Title: Cosmology and Unification

Speakers: Raman Sundrum

Series: Particle Physics

Date: April 04, 2023 - 1:00 PM

URL: https://pirsa.org/23040066

Abstract: Precision measurements of primordial correlators in the CMB, Large Scale Structure, and 21-cm cosmology may contain "on-shell" imprints of extremely heavy particle physics, with masses comparable to the inflationary Hubble scale, via the remarkable inflationary mechanism known as "cosmological collider physics". I will describe my research in (a) finding new robust mechanisms for extending the energy range and strength of such signals, (b) identifying motivated particle physics targets that may be discoverable, (c) showing how cosmological collider physics can probe the mechanism of inflation itself, and (d) demonstrating variants of the mechanism that may be observable in new cosmological "maps", such as stochastic gravitational wave backgrounds with significant anisotropies. While this is an ambitious program of research, there are major challenges to bring it to fruition, on the experimental, phenomenological and theoretical fronts, which I will sketch.

Zoom Link: https://pitp.zoom.us/j/98923687484?pwd=cjgweEhoejVCeHAvc0RBSDEvVkZldz09

COSMOLOGY & UNIFICATION

Raman Sundrum
University of Maryland

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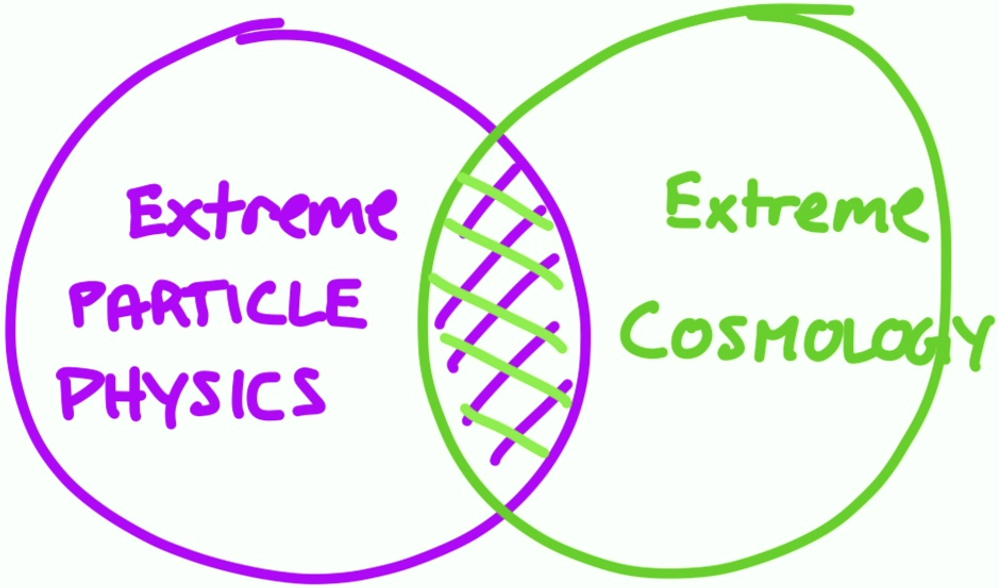
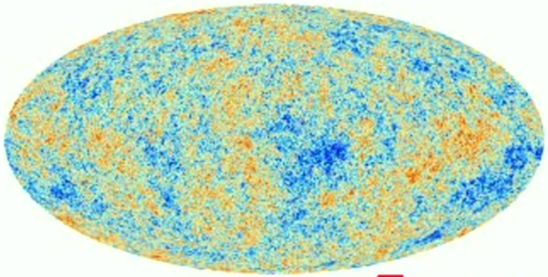
INTRODUCTION

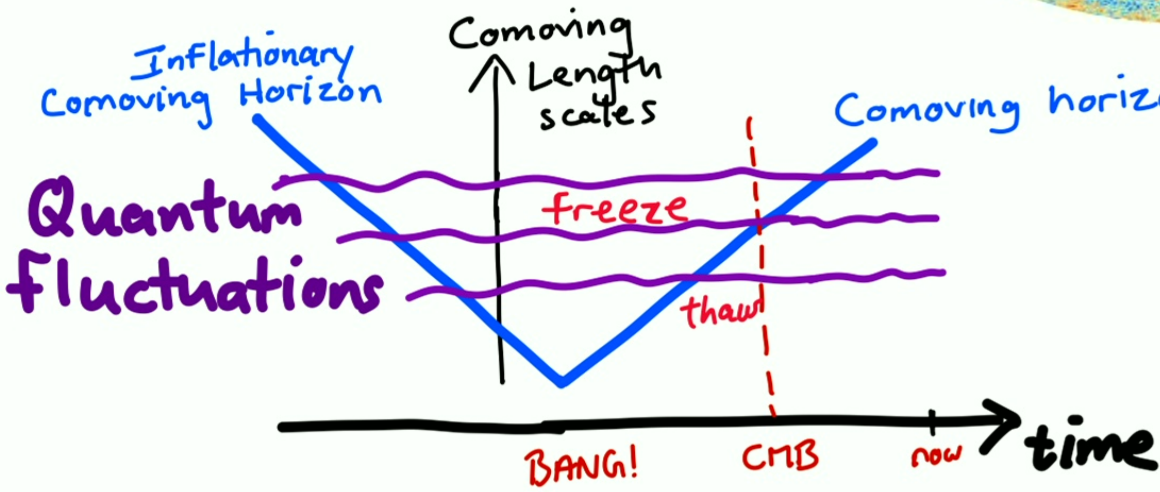


2

PRIMORDIAL INHOMOGENEITIES SEEDED BY COSMIC INFLATION

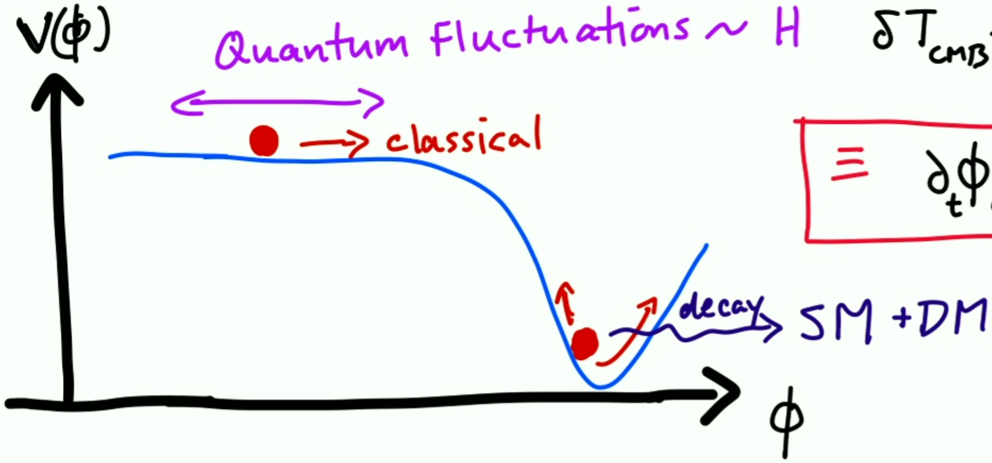


Planck



3

SLOW-ROLL INFLATION



$$\delta T_{CMB} \sim \delta t_{reheat} \sim \frac{\delta\phi}{\dot{\phi}_{classical}}$$

$$\boxed{\equiv \quad \partial_t \phi_{classical} \sim 10^4 H^2}$$

Approximate de Sitter phase

$$ds^2 \approx dt^2 - e^{2Ht} d\vec{x}^2 = \frac{d\eta^2 - d\vec{x}^2}{\eta^2} \qquad \eta < 0$$

$H \equiv 1$ units

Time translation inv.

