YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

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Toward Cosmic Landscape

- geemunu, geemunu, geemunu... -

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a bit of 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/DMR 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, 中間発表会, in '90s)

(chukan-happyo-kai)

so WE (at least I) need fairy tales...

Gravity Today

- No deviation from General Relativity

cf. C Will; living review '06

- solar system tests – PPN parameters

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

$|\gamma - 1| < 2.3 \times 10^{-5}$: 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

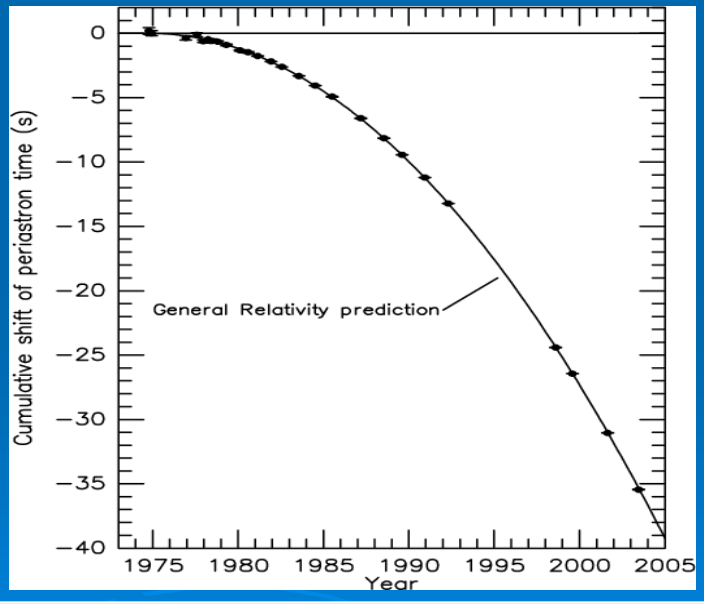
Hulse-Taylor binary (B1913+16)

