Ewha Womans U
23 December, 2015

General Relativity in Japan
– a historical perspective –

personal, highly biased

Misao Sasaki
YITP, Kyoto University

History: two main streams

Research Institute for Theoretical Physics, Hiroshima University

1944-1990

Yoshitaka Mimura

wave geometry

+

field theory

classical & quantum gravity

cosmology

Research Institute for Fundamental Physics, Kyoto University

1953-(1990)

Hideki Yukawa

particle/nuclear theory

+

solid state physics

biophysics

astrophysics + cosmology

Yukawa Institute for Theoretical Physics

1990 ~

RITP Hiroshima University

Established in 1944, during the 2nd world war

Mimura insisted "This institute won't be any use for the war. It will be solely devoted to progress in basic science."

Ministry of Education and Culture (Monbu-sho) finally agreed:
The purpose of the institute was announced as
" to perform integrated research on basic theories of physics"

This was possible thanks to Mimura's extensive work on wave geometry which looked quite promising as an approach to quantum gravity.

wave geometry:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \Rightarrow ds = \gamma_\mu dx^\mu$$

in short, fermionization of the geometry

RITP Hiroshima University

The institute was destroyed by the atomic bomb.

After the war it was rebuilt in Takehara, a small town about 50 km from Hiroshima along the inland sea.

Until ~ 1970, RITP was the center of GR research in Japan.

GR related research at RITP

- ADM formalism in expanding universe

  H. Nariai and T. Kimura, PTP 28 ('62) 529.

- Quantization of gravitational waves and mater fields in expanding universe

  H. Nariai and T. Kimura,

  PTP 29 ('63) 269; 29 ('63) 915; 31 ('64) 1138.

  [cf. L. Parker, PRL 21 ('68) 562]

- Discovery of gravitational anomaly

  T. Kimura, PTP 42 ('69) 1191; 44 ('70) 1353.

GR related research at RITP

- 2nd post-Newtonian formalism for many body systems

  T. Ohta, H. Okamura, K. Hiida and T. Kimura,
  PTP 50 ('73) 492; 51 ('74) 1220; 51 ('74) 1598.

- Gradient expansion for cosmological perturbations

  K. Tomita, PTP 54 ('75) 730.
  [cf. Salopek and Bond, PRD42 ('90) 3936.]

- Curvature perturbation from inflation

  MS, PTP 76 ('86) 1036.

- (2+1) dimensional quantum gravity

  A. Hosoya and K. Nakao, PTP 84 ('90) 739.

RIFP Kyoto University

Established in 1953 as the first joint-research center for theoretical physics, which is a new type of research center with its facilities open for use for research collaborations by the entire community of theoretical physicists in Japan.

Apparently this was possible thanks to Yukawa's Nobel Prize.

Yukawa advocated astrophysics and cosmology, but not GR much.

GR became an important area after Humitaka Sato joined RIFP in 1971.

GR related research at RIFP

- Tomimatsu-Sato solution (distorted Kerr)

  A. Tomimatsu and H. Sato, PRL 29 ('72) 1344.

- Cosmological/astrophysical constraints on Higgs mass

  K. Sato and H. Sato, PTP 54 ('75) 1564.

- Annual workshops on Nuclear Astrophysics (which includes GR and cosmology): '55 ~ '90

  lead by C. Hayashi and later by H. Sato.

- GRG workshops: '74, '75, '76.

  lead by R. Uchiyama, H. Nariai and H. Sato.

JGRG annual workshops (1991~)

http://www-tap.scphys.kyoto-u.ac.jp/jgrg/index.html

Unification of RITP Hiroshima U and RIFP Kyoto U to form Yukawa Institute for Theoretical Physics was a stimulative event that lead to expansion of the GR community in Japan.

At the same time, various GW detector projects worldwide made research in GR more observationally important.

Also progress in cosmology made GR indispensable for proper understanding of physics of the early universe and its observational consequences.

This year we celebrated 25th anniversary of JGRG workshops

(# of JGRG members ~ 200)

Gravity Today

- No deviation from General Relativity

e.g., C. Will's living review

- solar system tests – PPN parameters

$$g_{00} = -1 + 2\psi - 2\beta\psi^2 + \cdots : \quad \beta_{GR} = 1$$

$$g_{ij} = \delta_{ij}\left(1 + 2\gamma\psi + \cdots\right) \quad : \quad \gamma_{GR} = 1$$

$|\gamma - 1| < 2.3 \times 10^{-5}$: Shapiro time delay (Bertotti et al. '03)

$|4\beta - \gamma - 3| < 4.4 \times 10^{-4}$: Strong EP (Baessler et al. '99)

- constancy of gravitational constant

$|d\log G/dt| < 10^{-12}\ \mathrm{yr}^{-1}$: Lunar laser ranging (Williams et al '04)

• binary pulsar – GW emission rate

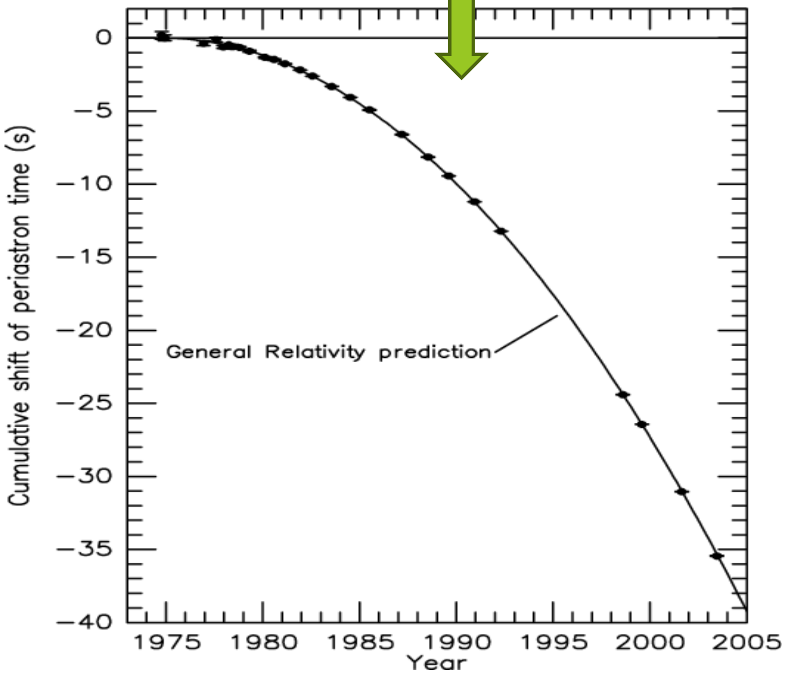
Hulse-Taylor binary (B1913+16)

