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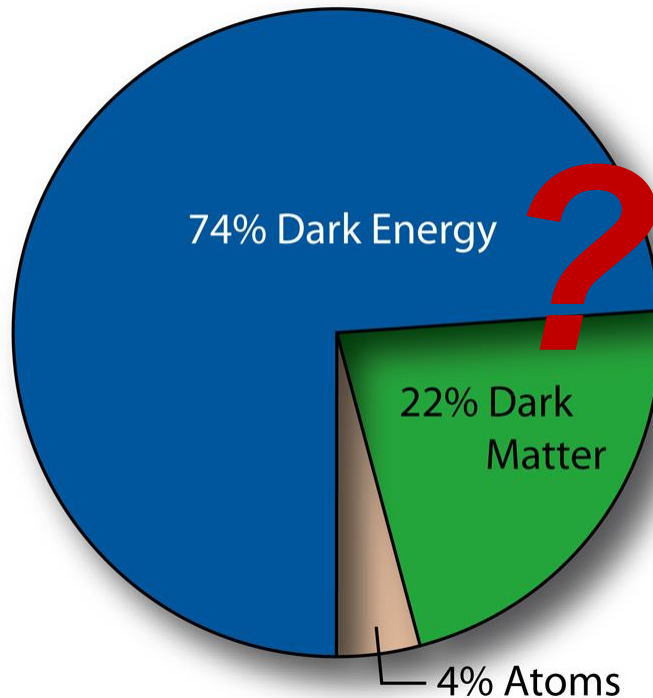
PBH probes of BSM physics

Invited talk in the framework of the program of the Initiative "Zooming in on primordial black holes"

Online 5 December 2022

Outlines

- BSM Physical basis of the SM cosmology

- BSM cosmology that follows from BSM physics.

- Primordial Black Holes (PBHs) as cosmological reflection of particle symmetry.

- Strong Primordial nonhomogeneities and Massive PBH clusters from models of inflation.

Composition of the Modern Unverse

74% Dark Energy

?

22% Dark Matter

4% Atoms

$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_b \approx 0.044 \qquad \Omega_{CMB} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{DM} \approx 0.20$$

$$\Omega_\Lambda \approx 0.7$$

$$\boxed{\Omega_{tot} \approx 1.0}$$

In the modern Universe dominate dark energy and dark matter – their nature is related to the new physics – physics beyond the Standard model, on which the bedrocks of modern cosmology are based

The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:
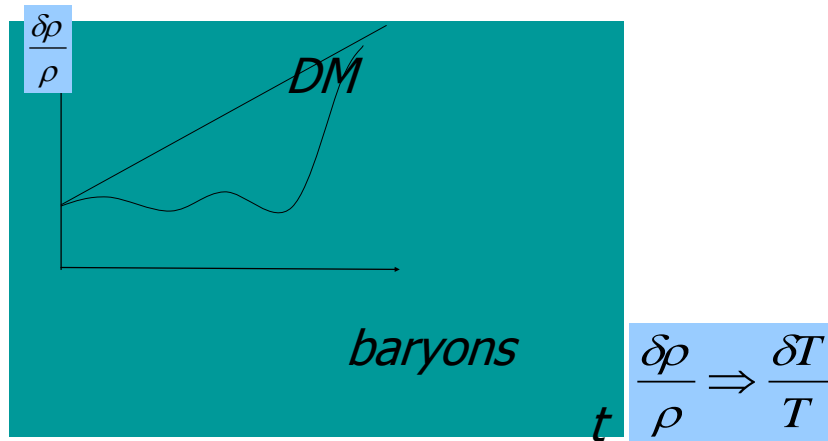
- Inflation
- Baryosynthesis
- Dark matter/energy

Physics beyond the Standard model, describing these phenomena inevitably predicts additional model dependent effects, in which NS and BH play important role.

Cosmological Reflections of Microworld Structure

- **(Meta-)stability of new particles reflects some Conservation Law, which prohibits their rapid decay. Following Noether's theorem this Conservation Law should correspond to a (nearly) strict symmetry of microworld. Indeed, all the particles - candidates for DM reflect the extension of particle symmetry beyond the Standard Model.**

- **In the early Universe at high temperature particle symmetry was restored. Transition to phase of broken symmetry in the course of expansion is the source of topological defects (monopoles, strings, walls…).**

- **Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, retaining in the Universe after these structures decay.**

Cosmological Dark Matter

Cosmological Dark Matter explains:
- **virial paradox in galaxy clusters,**
- **rotation curves of galaxies**
- **dark halos of galaxies**
- **effects of macro-lensing**

But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB

$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale.

Baryon density estimated from the results of BBN (mainly from Primordial deuterium) is not sufficient to explain the matter content of the modern Universe

Dark Matter – Cosmological Reflection of Microworld Structure

Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.

This stabilty reflects some Conservation Law, which prohibits DM decay.

Following Noether's theorem this conservation law should correspond to a (nearly) strict symmetry of microworld.

BSM physics of dark matter

- Extension of SM symmetry provides new conservation laws and stability of lightest particles that possess new conserved charges (R-parity in Supersymmetry, mirrority of mirror (shadow) matter, PQ symmetry in axion models etc)

- Mechanisms of symmetry breaking in the early Universe lead to primordial nonlinear structures and macroscopic forms of DM – like PBHs and PBH clusters

PBH PROBES FOR PHYSICS OF EARLY UNIVERSE

Primordial Black Holes

- Any object of mass M can form Black hole, if contracted within its gravitational radius.

$$r \leq r_g = \frac{2GM}{c^2}$$

- It naturally happens in the result of evolution of massive stars (and, possibly, dense star clusters).

