Title: Explorations in Numerical Relativity - Lecture 6

Date: Apr 11, 2011 09:00 AM

URL: http://pirsa.org/11040047

Abstract:

- Futurology: graves waves to be 'heard' this decade

- Detection/physics extraction: require at least some theoretical understanding of possible phenomenology
  - For binary black holes: status is pretty good [next week]
  - For bh-ns / ns-ns binaries: far from being so
    - Parameter space (physics ingredients) is quite messy/more difficult to explore. Still, rich pay off GW, NS eqn of state, probe of mag fields
  - *Exciting possibility: catch systems in both GW and EM bands*
    - Must understand different systems deep enough (to the extent possible) → Cosmology; Astrophysics; etc..
  - Aside of GravWaves. Plenty of systems where curvature

Goal:

Study systems likely to produce emission

- 'indirectly' by curvature affecting surrounding material: bh(s) + accretion disk
- 'directly' by the behavior of matter/plasmas in the system as affected by strong / highly dynamical curvature

Tall order: gravity + hydro + magnetic fields + ...

- Typically done in a piece meal way assuming different regimes
  - Inertia dominated : ideal MHD [e.g. stars..] $(j/\sigma \dashrightarrow 0)$
  - Plasma dominated: Force free [e.g. jets...] $(\rho_{EM} E + j_{EM} \times B = 0)$
  - Distant regions: Maxwell without currents

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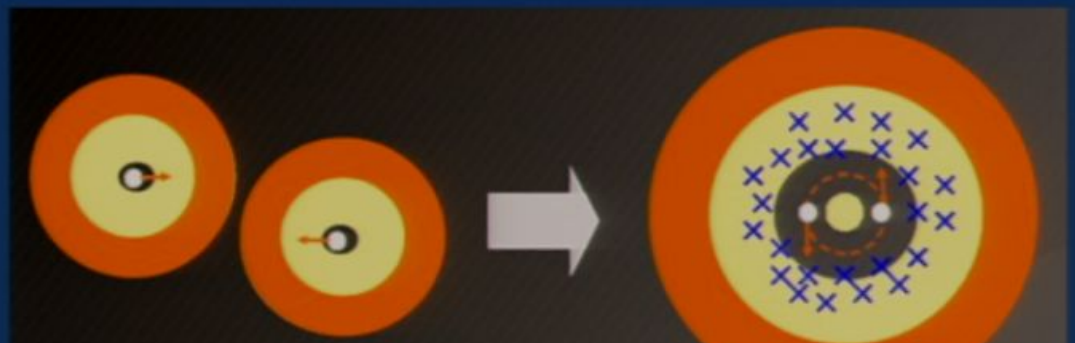
Binary black holes and emissions

- Different possible options.
  - Postmerger events from circumbinary disks around BHs

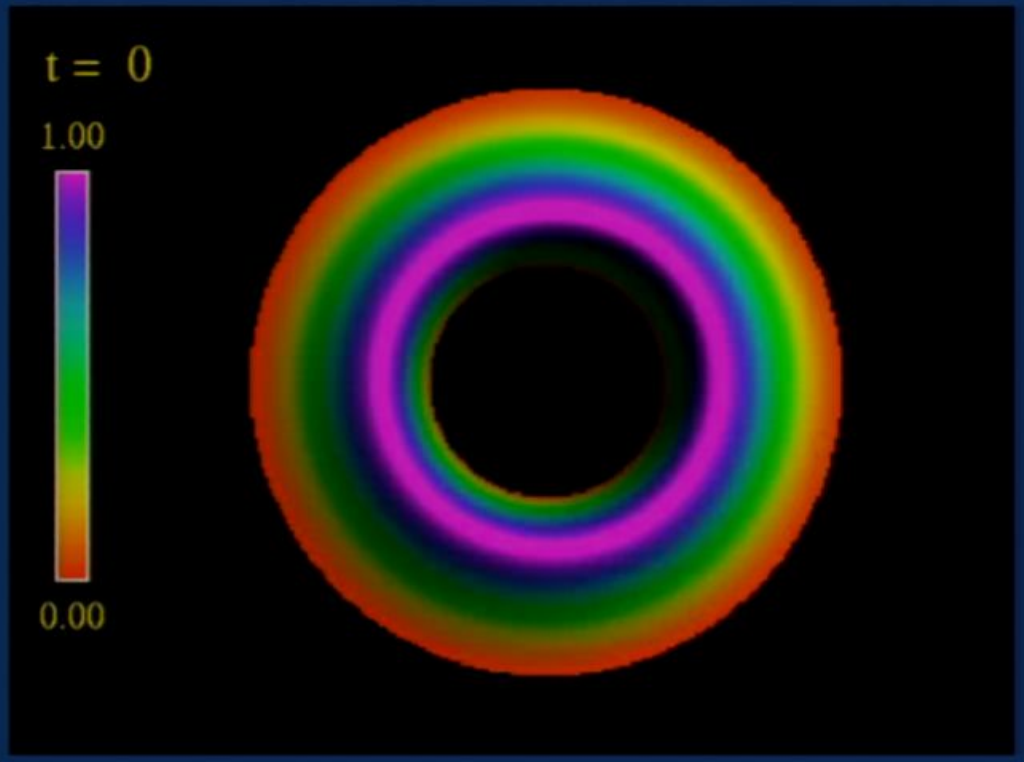
[Milosavljevic-Phinney; Lipai-Loeb; *Lipai et.al, Bonning et.al; Bode et.al; Megevand et.al*]

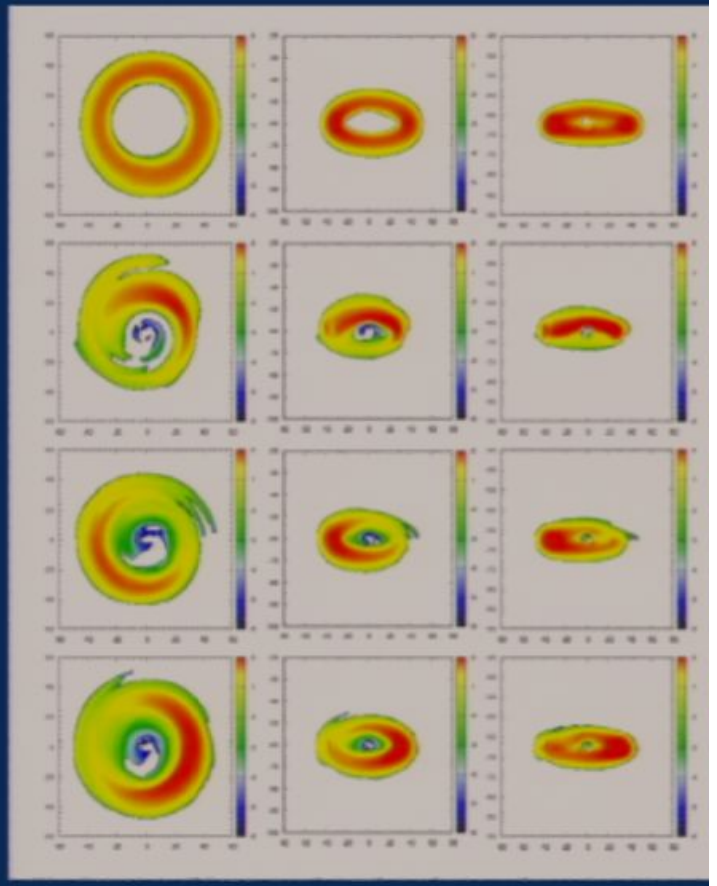
  - Pre/merger events from gas in between BHs / torques on dis



[Armitage et.al; MacFadyen et.al.; Dotti et.al; *Chang. et.al.; Palenzuela et.al.*]

Postmerger emission





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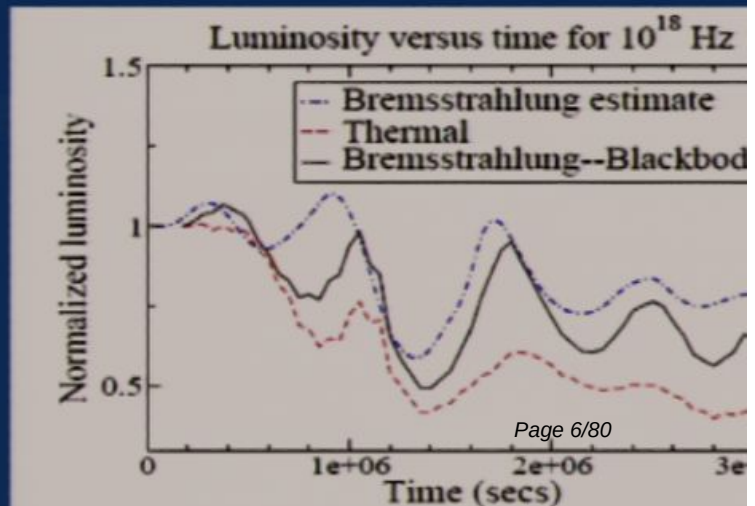

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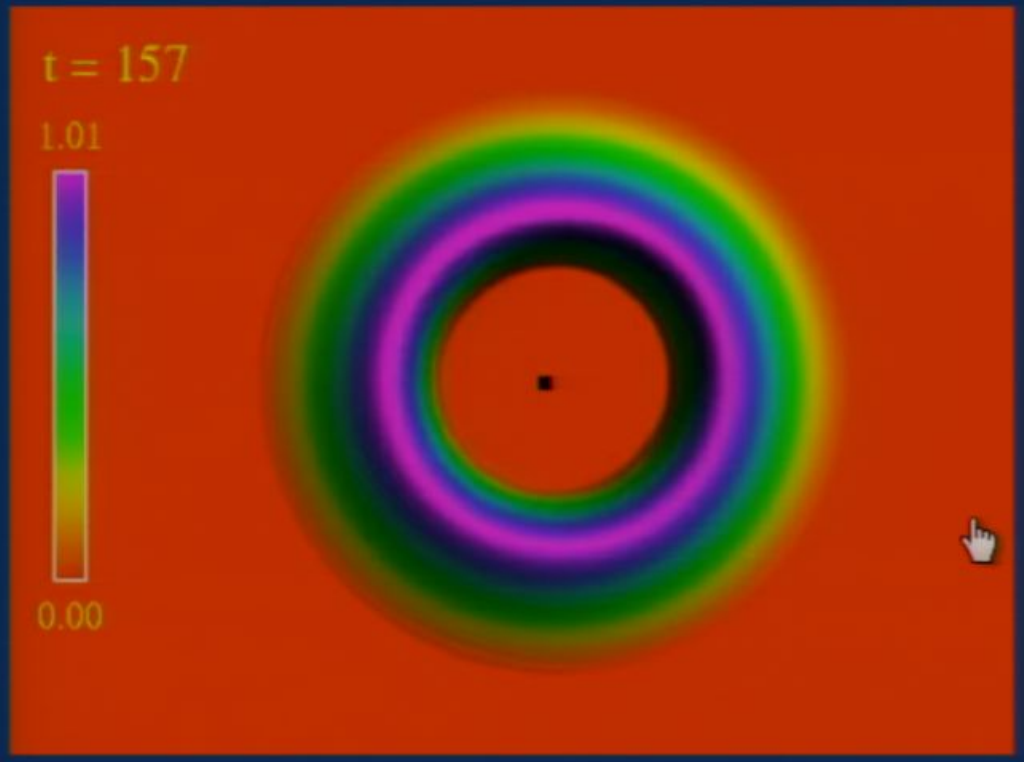

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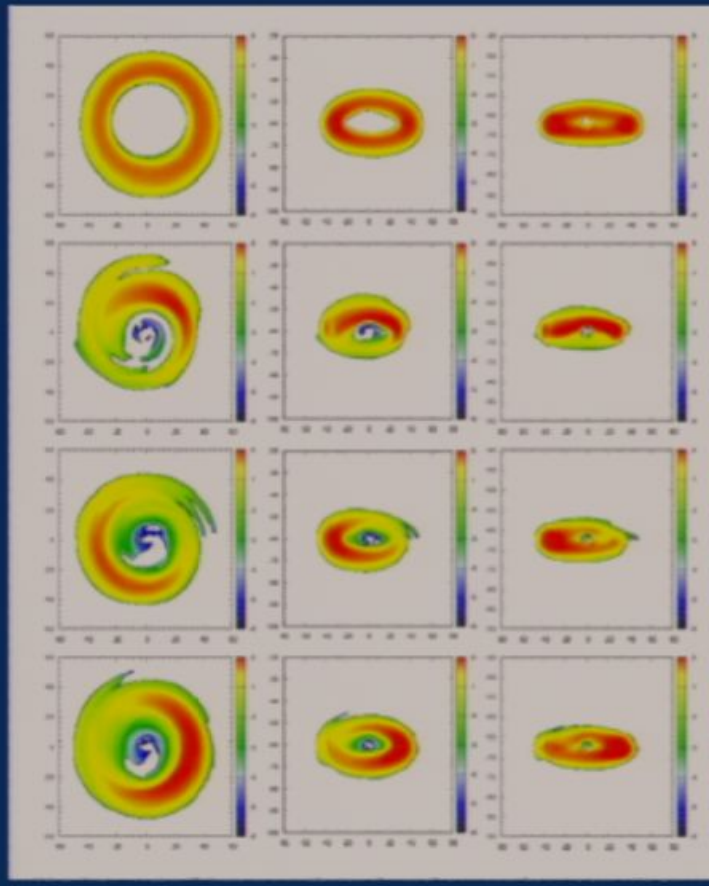

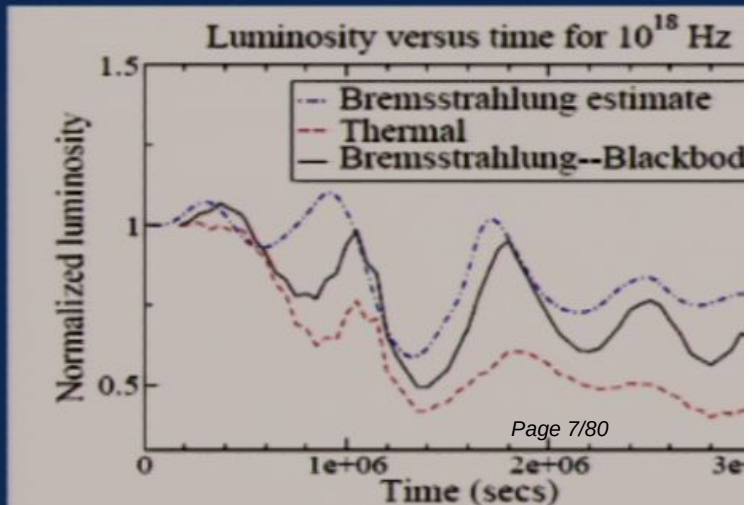

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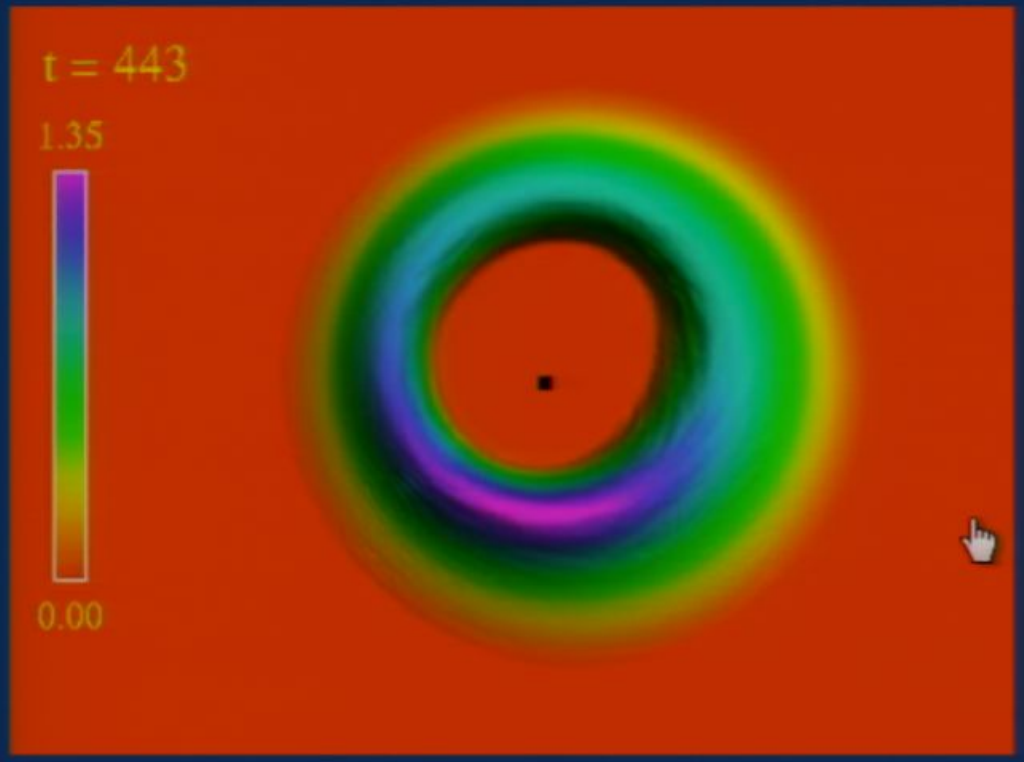

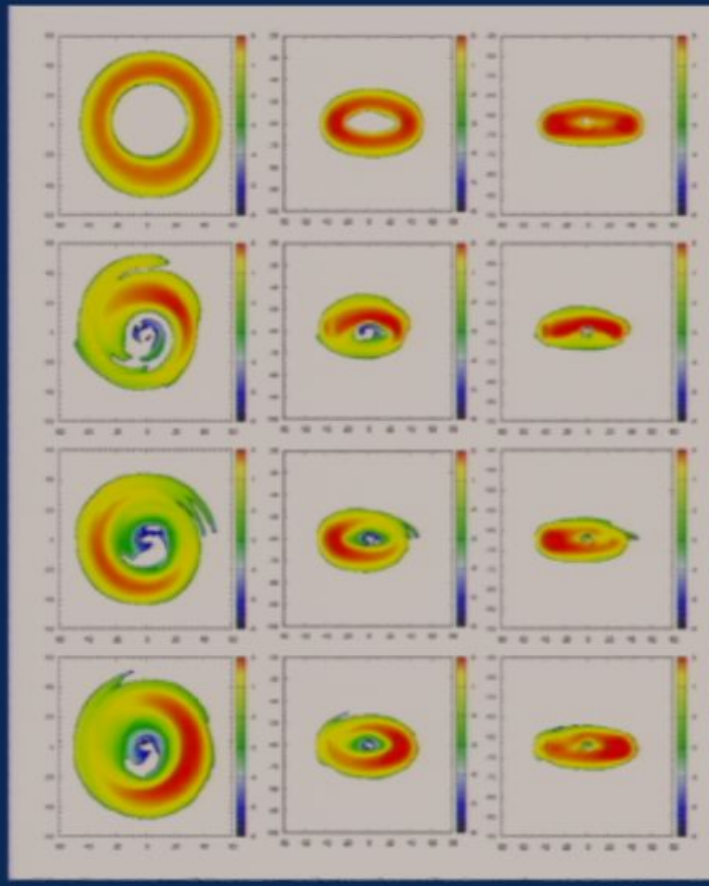

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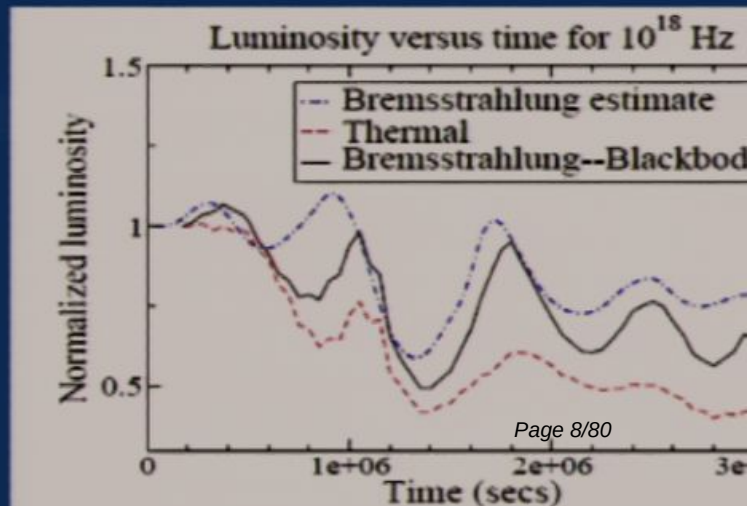

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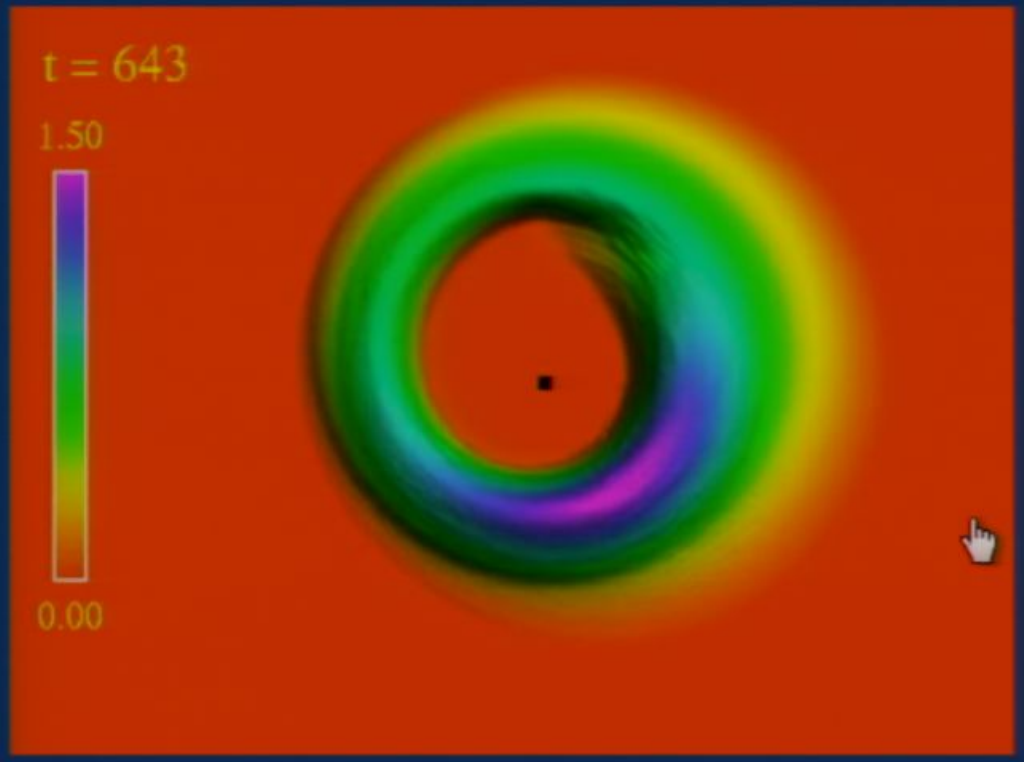

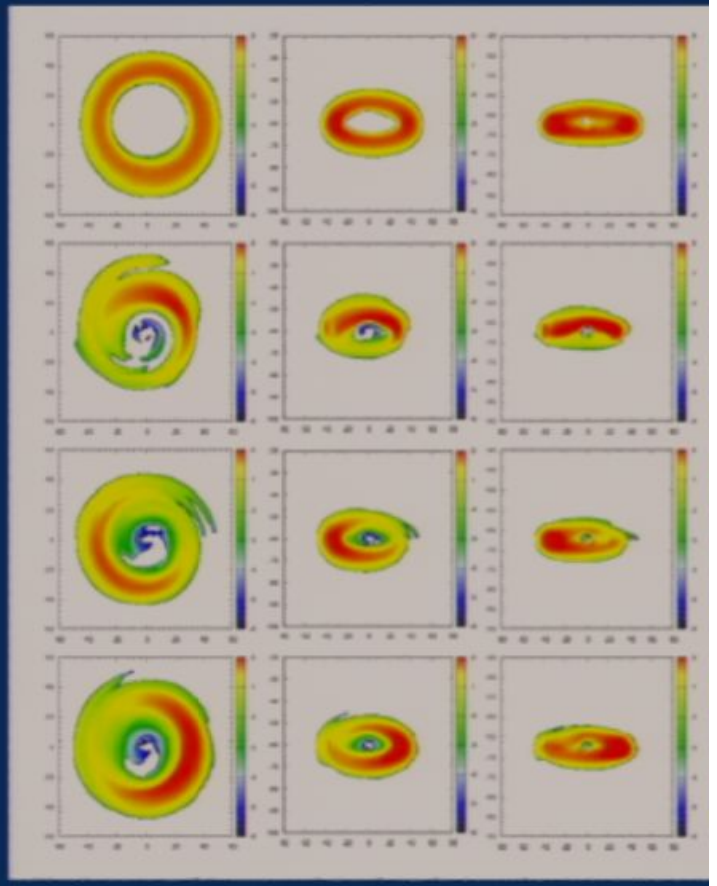

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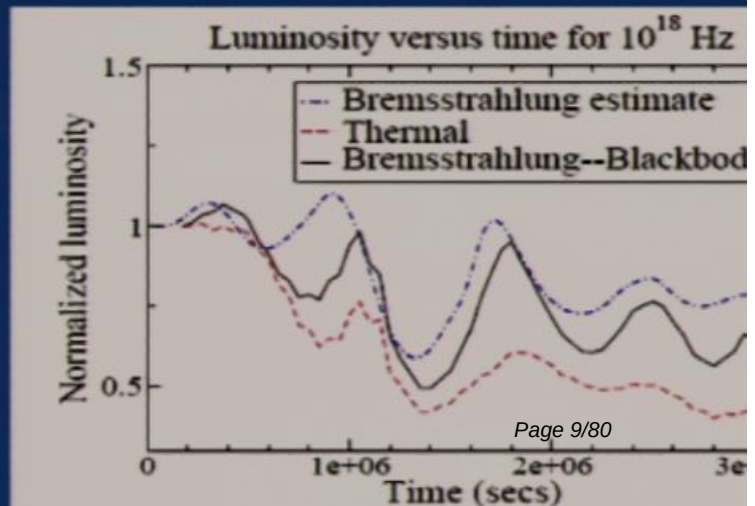

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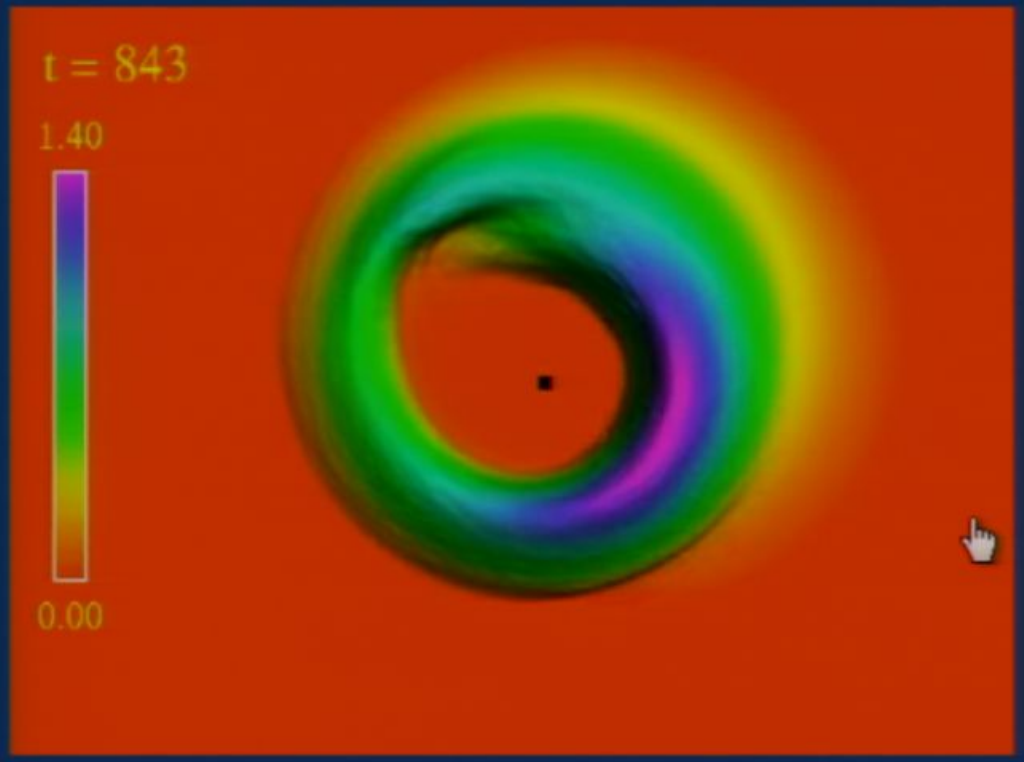

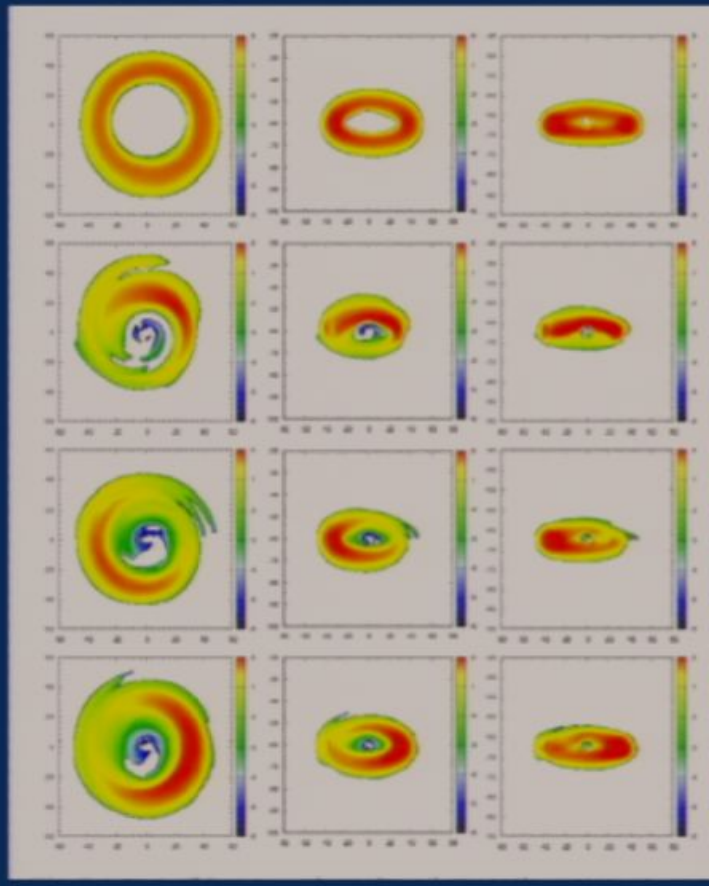

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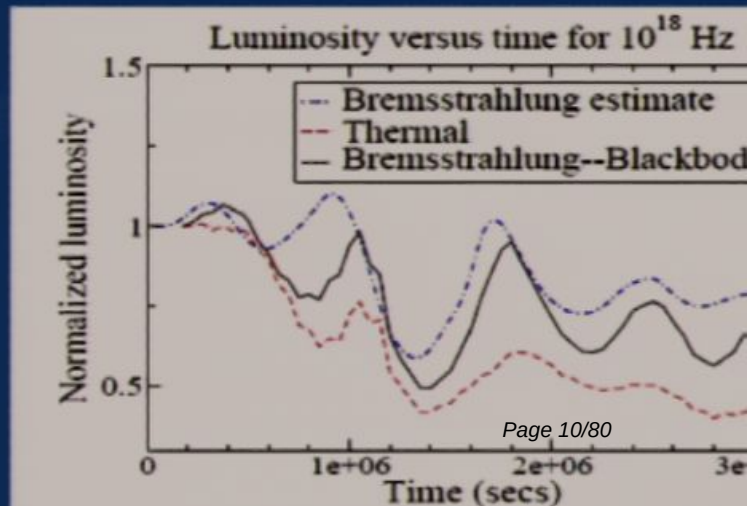

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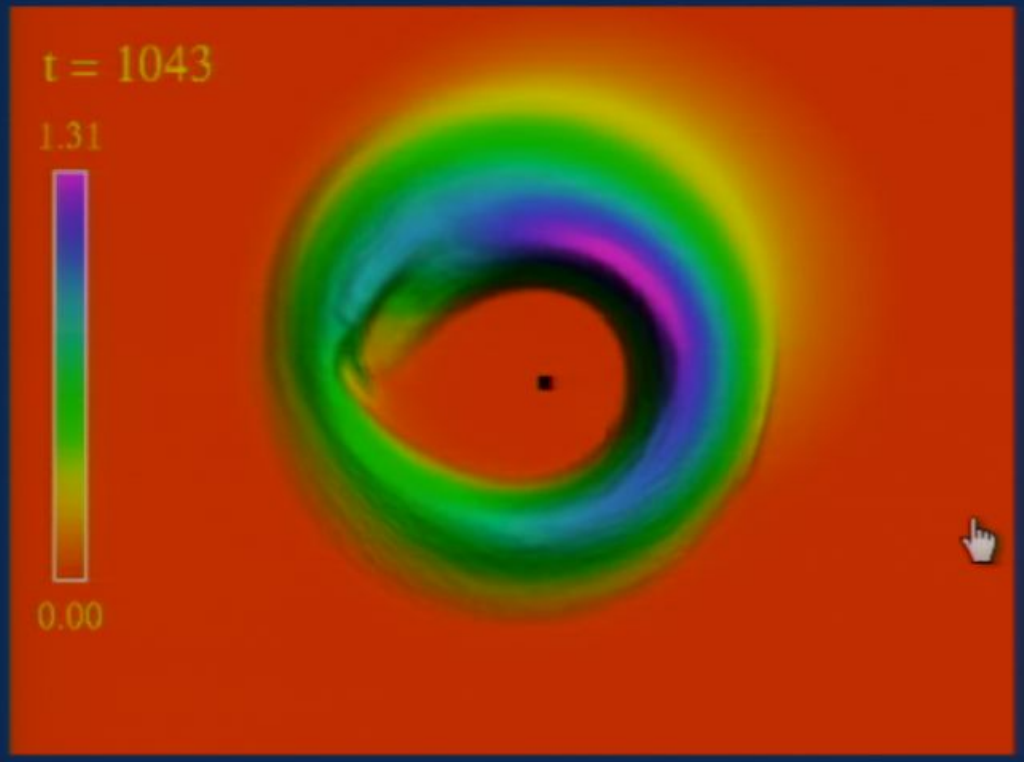

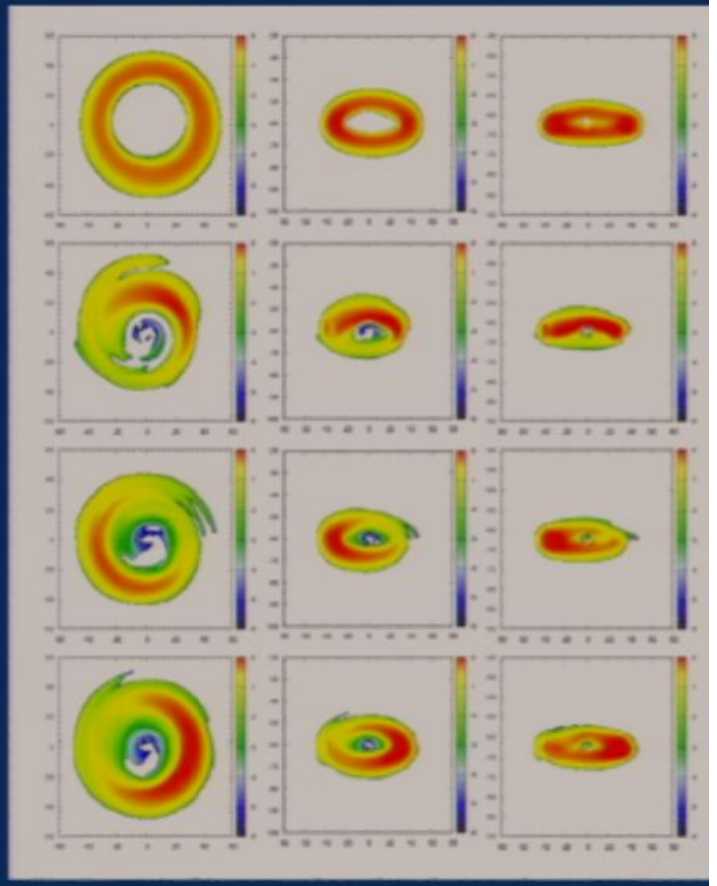

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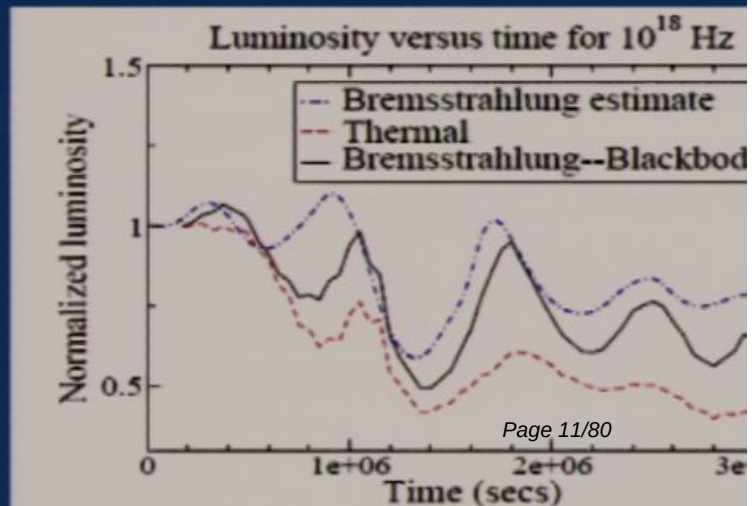

