Title: Axions: Past, Present and Future

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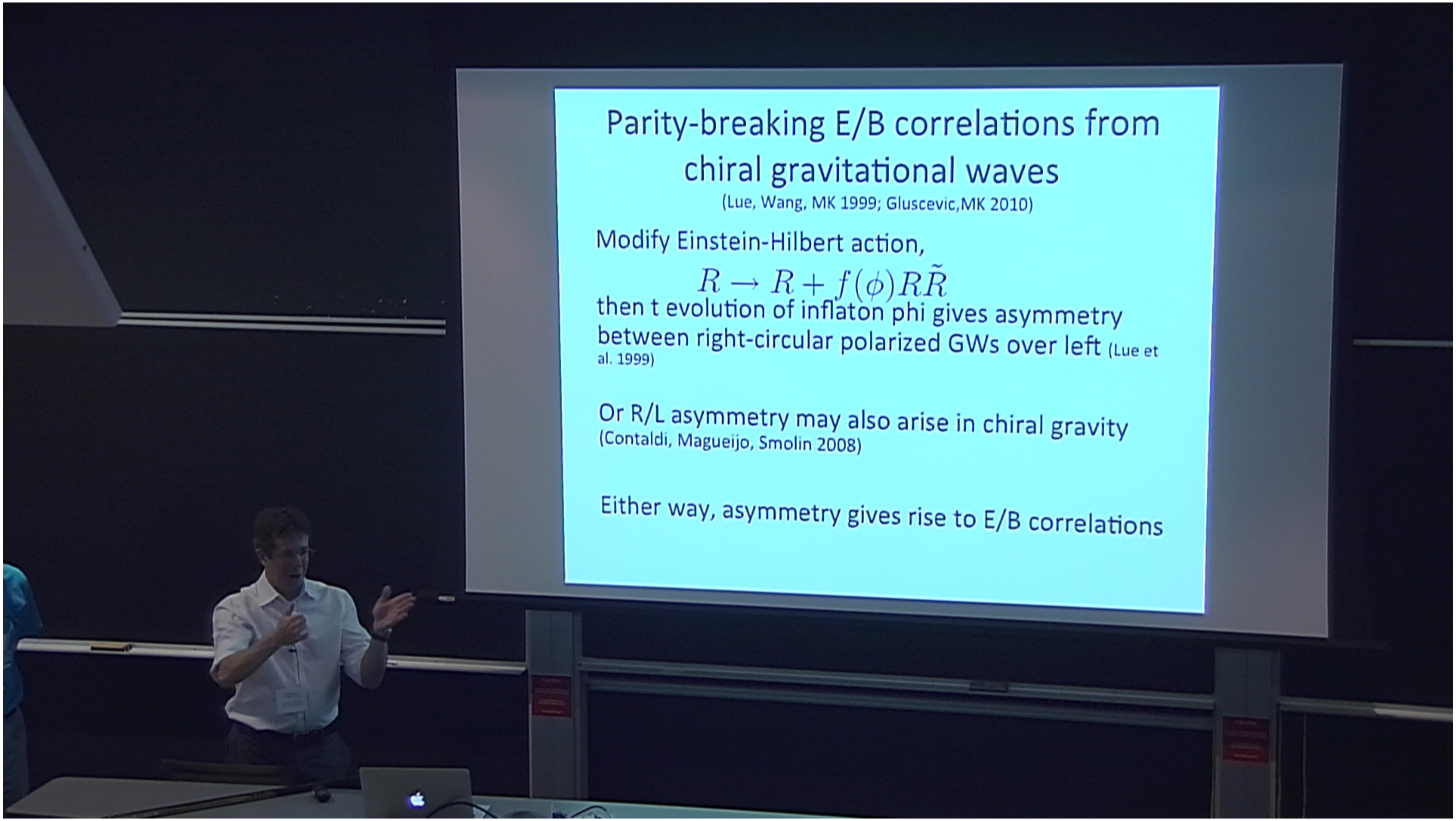
Abstract: I will review the theoretical motivations for axion and axion-like-particles. I will then discuss bounds on such particles and highlight ways to experimentally probe them.



Parity-breaking E/B correlations from chiral gravitational waves

(Lue, Wang, MK 1999; Gluscevic,MK 2010)

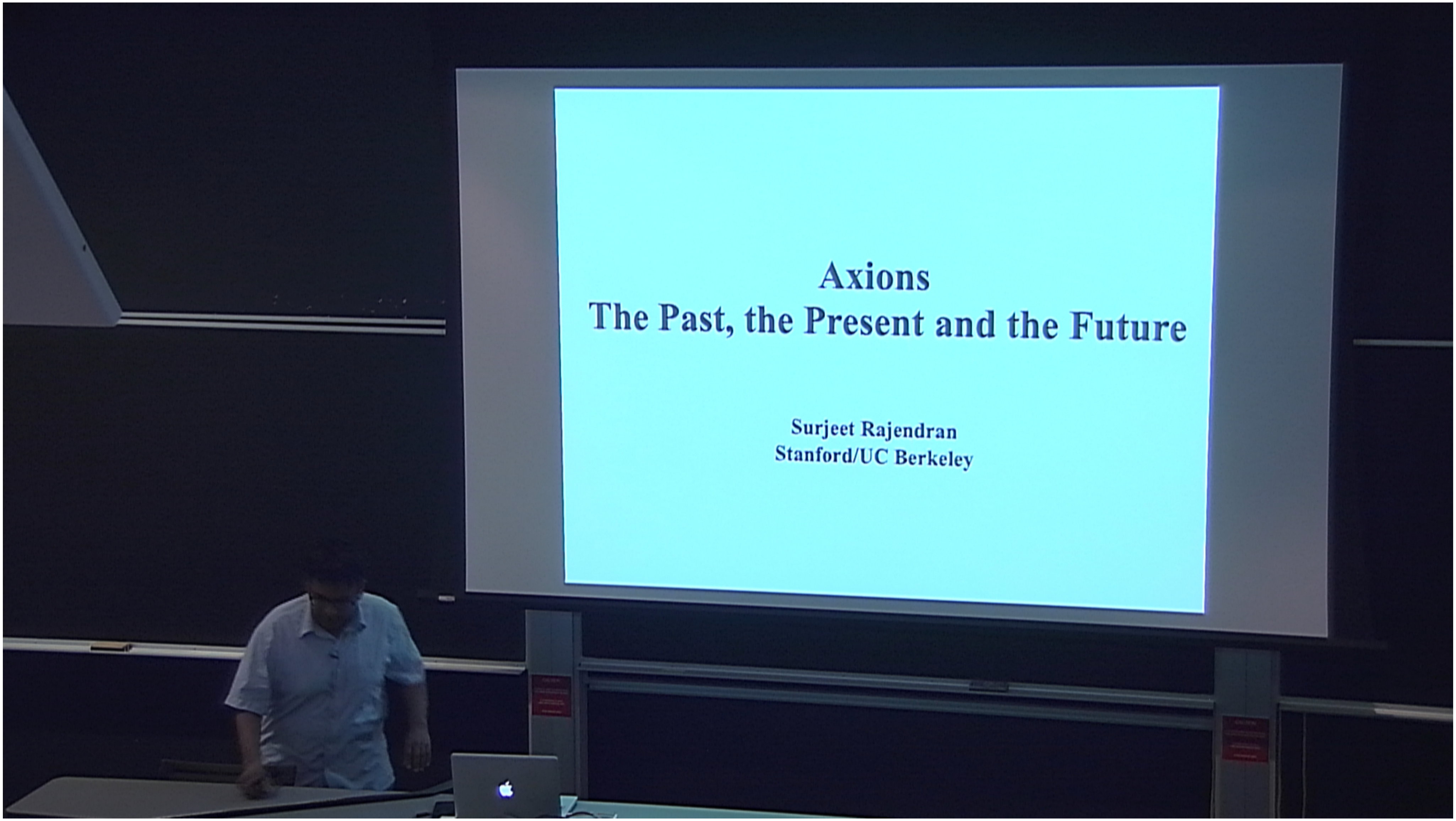
Modify Einstein-Hilbert action,

$$R \to R + f(\phi) R\tilde{R}$$

then t evolution of inflaton phi gives asymmetry between right-circular polarized GWs over left (Lue et al. 1999)

Or R/L asymmetry may also arise in chiral gravity (Contaldi, Magueijo, Smolin 2008)

Either way, asymmetry gives rise to E/B correlations



Axions
The Past, the Present and the Future

Surjeet Rajendran
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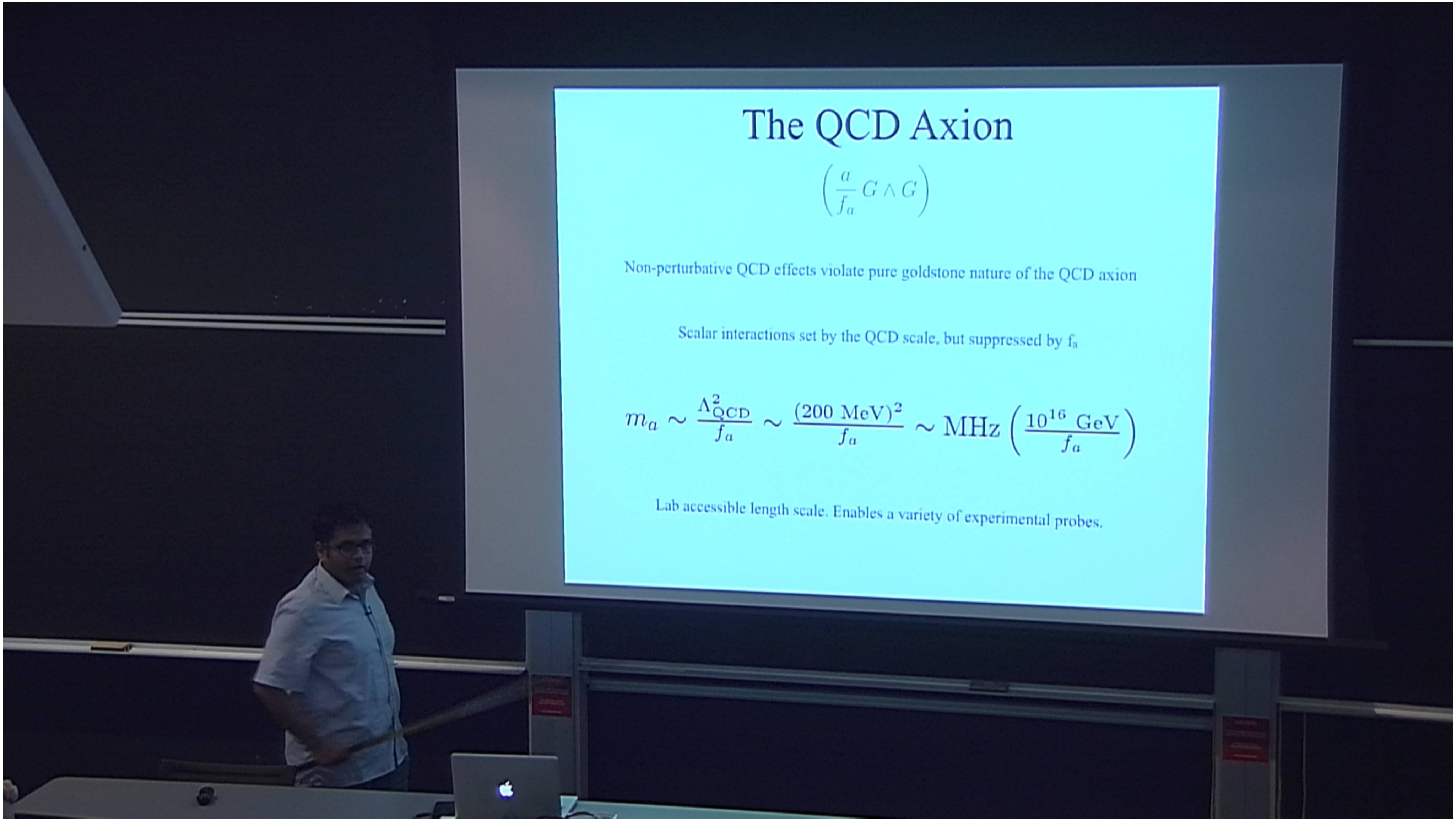


The QCD Axion

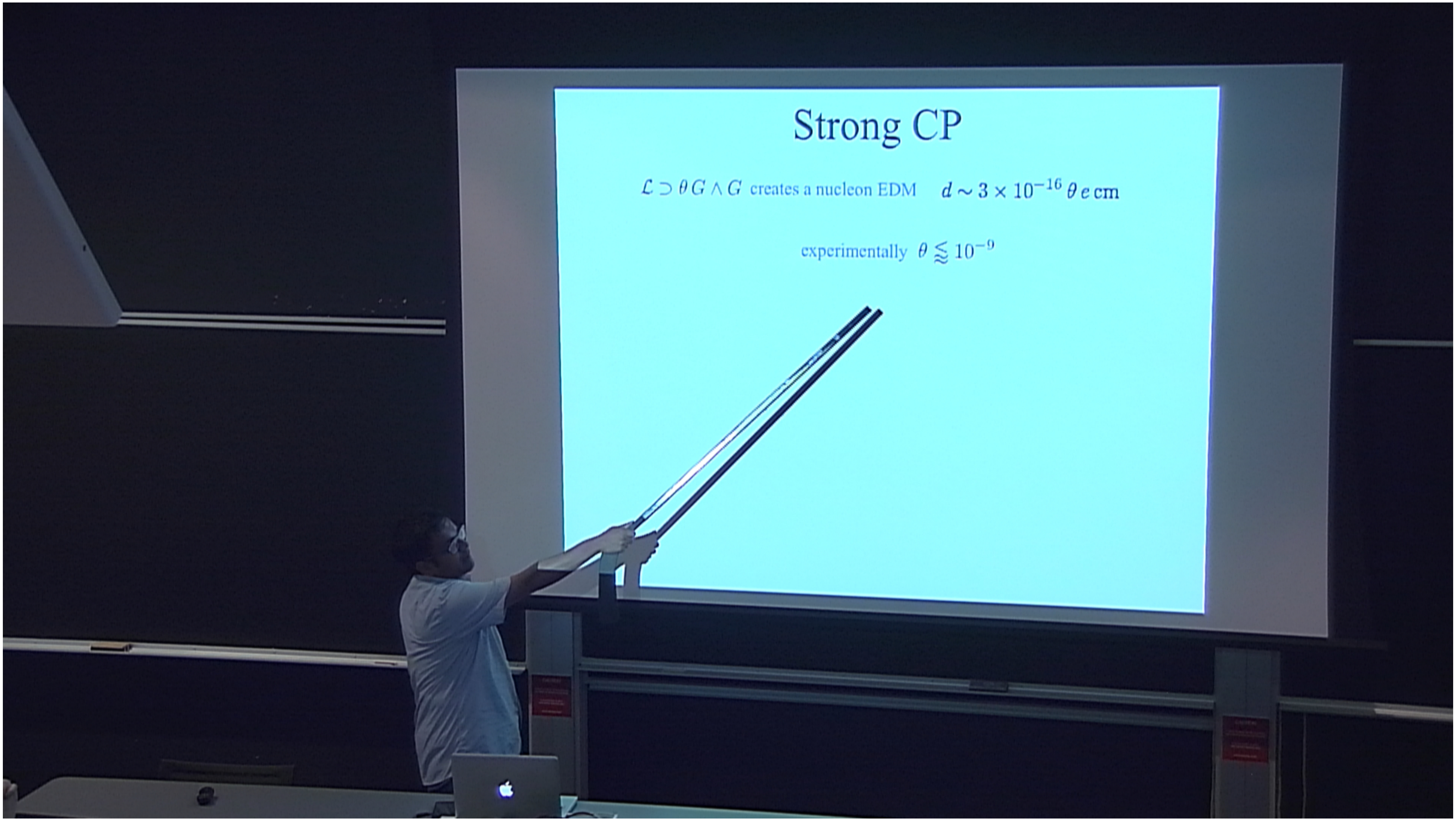
$$\left(\frac{a}{f_a} G \wedge G\right)$$

Non-perturbative QCD effects violate pure goldstone nature of the QCD axion

Scalar interactions set by the QCD scale, but suppressed by f_a

$$m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f_a} \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$

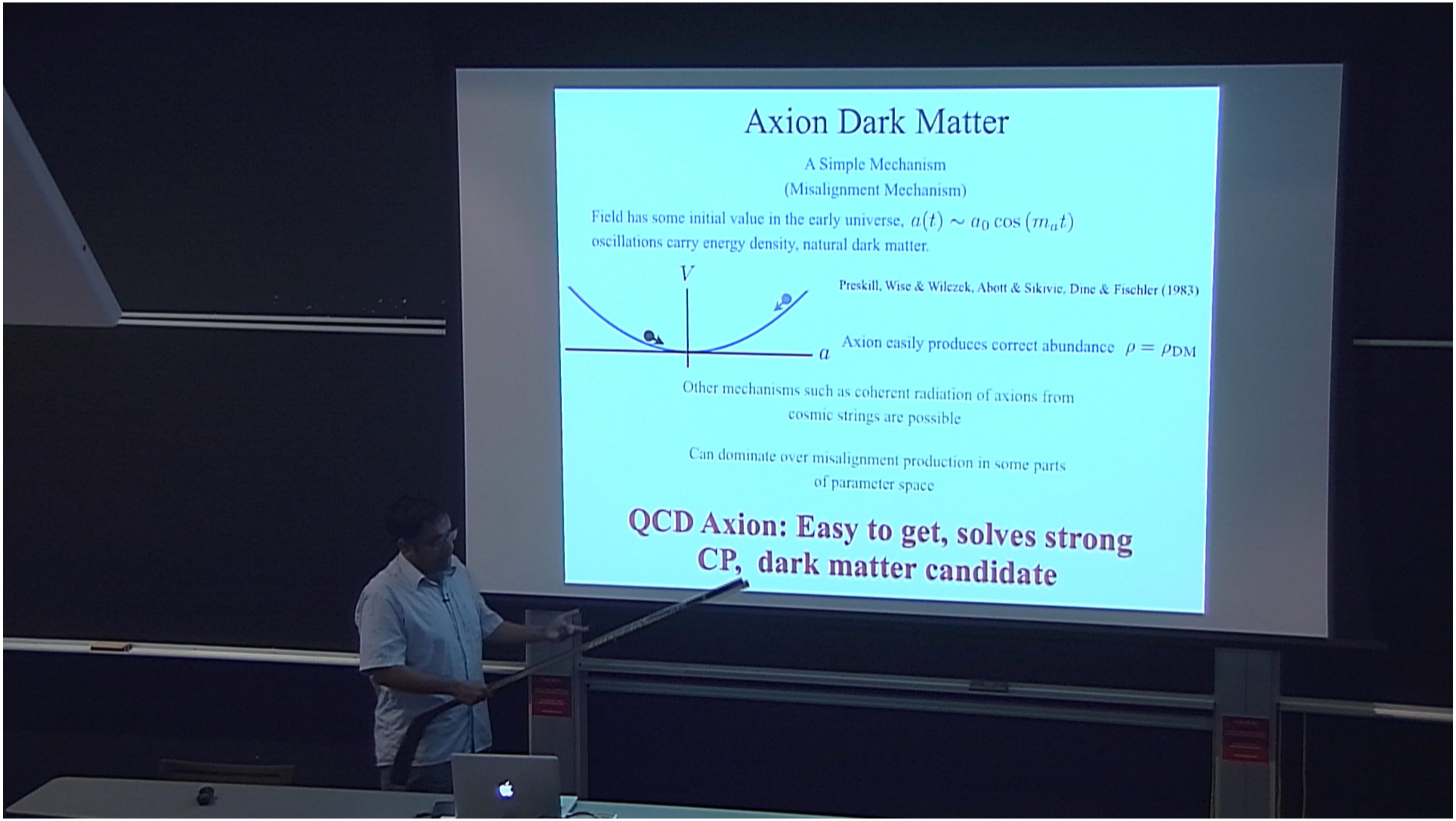
Lab accessible length scale. Enables a variety of experimental probes.



