Inflationary cosmology

& connections to string theory

Background & status, near-term opportunities and future directions

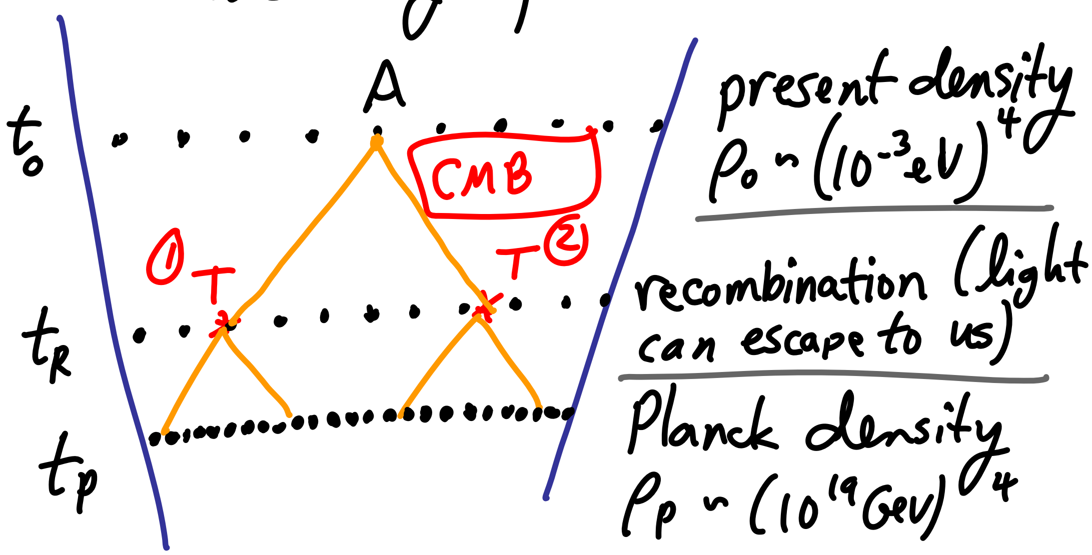
Early universe cosmology research ranges from precise observations to conceptual/formal theory, with connections between them.

No/few refs, many collaborators and contributors (See e.g. TASI 2015 lectures and other reviews online). This subject benefits tremendously from Iranian contributions and collaborations across borders.

There is strong evidence for accelerated expansion $\ddot{a} > 0$ (Inflation) $ds^2 = -dt^2 + a^2(t)d\vec{x}^2$ in the early universe. (Guth, Linde, Albrecht/Steinhart ...)

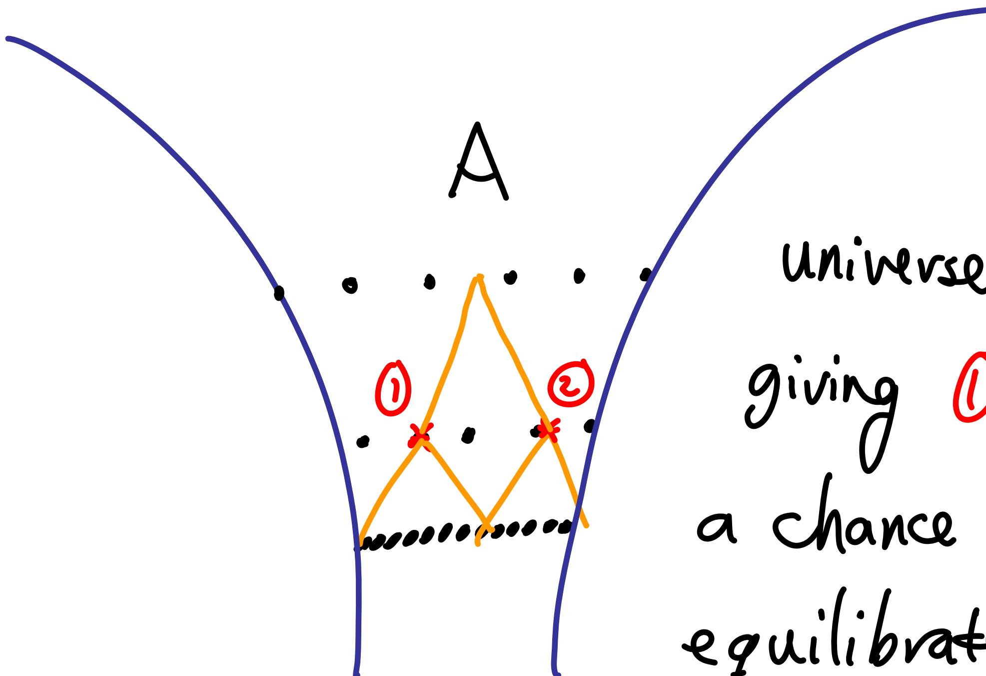
Early motivations: extrapolating known expansion back in time

→ causality puzzle



$T_{①} = T_{②} \doteq 3K$ but ① + ② not in causal contact

An approach to this is to postulate an early period of accelerated expansion (inflation)



universe older, giving 1 & 2 a chance to equilibrate.

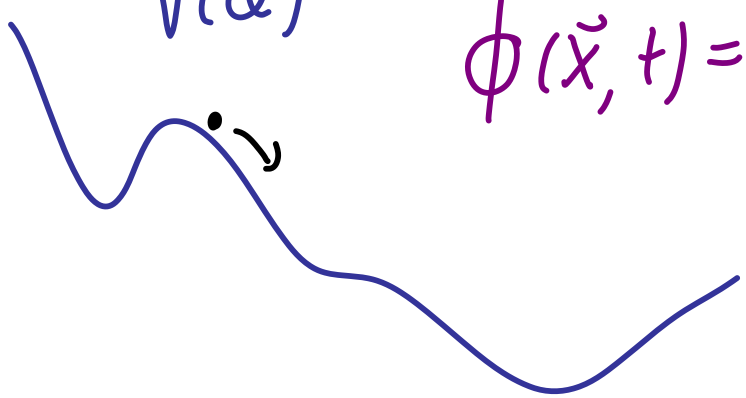
This also dilutes any ambient curvature: $\left(\frac{\dot{a}}{a}\right)^2 = \underbrace{\Lambda}_{\text{wins as a grows}} - \frac{k}{a^2} + \cdots$

as well as unseen high-scale relics like monopoles.

A striking prediction of inflationary models is a primordial spectrum of fluctuations in the CMB, seeding structure.

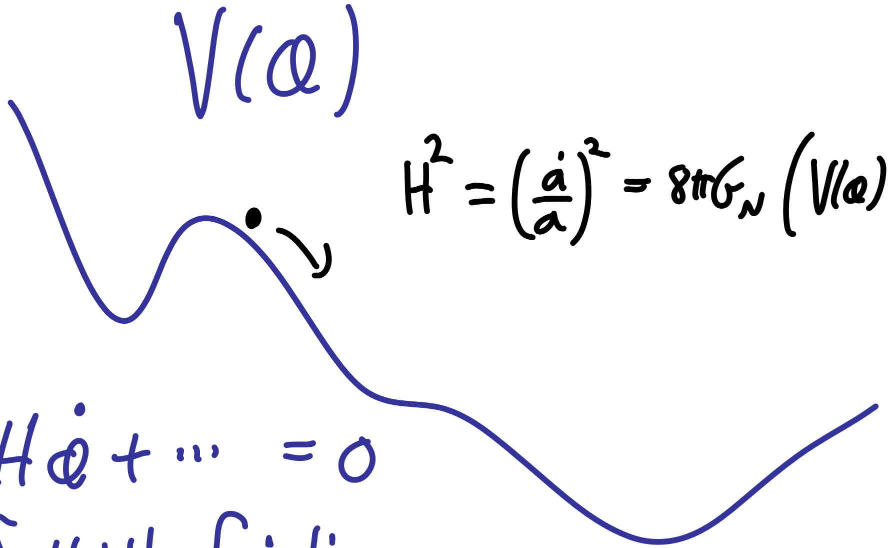
To match inflation onto late time FRW expansion $\frac{\rho_m}{a^3}$, the inflationary Λ must go away. This can be obtained theoretically by adding rolling scalar field(s) $\phi(x)$, with appropriate potential + kinetic energy:

$V(\phi)$



$$\phi(\vec{x},t) = \phi_0(t) + \underbrace{\delta\phi(\vec{x},t)}_{\text{Quantum}}$$

$$\langle \delta\phi\, \delta\phi \rangle \neq 0$$



$$H^2 = \left(\frac{\dot a}{a}\right)^2 = 8\pi G_N \left(V(\varphi) + \rho_{\text{kinetic}}(\dot\varphi) + \cdots\right)$$

$$\ddot\varphi + 3H\dot\varphi + \cdots = 0$$

↖ Hubble friction

- One can show that $\rho_{kin} \ll V(\varphi)$ gives accelerated expansion.
- To solve the flatness, monopole, horizon problems, one needs inflation to last a long time:

$$\frac{a_{end}}{a_{start}} = e^{N_e} \qquad N_e = 60 \text{ for } H \sim 10^{14}\,\text{GeV}$$

Timescales disambiguation

$$a(t) = e^{Ht}, \quad \phi(t)$$

3 basic ways of measuring duration:

- $$a_{end} \sim \left(e^{60} \sim 10^{26}\right) a_{start}$$
- $$\Delta t \sim \frac{60}{H} \sim 60 \frac{M_p}{H} \times \frac{1}{M_p}$$
  $$\sim 60 \frac{M_p}{H} \times 10^{-43} s$$
- $$\Delta \phi \gtrsim M_p$$

Homogeneous Dynamics

$$H(t)^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{\rho}{3M_p^2} \; ; \; \frac{2\ddot a}{a} + H^2 = -\frac{p}{M_p^2}$$

Require $\frac{\dot H}{H^2} \, , \, \frac{\ddot H}{H^3} \lesssim 10^{-2}$

Wide range of dynamics that could drive inflation:

$$S = \int \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, \mathcal{L}\left((\partial\phi)^2, \phi, \ldots\right)$$

$$\text{e.g. } S_{SR} = \int d^4x \sqrt{-g} \left((\partial\phi)^2 - V(\phi)\right)$$ single-field slow roll

$$\vdots$$

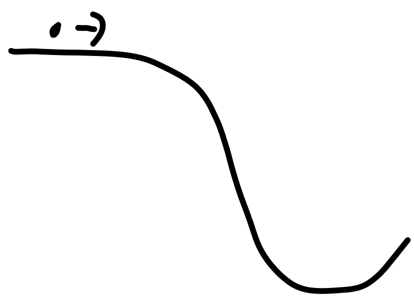
$$S_{DBI} = \int d^4x \sqrt{-g} \left\{ -\frac{\phi^4}{\lambda} \sqrt{1 - \frac{\lambda(\partial\phi)^2}{\phi^4}} - V(\phi) \right\}$$

...

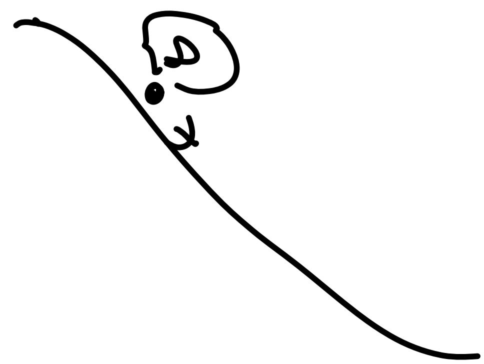
Roughly Speaking,

2 classes of Inflation Mechanisms:

→ Slowly diluting potential energy



flat potential



Steep potential, but interactions slow the field.

↳ e.g. brane motion limited by speed of light (DBI)

$$\dot{\phi}^2 < \frac{\phi^4}{\lambda}.$$

+ many new effects for multiple fields

Slow Roll case (homogeneous)

$$V \gg \rho_{kin} \Rightarrow \frac{\dot\phi^2}{3M_p^2H^2} \equiv \varepsilon \ll 1$$

$\shortparallel$S

$3H^2M_p^2$

$$\delta\left(\int d^4x\sqrt{-g}\left(\tfrac{1}{2}\dot\phi^2 - V(\phi)\right)\right) = 0$$

Look for regime $\ddot\phi + 3H\dot\phi + V' = 0$

$\ddot\phi \leftarrow 0$

Requires $\eta \equiv -\dfrac{\ddot\phi}{3H\dot\phi} \ll 1$

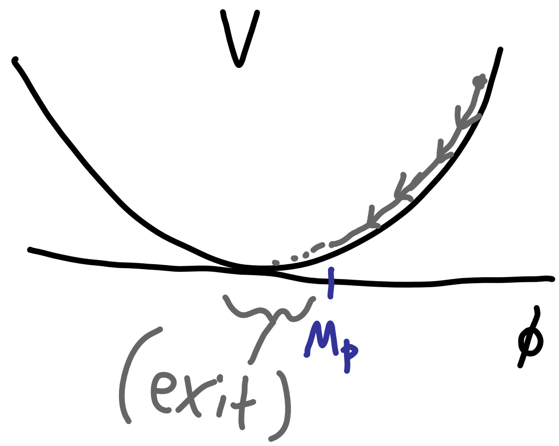
$$\dot\phi = -\frac{V'}{3H} \Rightarrow \eta \sim \frac{\frac{V''}{3H}\dot\phi - \frac{V'}{3H^2}\dot H}{H\dot\phi} \ll 1$$

$$\dot H = \frac{1}{2H}\frac{d(H^2)}{dt} = \frac{1}{2H}\frac{V'}{3M_p^2}\dot\phi$$

$\Rightarrow \left(\dfrac{V'}{V}M_p\right)^2 \ll 1$, $\dfrac{V''}{V}M_p^2 \ll 1$ sufficient

Example ('simplest' $\doteq$ origin of parameter space)

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$



$$\underbrace{3H}_{\sim \frac{m\phi}{M_p}} \dot{\phi} \simeq -m^2 \phi \qquad \text{(SR)}$$

$$\Rightarrow \dot{\phi} \sim m M_p$$

Then $\varepsilon \sim \dfrac{\dot{\phi}^2}{V} \ll 1 \Rightarrow m^2 M_p^2 \ll m^2 \phi^2$

$$\Rightarrow \boxed{\phi \gg M_p} \qquad \text{also } \eta \sim \frac{V'' M_p^2}{V} \sim \left(\frac{M_p}{\phi}\right)^2$$

- Disfavored by data $\Rightarrow$ discovery of parameter (beyond m)

Deceptively simple. Significantly affected by 'UV' physics, even at scale $M_{uv} \gg H$.

$(\text{mass} > H)$

<u>Heavy</u> fields affect

results adjust in response

to inflationary potential energy.

QFT toy model

$$V(\varphi_L, \varphi_H) = g^2 \varphi_L^2 \varphi_H^2 + m^2 (\varphi_H - \varphi_0)^2$$

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2 \varphi_L^2}{g^2 \varphi_L^2 + m^2} m^2 \varphi_0^2$$

($\dot{\varphi}_H^2$ term subdominant)

flatter: energetically favorable.

String theory examples: $\phi^2 \rightarrow \phi^{p<2}$

So far, everything I explained can be described in quantum field theory and general relativity.

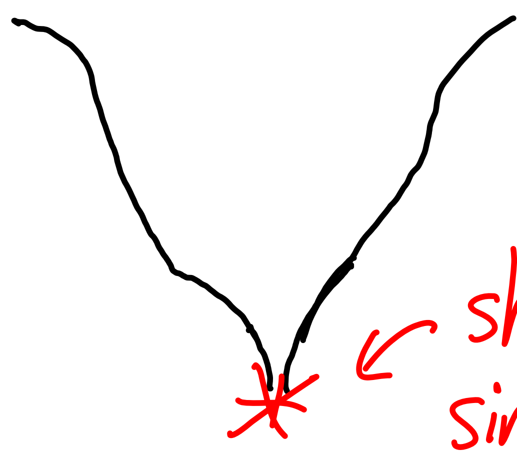
However, these do not provide a complete model. To see this, first note that the effective interaction strength of gravity <u>increases</u> with energy:

$$\lambda_G \sim G_N E^2 \sim \left(\frac{E}{M_p}\right)^2 \quad M_p \leftarrow 10^{19}\,\text{GeV}$$

At short distances, quantum effects become important, along with any new degrees of freedom involved in a "UV completion" of the theory. This affects cosmology in several ways.

1)

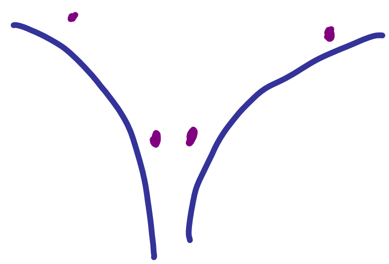
Far past:



short-distance singularity

and/or "eternal inflation"

There is <u>much</u> more to do to understand initial conditions for cosmology. This is conceptually interesting, and may ultimately provide some sort of probability distribution for late time physics.

