Inflation & Cosmology I

- A Historical Perspective on Particle Cosmology -

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Progress in Particle Cosmology (1)

1\textsuperscript{st} stage: 1945 \sim 1975

- 1916\sim GR/Friedmann-Lemaitre model
- 1929 Hubble’s law: V=H_0 R
- 1946\sim Big-Bang theory/Nuclear astrophysics
- 1960\sim High redshift objects/Quasars
- 1965 Discovery of relic radiation from Big-Bang
  Cosmic Microwave Background (CMB) \sim 3K
- 1966 Sakharov’s condition
  (but didn’t attract much attention)
- 1970\sim Big-Bang Nucleosynthesis vs Observed Abundance
  \rightarrow Existence of Dark Matter (DM)

\[ H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{K}{a^2} \]
Big Bang Nucleosynthesis (BBN)

George Gamov: pioneer in particle cosmology (1940’s)

- 1st application of nuclear physics to cosmology
- explain light element abundance in the Universe

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundance of various elements was not accounted for by the above process. According to the theory of various elements, the following increase of the periodic system, the elements in the period must be transformed into elements of the next lower period, and thus also into elements of the third period. Using Eqs. (1) and (2) we can calculate the abundance of various elements in the still remaining elements. The non-existence of elements lighter than hydrogen is easily explained by the fact that the high temperature of the neutron gas was at that time. The transformation was taking place, and the subsequent neutron capture resulted in the building up of heavier and heavier nuclei. It must be remembered here, that due to the comparatively short life allowed for this process, the building up of heavier nuclei must have proceeded just above the upper energy of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of a balance of their electric charges by e-decay.

Thus the observed shape of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the process. Hence, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

\[ \frac{dn_i}{dt} = \frac{1}{2} \sum_{j} \sigma_{n_i} n_j \]

where \( n_i \) and \( \sigma_{n_i} \) are the relative numbers and capture cross sections for the nuclei of atomic weight \( i \), and where \( f \) is a factor characterizing the decrease of the density with time.
Chushiro Hayashi: father of astro-particle physics in Japan

- $\alpha \beta \gamma$ incorrectly assumed the Universe was totally filled by neutrons.

- Hayashi realized that the weak interaction must be in thermal equilibrium. (1950)

**correct initial cond. for BBN**

\[
\frac{n_N}{n_p} = \exp\left[-\frac{m_N - m_p}{T}\right]
\]

\[m_N - m_p = 1.293 \text{ MeV}\]

\[
\frac{n_N}{n_p} \approx 0.2 \text{ at } T = 10^{10} \text{ K}
\]
discovery of CMB (1964) = victory of Bing Bang Theory

- **Experiment**
  - 60’s ~70’s: golden age of particle physics
  - dawn of high energy physics: \( E \gg \text{GeV} \)
  - accelerator experiments > cosmic ray observations
    - CERN, Fermilab, DESI, SLAC, KEK, ...
    - neutral current 1973, \( J/\psi \) 1974, ...

- **Theory**
  - “Spontaneous Symmetry Breakdown”
  - success of Gauge Unification: Weinberg-Salam (1967)
  - Standard (Glasho-Weinberg-Salam) Model
  - \( SU(3) \times SU(2) \times U(1) \)
  - but no much was done in particle cosmology except for BBN computations...
Progress in Particle Cosmology (2)

2nd stage: 1975 ~ 1995

- 1975 Sato-Sato: Cosmological Constraints on Higgs
- 1977 Sato-Kobayashi: Constraints on Neutrino Mass & Species
- 1977 Yoshimura: Baryogenesis in Grand Unified Theory (GUT)

Dawn of Particle Cosmology/Inflationary Universe

- 1980~ Large Scale Structure: Cold DM (CDM)
  - Slow-roll Inflation / Cosmological Perturbation Theory
- 1992 CMB anisotropy by COBE: 1st Evidence for Inflation
  - hundreds of models of inflation

motivation/driving force

Brout, Englert & Gunzig ’77, Starobinsky ’79, Guth ’81, Sato ’81, Linde ’81, ...
Katsuhiko Sato: a great mind of our time
pioneer of modern particle cosmology

1st application of cosmology to “undiscovered” particles

1st systematic study on ν mass & no. of species
What is Inflation?

