Title: Axions

Speakers: Luna Zagorac

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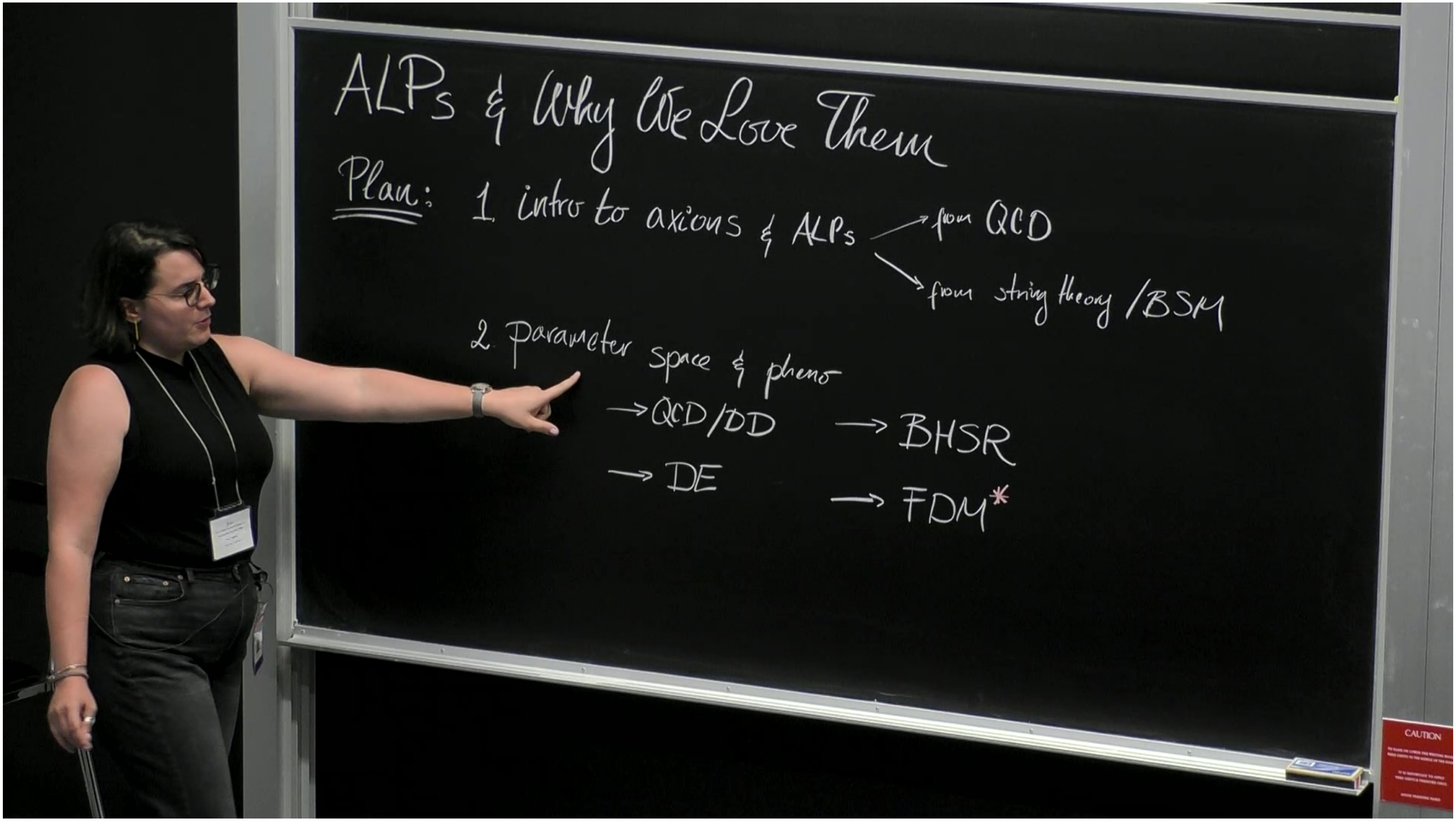
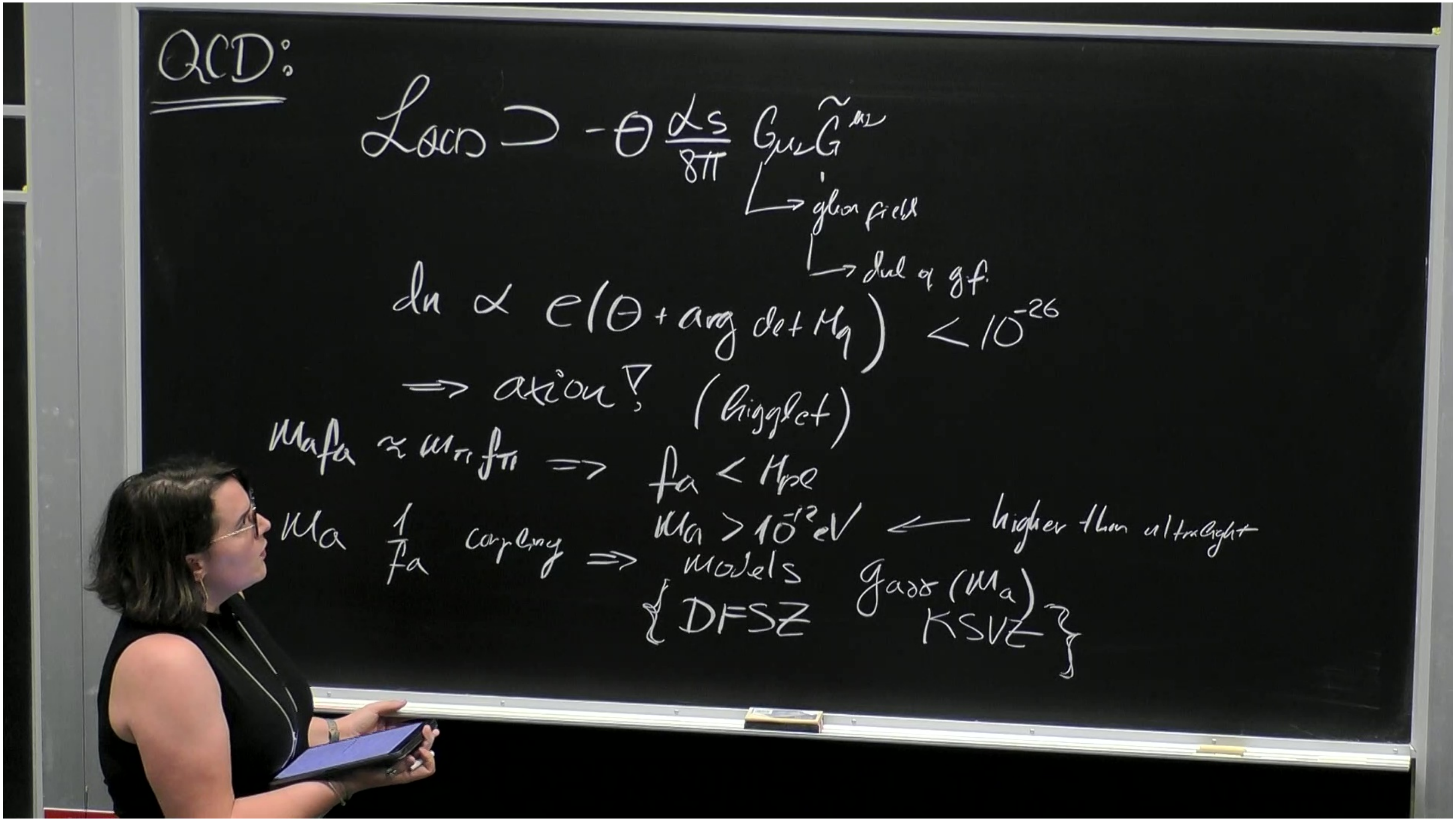


ALPs & Why We Love Them

Plan: 1. intro to axions & ALPs → from QCD
→ from string theory / BSM

2. parameter space & pheno
→ QCD/DD → BHSR
→ DE → FDM*



QCD:

$$\mathcal{L}_{QCD} \supset -\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

↳ gluon field

↳ dual of g.f.

$$d_n \propto e(\theta + \arg\det M_q) < 10^{-26}$$

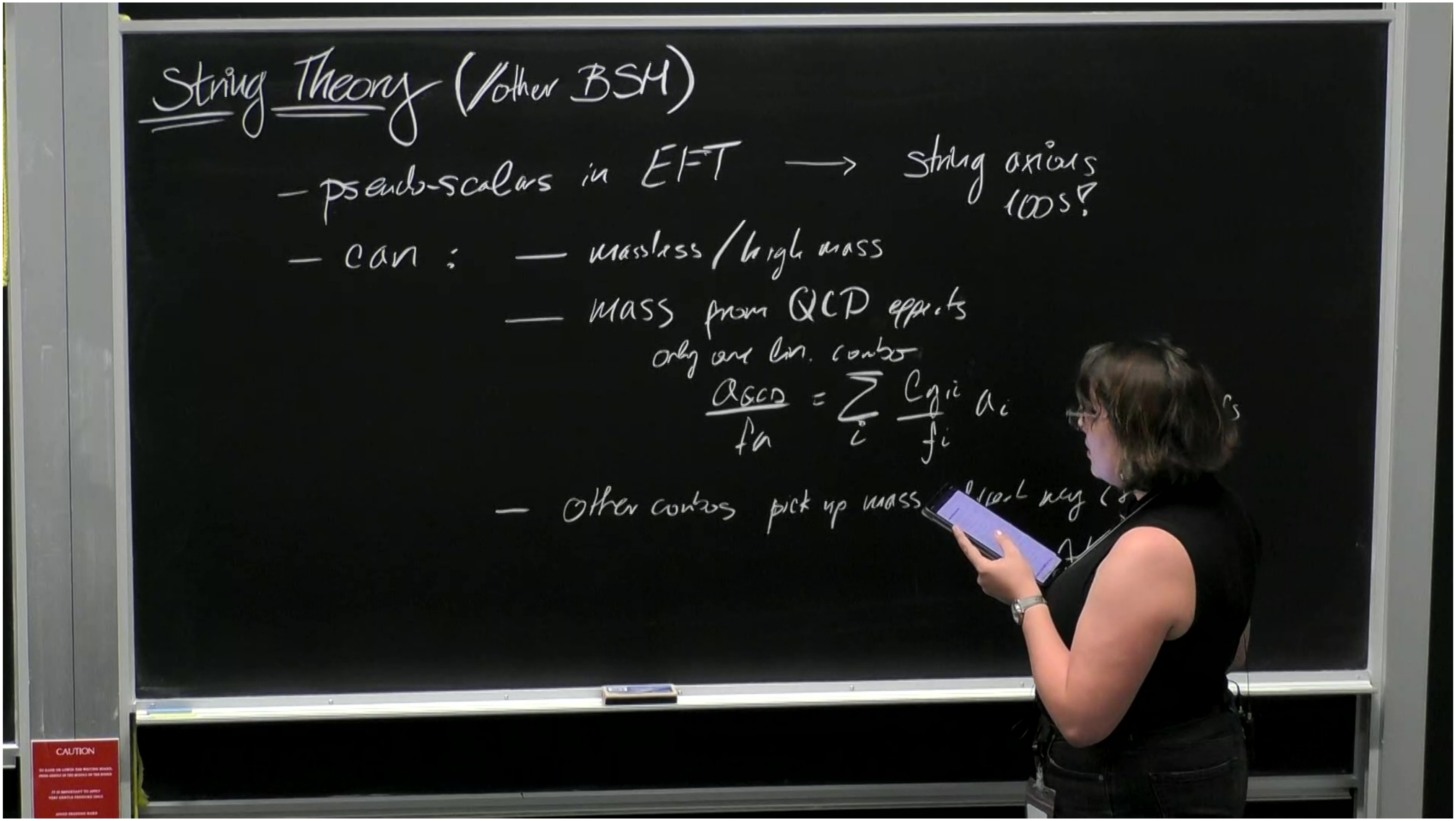
$\Rightarrow$ axion! (higglet)