However, if it occurred, inflation diluted most relics of this early time , so let us move on to inflation in string theory & observables

Effective Field Theory and `dangerous irrelevance':

a more subtle sensitivity to QG than singularity. Standard method parameterizing our ignorance of high(er) energy physics:

GR breaks down for $\lambda_G \to 1$ (or before)

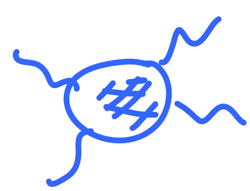
Classical & Quantum corrections

$$S = \int \left(\frac{R}{G_N} - V(\phi)\right)\left(1 + R\left(\frac{c_1}{M_*^2} + \tilde{c}_1 G_N\right) + \cdots\right)$$

$$+ \int (\partial\phi)^2 + k_1 \frac{(\partial\phi)^4}{M_*^2} + \cdots$$

$\leftarrow$ scale of "new physics"

with corrections sensitive to short-distance physics



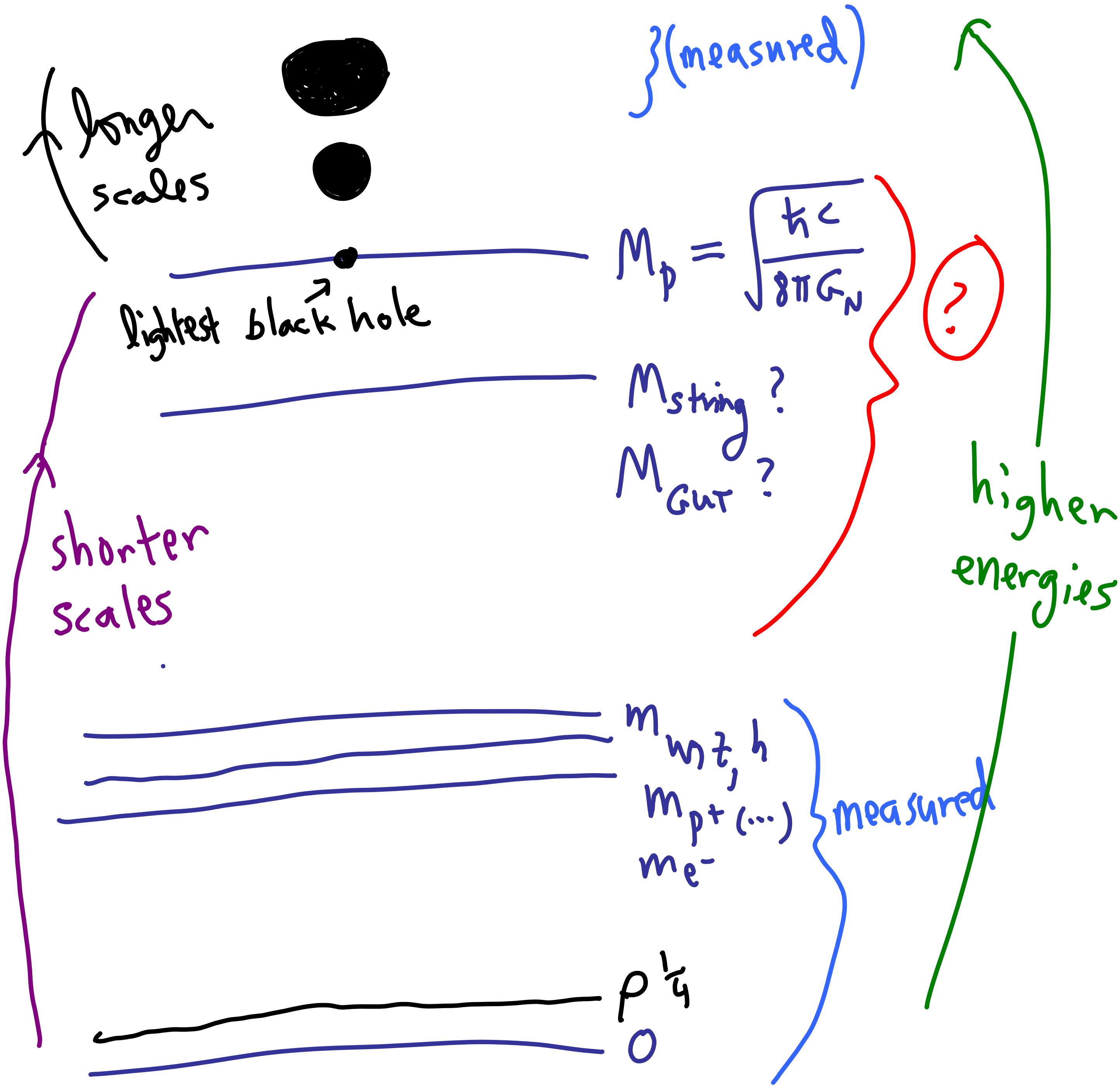
$$\mathcal{O}_\Delta \text{ corrections} \sim \left(\frac{\text{Energy}}{M_*}\right)^{\Delta - 4}$$

There is an infinite sequence of \`irrelevant' perturbations, those with $\Delta > 4$. Since these die out at low energy, we can often make reliable physical predictions despite our ignorance of this infinite sequence.

However, physics *can* become sensitive to \`UV completion' even in systems with low input energies.

This subtlety arises in the presence of long time evolution and/or large field excursions.

Separation of energy scales and `dangerous irrelevance'

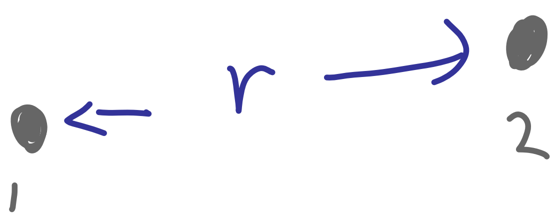


How do we ever do physics with so much that is unknown?

Wilsonian effective field theory (basic idea):

Physical quantity, such as force between two objects, or scattering probability, has a leading contribution at low energies, and subleading corrections that have to do with unknown higher energy physics.

e.g.



$G_N \sim \frac{1}{M_p^2}$

$$F = -\frac{G_N m_1 m_2}{r^2}\left(1 + \underbrace{\cdots}_{c_1 \frac{G_N}{r^2} + c_2\left(\frac{G_N}{r^2}\right)^2 + \cdots}\right)$$

infinite sequence of `irrelevant' terms.

For many purposes, at long distances (low energies) we can ignore the infinite sequence of unknowns.

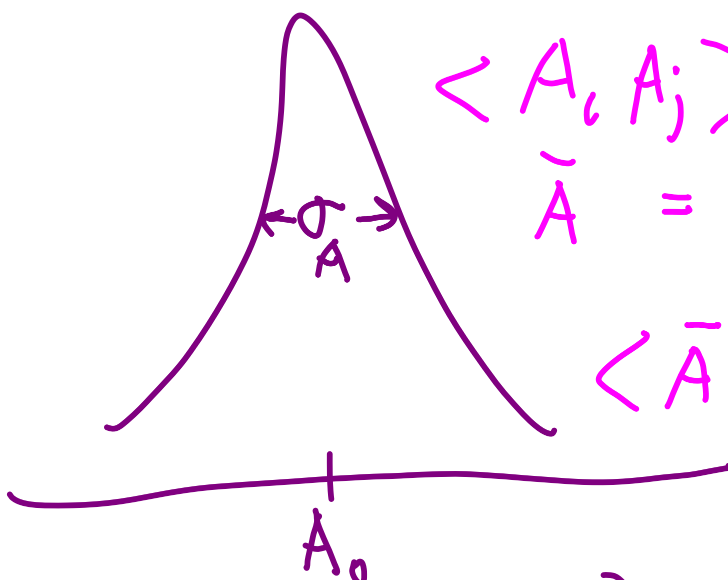
But for a process that goes over sufficiently long time periods, or over sufficiently large ranges of fields (and/or with sufficient amounts of data), sensitivity to higher energy physics can develop.

proton decay mediated by GUT-scale (heavy !) particle highly constrained

CMB Data reach:

10^6 pixels

Statistical noise from the quantum fluctuations themselves.
More data => more independent tests => smaller error bars. Roughly:



$$\langle A_i A_j \rangle = \delta_{ij} \sigma_A$$

$$\bar{A} = \frac{1}{N_{exp}} \sum_{i=1}^{N_{exp}} A_i$$

$$\langle \bar{A}^2 \rangle = \frac{\sigma_A^2}{N_{exp}}$$

$$\sigma_A^{(N_{pix})} \sim \frac{\sigma_A}{\sqrt{N_{pix}}} \sim 10^{-3} \sigma_A$$

Data increasing (+large-scale structure)

$\mathcal{O}_\Delta$ corrections $\cdot \left(\dfrac{\text{Energy}}{M_*}\right)^{\Delta-4}$

$\uparrow$

e.g. $V(\phi) = v_1(\phi-\phi_0) + v_2(\phi-\phi_0)^2$

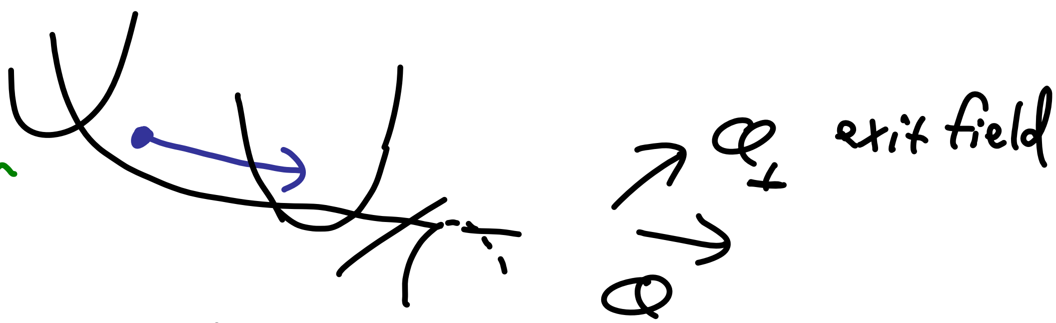
$$+ \lambda_6 \frac{(\phi-\phi_0)^6}{M_*^2} + \cdots$$

The higher-dimension (`irrelevant') terms can become important if the field ranges over a sufficiently large range in field space. This is automatic in inflationary cosmology:

UV sensitivity of Inflation and dangerous irrelevance.

A seemingly simple way to obtain inflation is to postulate a very flat potential for the inflaton $\varphi(x)$.

Linde '93
hybrid inflation

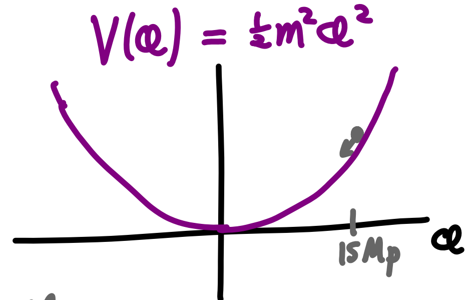


$$\varepsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv M_p^2\left|\frac{V''}{V}\right| \ll 1$$

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\varphi, \partial\varphi)$: $\frac{V(\varphi-\varphi_0)^2}{M_p^2} \rightarrow \Delta\eta \sim 1$

This UV Sensitivity is greatest in the case of "chaotic inflation" A. Linde '83 where the inflaton φ ranges over more than a distance M_p

e.g. $V(\varphi) = \frac{1}{2} m^2 \varphi^2$



$$\left\{ \begin{array}{l} \varepsilon = \frac{1}{2}\left(\frac{V'}{V} M_p\right)^2 \\ \eta = M_p^2 \left|\frac{V''}{V}\right| \end{array} \right\} \sim \left(\frac{M_p}{\varphi}\right)^2 \Rightarrow \varphi \sim 15\, M_p$$

We will find an extremely interesting relation:

$$\boxed{\star \text{ "Lyth Bound"}: \quad \underbrace{\frac{\Delta\varphi}{M_p}}_{\text{UV sensitive if } \gtrsim 1} \sim \underbrace{\left(\frac{r}{0.01}\right)^{\frac{1}{2}}}_{\text{observable}}}$$

→ Control with approximate shift symmetry (Wilsonian 'natural')

String theory and Inflation

Despite the complications of the landscape of string compactifications -- for which there is much to study -- clear mechanisms for inflation emerge, some of which are falsifiable based on CMB data (e.g. primordial gravitational waves or shapes of non-Gaussianity).

These lead to a more systematic low energy effective field theory analysis of inflation and signatures, as well as new data searches.

*A rare opportunity to do some traditional science with string theory. No claim of a global prediction of ST, just like QFT in having multiple distinct models/mechanisms

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At the same time, the rich structure of string compactifications demands further study, and conceptually we do not have a complete framework for cosmology.

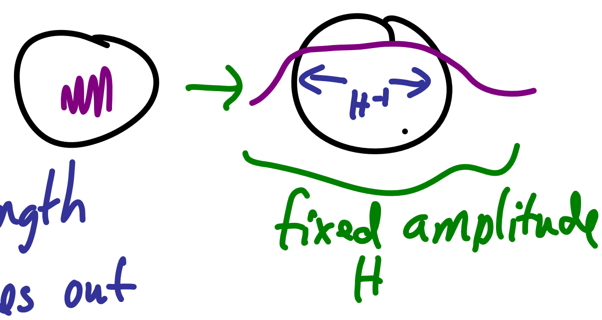
Next : inhomogeneities

& signatures

Inflation $\Rightarrow$ 0-point fluctuations of ϕ and $g_{\mu\nu}$ (the spacetime geometry) evolve into primordial density perturbations which seed structure:
(cf time-dependent oscillator)

$$\delta\phi = \int dk\, e^{i\vec{k}\cdot\vec{x}}\, \delta\phi_{\vec{k}}(t) \qquad \delta\phi_{\vec k}(t) \propto \boxed{\frac{e^{i|\vec{k}|t}}{\sqrt{k}}} \ \text{for}\ \frac{|\vec{k}|}{a} \gg H$$

$$\delta\ddot\phi + 3H\,\delta\dot\phi + \underbrace{\frac{k^2}{a^2(t)}}_{\text{physical wavelength } a(t)/k \text{ stretches out}}\delta\phi = 0$$



Mukhanov

<u>Amplitude</u>: on physical scale L, mode $\delta\phi_L = X/L^{3/2}$ homogeneous in volume $L^3 \rightarrow S \sim \frac{1}{2}\int(\dot{X}^2 + \ldots)dt$
$\rightarrow$ conjugate momentum $P = \dot{X} \sim \Delta X/L$ $\left(\omega \simeq \frac{k}{a} \sim \frac{1}{L}\right)$

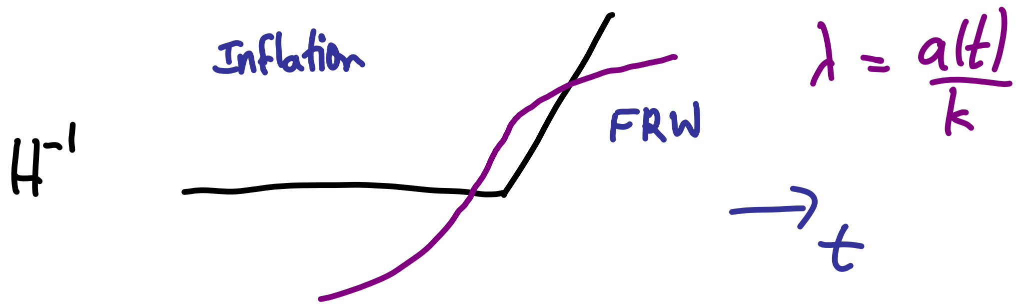
$$\Delta X\, \Delta P \sim 1 \qquad \frac{(\Delta X)^2}{L} \sim 1 \Rightarrow \Delta X_{min} \sim \sqrt{L},\ \delta\phi_L \sim \frac{1}{L}$$

$$\delta\phi_L \sim |\delta\phi_k|\, k^{3/2} \Rightarrow \boxed{|\delta\phi_k| \sim \frac{1}{a\sqrt{k}}}.$$

After stretches to $\frac{k}{a} \sim H$,

$$\boxed{\delta_\phi(k) \sim |\delta\phi_k|\, k^{3/2} \sim \frac{k}{a} \sim H}$$

When inflation ends, these modes reenter the Hubble horizon during decelerating FRW phase.



$$ds^2 = -N^2 dt^2 + h_{ij}\left(dx^i + N^i dt\right)\left(dx^j + N^j dt\right)$$

$$h_{ij} = a^2(t)\left[e^{2\zeta}\delta_{ij} + \gamma_{ij}\right]$$

$a^2(t) \simeq e^{2Ht}$

Scalar perturbation ($\delta\phi = 0$ gauge) remains constant outside horizon

$\partial_i \gamma_{ij} = 0 = \gamma_{ii}$

tensor perturbations

B modes

The fluctuations are in some quantum state

$$\Psi\big[\zeta(\vec{x}), \gamma(\vec{x}); \underbrace{\chi(\vec{x})}_{\substack{\text{additional}\\ \text{sectors of fields}}}, t\big]$$

(Generically a mixed state

$$\rho = \mathrm{Tr}_{\chi} \, |\zeta, \gamma; \chi\rangle\langle \zeta, \gamma; \chi|$$

$$P[\zeta, \gamma] = \int D\chi \, \big|\Psi[\zeta, \gamma; \chi]\big|^2 \,)$$

For free scalar fields, the ground state is Gaussian. Otherwise Ψ is non-Gaussian.

