Title: Cosmology â€“ Observations: Gravitational lensing

Date: Jul 15, 2015 04:00 PM

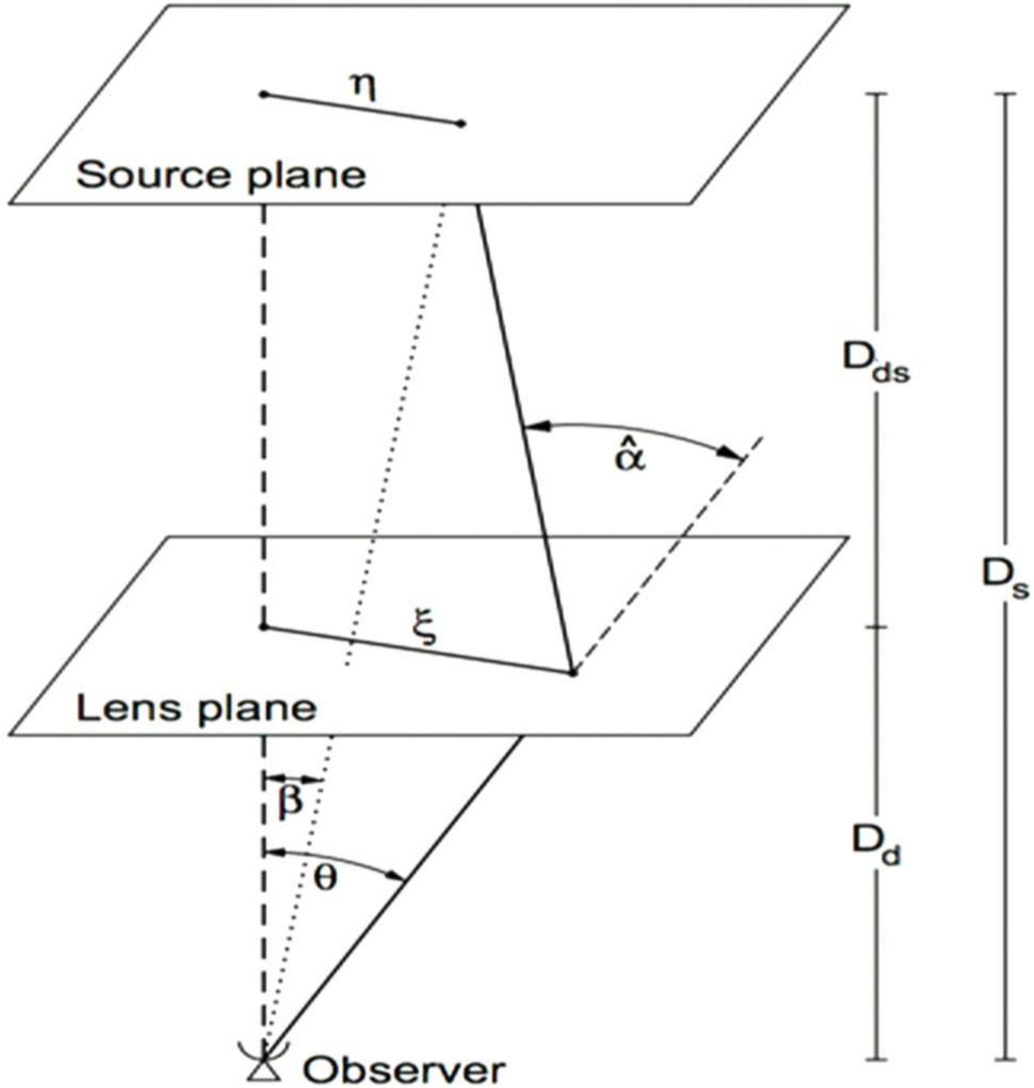
URL: http://pirsa.org/15070051

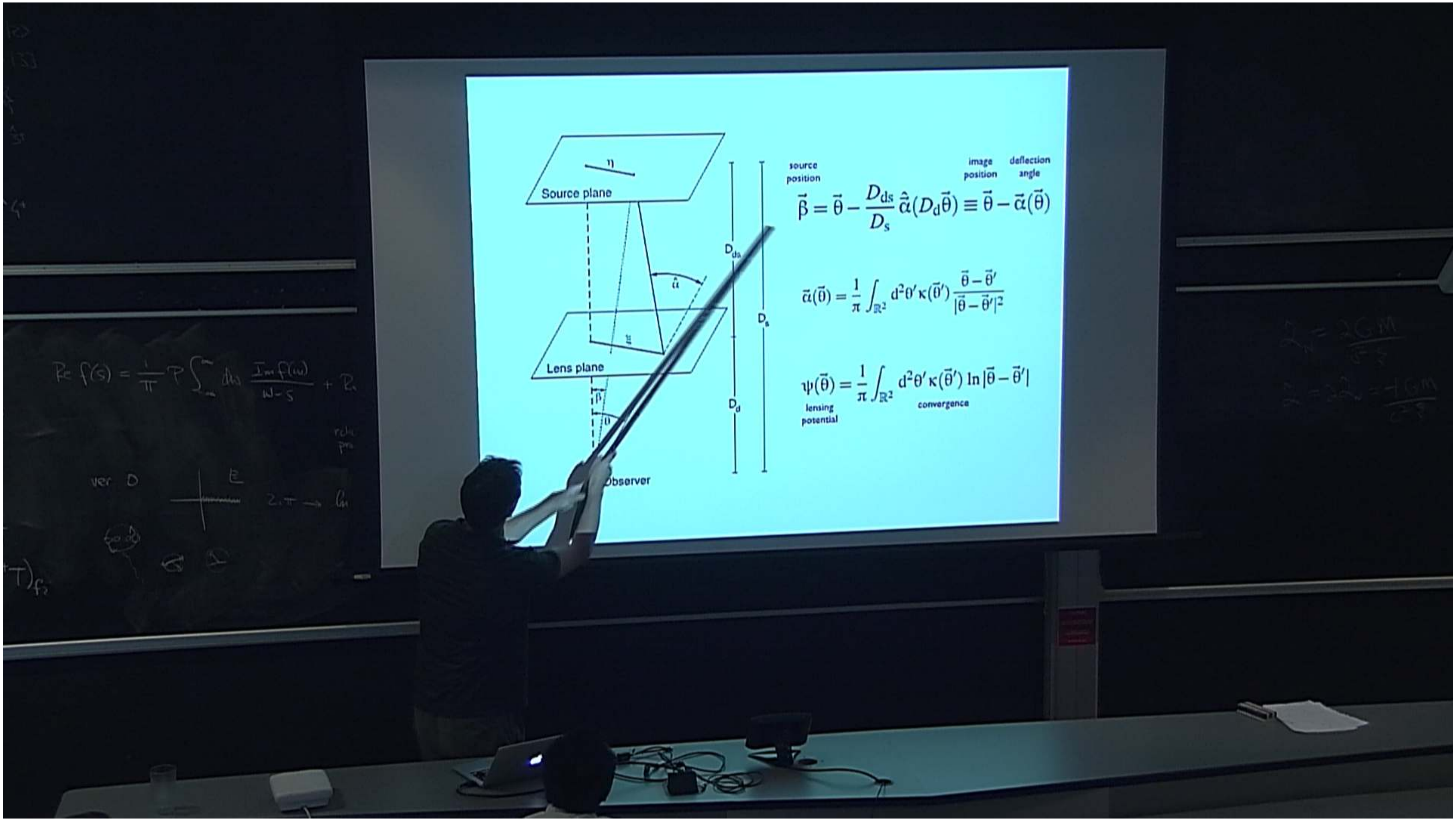
Abstract:

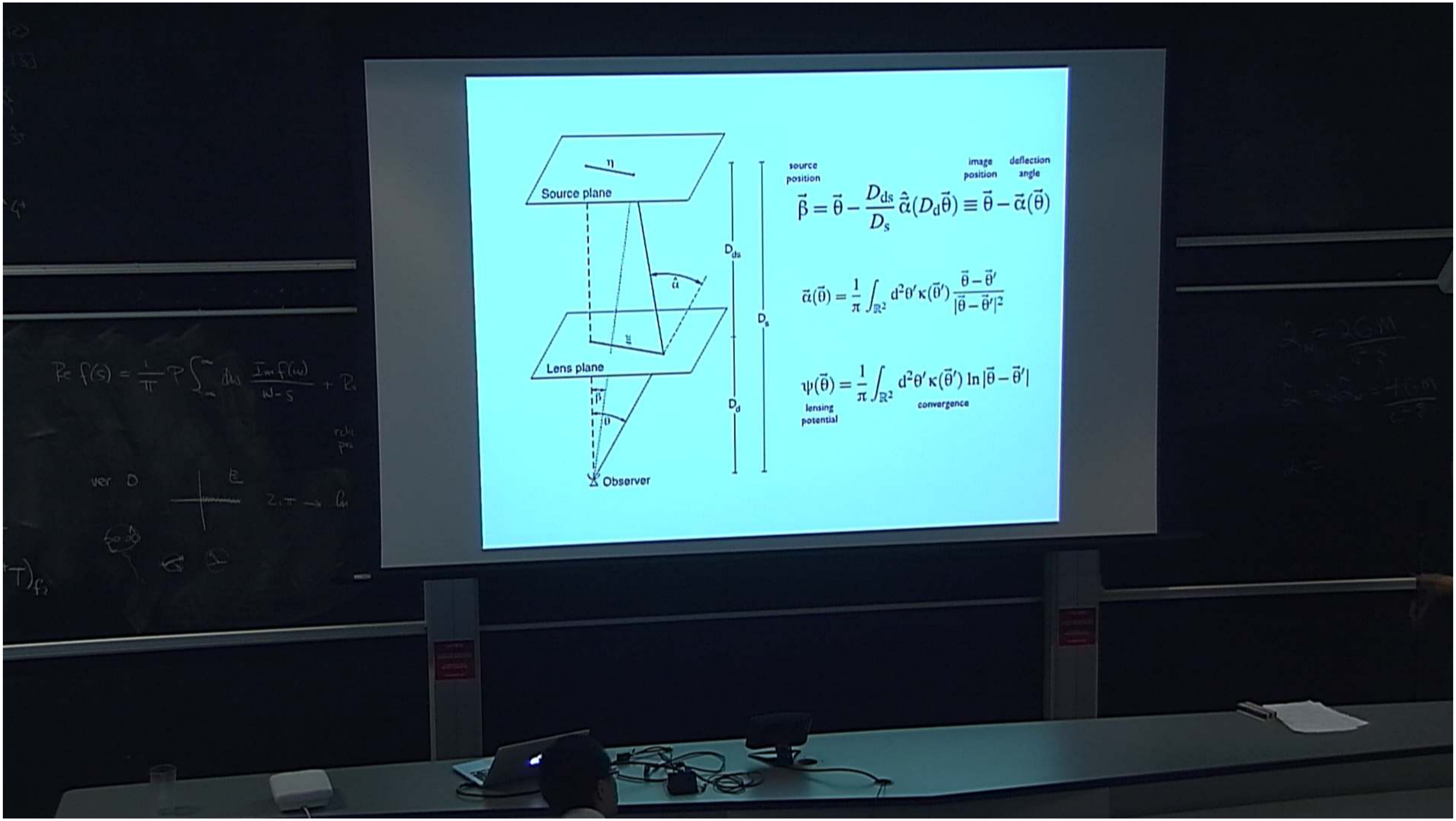
Gravitational lensing

$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

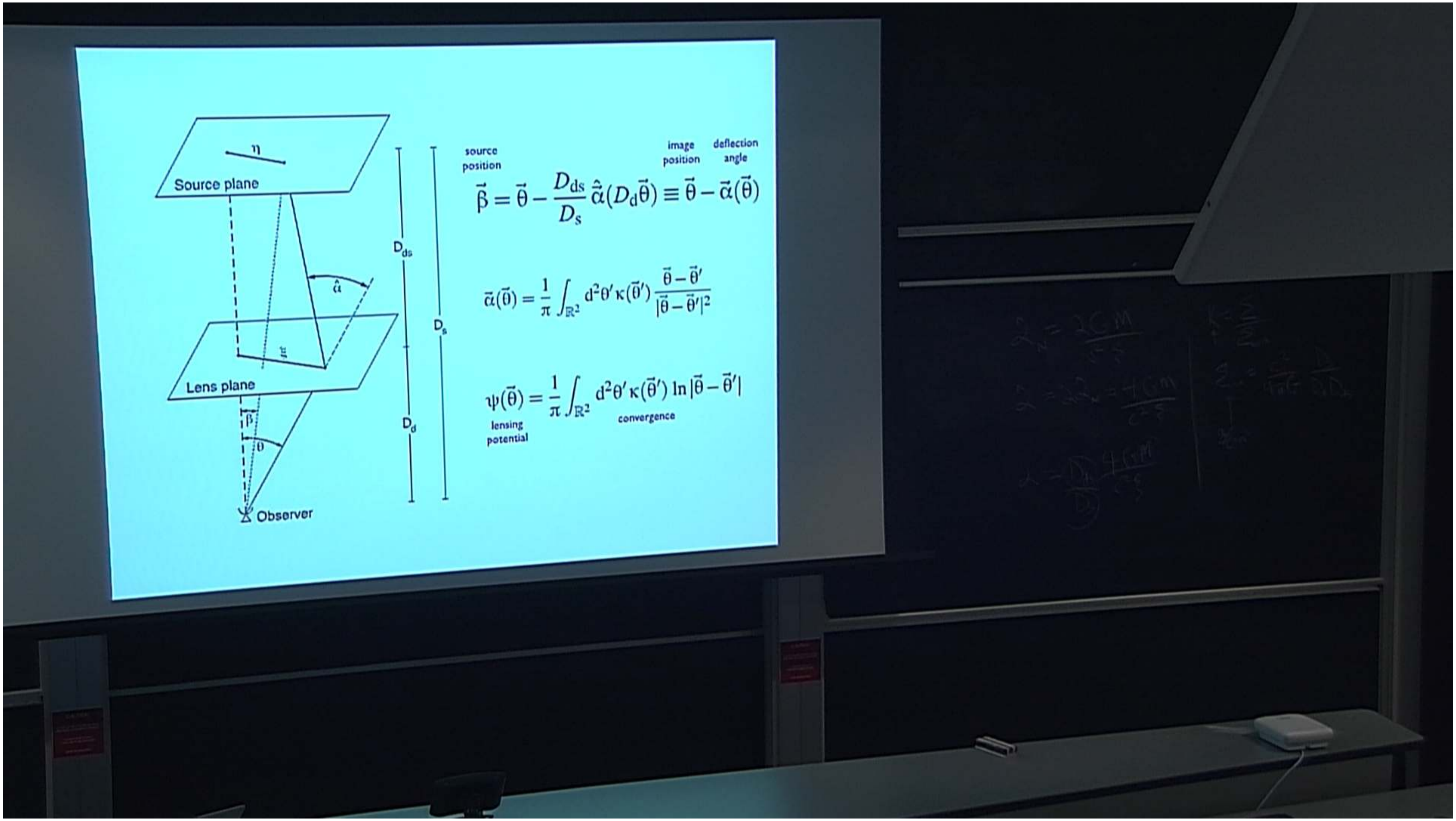
Bartelmann & Schneider
http://arxiv.org/abs/astro-ph/9912508

