

Title: Dark Energy, Lorentz Violation and Ghosts

Date: May 20, 2007 02:00 PM

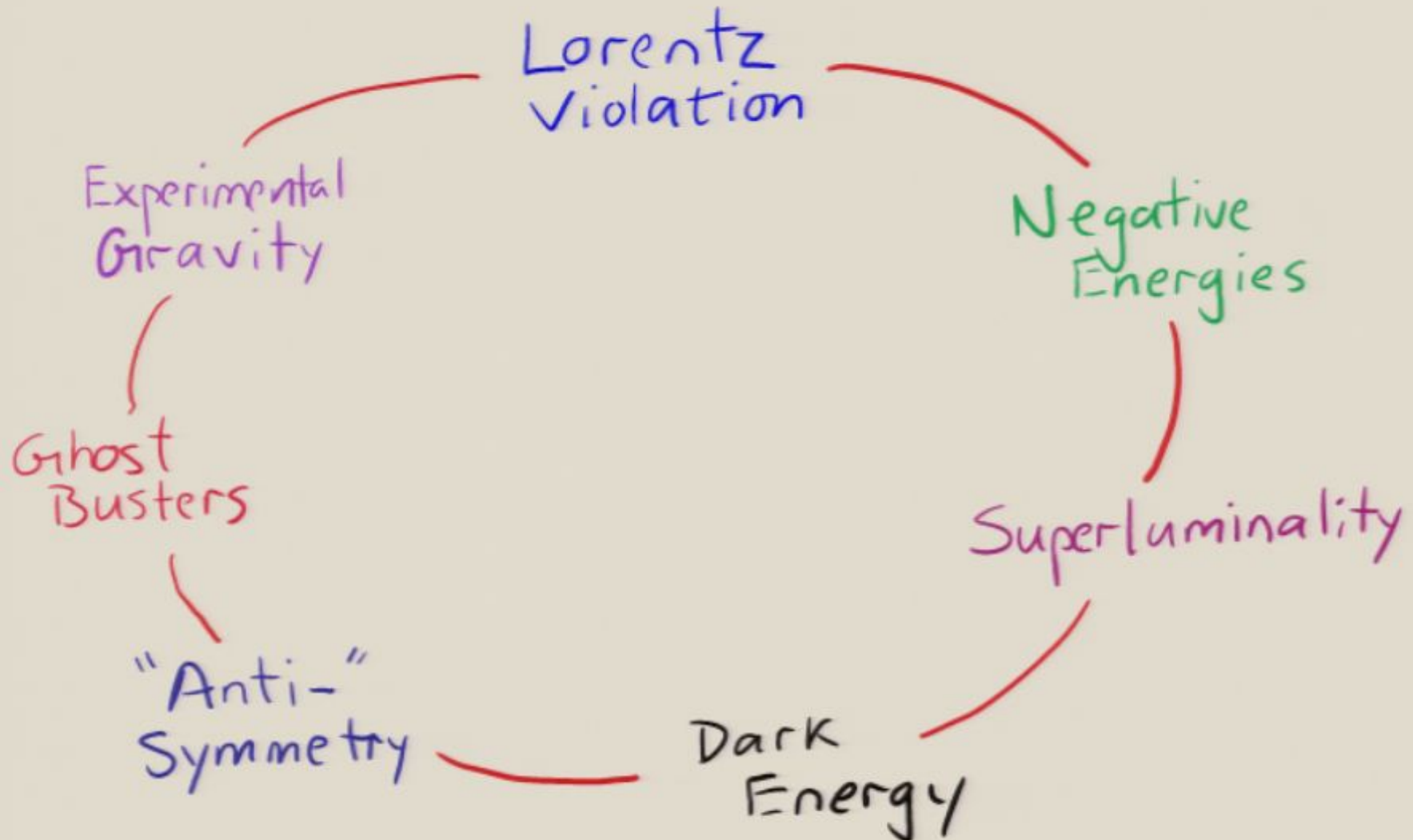
URL: <http://pirsa.org/07050042>

Abstract: <span>I describe how vacuum energy can be controlled by a symmetry principle that necessitates a ghost sector. I argue that the implied instability of Minkowski spacetime is natural and consistent with experience if gravity is fundamentally Lorentz-violating, and describe attempts to construct such exotic dynamics. I briefly discuss the more robust experimental/observational signatures of such a scenario.</span>

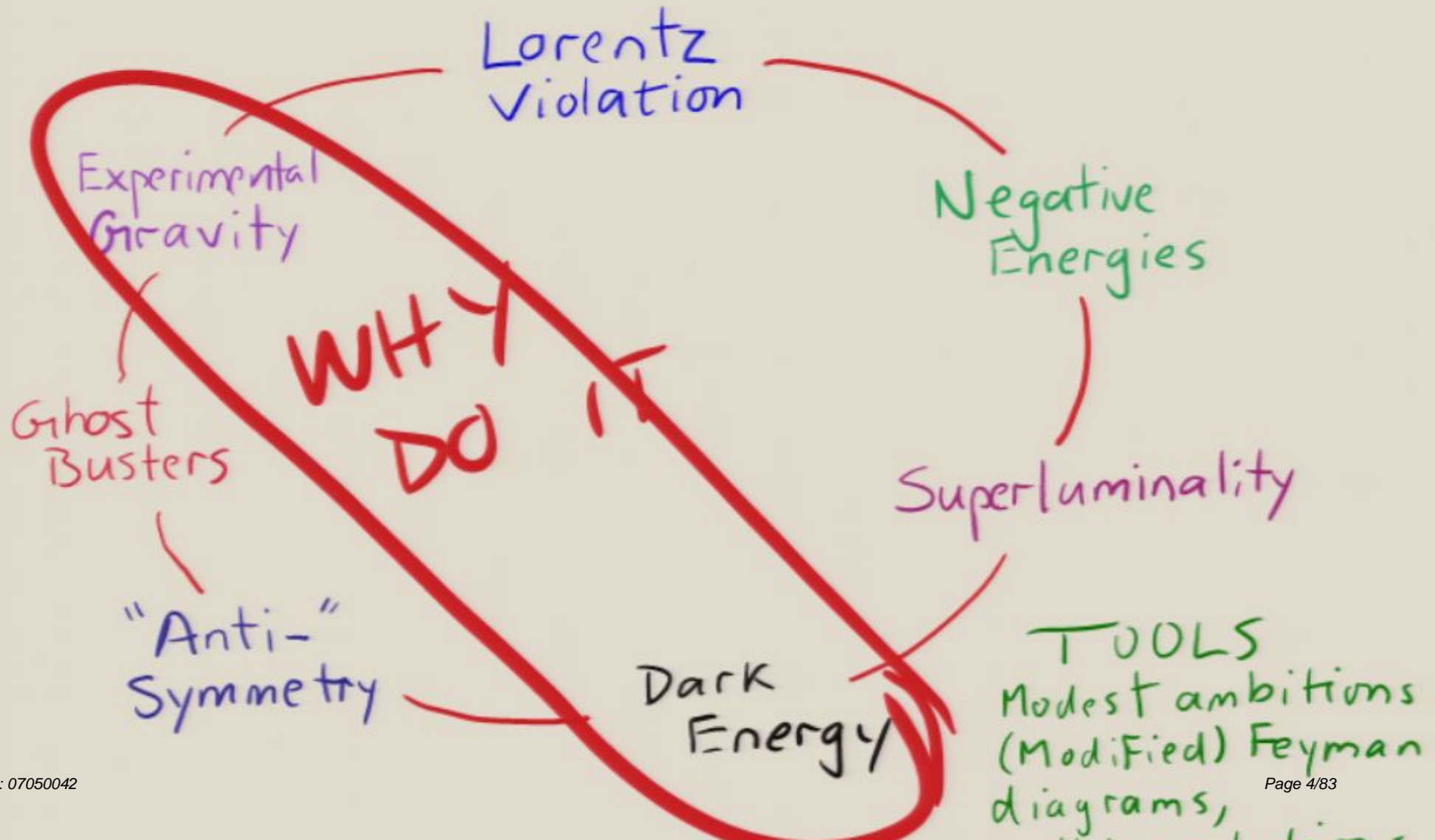
DARK ENERGY,  
LORENTZ VIOLATION,  
& GHOSHS

Raman Sundrum  
Johns Hopkins University

# OUTLINE

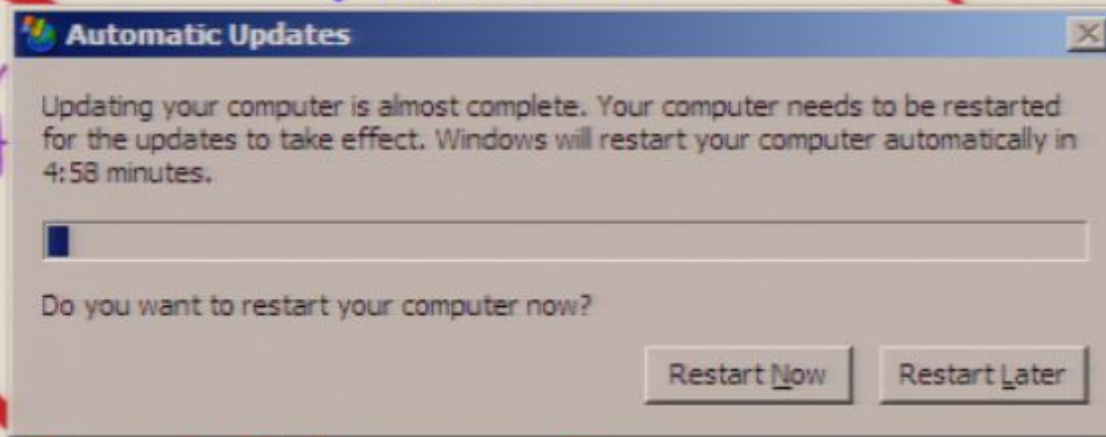


# OUTLINE



# OUTLINE

Lorentz violation



Experimental Gravitation

High Energies

Ghost Busters

Superluminality

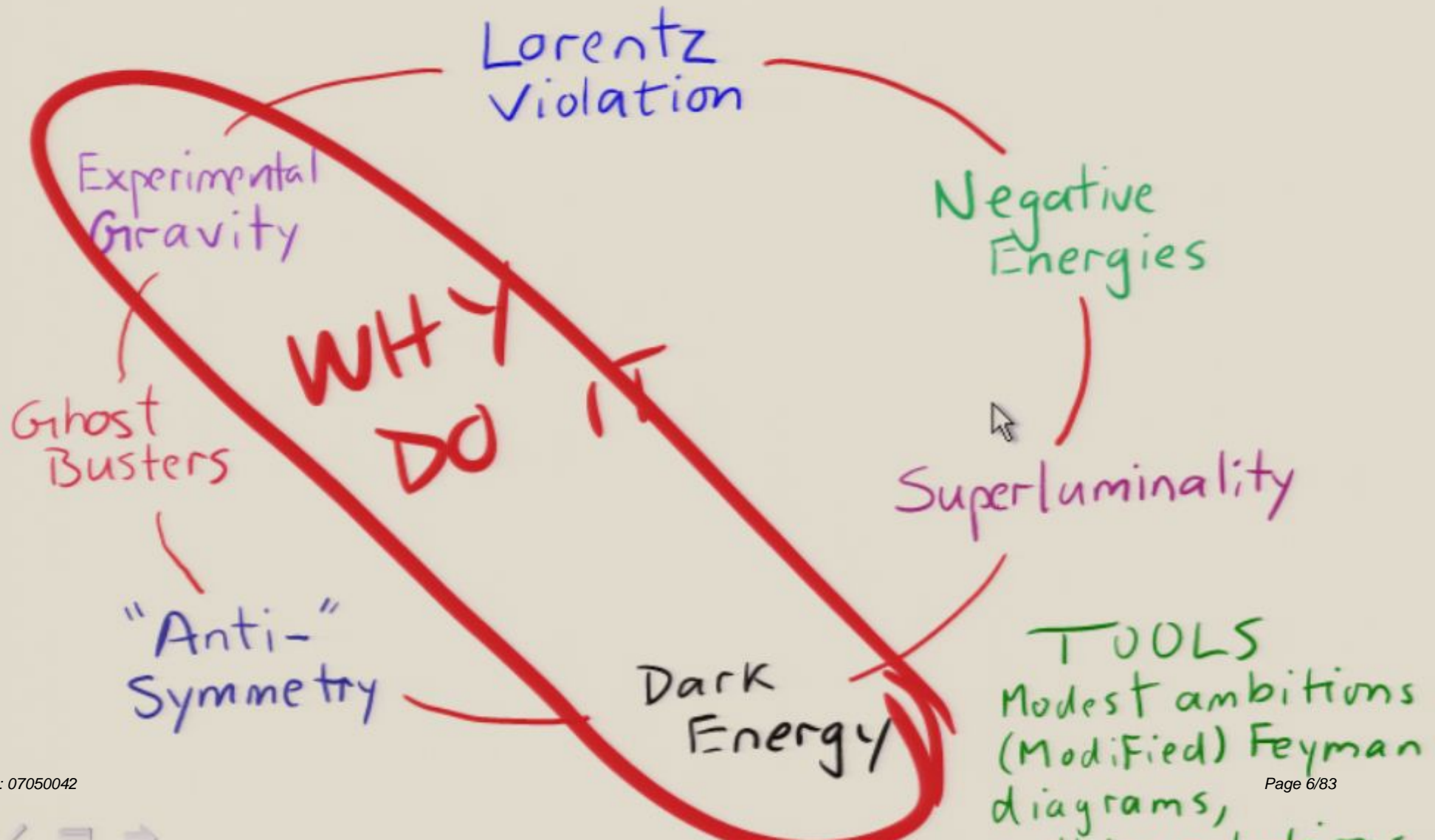
"Anti-Symmetry"

Dark Energy

TOOLS  
Modest ambitions  
(Modified) Feynman diagrams,



# OUTLINE



# EMERGENT RELATIVITY

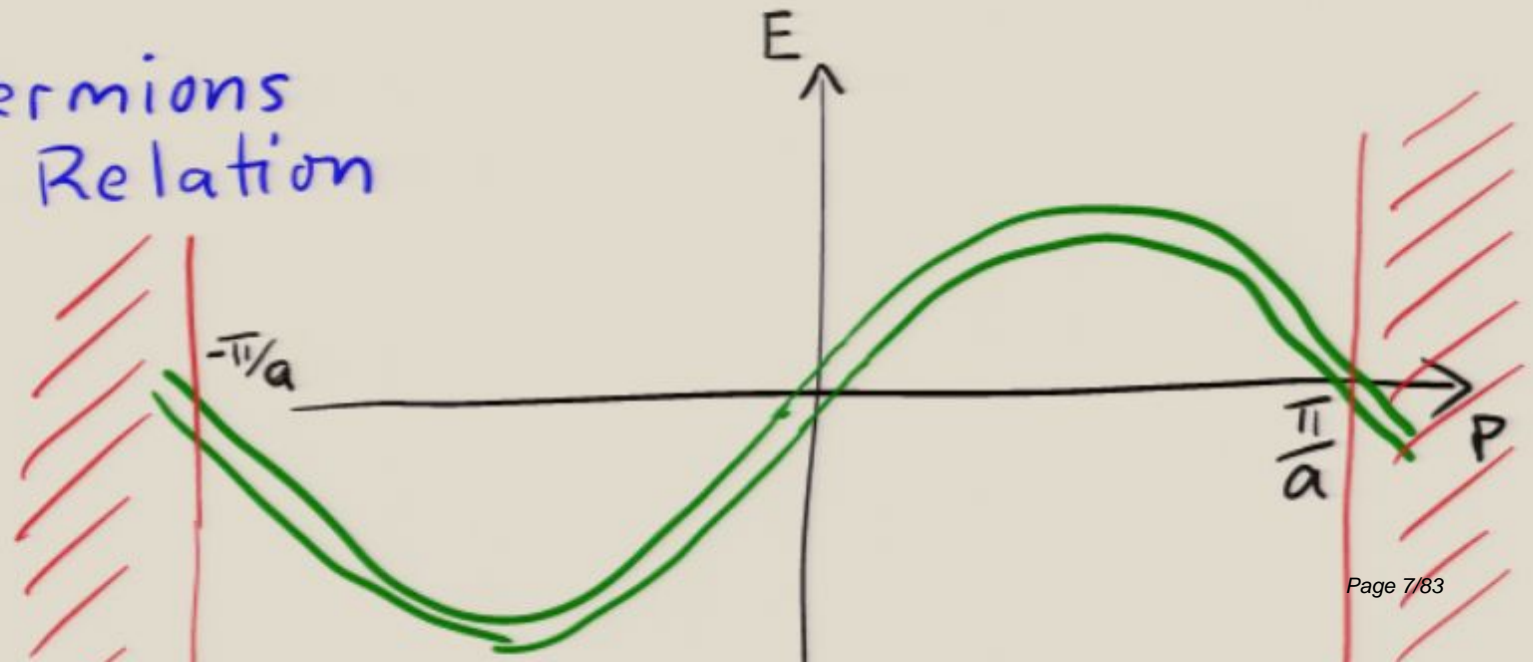
(without gravity)

Quantum Spin Chain:



$\longleftrightarrow$   
 $a$  not boost-invariant

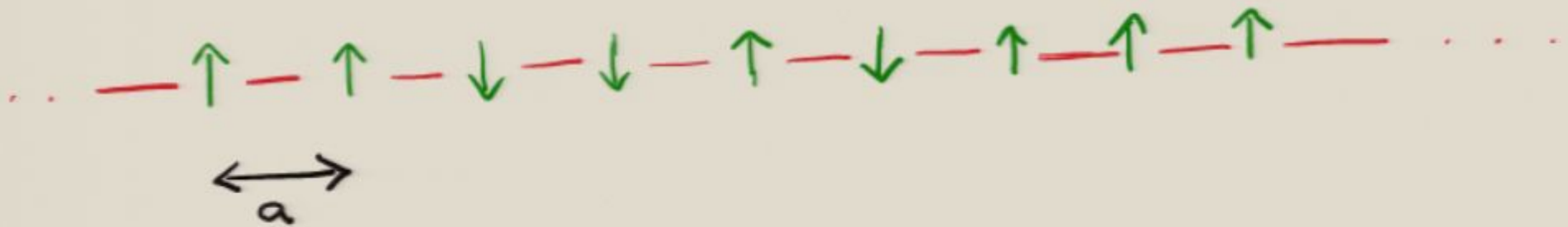
Lattice Fermions  
Dispersion Relation



# EMERGENT RELATIVITY

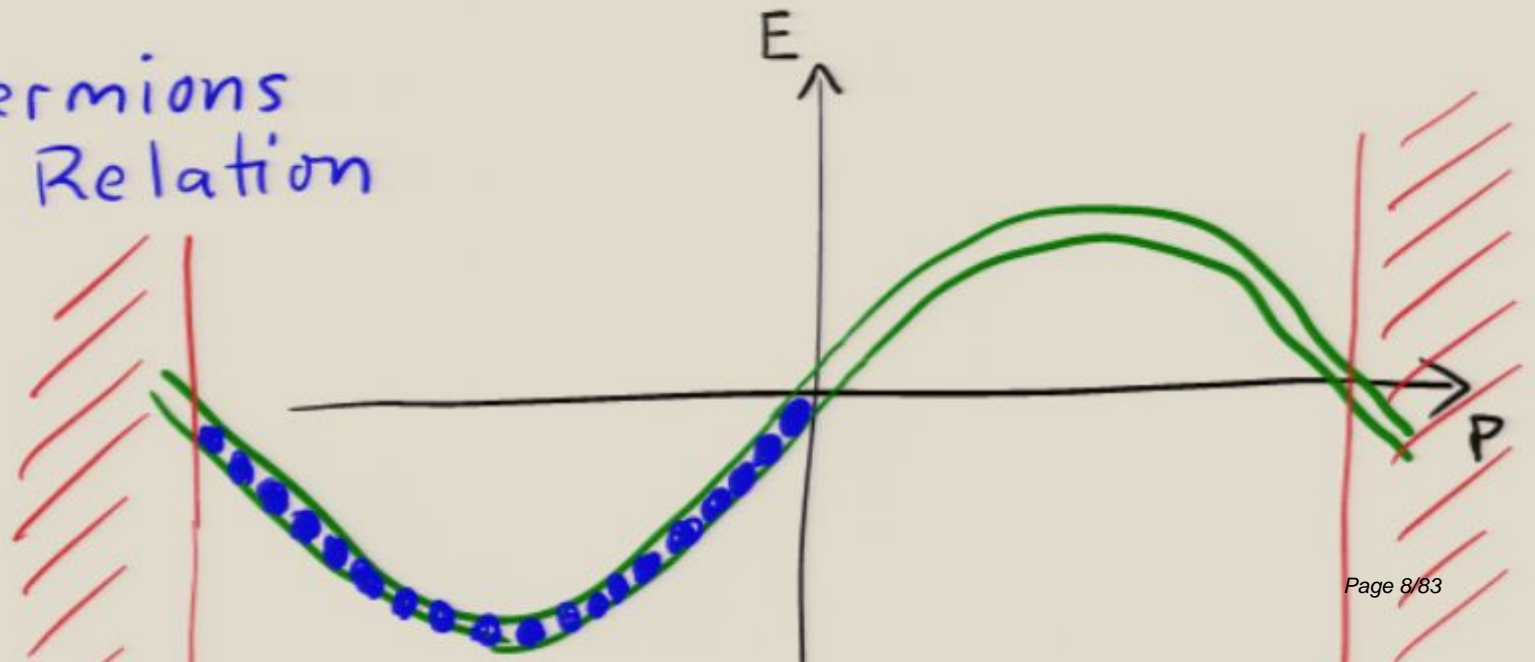
(without gravity)

Quantum Spin Chain:



Lattice Fermions  
Dispersion Relation

$|0\rangle$   
"Minkowski"

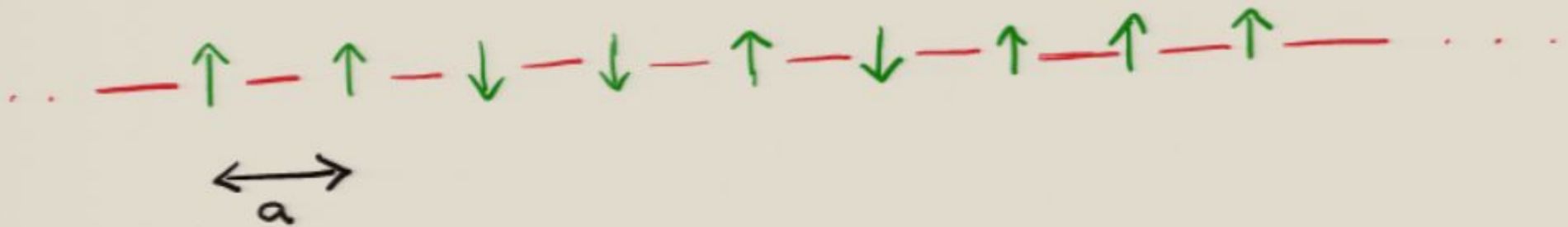




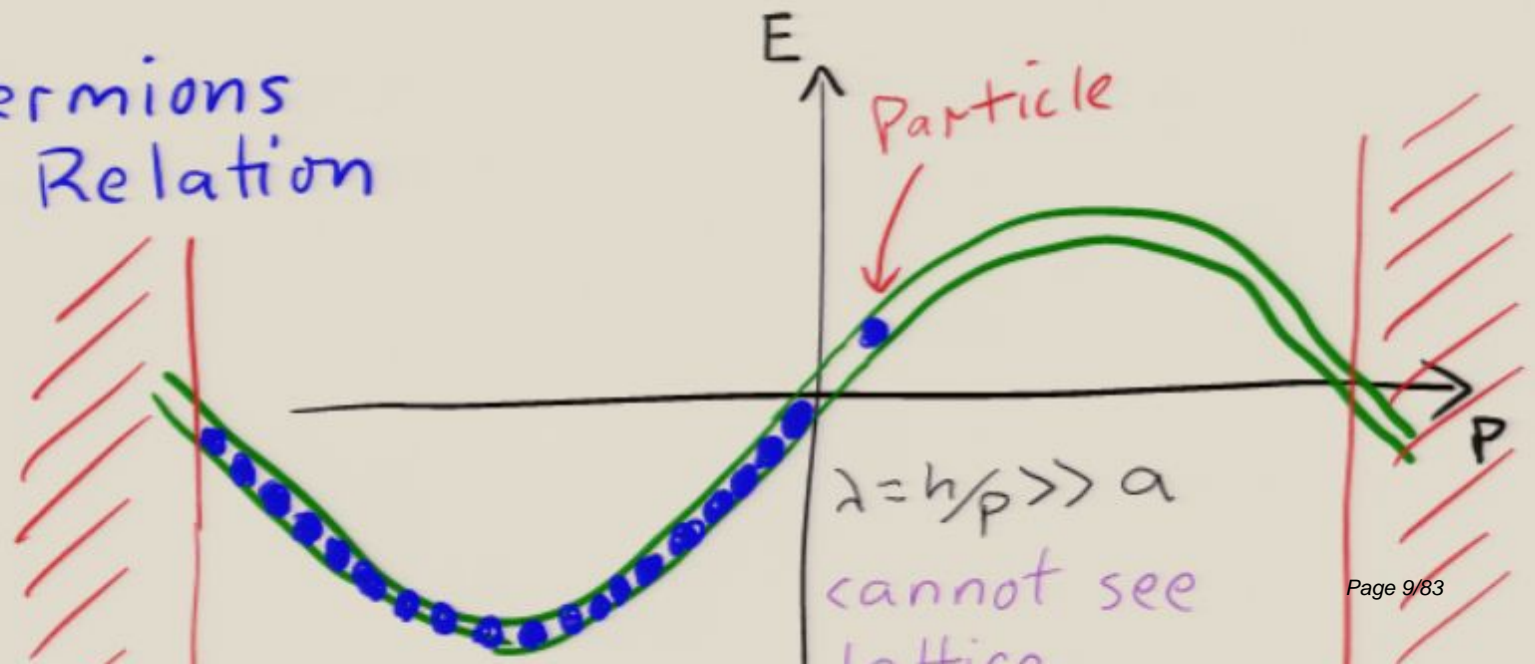
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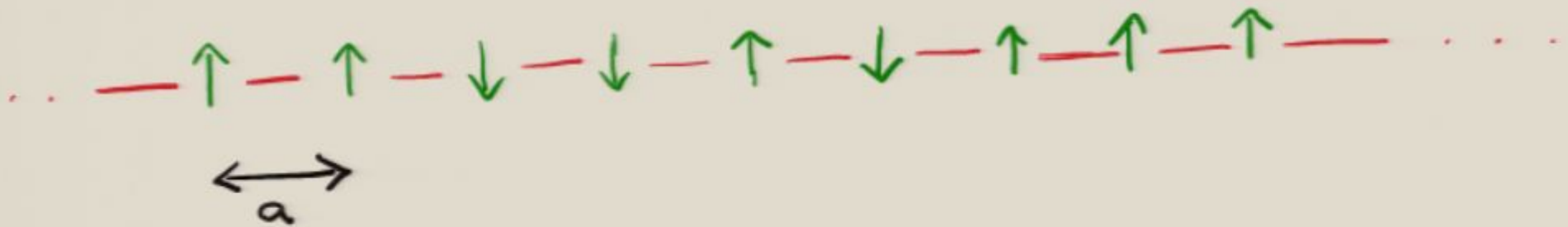
Lattice Fermions  
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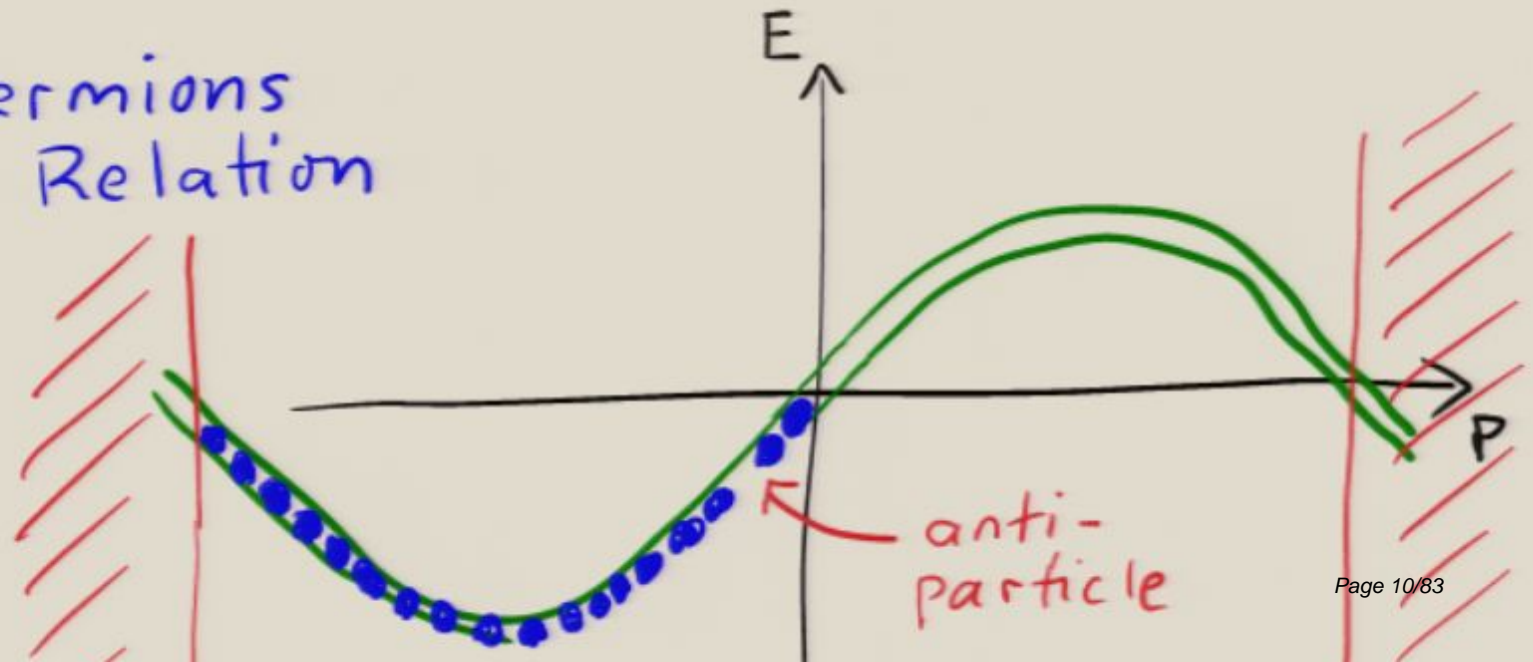
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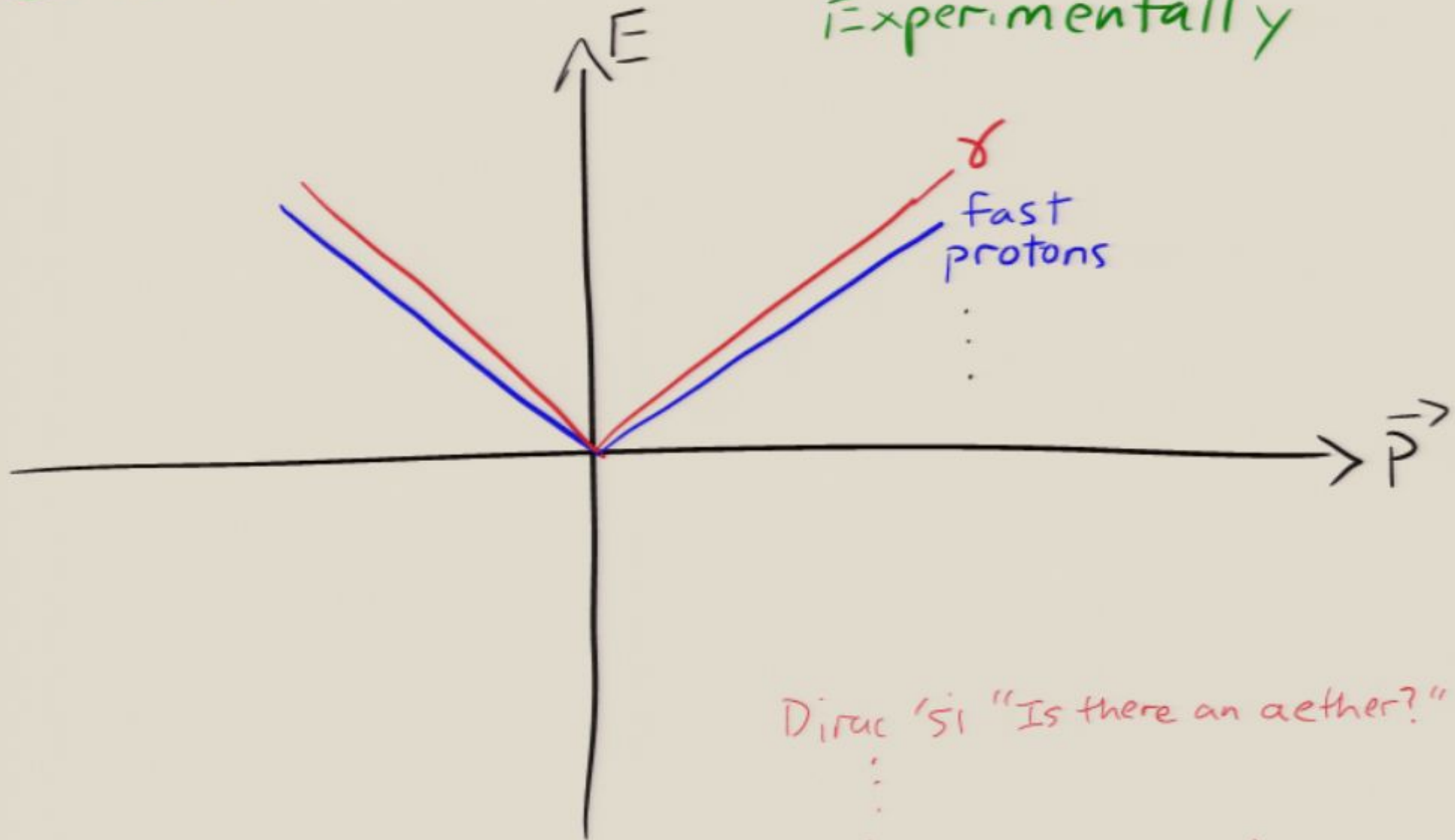