Free scalar f in de Sitter spacetime:

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$
$$= a(\eta)^2(-d\eta^2 + d\vec{x}^2) = \frac{1}{H^2\eta^2}(-d\eta^2 + d\vec{x}^2)$$

$$a(t) = a_0 e^{Ht} \rightarrow a = -\frac{1}{\eta H}$$

$$S = \int d^4x \sqrt{-g}\, g^{\mu\nu} \partial_\mu f \partial_\nu f$$

$$\delta S = 0 \Rightarrow \partial_\mu\left(\sqrt{-g}\, g^{\mu\nu} \partial_\nu f\right) = 0$$

In dS, find simple solution

$$f = \frac{H}{\sqrt{2k^3}}\Big[c_+ (1 - ik\eta) e^{ik\eta} e^{i\vec{k}\cdot\vec{x}}$$
$$+ c_- (1 + ik\eta) e^{-ik\eta} e^{i\vec{k}\cdot\vec{x}}\Big]$$

(= Minkowski modes for $\Delta t \ll \frac{1}{H}$)

The wavefunctional of $f_c(\vec{x})$ at $\eta=\eta_c$ is

$$\Psi[f] = \int Df \Big|_{\substack{f(\vec{x},\eta)\to f_c(\vec{x}) \\ \eta\to\eta_c,}} e^{iS[f]}$$

with some boundary condition at early times

e.g. $f(\vec{x}, \eta\to -\infty) \propto e^{ik\eta}$ for ground state

This is just a set of harmonic oscillators

$$S = \int dt \left(\dot{x}^2 - \omega^2 x^2\right)$$

evolution op

$\mathcal{T}\left(e^{-i\int^t H}\right)$

$$\Psi_0[x_c, t_c] = \int Dx \Big|_{x(t)\to x_c,\ t\to t_c} e^{i\int_{-\infty(1-i\varepsilon)}^{t_c} dt\, \mathcal{L}} \sim \langle x_c | U | \Omega\rangle$$

vacuum

Saddle for our Gaussian path integral:

$$f_{*k} = f_{c\tilde{k}} \, \frac{(1-ik\eta)\,e^{ik\eta}}{(1-ik\eta_c)\,e^{ik\eta_c}}$$

Plug back into action → surface term (since we solved eqns of motion).

$$iS \simeq i\int \frac{d^3\vec{k}}{(2\pi)^3}\,\frac{1}{H^2\eta_c^2}\, f^c_{-\tilde{k}}\, \underbrace{\partial_\eta f_{\tilde{k}}\Big|_{\eta=\eta_c}}_{\frac{f_{\tilde{k}c}\,(-k^2)\,\eta_c}{1-ik\eta_c}}$$

$$iS \sim \int \frac{d^3\vec{k}}{(2\pi)^3} \frac{1}{H^2} \left(\frac{ik^2}{\eta_c} - k^3 + \cdots \right) f^c_{-\vec{k}} f^c_{\vec{k}}$$

$$\Rightarrow |\Psi[f]|^2 \sim e^{-\int \frac{d^3\vec{k}}{(2\pi)^3} \frac{k^3}{H^2} f^c_{-\vec{k}} f^c_{\vec{k}}}$$

$$\| $$

$$P[f]$$

Gaussian, with covariance diagonal in $\vec{k}$ space

One consequence : 2 point correlation ftn

$$\langle \Omega | f_{\vec{k}} \, f_{\vec{k}'} | \Omega \rangle_{\substack{dS \\ \text{free scalar}}} \sim \delta(\vec{k}+\vec{k}') \frac{H^2}{k^3}$$

For non-free scalar, and/or away from ground state, have more general state $\Psi[f]$

$$ds^2 = -N^2 dt^2 + h_{ij}\,(dx^i + N^i dt)(dx^j + N^j dt)$$

$$h_{ij} = a^2(t)\left[e^{2\zeta}\delta_{ij} + \gamma_{ij}\right]$$

In single-field SR, $f \simeq \delta\phi \simeq \frac{\delta\phi}{\delta t}\,\delta t$ $\sim \zeta / H$

$$\langle\Omega|\,\zeta_{\underset{\sim}{k}}\,\zeta_{\underset{\sim}{k}'}\,|\Omega\rangle \simeq \frac{H^4}{\dot\phi^2}\,\frac{1}{k^3}\,\delta(\underset{\sim}{k}+\underset{\sim}{k}')$$

$$\langle\Omega|\,\gamma_{\underset{\sim}{k}}\,\gamma_{\underset{\sim}{k}'}\,|\Omega\rangle \simeq \frac{H^2}{M_p^2}\,\frac{1}{k^3}\,\delta(\underset{\sim}{k}+\underset{\sim}{k}')$$

Again, <u>general</u> observables characterized by $P[\zeta(\tilde{x}), \gamma(\tilde{x}); t_c] = \int D\chi_\perp\,|\Psi|^2$

with $\langle\zeta^N\rangle = \int D\zeta\,\zeta^N P[\zeta]$ etc.

Thus far, all data consistent with

$$\langle \zeta_k \zeta_{k'} \rangle \sim P(k)\, \delta_{k+k'}$$

$$P(k) \sim \frac{H_{fr}^4}{\dot\phi^2} \frac{1}{k^3} \sim \frac{10^{-10}}{k^{3+(1-n_s)}} \qquad n_s < 1 \ (5\sigma)$$

$\downarrow$ power as $\uparrow k \leftrightarrow \uparrow t_{\text{freeze-out}}, \downarrow H, \uparrow \dot\phi$

$$\frac{k}{a(t_{fr})} = H(t_{fr})$$

$$n_s - 1 = \frac{d}{d\log k} \log\left(\frac{H_{fr}^4}{\dot\phi_{fr}^2}\right) < 0$$

Also, tensor modes of the graviton are sensitive to scale H^*:

$$P_\gamma \sim \frac{H^2}{M_p^2} = r\, P_s \qquad r < .07 \quad (2\sigma)$$

* and field range $\Delta\Phi$, assuming no secondary sources.

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

$$h_{ij} = a^2(t)\left[\underbrace{e^{2\zeta}}\delta_{ij} + \underbrace{\gamma_{ij}}\right]$$

$a^2(t)$ $\simeq$ e^{2Ht}

scalar perturbation ($\delta\phi = 0$ gauge) remains constant outside horizon

$\partial_i \gamma_{ij} = 0 = \gamma_{ii}$ tensor perturbations

B modes

Basic Observables

tilt n_s : $P_\zeta = \dfrac{\text{const}}{k^{3+(1-n_s)}}$

tensor/scalar ratio r : $r = \dfrac{P_\gamma}{P_\zeta}$

Non-Gaussianity : $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{-\vec{k}_1-\vec{k}_2} \rangle$

$\hookrightarrow \ldots$

Lyth "~~Bound~~": $\boxed{\sqrt{\frac{r}{r_{detectable}}} \sim \frac{\Delta\phi}{M_p}}$

$$N_e = \int \frac{da}{a} = \int \frac{da}{dt}\frac{dt}{a} = \int H dt$$

$$= \int \frac{H M_p}{\dot{\phi}} \frac{d\phi}{M_p} = \sqrt{8}\, r^{-\frac{1}{2}} \frac{\Delta\phi}{M_p}$$

using

$$r = \frac{\gamma\gamma}{\zeta\zeta} = \frac{\text{tensor}}{\text{Scalar}} \sim \frac{\frac{H^2}{M_p^2}}{\frac{H^4}{\dot{\phi}^2}}$$

and assuming no strong variation of $HM_p/\dot{\phi}$, and no exotic sources

Cosmological data (primorial power spectrum & non-Gaussianity, polarization, ...) is remarkably sensitive to dynamics (field/string content, interactions, inflationary mechanism) happening 14 billion years ago.

*Even null results very informative given well-defined theories. Large space of possibilities; <u>some</u> constrained by extensive analysis (CMB, LSS...)

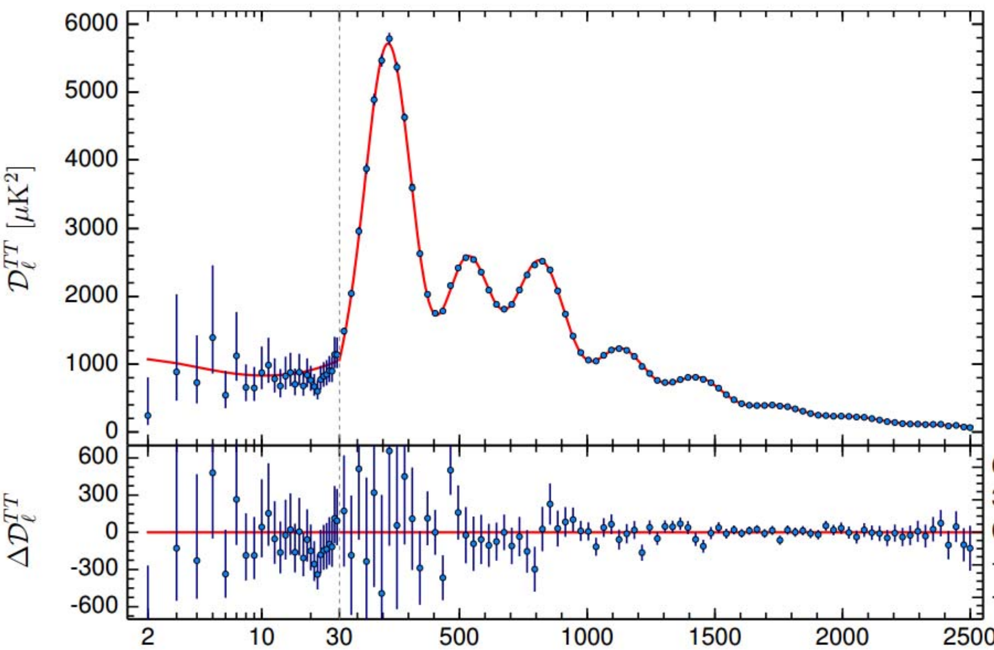
*Some of these were actually derived via string theory (ST) -- motivated by the UV sensitivity of inflation) -- then incorporated into low energy effective quantum field theory (EFT).

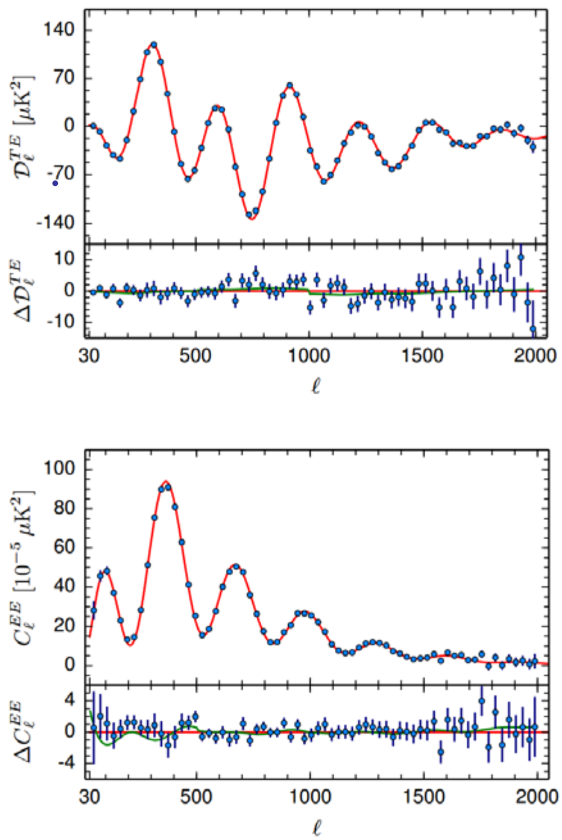
New/ongoing development: physics & analysis of strongly non-Gaussian features.

Big Picture

Power spectrum function → 2 parameters

Planck Collaboration: Cosmological parameters



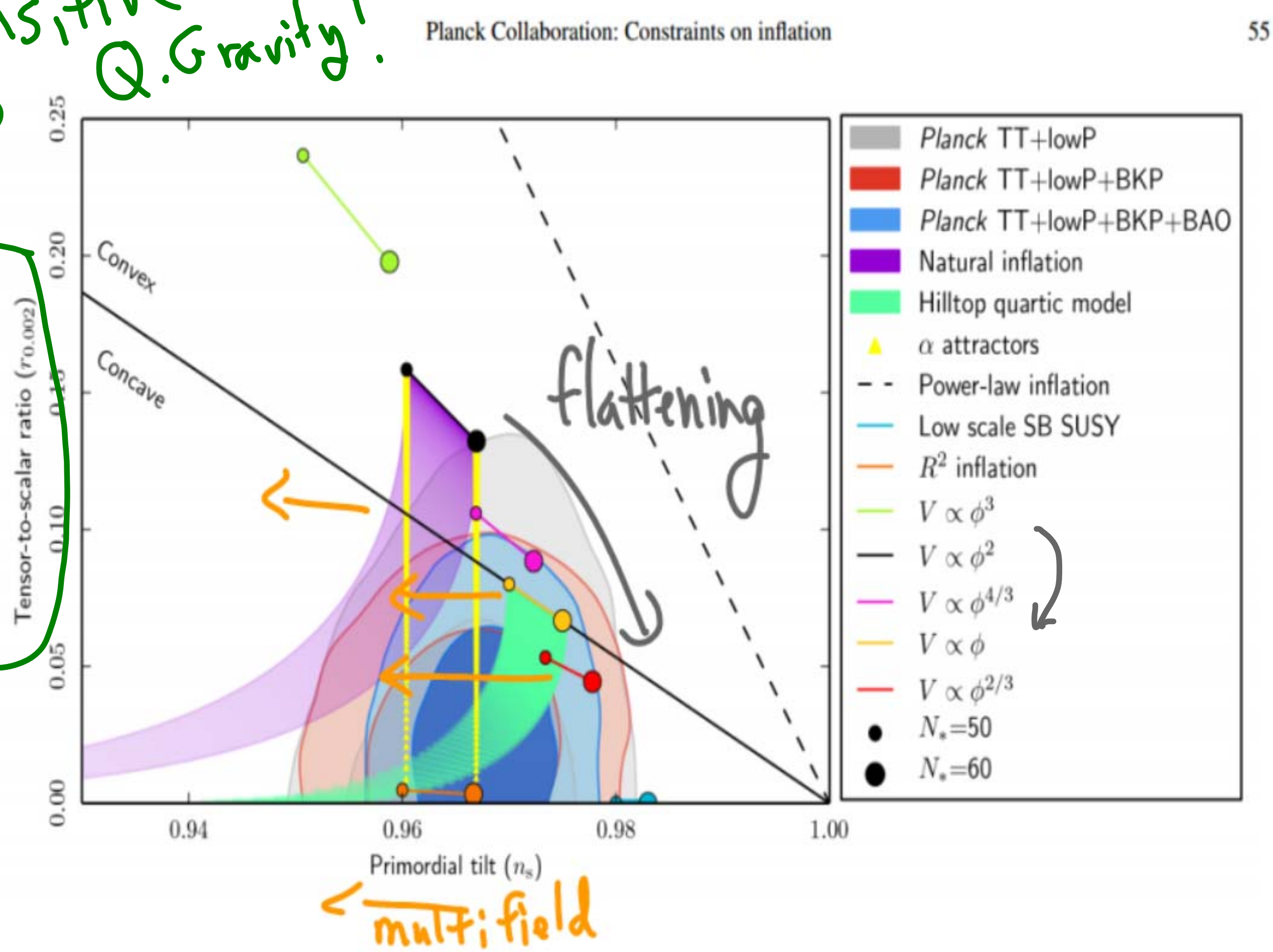


$\ell \geq 30$ we show the maximum likelihood frequency averaged
kelihood with foreground and other nuisance parameters deter-
the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum
puted over 94% of the sky. The best-fit base ΛCDM theoretical
pper panel. Residuals with respect to this model are shown in

Small perturbations from ΛCDM allowed (tensors, features/oscillations, non-Gaussianity), but wildly dramatic effects highly constrained

Tilt and tensor/scalar ratio

sensitive to Q.Gravity!



<– multifield

Additional massive fields occur in many theories. Coupling of massive fields to inflaton can lead to energetically favorable flattening of potential. This is a simple way of understanding the flattened potentials of axion monodromy (large-field inflation in ST), and why this and other ST inflationary mechanisms still viable (so far...). At the same time, much ongoing work on the structure of inflationary mechanisms in string theory, controlling against instabilities, etc.

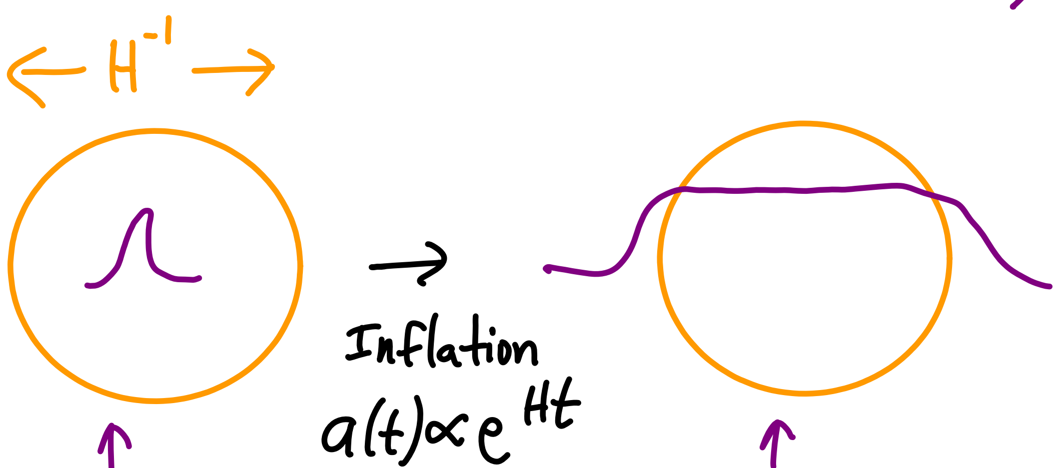
Lecture II

1. Review of basics from last time (less technical).

2. Some examples of UV complete physics in inflation and signatures.

Inflation plus quantum uncertainty principle:

intrinsic Quantum fluctuations in inflaton ϕ

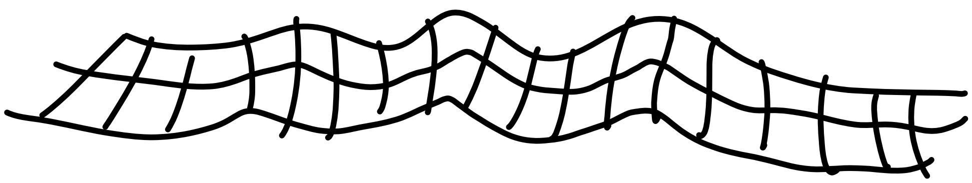


fluctuation $\delta\phi$ wavelength λ

$\delta\phi$ freeze out wavelength λe^{Ht}

Amplitude fixed by uncertainty principle to be about $\delta\phi \simeq H \simeq$ constant

* Similar results hold for fluctuations in the spacetime geometry itself:

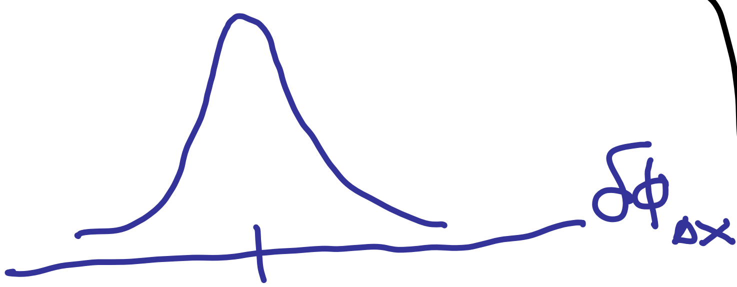


$$ds^2 = g_{tt}(t,x,\ldots)\,dt^2 + g_{tx}(t,x,\ldots)\,dt\,dx + \cdots$$

The metric coefficients are dynamical, so just like ϕ they must fluctuate according to the Heisenberg uncertainty principle.

