Title: Mode creation in expanding universes, through dissipative effects

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Abstract:

PI '06

Mode creation in expanding universes

(by dissipative effects)

Parentani
LPT-Orsay

1st Motivation.

unknown high energy processes might break Lorentz invariance by **dissipative effects.**

$\Rightarrow$ introducing
- a UV scale Λ_{LV}
- a prefered frame

1st Aim:

The <u>phenomenology</u> of this possibility in Minkowski space, in vacuo.

2^d Motivation.

address the trans-Planckian question (of inflationary cosmology) when (strong) dissipative effects exist above $\omega = \Lambda_{LV}$

- So far only dispersion was studied

2^d Aim:

provide a class of dissipative models wherein $P(k)$ can be computed

3^{rd} Motivation.

confront the question of

mode creation in expanding universe

- assuming that the mode density

$$\rho_{\Omega} < \infty,$$

$\Rightarrow$ • Either the number of modes $= c^{st}$

$\Rightarrow \rho_{\Omega} \propto 1/a^3$ (absurd)

- Or $\rho_{\Omega} = c^{st}$

$\Rightarrow$ Mode creation.

⇒ 2 questions:

1. how to describe mode creation in QFT?

2. What fixes the **state** of the newly born modes?

3rd Aim:

provide hamiltonian (closed) models wherein (underdamped) modes are "created" so that their density stays fixed as the universe expands.

4th Motivation / Aim

- identify the relevant properties of the environment ψ governing dissipative effects on ϕ so as to

1. identify equivalent classes
2. cover the generic case (anti-ad-hoc)

in order to 3. be able to meet **additional** requirements.
(e.g. general covariance)

Two basic requierements

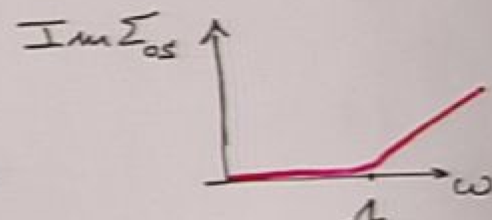
QFT

1) Models with dissipation

- on shell
- in Mink. space time
- in vacuum (true interacting)
- above $\omega = \Lambda_{LV}$
- preserving $\left\{ \begin{array}{l} \text{homogeneity, isotropy} \\ \text{stationarity.} \end{array} \right.$

separately

$$\Rightarrow \quad G_F(\omega,k) = \left(-\omega^2 + k^2 + \Sigma(\omega,k)\right)^{-1}$$



ex: $\Sigma_n = \frac{i\omega}{\Lambda} k^2 \left(\frac{k}{\Lambda}\right)^n$

Two basic requierements

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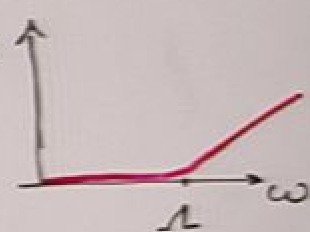

ex: $\Sigma_n = \frac{i\omega}{\Lambda} k^2 \left(\frac{k}{\Lambda}\right)^n$

Note: the dispersion relation is defined from the poles of $G(\omega,k)$

2d requierement.

"hamiltonian (closed)" : unitary

$$G(x,x') = T_r\left[\hat{\rho}_{in}\ \hat{\phi}_H(x)\ \hat{\phi}_H(x')\right]$$

where
- $\hat{\rho}_{in} = \hat{\rho}_\phi \otimes \hat{\rho}_{env.\,\psi}$,
- $\hat{\phi}_H(x)$: Heisenberg f. op. evolving with $\hat{H}_T$

Note: Fenster-Jacobson's model is not H and U. nor Kempf's and Ted's ones

Link with Quantum Gravity.

- Suppose that when approaching Λ, the smooth manifold is replaced by a new structure.

