Gravitational Waves from Mirror World

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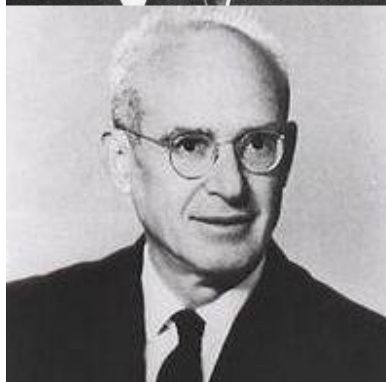
Theory of GWs

Gravitational Waves (**GW**) is considered to be the fluctuations in space-time curvature that propagate through the Universe. The main stages in development of the **GW** theory are:

- In **1916 Albert Einstein** claimed that gravitational waves were an inevitable consequence of the linearized General Relativity.
- In **1936 Einstein**, together with **Nathan Rosen**, derived the opposite result and submitted the paper "*Do gravitational waves exist?*" to ***Physical Review***.
- On semi-centennial conference in **Bern** (**1955**) **Rosen** showed that the energy-momentum pseudo-tensor for **Einstein-Rosen** waves is vanishing.
- On **Chapel Hill** conference in **1956 Richard Feynman** proposed "sticky-bead" experiment to show that gravitational waves carry energy.


Linear GWs are Unobservable

It is assumed that gravitational waves of distant sources can be described by linearized General Relativity. In the linear approximation, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, **Einstein**'s equations can be represented by the system:

$$\Box\left(h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h\right) = -\frac{16\pi G}{c^4}T_{\mu\nu}, \qquad \partial^{\mu}\left(h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h\right) = 0\,.$$

If we use expansion similar to electromagnetic or **Newtonian** cases, $h_{ij} \leftrightarrow \eta_{ij}\,\varphi$, for the propagating field we find:

$$h_{ij} \approx -\frac{G}{2c^4 r}\frac{d^2}{dt^2}\left(I_{ij} - \frac{1}{3}\delta_{ij}I\right), \qquad I_{ij} = \int \rho\, x_i x_j dV\,.$$

There is fundamental difference between electromagnetic and gravitational waves. The linearity of electrodynamics restricts the current to be conserved, but has no implications for $T_{\mu\nu}$, because it does not enter **Maxwell** equations.

On the other hand, $T_{\mu\nu}$ is the source of **Einstein**'s equations and in the linear approximation it is strictly conserved. Thus a mechanical system cannot lose energy in the form of linear gravitational waves. The quadrupole radiation formula gives a correct answer, but the energy and momentum are transported away not by linear, but by non-linear waves.

Second-Order Perturbations

To the weak field limit we keep terms which are linear in the metric perturbations $h_{\alpha\beta}^{(1)}$. However, in order to keep track of the energy carried by the **GW**s, we will have to extend our calculations to at least second order,

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}^{(1)} + h_{\alpha\beta}^{(2)} .$$

The second-order version of free **Einstein**'s equations consists of all terms either quadratic in $h_{\alpha\beta}^{(1)}$ or linear in $h_{\alpha\beta}^{(2)}$,

$$G_{\alpha\beta}^{(1)}(\eta + h^{(2)}) + G_{\alpha\beta}^{(2)}(\eta + h^{(1)}) = G_{\alpha\beta}^{(1)}(\eta + h^{(2)}) - 8\pi G t_{\alpha\beta} = 0 .$$

The terms quadratic in $h_{\alpha\beta}^{(1)}$ are assumed to form an energy-momentum tensor for the gravitational field (at least in the weak field regime),

$$t_{\alpha\beta} = - G_{\alpha\beta}^{(2)}(\eta + h^{(1)}) /8\pi G ,$$

as in usual field theory where the energy-momentum tensors are quadratic in fields. Also the **Bianchi** identity implies that $t_{\alpha\beta}$ is conserved in the flat space.

However, there are some inconsistencies:

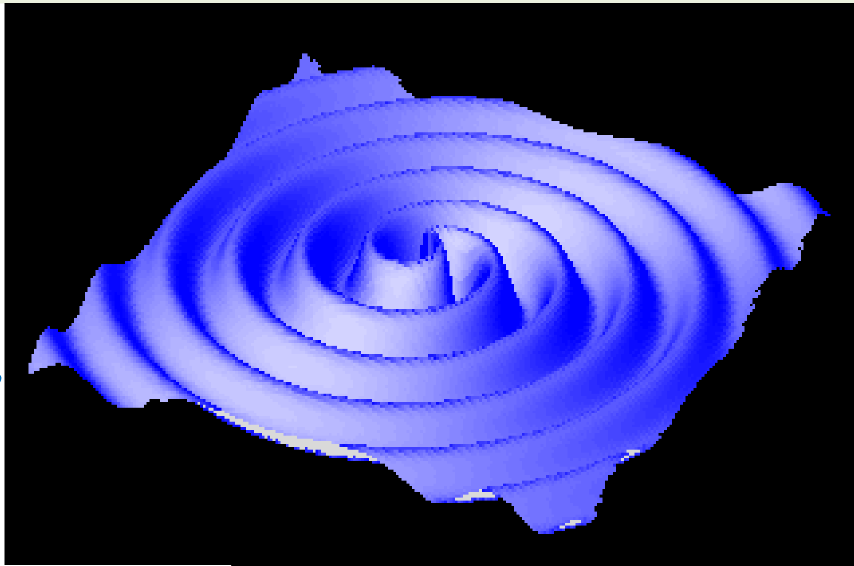
1). $t_{\alpha\beta}$ is a pseudo-tensor and it is not invariant under gauge transformations;

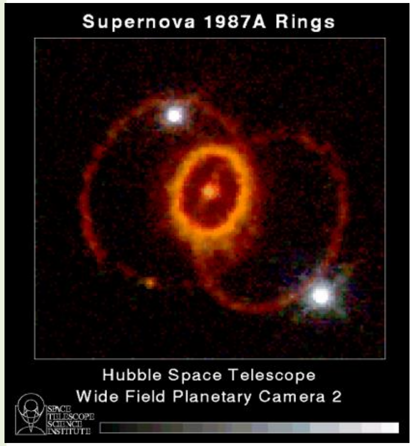
2). It is assume that test particles move along geodesics in **Minkowski** space.

Then the total energy on a surface of constant time $\int t_{00} d^3x$ and the total energy radiated through it $\int t_{0\alpha} n^\alpha d^2x dt$, which are invariant under special gauge transformations that vanish sufficiently rapidly at infinity, are constructed.

