LIGO Signals from the Mirror World

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თბილისის სახელმწიფო უნივერსიტეტი

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Plan of the Talk

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3. UNEXPECTED LIGO EVENTS
4. WORLD IS RULED BY DARK FORCES

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- CP-violation
- Mirror Partners
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- Problems with LIGO Data
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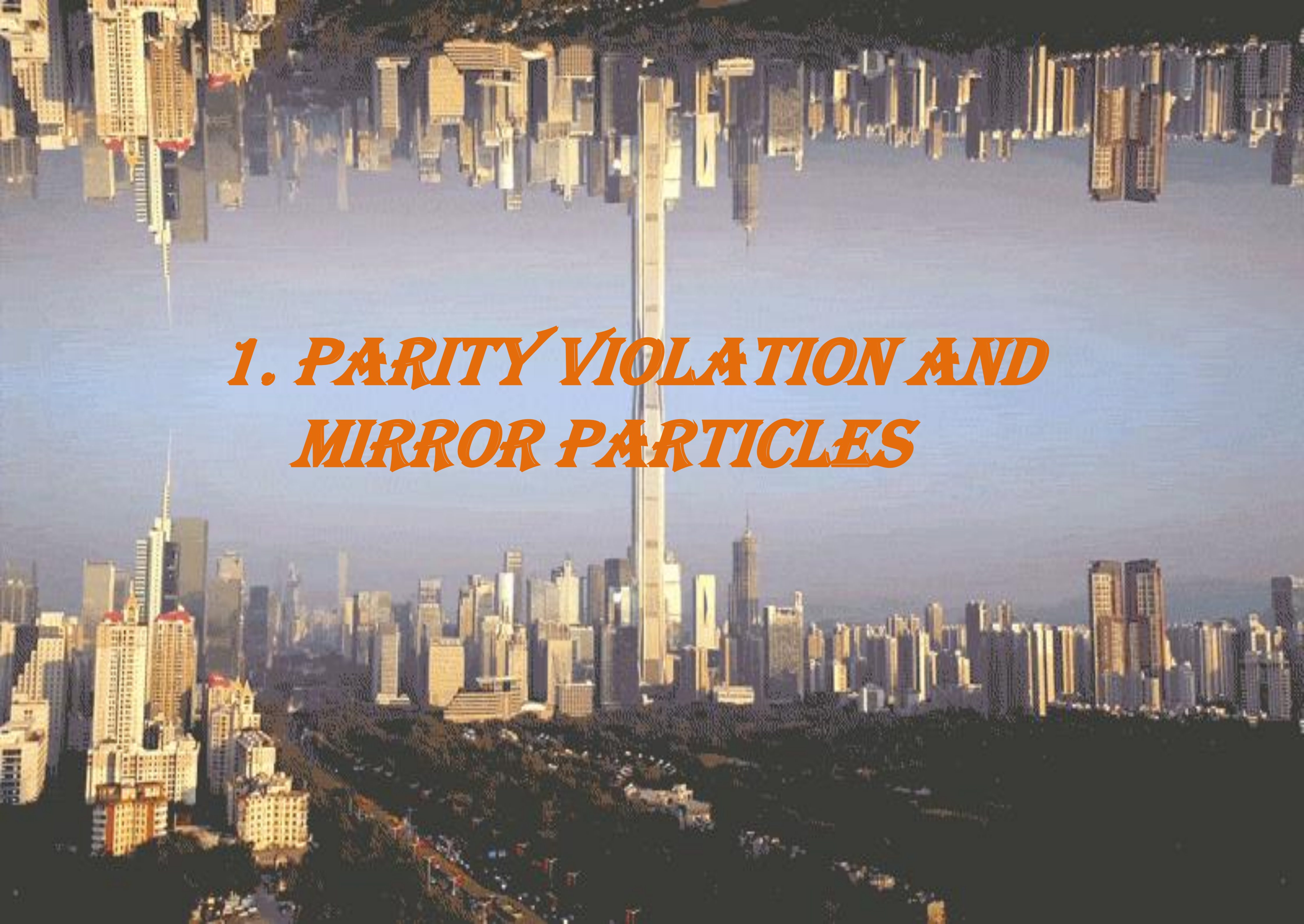


1. PARITY VIOLATION AND MIRROR PARTICLES

Parity Violation

τ–θ puzzle: Two different decays were found for charged strange mesons:

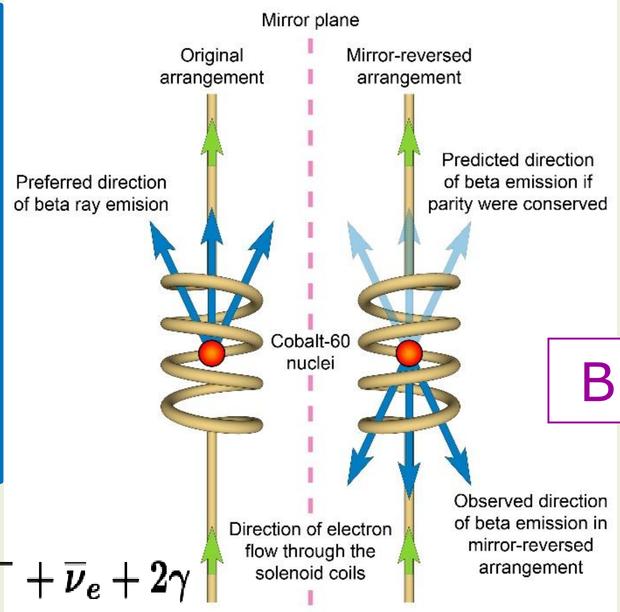
$$\theta^+ \to \pi^+\pi^0 \qquad \text{parity} = +1$$

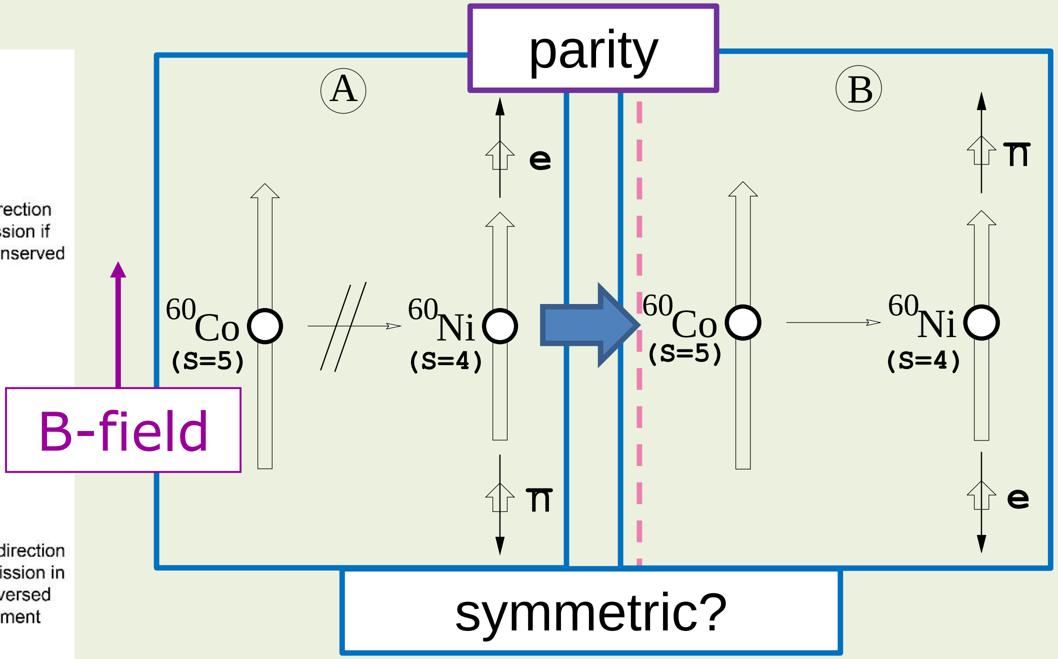
$$\tau^+ \to \pi^+\pi^+\pi^- \qquad \text{parity} = -1$$

