Title: PSI 2015/2016 Relativity - Neil Turok - Lecture 9

Date: Sep 18, 2015 09:00 AM

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Abstract:

Gravitational waves

$R = 2R \Rightarrow R = 0$

$R_{\mu\nu} = \frac{1}{2} g_{\mu\nu} R$

Vacuum Einstein equations (ignore Λ) : $G_{\mu\nu} = 0 \Rightarrow R_{\mu\nu} = 0$

to linear order in $h_{\mu\nu}$,

$$R_{\mu\nu} = \frac{1}{2}\left(h^{\sigma}_{\nu,\rho\sigma} - h_{\mu\nu,}{}^{\sigma}{}_{\sigma} - h^{\sigma}{}_{\sigma,\rho\nu} - h_{\rho\sigma,}{}^{\sigma}{}_{\nu}\right)$$

$$= \frac{1}{2}\left(-\Box h_{\rho\nu} + h^{\sigma}_{\nu,\rho\sigma} + h^{\sigma}_{\rho,\nu\sigma} - h^{\sigma}{}_{\sigma,\rho\nu}\right)$$

$$\left(h^{\sigma}_{\nu,\sigma} - \tfrac{1}{2} h^{\sigma}_{\sigma,\nu}\right)_{,\rho} + \left(h^{\sigma}_{\rho,\sigma} - \tfrac{1}{2} h^{\sigma}_{\sigma,\rho}\right)_{,\nu}$$

$\eta^{\sigma\alpha}\partial_\alpha\partial_\nu = \partial^{\sigma}\partial_{\sigma} = \Box$ (Minkowski)

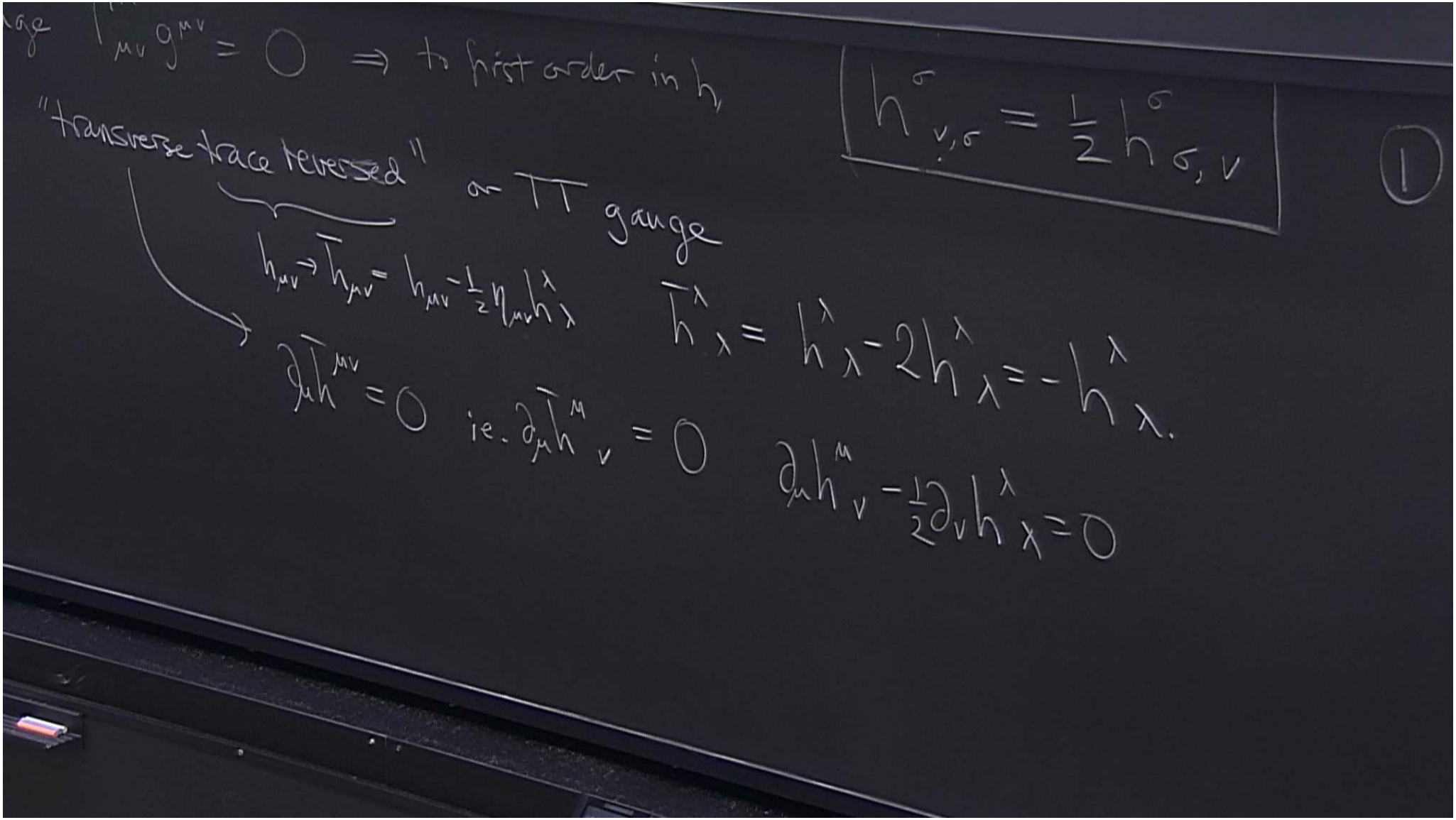
(Minkowski)

$$\left(h^{\sigma}_{\nu\sigma}-\tfrac{1}{2}h^{\sigma}_{\sigma,\nu}\right)_{,\rho}+\left(h^{\sigma}_{\rho\sigma}-\tfrac{1}{2}h^{\sigma}_{\sigma,\rho}\right)_{,\nu}$$

harmonic gauge $\Gamma^{\lambda}_{\mu\nu}g^{\mu\nu}=0 \Rightarrow$ to first order in h $\quad \boxed{h^{\sigma}_{\nu,\sigma}=\tfrac{1}{2}h^{\sigma}_{\sigma,\nu}}$ (1)

"transverse trace reversed" or TT gauge

$h_{\mu\nu}\to\bar{h}_{\mu\nu}=h_{\mu\nu}-\tfrac{1}{2}\eta_{\mu\nu}h^{\lambda}_{\lambda}$ $\quad \bar{h}^{\lambda}_{\lambda}=h^{\lambda}_{\lambda}-2h^{\lambda}_{\lambda}=-h^{\lambda}_{\lambda}$.


$\Gamma^{\lambda}_{\mu\nu} g^{\mu\nu} = 0 \Rightarrow$ to first order in h
$h^{\sigma}_{\nu;\sigma} = \frac{1}{2} h^{\sigma}_{\sigma,\nu}$
(1)
"transverse trace reversed" or TT gauge
$h_{\mu\nu} \to \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h^{\lambda}_{\lambda}$
$\bar{h}^{\lambda}_{\lambda} = h^{\lambda}_{\lambda} - 2h^{\lambda}_{\lambda} = -h^{\lambda}_{\lambda}$.
$\partial_\mu \bar{h}^{\mu\nu} = 0$ ie. $\partial_\mu \bar{h}^{\mu}_{\nu} = 0$
$\partial_\mu h^{\mu}_{\nu} - \frac{1}{2}\partial_\nu h^{\lambda}_{\lambda} = 0$

$\eta^{\sigma\alpha}\partial_\alpha\partial_\sigma = \partial^\sigma\partial_\sigma = \Box$ (Minkowski)

$= \frac{1}{2}\left(-\Box h_{\rho\nu} + h^{\sigma}_{\nu,\rho\sigma} + h^{\sigma}_{\rho,\nu\sigma} - h^{\sigma}_{\sigma,\rho\nu}\right)$

$\left(h^{\sigma}_{\nu,\sigma} - \frac{1}{2}h^{\sigma}_{\sigma,\nu}\right)_{,\rho} + \left(h^{\sigma}_{\rho,\sigma} - \frac{1}{2}h^{\sigma}_{\sigma,\rho}\right)_{,\nu}$

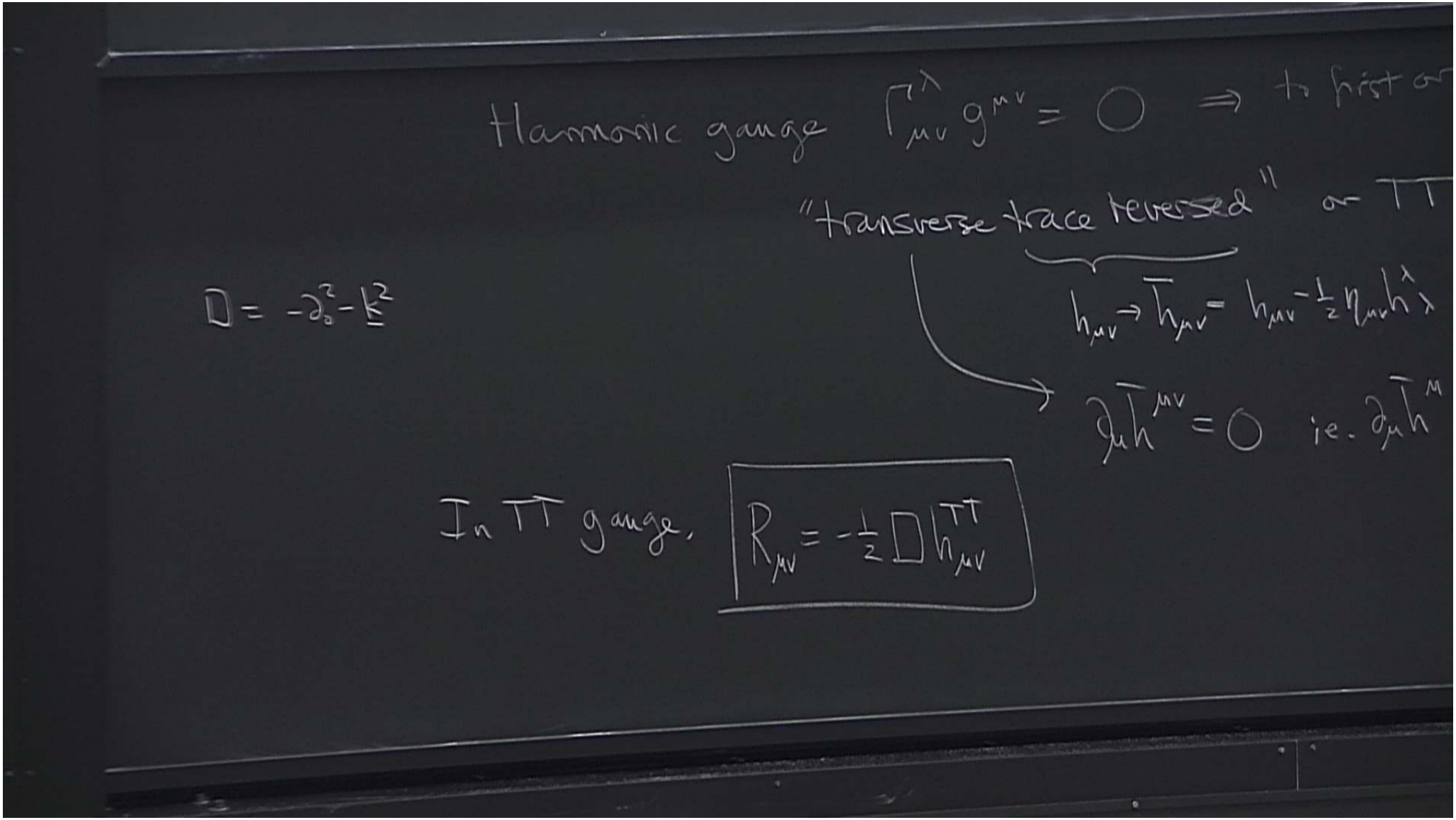
harmonic gauge $\Gamma^{\lambda}_{\mu\nu}g^{\mu\nu} = 0 \Rightarrow$ to first order in h $\boxed{h^{\sigma}_{\nu,\sigma} = \frac{1}{2}h^{\sigma}_{\sigma,\nu}}$ (1)

