Hideo Kodama, JGRG 22(2012)111504

"Charmed by spacetime physics – from four to higher dimensions"

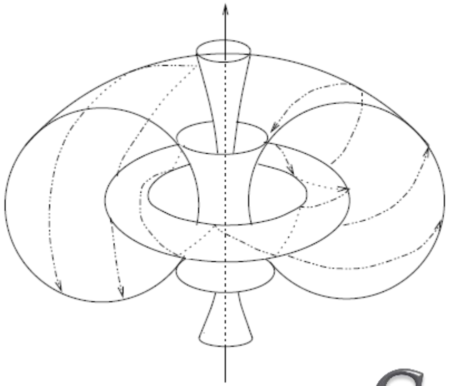
RESCEU SYMPOSIUM ON

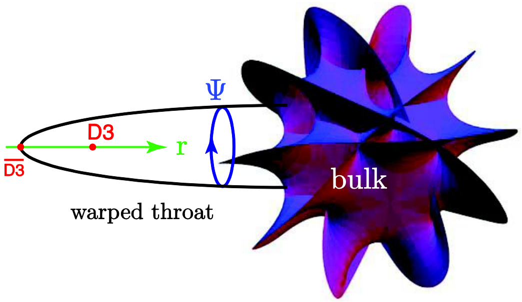
GENERAL RELATIVITY AND GRAVITATION

JGRG 22

November 12-16 2012

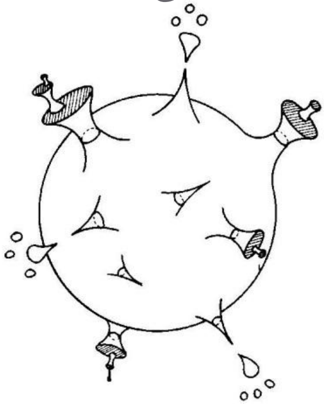
Koshiba Hall, The University of Tokyo, Hongo, Tokyo, Japan



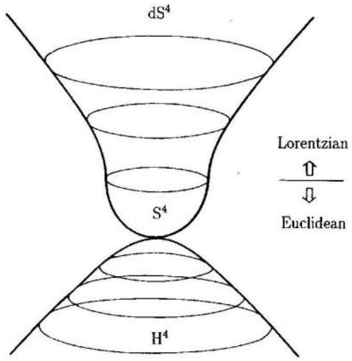


Charmed by Spacetime Physics

— From Four to Higher Dimensions —



Hideo Kodama
Theory Center, KEK



The 22th JGRG symposium
2012.11.15 Koshiba Hall, University of Tokyo

In Hayashi School

- 1975-1983

Bitter start

1975/4 Nuclear Astrophysics Group
led by late Prof. Chushiro Hayashi
in Kyoto University.

- 1969 Lagrangian quantum cosmology (Misner)

  Particle creation in an expanding universe (Parker)
- 1970 Singularity theorems (Hawking, Penrose)
- 1973 BH entropy (Bekenstein)

  Hawking –Ellis textbook
- 1974 BH evaporation (Hawking)

1975　研究室ハイキング、洛南鷲峰山の行者場、回想：鈴木博子君も非常に険しい道を降り下った

1999 佐藤文隆氏の紫綬褒章受賞祝賀会、於京都ロイヤルホテル、写真の左半分

同写真の右半分

Bitter start

1975/4 Nuclear Astrophysics Group
led by late Prof. Chushiro Hayashi
in Kyoto University.

1975/7 My daughter was born.

1977/1 My son was born.

1977/12 Two papers on quantum gravity.

- "Quantization of Gauge Fields by the Reduce
Formalism. 1. The Case of the Yang-Mills Fiel
- "Quantization of Gauge Fields by the Reduce
Formalism. 2. The Case of the Gravitational F

Both were rejected!!

Lesson 1

Do not be too self-confident !

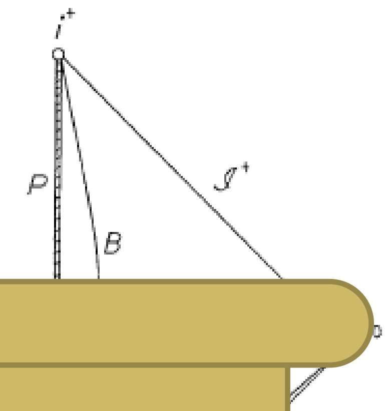
First Papers

After struggles of two years,

- "Inevitability of a naked singularity associated with the black hole evaporation", *Kodama H: PTP 62, L1434-1435 (1979)* .

