Inflation before Inflation:
From Supernovae to Multiproduction of Universes

Katsuhiko Sato

1)Department of Physics
2)Research Center for the Early Universe (RESCEU)
3)Institute for the Physics and Mathematics of the Universe (IPMU)
The University of Tokyo

Three papers 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 K. Sato. submitted 1980 February 4.

   Make possible the universe of the baryon anti-baryon domain structure. Annihilation is suppressed because the domains are extended over the usual horizon.

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

   Generation of the seeds of super-horizon scale structure of the universe

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

During my stay in NORDITA (1979-1980), I realized the universe expands exponentially and is heated up by latent heat, and this model solve three problems.

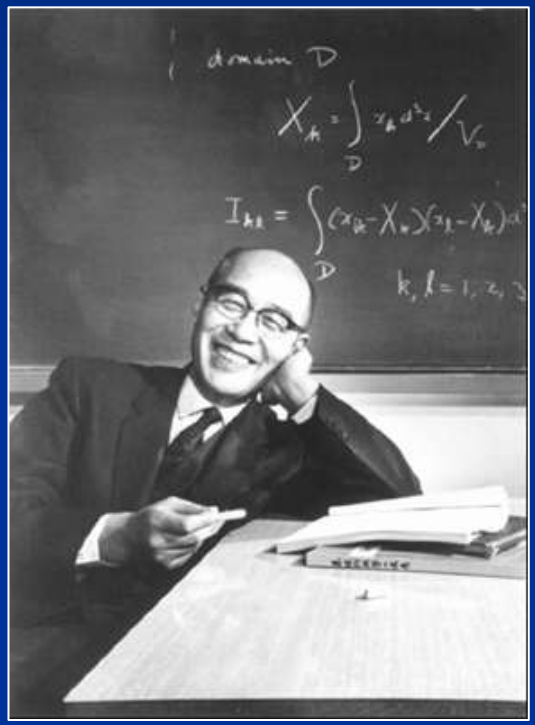
Successively, we proposed Multiproduction of Universes:

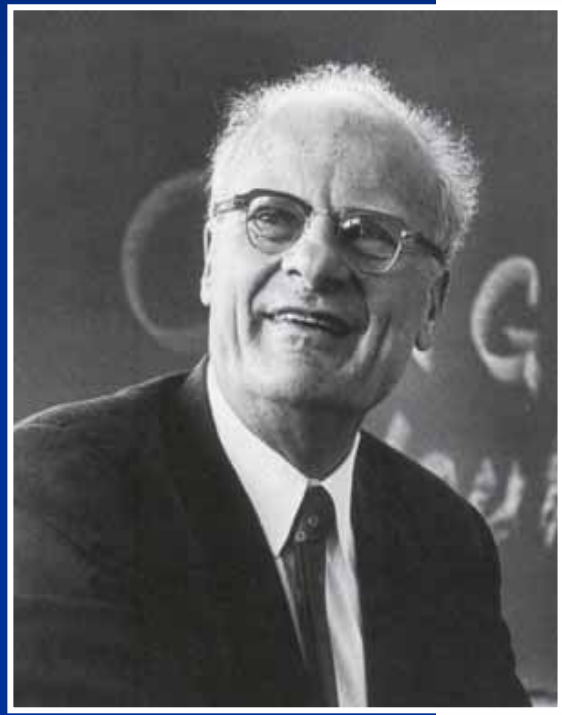
Inflation necessary predicts universes are created copiously via **wormholes**.

- **Creation of Wormholes ….** Prog. Theor. Phys. **65** (1981), 1443-1446
- **Creation of Schwarzschild-de Sitter Wormholes ….**Phys. Lett. **108B** (1982), 98-102
- **Multi-Production of Universes by First-Order Phase Transition of a Vacuum**
  Phys. Lett. **108B** (1982), 103-107. K. Sato, H. Kodama, M. Sasaki and K. Maeda

We discussed **Multiproduction of Universes** on the first order phase transition scenario, but this holds for various inflation models universally .

H.A.Bethe came to Kyoto, Yukawa Inst. as a guest of Prof. Yukawa in 1969.





Astron. & Astrophys. 7, 279—288 (1970)

Nuclei in Neutron Matter

H. A. Bethe
Cornell University, Ithaca, N. Y.

G. Börner
Max-Planck-Institut für Physik und Astrophysik, München

Katsuhiko Sato
Kyoto University, Kyoto

Received March 25, 1970

e equation of state at densities somewhat below nuclear is re-examined. The results a
ient with previous authors, but there are quantitative differences. Up to $\varrho_1 = 2.8 \cdot 10^{1}$
n-rich nuclei and electrons; between ϱ_1 and $\varrho_2 = 4.34 \cdot 10^{13}$ g/cm³ there is in addition a gas
nuclei disappear rather suddenly, and are replaced by protons. As long as nuclei exist,
increase monotonically with ϱ; both Z and A are definite functions of ϱ.

ords: neutron star — nuclei

H. Yukawa (1907〜1981)

H.A.Bethe (1906~6 March 2005)

I could collaborate with H.A. Bethe on the melting of nuclei with increasing the matter density.