"transverse trace reversed" or TT gauge

$h_{\mu\nu} \to \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^{\lambda}_{\lambda}$ $\quad \bar{h}^{\lambda}_{\lambda} = h^{\lambda}_{\lambda} - 2h^{\lambda}_{\lambda} = -h^{\lambda}_{\lambda}$.

$\partial_\mu\bar{h}^{\mu\nu} = 0$ ie. $\partial_\mu\bar{h}^{\mu}_{\nu} = 0$ $\quad \partial_\mu h^{\mu}_{\nu} - \frac{1}{2}\partial_\nu h^{\lambda}_{\lambda} = 0$

In TT gauge. $\boxed{R_{\mu\nu} = -\frac{1}{2}\Box h^{TT}_{\mu\nu}}$


Harmonic gauge $\Gamma^{\lambda}_{\mu\nu} g^{\mu\nu} = 0 \Rightarrow$ to first or
"transverse trace reversed" or TT
$\Box = -\partial_0^2 - \underline{k}^2$
$h_{\mu\nu} \to \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h^{\lambda}{}_{\lambda}$
$\partial_\mu \bar{h}^{\mu\nu} = 0$ ie. $\partial_\mu \bar{h}^{\mu}$
In TT gauge, $R_{\mu\nu} = -\frac{1}{2}\Box h^{TT}_{\mu\nu}$

$\epsilon_{\mu\nu}(\underline{k})\, e^{ik\cdot x} + \epsilon^{*}_{\mu\nu}(\underline{k})\, e^{-ik\cdot x}\Big)$

$k\cdot x = k_\mu x^\mu = k_0 x^0 + \underline{k}\cdot\underline{x}$

$= -k^0 x^0 + \underline{k}\cdot\underline{x}$

$\partial_\mu \to ik_\mu$ or $-ik_\mu$

$\Box = 0 \Rightarrow k^2 = \underline{k}^2 \Rightarrow k^0 = |\underline{k}|$

$\Rightarrow \quad k_\mu \epsilon^\mu{}_\nu = \frac{1}{2} k_\nu \epsilon^\mu{}_\mu$

$\epsilon_{\mu\nu}$ $10 - 4 = 6$ free parameters?

$\Longrightarrow$ waves travelling at c

general solution $h_{\mu\nu}(x^\alpha) = \sum_{\underline{k}} \left(\epsilon_{\mu\nu}(\underline{k})\, e^{ik.x} + \epsilon^*_{\mu\nu}(\underline{k}) \right)$

$\Box x^\mu = 0$ gauge conditions : $\partial_\mu \to ik_\mu$ or $-ik_\mu$

$$① \Rightarrow \quad k_\mu \epsilon^\mu{}_\nu = \frac{1}{2} k_\nu \epsilon^\mu{}_\mu$$

remaining gauge freedom $x'^\mu = x^\mu + \epsilon^\mu(x)$, with $\Box \epsilon^\mu = 0$.

$$\mathcal{L}_\epsilon : \quad h'_{\mu\nu} = h_{\mu\nu} - \epsilon_{\mu,\nu} - \epsilon_{\nu,\mu}$$

$$\sum_{\underline{k}} \left(\epsilon_{\mu\nu}(\underline{k})\, e^{ik\cdot x} + \epsilon^{*}_{\mu\nu}(\underline{k})\, e^{-ik\cdot x} \right)$$

$k\cdot x = k_\mu x^\mu = k_0 x^0 + \underline{k}\cdot\underline{x}$

$= -k^0 x^0 + \underline{k}\cdot\underline{x}$

$\Box = 0 \Rightarrow k^2 = \underline{k}^2 \Rightarrow k^0 = |\underline{k}|$

$\partial_\mu \to ik_\mu$ or $-ik_\mu$

$\epsilon_{\mu\nu}$ $10 - 4 = 6$ free parameters?

$① \Rightarrow k_\mu \epsilon^\mu{}_\nu = \frac{1}{2} k_\nu \epsilon^\mu{}_\mu$

, with $\Box \epsilon^\mu = 0$.

$-\epsilon_{\nu\mu}$: $①' \; - \epsilon^\sigma{}_{\nu,\sigma} - \epsilon_{\nu,\sigma}{}^\sigma = - \epsilon^\sigma{}_{;\sigma\nu} \Rightarrow ①$ still valid if $\epsilon_{\nu,\sigma}{}^\sigma = 0$ ie. $\Box \epsilon_\nu = 0$,

order in h and ϵ)

$\Rightarrow$ waves travelling at c

general solution $h_{\mu\nu}(x^\alpha) = \sum_{\underline{k}} \left(\epsilon_{\mu\nu}(\underline{k}) e^{ik\cdot x} + \epsilon^*_{\mu\nu}(\underline{k}) \right.$

$\Box x^\mu = 0$ gauge conditions : $\partial_\mu \to ik_\mu$ or $-ik_\mu$

$① \Rightarrow \quad k_\mu \epsilon^\mu{}_\nu = \frac{1}{2} k_\nu \epsilon^\mu{}_\mu$

remaining gauge freedom $x'^\mu = x^\mu + \epsilon^\mu(x)$, with $\Box \epsilon^\mu = 0$.

$\mathcal{L}_\epsilon$: $h'_{\mu\nu} = h_{\mu\nu} - \epsilon_{\mu,\nu} - \epsilon_{\nu,\mu}$: $①' - \epsilon^\sigma{}_{,\nu\sigma} - \epsilon_{\nu,\sigma}{}^\sigma$

(to linear order in h and ϵ)

takes $\epsilon_{\mu\nu}(k)$ to

$\epsilon_{\mu\nu}(k) + k_\nu C_\mu(k)$

so we really have

$10 - 4 - 4 = 2$ remaining gauge invariant massless waves

(to linear order in h and ϵ)

Choose $\epsilon_\mu = \sum_{\underline{k}} \left(i C^\mu(\underline{k}) e^{ik.x} - i C^{*\mu}(\underline{k}) e^{-ik.x} \right)$

then, a harmonic coord transformation $x'^\mu \to x^\mu + \epsilon^\mu$, takes $\epsilon_{\mu\nu}(\underline{k})$

$$\epsilon'_{\mu\nu}(\underline{k}) = \epsilon_{\mu\nu}(\underline{k}) + k_\mu C_\nu(\underline{k}) + k_\nu C_\mu(\underline{k})$$

Explicitly, let us choose $\underline{k}$ to be in the z direction : $k^\mu = (k, 0, 0, k)$

(every other wave related by a rotation)

(to linear order in h and ϵ)

$$C^{\mu}(k)\, e^{ik\cdot x} - i\, C^{*\mu}(k)\, e^{-ik\cdot x}\Big)$$

coord transformation $x'^{\mu} \to x^{\mu} + \epsilon^{\mu}$, takes $\epsilon_{\mu\nu}(k)$ to

$$\epsilon'_{\mu\nu}(k) = \epsilon_{\mu\nu}(k) + k_{\mu} C_{\nu}(k) + k_{\nu} C_{\mu}(k)$$

so we really have

$10 - 4 - 4 = 2$ rema

be in the z direction : $k^{\mu} = (k, 0, 0, k)$

invariant massless wa

ated by a rotation) $k_{\mu} = (-k, 0, 0, k)$

$$k^\mu \epsilon_{\mu\nu} = \frac{1}{2} k_\nu \epsilon^\mu{}_\mu$$

$\nu = 0$ $\quad k(\epsilon_{00} + \epsilon_{30}) = -\frac{1}{2} k(-\epsilon_{00} + \epsilon_{11} + \epsilon_{22} + \epsilon_{33})$

3 $\quad k(\epsilon_{03} + \epsilon_{33}) = +\frac{1}{2} k(\quad\quad 11 \quad\quad)$

