# LIGO Signals from the Mirror World

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# Plan *of the* Talk

# 1. PARITY VIOLATION AND MIRROR PARTICLES

# Parity Violation

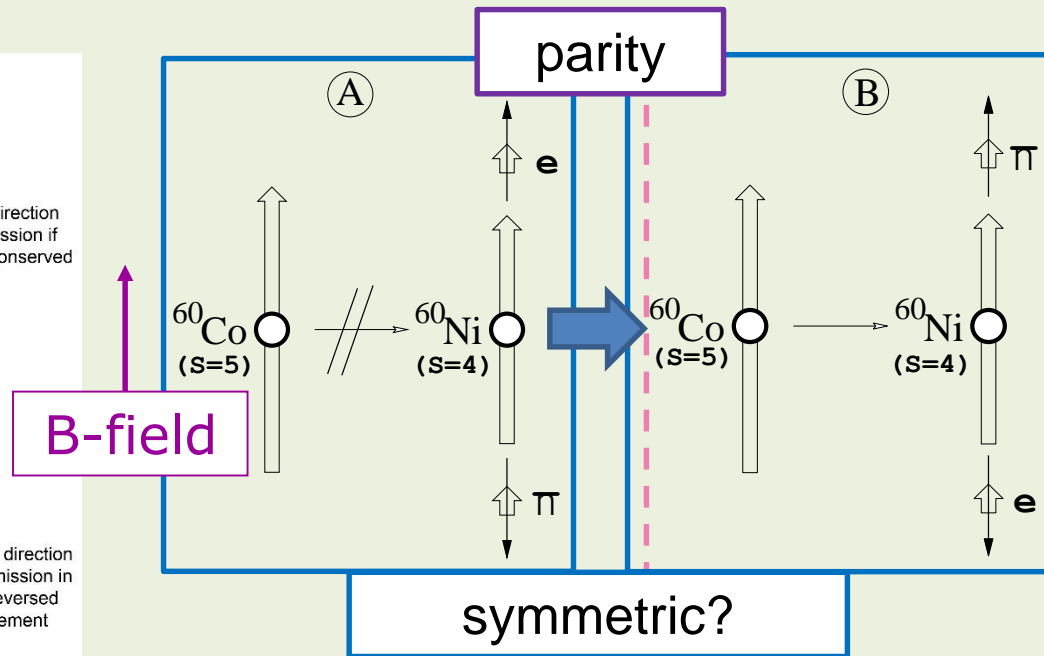$\tau-\theta$ **puzzle**: Two different decays were found for charged strange mesons:

$$\theta^+ \rightarrow \pi^+\pi^0 \qquad \text{parity} = +1$$
$$\tau^+ \rightarrow \pi^+\pi^+\pi^- \qquad \text{parity} = -1$$

Both reactions represent decay of the same particle, $K^+$, with violation of parity.



C.S. Wu

(1957)

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni = e^- + \bar{\nu}_e + 2\gamma$$

Mirror plane

Original arrangement

Mirror-reversed arrangement

Preferred direction of beta ray emision

Predicted direction of beta emission if parity were conserved

Cobalt-60 nuclei

Direction of electron flow through the solenoid coils

Observed direction of beta emission in mirror-reversed arrangement

parity

A

B

$^{60}Co$ (S=5)   $^{60}Ni$ (S=4)   $^{60}Co$ (S=5)   $^{60}Ni$ (S=4)

e

π

π

e

B-field

symmetric?

**"I cannot believe God is a weak left-hander"** Wolfgang Pauli

# *Mirror Asymmetry*



Nobel Prize 1957

**z** ... **y** ... **x** — Ordinary particles

**z** ... **x** ... **y** — Ordinary particles
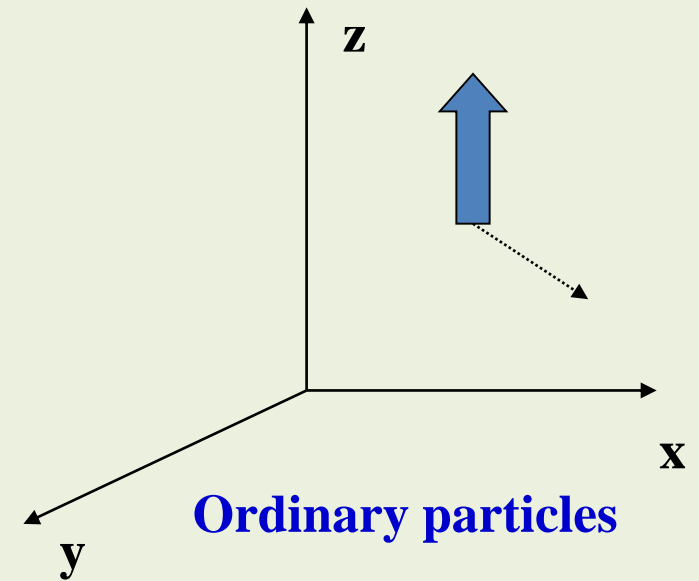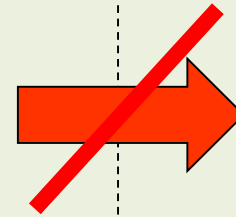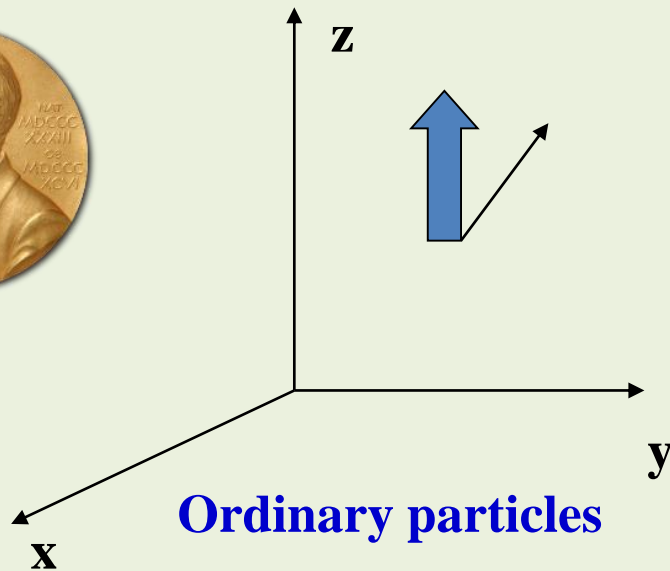
T.D. Lee

C.N. Yang

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*, *Yang* - *1956*).

