Title: Superfluid Dark Matter

Date: Oct 20, 2015 11:00 AM

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Abstract: <p>I will talk about a novel theory of dark matter superfluidity that matches the success of LCDM model on cosmological scales while simultaneously reproducing the MOND phenomenology on galactic scales.</p>

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October 20, 2015

LB, Justin Khoury arXiv:1506.07877, arXiv:1507.01019


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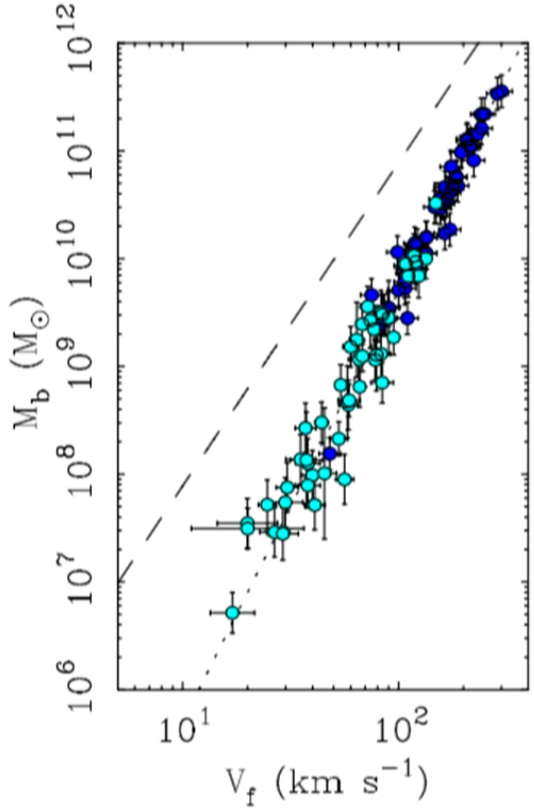
DM halos have cuspy cores $\rho \sim r^{-1}$.

Flat rotation curves require $\rho \sim r^{-2}$.

BTFR:



$M_b \sim v_c^4$

CDM: $M_{vir} \sim v_{vir}^3$

Famaey and McGaugh '12

MOND:

Milgrom '83

$$a = \begin{cases} a_{\mathrm{N}} & a_{\mathrm{N}} \gg a_0 \\ \sqrt{a_{\mathrm{N}} a_0} & a_{\mathrm{N}} \ll a_0 \end{cases}$$

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MOND fails on cosmological scales.

DM-MOND Hybrids:

MOND and CDM are each successful in mutually exclusive regimes.

Hybrids consist of two distinct components: DM component and modified-gravity component.

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Fractional Powers?

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Upon BEC, it exhibits the superfluidity.

