Ciao Tutti!

Effective Field Theory approach for Dark Energy/ Modified Gravity

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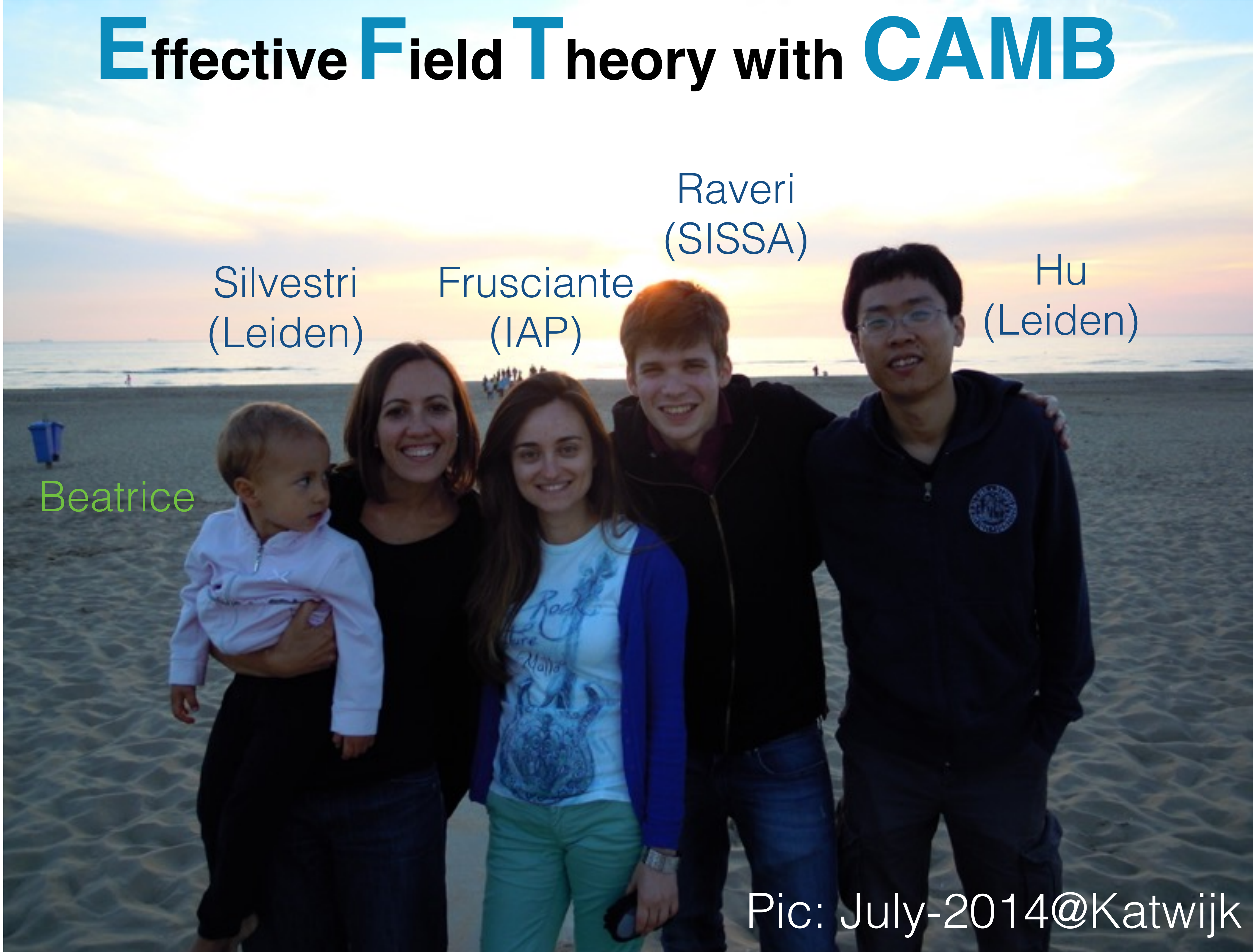
EFTCAMB team

Effective Field Theory with CAMB



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

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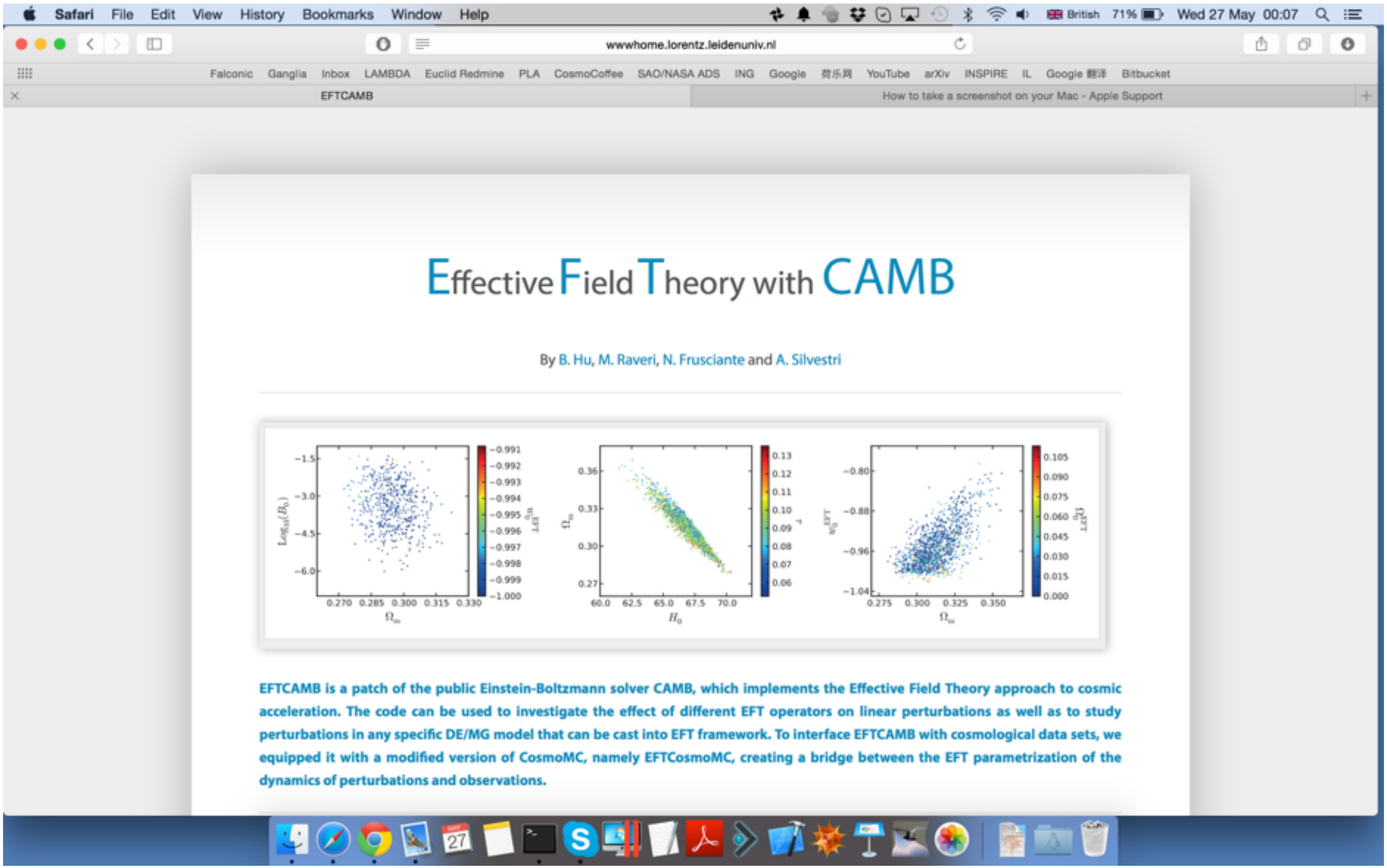