1 $\quad k(\epsilon_{01} + \epsilon_{31}) = 0$

2 $\quad k(\epsilon_{02} + \epsilon_{32}) = 0$

$\epsilon_{00} + \epsilon_{11} + \epsilon_{22} + \epsilon_{33}$) A

11) B

$\epsilon_{01} = -\epsilon_{31}$

$\epsilon_{02} = -\epsilon_{32}$

A+B $\epsilon_{03} = -\frac{1}{2}(\epsilon_{00} + \epsilon_{33})$

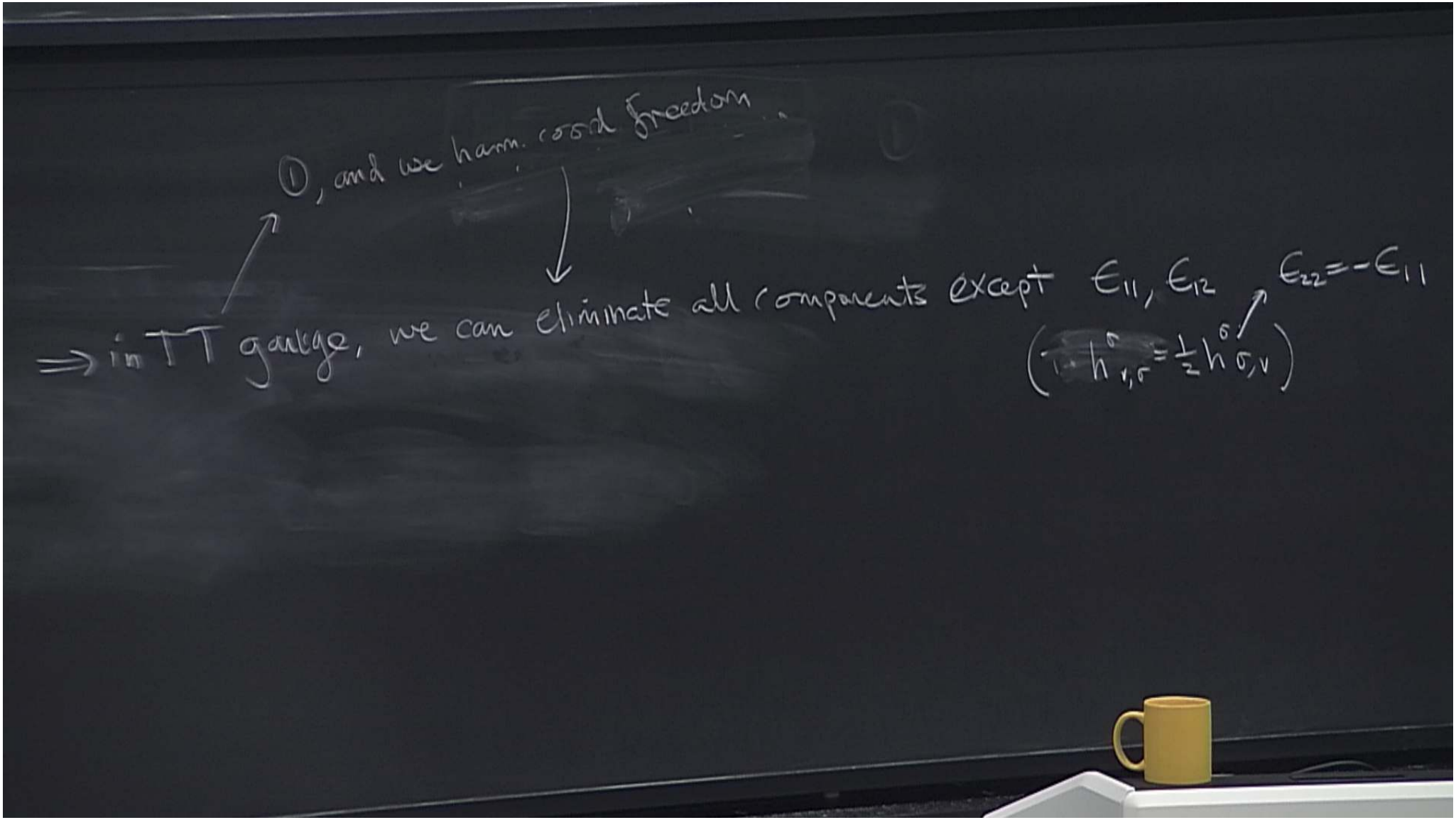
A-B $\epsilon_{22} = -\epsilon_{11}$

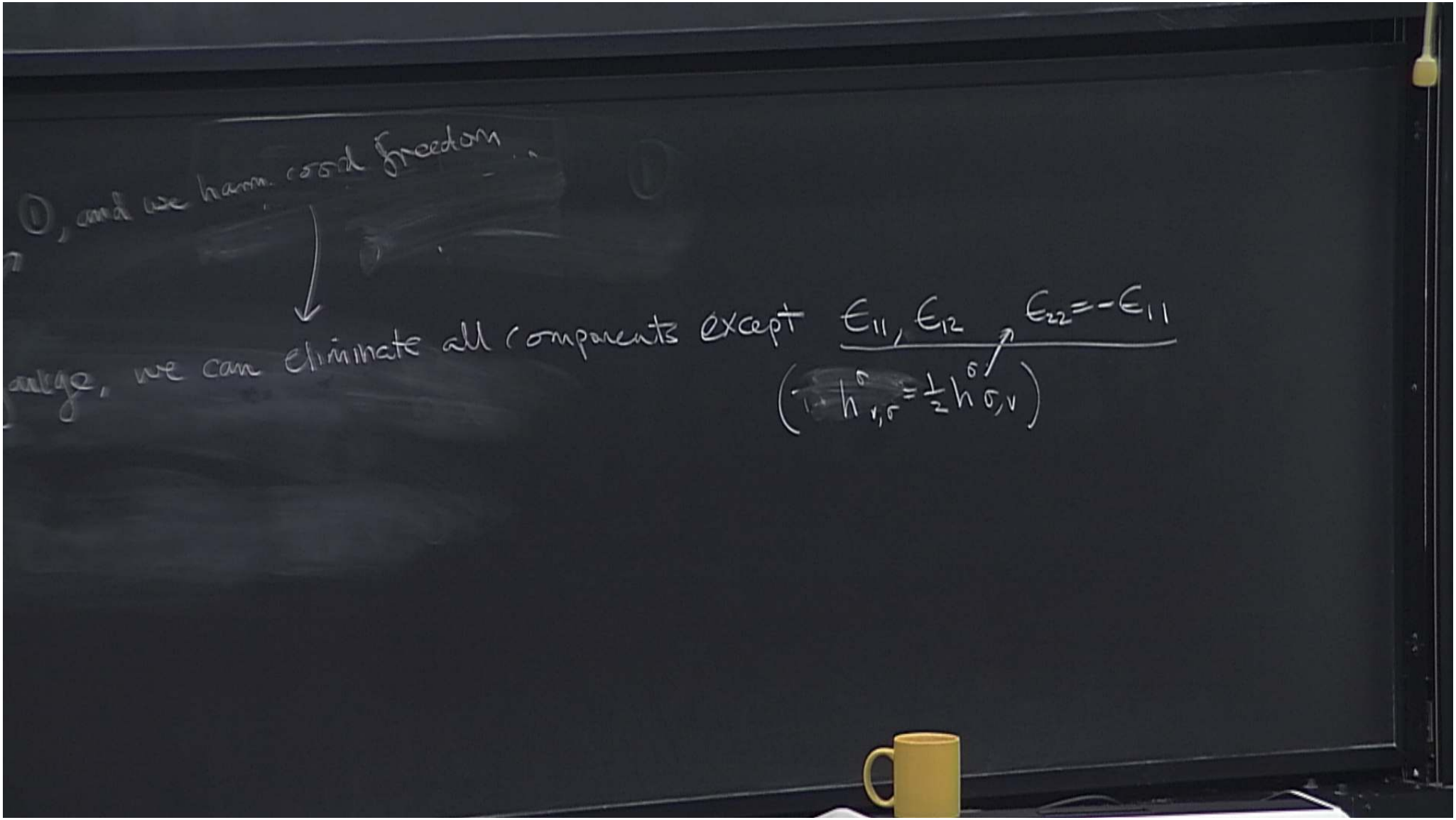
} eliminates $\epsilon_{01}, \epsilon_{02}, \epsilon_{03}, \epsilon_{22}$

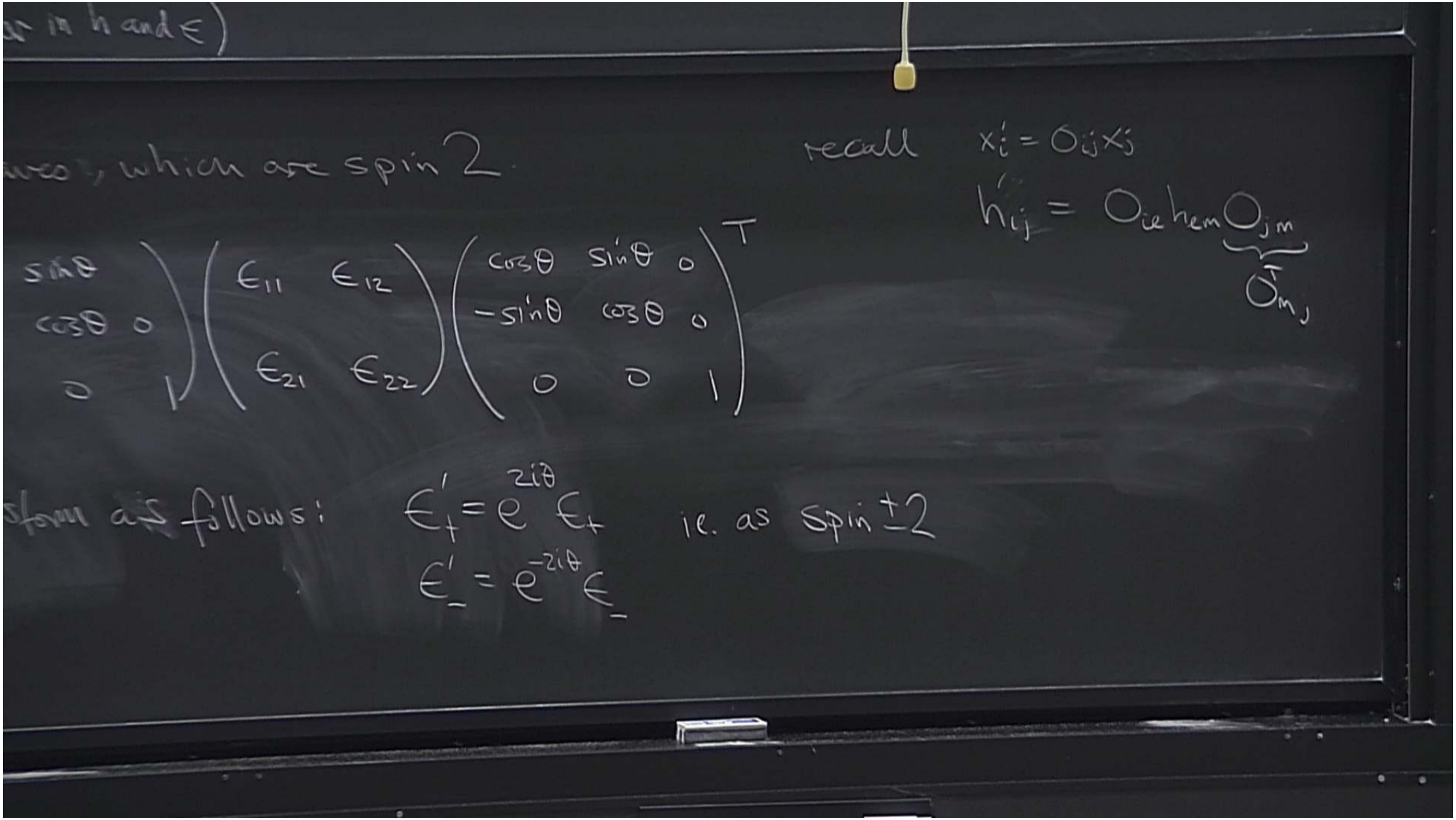
harmonic coordtrans.

$$\epsilon'_{\mu\nu} = \epsilon_{\mu\nu} + k_\mu C_\nu + k_\nu C_\mu$$

$$\left.\begin{aligned}
\epsilon'_{00} &= \epsilon_{00} - 2kC_0 \\
\epsilon'_{13} &= \epsilon_{13} + kC_1 \\
\epsilon'_{23} &= \epsilon_{23} + kC_2 \\
\epsilon'_{33} &= \epsilon_{33} + 2kC_3 \\
\epsilon'_{11} &= \epsilon_{11} \\
\epsilon'_{12} &= \epsilon_{12}
\end{aligned}\right\}$$ set these zero.


