

Ciao Tutti!

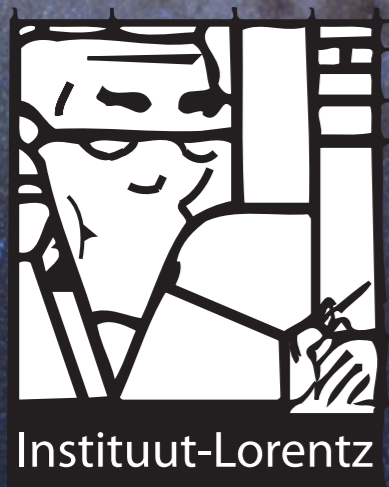
Effective Field Theory approach for Dark Energy/ Modified Gravity



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Padova, May, 2015



Instituut-Lorentz

Effective Field Theory with CAMB



[Hu et.al. [PRD89,103530\(2014\)](#); [PRD90,043513\(2014\)](#); [PRD91,063524\(2015\)](#)]

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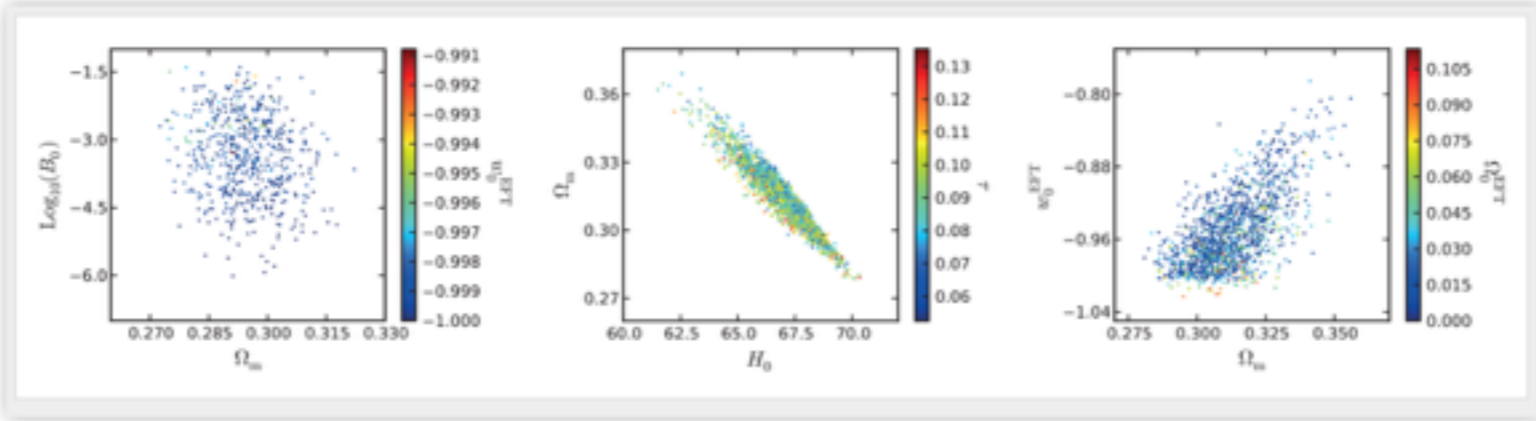
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EFTCAMB How to take a screenshot on your Mac - Apple Support

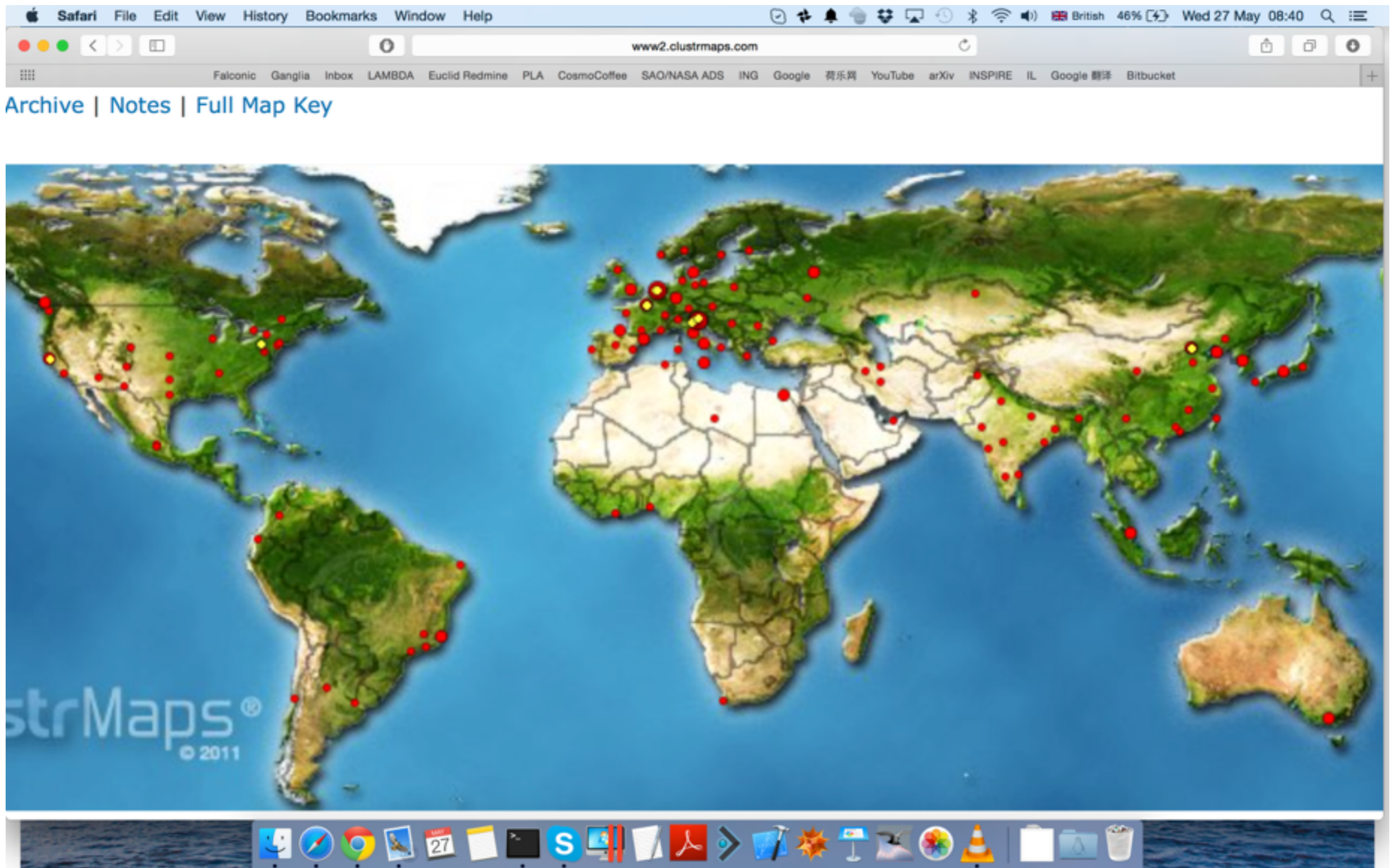
Effective Field Theory with CAMB

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.

System tray icons: Mail, Safari, Chrome, Calendar (27), Notes, Terminal, Slack, VS Code, PDF Reader, File Explorer, System Settings, Network, Volume, Bluetooth, Wi-Fi, Power.



clicked 1500+ times
but 300+ from italy and 300+ from Leiden

Outline

1. The test of gravity at linear perturbation level:
EFT for DE/MG
2. The structure of EFTCAMB
3. The results from EFTCosmoMC and Planck-2015
4. Conclusion

1. The test of gravity at linear perturbation level: EFT for DE/MG

- Effective Field Theory (EFT) approach provides generic parametrisation of the action of the scalar **perturbation** DE/MG with **single** scalar field.

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

[Bloomfield et. al. JCAP08(2013)010]

[Gubitosi et. al. JCAP 1302 (2013) 032]

* There are **7 independent** functions at linear level, EFT functions

* Ω , Λ and c relate with background operators, only one are independent

* EFT functions depend on **time** only

$$\mathcal{H}^2 = \frac{a^2}{3m_0^2(1+\Omega)}(\rho_m + 2c - \Lambda) - \mathcal{H}\frac{\dot{\Omega}}{1+\Omega},$$

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

$$c = -\frac{m_0^2\ddot{\Omega}}{2a^2} + \frac{m_0^2\mathcal{H}\dot{\Omega}}{a^2} + \frac{m_0^2(1+\Omega)}{a^2}(\mathcal{H}^2 - \dot{\mathcal{H}}) - \frac{1}{2}(\rho_m + P_m),$$

$$\Lambda = -\frac{m_0^2\ddot{\Omega}}{a^2} - \frac{m_0^2\mathcal{H}\dot{\Omega}}{a^2} - \frac{m_0^2(1+\Omega)}{a^2}(\mathcal{H}^2 + 2\dot{\mathcal{H}}) - P_m.$$

1.1 The logic of construction of the action

1. Choose the time coordinate (clock), by asking

$$\delta\varphi(t, \vec{x}) \equiv \varphi(t, \vec{x}) - \bar{\varphi}(t) = 0$$

(breaking time translation
diffeomorphism)

