Title: Review of models

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Abstract:

Models of Changing Couplings

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Outline of the talk

1. Introduction. Searches of variations of couplings and masses in space and time. Its place in a bigger picture.
2. Review of Bekenstein model.
3. Extending Bekenstein model $\equiv$ Interacting quintessence.
4. Discussion of naturalness.
5. Shielding gravity. Environmental dependence of masses and coupling constants.
6. Do all coupling change? Infrared modification of α.
7. Conclusions

Motivations

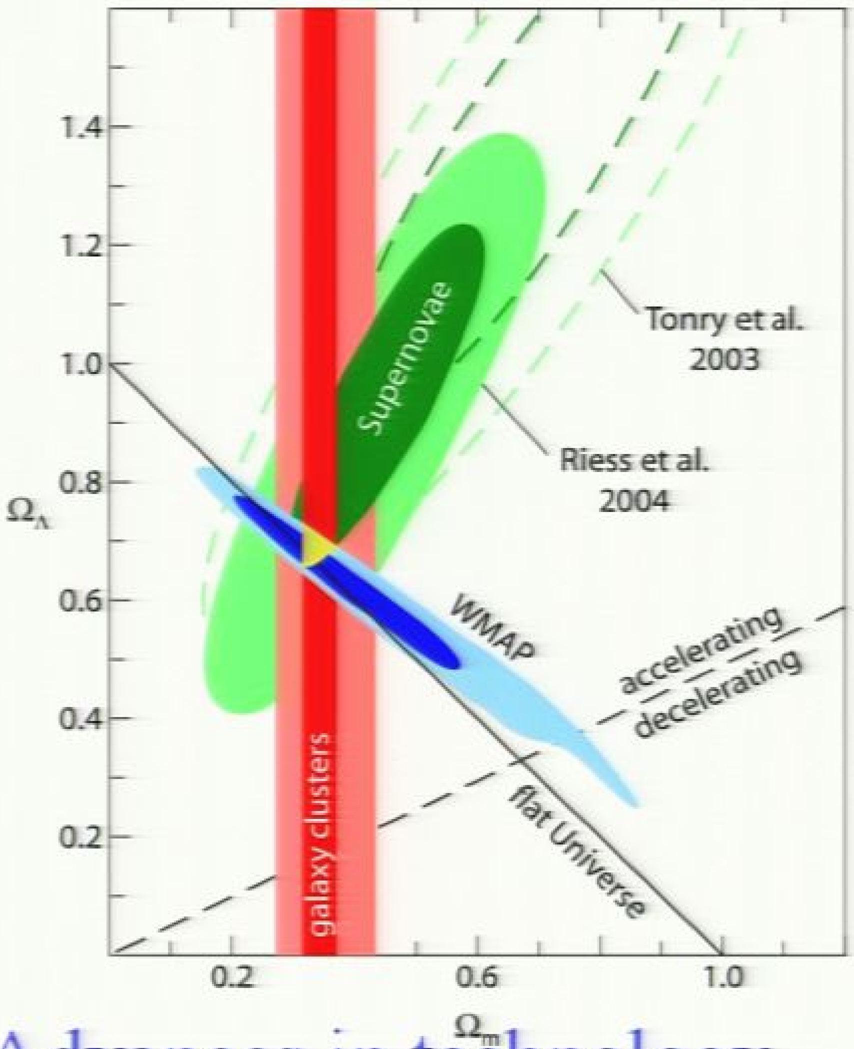
1. Existence of dark energy is an established experimental fact.

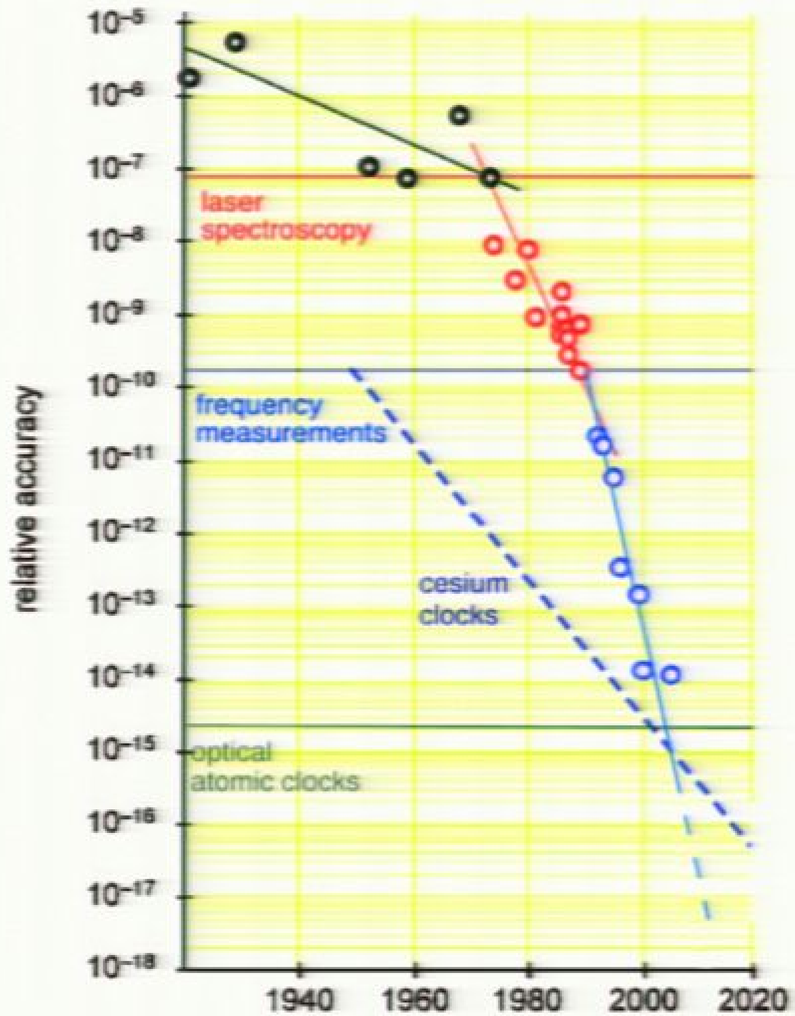
(Merriam-Webster announced over the weekend that **dark energy** has been admitted into the new edition of its *Collegiate Dictionary* along with more than 100 other up-and-coming terms–from **air quotes** and **edamame** to **dirty bomb**, **malware**, **mondagreen**, and **wing nut…So, it is official!)**

1. It may not be a simple cosmological constant Λ, but a modification of gravity or an ultra-soft dynamical field ϕ that can evolve in time/space
2. Possible coupling of ϕ to normal matter may manifest itself in a number of "strange" phenomena, including "variation of couplings" and there are endless possibilities to search for that.
3. Are there sensible models that further legitimize such searches?

(Do we need models at all?)