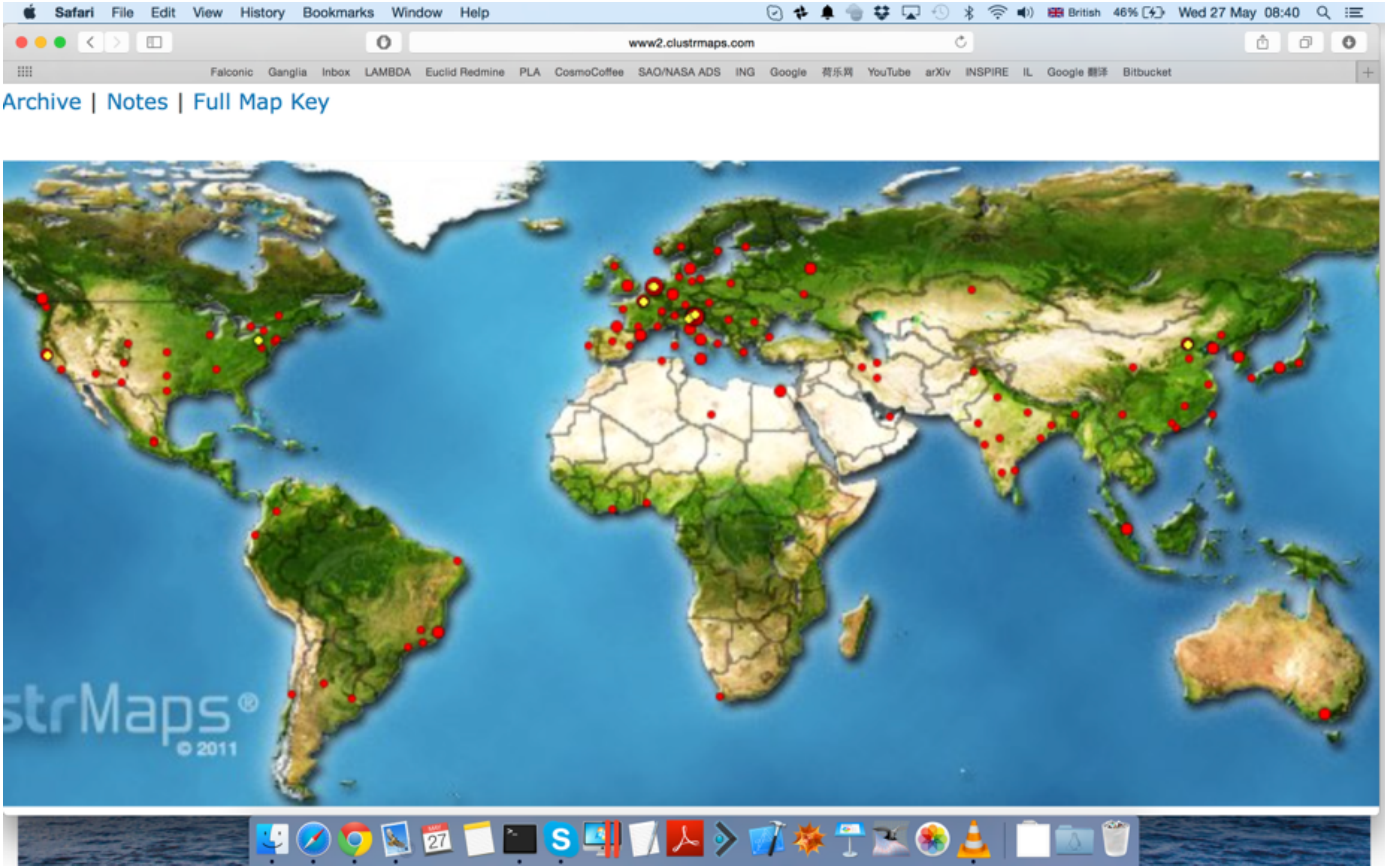

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Outline

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.

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

[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

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

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

1.1 The logic of construction of the action

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

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

(breaking time translation diffemorphism)

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

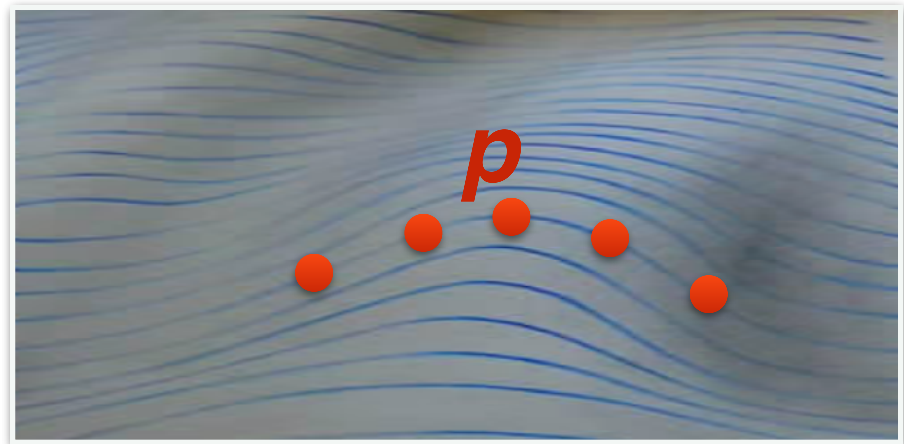
$$\boxed{\delta g^{00},\ \delta K_{\mu\nu},\ \delta R_{\mu\nu\rho\sigma}\ (\text{or } C_{\mu\nu\rho\sigma}),\ \delta R_{\mu\nu},\ \text{and } \delta R,}$$

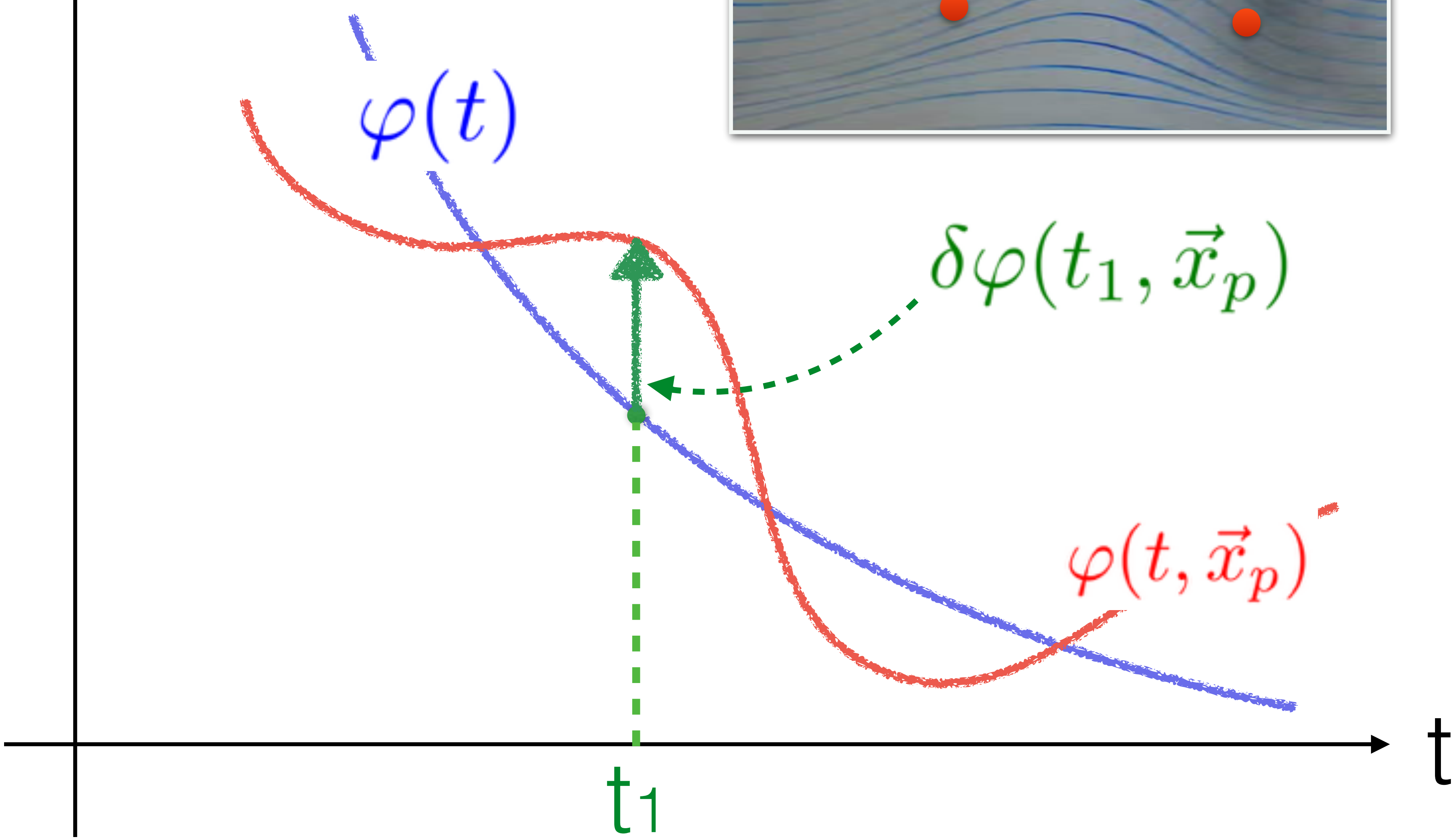
3. Multiply these operators by a only time dependent function