- In the early Universe Black hole can be formed, if expansion can stop within cosmological horizon [Zeldovich, Novikov, 1966]. It corresponds to strong nonhomogeneity in early Universe

$$\delta \equiv \frac{\delta\rho}{\rho} \sim 1$$

PBHs as indicator of early dust-like stages

- In homogeneous and isotropic Universe ($\delta_0 << 1$) with equation of state $p = k\varepsilon$ probability of strong nonhomogeneity $\delta \sim 1$ is exponentially suppressed

$$P(\delta) = A(\delta, \delta_0) \exp\left(-\frac{k^2 \delta^2}{2\delta_0^2} \right)$$

- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

$$A(\delta, \delta_0) \geq \left(\frac{\delta_0}{\delta} \right)^5 \left(\frac{\delta_0}{\delta} \right)^{3/2} = \left(\frac{\delta_0}{\delta} \right)^{13/2}$$
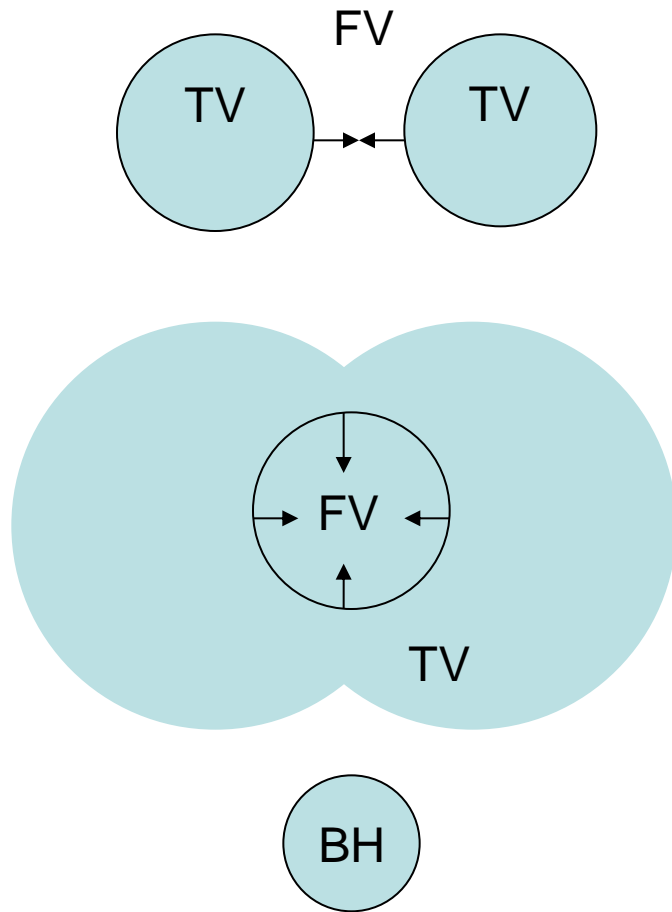
Dominance of superheavy particles

- Superheavy particles with mass m and relative concentration $r = n / n_\gamma$ dominate in the Universe at $T < r\ m$.

- Coherent oscillations of massive scalar field also behave as medium with $p=0$.

- They form BHs either directly from collapse of symmetric and homogeneous configurations, or in the result of evolution of their gravitationally bound systems (pending on particle properties they are like « stars » or « galaxies »).

Spectrum of PBHs from early MD stage

- Direct mechanism gives flat spectrum from mass within the horizon in the beginning of MD to the maximal mass, corresponding to configurations, which decouple from expansion and start to contract at the end of MD stage.

- Evolution of gravitationally bound systems depends on whether the matter is collisionless gas or dissipational medium. In the latter case (as in the example of magnetic monopole-antimonopole plasma dominance) such evolution is rapid and formation of PBHs with the mass of formed gravitationally bound "stars" is very effective.
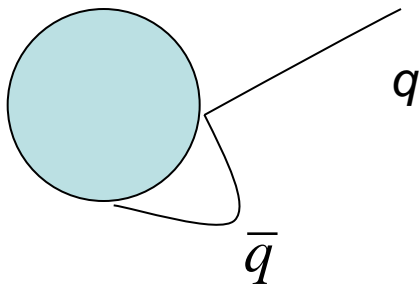
PBHs as indicator of first order phase transitions

FV

TV   TV

FV

TV

BH

- Collision of bubbles with True Vacuum (TV) state during the first-order phase transition results in formation of False Vacuum (FV) bags, which contract and collapse in Black Holes (BH).

PBH evaporation

- According to S. Hawking PBH with mass M evaporate due to creation of pairs by its nonstationary gravitational field. Products of evaporation have black body spectrum with

q

$\bar{q}$

$$T_{PBH} \propto 1/r_g$$

$$T_{PBH} \approx 10^{13} GeV \left(\frac{1g}{M} \right)$$

- The rate of evaporation is given by

$$\frac{dM}{dt} = -\kappa T_{PBH}^4 r_g^2 \propto 1/r_g^2 \propto 1/M^2$$
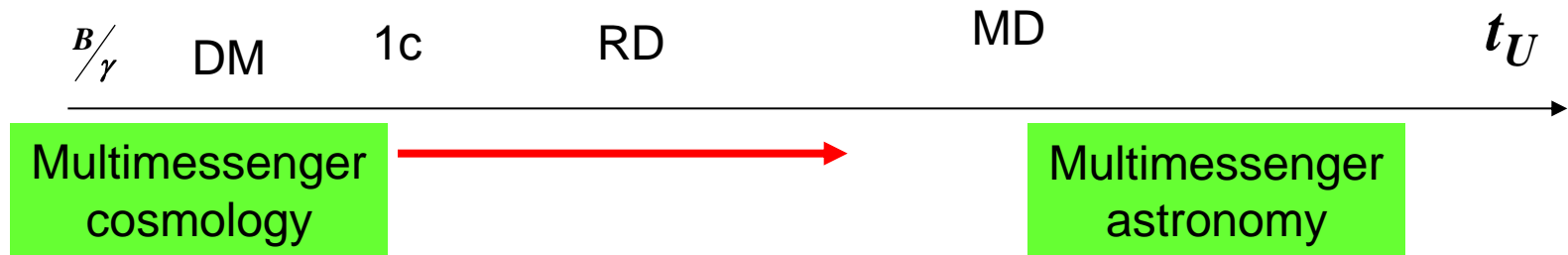
- The evaporation timescale is