# CP-violation and Mirror Symmetry

**Lee**, **Landau**,… (**1957**) an economic solution: **CP**-invariance assumes that antiparticles play the role of mirror partners. Then non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

**Dirac theory is symmetric under CP transformations!**
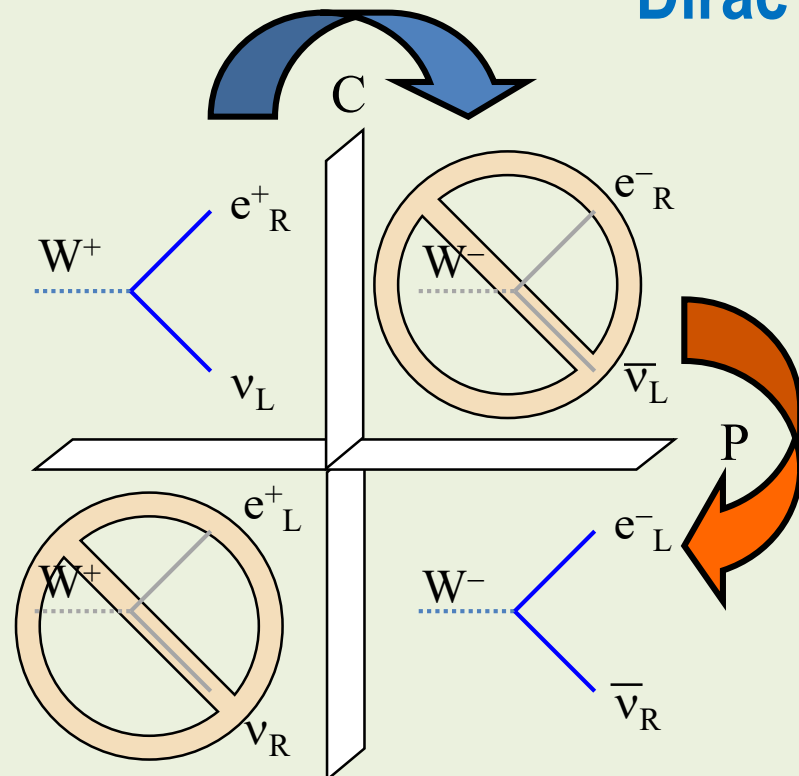


Discovery of **CP**-violation in certain types of weak decay (**1964**) put again the question of proper choice for the set of mirror partners.

# CP-transformations

**Black**

**Wight**

**C**

**P**

Anti-world

**CP**

**Left**

**Right**
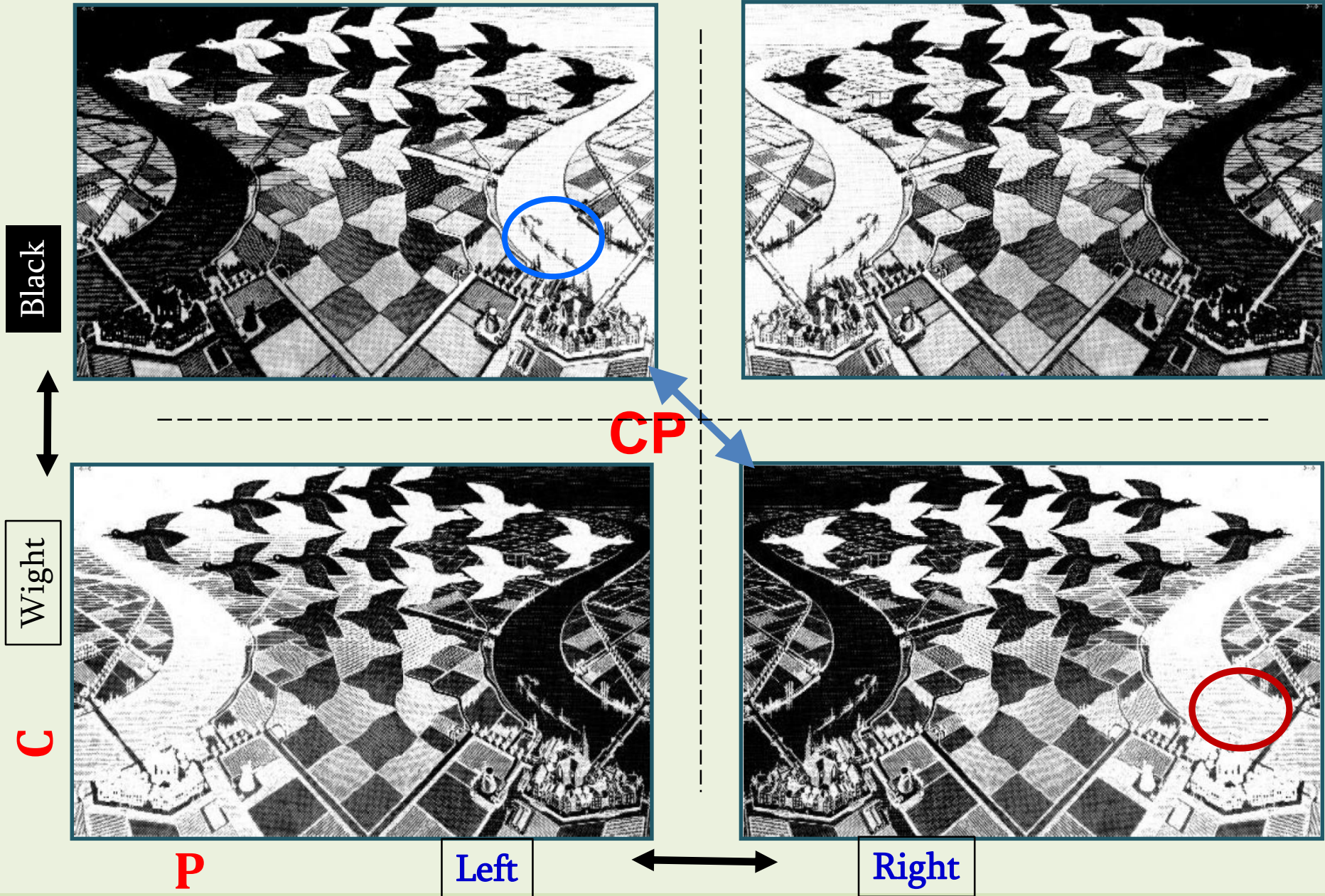
# Mirror Partners

*Kobzarev, Okun, Pomeranchuk (1966)*



$$(O) \equiv \begin{pmatrix} \nu \\ e \\ p \\ n \end{pmatrix}_O \qquad \qquad (M) \equiv \begin{pmatrix} \nu \\ e \\ p \\ n \end{pmatrix}_M$$