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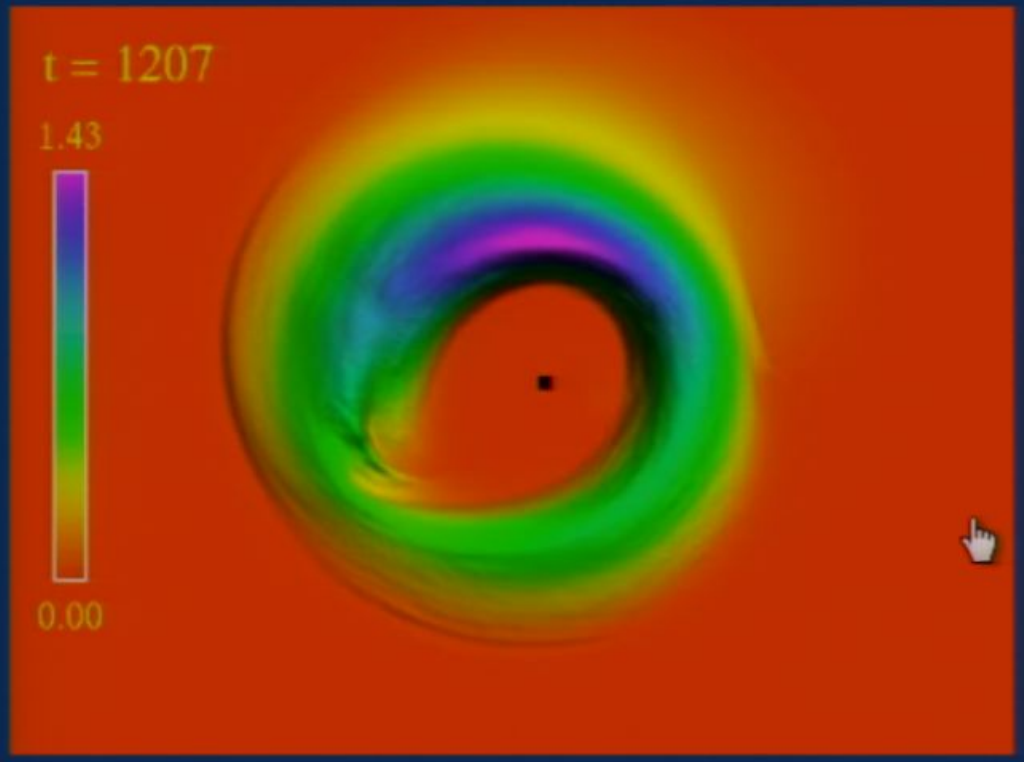

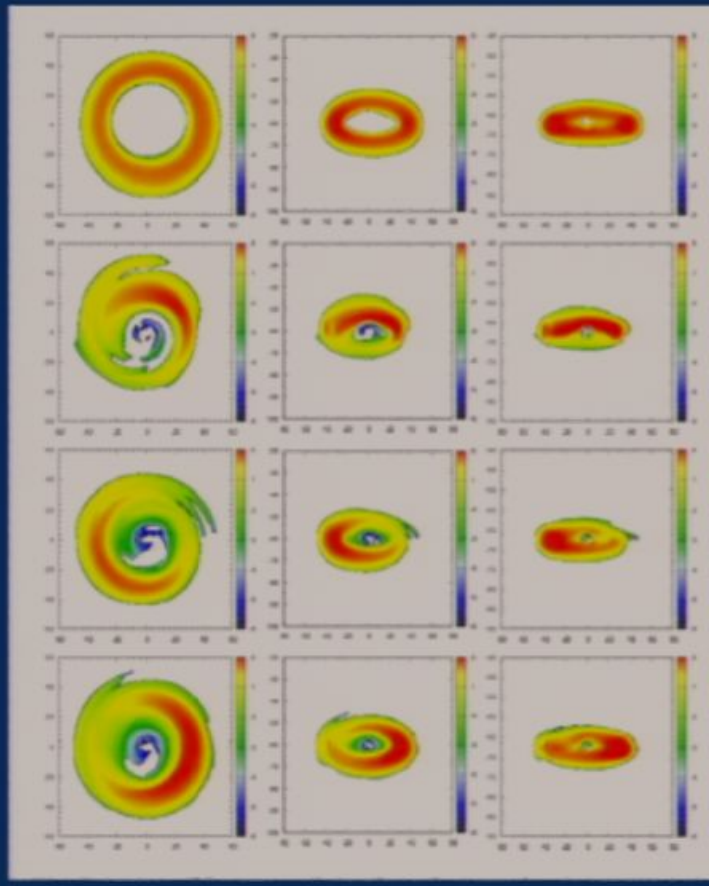

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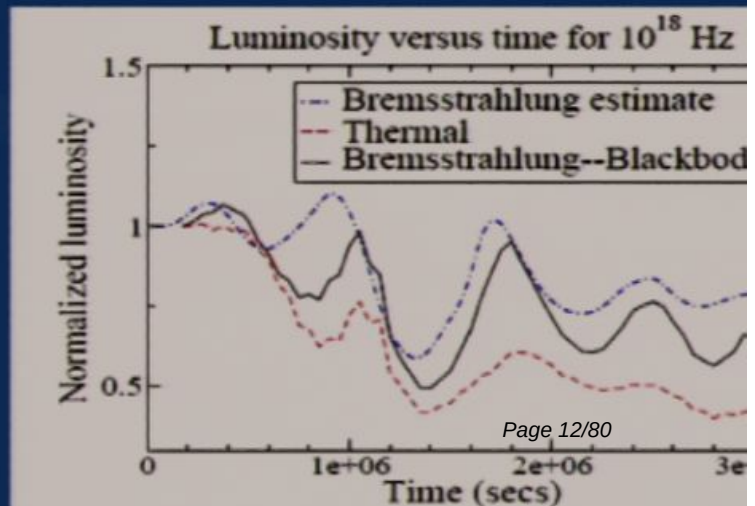

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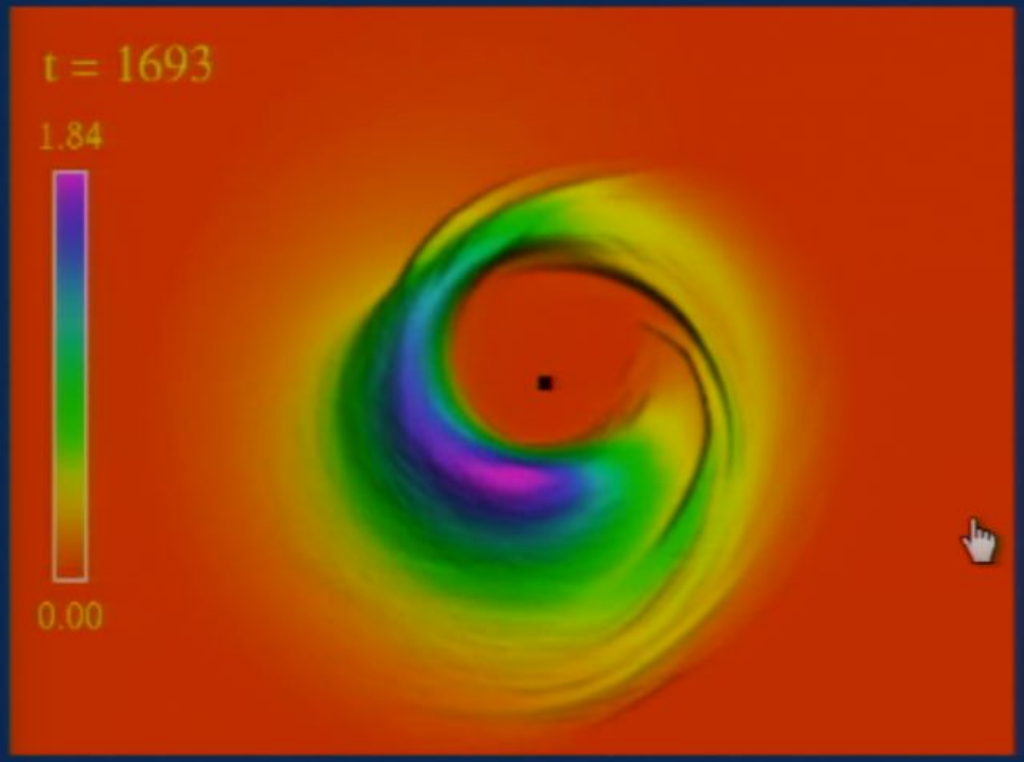

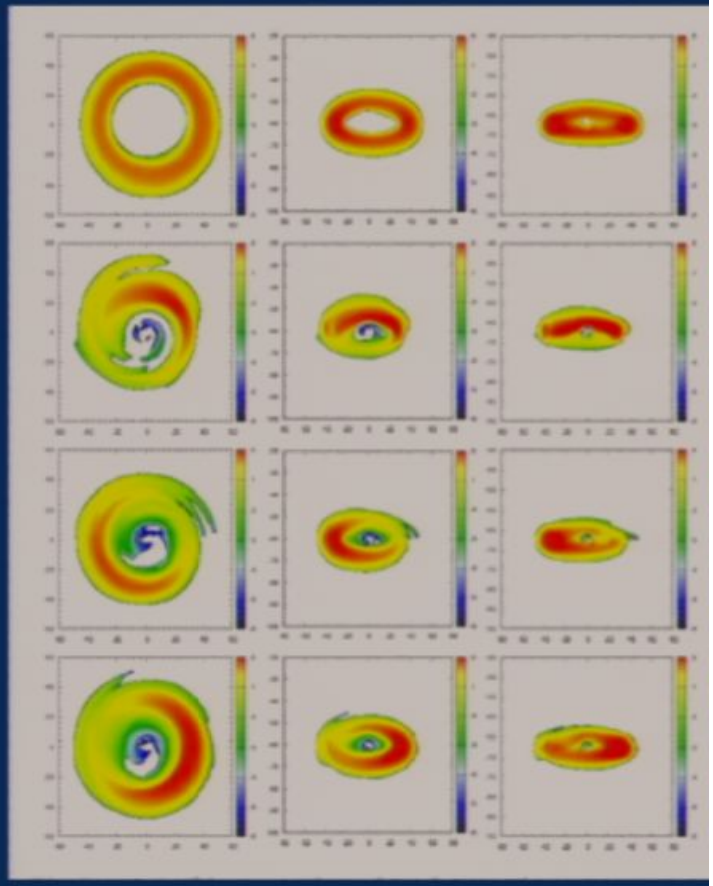

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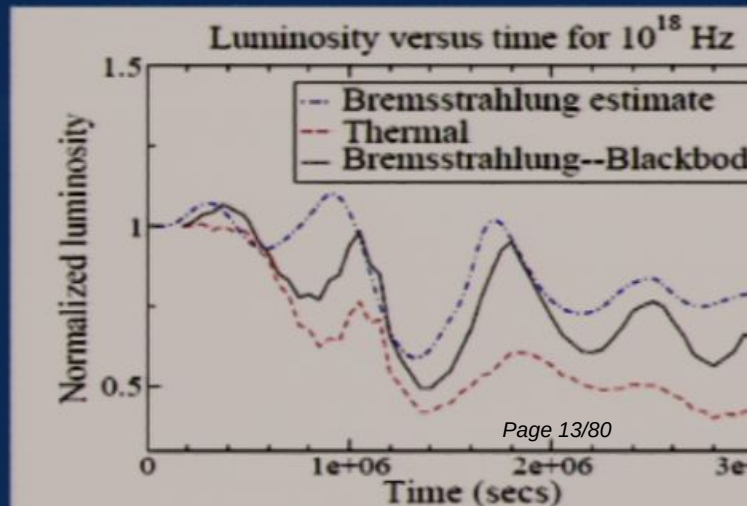

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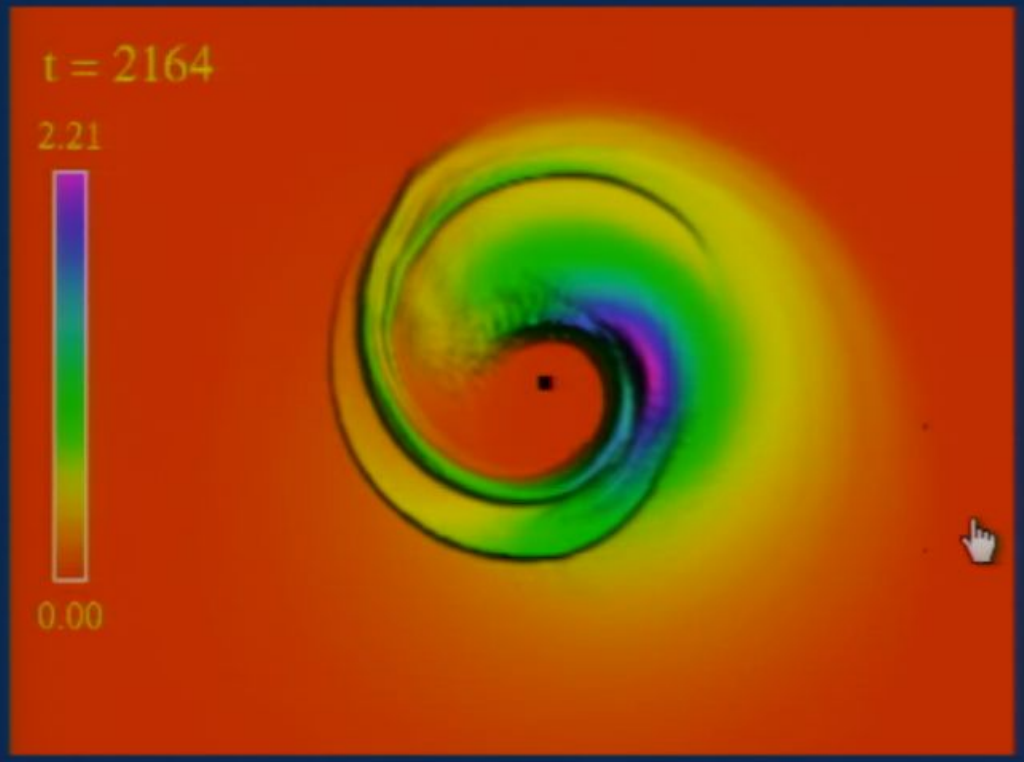

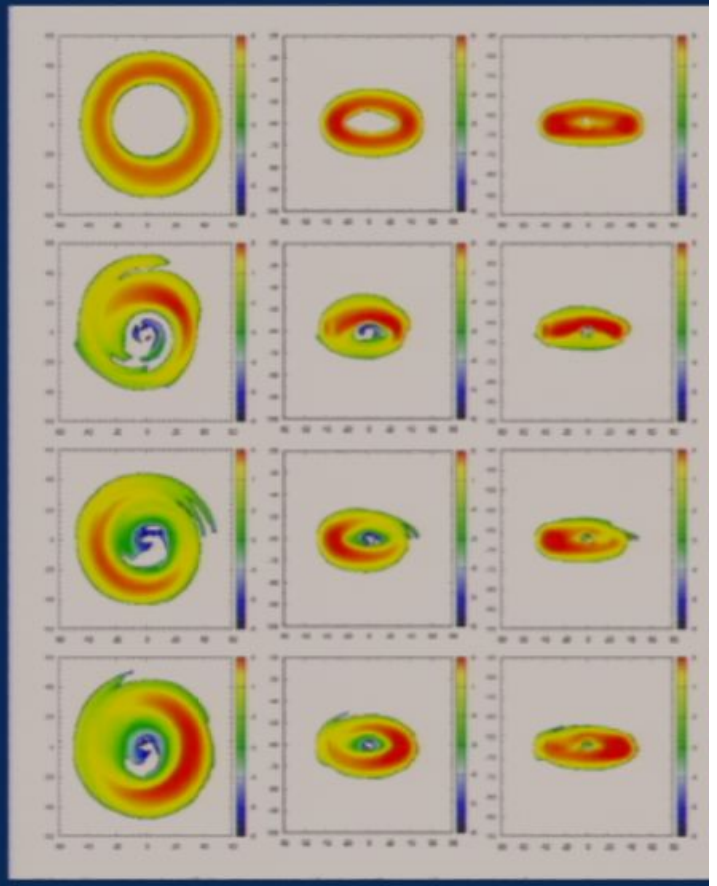

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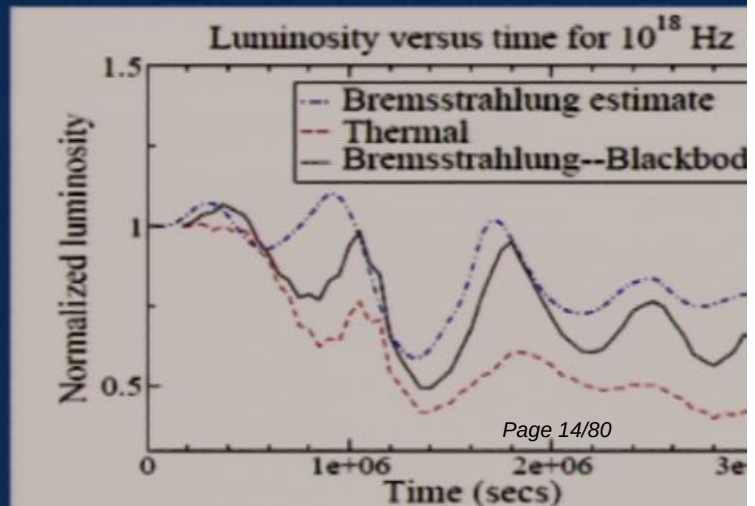

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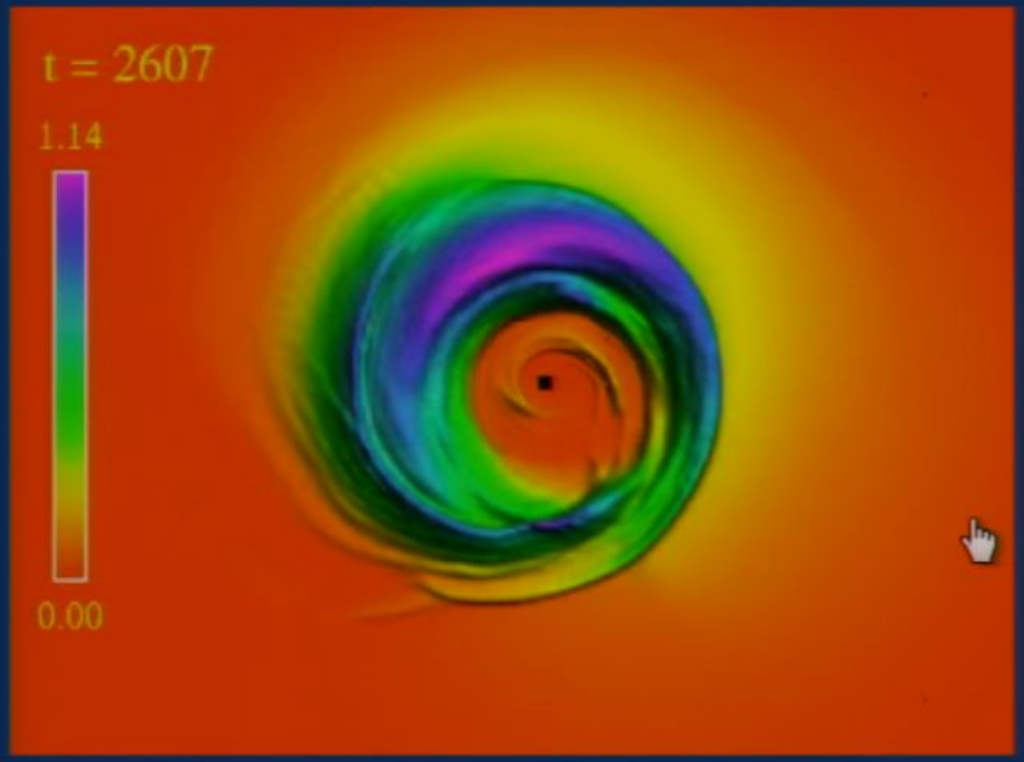

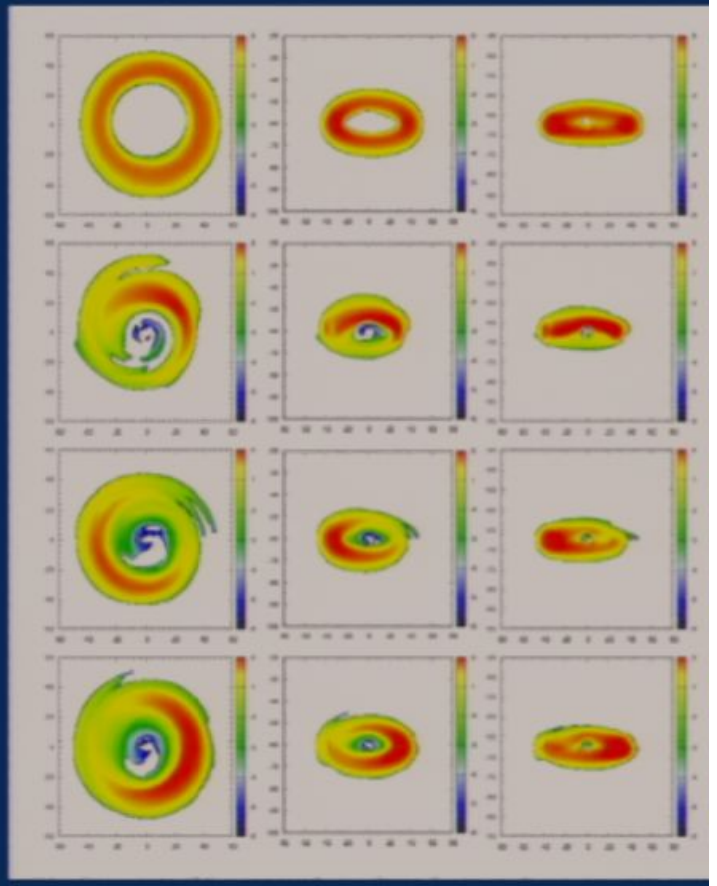

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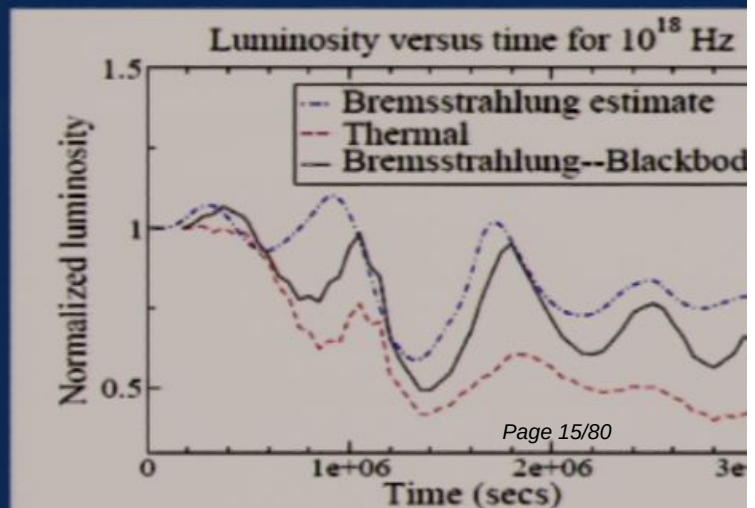

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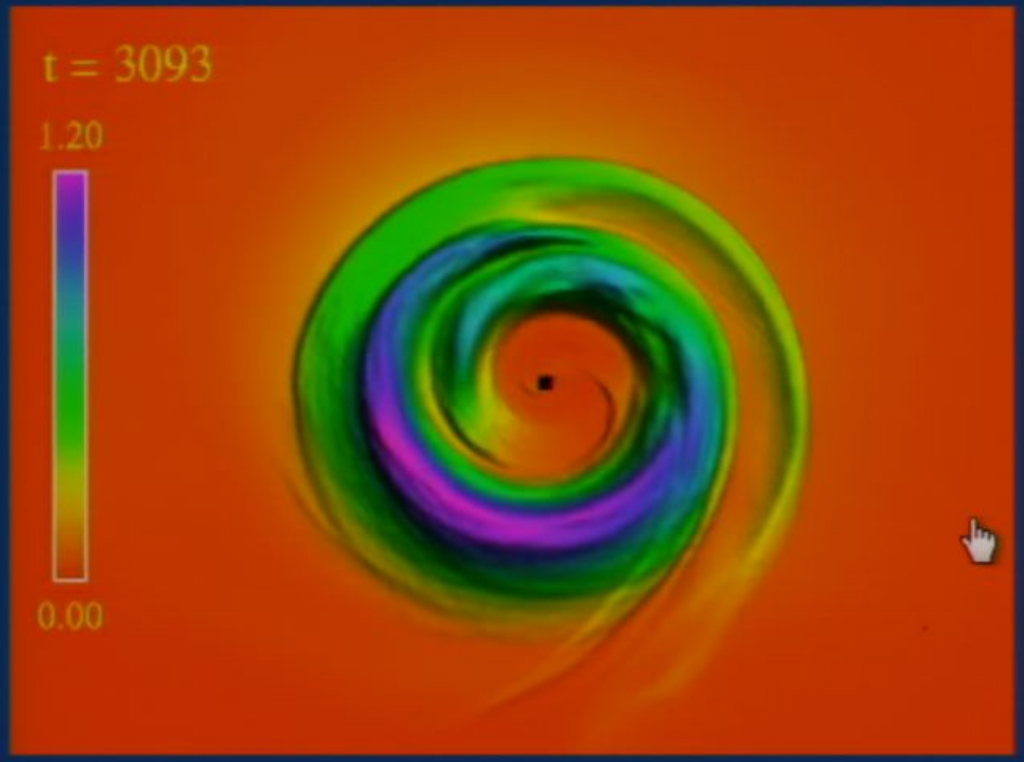

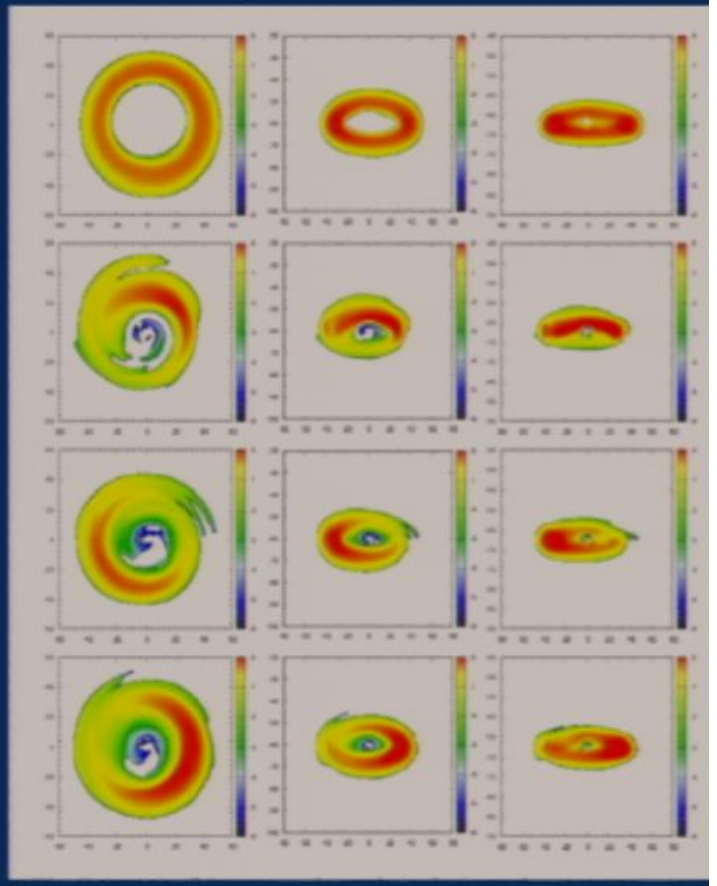

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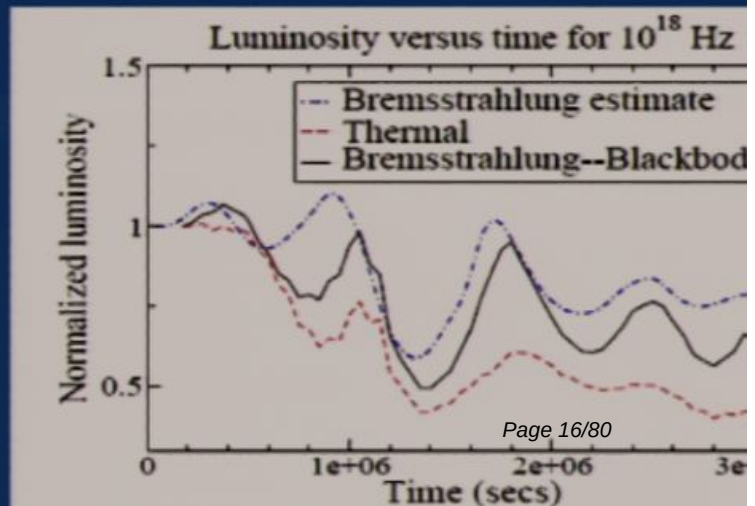

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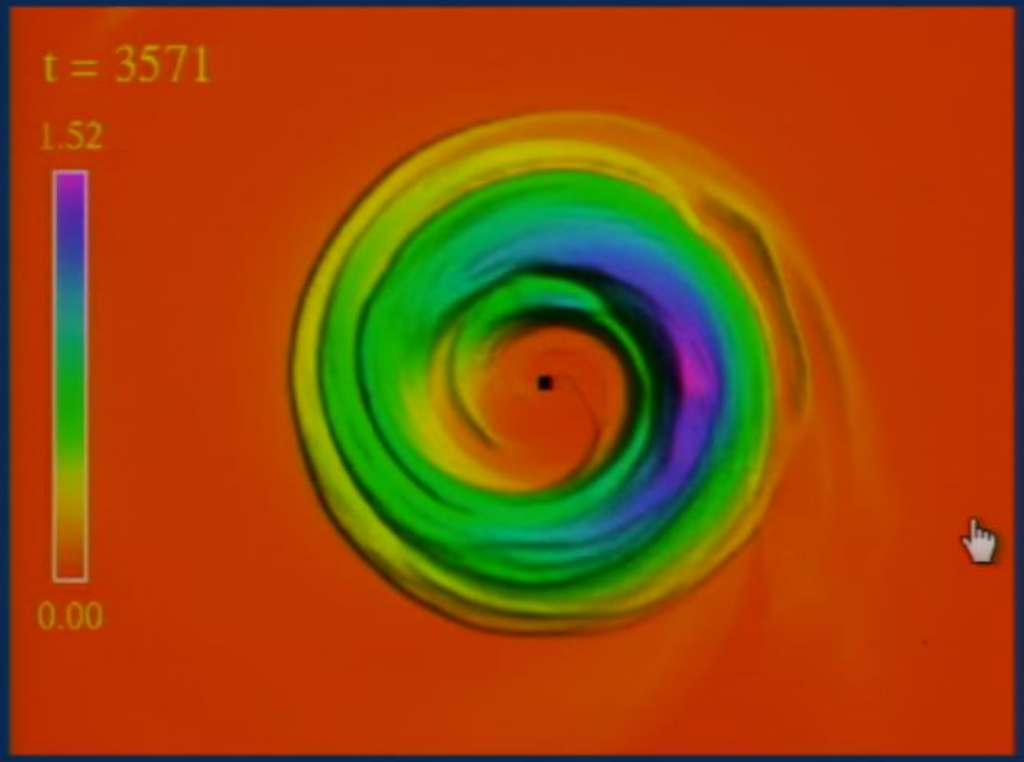

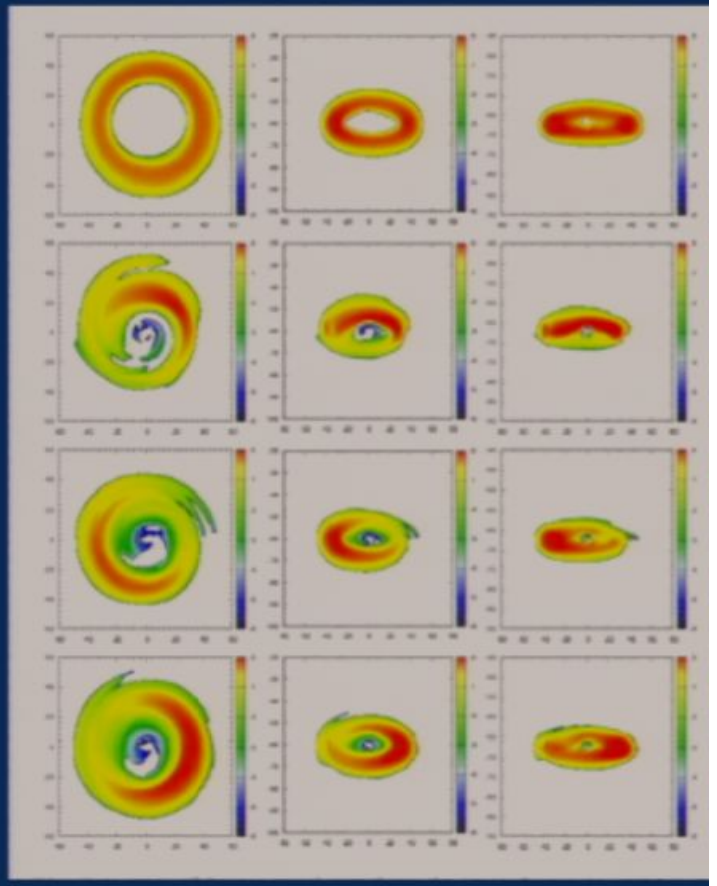

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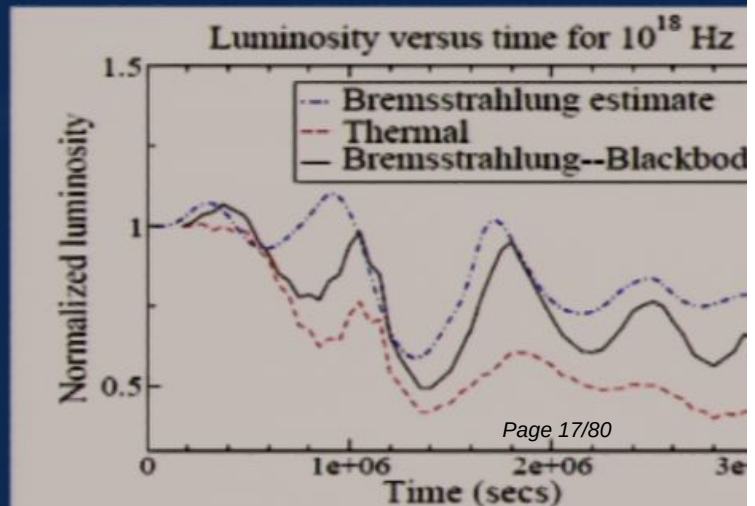

