

Title: Soft photons, gravitons, and their quantum information content

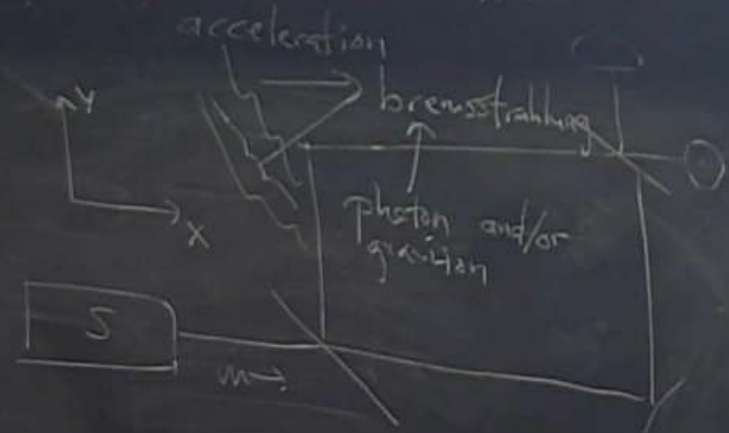
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URL: <http://pirsa.org/18060003>

Abstract:

In brief

$$|p, \hat{x}\rangle \rightarrow \frac{1}{\sqrt{2}} |p, \hat{x}\rangle + \int_{\text{rad}} \lambda_{\text{rad}} |p, \hat{y}, \text{rad}\rangle$$

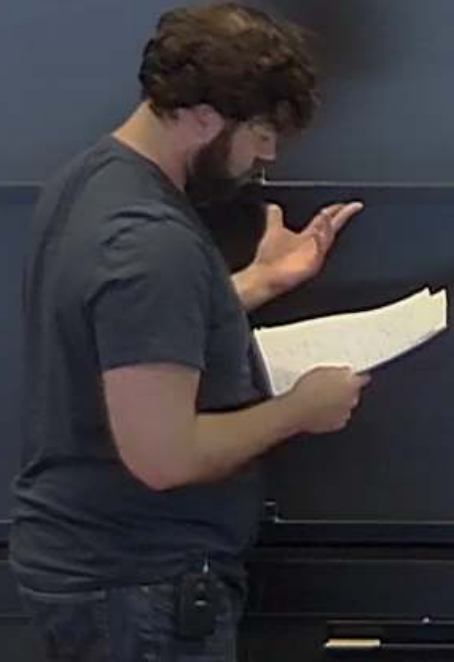


Radiation: massless

- can radiate arb. large # quanta (arb. small energy each)

IR catastrophe

- $E_{\text{detector}} > 0 \Rightarrow$ can't detect rad
 - \Rightarrow since
 - \Rightarrow decohere massive "local" particles

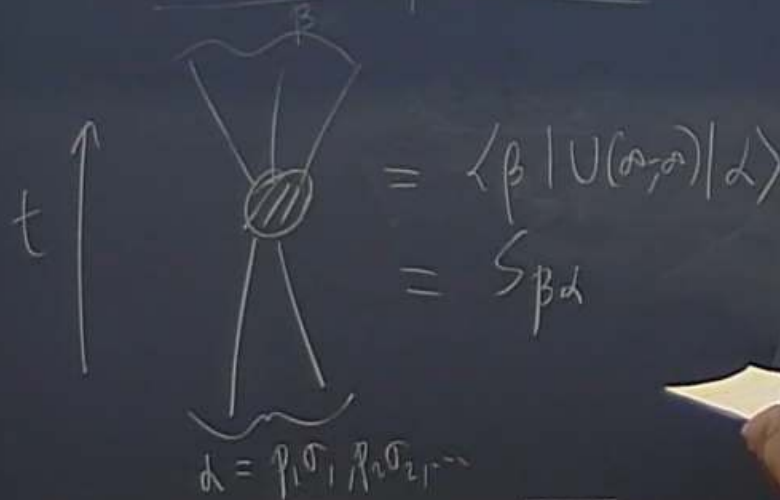


IR catastrophe

- $E_{\text{detector}} > 0 \Rightarrow$ can't detect and
 - \Rightarrow trace
 - \Rightarrow decohere massive "hard" particles