$$t_{PBH} \approx 10^{27} s \left(\frac{M}{1g} \right)^3$$
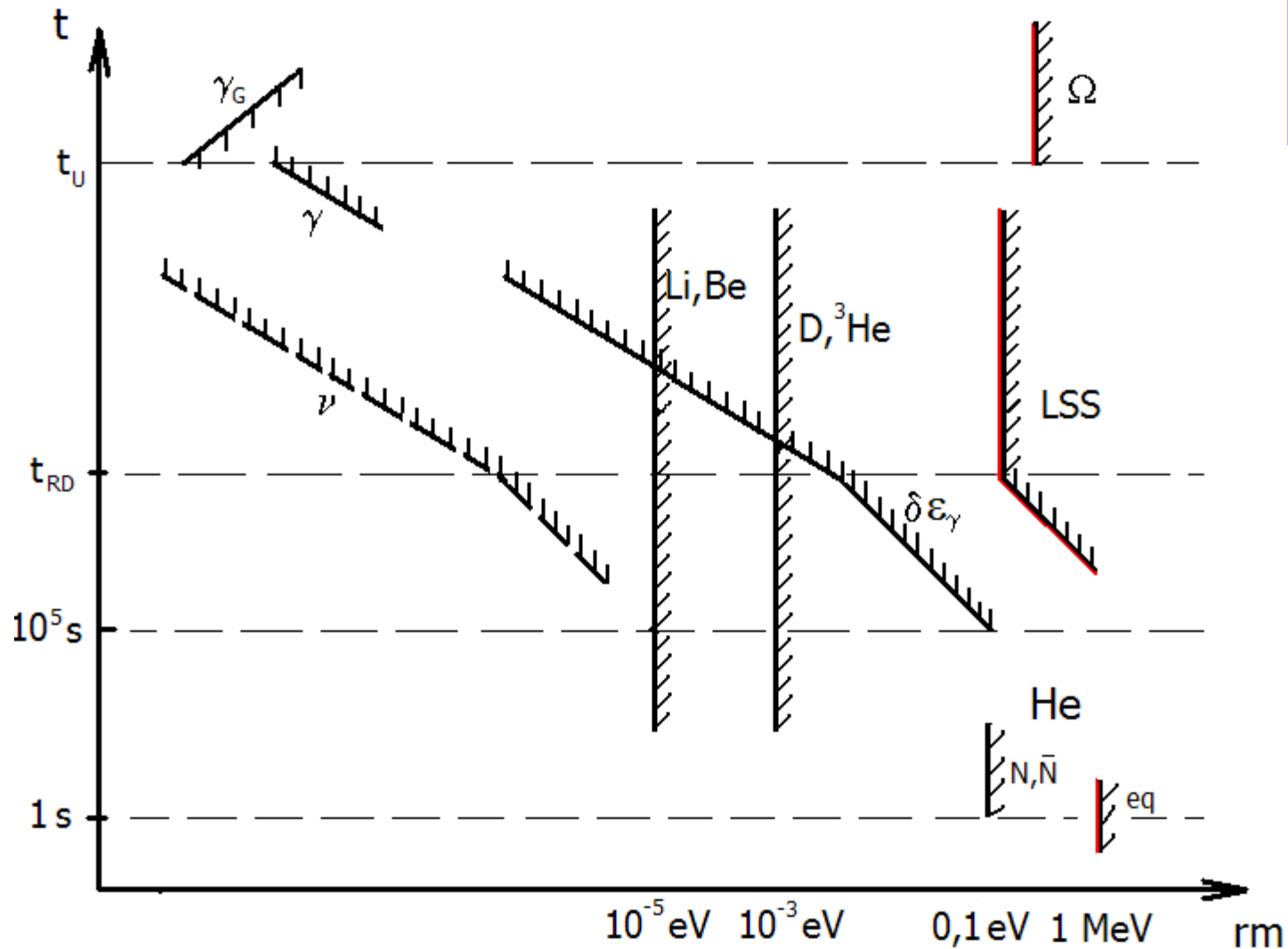
Any particle with $m \leq T_{PBH}$

is created – UNIVERSAL source

Cosmoarcheology treats the set of astrophysical data as the experimental sample sheding light on possible properties of new physics. Its methods provide *Gedanken Experiment*, in which multimessenger cosmology of new physics is considered as the source, while its effects on later stages of expansion are considered as detector, fixing the signatures for these effects in the multimessenger astronomical data.

B/γ DM 1c RD MD t_U

Multimessenger cosmology

Multimessenger astronomy

These « detectors of the Universe » can be « integral » (sensitive to very existence of new forms of matter) and « differential » (sensitive to some particular effect of such forms of matter)

Laboratory of the Universe

Non-equilibrium particles

- Decays of unstable particles, antimatter domain annihilation, PBH evaporation… are the source of particles with energy E>>T or of such particles, which are absent in equilibrium at this temperature T (e.g. antiprotons in baryon asymmetrical Universe after the first microsecond of expansion).