- orbital change due to GW emission

$$\frac{\dot{P}_{\mathrm{B1913+16}}}{\dot{P}_{GR}} = 1.0013 \pm 0.0021$$

perfect match with GR predictions

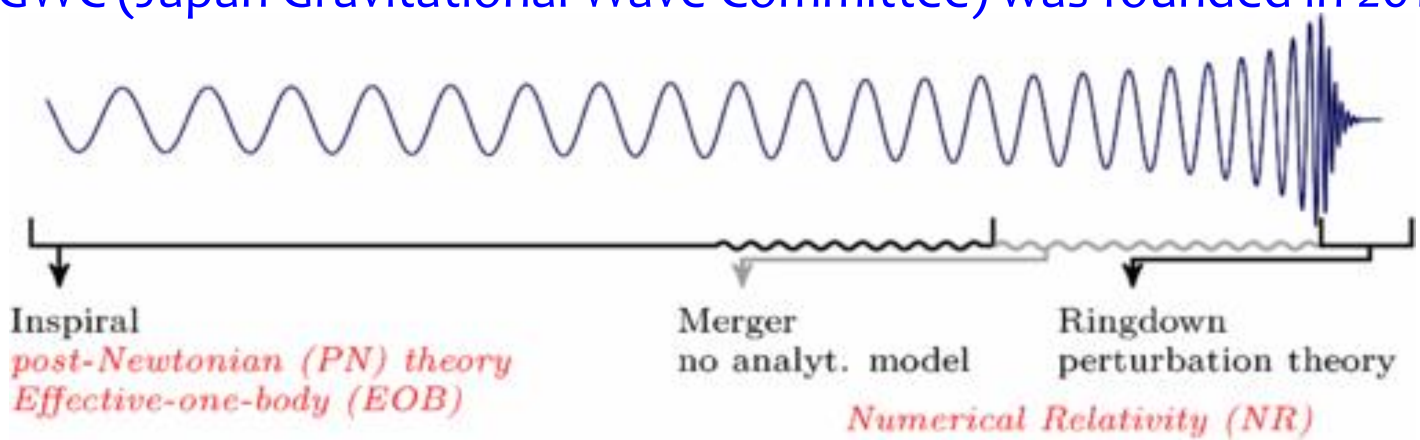
- periastron time shift



GW physics/astronomy

- Dawn of GW physics/astronomy
  - LIGO has started operation
  - VIRGO will start to operate soon
  - KAGRA will start to operate by 2017

[JGWC (Japan Gravitational Wave Committee) was founded in 2013]