Lattice Fermions  
Dispersion Relation



# BUT TIGHTLY CONSTRAINED

$\vec{E}$  experimentally



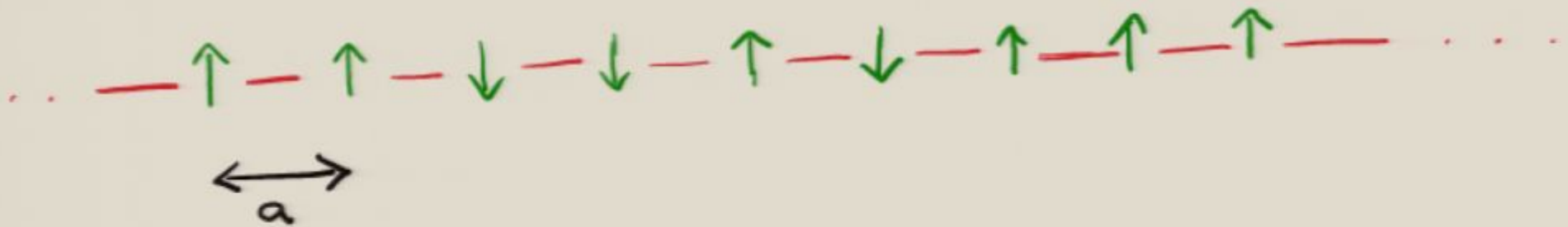
Dirac '51 "Is there an aether?"

⋮  
review: Mattingly '05

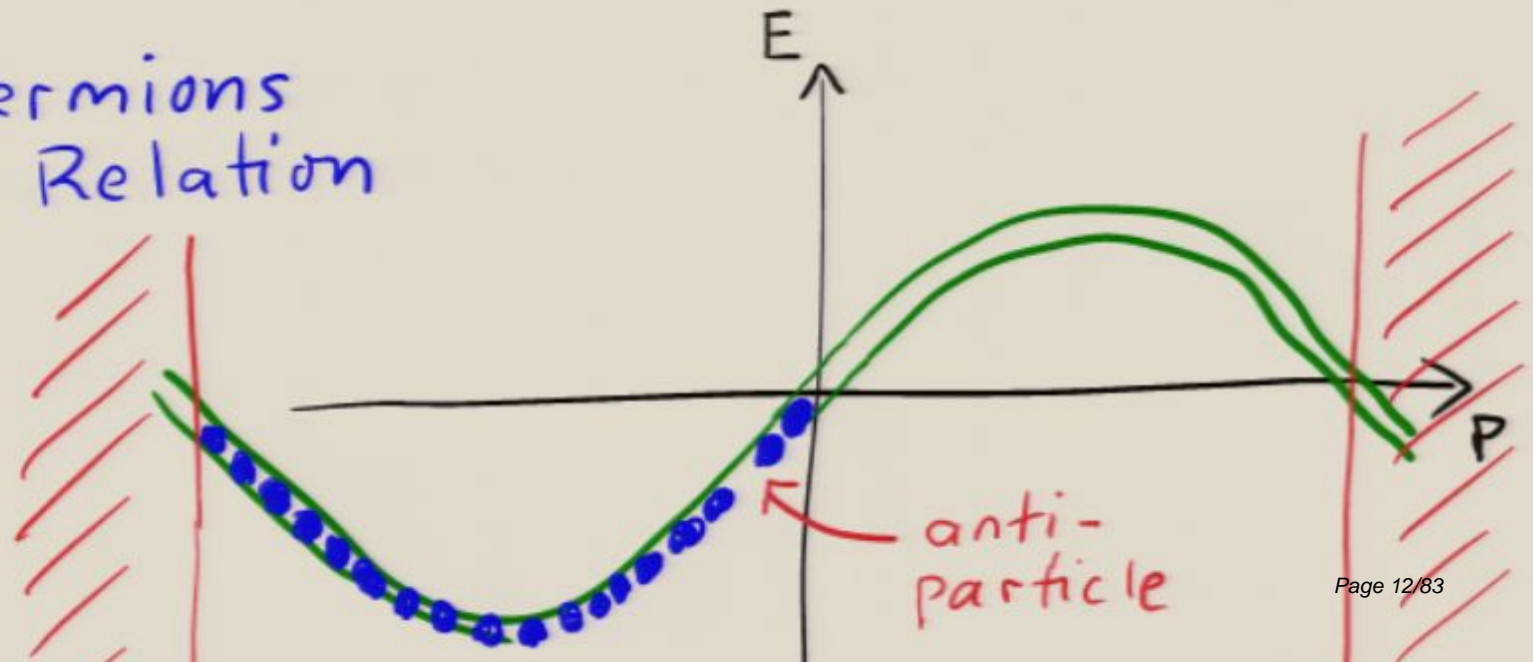
# EMERGENT RELATIVITY

(without gravity)

Quantum Spin Chain:



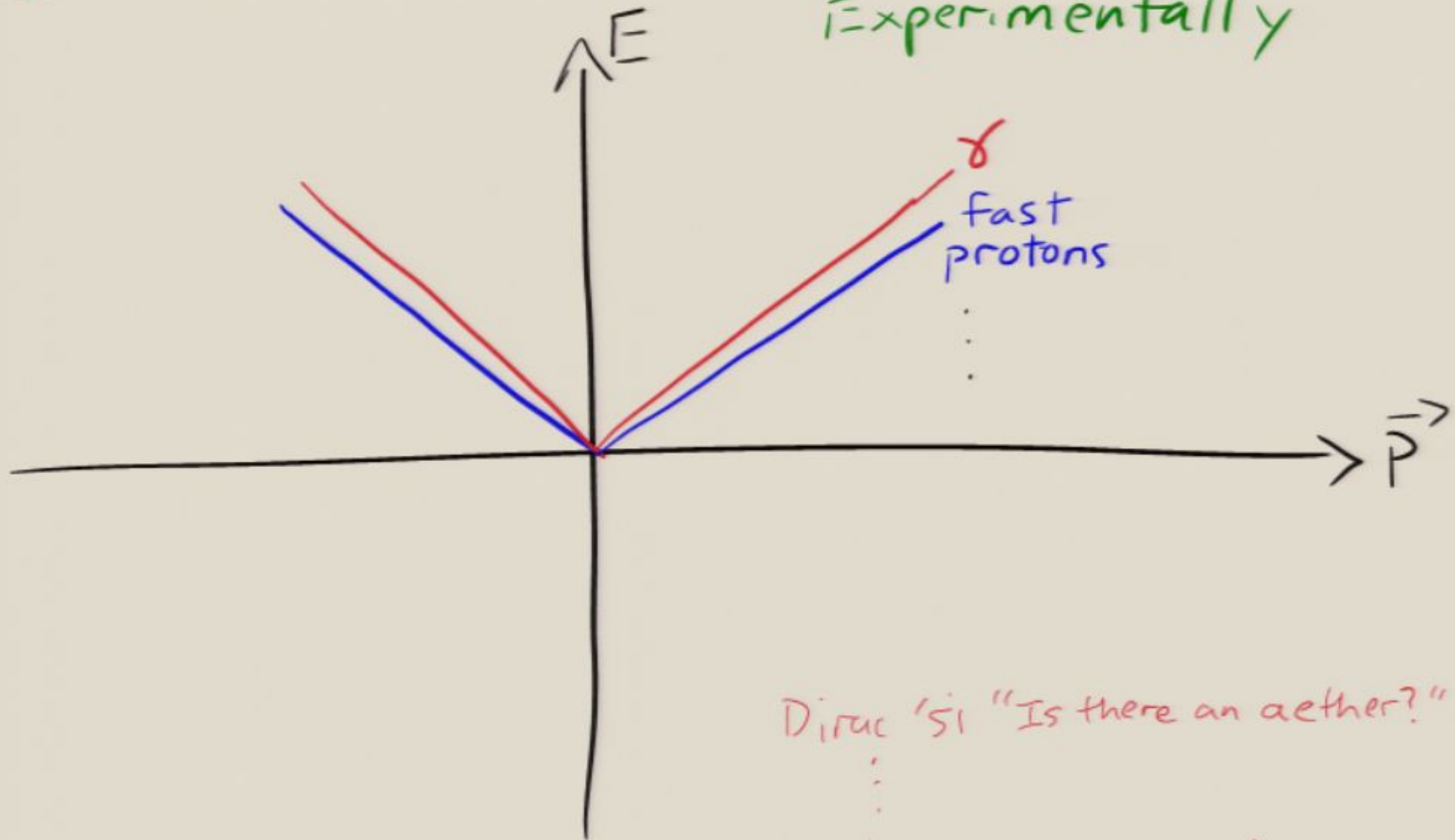
Lattice Fermions  
Dispersion Relation





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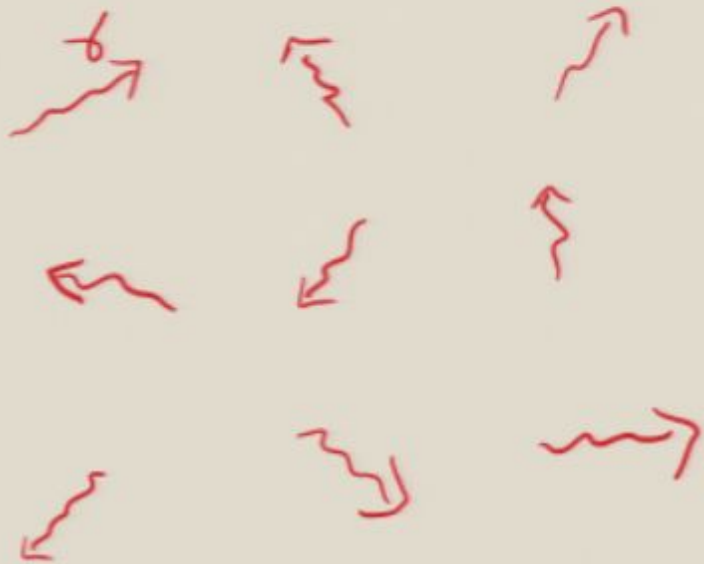


Dirac '51 "Is there an aether?"

review: Mattingly '05

# GRAVITATIONAL ~~LORENTZ~~

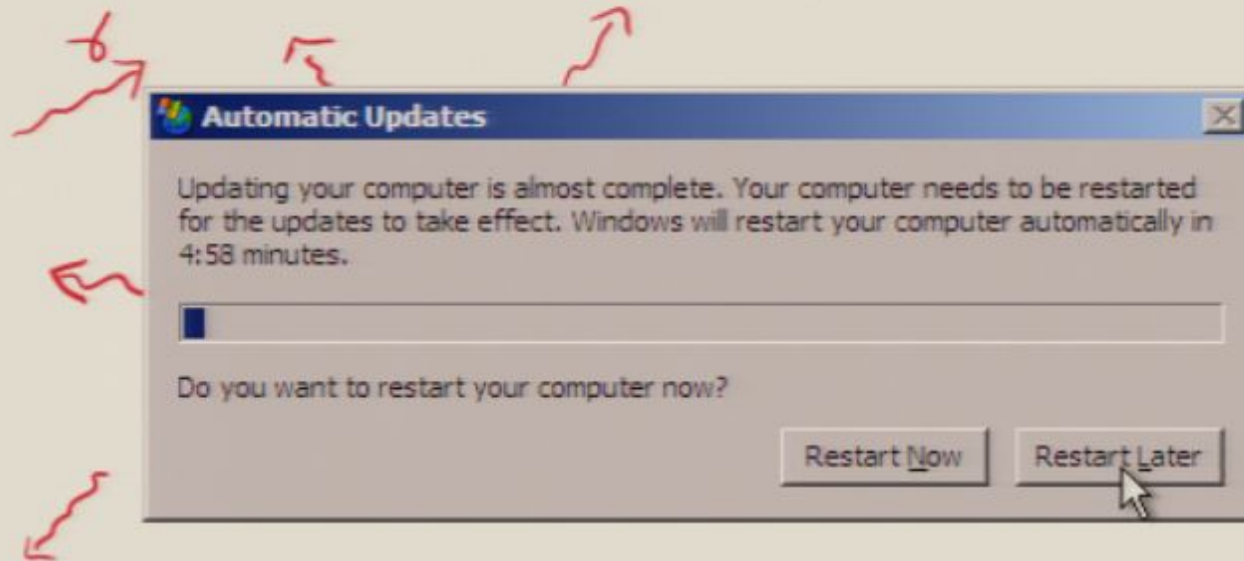
Precedent for local Lorentz violation:



Cosmic Microwave Background

# GRAVITATIONAL ~~LORENTZ~~

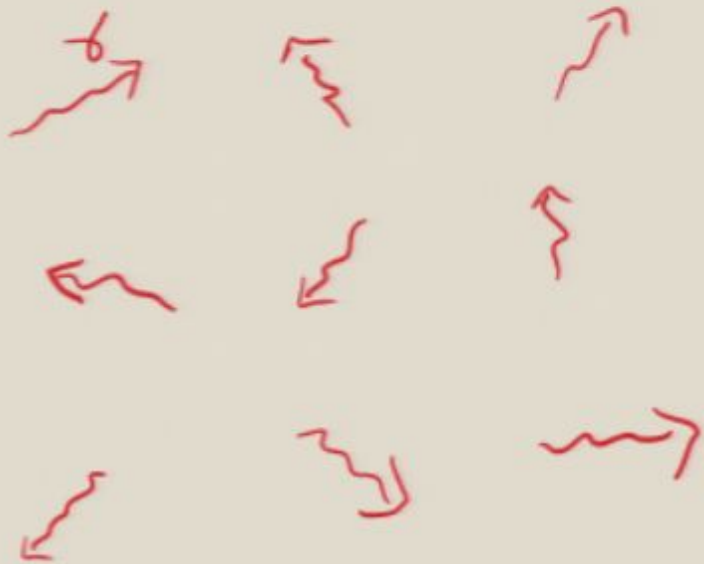
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# GRAVITATIONAL ~~LORENTZ~~

Precedent for local Lorentz violation:



Cosmic Microwave Background



# GRAVITATION-L ~~LORENTZ~~

Precedent for local Lorentz violation:



Cosmic Microwave Background

"trivially" gives a preferred coordinate system, breaking general coordinate invariance

# OTHER DIRECTION ...

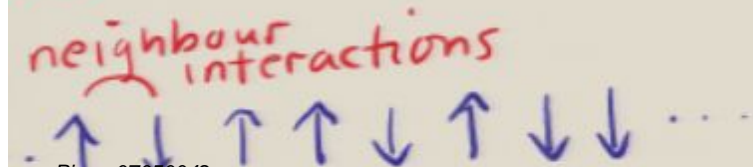
IF there is a preferred frame,

DYNAMICAL SPACETIME  $\Rightarrow$  DYNAMICAL FRAME

$\Rightarrow$  some type of dynamical AETHER  
*Jacobson, Mattingly '01*

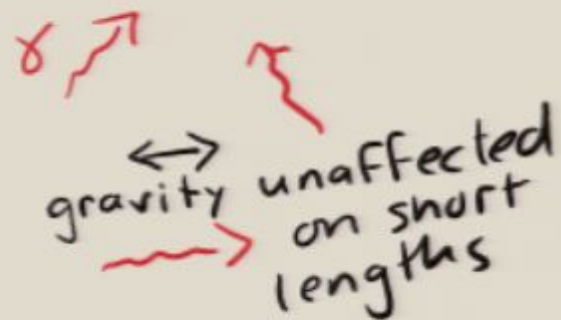
Revolutionary if part of spacetime fabric:

Superluminality  
or spatial non-locality  
without acausality,  
as on lattice

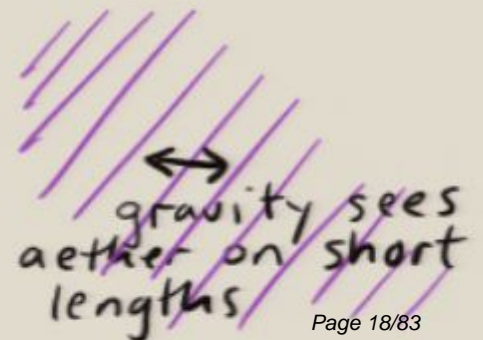


Pirsa: 07050042

Can affect gravity at  
arbitrarily short distance



CMBR

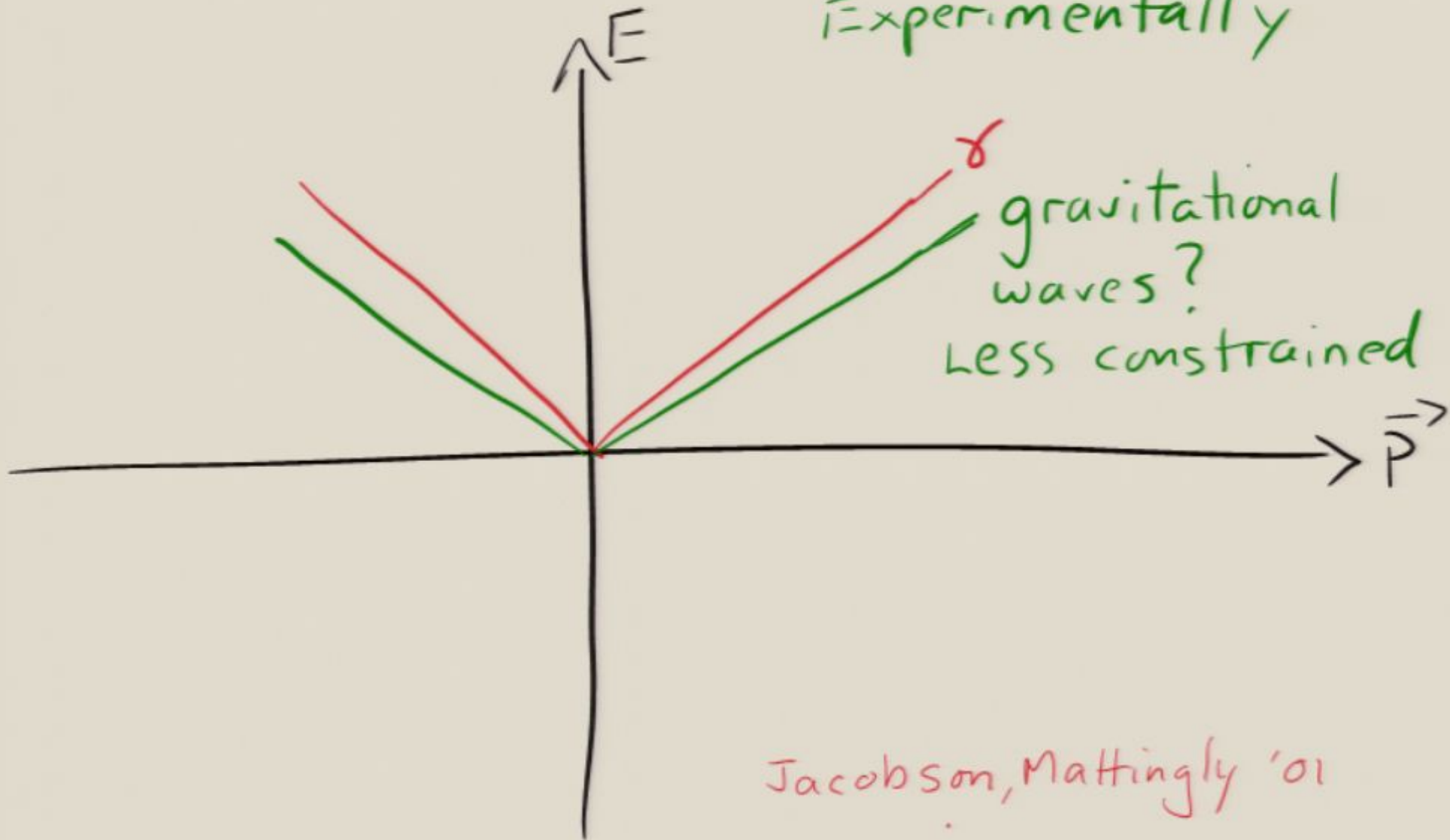


AETHER

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# LESS TIGHTLY CONSTRAINED

$\vec{E}$  experimentally

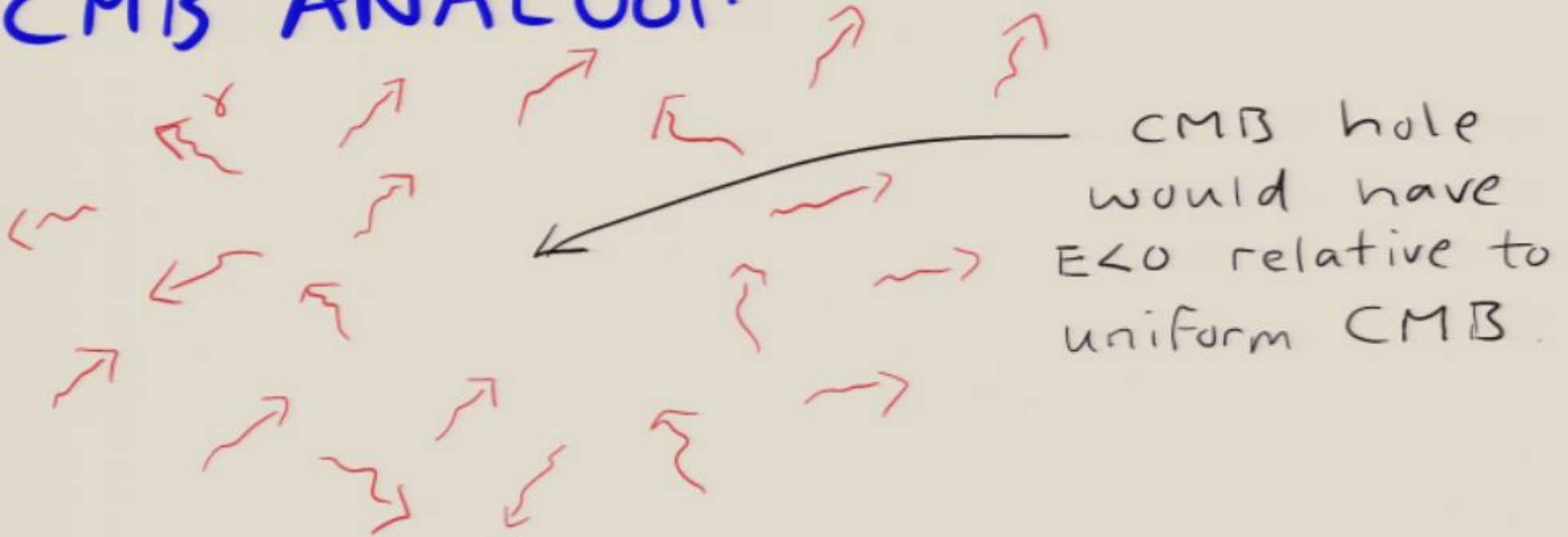


Jacobson, Mattingly '01  
⋮



# ~~LORENTZ~~ $\Rightarrow$ NEGATIVE $E$ ?

## CMB ANALOG:

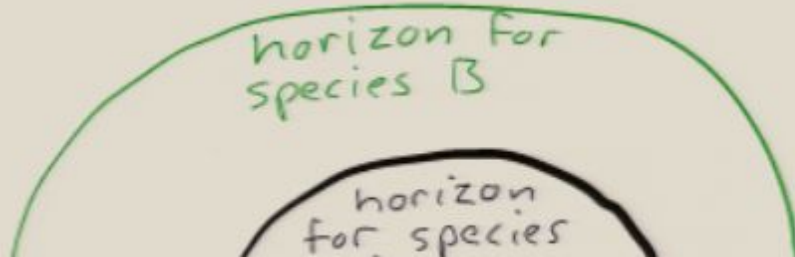


CMB hole would have  $E < 0$  relative to uniform CMB.