- Late sources of non-equilibrium particles directly contribute in fluxes of cosmic rays.

- If the source of particles acts sufficiently early, interaction of non-equilibrium particles with plasma and radiation can lead to observable effect

Effects of Primordial Black Holes

- PBHs behave like a specific form of Dark Matter
- Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars). PBHs with mass $M < 10^{15} g$ evaporate and their astrophysical effects are similar to effects of unstable particles.
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

STRONG PRIMORDIAL INHOMOGENEITY PROBES FOR INFLATION AND BARYOSYNTHESIS

Strong nonhomogeneities in nearly homogeneous and isotropic Universe

- **The standard approach is to consider homogeneous and isotropic world and to explain development of nonhomogeneous structures by gravitational instability, arising from small initial fluctuations.**

$$\delta \equiv \delta\rho / \rho << 1$$

- **However, if there is a tiny component, giving small contribution to total**

$$\rho_i << \rho \qquad \text{its strong nonhomogeneity} \qquad \delta_i \equiv (\delta\rho / \rho)_i > 1$$

is compatible with small nonhomogeneity of the total density

$$\delta = (\delta\rho_i + \delta\rho) / \rho \approx (\delta\rho_i / \rho_i)(\rho_i / \rho) << 1$$

Such components naturally arise as consequences of particle theory, sheding new light on galaxy formation and reflecting in cosmic structures the fundamental structure of microworld.

Strong Primordial nonhomogeneities from the early Universe

- Cosmological **phase transitions** in inflationary Universe can give rise to unstable cosmological defects, retaining a replica in the form of primordial **nonlinear** structures (massive PBH clusters, archioles).

- Nonhomogenous baryosynthesis (including spontaneous baryosynthesis and leptogensis) in its extreme form can lead to **antimatter** domains in baryon asymmetrical inflationary Universe.

Strong nonhomogeneities of total density and baryon density are severely constrained by CMB data at large scales (and by the observed gamma ray background in the case of antimatter). However, their existence at smaller scales is possible.

Cosmological Phase transitions 1.

- At high temperature $T > T_{cr}$ spontaneously broken symmetry is restored, owing to thermal corrections to Higgs potential

$$V(\varphi, T = 0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi, T) = \left(C\lambda T^2 - \frac{m^2}{2} \right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

- When temperature falls down below

$$T = T_{cr} \cong \langle \varphi \rangle = \frac{m}{\sqrt{\lambda}}$$

transition to phase with broken symmetry takes place.

Cosmological Phase transitions 2.

- Spontaneously broken symmetry can be restored on chaotic inflationary stage, owing to corrections in Higgs potential due to interaction of Higgs field with inflaton

$$V(\varphi, \psi = 0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi, \psi) = \left(\varepsilon\psi^2 - \frac{m^2}{2}\right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

- When inflaton field rolls down below

$$\psi = \psi_{cr} \cong \frac{m}{\sqrt{\varepsilon}}$$

transition to phase with broken symmetry takes place.

Topological defects

- In cosmological phase transition false (symmetric) vacuum goes to true vacuum with broken symmetry. Degeneracy of true vacuum states results in formation of topological defects.

- Discrete symmetry of true vacuum $\langle \varphi \rangle = \pm f$ leads to domains of true vacuum with $+f$ and $-f$ and false vacuum wall on the border.

- Continuous degeneracy $\langle \varphi \rangle = f \exp(i\theta)$ results in succession of singular points surrounded by closed paths with $\Delta\theta = 2\pi$. Geometrical place of these points is line – cosmic string.

- SU(2) degeneracy results in isolated singular points – in GUTs they have properties of magnetic monopoles.

ALP U(1) model

$$V(\psi) = \frac{\lambda}{2}\left(\psi^2 - f^2\right)^2$$

After spontaneous symmetry breaking infinitely degenerated vacuum

$$\psi = fe^{i\varphi/f}$$

experiences second phase transition due to the presence (or generation by instanton effects)
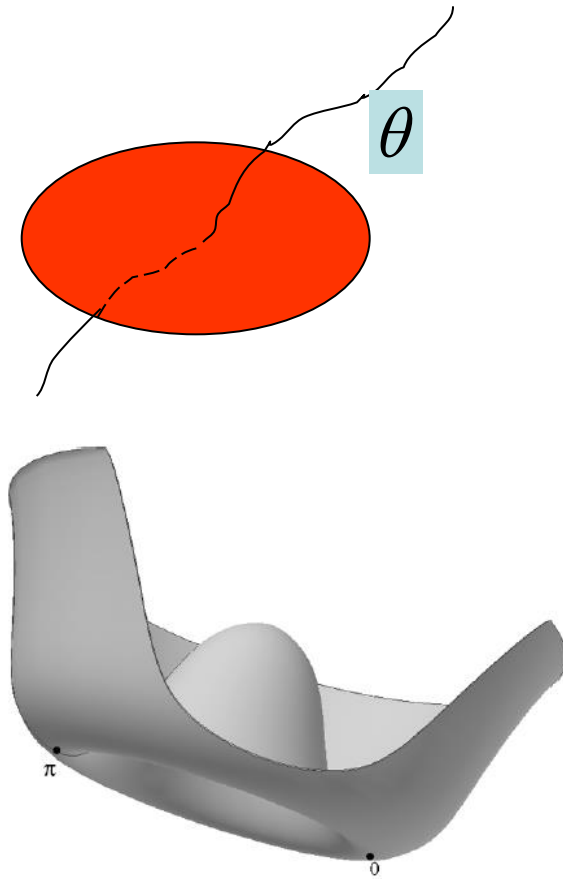
$$V(\varphi) = \Lambda^4\left(1 - \cos\left(\varphi/f\right)\right)$$

to vacuum states

$$\theta \equiv \varphi/f = 0, 2\pi, \ldots$$

In particular, this succession of phase transitions takes place in axion models

Topological defects

θ

- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.