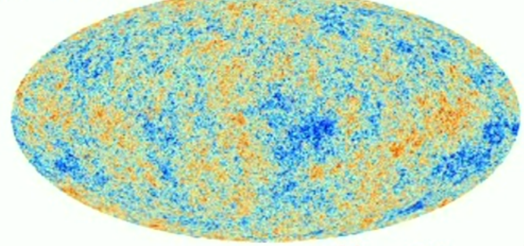
"Scale Invariance"

$$t \to t - \lambda \;\equiv\; \eta \to e^{\lambda}\eta$$
$$\vec{x} \to e^{\lambda}\vec{x}$$

reduces to spatial scale inv.

at reheating $\eta \approx 0$, $\boxed{\vec{x} \to e^{\lambda}\vec{x}}$ $\Rightarrow$ Scale-Invariant fluctuations

FUNDAMENTAL PHYSICS FROM COSMIC INFLATION



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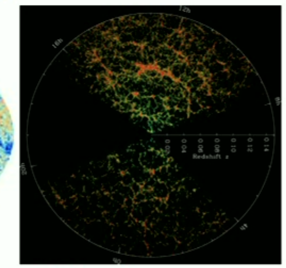
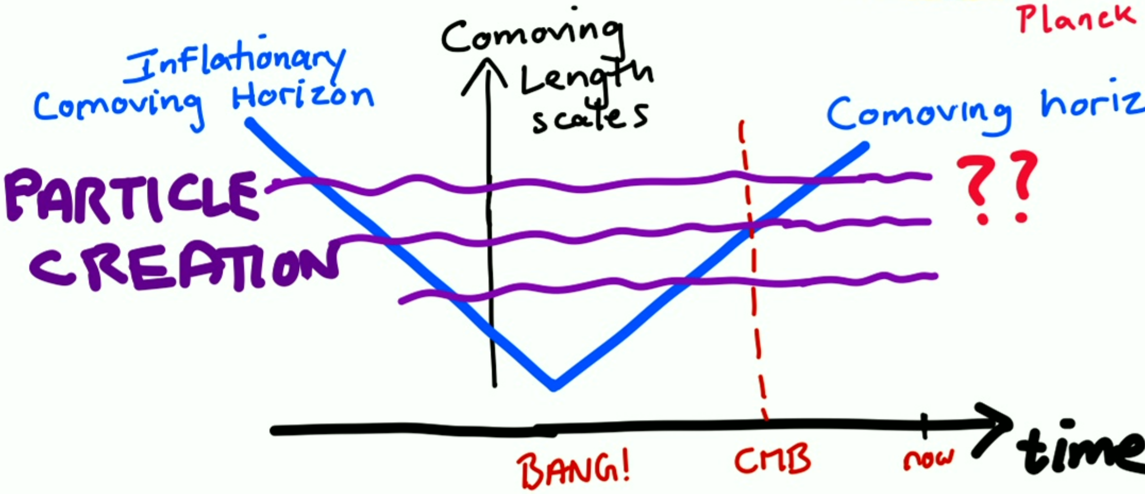


Blanton & SDSS



$$E = mc^2 \equiv i\hbar\partial_t \sim \frac{\partial_t a}{a} \equiv H_{\text{inflation}} < 5\times10^{13}\,\text{GeV} \,!$$

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MASSIVE FIELDS IN DE SITTER

$$S = \int d^3\vec{x}\, d\eta \left\{ \sqrt{-g}\, g^{\mu\nu} \partial_\mu \sigma\, \partial_\nu \sigma - m^2 \sigma^2 \right\}$$

$$= \int d^3\vec{k}\, d\eta \left\{ \frac{1}{\eta^2} |\partial_\eta \sigma_{\vec{k}}|^2 - \frac{\vec{k}^2}{\eta^2} |\sigma_{\vec{k}}|^2 - \frac{m^2}{\eta^4} |\sigma_{\vec{k}}|^2 \right\}$$

Equations of motion of Bessel type:

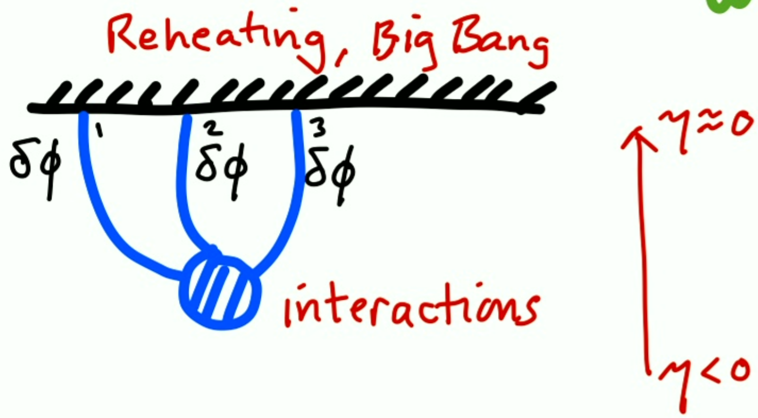
$$\sigma_{\vec{k}}(\eta) = e^{-\pi\sqrt{m^2 - 9/4}/2}\, H^{(1)}_{i\sqrt{m^2-9/4}}(-k\eta) \underset{m \gg H}{\approx} e^{-\pi m/2} H^{(1)}_{im}(-k\eta)$$

$$\xrightarrow[|k\eta| \gg m]{\text{early}} \frac{1}{\sqrt{2k}} e^{-ik\eta}$$

positive energy (& boosted by blue shift)

BUT ... $\xrightarrow[|k\eta| \ll m]{\text{late}} e^{-imt} + \underbrace{e^{imt}}_{\text{negative energy!}} e^{-\pi m}$

PRIMORDIAL NON-GAUSSIANITIES from "in-in" correlators with interactions



$$\langle \delta T(\vec{x}_1)\, \delta T(\vec{x}_2)\, \delta T(\vec{x}_3) \rangle$$

$$\underset{\text{spatially flat gauge}}{\propto} \langle 0 |\, e^{i\int_{-\infty(1+i\varepsilon)}^{\infty} dt\, H(t)}\, \delta\phi(\vec{x}_1)\, \delta\phi(\vec{x}_2)\, \delta\phi(\vec{x}_3)\, e^{-i\int_{-\infty(1-i\varepsilon)}^{\infty} dt\, H(t)}\, | 0 \rangle$$

$$\xrightarrow{\text{Fourier transform}} \underbrace{\langle \delta\phi_{\vec{k}_1}\, \delta\phi_{\vec{k}_2}\, \delta\phi_{k_3} \rangle'}_{\text{BISPECTRUM}}\, \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$$

← separate out δ-function

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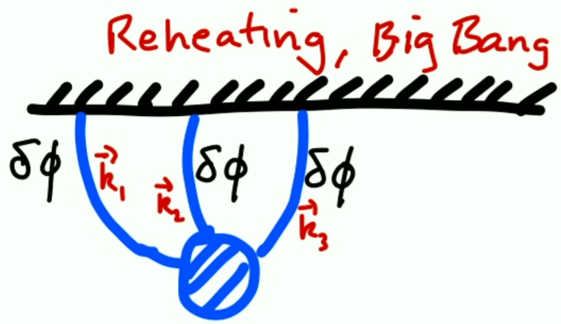
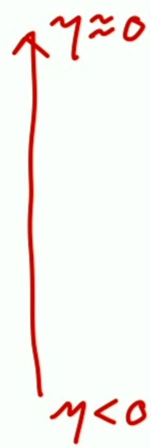
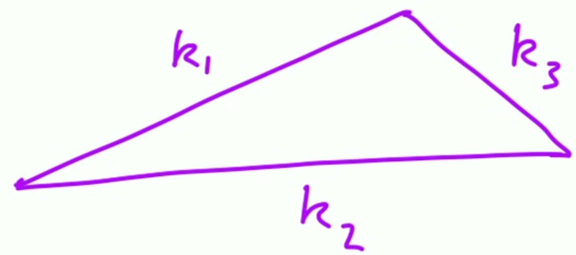






