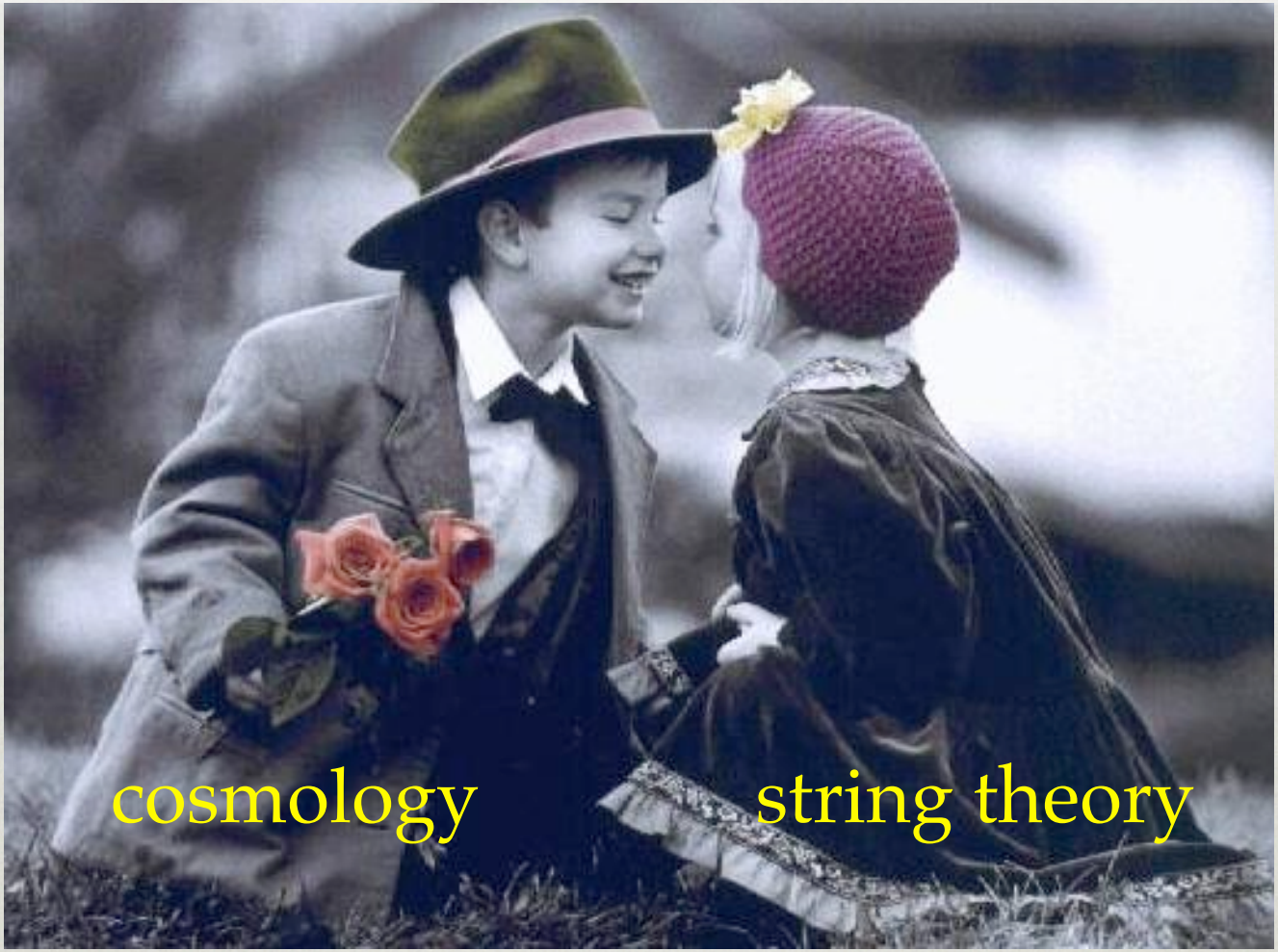
String Cosmology?



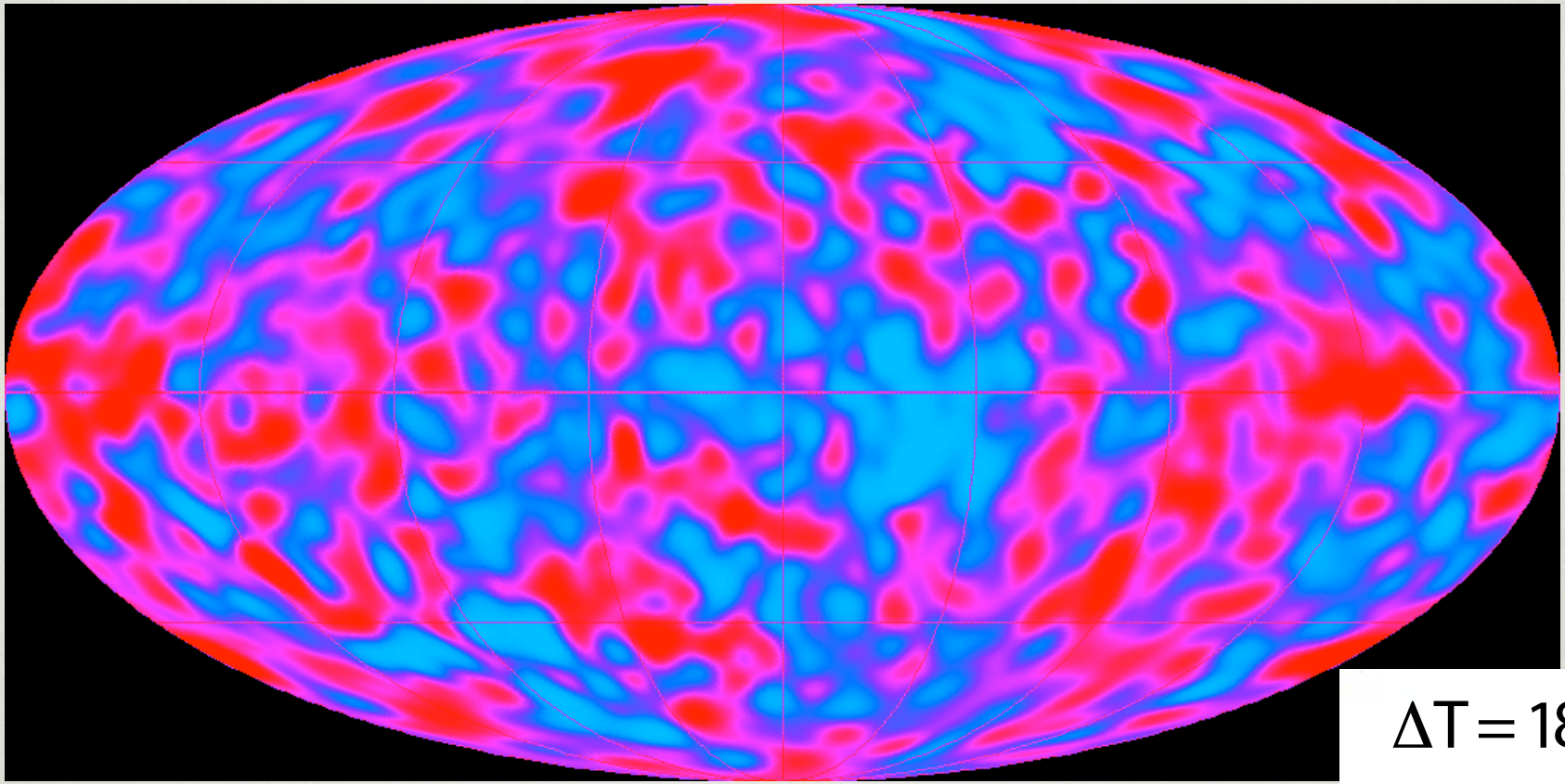
Yeuk-Kwan Edna Cheung
Department of Physics
Nanjing University