- "Conserved energy flux for the sphericall symmetric system and the back reaction problem in the black hole evaporation", *Kodama H: PTP 63, 1217-1228 (1980).*

$$K := *(dr \wedge r^n \Omega_n), \quad S^\mu := G^\mu_\nu K^\nu \Rightarrow \quad \nabla_\mu S$$



Lesson 2

The origial motivation of a paper will be soon forgotten !

Moving to Physical Cosmology

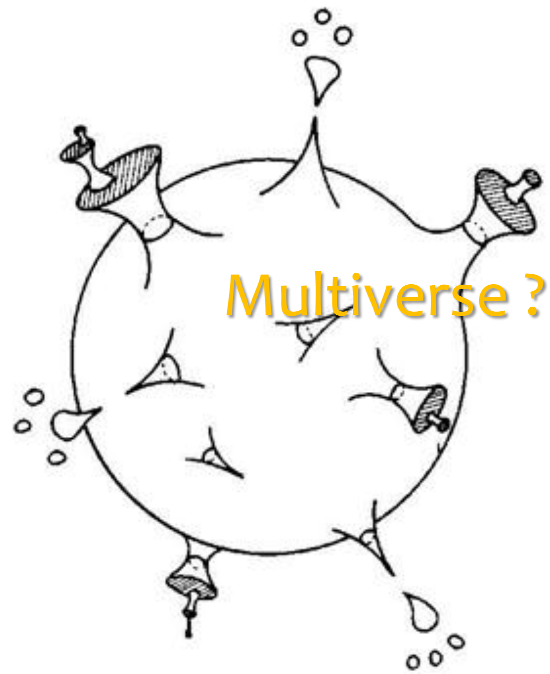
1981/3 Degree of DS

"On the particle-defining modes for a free neutral scalar field in spatially homogeneous and isotropic universes"

Kodama H: PTP65, 507-524 (1981).

But, I was still struggling …

1981-82 Invited to collaboration on the inflationary universe model by Katsuhiko Sato (with Maeda K, Sasaki M)



This collaboration opened up a new research avenue for me!!

K. Sato's New Group in U. Tokyo

- 1983-1987

The Early History of Inflation Theory

1974 SU(5) GUT (George H & Glashow SL)

1980 GUT inflation (Sato K, Kazanas D, Guth A)

1981 New inflation model (Linde A, Albrecht & Steinhardt)

1982 Cosmological perturbations from quantum fluctuations (Linde A, Hawking SW & Moss I, Starobinsky AA)

Creation of the Universe from Nothing (Vikenkin A)

1983 Wave function of the universe (Hartle J, Hawking SW)

Chaotic inflation (Linde A)