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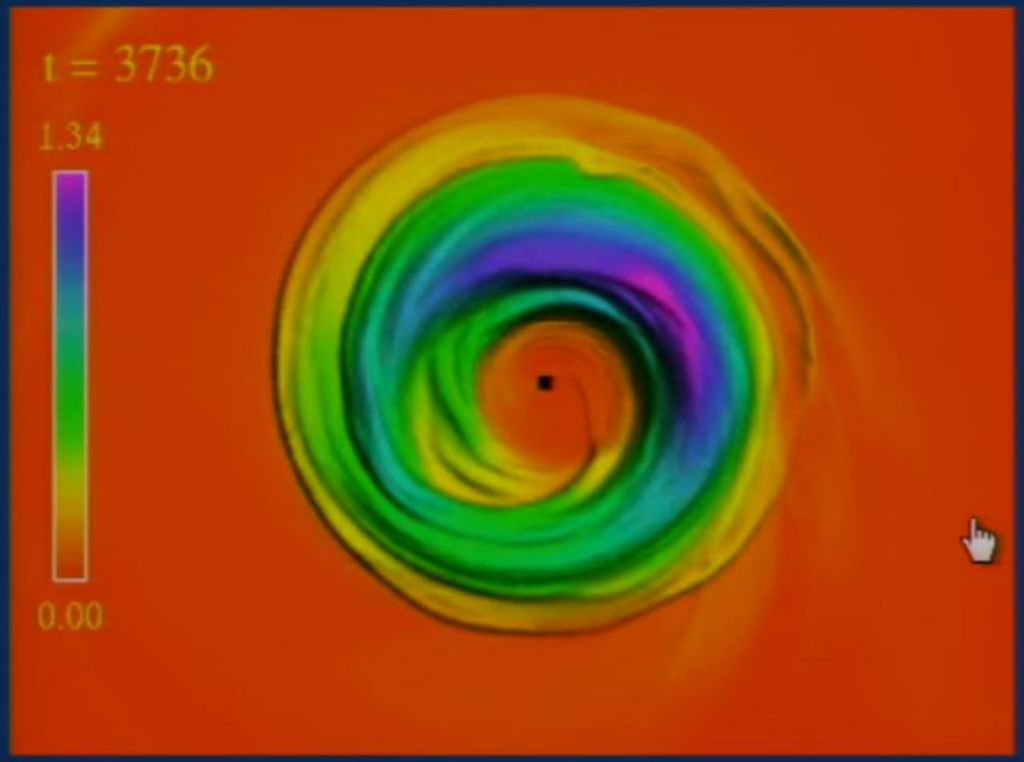

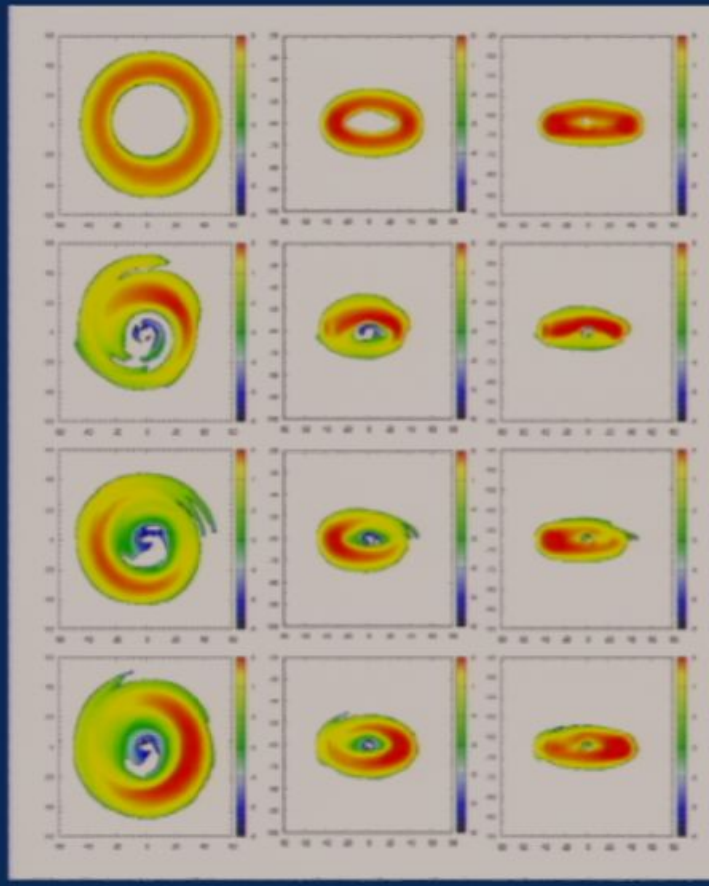

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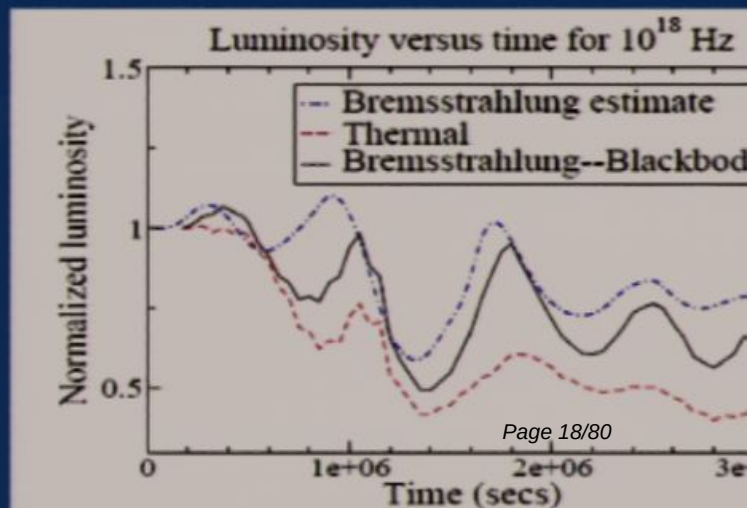

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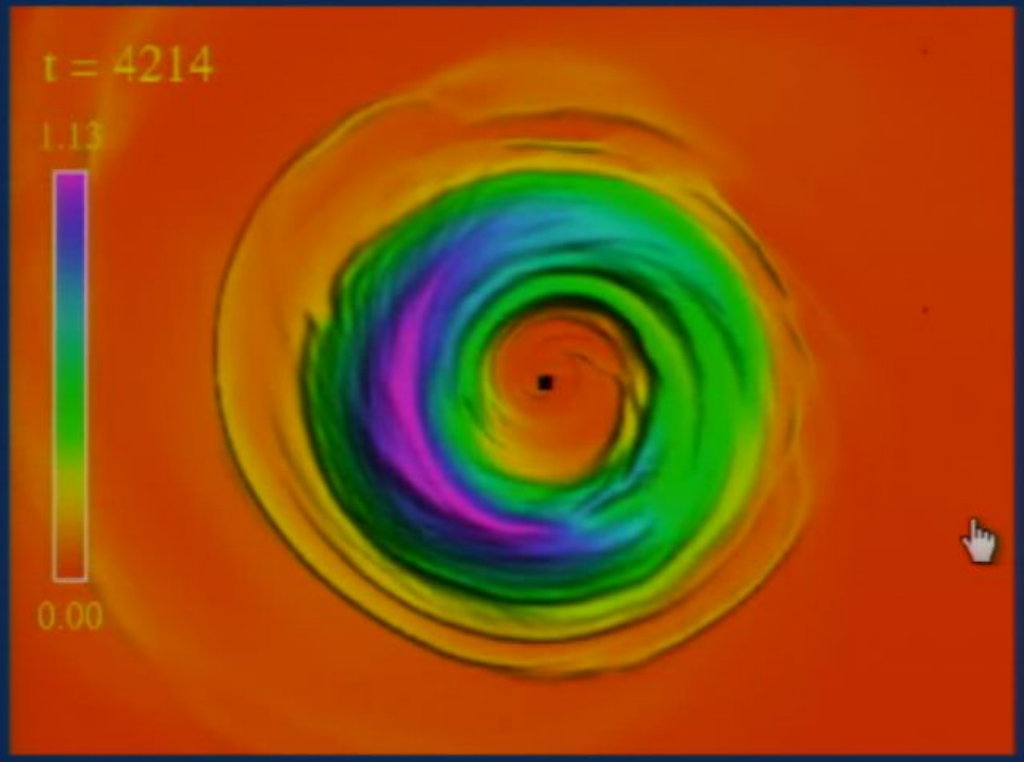

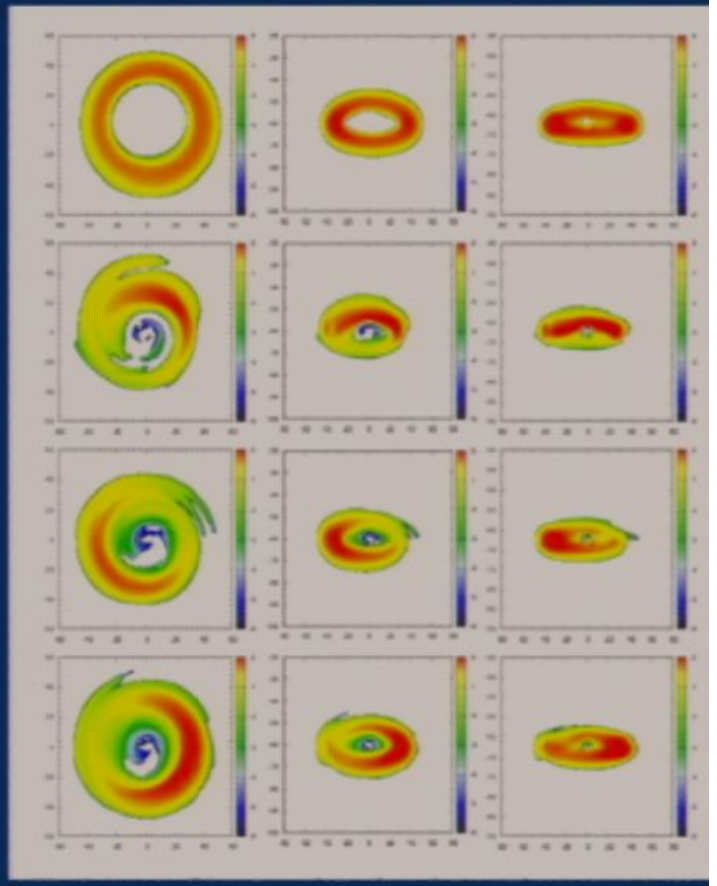

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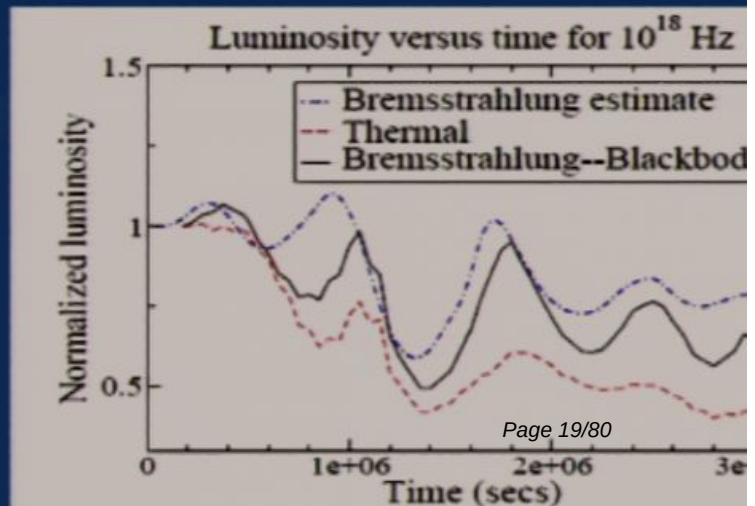

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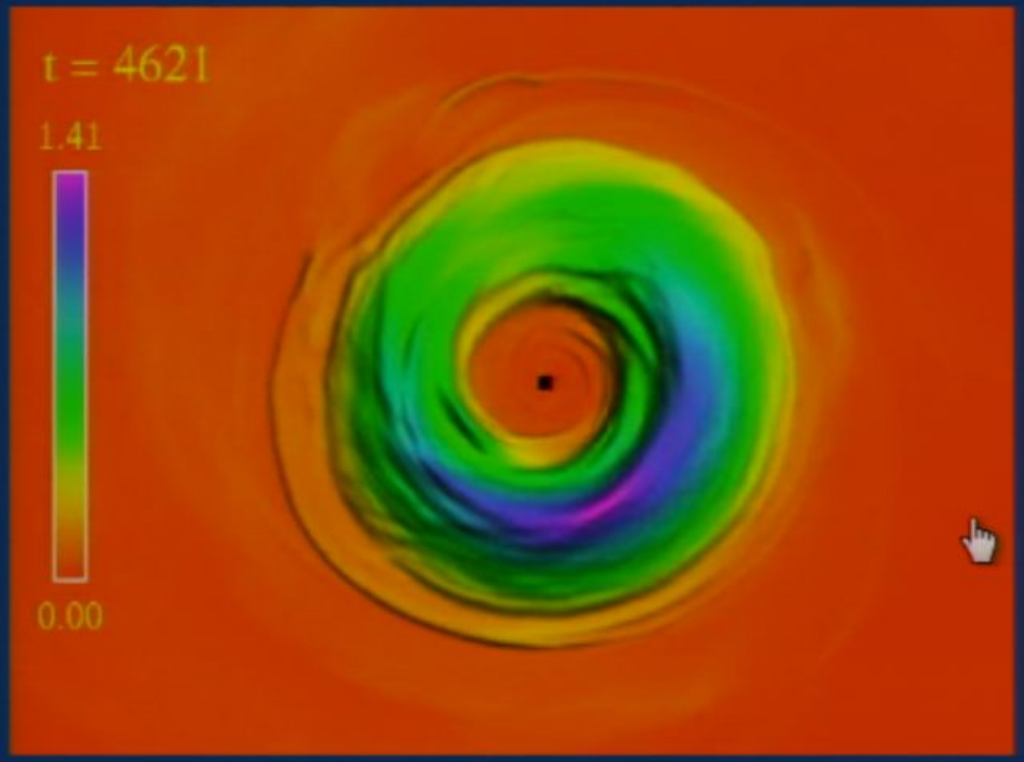

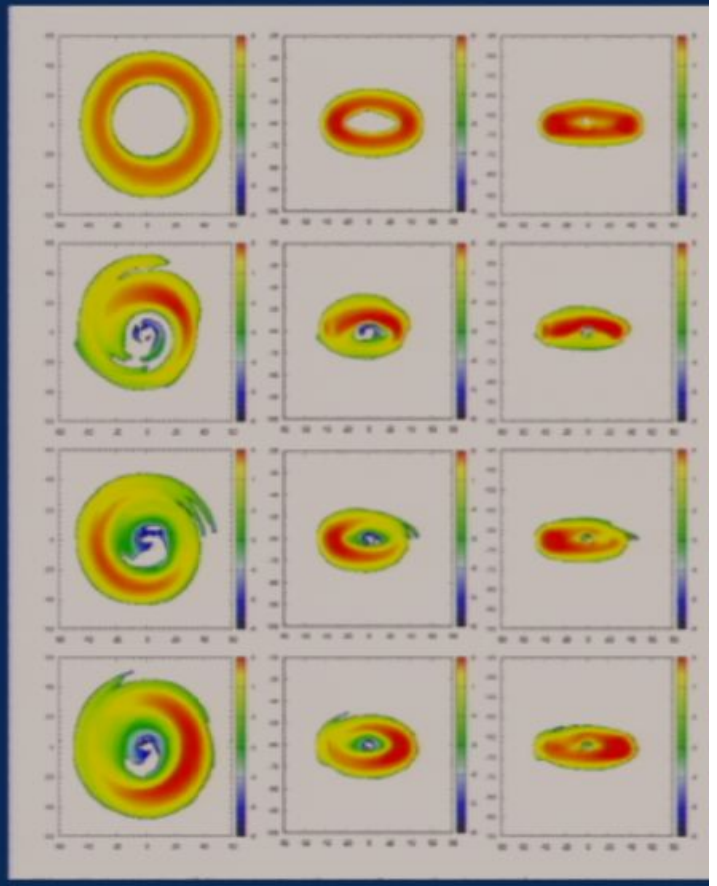

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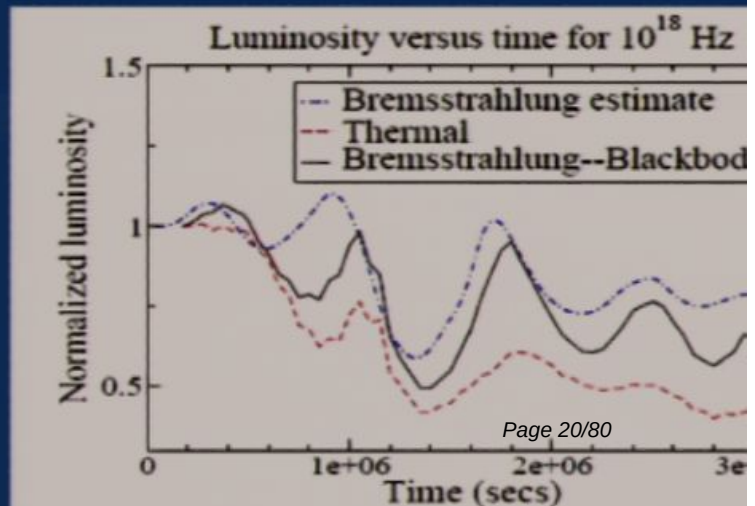

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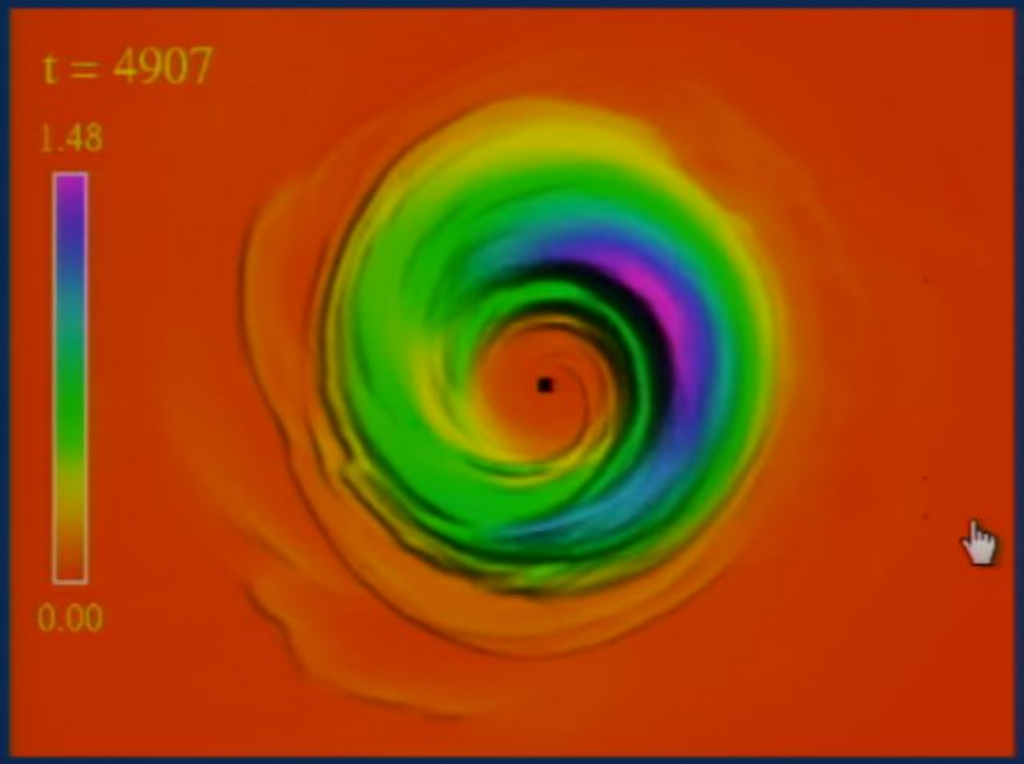

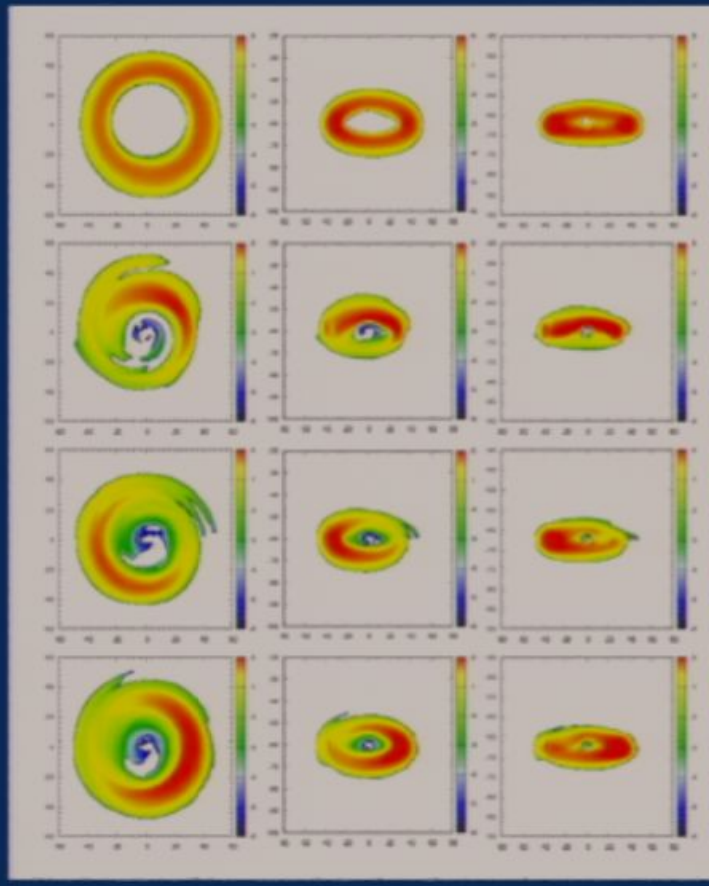

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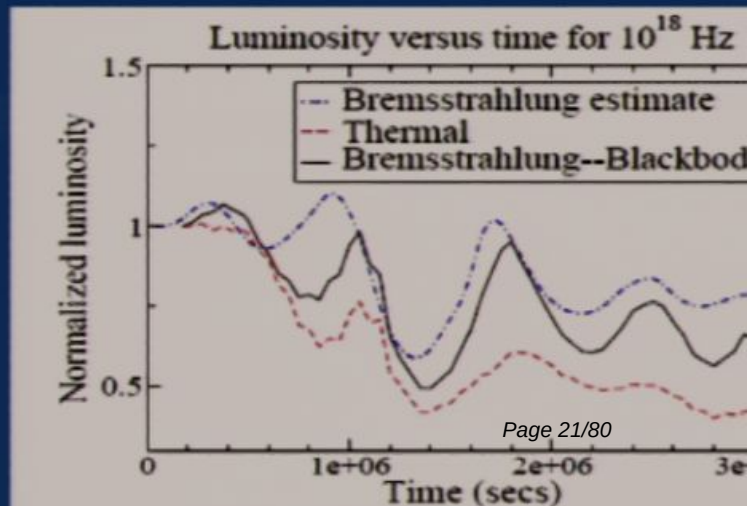

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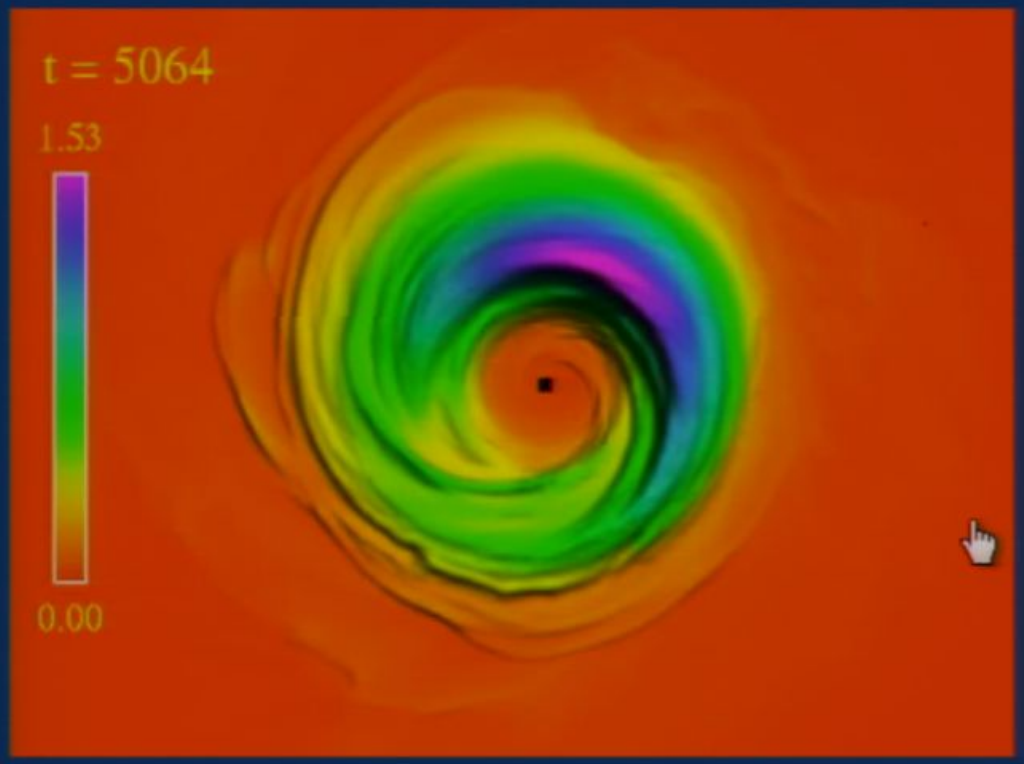

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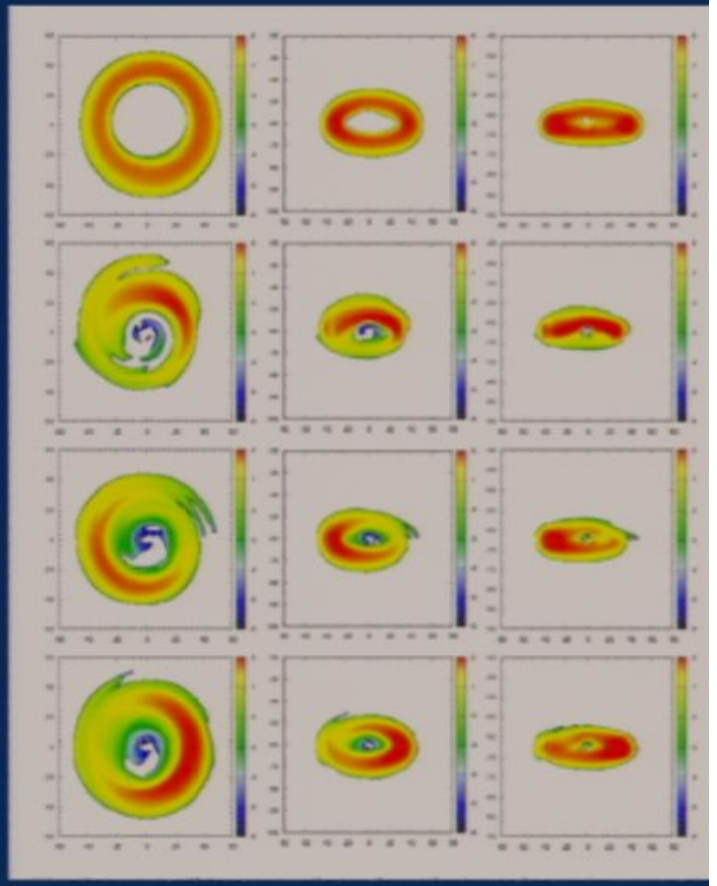
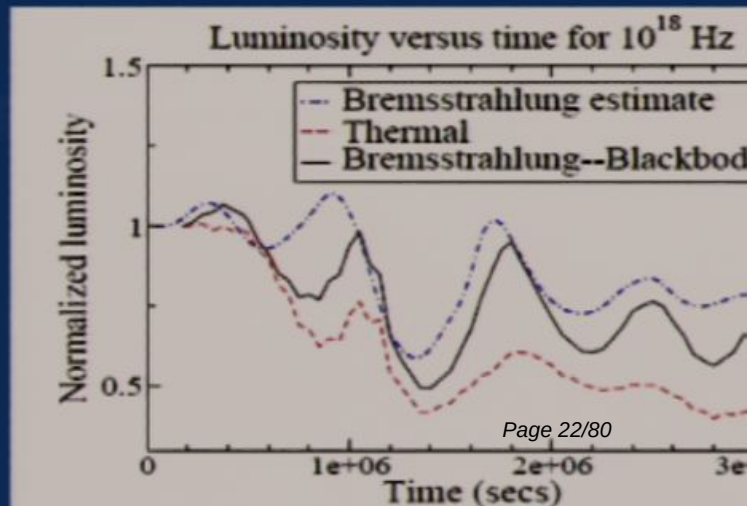
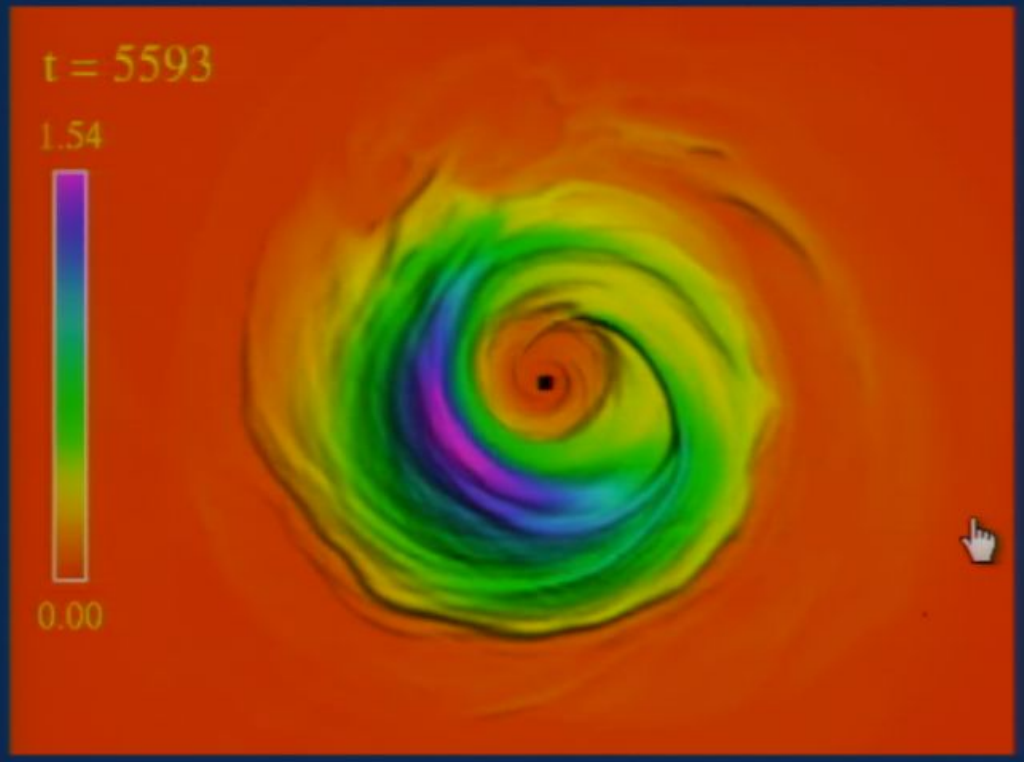
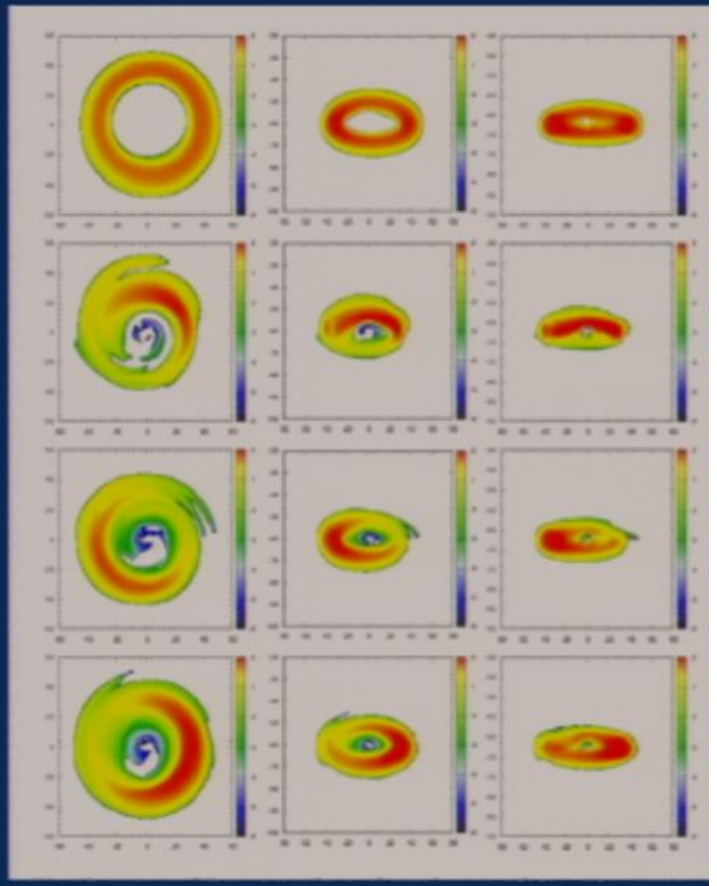


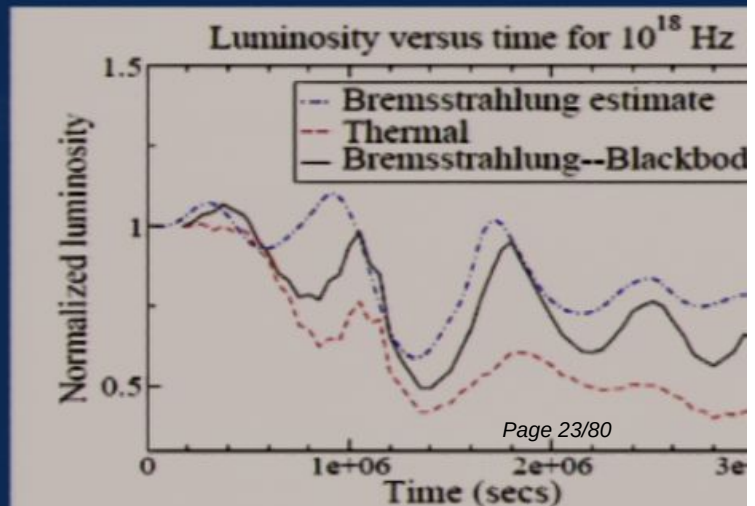


Postmerger emission





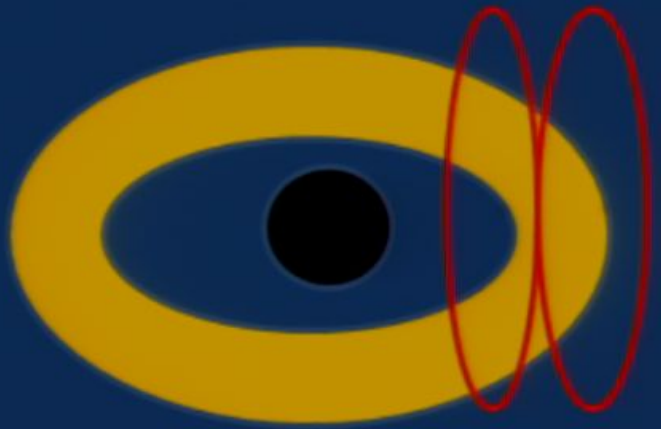
egevand,Anderson,LL,Neilsen;2010]
egevand, Anderson,Frank,LL,Liebling,Neilsen,Motl; 2009]

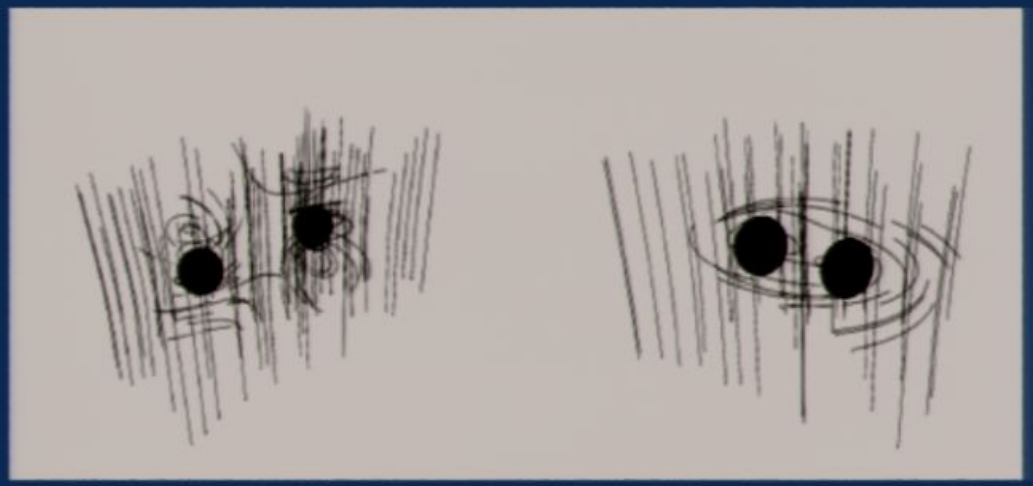


Binary black holes as blenders: 'B-Z' for binaries

How does the curvature influence EM fields?

