From Supernovae to Inflation

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Research Subjects

I. Collapse- driven supernovae

H.A. Bethe, G. Boerner, J. Wilson, S. Dalhead, A. Burrows, A.Thompson…

M. Takahara, M. Kiguchi, R. Ogasawara, H. Suzuki, S. Yamada,
T. Shimizu, G. Watanabe, S. Nagataki, K. Iida, T. Totani , M.Watanabe
K. Takahashi, S. Ando, K. Kotake, T. Takiwaki, H.Sonoda, S.Horiuchi, Y. Suwa,
S. Ishikawa., M.Hashimoto, T. Maruyama, T. Ebisuzaki, S. Fujimoto….

II. Particle cosmology and early universe

M.Einhorn, A. Dolgov, H. Reeves, J. Richer ….H. Sato, M. Kobayashi, S. Miyama

K.Maeda, H.Kodama, M. Sasaki,T. Nakamura, M. Izawa, Y. Suto, N. Sugiyama,
M. Kawasaki, J. Yokoyama, N. Sato, N.Terasawa, K. Iso, N.Nagasawa, Y.Furihata,
K. Narahara, K. Ikumi, H. Ochiai, K. Kohri, Y. Sendouda, S. Kinoshita, S. Matsuura,
H. Kudoh, Y. Yoshii…..

III. Ultra high energy cosmic rays

S. Nagataki S.Tsubaki, Y. Ide, H. Yoshiguchi, S. Okamura, N. Ohama, H. Takami ,..

Research Subjects

I. Collapse- driven supernovae

1. Melting of Nuclei in Neutron Stars and Supernova Matter
2. Neutrino Trapping in Supernova Cores and theoretical prediction of the Neutrino Burst
3. Magneto-rotational collapse of stellar cores and formation of GRB engine, and emission of GW
4. Nucleosynthesis in supernovae

=>Kotake's Talk

II. Particle cosmology and Early universe

III. Ultra high energy cosmic rays

Research Subjects

I. Collapse- driven supernovae

II. Particle cosmology and Early universe

1. Cosmological and astrophysical constraints on weakly interacting particles
2. Vacuum phase transition and Inflation
3. Big Bang Nucleosynthesis (in particular, inhomogeneous universe)
4. Brane world models and constraints from observations.

III. Ultra high energy cosmic rays

See, Takami's Poster

I. Collapse- driven supernovae

1. Melting of Nuclei in Neutron Stars and Supernova Matter

Bethe, Boerner, Ogasawara, Iida, Watanabe, Sonoda

- In 1969, I started the research gravitational collapse of stellar cores & supernovae. (Though interested in the early universe)
- An important basic problem remained:

  how nuclei melt with increasing the matter density?

  EOS and Neutrino opacity depends on what nuclei exist.
- Additionally, this problem was important for Pulsar glitch (sudden increase of the period: star quake), which depends on the shear modulus of neutron star crust, and what nuclei exist therein.

I could collaborated with H.A. Bethe & G. Boerner when I was a MC student.

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

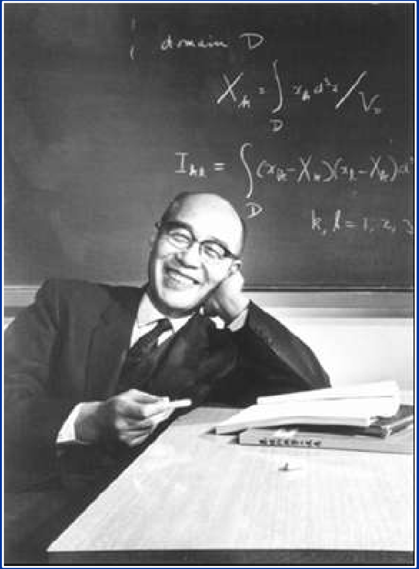
Received March 25, 1970

The equation of state at densities somewhat below nuclear is re-examined. The results are in qualitative agreement with previous authors, but there are quantitative differences. Up to $\varrho_1 = 2.8 \cdot 10^{11}$ g/cm^3 there are neutron-rich nuclei and electrons; between ϱ_1 and $\varrho_2 = 4.34 \cdot 10^{13}$ g/cm^3 there is in addition a gas of free neutrons. At ϱ_2, nuclei disappear rather suddenly, and are replaced by protons. As long as nuclei exist, their mass and charge increase monotonically with ϱ; both Z and A are definite functions of ϱ.

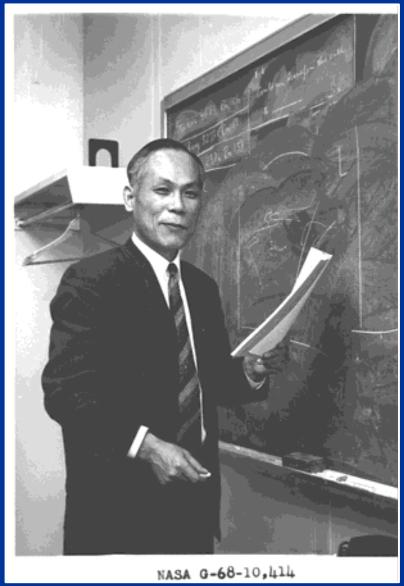
Key words: neutron star — nuclei

Just after the glitches of Crab pulsars were discovered.

H.A.Bethe came to Kyoto, Yukawa Inst. as a guest of Prof. Yukawa, and G. Boerner came as a PD by strong recommendation by W. Heisenberg in 1969.

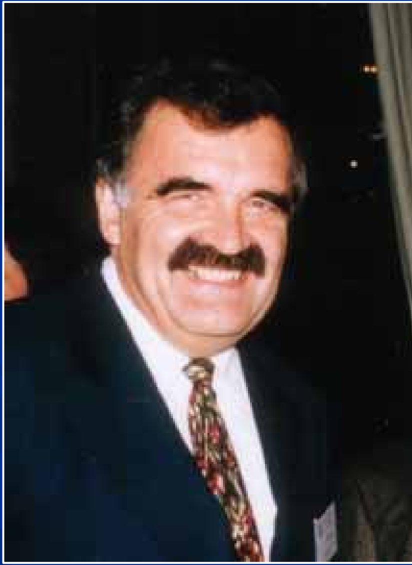


H. Yukawa (1907〜1981)



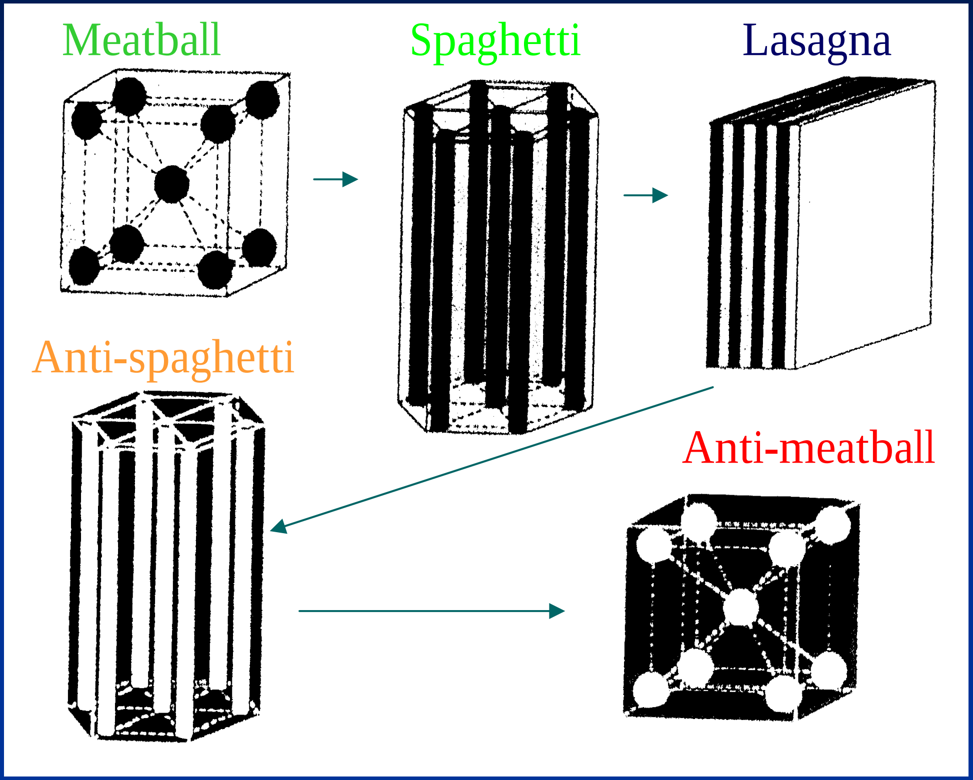
C.Hayashi (1920~)

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



G.Boerner (1941~)

Nuclear Pasta Structure



Oyamatsu,93

With increasing matter density, the shape of nuclei changes from sphere to cylinder, slab, cylindrical bubble and spherical bubble, successively, and eventually becomes homogeneous nuclear matter. (Ravenhall & Pethick.,83, Hashimoto et al, 84,)

Essentially this change is described by the surface energy

$$g \equiv \frac{surface area}{(volume)^{2/3}}$$

minimum principle.