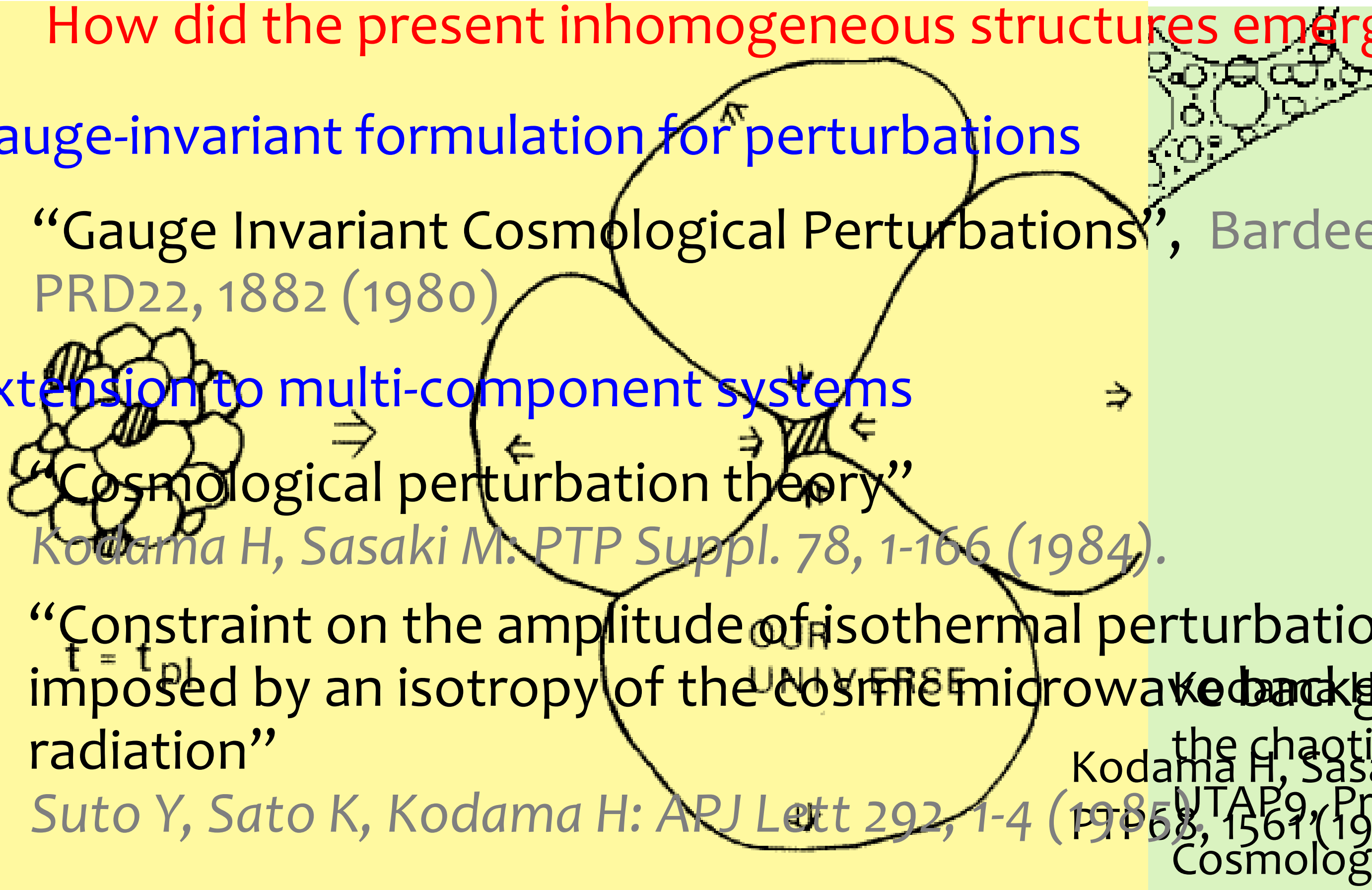
1984 Birth of superstring theories

From Inflation to Cosmological Perturbations

The old inflation model ➔ too inhomogeneous universe.

The new inflation model ➔ too "bold" universe.

How did the present inhomogeneous structures emerge?



Gauge-invariant formulation for perturbations

"Gauge Invariant Cosmological Perturbations", Bardeen J: PRD22, 1882 (1980)

Extension to multi-component systems

- "Cosmological perturbation theory"
  Kodama H, Sasaki M: PTP Suppl. 78, 1-166 (1984).
- "Constraint on the amplitude of isothermal perturbations imposed by an isotropy of the cosmic microwave background radiation"
  Suto Y, Sato K, Kodama H: APJ Lett 292, 1-4 (1985).

Kodama H, Sasaki M, Sato K: PTP68, 1561 (1982)

Kodama H: "Comments on the chaotic inflation", UTAP9, Proc. GUT & Cosmology, Tsukuba 1983.

More on Cosmology

We introduced the concept of "isocurvature perturbations" and studied their cosmological consequences.

- "Evolution of isocurvature perturbations I: Photon-baryon universe"
  Kodama H , Sasaki M: IJMP A 1, 265-301 (198
- "Evolution of isocurvature perturbations
  universe"
  Kodama H, Sasaki M: IJMP A 2, 491-560 (198

- Decaying CDM (with Suto & Sato)
- Baryogenesis after inflation (with Yokoya
- Dynamics of quark –hadron phase transit o)

Lesson 3

Do not insist on your preference wrt research subjects !

Back to Kyoto U.