Primordial Non-Gaussianity (NG):

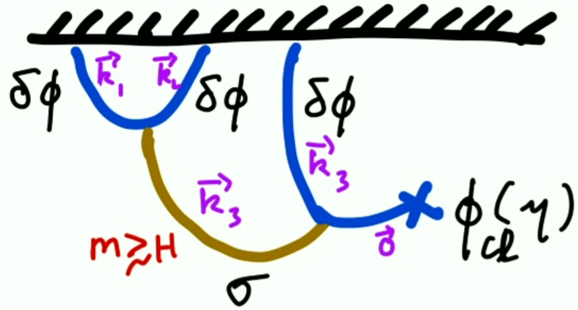
$$F(k_1,k_2,k_3) \equiv \frac{\underbrace{-\partial_t \phi_{cl}}_{\sim 10^4} \langle \delta\phi_{\vec{k}_1}\, \delta\phi_{\vec{k}_2}\, \delta\phi_{\vec{k}_3} \rangle'}{\langle \delta\phi_{\vec{k}_1}\, \delta\phi_{-\vec{k}_1} \rangle' \langle \delta\phi_{\vec{k}_3}\, \delta\phi_{-\vec{k}_3} \rangle'}$$

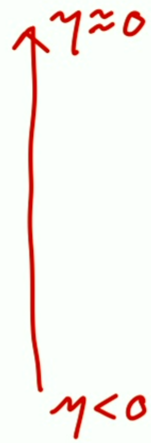
$$f_{NL} \equiv \tfrac{5}{18} F(k,k,k) \underset{\text{Planck}}{<} \mathcal{O}(10)$$

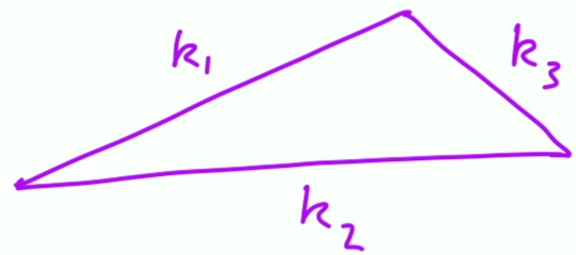
"COSMOLOGICAL COLLIDER PHYSICS"

$$\mathcal{L}_{int.} = \sqrt{-g}\, g^{\mu\nu} \underbrace{\partial_\mu\phi\,\partial_\nu\phi}_{\text{Radiative stability of } V_{\text{inflation}}}\ \sigma \Big/ \Lambda \qquad \leftarrow m \gtrsim H$$

Chen, Wang '09; Baumann, Green '11
Noumi et. al. '12
Arkani-Hamed, Maldacena '15
Lee et. al. '16; Meerburg et. al. '16
⋮







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$$\langle \delta\phi_{\vec{k}_1}\delta\phi_{\vec{k}_2}\delta\phi_{\vec{k}_3}\rangle' \sim \frac{\partial_t \phi_{cl}}{\Lambda^2}\, e^{-\pi m}\, e^{-im(t_{late}-t_{early})}$$

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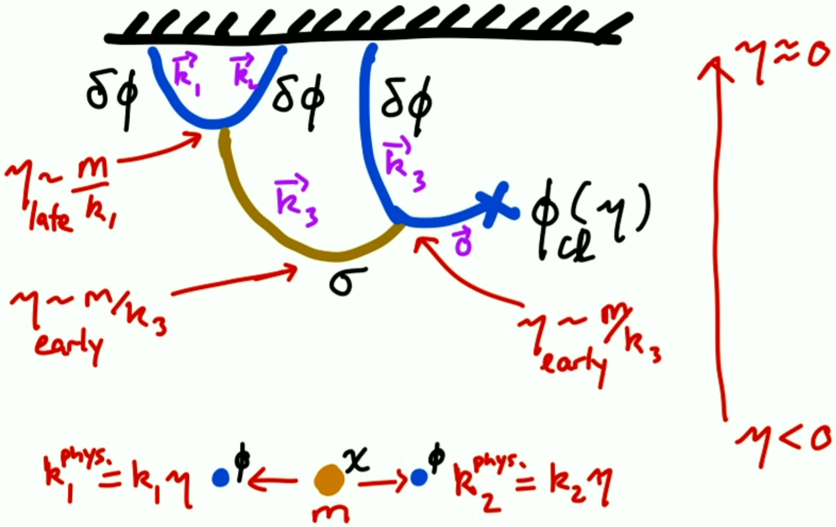
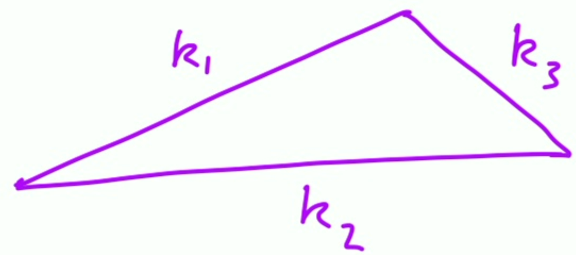


SQUEEZED LIMIT:



$$k_3 \ll k_1 \approx k_2$$

$$\langle \delta\phi_{\vec{k}_1} \delta\phi_{\vec{k}_2} \delta\phi_{\vec{k}_3} \rangle' \sim \frac{\partial_t \phi_{cl}}{\Lambda^2} e^{-\pi m} e^{-im(t_{late} - t_{early})} \propto e^{-\pi m} \left(\frac{k_3}{k_1}\right)^{im}$$

non-analytic $\equiv$ on-shell propagation

OUTLINE

Higher-dimensional Grand Unification
& Kaluza-Klein Graviton

Probing Inflaton Partners

"Heavy-Lifting" of Gauge-Higgs Dynamics
& Naturalness

Curvaton Scenario → Stronger Signals

"Chemical Potential" → Larger Window
of Opportunity

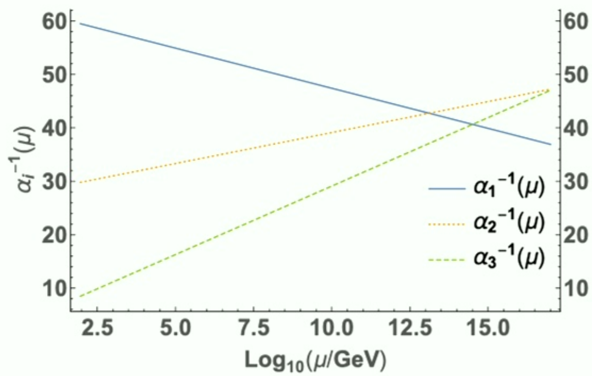
New maps from Stochastic Gravitational
Waves & Classical production of Heavy Fields

(Non-supersymmetric)
GRAND UNIFICATION

$$SO(10) \supset SU(5) \xrightarrow[\text{mechanism}]{\text{Higgs}} SU(3) \times SU(2) \times U(1)$$