Brout, Englert & Gunzig ’77, Starobinsky ’79, Guth ’81, Sato ’81, Linde ’81,…

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at $t \sim 10^{-36}$ sec.
- It is the origin of Hot Bing-Bang Universe
- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:
  - if any of them can be said to be solved depends on precise definitions of the problems.
- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.
- Cosmic gravitational wave background is also generated.
Length Scales of Inflationary Universe

$\log L$

$\log a(t)$

$L = H_0^{-1}$

End of Inflation

- superhorizon scales
  \[ \frac{k^2}{H^2a^2} < 1 \]
  \[ L \propto a(t) \]
  \[ k = \text{const.} \]

- subhorizon scales
  \[ \frac{k^2}{H^2a^2} > 1 \]

Size of the observable universe

Inflationary Universe

Bigbang Universe

$k^2 < H^2a^2$
Pioneers of Inflation

Brout, Englert & Gunzig ’77

The Creation of the Universe as a Quantum Phenomenon

R. Brout, F. Englert, and E. Gunzig

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
Received July 7, 1977

In summary, the picture that emerges is in complete accord with the kinematic.

Now in the context of causal cosmology presented in Section 2. For \( y < y_0 \), one has \( p < 0 \) \( (p \approx -\sigma) \). For \( y > y_0 \), \( p \) becomes positive and \( \lambda \) undergoes an inflection. The situation is summarized in Figs. 1 and 2.

\[
\begin{align*}
    ds^2 &= -dt^2 + a^2(t)dH^2(3); \\
    a(t) &\approx H^{-1} \sinh Ht
\end{align*}
\]

Creation of Open Universe!

Now in the context of String Theory Landscape

Fig. 1. \( \lambda \) as a function of kinematical time \( \tau \) for \( \delta = 0 \). Time scales are calculated for \( m = 1 \) GeV.
Spectrum of relict gravitational radiation and the early state of the universe

A. A. Starobinskii
L.D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
(Submitted 25 October 1979)
Pis'ma Zh. Eksp. Teor. Fiz. 30, No. 11, 719–723 (5 December 1979)

A phenomenological model of the universe, in which the universe was in a maximum symmetrical quantum state before the beginning of the classical Friedman expansion, is examined. The spectrum of long-wave, background, gravitational radiation is calculated in this model. The possibility of detecting this radiation in the range $10^{-3} - 10^{-5}$ Hz is promising.

$$\epsilon (\nu) = \frac{2}{3\pi} s^2 \epsilon_0 \nu^{-1}$$

A NEW TYPE OF ISOTROPIC COSMOLOGICAL MODELS WITHOUT SINGULARITY

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Received 11 January 1980

The Einstein equations with quantum one-loop contributions of conformally covariant matter fields are shown to admit a class of nonsingular isotropic homogeneous solutions that correspond to a picture of the Universe being initially in the most symmetric (de Sitter) state.
Old Inflation

inflation as a 1st order phase transition

Sato ’81, Guth ’81

Inflationary universe: A possible solution to the horizon and flatness problems


The standard model of big bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separate regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

Summary. The progress of a first-order phase transition of a vacuum in the expanding Universe is investigated. The expansion of bubbles of a stable vacuum is calculated simultaneously with the cosmic expansion with the aid of the following two simplified nucleation rates of bubbles: (i) $p = p_T T_c \delta (T - T_c)$ in the hot Universe models, (ii) $p = 0$ for $n > n_c$ and $n = p_0$ for $n < n_c$ in the cold Universe models, where $T$ is the cosmic temperature, $T_c$ the critical temperature, $n$ the cosmic number density of the fermions coupled to the order parameter of the vacuum, $\nu_c$ the critical density, and $p_T$ and $p_0$ are parameters.