What Might Make GWs

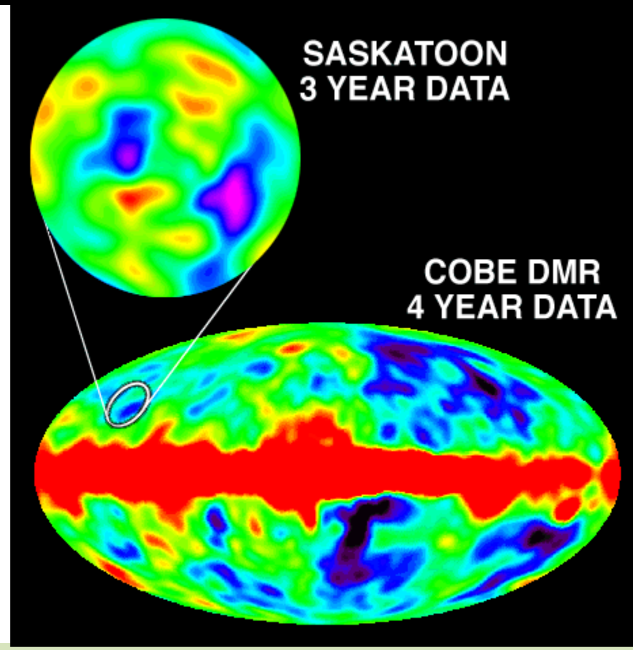
Compact binary inspiral: *"chirps"*

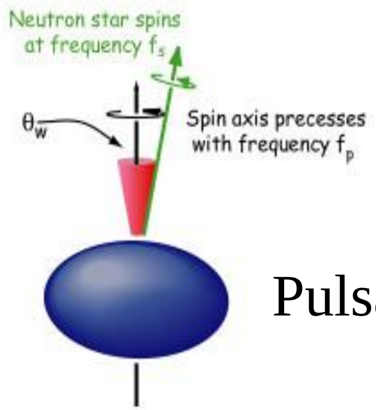




Supernovae: *"bursts"*

Cosmological Signal: *"stochastic background"*





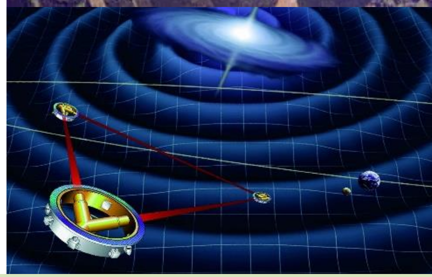
Pulsars in our galaxy: *"periodic"*

GWs Detection Efforts

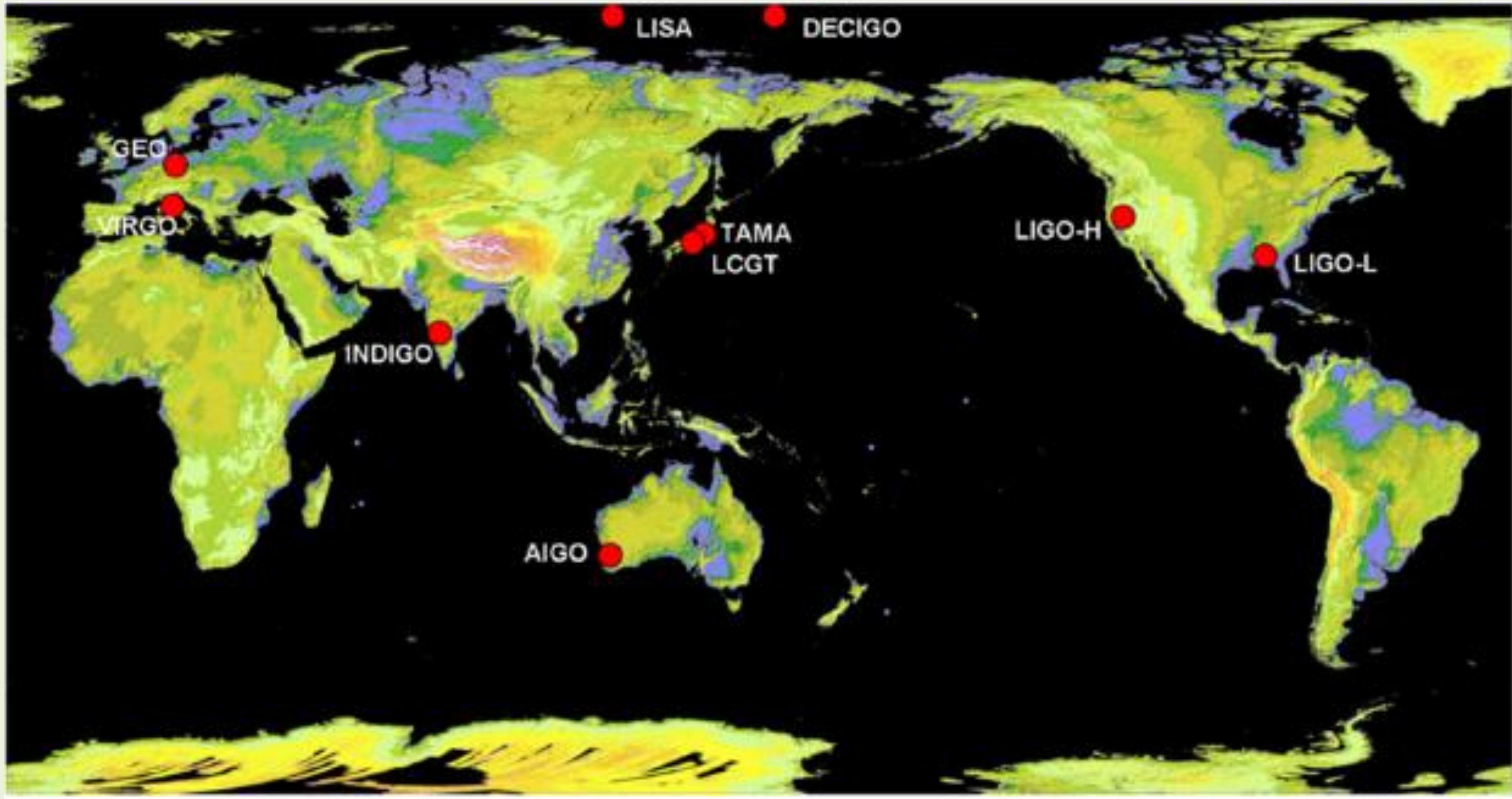
The main stages in the **GW** detection are:

- First attempts were made in the **1960**s by **Weber** by means of aluminum resonant bar detectors.
- In **1963** **Gertsenshtein** and **Pustovoit** suggested to use **Michelson-Morley** type interferometers.
- In **1974** **Taylor** and **Hulse** detected binary pulsar system **PSR B1913+16**. Later, some more relativistic binary pulsars were discovered. Orbital period decay in all cases is consistent with the energy loss predicted by General Relativity. **Nobel** Prize for Physics in **1993** for the first observational evidence for **GW**.
- On **11** February **2016**, the **LIGO/Virgo** collaboration announced the first direct observation of **GW**s in September **2015**. The **2017** **Nobel** Prize in Physics - **Barish**, **Thorne** and **Weiss**.
- The space missions: **LISA** (**ESA**, launch in **2034**?) and **DECIGO** (Japan, launch in **2027**?) were proposed.



Network of Interferometers



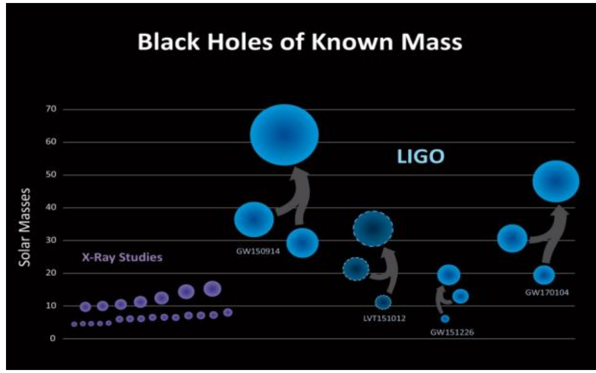
Ground based detectors: **LIGO** (USA), **VIRGO** (Italy), **GEO** (Germany), **TAMA, KAGRA** (Japan), **INDIGO** (India), **AIGO** (Australia).