Fluctuations of ϕ and of the geometry

$$ds^2 = -dt^2 + e^{2\zeta} a(t)^2 \left(dx^2 + dy^2 + dz^2 + \gamma_{xx}\, dx^2 + \gamma_{xy}\, dx\, dy + \dots\right)$$



$$\langle \delta\phi^2 \rangle \sim H^2$$

$$\zeta \sim H\,\delta t \sim H \frac{\delta t}{\delta \phi}\,\delta\phi \sim \frac{H}{\dot\phi}\,\delta\phi \sim \frac{H^2}{\dot\phi}$$

$$\Rightarrow \langle \zeta^2 \rangle \sim \frac{H^4}{\dot\phi^2}$$

$$\langle \gamma^2 \rangle \sim \frac{H^2}{M_p^2}$$

Primordial gravitational waves!

$$r = \frac{\langle \gamma^2 \rangle}{\langle \zeta^2 \rangle} \sim \frac{\dot\phi^2}{M_p^2 H^2}$$

$$ds^2 = -N^2 dt^2 + h_{ij}\left(dx^i + N^i dt\right)\left(dx^j + N^j dt\right)$$

$$h_{ij} = a^2(t)\left[\underbrace{e^{2\zeta}}_{\substack{\text{scalar perturbation}\\ (\delta\phi = 0 \text{ gauge})\\ \text{remains constant outside horizon}}}\delta_{ij} + \underbrace{\gamma_{ij}}_{\text{tensor perturbations}}\right]$$

$a^2(t) \simeq e^{2Ht}$

$\partial_i \gamma_{ij} = 0 = \gamma_{ii}$

tensor perturbations

B modes

Basic Observables

$$P[\zeta, \gamma] = \int D\chi \left|\Psi[\zeta, \gamma; \chi]\right|^2$$

tilt n_s : $P_\zeta = \dfrac{\text{const}}{k^{3+(1-n_s)}}$

tensor/scalar ratio r : $r = \dfrac{P_\gamma}{P_\zeta}$

Non-Gaussianity : $\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{-\vec{k}_1-\vec{k}_2} \rangle \hookrightarrow \ldots$

Lyth "~~Bound~~" : $\boxed{\sqrt{\frac{r}{r_{\text{detectable}}}} \sim \frac{\Delta\phi}{M_p}}$

$$N_e = \int \frac{da}{a} = \int \frac{da}{dt}\frac{dt}{a} = \int H\,dt$$

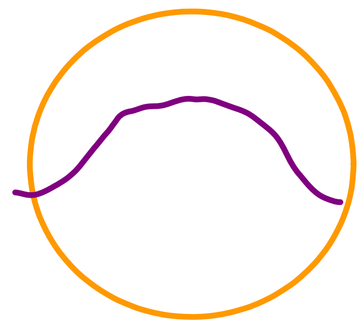
$$= \int \frac{HM_p}{\dot{\phi}}\frac{d\phi}{M_p} = \sqrt{8}\, r^{-\frac{1}{2}} \frac{\Delta\phi}{M_p}$$

using

$$r = \frac{\gamma\gamma}{\zeta\zeta} = \frac{\text{tensor}}{\text{Scalar}} \sim \frac{\frac{H^2}{M_p^2}}{\frac{H^4}{\dot{\phi}^2}}$$

and assuming no strong variation of $HM_p/\dot{\phi}$, and no exotic sources

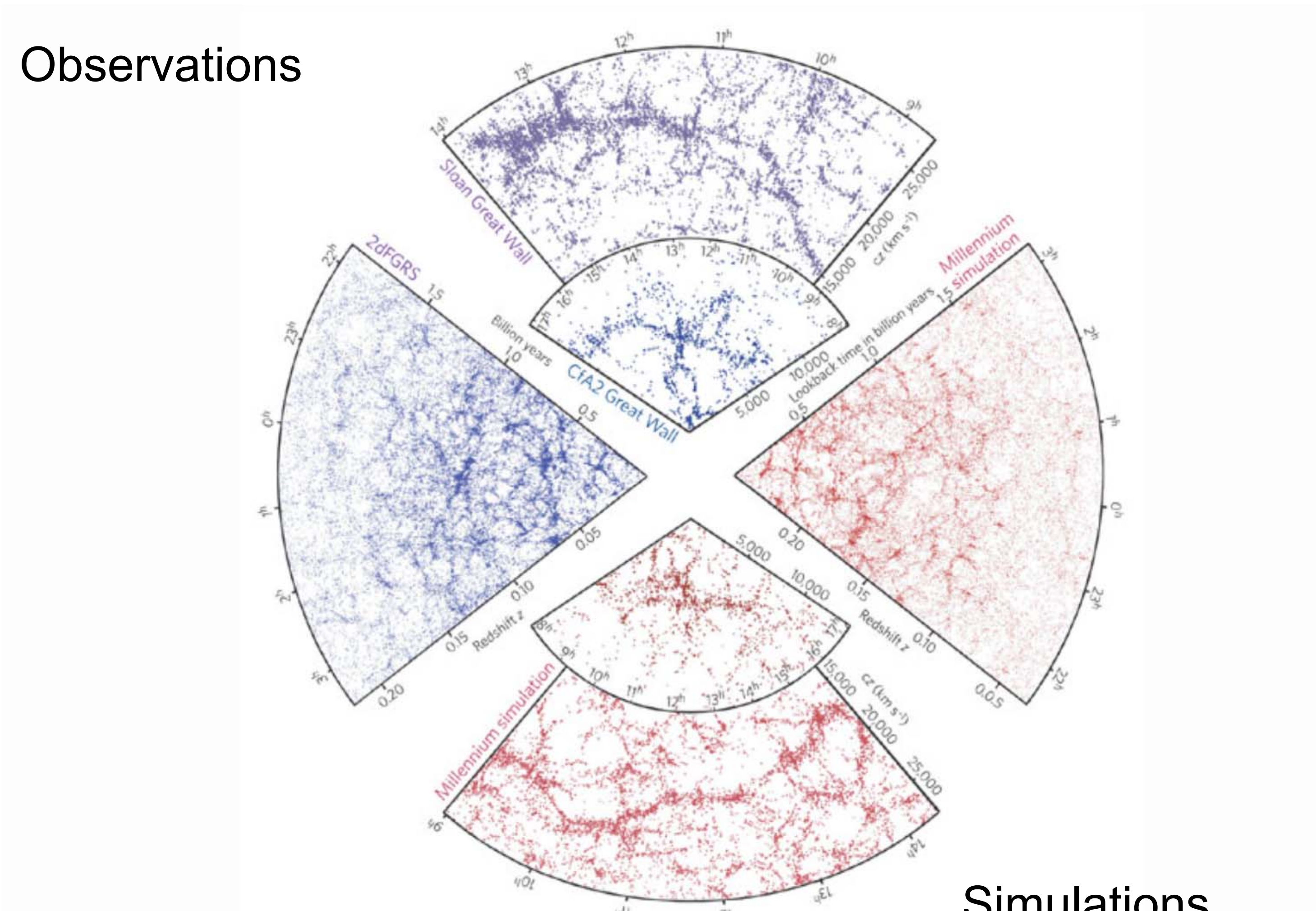
When inflation ends, the fluctuations $\delta\phi$ re-enter the "Hubble horizon"



and seed structure.

Extensive calculations show how this initial seed evolves to the distribution of structure (galaxy clusters, galaxies, ...) which we see.

(other lectures at the school)



Springel, Frenk, White

Accelerated expansion of space

+ quantum fluctuations + gravity & other forces

→ Structure in the universe

Bock et al

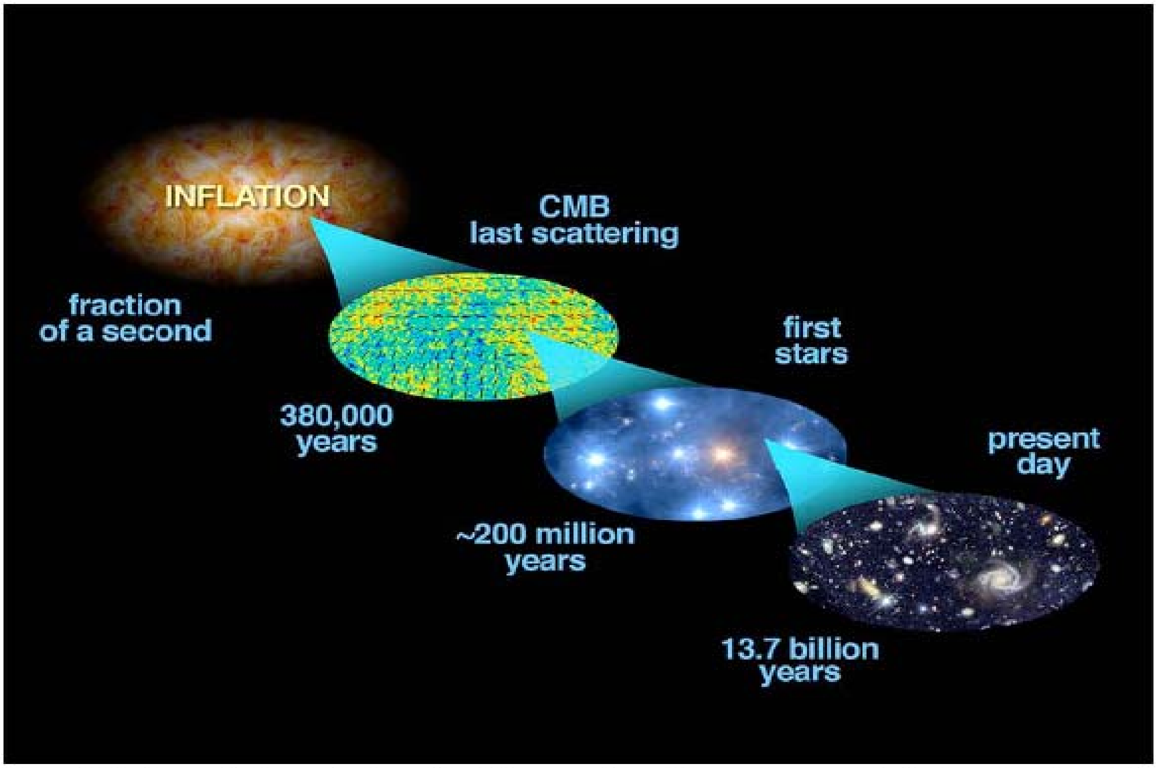
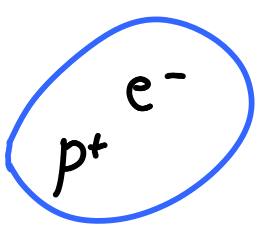


Figure 1.1: Stages in the evolution of the Universe. According to the cosmological standard model, inflation stretches microscopic quantum fluctuations into astronomical density fluctuations that leave an imprint on the cosmic microwave background (CMB), and then grow into the present day galaxy distribution. This report presents a roadmap for measuring CMB polarization (illustrated by black rods), which encodes a signature of inflation.

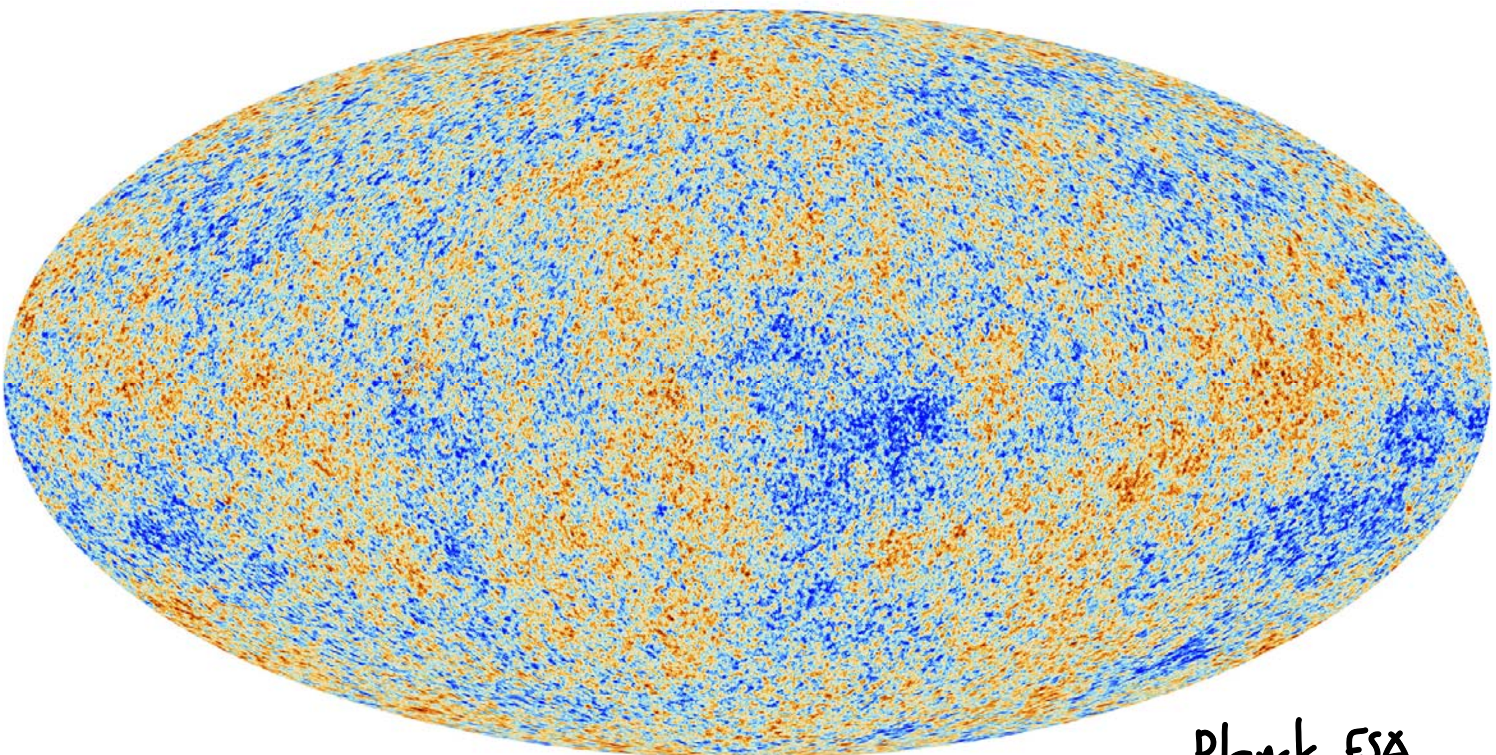
The CMB emerges from the earliest time that light can propagate freely to us.



protons & electrons bound into hydrogen

The Big Picture

Cosmic Microwave Background (CMB)

