Title: Welcome

Date: Jun 16, 2014 09:00 AM

URL: http://pirsa.org/14060007

Abstract:

Intro theory talk to "New ideas in low-energy probes of fundamental physics"

Maxim Pospelov
University of Victoria/Perimeter Institute, Waterloo

On behalf of the theory part of the organizing committee
(Andrei Derevianko, Asimina Arvanitaki, Peter Graham)

University of Victoria | British Columbia Canada

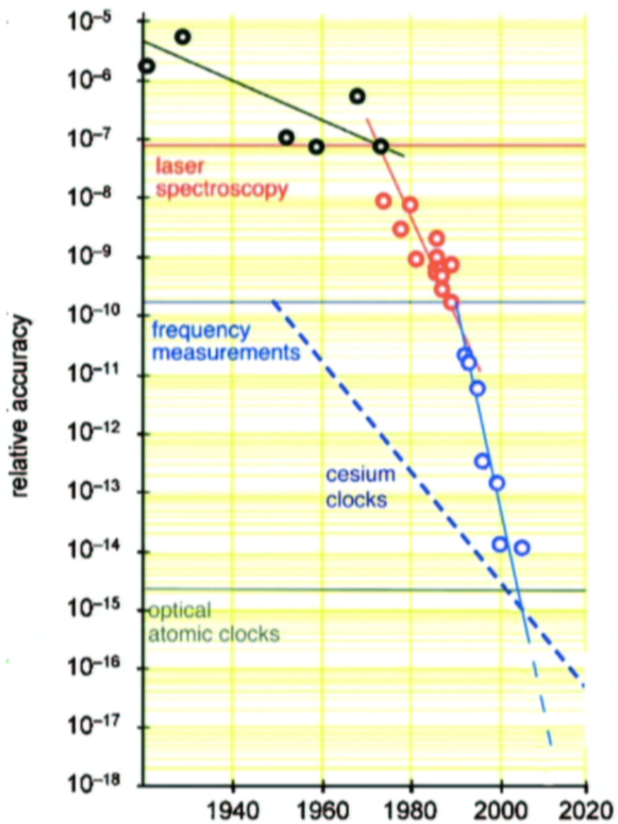
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Welcome to Perimeter Institute!

1. We have an impressive list of participants with various skills, expertise and backgrounds varying from … geophysics to … string theory.
2. Some of our guests are "PI regulars", some participated only in one or two events previously, and some are totally new to PI. *Welcome everyone*!
3. *What are the "new ideas"*??? The main idea is to put together a group of experts and generate some "new ideas" for *fundamental physics applications of low-energy experiments*.
4. The time to do it is *now*: there are many experimental developments in particle physics, cosmology, AMO etc, and many more physicists willing to think how to use this for fundamental physics.
5. We hope to have a productive workshop with active participation of everyone. *No questions is bad, but there are no bad questions.*

2

Progress in AMO vs fundamental physics?

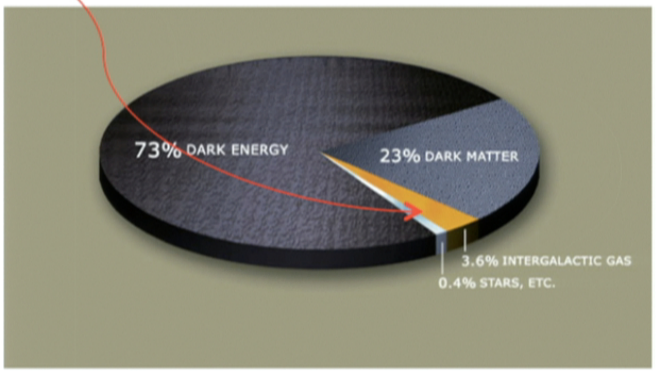


Hansch's Nobel lecture 2005

There have been tremendous advances in the last ~15 yr in AMO physics. There is a lot of appetite for fundamental [cosmological] applications.

So far applications of this progress have been focused on "traditional subjects": changing couplings (goes back to Dicke, Dirac) or "space isotropy/Lorentz violation", (Hughes, and probably someone earlier)

In case you did not hear about it…



Year 2013 marks the discovery of the Higgs boson – new/old particle and the fundamental Yukawa force (so it looks like now). And yet the now-complete SM is only ~ 5% in the overall energy budget of the Universe. (March-April 2014 are the months of the BICEP-2…..)

Main Challenges in DM/DE issues?

Dark energy: very few good ideas other than cosmological constant. Even that one is challenging to comprehend due to its extremely [theorists think] unnatural value.

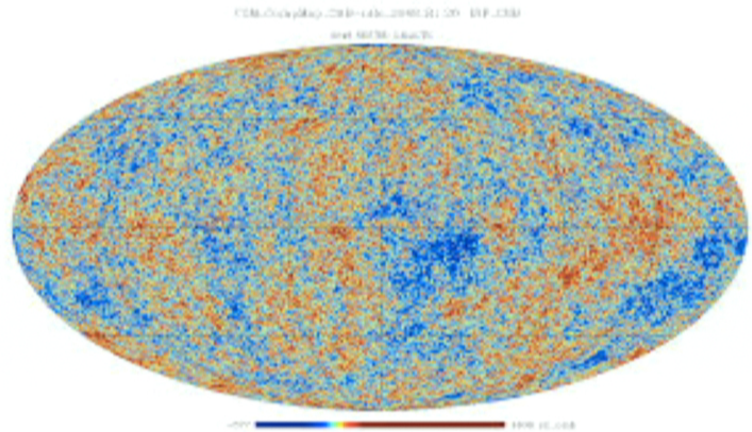
Dark matter: too many possibilities, many are quite reasonable from theoretical perspective.

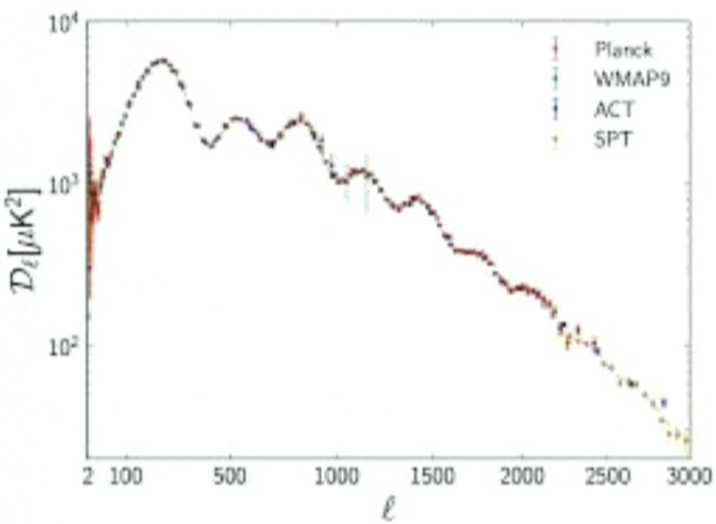
Experimental challenge in Dark Matter: Should we report in

(solar mass)/(parsec)^3 or GeV/(cm)^3 ?

extrapolate from kpc scales (~10^{21} cm) down to 1 meter scale. (*But it turns out we can successfully extrapolate back in time*!)

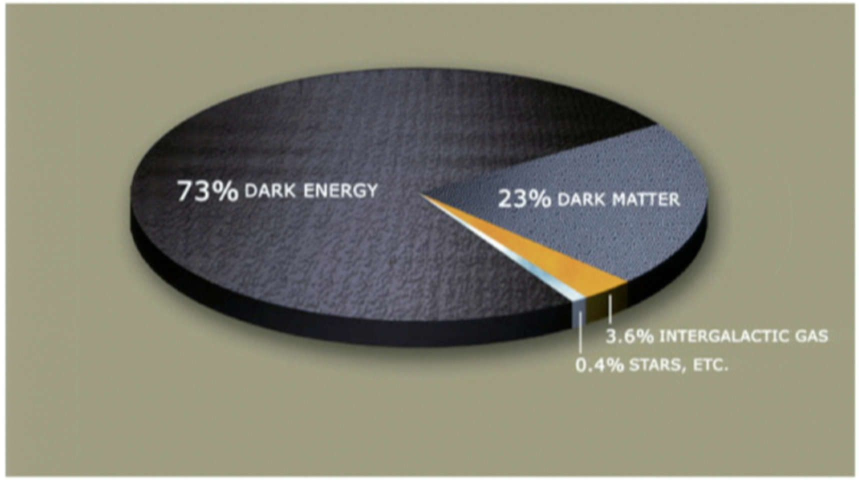
Celestial pointillism





Temperature map on the sky comes from CMB decoupled when the Universe was ~1000 times smaller. We get rich statistical information on the sky – well fit by a relatively simple cosmological model. Origin of density perturbation – most ancient epoch, possibly inflation.