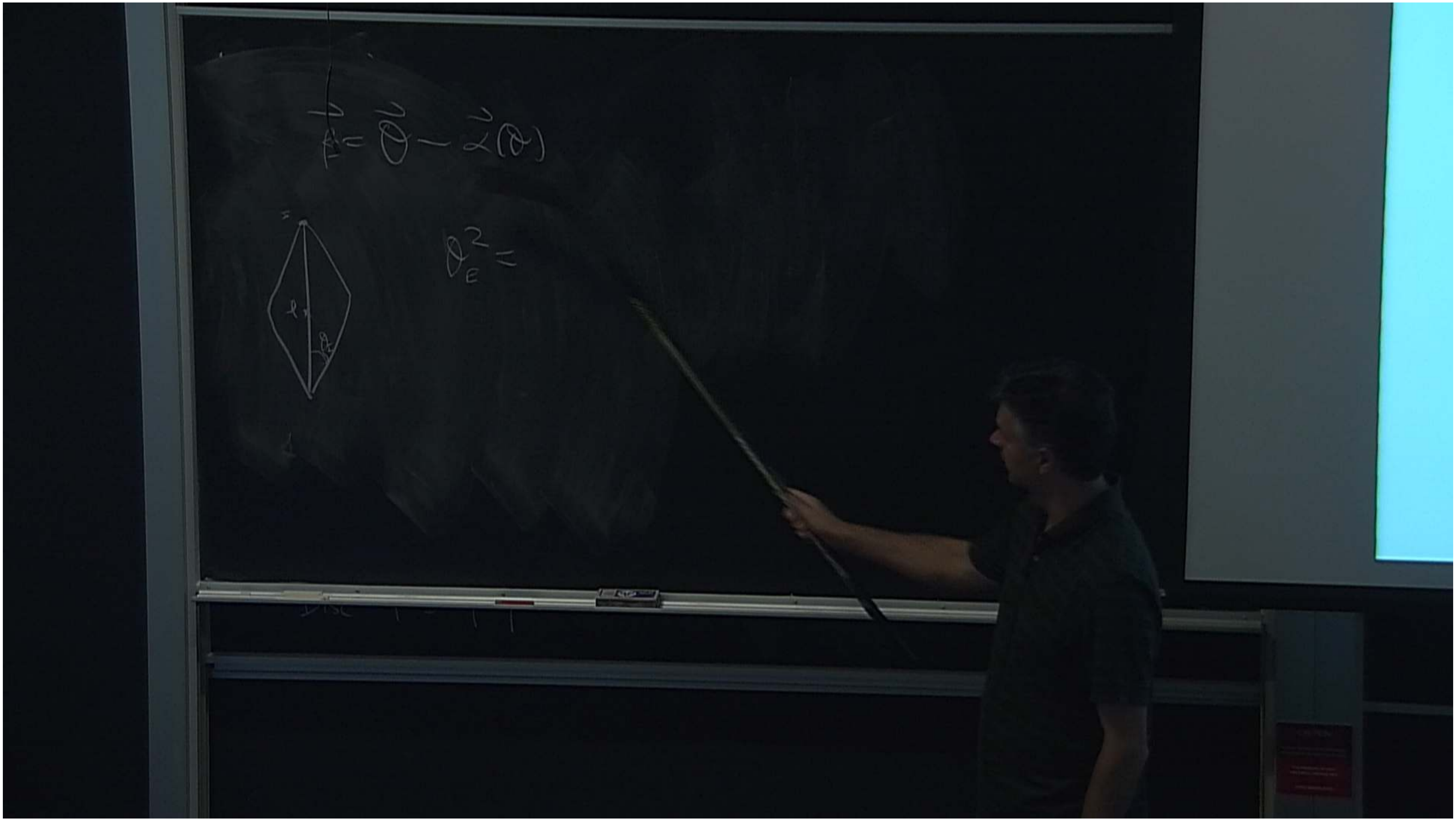


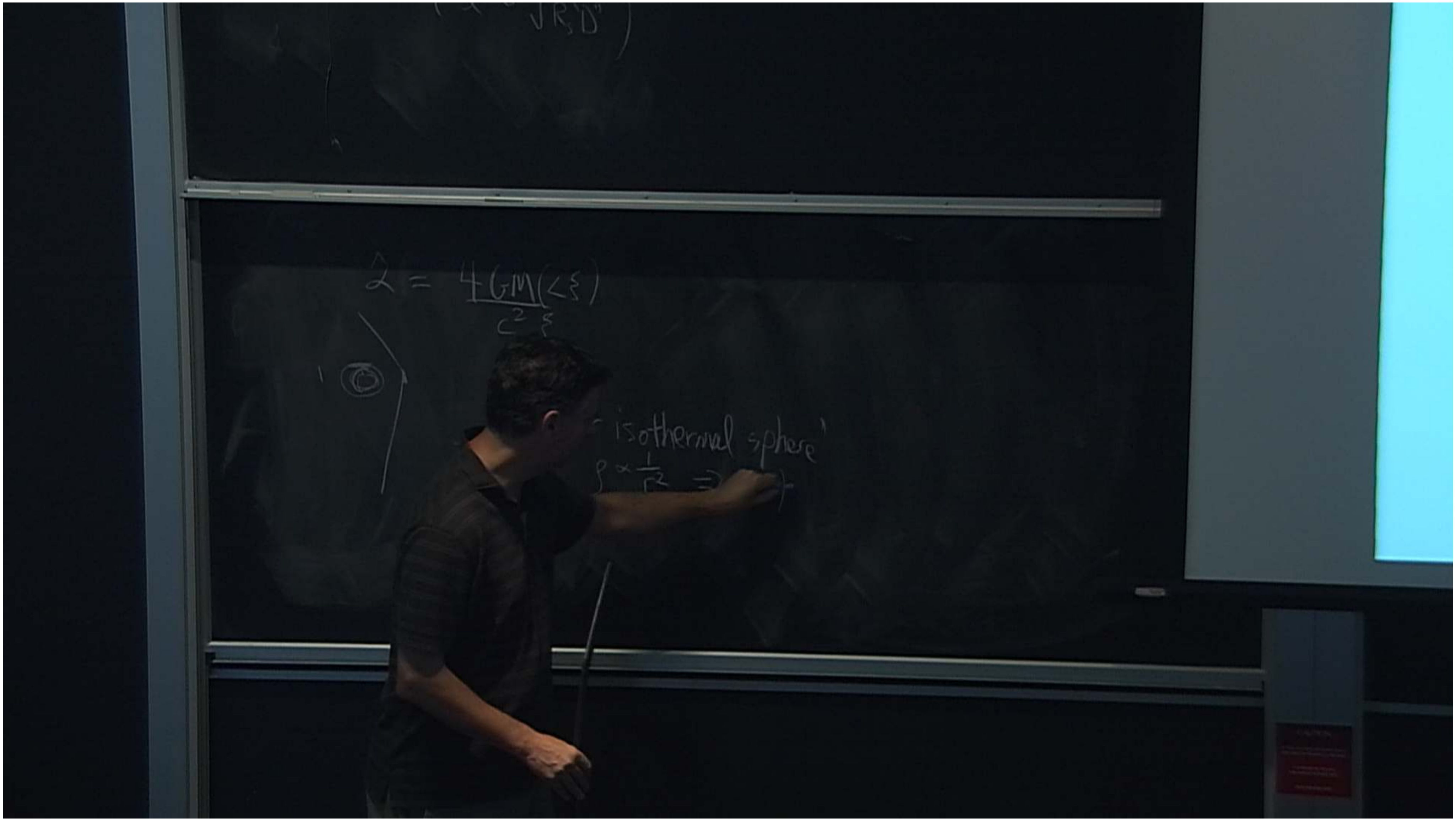

Source plane
Lens plane
Observer
source position
image position
deflection angle
$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$
$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta' \kappa(\vec{\theta}') \frac{\vec{\theta}-\vec{\theta}'}{|\vec{\theta}-\vec{\theta}'|^2}$
$\psi(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta' \kappa(\vec{\theta}') \ln|\vec{\theta}-\vec{\theta}'|$
lensing potential
convergence

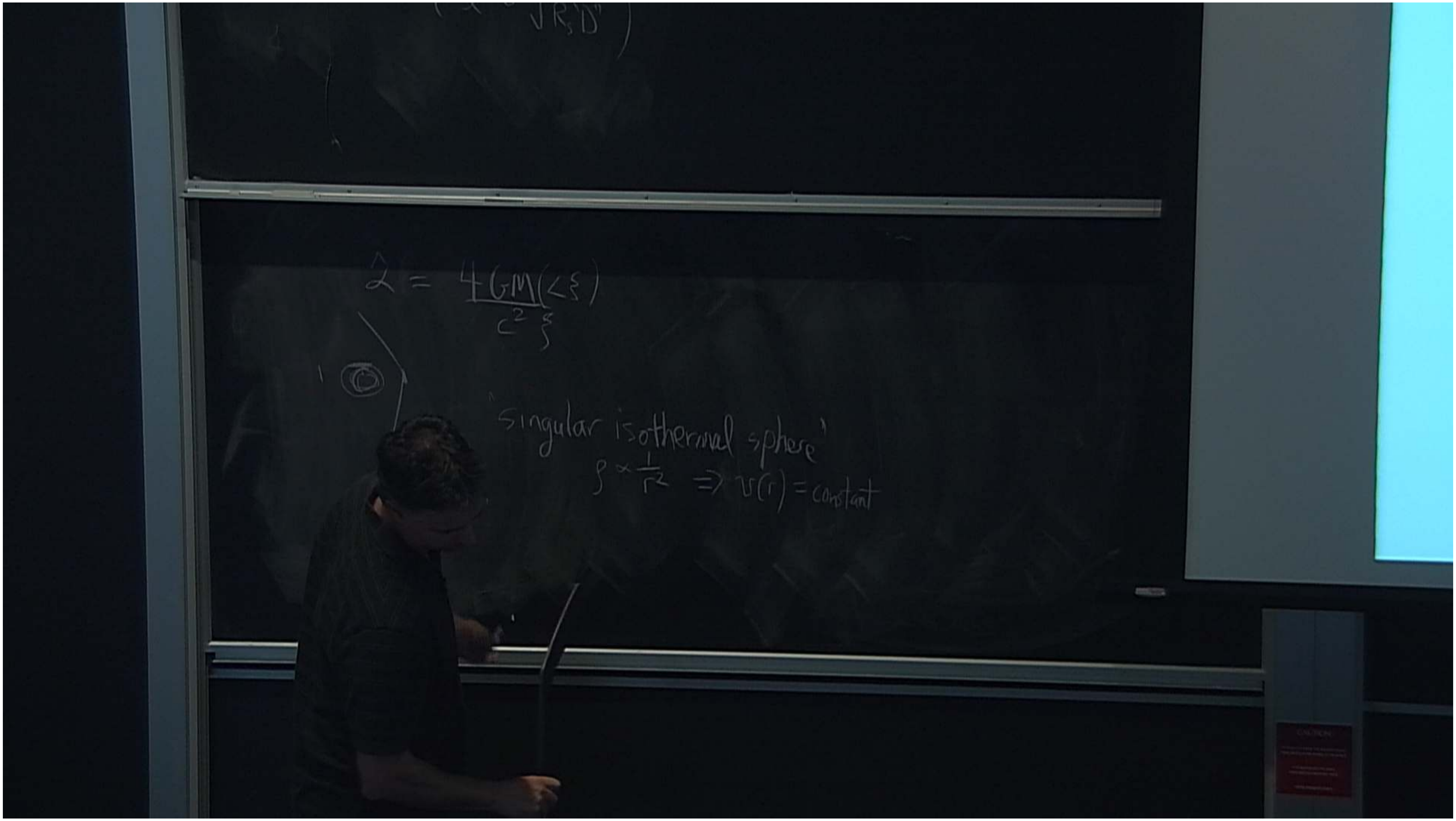


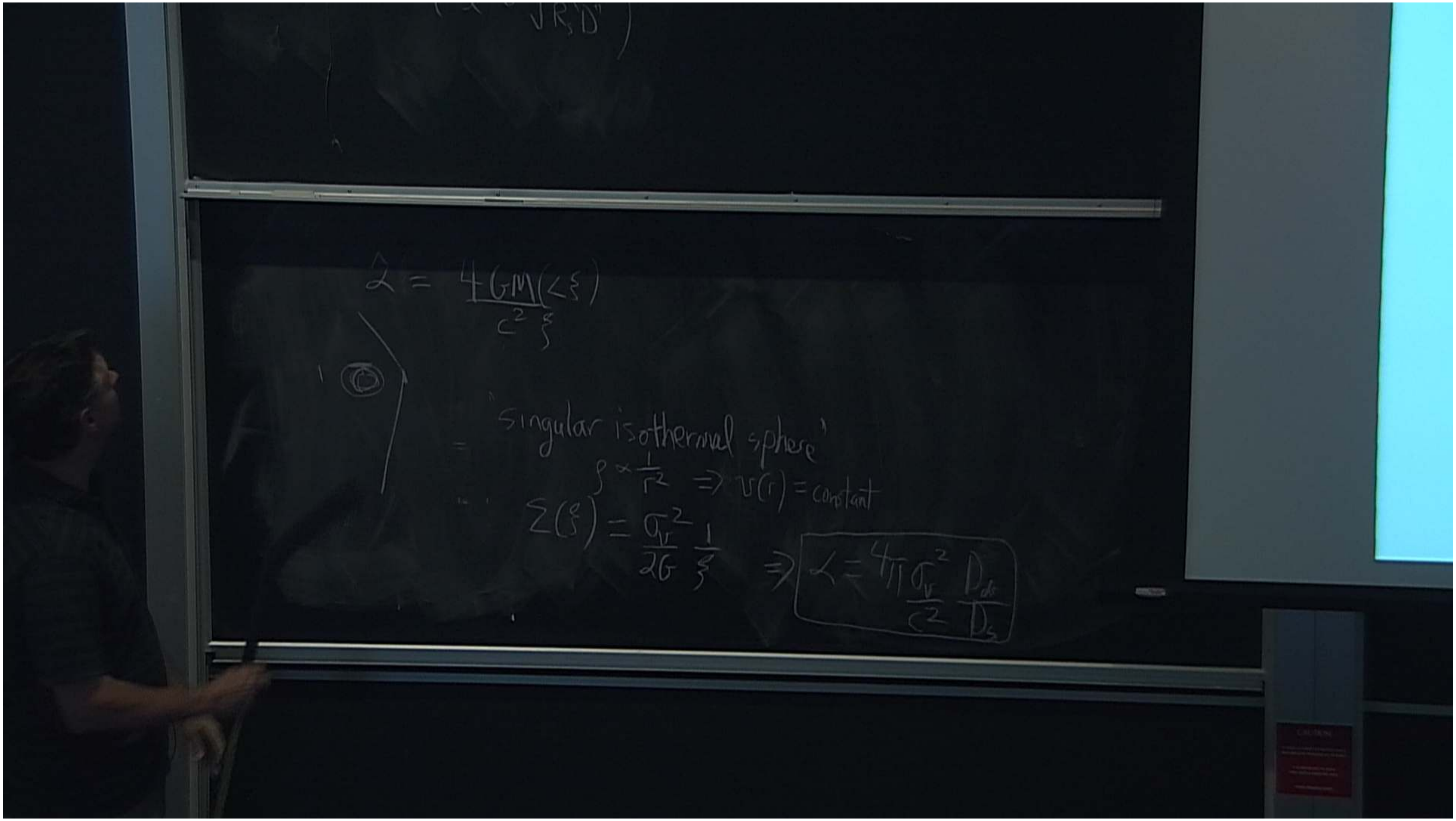
Source plane
Lens plane
Observer
D_{ds}
D_s
D_d
source position
image position
deflection angle
$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$
$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta' \kappa(\vec{\theta}') \frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|^2}$
$\psi(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta' \kappa(\vec{\theta}') \ln|\vec{\theta} - \vec{\theta}'|$
lensing potential
convergence

