Title: Astrophysical and cosmological aspects of feebly-interacting light species

Date: Jun 18, 2014 12:00 PM

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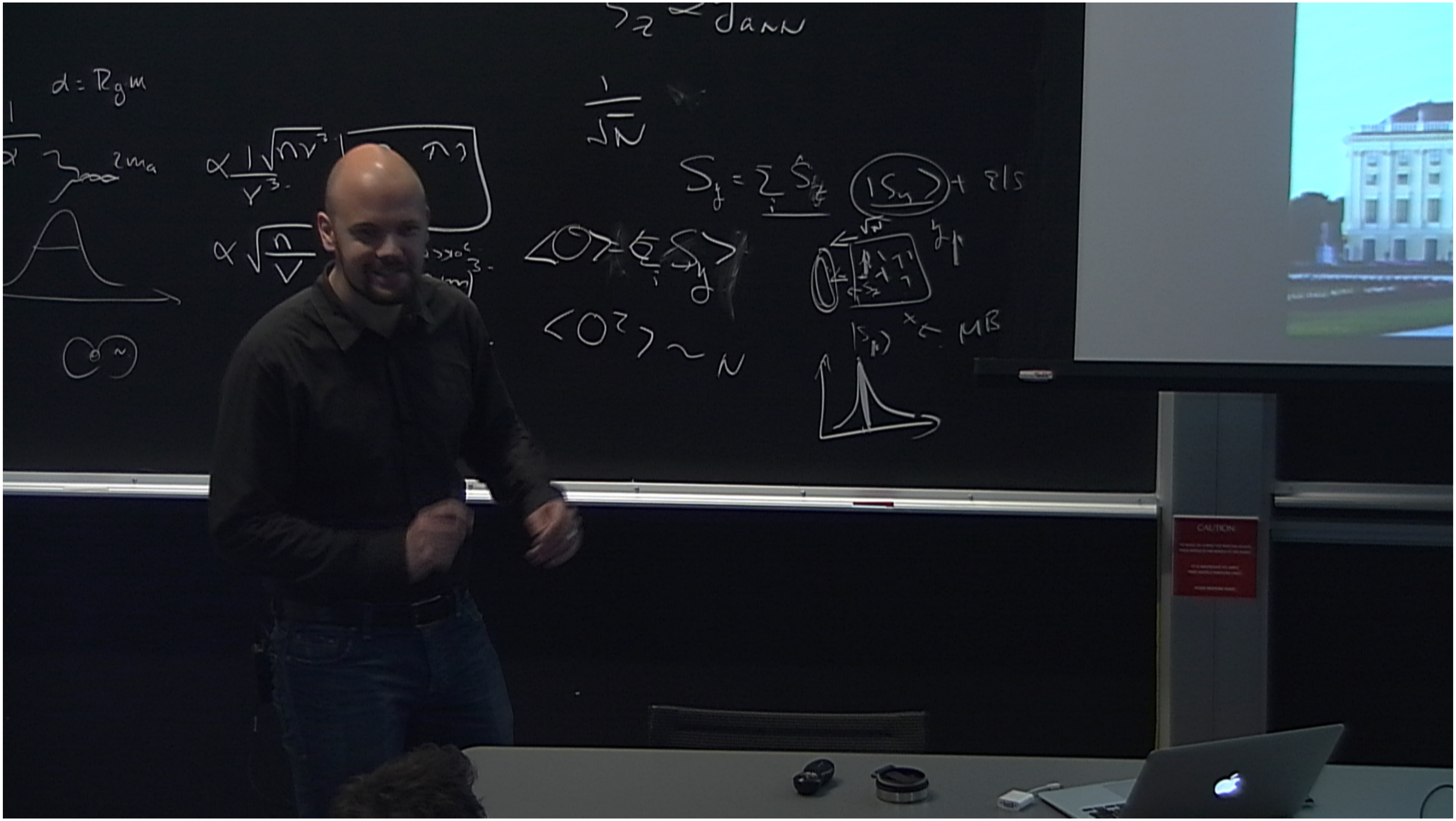
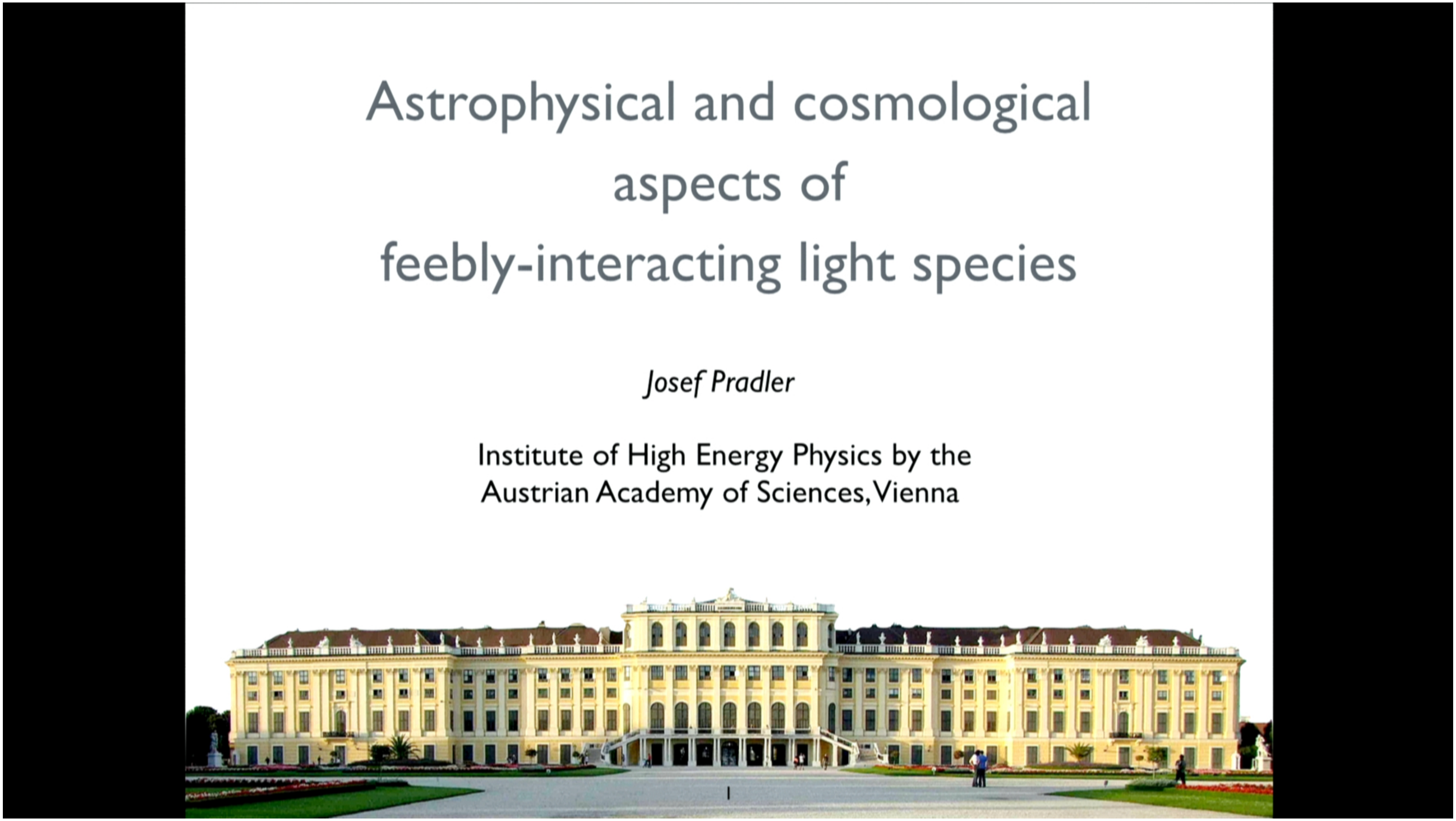
Abstract: More often than not, astrophysical probes are superior to direct laboratory tests when considering light, very weekly interacting particles and it takes clever strategies and/or ultra-pure experimental setups for direct tests to be competitive. In this talk, I will review the astrophysical side of the story with a particular focus on dark photons and axion-like particles. I will also present some recent results on the emission process of dark photons with mass below 10 keV from the interior of stars. Compared to previous analyses, limits on dark photons are significantly improved, to the extent that many dedicated experimental searches find themselves inside astrophysically excluded regions. However, constraints on the atomic ionization rate from a solar flux imposed by Dark Matter experiments offer a new test of such states, surpassing even the most stringent astrophysical limits. The model also serves as a prototype scenario for energy injection in the early Universe and I will show how cosmology offers unique sensitivity when laboratory probes are out of reach. Time permitting, I may also briefly comment on very light axions and their cosmology.



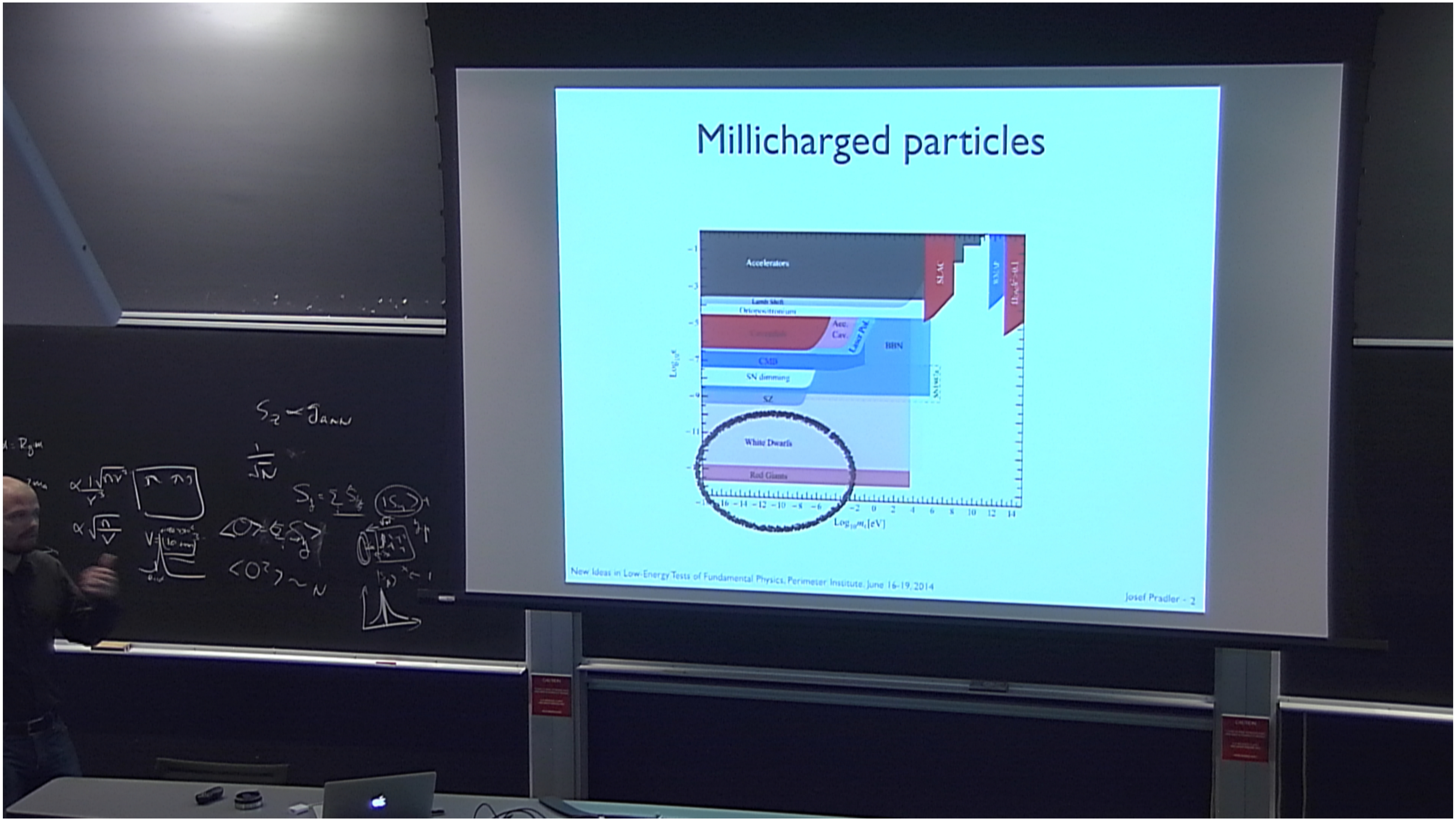
d = R_g m
1/√N
S_y = Σ_i S_iy
|S_y⟩ + c/s
⟨O⟩ = Σ_i ⟨S_iy⟩
⟨O²⟩ ~ N
MB