Strong CP

$\mathcal{L} \supset \theta\, G \wedge G$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$

experimentally $\theta \lessapprox 10^{-9}$



Axion Dark Matter

A Simple Mechanism
(Misalignment Mechanism)

Field has some initial value in the early universe, $a(t) \sim a_0 \cos(m_a t)$
oscillations carry energy density, natural dark matter.

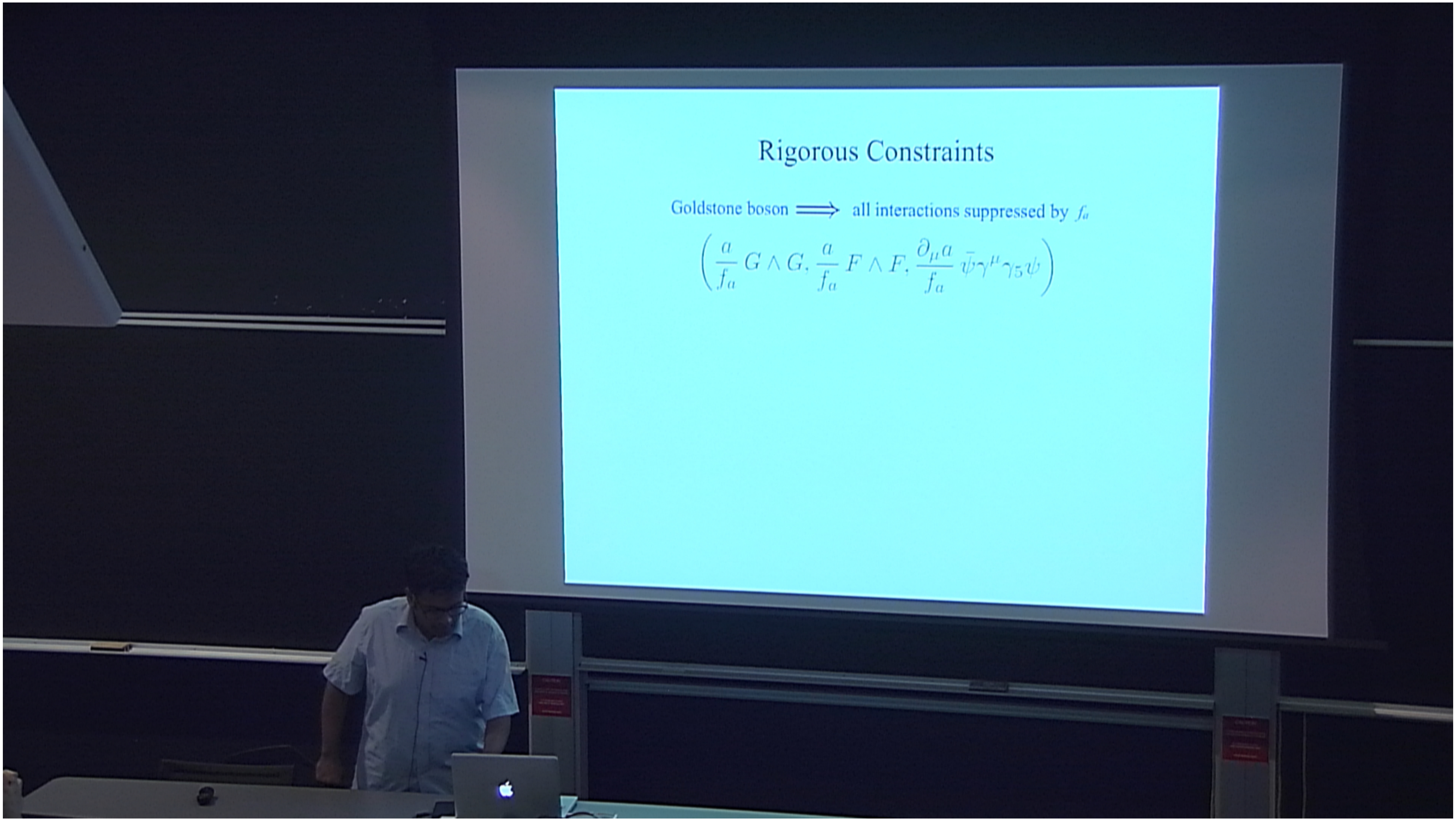
Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

Axion easily produces correct abundance $\rho = \rho_{\rm DM}$

Other mechanisms such as coherent radiation of axions from cosmic strings are possible

Can dominate over misalignment production in some parts of parameter space

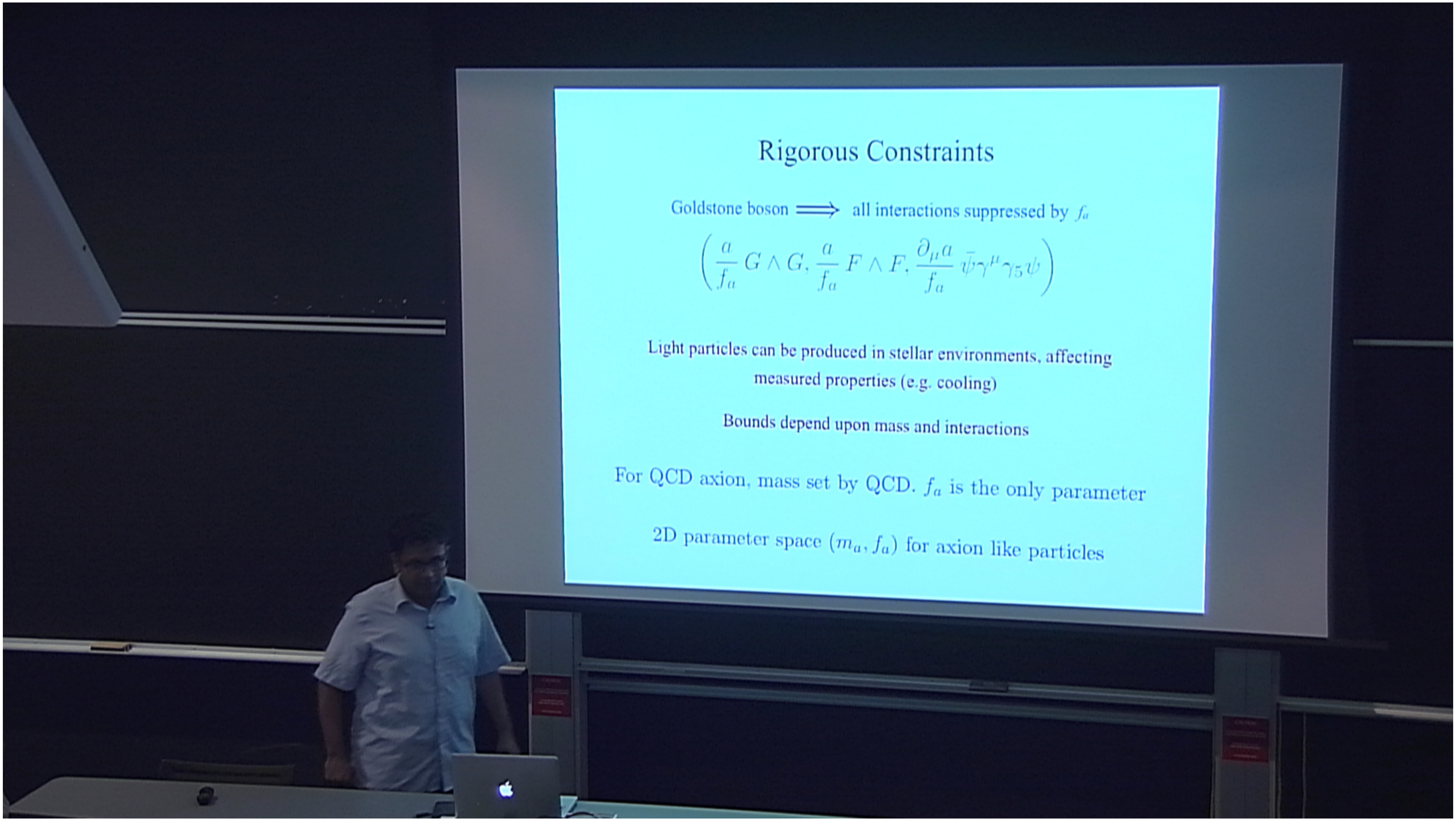
QCD Axion: Easy to get, solves strong CP, dark matter candidate



Rigorous Constraints

Goldstone boson $\Longrightarrow$ all interactions suppressed by f_a

$$\left(\frac{a}{f_a}\, G\wedge G,\ \frac{a}{f_a}\, F\wedge F,\ \frac{\partial_\mu a}{f_a}\,\bar{\psi}\gamma^\mu\gamma_5\psi\right)$$



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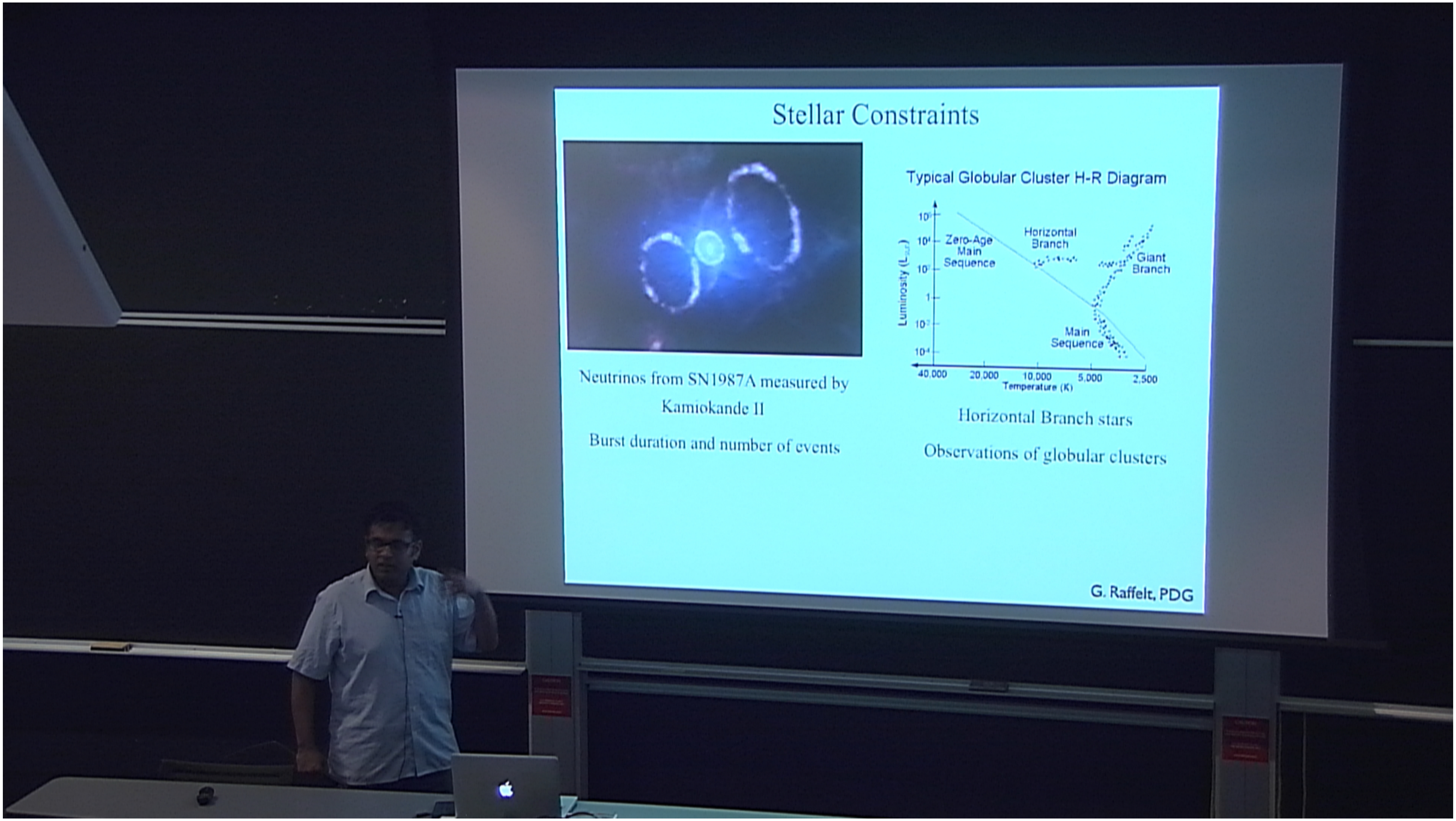
Light particles can be produced in stellar environments, affecting measured properties (e.g. cooling)

Bounds depend upon mass and interactions

For QCD axion, mass set by QCD. f_a is the only parameter

2D parameter space (m_a, f_a) for axion like particles



Stellar Constraints

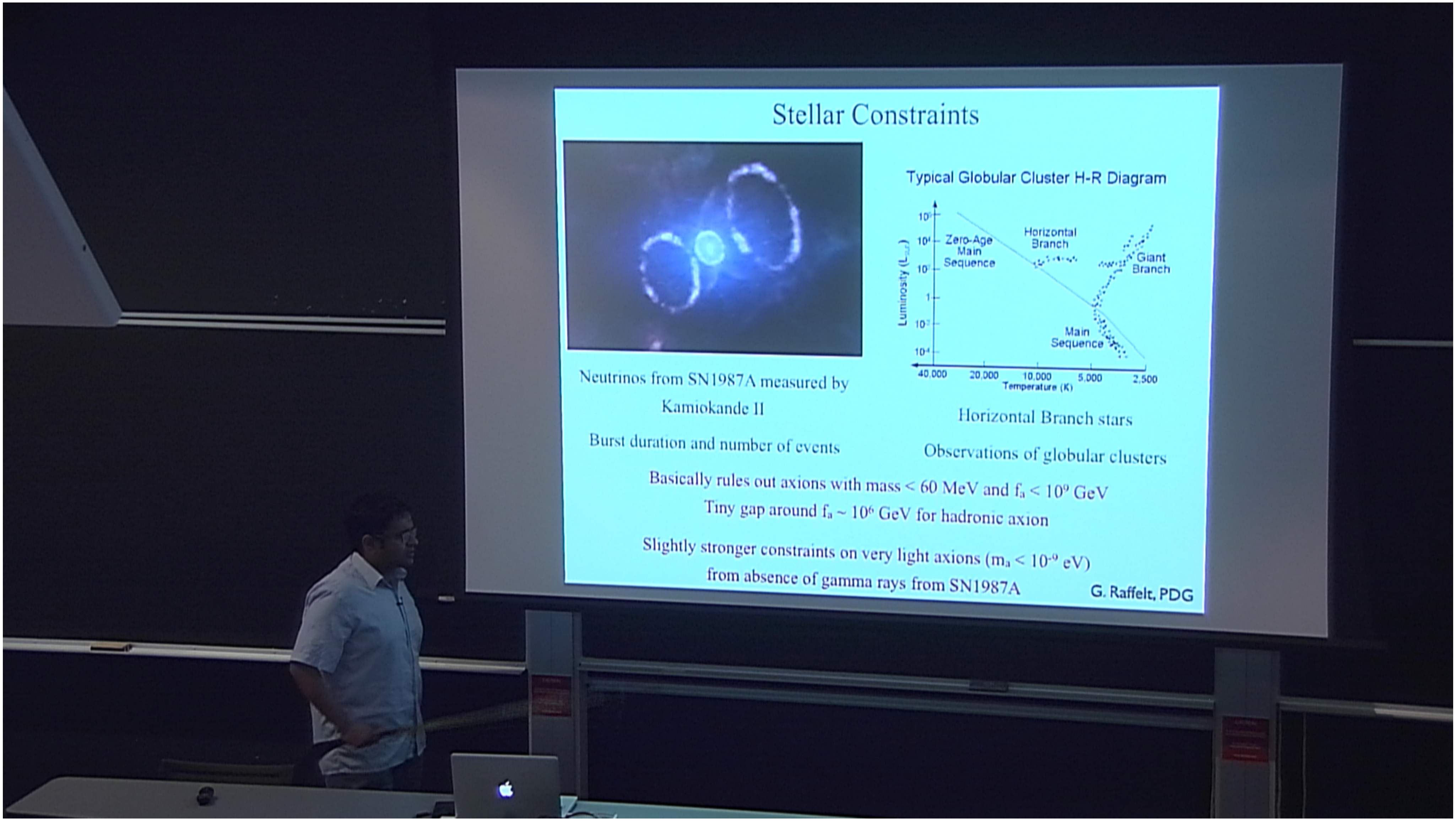
Neutrinos from SN1987A measured by Kamiokande II