Two impressive plots





Advances in technology

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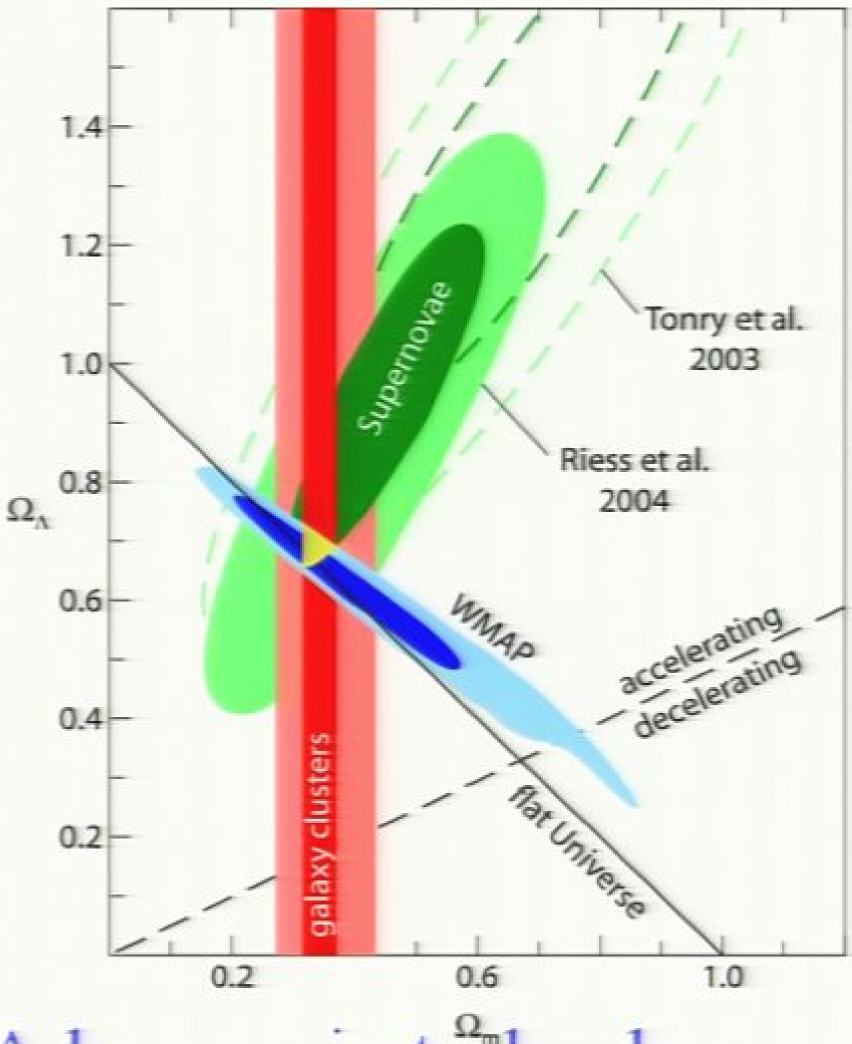
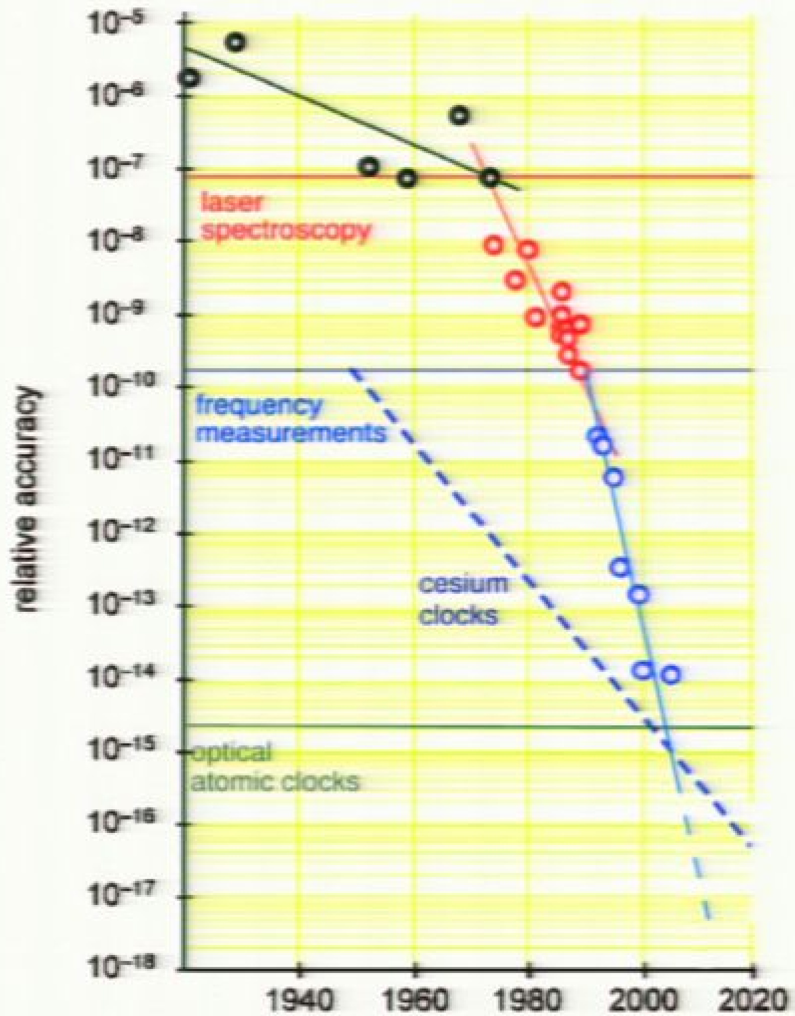




Advances in technology

4

Do we need models of $\Delta\alpha$, Δm_e etc?

Physicists search for

1. New long-range forces distinct from Einstein's GR
2. Deviations of $w_{\text{Dark Energy}}$ from -1.
3. Variations of masses and couplings
4. Birefringent parity-violating effects for photons propagating over large distances
5. Photon-axion oscillation
6. Non-GR couplings of spins to gravitational fields

What possible connection could exist between all these "shots in the dark" without a well-formulated model?

Example

Take QED and extend it by one scalar field!

$$L = -\frac{1}{4} F_{\mu\nu} F_{\mu\nu} + \bar{\psi}(i\gamma_\mu \partial_\mu - m_e)\psi + \frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi)$$

$$+ c_1 \varphi F_{\mu\nu} F_{\mu\nu} + c_2 \varphi \tilde{F}_{\mu\nu} F_{\mu\nu} + c_3 \varphi m_e \bar{\psi}\psi + c_4 \varphi m_e \bar{\psi} i \gamma_5 \psi$$

Using this model you can calculate local $\phi(\mathbf{r})$, cosmological $\phi(t)$ profiles, and discover that *all seemingly unrelated phenomena are actually related.*

Do we need models of $\Delta\alpha$, Δm_e etc? - Yes

1. New long-range forces distinct from Einstein's GR c_3 , c_1
2. Deviations of $w_{\text{Dark Energy}}$ from -1. $V(\phi)$, c_3, c_1
3. Variations of masses and couplings c_3 , c_1
4. "Preferred frame" parity-violating effects for photons propagating over large distances c_2
5. Photon-scalar conversion c_1 , c_2
6. Non-GR couplings of spins to gravitational fields c_2 , c_4

In fact, all of these phenomena result from one new field and a few new couplings.

Necessarily, $V(\phi)$ has to be "very flat" !

Benchmark point for the change of α

- QSO absorption spectra; Murphy et al. (1998-2007)

$$\frac{\Delta\alpha}{\alpha}(z = 0.2 - 4.2) = (-0.543 \pm 0.116) \times 10^{-5}$$

- QSO absorption spectra; Srianand et al. (2004)

$$\frac{\Delta\alpha}{\alpha}(z \propto 1) = (-0.06 \pm 0.06) \times 10^{-5}$$

Will hear about it today!!! I will use O(10^{-5}) at z~1 as a "benchmark point" sensitivity

Bekenstein (1983) model of $\alpha(t)$

$$L = L_{SM} + \frac{M_*^2}{2}\left(\partial_\mu \varphi\right)^2 - \frac{\varsigma_F}{4}\varphi F_{\mu\nu}F_{\mu\nu}$$

$\varphi -$ dependence of α: $\quad \alpha_{\text{eff}} = \alpha/(1+\varsigma_F \varphi)$

Cosmological evolution equation:

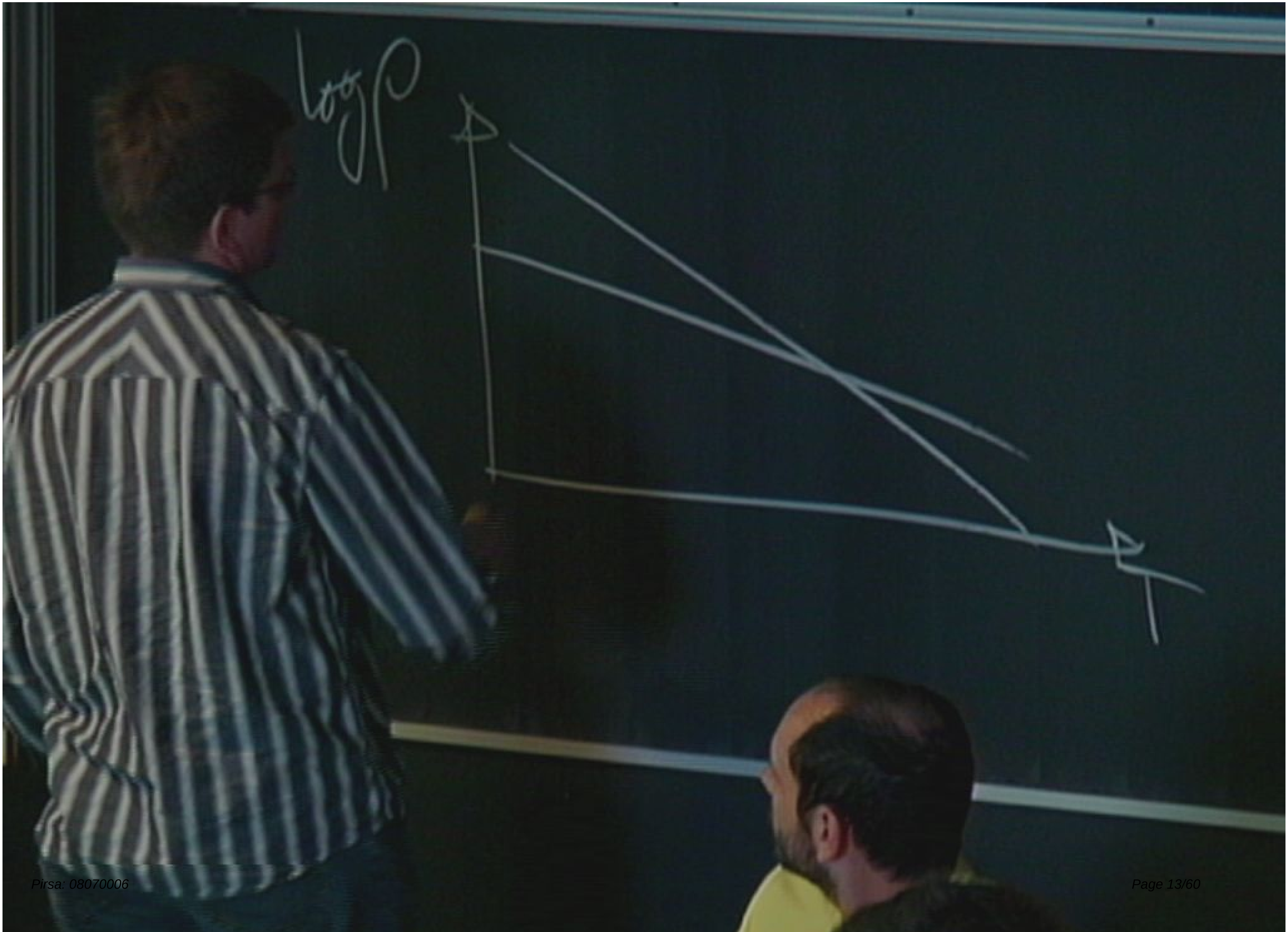
$$\partial_\mu \partial^\mu \varphi = \frac{\varsigma_F}{M_*^2}\left\langle \frac{1}{4} F_{\mu\nu}F_{\mu\nu} \right\rangle$$