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

(1957)

$^{60}_{27}\text{Co} \to ^{60}_{28}\text{Ni} = e^- + \overline{\nu}_e + 2\gamma$

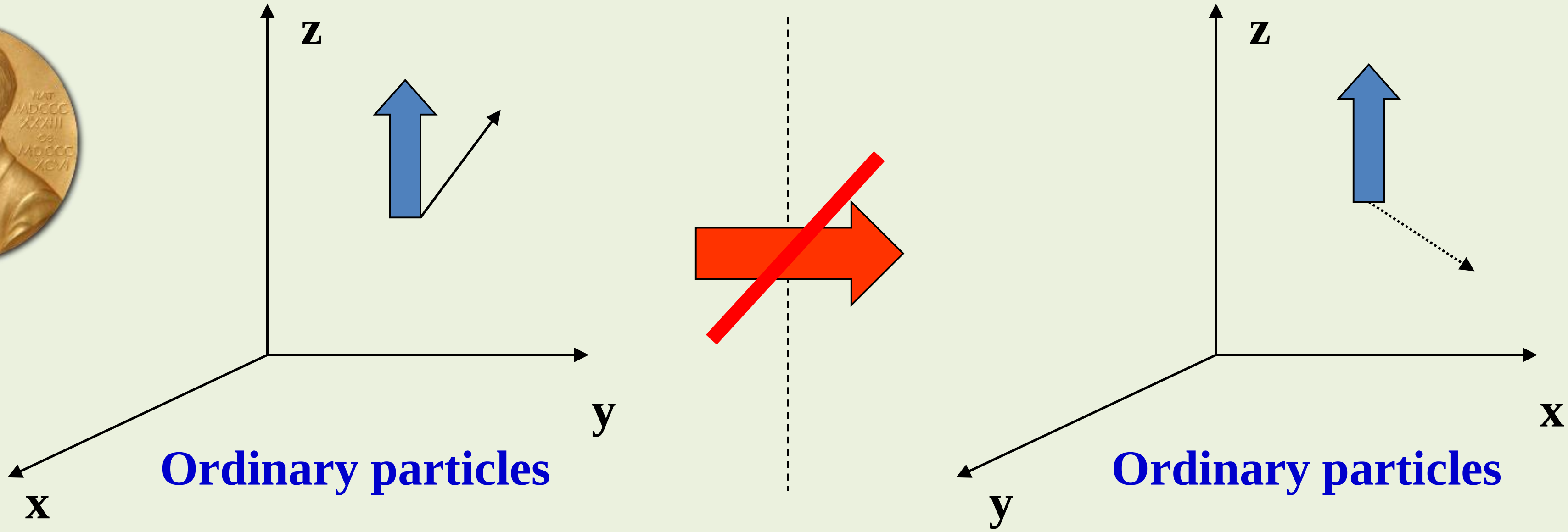




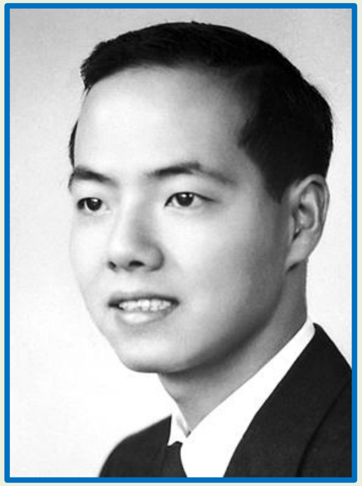
"I cannot believe God is a weak left-hander" Wolfgang Pauli