Burst duration and number of events

Horizontal Branch stars

Observations of globular clusters

G. Raffelt, PDG



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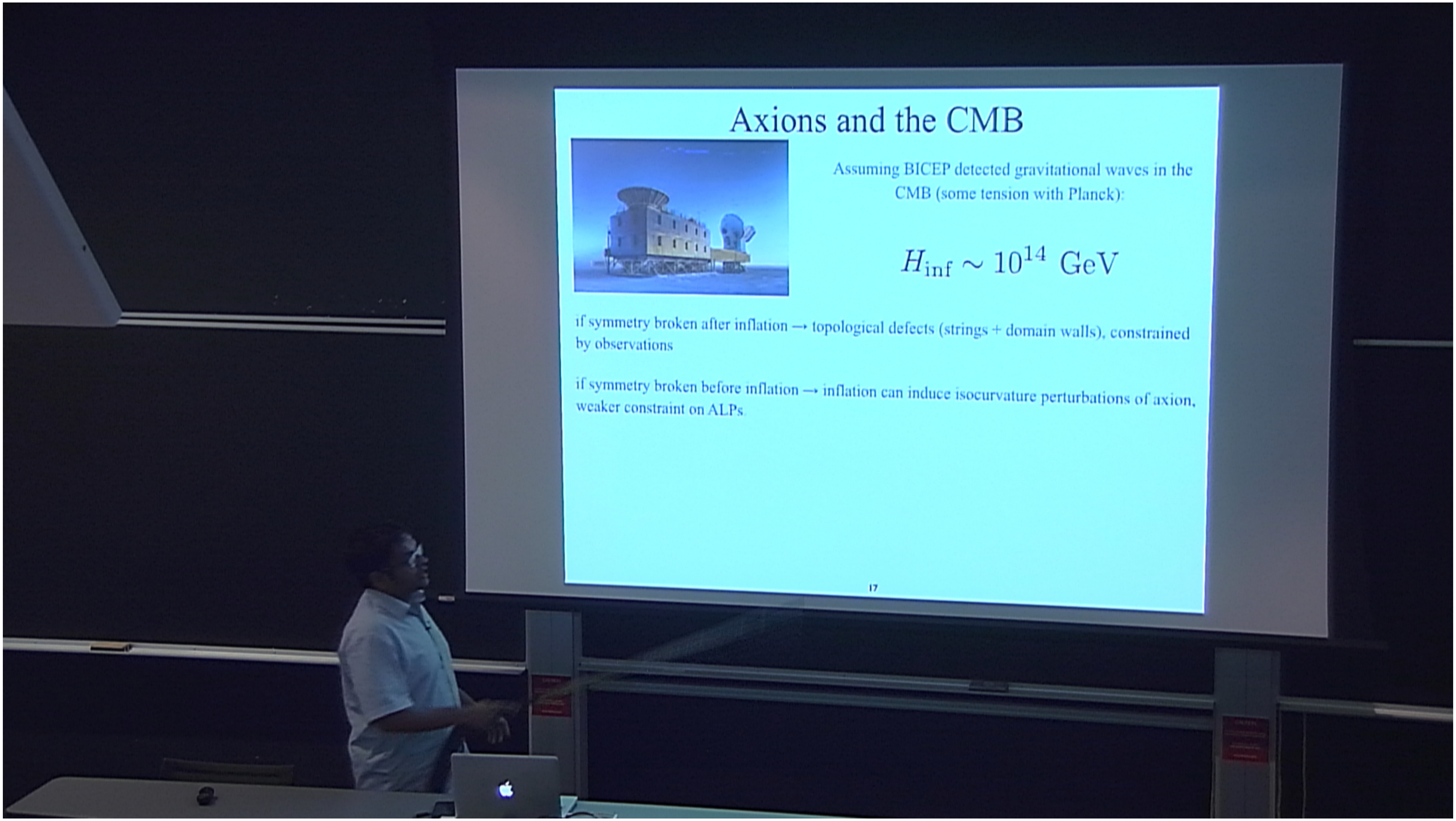
Basically rules out axions with mass < 60 MeV and $f_a < 10^9$ GeV

Tiny gap around $f_a \sim 10^6$ GeV for hadronic axion

Slightly stronger constraints on very light axions ($m_a < 10^{-9}$ eV) from absence of gamma rays from SN1987A

G. Raffelt, PDG



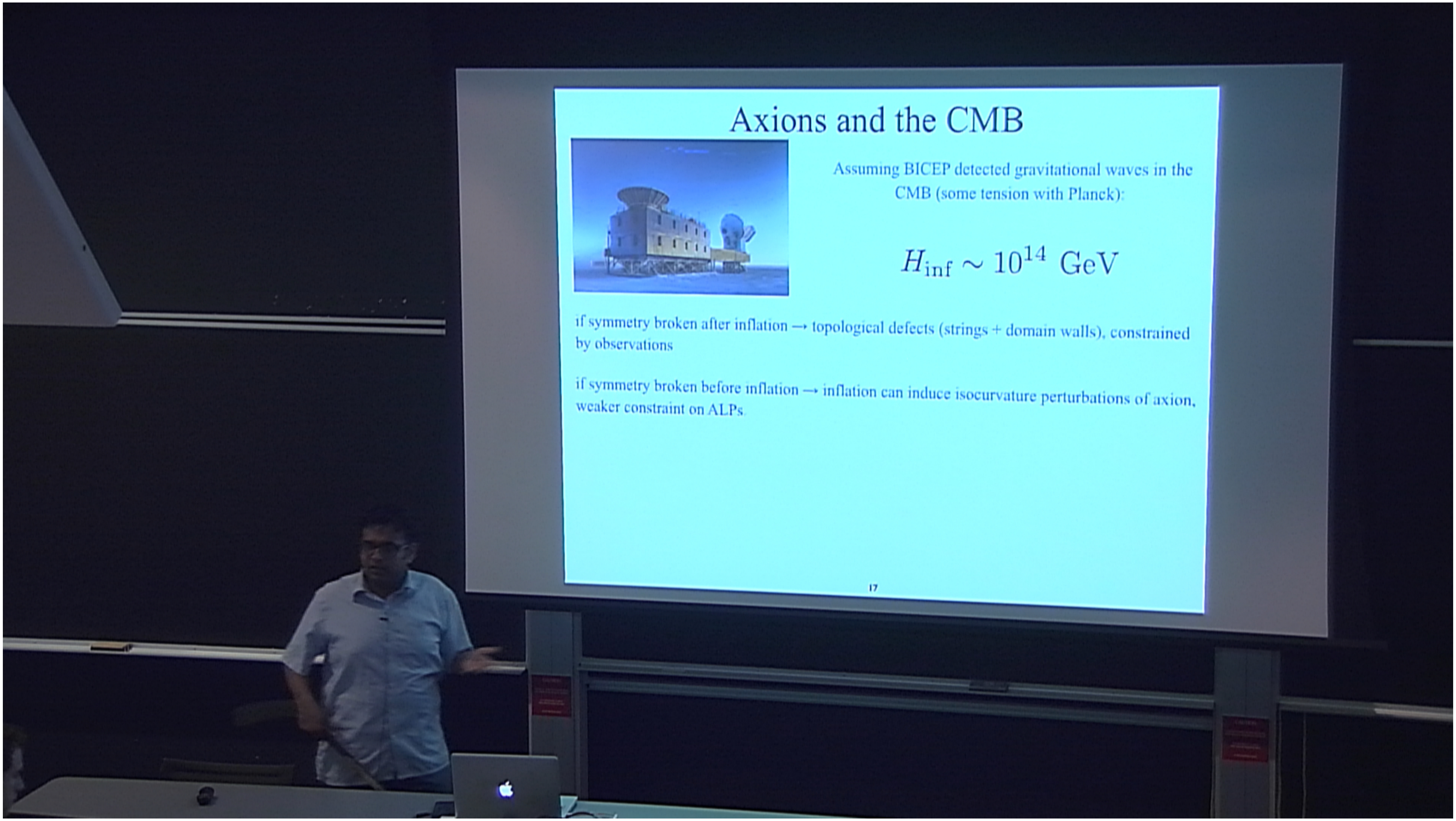
Axions and the CMB

Assuming BICEP detected gravitational waves in the CMB (some tension with Planck):

$$H_{\rm inf} \sim 10^{14}\ {\rm GeV}$$

if symmetry broken after inflation → topological defects (strings + domain walls), constrained by observations

if symmetry broken before inflation → inflation can induce isocurvature perturbations of axion, weaker constraint on ALPs



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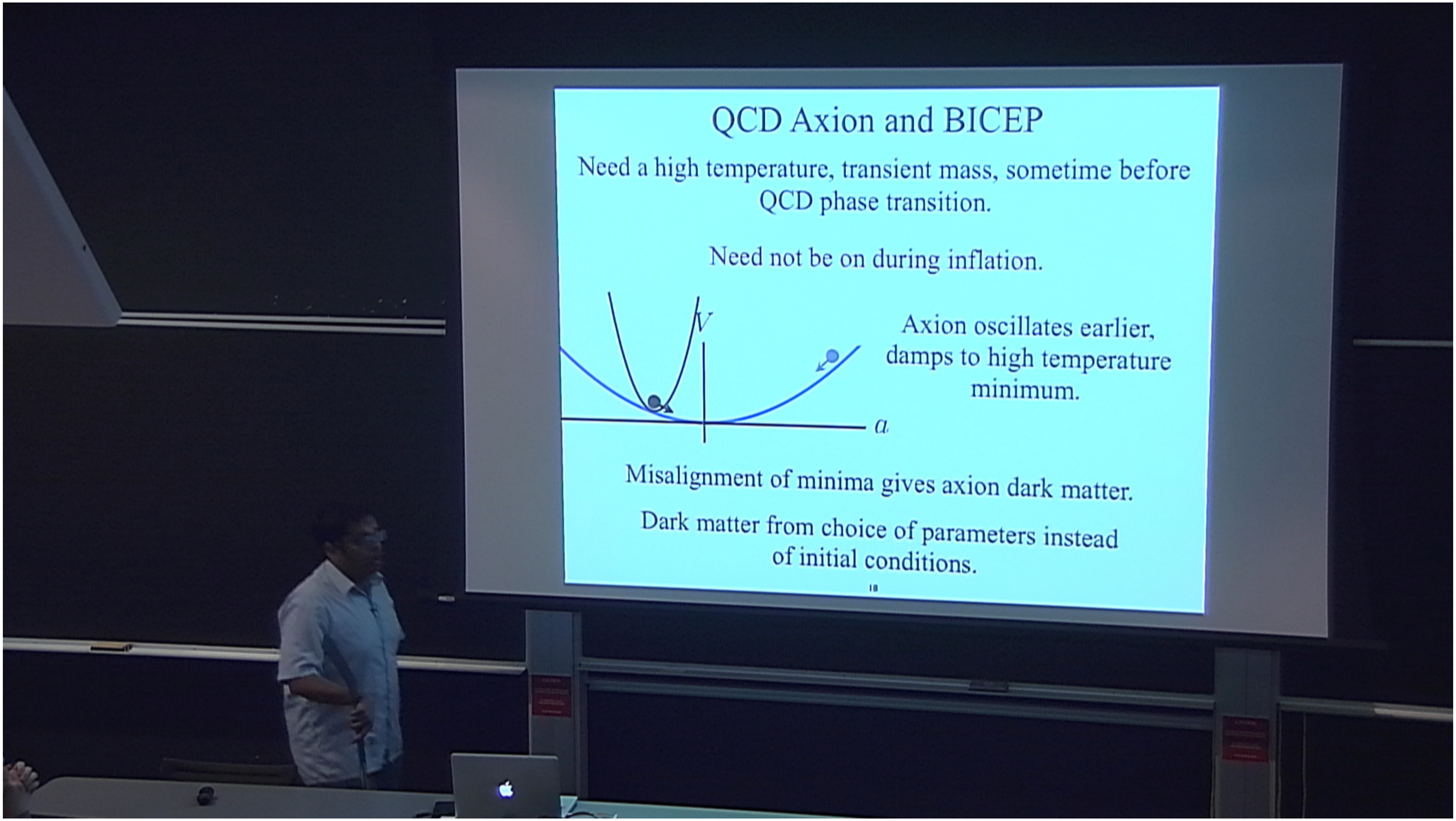


QCD Axion and BICEP

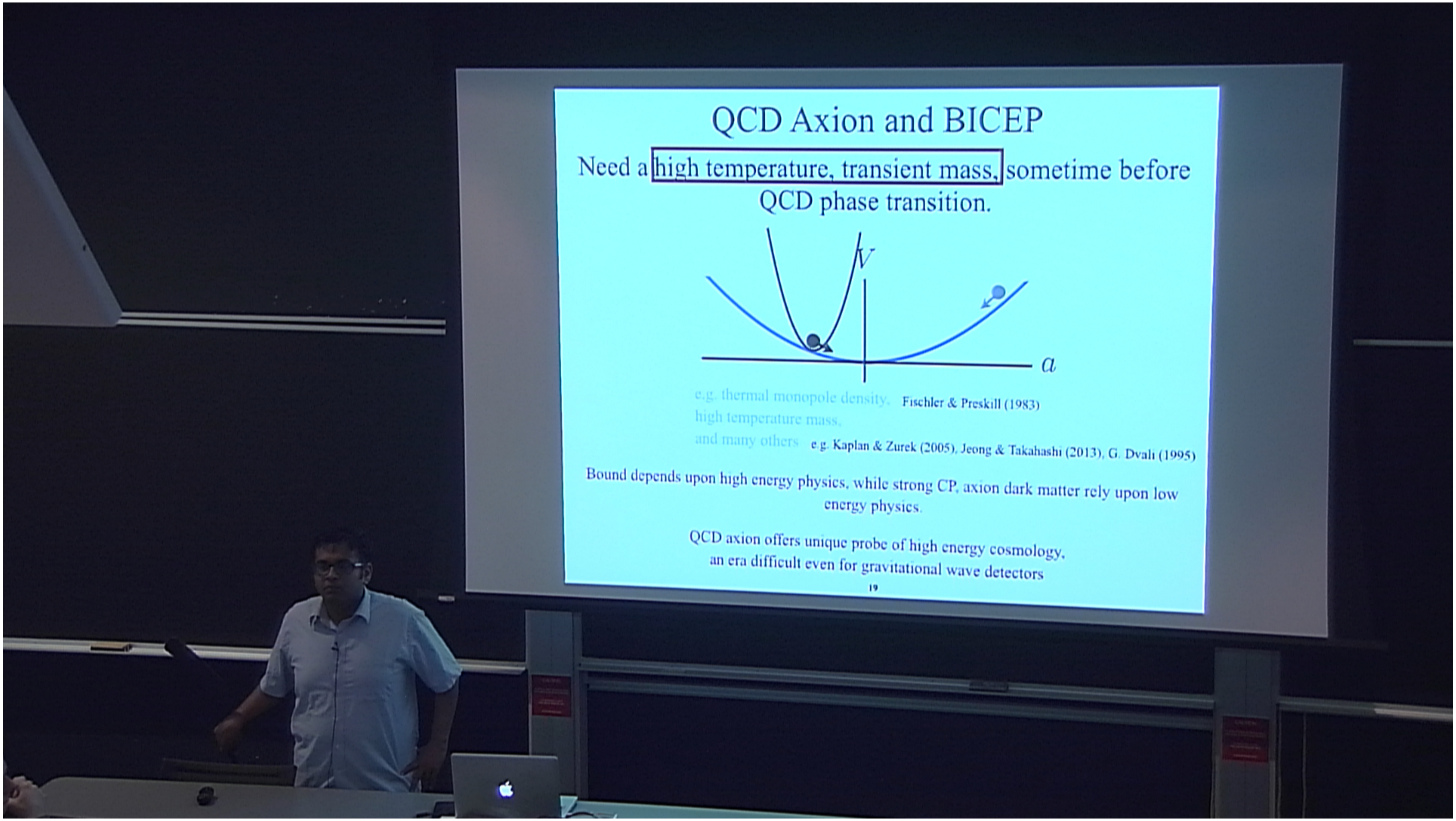
Need a high temperature, transient mass, sometime before QCD phase transition.

Need not be on during inflation.

Axion oscillates earlier, damps to high temperature minimum.

Misalignment of minima gives axion dark matter.

Dark matter from choice of parameters instead of initial conditions.