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

1.2 Another point of view of EFT

Covariant approach





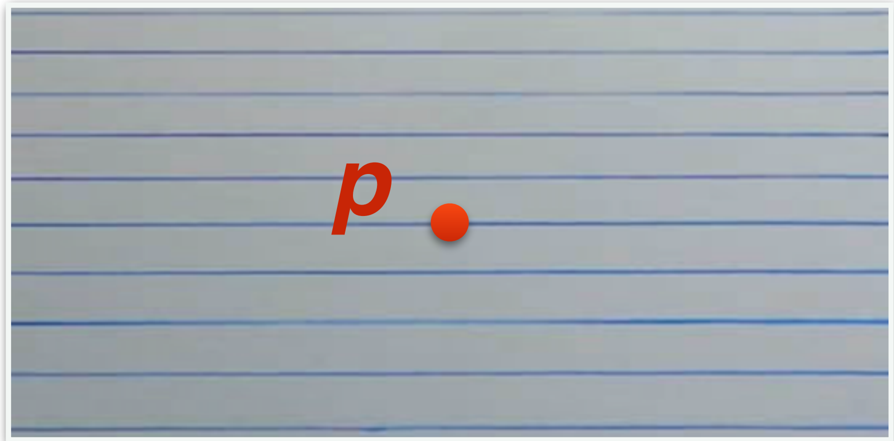
$\varphi(t)$: background field config

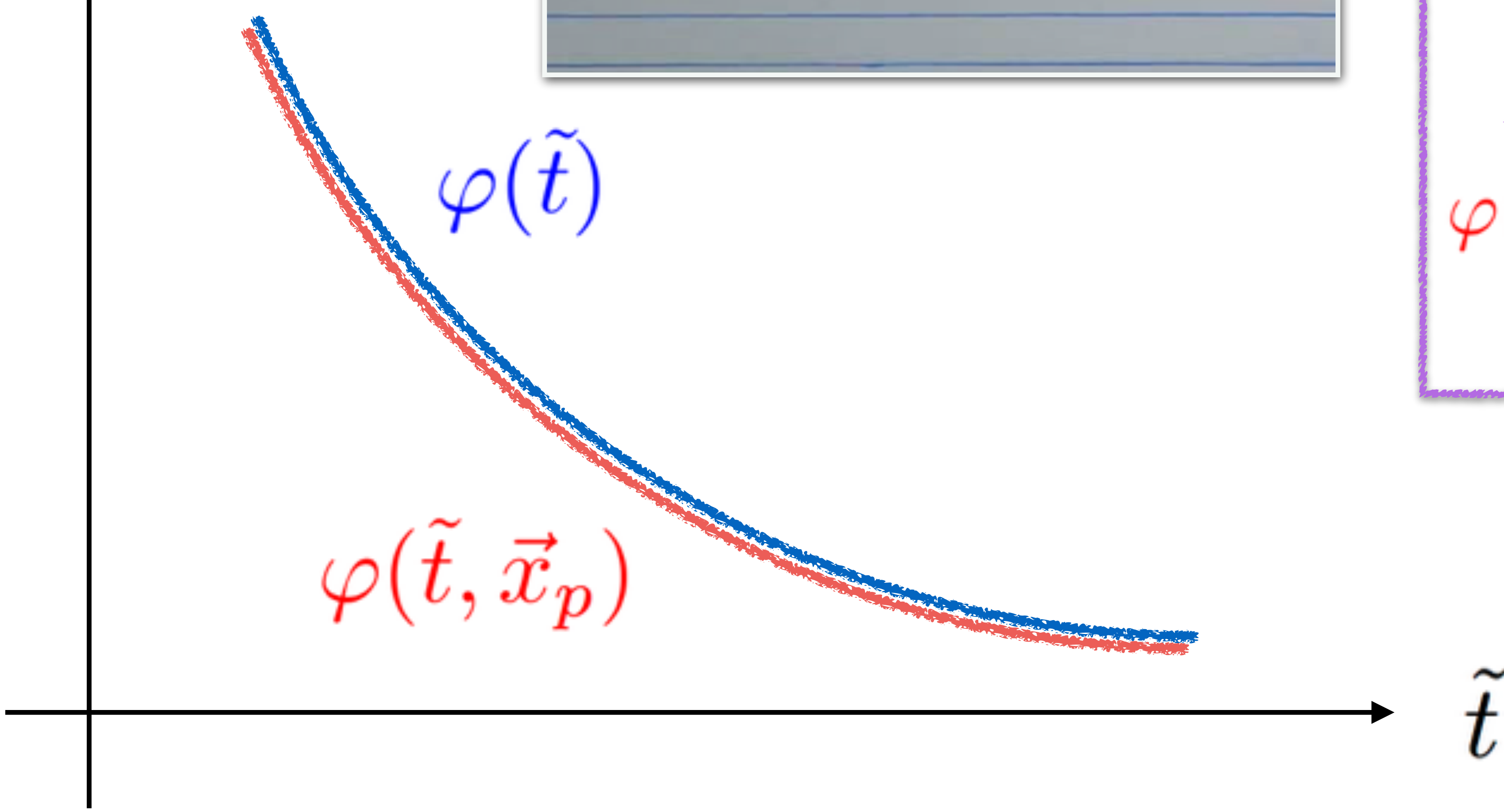
$\varphi(t, \vec{x}_p)$: field config at point 'p'

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

Valid in ***ALL*** the gauge

EFT approach





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

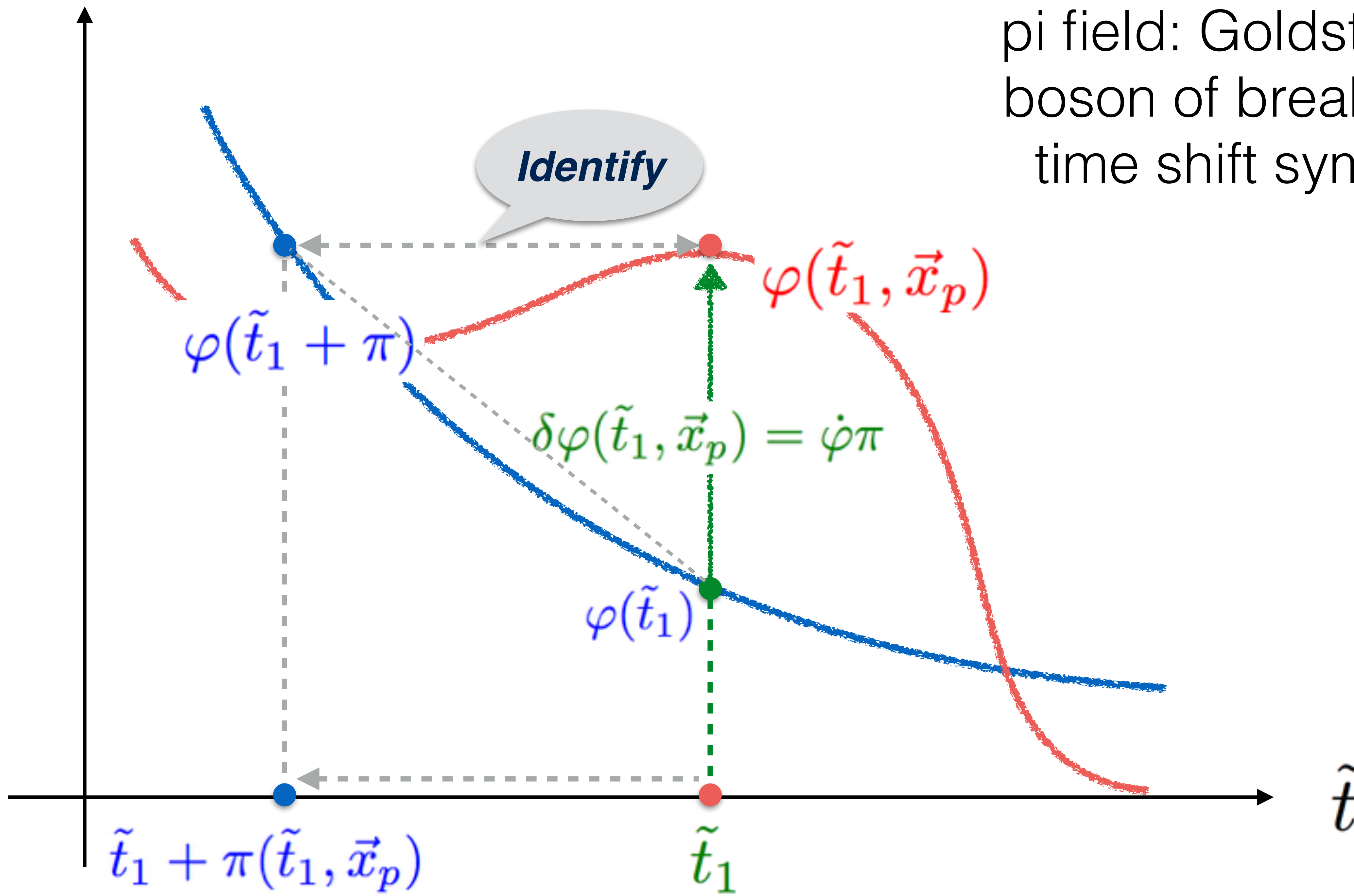
$\varphi(\tilde{t}, \vec{x}_p)$: field config at point $'\mathrm{p}'$