$m_a f_a \approx m_\pi f_\pi \Rightarrow f_a < M_{pl}$

m_a $\frac{1}{f_a}$ coupling $\Rightarrow$ $m_a > 10^{-12}$ eV ← higher than ultralight

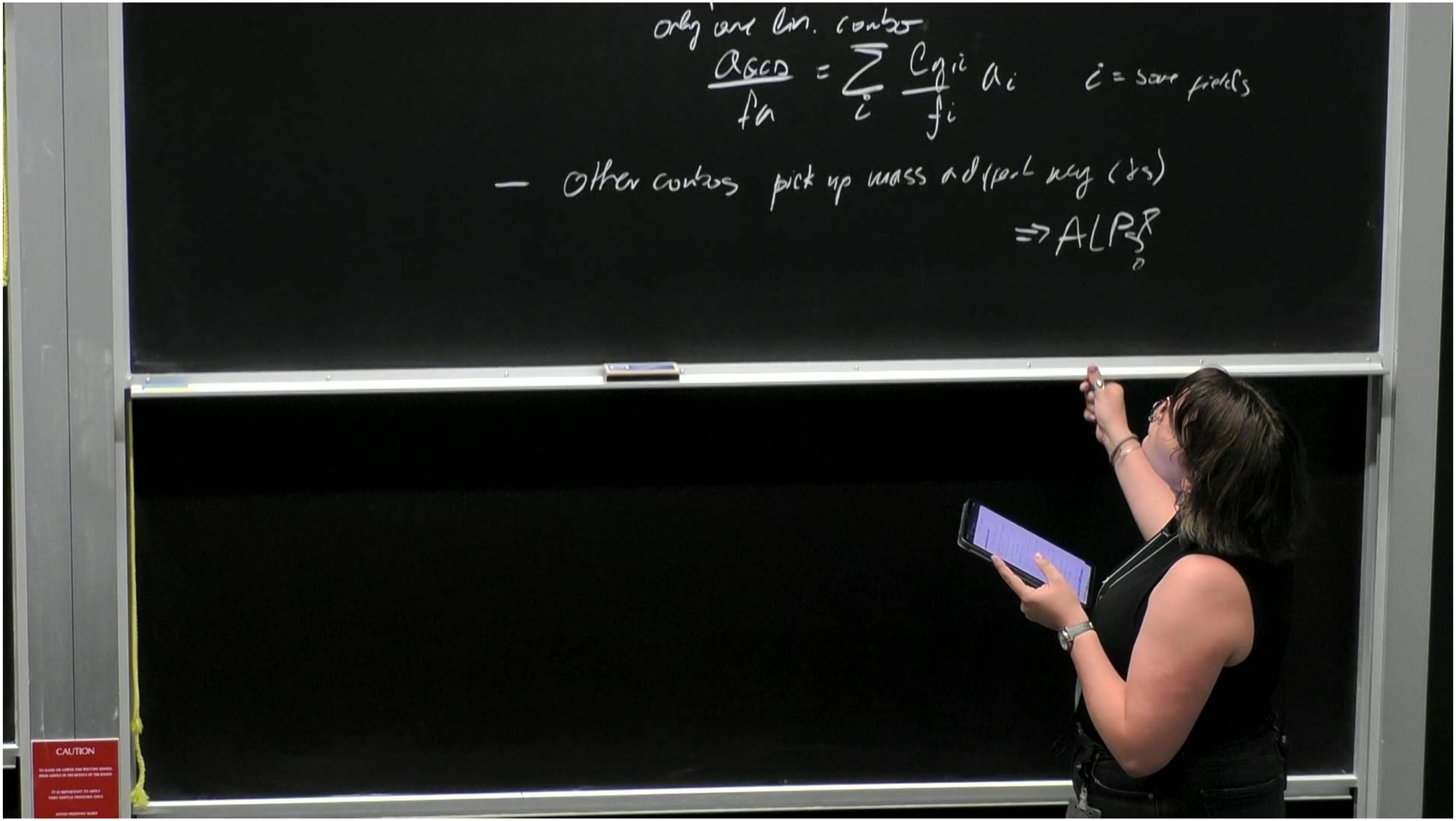
models $g_{a\gamma\gamma}(m_a)$

$\{$ DFSZ KSVZ $\}$



String Theory (/other BSM)

- pseudo-scalars in EFT ⟶ string axions
  100s?
- can: — massless / high mass
  - mass from QCD effects
    only one lin. combo
    $$\frac{a_{QCD}}{f_a} = \sum_i \frac{C_{gi}}{f_i} a_i$$
  - other combos pick up mass [illegible]

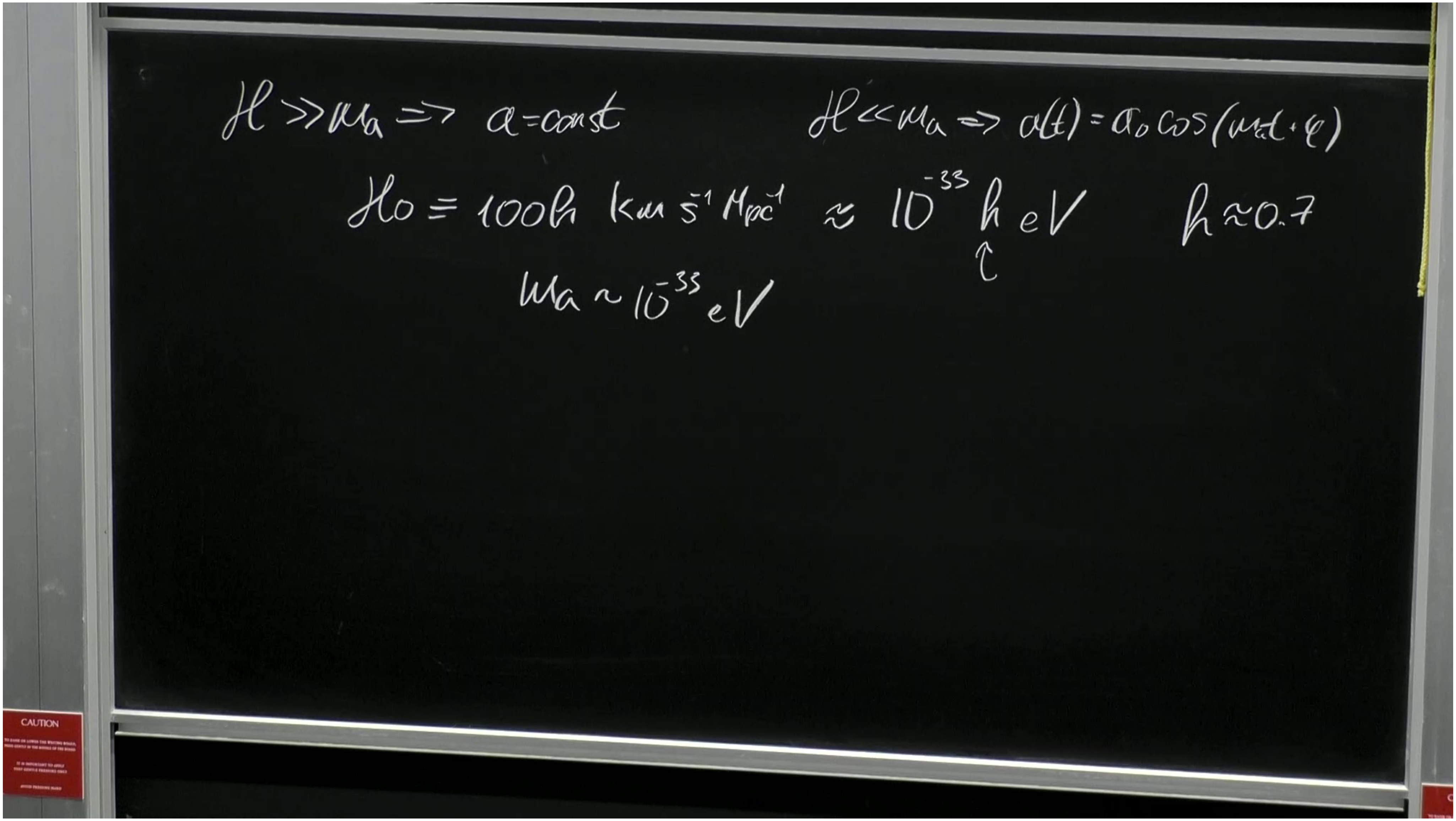


only one lin. combo

$$\frac{a_{QCD}}{f_a} = \sum_i \frac{C_g^i}{f_i} a_i \qquad i = \text{some fields}$$

— other combos pick up mass and [illegible] (γs)