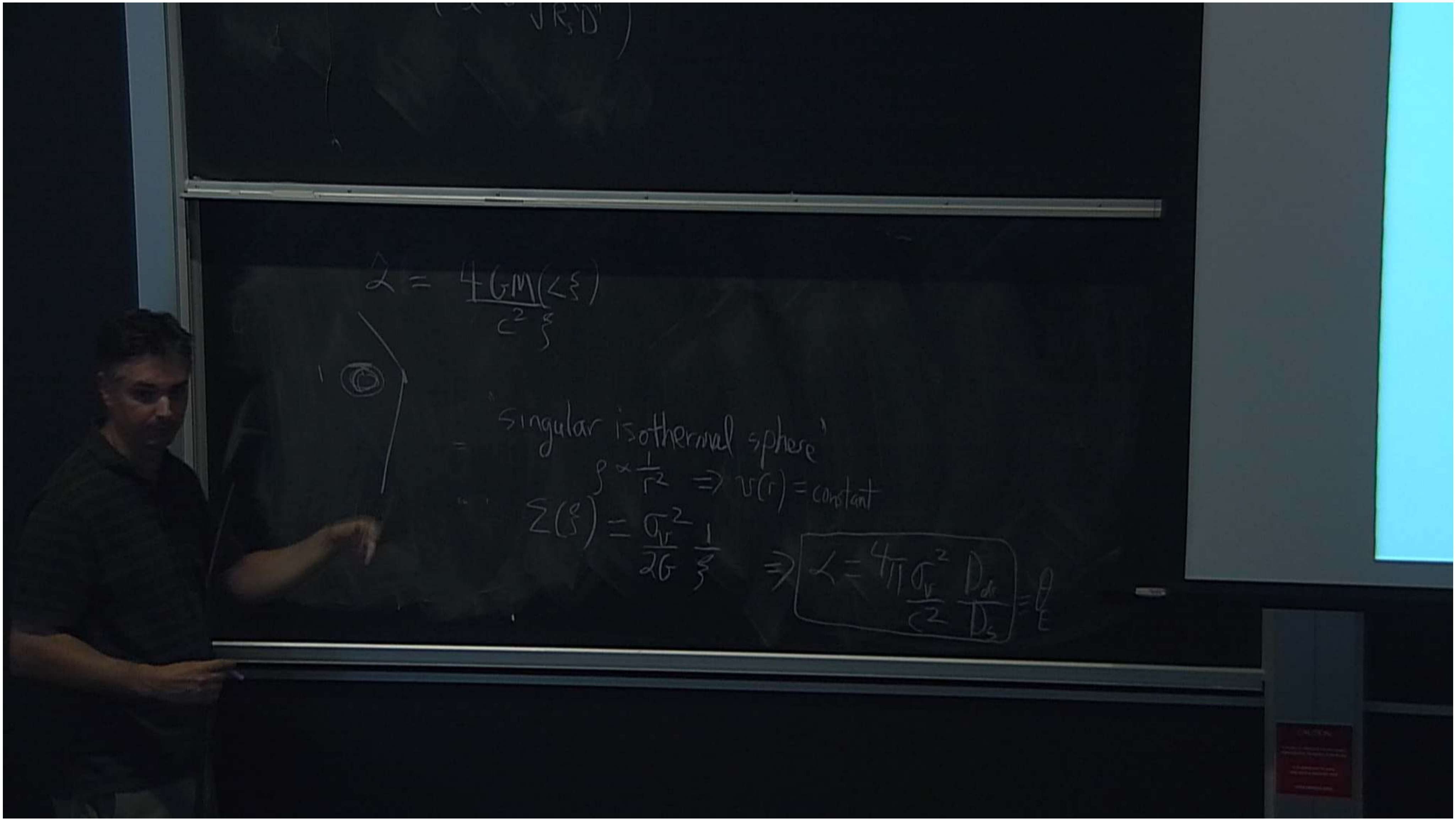

η
Source plane
D_{ds}
$\hat{\alpha}$
D_s
ξ
Lens plane
β
θ
D_d
Observer
source position
image position
deflection angle
$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$
$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta'\,\kappa(\vec{\theta}')\,\frac{\vec{\theta}-\vec{\theta}'}{|\vec{\theta}-\vec{\theta}'|^2}$
$\psi(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} d^2\theta'\,\kappa(\vec{\theta}')\,\ln|\vec{\theta}-\vec{\theta}'|$
lensing potential
convergence

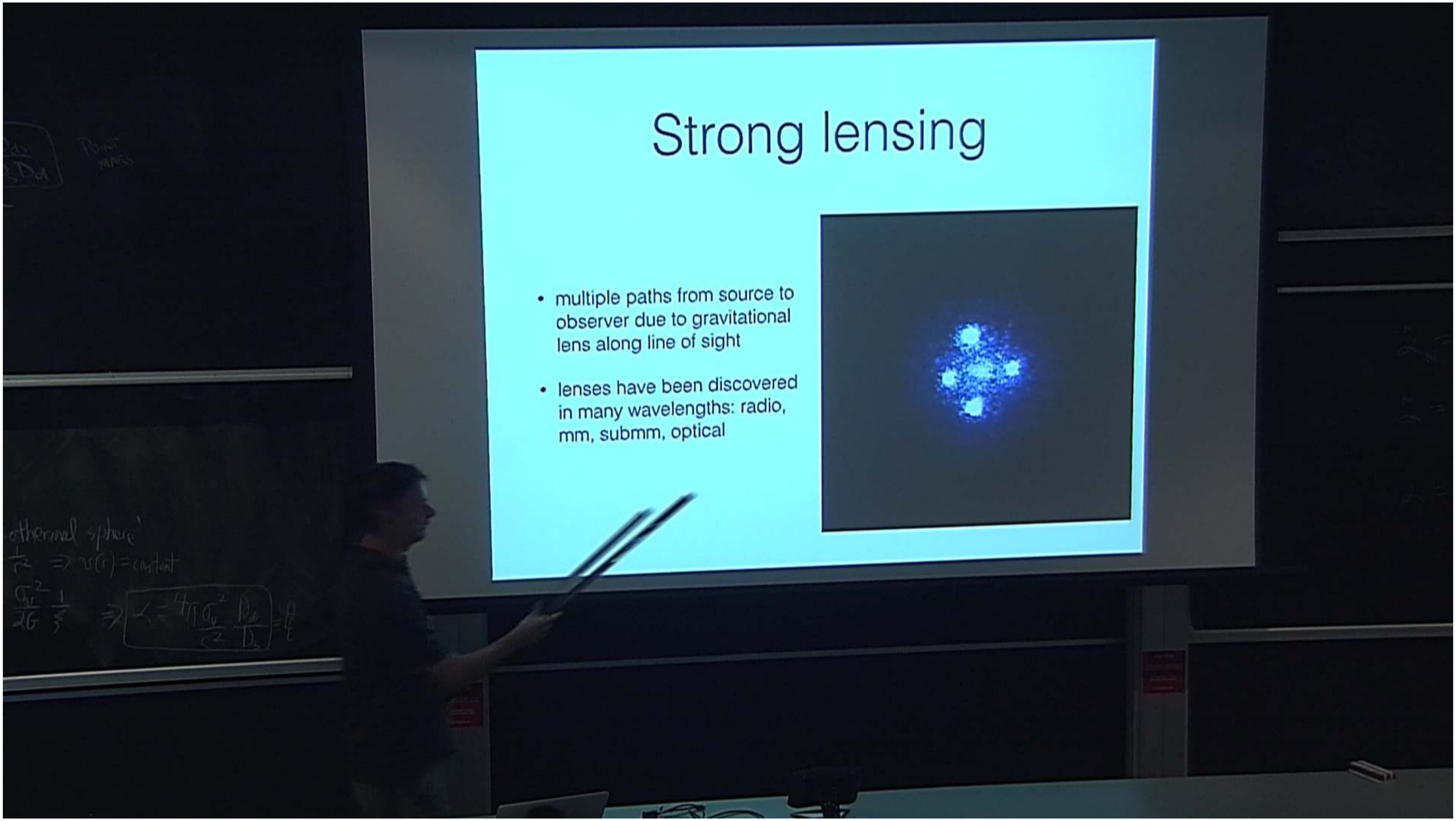

$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\theta)$
$\theta_E^2 =$

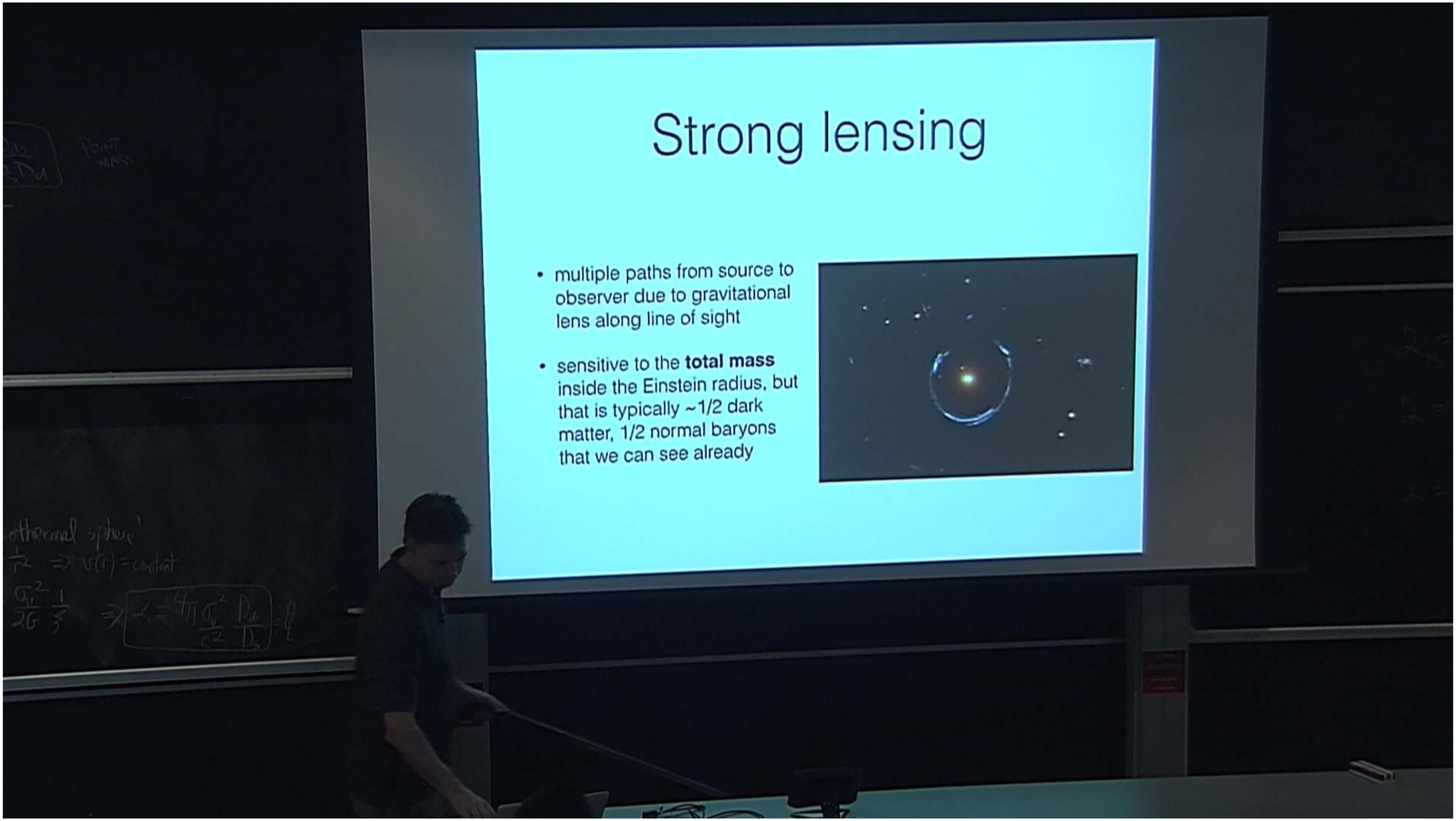

isothermal sphere

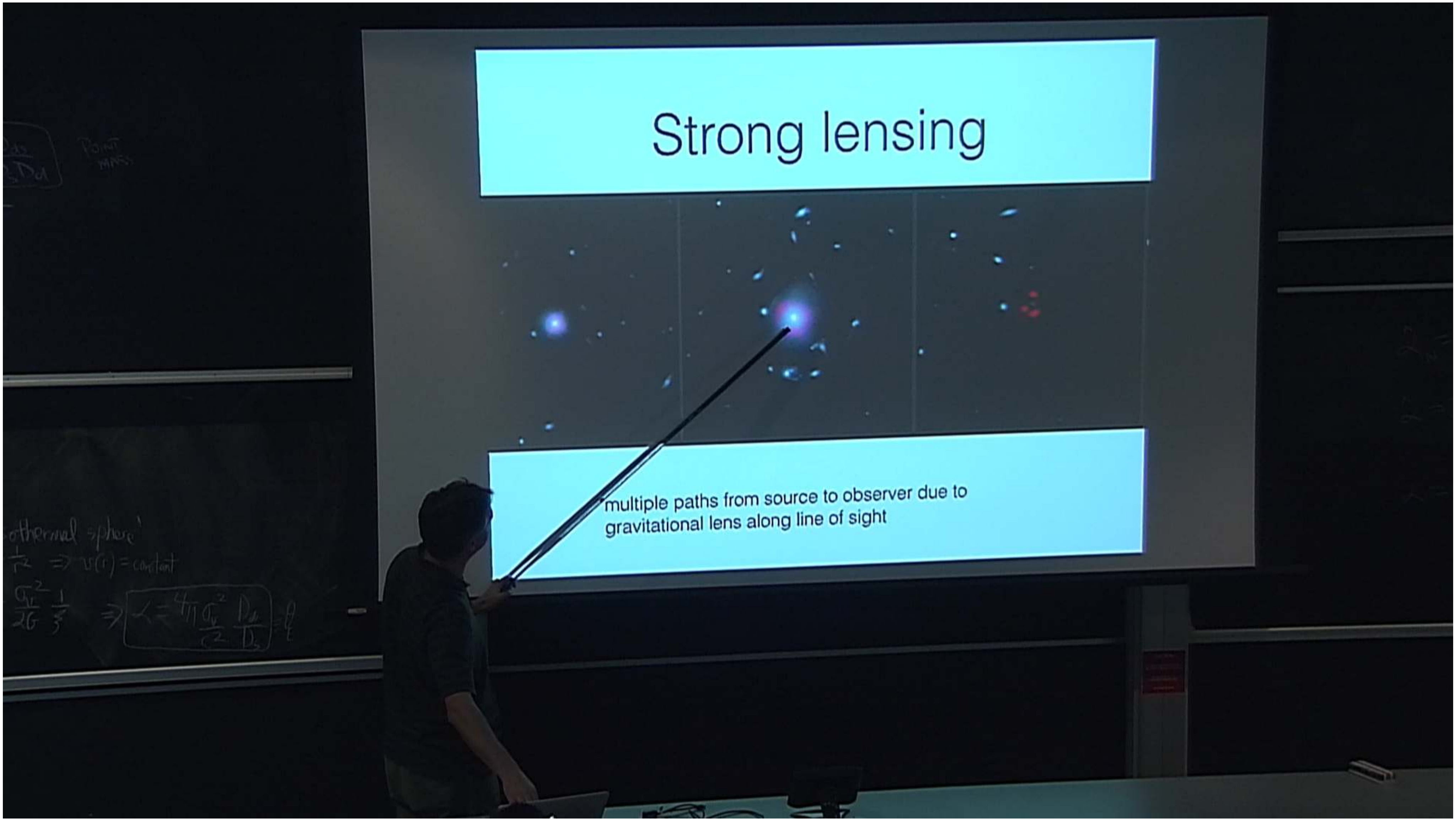

α = 4GM(<ξ) / c^2 ξ
"singular isothermal sphere"
ρ ∝ 1/r^2 ⇒ v(r) = constant


α = 4GM(<ξ) / c² ξ
"singular isothermal sphere"
ρ ∝ 1/r² ⇒ v(r) = constant
Σ(ξ) = σ_v² / 2G · 1/ξ
⇒ α = 4π σ_v²/c² · D_ds/D_s