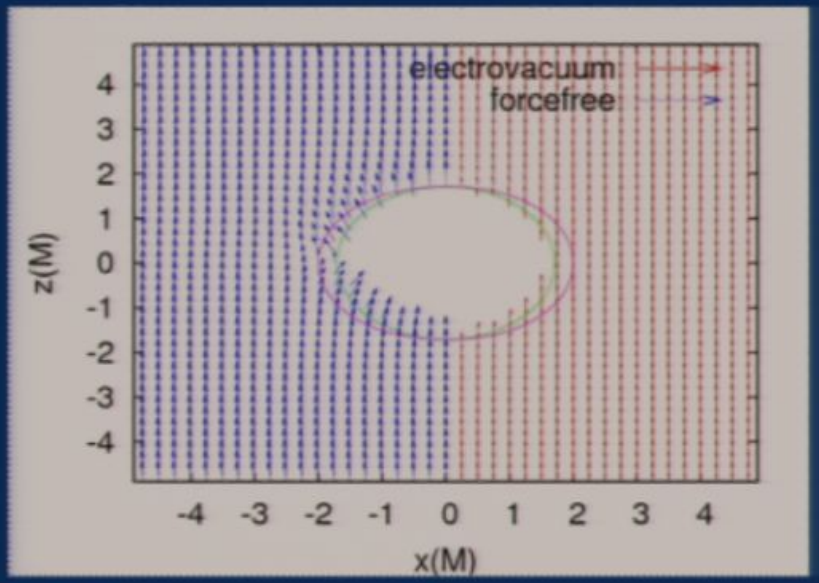
- Ingredients: GR + Maxwell Eqns (ElectroVac)
  - Binary black holes interacting with magnetic field anchored at a circumbinary disk

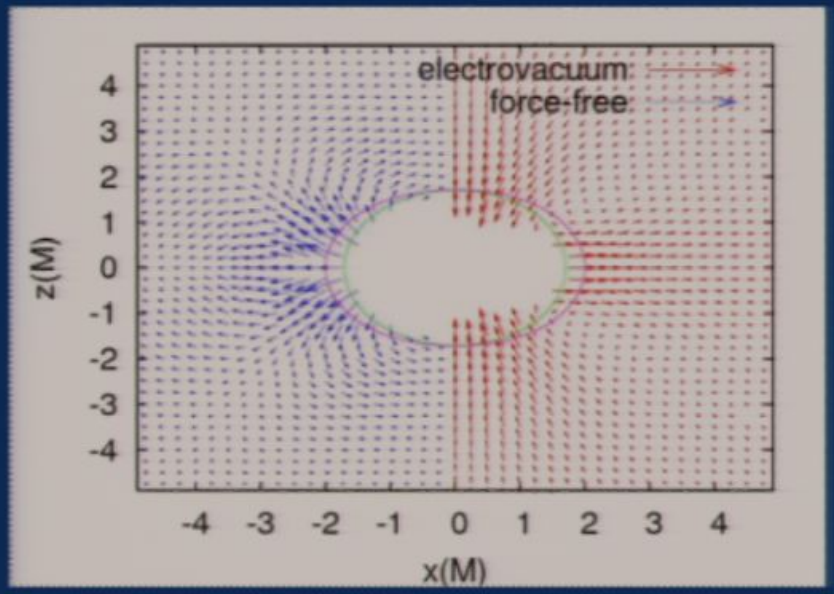


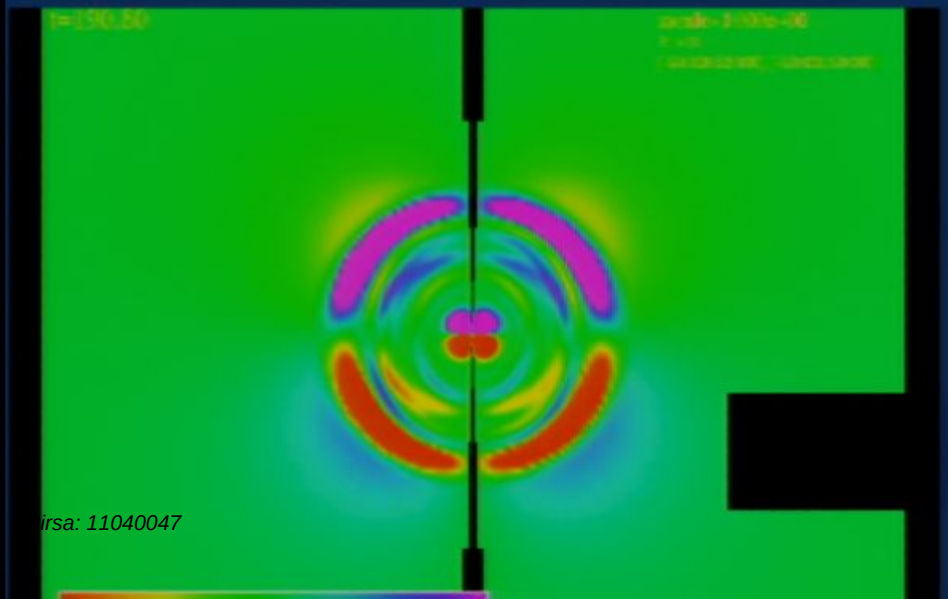


[Palenzuela,LL,Anderson,Liebling, Neilsen, PRL 2009 ;
Palenzuela LL Yoshida, PRD2010;

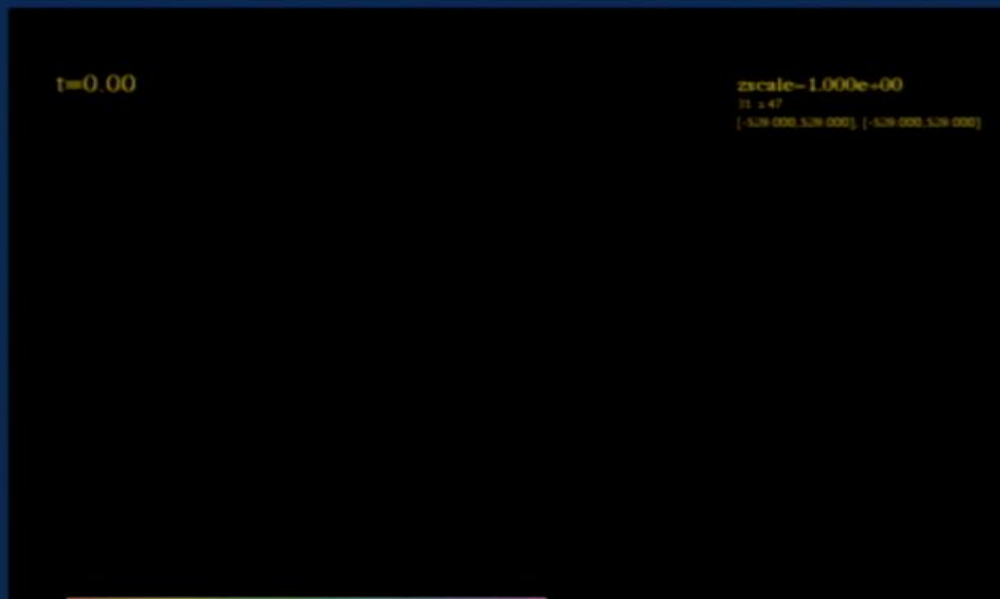
But… plasma will be generated around the BHs, must do better: Force Free approx.



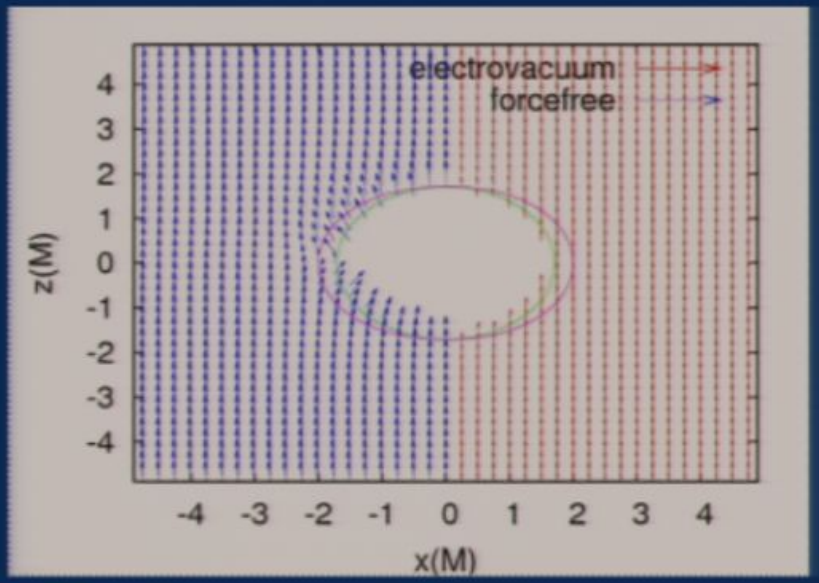


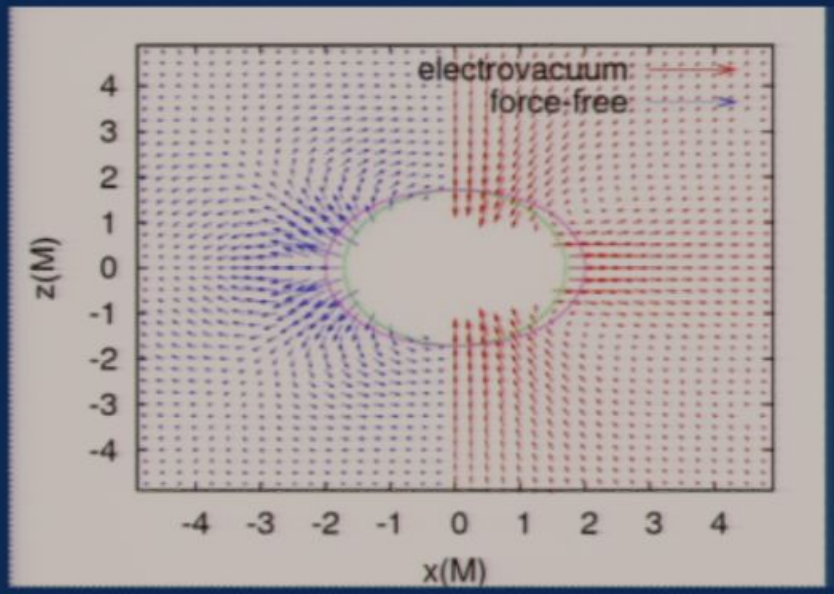


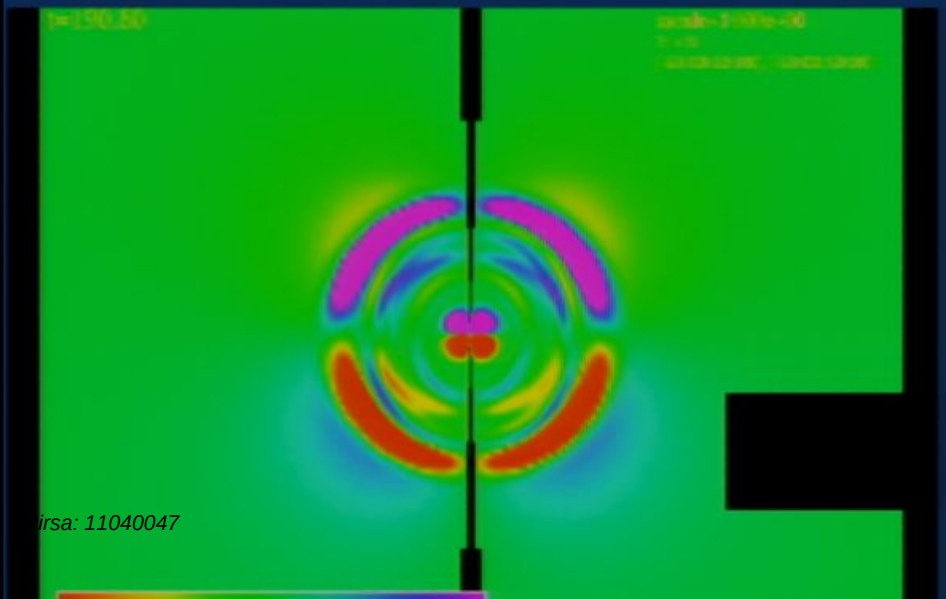
irsa: 11040047

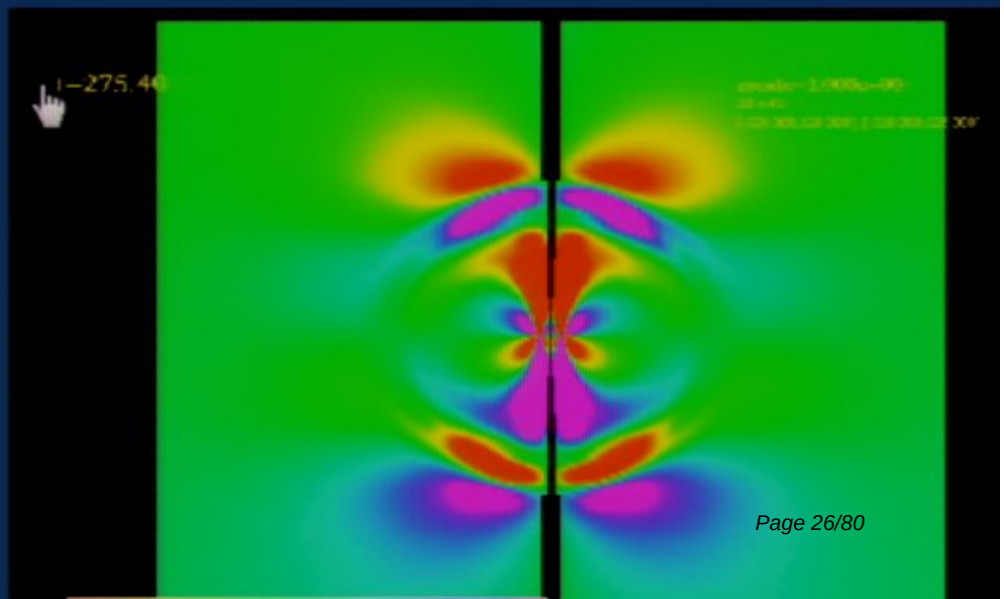


But… plasma will be generated around the BHs, must do better: Force Free approx.



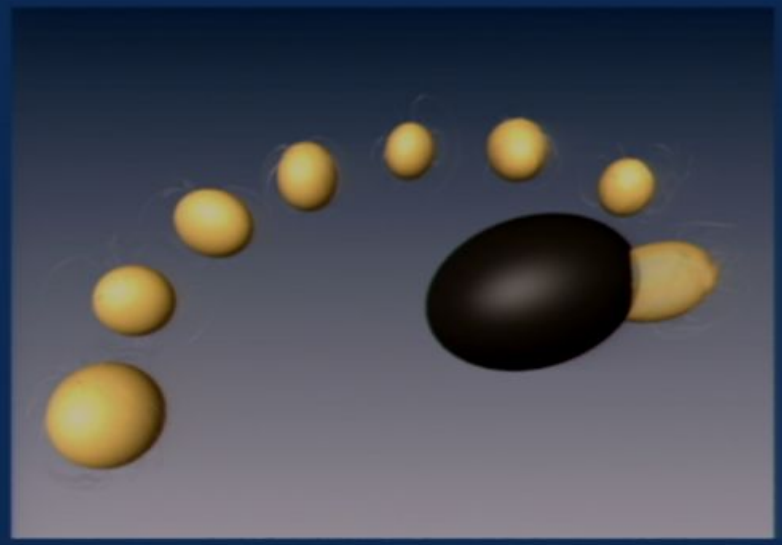






BH-NS

- GR studies ongoing (NS: polytrope or via Shen eos)
  - Sizeable disks if sufficiently high spins (>~ 0.5)
  - 'competition' with mass ratio
  - *Magnetic field effects?*



Neutron Star: Irrotational, $\Gamma = 2$
R = 15 [km] M = 1.4 $M_{solar.}$

Initial dipole field of strength 10^{12} [Gauss]

Black Hole:M = 7 M_{solar} ; a/M = 0, 0.5

Initial separation of 100 [km]
Grid extends to ± 443 [km]
Peak resolution of 0.73 [km] or 40 points across initial neutron star

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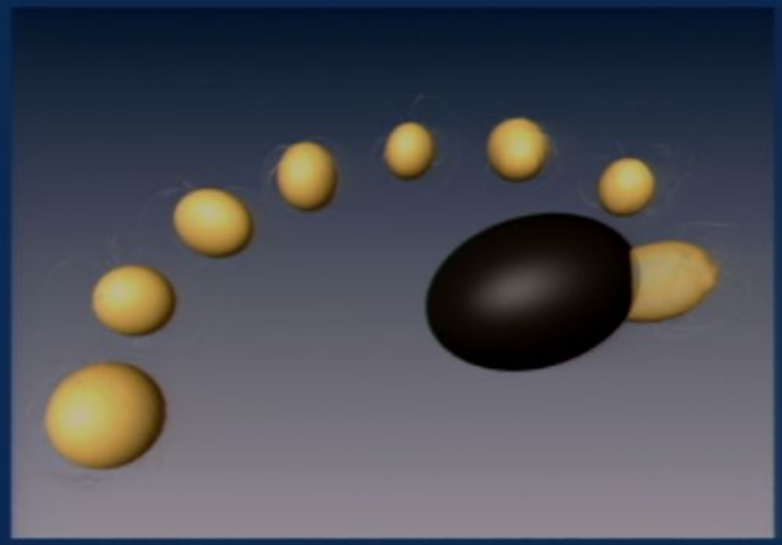

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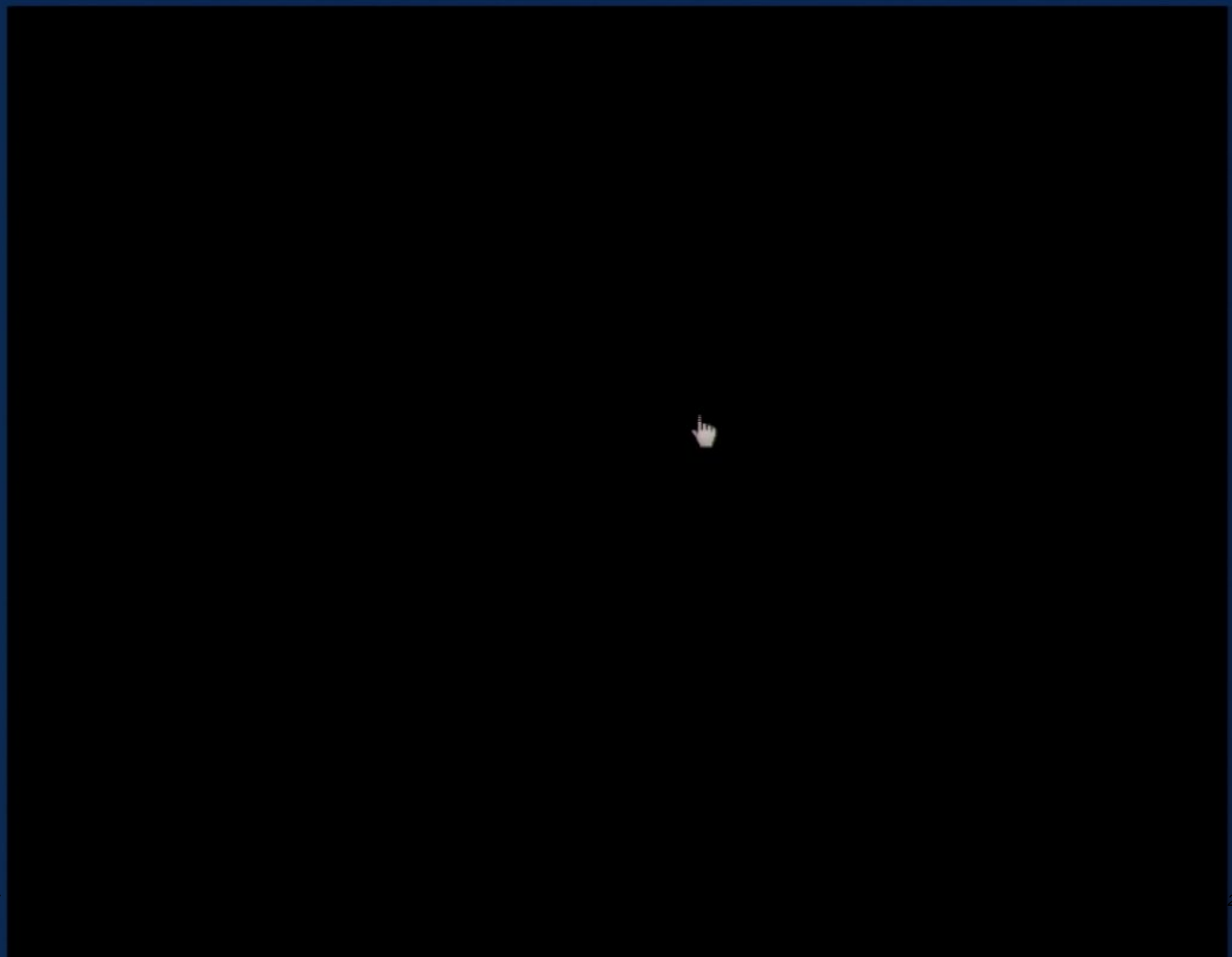
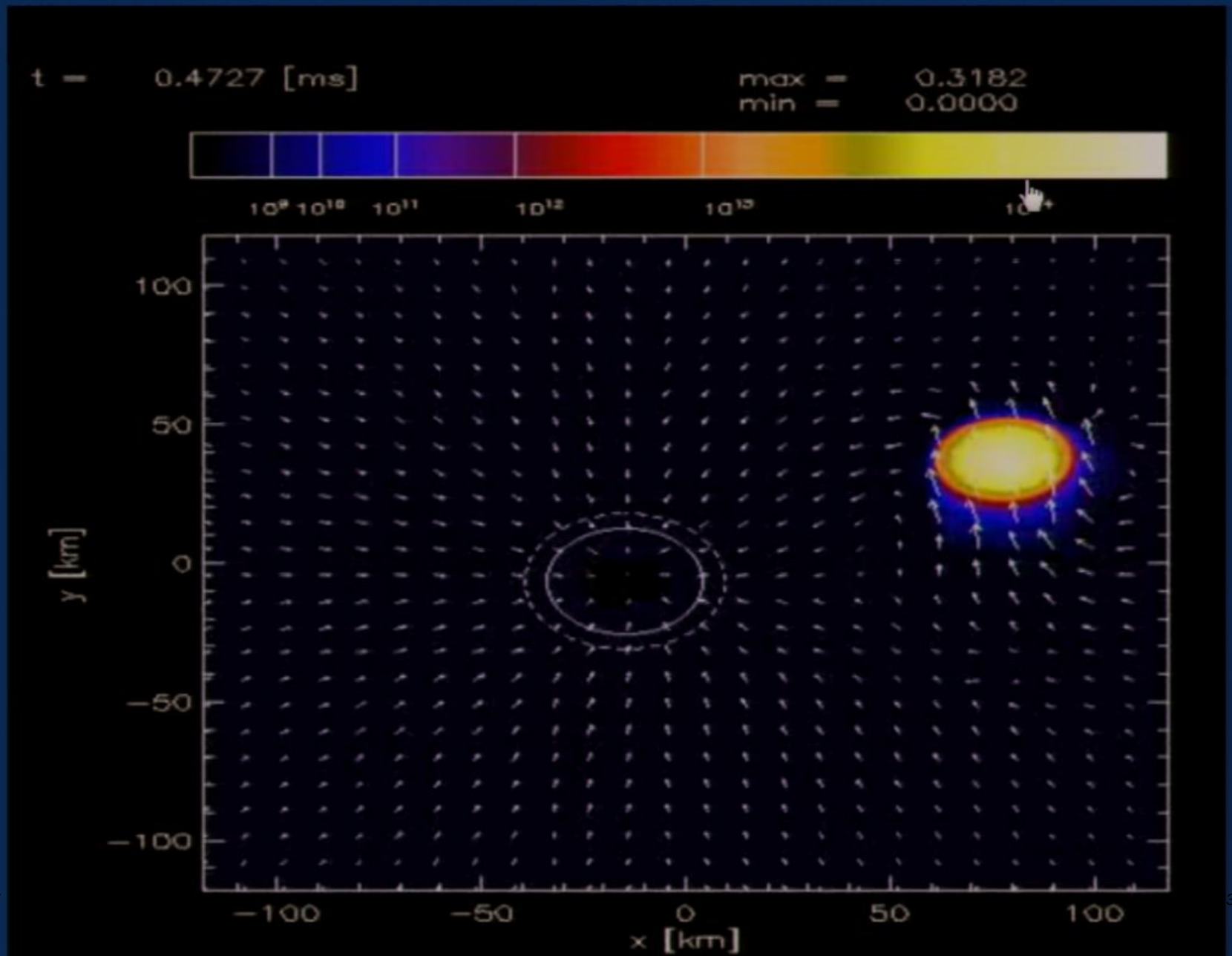
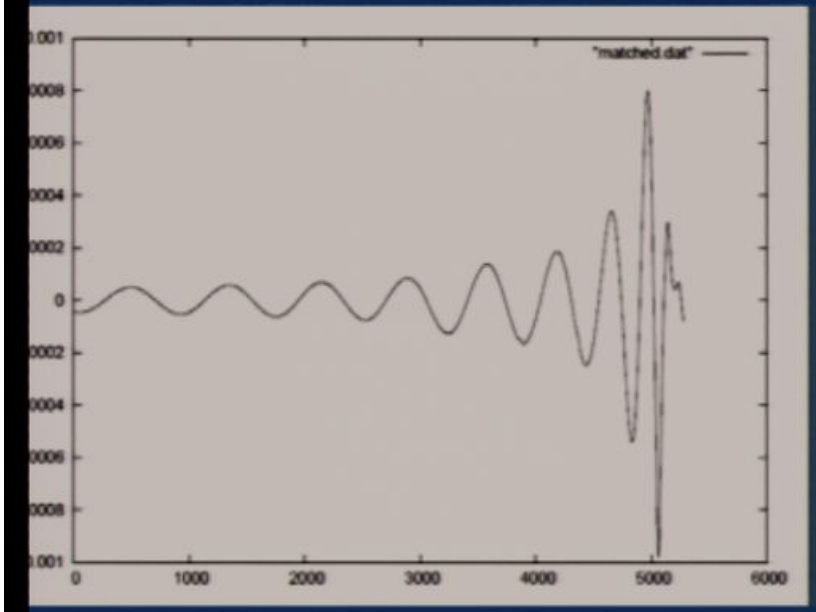


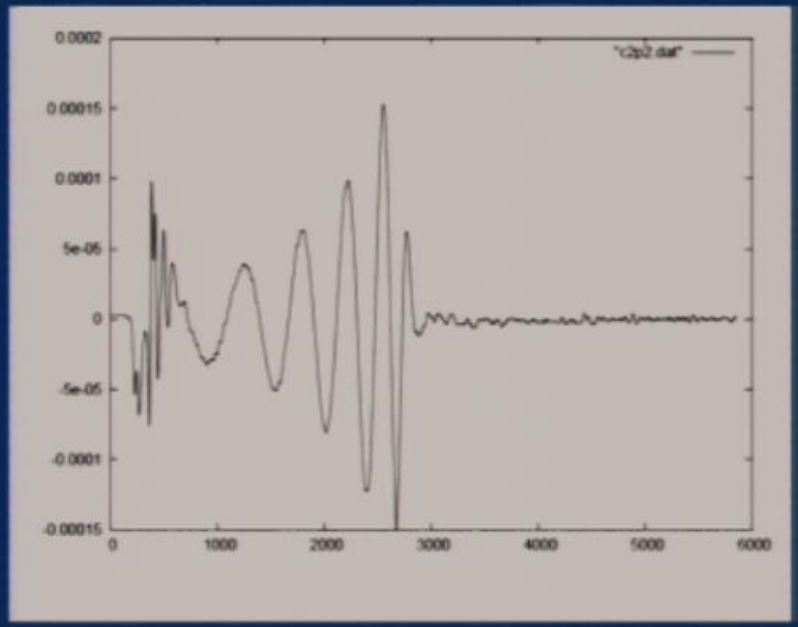

t = 0.4727 [ms]
max = 0.3182
min = 0.0000
10^{9} 10^{10} 10^{11} 10^{12} 10^{13}
100
50
0
−50
−100
y [km]
−100
−50
0
50
100
x [km]

Grav. Waves...



$a = 0, B = 10^{12}$

Reasonably clean Quasi-normal ringing

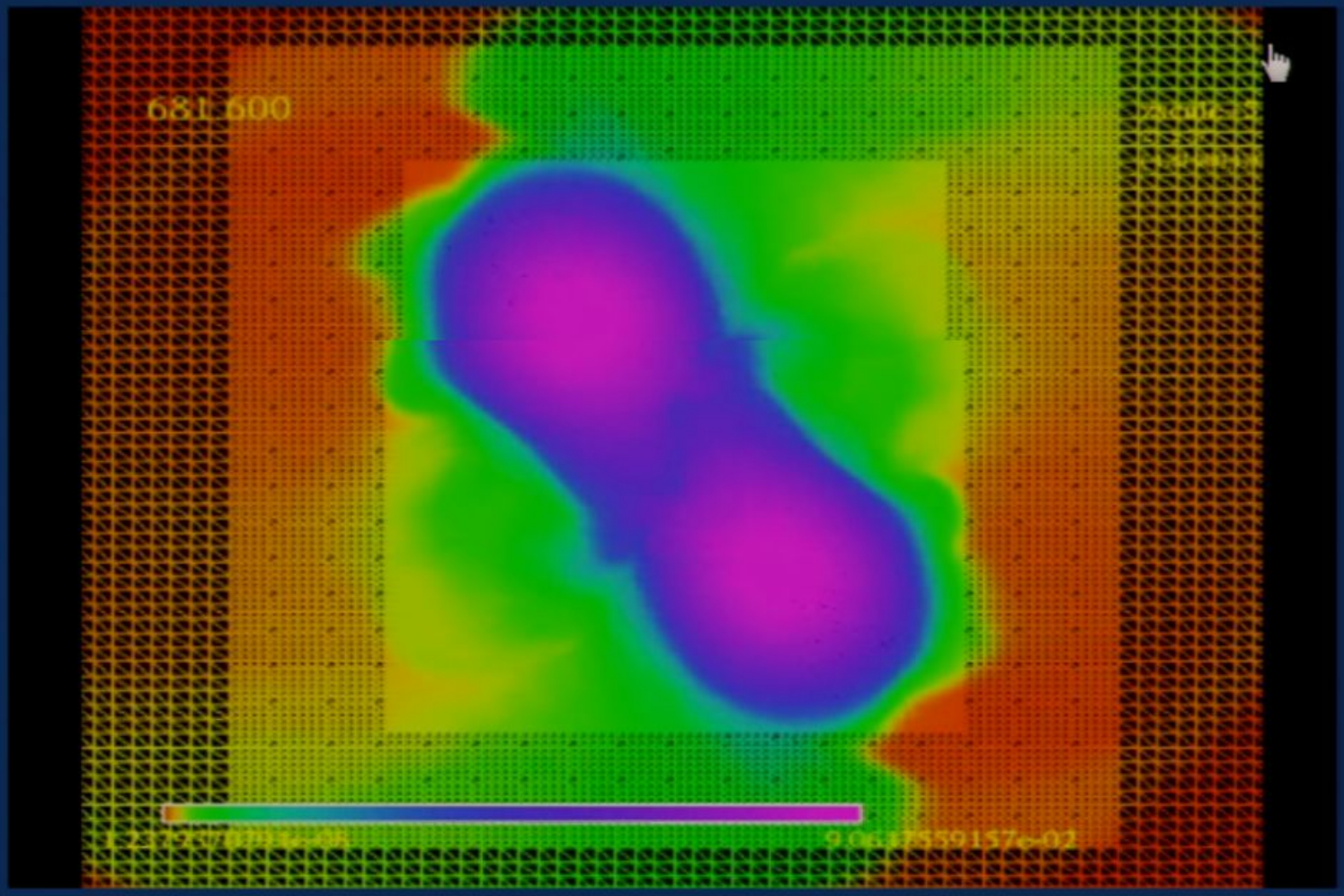


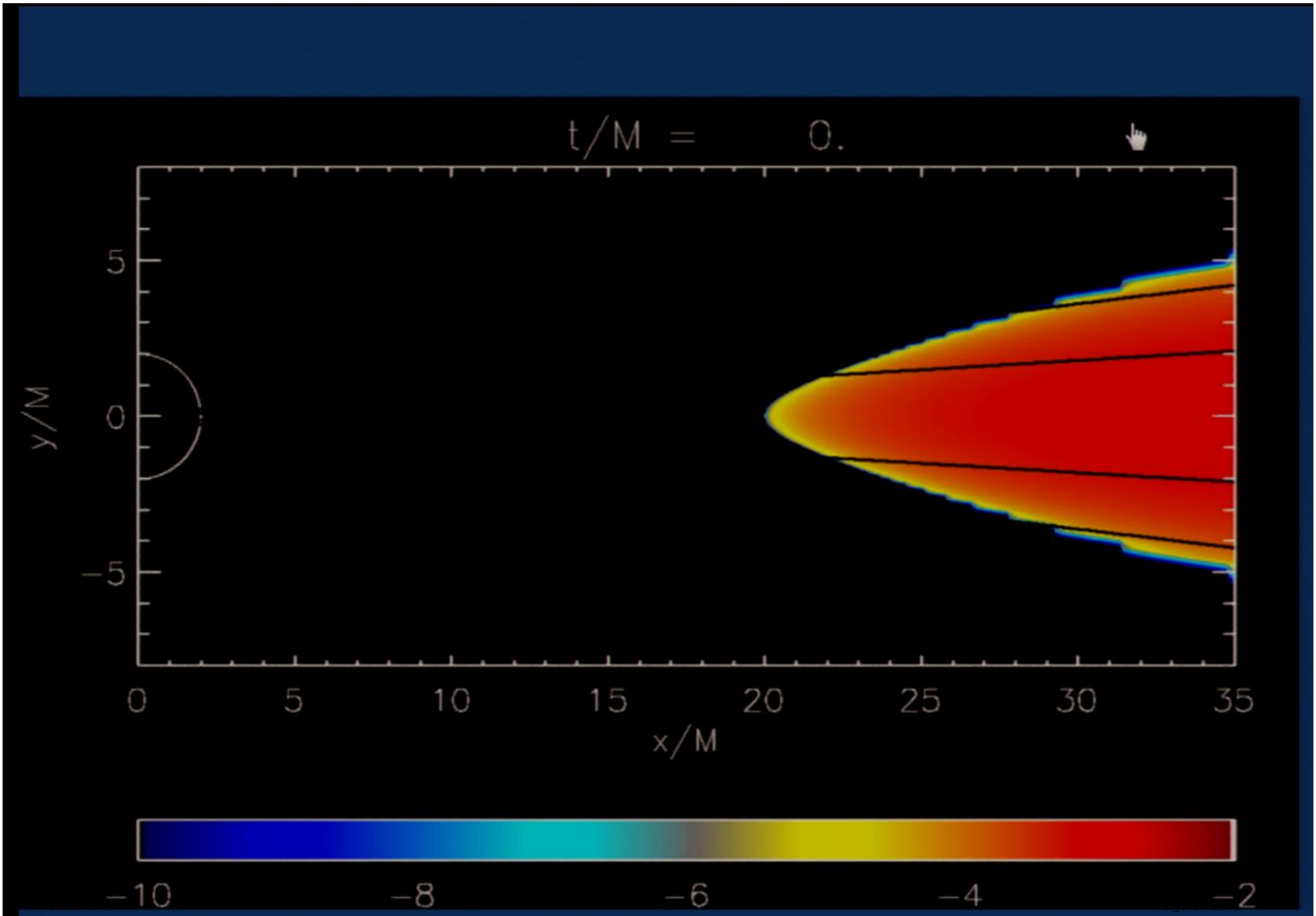
$a = 0.5, B = 10^{12}$

Quasi-normal ringing suppresed!