Meatball
Spaghetti
Lasagna
Anti-spaghetti
Anti-meatball
→"Pasta" Phases

Quantum Molecular Dynamics

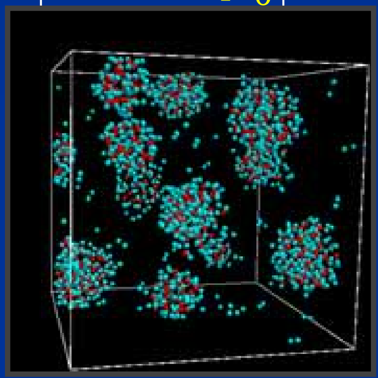
Watanabe et al, '01,….'06

Sonoda et al , '07

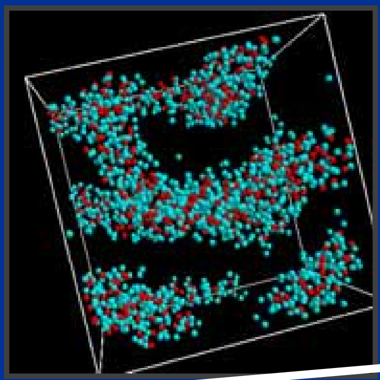
- No assumptions on nuclear shapes, since nuclear system is treated in degrees of freedom of nucleons.
- Thermal fluctuations are necessarily included.

Pasta at zero temperature

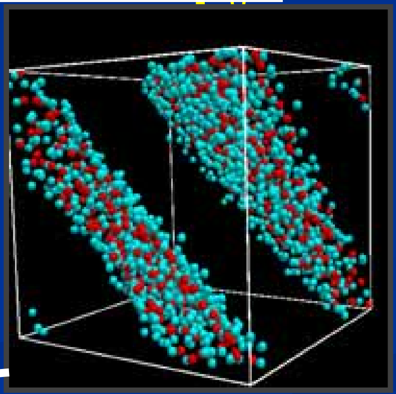
Sphere $0.100\ \rho_0$

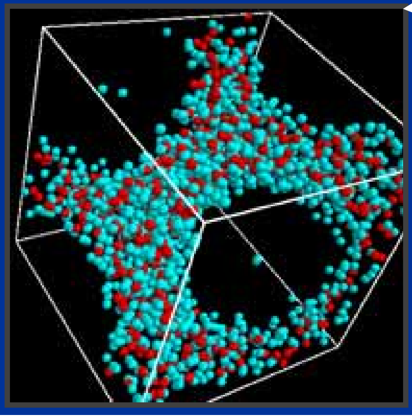


cylinder $0.200\ \rho_0$

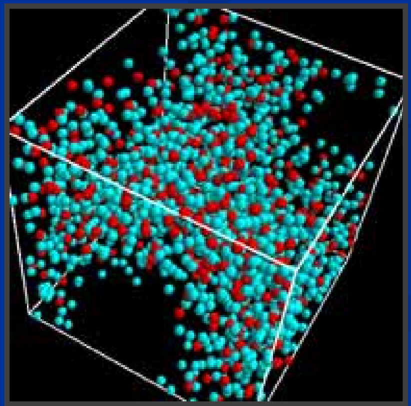


Slab $0.393\ \rho_0$





cylinder-like Holes $0.490\ \rho_0$



Spherical Holes $0.575\ \rho_0$

Red : Protons
Blue: Neutrons

$\rho_0 = 0.168\ \mathrm{fm}^{-3}$
(Nuclear density)

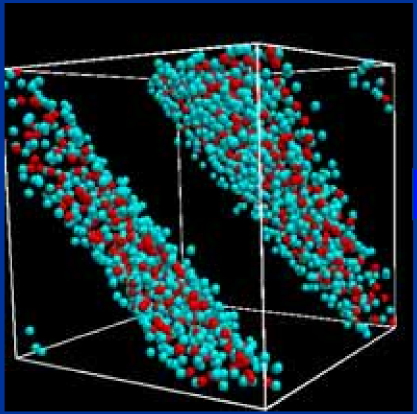
Pasta at finite temperatures

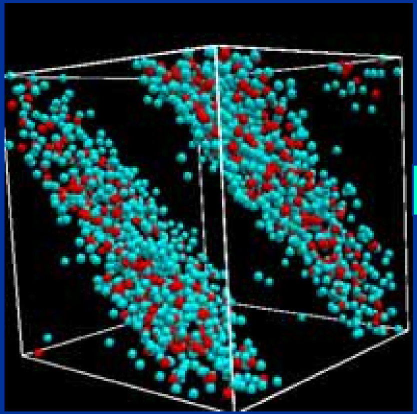
Sonoda et al PR C, 2007

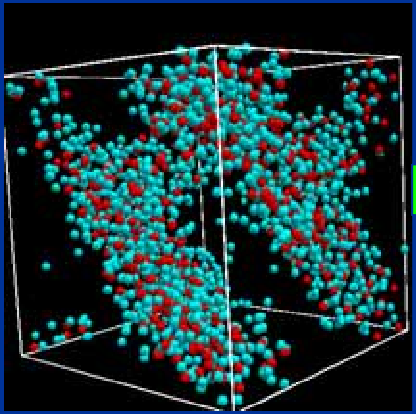
Model 1

0.393 $\boldsymbol{\rho}_0$ (Slab nuclei at zero temperature)

T= 0 MeV **T= 1 MeV** **T= 2 MeV**







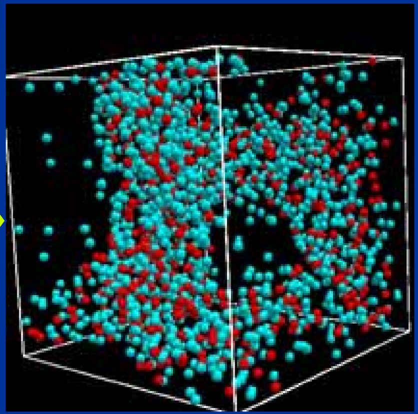
Slab Nuclei Evaporated Neutrons Connected Slab