Astrophysical and cosmological aspects of feebly-interacting light species

Josef Pradler

Institute of High Energy Physics by the
Austrian Academy of Sciences, Vienna



Millicharged particles

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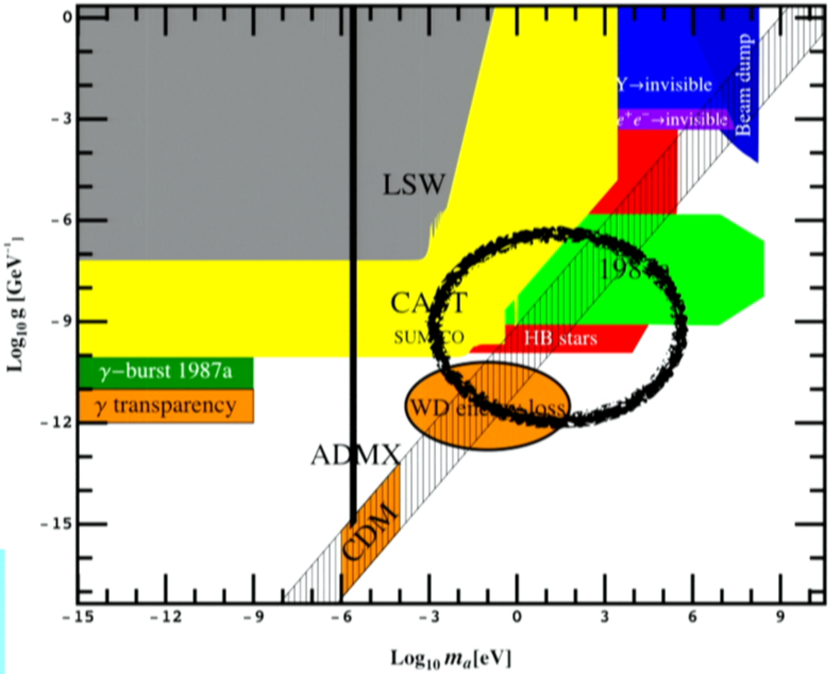
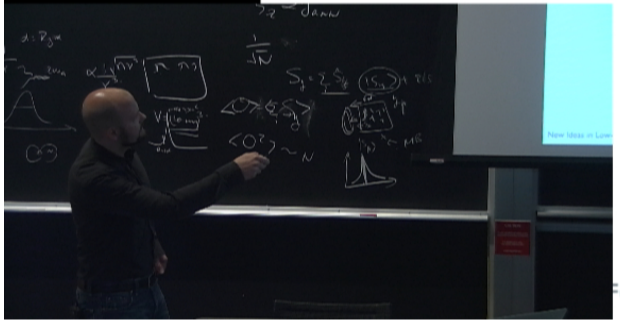
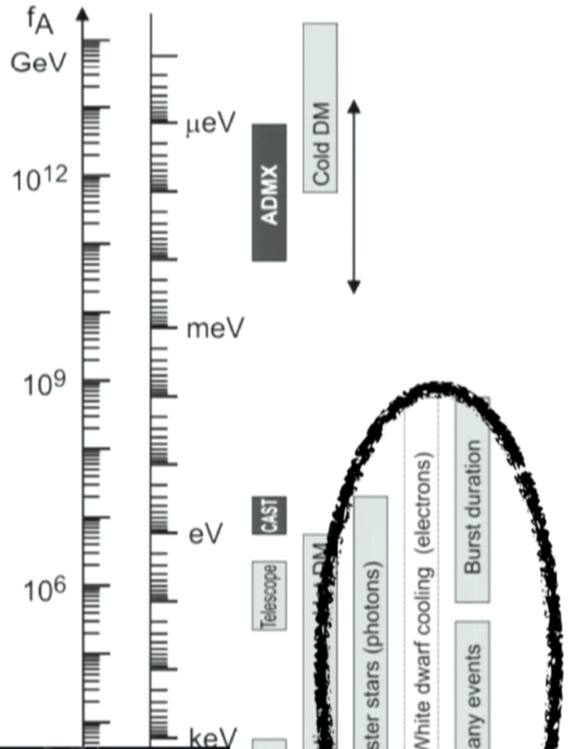
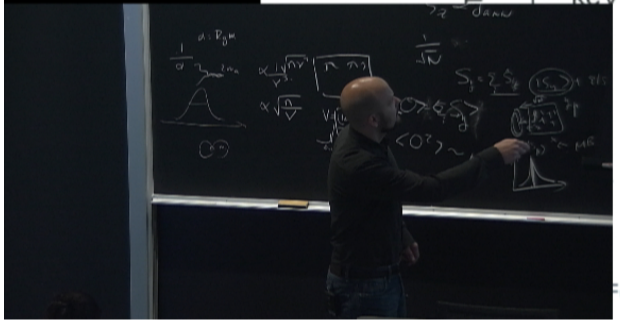
Axion-like particles





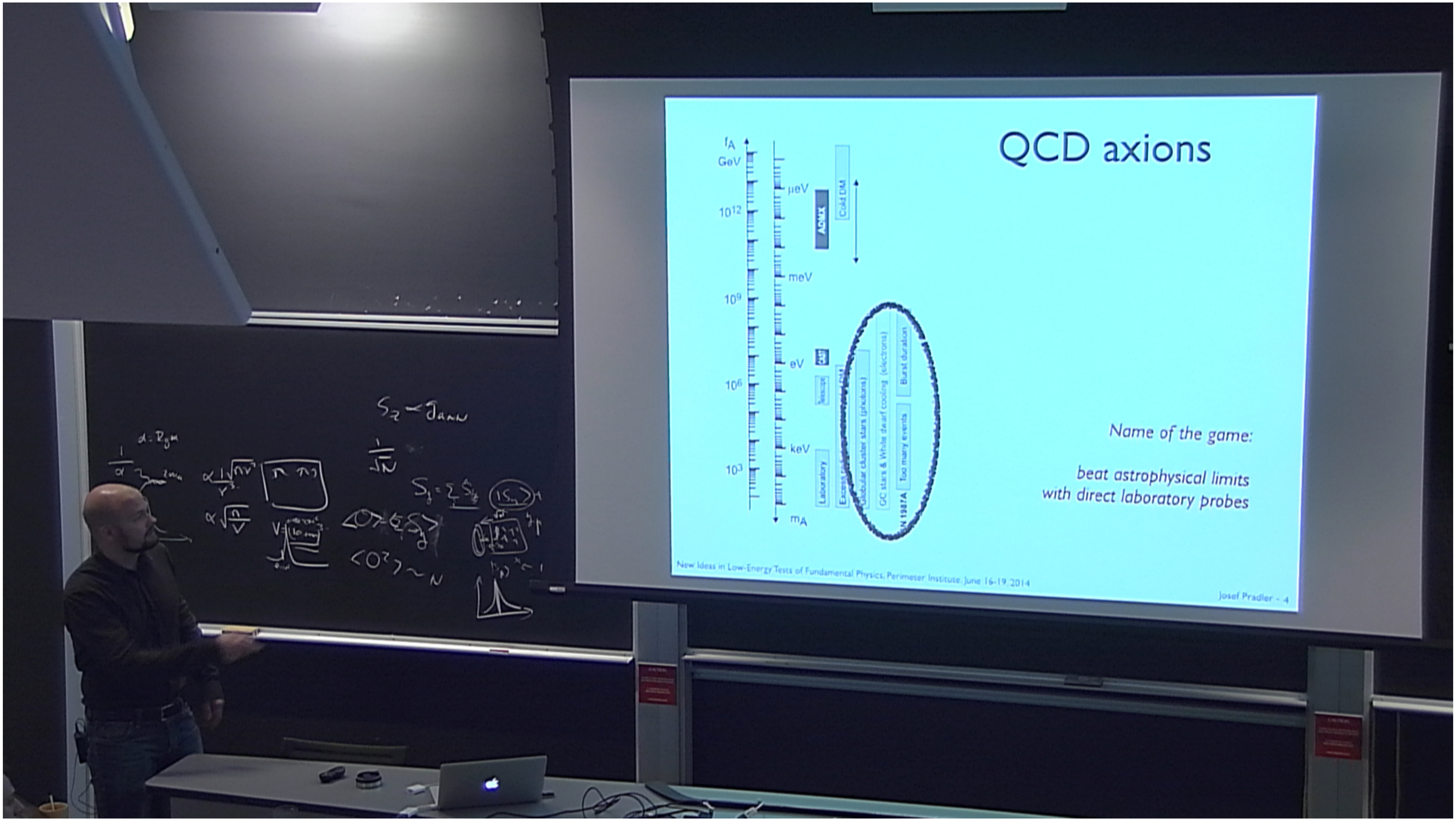
QCD axions





Name of the game:

beat astrophysical limits
with direct laboratory probes



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Plan

1. Review of astrophysical probes of light, weakly interacting states

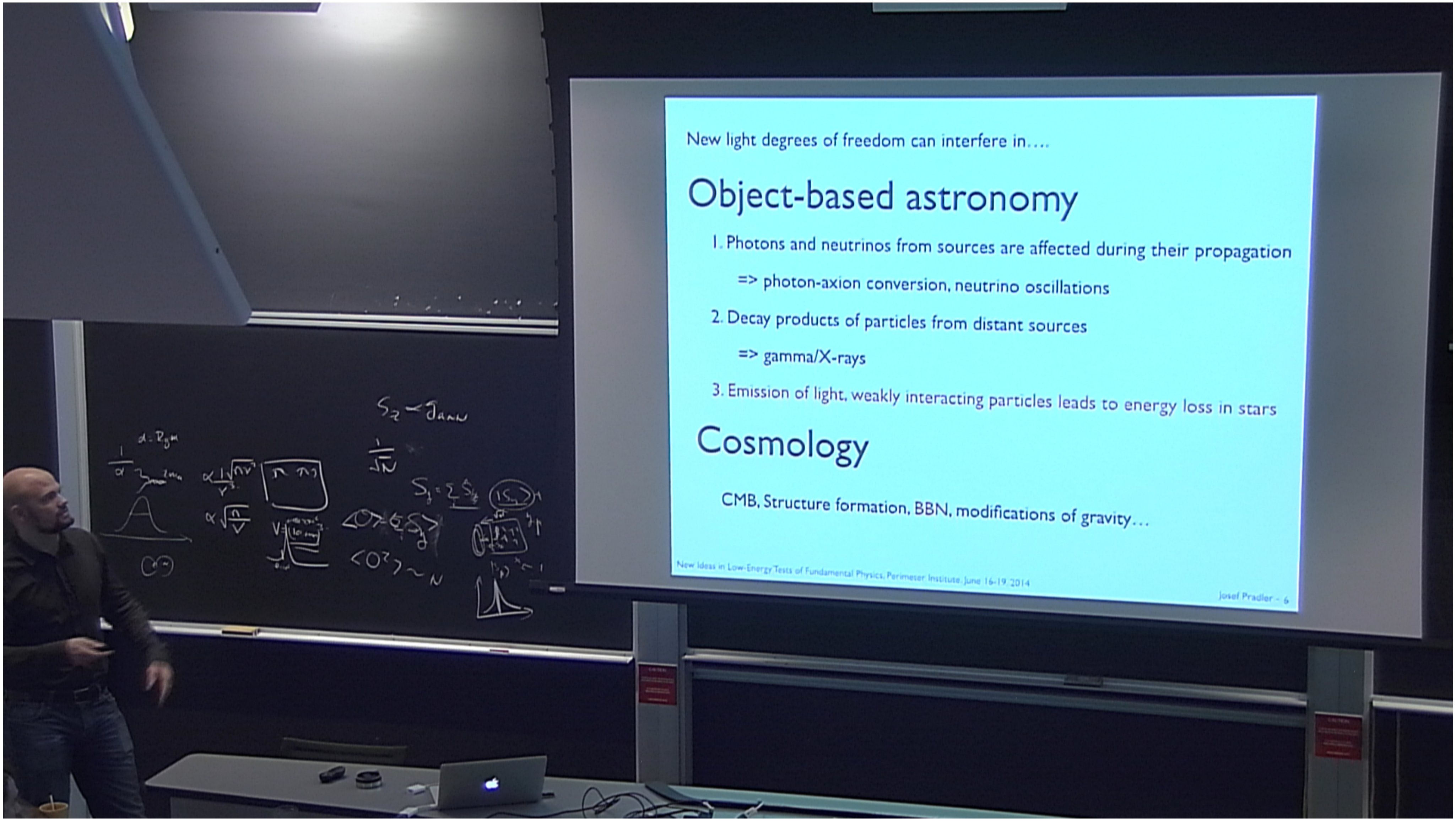
2. Dark Photons

   - more recent progress on stellar emission and laboratory detection

     H. An, M. Pospelov, JP, PLB+PRL 2013

   - cosmological constraints from light element observations

     A. Fradette, M. Pospelov, JP, A. Ritz (in preparation)



New light degrees of freedom can interfere in….

