YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

別府
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Testing the string theory landscape in cosmology

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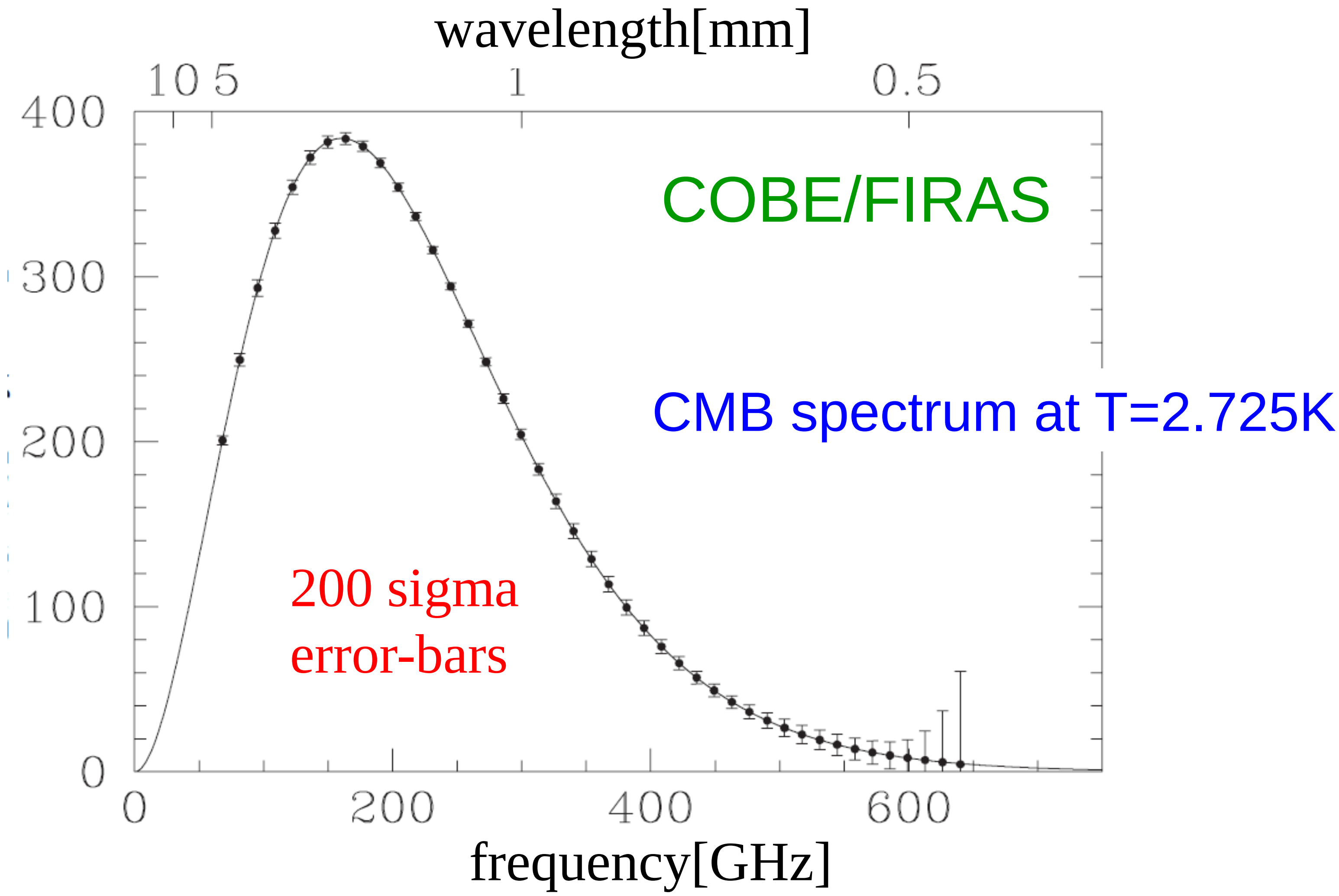
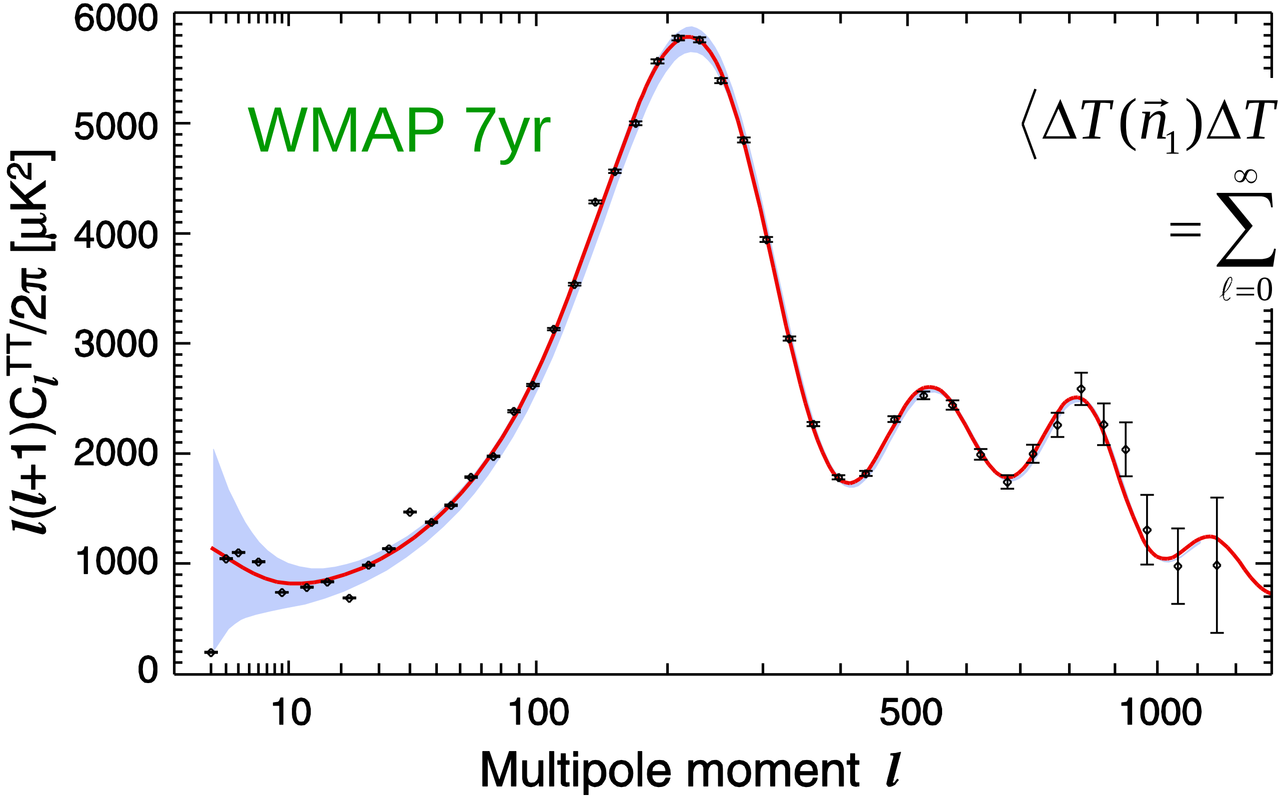
1. Cosmology Today

- Big Bang theory has been firmly established



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?)