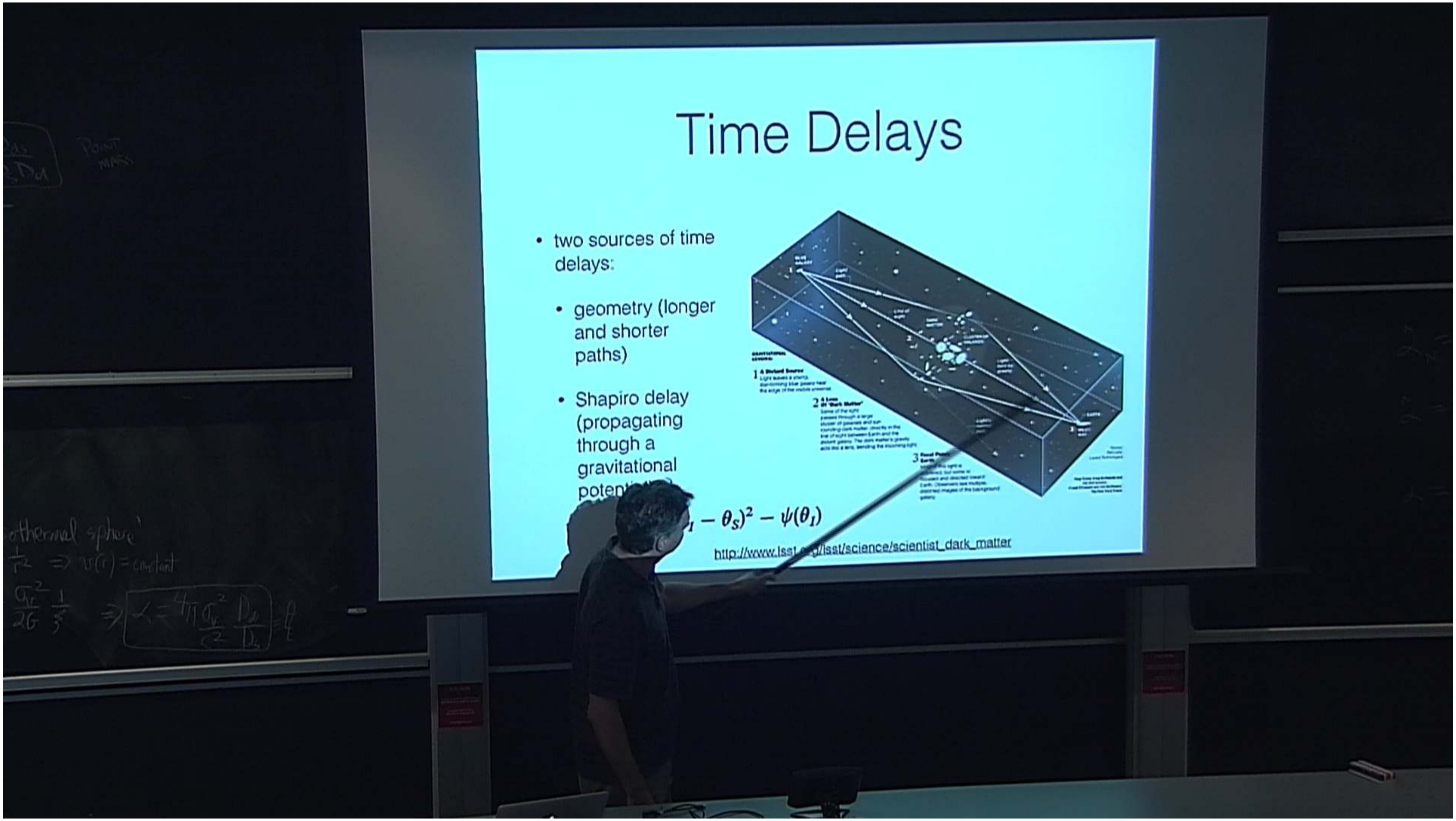

"singular isothermal sphere"
v(r) = constant

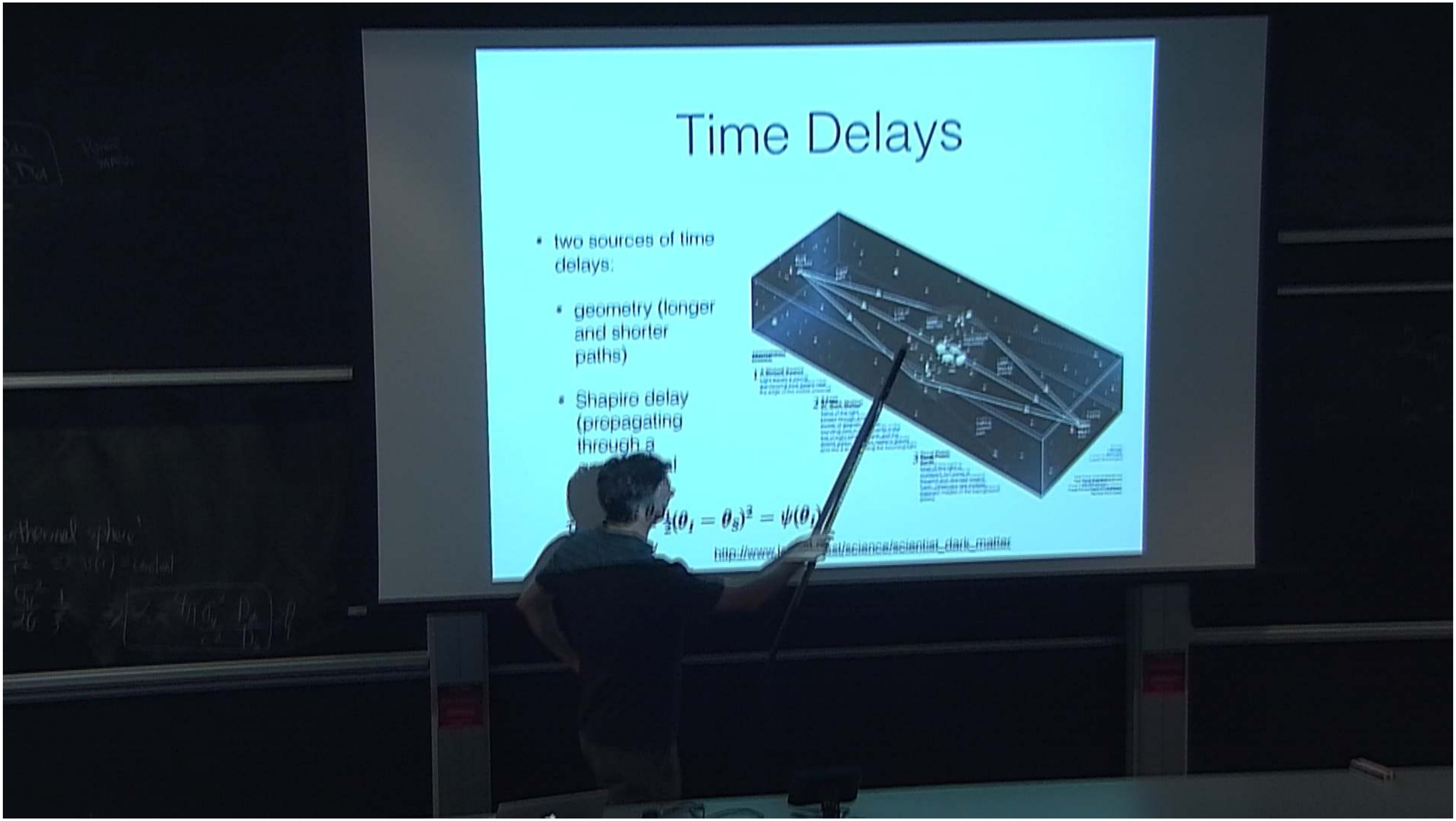

Strong lensing
• multiple paths from source to observer due to gravitational lens along line of sight
• lenses have been discovered in many wavelengths: radio, mm, submm, optical

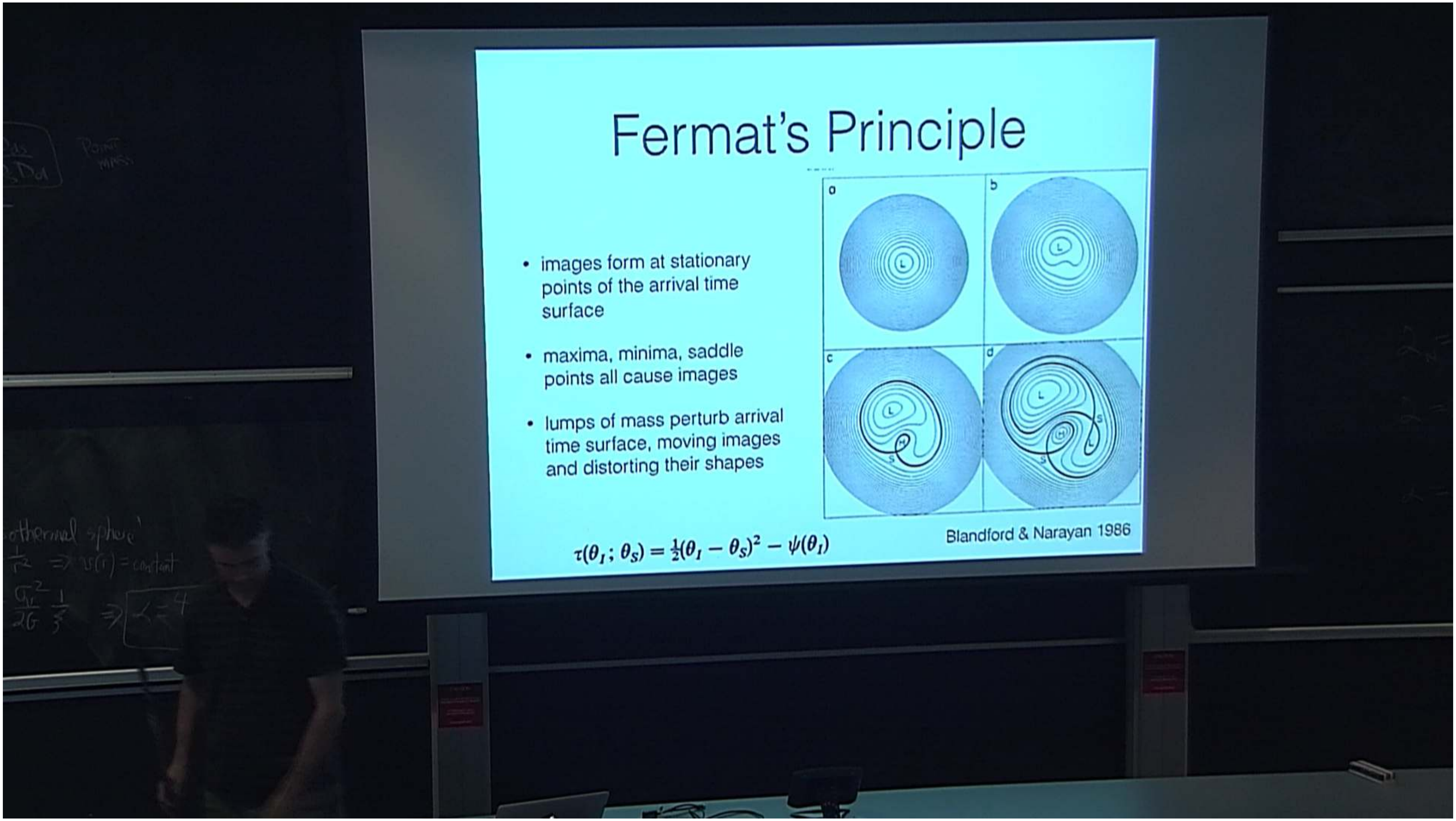

Strong lensing
• multiple paths from source to observer due to gravitational lens along line of sight
• sensitive to the total mass inside the Einstein radius, but that is typically ~1/2 dark matter, 1/2 normal baryons that we can see already