~~Lorentz~~ aethers exhibit "pathologies" with similar flavor, near black holes:

Dubovskiy, Sibiryakov '06

Eling, Foster, Jacobson, Wall '07

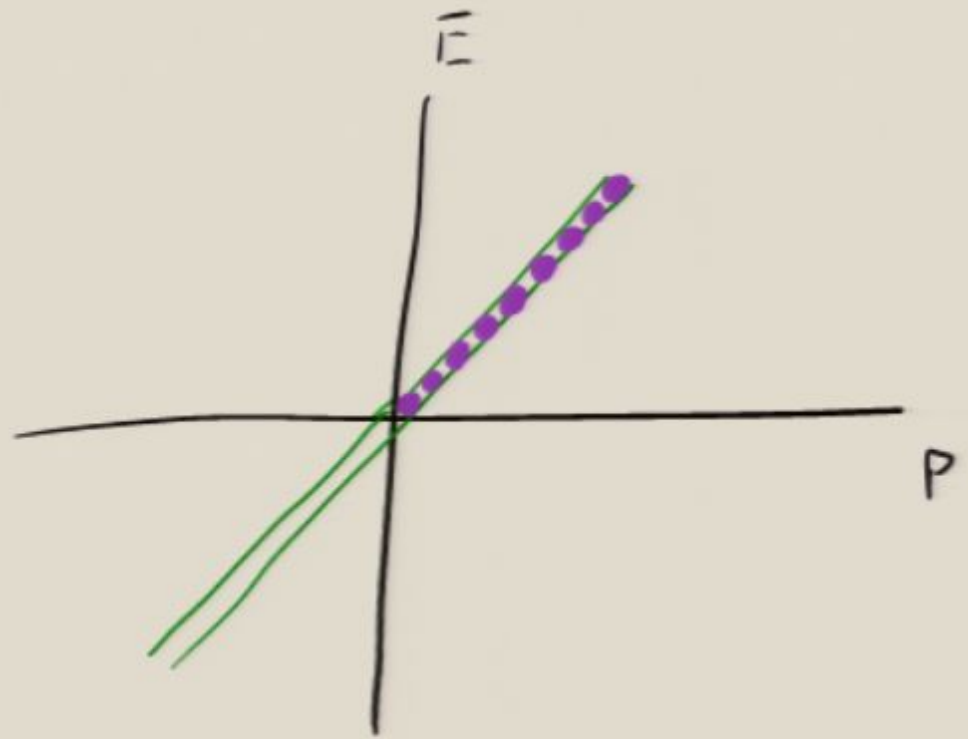
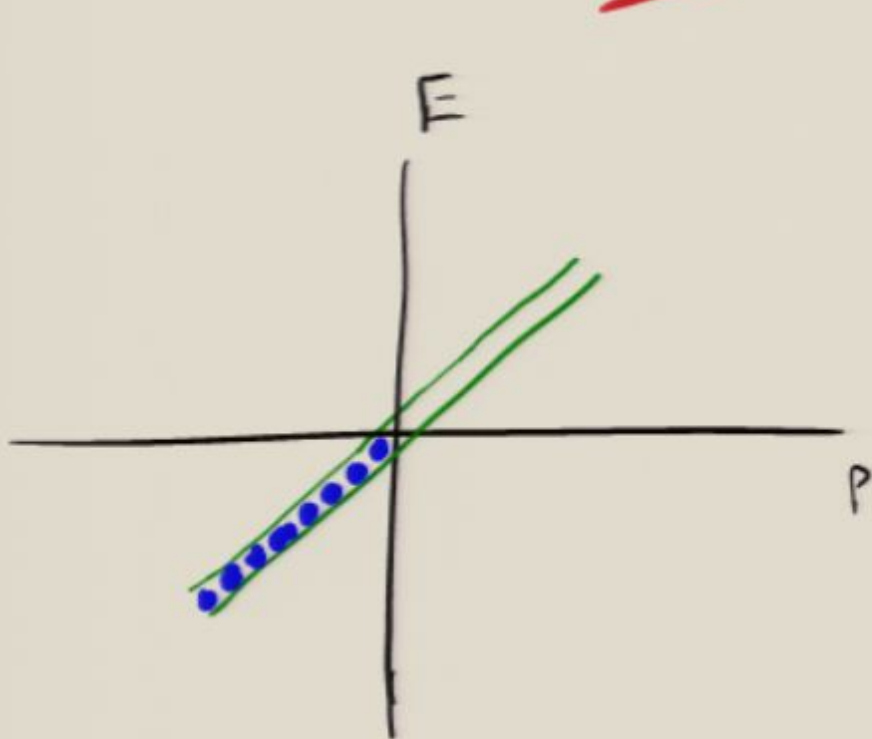


$$c_A > c_B$$
$$T_A > T_B$$

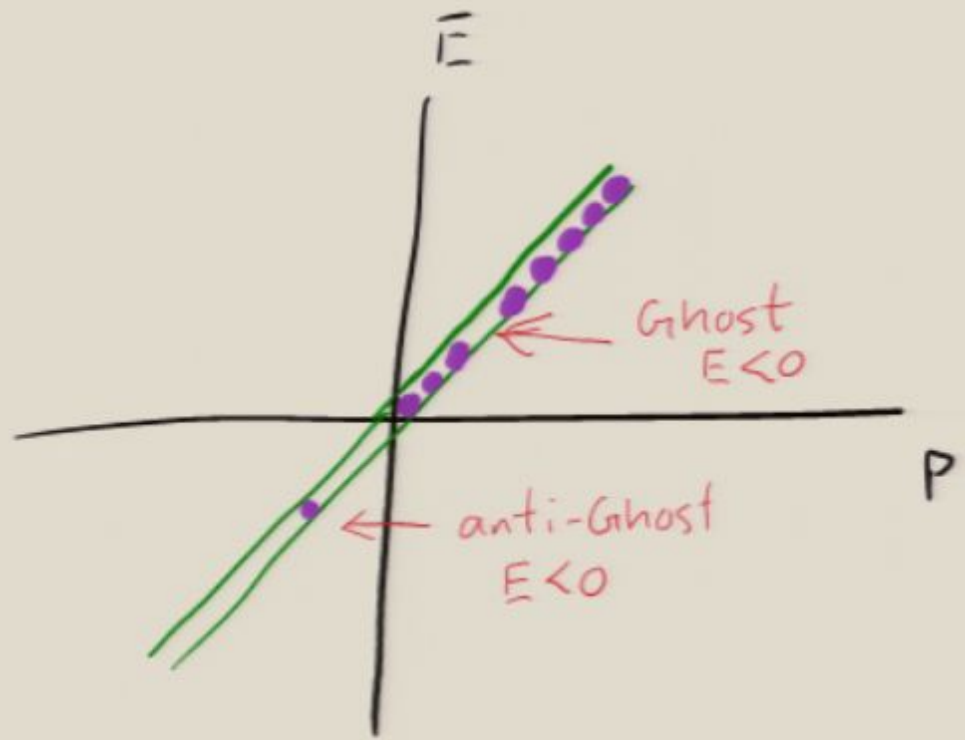
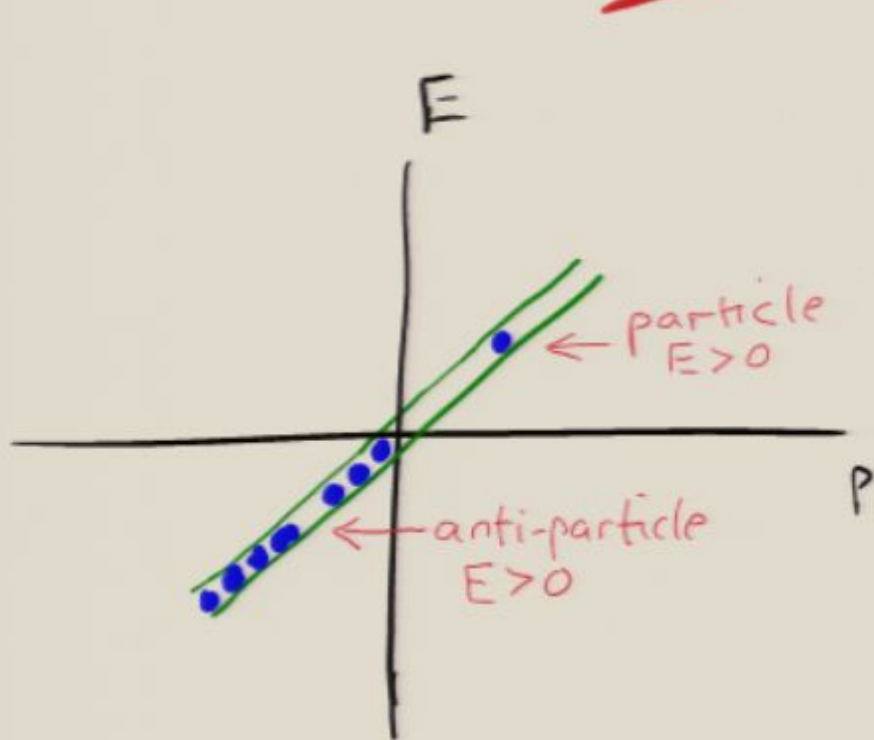
despite  $\neq$



# NEGATIVE ENERGIES $\Rightarrow$ ~~LORENTZ~~



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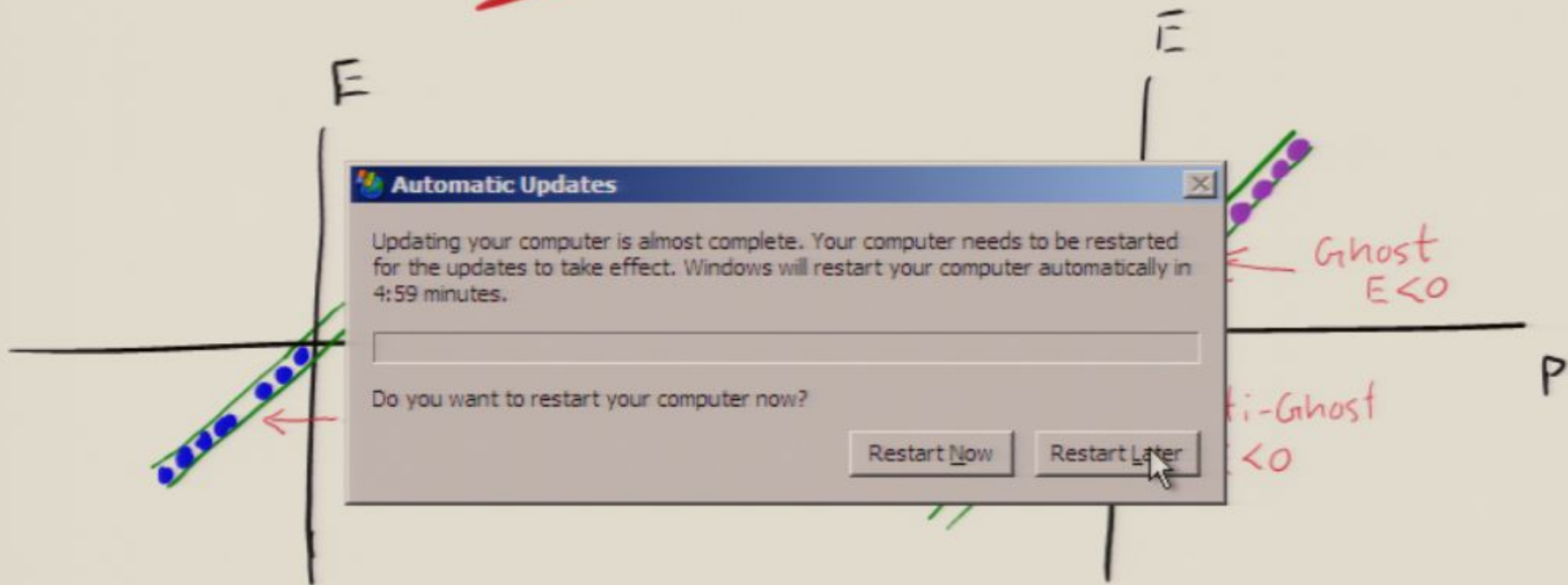


$$\frac{1}{\tau_{10}} = \int d\text{boost}$$

Lorentz invariance

$= \infty, \tau_{10} = 0$

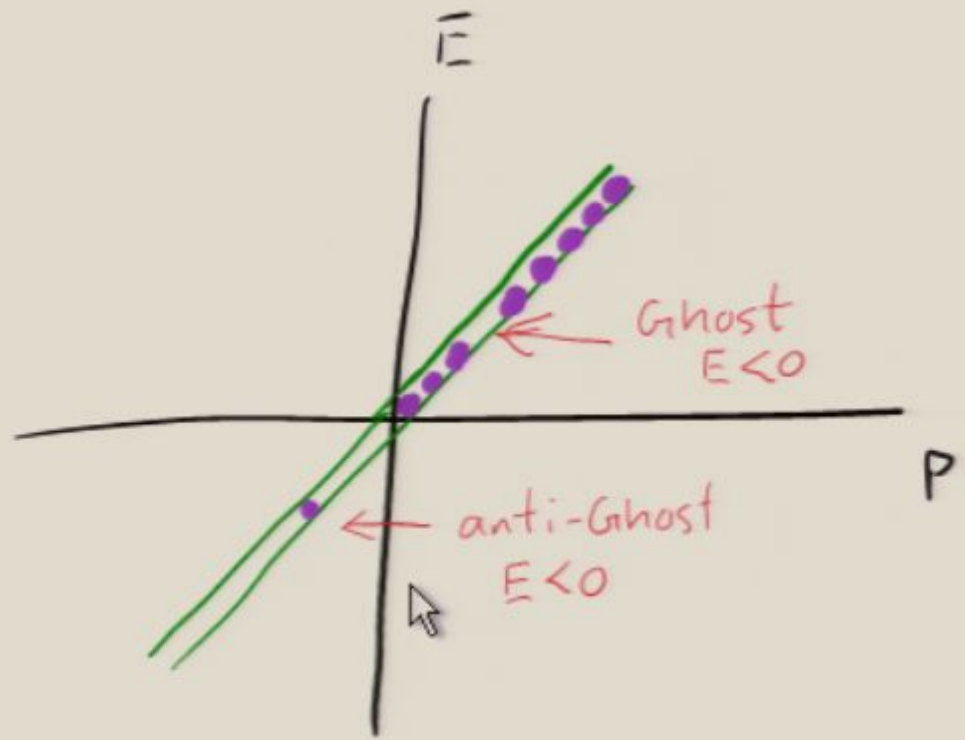
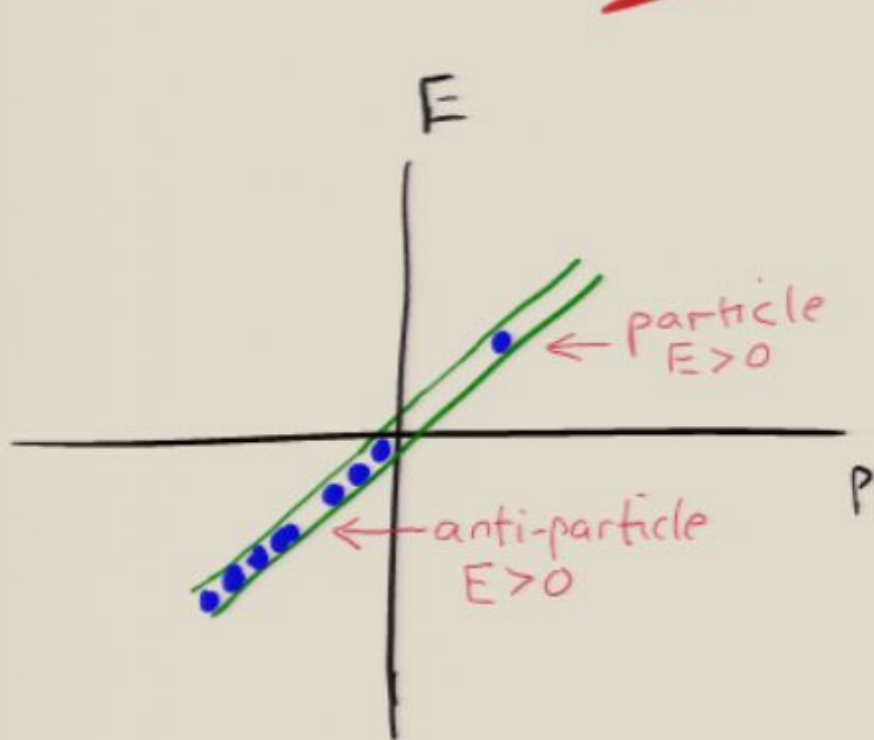
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Lorentz invariance

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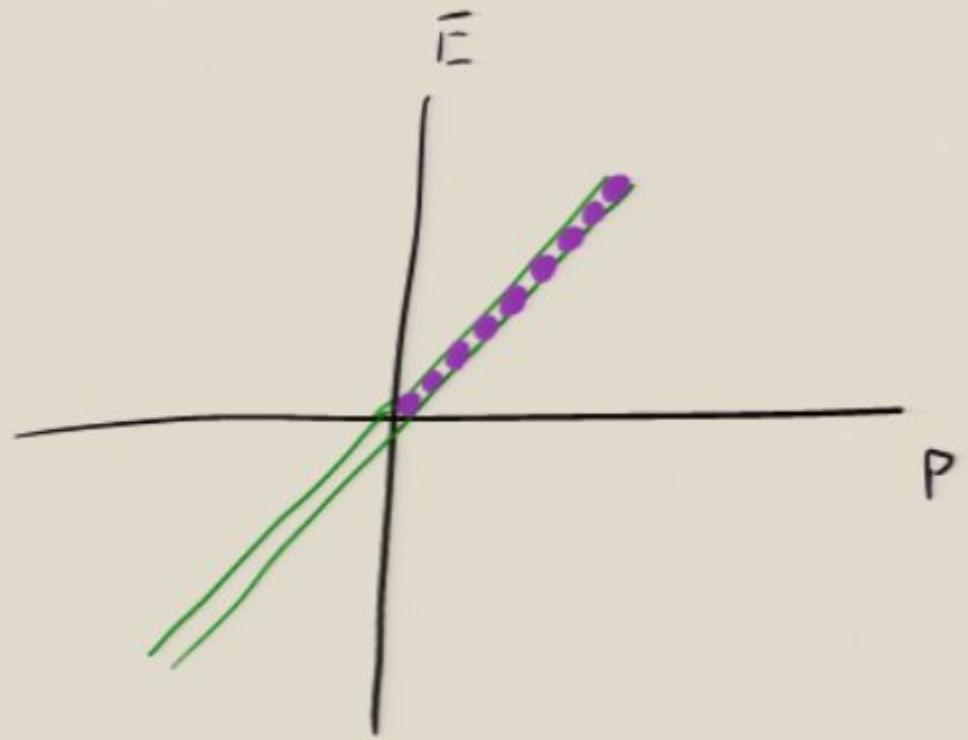
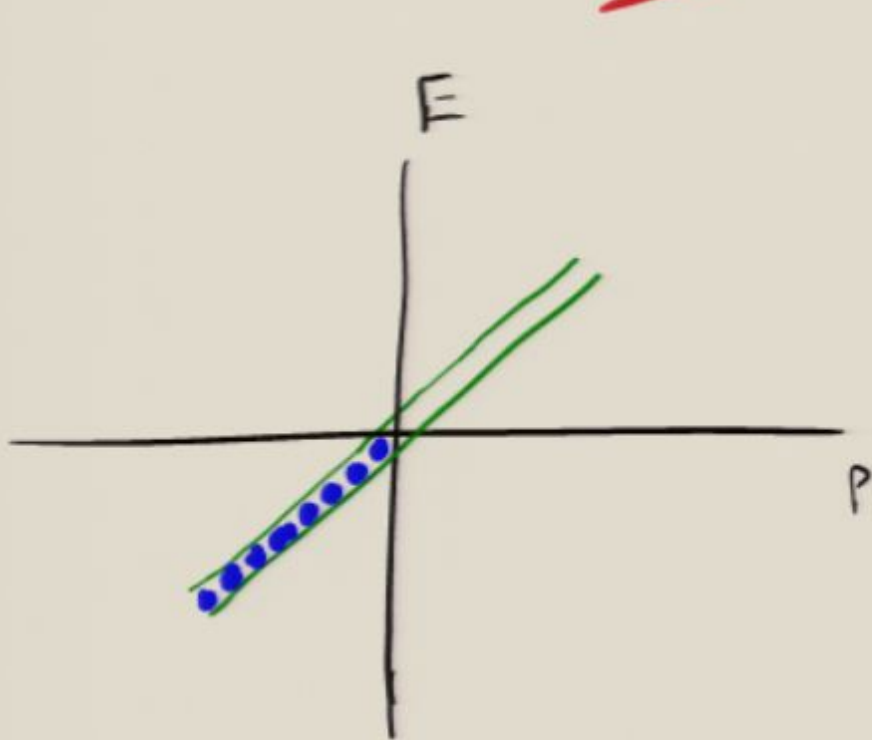
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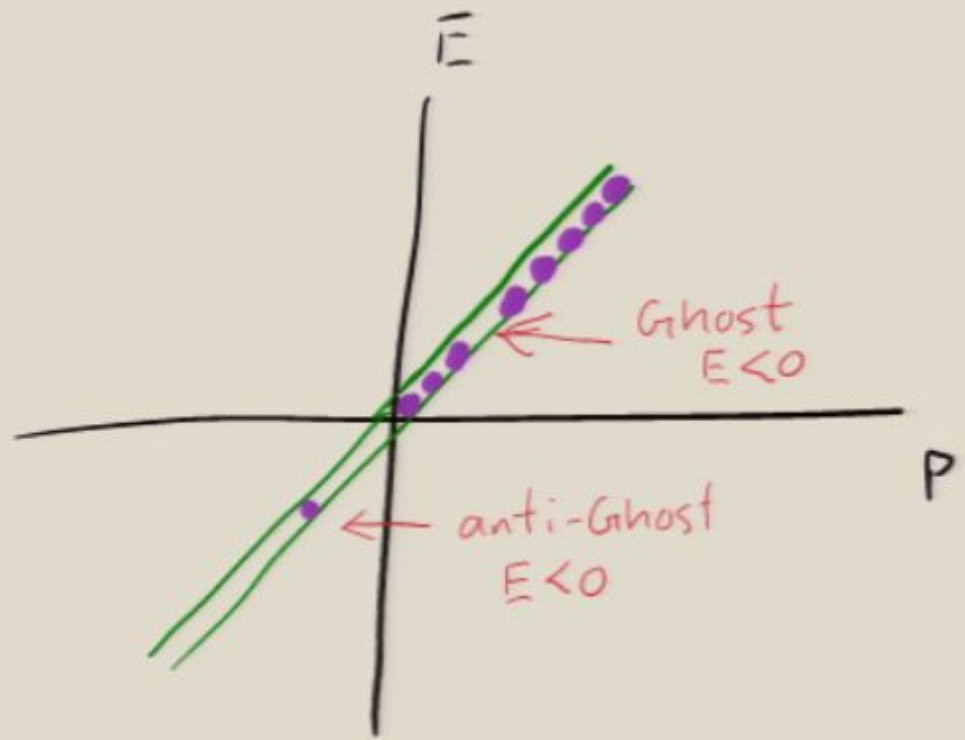
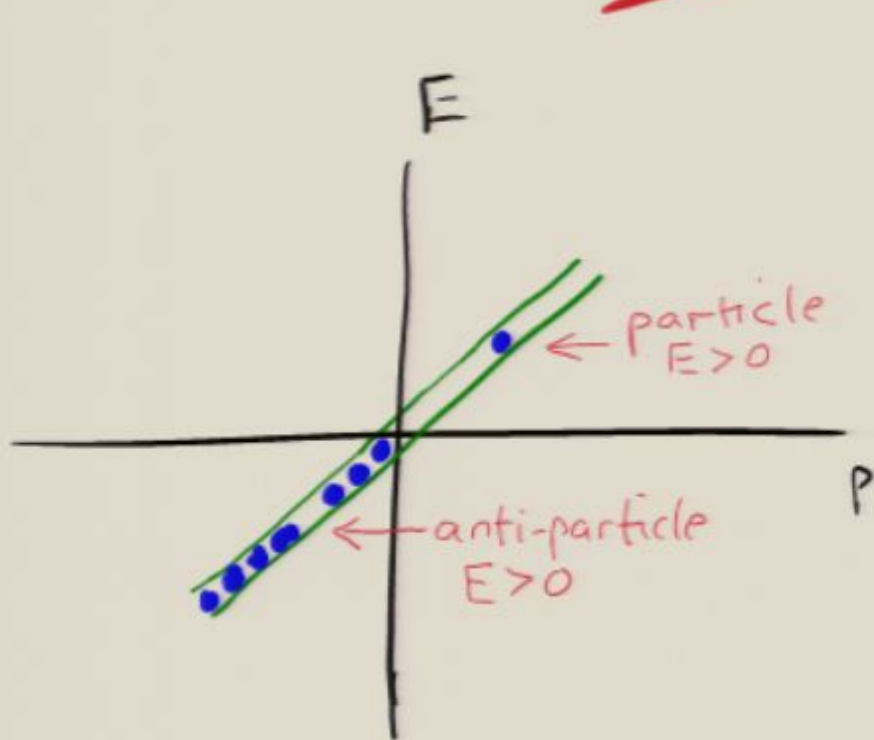
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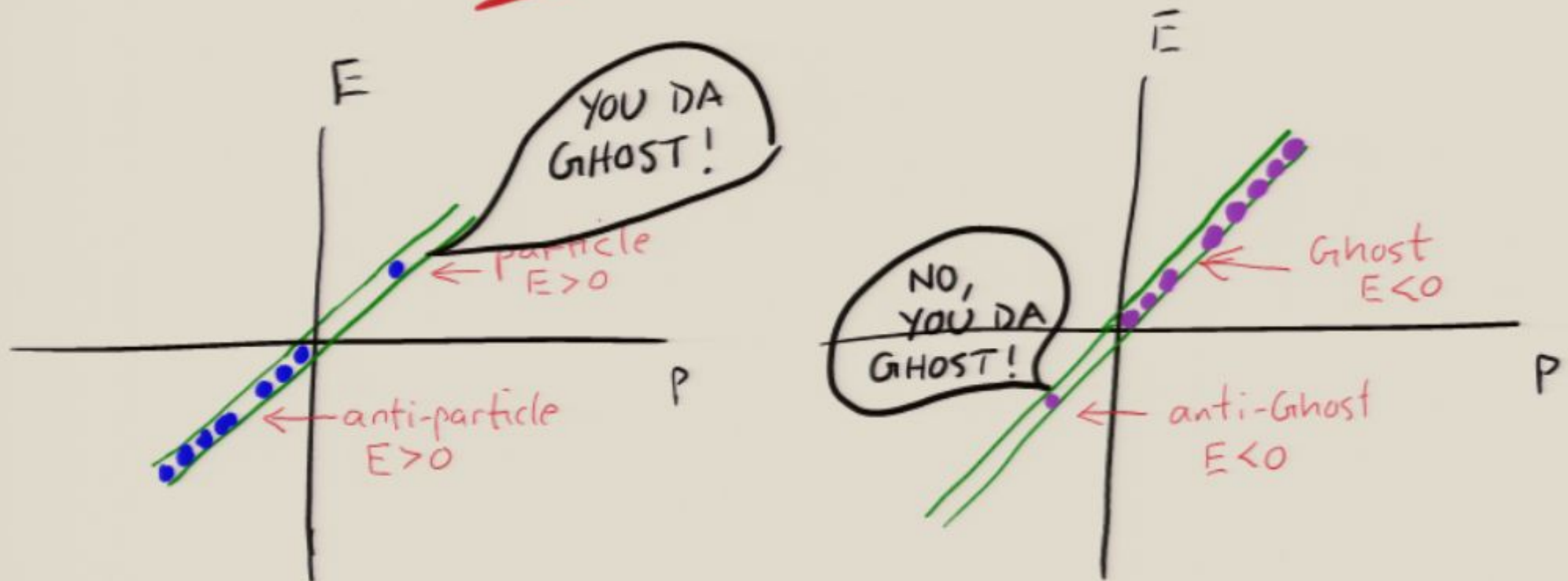


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# NEGATIVE ENERGIES $\Rightarrow$ ~~LORENTZ~~



"Ghost" is a relative word.