Important consequences:

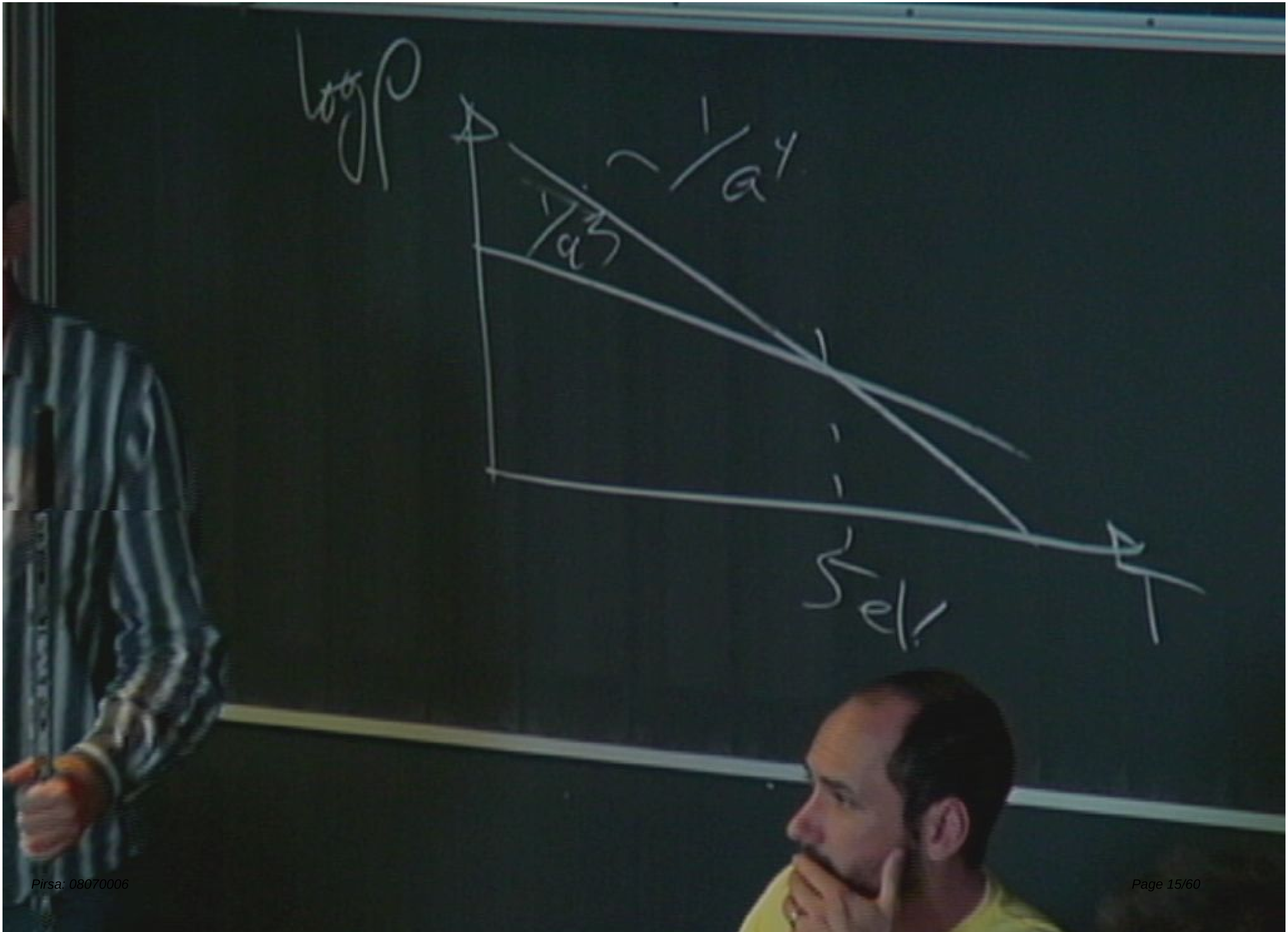
- No evolution between ~ 5 eV < T < 0.5 MeV
- All observables will depend on one combination ζ_F^2/M^2_*
- Linear evolution with ln(z) during matter domination:

$\Delta\alpha/\alpha \sim \ln(1+z) \quad \zeta_F^2 M_{\text{Pl}}^2/M^2_* \quad \Omega_b \times \delta_{\text{EM}}$

$\delta_{\text{EM}} \simeq$ few $\times 10^{-4}$ is the EM fraction of proton mass