- 1987-1993

Back to Quantum Gravity

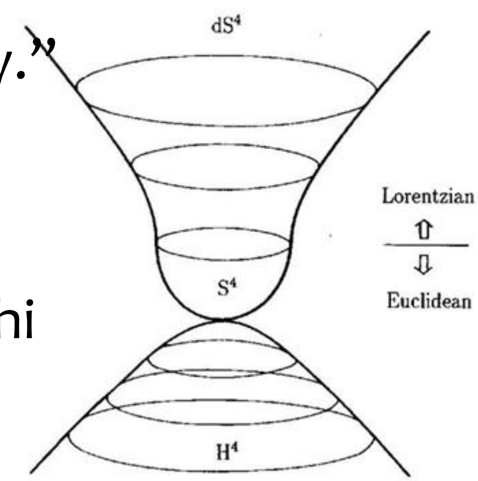
Interpretation of quantum cosmology

- "Quantum Cosmology In Terms Of The Wigner Function." , Kodama H(1988), MG5 (Perth, Australia)

I was struggling again. ..

New canonical formulation by Ashtekar.

"New Variables for Classical and Quantum Gravity."
Ashtekar A: PRL 57, 2244-2247 (1986)



Application to cosmology.

- "Specialization of Ashtekar's Formalism to Bianchi Cosmology"
  Kodama H: PTP 80, 1024-1040 (1988).
- "Holomorphic Wavefunction of the Universe"
  Kodama H: PRD 42, 2548-2565 (1990).

$$\Psi = \exp\left(-\frac{i}{\Lambda} S_{\rm CS}[\mathscr{A}]\right)$$

New Research Group

Compact Bianchi models

- "Comments on closed Bianchi models"
  Fujiwara Y, Ishihara H, Kodama H: CQG 10, 859-868 (1993)

Domain wall dynamics

- "Does a domain wall emit gravitational w
  invariant perturbative treatment"
  Kodama H, Ishihara H, Fujiwara Y: PRD 50, 7

Maximum mass of dS BH

- "Can Large Black Holes Collide in de Sitte
  Inflationary Scenario of Inhomogeneous U
  Shiromizu T, Nakano K, Kodama H, Maeda
  (1993).

Lesson 4

Do not do research alone!

In Yukawa Institute (Uji Branch)

- 1993-1995

New Formulation for Canonical QG

Dirac formalism for the canonical quantum gravity

$$\mathscr{C}_g \Psi = 0, \ \mathscr{H}_m \Psi = 0, \ \mathscr{H}_\perp \Psi = 0$$

$$H = \langle N^\alpha, \mathscr{H}_\alpha \rangle \approx 0$$

$$T \text{ is a time variable} \quad \Leftrightarrow \quad [H, T] \not\approx 0$$

$$X \text{ is a Dirac observable} \quad \Leftrightarrow \quad [\mathscr{H}_\alpha, X] \approx 0.$$

New quantum formulation for totally constrained systems.

- "Dynamics of Totally Constrained Systems I. Classical Theory"

  Kodama H : PTP 94, 475-501 (1995)

- "Dynamics of Totally Constrained Systems II. Quantum Theory"

  Kodama H : PTP 94, 937-987 (1995)

These are the the least cited papers among my papers, but I believe that these are the most original and deep work in my life.

Web Formalism for a Totally Constrained System

Totally Constrained System

$$H = n^{\alpha} h_{\alpha} : \quad [h_{\alpha}, h_{\beta}] = h_{\gamma} f^{\gamma}_{\alpha\beta}$$

The state vector is just a bookkeeper of measurement info:

$$\Phi \in \mathscr{H} \to P(x_n) = |\langle x_n|\Phi\rangle|^2, \; X|x_n\rangle = x_n|x_n\rangle$$

The c… mposed on an unbounded linear funct… escribes dynamics:

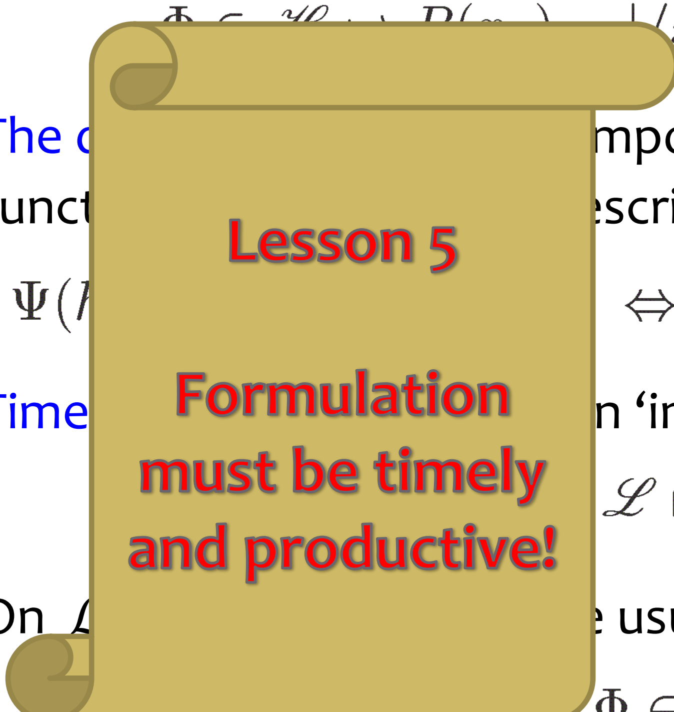
$$\Psi(… \Leftrightarrow \quad \Psi(\mathscr{N}) = 0, \; \mathscr{N} = \sum \mathrm{range}\ h_{\alpha}$$

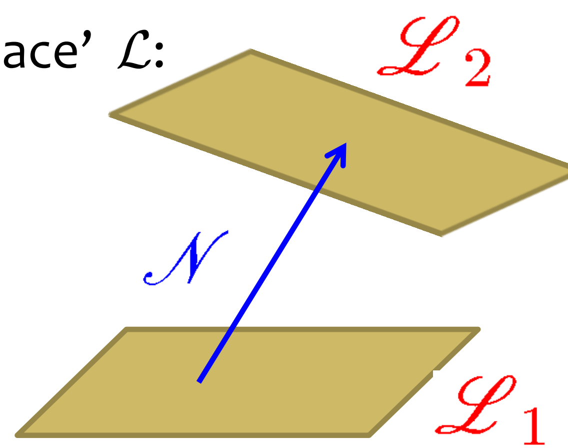
Time … n 'instantaneous state space' $\mathscr{L}$:

$$\mathscr{L} \cap \mathscr{N} = 0$$

On $\mathscr{L}$ … e usual wavefunction:

$$… \quad \Phi \in \mathscr{L}$$





In Yukawa Institute (Kitashirakawa)

1995-2007

Biianchi Cosmology

Hosoya Group in Titech

"Compact homogeneous universes."
Koike T, Tanimoto M, Hosoya A: JMP35 , 4855 (1994) [grcq/9405052]

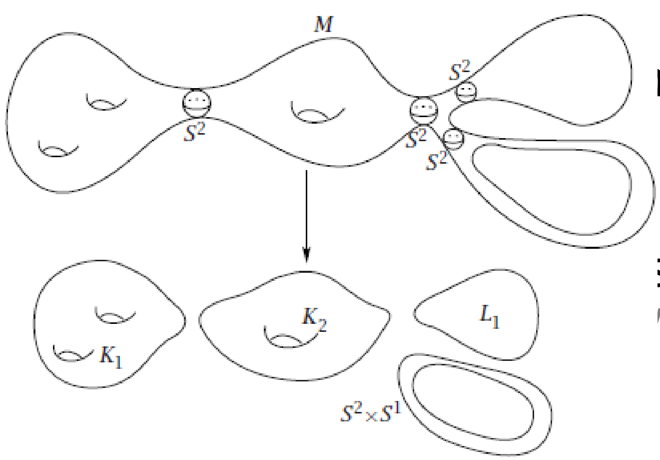
Thurston conjecture (=> proved by G Perelman 2002-2003)

Locally homogeneous & compact 3D ➔ $M = \tilde{M}/\Gamma$

$$\tilde{M} = E^3,\ S^3,\ H^3,\ S^2 \times E^1,\ H^2 \times E^1, \mathrm{Nil}, \mathrm{Sol}, \widetilde{\mathbf{SL_2}\mathbb{R}}$$

Hamiltonian stru … hi models

- "Canonical Str … eous Systems on Compact Closed 3-Mani … l"
  Kodama H : PT … 705066].
- "Phase Space … s with Fluid"
  Kodama H : PT … 0109064].