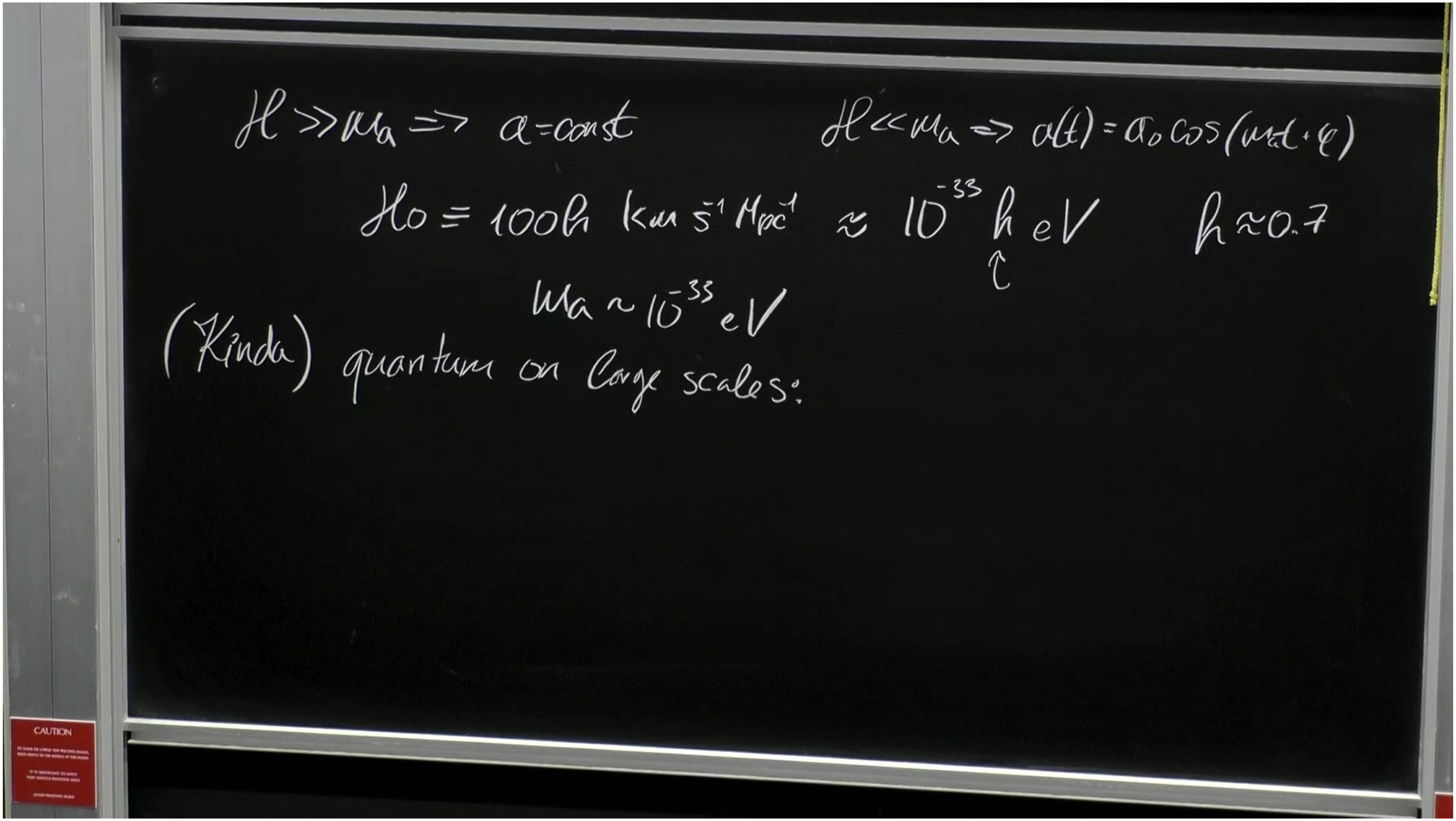
⇒ ALPs?



$$\mathcal{H} \gg m_a \Rightarrow a = \text{const} \qquad \mathcal{H} \ll m_a \Rightarrow a(t) = a_0 \cos(m_a t + \varphi)$$

$$H_0 = 100h \ \text{km}\, s^{-1}\, \text{Mpc}^{-1} \approx 10^{-33} \underset{\uparrow}{h}\ \text{eV} \qquad h \approx 0.7$$

$$m_a \sim 10^{-33}\ \text{eV}$$



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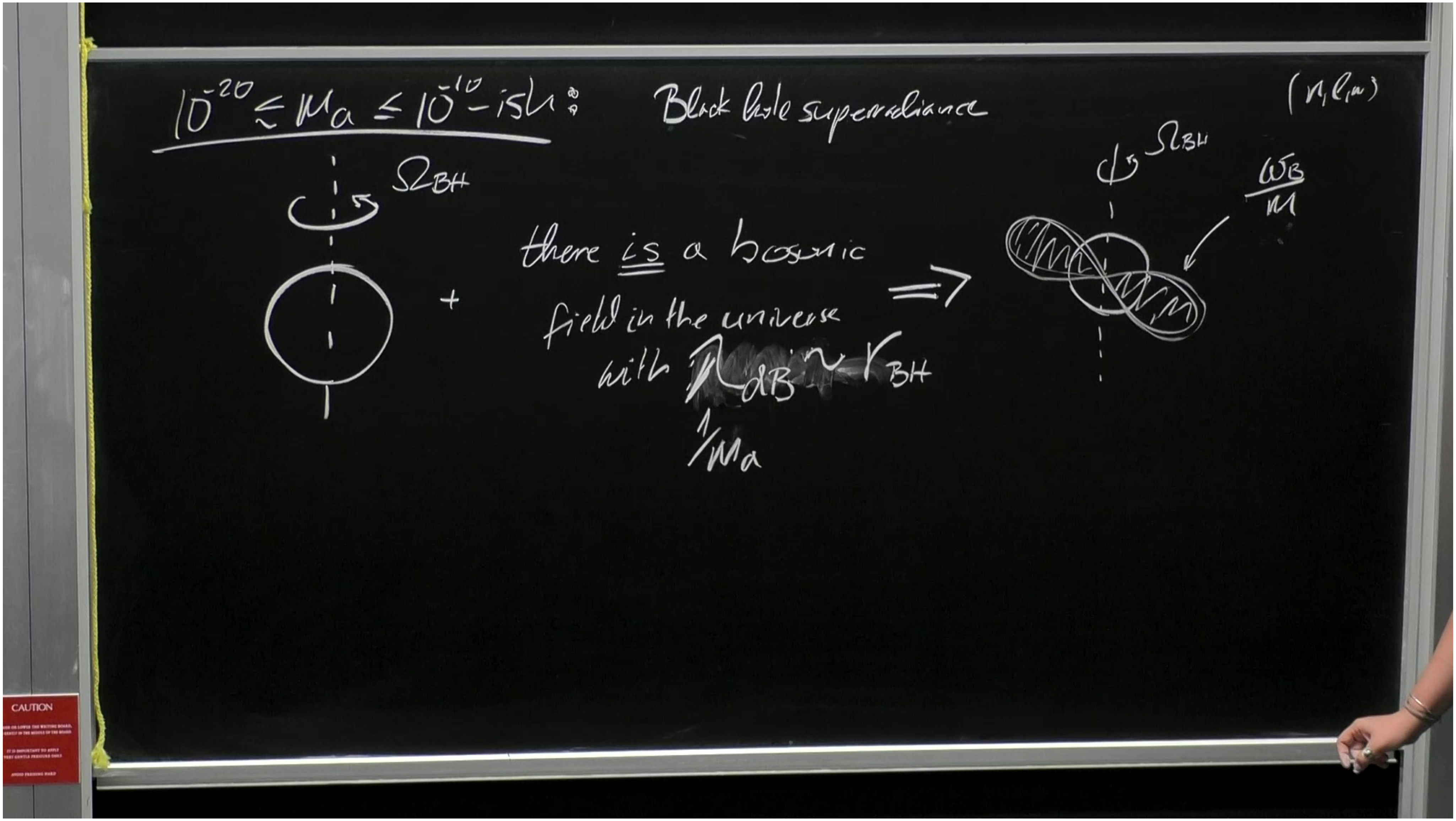
$h \approx 0.7$

$m_a \sim 10^{-33} \text{ eV}$

(Kinda) quantum on large scales:



$10^{-20} \lesssim m_a \lesssim 10^{-10}$-ish :

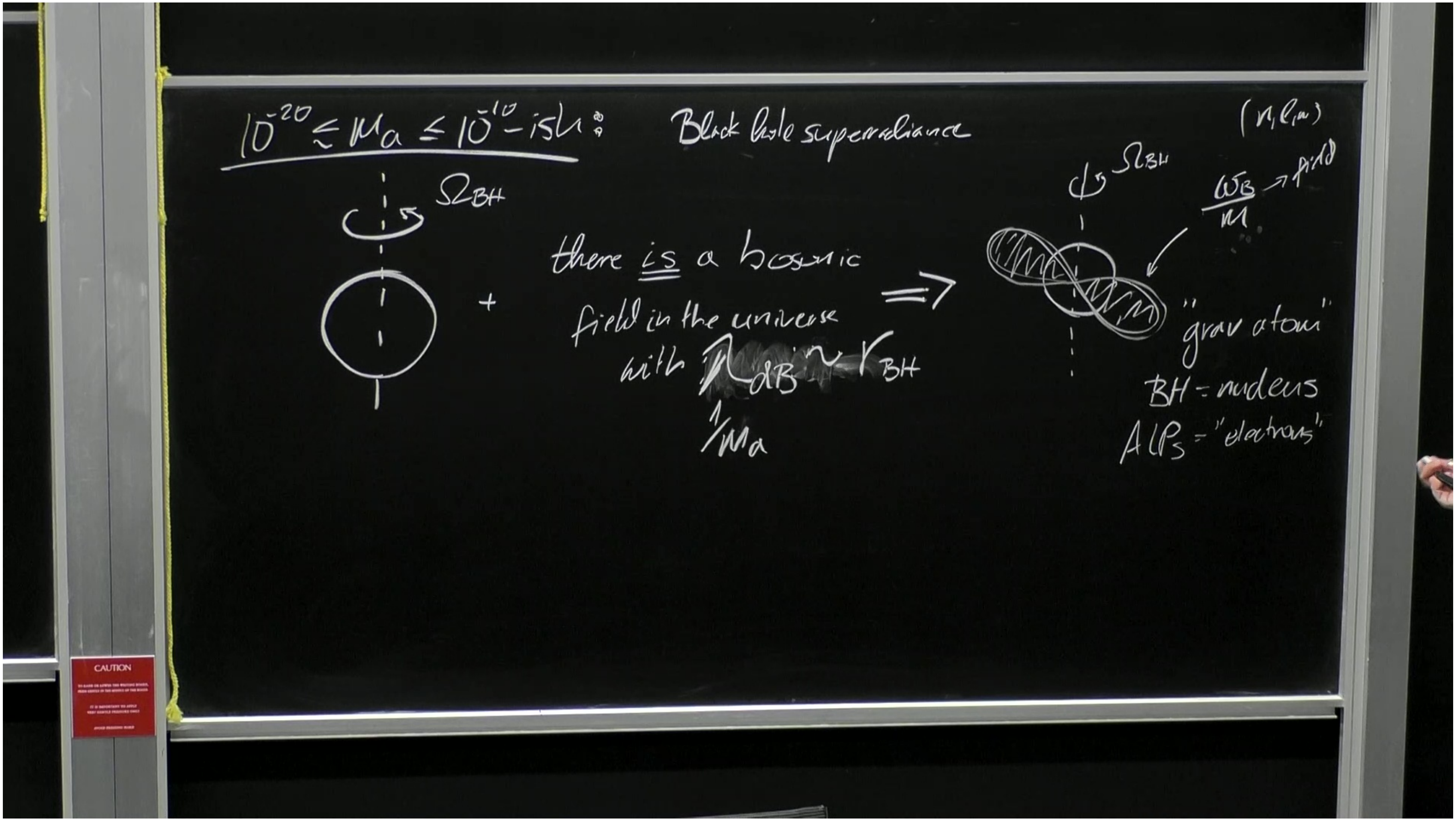
Black hole superradiance

(n, ℓ, m)

Ω_{BH} $+$ there is a bosonic field in the universe with $\lambda_{dB} \sim r_{BH}$

$1/m_a$

$\Longrightarrow$ Ω_{BH} $\frac{\omega_B}{m}$



$10^{-20} \lesssim m_a \lesssim 10^{-10}$-ish: Black hole superradiance

Ω_{BH}

$+$

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$1/m_a$

$\Longrightarrow$

(n, l, m)

