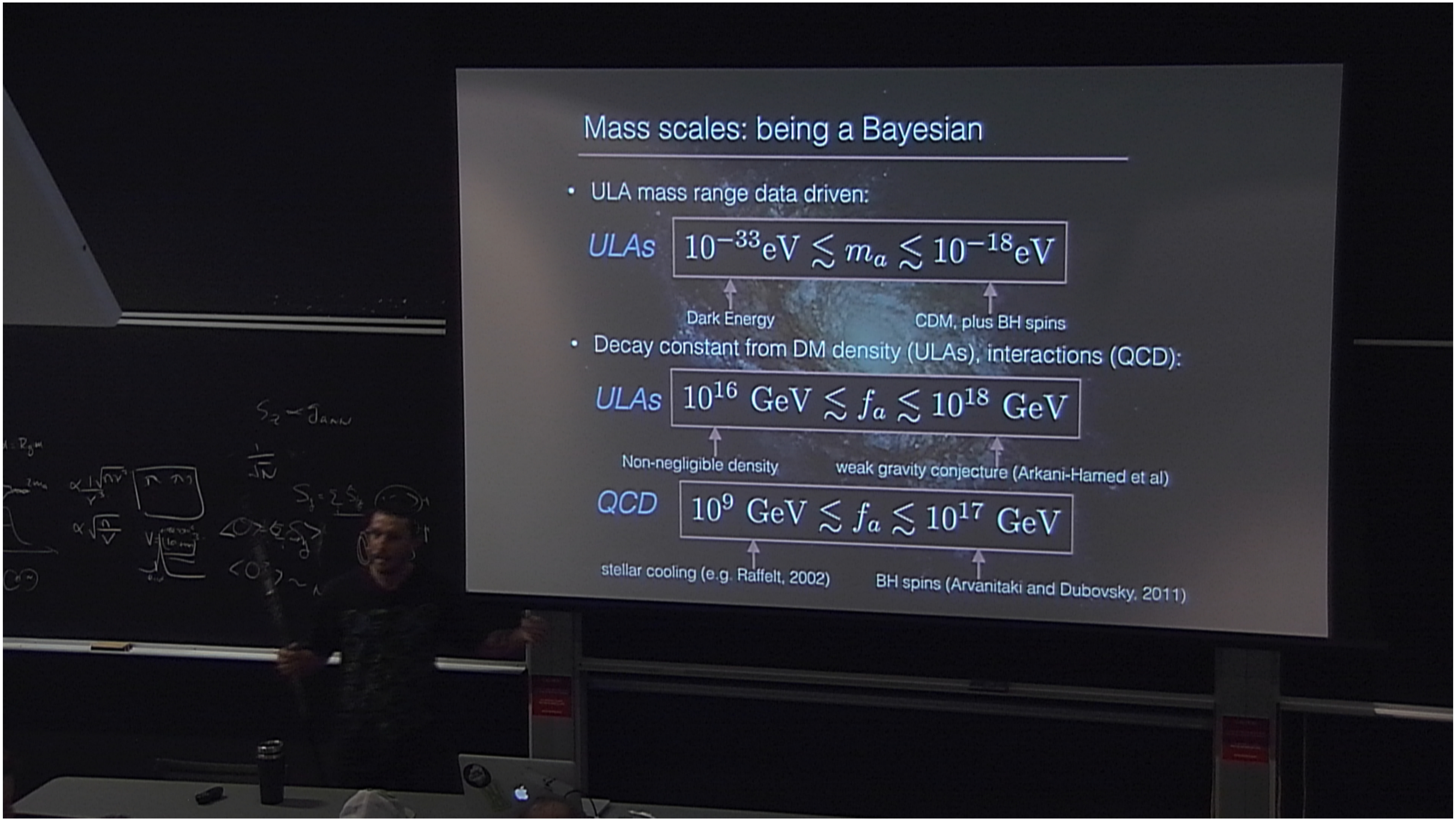
Title: Cosmological Constraints on Ultra-light Axions

Date: Jun 18, 2014 11:30 AM

URL: http://pirsa.org/14060026

Abstract: Ultra-light axions (ULAs) with masses in the range 1e-33 eV< m < 1e-18 eV can constitute a novel component of the dark matter, which can be constrained by cosmological observations. ULA dark matter (DM) is produced non-thermally via vacuum realignment in the early universe and is cold. Pressure perturbations, however, manifest a scale in the clustering (also the de Broglie scale). For the range of masses considered this spans the Hubble scale down to sub-galactic scales. In the model-independent adiabatic mode of initial conditions, one can gain strong constraints on ULAs as DM from the CMB and large scale structure (LSS). I will present constraints from Planck and WiggleZ, constraining m~1e-33 eV to 1e-25 eV at the percent level. In the range m\gtrsim 1e-22 eV ULAs may also solve the "small-scale problems" of CDM, and suggest other constraints from LSS and high-z observations, constraining m\lesssim 1e-22 eV to be sub-dominant in DM. Future prospects from CMB lensing, and from Euclid galaxy weak lensing, will make sub-percent constraints out to m~1e-21 eV. Model-dependent couplings between axions and photons provide still other bounds from CMB spectral distortions. Finally, if the inflationary energy scale is high, corresponding to an observable tensor-to-scalar ratio, then CMB isocurvature perturbations provide the strongest constraints on m>1e-24 eV, ruling out ULA dark matter in the simplest inflationary scenarios over the entire range considered, as well as the "anthropic window" for the QCD axion.


Mass scales: being a Bayesian
• ULA mass range data driven:
ULAs $10^{-33}\mathrm{eV} \lesssim m_a \lesssim 10^{-18}\mathrm{eV}$
Dark Energy
CDM, plus BH spins
• Decay constant from DM density (ULAs), interactions (QCD):
ULAs $10^{16}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{18}\ \mathrm{GeV}$
Non-negligible density
weak gravity conjecture (Arkani-Hamed et al)
QCD $10^{9}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{17}\ \mathrm{GeV}$
stellar cooling (e.g. Raffelt, 2002)
BH spins (Arvanitaki and Dubovsky, 2011)

Mass scales: being a Bayesian

- ULA mass range data driven:

ULAs $10^{-33}\mathrm{eV} \lesssim m_a \lesssim 10^{-18}\mathrm{eV}$

Dark Energy — CDM, plus BH spins

- Decay constant from DM density (ULAs), interactions (QCD):

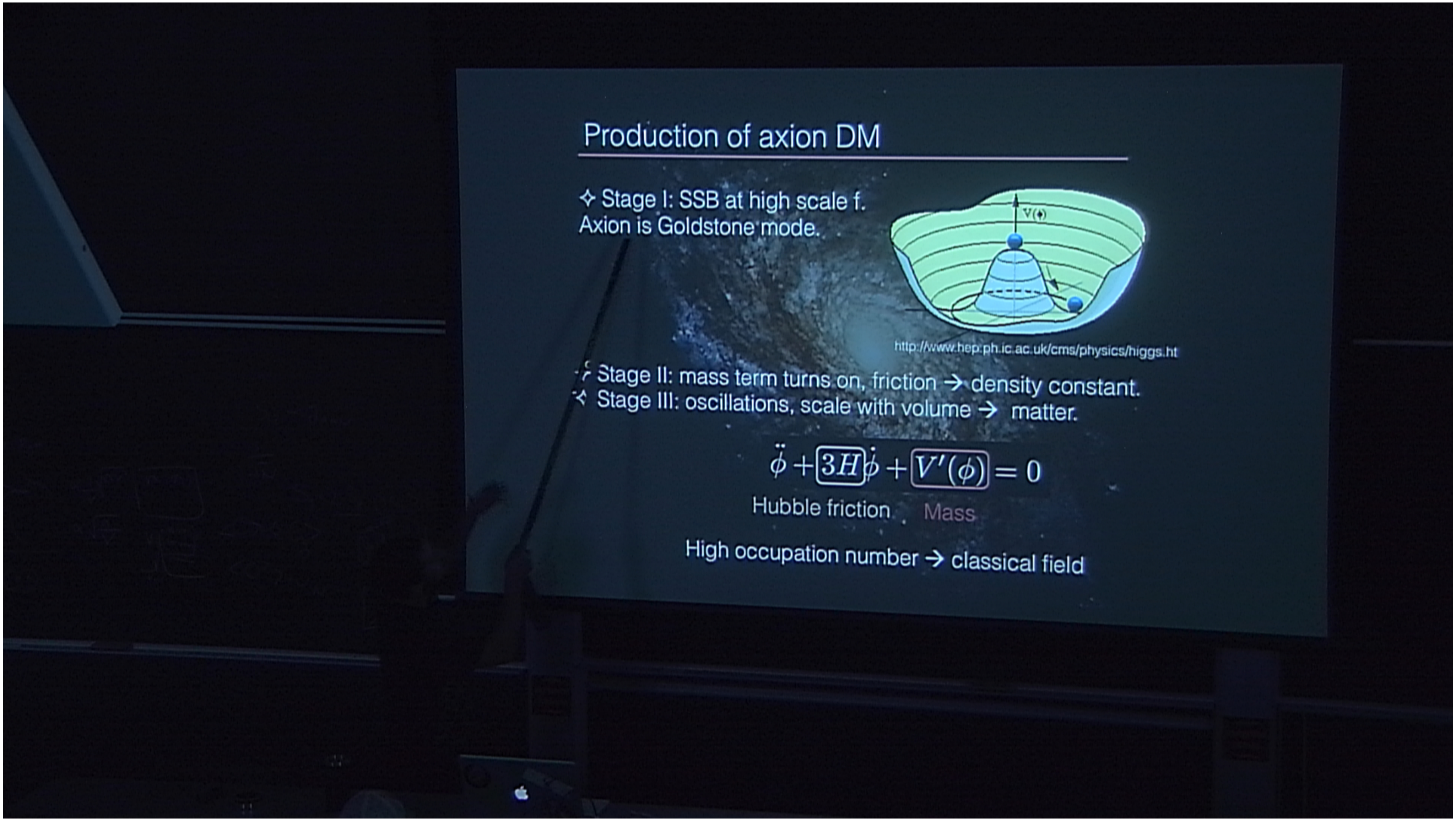
ULAs $10^{16}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{18}\ \mathrm{GeV}$

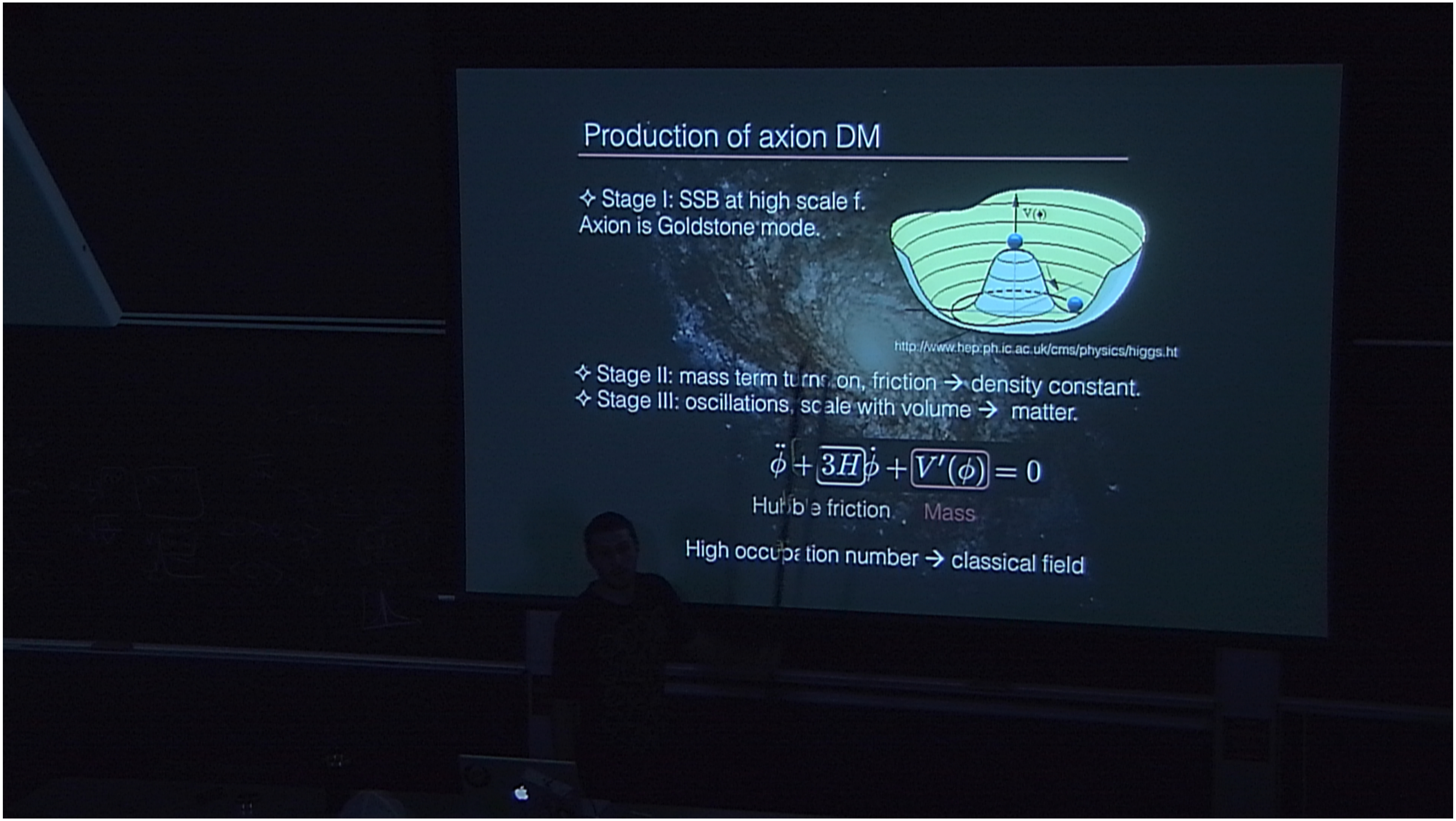
Non-negligible density — weak gravity conjecture (Arkani-Hamed et al)

