Title: Astroparticle Physics â€“ Observations: Dark matter

Date: Jul 13, 2015 04:00 PM

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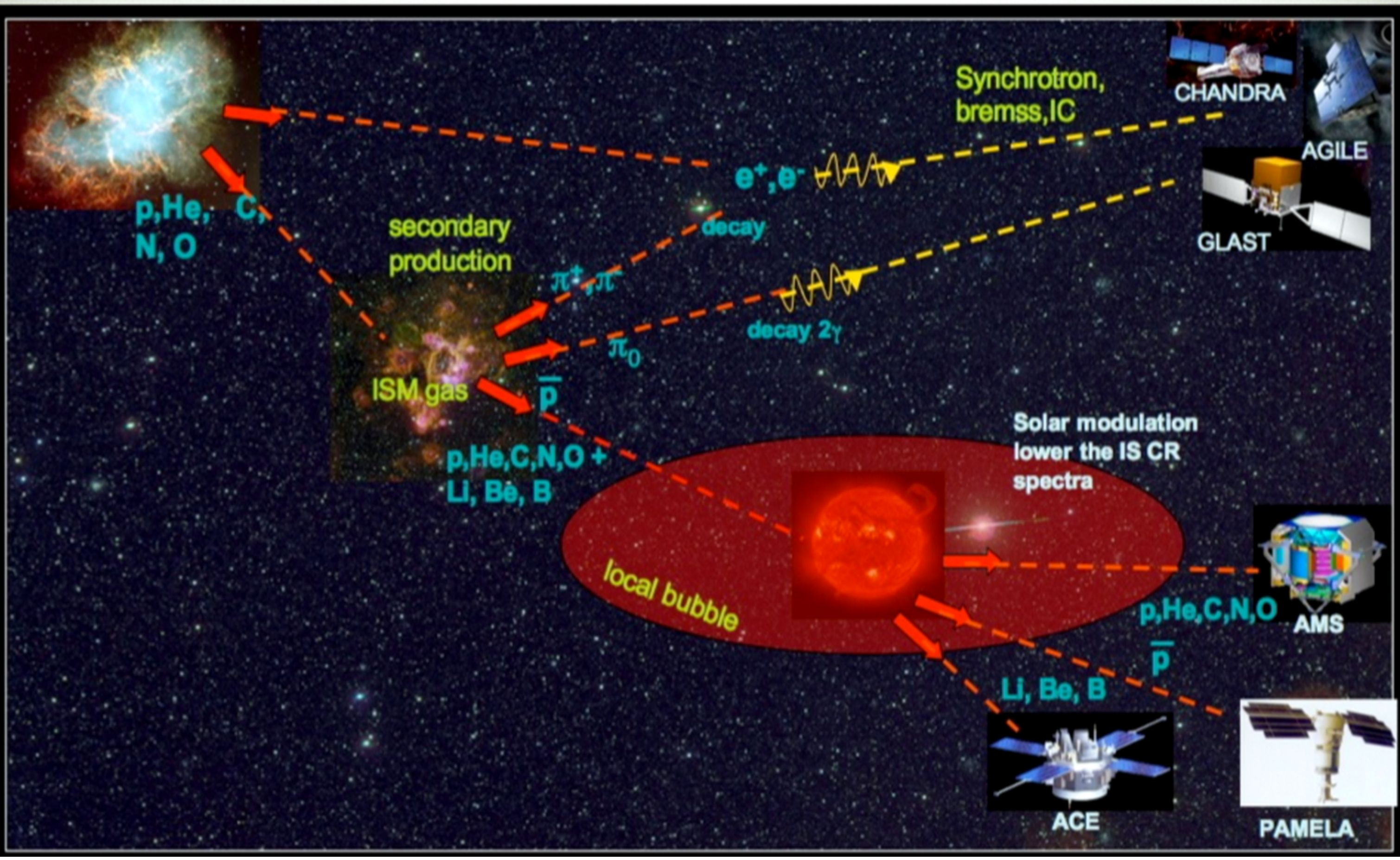
Abstract:

Cosmic-ray Propagation



Cosmic-ray Propagation

- After escaping the source, CRs travel into interstellar space
- As they propagate through the galaxy, they experience energy losses and changes in trajectory because of interactions with the interstellar medium and magnetic fields
- At the Earth, they are (mainly) isotropically distributed
- How well do we understand propagation? We infer a lot of information through the products of the interaction of the primary CRs (accelerated at the source and measured locally) as they propagate in interstellar space: secondary nuclei , anti-particles, gamma rays, synchrotron radiation

Diffusion

- The isotropy of CRs and abundance of secondary CRs (i.e. nuclei accelerated at the source like p, C, Fe,… vs nuclei produced by spallation in the interstellar gas, like B, Be, …) indicates that CRs must travel diffusively through the Galaxy
  - ➡ **Galactic magnetic fields are critical for this process**
- The measured boron to carbon ratio (B/C) determines the *grammage* X, which is related to the amount of material traversed and the escape time τ_{esc}:

density x thickness

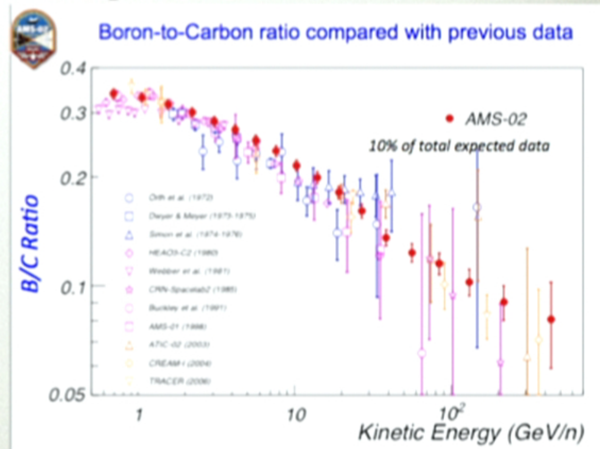
$$X(E) = \bar{n}\mu v \tau_{esc}(E)$$

$$X(10\ GeV/n) \sim 10 g/cm^2$$

$\bar{n}$: mean gas density

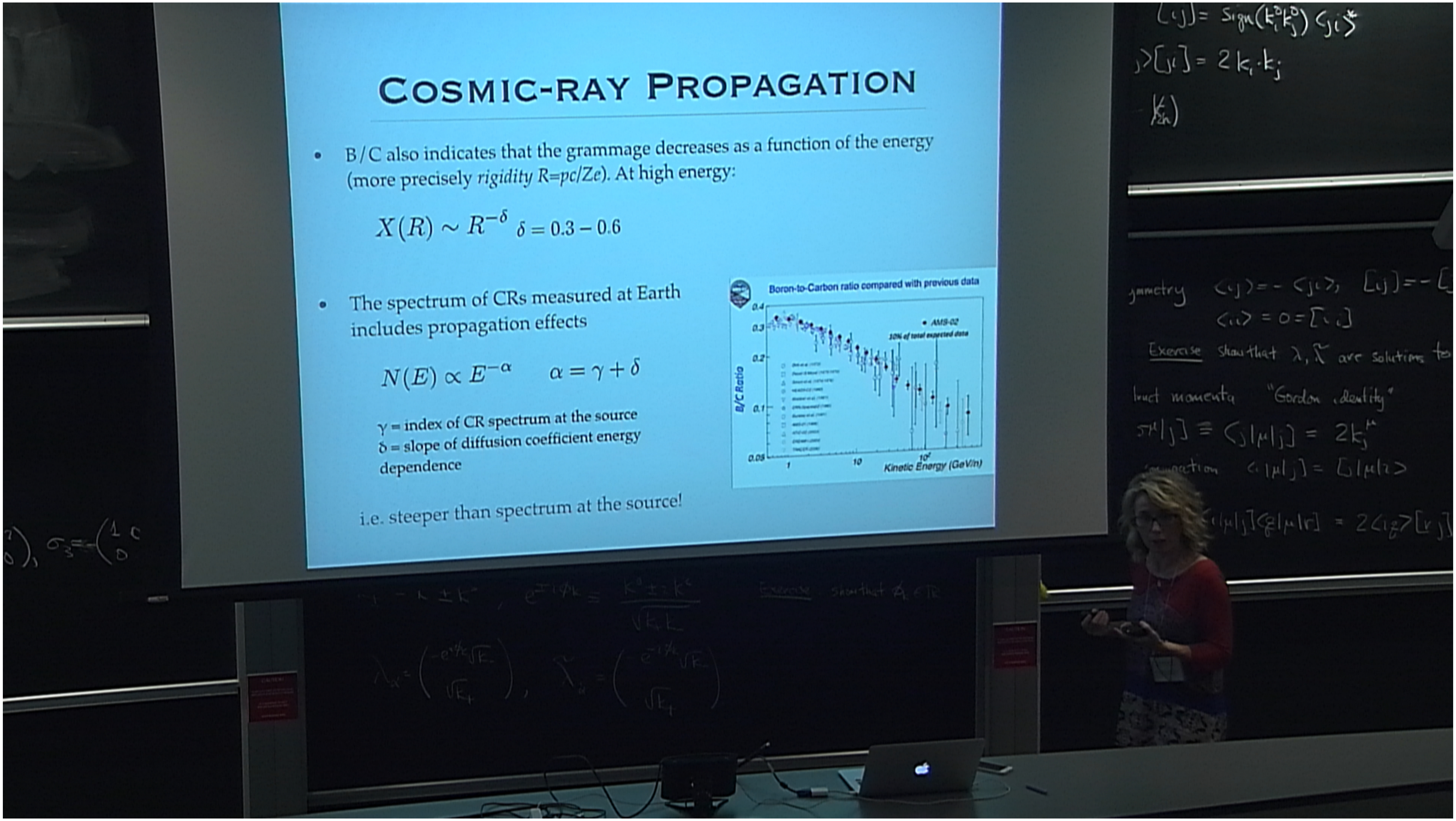
μ : mean gas mass

v : particle speed



- This yields escape times much larger (~100 Myr) than determined by propagation in straight lines (~10-100 kyr)

➡ **CRs diffuse through the Galaxy**


Cosmic-ray Propagation
B/C also indicates that the grammage decreases as a function of the energy (more precisely rigidity R=pc/Ze). At high energy:
$X(R) \sim R^{-\delta}$ $\delta = 0.3 - 0.6$
The spectrum of CRs measured at Earth includes propagation effects
$N(E) \propto E^{-\alpha}$ $\alpha = \gamma + \delta$
γ = index of CR spectrum at the source
δ = slope of diffusion coefficient energy dependence
i.e. steeper than spectrum at the source!
Boron-to-Carbon ratio compared with previous data
AMS-02
10% of total expected data
B/C Ratio
Kinetic Energy (GeV/n)

Cosmic-ray Propagation

- B/C also indicates that the grammage decreases as a function of the energy (more precisely *rigidity* $R=pc/Ze$). At high energy:

$$X(R) \sim R^{-\delta} \quad \delta = 0.3 - 0.6$$

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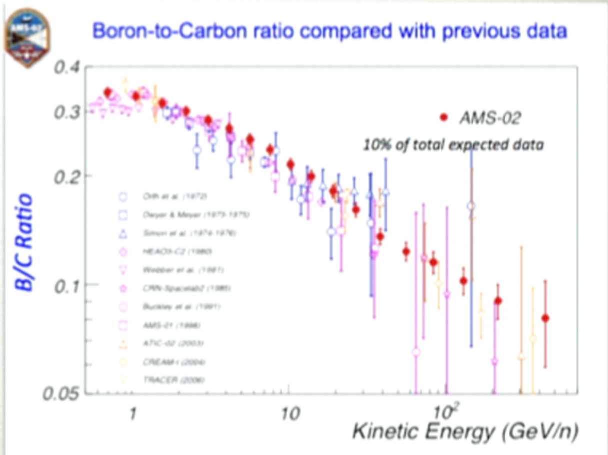

$$N(E) \propto E^{-\alpha} \qquad \alpha = \gamma + \delta$$

γ = index of CR spectrum at the source
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i.e. steeper than spectrum at the source!

Cosmic-ray Propagation

- More complete formulation for CR propagation in the galaxy:

density of CRs

source term
(includes primary source+spallation and decay)

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi)$$

$$+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

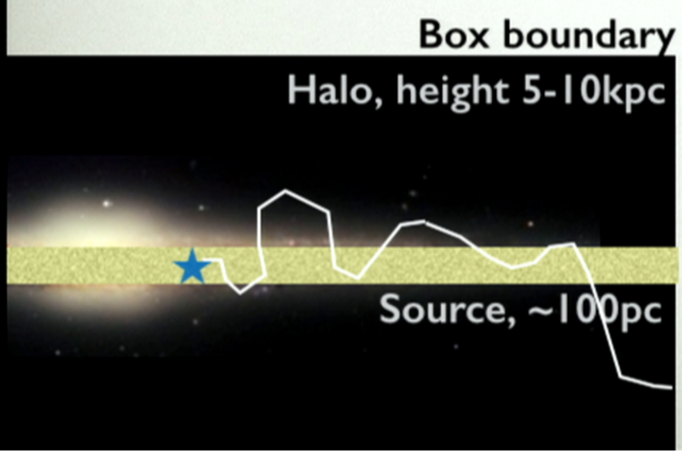
spatial diffusion coefficient

fragmentation

re-acceleration

convection in galactic winds

radioactive decay



Leaky box: assume some escape of CRs into intergalactic space, characterized by the escape time τ_{esc}

Steady-state: assume $d\psi/dt=0$

From CR data: $D_{xx} \sim (3-5)\times 10^{28}\mathrm{cm}^2/\mathrm{s}$

Cosmic-ray Propagation

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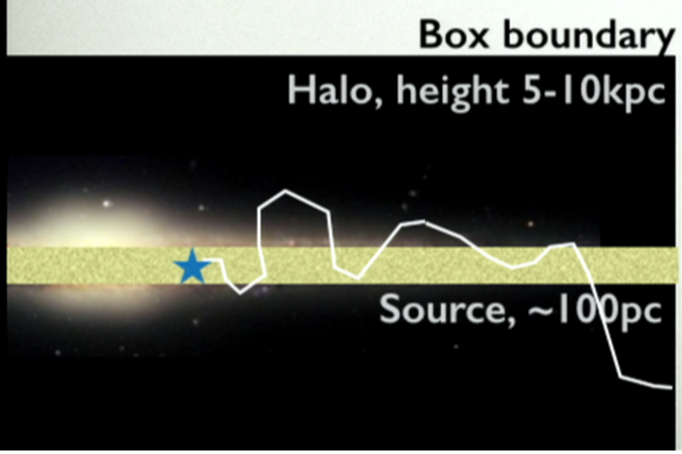