- "standard" cosmological model
  = ΛCDM with scale inv spectrum

cosmological parameters (~ 5% accuracy)

baryon density	$\Omega_b h^2$	$0.02313^{+0.00073}_{-0.00072}$
CDM density	$\Omega_c h^2$	$0.1068^{+0.0062}_{-0.0063}$
vacuum density	Ω_Λ	0.757 ± 0.031
curvature pert amplitude	$\Delta^2_{\mathcal{R}}$	$(2.28 \pm 0.15) \times 10^{-9}$
spectral index	n_s	$0.982^{+0.020}_{-0.019}$
reionzation optical depth	τ	0.091 ± 0.015
tensor/scalar ratio	r	< 0.36 (95% CL)

Larson et al '10

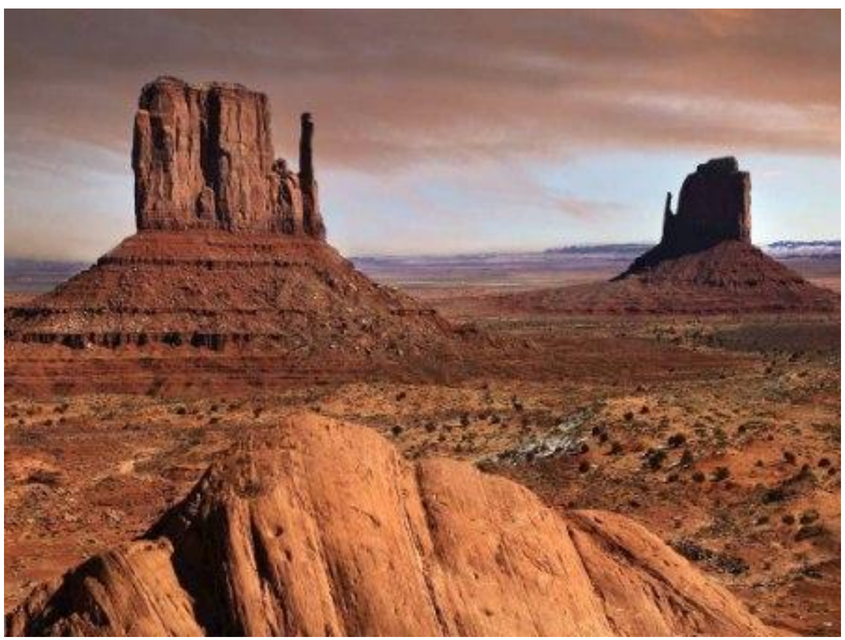
1% accuracy expected by PLANCK

What’s next?

2. String theory landscape

Lerche, Lust & Schellekens ('87), 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 $\rho_v \ll M_P^4$



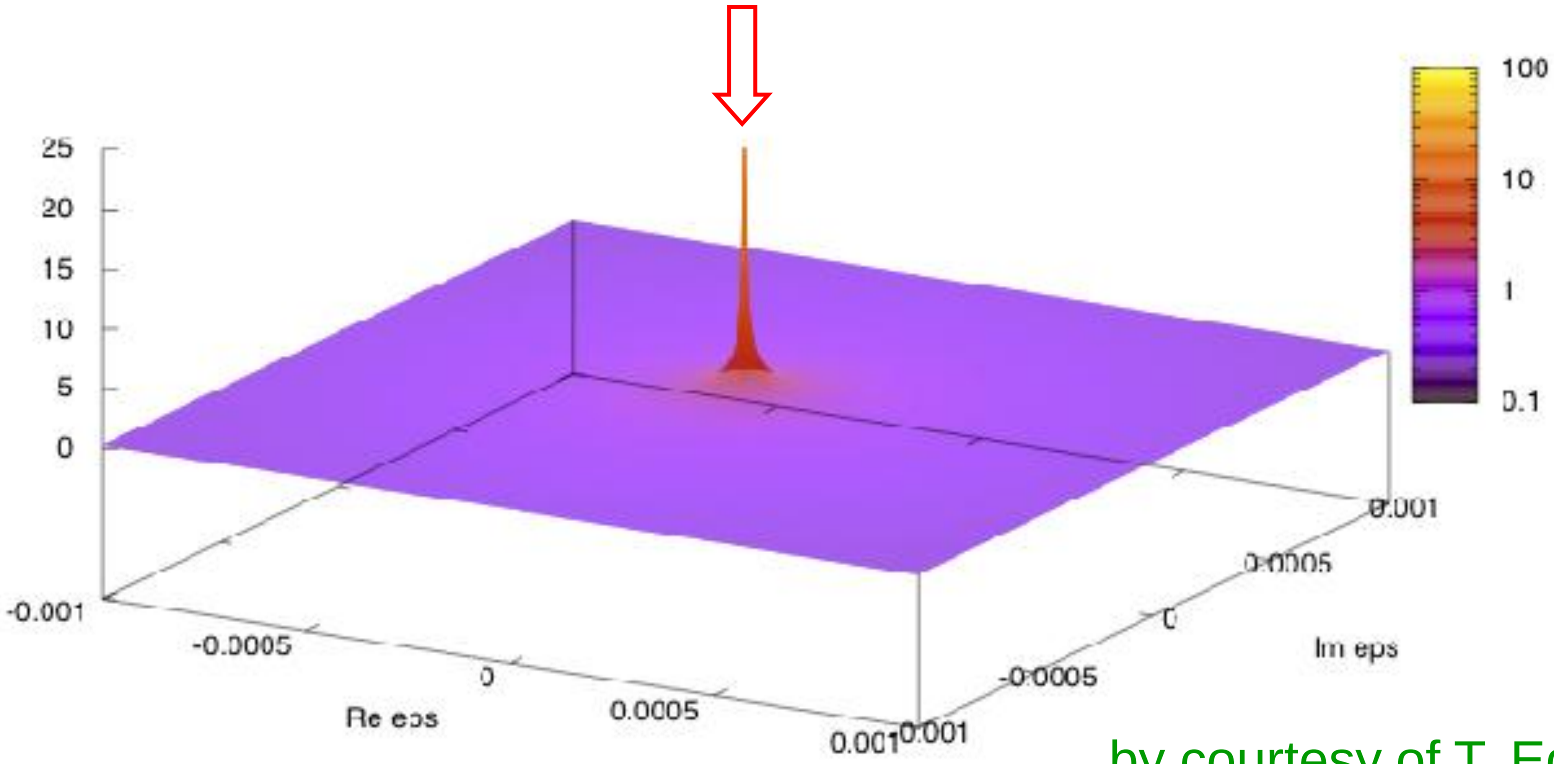
which ?

Is there any way to know what kind of landscape we live in?

Or at least to know what kind of neighborhood we live in?