Object-based astronomy

1. Photons and neutrinos from sources are affected during their propagation

   => photon-axion conversion, neutrino oscillations

2. Decay products of particles from distant sources

   => gamma/X-rays

3. Emission of light, weakly interacting particles leads to energy loss in stars

Cosmology

CMB, Structure formation, BBN, modifications of gravity…

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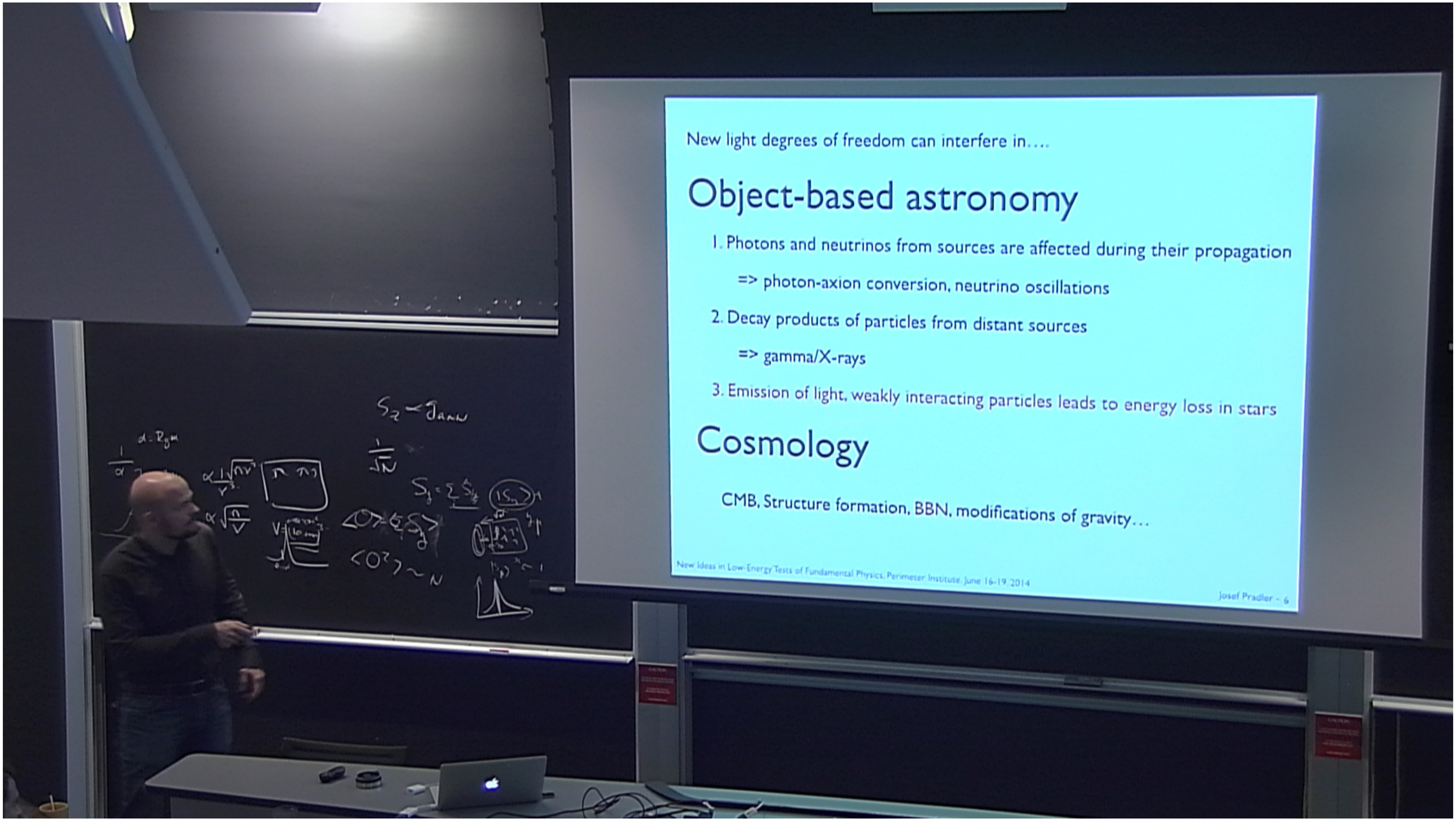

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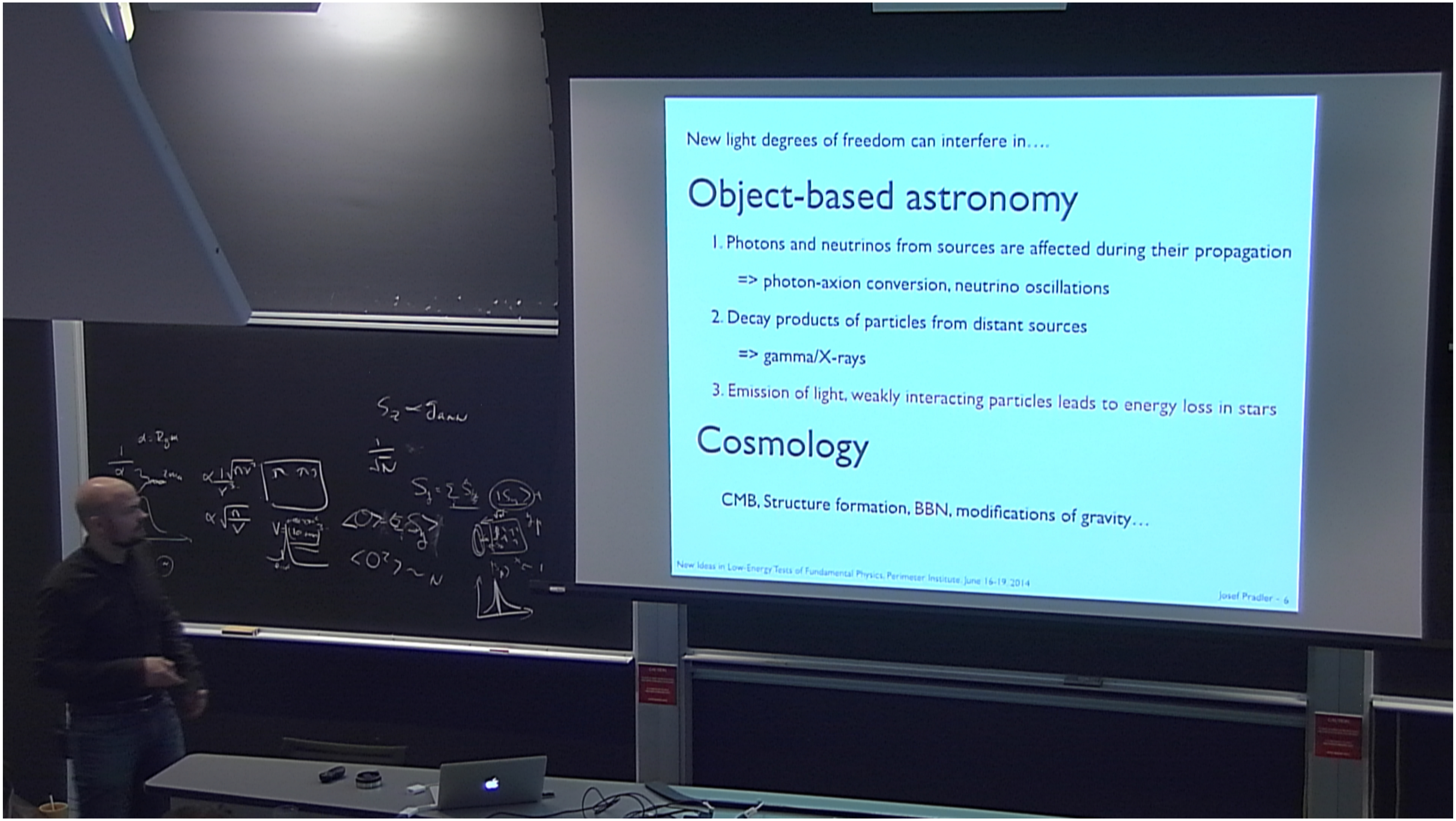

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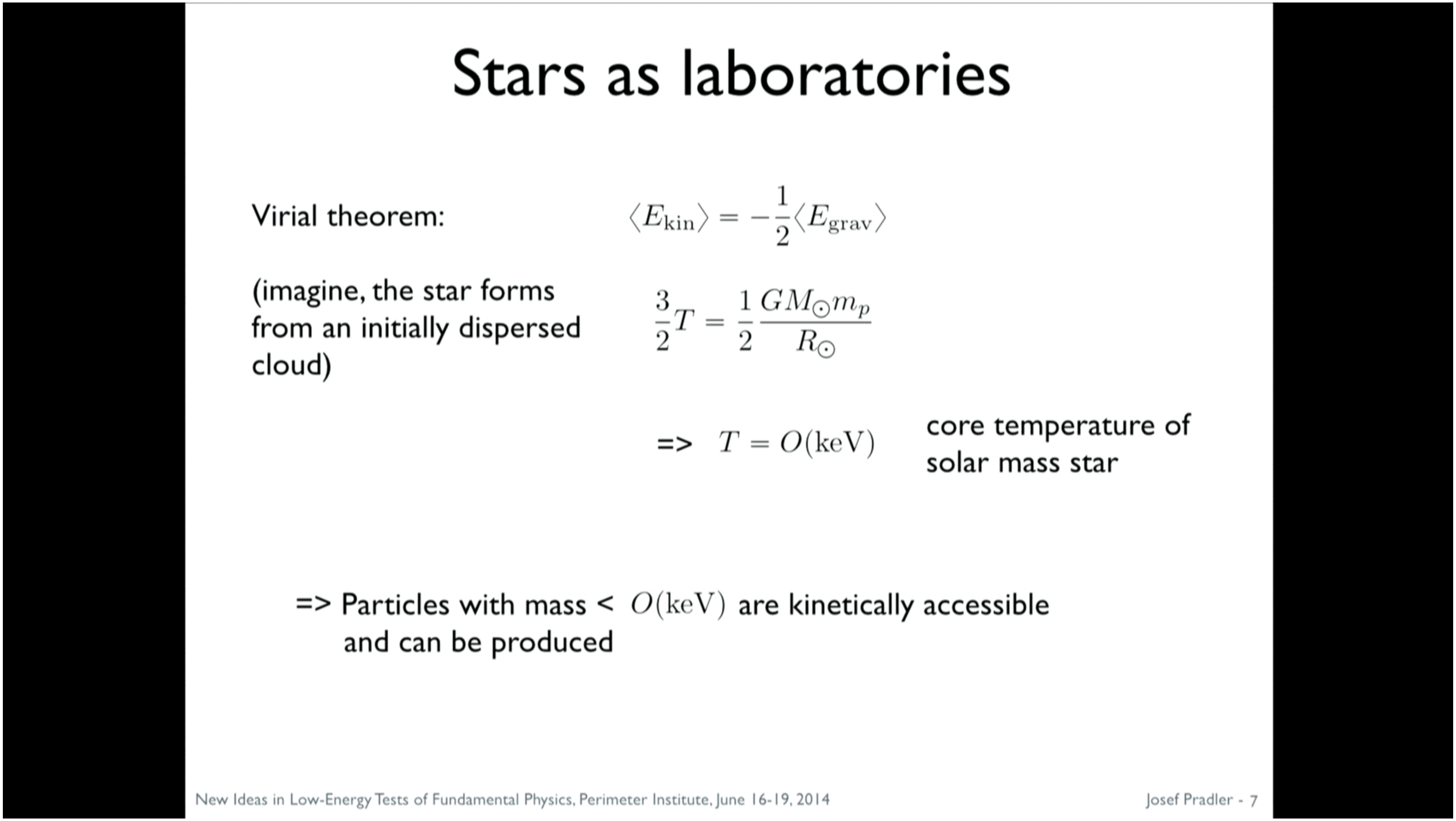