① , and we harm. coord freedom
⇒ in TT gauge, we can eliminate all components except $\epsilon_{11}, \epsilon_{12}$ $\epsilon_{22} = -\epsilon_{11}$
$h^0_{i,0} = \frac{1}{2} h^0_{0,i}$


0, and we have coord freedom
antge, we can eliminate all components except $\epsilon_{11}, \epsilon_{12}$ $\epsilon_{22} = -\epsilon_{11}$
$h^{\sigma}_{\mu,\sigma} = \frac{1}{2} h^{\sigma}_{\sigma,\nu}$


s in h and ϵ)
which are spin 2
recall $x_i' = O_{ij} x_j$
$h_{ij}' = O_{ie} h_{em} \underbrace{O_{jm}}_{O^T_{mj}}$
$\begin{pmatrix} \sin\theta & & \\ \cos\theta & 0 & \\ 0 & & 1 \end{pmatrix} \begin{pmatrix} \epsilon_{11} & \epsilon_{12} \\ \epsilon_{21} & \epsilon_{22} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}^T$
sform as follows: $\epsilon_+' = e^{2i\theta} \epsilon_+$ i.e. as spin ± 2
$\epsilon_-' = e^{-2i\theta} \epsilon_-$

spin 2.

recall $x_i' = O_{ij} x_j$

$h_{ij}' = O_{ie} h_{em} \underbrace{O_{jm}}_{O^T_{mj}}$

$$\begin{pmatrix} \epsilon_{12} \\ \epsilon_{22} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}^T$$

$\epsilon_+' = e^{2i\theta} \epsilon_+$

$\epsilon_-' = e^{-2i\theta} \epsilon_-$

i.e. as spin ± 2 components of a massless d.o.f. with helicity 2.

(to linear order in h and ϵ)

reedom describe transverse tensor waves, which are spin 2

about the z axis $\quad \epsilon'_{ij} = \begin{pmatrix} \cos\theta & \sin\theta & \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \epsilon_{11} & \epsilon_{12} \\ \epsilon_{21} & \epsilon_{22} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}^T$

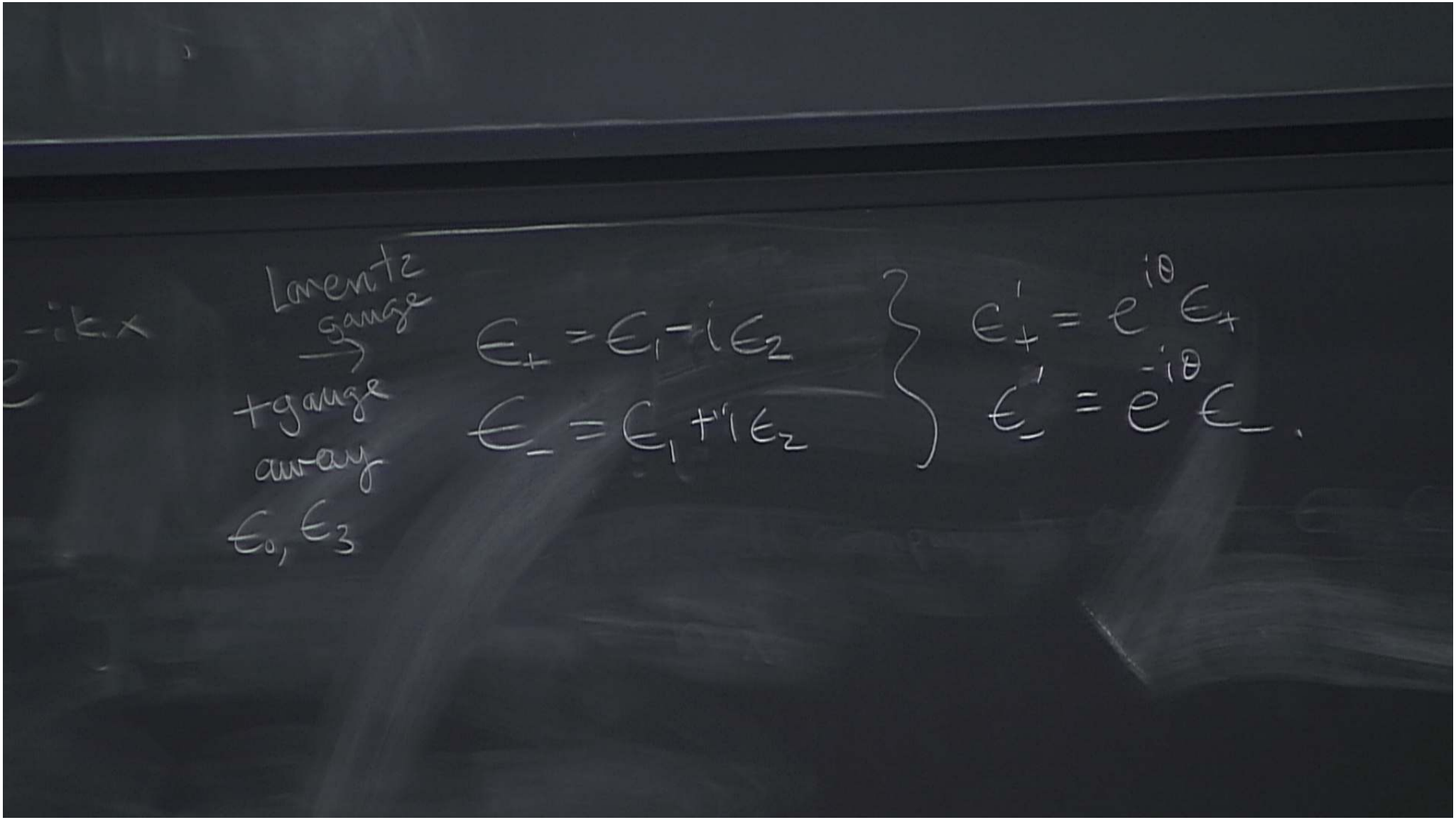
$\Rightarrow$ Show that $\epsilon_+ = \epsilon_{11} - i\epsilon_{12}$, $\epsilon_- = \epsilon_{11} + i\epsilon_{12}$ transform as follows: $\epsilon'_+ = e^{2i\theta}\epsilon_+$, $\epsilon'_- = e^{-2i\theta}\epsilon_-$ i.e. a

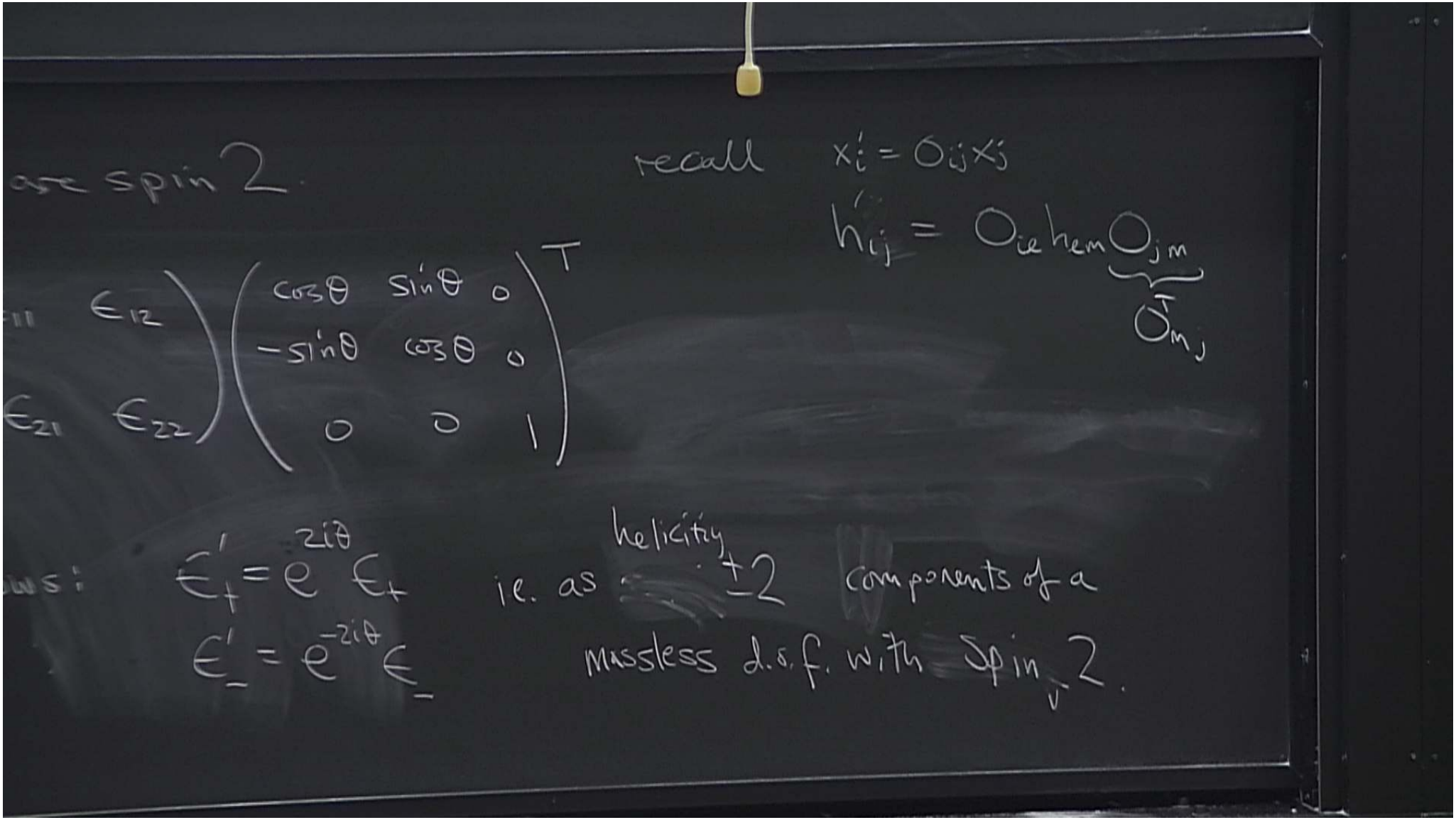
$$A_\mu = \sum \epsilon_\mu e^{ik\cdot x} + \epsilon_\mu^* e^{-ik\cdot x}$$

