

# EFT & Beyond

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2021 / Aug / 10

原子核三者夏の学校

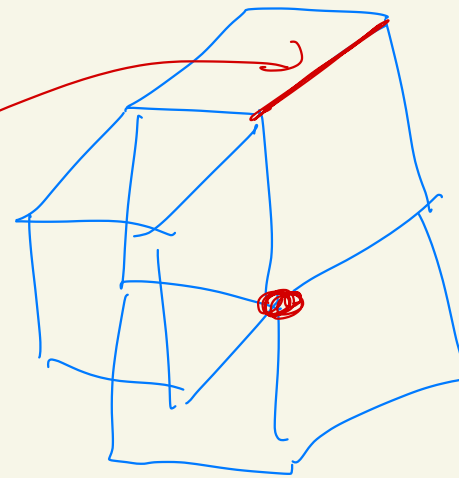
Lec III

# X-cube model defined on 3D lattice

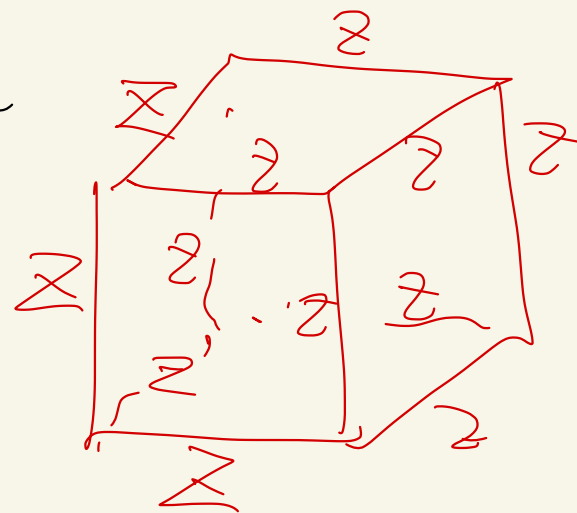
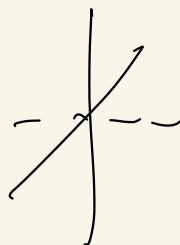
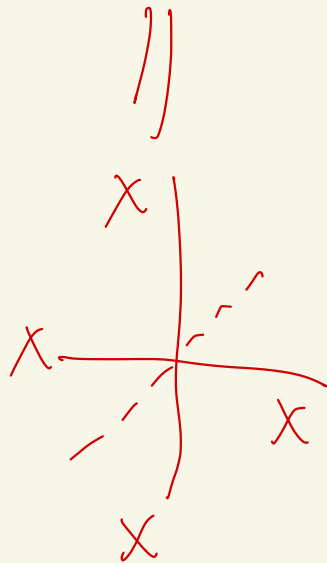
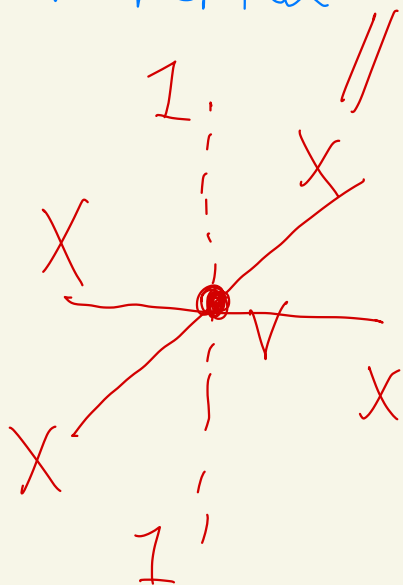
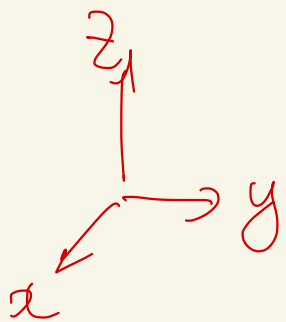
$A_{xy/yz/zx}^V = \pm 1$   
 $B^C$  on VAC