dripped neutrons Increases
nuclear surfaces become more diffusive

Pasta at finite temperature

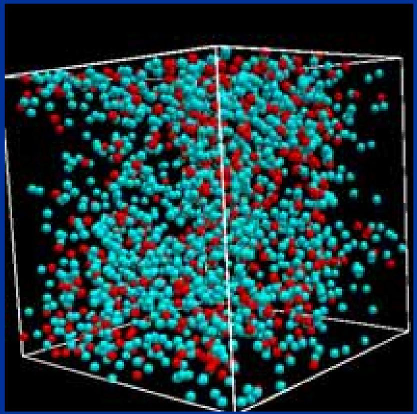
Sonoda et al PR C, 2007

T=3MeV



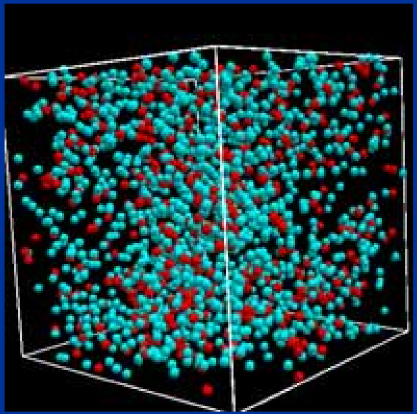
cylindrical hole-like structure

T=5MeV



Cannot identify nuclear surface

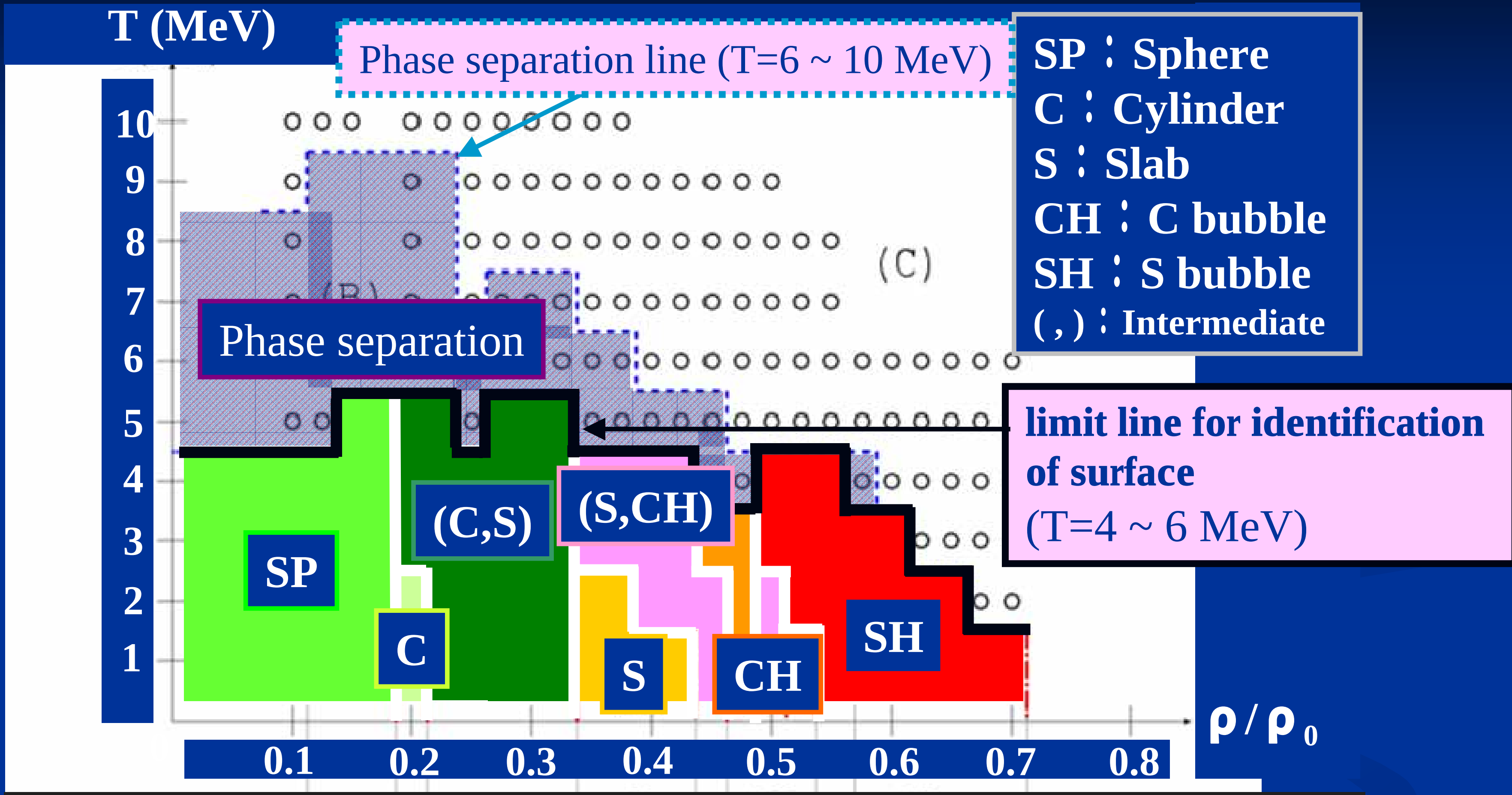
T=6MeV



Phase separation disappears

Phase transition, Melting surface, Dripped protons, Disappearance of phase separation occur successively

Phase diagram at finite temperatures



Thermal fluctuation increases volume fraction of nuclei.
Above T= 4 ~ 6 MeV, cannot identify surface.
At T= 6 ~ 10 MeV, Liquid-gas phase separation.

Sonoda et al PR C, 2007

Neutrino Opacity of Pasta Phases

Sonoda PhD Thesis (in preparation)

Neutrino transport
--- a key element for success of supernovae

- Neutrinos are trapped in collapsing phase by coherent scattering with nuclei (K.Sato,75)
  Lepton fraction , Y_{lep}, affects EOS.

How pasta phases change neutrino transport in collapsing cores ?

Cross section of neutrino-Pasta

Cross section of neutrino-nucleon system coherent scattering

$$\frac{1}{N}\frac{d\sigma}{d\Omega}(\mathbf{q}) = \frac{G_F^2 E_\nu^2}{4\pi^2}(1+\cos\theta)\cdot c_v^{(n)2} \times \overline{S}(\mathbf{q})$$

Neutrino-neutron cross section

Amplification factor
(Static structure factor)

Because collapsing cores are poly-crystalline, the opacity would be well characterized by the angle-average of S(q).

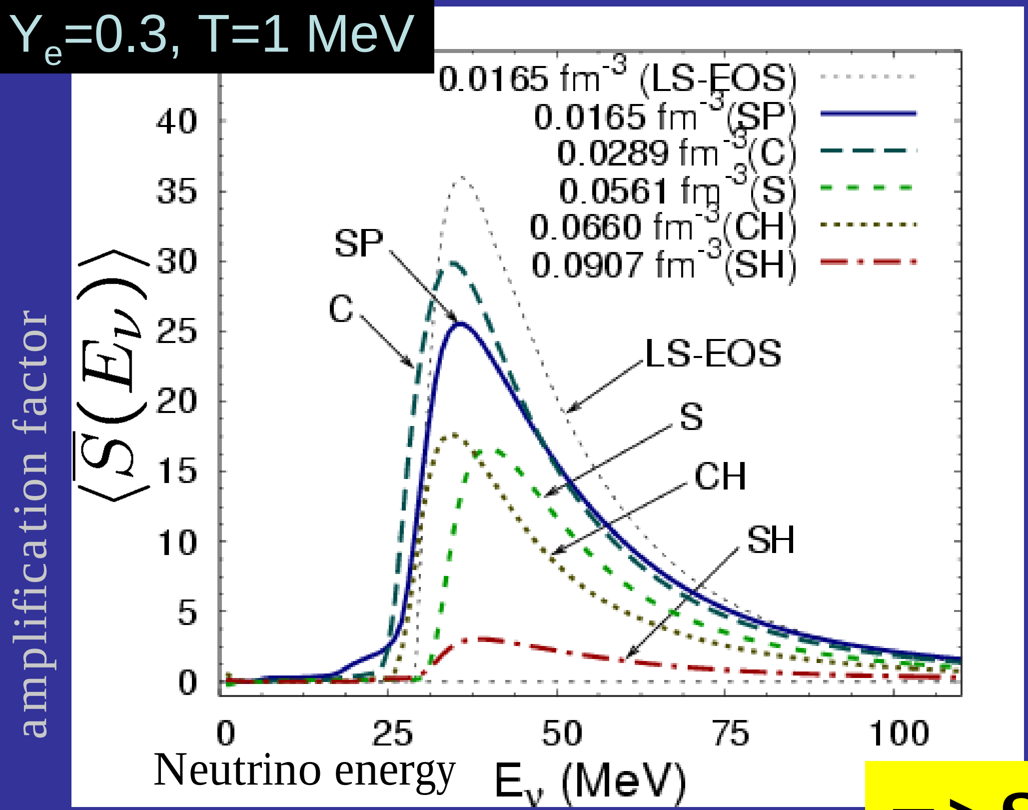
Total transport cross section: $\sigma_t = \langle \overline{S}(E_\nu)\rangle \sigma_t^0$

$$\sigma_t^0 = \frac{2G_F^2 E_\nu^2}{3\pi} c_v^{(n)2}$$

$\langle \overline{S}(E_\nu)\rangle$ → Angle-averaged amplification factor by pasta structure

QMD results : change of the amplification factors with increasing density

Y_e=0.3, T=1 MeV



Compared with the Lattimer- Swesty model (no pasta, spherical nuclei),

- the energy of peaks are lower, and
- the width of peaks are wider,

due to lattice disorder and irregularity of nuclei.

=>See, Sonoda's Poster

Difficult to discuss the effects on supernova explosion at present stage. More systematic survey is necessary.

I.-2 Supernova Neutrinos

H. Suzuki, S. Nagataki, T. Totani ,K. Takahashi, S. Ando

M. Takahara, S. Yamada, K. Kotake, T. Takiwaki, Y. Suwa

- Neutrino Trapping in Cores by Neutral Current Interaction (1975)
- SN1987A, Neutrino Burst and Neutrino OSC in SN (1987-present)

Neutrino Trapping in Cores by Neutral Current Interaction

In early 1970 era, I started collapse-driven SNe, but theoretical investigations showed core collapse supernovae don't work .The energy released gravitational collapse, which should be used for the explosion, has lost by the neutrino emission from the core.

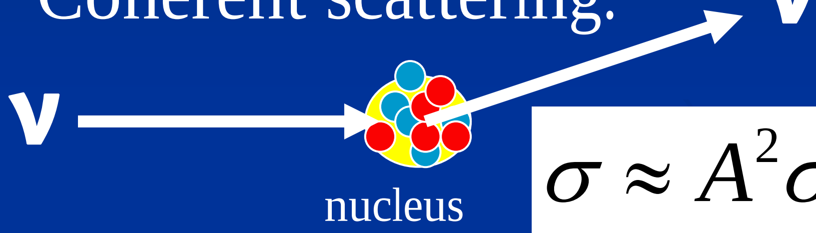
KEK Home Page: http://www.kek.jp/ja/news/topics/2007/EPSprize.html

I frequently talked Maskawa and Kobayashi about SN and neutrinos. Maskawa introduced me W-S theory, which have the neutral current interaction.

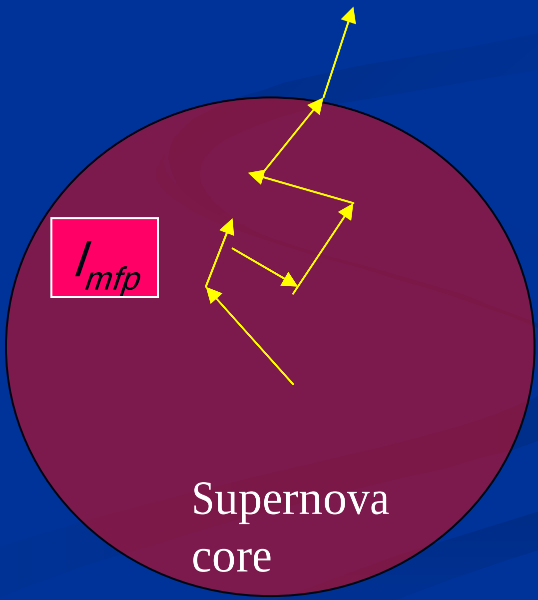
Neutrino Trapping in Cores by Neutral Current Interaction

- The, 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.
- I realized neutrinos are trapped (τ_d~10 s)
- and are Fermi-degenerate strongly (EF~ 100MeV) in collapsing stellar cores.