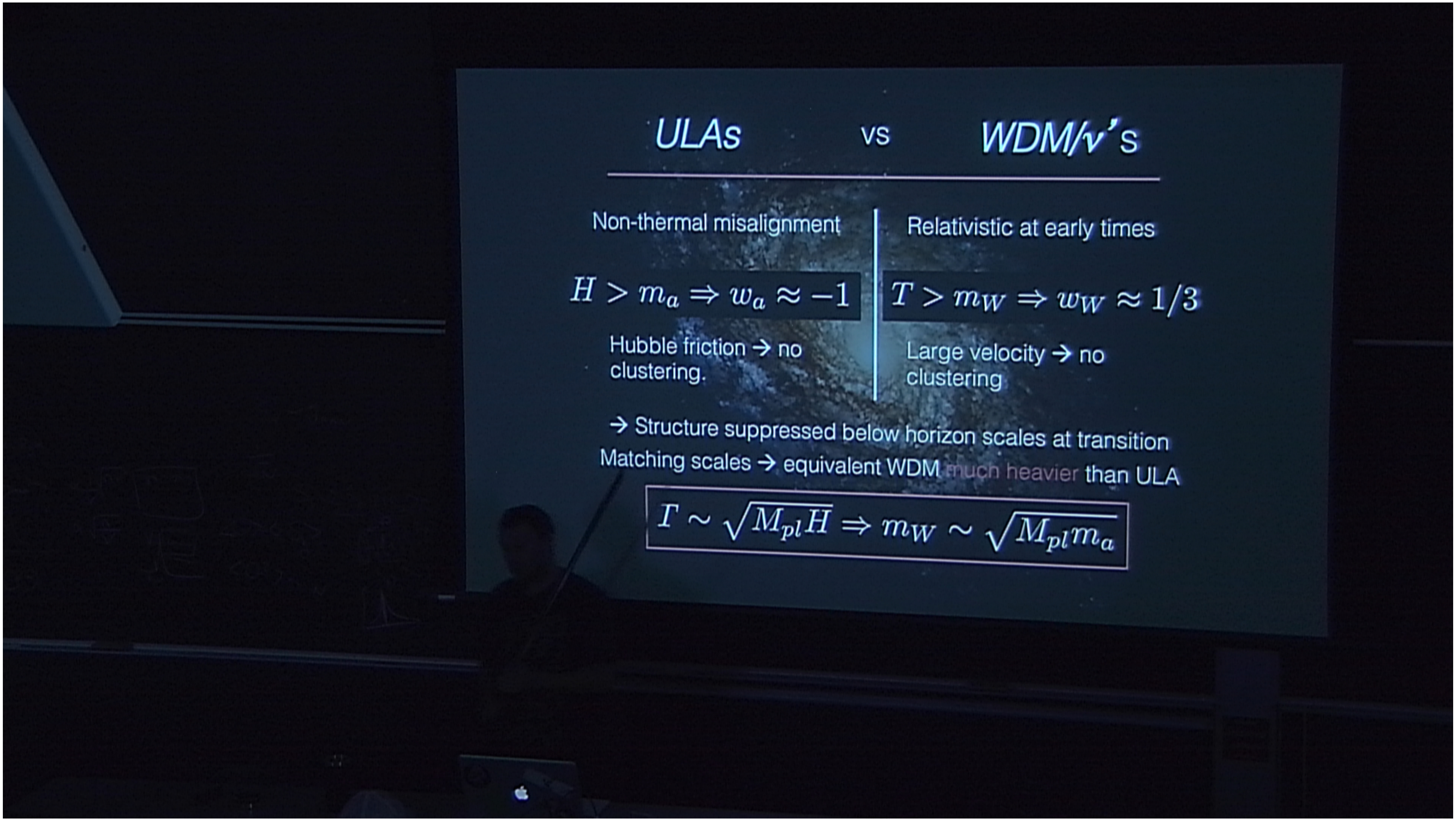
QCD $10^{9}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{17}\ \mathrm{GeV}$

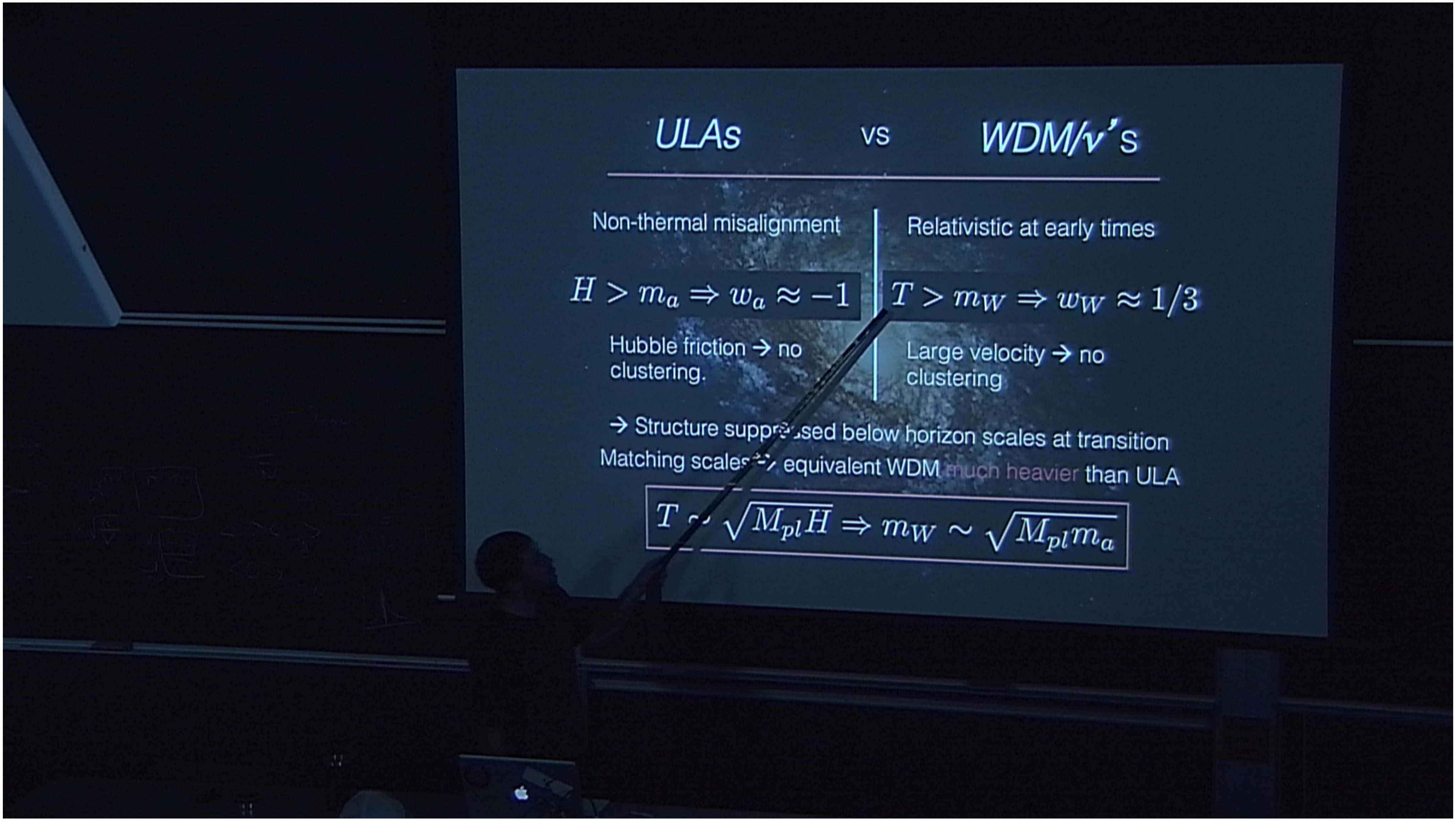
stellar cooling (e.g. Raffelt, 2002) — BH spins (Arvanitaki and Dubovsky, 2011)

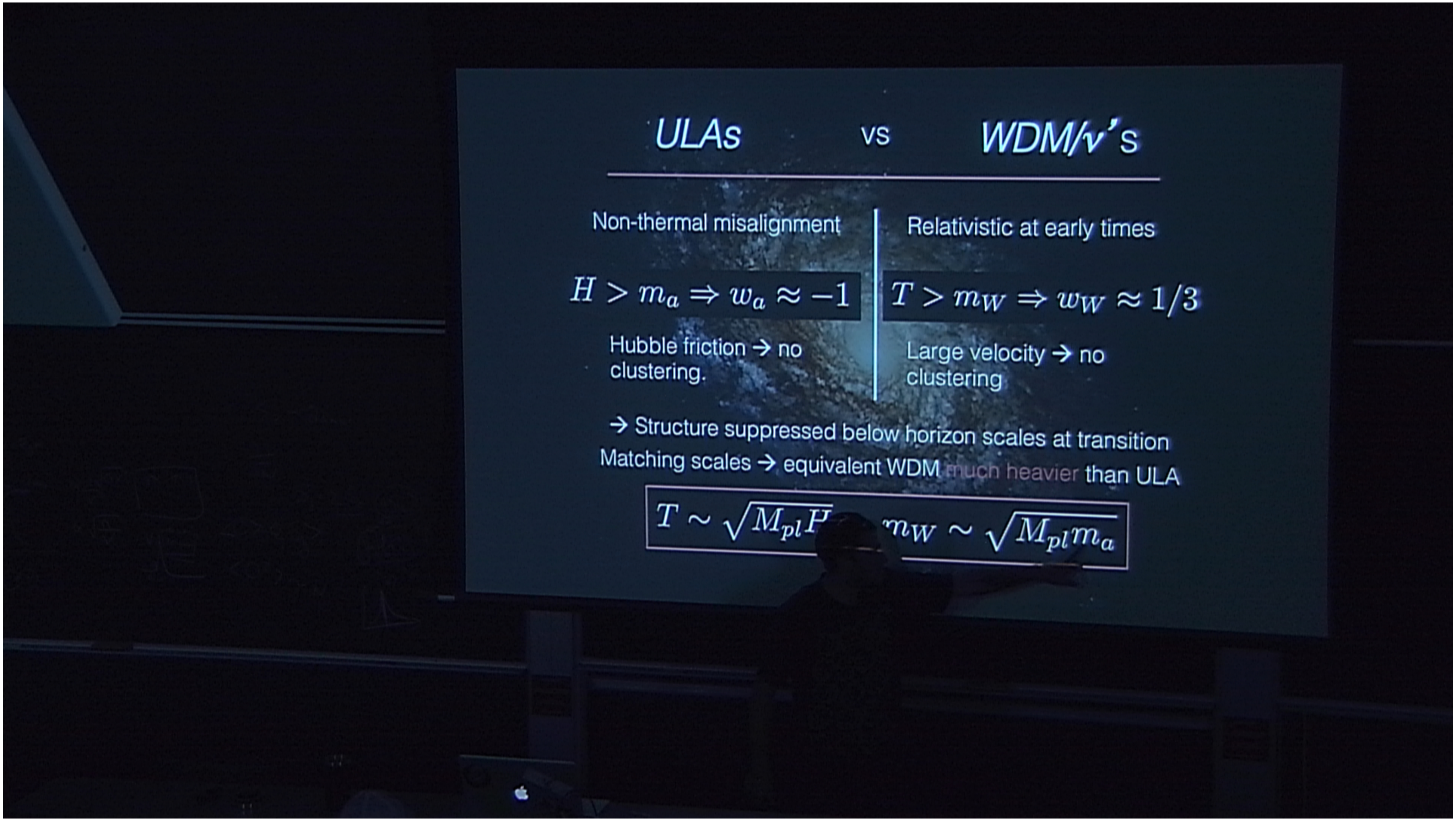

Production and Initial Conditons


Production of axion DM
✧ Stage I: SSB at high scale f.
Axion is Goldstone mode.
V(ϕ)
http://www.hep.ph.ic.ac.uk/cms/physics/higgs.ht
✧ Stage II: mass term turns on, friction → density constant.
✧ Stage III: oscillations, scale with volume → matter.
$\ddot{\phi} + \boxed{3H}\dot{\phi} + \boxed{V'(\phi)} = 0$
Hubble friction
Mass
High occupation number → classical field