Mirror Symmetry

Nobel Prize 1957



T.D. Lee



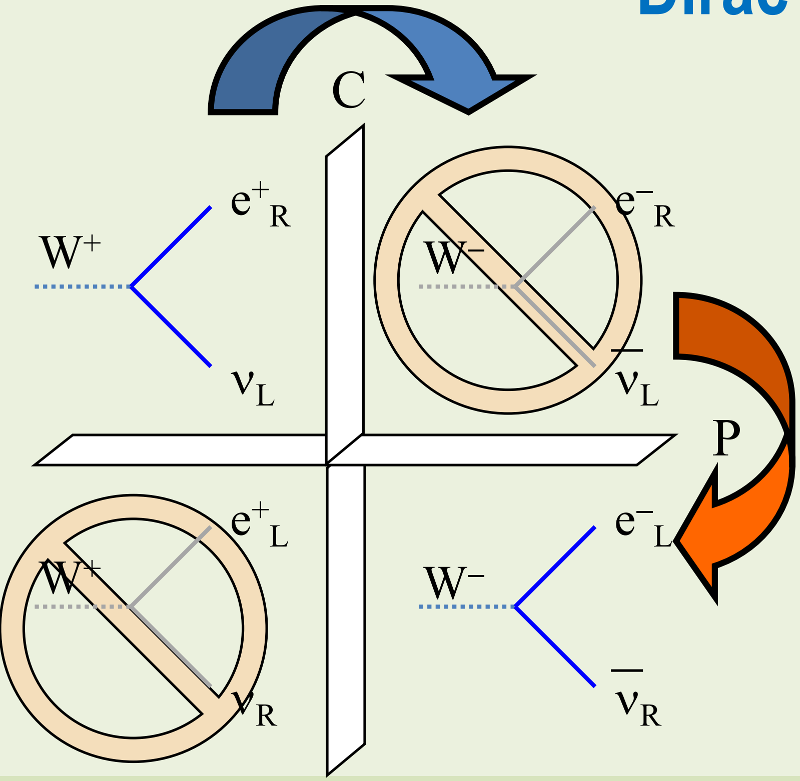
C.N. Yang

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

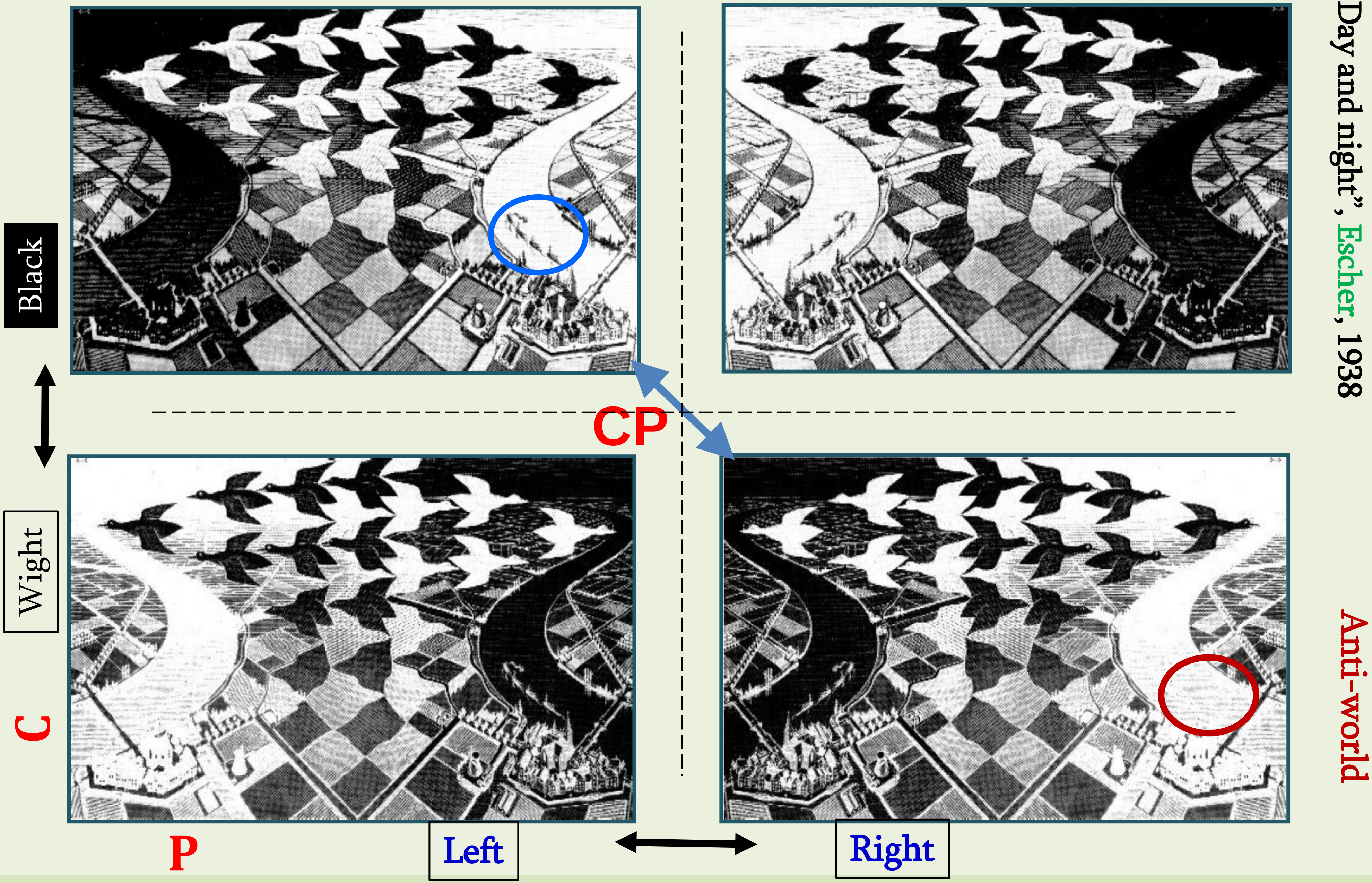
Lee, **Landau**,… (**1957**) an economic solution: **CP**-invariance assumes that antiparticles play the role of mirror partners. Then non-conservation of parity can be introduced without assuming asymmetry of space with respect to inversion.

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.

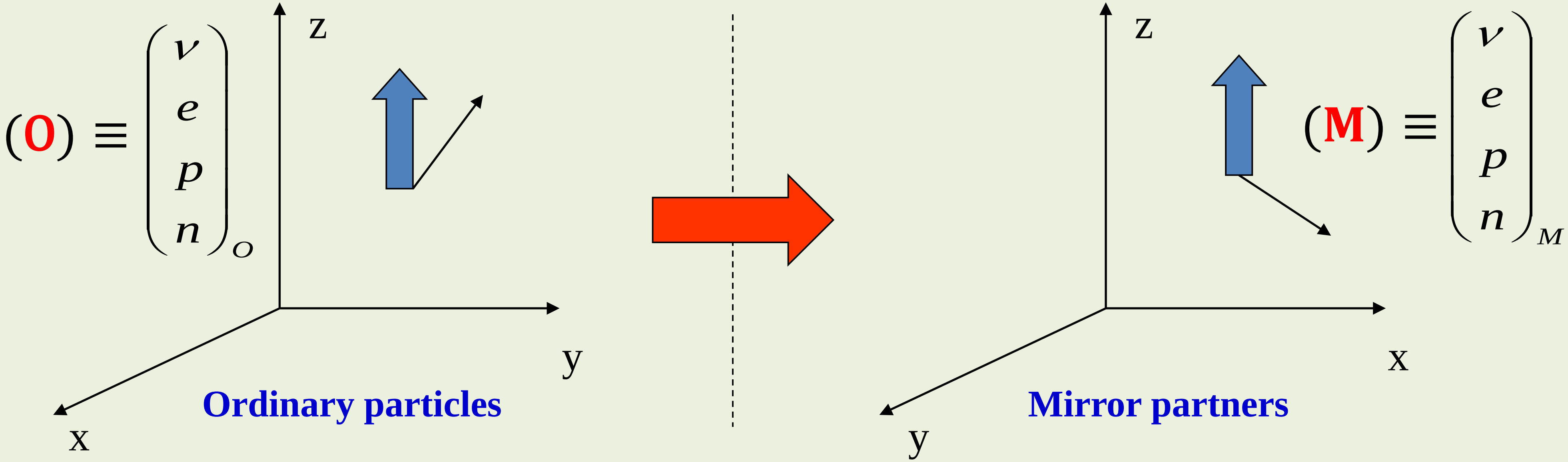
CP-violation



"Day and night", Escher, 1938

Mirror Partners

Kobzarev, Okun, Pomeranchuk (1966)



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

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.

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 has shown that (***O***) and (***M***) also can not share ***W*** and ***Z*** boson mediated weak interaction.

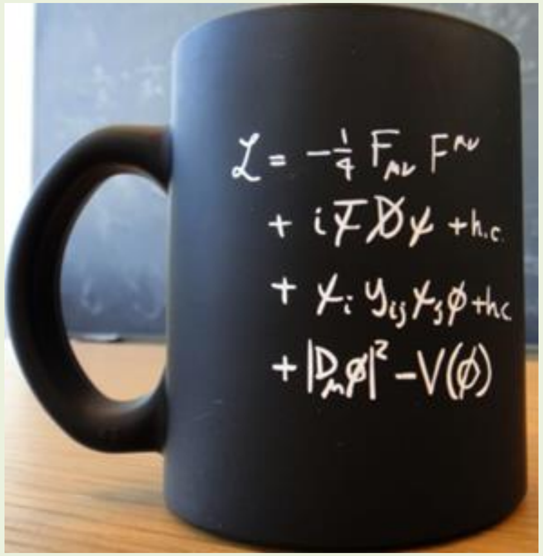
Mirror World

Blinnikov, Khlopov, Berezhiani (1980-90s)

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

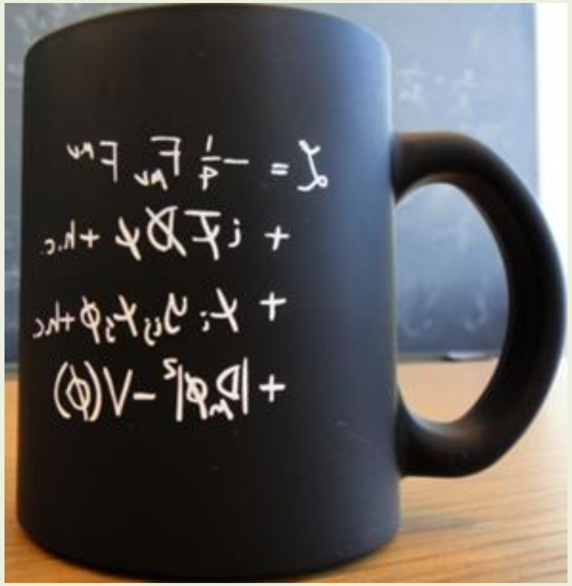
$$(\mathbf{M}) \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_M \quad (W)_M \quad (\gamma)_M \quad (q,g)_M$$

Ordinary particles



Only **L**-handed

Only **R**-handed



Mirror partners

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'

L-R symmetric

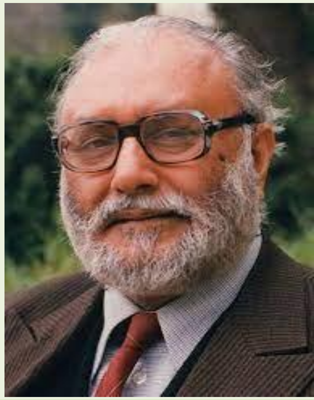
SM

SM'

L-R symmetric

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

$L = L_{SM} + L'_{SM} + L_{int}$ 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 interaction 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 ✓

Exact parity symmetry ↔ mirror particles ?