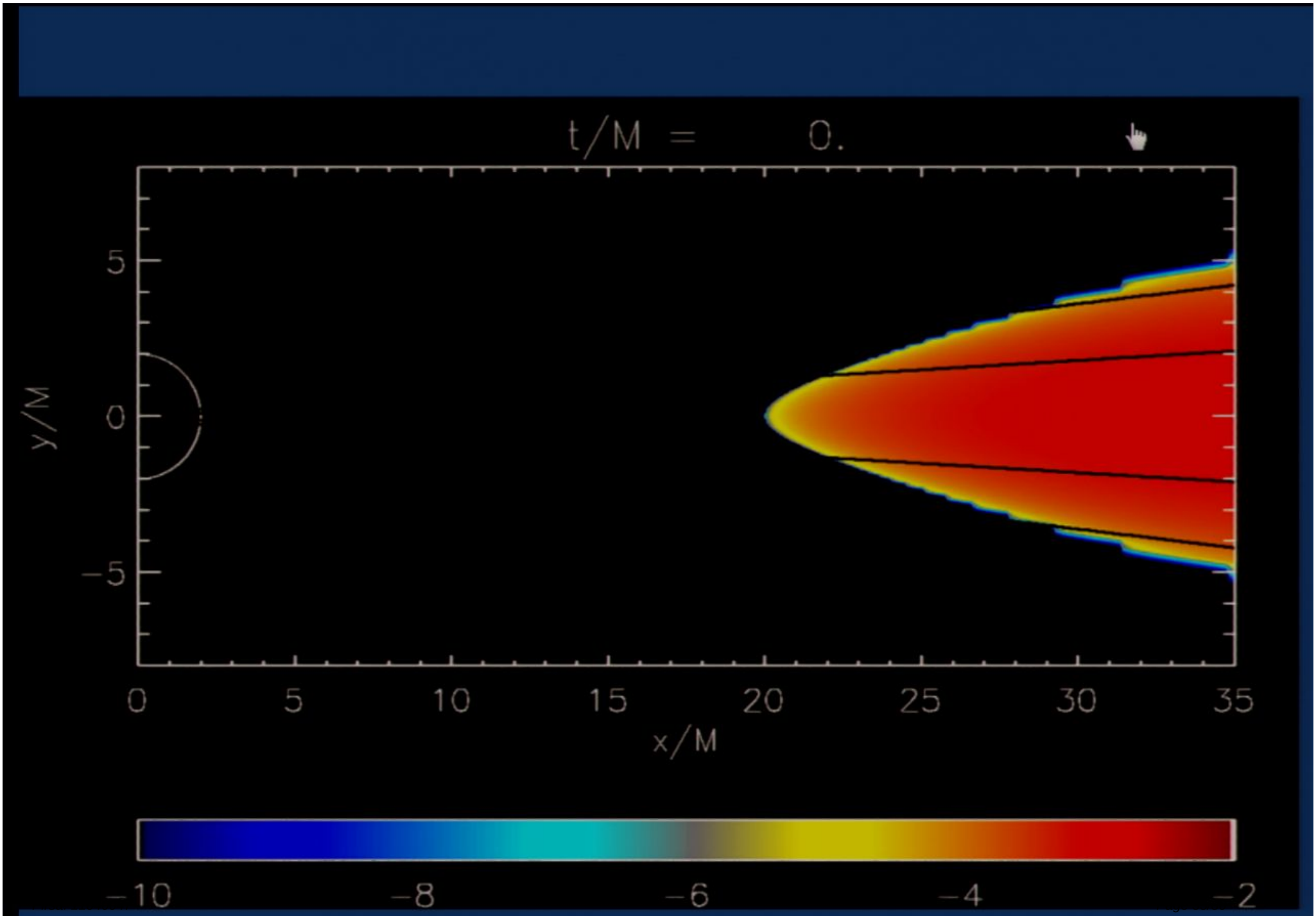
- NS-NS

- NS-NS



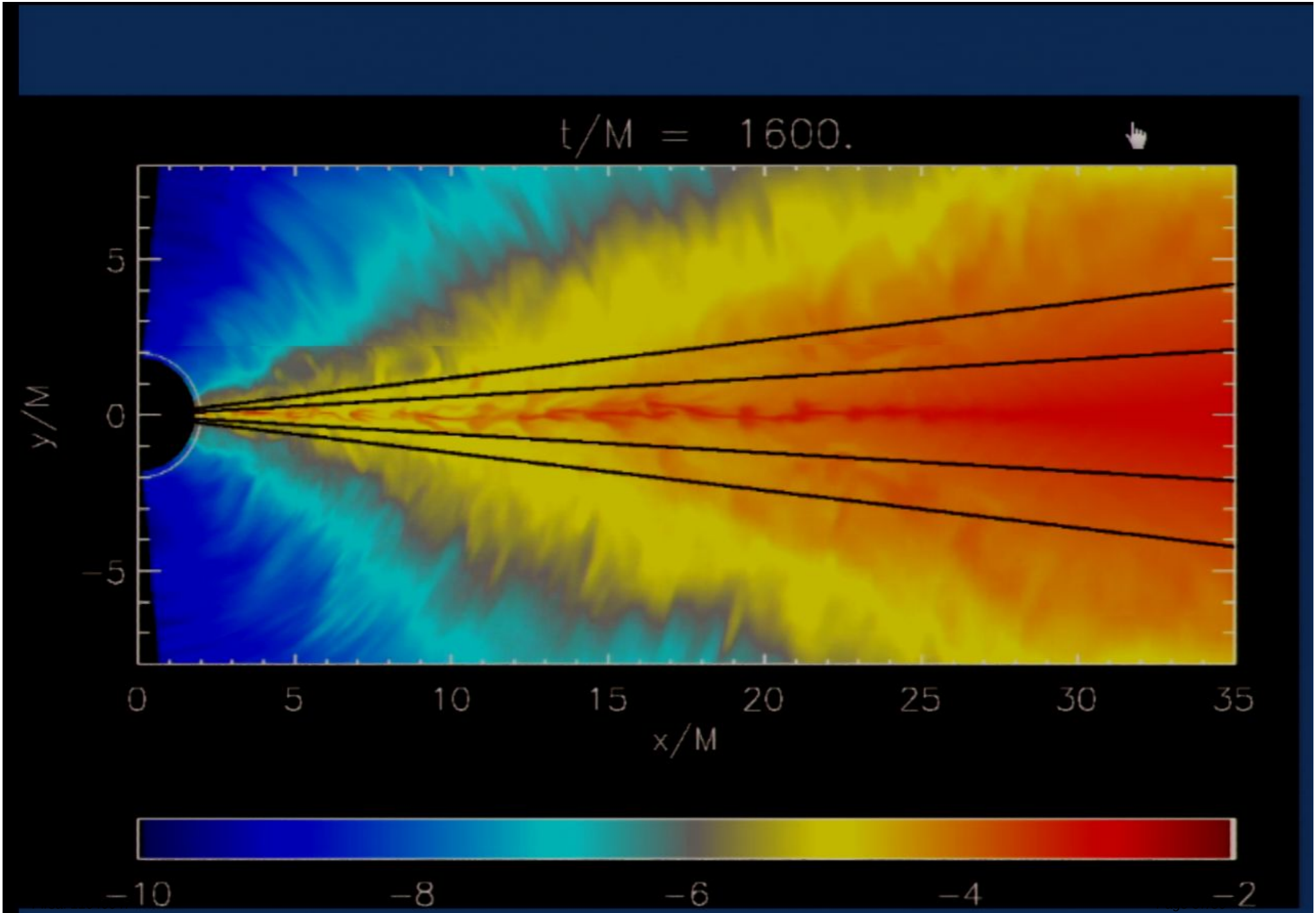


rest-mass density over time in r theta plan, for a thin disk, h/r=0.05, a_bh = 0



rest-mass density over time in r theta plan, for a thin disk, h/r=0.05, a_bh = 0

same data as in Movie1 plus magnetic fields
[Noble, Krolik & Hawley 2010]



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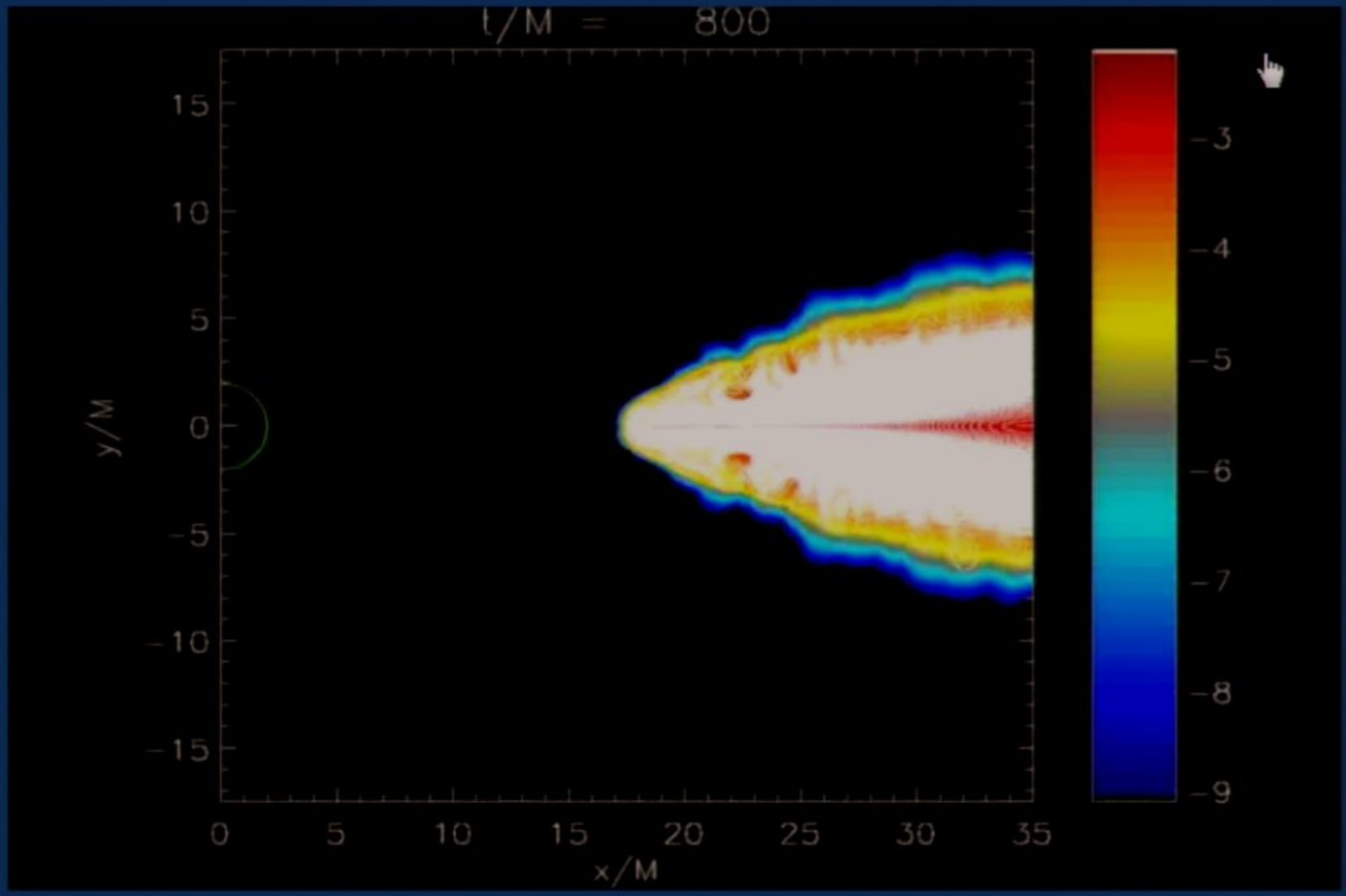

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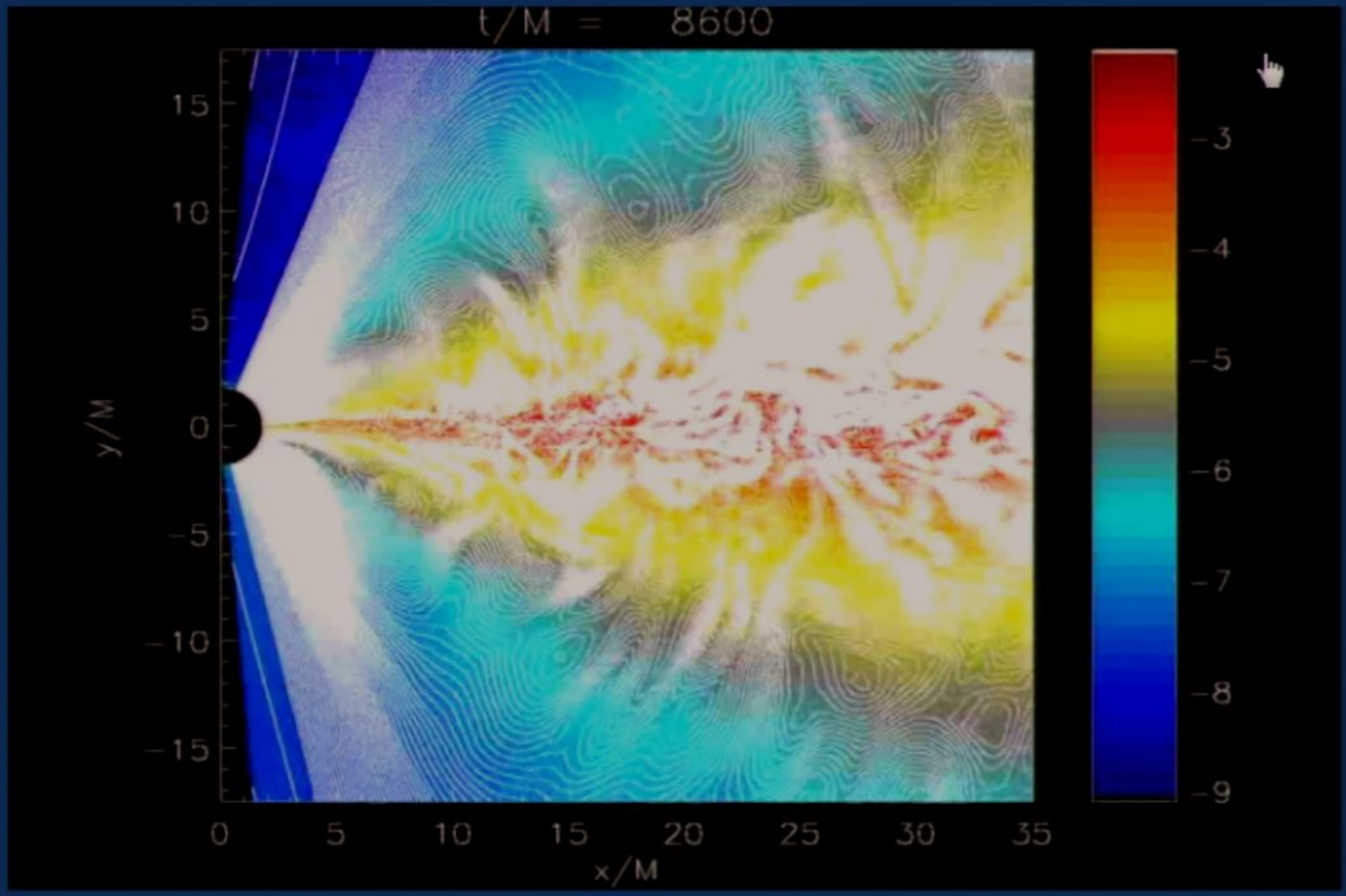

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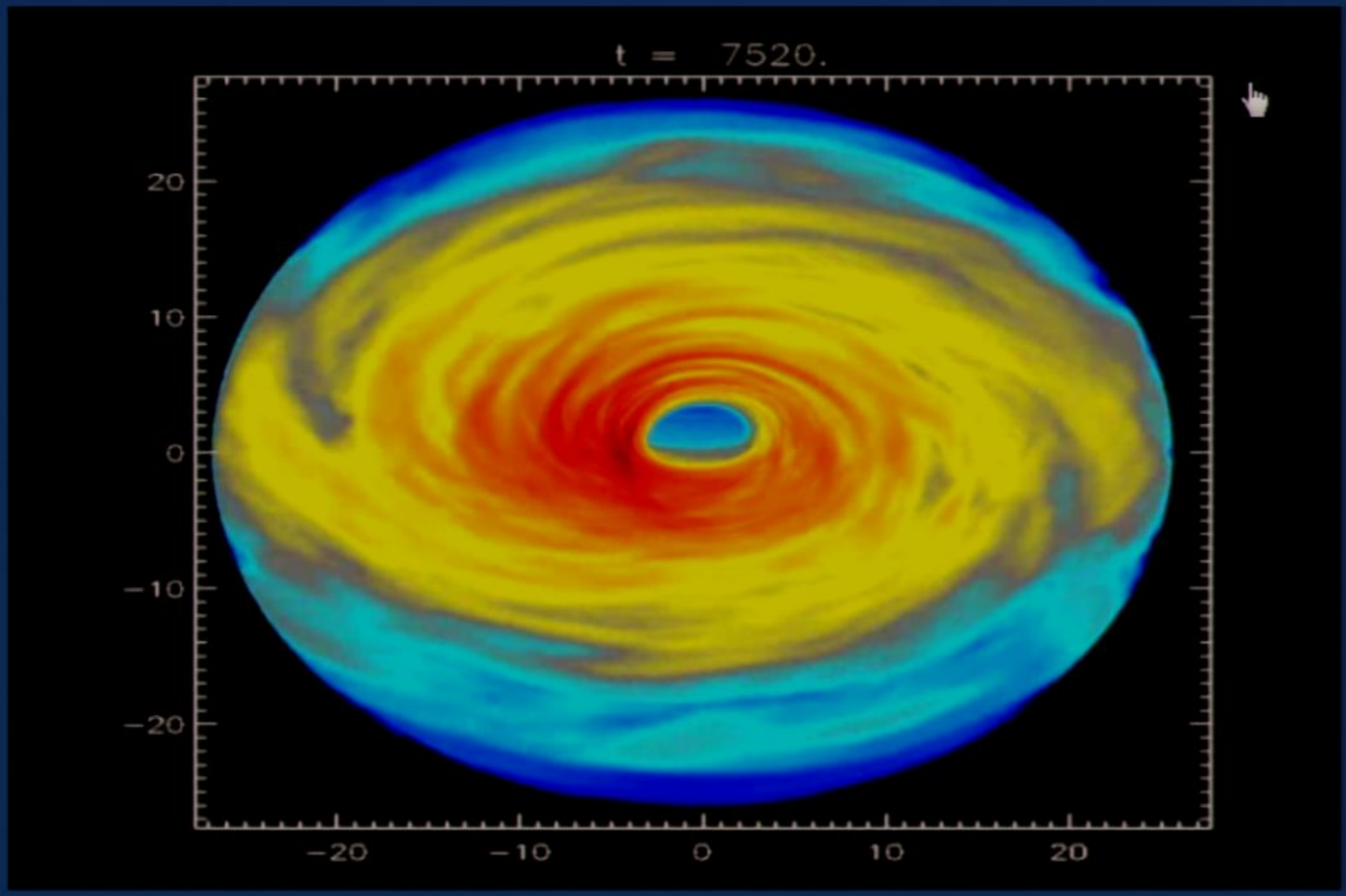
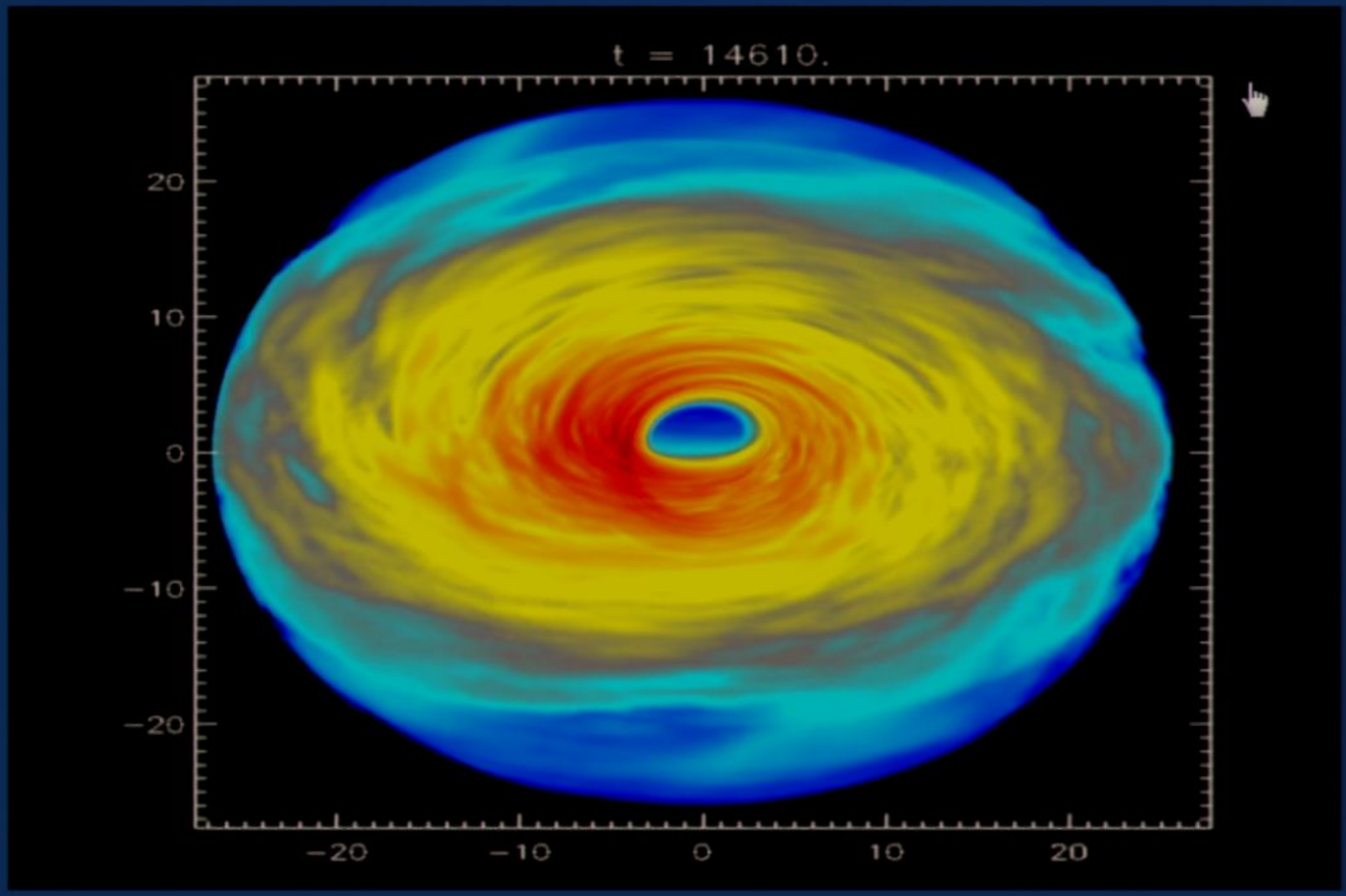


Model of X-ray coronal emission from a thin disk about a spinning (a=0.9) black ho
[Noble & Krolik 2009]



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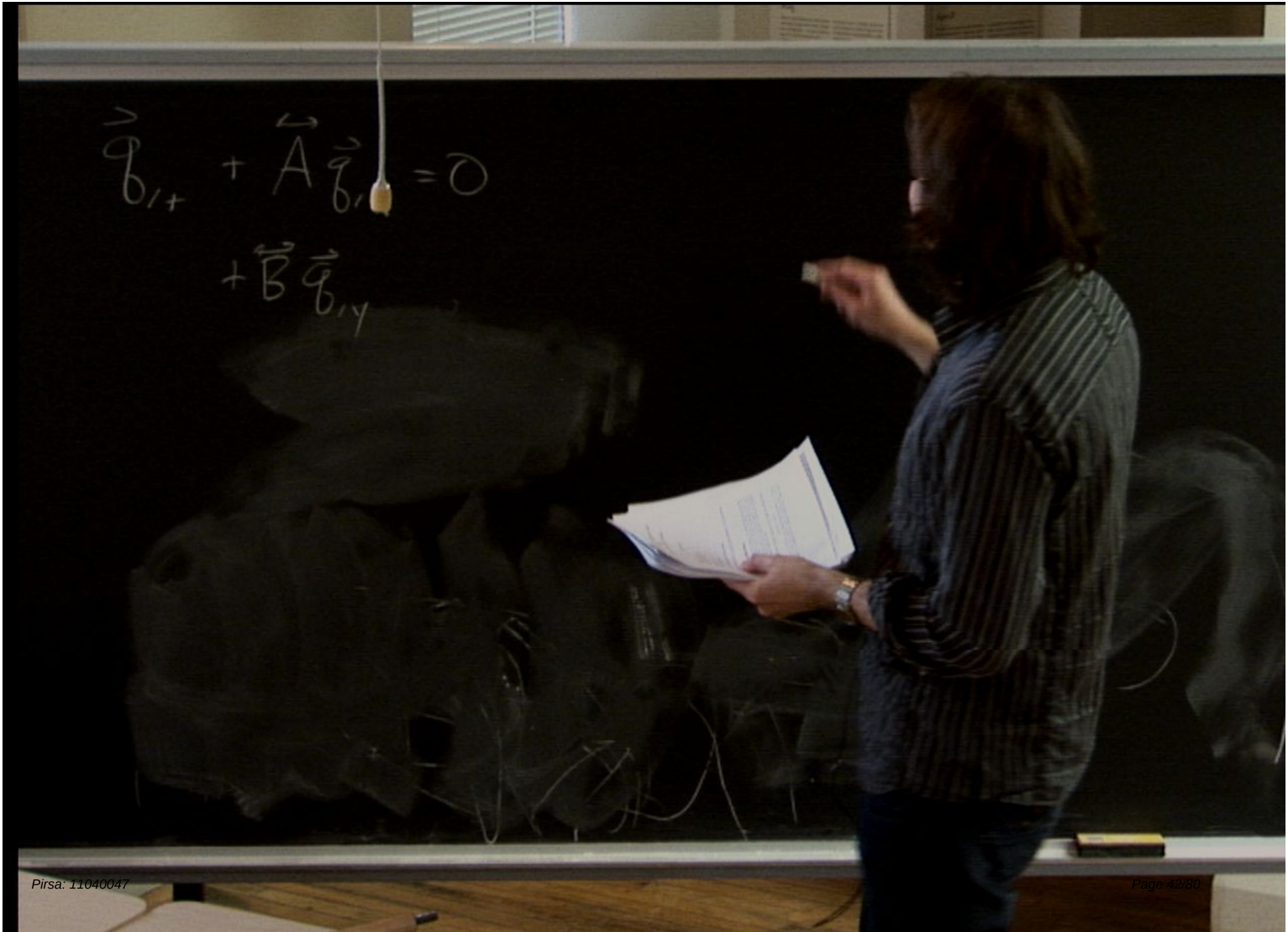
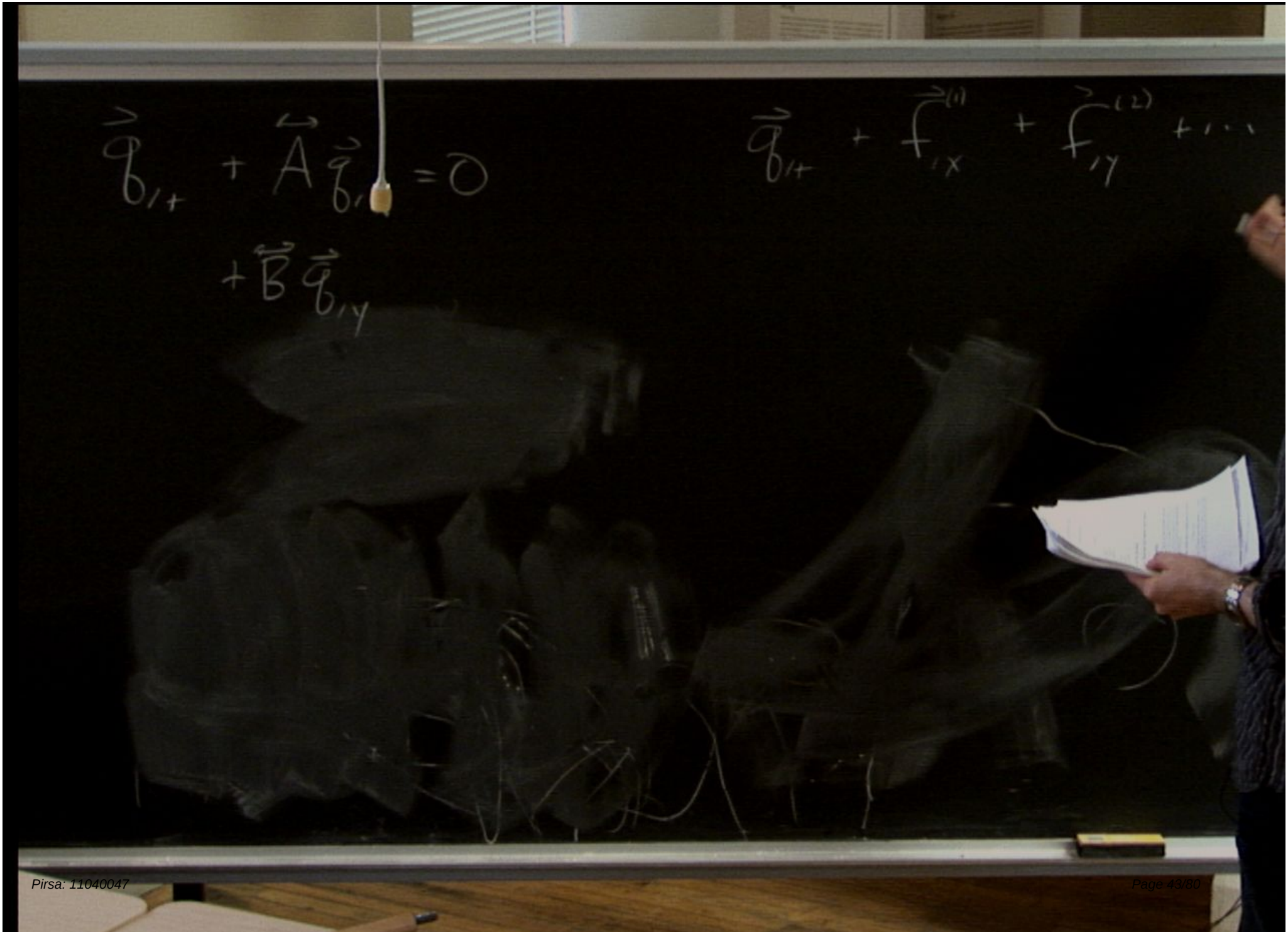
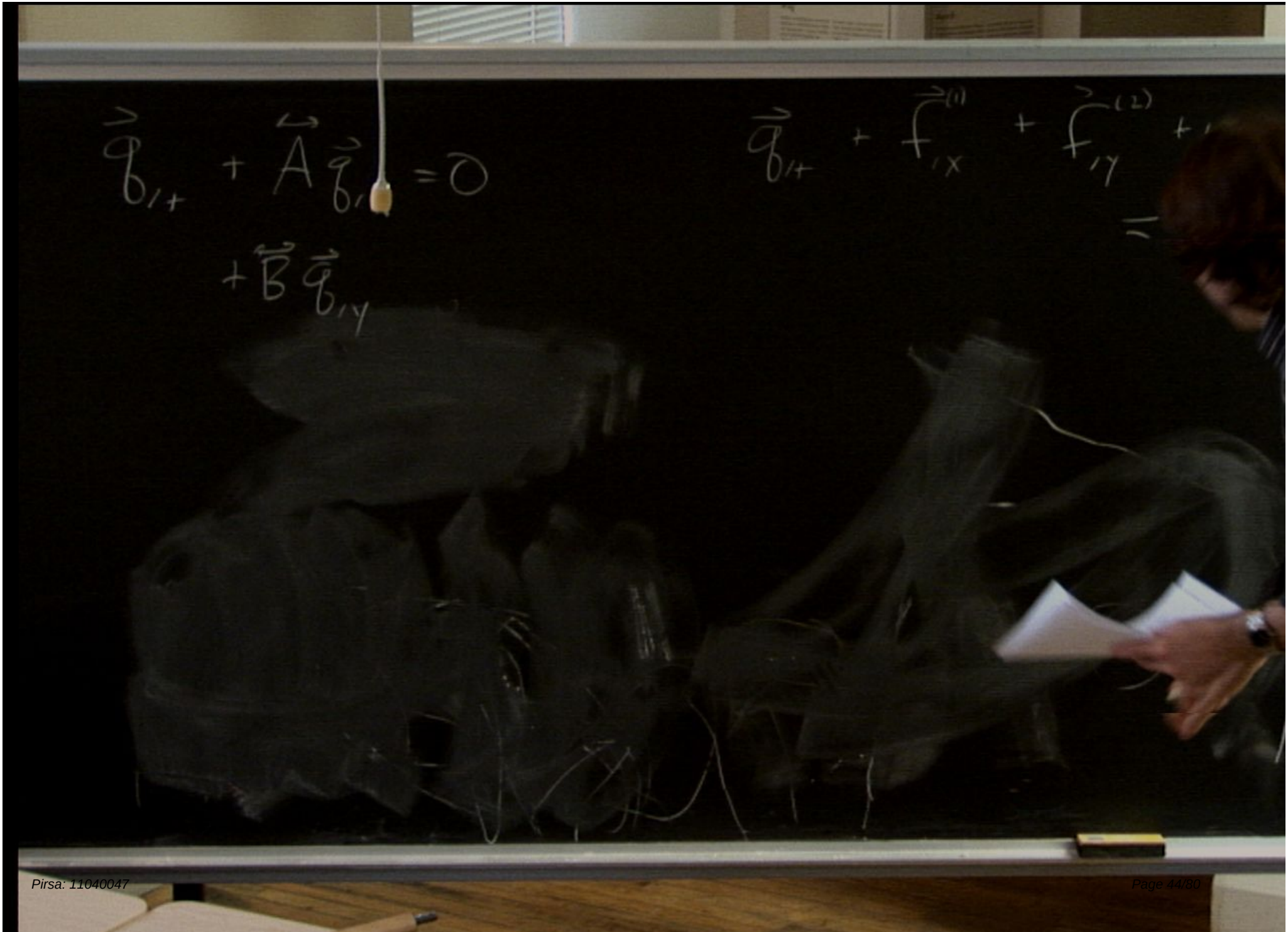
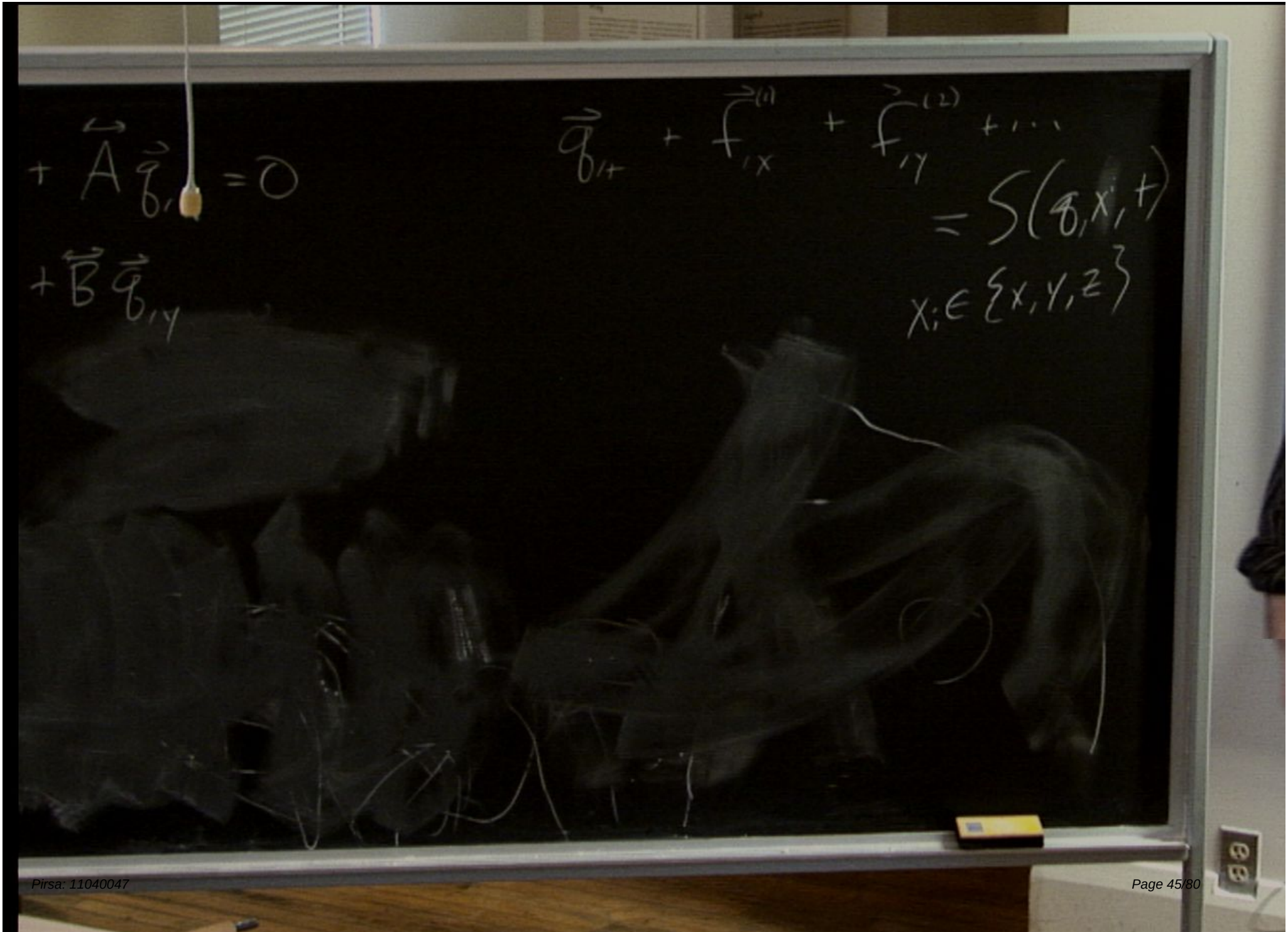
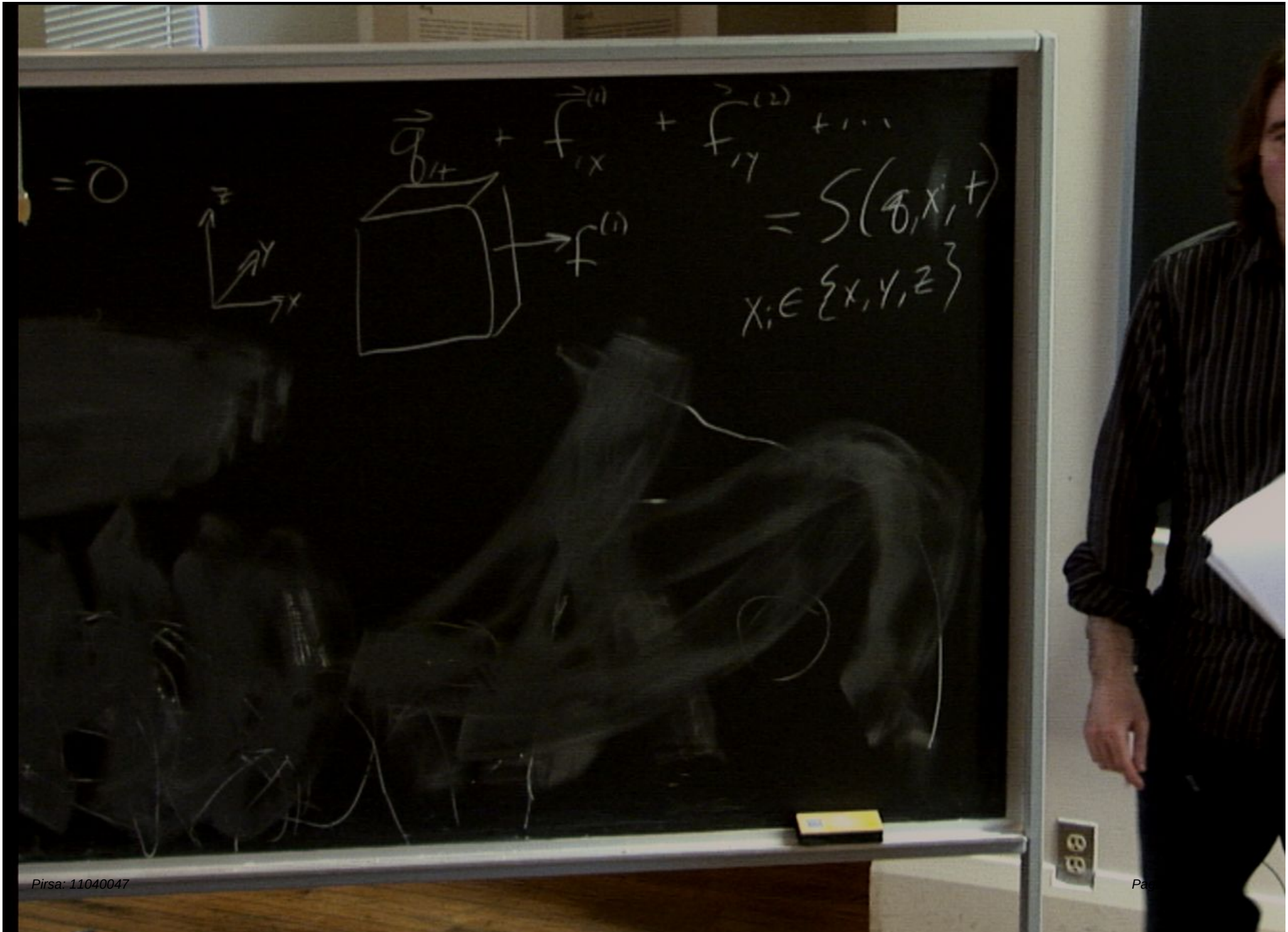
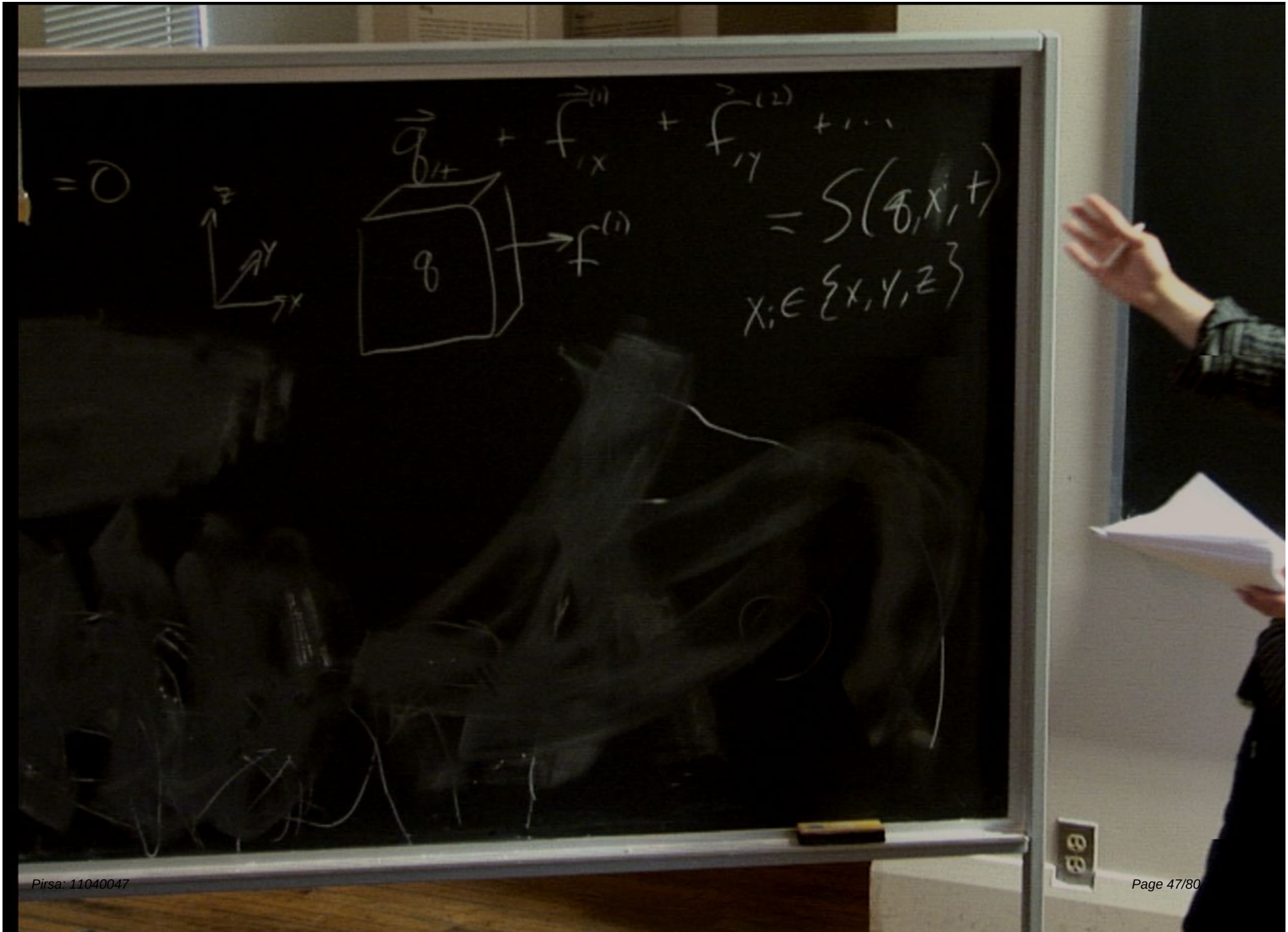