Lorentz gauge → +gauge away ϵ_0, ϵ_3

$\epsilon_+ = \epsilon_1 - i\epsilon_2$

ϵ_-


e^{-ikx}
Lorentz gauge
→
+ gauge away
ϵ_0, ϵ_3
$\epsilon_+ = \epsilon_1 - i\epsilon_2$
$\epsilon_- = \epsilon_1 + i\epsilon_2$
$\epsilon_+' = e^{i\theta}\epsilon_+$
$\epsilon_-' = e^{-i\theta}\epsilon_-$.


are spin 2.
recall $x_i' = O_{ij} x_j$
$h'_{ij} = O_{ie} h_{em} \underbrace{O_{jm}}_{O^T_{mj}}$
$\begin{pmatrix} \epsilon_{11} & \epsilon_{12} \\ \epsilon_{21} & \epsilon_{22} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}^T$
ows: $\epsilon_+' = e^{2i\theta} \epsilon_+$
$\epsilon_-' = e^{-2i\theta} \epsilon_-$
helicity
ie. as ± 2 components of a
massless d.o.f. with spin 2.

do same thing for E&M, $A_\mu = \sum \epsilon_\mu$

photon has spin 1 → helicity ± 1.

graviton " " 2 → " ± 2

$A_\mu = \sum \epsilon_\mu e^{ik\cdot x} + \epsilon_\mu^* e^{-ik\cdot x}$

Lorentz gauge → + gauge away ϵ_0, ϵ_3

$\epsilon_+ = \epsilon_1 - i\epsilon_2$

$\epsilon_- = \epsilon_1 + i\epsilon_2$

$\epsilon_+' =$

$\epsilon_-' =$

± 1

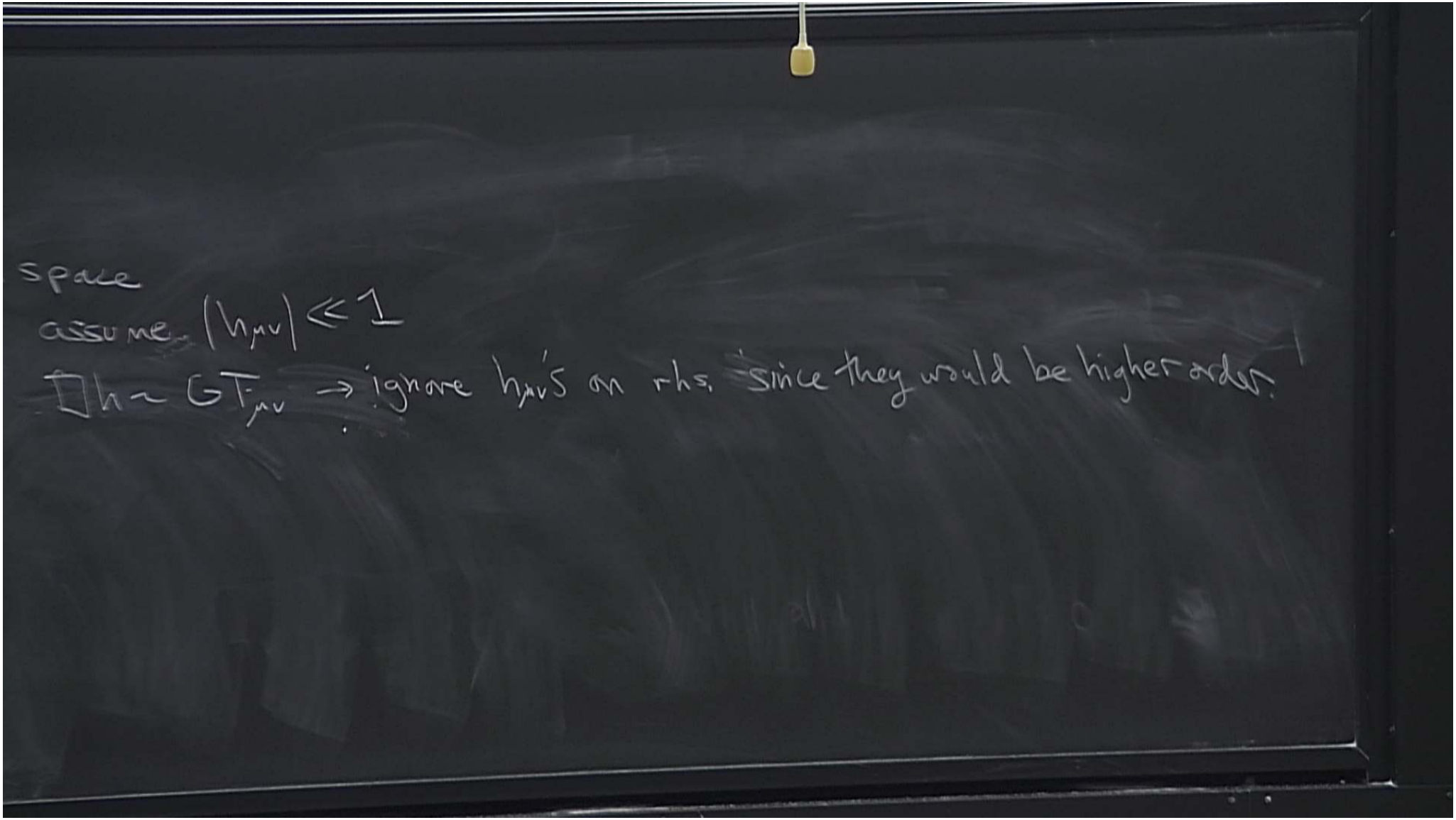
± 2

do same thing for E&M, $A_\mu = \sum \epsilon_\mu e^{ik\cdot x} + \epsilon_\mu^* e^{-ik\cdot x}$

String theory

hoton has spin 1 → helicity ±1.

graviton " " 2 → " ±2


space
assume $|h_{\mu\nu}| \ll 1$
$\Box h \sim G T_{\mu\nu}$ → ignore $h_{\mu\nu}$'s on rhs. since they would be higher order

Gravitational Radiation

In harmonic gauge $\quad R_{\mu\nu} = -\frac{1}{2}\Box h_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T^{\lambda}_{\ \lambda}\right)$

· source: assume localised

space

assume $|h_{\mu\nu}| \ll 1$

$\Box h \sim G T_{\mu\nu}$ → ignore $h_{\mu\nu}$'s on rhs. since they would be higher order.

i.e. replace metric on rhs by $\eta_{\mu\nu}$.

ntational Radiation

· source: assume localised in space

$$R_{\mu\nu} = -\frac{1}{2}\Box h_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T^{\lambda}{}_{\lambda}\right) \quad (*)$$

assume

$\Box h \sim$

– "linearised gravity"

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^{\lambda}{}_{\lambda} \;:\; (*) \Rightarrow \boxed{\Box \bar{h}_{\mu\nu} = -16\pi G T_{\mu\nu}}$$

$$\left(G_{\mu\nu} = -\frac{1}{2}\Box\bar{h}_{\mu\nu} = 8\pi G T_{\mu\nu}\right)$$

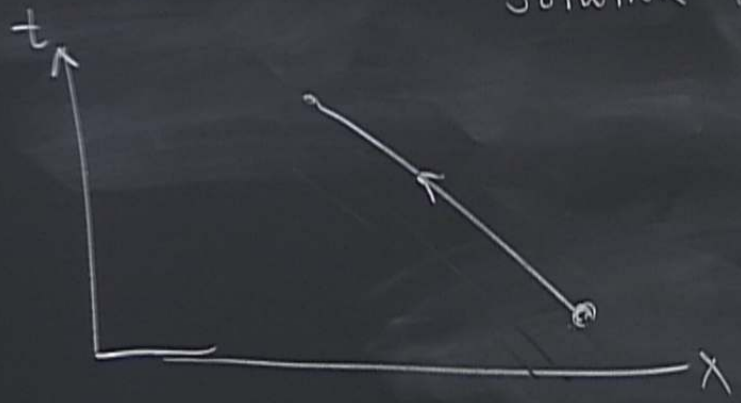
$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h^{\lambda}{}_{\lambda} \quad : (*) \Rightarrow \boxed{\Box \bar{h}_{\mu\nu} = -16\pi G T_{\mu\nu}}$$

$$\left(G_{\mu\nu} = -\frac{1}{2} D \bar{h}_{\mu\nu} = 8\pi G T_{\mu\nu} \right)$$

Solution is $\bar{h}_{\mu\nu} = -4G \int \frac{d^3 \underline{x}'}{|\underline{x} - \underline{x}'|} T_{\mu\nu}\left(t - |\underline{x} - \underline{x}'|, \underline{x}'\right)$

$$\left(G_{\mu\nu} = -\frac{1}{2}D\bar{h}_{\mu\nu} = 8\pi G T_{\mu\nu}\right)$$

Solution is $\bar{h}_{\mu\nu}(t,\underline{x}) = -4G\int \frac{d^3\underline{x}'\; T_{\mu\nu}\left(t-|\underline{x}-\underline{x}'|,\,\underline{x}'\right)}{|\underline{x}-\underline{x}'|}$



$h_{\mu\nu} = 8\pi G T_{\mu\nu}$)