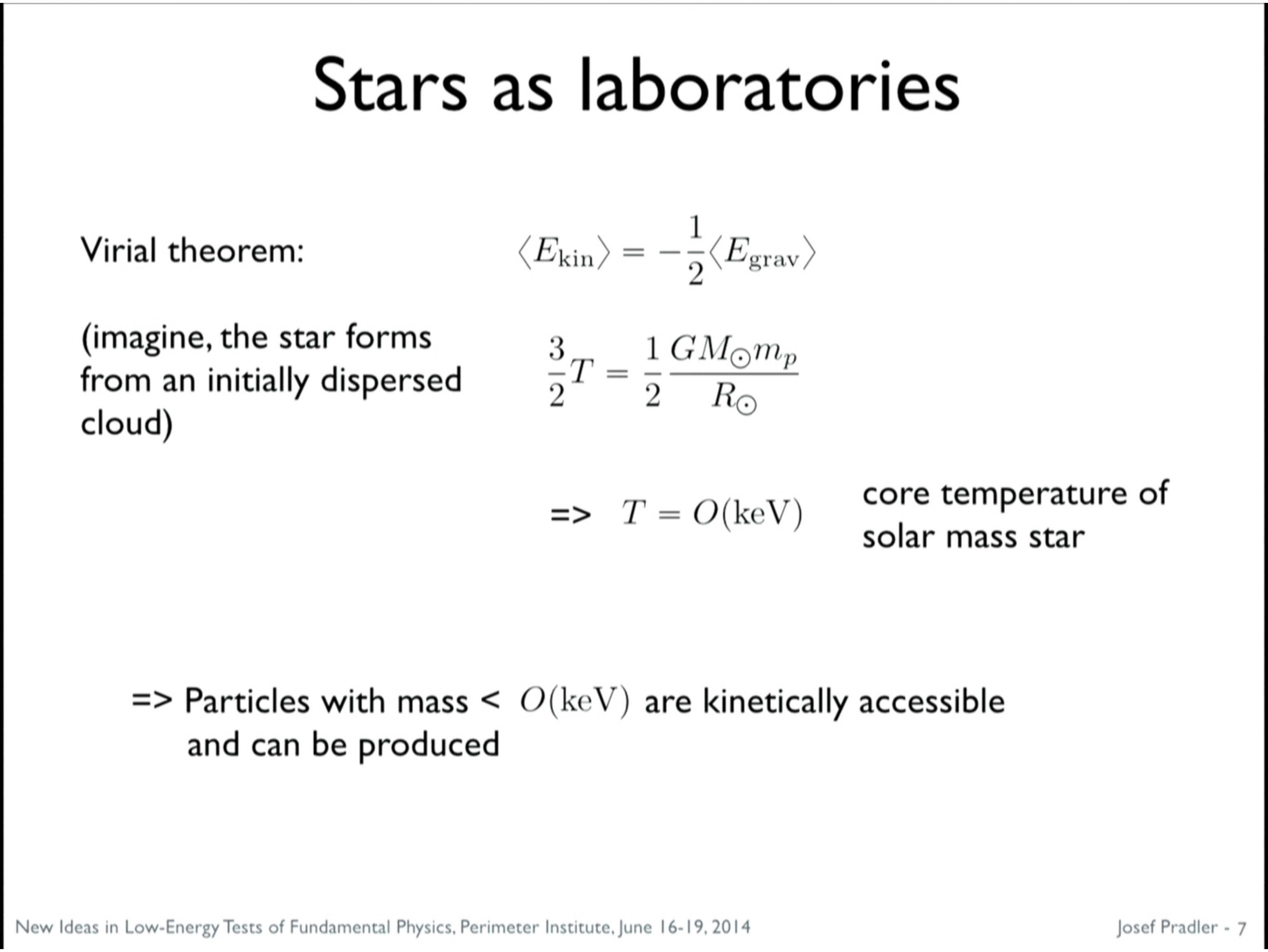
Stars as laboratories

Virial theorem: $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$

(imagine, the star forms from an initially dispersed cloud) $\frac{3}{2}T = \frac{1}{2}\frac{GM_\odot m_p}{R_\odot}$

=> $T = O(\mathrm{keV})$ core temperature of solar mass star

=> Particles with mass < $O(\mathrm{keV})$ are kinetically accessible and can be produced



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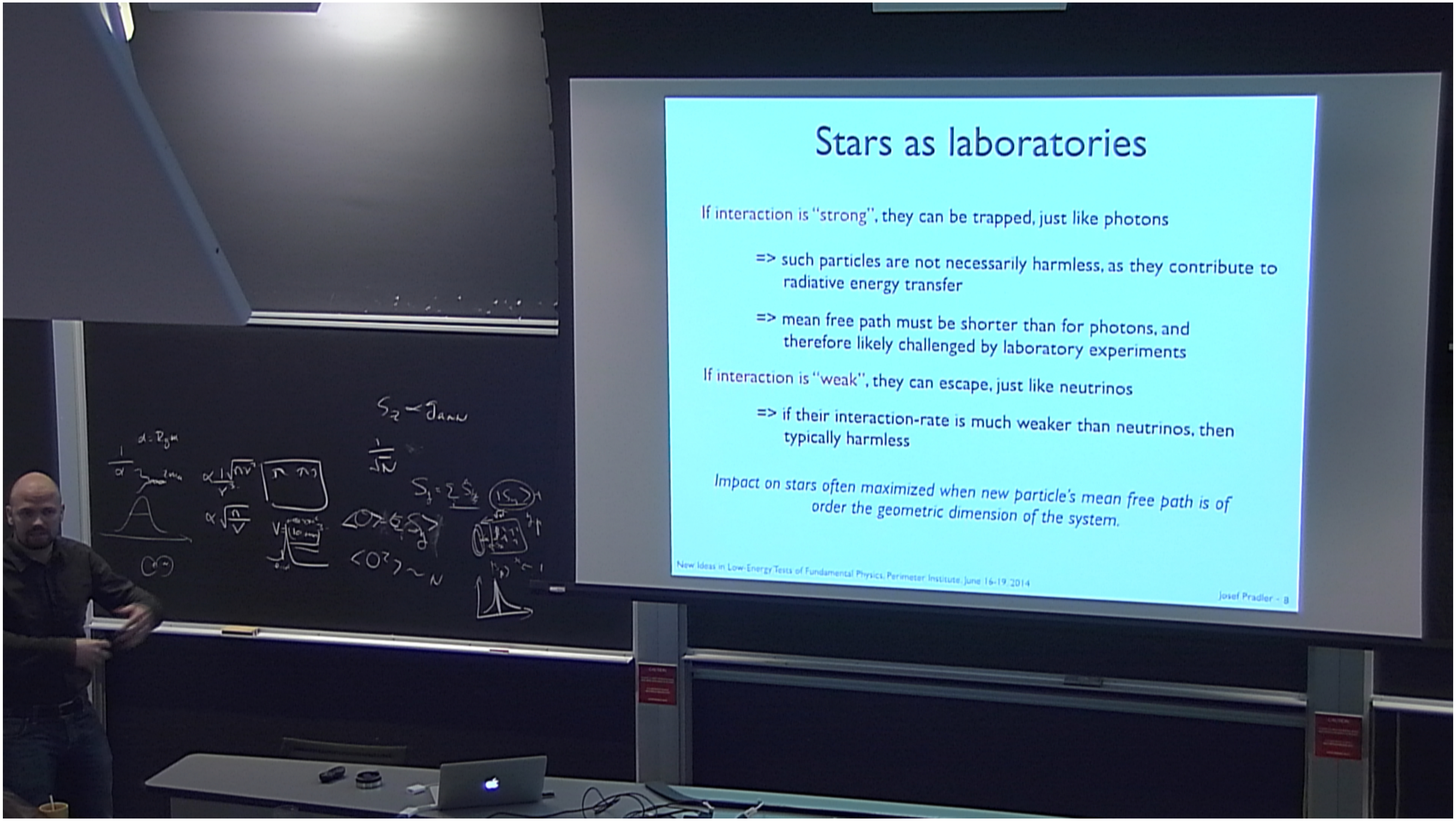


Stars as laboratories

If interaction is "strong", they can be trapped, just like photons

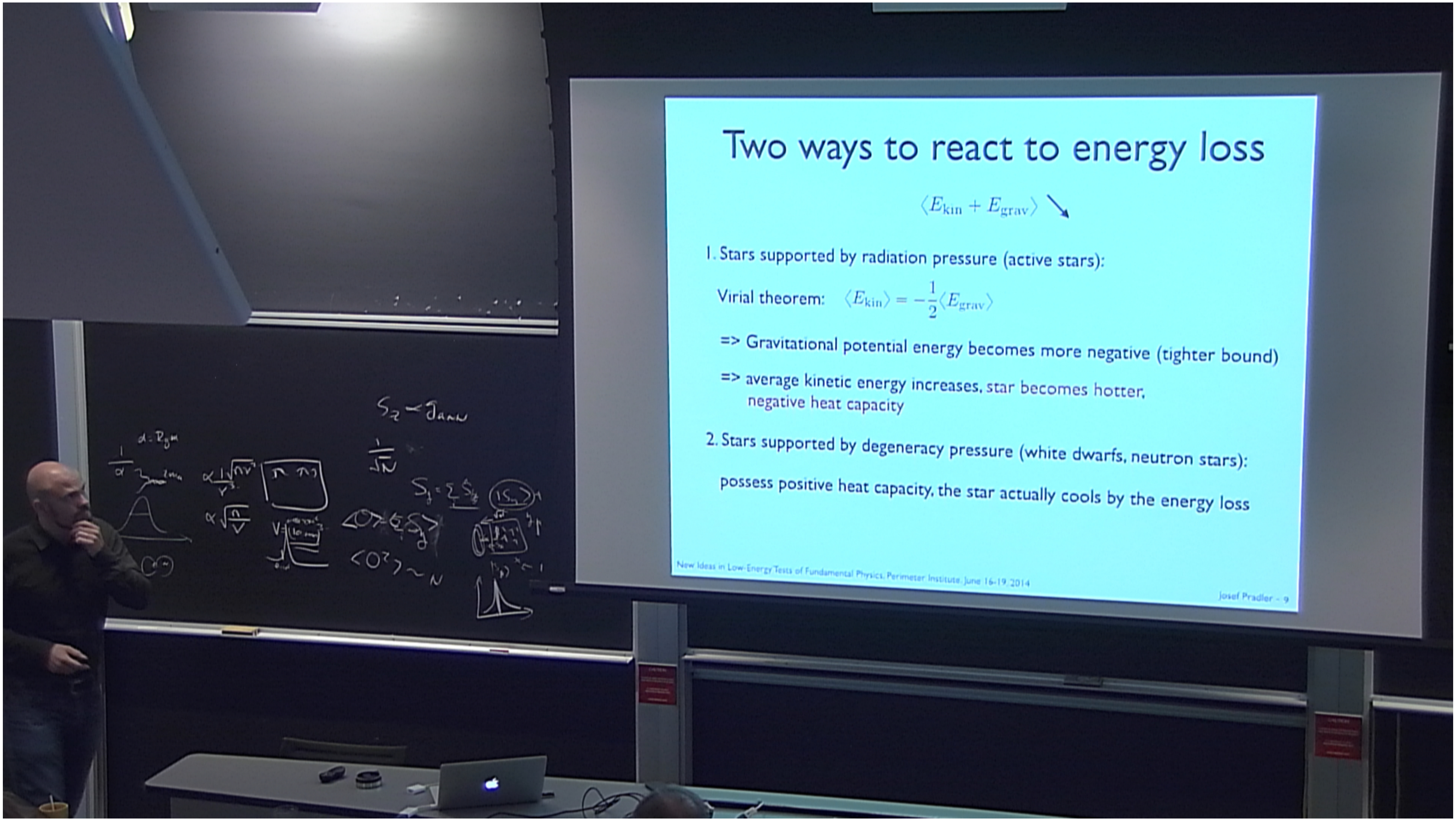
=> such particles are not necessarily harmless, as they contribute to radiative energy transfer

=> mean free path must be shorter than for photons, and therefore likely challenged by laboratory experiments

If interaction is "weak", they can escape, just like neutrinos

=> if their interaction-rate is much weaker than neutrinos, then typically harmless

Impact on stars often maximized when new particle's mean free path is of order the geometric dimension of the system.



Two ways to react to energy loss

$$\langle E_{\rm kin} + E_{\rm grav} \rangle \searrow$$

1. Stars supported by radiation pressure (active stars):

Virial theorem: $\langle E_{\rm kin} \rangle = -\frac{1}{2}\langle E_{\rm grav} \rangle$

=> Gravitational potential energy becomes more negative (tighter bound)