$\vec{q}_{i+} + \overleftrightarrow{A}\vec{q}_i = 0$
$+\overleftrightarrow{B}\vec{q}_{i-}$

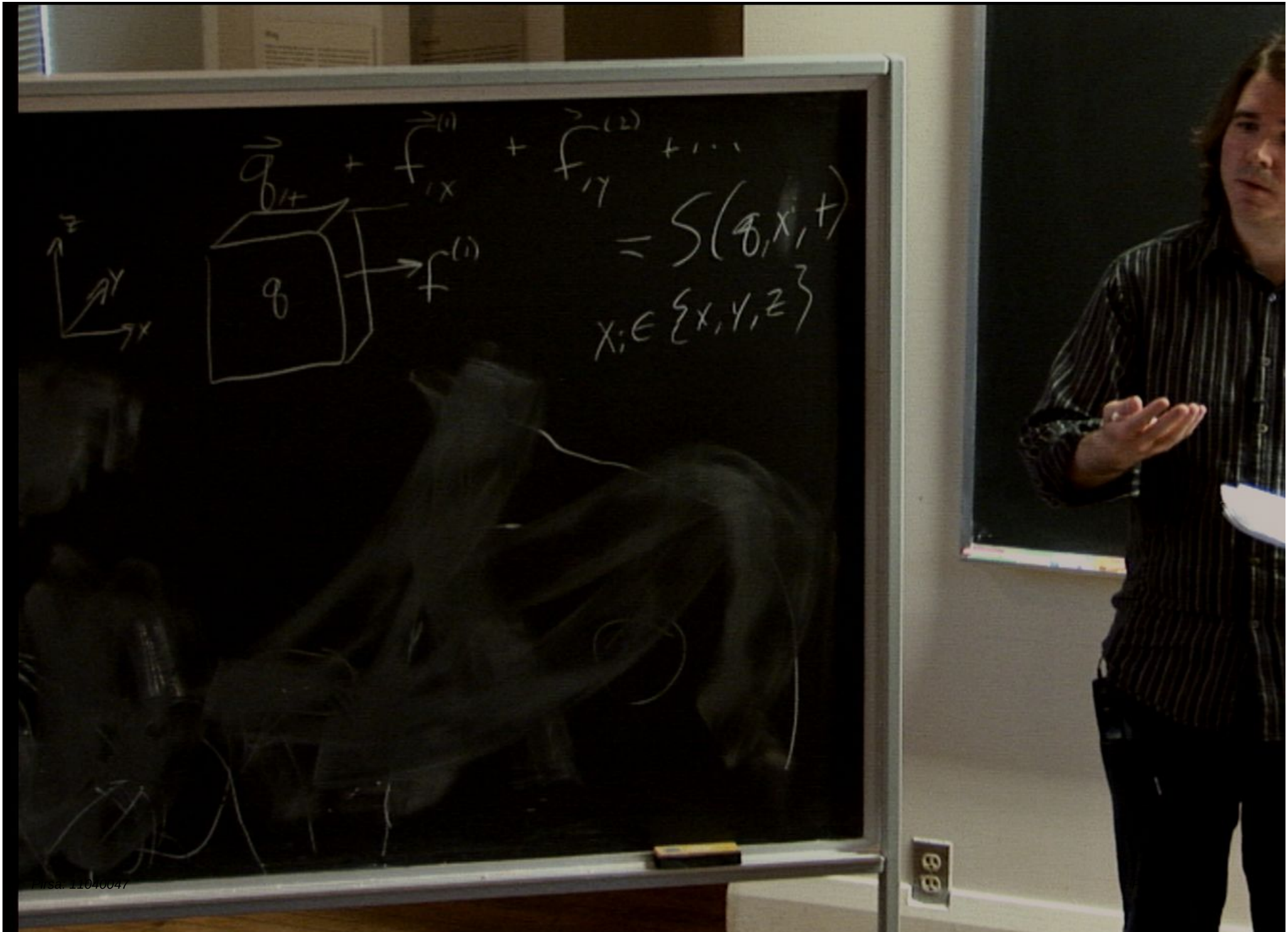

$\ddot{\vec{q}}_{1+} + \overleftrightarrow{A}\vec{q}_1 = 0$
$+\overleftrightarrow{B}\vec{q}_{1+}$
$\ddot{\vec{q}}_{1+} + \vec{f}_{1x}^{(1)} + \vec{f}_{1y}^{(2)} + \cdots$

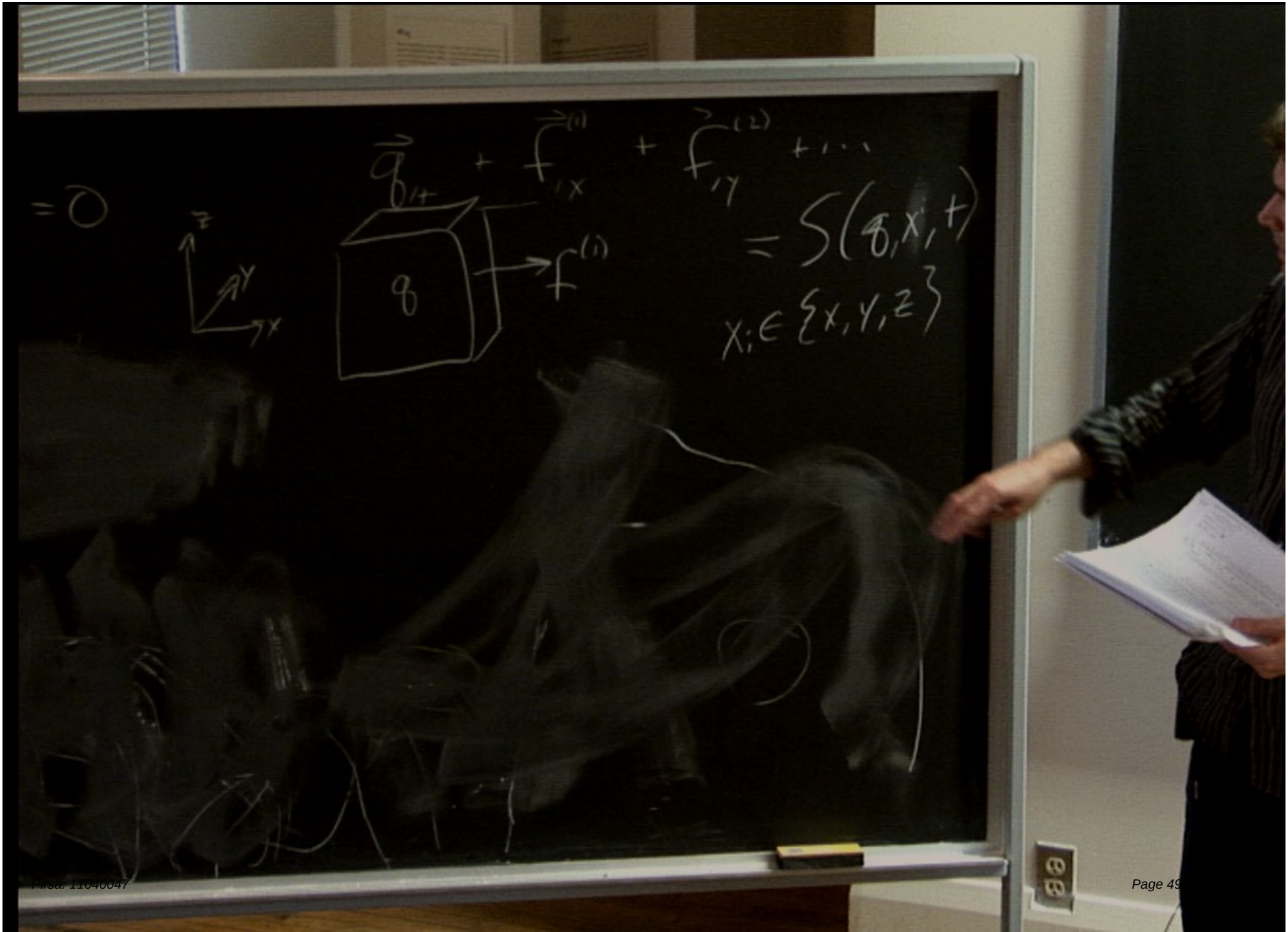

$\ddot{\vec{q}}_{i+} + \overleftrightarrow{A}\vec{q}_{i} = 0$
$+\overleftrightarrow{B}\vec{q}_{i-}$
$\ddot{\vec{q}}_{i+} + \vec{f}_{ix}^{(1)} + \vec{f}_{iy}^{(2)} +$
$=$


$+\overleftrightarrow{A}\vec{q}_{i,} = 0$
$+\vec{B}\vec{q}_{i,y}$
$\vec{q}_{i+} + \vec{f}^{(1)}_{ix} + \vec{f}^{(2)}_{iy} + \cdots$
$= S(q, x_i, t)$
$x_i \in \{x, y, z\}$

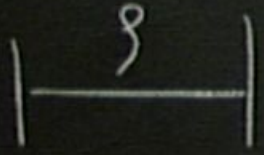

$\vec{g}_{tot}$
$+ \vec{f}^{(1)}_{ix} + \vec{f}^{(2)}_{ij} + \cdots$
$= 0$
$f^{(1)}$
$= S(q, x_i, t)$
$x_i \in \{x, y, z\}$
z
y
x


$\vec{q}_{net}$
$\vec{f}^{(1)}_{1x}$
$\vec{f}^{(2)}_{1y}$
$+ \cdots$
$= 0$
z
y
x
q
$f^{(1)}$
$= S(q, x_i, t)$
$x_i \in \{x, y, z\}$

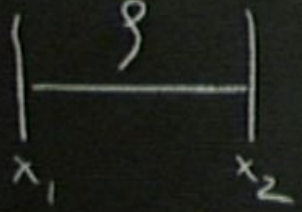

$\vec{q}_{i+} + \vec{f}_{ix}^{(1)} + \vec{f}_{iy}^{(2)} + \cdots$
$= S(q, x_i, t)$
$x_i \in \{x, y, z\}$
q
$f^{(1)}$
z
y
x

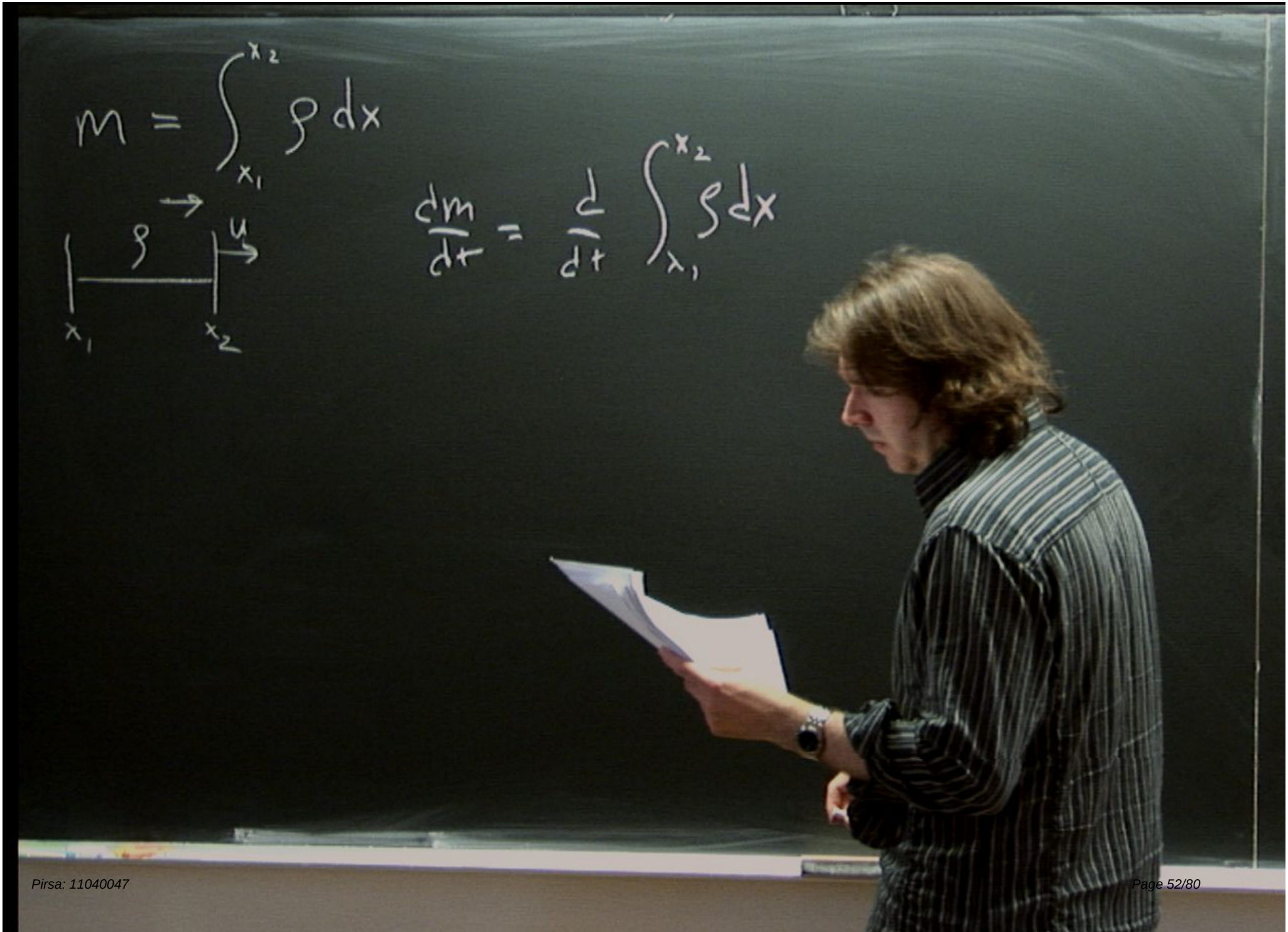

=0
z
y
x
q
f(1)
= S(q, xi, t)
xi ∈ {x, y, z}

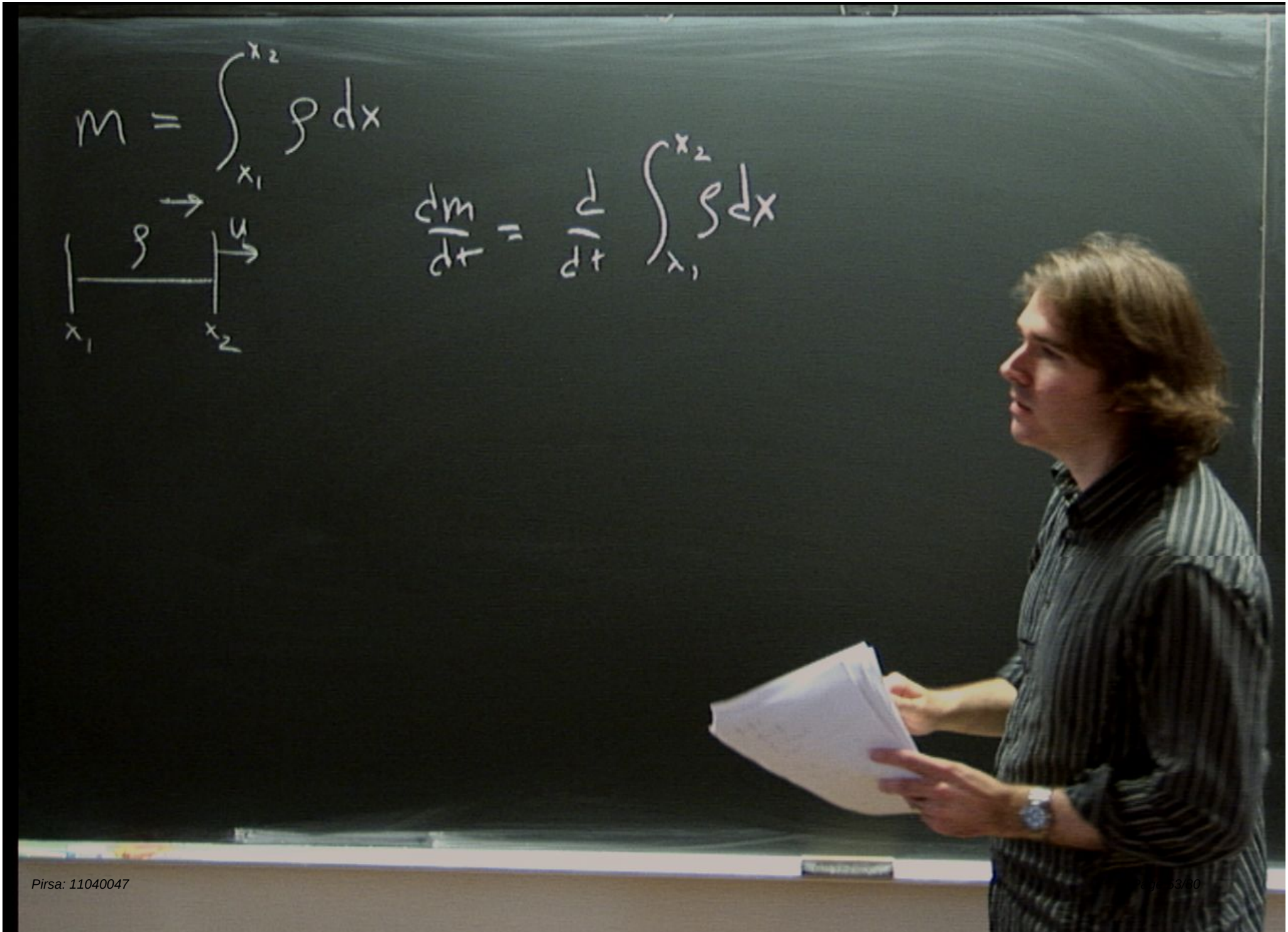
$$m = \int_{x_1}^{x_2}$$



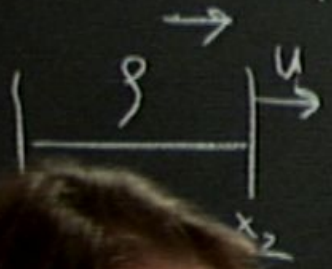
$$m = \int_{x_1}^{x_2} \rho \, dx$$




$m = \int_{x_1}^{x_2} \rho \, dx$
$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx$
ρ
u
x_1
x_2

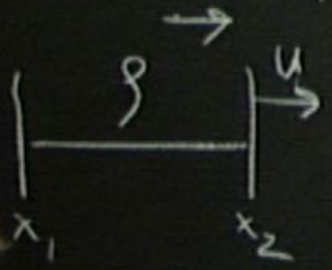

$m = \int_{x_1}^{x_2} \rho \, dx$
$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx$
ρ
u
x_1
x_2

$$m = \int_{x_1}^{x_2} \rho \, dx$$



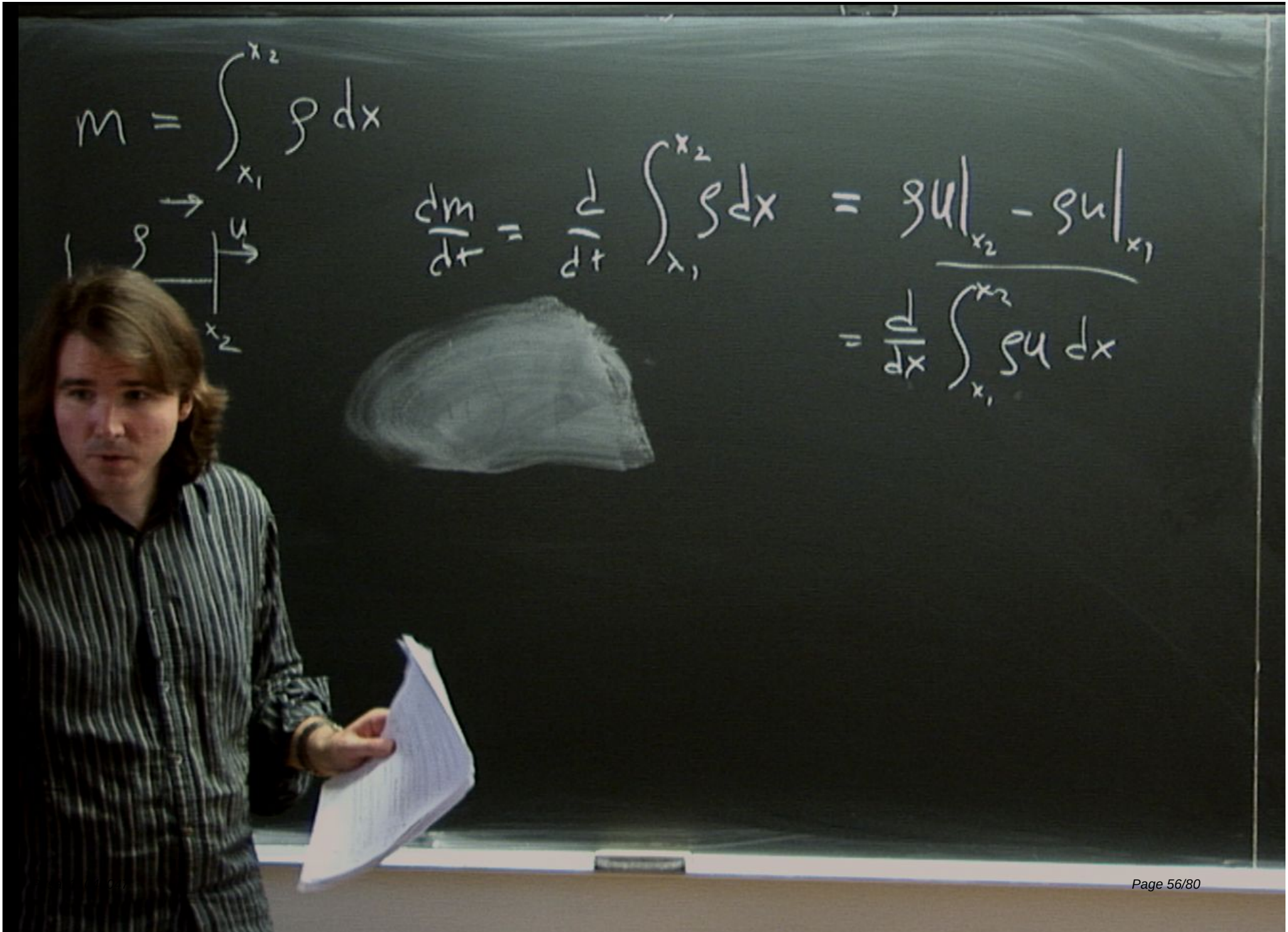
$$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u \Big|_{x_2} - \rho u \Big|_{x_1}$$

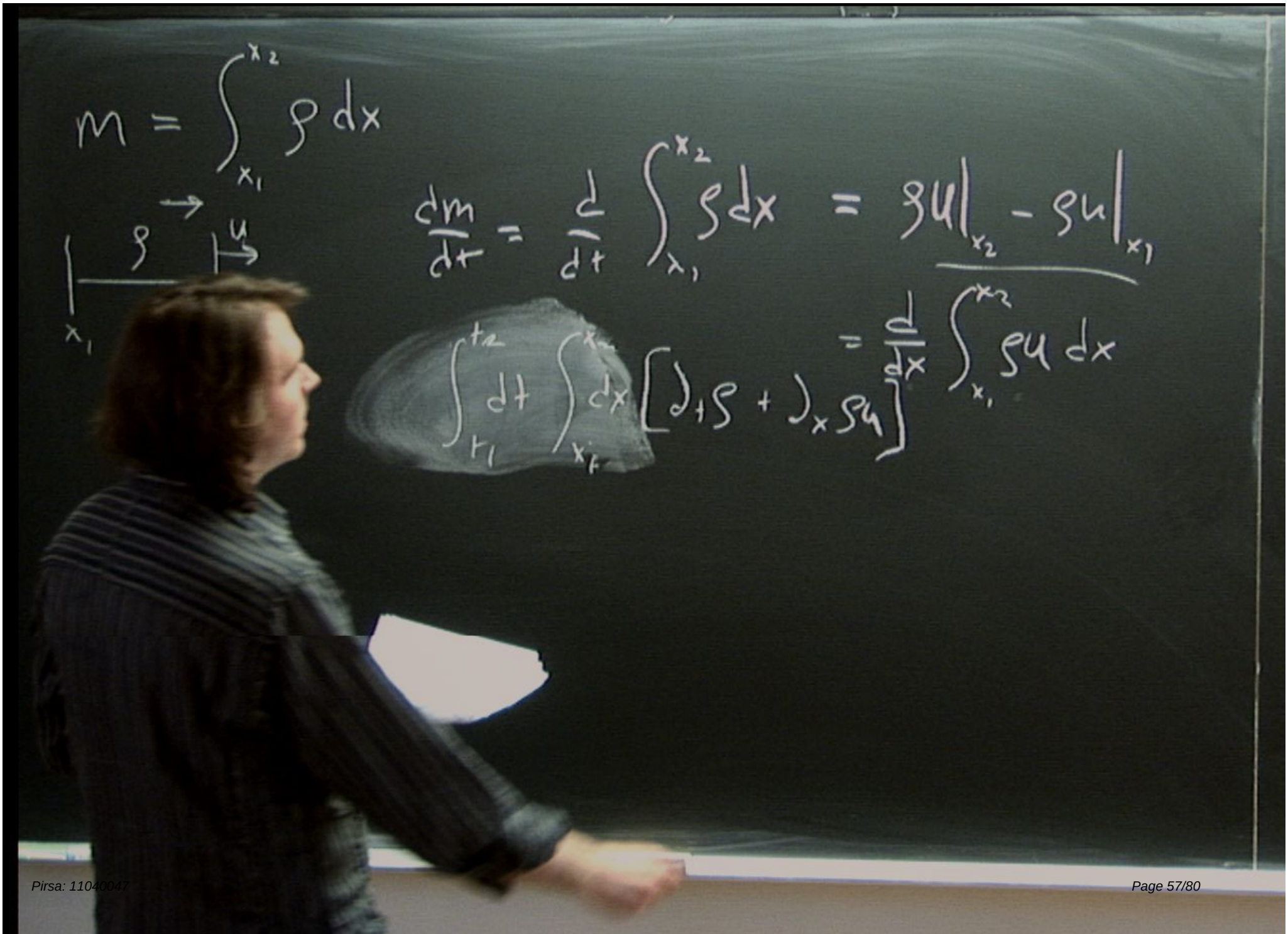
$$m = \int_{x_1}^{x_2} \rho \, dx$$



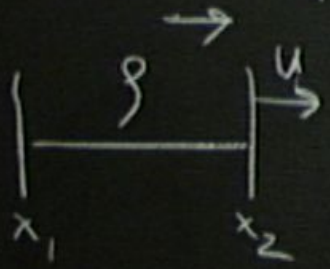
$$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u \Big|_{x_2} - \rho u \Big|_{x_1}$$

$$= \frac{d}{dx} \int_{x_1}^{x_2} \rho u \, dx$$


$m = \int_{x_1}^{x_2} \rho \, dx$
$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u|_{x_2} - \rho u|_{x_1}$
$= \frac{d}{dx} \int_{x_1}^{x_2} \rho u \, dx$
ρ
u
x_2