Weinberg-Salam Theory as the model of Supernova neutrino interaction

- In 1970, I started SN neutrino research by using Weinberg-Salam Model, which was not established, rather was thought doubtful.
- Neutral current Interaction in weak force was discovered by GARGAMEL in 1973.
- D. Z. Freedman pointed out neutrinos are coherently scattered by nuclei.

Neutrino Burst of Supernova **1 9 8 7** A

11 events by Kamiokande
8 events by IMB.

Observed durations are very consistent with Neutrino trapping theory, observationally approved.

Neutrino Trapping Theory :

Neutrinos are trapped (τ_d~10 s) by NC interactions.

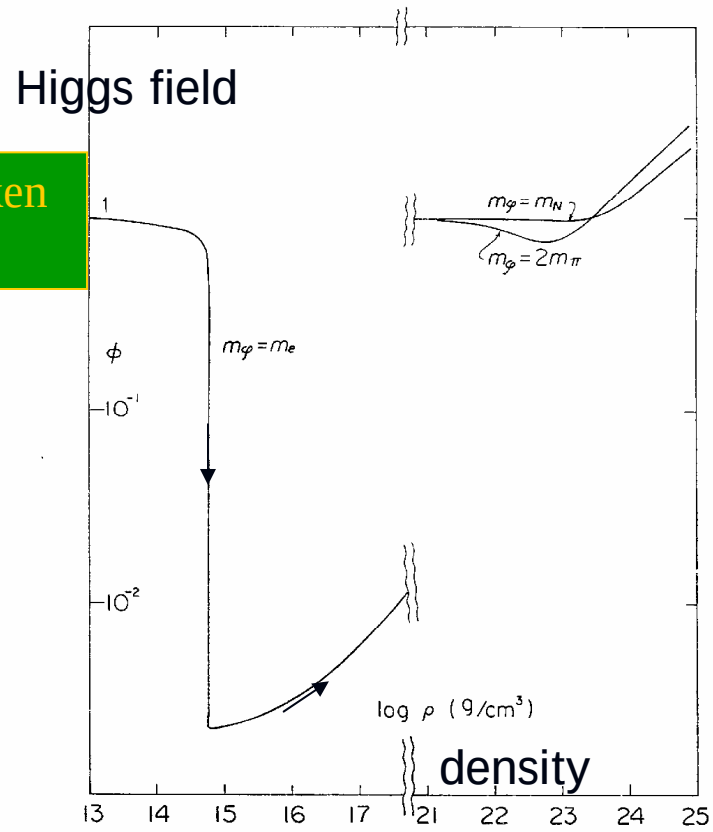
From WS phase transition to Inflation

- I learned the Weinberg-Salam Theory in order to apply supernova neutrino interactions.
- I recognized it stands on the idea of phase transition of vacuum, and found it predicts interesting astrophysical and cosmological predictions.

1) The broken symmetry of the vacuum is restored in ultra dense matter. Moreover, the symmetry is again broken with increasing the matter density by the effects of neutral current interaction.

Phase Transition in WS theory

Broken state



In 1976, A.D. Linde sent me Lebedev Inst. preprints, and gave letters that he obtained similar result in Abelian gauge field model.

Kirzhnits and Linde (72) are first persons to predict cosmological vacuum phase transition.

Linde is a nice magician.

By Linde magic, Efstashiou face became soot covered !

1. Baryon-antibaryon domain structure of Universe

(Phys. Lett. **99B** (1981), 66-70)

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

- This scenario 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.

- If Inflation occurs after spontaneous symmetry breakdown of CP-conservation, the domain sizes are extended exponentially. Then annihilation is avoided.