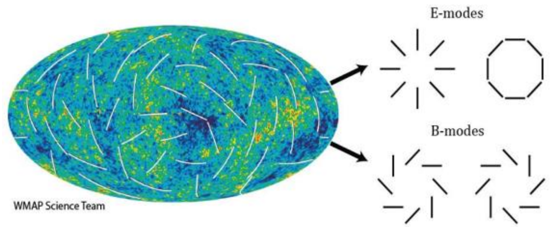
Space-based detectors (proposed): **LISA** (ESA), **DECIGO** (Japan).

Detection Confidence; Location of Sources; Polarization Decomposition

Present Situation

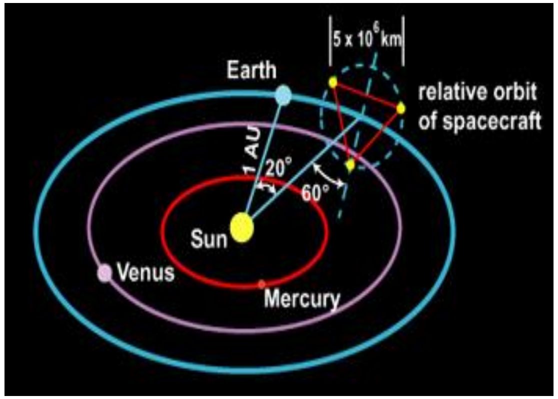
Intensive efforts to find burst, binary coalescence, continuous wave, stochastic **GWs** in coincidence with **EM** and neutrino signals;



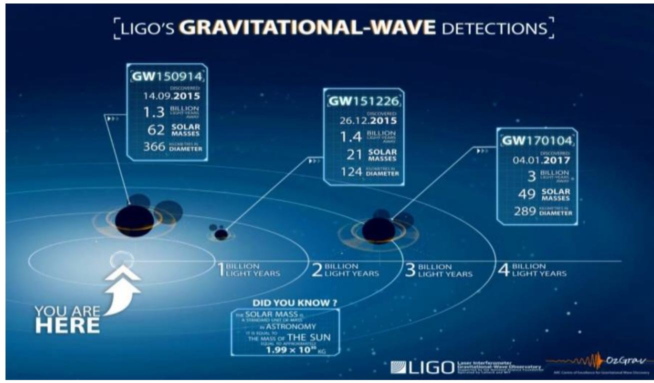


Stochastic background of relict **GWs** could be observed in a few years;

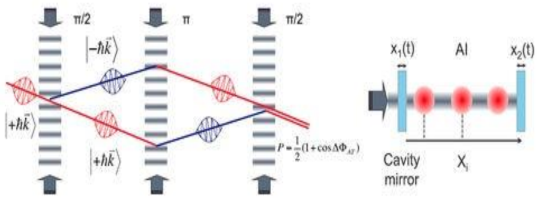
The universe has more stellar mass **BHs** than expected;



LISA (ESA): three Interferometers **2.5×10^6 km** arm lengths. Planned launch **2034** (earlier launch **2028**?);

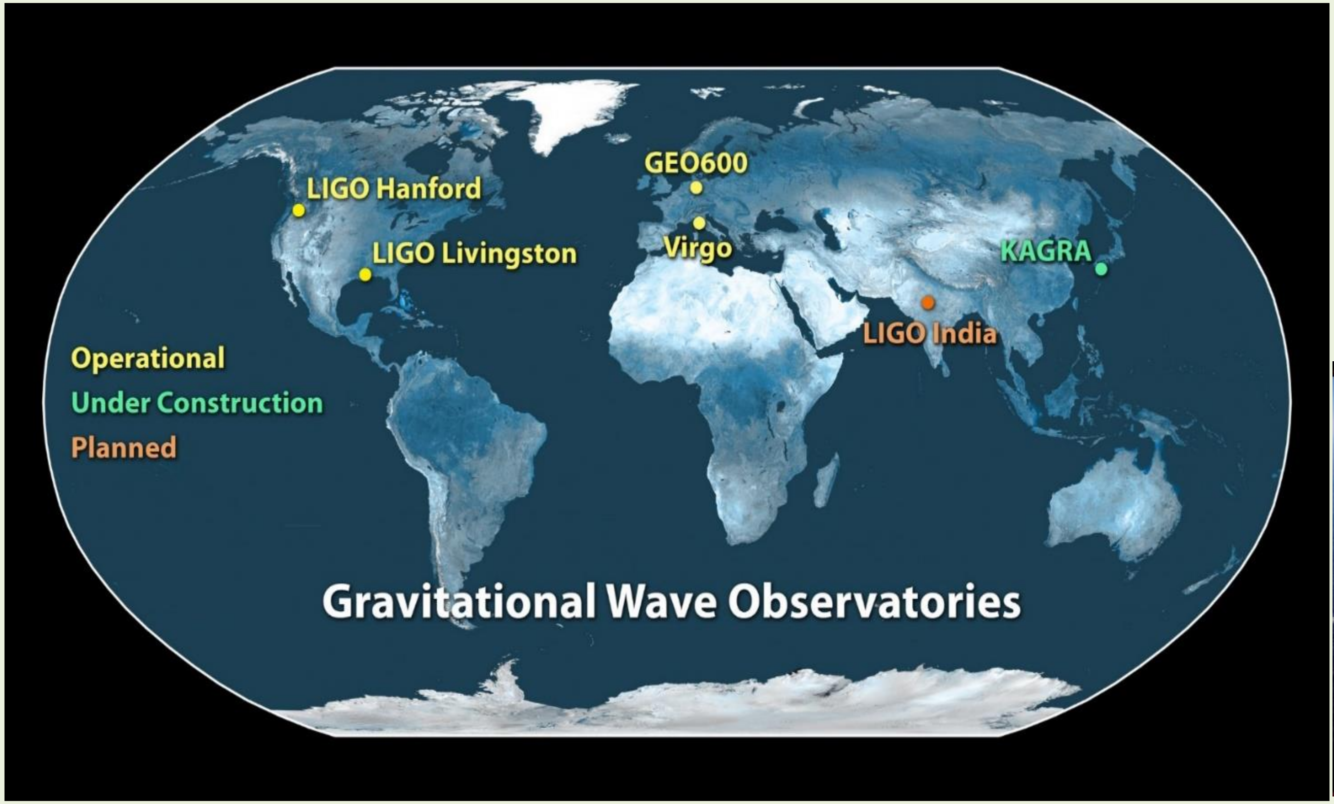


Virgo joined in August **2017**; **LIGO 3rd** run began on April **2019** and is planned to last 1 year; **KAGRA** will join this year after the present commissioning phase.



3rd generation detectors: **Einstein Telescope** (EU) and **Cosmic Explorer** (US), with atom interferometers in **0.1–10 Hz** (between **LISA** and **LIGO-Virgo**).