- The tilt in potential breaks continuous degeneracy of vacua. In the result string network converts into walls-bounded-by-strings structure in the second phase transition. This structure is unstable and decay, but the initial values of phase define the energy density of field oscillations.

Unstable topological defects

- This picture takes place in axion cosmology.
- The first phase transition gives rise to cosmic axion string network.
- This network converts in the second phase transition into walls-bounded-by-strings structure (walls are formed between strings along the surfaces $\alpha = \pi$), which is unstable.
- However, the energy density distribution of coherent oscillations of the field α follows the walls-bounded-by-strings structure.
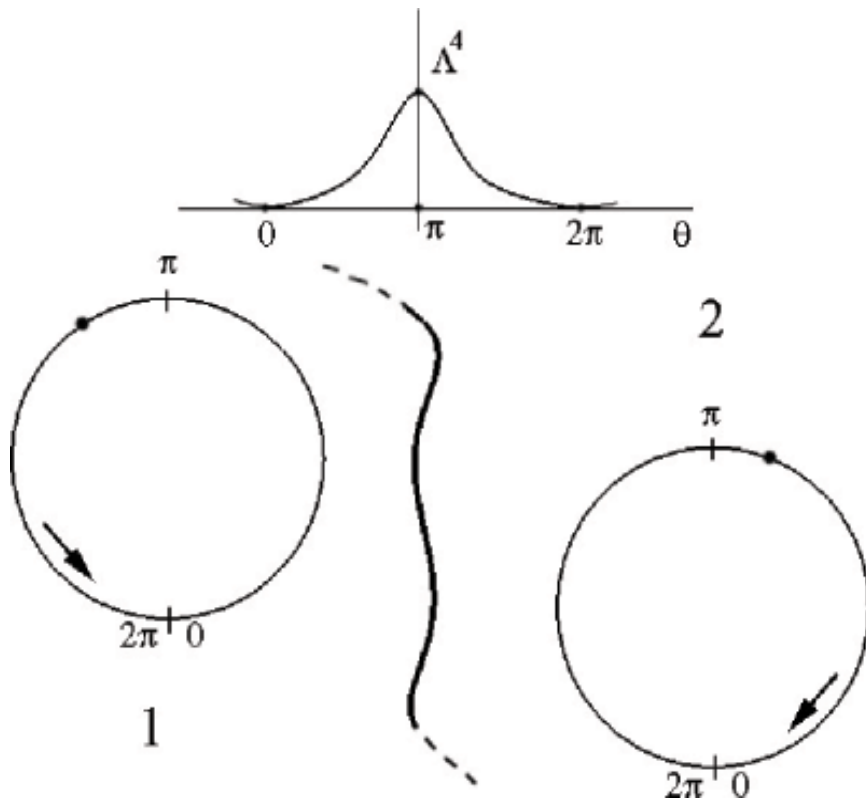
Archioles structure

- **Numerical studies revealed that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.**
- **The fact that the energy density of coherent axion field oscillations reflects this property is much less known. It leads to a large scale correlation in this distribution, called archioles.**
- **Archioles offer possible seeds for large scale structure formation.**
- **However, the observed level of isotropy of CMB puts constraints on contribution of archioles to the total density and thus puts severe constraints on axions as dominant form of Dark Matter.**

Massive Primordial Black Holes

- Any object can form Black hole, if contracted within its gravitational radius. It naturally happens in the result of evolution of massive stars (and, possibly, star clusters).

- In the early Universe Black hole can be formed, if within cosmological horizon expansion can stop [Zeldovich, Novikov, 1966]. Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars).

- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.
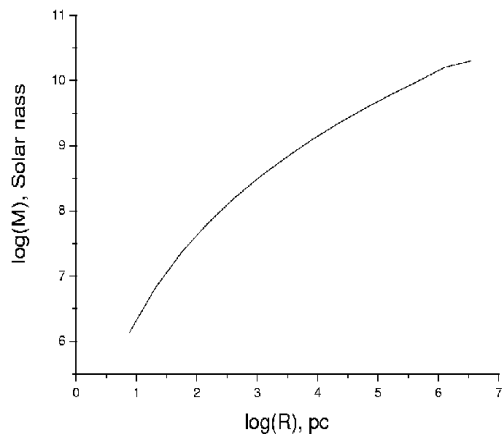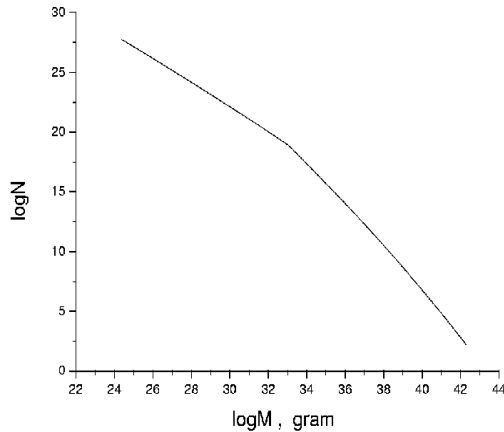
Closed walls formation in Inflationary Universe

If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

$$\Delta\theta \approx H_{\text{infl}}/(2\pi f)$$

Such fluctuations can cross π

and after coherent oscillations begin,regions with $\theta > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls

Massive PBH clusters

Each massive closed wall is accompanied by a set of smaller walls.
As soon as wall enters horizon, it contracts and collapses in BH.
Each locally most massive BH is accompanied by a cluster of less massive BHs.
The structure of such massive PBH clusters can play the role of seeds for galaxies and their large scale distribution.

