# COSMOLOGY & UNIFICATION

Raman Sundrum
University of Maryland
in collaboration with Soubhik Kumar

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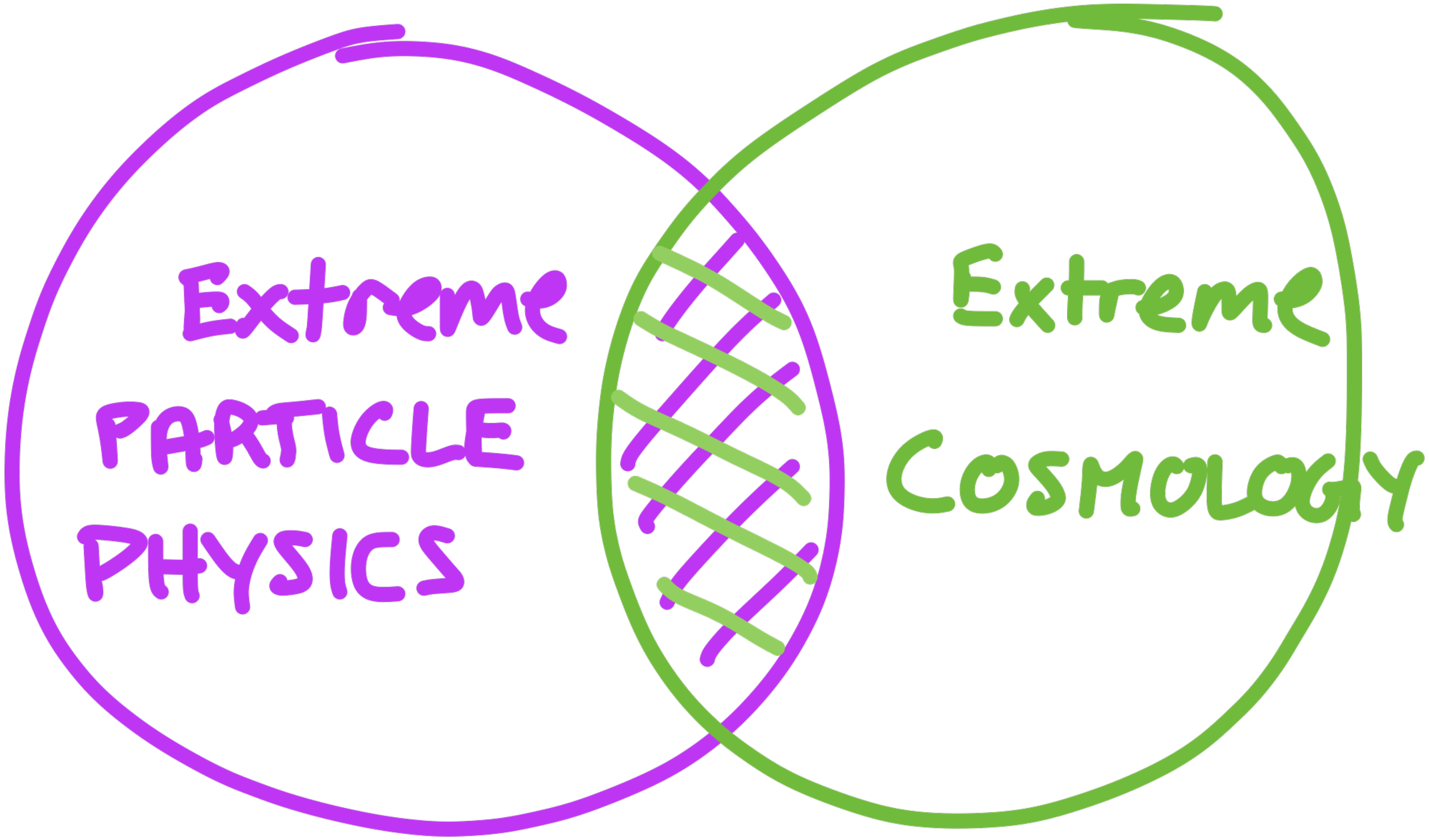
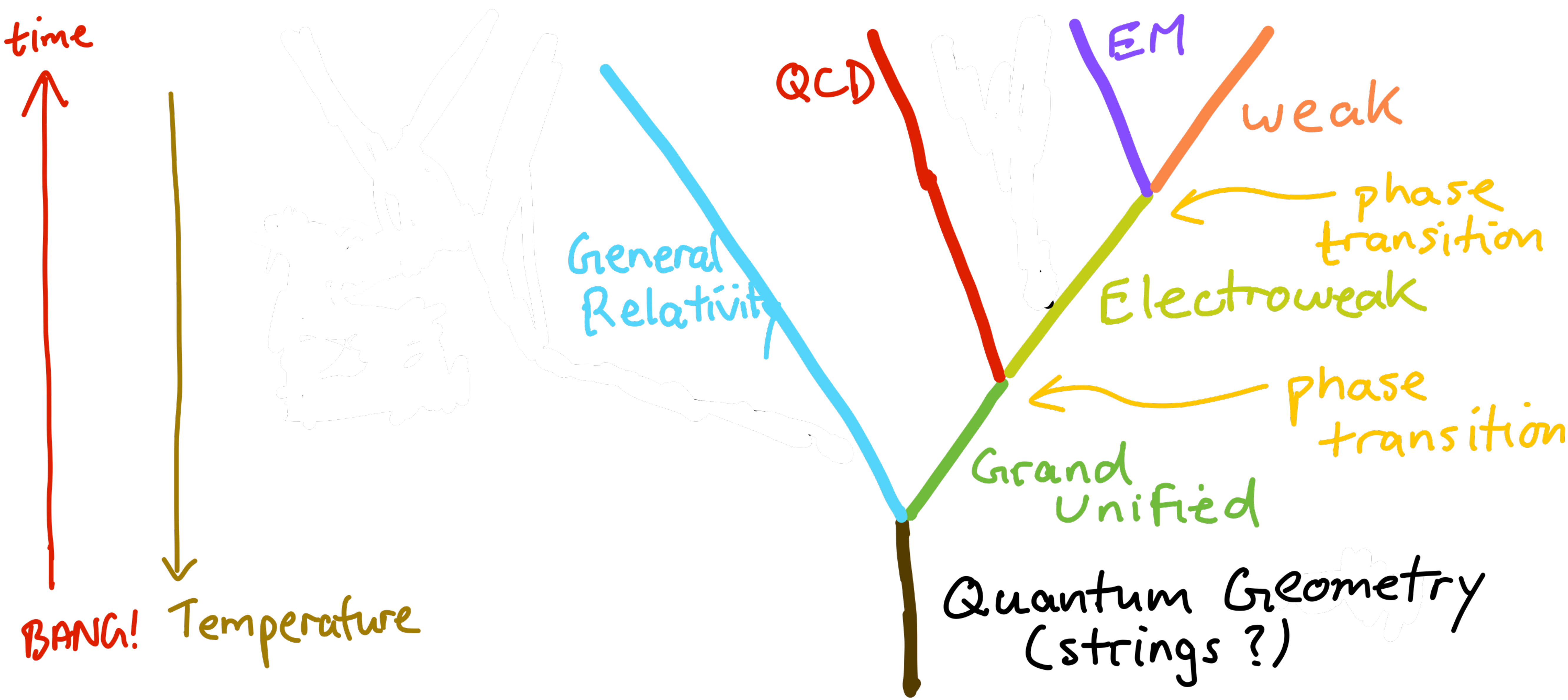

Extreme
PARTICLE
PHYSICS
Extreme
COSMOLOGY

# FAMILY TREE OF FUNDAMENTAL PHYSICS



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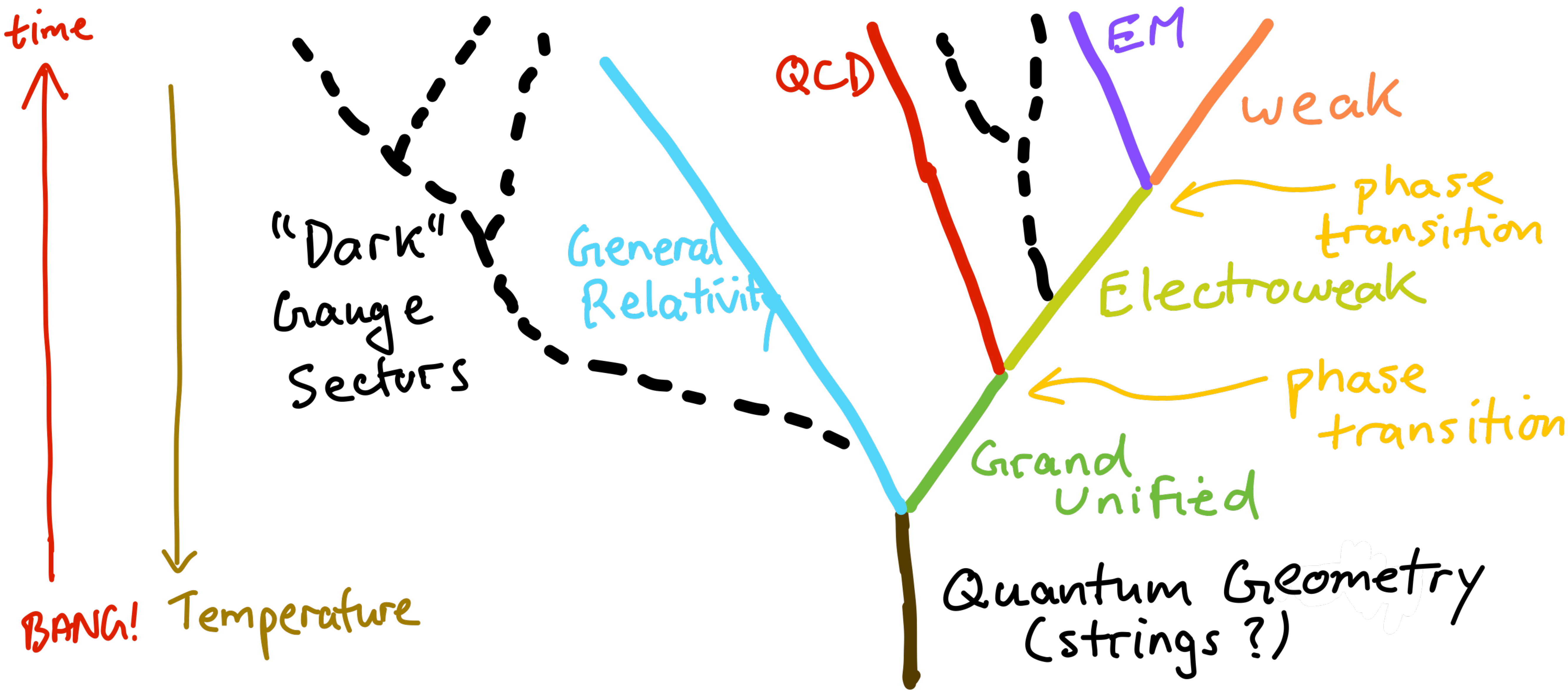
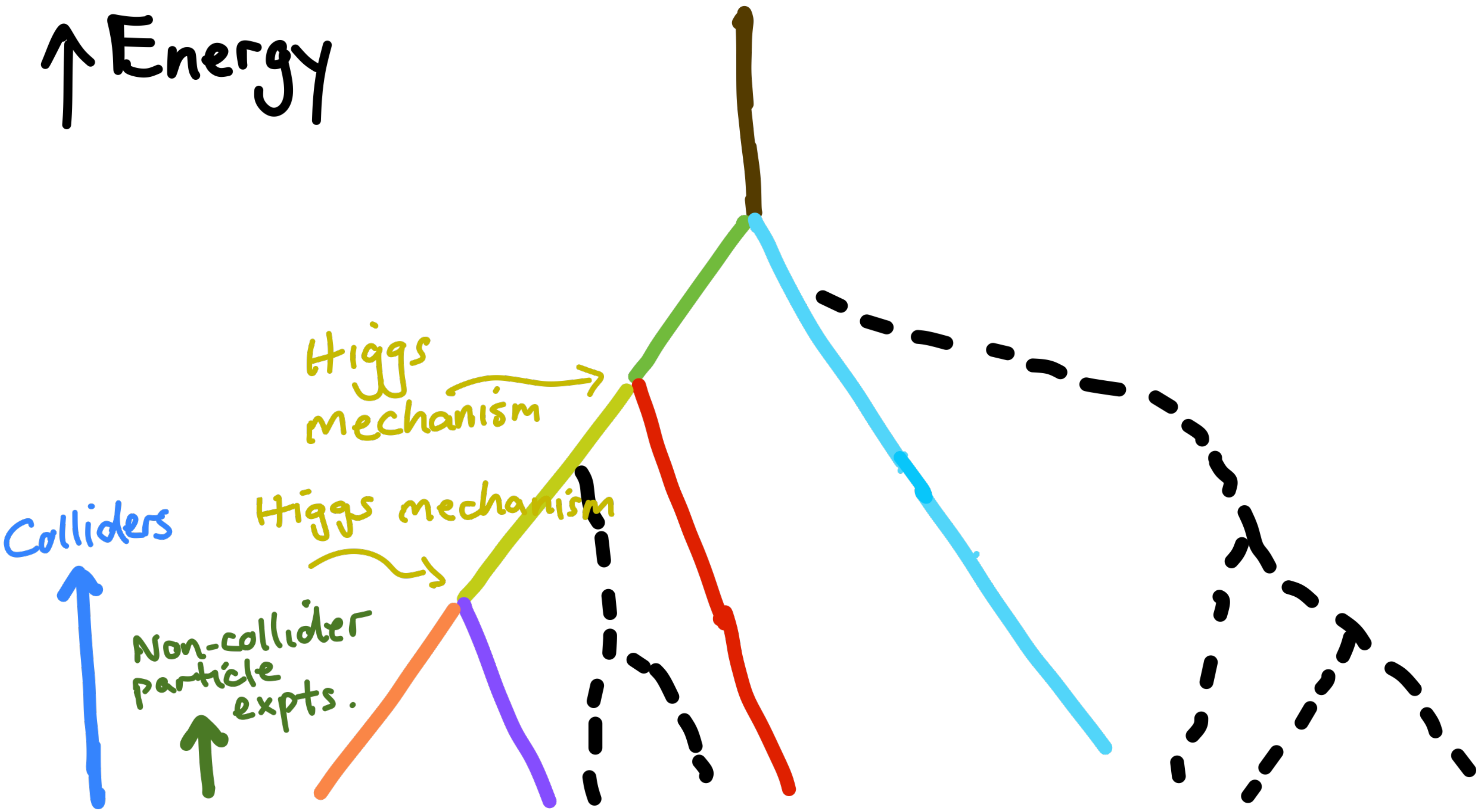


# FAMILY TREE OF FUNDAMENTAL PHYSICS

Brout-Englert-Higgs = Unification spelled backwards



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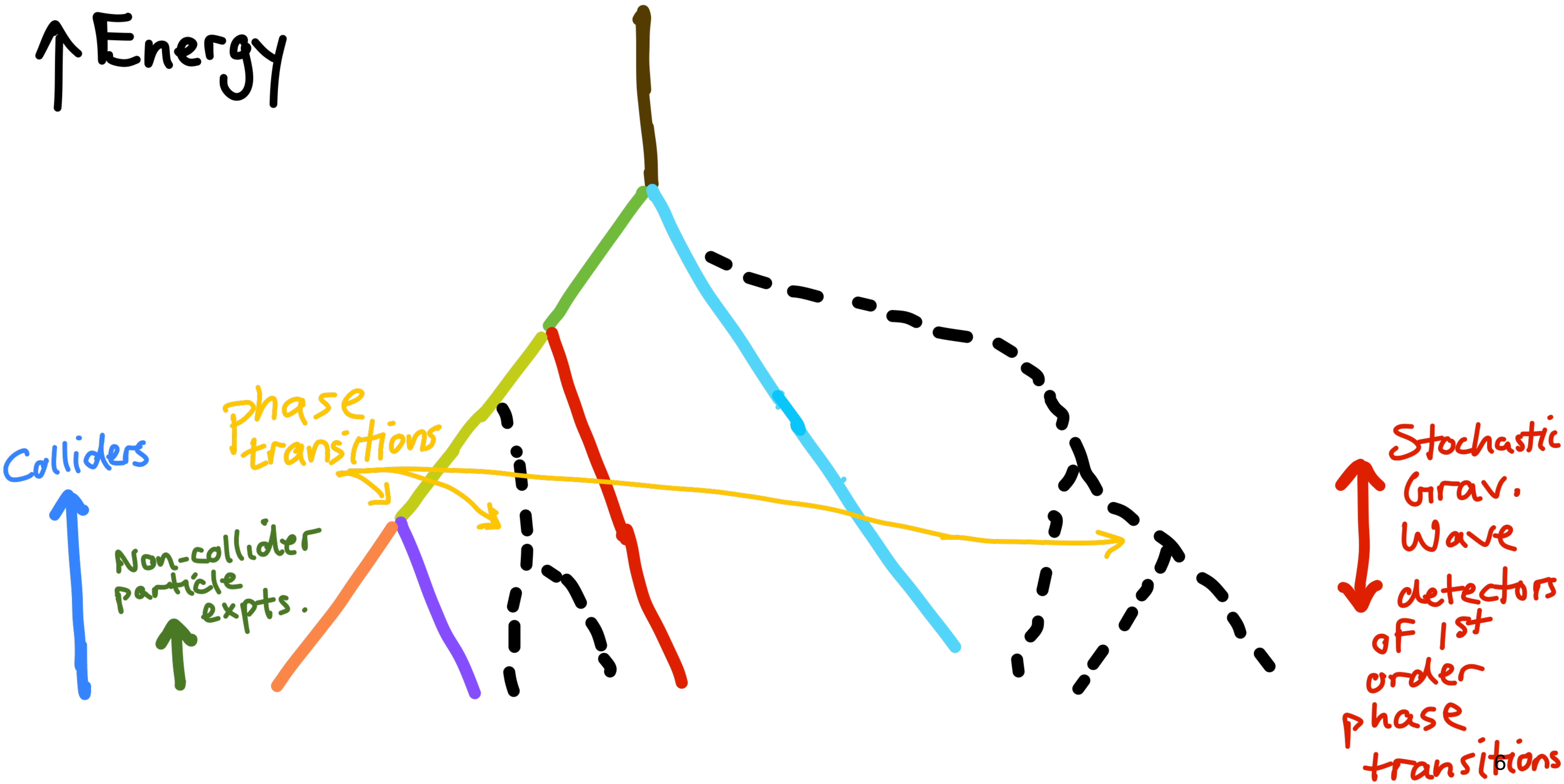