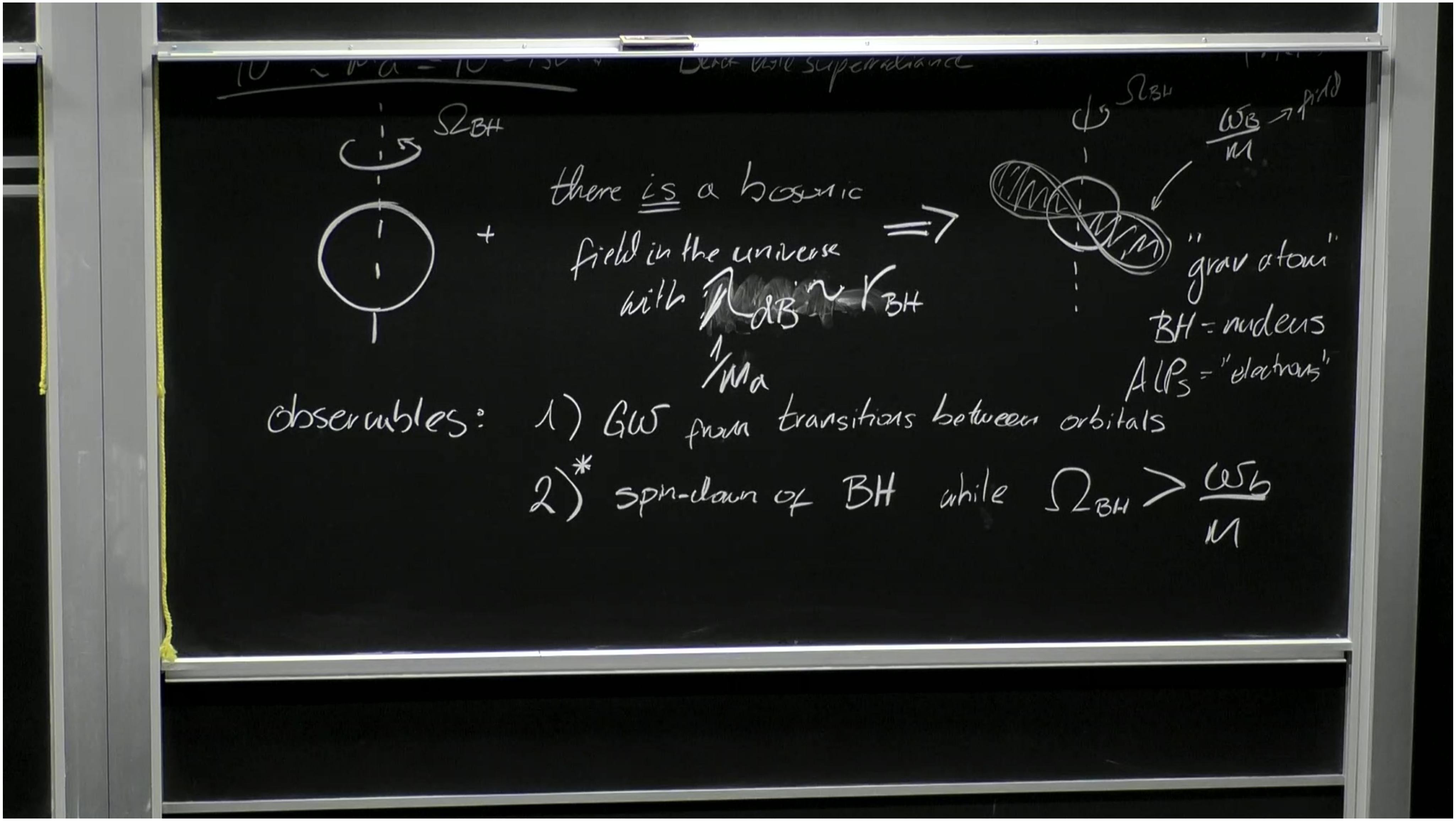
Ω_{BH}

$\frac{\omega_B}{m} \to$ field

"grav atom"

BH = nucleus

ALPs = "electrons"



$10^{\cdot} \lesssim m_a \lesssim 10^{\cdot}$ eV   Black hole superradiance

Ω_{BH}

\+ there is a bosonic field in the universe with $\lambda_{dB} \sim r_{BH}$

$1/m_a$

$\Longrightarrow$

Ω_{BH}

$\frac{\omega_B}{M} \to$ field

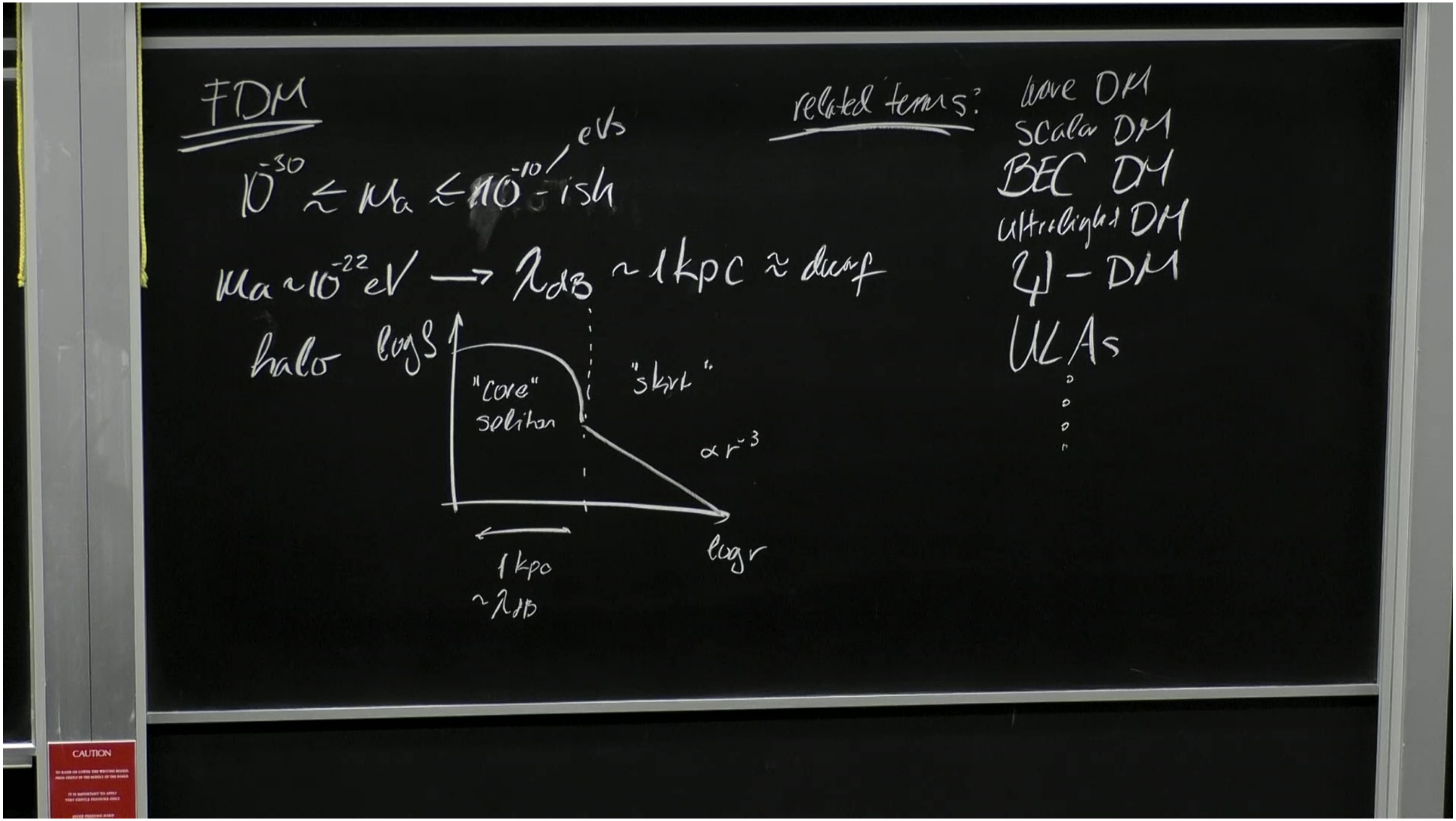
"grav atom"

BH = nucleus

ALPs = "electrons"

observables: 1) GW from transitions between orbitals

2)* spin-down of BH while $\Omega_{BH} > \frac{\omega_b}{M}$



FDM

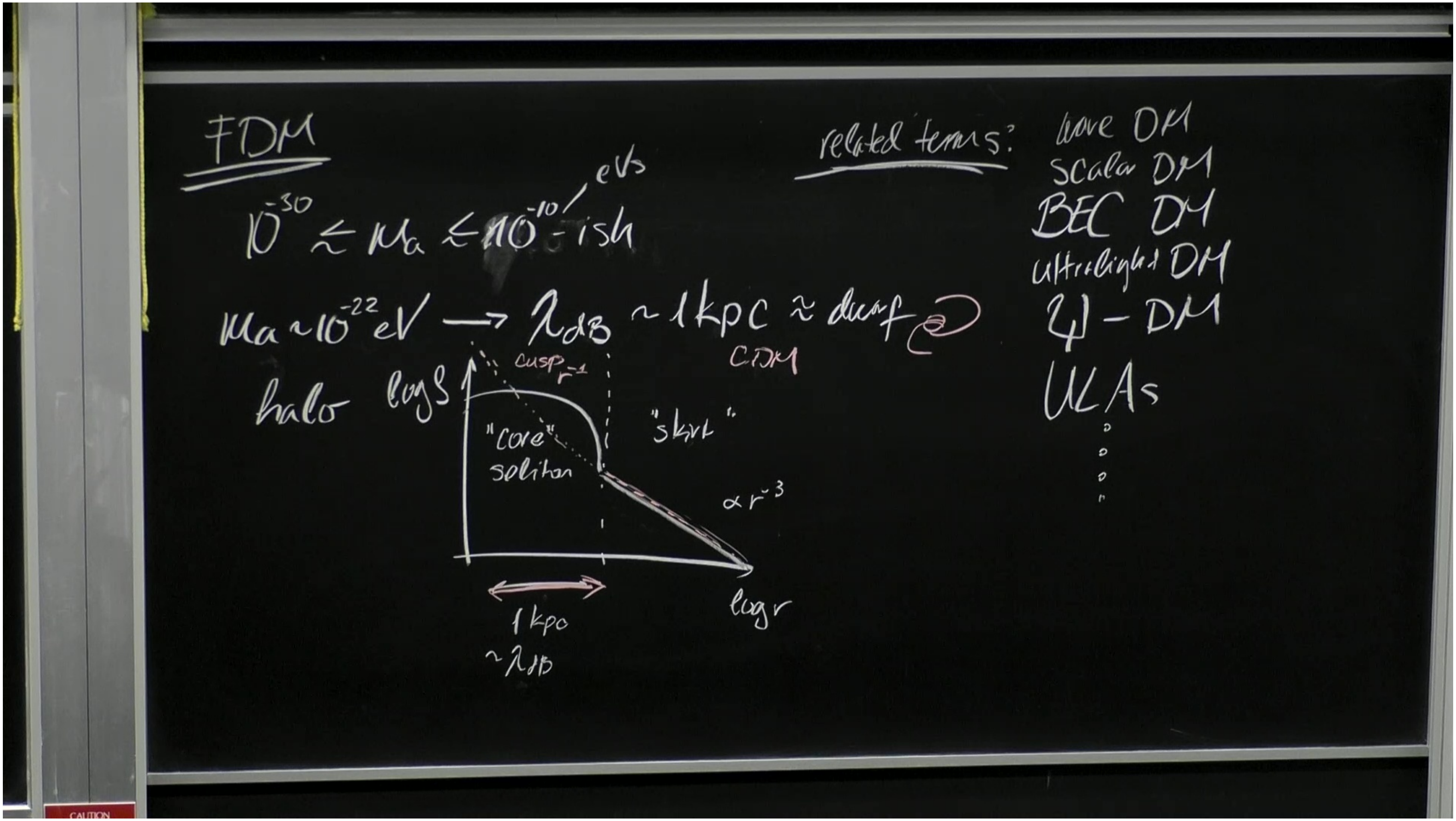
$10^{-30} \lesssim m_a \lesssim 10^{-10}$ - ish eVs