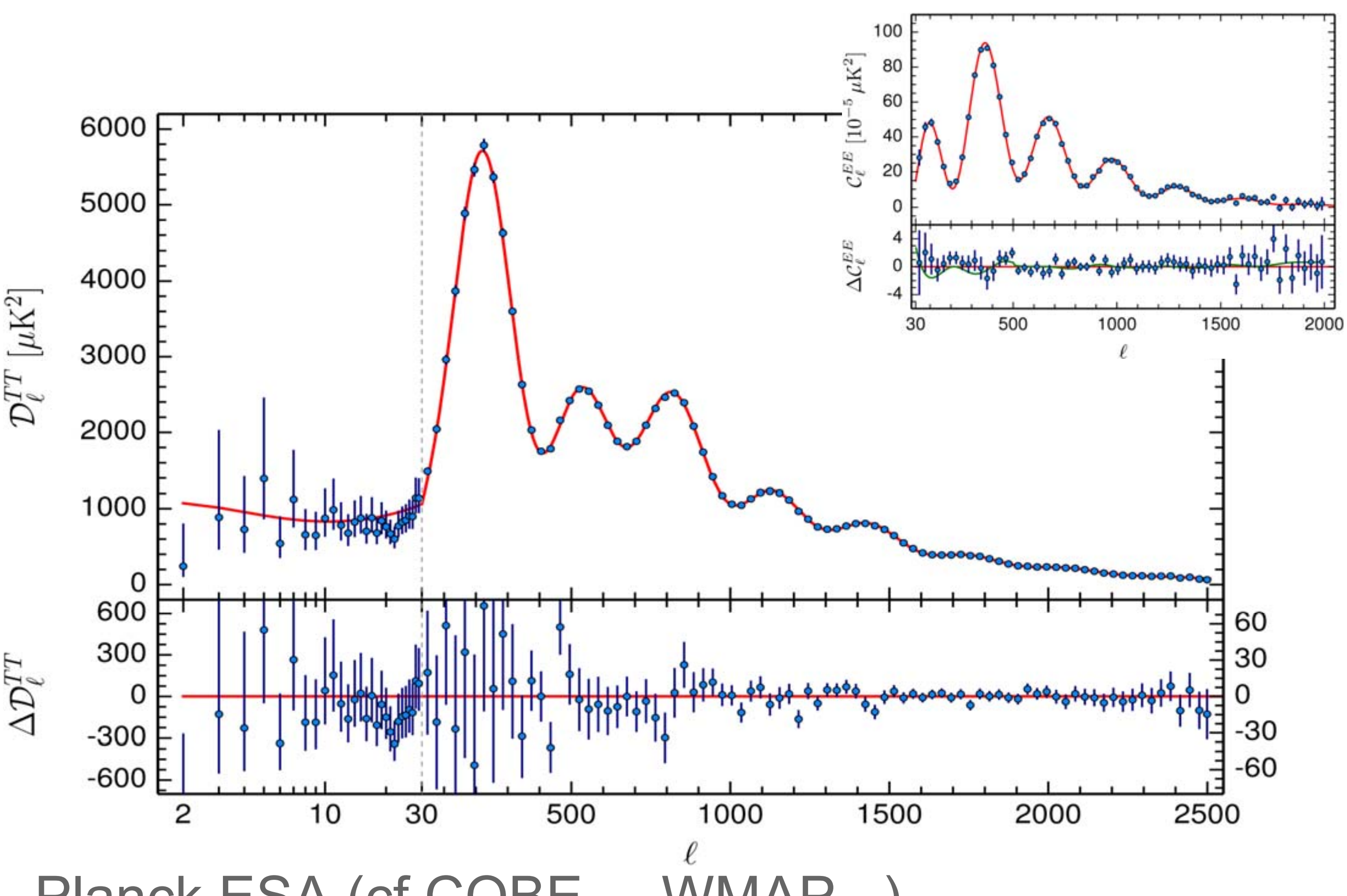


Planck ESA

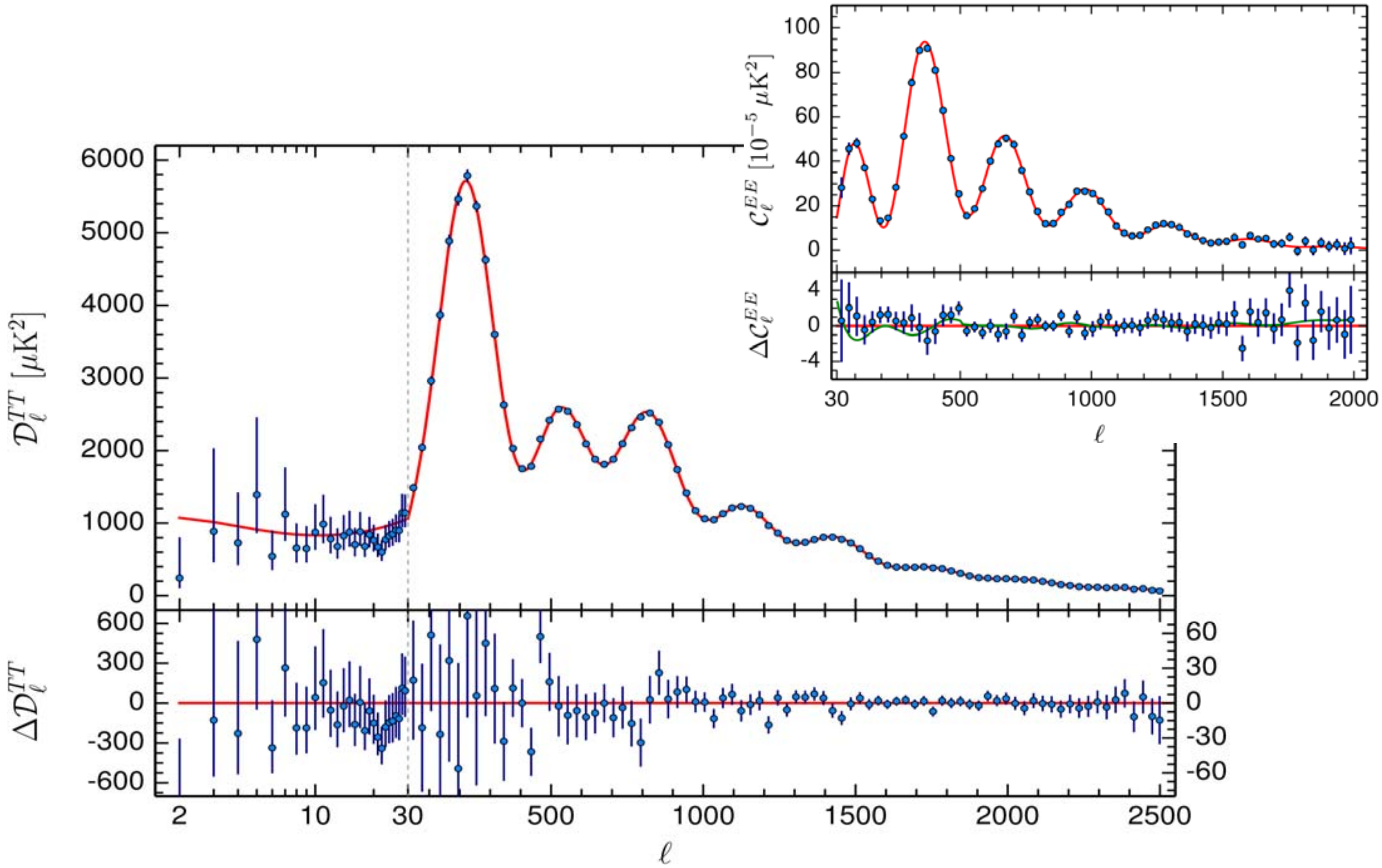
The temperature T of the light is approximately the same in all directions

$$\frac{\Delta T}{T} \cong 10^{-5} \ll 1$$

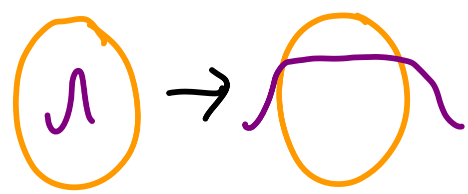
Measurements of the frequency dependence (black body) and tiny spatial fluctuations of the light, including its polarization, have helped precisely constrain the model of the expanding universe, requiring so far only 6 parameters



Planck ESA (cf COBE,...,WMAP...)



Superhorizon perturbations:



*Fluctuations correlated on scales longer than the size of the horizon at the time when atoms formed.

**The polarized light created at this time, no further inside-horizon sources that could mimic its structure.

(Spergel/Zaldarriaga, cf Turok)

Alternative(s?):

I. Cosmic strings: well-defined theory, ruled out as leading seeds of structure.

Pen, Seljak, Turok '97.

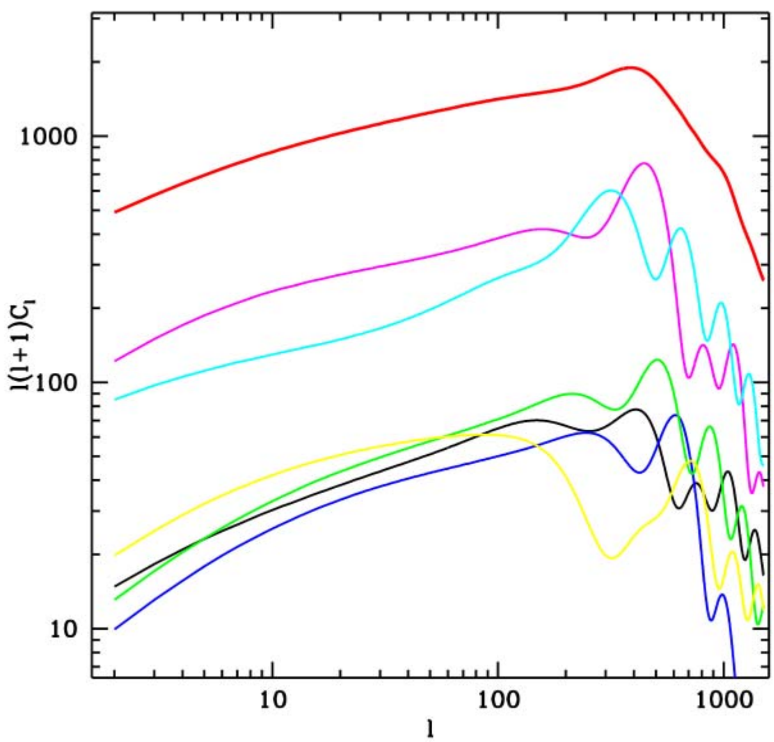
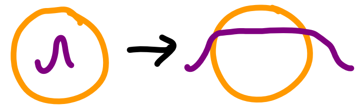


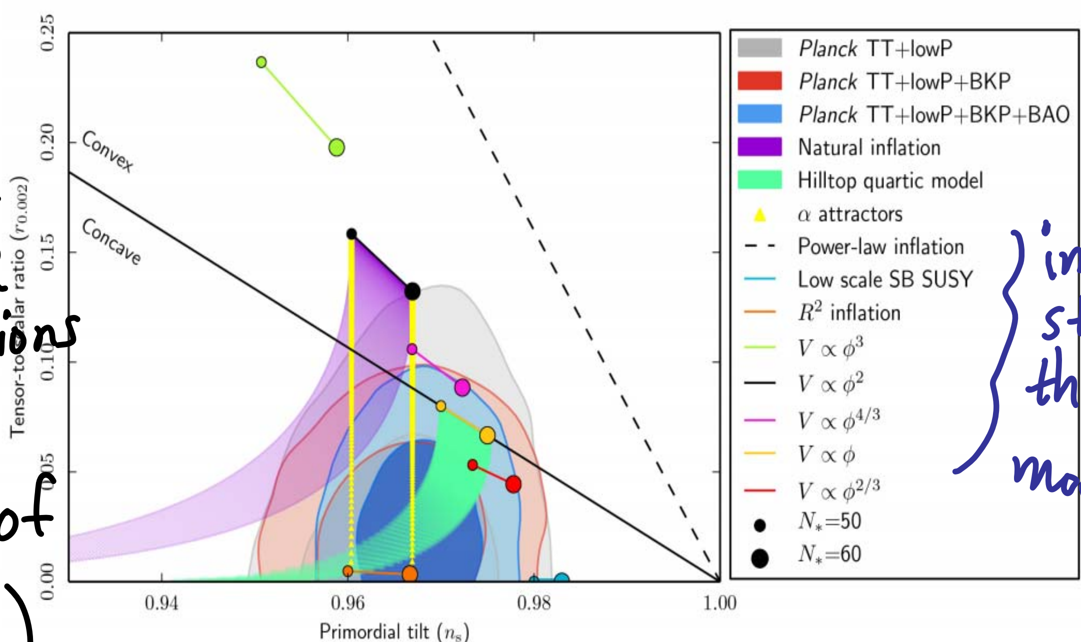
FIG. 1. Angular power spectrum of anisotropies generated by the scalar component of the source stress energy for global strings. The upper curve shows the total spectrum, the lower ones contributions from individual eigenvectors. This Figure illustrates decoherence: each eigenvector individually produces an oscillatory C_l spectrum, but these oscillations all cancel in the sum.

II. Bounce? Clever idea (super-horizon for different reason), but much more difficult to control. Existing examples either don't bounce, or do using exotic energy sources incompatible with black hole thermodynamics (see below). Regardless, spacetime singularity resolution is a great problem.

So far, observations have confirmed the basic predictions of inflation:



The fluctuations are approximately independent of wavelength



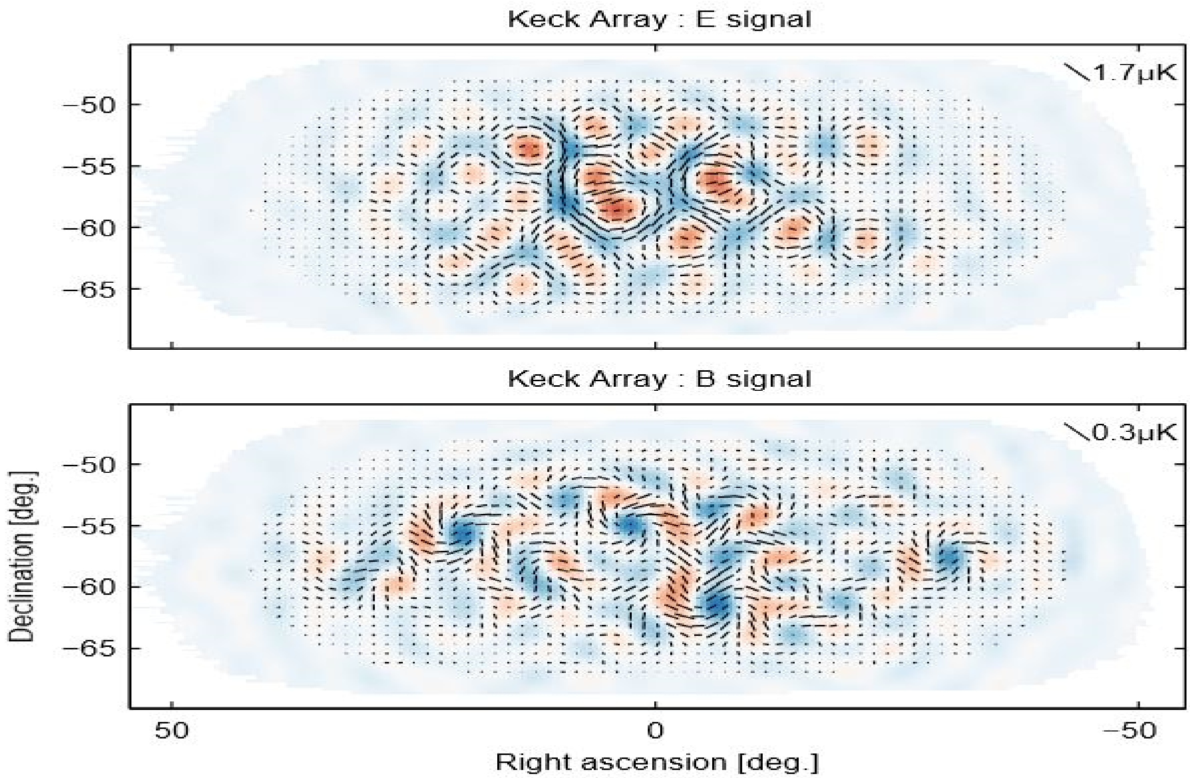
Gravity waves (fluctuations of the shape of space)

includes string theory models...

Fig. 54. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

slight dependence on wavelength because of slowly decreasing energy $V(\phi)$

Primordial gravitational wave search:

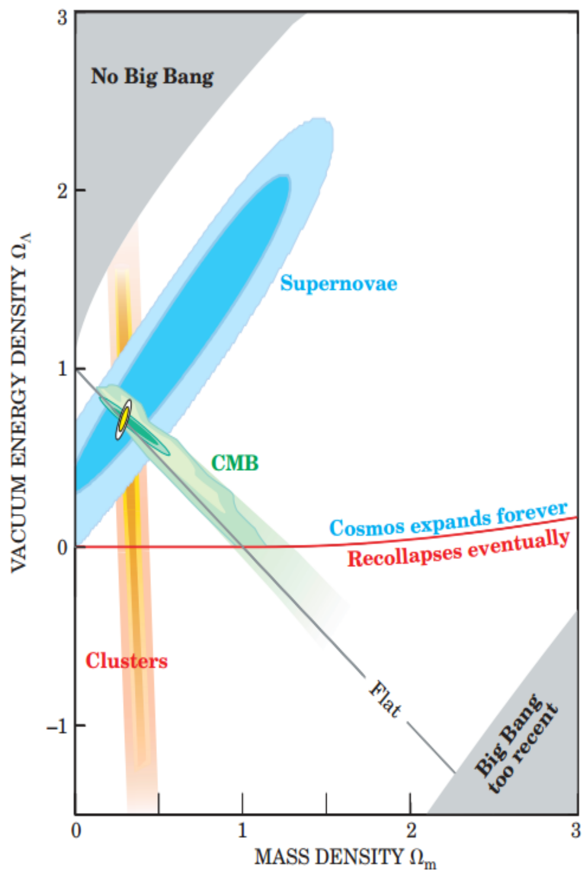


BICEP/Keck(+Planck), SPIDER, SPT, ABS, PolarBear, Simons Observatory, CMBS4, LiteBird, CLASS,...

The next round will test field range $\Delta\phi$ between ~10 Mp and ~ 1 Mp. This is extraordinary reach.

(Instant gratification for a string theorist!)

Figure 5. In the cosmological parameter space of the normalized mass and vacuum energy densities Ω_m and Ω_Λ, three independent sets of observations—high-redshift supernovae, galaxy cluster inventories, and the cosmic microwave background—converge nicely near $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The small yellow contour in this region indicates how well we expect the proposed SNAP satellite experiment to further narrow down the parameters. The inflationary expectation of a flat cosmos ($\Omega_m + \Omega_\Lambda = 1$) is indicated by the black diagonal. The red curve separates an eternally expanding cosmos from one that ends in a "Big Crunch."



stant, with the goal of solving the coincidence problems. (See the Reference Frame article by Michael Turner on page 10 of this issue.)

The experimental physicist's life, however, is dominated by more prosaic questions: "Where could my measurement be wrong, and how can I tell?" Crucial questions of replicability were answered by the striking agreement between our results and those of the competing team, but there remain the all-important questions of systematic uncertainties. Most of the two groups' efforts have been devoted to hunting down these systematics.[15,16] Could the faintness of the supernovae be due to intervening dust? The color measurements that would show color-dependent dimming for most types of dust indicate that dust is not a major factor.[12,13] Might the type Ia supernovae have been intrinsically fainter in the distant past? Spectral compar-

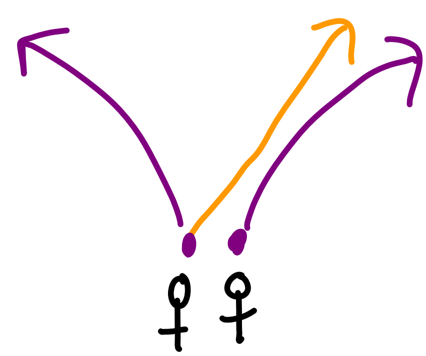
Small positive cosmological constant (at least approximately) discovered in '98. Just one number, but makes enormous difference (change in causal structure of spacetime). B modes (r) also a single number of great importance.

This is just the beginning.

The large amount of data collected also enables us to distinguish qualitatively distinct inflation mechanisms. Also test for more subtle effects of particles and fields operating during inflation (nearly 14 billion years ago). These are subleading to the essential features of inflation already tested.

Inflation and its observables -- especially those testable with the gravitational wave search -- are sensitive to quantum gravity.

We lack a complete theory of cosmology as a whole, related to puzzling features of horizons as well as strongly-curved \`singularities'.



