Title: Probing Cosmic Acceleration

Date: Sep 20, 2016 11:00 AM

URL: http://pirsa.org/16090036

Abstract: <p>If we want a mechanism for the current cosmic expansion that is alternative to (and possibly more â€œnaturalâ€• than) the cosmological constant, there exist intriguing proposals within the dark energy and modified gravity realm.</p>

<p>First, I will briefly review the status of one of the most promising ideas, massive gravity: cosmological solutions, some formal aspects and recent developments. Then, I will present recent work aimed at constraining such models with LSS probes. </p>

Probing Cosmic Acceleration

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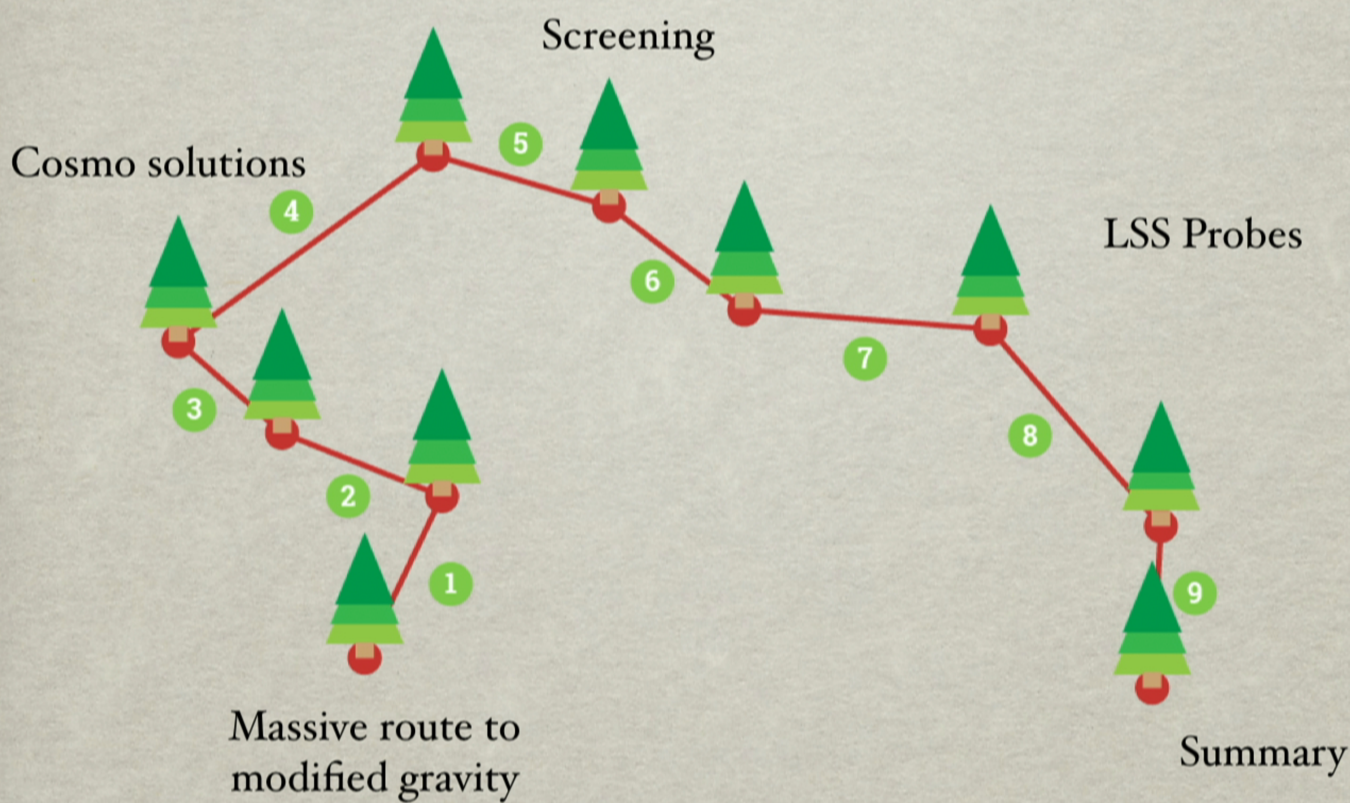
September 20th, 2016, Perimeter Institute

Outline


Screening
Cosmo solutions
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Massive route to modified gravity
Summary

Motivations

Why modified gravity ? Technically natural mechanism for cosmic acceleration

Why not Λ then ?

- Old: "understand why the vacuum energy is so small" ✗

  Weinberg, arXiv:astro-ph/0005265

- New: "why it is comparable to the present mass density" ✓

Instrument of Choice

Non-linear massive gravity (dRGT) + extensions

$\Uparrow$

Ghost-free, Lorentz-invariant 4-d theory of a ~~massless~~ massive spin 2 field

Linearly

Fierz and Pauli (1939)

$$\underbrace{-\frac{1}{4}h^{\mu\nu}\hat{\mathcal{E}}^{\alpha\beta}_{\mu\nu}h_{\alpha\beta}}_{\mathrm{E-H}} \quad \underbrace{-\frac{1}{8}m^2\left(h^2_{\mu\nu}-h^2\right)}_{\mathrm{F-P}}$$; 5 dof of healthy massive spin 2

↳ breaks diff invariance: $h_{\mu\nu} \to h_{\mu\nu} + \partial_{(\mu}\xi_{\nu)}$

vDVZ discontinuity

$$\mathrm{Theory}_{m\to 0} \neq \mathrm{Theory}_{m=0}$$

At odds w/ observations: angle for the bending of light at impact parameter b off by 25% w.r.t. GR

Non-linearities better play a crucial role,  they do

Non Linearly

Vainshtein effect: non-linearities screen helicity-0 mode in the presence of matter

$$r_V = \left(\frac{M}{M_P^2 m^2}\right)^{1/3}$$

Most of what is verified analytically is static and spherical

screening in an area within rv, where GR is recovered ✓ linearized theory good outside

Not easy

$$\mathcal{L}^{n-l}_{\mathrm{F-P}} = -m^2 M_{\mathrm{Pl}}^2 \sqrt{-g}\left([(\mathbb{I}-\mathbb{X})^2] - [\mathbb{I}-\mathbb{X}]^2\right)$$

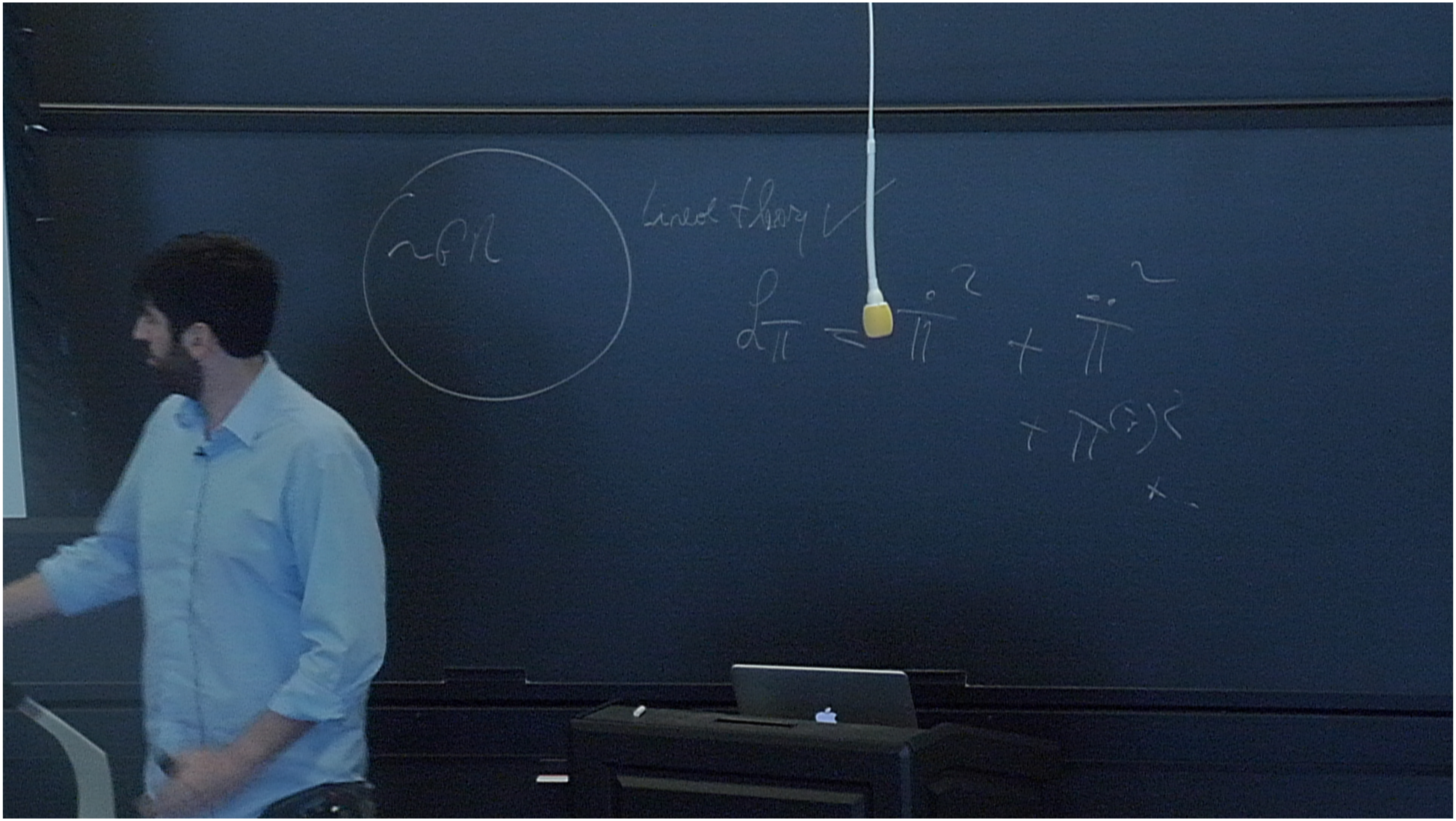
where $\mathbb{X}^\mu_\nu = g^{\mu\alpha}\tilde{f}_{\alpha\nu}$

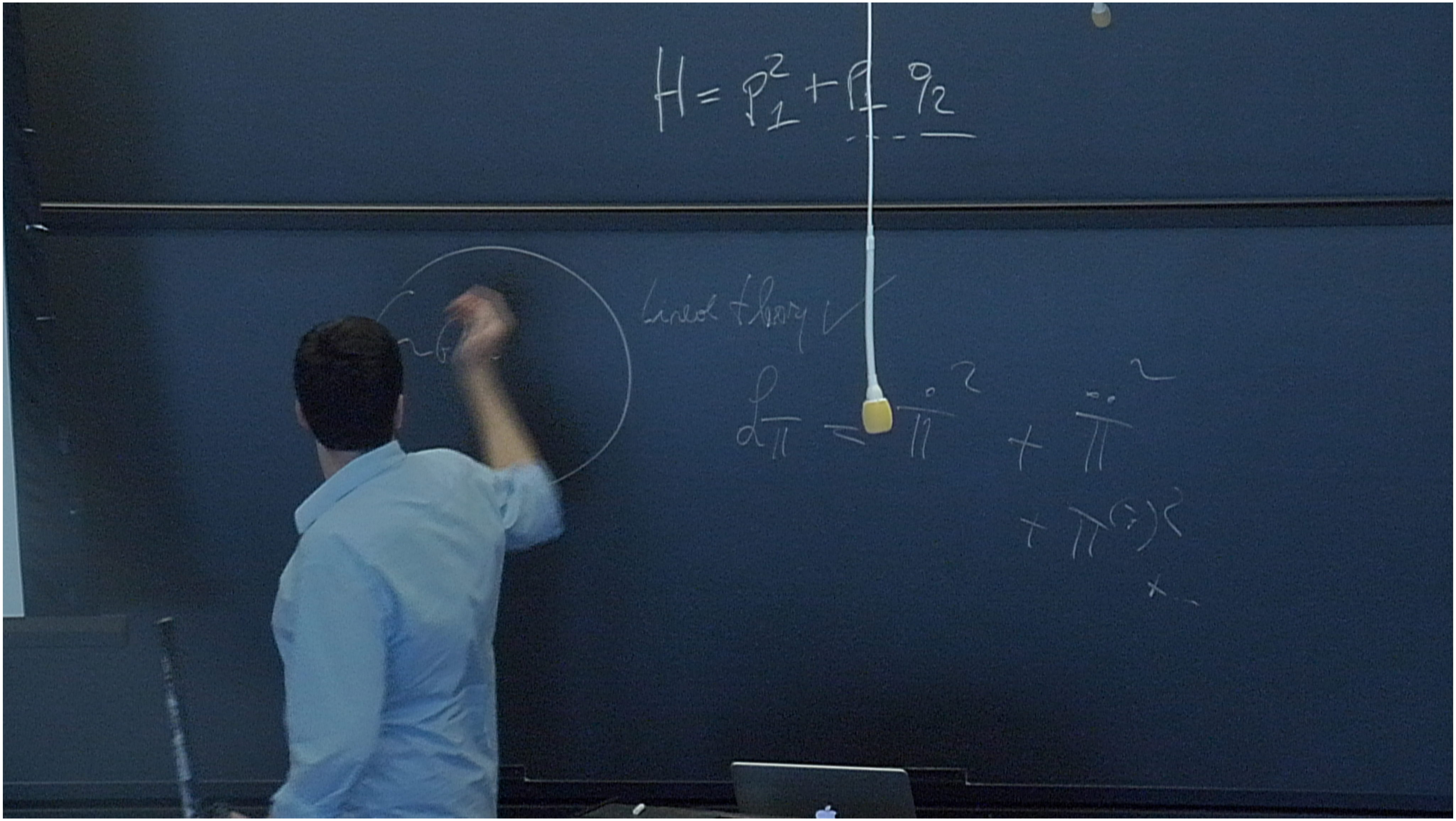
helicity-0 mode π

$$\mathbb{X}^\mu_\nu = \delta^\mu_\nu - \frac{2}{M_{\mathrm{Pl}} m^2}\partial^\mu\partial_\nu\pi + \frac{1}{M_{\mathrm{Pl}}^2 m^4}\partial^\mu\partial_\alpha\pi\partial^\alpha\partial_\nu\pi$$