Only Valid in the unitary gauge

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

EFT approach=> Covariant approach

pi 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 PRD**76,** 064004 (2007)]

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

(Work in progress with Rizzato et. al.)

2. Pure EFT parametization

(Phenomenological param)

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

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

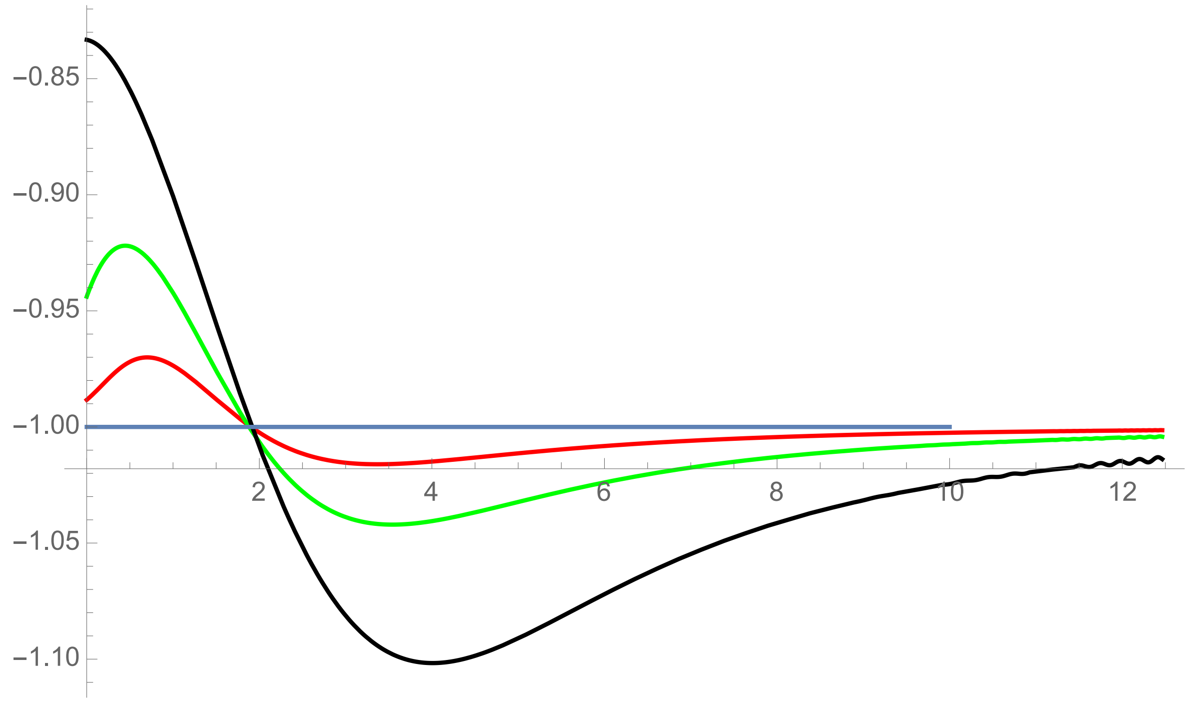
Power law models: $\Omega(a) = \Omega_0 a^s$;

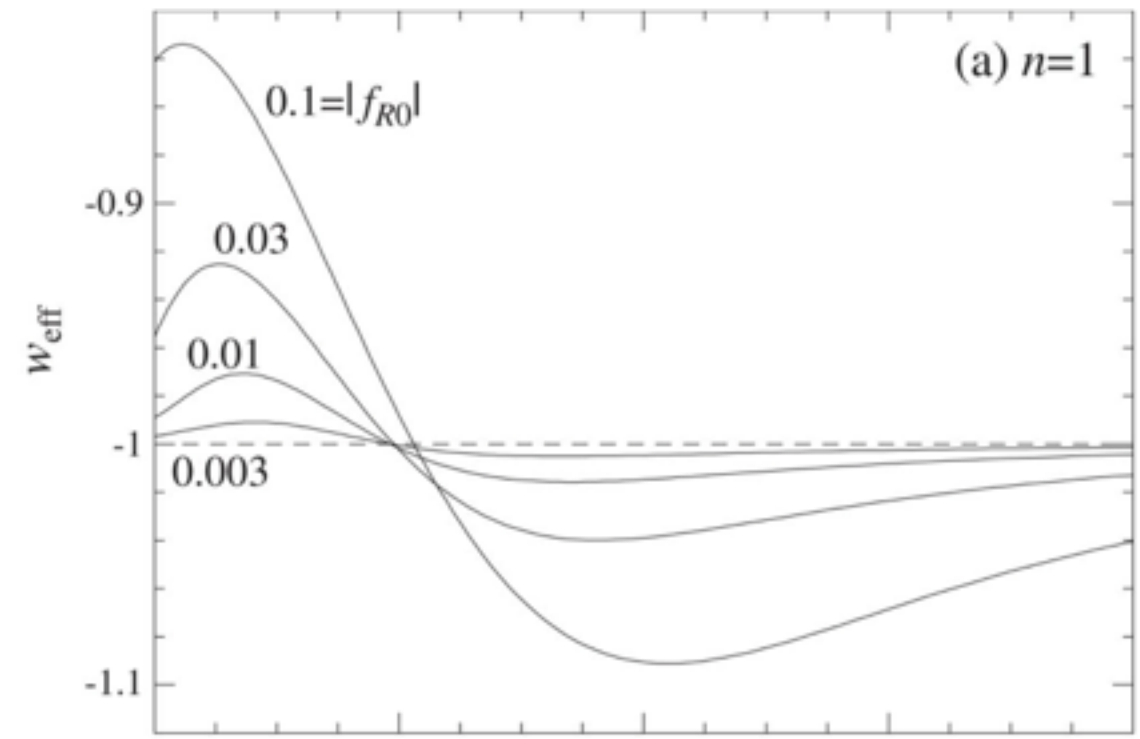
Exponential models: $\Omega(a) = \exp\left(\Omega_0 a^s\right) - 1$.