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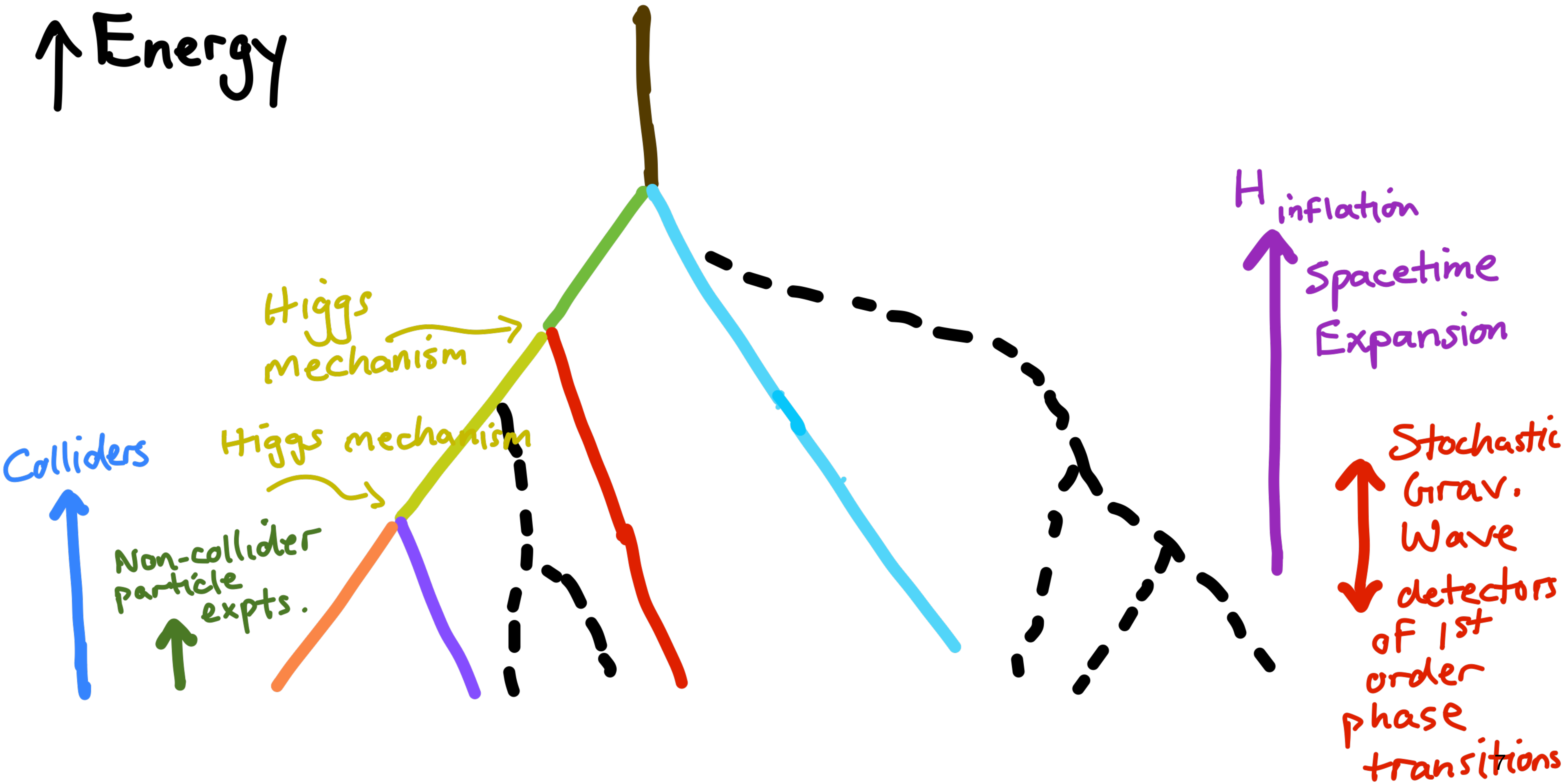
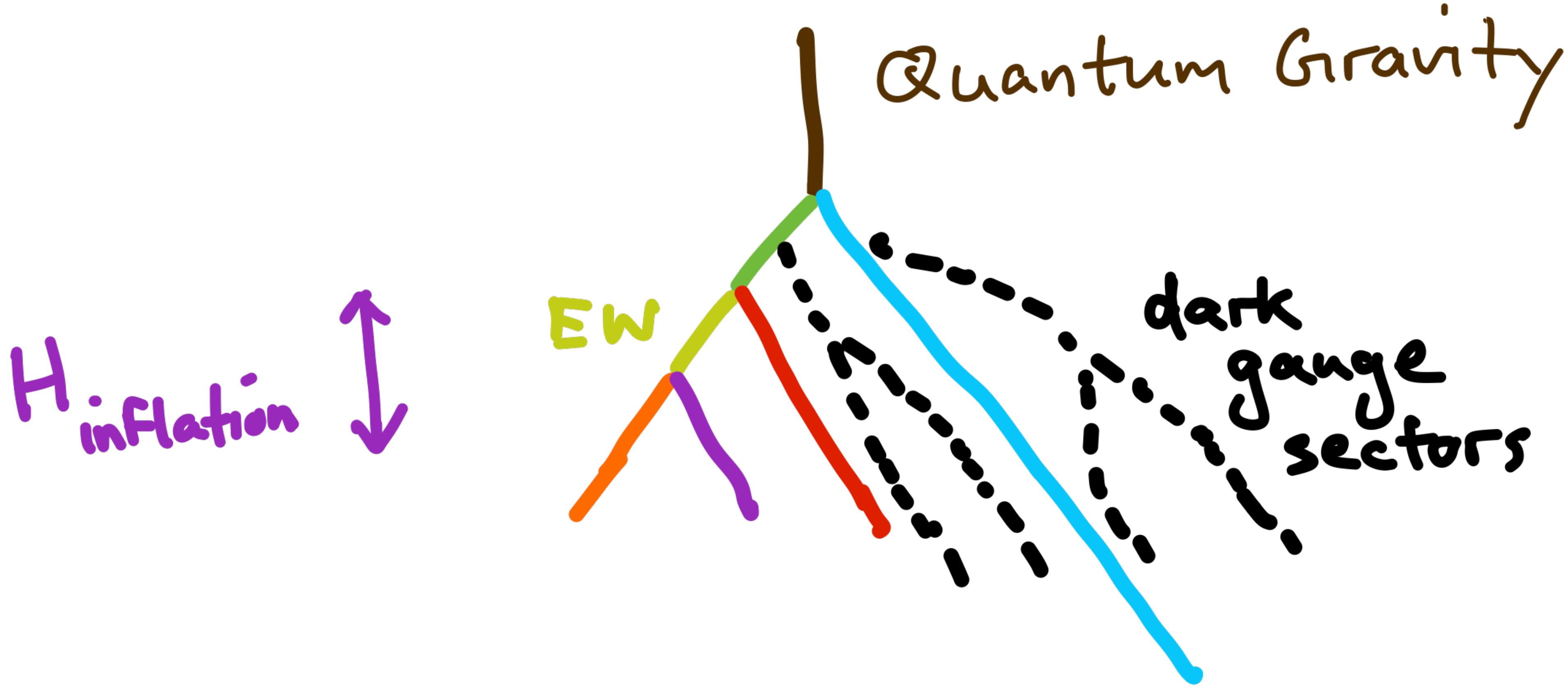
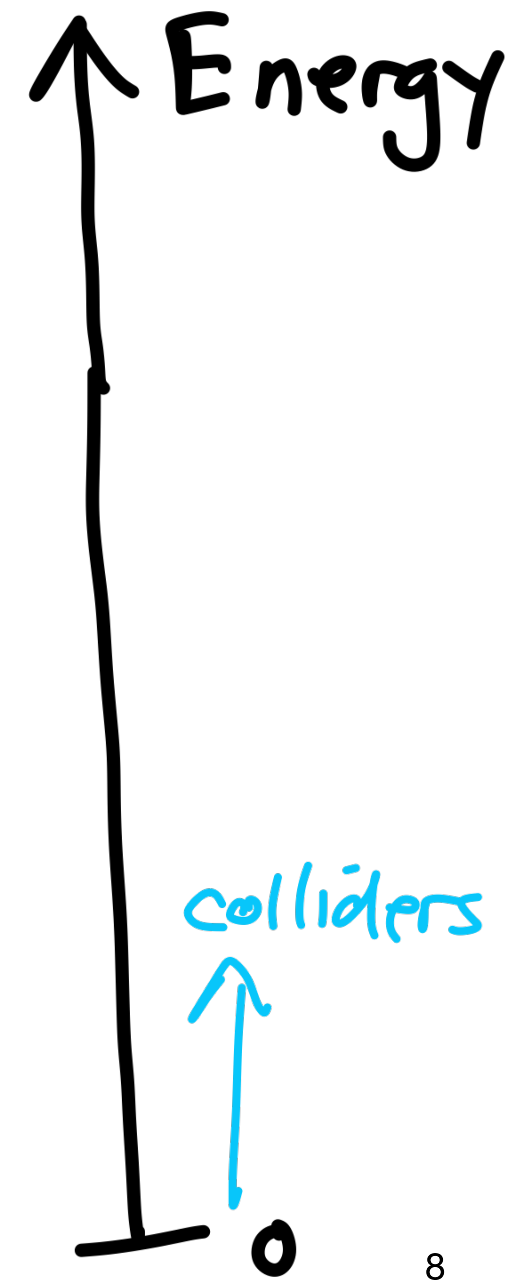


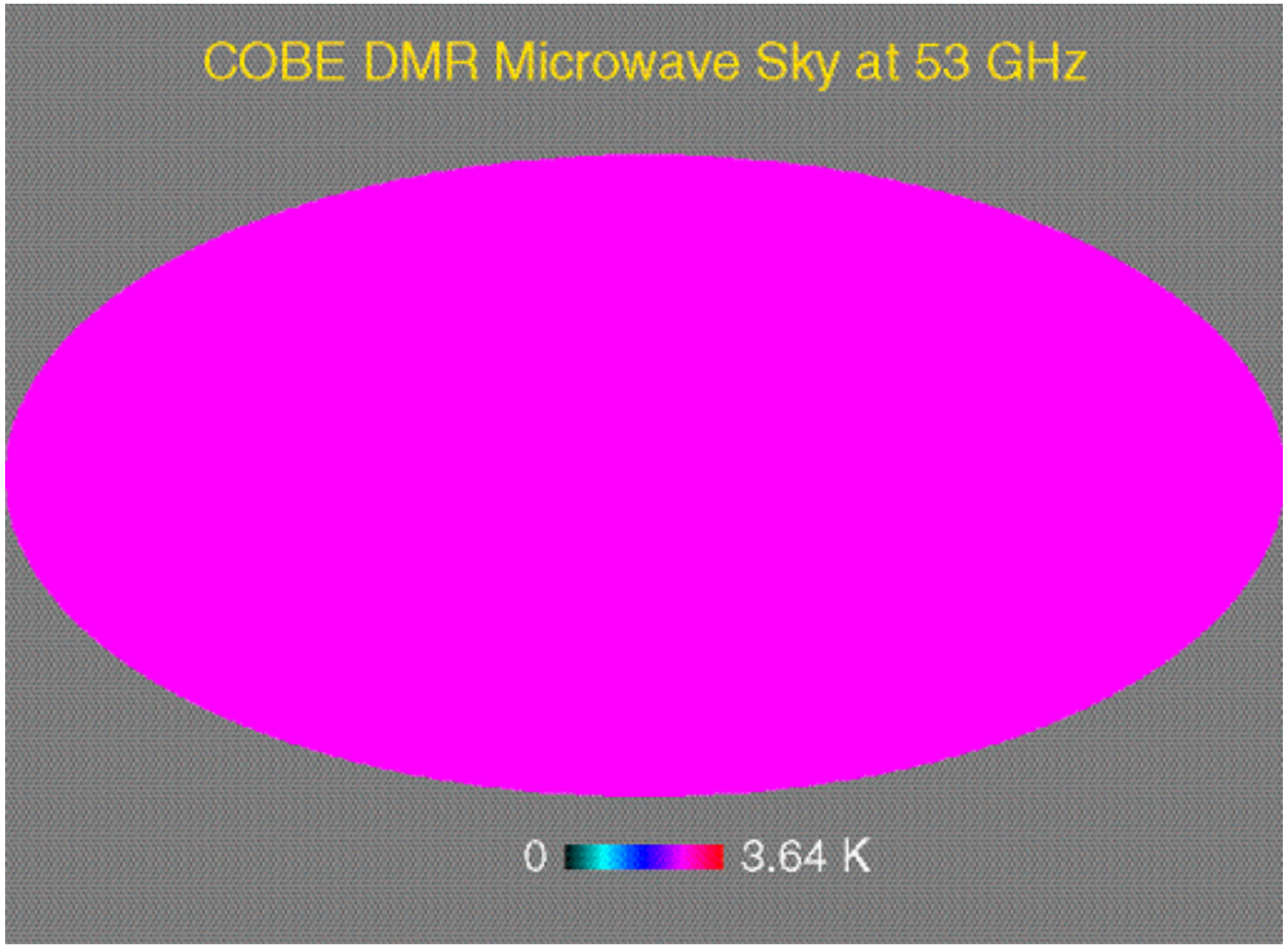
# FAMILY TREE AS A SAPLING




Mass/Higgsing scales naturally much higher during inflation

# Cosmic Microwave "Snapshot" of Early Universe at photon decoupling




scale factor

$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2$$

$$\equiv a^2(\eta)\left(d\eta^2 - d\vec{x}^2\right)$$

conformal time

Comoving $\vec{x}$

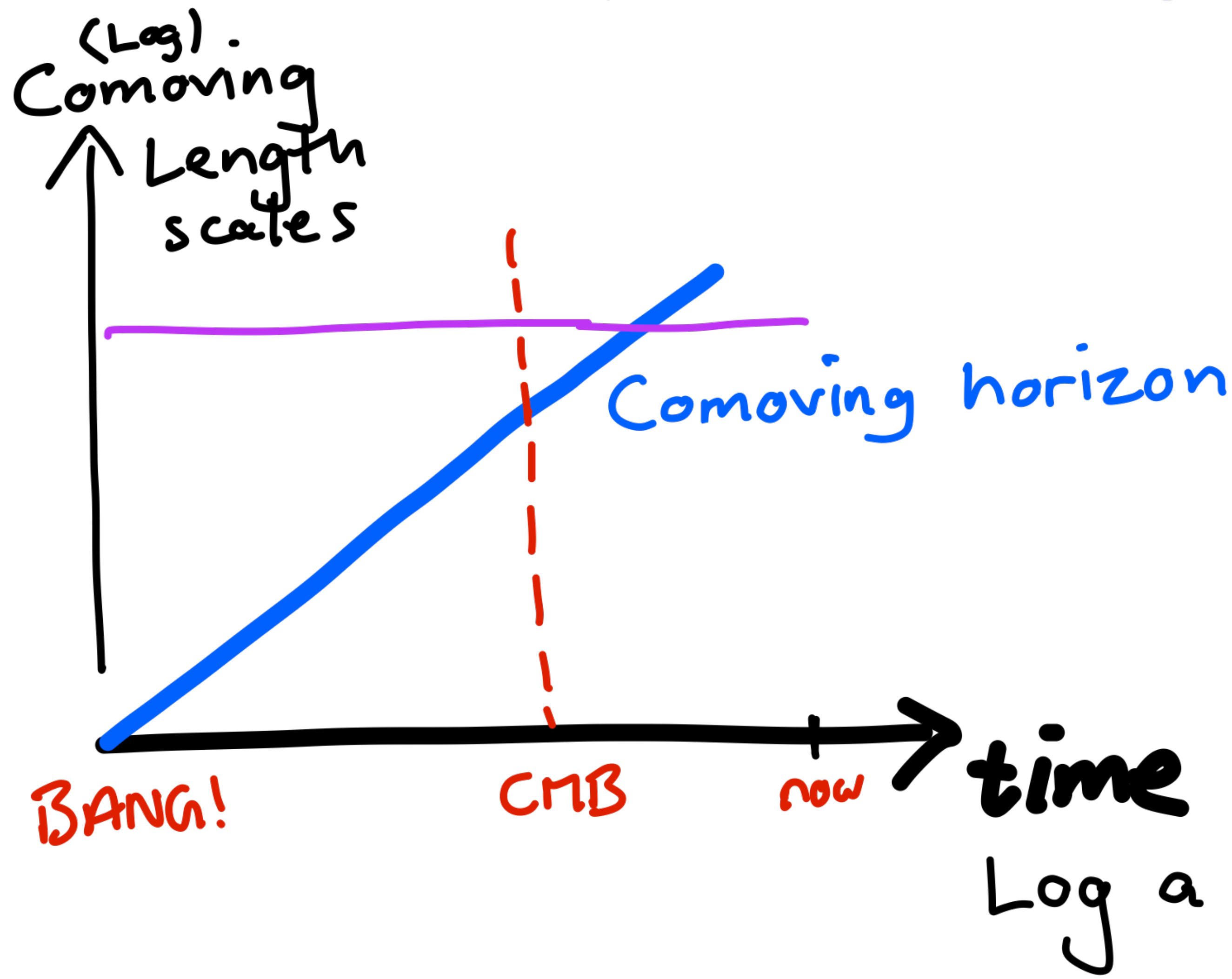
$\Rightarrow -i\nabla_{\vec{x}} \equiv \vec{k}$

Momentum CONSERVED

# HORIZON PROBLEM as motivation for COSMIC INFLATION

Light rays $\Rightarrow d\eta^2 = d\vec{x}^2 \Rightarrow \eta$ is co-moving horizon

Length scales we see today would not have equilibrated when CMB was produced, as they were out of causal contact



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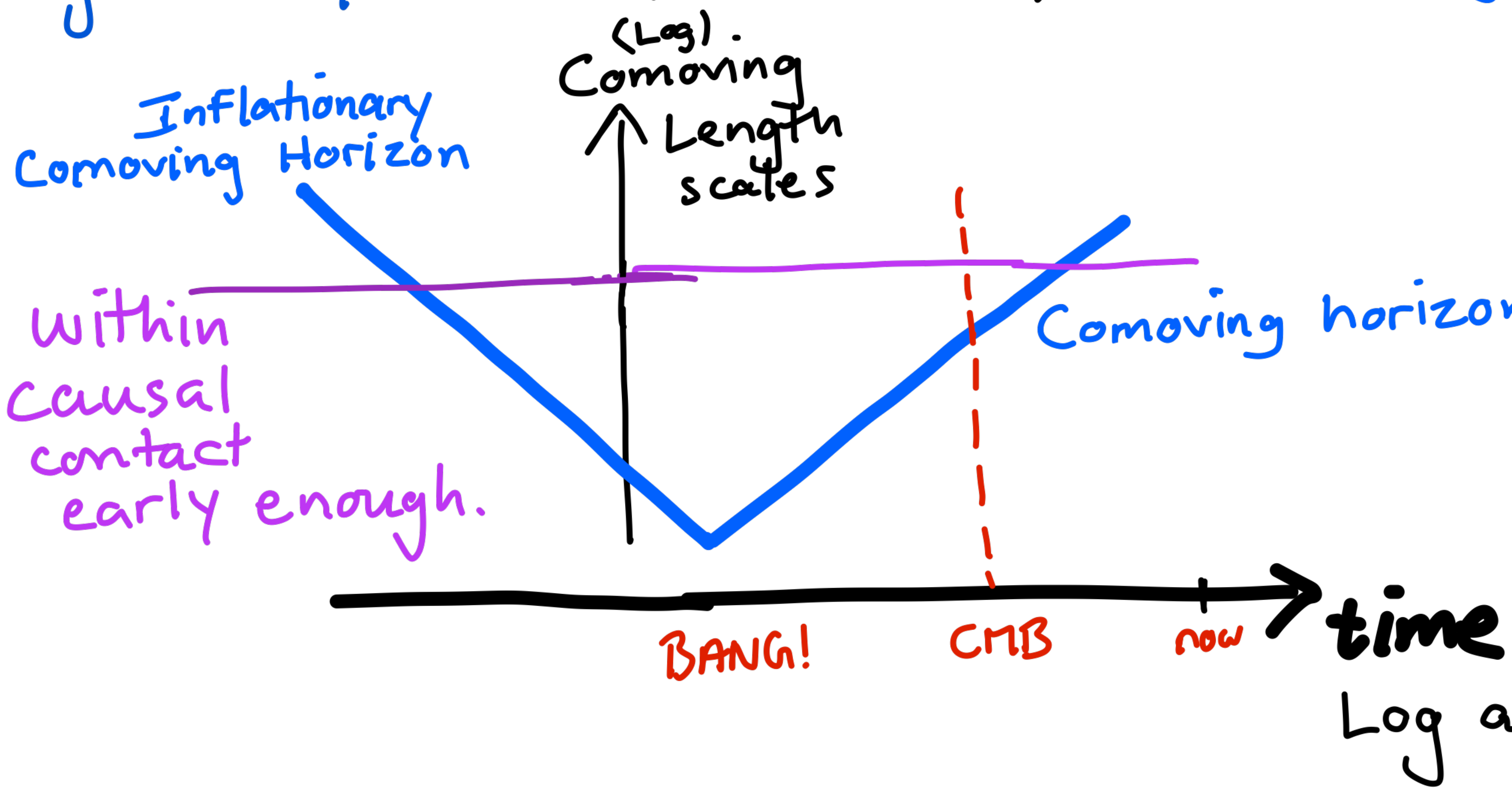
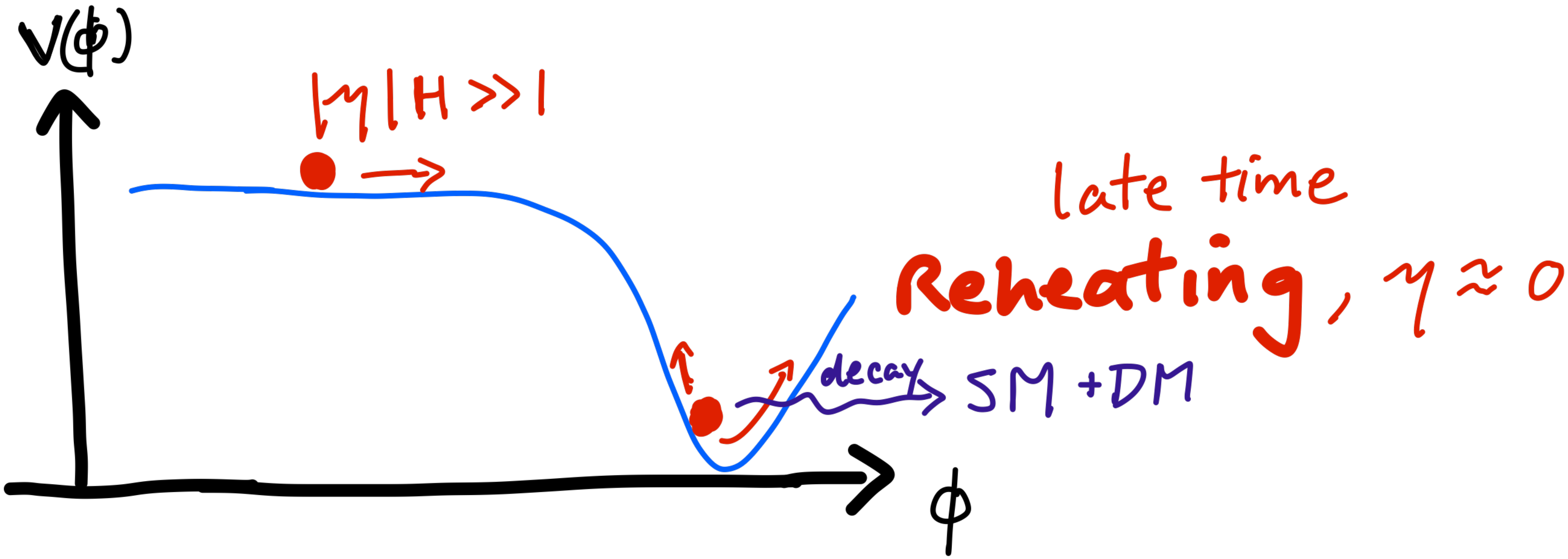


# SLOW-ROLL INFLATION




Approximately de Sitter phase

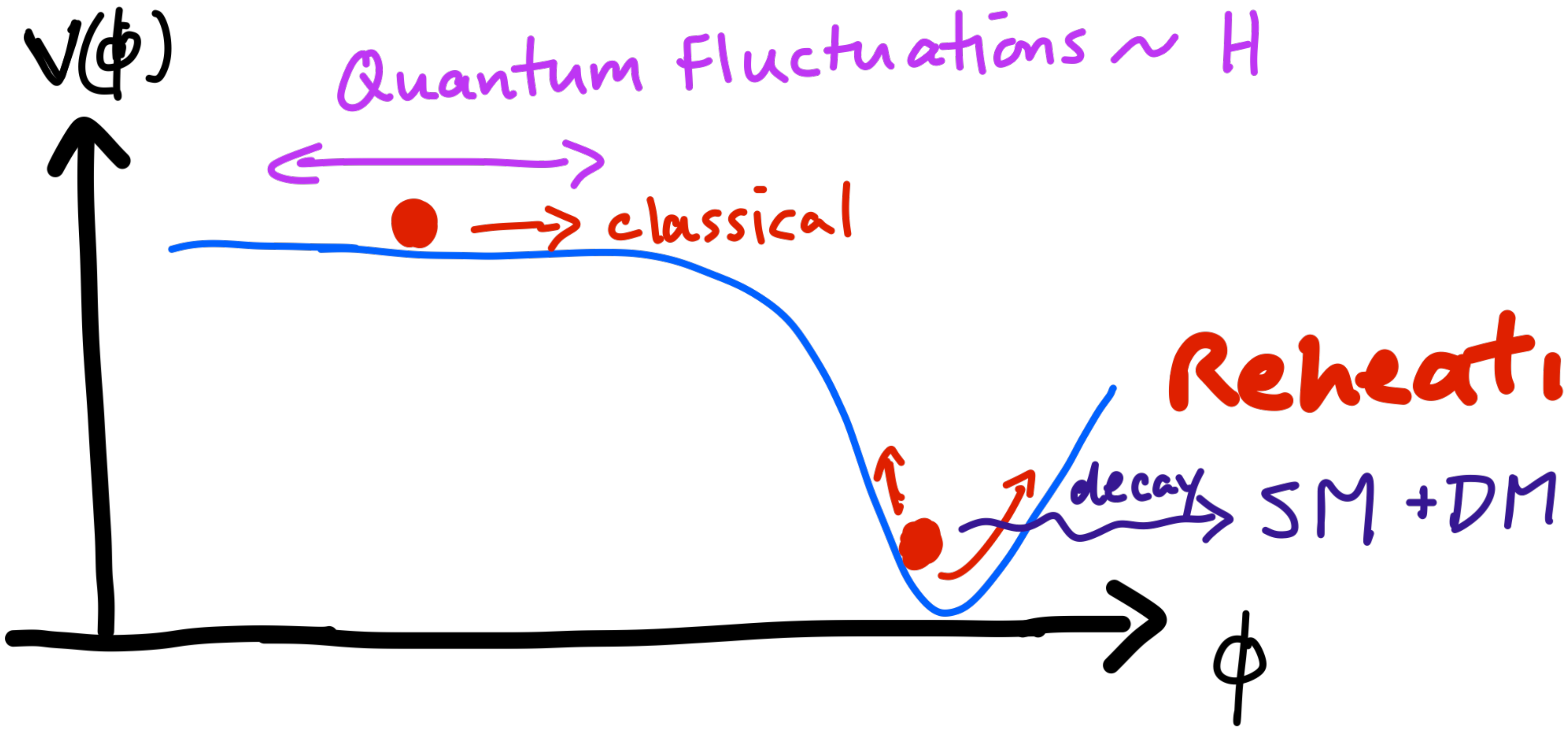
$$ds^2 \approx dt^2 - e^{2Ht} d\vec{x}^2$$

$$\equiv \frac{d\eta^2 - d\vec{x}^2}{H^2 \eta^2}, \quad -\infty < \eta = -\frac{e^{-Ht}}{H} < 0$$

$$H^2_{\text{inflation}} \sim G_N V_{\text{plateau}} \approx \text{constant}$$

**$H_{\text{inf.}} \equiv 1$ units**

# SLOW-ROLL INFLATION




**Reheating** $\eta \approx 0$

Approximate de Sitter phase

$$ds^2 \approx \frac{d\eta^2 - d\vec{x}^{\,2}}{\eta^2}$$

Time translation inv.