$X = \sigma_x$   
 $Y = \sigma_y$   
 $Z = \sigma_z$

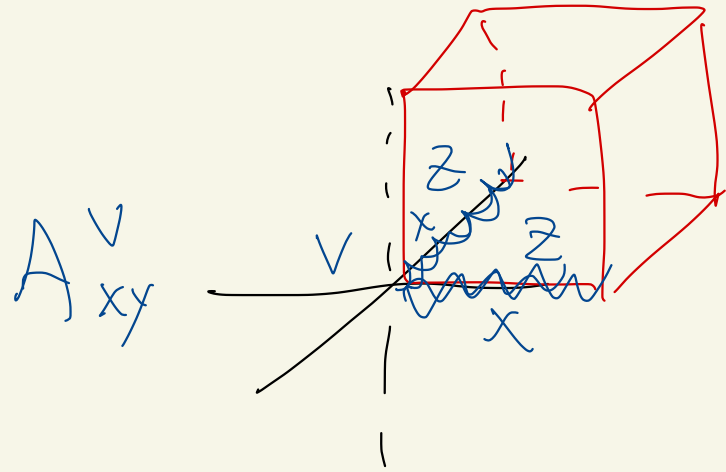
$Z_2$  spin  
 $|\uparrow\rangle$   
 $|\downarrow\rangle$



$$H = - \sum_{V: \text{Vertex}} (A_{xy}^V + A_{yz}^V + A_{zx}^V) - \sum_{C: \text{cube}} B^C$$