- <u>Question:</u> how will **this** manifest itself in Green functions of matter fields?

$$G(x,x') = \text{"}\,\mathrm{Tr}\,[\rho\ \phi(x)\,\phi(x')]\,\text{"}$$

$$G(t,t';k) = \frac{1}{2\omega_k}\, e^{-i\omega_k (t-t')}$$

in the free QFT vacuum in Minkowski sp.

$$= \ ? \ \text{ in QG}$$

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in the true QFT vacuum in Minkowski sp.

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Link with Quantum Gravity.

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Note: $P_k(t) = G(t,t;k)$ in inflation

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Finite mode density

- Free field, solution of $\Box \phi = 0$ in Minkowski sp. time.

- $$\phi(t,\underline{x}) = \underbrace{\int d^3\underline{k}}_{\text{SOM}} \; \overbrace{e^{i\underline{k}\cdot\underline{x}} \; \phi_{\underline{k}}(t)}^{\text{mode op.}}$$

  Sum over modes

- each mode $(\partial_t^2 + \underbrace{\omega_k^2}_{=|k|^2}) \phi_k = 0.$ (HO)

- hamiltonian:

  $$\hat{H} = \underbrace{\int d^3k}_{\text{SOM}} \hat{H}_{\underline{k}} \,, \qquad \hat{H}_{\underline{k}} = \omega_k \, \hat{a}^{\dagger}_{\underline{k}} \hat{a}_{\underline{k}}$$

- state of the field

  $$|\Psi\rangle = \underbrace{\prod_{\underline{k}}}_{\text{POM}} \otimes \underbrace{|\Psi_{\underline{k}}\rangle}_{\text{state of the mode } \underline{k}}$$

• density of particles / quanta: $\bar{n}_Q$

* $\dfrac{\bar{N}_Q}{V_3} = \underline{\bar{n}_Q} = \int d^3k \ \underbrace{\bar{n}_k}$

mean occ. number

$(= (e^{\beta\omega} - 1)^{-1}$ in th. bath

• ___________ •

• density of modes : ρ_M

$\dfrac{N_{\text{Modes}}}{V_3} = \rho_M = \int d^3k \ \ 1$

• IF Lorentz invar. $\Rightarrow$ $\rho_M = \infty$.

• IF UV cutoff : $|\vec{k}_{max}|^2 = \Lambda^2$

$\Rightarrow \boxed{\rho_\Lambda = \Lambda^3}$

In the absence of cosmic expansion, Λ does not modify observables in QFT.

ex: • in a thermal bath:

$$\bar{n}_Q^{\Lambda} = \int^{\Lambda} d^3k \;\; \bar{n}_k$$

$$= \bar{n}_Q^{\Lambda=\infty} + \underbrace{O(e^{-\beta\Lambda})}_{\text{negligeable}}$$

when $T \ll \Lambda$.

• Casimir. (vacuum effect)

$$F_{\Lambda} = F_{\Lambda=\infty} + O\left(\frac{1}{L\Lambda}\right)^{\alpha} \quad ; \quad \alpha \geq 1$$

L: size of the cavity.

. However ⚠ to large boosts !

(Unruh effect).

• In expanding RW universes, 18

$$ds^2 = -dt^2 + a^2(t) \underbrace{d\underline{x}^2}_{\text{comoving coord.}} ,$$

• Modes still exist:

$$\hat{\phi} = \underbrace{\int d^3k}_{\text{SOM}} \, e^{i\underline{k}\cdot\underline{x}} \, \phi_{\underline{k}}(t)$$

$$\hat{H} = \overline{\int d^3k} \, \hat{H}_{\underline{k}} \quad ; \quad |\Psi\rangle = \underbrace{\Pi_{\underline{k}}}_{\text{POM}} \otimes |\Psi_{\underline{k}}\rangle$$

• $\omega_{\underline{k}}^2 = \underline{k}^2 - \frac{a''}{a}$, conformal frequency $\left(d\eta = \frac{dt}{a} \right)$

• proper frequency $\Omega(\eta) = \frac{\omega_k}{a(\eta)}$, $\vec{p} = \frac{\vec{k}}{a(\eta)}$

$\Rightarrow$ Modes are labeled by conf. momentum $\vec{k}$.
and not by physical mom. $\vec{p}$.