=> average kinetic energy increases, star becomes hotter, negative heat capacity

2. Stars supported by degeneracy pressure (white dwarfs, neutron stars):

possess positive heat capacity, the star actually cools by the energy loss

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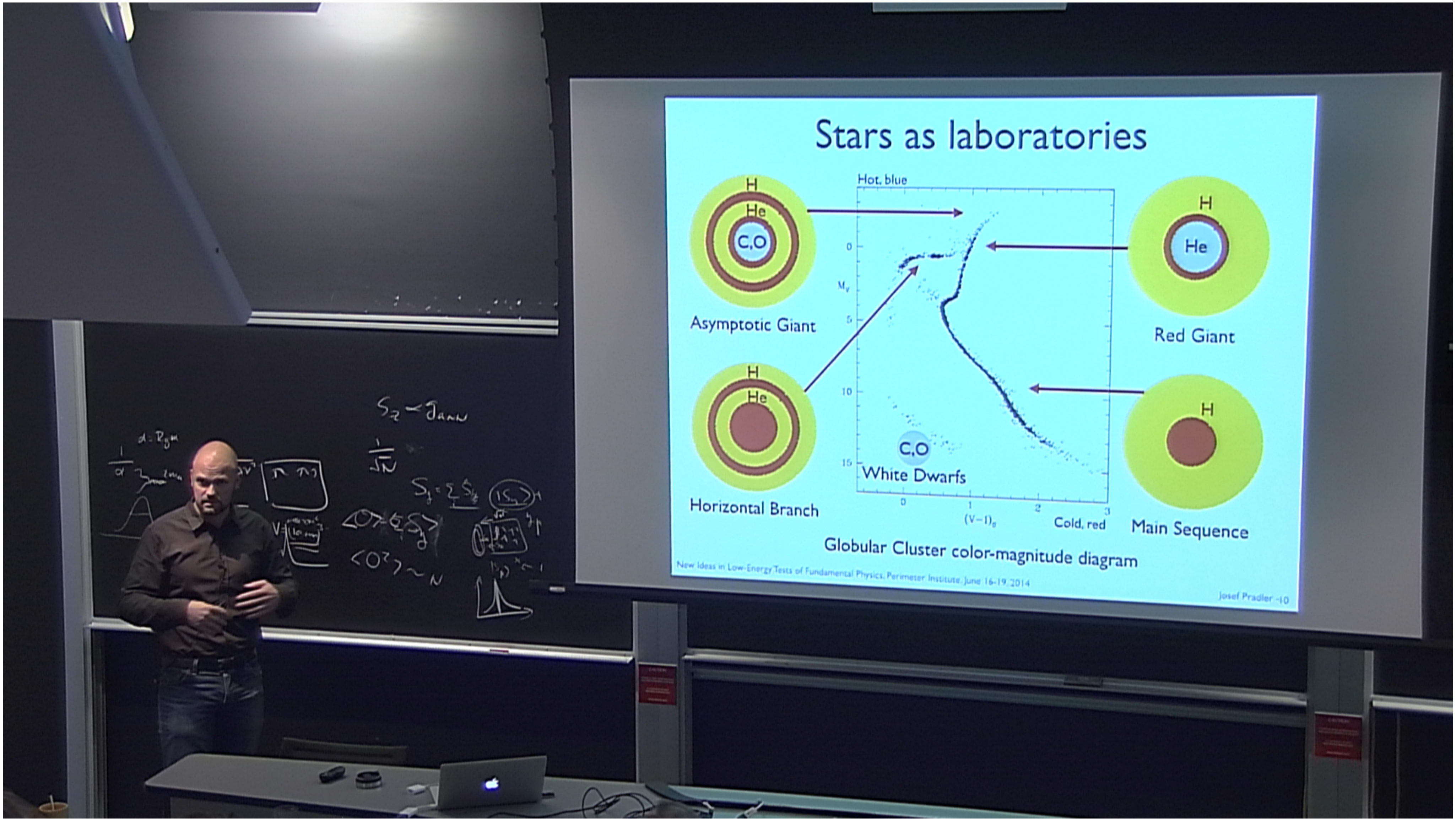

Stars as laboratories

Globular Cluster color-magnitude diagram

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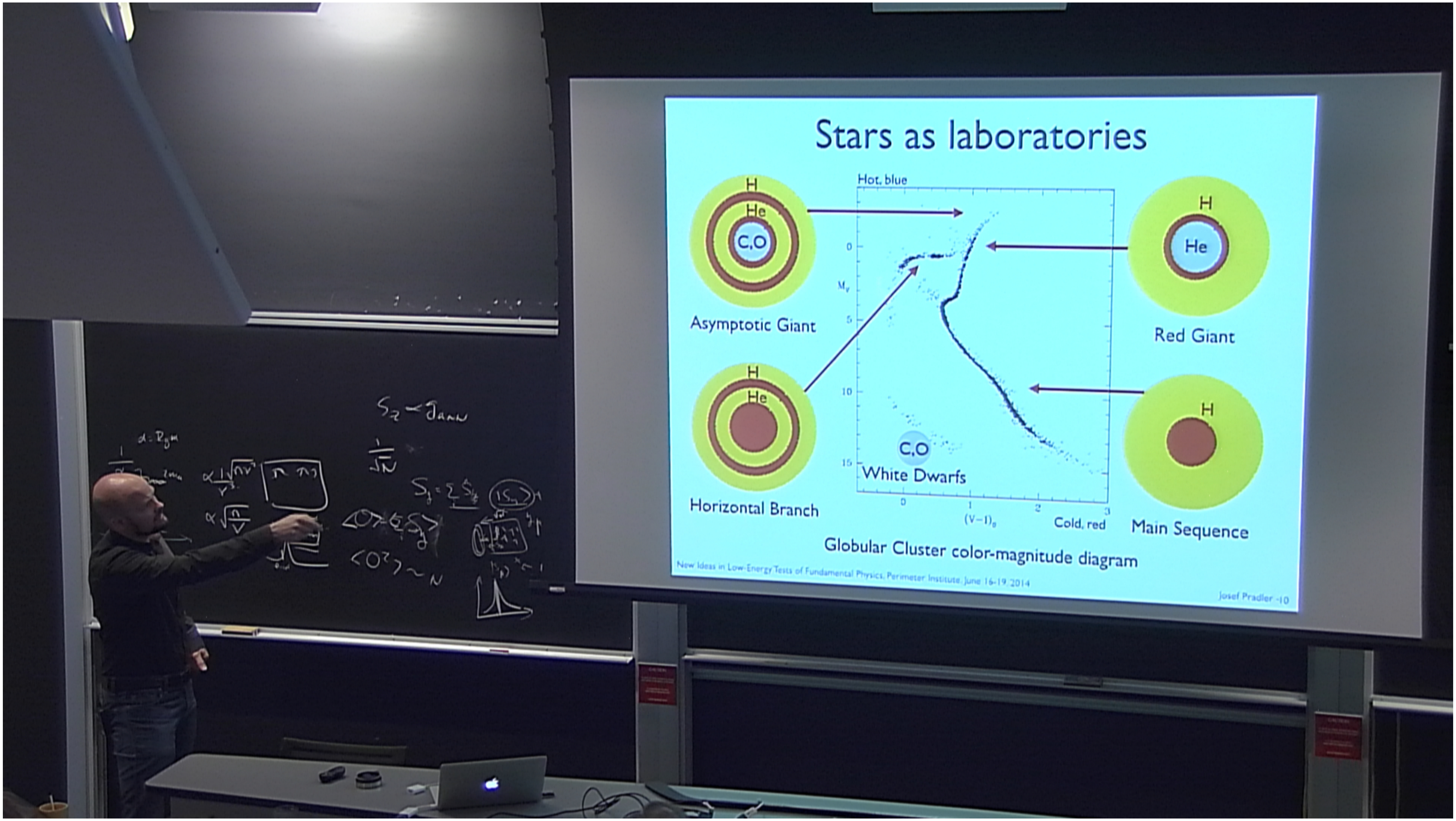

Stars as laboratories

Hot, blue

Asymptotic Giant

Red Giant

Horizontal Branch

White Dwarfs

Cold, red

Main Sequence

Globular Cluster color-magnitude diagram

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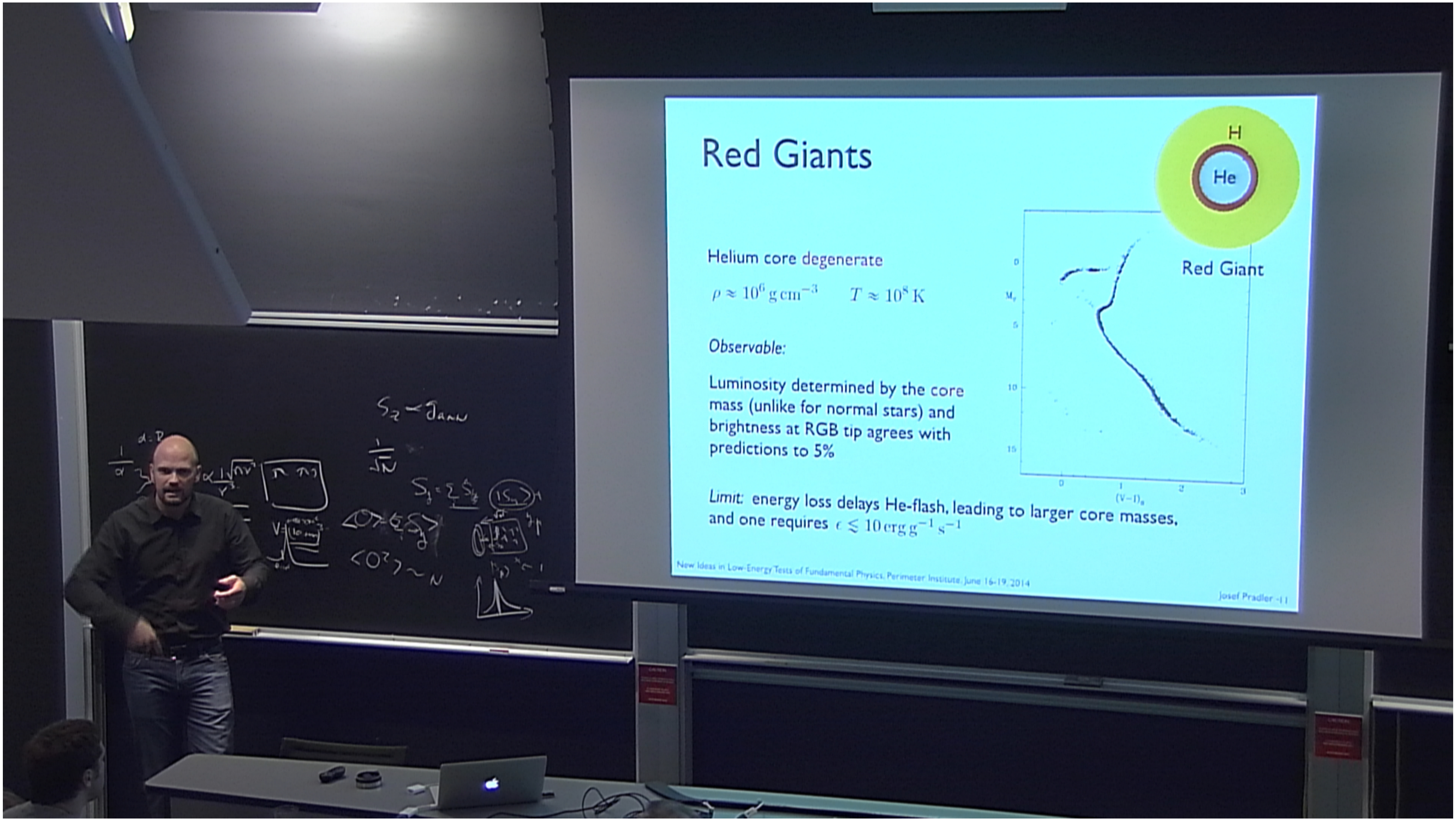

Red Giants

Helium core degenerate

$\rho \approx 10^6\,\mathrm{g\,cm^{-3}}$ $\quad T \approx 10^8\,\mathrm{K}$

Observable:

Luminosity determined by the core mass (unlike for normal stars) and brightness at RGB tip agrees with predictions to 5%

Limit: energy loss delays He-flash, leading to larger core masses, and one requires $\epsilon \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$

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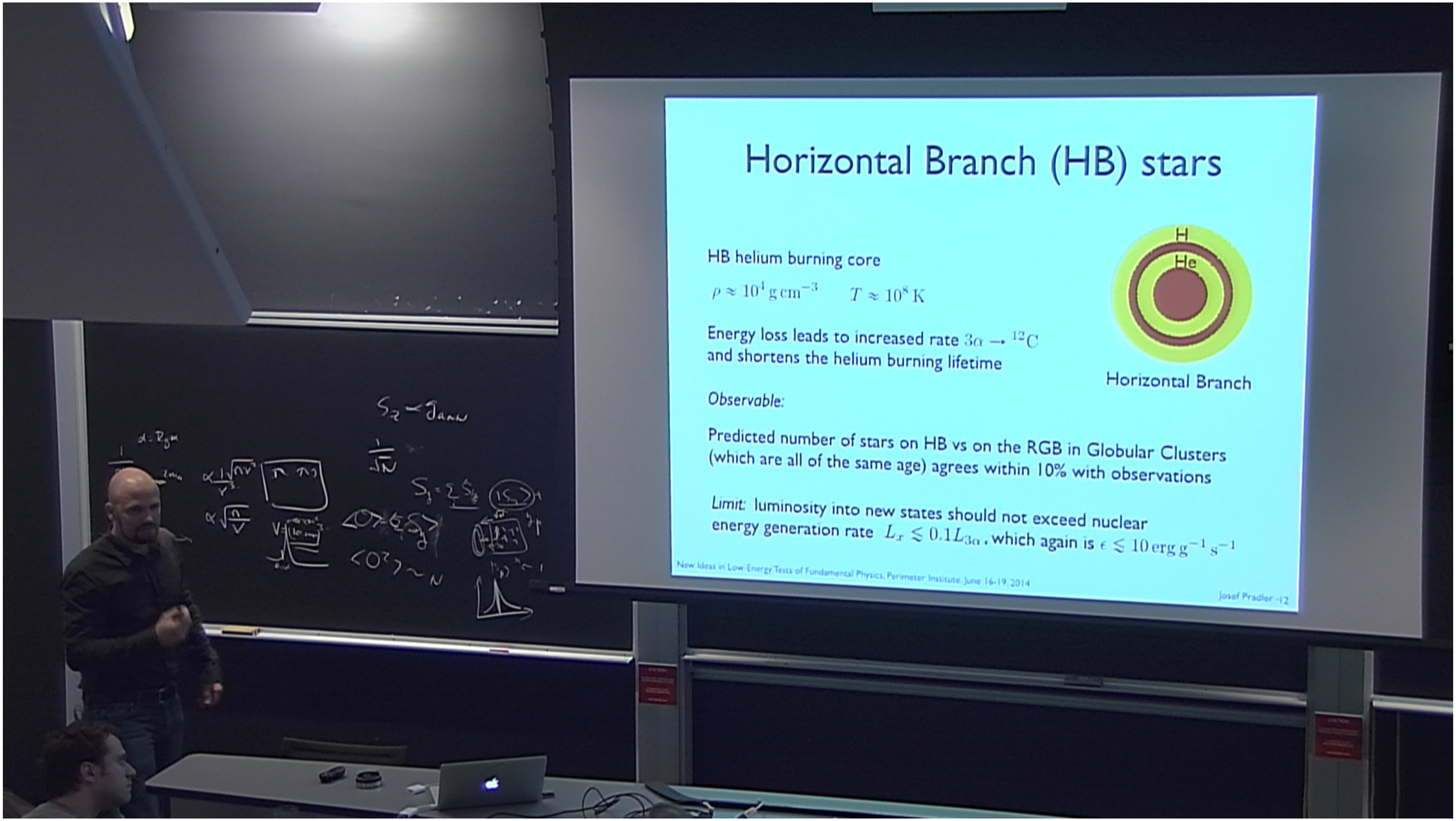