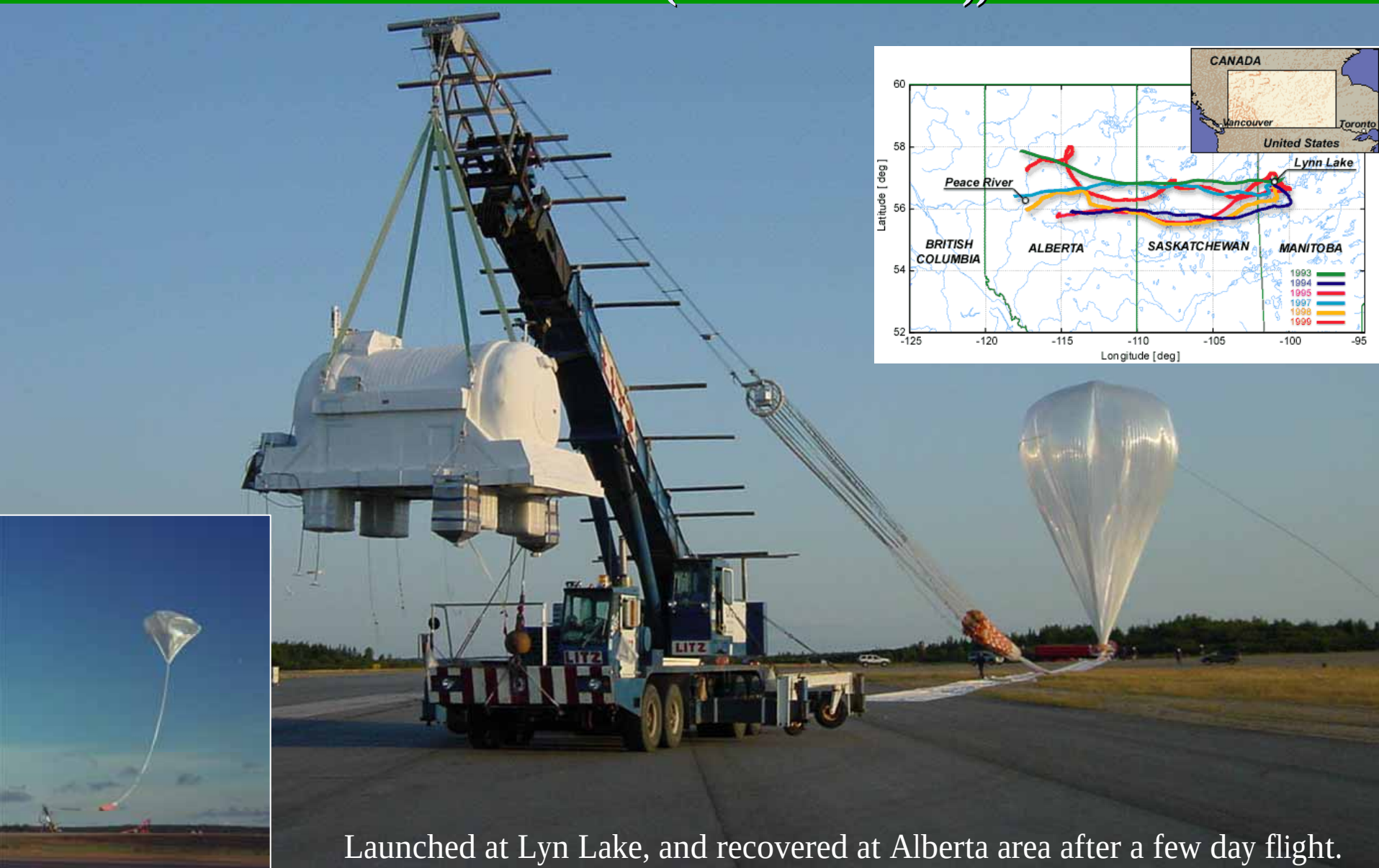
Universe with matter-antimatter domain structure

- Our region is a huge baryon domain, but antimatter regions may exist nearby.
- Then antimatter cosmic rays (antiprotons, anti-heliums,….) may come to Earth.
- Since antiprotons are copiously created by the high energy interactions in our Galactic space, detection of antiproton does not mean the existence of antimatter worlds.
- But if anti-helium cosmic rays are observed, it is a direct evidence of the antimatter world.

Recently, BESS experiment (Japan-US collaboration project) obtained the most stringent upper limit on the anti-helium cosmic ray flux.

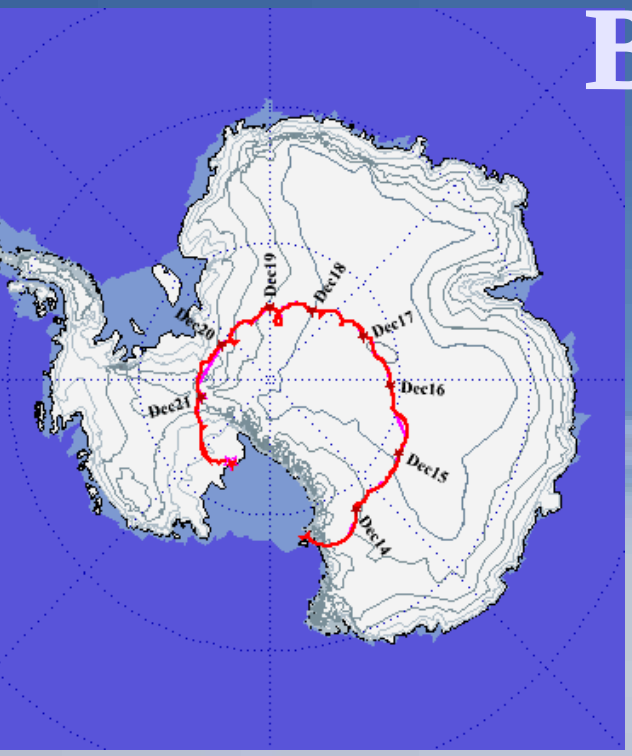
BESS (Balloon Experiment with Superconducting Spectrometer)

Japan –US Collaboration (initiated by late Prof. Orito, a member of RESCEU, now PI is Yamamoto (KEK & RESCEU))



Launched at Lyn Lake, and recovered at Alberta area after a few day flight.