Coherent scattering:



$$\sigma \approx A^2 \sigma_0$$



Duration of SN Neutrino burst is not ~ 10msec, but ~ 10 sec.

Supernova１９８７A
in LMC ２３Feb.７：３５AM (UT)，１９８７

http://www.aao.gov.au/images/captions/aat048a.html

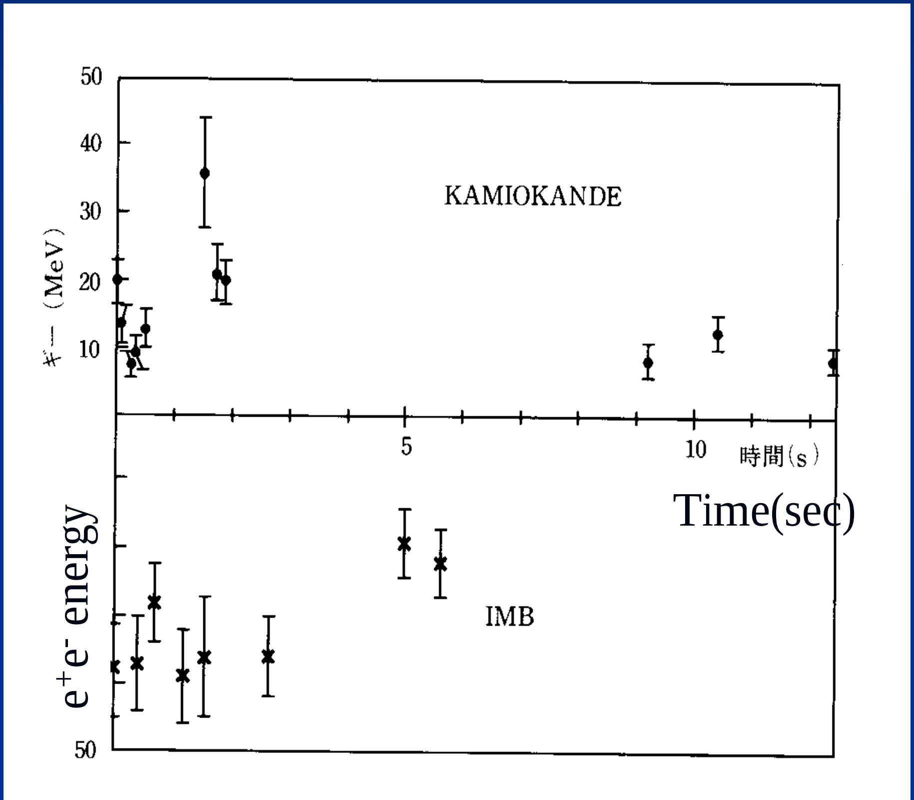
10 trillion neutrinos passed through your body.

Huge water Cherenkov counters deeply embedded in the Earth could detect this neutrino burst,

11 events by Kamiokande (Japan) &

8 events by IMB (USA).

Duration of the burst corresponds to the cooling time of proto-neutron stars (diffusion time)



Many people including W. Hillebrandt ,Sato and Suzuki made analysis of the observed data, and showed that they are very consistent with theoretical predictions,

1) total energy; ~3x10^{53}erg
2) Temperature 3-4MeV

3) Duration ~10 sec

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

In 2003

Nobel Prize was awarded to Dr. M. Koshiba,

the head of Kamiokande, Distinguished University Professor.

From http:/ /www.nobel.se/

We had been waiting the prize more than 15 years !

Neutrino OSC & Neutrino Burst from Supernovae

SK and SNO showed clearly neutrinos (electron-, muon- and tau types) have masses, and mixing among different flavors from the observations of solar and atmospheric neutrinos.

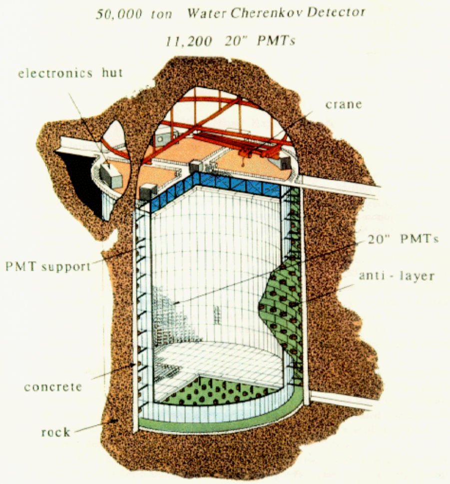
It is very natural to question what are effects on supernova explosion and observations of the neutrino burst, since they convert each other in SN.

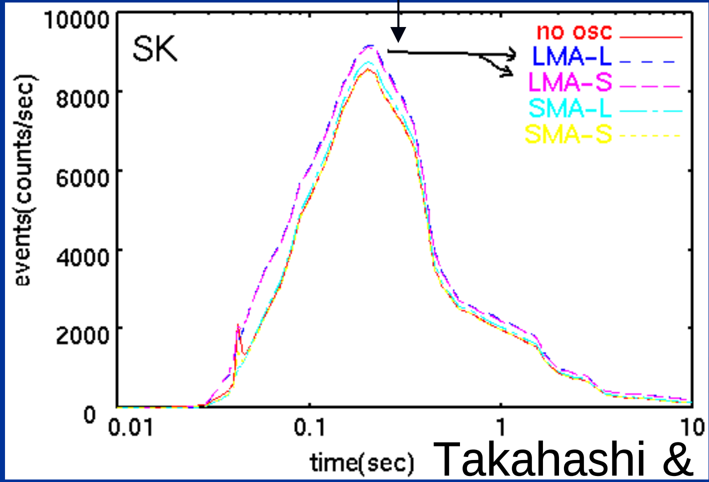
If a Galactic supernova appears, in addition to the information on the explosion mechanism of supernovae, we are able to obtain valuable implications on neutrino physics, i.e., Mixing angle θ_{13}、Mass Hierarchy,

Neutrino burst signals to be observed by SK for a Galactic center SN for various OSC models and mass hierarchy. (Totani, Takahashi, Ando, K.S..1995,…..2006)

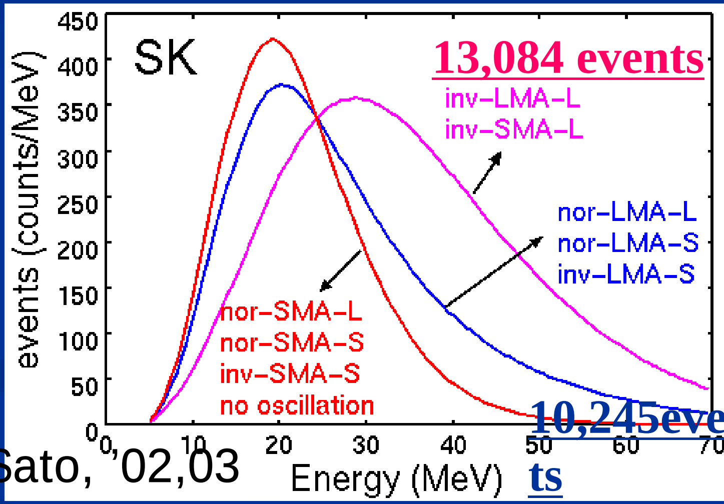
Burst Time evolution

Time-integrated Spectra





Takahashi & Sato, '02,03



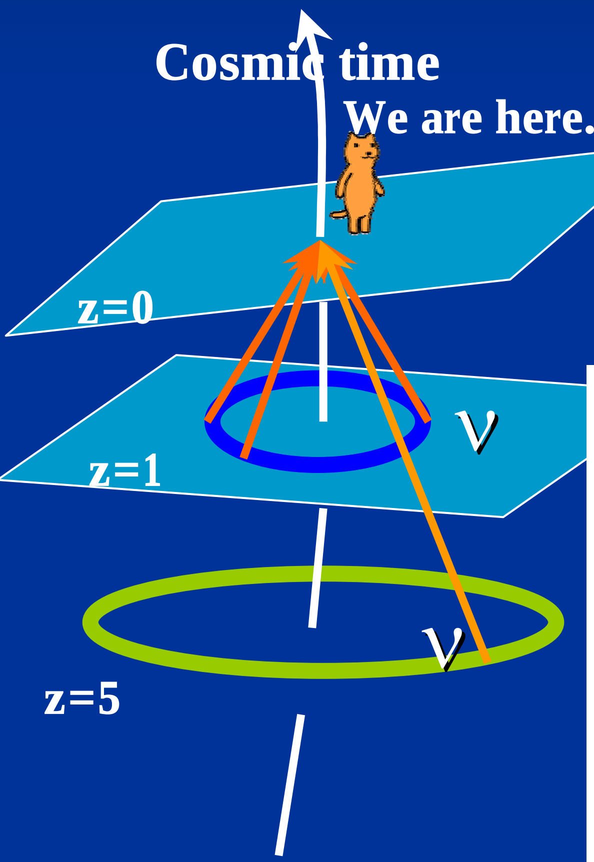
Information on the mixing angle θ13、 mass hierarchy would be obtained from the ratios of high/low energy neutrinos observed neutrino spectra by SK and SNO .