EFT for phonons is

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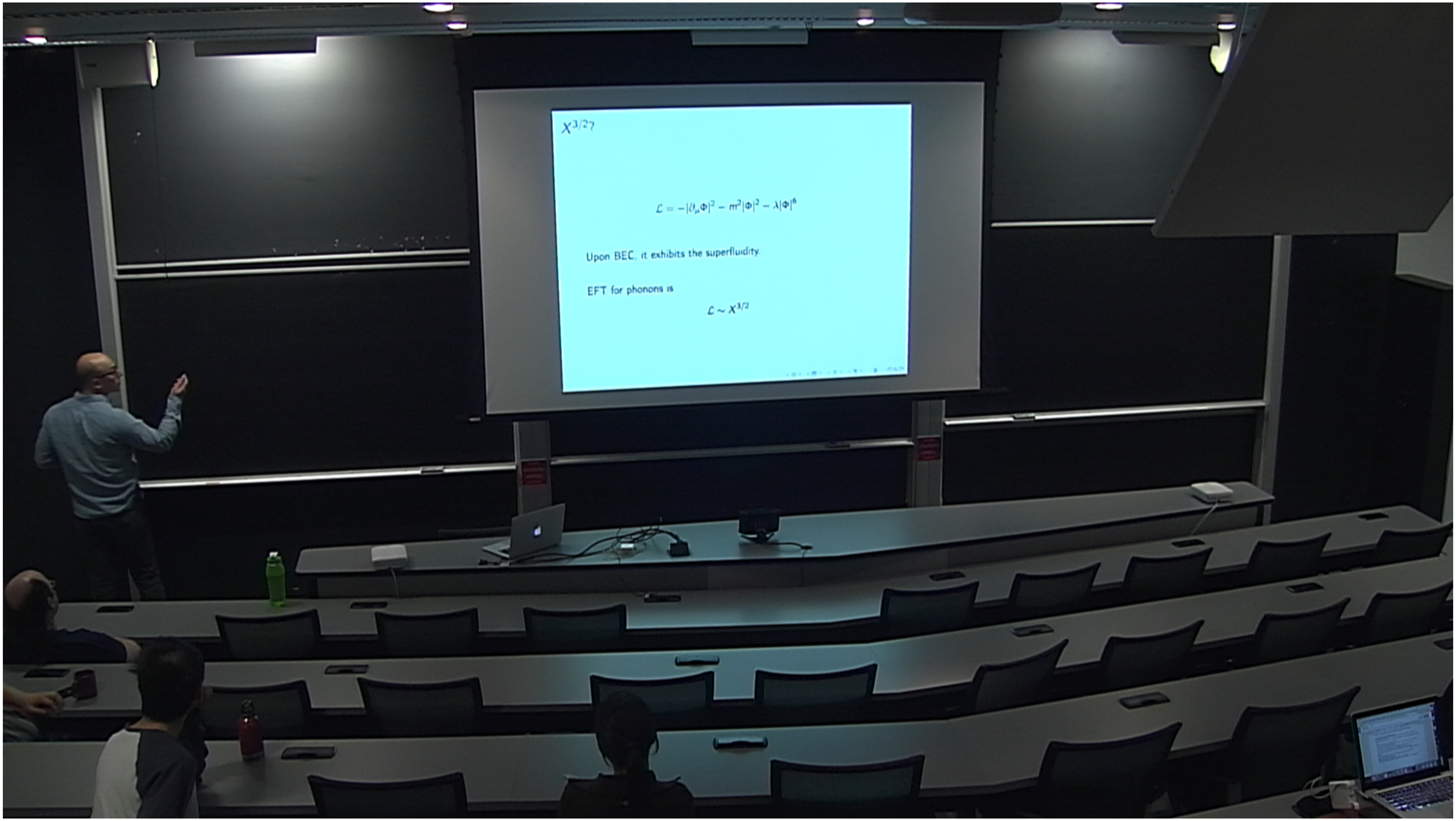
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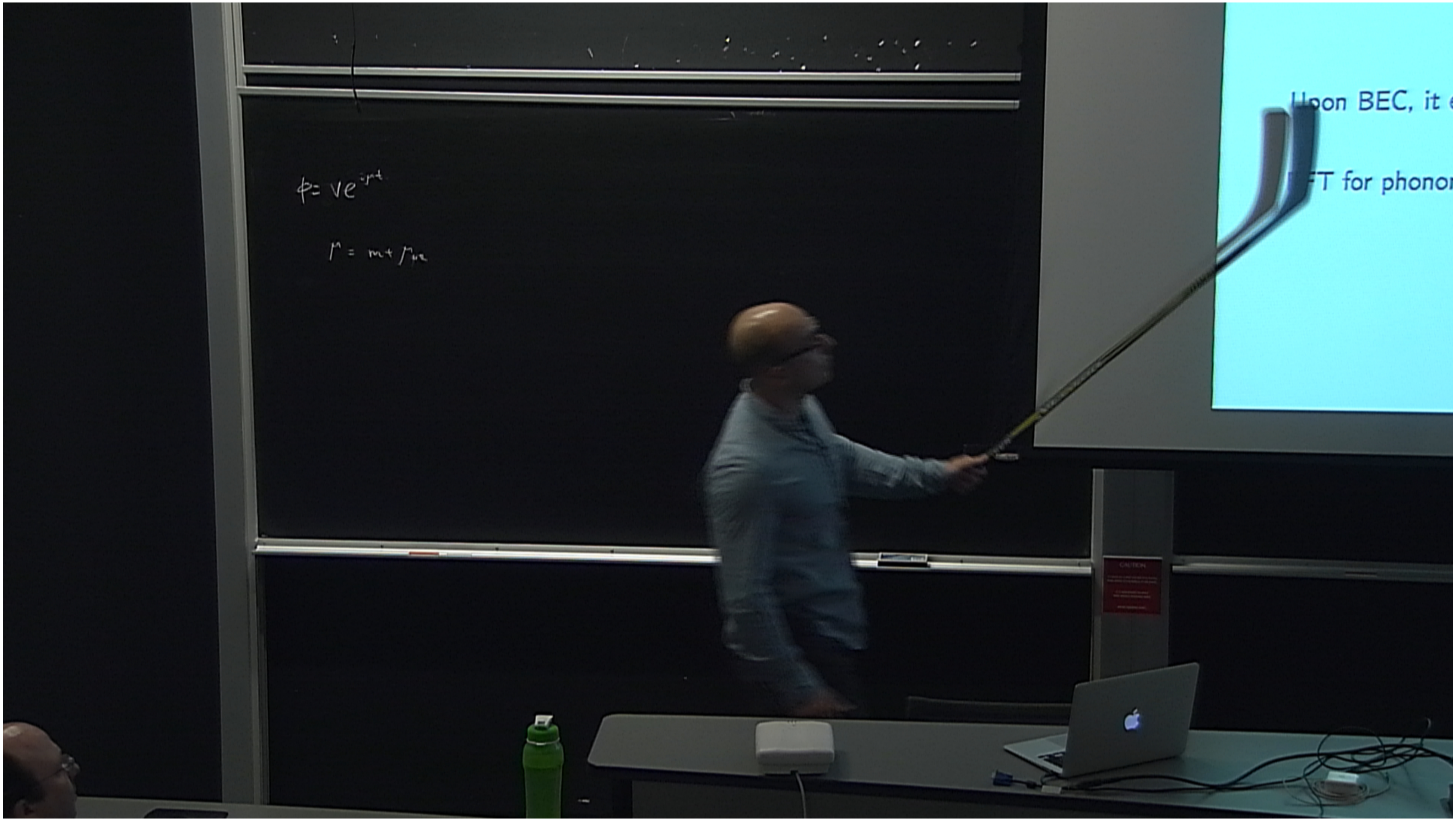
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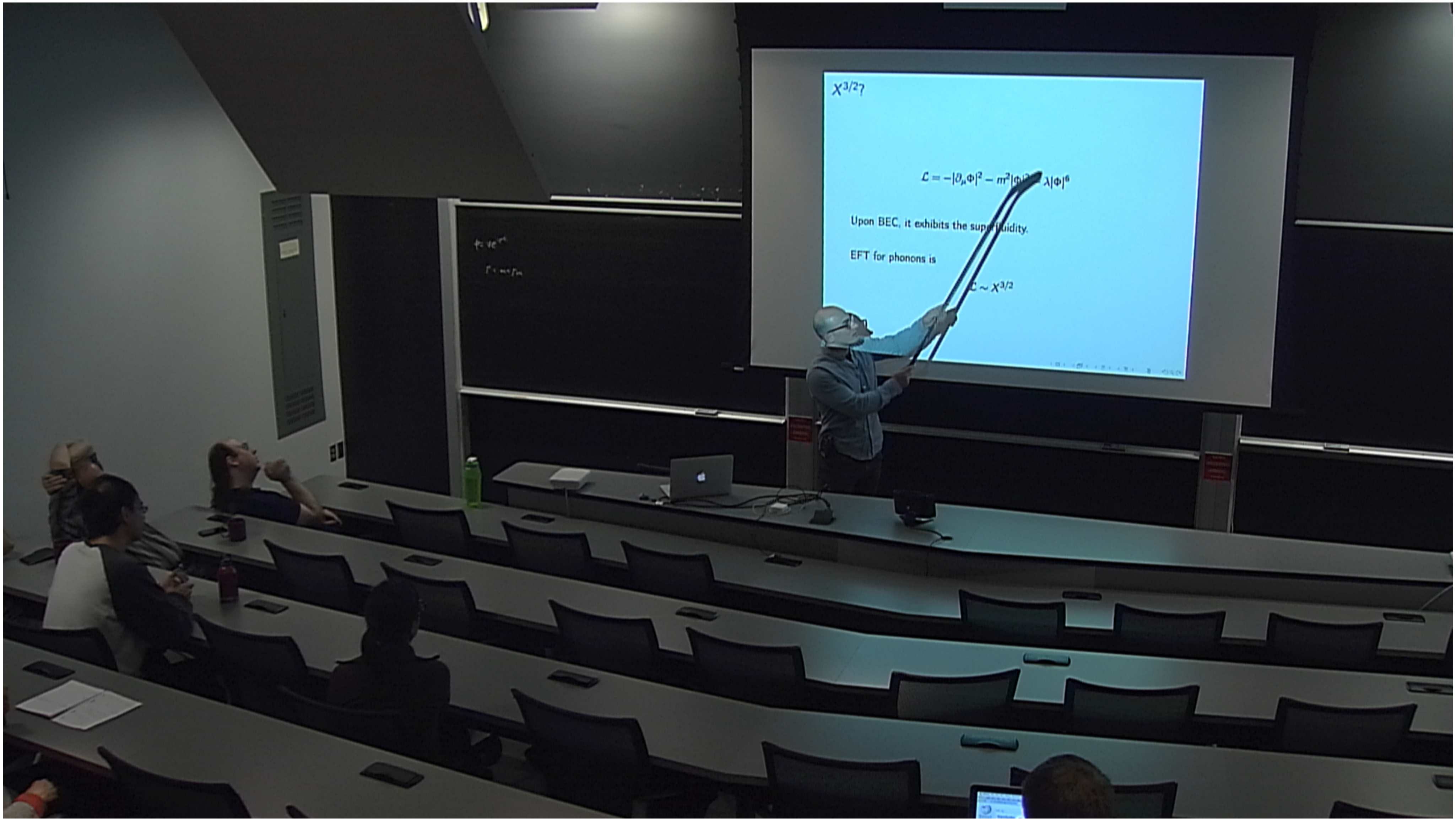
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BEC of Dark Matter