Cross-strait workshop on particle physics and cosmology, April 1-5, 2011
Tsinghua University

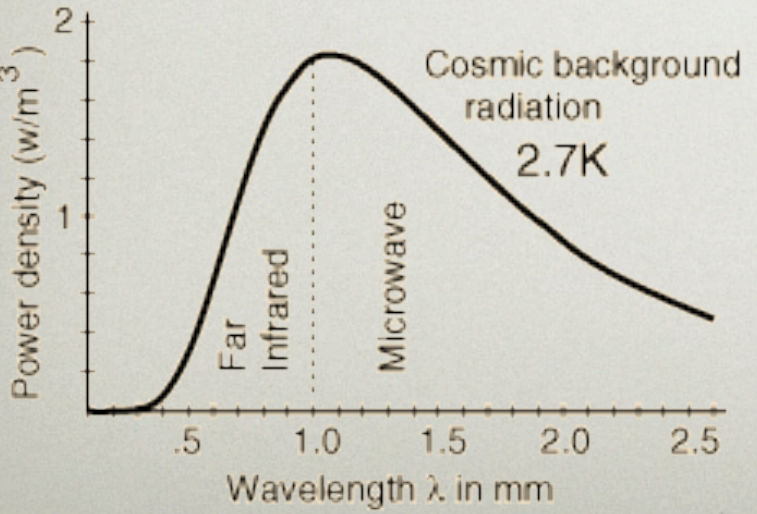
"The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science. Whoever does not know it and can no longer wonder, no longer marvel, is as good as dead, and his eyes are dimmed. It was the experience of mystery -- even if mixed with fear -- that engendered religion. A knowledge of the existence of something we cannot penetrate, our perceptions of the profoundest reason and the most radiant beauty, which only in their most primitive forms are accessible to our minds: it is this knowledge and this emotion that constitute true religiosity. In this sense, and only this sense, I am a deeply religious man.... I am satisfied with the mystery of life's eternity and with a knowledge, a sense, of the marvelous structure of existence -- as well as the humble attempt to understand even a tiny portion of the Reason that manifests itself in nature."

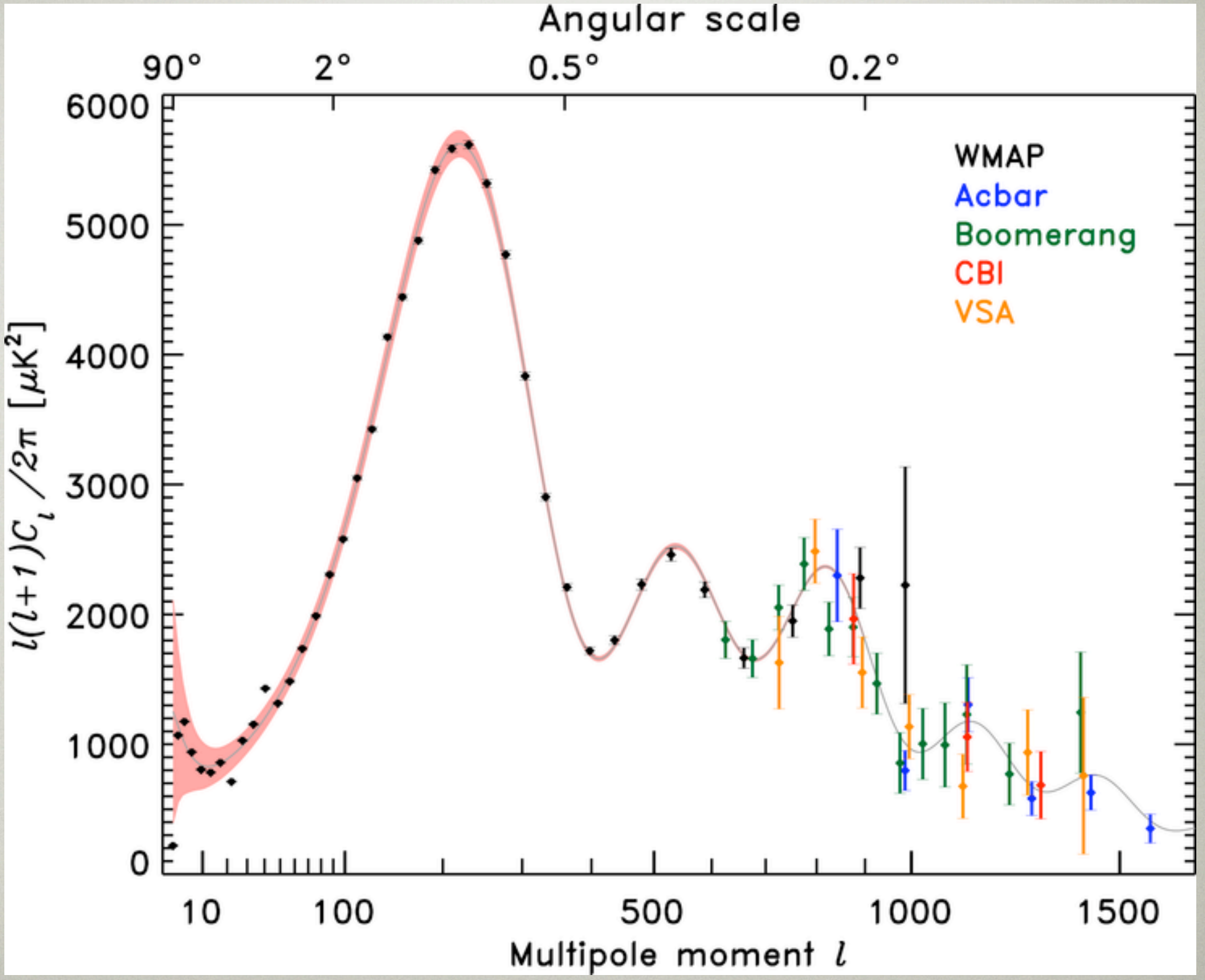
-- Einstein, "The World As I See It"

Anisotropy in Cosmic Microwave Background Radiation '92



$\Delta T = 18\,\mu K$




Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l

PRECISION COSMOLOGY

CMB: WMAP, PolarbeaR, Planck, Clover, QUIET, BiCEP

Large Scale Structures: SDSS, 2dFGRS, SNAP, SPT, ACT, SZA,

LAMOST, LSST, ALMA, Dome-A, FAST

21CMA&YBJ, GMRT, MWA, LOFAR, PAPER, SKA

weak lensing observations

Dark Matter detectors

Gravitational Waves: VIRGO, LIGO, AIGO, and LISA (Chinese LISA)

The Golden Era for Cosmology!!!