Back to Inflationary Cosmology

Is the Bardeen parameter conserved during reheating?

- "Evolution of cosmological perturbations in a stage dominated by an oscillatory scalar field"
  Kodama H, Hamazaki T : PTP 96, 949 (1996)[gr-qc/9608022].
- "Evolution of cosmological perturbations during reheating"
  Hamazaki T, Kodama H: PTP96, 1123 (1996)[gr-qc/9609036].
- "Evolution of Cosmological Perturbations in the Long Wavelength Limit"
  Kodama H, Hamazaki T: PRD 57, 7177(1998) [gr-qc/9712045].

To Higher Dimensions

Braneworld model

"A Large mass hierarchy from a small extra dimension"
Randall L , Sundrum R: PRL83 , 3370-3373 (1999)
"An Alternative to compactification"
Randall L, Sundrum R: PRL83 , 4690-4693 (1999)

Perturbations with model generalisation

$$\tilde{M} = \mathcal{N} \times K : \quad ds^2 = g_{ab}(y)dy^a dy^b + r(y)^2 d\sigma_K^2$$

- Brane World Cosmology — Gauge-Invariant Formalism for Perturbation —
  Kodama H, Ishibashi A, Seto O: PRD62, 064022(2000)[hep-th/0004160].

Cf. "Gauge invariant gravitational perturbations of maximally symmetric space-times", Mukohyama S: PRD62, 084015 (2000)[hep-th/0004067]

Higher-Dimensional Black Holes

Static black holes in higher dimensions

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\sigma_n^2$$

Three types of perturbations

- tensor perturbations : trivial
- vector perturbations : easy
- scalar perturbations : difficult ➔ Original paper by Zerilli

Generalisation of the Regge-Wheeler & Zerilli equations

- "A master equation for gravitational perturbations of maximally symmetric black hole in higher dimensions"
  Kodama H, Ishibashi A.: PTP110, 701-722 (2003)
- "Stability of higher-dimensional Schwarzschild black holes"
  Ishibashi A, Kodama H : PTP110, 901-919 (2003)
- "Master equations for perturbations of generalized static black holes with charge in higher dimensions"
  Kodama H, Ishibashi A.: PTP111, 29-73 (2004)

Thanks to Maple!!

To HD Unified Theories

The first realistic string inflation model (KKLT):

“de Sitter Vacua in String Theory”

Kachru S, Kallosh R, Linde A, Trivedi S : PRD68, 046005 (2003).

Systematic classification of BPS solutions to sugra of D=5 – 11:

Gauntlett JP, Gutowski JB (2003), …

Dynamics of warped compactification

- “Moduli Instability in Warped Compactifications of the Type IIB Supergravity

  Kodama H. and Uzawa K.: JHEP 0507, 061:1-16 (2005) [hep-th/0504193].

- “Comments on the four-dimensional effective theory for warped compactification”

  Kodama H. and Uzawa K.: JEHP 0603, 053:1-18 (2006) [hep-th/0512104].

Bottom Up Analysis

Standard model ⇒ GUT: gauge-sector unification

- αunification, hypercharge structure, neutrino mass
- Baryon asymmetry, strong CP(Peccei-Quinn symmetry)

GUT ⇒ SGUT: boson-fermion correspondence

- Dark matter, Λ problem, hierarchy problem

SGUT ⇒ Sugra GUT: inclusion of gravity

- Flat inflaton potential

Sugra GUT ⇒ HD Sugra GUT: matter sector unification

- Generation repitition, Cabibo/neutrino mixing, CP violation
- Origin of the Higgs in the adjoint representation

HD Sugra GUT ⇒ Superstring/M theory

- Consistency as a quantum theory, finite control parameters
- No Λ freedom (M-theory)

Research History

GUT inflation model

1981〜82, 1987〜88

QFT in curved spacetime

1979〜81

Cosmological Particle Creation

BH evaporation

Galaxy f
anisotro

larity

Cosmo
pertur

1984

I decided to push forward my research in my remaining time, believing that our universe is really higher-dimensional microscopically !!