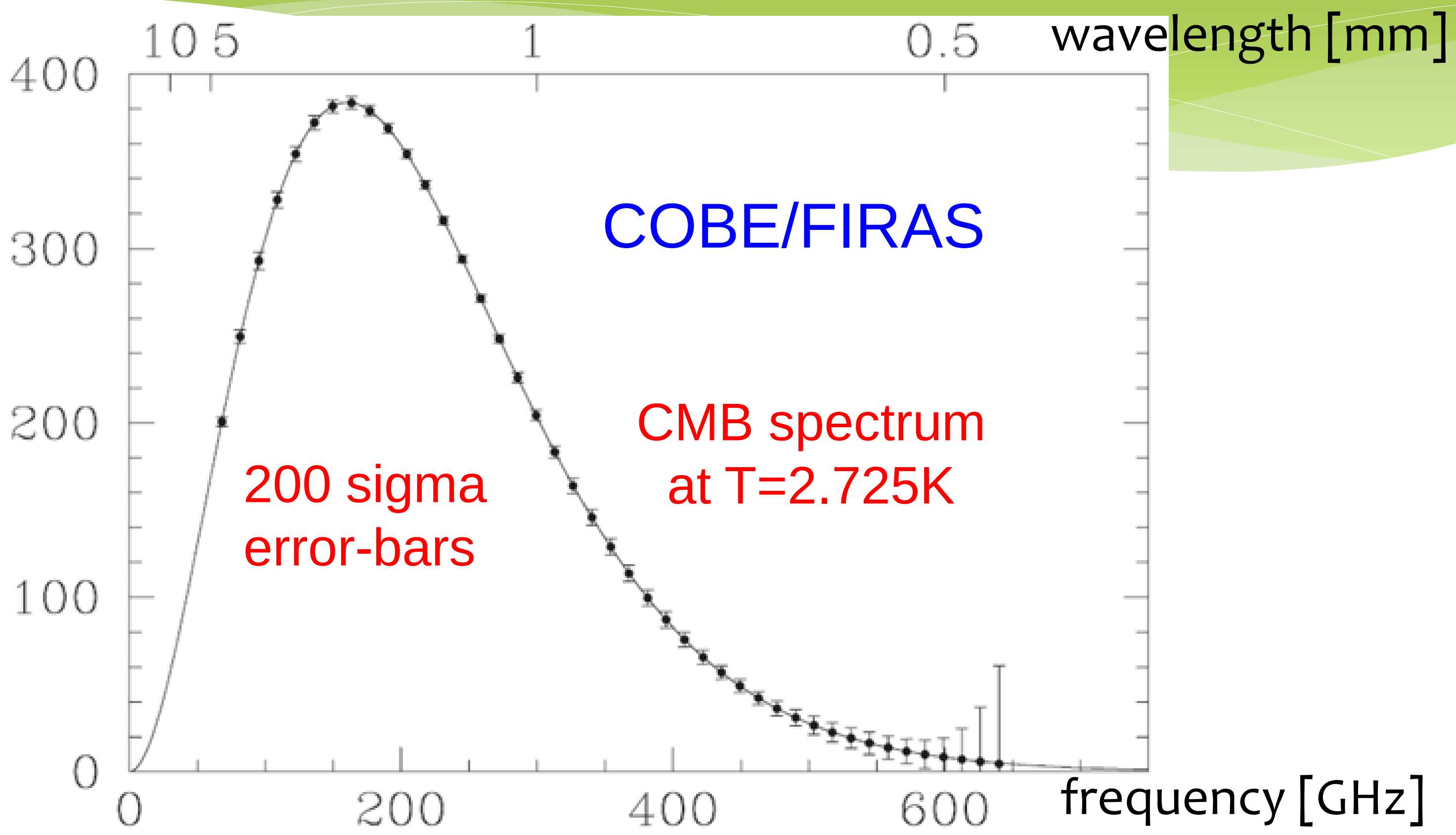


taken from A. Sesana, arXiv:1307.4086

more accurate, strong field tests of GR

Cosmology Today

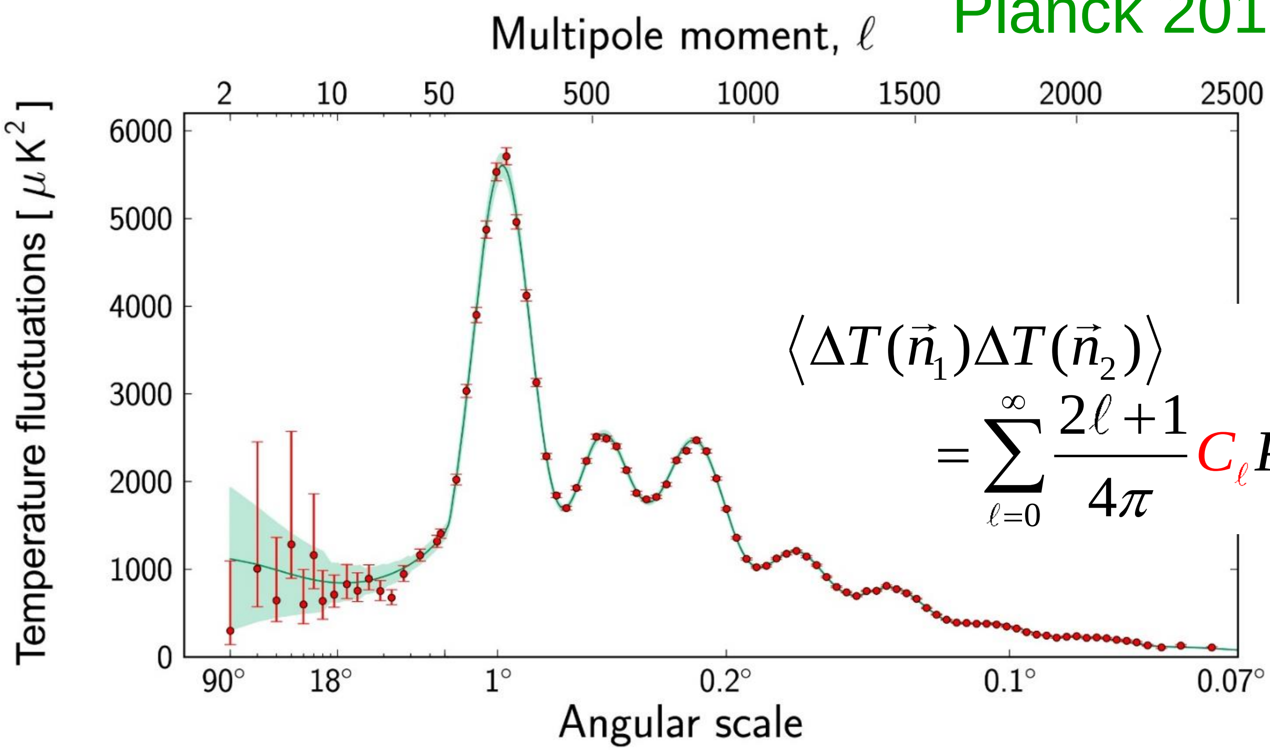
- Big-Bang theory has been firmly established



another strong evidence for GR

Strong evidence for inflation

Planck 2013



$$\left\langle \Delta T(\vec{n}_1)\Delta T(\vec{n}_2)\right\rangle = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta).$$

- highly Gaussian fluctuations
- almost scale-invariant spectrum

only to be confirmed (by tensor modes?)

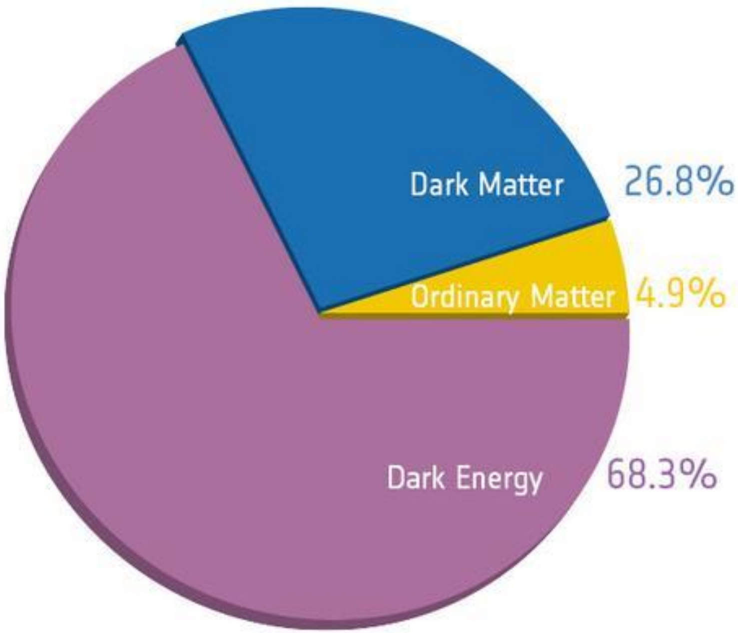
Fundamental(?) Issues

- Dark Matter

Is it really `matter'?

Perhaps yes,
because it gravitates.

fermion? boson?
primordial BH?
something else?



Is there a way to generically distinguish them?

- Dark Energy

  - apparent accelerated expansion of the universe

    Is the expansion really accelerating?

    observational bias? theoretical prejudice?

    How can we confirm acceleration?

  - modified gravity vs unknown matter field

    How to distinguish?

    large scale structure formation

    $w<-1$ implies modified gravity, etc...

    Can we falsify GR?

    any other effective discriminators?

comments on modified gravity

IR modification ⇐ GR ⇒ UV modification

⇕ ? ⇕ ?

long distance short distance

- time is important in spacetime!
- any smooth function f(x) contains infinitely large Fourier modes ...
- amplitude of Riemann? in which frame?

conformal (& disformal) frames?

• Inflation

➢ How did inflation begin?

what guarantees homogeneity and isotropy?

quantum cosmology/gravity?

frame-independent definition of inflation?

➢ What is ‘inflaton’?

what determines the end of inflation / reheating?

flatness / open inflation?

non-Gaussianity? tensor-scalar ratio?

new guiding principle / working hypothesis?