log p


$1/a^3$
$\sim 1/a^4$


log ρ
~ 1/a⁴
1/a³
ζ_ell
T

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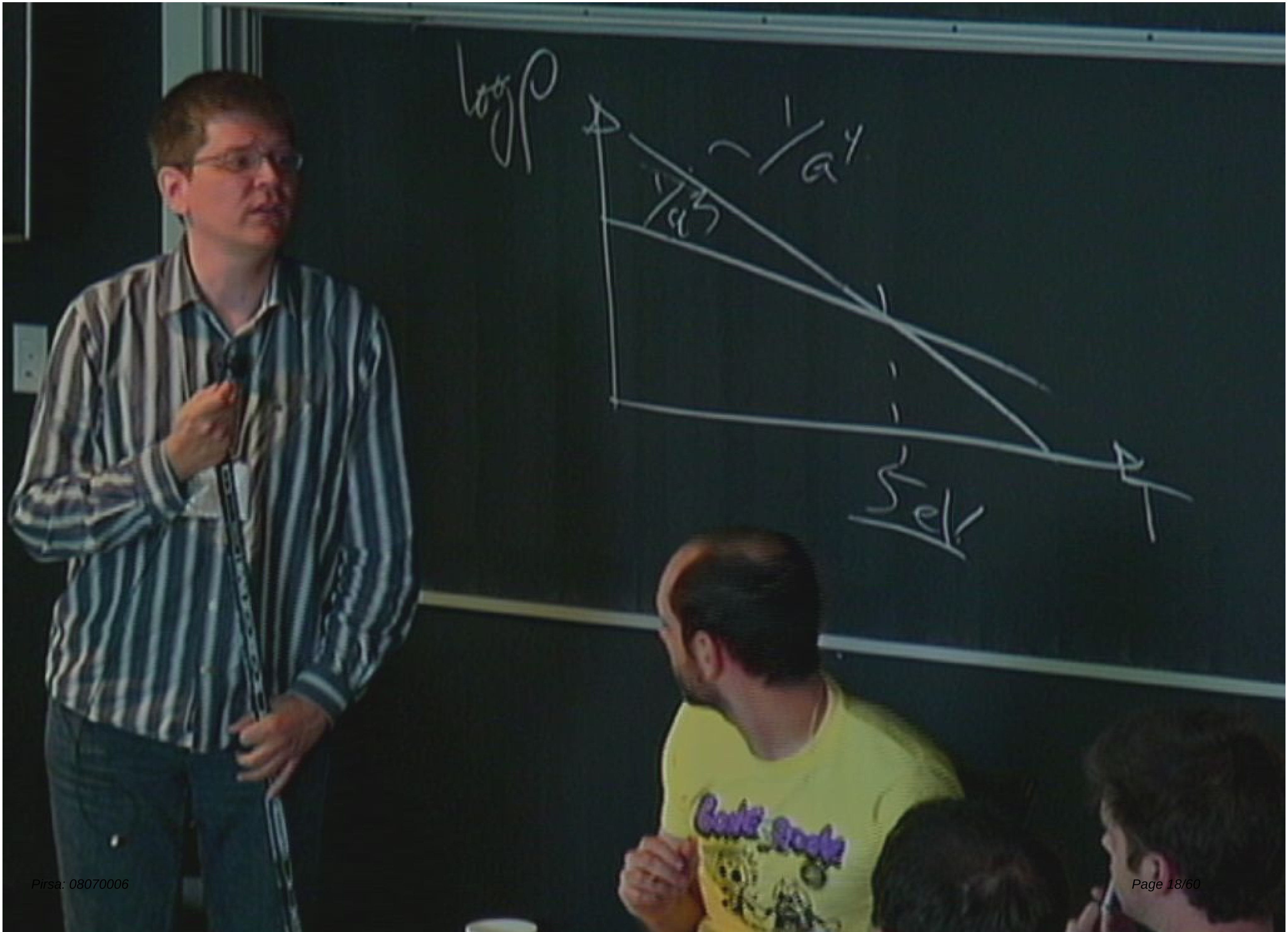
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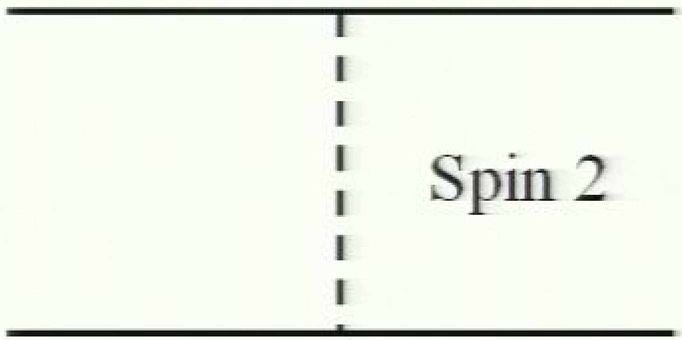
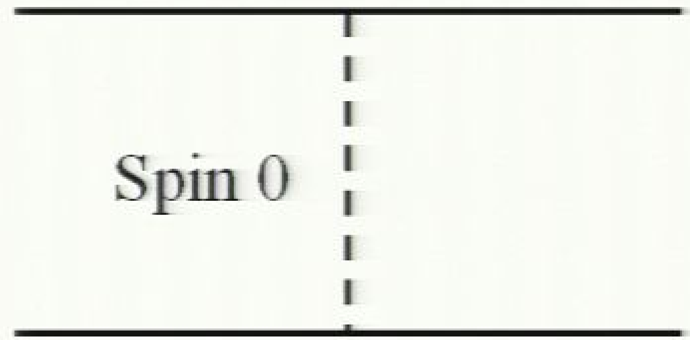
Bekenstein model is killed by gravity tests





Universal force, G_N

Non-universal force;

$\Delta G_N \sim \zeta_F^2 \delta_{EM}^2 / M_*^2$

The absence of non-universal force is checked with accuracy better than 10^{-13} . Then it follows that $\zeta_F^2 M_{Pl}^2 / M_*^2 < 10^{-5}$
Therefore one can conclude that

$(\alpha(\text{then})-\alpha(\text{now}))_{max}/\alpha \simeq + \text{few} \times 10^{-10}$

and Bekenstein model cannot give $O(10^{-5})$ shift

Spatial change of α in Bekenstein model? Not a chance!

Spatial change of couplings:

$$\Delta\alpha/\alpha \sim \zeta_F \Delta\phi(\mathbf{r}) \sim \delta_{EM}\, \zeta_F{}^2 (M_{pl}/M_*)^2 \Delta\phi_{grav}(\mathbf{r}) < 10^{-8}\, \Delta\phi_{grav}(\mathbf{r})$$

This is $O(10^{-18})$ for a satellite orbit and $O(10^{-24})$ for the lab environment
This is far away from modern capabilities

Referring to recent studies of atomic clocks w.r.t. the eccentricity of Earth's orbit: predicted $\Delta\alpha/\alpha < 10^{-18}$

(Very nice benchmark for the atomic clocks to take!)

Is there a way of making this difference larger and be consistent with gravitational constraints?

Modified Bekenstein-type model (predictivity is lost)

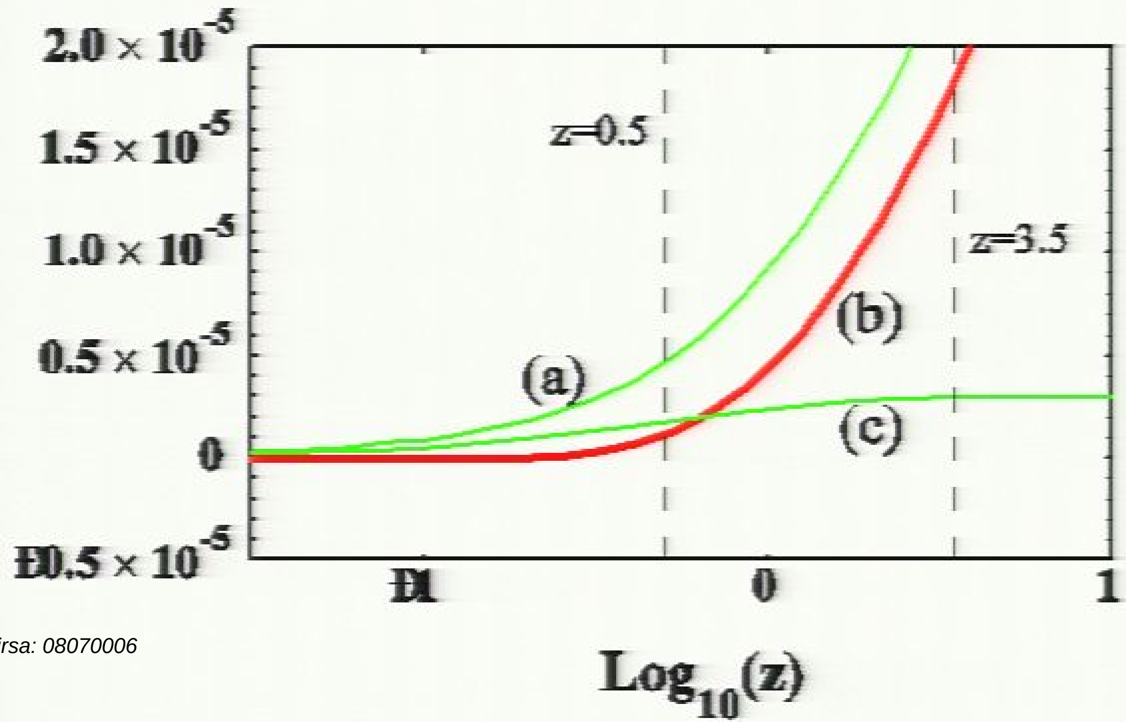
1. Drive the scalar field by coupling to Dark Matter:

$$\phi F_{\mu\nu} F_{\mu\nu} \to \phi \left(F_{\mu\nu} F_{\mu\nu} + \bar{\chi} \partial \chi \right)$$

2. Make it move by adding $V(\phi)$ and choosing $\zeta_F M_*^{-1} \sim 10^{-5} M_{pl}$

Predictivity is partially or totally lost:

(K. Olive, M.Pospelov, 2001)



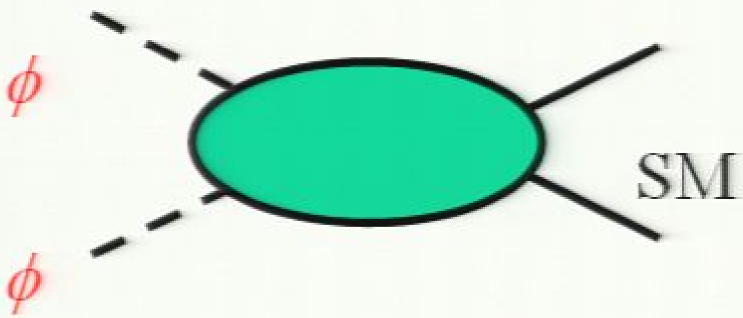
$\zeta_F = 10^{-5}$ a: $\zeta_m=1$; $\zeta_\Lambda=0$

b: $\zeta_m=1$; $\zeta_\Lambda=-2$

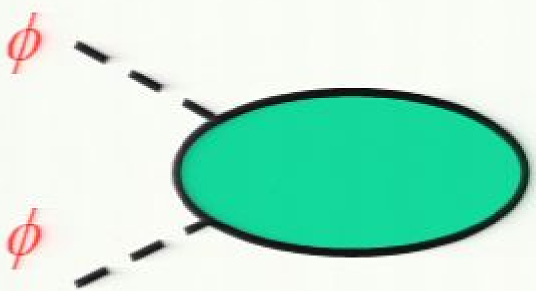
c: $\zeta_m=0$; $\zeta_\Lambda=1$

Changing α models are unnatural !!!