A's & B's mutually commute



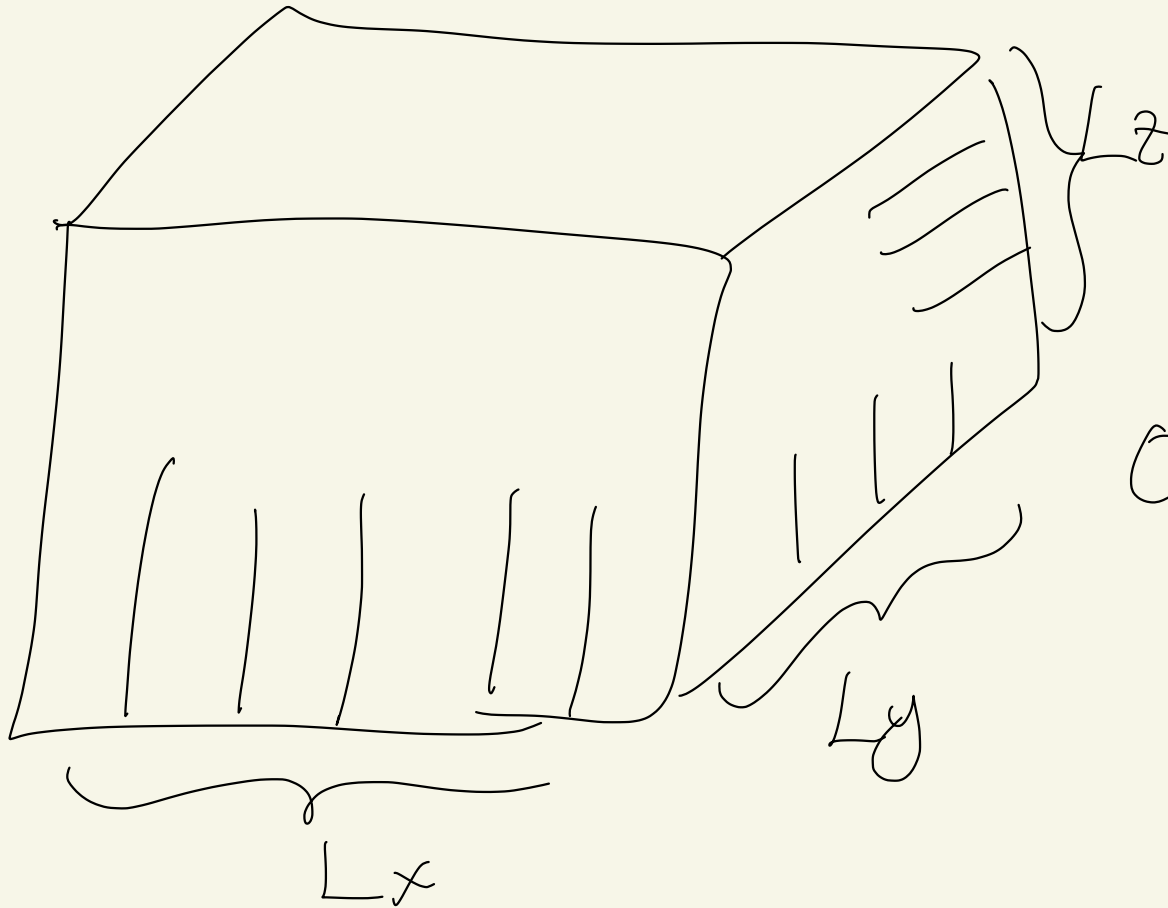
$B^C$

$$(\pm 1)^2 = +1$$

$$A^V |VAC\rangle = \pm |VAC\rangle$$

$$B^C |VAC\rangle = (\pm 1) |VAC\rangle$$

$$\mathcal{R}: \underbrace{L_x L_y L_z}$$



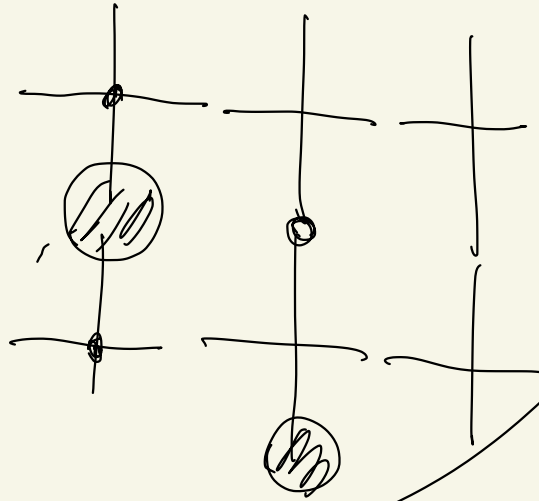
Q: How many independent constraints?

A:  $A_{xy}^v A_{yz}^v A_{zx}^v = 1$

$\Downarrow A_{xy}^v = 1$

yz

$L_x (L_y L_z - 1)$



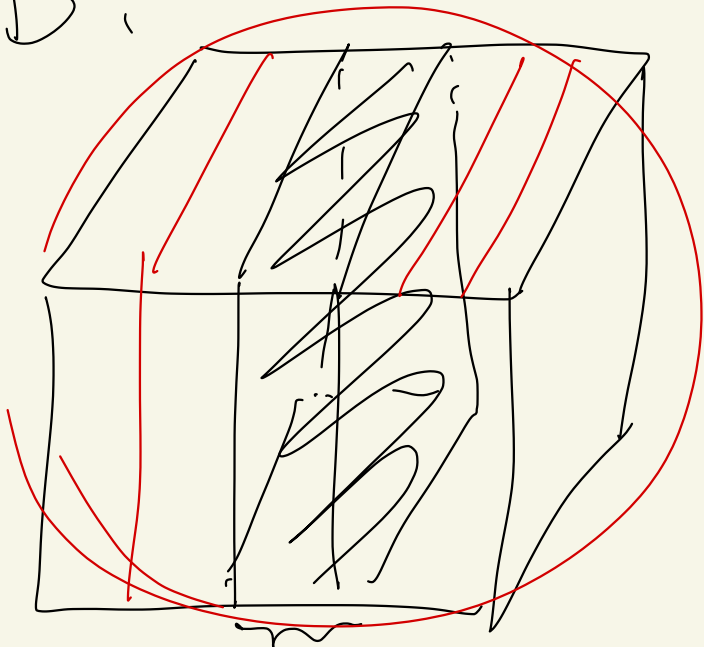
$(L_x L_y - 1) L_z$

$2L_x L_y L_z$

$-L_x - L_z - L_y$

$+ 1$

B:



$\prod B_c = 1$   
c: plane

$3L_x L_y L_z - 2(L_x + L_y + L_z) + 3$

$L_x L_y L_z - (L_x - 1) - (L_y - 1) - (L_z - 1) - 1$

$= L_x L_y L_z - L_x - L_y - L_z + 2$

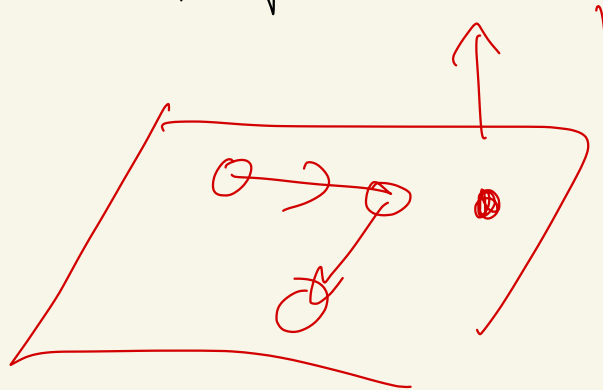
ground state deg =  $2 \underbrace{2L_x + 2L_y + 2L_z - 3}_{\mathcal{O}(L)}$  !