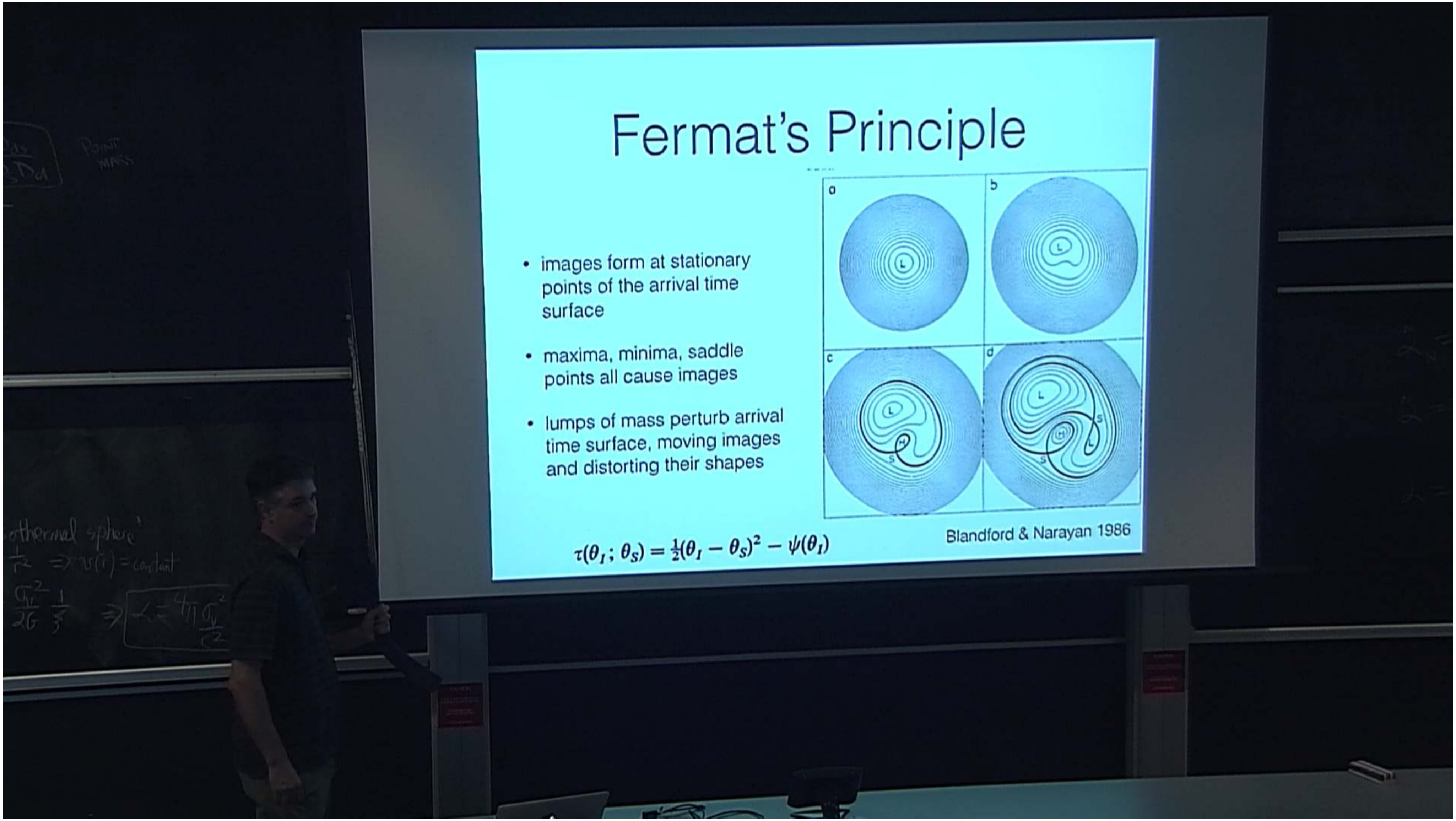

Strong lensing
multiple paths from source to observer due to
gravitational lens along line of sight

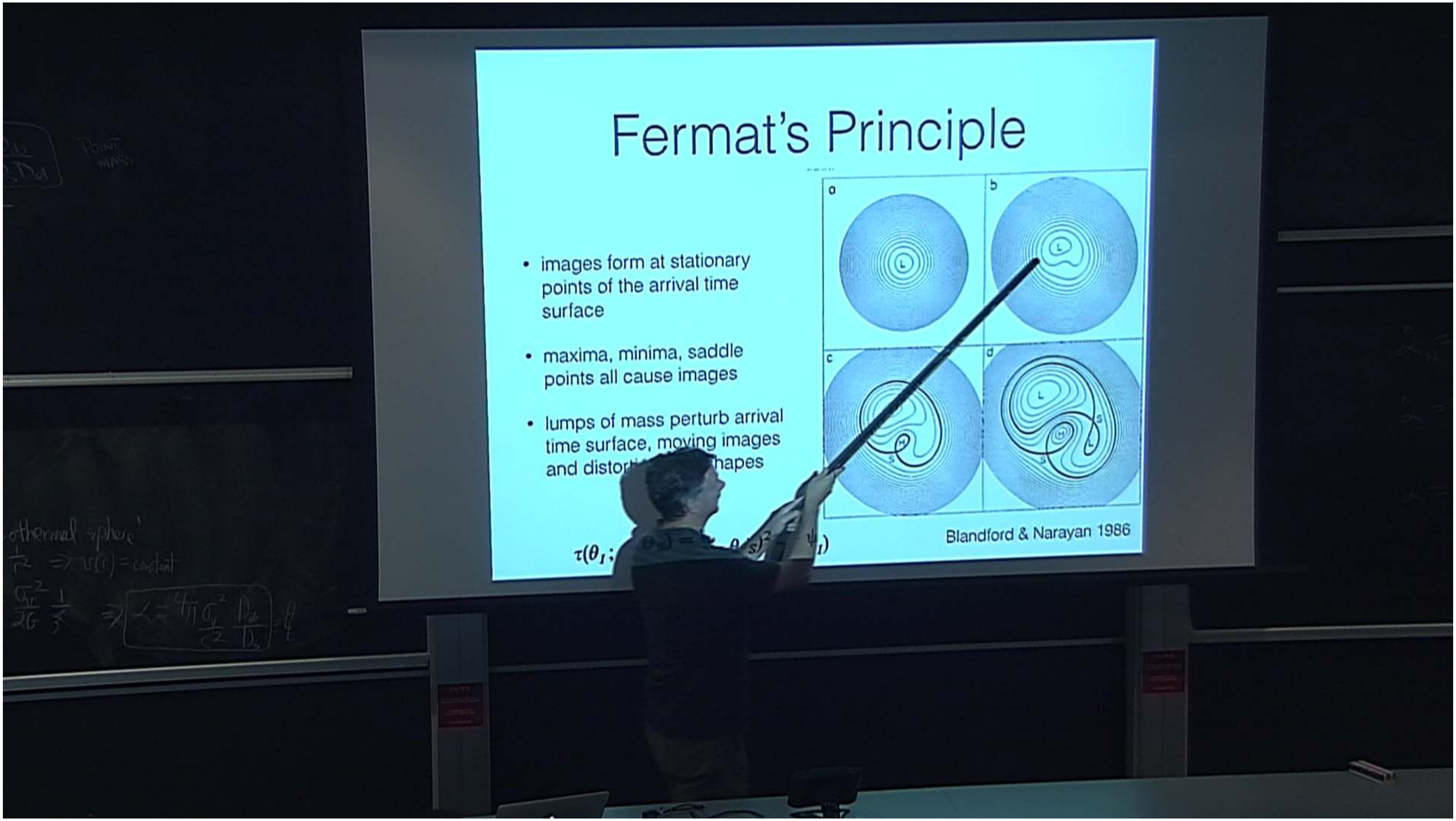

othermal sphere'
⇒ v(r) = constant

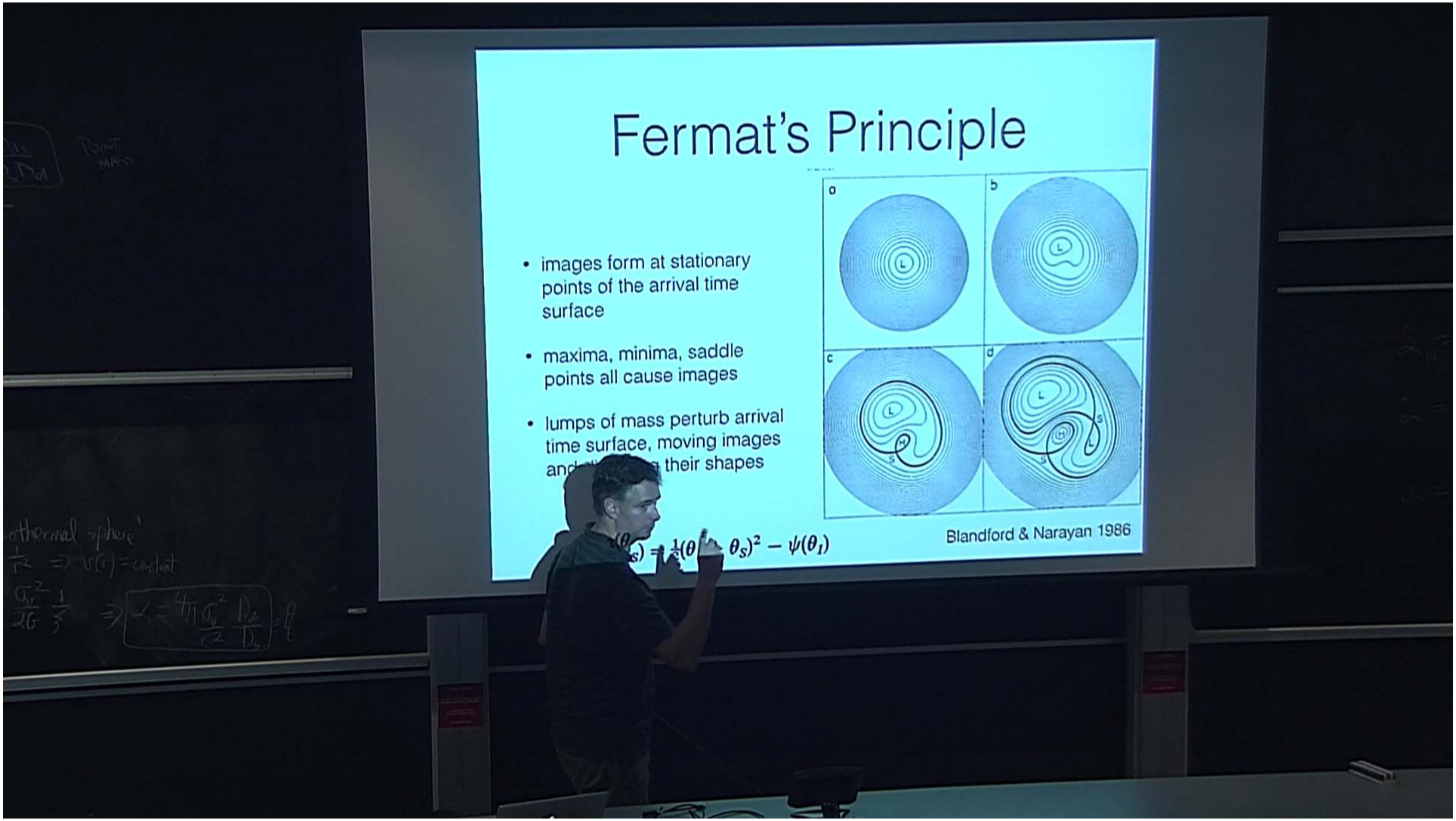

Time Delays
• two sources of time delays:
• geometry (longer and shorter paths)
• Shapiro delay (propagating through a gravitational poten
http://www.lsst.org/lsst/science/scientist_dark_matter

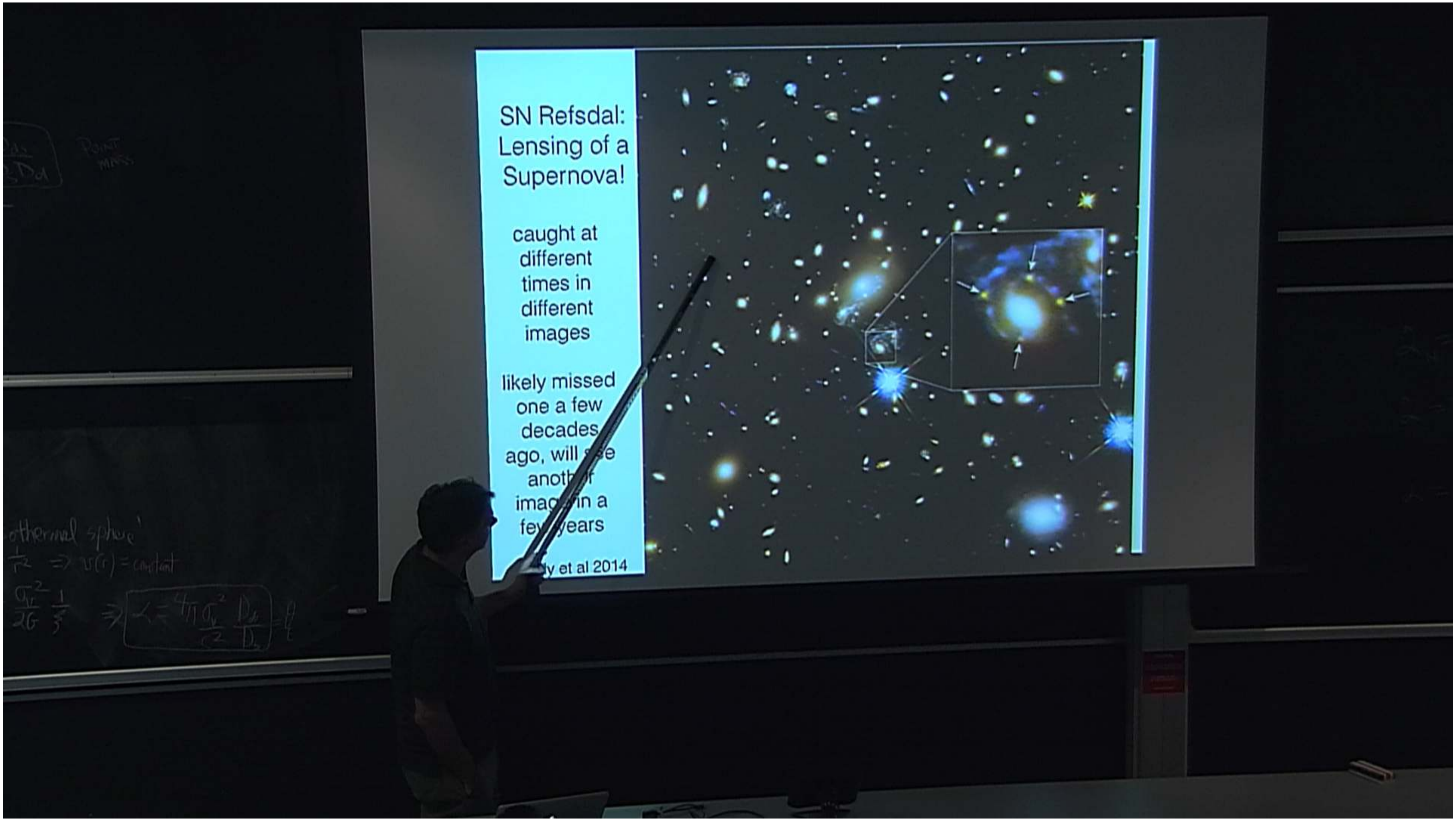

Time Delays
two sources of time delays:
geometry (longer and shorter paths)
Shapiro delay (propagating through a