- orbital change due to GW emission

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

perfect match with GR predictions

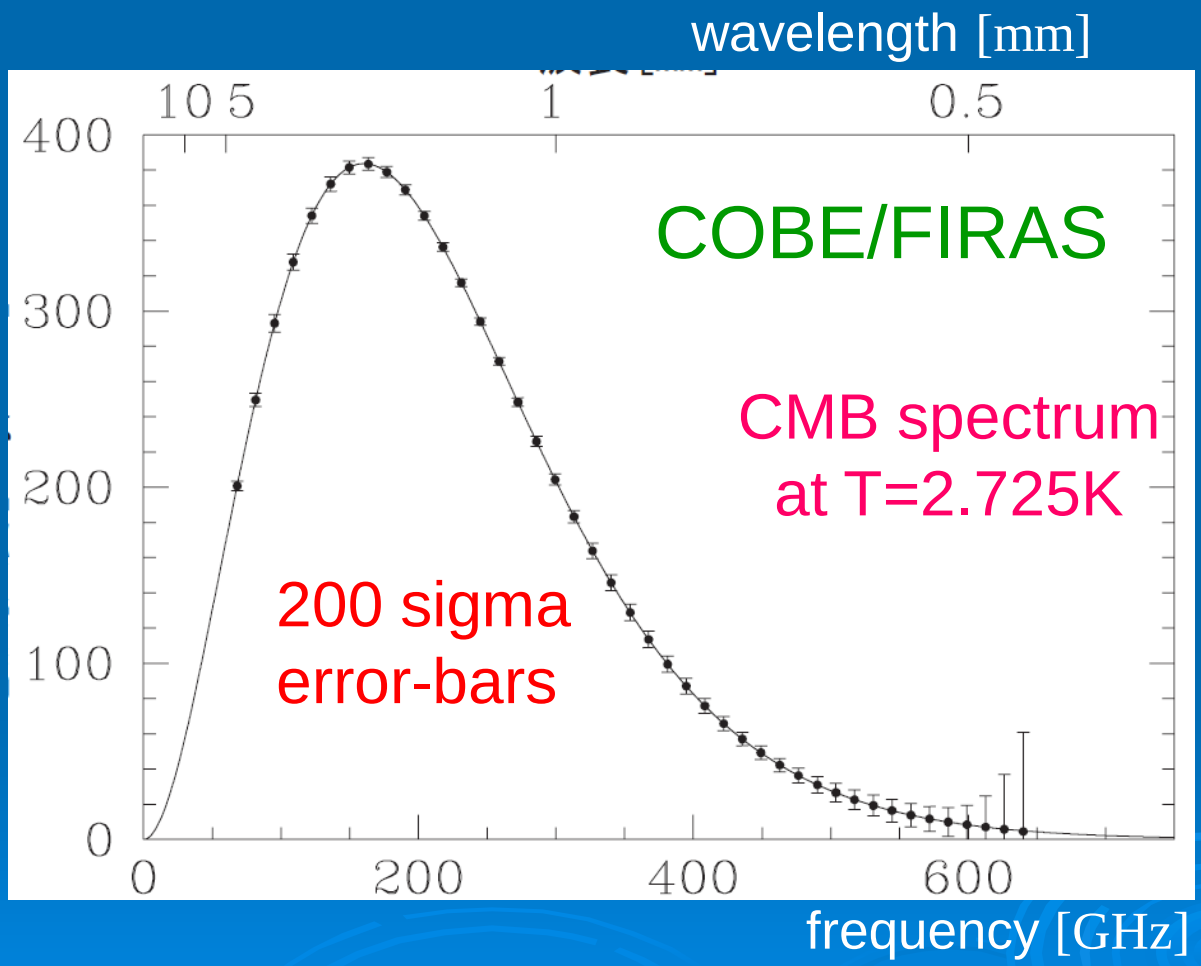
- periastron time shift



gravitational wave astronomy will further test GR

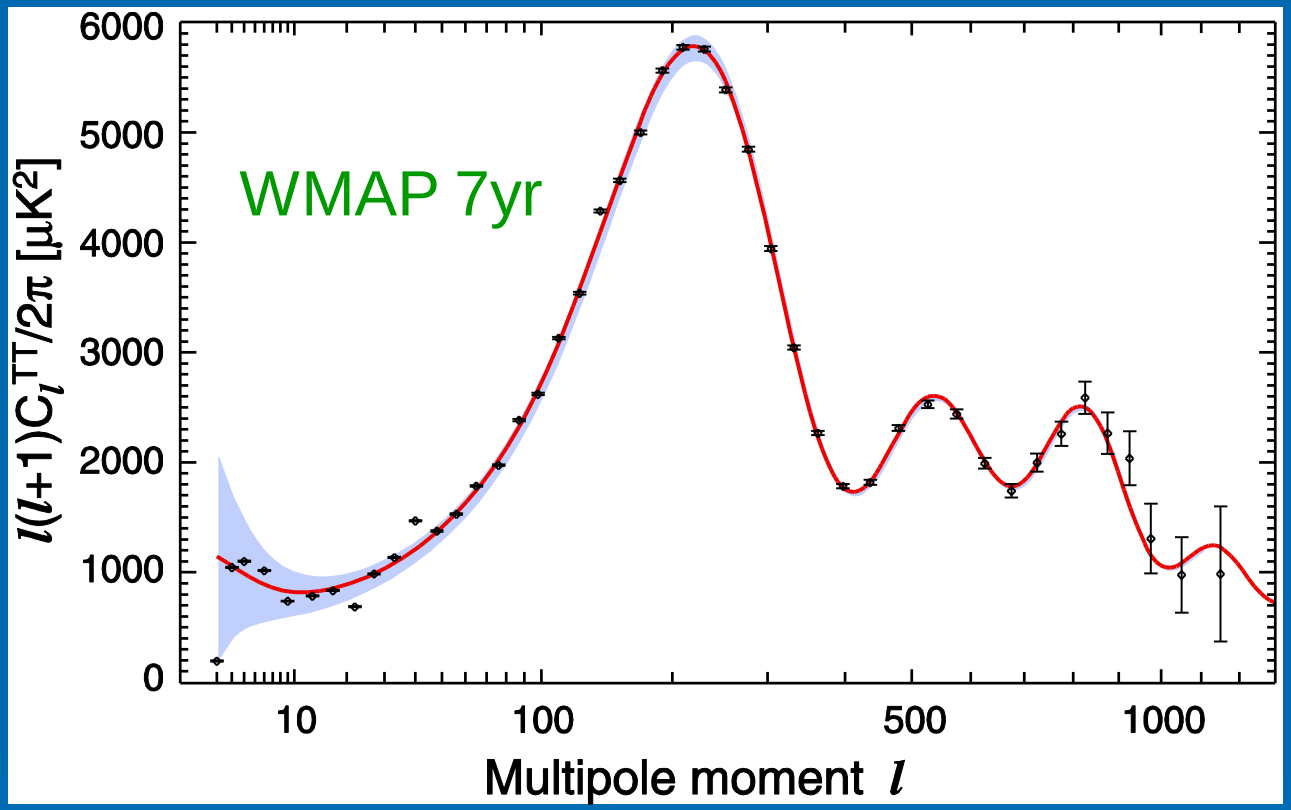
Cosmology Today

- Big Bang theory has been firmly established



another strong evidence for GR

Strong evidence for Inflation



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

- 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?
    e.g. inhomogeneous universe models

    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?

- Inflation

- How did inflation begin?

  what guarantees homogeneity and isotropy?

  quantum cosmology/gravity?

- What is ‘inflaton’?

  what determines the end of inflation?

  flatness / open inflation?

  non-Gaussianity? tensor-scalar ratio?

  eternal inflation, anthropic principle, probability measure,…

new guiding principle / working hypothesis?

What's next?
Which direction?

With a bit of 我田引水 (ga den-in sui)

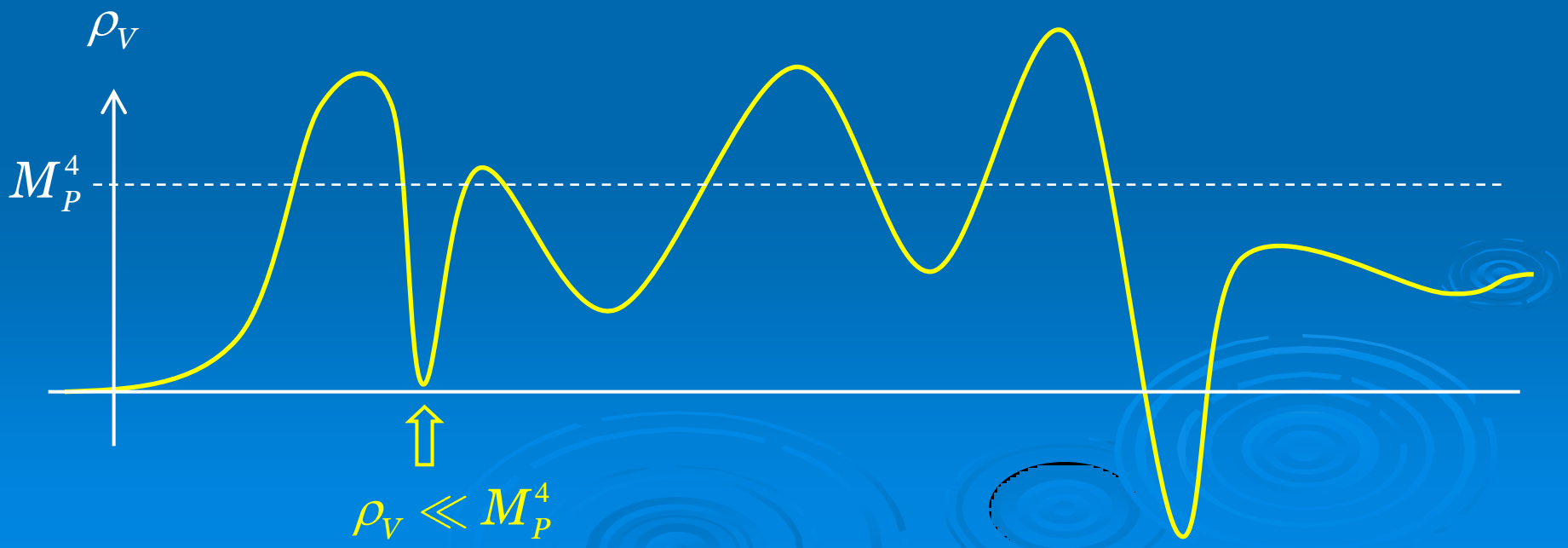
which means ‘self advocacy’, more or less…

String Theory Landscape!

String theory landscape

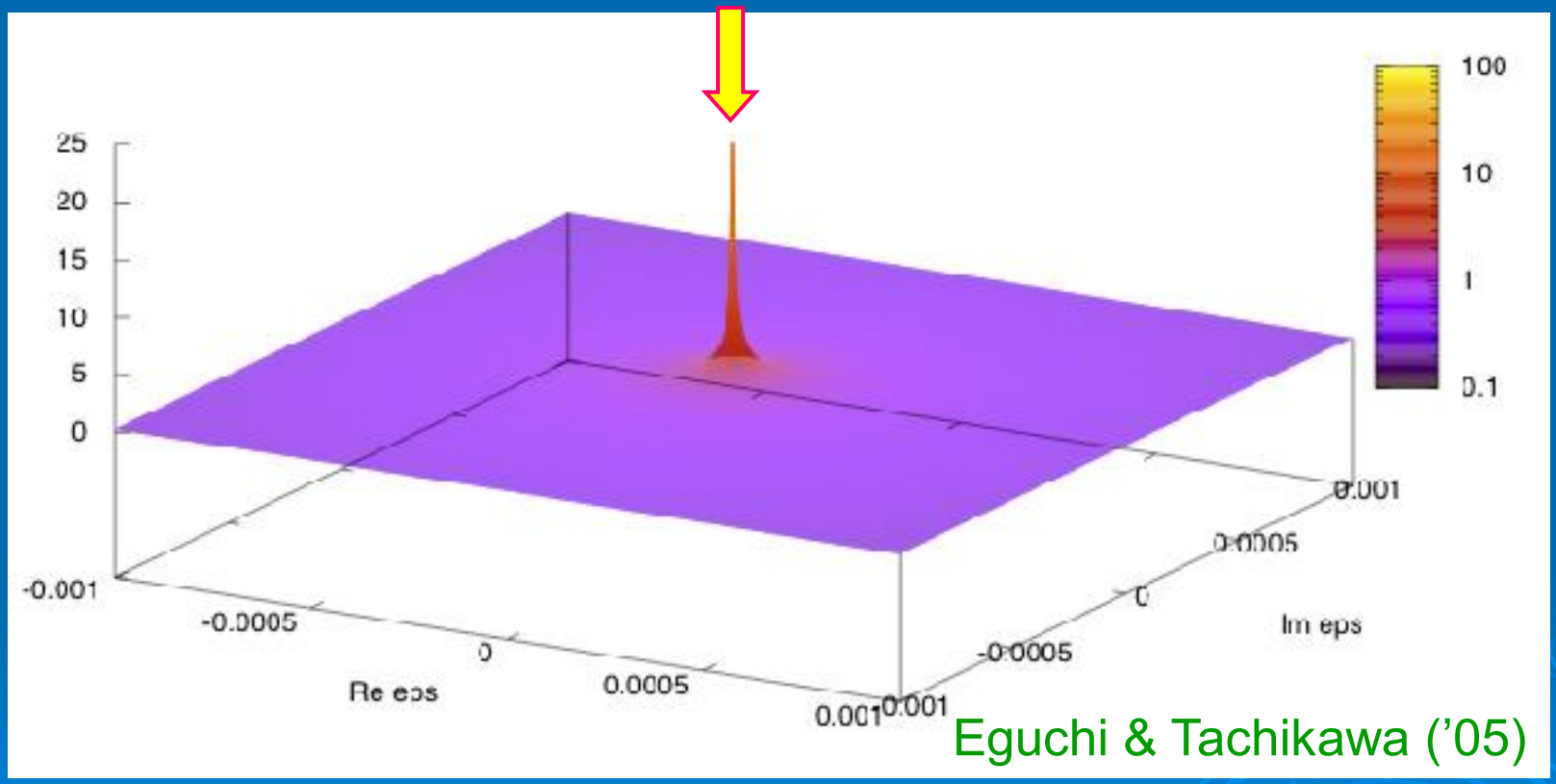
Bousso & Pochinski (’00), Susskind, Douglas, KKLT (’03), ...