Spectrum of Massive BHs

- The minimal mass of BHs is given by the condition that its gravitational radius exceeds the width of wall ($d \approx 2f/\Lambda^2$)

$$r_g = \frac{2M}{m_{Pl}^2} > d = \frac{2f}{\Lambda^2} \Rightarrow M_{min} = f\left(\frac{m_{Pl}}{\Lambda}\right)^2$$

- The maximal mass is given by the condition that pieces of wall do not dominate within horizon, before the whole wall enters the horizon

$$R < \frac{3\sigma_w}{\rho_{tot}} \Rightarrow M_{max} = f\left(\frac{m_{Pl}}{f}\right)^2\left(\frac{m_{Pl}}{\Lambda}\right)^2 \Rightarrow \frac{M_{max}}{M_{min}} = \left(\frac{m_{Pl}}{f}\right)^2$$

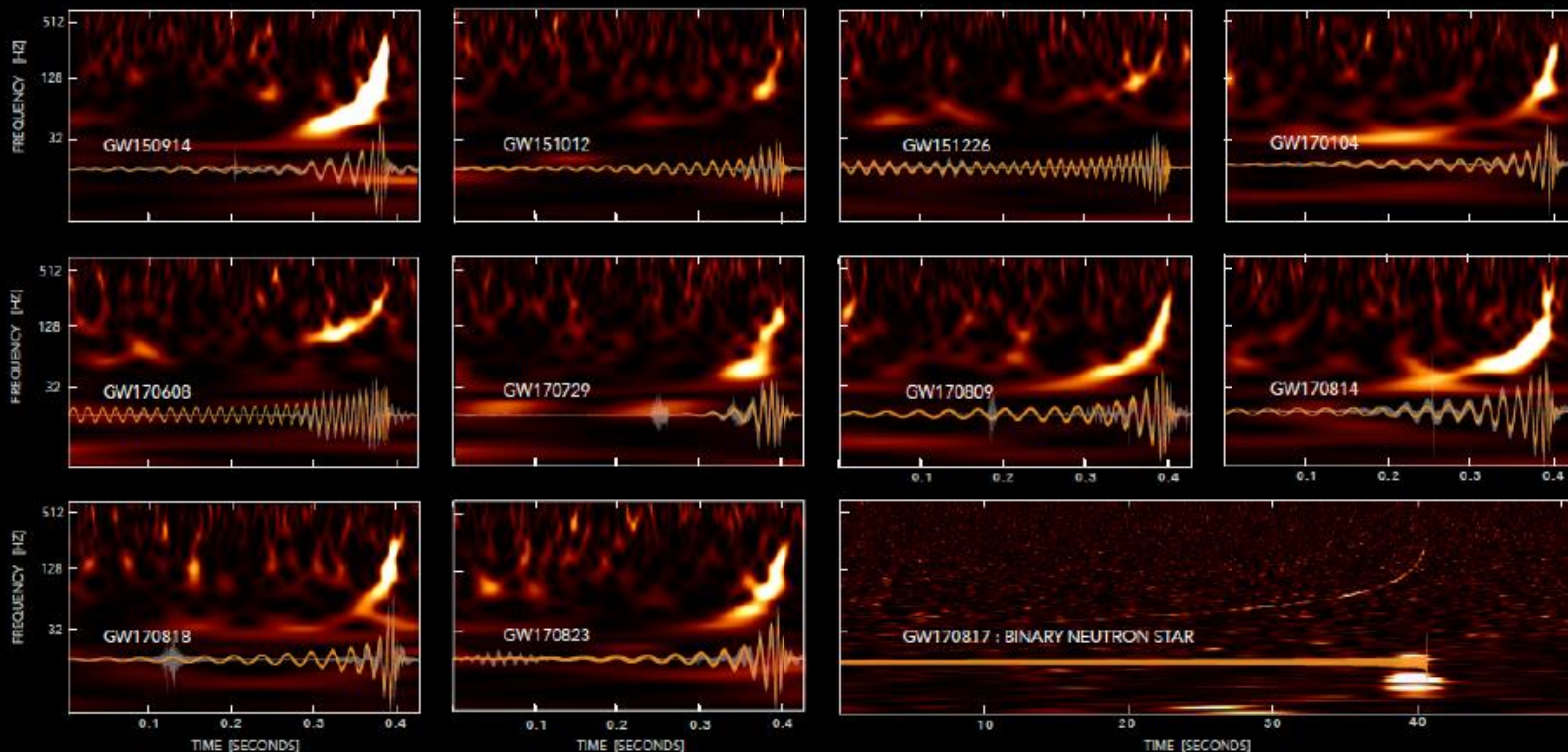# GW signals from closed wall collapse and BHs merging in clouds

- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

$$\Omega_{GW} \approx 10^{-4} \left(f / m_{Pl} \right)$$

- At $f \sim 10^{14} GeV$ $\quad$ $\Omega_{GW} \sim 10^{-9}$

- For $1 < \Lambda < 10^8 GeV$ $\quad$ $3 \cdot 10^{-3} Hz < \nu_0 < 3 \cdot 10^5 Hz$