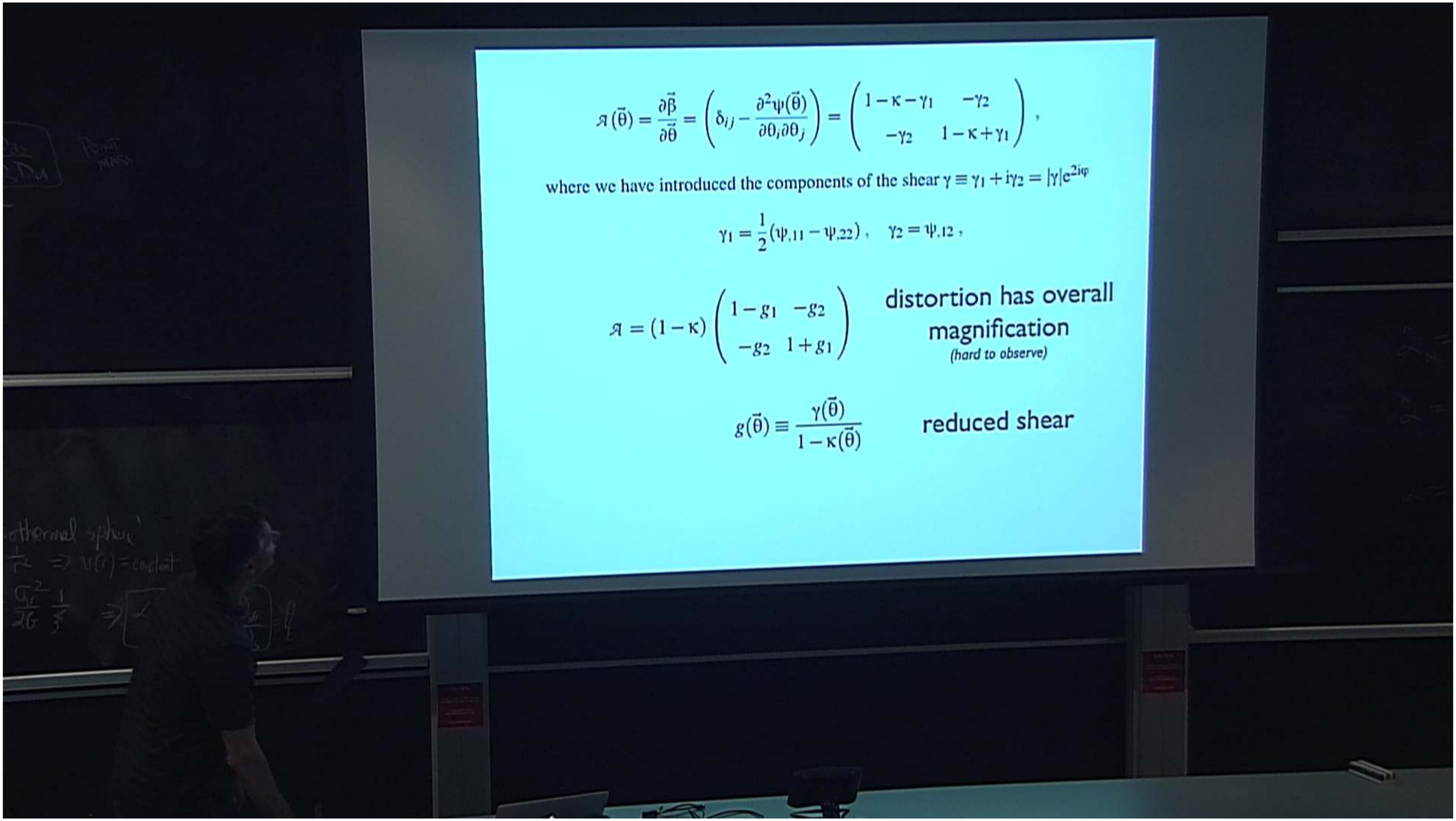

Fermat's Principle
• images form at stationary points of the arrival time surface
• maxima, minima, saddle points all cause images
• lumps of mass perturb arrival time surface, moving images and distorting their shapes
$\tau(\theta_I;\theta_S) = \frac{1}{2}(\theta_I - \theta_S)^2 - \psi(\theta_I)$
Blandford & Narayan 1986
a
b
c
d

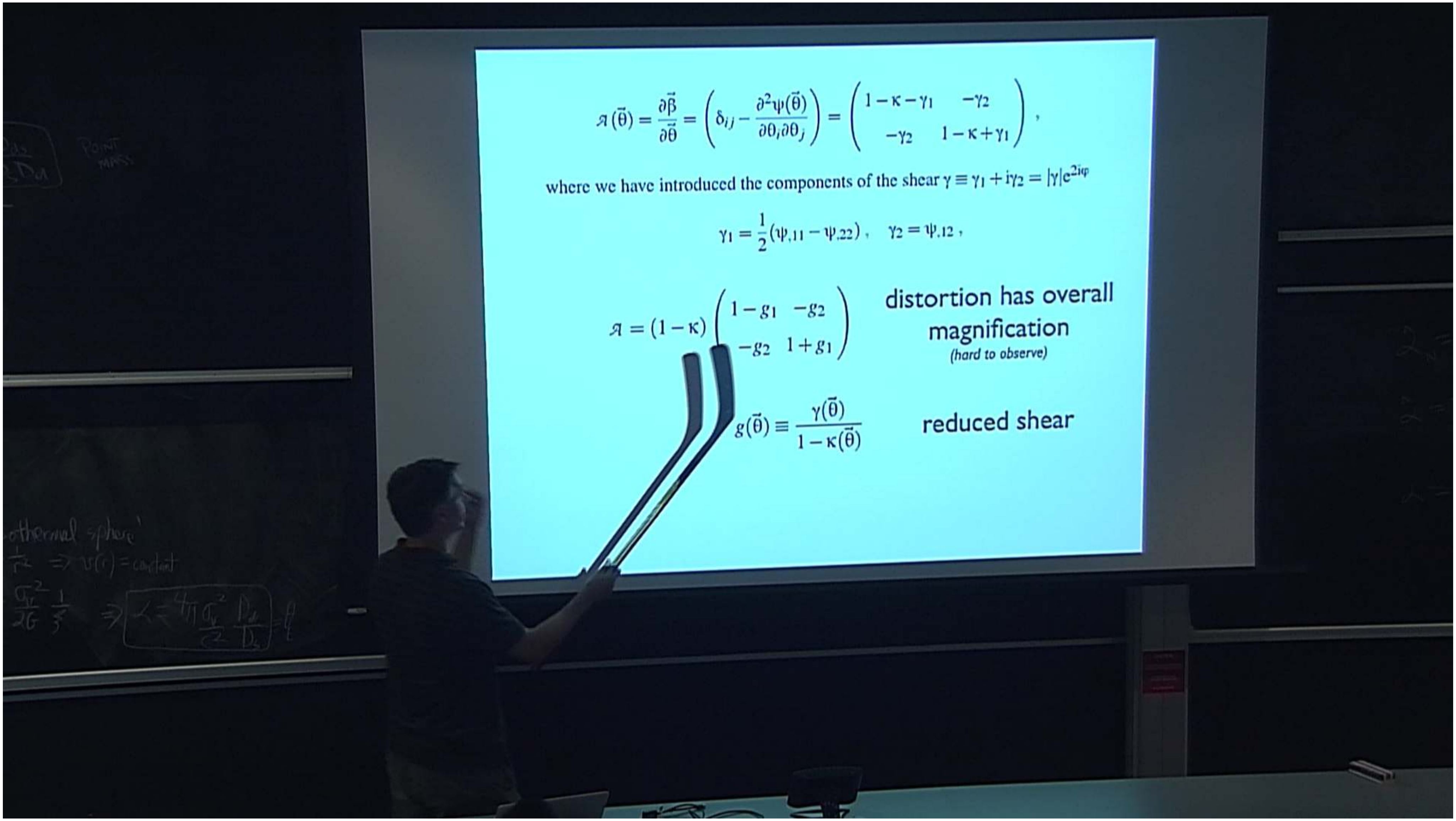

Fermat's Principle
• images form at stationary points of the arrival time surface
• maxima, minima, saddle points all cause images
• lumps of mass perturb arrival time surface, moving images and distorting their shapes
$\tau(\theta_I;\theta_S) = \frac{1}{2}(\theta_I - \theta_S)^2 - \psi(\theta_I)$
Blandford & Narayan 1986

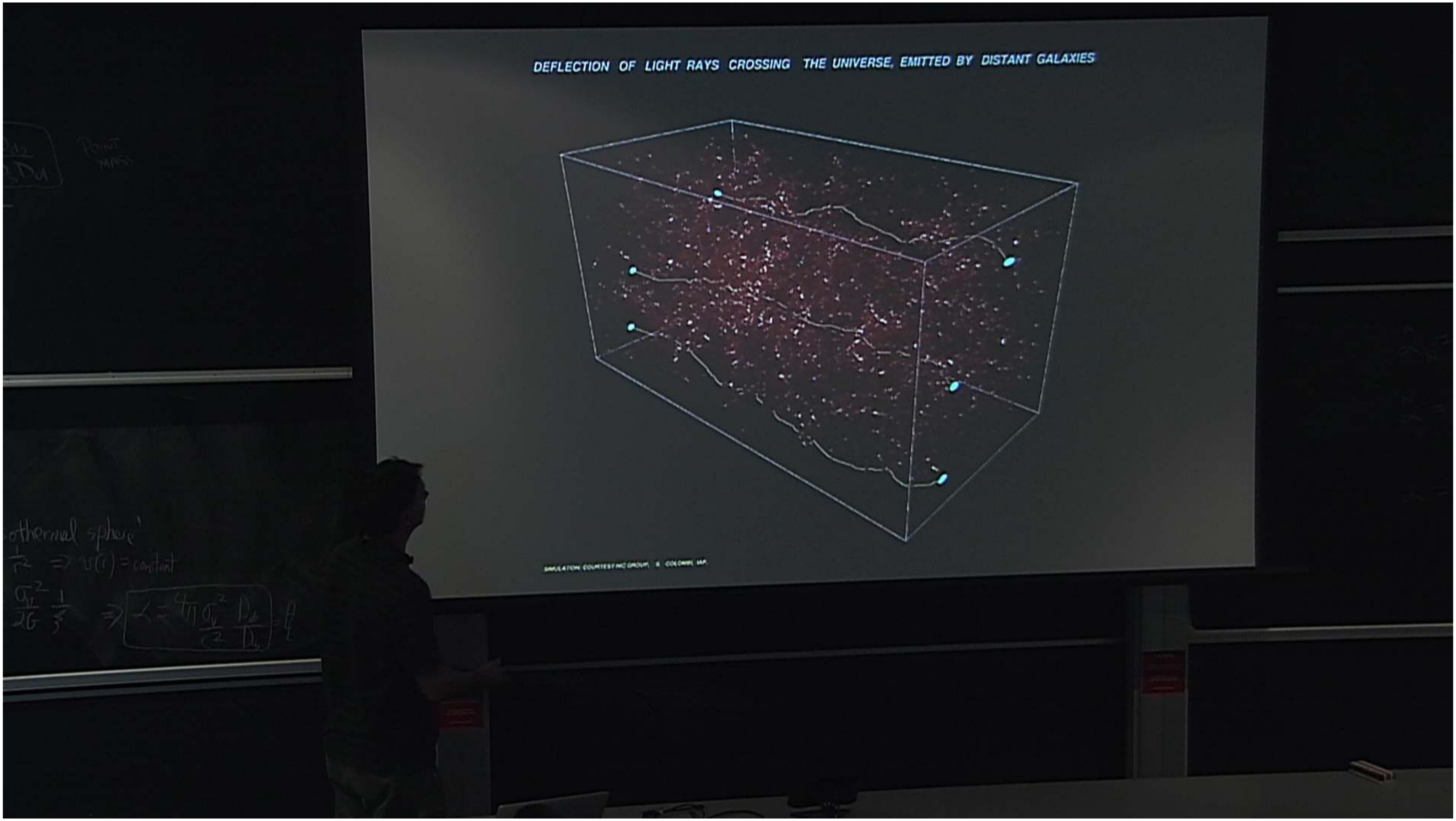

Fermat's Principle
• images form at stationary points of the arrival time surface
• maxima, minima, saddle points all cause images
• lumps of mass perturb arrival time surface, moving images
Blandford & Narayan 1986


Fermat's Principle
• images form at stationary points of the arrival time surface
• maxima, minima, saddle points all cause images
• lumps of mass perturb arrival time surface, moving images
their shapes
a
b
c
d
Blandford & Narayan 1986

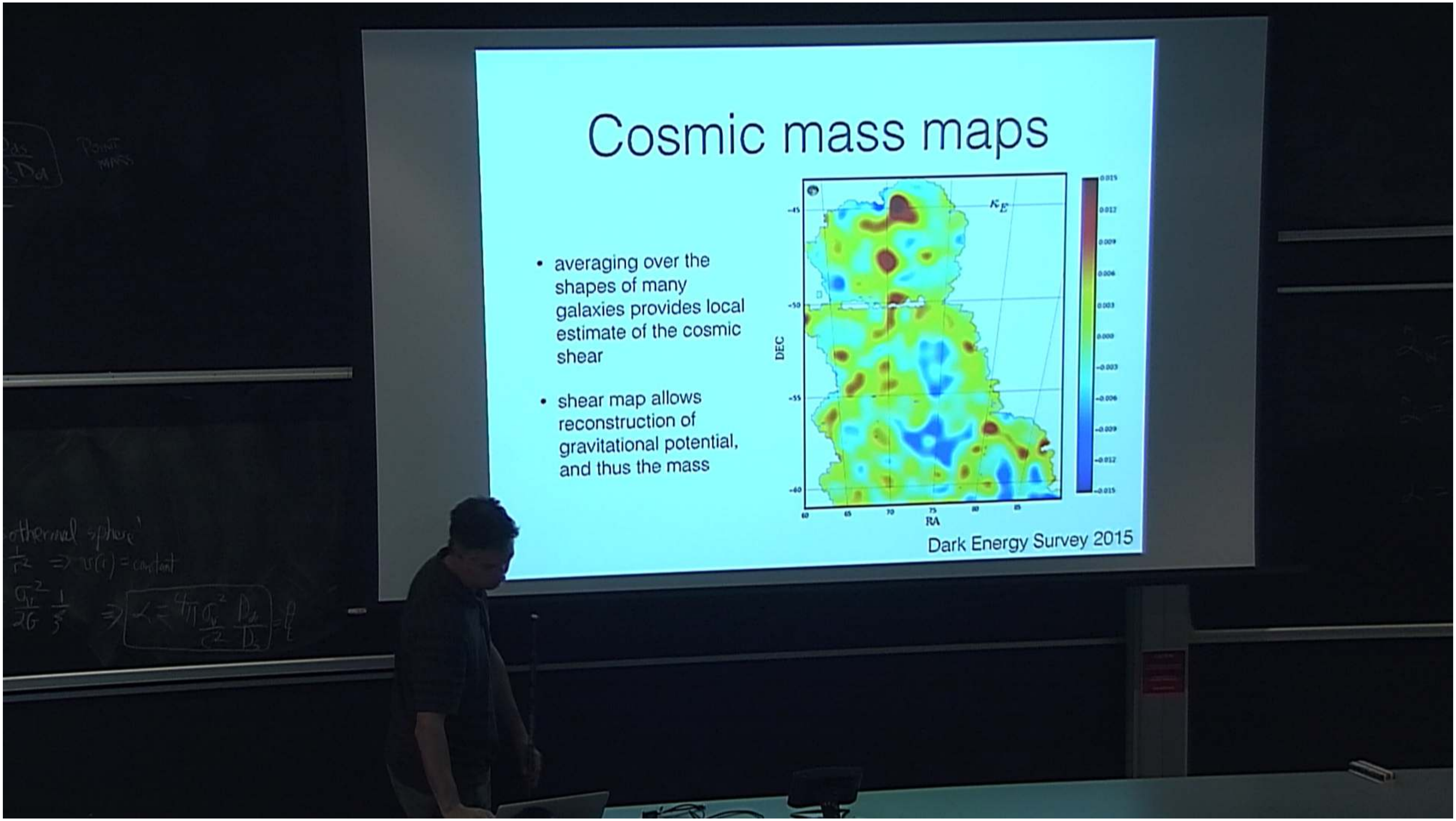

SN Refsdal:
Lensing of a
Supernova!
caught at
different
times in
different
images
likely missed
one a few
decades
y et al 2014