distribution function in flux space

Vacua with enhanced gauge symmetry

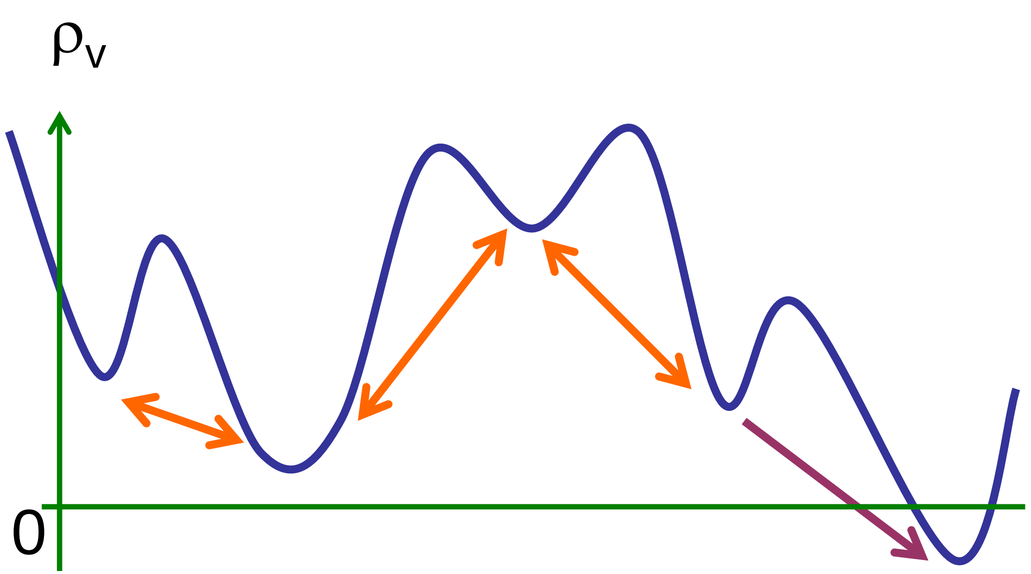


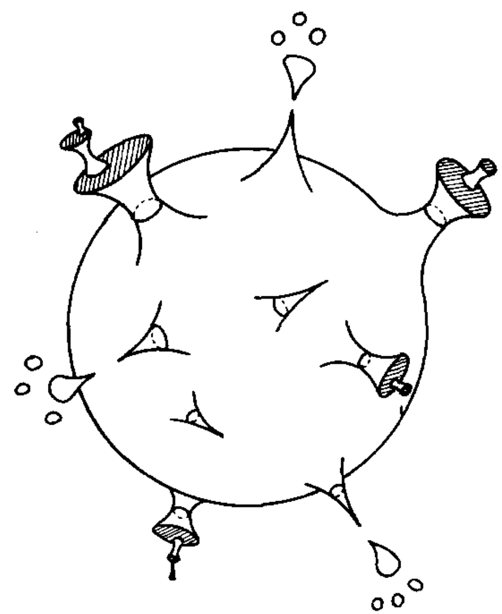
by courtesy of T. Eguchi

may explain the origin of gauge symmetry
in our Universe

- A universe jumps around in the landscape by quantum tunneling
  - it 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 $t \sim M_P/|\rho_v|^{1/2}$.
  - so we may focus on vacua with positive ρ_v: dS vacua





Sato et al. (' 81)

➢Anthropic landscape

- Not all of dS vacua are habitable.

"anthropic" landscape Susskind ('03)

- A universe jumps around in the landscape and settles down to a final vacuum with $\rho_{v,f} \sim M_P^2 H_0^2 \sim (10^{-3}\mathrm{eV})^4$.

$\rho_{v,f}$ must not be larger than this value in order to account for the formation of stars and galaxies.

- Just before it has arrived the final vacuum (=present universe), it must have gone through an era of (slow-roll) inflation and reheating, to create "matter and radiation."

$\rho_{vac} \longrightarrow \rho_{matter} \sim T^4$: birth of Hot Bigbang Universe

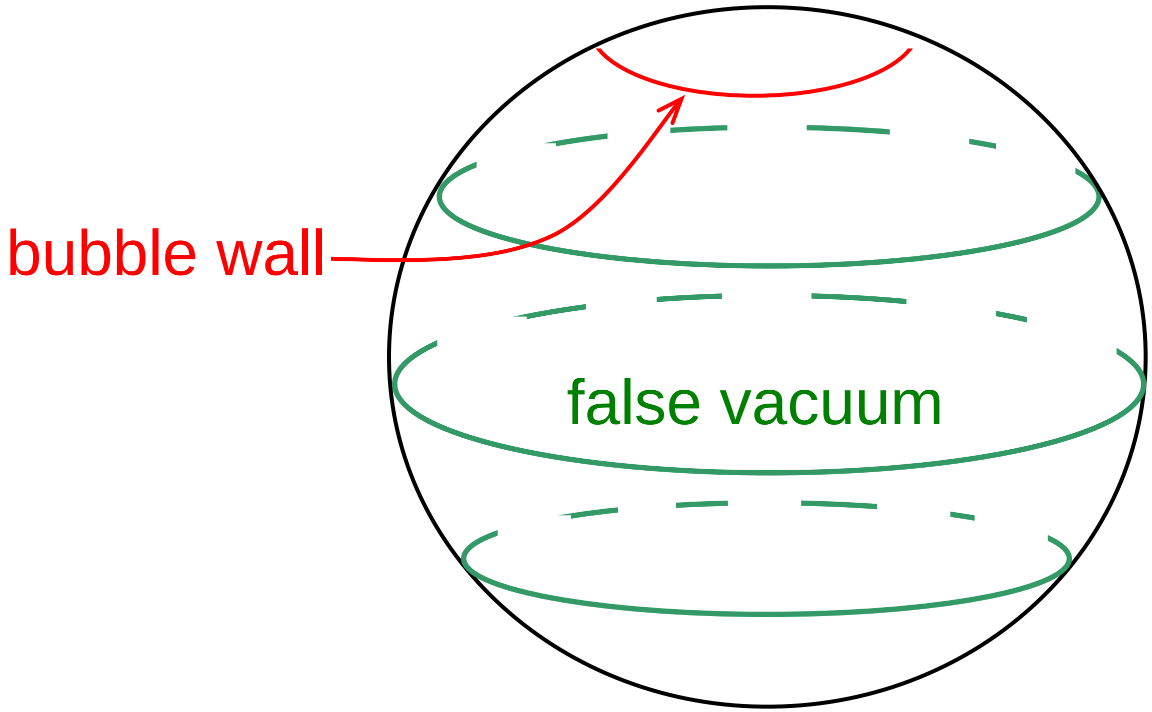
- Most plausible state of the universe before inflation is a dS vacuum with $\rho_v \sim M_P^4$. dS = O(4,1) → O(5) ~ S^4

false vacuum decay via O(4) symmetric (CDL) instanton

Coleman & De Luccia ('80)

O(4) → O(3,1)

inside bubble is an open universe



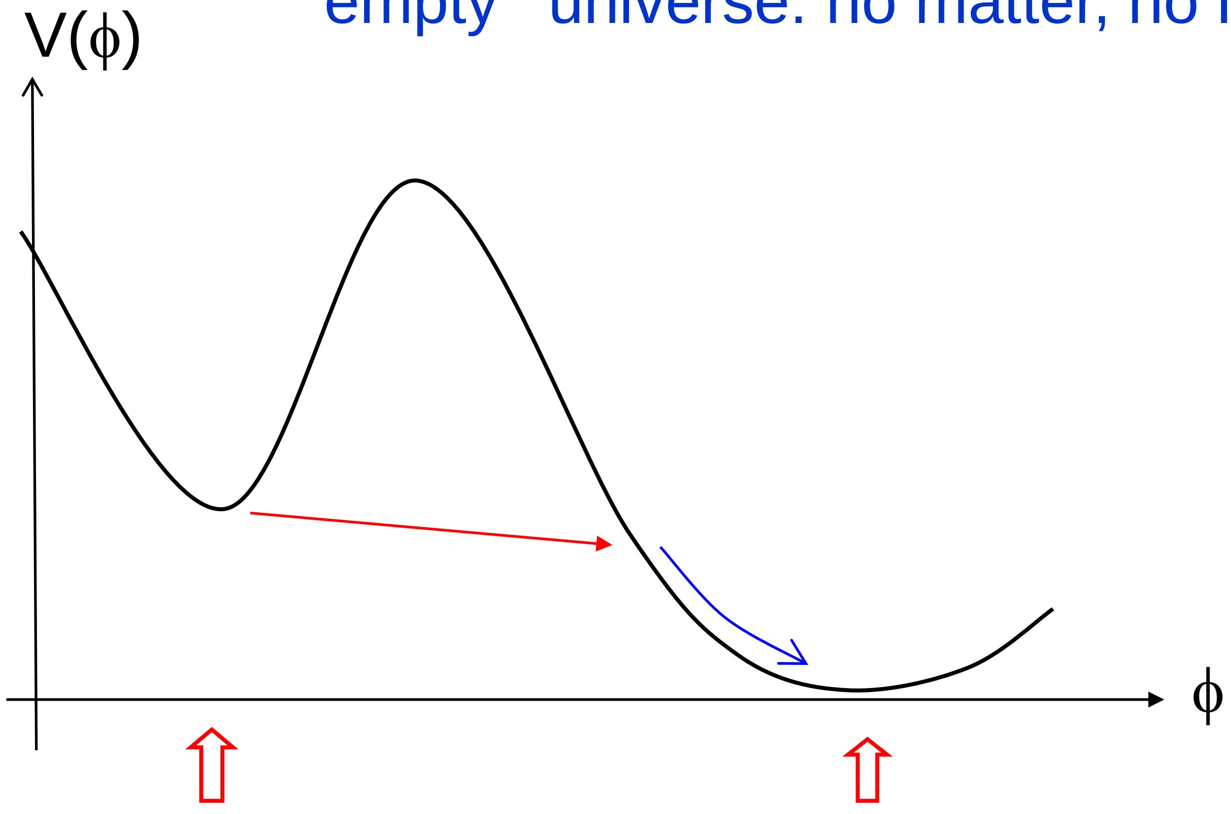
$$\tau^2 + \vec{x}^2 = R^2$$

⇩

$$-t^2 + \vec{x}^2 = R^2$$

- Natural outcome would be a universe with $\Omega_0 << 1$.