2. Build the block of the EFT by the operators which keep the unbroken 3D spatial Diffs

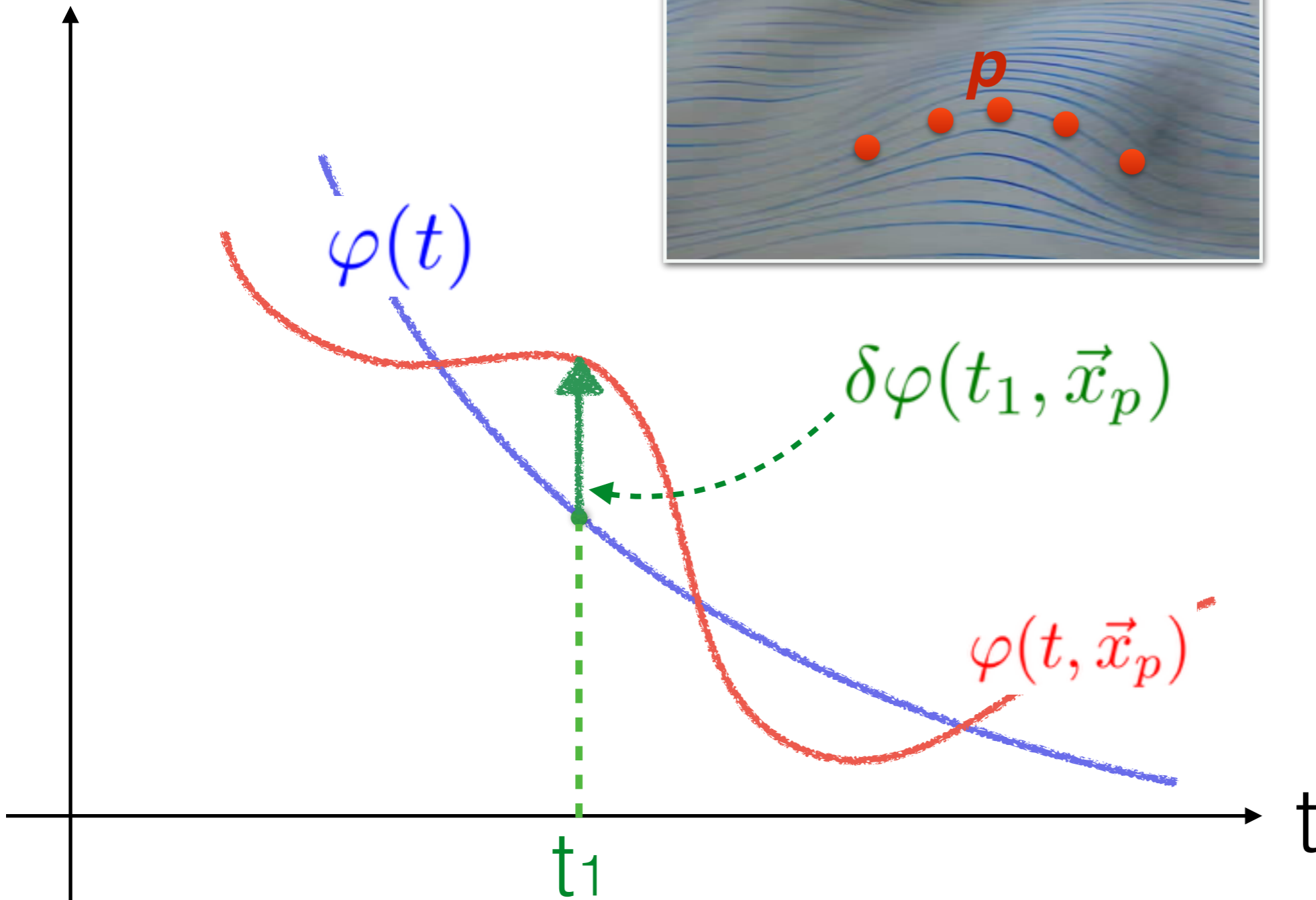
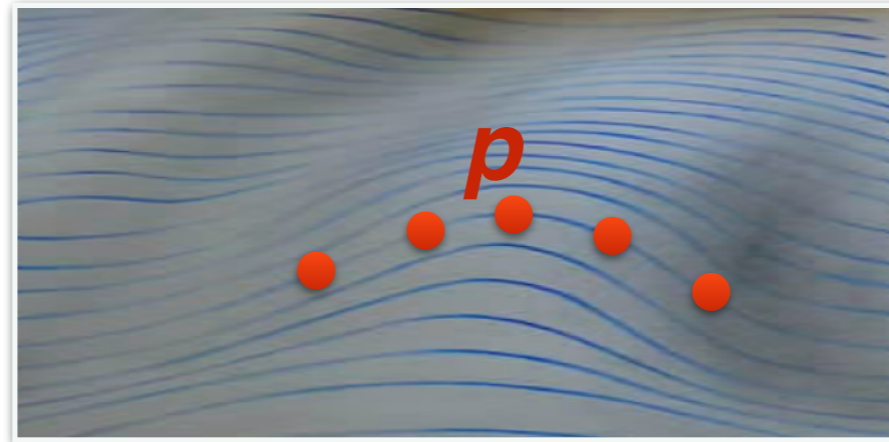
$$\delta g^{00}, \delta K_{\mu\nu}, \delta R_{\mu\nu\rho\sigma} \text{ (or } C_{\mu\nu\rho\sigma}), \delta R_{\mu\nu}, \text{ and } \delta R,$$

3. Multiply these operators by a only time dependent function

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

1.2 Another point of view of EFT

Covariant approach



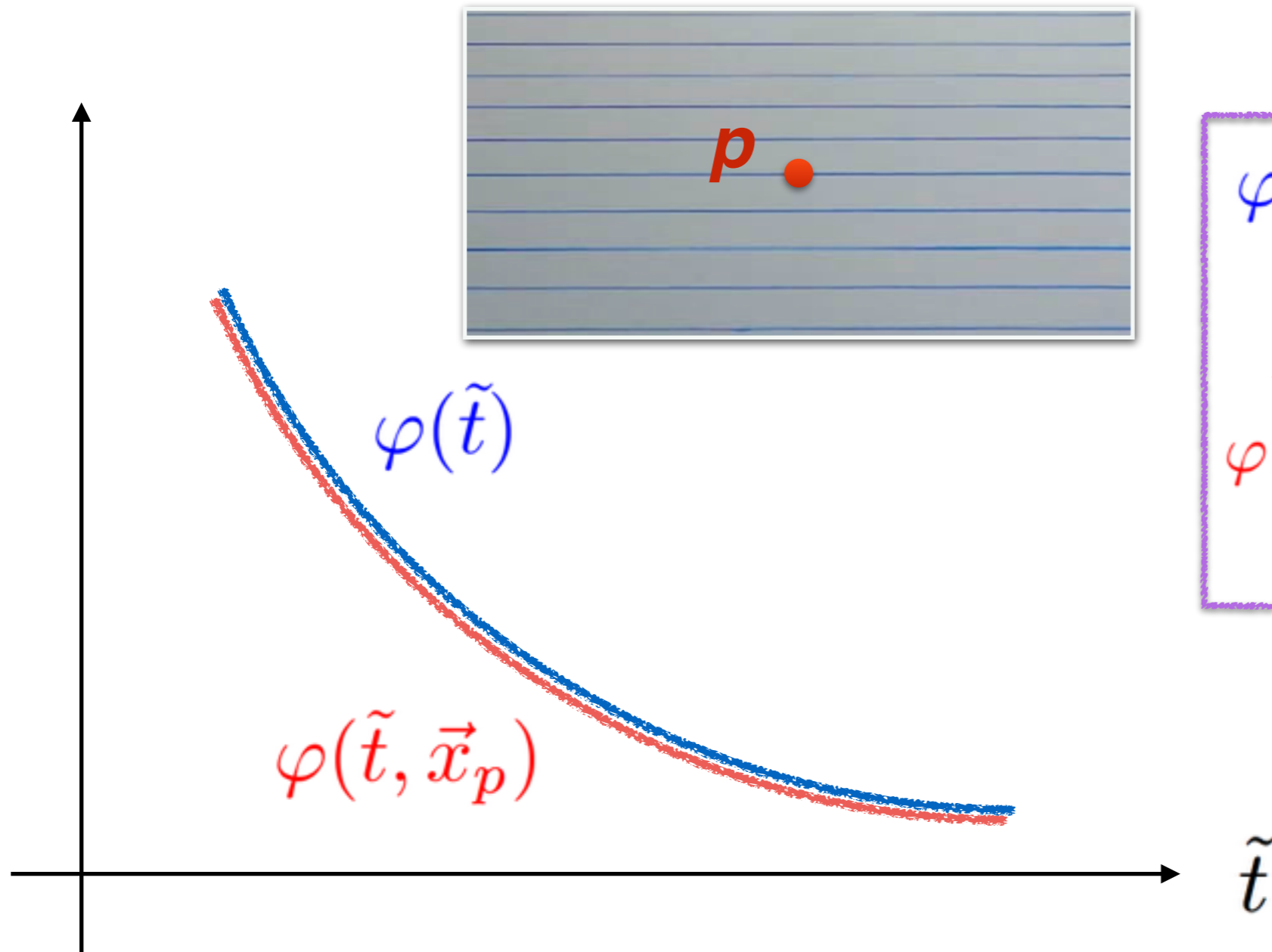
$\varphi(t)$: background
field config

$\varphi(t, \vec{x}_p)$: field config
at point 'p'

$\delta\varphi(t_1, \vec{x}_p)$: field fluct.
at point 'p'