$m = \int_{x_1}^{x_2} \rho \, dx$
$\rho \mapsto u$
$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u|_{x_2} - \rho u|_{x_1}$
$= \int_{t_1}^{t_2} dt \int_{x_1}^{x_2} dx \left[\partial_t \rho + \partial_x \rho u \right] = \frac{d}{dx} \int_{x_1}^{x_2} \rho u \, dx$

$$m = \int_{x_1}^{x_2} \rho \, dx$$



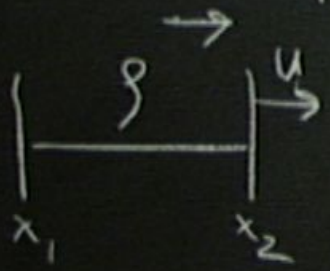
$$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u \Big|_{x_2} - \rho u \Big|_{x_1}$$

$$= \frac{d}{dx} \int_{x_1}^{x_2} \rho u \, dx$$

$$\int_{t_1}^{t_2} dt \int_{x_1}^{x_2} dx \left[\partial_t \rho + \partial_x \rho u \right] = 0$$

$$\partial_t \rho + \partial_x \rho u = 0$$

$$m = \int_{x_1}^{x_2} \rho \, dx$$

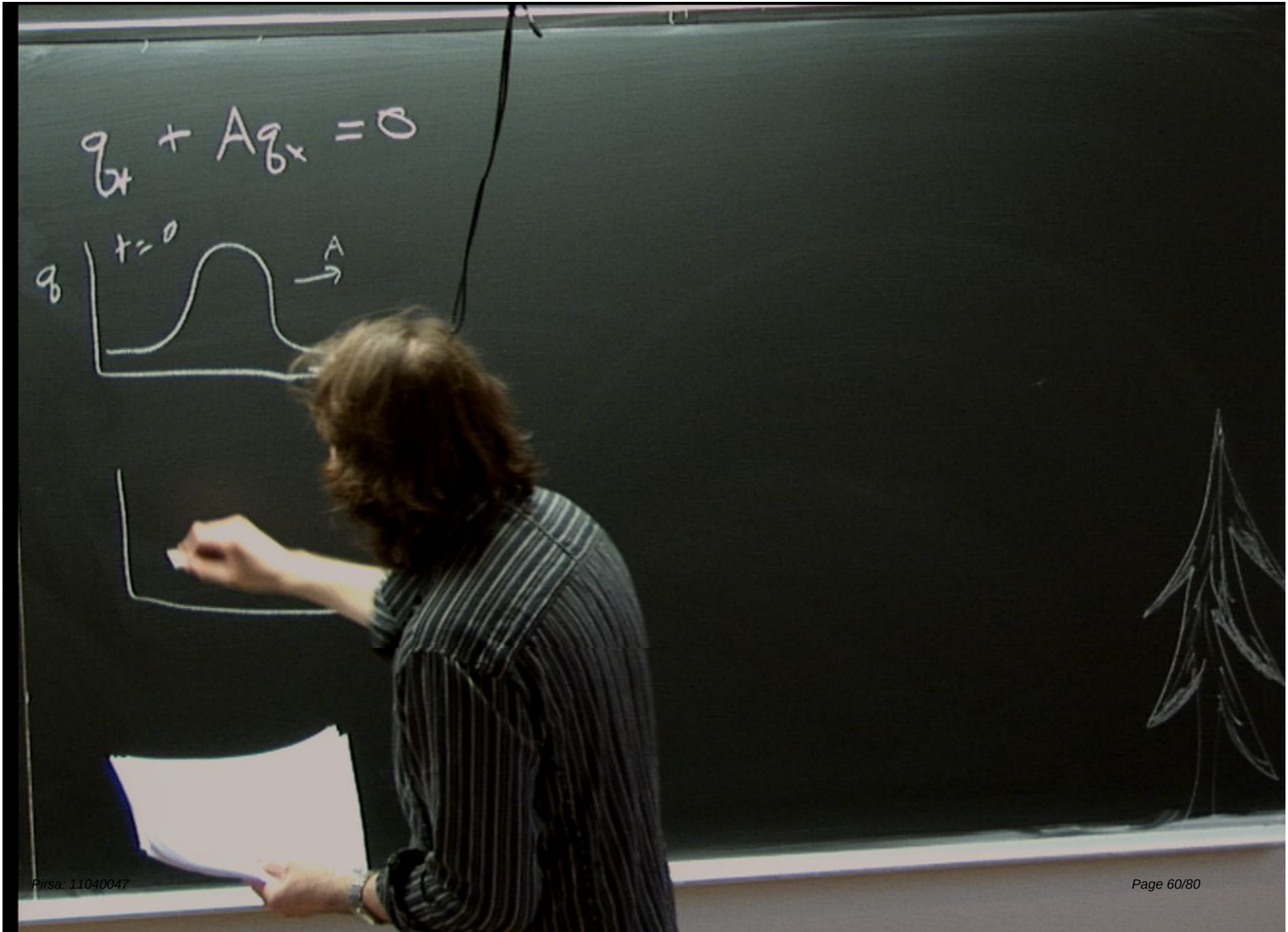


$$\frac{dm}{dt} = \frac{d}{dt} \int_{x_1}^{x_2} \rho \, dx = \rho u \Big|_{x_2} - \rho u \Big|_{x_1}$$

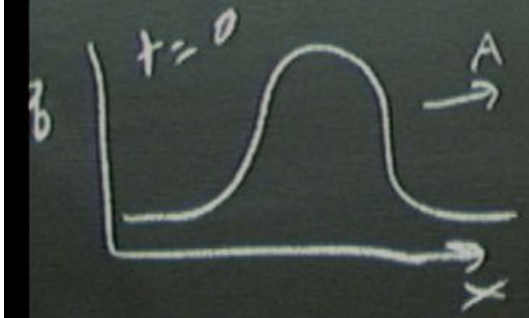
$$= \frac{d}{dx} \int_{x_1}^{x_2} \rho u \, dx$$

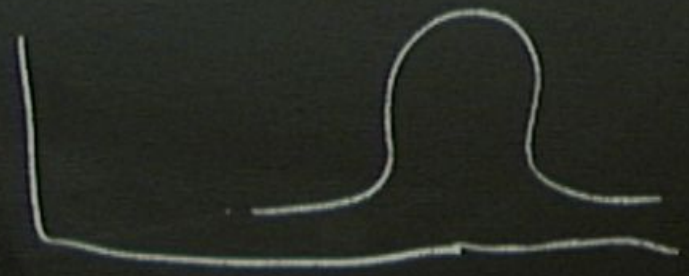
$$\int_{t_1}^{t_2} dt \int_{x_1}^{x_2} dx \left[\partial_t \rho + \partial_x \rho u \right] = 0$$

$$\partial_t \rho + \partial_x \rho u = 0$$


$q_t + A q_x = 0$
$t = 0$
q
A

$q_t + A q_x = 0$



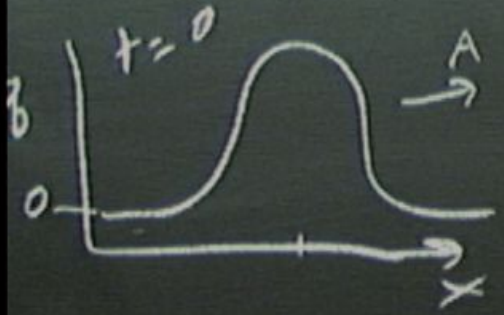


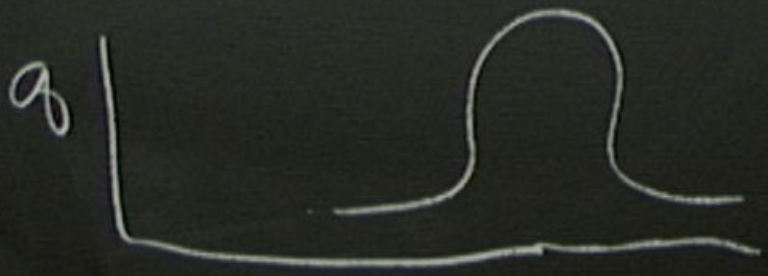
$q_t + q q_x = 0$

$q_t + f(q)_x = 0$

$f(q) = \frac{q^2}{2}$

$q_t + A q_x = 0$



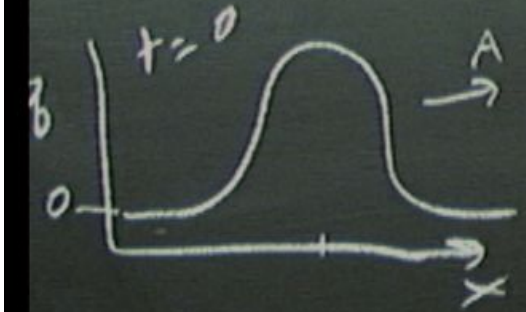


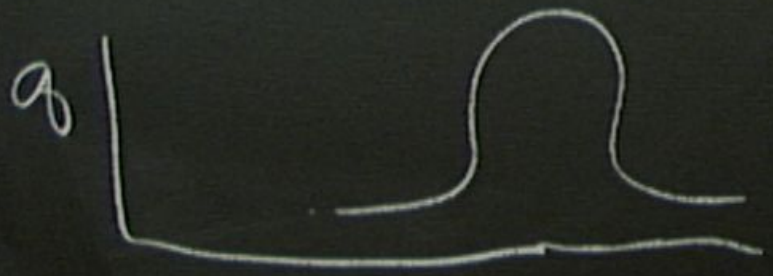
$q_t + q q_x = 0$

$q_t + f(q)_x = 0$

$f(q) = \frac{q^2}{2}$

$q_t + A q_x = 0$

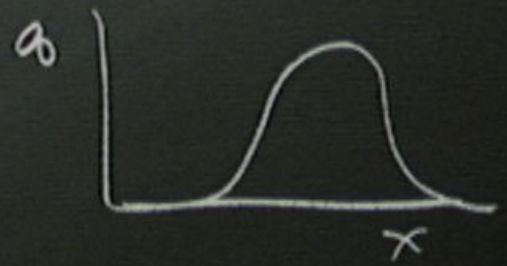




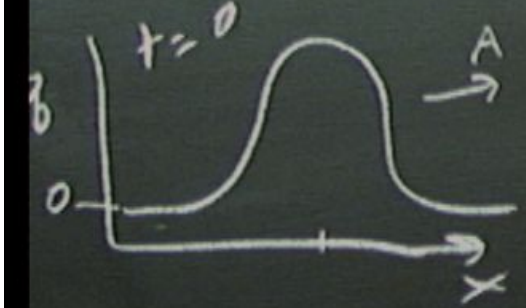
$q_t + q q_x = 0$

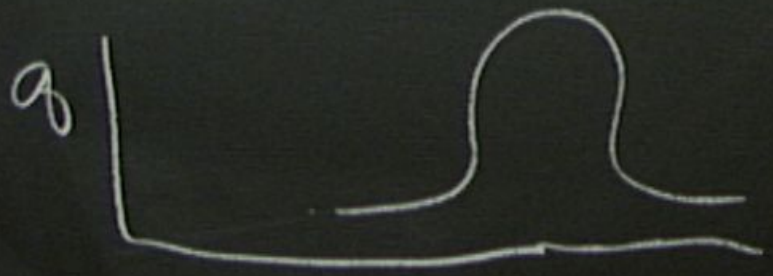
$q_t + f(q)_x = 0$

$f(q) = \frac{q^2}{2}$



$q_t + A q_x = 0$

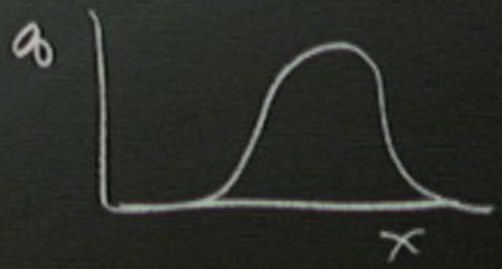


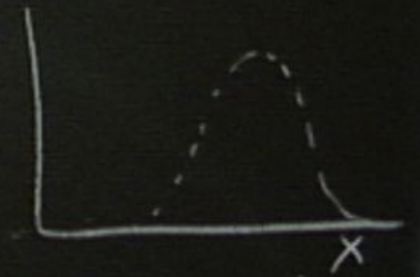


$q_t + q q_x = 0$

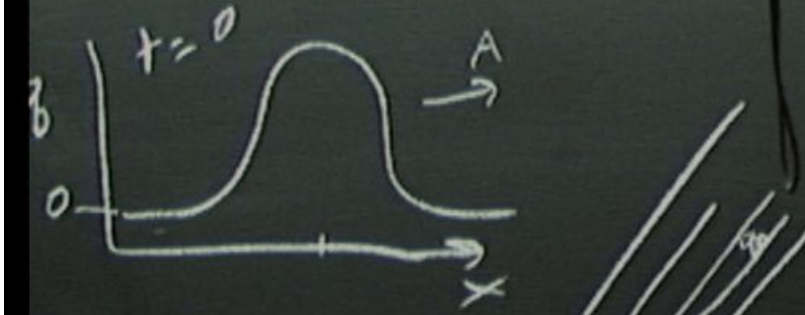
$q_t + f(q)_x = 0$

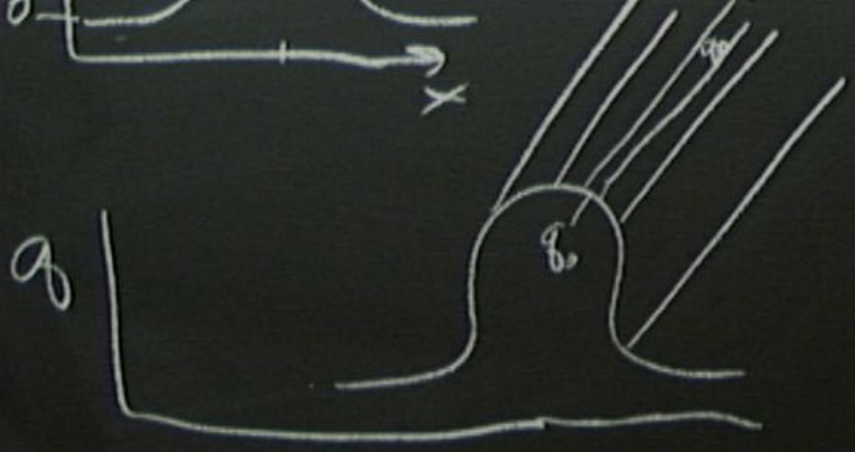
$f(q) = \frac{q^2}{2}$





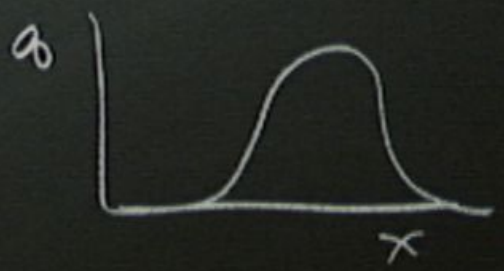
$q_t + A q_x = 0$

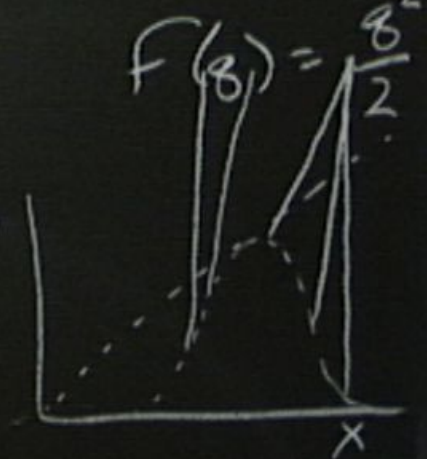




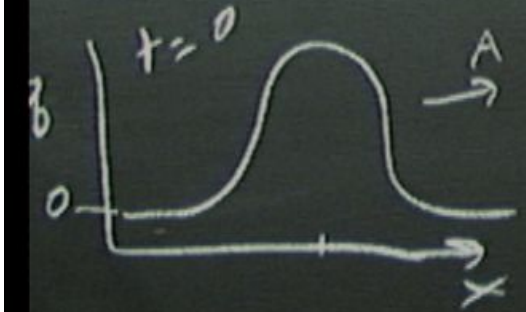
$q_t + q q_x = 0$

$q_t + f(q)_x = 0$



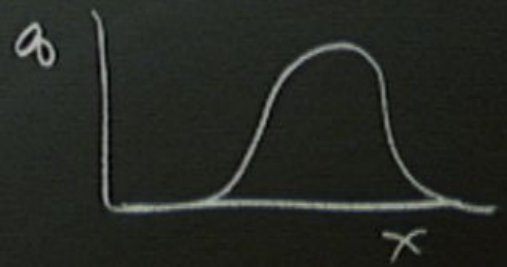


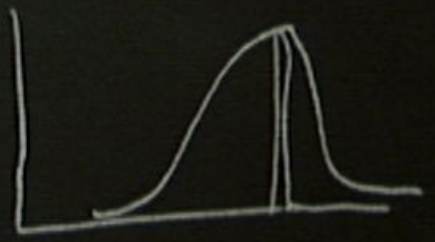
$q_t + A q_x = 0$

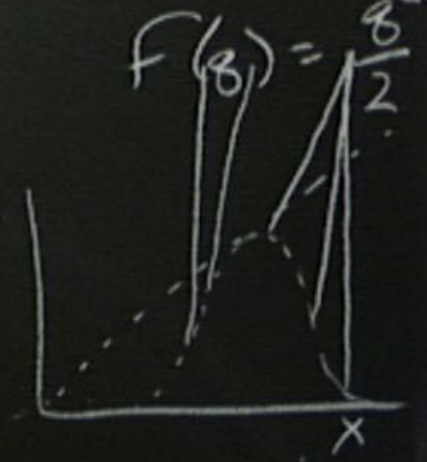


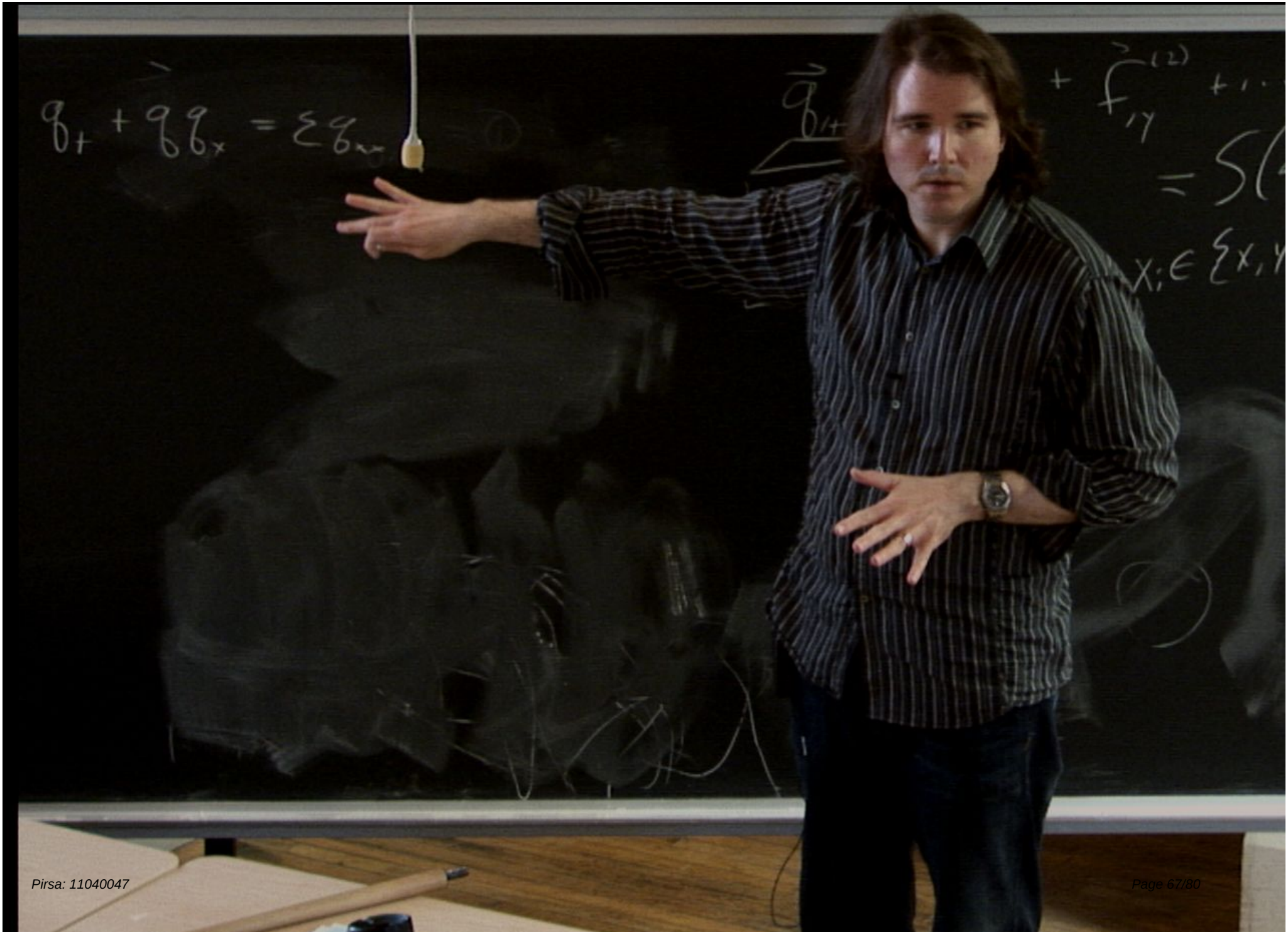
$q_t + q q_x = 0$

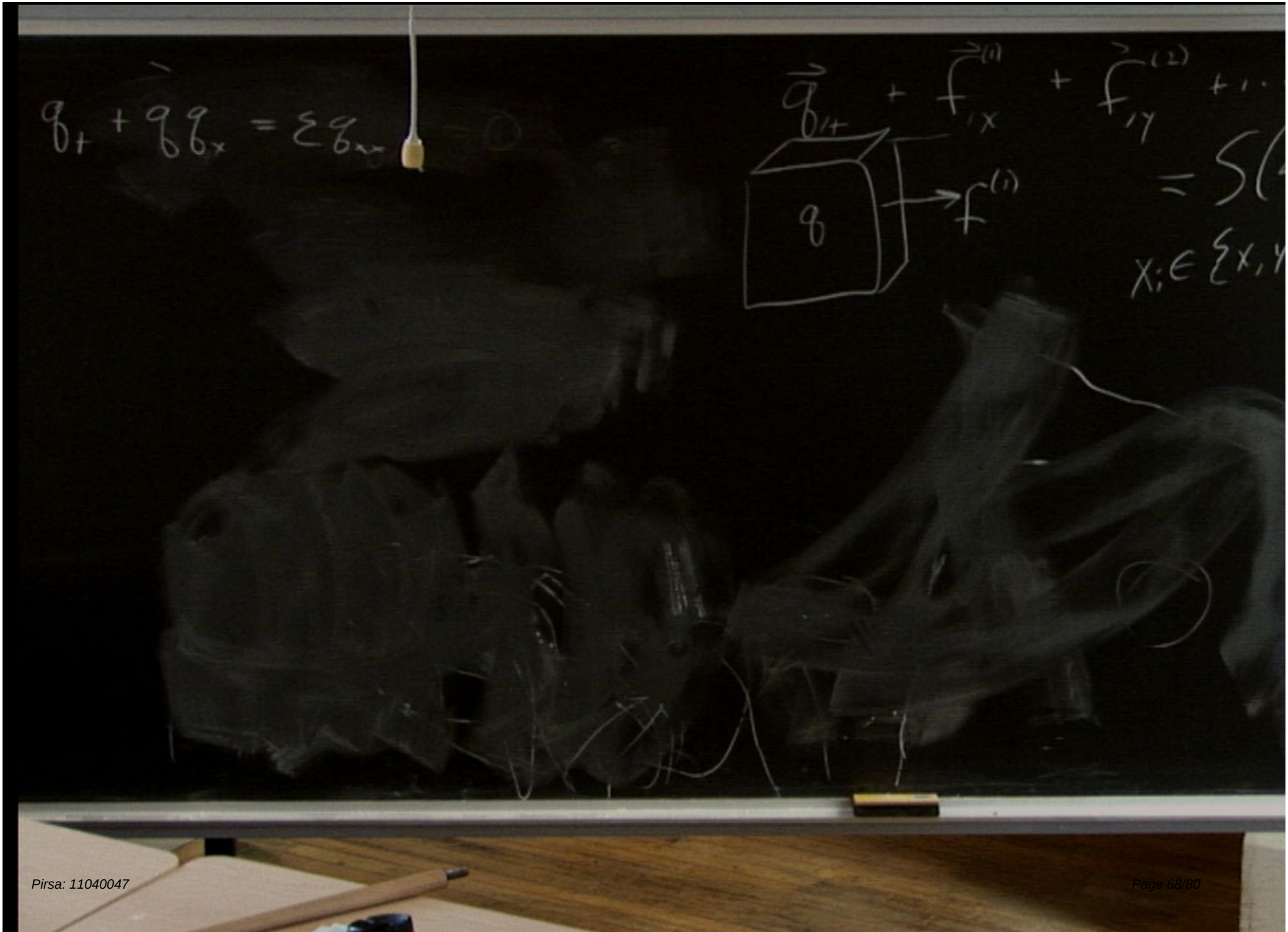
$q_t + f(q)_x = 0$

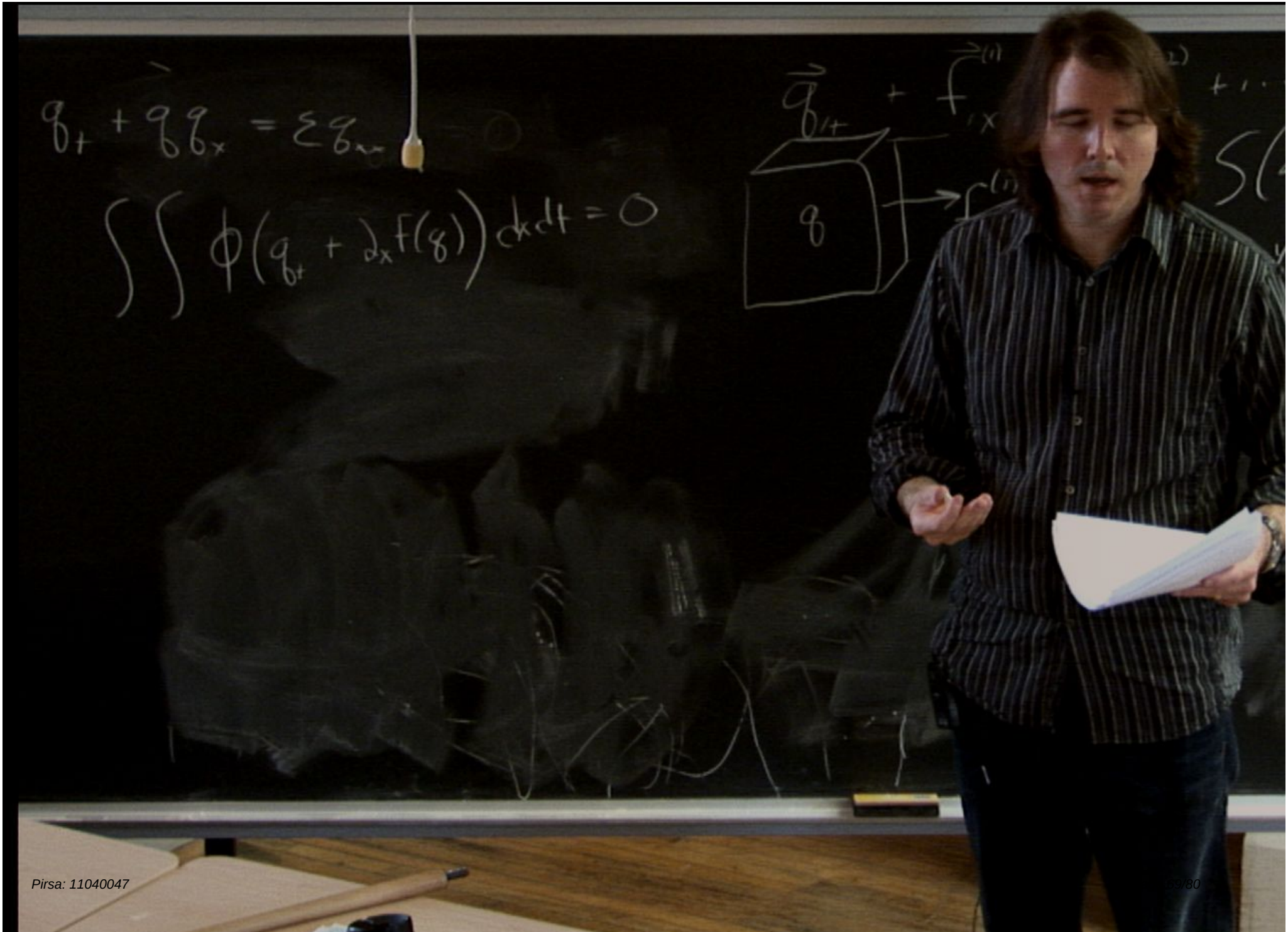


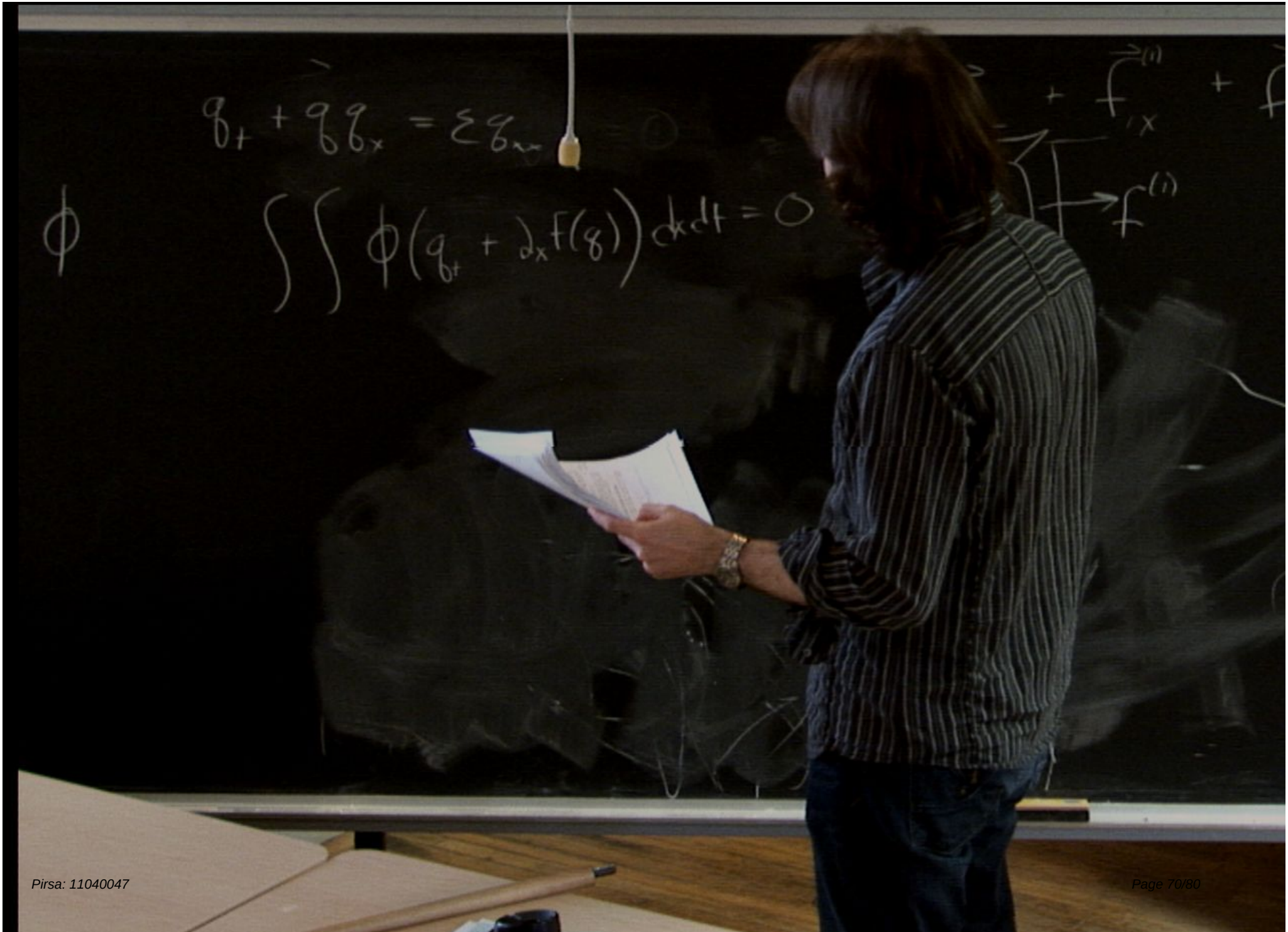


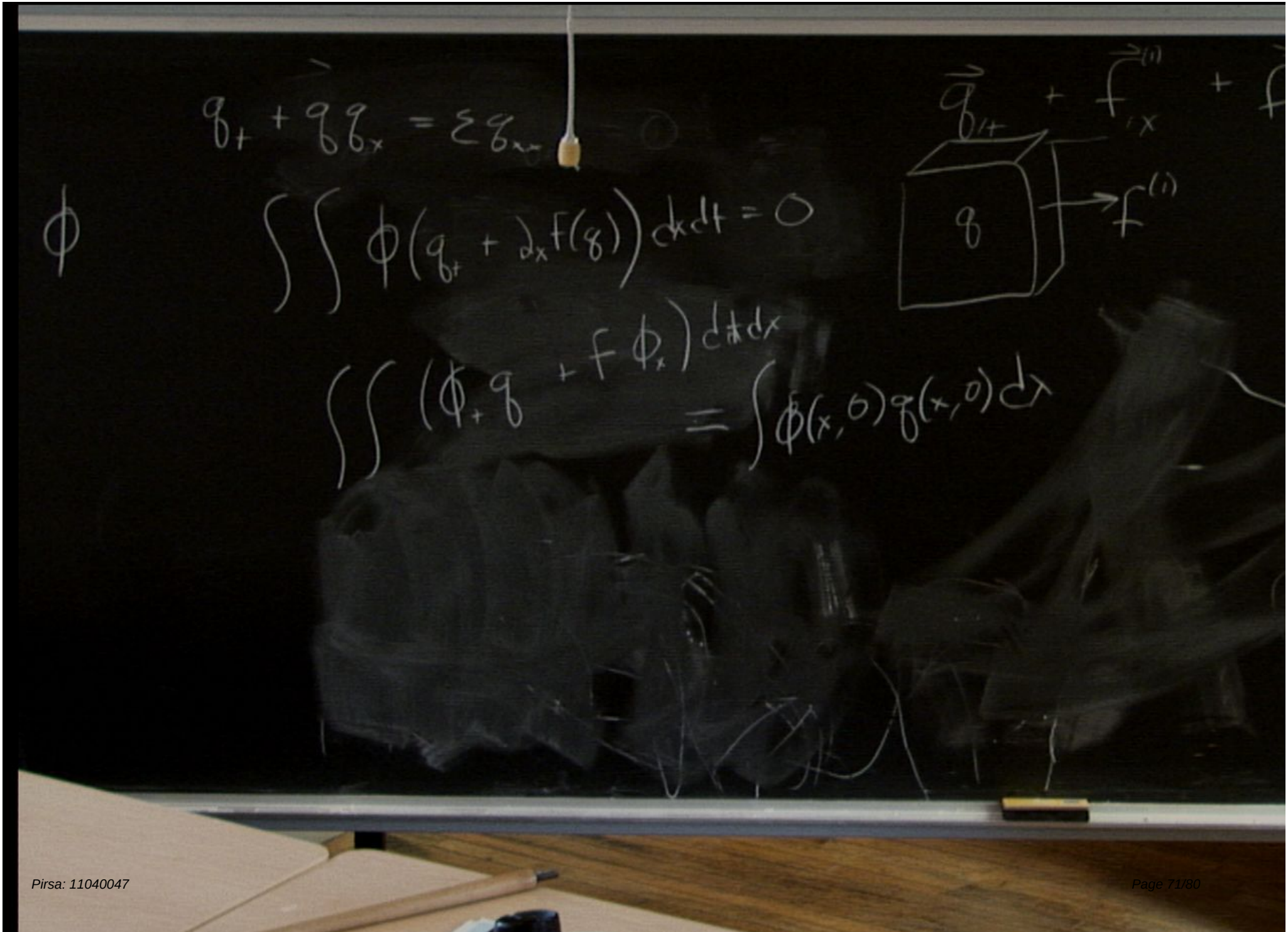




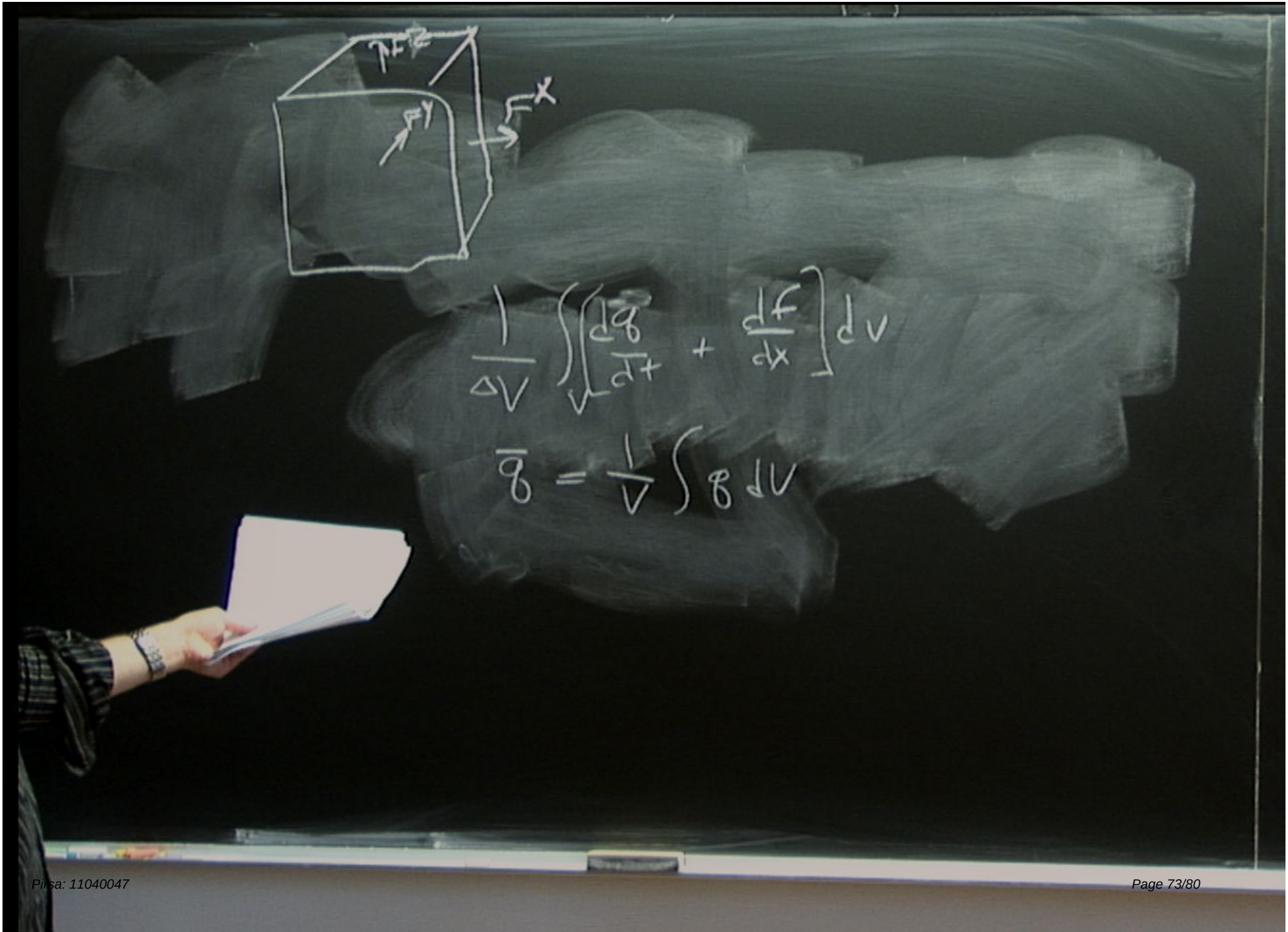

$q_t + qq_x = \varepsilon q_{xx}$
$\vec{q}_{i+}$
$\vec{f}_{ix}^{(1)}$
$\vec{f}_{iy}^{(2)}$
q
$f^{(1)}$
$x_i \in \{x, y$

