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SUMMER SCHOOL ON PARTICLE PHYSICS

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Physics of Extra Dimensions - *Addendum*

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EXTRA DIMENSIONS / BRANE WORLDS AS A THEORETICAL LABORATORY

ALREADY STARTED TO EXPLORE THIS ROUTE:

- CONSISTENCY OF (APPARENT) NON-CONSERVATION OF ENERGY /ELECTRIC CHARGE/ WITH 4D NEWTON'S LAW /GAUSS' LAW/ ← YES

- ROBUSTNESS OF INFLATIONARY PREDICTIONS FOR DENSITY PERTURBATIONS AND GRAVITY WAVES ←

YES, IN LORENTZ-INVARIANT SET UP.

1. WHAT IF LORENTZ-INVARIANCE DOES NOT HOLD AT SHORT DISTANCES?

WHAT'S THE PROBLEM?

- INFLATION = EXPONENTIAL EXPANSION OF THE UNIVERSE

$$ds^2 = dt^2 - R^2(t)\, dx^i dx^i \qquad 4d$$

$$R(t) = e^{Ht}, \quad H \approx \text{const}$$

- COORDINATE MOMENTA $\vec{p}$ STAY CONSTANT,

$$\phi \propto e^{i\vec{p}\vec{x}}\, \varphi_p(t)$$

$$\Downarrow$$

PHYSICAL MOMENTA GET REDSHIFTED,

$$p_{phys} = \frac{p}{R(t)} = p \cdot e^{-Ht}$$

- ORIGIN OF COSMOLOGICAL PERTURBATIONS: PARTICLE CREATION BY TIME-DEPENDENT BACKGROUND METRIC = ENHANCEMENT OF VACUUM FLUCTUATIONS OF INFLATON AND GRAVITATIONAL FIELDS.

INTERESTING WAVELENGTHS TODAY

$$\lambda_{today} \lesssim 10^{28}\ \text{cm}$$ (Size of visible Universe)

$$\Updownarrow$$

VERY SHORT WAVELENGTHS AT BEGINNING OF INFLATION

$$\lambda_{initial} \sim \lambda_0 \cdot e^{-H_{inft} \cdot (\Delta t)_{infl}}$$

TYPICALLY $\lambda_{initial} \ll M_{Pl}^{-1}$!

WE CAN HARDLY EXTRAPOLATE TO SO SHORT DISTANCES! DOES UNKNOWN SHORT-DISTANCE PHYSICS AFFECT INFLATIONARY PREDICTIONS FOR COSMOLOGICAL PERTURBATIONS?

NB: NO QUESTION IN PERFECTLY LORENTZ-INVARIANT THEORIES: SHORT DISTANCES EQUIVALENT TO LONG DISTANCES BY BOOSTS.

(ON-SHELL ANALYSIS NEEDED ONLY TO DESCRIBE PARTICLE CREATION)

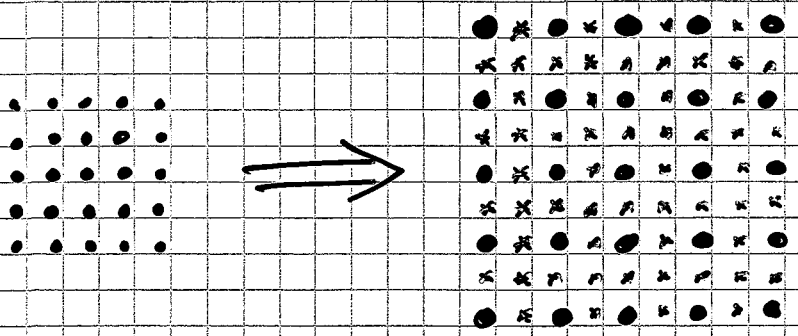
POSSIBLE SCENARIO:

NO WAVELENGTHS SHORTER THAN "FUNDAMENTAL LENGTH" l_0.

E.G. IF SPACE = LATTICE OF SPACING l_0.

