a brief introduction
to cosmology

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what a cosmologist wants from string theory

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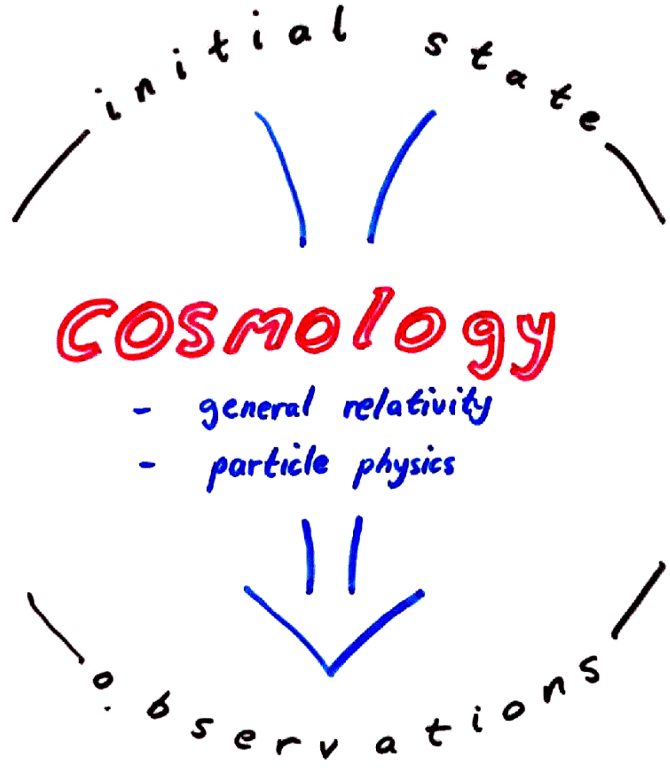

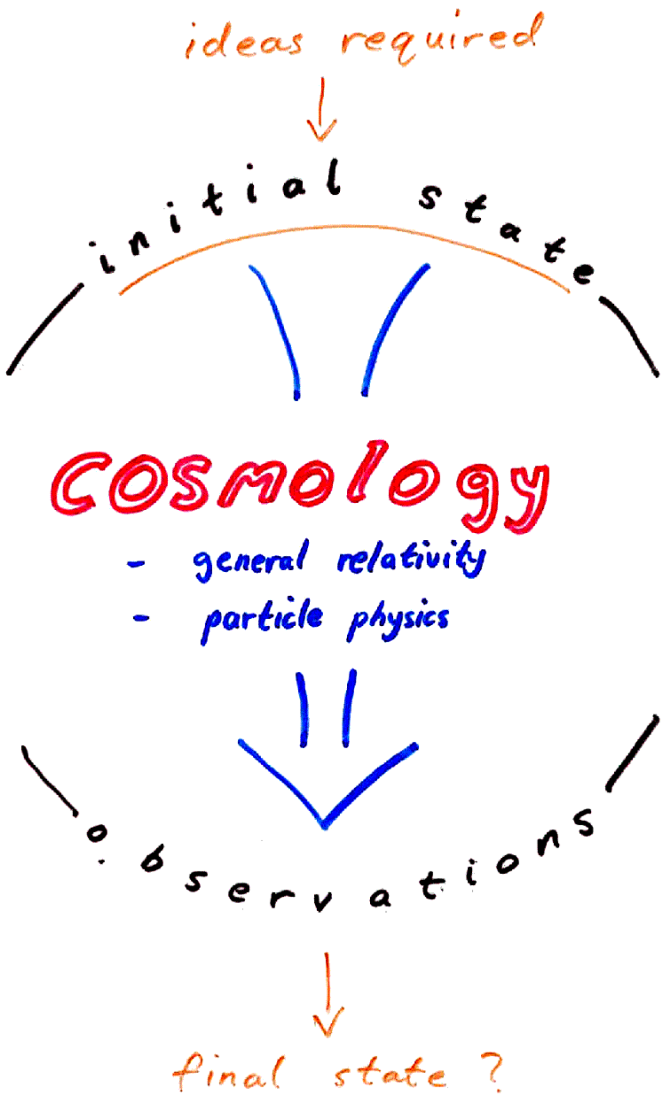

the cosmological standard model

simple (+ special) initial state
evolved (general relativity
+ particle physics)
into observed distribution of matter

e.g.
- abundances of light elements (BBN)
- anisotropies in cosmic microwave background sky (CMB)
- line-of-sight distribution of pre-galactic hydrogen (Ly-α clouds)
- abundance of galaxy clusters versus redshift
- luminosity vs. redshift of supernovae
- weak grav.-lensing by foreground dark matter
- 3D distribution of galaxies

standard model parameters

Ω_k	spatial curvature
$\langle R^2 \rangle$	scalar metric pertbns
$n-1$	spectral tilt
$\langle T^2 \rangle$	tensor metric pertbns
n_T	tensor tilt
Ω_B	baryon density
Ω_γ	radiation density
Ω_{cdm}	cold dark matter
Ω_ν	neutrino density
b	bias light : mass
τ	optical depth to lss
H_0	present Hubble expansion
Ω_Λ	vacuum energy density
w_Λ	"vacuum" equation of state