"empty" universe: no matter, no life



"previous" vacuum

$V \sim M_P^4$

"present" vacuum

$V \sim M_P^2 H_0^2$

- Anthropic principle suggests that # of e-folds of inflation inside the bubble ($N=H\Delta t$) should be ~ 50 – 60 : just enough to make the universe habitable.

Garriga, Tanaka & Vilenkin ('98), Freivogel et al. ('04)

- Observational data excluded open universe with $\Omega_0 <1$.

- Nevertheless, the universe may be slightly open:

$$1-\Omega_o = 10^{-2} \sim 10^{-3}$$

may be tested by PLANCK+BAO

Colombo et al. ('09)

What if $1-\Omega_0$ is actually confirmed to be non-zero: $\sim 10^{-2}$ - 10^{-3}?

revisit open inflation!

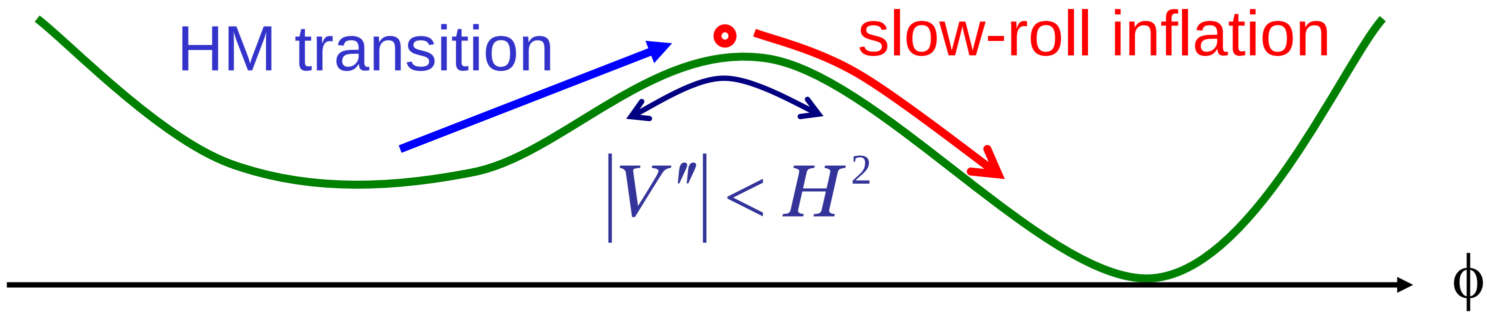
see if we can say anything about Landscape

3. Open inflation in the landscape

– constraints from scalar-type perturbations –

- Simplest polynomial potential
  - ϕ^4 potential: $V = \frac{m^2}{2}\phi^2 - \frac{\nu}{3}\phi^3 + \frac{\lambda}{4}\phi^4$
  - tunneling to a potential maximum ~ stochastic inflation

Hawking & Moss ('82) Starobinsky ('84)



- too large fluctuations of ϕ unless # of e-folds >> 60

Linde ('95)

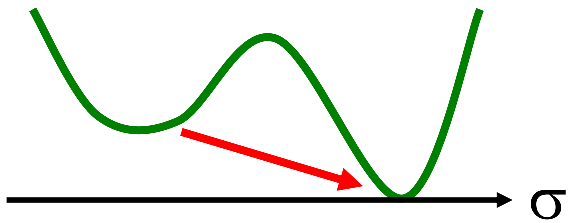
➢ Two- (multi-)field model: "quasi-open inflation"

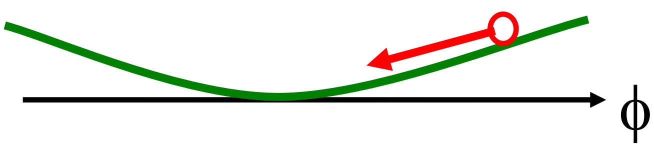
Linde, Linde & Mezhlumian ('95)

- "heavy" field σ = false vacuum decay
- "light" field ϕ = inflaton

$$V(\phi,\sigma) = V_\sigma(\sigma) + \frac{m_\phi^2}{2}\phi^2$$

~ perhaps naturally/easily realized in the landscape





- If N ~< 60, too large supercurvature perturbation of ϕ

$$p^2 = p_{sc}^2 \approx -|K|; \quad \left[\overset{(3)}{\Delta}_K + p^2 + |K| \right] Y_{plm}(r,\Omega) = 0$$

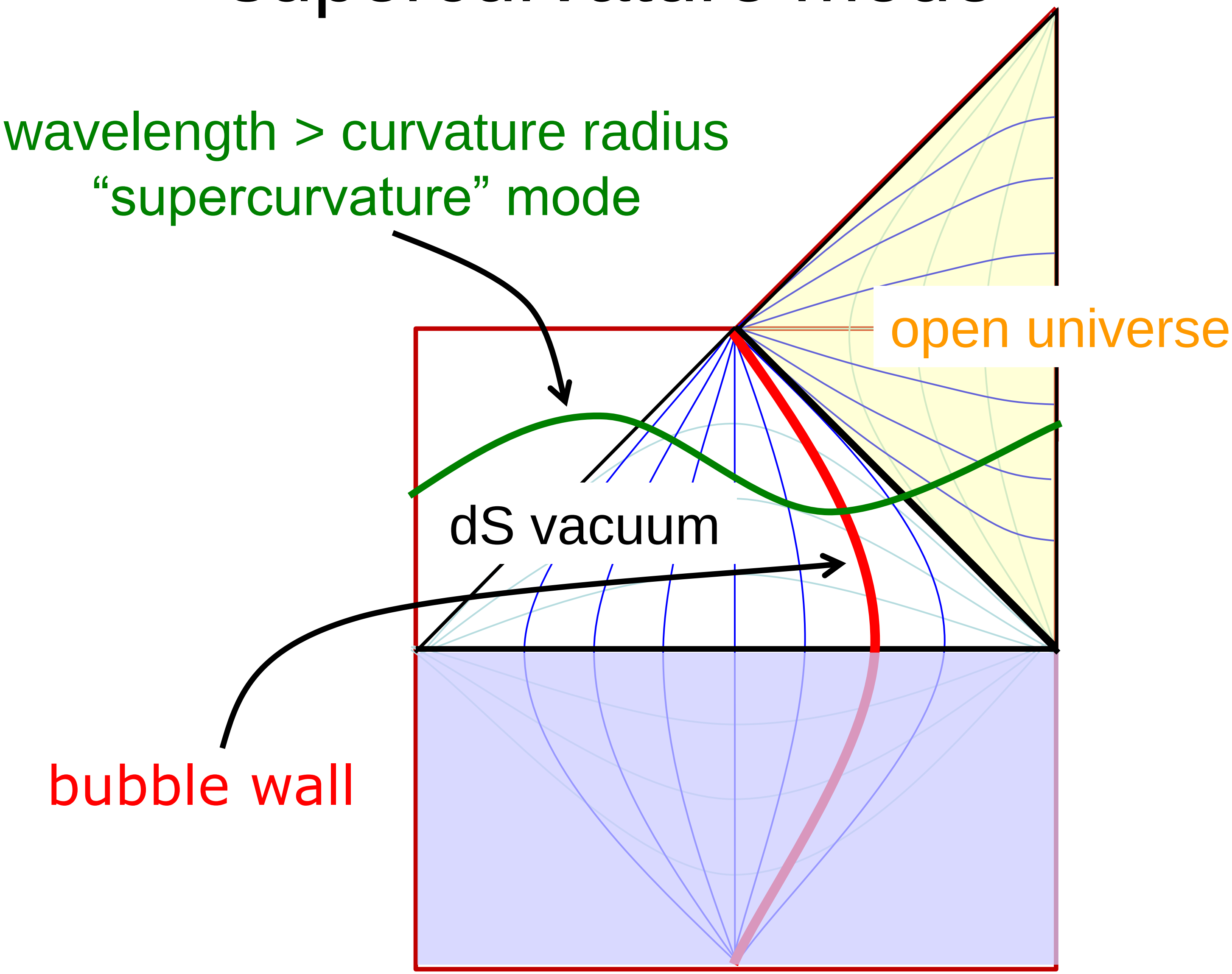
$$\delta\phi_{sc} \sim \frac{H_F}{2\pi} ? \frac{H_R}{2\pi}$$