**Ordinary particles**          **Mirror partners**
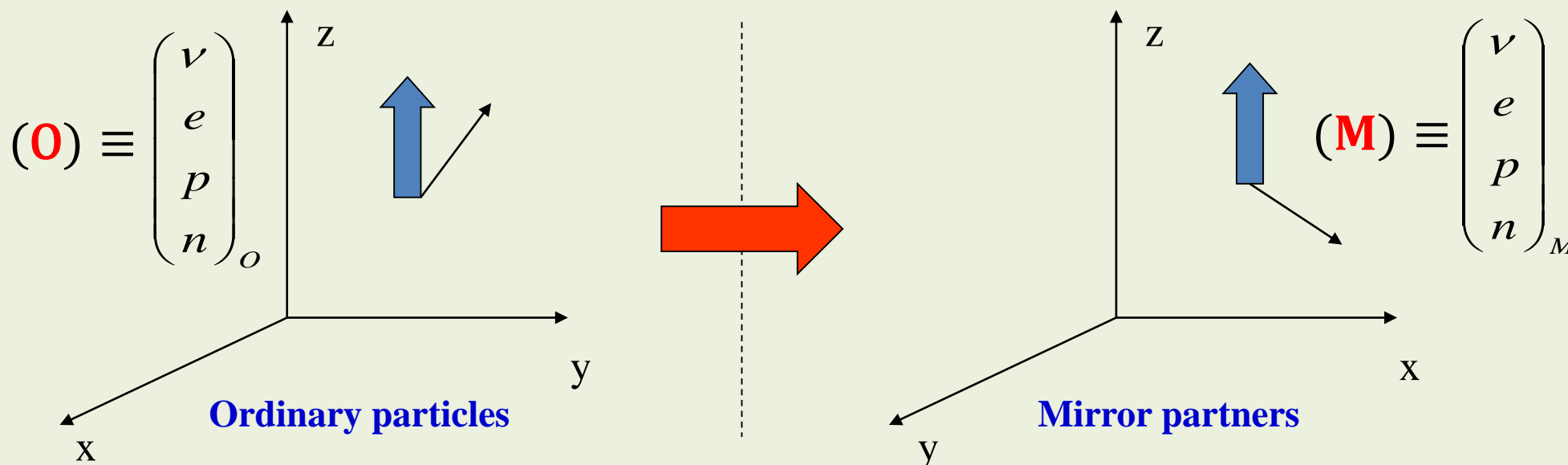
The equivalence between **L** and **R** systems is restored if a hidden mirror sector exists in which parity is violated in the opposite way and reflection is accompanied by change of ordinary particles by their mirror partners.

If mirror partners are strictly symmetric to ordinary particles and they can not have usual electromagnetic, weak and strong interactions (doubling of atomic levels, pion states, etc.).

# *Mirror World*

## *Blinnikov, Khlopov, Berezhiani (1980-90s)*

$$(O) \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_O \quad (W)_O \quad (\gamma)_O \quad (q,g)_O$$

$$(M) \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_M \quad (W)_M \quad (\gamma)_M \quad (q,g)_M$$

**Ordinary particles**

**Only L–handed**
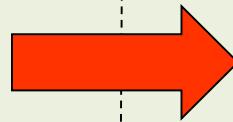
**Only R–handed**

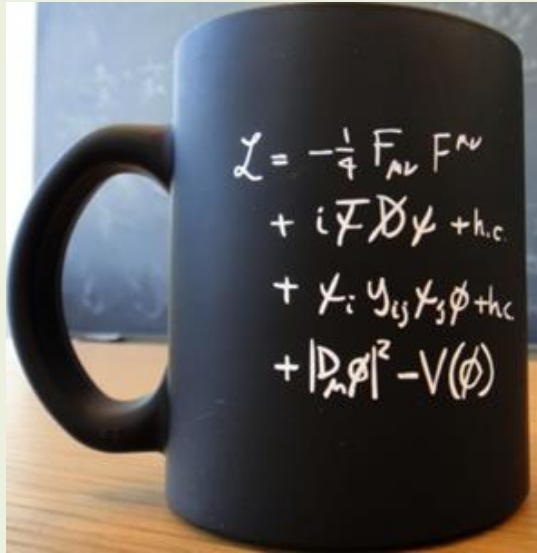**Mirror partners**



$$\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{F} \not{D} \psi + h.c. + \psi_i \, y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$
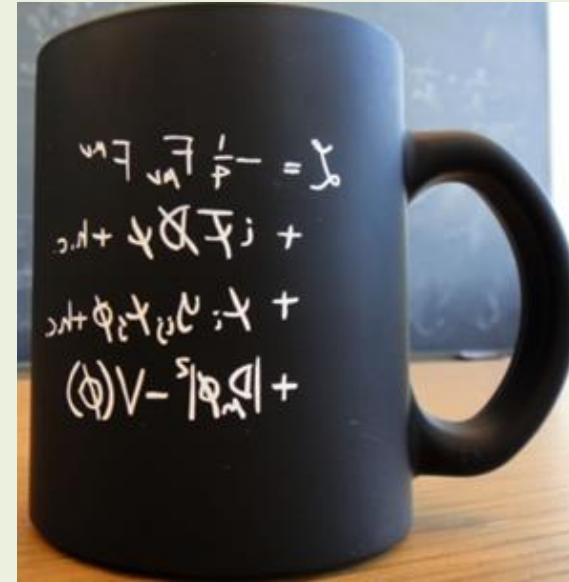
**Mirror matter**, also called **Shadow matter** or **Alice matter**, is a hypothetical counterpart to ordinary matter. One needs to suppose that there is no (or very weak) common interaction between ordinary particles and their mirror partners, except of gravity. Initially it was assumed that all initial conditions, masses and coupling constants of mirror particles were strictly symmetric to ordinary ones.

# *If our Universe = SM + SM'*

**Everything can be explained by SM, but there could be more than one SM!**

**L - R** symmetric                    **L - R** symmetric

**SM**                    **SM'**



$$G = G_{SM} \times G'_{SM} = [SU(3)_c \times SU(2)_L \times U(1)_Y] \times [SU(3)_c' \times SU(2)_R' \times U(1)_Y']$$

$L = L_{SM} + L'_{SM} + L_{int}$ is symmetric under parity exchange: $L_{SM} \leftrightarrow L'_{SM}$

The **Pati-Salam** model (the first **GUT - 1974**) is **L – R** symmetric. Predicts a high energy **R**-handed weak interactions with heavy **W'** and **Z'** bosons and **R**-neutrinos. **Gauge symmetry group:** $(SU(4) \times SU(2)_L \times SU(2)_R)/Z_2$
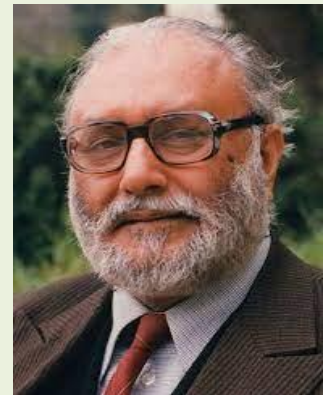
# *Motivations*

**Elegance suggests exact parity conservation** ➡ **MIRROR MATTER**

**Historic precedence:**   Lorentz invariance   ↔   antiparticles    ✓

                        Parity symmetry     ↔    mirror particles   **?**

**Mirror matter can explain several physical phenomena:**

*In astrophysics:*

- **MACHOs;**
- **Isolated planets and stars;**
- **Drag force on Pioneer 10, 11;**
- **Missing comets;**
- **Mirror bodies bombardment.**

*In particle physics:*

➢ **Higgs – mirror Higgs mixings;**

➢ **Neutrino sterile neutrino mixings;**

➢ **Photon-mirror photon kinetic mixing;**

➢ **Anomalous disappearance of neutrons.**

*In cosmology:*

- ❖ **Viable DM Candidate;**
- ❖ **High energy cosmic events.**

**Yin-Yang** **duality**

**(in Chinese, Dark-Bright)**



**Opposite forces are complementary, connected and interdependent**

# Shadow Particles

**Properties:**

- ➤ Feebly coupled to **SM** particles and have the same masses;
- ➤ Interact with each other with shadow (**SM'**) interactions;
- ➤ Stable, singlets under **SM**;
- ➤ Scarce at the scale of the solar system but could dominate on a larger scale.