Mirror matter can explain several physical phenomena:

In cosmology:

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

In astrophysics:

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

In particle physics:

- **Higgs – mirror Higgs mixings;**
- **Neutrino sterile neutrino mixings;**
- **Photon-mirror photon kinetic mixing;**
- **Anomalous disappearance of neutrons.**

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.

Arkani-Hamed, Dimopoulos, Dvali, Kaloper, JHEP ***0012*** *(2000) 010*

Can interact with us via:

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

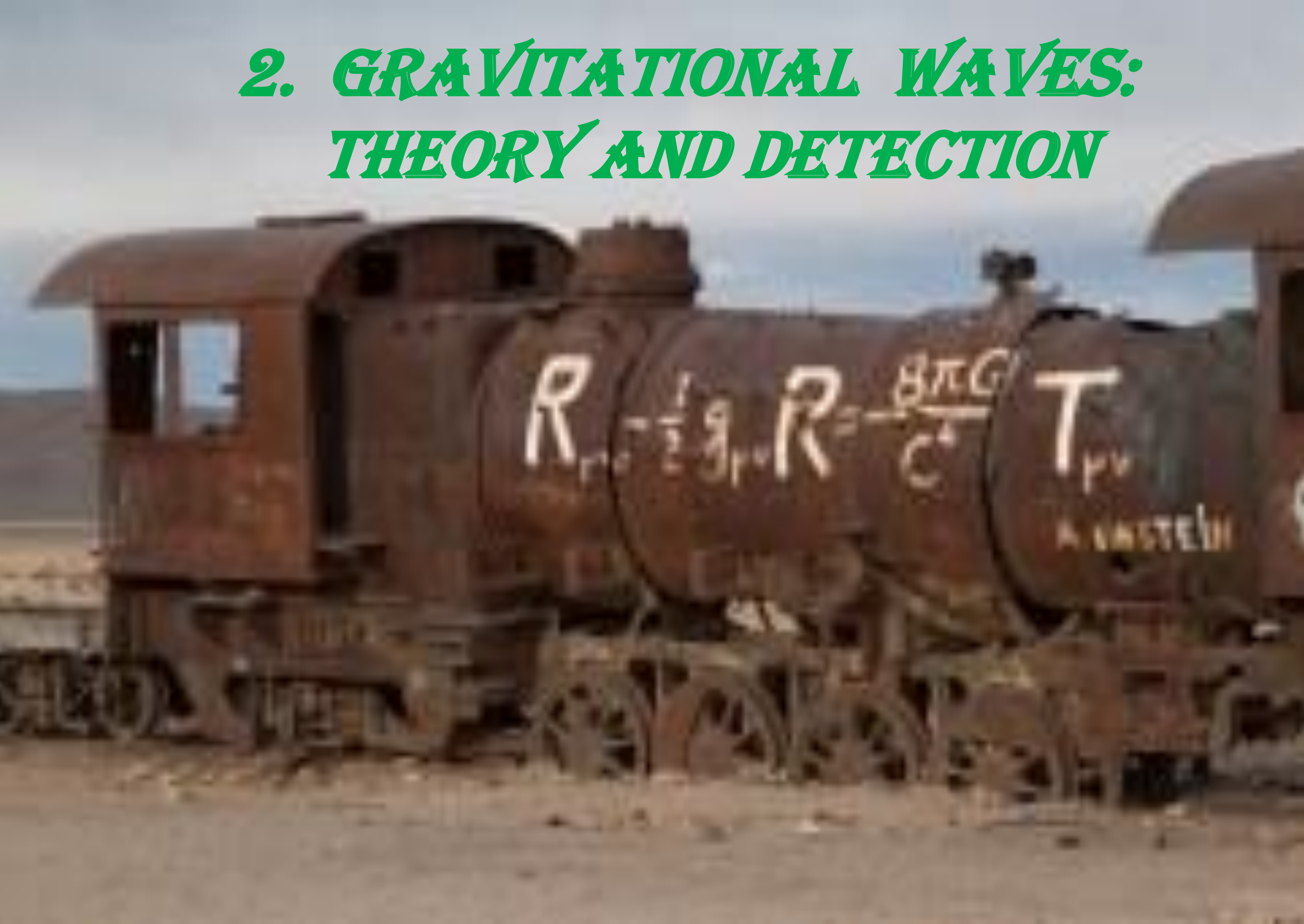
Problems:

- 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.

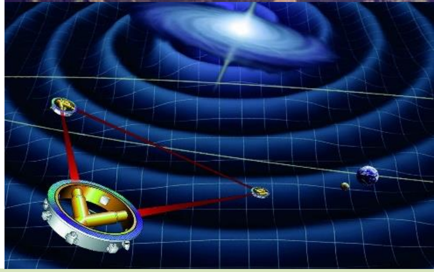
The main stages in development of the **GW** theory are:

- 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:

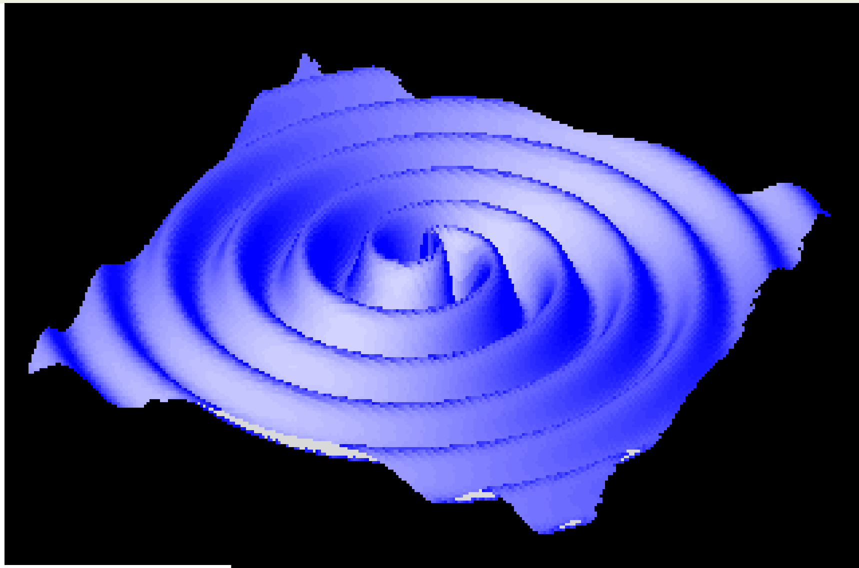
- First attempts were made in the **1960**s by **Weber** by means of aluminum resonant bar detectors;
- In **1963** **Gertsenshtein** and **Pustovoit** suggested using **Michelson-Morley** type interferometers;
- In **1974** **Taylor** and **Hulse** detected the binary pulsar **PSR B1913+16**. Later, 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 for Physics in **1993** for the first observational evidence for **GW**;
- On **11** Feb. **2016**, the **LIGO/Virgo** collaboration announced the first direct observation of **GW**s in Sep. **2015**. The **2017** **Nobel** Prize in Physics - **Barish**, **Thorne** and **Weiss**;
- The space missions: **LISA** (**ESA**, to launch in **2037**?) and **DECIGO** (Japan, to launch in **2027**?) were proposed.