Brane
its pe

y

1993〜2002

2003

2000〜02

Uniqueness and stability of higher-dim BHs

2003〜

Cosmology based on higher-dimensional sugra/string theory

2004〜

New Group in KEK

- 2007 -- 2016

Cosmophysics Group Key Projects

- Test unified theory of all interactions including gravity by the early evolution of the Universe
- High energy physics of cosmic jets and black holes

Problems to be solved in HUnT

- Dark Energy / Inflation Problems
  - Supersymmetry is necessary to control the vacuum energy but not sufficient to make it small.
    ☞ New symmetry?
  - How to circumvent the No-Go theorem against inflation?
    ☞ Higher-order corrections? Singularities? Open extra-dimensions?
- Compactification problem
  - No compactification with stabilised moduli consistent with the SM has been found.
    ☞ Can we reproduce the SM ?
  - Landscape problem, breaking and restoration of SUSY
    ☞ Dynamical comparison of compactification and ground states.

Messengers of Fundamental Physics in Cosmophysics

- Indirect

  CMB /LSS ➔ Inflation

- Direct

  DM: neutralinos $E \sim E_{SUSY} = 1\text{TeV} \sim 10^{10}$ GeV

  gravitinos $E \sim E_{SUSY}$, almost undetectable

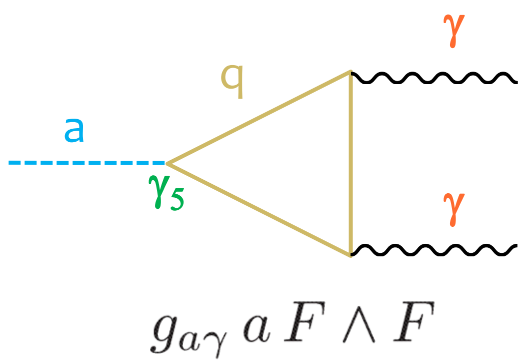
  axions $E \sim f_a = 10^8$ GeV $\sim m_{pl}$

  GW: $E \lesssim m_{pl}$

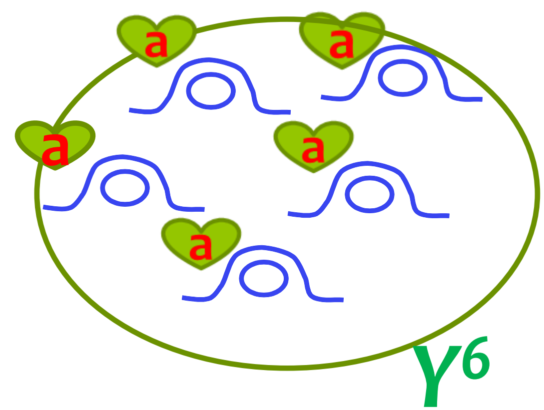
  Dark radiations ???

Axiverse

Among these, axions are quite unique in the following points:



- The shift symmetry leads to Chern-Simons interactions producing interesting and rich cosmophysical phenomena.
- Non-perturbative effects produce vey tiny mass, which is consistent with experiments due to its pseudo-scalar nature. The Compton wavelength can be of cosmological scales.
- Axion is an indispensable ingredient in the anomaly cancelation and appears ubiquitously in string compactification.



Thus, axions provide us the possibility to probe physics on the highest energy scales by low energy cosmophysical phenomena.

Back to Four Dimensions

I believe that axion is the most promising research subject in the future.

So, on the occasion of my becoming 60 years old,
I propose the subject "axion cosmophysics"
as the baton to the next generation.

	1	2	3	4	5	6	7	8	9	10
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	子	丑	寅	卯	辰	巳	午	未	申	酉
	11	12	13	14	15	16	17	18	19	20
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	戌	亥	子	丑	寅	卯	辰	巳	午	未
	21	22	23	24	25	26	27	28	29	30
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	申	酉	戌	亥	子	丑	寅	卯	辰	巳
	31	32	33	34	35	36	37	38	39	40
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	午	未	申	酉	戌	亥	子	丑	寅	卯
	41	42	43	44	45	46	47	48	49	50
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	辰	巳	午	未	申	酉	戌	亥	子	丑
	51	52	53	54	55	56	57	58	59	60
十 干	甲	乙	丙	丁	戊	己	庚	辛	壬	癸
十二支	寅	卯	辰	巳	午	未	申	酉	戌	亥

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AXION
COSMOPHYSICS
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Invited Speakers: