Title: Gravitational Wave Astronomy - Lecture 2

Date: Jun 24, 2009 11:30 AM

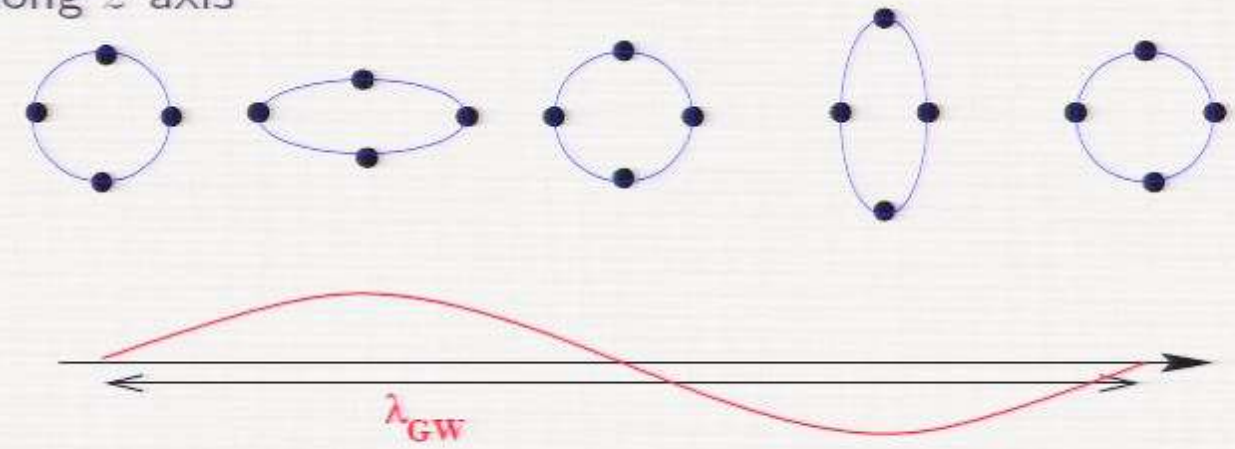
URL: http://pirsa.org/09060065

Abstract:

Interaction between GW and ring of free-falling particles

GW propagating along z-axis

- Case: $h_+ \neq 0$, $h_\times = 0$



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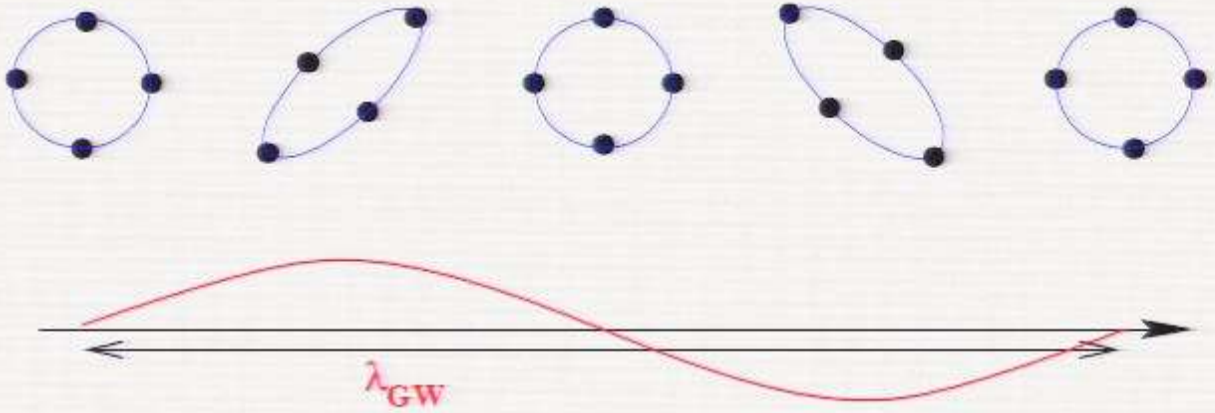
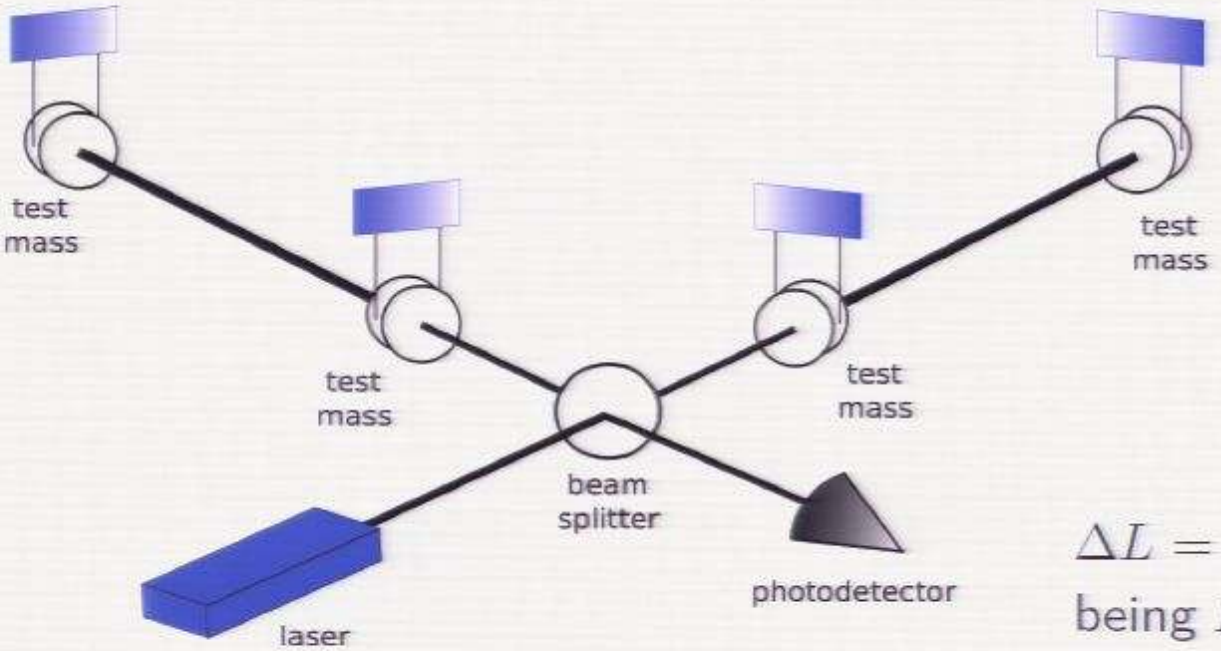


How to measure gravitational waves

Use light beams to measure the stretching and squeezing induced by GWs

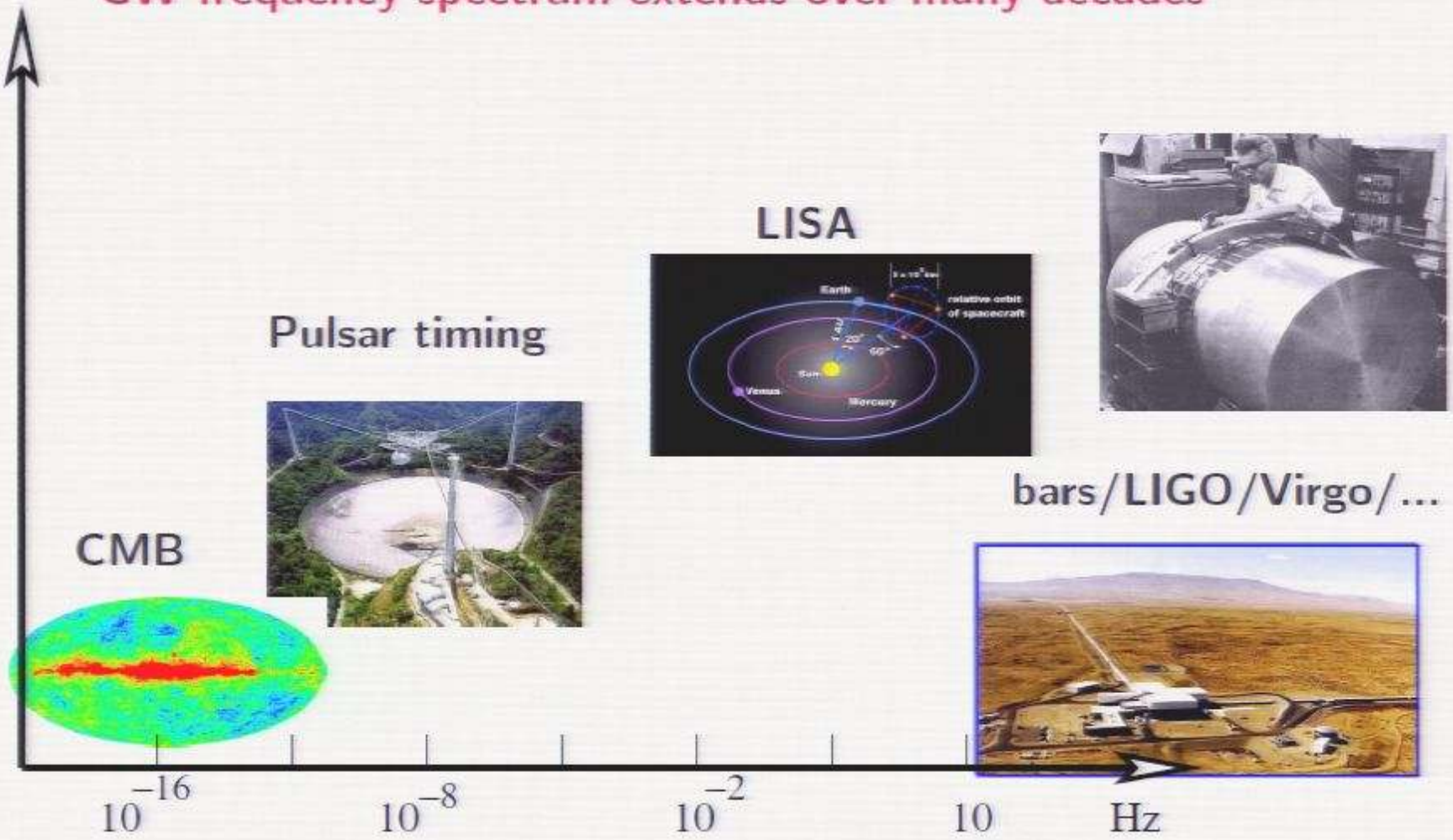


$\Delta L = L\,h \sim 10^{-16}$ cm

being $L = 4$km and $h \sim 10^{-21}$

$\Delta\phi \sim 10^{-8}$ rad

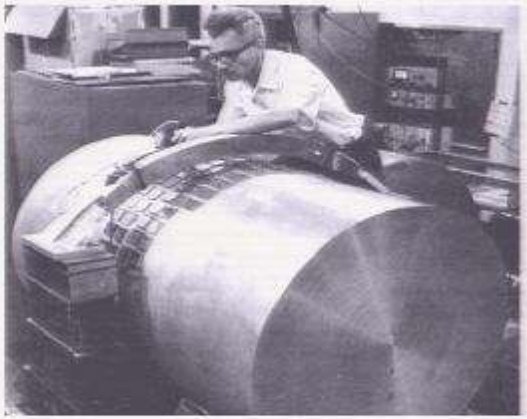
GW frequency spectrum extends over many decades

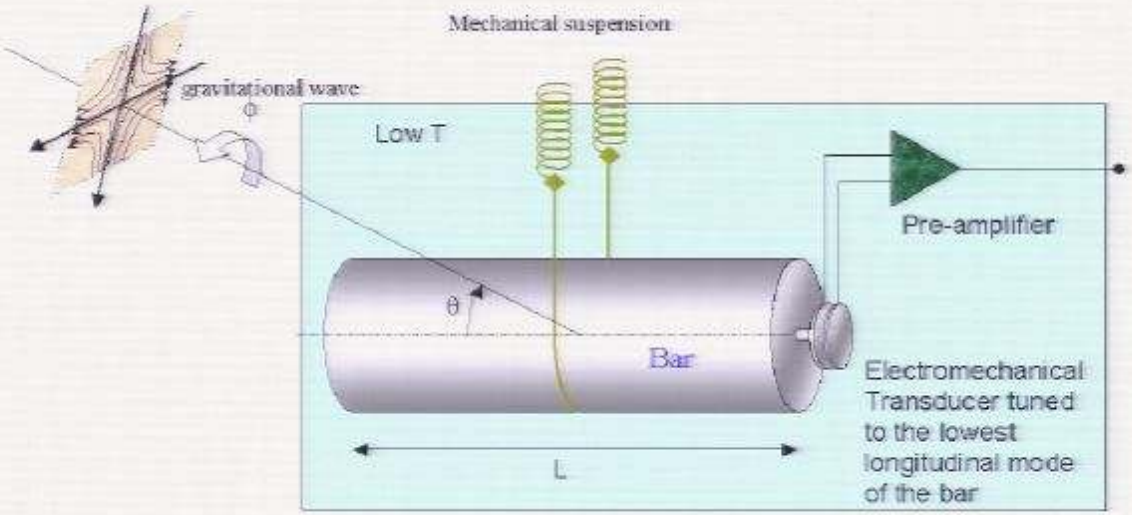


Direct observation with resonant-mass detectors

- Pioneering work by

Joe Weber at Maryland U





Resonant-mass detectors in the world

Resonant bar or sphere detectors (GW frequency $\sim$ 1 kHz)

Nautilus (Rome) Explorer (CERN) Schenberg (Brasil) MiniGRAIL (Belgium)

Allegro (Louisiana) Niobe (Perth) Auriga (Padova)

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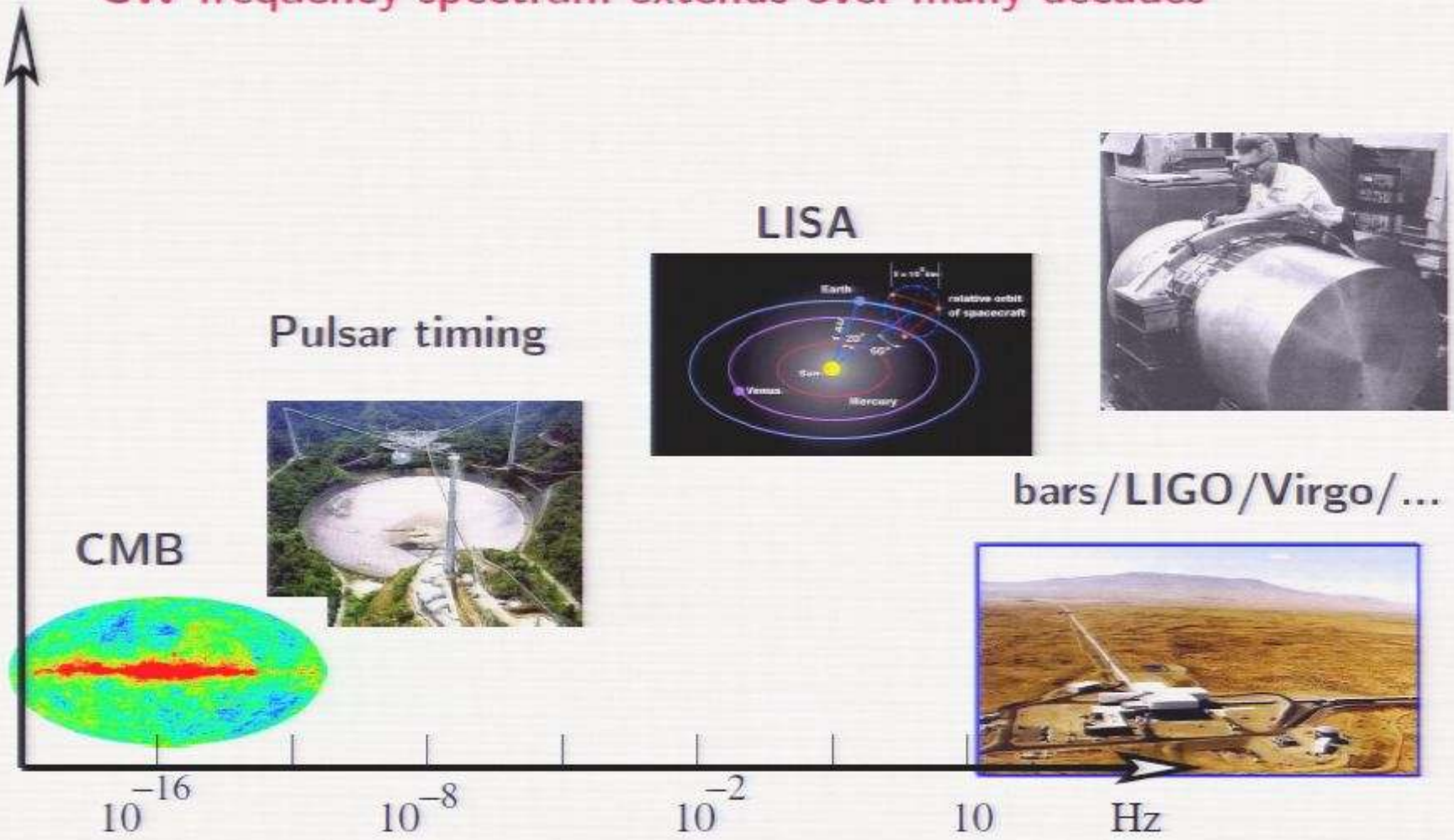

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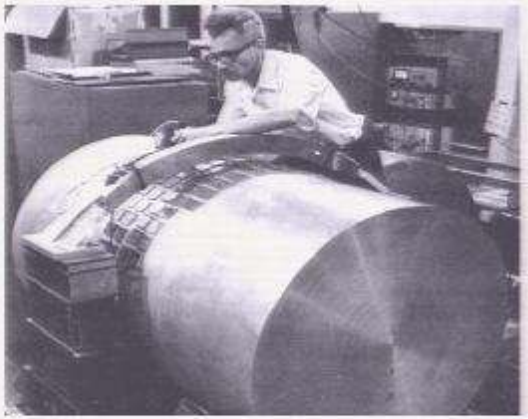

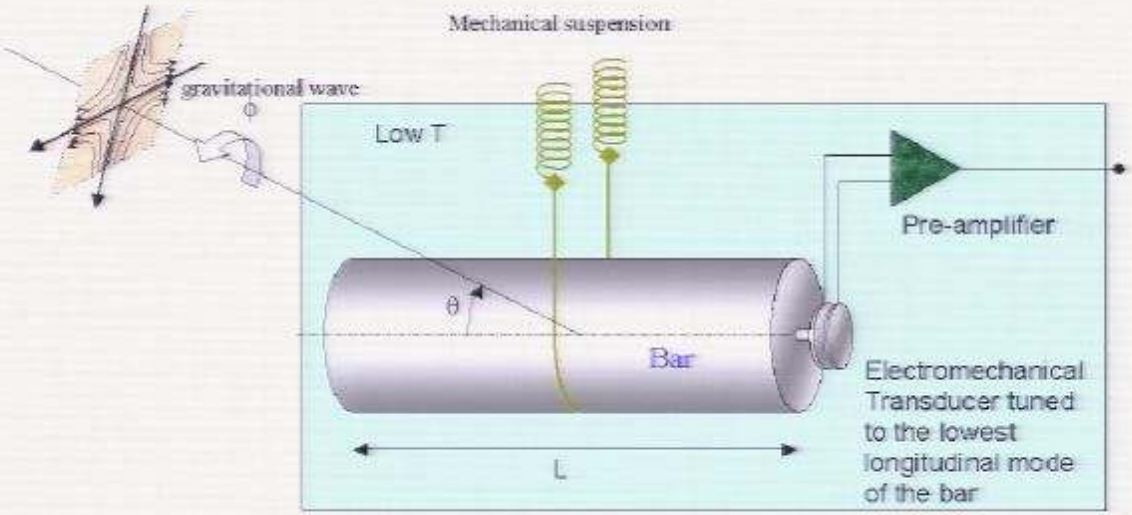

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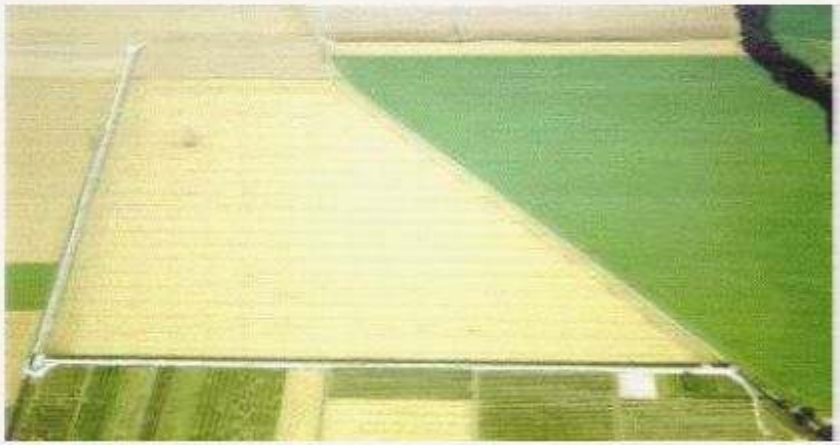
International network of GW interferometers (frequency band ~ 10–10^3 Hz)

LIGO at Livingston (Lousiana) $\Rightarrow$

$\Leftarrow$ LIGO at Hanford (Washington State)

Virgo (France-Italy) ⇒



⇐ GEO 600 (UK-Germany)

TAMA 300 (Japan)

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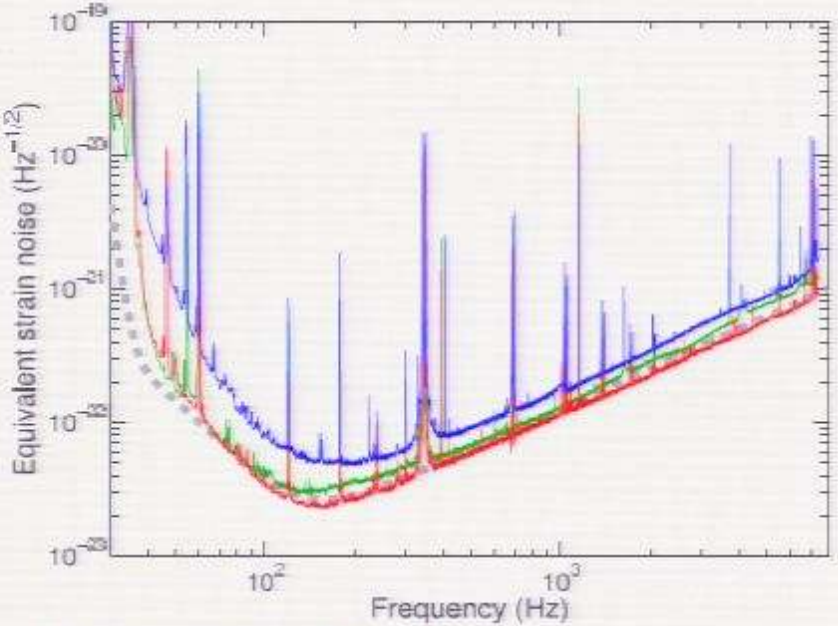
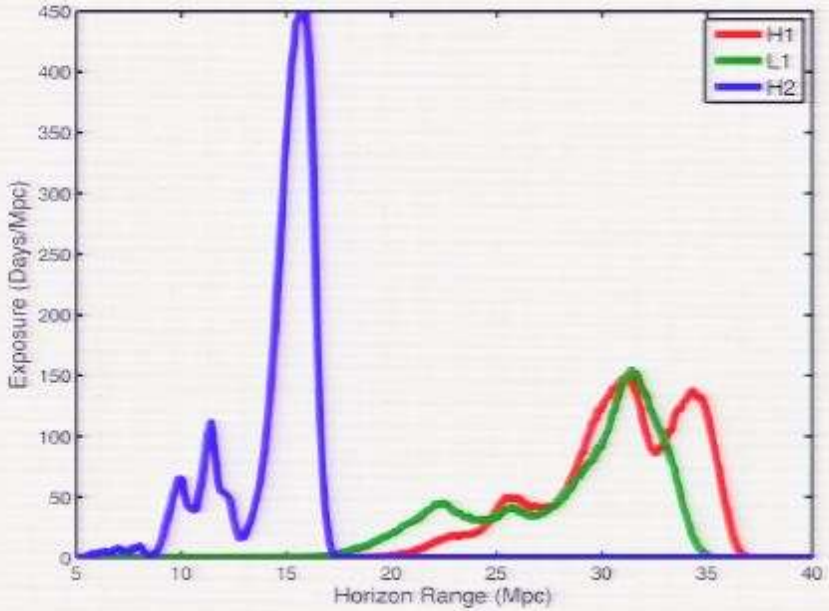
Current status of LIGO detectors





Astrophysical reach:

NS-NS ($1.4M_\odot + 1.4M_\odot$): 31 Mpc, 250 L_{10} **Our own Milky Way galaxy has $\sim 1.7\, L_{10}$**

BH-BH ($10M_\odot + 10M_\odot$): 125 Mpc, 20,000 L_{10}

Data of S5 run at design sensitivity are currently under investigation

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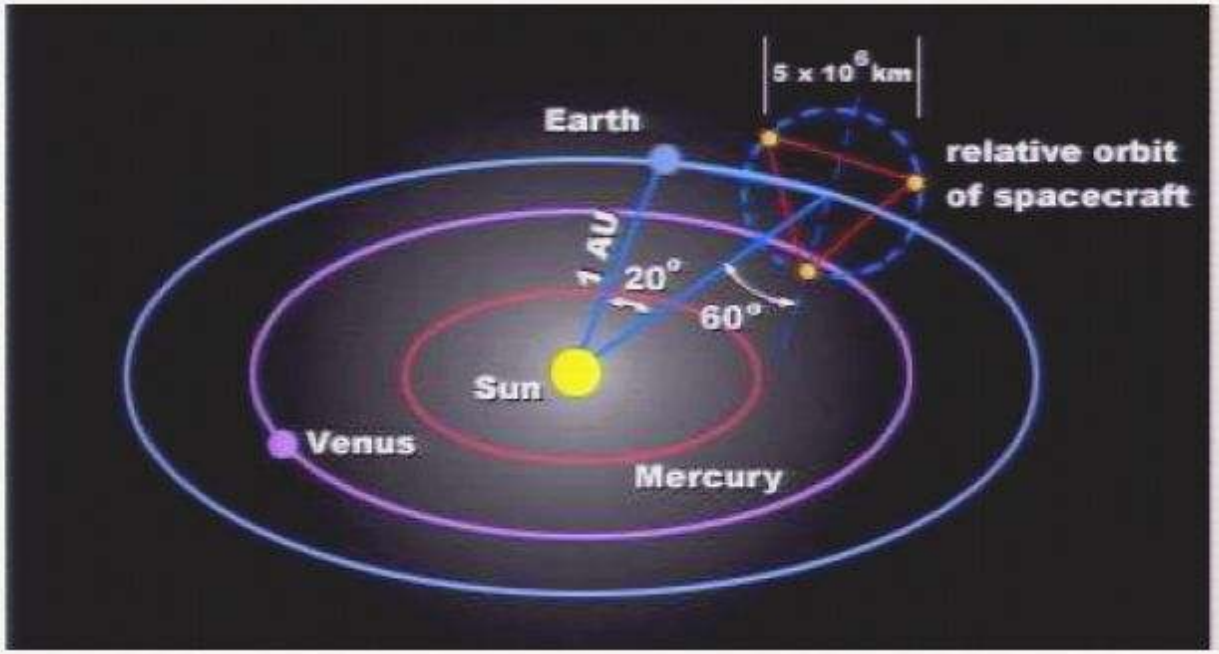
LISA: Laser Interferometer Space Antenna (frequency band: $10^{-4} - 0.1$ Hz)

LISA science goals complementary to ground-based interferometer ones

ESA/NASA mission in 2020?



GWs on the Earth: comparison with other kind of radiation

Supernova at 20 kpc:

- From GWs: $\sim 400 \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}} \left(\frac{f_{\mathrm{GW}}}{1\mathrm{kHz}}\right)^2 \left(\frac{h}{10^{-21}}\right)^2$ during few msecs
- From neutrino: $\sim 10^5 \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}}$ during 10 secs
- From optical radiation: $\sim 10^{-4} \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}}$ during one week

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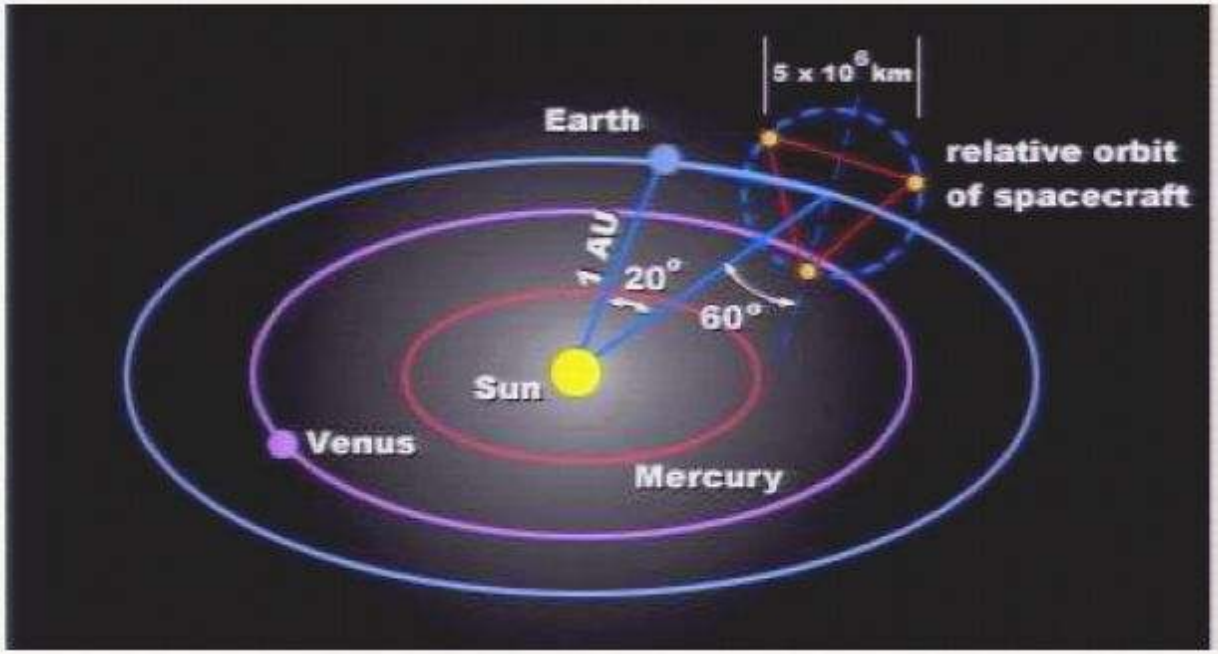

$$\delta g(t) = \frac{h_x}{2} X_0 \sin\omega t$$

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$$

1. $\bar{g}_{\mu\nu}$ has typical scale L_B

$h_{\mu\nu}$ " " wavelength λ_{GW} } $\lambda_{GW} \ll L_B$

$\delta y(t) = \frac{h_x}{2} X_0 \sin\omega t$

2. $\bar{g}_{\mu\nu}$ has freque up to f_B

$h_{\mu\nu}$ is different from zero around f } $f >> f_B$

$\delta y(t) = \frac{h_x}{2} X_0 \sin\omega t$

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$h, \tilde{\Lambda}_{GW} / L_8 \left(f_B / f \right)$

