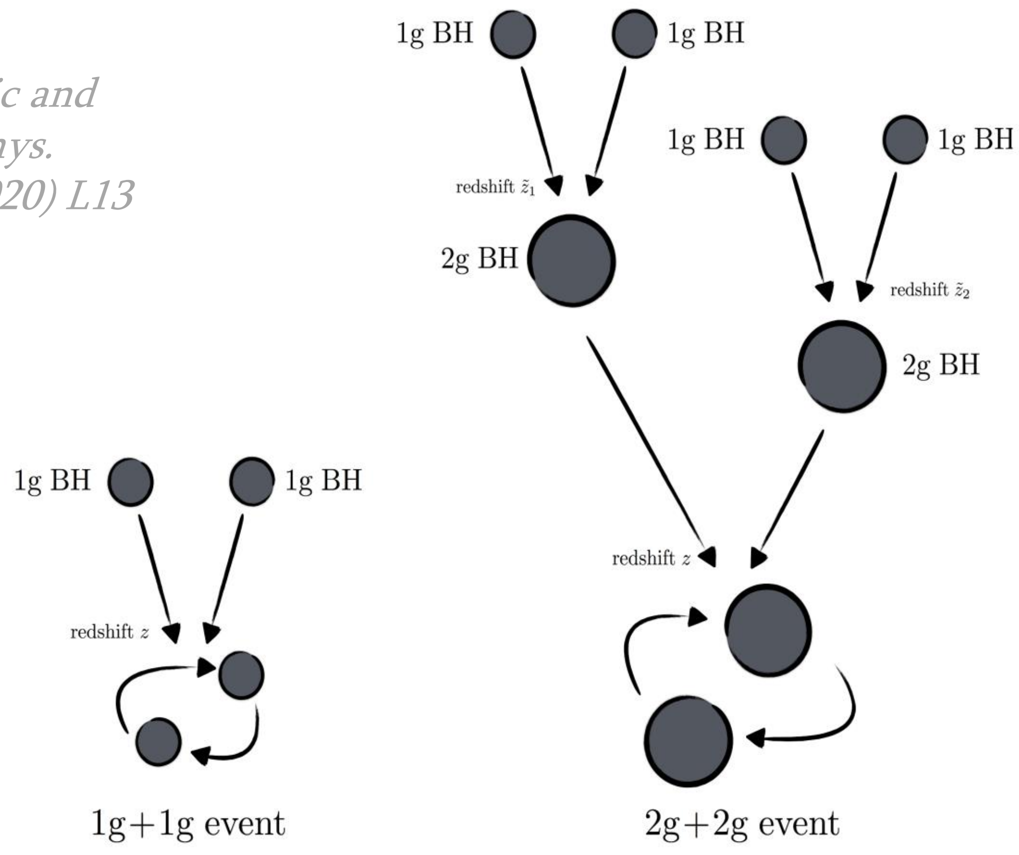
$$f_{\rm 1G} \sim (10 - 100)\ {\rm Gpc}^{-3}{\rm yr}^{-1}$$