generic non-linear interaction will carry an Ostrogradski ghost


Linear theory




H = p1² + p1 q2
linear theory

Non Linear with Special Structure, *dRGT*

de Rham, Gabadadze (2010)
de Rham, Gabadadze, Tolley (2010)

$$S_{\rm mGR} = \frac{M_{\rm Pl}}{2} \int d^4x \sqrt{-g} \left(R[g] + \frac{m^2}{2} \sum_{n=0}^{4} \alpha_n \mathcal{L}_n[\mathcal{K}[g,f]] \right)$$

where $\mathcal{K}^\mu_\nu = \delta^\mu_\nu - \sqrt{g^{\mu\alpha} f_{\alpha\nu}}$ and

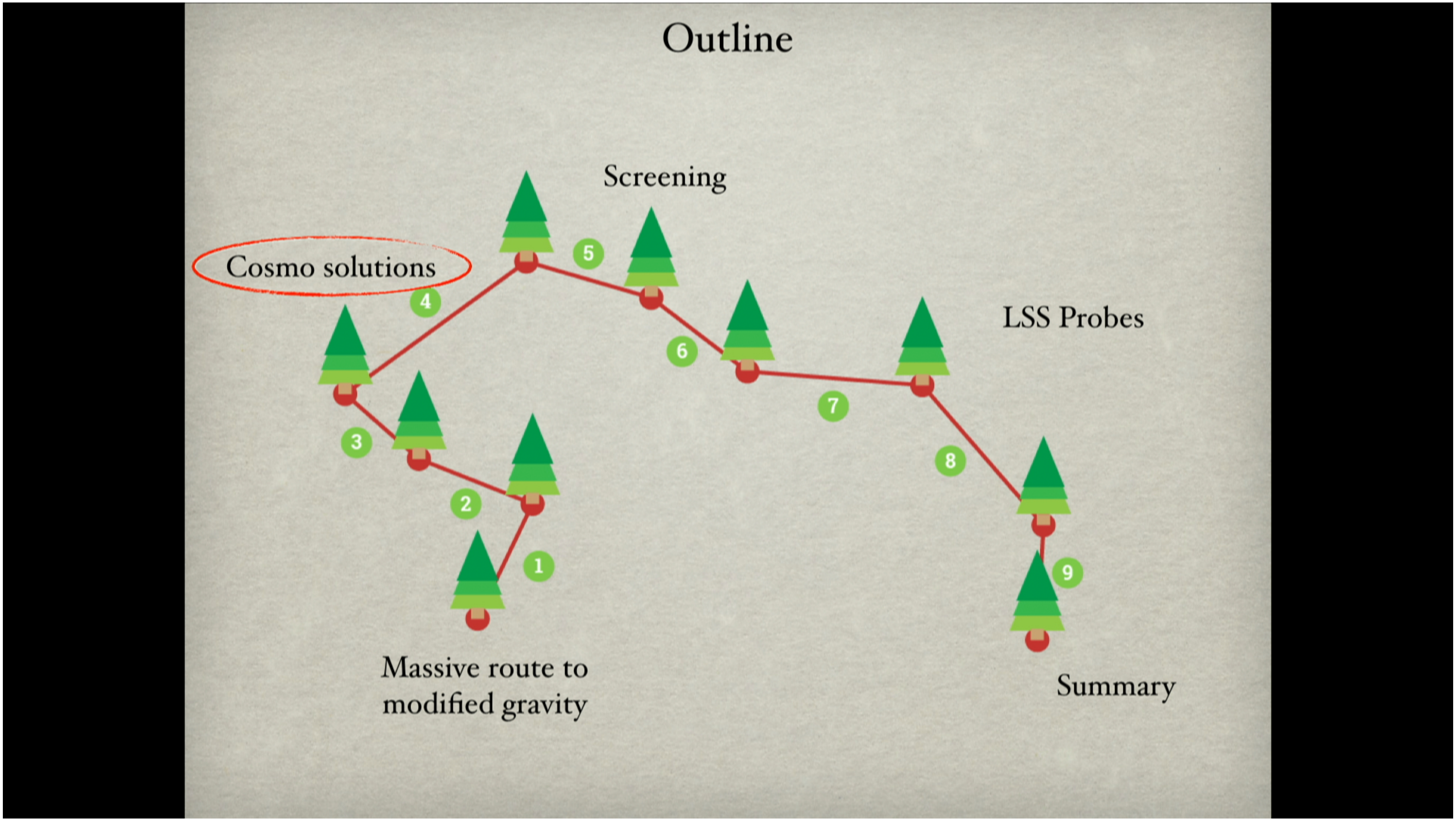
$$\begin{aligned}
\mathcal{L}_0[\mathcal{K}] &= 4! \\
\mathcal{L}_1[\mathcal{K}] &= 3!\,[\mathcal{K}] \\
\mathcal{L}_2[\mathcal{K}] &= 2!([\mathcal{K}]^2 - [\mathcal{K}^2]) \\
\mathcal{L}_3[\mathcal{K}] &= ([\mathcal{K}]^3 - 3[\mathcal{K}][\mathcal{K}^2] + 2[\mathcal{K}^3]) \\
\mathcal{L}_4[\mathcal{K}] &= ([\mathcal{K}]^4 - 6[\mathcal{K}]^2[\mathcal{K}^2] + 3[\mathcal{K}^2]^2 + 8[\mathcal{K}][\mathcal{K}^3] - 6[\mathcal{K}^4])
\end{aligned}$$

Absence of ghosts verified in countless ways at full non-linear level

Hassan, Rosen (2011,2011)

Extensions, e.g. bigravity = massive gravity + H-E for metric f; 7 healthy dof

Evidence that structure of the potential is preserved under quantum corrections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Is it empty?

Is is stable?

Is is observationally viable?

No FRW solutions in dRGT if "f" Minkowski*

D'Amico, de Rham, Dubovsky, Gabadadze, Pirtskhalava, Tolley

Yes, we can live with inhomogeneities

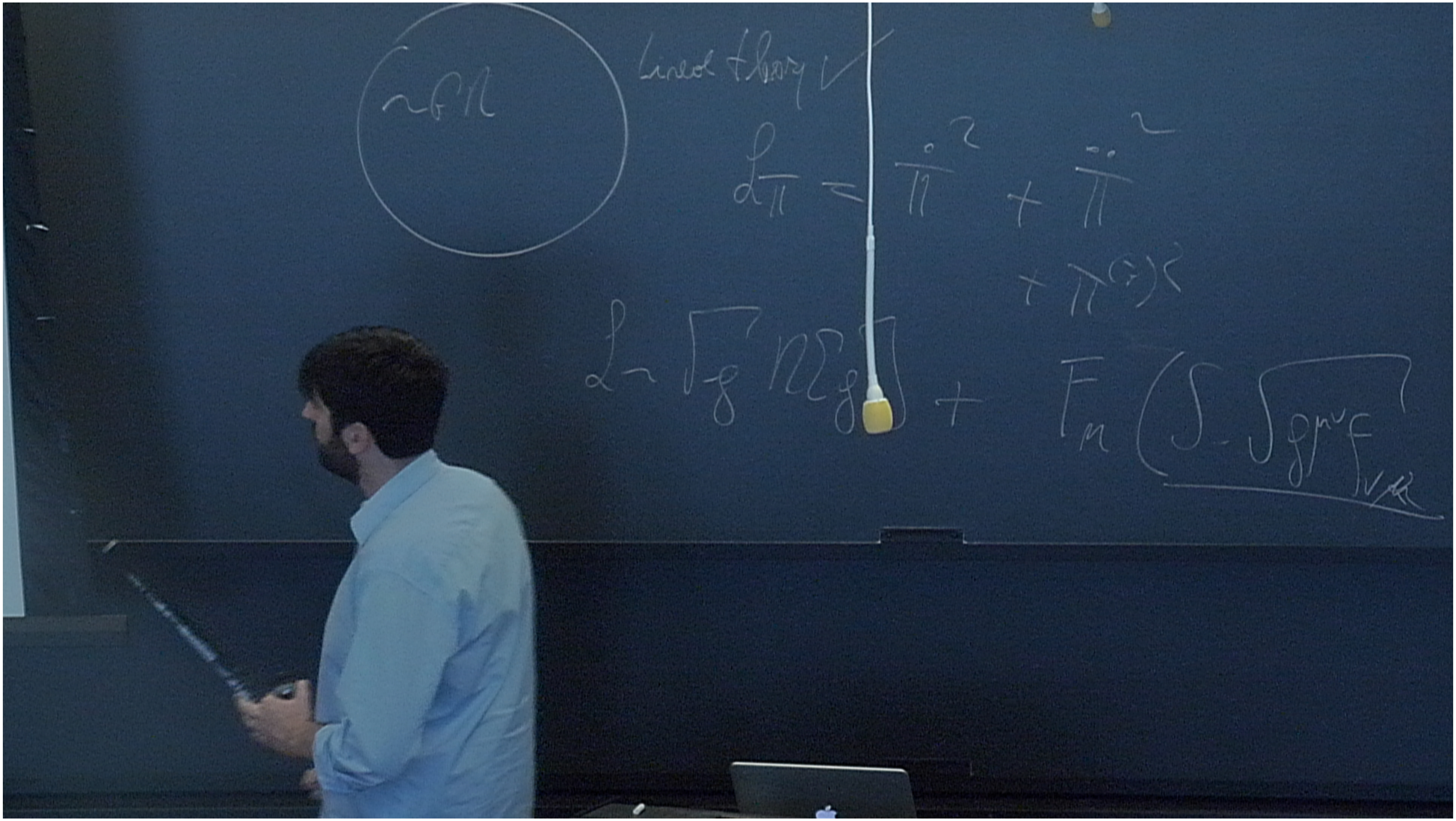
Vainshtein guarantees inhomogeneities unobservable before late times

Inhomogenities only appear on scale set by inverse graviton mass

Volkov; Koyama; Gumrukcuoglu et al; Gratia, Hu, Wyman; Kobayashi et al; DeFelice et al; Tasinato et al; Not updated, many many more!!

*natural for interacting massive spin-2 representation of Poincare` group

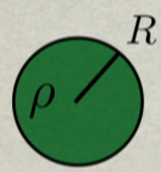
INHOMOGENEOUS SOLS



Inhomogeneities carried by Stueckelbergs fields

$$M_P^2\, m^2\, \mathcal{L}(\mathcal{K})$$

$$\mathcal{K}^\mu_\nu = \delta^\mu_\nu - \sqrt{g^{\mu\alpha} f_{\alpha\nu}} \qquad\qquad f_{\mu\nu} = \partial_\mu \phi^a \partial_\nu \phi^b \bar{f}_{ab}$$



$$r_* = \left(\frac{\rho}{3 M_P^2 m^2} \right)^{1/3} R$$

$\rho_{\rm co}$

the Universe filled with pressure-less dust of density ρ

2 regimes

$$\rho > \rho_{co} \ ; \qquad \rho < \rho_{co} \ ;$$

$\rho > \rho_{co}$ In a Hubble patch $1/H \sim (\rho/3M_P^2)^{1/2}$

inside the Vainshtein and therefore small corrections, $\propto \left(\frac{m}{H}\right)^k$

$\rho < \rho_{co}$ vDVZ regime, far from GR

} matching...