LIGO Observatory



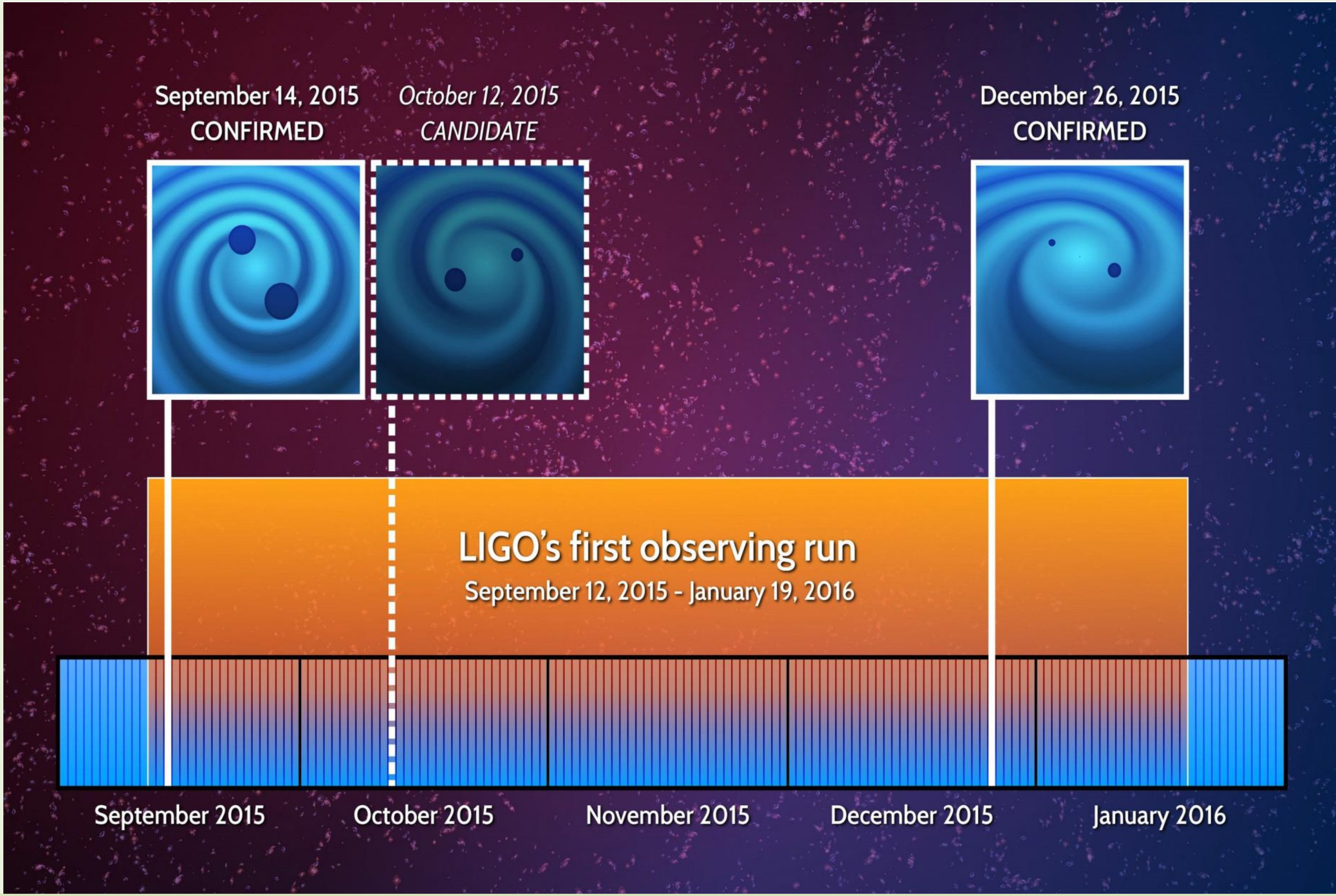
L I G O - GW detectors in **Hanford** and **Livingston, 4 km** tunnels separated by **3000 km.** **V I R G O** - GW detector in **Cascina, Italy**.

First and second observing runs detected: **1** event from Binary Neutron Star (**BNS**) merger. **10** events from Binary Black Hole (**BBH**) mergers.

BNS merger was accompanied by Gamma-Ray Burst.

BBH mergers had no counterpart electromagnetic radiation.

LIGO First-Run Events



Ongoing Observing Run 3

O3 began on **1st April 2019**, commissioning break during **1-30 October 2019**, will end about **31 April 2020**. So far it detected about 30 candidate events; Among the candidate events are the first ever Black Hole - Neutron Star (**BH-NS**) binary systems and several other possible **BNS** mergers.

BNS merger must always be accompanied by Gamma-Ray Bursts;

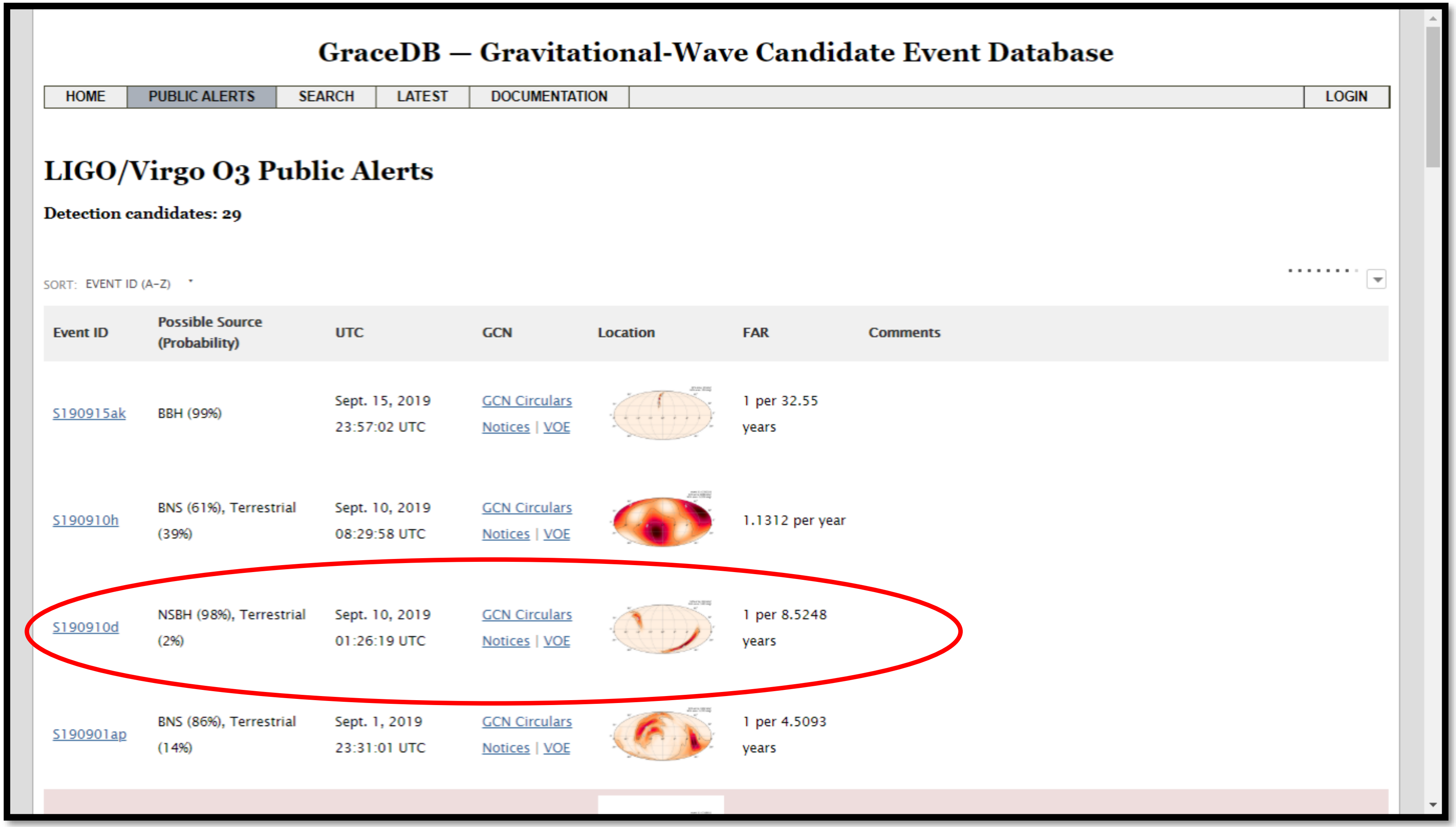
BH-NS mergers in many configurations should emit EM-radiation;