Big Questions in Dark Matter Physics



Does dark matter (and also dark energy) have non-gravitational interactions?

Can we detect it?

What is the space of theoretical possibilities for dark matter? [very large, for sure …]

Evolution of theoretical interest to DM

Mid 90's: In the 0^{th} approximation: SUSY neutralino as WIMPs and axion models as "super-cold" DM.

↓

Last ~15 years – O(few 100) or more models of WIMPs (sometimes much simpler than MSSM neutralino), super-WIMPs, and super-cold DM are developed. Some models have a much *broader* observational consequences than "neutralinos and/or axions". Some have no *observable properties* other than gravitational interactions.

↓

Future? Any model of DM that has a chance of satisfying abundance (+may be some theory priors of "technical naturalness") is worth searching for.

Simple classification of *particle* DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

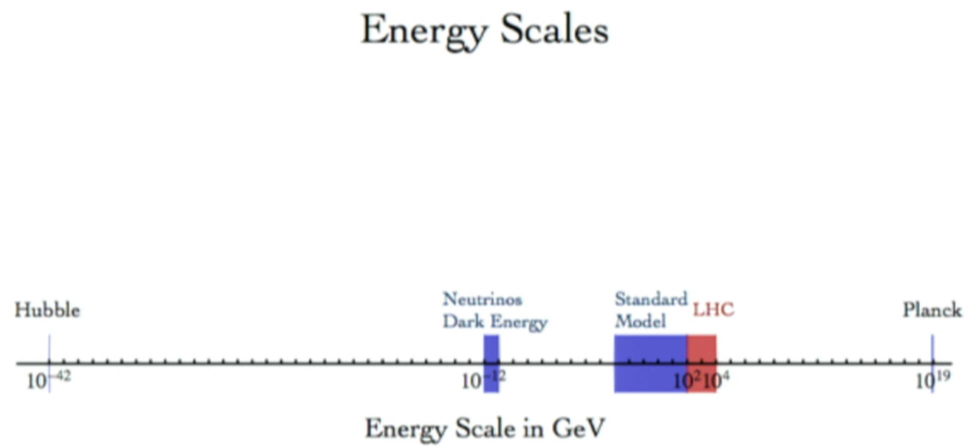
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim 10^{10}$. "Super-cool DM". Must be bosonic. **Axions**, or other very light scalar fields – call them **super-cold DM**.

Signatures can be completely different. WIMPs are most searched for.

Do we now what scale DM comes from?

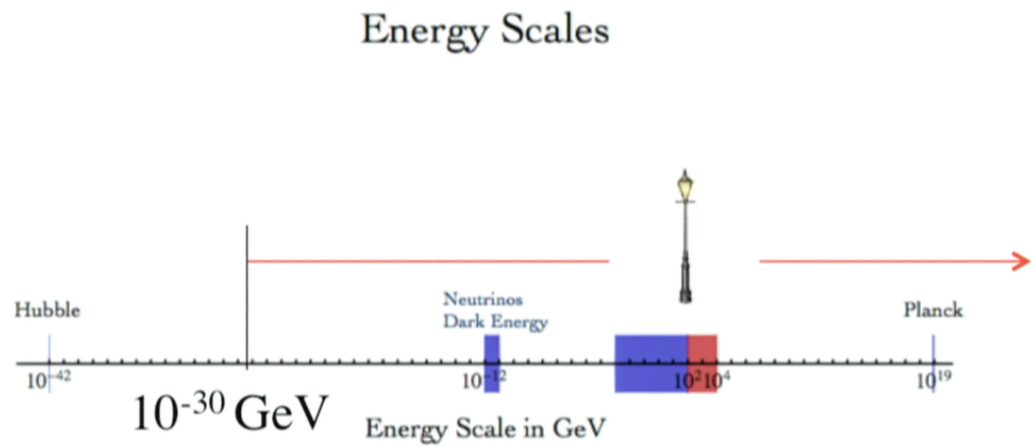


There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet

Plank mass / Hubble constant = 61 orders of magnitude.

10

Do we now what scale DM comes from?



There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- Hamlet

There is a bound on DM mass from below. Other than that….

11

WIMP lamppost

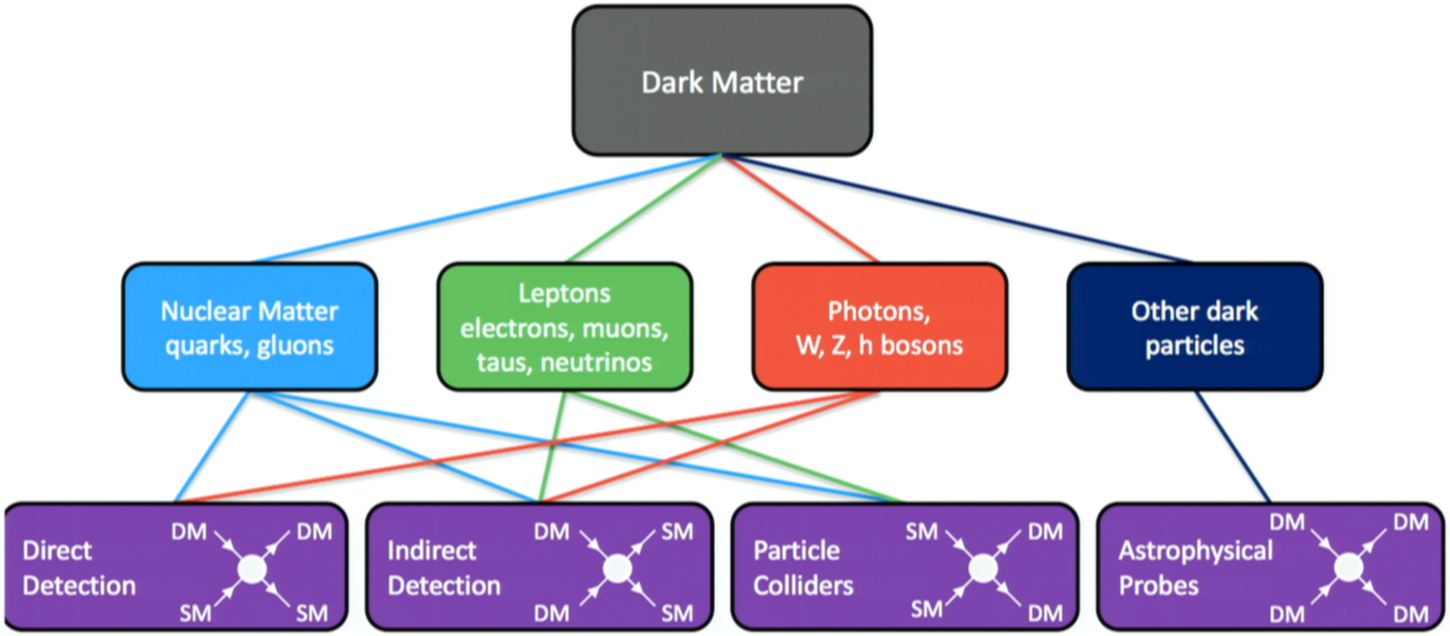
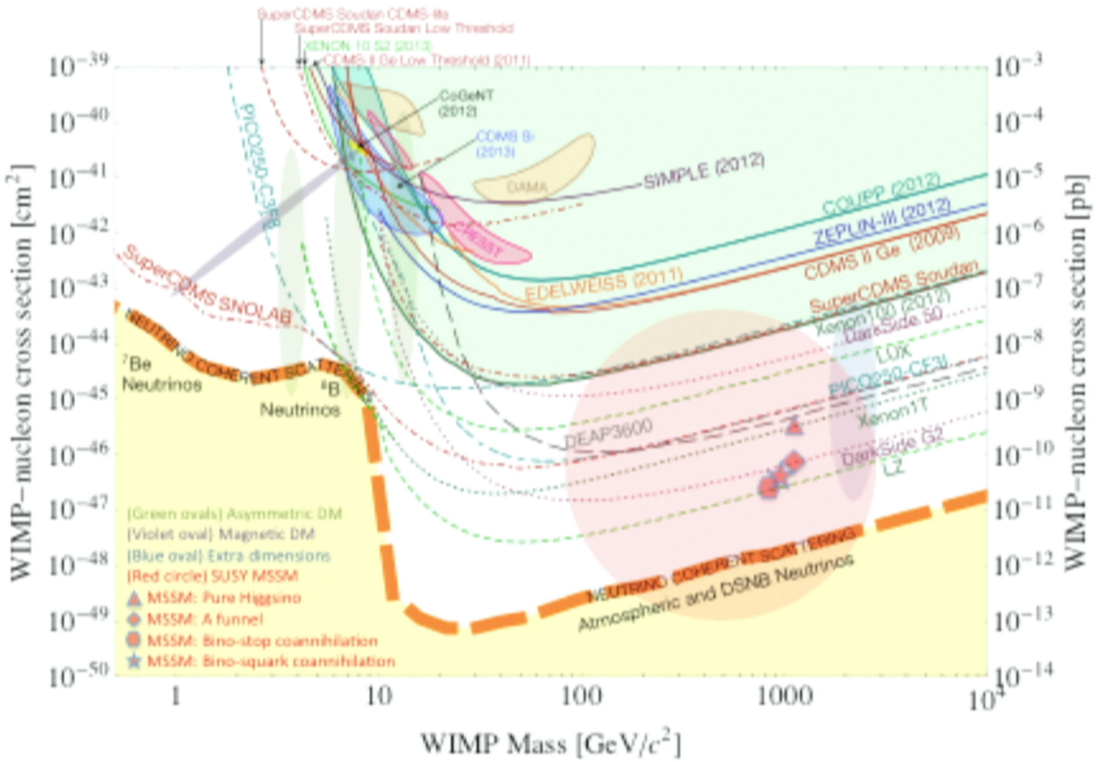