The following results are obtained: (1) If the nucleation rates are small and the vacuum stays at the metastable state for a long time, the Universe begins to expand exponentially. As a result, the progress of the phase transition is delayed more and more by the rapid cosmic expansion. In particular, in model (i), if $p_T$ is less than a critical value, the phase transition never finishes. (2) The lower limits of the nucleation parameter $p_T$ and $p_0$ are obtained from observation of the number ratio of photons to baryons in the present Universe. (3) If the phase transition of the vacuum in SU(5) GUT is of first order or if there exists a hypothetical first-order phase transition of the vacuum in the very early stage in which baryon number is not conserved, the density and the velocity fluctuations created by the phase transition may account for the origin of galaxies.

MULTI-PRODUCTION OF UNIVERSES BY FIRST-ORDER PHASE TRANSITION OF A VACUUM

Katsuhiko SATO, Hideo KODAMA, Misao SASAKI and Keiichi MAEDA


Gauge theories with spontaneously broken symmetries give rise to a cosmological phase transition if the phase transition is of first order. Such phase transitions, combined with general prediction, although the Creator might have made a unitary universe, many mini-universes are ward as a result of the phase transition.
New (slow-roll) Inflation
+ almost scale-invariant spectrum from vacuum fluctuations
Linde ’81, Mukhanov & Chibisov ’81

A NEW INFLATIONARY UNIVERSE SCENARIO: A POSSIBLE SOLUTION
OF THE HORIZON, FLATNESS, HOMOGENEITY, ISOTROPY AND
PRIMORDIAL MONOPOLE PROBLEMS

A.D. LINDE
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Received 29 October 1981

A new inflationary universe scenario is suggested, which is
possible solution of the horizon, flatness, homogeneity and in-
mortal monopole problem in grand unified theories.

CHAOTIC INFLATION

A.D. LINDE
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Received 6 June 1983

\[ H = \left( \frac{2}{3} \pi V(\phi)/M_p^2 \right)^{1/2} = \left( \frac{2}{3} \pi \lambda \right)^{1/2} \phi^2 / M_p \]  \hspace{1cm} (1)

The equation of motion of the field \( \varphi \) inside this do-
main is

\[ \ddot{\varphi} + 3H\dot{\varphi} = -\lambda \varphi^3 \] \hspace{1cm} (2)

A new scenario of the very early stages of the evolution of the universe is suggested. According to this scenario, infla-
tion is a natural (and may be even inevitable) consequence of chaotic initial conditions in the early universe.

Quantum fluctuations and a nonsingular universe

V. F. Mukhanov and G. V. Chibisov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
(Submitted 26 February 1981; resubmitted 15 April 1981)

Over a finite time, quantum fluctuations of the curvature disrupt the
nonsingular cosmological solution corresponding to a universe with a polarized
vacuum. If this solution held as an intermediate stage in the evolution of the
universe, then the spectrum of produced fluctuations could have led to the
formation of galaxies and galactic clusters.

\[ Q(k) = 3 \pi M \left( 1 + \frac{1}{2} \ln \frac{H}{k} \right) \]

The fluctuation spectrum is thus nearly flat.
Slow-roll Inflation

Linde (1981),…

Universe dominated by a scalar (inflaton) field

For sufficiently flat potential:

\[ H^2 \approx \frac{8\pi G}{3} V(\phi) \left( \frac{1}{2} \dot{\phi}^2 \ll V(\phi) \right) \]

\[ \Rightarrow \frac{\dot{H}}{H^2} = \frac{3\dot{\phi}^2}{2V(\phi)} \ll 1 \]