$\rightarrow$ "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 $\eta \approx 0$,

$$\boxed{\vec{x} \to e^{\lambda}\vec{x}}$$

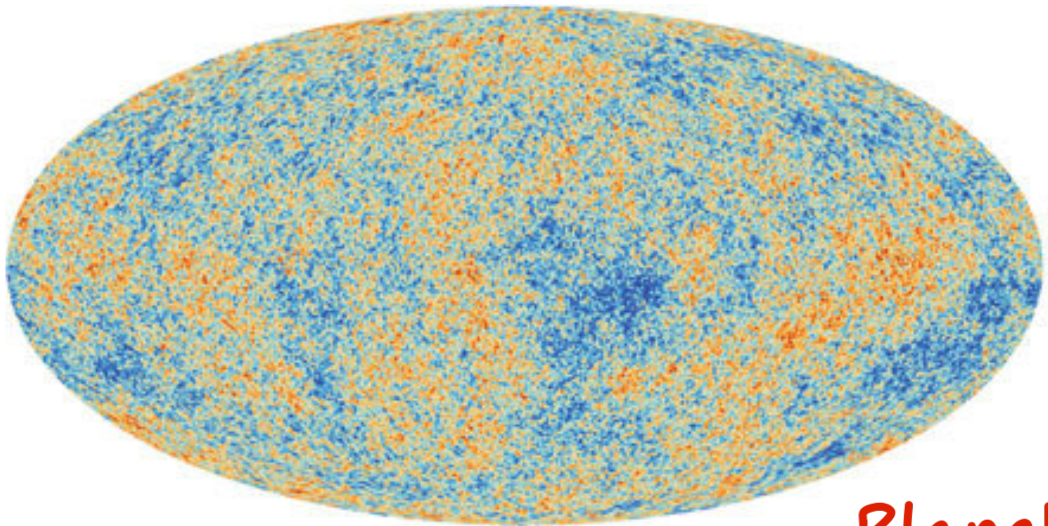
# OBSERVED INHOMOGENEITIES

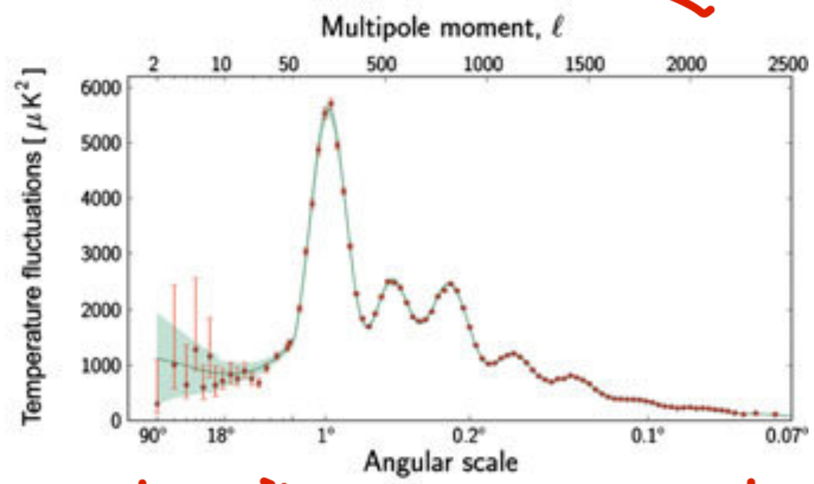
attractively fit by evolution

$\langle T(\theta_1,\varphi_1)\, T(\theta_2,\varphi_2) \rangle$

$\downarrow$

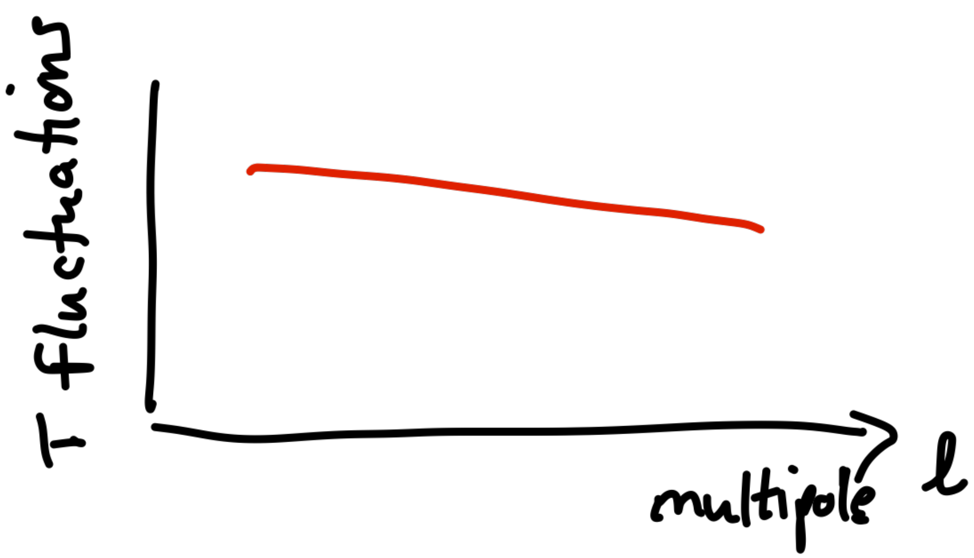
spherical harmonics



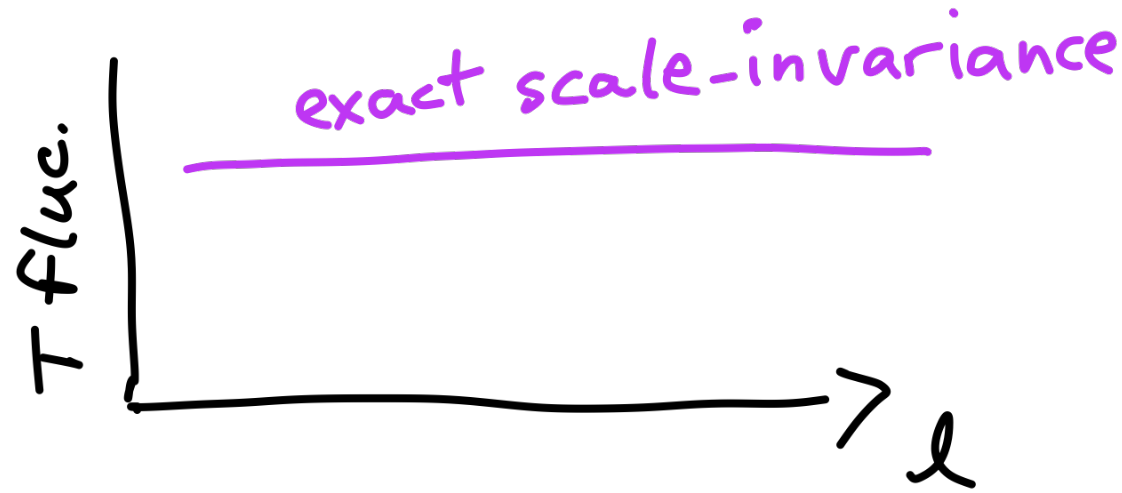



Planck Satellite, Temperature fluctuations

from approximately scale-invariant Gaussian
PRIMORDIAL FLUCTUATIONS




$\approx$



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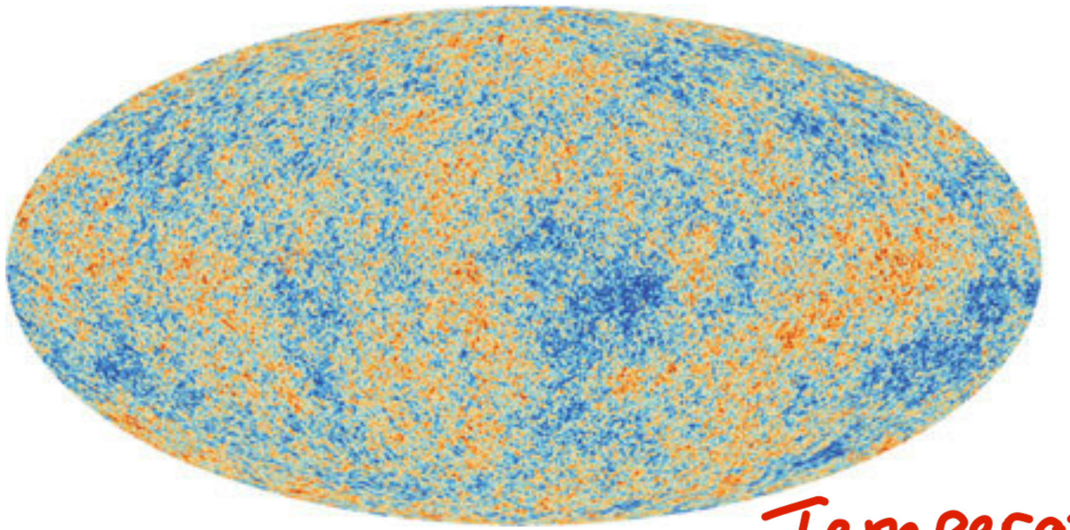
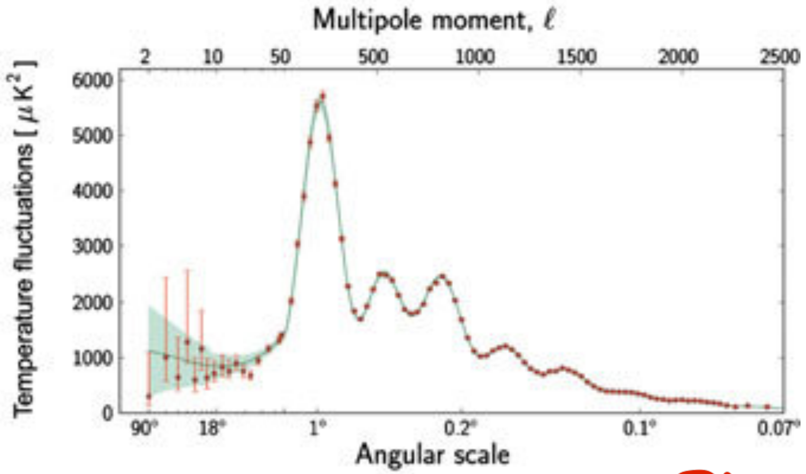





Temperature fluctuations, Planck Satellite

from approximately scale-invariant Gaussian

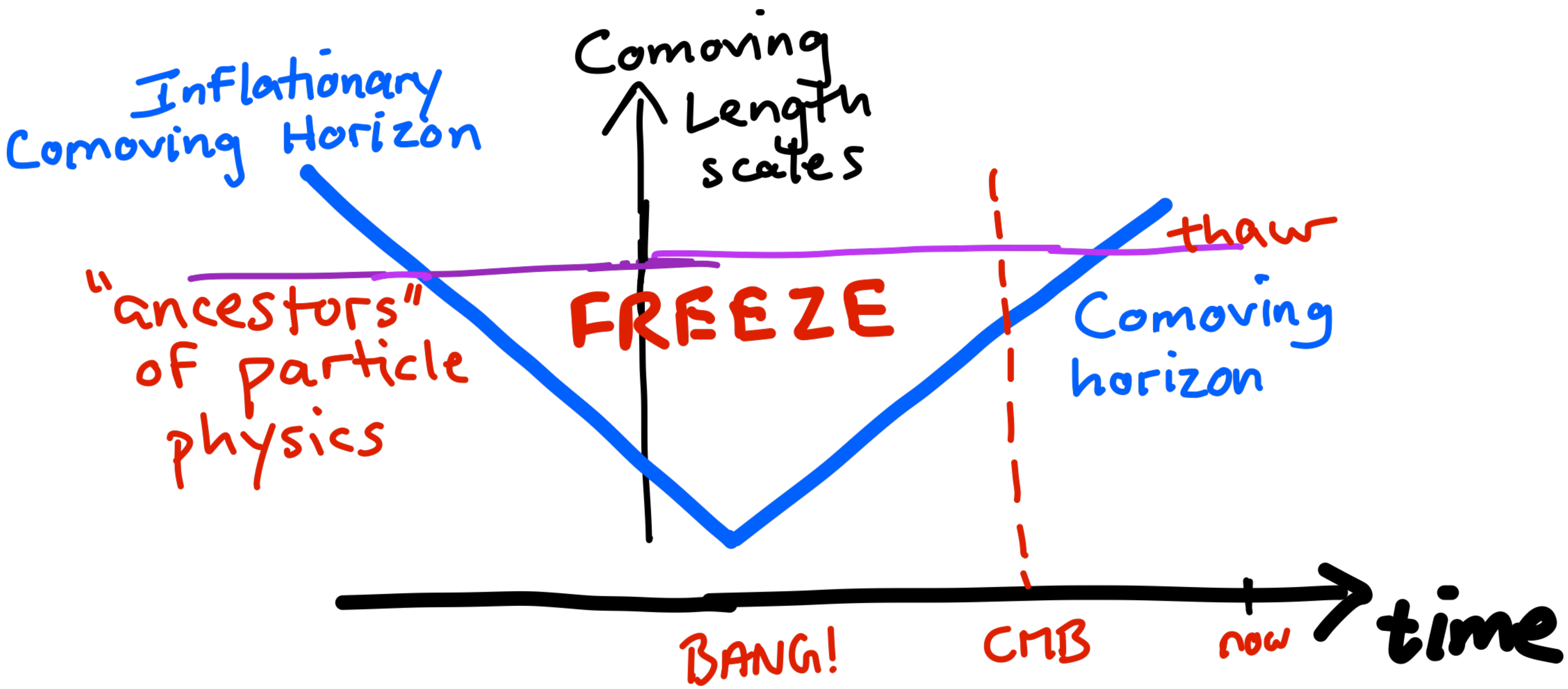
# PRIMORDIAL FLUCTUATIONS

$$\boxed{H_{inflation} < 5\times10^{13}\,\text{GeV}} \equiv 1 \text{ units}$$

$$\delta T(\vec{x}) \sim \delta t(\vec{x})_{reheat} \sim -\frac{\overset{H}{\widetilde{\delta\phi(\vec{x})}}}{\frac{d\phi}{dt}} \Rightarrow \boxed{\frac{d\phi_{cl}}{dt} \sim 10^4}$$

# OPPORTUNITY

to see $e^{-im_{\text{ancestor}}t}$



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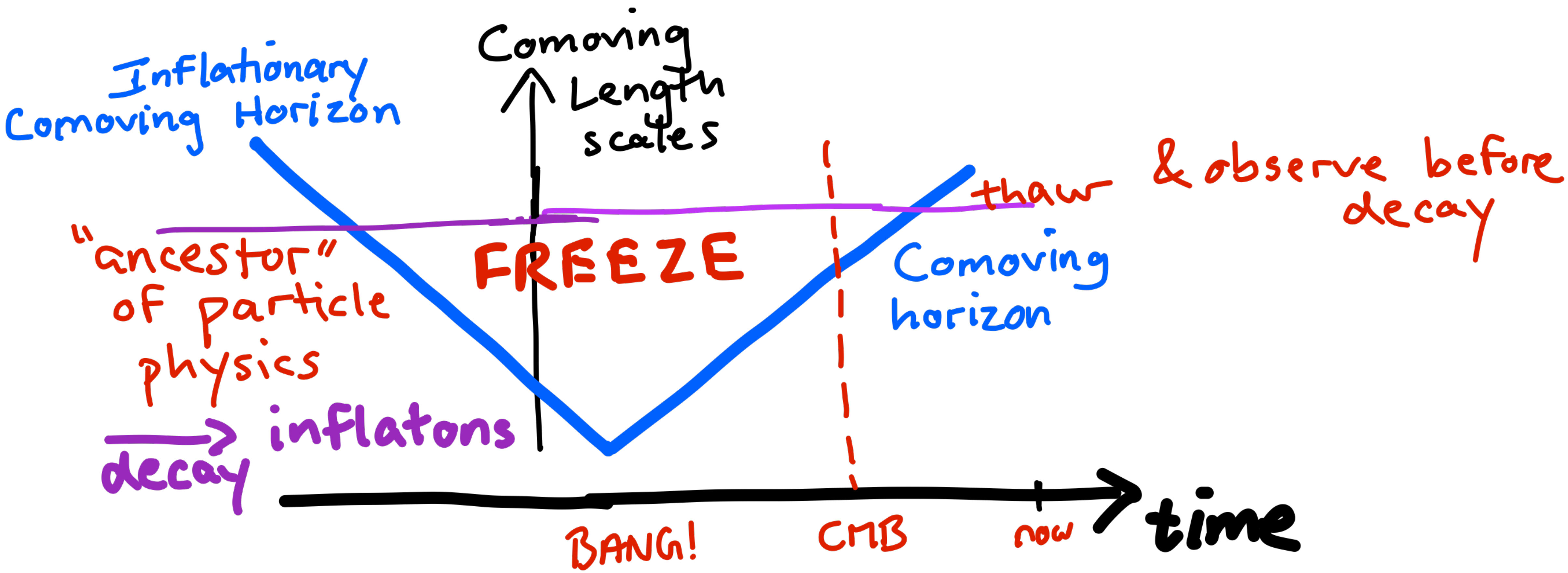

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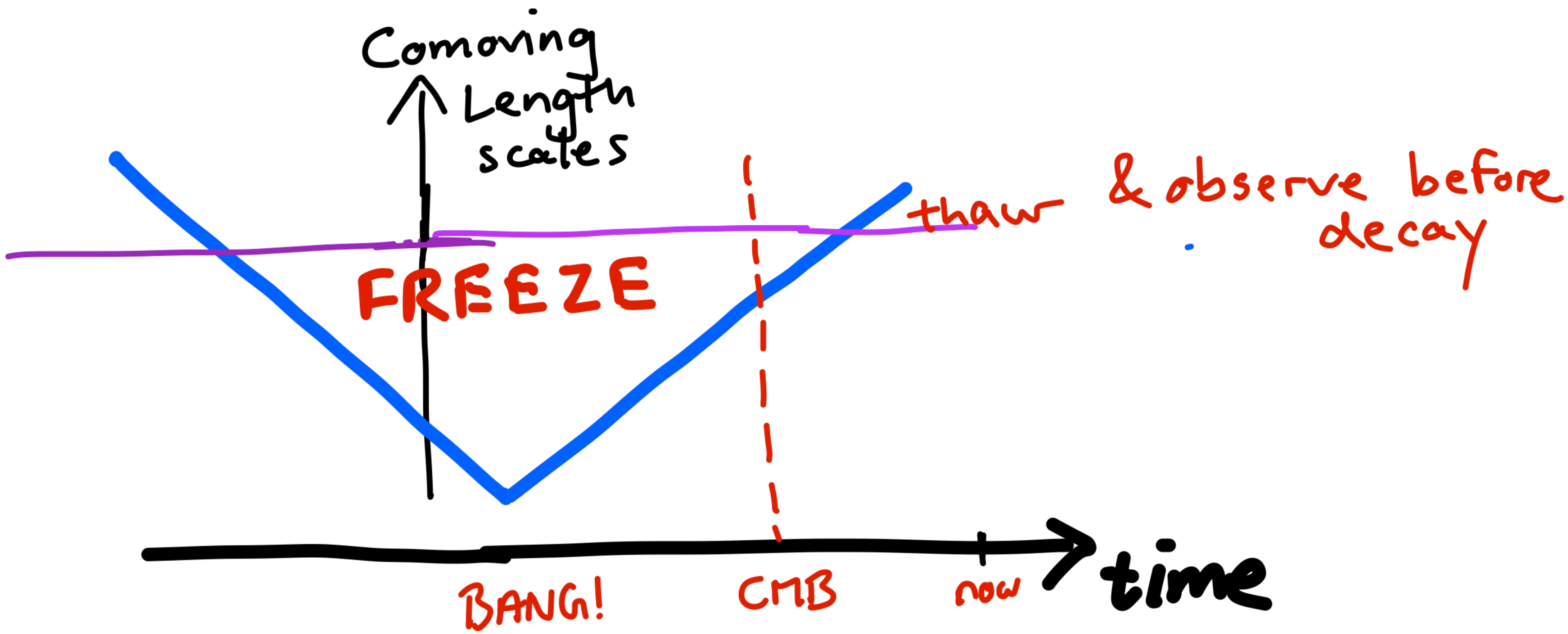
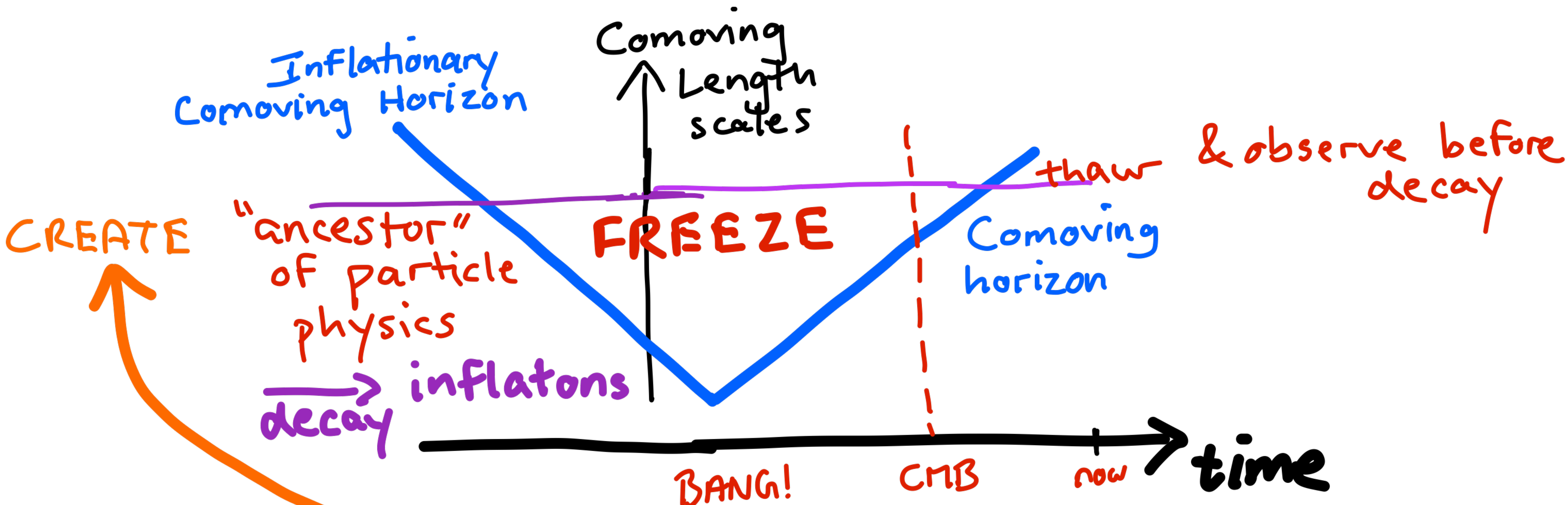



But isn't this empty, everything inflated away?!