Inflation Scenario

The early universe underwent a period of exponential growth in size.

- spatially flat universe
- why is the universe so big?
- homogenous matter distribution at large scale
- provides a mechanism for the origin of structure in the universe based on causal physics
  - quantum vacuum fluctuations of the inflaton field are predicted to be responsible for the structure we observe today

Problems of Inflation

- what is the inflaton?
- slow-roll conditions to get enough inflation: "fine tuning"
- hierarchy problem: correct amplitude of density fluctuations needs $\frac{V(\phi)}{\Delta\phi^4} \leq 10^{-12}$
- the "big bang" singularity is unavoidable with scalar fields
  - the theory must be incomplete--only an effective theory
  - based on using the wrong fundamental physics input close to singularity
- trans-Plankian problems:
  - Plankian physics shows up after sufficient inflation
  - structure formation computation at doubt

★ effective field theory: going beyond the validity of the GR

Calling for a quantum theory of gravity...

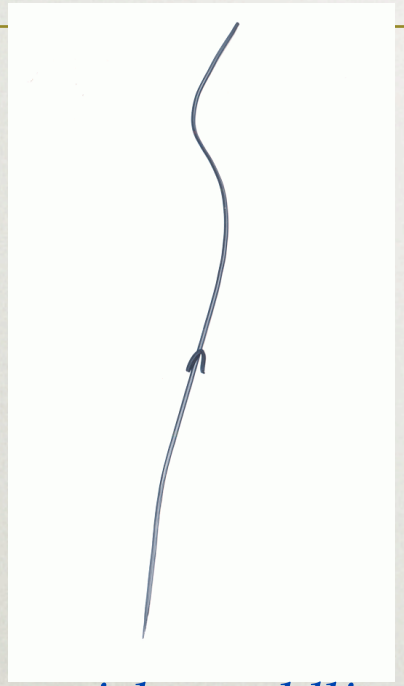
WHAT IS A STRING?

point particle and gauge field:

$\int A \cdot dX \qquad F = dA$

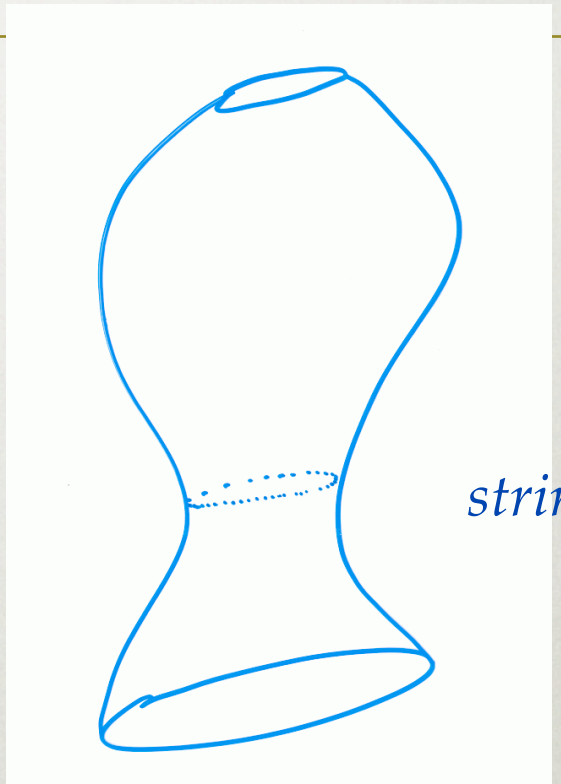
string and its gauge potential:

$\int B \cdot dS \qquad H = dB$



particle worldline

TIME



string worldsheet

If strings are indeed fundamental objects, then

$B_{\mu\nu}$ *will play a role as fundamental as* A_μ *does.*

WHAT IS A STRING?

fundamentally change our notion of spacetime yet again!!!

a lot of symmetries we do not yet understand!!

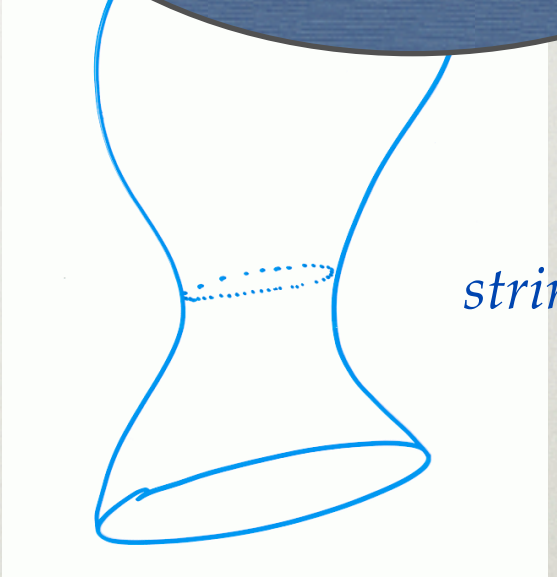
field:

str

al:

particle worldline

TIME



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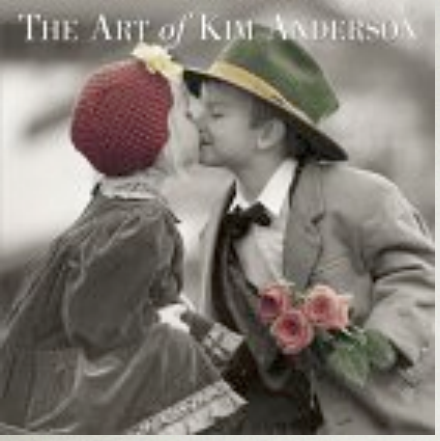


Inflation--highly successful phenomenology needing a fundamental theory

- *CMB fluctuations confirm an inflationary universe at the early time.*
- *But it is hard to understand how it follows from any known microscopic physics.*
- *all scalar fields inevitably encounter singularities when extrapolated back in time.*

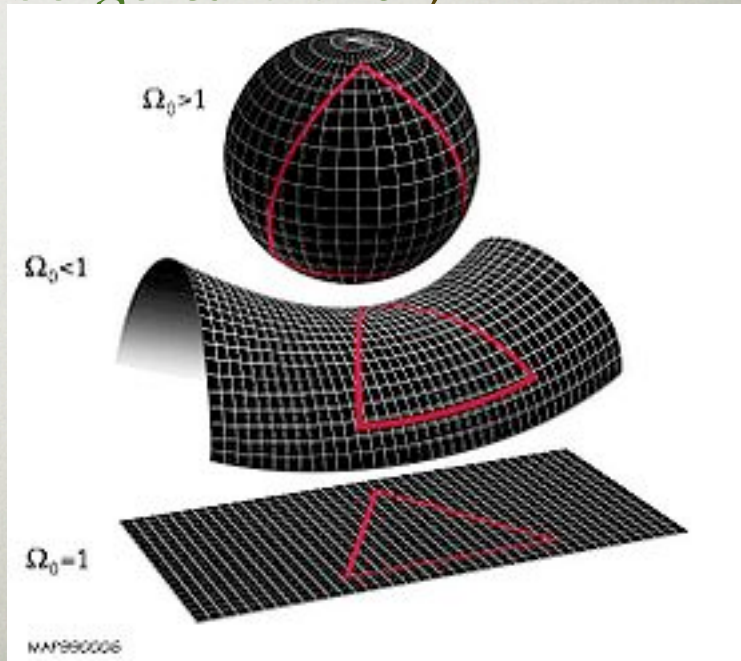
String theory--a beautiful fundamental theory that provides a consistent description of gravity at high energy--looking for experimental confirmation

