

The Effective Field Theory approach to Dark Energy and Modified Gravity phenomenology

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Lecture for KICP Cosmology Class
Feb 24, 2017

1. Why Dark Energy (DE)?

[Everything You Always Wanted To Know About The Cosmological Constant Problem (But Were Afraid To Ask), arXiv:1205.3365v1]

2. Why Modified Gravity (MG)?

[Modified Gravity and Cosmology, arXiv:1106.2476]

3. Why both???

4. EFT approach:

- **how to build the EFT of DE/MG**
- **conformal invariance**
- **why a scalar field?**
- **possible generalizations**
- **stability**
- **how to use the EFT (mapping other theories)**
- **cosmological phenomenology (EFTCAMB)**

4. EFT approach:

- **how to build the EFT of DE/MG**
[arXiv:1210.0201, arXiv:1211.7054,
arXiv:1304.4840, arXiv:1601.04064,
arXiv:1609.00716]
- **stability**
[... + arXiv:1609.03599]
- **how to use the EFT (mapping other theories)**
[... + arXiv:1601.04064]
- **cosmological phenomenology (EFTCAMB)**
[... + arXiv:1312.5742, arXiv:1405.1022,
arXiv:1405.3590]

Invitation

One of the greatest problems of modern physics:

we developed our theory of gravity on the earth,

it works perfectly at the solar system level,

as soon as we consider the Universe it drastically fails.

Cosmic Acceleration Problem:

Cosmological Principle

Solar System GR

Ordinary matter + Dark matter

Invitation

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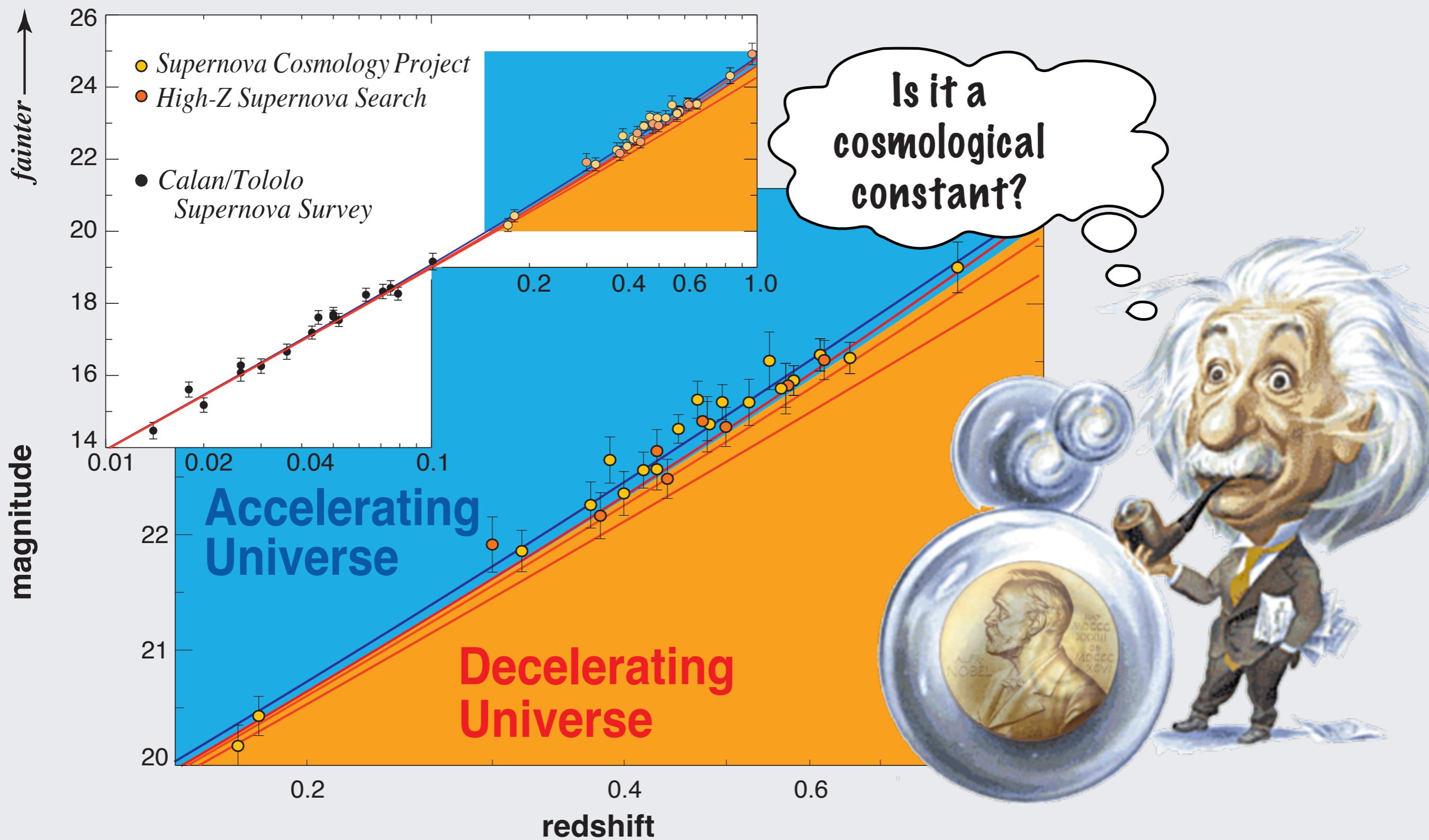
Cosmic Acceleration

does not work!

Cosmological Principle

Solar System GR

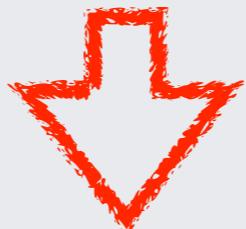
Ordinary matter + Dark matter



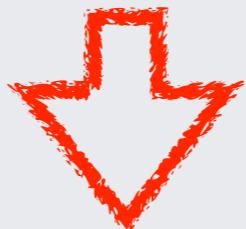
(Science “Breakthrough of the year” 1998; Perlmutter, Physics Today (2003); Discovery awarded with the Nobel Prize in 2011)

The Cosmological Constant problem

The cosmological constant **can be there:**
 it is allowed by the requirements used to build General Relativity
(Lovelock's theorem)



$$S_{\text{EH}} = \int d^4x \sqrt{-g} \frac{M_P^2}{2} (R - 2\Lambda_B) + S_{\text{matter}}[g_{\mu\nu}, \Psi], \quad M_P^2 = \frac{c^4}{8\pi G}$$



Gravitational field equations:

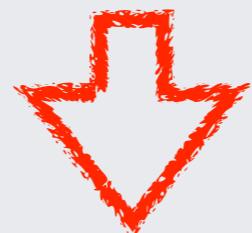
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_B g_{\mu\nu} = \frac{1}{M_P^2}T_{\mu\nu} \quad T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta S_{\text{matter}}}{\delta g^{\mu\nu}}$$

GR is a well defined “classical” theory

Take:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_B g_{\mu\nu} = \frac{1}{M_P^2}T_{\mu\nu} \quad \nabla_\mu T^{\mu\nu} = 0$$

fit to the data, get a good fit (?), end of the story.



There is no “classical” CC problem

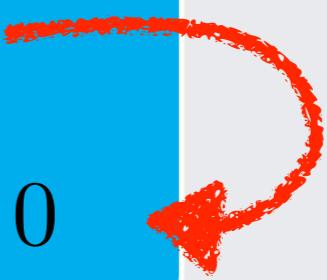
The problem arises when one takes into account quantum field theory.

$$\langle 0 | T_{\mu\nu} | 0 \rangle = -\rho_{\text{vac}} g_{\mu\nu} \neq 0$$

Why: in flat space-time the only invariant tensor is $\eta_{\mu\nu}$
Since the vacuum state must be the same for all observers, one necessarily has

$$\langle T_{\mu\nu} \rangle \propto \eta_{\mu\nu}$$

$$\langle T_{\mu\nu} \rangle = -\rho_{\text{vac}}(t, x) g_{\mu\nu} \neq 0$$



To curved
space-times

This does not necessarily guarantee that ρ_{vac} is constant...
(Running Vacuum Cosmology)

[A. Sakharov, Sov. Phys. Dokl. 12, 1040 (1968)]

Now assume that vacuum gravitates:

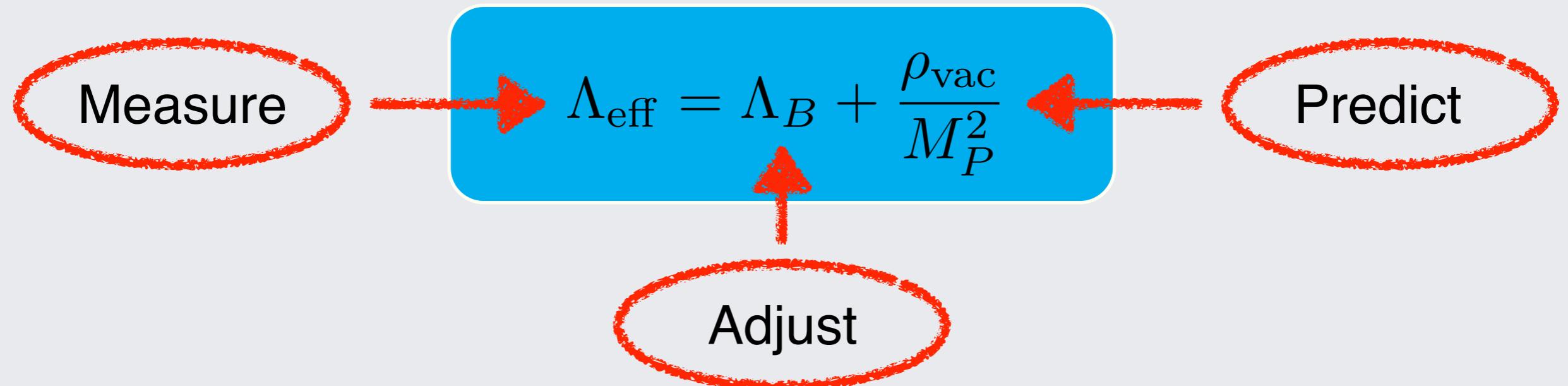
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_B g_{\mu\nu} = \frac{1}{M_P^2}T_{\mu\nu} + \frac{1}{M_P^2}\langle T_{\mu\nu} \rangle$$

rewrite:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_{\text{eff}} g_{\mu\nu} = \frac{1}{M_P^2}T_{\mu\nu}$$

where:

$$\Lambda_{\text{eff}} = \Lambda_B + \frac{\rho_{\text{vac}}}{M_P^2}$$



Standard calculation

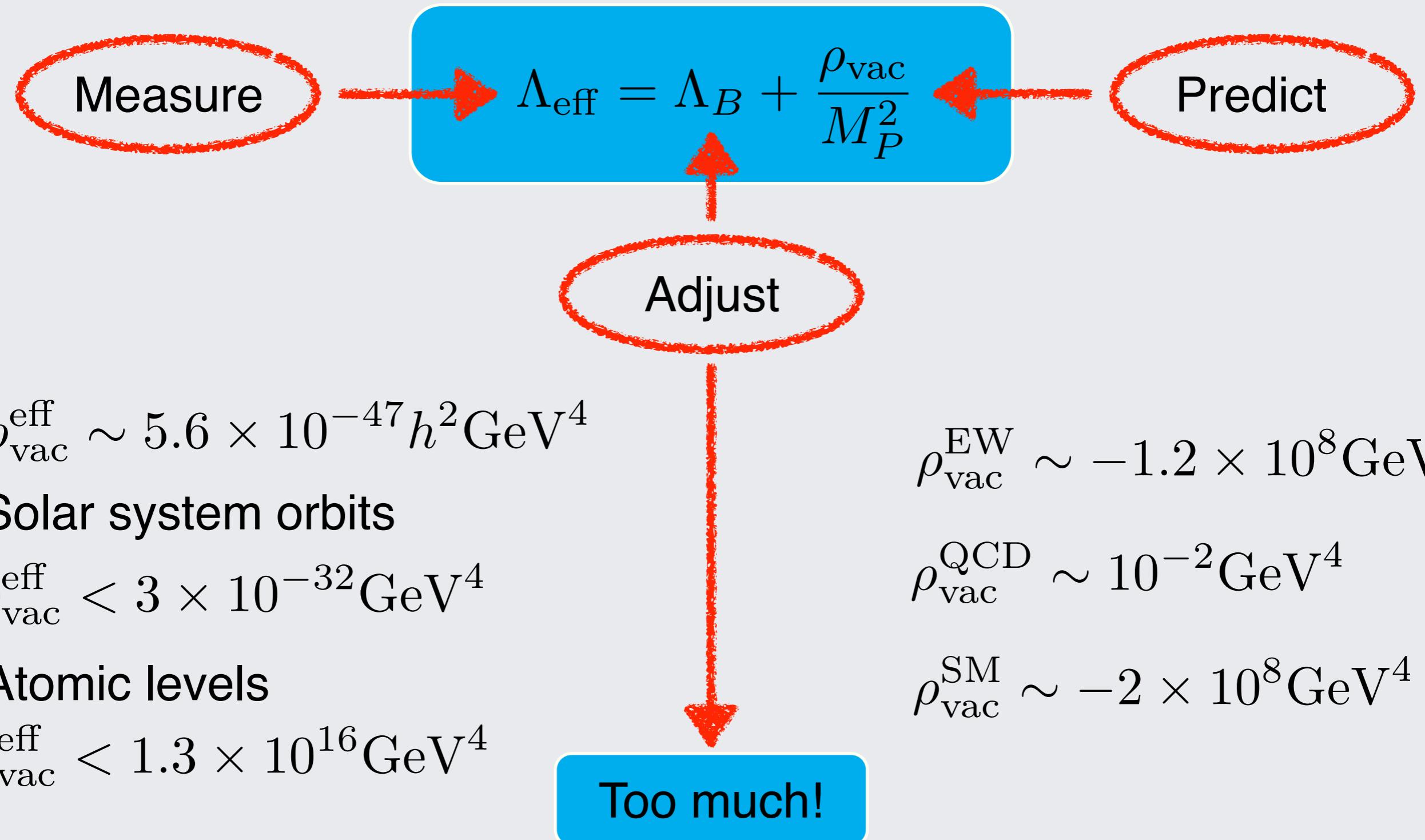
$$\begin{aligned}\langle \rho_{\text{vac}} \rangle &= \frac{1}{2(2\pi)^3} \int d^3k \omega(k) = \frac{1}{4\pi^2} \int_0^M dk k^2 \sqrt{k^2 + m^2} \\ &= \frac{M^4}{16\pi^2} \left(1 + \frac{m^2}{M^2} + \dots \right)\end{aligned}$$

which turns out to be wrong...

$$\langle p_{\text{vac}} \rangle = \frac{1}{3} \frac{M^4}{16\pi^2} \left(1 + \frac{m^2}{M^2} + \dots \right)$$
 wrong equation of state!

Is this a low energy problem?

<i>Quantum Gravity cut-off</i>	$(10^{18} \text{ GeV})^4$	<i>fine tuning to 120 decimal places</i>
<i>SUSY cut-off</i>	$(TeV)^4$	<i>fine tuning to 60 decimal places</i>
<i>EW phase transition</i>	$(200 \text{ GeV})^4$	<i>fine tuning to 56 decimal places</i>
<i>QCD phase transition</i>	$(0.3 \text{ GeV})^4$	
<i>muon</i>	$(100 MeV)^4$	<i>fine tuning to 44 decimal places</i>
<i>electron</i>	$(MeV)^4$	<i>fine tuning to 36 decimal places</i>
	$(meV)^4$	<i>observed value</i>



...and not radiatively stable [arXiv:1502.05296v1]

We do not know how to do this calculation...

What does the space of solutions look like?

We do not know how to do this calculation...

What does the space of solutions look like?

Second face of Lovelock's theorem:
any extension of GR is not going to look like GR...

We do not know how quantum vacuum gravitates...

$$\frac{\Lambda}{M_P^2} \sim 10^{-120} \text{ but } \frac{\Lambda}{H_0^2} \sim 1$$

Dark energy

Save the geometrical structure of GR and add components to the energy budget of the universe

For example add a simple scalar field:

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - V(\phi) \right] + S_{\text{matter}}[g_{\mu\nu}, \Psi]$$



Standard term



kinetic term



potential

Dark energy

Save the geometrical structure of GR and add components to the energy budget of the universe

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$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - V(\phi) \right] + S_{\text{matter}}[g_{\mu\nu}, \Psi]$$

Warning Weinberg's no-go theorem

Modifications of gravity

Intriguing idea:

$$\Lambda_{\text{eff}} = \Lambda_B + \frac{\rho_{\text{vac}}}{M_P^2}$$

Realized in some models [arXiv:1309.6562]

Give up (some of) the geometrical structure of GR and
try to source cosmic acceleration

$$S = \int d^4x \sqrt{-g} \frac{M_P^2}{2} F(R) + S_{\text{matter}}[g_{\mu\nu}, \Psi]$$

There are other reasons why we might want to modify gravity

1

GR is not UV complete



At some point GR needs to be modified

Doomed by Lovelock's theorem



+

the CC problem is a UV problem

$$\langle \rho_{\text{vac}} \rangle = \frac{M^4}{16\pi^2} \left(1 + \frac{m^2}{M^2} + \dots \right)$$

There are other reasons why we might want to modify gravity

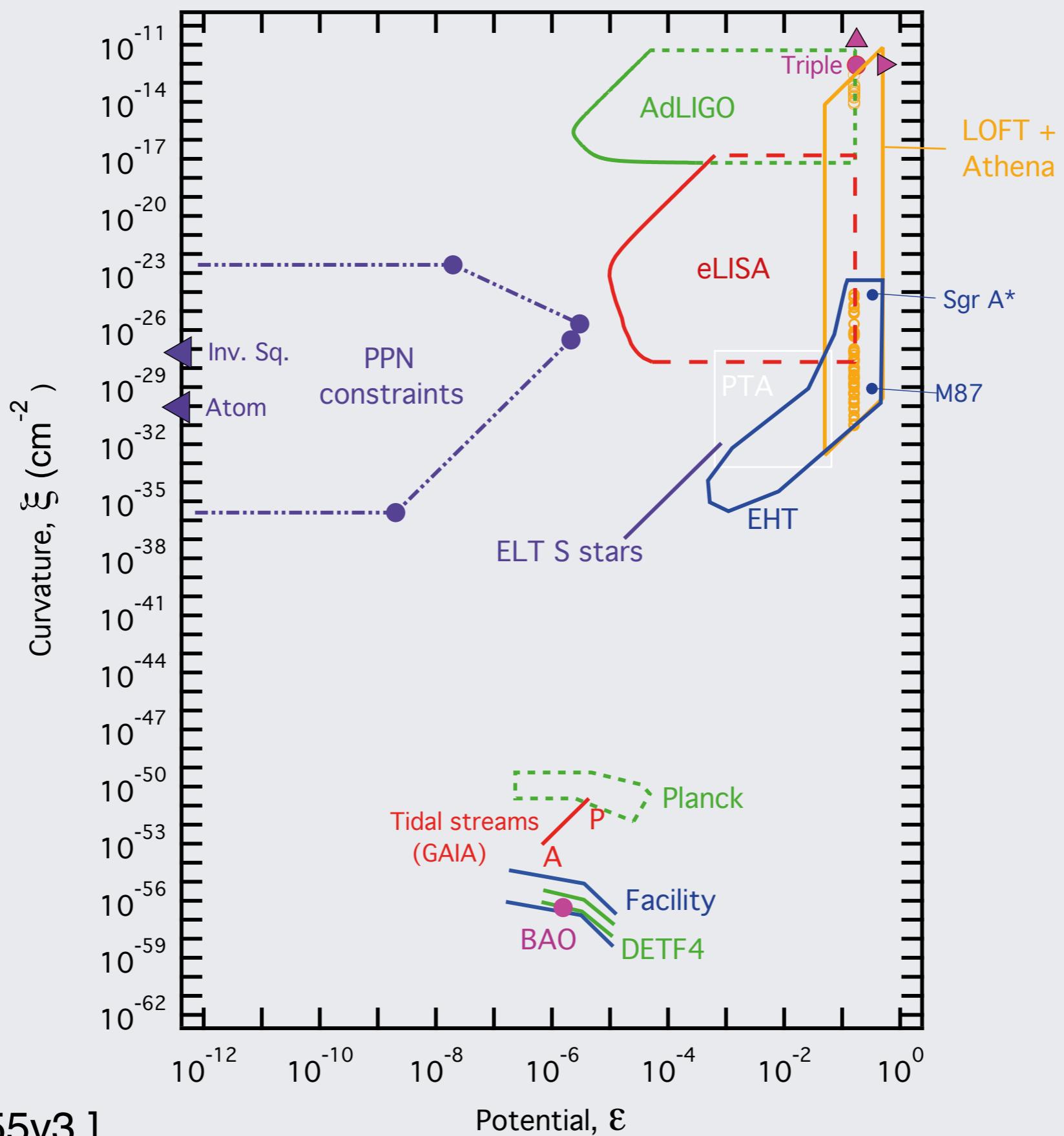
2

because we can

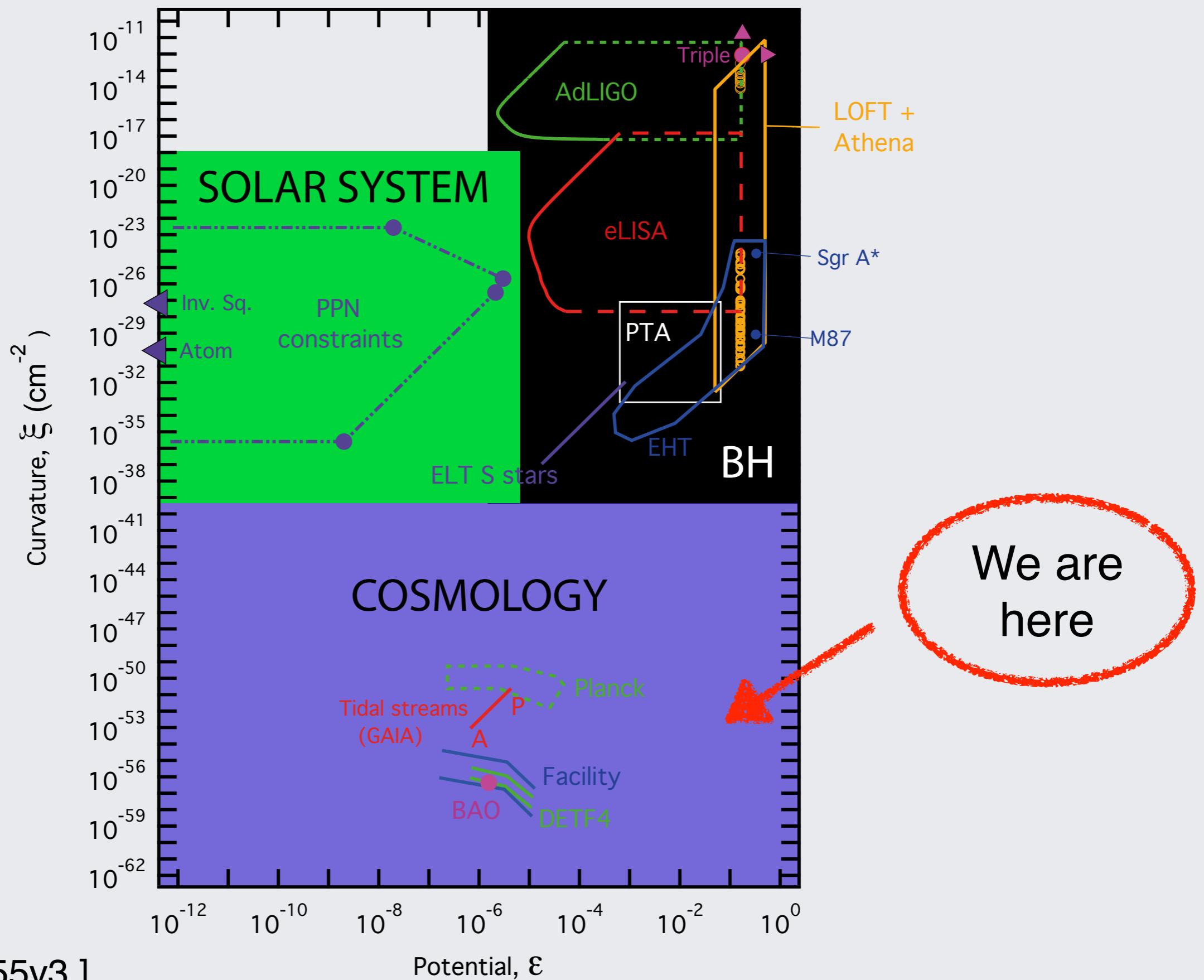


GR has been tested on solar system scales

other regimes: GW and black holes, cosmology



[arXiv:1412.3455v3]



[arXiv:1412.3455v3]

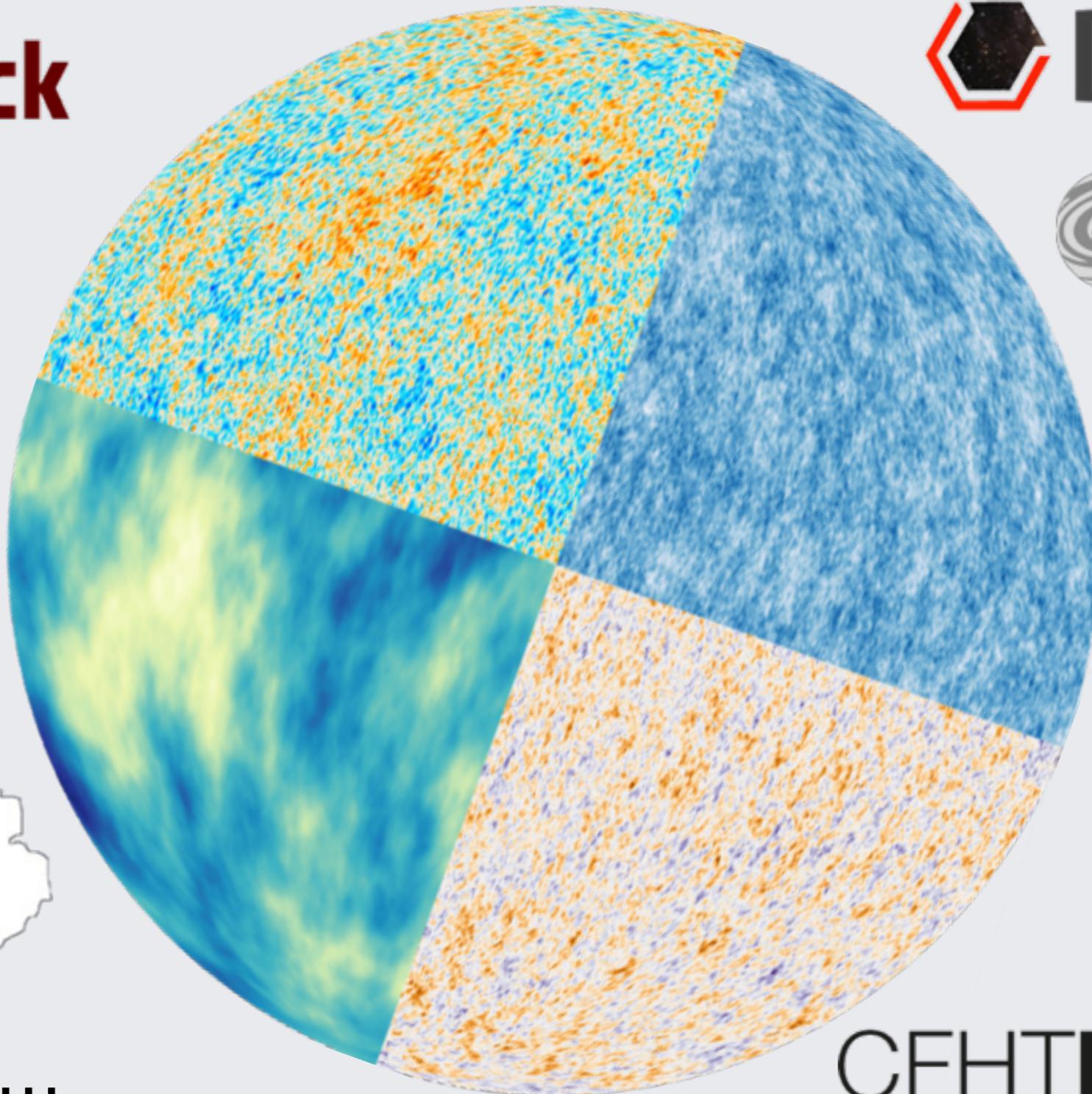


WMAP

CMB-S4



+ many more...



WiggleZ

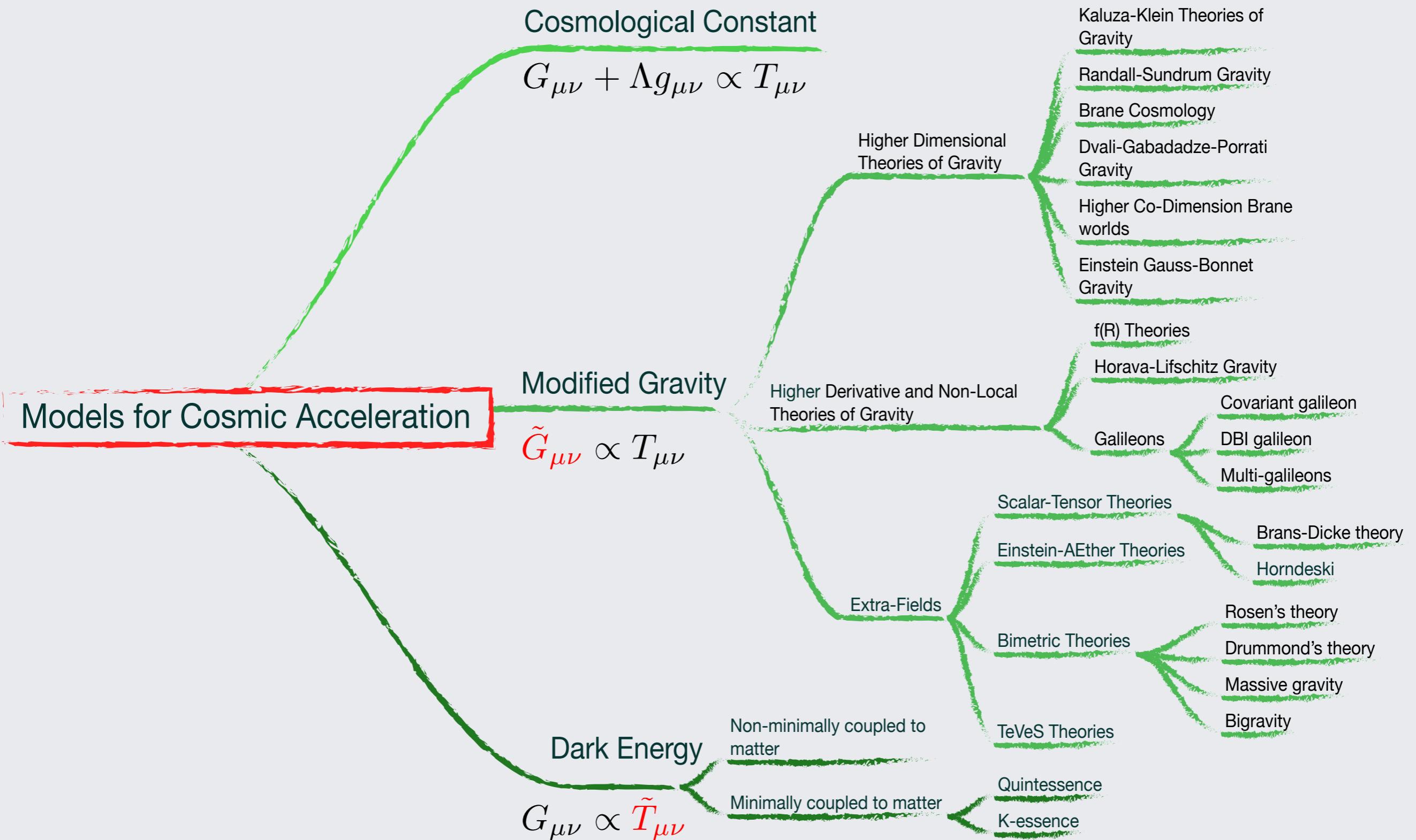


CFHTLenS



(CMB temperature, CMB lensing, galaxy weak lensing convergence and number counts fluctuations: the cosmological pie that I like)

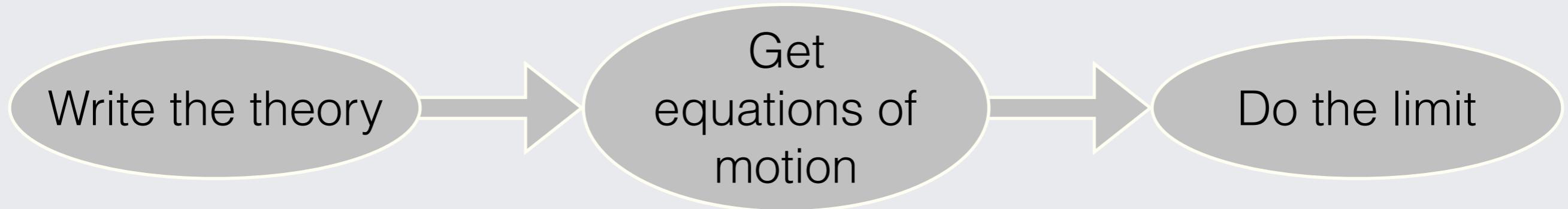
The situation in model space:



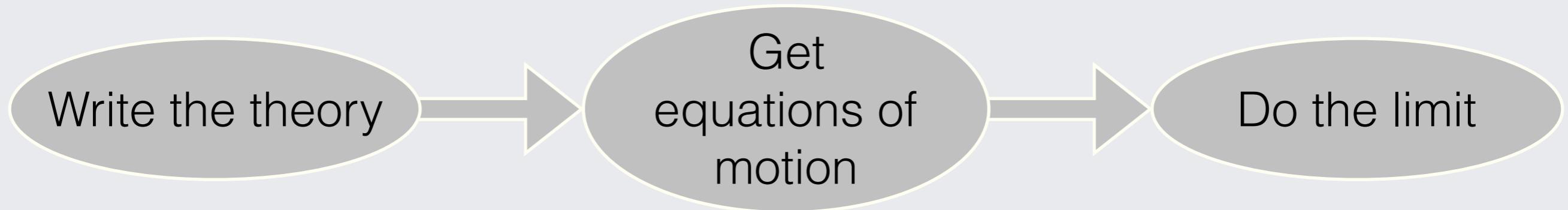
[based on arXiv:1106.2476, by far not complete...]

The EFT approach

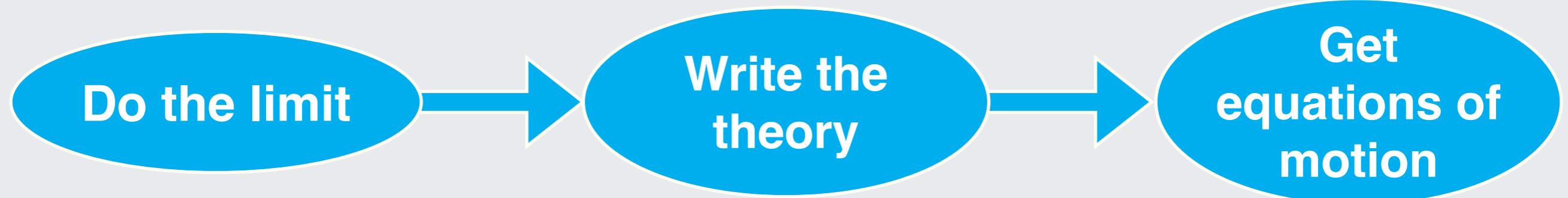
The standard way:



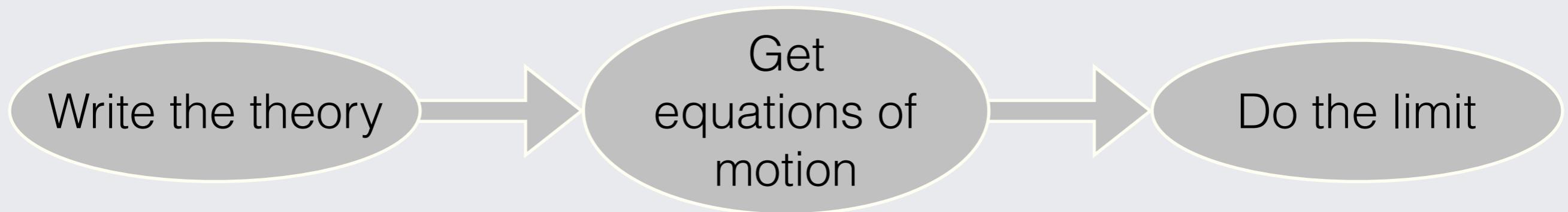
The standard way:



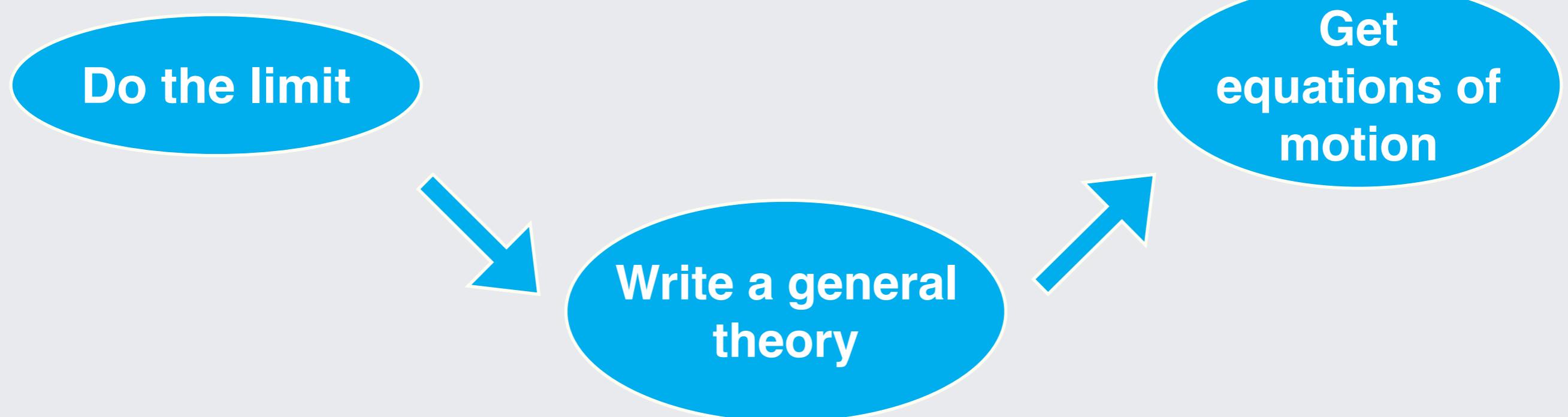
The EFT way:



The standard way:



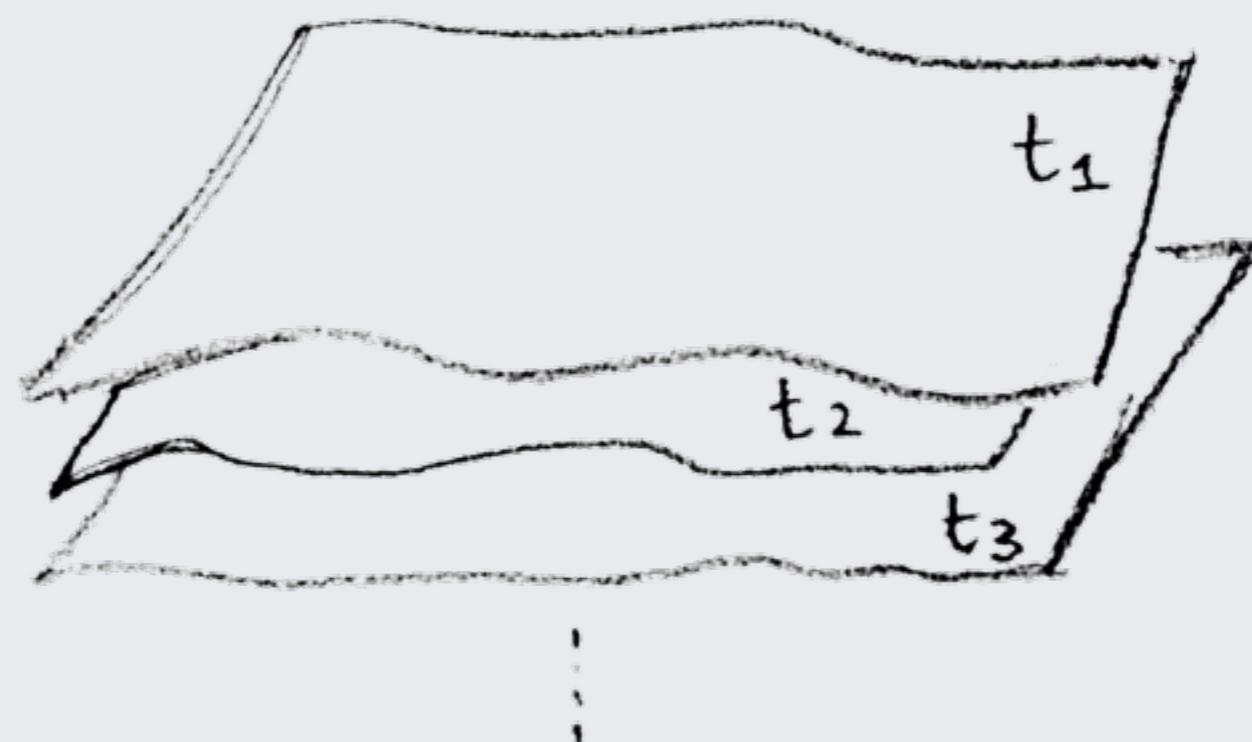
The EFT way:



The Cosmological Principle:
the universe is homogeneous and isotropic if seen by a comoving observer

Relevant limit: cosmological perturbations

As a consequence it has a maximally symmetric 3+1 foliation



[arXiv:1304.4840]

The ADM metric:

$$ds^2 = -N^2 dt^2 + h_{ij} (dx^i + N^i dt) (dx^j + N^j dt)$$

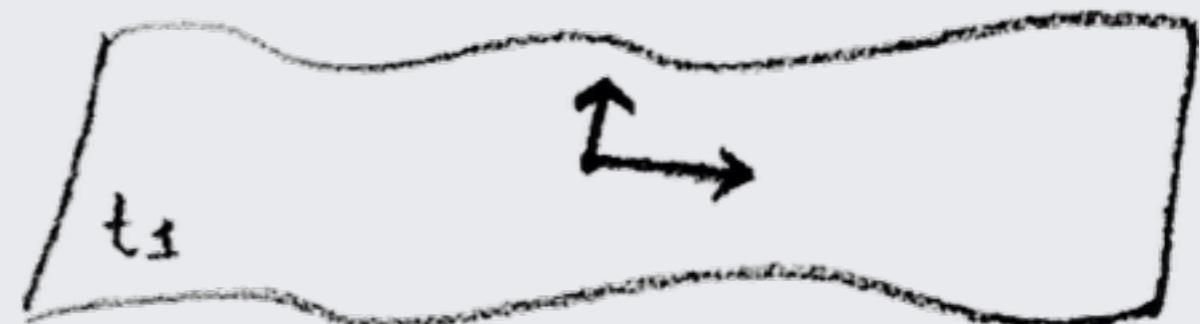
$N(t, x)$ = lapse

$N^i(t, x)$ = shift

h_{ij} = 3D metric

Normal vector, extrinsic and intrinsic curvature:

$$n_\mu = N \delta_{\mu 0}, \quad K_{\mu\nu} = h_\mu^\lambda \nabla_\lambda n_\nu$$



What are all the scalar quantities that we can define here:

$$\begin{aligned} K &\equiv K^\mu_\mu, & \mathcal{R} &\equiv R^{(3)}, \\ \mathcal{S} &\equiv K_{\mu\nu}K^{\mu\nu}, & \mathcal{Z} &\equiv R_{\mu\nu}^{(3)}R_{(3)}^{\mu\nu} \end{aligned}$$

The most general theory of gravity on the foliation
will depend on all of them:

$$S = \int d^4x \sqrt{-g} \mathcal{L}(N, K, \mathcal{R}, \mathcal{S}, \mathcal{Z}; t)$$

Where to stop?

There are other quantities that we can add:

Lorentz violating terms:

$$\mathcal{Z}_1 = \nabla_i \mathcal{R} \nabla^i \mathcal{R}, \quad \mathcal{Z}_2 = \nabla_i \mathcal{R}_{jk} \nabla^i \mathcal{R}^{jk},$$
$$\alpha_1 = a^i a_i, \quad \alpha_2 = a^i \Delta a_i, \quad \alpha_3 = \mathcal{R} \nabla_i a^i, \quad \alpha_4 = a_i \Delta^2 a^i, \quad \alpha_5 = \Delta \mathcal{R} \nabla_i a^i,$$

[arXiv:1409.1984v2, arXiv:1601.04064v2] they didn't stop...

Higher order terms:

$$K^\mu_\alpha K^\alpha_\beta K^\beta_\mu$$

Now expand the EFT Lagrangian in perturbations:

$$\begin{aligned}\mathcal{L} \simeq & +\bar{\mathcal{L}} + \frac{\partial \mathcal{L}}{\partial N} \delta N + \frac{\partial \mathcal{L}}{\partial K} \delta K + \dots \\ & + \frac{1}{2} \left(+\delta N \frac{\partial}{\partial N} + \delta K \frac{\partial}{\partial K} + \dots \right)^2 \mathcal{L} + O(3)\end{aligned}$$

Now expand the EFT Lagrangian in perturbations:

Average Lagrangian

$$\mathcal{L} \simeq +\bar{\mathcal{L}} + \frac{\partial \mathcal{L}}{\partial N} \delta N + \frac{\partial \mathcal{L}}{\partial K} \delta K + \dots$$

First order action
Cosmological background

$$+ \frac{1}{2} \left(+\delta N \frac{\partial}{\partial N} + \delta K \frac{\partial}{\partial K} + \dots \right)^2 \mathcal{L} + O(3)$$

Second order action
Cosmological perturbations

Now expand the EFT Lagrangian in perturbations:

$$\begin{aligned}\mathcal{L} \simeq & +\bar{\mathcal{L}} + \frac{\partial \mathcal{L}}{\partial N} \delta N + \frac{\partial \mathcal{L}}{\partial K} \delta K + \dots \\ & + \frac{1}{2} \left(+\delta N \frac{\partial}{\partial N} + \delta K \frac{\partial}{\partial K} + \dots \right)^2 \mathcal{L} + O(3)\end{aligned}$$

Derivatives evaluated on the background -> **functions of time only**

See why we excluded higher powers of operators?

After some algebraic reshuffling this can be casted in a more familiar (?) form

only real trick is the Gauss-Codazzi relation

$$R = \mathcal{R} + K_{\mu\nu}K^{\mu\nu} - K^2 + 2\nabla_\nu(n^\nu\nabla_\mu n^\mu - n^\mu\nabla_\mu n^\nu).$$

If interested in the details here's the references...
[arXiv:1304.4840, arXiv:1601.04064]

$$\begin{aligned} S = \int d^4x \sqrt{-g} & \left\{ \frac{m_0^2}{2} [1 + \Omega(\tau)] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \right. \\ & + \frac{M_2^4(\tau)}{2} (a^2 \delta g^{00})^2 - \frac{\bar{M}_1^3(\tau)}{2} a^2 \delta g^{00} \delta K_\mu^\mu - \frac{\bar{M}_2^2(\tau)}{2} (\delta K_\mu^\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2} \delta K_\nu^\mu \delta K_\mu^\nu \\ & \left. + \frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)} + m_2^2(\tau) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00}) \partial_\nu (a^2 g^{00}) \right\} + S_m[g_{\mu\nu}] \end{aligned}$$

Where are we?

$$\begin{aligned}
 S = \int d^4x \sqrt{-g} & \left\{ \frac{m_0^2}{2} [1 + \Omega(\tau)] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \right. \\
 & + \frac{\bar{M}_2^4(\tau)}{2} (a^2 \delta g^{00})^2 - \frac{\bar{M}_1^3(\tau)}{2} a^2 \delta g^{00} \delta K_\mu^\mu - \frac{\bar{M}_2^2(\tau)}{2} (\delta K_\mu^\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2} \delta K_\nu^\mu \delta K_\mu^\nu \\
 & \left. + \frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)} + m_2^2(\tau) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00}) \partial_\nu (a^2 g^{00}) \right\} + S_m[g_{\mu\nu}]
 \end{aligned}$$

here, along with all other matter species

What are the assumptions about the matter sector?

$$S_m[g_{\mu\nu}, \Psi_m]$$

In writing this we implicitly assume that matter is minimally and universally coupled to the metric tensor

This means that particles of the m specie would travel on geodesics of g in absence of non-gravitational forces

Connection to the Einstein frame

The Einstein frame is a conformal frame where the EH part of the action is not modified

$$g_{\mu\nu} = f^{-1} \hat{g}_{\mu\nu}$$

$$\sqrt{-g} = f^{-2} \sqrt{-\hat{g}} ,$$

$$R = f \left(R_E + 3 \hat{\square} \ln f - \frac{3}{2} \hat{g}^{\mu\nu} \partial_\mu \ln f \partial_\nu \ln f \right)$$

Is GR conformal invariant?

After an appropriate conformal transformation

$$\begin{aligned} S = & \int d^4x \sqrt{-g} \left[\frac{RM_*^2}{2} - cg^{00} - \Lambda \right. \\ & + \frac{M_2^4}{2} (\delta g^{00})^2 + \frac{M_3^4}{3!} (\delta g^{00})^3 + \dots - \frac{\bar{m}_1^3}{2} \delta g^{00} \delta K - \frac{\bar{M}_2^2}{2} \delta K^2 + \dots \left. \right] \\ & + S_m [f^{-1}(t) g_{\mu\nu}, \psi_i] , \end{aligned}$$

details here: arXiv:1210.0201
notice difference in notation...sigh...

Is the structure of the EFT unchanged?

Where is the trick?

We have broken time translations

$t \rightarrow t + \alpha$ does not leave invariant the action

Stuckelberg trick

$$t \rightarrow t + \pi(x^\mu)$$

Now under an infinitesimal coordinate transformation:

$$\tilde{t} = t + \xi^0(x^\mu), \quad \tilde{\pi} = \pi - \xi^0(x^\mu)$$

$t + \pi$ is invariant

Apply this to the EFT action: transform all pieces and expand

$$f(t) \rightarrow f(t + \pi) \approx f(t) + \dot{f}(t)\pi + \frac{\ddot{f}(t)}{2}\pi^2 + \dots$$

$$g^{00} \rightarrow \frac{\partial(t + \pi(x^\lambda))}{\partial x^\mu} \frac{\partial(t + \pi(x^\lambda))}{\partial x^\nu} g^{\mu\nu} = g^{00} - 2\dot{\pi} + 2\dot{\pi}\delta g^{00} + 2\tilde{\nabla}_i \pi g^{0i} - \dot{\pi}^2 + \frac{(\tilde{\nabla}\pi)^2}{a^2},$$

$$\begin{aligned} K^0{}_0 &\rightarrow K^0{}_0, \\ K^0{}_i &\rightarrow K^0{}_i + H\tilde{\nabla}_i \pi, \\ K^i{}_0 &\rightarrow K^i{}_0 - H\frac{\tilde{g}^{ij}}{a^2}\tilde{\nabla}_j \pi, \\ K^i{}_j &\rightarrow K^i{}_j + \frac{\tilde{g}^{ik}}{a^2}\tilde{\nabla}_k \tilde{\nabla}_j \pi. \end{aligned}$$

details here [arXiv:1211.7054]

Apply this to the EFT action

$$\begin{aligned}
S = \int d^4x \sqrt{-g} & \left\{ \frac{m_0^2}{2} [1 + \Omega(\tau + \pi)] R + \Lambda(\tau + \pi) - c(\tau + \pi)a^2 \left[\delta g^{00} - 2\frac{\dot{\pi}}{a^2} + 2\mathcal{H}\pi \left(\delta g^{00} - \frac{1}{a^2} - 2\frac{\dot{\pi}}{a^2} \right) + 2\dot{\pi}\delta g^{00} \right. \right. \\
& + 2g^{0i}\partial_i\pi - \frac{\dot{\pi}^2}{a^2} + g^{ij}\partial_i\pi\partial_j\pi - \left(2\mathcal{H}^2 + \dot{\mathcal{H}} \right) \frac{\pi^2}{a^2} + \dots] \\
& + \frac{M_2^4(\tau + \pi)}{2} a^4 \left(\delta g^{00} - 2\frac{\dot{\pi}}{a^2} - 2\frac{\mathcal{H}\pi}{a^2} + \dots \right)^2 \\
& - \frac{\bar{M}_1^3(\tau + \pi)}{2} a^2 \left(\delta g^{00} - 2\frac{\dot{\pi}}{a^2} - 2\frac{\mathcal{H}\pi}{a^2} + \dots \right) \left(\delta K^\mu{}_\mu + 3\frac{\dot{\mathcal{H}}}{a}\pi + \frac{\bar{\nabla}^2\pi}{a^2} + \dots \right) \\
& - \frac{\bar{M}_2^2(\tau + \pi)}{2} \left(\delta K^\mu{}_\mu + 3\frac{\dot{\mathcal{H}}}{a}\pi + \frac{\bar{\nabla}^2\pi}{a^2} + \dots \right)^2 \\
& - \frac{\bar{M}_3^2(\tau + \pi)}{2} \left(\delta K^i{}_j + \frac{\dot{\mathcal{H}}}{a}\pi\delta^i{}_j + \frac{1}{a^2}\bar{\nabla}^i\bar{\nabla}_j\pi + \dots \right) \left(\delta K^j{}_i + \frac{\dot{\mathcal{H}}}{a}\pi\delta^j{}_i + \frac{1}{a^2}\bar{\nabla}^j\bar{\nabla}_i\pi + \dots \right) \\
& + \frac{\hat{M}^2(\tau + \pi)}{2} a^2 \left(\delta g^{00} - 2\frac{\dot{\pi}}{a^2} - 2\frac{\mathcal{H}}{a^2}\pi + \dots \right) \left(\delta R^{(3)} + 4\frac{\mathcal{H}}{a}\bar{\nabla}^2\pi + \dots \right) \\
& \left. + m_2^2(\tau + \pi) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00} - 2\dot{\pi} - 2\mathcal{H}\pi + \dots) \partial_\nu (a^2 g^{00} - 2\dot{\pi} - 2\mathcal{H}\pi + \dots) + \dots \right\} + S_m[g_{\mu\nu}, \chi_i],
\end{aligned}$$

Why a scalar field?

It's the Goldstone boson of time translations

FRW background itself breaks time translations

everything that respects the FRW background is going
to have at least this form

(connection with unitary gauge)

Is there any difference between DE and MG?

Possible extensions

The ultimate limit of the idea of the EFT of DE/MG
is the cosmological principle

- Additional scalar, vector and tensor fields [arXiv:1604.01396]
- Non-universal couplings [arXiv:1504.05481, arXiv:1609.01272]
- Higher order terms in derivatives [arXiv:1409.1984, arXiv:1601.04064]
- Higher order in perturbation theory [?]

How to use the EFT

Two ways to approach the EFT

1 fix the form of the EFT functions with a model

2 study the EFT functions

Map models into the EFT framework

1

quintessence

$$\mathcal{S}_\phi = \int d^4x \sqrt{-g} \left[\frac{m_0^2}{2} R - \frac{1}{2} \partial^\nu \phi \partial_\nu \phi - V(\phi) \right],$$

$$\Omega(t) = 0, \quad c(t) = \frac{\dot{\phi}_0^2}{2}, \quad \Lambda(t) = \frac{\dot{\phi}_0^2}{2} - V(\phi_0).$$

Map models into the EFT framework

2

f(R) gravity

$$\mathcal{S}_f = \int d^4x \sqrt{-g} \frac{m_0^2}{2} [R + f(R)],$$

$$\Omega(t) = f_R(R^{(0)}), \quad \Lambda(t) = \frac{m_0^2}{2} f(R^{(0)}) - R^{(0)} f_R(R^{(0)}).$$

Map models into the EFT framework

3

Galileons/Horndeski

4

Beyond Horndeski

5

Horava gravity

...

...many more...

Stability of perturbations

Positive Newtonian constant

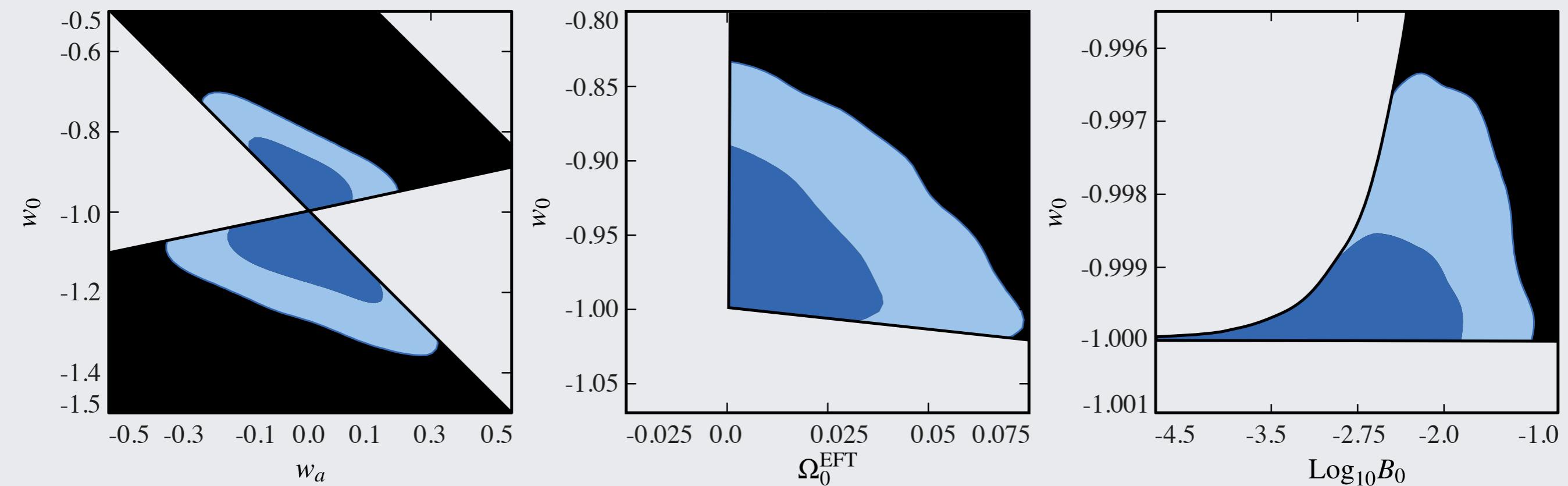
No ghost instabilities

No gradient instabilities

Positive mass of the scalar

Priors for the model

Very technical (and complicated) discussion.
Some of it in all EFT of DE/MG papers.
Especially [arXiv:1609.03599v1].



minimally coupled 5e
on CPL background

linear Omega
on wCDM background

designer $f(R)$ on
wCDM background

Phenomenology

Cosmological background

Linear scalar perturbations

Linear tensor perturbations

Non-linear perturbations

Cosmological background

$$\begin{aligned}\mathcal{H}^2 &= \frac{a^2}{3m_0^2(1+\Omega)}(\rho_m + 2c - \Lambda) - \mathcal{H}\frac{\dot{\Omega}}{1+\Omega}, \\ \dot{\mathcal{H}} &= -\frac{a^2}{6m_0^2(1+\Omega)}(\rho_m + 3P_m) - \frac{a^2(c+\Lambda)}{3m_0^2(1+\Omega)} - \frac{\ddot{\Omega}}{2(1+\Omega)}.\end{aligned}$$

Complete freedom at the background level

$$\mathcal{H}^2 = \frac{8\pi G}{3}a^2(\rho_m + \rho_{\text{DE}} + \rho_\nu),$$

$$\rho_{\text{DE}} = \frac{3H_0^2}{8\pi G}\Omega_{\text{DE}}^0 \exp\left[-3\int_1^a \frac{(1+w_{\text{DE}}(a))}{a} da\right],$$

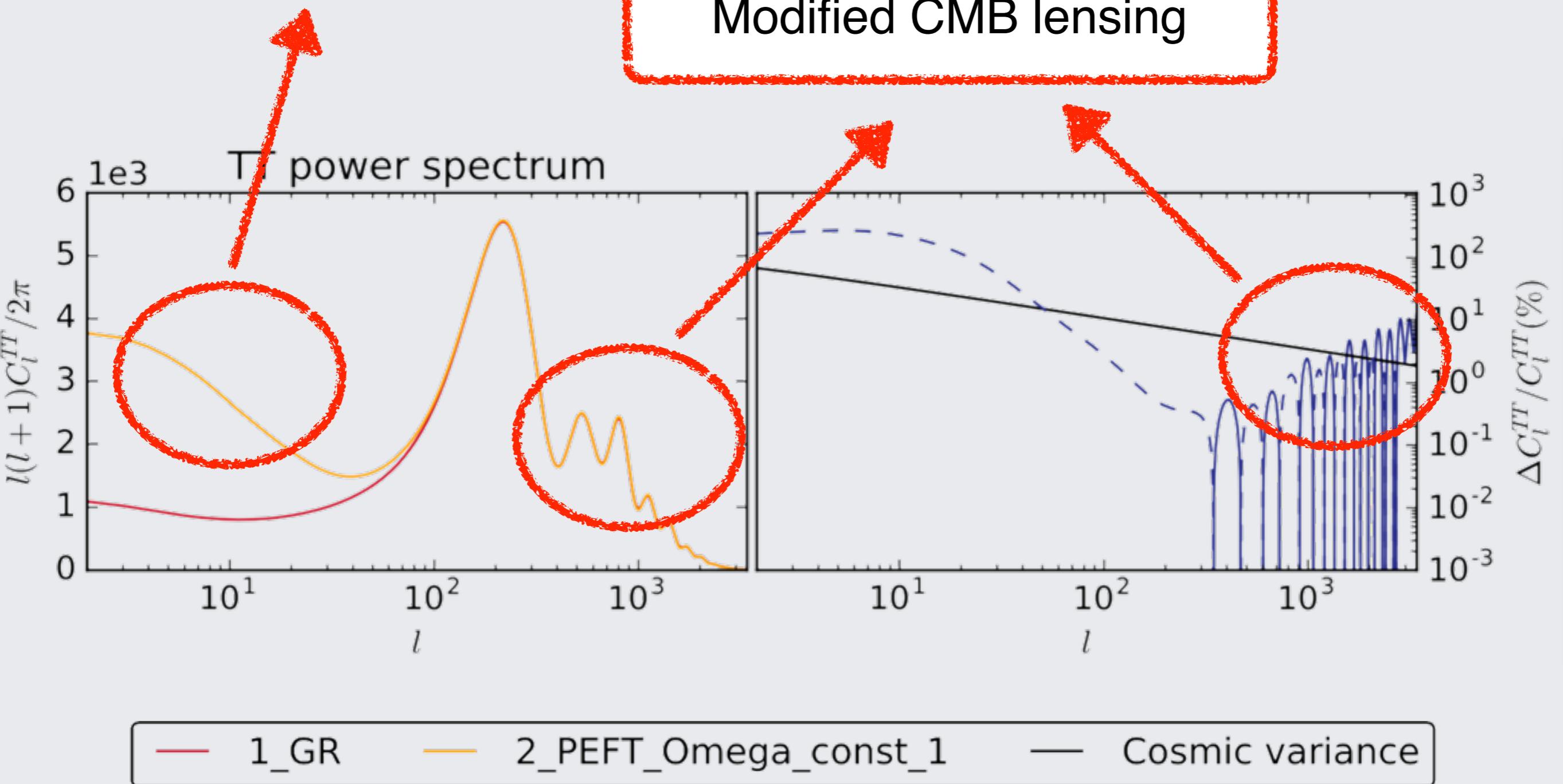
Linear scalar perturbations

Behavior is strongly model dependent.

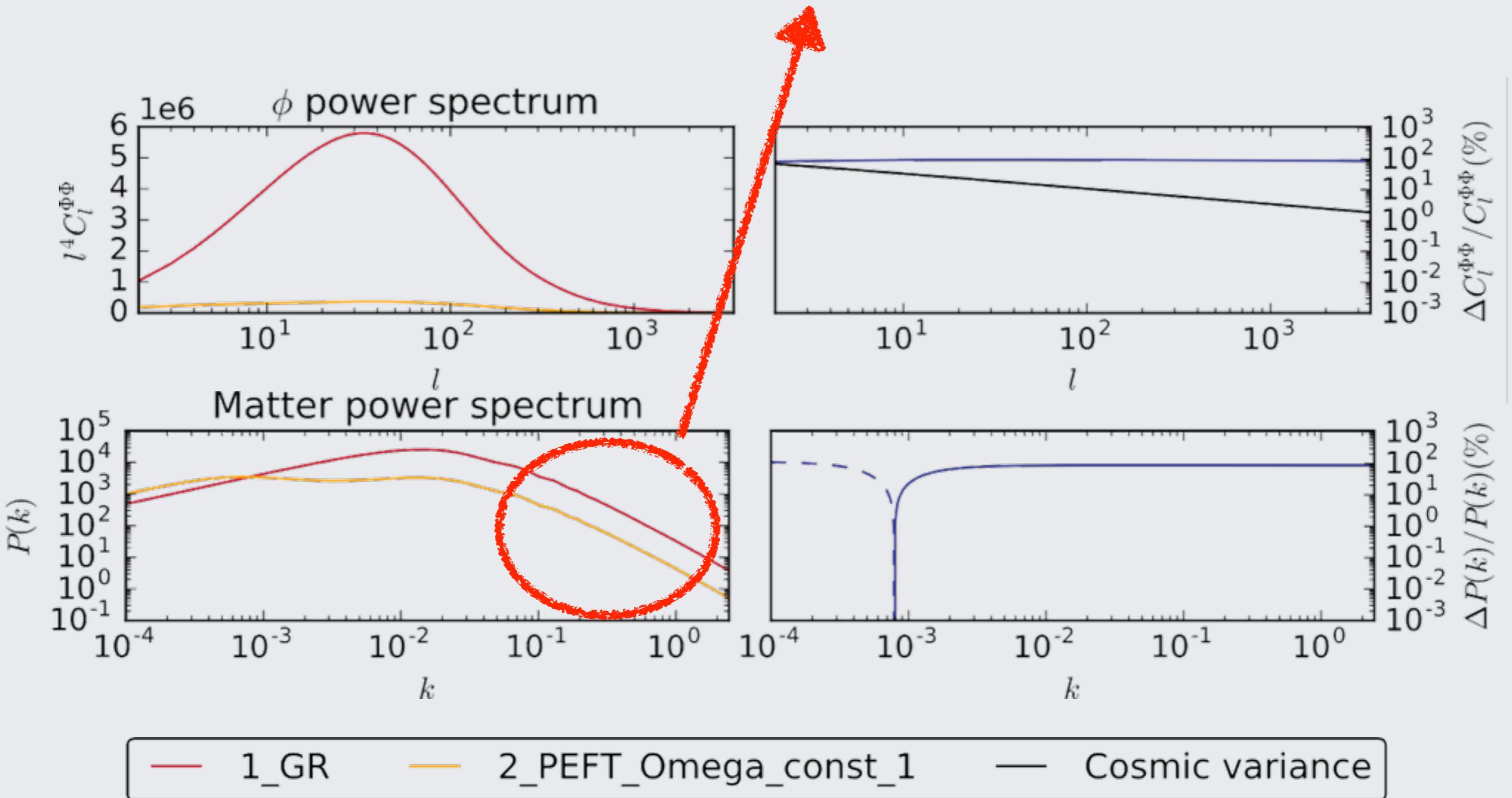
Very difficult (if not impossible) to get non-approximate
and general analytic results

Modification of the ISW effect

Modified CMB lensing

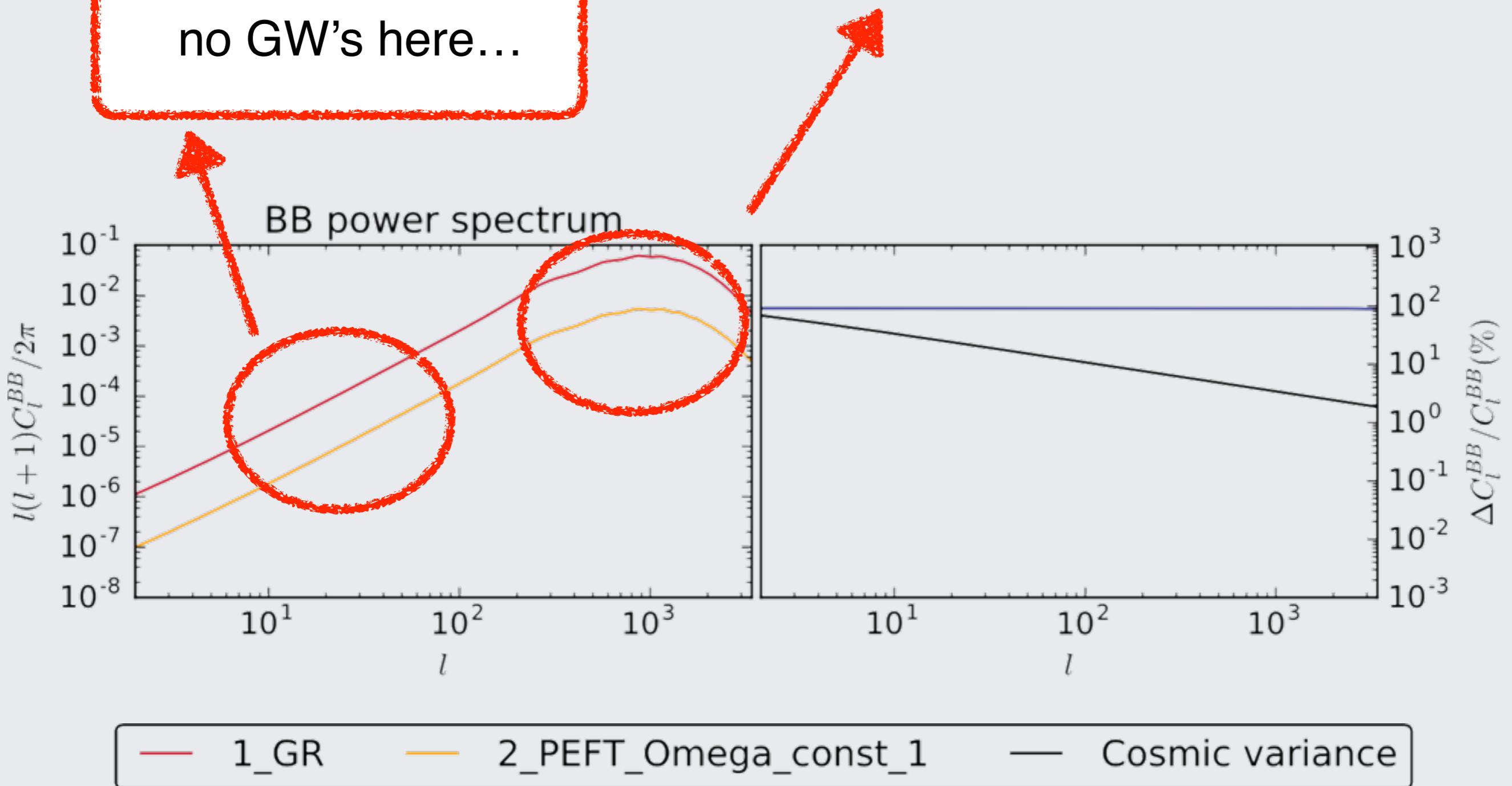


Modified growth of perturbations: $\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} - 4\pi G\delta\rho_0 = 0.$



The price of modifying lensing...

no GW's here...



Linear tensor perturbations

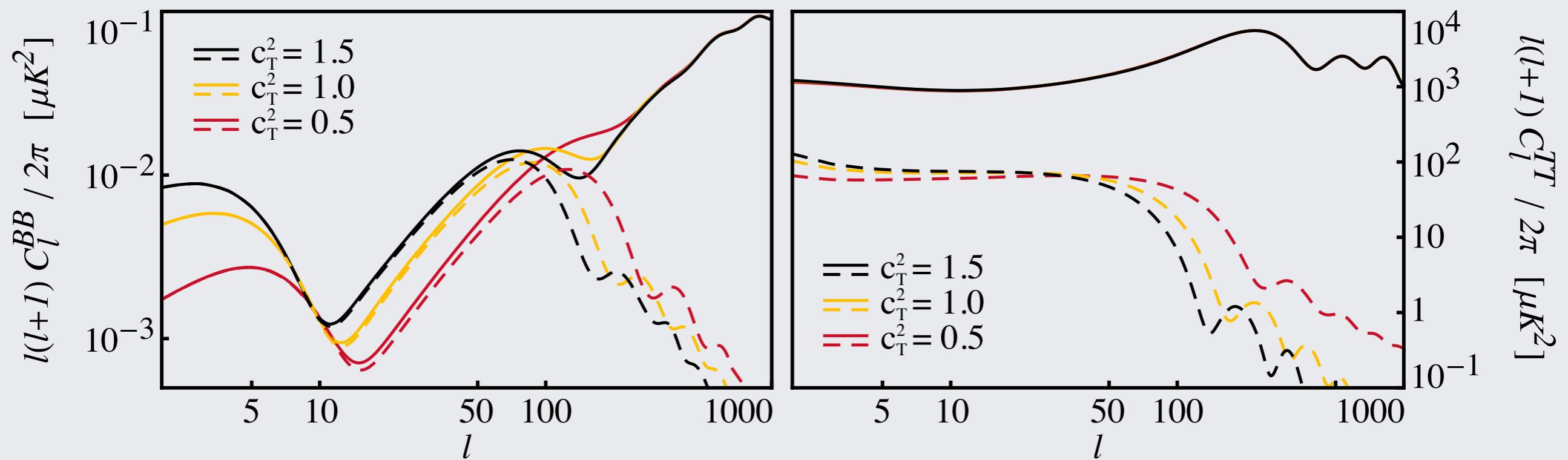
$$A_T(\tau)\ddot{h}_{ij} + B_T(\tau)\dot{h}_{ij} + D_T(\tau)k^2 h_{ij} + E_{Tij} = 0,$$

$$A_T = 1 + \Omega - \gamma_4 ,$$

$$D_T = 1 + \Omega ,$$

$$B_T = 2\mathcal{H} \left(1 + \Omega - \gamma_4 + \frac{a\Omega'}{2} - a\frac{\gamma_4'}{2} \right) ,$$

$$E_{Tij} = \frac{a^2}{m_0^2} \delta T_{ij} ,$$



Non-linear perturbations



[arXiv:1611.07966]

EFTCAMB

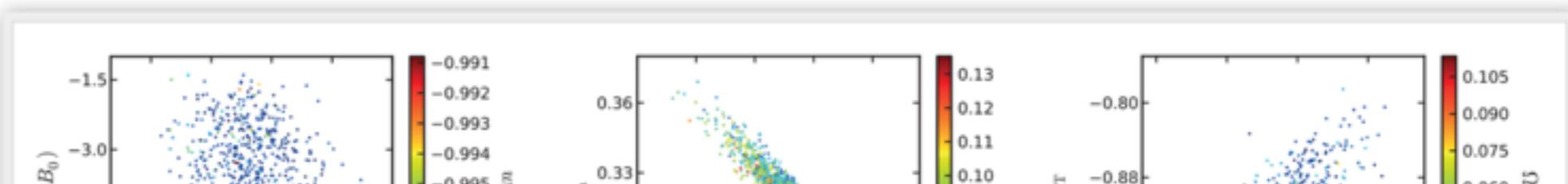
- Patch of CAMB/CosmoMC: full perturbative Boltzmann-Einstein equations;
- No approximations: NO quasi-static, NO sub-horizon;
- Complete set of perturbative equations: include all second order EFT operators;
- Various expansion histories: LCDM, wCDM, CPL +...
- Pure EFT mode: study the underlying DE/MG theory through a parametrization of the EFT functions;
- Mapping EFT mode: study a single model. Built-in $f(R)$, minimally coupled quintessence, Horava gravity. More to come very soon!
- Exploration of parameter space and comparison with cosmological datasets with a built in theoretical viability check.



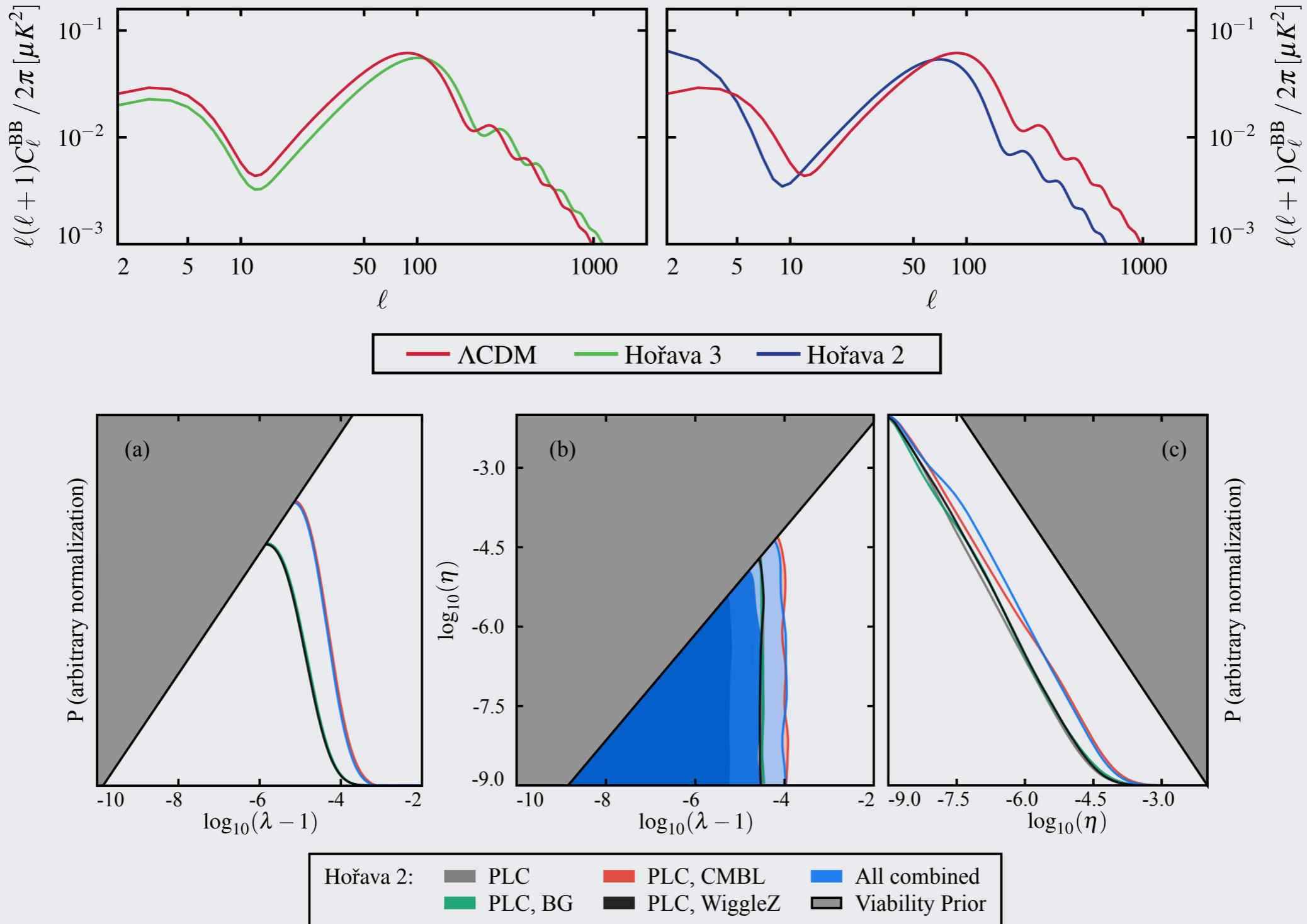
Effective Field Theory with CAMB

By [B. Hu](#), [M. Raveri](#), [N. Frusciante](#) and [A. Silvestri](#)

EFTCAMB is a patch of the public Einstein-Boltzmann solver CAMB, which implements the Effective Field Theory approach to cosmic acceleration. The code can be used to investigate the effect of different EFT operators on linear perturbations as well as to study perturbations in any specific DE/MG model that can be cast into EFT framework. To interface EFTCAMB with cosmological data sets, we equipped it with a modified version of CosmoMC, namely EFTCosmoMC, creating a bridge between the EFT parametrization of the dynamics of perturbations and observations.

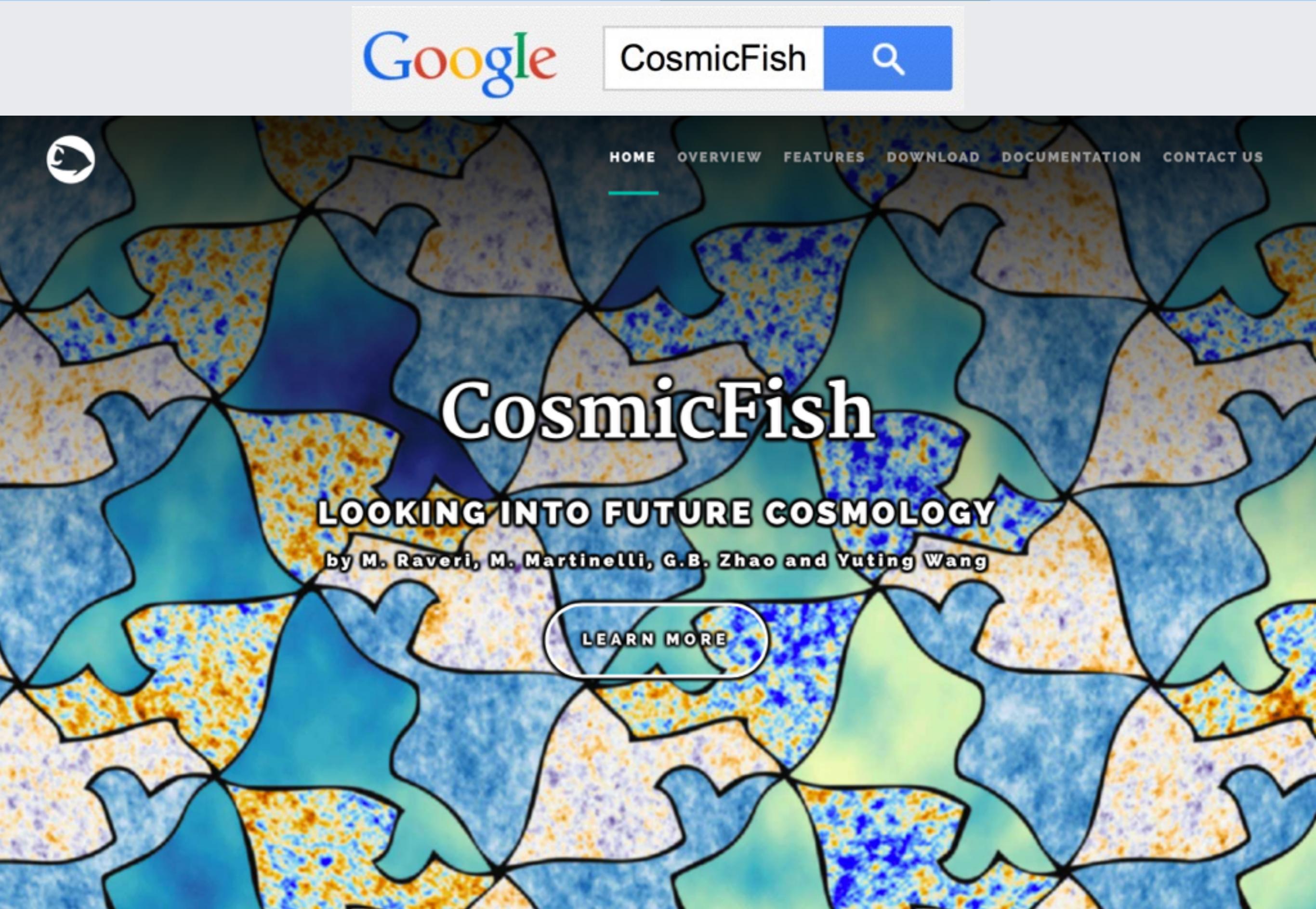


From the cosmology of a model to data constraints

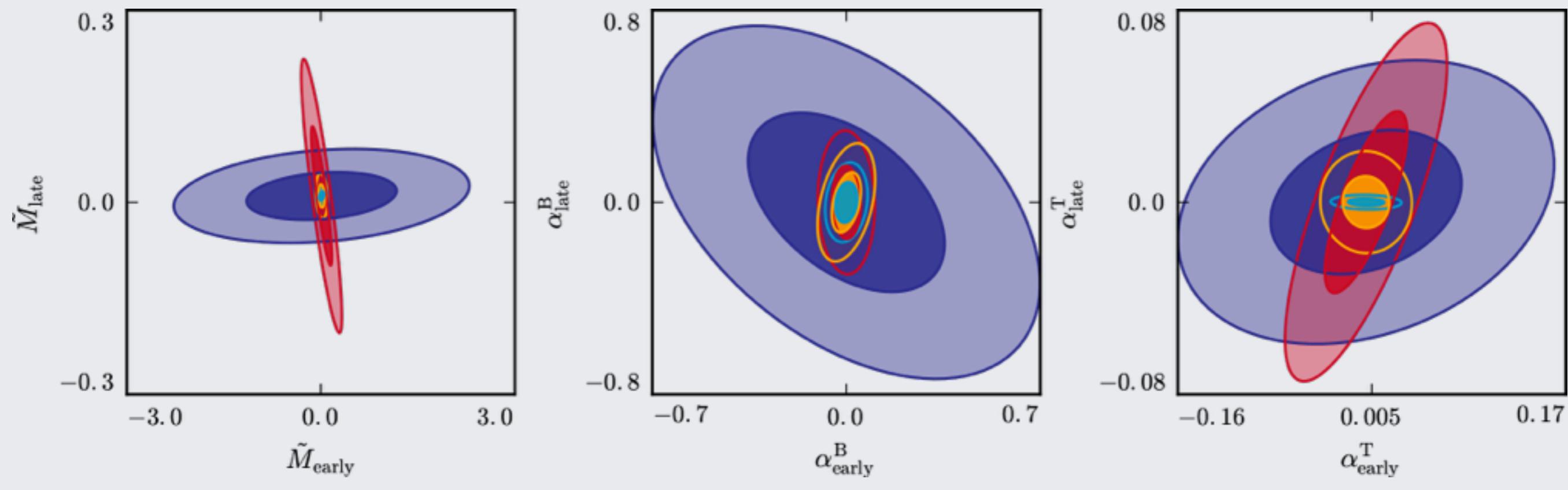


CosmicFish

- Standalone code to perform Fisher matrix forecasts;
- Most of the cosmological observables of interest;
- State of the art algorithm and strongly optimized;
- Modern software design: fully modular, unit testing, complete documentation, ...;
- Uses EFTCAMB to ensure wide coverage of DE/MG models;



...to the future of a model



JOIN THE DARK SIDE



RULE THE UNIVERSE

- Modern approaches to DE and MG phenomenology;
- Unify in a single box these two types of models;
- Possibly capture phenomenological features of models in the space of solutions to the CC problem;
- Use it to test gravity on cosmological scales if not possible;
- Gear them up to be stand the experimental challenge of the next decade.

EFTCAMB

May the fifth force be with you

the EFTCAMB team