INHOMOGENEOUS SOLS

(Slightly) Modify Assumptions to allow for FRW

- Open Universe solutions (Gumrukcuoglu et al, Vakili et al) unstable
- Make reference metric dS (MF, Tolley)… 2 slides away
- Generalized massive gravity, but keep the 5 d.o.f. (de Rham, MF, Tolley)… later

Bigravity: Reference metric dynamical

Significant modifications (not just) to allow for FRW

- Lorentz violating massive gravity
- Quasi-dilaton massive gravity + generalizations
- Varying Mass
- Multi-vierbeins
- Extended massive gravity
- Nonlocal massive gravity

Solutions with metric "f" as dS or FRW

MF, Tolley

Add matter content to gauge model independence

$$\mathcal{L}_M \sim \int d^4x\sqrt{-g}\Big[\frac{1}{2}(\partial\phi)^2 + V(\phi)\Big]$$

Simple algorithm

Existence of the solution

Check stability of the theory

Early + late-time dynamics from Friedman equation

CHANGE F

Stability bound

$$H = \alpha\, p^2 + \beta\, q^2 + \gamma(\nabla q)^2 + \ldots$$

<u>coefficient of kinetic term</u> > 0

tachyon inst.

gradient inst.

Quickest route to the Higuchi/unitarity bound in dS:

"In the the linear (massive) theory there exist a unitary spin 2 representation of the dS group <u>iff</u>:"

	$m^2 = 0$	G.R.
	$m^2 = 2H^2$	Partially massless theory
Higuchi bound in massive gravity →	$m^2 > 2H^2$	Massive

CHANGE F

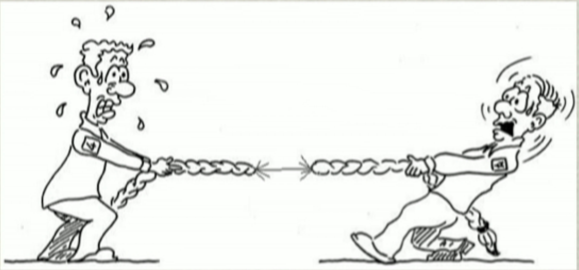
Bound from Observations

Before Dark Energy epoch sets in, G.R. good description:

$$3H^2 = \Lambda + 3m^2 \times \Theta(1) + \ldots$$

$$m^2 \lesssim H^2$$

combining Stability and Observations then:



want our theory to be stable

$$m^2 > 2H^2$$

GR over many cosmo epochs

$$m^2 \lesssim H^2$$

CHANGE F

Generalized Higuchi:

$$\tilde{m}^2(H) = m^2\frac{H}{H_f}\left((3+3\alpha_3+\alpha_4) - 2(1+2\alpha_3+\alpha_4)\frac{H}{H_f} + (\alpha_3+\alpha_4)\frac{H^2}{H_f^2}\right) \geq 2H^2$$

N.B. independent on precise form of matter

Friedman Side:

$$m^2\left(\frac{2}{3}(-6-4\alpha_3-\alpha_4) + 2\left(\frac{H}{H_f}\right)(3+3\alpha_3+\alpha_4) - 2\left(\frac{H}{H_f}\right)^2(1+2\alpha_3+\alpha_4) + \frac{2}{3}\left(\frac{H}{H_f}\right)^3(\alpha_3+\alpha_4)\right) \ll 2H^2$$

Combined:

$$\frac{\mathrm{poly}_1^{(k)}(z)}{\mathrm{poly}_2^{(k)}(z)} \gg 1$$

Hard to satisfy even using α_3, α_4

Impossible when we account $H = H(t)$

CHANGE F

What now? Go bigravity !

$$\mathcal{L} = \frac{1}{2}\sqrt{-g}\left[M_P^2\, R(g) - m^2 \sum_{n=0}^{4} \beta_n \mathcal{U}_n\left(g^{-1}f\right)\right] + \frac{1}{2}\sqrt{-f} M_f^2\, R(f) + \mathcal{L}_M$$

$$g_{\mu\nu} \leftrightarrow f_{\mu\nu},\;\; M_P \leftrightarrow M_f,\;\; \beta_n \leftrightarrow \beta_{4-n} \;\; {}^{*}$$

This fact must be reflected on the bound itself

Crucial for Galileon Duality

BIGRAVITY

*Matter breaks this

Stability Bound in Bigravity

MF, Tolley

Soon in a more symmetric form

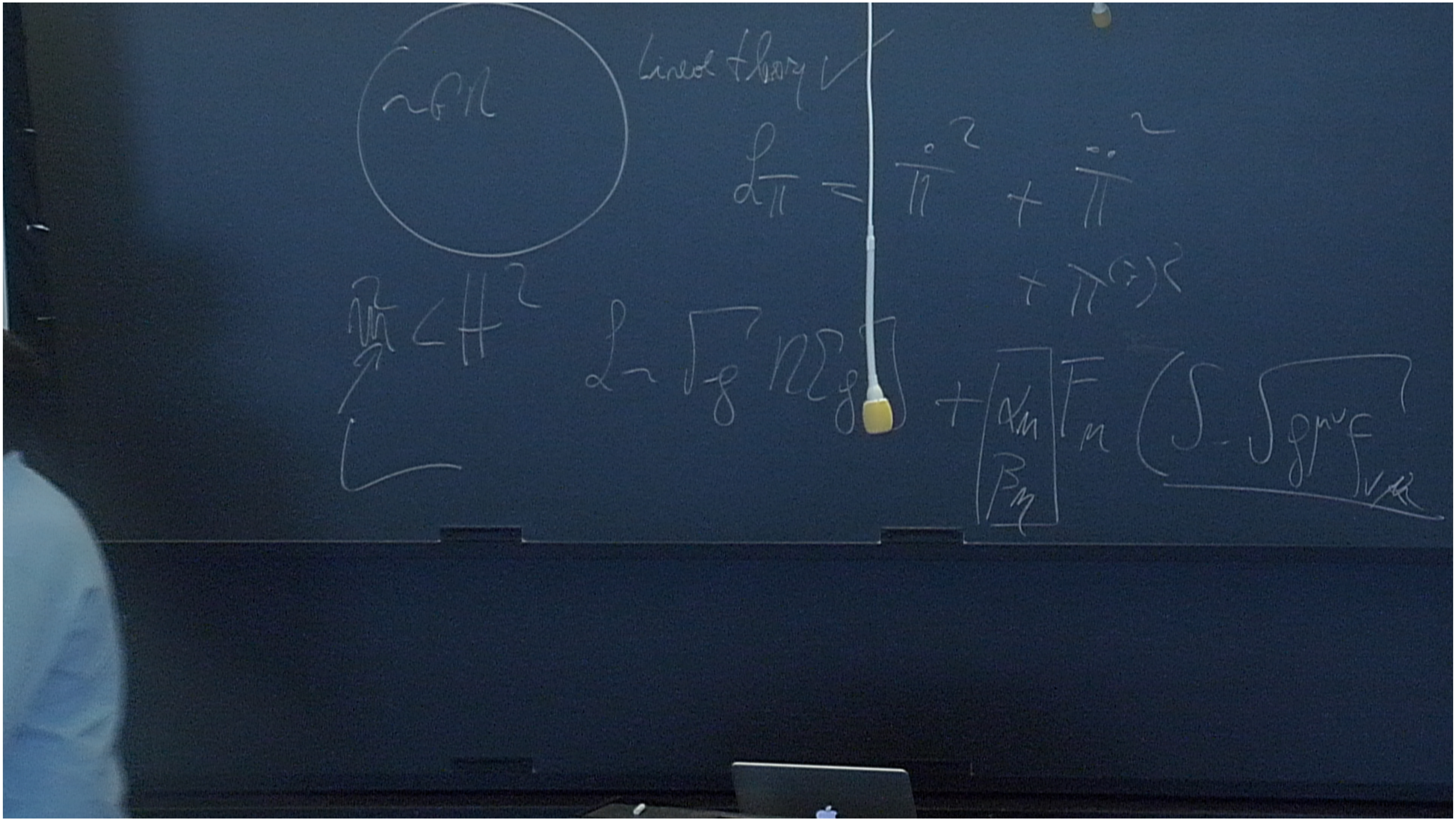
Stability bound

$$\tilde{m}^2\left[1+\left(\frac{H_f/M_f}{H/M_P}\right)^2\right]\geq 2H^2$$

- Minisuperspace action ✓
- Decoupling limit ✓
- PM check ✓
- Symmetric ✓

Recover Massive gravity bound in the limit $M_f\to\infty,\ M_P, H_f$ finite.

BIGRAVITY


Linear theory

Not possible before: $\boxed{\dfrac{H_f}{M_f} \gg \dfrac{H}{M_P}}$ not directly invoking m

Friedman side

$$H^2 = \frac{1}{3M_P^2}\left[\rho(a) + \sum_{n=0}^{3} \frac{3m^2\beta_n}{(3-n)!n!}\left(\frac{H}{H_f}\right)^n\right] \quad ; \quad H_f^2 = \frac{1}{3M_f^2}\left[\sum_{n=0}^{3} \frac{3\beta_{n+1}}{(3-n)!n!}\left(\frac{H}{H_f}\right)^{(n-3)}\right]$$

$m^2 \times \Theta(1) \ll H^2$ it's the <u>only direct requirement</u> on m, but now:

In the $\frac{H_f}{M_f} \gg \frac{H}{M_P}$ region with $\beta_1 \neq 0$ solve for $\tilde{m}^2$, Hf, bound reads:

$$3H^2 > 2H^2 \checkmark$$

The (most pressing) stability vs observations tension is resolved in bigravity !

BIGRAVITY

Stable Self-accelerating Solution

Akrami, Koivisto, Sandstad (2012,2013)

Set: $\beta_2 = 0 = \beta_3;\ \beta_1 = 2M_P^2$

$$H^2 = \frac{1}{6M_P^2}\left(\rho(a) + \sqrt{\rho(a)^2 + \frac{12\,m^4 M_P^6}{M_f^2}}\right)$$

Model	B_0	B_1	B_2	B_3	B_4	Ω_m	χ^2_{min}	p-value	log-evidence
ΛCDM	free	0	0	0	0	free	546.54	0.8709	-278.50
(B_1, Ω_m^0)	0	free	0	0	0	free	551.60	0.8355	-281.73

Observationally viable (?) ! Small part of the whole table

Stability bound? It reduces to

$$\left(\frac{1}{M_P^2} + \frac{12M_f^2}{m^4\beta_1^2}H^4\right) > 0 \quad \checkmark$$

Stable as well.

BIGRAVITY

Further work on Cosmo Solutions

Our focus has been on unitarity (Higuchi), but ought to check gradient instability

$$H = \alpha p^2 + \beta q^2 + \gamma(\nabla q)^2$$

Comelli et al (2012); Konnig et al; Comelli et al #2

Non-linearities via Vainshtein? (in progress...)

Viable (in a reduced parameter space region) bigravity model put forward by

especially useful in the "low energy regime"

De Felice et al (2014)
De Felice et al (2013)

$$h_{ij} T^{ij} = \left(H^{+}_{ij} + C_{(\mathrm{r})} H^{-}_{ij}\right) T^{ij}$$

massive(massless) tensors decouple and simplify analysis of e.g. gravitational waves

MF, Ribeiro

BIGRAVITY

Generalized Massive Gravity

De Rham, MF, Tolley (2014)

Let the $\alpha_n(\beta_n)$ now depend on the Stueckelbergs fields as

$$S = \frac{M_{Pl}^2}{2}\int d^4x\sqrt{-g}\left[R[g] + \frac{m^2}{2}\sum_{n=0}^{4}\tilde{\alpha}_n(\tilde{\phi}^a\tilde{\phi}_a)\,\mathcal{U}_n[\mathcal{K}]\right] + \mathcal{L}_{\rm matter}[g,\psi^{(i)}]$$