- *String theory dramatically modifies our notion of space-time and may improve the understanding of the early universe where quantum/high energy effects are crucial, where extra dimensions, if any, will come into play.*
- *The discovery of D-branes and progress in moduli-fixing* → *models.*
  (Polchinski '95, Dvali-Tye '99, Giddings-Kachru-Polchinski '02, KKLT '03, ...)
- *But are we really using string theory, or just effective field theory?*

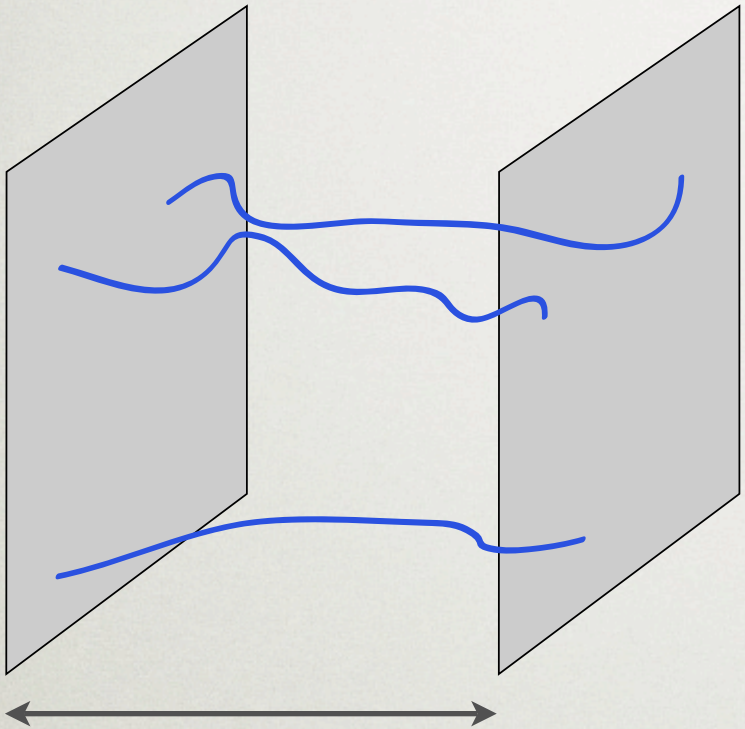
- cosmic singularities: losing predictability!
- scalar inflation model: C.S. is unavoidable! *Brandenberger '03*
- Null/Weak/Dominant/Strong Energy Conditions need to be broken for bouncing universe with k=0, *Molina-Paris, Visser '98*
- a window of opportunity:
  - bounce with $k = 1$ and $\ddot{a}_{min} \leq a_{min}^{-1}$
  - cosmic singularity can be avoided: string Hagedorn phase
    - Brandenberger, Vafa '89; Nayeri,Brandenberger&Vafa '07; ....
  - obey second law of thermodynamics

getting rid of the BB singularity...

Cyclic Universe

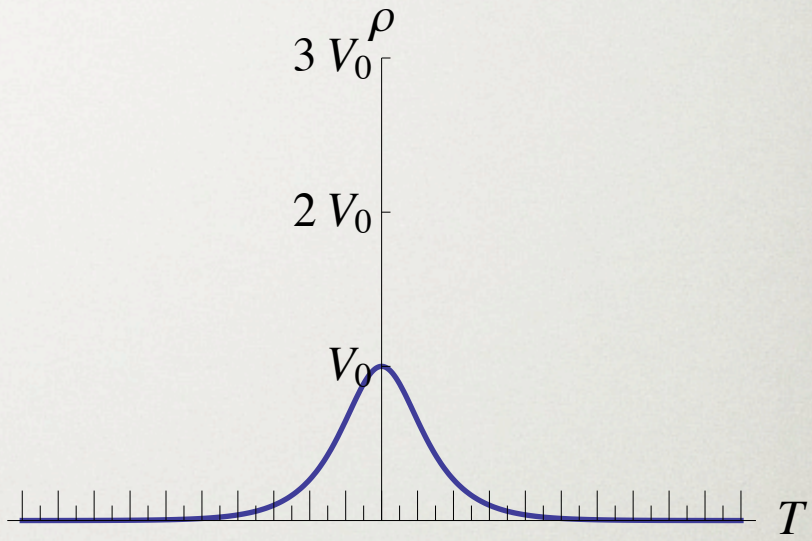


when branes and anti-branes collide...



ϕ

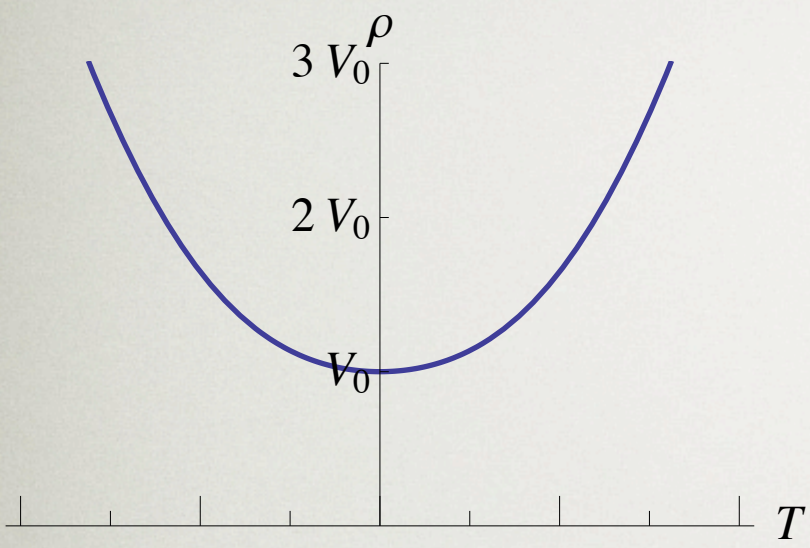
a tachyon (instability) is developed...