Valid in **ALL** the gauge

EFT approach



$\varphi(\tilde{t})$: background
field config

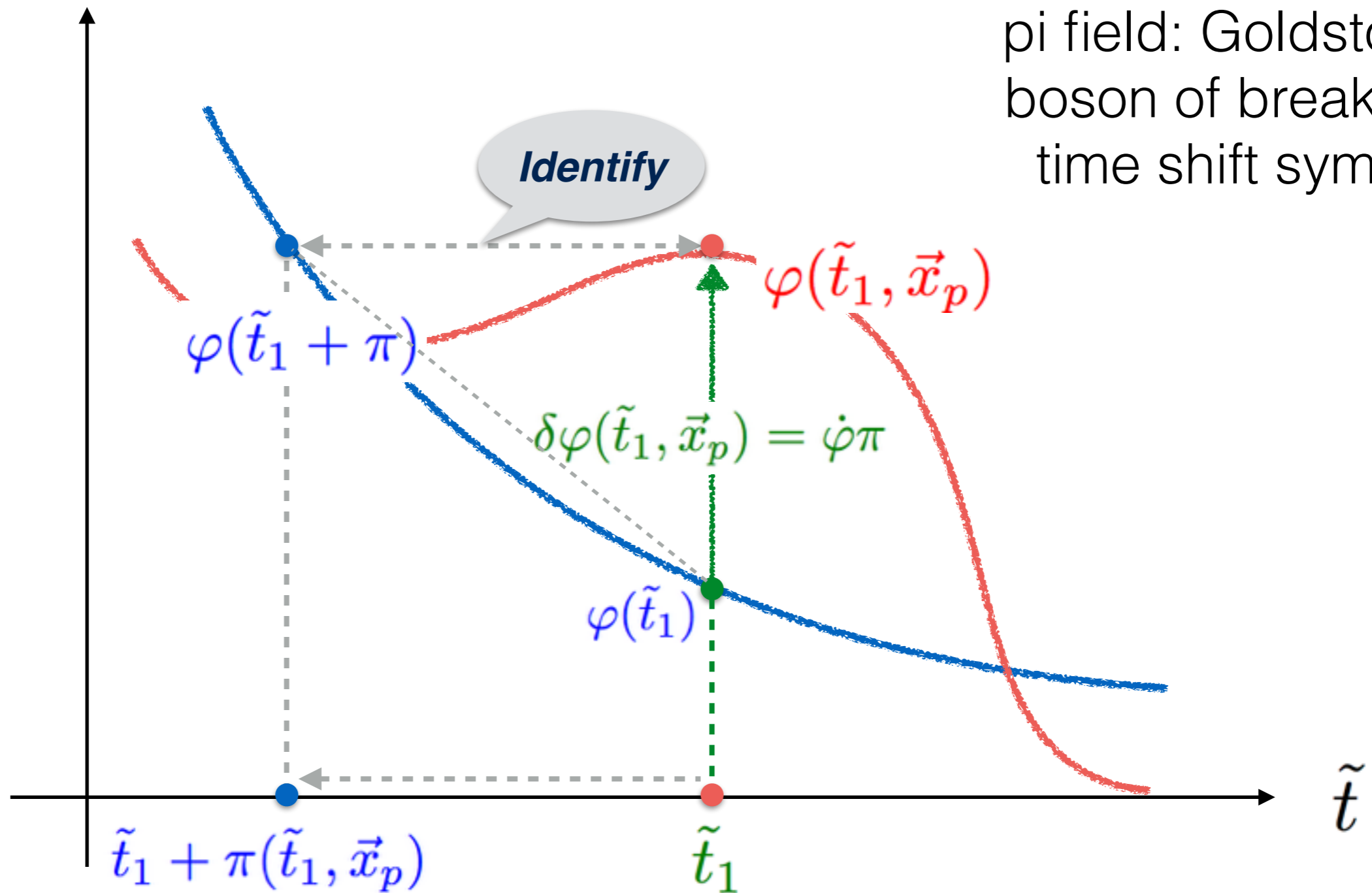
$\varphi(\tilde{t}, \vec{x}_p)$: field config
at point ' p '

Only Valid in the unitary gauge

$$\delta\varphi(t, \vec{x}) \equiv \varphi(t, \vec{x}) - \bar{\varphi}(t) = 0$$

EFT approach \Rightarrow Covariant approach

π field: Goldstone boson of breaking time shift symm



Stuckburg trick: restore full covariance

1.3 Parametrizations

1. Full mapping

(From the covariant form)

e.g.

$$f(R) = -m^2 \frac{c_1(R/m^2)^n}{c_2(R/m^2)^n + 1},$$

[Hu,Sawicki PRD76, 064004 (2007)]

$$\Lambda = \frac{m_0^2}{2} [f - Rf_R] \quad ; \quad c = 0 \quad ; \quad \Omega = f_R$$

(Work in progress with Rizzato et. al.)

2. Pure EFT parametrization

(Phenomenological param)

Constant models: $\Omega(a) = \Omega_0$;

Linear models: $\Omega(a) = \Omega_0 a$;

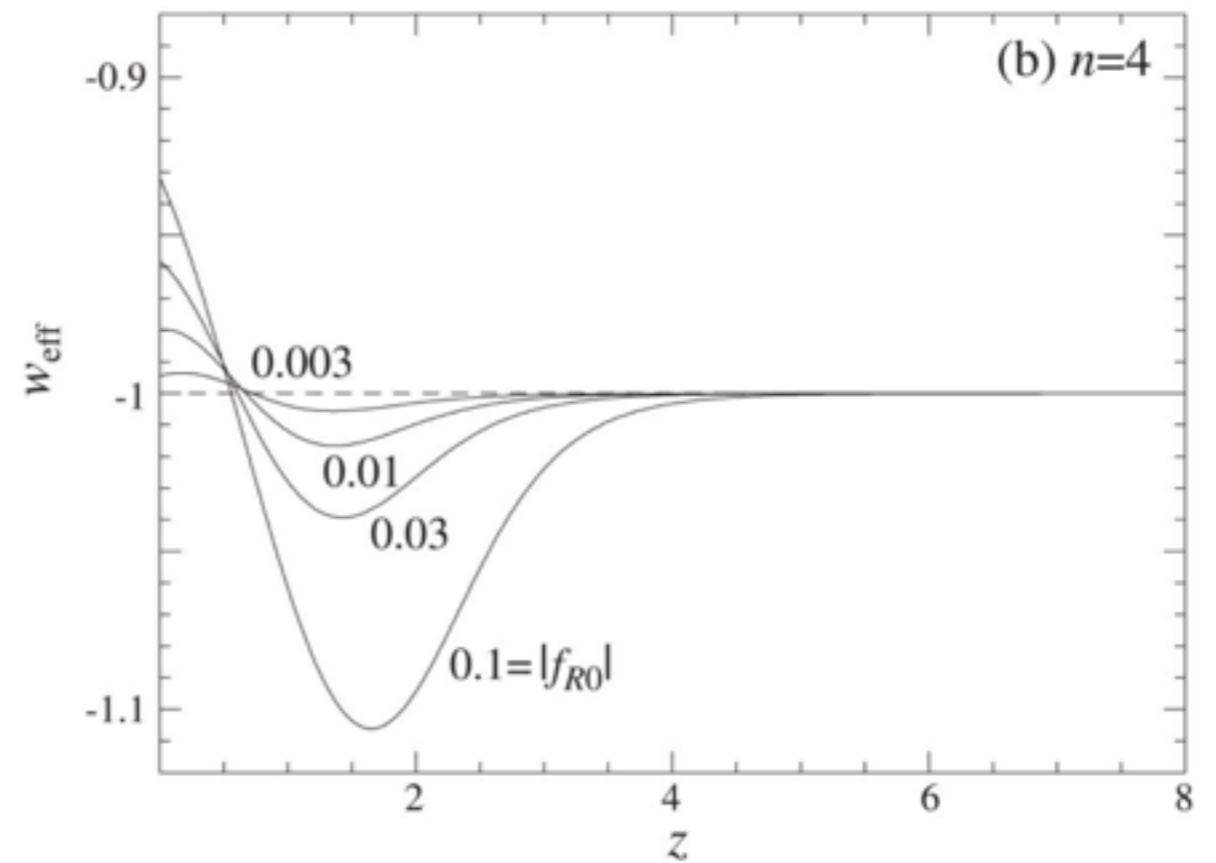
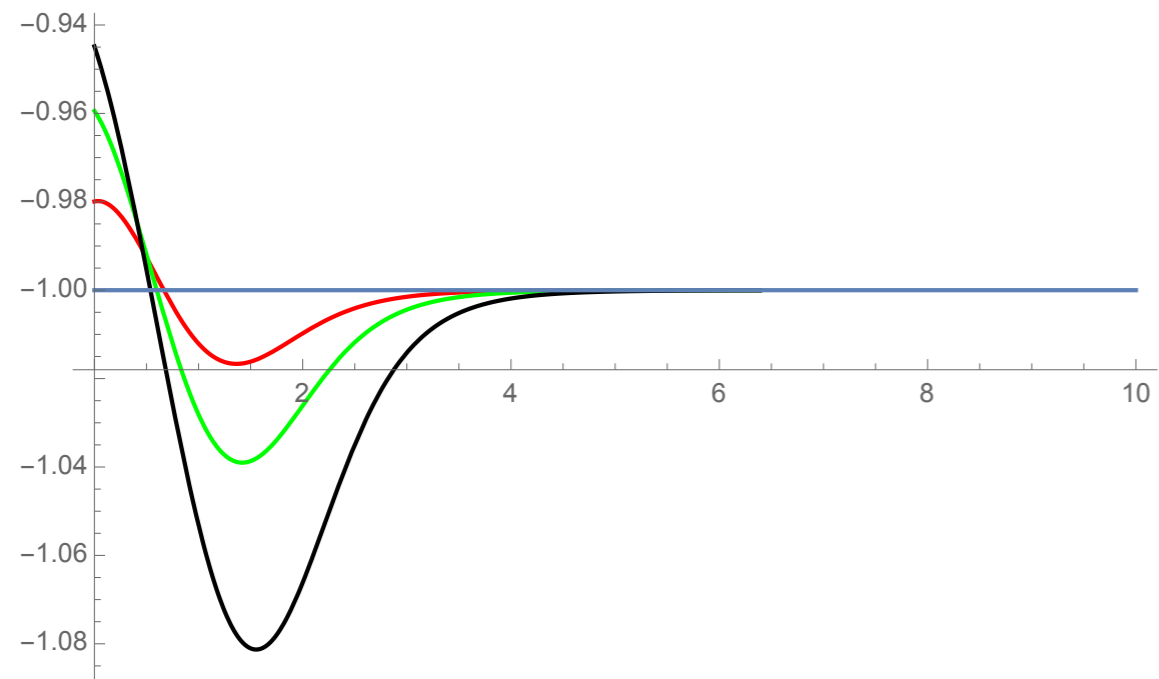
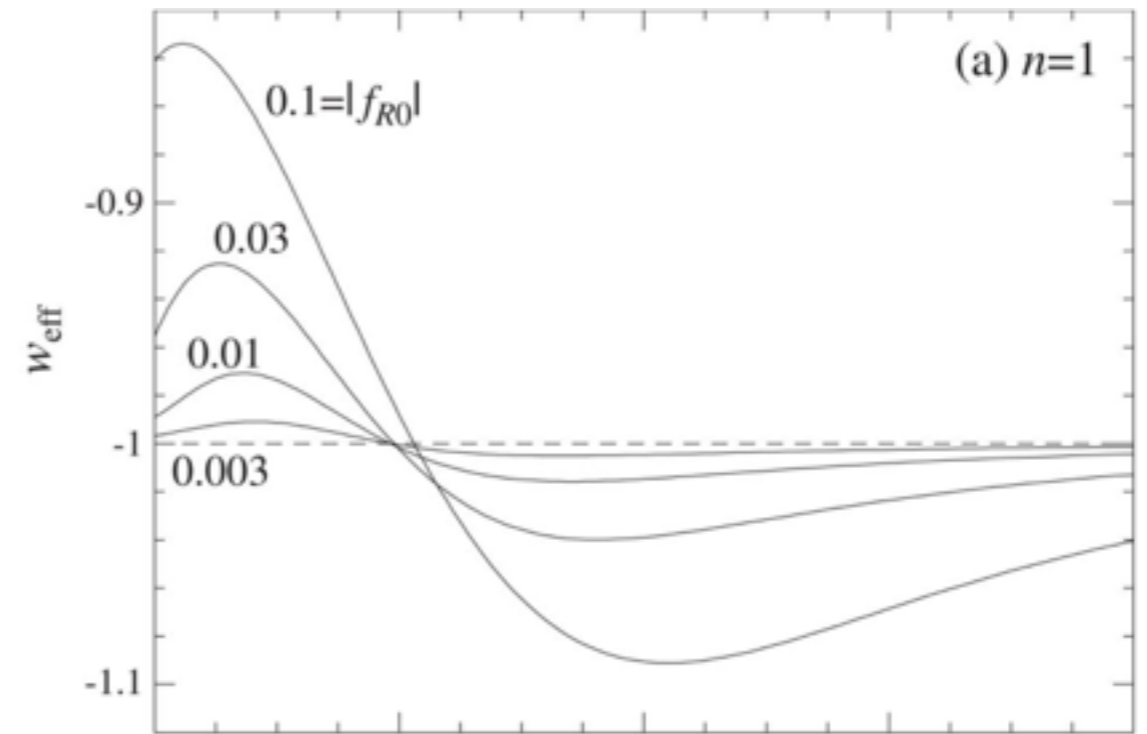
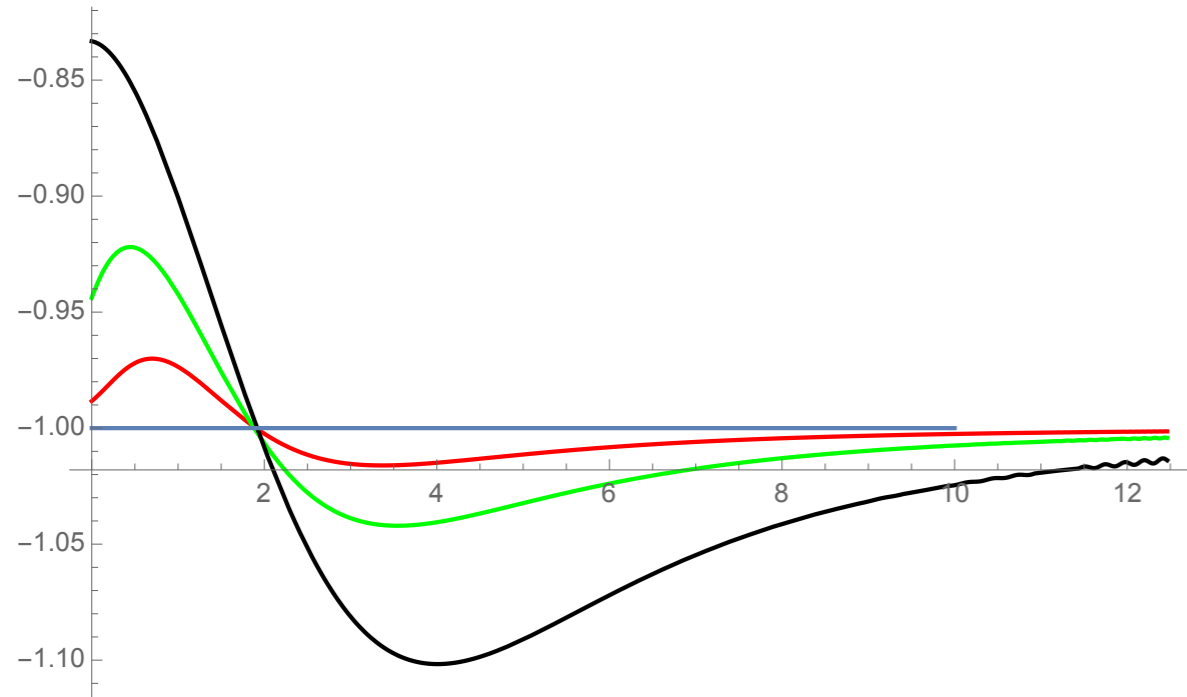
Power law models: $\Omega(a) = \Omega_0 a^s$;