Next:

I. Some recent developments on non-Gaussianity

II. String theory & inflation, and primordial gravitational waves.

Non-Gaussianity: full probability distribution function

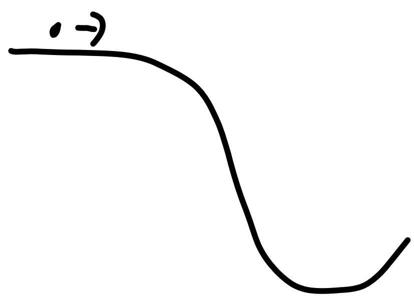
$$P[\zeta(\vec{x})] = |\Psi[\zeta(\vec{x})]|^2$$

This generates N-point correlation functions.
Previous CMB searches address certain shapes at low N (=3, sometimes 4).
Recently, we found that simple non-adiabatic dynamics involving heavy fields can generate signal/noise that grows with N, requiring analysis of fuller probability distribution. Leads to a new type of NG search, sensitive to fields 100 times heavier than Hubble during inflation. Moreover, in greater generality large N point functions are combinatorially enhanced...may lead to more optimal constraints than 3 point ftns.

Non-Gaussianity Roughly Speaking,

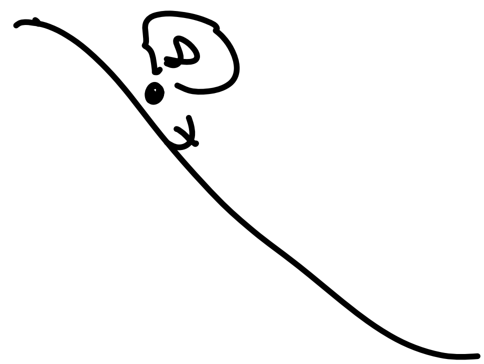
2 classes of Inflation Mechanisms:

Slowly diluting potential energy



Flat potential

NG only from substructure, e.g. oscillations, in $V(\phi)$



Steep potential, but interactions slow the field. $\Rightarrow$ NG.

↳ e.g. brane motion limited by Speed of light (DBI)

+ many new effects for multiple fields

The interactions which enforce the speed limit $\Rightarrow$ Correlations in the CMB (Alishahiha et al '04)

Falsifiable

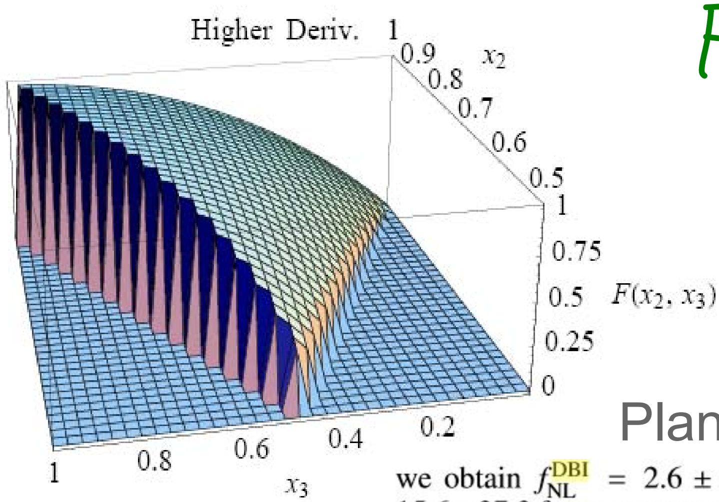


Figure 3: Plot of the function $F(1, x_2, x_3)\, x_2^2 x_3^2$ for
interactions (12) and in the DBI model of inflatior
1 for equilateral configurations $x_2 = x_3 = 1$ and set

Planck

we obtain $f_{\rm NL}^{\rm DBI} = 2.6 \pm 61.6$ from temperature data ($f_{\rm NL}^{\rm DBI} = 15.6 \pm 37.3$ from temperature and polarization) at 68 % CL (with ISW-lensing and point sources subtracted, see Table 23) implies

$$c_s^{\rm DBI} \geq 0.069 \qquad 95\,\%\ \text{CL}\ (T\text{-only})\,, \tag{84}$$

and

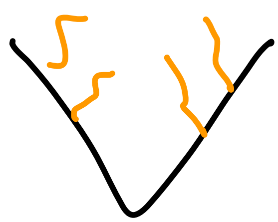
$$c_s^{\rm DBI} \geq 0.087 \qquad 95\,\%\ \text{CL}\ (T{+}E)\,. \tag{85}$$

$$c_s = \sqrt{1 - v_{br}^2} \geq .087$$

Strongly Non-Gaussian Perturbations

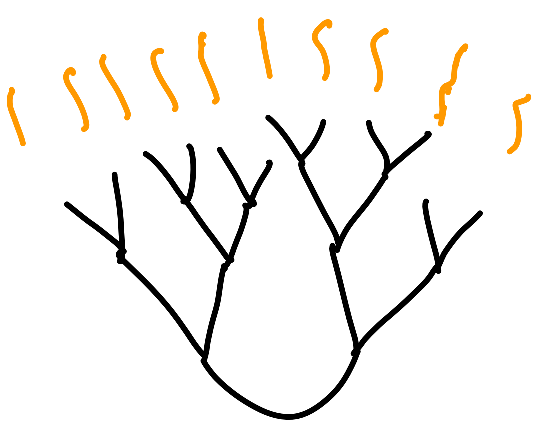
one of the new signatures: Flauger, Mirbabayi, Senatore '16,
work in progress w/ Munchmeyer/Planck, Smith,...

*New forms of NG can constrain massive fields (or strings) interacting with the inflaton. => strongly non-Gaussian statistics (high N point functions or position space analysis or δT histogram better than bispectrum search).



$\sim C^N \qquad C>1$

*Large-N point functions in general



$\sim N!\,\lambda^N$

$\lambda<1$

plus quantum corrections

Theoretical big picture: a probability distribution computed by a QFT path integral

$$P[\delta\phi^0(\mathbf{x})] = \int D\chi^0 |\Psi[\delta\phi^0(\mathbf{x}), \chi^0(\mathbf{x})]|^2$$

where

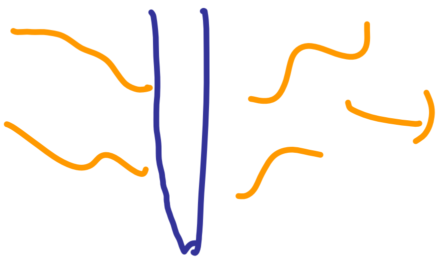
$$\Psi[\delta\phi^0(\mathrm{x}), \chi^0(\mathrm{x})] = \int D\delta\phi(\mathrm{x}, t)|_{\delta\phi(t=t_C)=\delta\phi^0(\mathrm{x})} D\chi(\mathrm{x}, t)|_{\chi(t=t_C)=\chi^0(\mathrm{x})} e^{iS[\delta\phi(\mathrm{x},t),\chi(\mathrm{x},t)]}$$

Ideally, would evaluate this on the map.
Instead, reduce it:
--bispectrum, trispectrum,...
--(N-1)-spectrum
--Histogram of temperature fluctuations
--position space features

Inflaton ϕ coupled to

heavy χ $\longrightarrow$ $m_\chi(\phi(t)+\delta\phi(t,x))$

time-dependent



$\delta\phi$ radiation

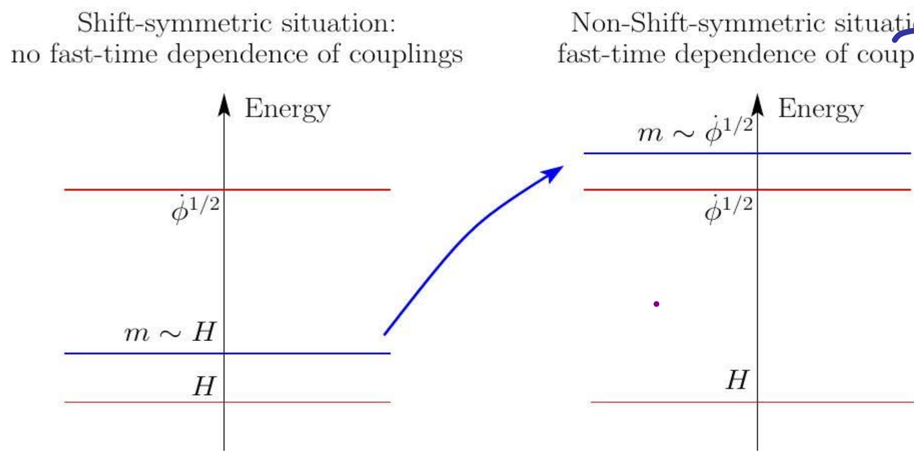
χ production

$$n \sim \left(\frac{\dot\phi}{H^2}\right)^{3/2} e^{-\frac{\pi\mu^2}{2\dot\phi}} \sim \frac{1}{\sqrt{N_{pixel}}}$$

sensitivity to heavy χ fields

Novel shape $\langle \delta\phi_{k_1} \cdots \delta\phi_{k_N} \rangle$

and $(S/N)_{N+1} / (S/N)_N > 1$ possible for a range of N!



O(.1-1) couplings to inflaton (preserving inflation overall)

Figure 1: Pictorial representation of our findings: in an inflationary theory with an approximate continuous shift symmetry for the inflaton, only particles that are not much heavier than the Hubble scale H are relevant for the dynamics of the fluctuations. However, as we will see, if the continuous shift symmetry is broken, e.g. to a discrete shift symmetry, heavier particles can become relevant as depicted on the right. In the scenarios studied in this work, the new scale is set by $\dot\phi$. The basic estimate $\exp(-\pi m^2/\dot\phi) \sim 1/\sqrt{N_{\rm modes}}$ suggests observational sensitivity to these massive particles, which we confirm in a detailed analysis.

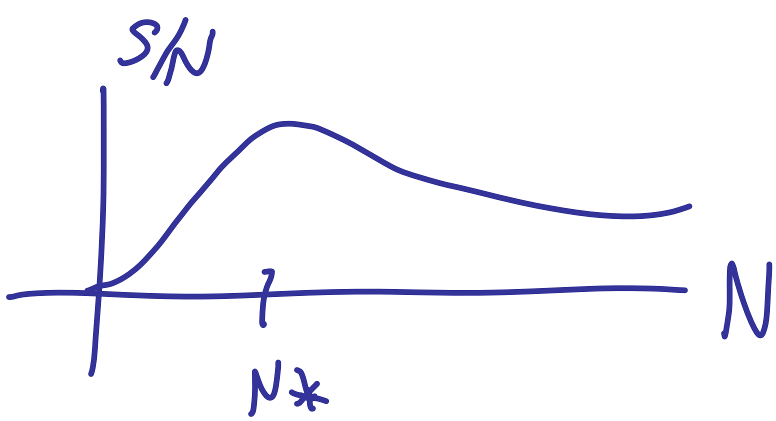
Precision of data means we can test for very heavy fields ($m_\chi \gtrsim \dot\phi^{\frac{1}{2}}$)!

Results will be either concrete bounds on masses/couplings of particles propagating ~14 billion years ago, or discovery of parameter consistent with their existence. (Standard scientific methodology.)

Flauger, Mirbabayi, Senatore, ES, Munchmeyer/ Planck, Smith, Wenren, cf Peiris, Easther, Komatsu/Spergel/Wandelt,...

$$(S/N)^2 = \int_{\{k\}} \frac{|\langle \zeta_1 \ldots \zeta_N \rangle|^2}{N! \prod P(k_i)}$$

$$\sim \frac{A\left(g\sqrt{\frac{\omega}{H}}\right)^{2N}}{N!} + \left(\ldots\right)$$

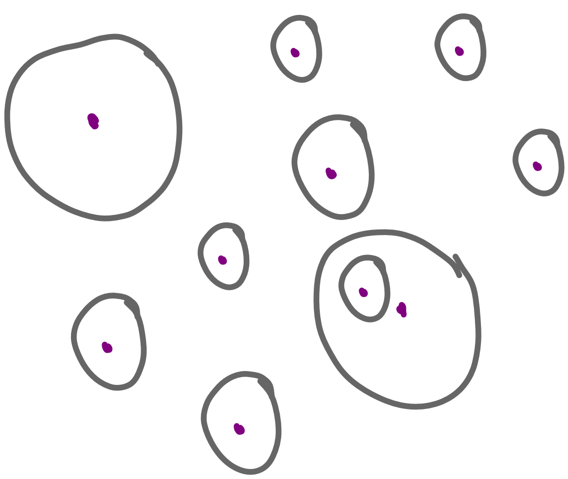


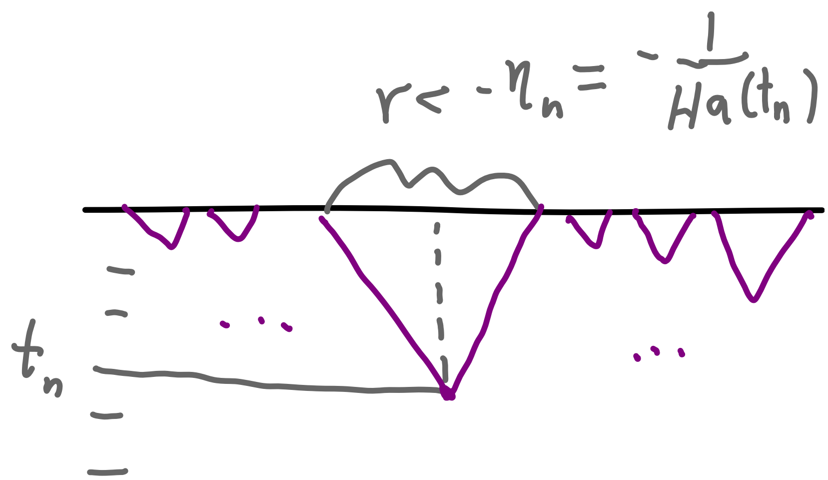
Can formulate optimal estimator resumming over N for factorized component of the shape. (Its statistics determined by an interesting QFT path integral).

Machine learning for other components??

Position space features

$$\zeta(0,\boldsymbol{r}) = -\frac{H}{8\pi\epsilon M_{\rm pl}^2}\left[m(t_r - t_n) - m(t_n)\right]$$

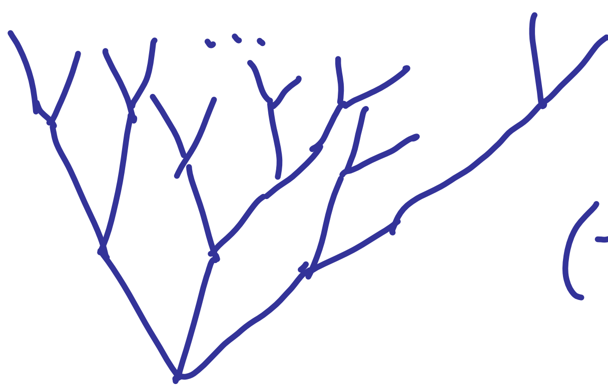




Similar picture+search for strings

Combinatorics and large N:

$$\langle \zeta_1 \cdots \zeta_N \rangle \propto N!$$



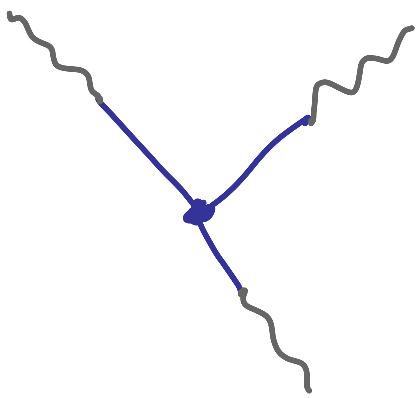
Tree level
(even single-field)

General feature of QFT, raises question of optimizing NG searches even in the classic cases.

Some literature in particle physics on whether this N! amplifies (Higgs-->many SM particles) in some useful way. (Voloshin, Rubakov, D. T. Son, Argyres et al, Khoze,...)

$$\lambda_3 \chi^3 + \rho \chi \dot{\pi}$$

$$\langle \zeta_1 \cdots \zeta_N \rangle = N!\, \bar{\lambda}_3^N \bar{\rho}^N \times \left(1 + c_1 (\bar{\lambda}_\chi N)^2 + \cdots\right)$$



Bispectrum constraint

$$\rho^3 \bar{\lambda}_3 < \frac{1}{\sqrt{N_{pix}}}$$

Is this optimal?

Consider the minimal theory that generates `local f_NL': two fields ϕ and χ. The χ sector has interactions (at least a cubic coupling λ) and there is a second parameter κ describing the mixing between sectors (e.g. at end).

$$e^{-iH_{mix}\Delta t} = e^{-i\int d\vec{x}\, \Pi_{\delta\phi} f(\chi)\lambda_{mix}\Delta t}$$

$$P(\delta\phi) = \int D\chi\ |\psi_\perp(\chi, t_0)|^2\ |\Psi_G(\delta\phi + \underbrace{\lambda_{mix}\Delta t}_{=\kappa} f(\chi))|^2$$

ultralocal evolution outside horizon $\longrightarrow$

$\chi_0 = \chi(t_0)$ determined classically, e.g. slow roll in χ

$$P(\delta\phi) = \mathcal{N}\int D\chi_c P_G(\delta\phi - \underline{\kappa\chi_0(\chi_c)})P_\perp(\chi_c)$$

A Fisher matrix analysis suggests that better constraints arise from the full probability distribution than from just the 3 point function (local f_{NL}). Still analyzing precisely where this is coming from here, as well as other scenarios with tree-level N! enhancements.

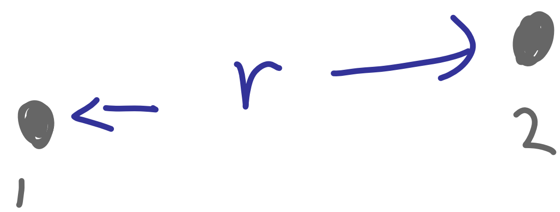
In general, the theory and analysis of strongly NG effects is an interesting current/future direction.

Next, we will discuss a little bit of string theory including the connection to another important observable (B modes).