Figure 5. *Dark matter may have non-gravitational interactions with any of the known particles as well as other dark particles, and these interactions can be probed in several different ways.*

From the Snowmass 2013 summary, 1310.8327

Huge investment into WIMP searches



An O(30) experiments around the world, with very impressive progress in recent years. *No convincing signal from WIMP dark matter reported thus far*. We need to invest in alternative dark matter searches.

We are attracted to existing WIMP models of DM because of their relative simplicity and predictivity. But it may not be what nature chooses. Do we make enough efforts to search for other forms of DM?

Specifically, how to search for light bosonic fields (axion and its relatives) that can form dark matter and will be coherent on the scale of terrestrial experiments?

New lampposts for DM?

New lampposts in DM searches

- Light bosonic fields (scalars, pseudoscalars, vectors) that are displaced from the minimum of energy and remain frozen at early times: $(a'' + 3\,H\,a' + V'(a) = 0$ ← field "doesn't oscillate before H gets smaller than m_a)
- Light scalar fields may lead to new coherent forces between particles. (Forces acting on spins, and forces between masses.)
- Oscillating scalar fields may lead to oscillating properties of elementary particles (e.g. oscillating electric dipole moments, "oscillating" masses and couplings….)
- Nontrivial form to V(a) may create lumps of energy, which can be stable for certain (e.g. topological) reasons, in which case one should expect *transient effects* in time during atom-DM overlap.

15

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fields that could form DM. (More often than not more than 1 field is involved). Let us represent SM field by an electron, and a nucleon.

Interactions can be organized as "*portals*": coeff × $O_{\text{dark}} O_{\text{SM}}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi} \gamma_\mu \gamma_5 \psi \quad \text{axionic portal}$$

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi} \psi \quad \text{scalar portal}$$

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi} \psi \quad \text{quadratic scalar portal}$$

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi} \gamma_\mu \psi \quad \text{current} - \text{current portal}$$

An atom inside a defect will have addt'l contributions to its energy levels

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fieldsthat could form DM. (More often than not more than 1 field is involved). Let us represent SM field by an electron, and a nucleon.

Interactions can be organized as "portals": coeff × $O_{dark}O_{SM}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\rm SM\ particles} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$ Torque on spin

B. $$\frac{\phi}{M_*} \sum_{\rm SM\ particles} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$ Shift of ω + extra gr. force

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\rm SM\ particles} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$ Shift of ω + extra gr. force

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\rm SM\ particles} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$ extra gr. force

An atom inside a defect will have addt'l contributions to its energy levels

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fields that could form DM. (More often than not more than 1 field is involved). Let us represent SM field by an electron, and a nucleon.

Interactions can be organized as "portals": coeff × $O_{\text{dark}} O_{\text{SM}}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi} \gamma_\mu \gamma_5 \psi \quad \text{axionic portal}$$ $f_a > 10^9$ GeV (astro)

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi} \psi \quad \text{scalar portal}$$ $M_* > 10^{21}$ GeV (5^{th} force)

C. $$\frac{\phi_1^2 + \phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi} \psi \quad \text{quadratic scalar portal}$$ $M_* > 10^4$ GeV (5^{th} force+ast)

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi} \gamma_\mu \psi \quad \text{current} - \text{current portal}$$ $M_* > 10^4$ GeV (5^{th} force+ast)

An atom inside a defect will have addt'l contributions to its energy levels

The issue of technical naturalness

Any tree level potential

$V^{tree}(\phi) = c^{tree}{}_0 + c^{tree}{}_1\phi + c^{tree}{}_2\phi^2 + \ldots.$

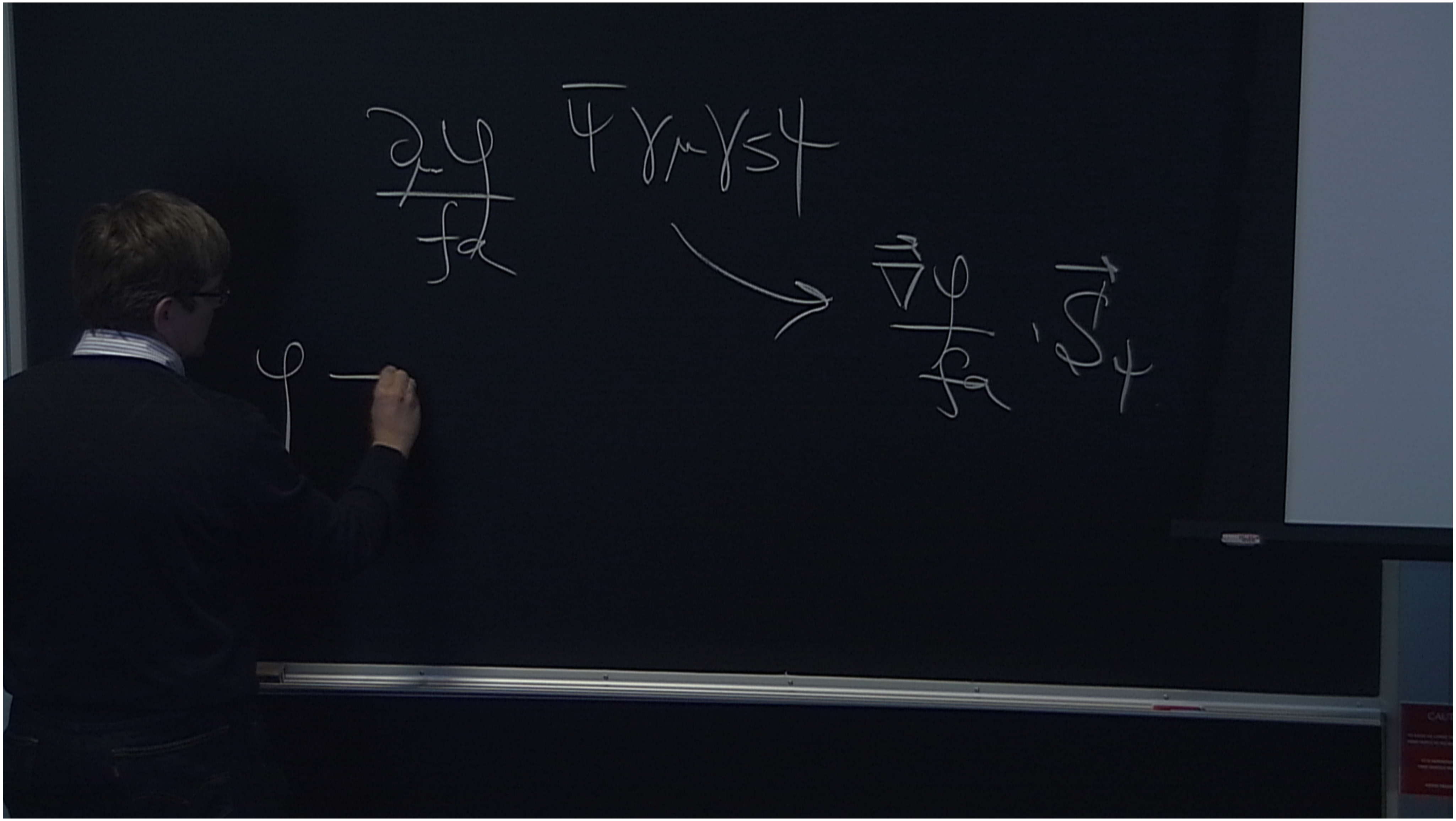
Would have to have coefficients $c^t{}_i$ very small to keep evolution *slow*. Loops generate *larger* corrections

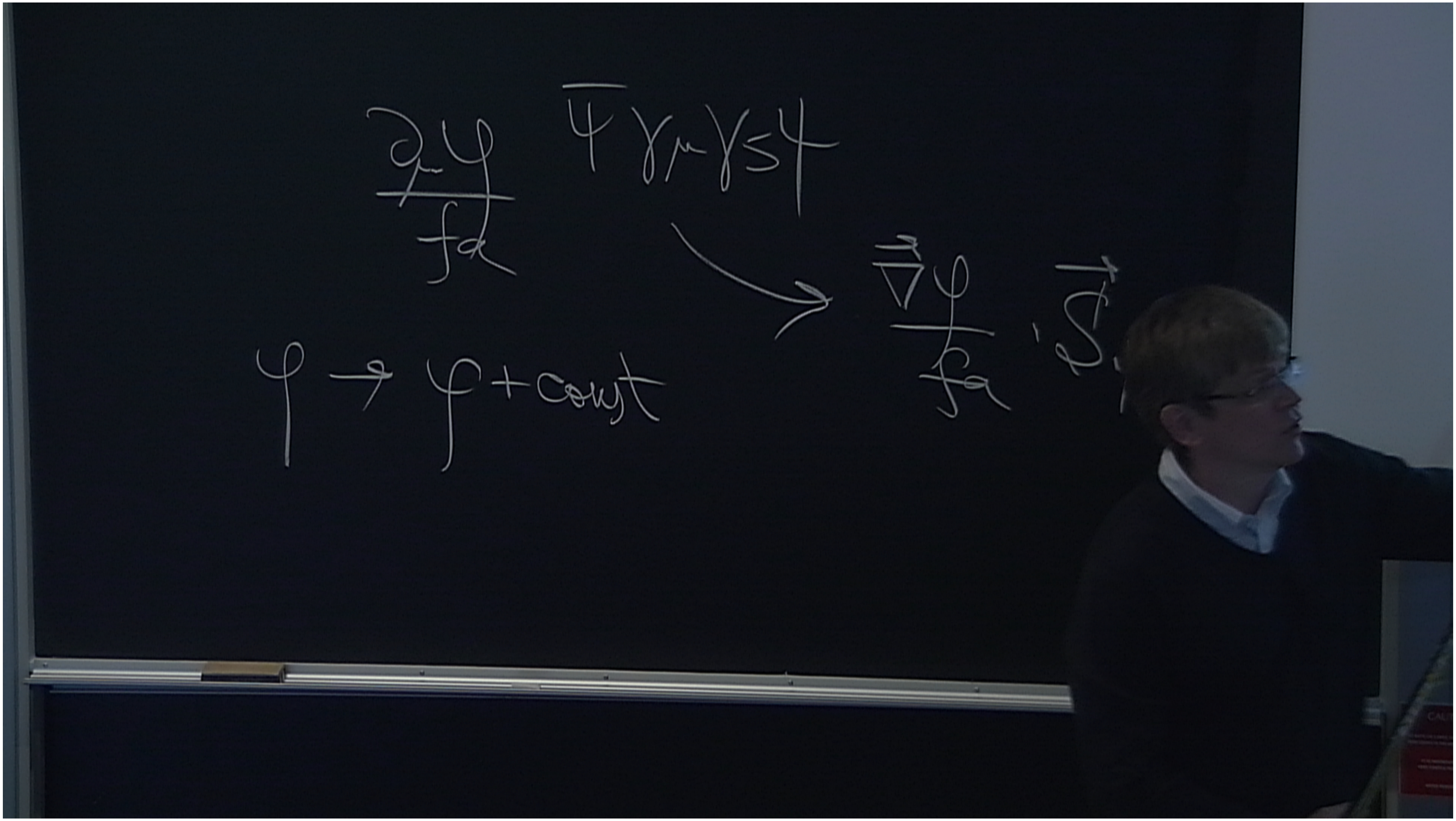
$V^{loop}(\phi) = c^{loop}{}_0 + c^{loop}{}_1\phi + c^{loop}{}_2\phi^2 + \ldots.$

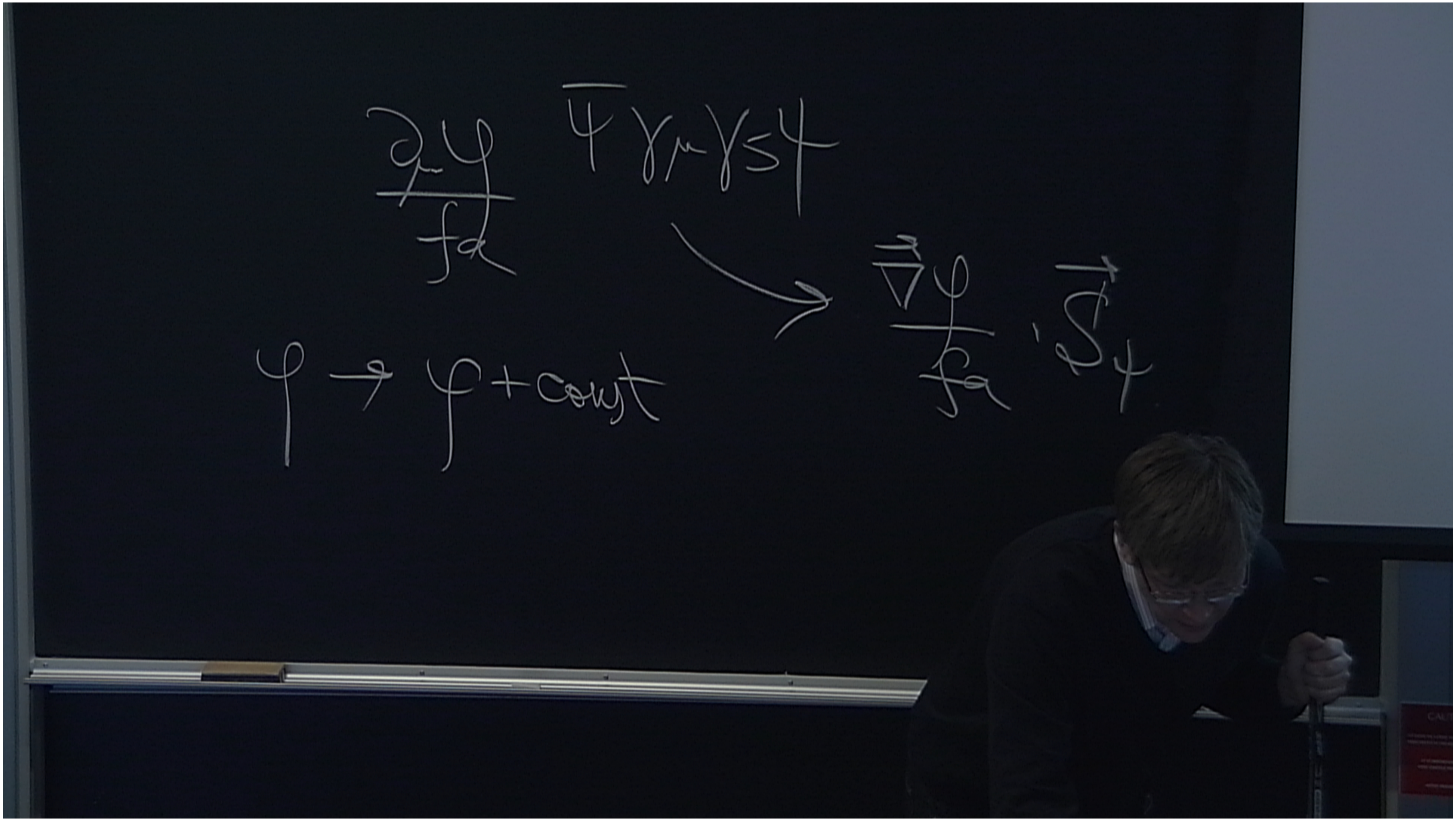
so that $c^{loop}{}_i >> c^{tree}{}_i$, One has to start with large and opposite tree-vs-loop coefficients $c^{loop}{}_i = - c^{tree}{}_i$ to ensure tight cancellation for several terms in the series… Very unnatural! *Standard problem for scalar portals. (well known in the context of changing α)*

Importantly, same pessimistic argument does not apply to interactions protected by shift symmetry, the axionic portal for example.

(* *But may be the approach idea of having rigid technical naturalness built in a model is not "quite" right, and we would miss out on interesting physics* *)


∂μφ / fa
ψ̄ γμ γ5 ψ
∇φ / fa · S ψ
φ —


$\frac{\partial_\mu \varphi}{f_a}$
$\bar{\Psi}\gamma_\mu\gamma_5\Psi$
$\frac{\vec{\nabla}\varphi}{f_a}\cdot\vec{S}$
$\varphi \to \varphi + \text{const}$


∂μφ/fa ψ̄γμγ5ψ
∇φ/fa · S ψ
φ → φ + const

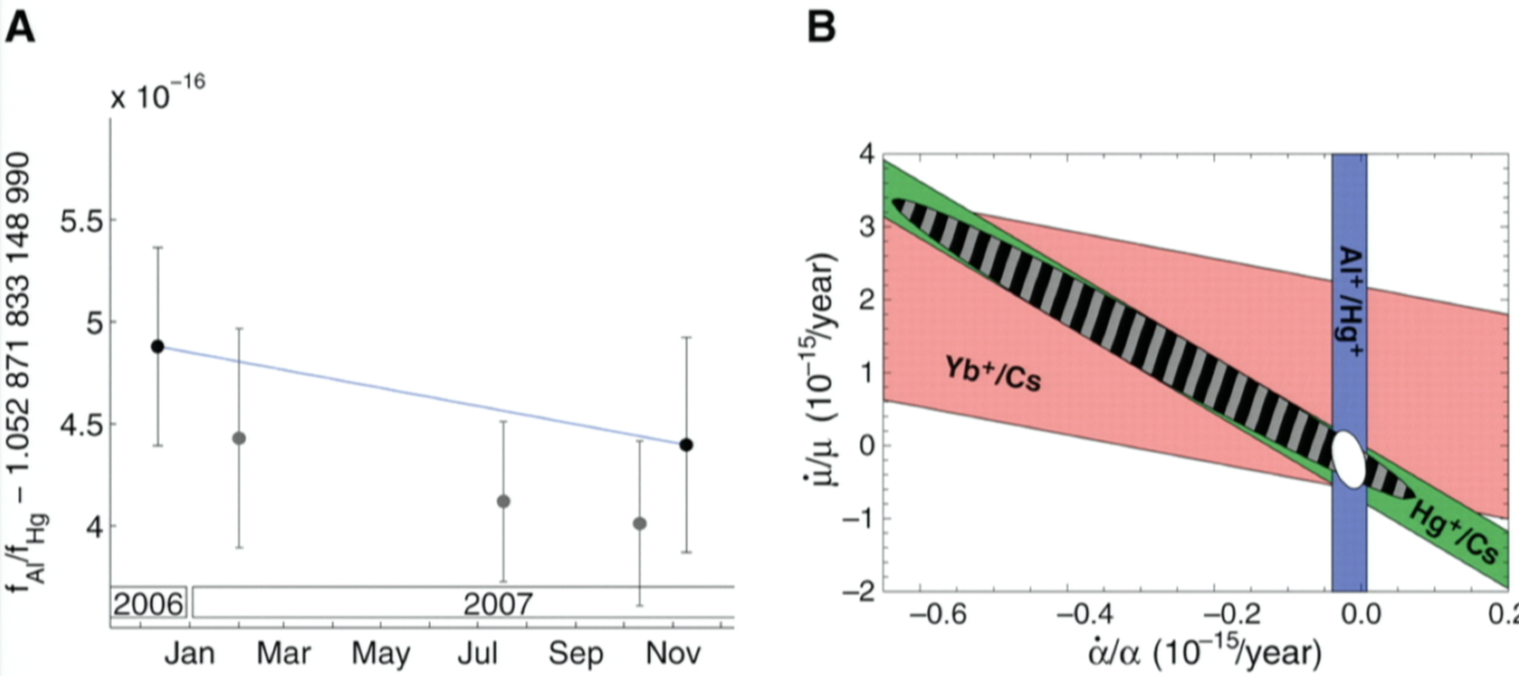
Have we tested long-range forces enough?

Are there other examples of light field models (other than axions) with observable consequences that can be made "technically natural"?

Astrophysical constraints on light particles/fields can be very strong: are there examples of terrestrial experiments providing better sensitivity than astrophysical bounds?

Can we ever surpass astrophysical bounds on axions in the direct search experiments?

New possibility for "changing couplings"



Atomic clocks surpassed the level of sensitivity suggested by a non-zero variation claim of Webb et al, (2001) – finding change of couplings being perfectly consistent with 0.

"transient LV" and "transient $\Delta\alpha/\alpha$ "

Typical "LV" experiment looks for $b_\mu \bar{\psi}\gamma^\mu\gamma_5\psi$
that one can generalize as interaction os a spin i to with the *fixed* gradient of the scalar field a, $f_i{}^{-1}\partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$

Similarly, existing terrestrial checks of $\Delta\alpha/\alpha$ etc look for a smooth dα/dt signal, that is a *constant in time*.

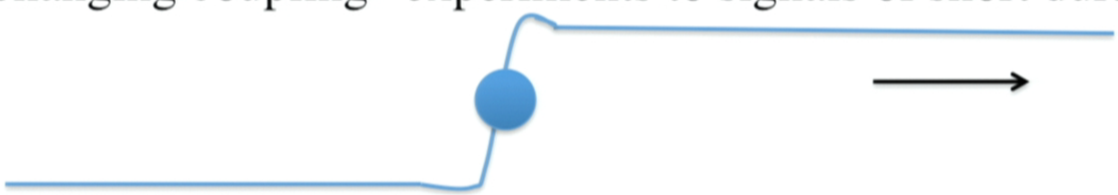
And of course TD transient signal can be viewed as generalization of LV and "changing coupling" experiments to signals of short duration.

“transient LV” and “transient $\Delta\alpha/\alpha$ “

Typical “LV” experiment looks for $b_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$
that one can generalize as interaction os a spin i to with the *fixed* gradient of the scalar field a, $f_i{}^{-1} \partial_\mu a \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$

Similarly, existing terrestrial checks of $\boldsymbol{\Delta\alpha/\alpha}$ etc look for a smooth dα/dt signal, that is a *constant in time*.

And of course TD transient signal can be viewed as generalization of LV and “changing coupling” experiments to signals of short duration.



What are the perspectives for adding “time” into searches of “changing couplings and Lorentz violation” ?

What are the best systems and strategies to look for oscillating patterns of mass scales, couplings, particle’s properties ?

What are the best systems and strategies to look for transient effects on mass scales and couplings ?

Is there much gain from using networks of devices?

What are backgrounds for searches of transient phenomena?