$\downarrow$   
 "UV/IR mixing"

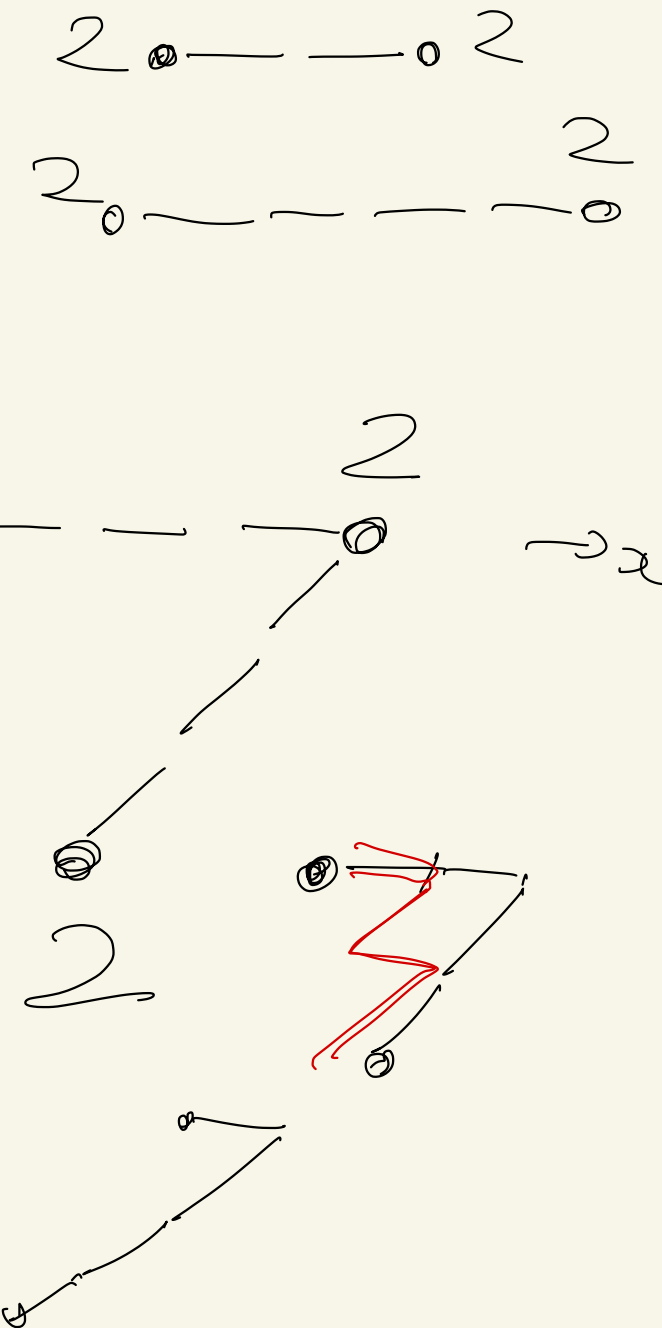
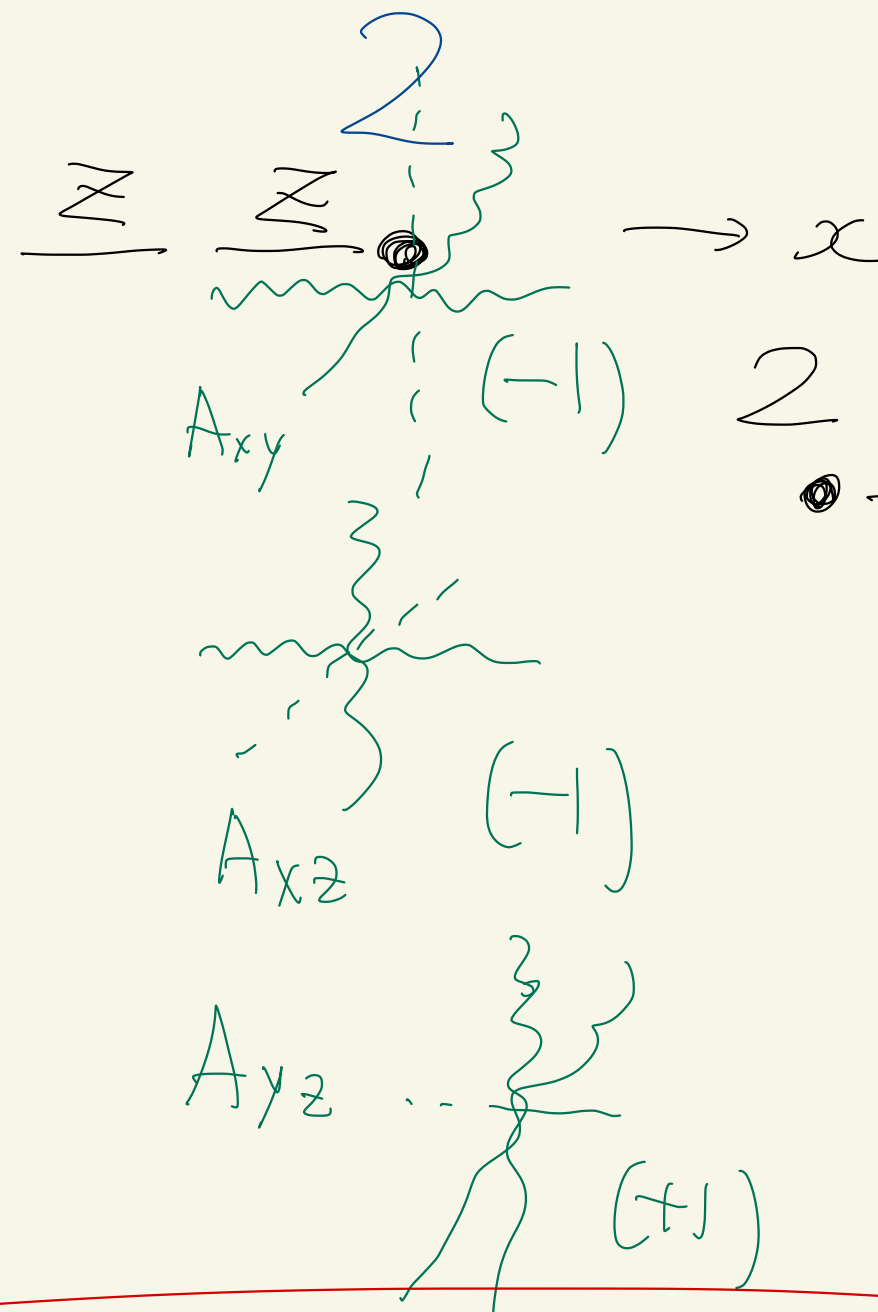
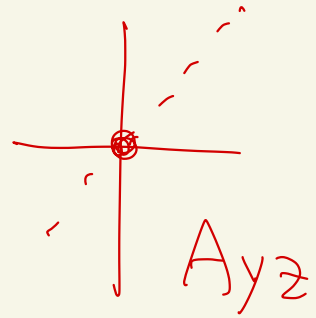
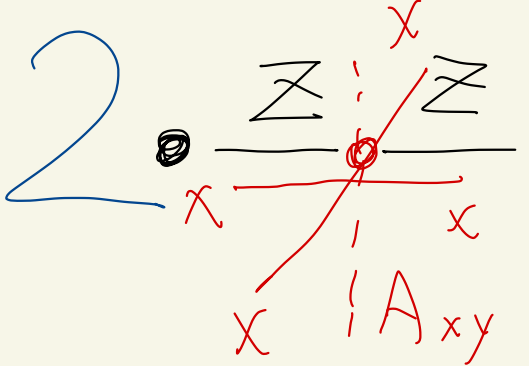
- ~~Lorentz sym~~