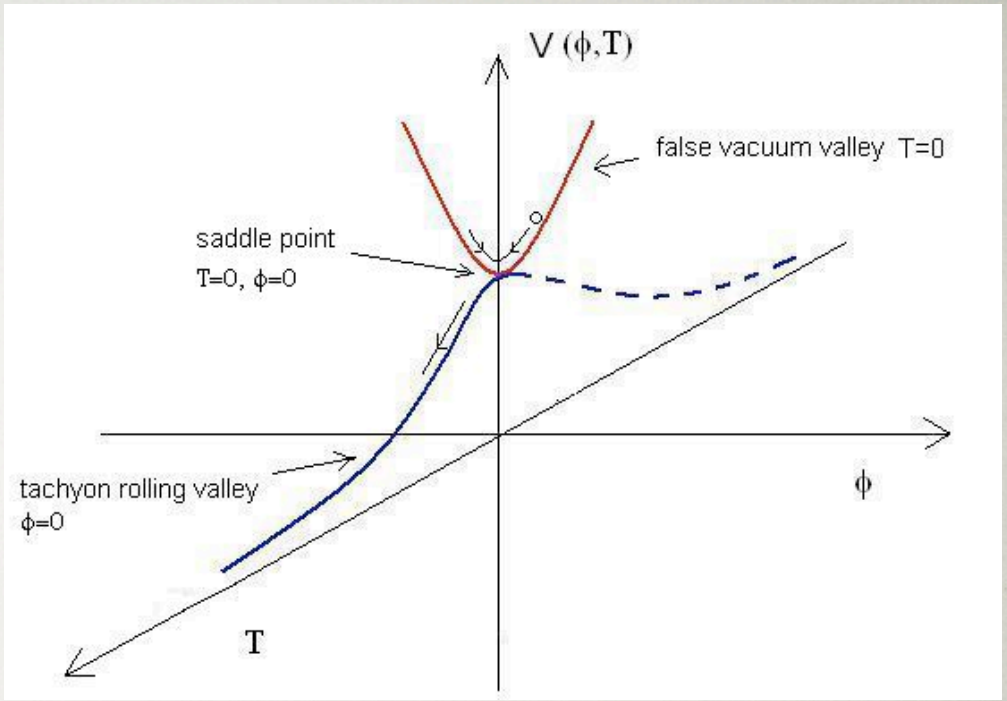


introducing a coupling between ϕ and tachyon, T:

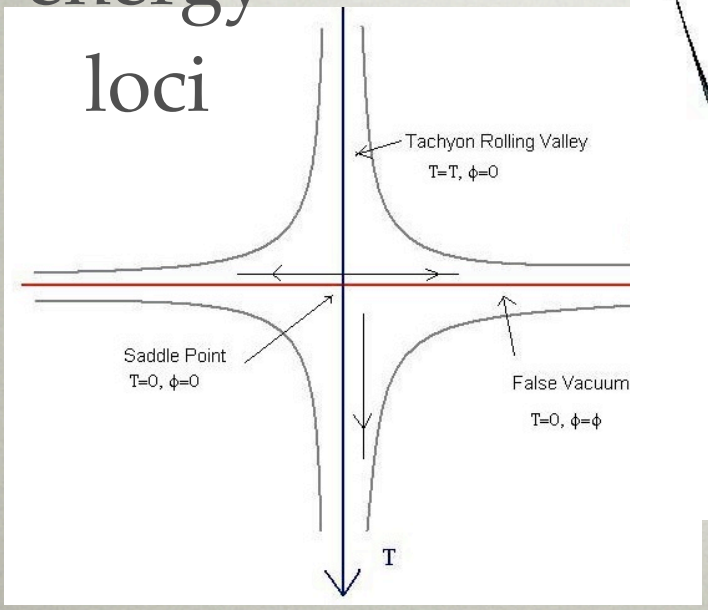
$$\lambda\phi^2 T^2$$

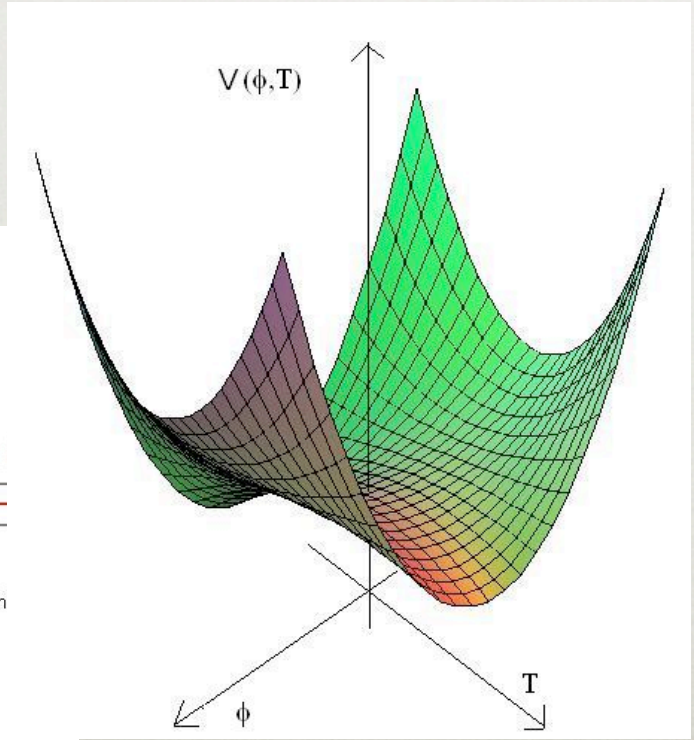
large ϕ:



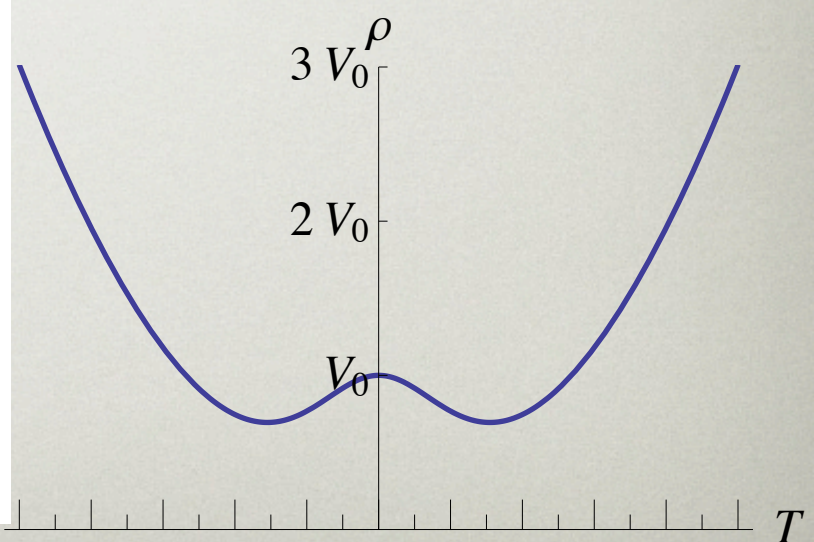


lowest energy loci





small ϕ:



Inflation without the inflaton

Inspired by many earlier works: Sen, Gibbons, Felder et al...