$\mathcal{A}(\vec{\theta}) = \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$,
where we have introduced the components of the shear $\gamma \equiv \gamma_1 + i\gamma_2 = |\gamma| e^{2i\varphi}$
$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22})\,, \quad \gamma_2 = \psi_{,12}\,,$
$\mathcal{A} = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$
distortion has overall magnification
(hard to observe)
$g(\vec{\theta}) \equiv \frac{\gamma(\vec{\theta})}{1-\kappa(\vec{\theta})}$
reduced shear

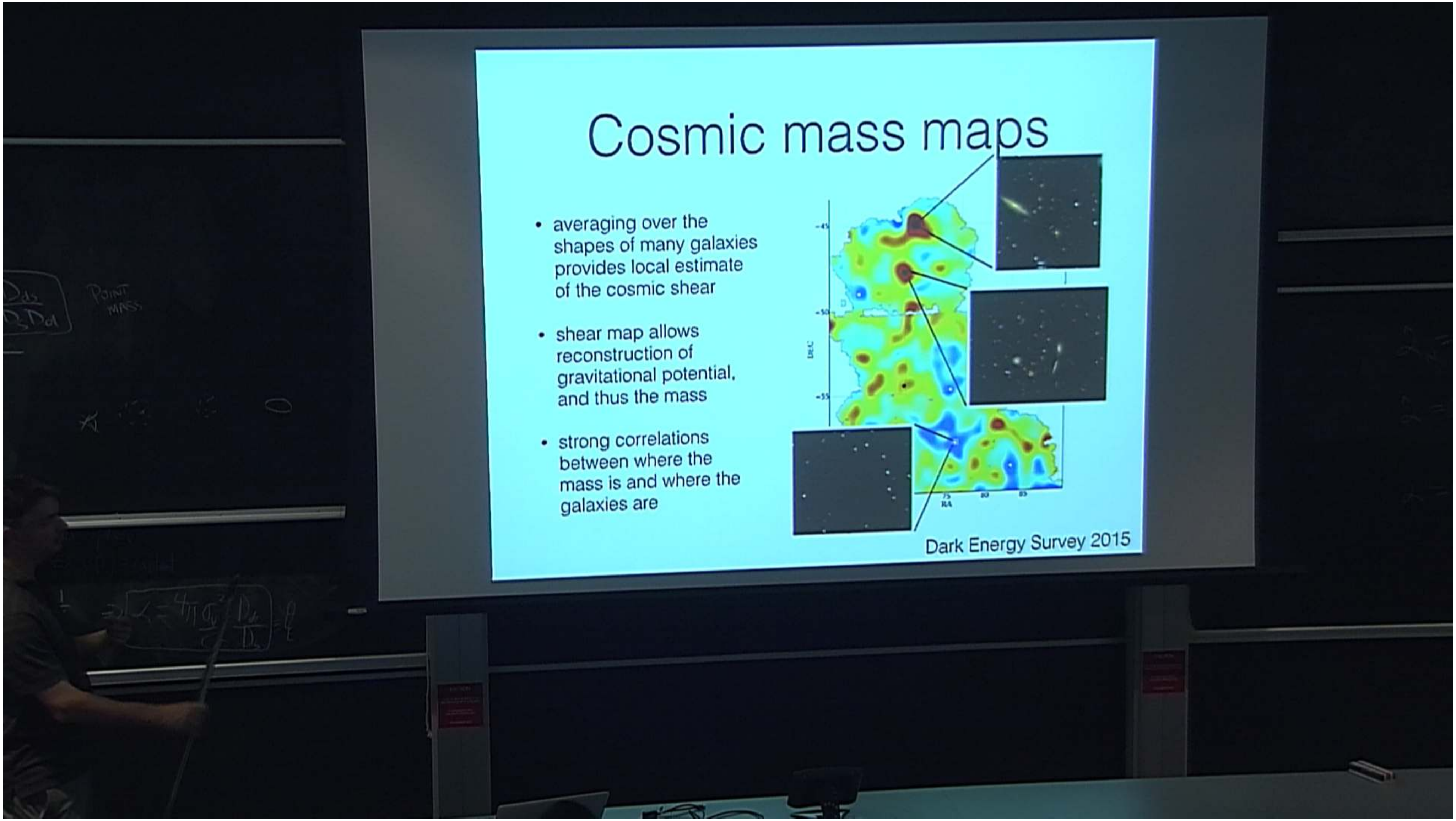

$\mathcal{A}(\vec{\theta}) = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$,
where we have introduced the components of the shear $\gamma \equiv \gamma_1 + i\gamma_2 = |\gamma|e^{2i\varphi}$
$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22})$, $\gamma_2 = \psi_{,12}$,
$\mathcal{A} = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$
distortion has overall magnification
(hard to observe)
$g(\vec{\theta}) \equiv \frac{\gamma(\vec{\theta})}{1-\kappa(\vec{\theta})}$
reduced shear

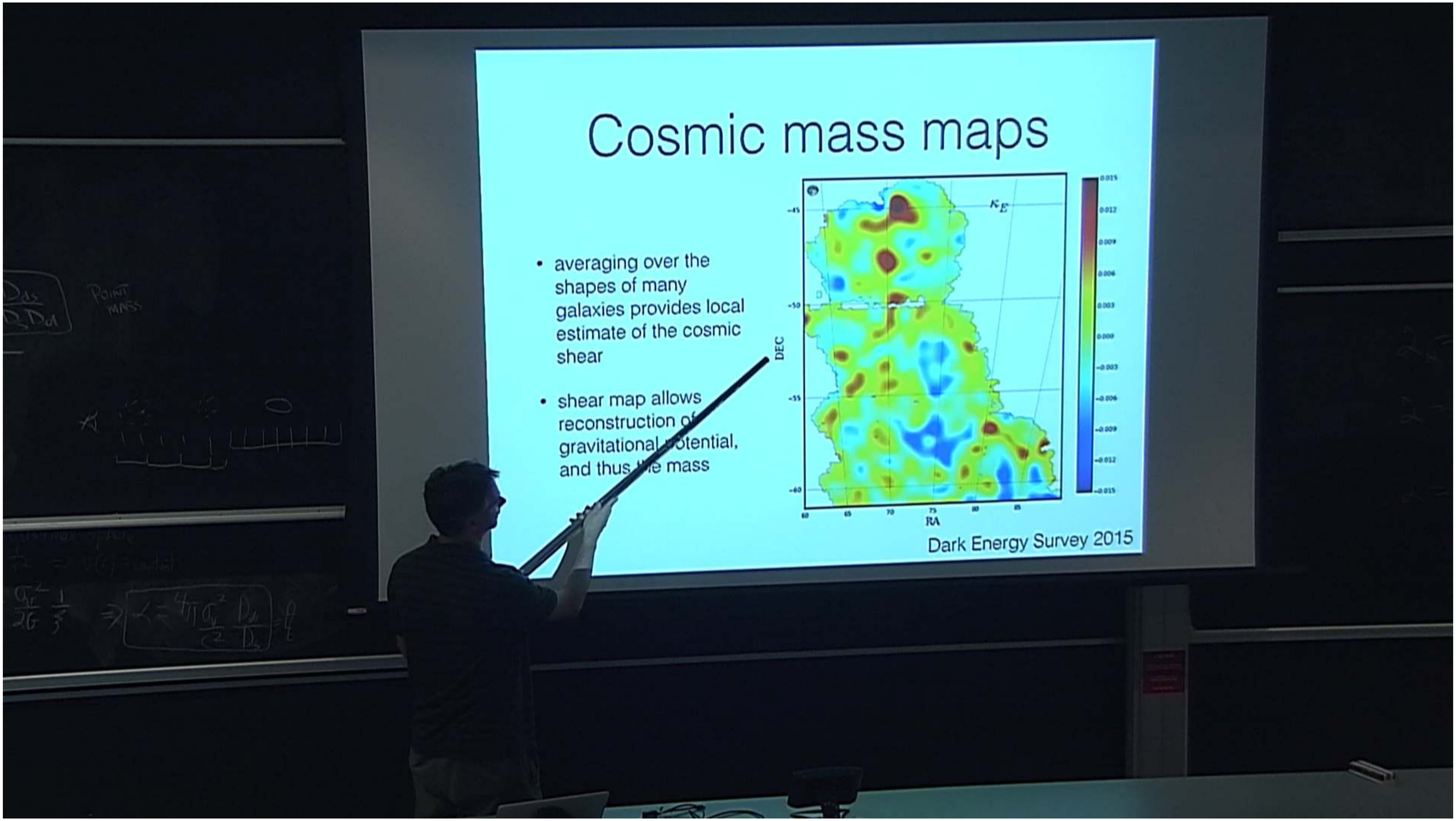

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

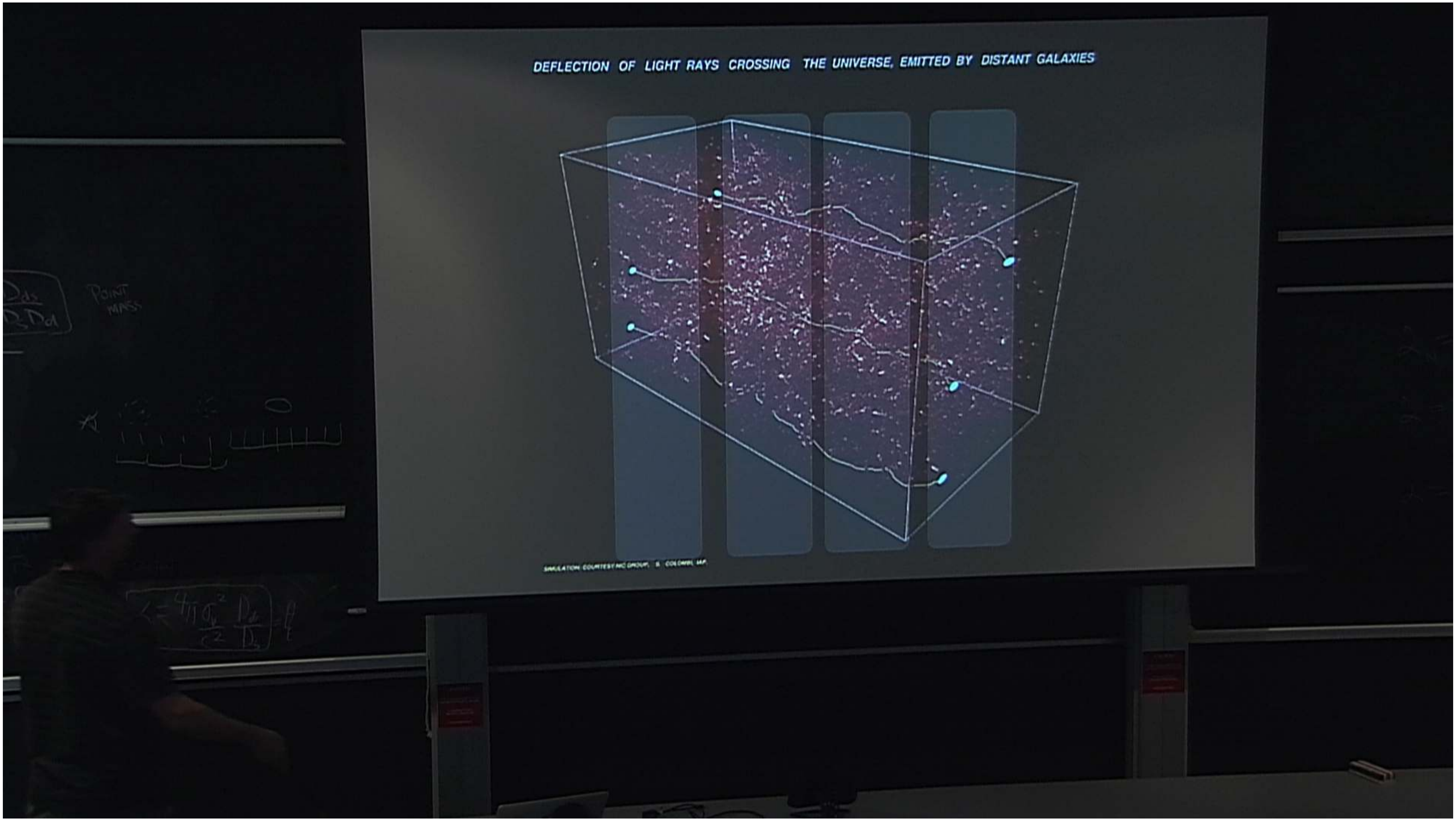

Galaxies are not round
individual galaxies have complex morphologies
solution: average over many galaxies
© Anglo-Australian Observatory