For degeneracy

$$\lambda_{\rm dB} \sim \frac{1}{mv} \qquad > \qquad \ell \equiv \left(\frac{m}{\rho}\right)^{1/3}$$

BEC of Dark Matter

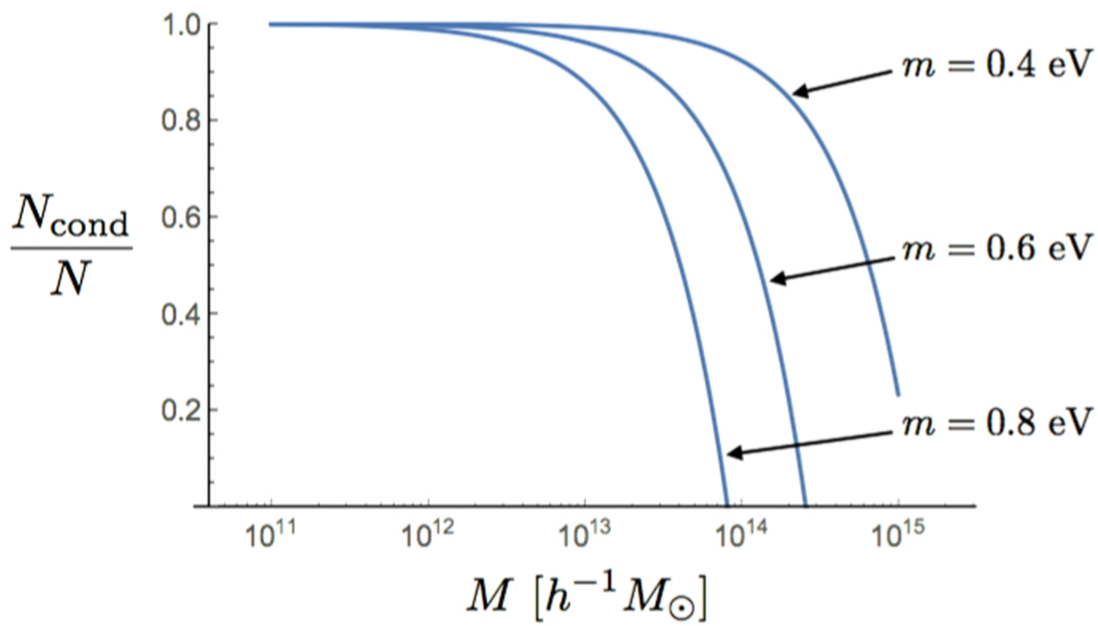
Thermalization requirement

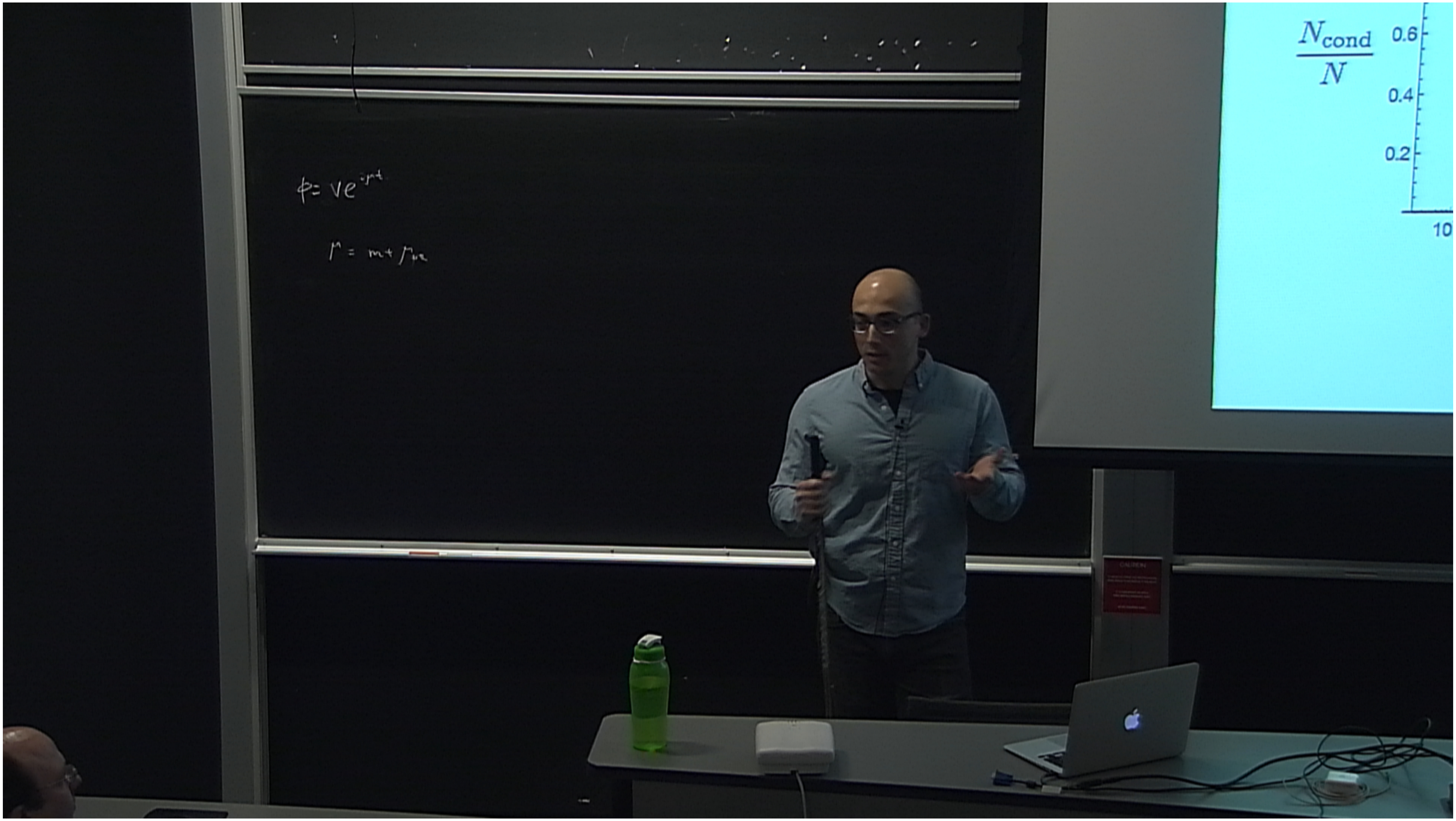
$$\Gamma \gtrsim t_{\rm dyn}^{-1}$$

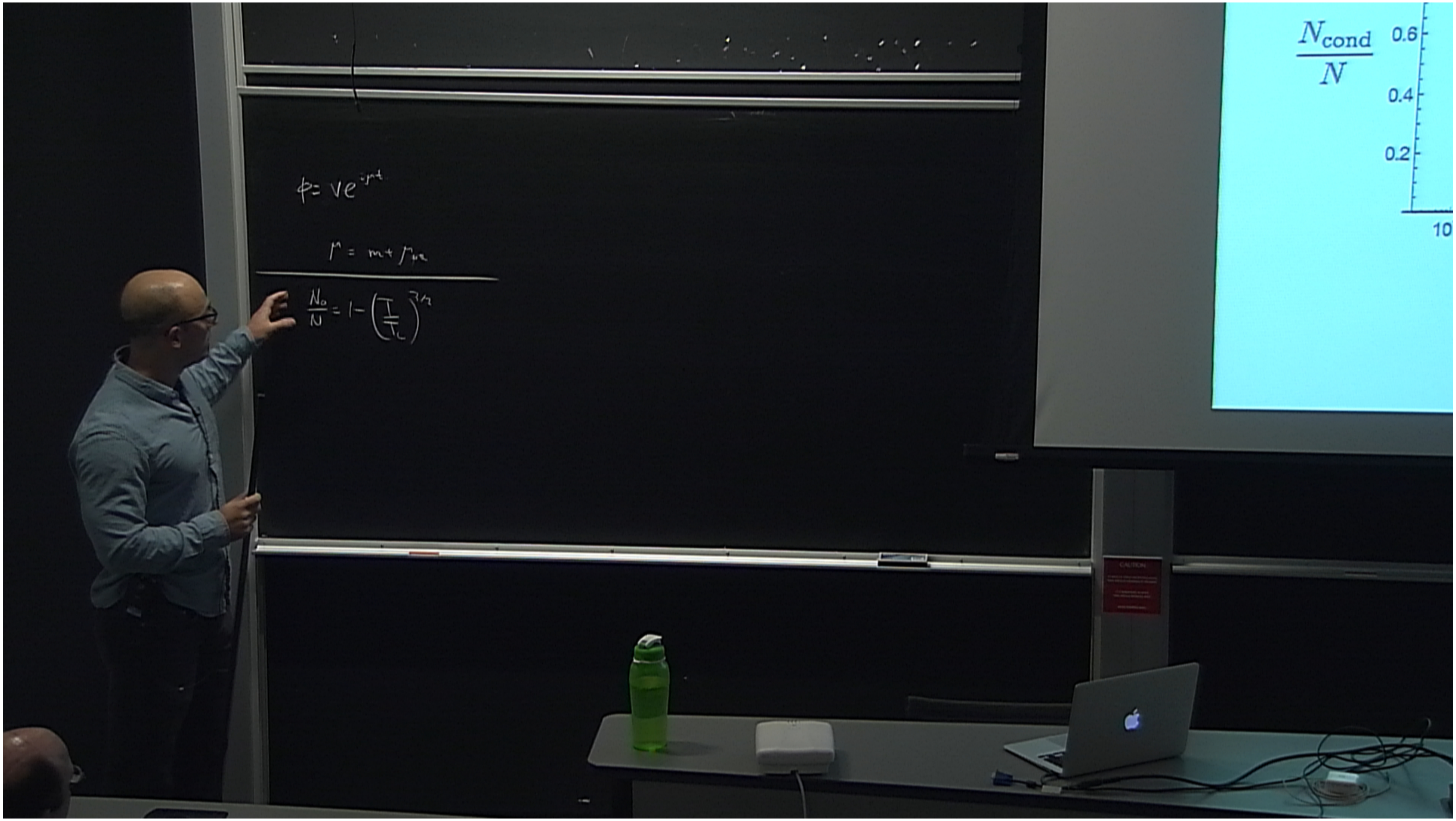