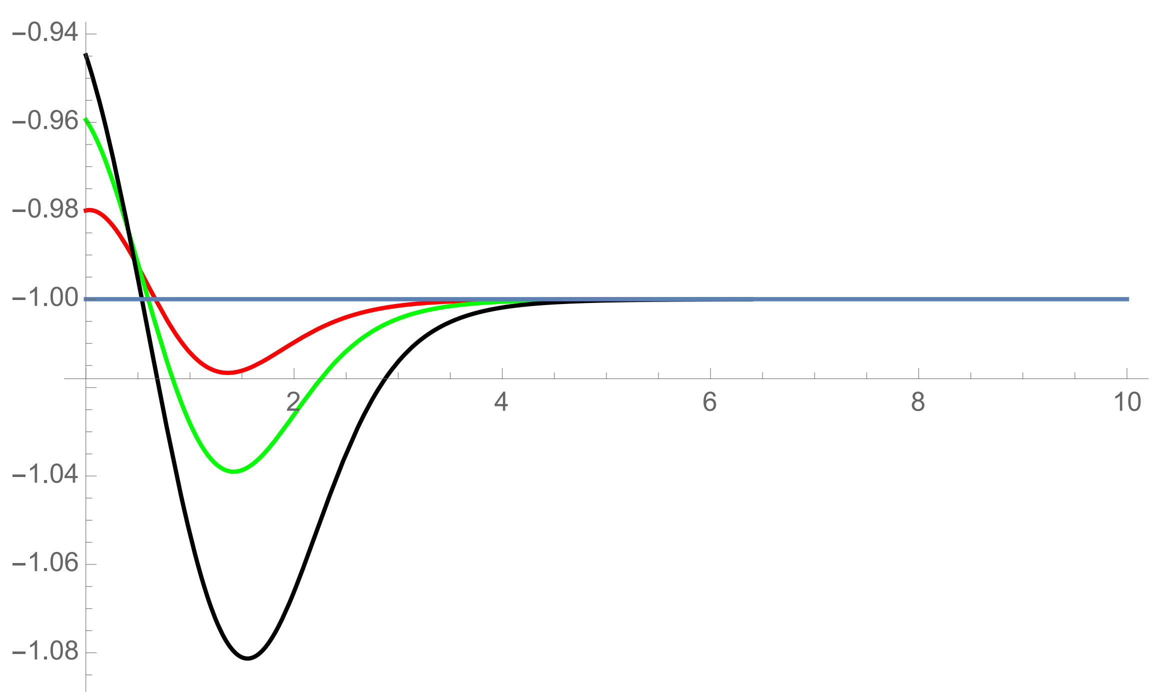
Have to make sure that your parametrisation to be viable, e.g. ghost-free!

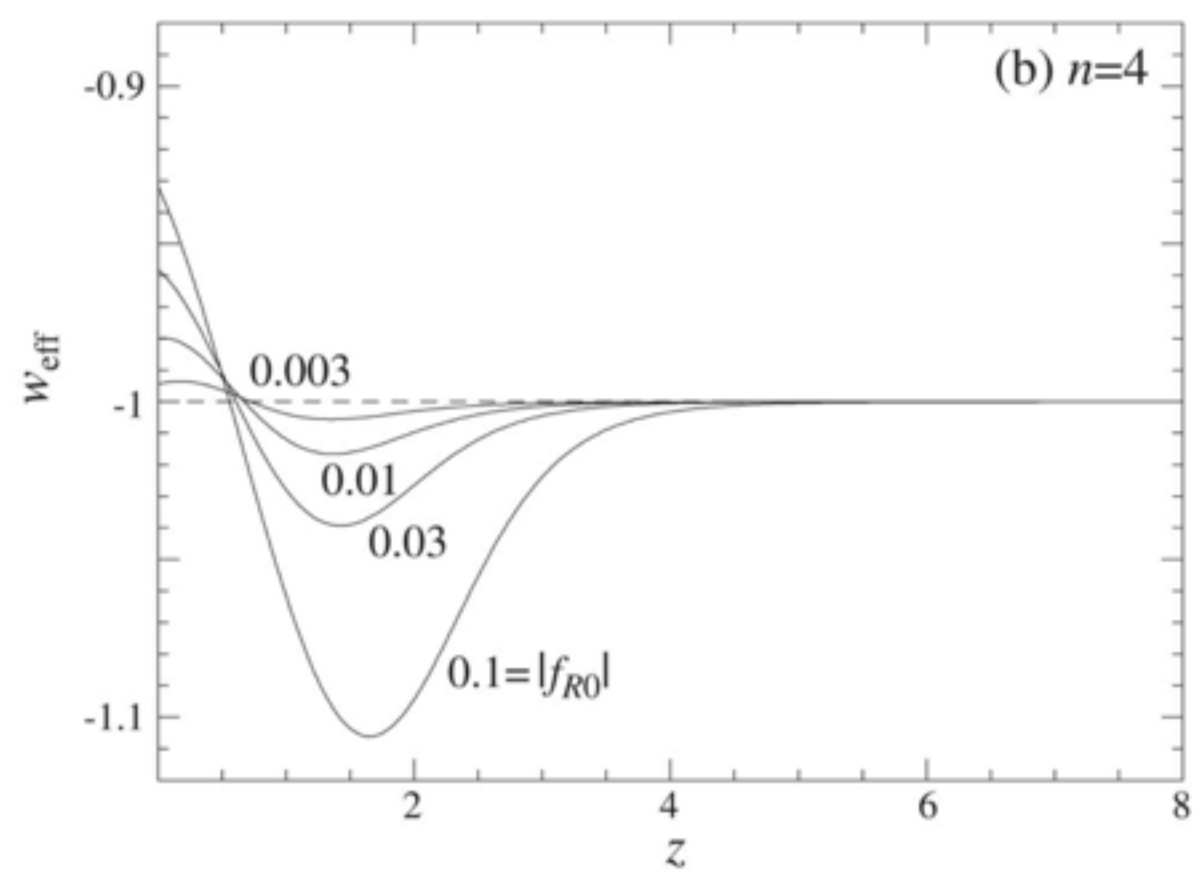
(Plots from Matteo Rizzato)

[Hu,Sawicki PRD**76,** 064004 (2007)]