Production of axion DM
✧ Stage I: SSB at high scale f.
Axion is Goldstone mode.
V(ϕ)
http://www.hep.ph.ic.ac.uk/cms/physics/higgs.ht
✧ Stage II: mass term turns on, friction → density constant.
✧ Stage III: oscillations, scale with volume → matter.
$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$
Hubble friction
Mass
High occupation number → classical field


ULAs vs WDM/ν's
Non-thermal misalignment
$H > m_a \Rightarrow w_a \approx -1$
Hubble friction → no clustering.
Relativistic at early times
$T > m_W \Rightarrow w_W \approx 1/3$
Large velocity → no clustering
→ Structure suppressed below horizon scales at transition
Matching scales → equivalent WDM much heavier than ULA
$\Gamma \sim \sqrt{M_{pl} H} \Rightarrow m_W \sim \sqrt{M_{pl} m_a}$


ULAs vs WDM/ν's
Non-thermal misalignment
$H > m_a \Rightarrow w_a \approx -1$
Hubble friction → no clustering.
Relativistic at early times
$T > m_W \Rightarrow w_W \approx 1/3$
Large velocity → no clustering
→ Structure supp
sed below horizon scales at transition
Matching scales → equivalent WDM much heavier than ULA
$T \sim \sqrt{M_{pl}H} \Rightarrow m_W \sim \sqrt{M_{pl}m_a}$


ULAs vs WDM/ν's
Non-thermal misalignment
$H > m_a \Rightarrow w_a \approx -1$
Hubble friction → no clustering.
Relativistic at early times
$T > m_W \Rightarrow w_W \approx 1/3$
Large velocity → no clustering
→ Structure suppressed below horizon scales at transition
Matching scales → equivalent WDM much heavier than ULA
$m_W \sim \sqrt{M_{pl} m_a}$

ULAs vs *WDM/ν's*

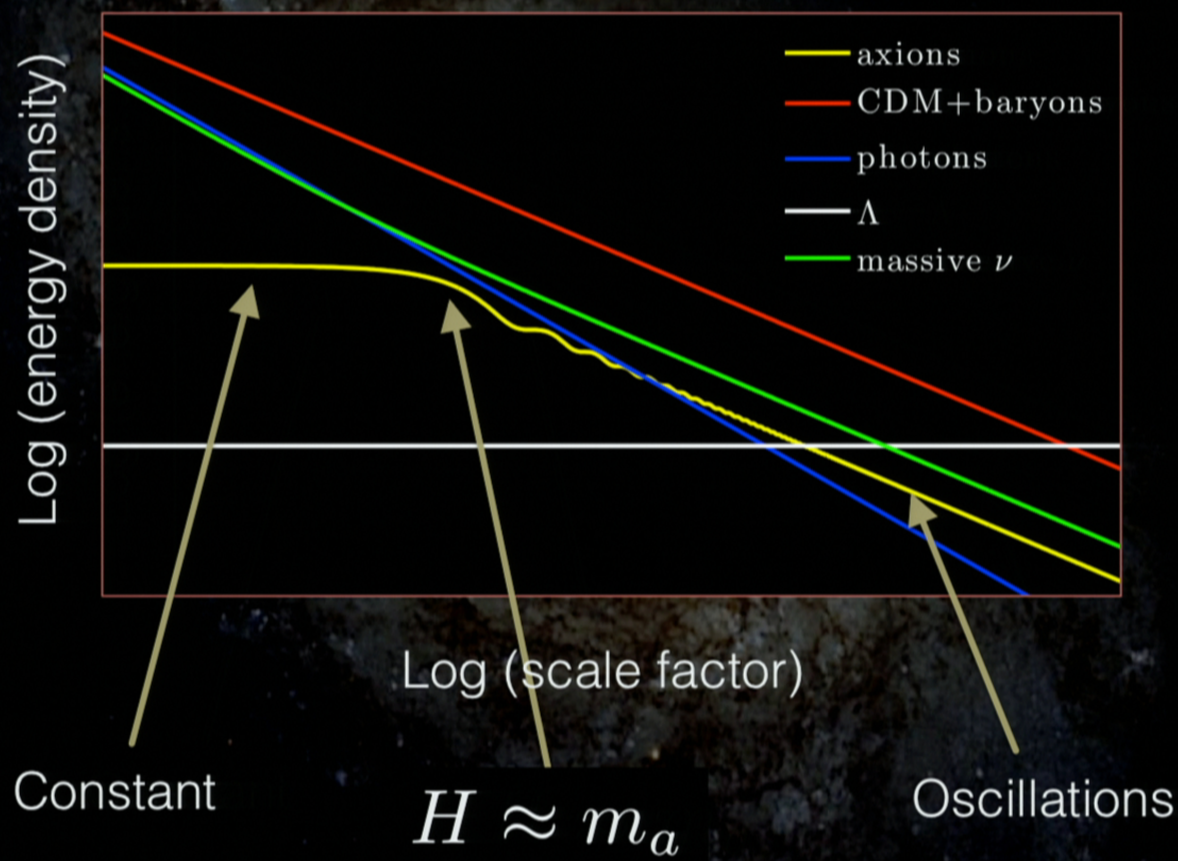
Non-thermal misalignment	Relativistic at early times
$H > m_a \Rightarrow w_a \approx -1$	$T > m_W \Rightarrow w_W \approx 1/3$
Hubble friction → no clustering.	Large velocity → no clustering

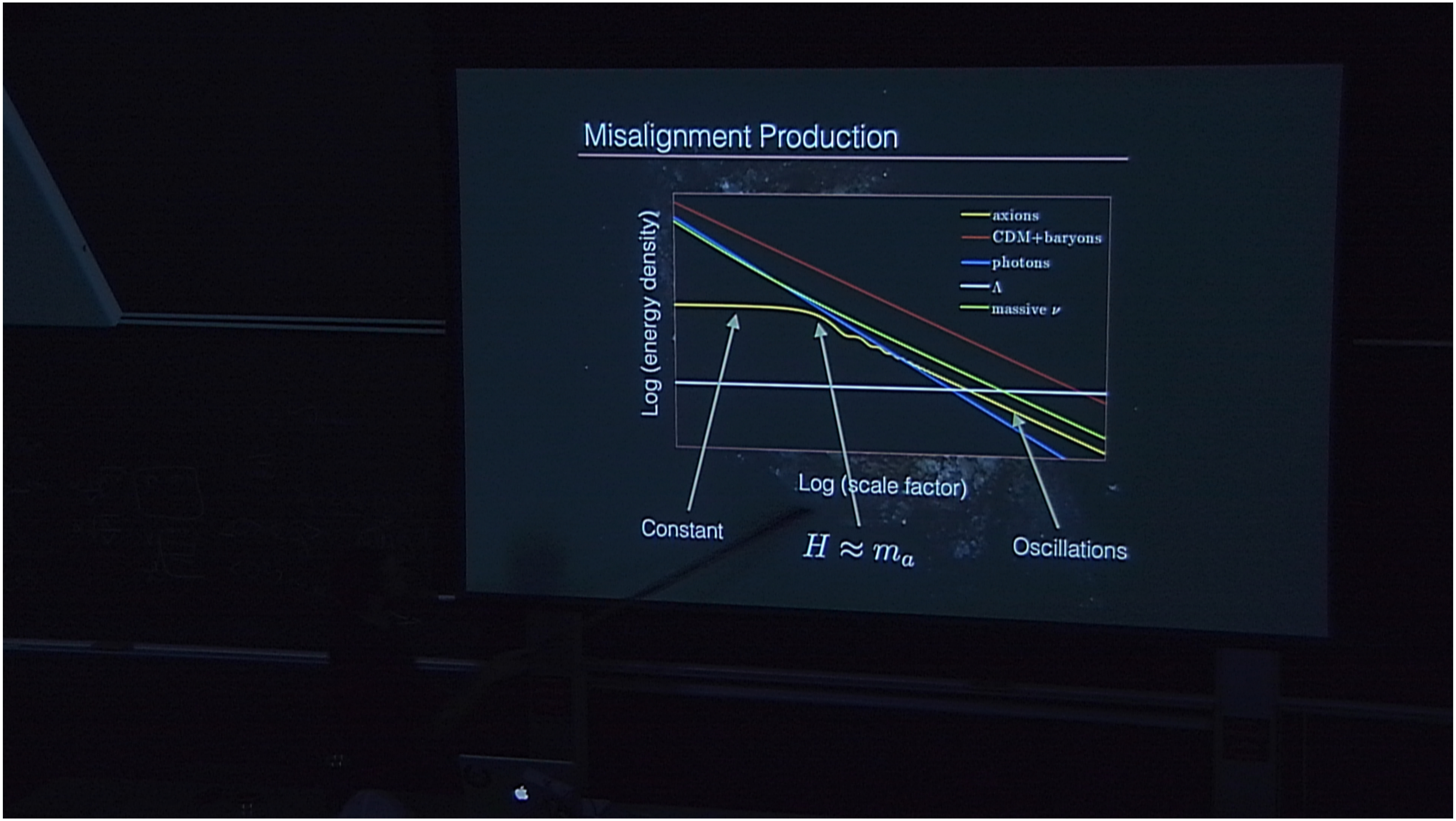
→ Structure suppressed below horizon scales at transition

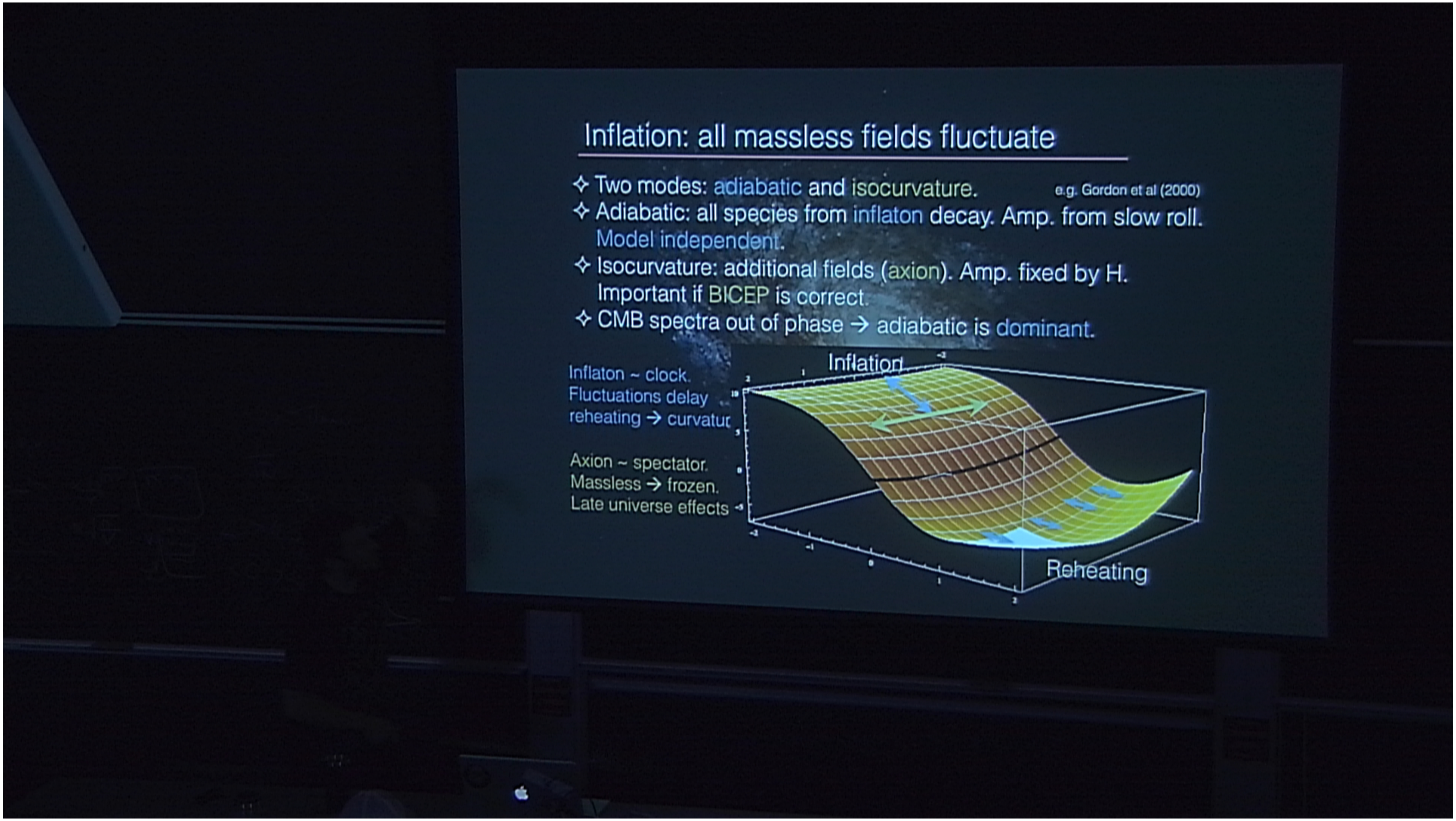
Matching scales → equivalent WDM much heavier than ULA