Exponential models: $\Omega(a) = \exp(\Omega_0 a^s) - 1$.

**Have to make sure
that your parametrisation
to be viable, e.g. ghost-free!**

(Plots from Matteo Rizzato)

[Hu, Sawicki PRD76, 064004 (2007)]



2. The structure of EFTCAMB

EFTCAMB STRUCTURE
(Main EFT flag: **EFTflag**)

0: GR code
Standard CAMB

1: pure EFT
Use some parametrized forms for the EFT functions

2: designer matching EFT
Use a theory whose background mimics exactly the one specified

Background DE equation of state:
(Flag: **EFTwDE**)

Pure EFT Ω model selection:
(Flag: **PureEFTmodelOmega**)

Pure EFT α_1 model selection:
(Flag: **PureEFTmodelAlpha1**)

Pure EFT α_2 model selection:
(Flag: **PureEFTmodelAlpha2**)

Pure EFT α_3 model selection:
(Flag: **PureEFTmodelAlpha3**)

Pure EFT α_4 model selection:
(Flag: **PureEFTmodelAlpha4**)

Pure EFT α_5 model selection:
(Flag: **PureEFTmodelAlpha5**)

Pure EFT α_6 model selection:
(Flag: **PureEFTmodelAlpha6**)

Designer EFT model selection:
(Flag: **DesignerEFTmodel**)

Background DE equation of state:
(Flag: **EFTwDE**)

- 0: LCDM
- 1: wCDM
- 2: CPL
- 3: JBP
- 4: Turning point
- 5: Taylor expansion
- 6: User defined

- 0: Zero
- 1: Constant
- 2: Linear model
- 3: Power law model
- 4: Exponential model
- 5: User defined

- 1: $f(R)$
- 2: minimally coupled quintessence
- 3: non-minimally coupled quintessence
- 4: k-essence
- 5: Horndeski
- 6: Brans-Dicke
- 7: ...

- 0: LCDM
- 1: wCDM
- 2: CPL
- 3: JBP
- 4: Turning point
- 5: Taylor expansion
- 6: User defined

EFTCAMB_V1.1

Structure of EFTCAMB

2.1 Background parametrization—EoS

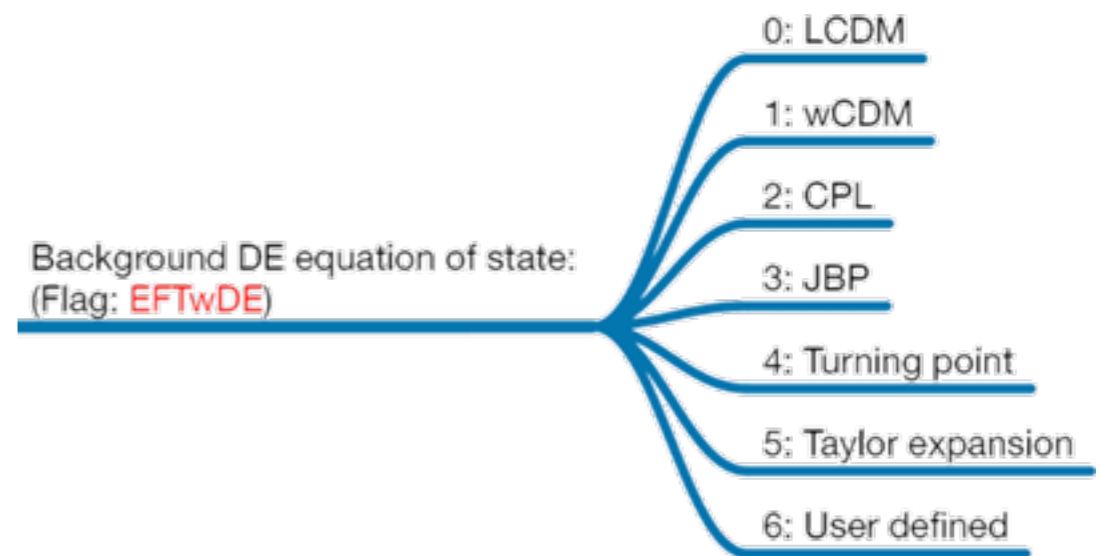
EFTCAMB provides 6 different kinds of parametrization of EoS (Flag: **EFTwDE**), including:

ΛCDM ($w=-1$),

wCDM ($w=w_0$),

CPL ($w=w_0+w_a \cdot a$),

.....