- rotational sym  $\leftarrow$  discrete

- excitation: mobility restricted  
 linear / planon / Area Law



e.g. lineon



excitation confined to a line

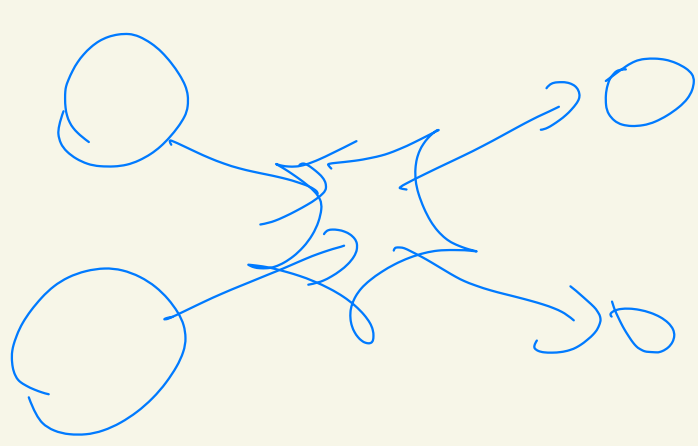
Gravity

A hand-drawn underline for the word "Gravity". The underline is a single, continuous, slightly wavy line that starts under the 'G', goes under the 'r', dips slightly under the 'o', rises slightly under the 'v', dips again under the 'i', and ends under the 'y'.