In pure mGR, isometry group of the reference metric is Poincare'

$$f_{\mu\nu} = \partial_\mu\phi^a\partial_\nu\phi^b\eta_{ab}$$

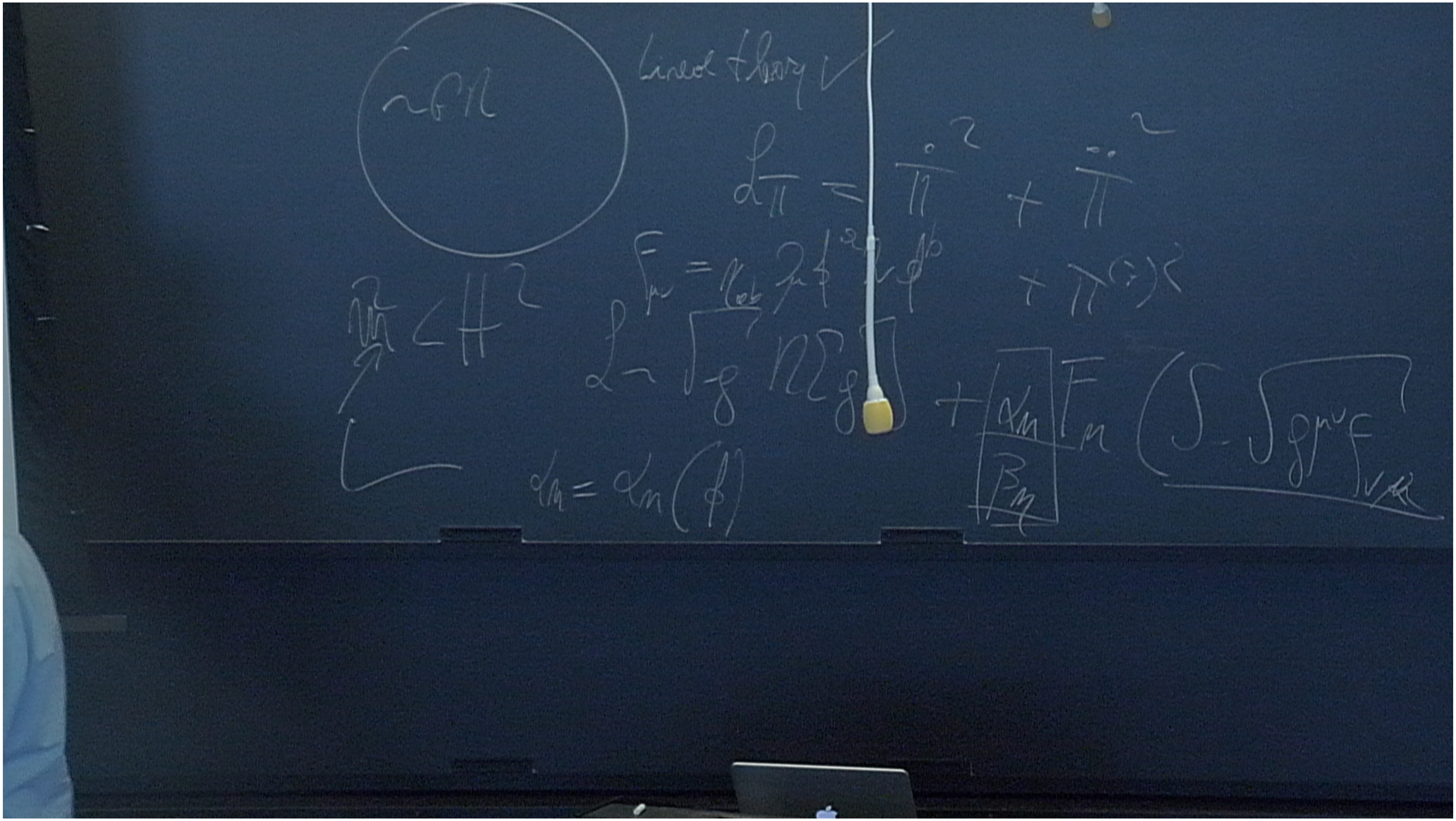
Now:

- keep: Lorentz ✓
- give up: Translations ✗

Gen. mGR theory still has 5 d.o.f. proven ghost-free

De Rham, Keltner, Tolley (2014)

GMG


Linear theory

①

New Solutions

$$m^2 H \left[\frac{3}{2}\beta_1 a^2 + \beta_2 a + \frac{1}{4}\beta_3\right] = \frac{m^2}{2a}\left[4\beta_0' a^3 + 3\beta_1' a^2 + \beta_2' a + \frac{1}{6}\beta_3'\right]$$

zero in pure massive gravity, hence
lack of solution for f Minkowski

②

Hints of self-acceleration

$$3M_{\rm PL}^2 H^2 = \rho + \frac{m^3 M_{\rm PL}^2}{2H}\left[\frac{\left(4\bar\beta_{0,1} + 3\bar\beta_{1,1} a^{-1}\right)^2}{\bar\beta_{1,1}}\right] - 2m^2 M_{\rm PL}^2 \frac{\bar\beta_{0,1}\bar\beta_2}{a\bar\beta_{1,1}}$$

$(\bar\beta_{0,1}\,,\ \bar\beta_{1,1}\,,\ \bar\beta_2 \neq 0 = \forall_{\rm else})$

③

Stability

- Higuchi bound
- Gradient instability
- ✓ Coupling with matter
- Vector sector
- Tensor sector as usual

Full-fledged
analysis

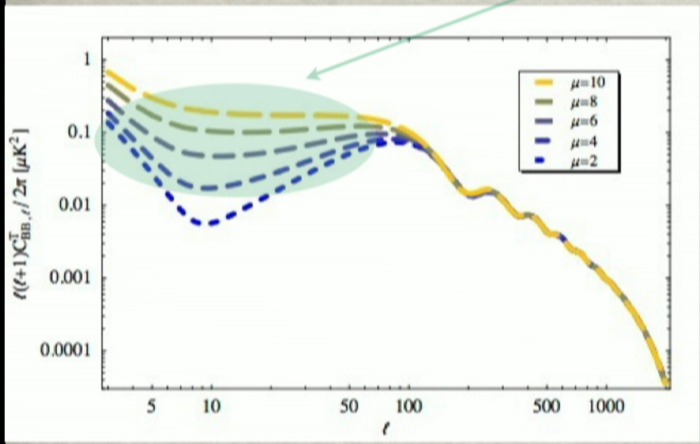
GMG

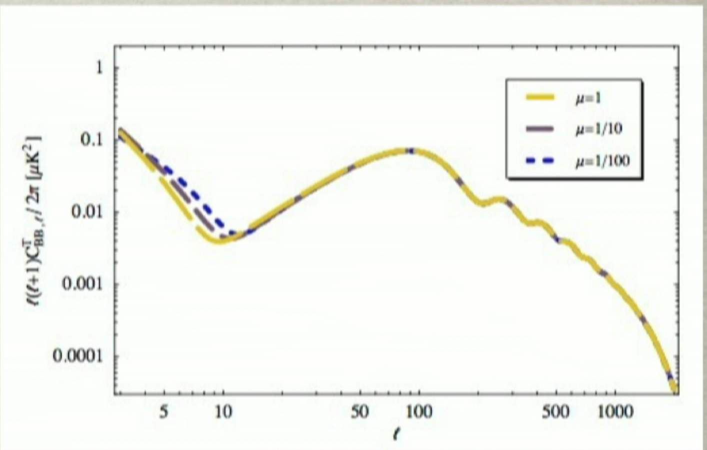
GW in L-B massive gravity and L-I bigravity

Dubovsky et al

MF, Ribeiro

For effective mass smaller than Hr, low multiples would be enhanced w.r.t massless case