Horizontal Branch (HB) stars

HB helium burning core

$\rho \approx 10^4\,\mathrm{g\,cm^{-3}}$ $T \approx 10^8\,\mathrm{K}$

Energy loss leads to increased rate $3\alpha \to {}^{12}\mathrm{C}$ and shortens the helium burning lifetime

Observable:

Predicted number of stars on HB vs on the RGB in Globular Clusters (which are all of the same age) agrees within 10% with observations

Limit: luminosity into new states should not exceed nuclear energy generation rate $L_x \lesssim 0.1 L_{3\alpha}$, which again is $\epsilon \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$

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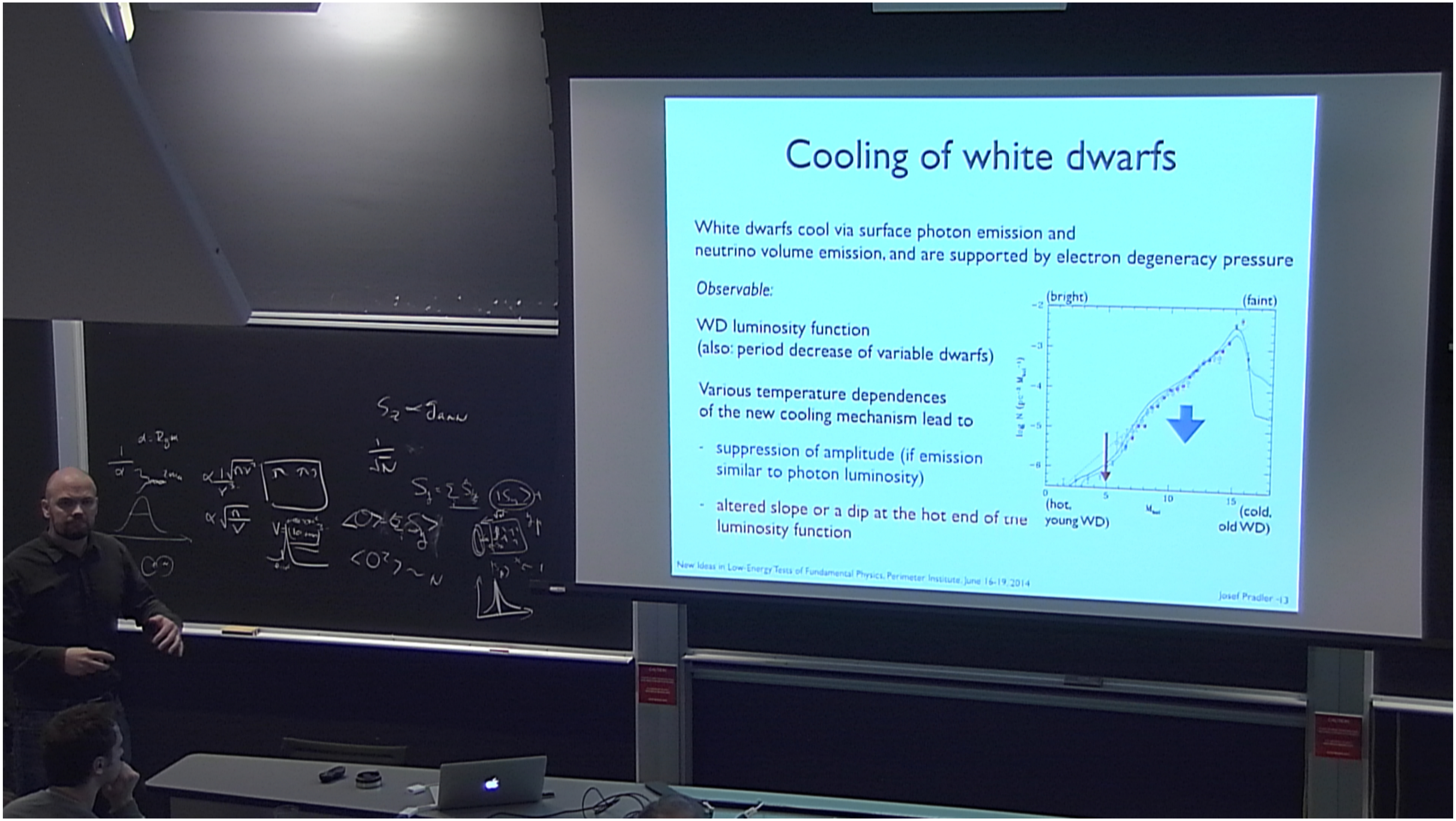

Cooling of white dwarfs

White dwarfs cool via surface photon emission and neutrino volume emission, and are supported by electron degeneracy pressure

Observable:

WD luminosity function
(also: period decrease of variable dwarfs)

Various temperature dependences of the new cooling mechanism lead to

- suppression of amplitude (if emission similar to photon luminosity)
- altered slope or a dip at the hot end of the luminosity function

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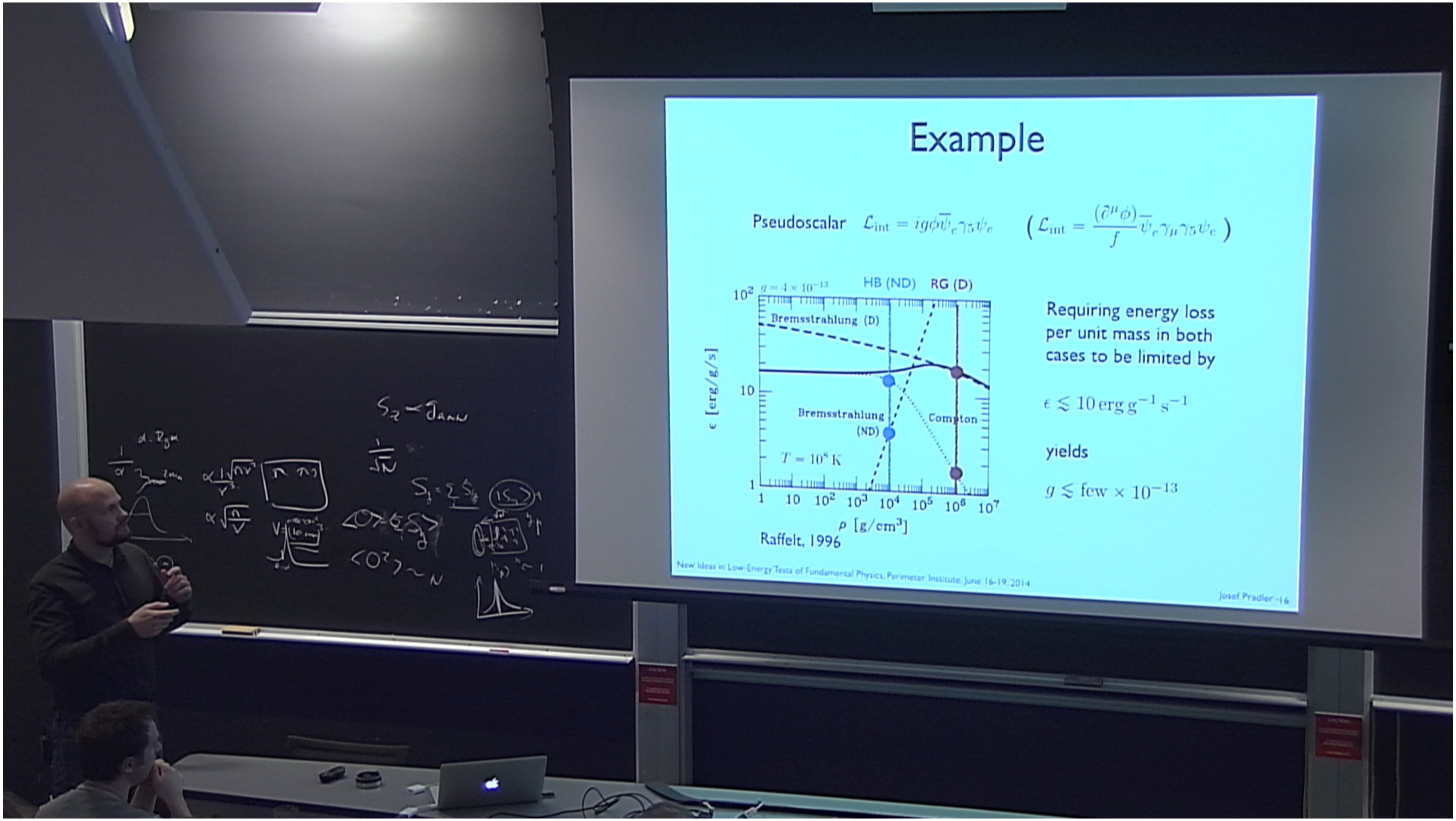

Example

Pseudoscalar $\mathcal{L}_{\rm int} = ig\phi\bar{\psi}_e\gamma_5\psi_e$ $\left(\mathcal{L}_{\rm int} = \frac{(\partial^\mu\phi)}{f}\bar{\psi}_e\gamma_\mu\gamma_5\psi_e\right)$

Raffelt, 1996

Requiring energy loss per unit mass in both cases to be limited by

$\epsilon \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$

yields

$g \lesssim \text{few} \times 10^{-13}$

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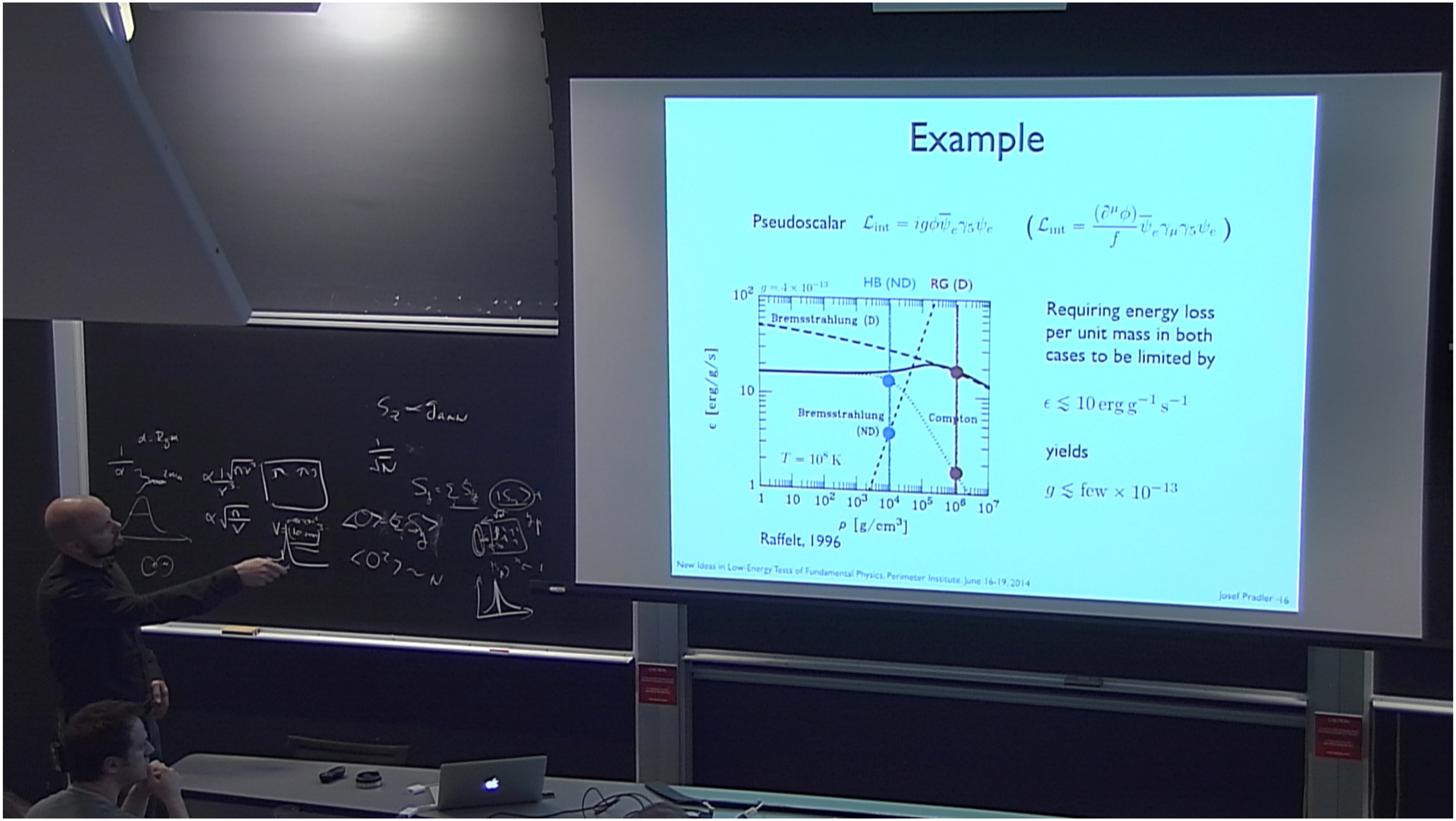