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190915ak	BBH (99%)	Sept. 15, 2019 23:57:02 UTC	GCN Circulars Notices | VOE		1 per 32.55 years	
S190910h	BNS (61%), Terrestrial (39%)	Sept. 10, 2019 08:29:58 UTC	GCN Circulars Notices | VOE		1.1312 per year	
S190910d	NSBH (98%), Terrestrial (2%)	Sept. 10, 2019 01:26:19 UTC	GCN Circulars Notices | VOE		1 per 8.5248 years	
S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years	

No sign of accompanied EM-radiation have been reported yet!

https://gracedb.ligo.org/superevents/public/O3/

NS-BH Candidate Events (O3)



GraceDB — Gravitational-Wave Candidate Event Database

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LIGO/Virgo O3 Public Alerts

Detection candidates: 29

SORT: EVENT ID (A-Z)

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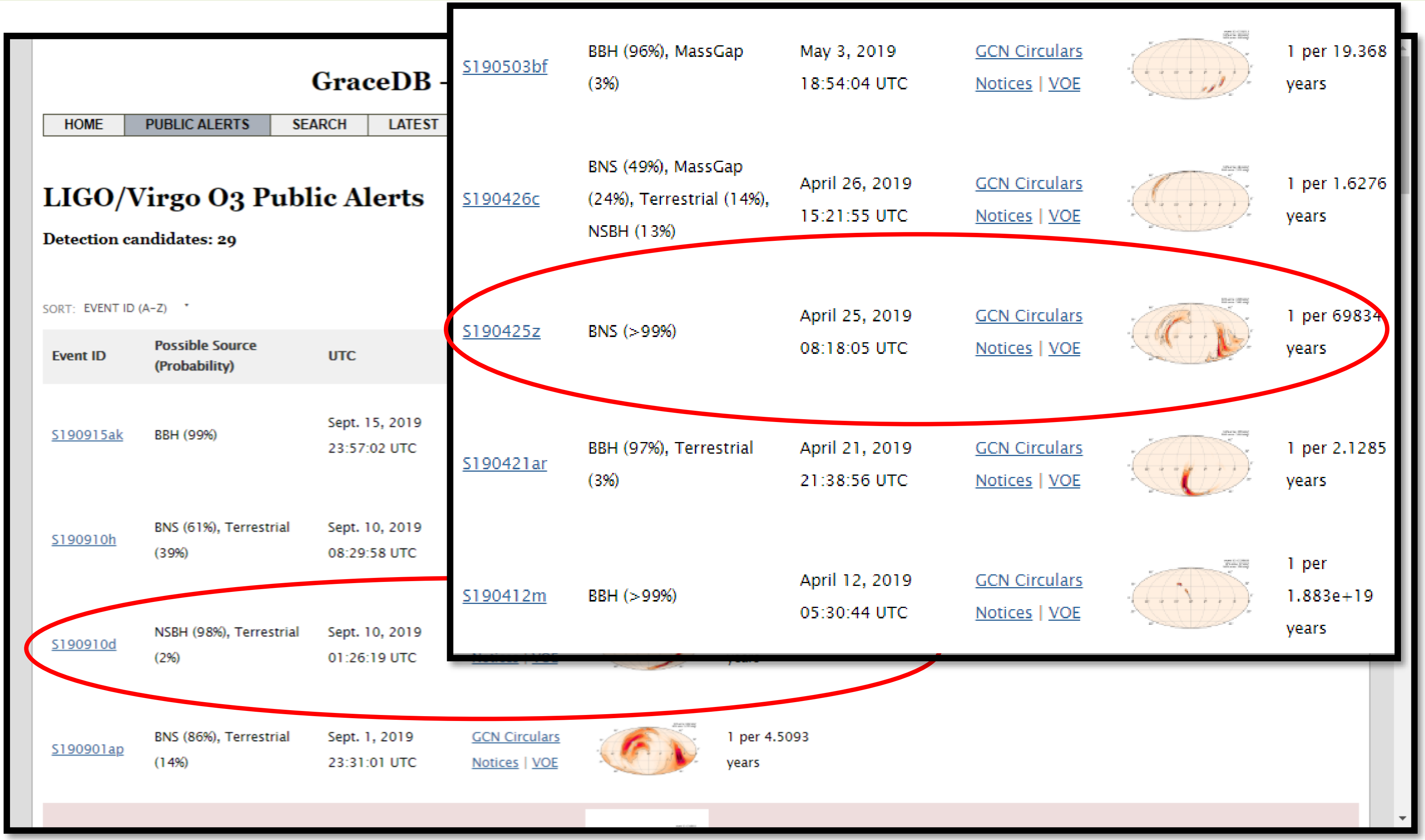
https://gracedb.ligo.org/superevents/public/O3/

BNS Candidate Events (O3)



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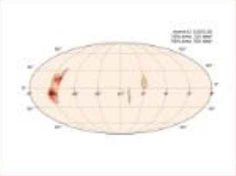
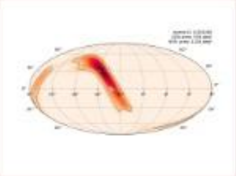
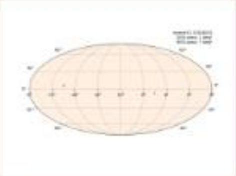
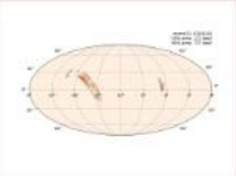
S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years