# GHOSTS IN FIELD THEORY

Classically,

$$\mathcal{L} = \sqrt{-g} \left\{ M_{Pl}^2 R - \rho + \mathcal{L}_{\text{matter}}(\psi, D_\mu) - \mathcal{L}_{\text{matter}}(\hat{\psi}, D_\mu) \right\}$$

Ghosts



as proposed by Linde '84

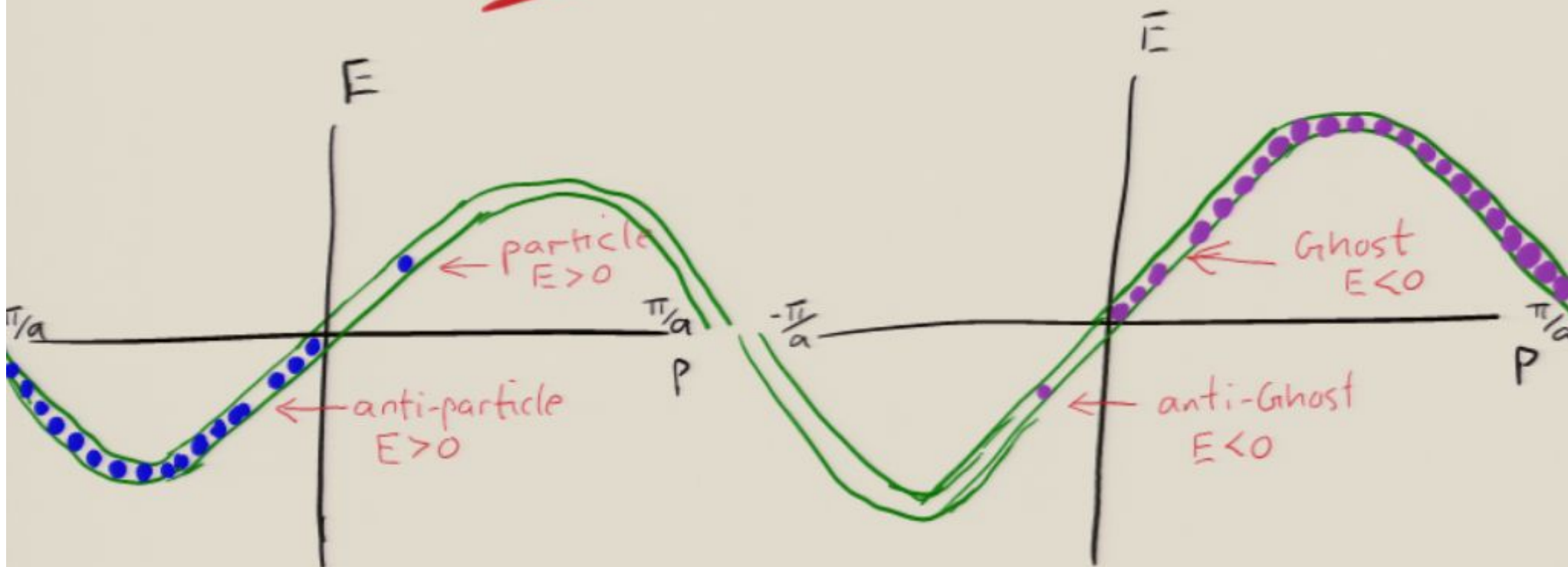
Perturbative Quantization:

Non-Ghosts  $\frac{i}{p^2 - m^2 + i\epsilon}$

Ghosts  $\frac{-i}{p^2 - m^2 - i\epsilon}$   $(i \rightarrow -i)$



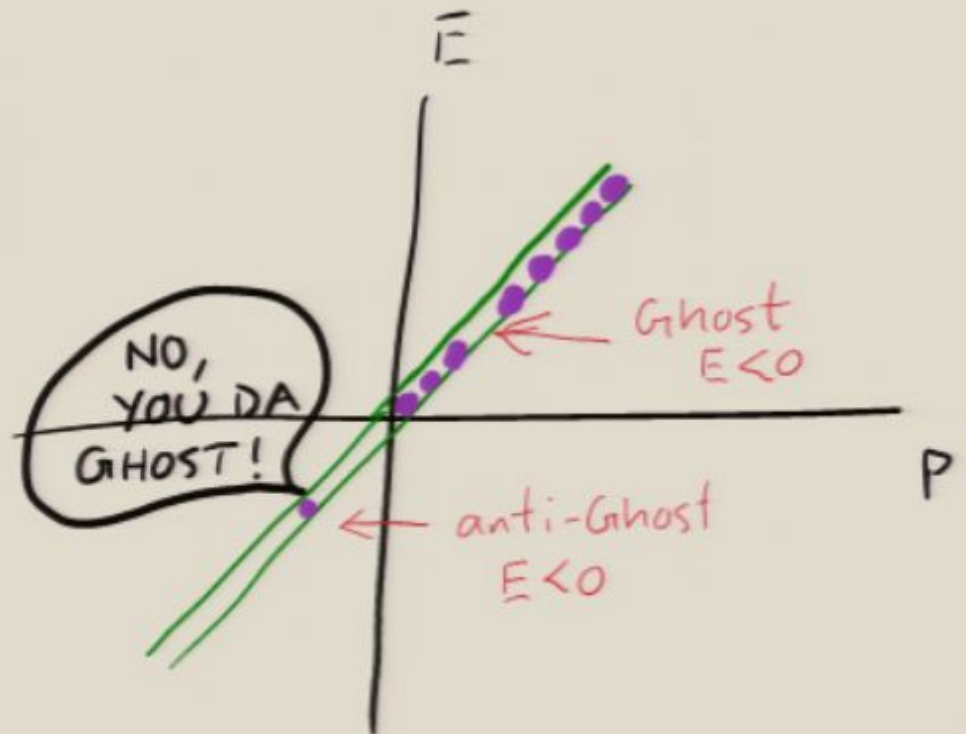
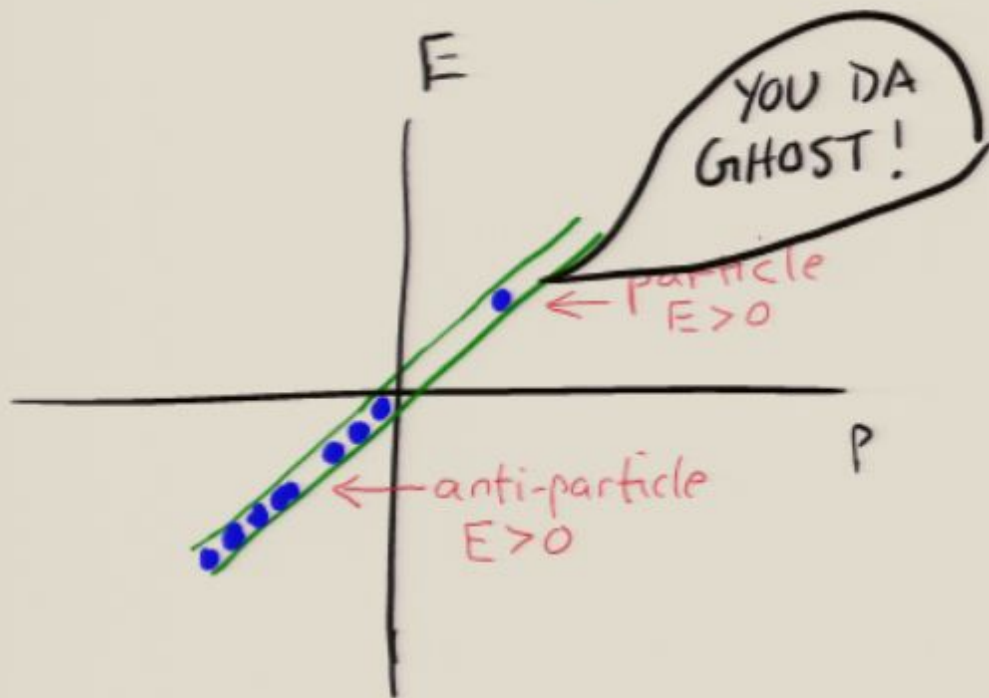
# NEGATIVE ENERGIES $\Rightarrow$ ~~LORENTZ~~



"Minkowski vacuum" is an excited state ...

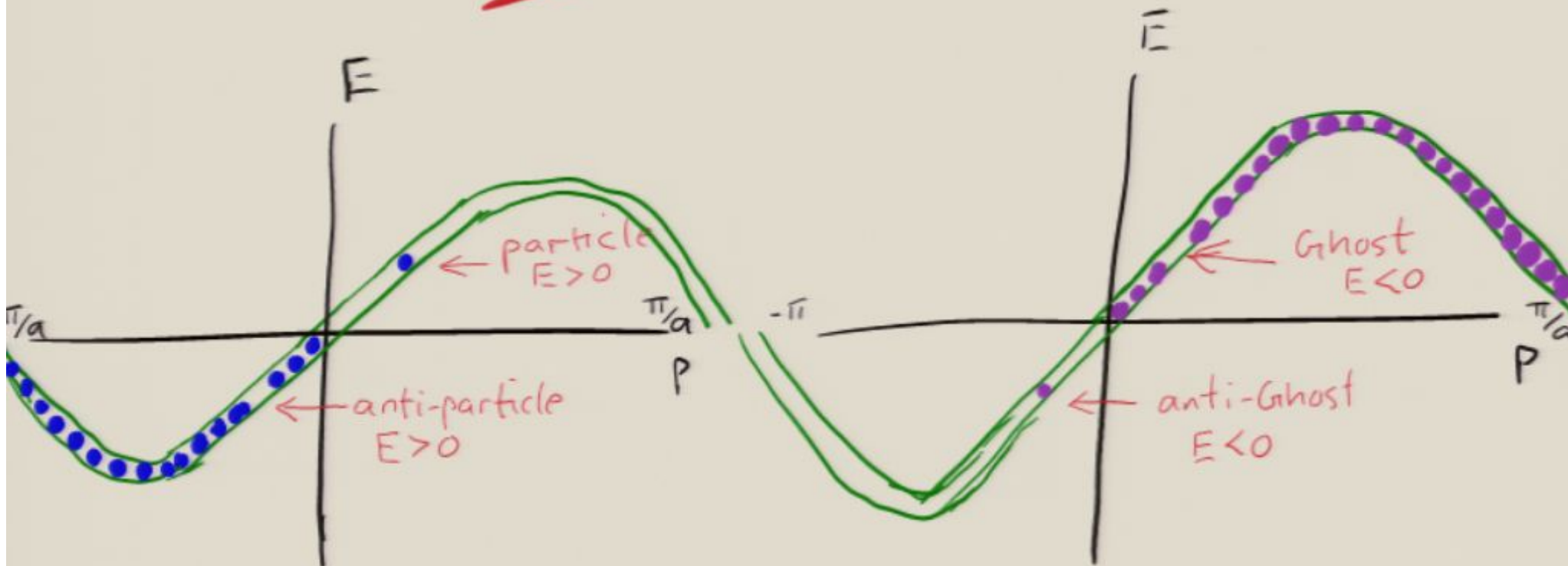
Spin Chain analog:  
Sundrum?

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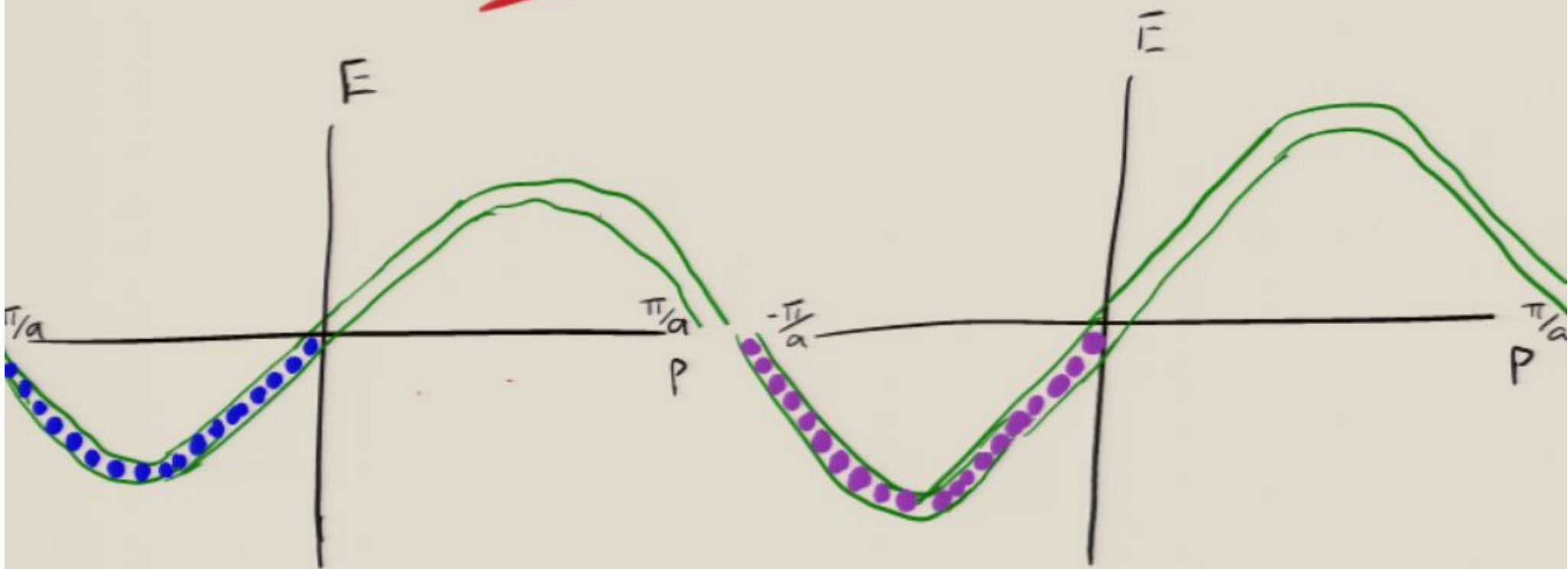


"Minkowski vacuum" is an excited state ...

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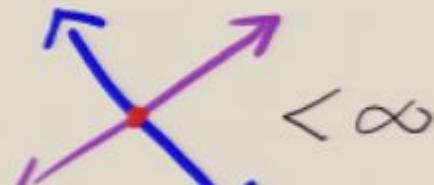
# NEGATIVE ENERGIES $\Rightarrow$ ~~LORENTZ~~



"Minkowski vacuum" is an excited state ...  
of a non-relativistic true  $|0\rangle$ .

$$|p| < \pi/a$$

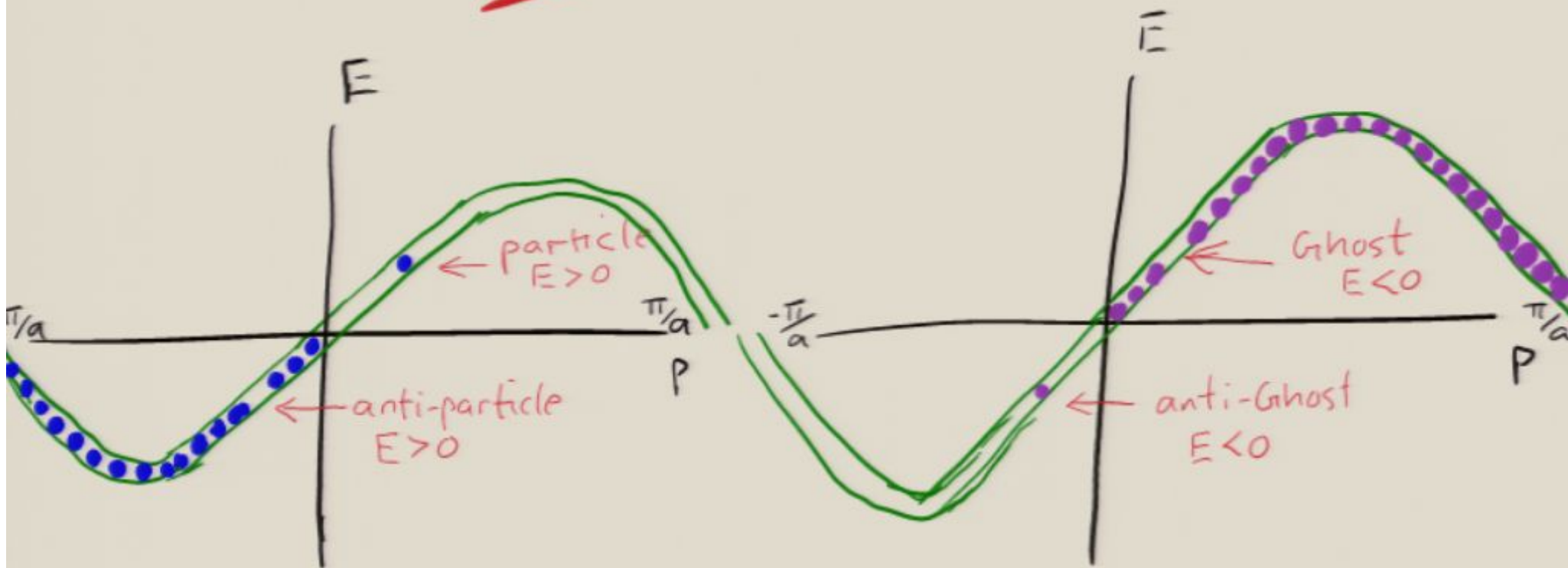
$$\int d\text{boost}$$



Caroll, Hoffman  
Trodden '03;  
Cline, Jeon, Moore



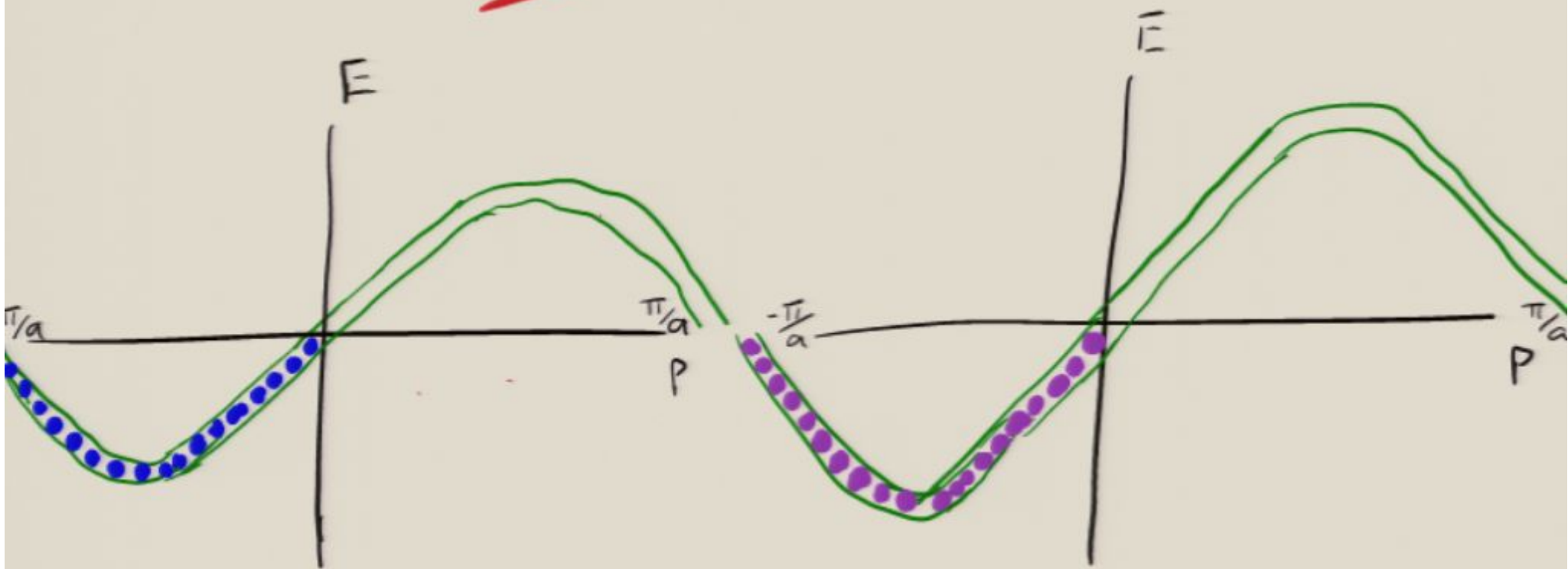
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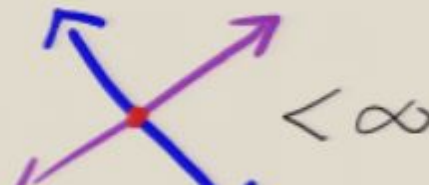
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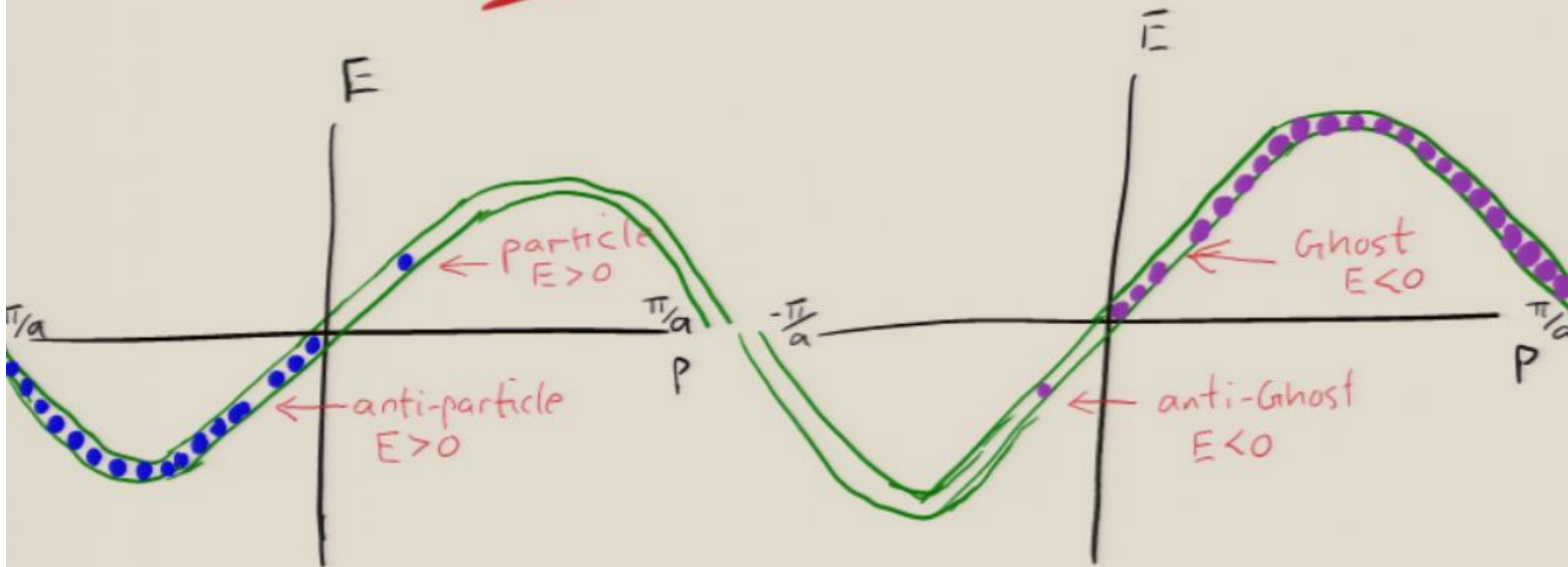
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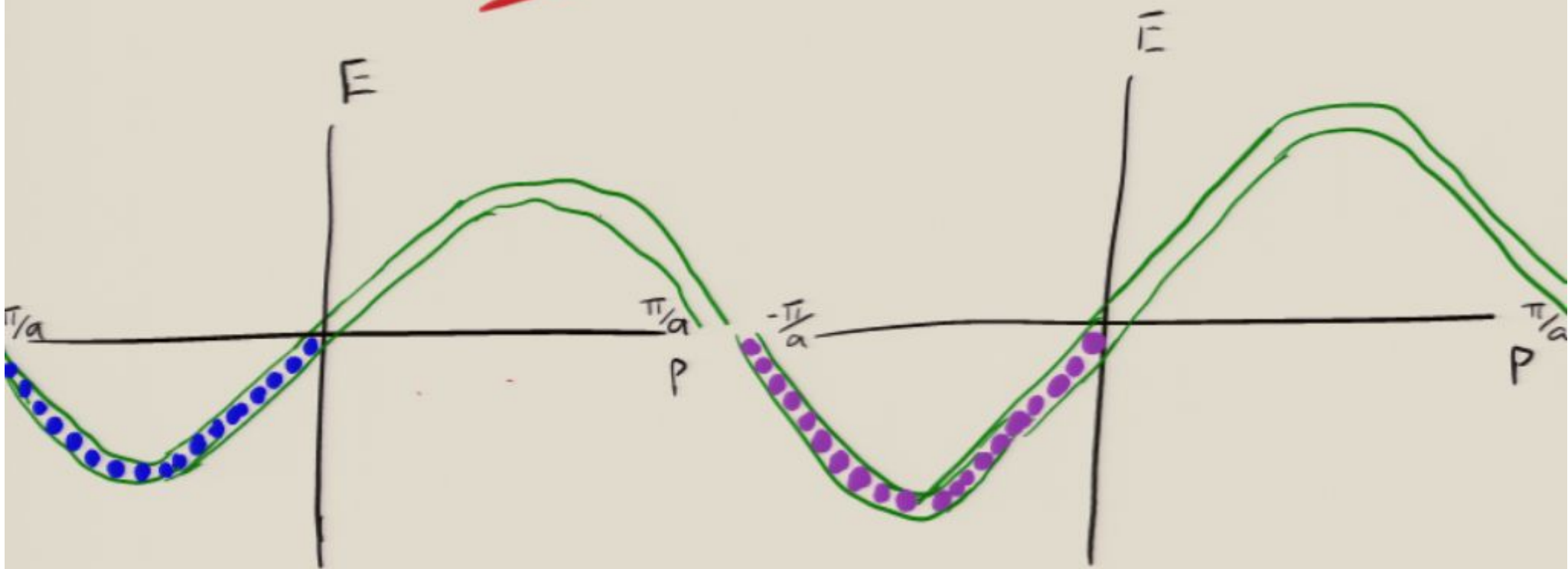


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Spin Chain analog:  
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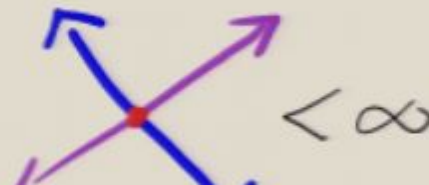
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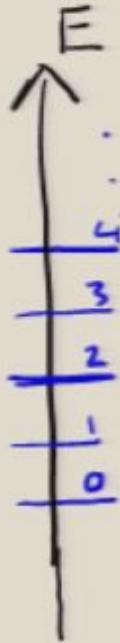


(ANTI-)

# SYMMETRY FOR $E_{|0\rangle}$

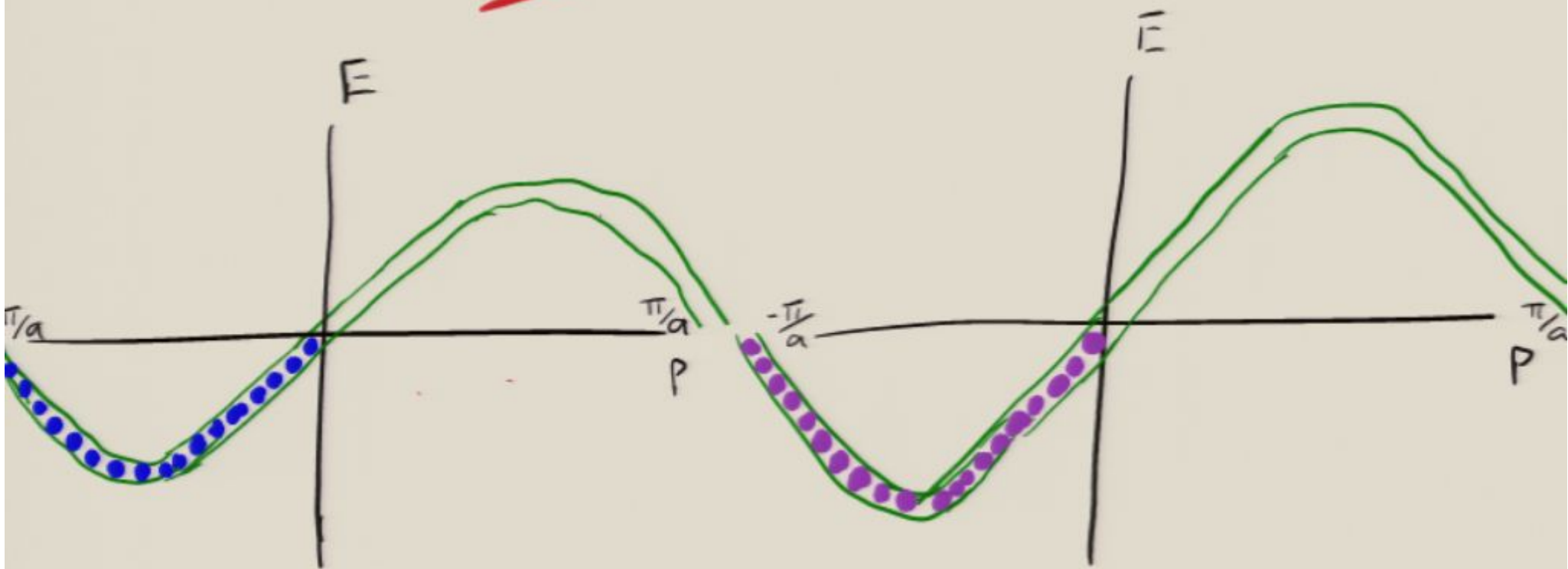
Kaplan, Sundrum '05

→ Dark Energy



Particles  
of momentum  $\vec{p}$

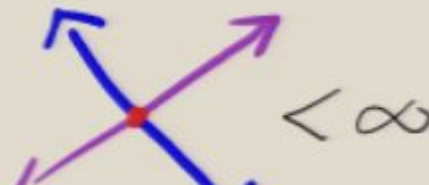
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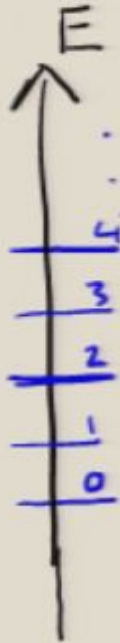
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(ANTI-)