**Can interact with us via:**

- ☐ Gravity;
- ☐ Mixing with ordinary particles in the neutral sectors.

**Problems:**

- ▪ Symmetric initial conditions ➡ equal $M$ and $O$ baryonic densities;
- ▪ Mirror particles double species in **BBN** ➡ **He** abundance **> 28%**.

**Solution:**

The temperature of the mirror sector is a few times smaller!

# 2. GRAVITATIONAL WAVES:
# THEORY AND DETECTION

# Theory of GWs

Gravitational Wave (**GW**) solution of linearized **Einstein** equations correspond to space-time fluctuations 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 (**1956**) **Richard Feynman** proposed a "sticky-bead" experiment to show that **GW**s carry energy.

# GWs Detection Efforts

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

- ❑ First attempts in **1960**s by **Weber** using aluminum resonant bar detectors;

- ❑ In **1963 Gertsenshtein** and **Pustovoit** suggested **Michelson-Morley** type interferometers;

- ❑ In **1974 Taylor** and **Hulse** detected the binary pulsar **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 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**;

- ❑ On **28** June **2023**, the **NANOGrav** collaboration announced evidence for a **GW stochastic background** using observational data from an array of millisecond pulsars.

- ❑ The space missions: **LISA** (**ESA**, to launch in **2037**?) and **DECIGO** (Japan, to launch in **2027**?) were proposed.
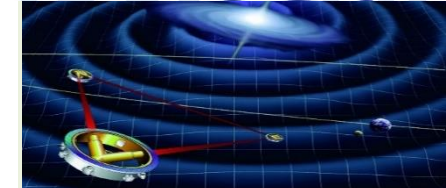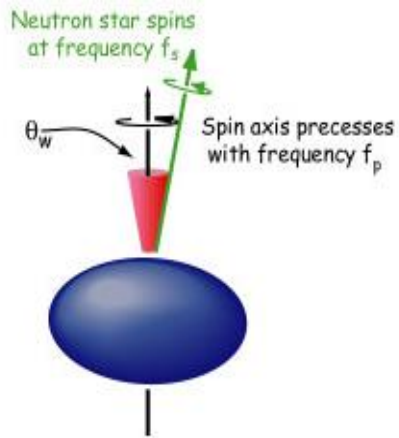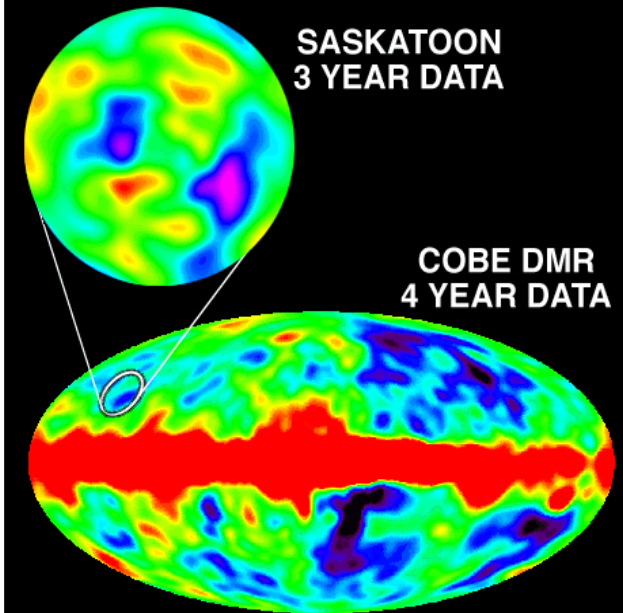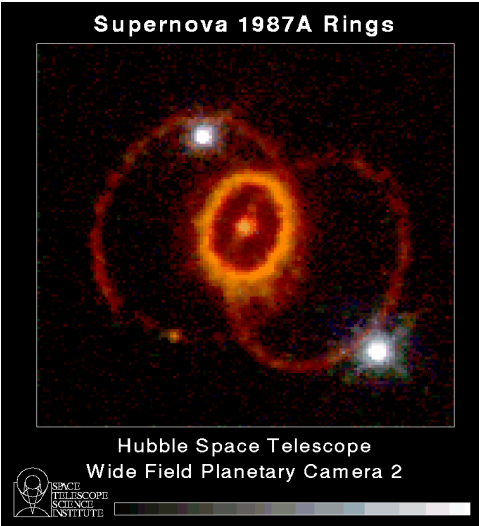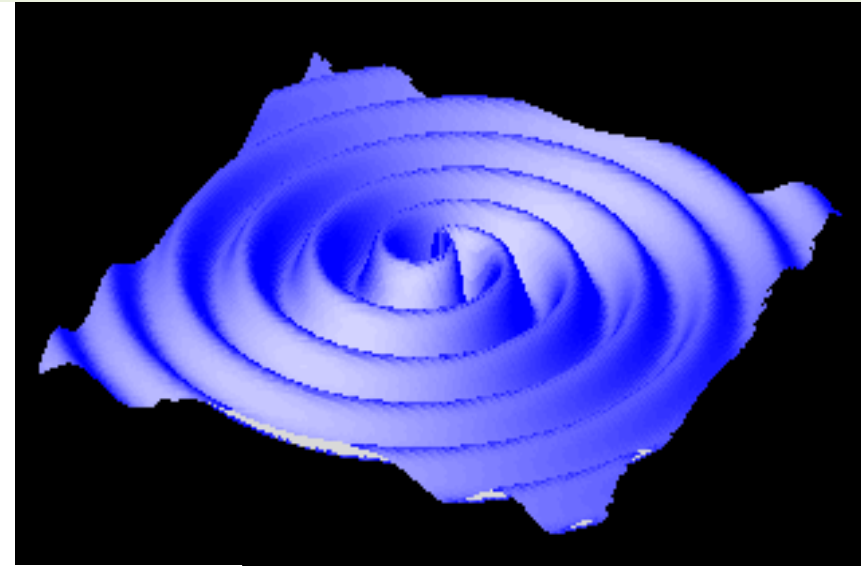
# *What Might Make GWs*