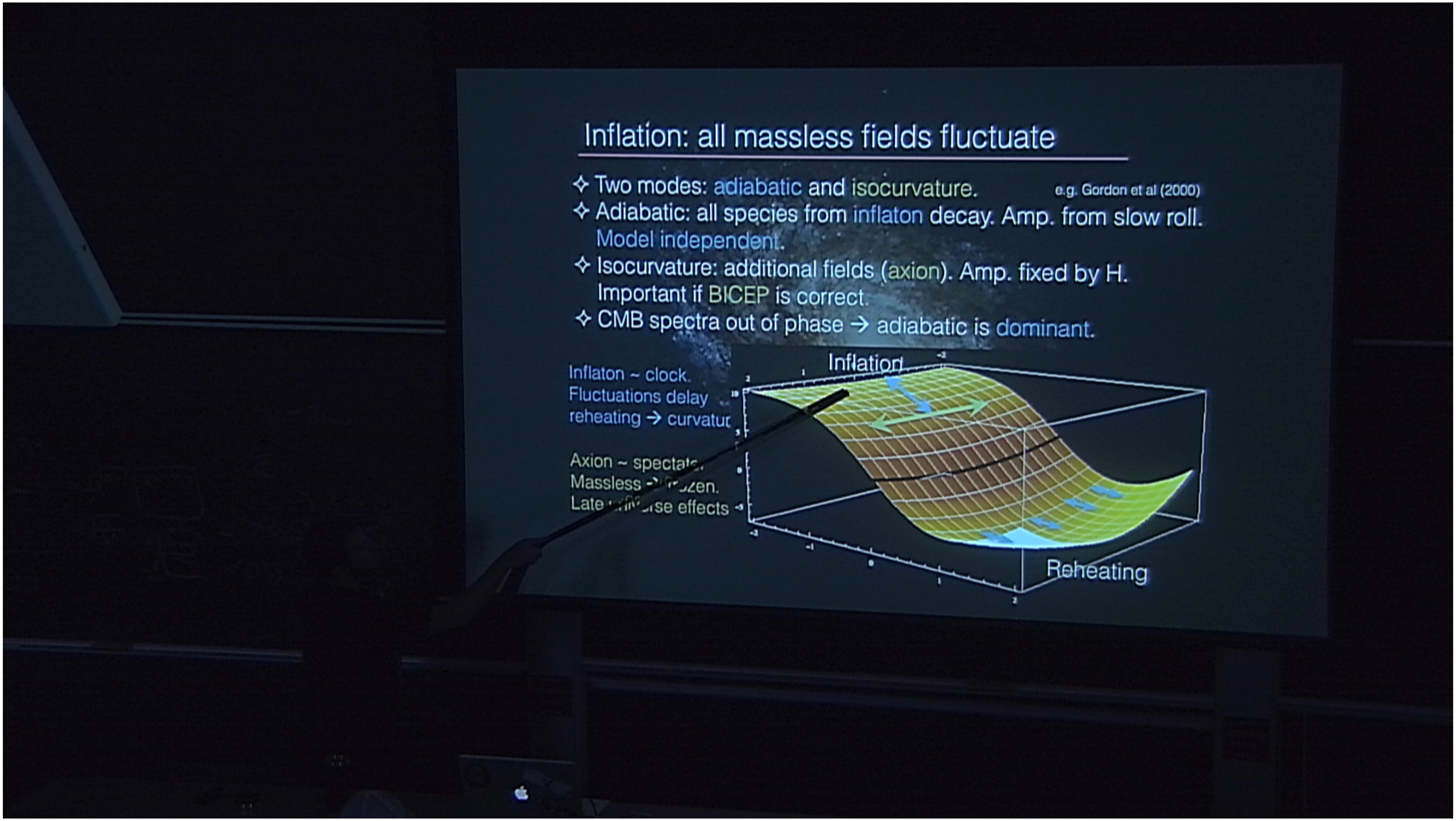
$$T \sim \sqrt{M_{pl} H} \Rightarrow m_W \sim \sqrt{M_{pl} m_a}$$

Misalignment Production

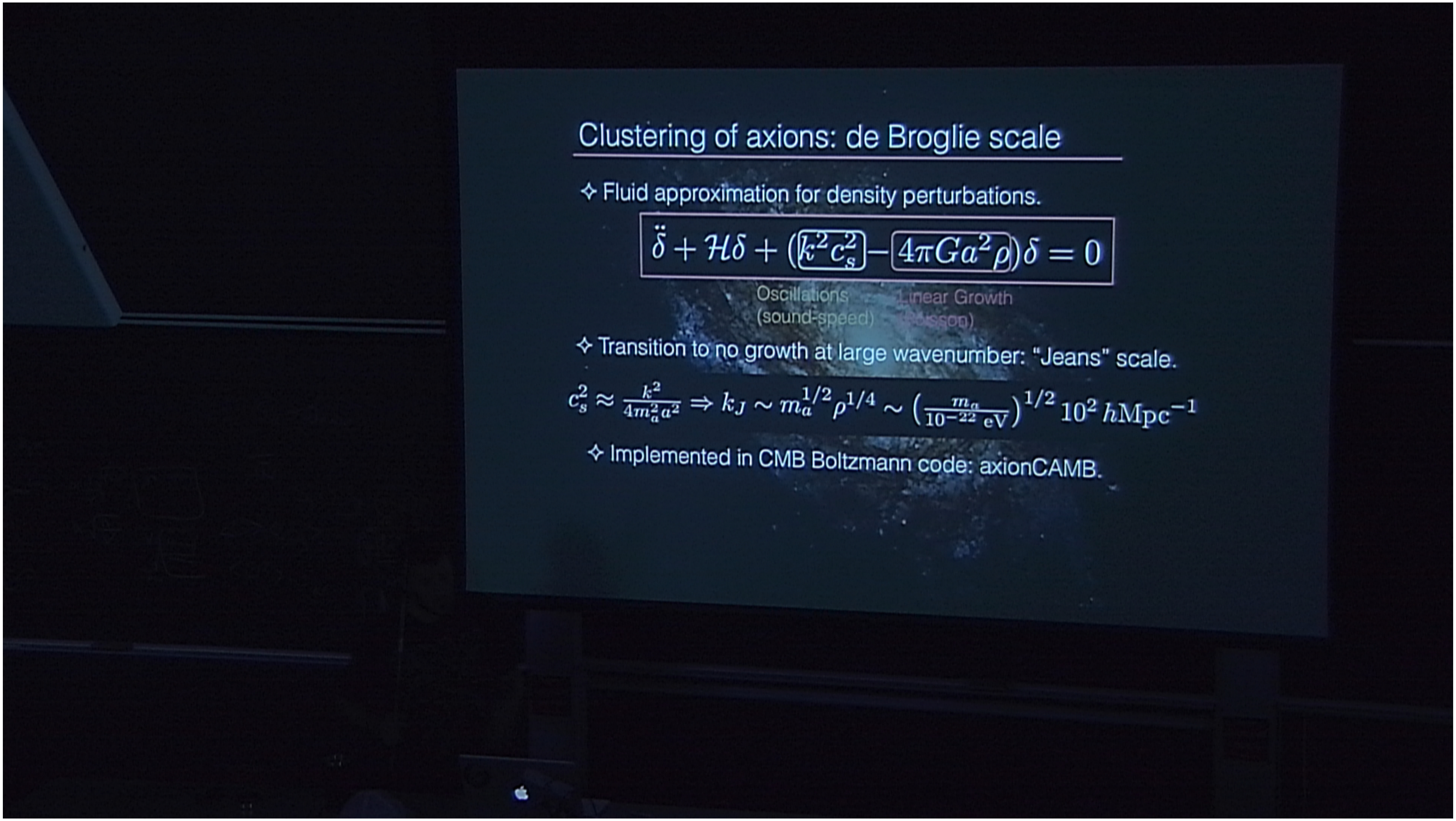


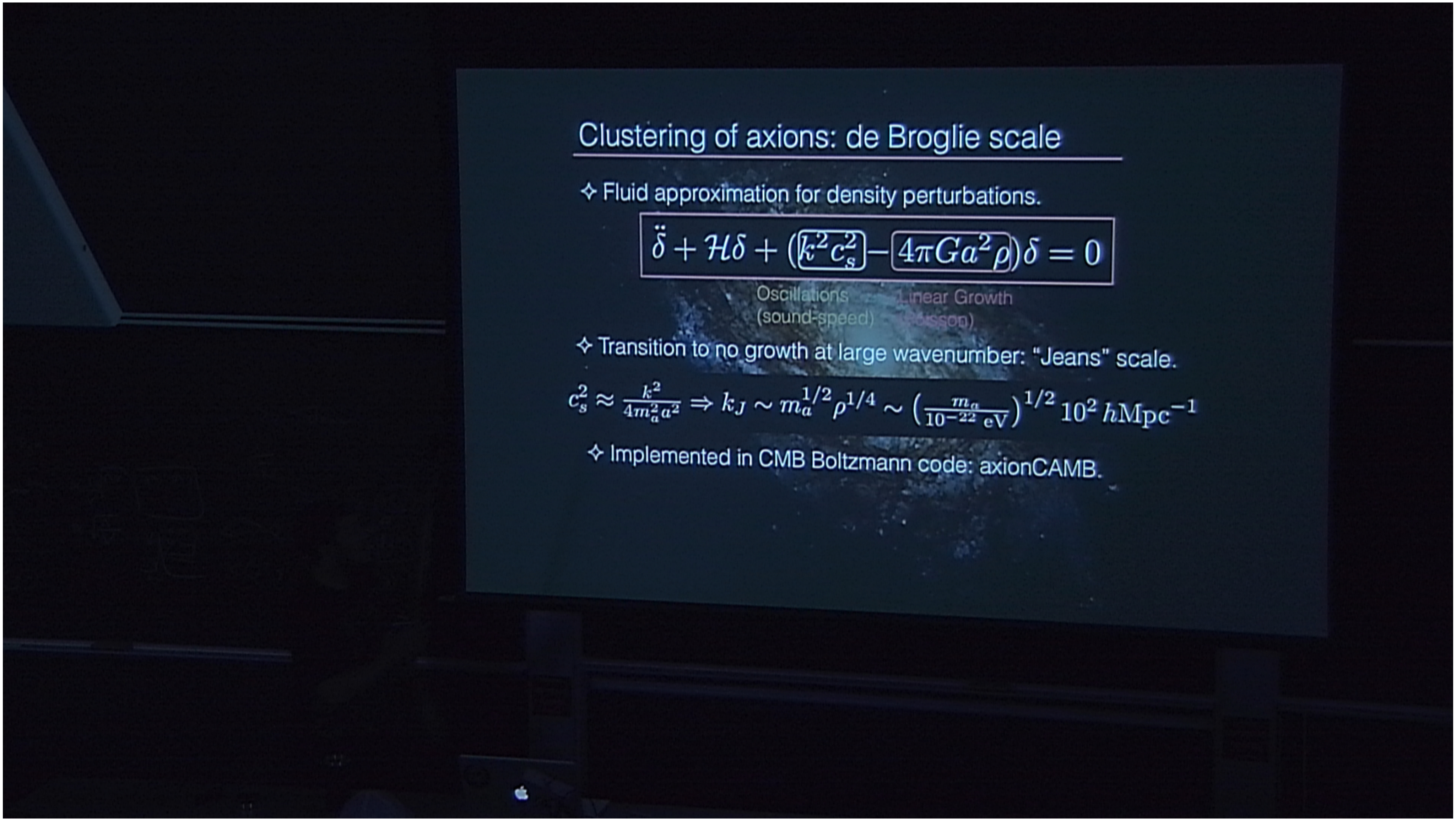

Misalignment Production
axions
CDM+baryons
photons
Λ
massive ν
Log (energy density)
Log (scale factor)
Constant
$H \approx m_a$
Oscillations

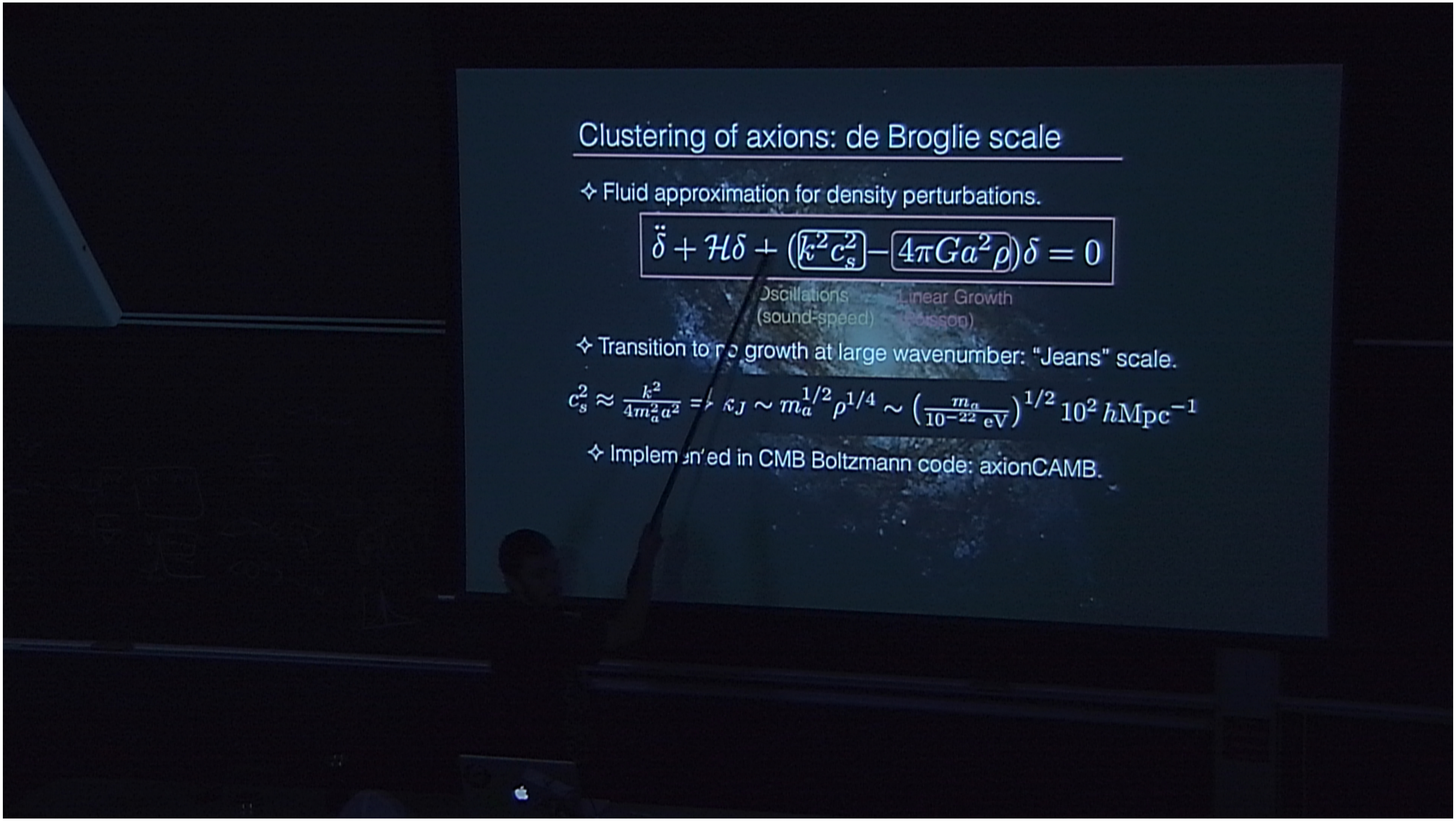

Inflation: all massless fields fluctuate
✧ Two modes: adiabatic and isocurvature.
e.g. Gordon et al (2000)
✧ Adiabatic: all species from inflaton decay. Amp. from slow roll. Model independent.
✧ Isocurvature: additional fields (axion). Amp. fixed by H. Important if BICEP is correct.
✧ CMB spectra out of phase → adiabatic is dominant.
Inflaton ~ clock.
Fluctuations delay
reheating → curvatur
Axion ~ spectator.
Massless → frozen.
Late universe effects
Inflation
Reheating



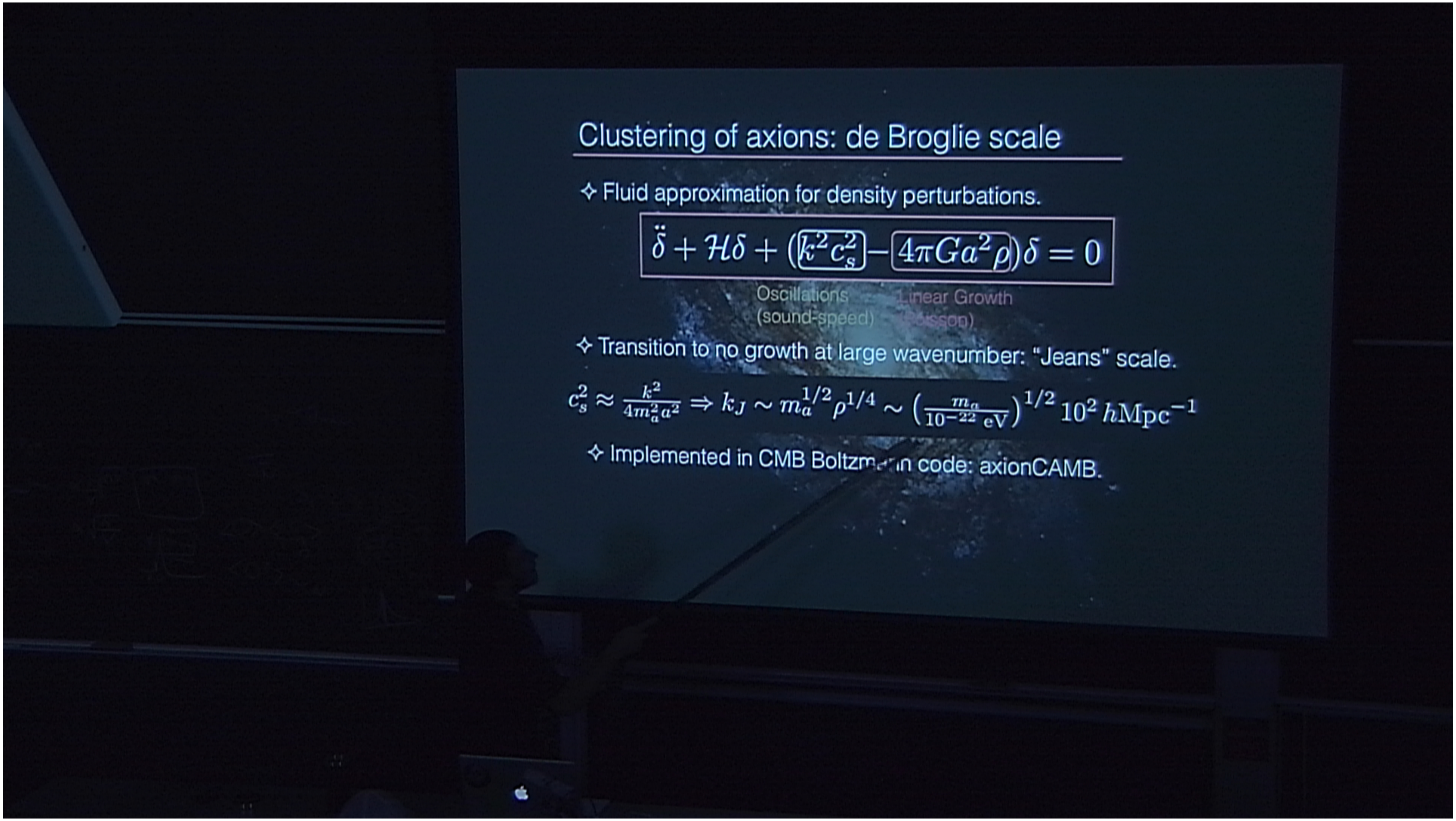
Inflation: all massless fields fluctuate
✧ Two modes: adiabatic and isocurvature.
e.g. Gordon et al (2000)
✧ Adiabatic: all species from inflaton decay. Amp. from slow roll. Model independent.
✧ Isocurvature: additional fields (axion). Amp. fixed by H. Important if BICEP is correct.
✧ CMB spectra out of phase → adiabatic is dominant.
Inflaton ~ clock.
Fluctuations delay
reheating → curvatur
Axion ~ spectat
Massless
Late
rse effects
Inflation
Reheating

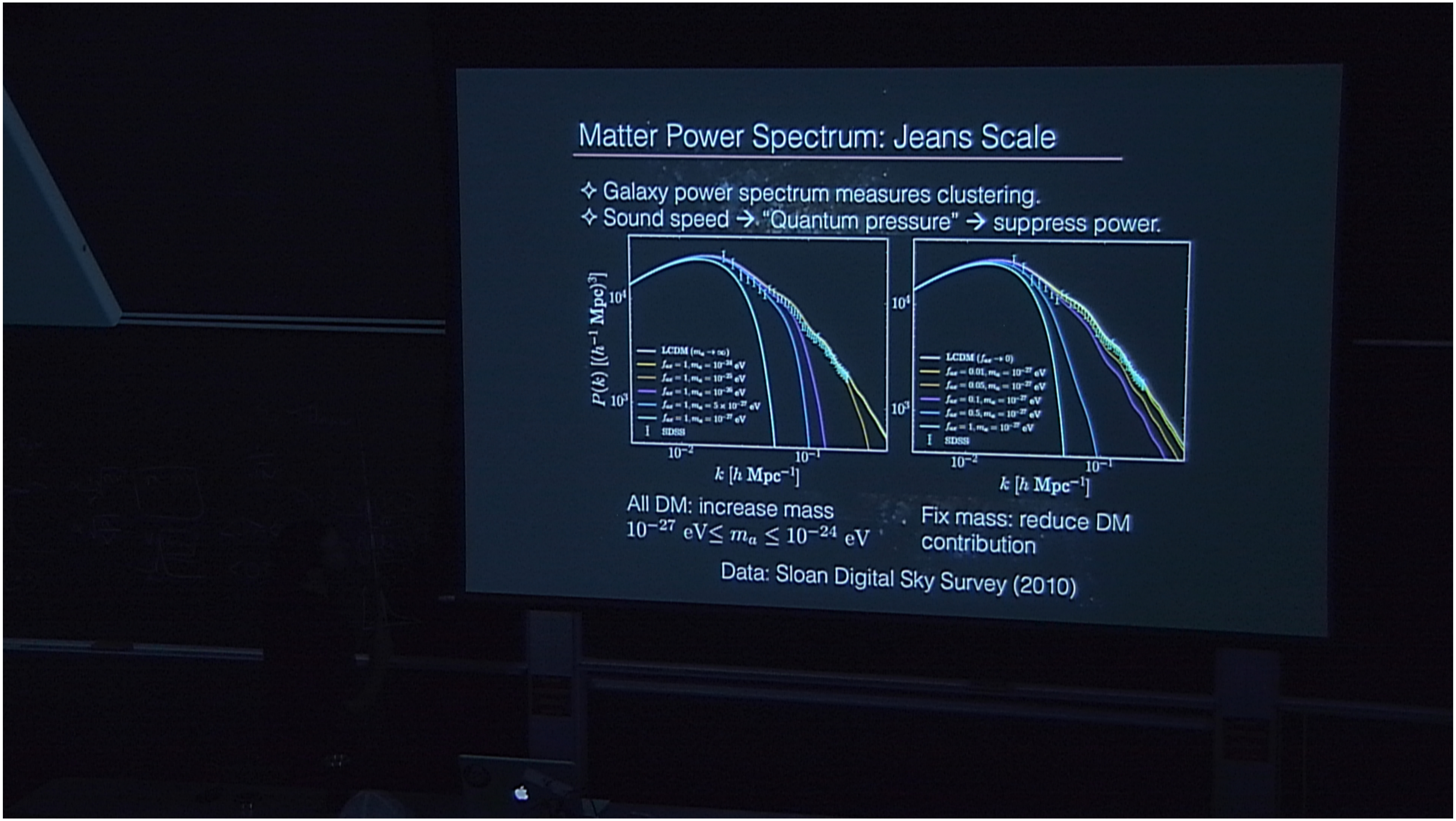

Clustering of axions: de Broglie scale
✧ Fluid approximation for density perturbations.
$\ddot{\delta} + \mathcal{H}\delta + (k^2 c_s^2 - 4\pi G a^2 \rho)\delta = 0$
Oscillations
(sound-speed)
Linear Growth
✧ Transition to no growth at large wavenumber: "Jeans" scale.
$c_s^2 \approx \frac{k^2}{4m_a^2 a^2} \Rightarrow k_J \sim m_a^{1/2}\rho^{1/4} \sim \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} 10^2\, h\mathrm{Mpc}^{-1}$
✧ Implemented in CMB Boltzmann code: axionCAMB.