Spinor representation $\supset$ entire SM matter generation

weak isospin 2 + color 3



1-loop SM RGE

(Non-supersymmetric)
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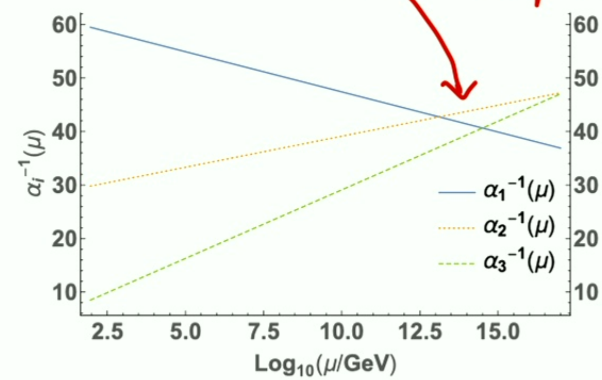
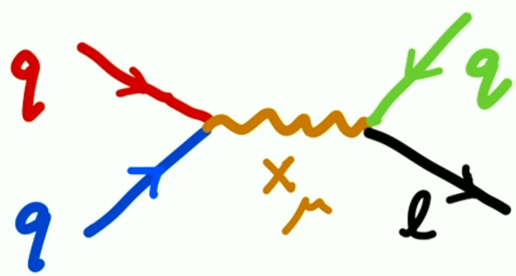
striking, but why imperfect?



1-loop SM RGE

PROTON DECAY?



$$m_X > 5\times10^{15}\,\mathrm{GeV}$$

Super-K '16

15

(Non-supersymmetric)

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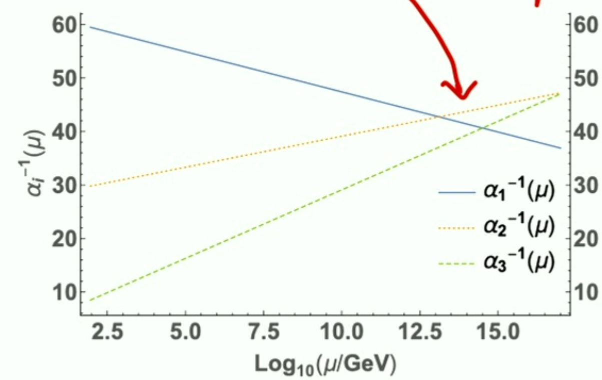

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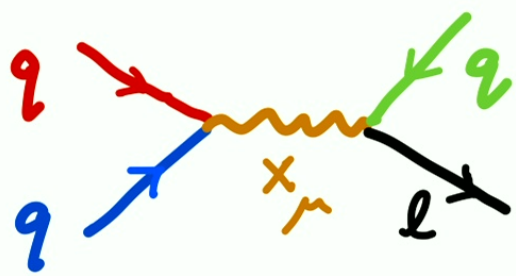


$$m_X > 5 \times 10^{15}\,\mathrm{GeV}$$

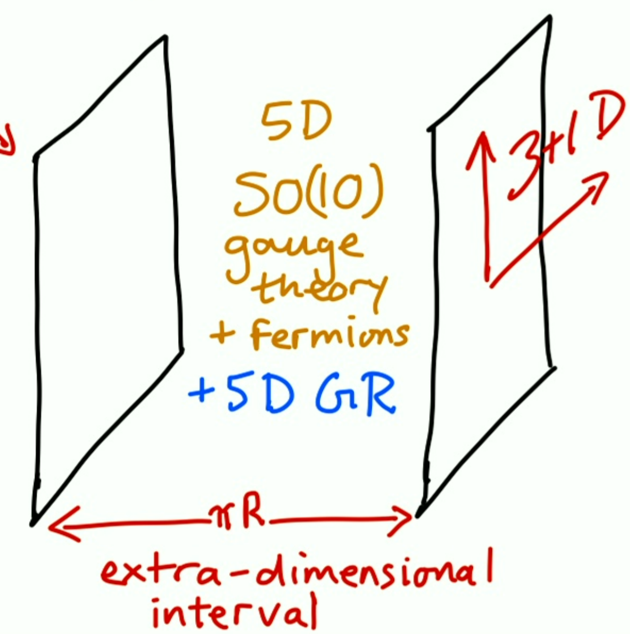
Super-K '16

15

ORBIFOLD GUTS

Kawamura '99, '00
Hall, Nomura '01, '03

Higher-dimensional SO(10) gauge theory,
with extra-dimensional boundary conditions (eg. Neumann, Dirichlet)
respecting only $SU(3) \times SU(2) \times U(1)$, & global $U(1)_{baryon}$



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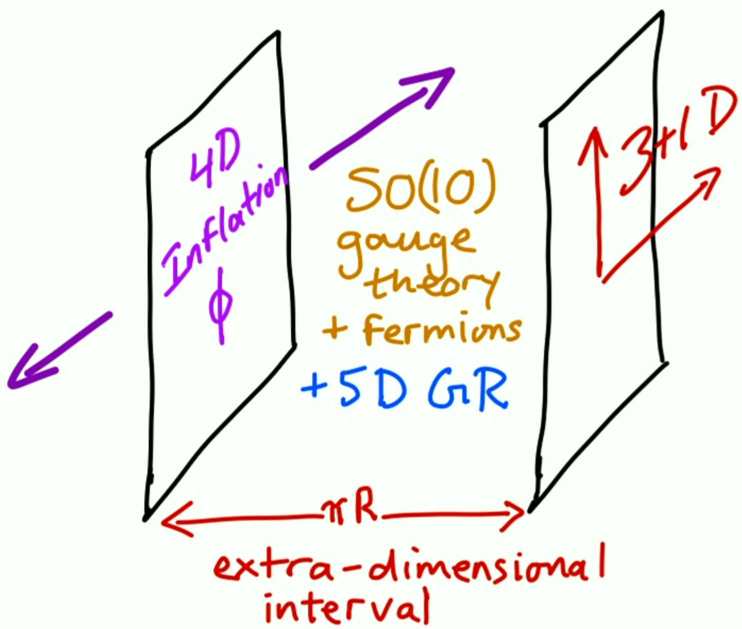
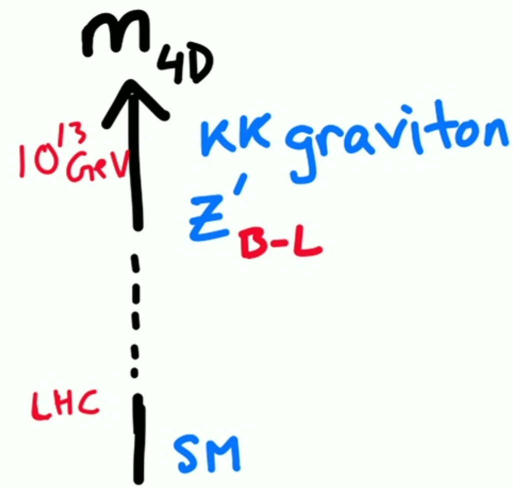
ADD BOUNDARY-LOCALIZED 4D INFLATION . . .