Compact binary inspiral:
*"chirps"*

Supernovae:
*"bursts"*

Cosmological Signal:
*"stochastic background"*

Pulsars in our galaxy:
*"periodic"*

# LIGO Observatory



Gravitational Wave Observatories
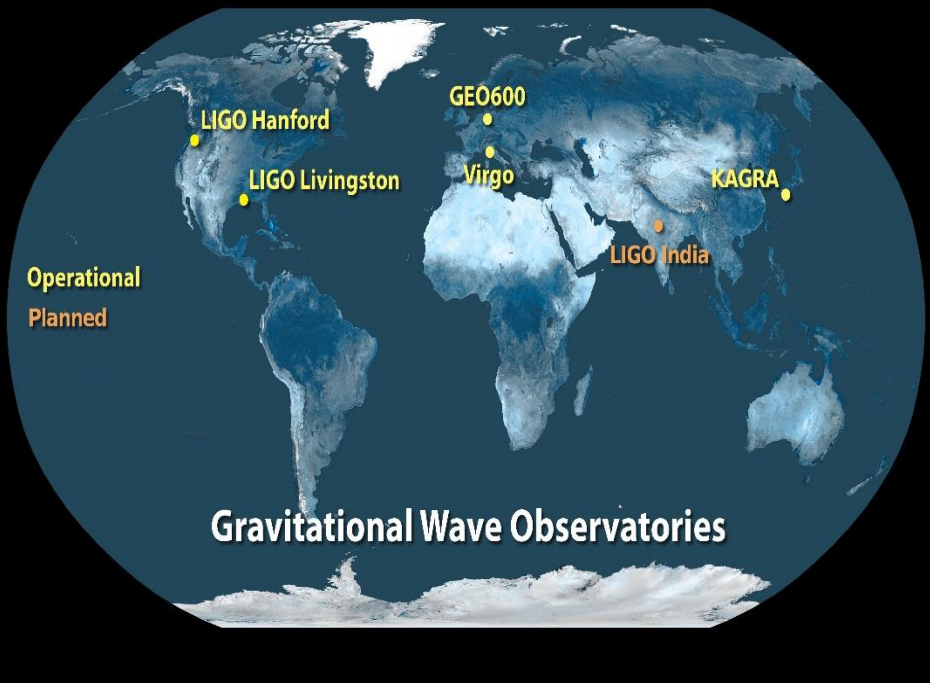
**LIGO** - gravitational wave detectors in **Hanford** and **Livingston**, **4 km** tunnels, separation **3,000 km**. **VIRGO** - in **Cascina, Italy** **KAGRA** – in **Kamioka, Japan**



Hanford, WA



Livingston, LA

## New Era of Multi-Messenger Astrophysics!

*„Observation of GWs from a **Binary Black Hole** Merger"* LIGO/Virgo, Phys. Rev. Lett. **116**, 061102 (11 February 2016)

*„GW170817: Observation of GWs from a **Binary Neutron Star** Inspiral"* LIGO/Virgo, Phys. Rev. Lett. **119**, 161101 (16 October 2017)

Nobel Prize 2017

# *Present Situation*
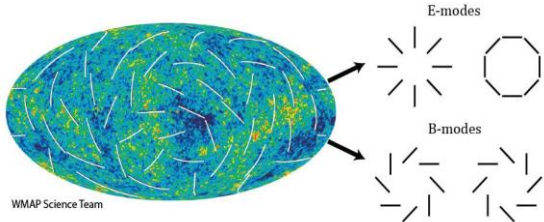
Intensive efforts to find burst, binary coalescence, continuous wave, stochastic **GW**s in coincidence with **EM** and neutrino signals;



Stochastic background of relict **GW**s probably was observed in **2023**;

The universe has more stellar mass **BH**s than expected;
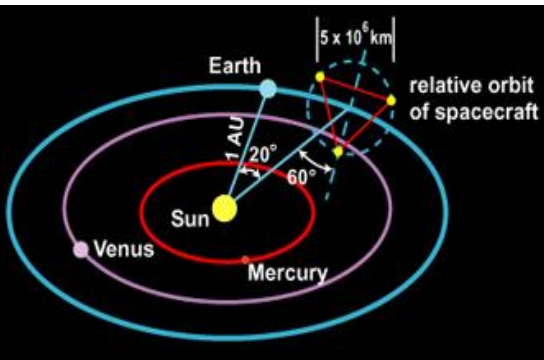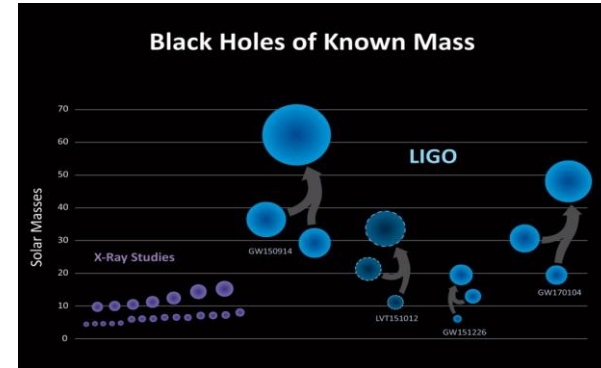


**LISA** (ESA): three Interferometers $2.5 \times 10^6$ **km** arm lengths. Planned launch **2037** (earlier launch **2034**?);
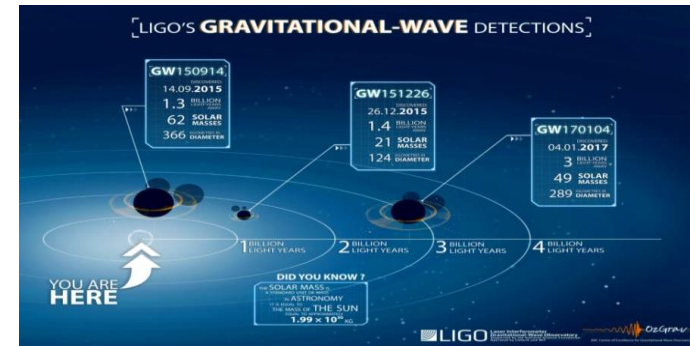
First **KAGRA** detections with **LIGO/Virgo** were reported on **11** November **2021**. The **O4** Observing Run was started on **25** May **2023**.
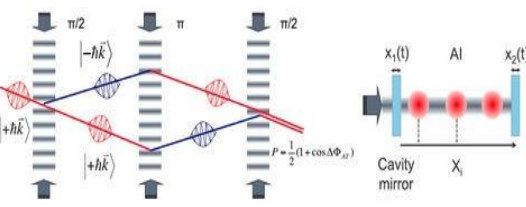
$3^{rd}$ generation detectors: **Einstein Telescope** (EU) and **Cosmic Explorer** (US), with atom interferometers in **0.1–10 Hz** (between **LISA** and **LIGO-Virgo-KAGRA**).