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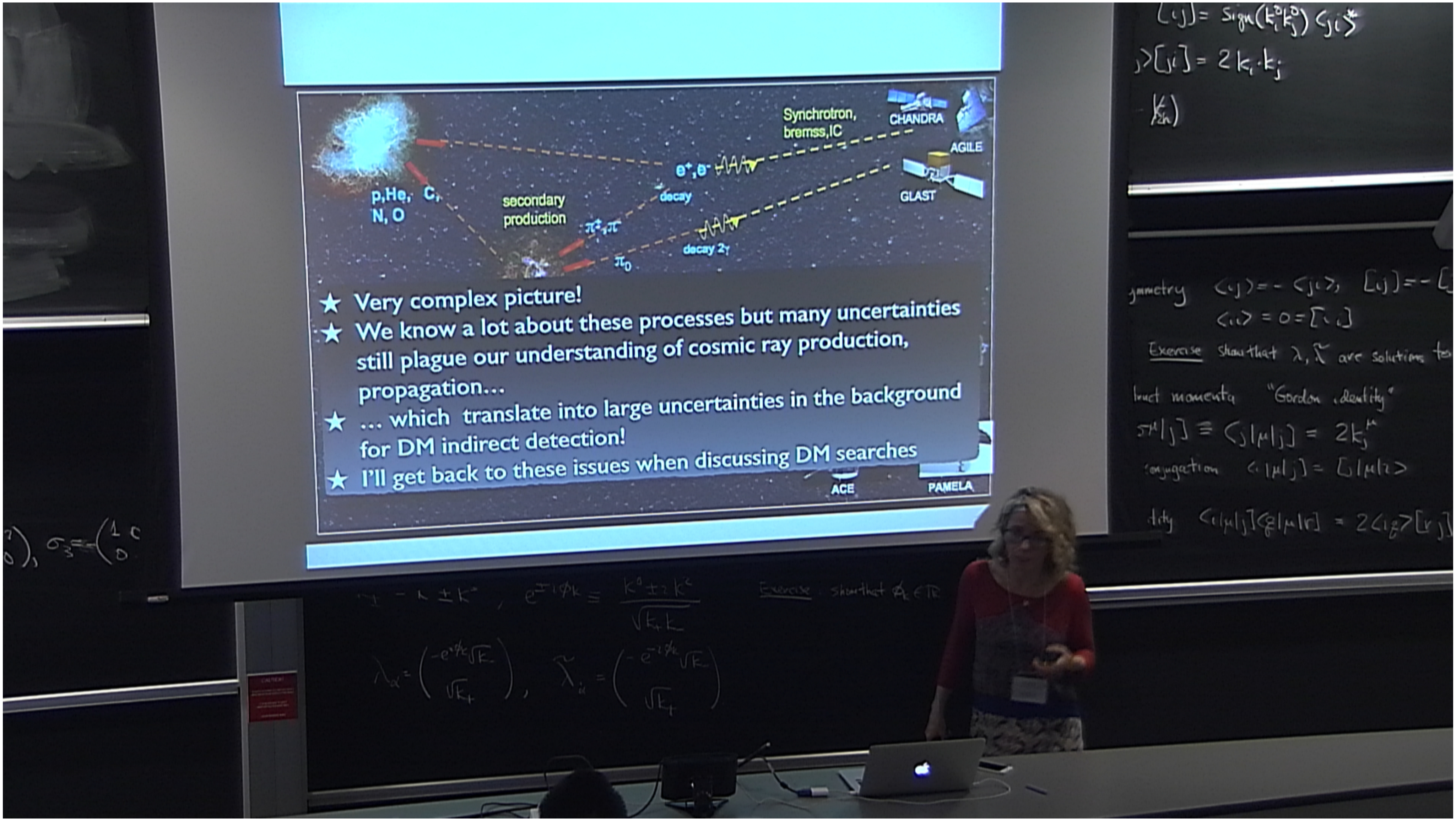
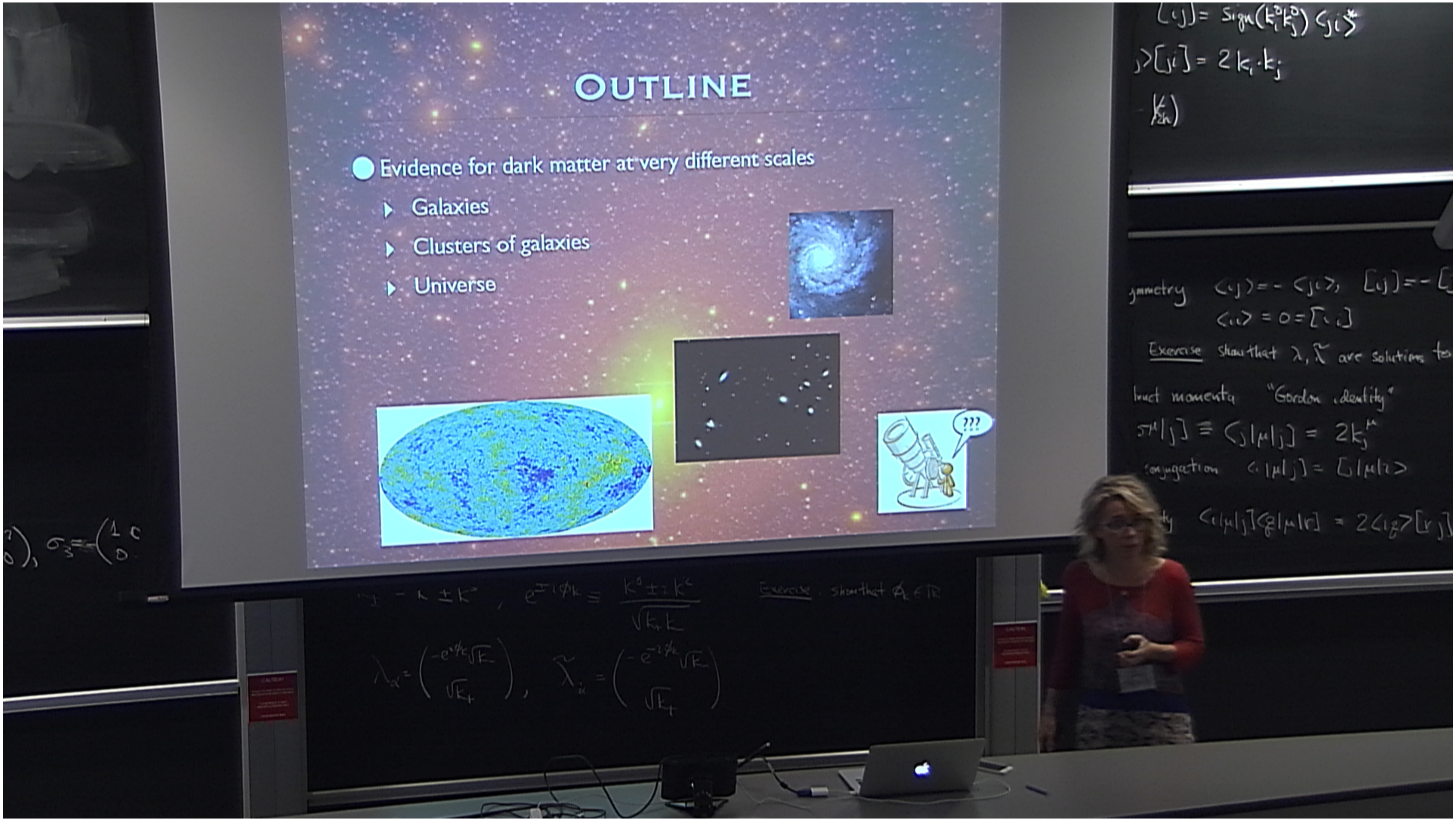
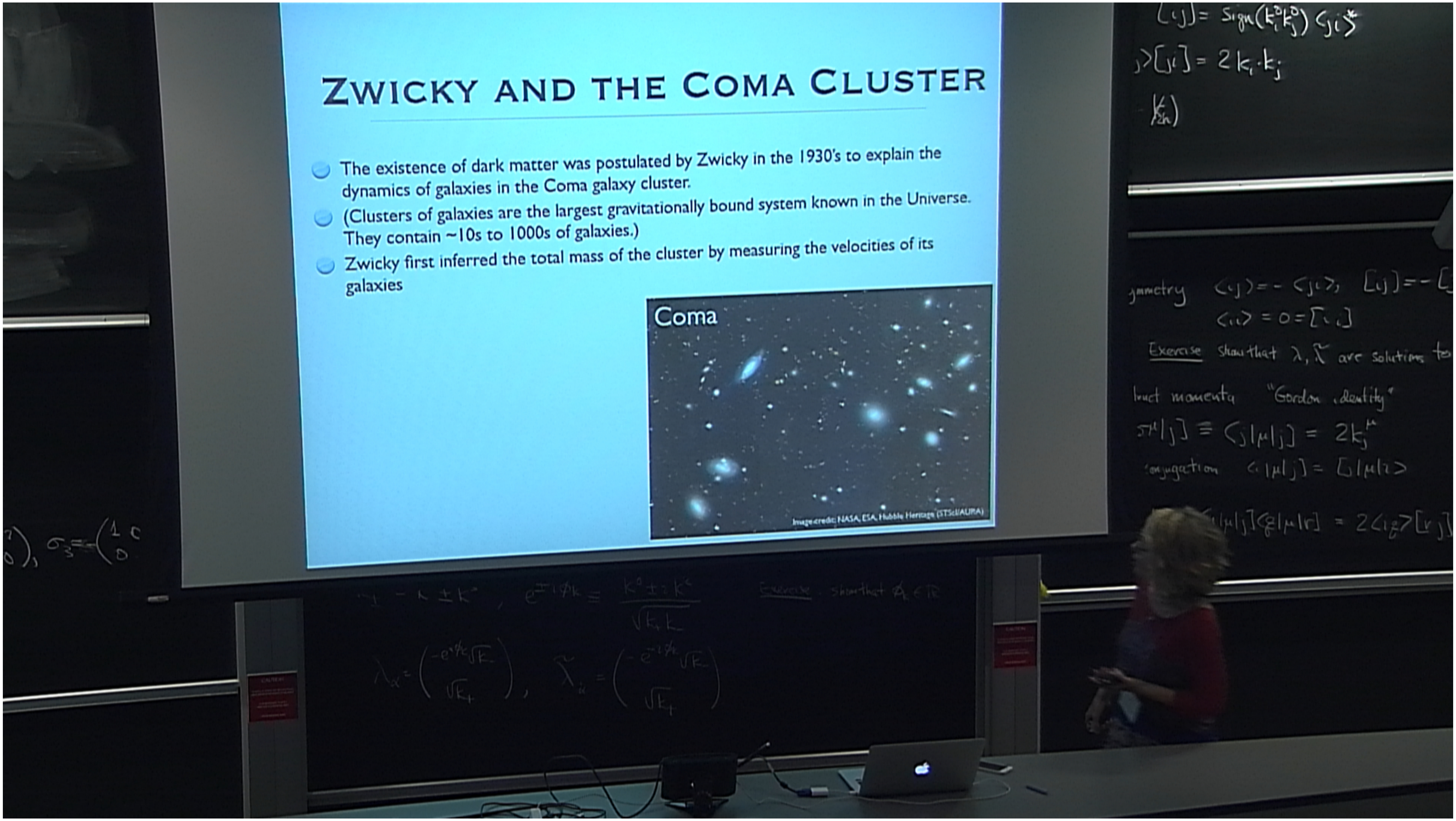
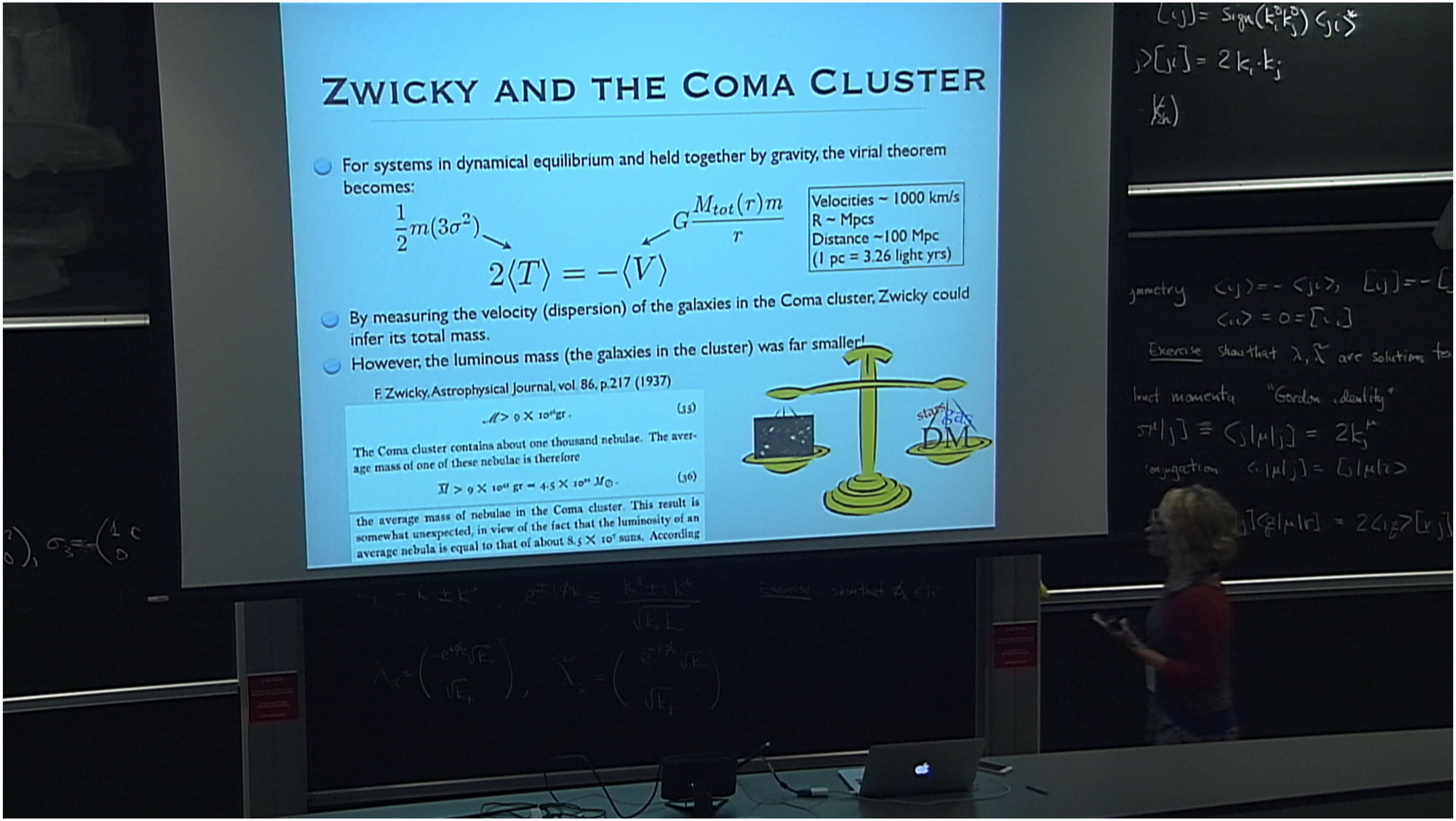
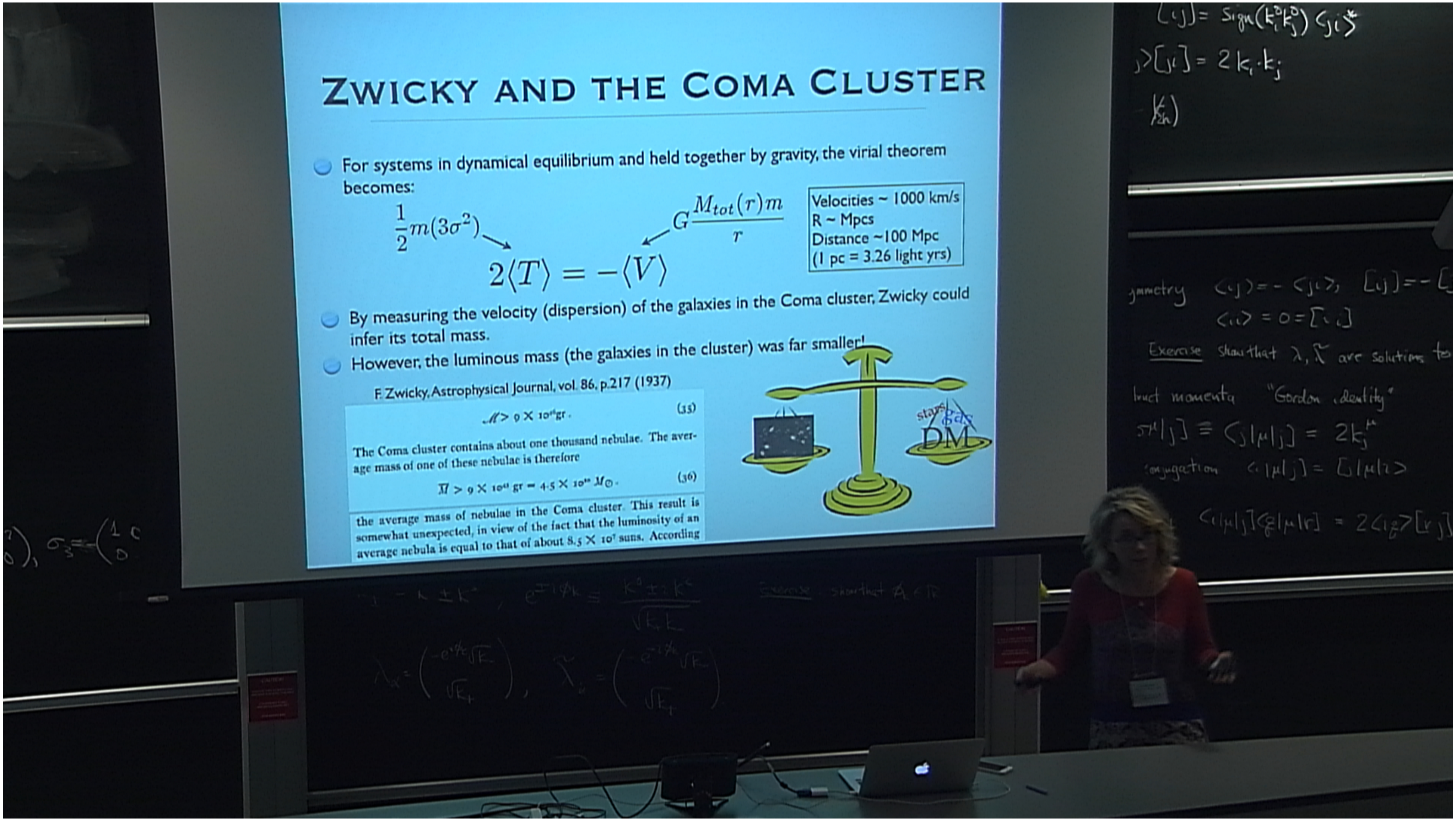

Synchrotron,
bremss,IC
CHANDRA
AGILE
GLAST
p,He, C,
N, O
secondary
production
e+,e-
decay
decay 2γ
ACE
PAMELA
★ Very complex picture!
★ We know a lot about these processes but many uncertainties still plague our understanding of cosmic ray production, propagation…
★ … which translate into large uncertainties in the background for DM indirect detection!
★ I'll get back to these issues when discussing DM searches


OUTLINE
Evidence for dark matter at very different scales
Galaxies
Clusters of galaxies
Universe
???


ZWICKY AND THE COMA CLUSTER
The existence of dark matter was postulated by Zwicky in the 1930's to explain the dynamics of galaxies in the Coma galaxy cluster.
(Clusters of galaxies are the largest gravitationally bound system known in the Universe. They contain ~10s to 1000s of galaxies.)
Zwicky first inferred the total mass of the cluster by measuring the velocities of its galaxies
Coma
Image credit: NASA, ESA, Hubble Heritage (STScI/AURA)


ZWICKY AND THE COMA CLUSTER
For systems in dynamical equilibrium and held together by gravity, the virial theorem becomes:
$\frac{1}{2}m(3\sigma^2)$
$G\frac{M_{tot}(r)m}{r}$
$2\langle T\rangle = -\langle V\rangle$
Velocities ~ 1000 km/s
R ~ Mpcs
Distance ~100 Mpc
(1 pc = 3.26 light yrs)
By measuring the velocity (dispersion) of the galaxies in the Coma cluster, Zwicky could infer its total mass.
However, the luminous mass (the galaxies in the cluster) was far smaller!
F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore
the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5 × 10⁷ suns. According
stars
gas
DM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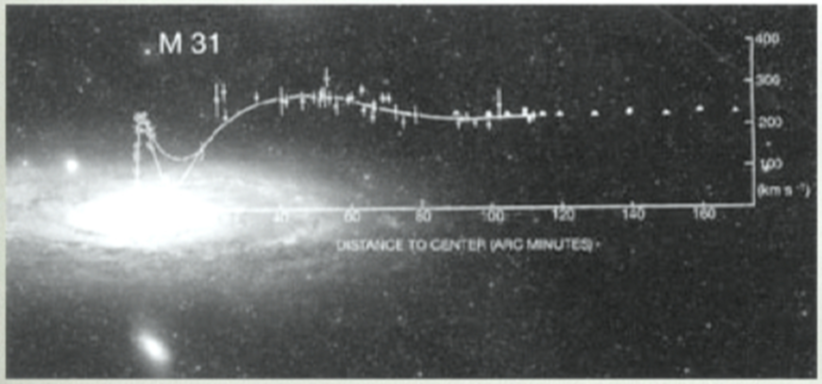
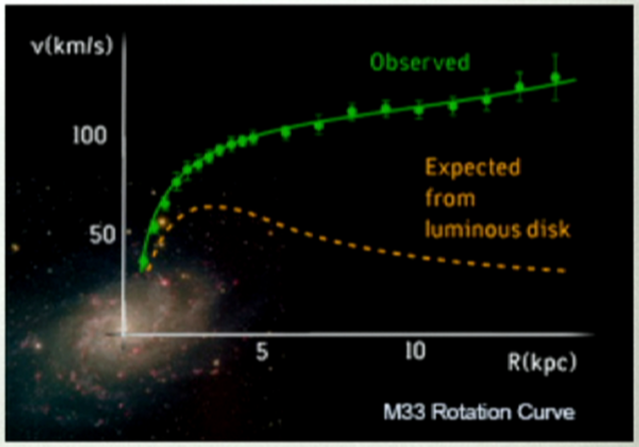
$\mathcal{M} > 9 \times 10^{46}$ gr. (35)
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore
$\bar{M} > 9 \times 10^{43}$ gr $= 4.5 \times 10^{10} M_{\odot}$. (36)
the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According
stars
gas
DM

Rotation Curves of Galaxies

- Departures from the predictions of newtonian gravity became apparent also at galactic scales with the measurement of rotation curves of galaxies (Rubin et al, 1970)





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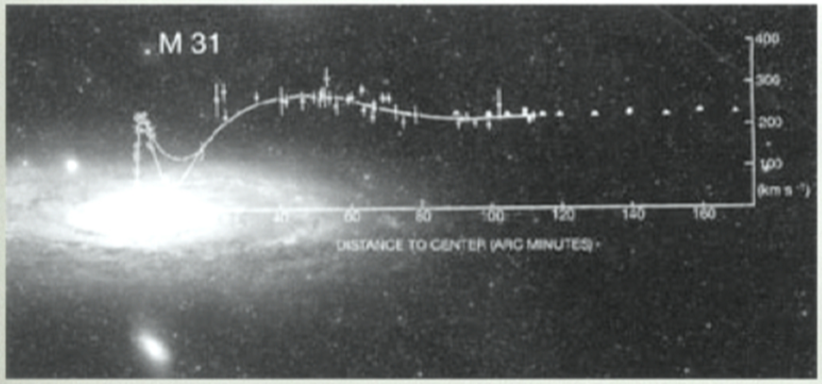
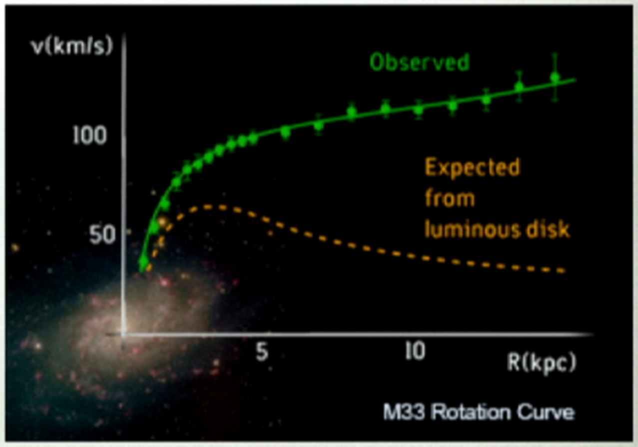


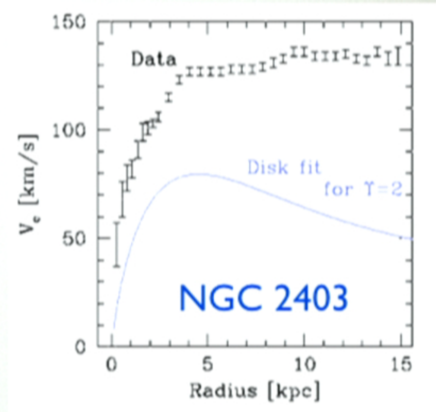


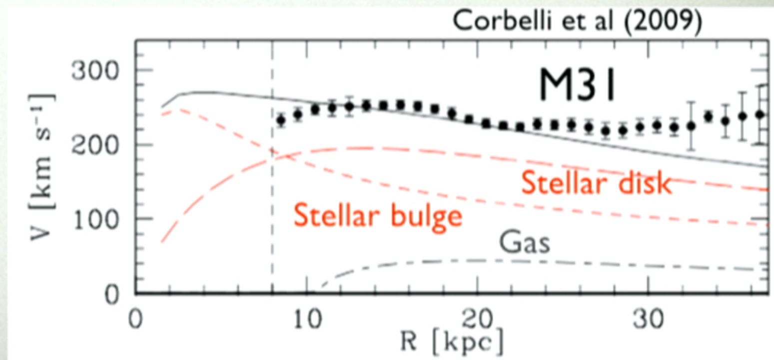
Rotation Curves of Galaxies

- From newtonian dynamics:

$$F = \frac{mv^2}{r} = G\frac{mM}{r^2}$$

$$v(r) \propto r^{-1/2}$$





Rotation Curves of Galaxies

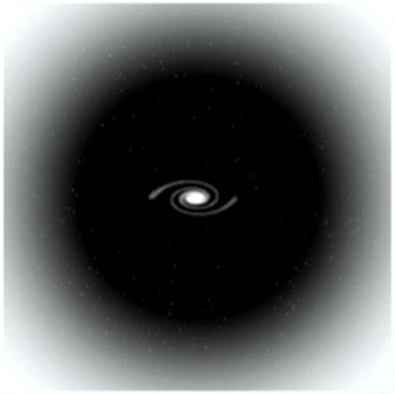
- From newtonian dynamics:

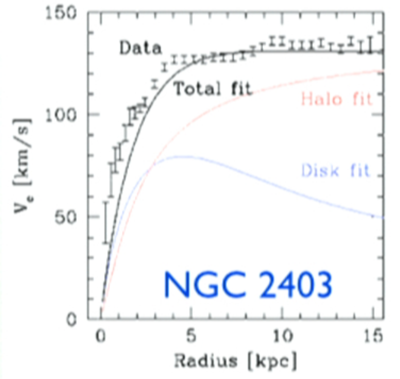
$$F = \frac{mv^2}{r} = G\frac{mM}{r^2}$$

$$v(r) \propto r^{-1/2}$$

- For constant v:

$$M(r) \propto r \qquad \rho(r) \propto r^{-2}$$

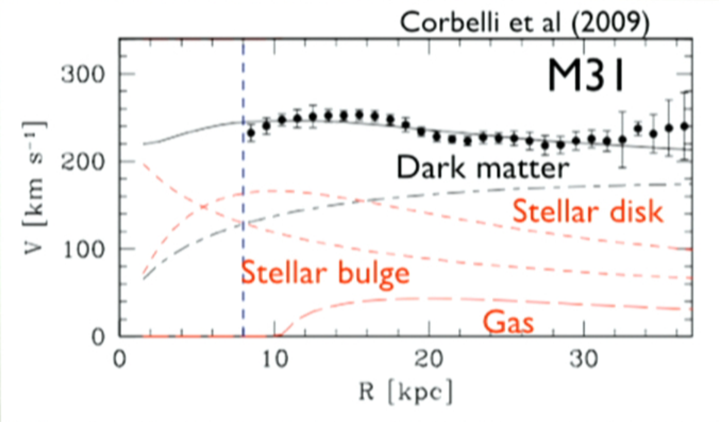




Mass density not as steeply falling as star density (exponential)!

➡ By adding extended dark matter halo get good fit to the data.