- 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 $\rho_v << M_P^4$



distribution function in flux space

Vacua with enhanced gauge symmetry



Eguchi & Tachikawa (’05)

may explain the origin of gauge symmetry
in our Universe

testing string theory landscape in cosmology?

Cosmic Landscape

various vacua realized in the early universe

credit: unknown, taken from a Chinese website.

distribution determined by various factors

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

quantum transitions among various vacua

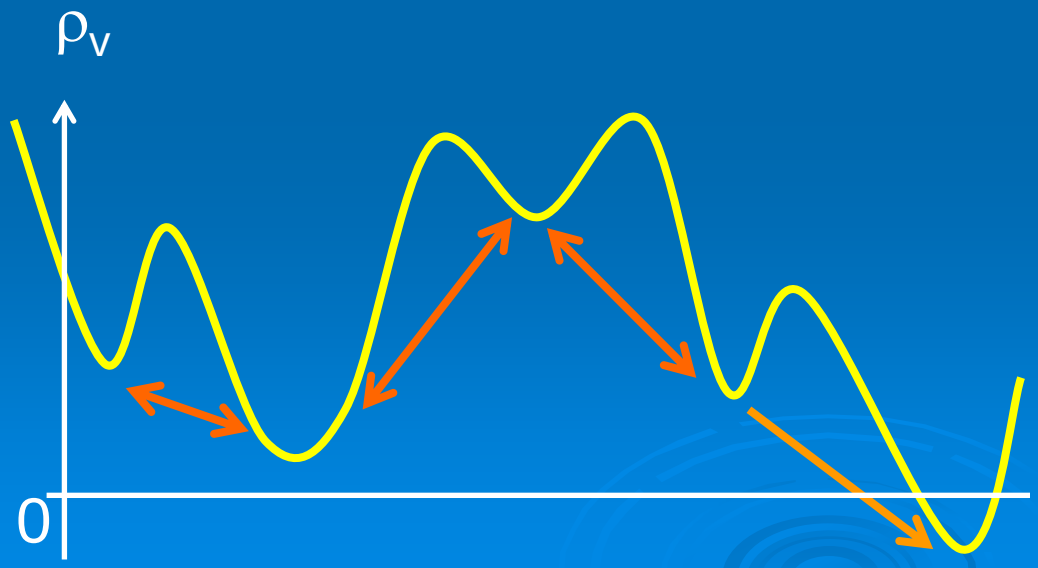
- a universe can go up to a vacuum with larger ρ_v

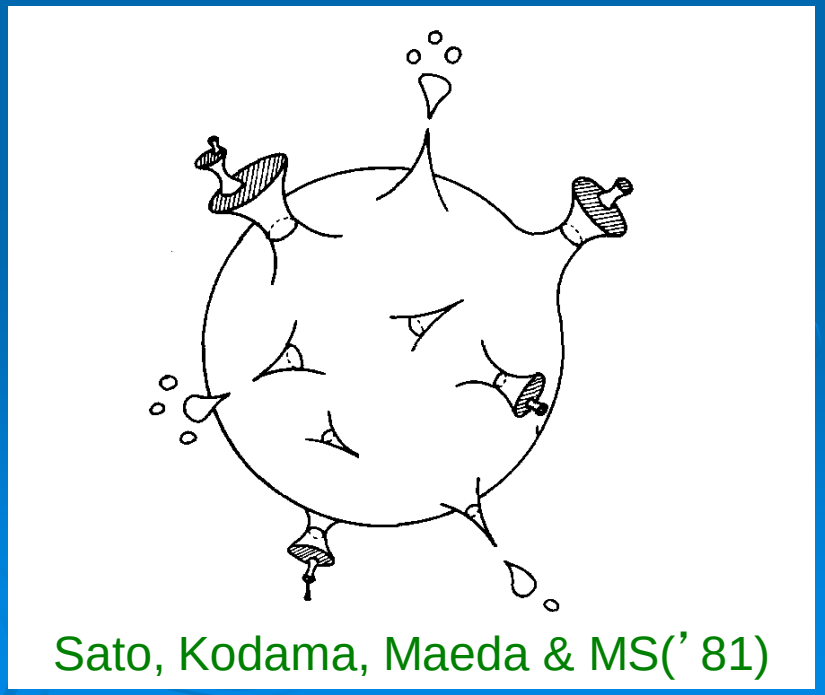
  (dS space ~ thermal state with $T = H/2\pi$)