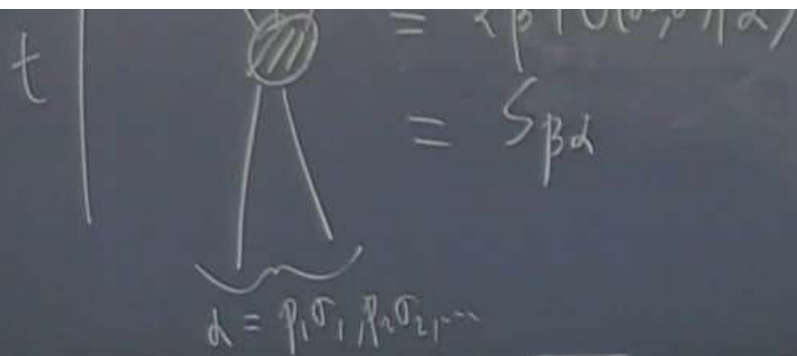
IR catastrophe redux

(Bloch-Nordsieck QED
Lambert Pert. grav)



$$= \langle \beta | U(\infty, -\infty) | d \rangle$$

$$= \int_{\beta, d}$$



λ = IR regulator (IR)

 goal $\lambda \rightarrow 0$ at end

 Λ = define virtual soft

 E = define soft emitted (detector resolution)

 ~~$\lambda < \Lambda$~~

 ~~$\lambda > E$~~

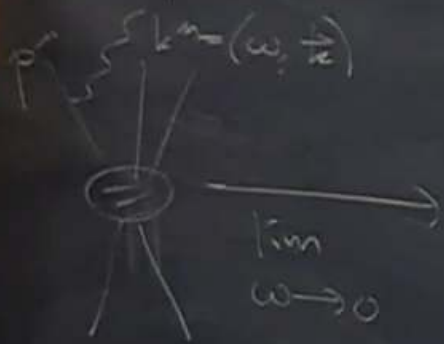
Radiation is massless

- can radiate arb. large # quanta (arb. small energy each)

IR catastrophe

- $E_{\text{detector}} > 0 \rightarrow$ can't detect rad
 - \Rightarrow divergence
 - \Rightarrow decohere massive "hard" particles

Soft theorem



photon

$$\left(\frac{e p^\mu \cdot \epsilon_\nu(k)}{p \cdot k} \right)$$

graviton

$$\text{or } \left(\frac{p^\mu p^\nu \epsilon_{\mu\nu}}{M_{\text{pl}}^2 p \cdot k} \right)$$

poles as $\omega \rightarrow 0$

Soft thms \Rightarrow return all soft contributions

$$\sum_{\text{loops w/ } \lambda \text{ and } \Lambda} = \underbrace{\int \beta d}_{\text{no IR loop}} + \left(\frac{\lambda}{\Lambda} \right)^{A+B}$$

$$(EM) \quad A = \sum_{n,m} e_n e_m \gamma_n \gamma_m f_{nm}(\beta_{nm}) \geq 0$$

inward particles

+1 inc.
-1 out.

relative velocity

$$\Rightarrow \int_{\beta < 0} \rightarrow 0$$

$$(GR) \quad B = \sum_{nm} \frac{m_n m_m}{M_p} \gamma_n \gamma_m g_{nm}(\beta_{nm}) \geq 0 \quad (IR \text{ catastrophe})$$