Recall: `Dangerous irrelevance'

Recall idea of a series of correction terms

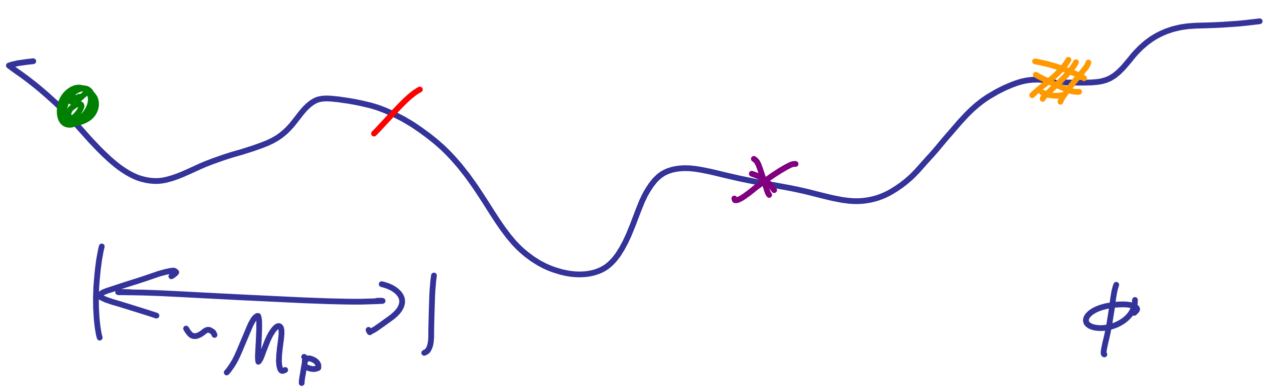
e.g.



$G_N \sim \frac{1}{M_p^2}$

$$F = -\frac{G_N m_1 m_2}{r^2}\Big(1 + \underbrace{\cdots}_{c_1 \frac{G_N}{r^2} + c_2\left(\frac{G_N}{r^2}\right)^2 + \cdots}\Big)$$

For V(ϕ) this is



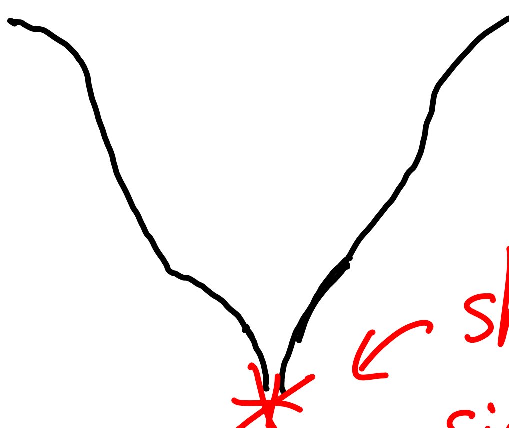
$$V(\phi) = V_0(\phi)\left(1 + c_1 \frac{(\phi - \phi_0)}{M_p} + \cdots\right)$$

Quantum Gravity & String Theory

General Relativity (Einstein's theory of gravity) breaks down at short distances:

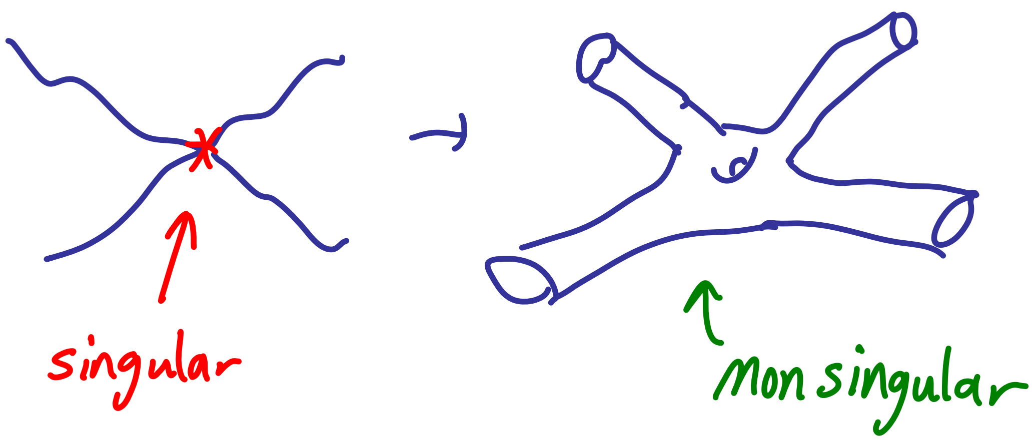
Space-time typically becomes highly curved in some regions

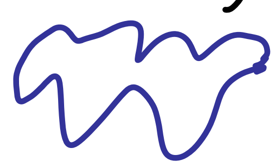
Far past:



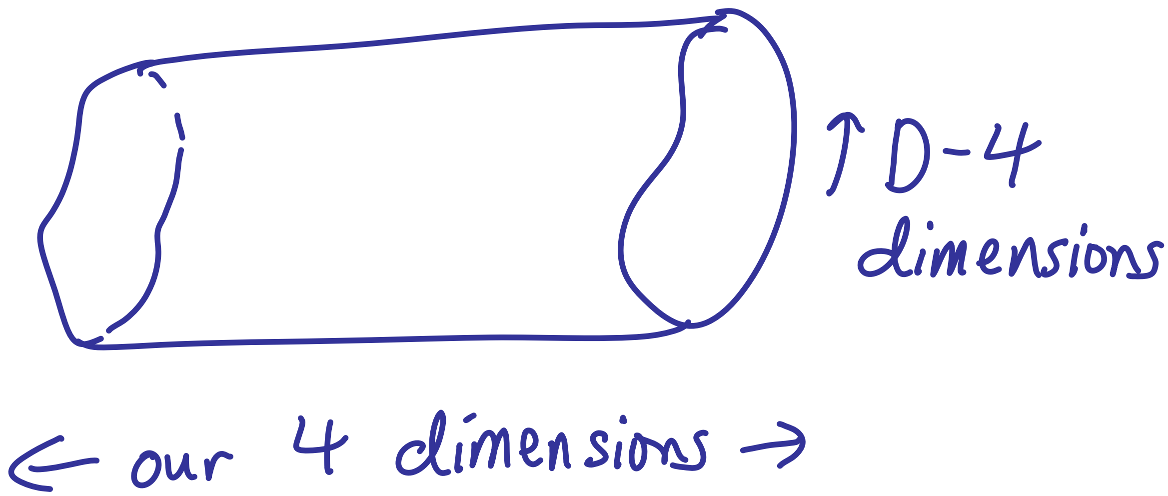
short-distance singularity

String theory, a candidate completion of general relativity and particle physics, smooths out spacetime singularities via new degrees of freedom:

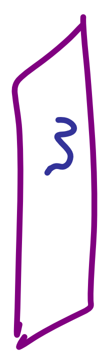


In addition to ordinary particles and gravitational fluctuations, string theory introduces  a tower of oscillating strings ...

… and extra dimensions,



higher-dimensional mem-"branes",



and new types of particles and forces.

This is a lot of extra degrees of freedom, way beyond those observed.

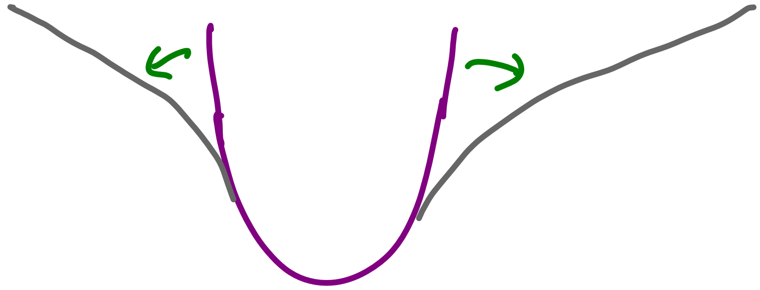
Various versions (for example, different D) are connected dynamically: one theory, many solutions.
*Almost all have positive potential energy (and not low energy supersymmetry).
*Enough to plausibly find ones with realistic features like the small late-time accelerated expansion (no other explanation yet forthcoming...).

The theory has passed stringent thought-experimental tests internal consistency checks.
For example, black holes have a course-grained description in terms of general relativity. In certain cases, string theory provides a fine-grained account of the many microstates of the system.

A simple effect:

Without string theory:

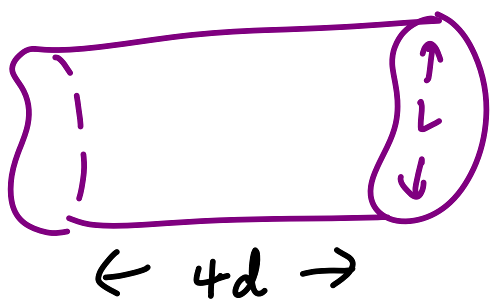
$V(\phi)$ is a parabola



With string theory, for example, we find additional heavy degrees of freedom that adjust, producing a flatter potential. (Dong et al 2010)

This can also destabilize the system in some directions, so research aimed at balance of forces to avoid runaway instabilities.

Modeling inflation in string theory is a laborious process:



(D-4) dimensional compactification X_{D-4}

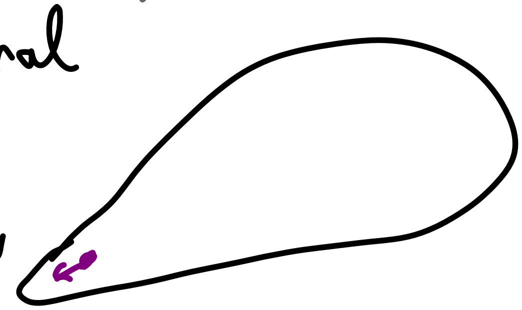
must first stabilize X_{D-4}: many scalar field "moduli" with generically steep potential $U_{mod}(L, g, \dots)$

- Many scalar field "moduli" with generically steep potential $\mathcal{U}_{mod}(L, g, \dots)$

  size ↗ ↖ coupling

- Many <u>angular</u> moduli θ such as axions, certain brane positions, etc. with more shallow potential at weak coupling → Natural candidate inflatons

e.g. KKLMMT
slow-roll D3-brane inflation



+ DBI (Alishahiha et al), ..., N-flation, gauged M-flation (Ashoorioon, Sheikh-Jabbari), Monodromy, ...

Variety of inflationary mechanisms in string theory

Many contributors (Baumann/McAllister book)

$V(\phi)$ flat

$\Delta\phi \lesssim M_p$

Accidental 1% cancellation

KKLMMT, Roulette,

LARGE

Fibre

[cosmic strings]

$V(\phi)$

steep

Self-interactions slowing ϕ

e.g. DBI

λ

Trapped

NG

$V(\phi)$ flat, $\Delta\phi > M_p$

Monodromy

L (impact parameter)

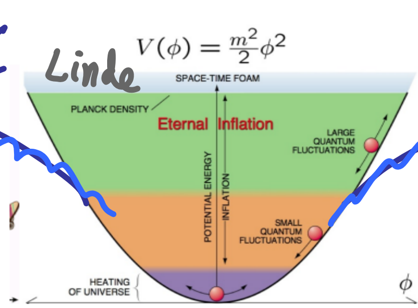
N-axion Alignment

Gauge fields, ...

Linde

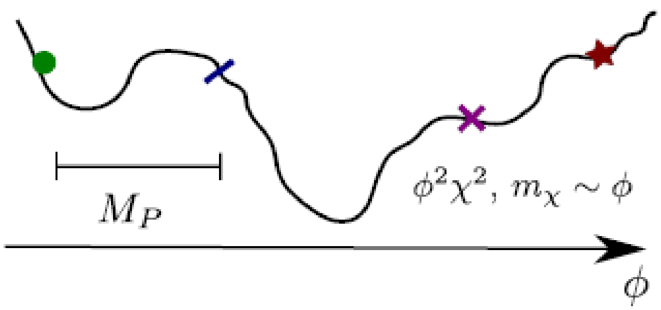
$p_0 = 2$

$p < 2$



[drifting $\boxed{r}$, oscillations]

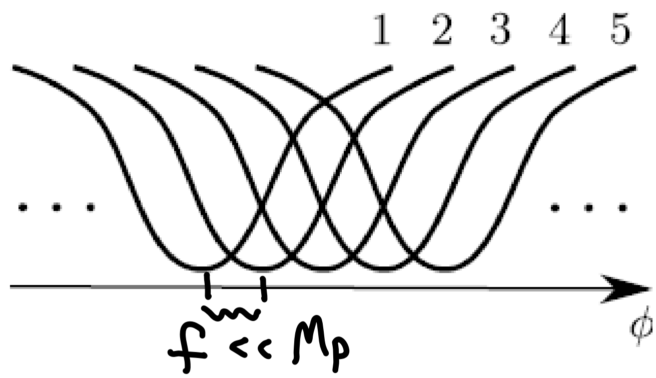
Parameterized ignorance of quantum grav.



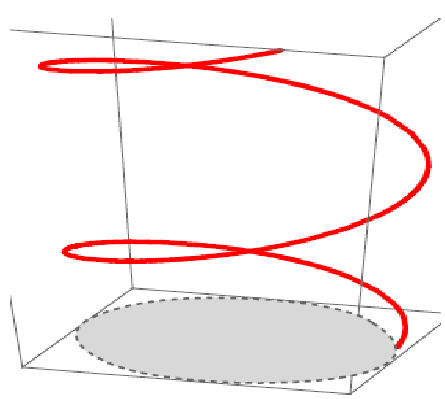
New degrees of freedom each

$\Delta\Phi = \mathrm{Mp}$

String Theory `axion' fields



From ubiquitous Axion-Flux couplings



$$\int d^D x \sqrt{G} \sum_q \Big| \overbrace{F_q - C_{q-3}\wedge H + F_{q-2n}\, B\wedge\cdots\wedge B}^{\tilde{F}_q \text{ Gauge-invar.}} \Big|^2$$

This generalizes Stueckelburg couplings in electromagnetism

$$S = \int d^4x \left\{ F^2 - \rho^2 (\partial\theta - A)^2 \right\}$$

Gauge symmetry $A_\mu \to A_\mu + \partial_\mu \Lambda$

$\theta \to \theta - \Lambda$

In string theory, the string sources a <u>2-index</u> gauge potential B_{MN} analogously to how a charged particle sources A_μ in Electromagnetism

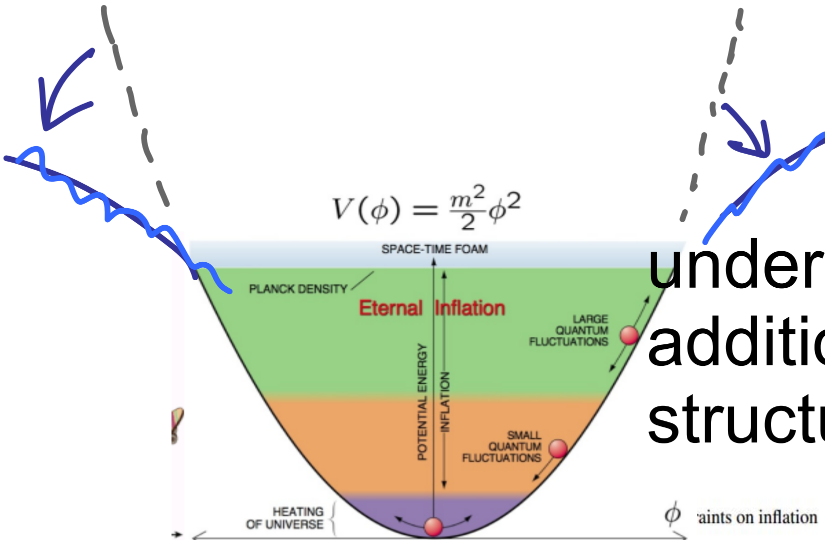
$$\text{axions} = B_{MN}\text{-modes}$$

(and duals)

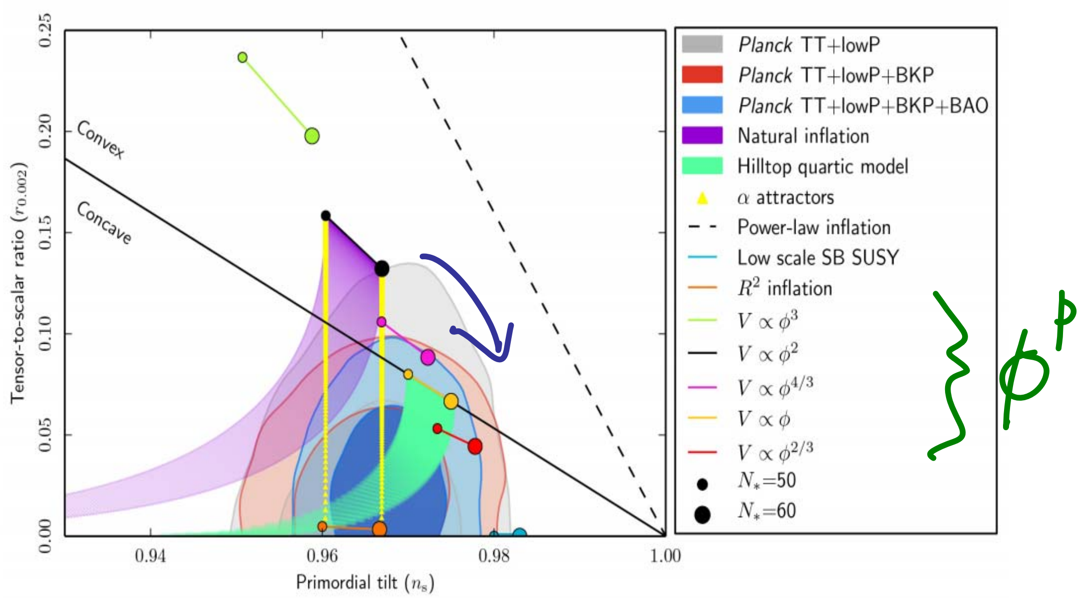
Is there a corresponding unbroken phase?