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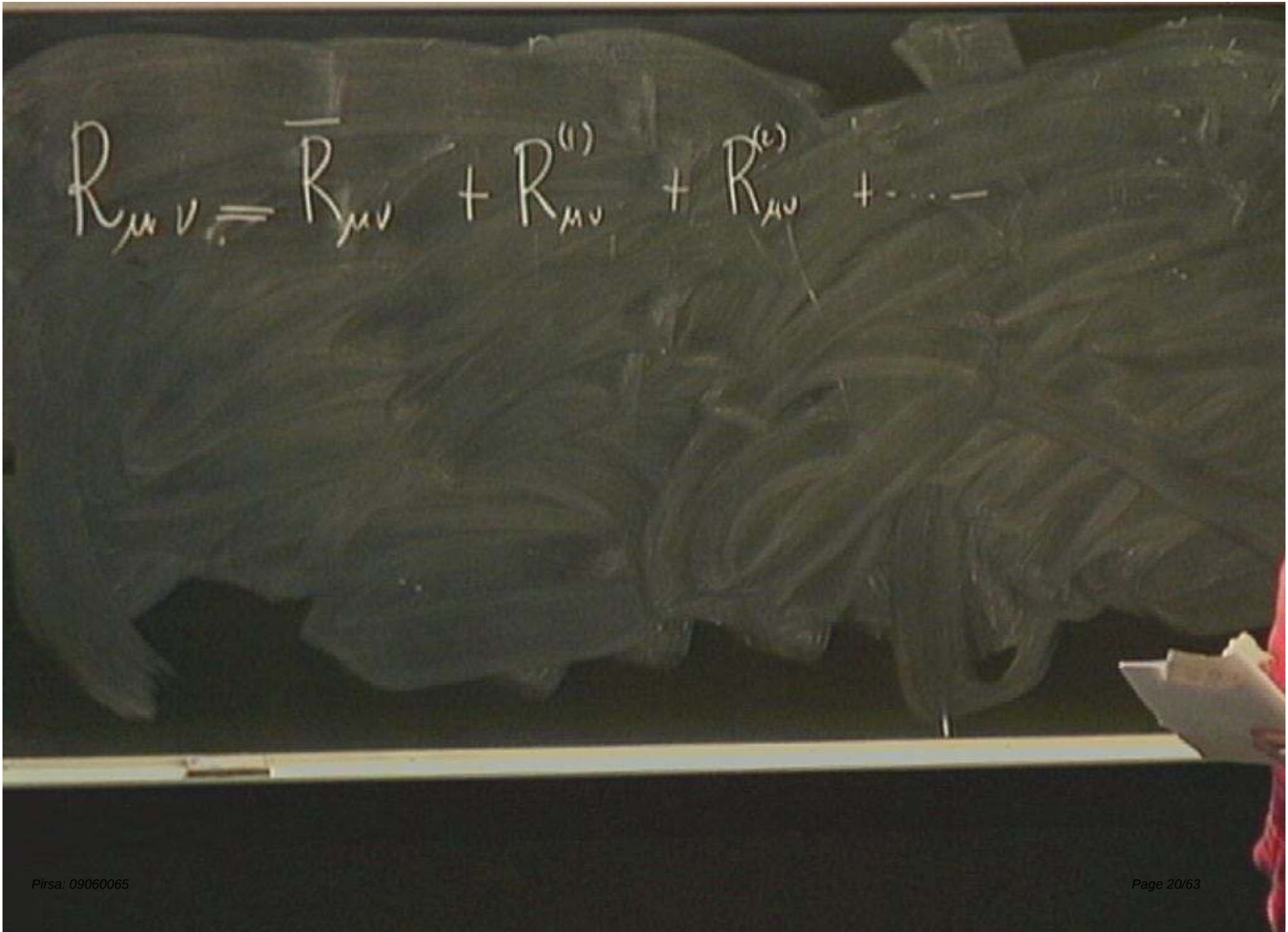
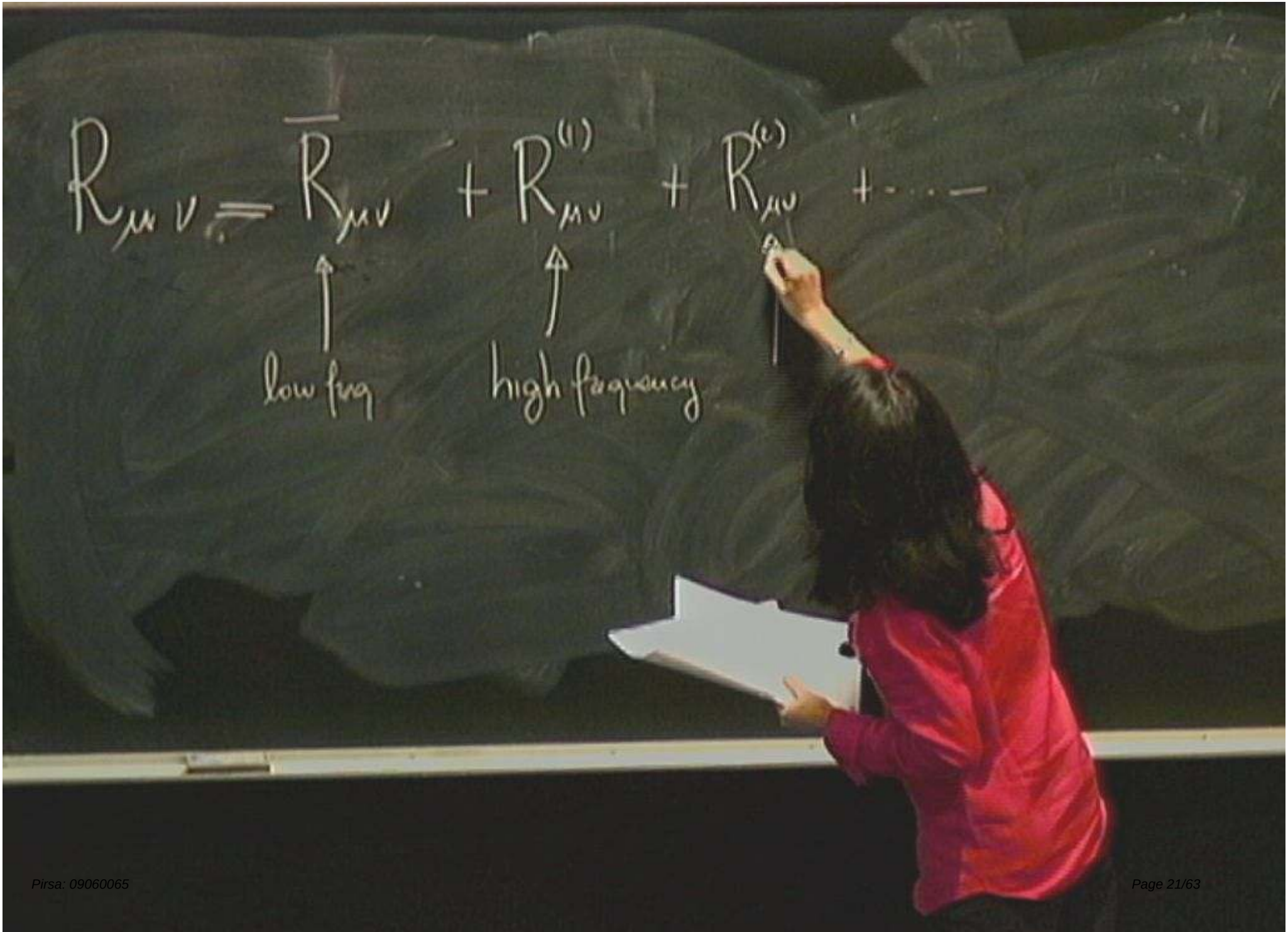
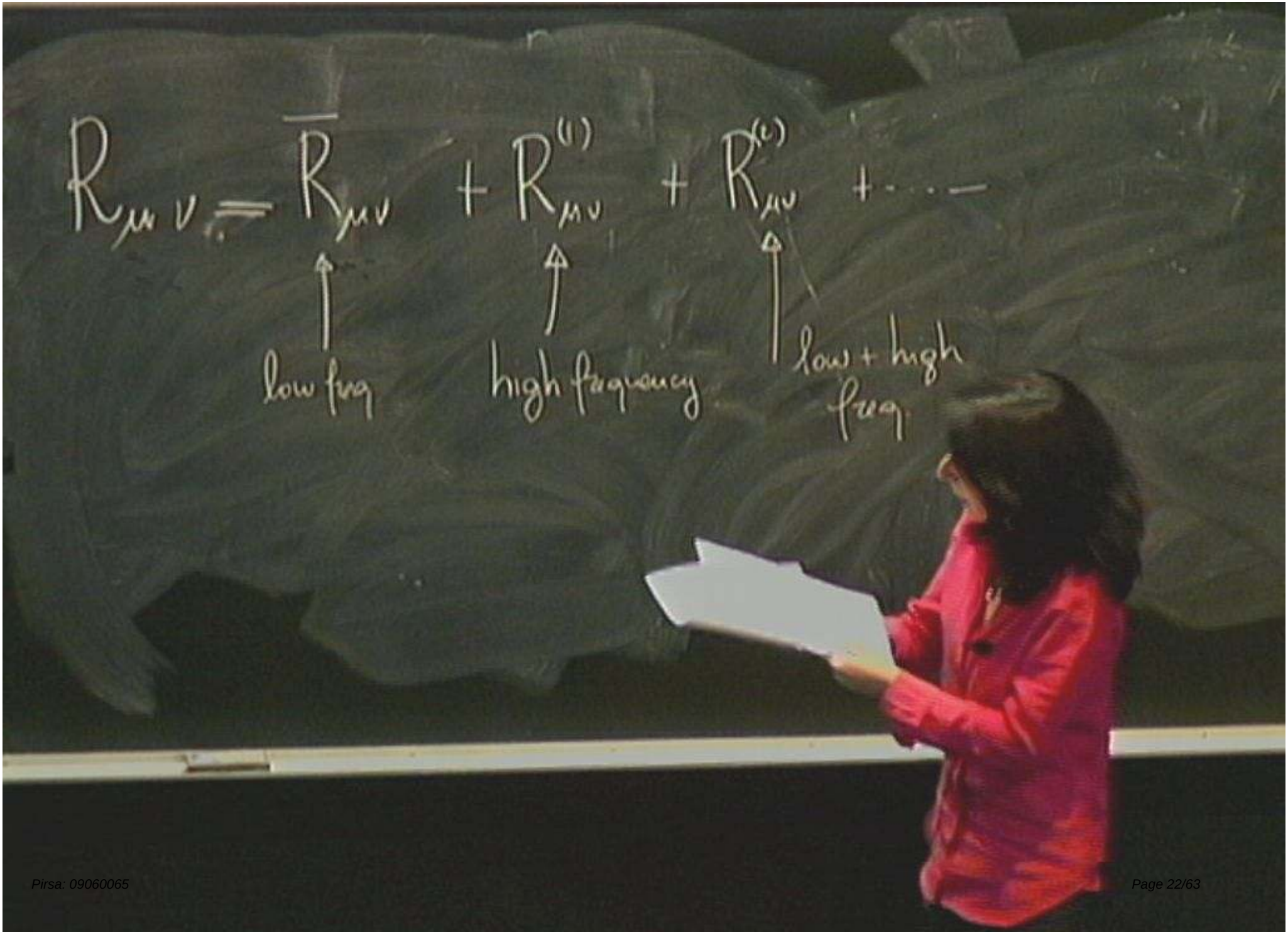