For Milky Way-like galaxy

$$\frac{\sigma}{m} \gtrsim \left(\frac{m}{\rm eV}\right)^4 \frac{\rm cm^2}{\rm g}$$

Halo as a Superfluid at Finite Temperature




$\phi = v e^{i\mu t}$
$\mu = m + \mu_{nr}$
$\frac{N_{cond}}{N}$
0.6
0.4
0.2
10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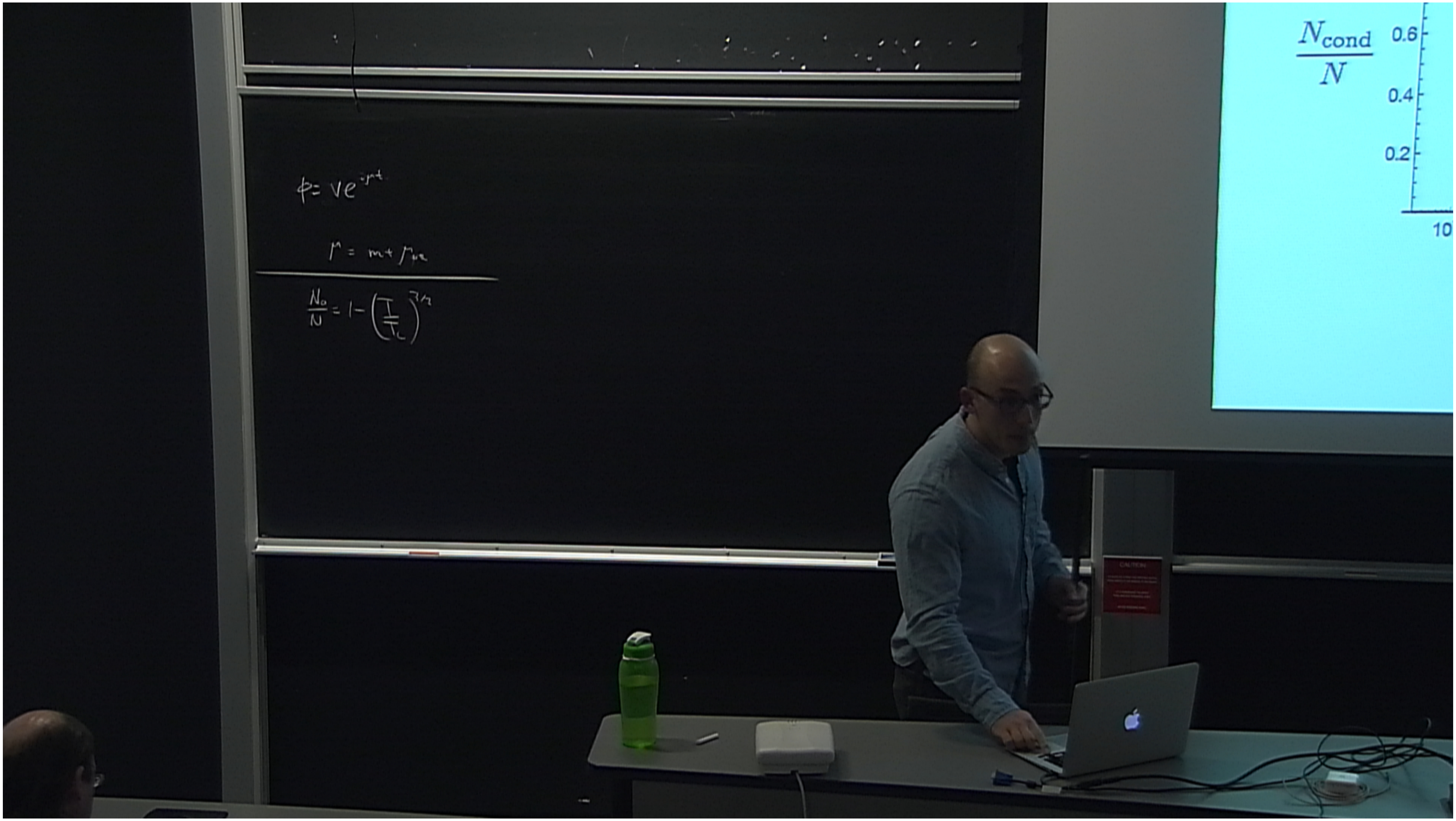