H_F : Hubble at false vacuum

H_R : Hubble after fv decay

MS & Tanaka ('96)

creation of open universe & supercurvature mode



4. Tensor perturbation in open inflation

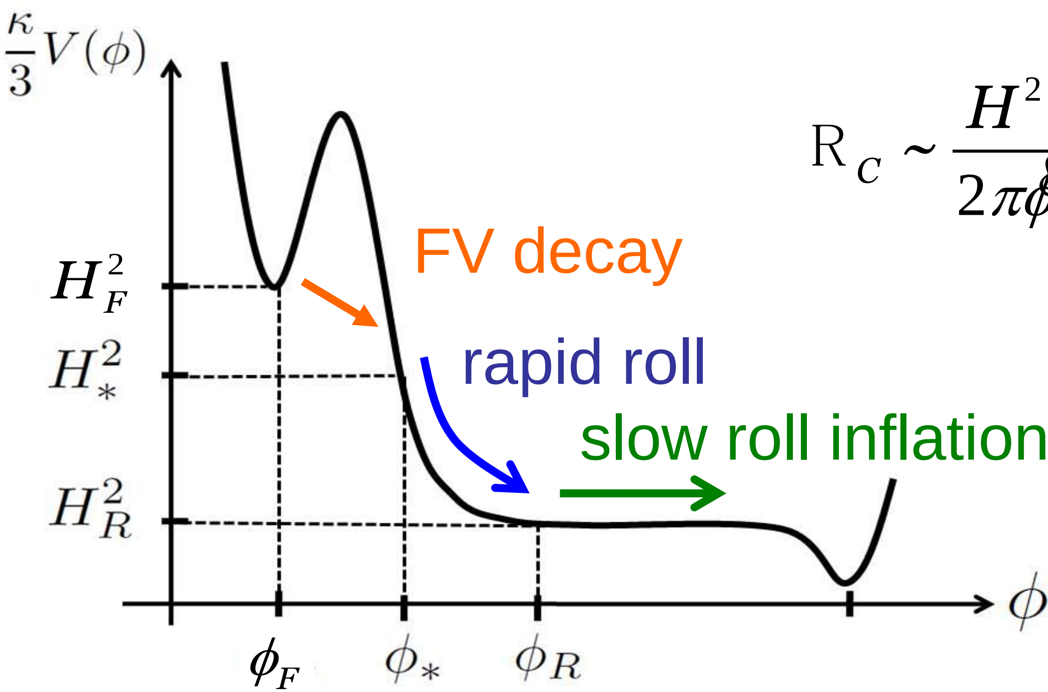
Yamauchi, Linde, MS, Naruko & Tanaka ('11)

- if $\rho_{fv} \sim M_p^4$, the universe will most likely tunnel to a point where the energy scale is still very high.

Linde, MS & Tanaka (' 99)

⇨ rapid-roll stage will follow right after tunneling.

- perhaps no strong effect on scalar-type pert' s:



$$\mathcal{R}_c \sim \frac{H^2}{2\pi\dot{\phi}}$$

suppressed by $1/\dot{\phi}$ at rapid-roll phase

need detailed analysis … future issue

but tensor perturbations may not be suppressed at all.

$$h^{TT} \sim \frac{H}{M_P} \quad ?$$

Memory of H_F (Hubble rate in the false vacuum) may remain in the perturbation on the curvature scale

⇩

could lead to strong constraints/implications

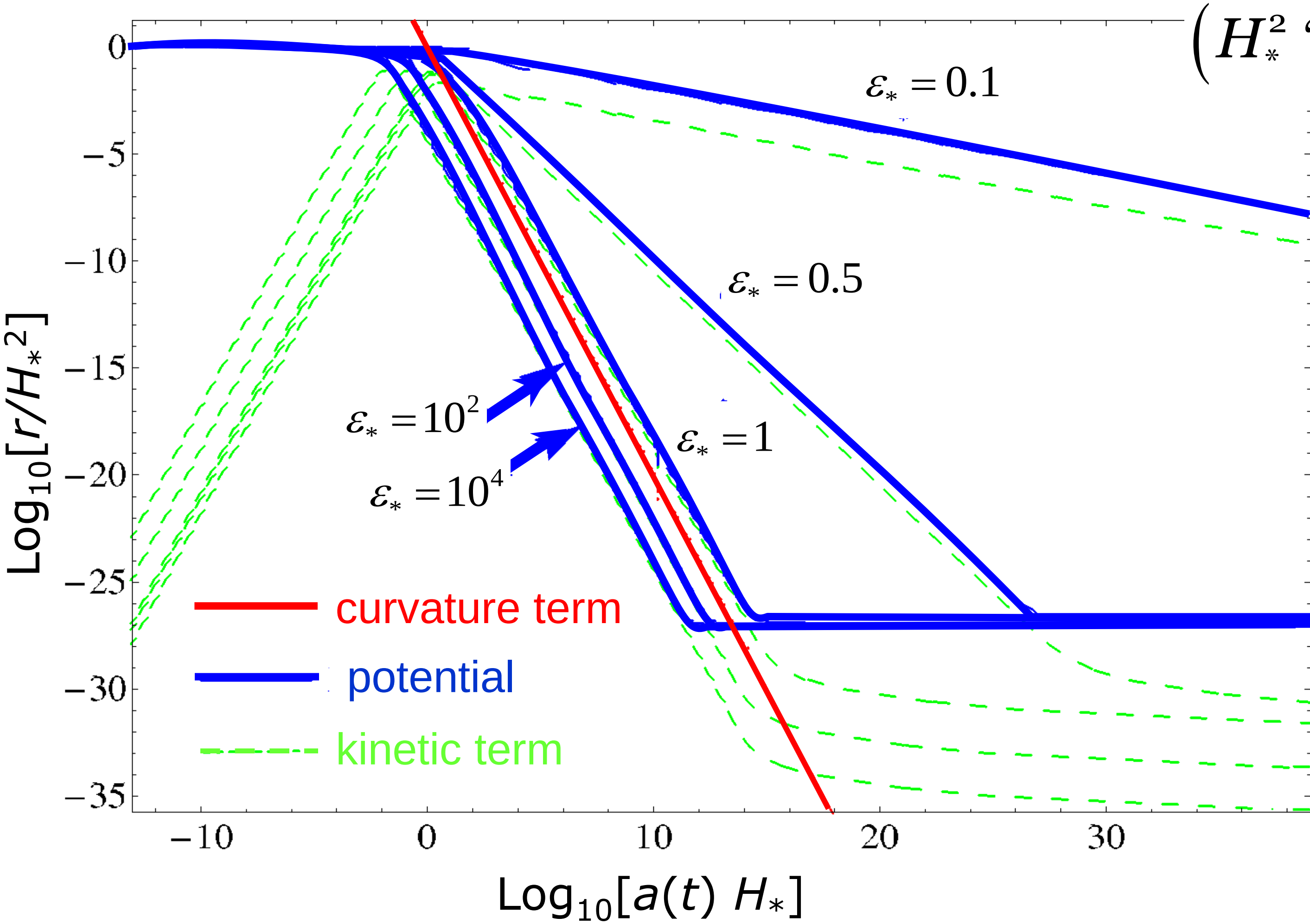
➢ potential inside bubble: exponential model

$$V \propto \exp\left(\sqrt{2\varepsilon}\,\phi / M_P\right) \Longrightarrow V'/V = \text{const.} \Longrightarrow \varepsilon = \text{const.}$$