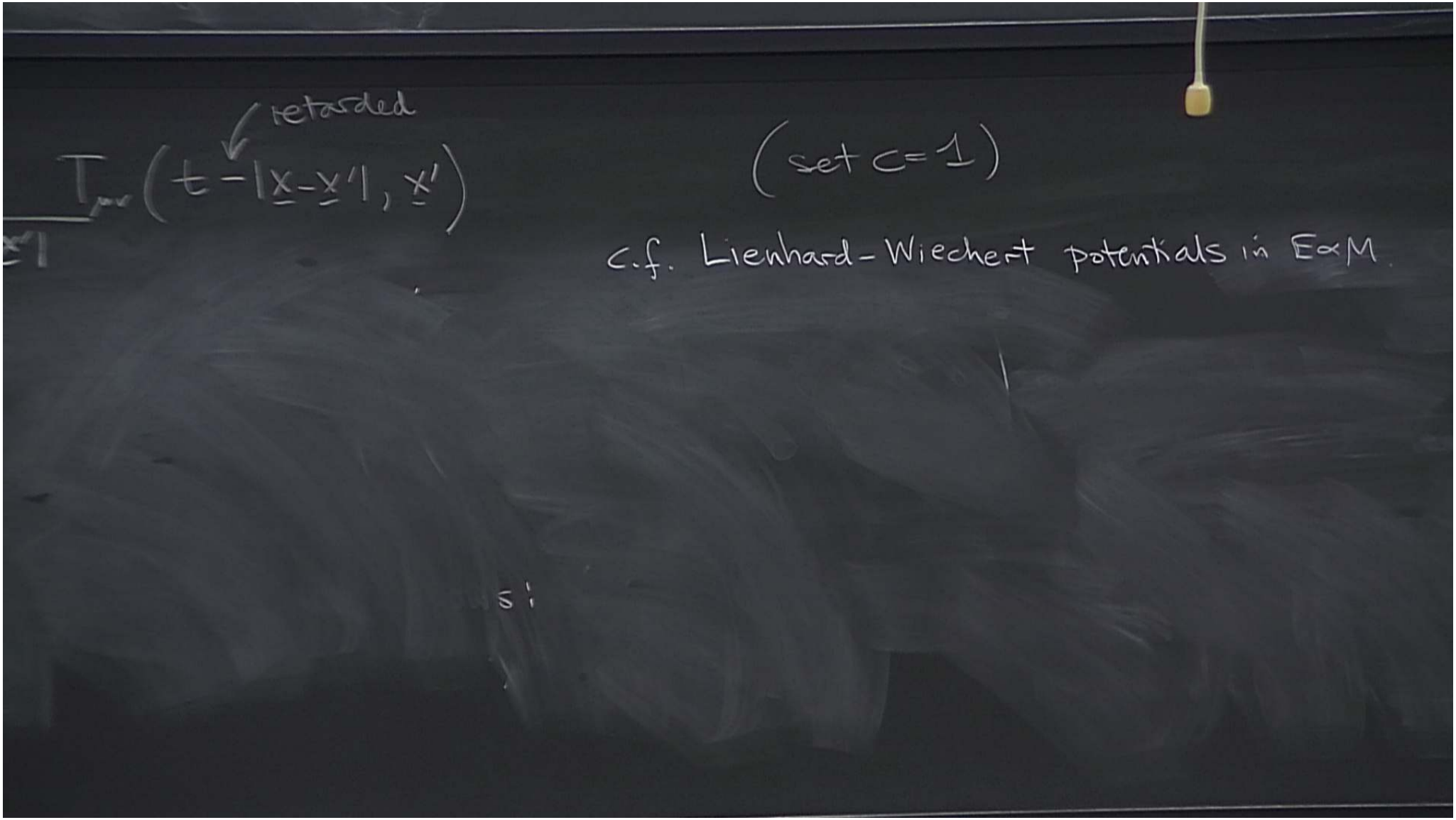
retarded

$$t,\underline{x}) = -4G \int \frac{d^3\underline{x}'}{|\underline{x}-\underline{x}'|} T_{\mu\nu}\left(t - |\underline{x}-\underline{x}'|, \underline{x}'\right)$$

(set c=

c.f. Lienhard-Wi

s:


retarded
$T_{\mu\nu}\left(t-|\underline{x}-\underline{x}'|, \underline{x}'\right)$
(set $c=1$)
c.f. Lienhard-Wiechert potentials in E&M

(set $c=1$)

c.f. Lienhard-Wiechert potentials in E&M.

$r = |\underline{x}|$

$$\sqrt{(\underline{x}-\underline{x}')^2} = r\sqrt{1 - 2\frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{\underline{x}'^2}{r^2}} \approx r\left(1 - \frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{1}{2}\frac{\underline{x}'^2}{r^2}\right) \text{etc.}$$

$$h_{\mu\nu}(t,\underline{x}) = -4G\int \frac{d^3\underline{x}'\; T_{\mu\nu}\left(t - |\underline{x}-\underline{x}'|, \underline{x}'\right)}{|\underline{x}-\underline{x}'|}$$

retarded

c.f. Lienh

expand in $\frac{|\underline{x}'|}{|\underline{x}|}$

$\sqrt{(\underline{x}-\underline{x}')^2}$

i.e. we are far from source.

$$\Rightarrow h_{\mu\nu} \simeq \frac{4G}{r}\int d^3\underline{x}'\, T_{\mu\nu}(t-r, \underline{x}')$$

(expansion in $1/r$)

(set $c=1$)

c.f. Lienhard-Wiechert potentials in E&M.

$r = |\underline{x}|$

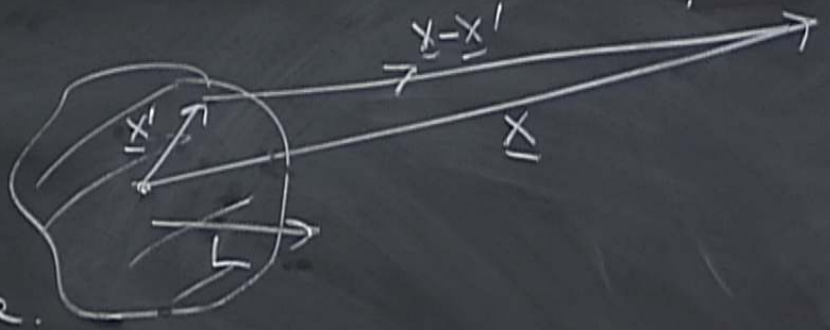
$$\sqrt{(\underline{x}-\underline{x}')^2} = r\sqrt{1 - 2\frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{\underline{x}'^2}{r^2}} \approx r\left(1 - \frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{1}{2}\frac{\underline{x}'^2}{r^2}\right) \text{etc.}$$

$$h_{\mu\nu}(t,\underline{x}) = -4G\int \frac{d^3\underline{x}'\; T_{\mu\nu}\left(t - |\underline{x}-\underline{x}'|, \underline{x}'\right)}{|\underline{x}-\underline{x}'|}$$

retarded

c.f. L

$\sqrt{(\underline{x}-\underline{x}'$



expand in $\frac{|\underline{x}'|}{|\underline{x}|}$

i.e. we are far from source.

$$\Rightarrow h_{\mu\nu} \simeq \frac{4G}{r}\int d^3\underline{x}'\, T_{\mu\nu}(t-r, \underline{x}')$$

(expansion in L/r)

ok if source varies only on scale L.

(set $c=1$)

c.f. Lienhard-Wiechert potentials in E&M.

$$r = |\underline{x}|$$

$$\sqrt{(\underline{x}-\underline{x}')^2} = r\sqrt{1 - 2\frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{\underline{x}'^2}{r^2}} \approx r\left(1 - \frac{\underline{x}\cdot\underline{x}'}{r^2} + \frac{1}{2}\frac{\underline{x}'^2}{r^2}\right) \text{etc.}$$

$$\Rightarrow \bar{h}_{kl} \sim \frac{G}{r}\int T_{kl}\, d^3\underline{x}$$

$$\frac{1}{2}\frac{d^2}{dt^2}\int d^3\underline{x}\, x^k x^\ell T^{00}(t,\underline{x})$$

$$= \frac{1}{2}\int d^3\underline{x}\, \partial_n \partial_m T^{nm}\, x^k x^\ell$$

for any $T^{\mu\nu}$ obeying $\partial_\mu T^{\mu\nu} = 0$

$$\partial_0 T^{00} = -\partial_i T^{i0}$$

$$\partial_0 T^{i0} = -\partial_j T^{ij}$$

$$= \frac{1}{2}\frac{d^2}{dt^2}\int d^3\underline{x}\, x^k x^\ell T^{00}(t,\underline{x})$$

$$= \frac{1}{2}\int d^3\underline{x}\, \partial_n\partial_m T^{nm}\, x^k x^\ell$$

$$= -\frac{1}{2}\int d^3\underline{x}\, \partial_m T^{nm}\left(\delta^{kn}x^\ell + \delta^{\ell n}x^k\right)$$