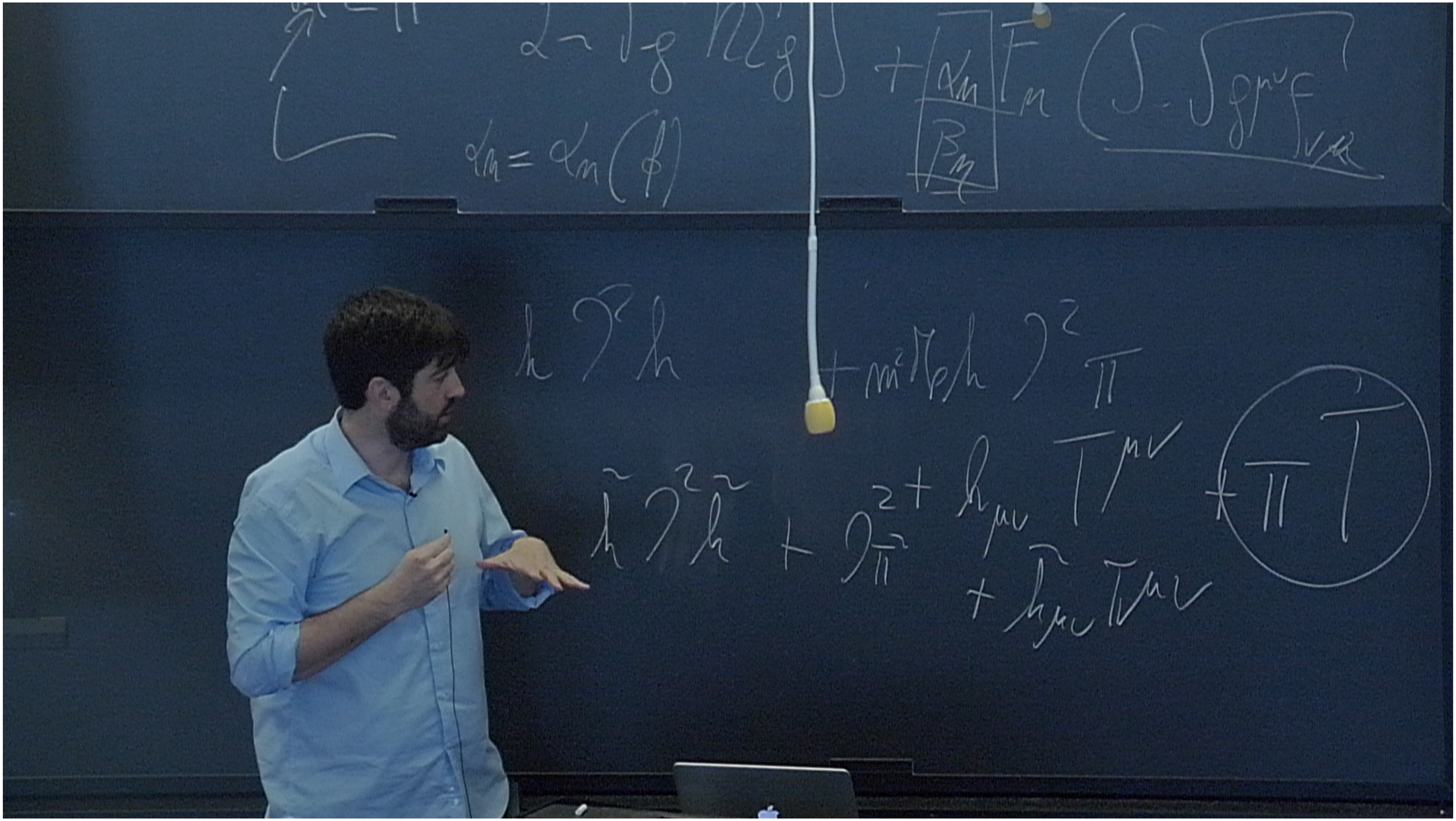


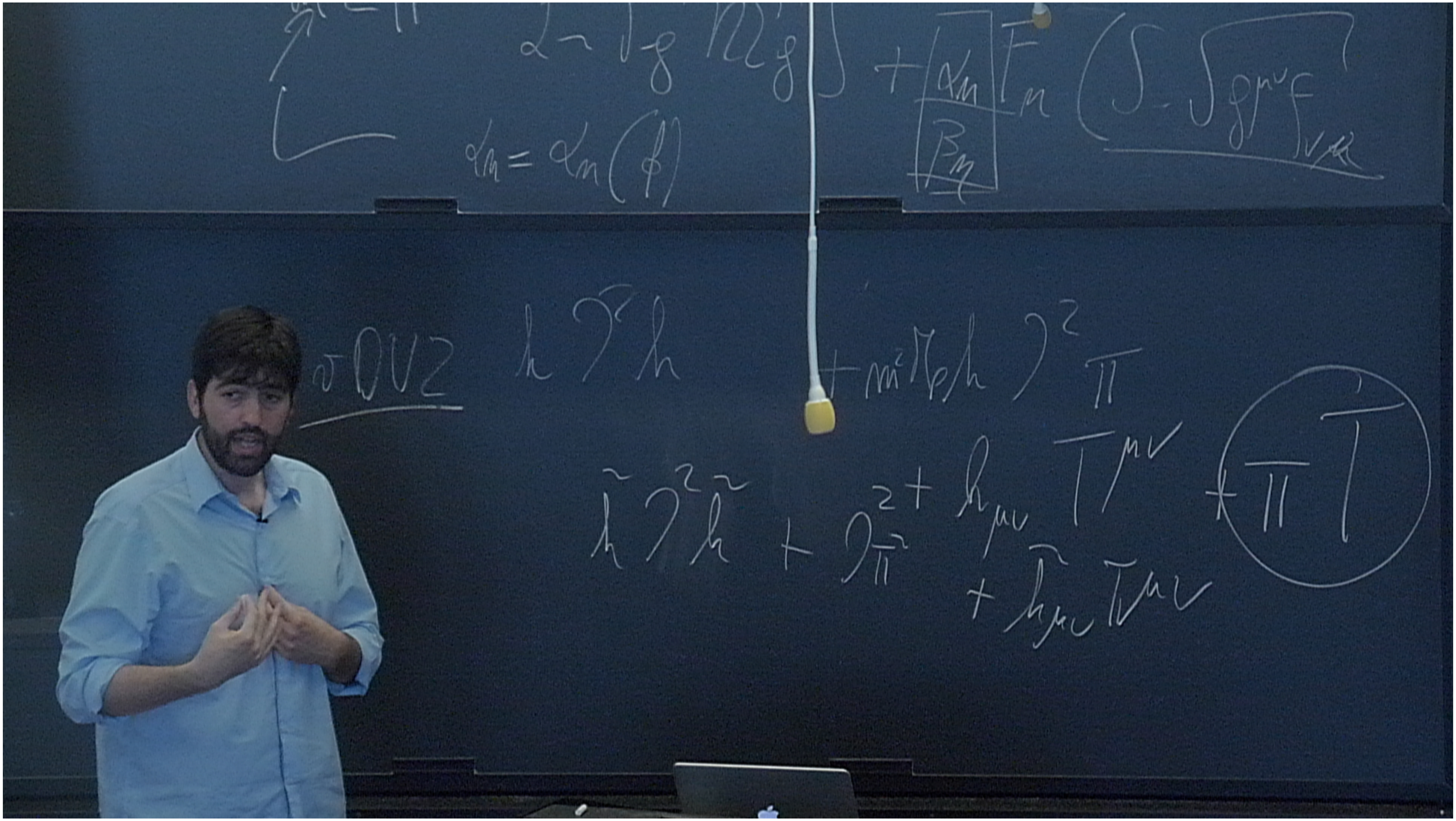
$$\frac{1}{10}H_r < m_{\rm eff} < H_r$$

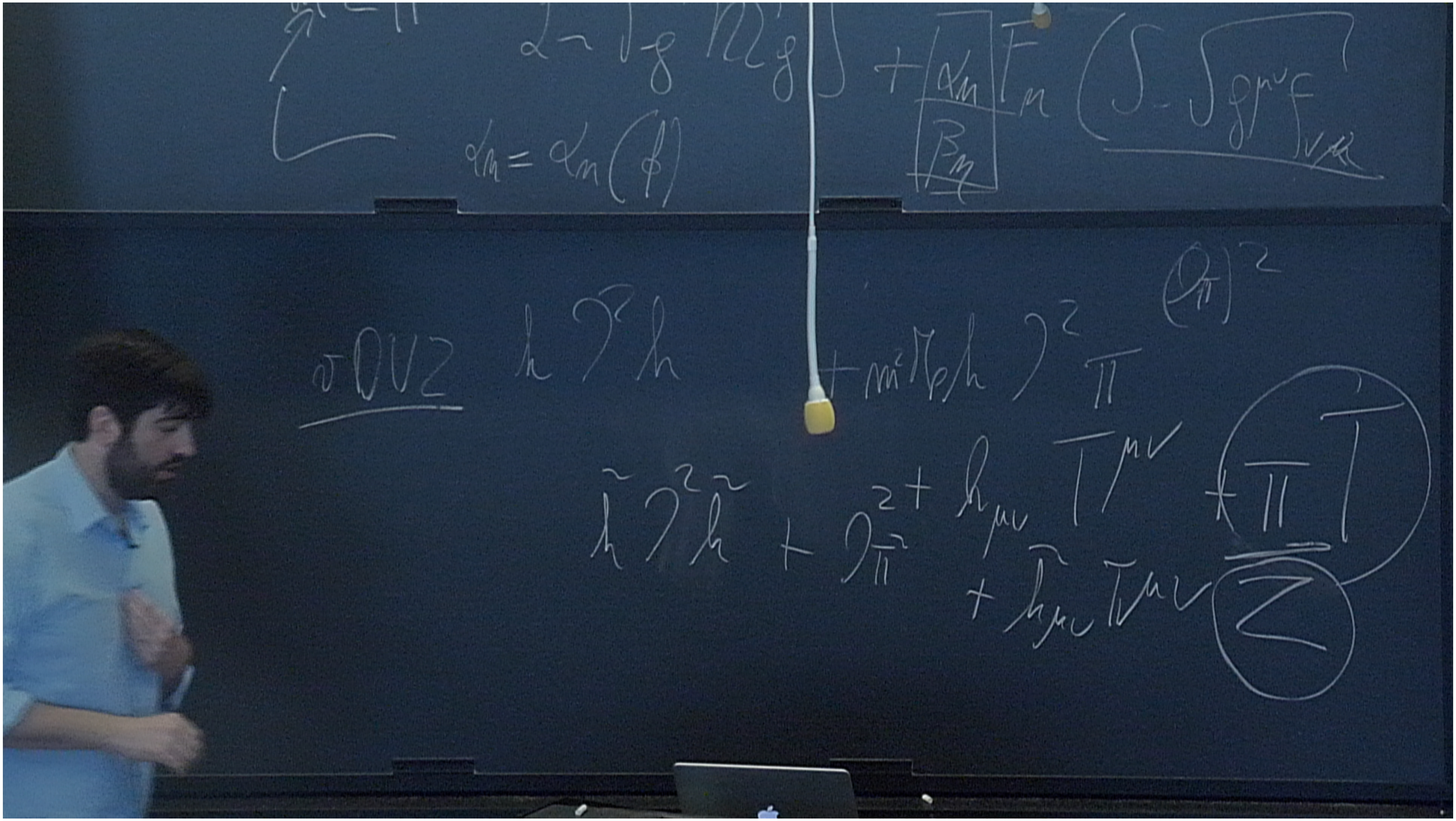
$$10^{-30}{\rm eV} < m_{\rm eff} < 10^{-29}{\rm eV}$$

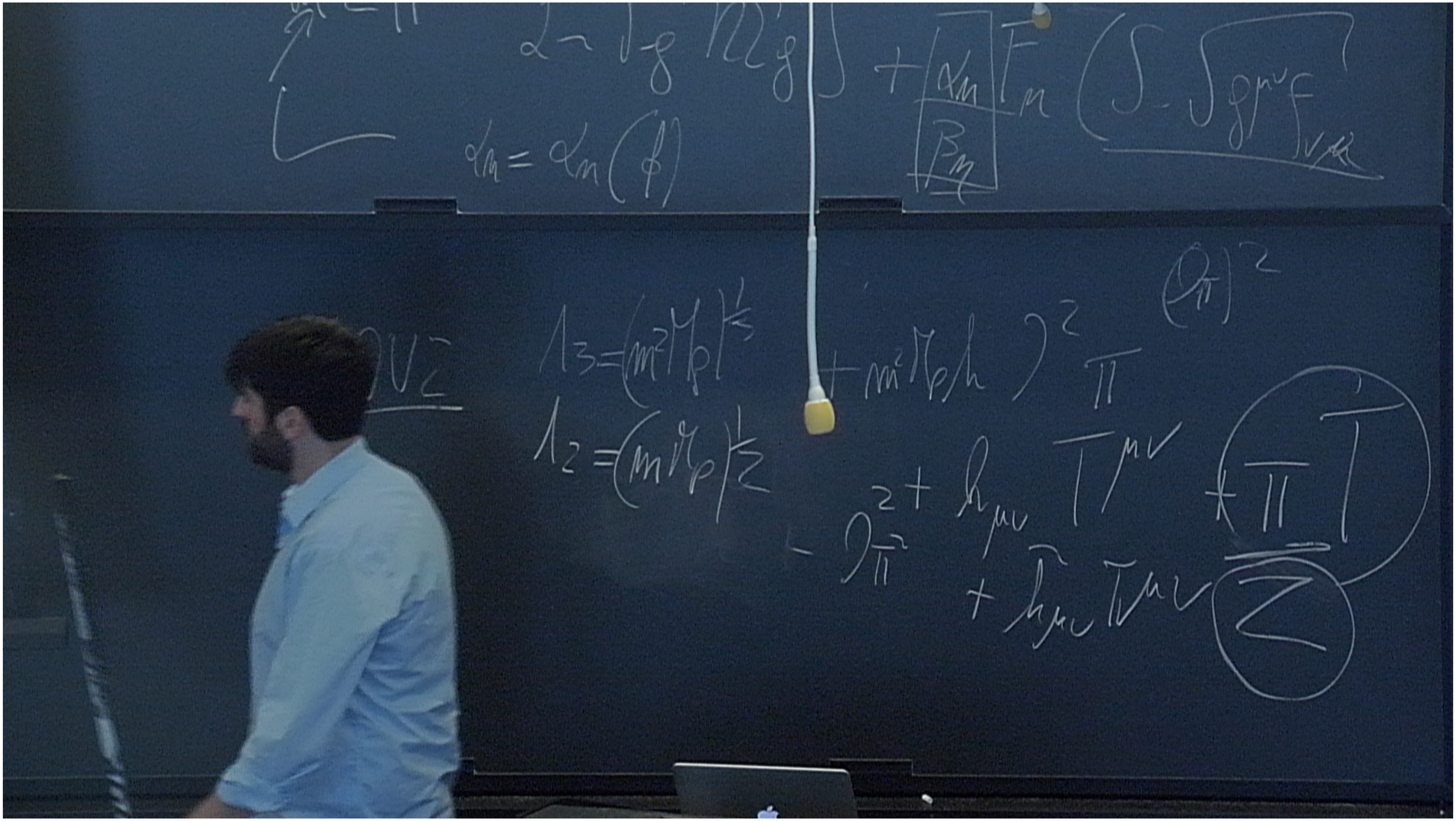
$$m_{\rm eff} < \frac{1}{10}H_r$$

N.B. All plots of multipole coefficients presented here are for a massive graviton only, and were obtained through CAMB by Dubovsky et al. (2010)









More...

different
backgrounds altogether
or non-trivial b. for Stueckelberg fields

$$\Phi^a \neq x^a$$

no vDVZ

Porrati (2001)
AdS

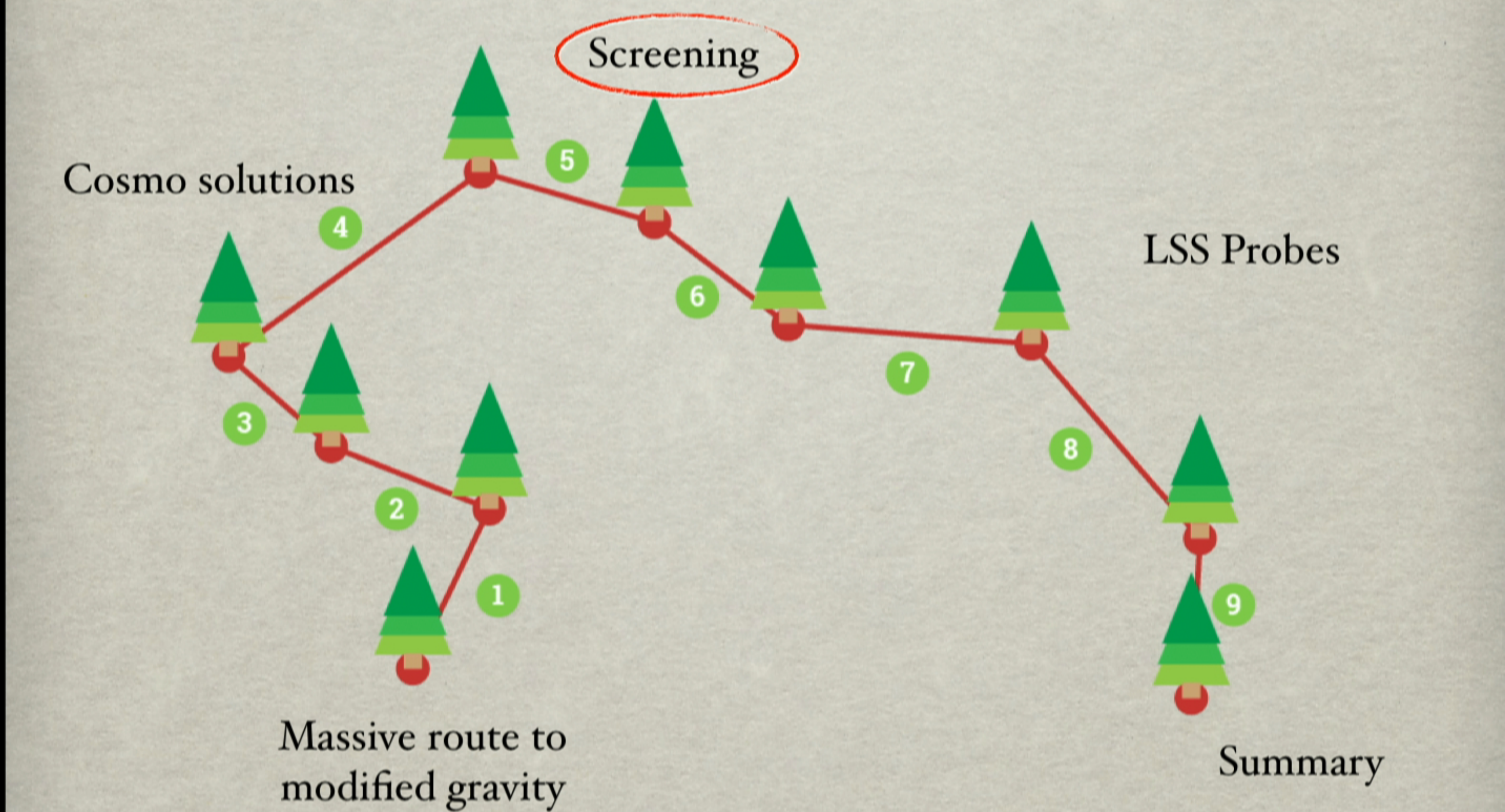
Higuchi
and
gradient ✓

Aoki, Maeda, Namba (2015)
almost FLRW but
non-linearities in
Stueckelberg

Raise strong
coupling scale

De Rham, Tolley, Zhou (2015)
Lorentz-breaking vacua but on
the Stueckelberg side

Outline



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Solar system tests
Lue, Starkman (2006, i.e. DGP)
Dvali et al (2003, i.e. DGP)
...