Clustering of axions: de Broglie scale
✧ Fluid approximation for density perturbations.
$\ddot{\delta} + \mathcal{H}\delta + (k^2 c_s^2 - 4\pi G a^2 \rho)\delta = 0$
Oscillations (sound-speed)
Linear Growth (Poisson)
✧ Transition to no growth at large wavenumber: "Jeans" scale.
$c_s^2 \approx \frac{k^2}{4m_a^2 a^2} \Rightarrow k_J \sim m_a^{1/2}\rho^{1/4} \sim \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} 10^2\, h\mathrm{Mpc}^{-1}$
✧ Implemented in CMB Boltzmann code: axionCAMB.

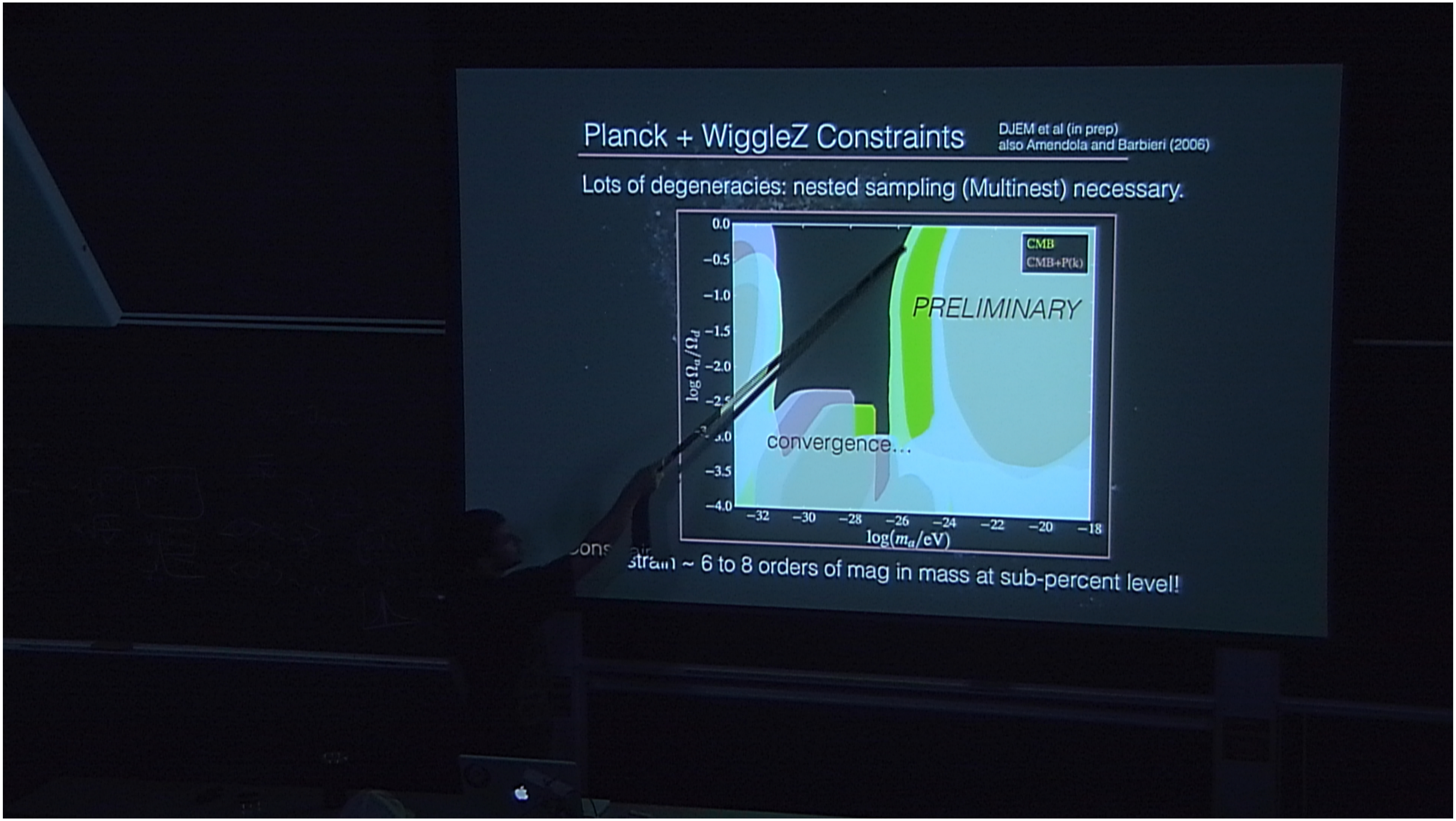


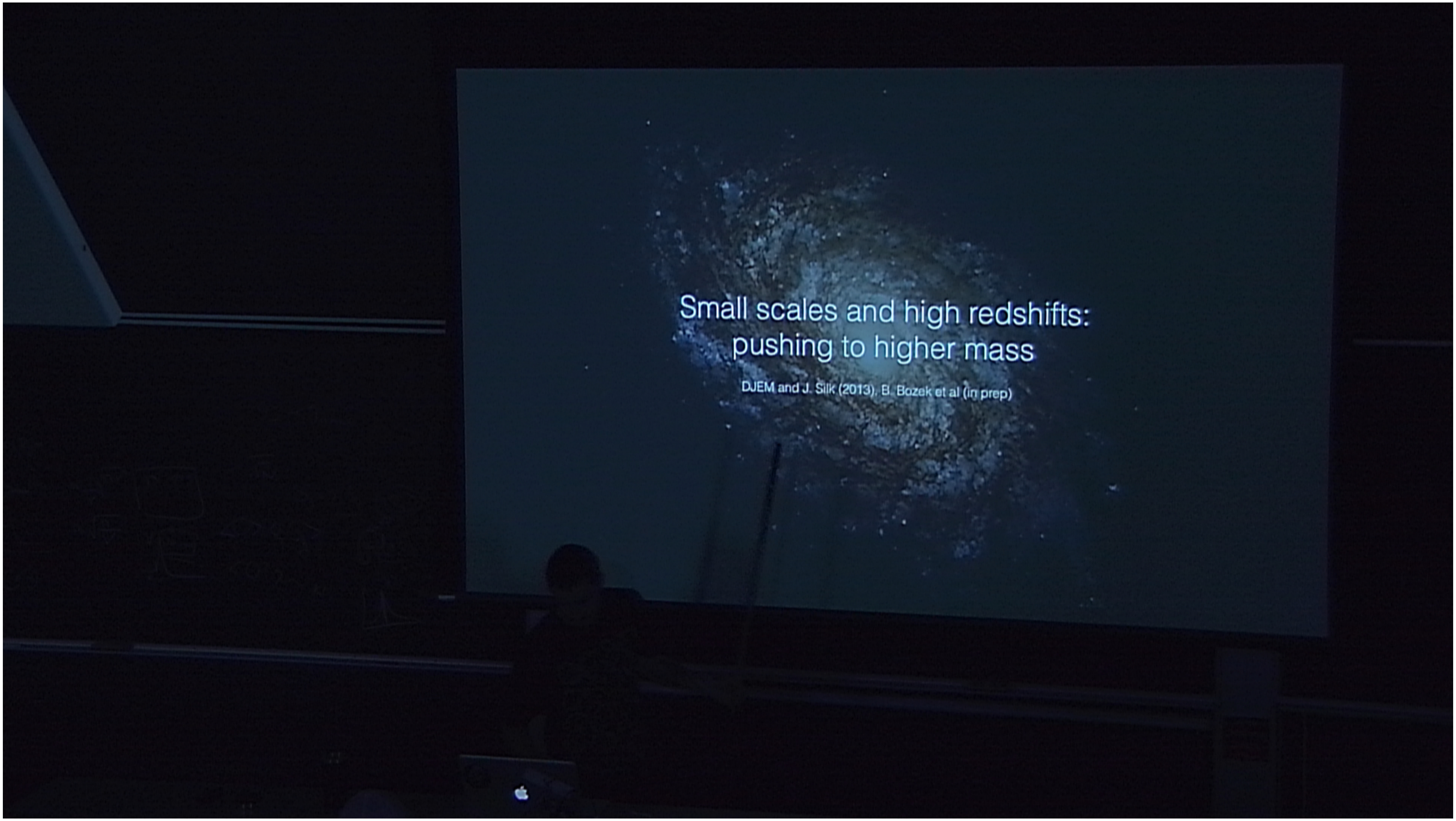
Clustering of axions: de Broglie scale
✧ Fluid approximation for density perturbations.
$\ddot{\delta} + \mathcal{H}\delta + (k^2 c_s^2 - 4\pi G a^2 \rho)\delta = 0$
Oscillations (sound-speed)
Linear Growth
✧ Transition to no growth at large wavenumber: "Jeans" scale.
$c_s^2 \approx \frac{k^2}{4m_a^2 a^2} \Rightarrow k_J \sim m_a^{1/2}\rho^{1/4} \sim \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} 10^2\, h\mathrm{Mpc}^{-1}$
✧ Implemented in CMB Boltzmann code: axionCAMB.

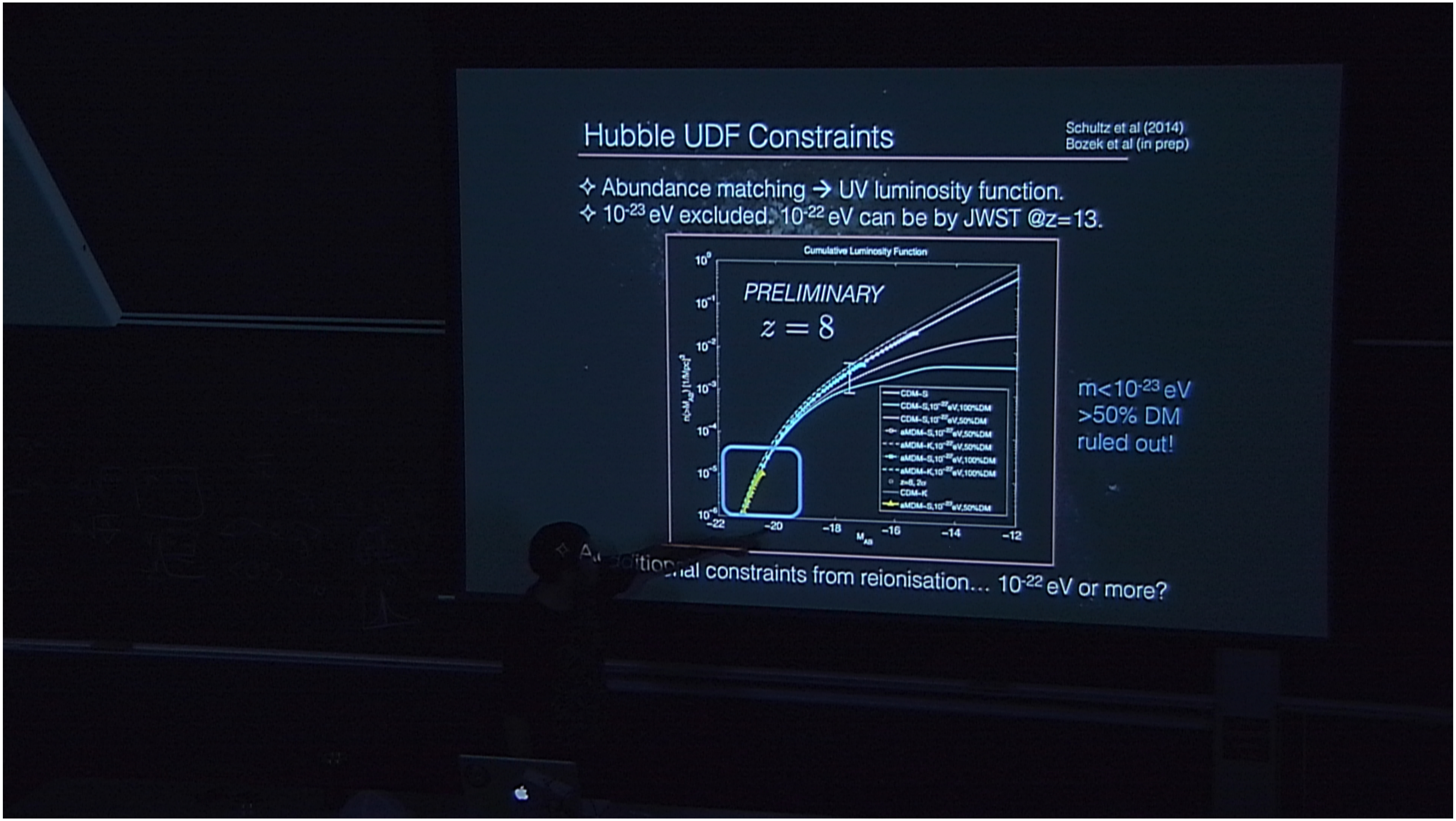

Clustering of axions: de Broglie scale
✧ Fluid approximation for density perturbations.
$\ddot{\delta} + \mathcal{H}\delta + (k^2 c_s^2 - 4\pi G a^2 \rho)\delta = 0$
Oscillations
(sound-speed)
Linear Growth
✧ Transition to no growth at large wavenumber: "Jeans" scale.
$c_s^2 \approx \frac{k^2}{4m_a^2 a^2} \Rightarrow k_J \sim m_a^{1/2}\rho^{1/4} \sim \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} 10^2\, h\mathrm{Mpc}^{-1}$
✧ Implemented in CMB Boltzm n code: axionCAMB.



