Birth of cosmic inflation -as a personal recollection-

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Congratulations!

LiteBIRD has selected a mission for L-class slot of ISAS/JAXA

This is what we have been waiting for long time.

We honor the tireless efforts of the team members, including Professor Hazumi.

"Cosmic Inflation "is the theory that creates a fireball universe and solves the difficulties of the traditional Big Bang Model, and was proposed by several researchers including A. Guth.

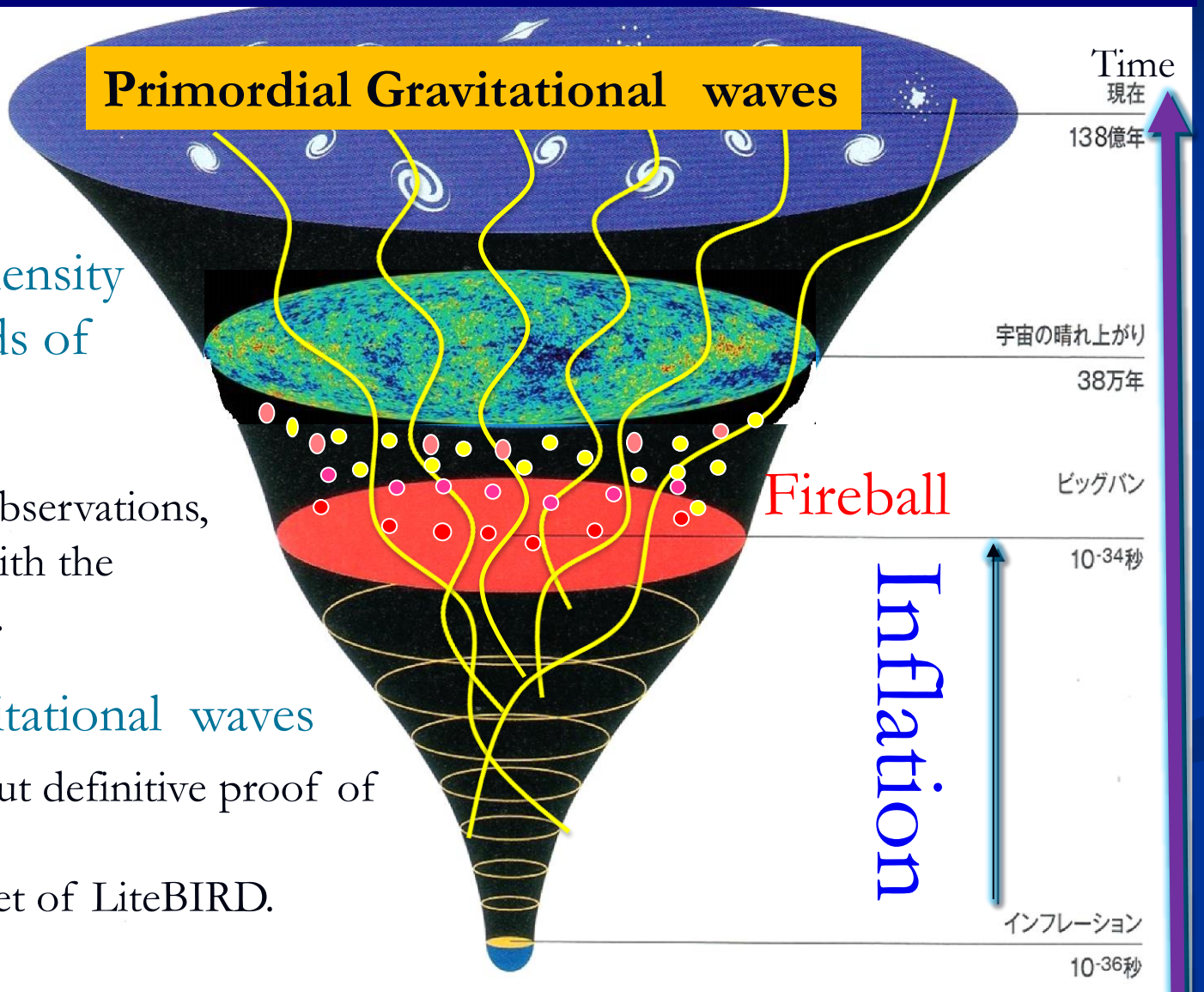
Two important Predictions

1. Super-horizon density fluctuations as seeds of large structure

Discovered by CMB observations, precisely consistent with the theoretical predictions.