What's next?
Which direction?

my personal recollections

cosmological perturbation theory (CPT)

collaboration with
H Kodama

Progress of Theoretical Physics Supplement No. 78, 1984

Cosmological Perturbation Theory

Hideo KODAMA and Misao SASAKI*

Department of Physics, University of Tokyo, Tokyo 113
**Department of Physics, Kyoto University, Kyoto 606*

(Received September 5, 1984)

The linear perturbation theory of spatially homogeneous and isotropic universes is reviewed and reformulated extensively. In the first half of the article, a gauge-invariant formulation of the theory is carried out with special attention paid to the geometrical meaning of the perturbation. In the second half of the article, the application of the theory to some important cosmological models is discussed.

gravitational waves (GW)

collaboration with
T Nakamura

Progress of Theoretical Physics, Vol. 67, No. 6, June 1982

itational Radiation from a Kerr Black Hole. I

rmulation and a Method for Numerical Analysis ——

Misao SASAKI and Takashi NAKAMURA

Research Institute for Fundamental Physics
Kyoto University, Kyoto 606

(Received November 28, 1981)

A class of new inhomogeneous equations governing gravitational perturbations of the Kerr geometry is presented. It is shown that, contrary to the case of the Teukolsky equation, the perturbation equations have short-range potential and no divergent source terms for large distance. Using one of such equations which seems to be the simplest, we have computed the spectrum and the energy of gravitational radiation induced by a test particle of mass μ falling along the z-axis into a Kerr black hole of mass $M(\gg\mu)$ and angular momentum $Ma(a<M)$. It is found that the total energy radiated is $0.0170\mu c^2\ (\mu/M)$ when $a=0.99M$, which is 1.65 times larger than that when $a=0$, i.e., the Schwarzschild case.

§ 1. Introduction

my personal recollections

cosmological perturbation theory (CPT)

gravitational waves (GW)

- during 80's, GWs were regarded as more realistic, of firm GR foundation.
- during 90's, CPT became realistic, thanks to COBE measured anisotropy.
- during 00's, both became realistic. But…

fairy tales are necessary for healthy growth of children
(H Sato at a theory group workshop in '90s)

so WE need fairy tales…

With a bit of **我田引水**（ga-den-in-sui)

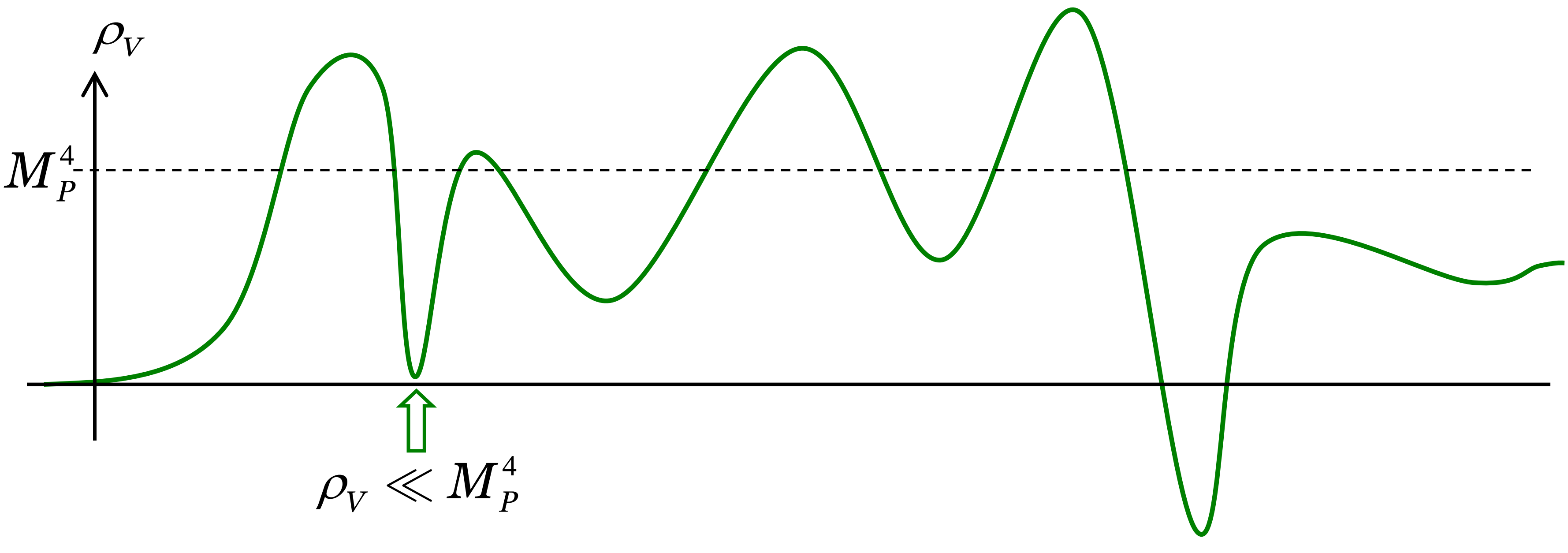
which means ‘self advocacy’, more or less…

String Theory Landscape!

String theory landscape

Bousso & Pochinski ('00), Susskind, Douglas, KKLT ('03), ...

- There are ~ 10^{500} vacua in string theory
  - vacuum energy ρ_v may be positive or negative
  - typical energy scale ~ M_P^4
  - some of them have $\rho_v \ll M_P^4$



testing string theory landscape in cosmology?