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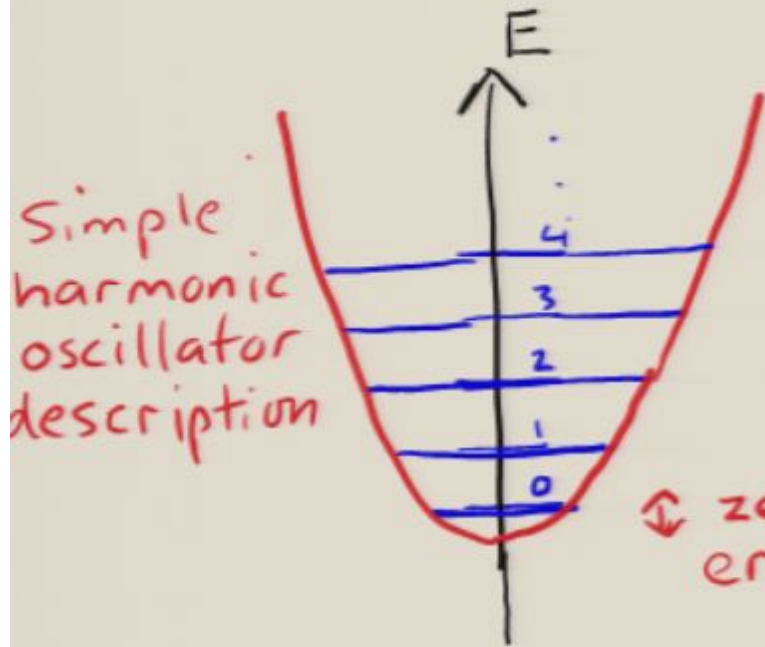
Kaplan, Sundrum '05

→ Dark Energy



Particles  
of momentum  $\vec{p}$

# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$



Simple harmonic oscillator description

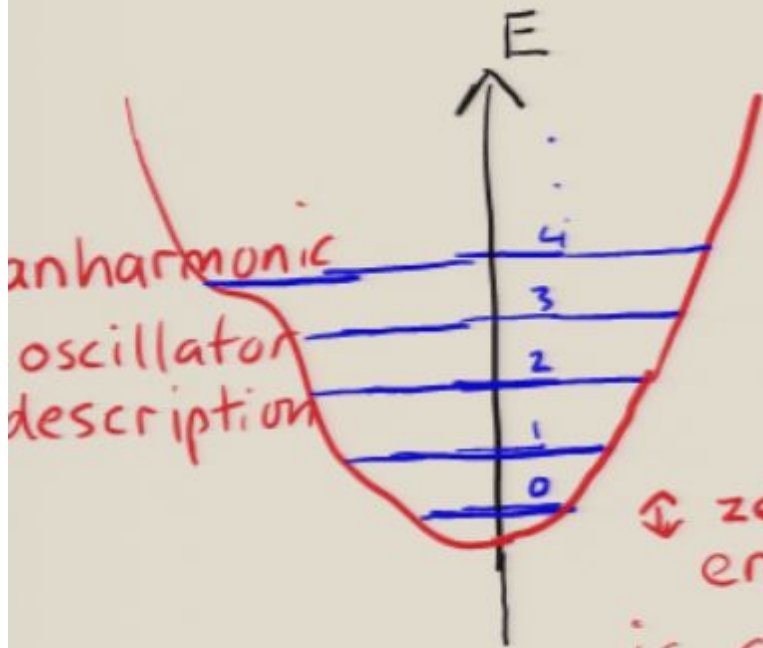
Particles of momentum  $\vec{p}$

↕ zero-point energy

→ Dark Energy



# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$



→ Dark Energy

Particles of momentum  $\vec{p}$  interact with themselves & other momenta

↕ zero-point energy

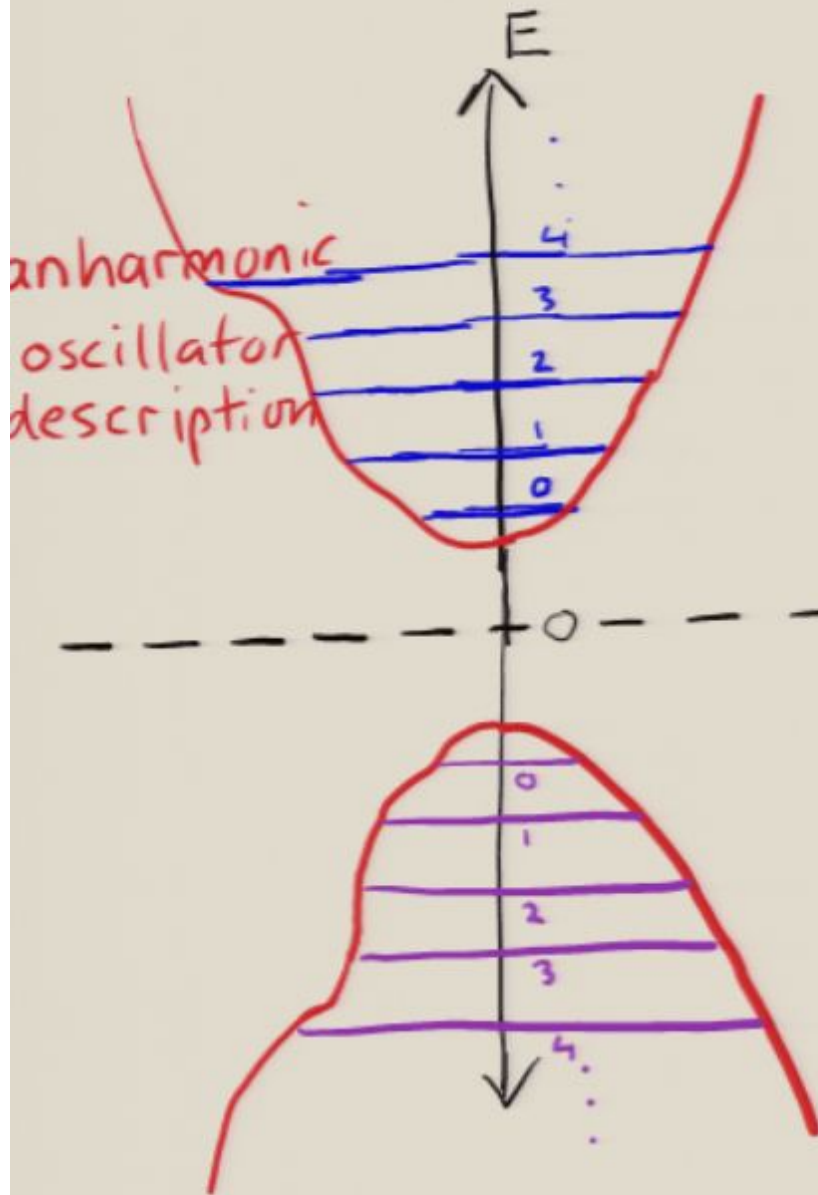
is complicated function of masses & interactions

⇒ observed dark energy

# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$

Kaplan, Sundrum '05

→ Dark Energy



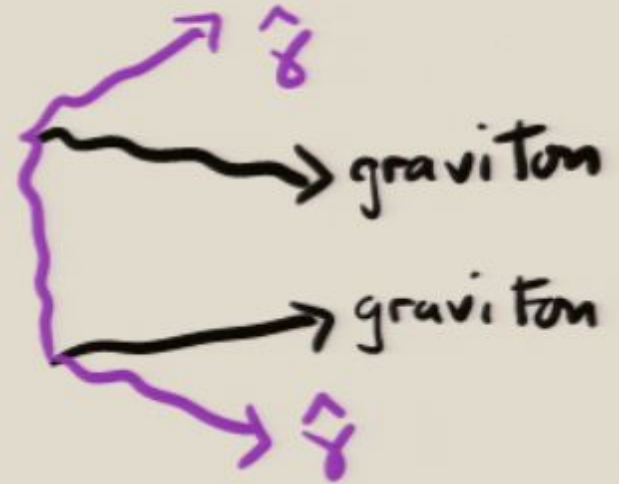
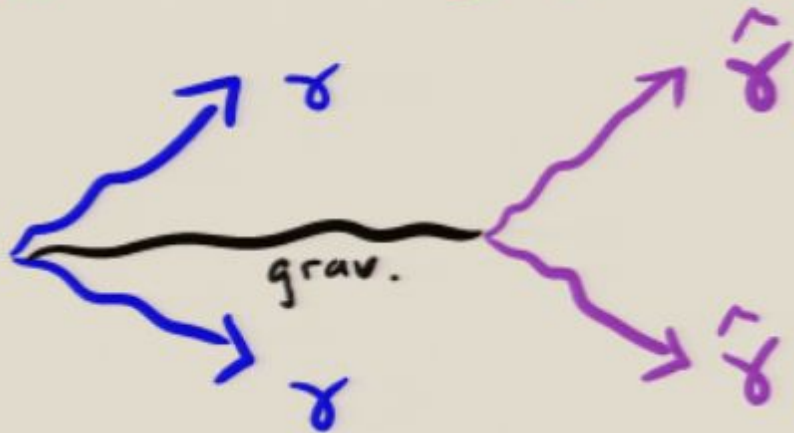
Energy Parity

$$\{H, P\} = 0$$

$$E_{|0\rangle} = E_{|0\rangle} + E_{|0\rangle} = 0$$

- Gravity must couple both sectors, mediating  $|0\rangle$  decay
- Graviton oscillators must "pick a side", (weakly) breaking symmetry

# VACUUM DECAY CONSTRAINTS



$$\frac{\text{Probability}}{\text{Vol. time}} \sim \frac{1}{256 \pi^5} \frac{\Lambda^8}{M_{\text{pl}}^4}$$

$\Lambda \equiv$  ~~Lorentz~~  $E, \vec{p}$  cutoff

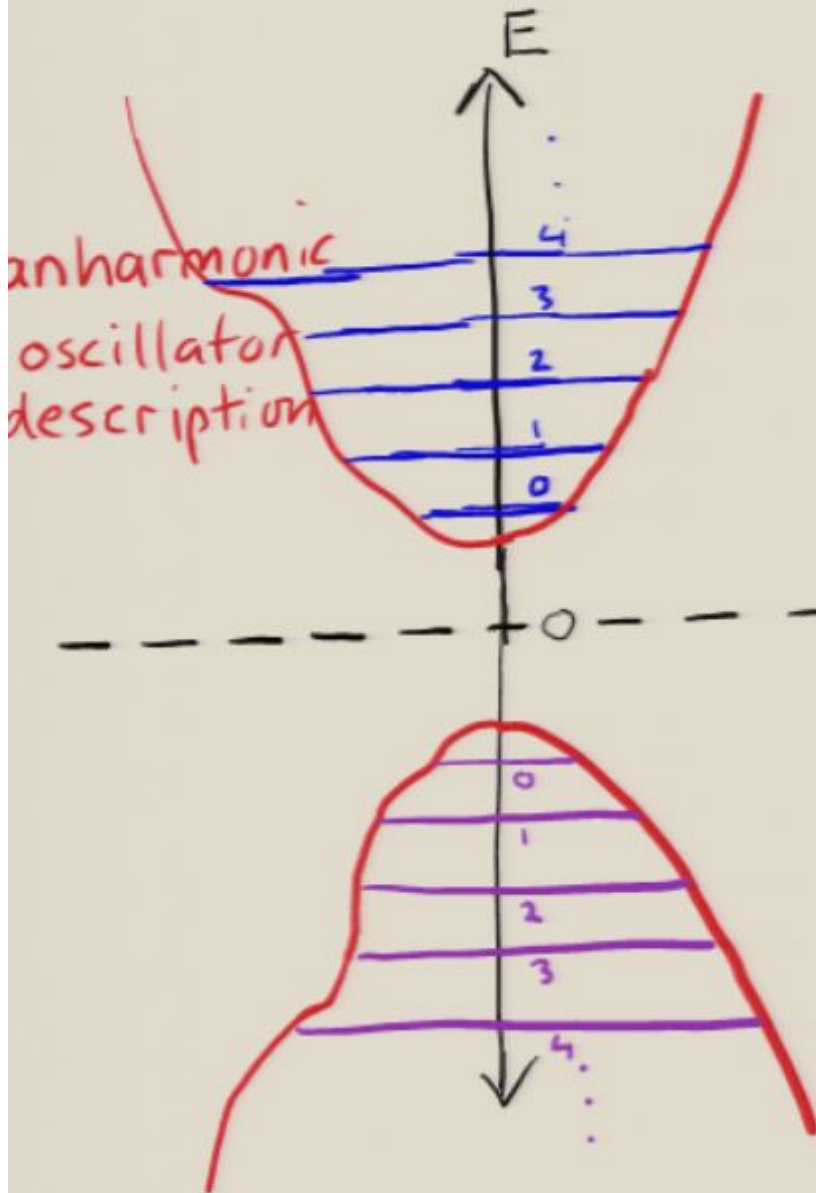
Consistency with cosmic  $\gamma$  background  $\Rightarrow \Lambda < \text{MeV}$   
 $\doteq$  Cline, Jeon, Moore '04  
 analysis of Phantom Dark Energy



# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$

Kaplan, Sundrum '05

→ Dark Energy



Energy Parity

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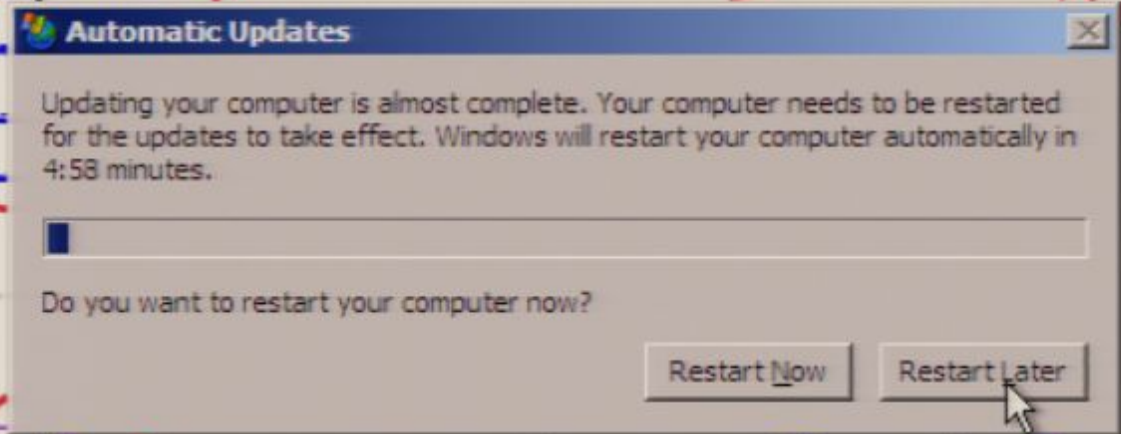
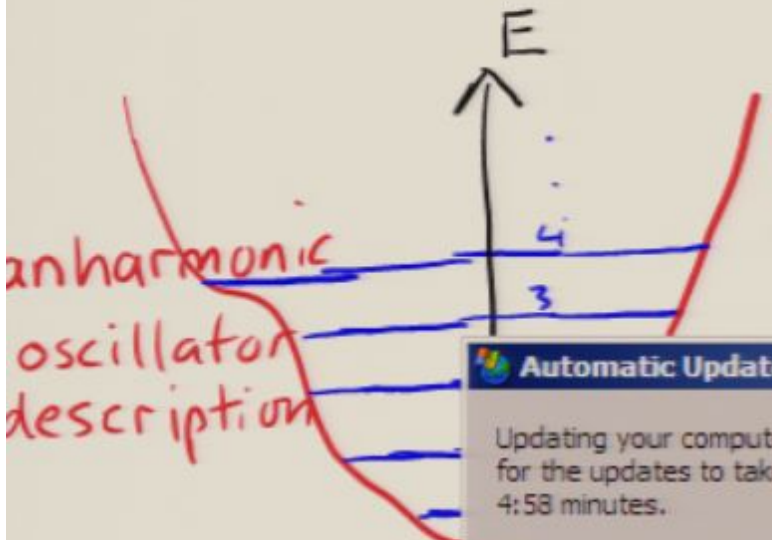
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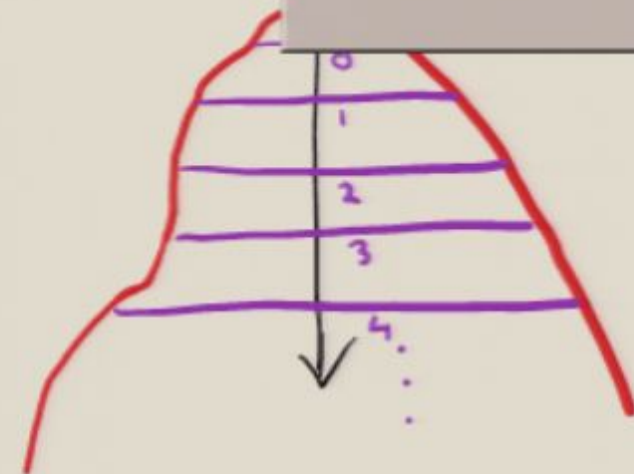
# (ANTI-) SYMMETRY FOR $E_{10}$

Kaplan, Sundrum '05

→ Dark Energy



Parity



$$E_{10} = E_{10} + E_{10} = 0$$

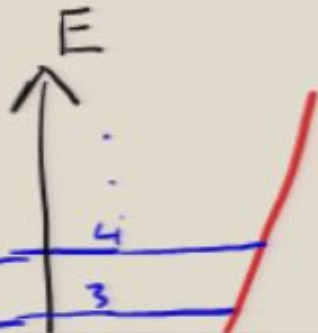
- Gravity must couple both sectors, mediating  $10$  decay
- Graviton oscillators must "pick a side", (weakly)

# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$

Kaplan, Sundrum '05

→ Dark Energy

anharmonic oscillator description



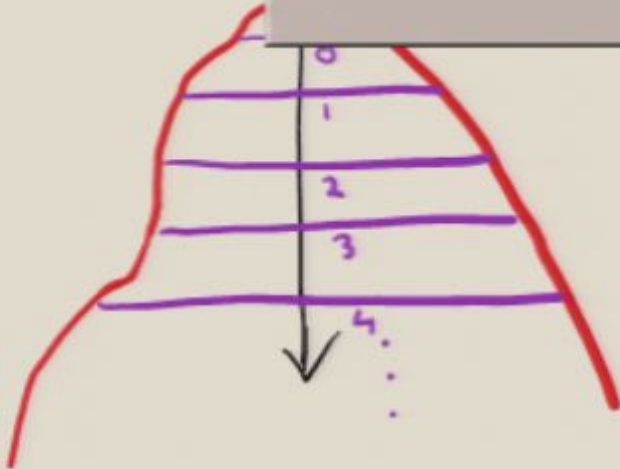
**Automatic Updates**

Updating your computer is almost complete. Your computer needs to be restarted for the updates to take effect. Windows will restart your computer automatically in 4:49 minutes.

Do you want to restart your computer now?

Restart Now    Restart Later

Parity



$$E_{|0\rangle} = E_{|0\rangle} + E_{|0\rangle} = 0$$

- Gravity must couple both sectors, mediating  $|0\rangle$  decay
- ... must

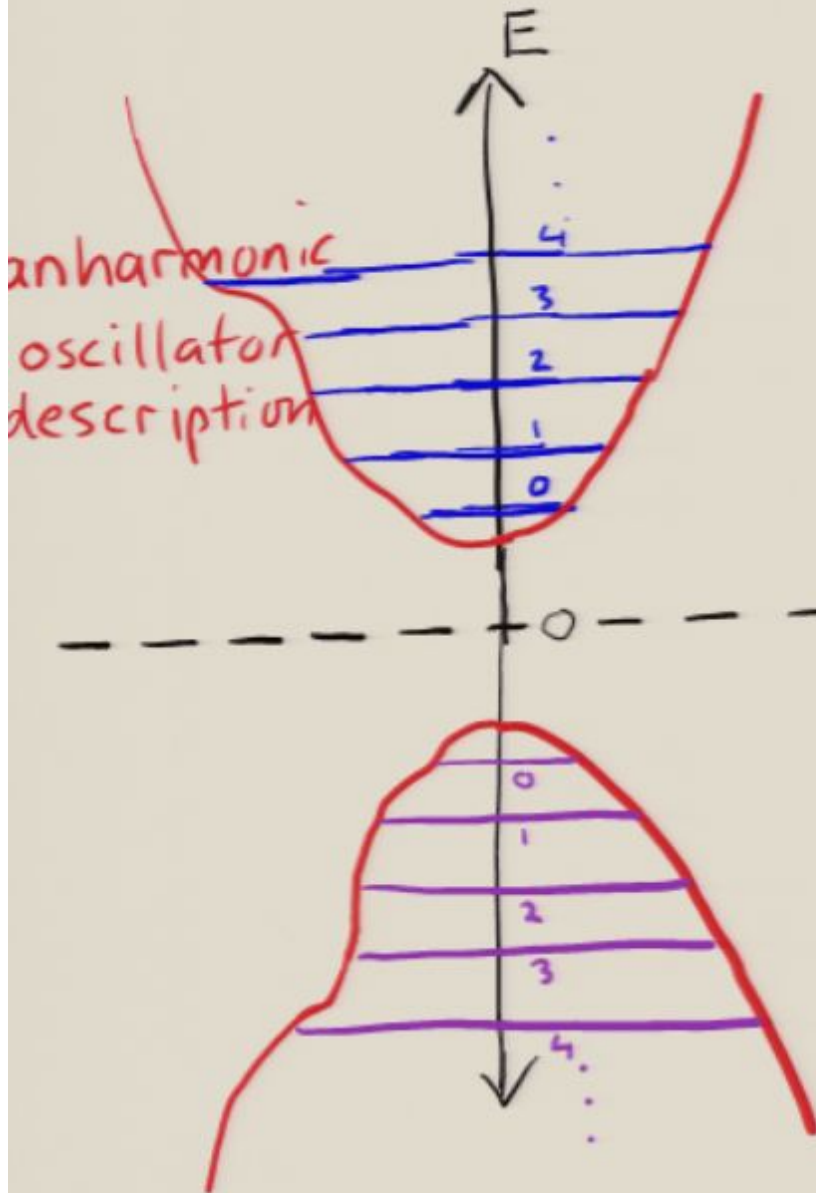
**Wireless Network Connection is now connected**

Connected to: GuestPass  
Signal Strength: Excellent

# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$

Kaplan, Sundrum '05

→ Dark Energy



anharmonic oscillator description

Energy Parity

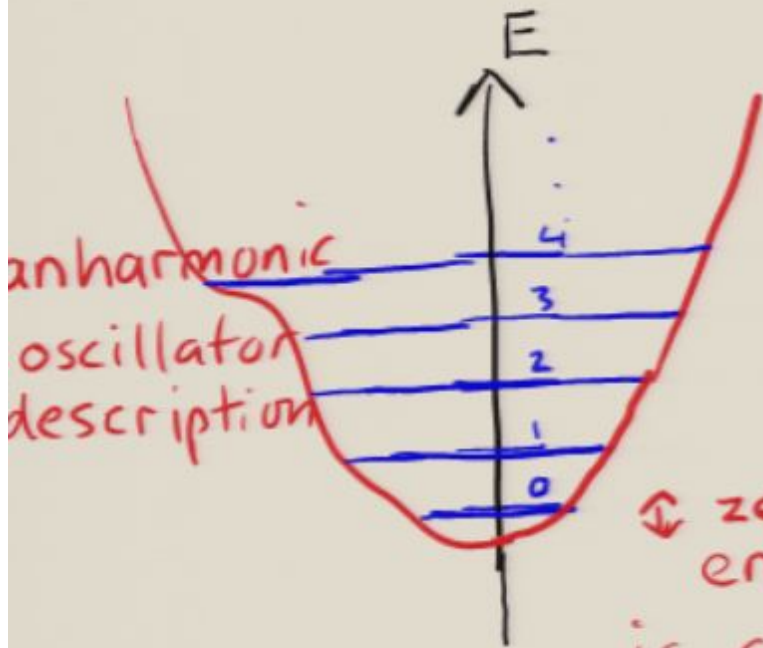
$$\{H, P\} = 0$$

$$E_{|0\rangle} = E_{|0\rangle} + E_{|0\rangle} = 0$$

- Gravity must couple both sectors, mediating  $|0\rangle$  decay
- Graviton oscillators must "pick a side", (weakly) breaking symmetry



# (ANTI-) SYMMETRY FOR $E_{|0\rangle}$



anharmonic  
oscillator  
description

→ Dark Energy

Particles  
of momentum  $\vec{p}$   
interact with  
themselves & other  
momenta