• proper volume: $V_p(t) = a^3(t)\, V_{conf.}$

$\Rightarrow$ particle density

$$\bar{n}_Q(t) = n_Q(0) \left(\frac{a_0}{a(t)}\right)^3 \propto \frac{1}{a^3}$$

$\Rightarrow$ What about mode density ?

• if today $\rho_0 = (M_{Pl})^3$; and no mode creation

$\Rightarrow$ the density of these modes was:

$$\rho_M(t) = \rho_0 \left(\frac{a_0}{a(t)}\right)^3$$

$$= \rho_0 (10^{10})^3 \quad \text{at PNS}$$

$$= \rho_0 (10^{50})^3 \quad \text{at the begining of}$$

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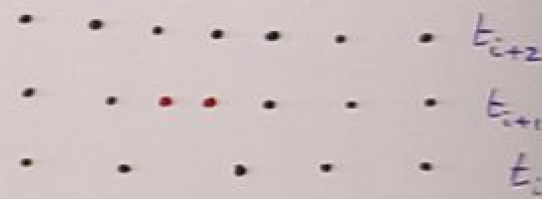
The Forster/Jacobson proposal (2004).

- growing lattice:

"a pair of points is added at t_{i+1}."



- $\Rightarrow$ a pair of modes is "created" at t_{i+1}.
- choose some state for these "birth modes"
- compute the "growth-induced particle creation".

Remarks

- mode $\left\{\begin{array}{l}\text{addition}\\ \text{creation}\end{array}\right.$ is specified from the outset.
- the state is also chosen " " " .
- virtue of their analysis:

  reveal the problems raised by formalizing mode creation.

The dissipative model

- **Why dissipation?**

- Dissipation is **GENERIC** in the absence of Lorentz invariance:

- When increasing the energy, NEW channels open. ⇒ dissipation.

Ex. : GZK, above a critical energy, protons scattered by γ_{CMB} "decay" into pions.

$$\mathrm{Im}\,\Sigma_k \neq 0 \quad \text{for} \quad E_k > E_c .$$

So:

- if there exist Planckian d° of freedom, when the mode energy $\omega_p = \frac{k}{a} \sim M_{Planck}$ NEW channels open

causing $\mathrm{Im}\,\Sigma_k \neq 0$.

How to handle **dissipation** in QFT.

I Free modes $\Rightarrow$ Wronskian conserved.

II Interactions with new d° of freedom Ψ

III Simple models $\rightarrow$ $\mathrm{Im}\,\Sigma_k \neq 0$.

- unitarity
- the **relevant** kernels (N and D)
- the limit $g^2 t_{in} \to \infty$, $g^2 \to 0$.

IV Application to QFT and cosmology.

- Stationarity of Λ_{LV} **dynamically realized** by that of D and N.

I Free evolution

modes obeys:

$$\left[\frac{\partial^2}{\partial t^2} + \omega_k^2 \right] \phi_k(t) = 0 \qquad (1)$$

- second order
- homogeneous: no source
- time reversible: no odd term in $\frac{\partial}{\partial t}$

$\Rightarrow$ ETC: $\frac{1}{i}[\phi_k(t), \dot{\phi}_k(t)] = 1$ (all time)

$\Leftrightarrow$ $[\hat{a}_k, \hat{a}_k^\dagger] = 1$

because Wronskian $\phi_k^* i \overleftrightarrow{\partial_t} \phi_k = 1$ all time

But: IF $\gamma \frac{\partial}{\partial t}$ present in (1)

$\Rightarrow$ no Wronskian conservation

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But: IF $\gamma\frac{\partial}{\partial t}$ present in (1)

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$\Rightarrow$ unitarity ? ETC ?