# OPPORTUNITY




QUANTUM MECHANICS

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

Planck

# MASSIVE PARTICLES IN DE SITTER

$$S = \int d^3\vec{x}\, d\eta \left\{ \sqrt{-g}\, g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - m^2 \chi^2 \right\}$$
$$= \int d^3\vec{k}\, d\eta \left\{ \frac{1}{\eta^2} |\partial_\eta \chi_{\vec{k}}|^2 - \frac{\vec{k}^2}{\eta^2} |\chi_{\vec{k}}|^2 - \frac{m^2}{\eta^4} |\chi_{\vec{k}}|^2 \right\}$$

Equations of motion of Bessel type:

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

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

positive energy (& boosted by blue shift)

BUT ...

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

# MASSIVE PARTICLES IN DE SITTER

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Pair creation amplitude at $\eta \sim -m/k$:

$A \sim e^{-\pi m}$ "Boltzman" suppression

$|A|^2 \sim e^{-m/T_{\text{Hawking}}}$

$H/2\pi$

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

positive energy (& boosted by blue shifted)

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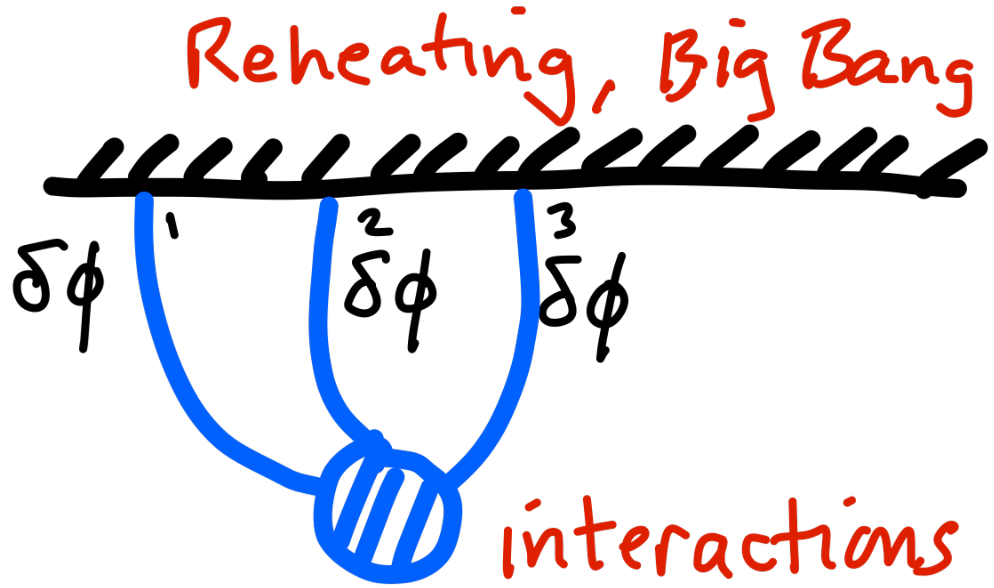
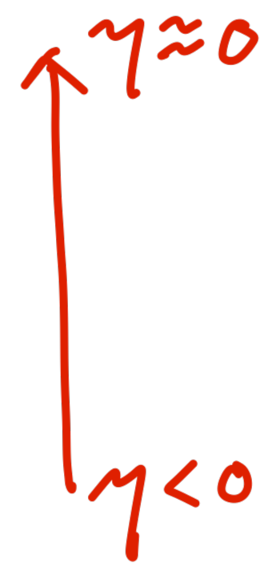
# PRIMORDIAL NON-GAUSSIANITIES from "in-in" correlators with interactions



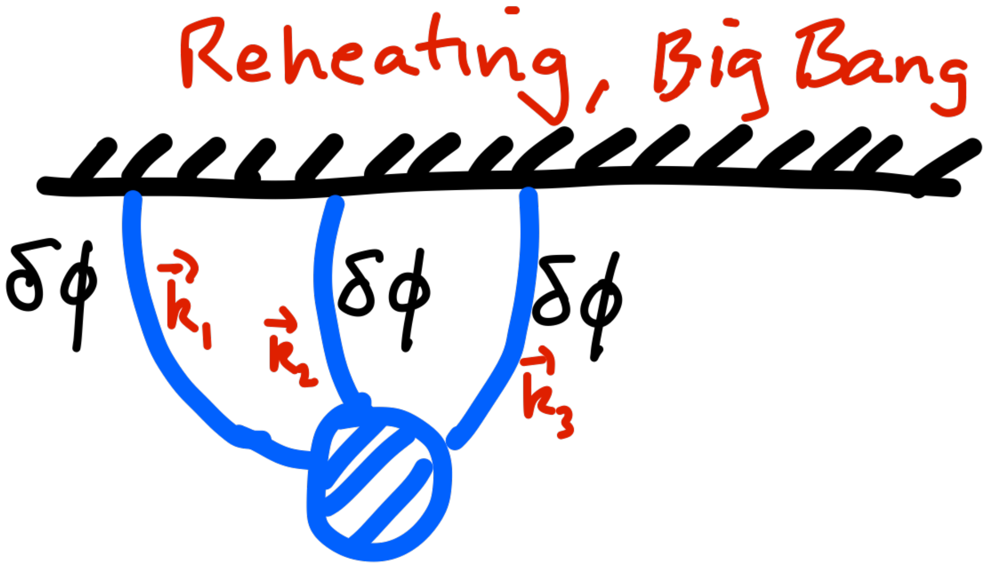

$$\langle \delta T(\vec{x}_1)\, \delta T(\vec{x}_2)\, \delta T(\vec{x}_3) \rangle$$

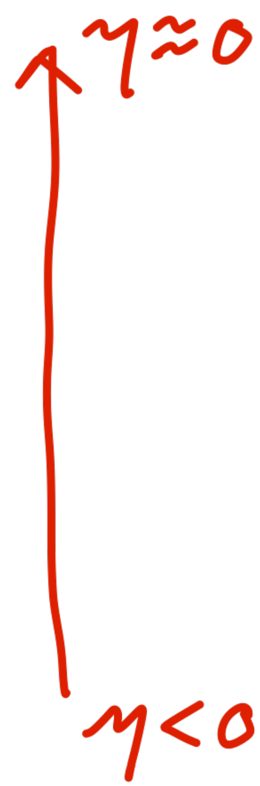
$$\propto \langle 0 |\, e^{i\int_{-\infty(1+i\varepsilon)}^{\infty} dt\, H(t)}\, \delta\phi(\vec{x}_1)\, \delta\phi(\vec{x}_2)\, \delta\phi(\vec{x}_3)\, e^{-i\int_{-\infty(1+i\varepsilon)}^{\infty} dt\, H(t)} \,| 0 \rangle$$

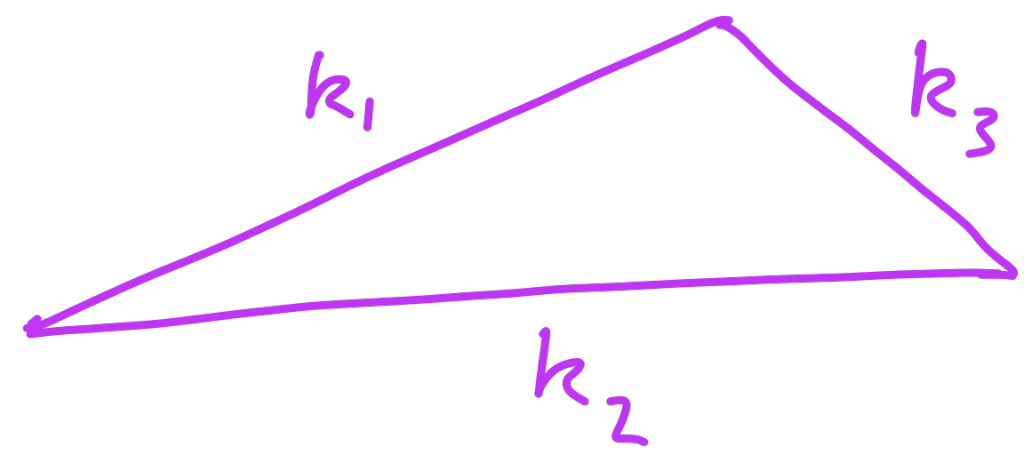
separate out $\delta$-Function

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

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




Primordial Non-Gaussianity (NG):

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

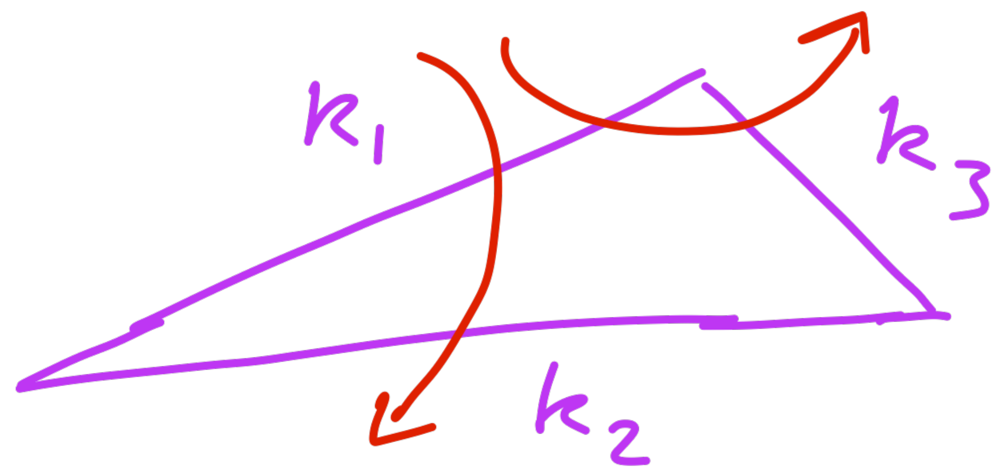
$$f_{NL} \equiv \tfrac{5}{18} F(k,k,k) \underset{\text{Planck}}{<} \mathcal{O}(10)$$

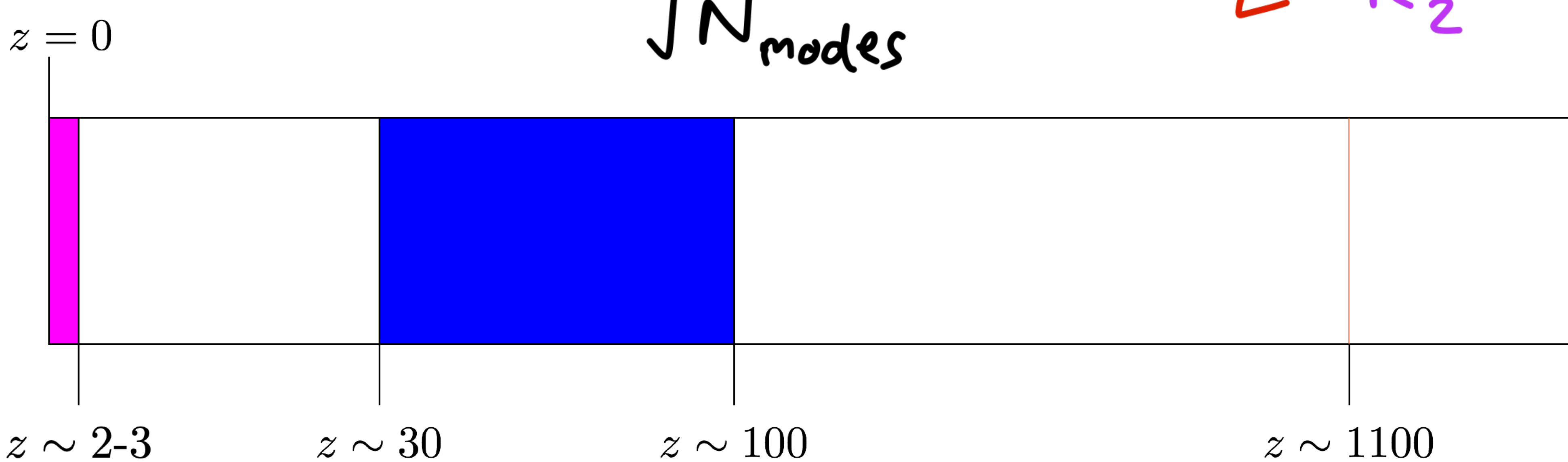
# EXTREME PRECISION

Only one sky to measure quantum expectations.

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

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




Alvarez et. al. ’14

Loeb, Zaldarriaga ’03

$\rightarrow z = \frac{1}{a} - 1$

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

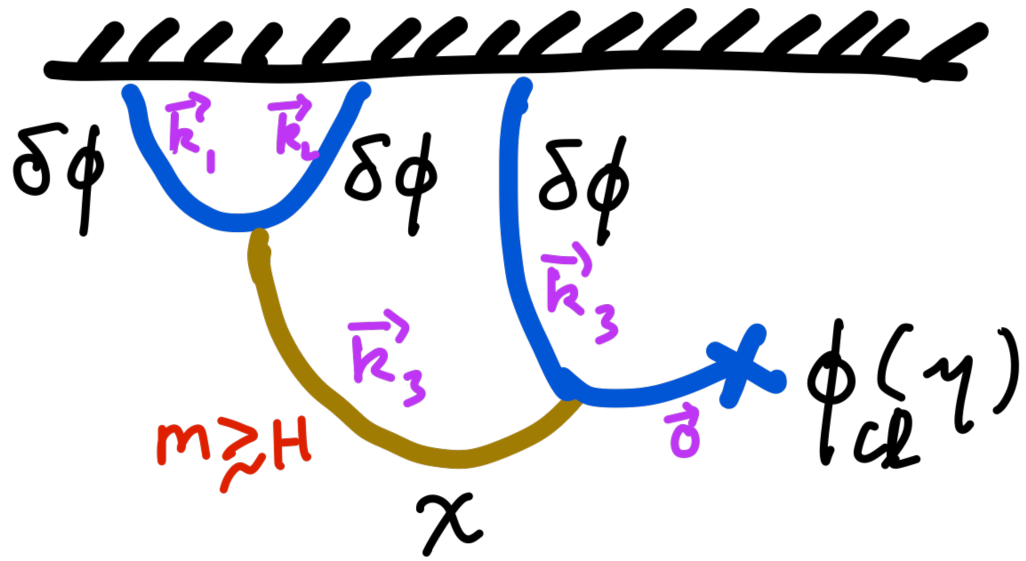
**LSS**: $N_{\rm modes} \sim 10^9 \Rightarrow \delta f_{\rm NL} \sim 1$ **(EUCLID, DESI, SPHEREx …)** **2022**

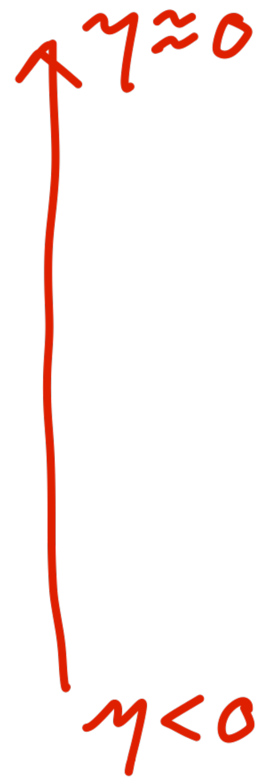
**21-cm Cosmology**: $N_{\rm modes} \sim 10^{16} \Rightarrow \delta f_{\rm NL} \sim 10^{-4} - 10^{-3}$ **20??**

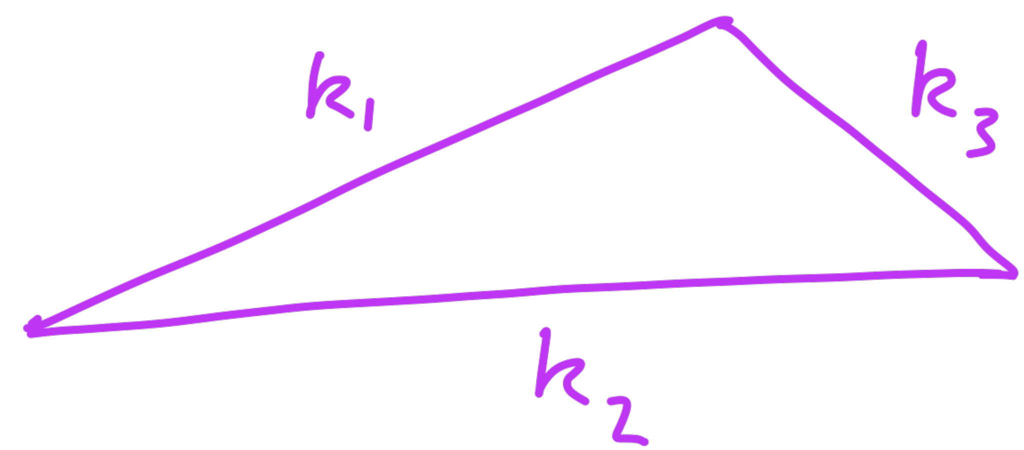
# "COSMOLOGICAL COLLIDER PHYSICS"

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

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




Primordial Non-Gaussianity (NG):

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

# COSMOLOGICAL COLLIDER PHYSICS

$$\mathcal{L}_{int.} = \sqrt{-g}\, g^{\mu\nu}\, \underbrace{\partial_\mu \phi}_{\text{Radiative stability of } V_{inflation}}\, \partial_\nu \phi\, \chi / \Lambda$$