# Intuition:

- IR / UV separation : breaks down at Planck scale (EFT)
- Planck scale scale  $\rightarrow$  creates black hole



$m \sim m_{\text{pl}}$

usually  $\rightarrow$

$$\lambda \sim \frac{h}{mc}$$

Compton wavelength

$$r_{\text{BH}} \sim \frac{2Gm}{c^2}$$

BH radius

backreaction

$$r_{\text{BH}} \sim \lambda$$

$$m \sim m_{\text{pl}} \sim \sqrt{\frac{\hbar c}{G}}$$

$$l_{\text{pl}} \sim \sqrt{\frac{\hbar G}{c^3}}$$

# Bekenstein bound

$$\frac{S}{E} < \frac{2\pi k_B R}{\hbar c}$$

Saturated by BH

2nd law

$$\frac{d}{dt} (S_{BH} + S_{rest}) \geq 0$$

$$"S \lesssim R^2"$$

$$S_{BH} = \frac{k_B A}{4\ell_p^2} = \frac{k_B (4\pi R^2) c^3}{4G\hbar}$$

$\ell_p = \sqrt{\hbar G/c^3}$

$$R = \frac{2GM}{c^2}$$

$$M = \frac{c^2 R}{2G}$$

$$\frac{S_{BH}}{E_{BH}} = \frac{k_B (4\pi R^2) c^3}{4G\hbar M c^2}$$

$$= \frac{2\pi k_B R}{\hbar c}$$

# Bekenstein bound

$$S \leq S_{\text{BH}} \approx \underbrace{R^2}_{\text{wavy}} M_{\text{pl}}^2$$

$$\underbrace{R^3}_{\text{wavy}} \underbrace{\Lambda^3}_{\text{double underline}}$$

$$\rightarrow \Lambda \lesssim \left( \frac{M_{\text{pl}}^2}{R} \right)^{1/3}$$

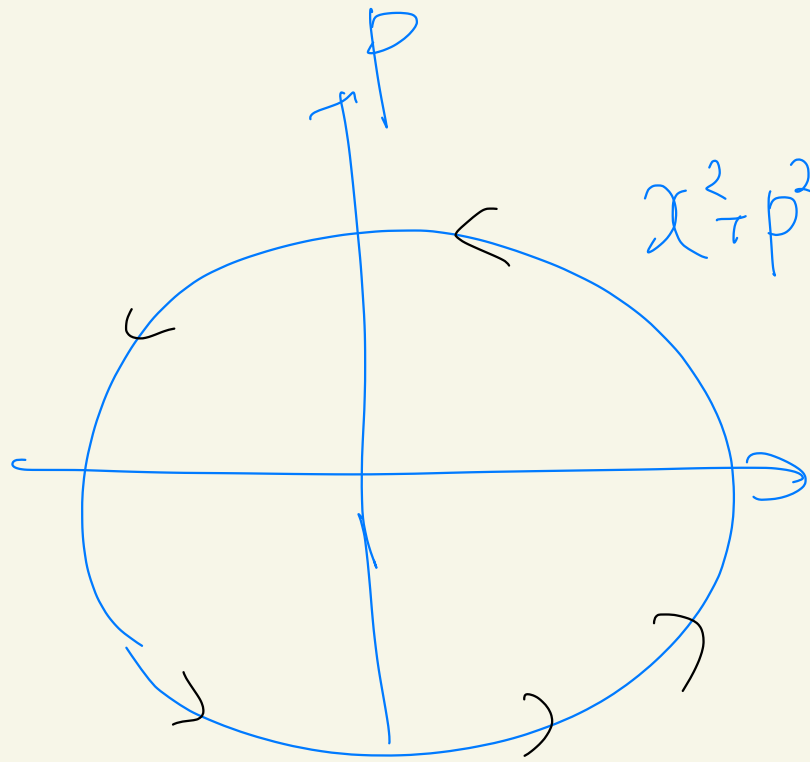
"UV/IR mixing"

$R \rightarrow \infty$   
 $R$ : IR cutoff  
 $\Lambda$ : UV cutoff  
 $\Lambda \rightarrow \infty$

(cf. Cohen-Kaplan-Nelson bound)