More questions…

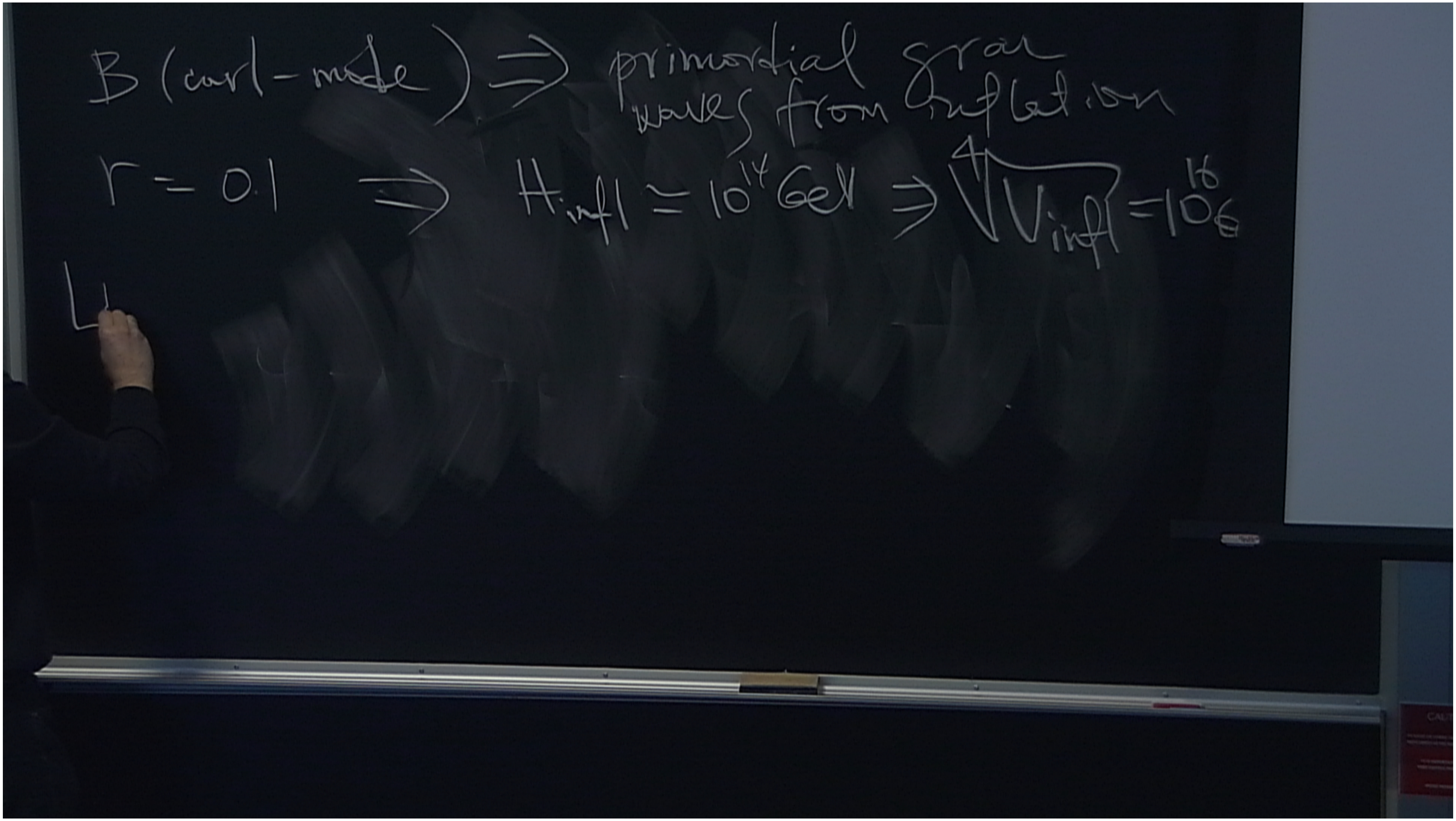
What are the latest developments in Atom Interferometry and Atomic Clocks, NMR and precision magnetometry? What other technologies are emerging in the precision frontier? What does the near future hold?

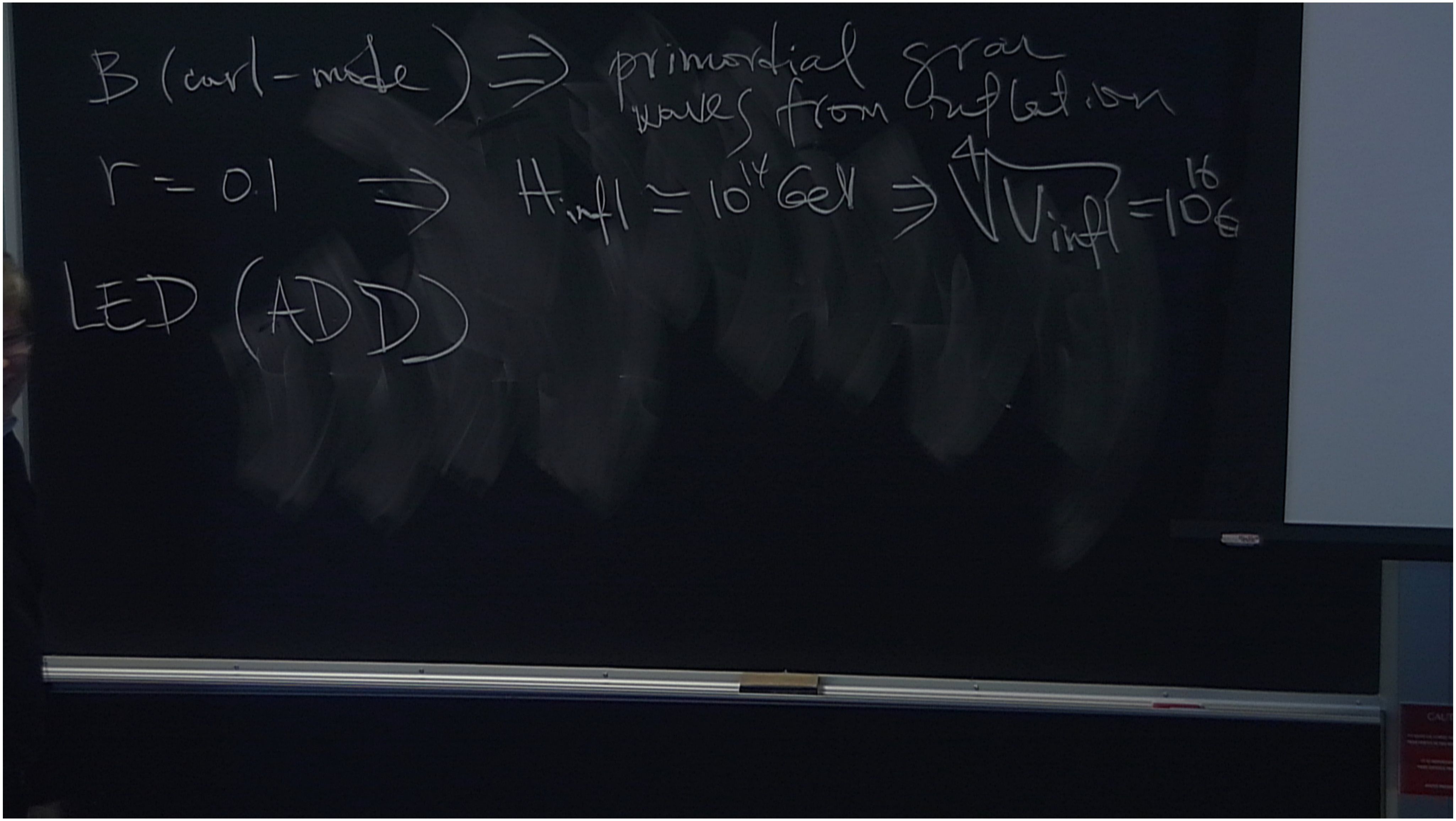
What are the best motivated things to be looking for at energies well below the LHC? Are there any good DM candidates? Can we say anything about Gravity and Quantum Mechanics?