$m \gtrsim H$

Chen, Wang '09; Baumann, Green '11
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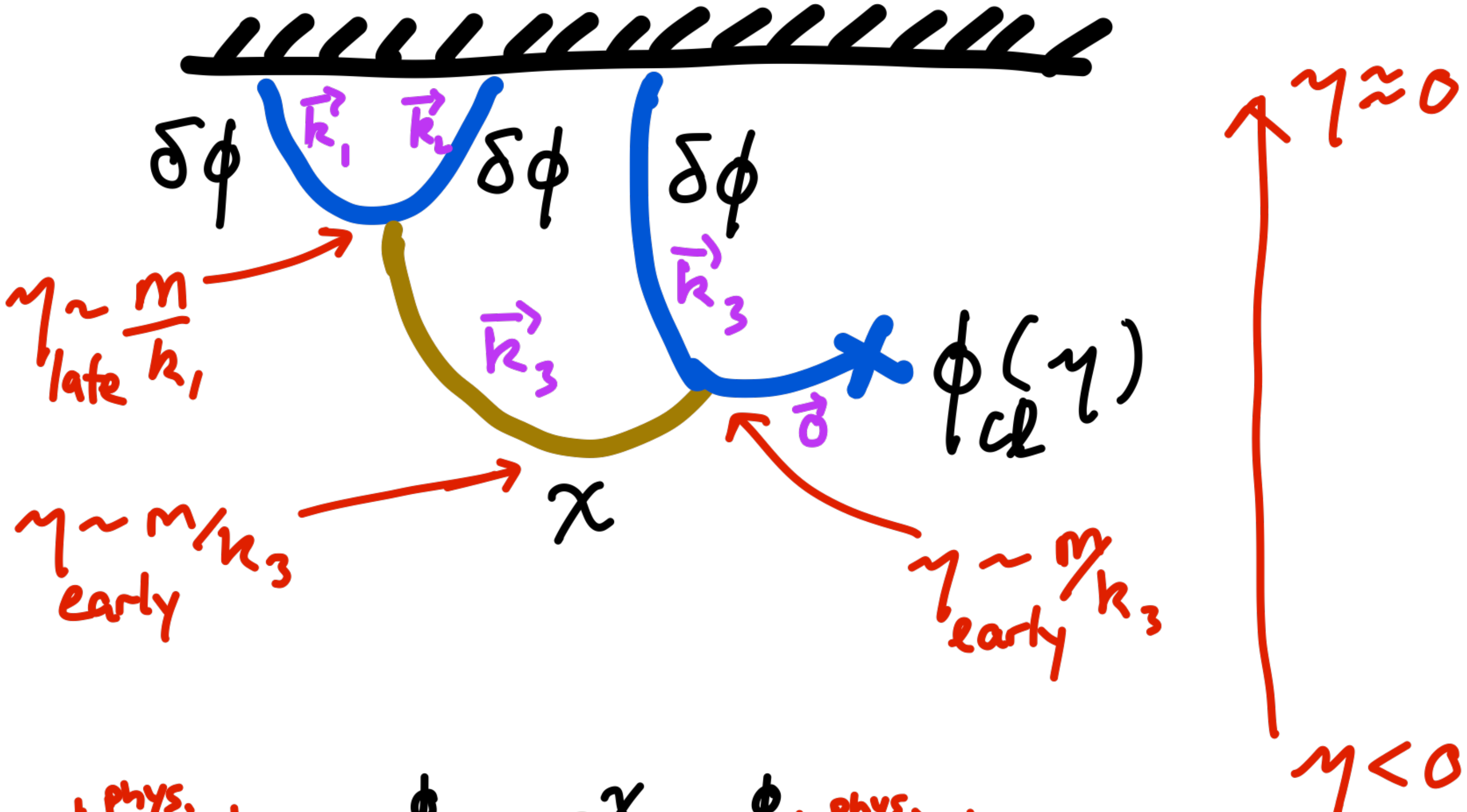
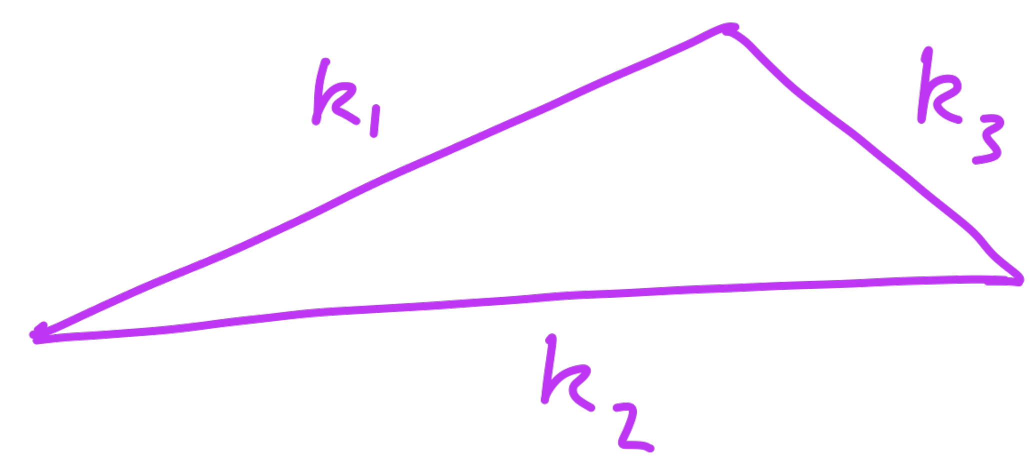



$k_1^{phys.} = k_1 \eta$ $\phi \leftarrow \chi\, m \rightarrow \phi$ $k_2^{phys.} = k_2 \eta$

## SQUEEZED LIMIT:




$$k_3 \ll k_1 \approx k_2$$

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

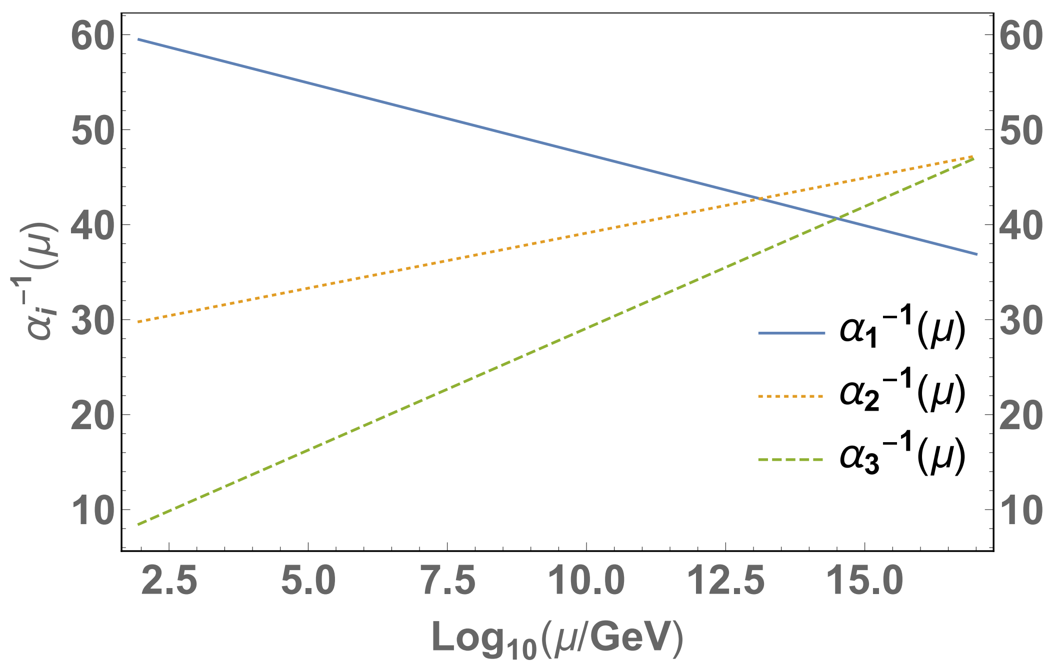
non-analytic ≡ on-shell propagation

# (Non-supersymmetric)
# GRAND UNIFICATION

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

Spinor representation
⊃ entire SM matter generation

weak isospin 2
+ color 3




1-loop SM RGE

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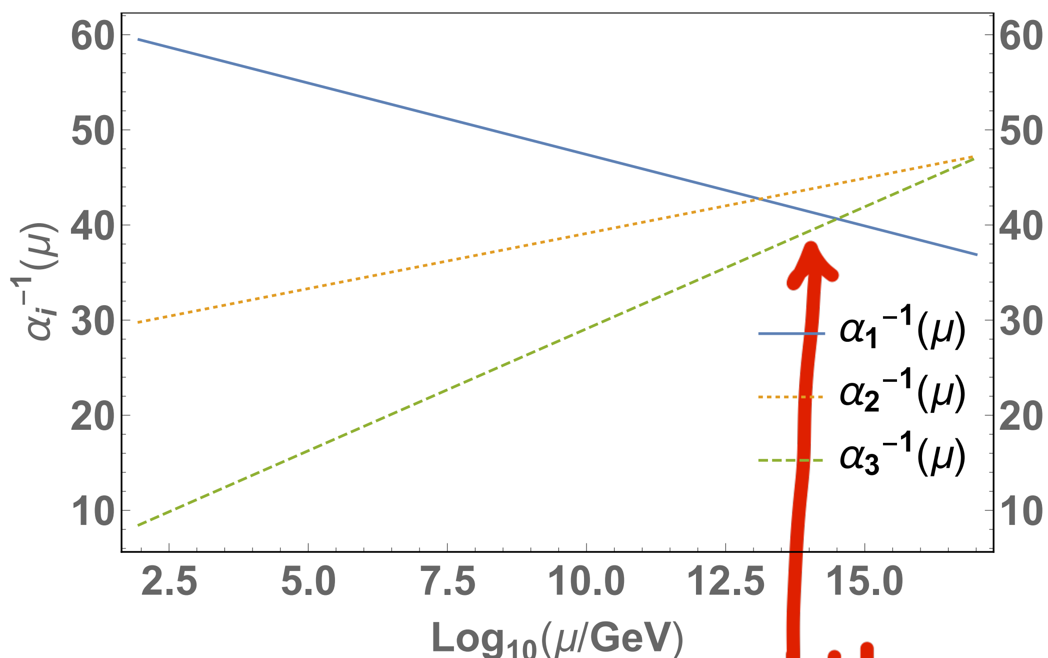


$H_{\text{inflation}}$?

1-loop SM RGE

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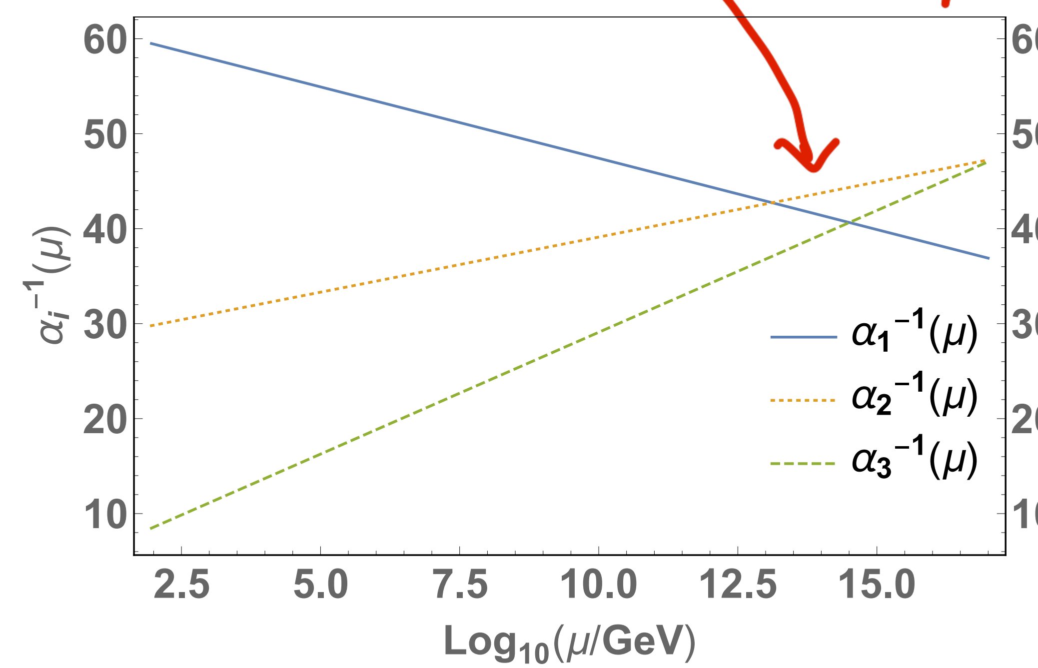
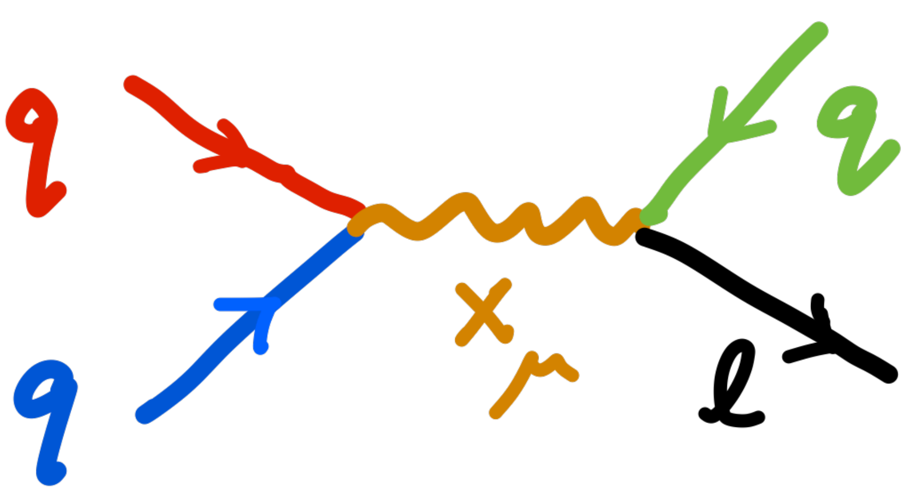
weak isospin 2 + color 3

striking, but why imperfect?