MODE GENERATION

- AS THE UNIVERSE EXPANDS, NEW MODES ARE "BORN"



NEW DEGREES OF FREEDOM COME INTO BEING.

DOES THIS AFFECT THEORY OF COSMOLOGICAL PERTURBATIONS?

POSSIBILITIES: - Conservative: $l_0 \sim l_{pl} \ll H_{infl}^{-1}$

- "EXTREME": $l_0 \lesssim H_{infl}^{-1}$

HARD TO IMPLEMENT IN A CALCULABLE FRAMEWORK IN 4D.

5D WARPED GEOMETRY WITH LORENTZ-VIOLATION

$$ds^2 = a^2(y)\,dt^2 - b^2(y)\,dx^i dx^i - dy^2$$

(STILL STATIC)

SCALAR FIELD IN SOME POTENTIAL

IN THIS BACKGROUND: $\phi = e^{i\omega t - i\vec{p}\vec{x}}\phi(y)$

$$\omega^2\phi = \frac{a^2(y)}{b^2(y)}\,\vec{p}^{\,2}\cdot\phi + \mathcal{H}_T\,\phi$$

$\mathcal{H}_T$: TRANSVERSE OPERATOR.

- Take $\frac{a^2}{b^2} = 1$ at $y=0$ (brane position)

coordinate choice

$$\frac{a^2}{b^2} \to 0 \quad \text{as} \quad |y| \to \infty$$

- Let $\mathcal{H}_T$ HAVE A ZERO MODE (BOUND STATE)

⇓

- LOCALIZED MODE AT $\vec{p}=0$ AND SMALL $|\vec{p}|$
- NO LOCALIZED MODES AT HIGH $|\vec{p}|$.

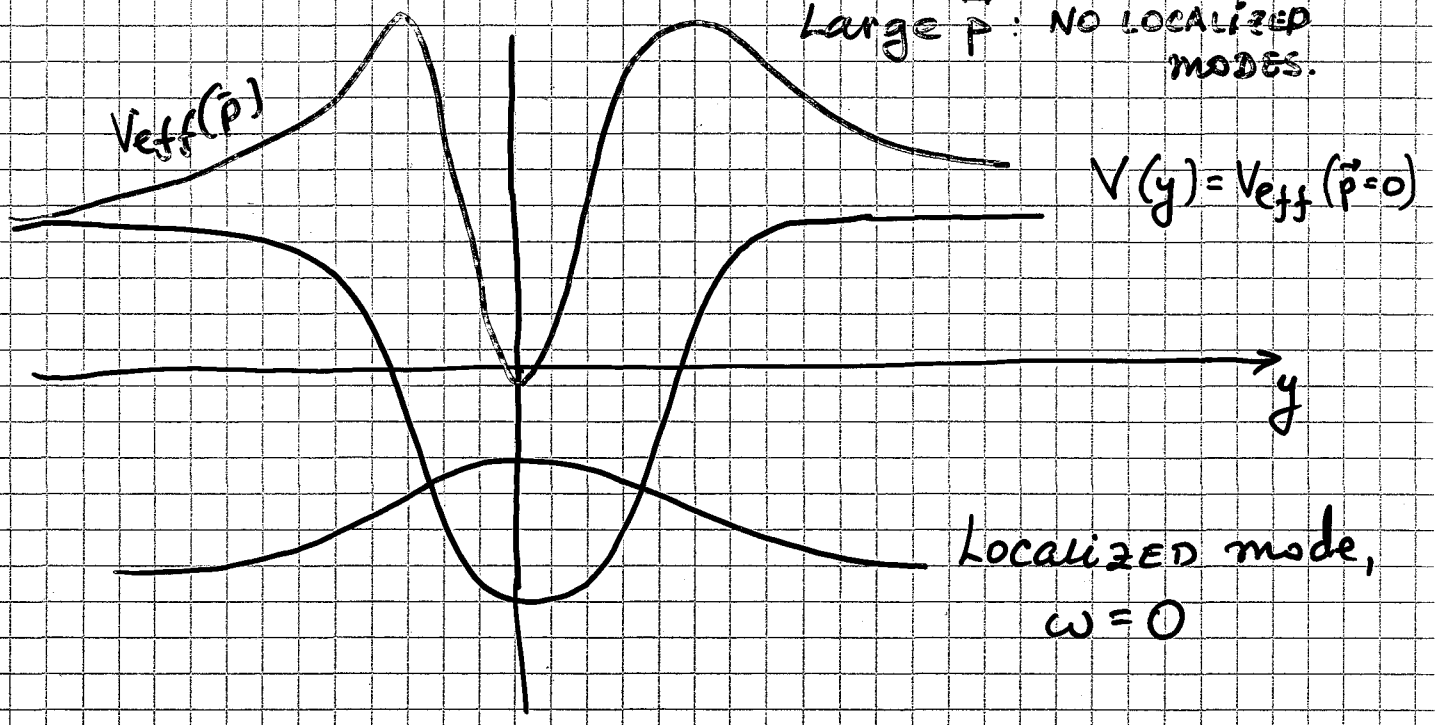
MODE GENERATION!