See our REVIW;

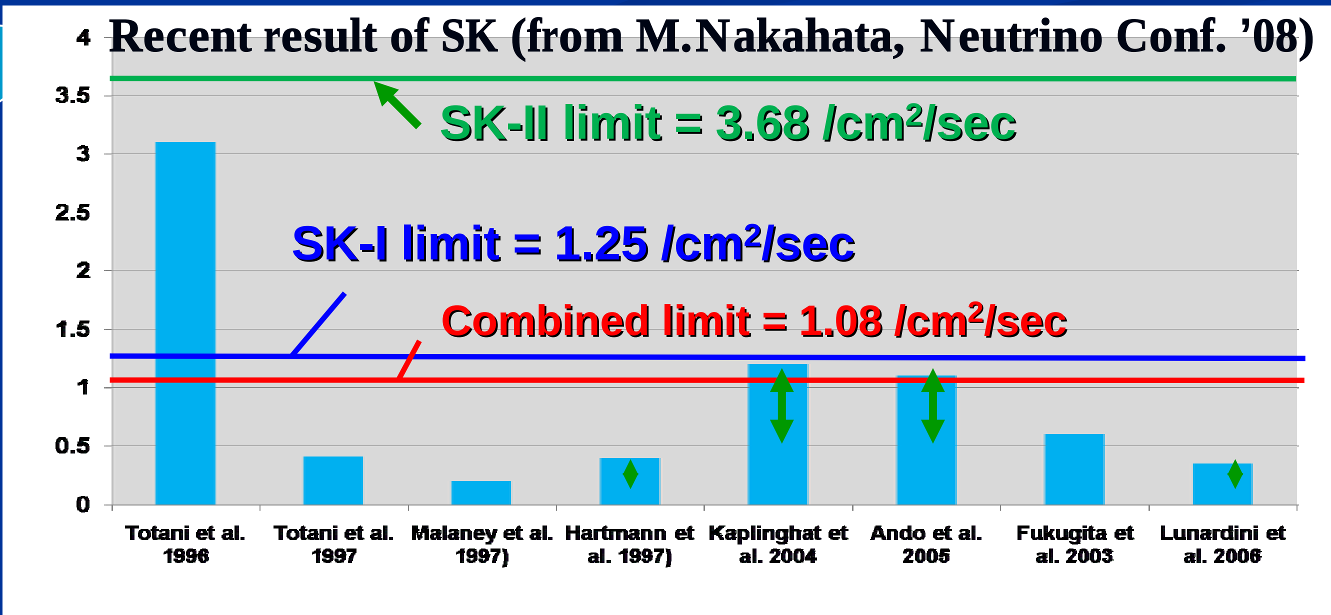
Reports on Progress in Physics 69 (2006), 971-1144. K. Kotake, K. Sato, K. Takahashi

Relic neutrino background from cosmological supernovae and effects of Neutrino OSC

Totani, Ando, KS ’95,…..-’04



Relic neutrino background from cosmological supernovae
New J. Phys. **6** (2004) 170 (27p), IOP SELECT PAPERS
Shin'ichiro Ando and Katsuhiko Sato



From Ando’s slide

II. Particle cosmology

1. Cosmological and astrophysical constraints on weakly interacting particles

- I learned the Weinberg-Salam Theory in order to apply supernova neutrino interactions following the suggestion by Kobayashi & Maskawa.

KEK Home Page: http://www.kek.jp/ja/news/topics/2007/EPSprize.html

- I learned it predicts

1) hypothetical Higgs particles, and

2) phase transition of vacuum (Higgs field),

and found

1) Cosmological and astrophysical constraints on Higgs mass and lifetime, and

2)it predicts interesting astrophysical and cosmological predictions.

Cosmological and astrophysical constraints on Higgs mass and lifetime

K. Sato & H. Sato, 1975a, b

- 3K-CMB is deformed by the radiative decay of Higgs particles.

  mass range $0.1\text{eV} < m_H < 100\text{eV}$ should be ruled out.

- Stellar evolutions are modified by Higgs emission from stellar cores if $m_H < 0.3\text{MeV}$.

Present lower limit of Higgs mass is 110 MeV, but such small masses had not ruled out by theoretical discussions and experiments at this time.

Cosmological Constraints on the Mass and the Number of Heavy Lepton Neutrinos

K. Sato and M. Kobayashi , 1977

- In 1976, anomalous μe events in e-e+ annihilation experiment in SLAC suggested the existence of heavy lepton(τ).

  Naturally associated neutrinos should exist.

- Immediately, we realized constraints on the mass, lifetime and number of heavy lepton neutrinos are imposed by cosmology and astrophysics.

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510

and

Steven Weinberg[c]
Stanford University, … d, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Only constraint on mass

red.

(Copy right :Kyodo, 08 Oct.'08 at JSPS)

Cosmological Constraints on the Mass and the Number of Heavy Lepton Neutrinos

Katsuhiko SATO and Makoto KOBAYASHI

Department of Physics, Kyoto University, Kyoto 606

(Received May 23, 1977)

If the neutrinos associated with the heavy leptons have the masses, they may decay into the lower mass neutrinos. We discuss implications of the decays of those massive neutrinos in the standard big bang model of the universe and derive the constraints on their masses and the number from the cosmological observations, i.e., 1) the lower limit of the

Cosmological Upper Bound on Heavy-Neutrino Lifetimes

Duane A. Dicus[a] and Edward W. Kolb[a]
Center for Particle Theory, University of Texas at Austin, Austin, Texas 78712

and

Vigdor L. Teplitz[b]
Department of Physics, Virginia Pc … iversity, Blacksburg, Virginia 24061

(Received 31 May 1977)

An upper bound on the lifetime of a massive, neutral, weakly interacting lepton, ν_H, is derived from standard big-bang cosmology. Saturation of the bound and reasonable assumptions about the weak interaction of the ν_H then yield a prediction of approximately 10 MeV for its mass.

Observational Constraints

I. The lower limit of the age of the universe and upper limit of the deceleration parameter
II. The upper limit of the observed cosmic background radiation
III. The upper limit of primordial abundance of 4He.

Number ratio to photos: $n_{\nu_\xi}(t)/n_\gamma(t) \sim 3/11 \cdot \mathrm{Min}\{1, (10\ \mathrm{MeV}/m_{\nu_\xi})^3\}$

The constraint I: $m_\nu \exp(-t_0/\tau)\,\mathrm{Min}\{1, (10\ \mathrm{MeV}/m_\nu)^3\} < 70\ \mathrm{eV}$

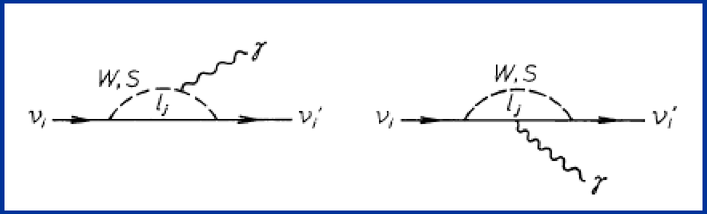
If the lifetime、 τ 、 is infinite, the mass should be m_ν <70eV or 2GeV<m_ν. (called Lee-Weinberg limit, but our paper was submitted almost same time)

Lifetime (radiative decay)

Neutrino mixing

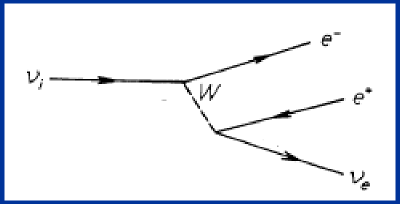
$$\begin{pmatrix} \sum_i U_{e\nu_i}\nu_i \\ e \end{pmatrix}_L, \begin{pmatrix} \sum_i U_{\mu\nu_i}\nu_i \\ \mu \end{pmatrix}_L, \cdots \begin{pmatrix} \sum_i U_{l_j\nu_i}\nu_i \\ l_j \end{pmatrix}_L \cdots$$

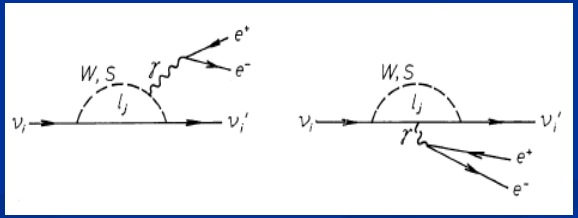
Radiative decay



$\tau_j > 6.0\times10^7\ (m_{\nu_i}/1\ \mathrm{MeV})^{-5}\ \mathrm{sec}$

If $m_{\nu i} \geq 2m_e$, e-e+ ν decays occurs.