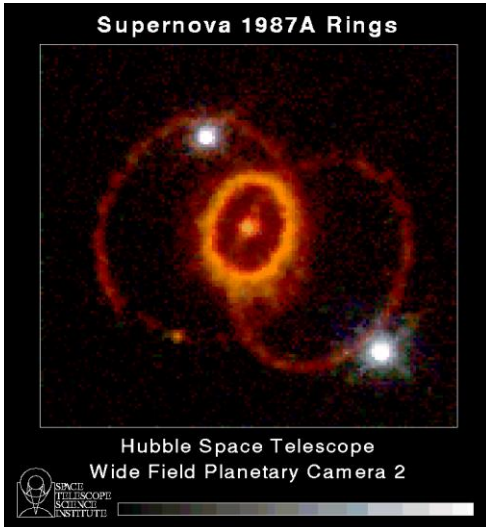


What Might Make GWs

Compact binary inspiral:

“chirps”



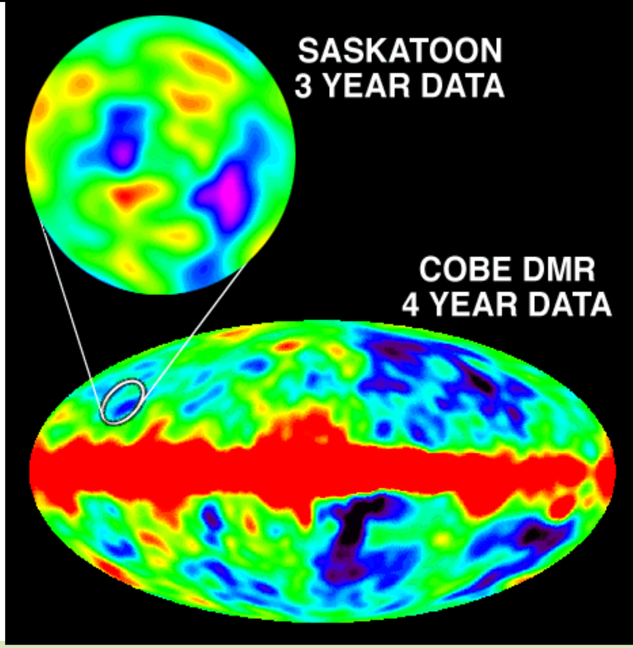


Supernovae:

“bursts”

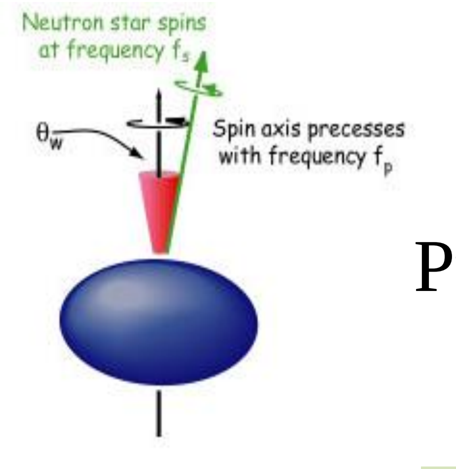
Cosmological Signal:

“stochastic background”

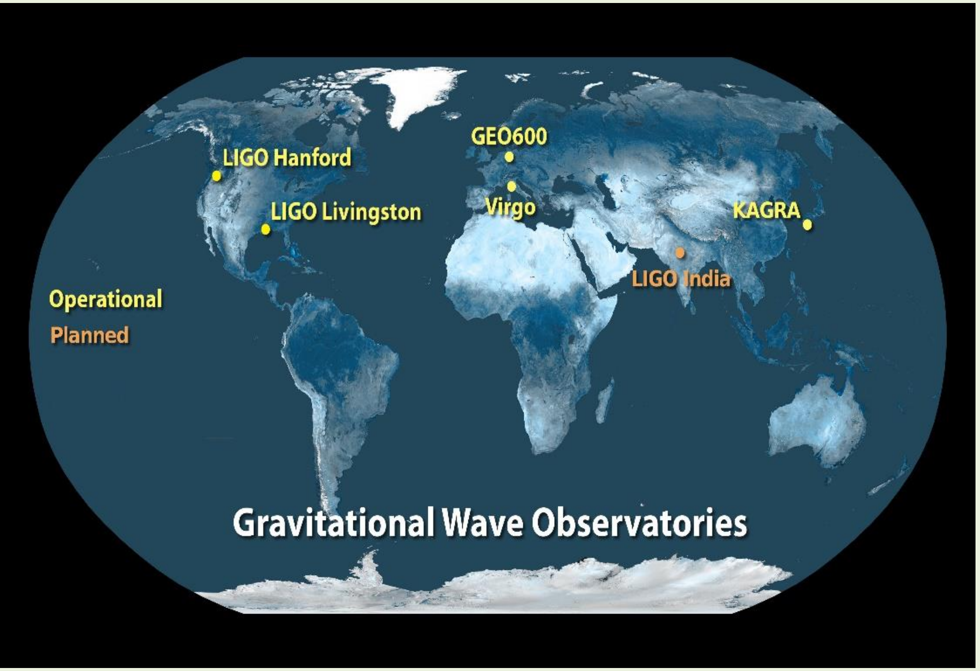


Pulsars in our galaxy:

“periodic”



LIGO Observatory



LIGO - gravitational wave detectors in **Hanford** and **Livingston**, **4 km** tunnels, separation **3,000 km**.


Hanford, WA


Livingston, LA

VIRGO - in **Cascina, Italy**

New Era of Multi-Messenger Astrophysics!

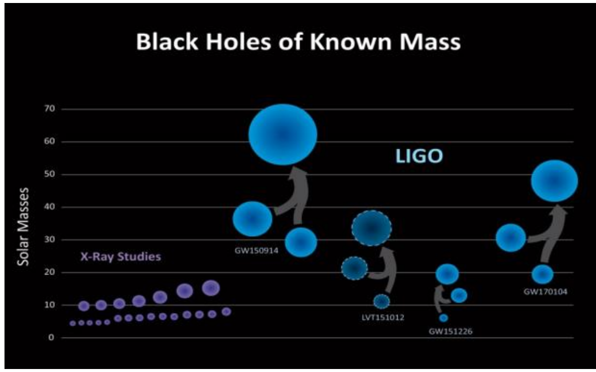
„Observation of Gravitational Waves from a **Binary Black Hole** Merger"
LIGO/ Virgo, Phys. Rev. Lett. **116**, 061102 (11 February 2016)

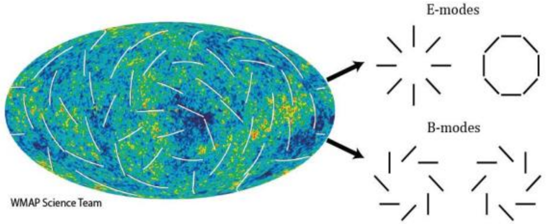
„GW170817: Observation of Gravitational Waves from a **Binary Neutron Star** Inspiral"
LIGO/Virgo, Phys. Rev. Lett. **119**, 161101 (16 October 2017)

Nobel Prize 2017

Present Situation

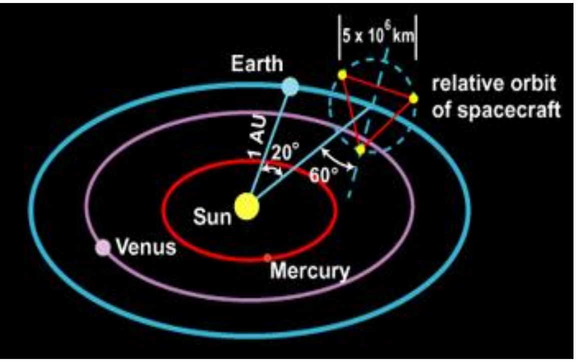
Intensive efforts to find burst, binary coalescence, continuous wave, stochastic **GW**s in coincidence with **EM** and neutrino signals;