Lensing
Wyman (2011)

Binary pulsars
de Rham, Tolley, Wesley (2012)
de Rham, Matas, Tolley (2013)
Jimenez, Piazza, Velten (2016)

Compact obj. *vs* non-rel. stars
Hui, Nicolis

LSS
Falck et al (2014)
Falck, Koyama, Zhao(2015)
Gronke, Mota, Winther (2015)
Ivarsen et al(2016)
Perturbative approach

Horndeski extensions
Koyama, Niz, Tasinato (2013)
Koyama, Sakstein (2015)
Sakstein, Koyama (2015)
Langlois (2016)
Sakstein et al(2016)

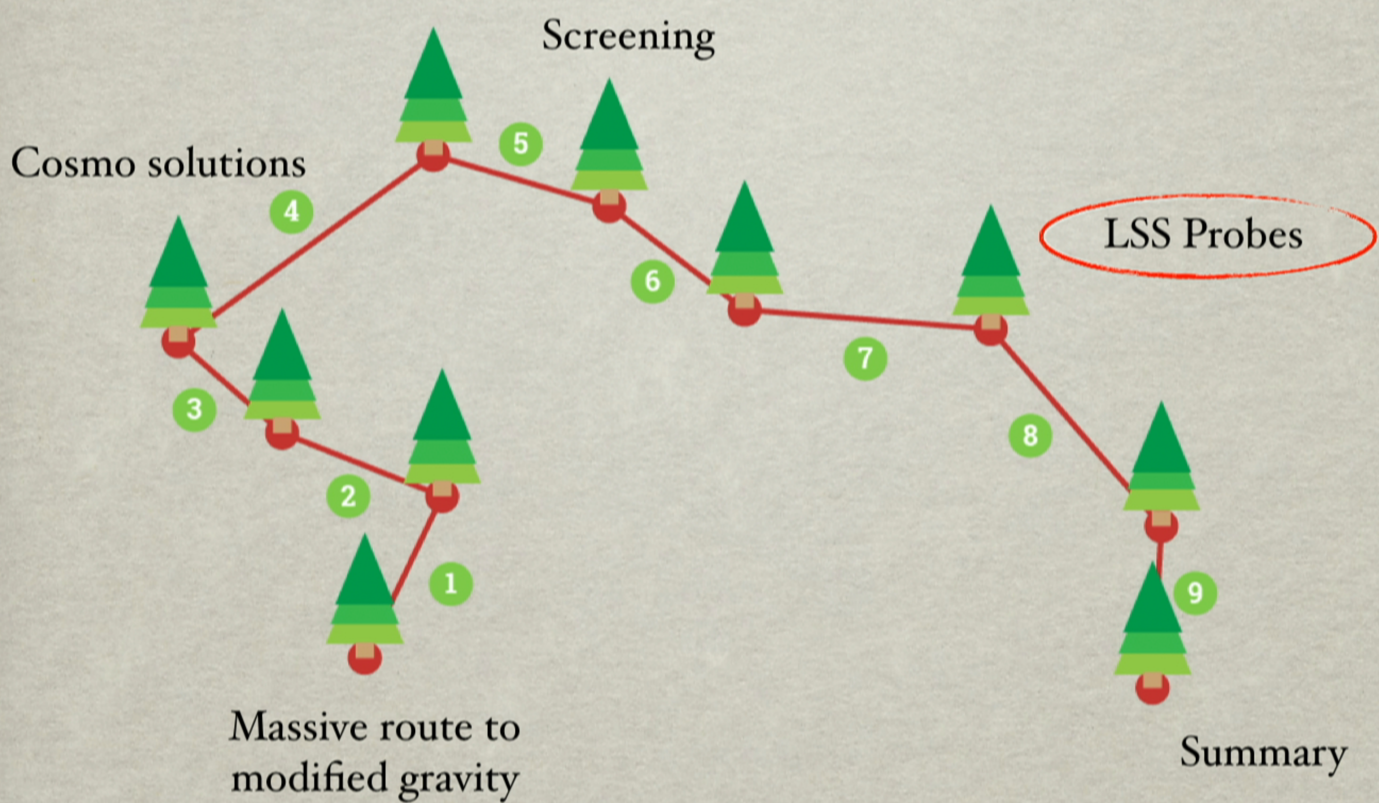
Tensors
not screened, possible GW signatures in e.g. bigravity,

Vainshtein Screening

Numerical

Analytical handle
highly symmetric, idealized setups
(static, sph. symm etc)

Outline



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Extra Scalar

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \partial^2\phi, ..)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T$$

Screening where GR extremely well-tested, e.g. Solar system

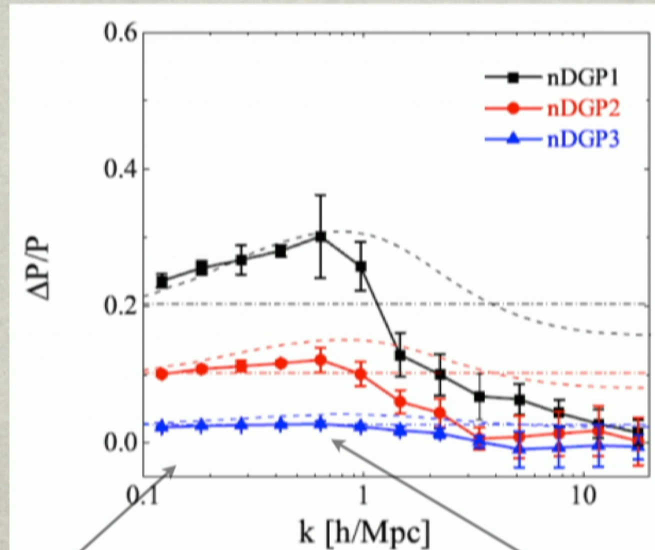
$$V(r) \sim -\frac{g^2(\phi)}{Z(\phi)} \frac{e^{-\frac{m(\phi)}{\sqrt{Z(\phi)}} r}}{4\pi r} \mathcal{M}$$

Symmetron

Vainshtein

Chameleon

N-body



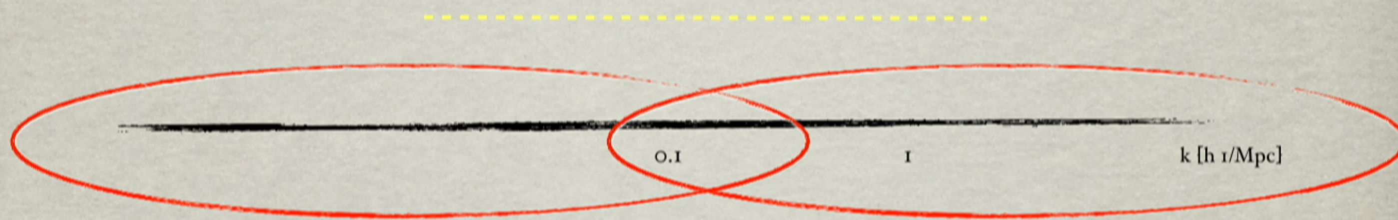
Falck, Koyama, Zhao (2015)

Linear scales

Onset Vainshtein Screening

Perturbation Theory

screening



full perturbative control

bulk of the information on growth

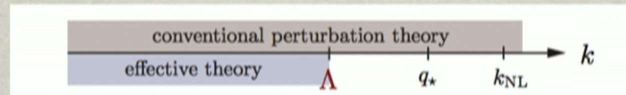
A lot going on to conquer the quasi-linear scales

RPT (Crocce, Scoccimarro)
TRG (Matarrese, Pietroni; Pietroni)
TSPT(Blas et al)
....
Lagrangian approach
(Matsubara; Porto et al; Vlah et al)
...
EFT of LSS

Perturbative approaches to LSS

conquering quasi-linear scales

EFT of LSS



Baumann et al (2010)

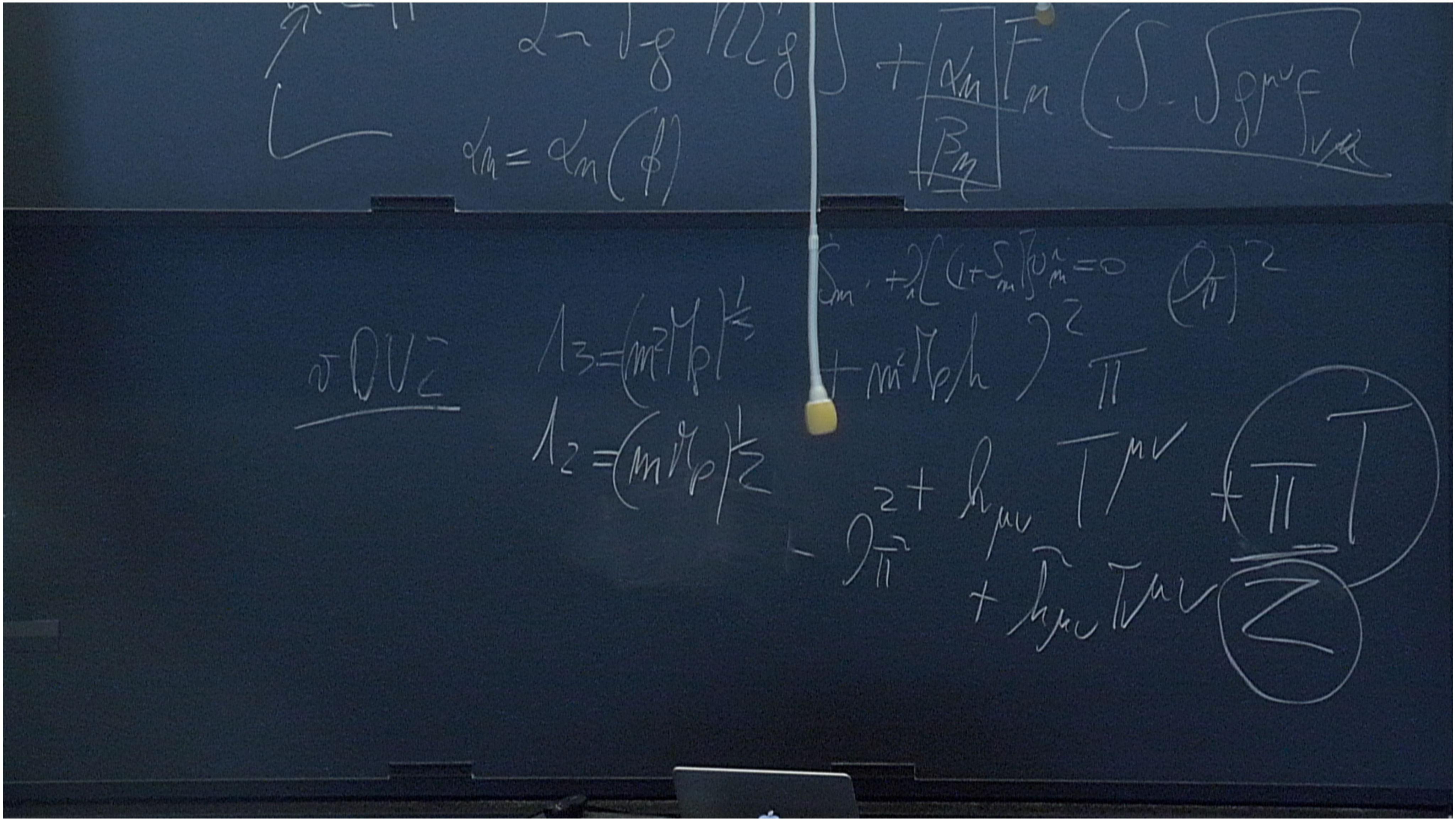
For dark matter (or more), use fluid description