• \( H \) is almost constant \( \sim \) exponential expansion = inflation

• \( \phi \) slowly rolls down the potential: slow-roll (chaotic) inflation

• Inflation ends when \( \phi \) starts damped oscillation.

\[ \Rightarrow \phi \text{ decays into thermal energy (radiation)} \]

Birth of Hot Bigbang Universe
Length Scales of Inflationary Universe

\[ L = H_o^{-1} \]

**End of Inflation**

superhorizon scales

\[ \frac{k^2}{a^2} < H^2 \]

Inflationary Universe

**L \propto a(t)**

k=const.

subhorizon scales

\[ \frac{k^2}{a^2} > H^2 \]

Bigbang Universe

Size of the observable universe

Logarithmic scale

\[ \log L \]

\[ \log a(t) \]
Generation of curvature perturbation

scalar field vacuum fluctuation (on “flat” slices): $\delta \phi_f$ (on “superhorizon”)

$\ddot{\delta \phi}_{f,k} + 3H \dot{\delta \phi}_{f,k} + \frac{k^2}{a^2(t)} \delta \phi_{f,k} \approx 0 : \delta \phi_{f,k} \rightarrow \text{const.}$ as $\frac{k^2}{H^2 a^2} \rightarrow 0$

comoving curvature perturbation $R_c \sim -$ Newton potential

• $\delta \phi$ is frozen on “flat” ($R=0$) 3-surface ($t=$const. hypersurface)
• Inflation ends/damped osc starts on $\phi =$const. 3-surface.

$T = \text{const.}, \quad R \equiv R_c \neq 0$

end of inflation

$\delta \phi \equiv \delta \phi_f \neq 0$

$R_c = -\frac{H}{\dot{\phi}} \delta \phi_f$

hot bigbang universe
Intermission: going back and forth...

Nuffield Workshop
June-July 1982

apparently, a lot of confusion
even among “big names”.

The history of the derivation of the spectrum of adiabatic perturbations in new inflation,
as presented in the talk by M.S. Turner at the Nuffield workshop in June 1982. To the best
of my knowledge, the only person who did not change his results during the workshop
was Alexei Starobinsky.

figure and text: courtesy of V. Mukhanov
Curvature Perturbation Formula

Mukhanov-Sasaki variable: $\mathcal{R}_m$ [now often denoted by $\zeta$]

Gravitational instability of the universe filled with a scalar field

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(Submitted 21 February 1985)

Pis'ma Zh. Eksp. Teor. Fiz. 41, No. 9, 402–405 (10 May 1985)

A self-consistent problem involving the behavior of small perturbations in an isotropic homogeneous universe filled with a scalar field is considered. Solutions describing the evolution of perturbations in the case of an arbitrary scalar-field potential are obtained.

$$ds^2 = (1 + 2\mathcal{D}) dt^2 - (1 - 2\mathcal{D}) a^2(t) \delta_{\alpha\beta} dx^\alpha dx^\beta,$$

$$\mathcal{D} = \frac{1}{5} H \left( \frac{\dot{\phi}}{\varphi_0} \right).$$

Quantum perturbations of the gauge-invariant quantities are considered. The action for the perturbations is obtained, and this action is expressed in terms of a gauge-invariant variable which completely characterizes the perturbations. A consistent quantum theory of such perturbations is constructed. The spectrum of inhomogeneities in inflationary models of the evolution of the universe is calculated.

$$\mathcal{D} = \frac{1}{5} H \left( \frac{\dot{\phi}}{\varphi_0} \right).$$

Large Scale Quantum Fluctuations in the Inflationary Universe

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(Received June 21, 1986)

Quantum fluctuations of an inflation-driving scalar field are evaluated in a way manifestly independent of the choice of coordinate gauge conditions. It is found that the dynamical degree of freedom of the fluctuating field is represented in terms of a nearly massless conformal scalar field in the unperturbed de Sitter background. Implications of the result are discussed. In particular, it is argued that classical cosmological density perturbations may not be generated in the sense as discussed in the literature.