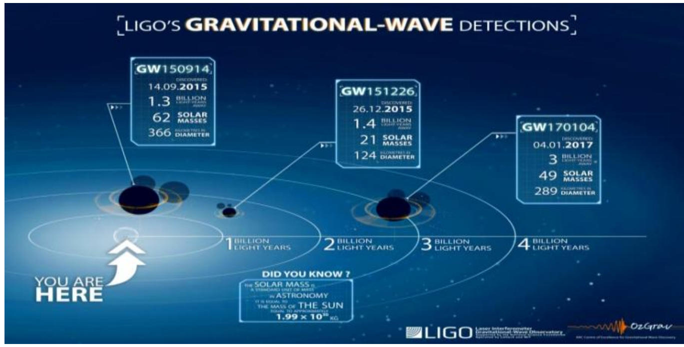


Stochastic background of relict **GW**s could be observed in a few years;

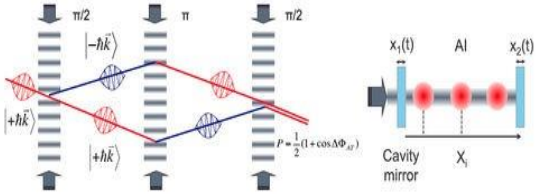
The universe has more stellar mass **BH**s than expected;



LISA (ESA): three Interferometers **2.5×10^6 km** arm lengths. Planned launch **2037** (earlier launch **2034**?);



First **KAGRA** detections with **LIGO/Virgo** were reported on **11** November **2021**. The start of **O4** Observing Run is scheduled for March **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**).

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.

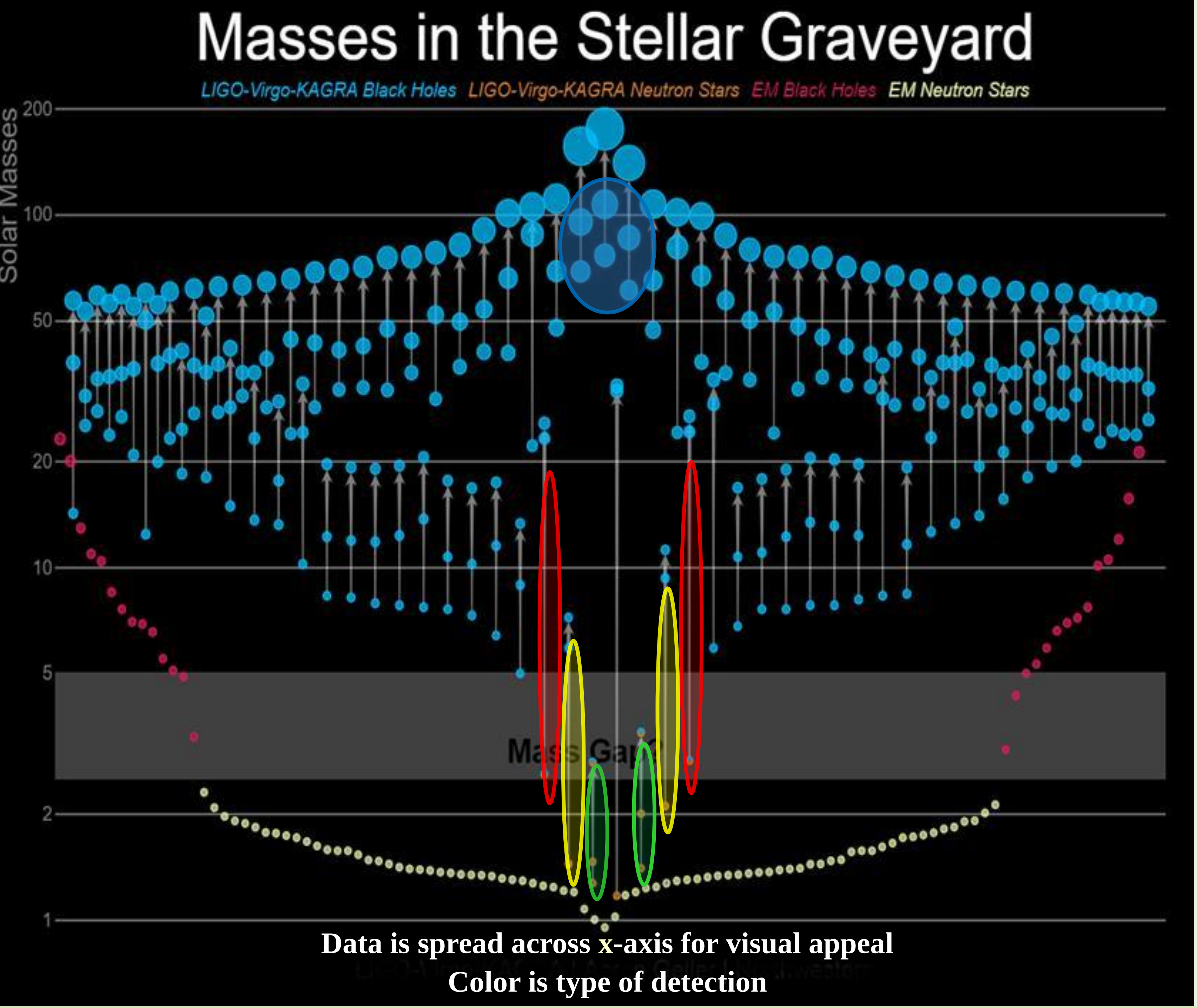
"GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run"

LIGO & VIRGO & KAGRA,
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 an accompanying Electromagnetic counterpart!

3. UNEXPLAINED LIGO EVENTS



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

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

- 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 (e^+e^- pairs)	Explodes – no remnant
$\gtrsim 135M_\odot$	Direct collapse into BH	$\gtrsim 135M_\odot$

Hierarchical Mergers

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

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

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

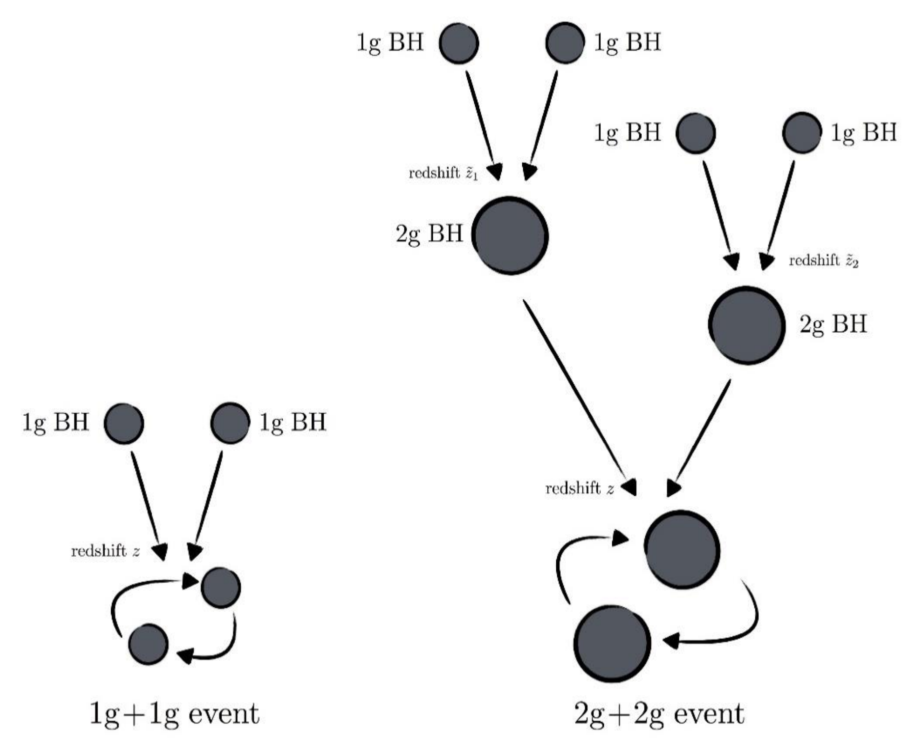
Theoretical estimate:

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

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

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

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



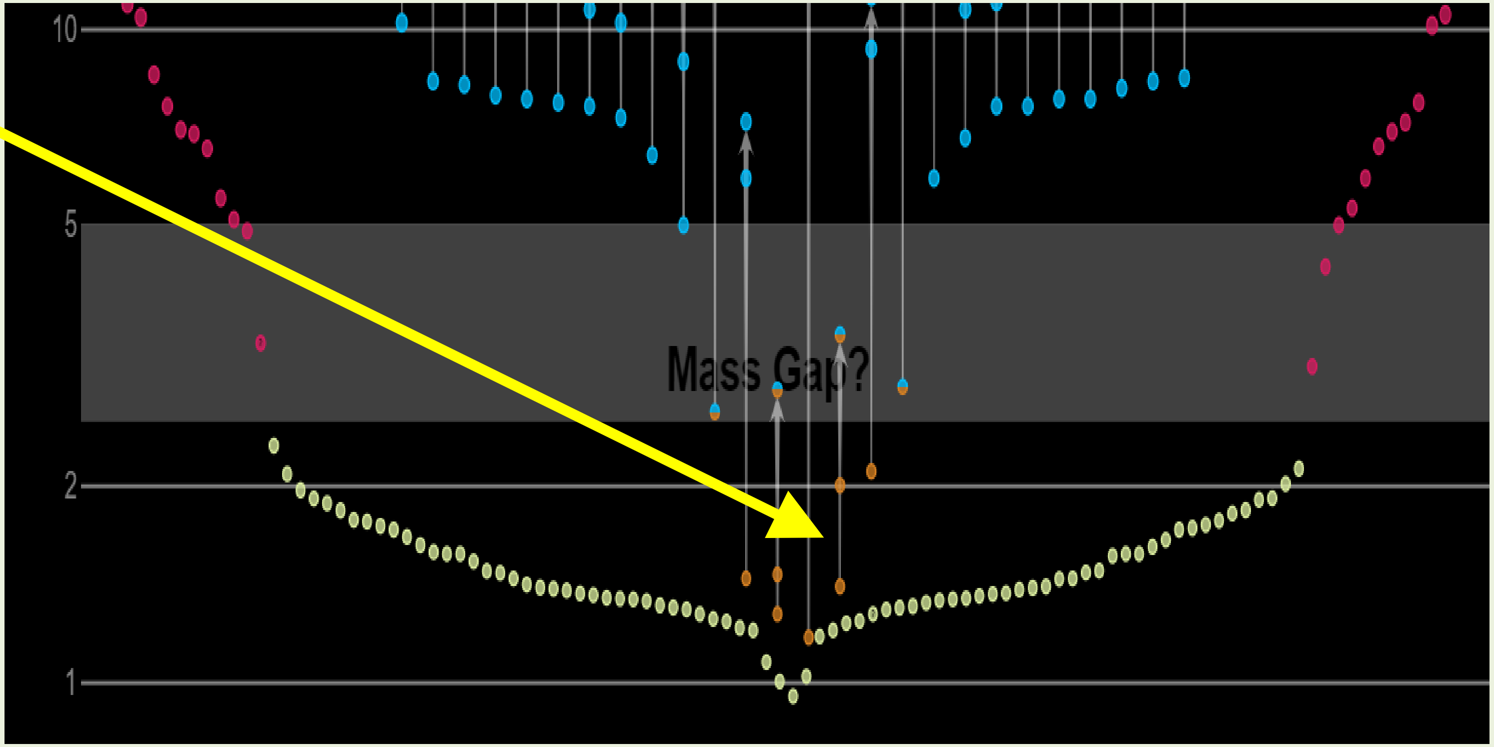
Gerosa. & Berti, Phys. Rev. D ***95*** *(2017)*

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

$$f_{theor} = 0.6 - 6\ \mathrm{Gpc}^{-3} yr^{-1}$$

In price of extremal assumptions!

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



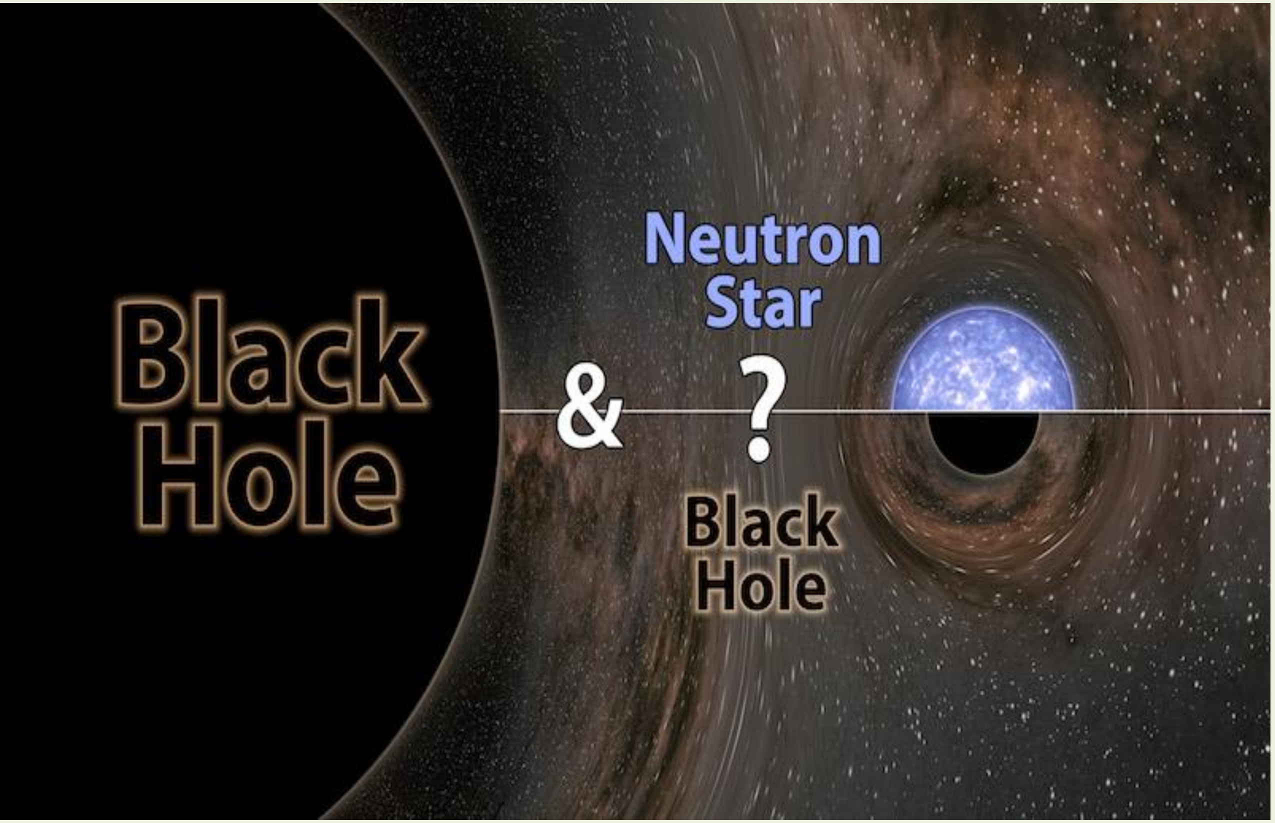
X-ray binaries (normal star and a collapsed star) give the lower mass gap 2-5$M_\odot$ for BHs!