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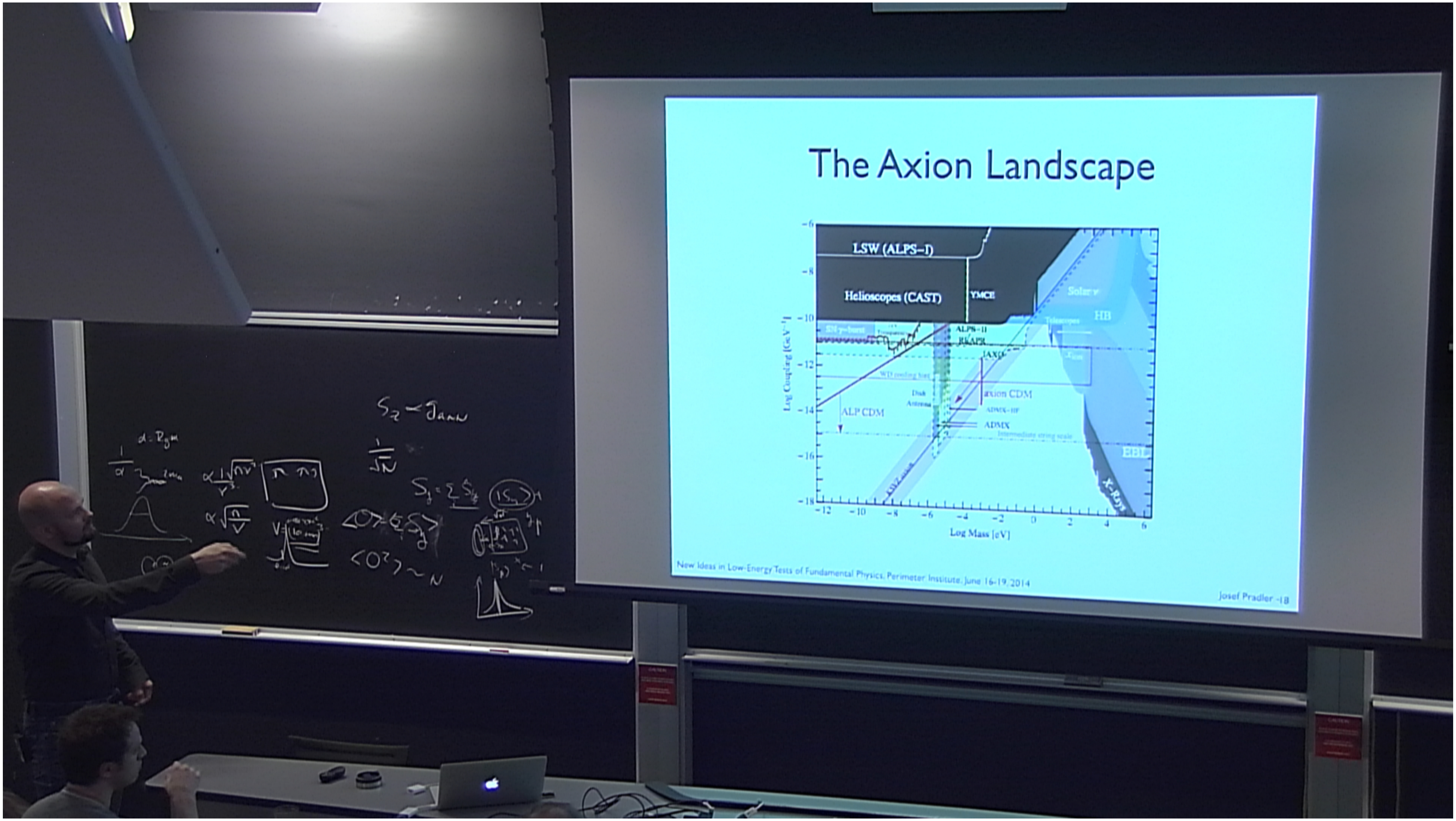

The Axion Landscape

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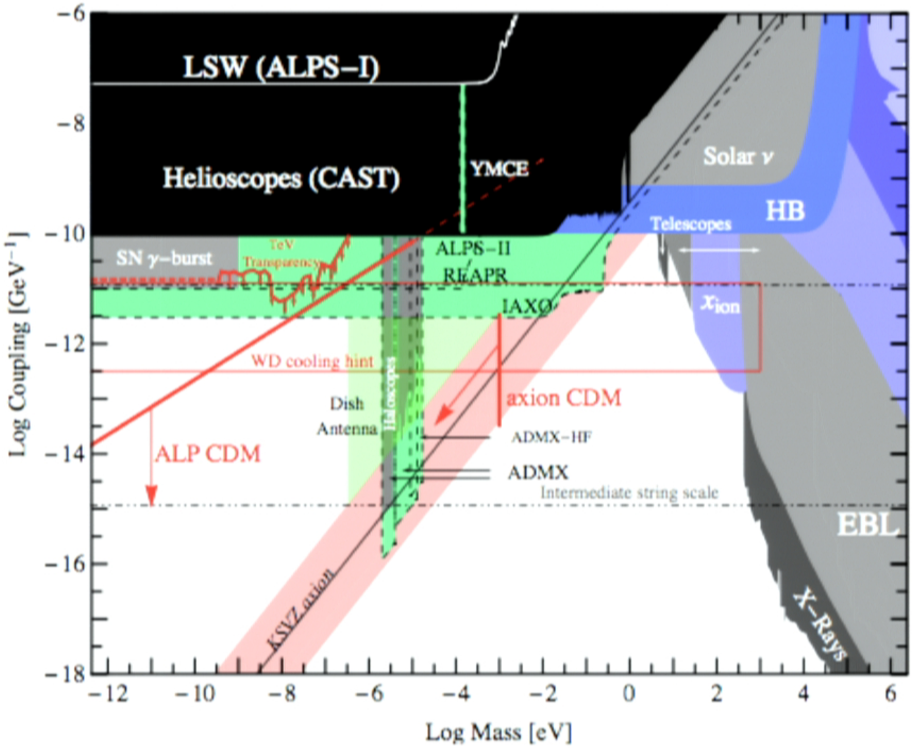
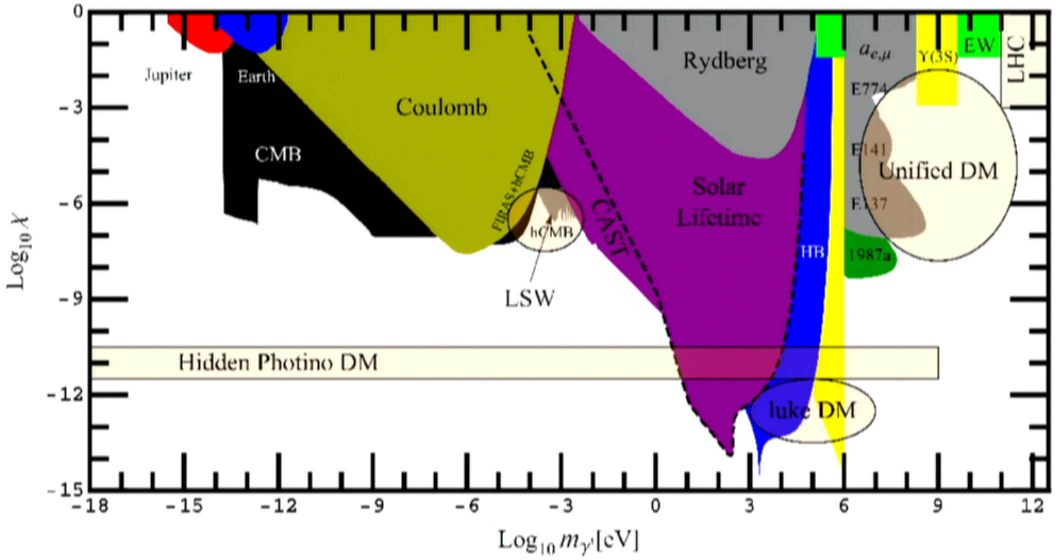


The Dark Photon Landscape



Dark Photons as example

Model parameters

$\kappa,\ m_V,\ (e',\ m'_h)$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \underbrace{\mathrm{U}(1)_Y \times U(1)'}$$ with Vector V_μ

$$-\frac{\kappa'}{2} F^Y_{\mu\nu} V^{\mu\nu} \xrightarrow[\text{scale}]{\text{below EW}} -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

$$\mathcal{L} = -\frac{1}{4} F^2_{\mu\nu} - \frac{1}{4} V^2_{\mu\nu} - \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^\mu_{\mathrm{em}} A_\mu$$

Stueckelberg case

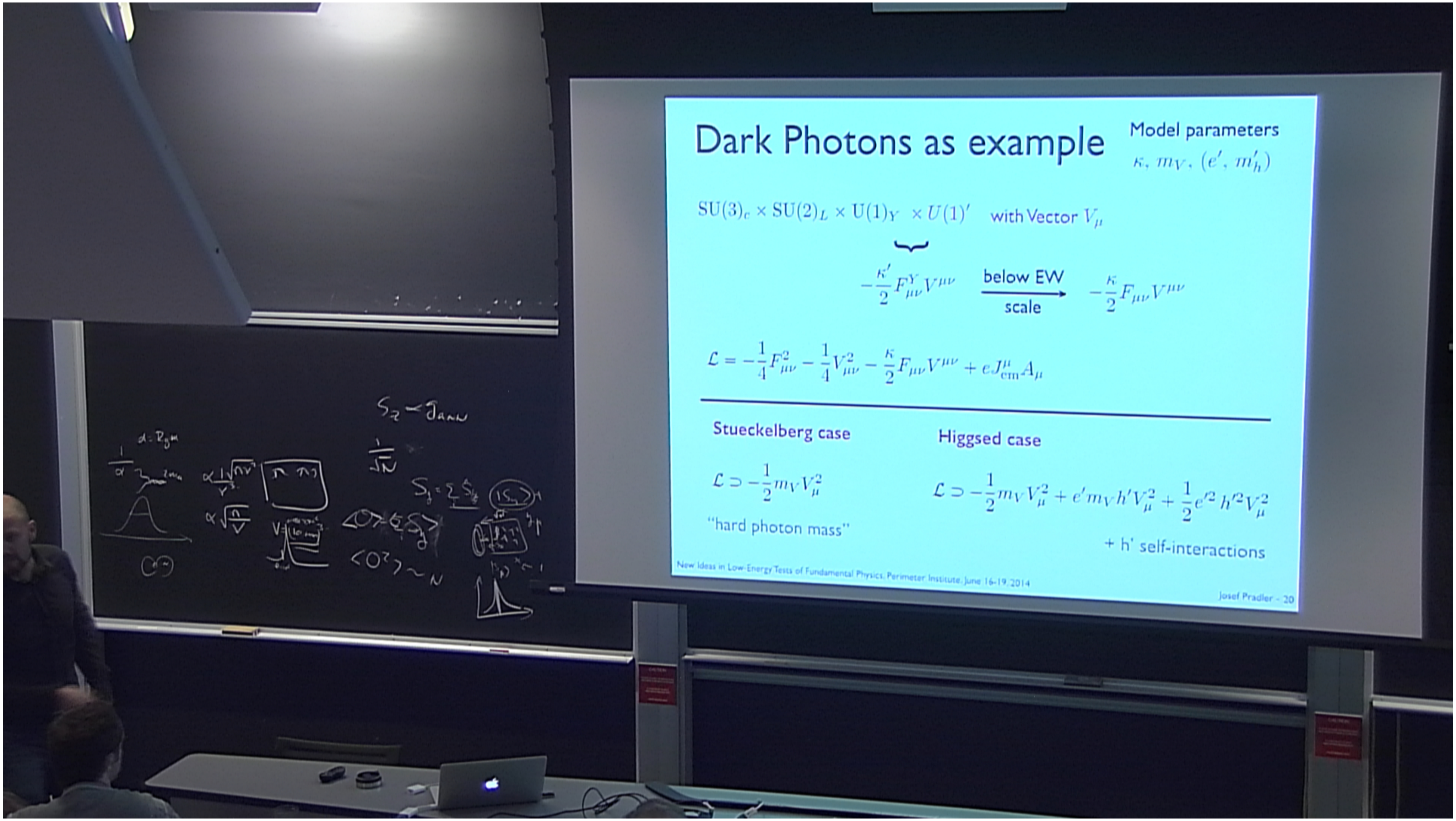
$$\mathcal{L} \supset -\frac{1}{2} m_V V_\mu^2$$