# Events Detected So Far

After the analysis of first three observing runs

**O1, O2, O3a & O3b**

there are **90** events with a probability of

$$P_{astro} > 0.5$$

being of astrophysical origin.

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

## Only one NS-NS merger had an accompanying Electromagnetic counterpart!

3. UNEXPLAINED LIGO EVENTS

# Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes   LIGO-Virgo-KAGRA Neutron Stars   EM Black Holes   EM Neutron Stars
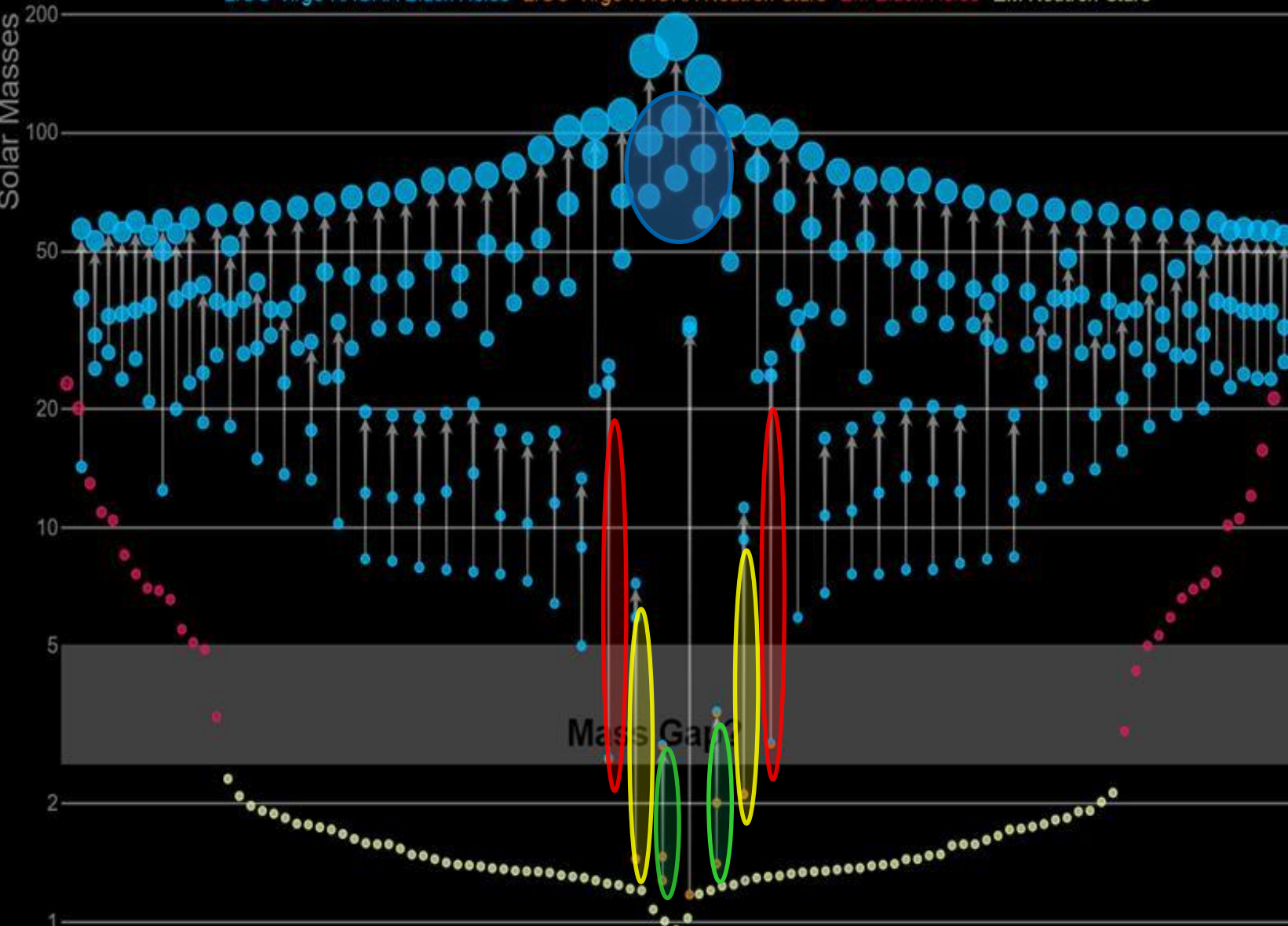
Mass Gap

**Data is spread across x-axis for visual appeal**
**Color is type of detection**

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 **BH**s

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

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

| $He$ core mass | Process | Remnant compact object |
|:---:|:---:|:---:|
| $32 - 65 M_\odot$ | Pulsational Pair-instability | $\lesssim 65 M_\odot$ |
| $65 - 135\ M_\odot$ | Pair-instability ($e^+e^-$ pairs) | Explodes – no remnant |
| $\gtrsim 135 M_\odot$ | Direct collapse into BH | $\gtrsim 135 M_\odot$ |

# Hierarchical Mergers

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

$$f_{exp} = 0.02 - 0.43 \text{ Gpc}^{-3} yr^{-1}$$

*LIGO /Virgo, ApJ. Lett. **900** (2020) L13*

Theoretical estimate:

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

*Liu & Lai, MNRAS **502** (2021) 2049*

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

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



1g BH    1g BH

1g BH    1g BH

redshift $\tilde{z}_1$

2g BH

redshift $\tilde{z}_2$

2g BH

1g BH    1g BH

redshift $z$

redshift $z$

1g+1g event    2g+2g event

*Gerosa. & Berti, Phys. Rev. D **95** (2017)*

$$f_{triple} \simeq 50 \% \qquad f_{survival} \simeq 60 \% \qquad f_{merger} \simeq 20 \%$$

$$f_{theor} = 0.6 - 6 \text{ Gpc}^{-3} yr^{-1}$$ **In price of extremal assumptions!**