II Interactions with Ψ

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- $S_T = S_\phi + S_\Psi + S_{\phi,\Psi}$

When hom + isotropy preserved,

$$\Rightarrow \quad G(x,x') \doteq \mathrm{Tr}\left[\rho_T \, \phi_H \, \phi_H\right]$$

$$= \int d^3k \; e^{-i\underline{k}(\underline{x}-\underline{x}')} \; G_k(t,t')$$

$G_k(t,t')$
- c-number
- always exists (ALL $\hat{\Psi}$)

(UNLIKE modes, Bogliubov coef, ..)

- in the true interacting vacuum, in Mink,

$$G_F(\omega,k) = \left[-\omega^2 + k^2 + \Sigma_F(\omega,k)\right]^{-1}$$

dissipation : $\mathrm{Im}\,\Sigma_{os} \neq 0$.

II Interactions with Ψ (15

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III Simple hamiltonian models [16.]
with $\mathrm{Im}\,\Sigma_k \neq 0$.

- QBM. (Cald. Leggett)
- decoherence

Assume:

$$S_T = \int d^3k \, \underbrace{\overbrace{S_T(\underline{k})}^{\text{indep. from each other.}}}$$;

$$S_T(k) = \frac{1}{2}\int dt \left[|\partial_t \phi_k|^2 + k^2 |\phi_k|^2 \right]$$

$$+ \sum_i \frac{1}{2}\int dt \left[|\partial_t \varphi_{k,i}|^2 + \Omega^2_{k,i}(t) |\varphi_{k,i}|^2 \right]$$

$$- \sum_i \int dt \; g_{k,i}(t) \; \phi_k \, \varphi^*_{k,i}$$

ANY dep. is allowed

EOM:

$$\begin{cases} [-\partial_t^2 + \omega_k^2]\,\phi_k = \sum_i g_{i,k}\,\psi_{k,i} \\ \underbrace{[-\partial_t^2 + \Omega_{k,i}^2]}_{\equiv \Box_{ik}}\,\psi_{k,i} = g_{ik}\,\phi_k \end{cases}$$

Solution:

retarded Green f.: $\Box R = \delta$

$$\psi_{k,i}(t) = \underbrace{\psi^{(0)}_{ki}(t)}_{\text{homogeneous solution.}} + \int dt'\, \overline{R^{(0)}_{ki}}(t',t)\,(g_{ik}\,\phi_k(t'))$$

$$[-\partial_t^2 + \omega_k^2]\,\phi_k = \sum_i g_{ik}\,\psi^{(0)}_{ki} + \sum_i g_{ik} \underbrace{\int dt'\, R^{(0)}_{ki}\, g_{ik}\,\phi_k(t')}_{\text{non local in } t}$$

$\Rightarrow$ expand:

$$\left(= \underline{\lambda(t)}\,\phi_k(t) + \underline{\lambda_1}\,\partial_t\phi_k + \underline{\lambda_2}\,\partial_t^2\phi_k + \underline{\lambda_3}\cdots \right)$$

Even terms: mass^2, wave function r., dispersion

Odd terms: dissipation (generically present).

EOM :

$$\begin{cases} [-\partial_t^2 + \omega_k^2]\,\phi_k = \sum_i g_{i,k}\,\psi_{k,i} \\ \underbrace{[-\partial_t^2 + \Omega_{k,i}^2]}_{\equiv \Box_{ik}}\,\psi_{k,i} = g_{ik}\,\phi_k \end{cases}$$

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Even terms: mass², wave function r., & <u>dispersion</u>

Odd terms: <u>dissipation</u> (generically present).