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

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

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

$$f_{\rm theo} = 0.6 - 6\ {\rm Gpc}^{-3}{\rm yr}^{-1}$$

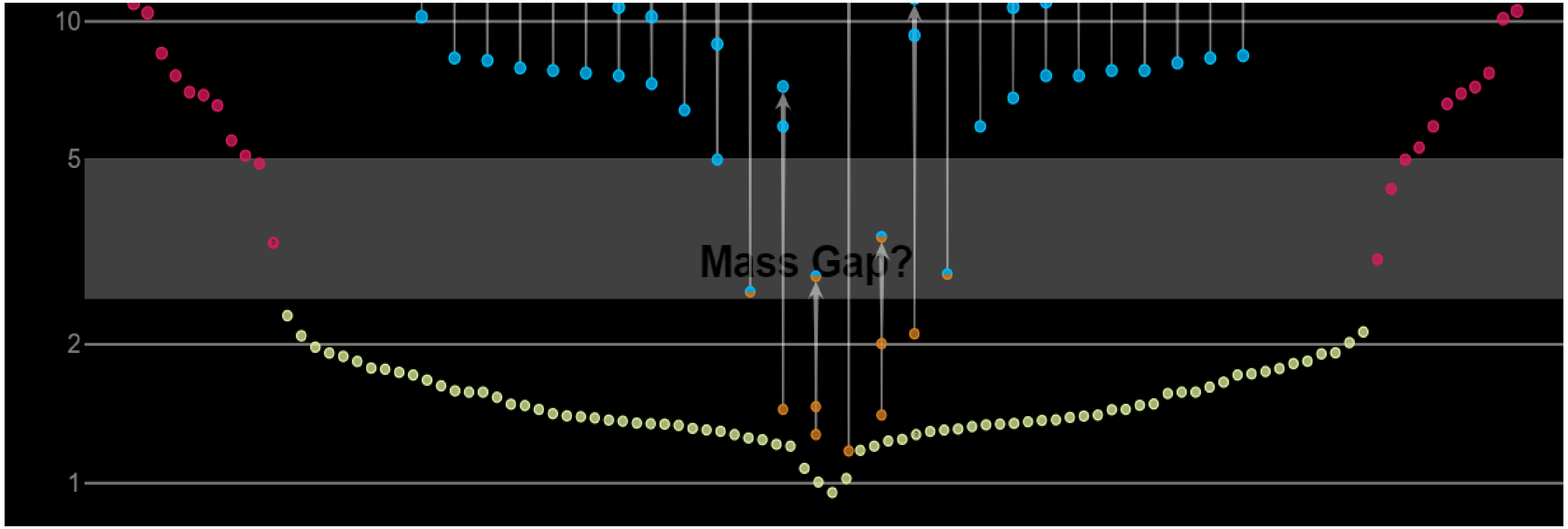


source: Gerosa D. & Berti E. (2017)

In price of extremal assumptions!

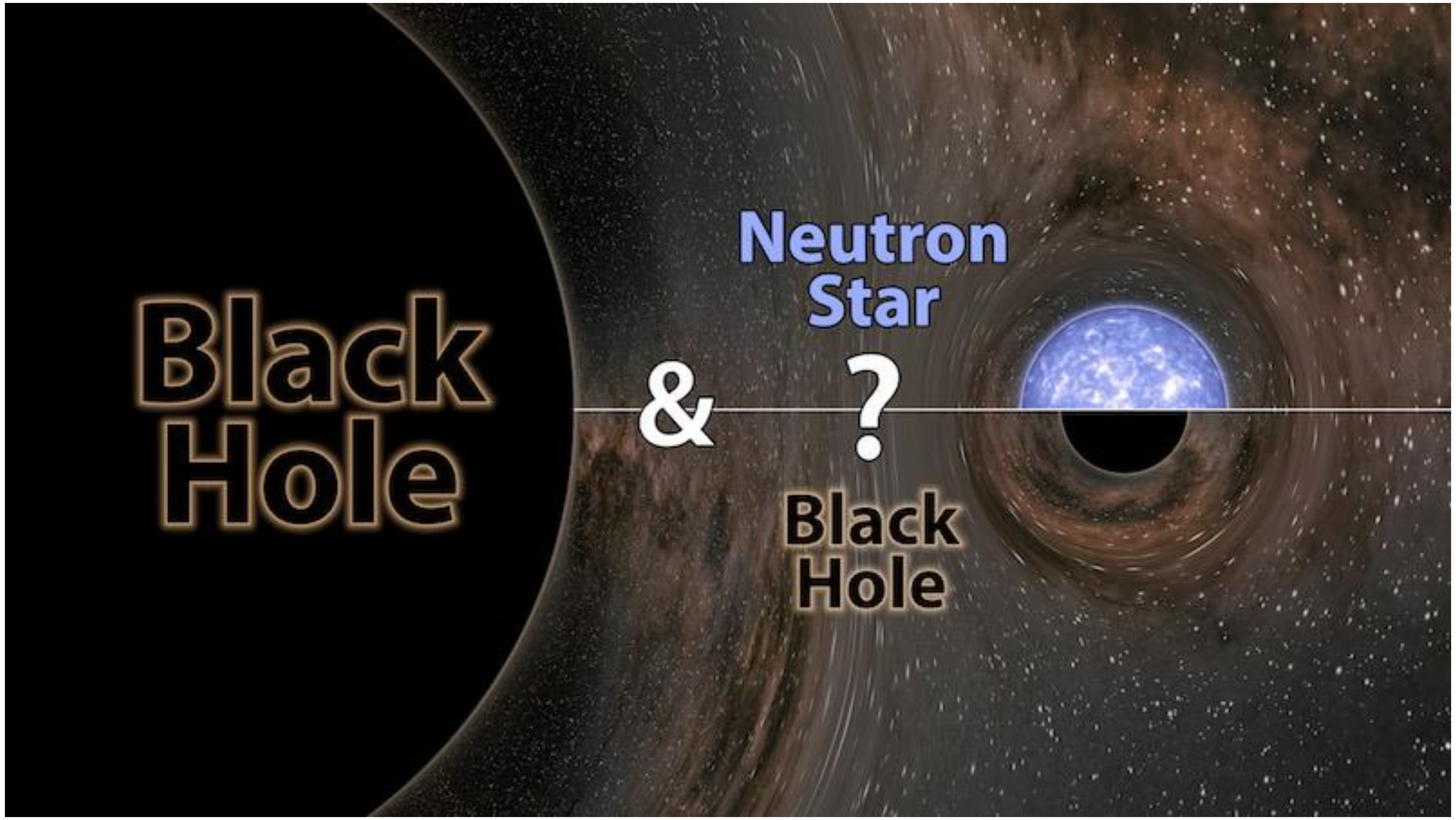
GW190425: Most massive binary NS system $3.4^{+0.3}_{-0.1}\ M_\odot$