$m_a \sim 10^{-22}$ eV $\longrightarrow \lambda_{dB} \sim 1$ kpc $\approx$ dwarf

halo

related terms:

- wave DM
- scalar DM
- BEC DM
- ultralight DM
- ψ - DM
- ULAs
- ⋮



FDM

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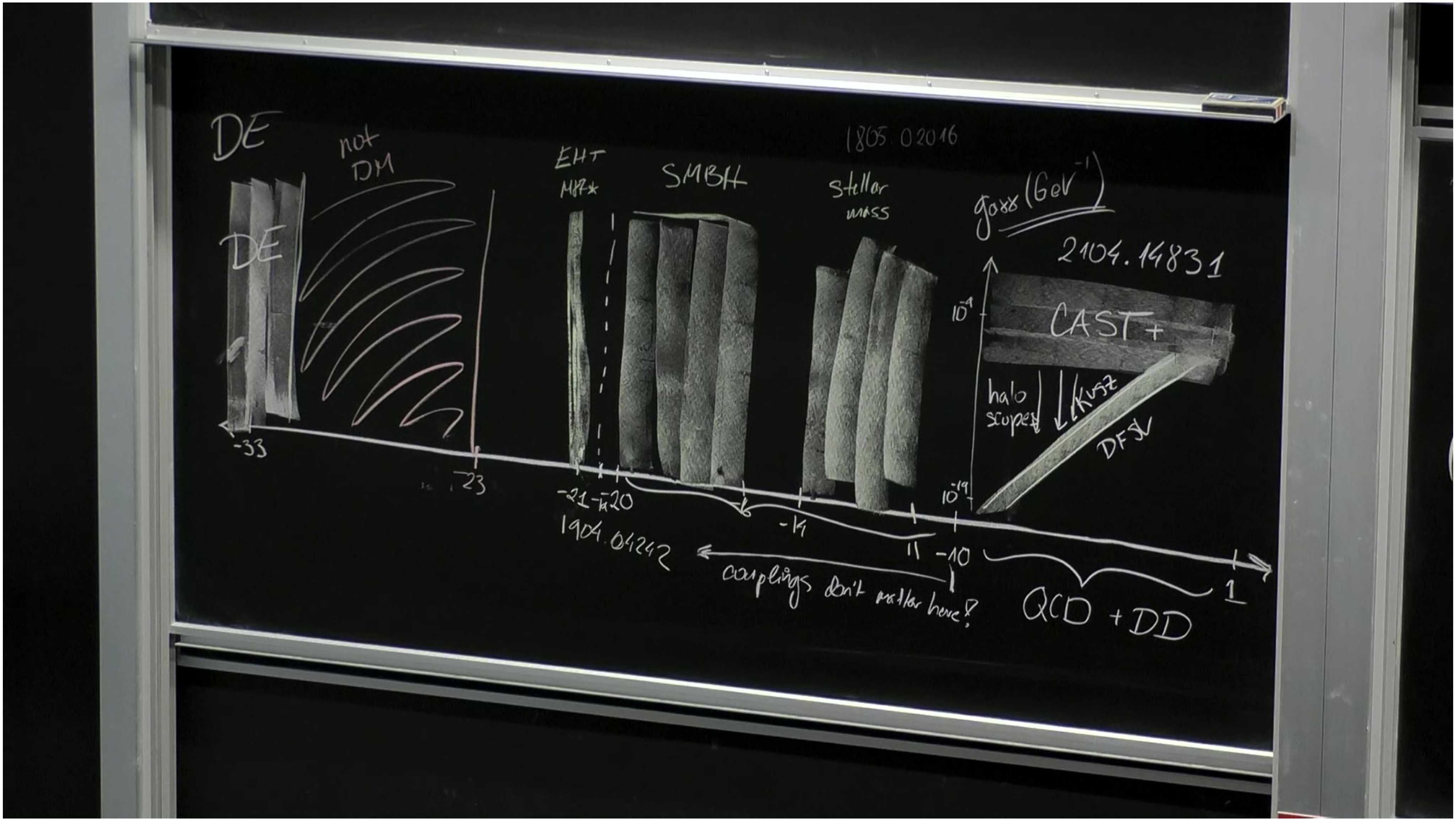
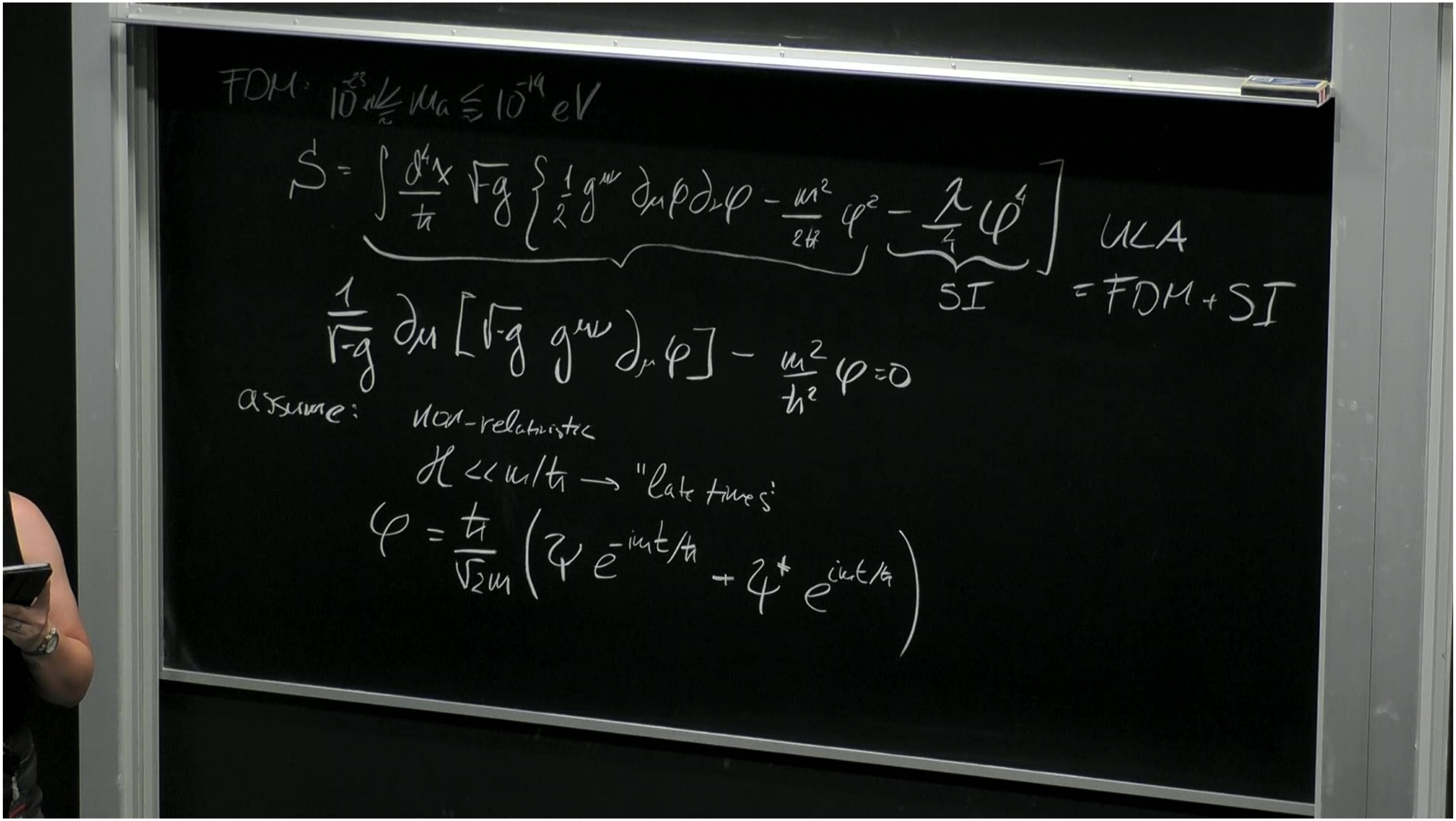

DE
not DM
DE
-33
-23
EHT
M87*
-21
-20
1904.04242
SMBH
stellar mass
-14
-11
-10
1805.02016
$g_{a\gamma\gamma}$ (GeV^{-1})
2104.14831
10^{-9}
CAST+
halo scopes
KSVZ
DFSZ
10^{-19}
couplings don't matter here!
QCD + DD
1



FDM: $10^{-23} \lesssim m_a \lesssim 10^{-19}\,\mathrm{eV}$

$$S = \underbrace{\int \frac{d^4x}{\hbar}\sqrt{-g}\Big\{\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{m^2}{2\hbar^2}\varphi^2}\underbrace{-\frac{\lambda}{4}\varphi^4}_{SI}\Big]$$