Kumar, Sundrum '18

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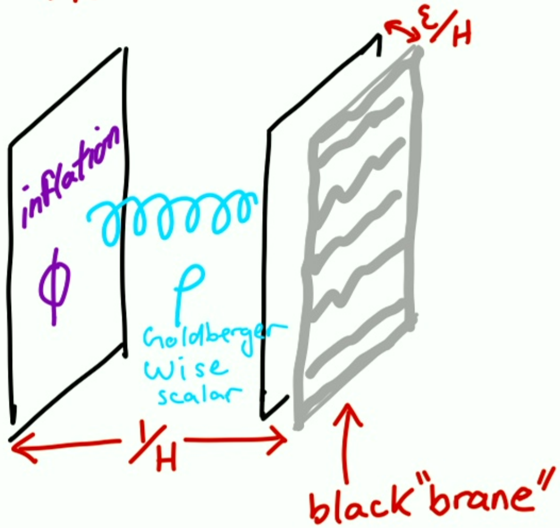
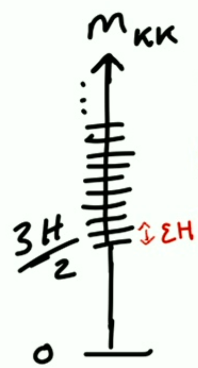
OPPORTUNITY ON THE HORIZON...

$m_{KK} = 1/R \sim H_{inflation} \Rightarrow$ significant backreaction to 5D geometry from boundary inflation

$$ds^2 \underset{m_{KK} \gg H}{=} dt^2 - e^{2Ht} d\vec{x}^2 - dx_5^2$$

$$\xrightarrow[1/R \sim H]{} (1 - Hx_5)^2 \left[dt^2 - e^{2Ht} d\vec{x}^2\right] - dx_5^2$$





Near-horizon analysis of Goldberger-Wise '99 extra-dimensional stabilization by 5D scalar ρ is possible for small

$$\varepsilon \equiv 1 - H\pi R$$

$$\Delta m_{KK} \sim \varepsilon H$$

Further backreacted ds^2 treated in ε-perturbation theory

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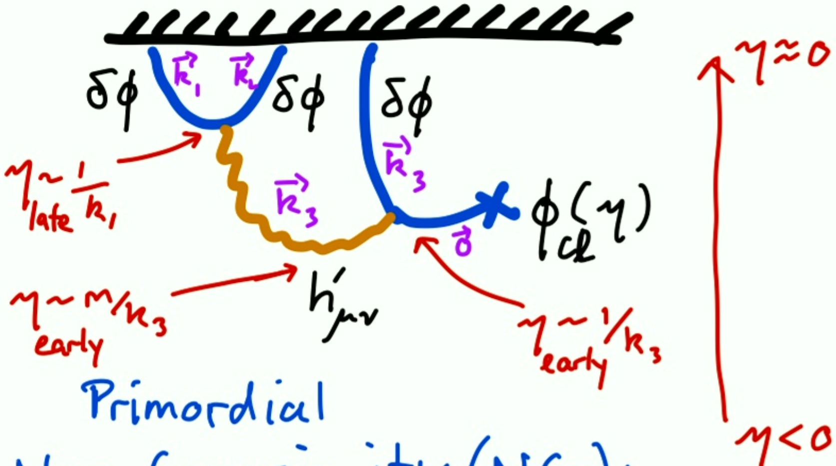
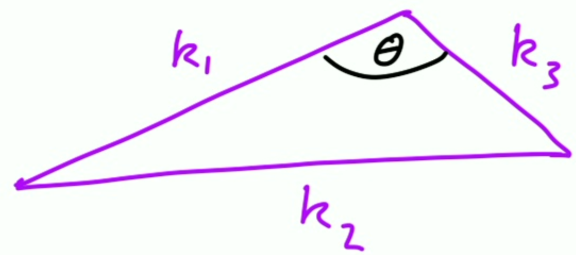
KALUZA-KLEIN GRAVITON

$$\mathcal{L}_{int.} = \sqrt{-g}\, \partial_\mu \phi\, \partial_\nu \phi\, \frac{h'^{\mu\nu}}{M_{Pl}}$$



SQUEEZED LIMIT:



$k_3 \ll k_1 \approx k_2$

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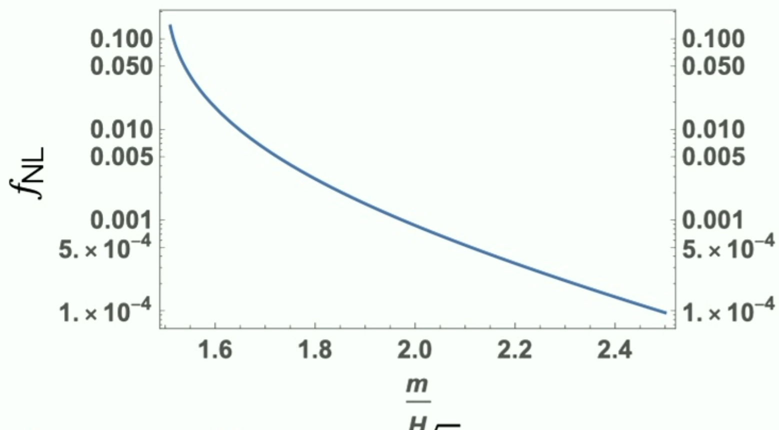
Subtle backreaction to 5D geometry

More carefully:

KK graviton mediated NG



$r = 0.1;$

Maximal $H_{inf.}$ allowed

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

$$F = \frac{r}{8} \times \left(\cos^2\theta - \frac{1}{3}\right) \frac{\sqrt{\pi}}{8(1+4\mu^2)^2 \cosh(\pi\mu)}$$

$$\times \left(A(\mu)(1 + i \sinh \pi\mu) \left(\frac{k_3}{k_1}\right)^{3/2+i\mu} + (\mu \to -\mu) \right)$$

$$A(\mu) = (-27 + 120i\mu + 152\mu^2 - 32i\mu^3 + 16\mu^4)\Gamma(5/2 + i\mu)\Gamma(-i\mu)2^{-2i\mu}$$

PROBING INFLATION

Inflation & reheating present naturalness (fine-tuning) puzzles, resolvable with new symmetries.

Symmetry partners of inflaton can appear in Cosmo Collider, such as the Sinflaton of SUSY Deshpande, Sundrum '21

or the Twinflaton of hybrid inflation with "twin" discrete symmetry Deshpande, Kumar, Sundrum '21

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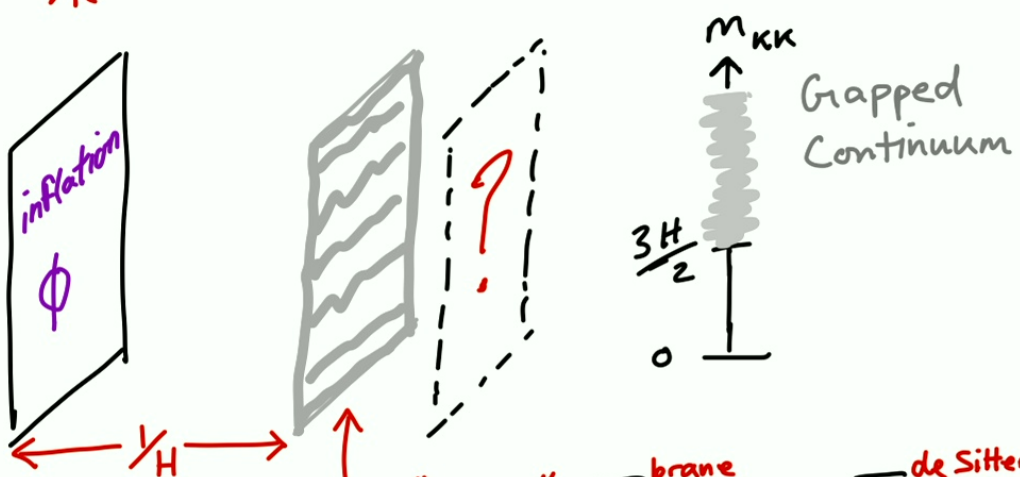
Vilenkin '83
Ipser, Sikivie '84
Kaloper, Linde '98
Kaloper '99