The general solution: <u>16"</u>

$$\phi_k(t) = \underbrace{\phi^d(t)}_{\text{DECAYING}} + \underbrace{\int dt' \, G_r(t,t') \, \varphi_0(t')}_{\text{DRIVEN}} \quad (1)$$

where

* $\phi^d(t)$: • exponentially decays $e^{-\gamma(t-t_i)}$

• depends on IC on ϕ

* $G_r(t,t')$: the dressed retarded Green f.

$$\Delta_g G_r = \delta(t-t')$$

$$(\Delta_g \phi^d = 0)$$

* the IC of φ_0 are in the <u>driven</u> solution

$$\varphi_0 \doteq \sum_i q_i \, \varphi_i^{(0)}$$

* (1) the <u>exact</u> exp. of the Heisenberg op. $\hat{\phi}_k(t)$

Properties of 2-point functions

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1) The commutator. (odd)

$$G_C(t,t') \doteq Tr\left[\rho_T \left[\phi_k(t), \phi_k(t') \right]_- \right]$$

$$= \left[\phi_k(t), \phi_k(t') \right]_- \text{ : State indep.}$$

$$= \left[\phi^d(t), \phi^d(t') \right]_- + \iint dt_1 dt_2\, G_R G_R \left[\varphi, \varphi \right]_-$$

decays $e^{-\gamma(t+t'-2t_{in})}$

$\parallel$ $D(t_1,t_2)$ (odd)

$\Rightarrow$ for $(t+t'-2t_{in}) \gg \gamma^{-1}$, only the driven solution matters

But $i\partial_t G_C(t,t')\Big|_{t=t'} = 1$ all t all φ

ETC

$\Rightarrow$ the **driven** term provides ALL non-commuting properties of $\phi_H(t)$ at late time.

[14]

Rem: if $\rho_{\phi,in}$, $\rho_{\psi,in}$ gaussian.

$\Rightarrow$ G_c and G_a are the only ϕ-observable block.

$\Rightarrow$ only $\begin{cases} N(t_1,t_2) \\ D(t_1,t_2) \end{cases}$ matter.

$\Rightarrow$ equivalent class.

$\Rightarrow$ How much should be known (imposed) on ψ ?

Fourier analysis

- Suppose 1. g_{ik}, ω_k^2, Ω_{ik}^2 constant.

2. $D = D(t_1 - t_2)$
$N = N(t_1 - t_2)$

$\Rightarrow$ Stationary situation.

$$\Rightarrow \quad \tilde{N}(\omega) = \tilde{D}(\omega)\big(2\underline{n(\omega)}+1\big)\ \mathrm{sign}(\omega)$$

↑ FD

↳ mean occupation number. (thermal state)

$$\Rightarrow \quad \tilde{G}_a(\omega) = \tilde{G}_c(\omega)\ (2n+1)\ \mathrm{sign}(\omega)$$

meaning: the ϕ field has reached equilibrium with its environement

20'

Proof:

$$\tilde{G}_C = |\tilde{G}_{ret}(\omega)|^2 \, \tilde{D}$$

$$\tilde{G}_A = |\tilde{G}_{ret}(\omega)|^2 \, \tilde{N}$$

(when the decaying parts can be neglected)

$\Rightarrow$ 2 consequences.

1. in the (true) vacuum : $m = 0$,

$$\Rightarrow \tilde{G}_c(\omega) = \tilde{G}_A(\omega)\ \mathrm{sign}(\omega)$$

$$\Rightarrow \tilde{G}_W(\omega) = \tilde{G}_c + \tilde{G}_A$$

$$= \tilde{G}_c\ \theta(\omega)$$

only positive frequency.

(• non perturbative in g^2)

$$S_T = \int d^3k \; \underbrace{S_T(k)}$$

2. this obtains for ALL
but φ obeying the vacuum FD)

φ cannot be
stochastic variable

(not even a cocktail of
Quantum and classical ones)

But. $\hat{\varphi} = \sum_i g_i \, \hat{\varphi}_i^{(0)}$ can be
any composite operator
made of canon. $\{\hat{x}_j\}$

linearity not necessary!

but φ obeying the vacuum F]

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⇒ • Ψ_i cannot be stochastic variables

(nor even a coktail of Quantum and classic. ones.)