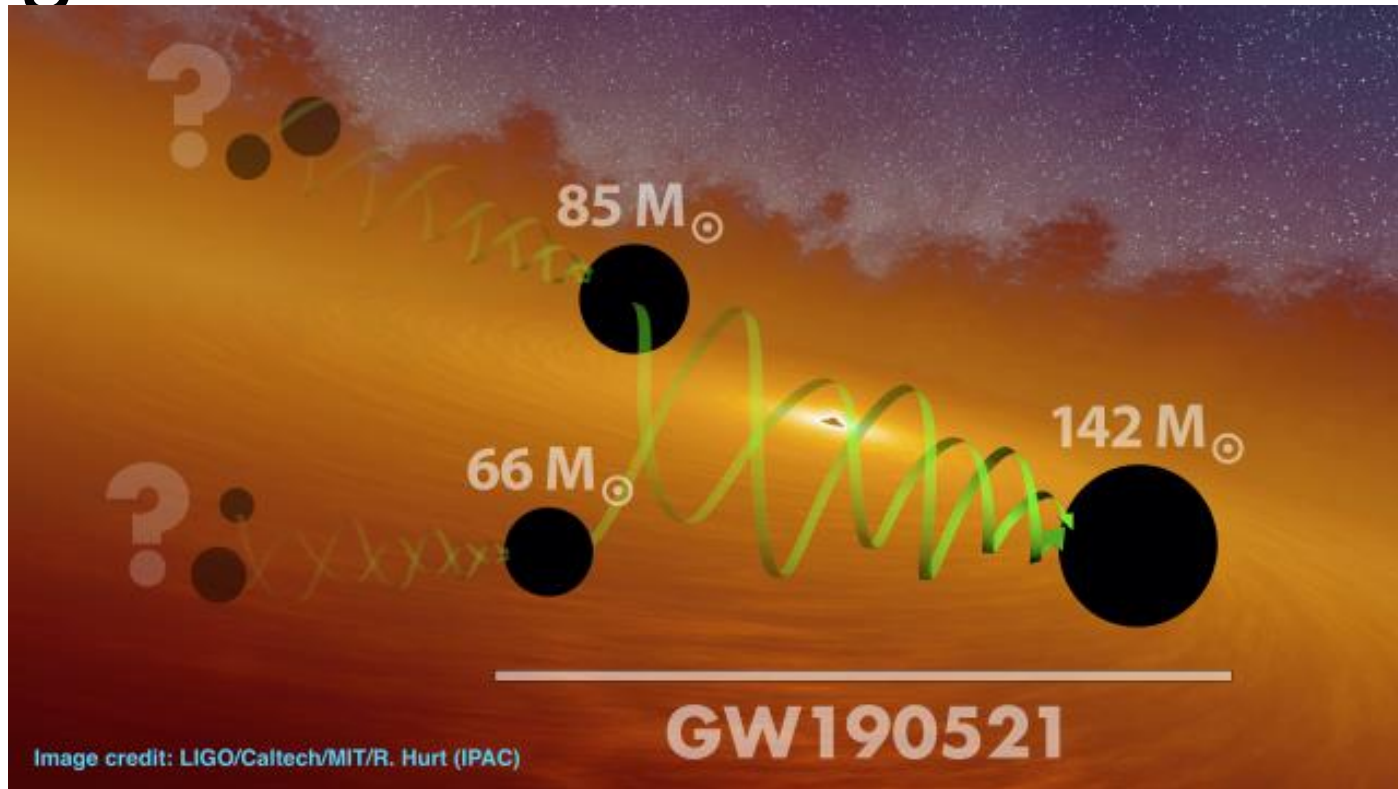- Merging of BHs in BH cluster is probably detected by LIGO!.

Parameter estimation

- Median values and 90% credible intervals based on two GR waveform models
- GW170729: highest mass and most distant BBH observed to date (median values); has moderate spin
- GW170818: best localised BBH to date - HLV detection
- Results consistent with previously published ones

Event	$m_1/\mathrm{M_\odot}$	$m_2/\mathrm{M_\odot}$	$\mathcal{M}/\mathrm{M_\odot}$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M_\odot}$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M_\odot}c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\ s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Binaries of massive PBHs?

- Massive PBHs are not distributed homogeneously in space, but are in clouds.

- It makes more probable formation of massive PBHs binaries.