Bekenstein's model and spin-offs are *technically unnatural:*



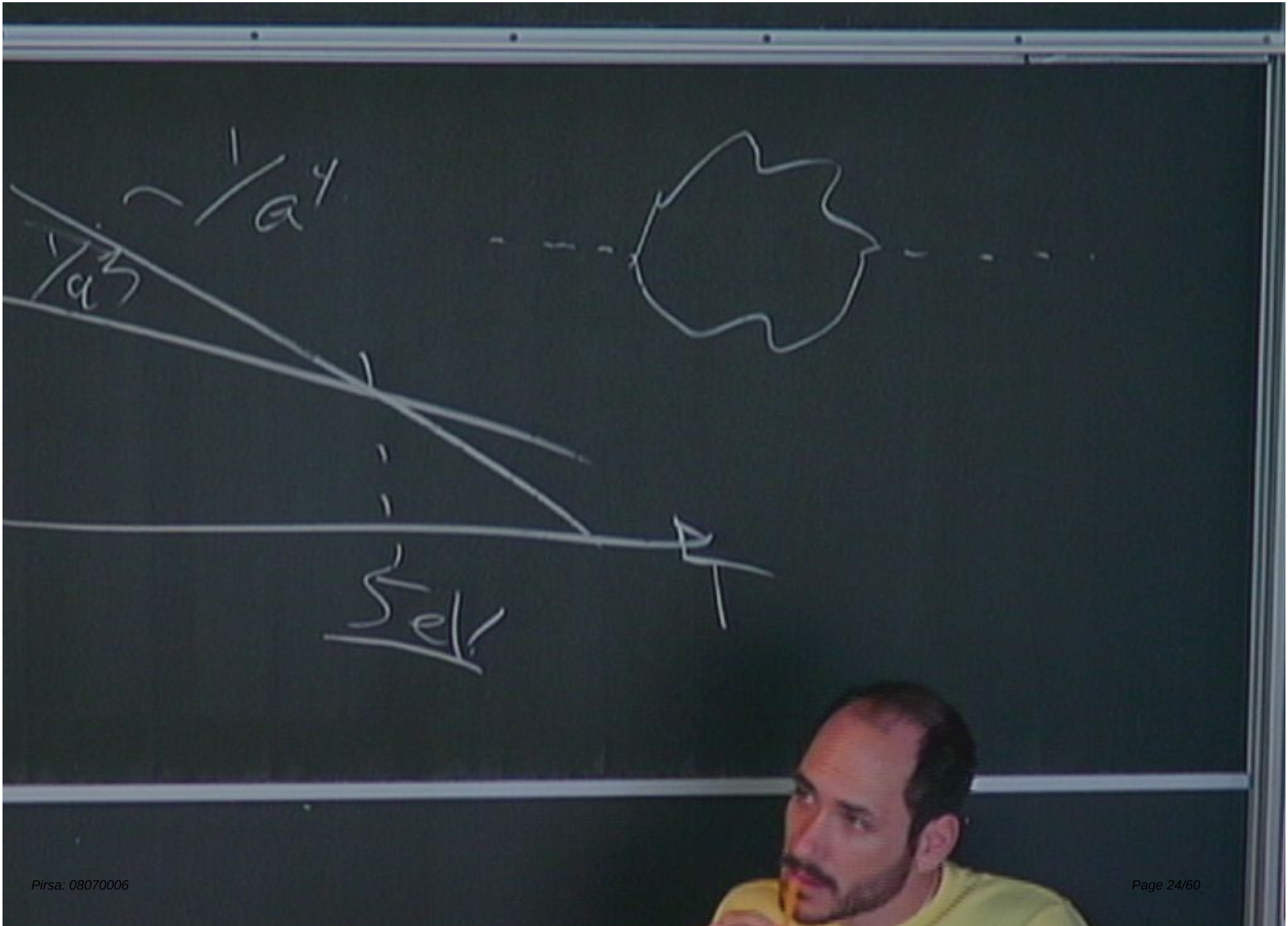
These loops are OK for any cutoff



These loops are a disaster:

$m_\phi \sim \Lambda_{UV}^2/M_* \sim 10^{-20}$ GeV

But to have cosmological evolution now one should have $m_\phi \sim 10^{-42}$ GeV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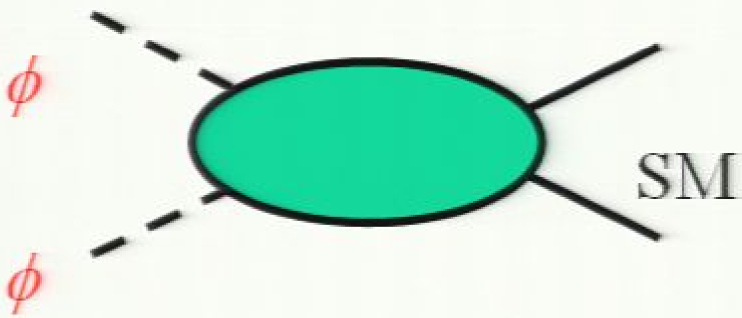

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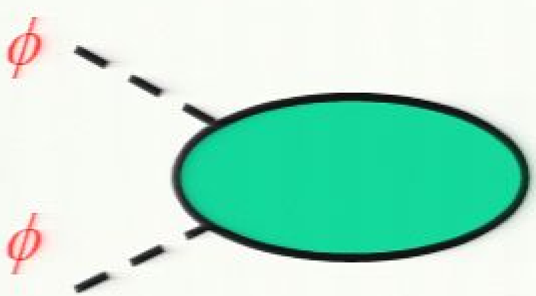

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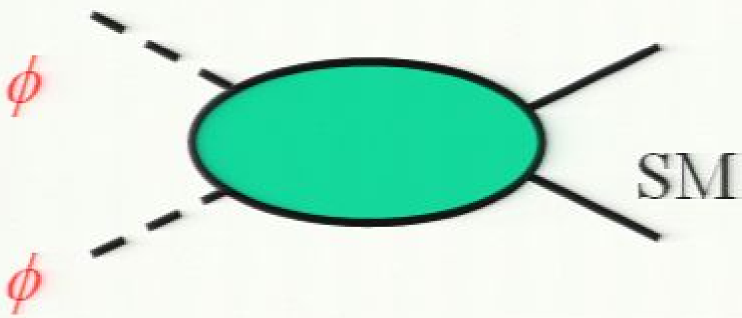

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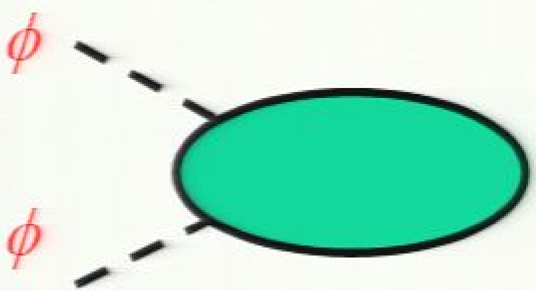

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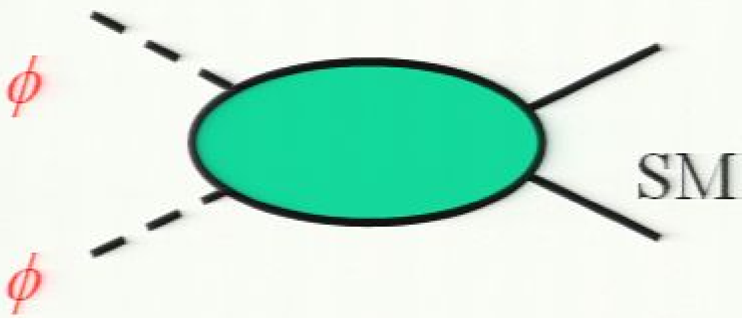

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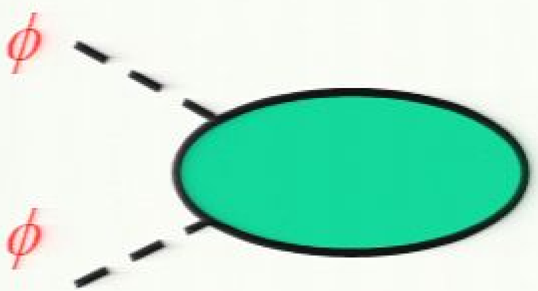

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Even “tree-level” gives contributions to the mass of ϕ

Consider ϕ that couples to QCD:

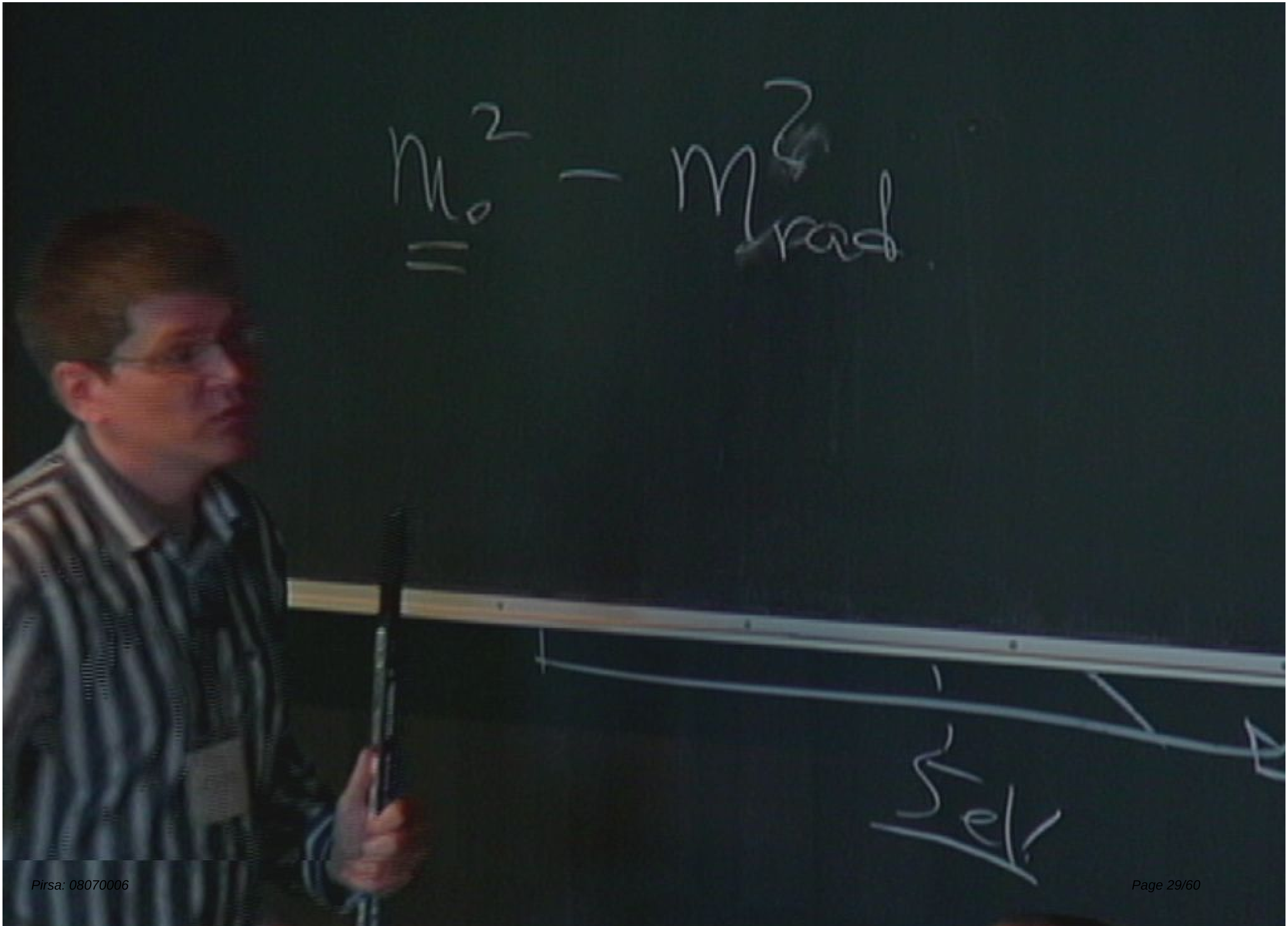
$\phi M_{pl}^{-1} G_{\mu\nu}^{2} \rightarrow \phi^2 \Lambda_{QCD}^{4}/M_{pl}^{2}$

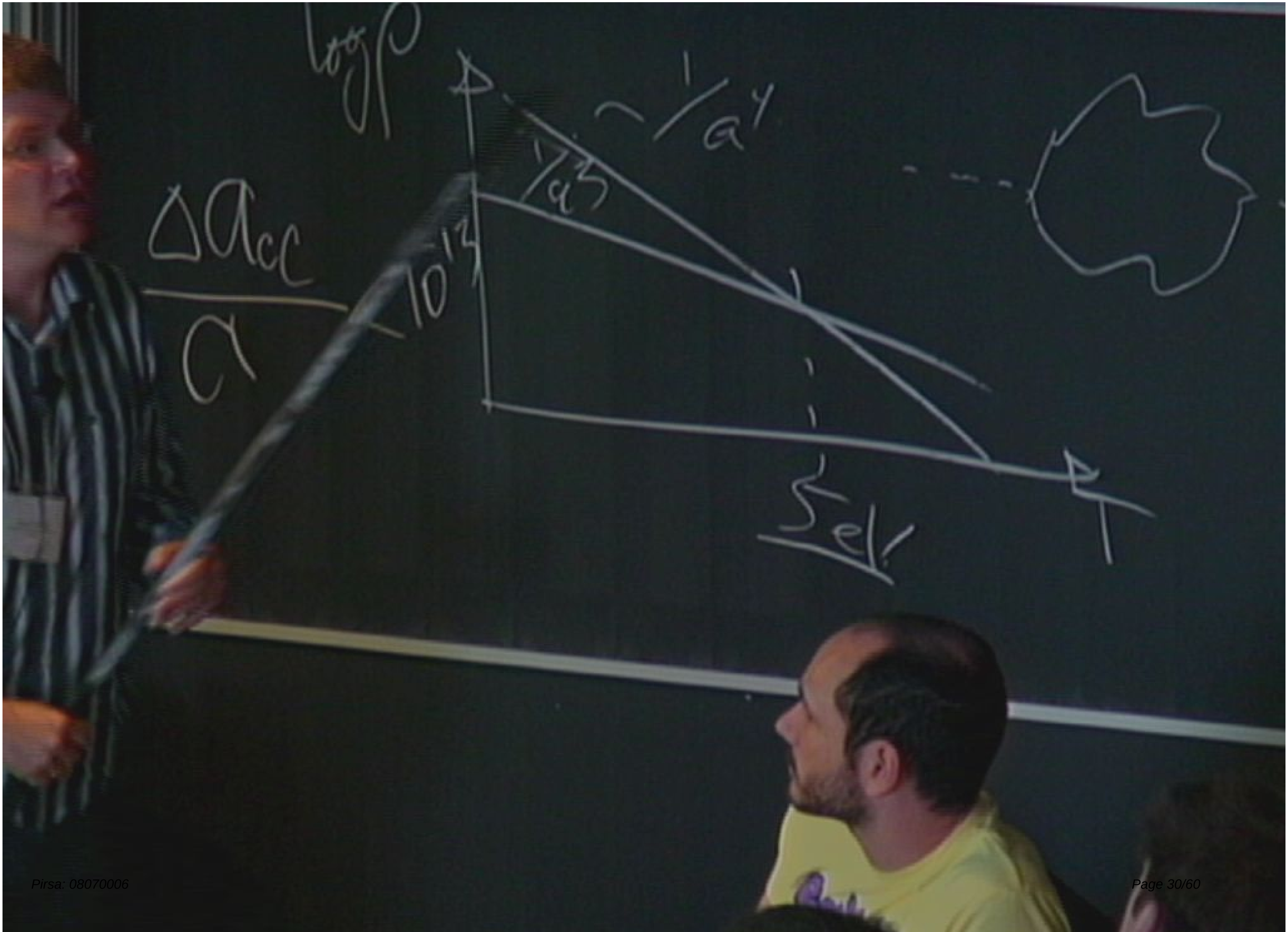
$m_{\phi}^{\text{induced}} \sim \Lambda_{\text{QCD}}^{2}/M_{\text{pl}} \sim 10^{-12}$ eV

You can say – this is rather small. No, it is HUGE, because you got to compare it with the Hubble expansion rate which is 10^{-33} eV now, and 10^{-15} eV back to the BBN times.

Easy to write down a model for $\Delta\alpha$ but try to find models of changing couplings that are technically natural - It is very hard!