Similar exercise for the Milky Way yields local DM density:
ρ(8.5 kpc)~0.2-0.5 GeV/cm³ (direct detection)

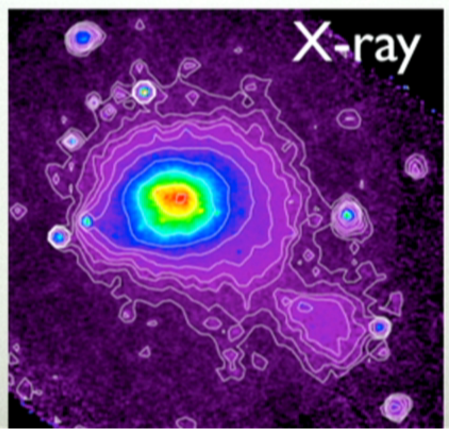


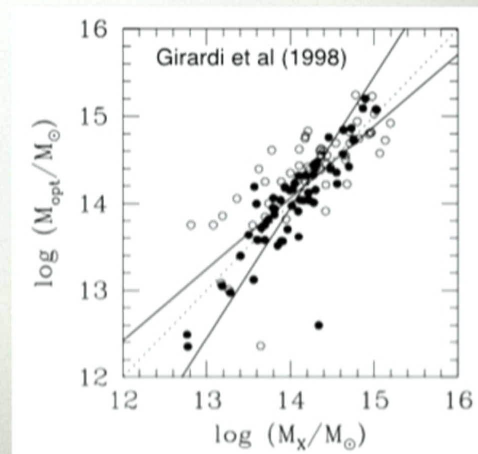
Galaxy clusters

- X-ray emitted by very hot intracluster gas (10^7-10^8K) through bremsstrahlung.
- Gas mass and total mass in galaxy clusters measured by X-ray (assuming thermal equilibrium), lensing
- Mass determination consistent with clusters being dark matter dominated

Galaxy cluster:
~1-2% stars, ~5-15% gas, remaining is dark matter

Coma galaxy cluster





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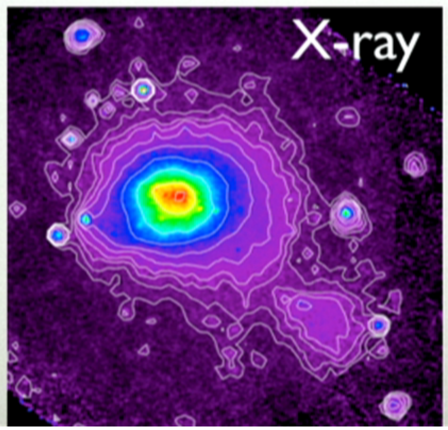
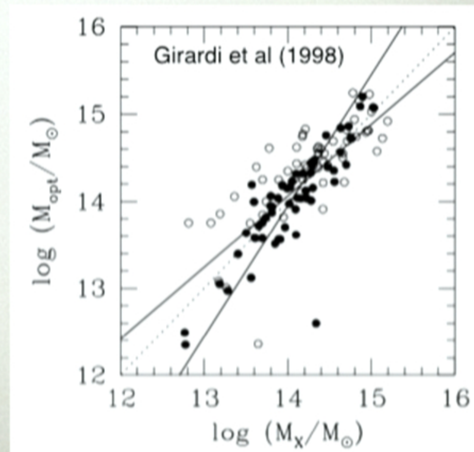
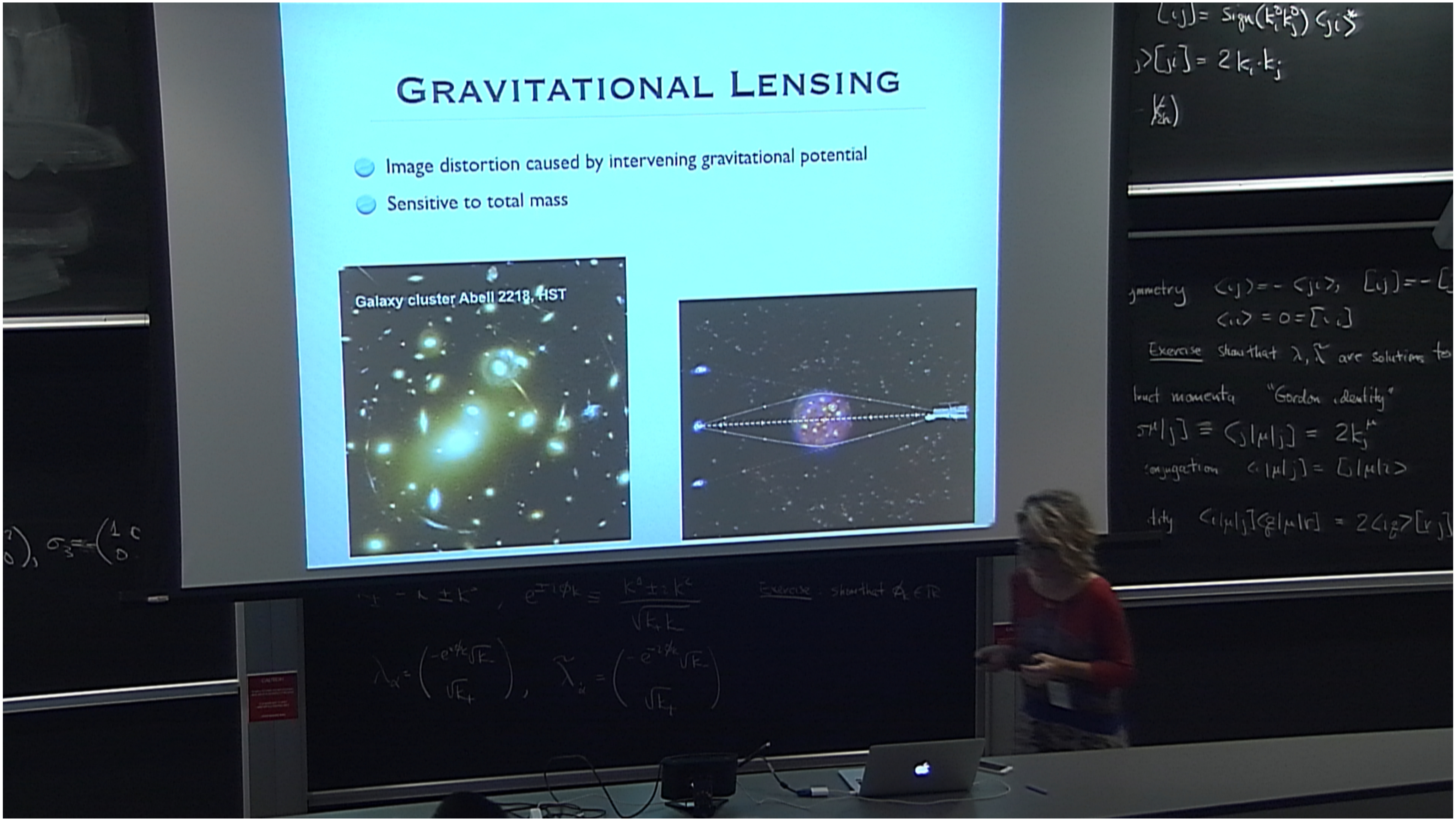
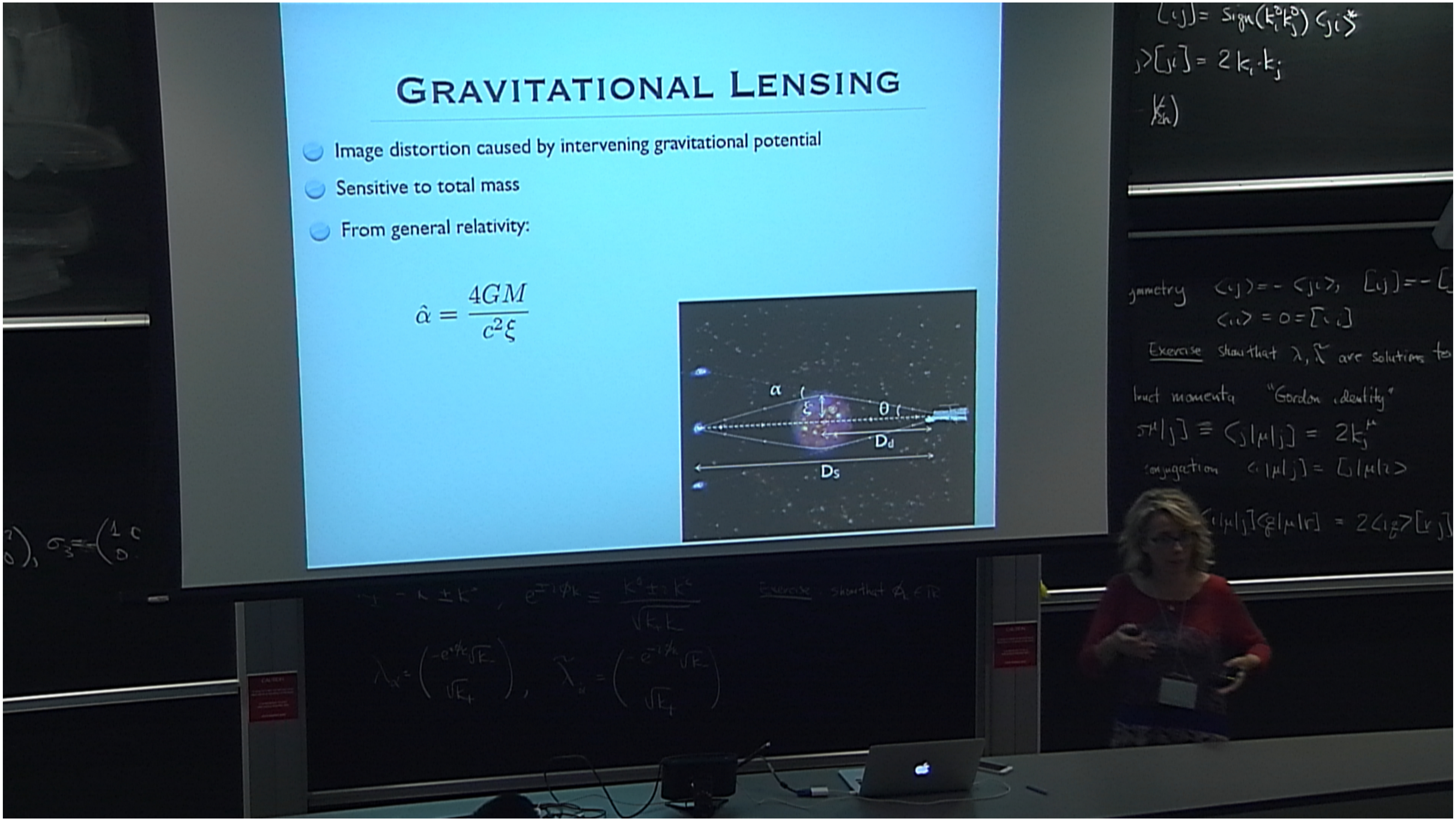
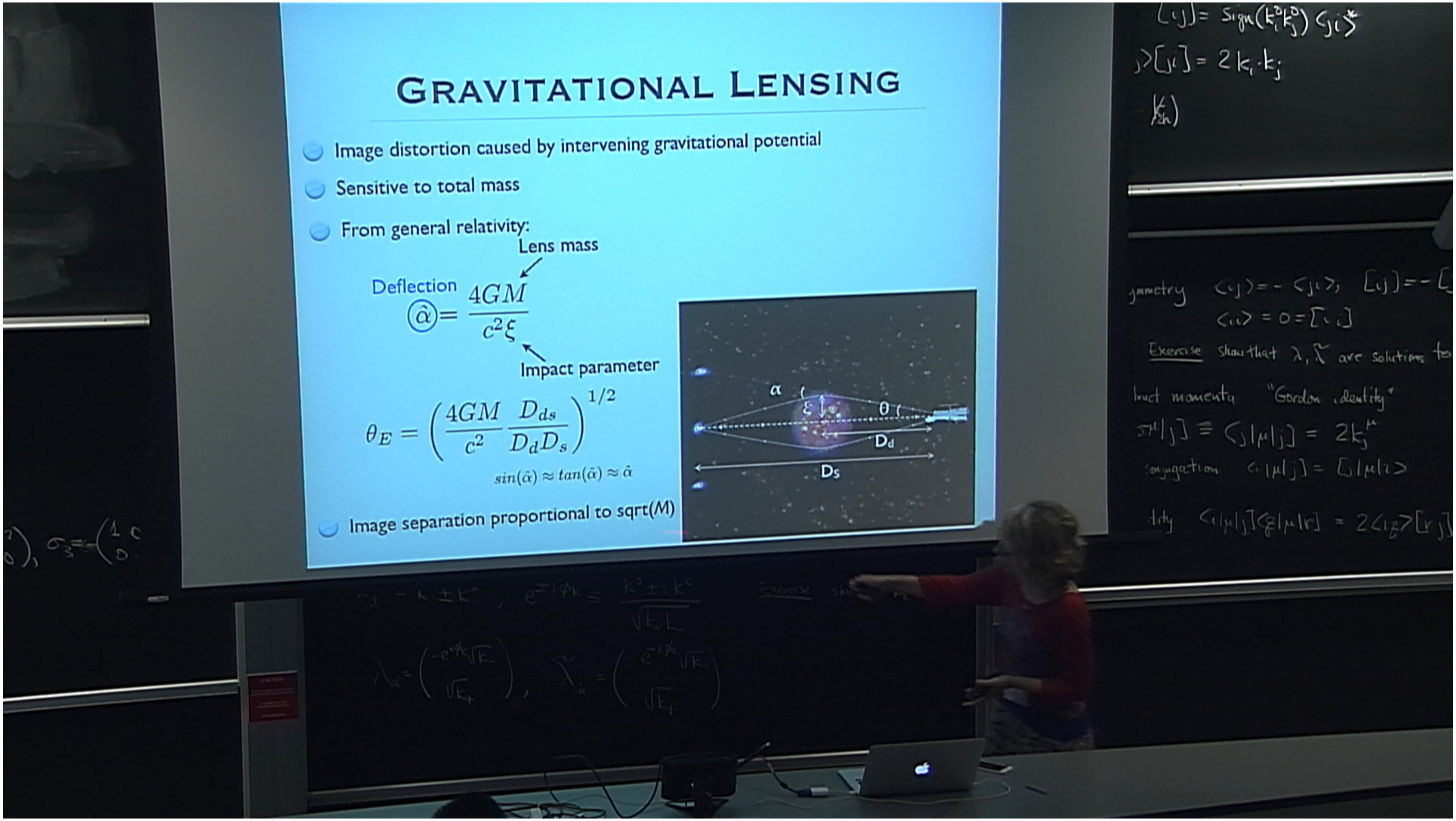


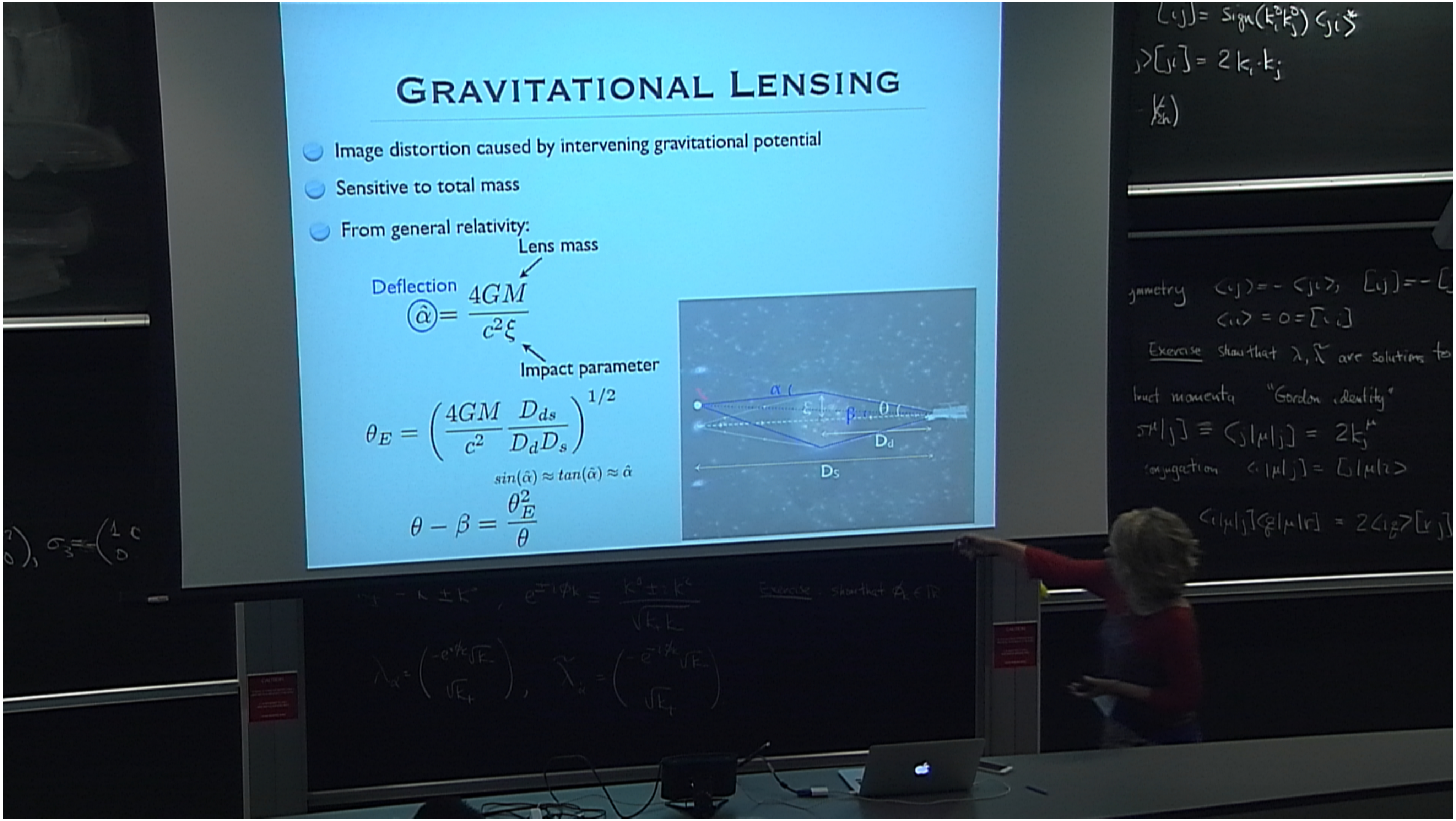


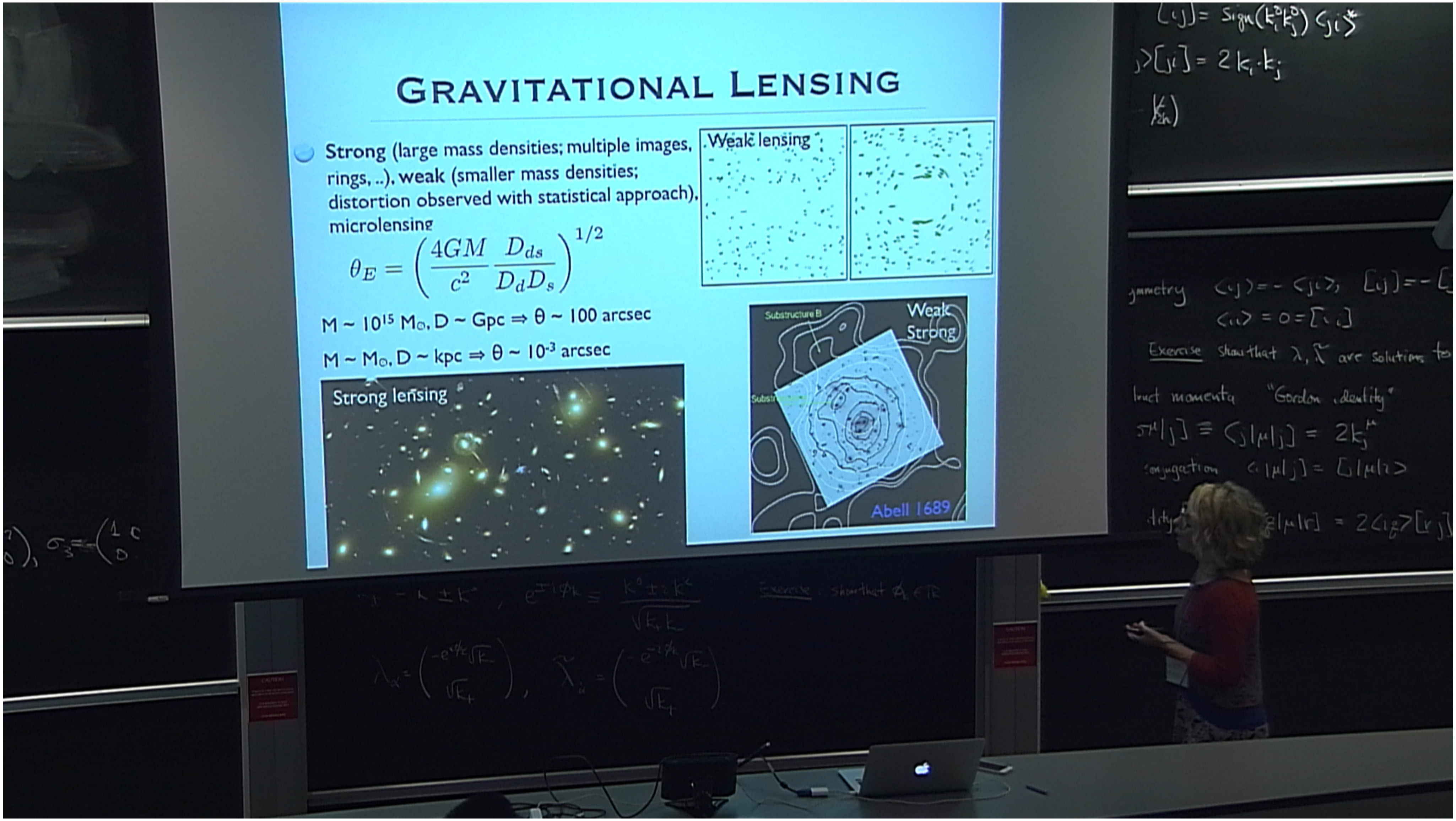

GRAVITATIONAL LENSING
Image distortion caused by intervening gravitational potential
Sensitive to total mass
Galaxy cluster Abell 2218, HST