- The problem of creation of stellar mass PBH clouds, their evolution and formation of BH binaries in them may be an interesting hot topic for a PhD thesis
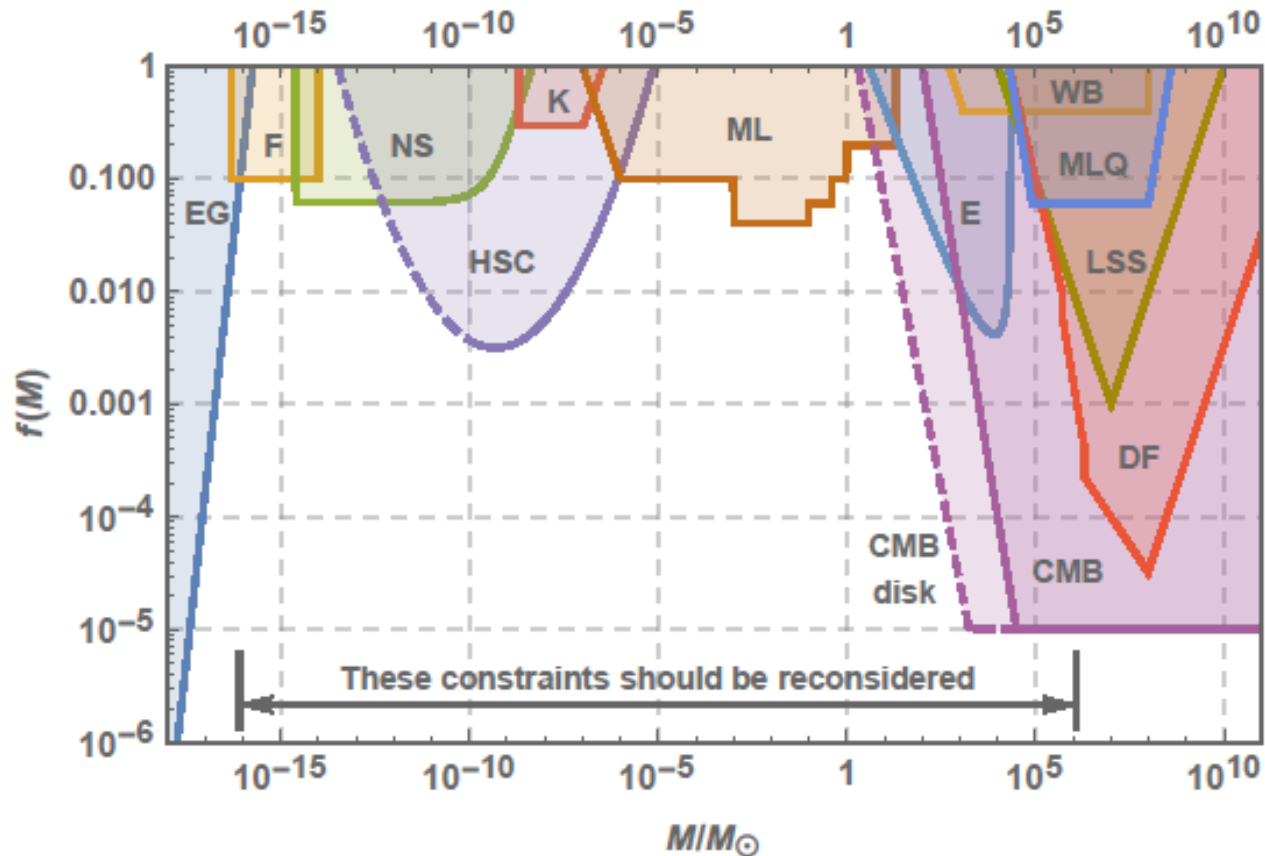
GW190521: A Binary Black Hole Merger with a Total Mass of 150 M_o

Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

The LIGO Scientific Collaboration, the Virgo Collaboration: Phys. Rev. Lett. 125, 101102 (2020)

Masses natural for PBHs in the gap for BHs of astrophysical origin
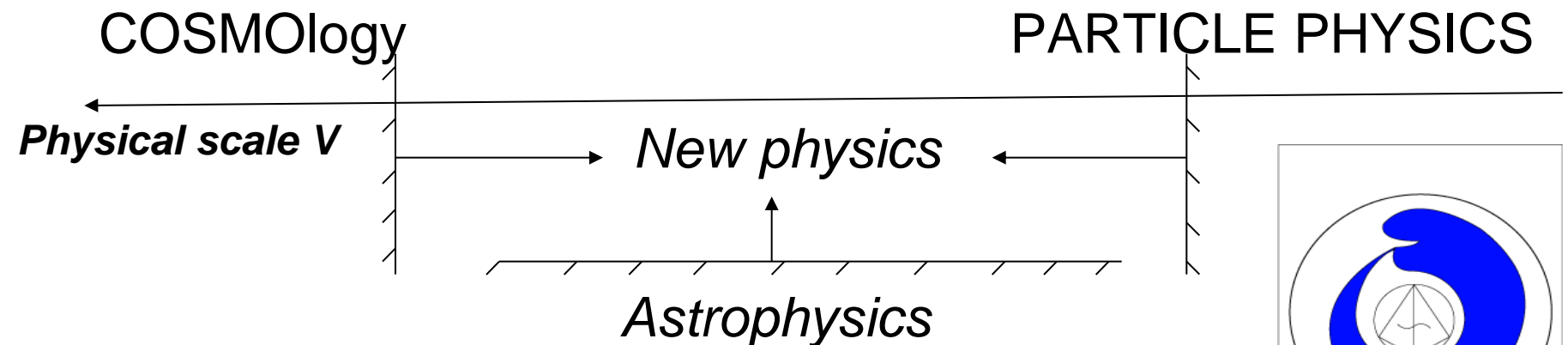
Constraints on PBH dark matter

The critical analysis of constraints on Primordial Black Holes (PBH)
dark matter releases a wide range of PBH masses for PBH DM

Conclusions

• **Physical basis of the modern cosmology implies new physics.**

• **PBHs provide probes for physics of very early Universe.**

• **Strong primordial nonlinear structures like massive PBH clusters provide cosmological probes for physics of inflationary models with baryosynthesis and dark matter.**

• **Positive evidence for PBHs would strongly restrict the allowed classes of BSM models, underlying cosmology of early Universe and provide the precision measurements of their parameters.**

• **In the context of cosmoparticle physics PBHs are the important element of multimessenger cosmology to be studied by multimessenger astronomical means**

Basic ideas of cosmoparticle physics

- **Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects**
- **New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.**
- **New stable particles should be present in the Universe. Breaking of new symmetries implies cosmological phase transitions. Cosmological and astrophysical constraints are supplementary to direct experimental search and probe the fundamental structure of particle theory at the scale V**
- **Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory**

COSMOlogy   PARTICLE PHYSICS

Physical scale V   *New physics*

Astrophysics

Extremes of physical knowledge converge in the
mystical Ouroboros vicious cycle of problems,
which can be resolved by methods of Cosmoparticle physics