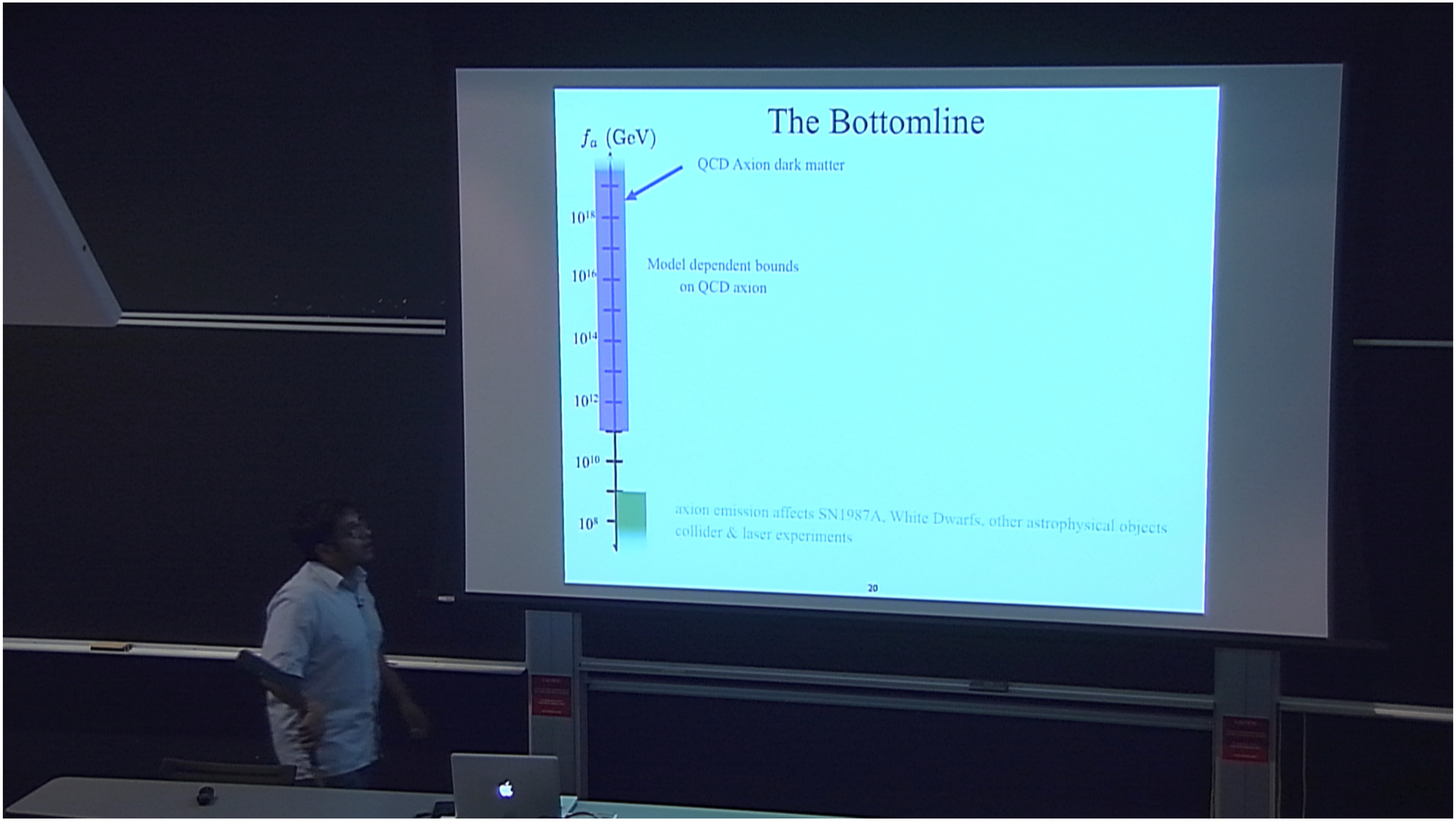
QCD Axion and BICEP

Need a high temperature, transient mass, sometime before QCD phase transition.

e.g. thermal monopole density, Fischler & Preskill (1983)
high temperature mass,
and many others e.g. Kaplan & Zurek (2005), Jeong & Takahashi (2013), G. Dvali (1995)

Bound depends upon high energy physics, while strong CP, axion dark matter rely upon low energy physics.

QCD axion offers unique probe of high energy cosmology,
an era difficult even for gravitational wave detectors

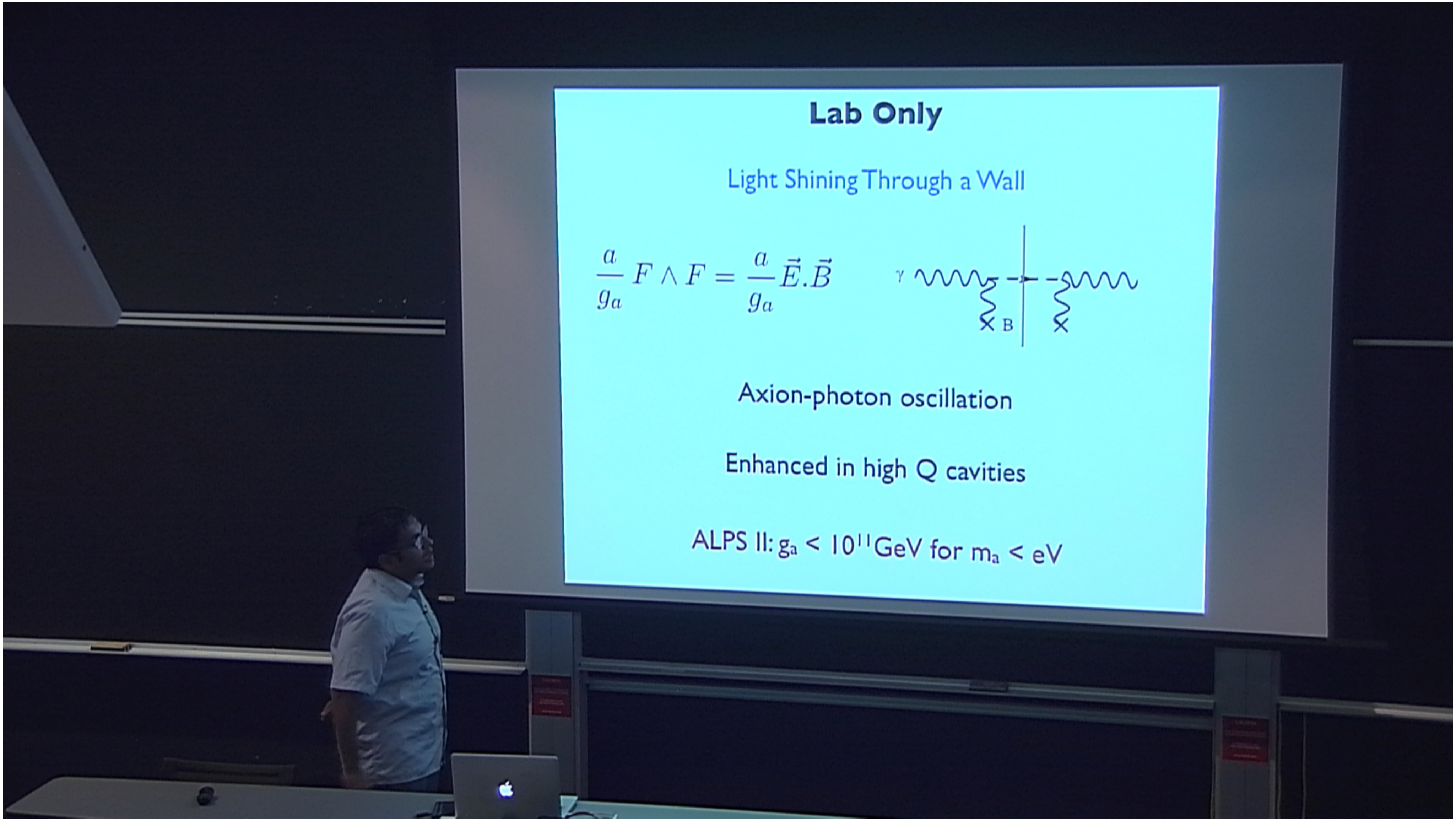


The Bottomline

QCD Axion dark matter

Model dependent bounds
on QCD axion

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments



Lab Only

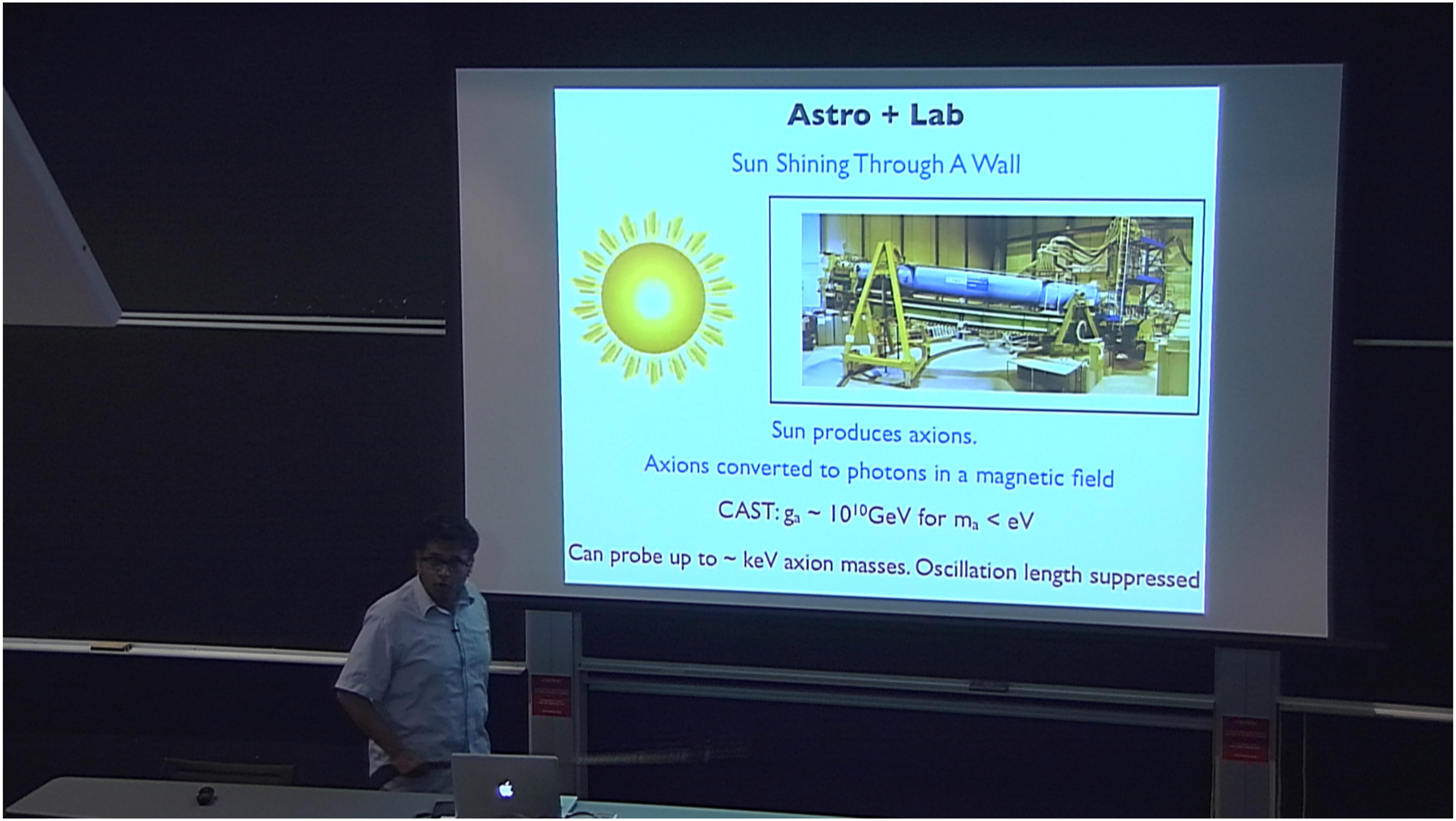
Light Shining Through a Wall

$$\frac{a}{g_a} F \wedge F = \frac{a}{g_a} \vec{E}.\vec{B}$$

Axion-photon oscillation

Enhanced in high Q cavities

ALPS II: $g_a < 10^{11}$GeV for $m_a <$ eV



Astro + Lab

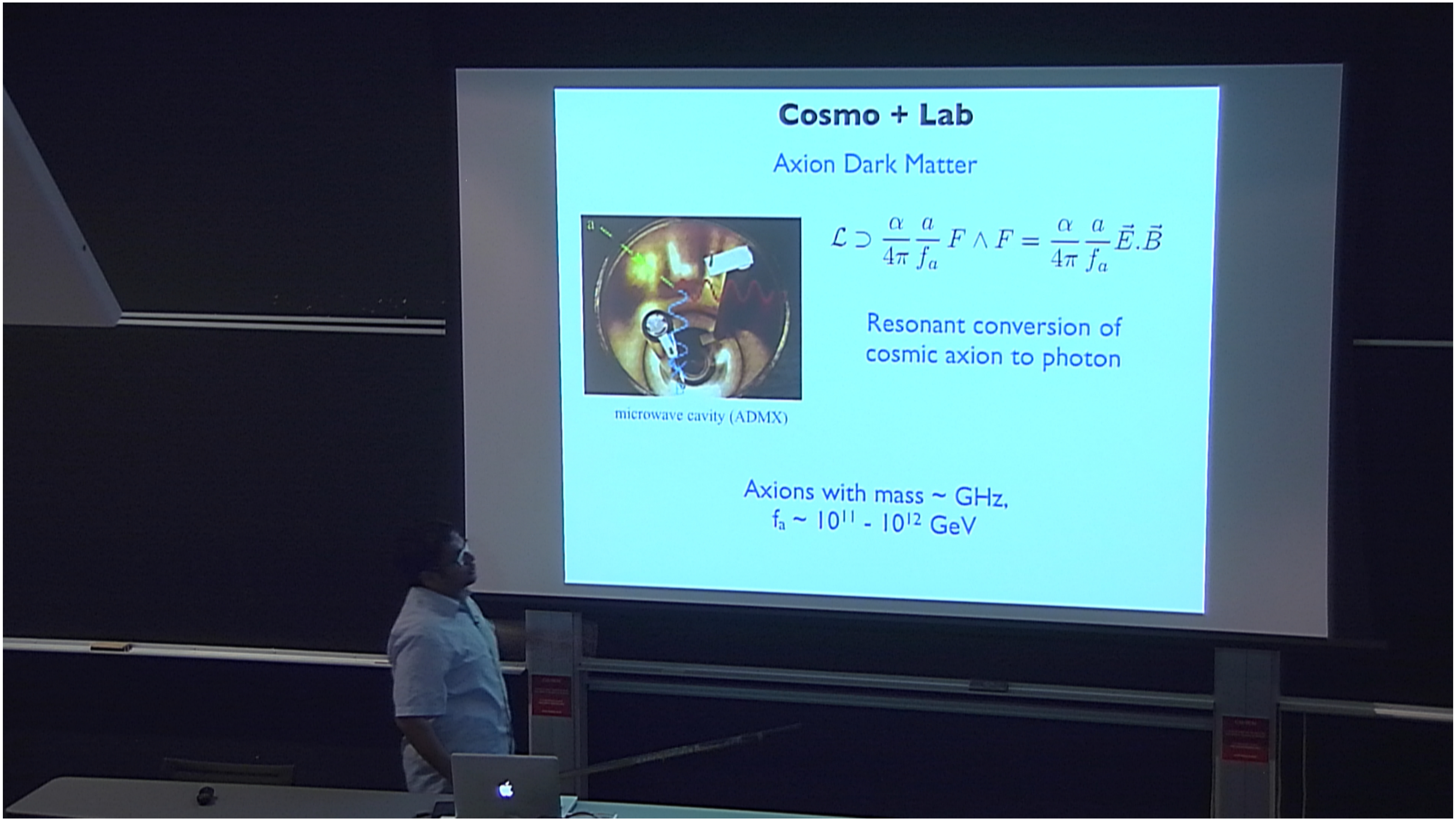
Sun Shining Through A Wall

Sun produces axions.

Axions converted to photons in a magnetic field

CAST: $g_a \sim 10^{10}$GeV for $m_a <$ eV

Can probe up to ~ keV axion masses. Oscillation length suppressed



Cosmo + Lab

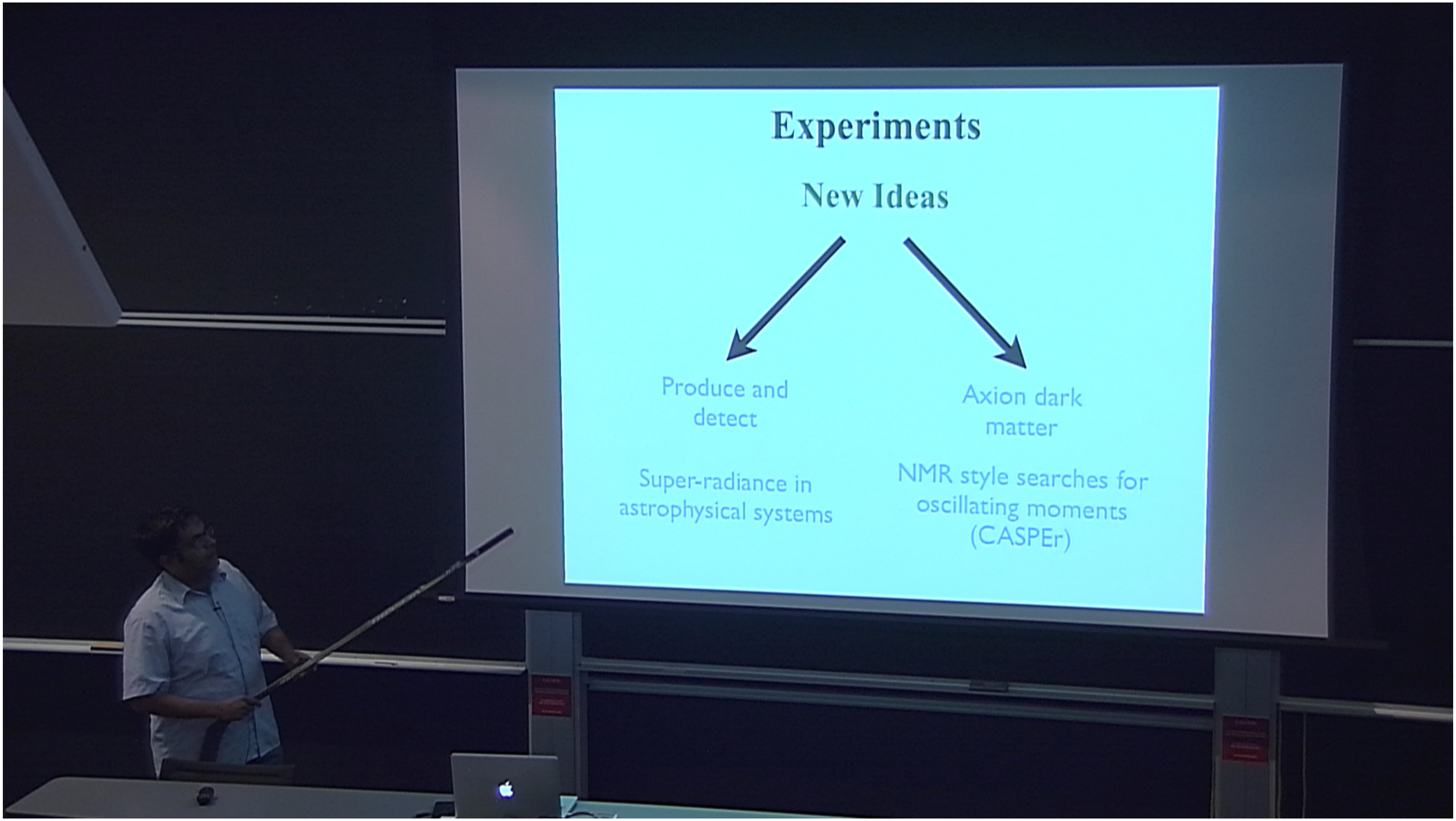
Axion Dark Matter

microwave cavity (ADMX)

$$\mathcal{L} \supset \frac{\alpha}{4\pi}\frac{a}{f_a} F \wedge F = \frac{\alpha}{4\pi}\frac{a}{f_a}\vec{E}.\vec{B}$$