$R_{\mu\nu} = \bar{R}_{\mu\nu} + R^{(1)}_{\mu\nu} + R^{(2)}_{\mu\nu} + \cdots$


$R_{\mu\nu} = \bar{R}_{\mu\nu} + R^{(1)}_{\mu\nu} + R^{(2)}_{\mu\nu} + \cdots$
low freq
high frequency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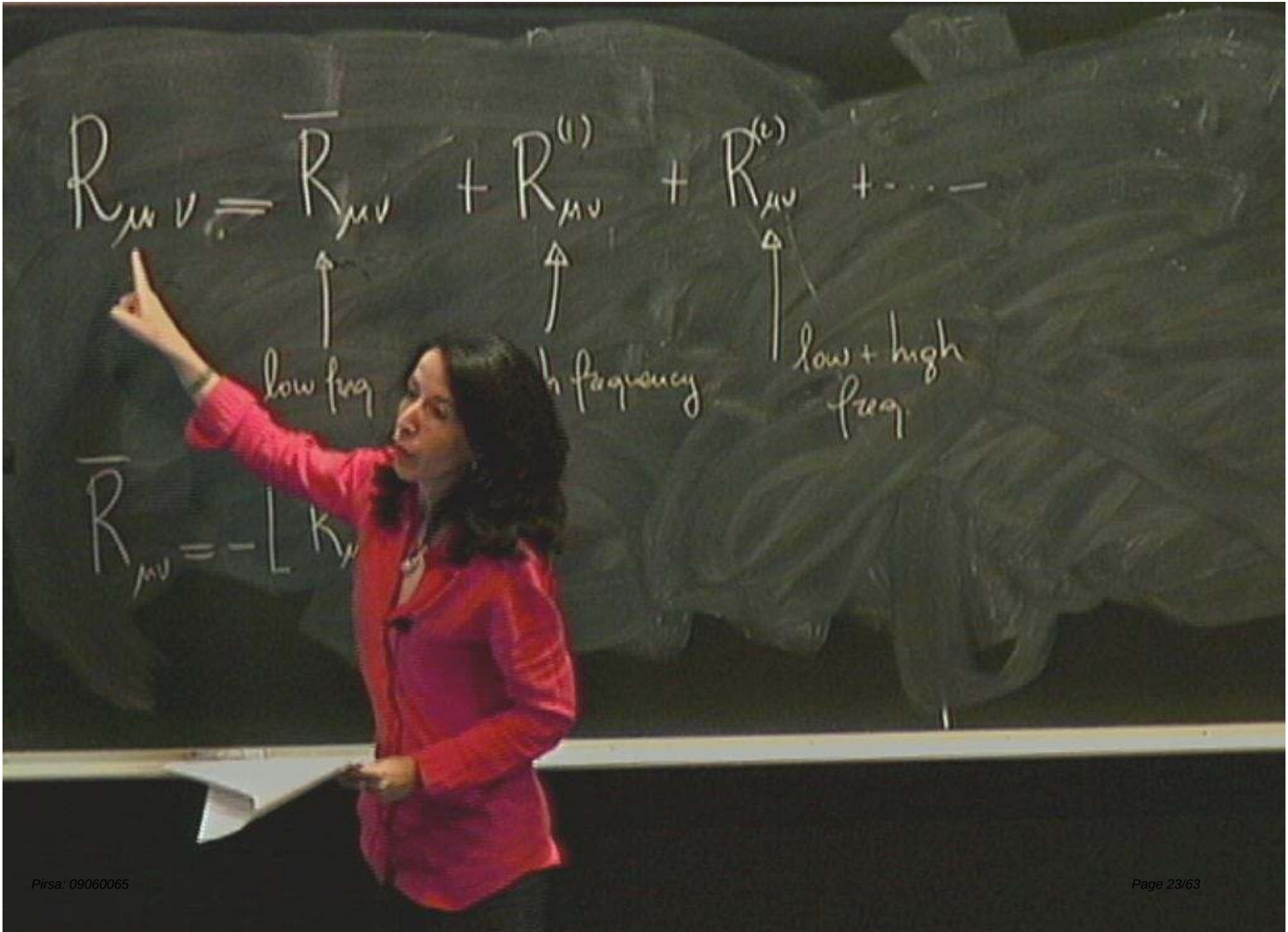
high frequency
low + high freq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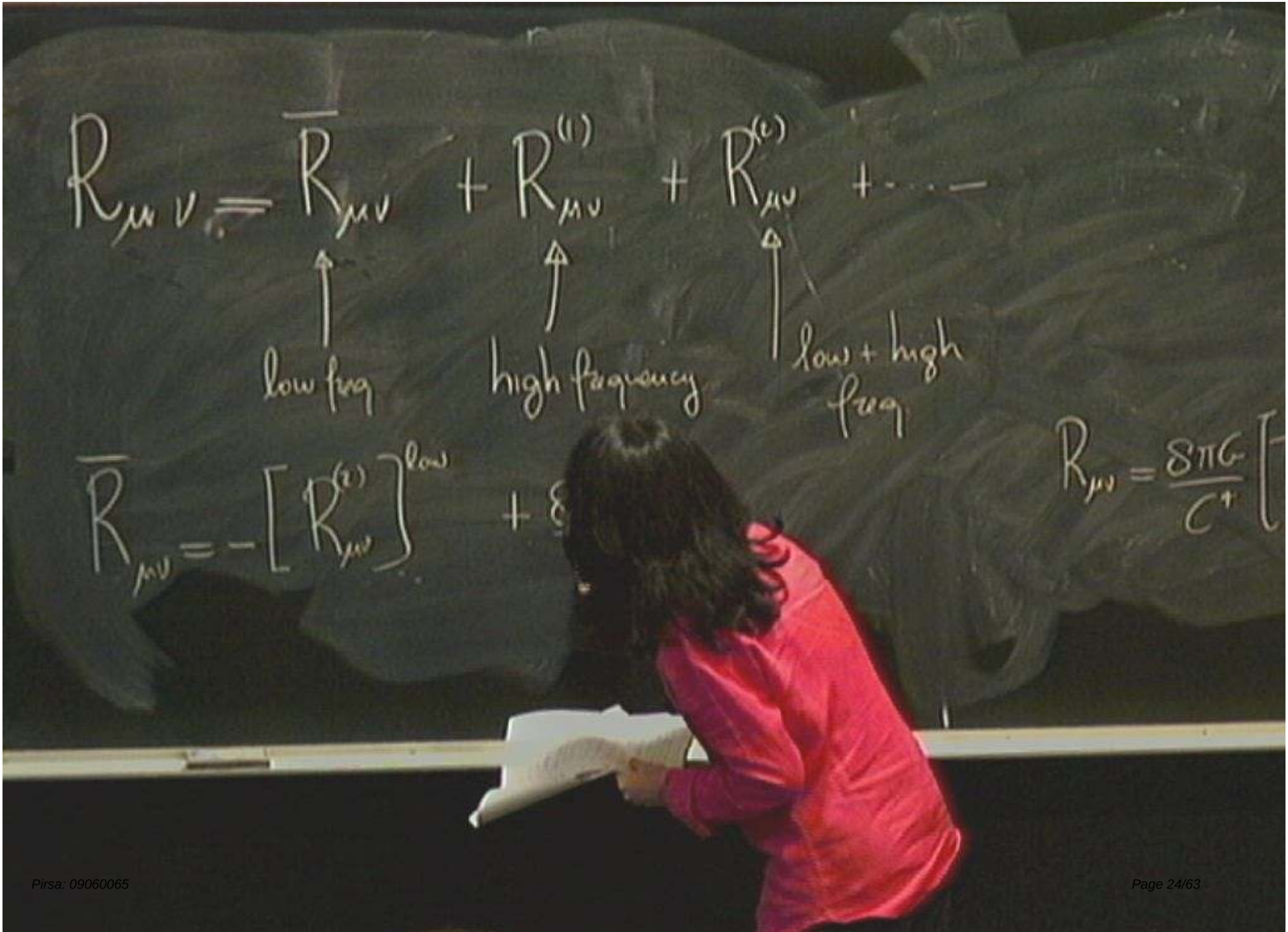
low freq
h frequency
low + high freq
$\bar{R}_{\mu\nu} = -L K_{\mu}$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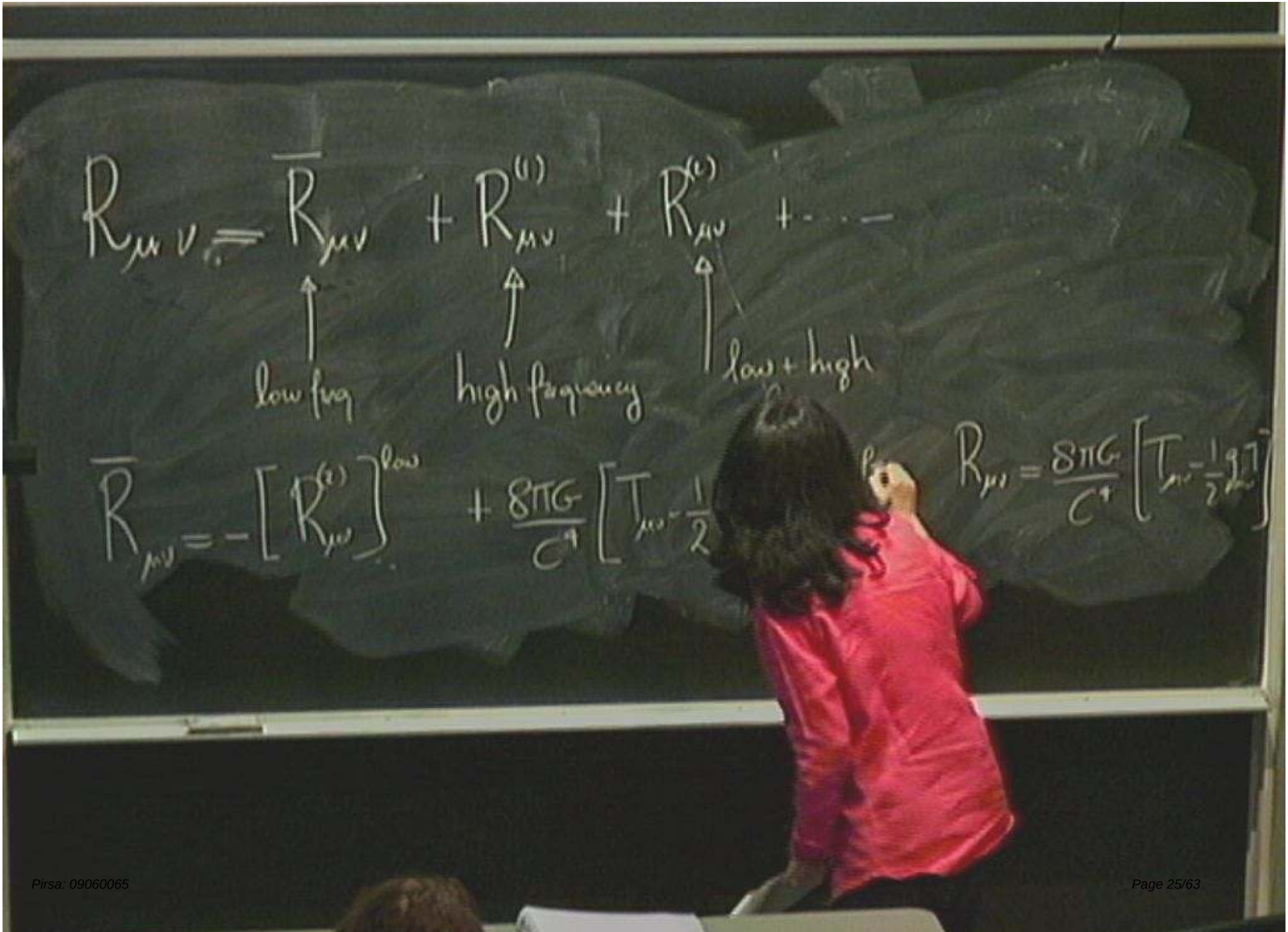
low freq
high frequency
low + high freq
$\bar{R}_{\mu\nu} = -\left[R^{(2)}_{\mu\nu}\right]^{low} + \mathcal{E}$
$R_{\mu\nu} = \frac{8\pi G}{c^4}$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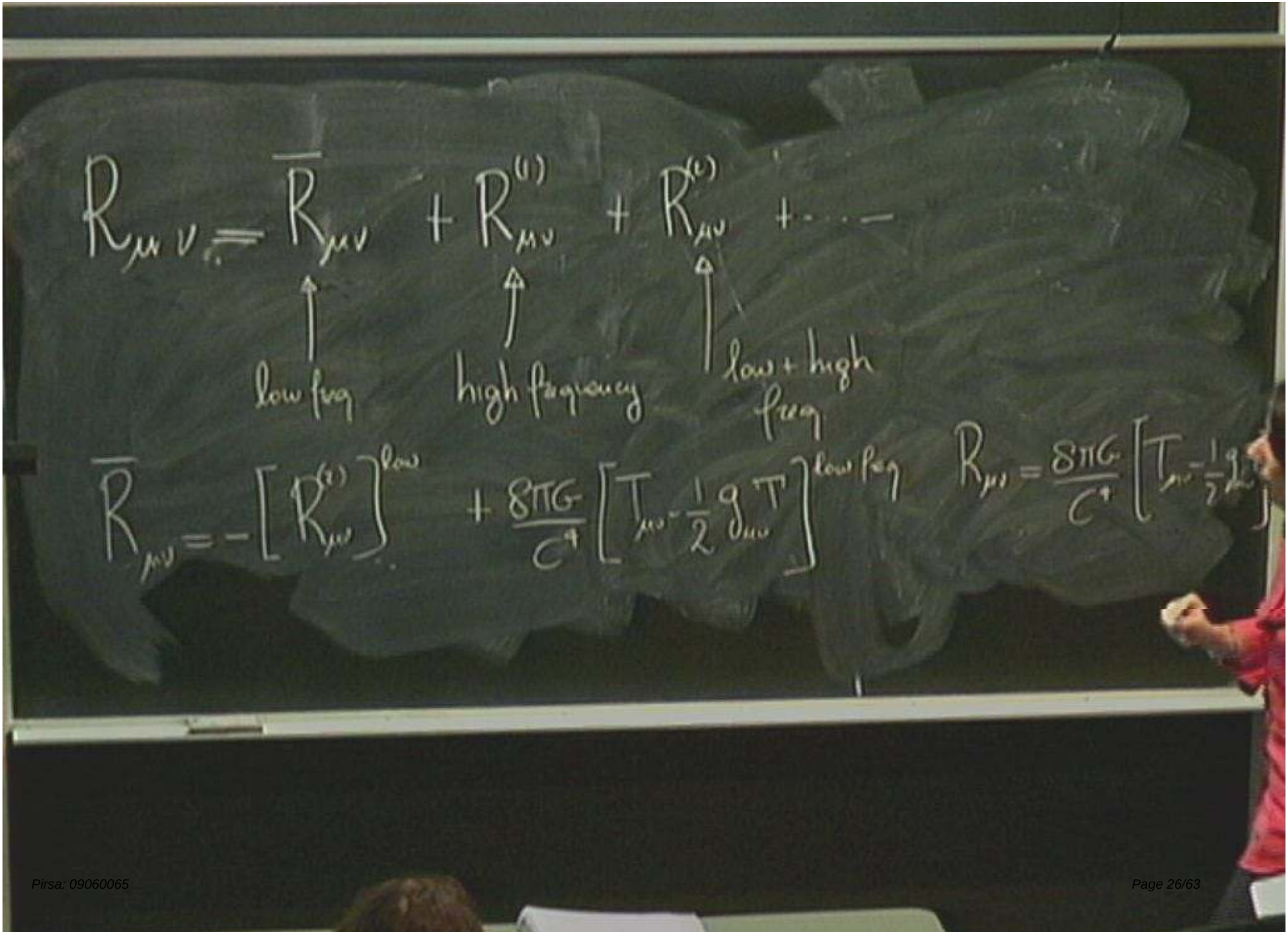
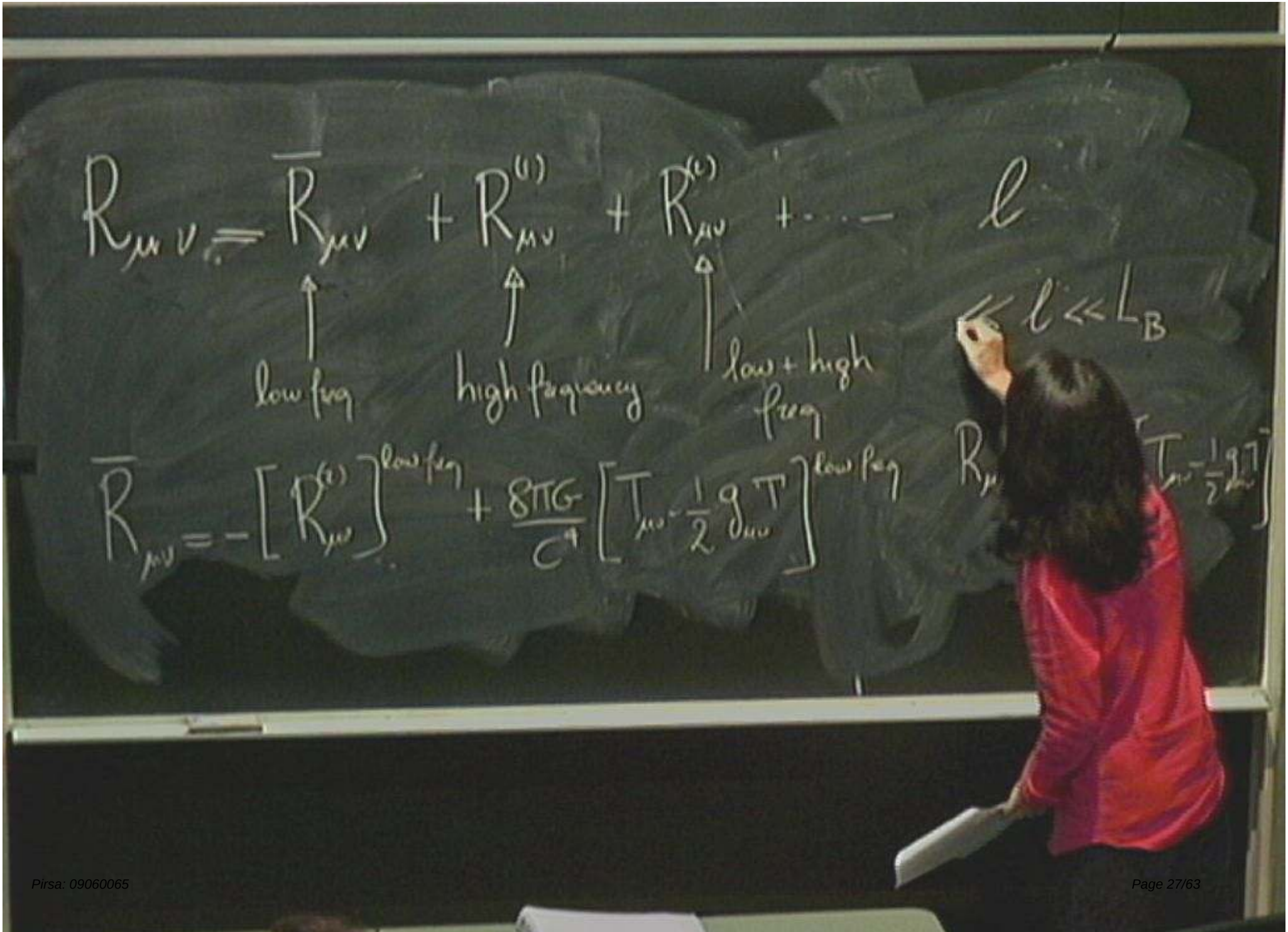
low freq
high frequency
low + high
$\bar{R}_{\mu\nu} = -\left[R^{(2)}_{\mu\nu}\right]^{low} + \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2}$
$R_{\mu\nu} = \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2}\right]$