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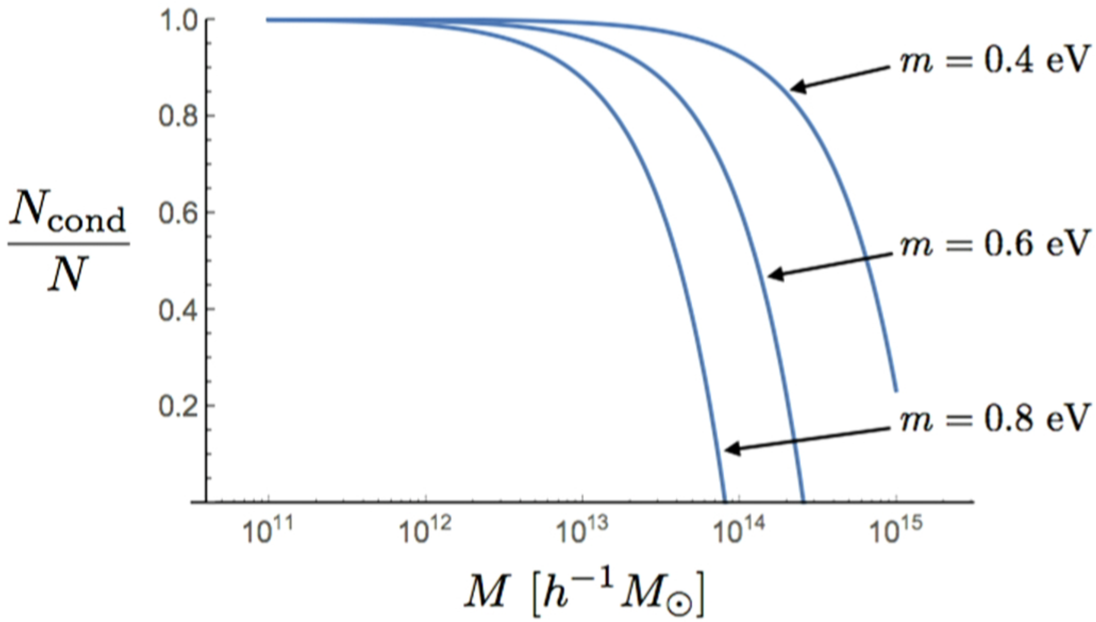

Cosmology:

DM in sub-eV mass range must be produced out of equilibrium. For instance, through axion-like vacuum displacement mechanism.

DM particles are generated when $H \sim m$, corresponding to

$$T_{\text{baryons}} \sim \sqrt{mM_{\text{pl}}} \sim 50 \text{ TeV}$$

Superfluid Properties:

Low energy degrees of freedom are phonons.
In general

$$\mathcal{L} = P(X), \qquad \text{with} \qquad X \equiv \mu + \dot{\varphi} - \frac{(\vec{\nabla}\varphi)2}{2m}$$

We conjecture that the superfluid has MOND-like action

$$P(X) = \Lambda m^{3/2} X \sqrt{|X|}$$

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Superfluid Properties:

The pressure of the condensate is

$$P(\mu) = \Lambda (m\mu)^{3/2}$$

The number density of condensed particles

$$n = \frac{\partial P}{\partial \mu}$$

The equation of state is

$$P = \frac{\rho^3}{12\Lambda^2 m^6}$$

The sound speed is given by $c_s = \sqrt{\frac{2\mu}{m}}$

Halo Profile:

Assuming hydrostatic equilibrium

$$\rho(r) \simeq \rho_0 \cos\left(\frac{\pi}{2}\frac{r}{R}\right); \qquad r \leq R$$