1-loop SM RGE

# PROTON DECAY?



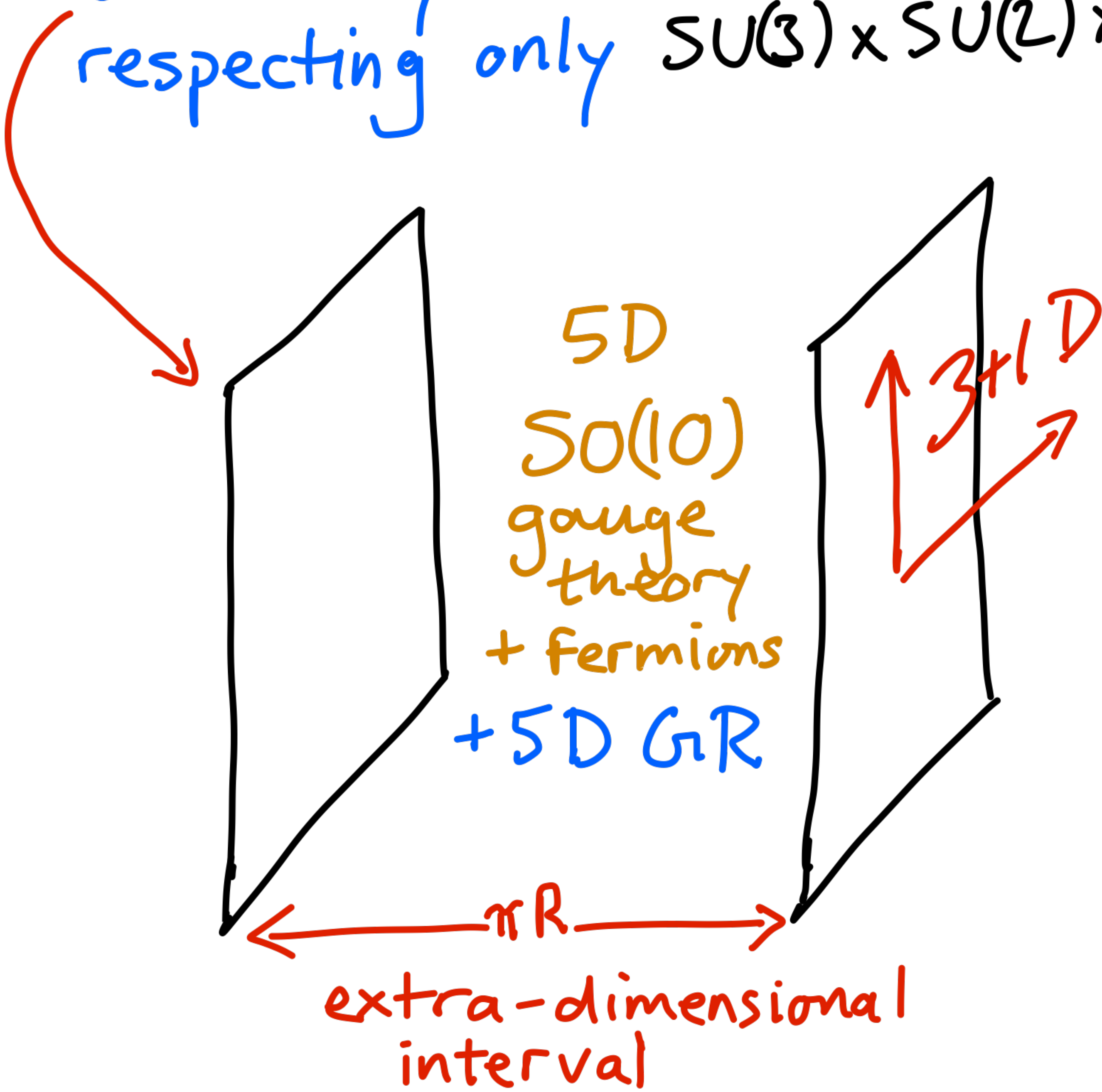

$$m_X > 5 \times 10^{15}\,\text{GeV}$$

Super-K '16

# ORBIFOLD GUTS

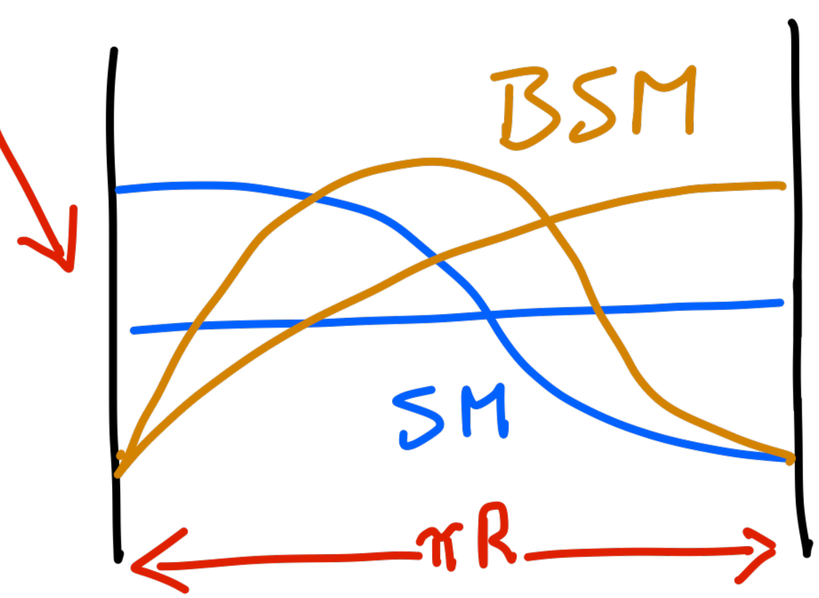
Kawamura '99, '00
Hall, Nomura '01, '03

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 $U(1)_{\text{baryon}}$

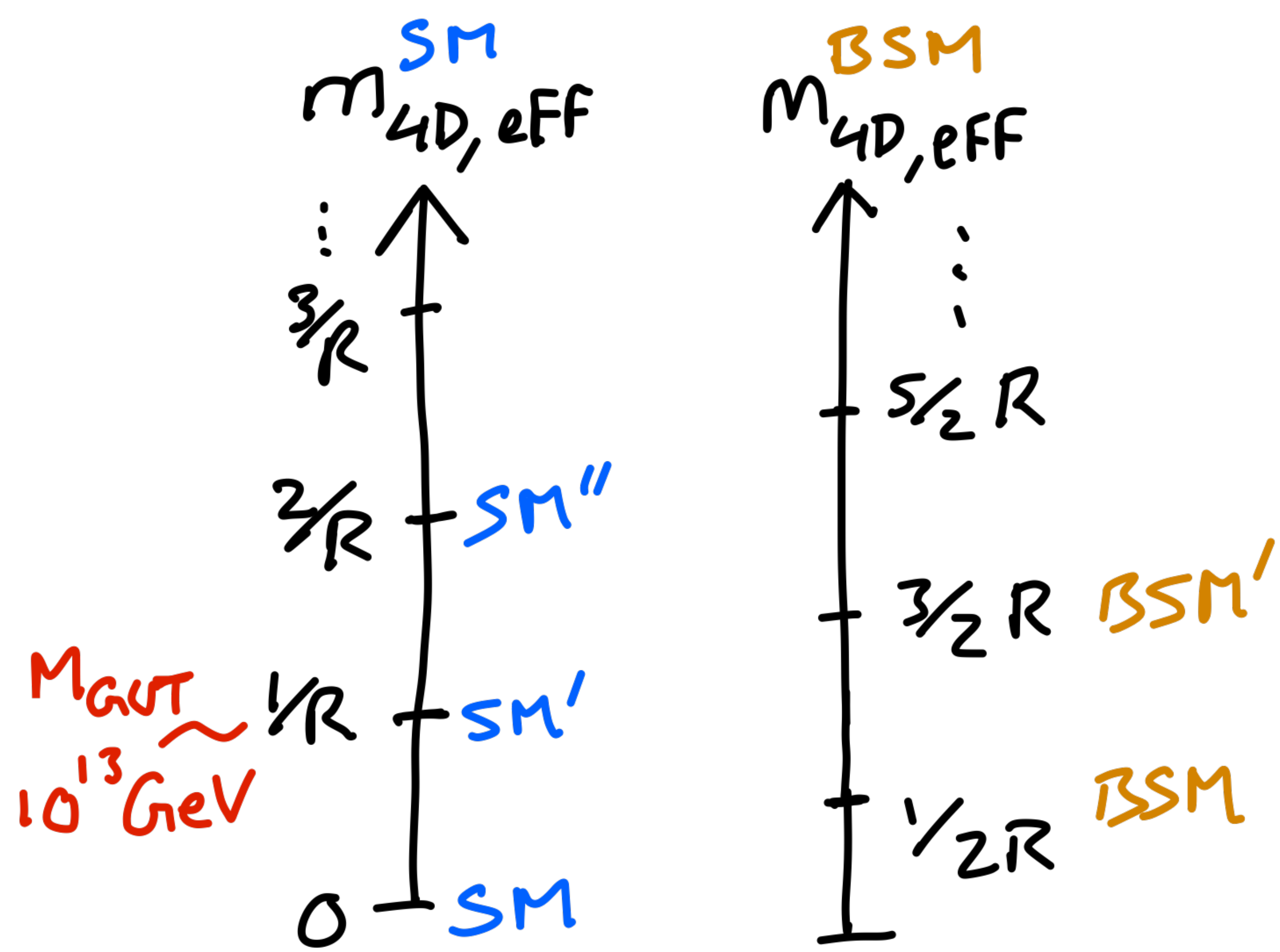


# ORBIFOLD GUTS

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 $U(1)_{baryon}$



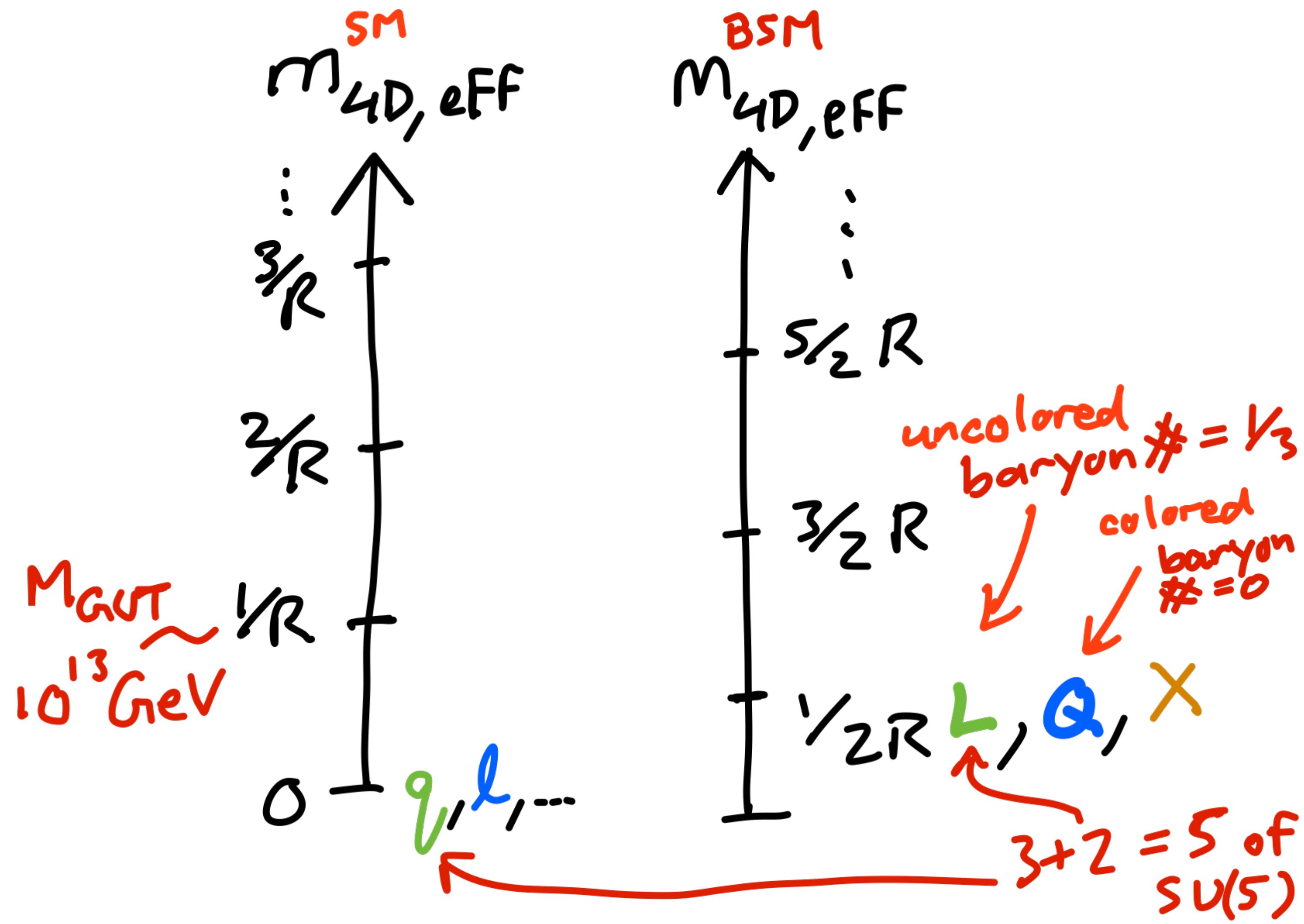

KALUZA-KLEIN MODES




(3+1)-D KALUZA-KLEIN TOWERS

# ORBIFOLD GUTS

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

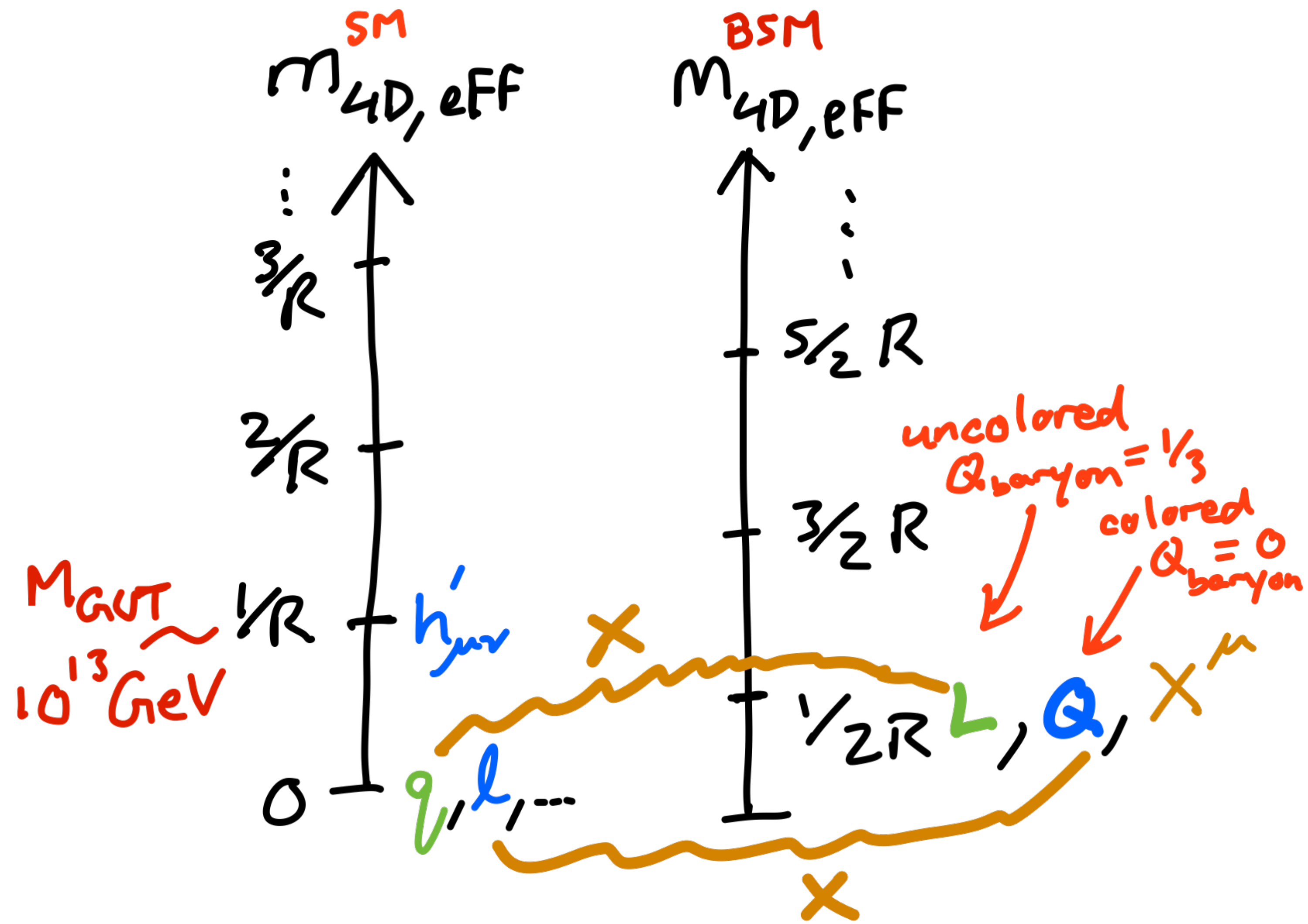



(3+1)-D KALUZA-KLEIN TOWERS

# ORBIFOLD GUTS

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 $U(1)_{baryon}$

## PROTON IS STABLE

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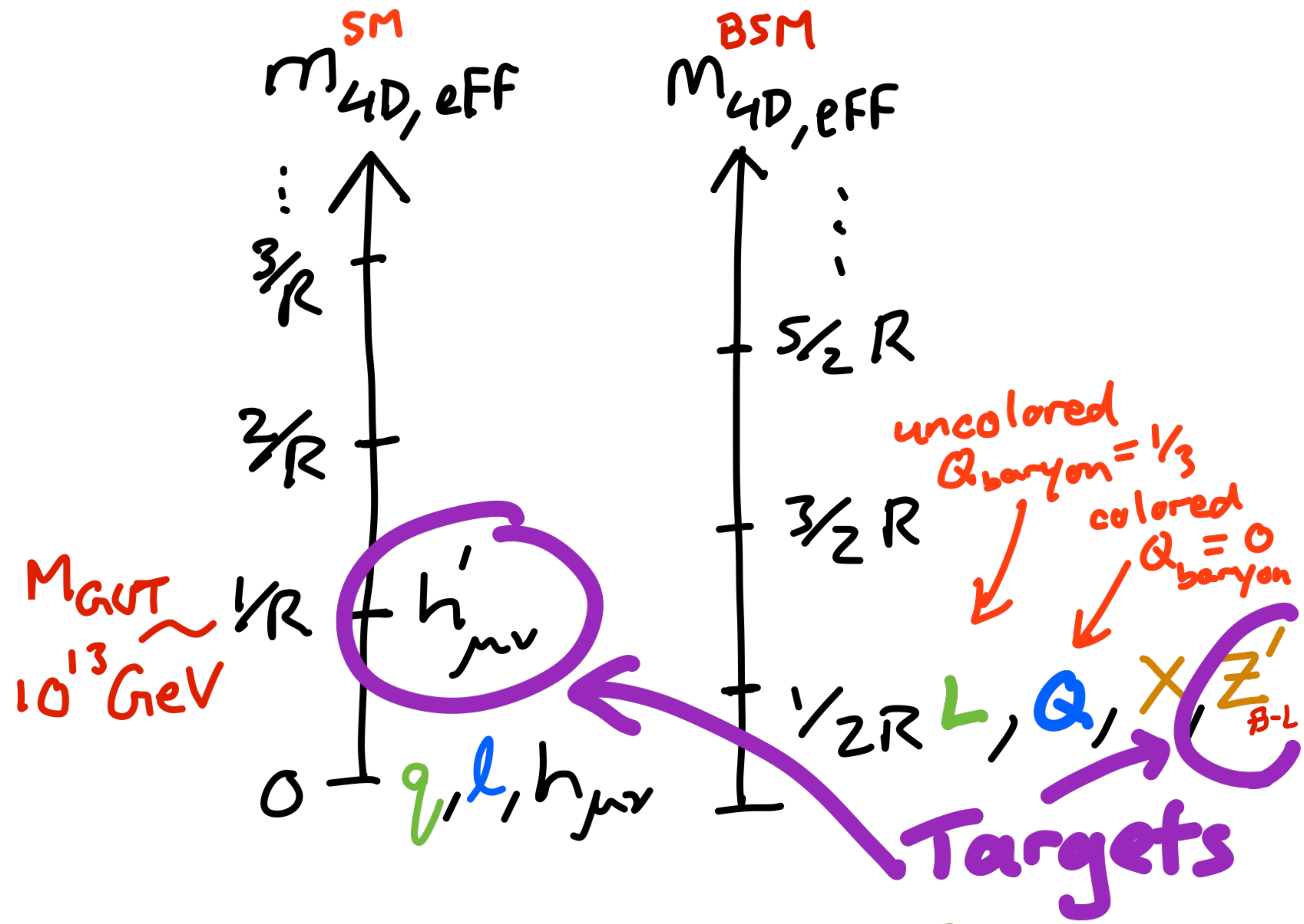
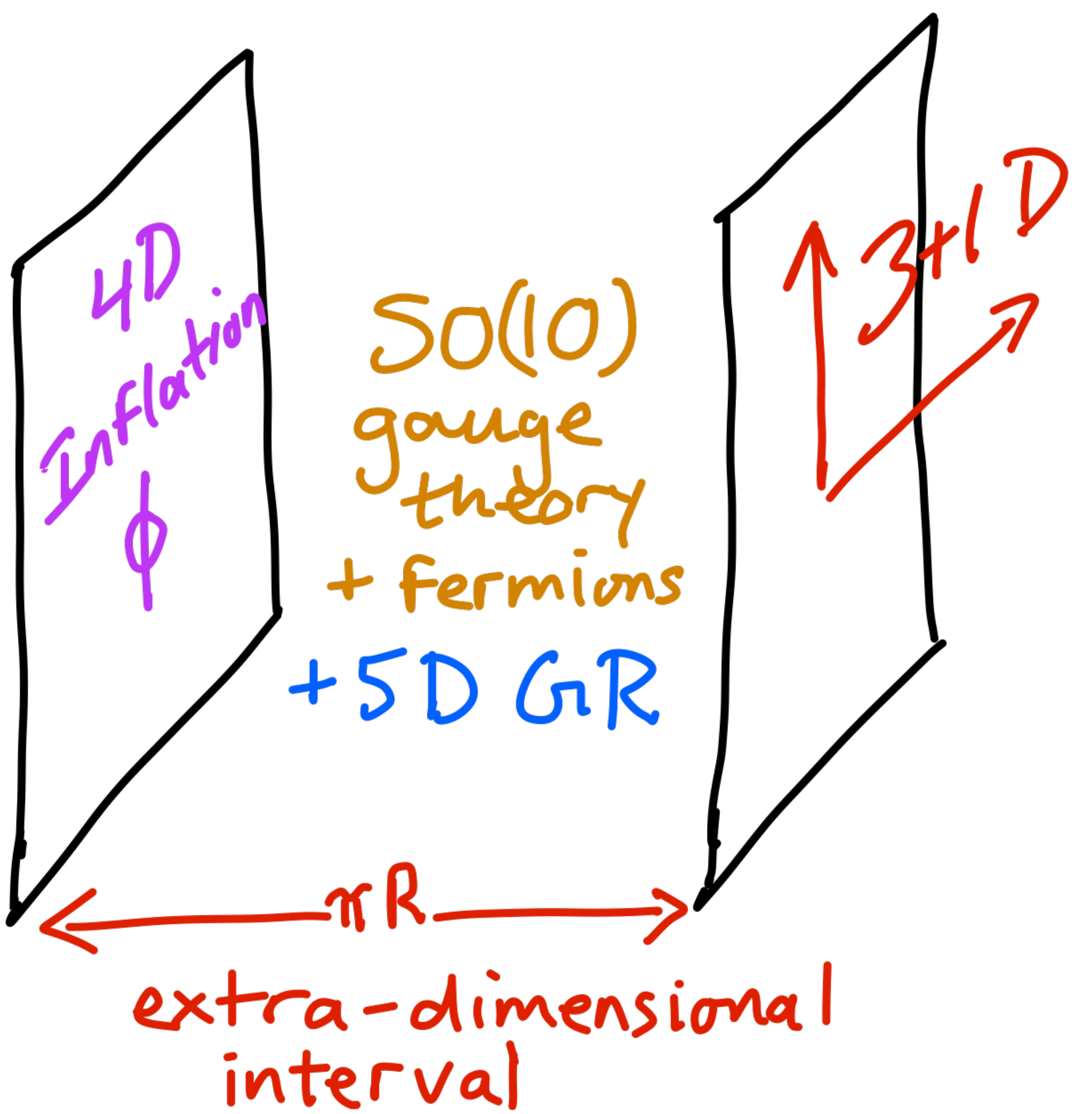
Higher-dimensional SO(10) gauge theory, with extra-dimensional boundary conditions (eg. Neumann, Dirichlet) respecting only $SU(3)\times SU(2)\times U(1)$, & global $U(1)_{\text{baryon}}$

⇒ MOTIVATED ACCESSIBLE TARGETS FOR COSMOLOGICAL COLLIDER PHYSICS



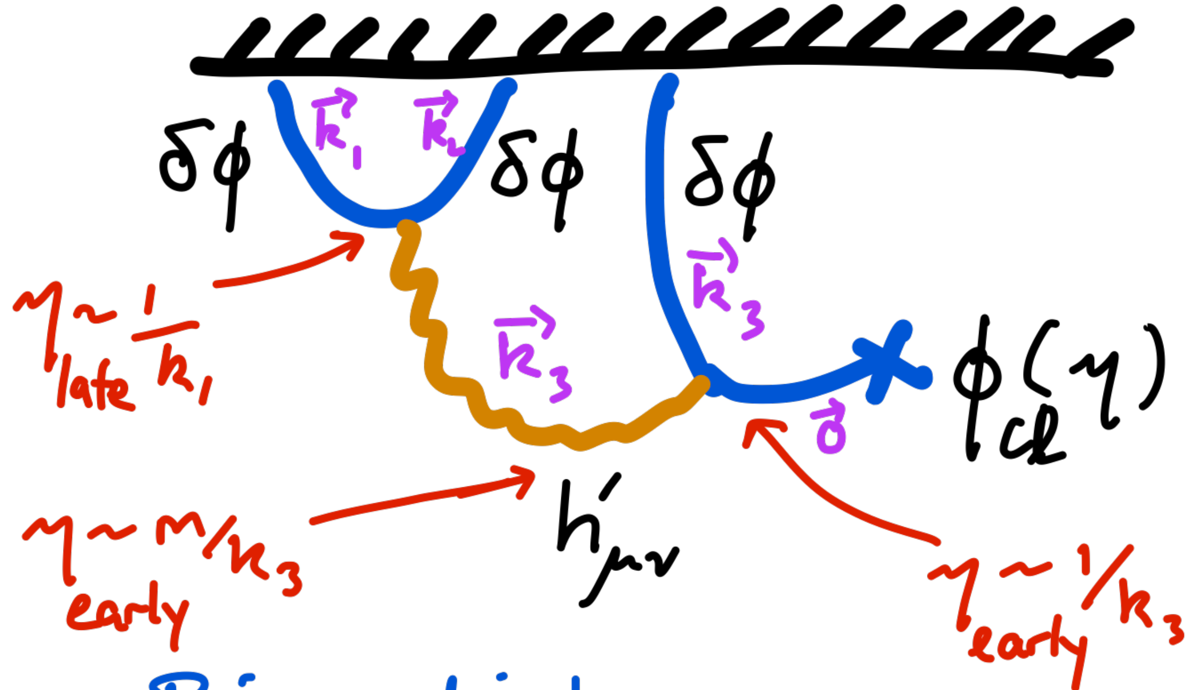

(3+1)-D KALUZA-KLEIN TOWERS

# ADD BOUNDARY-LOCALIZED 4D INFLATION . . .

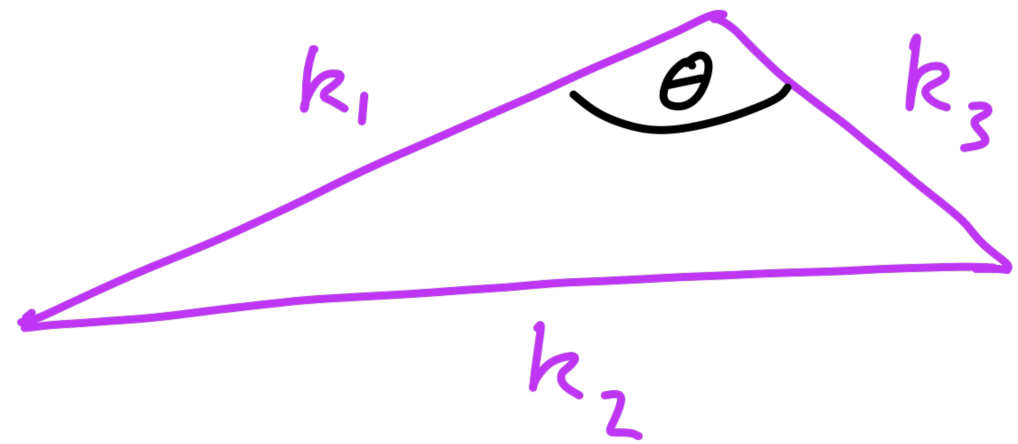


# KALUZA-KLEIN GRAVITON

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




**SQUEEZED LIMIT:**




$$k_3 \ll k_1 \approx k_2$$

Primordial Non-Gaussianity (NG):

$$F(\vec{k}_1, \vec{k}_2, \vec{k}_3) \sim \frac{(\partial_t \phi_{cl})^2}{M_{Pl}^2} e^{-\pi m_{KK}} \left(\frac{k_3}{k_1}\right)^{i m_{KK}} (\cos^2\theta - 1/3) < 10^{-2}$$

Challenging!

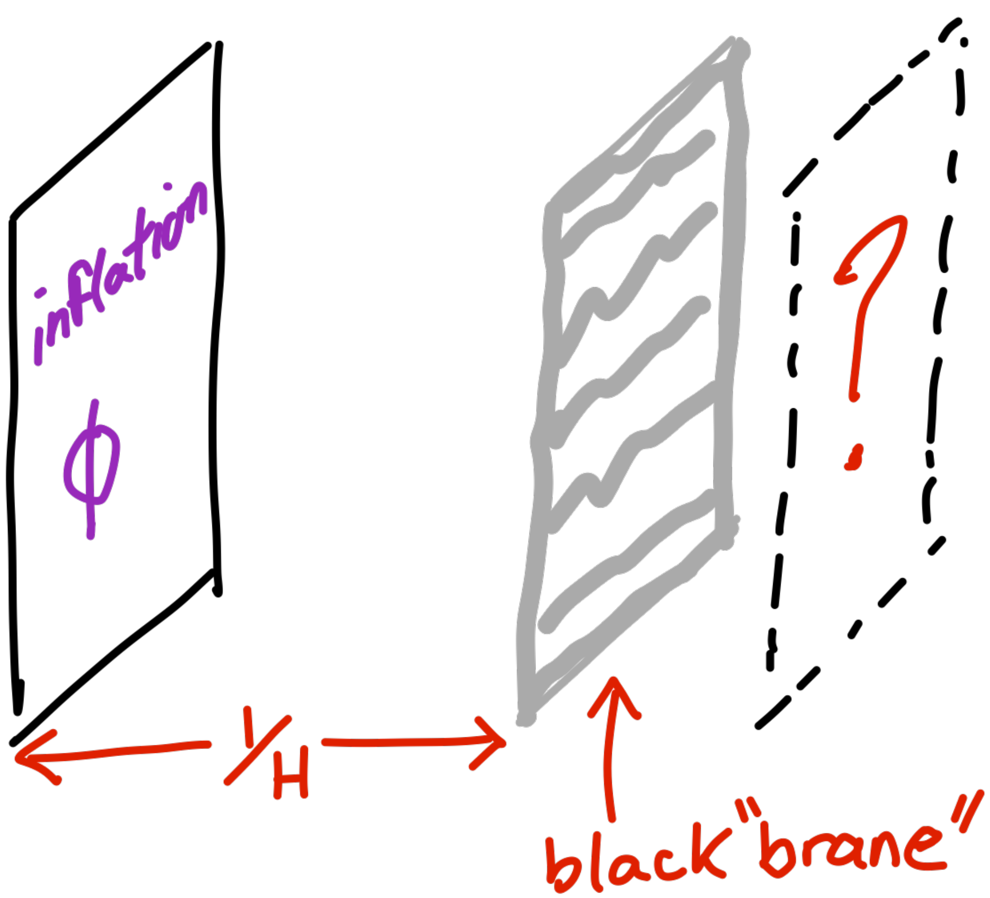
# TROUBLE ON THE HORIZON...