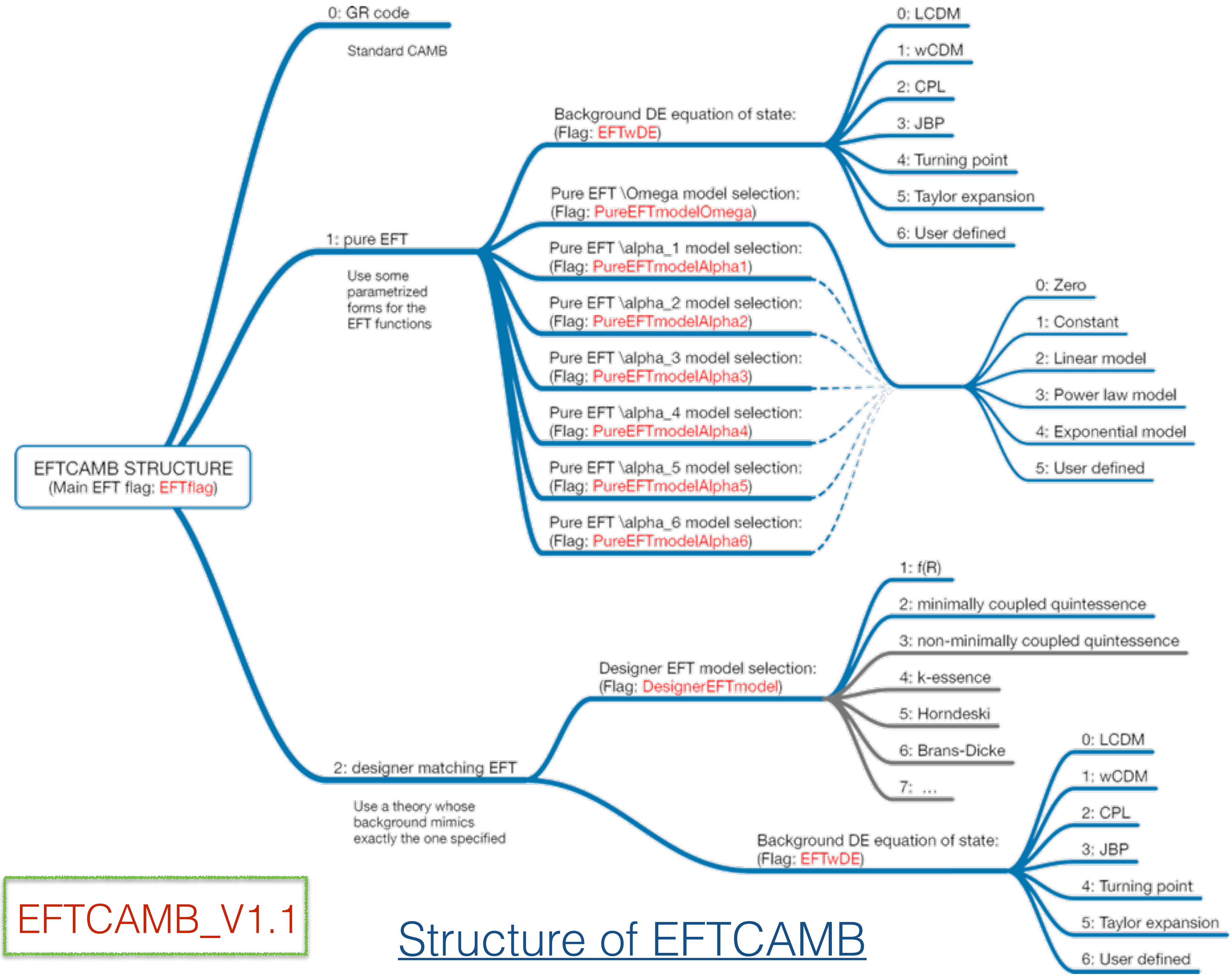








2. The structure of EFTCAMB



EFTCAMB_V1.1

Structure of EFTCAMB

2.1 Background parametrization—EoS

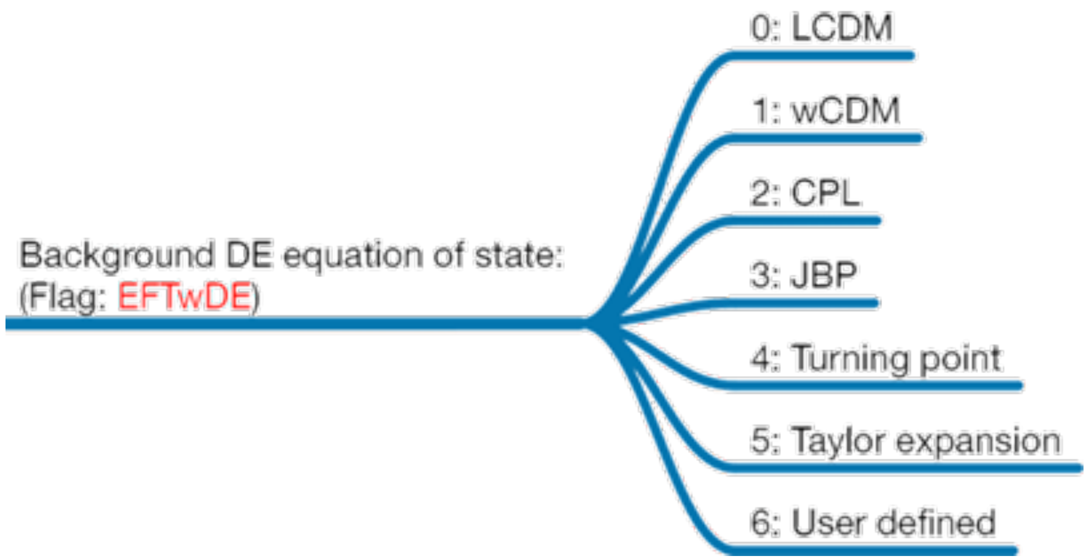
EFTCAMB provides 6 different kinds of parametrization of EoS (Flag: EFTwDE), including:

LCDM ($w=-1$),

wCDM ($w=w_0$),

CPL ($w=w_0+w_a*a$),

… …



2.2.1 EFT parametrization: Pure EFT

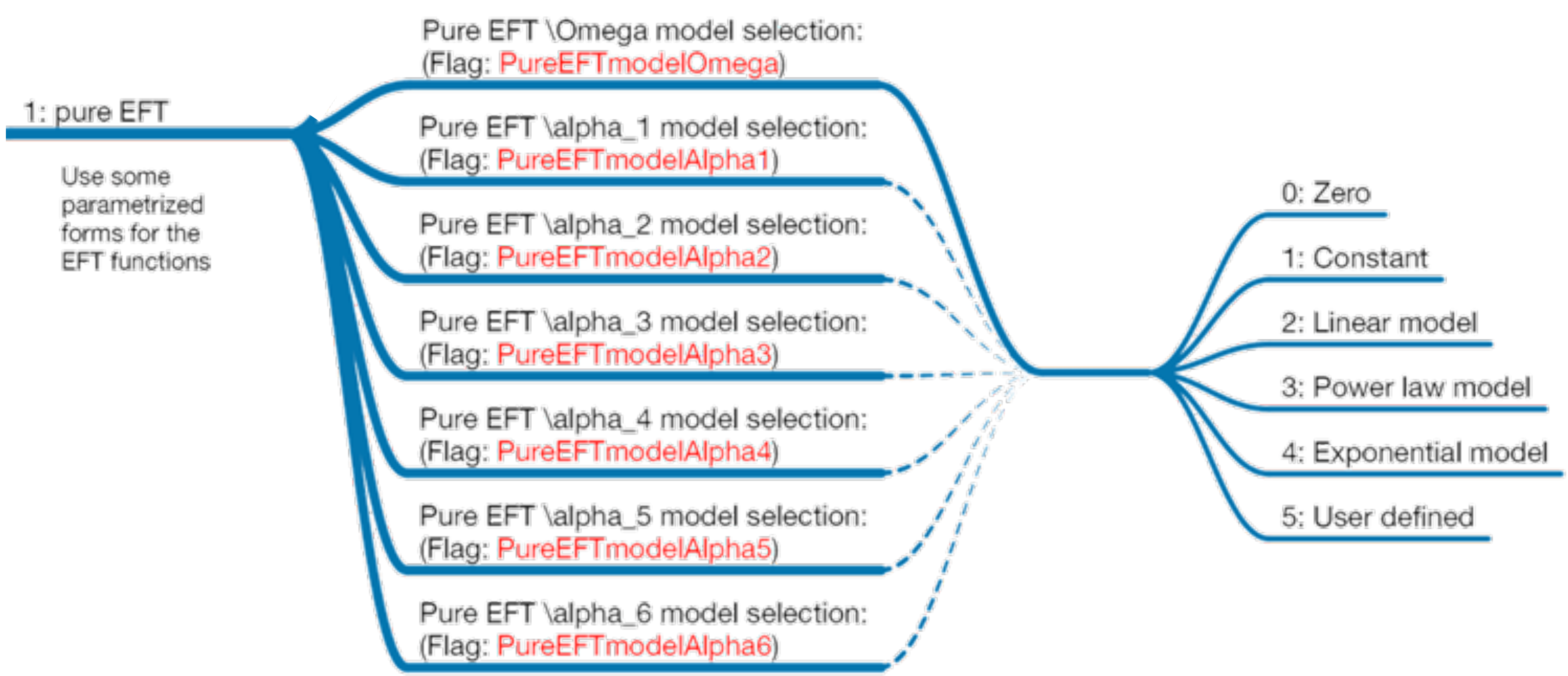
Phenomenological parametrization, e.g.

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

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

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

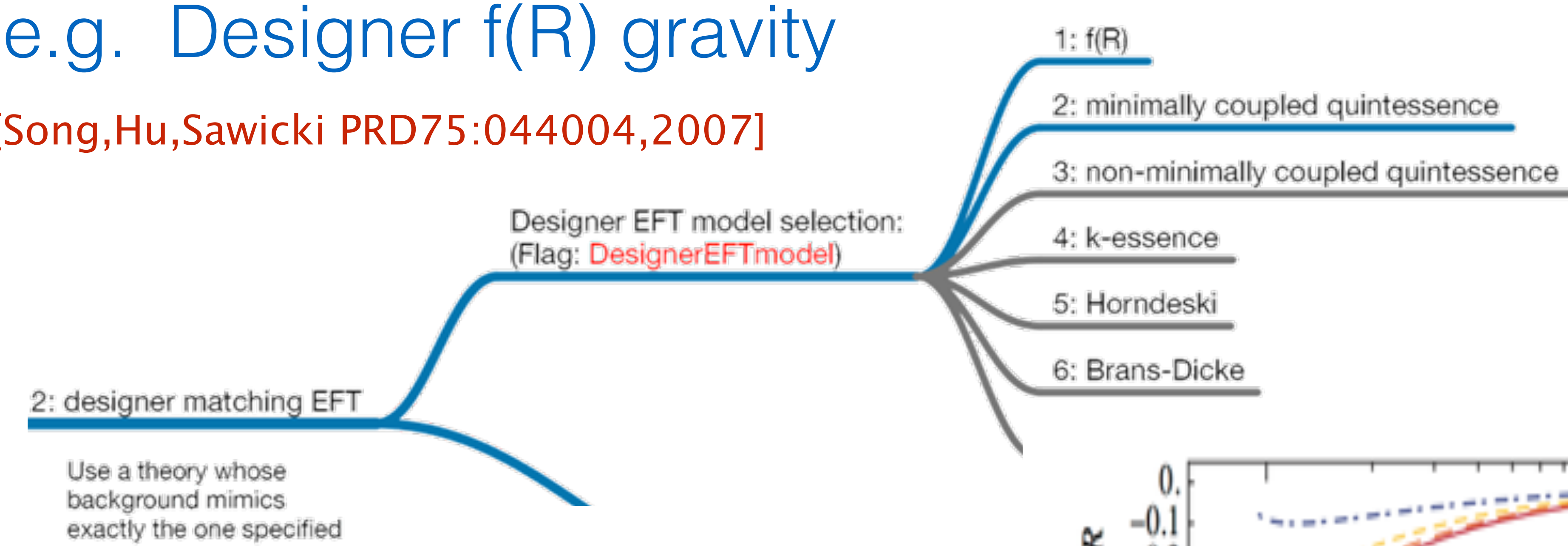
$$\text{Exponential models: } \Omega(a) = \exp\left(\Omega_0 a^s\right) - 1.$$