- if it tunnels to a vacuum with negative ρ_v , it collapses within t ~ $M_P/|\rho_v|^{1/2}$.

- so we may focus on vacua with $\rho_v>0$: dS vacua

  (NB. Garriga & Vilenkin '12)





Sato, Kodama, Maeda & MS('81)

Creation of open universe

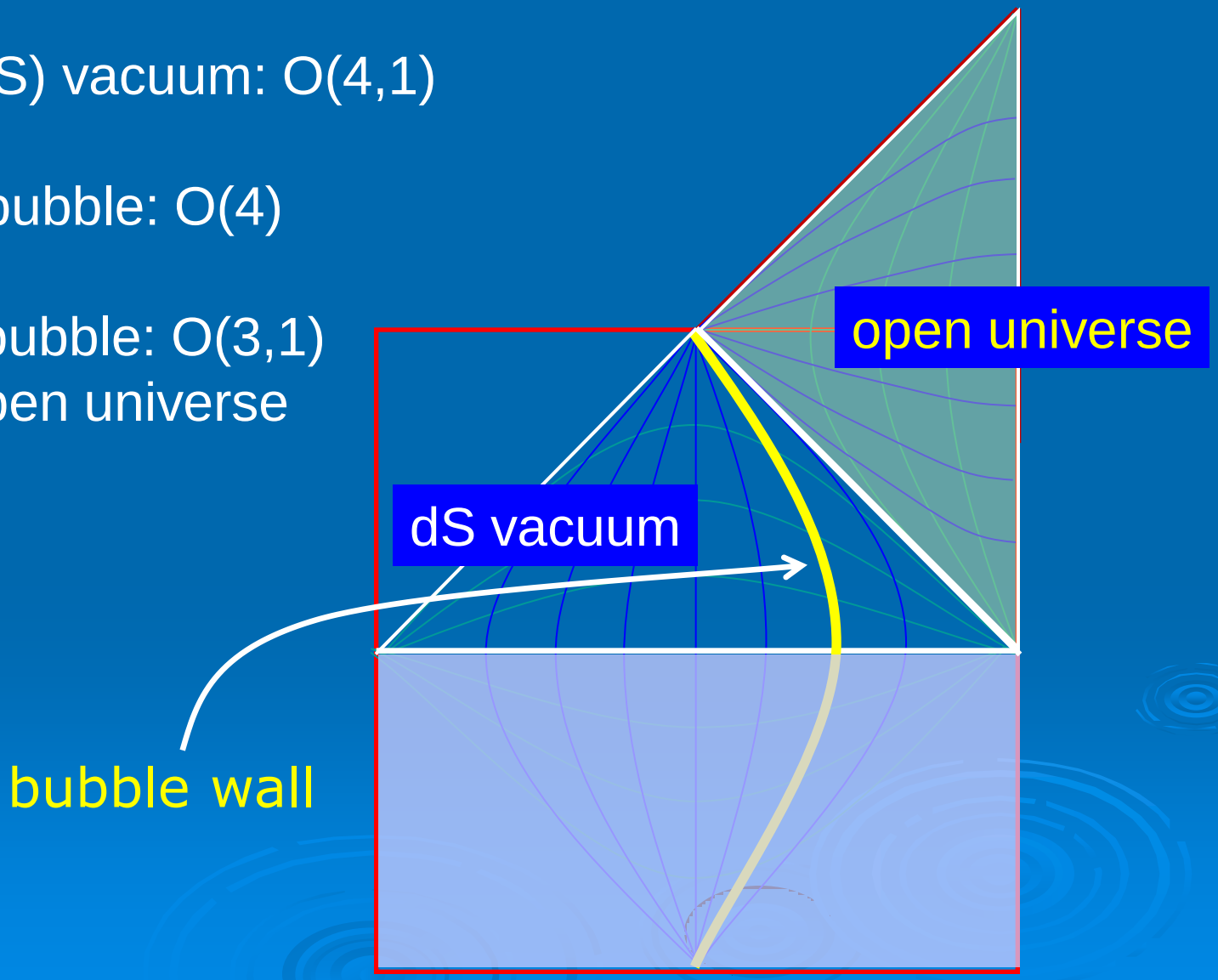
de Sitter (dS) vacuum: O(4,1)