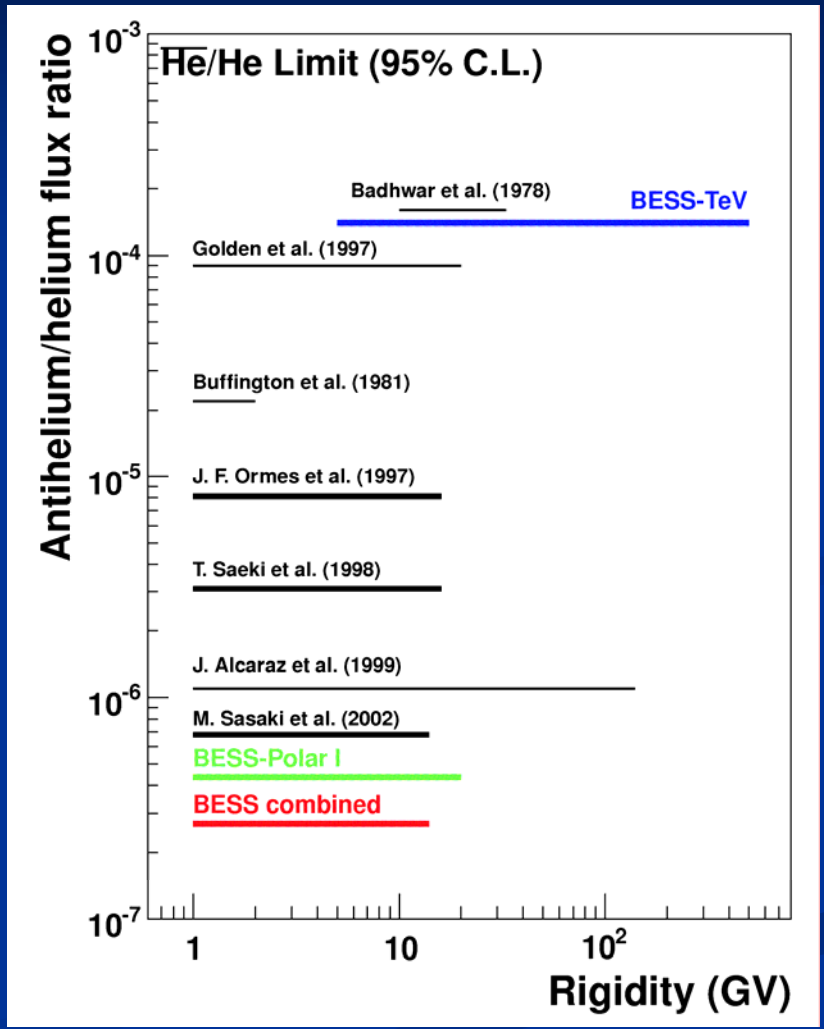
BESS-Polar I Experiment at Antarctica (Dec., 2004)



Antihelium Search with BESS

- **No antihelium candidate was found**
- BESS-TeV
  1 - 500 GV, 7×10^4 He events
- BESS-Polar
  0.6 - 20 GV, 10^6 He events
- BESS' combined upper limit for the Antihelium to Helium flux ratio
  2.7×10^{-7}

No evidence of anti matter world from cosmic rays.



From M. Sasaki et a., presented in COSPAR-06

To be published in Adv. Space Res.

Now BESS group is going to launch BESS polar II

BESS-Polar II and Crew at Antarctica, since Nov. 27, 2007 (From Yamamoto)

20-day flight of BESS-Polar II would give the upper limit of for the Antihelium to Helium flux ratio of 3×10^{-8}.

2.Generation the seed of large scale structure

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

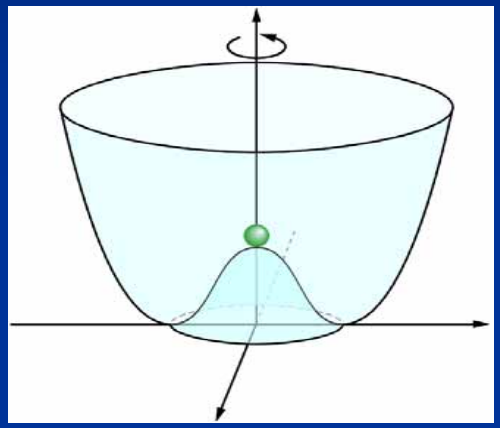
- In this paper, it was pointed out that density fluctuations created during the phase transition are extend by inflation, and the scale becomes easily larger than the horizon. But, later it was shown the amplitude of the density perturbation is too large.
- Present model is the slow roll over model with extremely flat scalar field potential, and the origin of the fluctuations is quantum fluctuations.
- However the essential mechanism that small scale fluctuations are extend by inflation is the same one proposed in this paper.

In Feb., 1980, in order to make propaganda of this paper which can make the super-horizon density fluctuations, I visited Cambridge, M. Rees, a Mecca of galaxy formation.