Cosmic Landscape

various vacua realized in the early universe

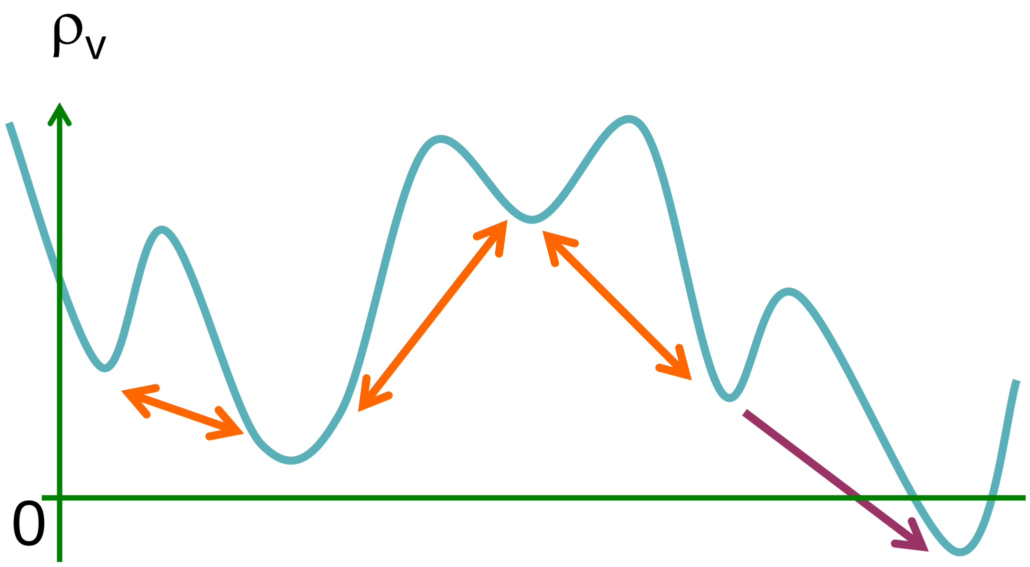
distribution determined by various factors

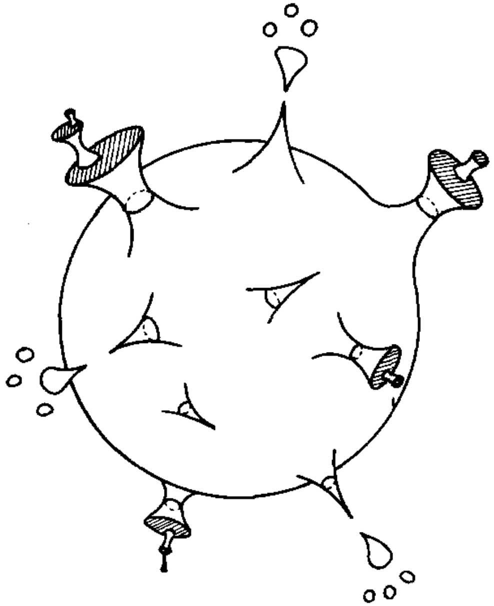
probability measure, density of states,
quantum equilibrium, ...

quantum transitions between various vacua

universe jumps around in the landscape by quantum tunneling

- it can go up to a vacuum with larger ρ_v
  de Sitter (dS) space ~ thermal state with $T = H/2\pi$
- if it tunnels to a vacuum with negative ρ_v , it collapses within $t \sim M_P/|\rho_v|^{1/2}$.
- so we may focus on vacua with positive ρ_v: dS vacua





Sato, Kodama, MS & Maeda ('81)

Creation of Open Universe

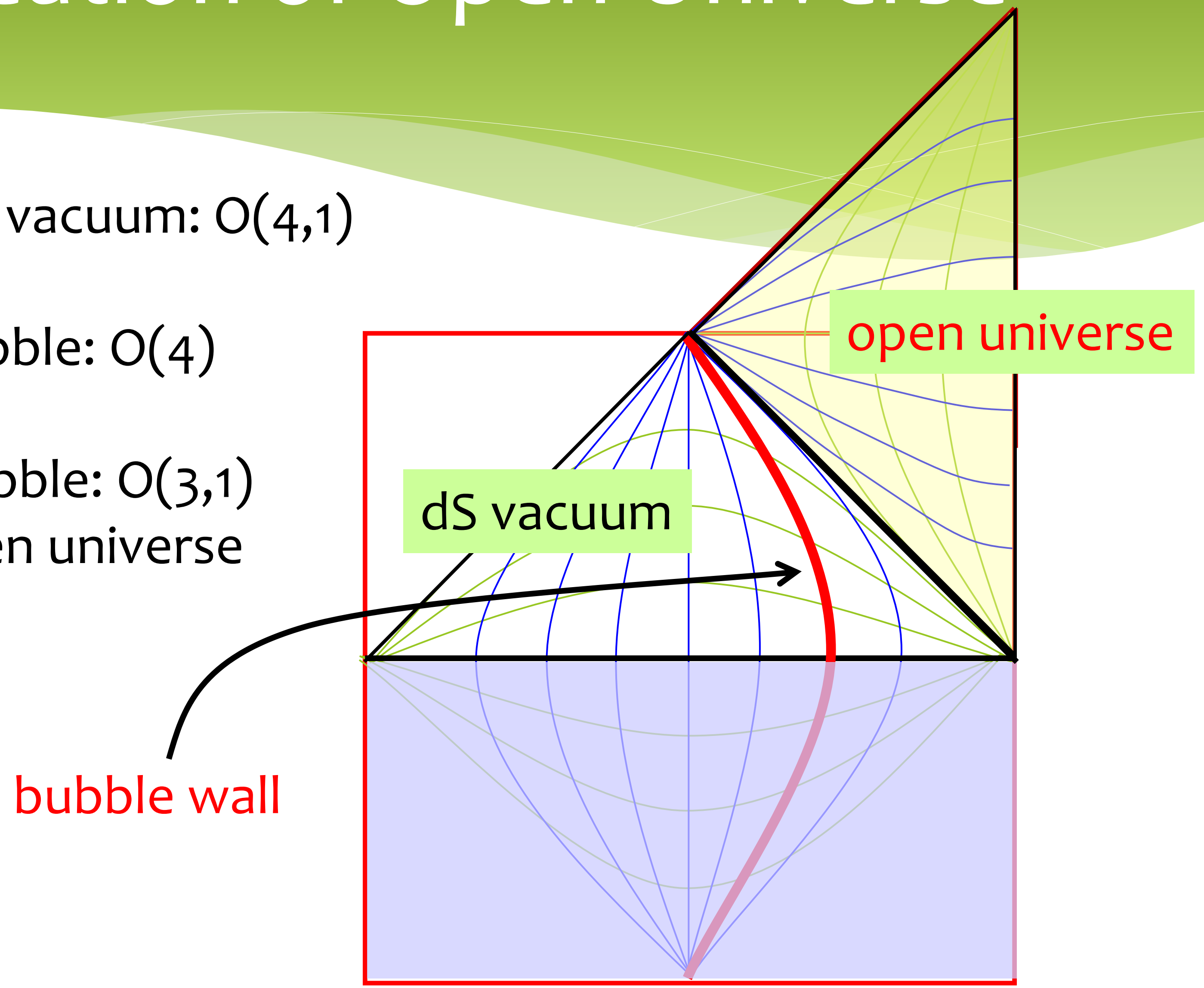
de Sitter (dS) vacuum: O(4,1)

⇩

Euclidean bubble: O(4)

⇩

nucleated bubble: O(3,1)
=open universe



Open Universe in the Landscape

Universe inside nucleated bubble = spatially open universe

Friedmann eq.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_P^2} + \frac{1}{a^2}$$

negative spatial curvature

$$1 = \frac{\rho}{3M_P^2 H^2} + \frac{1}{a^2 H^2} \equiv \Omega + \Omega_K$$

density parameter

Observational data indicate $1-\Omega_0 = \Omega_{K,0} \sim< 10^{-2}$: almost flat

("0" stands for current value)

what if this is the case?