↓

Euclidean bubble: O(4)

↓

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



Our Universe was born out of quantum tunneling!

- 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

Yamauchi, Linde, Naruko, Tanaka & MS (2011)

2. inflation after tunneling was long enough (N>>60)

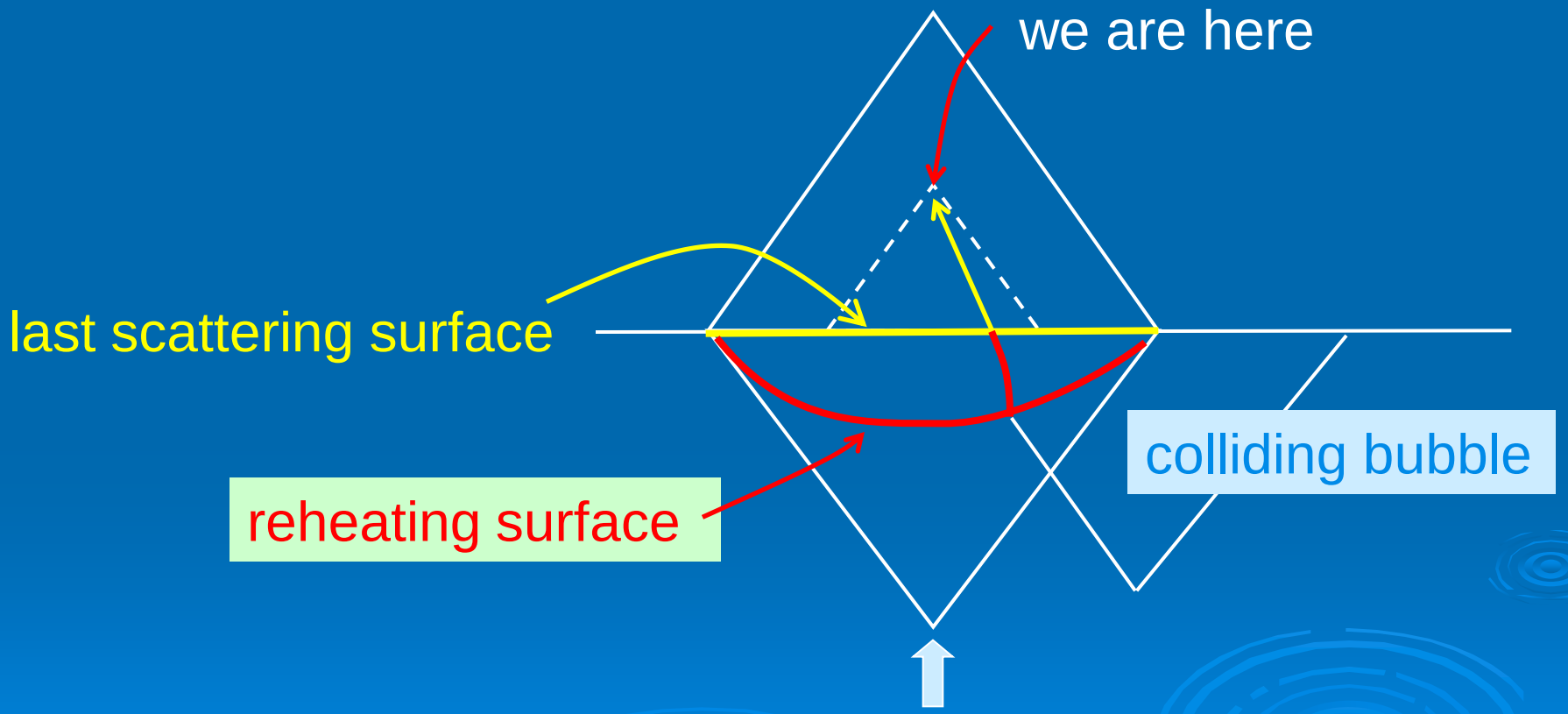
$$1-\Omega_0 \ll 1$$ "flat universe"