2.2.1 EFT parametrization: Pure EFT

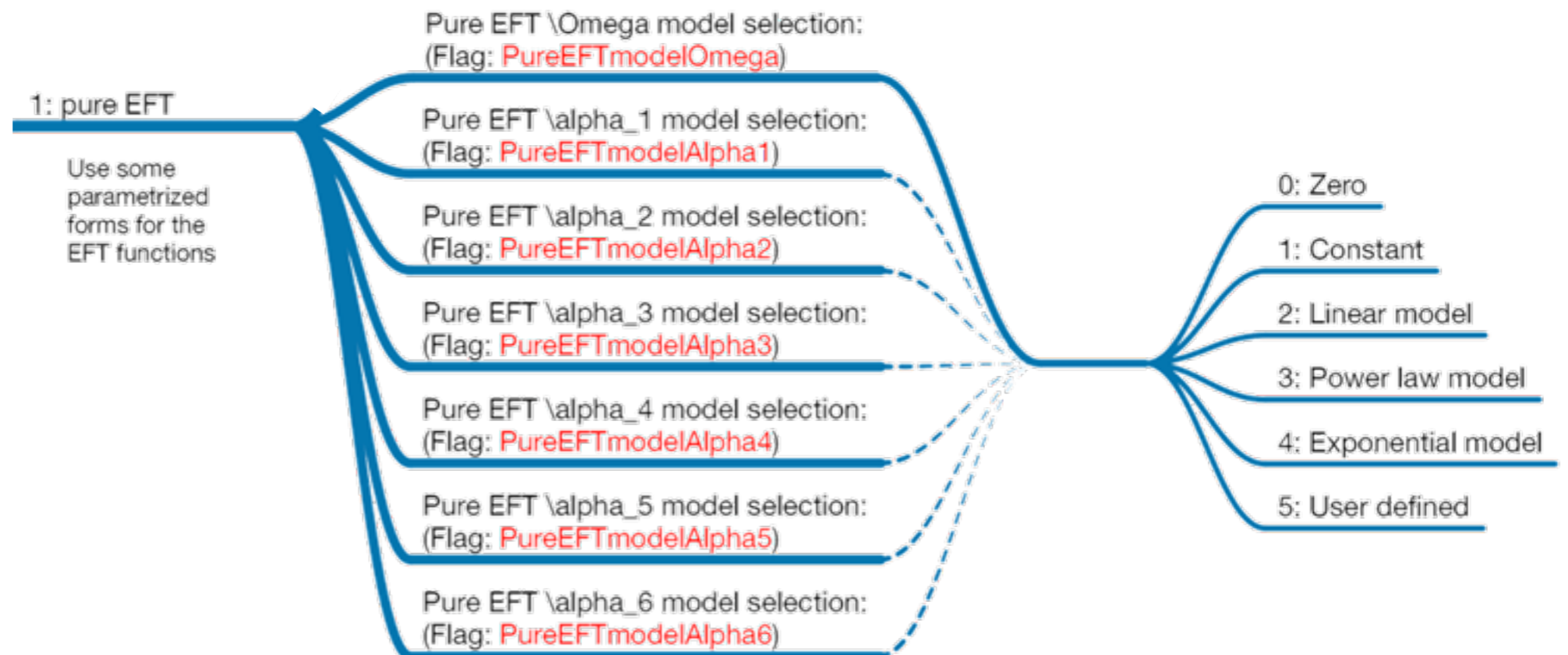
Phenomenological parametrization, e.g.

Constant models: $\Omega(a) = \Omega_0$;

Linear models: $\Omega(a) = \Omega_0 a$;

Power law models: $\Omega(a) = \Omega_0 a^s$;

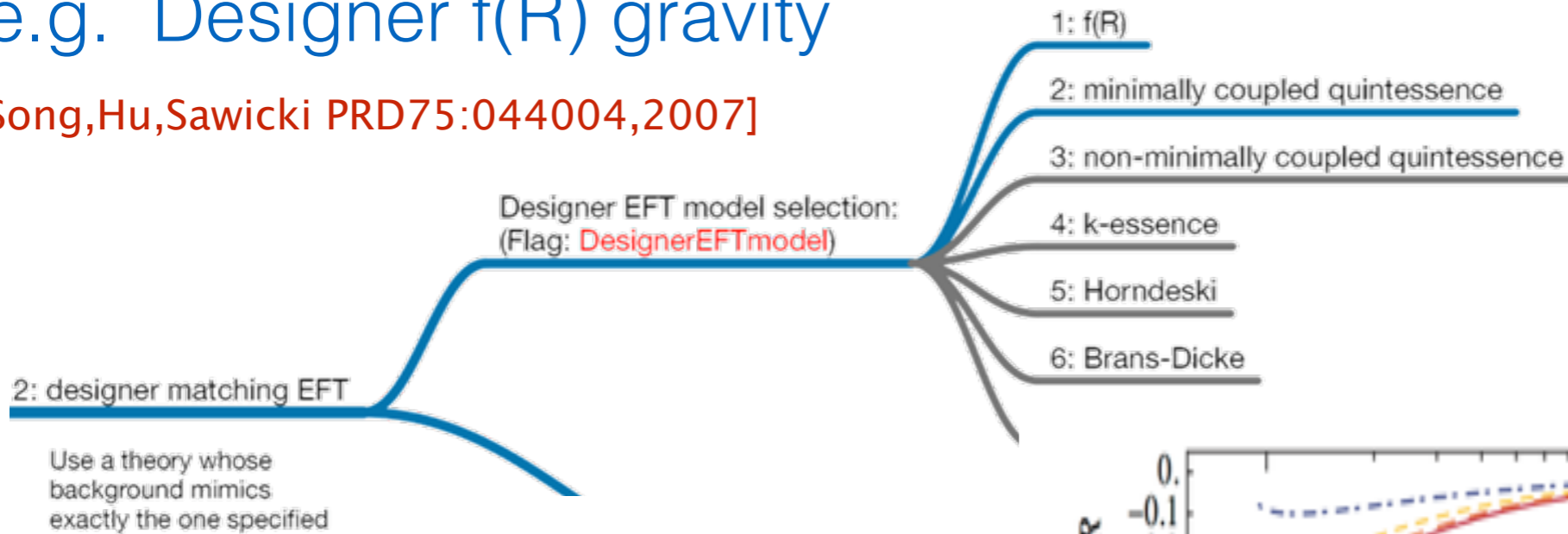
Exponential models: $\Omega(a) = \exp(\Omega_0 a^s) - 1$.



2.2.2 EFT parametrization: Full mapping—designer mapping

e.g. Designer $f(R)$ gravity

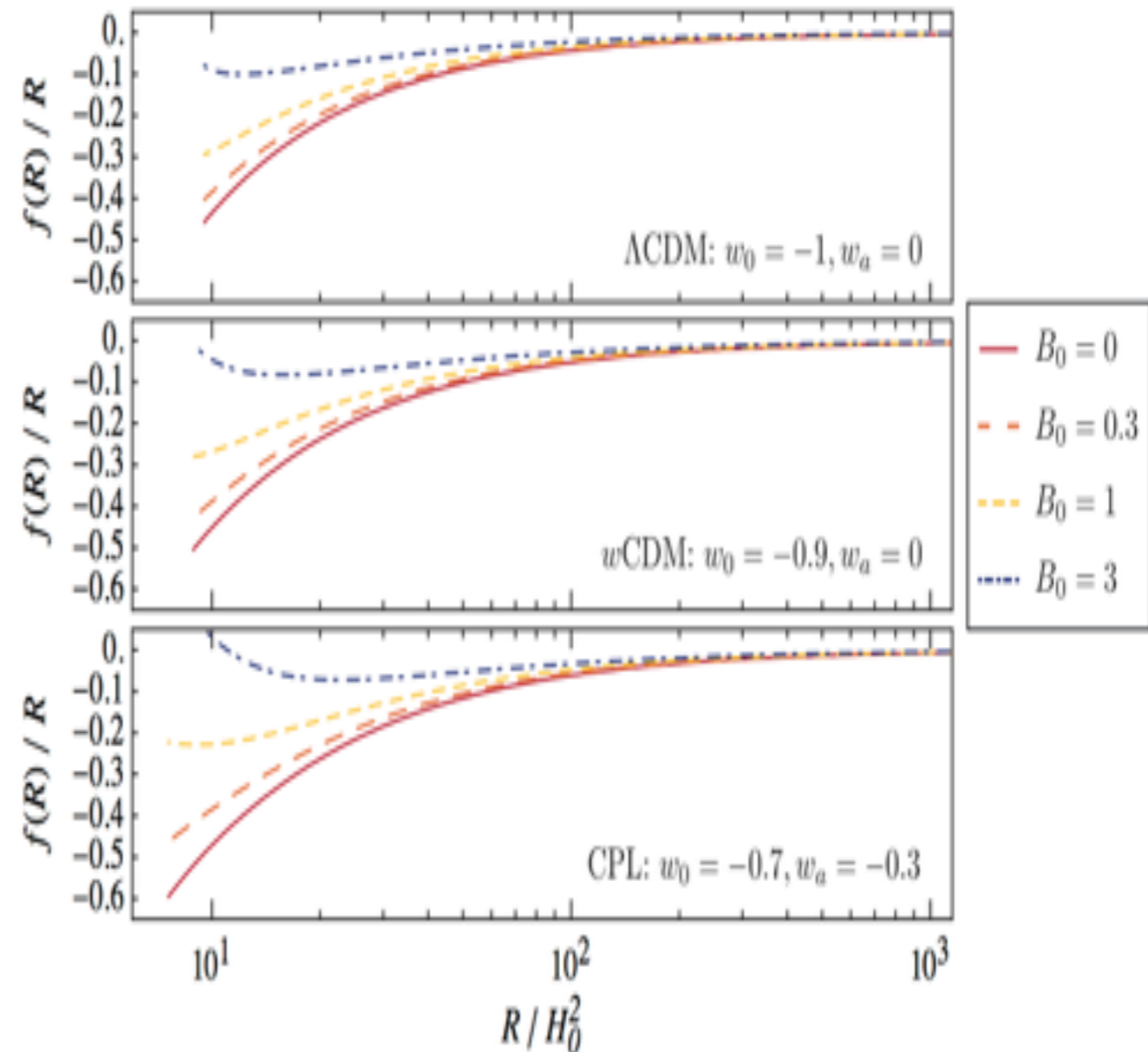
[Song, Hu, Sawicki PRD75:044004, 2007]



$$f'' - \left(1 + \frac{H'}{H} + \frac{R''}{R'}\right) f' + \frac{R'}{6H^2} f = -\frac{R'}{3M_P^2 H^2} \rho_{\text{DE}},$$

$$B_0 \sim \frac{6f_{RR}}{(1+f_R)} H^2 \Big|_{a=1}$$

GR limit: $B_0 \rightarrow 0$,
effective mass $\rightarrow \infty$



2.2.3 EFT parametrization: Full mapping (coming soon v2.0)

A few examples work in progress:

1. Hu-Sawicki $f(R)$ model (with Rizzato et.al.)
2. Horava gravity (with Frusciante, Raveri, Silvestri, Vernieri)
3. K-mouflage

Advantage: the stable parameter regime are fully controlled by the user instead of the code per se!

2.3 Perturbation equations

We implement the pi field into the Einstein-Boltzmann solver
CAMB \rightarrow **EFTCAMB**

Evolving the full **Einstein** equation, **Klein-Golden** equation (pi field), **fluid equation** (CDM, baryon, massive neutrino), **Boltzmann hierarchy** equation sets (CMB, massless neutrino)

- **EFT: Do NOT rely on QS approx!**

time-time Einstein equation:

$$k^2 \eta = -\frac{a^2}{2m_0^2(1+\Omega)} [\delta\rho_m + \dot{\rho}_Q \pi + 2c(\dot{\pi} + \mathcal{H}\pi)] + \left(\mathcal{H} + \frac{\dot{\Omega}}{2(1+\Omega)} \right) k\mathcal{Z} + \frac{\dot{\Omega}}{2(1+\Omega)} [3(3\mathcal{H}^2 - \dot{\mathcal{H}})\pi + 3\mathcal{H}\dot{\pi} + k^2\pi]$$

momentum Einstein equation:

$$\frac{2}{3}k^2(\sigma_* - \mathcal{Z}) = \frac{a^2}{m_0^2(1+\Omega)} [(\rho_m + P_m)v_m + (\rho_Q + P_Q)k\pi] + k\frac{\dot{\Omega}}{(1+\Omega)}(\dot{\pi} + \mathcal{H}\pi),$$

space-space off-diagonal Einstein equation:

$$k\dot{\sigma}_* + 2k\mathcal{H}\sigma_* - k^2\eta = -\frac{a^2 P\Pi_m}{m_0^2(1+\Omega)} - \frac{\dot{\Omega}}{(1+\Omega)}(k\sigma_* + k^2\pi),$$

space-space trace Einstein equation:

$$\begin{aligned} \ddot{h} = & -\frac{3a^2}{m_0^2(1+\Omega)} [\delta P_m + \dot{P}_Q \pi + (\rho_Q + P_Q)(\dot{\pi} + \mathcal{H}\pi)] - 2\left(\frac{\dot{\Omega}}{1+\Omega} + 2\mathcal{H}\right) k\mathcal{Z} + 2k^2\eta \\ & - 3\frac{\dot{\Omega}}{(1+\Omega)} \left[\ddot{\pi} + \left(\frac{\ddot{\Omega}}{\dot{\Omega}} + 3\mathcal{H}\right) \dot{\pi} + \left(\mathcal{H}\frac{\ddot{\Omega}}{\dot{\Omega}} + 5\mathcal{H}^2 + \dot{\mathcal{H}} + \frac{2}{3}k^2\right) \pi \right], \end{aligned}$$

- For Klein-Golden Eq. Of π field

$$\begin{aligned} & \left(c + \frac{3m_0^2}{4a^2} \frac{\dot{\Omega}^2}{(1+\Omega)} \right) \ddot{\pi} + \left[\frac{3m_0^2}{4a^2} \frac{\dot{\Omega}}{(1+\Omega)} \left(\ddot{\Omega} + 4\mathcal{H}\dot{\Omega} + \frac{(\rho_Q + P_Q)a^2}{m_0^2} \right) + \dot{c} + 4\mathcal{H}c - \frac{\dot{\Omega}}{2(1+\Omega)}c \right] \dot{\pi} \\ & + \left[\frac{3m_0^2}{4a^2} \frac{\dot{\Omega}}{(1+\Omega)} \left(\frac{(3\dot{P}_Q - \dot{\rho}_Q + 3\mathcal{H}(\rho_Q + P_Q))a^2}{3m_0^2} + \mathcal{H}\ddot{\Omega} + 8\mathcal{H}^2\dot{\Omega} + 2(1+\Omega)(\ddot{\mathcal{H}} - 2\mathcal{H}^3) \right) \right. \\ & \left. - 2\dot{\mathcal{H}}c + \left(\dot{c} - \frac{\dot{\Omega}}{2(1+\Omega)}c \right) \mathcal{H} + 6\mathcal{H}^2c + \left(c + \frac{3m_0^2}{4a^2} \frac{\dot{\Omega}^2}{(1+\Omega)} \right) k^2 \right] \pi \\ & + \left[c + \frac{3m_0^2}{4a^2} \frac{\dot{\Omega}^2}{(1+\Omega)} \right] k\mathcal{Z} + \frac{1}{4} \frac{\dot{\Omega}}{(1+\Omega)} (3\delta P_m - \delta\rho_m) = 0, \end{aligned}$$

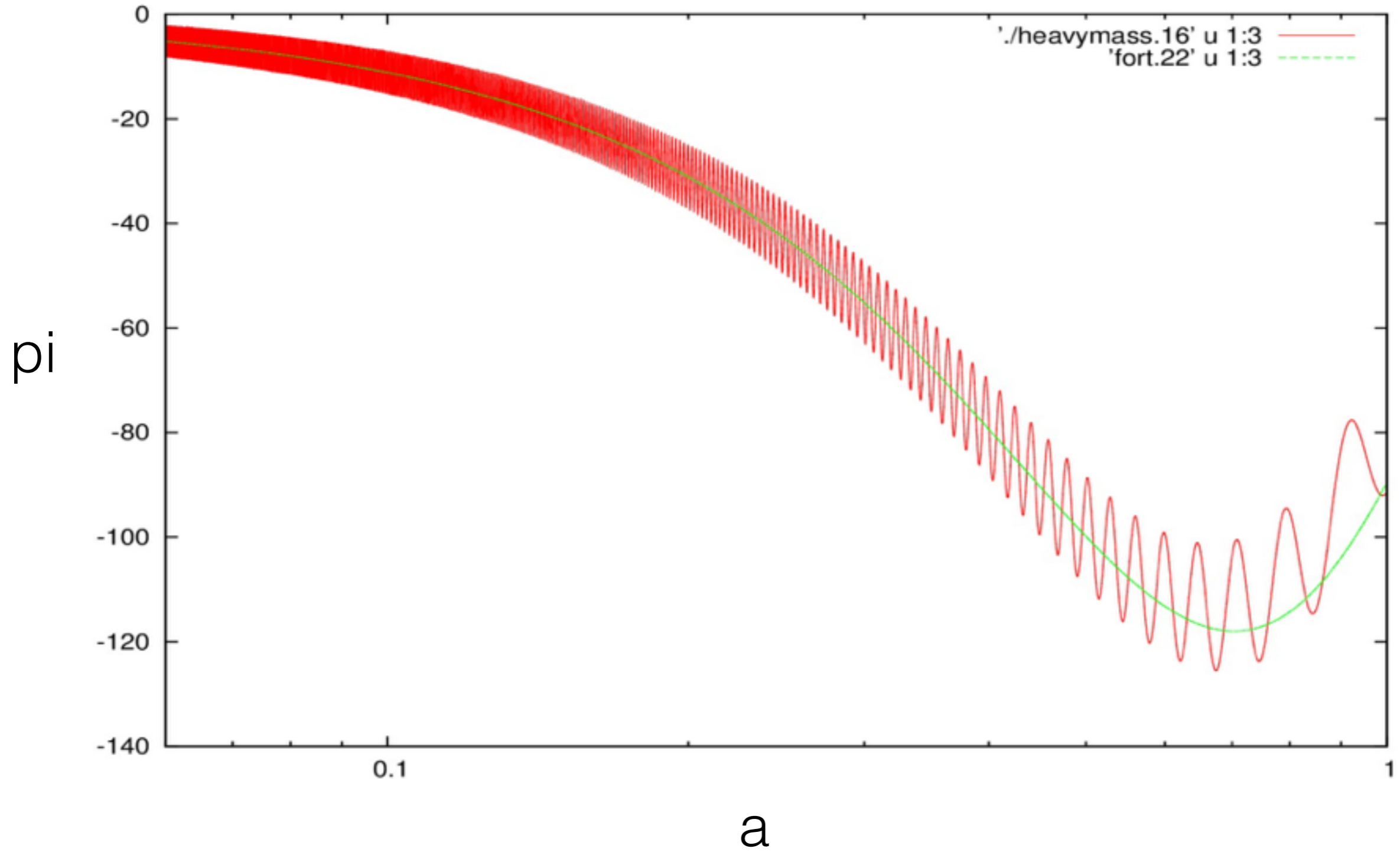
kinetic friction mass sound speed source

$$A(\tau) \ddot{\pi} + B(\tau) \dot{\pi} + C(\tau) \pi + k^2 D(\tau) \pi + E(\tau) = 0$$

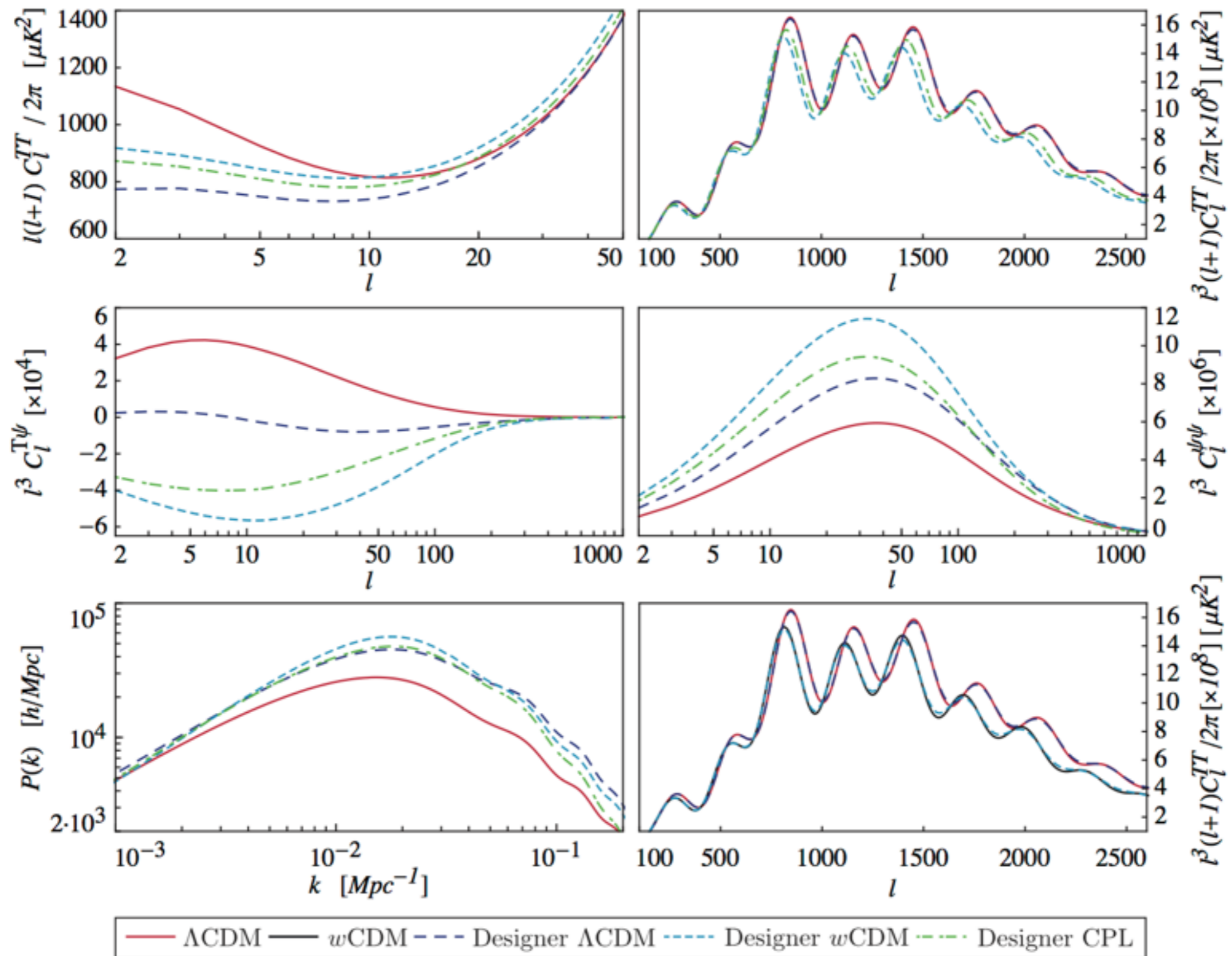
Have pass the viability condition:

1. Effective Newton constant does not change sign: $1+\Omega > 0$
2. ghost instability: $A > 0$
3. sound speed ≤ 1 : $D/A \leq 1$
4. mass square ≥ 0 : $C/A \geq 0$

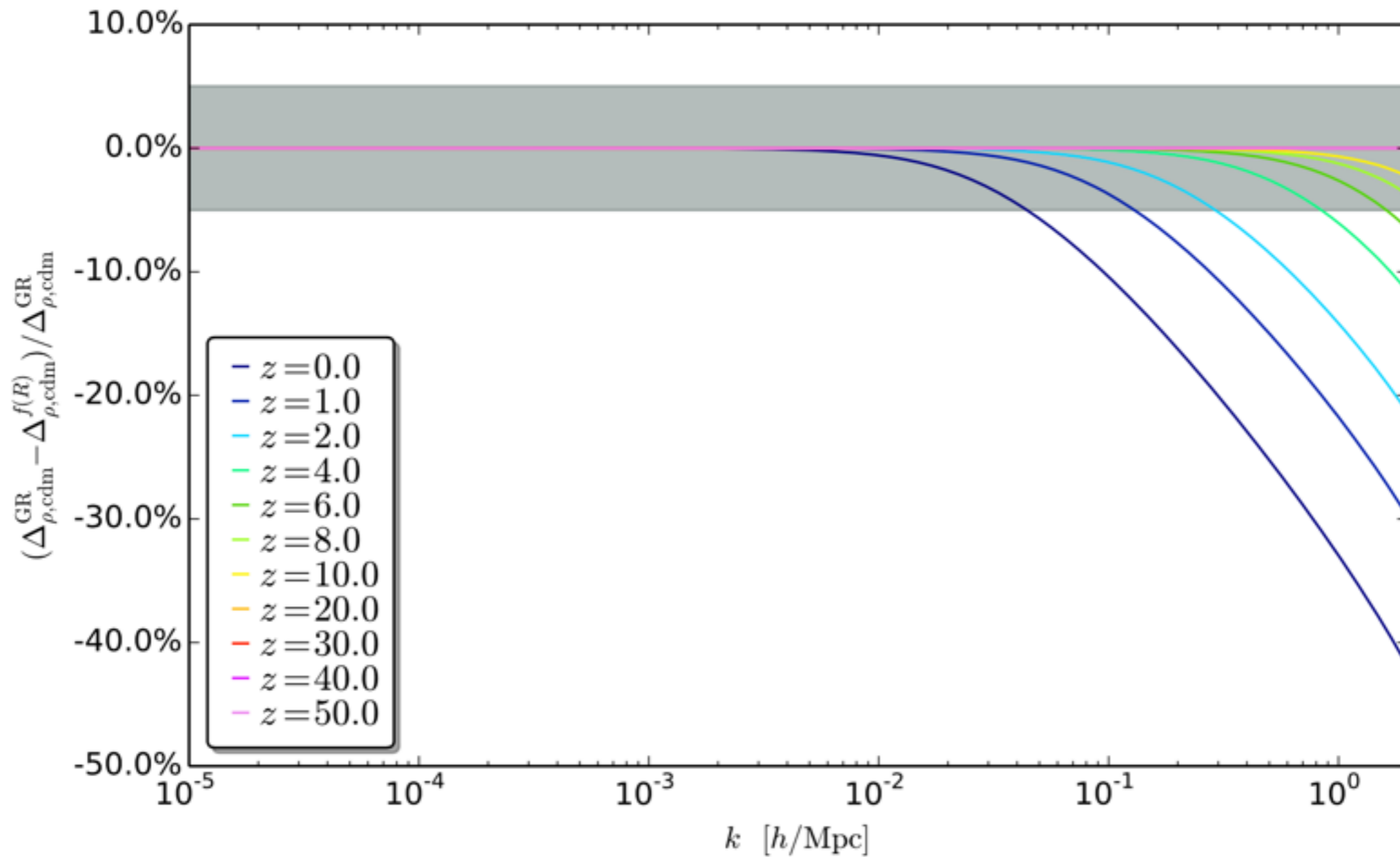
pi field solution: f(R) example



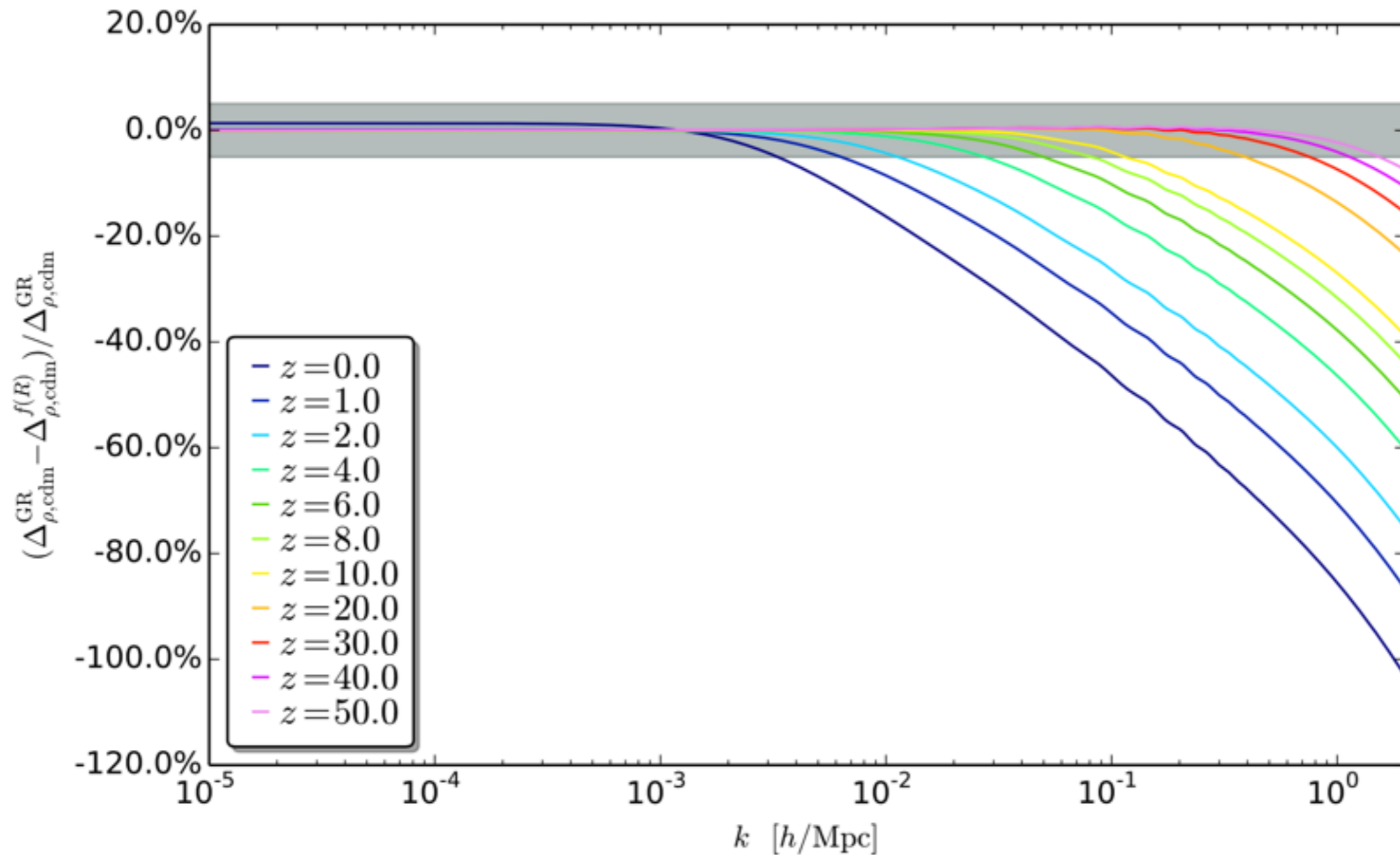
2.4 CMB spectra—example: f(R)



2.5 Transfer function of CDM



Designer $f(R)$ with LCDM background
 $B_0 = 0.001$

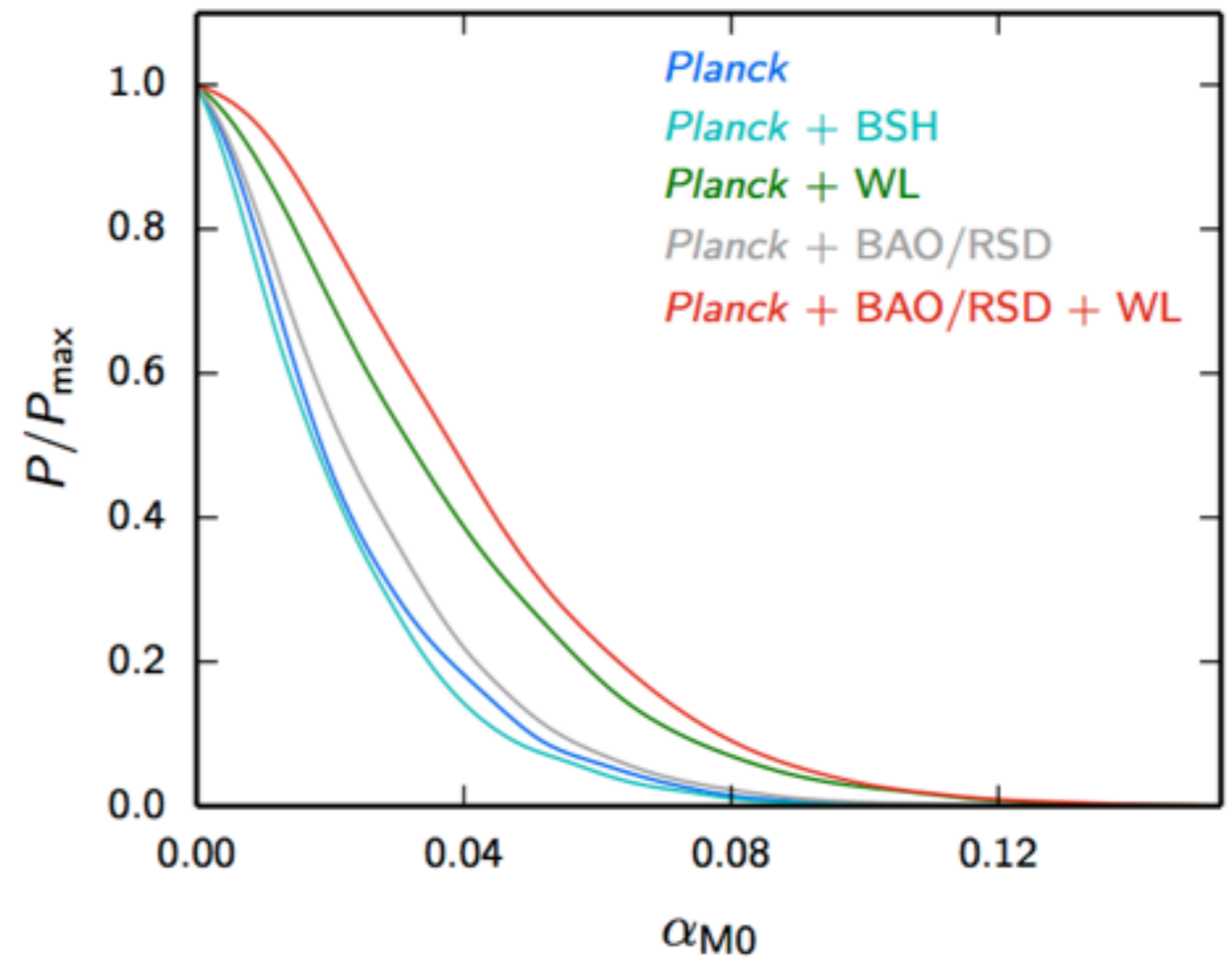
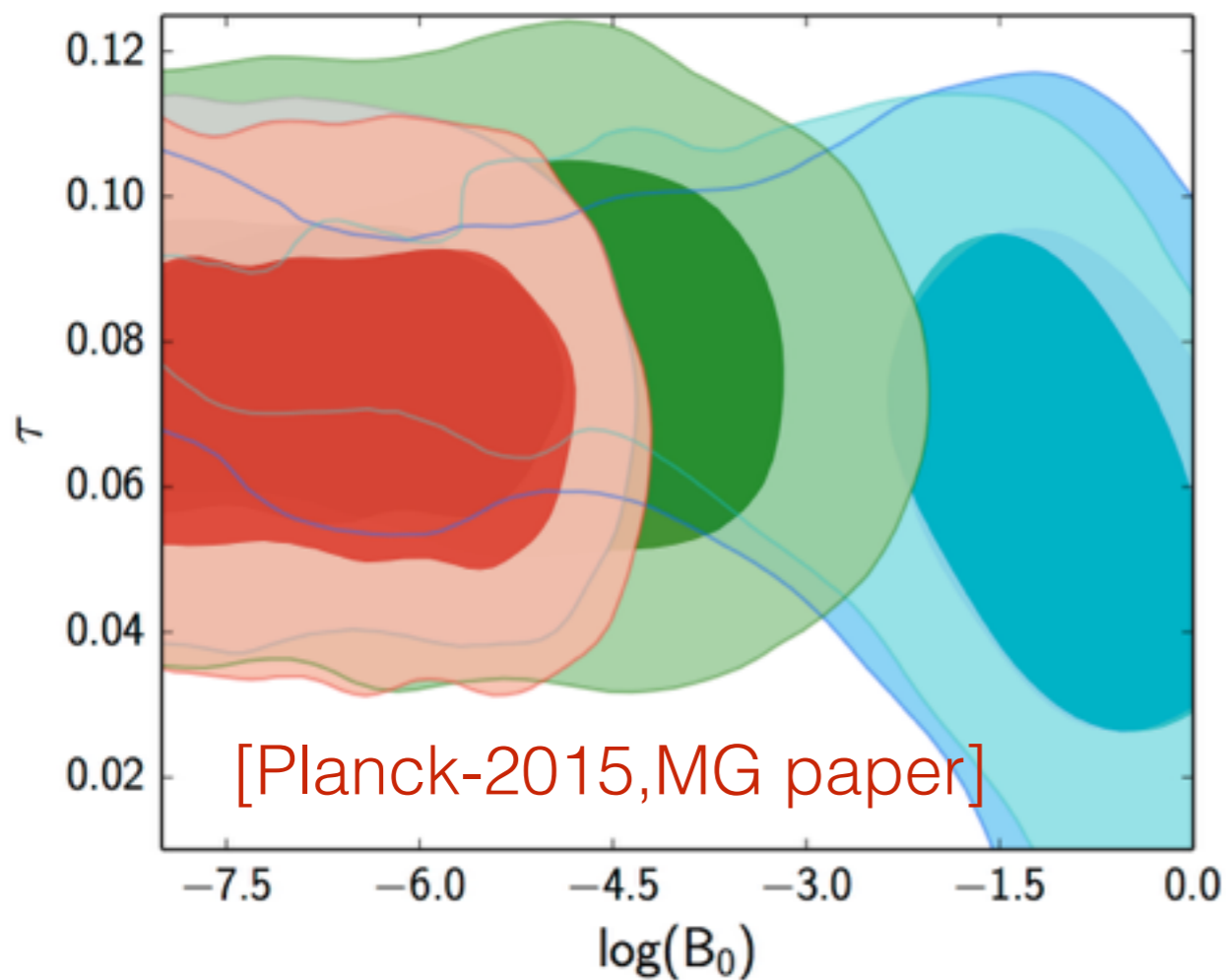


Designer $f(R)$ with w CDM background
 $B_0=0.01$ and $w=-0.95$

3. Parameter estimation results from EFTCosmoMC and Planck-2015

CosmoMC → **EFTCosmoMC**

Designer $f(R)$



Linear EFT

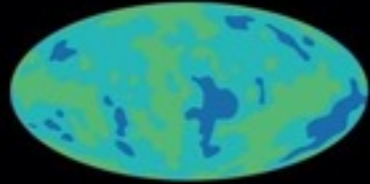
[Thank Sabino push this inside the collaboration!]

4. Conclusion

- **EFTCAMB include most of viable **single** field DE/MG model**
- **For scalar field: full perturbative treatment, does not rely on quasistatic approx**
- **Support LCDM/wCDM/CPL background**
- **Automatical stability check for given parameterization**
- **Selected by Planck 2015 data release**
- **Selected by Theory Working Group of Euclid**

A graphic consisting of several thick, curved lines in shades of blue and green that fan out from the top left towards the center. Below these are many thinner, curved lines in a grid-like pattern, transitioning from blue to yellow to orange.

EFTCAMB



KEEP
CALM
AND
TEST
GRAVITY

the EFTCAMB team

Thank you!