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)*

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

LIGO Scientific and VIRGO and KAGRA Scientific Collaborations
arXiv:2111.03634

Theoretical BBH merger rate

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

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

$P(\tau)$ - delay time distribution

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

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

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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:

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

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%).
- High He abundance increases **initial mass function:** $\mathrm{IMF}' \sim 1.5 \times \mathrm{IMF}$
- **Star formation** peaks at $t_{\mathrm{lookback}} \sim 13.3$ Gyr and so: $\mathrm{SFR}'(\mathrm{z}) \sim 1.3 \times \mathrm{SFR}(\mathrm{z})$
- Number of **stars:** $N'(m) \sim 5 \times N(m)$
- Number of **black holes:** $N'_{\mathrm{BH}} \sim 10 \times N_{\mathrm{BH}}$

LIGO signals from Mirror world

- Combining these factors,

$$\mathcal{R}_{\text{mirror}} \sim 10 \times \mathcal{R}_{\text{theor}} \sim 50 - 100 \ \text{Gpc}^{-3} \ \text{yr}^{-1}$$

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

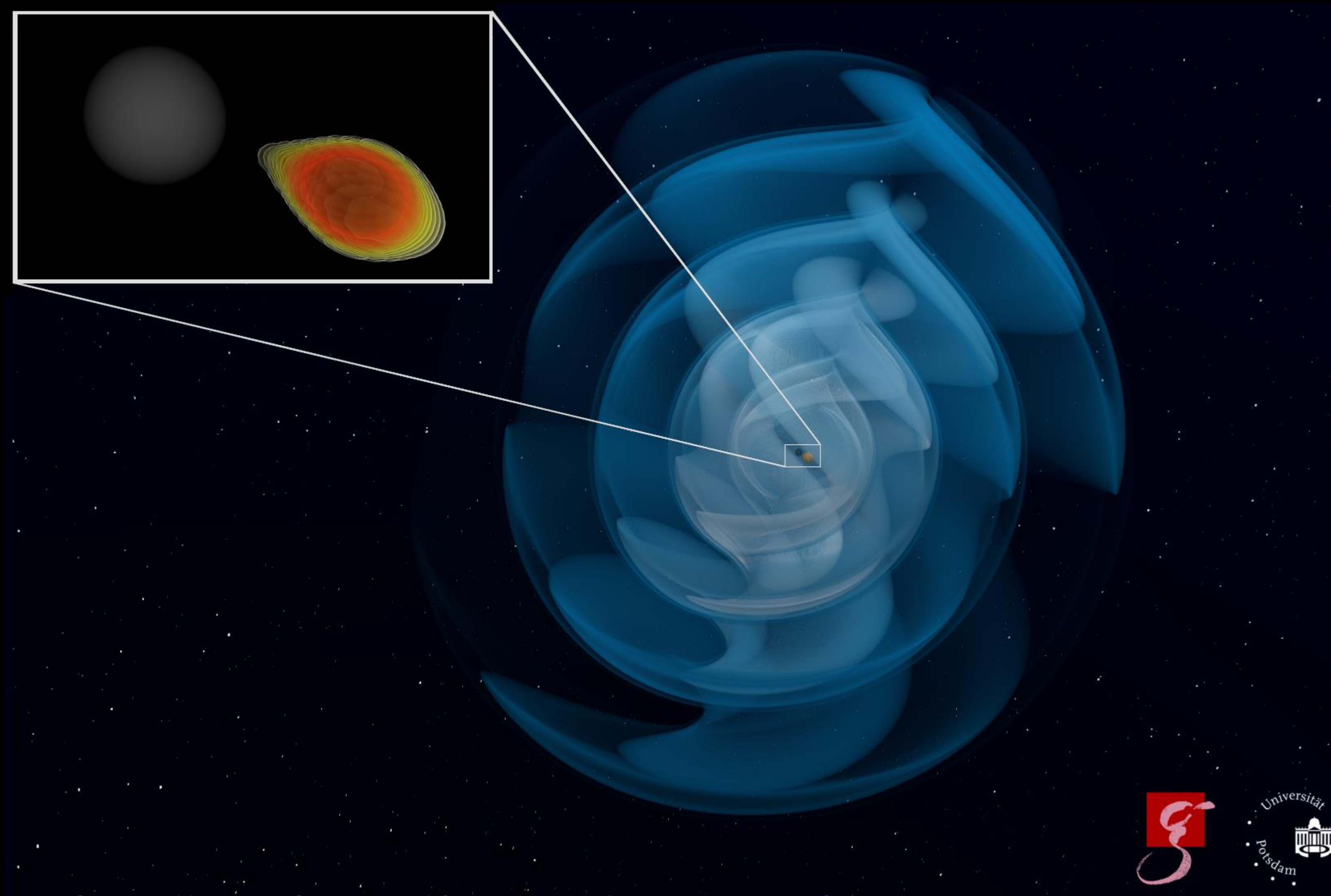
- Hierarchical mergers are more probable in Mirror World and merger rates of upper mass gap systems (GW190521 & GW190426_190642) would agree better even with less strict assumptions.

- 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 could 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 10 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