- two possibilities

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

$$1-\Omega_0 = 10^{-2} \sim 10^{-3}$$ "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)

$$1-\Omega_0 \ll 1$$ "flat universe"

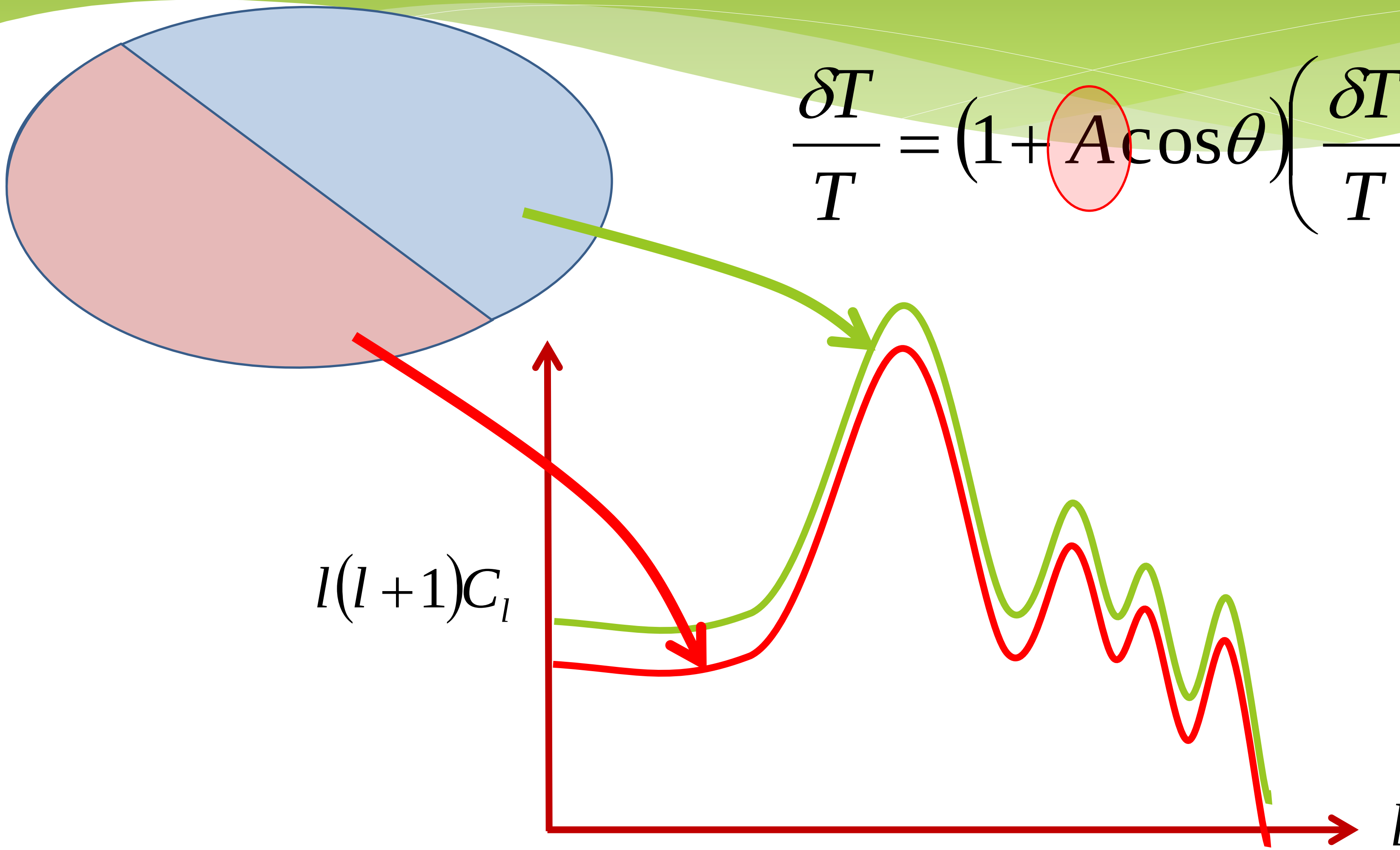
⇨ signatures from bubble collisions

Sugimura, Yamauchi & MS ('12)

dipolar statistical anisotropy

Kanno, MS & Tanaka ('13)

$$\frac{\delta T}{T} = \left(1 + A\cos\theta\right)\left(\frac{\delta T}{T}\right)_0$$