Resonant conversion of
cosmic axion to photon

Axions with mass ~ GHz,
$f_a \sim 10^{11} - 10^{12}$ GeV



Experiments

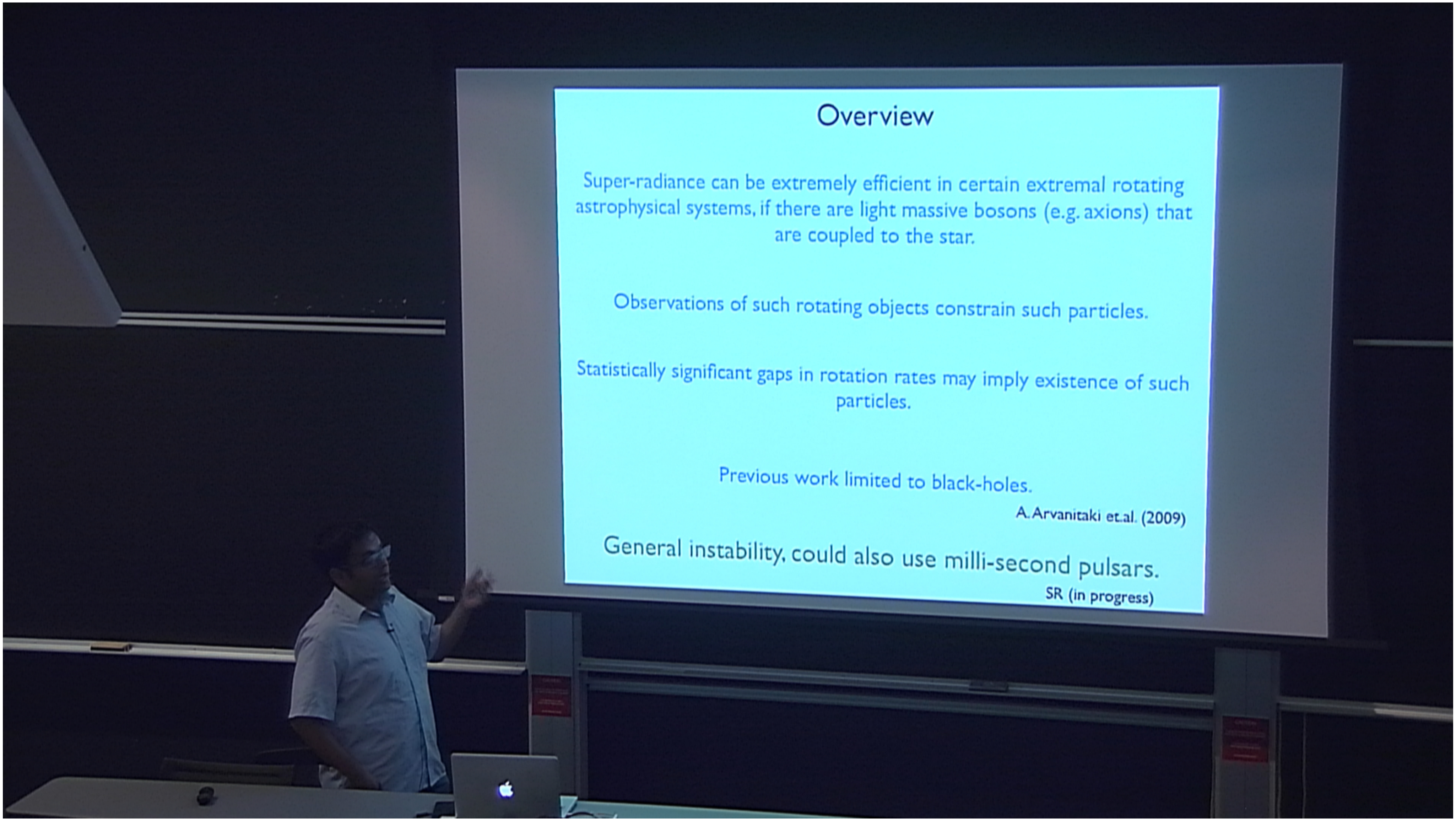
New Ideas

Produce and detect

Super-radiance in astrophysical systems

Axion dark matter

NMR style searches for oscillating moments (CASPEr)



Overview

Super-radiance can be extremely efficient in certain extremal rotating astrophysical systems, if there are light massive bosons (e.g. axions) that are coupled to the star.

Observations of such rotating objects constrain such particles.

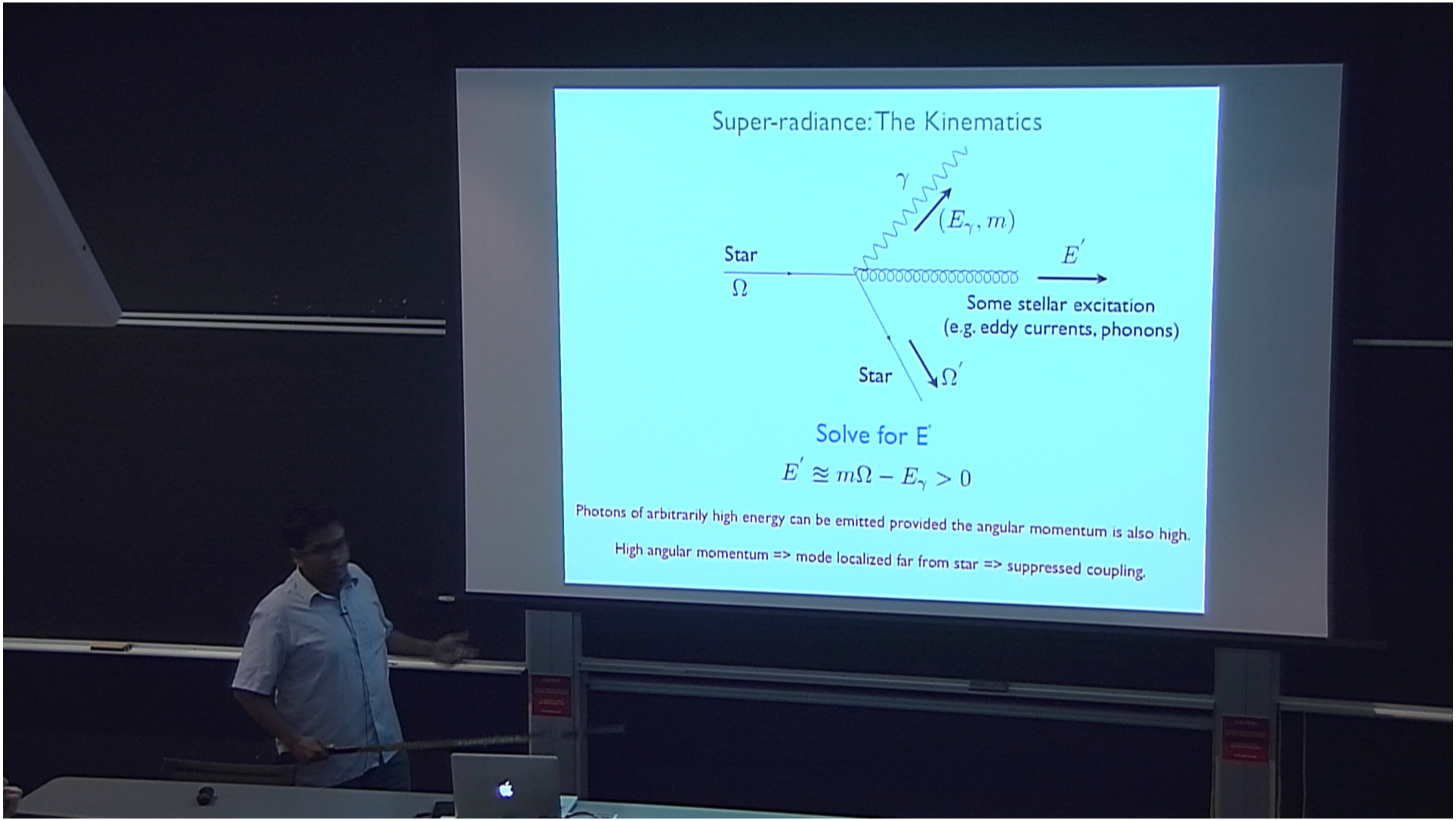
Statistically significant gaps in rotation rates may imply existence of such particles.

Previous work limited to black-holes.

A. Arvanitaki et.al. (2009)

General instability, could also use milli-second pulsars.

SR (in progress)



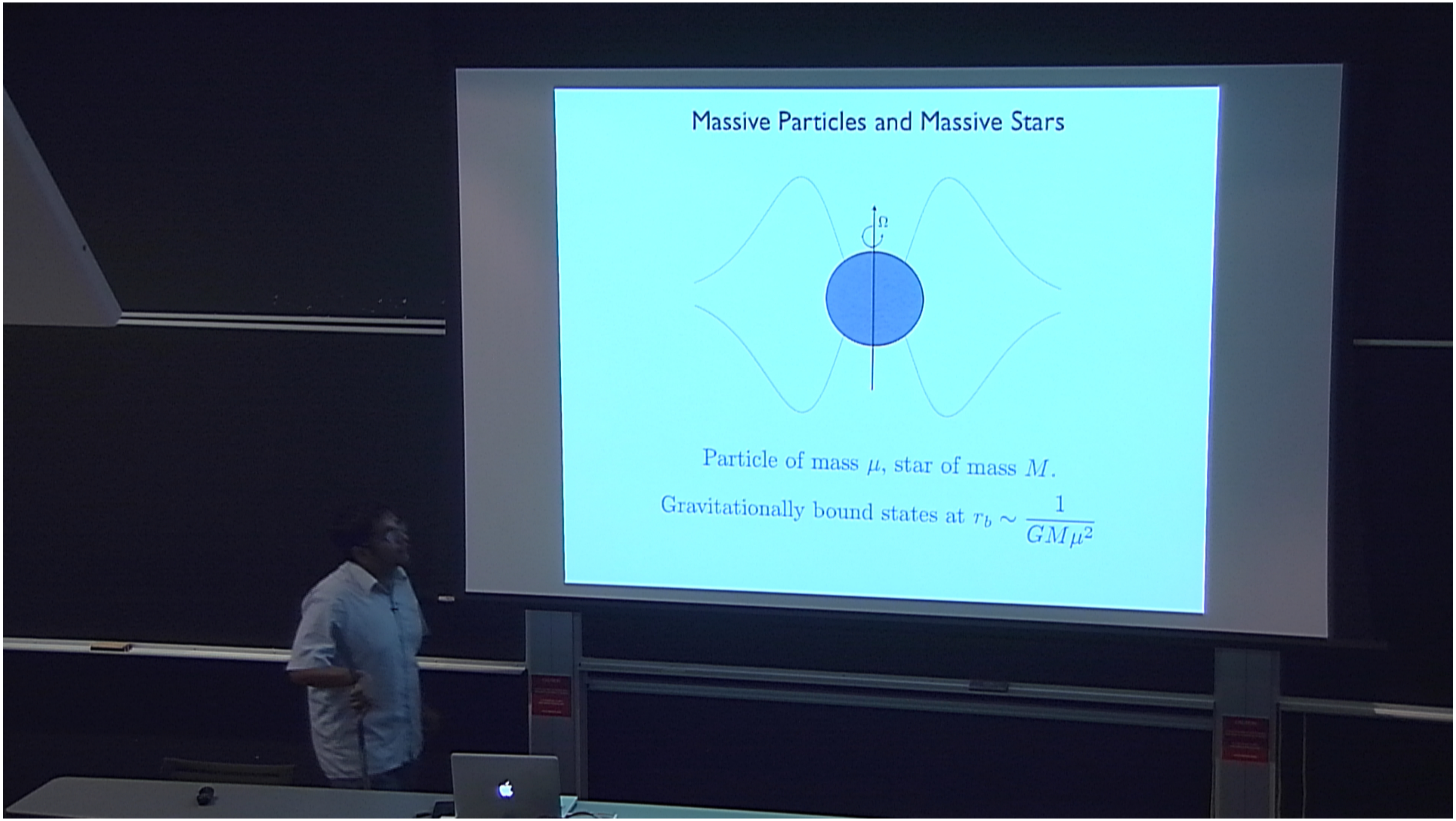
Super-radiance: The Kinematics

Solve for E'

$$E' \approxeq m\Omega - E_\gamma > 0$$

Photons of arbitrarily high energy can be emitted provided the angular momentum is also high.

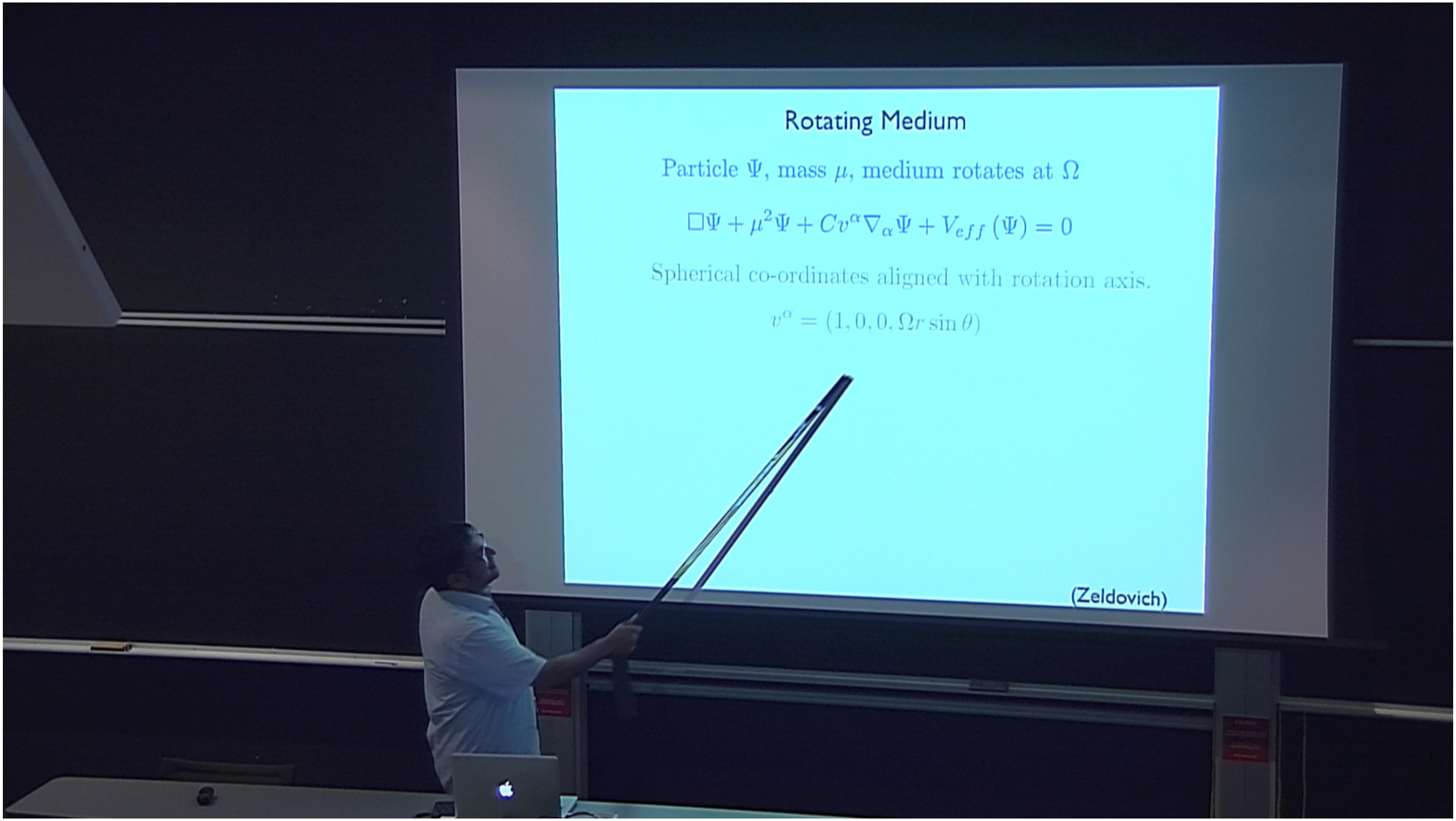
High angular momentum => mode localized far from star => suppressed coupling.



Massive Particles and Massive Stars

Particle of mass μ, star of mass M.