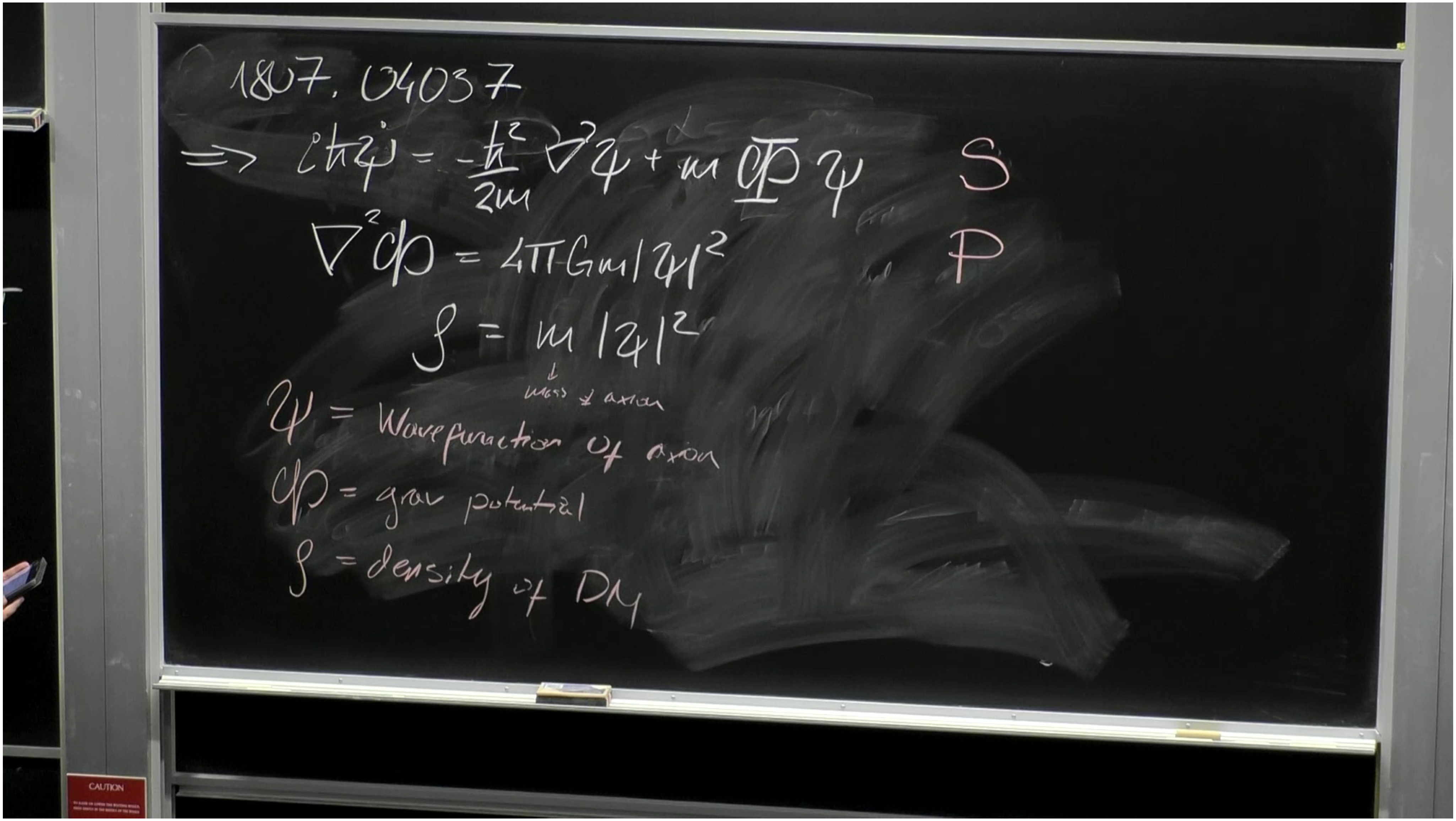
ULA = FDM + SI

$$\frac{1}{\sqrt{-g}}\partial_\mu\left[\sqrt{-g}\,g^{\mu\nu}\partial_\nu\varphi\right] - \frac{m^2}{\hbar^2}\varphi = 0$$

assume: non-relativistic

$H \ll m/\hbar \rightarrow$ "late times"

$$\varphi = \frac{\hbar}{\sqrt{2m}}\left(\psi e^{-imt/\hbar} + \psi^* e^{imt/\hbar}\right)$$



1807.04037

$$\Rightarrow \quad i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\nabla^2\psi + m\,\Phi\,\psi \qquad \text{S}$$

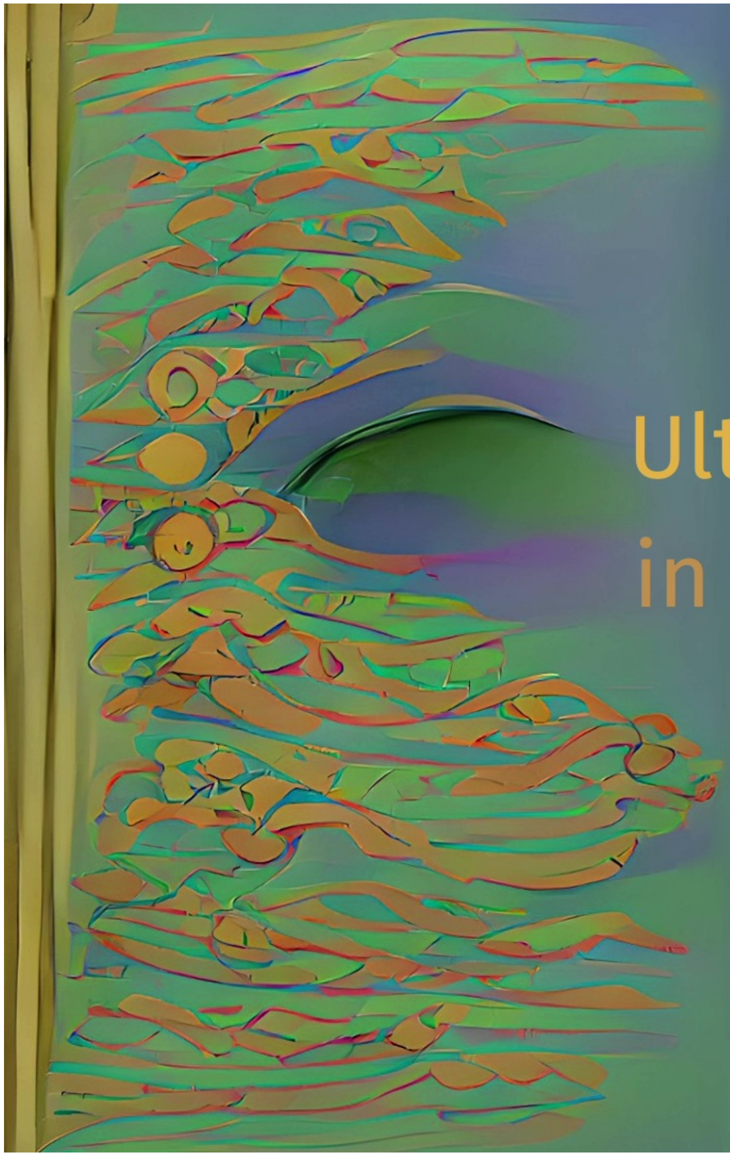
$$\nabla^2\Phi = 4\pi G m|\psi|^2 \qquad \text{P}$$

$$\rho = \underset{\substack{\downarrow \\ \text{mass of axion}}}{m}\,|\psi|^2$$

ψ = Wavefunction of axion

Φ = grav potential

ρ = density of DM



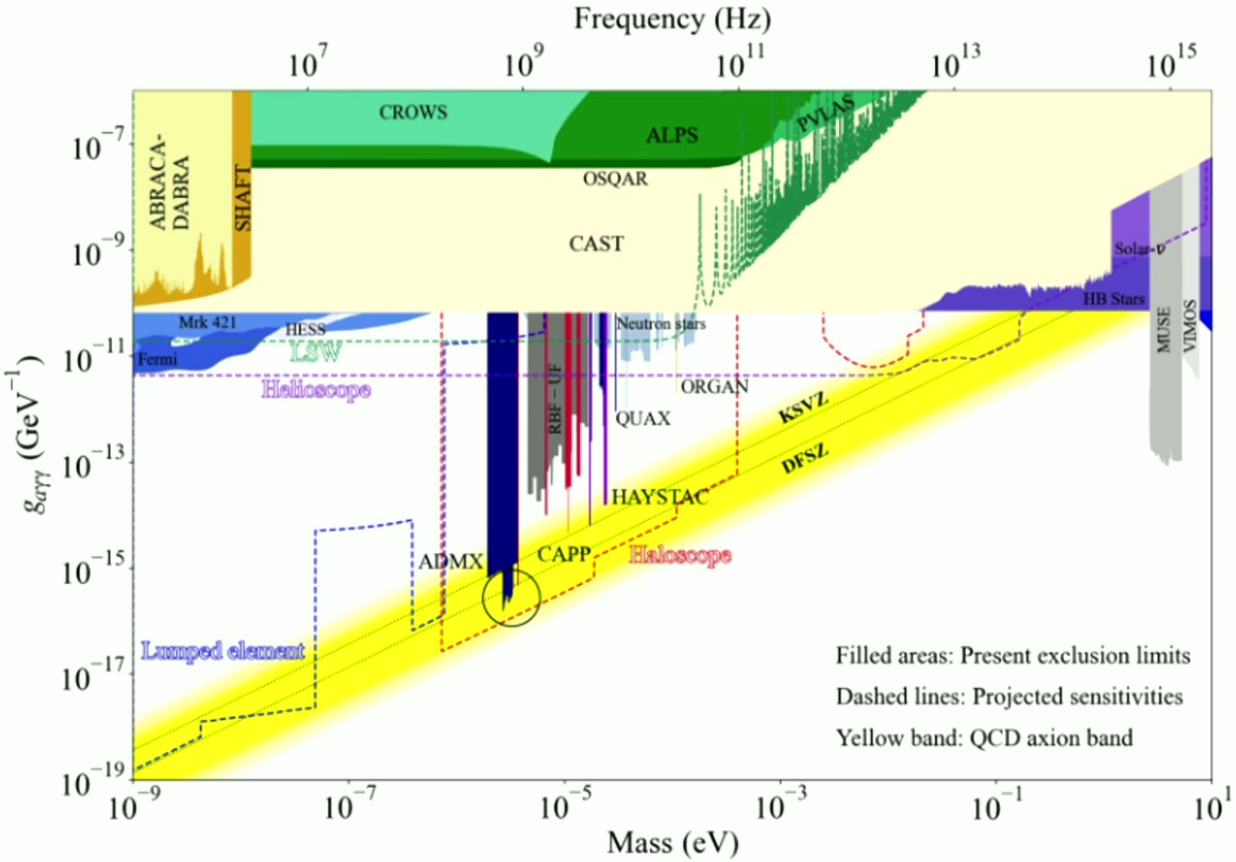
UltraLight Dark Matter Dynamics in the language of Eigenstates

J. Luna Zagorac

Jun 30th 2023
TRISEP
Waterloo, ON

PERIMETER INSTITUTE

QCD Axion Direct Detection Exclusion Plot Example



2104.14831

UltraLight Dark Matter Halos

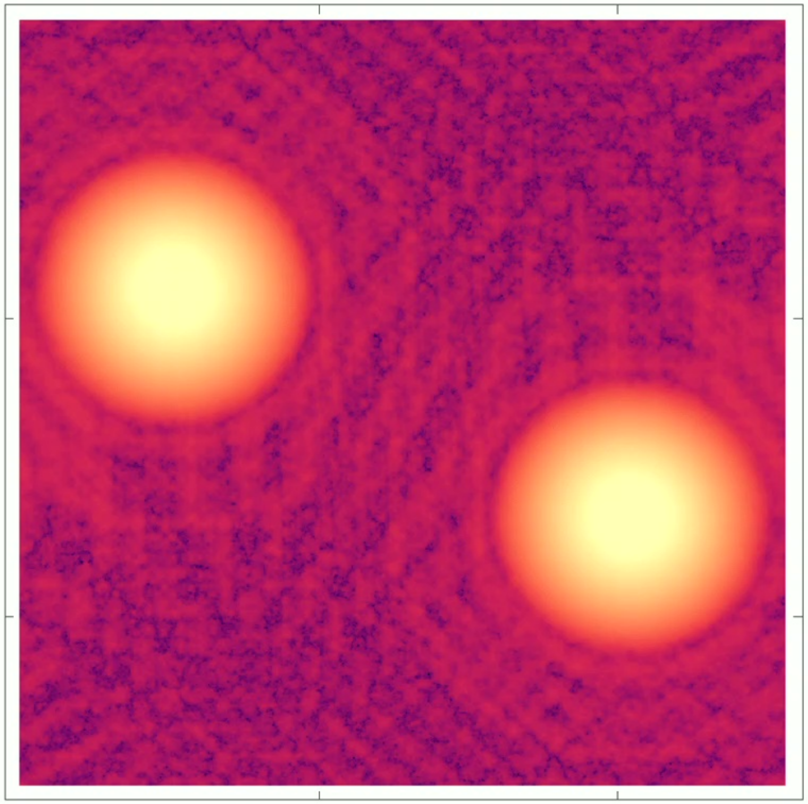
UltraLight Dark Matter (ULDM):