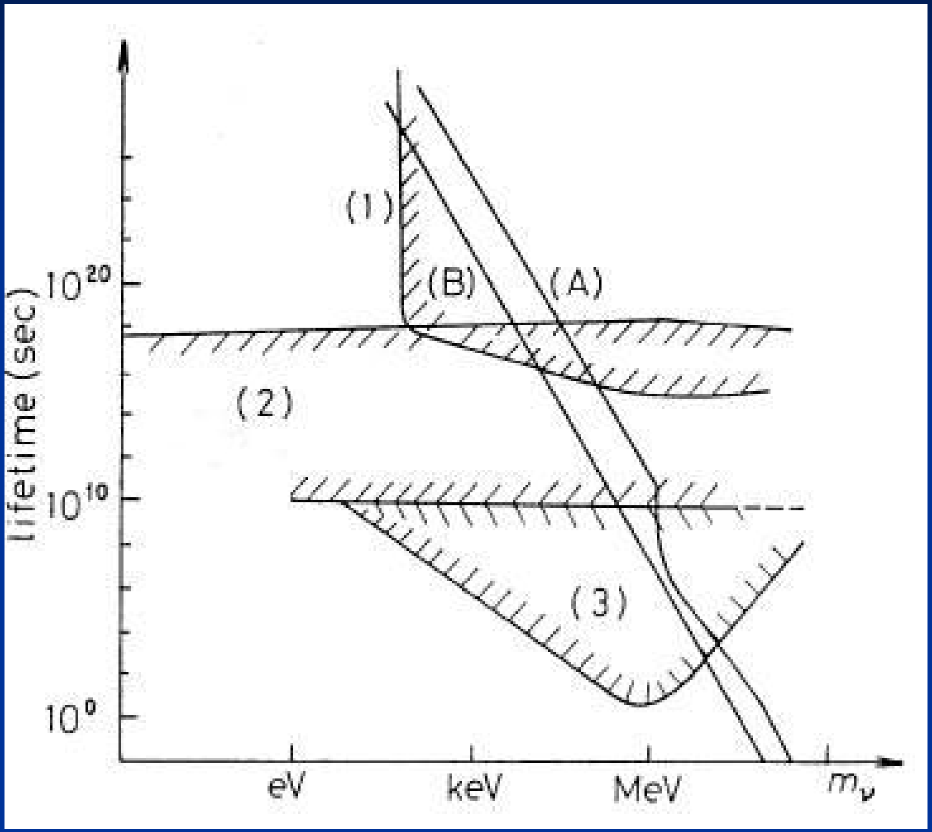


$\tau > 2.2\times10^6\ (m_{\nu_i}/1\ \mathrm{MeV})^{-3}\ \mathrm{sec}$

$\Gamma_\gamma^{-1} > 7.5\times10^{10}\ (m_{\nu_i}/1\ \mathrm{MeV})^{-5}\ \mathrm{sec}$

Lower limits of the lifetime were obtained from the upper limit of the mixing parameter imposed other weak processes such as π decay, and assumption of mass ratios, $m_{l_j} << M_W$, $m_{\nu_i} << m_{\nu_\mu}$.

Constraints on mass and lifetime



1)The lower limit of the age of the universe and upper limit of the deceleration parameter

2)The upper limit of the observed cosmic background radiation

3)The upper limit of primordial abundance of 4He.

A),B) Lower limit of the lifetime of heavy neutrinos

Mass region $70eV \le m_\tau \le 20MeV$ should be ruled out at least.

➔ Kawasaki, Kohri, .. Are exparts on this subject .

These methodologies are currently considered as standard tests in a sense that any new proposed model should pass so as to be viable. This is the pioneering work done more than 20 years ago.

II-2. Inflation
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.

Guth paper was submitted on 11 August.

These three papers were written during the stay in NORDITA (1979-1980).

Chris Pethick

Horger Nielsen

The most interesting person I met during my stay in NORDITA

He asked about my draft on “Phase transition of vacuum and Exponential expansion of universe”.

Stephen Wolfram

(from his Home page)

1959: Born August 29 in London

1979: Ph.D. in theoretical physics from Caltech (20 years old)

Spontaneous symmetry breaking and the expansion rate of the early universe

E. W. Kolb and S. Wolfram

Astrophys.J.239:428,1980

1. Baryon-antibaryon domain structure of Universe

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

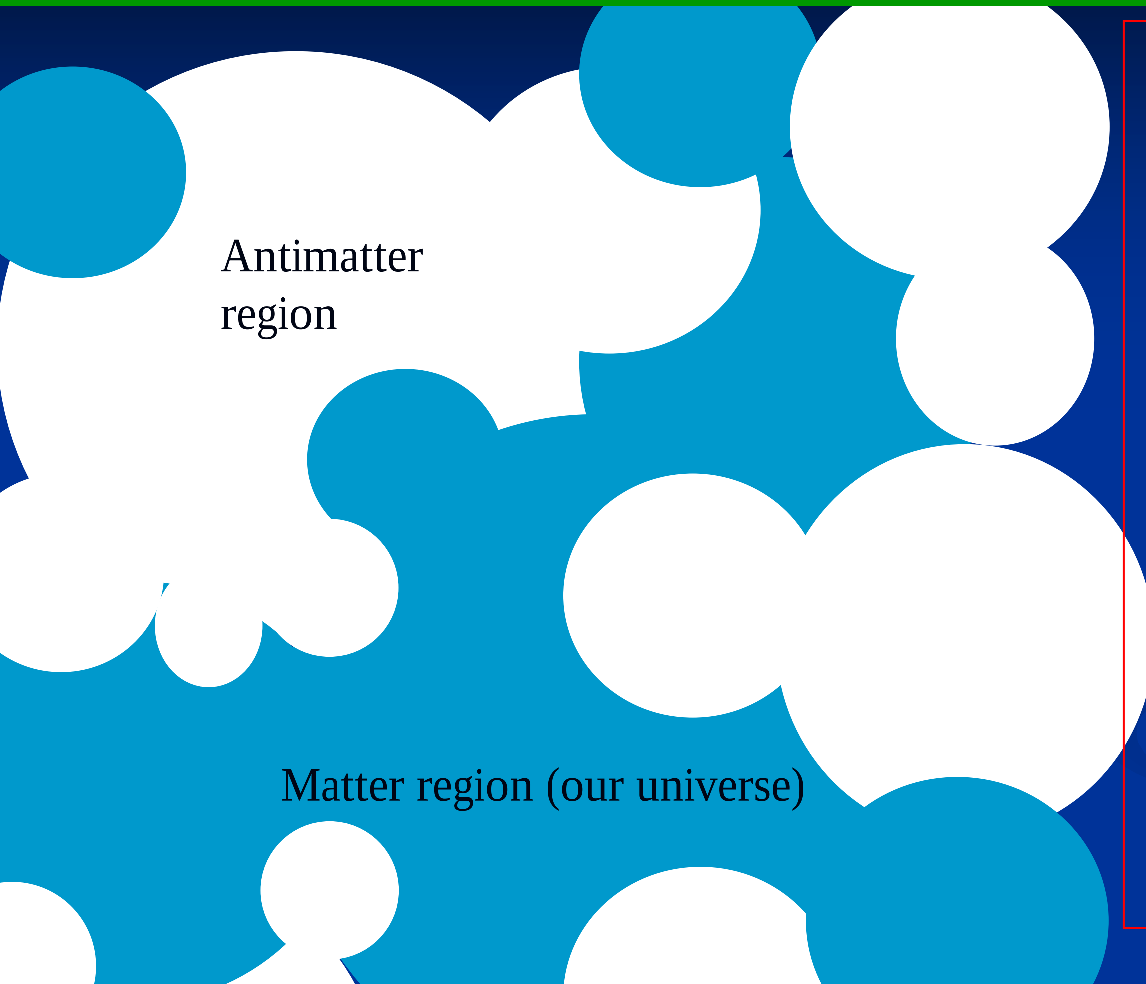
- Baryon number asymmetry of the universe is generated by CP breaking, baryon number –non conservation & large deviation from thermal equilibrium (Saharov '67,Kuzmin'70, *Yoshimura'78). But the basic law of physics should be symmetrical in principle, then CP-conservation should be broken spontaneously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

====➔ A. YAMAMO'Talk in this Symp.

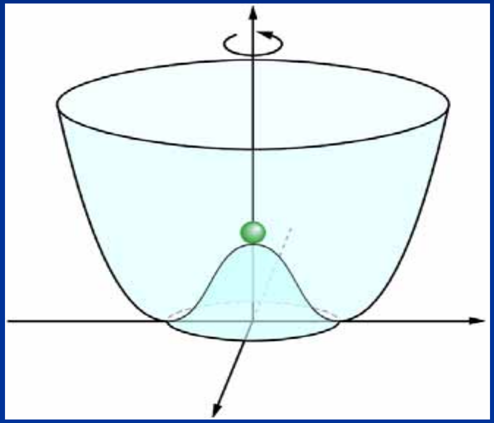
2.Generation the seed of large scale structure

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.