$R_{\mu\nu} = \bar{R}_{\mu\nu} + R^{(1)}_{\mu\nu} + R^{(2)}_{\mu\nu} + \cdots$
low freq
high frequency
low + high freq
$\bar{R}_{\mu\nu} = -\left[R^{(1)}_{\mu\nu}\right]^{low} + \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right]^{low\ freq}$
$R_{\mu\nu} = \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2}$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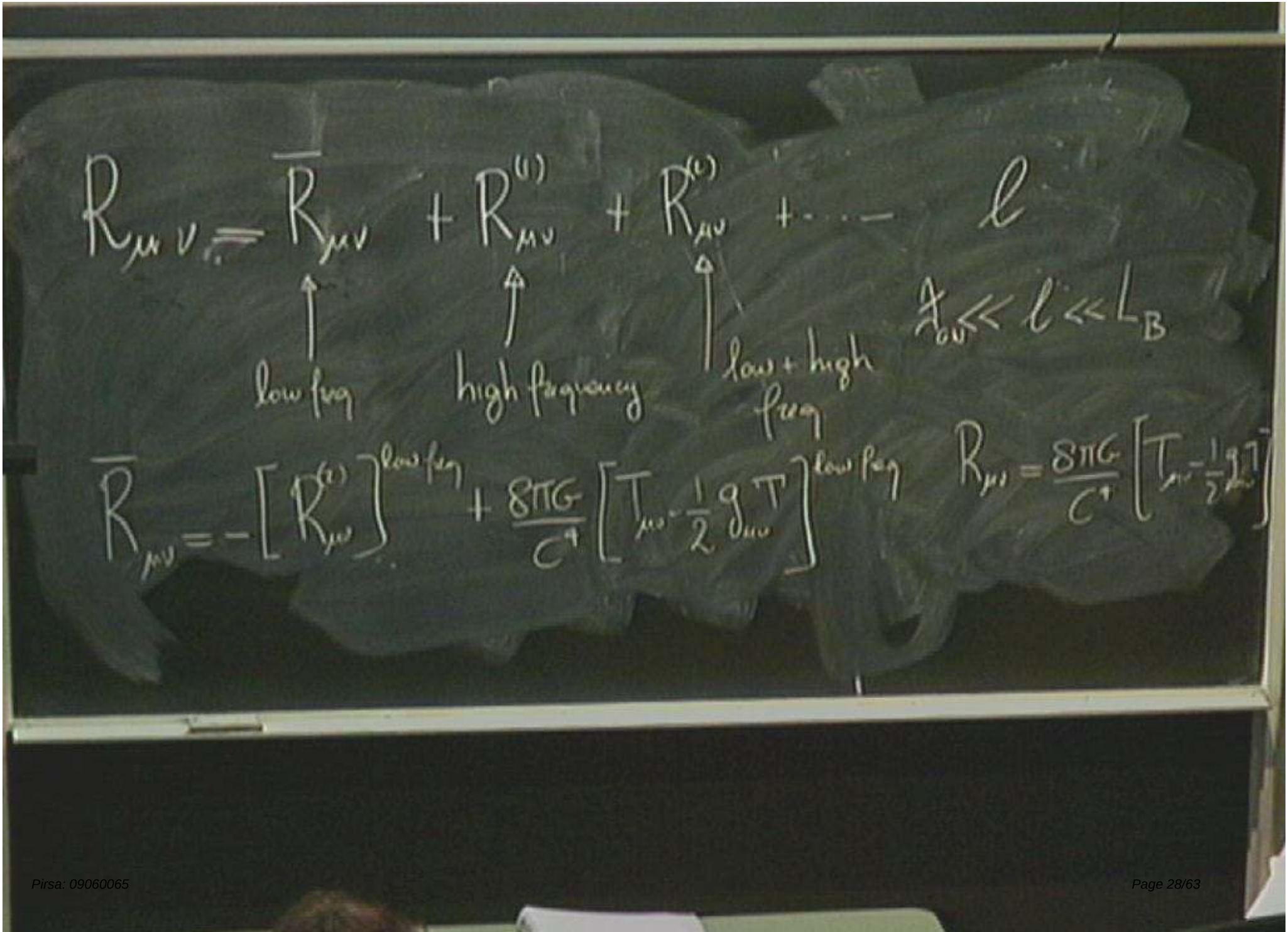
ℓ
low freq
high frequency
low + high freq
$\ell \ll L_B$
$\bar{R}_{\mu\nu} = -\left[R^{(2)}_{\mu\nu}\right]^{\text{low freq}} + \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right]^{\text{low freq}}$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low + high freq
$\lambda_{GW} \ll \ell \ll L_B$
$\bar{R}_{\mu\nu} = -\left[R^{(2)}_{\mu\nu}\right]^{\text{low freq}} + \frac{8\pi G}{c^4}\left[T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right]^{\text{low freq}}$
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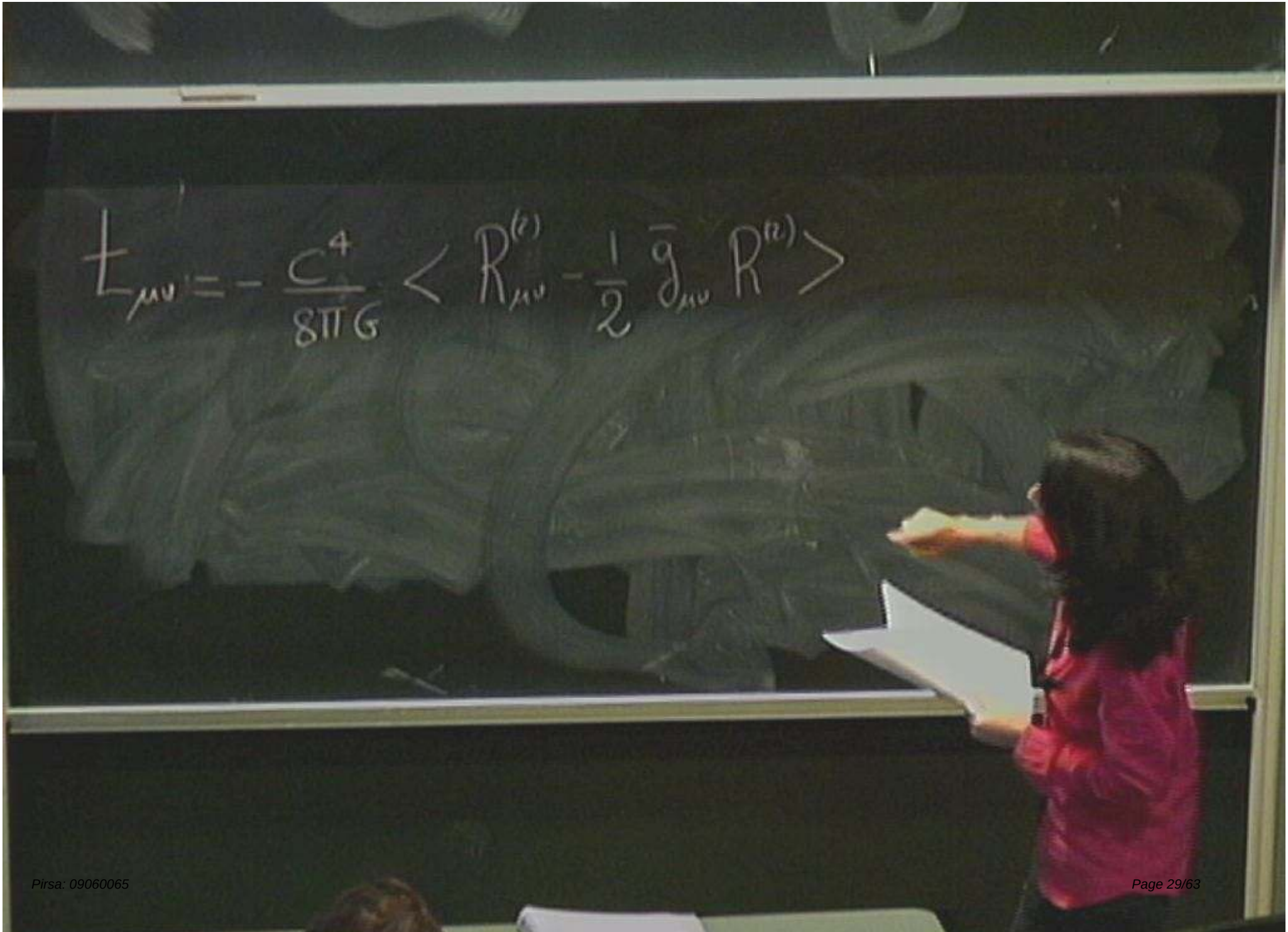
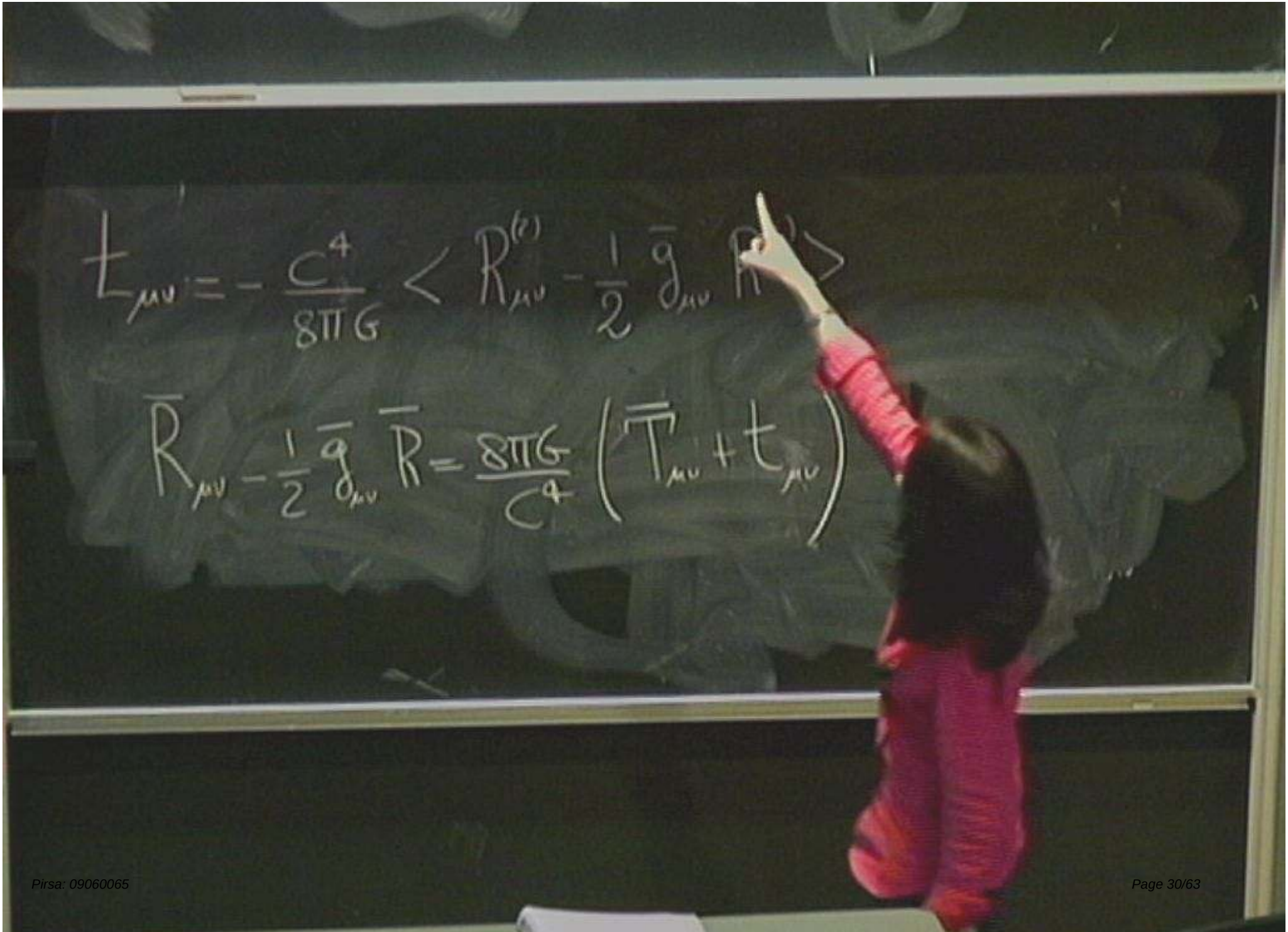

$t_{\mu\nu} = -\frac{c^4}{8\pi G} < R^{(1)}_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu} R^{(1)} >$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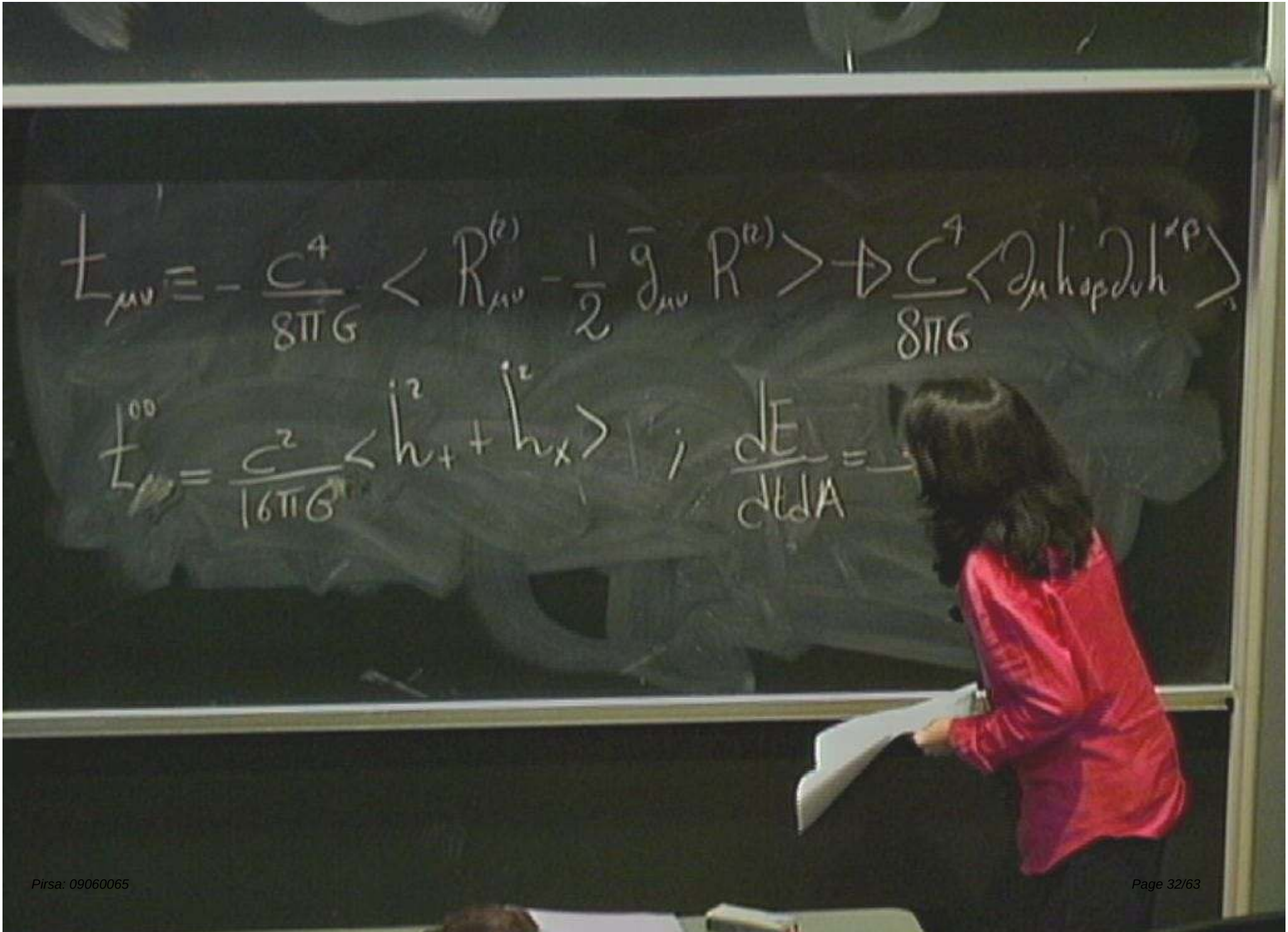
$\bar{R}_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}\bar{R} = \frac{8\pi G}{c^4}\left(\bar{T}_{\mu\nu} + t_{\mu\nu}\right)$

$$t_{\mu\nu} \equiv -\frac{c^4}{8\pi G}\left\langle R^{(2)}_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu} R^{(2)} \right\rangle \Rightarrow \frac{c^4}{8\pi G}\left\langle \partial_\mu h_{\alpha\beta} \partial_\nu h^{\alpha\beta} \right\rangle$$

$$t^{00}_{GW} = \frac{c^2}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$$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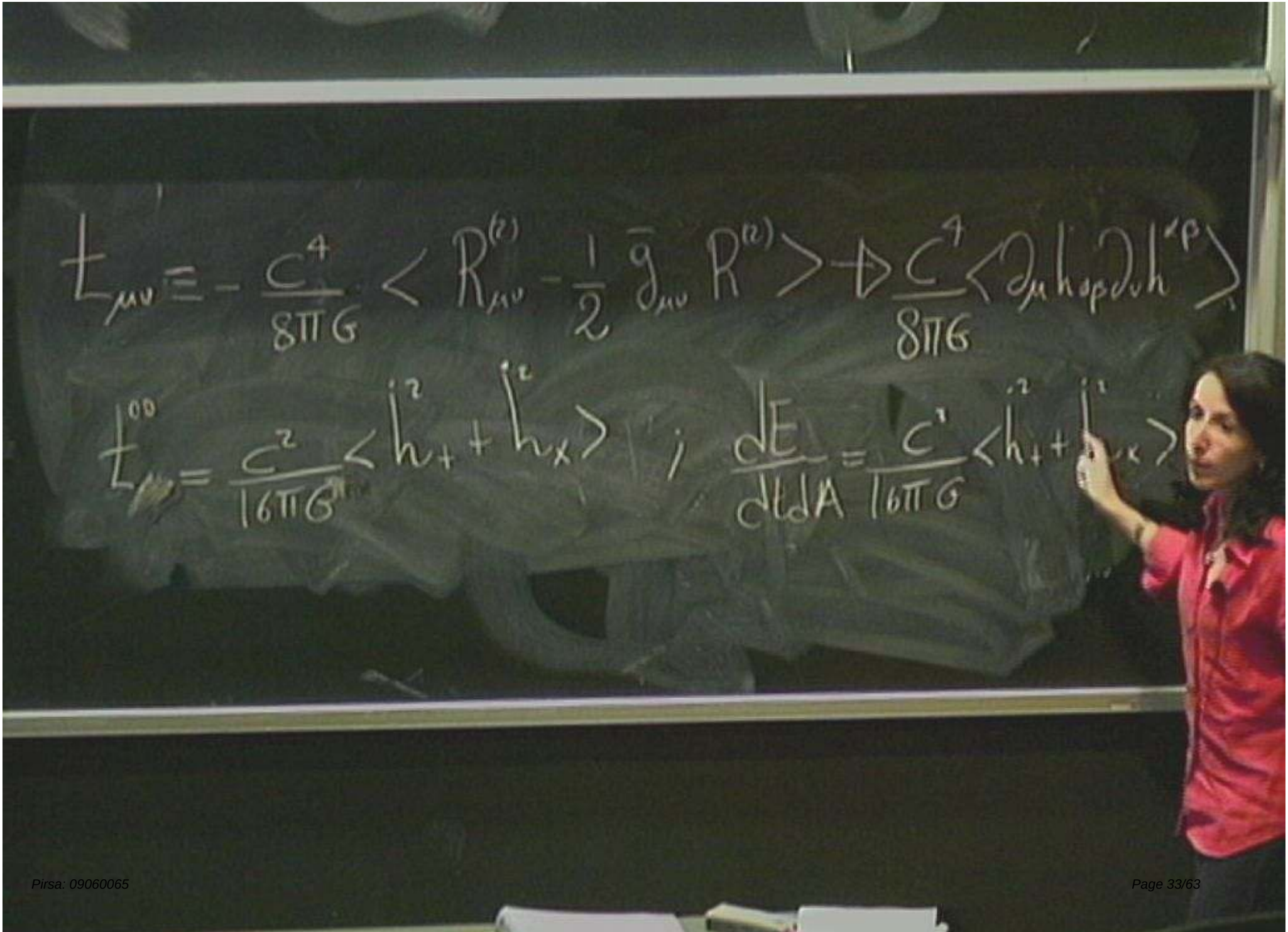
$t^{00} = \frac{c^2}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$; $\frac{dE}{dtdA} =$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$t^{00}_{GW} = \frac{c^2}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$; $\frac{dE}{dt\,dA} = \frac{c^3}{16\pi G}\left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle$

Multipolar decomposition of waves in linear gravity

- Multipole expansion in terms of mass moments (I_L) and mass-current moments (J_L) of the source

$$h \sim \overbrace{\frac{G}{c^2}\frac{I_0}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^3}\frac{\dot{I}_1}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^4}\frac{\ddot{I}_2}{r}}^{\text{mass quadrupole}} + \cdots$$

$$\cdots + \underbrace{\frac{G}{c^4}\frac{\dot{J}_1}{r}}_{\text{can't oscillate}} + \underbrace{\frac{G}{c^5}\frac{\ddot{J}_2}{r}}_{\text{current quadrupole}} + \cdots$$

- Typical strength: $h \sim \frac{G}{c^4}\frac{M\,L^2}{P^2}\frac{1}{r} \sim \frac{G(E_{\rm kin}/c^2)}{c^2\,r}$

If $E_{\rm kin}/c^2 \sim 1 M_\odot$, **depending on** $r \quad \Rightarrow \quad h \sim 10^{-23}$–$10^{-17}$

Quadrupole nature of GW emission [naive way]

EM theory: Luminosity $\propto \ddot{\mathbf{d}}^2$ $\mathbf{d} = e\,\mathbf{x} \Rightarrow$ electric dipole moment