Gravitationally bound states at $r_b \sim \dfrac{1}{GM\mu^2}$



Rotating Medium

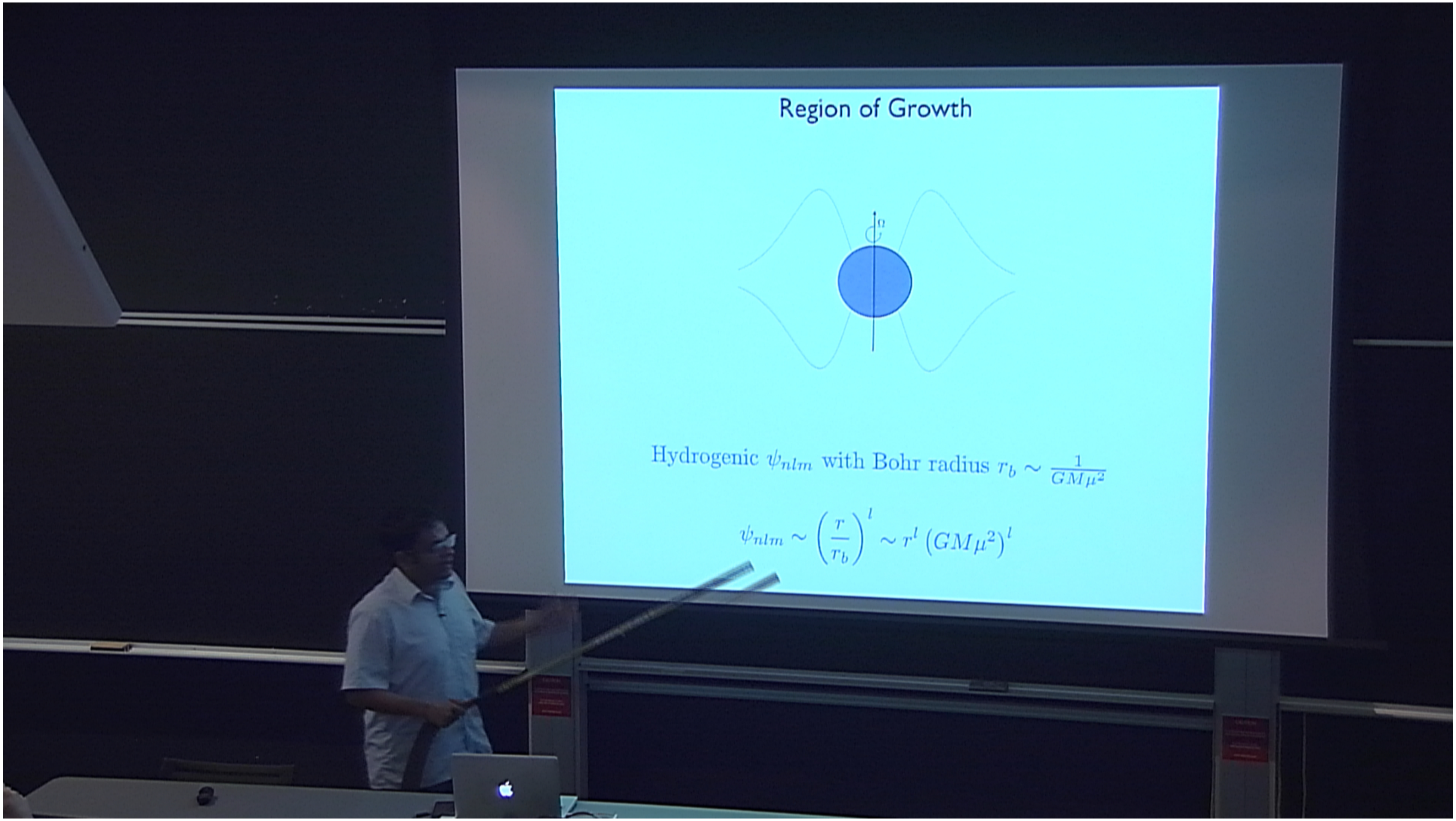
Particle Ψ, mass μ, medium rotates at Ω

$$\Box\Psi + \mu^2\Psi + Cv^\alpha\nabla_\alpha\Psi + V_{eff}(\Psi) = 0$$

Spherical co-ordinates aligned with rotation axis.

$$v^\alpha = (1, 0, 0, \Omega r \sin\theta)$$

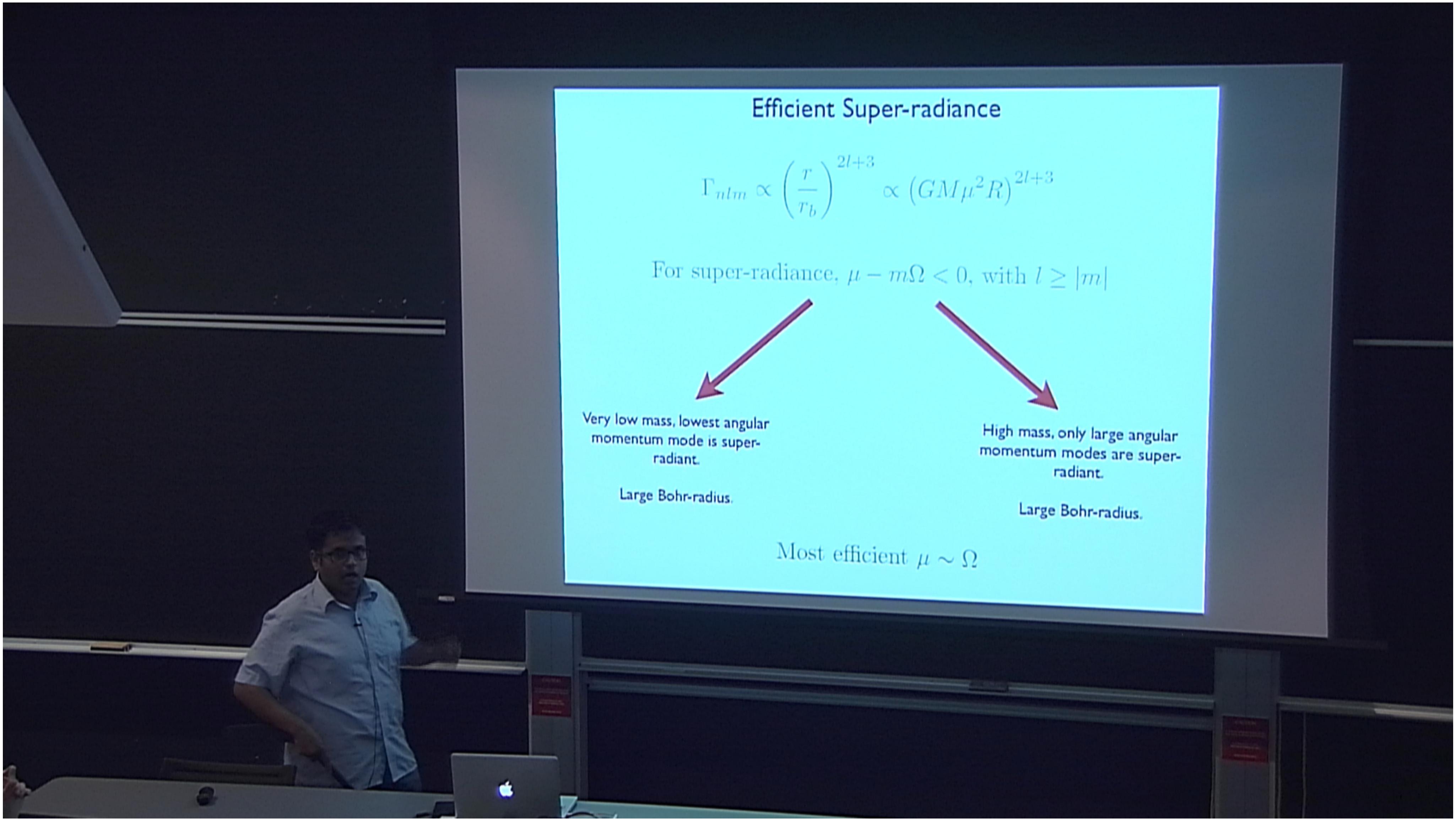
(Zeldovich)



Region of Growth

Hydrogenic ψ_{nlm} with Bohr radius $r_b \sim \frac{1}{GM\mu^2}$

$$\psi_{nlm} \sim \left(\frac{r}{r_b}\right)^l \sim r^l \left(GM\mu^2\right)^l$$



Efficient Super-radiance

$$\Gamma_{nlm} \propto \left(\frac{r}{r_b}\right)^{2l+3} \propto \left(GM\mu^2R\right)^{2l+3}$$

For super-radiance, $\mu - m\Omega < 0$, with $l \geq |m|$

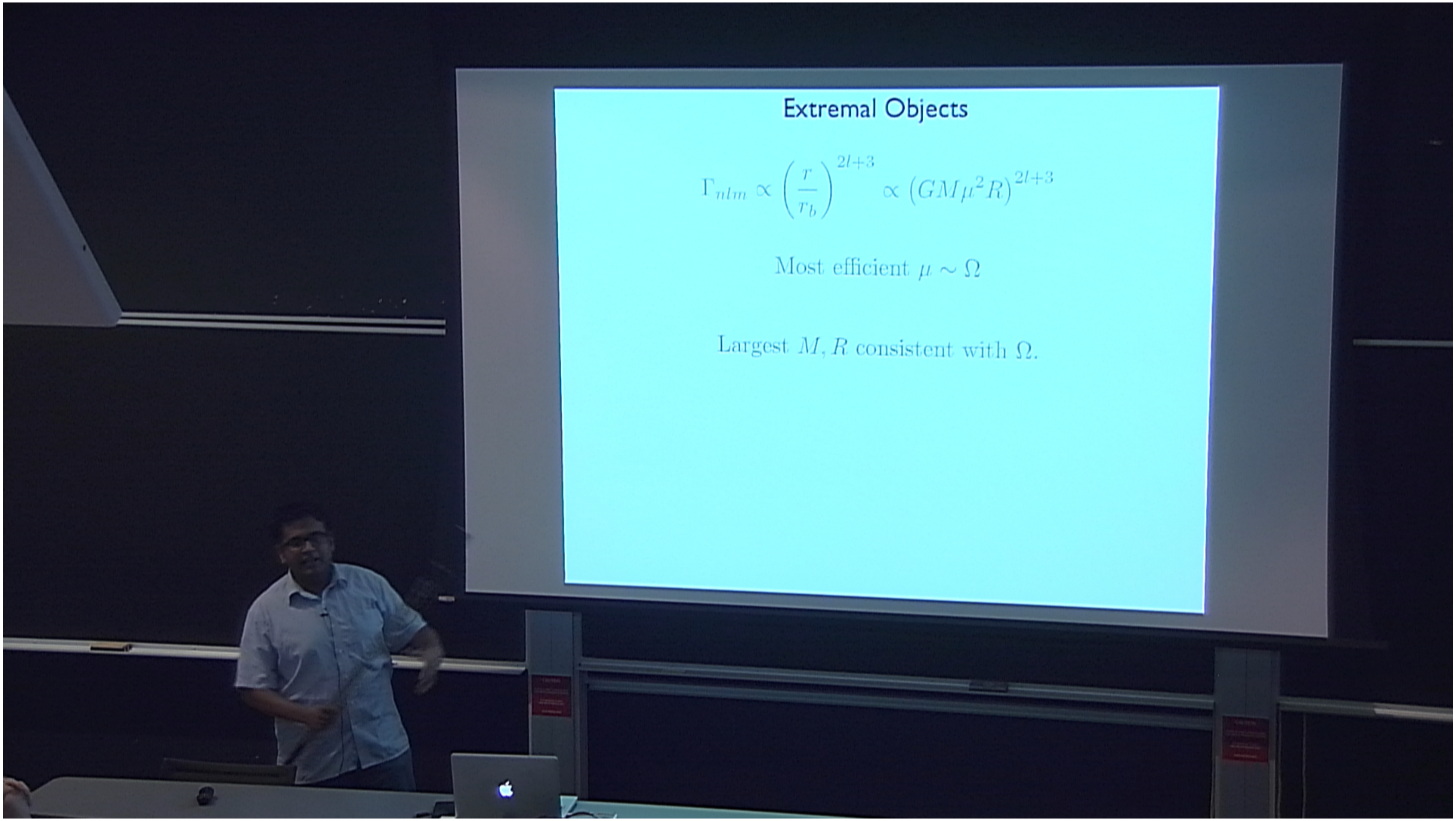
Very low mass, lowest angular momentum mode is super-radiant.

Large Bohr-radius.

High mass, only large angular momentum modes are super-radiant.

Large Bohr-radius.

Most efficient $\mu \sim \Omega$

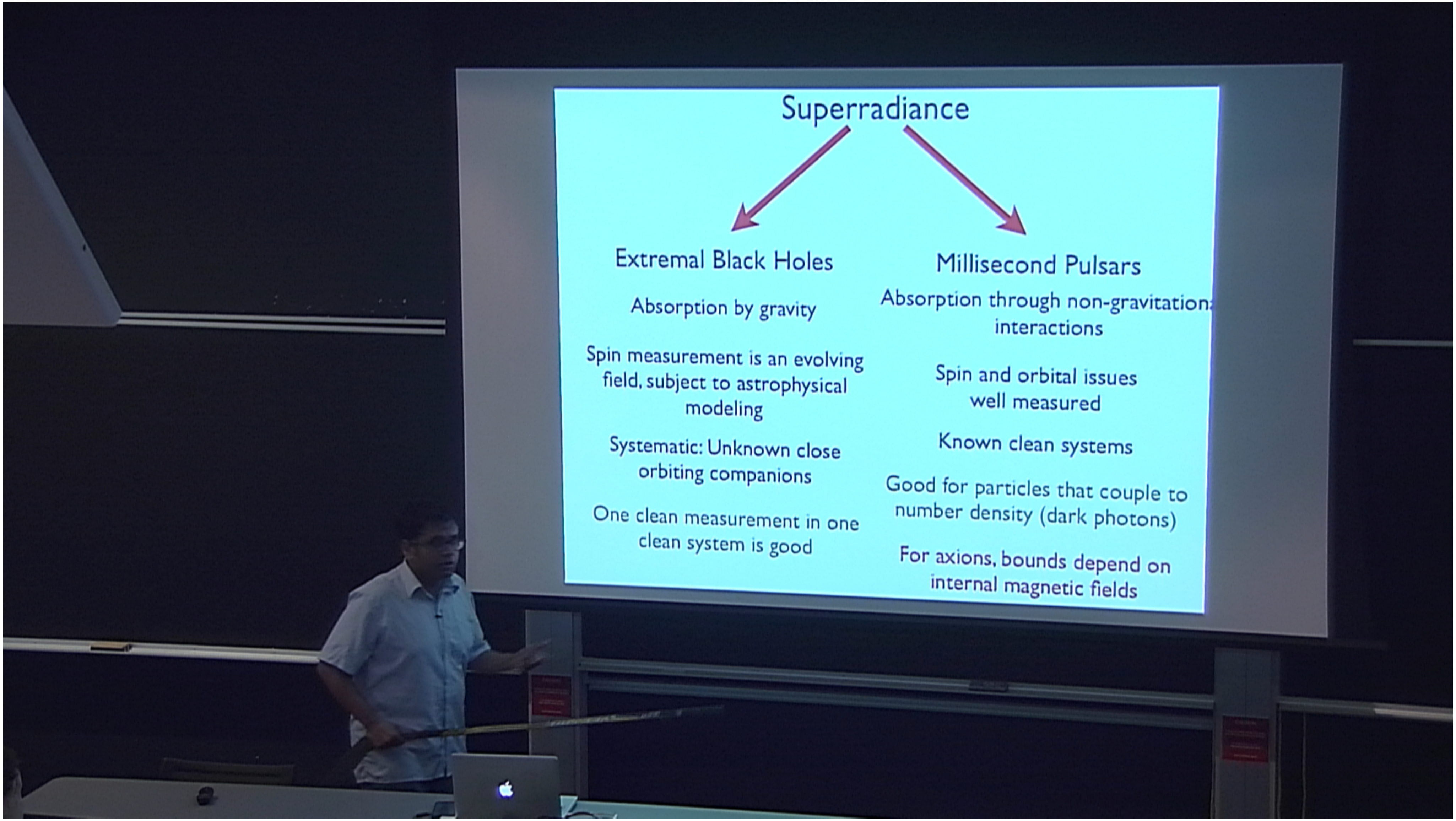


Extremal Objects

$$\Gamma_{nlm} \propto \left(\frac{r}{r_b}\right)^{2l+3} \propto \left(GM\mu^2 R\right)^{2l+3}$$

Most efficient $\mu \sim \Omega$

Largest M, R consistent with Ω.



Superradiance

Extremal Black Holes

Absorption by gravity

Spin measurement is an evolving field, subject to astrophysical modeling

Systematic: Unknown close orbiting companions

One clean measurement in one clean system is good

Millisecond Pulsars

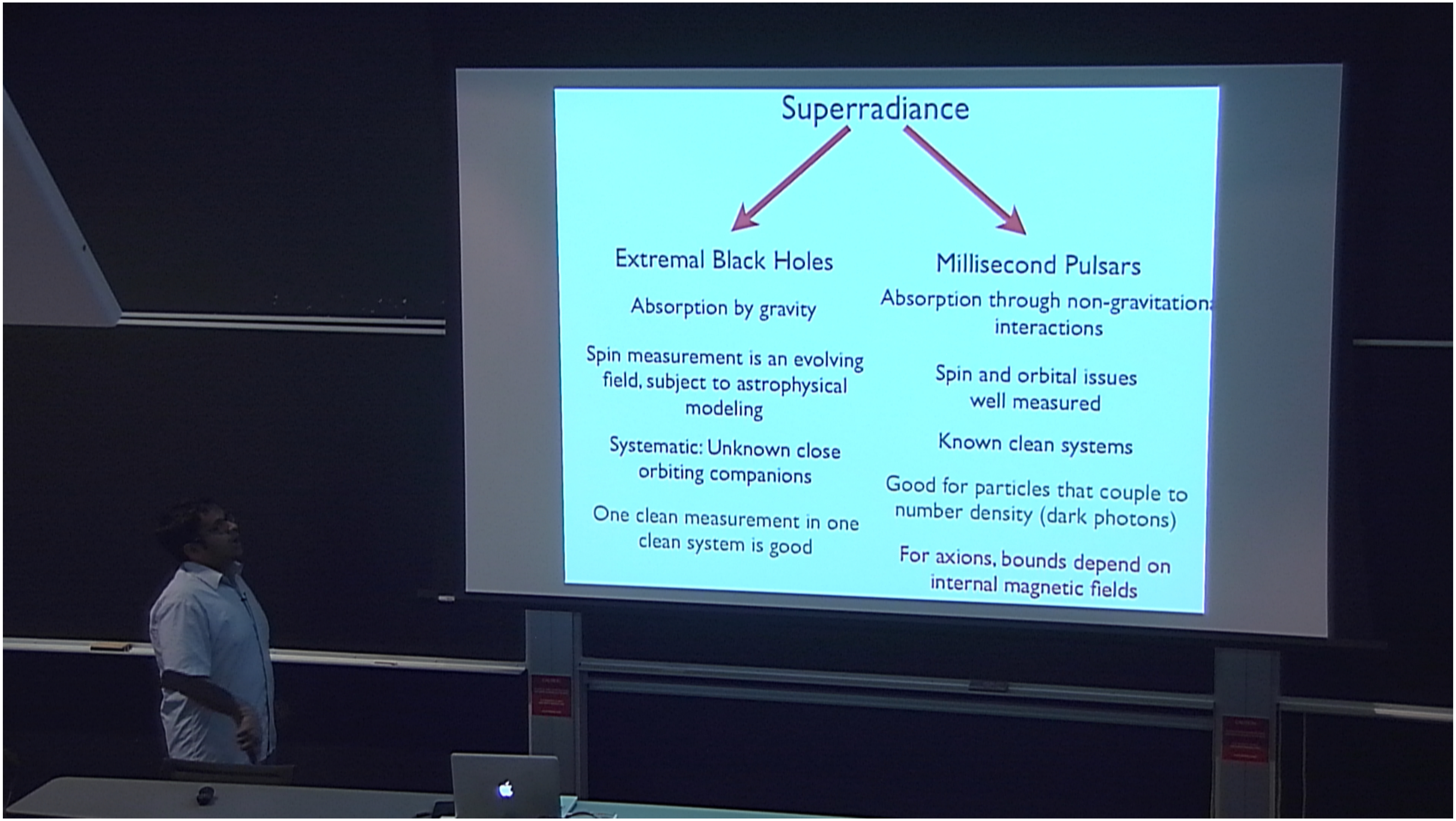
Absorption through non-gravitation interactions