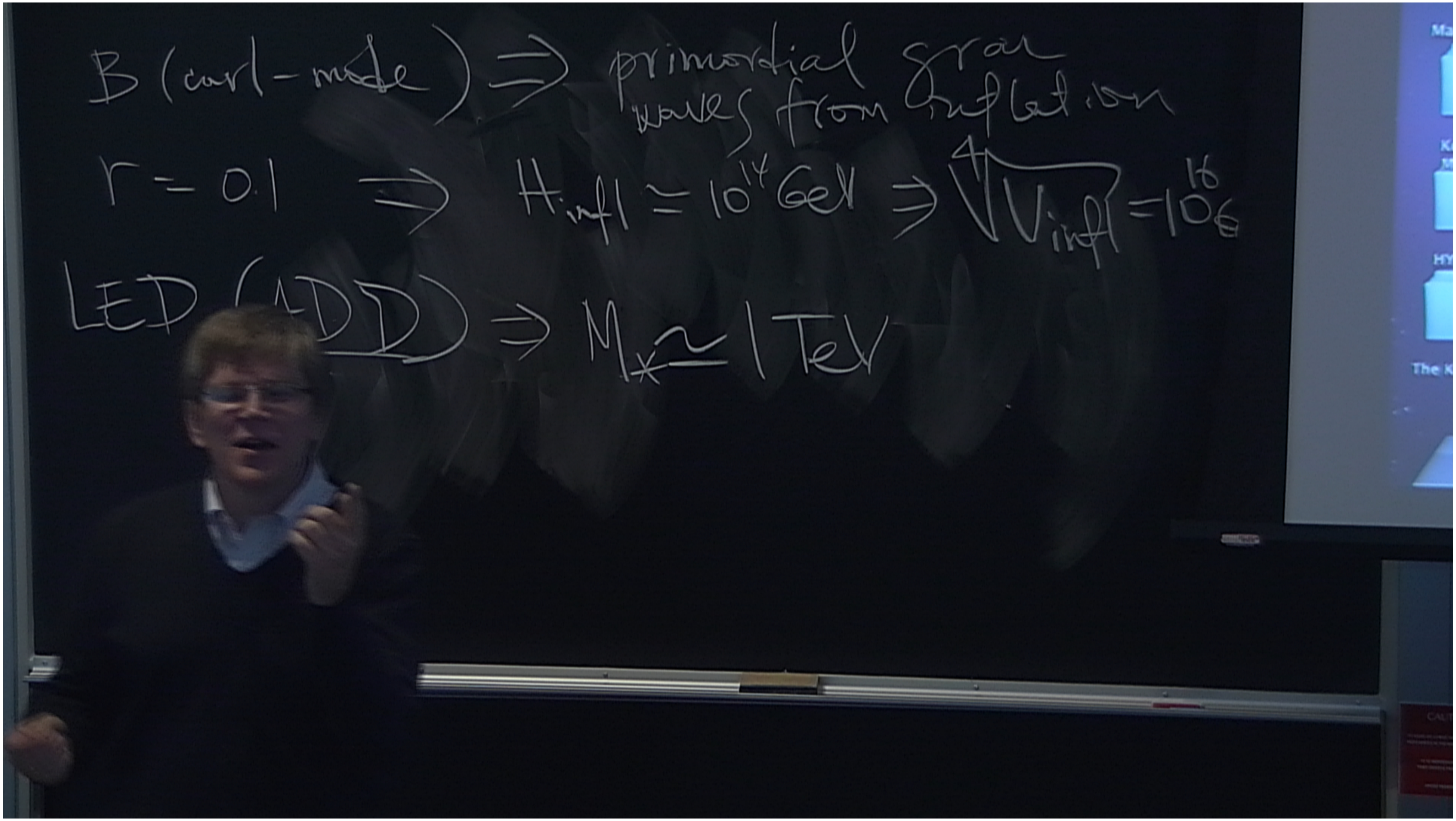
Many million $ question: will Bicep-2 results hold? Will it point indeed to a very high-energy scale during cosmic inflation? Will it disfavor models with low quantum gravity scales (e.g. large extra dimensions), and some ultra-light bosonic dark matter?

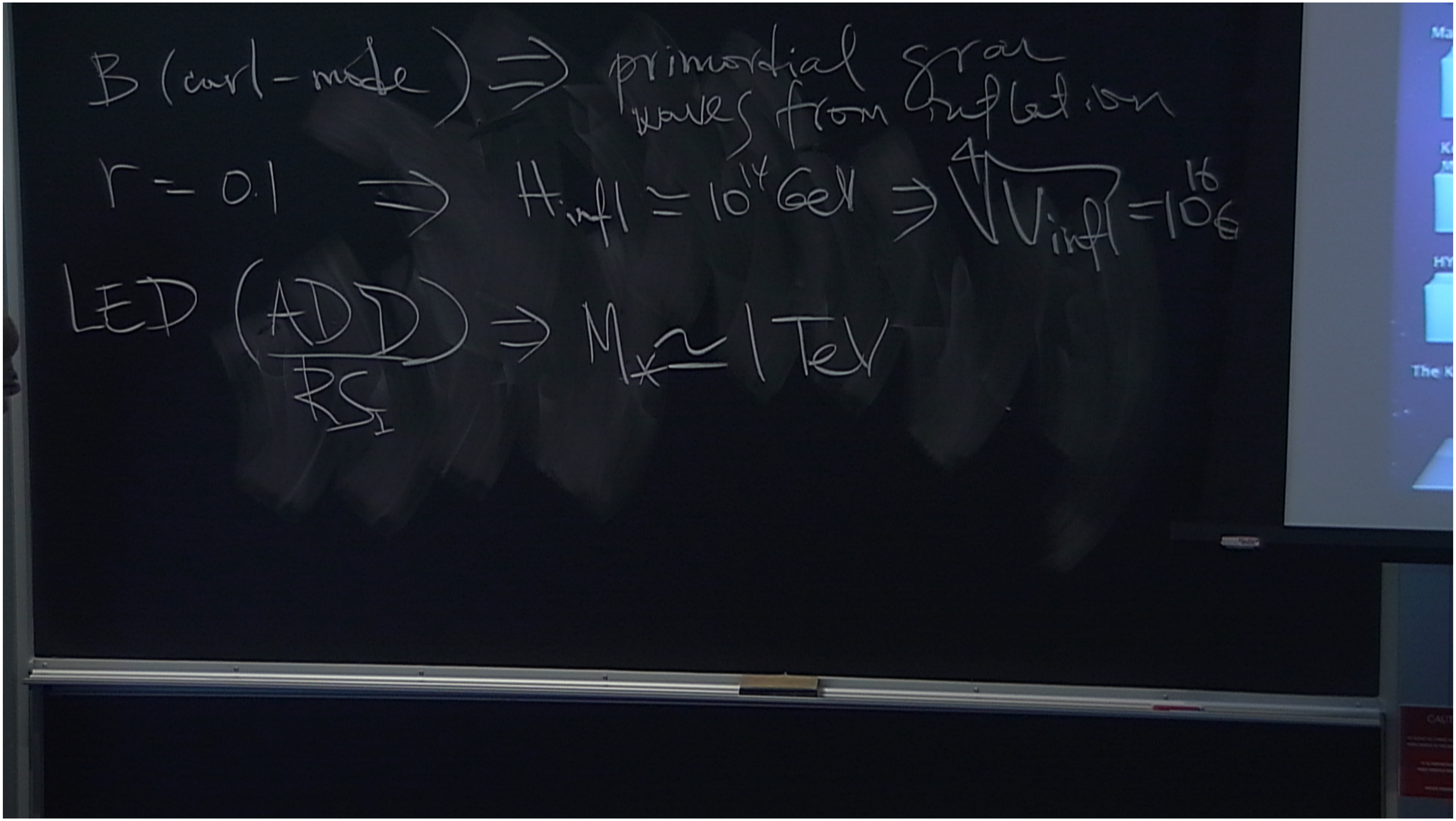
Are there more things to learn from CMB polarization? Birefringence?