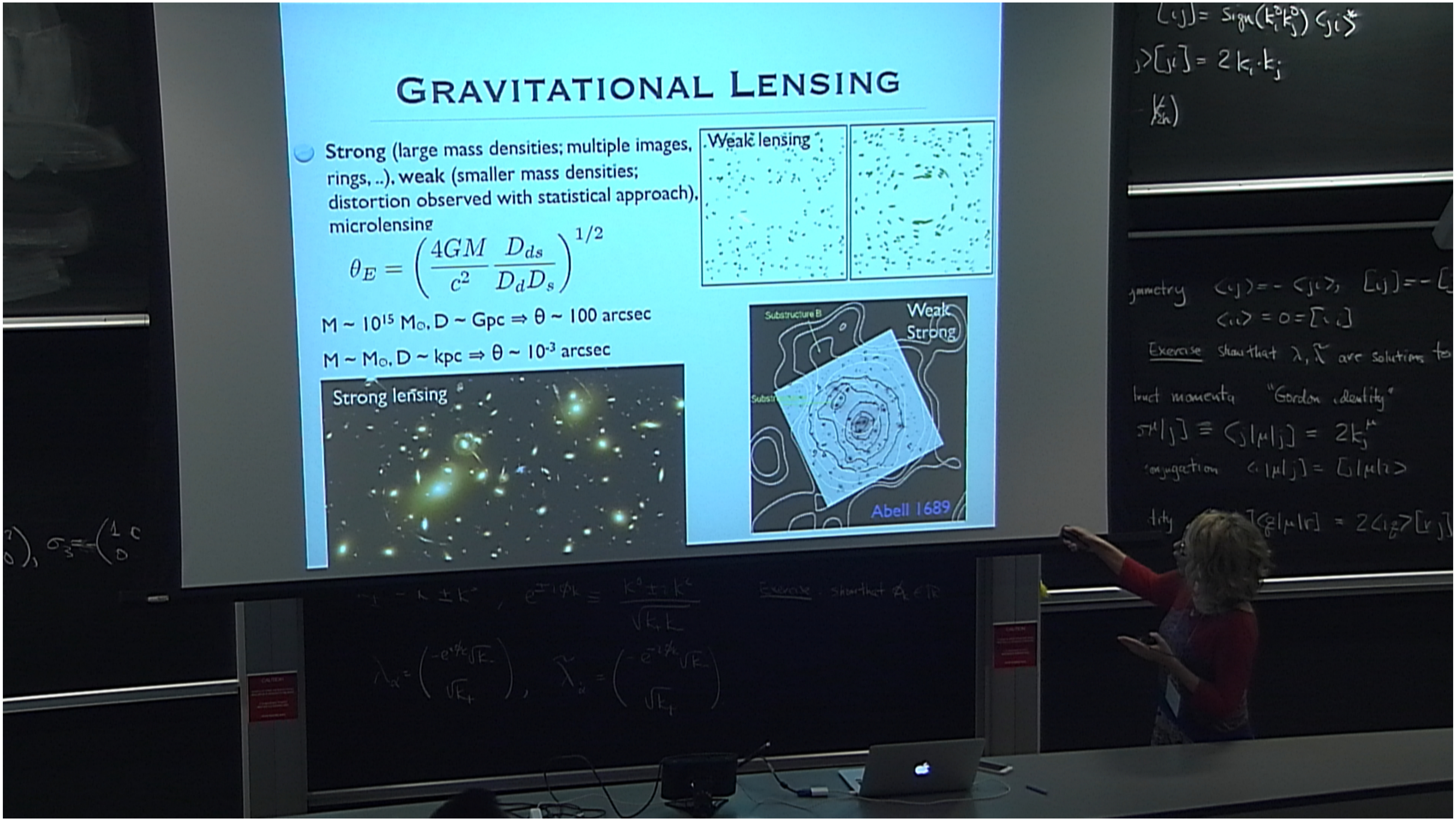

GRAVITATIONAL LENSING
Image distortion caused by intervening gravitational potential
Sensitive to total mass
From general relativity:
$\hat{\alpha} = \frac{4GM}{c^2\xi}$
α
ξ
θ
D_d
D_S

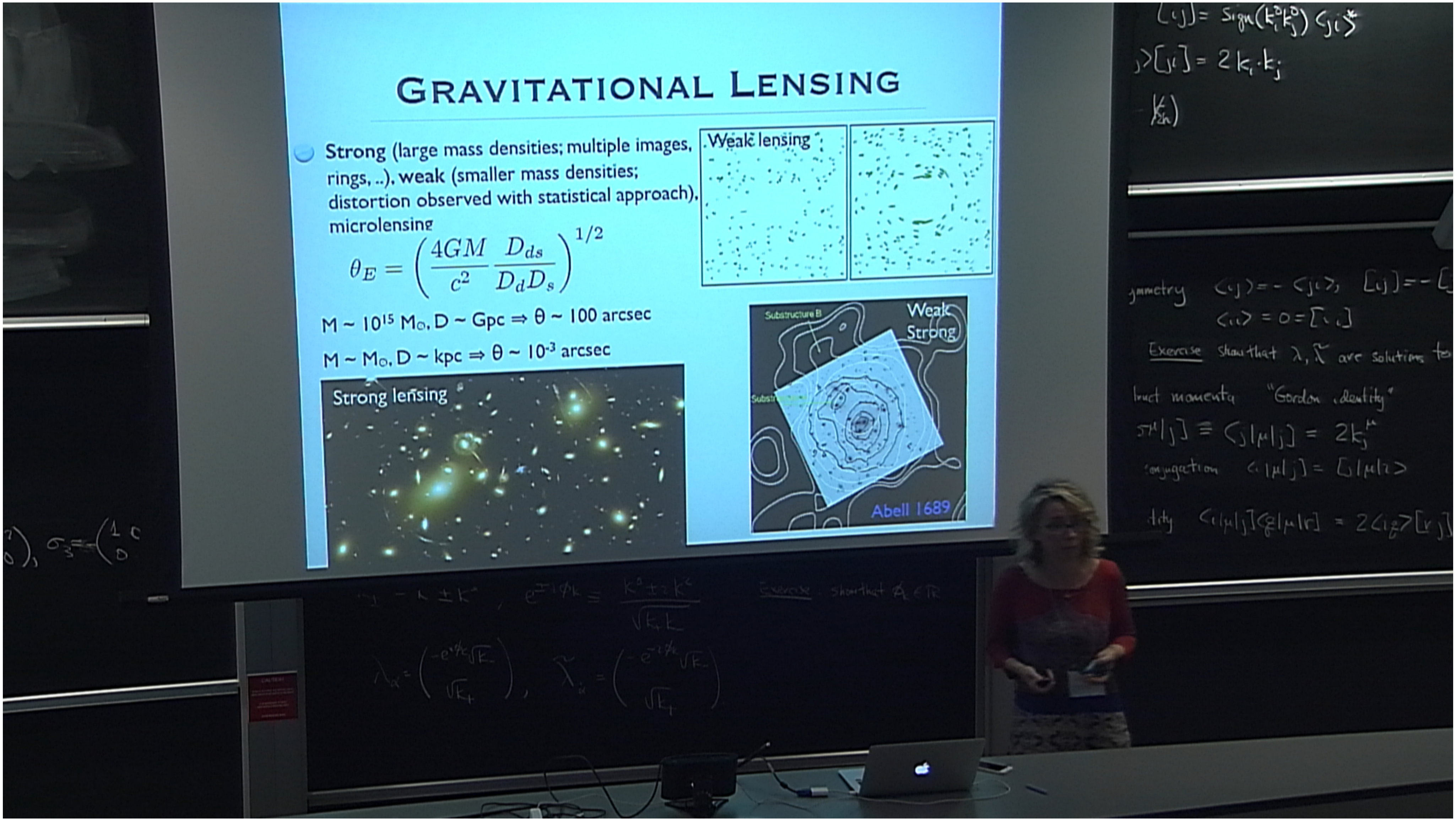


GRAVITATIONAL LENSING
Image distortion caused by intervening gravitational potential
Sensitive to total mass
From general relativity:
Lens mass
Deflection
$\hat{\alpha} = \frac{4GM}{c^2 \xi}$
Impact parameter
$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$
$sin(\hat{\alpha}) \approx tan(\hat{\alpha}) \approx \hat{\alpha}$
Image separation proportional to sqrt(M)
α
ξ
θ
Dd
Ds


Gravitational Lensing
Image distortion caused by intervening gravitational potential
Sensitive to total mass
From general relativity:
Lens mass
Deflection
$\hat{\alpha} = \frac{4GM}{c^2 \xi}$
Impact parameter
$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$
$sin(\hat{\alpha}) \approx tan(\hat{\alpha}) \approx \hat{\alpha}$
$\theta - \beta = \frac{\theta_E^2}{\theta}$
α
ξ
β
θ
Dd
Ds


GRAVITATIONAL LENSING
Strong (large mass densities; multiple images, rings, ..), weak (smaller mass densities; distortion observed with statistical approach), microlensing
$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$
$M \sim 10^{15} M_\odot$, $D \sim$ Gpc $\Rightarrow \theta \sim 100$ arcsec
$M \sim M_\odot$, $D \sim$ kpc $\Rightarrow \theta \sim 10^{-3}$ arcsec
Weak lensing
Strong lensing
Weak
Strong
Abell 1689


GRAVITATIONAL LENSING
Strong (large mass densities; multiple images, rings, ..), weak (smaller mass densities; distortion observed with statistical approach), microlensing
$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$
M ~ 10^{15} M☉, D ~ Gpc ⇒ θ ~ 100 arcsec
M ~ M☉, D ~ kpc ⇒ θ ~ 10^{-3} arcsec
Weak lensing
Strong lensing
Substructure B
Weak
Strong
Abell 1689



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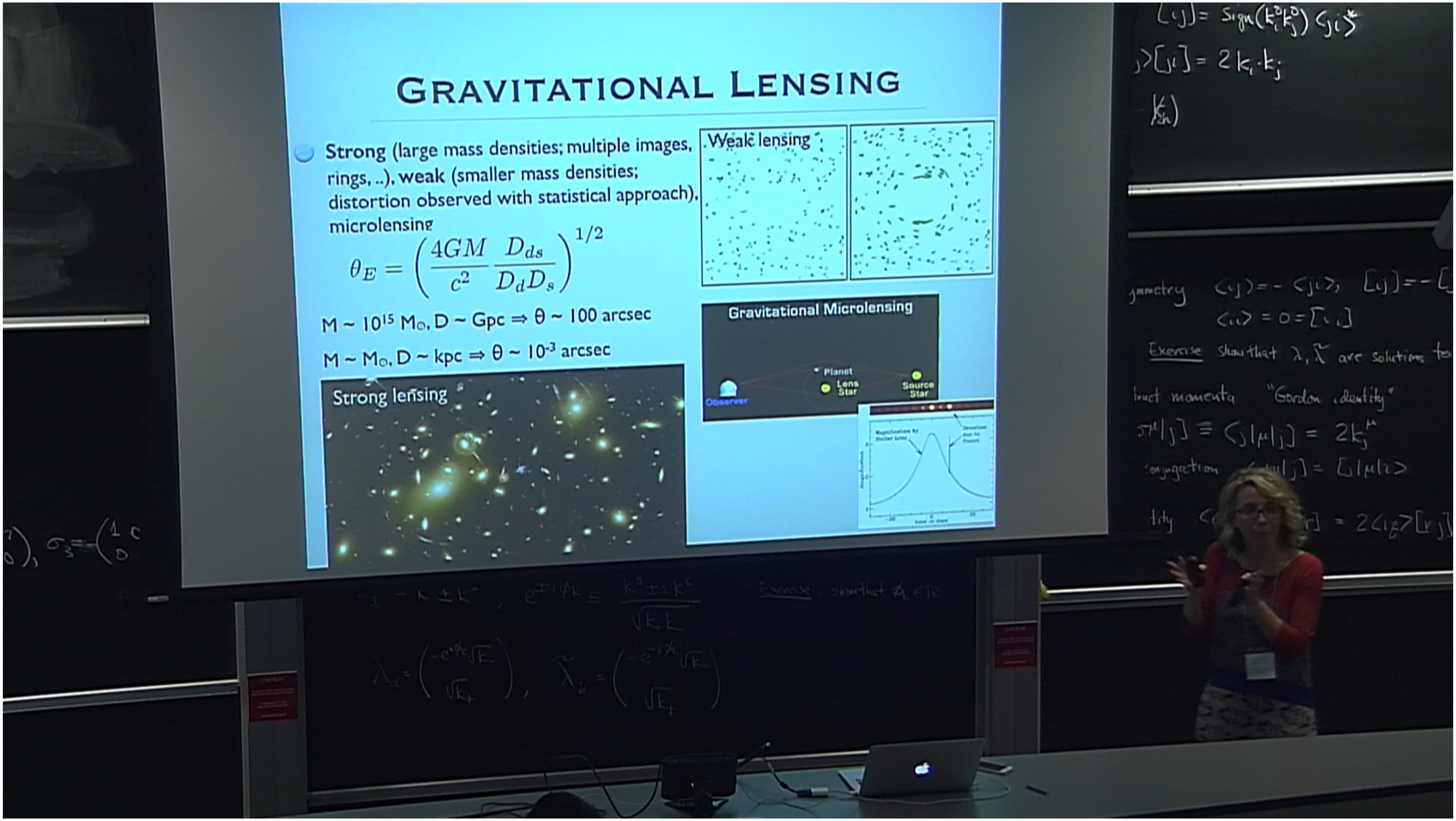
Weak lensing
Strong lensing
Substructure B
Weak
Strong
Abell 1689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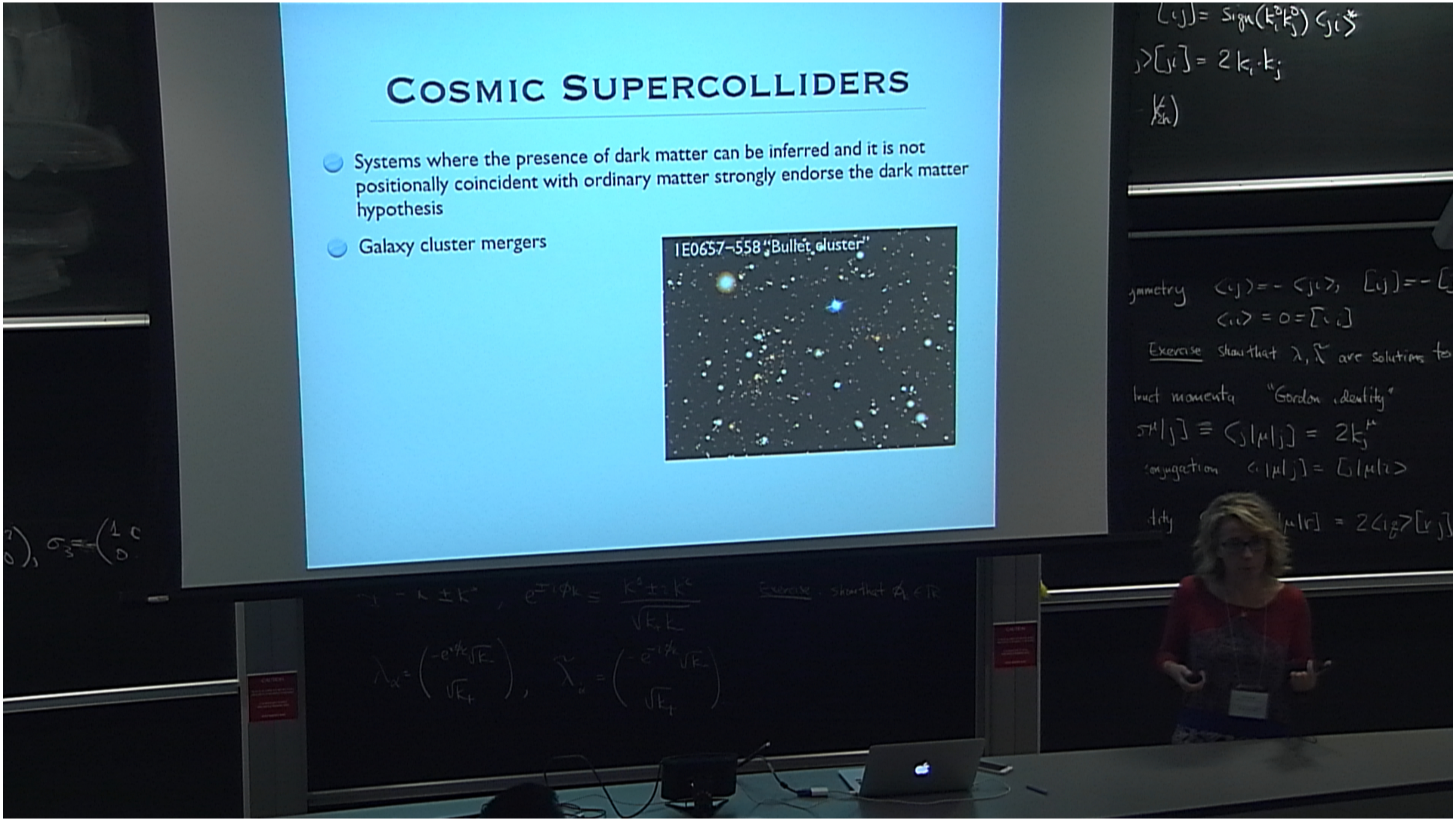
M ~ 10^{15} M☉, D ~ Gpc ⇒ θ ~ 100 arcsec
M ~ M☉, D ~ kpc ⇒ θ ~ 10^{-3} arcsec
Weak lensing
Strong lensing
Gravitational Microlensing
Planet
Lens Star
Source Star
Observer

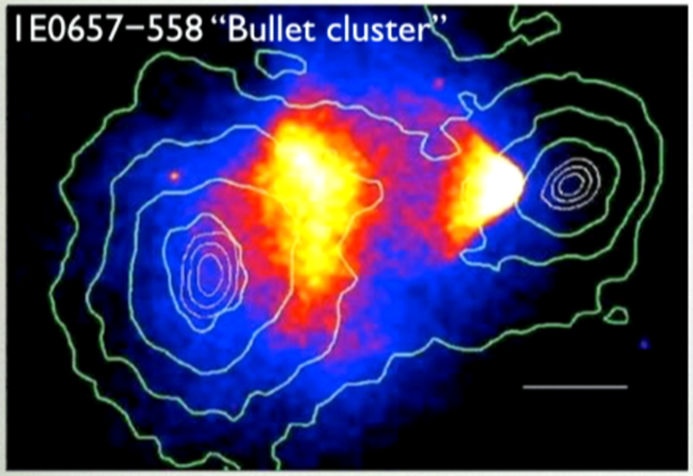

Cosmic Supercolliders
Systems where the presence of dark matter can be inferred and it is not positionally coincident with ordinary matter strongly endorse the dark matter hypothesis
Galaxy cluster mergers
1E0657-558 "Bullet cluster"

Cosmic Supercolliders

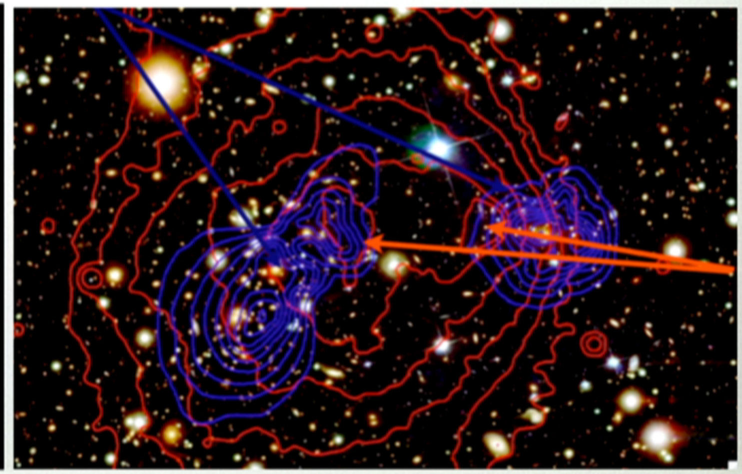
- Systems where the presence of dark matter can be inferred and it is not positionally coincident with ordinary matter strongly endorse the dark matter hypothesis
- Galaxy cluster mergers