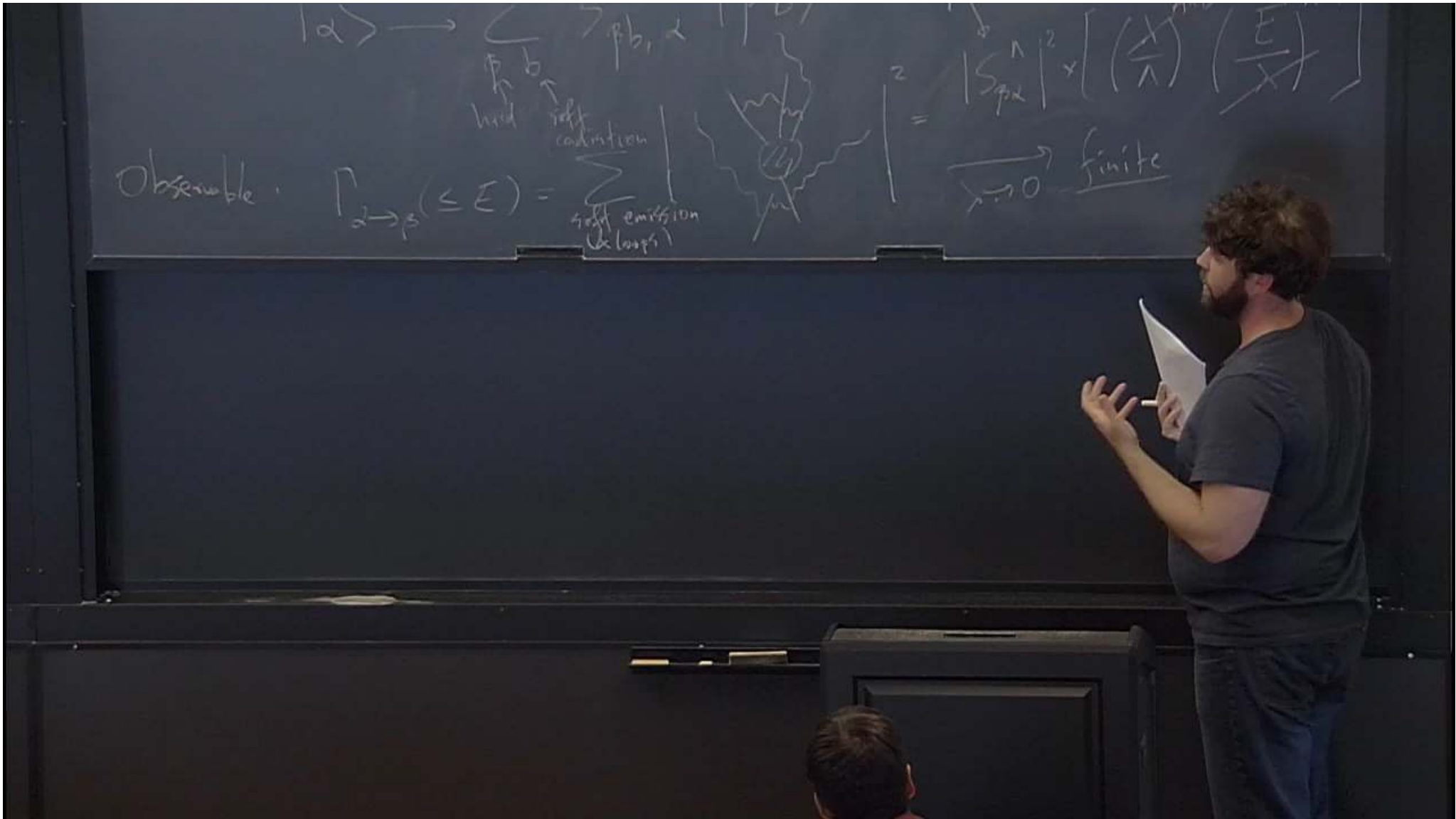
Solution: finite energy resolution \rightarrow should include soft emission

• Form inclusive quantities

$$|\alpha\rangle \rightarrow \sum_{\beta} S_{\beta, \alpha} |\beta\rangle$$

β
 \downarrow
hard

b
 \downarrow
soft
radiation




$|\alpha\rangle \rightarrow \left[\begin{array}{c} \text{photon } a \\ \text{photon } b \\ \text{soft radiation} \end{array} \right] \rightarrow \text{photon } a, b$

Observable: $\Gamma_{\alpha \rightarrow \beta}(\leq E) = \sum_{\text{soft emission (loops)}} \dots$

$\left| \sum_{\text{photon}} \right|^2 \times \left[\left(\frac{E}{\Lambda} \right) \left(\frac{E}{\Lambda} \right) \right]$

$\xrightarrow{\Lambda \rightarrow 0} \text{finite} \left(\text{factor } \frac{E}{\Lambda} \right)^{A+B}$



Decoherence What does this say about DM?