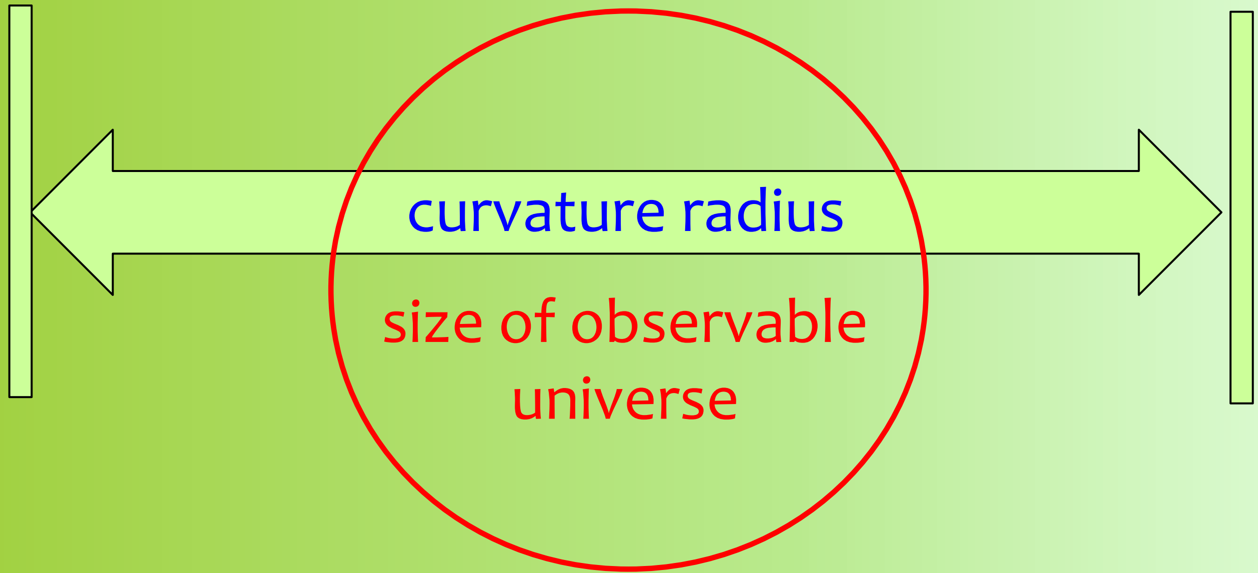
Planck XXIII

$$\frac{\delta T}{T} = (1 + A\cos\theta)\left(\frac{\delta T}{T}\right)_{iso}$$

$$A \approx 0.07$$

Data set	FWHM [°]	A	(l,b) [°]	$\Delta \ln \mathcal{L}$	Significance
Commander	5	$0.078^{+0.020}_{-0.021}$	$(227, -15) \pm 19$	8.8	3.5σ
NILC	5	$0.069^{+0.020}_{-0.021}$	$(226, -16) \pm 22$	7.1	3.0σ
SEVEM	5	$0.066^{+0.021}_{-0.021}$	$(227, -16) \pm 24$	6.7	2.9σ
SMICA	5	$0.065^{+0.021}_{-0.021}$	$(226, -17) \pm 24$	6.6	2.9σ
WMAP5 ILC	4.5	0.072 ± 0.022	$(224, -22) \pm 24$	7.3	3.3σ
Commander	6	$0.076^{+0.024}_{-0.025}$	$(223, -16) \pm 25$	6.4	2.8σ
NILC	6	$0.062^{+0.025}_{-0.026}$	$(223, -19) \pm 38$	4.7	2.3σ
SEVEM	6	$0.060^{+0.025}_{-0.026}$	$(225, -19) \pm 40$	4.6	2.2σ
SMICA	6	$0.058^{+0.025}_{-0.027}$	$(223, -21) \pm 43$	4.2	2.1σ
Commander	7	$0.062^{+0.028}_{-0.030}$	$(223, -8) \pm 45$	4.0	2.0σ
NILC	7	$0.055^{+0.029}_{-0.030}$	$(225, -10) \pm 53$	3.4	1.7σ
SEVEM	7	$0.055^{+0.029}_{-0.030}$	$(226, -10) \pm 54$	3.3	1.7σ
SMICA	7	$0.048^{+0.029}_{-0.029}$	$(226, -11) \pm 58$	2.8	1.5σ
Commander	8	$0.043^{+0.032}_{-0.029}$	$(218, -15) \pm 62$	2.1	1.2σ
NILC	8	$0.049^{+0.032}_{-0.031}$	$(223, -16) \pm 59$	2.5	1.4σ
SEVEM	8	$0.050^{+0.032}_{-0.031}$	$(223, -15) \pm 60$	2.5	1.4σ
SMICA	8	$0.041^{+0.032}_{-0.029}$	$(225, -16) \pm 63$	2.0	1.1σ
Commander	9	$0.068^{+0.035}_{-0.037}$	$(210, -24) \pm 52$	3.3	1.7σ
NILC	9	$0.076^{+0.035}_{-0.037}$	$(216, -25) \pm 45$	3.9	1.9σ
SEVEM	9	$0.078^{+0.035}_{-0.037}$	$(215, -24) \pm 43$	4.0	2.0σ
SMICA	9	$0.070^{+0.035}_{-0.037}$	$(216, -25) \pm 50$	3.4	1.8σ
WMAP3 ILC	9	0.114	$(225, -27)$	6.1	2.8σ
Commander	10	$0.092^{+0.037}_{-0.040}$	$(215, -29) \pm 38$	4.5	2.2σ
NILC	10	$0.098^{+0.037}_{-0.039}$	$(217, -29) \pm 33$	5.0	2.3σ
SEVEM	10	$0.103^{+0.037}_{-0.039}$	$(217, -28) \pm 30$	5.4	2.5σ
SMICA	10	$0.094^{+0.037}_{-0.040}$	$(218, -29) \pm 37$	4.6	2.2σ

Gradient of a field over the horizon scale = Super-curvature mode in open inflation



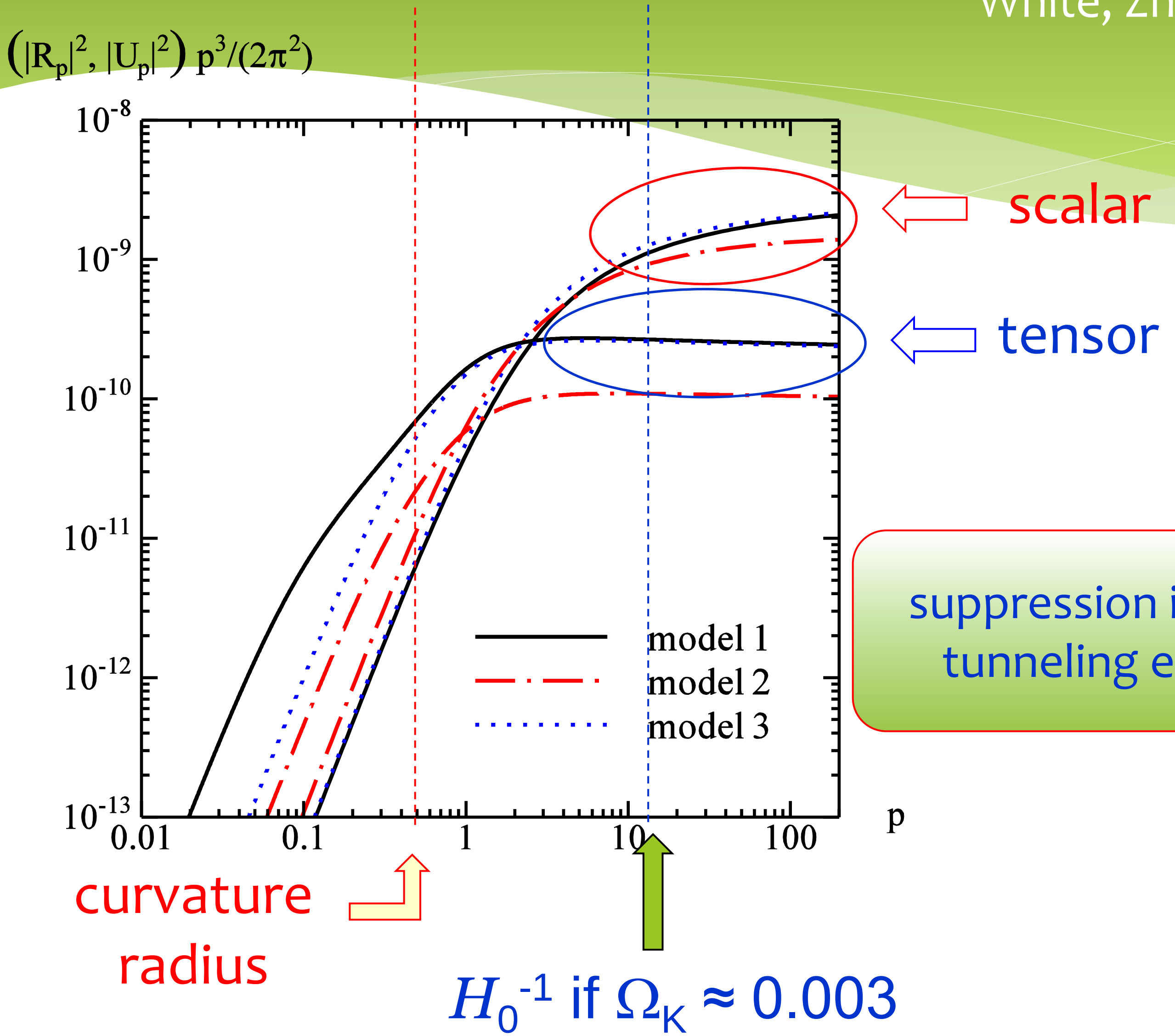
may modulate the amplitude of perturbation depending on the direction.