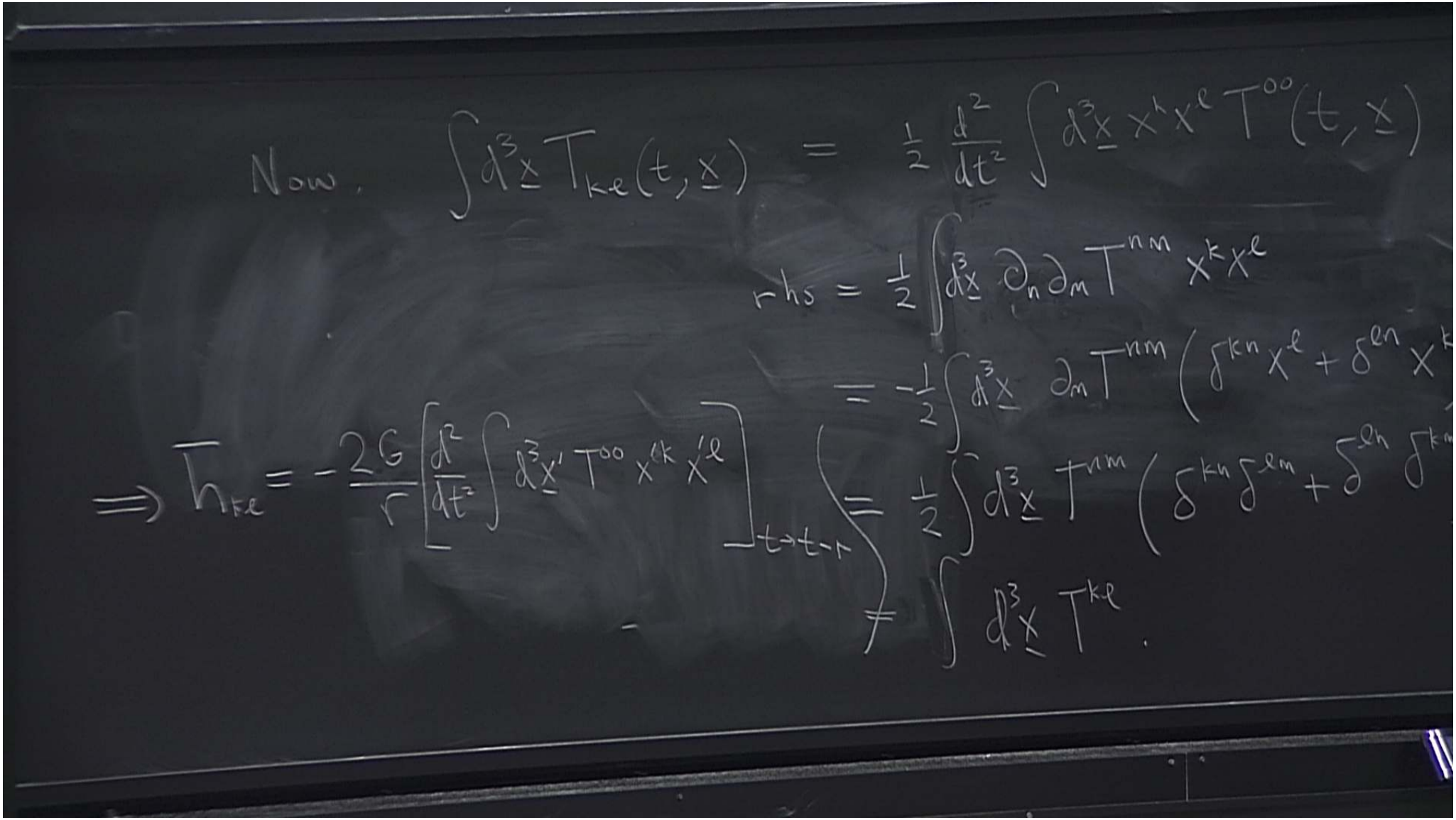
$$= \frac{1}{2}\int d^3\underline{x}\, T^{nm}\left(\delta^{kn}\delta^{\ell m} + \delta^{\ell n}\delta^{km}\right)$$

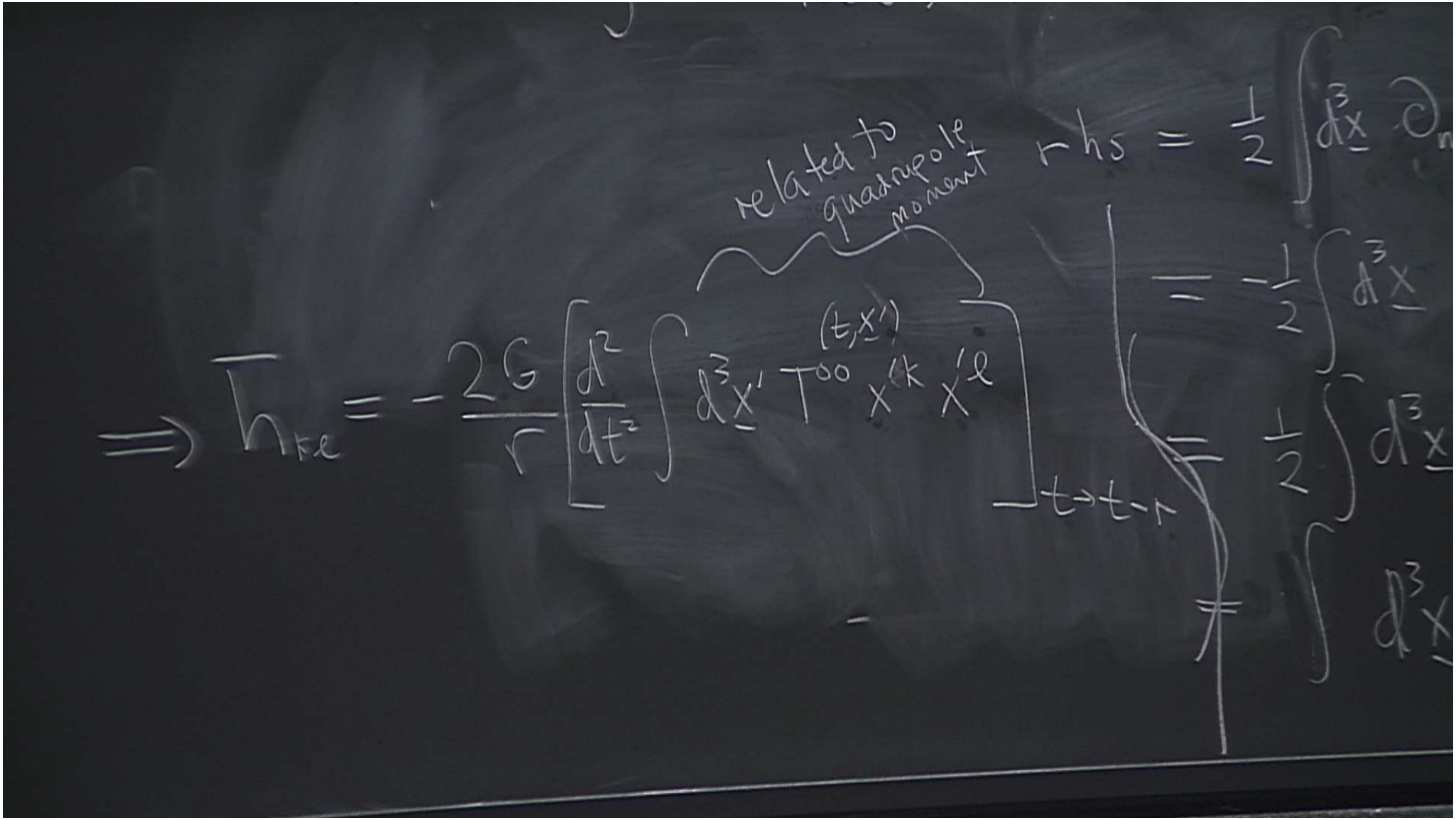
$$= \int d^3\underline{x}\, T^{k\ell}.$$

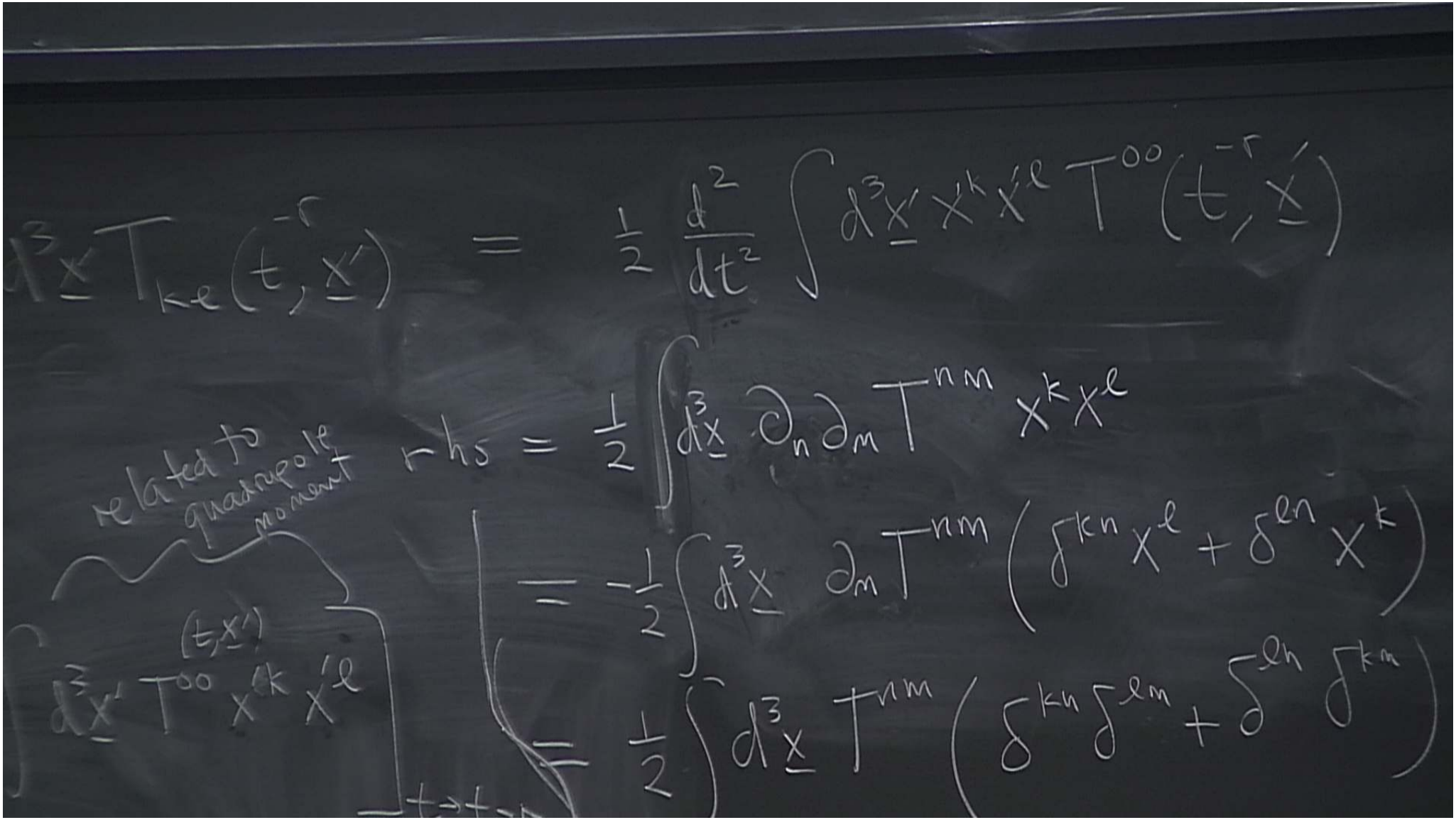
for any $T^{\mu\nu}$ obeying $\partial_\mu T^{\mu\nu} = 0$