➡ signatures from bubble collisions

Sugimura, Yamauchi & MS (2012)

poster no. 28
by Sugimura

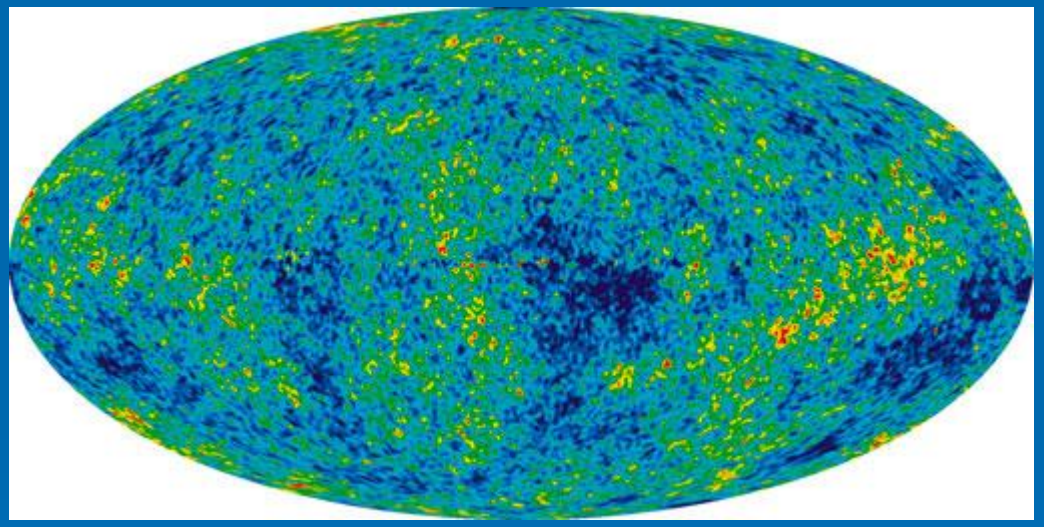
trace of bubble collisions



➢ simple model

- no (spherically symmetric) bubble seen in the CMB map

⇔ negligible effect on curvature perturbation (~Newton potential) at leading order



bubbles may be seen as “localized” non-Gaussianity

$$\Phi(x) = \Phi_{Gauss}(x) + f_{NL}(x)\Phi^2_{Gauss}(x) + \ldots$$

space-dependent

Non-Gaussian bubbles in the CMB Sky

"smiley" non-Gaussianity

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

see poster no.28 for details

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

Summary / random remarks...

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...

For cosmic landscape

C-M Yoo’s poster no.38

full GR+QFT techniques need be developed

+ QG if possible

extrapolating history...

bigbang theory 1940 ~
strong evidence 1965 (+25), confirmation 1990 (+50)

inflation theory 1980 ~
strong evidence 2000 (+20), confirmation 2020? (+40)

string landscape 2000 ~
strong evidence 2015? (+15), confirmation 2030? (+30)

landscape fairy tale may become real!

長寿と繁栄を！

Live long and prosper!