3. Overproduction problem of magnetic monopoles

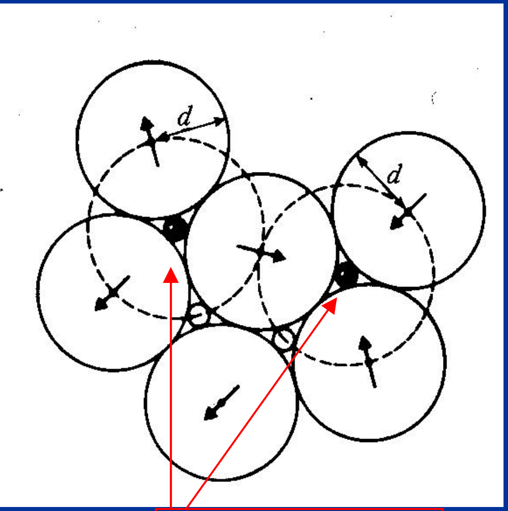
M.B. Einhorn and K. Sato Nucl. Phys. **B180** (1981), 385-404



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).

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



monopoles

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

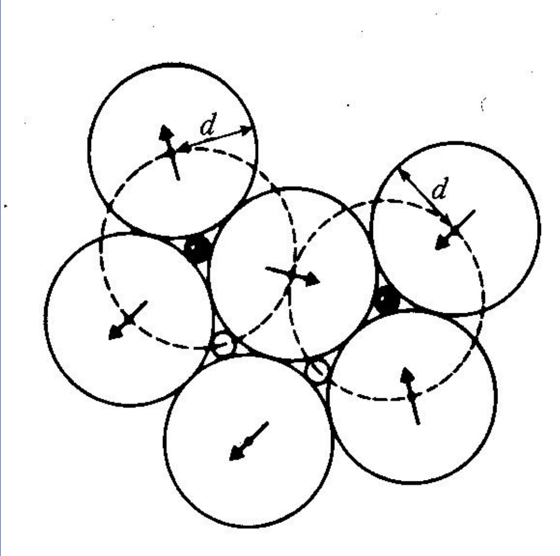
1. M.B. Einhorn, D.L. Stein and D. Toussaint, Phys. Rev. D21 (1980) 3295
2. A.H. Guth and S.-H. Tye, Phys.Rev.Lett., 44, (1980) 631

I found they didn't recognized INFLATION yet ! They 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.



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

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

Successively, we proposed Multiproduction of Universes:

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

- **Creation of Wormholes,** Sato et al Prog. Theor. Phys. **65** (1981), 1443
- **Creation of Schwarzschild-de Sitter Wormholes,** Maeda et al Phys. Lett. **108B** (1982), 98
- **Multi-Production of Universes by First-Order Phase Transition of a Vacuum**

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

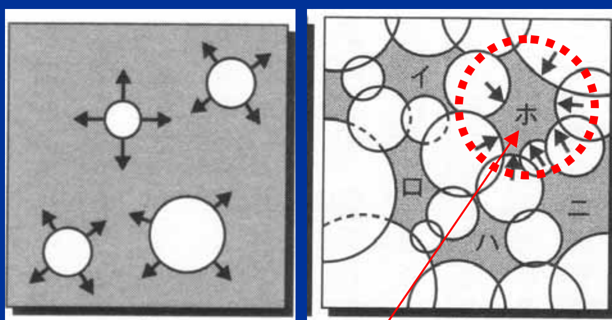
We discussed **Multiproduction of Universes** on the first order phase transition scenario, but this holds for various inflation models universally .

4.Multi-production of universes by inflation

Phys. Lett. **108B** (1982), 103-107

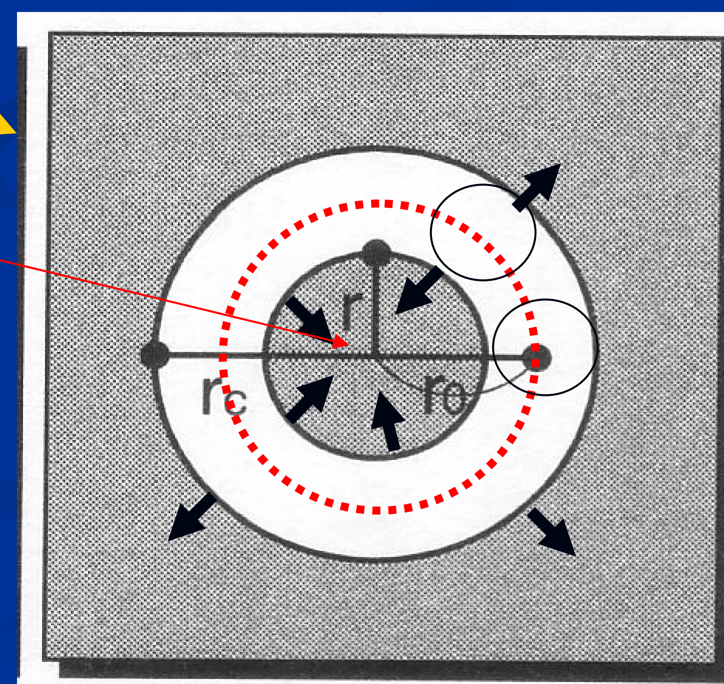
K. Sato, H. Kodama, M. Sasaki and K. Maeda

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.

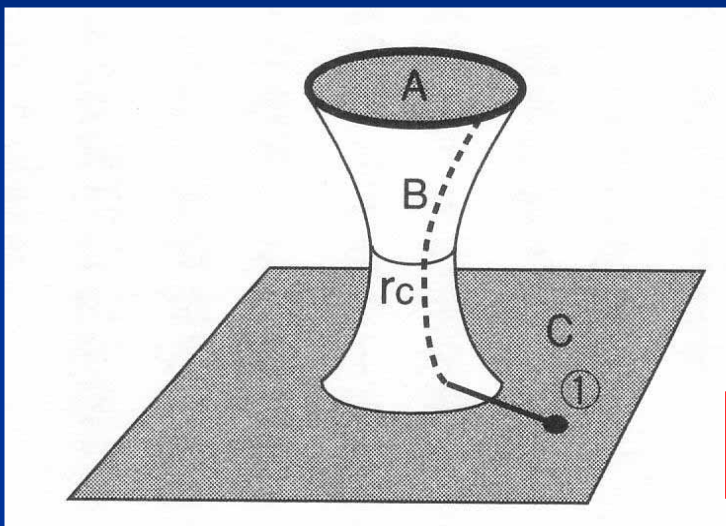
Spherical symmetric model of the trapped false vacuum region.

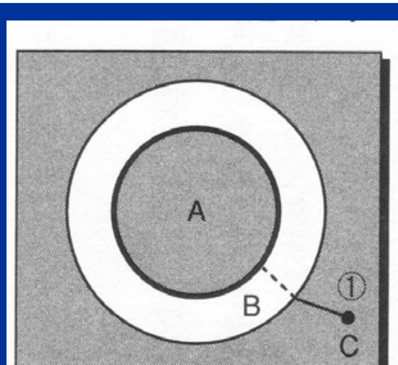


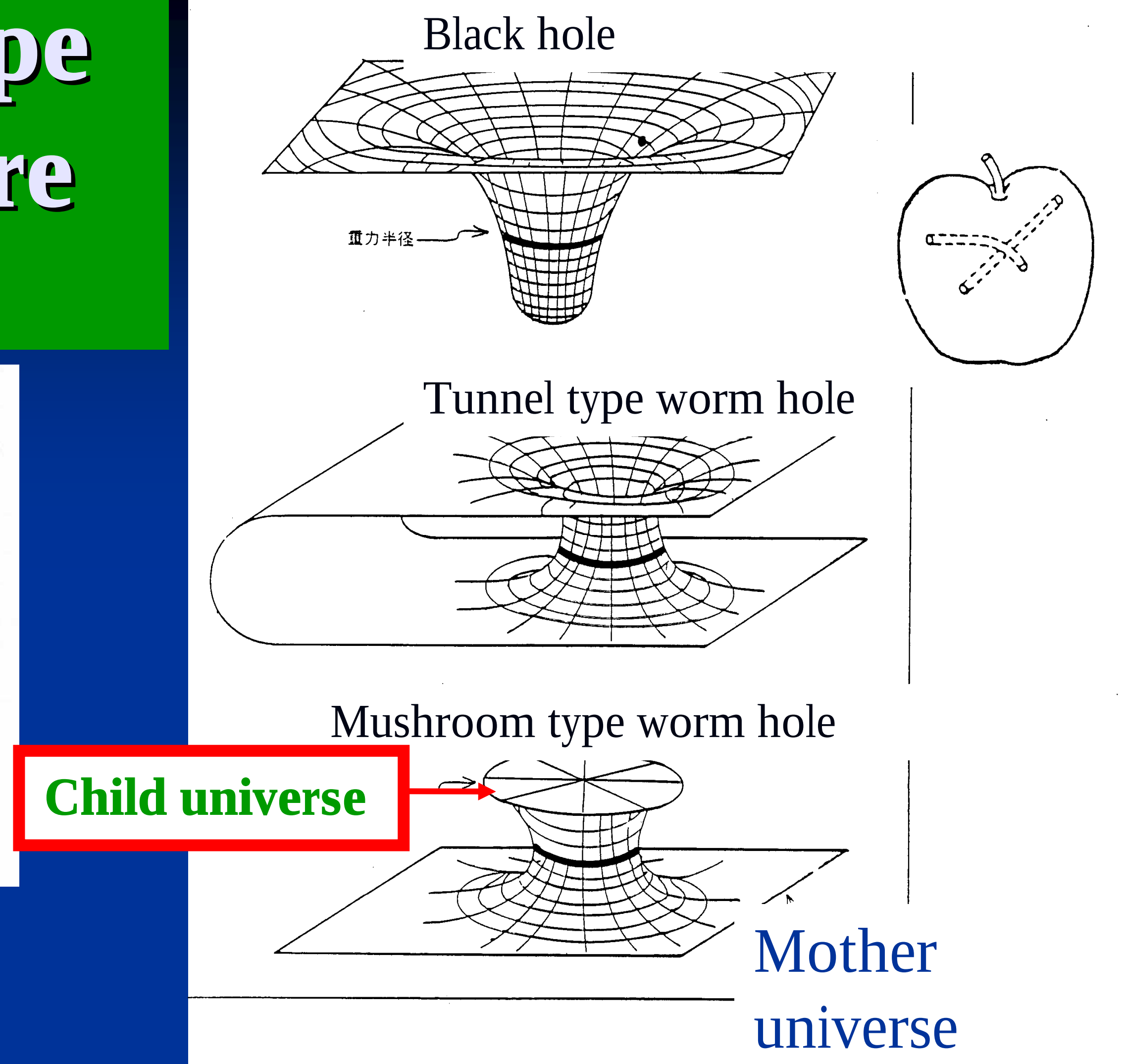
Consider the false vacuum region surrounded by true vacuum bubbles.
The surface is shrinking with light velocity, but the radius of the region becomes larger because of INFLATION, if the radius is greater than de Sitter horizon. This looks severe contradiction.