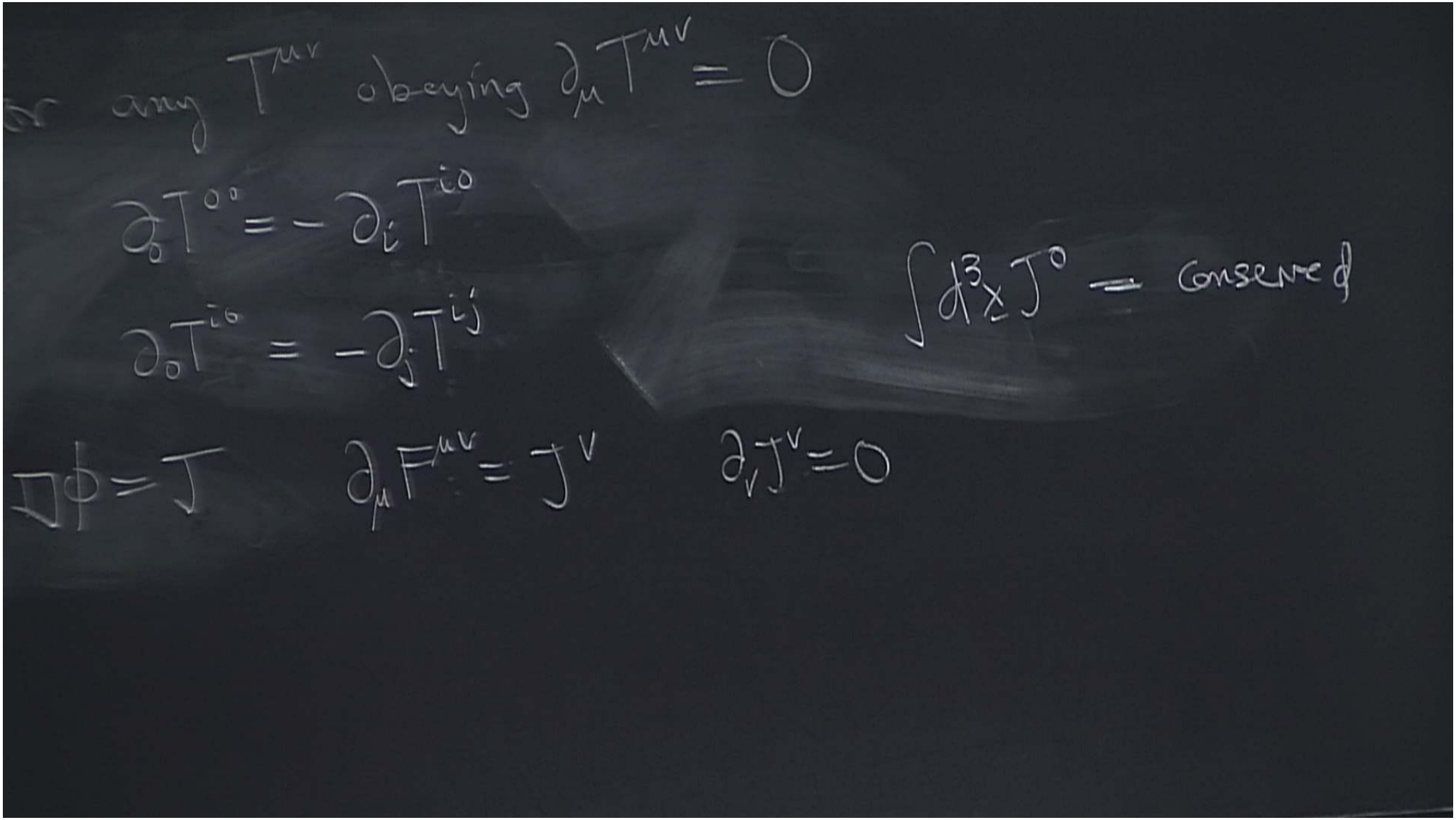
$$\partial_0 T^{00} = -\partial_i T^{i0}$$

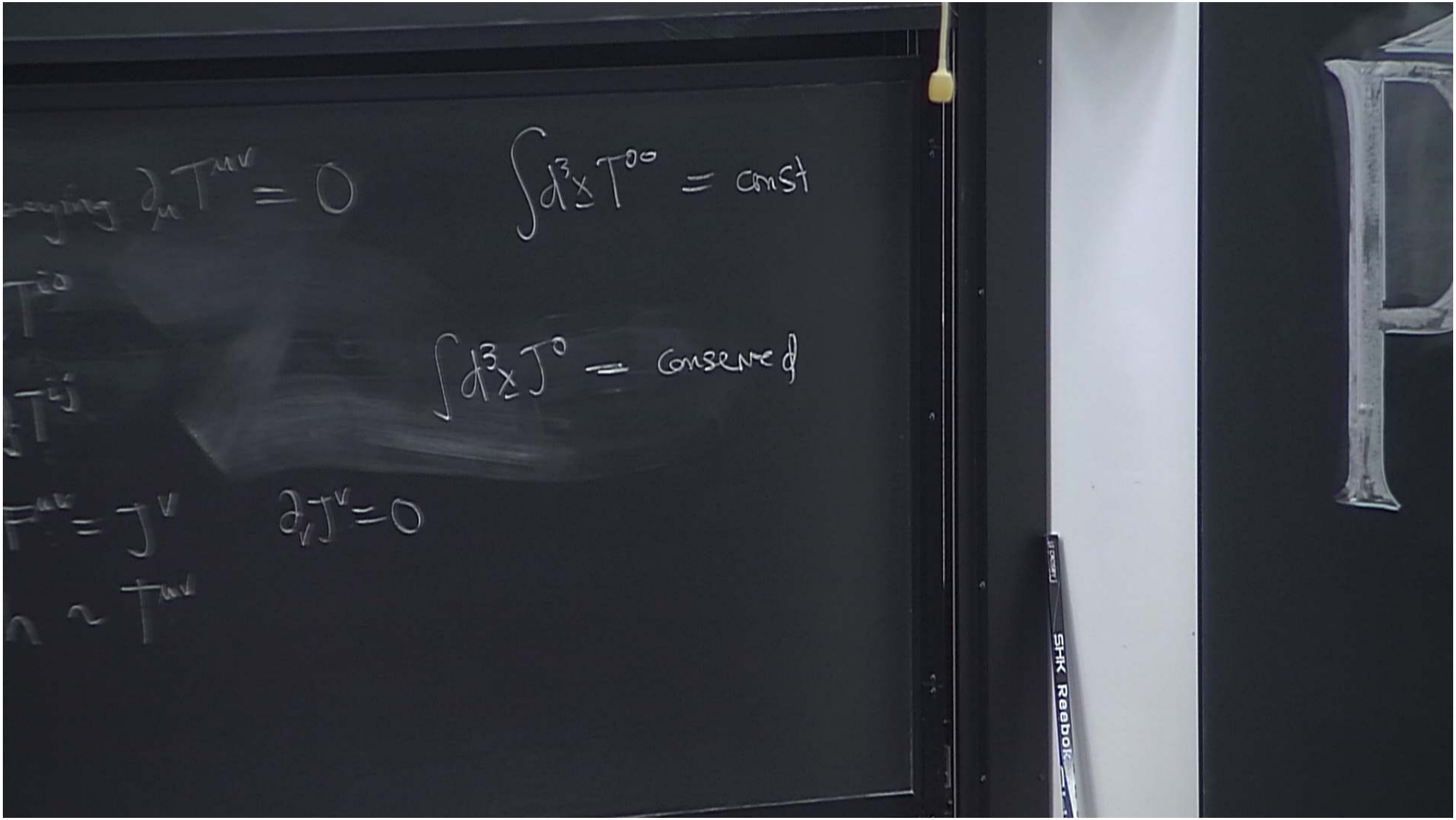
$$\partial_0 T^{i0} = -\partial_j T^{ij}$$


Now, $\int d^3\underline{x}\, T_{ke}(t,\underline{x}) = \frac{1}{2}\frac{d^2}{dt^2}\int d^3\underline{x}\, x^k x^e T^{00}(t,\underline{x})$
rhs $= \frac{1}{2}\int d^3\underline{x}\, \partial_n\partial_m T^{nm}\, x^k x^e$
$= -\frac{1}{2}\int d^3\underline{x}\, \partial_m T^{nm}\left(\delta^{kn}x^e + \delta^{en}x^k\right.$
$= \frac{1}{2}\int d^3\underline{x}\, T^{nm}\left(\delta^{kn}\delta^{em} + \delta^{en}\delta^{km}\right.$
$= \int d^3\underline{x}\, T^{ke}.$
$\Rightarrow h_{ke} = -\frac{2G}{r}\left[\frac{d^2}{dt^2}\int d^3\underline{x}'\, T^{00}\, x'^k x'^e\right]_{t\to t-r}$


related to quadrupole moment
$\Rightarrow h_{jk} = -\frac{2G}{r}\left[\frac{d^2}{dt^2}\int d^3x' T^{00}(t,x') x'^j x'^k\right]_{t\to t-r}$
$rhs = \frac{1}{2}\int d^3x \,\partial_n$
$= -\frac{1}{2}\int d^3x$
$= \frac{1}{2}\int d^3x$
$= \int d^3x$


$\int d^3\underline{x}\, T_{ke}(t,\underline{x}) = \frac{1}{2}\frac{d^2}{dt^2}\int d^3\underline{x}\, x^k x^e T^{00}(t,\underline{x})$
related to quadrupole moment
$rhs = \frac{1}{2}\int d^3\underline{x}\, \partial_n\partial_m T^{nm}\, x^k x^e$
$= -\frac{1}{2}\int d^3\underline{x}\, \partial_m T^{nm}\left(\delta^{kn} x^e + \delta^{en} x^k\right)$
$= \frac{1}{2}\int d^3\underline{x}\, T^{nm}\left(\delta^{kn}\delta^{em} + \delta^{en}\delta^{km}\right)$
$\int d^3\underline{x}\, T^{00}\, x^k x^e$
$(t,\underline{x})$
$t \to t$


any $T^{\mu\nu}$ obeying $\partial_\mu T^{\mu\nu} = 0$
$\partial_0 T^{00} = -\partial_i T^{i0}$
$\partial_0 T^{i0} = -\partial_j T^{ij}$
$\int d^3x J^0 =$ Conserved
$\Box\phi = J$
$\partial_\mu F^{\mu\nu} = J^\nu$
$\partial_\nu J^\nu = 0$


$\partial_\mu T^{\mu\nu} = 0$
$\int d^3x\, T^{00} = \text{const}$
$\int d^3x\, J^0 = \text{Conserved}$
$\partial_\nu J^\nu = 0$