- (homogeneous&isotropic) FRW with spatial S^3 : k=1
- gravity: $\mathcal{L}_{HE} = R$
- a tachyon: $\mathcal{L}_{tachyon} = \frac{V_0}{coshT} \cdot \sqrt{1 + g^{\mu\nu}\partial_\mu T \partial_\nu T}$
- a scalar: $\mathcal{L}_{scalar} = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m_\phi^2\phi^2$
- interaction: $\mathcal{L}_{scalar} = -\lambda\phi^2 T^2$
- Lagrangian: $\mathcal{L} = R - \frac{V_0}{cosh(T)}\sqrt{1 + g^{\mu\nu}\partial_\mu T \partial_\nu T}$
$-g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - m_\phi^2\phi^2 - \lambda\phi^2 T^2$

$$\rho = \frac{V(T)}{\sqrt{-\omega_T}} + \frac{1}{2}\dot{\phi}^2 + \left(\frac{1}{2}m^2 + \lambda T^2\right)\phi^2$$

$$m_\phi^2 = 2\lambda\langle T^2\rangle + m^2$$

$$m_T^2 = 2\lambda\langle\phi^2\rangle - \frac{V_0}{2^2},$$

$$\langle\phi_c^2\rangle = \frac{V_0}{4\lambda^2}$$

Left – Inflation

$$\rho \propto a^0, \quad \rho_k \propto a^{-2}$$

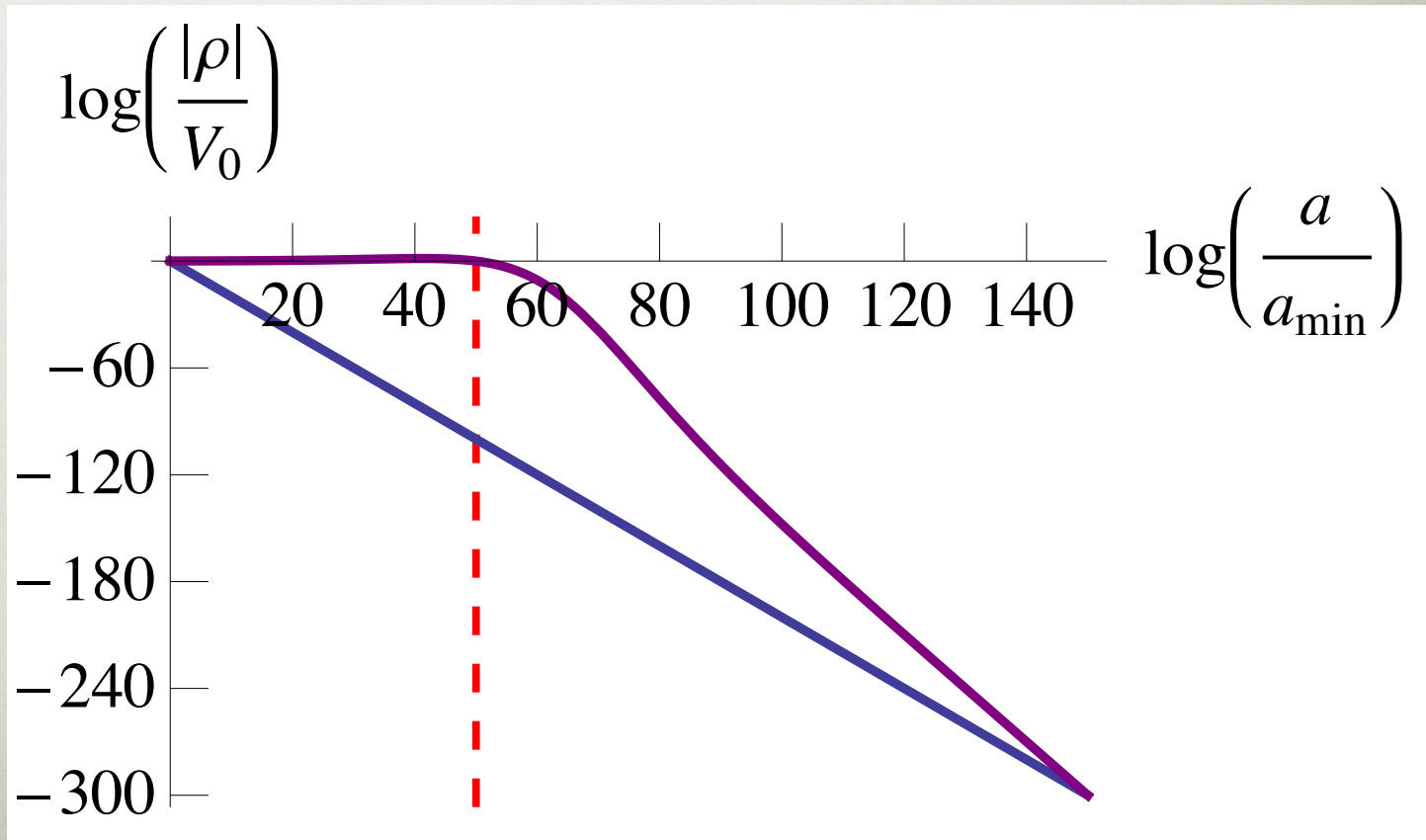
Curvature is left behind

Right – Matter Domination[1]

$$\rho \propto a^{-3}, \quad \rho_k \propto a^{-2}$$

Curvature catches up

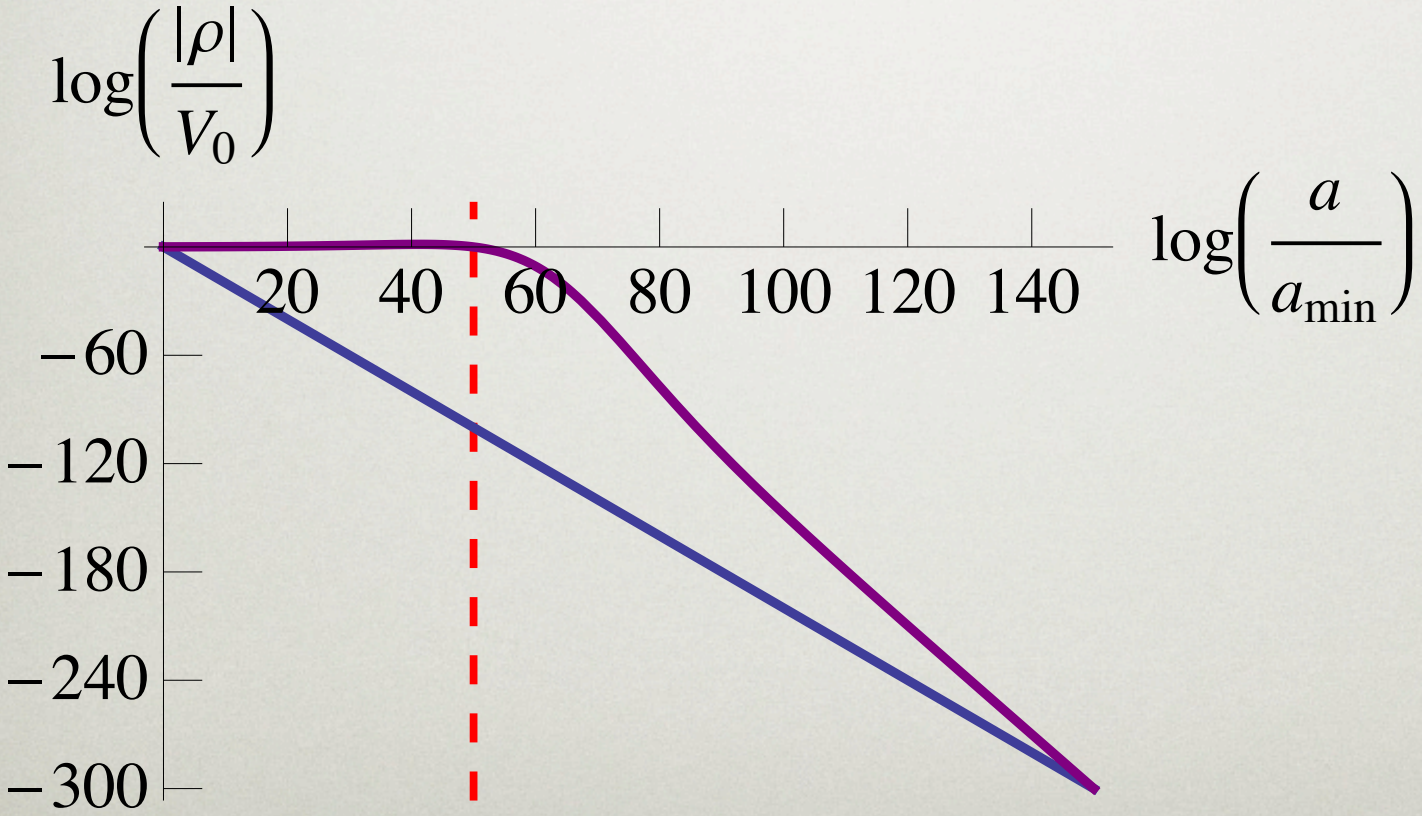
- Red dashed line: End of Inflation
- Blue line: Curvature ρ_k
- Purple curve: Others ρ