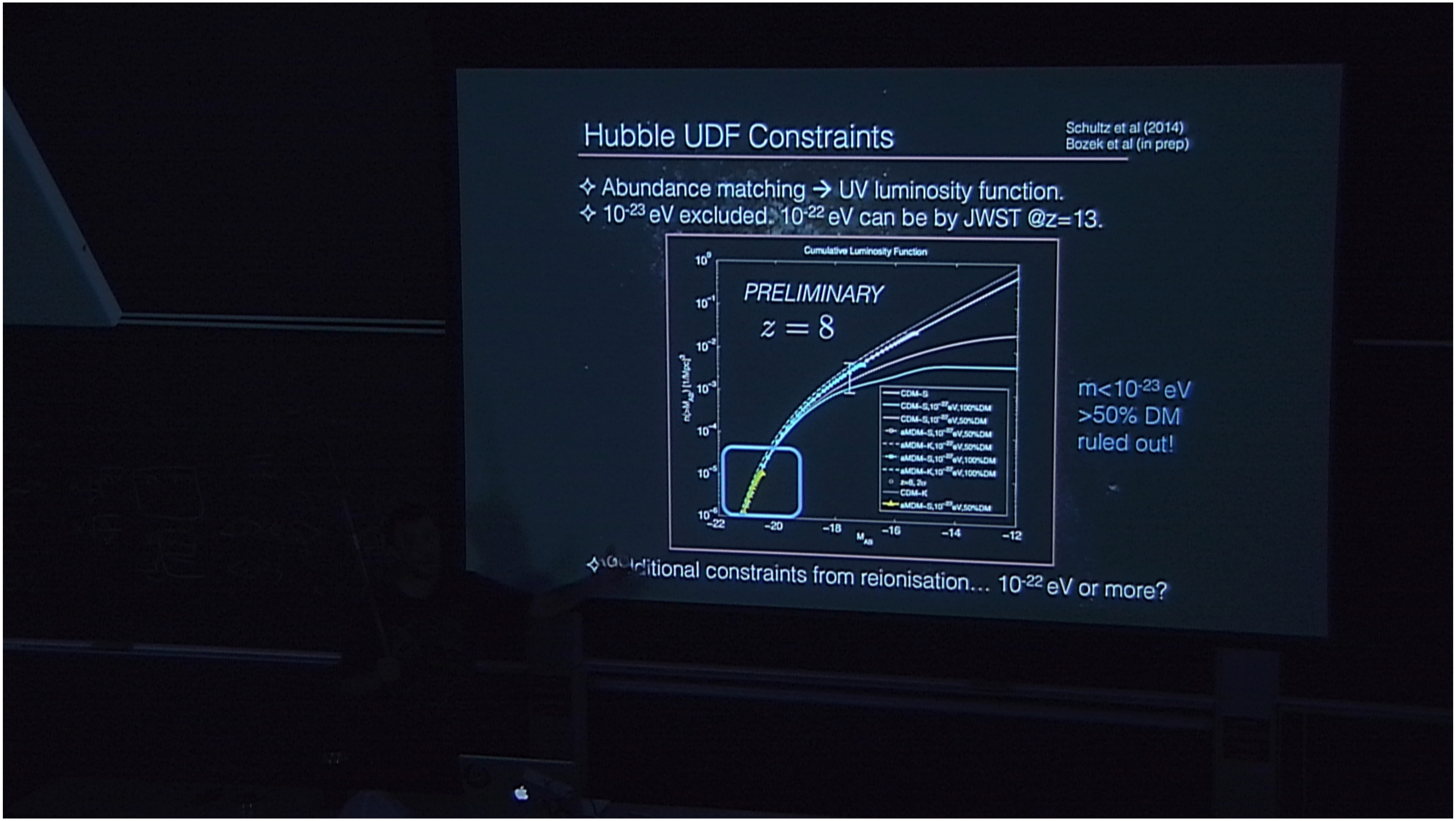
Matter Power Spectrum: Jeans Scale
✧ Galaxy power spectrum measures clustering.
✧ Sound speed → "Quantum pressure" → suppress power.
$P(k)$ [$(h^{-1}$ Mpc$)^3$]
10^4
10^3
LCDM ($m_a \to \infty$)
$f_{ax} = 1, m_a = 10^{-24}$ eV
$f_{ax} = 1, m_a = 10^{-25}$ eV
$f_{ax} = 1, m_a = 10^{-26}$ eV
$f_{ax} = 1, m_a = 5 \times 10^{-27}$ eV
$f_{ax} = 1, m_a = 10^{-27}$ eV
SDSS
10^{-2}
10^{-1}
k [h Mpc^{-1}]
LCDM ($f_{ax} \to 0$)
$f_{ax} = 0.01, m_a = 10^{-27}$ eV
$f_{ax} = 0.05, m_a = 10^{-27}$ eV
$f_{ax} = 0.1, m_a = 10^{-27}$ eV
$f_{ax} = 0.5, m_a = 10^{-27}$ eV
$f_{ax} = 1, m_a = 10^{-27}$ eV
SDSS
10^{-2}
10^{-1}
k [h Mpc^{-1}]
All DM: increase mass
10^{-27} eV$\leq m_a \leq 10^{-24}$ eV
Fix mass: reduce DM contribution
Data: Sloan Digital Sky Survey (2010)


Planck + WiggleZ Constraints
DJEM et al (in prep)
also Amendola and Barbieri (2006)
Lots of degeneracies: nested sampling (Multinest) necessary.
CMB
CMB+P(k)
PRELIMINARY
convergence...
log(m_a/eV)
strain ~ 6 to 8 orders of mag in mass at sub-percent level!

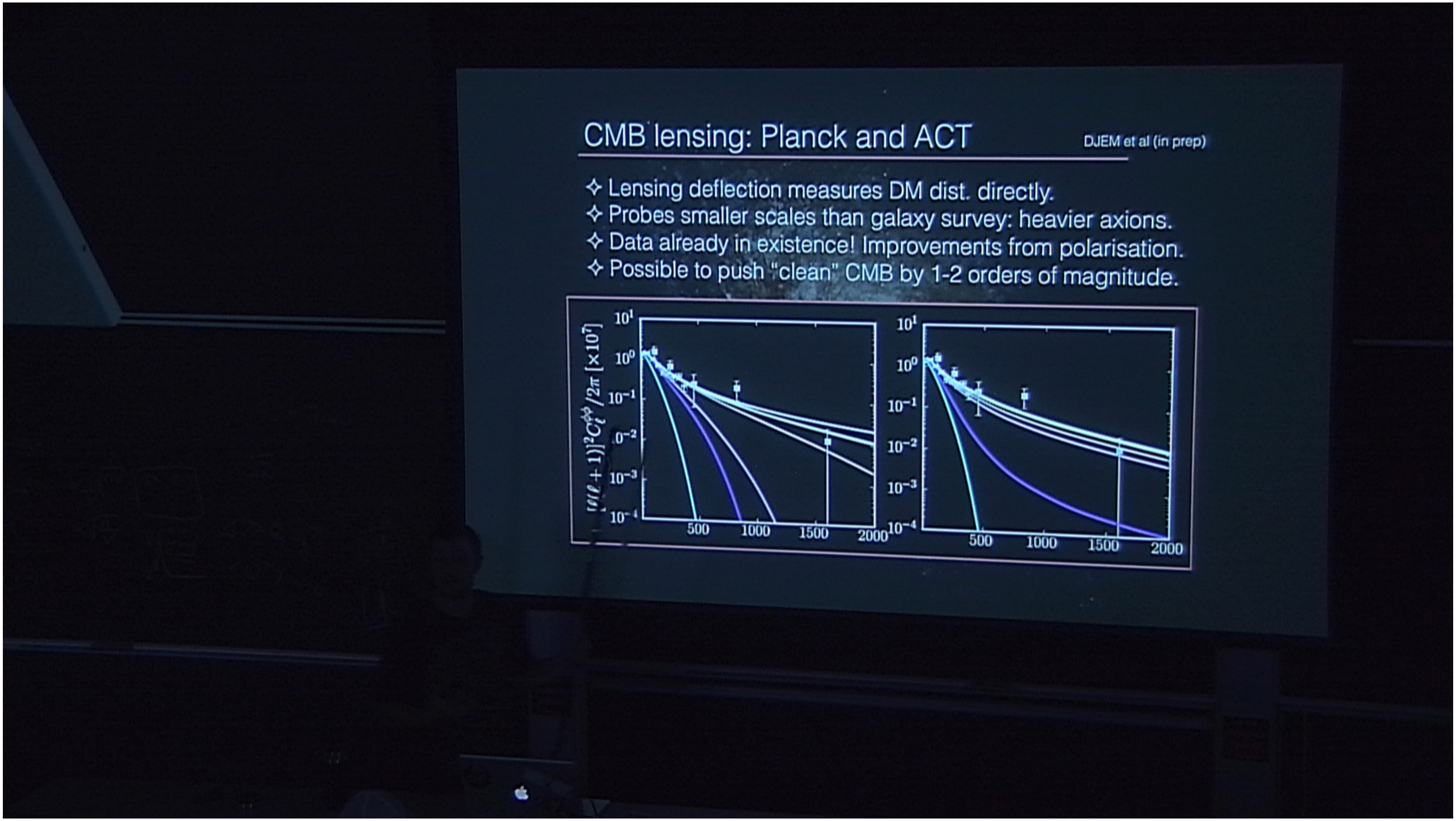

Small scales and high redshifts:
pushing to higher mass
DJEM and J. Silk (2013), B. Bozek et al (in prep)