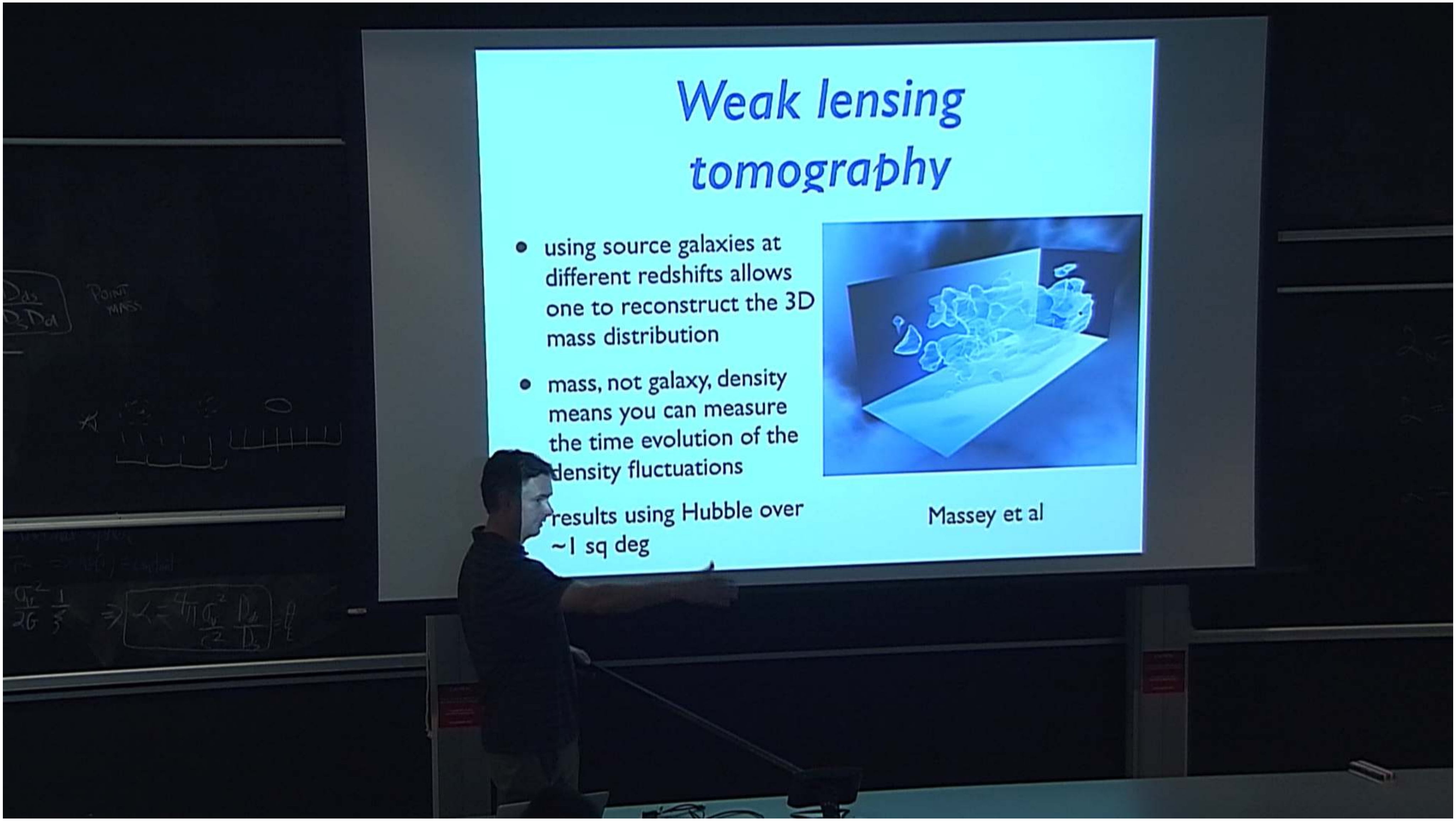


Cosmic mass maps
• averaging over the shapes of many galaxies provides local estimate of the cosmic shear
• shear map allows reconstruction of gravitational potential, and thus the mass
κ_E
DEC
RA
Dark Energy Survey 2015

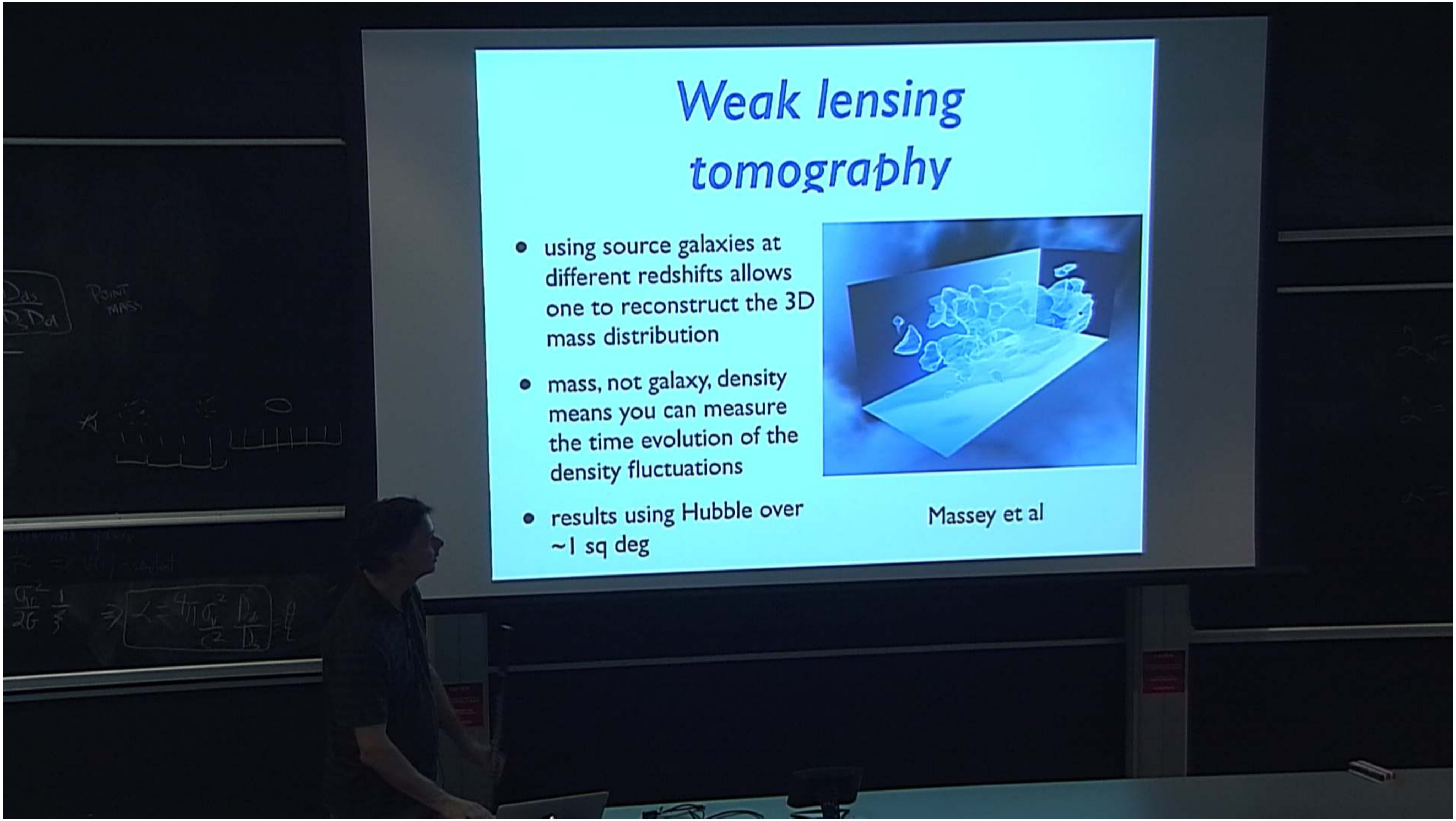

Cosmic mass maps
• averaging over the shapes of many galaxies provides local estimate of the cosmic shear
• shear map allows reconstruction of gravitational potential, and thus the mass
• strong correlations between where the mass is and where the galaxies are
Dark Energy Survey 2015

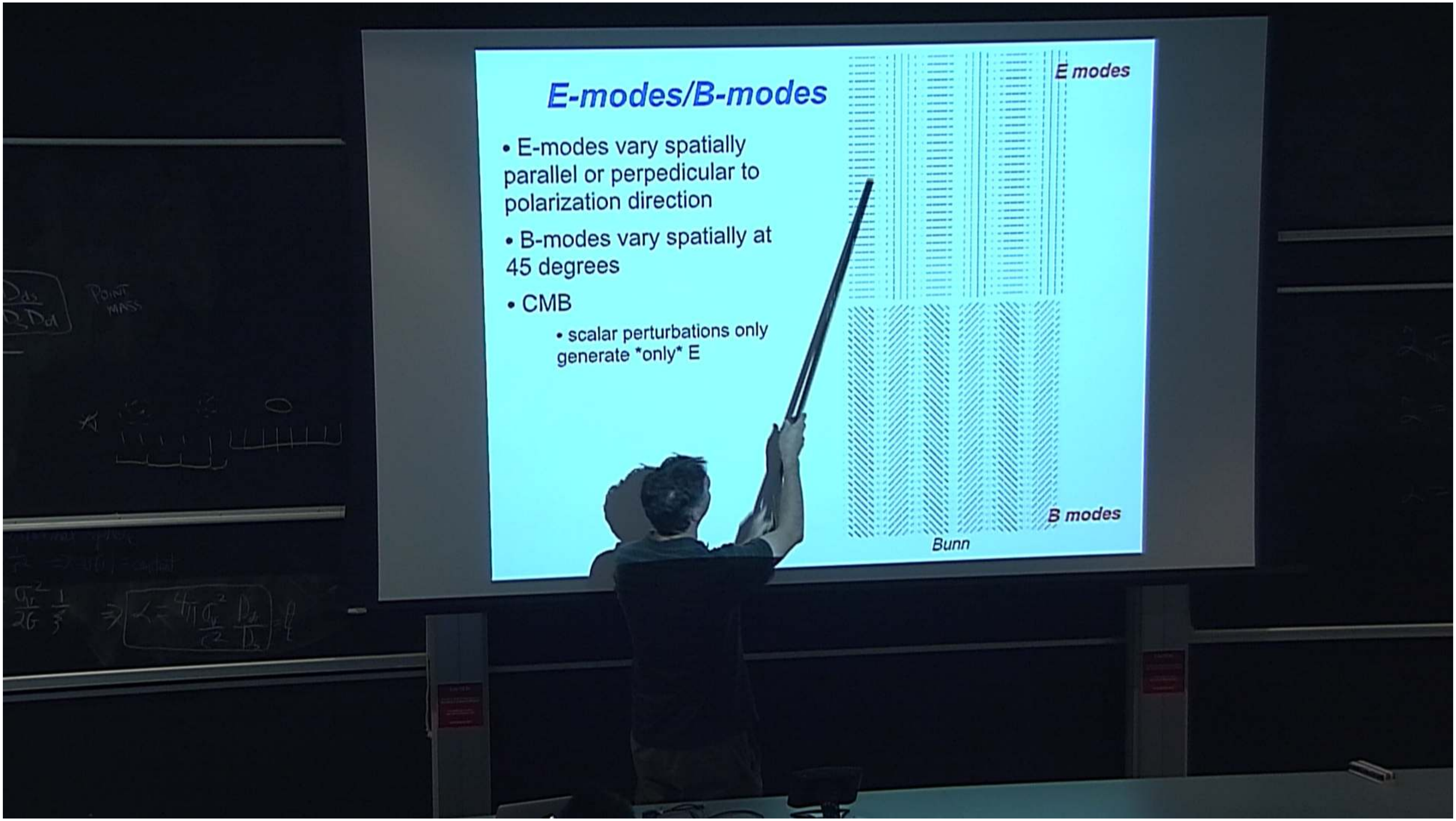

Cosmic mass maps
• averaging over the shapes of many galaxies provides local estimate of the cosmic shear
• shear map allows reconstruction of gravitational potential, and thus the mass
DEC
RA
κ_E
Dark Energy Survey 2015

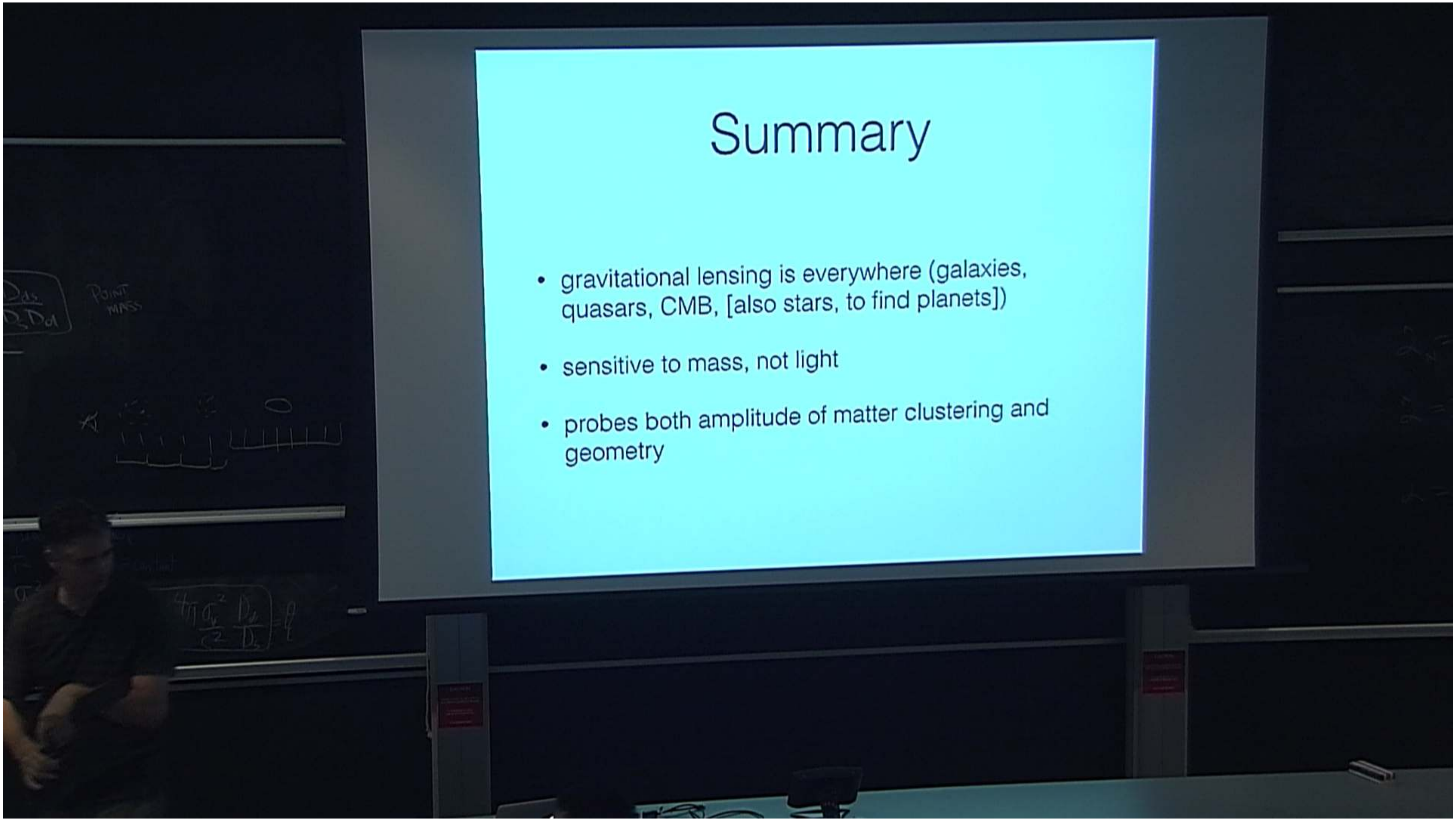

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES
SIMULATION: COURTESY MC GROUP, S. COLOMBI, IAP.



Weak lensing tomography
using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
mass, not galaxy, density means you can measure the time evolution of the density fluctuations
results using Hubble over ~1 sq deg
Massey et al


Weak lensing tomography
using source galaxies at different redshifts allows one to reconstruct the 3D mass distribution
mass, not galaxy, density means you can measure the time evolution of the density fluctuations
results using Hubble over ~1 sq deg
Massey et al


E-modes/B-modes
• E-modes vary spatially parallel or perpedicular to polarization direction
• B-modes vary spatially at 45 degrees
• CMB
• scalar perturbations only generate *only* E
E modes
B modes
Bunn


Summary
gravitational lensing is everywhere (galaxies, quasars, CMB, [also stars, to find planets])
sensitive to mass, not light
probes both amplitude of matter clustering and geometry