$$\Phi = \frac{3(1+w)}{3w+5} = -\frac{3}{5} \mathcal{R}_m \text{ for } w = 0$$

ones once they are outside the horizon, a typical amplitude of the perturbations on a comoving scale $k^{-1}$ approaches the value

$$\sqrt{\langle \mathcal{R}_m^2 \rangle_k} \approx \sqrt{\frac{4\pi k^3}{(2\pi)^3}} \mid r_k \mid^2 \approx \frac{H^2}{2\pi \dot{\phi}},$$

$$n = -a \frac{\dot{\phi}}{\alpha} \mathcal{R}_m = -a \frac{\dot{\phi}}{H} \mathcal{R}_m \quad (\alpha = H \dot{a}).$$
Theoretical Predictions

• Amplitude of curvature perturbation:

\[ \mathcal{R}_c = \left. \frac{H^2}{2\pi \dot{\phi}} \right|_{k/a = H} \]

Mukhanov (1985), MS (1986)

• Power spectrum index:

\[
\frac{4\pi k^3}{(2\pi)^3} P_S(k) = \left[ \frac{H^2}{2\pi \dot{\phi}} \right]^2_{k/a = H} = Ak^{n_s - 1} ; \quad n_s - 1 = M_p^2 \left( \frac{2}{V} - 3 \frac{V''}{V^2} \right)
\]

Stewart-Lyth (1993)

• Tensor (gravitational wave) spectrum:

\[
\frac{4\pi k^3}{(2\pi)^3} P_T(k) = Ak^{n_T} ; \quad n_T = -\frac{1}{8} \frac{P_S(k)}{P_T(k)} \equiv -\frac{r}{8}
\]

Liddle-Lyth (1992)

“consistency relation”
Progress in Particle Cosmology (3)

3rd stage: 1995~2015

- 1995 Hubble Deep Field: $z \sim 4-5$
- 1998 2dF Galaxy Redshift Survey
  $3 \times 10^5$ galaxies, $z \sim 0.2$
- 1998 Accelerated Expansion (SCP/HZT)
- 2003 Accurate CMB angular spectrum (WMAP)
  Confirming Flatness of the Universe
  Strong evidence for Dark Energy
- 2005~ Cosmic (String Theory) Landscape!
- 2000~ SDSS I/II/III, 2014- SDSS-IV, ...
  $> 10^6$ galaxies, high precision LSS data
- 2013 High precision CMB spectrum (Planck)
  Very strong evidence for Inflation
CMB anisotropy spectrum

Planck 2015 XI

$\Omega_{CDM}$
Planck+LSS constraints on inflation

Planck 2015 XX

- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$
- simplest $V \propto \phi^2$ model is almost excluded

$$n_s - 1 \equiv \frac{\frac{d}{d \log k} \log \left[ k^3 P_S(k) \right]}{d \log k}$$

$$r \equiv \frac{P_T(k)}{P_S(k)}$$
Summary: Current Status

- Standard (single-field, slow-roll) inflation predicts almost scale-invariant Gaussian curvature perturbations.
- Observational data are consistent with theoretical predictions.
  - almost scale-invariant spectrum: \( n_S = 0.965 \pm 0.005 \) (68% CL)
  - highly Gaussian fluctuations: \( f_{NL}^{\text{local}} = 2.5 \pm 5.7 \) (68% CL)

\[
R = R_{\text{gauss}} + \frac{3}{5} f_{NL}^{\text{local}} R_{\text{gauss}}^2 + \cdots
\]

- Simple standard models seem to be almost excluded...
  - detection of \( f_{NL}^{\text{local}} = O(1) \) would kill all the standard models.
- Tensor (gravitational wave) perturbation remains to be detected

\[
r = \frac{P_T(k)}{P_S(k)} \lesssim 0.05
\]
4th stage: 2015 ~ 20??