- is an axion-like scalar boson
- has low mass: $\sim 10^{-22}\,\mathrm{eV}$
- forms Bose-Einstein condensates
- described by Schrödinger-Poisson eqs:

$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi$$

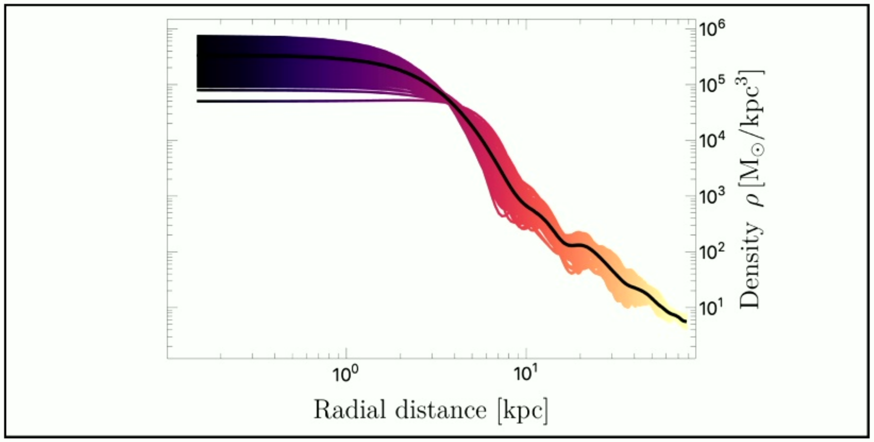
$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

$$\rho = m|\psi|^2$$



Eigenstates of Halos

arXiv: 2109.01920

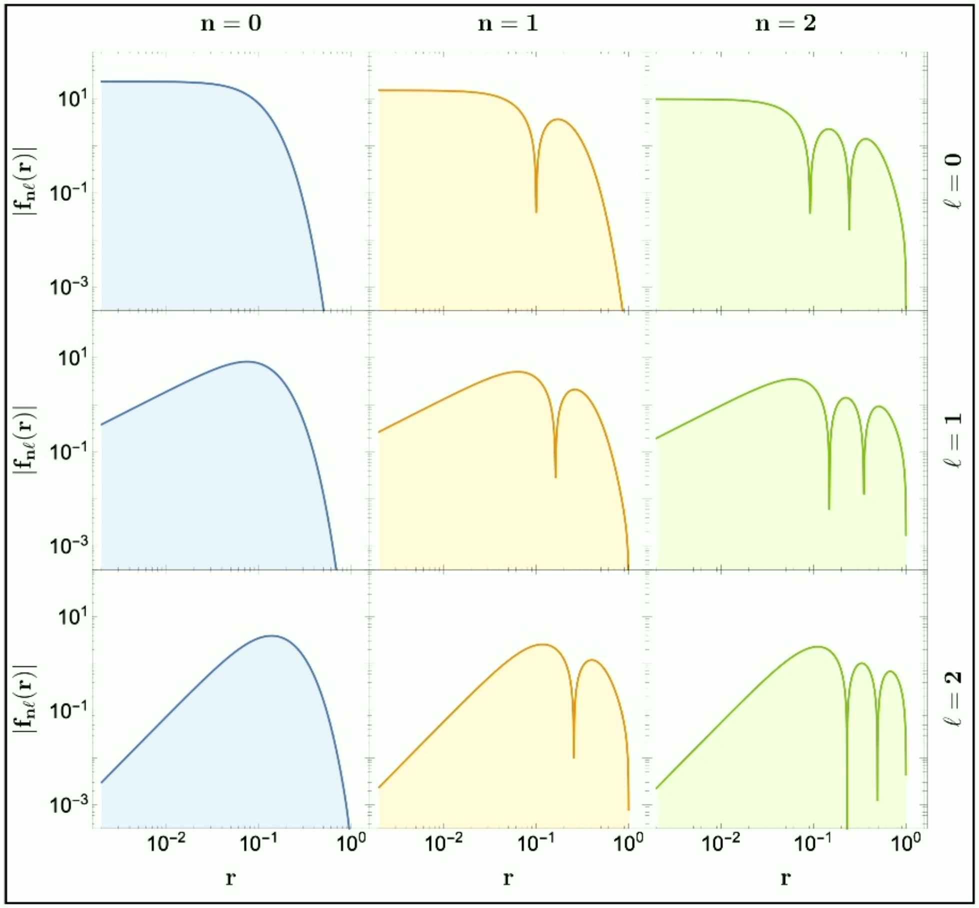


$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

$$\rho = m|\psi|^2$$

eigenstates!



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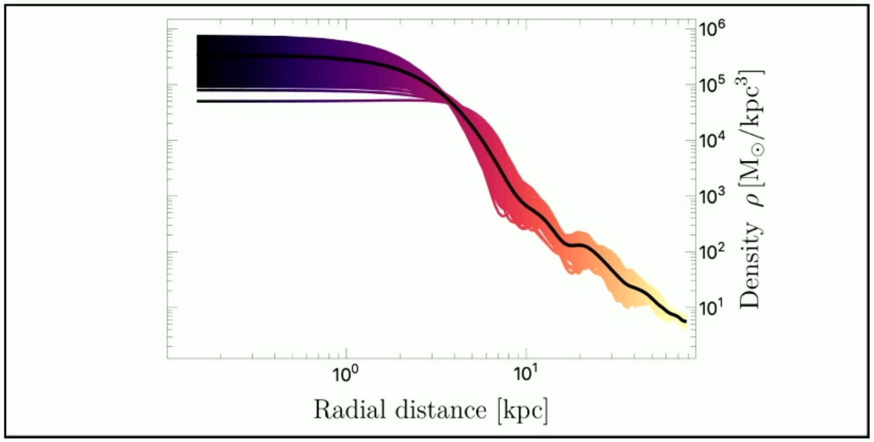

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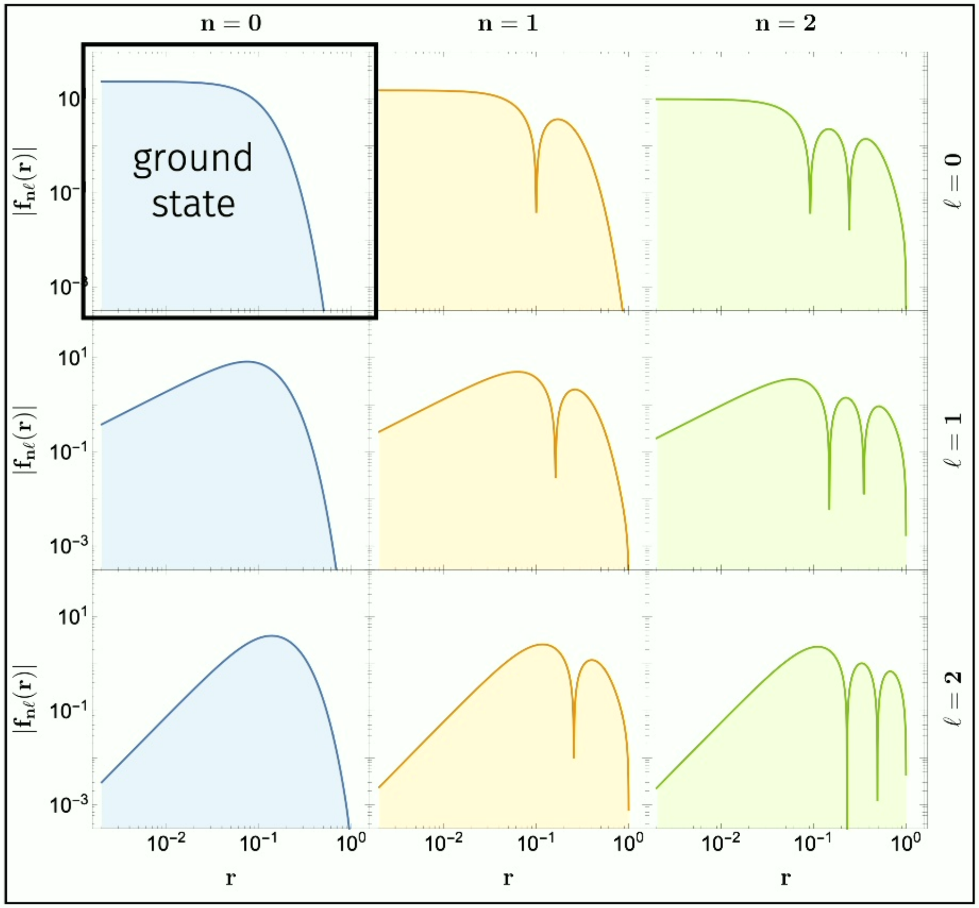
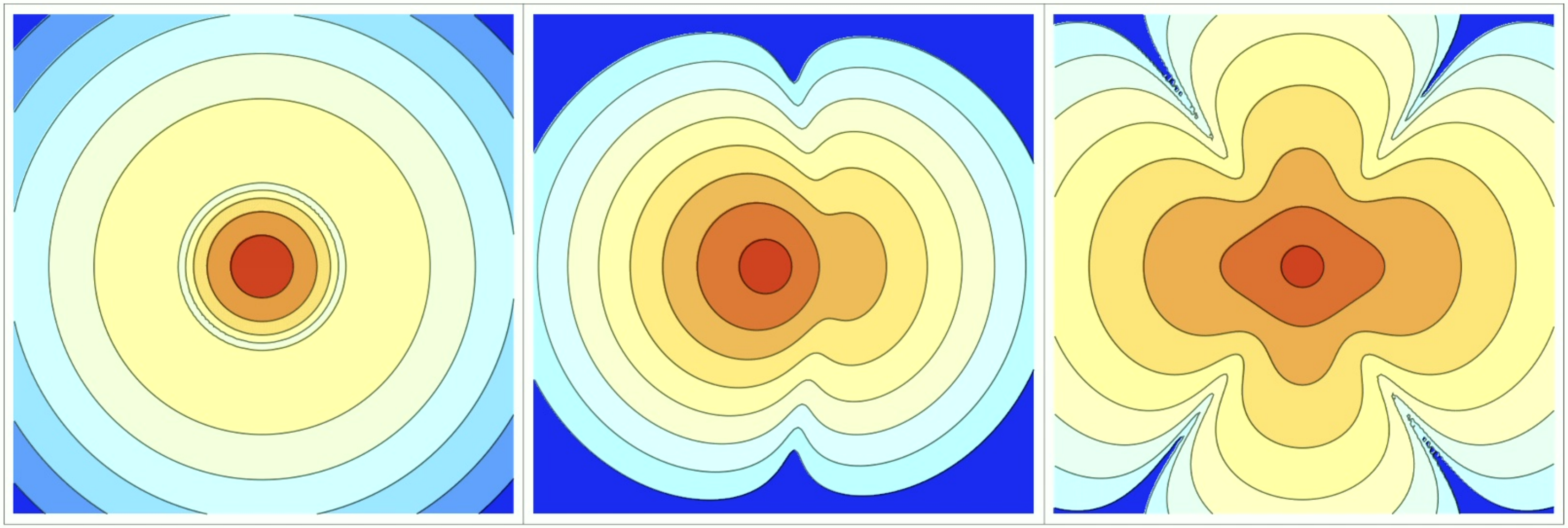
eigenstates!