Garriga, Sakai '99

black "brane"

$$T^{\text{brane}}_{\text{Hawking}} = T^{\text{de Sitter}}_{\text{Hawking}} = H/2\pi$$

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Subtle backreaction to 5D geometry

More carefully:

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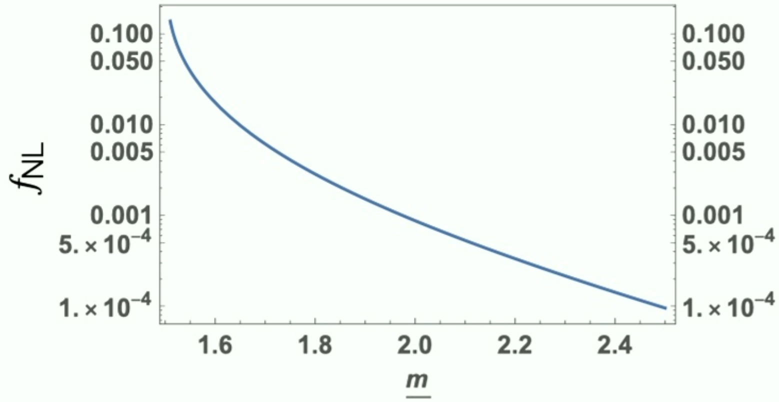

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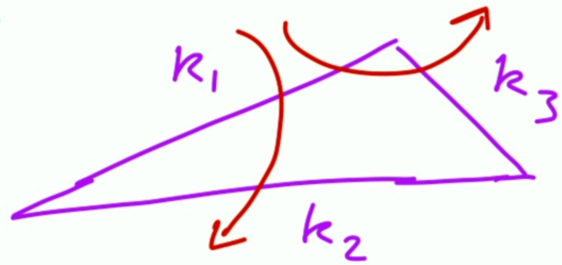
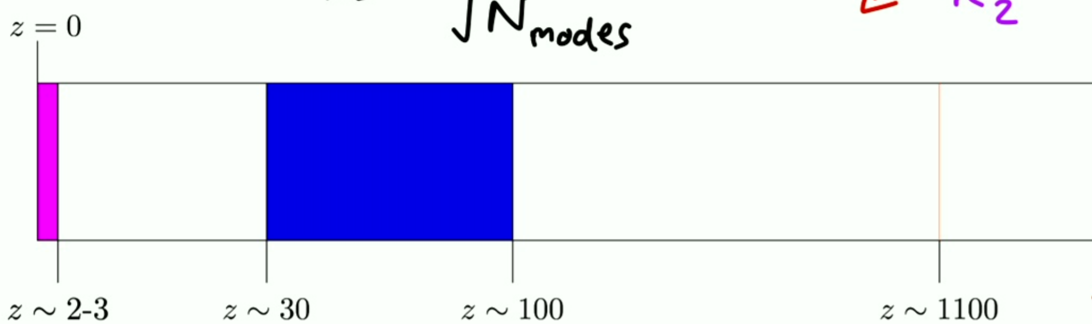
EXTREME PRECISION

Only one sky to measure quantum expectations.

But translation & rotation (& ≈ scale) symmetry allows us to make many measurements of same correlator :

$$\delta f_{NL} \sim \frac{10^4}{\sqrt{N_{modes}}}$$





Alvarez et. al. '14

Loeb, Zaldarriaga '03

$\longrightarrow z \equiv \frac{1}{a} - 1$

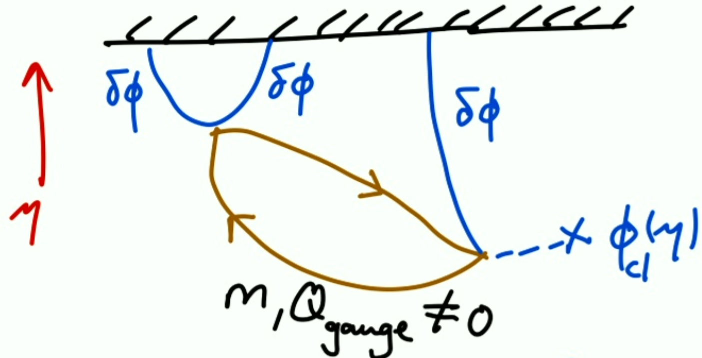
Planck: $N_{\text{modes}} \sim 10^7 \Rightarrow \delta f_{\text{NL}} \sim 10$ **Current bound**

LSS: $N_{\text{modes}} \sim 10^9 \Rightarrow \delta f_{\text{NL}} \sim 1$ **(EUCLID, DESI, SPHEREx ...)** **2022**

21-cm Cosmology: $N_{\text{modes}} \sim 10^{16} \Rightarrow \delta f_{\text{NL}} \sim 10^{-4} - 10^{-3}$ **20??**

GAUGE-HIGGS THEORY

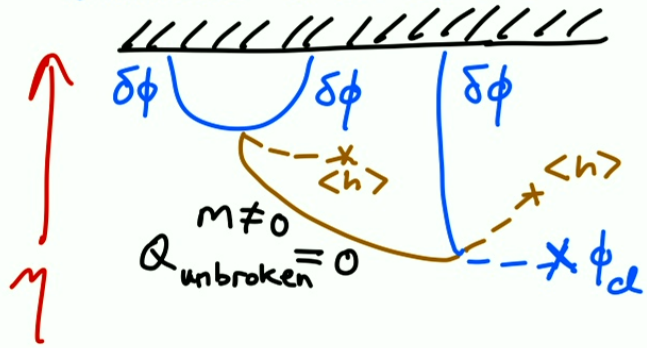
Gauge-charged particles can only appear in (suppressed) loops, as inflaton is singlet



unless rendered neutral after Higgsing:

Eg. Z^0

Kumar, Sundrum '17



"HEAVY-LIFTING" BY INFLATION

Kumar, Sundrum '17

Natural to have Higgs fields couple to curvature:

$$\mathcal{L}_{Higgs} = \sqrt{-g}\,\{ g^{\mu\nu} D_\mu h^\dagger D_\nu h + m^2 h^\dagger h - \lambda (h^\dagger h)^2 \pm \underbrace{O(1) R h^\dagger h}_{\sim H^2_{inf.} h^\dagger h} \}$$

$\uparrow$ tachyonic $\ll H^2_{inf.}$

during inflation, negligible today

$\Longrightarrow$ Higgs mechanisms at lower scales today, could have been at $\sim H_{inflation}$ during inflation!

This extreme volatility of Higgs mechanism is an aspect of the Hierarchy Problem.

But here, particles getting Higgs-generated masses, are "lifted" into the sights of the "Cosmological Collider":

$$V_{effective}(h) = -O(H^2_{inf.})\, h^\dagger h + \lambda (h^\dagger h)^2$$

$$m_Z \sim H_{inf.}$$

Not a "problem"!