2. Primordial gravitational waves

not yet discovered, but definitive proof of Cosmic Inflation.
Discovery is the target of LiteBIRD.



The list of articles on Cosmic Inflation cited in Scientific Background on the Nobel Prize in Physics

THE ACCELERATING UNIVERSE (2011)

1.A. Starobinsky, Phys. Lett., B91, 99-102, (1980); submitted January 1980
quantum gravity effects,
predicted primordial gravitational waves.

2. K. Sato, MNRAS 195, 467-479, (1981) submitted February 1980
GUT phase transition,
predicted super-horizon fluctuations for seeds of structure are created

3. A.H. Guth, Phys. Rev., D23, 347-356, (1981); submitted August 1980
GUT phase transition, horizon and flatness problems are solved,
gave wonderful name of Inflationary Universe Model

4. A.D. Linde, Phys. Lett., B108, 389-393, (1982);
5. A. Albrecht and P.J. Steinhardt, Phys. Rev. Lett., 48, 1220-1223, (1982),
by making fine tuning of GUT parameters, proposed slow roll over model.

I wrote not only above article 2., but also three papers on Inflation.

Three papers on Inflation submitted earlier than Guth's one

1. **Cosmological Baryon-Number Domain Structure and the First Order Phase Transition of a Vacuum**
   Phys. Lett. **99B** (1981), 66-70. submitted 4 February 1980 .

2. **First Order Phase Transition of a Vacuum and the Expansion of the Universe**
   Mon. Not. Roy. Astr. Soc. **195** (1981), 467-479. 21 February 1980 .

   (shown as the second paper in preceding slide)

3. **Monopole Production in the Very Early Universe in a First- Order Phase Transition**
   M.B. Einhorn and K. Sato, Nucl. Phys. **B180** (1981), 385-404. 30 July 1980 .

1. Baryon-antibaryon domain structure of Universe

Phys. Lett. **99B** (1981), 66-70 submitted 4 February 1980

- Baryon number asymmetry of the universe is generated by Sakharov condition; CP breaking, baryon number –non conservation & large deviation from thermal equilibrium (Sakharov '67,Kuzmin'70, *Yoshimura'78). But the basic law of physics should be symmetrical in principle, then CP-conservation should be broken spontaneously in the early universe.(Zeldovich et. al '74, Brown & Stcker,'79)

- This scenario naturally predicts that baryon- symmetric universe with local baryon number fluctuations (baryon-antibaryon domain structure).

- But in the old Big bang Model, the domain sizes (upper limit is the horizon) is extremely small. Domains annihilate each other and eventually reduce to baryon number free universe. (Steigman, 1976)

- I proposed a model like slow-roll-over Inflation, and showed that if Inflation occurs after spontaneous symmetry breakdown of CP-conservation, the domain sizes are extended exponentially. Then annihilation is avoided and the domain structure survive even now.

Explorations of antimatter nuclei in cosmic rays might give some indication on this model.

2.Generation the seed of large scale structure

Mon. Not. Roy. Astr. Soc. **195** (1981), 467-479

- The nucleation, expansion, and coalescence of bubbles were examined in detail and pointed out that the classical density fluctuations created by the phase transition are extend over the horizon during inflation, and **suggested these super-horizon fluctuations are seeds of cosmic structures.**

- At present, it was shown the amplitude of fluctuations is too large in this scenario, and the origin of the fluctuations should be quantum ones in slow roll phase.

- However the mechanism that small scale quantum fluctuations are extend by inflation is essentially the same one proposed in this paper.

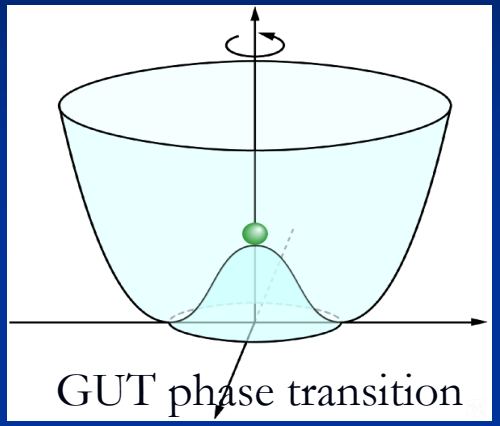
Just after completed the manuscript, Feb., 1980, I visited Cambridge, M. Rees, a Mecca of the theory of structure formation of Universe, in order to make propaganda of this paper which suggested the origin of seeds of cosmic structures.

Lord Martin Rees
Astronomer Royal

Following the suggestion of Rees, I submitted to M.N.R.A.S.

3. Overproduction problem of magnetic monopoles

M.B. Einhorn and K. Sato Nucl. Phys. **B180** (1981), 385-404

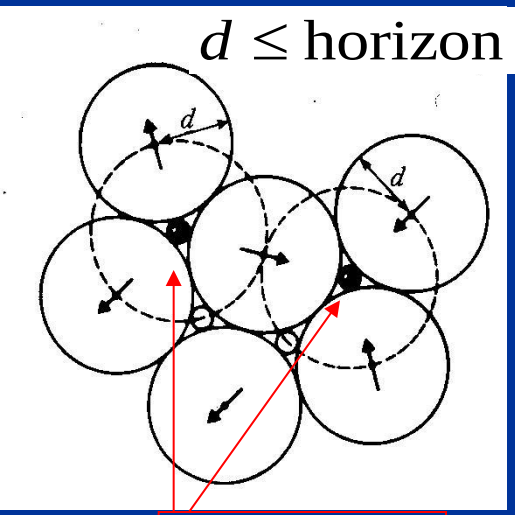


GUT phase transition

Overproduction problem was severe conflict between Big Bang Model and GUTs.

Monopoles are copiously produced by phase transition, since the domain size extremely small (<the horizon).

$$\frac{n_{monopole}}{n_{baryon}} \approx 10^{-2}$$



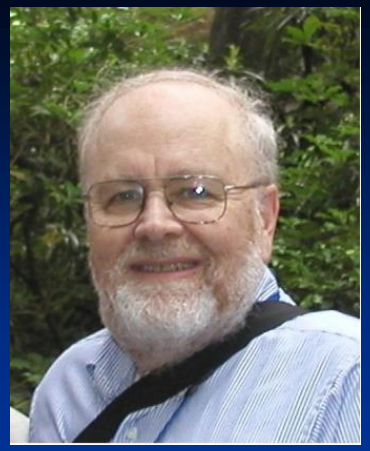
monopoles

After completed the first paper in early 1980, I found two papers,

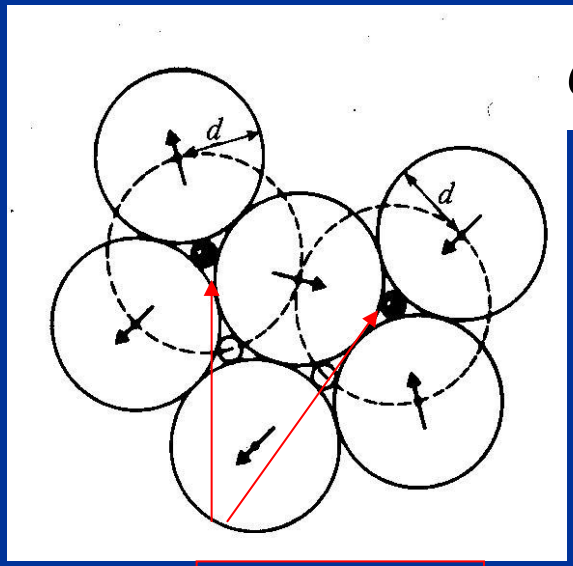
1. M.B. Einhorn, D.L. Stein and D. Toussaint, Phys. Rev. D21 (1980) 3295
2. A.H. Guth and S.-H. Tye, Phys.Rev.Lett., 44, (1980) 631

I found they didn't recognized INFLATION yet ! They assumed $a(t) \propto t^{1/2}$. They discussed only entropy production by first order transition.

Very fortunately, Martin Einhorn came to Copenhagen, and we started collaboration. Our paper was the first paper to solve Overproduction problem of magnetic monopoles by Inflation?