S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years
S190412m	BBH (>99%)	April 12, 2019 05:30:44 UTC	GCN Circulars Notices | VOE		1 per 1.883e+19 years

https://gracedb.ligo.org/superevents/public/O3/

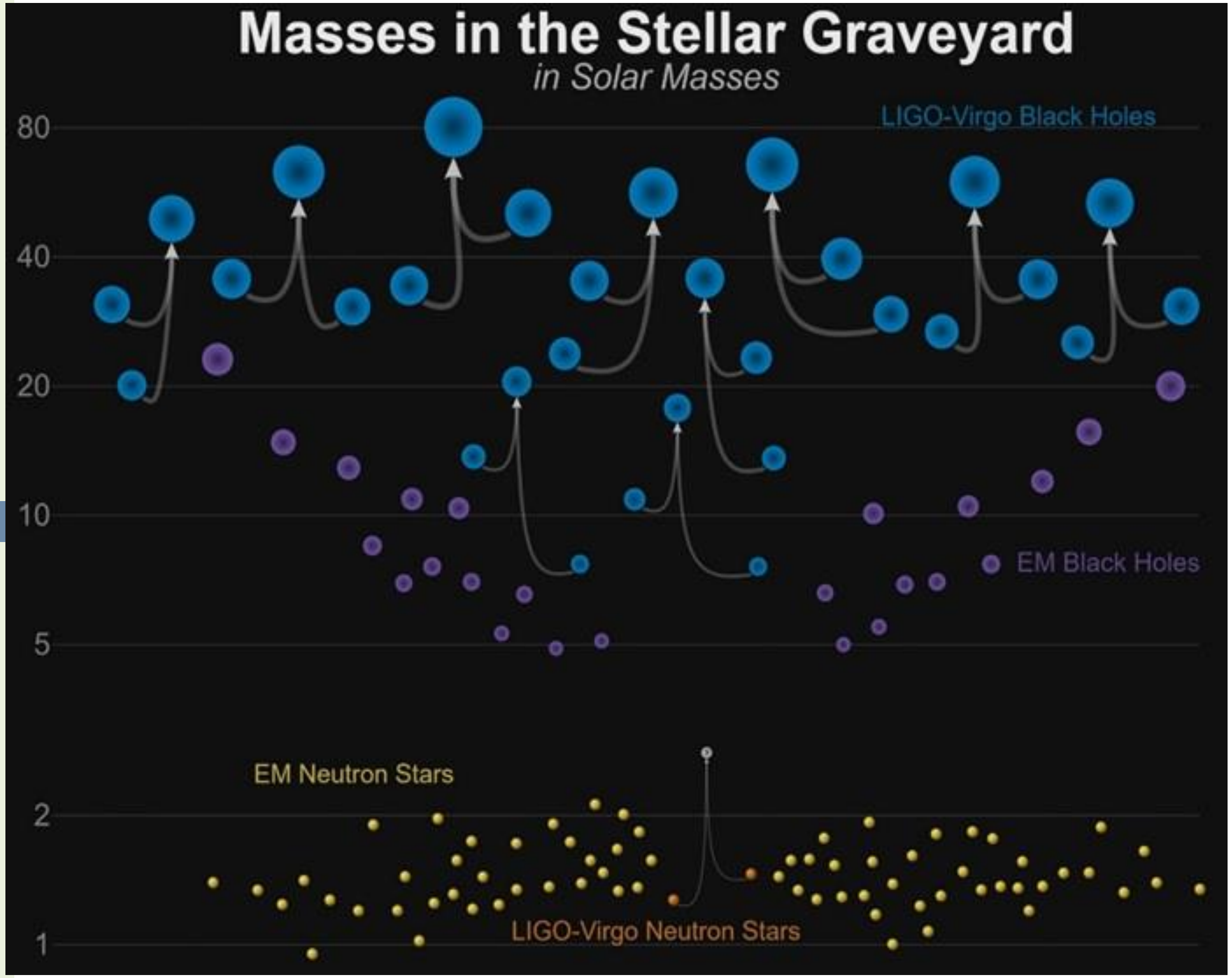
Retracted Events

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S191120at	MassGap (83%), Terrestrial (17%)	Nov. 20, 2019 20:08:37 UTC	GCN Circulars Notices | VOE		1 per 5.1871 years	RETRACTED
S191120aj	NSBH (61%), Terrestrial (39%)	Nov. 20, 2019 16:23:34 UTC	GCN Circulars Notices | VOE		1 per 1.1079 years	RETRACTED
S191117j	NSBH (>99%)	Nov. 17, 2019 06:08:22 UTC	GCN Circulars Notices | VOE		1 per 2.8433e+10 years	RETRACTED
S191110af		Nov. 10, 2019 23:06:44 UTC	GCN Circulars Notices | VOE	No public skymap image found.	1 per 12.681 years	RETRACTED
S191110x	MassGap (>99%)	Nov. 10, 2019 18:08:42 UTC	GCN Circulars Notices | VOE		1 per 1081.7 years	RETRACTED

All five November LIGO/VIRGO events have been retracted.

https://gracedb.ligo.org/superevents/public/O3/

Masses of Mergers



GW170729

Most massive, most distant

$M_{\rm total} = 85.1^{+15.6}_{-10.9}\ M_\odot$

$l_{\rm Lum} = 2750^{+1350}_{-1320}$ Mpc

LIGO discoveries confirm that: Massive ($\gtrsim 25 M_\odot$) BHs exist, they create binary systems and merge within Hubble time.

Merger rate: $\mathcal{R}_{\rm LIGO} = 9.7 - 101\ {\rm Gpc}^{-3}{\rm yr}^{-1}$

BBH Creation Mechanism

1. **Primordial Black Holes** *(Sasaki, Suyama, Tanaka & Yokoyama 2018)*

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

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

Main formation mechanisms predict low binary merging rates:

$$\mathcal{R}_{\text{theor}} \sim 5 - 10 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad < \mathcal{R}_{\text{LIGO}}$$

Theoretical BBH Merger Rate

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

$\epsilon \simeq 0.01 - 0.001$ - Efficiency coefficient

$P(\tau)$ - Delay time distribution

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

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

$\phi(m)$ - Galactic mass function

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

$f(Z,m)$ - Initial mass function

$\xi(M)$ - Metallicity distribution function

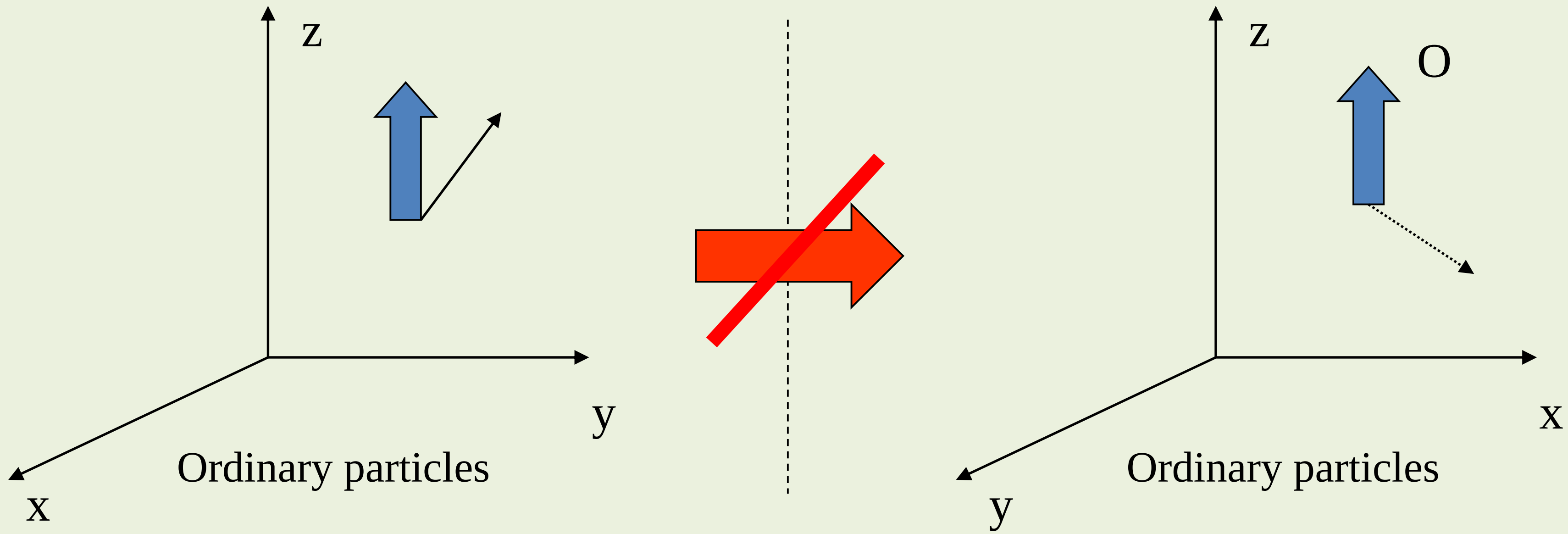
Star formation rate: *(Madau & Dickinson 2014)*