leading order effect is dipolar

if this is the case, then Ω ~>10^{-3}

scalar suppression on large scales

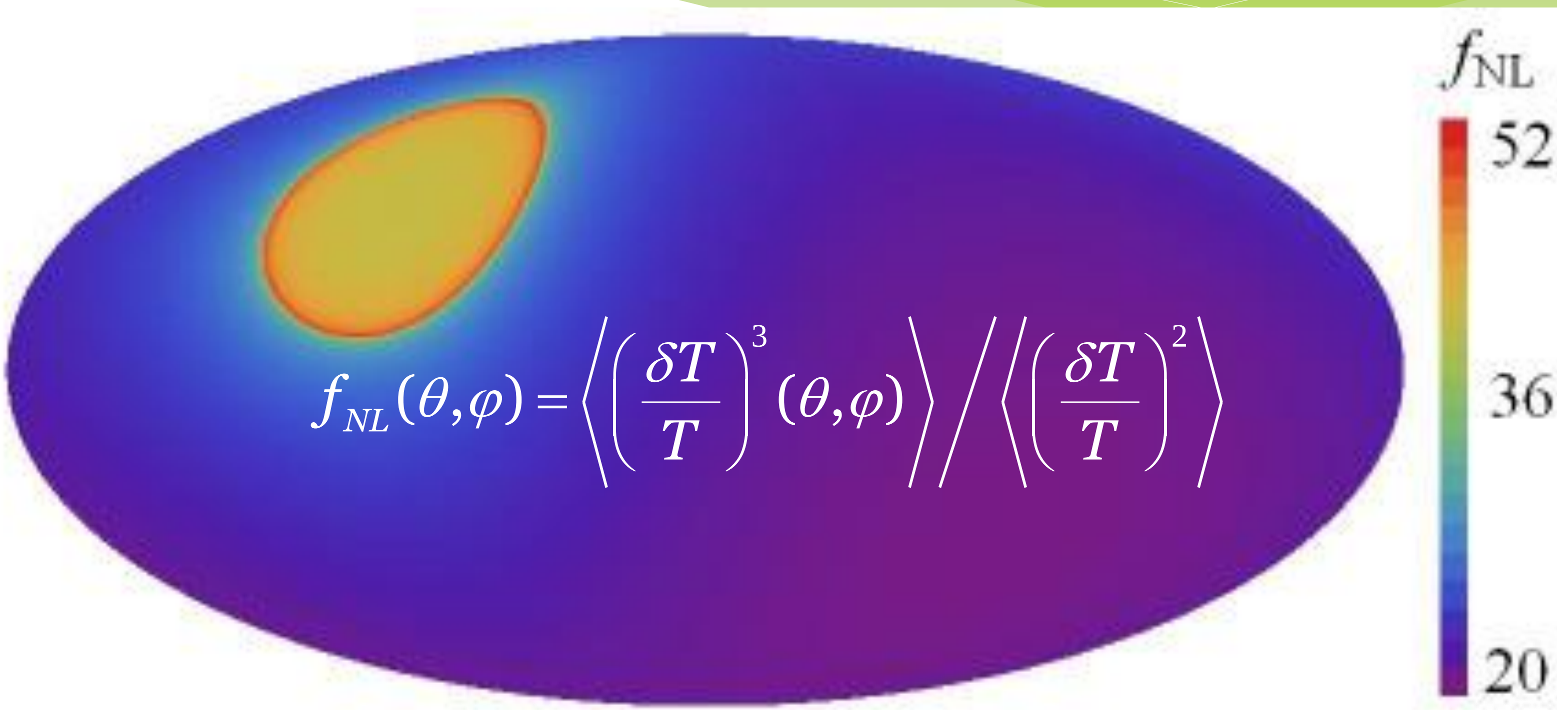
White, Zhang & MS ('14)



suppression is due to quantum tunneling effect on vacuum

non-Gaussian bubbles in the sky

Sugimura, Yamauchi & MS ('12)



$$f_{NL}(\theta,\varphi)=\left\langle\left(\frac{\delta T}{T}\right)^3(\theta,\varphi)\right\rangle\Big/\left\langle\left(\frac{\delta T}{T}\right)^2\right\rangle$$

detection of a spherically symmetric "localized" non-Gaussianity will be the first observational signature of string theory!

Summary: future perspectives

- We are entering an era of

  precision cosmology
  gravitational wave astronomy

- any tiny deviation from GR would be revolutionary

develop "realistic" GR cosmology

perturbative, non-perturbative, numerical, observational...

look for interesting "fairy tales"

string landscape, quantum cosmology, something exciting...