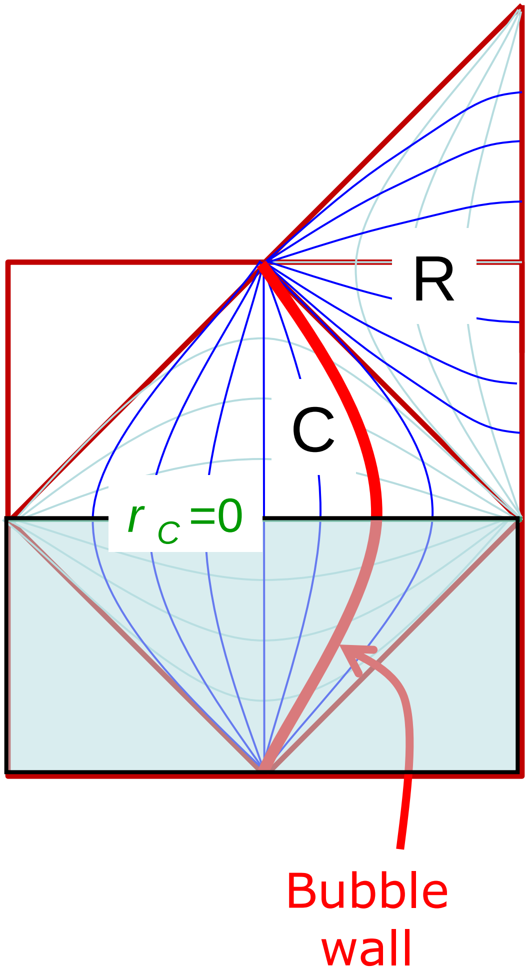
$$V = \left(H_*^2 - H_R^2\right)\exp\left(\sqrt{2\varepsilon_*}\,(\phi - \phi_*)/M_P\right) + H_R^2$$

this realizes slow-roll inflation

$$\left(H_*^2 \gg H_R^2\right)$$



- two effects from tunneling: bubble wall + rapid roll



- bubble-nucleation at r_c=0
- C-region: ~ outside the bubble

$$ds^2 = a_C^2(\eta_C)\left(d\eta_C^2 - dr_C^2 + \cosh^2 r_C d\Omega^2\right)$$

⇧ time

- R-region: inside the bubble

$$r_R = r_C + \frac{\pi}{2}i,\ \eta_R = -\eta_C - \frac{\pi}{2}i,\ a_R = i a_C$$

$$ds^2 = a_R^2(\eta_R)\left(-d\eta_R^2 + \underline{dr_R^2 + \sinh^2 r_R d\Omega^2}\right)$$