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

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

P-violation

Lee *and* ***Yang*** ***(1956)***

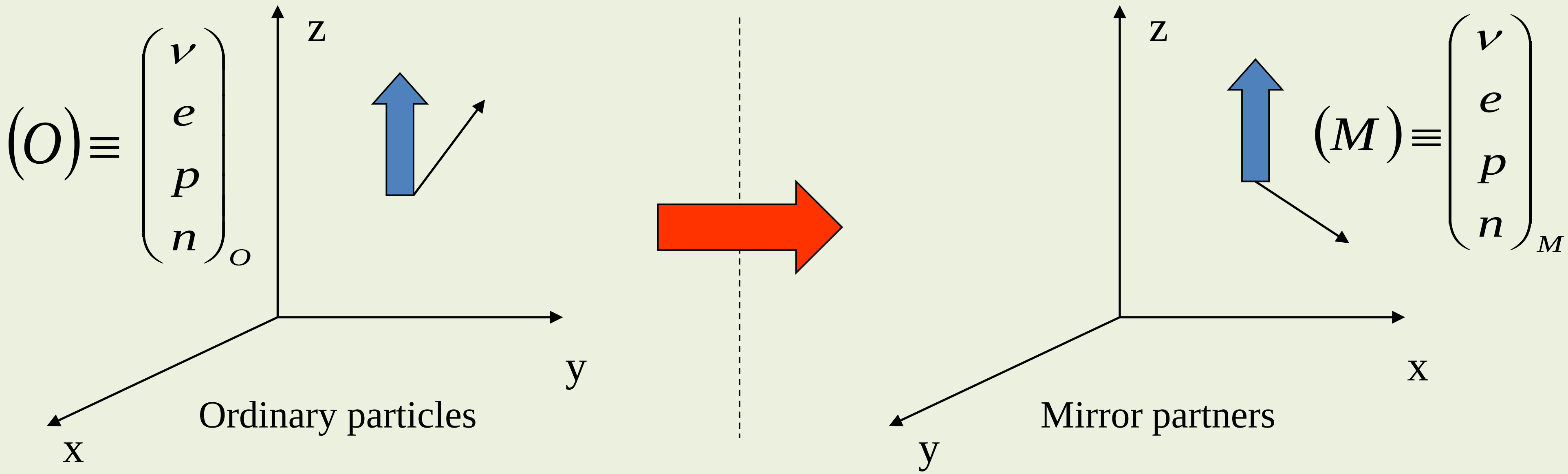


Parity (**P**) violation means non-equivalence of **Left**- and **Right**-handed coordinate systems. To restore the symmetry reflection should be generalized. Together with **P**-transformations, particles should be changed by their mirror partners.

Lee, **Landau**,… (**1957**) offered an economic solution: **CP**-invariance assumes that antiparticles play the role of mirror partners. Discovery of **CP**-violation in **1964** put again the question of proper choice for the set of mirror partners.

Mirror Particles!

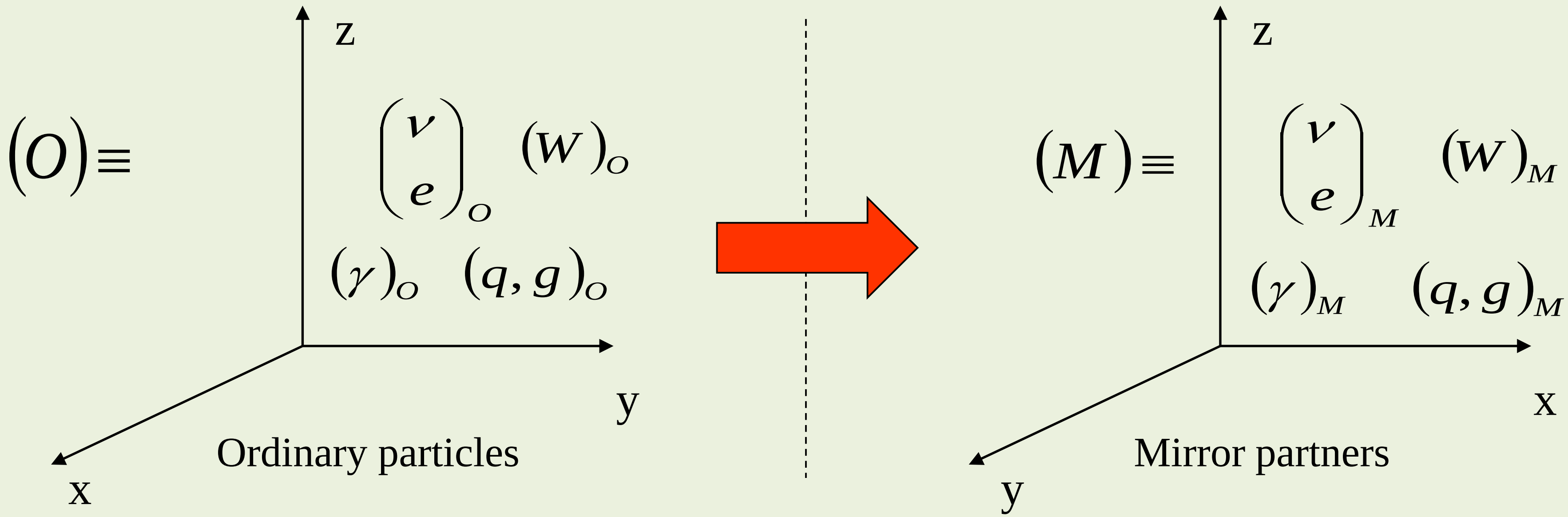
Kobzarev, Okun, Pomeranchuk (1966)



The equivalence between **Left**- and **Right**-handed coordinate systems is restored if reflection in mirror is accompanied by change of ordinary particles by their mirror partners. Mirror partners are strictly symmetric to ordinary particles. Therefore they can not have ordinary electromagnetic and strong interactions (doubling of atomic levels, or pion states). Successive analysis have shown that (***O***) and (***M***) also can not share ***W*** and ***Z*** boson mediated weak interaction.