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



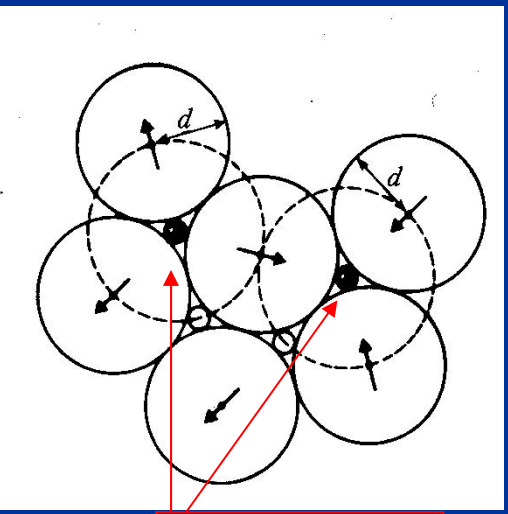
Overproduction problem was severe conflict between Big Bang Model and GUTs.

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

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

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



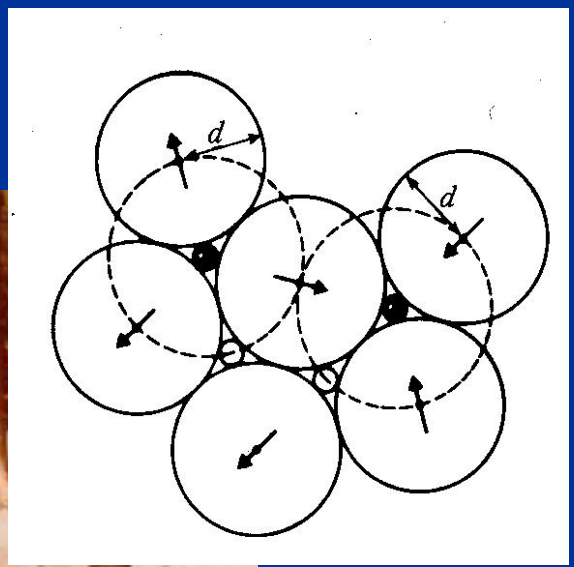
monopoles

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

Our paper was the first paper to solve Overproduction problem of magnetic monopoles by Inflation ?

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

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



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

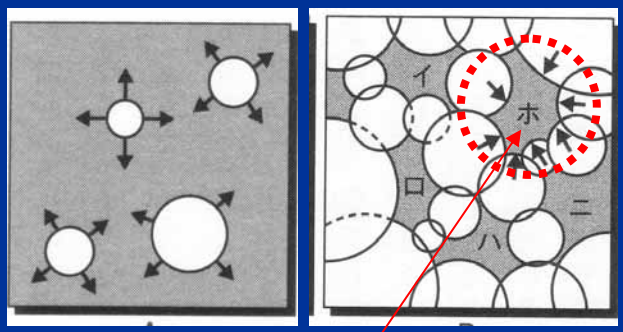
$$\frac{n_{monopole}}{n_{photon}} \approx \frac{1}{8}\frac{\left(d \cdot \exp(\tau/l)\right)^{-3}}{T_c^3} \Rightarrow 0$$

M. Einhorn came to Copenhagen, just February.

4.Multi-production of universes by inflation

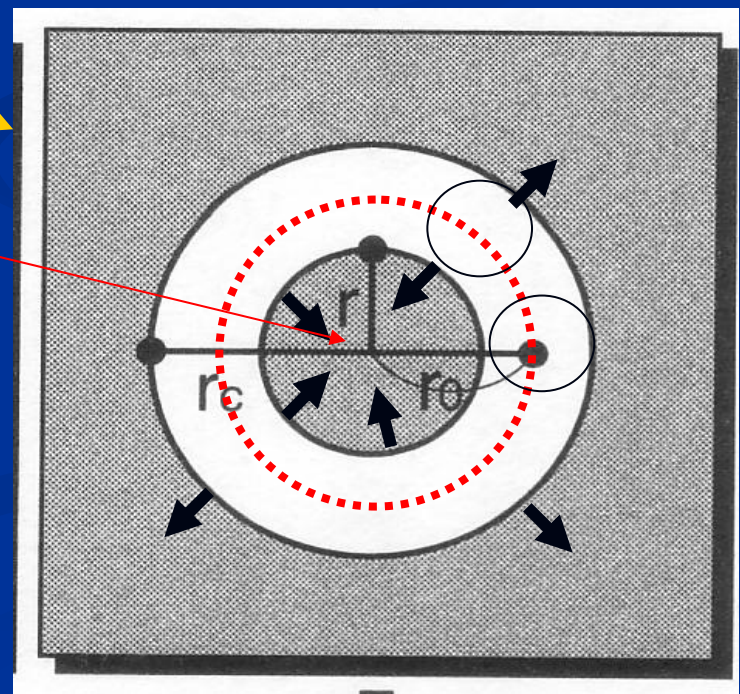
Phys. Lett. **108B** (1982), 103-107
K. Sato, H. Kodama, M. Sasaki and K. Maeda

A severe problem arises in the first order phase transition model:
Phase transition never finishes if nucleation rate of bubbles is smaller than a critical values even if the bubbles expand with light velocity.