# GW190425: Most Massive BNS $3.4^{+0.3}_{-0.1}\,M_\odot$

**X-ray binaries** (normal star and a collapsed star) **give the lower mass gap 2-5**$M_\odot$ **for BHs!**
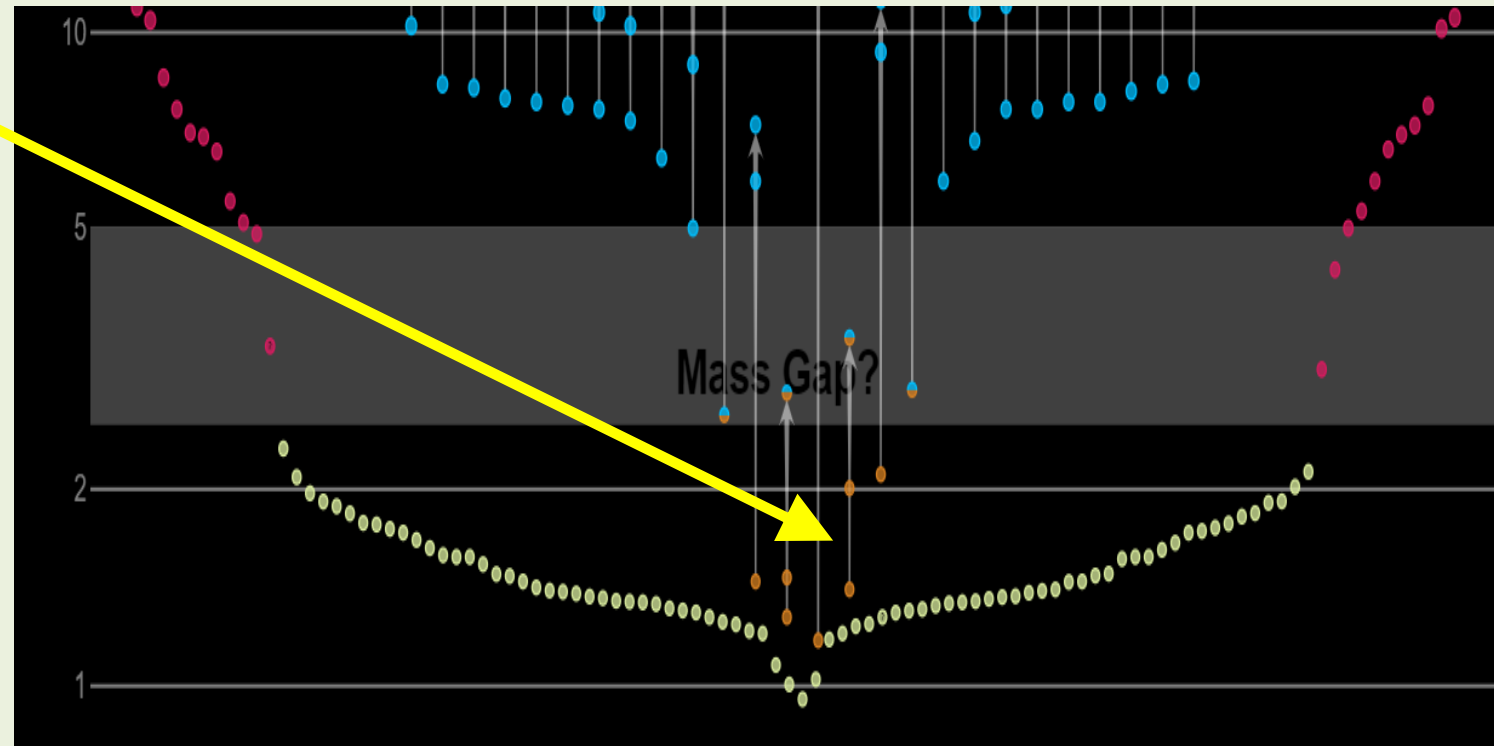


- ➢ **GW190425**-like systems could be obtained as a result of evolution of ultra-tight binary **He**-star – **NS** systems;

  *LIGO /Virgo, ApJ Lett.* **892** *(2020) L3*

- ➢ A phase of mass transfer from a post-helium main-sequence star onto **NS** is required.
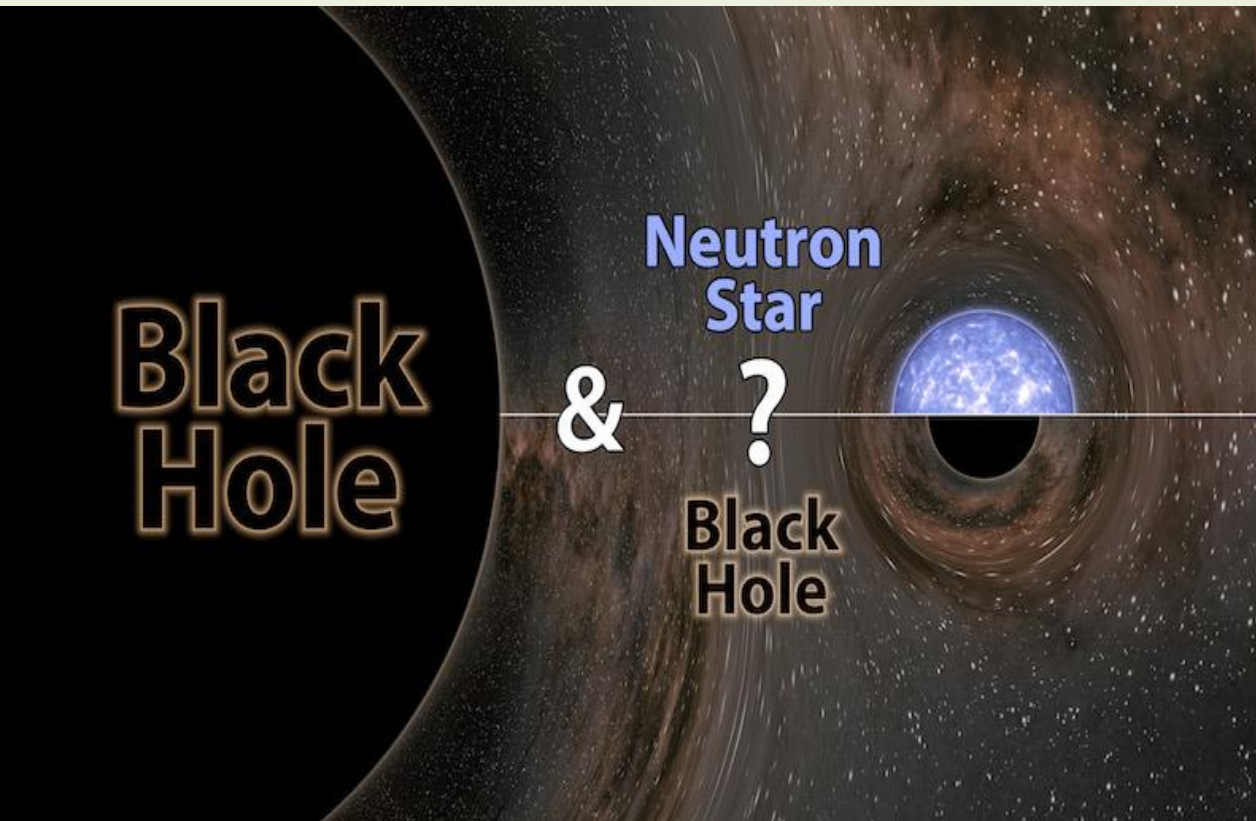
First components are clearly **BH**s.