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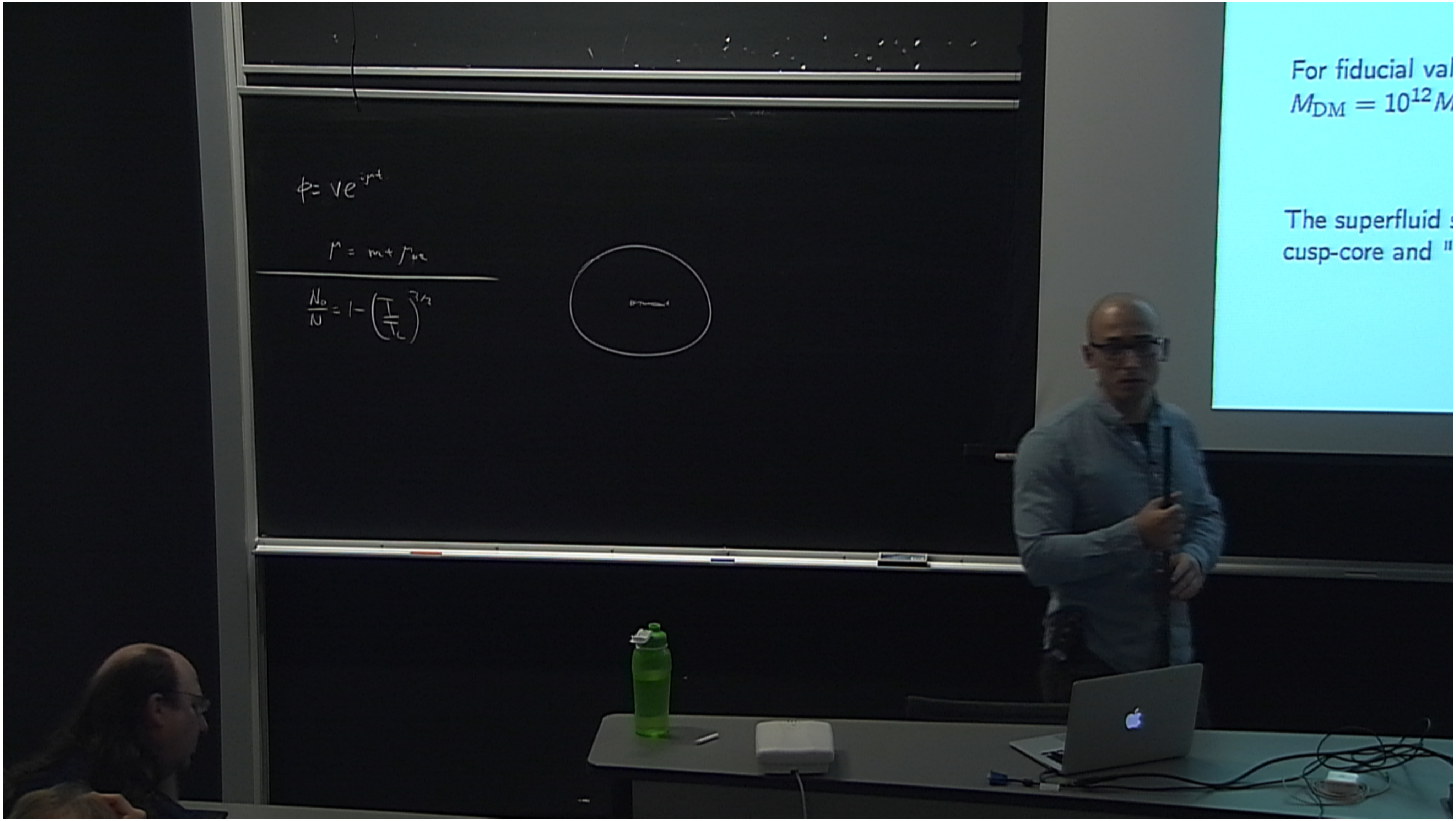
For fiducial values $m = 0.6\ \mathrm{eV}$ and $\Lambda = 0.2\ \mathrm{meV}$, for $M_{\mathrm{DM}} = 10^{12} M_{\odot}$, we have

$$R \simeq 125\ \mathrm{kpc}$$

The superfluid scenario provides the simple resolution to the cusp-core and "too-big-to-fail" problems.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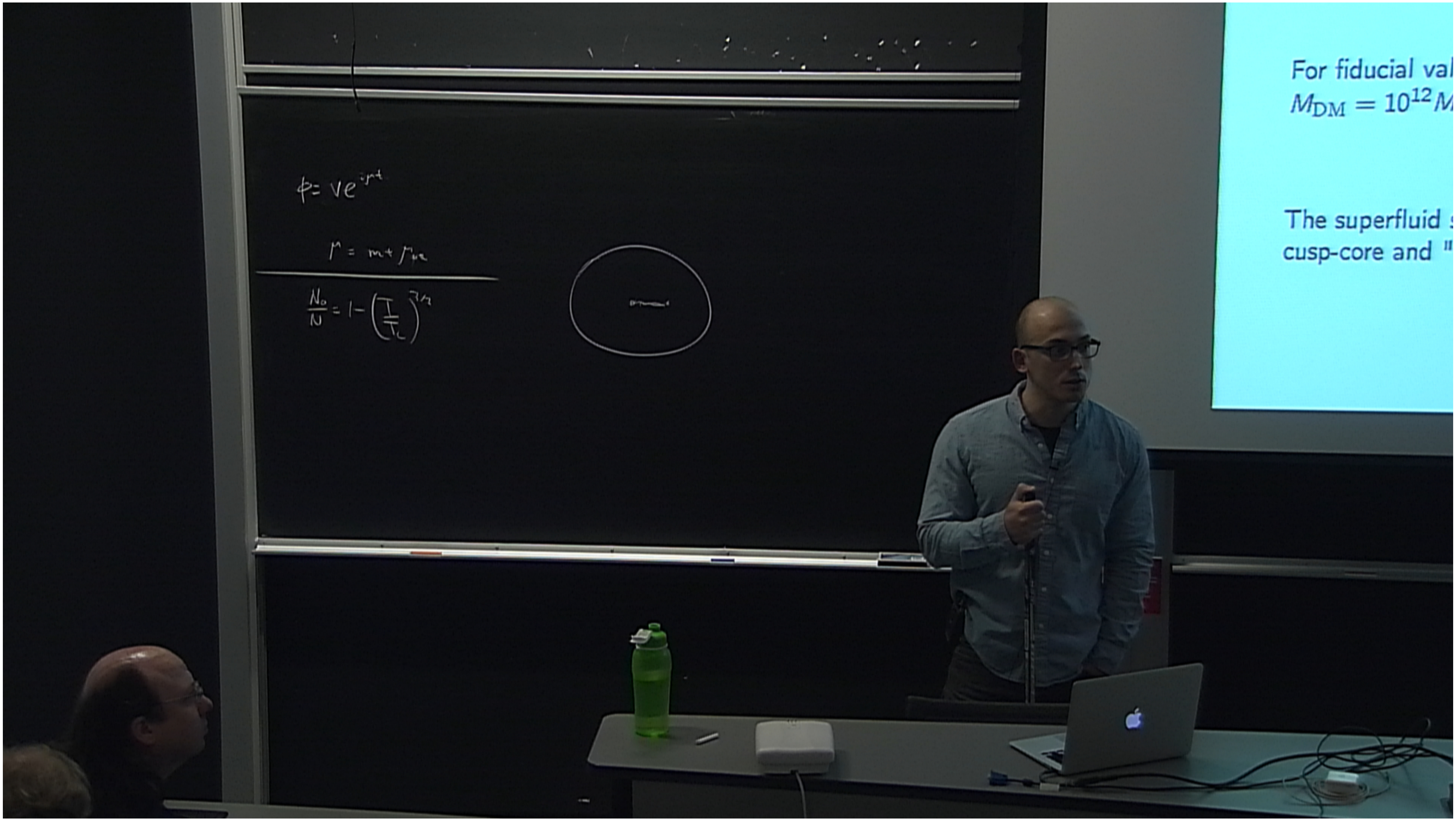
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Phonon-Mediated Force Between Baryons

For large phonon gradients

$$a_\phi(r) = \sqrt{\frac{\alpha^3 \Lambda^2}{M_{\rm Pl}} \frac{G_{\rm N} M_{\rm b}(r)}{r^2}}$$

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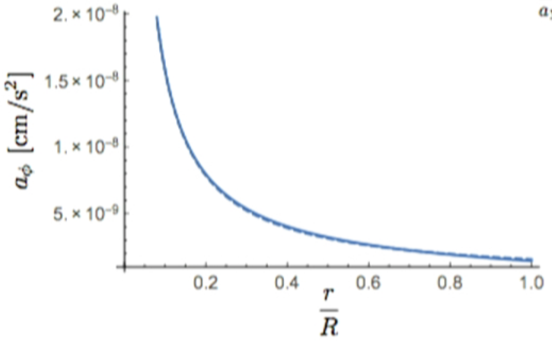