$$\rho = |\alpha\rangle\langle\alpha| \rightarrow \sum_{\substack{p,p' \\ b,b'}} S_{p,b|\alpha} S_{p',b'|\alpha}^* |p,b\rangle\langle p',b'|$$

trace
soft

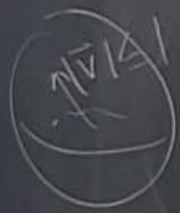
$$\sum_{p,p'} S_{p,\alpha}^\Lambda (S_{p',\alpha}^\Lambda)^* f_{p,p'|\alpha}(E,\Lambda) r_\lambda$$

$\Delta A + \Delta B$

Observable: $\Gamma_{\alpha \rightarrow \beta}(\leq E) = \sum_{\text{soft emission (loops)}} \dots \xrightarrow{\lambda \rightarrow 0} \text{finite} \left(\frac{E}{\lambda} \right)^{A+B}$

• What superpositions β, β' survive $\lambda \rightarrow 0$?

• Basically nothing. For each \vec{v} , let

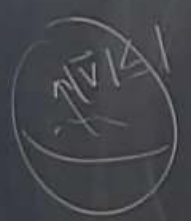


$$j_{\vec{v}}^{\text{EM}} = \sum_{\text{species}} e_i a_{\vec{v}}^+ a_{\vec{v}}^- = \text{total electric charge coming out w/ velocity } \vec{v}$$

$$j_{\vec{v}}^{\text{GR}} = \sum_i m_i a_{\vec{v}}^+ a_{\vec{v}}^- = \text{total mass}$$

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Thm: $\lim_{\lambda \rightarrow 0} \rho_{\text{hard}} \neq 0$ iff $\rho \equiv \rho'$ $\forall \rho$.

outgoing state:

$\rho \sim$

$$\begin{pmatrix} |S_{p\lambda}|^2 \left(\frac{\epsilon}{\lambda}\right) & 0 & 0 \\ 0 & |S_{l\lambda}|^2 \left(\frac{\epsilon}{\lambda}\right) & 0 \\ 0 & 0 & \dots \\ & & S_{12}^2 \left(\frac{\epsilon}{\lambda}\right) \end{pmatrix}$$

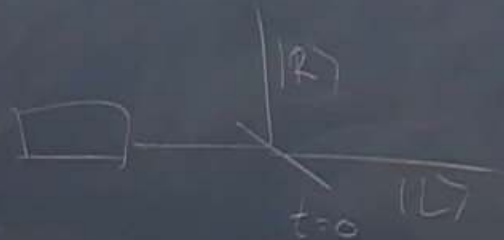
mostly diagonal



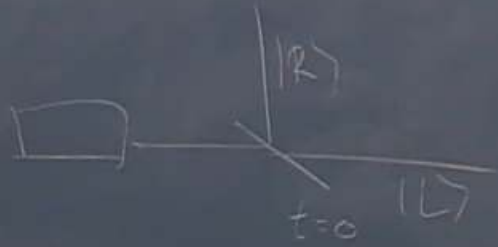
soft ρ_{soft} ρ_{hard}

Remarks

- Real life: (LHC): finite time T cuts off radiation spectrum.



$$P_{\text{LR}}(T) \sim P_{\text{LR}}(0) e^{-\left\{ \left(\frac{p}{M_{\text{Pl}} c} \right)^2 + \alpha^2 \right\} \ln(m c^2)}$$



$$\rho_{ER}(T) \sim \rho_{LR}(0) e^{\left\{ \left(\frac{p}{M_p c} \right)^2 + \alpha^2 \right\} \ln \left(\frac{m c^2 T}{\hbar} \right)}$$

nearly = 1 realistic

$$M_p c \sim \text{kg m/s}$$



$\int \vec{v}$ species

coming out w/ velocity?

$$j_{GR}^{\vec{v}} = \sum_i E_i \vec{a}_i^{\vec{v}} \vec{a}_i^{\vec{v}} = \text{total mass}$$

$M_{\text{pl}} c \approx 2.4 \times 10^{22} \text{ kg}$

Black hole info loss (cf. Strominger)

Make BH: $|+\rangle \rightarrow$ (Hawking) (thermal)

\rightarrow (Strominger) $\sum_n c_n |n\rangle |n\rangle$
soft hard

s.t. trace soft \rightarrow (hard) (thermal) (?)