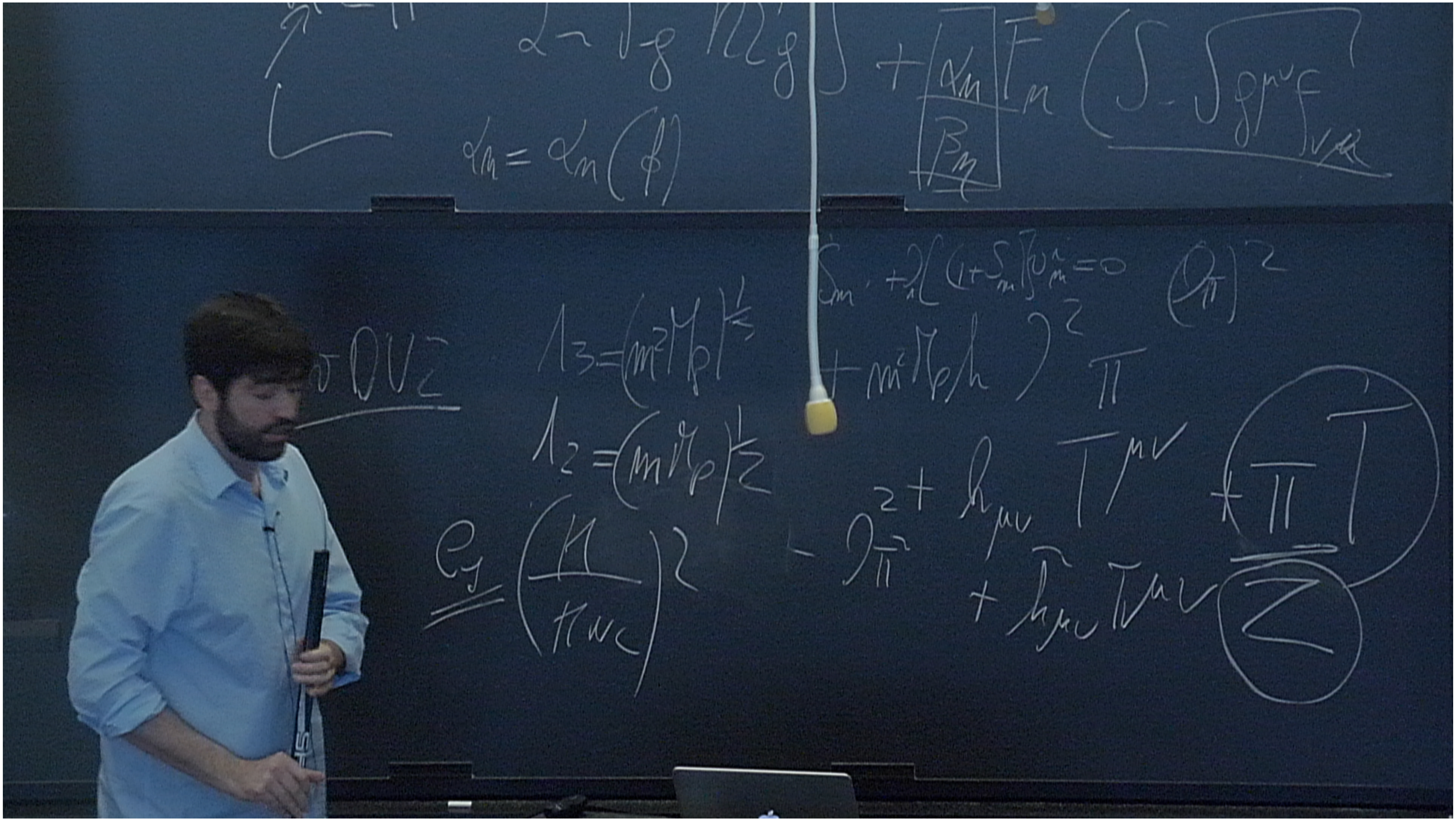
$$\dot{\theta}_\ell + \mathcal{H}\theta_\ell + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_\ell = -\frac{1}{\rho_\ell}\nabla_i \nabla_j \langle \tau_{ij} \rangle$$

the "EFTness" of the approach is in the fact one describes long-wavelength dynamic

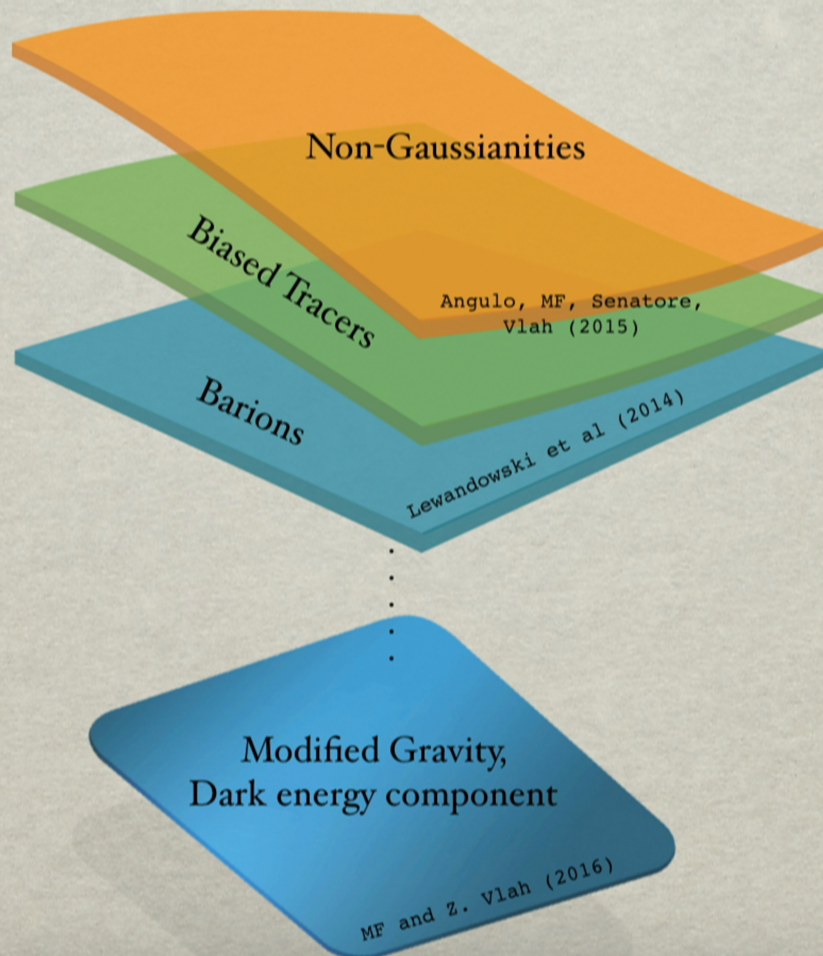
informed by a few UV inputs

$$\langle \tau_{ij} \rangle \;=\; \rho \left[c_1 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)_{ij} + c_2 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)^2_{ij} + \cdots \right] \phi_\ell \; + $$
$$+ \; \rho \left[\left(d_1^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right) + d_2^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right)^2 + \cdots \right) \left\{ v_\ell^2 , \, \delta_\ell \phi_\ell , \cdots \right\} \right]_{ij}$$


αm = αm(φ)
Λ3 = (m²Mp)^1/3
Λ2 = (mMp)^1/2



Layers of physics



Adding a MG or DDE component

Creminelli et al (2009);
Sefusatti, Vernizzi (2011);
Anselmi et al (2011);
D'Amico, Sefusatti (2011);

$$\begin{cases} \frac{\partial \delta_m}{\partial \tau} + \vec{\nabla} \cdot [(1+\delta_m)\vec{v}] = 0 \\ \frac{\partial \delta_Q}{\partial \tau} - 3\omega\mathcal{H}\delta_Q + \vec{\nabla} \cdot [(1+\omega+\delta_Q)\vec{v}] = 0 \\ \frac{\partial v}{\partial \tau} + \mathcal{H}\vec{v} + (\vec{v}\cdot\vec{\nabla})\vec{v} = -\nabla\Phi \end{cases}$$

clustering quintessence, $c_s=0$

$$\nabla^2\Phi = \frac{3}{2}\mathcal{H}^2\Omega_m\underbrace{(\delta_m + \delta_Q\frac{\Omega_Q}{\Omega_m})}_{\delta_T}$$

known exactly only up to quadratic order

All orders, integral & differential solutions

MF, Vlah (2016)

$$\delta_{\mathbf{k}}(\eta) \quad = \sum_{n=1}^{\infty} F_n^s(\mathbf{q}_1..\mathbf{q}_n,\eta) D_+^n(\eta)\delta^{\rm in}_{\mathbf{q_1}}..\delta^{\rm in}_{\mathbf{q_n}}$$

$$\Theta_{\mathbf{k}}(\eta) \quad = \sum_{n=1}^{\infty} G_n^s(\mathbf{q}_1..\mathbf{q}_n,\eta) D_+^n(\eta)\delta^{\rm in}_{\mathbf{q_1}}..\delta^{\rm in}_{\mathbf{q_n}}$$

$$F_n(\eta) = \int_{-\infty}^{\eta} \frac{d\tilde\eta}{C(\tilde\eta)} \left\{ e^{(n-1)(\tilde\eta-\eta)} \frac{\tilde f_+}{\tilde f_+ - \tilde f_-} \left[\left(\tilde h_\beta^{(n)} - \frac{\tilde f_-}{\tilde f_+} \tilde h_\alpha^{(n)} \right) + e^{\tilde\eta-\eta} \frac{D_-(\eta)}{\tilde D_-(\eta)} \left(\tilde h_\alpha^{(n)} - \tilde h_\beta^{(n)} \right) \right] \right\}$$

$$G_n(\eta) = \int_{-\infty}^{\eta} \frac{d\tilde\eta}{C(\tilde\eta)} \left\{ e^{(n-1)(\tilde\eta-\eta)} \frac{\tilde f_+}{\tilde f_+ - \tilde f_-} \left[\left(\tilde h_\beta^{(n)} - \frac{\tilde f_-}{\tilde f_+} \tilde h_\alpha^{(n)} \right) + e^{\tilde\eta-\eta} \frac{f_-}{f_+} \frac{D_-(\eta)}{\tilde D_-(\eta)} \left(\tilde h_\alpha^{(n)} - \tilde h_\beta^{(n)} \right) \right] \right\}$$

$$C = 1 + (1+\omega)\frac{\Omega_Q(\eta)}{\Omega_m(\eta)}$$

iteratively derived, first recursion are usual

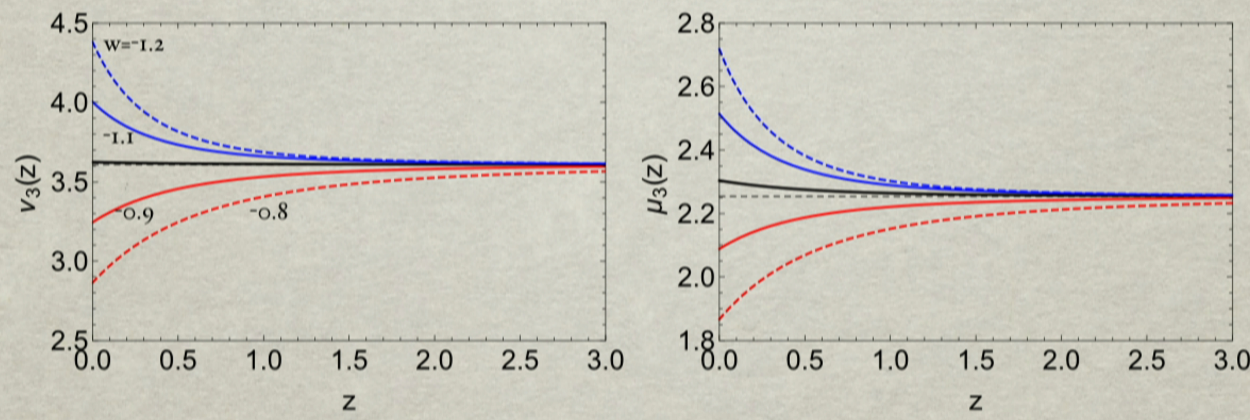
$\alpha(\mathbf{q}_1,\mathbf{q}_2)$, $\beta(\mathbf{q}_1,\mathbf{q}_2)$

related to

$\propto$ linear growth rate

$$F_3 = (1-\epsilon^{(2)})\mathcal{F}_3^{\epsilon} + \nu_3\mathcal{F}_3^{\nu_3} + (1-\epsilon^{(1)})\nu_2\mathcal{F}_3^{\nu_2} + \lambda_1\mathcal{F}_3^{\lambda_1} + \lambda_2\mathcal{F}_3^{\lambda_2}$$

$$G_3 = (1-\epsilon^{(2)})\mathcal{G}_3^{\epsilon} + \mu_3\mathcal{G}_3^{\mu_3} + (1-\epsilon^{(1)})\mu_2\mathcal{G}_3^{\mu_2} + \kappa_1\mathcal{G}_3^{\kappa_1} + \kappa_2\mathcal{G}_3^{\kappa_2}$$