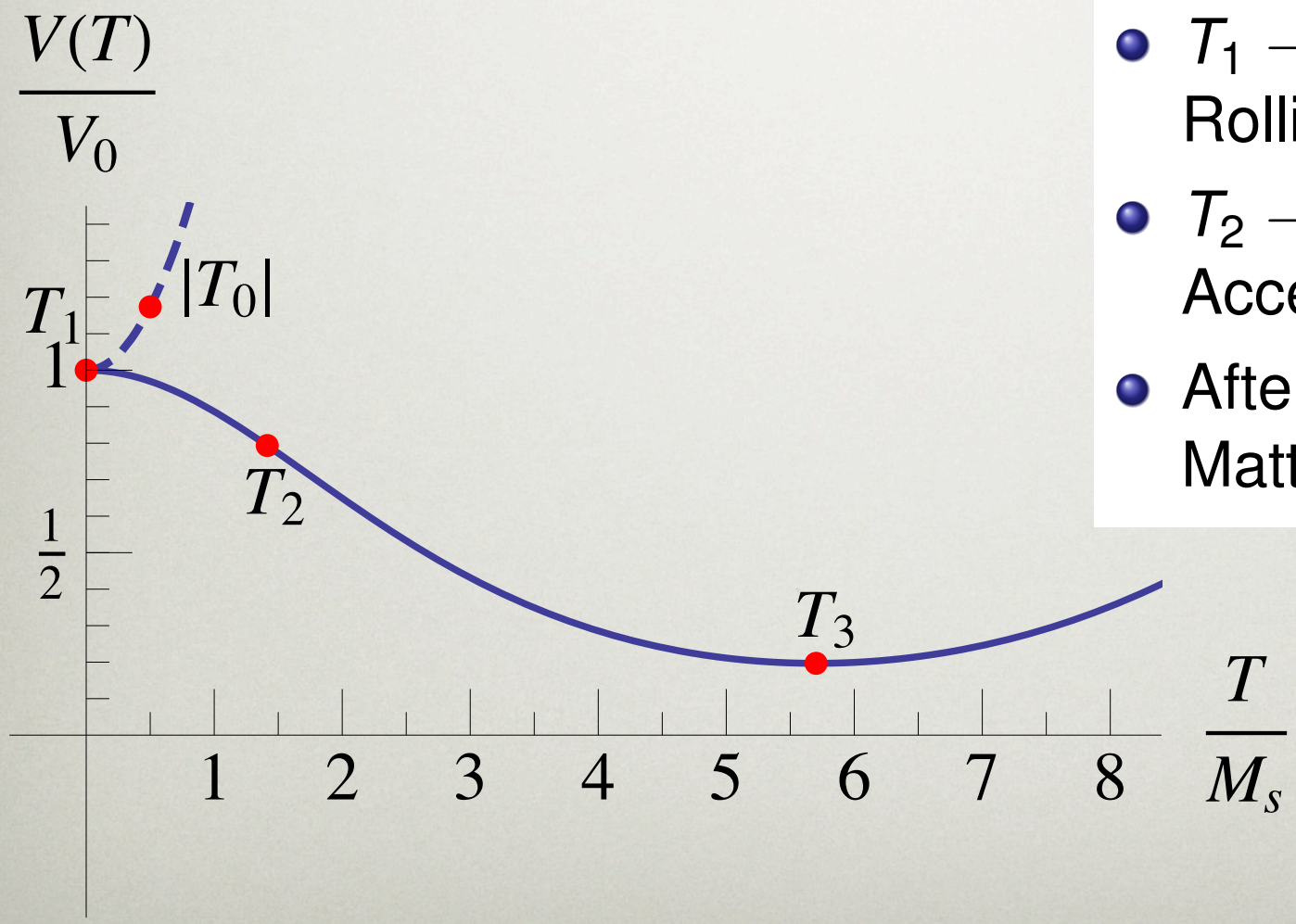


$$H^2 = \frac{8\pi}{3^2}\rho - \frac{k}{a^2} = \frac{8\pi}{3^2}\left(\rho + \rho_k\right) \qquad \rho_k = -\frac{3k^2}{8\pi a^2} < 0$$

Bounces and turnarounds at:

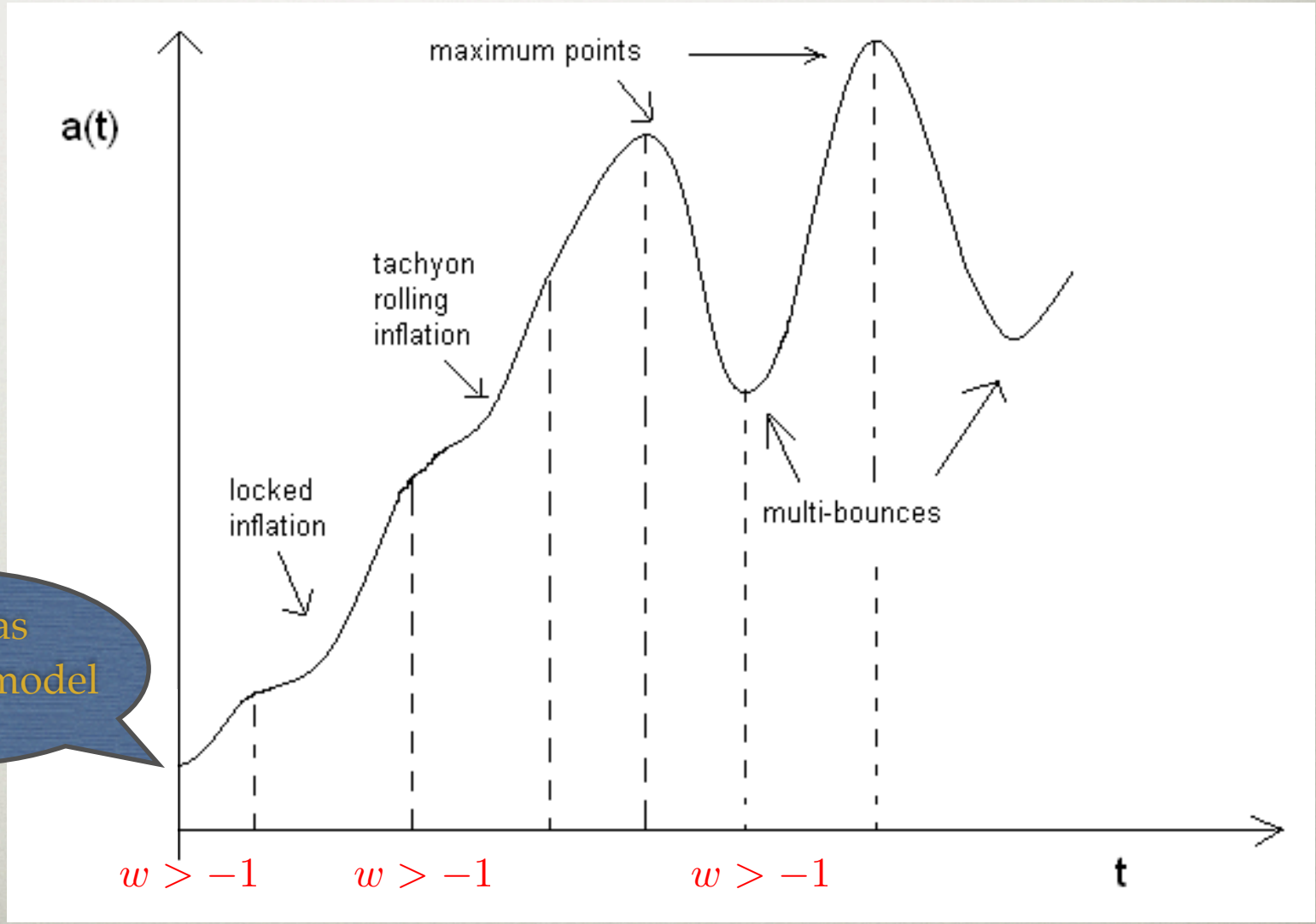
$$H^2 = 0 \Rightarrow \rho + \rho_k = 0$$