Assume bubbles are nucreated on the surface of sphere.

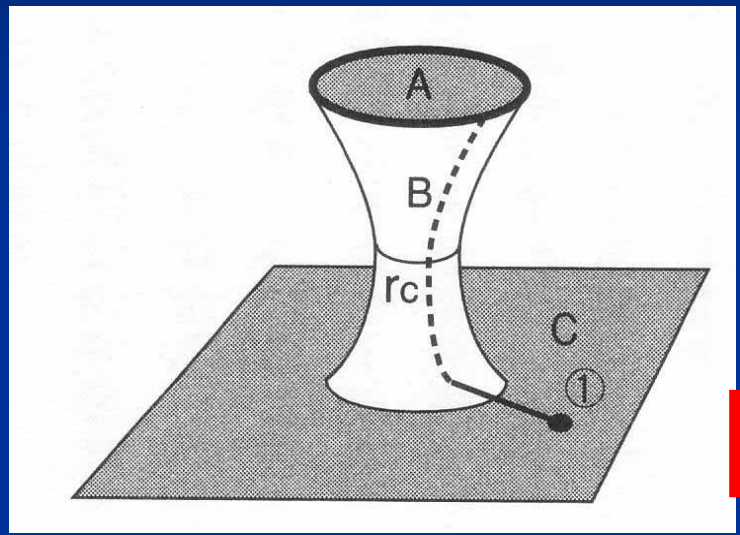
Spherical symmetric model of the trapped false vacuum region.

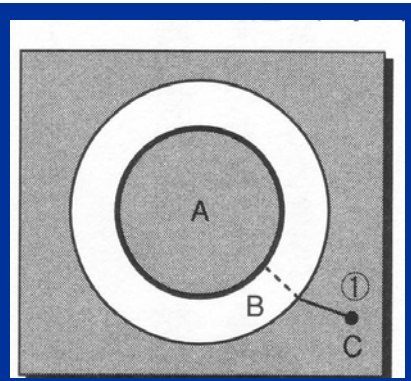


Consider the false vacuum region surrounded by true vacuum bubbles.
The surface is shrinking with light velocity, but the radius of the region becomes larger because of INFLATION, if the radius is greater than de Sitter horizon. This looks severe contradiction.

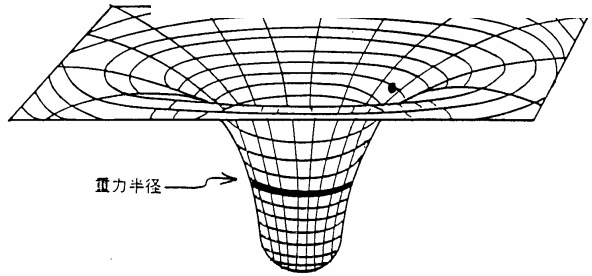
Why the radius increases in spite that the surface is shrinking?

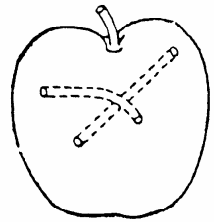
Mushroom type worm holes are created !



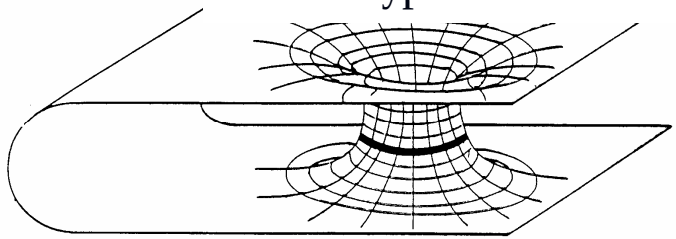


Black hole



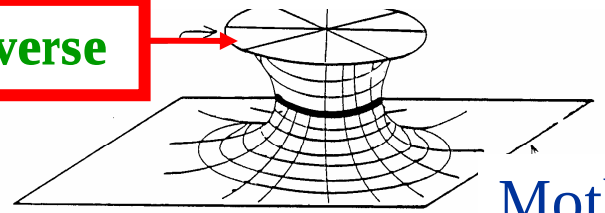


Tunnel type worm hole



Mushroom type worm hole

Child universe



Mother universe

Trapped false vacuum region is causally disconnected from the original mother universe by horizon.