But. $\hat{\Psi} = \sum_i g_i \hat{\Psi}_i^{(0)}$ can be any composite operator made of canon. $\{\hat{x}_j\}$

linearity not necessary !

Rem: when $\hat{\Psi}$ is composite,

- $\Sigma(\omega, k)$ = series in g^2
- higher order correlation functions $\neq 0$.
- $\tilde{G}_a = \tilde{G}_c \, (2n+1) \, \mathrm{sign}(\omega)$

  still exact.

The limit : $g^2 t_{in} \to \infty$ (1) (22')

followed by : $g^2 \to 0$ (2).

(1) implies that only the driven part remains.

$\Rightarrow \hat{\phi}_k$ is a composite op. in Ψ_0 Hilbert space.

(2) the free limit aplied to this compos. op.

• one has $\begin{cases} \tilde{N} \propto g^2 \to 0 \\ \tilde{R} \propto g^2 \to 0 \end{cases}$

• But $\begin{cases} \tilde{G}_c = |\tilde{\varphi}_{out}|^2 \tilde{\Sigma} \to \frac{1}{2\omega_k} \\ \tilde{G}_{ac} = |\tilde{\varphi}_{out}|^2 \tilde{N} \to \frac{2n_\omega + 1}{2\omega_k} \end{cases}$

i.e. the USUAL values of $\tilde{G}$ for free modes

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i.e. the [illegible] values of $\tilde{G}$ for free modes.

$\Rightarrow \hat{\phi}_k$, composite op., behaves

as if it possesses its own Hilbert … !

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i.e. the USUAL values of $\tilde{G}$ for free modes.

$\Longrightarrow$ $\hat{\phi}_k$, composite op., behaves as if it possesses its own Hilbert space!

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i.e. the <u>USUAL</u> values of $\tilde{G}$ for free modes.

$\Rightarrow \hat{\phi}_{\vec{k}}$, composite op., behaves as if it possesses its <u>own Hilbert space</u>!

• Implication

by analyzing $\hat{\phi}$-observables

we have no access

to the $\hat{\phi}$-constituents $\{\hat{\chi}_i\}$

in this limit.

• Remark:

to get $\mathrm{Im}\,\Sigma \neq 0$, a dense

set of φ_i is needed.