- GW theory: electric dipole moment $\Rightarrow$ mass dipole moment

$$\mathbf{d} = \sum_i m_i \mathbf{x}_i \Rightarrow \dot{\mathbf{d}} = \sum_i m_i \dot{\mathbf{x}}_i = \mathbf{P}$$

Conservation of momentum $\Rightarrow$ no mass dipole radiation exists in GR

- GW theory: magnetic dipole moment $\Rightarrow$ current dipole moment

$$\mu = \sum_i m_i \mathbf{x}_i \times \dot{\mathbf{x}}_i = \mathbf{J}$$

Conservation of angular momentum $\Rightarrow$ no current dipole radiation exists in GR

Quadrupole nature of GW emission [naive way]

EM theory: Luminosity $\propto \ddot{\mathbf{d}}^2$ $\mathbf{d} = e\,\mathbf{x} \Rightarrow$ electric dipole moment

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$$\mu = \sum_i m_i \mathbf{x}_i \times \dot{\mathbf{x}}_i = \mathbf{J}$$

Conservation of angular momentum $\Rightarrow$ no current dipole radiation exists in GR

Comparison between GW and EM luminosity

$$\mathcal{L}_{\rm GW} = \frac{G}{5c^5}\,(\dddot{I}_2)^2 \qquad I_2 \sim \epsilon\, M\, R^2$$

$R \rightarrow$ typical source's dimension, $M \rightarrow$ source's mass, $\epsilon \rightarrow$ deviation from sphericity

$$\dddot{I}_2 \sim \omega^3\, \epsilon\, M\, R^2 \text{ with } \omega \sim 1/P \quad \Rightarrow \quad \mathcal{L}_{\rm GW} \sim \frac{G}{c^5}\,\epsilon^2\,\omega^6\,M^2\,R^4$$

$$\mathcal{L}_{\rm GW} \sim \frac{c^5}{G}\,\epsilon^2\,\left(\frac{G\,M\,\omega}{c^3}\right)^6\,\left(\frac{R\,c^2}{G\,M}\right)^4 \Rightarrow \quad \frac{c^5}{G} = 3.6\times 10^{59} \text{ erg/sec (huge!)}$$

- For a steel rod of $M = 490$ tons, $R = 20$ m and $\omega \sim 28$ rad/sec:
  $GM\omega/c^3 \sim 10^{-32}$, $Rc^2/GM \sim 10^{25} \rightarrow \mathcal{L}_{\rm GW} \sim 10^{-27}$ erg/sec $\sim 10^{-60}\mathcal{L}^{\rm EM}_{\rm sun}$!
- If we introduce $R_S = 2GM/c^2$ and $\omega = (v/c)\,(c/R)$

$$\mathcal{L}_{\rm GW} = \frac{c^5}{G}\,\epsilon^2\,\left(\frac{v}{c}\right)^6\,\left(\frac{R_S}{R}\right) \underbrace{\Rightarrow}_{v\sim c,\, R\sim R_S} \mathcal{L}_{\rm GW} \sim \epsilon^2\,\frac{c^5}{G} \sim 10^{26}\,\mathcal{L}^{\rm EM}_{\rm sun}!$$

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$$h \sim \overbrace{\frac{G}{c^2}\frac{I_0}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^3}\frac{\dot{I}_1}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^4}\frac{\ddot{I}_2}{r}}^{\text{mass quadrupole}} + \cdots$$

$$\cdots + \underbrace{\frac{G}{c^4}\frac{\dot{J}_1}{r}}_{\text{can't oscillate}} + \underbrace{\frac{G}{c^5}\frac{\ddot{J}_2}{r}}_{\text{current quadrupole}} + \cdots$$

- Typical strength: $h \sim \frac{G}{c^4}\frac{M L^2}{P^2}\frac{1}{r} \sim \frac{G(E_{\rm kin}/c^2)}{c^2 r}$

If $E_{\rm kin}/c^2 \sim 1 M_\odot$, **depending on** $r \quad \Rightarrow \quad h \sim 10^{-23}$–$10^{-17}$

Pirsa: 09060065

Quadrupole nature of GW emission [naive way]

EM theory: Luminosity $\propto \ddot{\mathbf{d}}^2$ $\mathbf{d} = e\,\mathbf{x} \Rightarrow$ electric dipole moment

- GW theory: electric dipole moment $\Rightarrow$ mass dipole moment

$$\mathbf{d} = \sum_i m_i \mathbf{x}_i \Rightarrow \dot{\mathbf{d}} = \sum_i m_i \dot{\mathbf{x}}_i = \mathbf{P}$$

Conservation of momentum $\Rightarrow$ no mass dipole radiation exists in GR

- GW theory: magnetic dipole moment $\Rightarrow$ current dipole moment

$$\mu = \sum_i m_i \mathbf{x}_i \times \dot{\mathbf{x}}_i = \mathbf{J}$$

Conservation of angular momentum $\Rightarrow$ no current dipole radiation exists in GR

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Multipolar decomposition of waves in linear gravity

- Multipole expansion in terms of mass moments (I_L) and mass-current moments (J_L) of the source

$$h \sim \overbrace{\frac{G}{c^2}\frac{I_0}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^3}\frac{\dot{I}_1}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^4}\frac{\ddot{I}_2}{r}}^{\text{mass quadrupole}} + \cdots$$

$$\cdots + \underbrace{\frac{G}{c^4}\frac{\dot{J}_1}{r}}_{\text{can't oscillate}} + \underbrace{\frac{G}{c^5}\frac{\ddot{J}_2}{r}}_{\text{current quadrupole}} + \cdots$$

- Typical strength: $h \sim \frac{G}{c^4}\frac{M\,L^2}{P^2}\frac{1}{r} \sim \frac{G(E_{\rm kin}/c^2)}{c^2\,r}$

If $E_{\rm kin}/c^2 \sim 1 M_\odot$, **depending on** $r \quad \Rightarrow \quad h \sim 10^{-23}$–$10^{-17}$

Pirsa: 09060065

GWs on the Earth: comparison with other kind of radiation

Supernova at 20 kpc:

- From GWs: $\sim 400 \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}} \left(\frac{f_{\mathrm{GW}}}{1\mathrm{kHz}}\right)^2 \left(\frac{h}{10^{-21}}\right)^2$ during few msecs
- From neutrino: $\sim 10^5 \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}}$ during 10 secs
- From optical radiation: $\sim 10^{-4} \frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}}$ during one week

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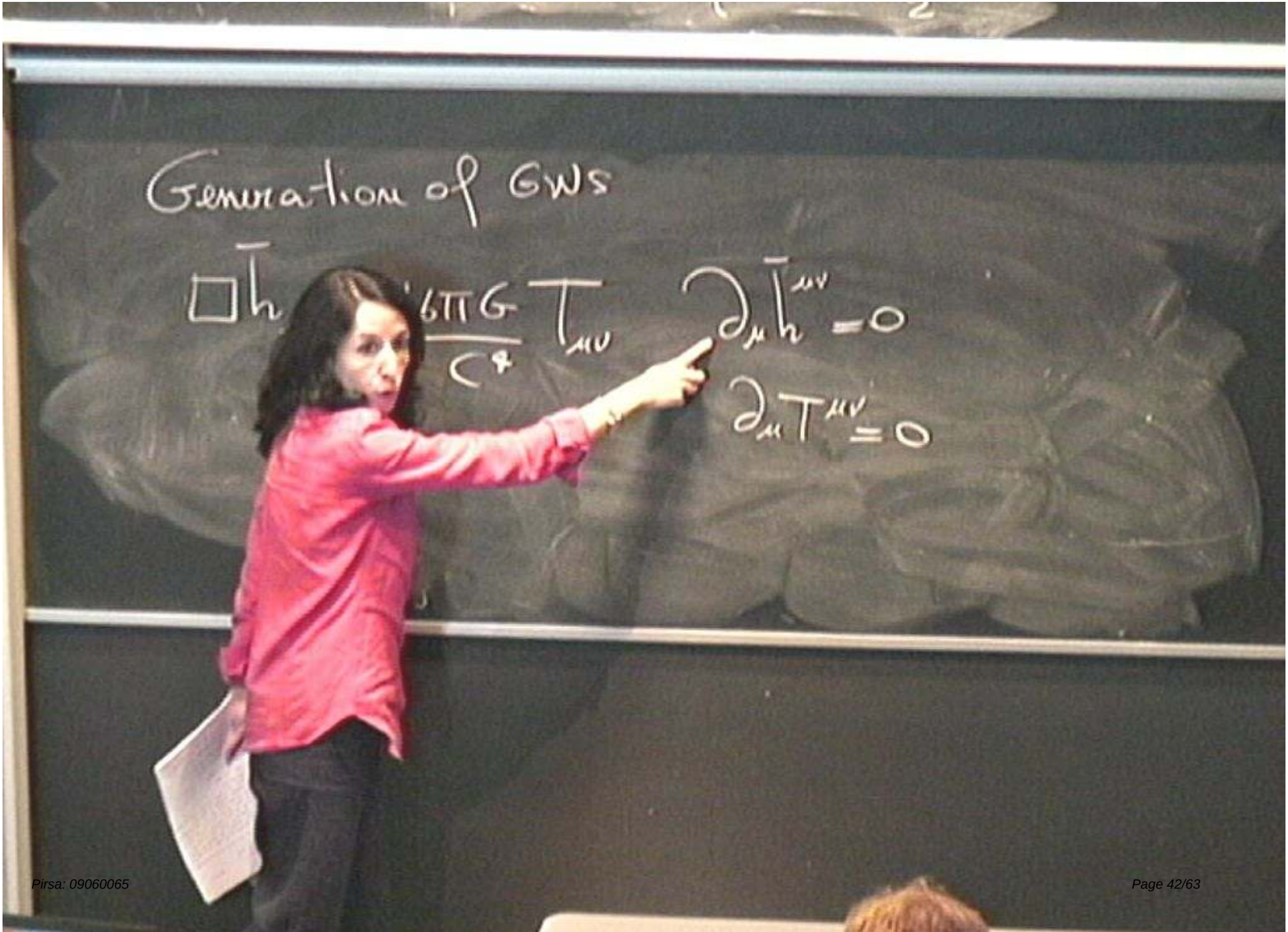
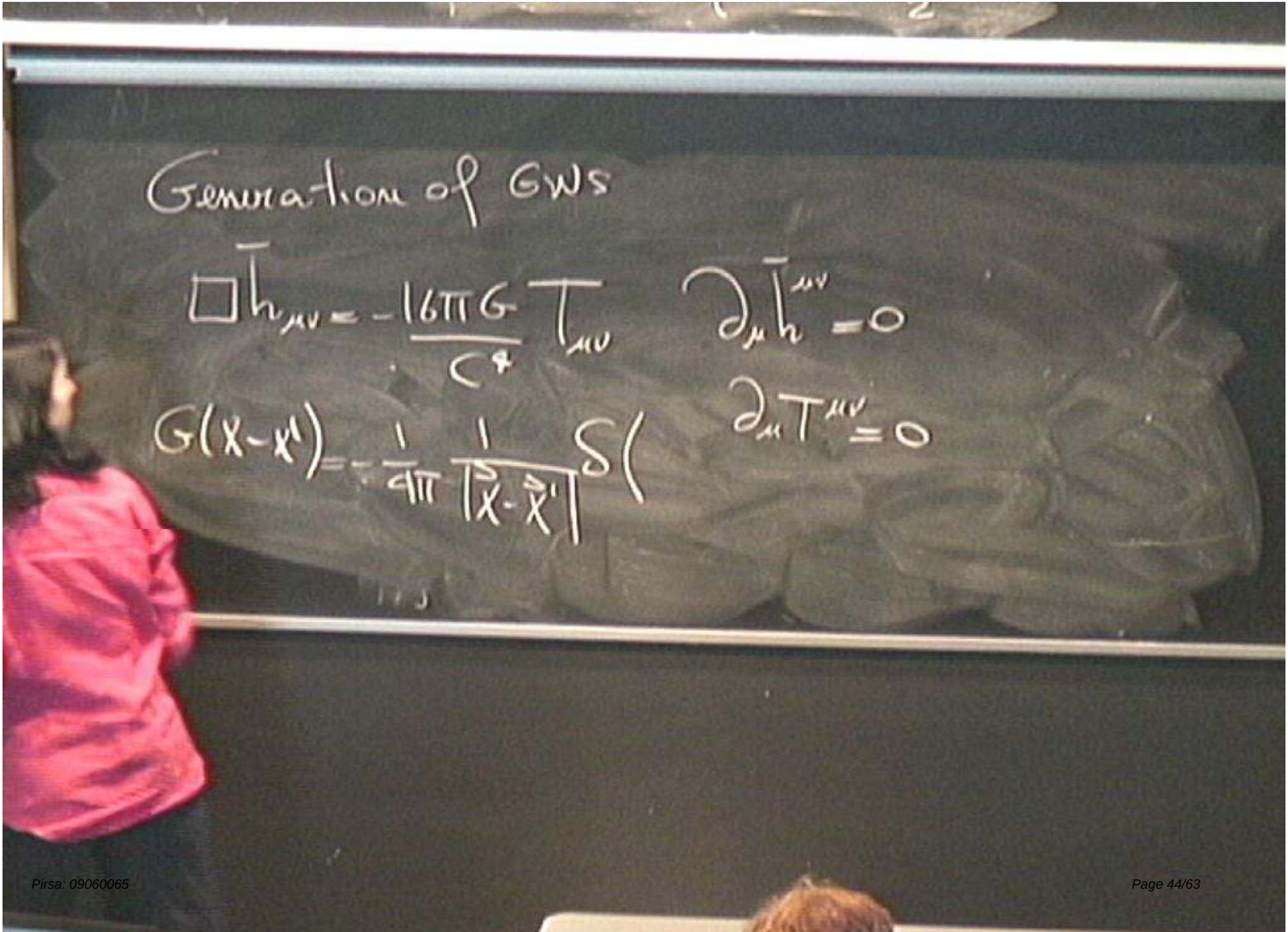

Generation of GWs
$\Box \bar{h} = \frac{16\pi G}{c^4} T_{\mu\nu}$
$\partial_\mu \bar{h}^{\mu\nu} = 0$
$\partial_\mu T^{\mu\nu} = 0$

Generation of GWs

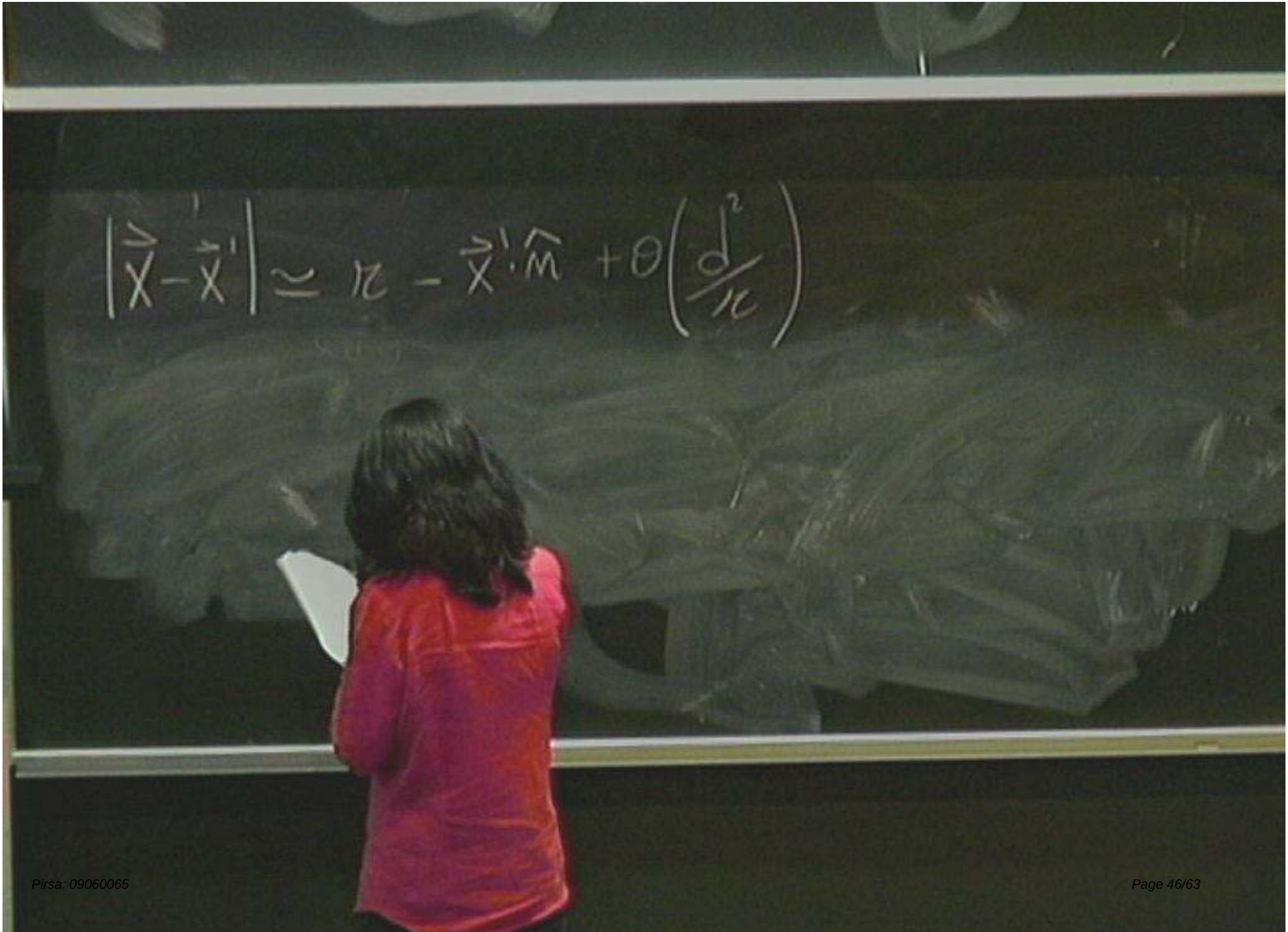
$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu} \qquad \partial_\mu \bar{h}^{\mu\nu} = 0$$

$$\partial_\mu T^{\mu\nu} = 0$$


Generation of GWs
$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$
$\partial_\mu \bar{h}^{\mu\nu} = 0$
$G(x-x') = -\frac{1}{4\pi} \frac{1}{|\vec{x}-\vec{x}'|} \delta($
$\partial_\mu T^{\mu\nu} = 0$