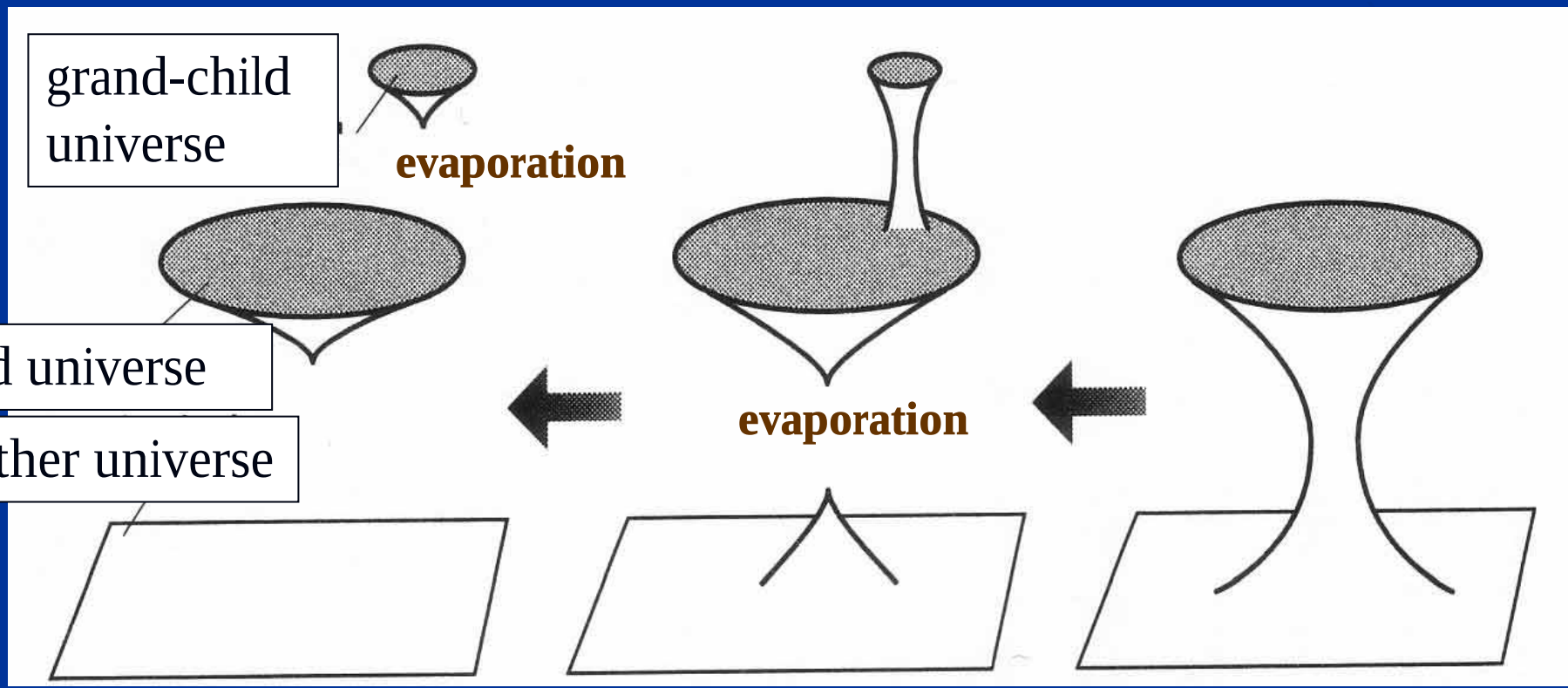
We may call the region is a child-universe.

Multiproduction of Universes

Wormholes are formed in child-universes copiously too.

Then grand-child universes are formed, and so on…..

Umbilical cord connected mother universe and child universe evaporates away by Hawking BH evaporation mechanics.



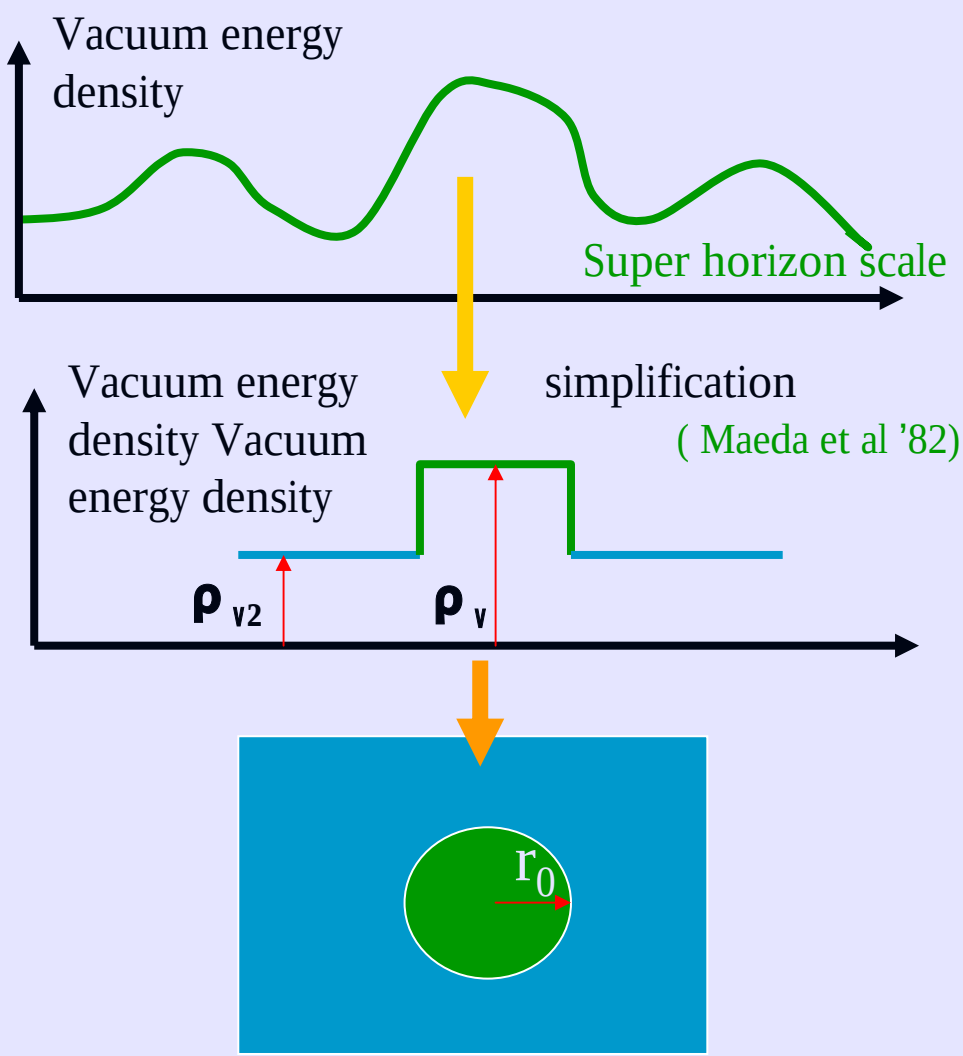
Multi-production of universes might be universal for various type Inflation models