Spin and orbital issues well measured

Known clean systems

Good for particles that couple to number density (dark photons)

For axions, bounds depend on internal magnetic fields



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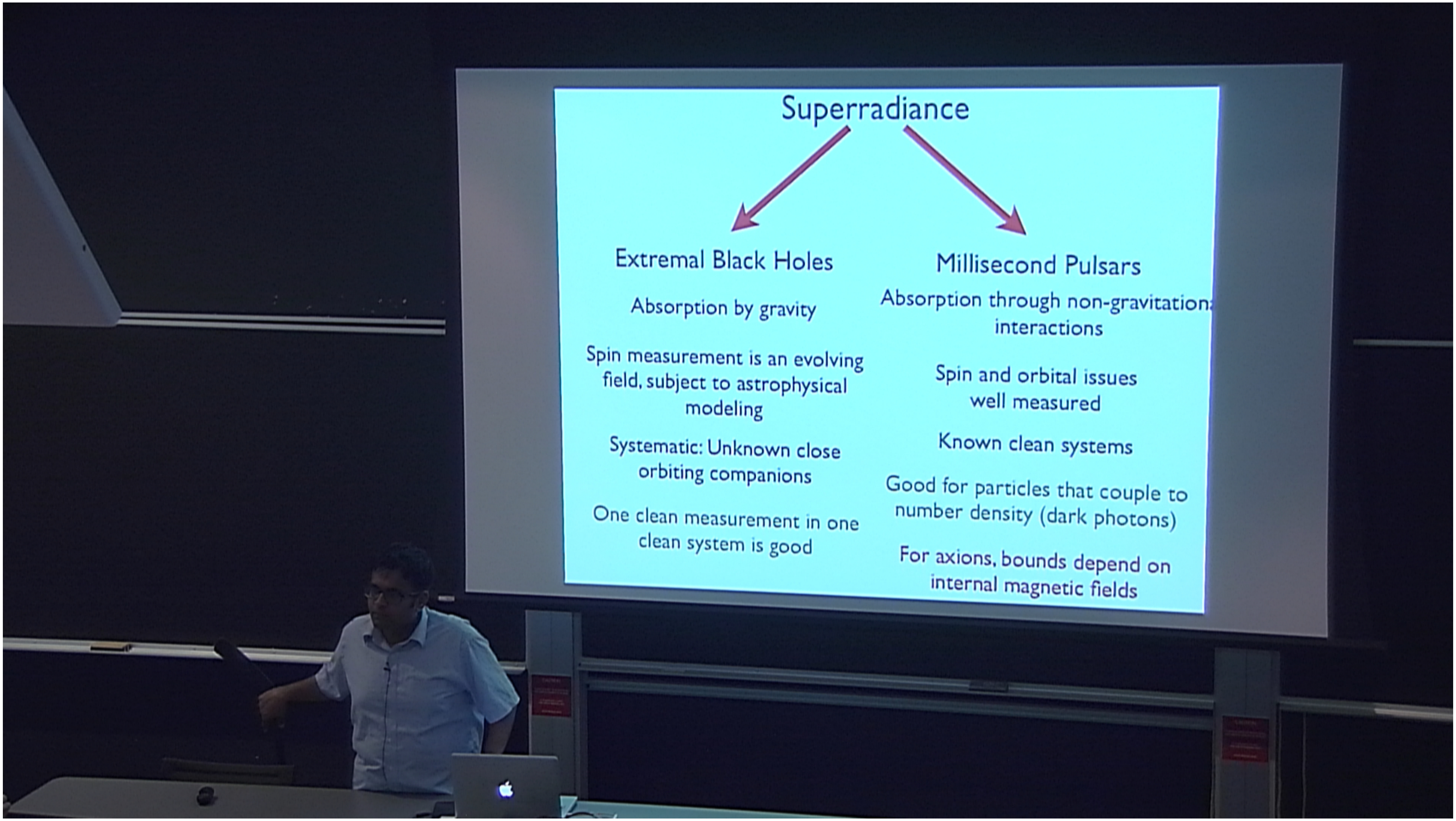

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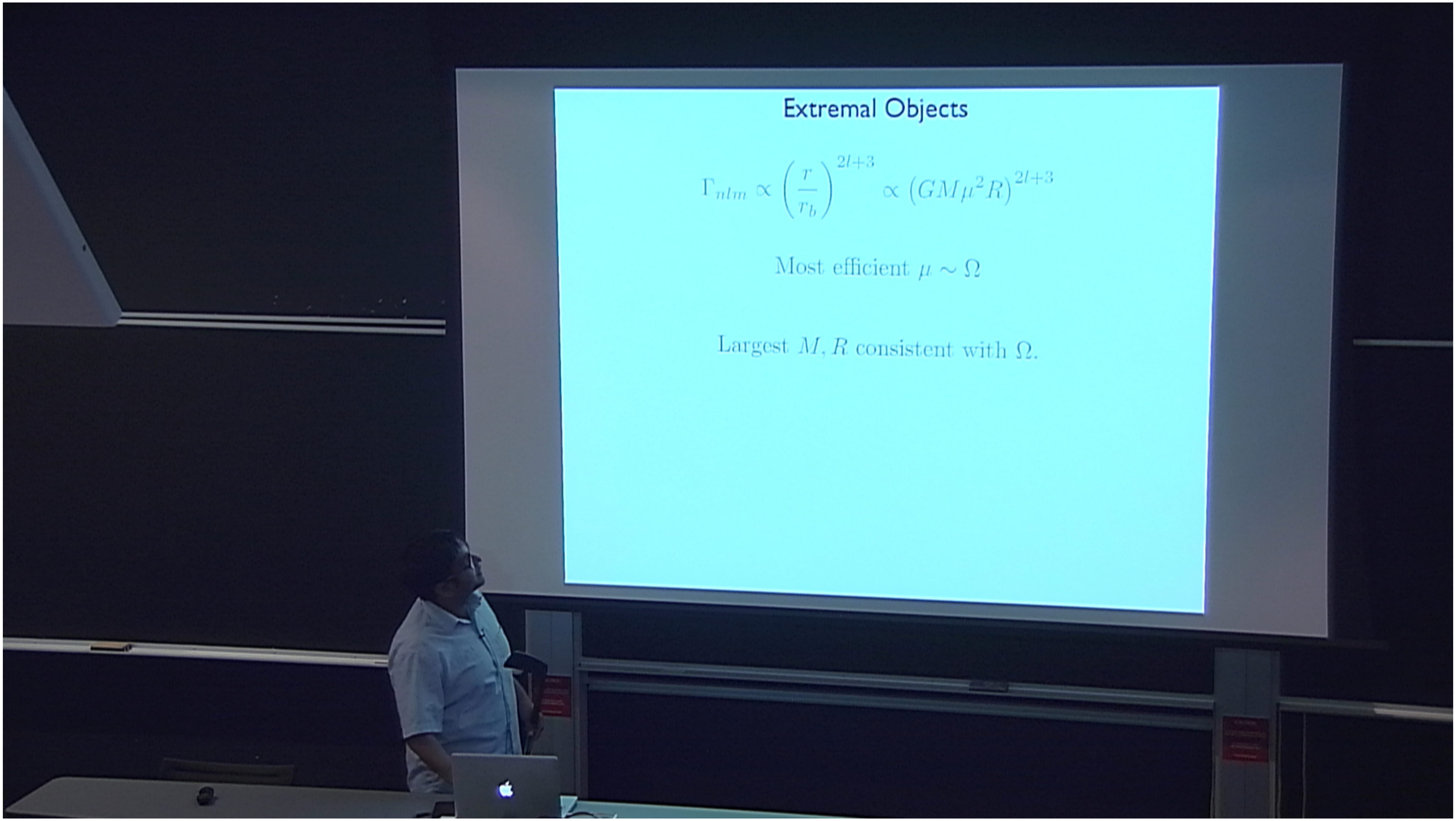

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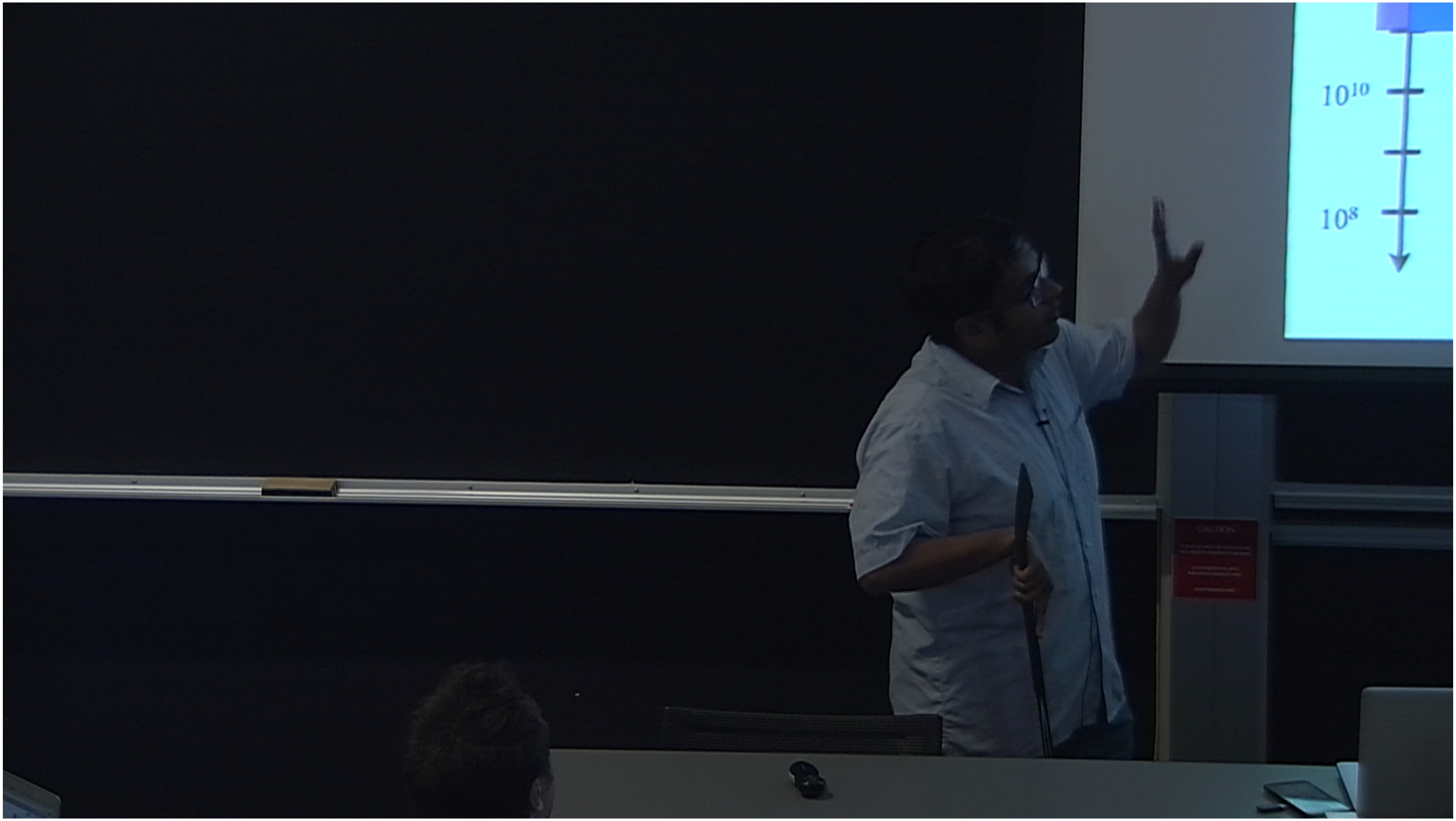
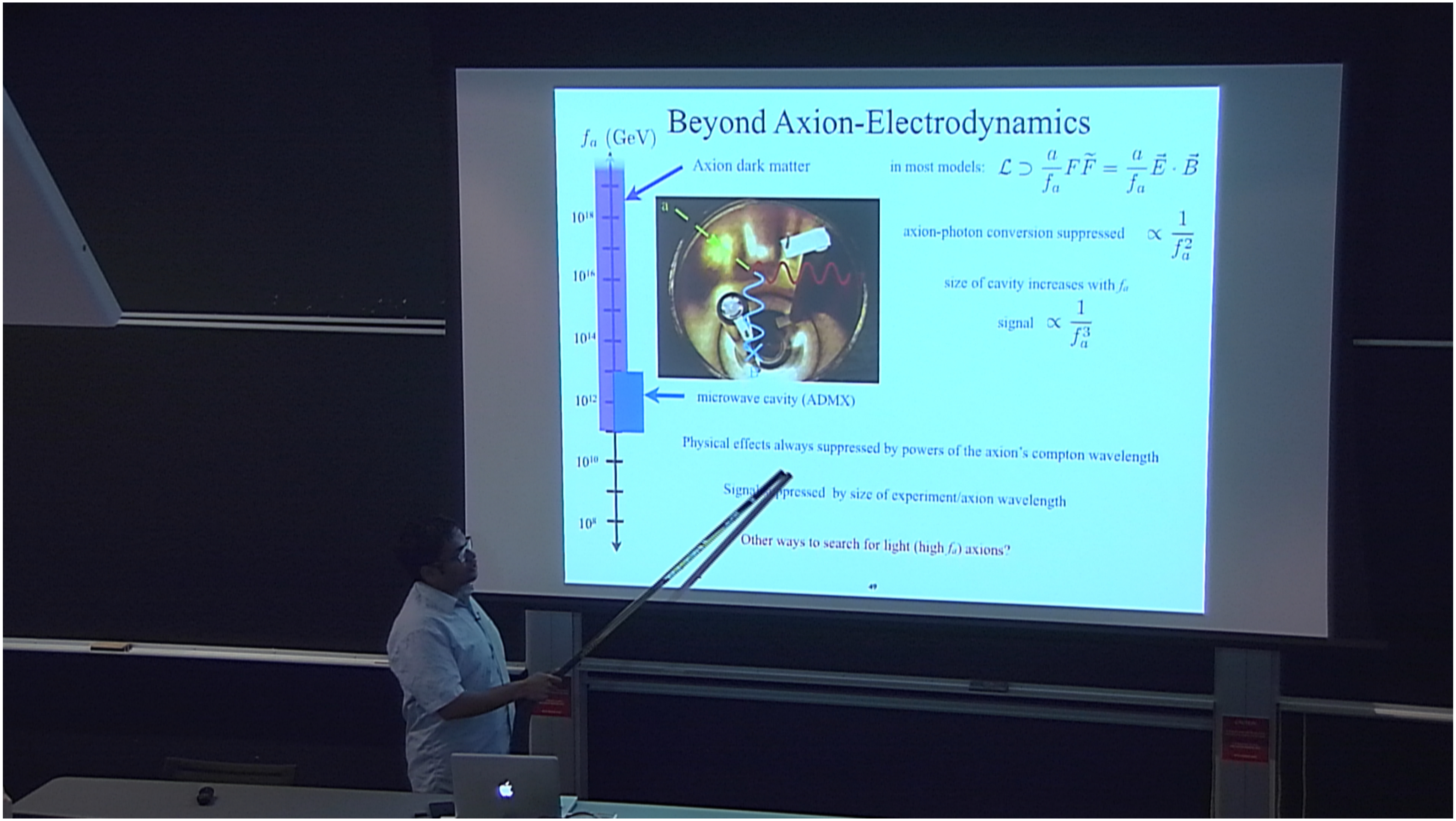

10^{10}
10^{8}
CAUTION



Beyond Axion-Electrodynamics

Axion dark matter

microwave cavity (ADMX)

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$

axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

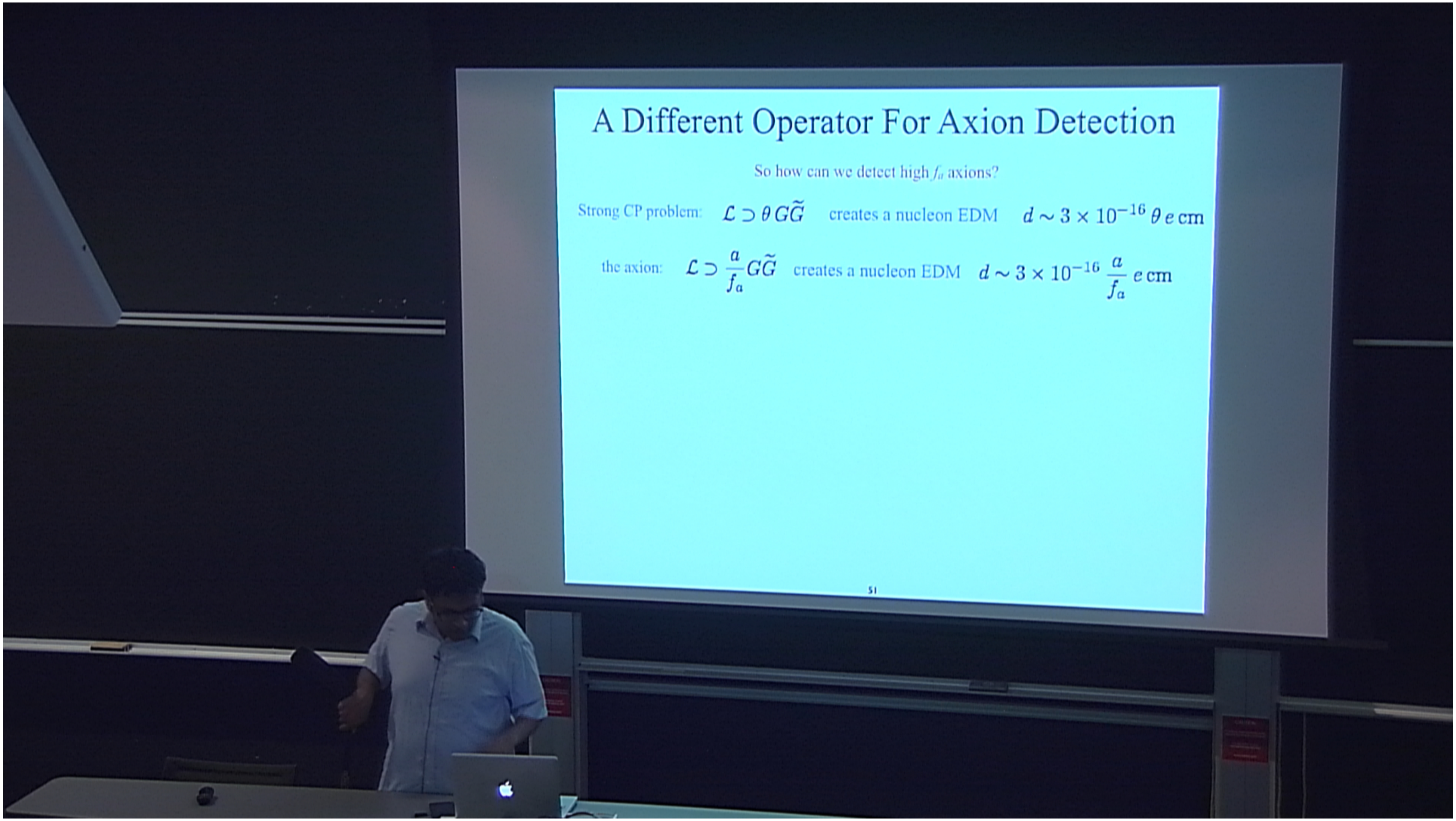
size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

Physical effects always suppressed by powers of the axion's compton wavelength

Signal suppressed by size of experiment/axion wavelength

Other ways to search for light (high f_a) axions?