[Models with pseudoscalar couplings do not suffer from this problem because interactions ~ $\partial\phi$]


$m_0^2 - m_{rad}^2$


log ρ
Δa_cc
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Sel!
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Same "concerns" with *technical* naturalness at quantum level refer to

- Interacting quintessence models
- f(R) models
- Any scalar-tensor theories including Brans-Dicke

Exception: mass varying neutrino models where loops can be protected by almost exact SUSY + $O(10^{-10})$-scale Yukawas. (Neil Weiner's talk at this meeting)

What to do:

1. Forget it and drop the subject. [pessimistic]
2. Keep hoping that solution to cosmological constant. problem would also allow light ϕ. [optimistic/naive]
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Recap:

1. It is relatively easy to write down models of changing couplings.
2. The simplest model of this kind, Bekenstein model, is *severely* constrained by the non-universality of the 5th force, and $\Delta\alpha/\alpha_{(z\sim1)} < 10^{-9}$.
3. You can "speed up" the evolution of ϕ by introducing a potential $V(\phi)$ and/or coupling to dark matter, which are far less constrained than the couplings to nucleons. Predictivity is lost, however.
4. Spatial variations are typically very small, being again inhibited after the 5th force constraints are satisfied.
5. Models are unnatural (do not believe words that $\Delta\alpha \neq 0$ between now and z=1 is predicted by string theory)

My objective for the second part of the talk:

1. Shield scalar gravity – to create "more room" for tests of $\Delta\alpha/\alpha$ etc
2. Create models that have significant spatial variations
3. Find models that may be still technically unnatural but renormalizable (UV complete)

Shielding Gravity: Damour-Polyakov and Chameleons

- There are two ideas [I am aware of] on how to circumvent prohibitive gravitational constraints on scalar-tensor theories. One has to go away from the linear regime.

1. Nordvedt-Damour-Polyakov idea:

$$M^2_{Pl}(\partial\phi)^2 + \phi O_{SM} \rightarrow M^2_{Pl}(\partial\phi)^2 + (\phi-\phi_0)^2 O_{SM}$$

Cosmological evolution pushes ϕ close to ϕ_0 so that today all spin-0 exchanges are suppressed by $(\phi_{today}-\phi_0)^2 \sim 10^{-8}$

2. "Chameleon" field idea (Khoury, Weltman).

$V(\phi) + \phi O_{SM}$ conspire to ensure that in-medium value for the scalar field mass is larger than 10^{-3} eV. May require steep potentials, e.g. const/ϕ^6 Stay for Justin's talk!

None of these models have a significant spatial change of couplings.

TeV-normalized Damour-Polyakov model

Olive, Pospelov, 2007

- **Main Idea:**

1. Make Polyakov-Damour model [in some sense] strongly coupled

$M^2_{Pl}(\partial\phi)^2 + (\phi-\phi_0)^2 O_{SM} \rightarrow \mathrm{TeV}^2(\partial\phi)^2 + (\phi-\phi_0)^2 O_{SM}$

Average O_{SM} (e.g. $m_q\psi\psi$ or $G_{\mu\nu}^2$ or $F_{\mu\nu}^2$) scales like ρ_{matter}

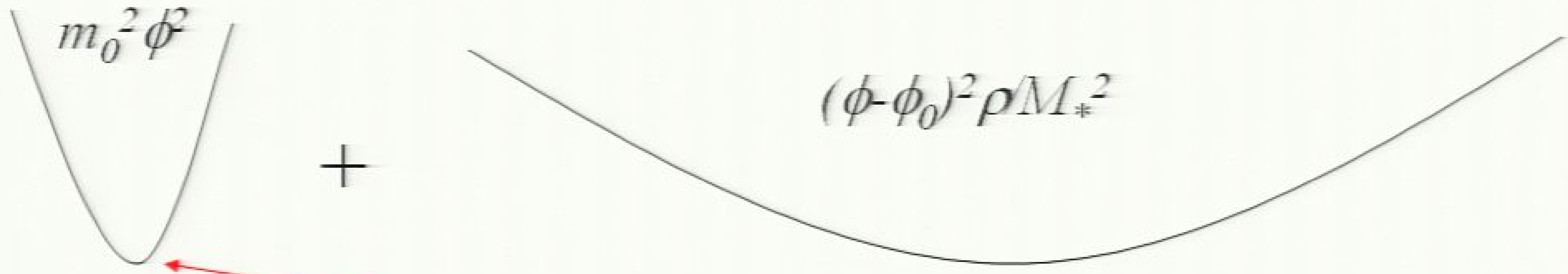
In-medium effective mass of ϕ can be large (no constraints from eq. principle)

2. *In vacuo* position of ϕ can be different, if vacuum (bare) mass is much larger than $m_\phi(\rho_{\mathrm{cosm}})$

3. Coupling constants can take different values depending where measured, at low or high ρ_{matter}.

Illustration

- Low density environments



- High density environments

Minimum shifts, range shrinks

Lagrangian of the model

$$L = L_{SM} + \frac{M_*^2}{2}\left(\partial_\mu \varphi\right)^2 - \sum \frac{\xi_O}{2}(\varphi - \varphi_m)^2 O_{SM} - V(\varphi)$$

Effective potential

$$V_{\text{eff}} \approx V(\varphi) + \frac{(\varphi - \varphi_m)^2 \rho}{2} \approx \Lambda_0 + \Lambda_2 \frac{\varphi^2}{2} + \frac{(\varphi - \varphi_m)^2 \rho}{2}$$

For an infinite extent medium the minimum is determined as

$$\varphi_{\min} = \varphi_m \frac{\rho}{\rho + \Lambda_2}, \quad m_{\text{eff}}^2 = \frac{\rho + \Lambda_2}{M_*^2},$$

while masses and Newton constant receive corrections

$$m_{N\text{eff}} = m_N \left(1 + \varphi_m^2 \frac{\Lambda_2^2}{2(\rho + \Lambda_2)^2} \right)$$

$$U(r) = -G_N \frac{m_N^2}{r} \left(1 + \exp(-r m_{\text{eff}}) \frac{2M_{\text{Pl}}^2}{M_*^2} \frac{\varphi_m^2 \Lambda_2^2}{(\rho + \Lambda_2)^2} \right)$$

In-medium range of the force

$$\lambda_{\text{eff}} = m_{\text{eff}}^{-1} = \left(\frac{\rho + \Lambda_2}{M_*^2} \right)^{-1/2} = 7 \times 10^{-3}\,\text{cm}\ \frac{M_*}{\text{TeV}} \left(\frac{10^{24}\,\text{GeV/cm}^3}{\rho} \right)^{1/2},$$

For large (terrestrial type) densities and TeV-scale couplings, the range of the force falls under a mm

We typically consider the range of the force in the atmosphere under 1 km so that $M_* < 10^9$ GeV

Environmental Dependence: $\alpha(\rho)$ and $m(\rho)$

Masses and coupling constants depend on ambient matter density. Assuming the hierarchy of densities, $\rho_d >> \Lambda_2 >> \rho_r$, we get

$$\frac{m_{Nr} - m_{Nd}}{m_N} \approx \frac{\varphi_m^2}{2}; \qquad \frac{\alpha_r - \alpha_d}{\alpha} \approx -\xi_F \frac{\varphi_m^2}{2}$$

Astrophysics constraints

Supernova emissions (and other star cooling and energy transfer mechanisms) kill e.g. axion models normalized on TeV-scale. However, relative to axion model the rate of emission scales as:

$$\Gamma_{axion} \sim T^3/f_a^{\,3}; \qquad \Gamma_\phi \sim T^5/M_*^{\,4}$$

More heavy masses in denominator. Γ_ϕ scaling with M_* is exactly like in ADD model with 2 extra dimensions

Astrophysics constraints

Considering two mechanisms of cooling:

I: $\gamma + \gamma \to \phi + \phi$

II: $N + N \to N + N + \phi + \phi$,

we get energy loss/volume/time

$$\Gamma_{2_{\gamma} \to 2_{\phi}} \simeq 0.03 \times \xi_F^2 T^9 M_*^{-4}$$

leading to a limit on M_*

$M_* \xi_F^{-1/2} > 3$ TeV

Bremsstrahlung mechanism gives a somewhat tighter bound:

$M_* > 15$ TeV

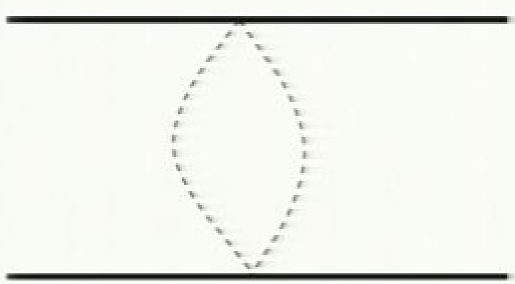
[Indeed very similar to models with 2 ADD dimensions]

Gravity Constraints

They come from two sources: double and single exchange by ϕ

Double exchange gives $1/r^3$ *potential (c.f.* ADD *again!)*

Recent U of Washington result limits $1/r^3$ interaction



such that $(4\pi)^{-1} M_*^{-2} m_N^2 < 2 \times 10^{-8}$

giving $M_* > 2$ TeV

Clock comparison/changing coupling constraints

- No Oklo bounds, no meteorite bounds on $\alpha(\rho)$!
- $\xi_F \phi_m{}^2 < 2\times10^{-5}$ from QSO data (assuming $\rho_{QSO} < \Lambda_2$)
- Comparison of clocks on orbit and on the ground gives a bound that is strongly dependent on λ_ρ.

$$\xi_F \phi^2{}_m \exp(-L_{sat}/\lambda_\rho) < 10^{-14}$$

No strong constraints for M_* below 100 TeV.