- Consider the inhomogeneous inflation in super horizon scale.
- Assume the vacuum energy density is inhomogeneous, and pick up a high density region, and assume it is spherical symmetric for simplicity:

the initial radius: r_0

the vacuum energy density in the sphere : ρ_v

the vacuum energy density outside : ρ_{v2}



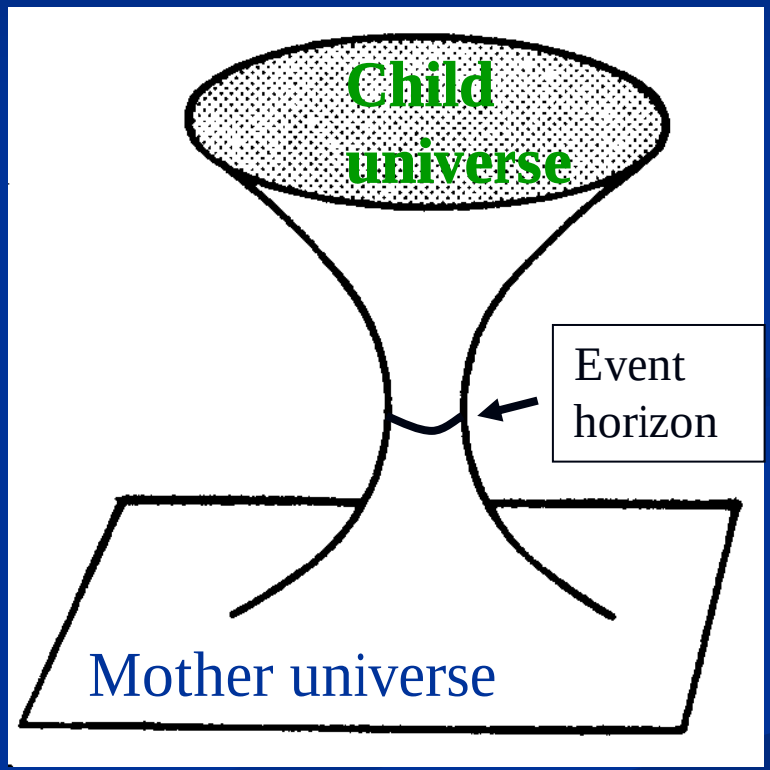
Assume spherical symmetric

Schwarzschild-de Sitter Black Hole and Worm hole are formed.

- Case I ($r_0 < \ell$) :
  a black hole is created.
  where $\ell \equiv \left(8\pi G\rho_v / 3 \right)^{-1/2}$
- Case II
  ($\ell < r_0 < r^*$ & $3 < \dfrac{\rho_v}{\rho_{v2}}$):
  a worm hole is created.

where $r^* \equiv \dfrac{1}{\sqrt{3}} \left(\dfrac{2}{x(1-x^2)} \right)^{1/3} \ell$ $x \equiv \sqrt{\rho_{v2} / \rho_v}$

- Other cases
  de Sitter like space



Multiproduction of universes happens in the case II.
Inflation necessary predicts "Multiverse".

Chinese people might know this type worm hole more than two thousand years before.

Story:

Mr. Hi went into the bottle following legendary wizard, and found that there existed an infinite heaven filled by delicious wines and all sorts of delicacies.

"Heaven in a bottle" appeared in a late Hang Dynasty book

Congratulation on the launching the new Centre for Theoretical Cosmology (CTC)!

"The Institute for the Physics and Mathematics of the Universe "

(IPMU)

was launched on Oct 1, 2007,
in the University of Tokyo.