- **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.

GW190814&GW200210_092254: BH Mass-gap



First components are clearly **BH**s.

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

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

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:

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

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

$N(m) = \frac{m}{\int M\xi(M)dM}$ - 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: $z \sim 2 \approx t_{lookback} \sim 10.3 \text{ Gyr}$

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:

GWs 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. $10M_\odot$ star with **75% He** evolves ~ **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

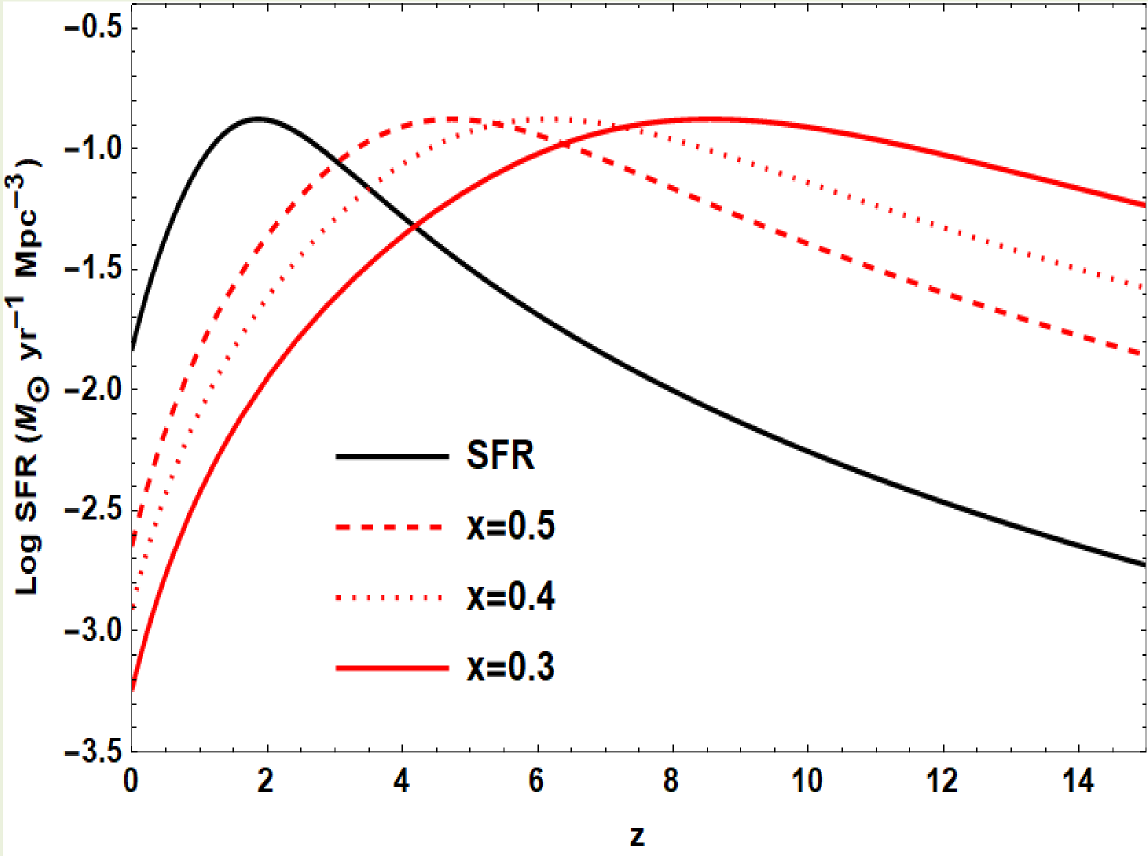
In the period $0 < z < 14$ more stars are formed in **Mirror World** relative to our:

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

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 ~ 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:

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

  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:

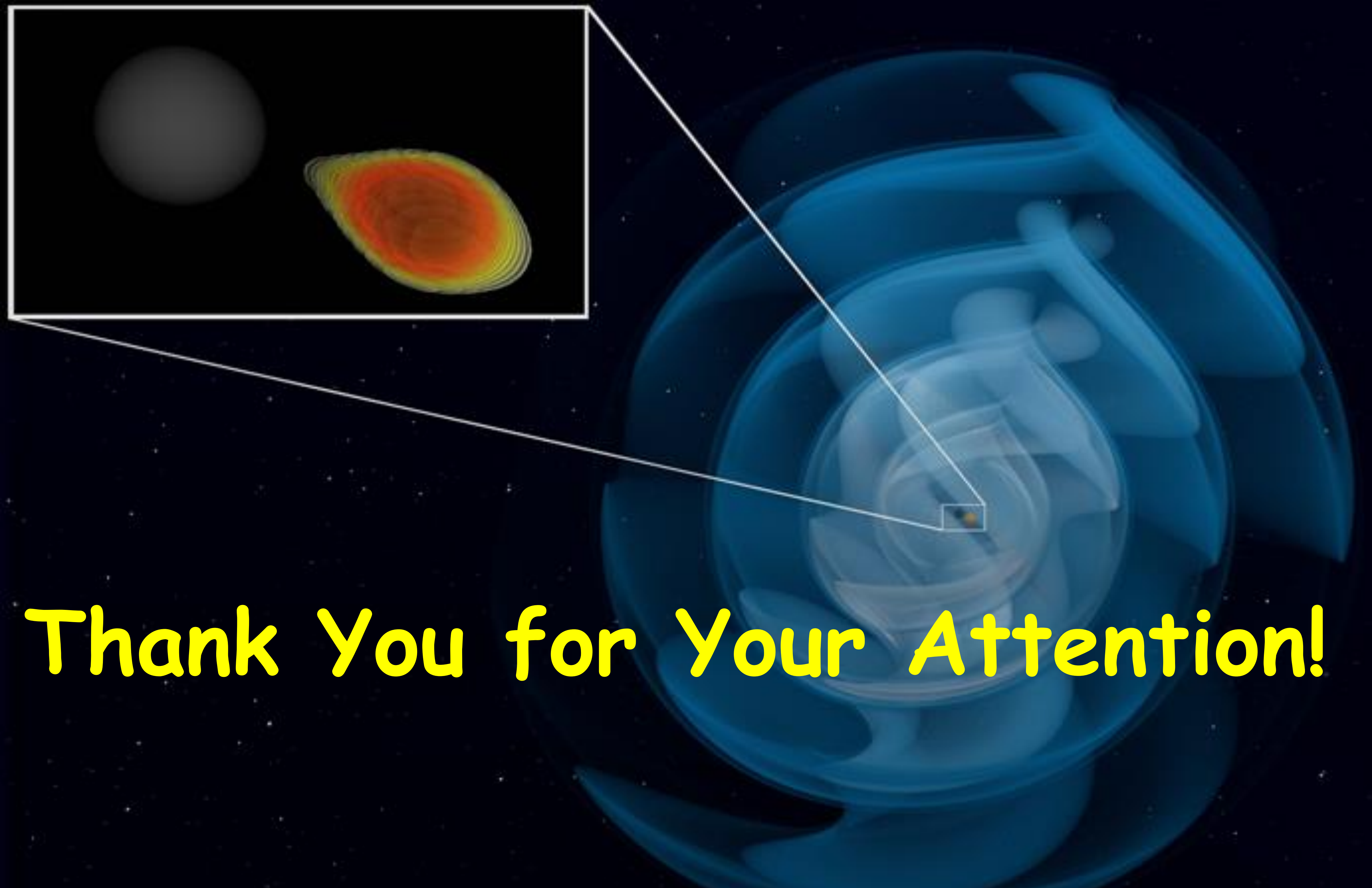
In the Mirror World scenario:

- **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!

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