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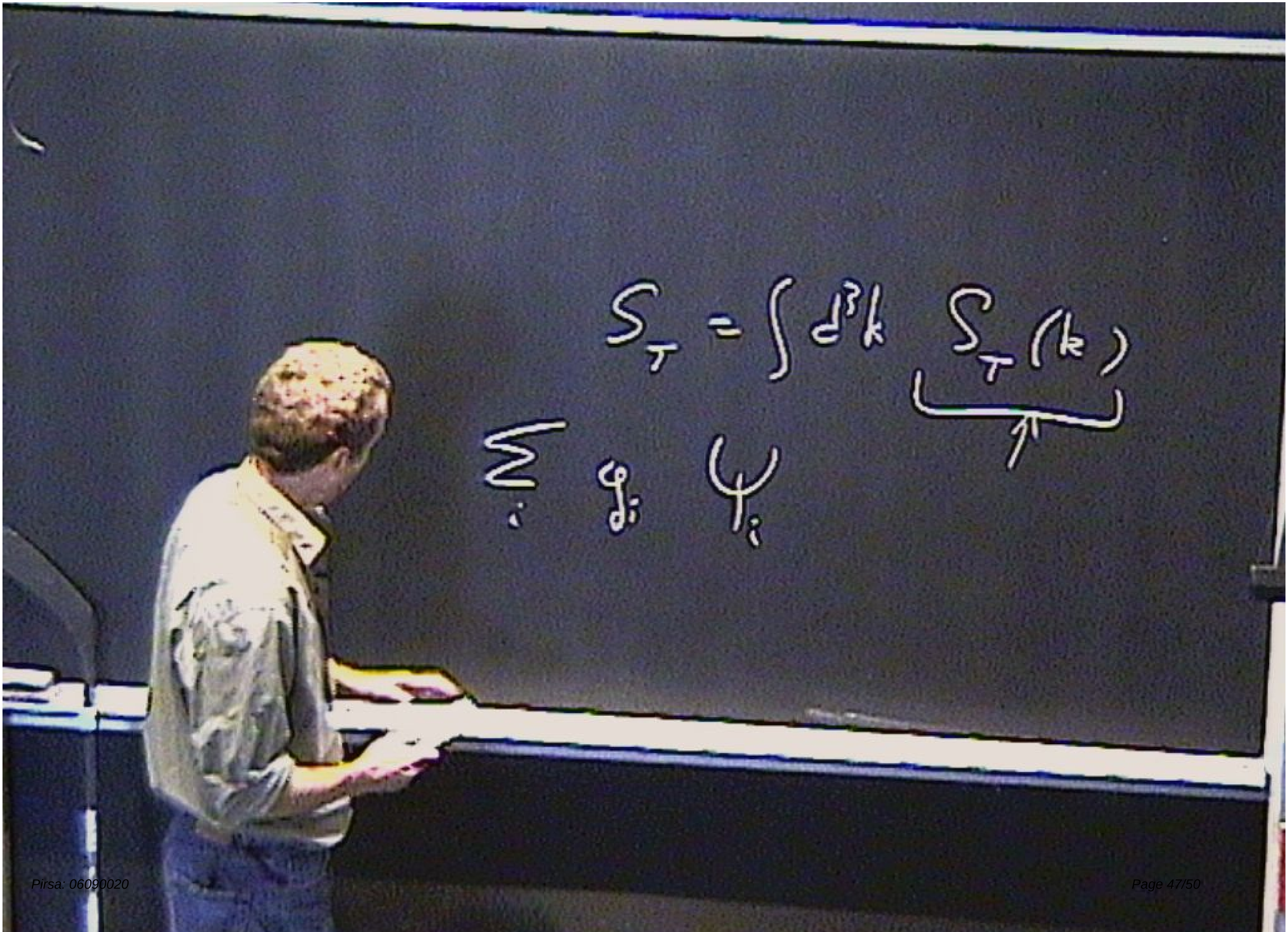
• ——— •

• Remark:

to get $\mathrm{Im}\,\Sigma \neq 0$, a dense
set of φ_i is needed.

$\Longrightarrow \sum_i \varphi_i \rightarrow \int dy\, \varphi(y)$

"extra dimension" Brane World Scenario.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$$\sum_i g_i \, \psi_i$$

$$\int dy \; \psi(y)$$

The basic G_F : $\tilde{G}_{ret}$. 23

• it obeys :

$$\left[-\omega^2 - \underbrace{2i\gamma_k\omega}_{\mathrm{Im}\,\tilde{\Sigma}_{ret}(\omega)} + \omega_k^2 \right] \tilde{G}_{ret}(\omega) = 1$$

• Analytic with two roots :

$$\omega_\pm = -i\gamma_k \pm \sqrt{\omega_k^2 - \gamma^2} \quad \in \mathrm{Im}^-$$

$\gamma_k = g^2/4 > 0$

• overdamped for $\omega_k < \gamma_k$
underdamped for $\omega_k > \gamma_k$

The basic G_F : G_{ret}.

• it obeys :

$$[-\omega^2 - \underbrace{2i\gamma_k\omega}_{\mathrm{Im}\,\tilde{\Sigma}_{ret}(\omega)} + \omega_k^2]\, \tilde{G}_{ret}(\omega) = 1$$

• Analytic with two roots :

$$\omega_\pm = -i\gamma_k \pm \sqrt{\omega_k^2 - \gamma^2} \qquad \in \mathrm{Im}^-$$

$$\gamma_k = g^2/4 > 0$$

• overdamped for $\omega_k < \gamma_k$

underdamped for $\omega_k > \gamma_k$

" $\rightarrow$ as g increases "