CALCULABLE FRAMEWORK.

E.G., $\mathcal{H}_T = -\partial_y^2 + V(y)$

$$\Downarrow$$

$$V_{eff}(y;\vec{p}) = V(y) + \frac{a^2(y)}{b^2(y)}\,\vec{p}^{\,2}$$



- Expanding setup:

$$ds^2 = a^2(y)\,dt^2 - R^2(t)\left[b^2(y)\,d\vec{x}^{\,2} - dy^2\right]$$

- SPECTRUM OF PERTURBATIONS CALCULABLE

parameters:

- H_{infl}
- l_0 : scale below which localized modes cease to exist.

- OUTCOME:

- $l_0 \ll H_{infl}^{-1}$, Lorentz-breaking at shorter length scale than horizon at inflation

STANDARD PREDICTIONS OF 4d inflation: flat spectrum; $\langle \phi^2 \rangle = H^2$, etc.

- $l_0 \gtrsim H_{infl}^{-1}$, time-independent

STILL FLAT SPECTRUM OF PERTURBATIONS.
NON-STANDARD OVERALL AMPLITUDE
Hard to distinguish observationally.

- $l_0 \cdot H_{infl} \gtrsim 1$, depends on time (even SLOWLY)

GROSS DEVIATIONS (ORDERS OF MAGNITUDE!)

CONSISTENT WITH OBSERVATIONS, BUT POSSIBLY MUCH MORE (OR MUCH LESS) POWER AT SHORT SCALES.
CHANCE FOR GRAVITY WAVE DETECTORS (LIGO, VIRGO, LISA) AND TIMING OF PULSARS.

JUST A TOY MODEL.

DIFFICULTY : HOW TO GET

$$a(y) \neq b(y) \quad ?$$

* NOT adS in BULK

⇓

$p \neq -\rho$ in BULK

WHAT KIND OF matter in BULK ?

* Same for brane :

jumps of $a'(y)$ and $b'(y)$ correspond to different components of $T_{\mu\nu}$ of the brane (through 5D EINSTEIN EQS.)

⇓

$p \neq -\rho$ on BRANE.

WHAT KIND OF matter on BRANE ?

↑ matter in our Universe!

KNOWN EXAMPLES : WEIRD...

YET WE'VE LEARNED A LESSON:

INFLATIONARY PREDICTIONS FOR PRIMORDIAL DENSITY PERTURBATIONS AND/OR GRAVITY WAVES ARE SENSITIVE TO SHORT-DISTANCE PHYSICS, provided that "short distance" $\ll H_{in}^{-1}$

EFFECTS OBSERVABLE (WITH LUCK).

PENDING: ANALYSIS OF (NON-)UNIVERSALITY OF HAWKING RADIATION FROM BLACK HOLES.