$d \rightarrow$ typical dimension of the source

$$h_{\mu\nu} = \frac{4G}{c^4} \int d^3x' \, \frac{1}{|\vec{x}-\vec{x}'|} \, T_{\mu\nu}\left(t - \frac{|\vec{x}-\vec{x}'|}{c}, \vec{x}'\right)$$


$|\vec{x} - \vec{x}'| \simeq r - \vec{x}' \cdot \hat{n} + O\left(\frac{d^2}{r}\right)$

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$$h^{TT}$$

$$|\vec{x} - \vec{x}'| \simeq r - \vec{x}' \cdot \hat{n} + O\left(\frac{d^2}{r}\right)$$

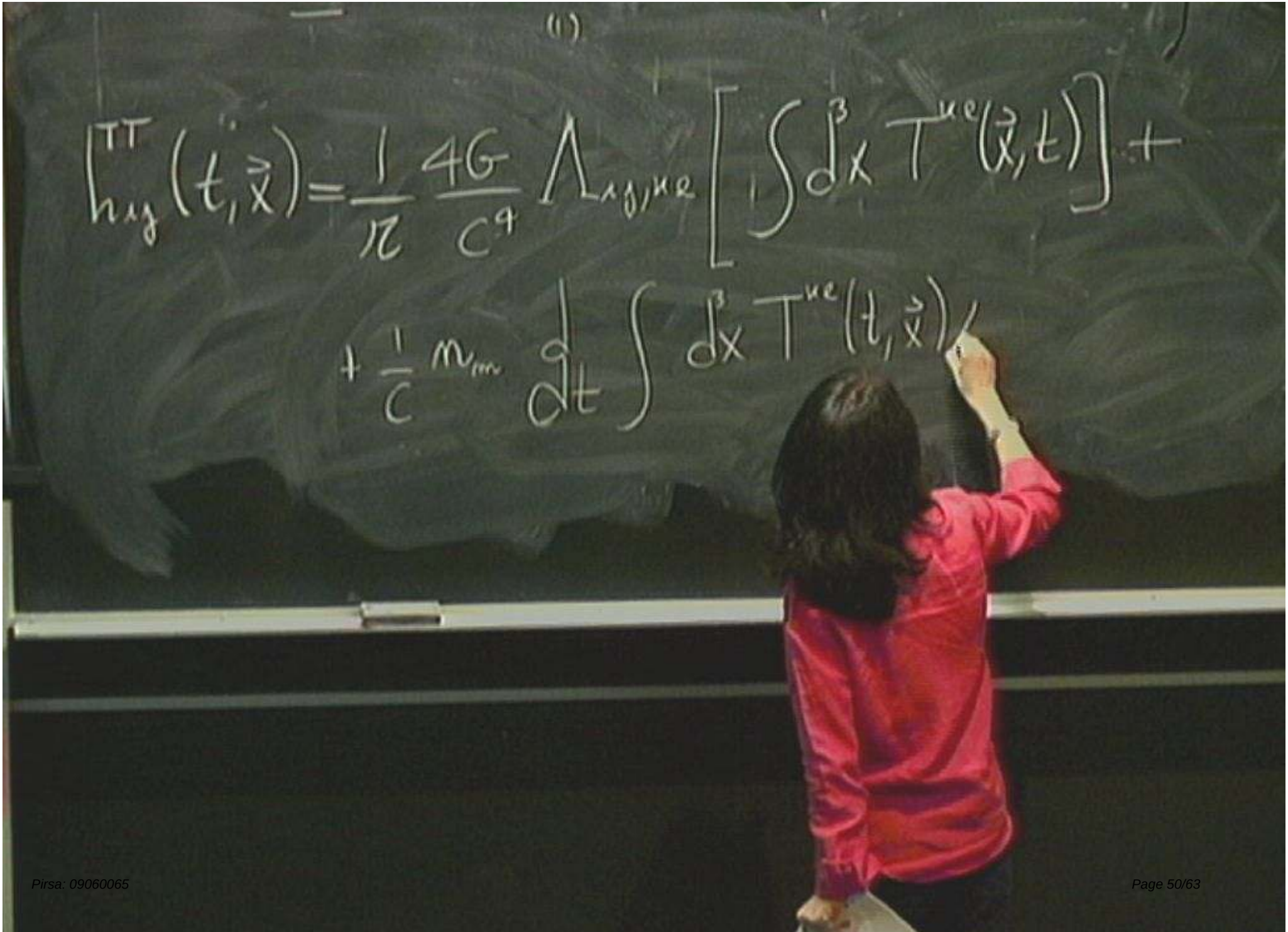
$$h^{TT}_{ij}(t, \vec{x}) \simeq \frac{1}{r} \frac{4G}{c^4} \Lambda_{ij,kl} \int_{|\vec{x}'|<d} d^3x' \, T_{kl}\left(t - \frac{r}{c} + \frac{\vec{x}' \cdot \hat{n}}{c}, \vec{x}'\right)$$

$$|\vec{x} - \vec{x}'| \simeq r - \vec{x}' \cdot \hat{n} + O\left(\frac{d^2}{r}\right)$$

$$\frac{\omega_s}{c} d \ll 1$$

slow motion

$$h^{TT}_{ij}(t, \vec{x}) \simeq \frac{1}{r} \frac{4G}{c^4} \Lambda_{ij,kl} \int_{|\vec{x}'|<d} d^3x' \, T_{kl}\left(t - \frac{r}{c} + \dots\right)$$


(1)
$h^{TT}_{ij}(t,\vec{x}) = \frac{1}{r}\frac{4G}{c^4}\Lambda_{ij,kl}\left[\int d^3x\, T^{kl}(\vec{x},t)\right] +$
$+ \frac{1}{c}\, m_{tm}\, \frac{d}{dt}\int d^3x\, T^{kl}(t,\vec{x})$

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$$+\frac{1}{c}n_m\frac{d}{dt}\int d^3x\, T^{kl}(t,\vec{x})x^m + \theta\left(\frac{1}{c^2}\right)\Bigg]$$

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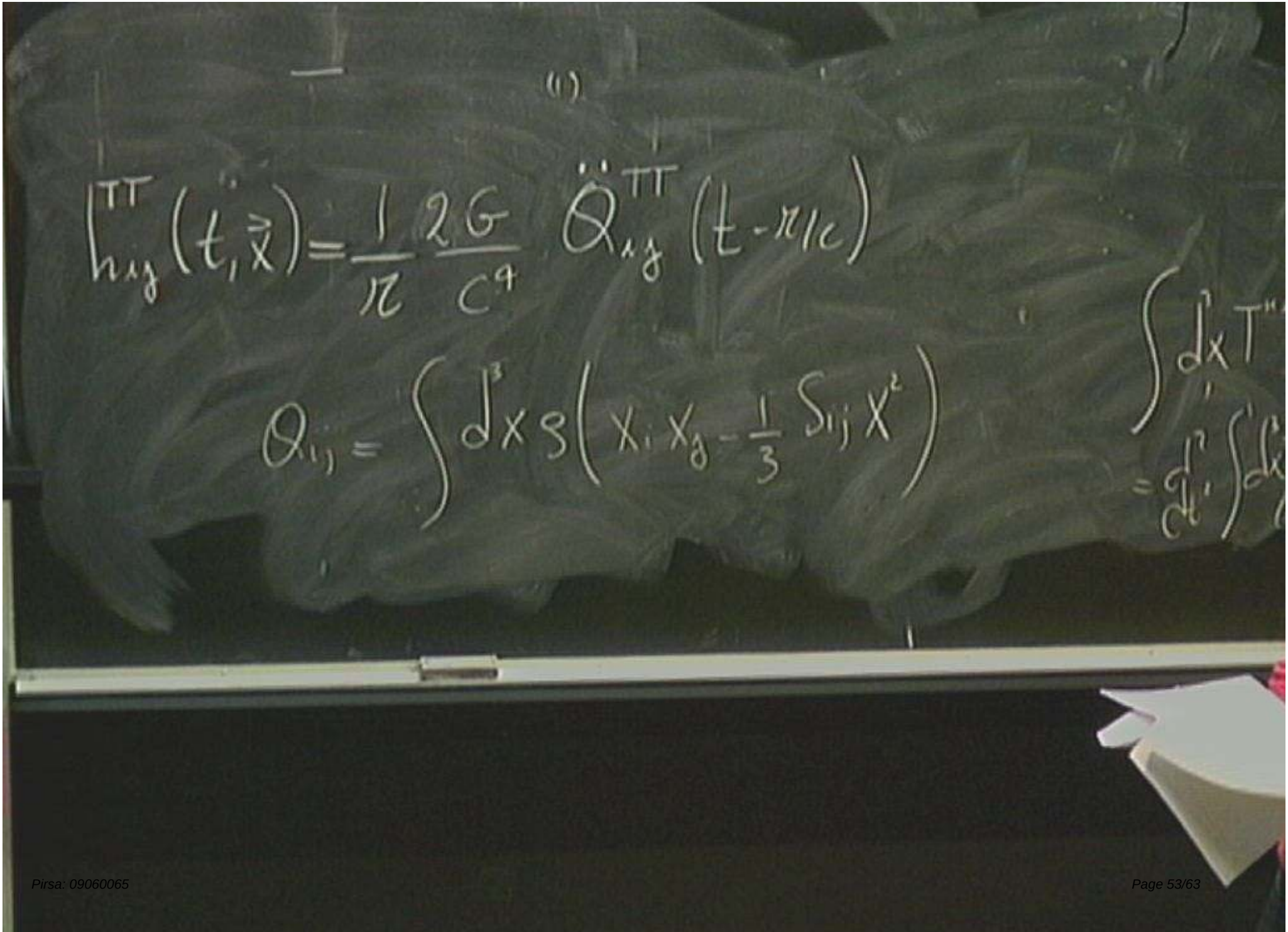
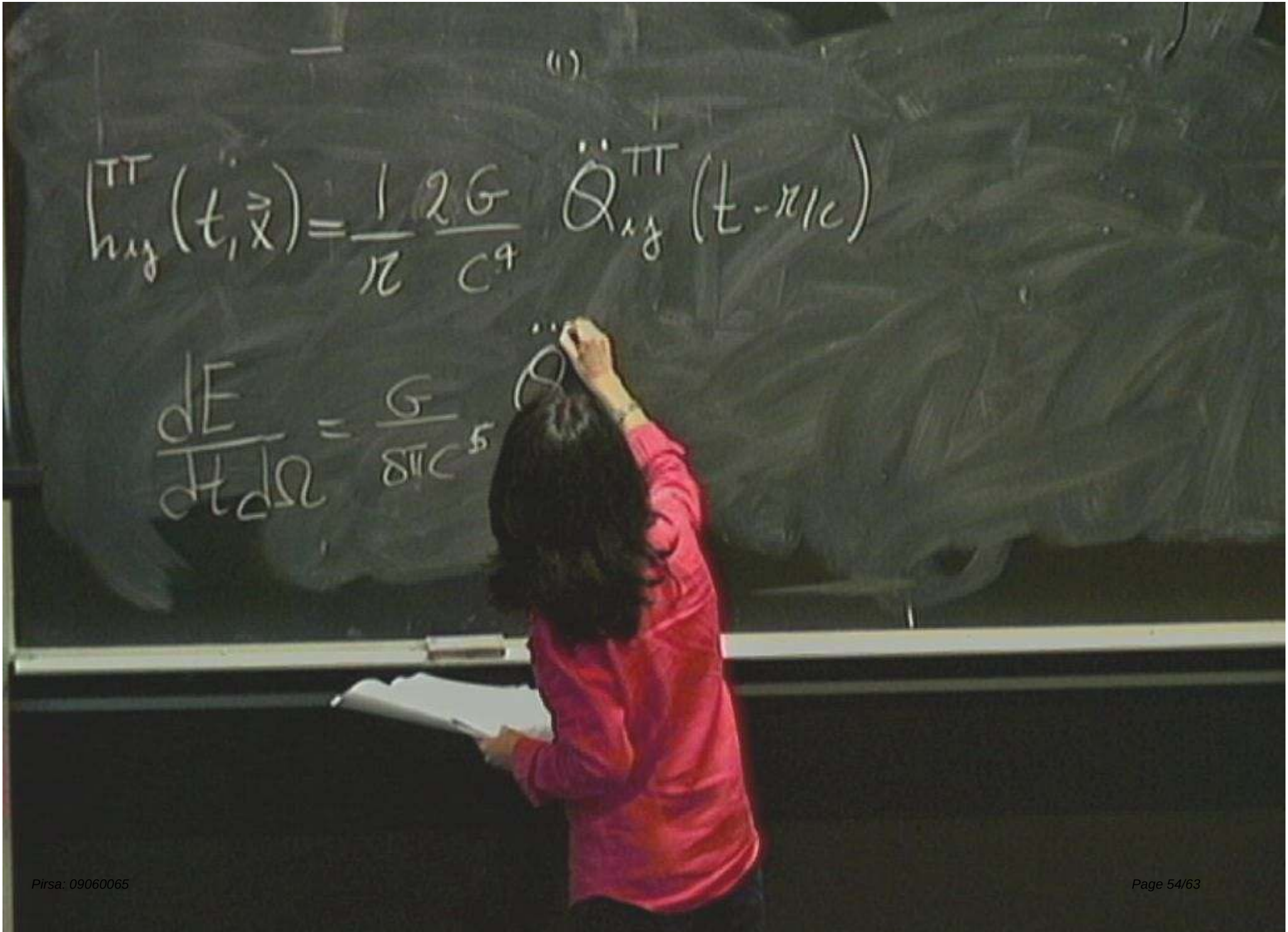
$$\frac{v}{c} \ll 1 \qquad \lambda_{GW} \gg d$$

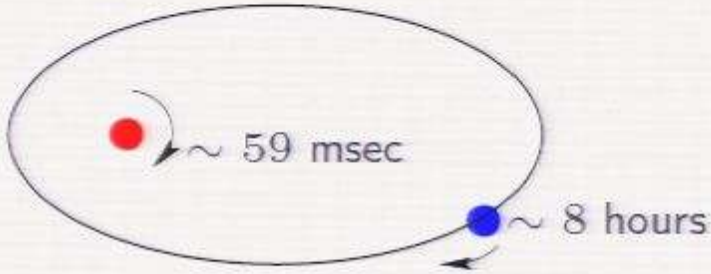

(1)
$h^{TT}_{ij}(t,\vec{x}) = \frac{1}{r}\frac{2G}{c^4}\ddot{Q}^{TT}_{ij}(t-r/c)$
$Q_{ij} = \int d^3x\, \rho\left(x_i x_j - \frac{1}{3}\delta_{ij}x^2\right)$
$\int d^3x\, T^{00}$
$= \frac{d^2}{dt^2}\int d^3x$


(1)
$h^{TT}_{ij}(t,\vec{x}) = \frac{1}{r}\frac{2G}{c^4}\ddot{Q}^{TT}_{ij}(t-r/c)$
$\frac{dE}{dt\,d\Omega} = \frac{G}{8\pi c^5}\dddot{Q}$