Cosmic Supercolliders

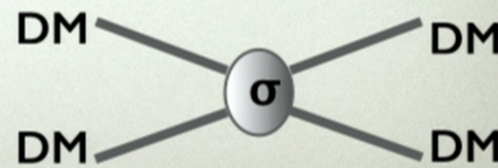
Weak lensing — Clowe et al 2006



Weak and strong lensing — Bradac et al 2006

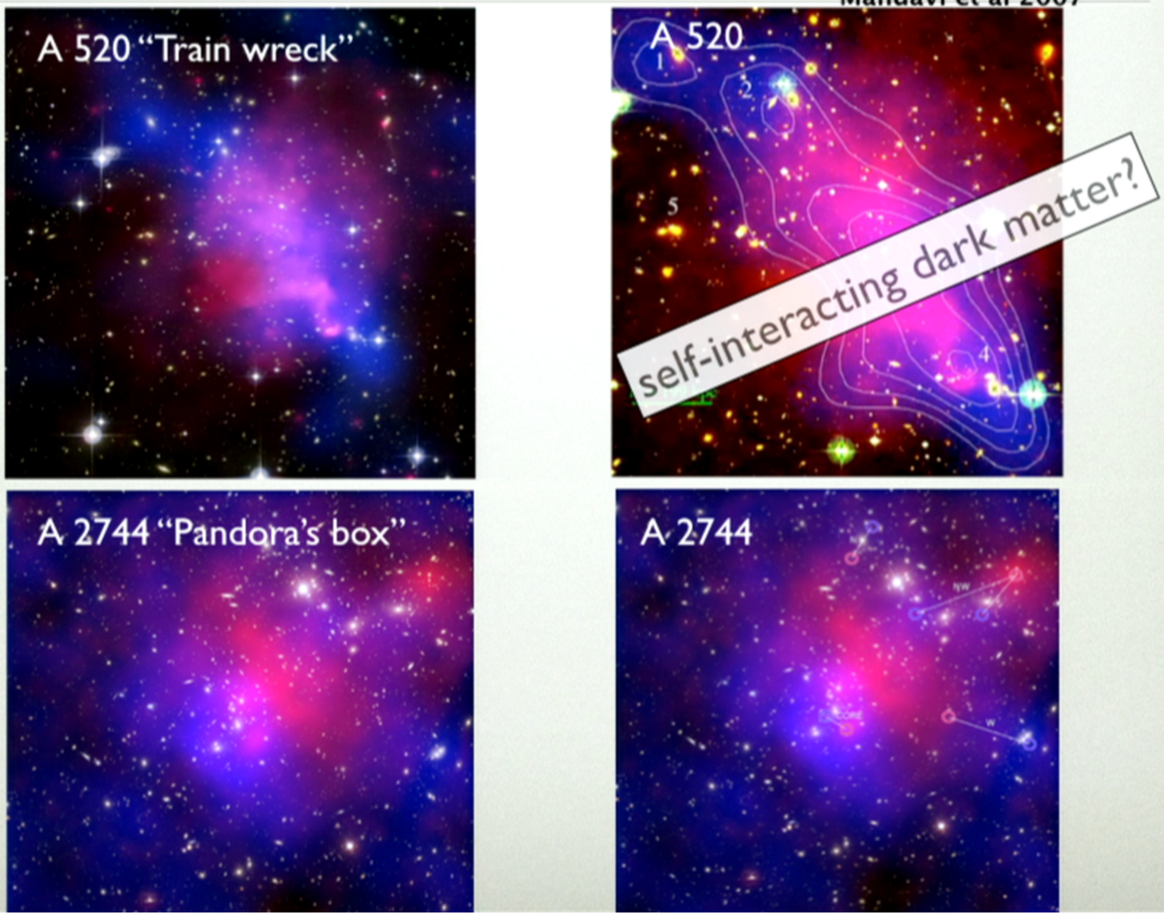


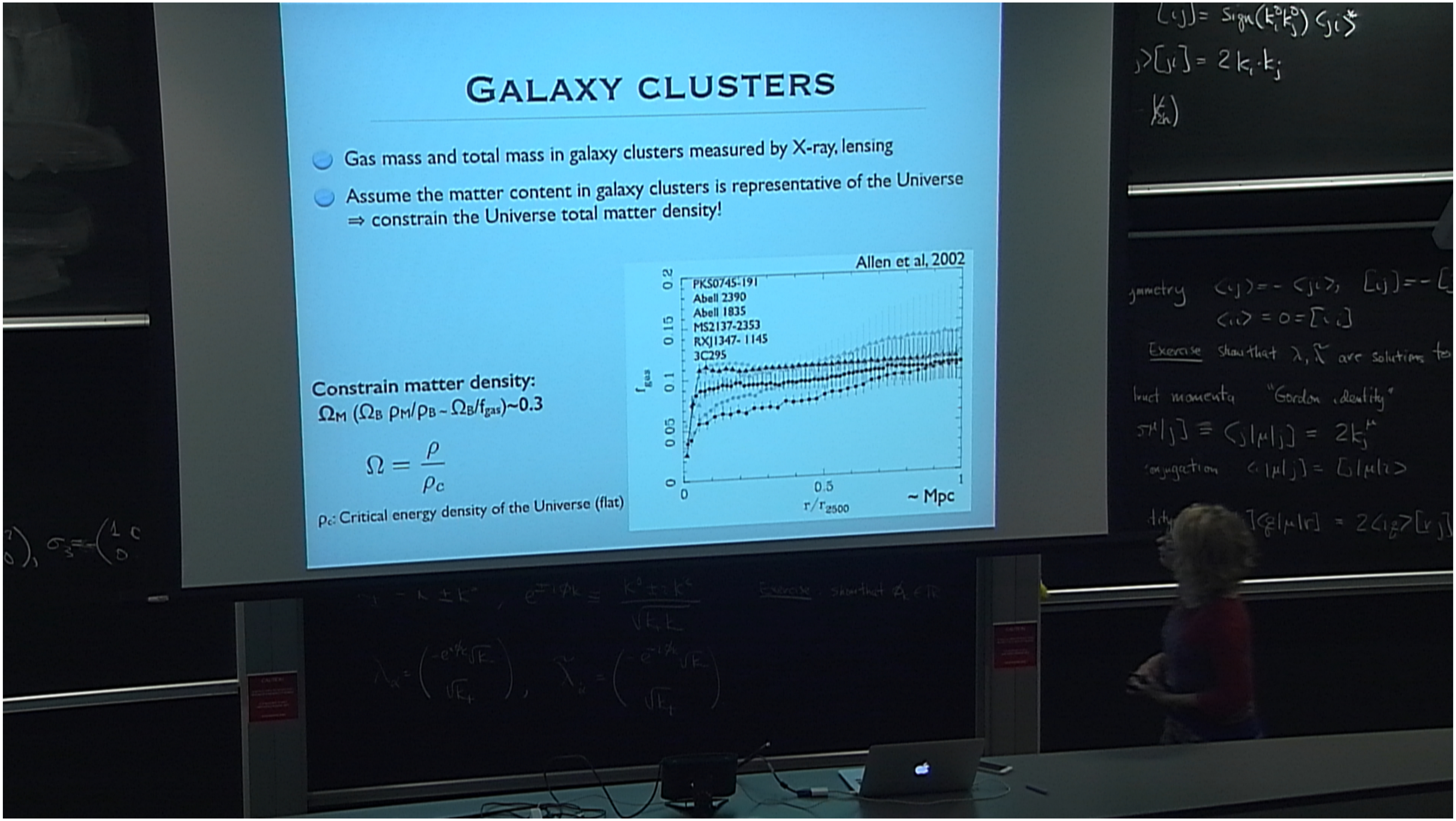
(*) Constraints on the self-interaction cross section:
$\sigma/m < 1.3$ barn/GeV (Randall et al 2008)

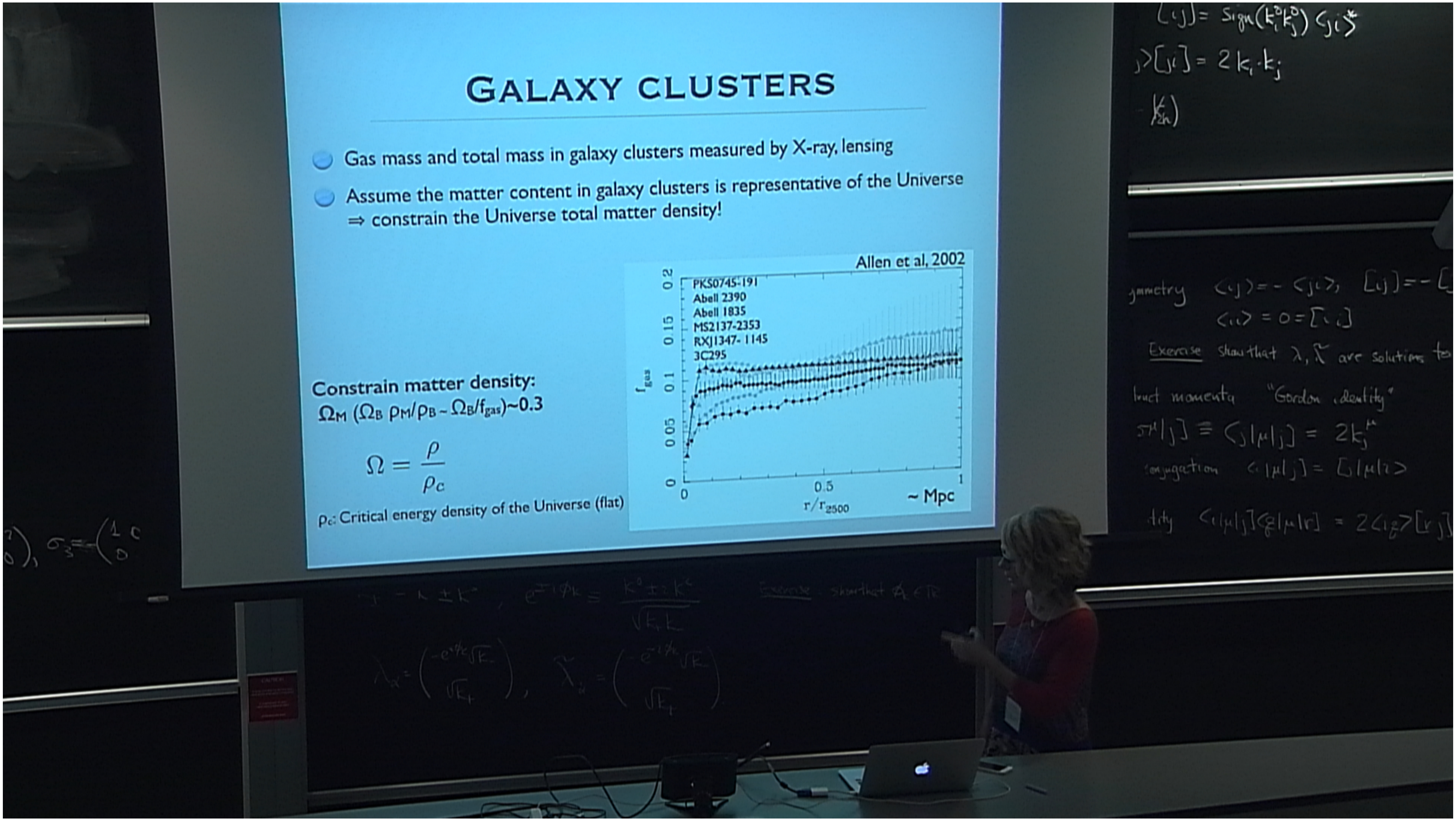


MORE COSMIC SUPERCOLLIDERS

Mahdavi et al 2007




Galaxy clusters
Gas mass and total mass in galaxy clusters measured by X-ray, lensing
Assume the matter content in galaxy clusters is representative of the Universe
⇒ constrain the Universe total matter density!
Allen et al, 2002
PKS0745-191
Abell 2390
Abell 1835
MS2137-2353
RXJ1347-1145
3C295
f_gas
r/r_2500
~ Mpc
Constrain matter density:
ΩM (ΩB ρM/ρB ~ ΩB/fgas)~0.3
Ω = ρ/ρc
ρc: Critical energy density of the Universe (flat)



Galaxy clusters
Gas mass and total mass in galaxy clusters measured by X-ray, lensing
Assume the matter content in galaxy clusters is representative of the Universe
⇒ constrain the Universe total matter density!
Allen et al, 2002
PKS0745-191
Abell 2390
Abell 1835
MS2137-2353
RXJ1347-1145
3C295
f_{gas}
r/r_{2500}
~ Mpc
Constrain matter density:
Ω_M (Ω_B $\rho_M/\rho_B \sim \Omega_B/f_{gas}$)~0.3
$\Omega = \frac{\rho}{\rho_c}$
ρ_c: Critical energy density of the Universe (flat)

Big Bang Nucleosynthesis

- As the Universe cools down (~100s sec after Big Bang, ~ MeV), light elements form (deuterium, helium, lithium). E.g.:

$$p + n \to D + \gamma$$

- (Much longer timescales for heavier elements to form, e.g. C, N, O)

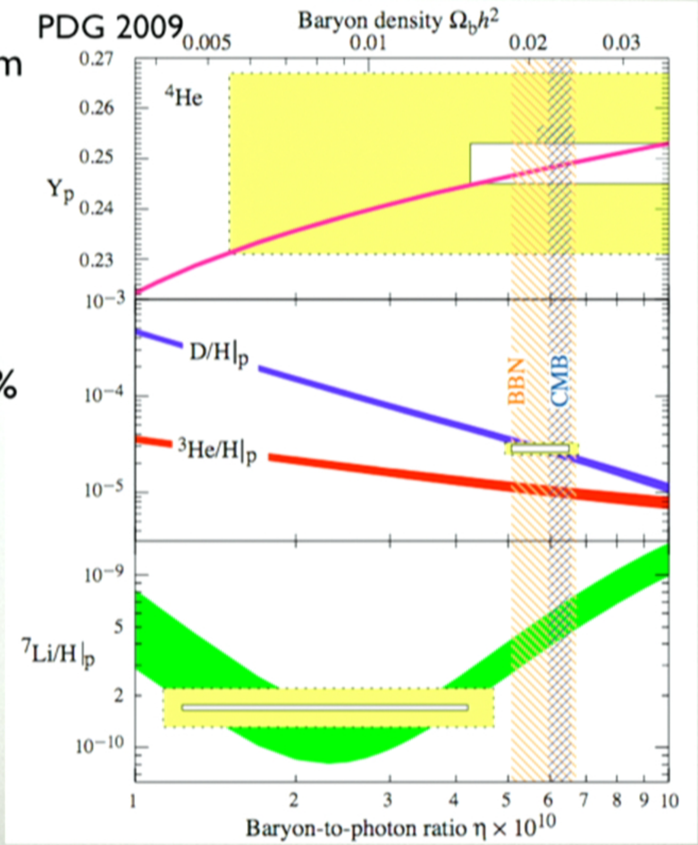
Constrains baryon density: Ω_B~ few %

$$\Omega = \frac{\rho}{\rho_c}$$

ρ_c: Critical energy density of the Universe (flat)

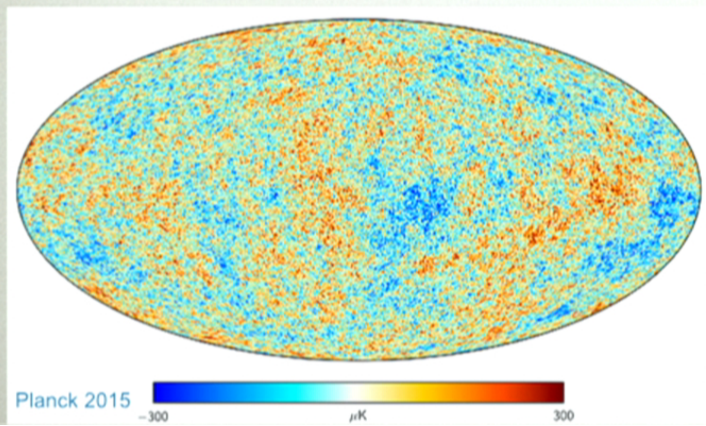
➡ Most matter in the Universe is non-baryonic

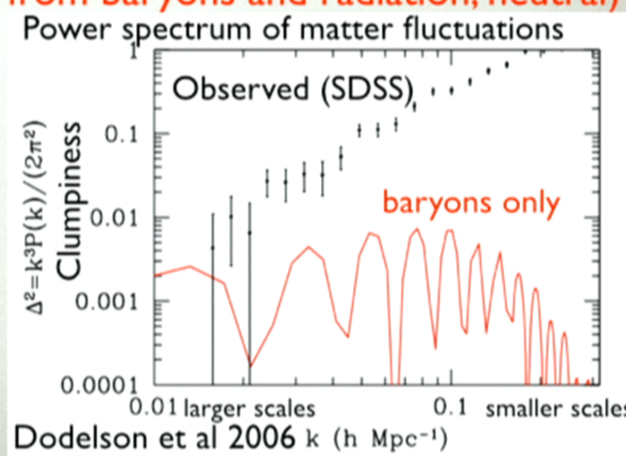
- Remarkable agreement with CMB estimate of baryon density (more next)



Cosmic Microwave Background

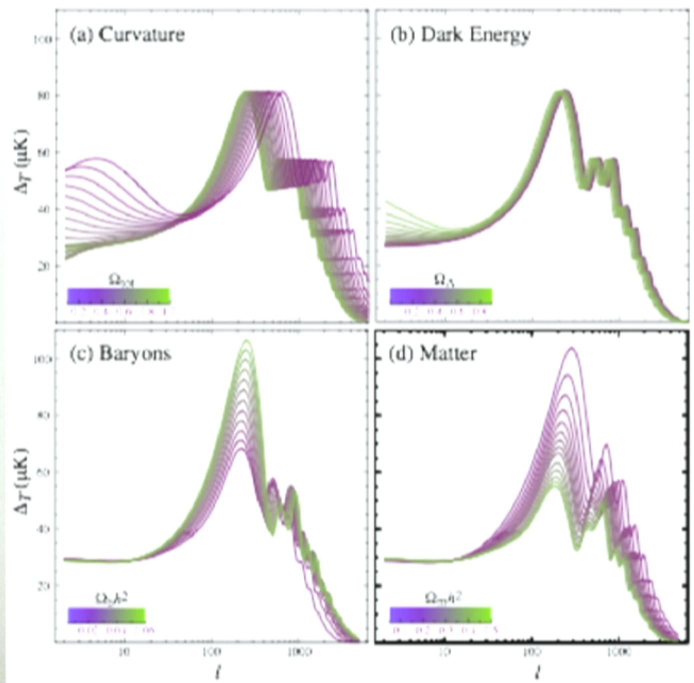
- Relic of a time in the early Universe when matter and radiation decoupled (protons and electron form neutral hydrogen and become transparent to photons, ~100,000s years after Big Bang, ~ eV)
- Universe was isotropic and homogeneous at large scales
- Very small temperature fluctuations, too small to evolve into structure observed today $T = 2.725$ K, $\Delta T \sim 200\ \mu K$ ➡ Require additional matter to start forming structure earlier (decoupled from baryons and radiation, neutral)





Cosmic Microwave Background

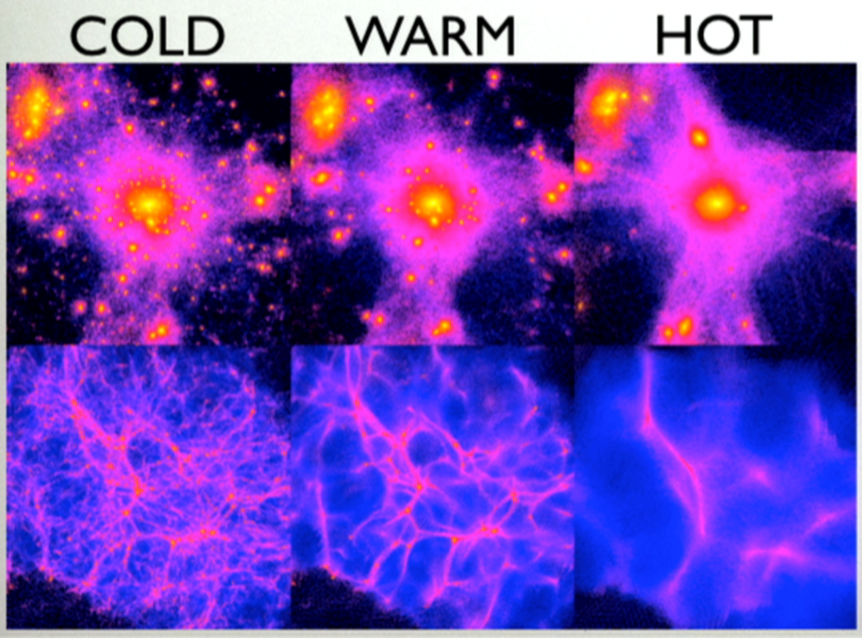
- The CMB angular power spectrum depends on several parameters, including Ω_B, Ω_M, Ω_Λ (Ω_Λ is the vacuum density)
- Matching location and heights of the peaks constrains these parameters and geometry of the Universe (flat, $\Omega_{total}=1$)



Hu et al (2002)

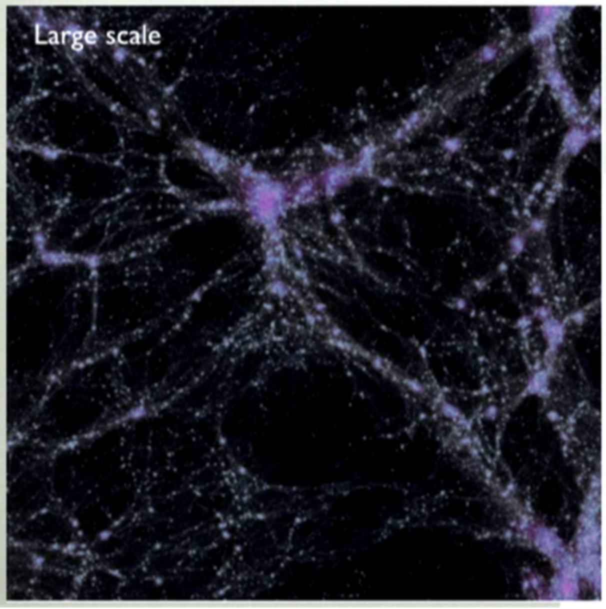
CDM

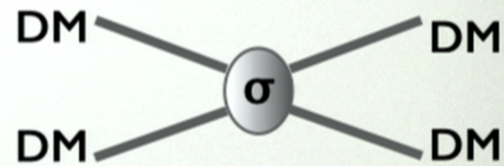
- CDM (Cold Dark Matter), i.e. non relativistic, consistent with observations
- Hot dark matter excluded (smooths out structure)