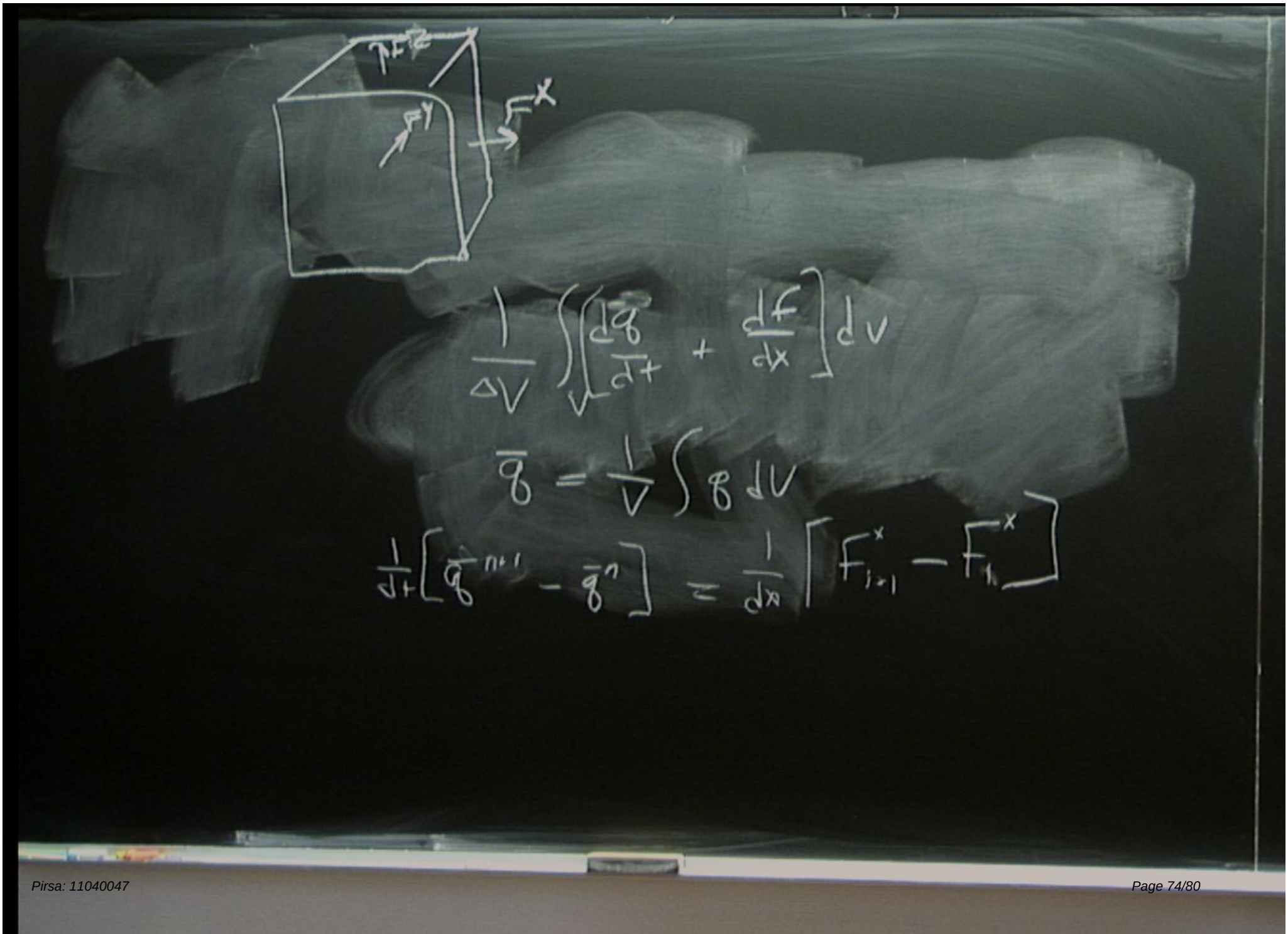

$q_t + qq_x = \varepsilon q_{xx}$
$\iint \phi(q_t + \partial_x f(q))\, dx\, dt = 0$
$\vec{q}_{i+}$
$\vec{f}^{(1)}$
$f^{(1)}$
q

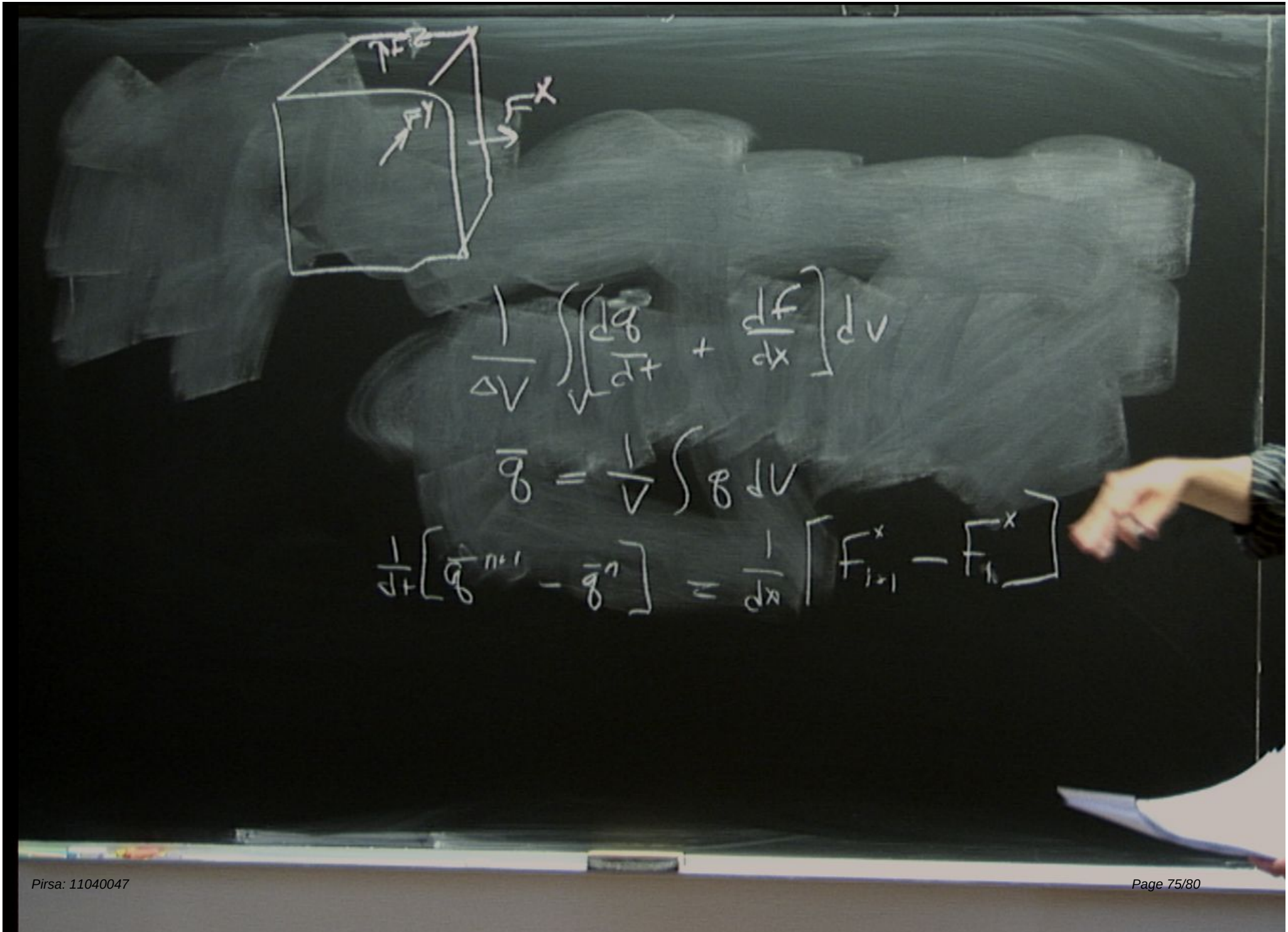

$q_t + qq_x = \varepsilon q_{xx}$
ϕ
$\int\int \phi(q_t + \partial_x f(q))\, dx\, dt = 0$
$f^{(1)}$
$f^{(1)}_x$

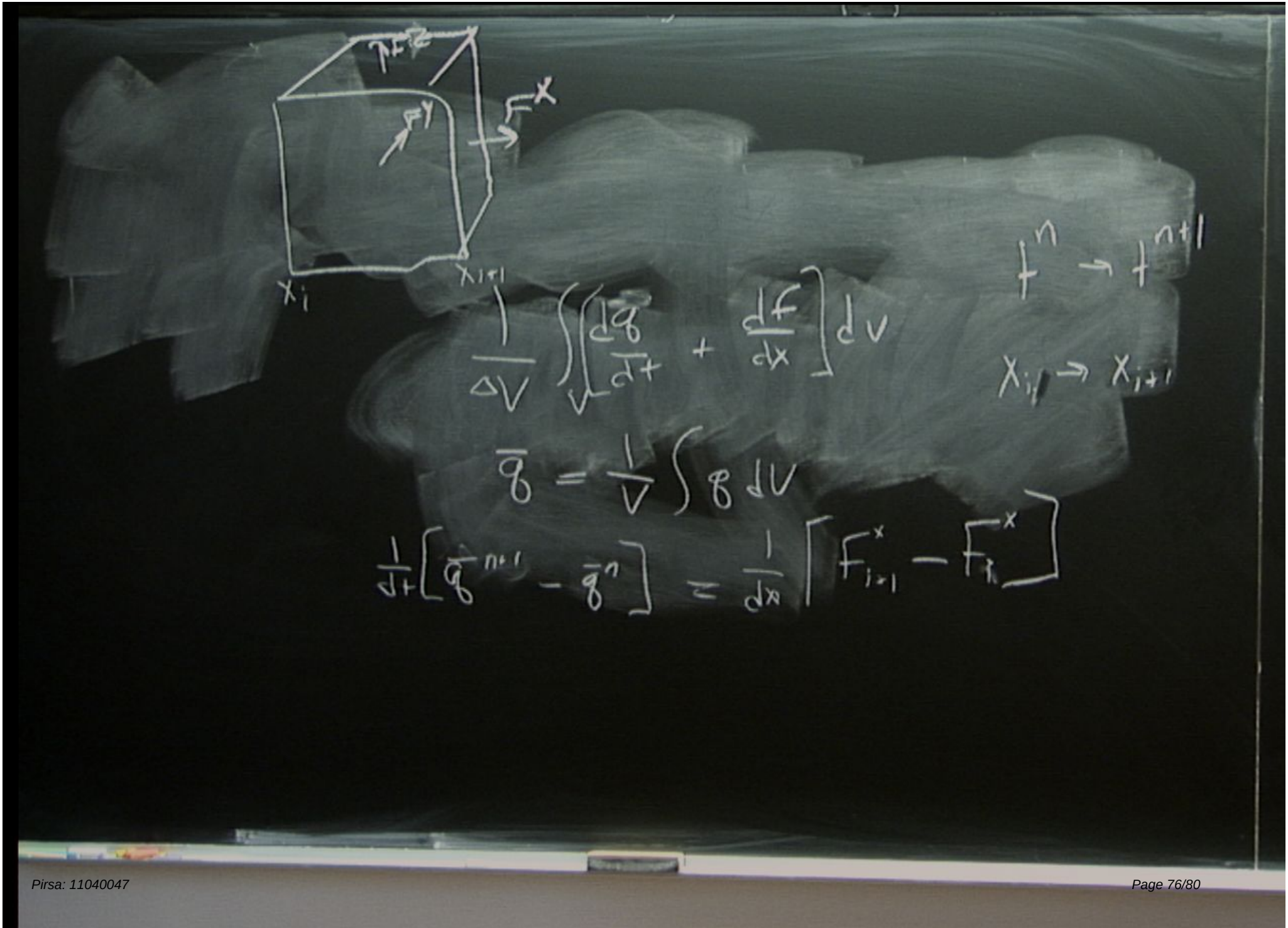

$q_t + qq_x = \varepsilon q_{xx}$
ϕ
$\iint \phi (q_t + \partial_x f(q)) \, dx \, dt = 0$
$\iint (\phi_t q + f \phi_x) \, dt \, dx$
$= \int \phi(x,0) q(x,0) \, dx$
$\vec{q}_t$
$\vec{f}^{(1)}$
q
$f^{(1)}$

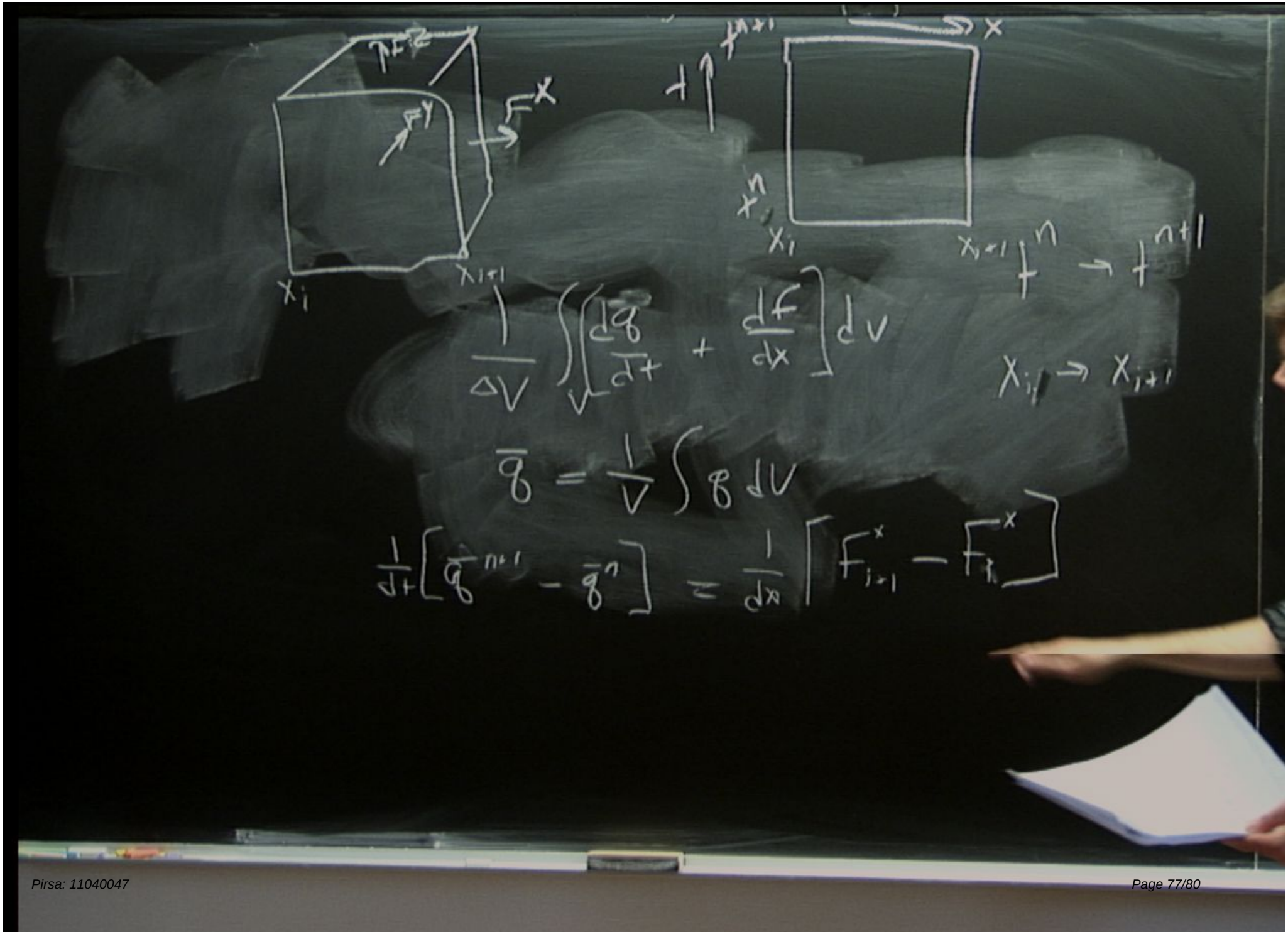

F^z
F^y
F^x

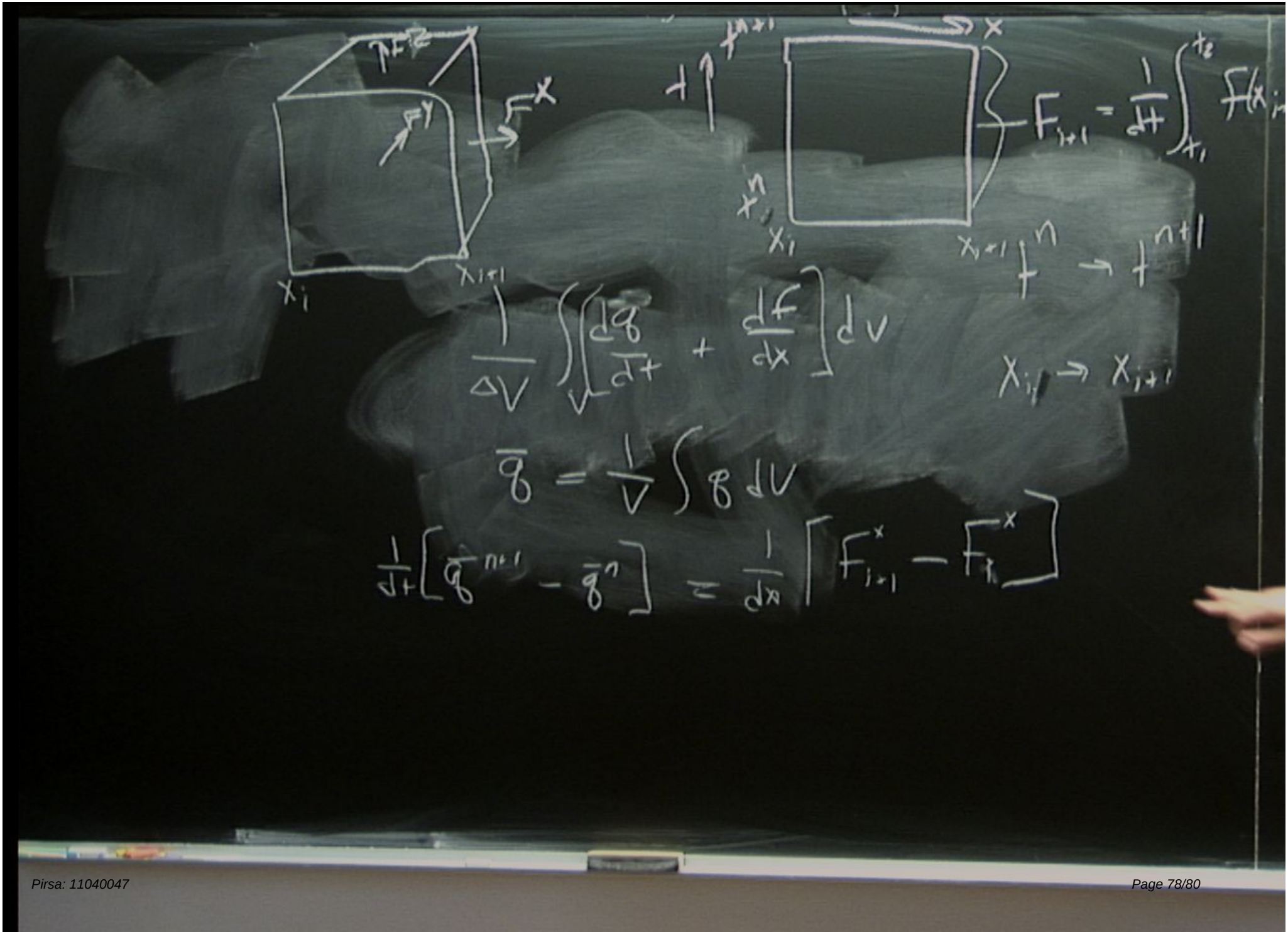

F^z
F^y
F^x
$\frac{1}{\Delta V}\int_V \left[\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x}\right] dV$
$\rho = \frac{1}{V}\int \rho \, dV$

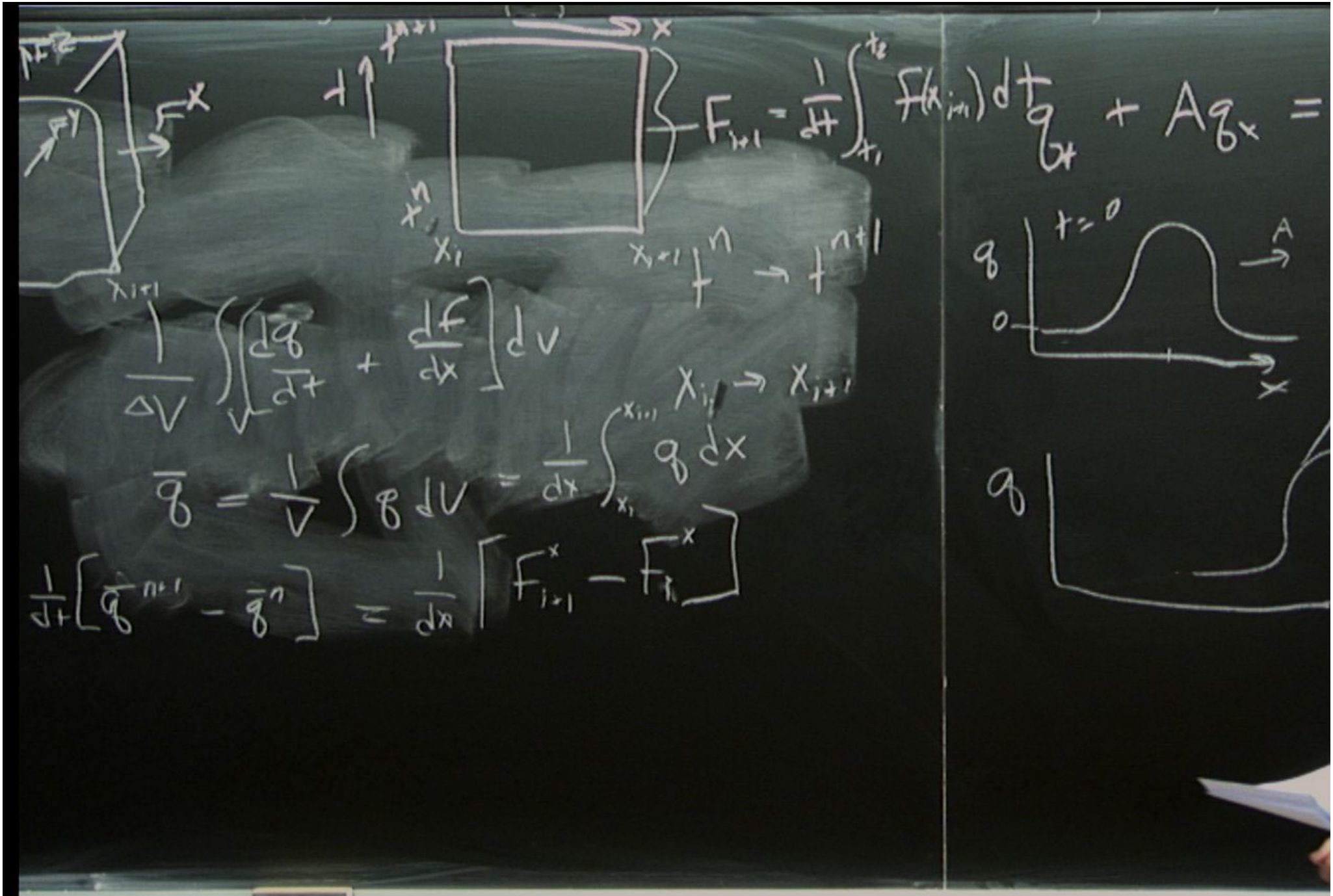

F^z
F^y
F^x
$\frac{1}{\Delta V}\int\left[\frac{d\bar{q}}{dt}+\frac{dF}{dx}\right]dV$
$\bar{q}=\frac{1}{V}\int q\,dV$
$\frac{1}{dt}\left[\bar{q}^{n+1}-\bar{q}^{n}\right]=\frac{1}{dx}\left[F^{x}_{i+1}-F^{x}_{i}\right]$

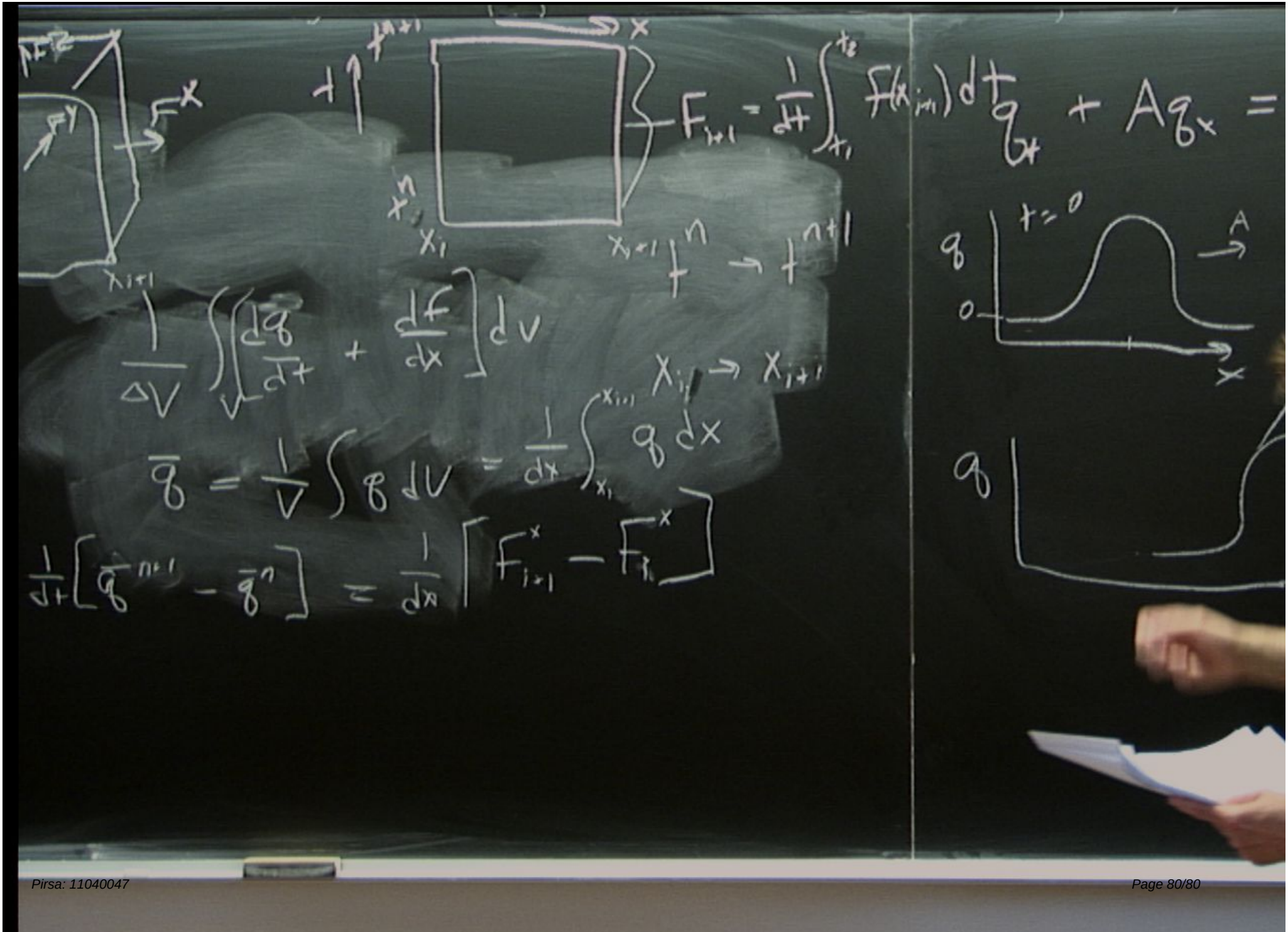

F^z
F^y
F^x
$\frac{1}{\Delta V}\int\left[\frac{d\rho}{dt} + \frac{dF}{dx}\right]dV$
$\bar{q} = \frac{1}{V}\int q\,dV$
$\frac{1}{dt}\left[\bar{q}^{n+1} - \bar{q}^{n}\right] = \frac{1}{dx}\left[F^x_{i+1} - F^x_{i}\right]$


F^z
F^y
F^x
x_i
x_{i+1}
$\frac{1}{\Delta V}\int\left[\frac{d\bar{q}}{dt}+\frac{dF}{dx}\right]dV$
$t^n \to t^{n+1}$
$x_i \to x_{i+1}$
$\bar{q}=\frac{1}{V}\int q\,dV$
$\frac{1}{dt}\left[\bar{q}^{n+1}-\bar{q}^n\right]=\frac{1}{dx}\left[F^x_{i+1}-F^x_i\right]$


F^x
F^y
x_i
x_{i+1}
t^n
t^{n+1}
$t \to t^{n+1}$
$x_i \to x_{i+1}$
$\frac{1}{\Delta V}\int\left[\frac{dq}{dt} + \frac{dF}{dx}\right]dV$
$\bar{q} = \frac{1}{V}\int q\,dV$
$\frac{1}{dt}\left[\bar{q}^{n+1} - \bar{q}^{n}\right] = \frac{1}{dx}\left[F^x_{i+1} - F^x_i\right]$


F^z
F^y
F^x
x_i
x_{i+1}
t^{n+1}
t^n
x_i^n
$F_{i+1} = \frac{1}{dt}\int_{t_1}^{t_2} f(x_i$
$t^n \to t^{n+1}$
$\frac{1}{\Delta V}\int_V \left[\frac{dq}{dt} + \frac{dF}{dx}\right] dV$
$x_i \to x_{i+1}$
$\bar{q} = \frac{1}{V}\int q\, dV$
$\frac{1}{dt}\left[\bar{q}^{n+1} - \bar{q}^n\right] = \frac{1}{dx}\left[F_{i+1}^x - F_i^x\right]$


F^x
F^y
$F_{i+1} = \frac{1}{dt}\int_{t_1}^{t_2} f(x_{i+1})\,dt$
$q_t + Aq_x =$
$t^n \to t^{n+1}$
$\frac{1}{\Delta V}\int\left[\frac{dq}{dt} + \frac{df}{dx}\right]dV$
$t=0$
q
0
A
x
$X_i \to X_{i+1}$
$\bar{q} = \frac{1}{V}\int q\,dV = \frac{1}{dx}\int_{x_i}^{x_{i+1}} q\,dx$
$\frac{1}{dt}\left[\bar{q}^{n+1} - \bar{q}^n\right] = \frac{1}{dx}\left[F^x_{i+1} - F^x_i\right]$


$F_{i+1} = \frac{1}{dt}\int_{t_1}^{t_2} f(x_{i+1})\,dt$
$q_t + Aq_x =$
$t = 0$
A
q
0
x
$t^n \to t^{n+1}$
$\frac{1}{\Delta V}\int\left[\frac{dq}{dt} + \frac{df}{dx}\right]dV$
$x_i \to x_{i+1}$
$\bar{q} = \frac{1}{V}\int q\,dV = \frac{1}{dx}\int_{x_i}^{x_{i+1}} q\,dx$
$\frac{1}{dt}\left[\bar{q}^{n+1} - \bar{q}^n\right] = \frac{1}{dx}\left[F^x_{i+1} - F^x_i\right]$