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

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

# 4. World is ruled by dark forces

# Binary Objects Creation Mechanisms

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 stellar clusters. *(Askar, et al. 2017)*

**Main formation mechanisms predict low binary merging rates:**

$$\mathcal{R}_{theor}^{BBH} \simeq 5 - 10 \, \mathbf{Gp}c^{-3}yr^{-1} < \mathcal{R}_{LIGO}^{BBH} = 17 - 45 \, \mathbf{Gp}c^{-3}yr^{-1}$$

*LIGO &VIRGO & KAGRA, arXiv: 2111.03634*

# Theoretical BBH Merger Rate

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

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

$P(\tau)$ - Delay time distribution (time to merging)

**Number of Black Holes:** *(Elbert, Bullock & Kaplinghat, 2018)*

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

$\varphi(m)$ - Galactic mass function     $\xi(M)$ - Initial mass function

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

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

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

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

**Peaks at:** $z \sim 2 \approx t_{lookback} \sim 10.3\ \mathbf{Gyr}$

# *Problems with LIGO Data*

➢ **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 **BH**s accrete matter they can also emit **EM-radiation**.

➢ **Mass gap events observed**

## *Suggestion:*

**GW**s detected by **LIGO** may be emitted by the **Mirror World** binaries!

# In Mirror World

$M$-world, along with $O$-world, was created by **Big Bang**, but with lower reheating $T$.

➤ Constrain from **Big Bang Nucleosynthesis**: $x \equiv T'/T < 0.64$

➤ Certain **leptogenesis** mechanism gives: $1 \leq n'_b/n_b \lesssim 10$

➤ **Mirror World** can explain all **Dark Matter**: $\Omega'_b/\Omega_b \approx 5$

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

➤ Stars are composed mostly of **He**, are more **massive** and evolve **faster**, e.g. $10 M_\odot$ star with **75% He** evolves $\sim$ **10** times faster than normal star (**24% He**).

➤ High **He** abundance increases **Initial Mass Function**: $\xi(M)' \sim 1.5 \times \xi(M)$

➤ **Star formation** peaks at $z \sim 10 \approx t_{lookback} \sim 13.3$ Gyr: $SFR'(z) \sim 2.3 \times SFR(z)$

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

➤ Number of **black holes**: $N'_{BH} \sim 10 \times N_{BH}$

*For a review on mirror world see*
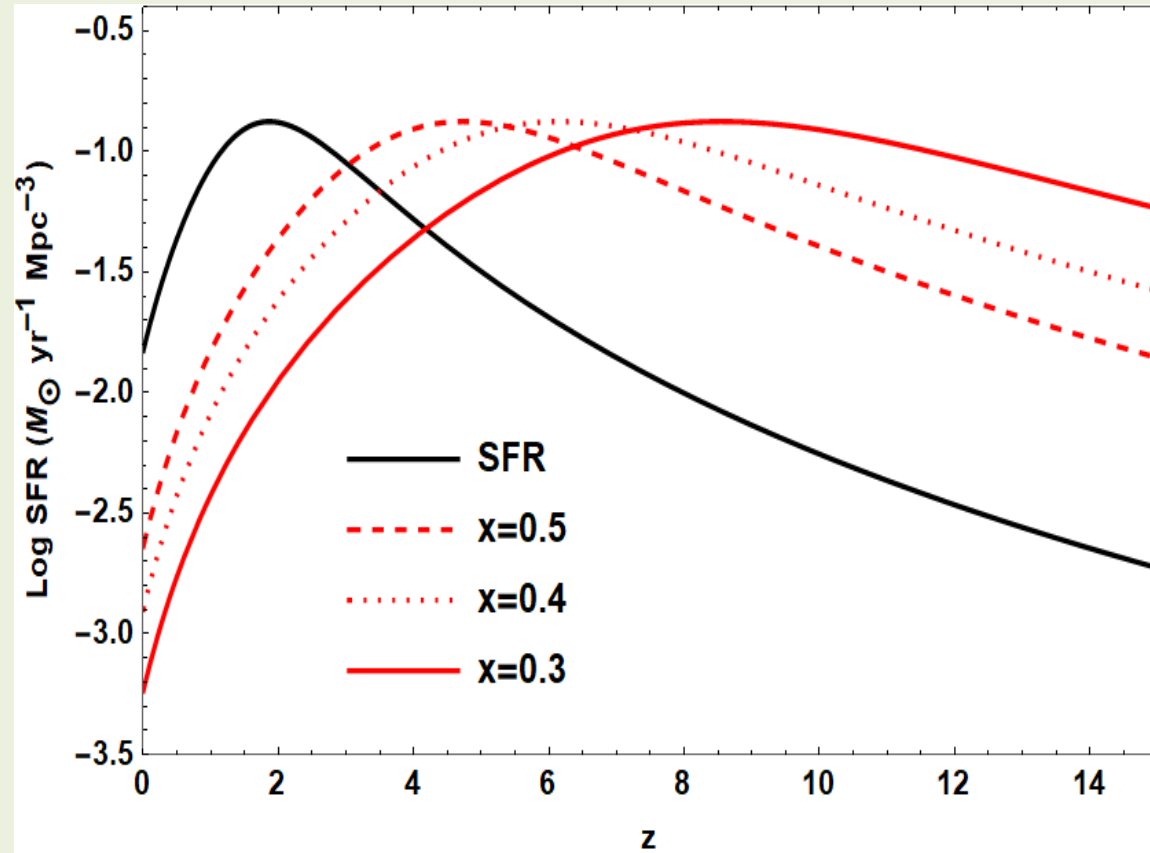*Z. Berezhiani, 2005*

# Star Formation Rate

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

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

The number of Mirror black holes

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

Even 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 $\sim 5$.



$SFR$ in the interval $0 < z < 14$

**In red: Mirror $SFR'$** for different temperatures $x = T'/T$.

(Madau & Dickinson 2014)

# LIGO Signals from Mirror World

➢ **Merging Rate** with combining **Mirror World** amplification factors:

$$\mathcal{R}_{mirror} \sim 10 \times \mathcal{R}_{theor} \sim 50 - 100 \, \mathbf{Gp}c^{-3} yr^{-1}$$

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 **NS**s' (**GW190425**) or lower mass gap objects (**GW190814** & **GW200210_092254**) are easier in **Mirror World**, as they are dominated by **He**.

# Conclusions:

## In the Mirror World scenario:

- Number of binary systems is **higher**;
- 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**.

## References:

1. "*Gravitational Waves from Mirror World*", *MDPI Physics* **1** (2019) 67;
2. "*LIGO Signals from the Mirror World*", *MNRAS* **487** (2019) 650;
3. "*Binary Neutron Star Mergers with Missing Electromagnetic Counterparts as Manifestations of Mirror World*", *Phys. Lett.* B **804** (2020) 135402;
4. "*Unexpected LIGO events and the Mirror World*", *MNRAS* **503** (2021) 2882.

**Thank You for Your Attention!**