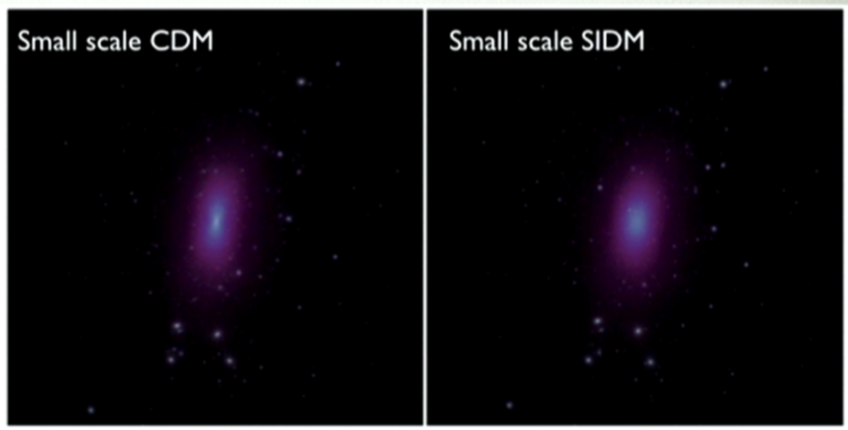
CDM

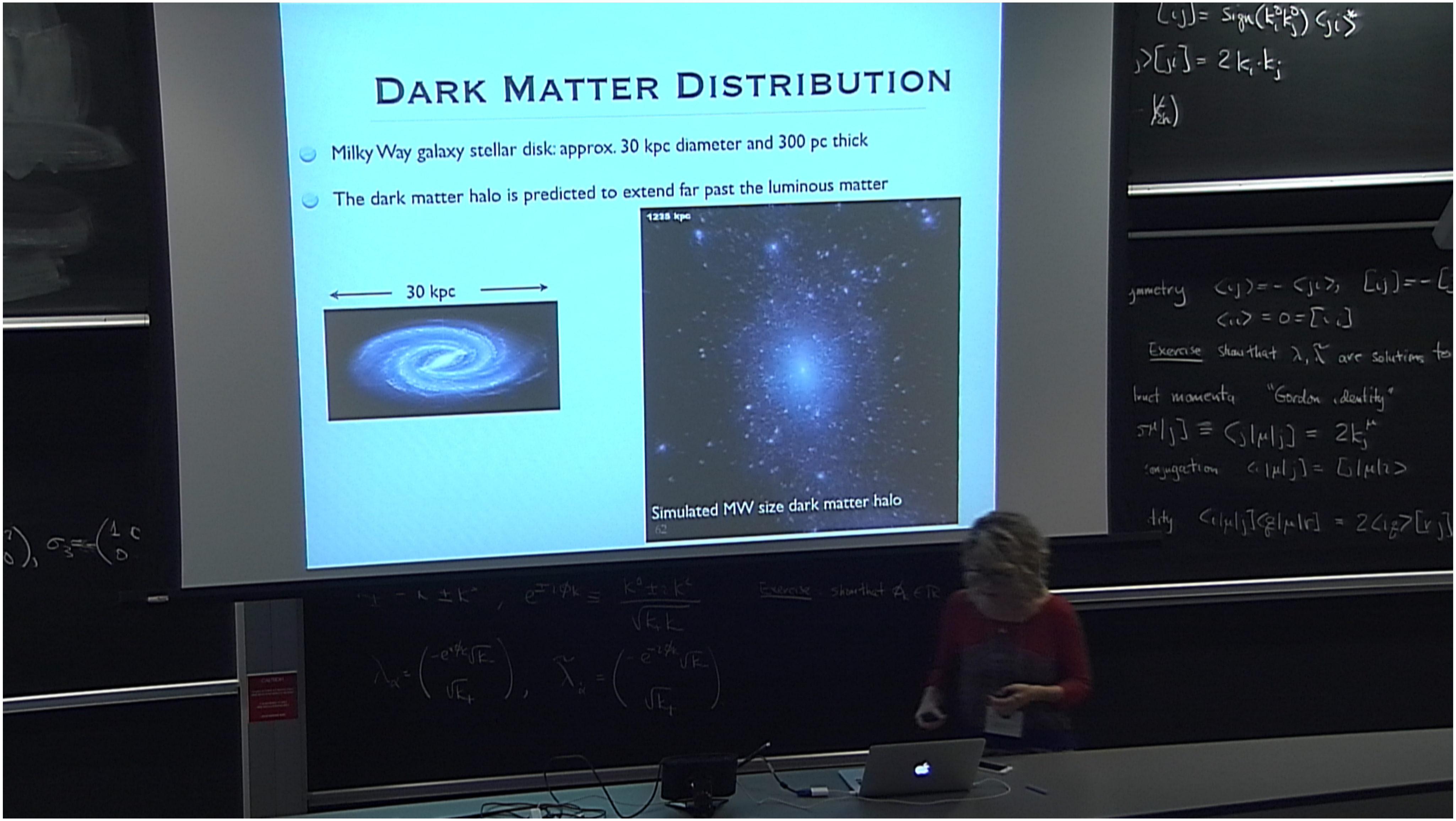
- CDM (Cold Dark Matter), i.e. non relativistic, consistent with observations
- Hot dark matter excluded (smooths out structure)
- Self-interactions would also smooth out dense DM regions, though wouldn't significantly affect large scale structure; consistent with observation





Rocha et al. 2012

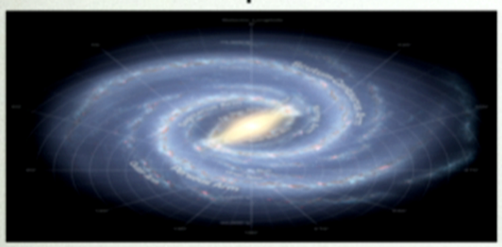


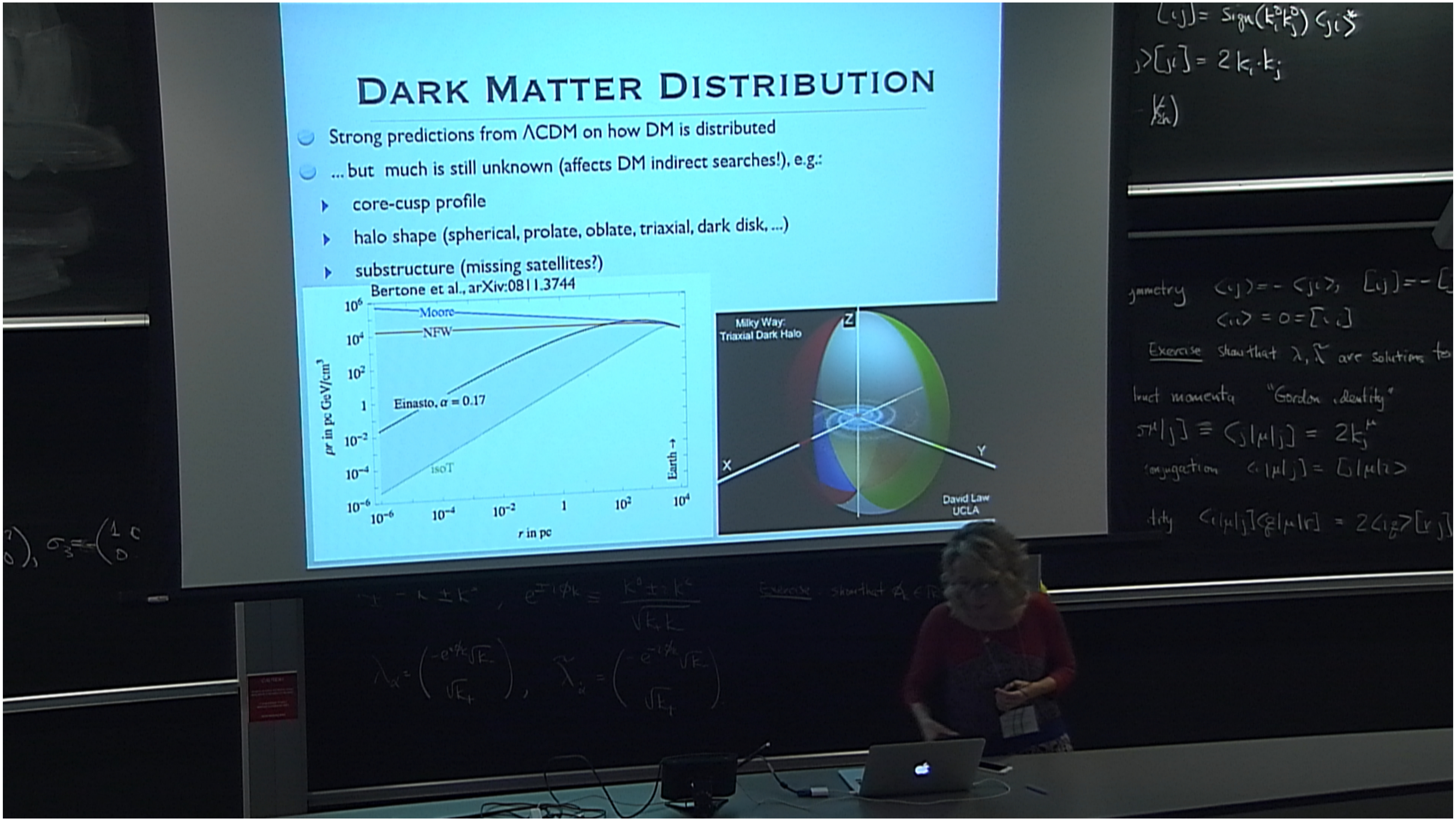

DARK MATTER DISTRIBUTION
Milky Way galaxy stellar disk: approx. 30 kpc diameter and 300 pc thick
The dark matter halo is predicted to extend far past the luminous matter
30 kpc
1225 kpc
Simulated MW size dark matter halo

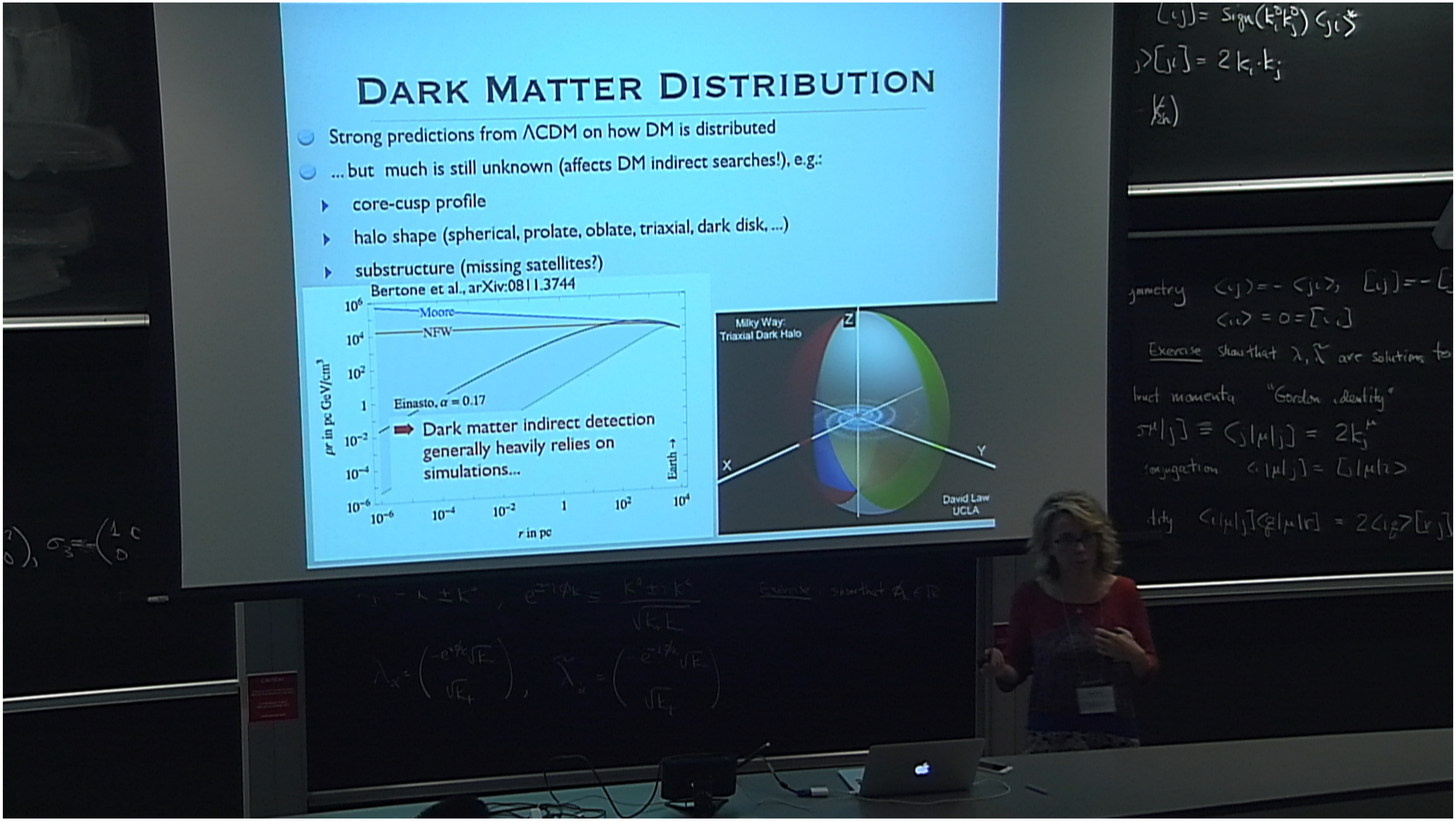
Dark Matter Distribution

- Milky Way galaxy stellar disk: approx. 30 kpc diameter and 300 pc thick
- The dark matter halo is predicted to extend far past the luminous matter

← 30 kpc →




DARK MATTER DISTRIBUTION
Strong predictions from ΛCDM on how DM is distributed
... but much is still unknown (affects DM indirect searches!), e.g.:
core-cusp profile
halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
substructure (missing satellites?)
Bertone et al., arXiv:0811.3744
Moore
NFW
Einasto, α = 0.17
isoT
Earth →
ρr in pc GeV/cm³
r in pc
Milky Way: Triaxial Dark Halo
David Law UCLA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ρ in pc GeV/cm³
r in pc
Earth
Dark matter indirect detection generally heavily relies on simulations...
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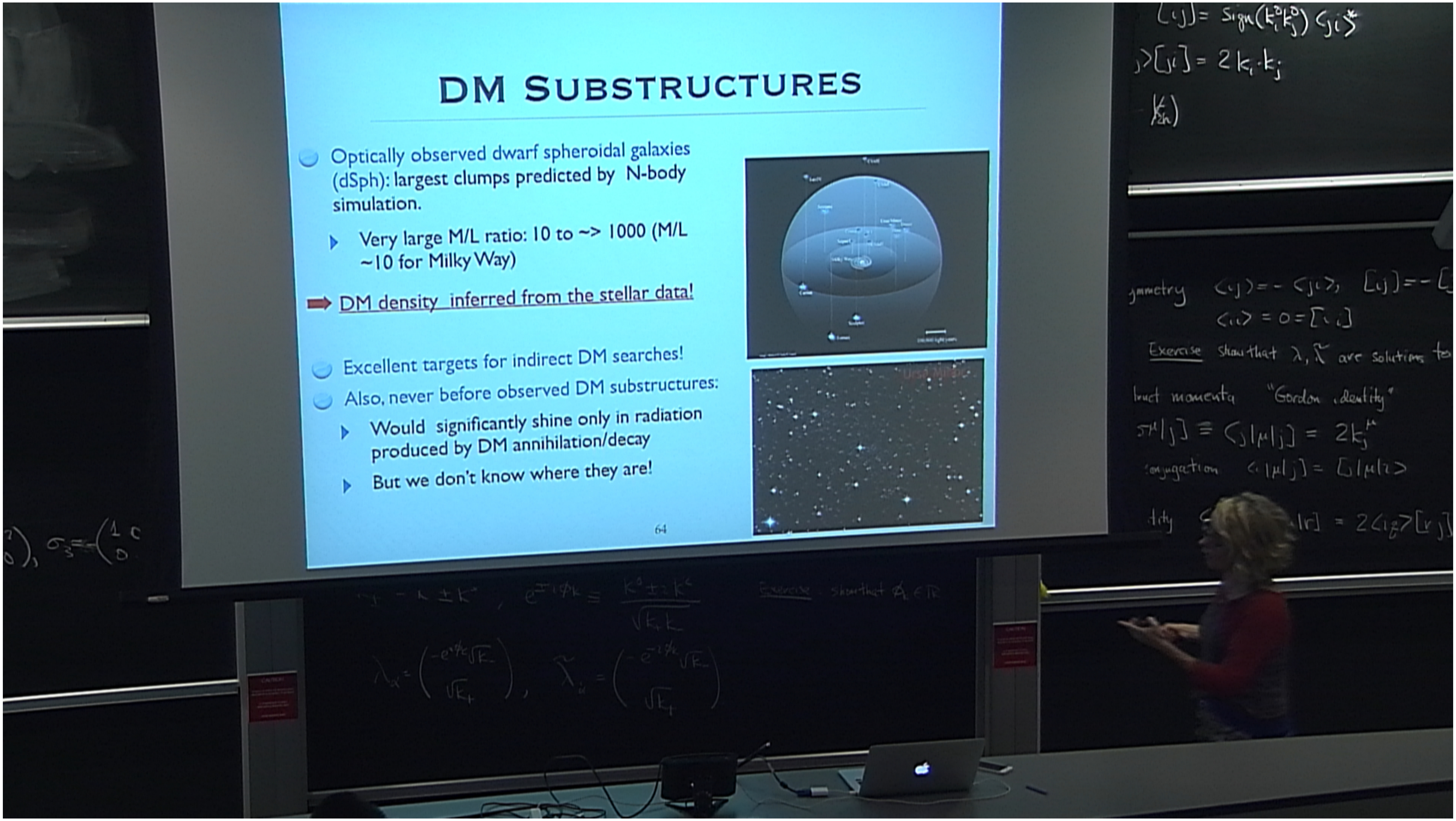
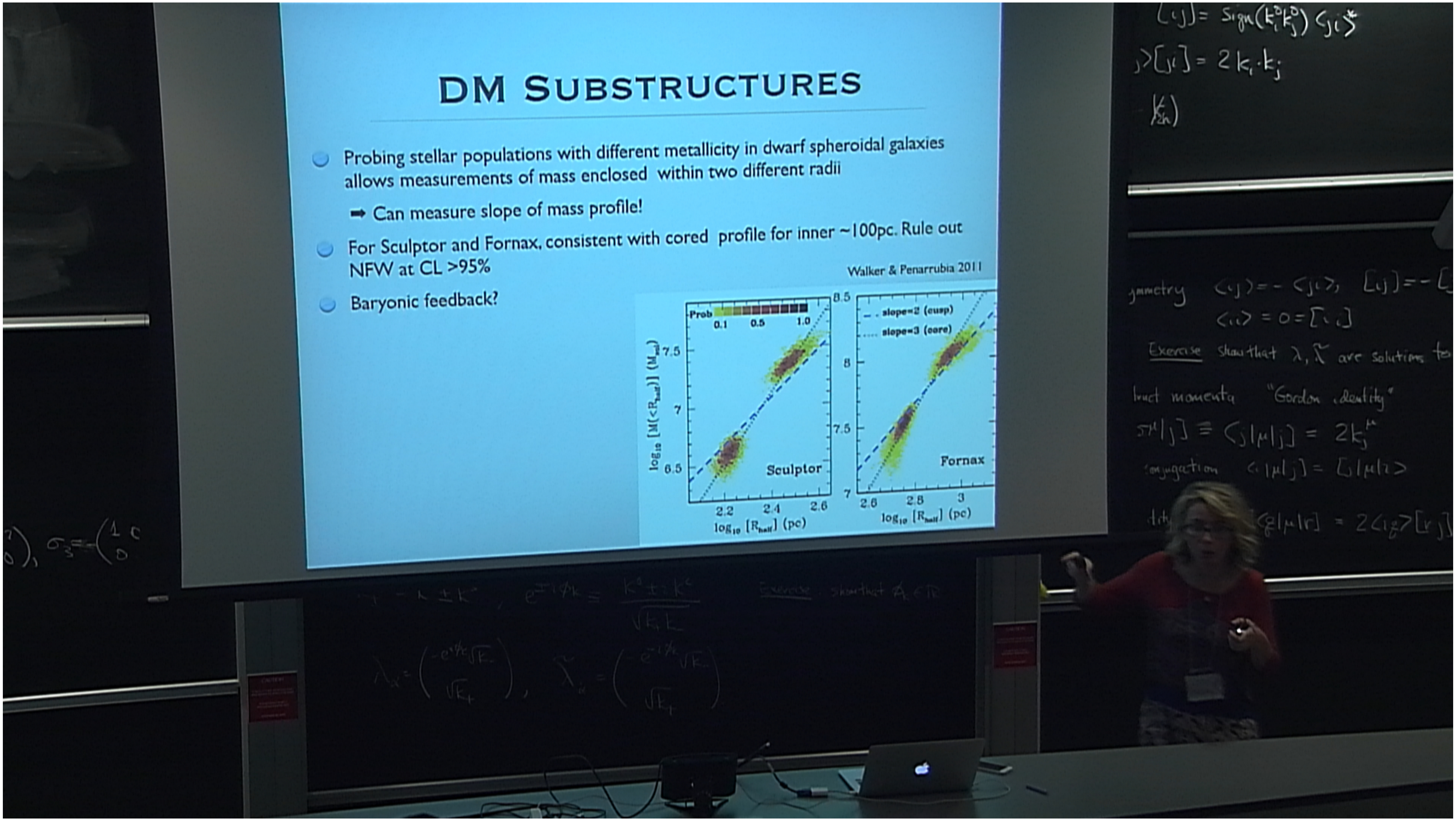
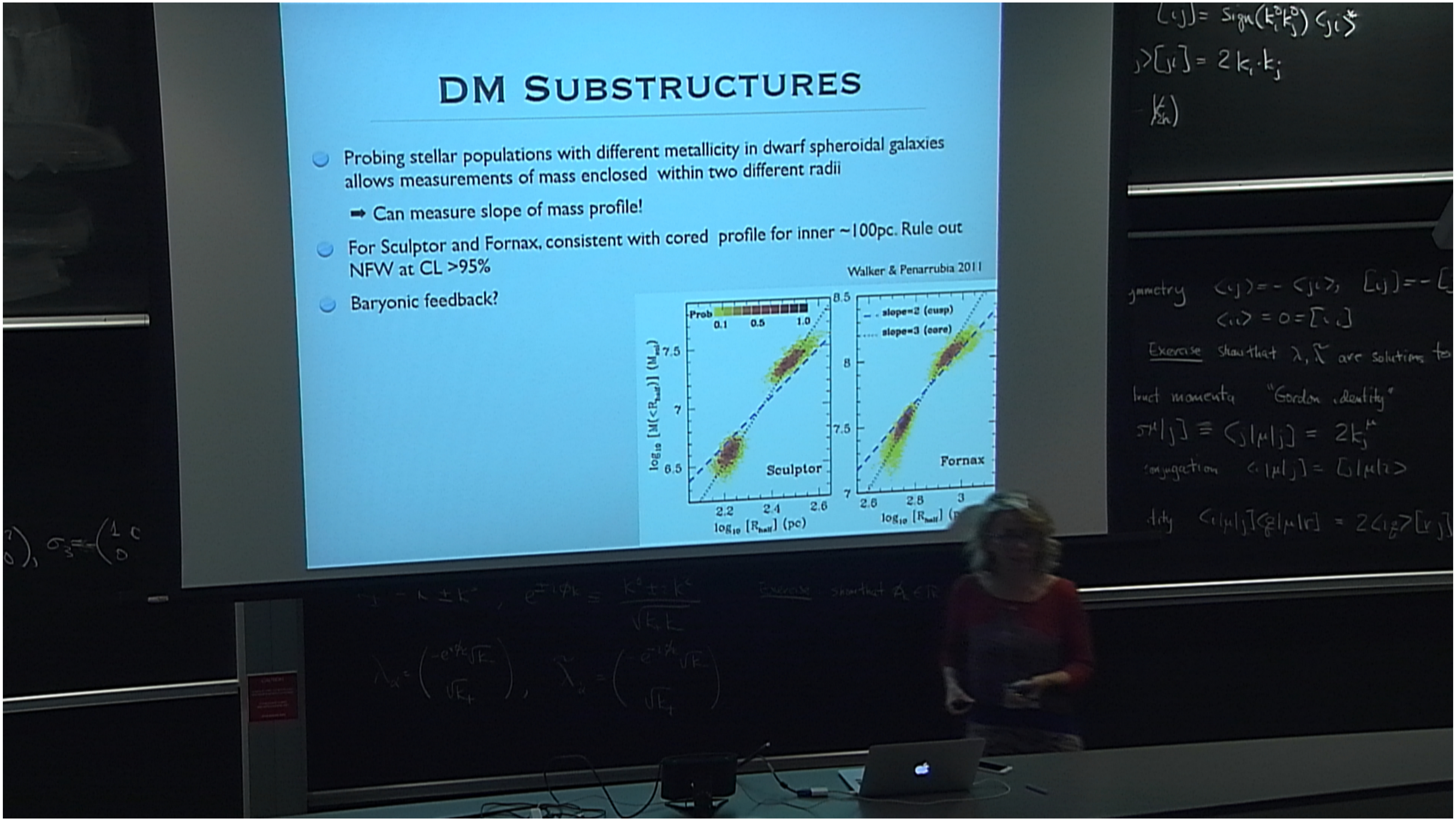
David Law UCLA