- **2015** First detection of GWs from Binary Black Holes (LIGO)
  - **Dawn of GW Astronomy**

- **2017** First detection of GWs & EMWs from Binary Neutron Stars (LIGO+VIRGO)
  - **Multi-messenger Astronomy**

- **2020+** Upgraded LIGO+VIRGO +KAGRA start operating

- **2020+** Deep & Wide LSS surveys (HSC-SSP/LSST/…)
  - Data precision will reach <1 %

- **2020+** CMB primordial B-modes (LiteBIRD/CORE/…)
  - Proving Inflation!?

- **2020+** Ultimate Theory of Inflation?
  - Evidence for Cosmic Landscape/Multiverse?

- String Theory as driving force
signature of primordial GWs

spacetime (~graviton) vacuum fluctuations from inflation

GWs: quadrupolar in nature

→ B-mode polarization in CMB anisotropy

Seljak & Zaldarriaga (1996)

• E-mode (even parity)

• B-mode (odd parity)

= cannot be produced from
density fluctuations
string theory suggests an intriguing picture of the early universe

Maybe we live in one of these vacua…

taken from http://ineedfire.deviantart.com/art/Psychedelic-Multiverse-104313536
Swampland conjecture?

$|\nabla V| < c \frac{V}{M_P} ; \quad c = O(1)$  
Obied, Ooguri, Spodyneiko & Vafa ‘18

$|\nabla V| < c \frac{V}{M_P} ; \quad c = O(1)$  
Ooguri, Palti, Shiu & Vafa ‘18

or

$\min(\nabla_i \nabla_j V) \leq \frac{-c'V}{M_P^2} ; \quad c' = O(1)$

In particular, de Sitter (dS) space is in swampland!

If dS exists in nature,

either swampland conjecture is false

or string theory is false!

let us assume (hope?) that the conjecture is false!
Universe jumps around string landscape by quantum tunneling

- It can go up to a vacuum with larger $\rho_v$
  - De Sitter (dS) space ~ thermal state with $T = \frac{H}{2\pi}$
  - $SO(4,1)$
- If tunnels to a vacuum with $\rho_v < 0$, it collapses in $t \sim M_P/|\rho_v|^{1/2}$
  - Focus on $\rho_v > 0$
- Inside a bubble with $\rho_v > 0$ is Open dS universe
  - $SO(3,1)$

Sato, Kodama, MS & Maeda ('81)
What if this is the case?

- **a few possibilities**

1. inflation after tunneling was short enough \((N \sim 60)\)

\[ \Omega_{K,o} = 1 - \Omega_o = 10^{-2} \sim 10^{-3} \quad \text{“open universe”} \]

- signatures in large angle CMB anisotropies?
  
  - Kanno, MS & Tanaka (’13), White, Zhang & MS (’14), ...

2. inflation after tunneling was long enough \((N >> 60)\)

\[ \Omega_{K,o} = 1 - \Omega_o \ll 1 \quad \text{“flat universe”} \]

- signatures from bubble collisions
  
  - Sugimura, Yamauchi & MS (’12), ...

3. quantum entanglement among multiverse?

- Maldacena & Pimentel (’13), Kanno (’14), ...
length scales in open inflation

- tunneling
- fast-roll
- slow-roll

- curvature radius
- curvature dominated phase
- fast-roll phase
- slow-roll phase

- current comoving Hubble radius
- break scale in $P(k)$
- $H^{-1}$

- log $L$
- log $N$
Inflationary cosmology in 21st Century

- **High Precision Cosmology**
  - gravitational waves from Inflation
  - extra dimensions / string cosmology
  - origin of dark energy
  - ...

- **Gravitational Wave Astronomy has begun**
  - LIGO (+VIRGO) detected GWs from BH & NS binaries

**Era of Multi-messenger Astronomy**

fundamental laws of nature may be revealed.
(“ultimate” theory?)

inflation = testbed for ultimate theory