PT: comparing amplitudes



$c_{nl}|nl\rangle = \sqrt{0.3}\,|10\rangle$ $c_{nl}|nl\rangle = \sqrt{0.3}\,|01\rangle$ $c_{nl}|nl\rangle = \sqrt{0.3}\,|02\rangle$

Dimensionless Power Spectrum of FDM

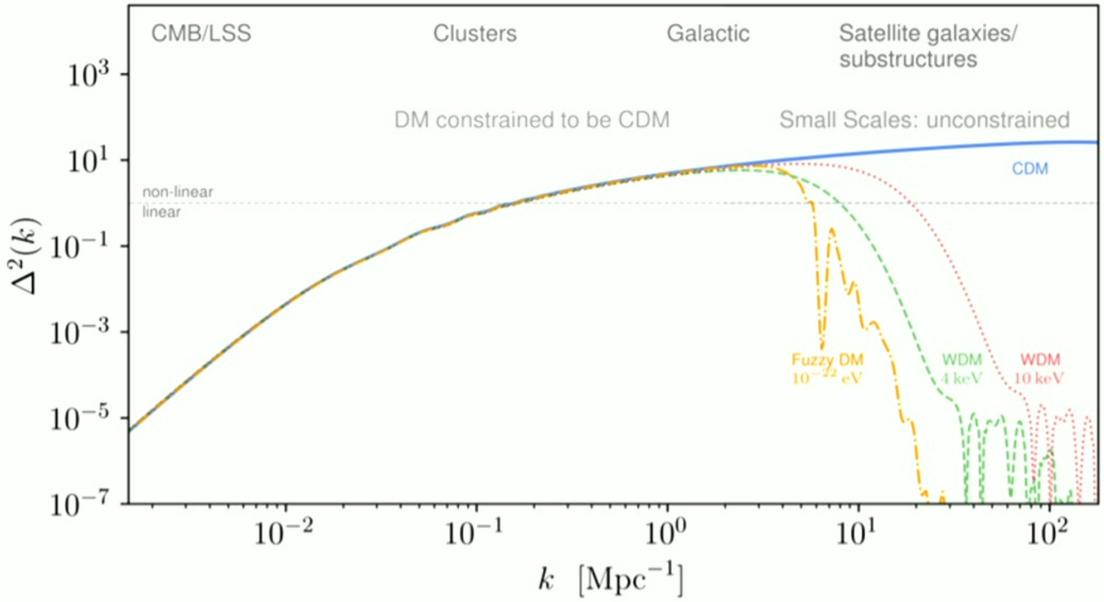


Fig. 2 In this figure, inspired from (Kuhlen et al. 2012), we show how the dimensionless power spectrum can be probed by many large scale and small scale observables, which can be seen as a function of the wavenumber k. The solid line shows the linear dimensionless power spectrum coming from a ΛCDM universe. To show how the small scales might reveal different behaviour for different DM components, we show the linear power spectrum of warm DM (WDM) with mass of 10 keV (red dotted line), WDM with mass of 4 keV (green dashed line), and for fuzzy DM with mass 10^{-22} eV (orange dash-dotted line). The gray dotted horizontal line represents the limit from linear to non-linear regime, where $\Delta \sim 1$. The power spectrum for ΛCDM and for WDM were generated using the Boltzmann code `CLASS` (Lesgourgues 2011; Lesgourgues and Tram 2011), and for the fuzzy DM using Axion`CAMB` (Lewis et al. 2000; Hložek et al. 2015)^{3}.

2005.03254

Some reported mass constraints on FDM

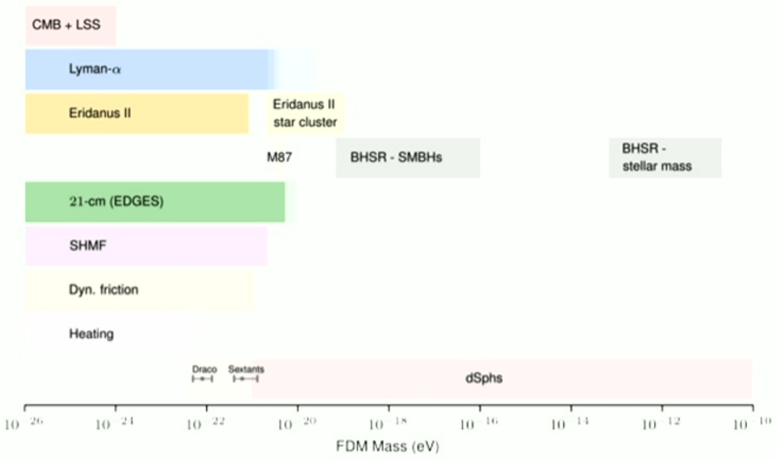


Fig. 18 Summary of most of the constraints on the mass of the FDM particle discussed in the section[49]. These bounds assume that FDM makes most of the DM in the universe. In this figure, the shaded regions represent the excluded regions. The CMB and LSS bounds come from (Hložek et al. 2015, 2018) using *Planck* (2015) TT CMB auto-power and the WiggleZ galaxy-galaxy auto-power spectrum. The Lyman-α constrains correspond different analysis made in the literature coming, from the darker to lighter, from (Nori et al. 2019; Armengaud et al. 2017; Iršič et al. 2017; Rogers and Peiris 2020), respectively. The Eridanus II constraint are both for its existence and for the survival of its star cluster from (Marsh and Niemeyer 2019). The next line presents the constraints from black hole superradiance (BHSR). The first constraint comes from bounds on the spin of the supermassive BH (SMBH) in M87, from the measurments obtained by the Event Horizon Telescope (Davoudiasl and Denton 2019). The second set of bounds comes from (Stott and Marsh 2018), which presents the stringiest bounds from BHSR of ultra-light particles from stellar BHs and from SMBHs. The global 21-cm signal detected by the EDGES team can also be used to put bounds on the mass of FDM as shown in (Lidz and Hui 2018; Schneider 2018). The next row refers to bounds on the FDM imposed by testing the suppression of the sub-halo mass function in comparison with the SHMF from WDM models constrained using strong gravitational lensing of quasars and from fluctuations in stellar streams (Schutz 2020). In (Lancaster et al. 2020) they compute the different description that dynamical friction has for the FDM and apply this to the Fornax globular cluster. The next bound comes from another dynamical effect, which is heating of the MW disk, that can be constrained measuring the velocity dispersion of stars in the solar neighbourhood (Church et al. 2019). We also include two constraints in the mass assuming that the measured central density of dSphs, Draco and Sextants should match maximum FDM core size, which should be smaller then the virial radius of these galaxies (Chen et al. 2017). This row also contains the results from the reanalysis of the bounds from dSphs from (González-Morales et al. 2017) starting at the lighter region, and (Safarzadeh and Spergel 2019) the darker shaded region.

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PULSARS!

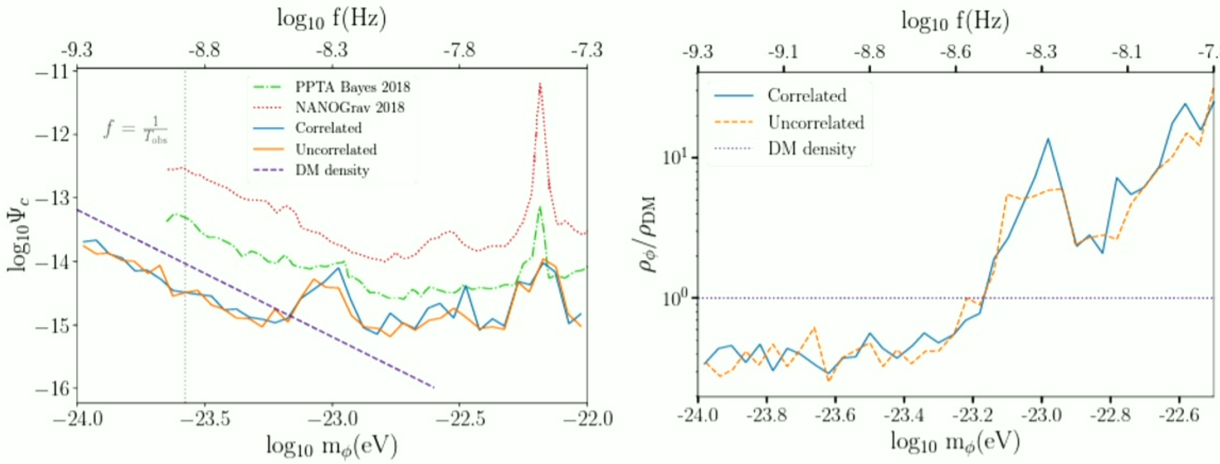

FIG. 1: Upper limits on ULDM, and namely on the dimensionless amplitude (Ψ_c, *left panel*) and the ULDM fraction of the local DM density ($\rho_\phi/\rho_{\rm DM}$, *right panel*), at 95% credibility. The bottom horizontal axes show the ULDM particle mass, whereas the top horizontal axes show the equivalent oscillation frequency of the scalar field. The upper limits from previous searches [37, 38] are shown for comparison. As a reference, we highlight the frequency $T_{\rm obs}^{-1}$. In the right panel, we zoom in on the excluded ULDM masses. The horizontal dotted line represents the value of ρ_ϕ that would saturate the local DM density. Notice that based on our results ULDM particles with mass -24.0 eV $< \log_{10} m_\phi < -23.4$ eV can only make up at most $30 - 40$ % of the total DM energy density.

- *uncorrelated* if the coherence length of ULDM is less than the average inter-pulsar and pulsar-Earth separation. In this case, $\hat{\phi}_E^2$ and $\hat{\phi}_P^2$ will thus be separate parameters;
- *correlated* if the coherence length of ULDM is larger than the inter-pulsar and pulsar-Earth separation. In this case, $\hat{\phi}_E^2 = \hat{\phi}_P^2$ for all the pulsars, and it can be absorbed in a redefinition of Ψ_c.

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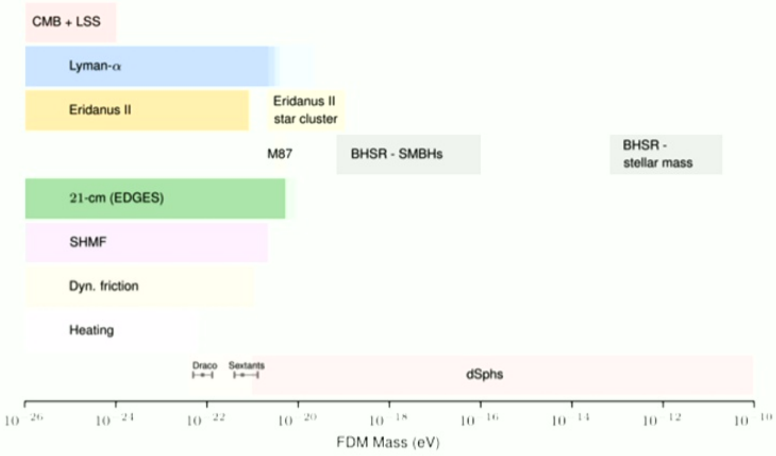
Some reported mass constraints on FDM



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