$$\underbrace{\Lambda_{\text{UV}}^4 L^3}_{\text{wavy}} \prec L M_{\text{pl}}^2$$

$\sim$   
 $r_{\text{BH}}$



$$x^2 + p^2 = E = \text{const.}$$

bounded

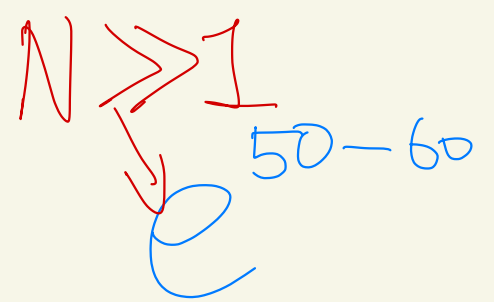
region

bounded  
entropy  
 $S$

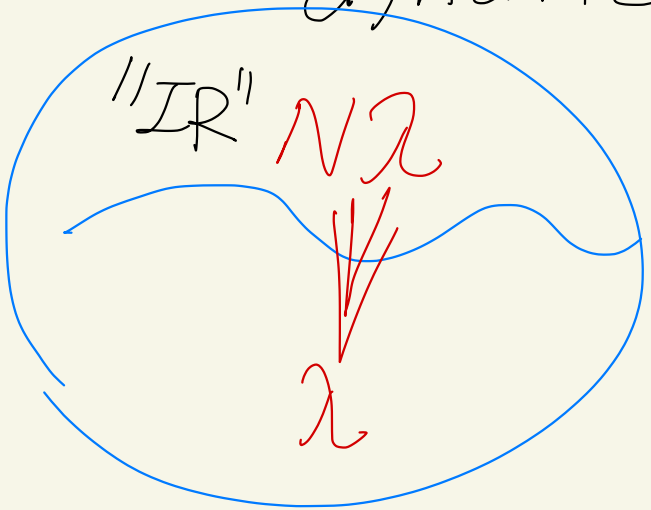
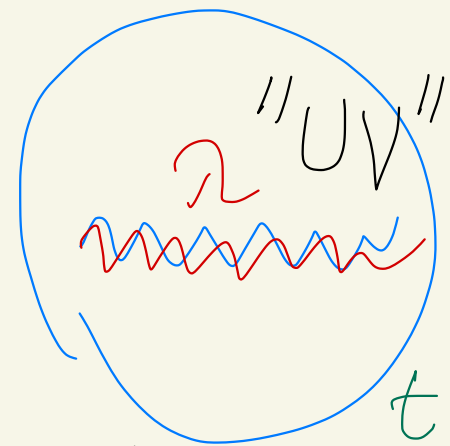
# Trans Planckian "Problem"

Q: what happens if  
I drastic scale change?

cosmology



dynamics?



large scale fluctuation  
↓  
CMB

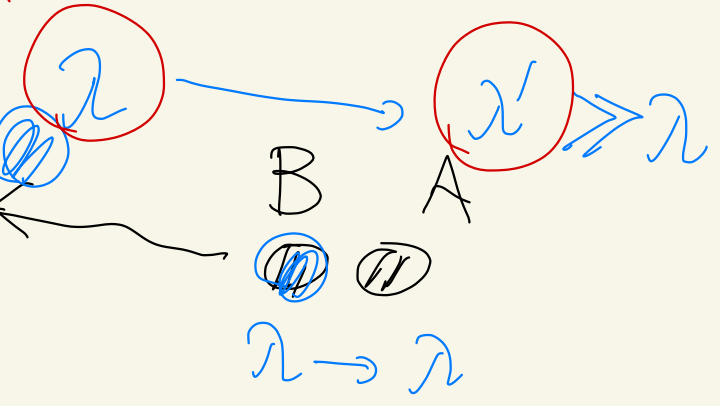
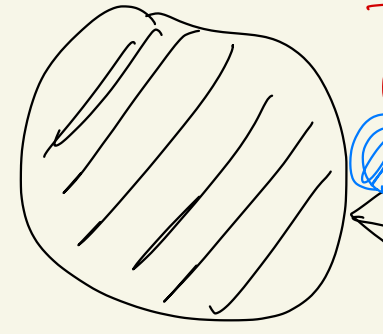
quantum fluctuation

$t \sim H^{-1} \log \left( \frac{M_{pl}^2}{H^2} \right)$   
 $(T_{ds})^{-1}$   
UV

Planck

subPlanckian

black hole



$t_{scrambling}$   
S

$\beta_{BH} \log S'_{BH}$

Quantum Gravity / String Theory UV ls

No Free Parameters!

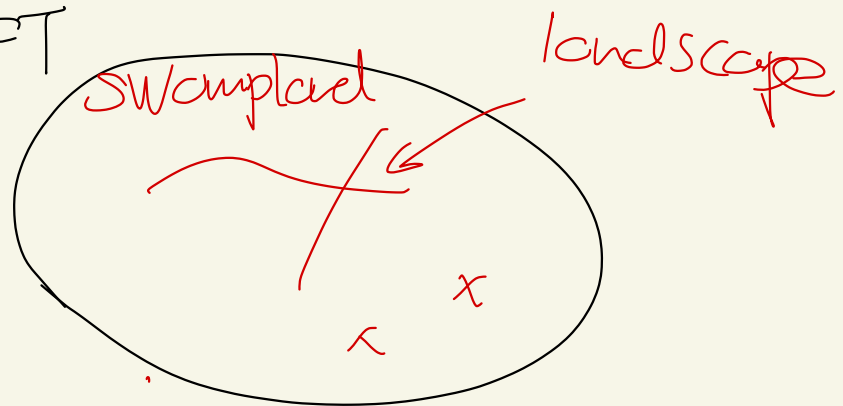
low-energy EFT IR  $g = e^{-\phi}$

$$\mathcal{L} = \mathcal{L}_0 + \sum_n \underbrace{c_n \mathcal{O}_n}_{\text{EFT}}$$