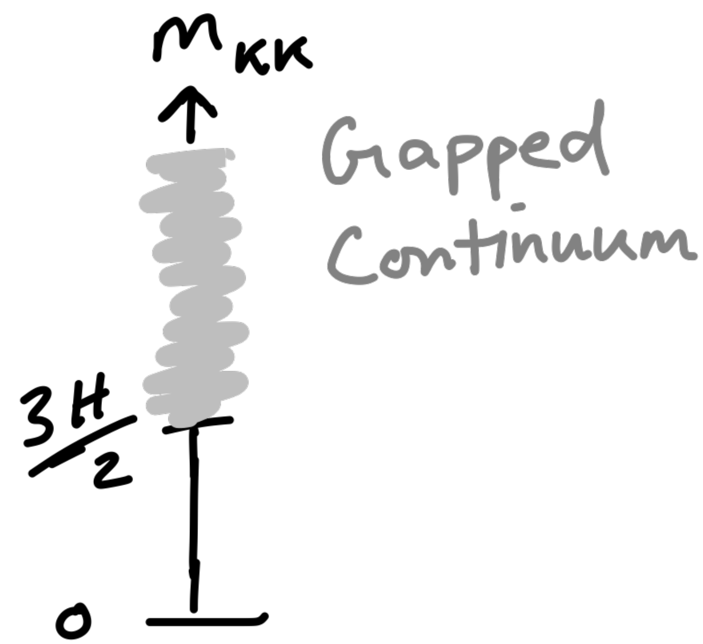
$m_{KK} = 1/R \sim H_{\text{inflation}} \Rightarrow$ significant backreaction to 5D geometry from boundary inflation

$$ds^2 \underset{1/R \gg H}{=} dt^2 - e^{2Ht} d\vec{x}^2 - dx_5^2$$

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

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




Garriga, Sakai '99

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

# OPPORTUNITY ON THE HORIZON...

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

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

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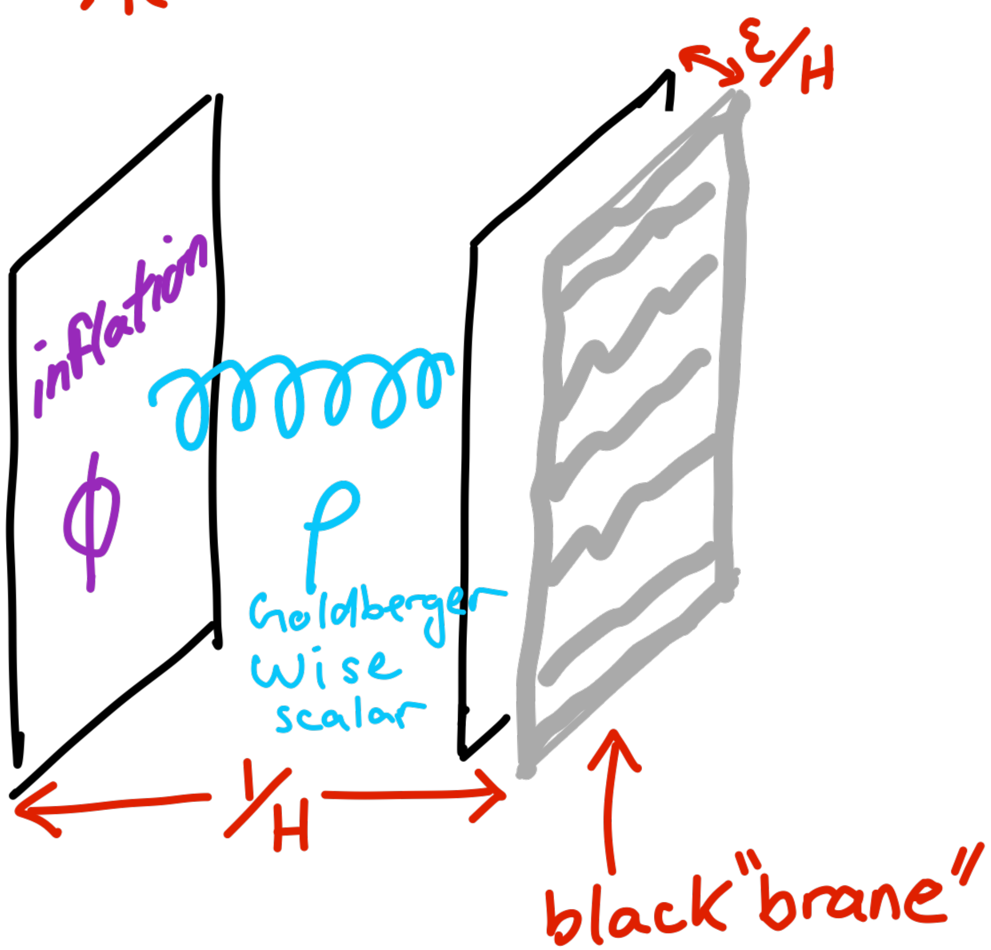
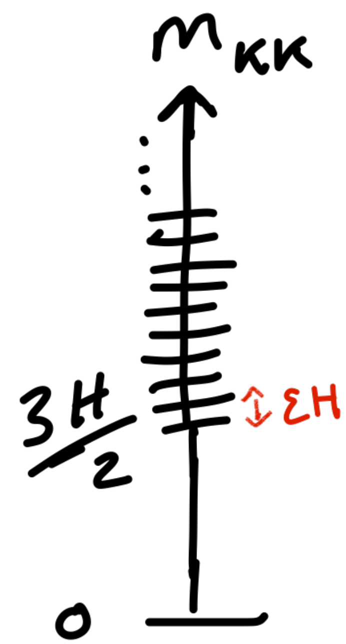


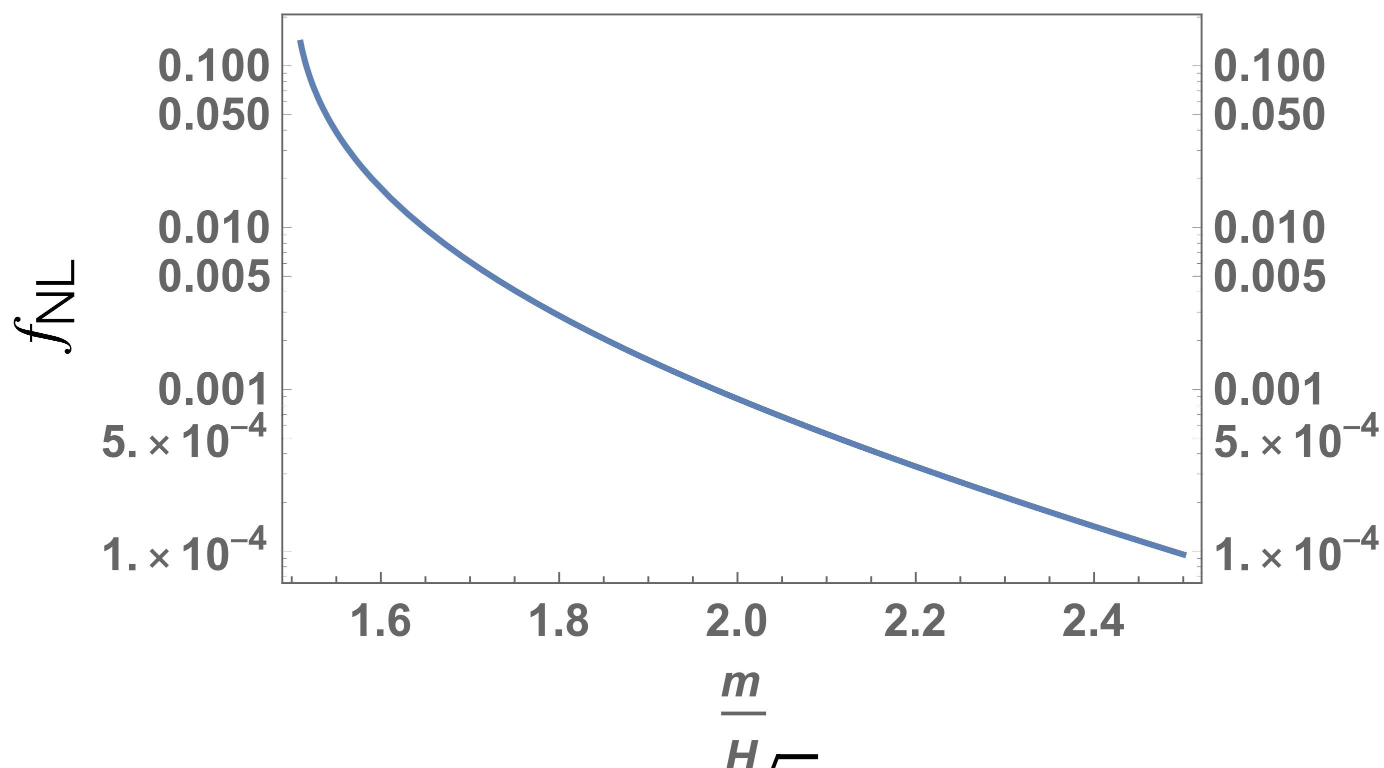

Near-horizon analysis of Goldberger-Wise '99 extra-dimensional stabilization by 5D scalar $\rho$ is possible for small

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

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

Further backreacted $ds^2$ treated in $\varepsilon$-perturbation theory

# KK graviton mediated NG




$r = 0.1;$

≡ maximally allowed H

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

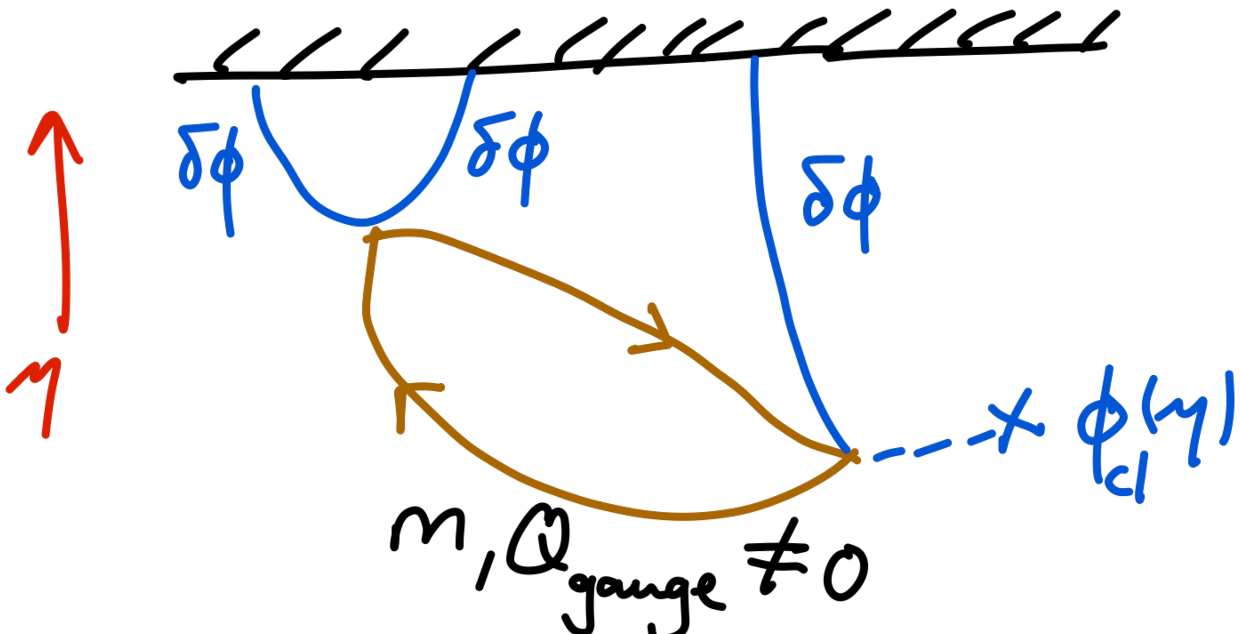
$$F = \frac{r}{8} \times \left(\cos^2\theta - \frac{1}{3}\right) \frac{\sqrt{\pi}}{8(1+4\mu^2)^2\cosh(\pi\mu)}$$

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

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

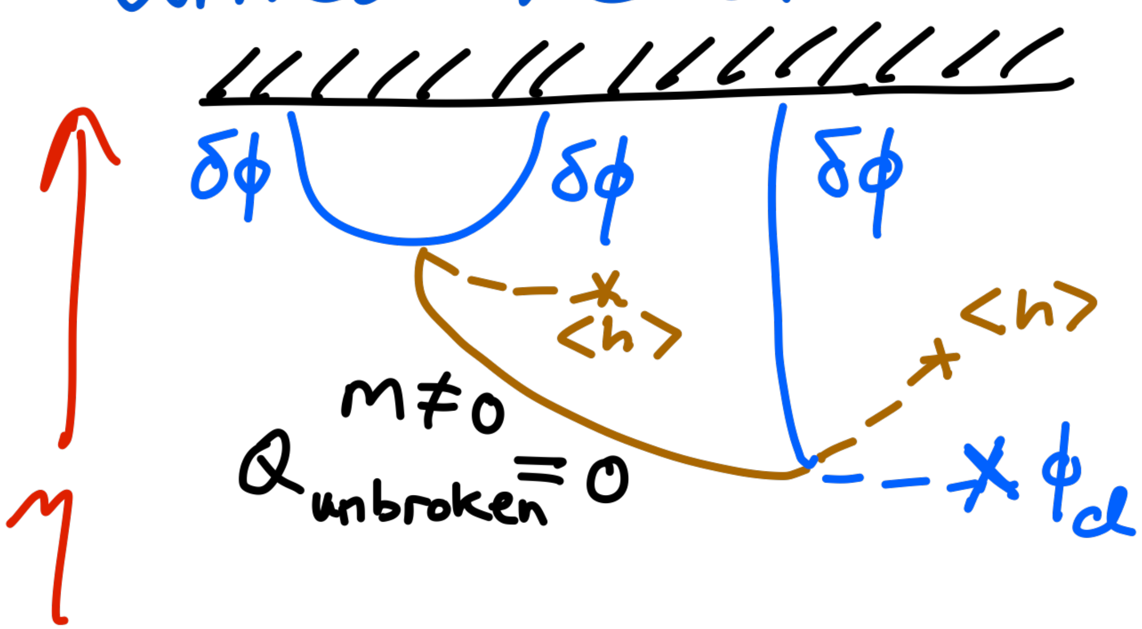
# GAUGE-HIGGS THEORY

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




unless rendered neutral after Higgsing:

Eg. $Z^0$



# HIGGSED GAUGE THEORY

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

mediator

integrate out $\chi$, $m_\chi > H$

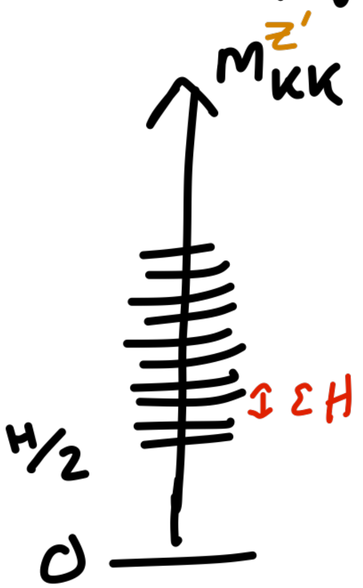
$\langle h \rangle \equiv v$

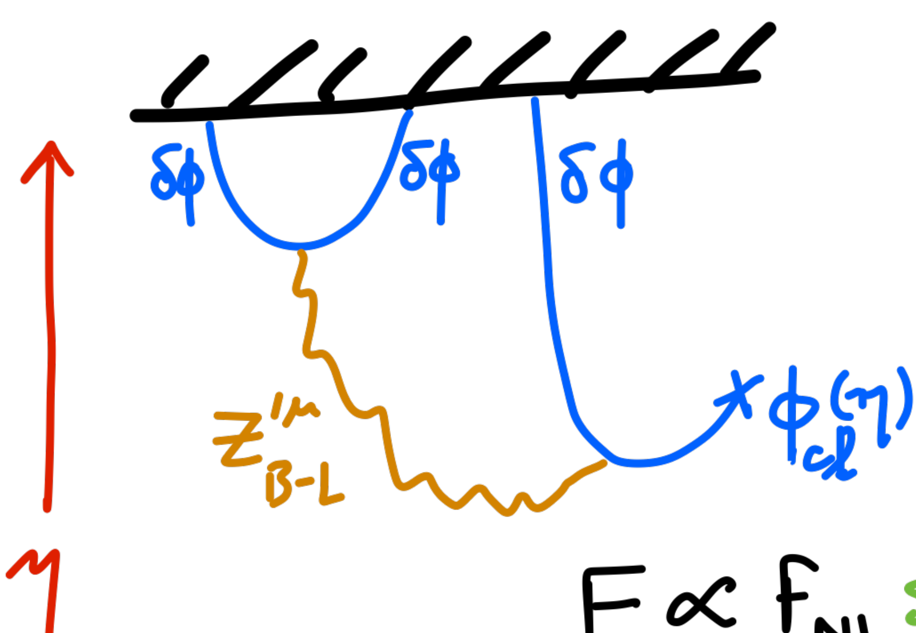
$$\sqrt{-g}\, g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi\, \partial_\alpha \phi\, Z'^\alpha \frac{v^2}{\Lambda^3 m_\chi^2}$$

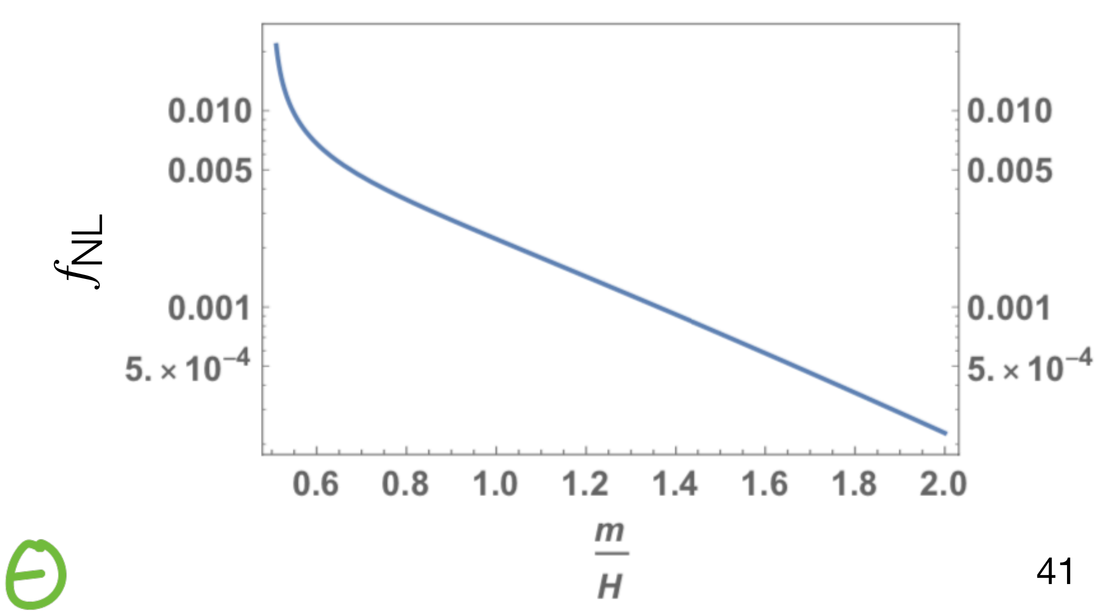
must be small enough to keep EFT control of $(\partial\phi)^n$ expansion

# ORBIFOLD GUTs

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

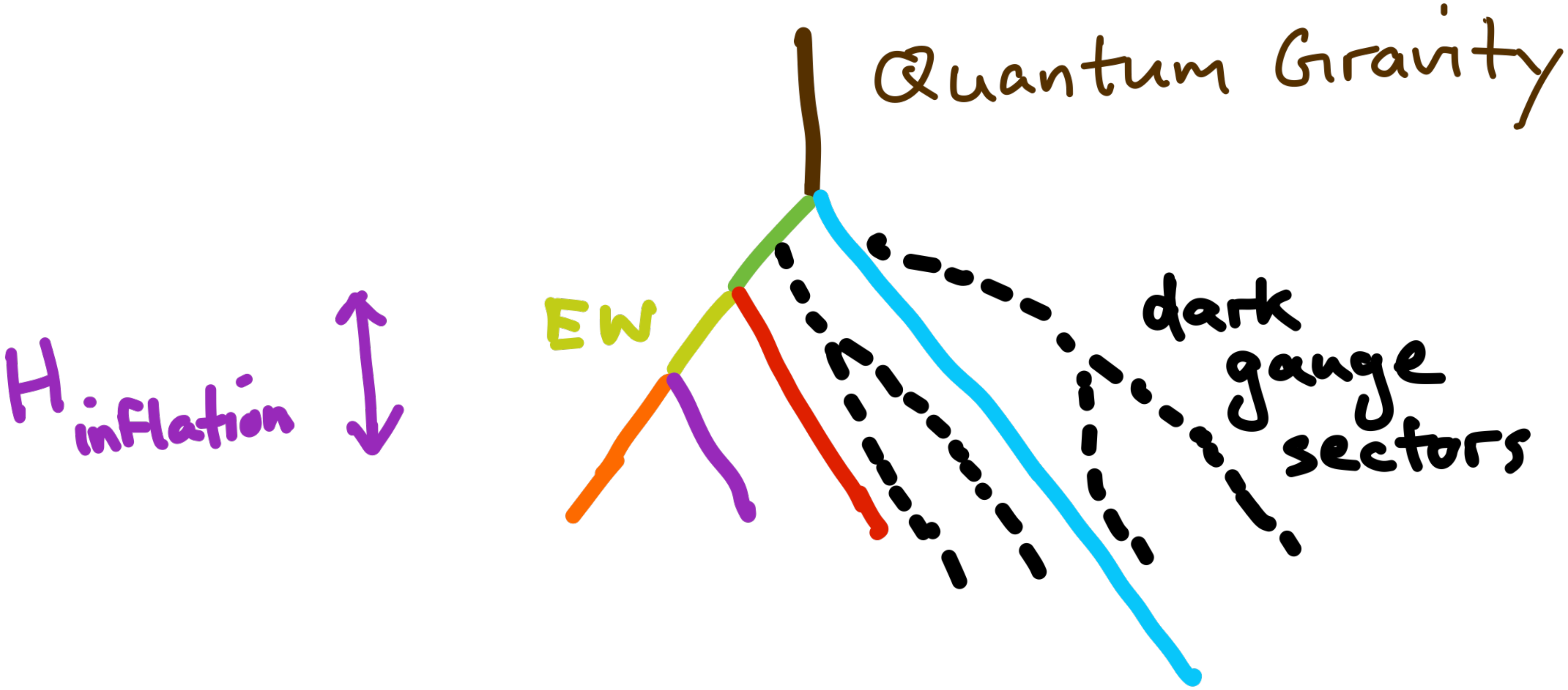



$F \propto f_{NL} \sin^2\theta$

# FAMILY TREE AS A SAPLING





Higgsing scales naturally much higher during inflation

# "HEAVY-LIFTING" BY INFLATION

Natural to have Higgs fields couple to curvature:

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

during inflation, negligible today

$\Rightarrow$ Higgs mechanisms at lower scales today, could have been at $\sim H_{\text{inflation}}$ 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":

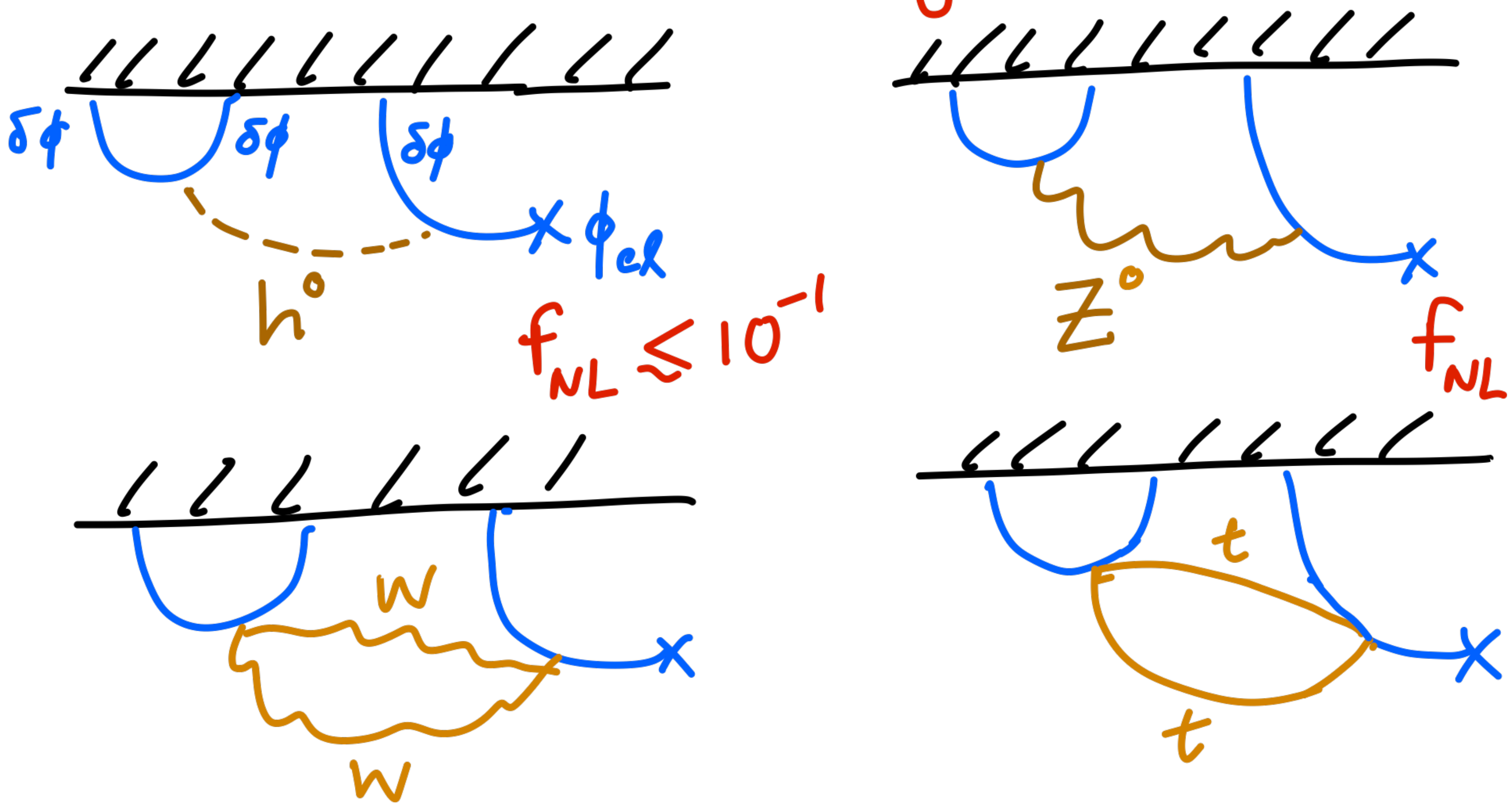
$$V_{\text{effective}}(h) = -O(H^2_{\text{inf.}})\, h^\dagger h + \lambda (h^\dagger h)^2$$

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

Not a "problem"!

# COULD WE SEE THE SM ?

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

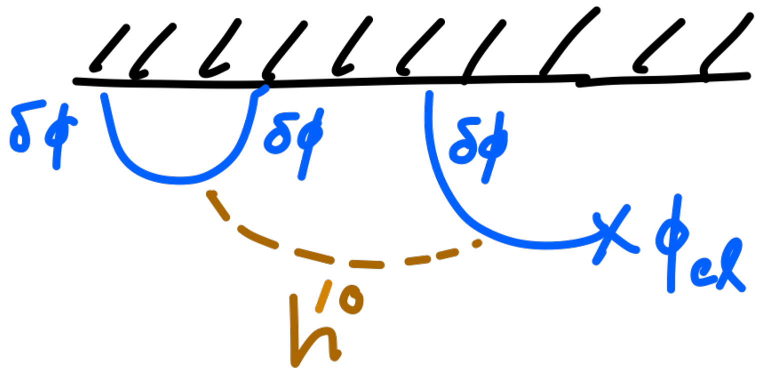


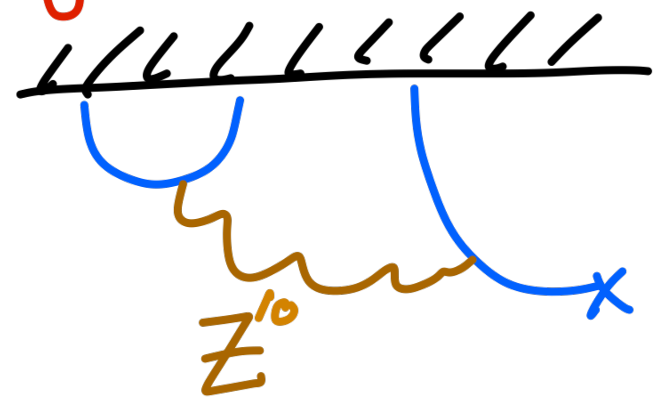

Loop suppressed

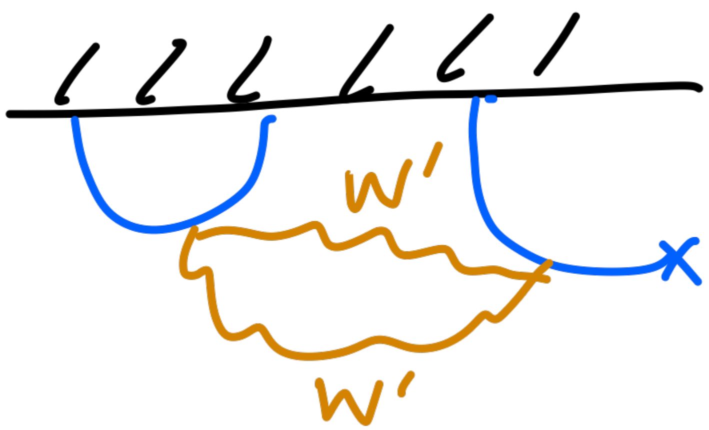
IF signals observable, the mass ratios eg. $\frac{m_W}{m_t} = \frac{g}{2y_t}$ would be unmodified, except for calculable RG effects!

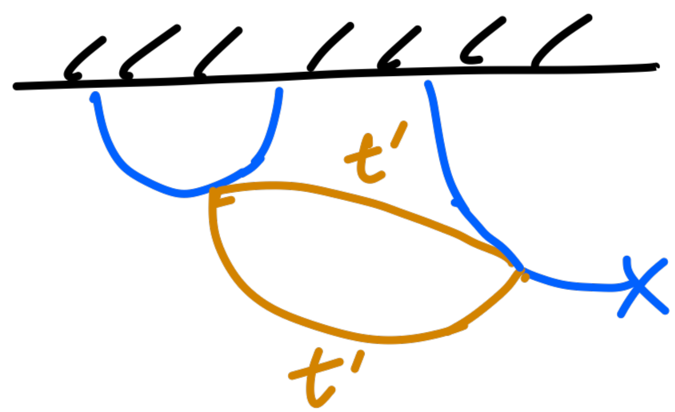
# OR DARK GAUGE SECTORS?

$h^{0\prime}_{\text{physical}}$, $Z^{0\prime}_{\mu}$, $\underbrace{W'^{\pm}_{\mu}, \; t'}_{\text{still charged}}$ all have comparable masses $\sim H_{\text{inf}}$



# COSMOLOGICAL COLLIDER PHYSICS & THE CURVATON

(or how to have bigger signals WITH theoretical control)

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

$\Rightarrow$ Non-renormalizable suppression $\Lambda > 60H$ Creminelli '03
for EFT control.

Curvaton ($\sigma$) 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

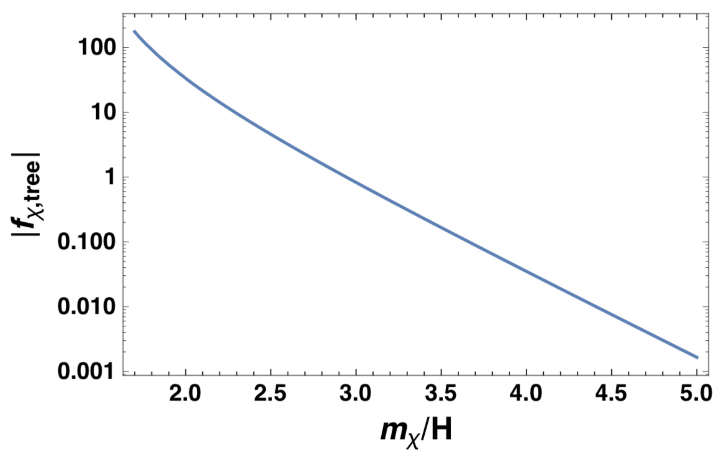
fluctuations: $\delta\sigma_{quantum} > \delta\phi_{quantum}$

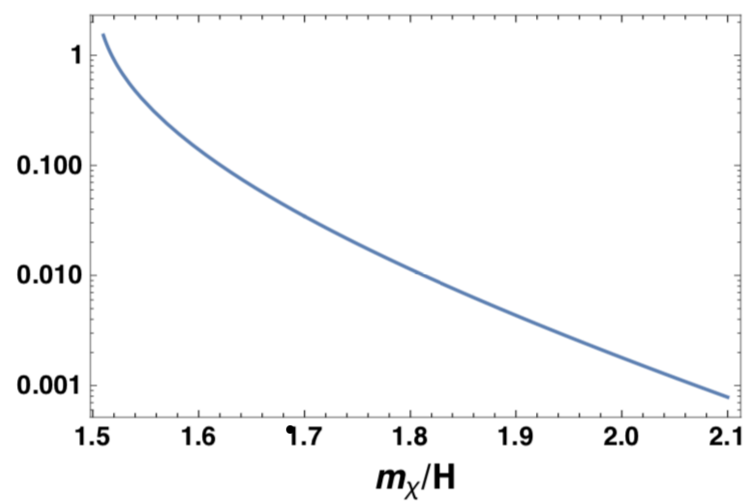
$\xrightarrow{\text{decay}}$ SM

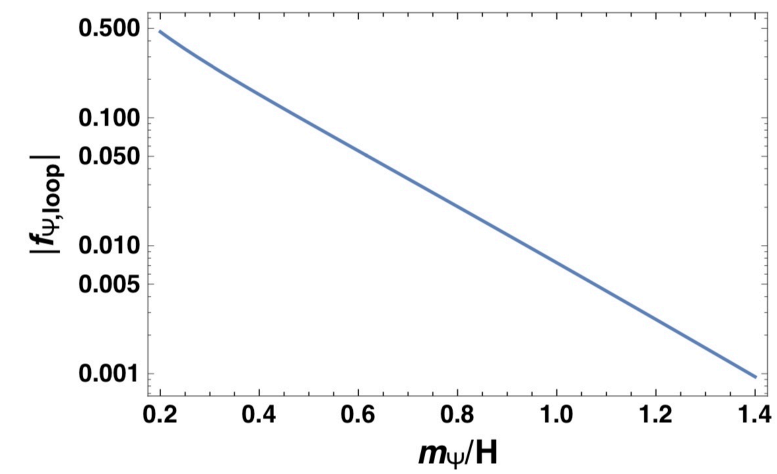
$\partial_t \sigma_{cl} \sim H^2$, $V_{curvaton}(\sigma_{cl}) \ll V_{inflaton}(\phi_{cl}) \Rightarrow \boxed{\Lambda_{\text{non-renormalizable}} \gtrsim \text{Few } H}$

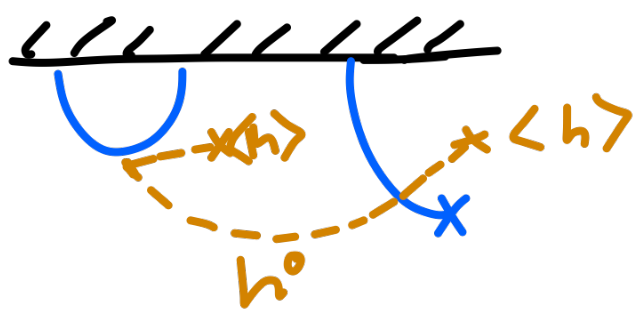
$$\mathcal{L}_{\text{interactions}} \sim \sqrt{-g}\,\chi\left\{ g^{\mu\nu}\partial_\mu\sigma\,\partial_\nu\sigma/\Lambda + h^\dagger h + \bar{t}_R h \begin{pmatrix} t \\ b \end{pmatrix}_L/\Lambda + g^{\mu\nu}\partial_\mu\sigma\, h^\dagger D_\nu h/\Lambda^2 + \dots \right\}$$

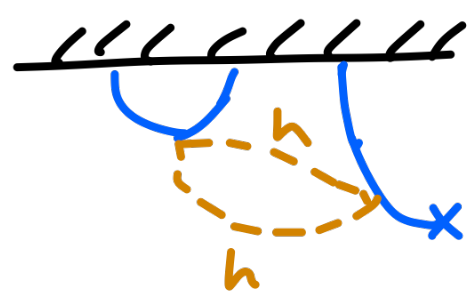
massive mediator, $m > H$, integrate out

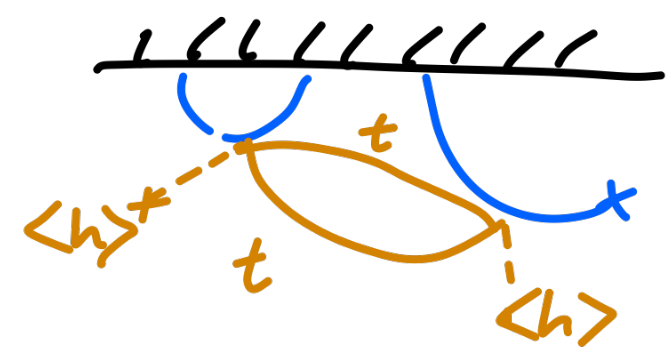


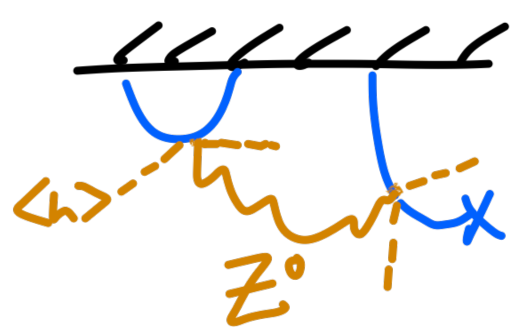



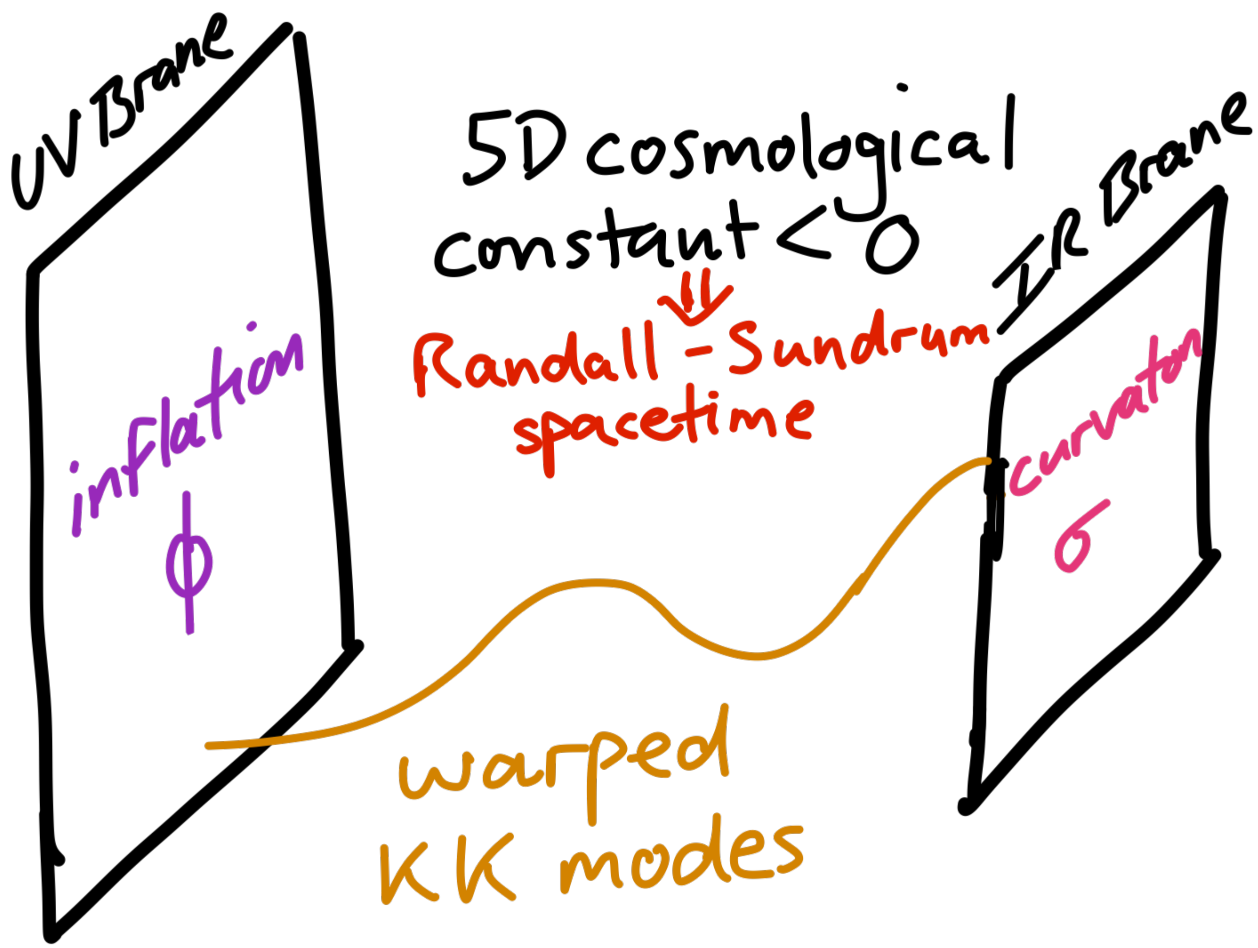




$f_{NL}^{Z^0} \sim \mathcal{O}(1)$



# THE WARPED CURVATON

in progress...




Warped KK modes "lean" to the IR brane & couple more strongly to brane-localized curvaton.

$$\mathcal{L}_{\text{interactions}} \supset \sqrt{-g}\, g^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma \frac{h^{\mu\nu}_{KK}}{M}$$

$M < M_{Pl}$

$\Rightarrow$ stronger, more observable NG mediated by spin-2

# CONCLUSIONS

Cosmological Inflation presents intriguing opportunity to probe extremely high energy particle physics in primordial Non-Gaussianity.

Gauge-Higgs & extra-dimensions among most promising plausible targets, either high-scale unified theories, or "heavy-lifted" lower-scale (dark) gauge theories

We still do not know the dynamics underlying inflation. This greatly affects the strength of NG & hence their observability.

# Signal strength & plausible targets

remain focus of ongoing research.

Eg. Enhanced NG from "chemical potential" couplings

$$\partial_\mu \phi \, J^\mu_{\text{Nöether}}$$

$$\Rightarrow \partial_t \phi_{cl} \, J^0$$

Chen, Wang, Xianyu '18
Hook, Huang, Racco '19
Wang, Xianyu '19, '20
Bodas, Kumar, Sundrum, to appear

Enhanced NG from modulated reheating

Dvali, Gruzinov, Zaldarriga '03
Lu, Wang, Xianyu '19

## Physical limits on NG precision?

Stochastic gravitational waves from 1st order phase transition illustrate a second "CMB" with many more "pristine" modes than CMB. (But detection is hard!) Geller, Hook, Tsai, Sundrum '18