Cosmological evolution

1. BBN constraints do not pose any danger. Field ϕ decouples from thermal bath earlier than neutrinos, and therefore $N_{eff}<0.5$
2. Cosmological history of ϕ: $\phi=\phi_m \rightarrow \phi=0$

   at scales where mass becomes comparable to Hubble rate

   (typically, $z>10^3$)
3. Energy transfer in this transition is very small ($< \phi_m{}^2\Lambda_2$) and does not lead to any observable change.
4. There are no oscillations around minima – they are redshifted too fast
5. If $\Lambda_2 \sim \rho_{closure}$ then the evolution of ϕ may still be occurring today towards $\phi=0$ cosmologically, while on Earth everything is frozen to $\phi = \phi_m$ (c.f. Barrow and Mota, 2003).

Recreating $\alpha(\rho_{\text{cosmo}})$ in the Lab

Having clocks in vacuum chamber and outside may allow to measure the environmental shifts in frequency
For a spherical evacuated chamber of radius R, we have

$$\frac{\alpha(r=R)-\alpha(r=0)}{\alpha} \approx \frac{\xi_F \varphi_m^2}{2} \begin{cases} \dfrac{\Lambda_2^2 R^4}{36 M_*^4} & \text{for} \quad R/\lambda_{vac} << 1 \\ 1 \quad \text{for} & R/\lambda_{vac} >> 1, \end{cases}$$

which after substituting for gravitational constraints takes the following form

$$\frac{\alpha(r=R)-\alpha(r=0)}{\alpha} \approx \frac{\xi_F \times \text{TeV}^2}{M_*^2} \begin{cases} 10^{-16}(R/1\text{m})^4 & \text{for} \quad R/\lambda_{vac} << 1 \\ 10^{-15} & \text{for} \quad R/\lambda_{vac} >> 1, \end{cases}$$

This is difficult but not impossible (compare with $O(10^{-25})$ effect in Bekenstein model).

Possibility for new tests inside our Galaxy

- $\alpha(\rho)$ idea can be tested by measuring $\alpha(\rho_{ISM})$
- There is no specific benefits for going after high z.
- Tests within our Galaxy can be done in absorption clouds and use very high quality lines
- The access to higher Z (atomic number) is possible, which increases sensitivity to α
- It has been done this year, and we shall hear about it from M. Kozlov.

Infrared modification of α – main idea

(partly explained in Copeland, Nunes, Pospelov, 2003)

I often hear "if α changes then surely all other constants change as well". This is incorrect.

Let us construct a model that is renormalizable. ($\phi F_{\mu\nu}^2$ model is not)

$\mathcal{L} = \mathcal{L}_{SM} + \kappa F_{\mu\nu} V_{\mu\nu} - 1/4\, V_{\mu\nu}^2 + m_V^2 V_\mu^2 + \mathcal{L}$(Higgs of the V-sector)

This is one of the most minimal extensions of the SM – fully renormalizable.

Such Lagrangian creates V-photon mixing and results in the anomalous dispersion for a an off-shell phton, e.g. modifies Coulomb interaction

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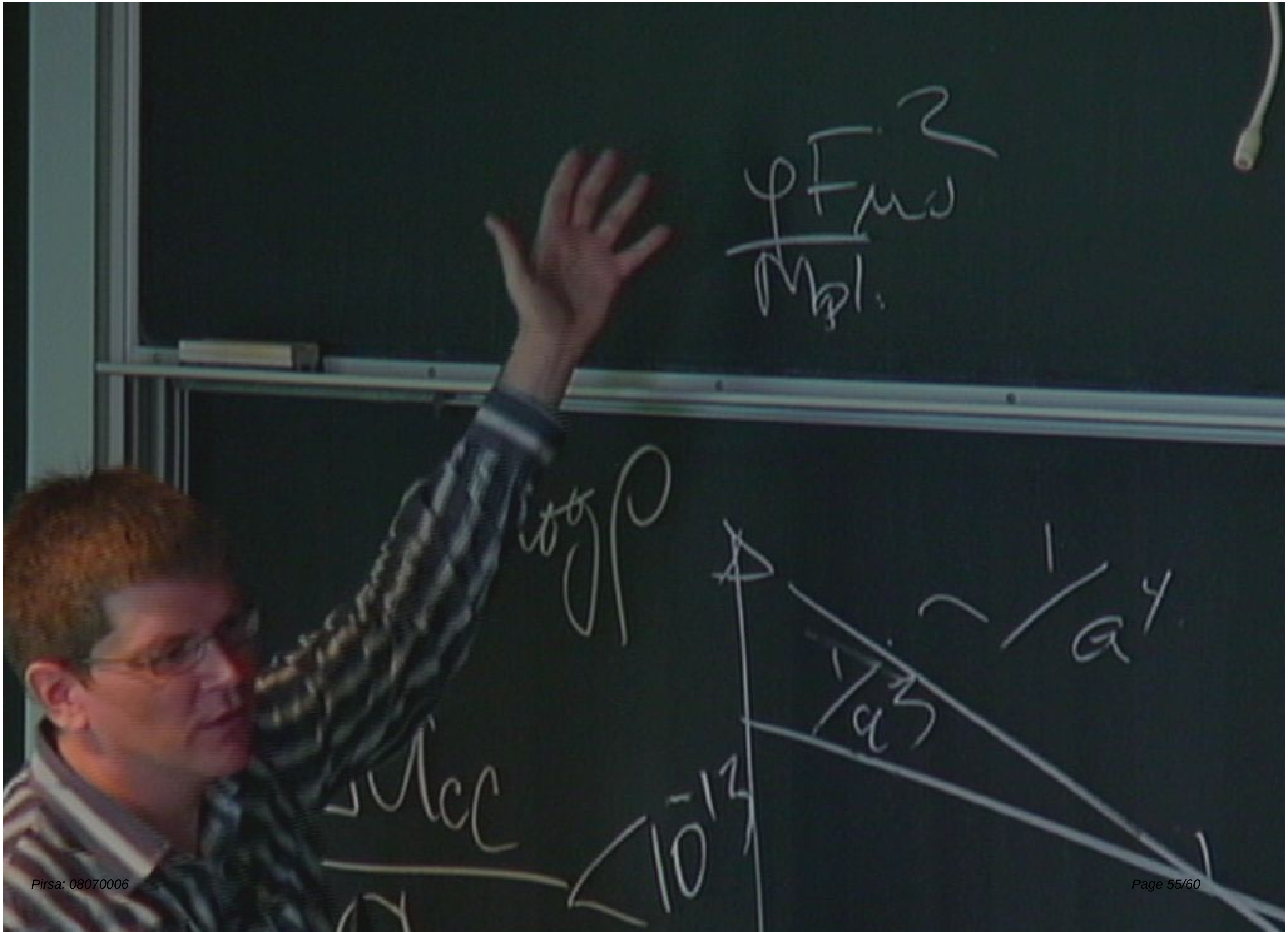
log ρ
~ 1/a^4
1/a^3
10^-13

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Short and long distance behaviour

$V_{Coulomb}(r) = \alpha\, [1/r \;+ \kappa^2 \exp(-\, m_V\, r\,) / r\,]$

For all physics with $q >> m_V$ we have $V = \alpha\,(1+\kappa^2) / r$

For all physics with $q << m_V$ we have $V = \alpha / r$

Suppose that m_V is on the order of changes in space/time due to some dynamics in the Higgs′ sector. Systems with size $L \sim m_V^{-1}$ will know about it, while small objects would not.

If m_V, for example, ~ inverse atomic size then its change can mainifest itself in atomic physics but will not lead to any significant changes in gravitational interactions, Oklo effect etc.

Problem of naturallness is relegated to the Higgs′ sector.

This model deserves further studies.

Conclusions

- **Models of "changing couplings" provide common framework to study many different phenomena.**
- **All models built so far have deficiencies like (un)naturallness.**
- **To enable sizable dependence $\alpha(\rho)$, and consequently allowing large spatial variations, we propose a strongly coupled variant of Polyakov-Damour model.**
- **Astrophysical and gravitational tests have sensitivity to $M_* \sim 10$ TeV but not beyond that.**
- **High-precision tests of $\alpha(\rho)$ in a laboratory, and within our Galaxy are possible and quite warranted.**