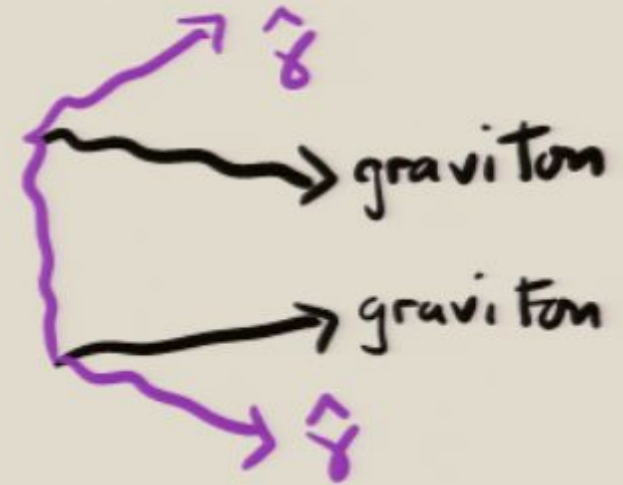
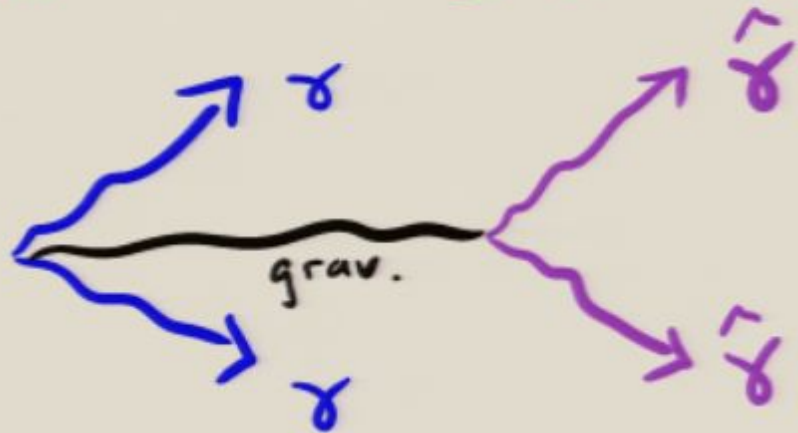
↕ zero-point  
energy

is complicated  
function of  
masses & interactions

⇒ observed dark energy



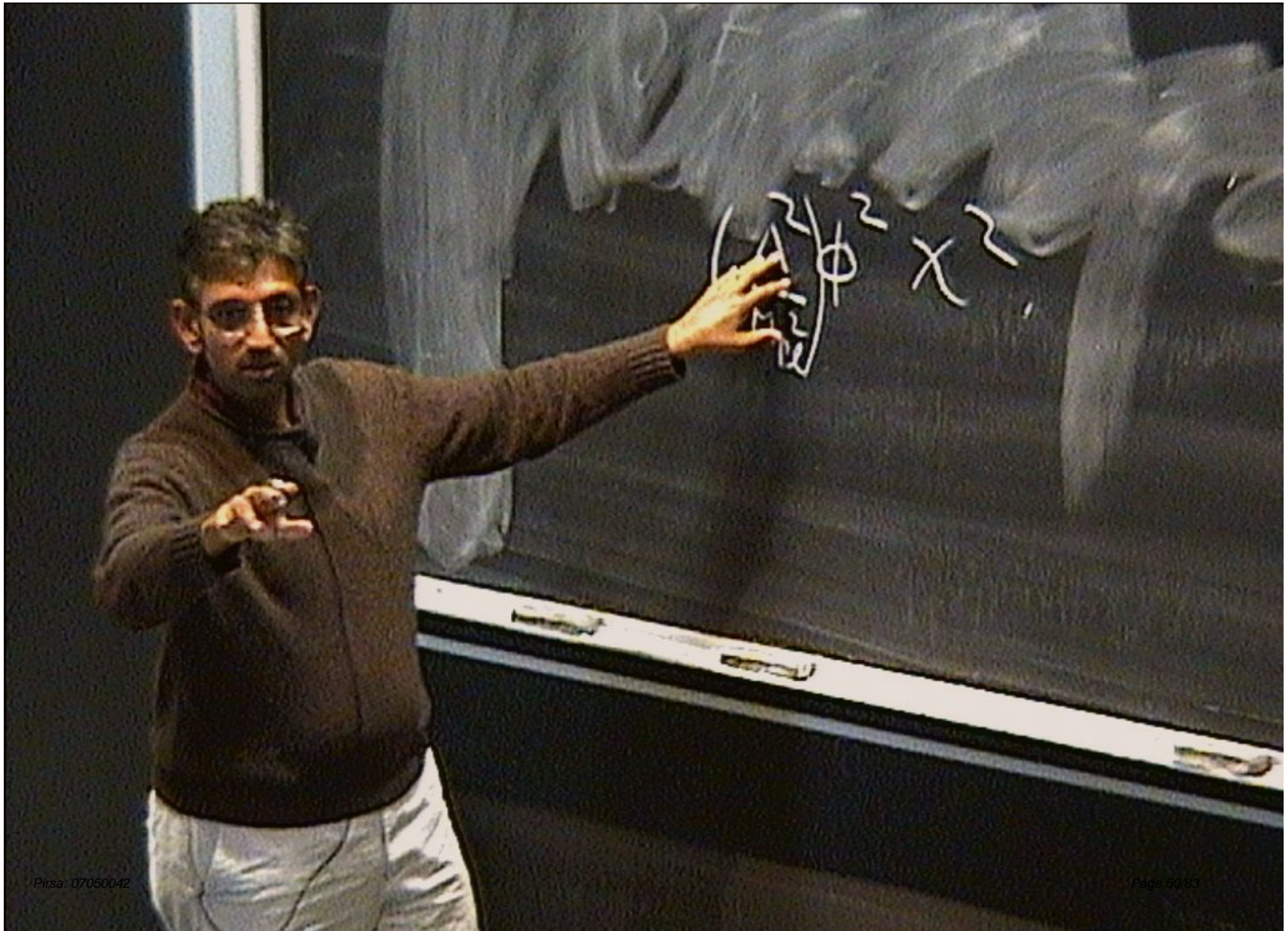
# VACUUM DECAY CONSTRAINTS



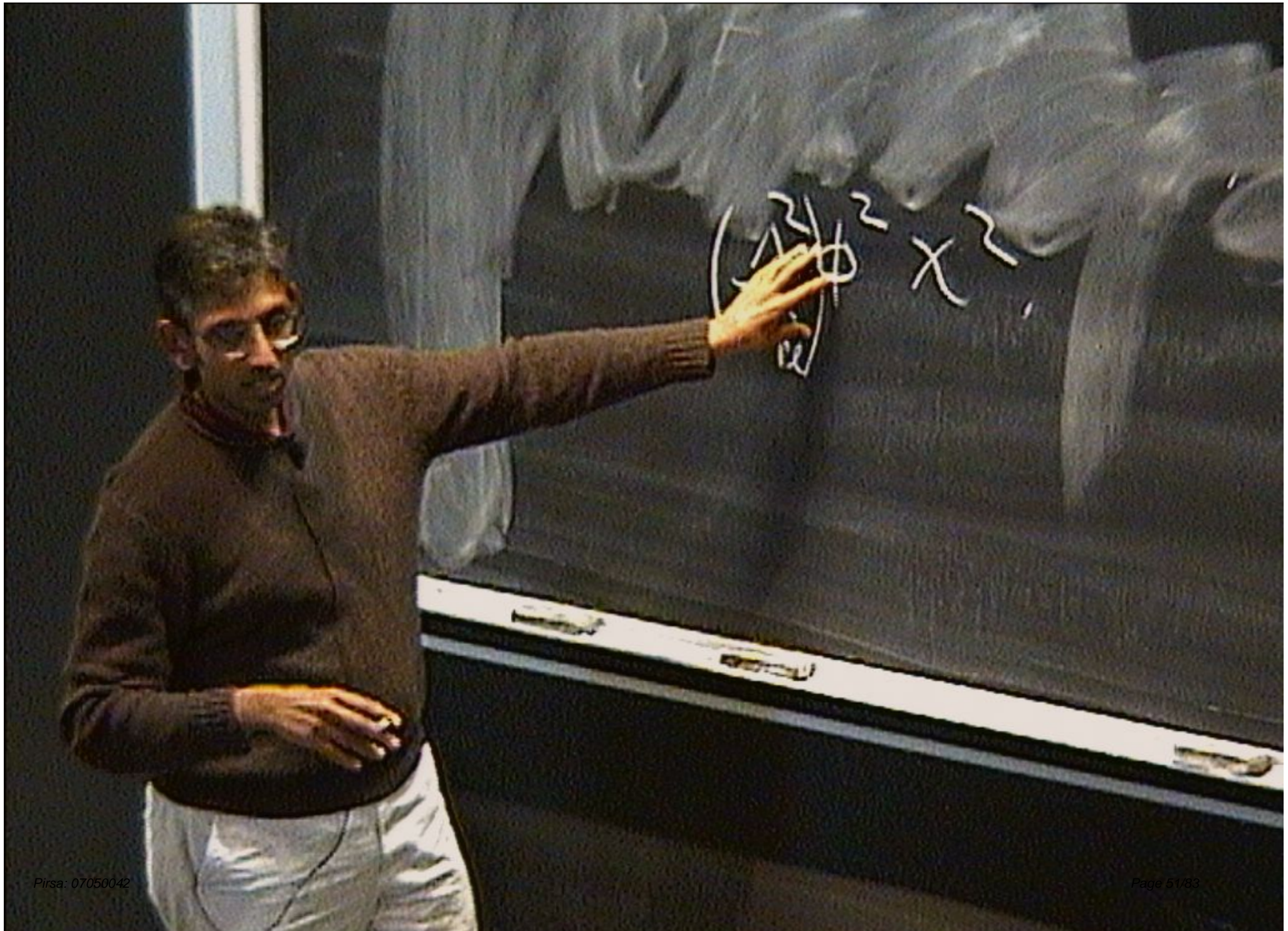
Probability / Vol. time  $\sim \frac{1}{256 \pi^5} \frac{\Lambda^8}{M_{pl}^4}$

$\Lambda \equiv$  ~~Lorentz~~  $E, \vec{p}$  cutoff

Consistency with cosmic  $\gamma$  background  $\Rightarrow \Lambda < \text{MeV}$   
 $\doteq$  cline, Jeon, Moore '04  
 analysis of Phantom Dark Energy



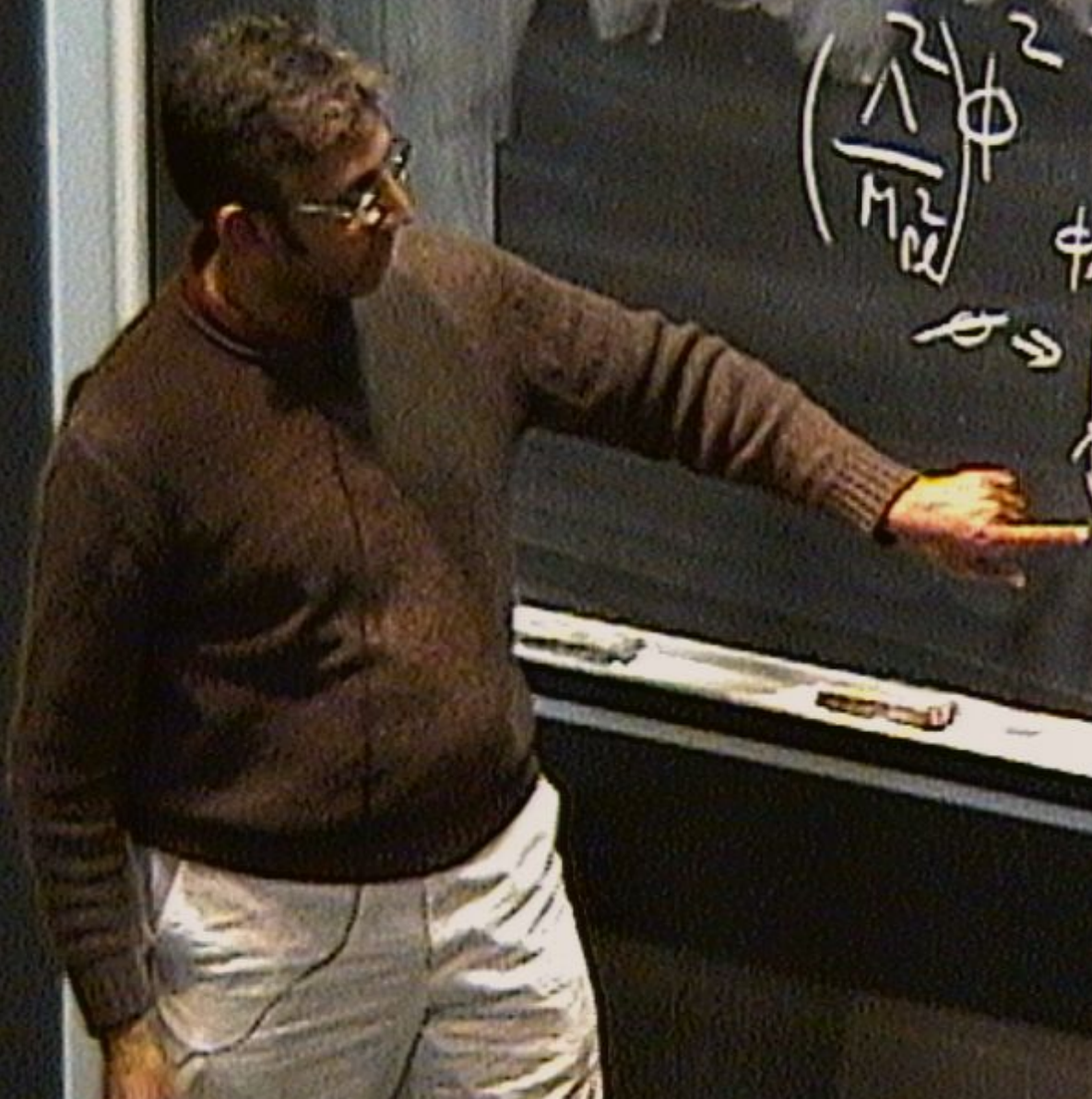




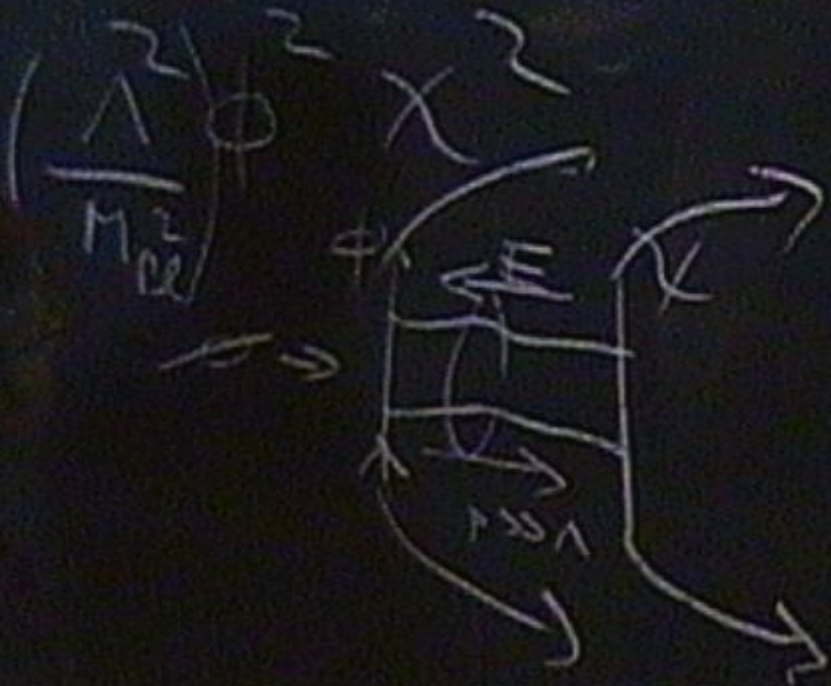




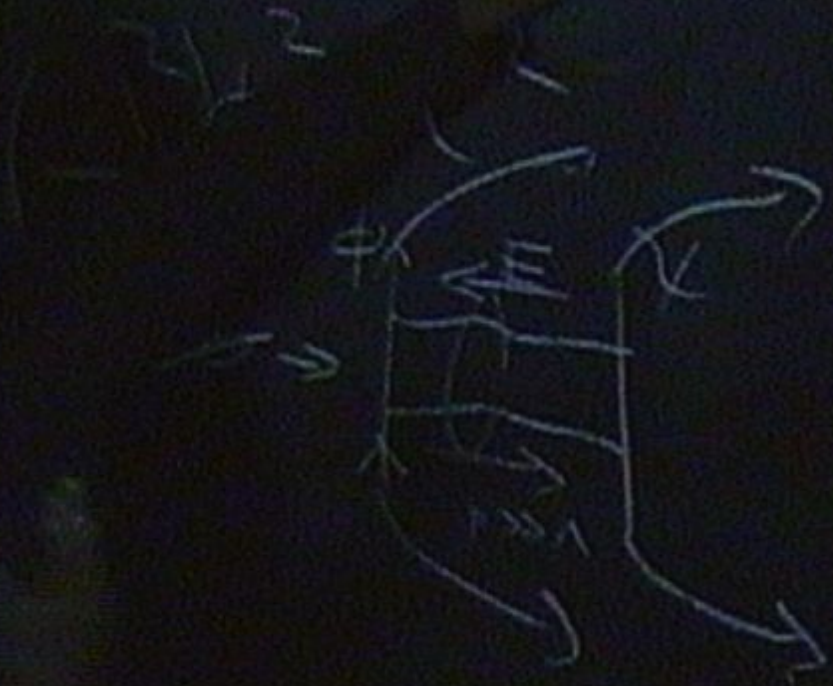




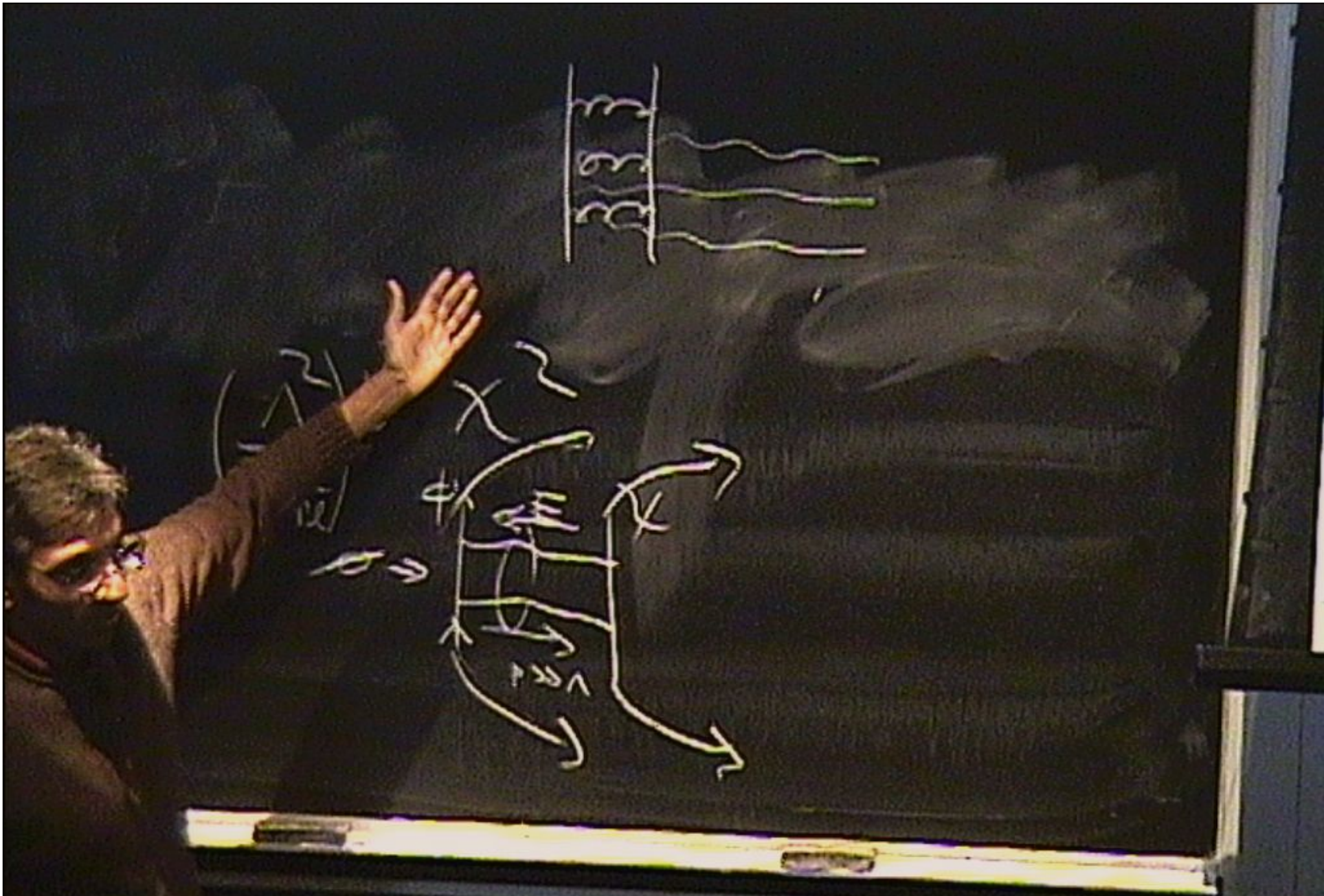




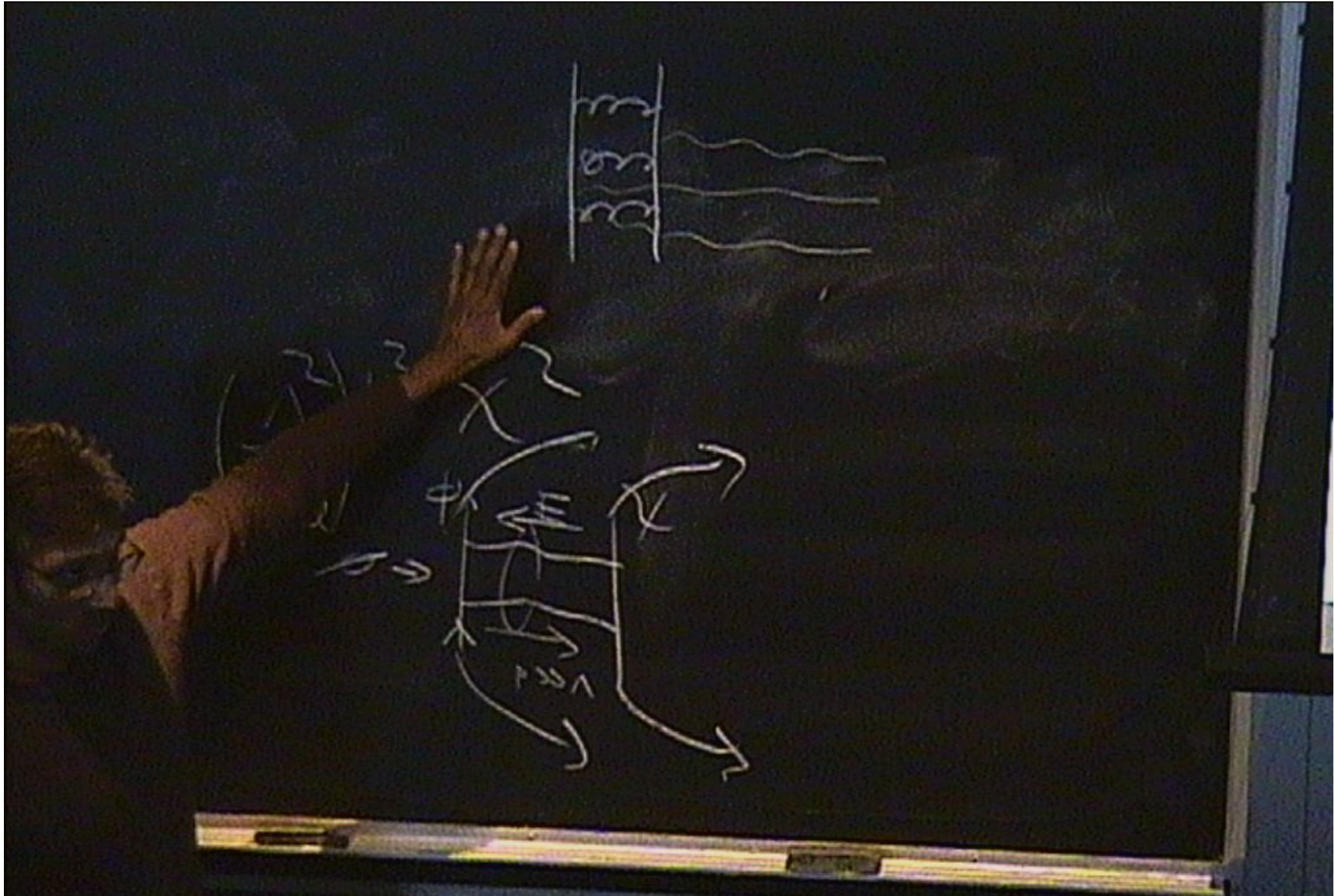




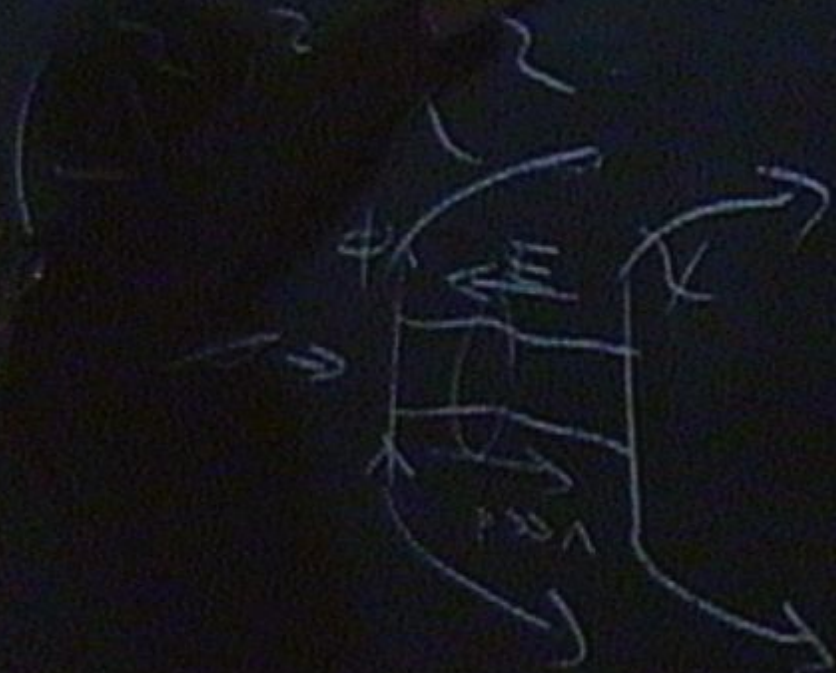
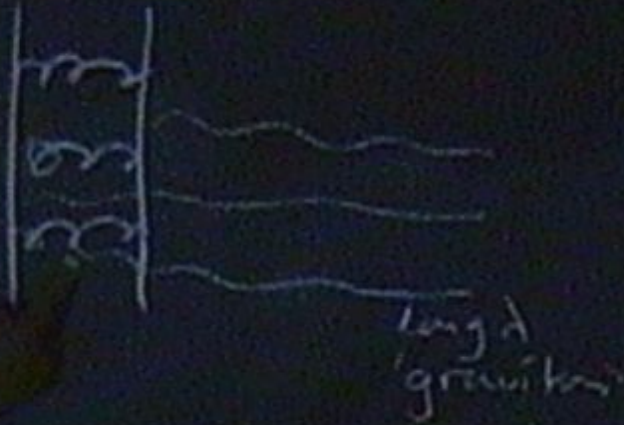