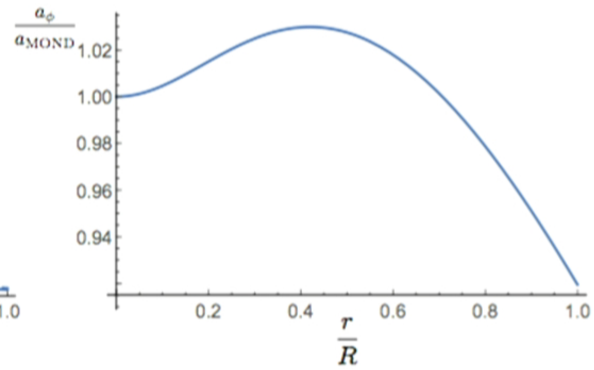

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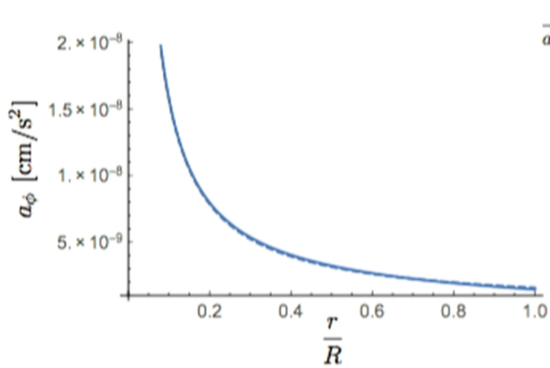

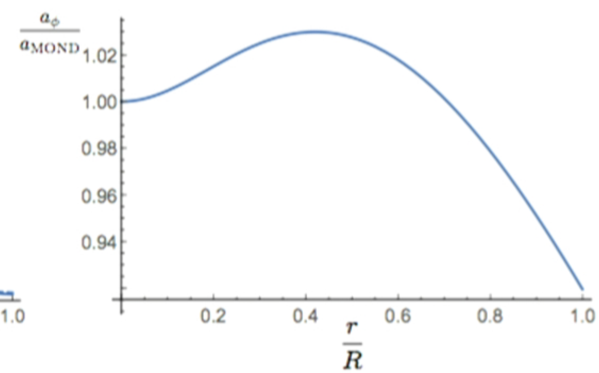

Gravitational force due to DM halo becomes relevant only at $r \sim 70$ kpc.

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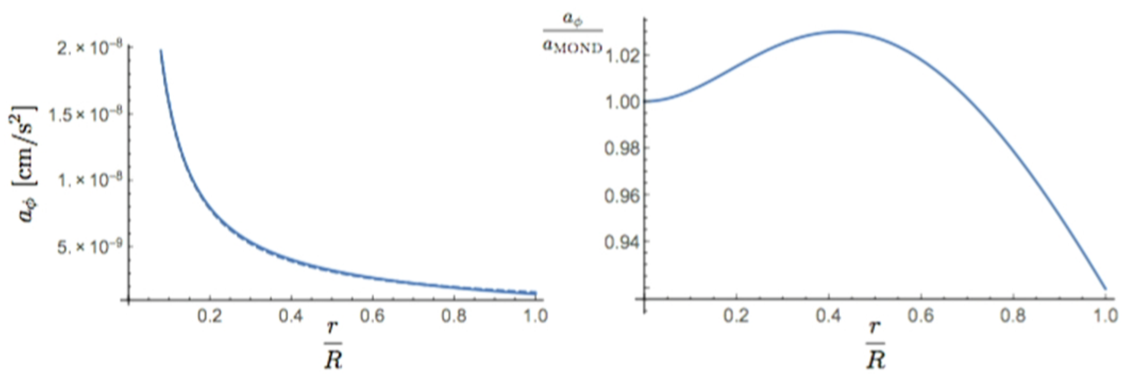

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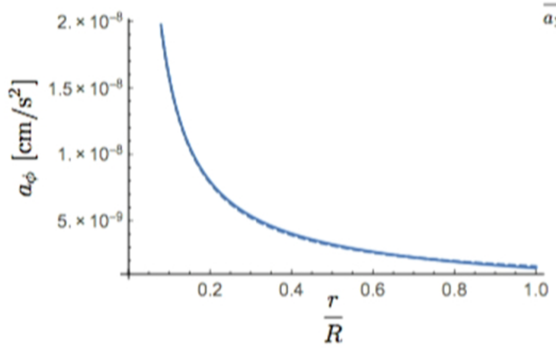
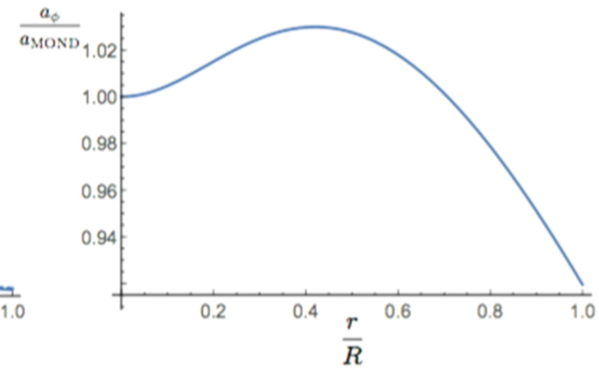
For the stability of perturbations we need to invoke the finite temperature effects.

Phonon-Mediated Force Between Baryons





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Cosmology

$$w = \frac{P}{\rho} = \frac{\rho^2}{12\Lambda^2 m^6}$$

In order to have $w \ll 1$ at matter radiation equality, we need

$$\Lambda \gg 0.5 \text{ eV}$$

This is four orders of magnitude larger than the fiducial value $\Lambda = 0.2 \text{ meV}$ assumed in galaxies.