DM Substructures
Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
DM density inferred from the stellar data!
Excellent targets for indirect DM searches!
Also, never before observed DM substructures:
Would significantly shine only in radiation produced by DM annihilation/decay
But we don't know where they are!
64


DM SUBSTRUCTURES
Probing stellar populations with different metallicity in dwarf spheroidal galaxies allows measurements of mass enclosed within two different radii
➡ Can measure slope of mass profile!
For Sculptor and Fornax, consistent with cored profile for inner ~100pc. Rule out NFW at CL >95%
Baryonic feedback?
Walker & Penarrubia 2011
Prob
0.1
0.5
1.0
Sculptor
Fornax
slope=2 (cusp)
slope=3 (core)
log10 [M(<Rhalf)] (M⊙)
log10 [Rhalf] (pc)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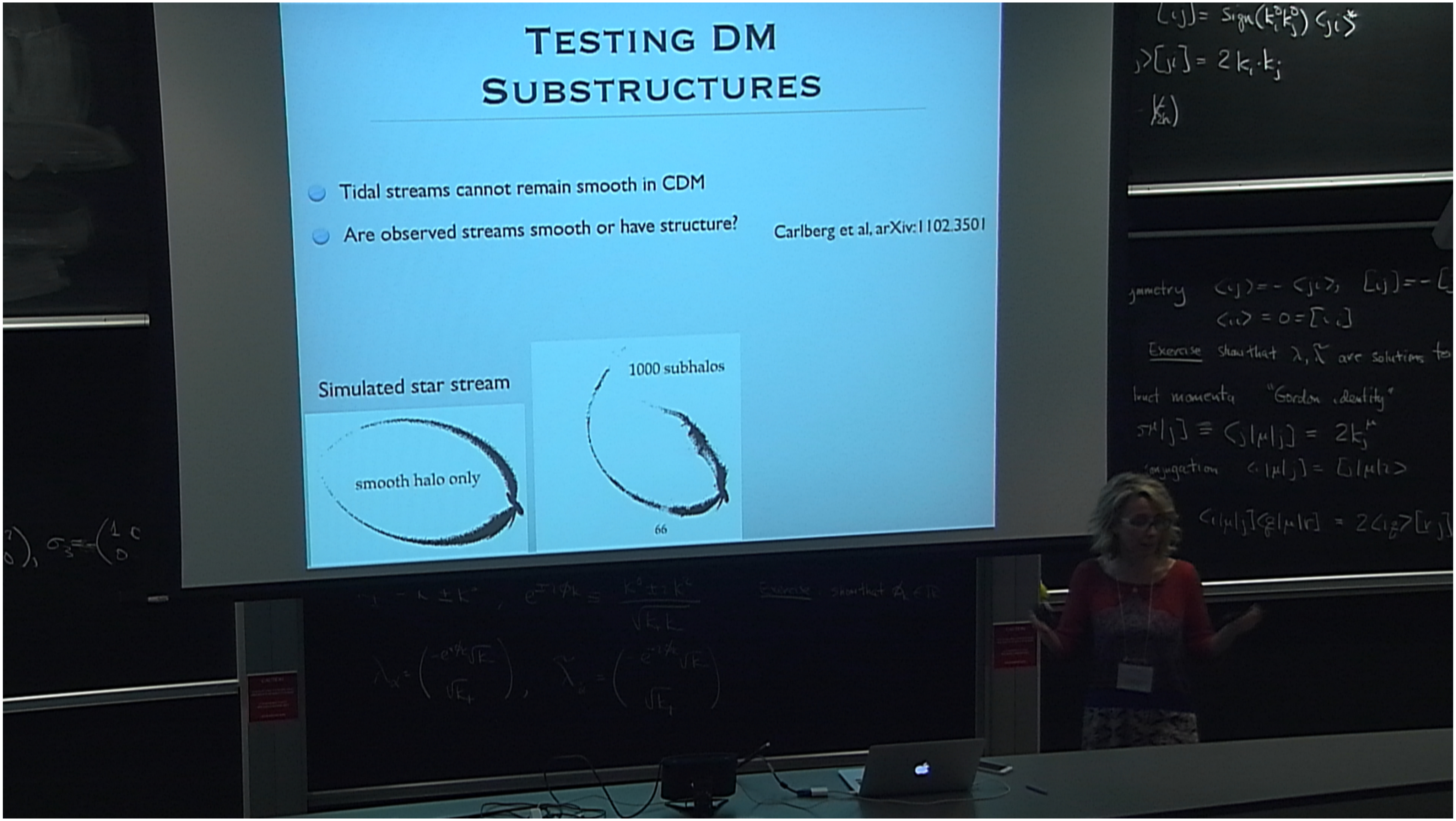
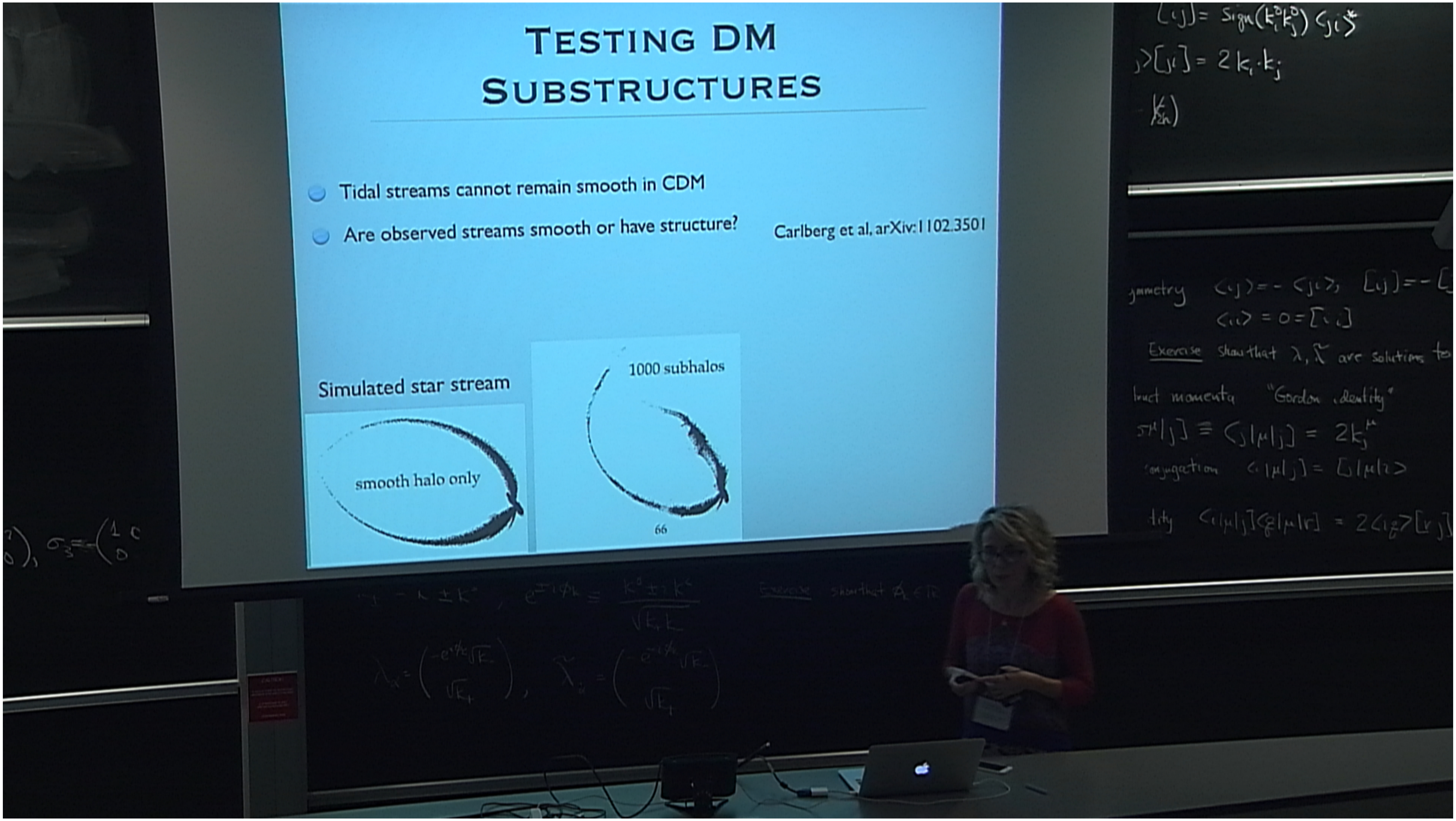

Testing DM
Substructures
Tidal streams cannot remain smooth in CDM
Are observed streams smooth or have structure?
Carlberg et al, arXiv:1102.3501
Simulated star stream
smooth halo only
1000 subhalos
66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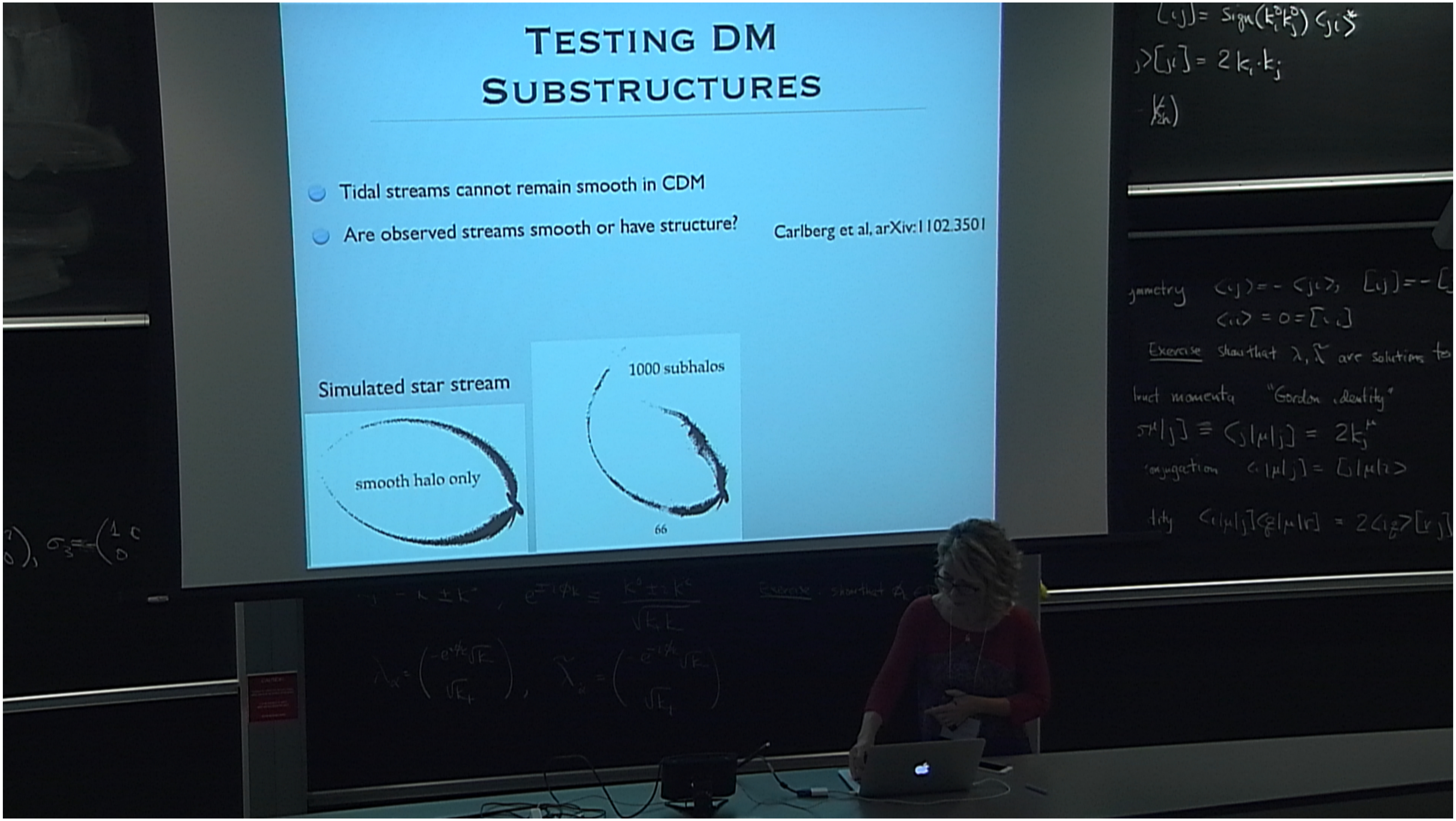
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Tidal streams cannot remain smooth in CDM
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Simulated star stream
smooth halo only
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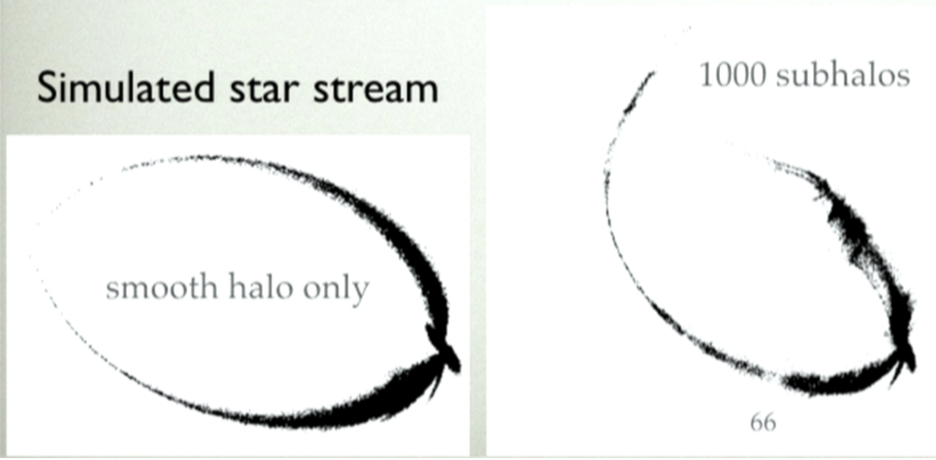
Testing DM Substructures

- Tidal streams cannot remain smooth in CDM
- Are observed streams smooth or have structure?

Measurements seem to be consistent with structure/gaps!

Simulated star stream



Star stream north-west of M31 (Andromeda)