Heavy fields adjust to produce flatter (hence viable!) potential energy V(ϕ)

$\phi^{p<2}$



underlying periodicity => additional testable structures

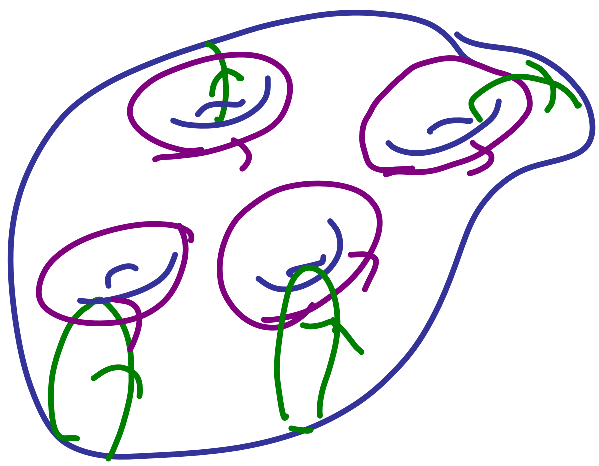


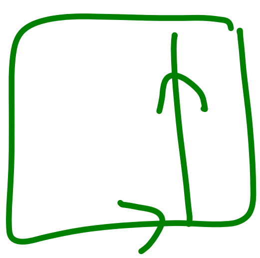
ϕ^p

Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

String theoretic version of two classic, now disfavored models remains so far viable as a result of unwinding and flattening V.

This effect also simplifies the stabilization of the extra dimenions of string theory, much to exploit here:





$$V \sim L_1 L_2 \left(\frac{\tilde{Q}_1^2}{L_1^2} + \frac{\tilde{Q}_2^2}{L_2^2} \right)$$

$$\Rightarrow \frac{L_1}{L_2} \sim \frac{\tilde{Q}_1}{\tilde{Q}_2}$$

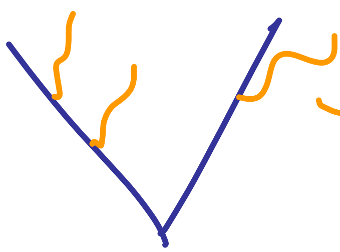
...while axion slowly rolls (rather than metastable minima). Also relevant for dark energy.

Recall:

Inflaton ϕ coupled to

heavy $\chi \longrightarrow m_\chi(\phi(t))$

time-dependent



$\rightarrow$ $\delta\phi$ radiation

non-adiabatic χ production

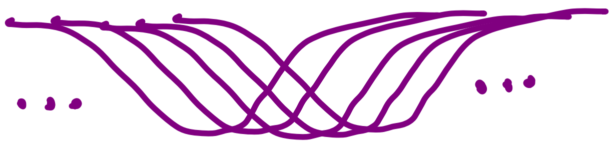
$$\left(\frac{\dot\phi}{H^2}\right)^{3/2} e^{-\frac{\pi\mu^2}{2\dot\phi}} \sim \frac{1}{\sqrt{N_{pixel}}}$$

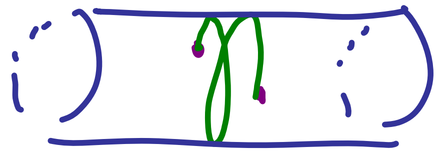
sensitivity to heavy χ fields

Novel shape $\langle \delta\phi_{k_1} \cdots \delta\phi_{k_N} \rangle$

and $(S/N)_{N+1} / (S/N)_N > 1$ possible for a range of N!

Two cases motivated by axion monodromy





both V and particle/string sectors

$$m^2_{\chi_n,(a)} = \mu_a^2 + \hat{\mu}_a^2(a(\phi) - 2\pi n)^2 \simeq \mu_a^2 + g_a^2(\phi - 2\pi n f)^2$$

Coleman-Weinberg

$$V = V_0(\phi;\chi) + \Lambda^4(\chi)\cos\left(\frac{\phi}{f}+\gamma\right)$$

$\rightarrow$ sinusoidally varying heavy moduli masses

$$m_\chi^2 = \mu^2 + 2g^2 f^2 \cos\frac{\phi}{f}$$

$$\eta_n = -\frac{1}{H} e^{2\pi n \frac{H}{\omega}}$$

More general $m_\chi(\phi)$, periodic or not, also interesting. (opposite extreme: random $m_\chi(\phi)$ cf Green; Amin Baumann)

Structure of String Compactifications:

*These Inflation mechanisms and signatures etc. are an outgrowth of the (in)famous `landscape' of solutions of string theory. Branched axion potentials, speed limits on certain fields' motion, matrix fields,etc. are concrete elements of this structure.

*There are many solutions, but <u>not</u> anything goes. No hard cosmological term in D dimensions, it is a scalar potential that runs away. Underlying axion periods sub-Planckian. etc.

*Most string backgrounds have large D, negatively curved extra dimensions, both of which produce positive potential energy (a good start for cosmology).

Much to do here

The majority of work in string theory presumes lower energy SUSY (choosing D=10, Calabi-Yau or equivalent). But well-defined solutions, beautiful dualities, and so on arise also for the more generic case.

T-duality

S^1 radius $R \leftrightarrow \dfrac{\alpha'}{R}$

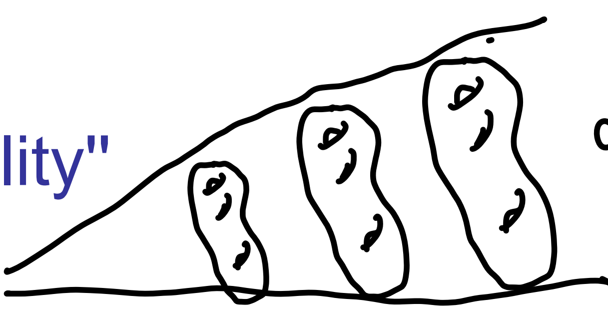
windings $\leftrightarrow$ momenta

Mirror Symmetry

$$T^3 \to CY$$
$$\downarrow$$
$$\Sigma_3$$

T-duality

``D-duality''



$a(t) \propto t$

$\mathcal{R} < 0$

UV windings (exponential growth) $\leftrightarrow$ IR spectrum of Laplacian

Milnor; ... Mirzakhani

String Theory: ∞ many weakly interacting limits, dynamically connected

$D_{eff} < 10$	$D_{eff} = 10$	$D_{eff} > 10$
		
Freund-Rubin	Calabi-Yau	... compact hyperbolic ...
$\mathcal{R} > 0$	$\mathcal{R} = 0$	$\mathcal{R} < 0$
$V_{classical} < 0$	$V_{classical} = 0$	$V_{classical}(g_s, L, \dots) > 0$
	$M_{susy} \ll M_{KK}$	$M_{\cancel{susy}} \gtrsim M_{KK}$

AdS/CFT

cosmology, e.g. models of inflation, singularity resolution etc.

This is one example of several approaches to simplifying and systematizing cosmological solutions, taking into account the rich, but highly constrained, structure of string theory.
(Many dynamical effects of multiple fields to understand...)

This is relevant both for phenomenology, and for developing a better conceptual understanding of cosmology.

One major question is how to understand the horizon entropy (and `holography') in cosmology.

Black Hole Physics:

$\Delta A \geq 0$ in classical GR

area of event horizon

$\Delta M = \kappa \, \Delta A$ in classical GR

surface gravity

$T \sim \kappa$ Quantum mechanically

Dynamics of BHs $\leftrightarrow$ Thermodynamics

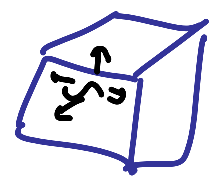
$\frac{\text{Area}}{G_N} \sim \left(\text{Area}\, M_p^2\right) \leftrightarrow$ Entropy S

n.b. Thought-experimental constraint that stress-energy sources respect these laws can be applied, e.g. in cosmology.

Gravity (d dimensions) $\neq$ Local QFT (d dimensions)

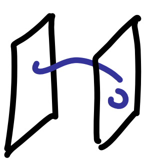
If you pack too much entropy in local region

$\Rightarrow$ form a BH, $S \sim$ Area



volume's worth of degrees of freedom

String theory : BH Stat. Mech.



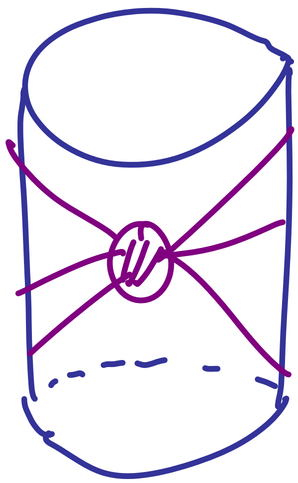
Explicit microstate count for tractable BH's ... $\longrightarrow$

Gravity (d dimensions, e.g. AdS) = Local QFT (d-1 dimensions) !

$\Rightarrow$ Unitary BH evolution

$\Lambda < 0$ (AdS_4) has a precise non-perturbative formulation.

4d GR + strings | QFT_3, no gravity



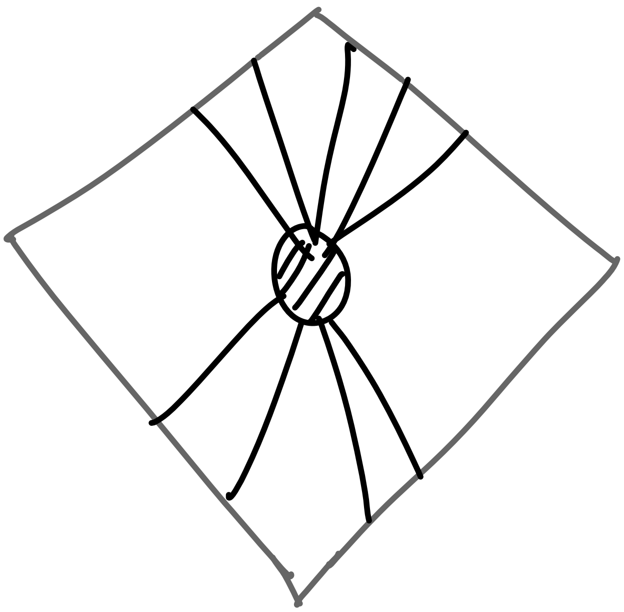
$|_{I}$ $\cong$ $CFT_3 \,|_{I}$

many distinct examples, don't mix, no horizon

Observables = QFT Correlation Functions.

For $\Lambda = 0$, the general framework

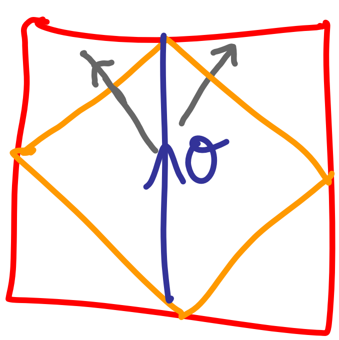
(an S-matrix is also known



An observer can causally collect the results.

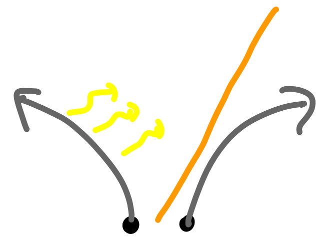
In contrast,

in dS :

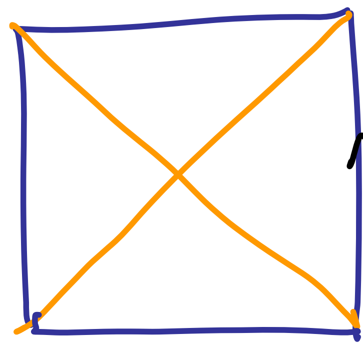


Mysteries of Dark Energy

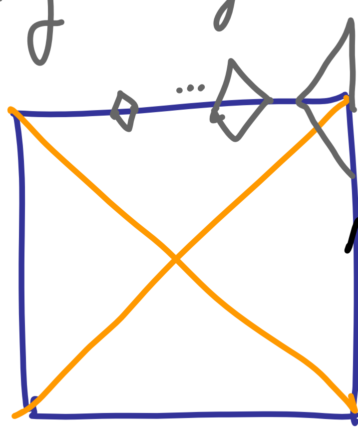
$w < -\frac{1}{3} \Rightarrow$ horizon



e.g. dS $w = -1$



Including decays:



Dynamical connections between different Λ, & different D, topology, fluxes, ...

Gibbons / Hawking : de Sitter

Horizon $\Rightarrow$ $S \sim \dfrac{M_p^2}{H^2}$

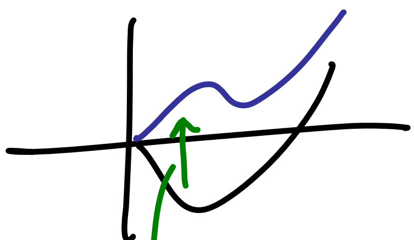
Invites a microstate count.

↪ Get parametrically by building up from AdS/CFT

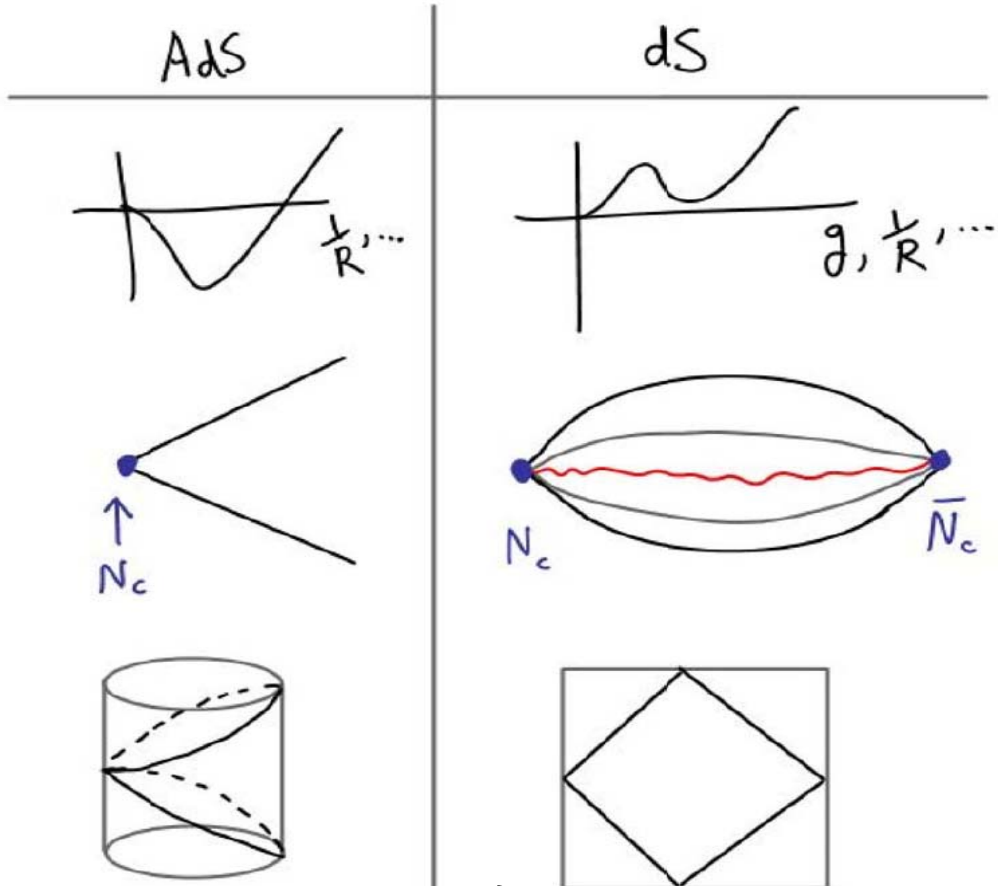
add ingredients to "uplift"

interpret new ingredients

magnetic matter



heavy branes overcoming $AdS \times S^5$ curvature



$$ds^2_{(A)dS} = \sin(h)^2 \frac{w}{L}\, ds^2_{dS_{d-1}} + dw^2$$

Figure 2: The structure of the string landscape – specifically its metastability – leads to a brane construction for de Sitter spacetime which nontrivially agrees with the macroscopic structure of de Sitter as a two-throated warped compactification. This would not have happened if string theory admitted a hard cosmological constant parameter. The left panel depicts AdS/CFT dual pairs arising from compactification on a positively curved Einstein space. This leads to the leading negative term in its potential, and appears as the base of the cone in the brane construction, D-branes probing the tip of a cone whose size satisfies a radial Friedmann equation. Trading the branes for flux and geometry, the resulting AdS solution has a warp factor that extends to the deep UV. The right panel depicts the effect on all this of uplifting to a metastable de Sitter solution. The leading term in the potential is now positive, e.g. coming from negative curvature. This combined with the second, negative term in the potential (e.g. from orientifolds) leads to a de Sitter analogue of the brane construction whose radial Friedmann equation implies that the size grows to a finite maximum before contracting. This fits perfectly with the dS/dS slicing of macroscopic de Sitter spacetime, which exhibits two warped throats cutoff at a finite UV scale. This structure occurs also in the computation of observables in the dS/CFT approach, which requires integrating over the $d-1$ dimensional metric. All this suggests that the matter sector in the appropriate holographic dual to de Sitter is a theory that is not UV complete (perhaps analogous to QED), in contrast to gauge/gravity duals with asymptotic boundaries.

In dS, the holographic dual still has gravity (in one less dimension), but given the ultimate decay to V=0 (an essential feature of string compactification), the gravity decouples at very late times.

There is a concrete example of this, but still rather complicated. It will be very interesting to simplify models of accelerated expansion, and use them to hone in on dual and observables.

Another direction related to horizon physics (including black holes) is the level of breakdown of EFT for infallers.

Cosmology and string theory are mature subjects, well grounded with data on one end of the spectrum and theoretical consistency on the other. But very basic, essential questions remain.

*What are the optimal constraints we can get on the power spectrum and statistics of the primordial perturbations? This requires theory, since the data set is large but finite, and EFT is important but does not boil it down to just a few tests.

*The constraint or detection of primordial GWs (B modes) is a key observable, sensitive to 10 (!) Planck units in field range. This motivates extensive research on large-field inflation in quantum gravity (e.g. string theory) from several points of view (mathematical, phenomenological, conceptual).