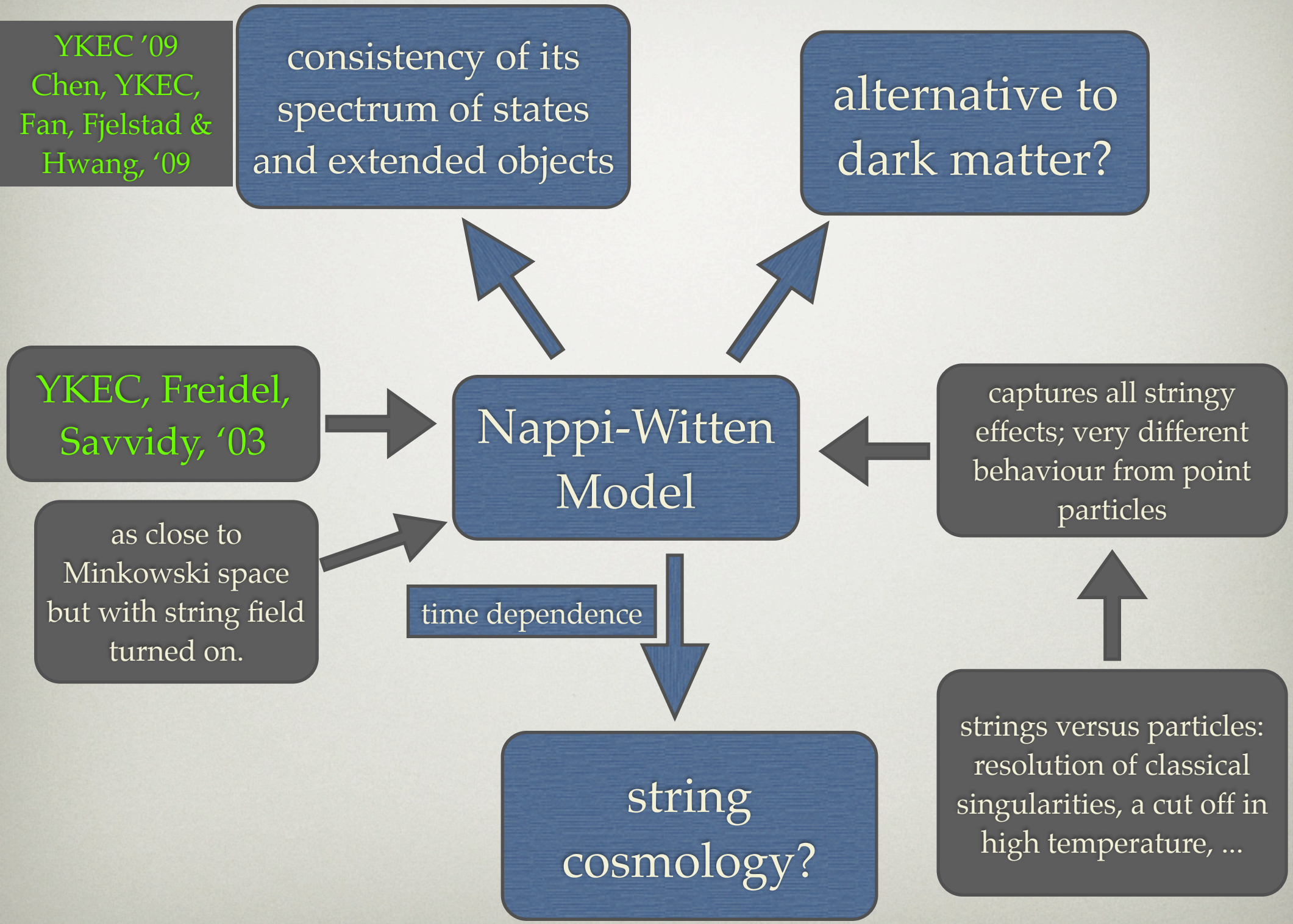


- T_0: Bounce
- $T_0 \to T_1$: Locked Inflation
- $T_1 \to T_2$: Rolling Inflation
- $T_2 \to T_3$: Accelerating Tachyon
- Afterwards: Matter-like Expansion

- collapse and bounce: $\dot{a} = 0$ & $\ddot{a} \neq 0$
- at each minimum: $\ddot{a}_{min} \leq a_{min}^{-1}$
- $a_{min}^{i} < a_{min}^{i+1}$, for $t_i < t_{i+1}$
- $w > -1 \ \forall \ t$



- no ghosts!
- NEC, WEC, DEC, SEC *all* satisfied!
- flatness & horizon?
- reheating? spectrum of density perturbations?
- embed it into String Gas Cosmology model?
  (SGC: Brandenberger,Vafa'89, Brandenberger,Patil,Watson'02, YKEC,Watson,Brandenberger'05)


YKEC '09
Chen, YKEC,
Fan, Fjelstad &
Hwang, '09
consistency of its spectrum of states and extended objects
alternative to dark matter?
YKEC, Freidel, Savvidy, '03
Nappi-Witten Model
captures all stringy effects; very different behaviour from point particles
as close to Minkowski space but with string field turned on.
time dependence
string cosmology?
strings versus particles: resolution of classical singularities, a cut off in high temperature, ...

merci!

So my advice to you: stay hungry. And stay foolish.

-- Steve Jobs @ a Stanford commencement