2.2.2 EFT parametrization: Full mapping—designer mapping

e.g. Designer f(R) gravity

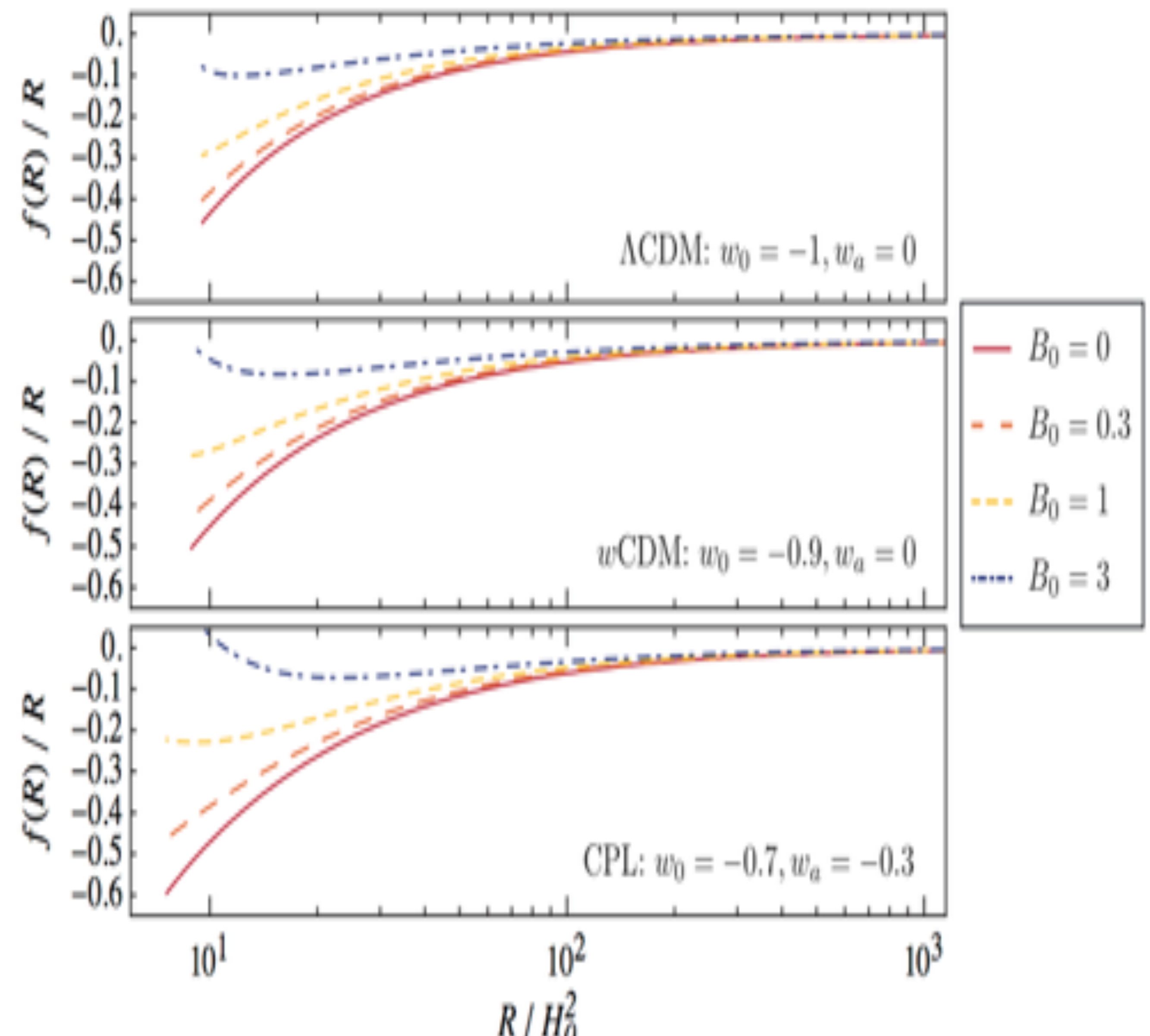
[Song,Hu,Sawicki PRD75:044004,2007]



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

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

GR limit: B0 —> 0,
effetive mass —> 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 —> **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:

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

momentum Einstein equation:

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

space-space off-diagonal Einstein equation:

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

space-space trace Einstein equation:

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

- **For Klein-Golden Eq. Of π field**

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

---

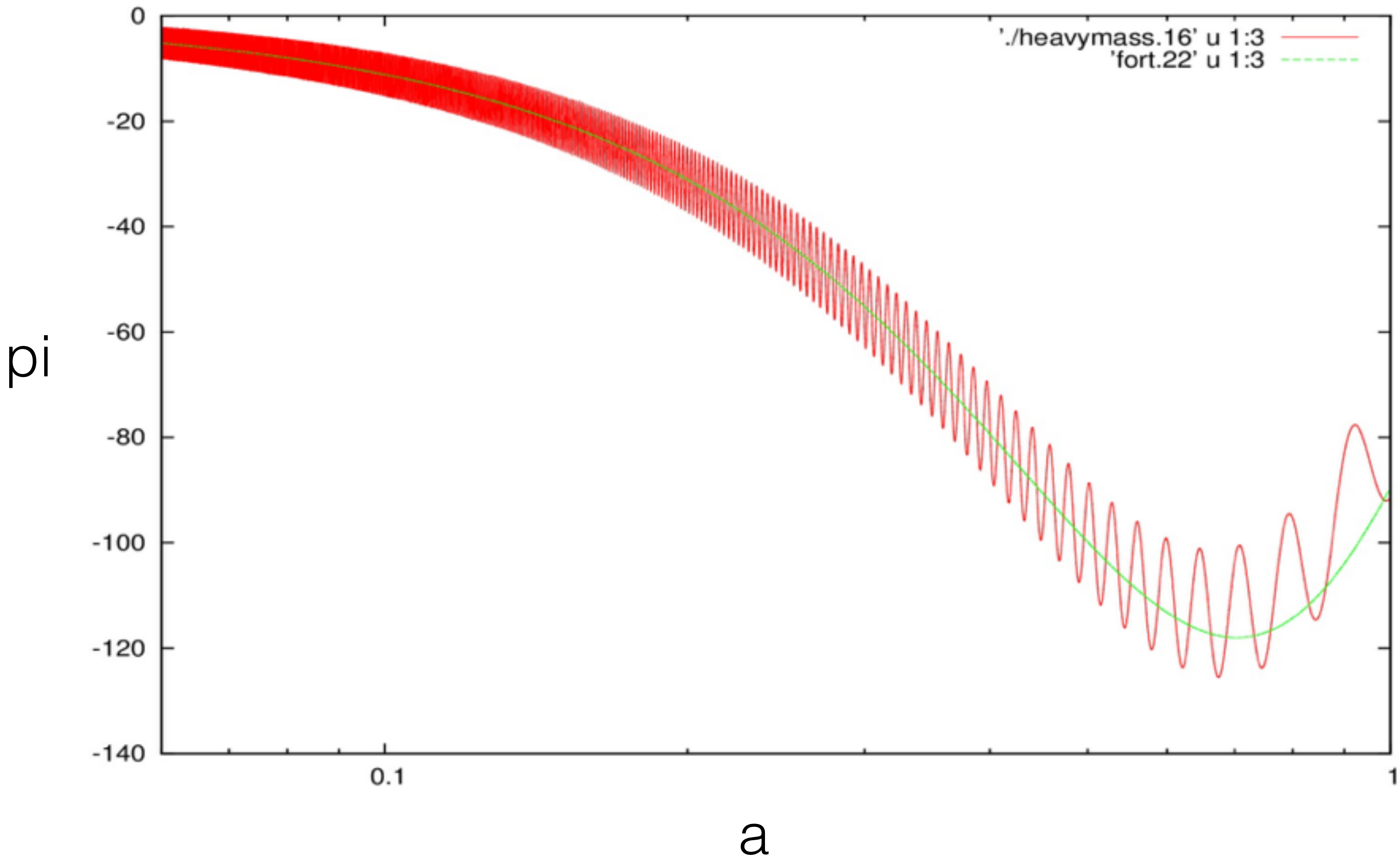
kinetic friction mass sound speed source