In the Inflation model, domain sizes are enlarged by exponential expansion. Monopoles are got rid of from our view.



monopoles

$$d \gg 10^{10}\,\text{lys}$$

$$\frac{n_{monopole}}{n_{photon}} \approx 10^{-11}$$

$$\frac{n_{monopole}}{n_{photon}} \approx \frac{1}{8}\frac{\left(d \cdot \exp(\tau/l)\right)^{-3}}{T_c^3} \Rightarrow 0$$

Background of "My Cosmic Inflation"

- All the three papers on Inflation were written in Copenhagen.
  invited as a visiting professor at NORDITA(1979 - 1980)

I was invited because works on nuclear astrophysics were appreciated.
Neutrino Trapping Theory in Supernova Cores (1974,1975),…

- I leaned Weinberg-Salam Theory for SN neutrino interactions, and pointed out neutrinos are trapped in supernova cores by the effect of coherent scattering with nuclei, and νs are Fermi -degenerate. Nuclear species were calculated extending our result "Nuclei in Neutron Matter"(1970), collaboration with H.A. Bethe.

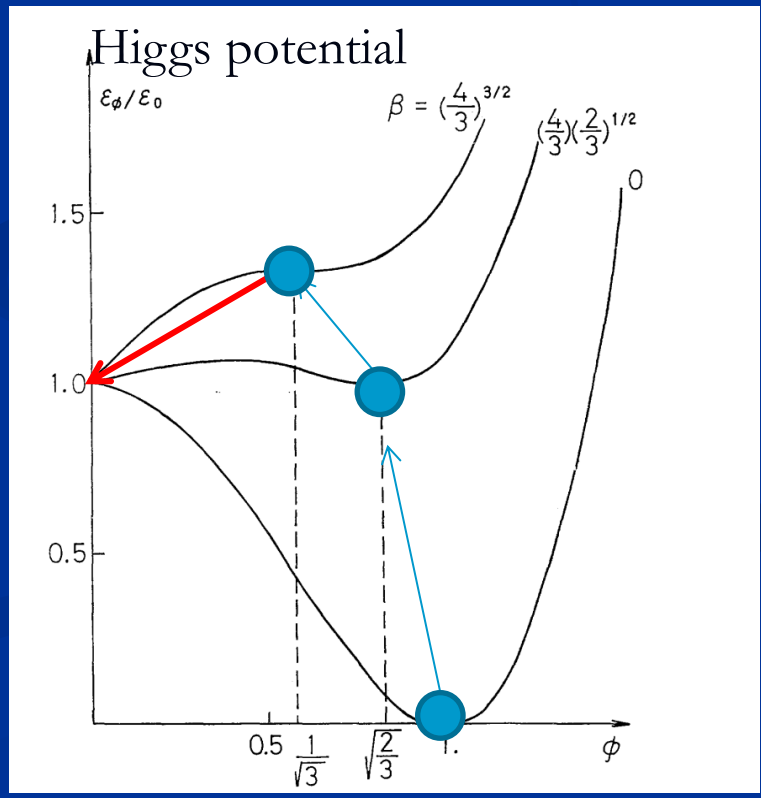
Neutrino Burst of Supernova1987A was detected by KAMIOKANDE and IMB. Observed durations is very consistent with Neutrino trapping theory.

From WS phase transition to Inflation

- From the studies of SN neutrinos, I noticed the Weinberg-Salam Theory stands on the idea of phase transition of vacuum, and found it predicts interesting astrophysical and cosmological predictions.

  - The broken symmetry of the vacuum is restored in super dense matter(hypothetical super dense stars, early universe, ..) by the interaction between Higgs particles and fermions (Sato, Nakamura, 1976).

With increasing density, the minima shifts to the upper left, and at the critical density ,the minima disappears and jumps to zero.



- **In 1976, A.D. Linde sent me Lebedev Inst. preprints, and gave a letter that he obtained similar type result on the phase transition in Abelian gauge field model.**

(Kirzhnits and Linde (72) is the first paper to discuss about cosmological vacuum phase transition.)

- Since then, we have been communicating, but at that time, it took a few months to receive answer, now days, a few minutes.

- Started work on GUT phase transition, but the phase transition of vacuum was considered to be completely irrelevant to reality, and the number of articles per year in the world was very small.

It was a really peaceful time compared with today's highly competitive Internet era.

Conclusion

- **At present, there is no definite inflation theory and a huge number of models have been proposed.**
- **Observations of primordial gravitational waves are expected to sort out which theories are appropriate.**

We hope greatly LiteBIRD will discover the PGWs by the observation of the highest sensitivity, and proves that inflation has surely occurred at the beginning of the universe.

Further, we hope that new paradigm on basic laws of physics would be suggested from the discrimination of inflation models.