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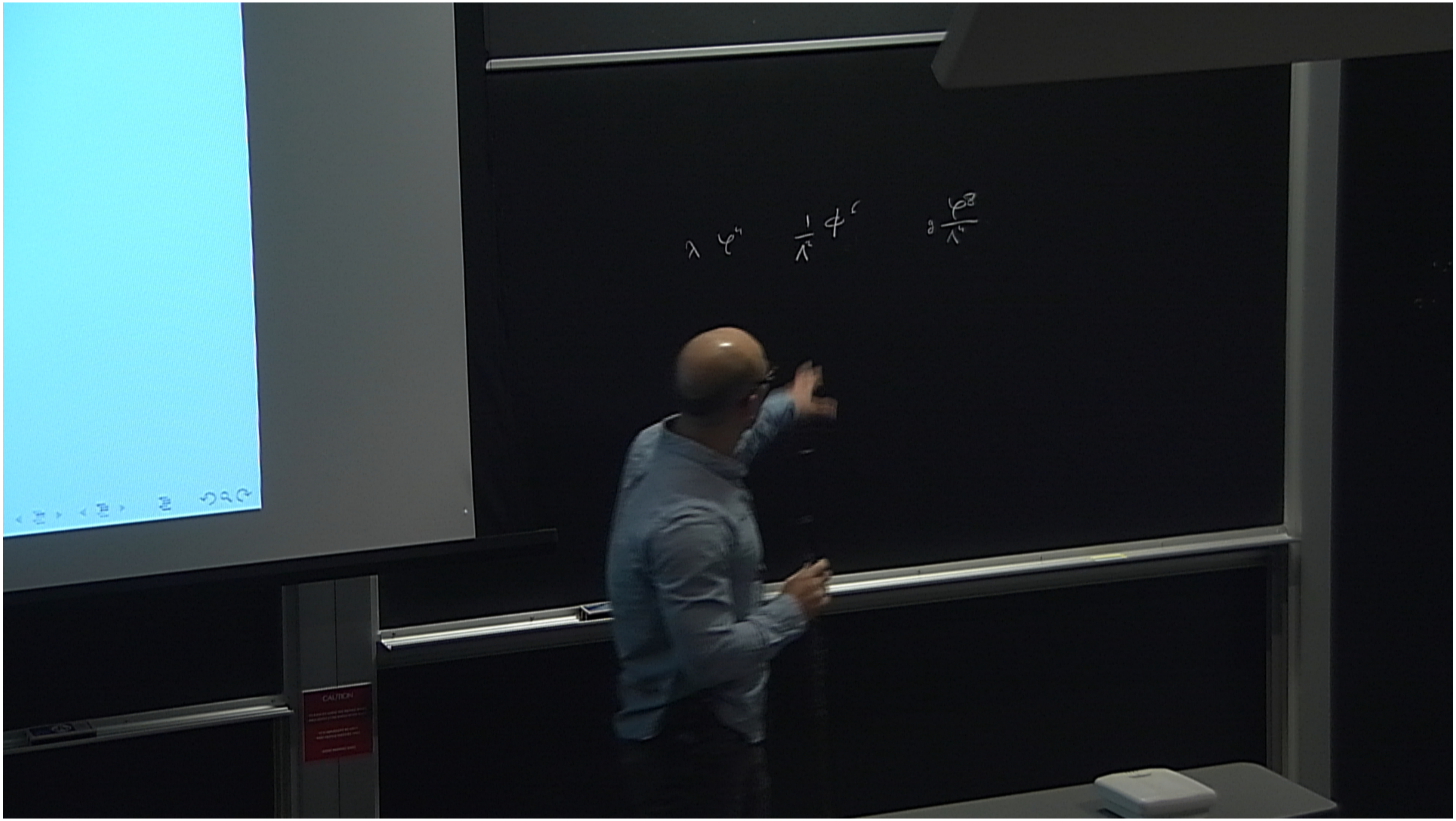
Recall that

$$\left(\frac{T}{T_c}\right)_{\text{cosmo}} \simeq 10^{-28}, \qquad \left(\frac{T}{T_c}\right)_{\text{MW}} \simeq 10^{-2}$$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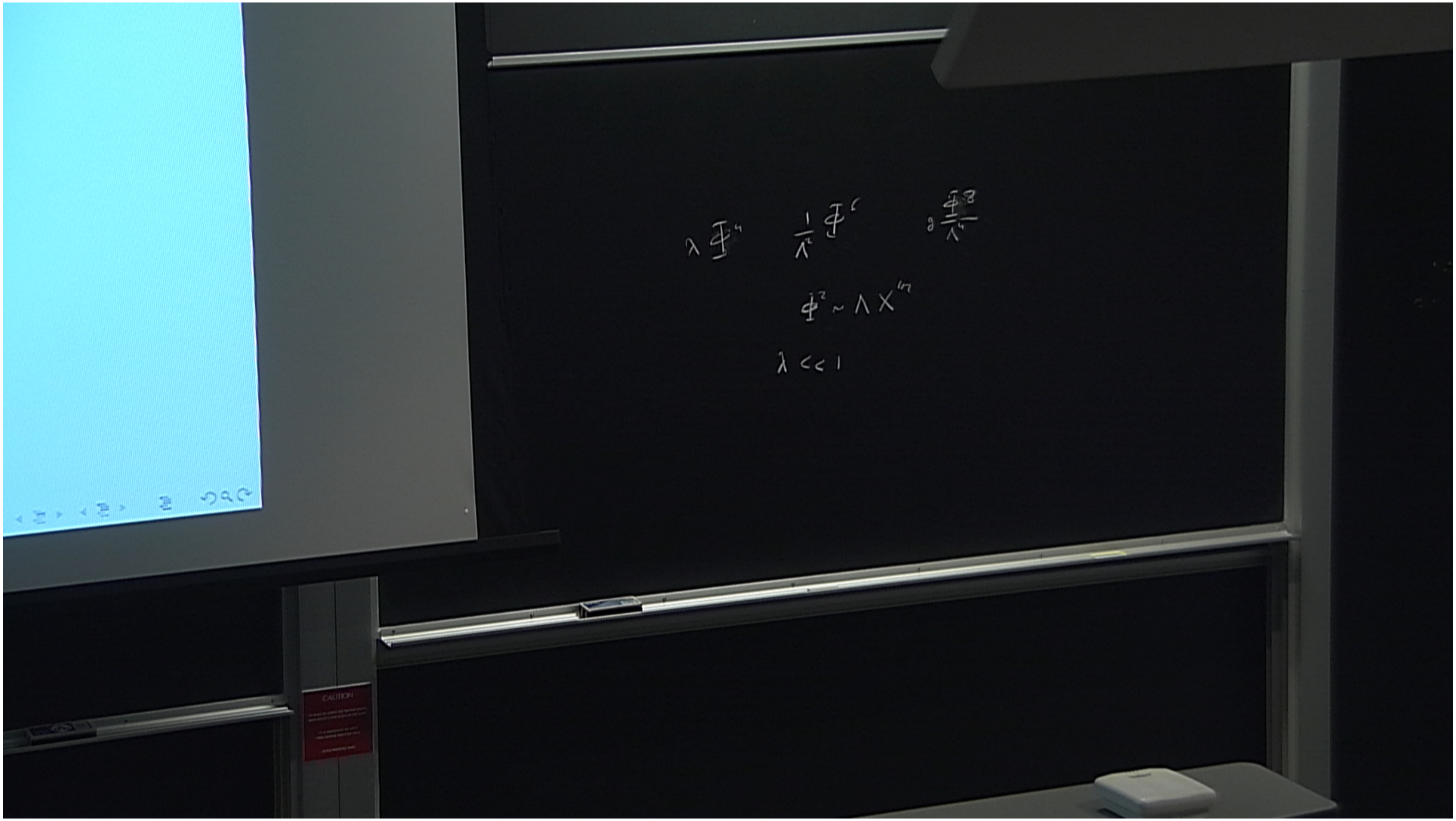
λ << 1