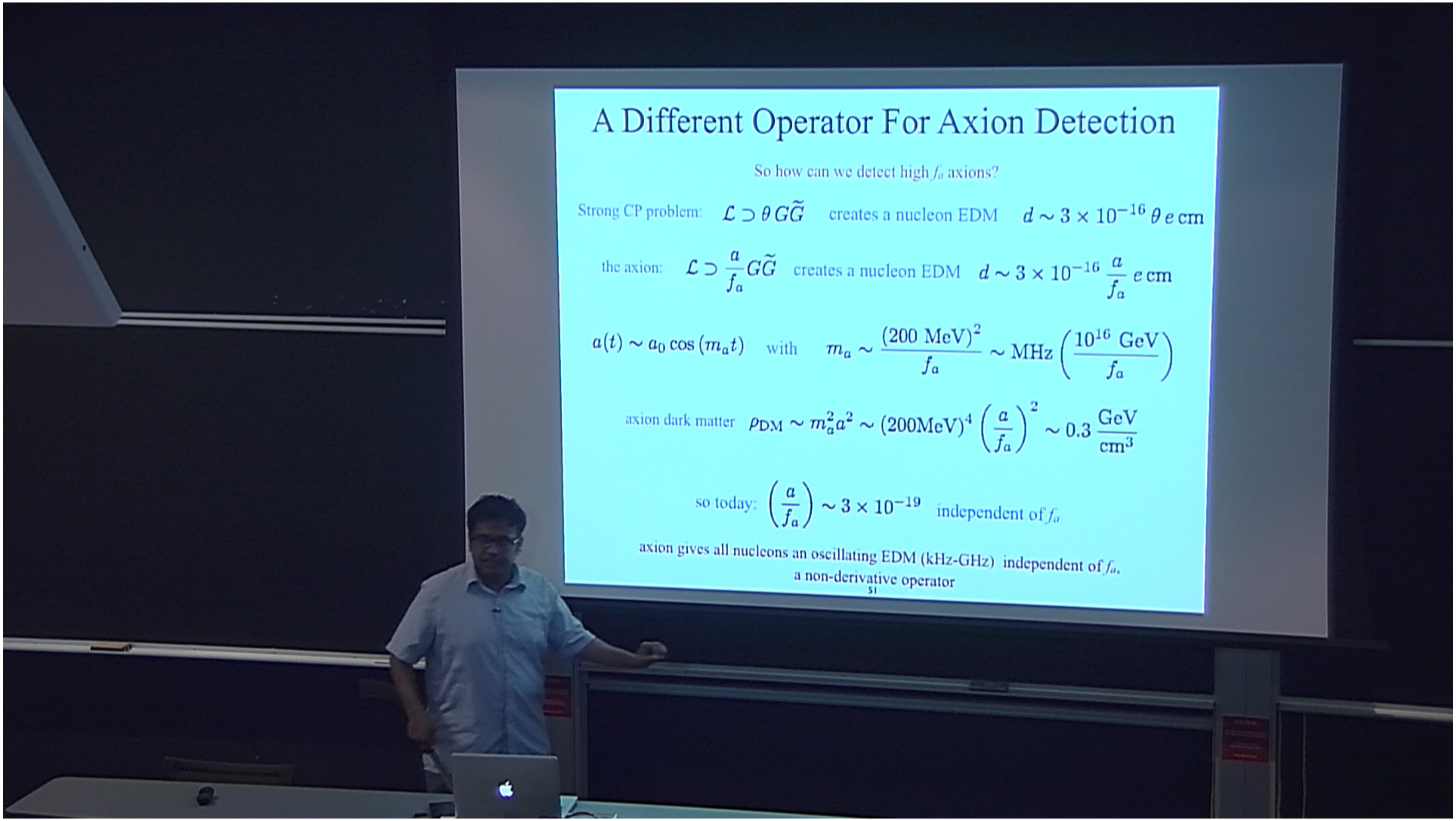


A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\,\theta\, e\,\mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\,\frac{a}{f_a}\, e\,\mathrm{cm}$



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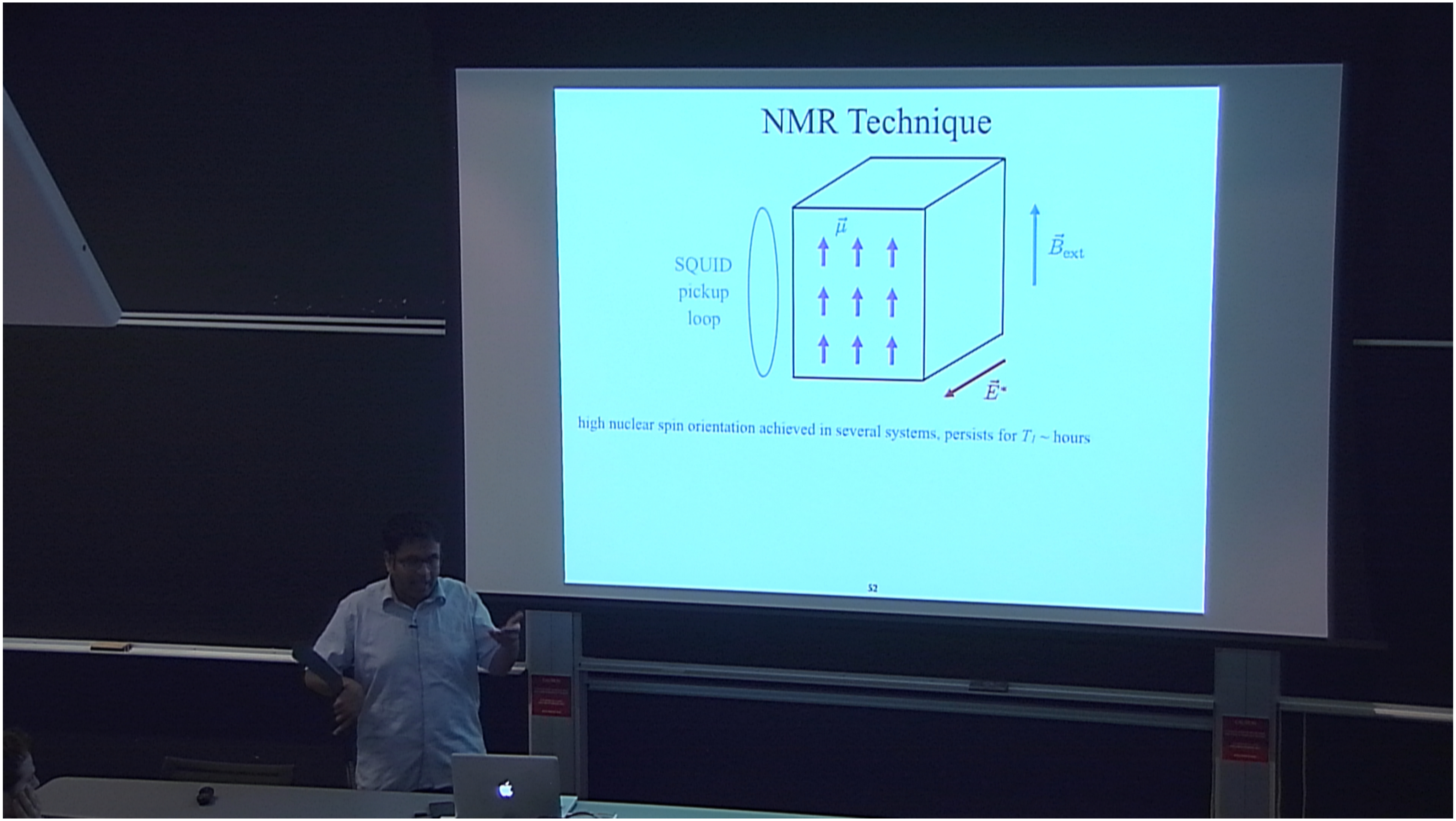
$a(t) \sim a_0 \cos(m_a t)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz} \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200\mathrm{MeV})^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

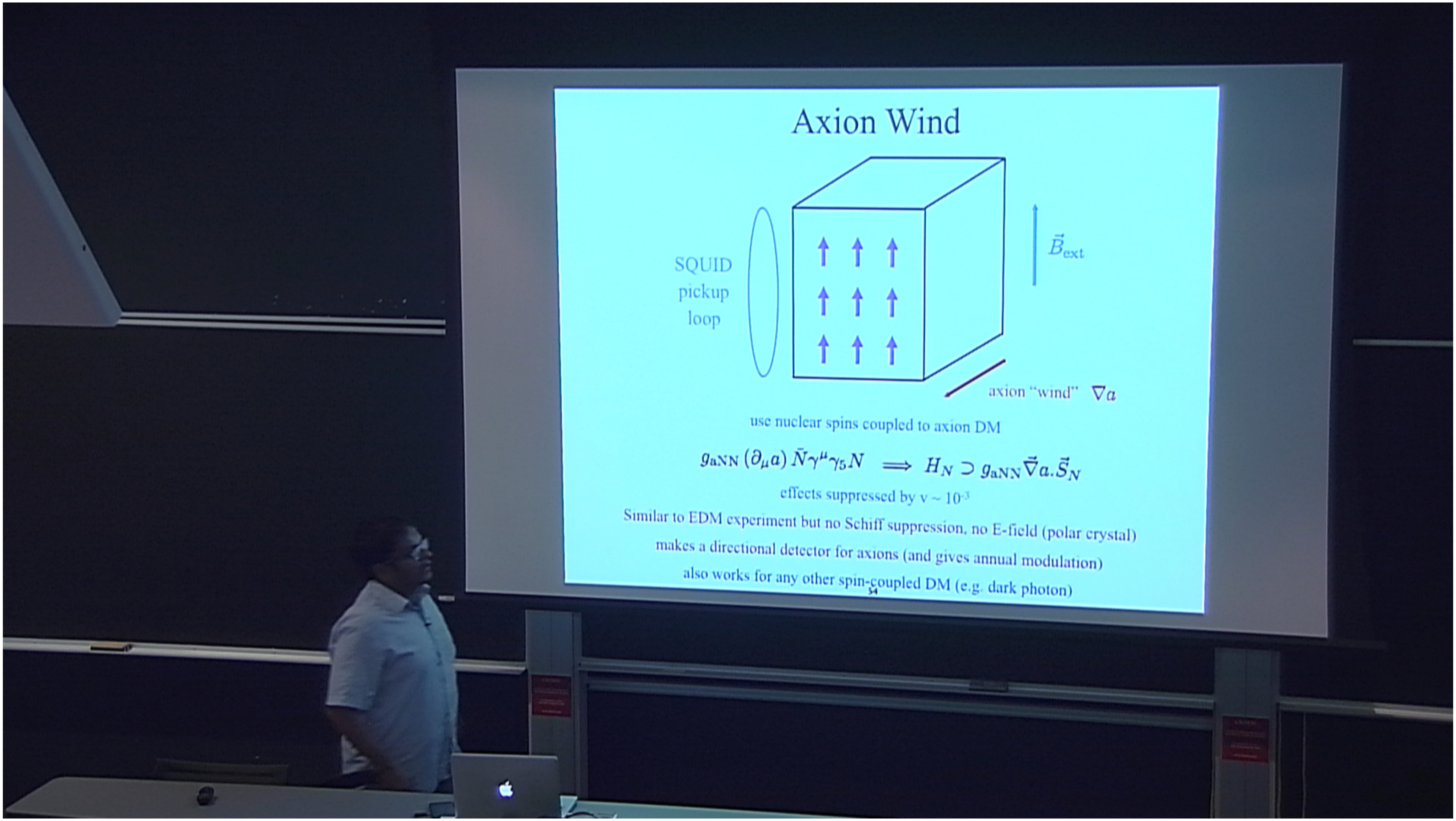
axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a.

a non-derivative operator



NMR Technique

high nuclear spin orientation achieved in several systems, persists for T_1 ~ hours



Axion Wind

use nuclear spins coupled to axion DM

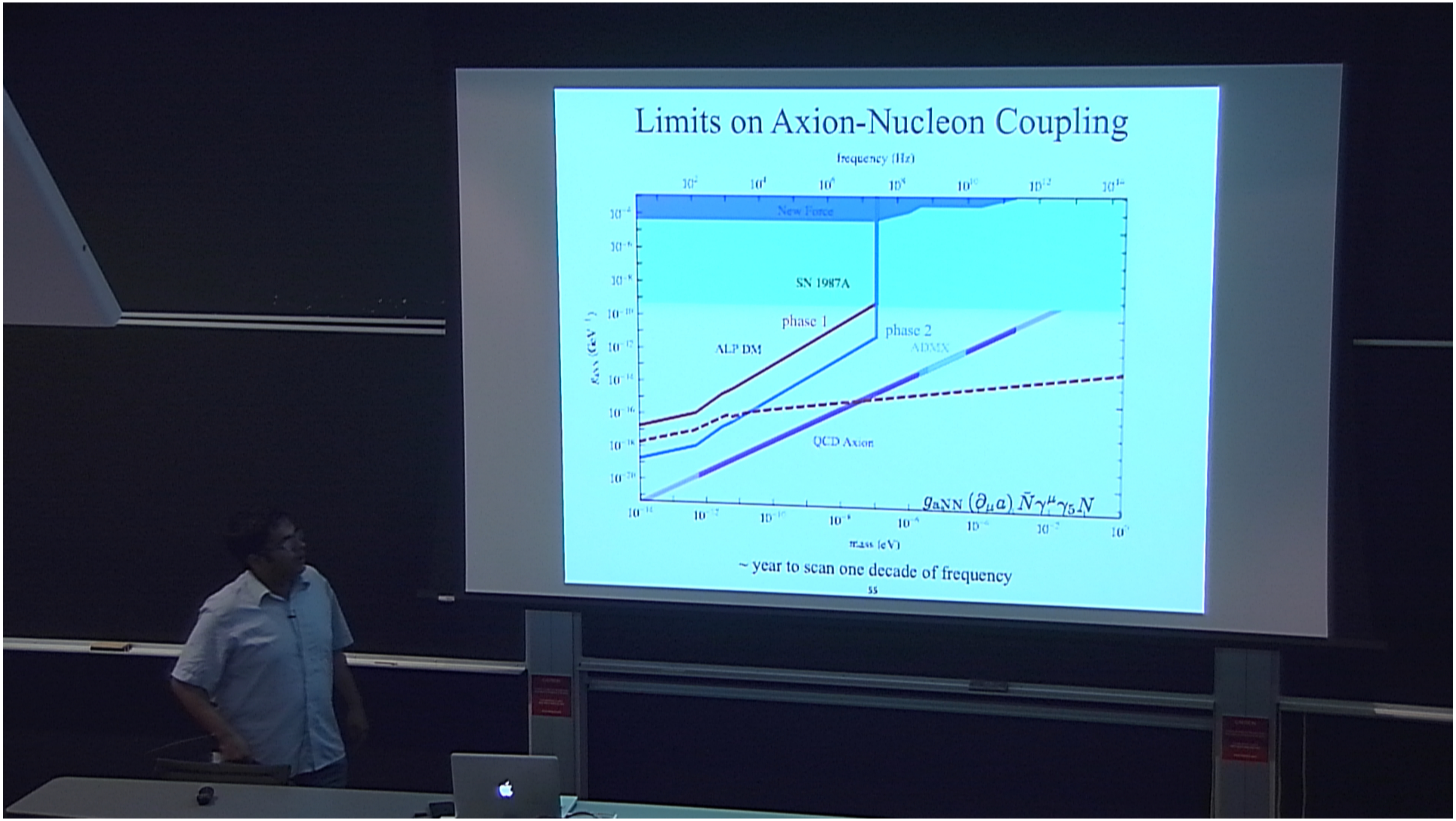
$$g_{\rm aNN}\,(\partial_\mu a)\,\bar{N}\gamma^\mu\gamma_5 N \implies H_N \supset g_{\rm aNN}\vec{\nabla}a.\vec{S}_N$$

effects suppressed by v ~ 10^{-3}

Similar to EDM experiment but no Schiff suppression, no E-field (polar crystal)

makes a directional detector for axions (and gives annual modulation)

also works for any other spin-coupled DM (e.g. dark photon)



Limits on Axion-Nucleon Coupling

~ year to scan one decade of frequency