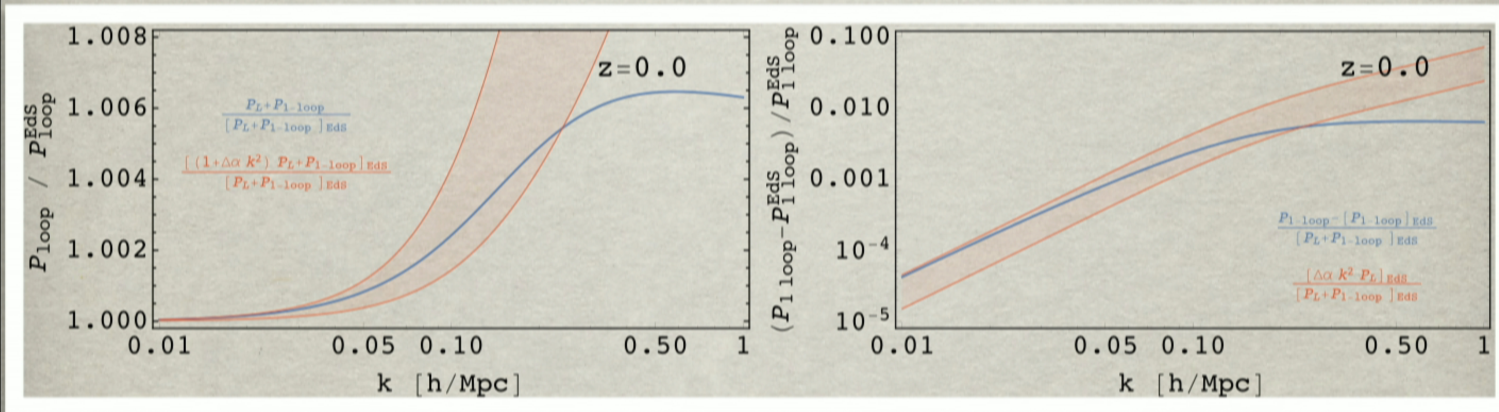


similarly for $\lambda_1, \lambda_2, \kappa_1, \kappa_2(z)$ while $\mathcal{F}_3 = \mathcal{F}_3(\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3)$

Observables

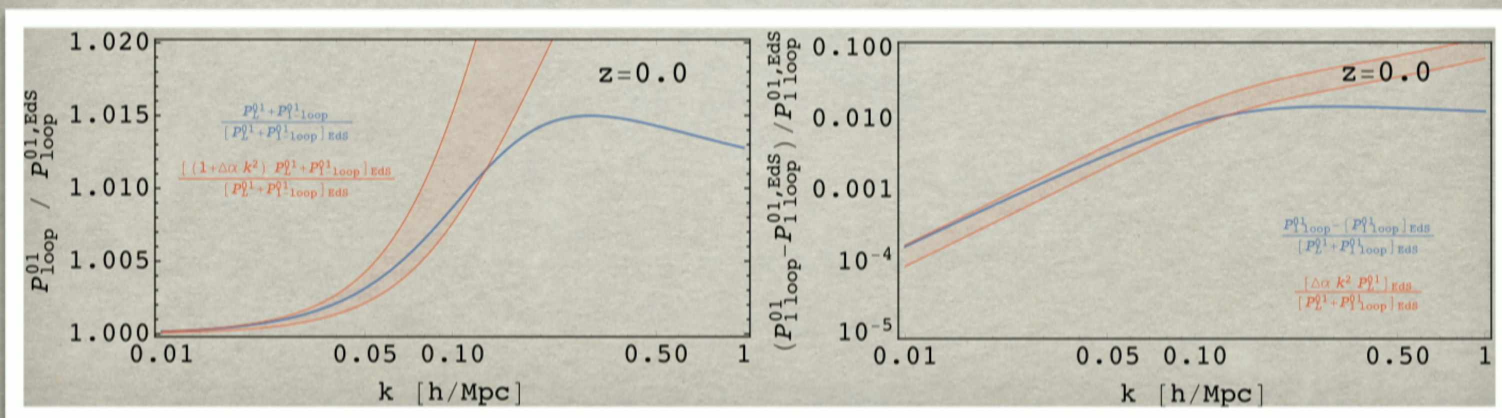
MF, Vlah (2016)

$$P_{1-\mathrm{loop}}(k,a) = P_{\mathrm{L}}(k,a) + P_{22}(k,a) + 2P_{13}(k,a) + P_{\mathrm{c.t.}}(k,a)$$

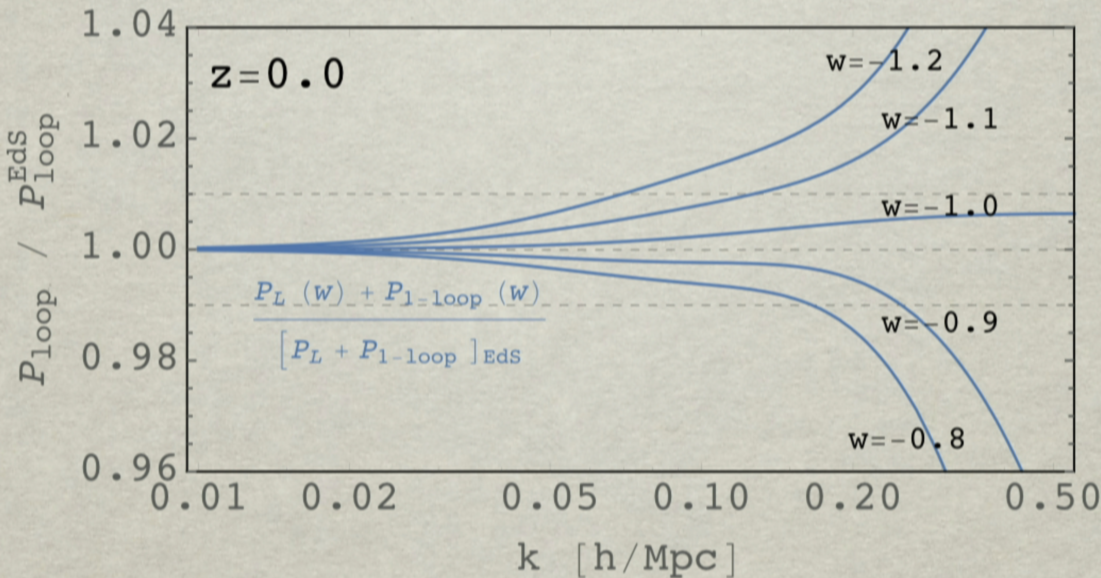


$C(\eta) = 1$

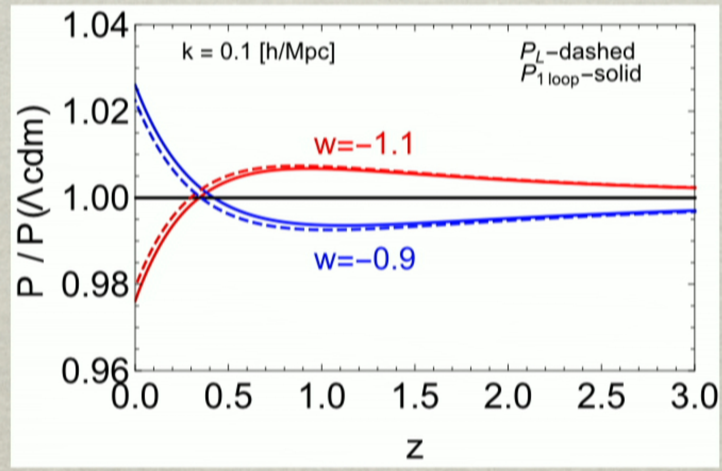
test with ΛCDM



MF, Vlah, to appear



MF, Vlah, to appear



Consistency Conditions

MF, Vlah, to appear

reduced system effectively 1 d.o.f.

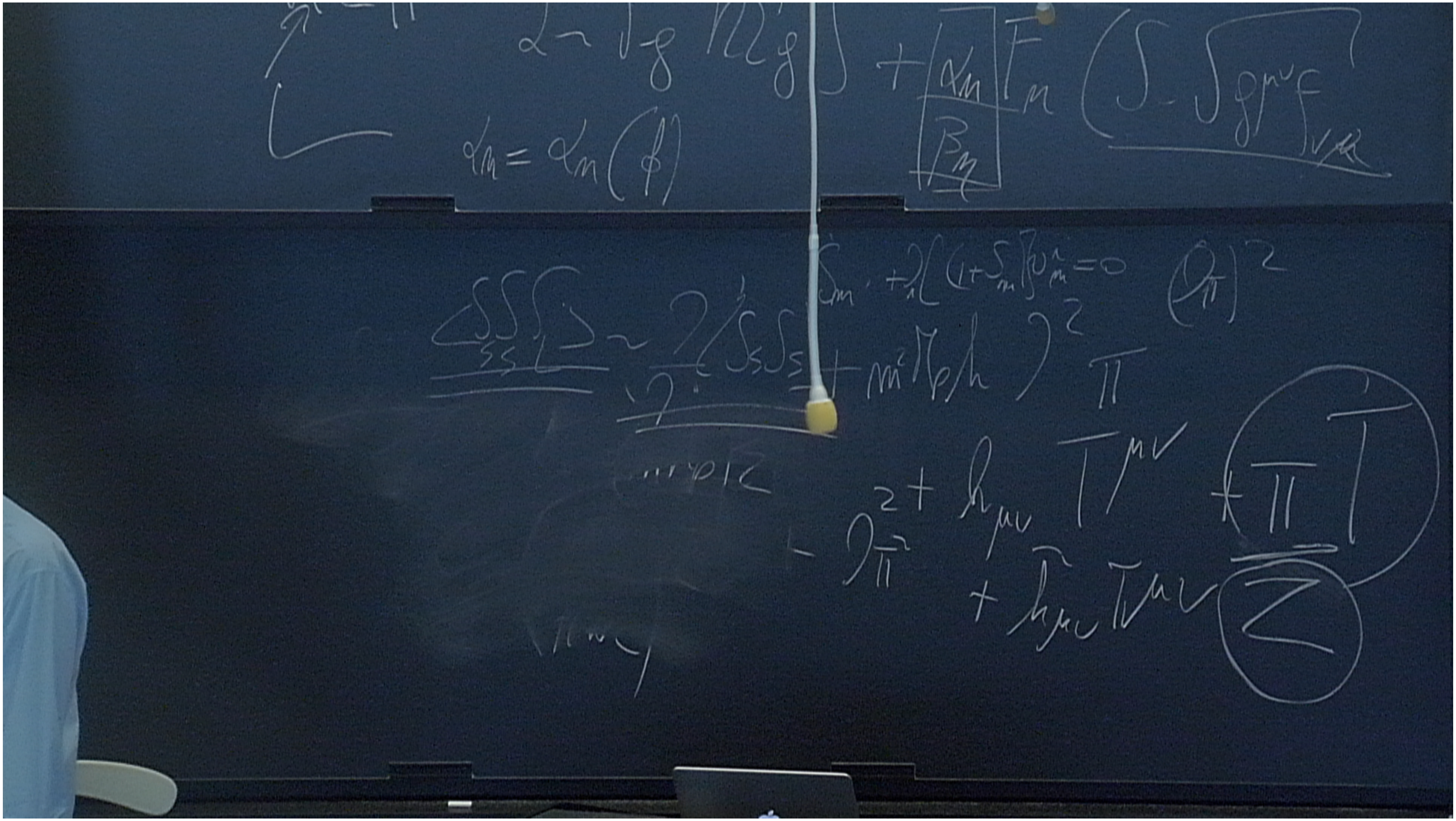
$$\begin{cases} \delta'_T + \partial_i[(C+\delta_T)v^i] = 0, \text{ with } C = 1 + (1+w)\dfrac{\Omega_Q}{\Omega_m} \\ \dfrac{\partial v^i}{\partial \tau} + \mathcal{H}v^i + v^j\partial_j v^i = -\nabla^i\Phi\,; \quad \nabla^2\Phi = \dfrac{3}{2}\mathcal{H}^2\Omega_m\delta_T\,, \end{cases}$$

Ccs checklist:

→ residual gauge symmetry ✓ $\begin{cases} \tau \to \tilde{\tau} = \tau\,;\; x^i \to \tilde{x}^i = x^i + n^i(\tau)\,;\; v^i \to \tilde{v}^i = v^i + n^{i'} \\ \delta_{m,Q} \to \tilde{\delta}_{m,Q} = \delta_{m,Q}\,;\; \Phi \to \tilde{\Phi} = \Phi - x^i(Hn^{i'} + n^{i''}) \end{cases}$

→ initial conditions: Gaussian ✓

→ adiabaticity ✓



What's next

MF, Vlah

IR properties of 1-loop power spectrum

Bispectrum

All ready for any w≠-1, need simulations to determine "counterterm" coefficient

CQ

Expand to more complex dynamics,
which include higher derivatives (e.g. Galileons) and screening

k_{nl} vs k_V
(and its model-dependence)