"hard photon mass"

Higgsed case

$$\mathcal{L} \supset -\frac{1}{2} m_V V_\mu^2 + e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

+ h' self-interactions



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$$\underbrace{}_{}$$

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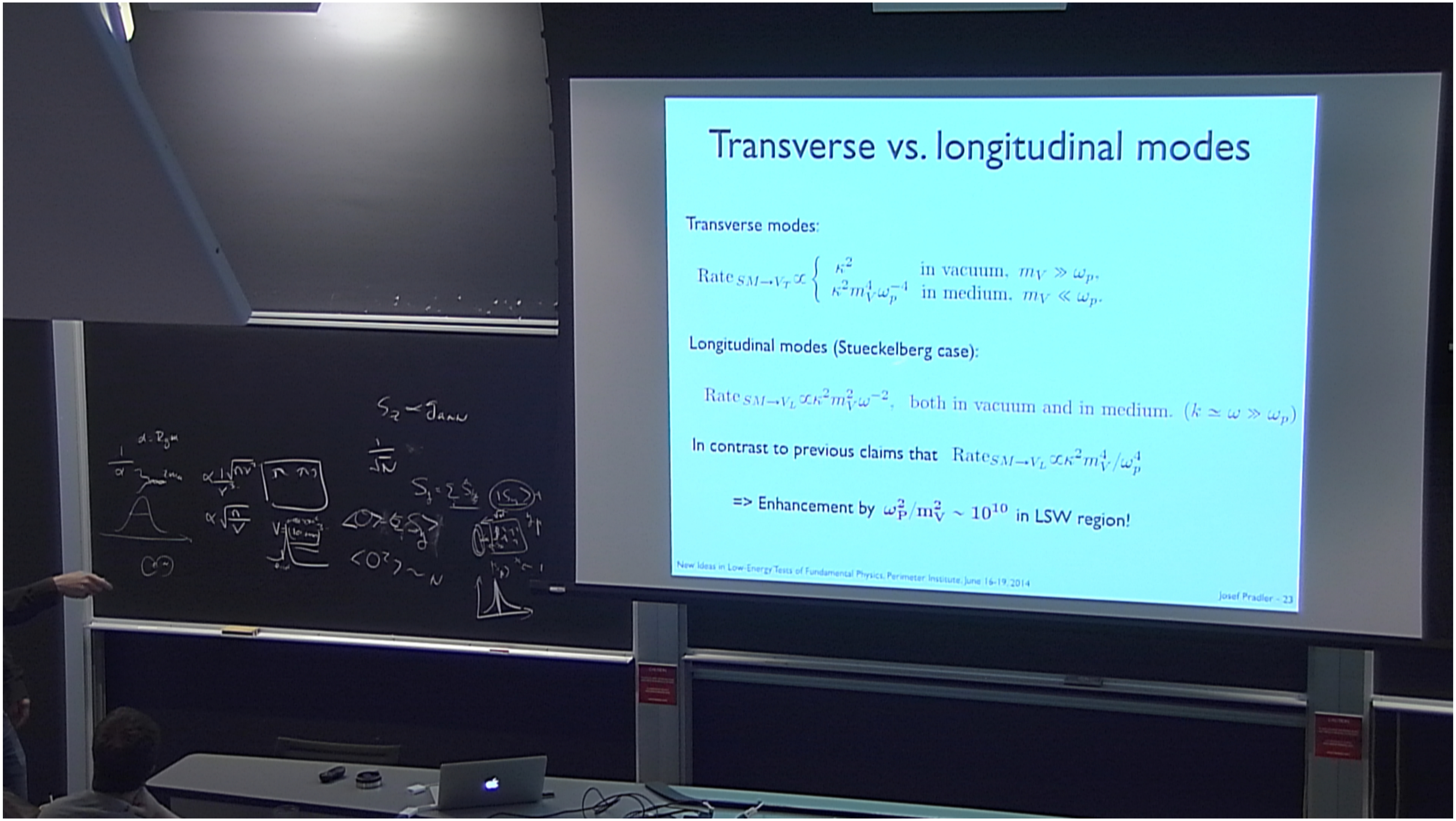

Transverse vs. longitudinal modes

Transverse modes:

$$\text{Rate}_{SM\to V_T} \propto \begin{cases} \kappa^2 & \text{in vacuum, } m_V \gg \omega_p, \\ \kappa^2 m_V^4 \omega_p^{-4} & \text{in medium, } m_V \ll \omega_p. \end{cases}$$

Longitudinal modes (Stueckelberg case):

$$\text{Rate}_{SM\to V_L} \propto \kappa^2 m_V^2 \omega^{-2}, \quad \text{both in vacuum and in medium.} \quad (k \simeq \omega \gg \omega_p)$$

In contrast to previous claims that $\text{Rate}_{SM\to V_L} \propto \kappa^2 m_V^4/\omega_p^4$

=> Enhancement by $\omega_P^2/m_V^2 \sim 10^{10}$ in LSW region!

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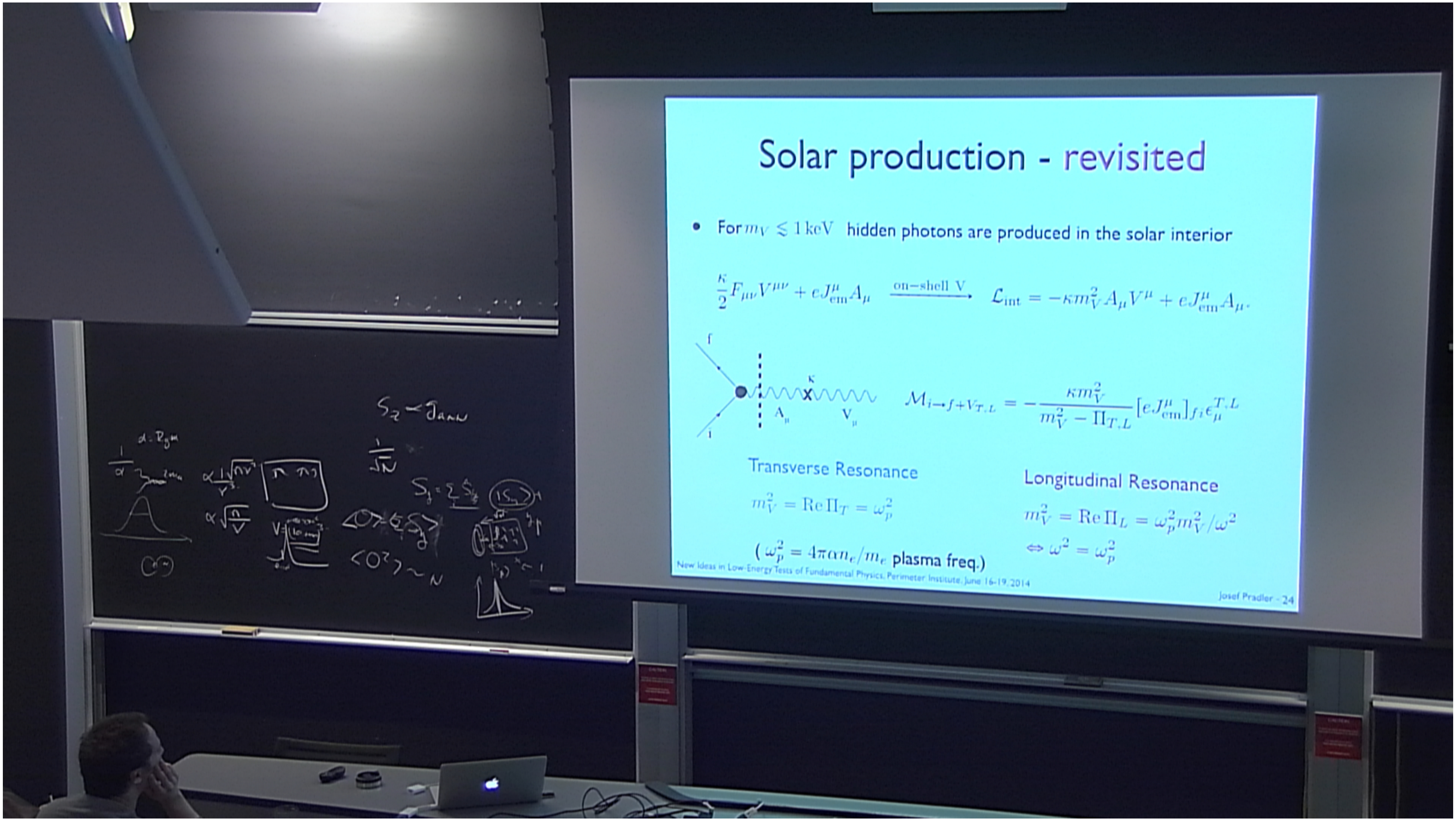

Solar production - revisited

- For $m_V \lesssim 1\,\mathrm{keV}$ hidden photons are produced in the solar interior

$$\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + eJ^{\mu}_{\mathrm{em}}A_{\mu} \xrightarrow{\text{on-shell V}} \mathcal{L}_{\mathrm{int}} = -\kappa m_V^2 A_\mu V^\mu + eJ^{\mu}_{\mathrm{em}}A_{\mu}.$$

$$\mathcal{M}_{i\to f+V_{T,L}} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}}[eJ^{\mu}_{\mathrm{em}}]_{fi}\,\epsilon^{T,L}_{\mu}$$

Transverse Resonance

$$m_V^2 = \mathrm{Re}\,\Pi_T = \omega_p^2$$

Longitudinal Resonance

$$m_V^2 = \mathrm{Re}\,\Pi_L = \omega_p^2 m_V^2/\omega^2$$

$$\Leftrightarrow \omega^2 = \omega_p^2$$

($\omega_p^2 = 4\pi\alpha n_e/m_e$ plasma freq.)

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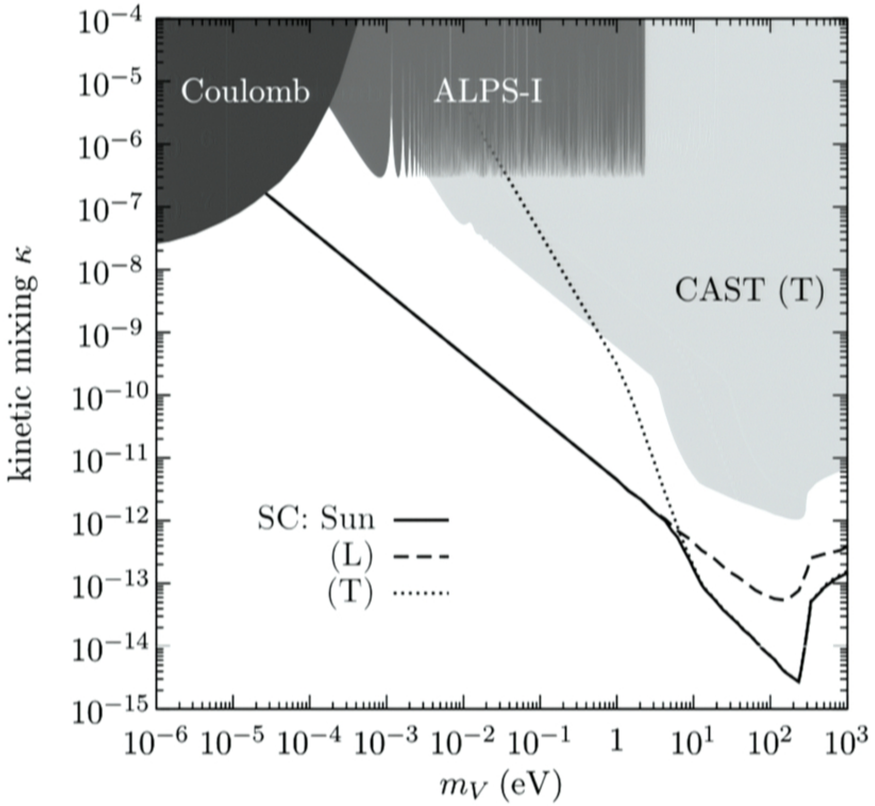
Stellar energy loss - revised



Energy loss constraint from sun:

Observable: SNO, 8B flux

$$L_{\text{dark}} \leqslant 0.1 L_{\odot}$$

$$L_{\odot} = 4 \times 10^{26}\ \text{Watt}$$

Helioscope and LSW experiments inside excluded regions

H. An, M. Pospelov, JP, PLB 2013

Extending our view through cosmology

Very Dark Photon V