Indirect observation of gravitational wa

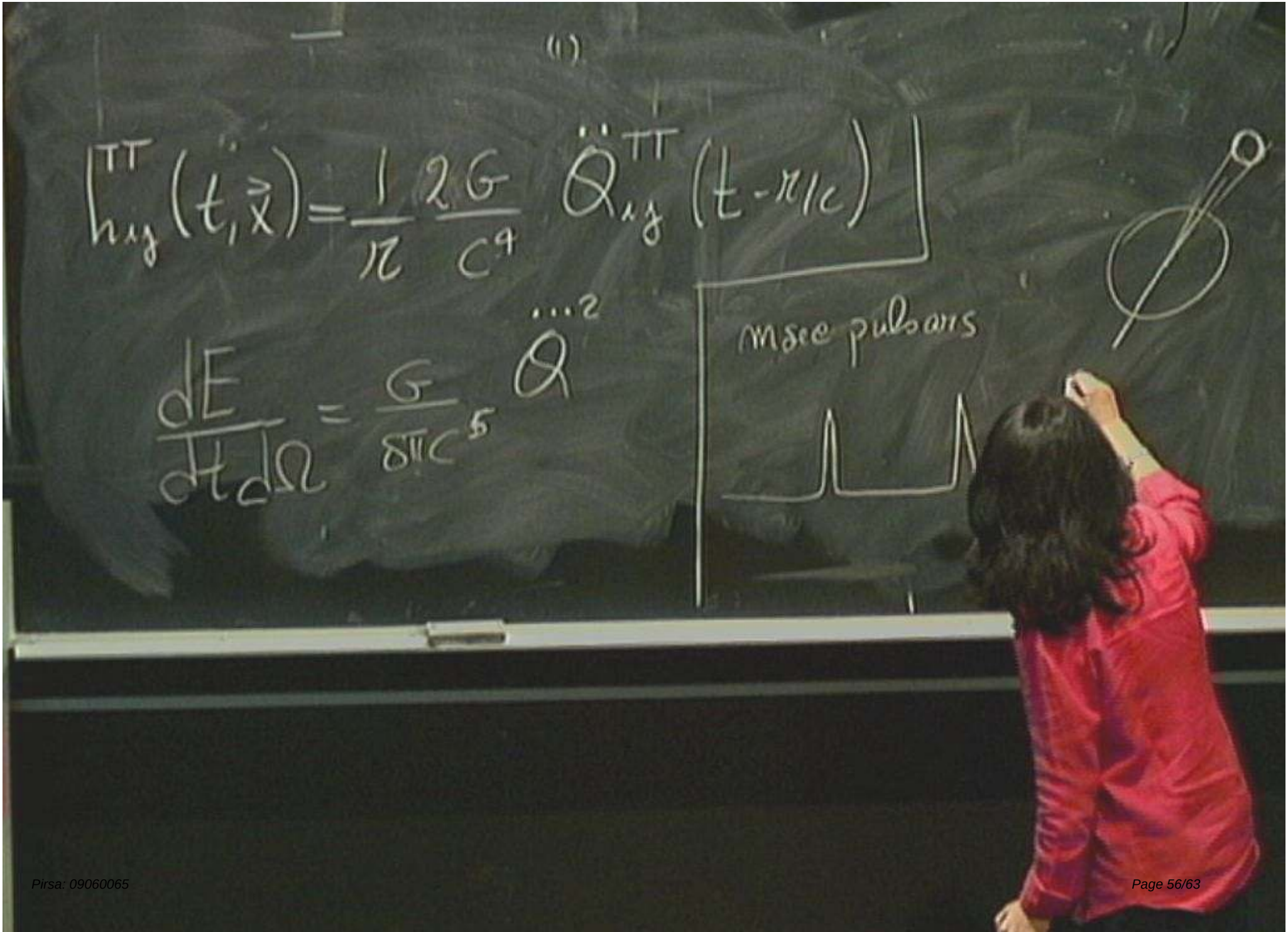
Neutron Binary System: PSR 1913 +16 - Timing Pulsars

Hulse & Taylor discovery (1974)



Separated by $\sim 10^6$ Km, $m_1 = 1.4 M_\odot$,
$m_2 = 1.36 M_\odot$, eccentricity $= 0.617$

- Prediction from GR: rate of change of orbital period
- Emission of gravitational waves:
  - due to loss of orbital energy
  - orbital decay in agreement with GR at the level of 0.5%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msec pulsars

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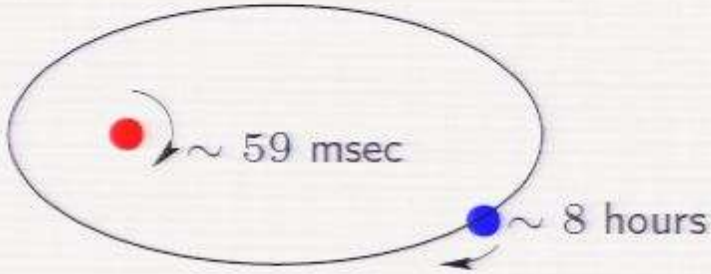

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Pirsa: 09060065

Hulse-Taylor binary: cumulative shift of periastron time

To show agreement with GR, they compared the *observed* orbital phase with a theoretical template phase

If f_b varies slowly with time, then to first order in a Taylor expansion

$$\Phi_b(t) = 2\pi\, f_b\, t + \pi \dot{f}_b\, t^2$$

Assuming that t_P is the periastron passage time defined as

$$\Phi(t_p) = 2\pi N \qquad N \text{ being an integer}$$

$$2\pi N = 2\pi f_b\, t_p + \pi \dot{f}_b\, t_p^2 \quad \Rightarrow \quad t_p - N/f_b = -\tfrac{1}{2}\dot{f}_b/f_b\, t^2$$

Pirsa: 09060065

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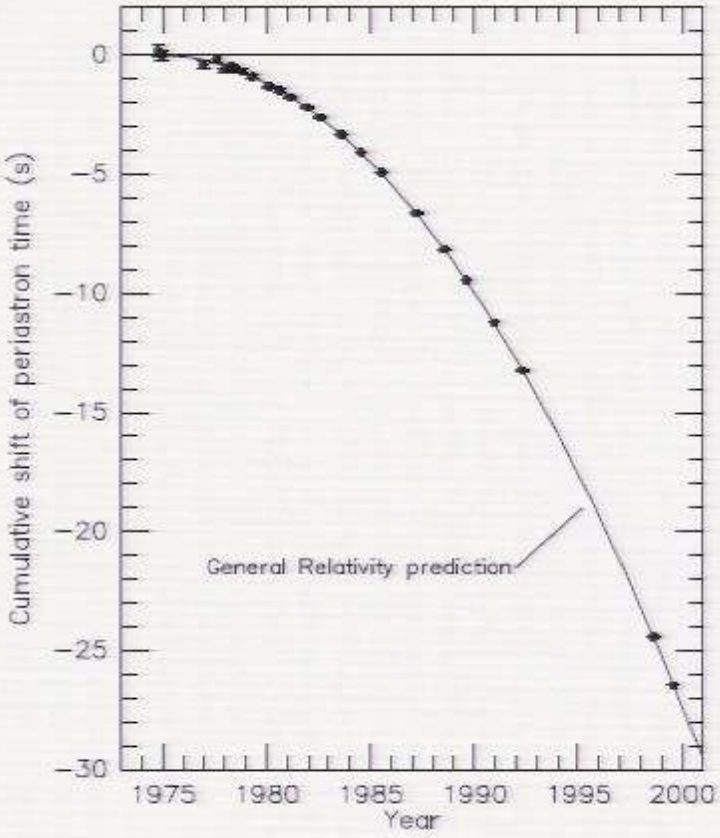
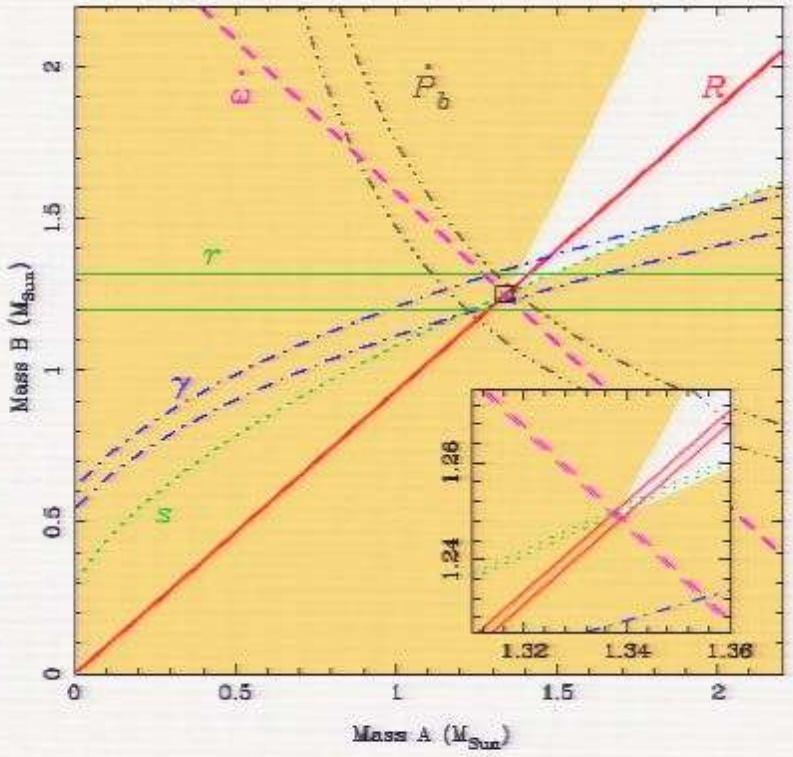


[from Taylor & Weisberg 2000]



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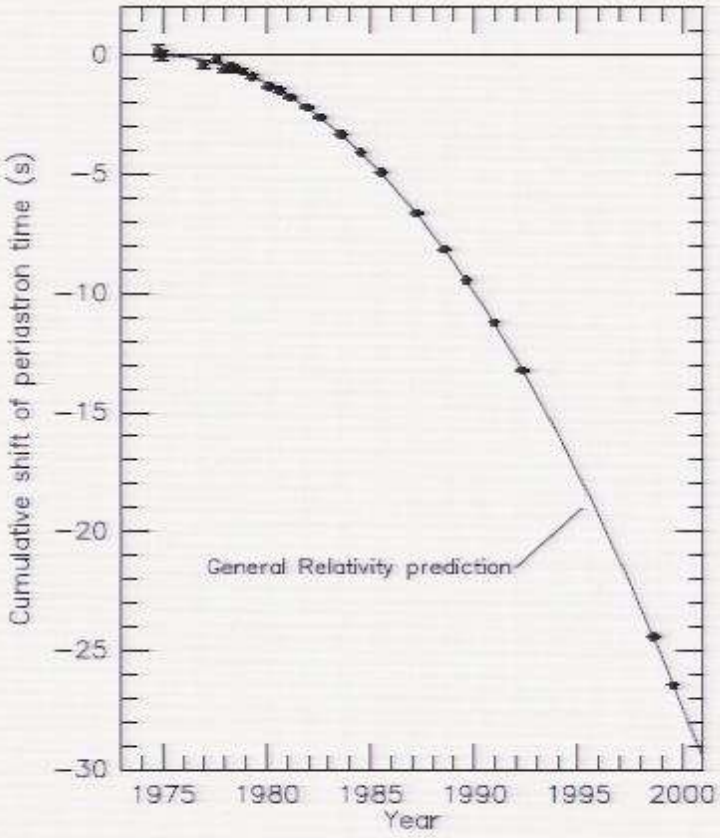

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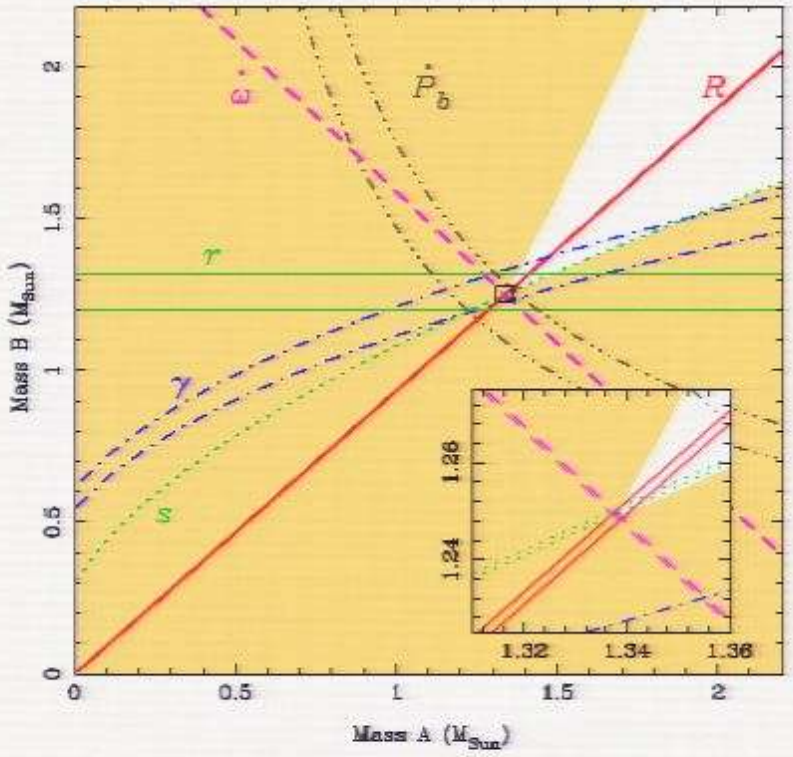

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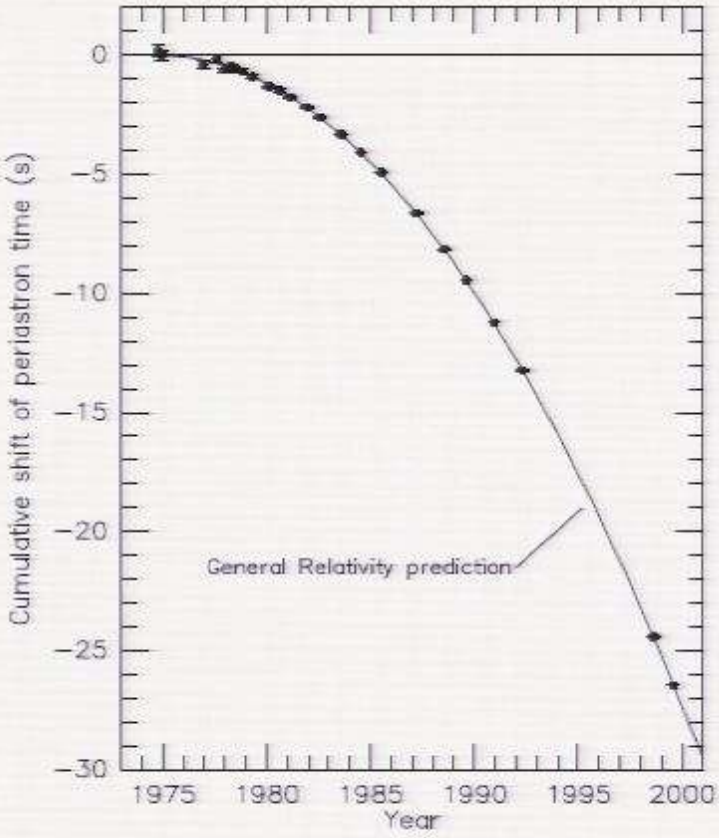

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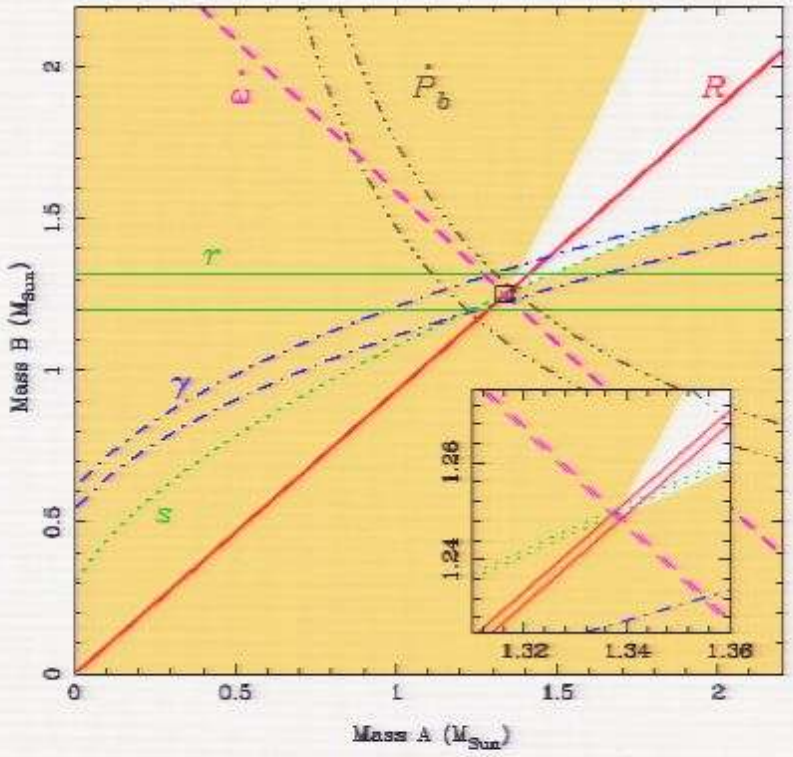

[from Kramer et al. 2005]

Known double pulsar binaries

PSR J0737-3039 [Burgay et al. 03; Lyne et al. 2004]

rot. period A 22.7 ms
rot. period B 2773.6 ms

orb. period 2 h and 45 min (will merge in 85 Myr!)
$e = 0.088$
distance $\sim 0.6kpc$ **(close!)**

$\Delta\phi = 16.900(2)\mathrm{deg/yr}$ **(large!)** $\dot{P} = -1.20(8)10^{-12}$

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