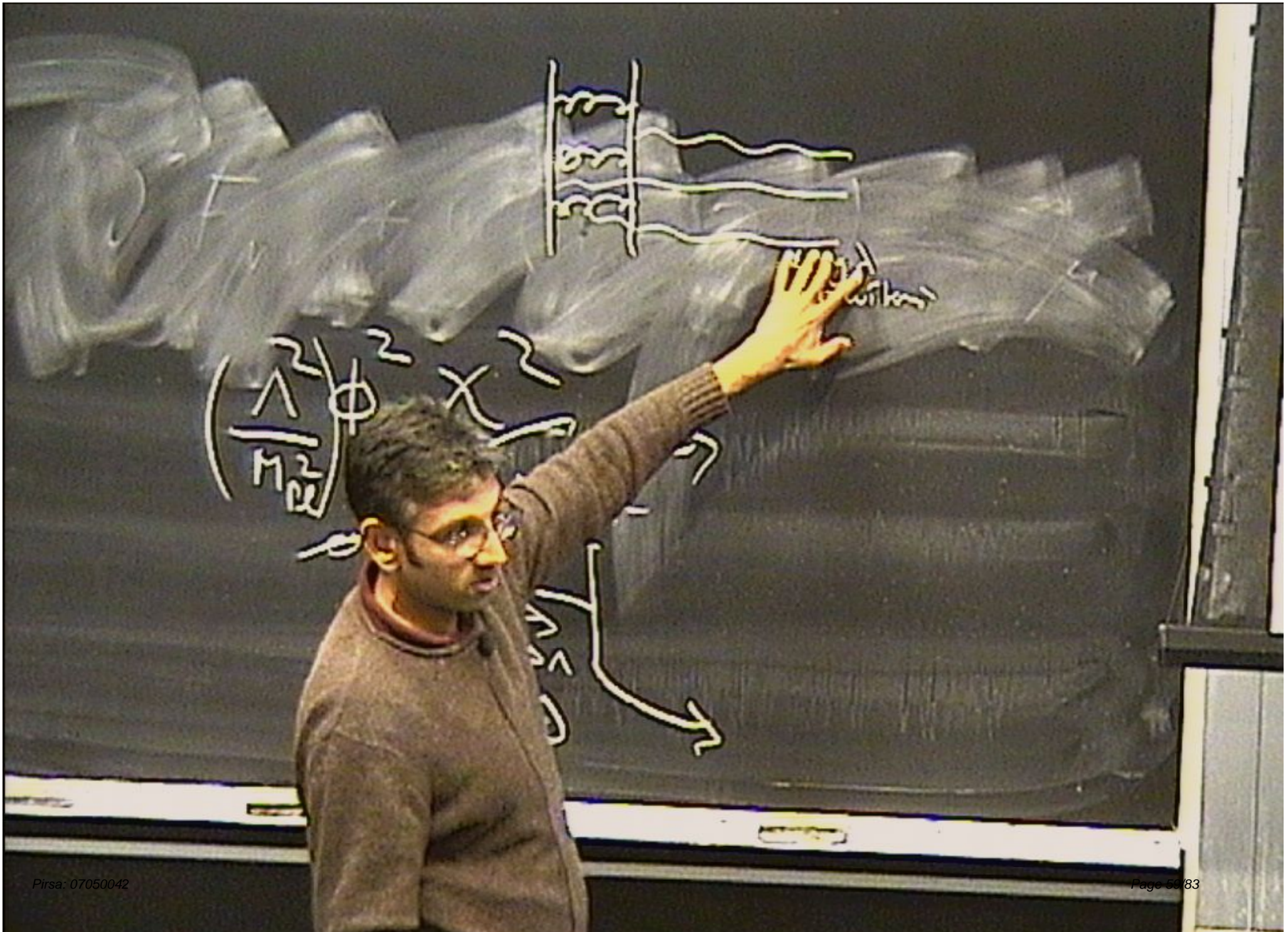




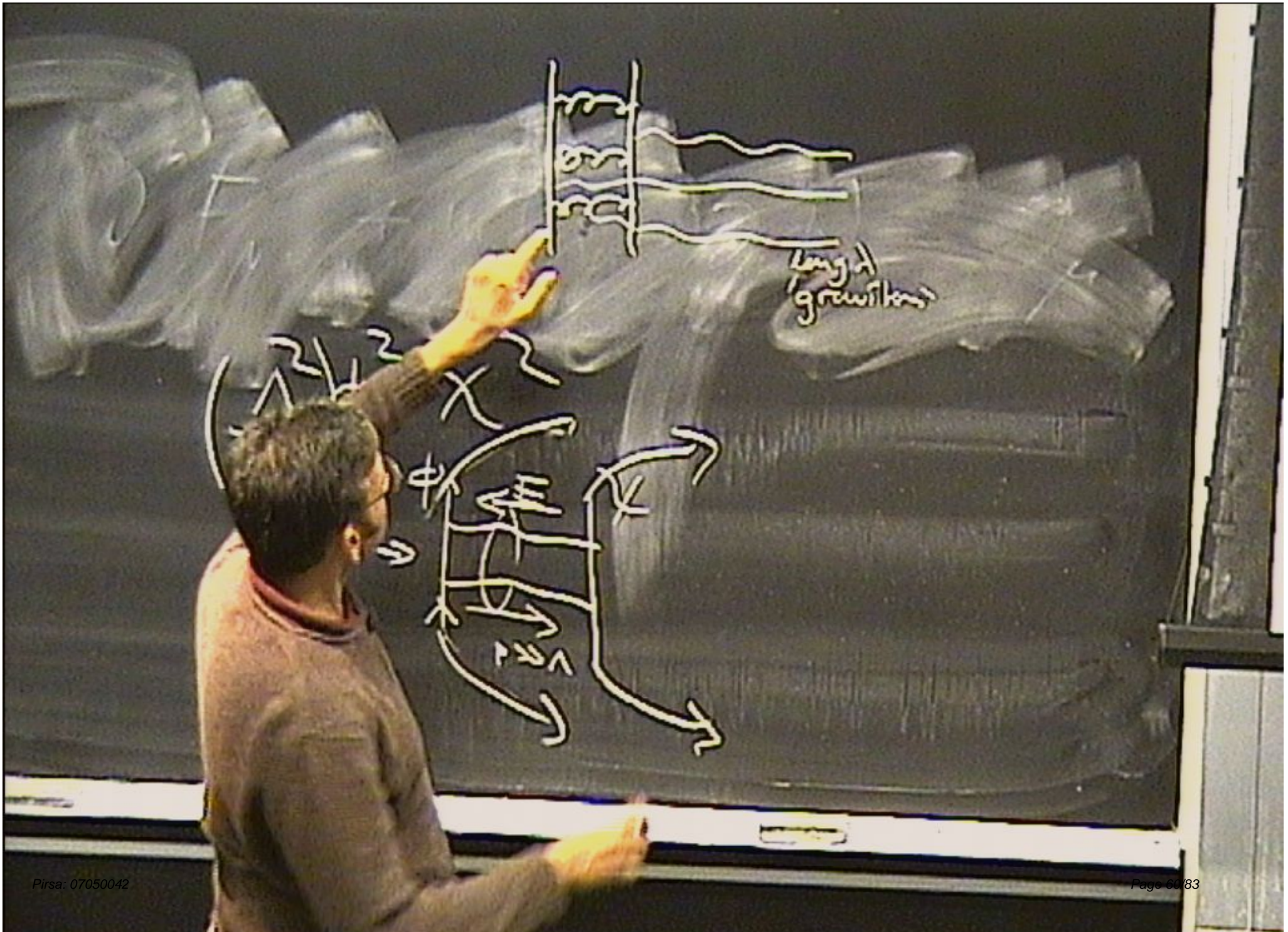




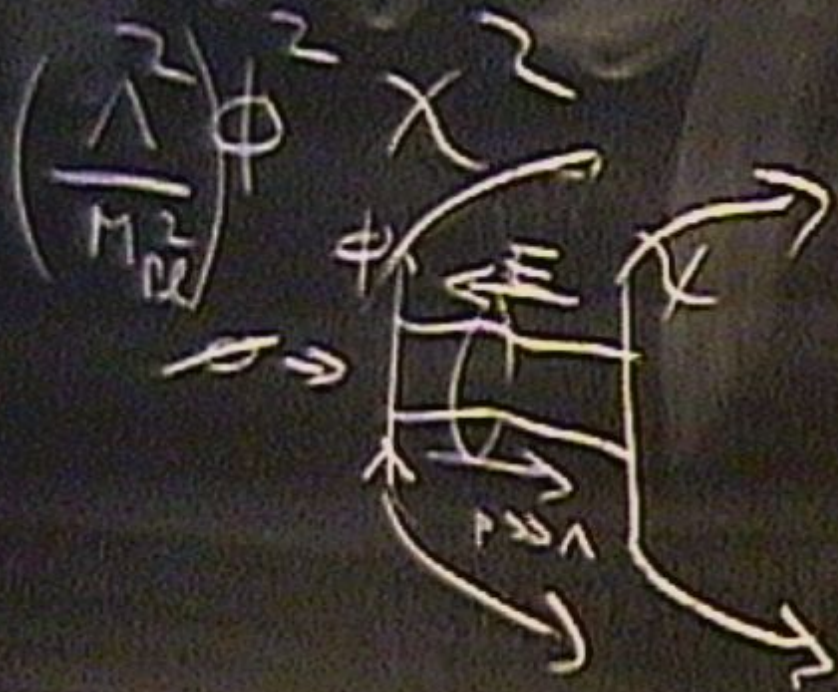
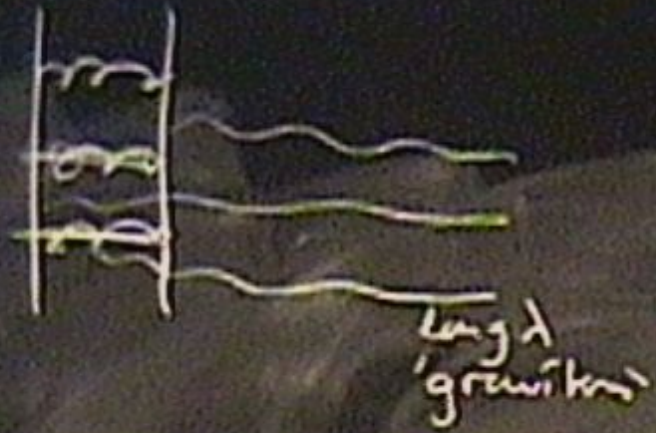




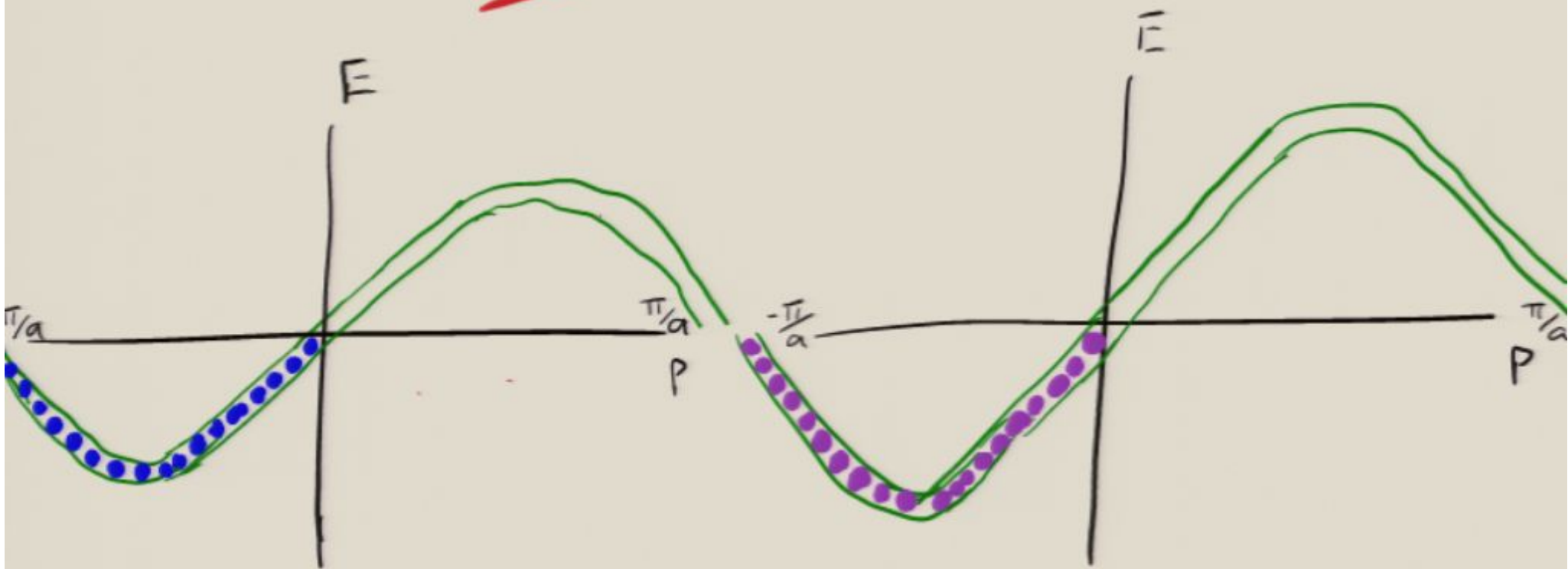








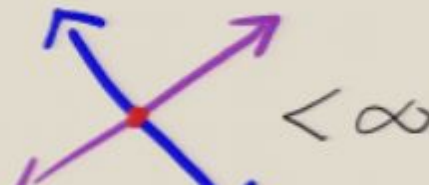
# NEGATIVE ENERGIES $\Rightarrow$ ~~LORENTZ~~



"Minkowski vacuum" is an excited state ...  
of a non-relativistic true  $|0\rangle$ .

$$|p| < \pi/a$$

$$\int d\text{boost}$$



Caroll, Hoffman  
Trodden '03;  
Cline, Jeon, Moore



# GHOSTS IN FIELD THEORY

Classically,

$$\mathcal{L} = \sqrt{-g} \left\{ M_{Pl}^2 R - \rho + \mathcal{L}_{\text{matter}}(\psi, D_\mu) - \mathcal{L}_{\text{matter}}(\hat{\psi}, D_\mu) \right\}$$

Ghosts



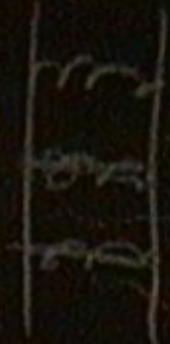
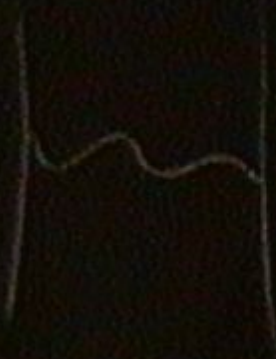
as proposed by Linde '84

Perturbative Quantization:

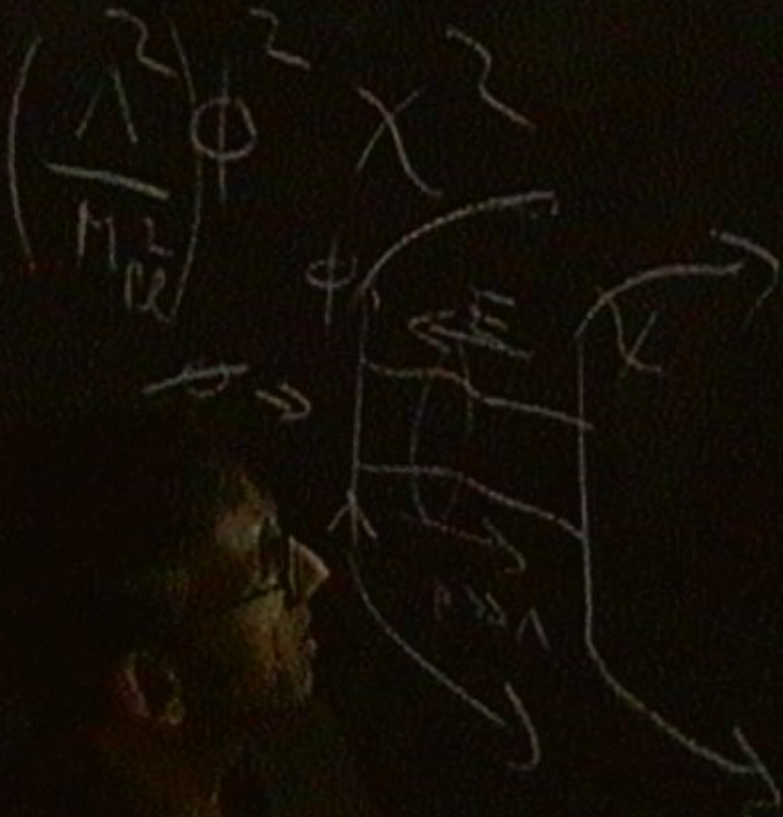
Non-Ghosts  $\frac{i}{p^2 - m^2 + i\epsilon}$

Ghosts  $\frac{-i}{p^2 - m^2 - i\epsilon}$   $(i \rightarrow -i)$



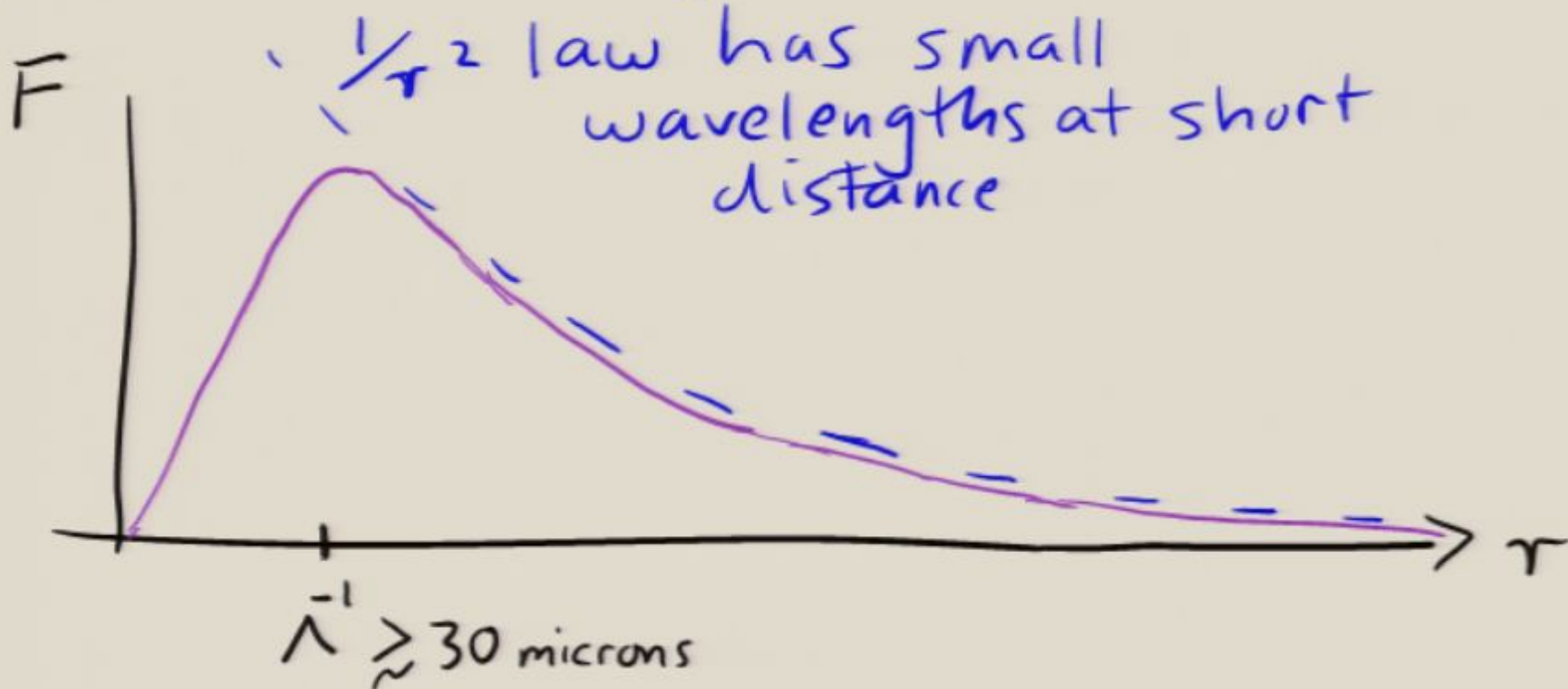


long  
gradient



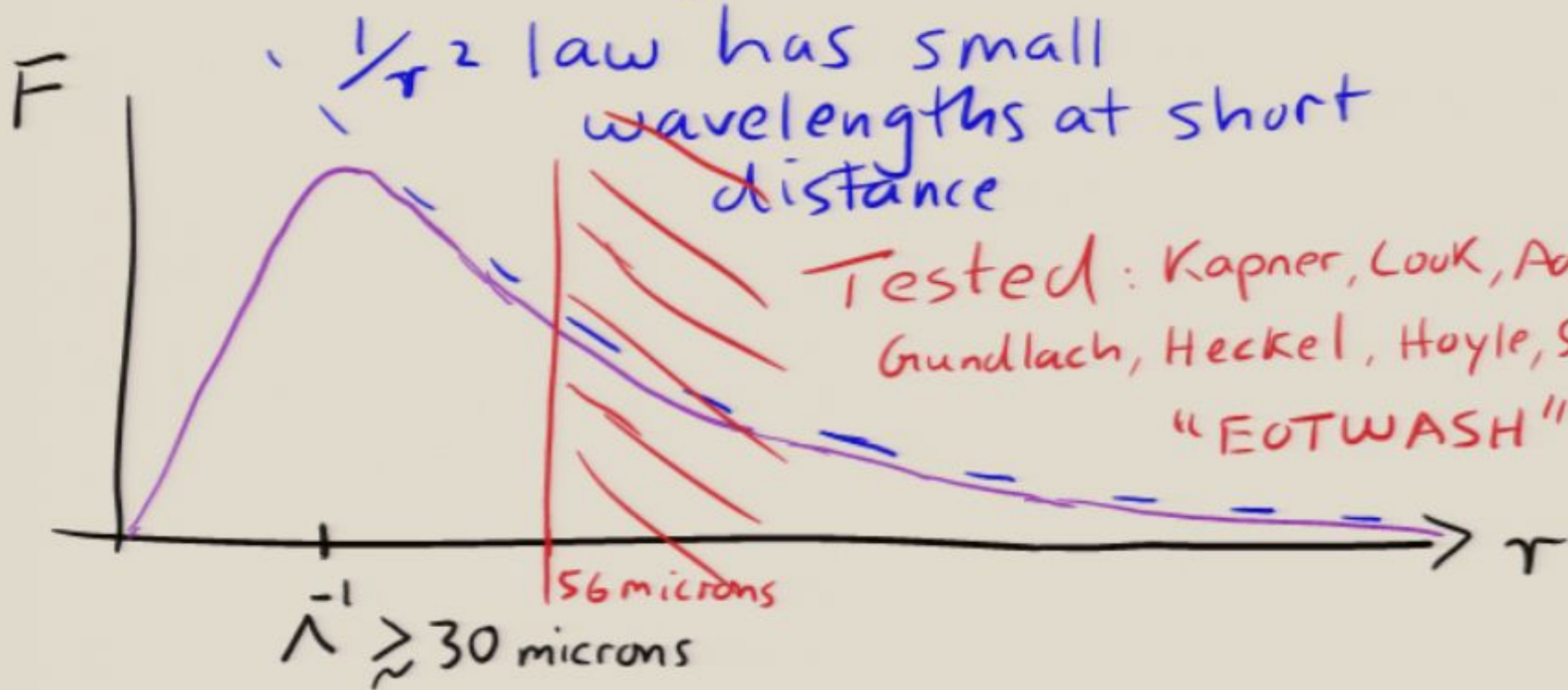
# Sub-mm Gravity tests

should reveal breakdown of Newton's Law due to grav.  $\vec{P}$  cutoff,  $\Lambda$ :



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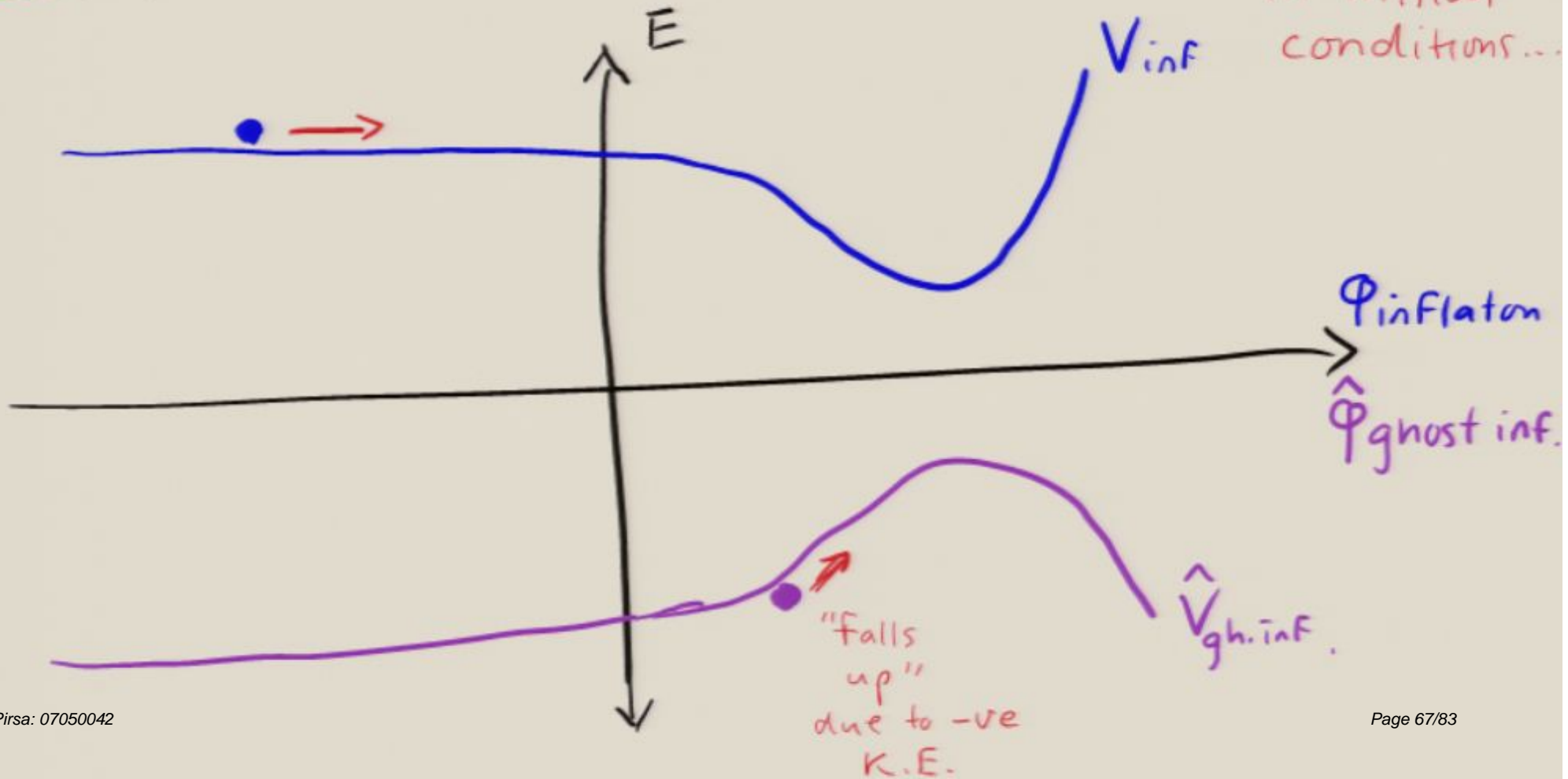


# GHOST BUSTERS

Why are ghosts so rare apparently?

Inflation

Linde '84: Initially, modest asymmetry in initial conditions...

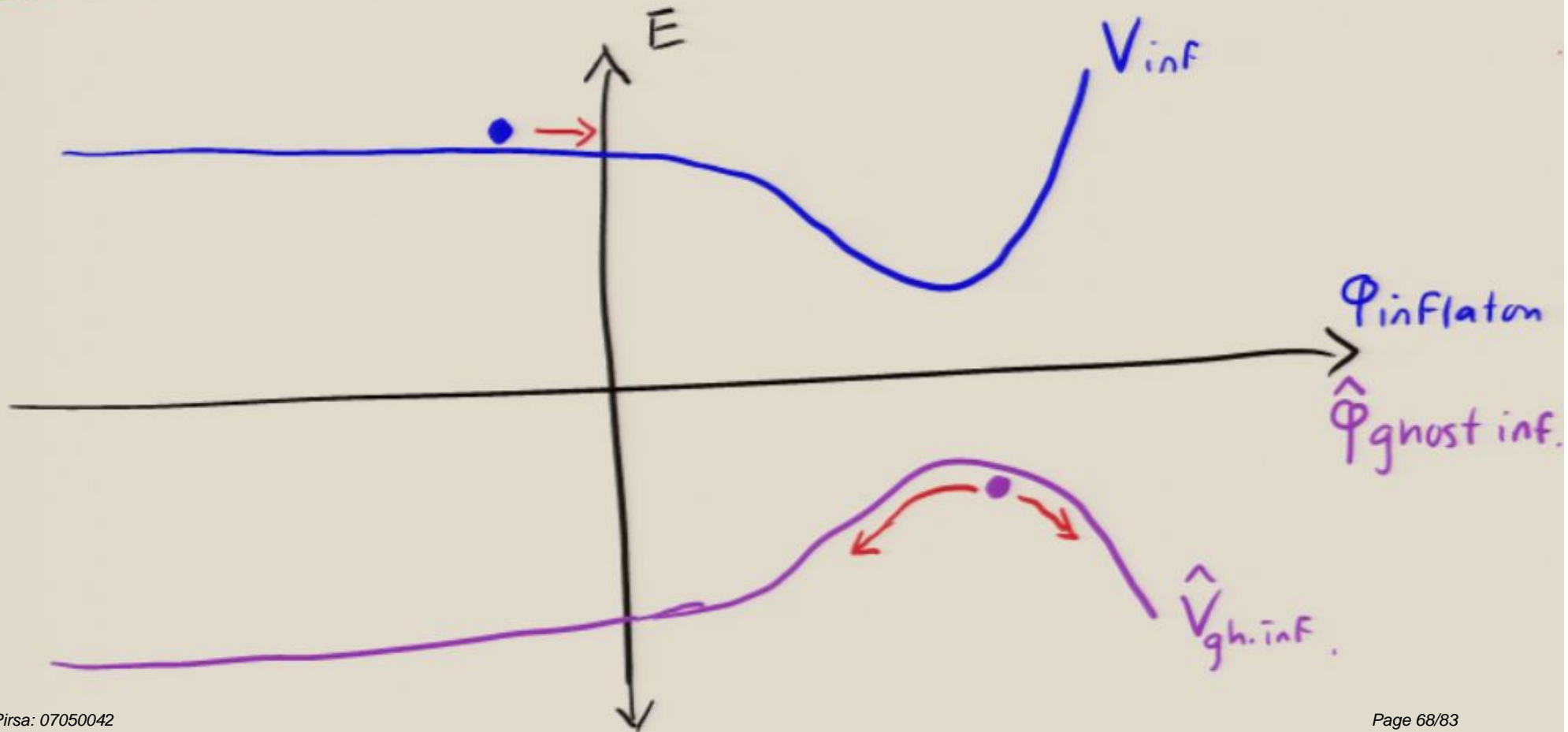


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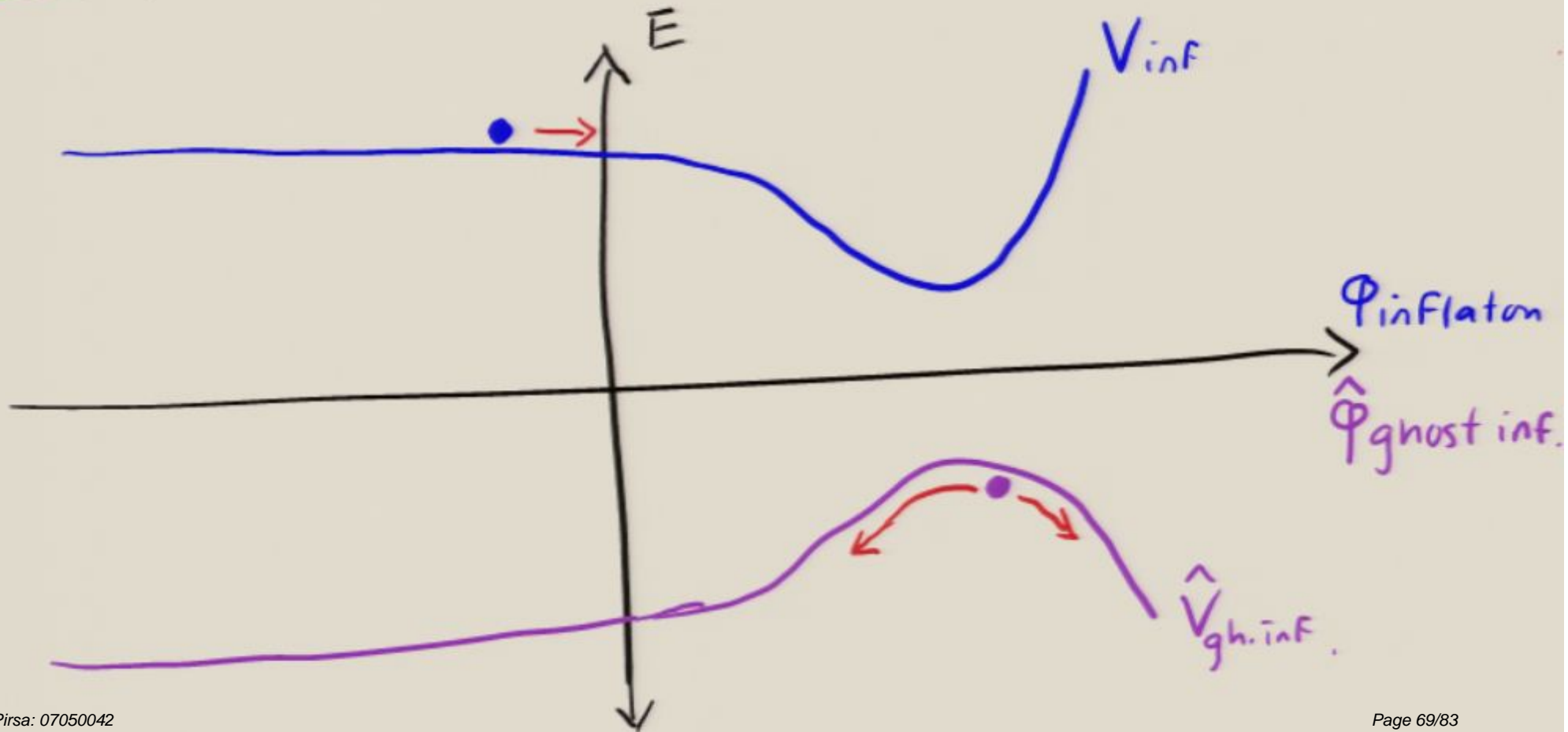