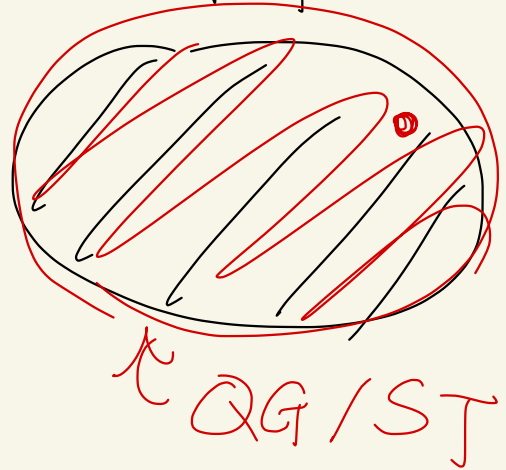
highly constrained?

pessimistic

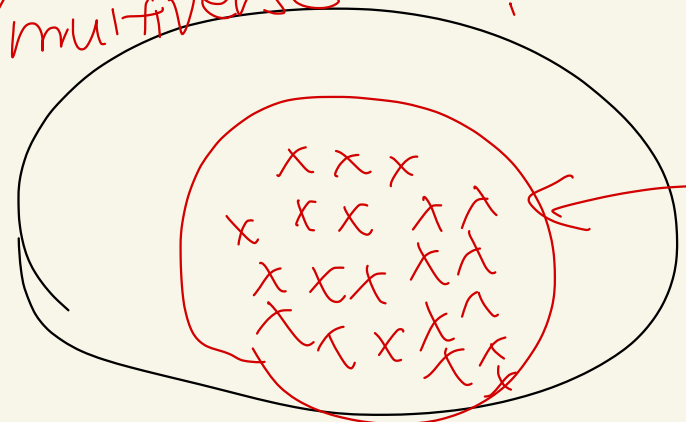
fine-tuning revisited?



possible EFT



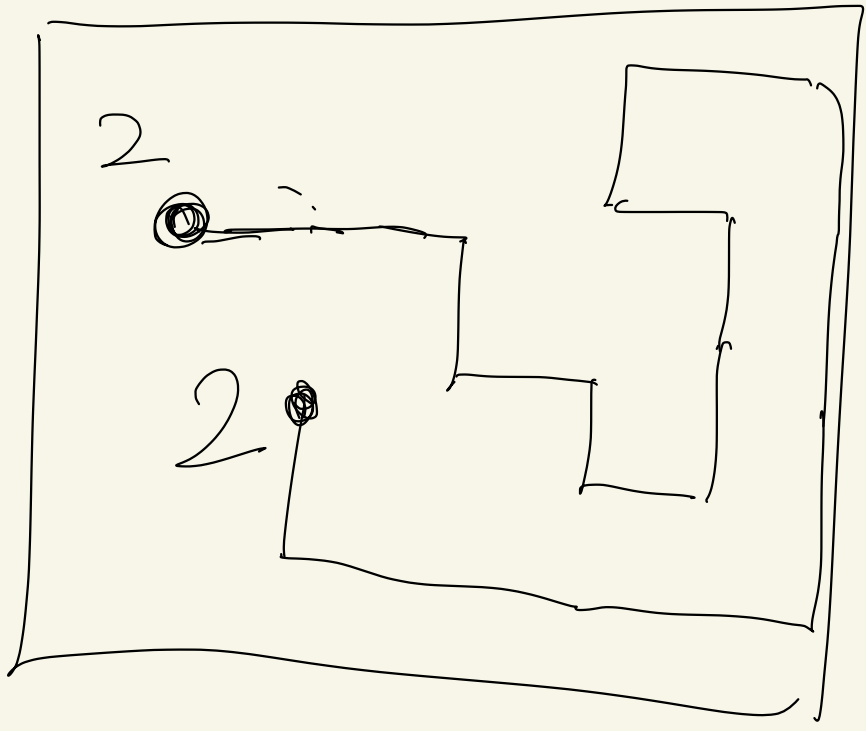
flux vacua / multiverse ?



optimistic

$\int B e^{-2\phi}$   
flux

TQFT



X-cube