⇧ time ↖ open space

Euclidean vacuum ➡ C-region ➡ R-region

➢ Effect of tunneling/bubble wall on $P_T(p)$

high freq continuum + low freq resonance

$p > 1$

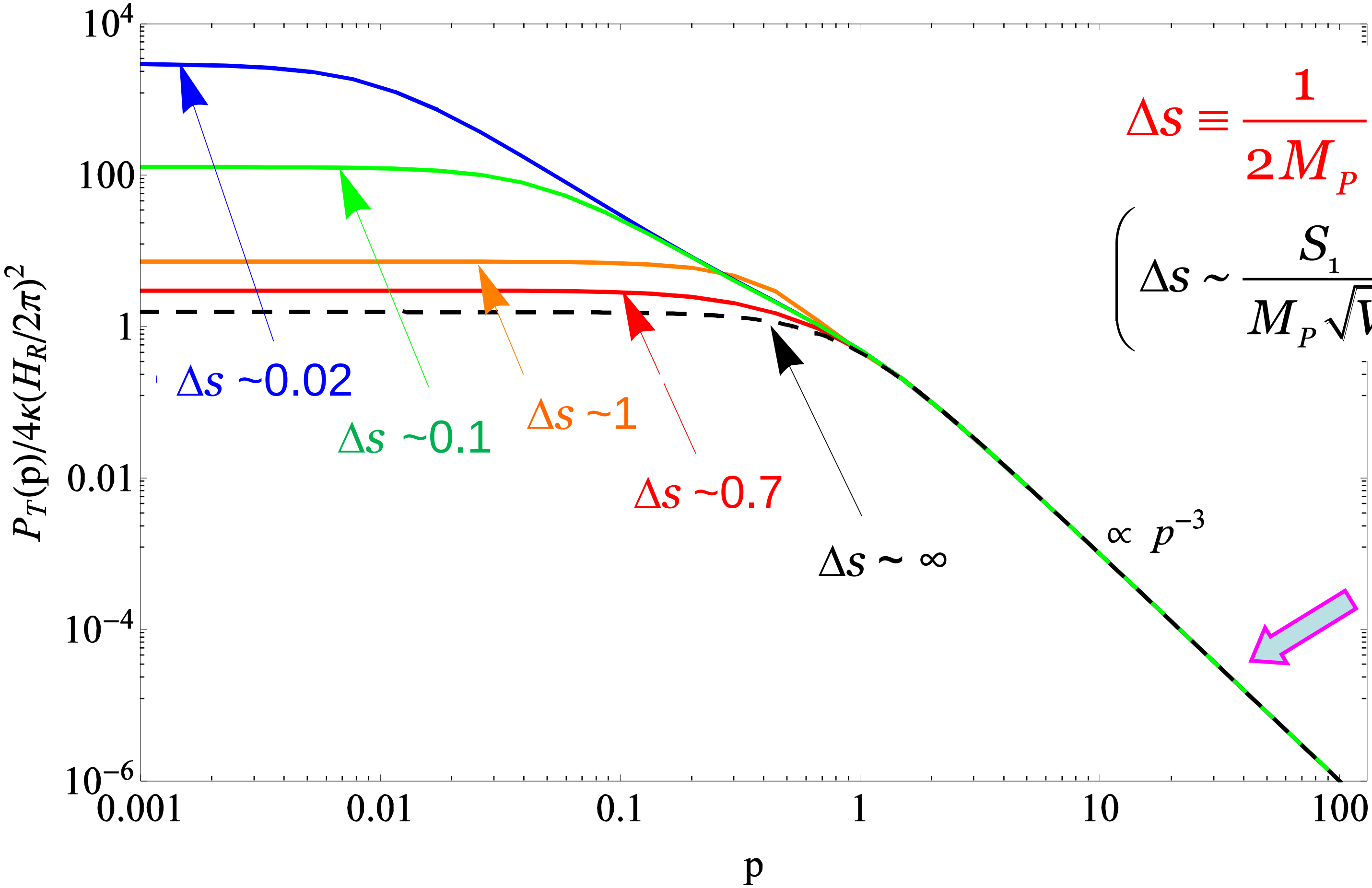
$p \sim 0$

wall fluctuation mode

$$\Delta s \equiv \frac{1}{2M_P}\int d\eta\, \phi'^2$$

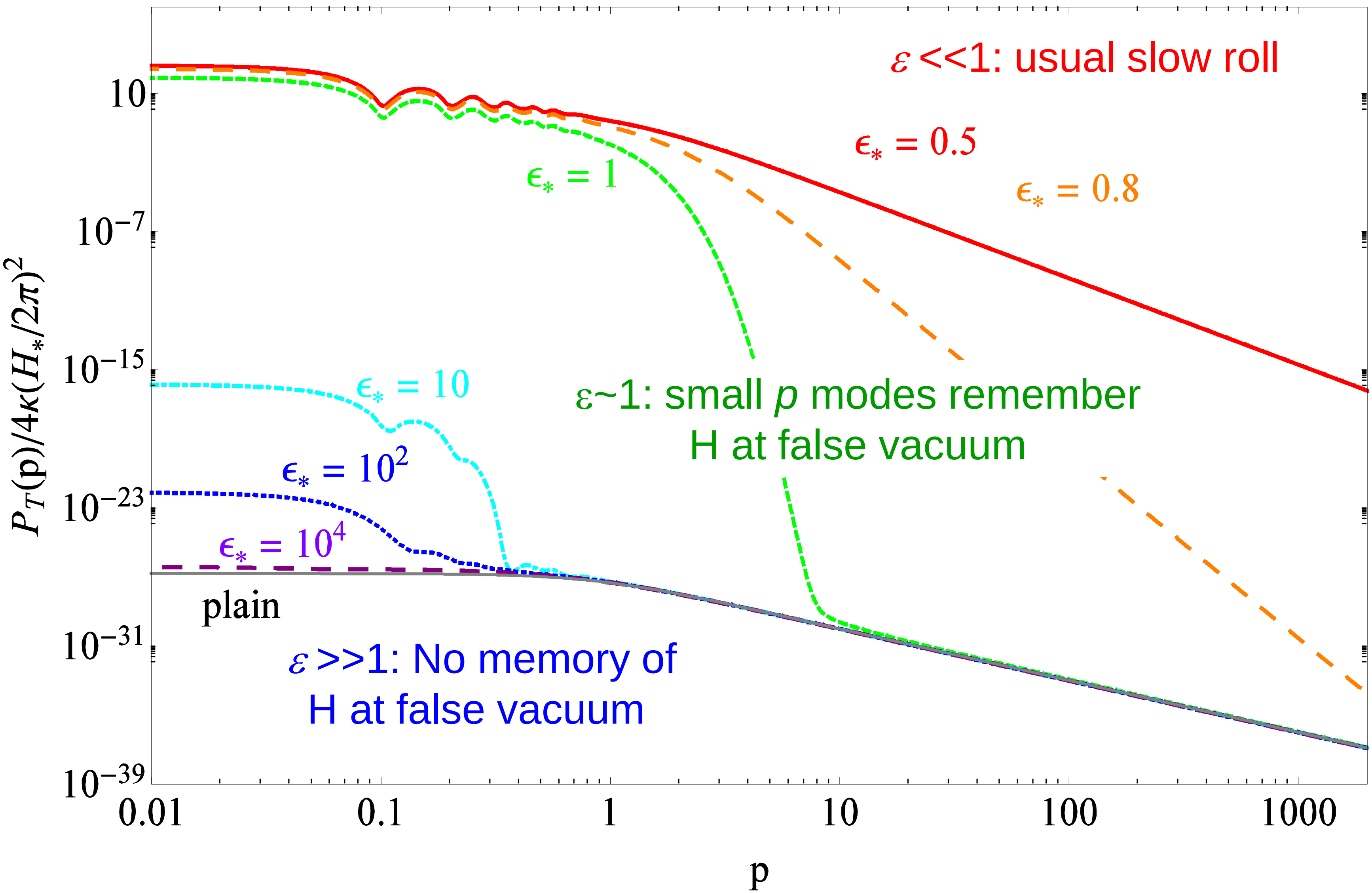
$$\left(\Delta s \sim \frac{S_1}{M_P\sqrt{V}};\ S_1 = \int dt_C \dot{\phi}^2\right)$$

⇧ wall tension



scale-invariant

➢ rapid-roll phase (ε_*-)dependence of P_T(p)



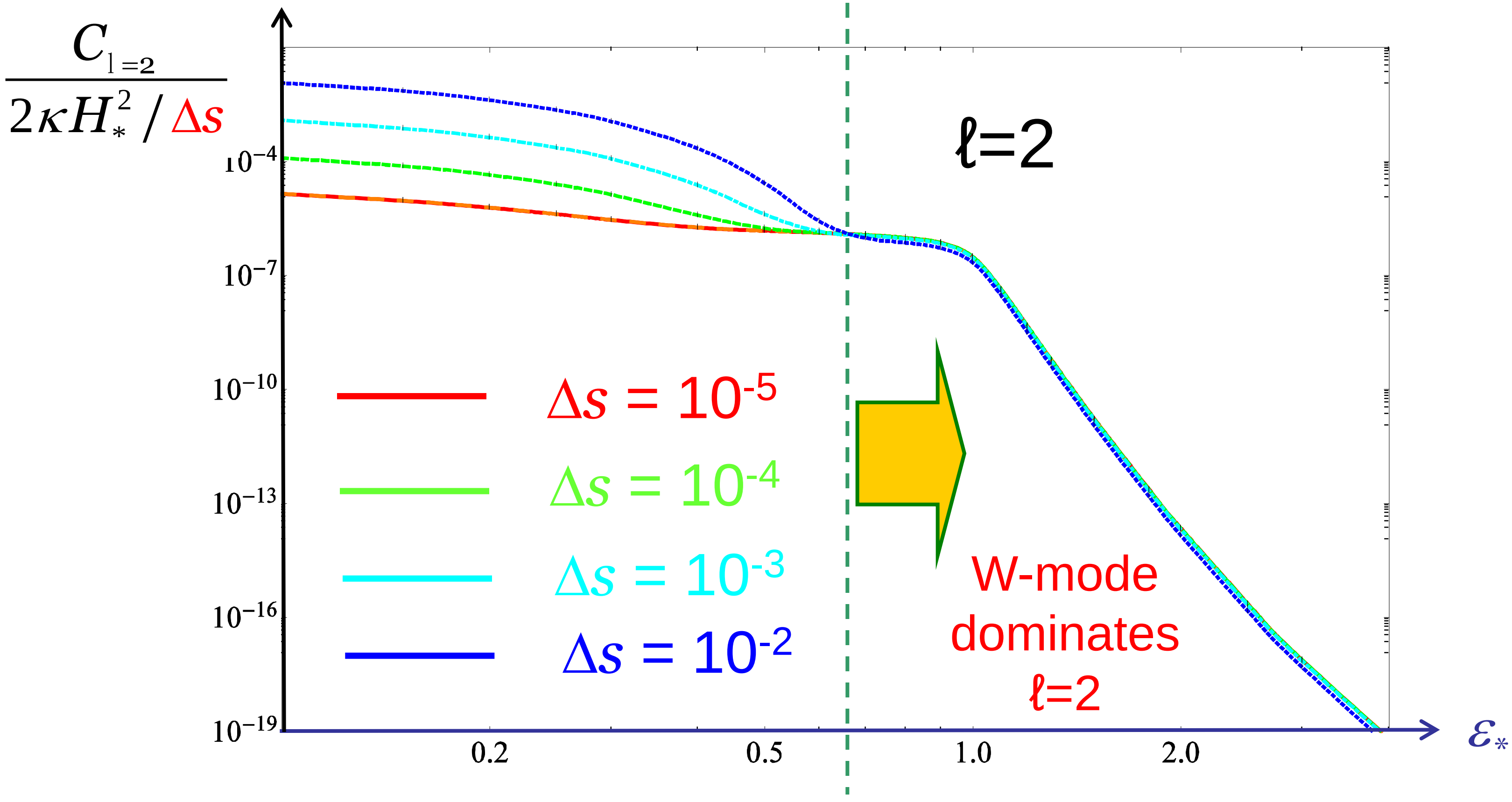
• CMB anisotropy due to wall fluctuation (W-)mode

MS, Tanaka & Yakushige ('97)