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

Mushroom type worm holes are created !







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

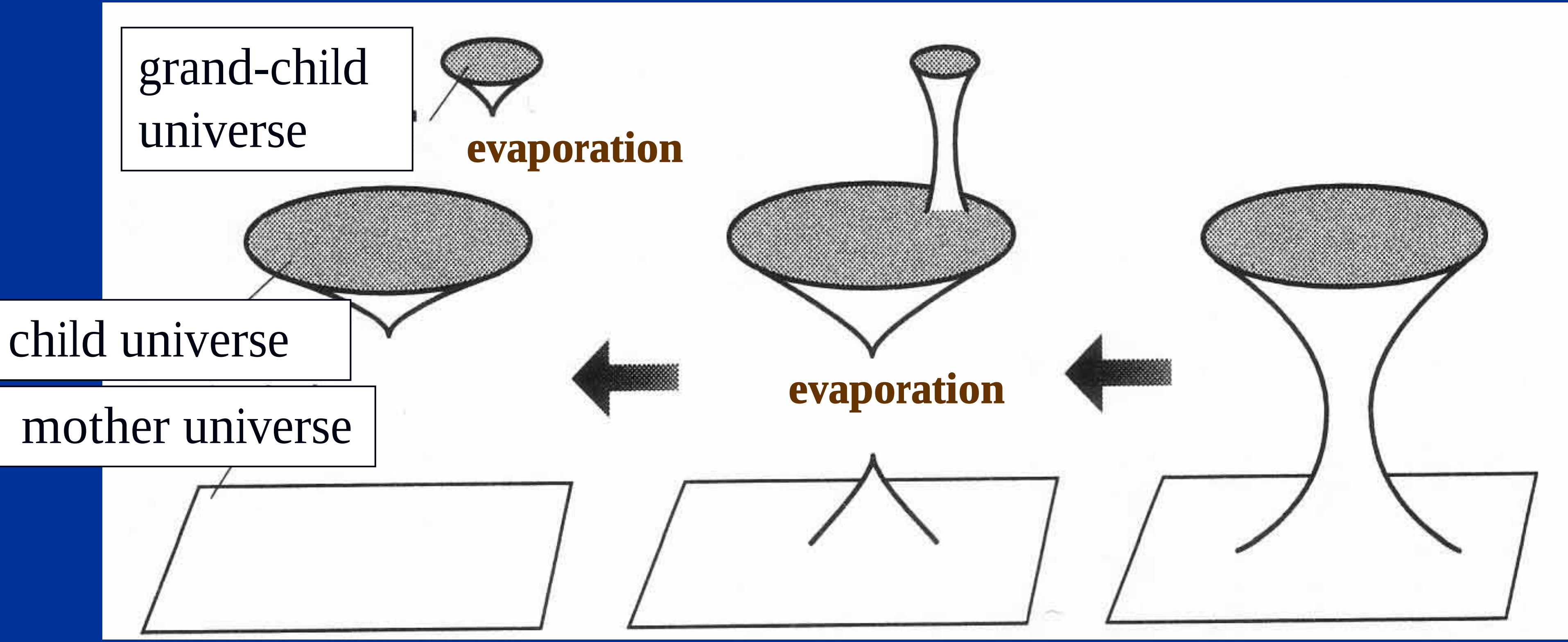
We may call the region is a child-universe.

Multiproduction of Universes

Wormholes are formed in child-universes copiously too.

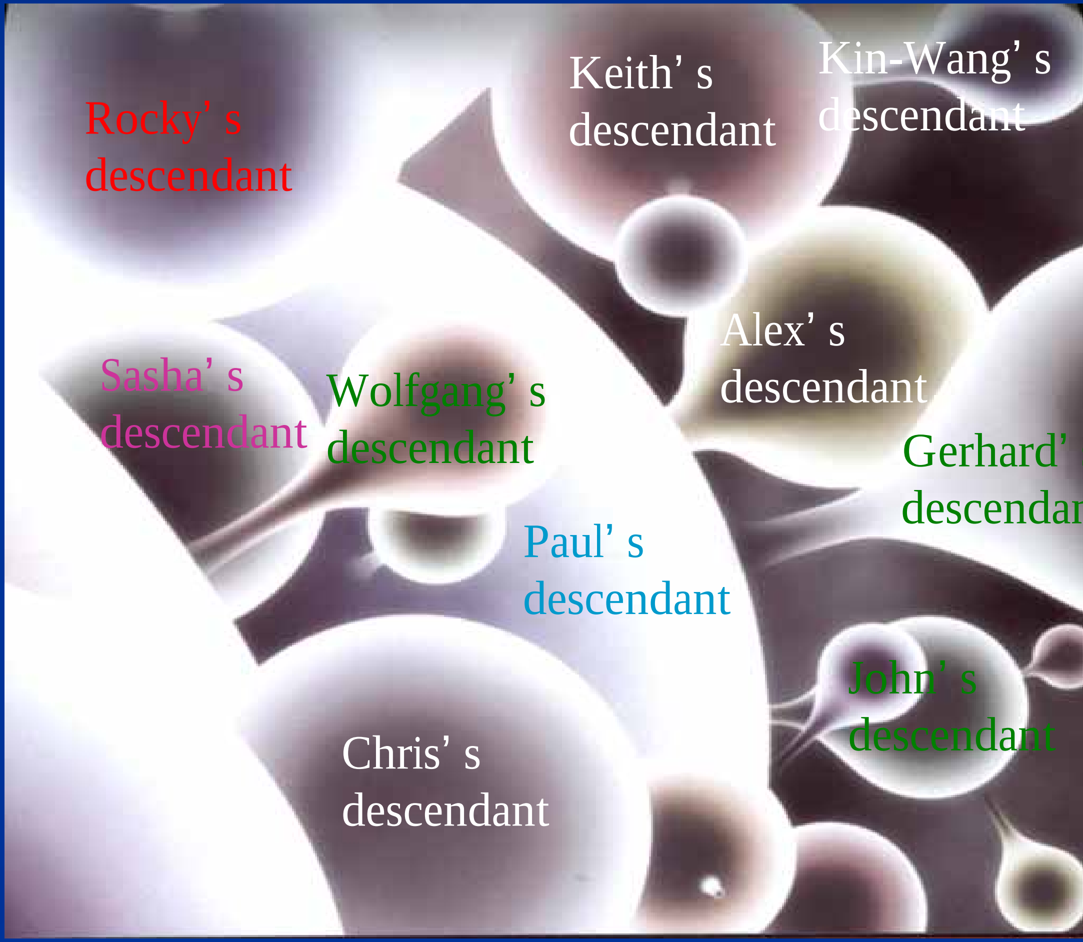
Then grand-child universes are formed, and so on…..

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



A speculative application of multi-production to the future of univerese

Present universe is filled by dark energy (vacuum energy) is the stage of second Inflation stage. it is naturally predicted universes are copiously produced if the phase transition occurs at a certain time in future . If our descendant still exist in this age, it is likely to be going to live in different child-universe respectively.



I will retire according to the retirement age next March.

December 1982 : moved to The University of Tokyo from Kyoto University , and established Theoretical Astrophysics Group.

No theoretical nor experimental astrophysics group exist in Physics Department. (except the experimental gravity group)

July 1995: RESCEU established. Activity on astrophysics and cosmology is greatly enhanced.

At present: RESCEU is going to the next stage of INFLATION under the leadership of Prof. Makishima.

As a PI of IPMU (Institute for the Physics and Mathematics of the Universe), I continue the research and hope to contribute the collaboration between IPMU, RESCEU and Physics Department (School of Science).

Thank all collaborators!

Happy to have a lot of

excellent advisors,

excellent colleagues and

excellent Juniors!