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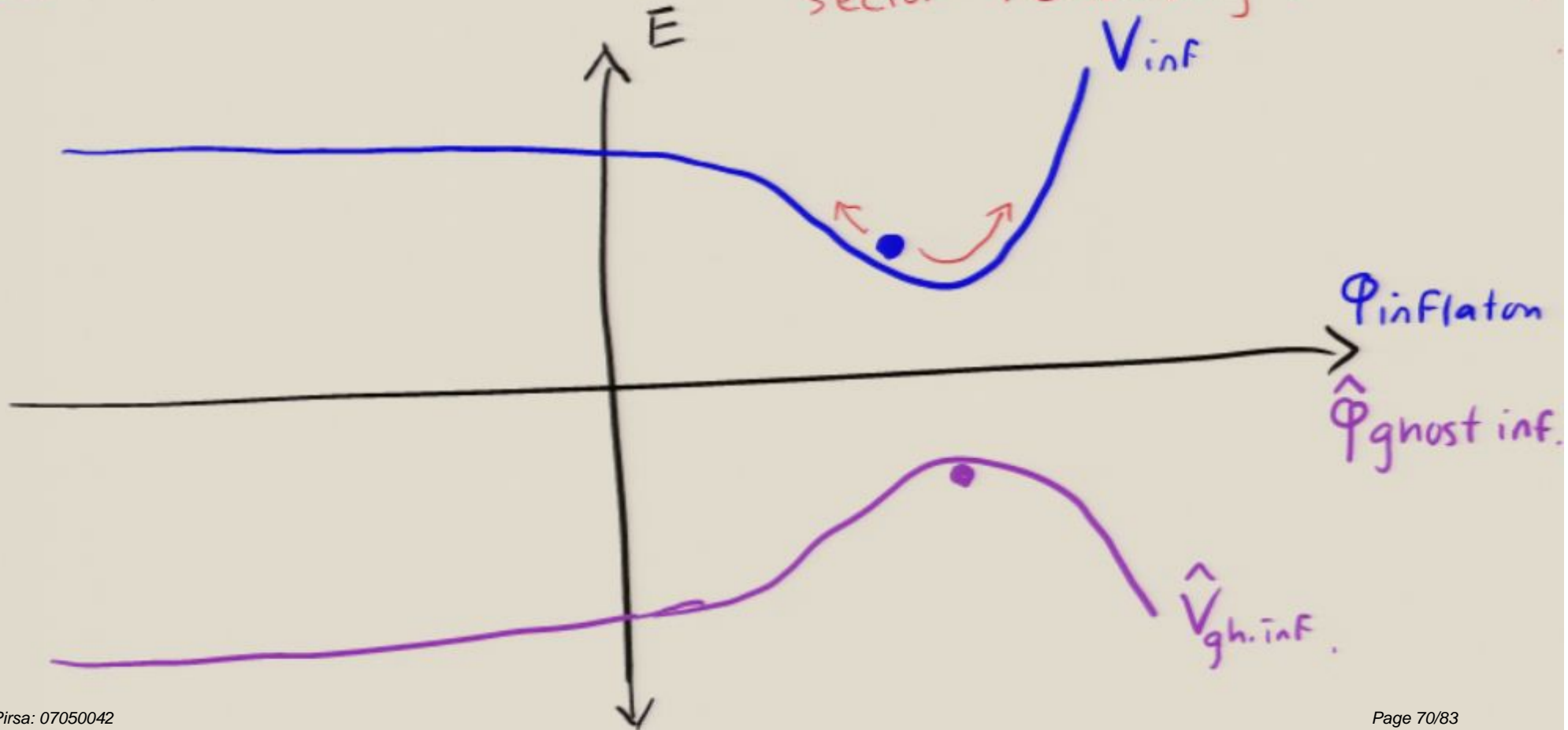


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Any remaining ghost matter is v. exotic dark matter. Can it be detected?

Newtonian forces:



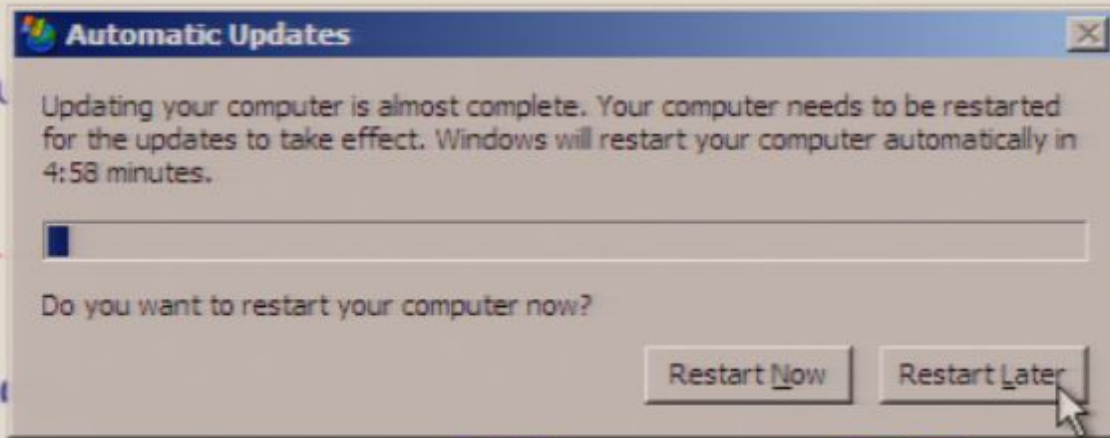
Relative forces:



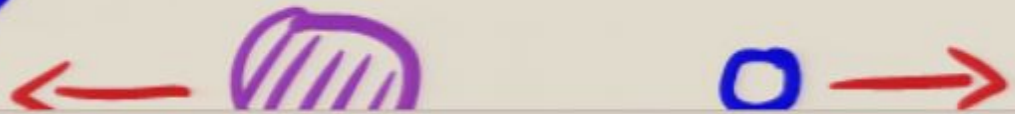
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Relative for





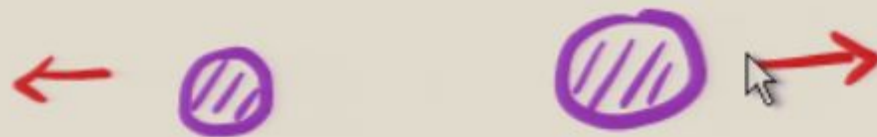
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# IMPLEMENTING $\Lambda$

Effective field theories of ~~Lorentz~~ gravity exist

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Arkani-Hamed, Cheng, Luty, Mukohyama '04

Dubovsky '05

Construction of ~~Lorentz~~ pure gravity theory  
with  $\vec{p}$ -cutoff  $\Lambda$

Schwartz, Sundrum

Impose  $\Lambda$  as (soft)  $\vec{p}$ -cutoff such as  $e^{\nabla^2/\Lambda^2} \equiv e^{-\frac{\vec{p}^2}{\Lambda^2}}$   
in  $\mathcal{L} \Rightarrow t$ -local,  $\vec{x}$ -nonlocal

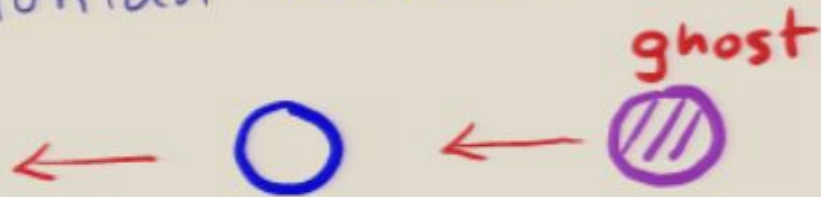
Work in co-moving coordinates of aether.

Implement  $\Lambda$  to maintain perturbative  
unitarity.

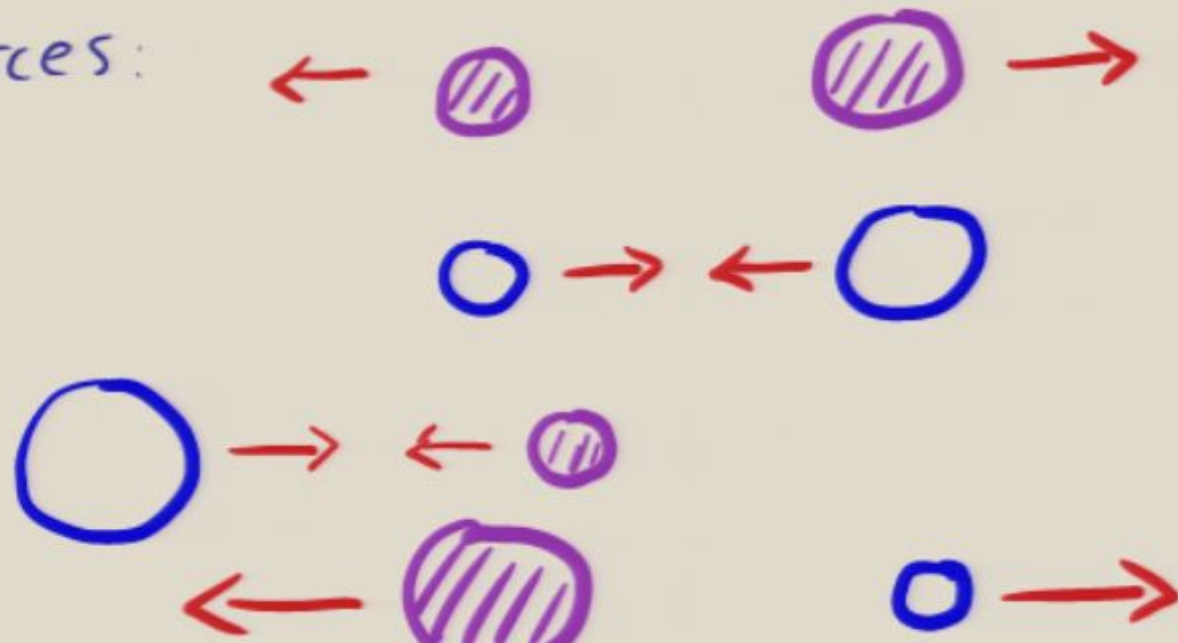
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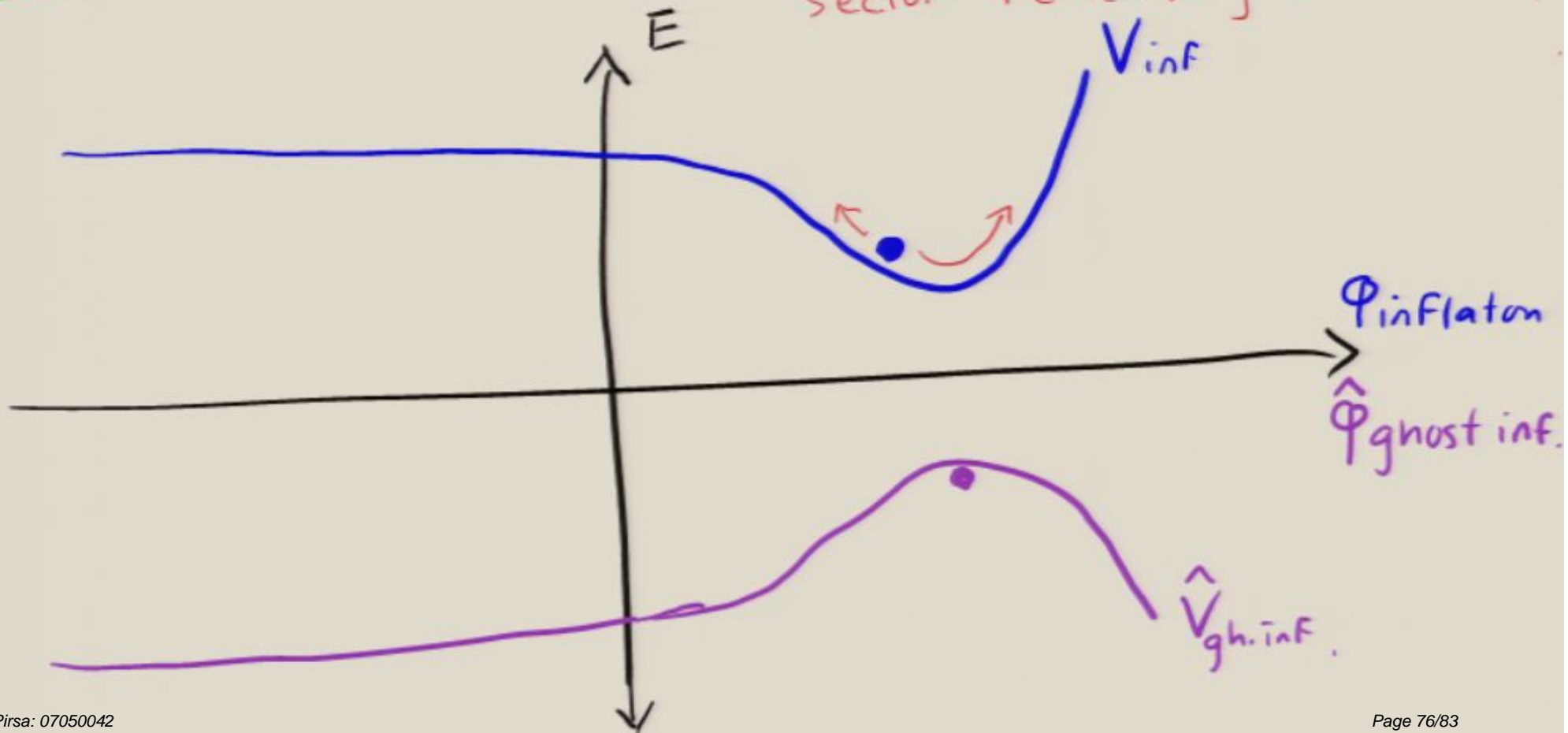


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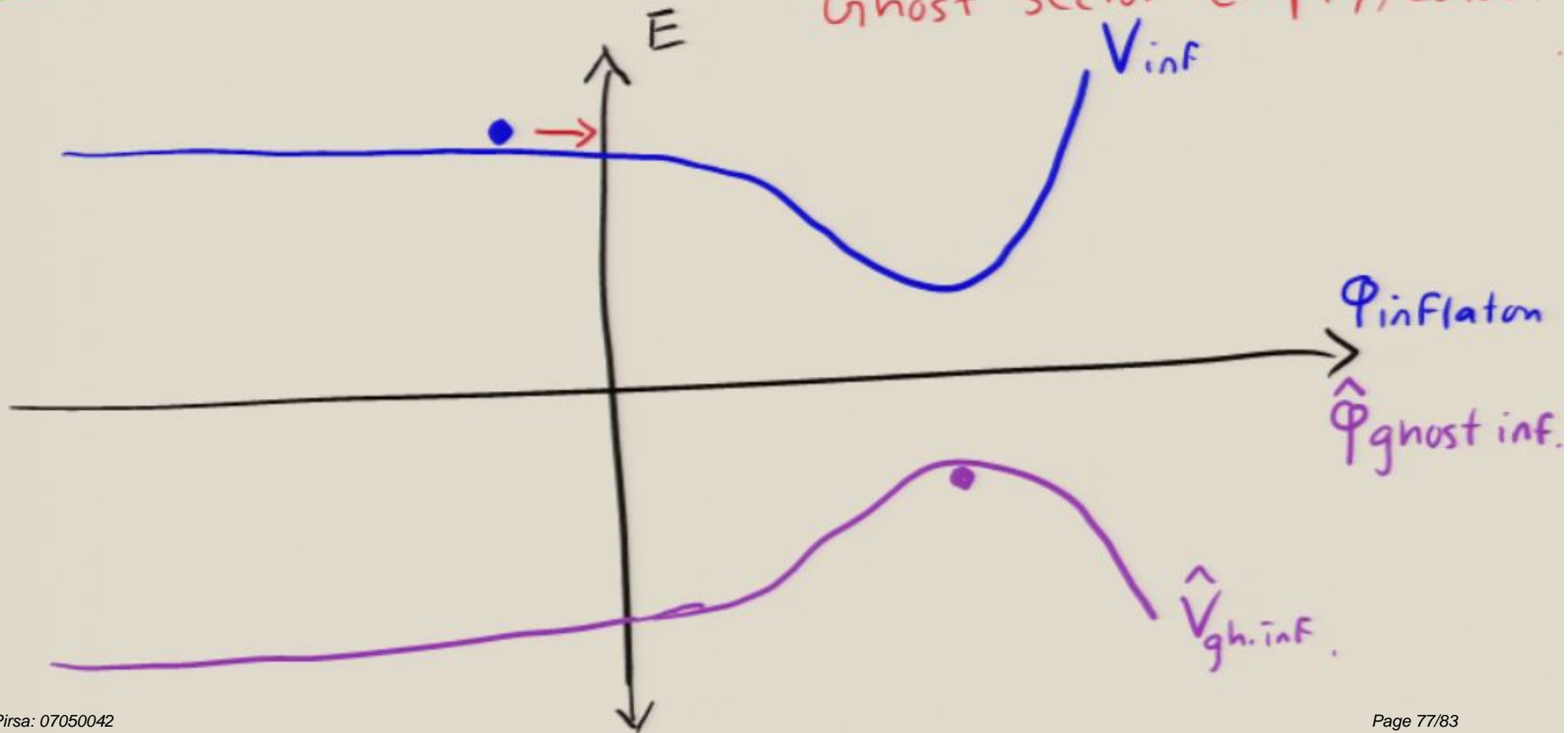


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Linde '84 : ... is inflated away.  
Ghost sector empty, cold.

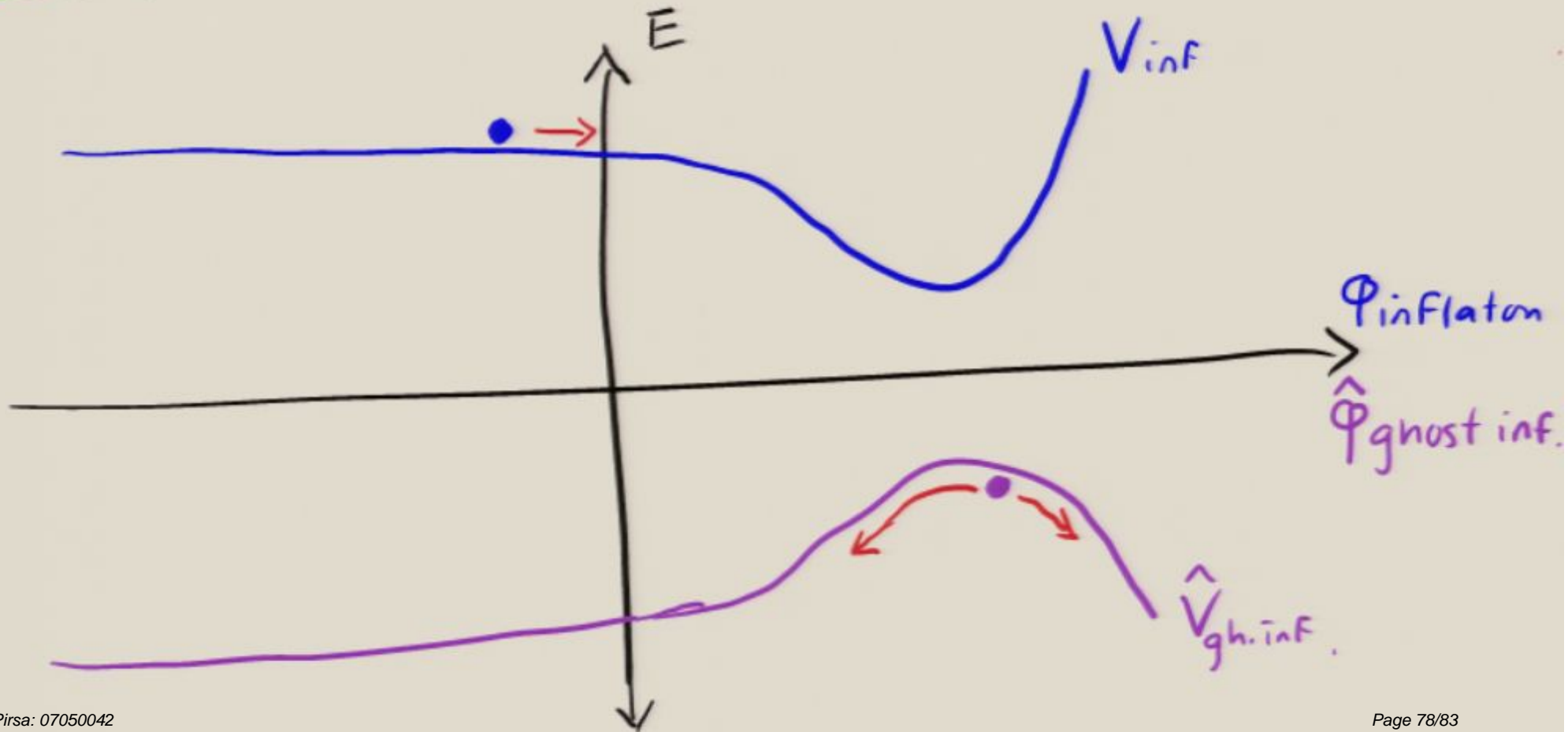


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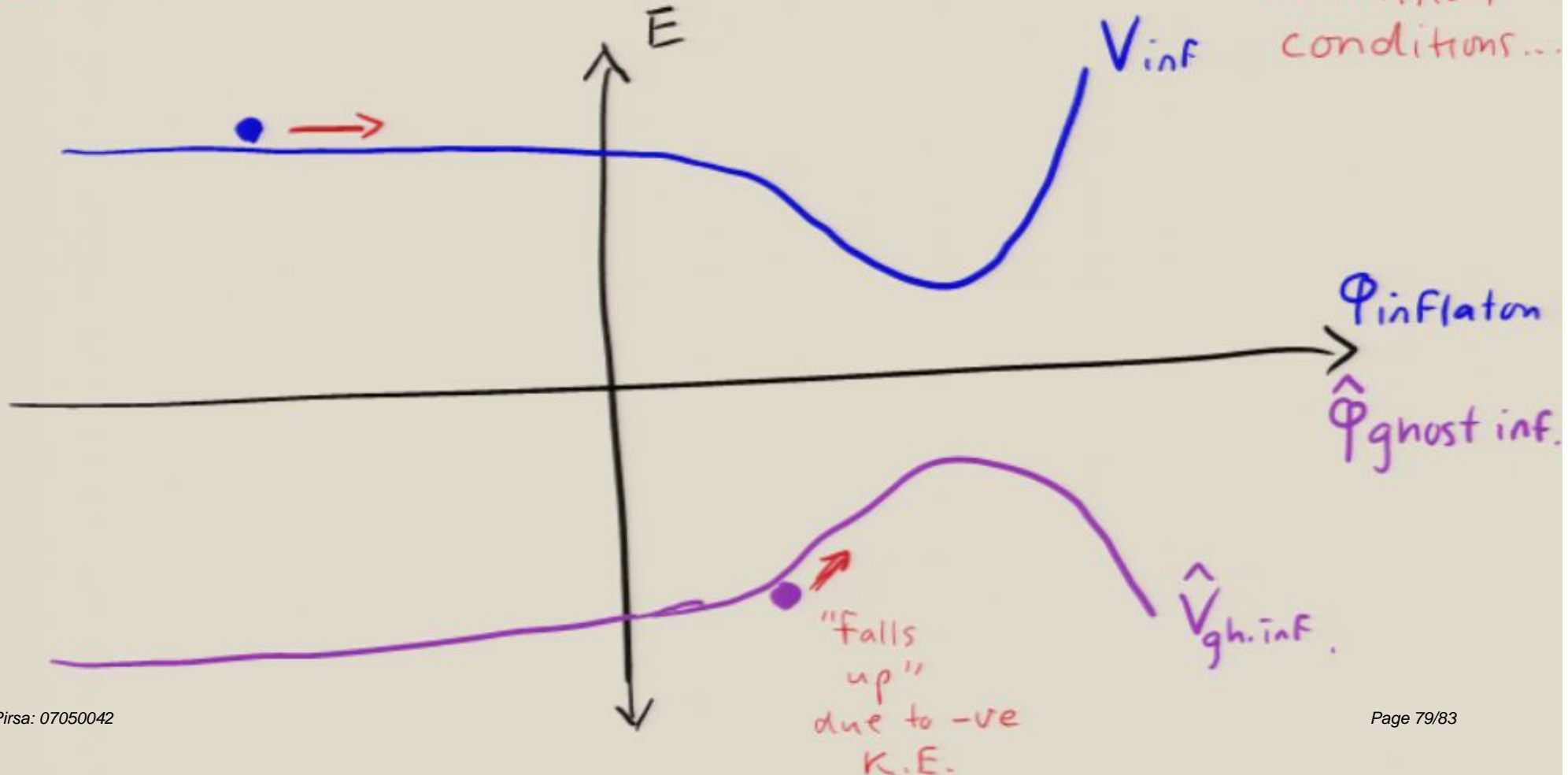


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Work in co-moving coordinates of aether.

Implement  $\Lambda$  to maintain perturbative  
unitarity.

# THE ISSUES

Unitarity requires  $\Lambda$ -deformation of a manifestly unitary gauge-fixing physical in presence of aether

Eg. Yang-Mills in  $\partial_i A_i^a = 0$  Coulomb gauge.

$$\mathcal{L}(A_\mu, \partial_\nu) = \mathcal{L}_2(A_\mu, \partial_\nu) + \mathcal{L}_{\text{int}}(A_\mu, \partial_\nu)$$

$$\rightarrow \mathcal{L}_2(A_\mu, \partial_\nu) + \mathcal{L}_{\text{int}}(e^{\nabla^2/\Lambda^2} A_\mu, \partial_\nu)$$

$\Rightarrow$  UV finite canonical quantization perturbation theory  
Gauge-fixing needed, else  $\mathcal{L}_2$  not invertible, but  $\mathcal{L}$  not gauge invariant  
Relativistic gauges would yield propagating -ve probability  
 $\Lambda$  reverts to standard gauge-fixed relativist



# STRONG COUPLINGS?

Similar issue to massive gravity,  
bad propagator behavior  $\Rightarrow$  strong couplings  
 $\lll M_{pl}$

Arkani-Hamed, Georgi, Schwartz '02

Eg. Coulomb gauge propagator

$$G_{ij} = \frac{\delta_{ij} - \frac{P_i P_j}{\vec{P}^2}}{E^2 - \vec{P}^2 + i\epsilon}$$

$$G_{00} = \frac{1}{\vec{P}^2} \gg \frac{1}{E^2 - \vec{P}^2} \text{ For } E \gg \vec{P}$$

cancelation of bad behavior,  $\equiv$  Feynman gauge,  
usual guaranteed by gauge invariance.

Presently investigating sufficient cancelation by subgroup  
of transformations  $\mathfrak{g}(+)$  (not  $\mathfrak{g}(\vec{x}, t)$ )

# FUTURE . . .

Build unitary, perturbative graviton amplitudes (+ matter) with  $\wedge$   $\vec{p}$ -cutoff to realize  $\bar{E}$ -parity idea.

Investigate non-perturbative instabilities,  
Large Redshifts

Consistency with holographic principles

Identify most promising experimental/observational tests.