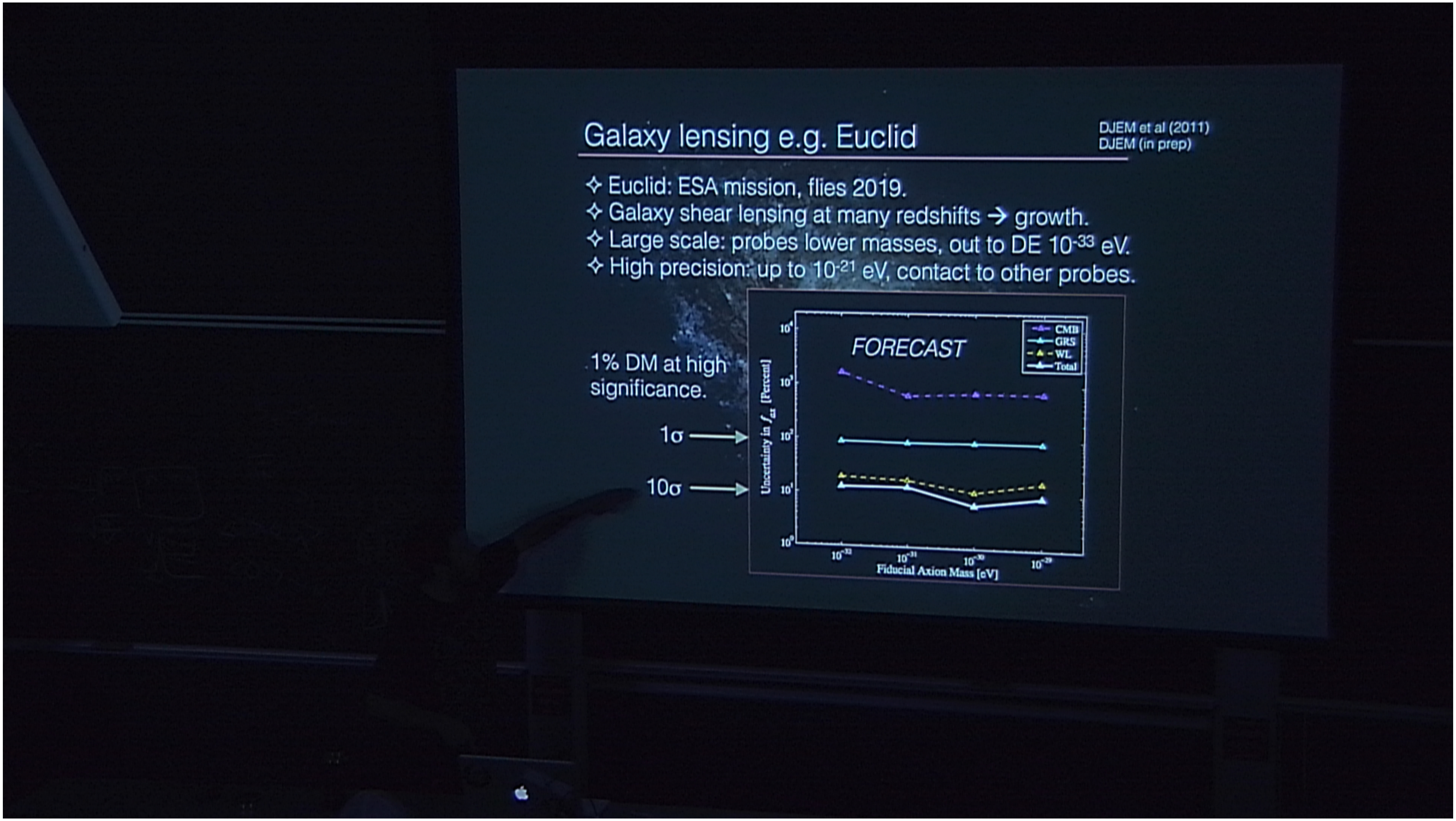
Hubble UDF Constraints
Schultz et al (2014)
Bozek et al (in prep)
✧ Abundance matching → UV luminosity function.
✧ 10^{-23} eV excluded. 10^{-22} eV can be by JWST @z=13.
Cumulative Luminosity Function
PRELIMINARY
$z = 8$
CDM-S
CDM-K
M_{AB}
m<10^{-23} eV
>50% DM
ruled out!
al constraints from reionisation… 10^{-22} eV or more?

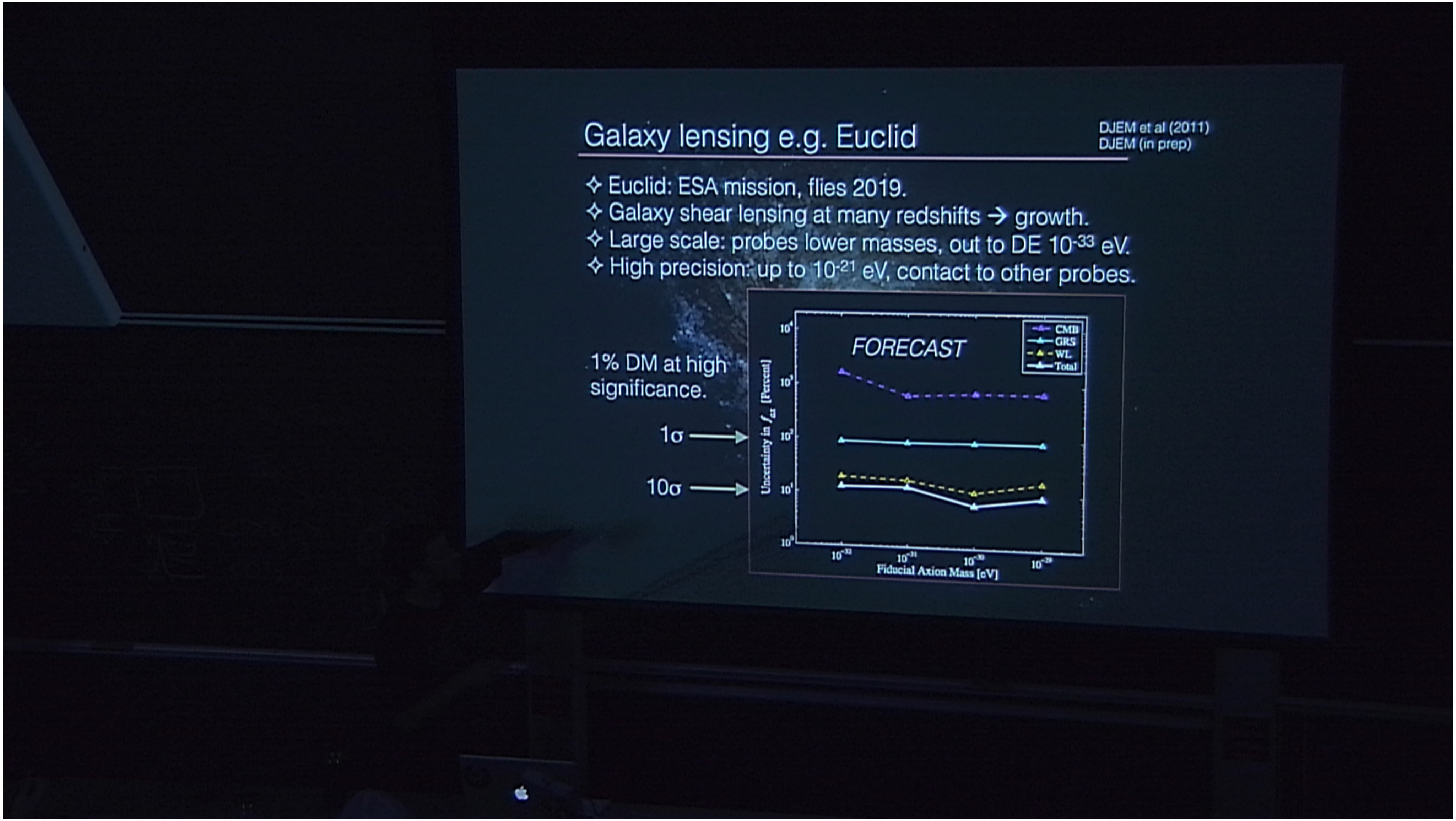


Hubble UDF Constraints
Schultz et al (2014)
Bozek et al (in prep)
✧ Abundance matching → UV luminosity function.
✧ 10^{-23} eV excluded. 10^{-22} eV can be by JWST @z=13.
Cumulative Luminosity Function
PRELIMINARY
$z = 8$
CDM-S
CDM-S,10^{-22}eV,100%DM
CDM-S,10^{-22}eV,50%DM
aMDM-S,10^{-22}eV,50%DM
aMDM-K,10^{-22}eV,50%DM
aMDM-S,10^{-22}eV,100%DM
aMDM-K,10^{-22}eV,100%DM
CDM-K
aMDM-S,10^{-23}eV,50%DM
M_{AB}
m<10^{-23} eV
>50% DM
ruled out!
✧ ...ditional constraints from reionisation… 10^{-22} eV or more?



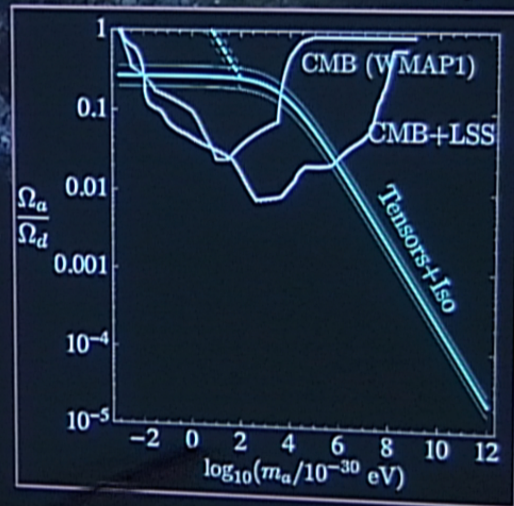
CMB lensing: Planck and ACT
DJEM et al (in prep)
✧ Lensing deflection measures DM dist. directly.
✧ Probes smaller scales than galaxy survey: heavier axions.
✧ Data already in existence! Improvements from polarisation.
✧ Possible to push "clean" CMB by 1-2 orders of magnitude.


Galaxy lensing e.g. Euclid
DJEM et al (2011)
DJEM (in prep)
✧ Euclid: ESA mission, flies 2019.
✧ Galaxy shear lensing at many redshifts → growth.
✧ Large scale: probes lower masses, out to DE 10^-33 eV.
✧ High precision: up to 10^-21 eV, contact to other probes.
1% DM at high significance.
1σ
10σ
FORECAST
CMB
GRS
WL
Total
Uncertainty in f_ax [Percent]
Fiducial Axion Mass [eV]

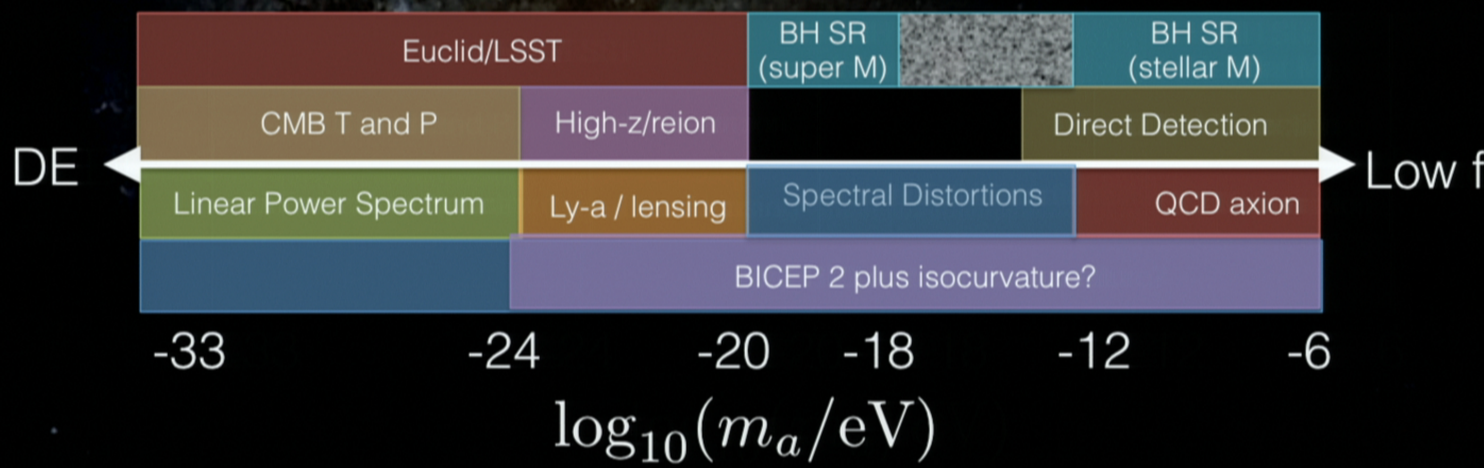

Galaxy lensing e.g. Euclid
DJEM et al (2011)
DJEM (in prep)
✧ Euclid: ESA mission, flies 2019.
✧ Galaxy shear lensing at many redshifts → growth.
✧ Large scale: probes lower masses, out to DE 10-33 eV.
✧ High precision: up to 10-21 eV, contact to other probes.
1% DM at high significance.
1σ
10σ
FORECAST
CMB
GRS
WL
Total
Uncertainty in f_ax [Percent]
Fiducial Axion Mass [eV]

Ultra-light Axions (II): Constraints

WMAP1/LSS: Amendola+2005. LSS assumes Ly-a valid.
Complimentary: push further, test consistency.



Summary



Cosmology can constrain ~13 orders of magnitude in axion mass, at percent or smaller fraction of the DM

(if BICEP2 holds up: even stronger!)

✧ Lensing and high-z observations can bridge gap to BHSR.
✧ Motivated by small-scale problems of CDM…


Planck + Wi
al (in prep)
endola and Barbieri (2006)
Lots of degenerac
itinest) necessary.
CMB
PRELIMINARY
convergence…
Constrain ~ 6 to 8 orders
ub-percent level!