standard model parameters

initial conditions	Ω_k	spatial curvature
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particle physics	Ω_B	baryon density
	Ω_γ	radiation density
	Ω_{cdm}	cold dark matter
	Ω_ν	neutrino density
astro-physics	b	bias light : mass
	τ	optical depth to lss
"clock"	H_0	present Hubble expansion
vacuum gravity	Ω_Λ	vacuum energy density
	w_Λ	"vacuum" equation of state

initial state

- (3+1) - dimensional spacetime
- ~~almost~~ statistically homogeneous & isotropic (perturbed FLRW spacetime)
- almost spatially flat ("$\Omega = 1$")
- expanding ($H > 0$)
- almost scale-invariant spectrum of Gaussian metric perturbations ($\delta g \sim 10^{-5}$)

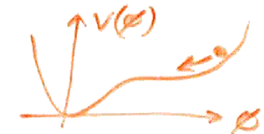
inflation in early universe

* constant vacuum energy

de Sitter attractor (for $H > 0$)

- homogeneous & isotropic
- $\Omega_k \to 0$ as $t \to \infty$

* slowly-rolling scalar fields



almost constant vacuum energy

- light fields ($m^2 \ll H^2$) acquire scale-invariant spectrum of pertbns
- vacuum energy → radiation at reheating after inflation
- scalar field perturbations → density perturbations

large-scale structure from scalar fields

small scale ($k \gg aH$) quantum vacuum under-damped oscillator → large scale ($k \ll aH$) perturbations over-damped

$$\delta\chi \propto \frac{e^{-ik\eta}}{\sqrt{2k}\,a} \qquad \langle \delta\chi^2 \rangle_{k=aH} \simeq \left(\frac{H}{2\pi}\right)^2$$

scalar metric perturbation

during inflation → after inflation

$$\mathcal{R} = \frac{H\,\delta\phi}{\dot\phi} \longrightarrow \mathcal{R} = \frac{H\,\delta\rho}{\dot\rho}$$

inflaton, ϕ — density, ρ

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isocurvature field perturbations

$$S_{ij} = H\left(\frac{\delta\phi_i}{\dot\phi_i} - \frac{\delta\phi_j}{\dot\phi_j}\right)$$

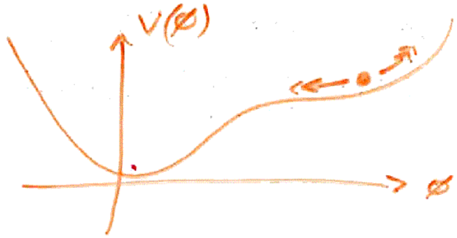
e.g. "curvaton" "modulated reheat"

$$S_{B\gamma} = H\left(\frac{\delta\rho_\gamma}{\dot\rho_\gamma} - \frac{\delta\rho_B}{\dot\rho_B}\right)$$

"entropy" perturbn.

stochastic inflation

- Starobinsky, Linde, Vilenkin ...



classical evolution dominated by quantum fluctuations for $H^2 > \dot{\phi}$

- "self-reproducing"
- inhomogeneous
- future eternal

Problems?

- non-linear gravtl back-reaction of quantum fluctuations
- past incomplete geodesics Vilenkin, Borde + Guth
- problem of measure

pre big bang

Gasperini + Veneziano '91

+ Khoury, Ovrut, Steinhardt + Turok '01

gravitational instability of vacuum

→ cosmological collapse (similarities with inflation!)

→ locally homogeneous attractor

→ quantum vacuum → large-scale perturbations

Problems?

- approaches cosmological singularity
- does not (in general) produce scale-invariant perturbations (probably need "entropy" perturbns)

Q:

what happens at a cosmological singularity ?

big bang, big crunch, big rip...

- higher order string / loop corrections to avoid singularity?
- non-perturbative dual description that is non-singular?

Q:

does time begin ?

e.g. quantum cosmology
+ no boundary proposal ?

or eternal stochastic inflation ?

or pre big bang phase ?

or eternal cyclic model ?

Q:

what is quantum vacuum for gravitational fields?

- 2-point function for trans-Plankian fields in curved spacetime
- 3-point function for self-gravitating fields (non-Gaussianity of primordial perturbation spectra)

Q:

is there a future asymptotic vacuum state?

- does $\Lambda \to 0$? ($\to M_4$)
  $\Lambda > 0$? ($\to dS_4$)
  $\Lambda < 0$? recollapse
  Kallosh, Linde, et al
- why does present vacuum weigh so little? Dvali et al

Q:

why are there (only ?) 3 large spatial dimensions ?

- are hidden dimensions
  compact / infinite ?
  universal / gravitational ?

- what is the topology
  of space ? and time ?

summary:

cosmology

successful standard model

seeks deep meaningful connection

with string theory

five questions :

① what happens at a cosmological singularity ?

② does time begin ?

③ what is the quantum vacuum for gravitational fields ?

④ is there a future asymptotic vacuum state ?

⑤ why only 3 large / visible spatial dimensions ?