HIGGSED GAUGE THEORY

$$\mathcal{L}_{int.} \supset \sqrt{-g}\, g^{\mu\nu} \left\{ \frac{\partial_\mu \phi \partial_\nu \phi \rho}{\Lambda} + \frac{\partial_\mu \phi h^\dagger D_\nu h \rho}{\Lambda^2} \right\}$$

mediator

$\Lambda^2 > \dot{\phi}_{cl}$

Creminelli '03

integrate out ρ, $m_\rho > H$

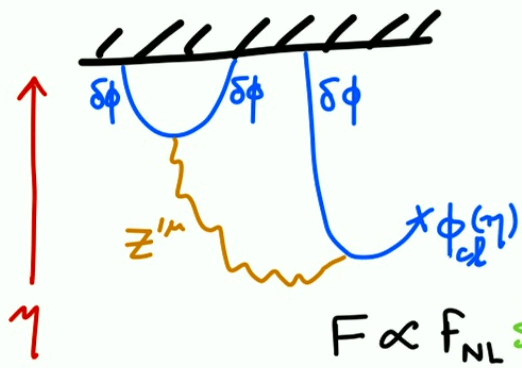
$\langle h \rangle \equiv v$

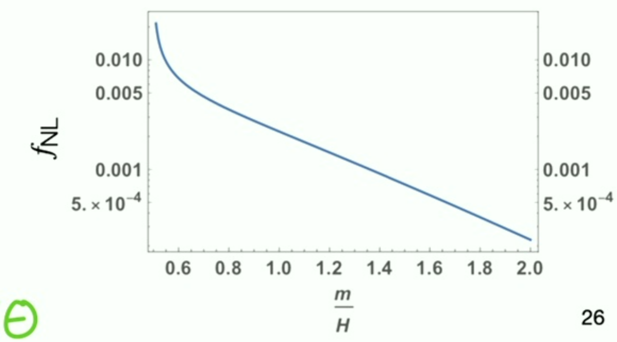
$$\sqrt{-g}\, g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi\, \partial_\alpha \phi\, Z'^{\alpha} \frac{v^2}{\Lambda^3 m_\chi^2}$$

must be small enough to keep EFT control of $(\partial\phi)^n$ expansion

ORBIFOLD GUTs

$$\mathcal{L}_{int} \supset \sqrt{-g}\, g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi\, \partial_\alpha \phi\, \partial_{x_5} Z'^{\alpha}_{B-L} / \Lambda^2 m_\chi^2$$





$F \propto f_{NL} \sin^2\theta$

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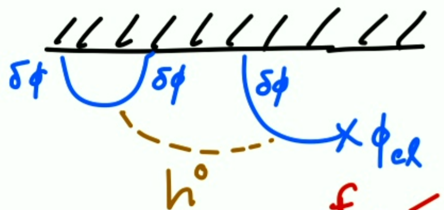
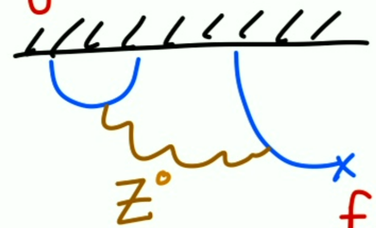
COULD WE SEE THE SM ?

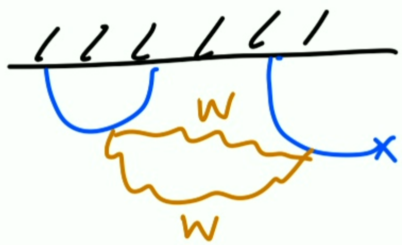
$h^0_{physical}$, Z^0_μ, $\underbrace{W^\pm_\mu,\ t}_{\text{still charged}}$ all have comparable $\sim H_{inf}$ masses

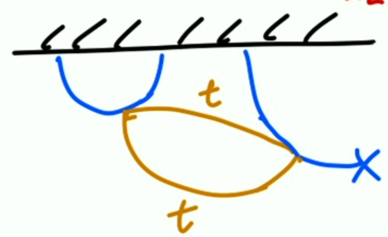


$f_{NL} \lesssim 10^{-1}$



$f_{NL} \lesssim 10^{-2}$





Loop suppressed

IF signals observable, the mass ratios eg. $\frac{m_W}{m_t} = \frac{g}{2y_t}$ would be unmodified, except for calculable RG effects!

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HIGGSED GAUGE THEORY

$$\mathcal{L}_{int.} \supset \sqrt{-g}\, g^{\mu\nu}\left\{\frac{\partial_\mu\phi\,\partial_\nu\phi\,\rho}{\Lambda} + \frac{\partial_\mu\phi\, h^\dagger D_\nu h\,\rho}{\Lambda^2}\right\}$$

mediator

$\Lambda^2 > \dot{\phi}_{cl}$

Creminelli '03

integrate out ρ, $m_\rho > H$

$\langle h \rangle \equiv v$

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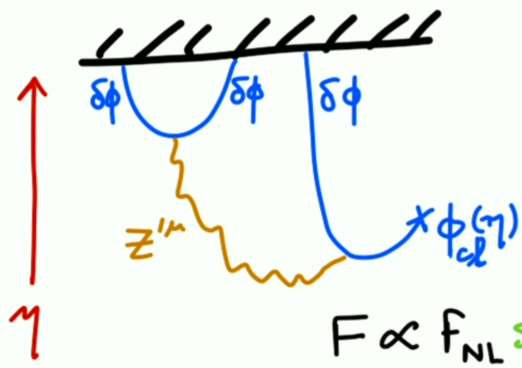

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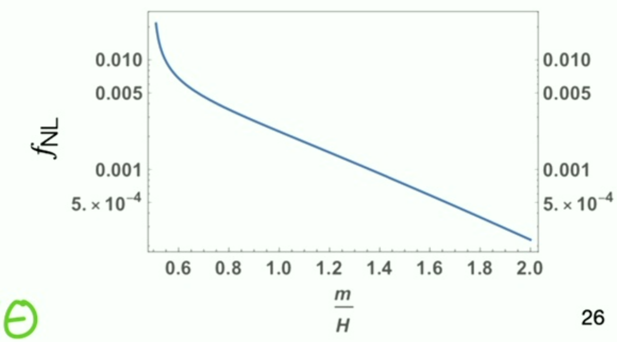

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COSMOLOGICAL COLLIDER PHYSICS &
THE CURVATON

Kumar, Sundrum '19

(or how to have bigger signals WITH theoretical control)

Single-Field (ϕ) Slow-Roll Inflation $\ni \partial_t \phi \sim (60H)^2$

$\Rightarrow$ Non-renormalizable suppression $\Lambda > 60H$ for EFT control.

Creminelli '03

Curvaton (χ) Scenario:

Enqvist, Sloth '01; Lyth, Wands '01; Moroi, Takahashi '01

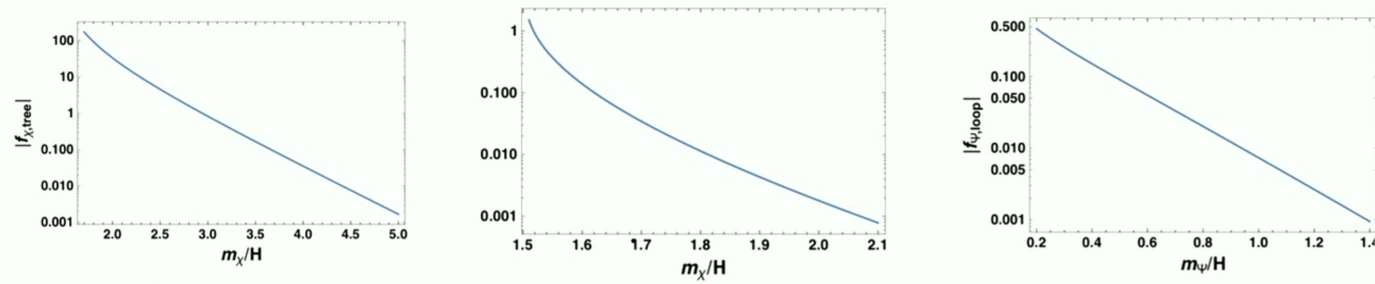
Job of driving inflation, $\phi_{cl}(\eta)$, $V_{inf.}(\phi_{cl})$ separated from job of seeding primordial fluctuations: $\delta\chi_{quantum} > \delta\phi_{quantum}$