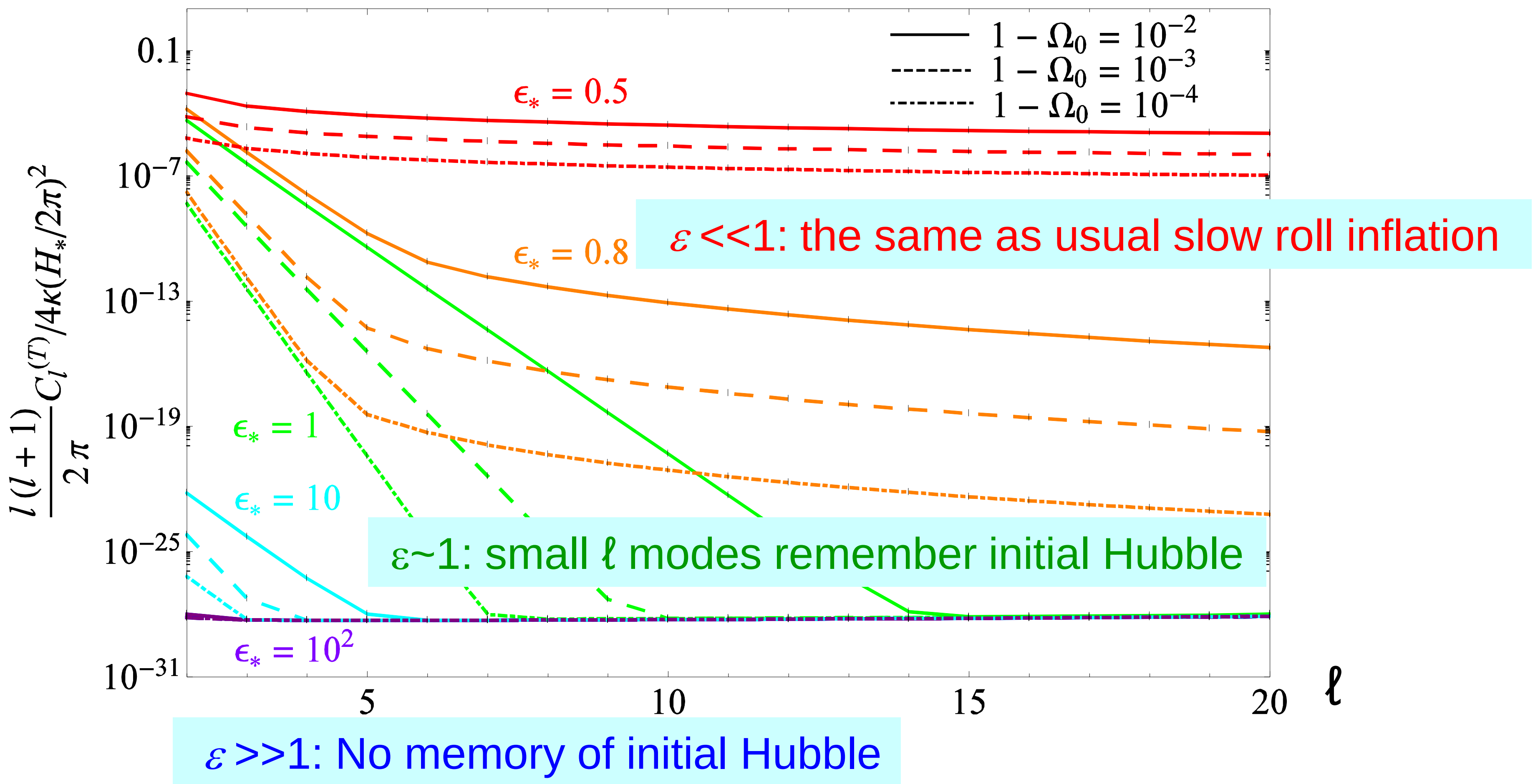
$$C_l = C_l^{(C)} + P_W \tilde{C}_l^{(W)}; \quad P_W = \int_0^\infty dp\, P_T(p) \propto \frac{1}{\Delta s}$$

scale-invariant part

$$\tilde{C}_l^{(W)} \propto (1-\Omega_0)^l$$



• CMB anisotropy from rapid roll phase



• scales as $(1-\Omega_0)^1$ at small ℓ, scale-invariant at large ℓ

small ℓ modes enhanced for $\varepsilon_* \sim 1$

5. Summary

- Open inflation has attracted renewed interest in the context of string theory landscape

  anthropic principle + landscape ⇨ $1-\Omega_0 \sim 10^{-2} - 10^{-3}$

- Landscape is already constrained by observations

  If inflation after tunneling is short (N ~ 60):

  - simple polynomial potentials $a\phi^2 - b\phi^3 + c\phi^4$ lead to HM-transition, and are ruled out

  - simple 2-field models, naturally realized in string theory, are ruled out

  due to large scalar-type perturbations on curvature scale

- Tensor perturbations may also constrain the landscape

  "single-field model"

  - not easy to implement models with short slow-roll inflation right after tunneling in the string landscape.

    if ε<<1, energy scale must have been already very low.

  - there will be a rapid-roll phase after tunneling.

    $$\varepsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \gtrsim 1$$ right after tunneling

  - unless ε>>1, the memory of pre-tunneling stage persists in the IR part of the tensor spectrum

    large CMB anisotropy at small ℓ $\propto (1-\Omega_0)^1$

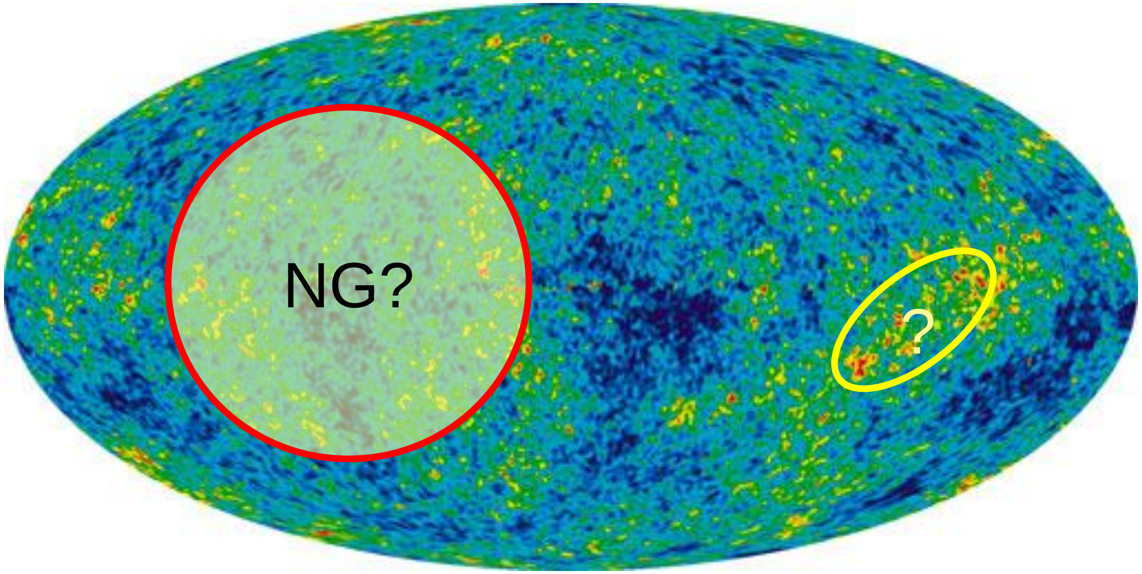
    due to either wall fluctuation mode
    or evolution during rapid-roll phase

We are already testing the landscape!

6. Other signatures?

- CMB cold/hot spots = bubble collision?

Aguirre & Johnson ’09, Kleban, Levi & Sigurdson ’11,...



- Non-Gaussianity from bubbles / NG hot spots?

Blanco-Pillado & Salem ’10, Sugimura et al. in progress

- Populating landscape / resonant tunneling?

  Tye & Wohns ’09, Brown & Dahlen ‘11

- Measure problem / etc. etc. ...

  Garriga & Vilenkin ‘08, Freivogel ’11, Vilenkin ’11, ...

finally, 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?)