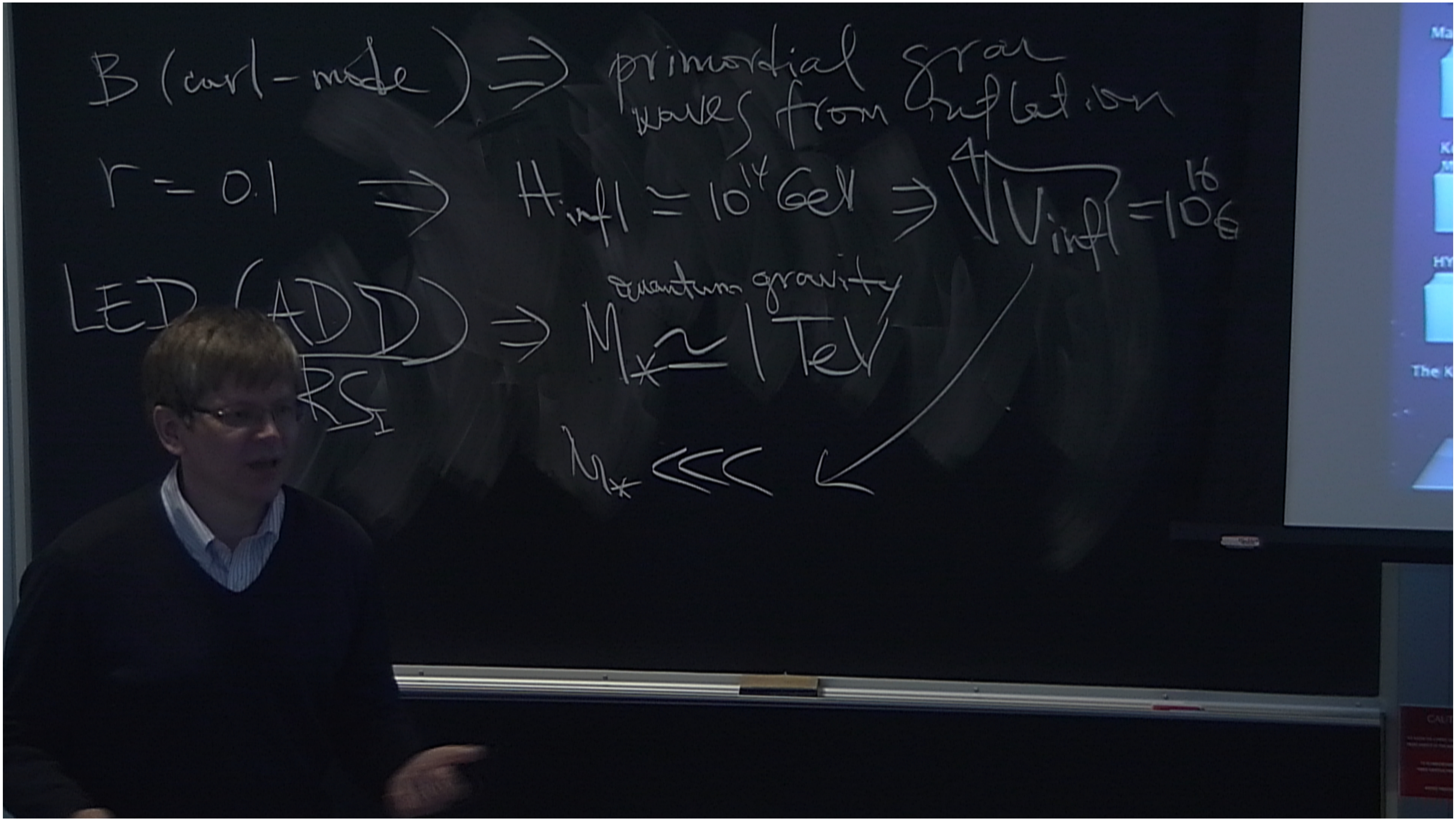
New force of nature at PI:

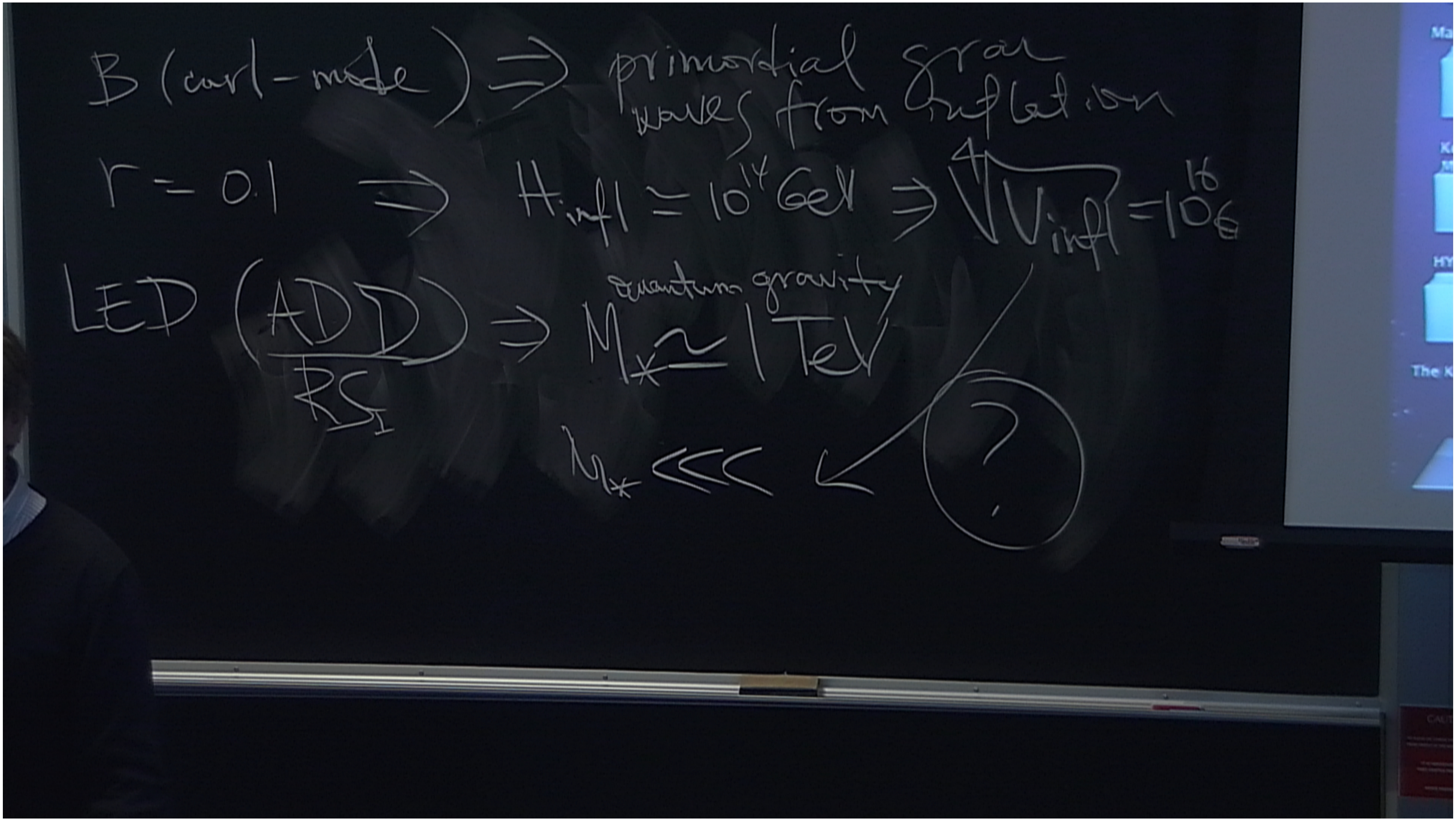

B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ H_infl ≃ 10^14 GeV ⇒ ⁴√V_infl = 10^16 GeV


B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ Hinfl ≃ 10^14 GeV ⇒ ⁴√Vinfl = 10^16 GeV
LED (ADD)


B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ H_infl ≃ 10^14 GeV ⇒ ⁴√V_infl = 10^16 GeV
LED (ADD) ⇒ M_* ≃ 1 TeV


B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ $H_{infl} \simeq 10^{14}$ GeV ⇒ $\sqrt[4]{V_{infl}} = 10^{16}$ GeV
LED (ADD / RS_I) ⇒ $M_* \simeq 1$ TeV


B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ $H_{infl} \simeq 10^{14}$ GeV ⇒ $\sqrt[4]{V_{infl}} = 10^{16}$ G
quantum gravity
LED (ADD) ⇒ $M_* \simeq 1$ TeV
RS_I
$M_* \lll$


B (curl-mode) ⇒ primordial grav waves from inflation
r = 0.1 ⇒ H infl ≃ 10^14 GeV ⇒ 4√V infl = 10^16 GeV
LED (ADD / RS I) ⇒ M* ≃ 1 TeV
quantum gravity
M* <<<
?