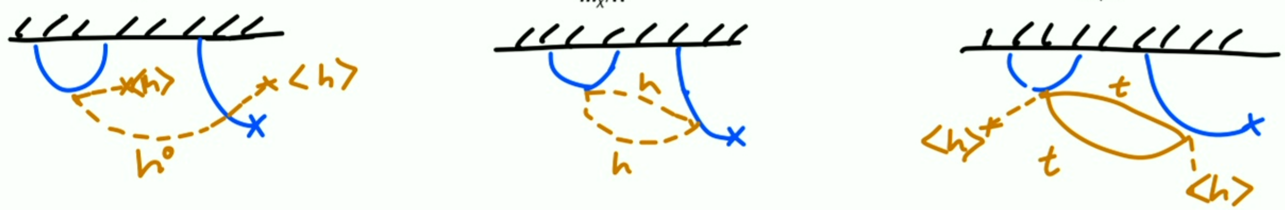
$$\chi \xrightarrow{\text{decay}} SM$$

$\partial_t \chi_{cl} \sim H^2$, $V_{curvaton}(\chi_{cl}) \ll V_{inflaton}(\phi_{cl}) \Rightarrow \boxed{\Lambda_{\substack{\text{non-}\\\text{renormalizable}}} \gtrsim \text{Few } H}$

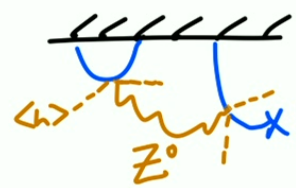
$$\mathcal{L}_{\text{interactions}} \sim \sqrt{-g}\,\rho\,\Big\{ g^{\mu\nu}\partial_\mu\chi\,\partial_\nu\chi/\Lambda + h^\dagger h + \bar{t}_R\, h \begin{pmatrix} t \\ b \end{pmatrix}_L \Big/ \Lambda + g^{\mu\nu}\partial_\mu\chi\, h^\dagger D_\nu h/\Lambda^2 + \dots \Big\}$$

massive mediator





$$f_{NL}^{Z^0} \sim O(1)$$



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"Chemical Potential"

Radiative stability of $V_{inf}(\phi)$:

$\Rightarrow$ Derivative couplings $(\partial\phi)^n \mathcal{O}_{\text{heavy particles}}$

Special case $n=1$: $\frac{\partial_\mu \phi}{\Lambda} J^\mu_{\text{heavy}} \supset \frac{\dot{\phi}_{cl}}{\Lambda} J^0_{\text{heavy}}$

Inflationary heavy particle production $\sim$ Boltzmann-ish $\sim e^{-m/T_{\text{Hawking}}}$

$\uparrow H/2\pi$

EFT control $\Rightarrow$ $\lambda \equiv \frac{\dot{\phi}_{cl}}{\Lambda} < \Lambda$ $\quad \lambda < \sqrt{\dot{\phi}_{cl}} \sim 60H$

Applied to non-zero spin heavy particles:

Chen, Wang, Xianyu '18; Adshead, Pearce, Peloso, Roberts, Sorbo '18; Wang, Xianyu '19; Hook, Huang, Racco '19

(Complex) Scalar Chemical Potential

Bodas, Kumar, Sundrum '20

$$J_\mu = \sigma^* D_\mu \sigma \,, \quad \sigma = \sigma_1 + i\sigma_2$$

2 real heavy scalar

Eliminate by "gauge transformation":

$$\sigma \longrightarrow e^{i\phi/\Lambda}\sigma$$

∴ only physical in non-symmetric terms:

$$\mathcal{L} \supset \mathcal{O}_{\cancel{sym}}(\sigma, \sigma^*) \longrightarrow e^{iq\phi/\Lambda}\mathcal{O}_{\cancel{sym}}(\sigma, \sigma^*)$$

$$\approx e^{\frac{iq\langle\dot\phi\rangle_{cl} t}{\Lambda} + iq\delta\phi/\Lambda}\, \mathcal{O}_{\cancel{sym}}(\sigma, \sigma^*)$$

v. high background frequency!

$$= e^{iq\lambda t}\, e^{iq\delta\phi/\Lambda}\, \mathcal{O}_{\cancel{sym}}(\sigma, \sigma^*)$$

"Chemical Potential"

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$T_{\text{Hawking}} = H/2\pi$

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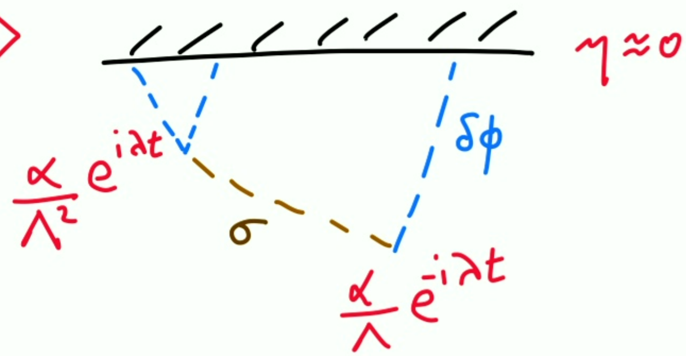
NEW PRIMORDIAL MAPS?

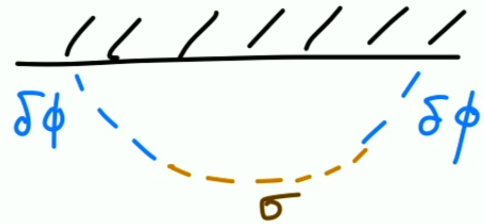
- CMB, LSS, (21-cm) consistent with single primordial source of fluctuations, via inflaton reheating
- New "map" of BSM origin may give complementary insights into inflation & extreme particle physics.
- Improved cosmic variance limitations?

Most simply:

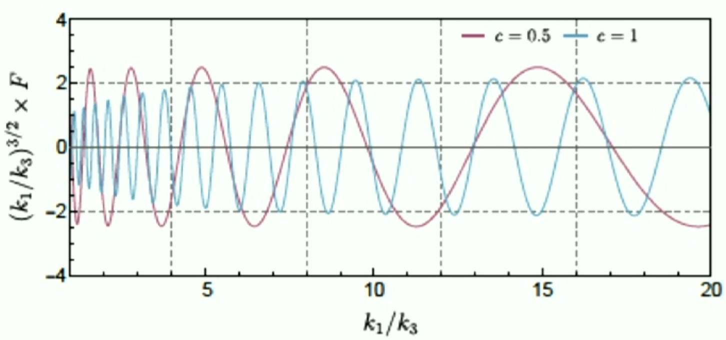
$$\mathcal{L} \supset \alpha(\sigma + \sigma^*) \longrightarrow \alpha e^{i\lambda t} e^{i\delta\phi/\Lambda} \sigma + \text{conjugate}$$

$\Rightarrow$





$\Rightarrow \frac{\alpha}{\Lambda} < 0.1\lambda$ to not be visible in CMB.



M ~ 30H
M ~ 5H
$\lambda \sim 40H$

"PRISTINE" COSMOLOGICAL STOCHASTIC GW MAPS

Essentially no cosmic variance limit in principle: spherical harmonics $\ell < 10^{14}$ outside horizon at time of PT & GW production!