Mirror World

Blinnikov, Khlopov (1980,1982,1984)



Mirror matter, also called **Shadow matter** or **Alice matter**, is a hypothetical counterpart to ordinary matter. One needs to suppose that there is no (or very weak) common interaction between ordinary particles and their mirror partners, except of gravity. It was assumed that all initial conditions and masses and coupling constants of mirror particles were strictly symmetric to ordinary ones.

Mirror Objects in Galaxy

- Strict symmetry in physics should result in symmetry in forms of astronomical objects of mirror matter and their evolution. There should be mirror stars, planets and interstellar gas of mirror matter.
- Mirror stars in halo can play the role of **MACHO**s and observed by effect of microlensing.
- Mirror gas can be accreted by ordinary stars and ordinary gas can be accreted by mirror stars.
- Mirror gas accreted by Sun can form a mirror planet inside the Sun, giving rise to Solar surface oscillations with $T = 160$ min.
- Ordinary gas, accreted by mirror **NS** and **BH**s can form a dense visible core giving rise to more rapid time variations than in ordinary **NS**s and **BH**s.
- Galactic disc should contain equal amount of ordinary and mirror stars.

Local Dark Matter

- In vicinity of Solar system the density should be two times larger due to invisible mirror stars and gas:

$$\rho_{dyn} \geq 2\rho_{vis}$$

- However, observations give

$$\rho_{dyn} = 0.098 \pm 0.011 \frac{M_{Sun}}{pc^3}$$

$$\rho_{vis} = 0.095 \frac{M_{Sun}}{pc^3}$$

- Such increase of local density can not be due to **Collisionless Dark Matter**, and evidences for it could be considered as favoring mirror matter.

Asymmetric Initial Conditions

Problems of strictly symmetrical astrophysics of mirror matter can be avoided, if initial cosmological conditions were different for ordinary and mirror matter (***Berezhiani 1996***).

- If temperature of mirror matter after reheating of Universe was few times smaller than for ordinary matter, symmetric mechanism of baryogenesis should lead to mirror baryon excess, larger than for ordinary matter;
- Smaller temperature of relativistic mirror species in the period of **BBN** reduces their unwanted influence on ***He*** abundance;
- Larger mirror baryon excess can provide mirror baryonic matter as the dominant form of **Dark Matter**.

However, constraints on **MACHO**s and on **Local Dark Matter** put forward a question about the dominant form of mirror baryons in the Galaxy.

Shadow World

- Asymmetry in physics of ordinary and mirror matter, e.g. by a scale factor in masses (***Mohapatra, Senjanovich***), **Okun**'s **y**-matter, **248** fundamental particles and **248** fundamental interactions of E_8' symmetry in $E_8' \otimes E_6$ **GUT** model of $E_8' \otimes E_8$ **Heterotic String** give examples of **Shadow World**.
- As shadow deforms an image of the original. Properties of shadow particles and their interactions may strongly differ from the ones of the ordinary matter, even if **Shadow World** results from breaking of initially strict mirror symmetry.
- Qualitative features of **Shadow World** can be analyzed with the use of methods of **Cosmo-Archeology**, while quantitative description of the Universe with shadow matter is strongly model dependent. This model dependence provides good example of relationship between cosmological scenarios and particle models, on which these scenarios are based.

Mirror World Summary

- Each **Standard Model** particle has its **Mirror Partner** with opposite chirality;
- **O**rdinary and **M**irror particles interact only by gravity;
- Mirror World also was created by **Big Bang**, but possibly with lower reheating temperature;
- Helium abundance in Mirror World is higher: *He* - 40-80 %
- Constraint from **Big Bang Nucleosynthesis**: $x \equiv \frac{T'}{T} < 0.64$
- Certain **Leptogenesis** mechanism naturally gives: $1 \leq \frac{n'_b}{n_b} \lesssim 10$
- Mirror World can explain all **Dark Matter**: $\frac{\Omega'_b}{\Omega_b} \approx 5$
- Stars in Mirror World are more massive and evolve faster.

*For the review of **Mirror World** see Berezhiani 2005*

GWs from Mirror World

GWs from **BBH**s has no counterpart electro-magnetic radiation, so they may have existed in **Mirror World**, where:

- Star formation peaks at **z = 9.3** ($t_{\text{lookback}} \sim 13.3$ Gyr), so:

$$\mathrm{SFR}'(z) \sim 1.3 \times \mathrm{SFR}(z)$$

- Due to ***He*** abundance initial mass function is higher:

$$\mathrm{IMF}' \sim 1.5 \times \mathrm{IMF}$$

- Number of stars is larger:

$$N'(m) \sim 5 \times N(m)$$

- Number of **BH**s is larger:

$$N'_{\mathrm{BH}} \sim 10 \times N_{\mathrm{BH}}$$

Merging Rate of binaries in **Mirror World**:

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

coincides with **LIGO**'s upper bound.

GRBs from BNS and BH-NS

While the **BBH** mergers without electromagnetic counterparts can be explained assuming that their progenitor stars composed isolated binaries **BNS** mergers is believed to be accompanied by **sGRB**s, which are detected at the rate

$$\mathcal{R}_{sGRB} = 1109^{+1432}_{-657}\ Gpc^{-3} yr^{-1}.$$

BNS and **BH-NS** merging rates can be estimated also using **LIGO** signals:

$$\mathcal{R}^{BNS}_{LIGO} = 110 - 3840\ Gpc^{-3}\ yr^{-1}, \qquad \mathcal{R}^{BH-NS}_{LIGO} < 610\ Gpc^{-3}\ yr^{-1}.$$

Detectability of **sGRB**s depends on the orientation of jets. In several models half-opening angle is $\theta = (16 \pm 10)^0$. This increases multi-messenger event rate, since the mergers occur very far and Earth will always fall in the jet angle.

Several **BNS** and **BH-NS** candidate events have been detected during **O3**. However, still no electromagnetic counterparts has been reported.

In **Mirror World** we can expect about **10** times more **BNS** and **BH-NS** systems. The uncertainties of calculated merging rates are large. However, in our scenario we can predict with a confidence that most of the detected **GW** events will not have electromagnetic counterparts.

We predict:

Order of **10** larger merger rates of **BBH**, **BNS** and **BH-NS** systems and only **1** of the **10 LIGO/VIRGO BNS** event may have **EM**-counterpart.

Conclusions:

Merger Rates of binaries observed by **LIGO/VIRGO** gravitational wave detectors exceed numbers predicted by majority of models, also none of the events (except one) was accompanied by another type of radiation. We suggest that major these signals emerged from **Mirror World** where:

- Number of binary systems is higher, since **Mirror Matter** is a candidate of **Dark Matter** having higher density;
- **Binary Merger Rate** is amplified, since mirror world is considered to be colder and star formation there started earlier;
- Non-detection of electro-magnetic radiation is natural, because mirror particles **do not** interact with ordinary particles;

We predict about **10×**larger Merger Rates for **LIGO/VIRGO** systems and only 1 of 10 **Binary Neutron Stars** event may have electro-magnetic counterpart.

References:

1. "***Binary Neutron Star Mergers with Missing Electromagnetic Counterparts as Manifestations of Mirror World***", arXiv: 1910.04567 [astro-ph.HE];
2. "***Gravitational Waves from Mirror World***", **MDPI Physics 1** (2019) 67;
3. "***LIGO Signals from the Mirror World***", **Mon. Not. Roy. Astron. Soc. 487** (2019) 650.


Thank You
for Your Attention