Carlberg et al, arXiv:1102.3501

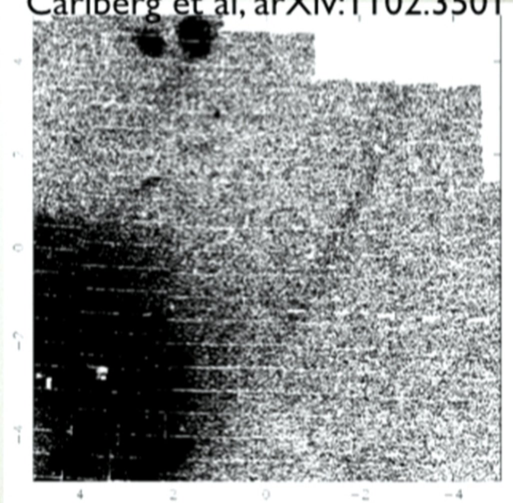
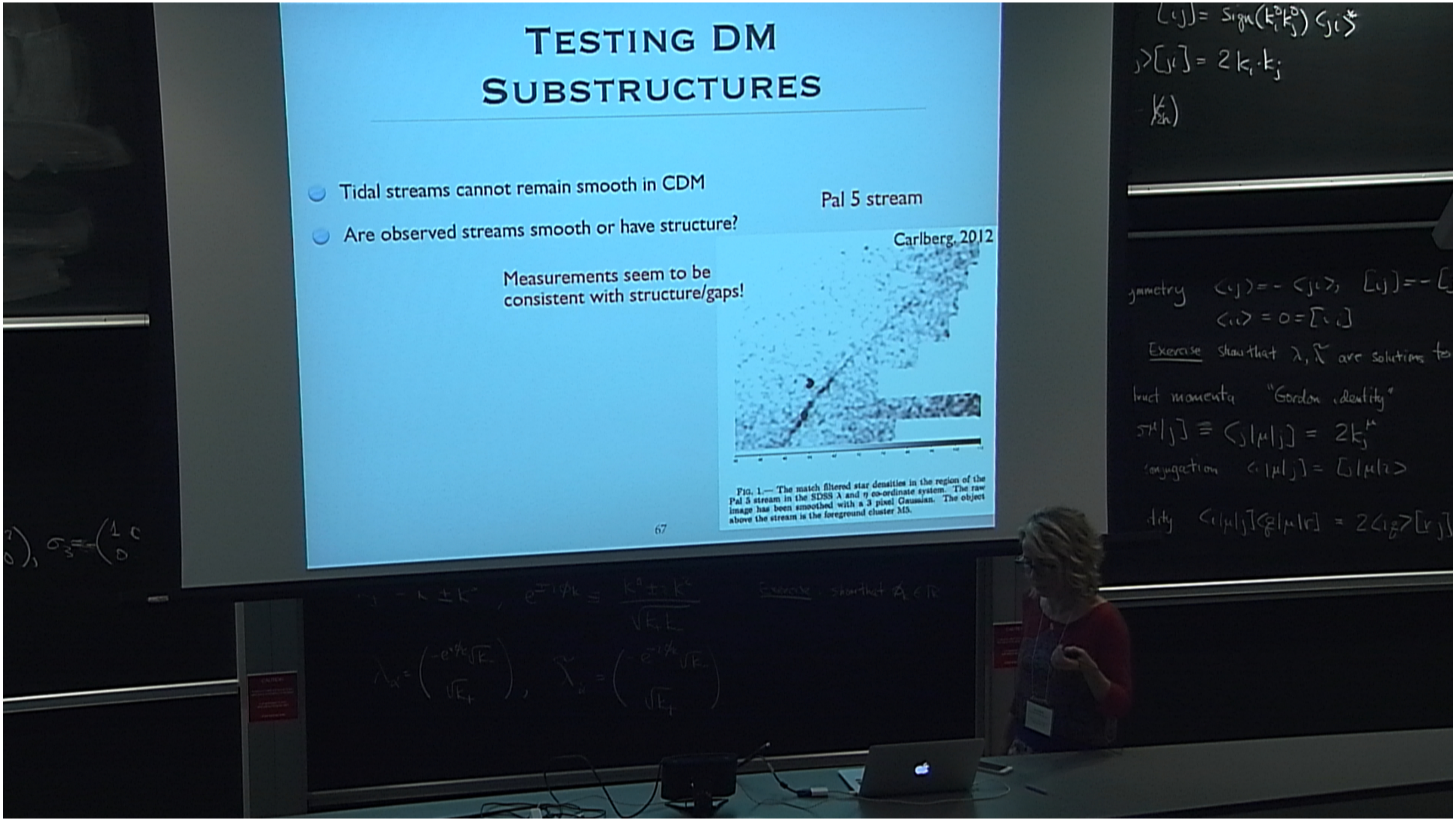
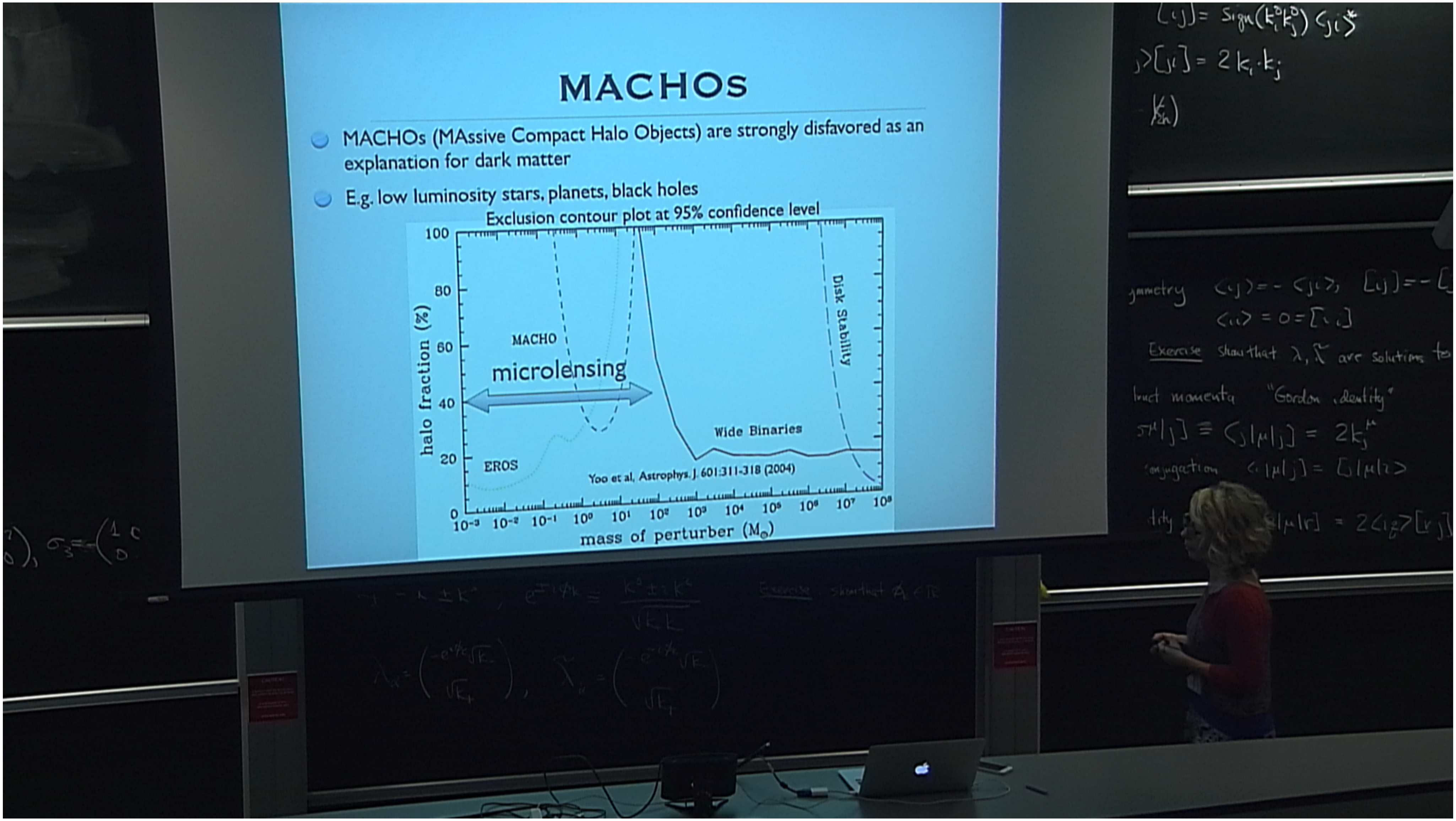
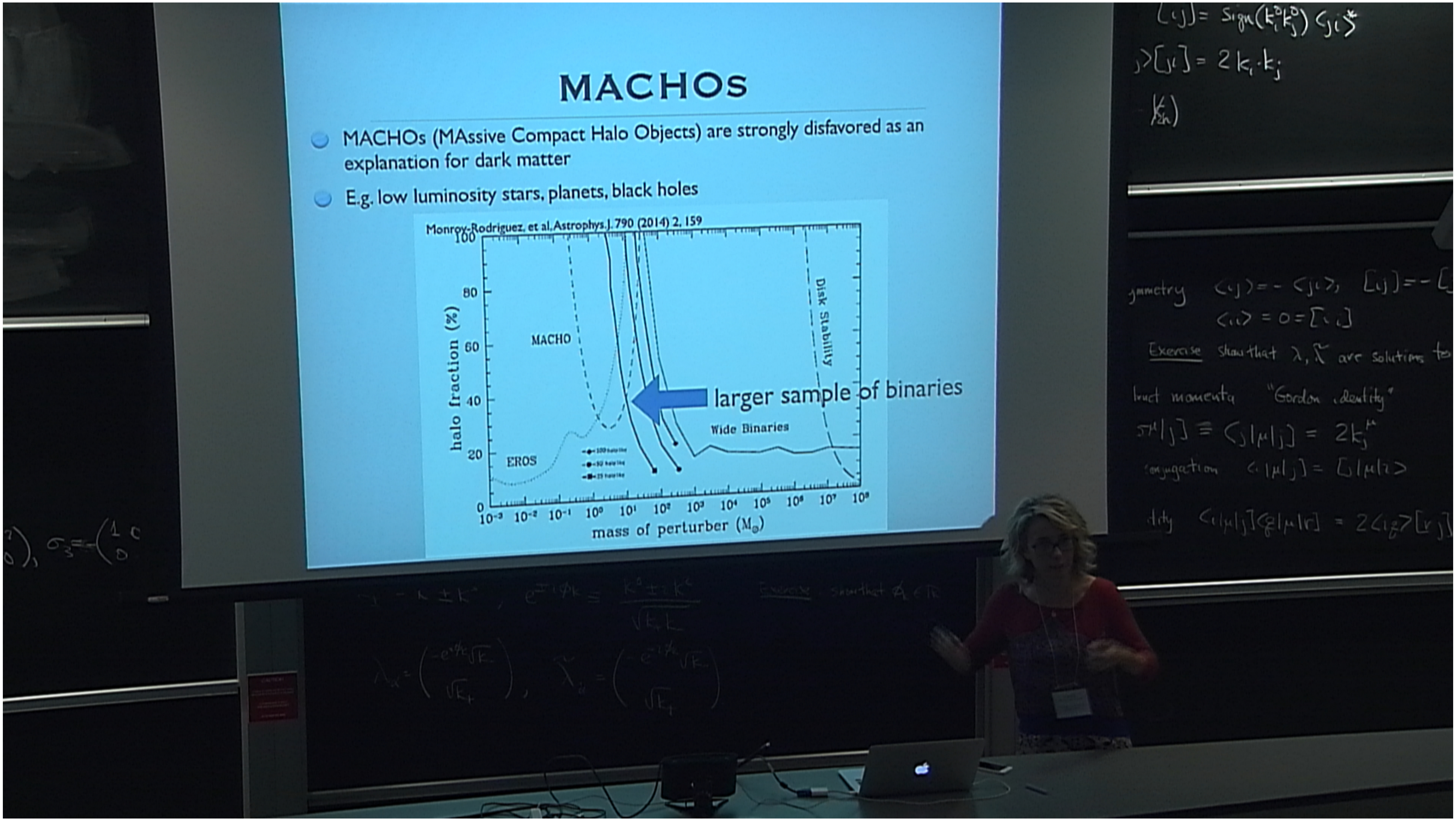


FIG. 1.— The spatial distribution of the [Fe/H]= [-0.6, -2.4] red giant stars in the NW region of M31. A full field version is presented in Richardson et al. (2011) The image is 10° across in the tangent projection co-ordinates, which are centered in the exact middle of this map.



Testing DM Substructures
Tidal streams cannot remain smooth in CDM
Are observed streams smooth or have structure?
Measurements seem to be consistent with structure/gaps!
Pal 5 stream
Carlberg, 2012
FIG. 1.— The match filtered star densities in the region of the Pal 5 stream in the SDSS λ and η co-ordinate system. The raw image has been smoothed with a 3 pixel Gaussian. The object above the stream is the foreground cluster M5.
67


MACHOs
MACHOs (MAssive Compact Halo Objects) are strongly disfavored as an explanation for dark matter
E.g. low luminosity stars, planets, black holes
Exclusion contour plot at 95% confidence level
halo fraction (%)
mass of perturber ($M_\odot$)
MACHO
microlensing
EROS
Wide Binaries
Disk Stability
Yoo et al, Astrophys. J. 601:311-318 (2004)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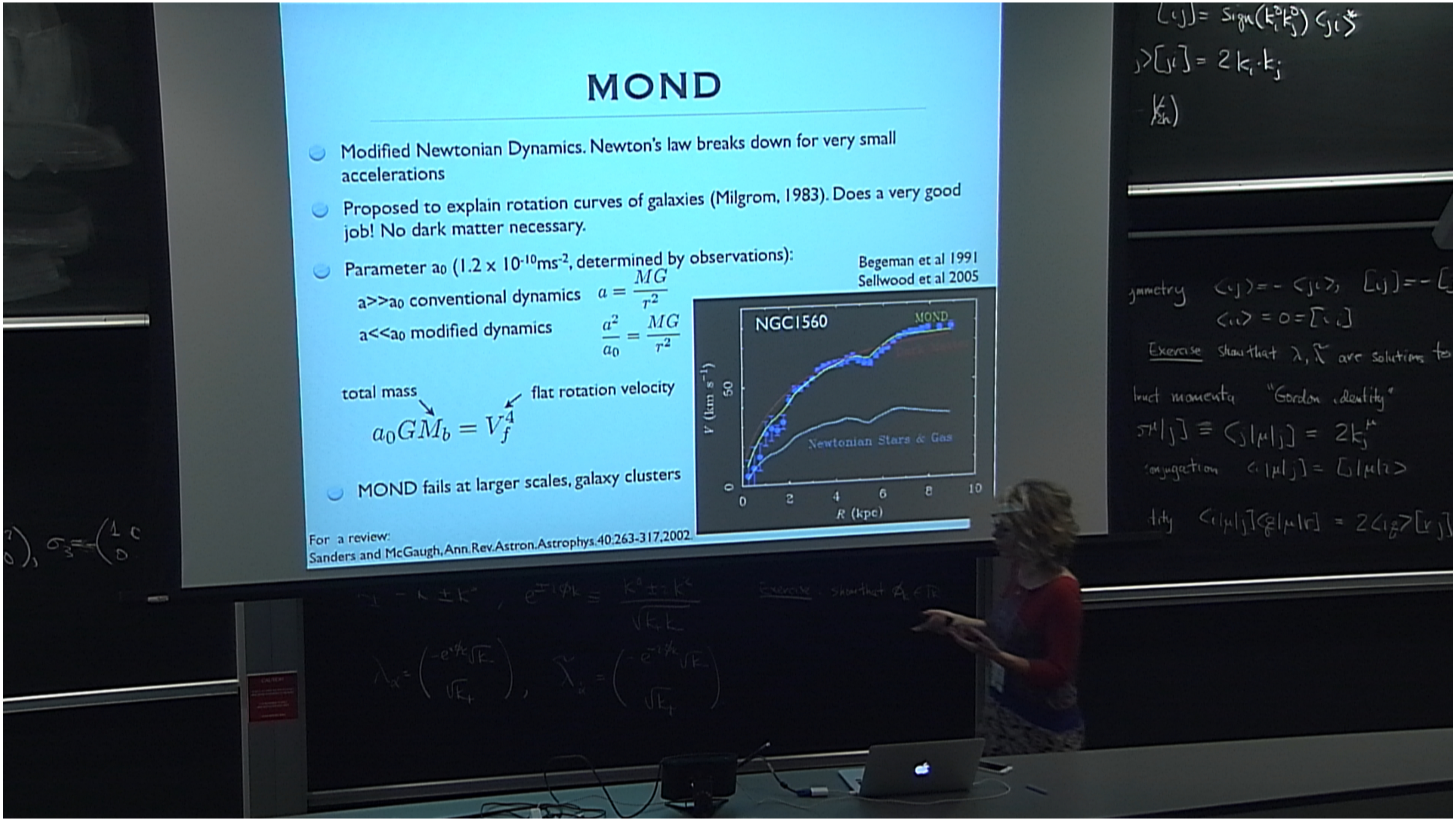
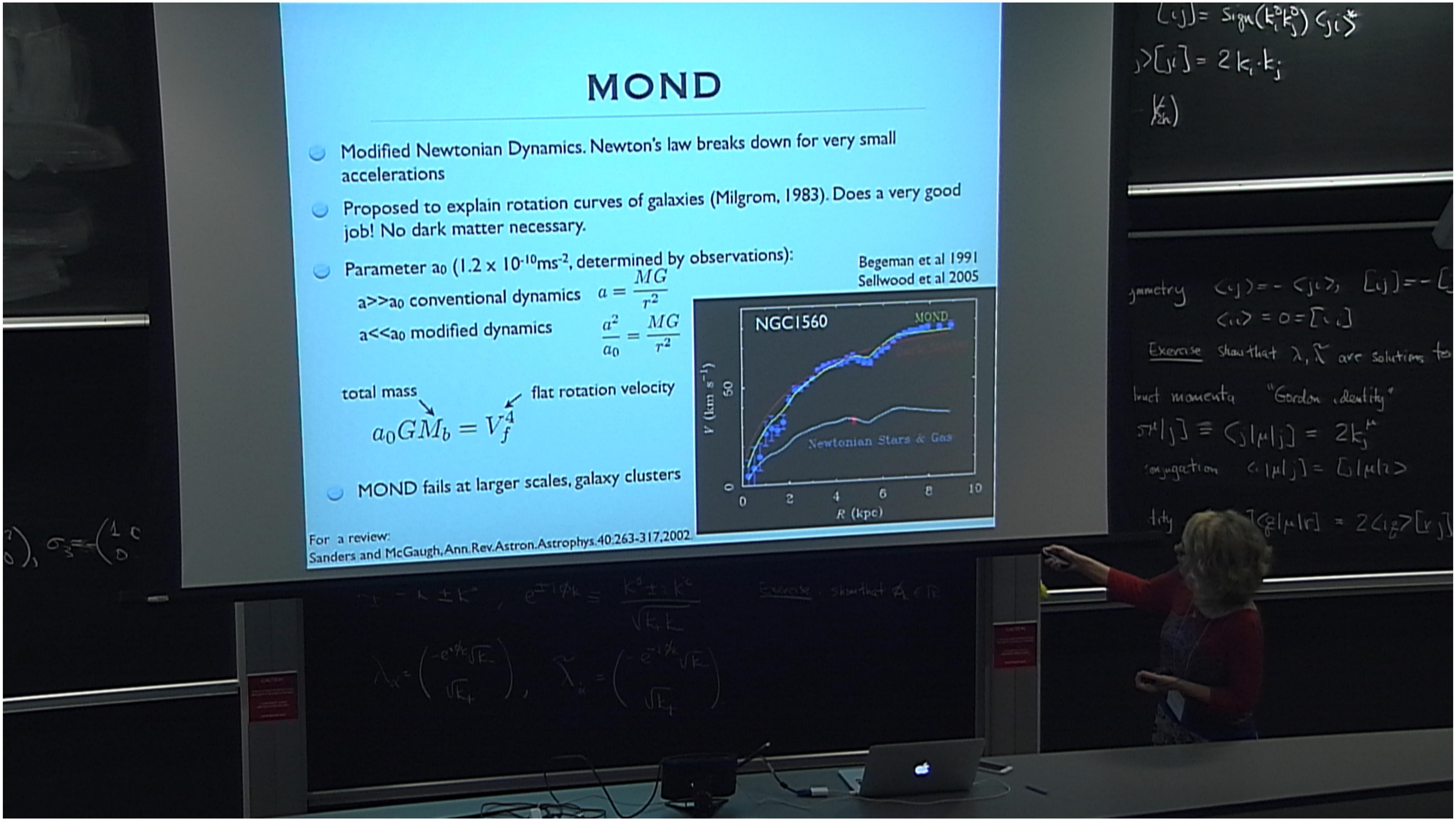
Monroy-Rodriguez, et al. Astrophys. J. 790 (2014) 2, 159
halo fraction (%)
mass of perturber ($M_\odot$)
MACHO
EROS
Disk Stability
Wide Binaries
larger sample of binaries


MOND
Modified Newtonian Dynamics. Newton's law breaks down for very small accelerations
Proposed to explain rotation curves of galaxies (Milgrom, 1983). Does a very good job! No dark matter necessary.
Parameter a0 (1.2 x 10-10ms-2, determined by observations):
a>>a0 conventional dynamics
a<<a0 modified dynamics
total mass
flat rotation velocity
MOND fails at larger scales, galaxy clusters
Begeman et al 1991
Sellwood et al 2005
NGC1560
MOND
Newtonian Stars & Gas
V (km s-1)
R (kpc)
For a review:
Sanders and McGaugh, Ann.Rev.Astron.Astrophys.40:263-317,2002.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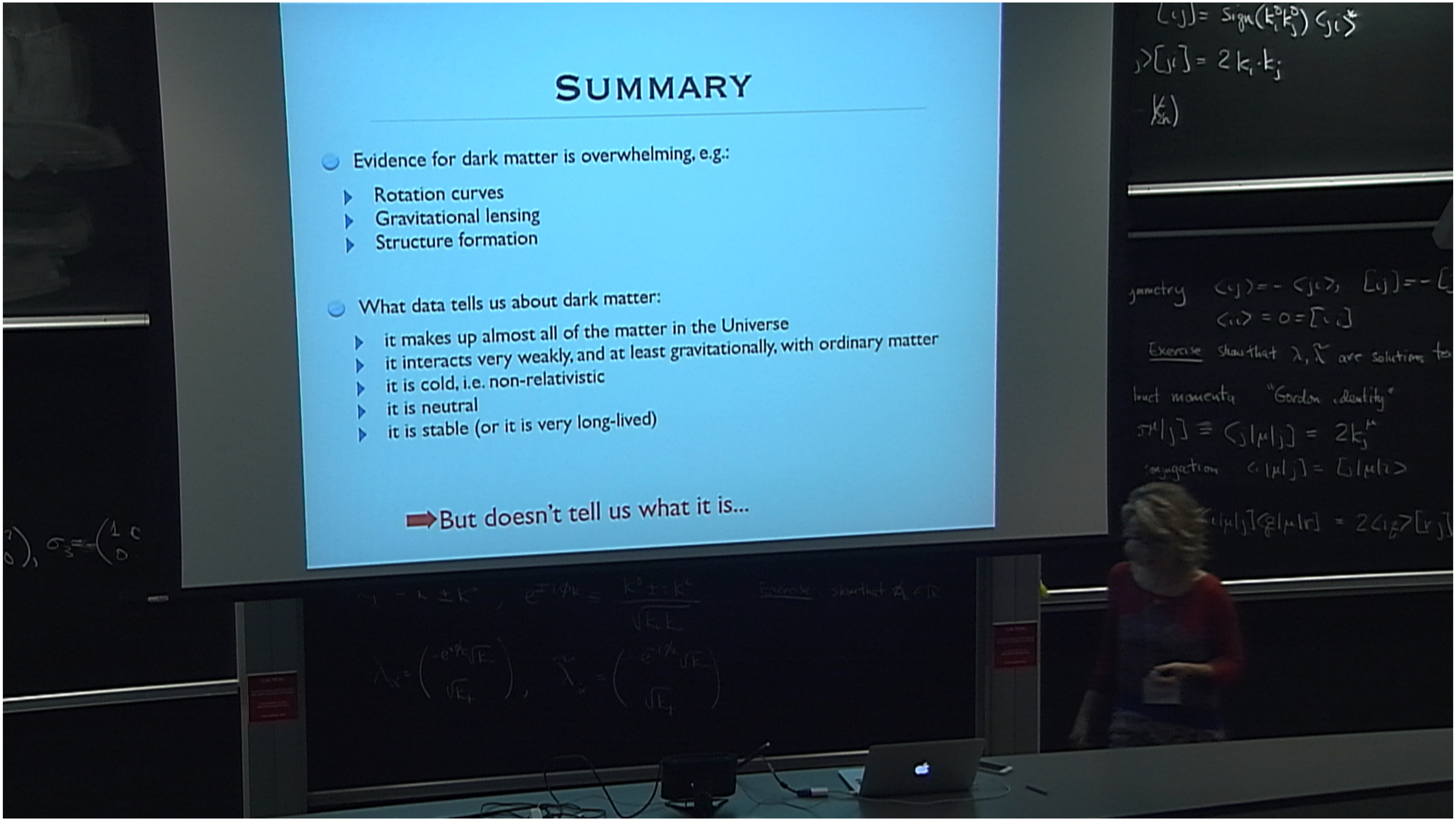
Parameter a_0 ($1.2 \times 10^{-10} ms^{-2}$, determined by observations):
$a >> a_0$ conventional dynamics $a = \frac{MG}{r^2}$
$a << a_0$ modified dynamics $\frac{a^2}{a_0} = \frac{MG}{r^2}$
total mass
flat rotation velocity
$a_0 G M_b = V_f^4$
MOND fails at larger scales, galaxy clusters
For a review:
Sanders and McGaugh, Ann.Rev.Astron.Astrophys.40:263-317,2002.
Begeman et al 1991
Sellwood et al 2005
NGC1560
MOND
Newtonian Stars & Gas
V (km s⁻¹)
R (kpc)
0
50
0
2
4
6
8
10


SUMMARY
Evidence for dark matter is overwhelming, e.g.:
Rotation curves
Gravitational lensing
Structure formation
What data tells us about dark matter:
it makes up almost all of the matter in the Universe
it interacts very weakly, and at least gravitationally, with ordinary matter
it is cold, i.e. non-relativistic
it is neutral
it is stable (or it is very long-lived)
But doesn't tell us what it is...