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

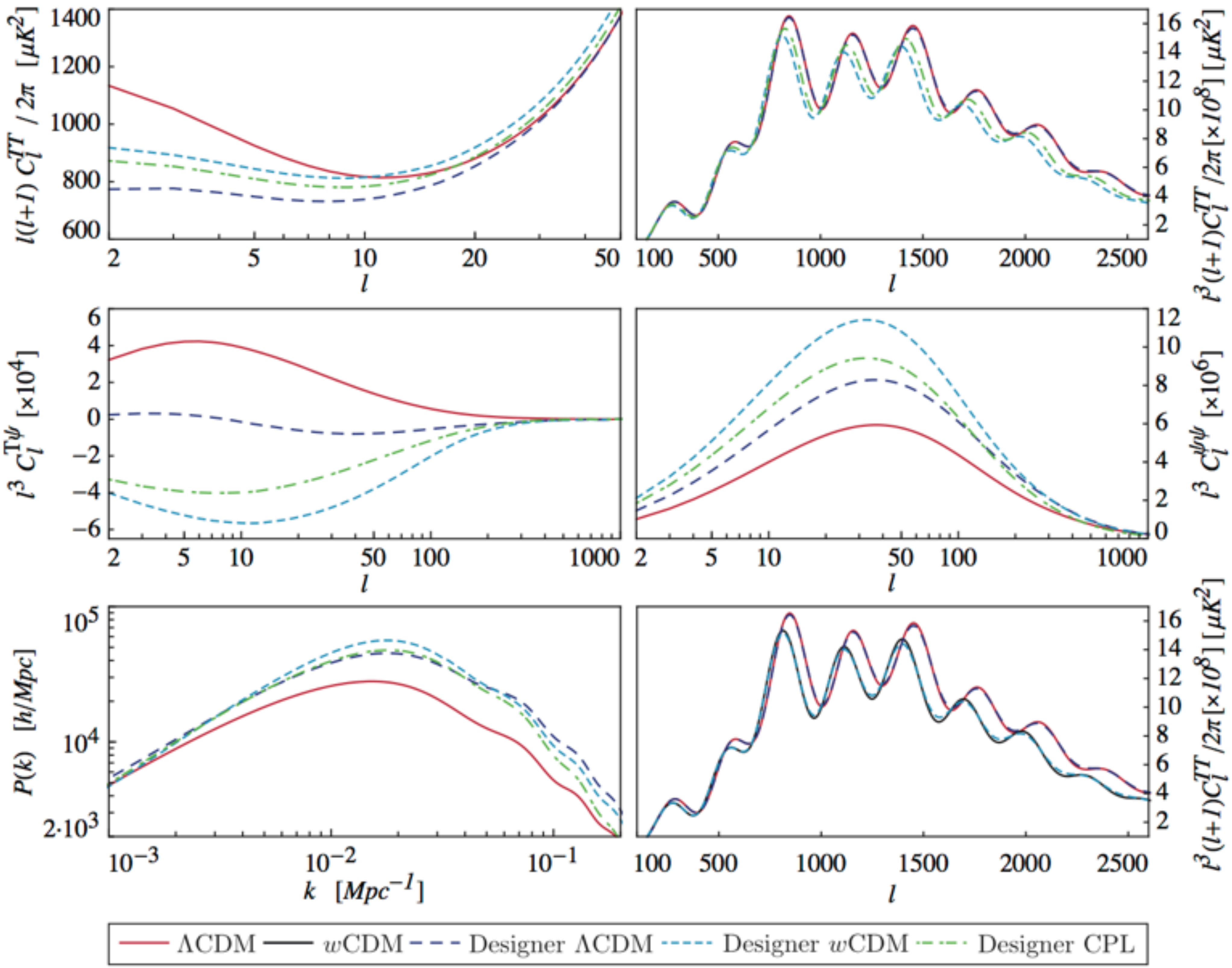
Have pass the viability condition:

1. Effective Newton constant does not change sign: 1+Ω>0
2. ghost instability: A>0
3. sound speed <=1: D/A<=1
4. mass square >= 0: C/A>=0

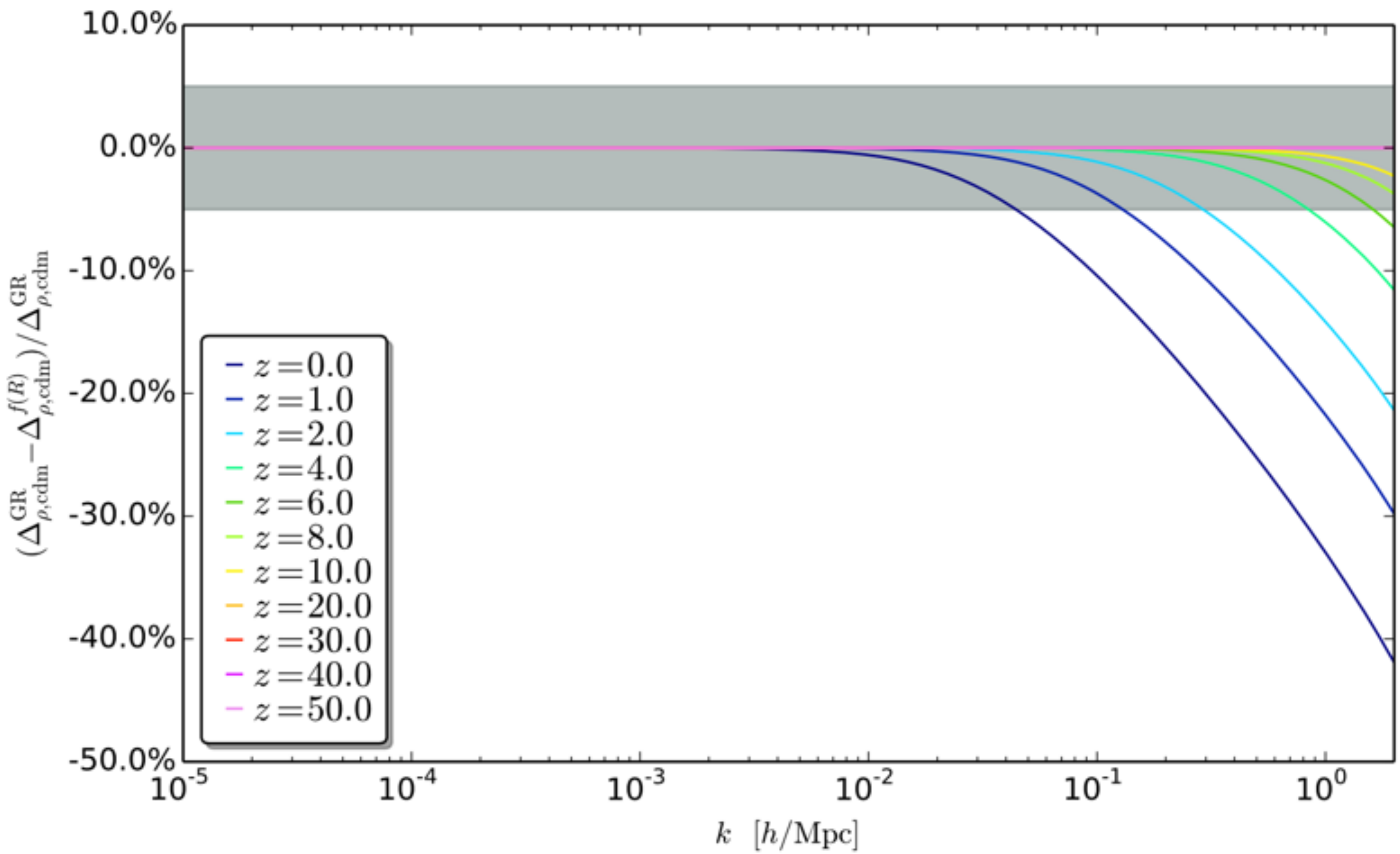
pi field solution: f(R) example



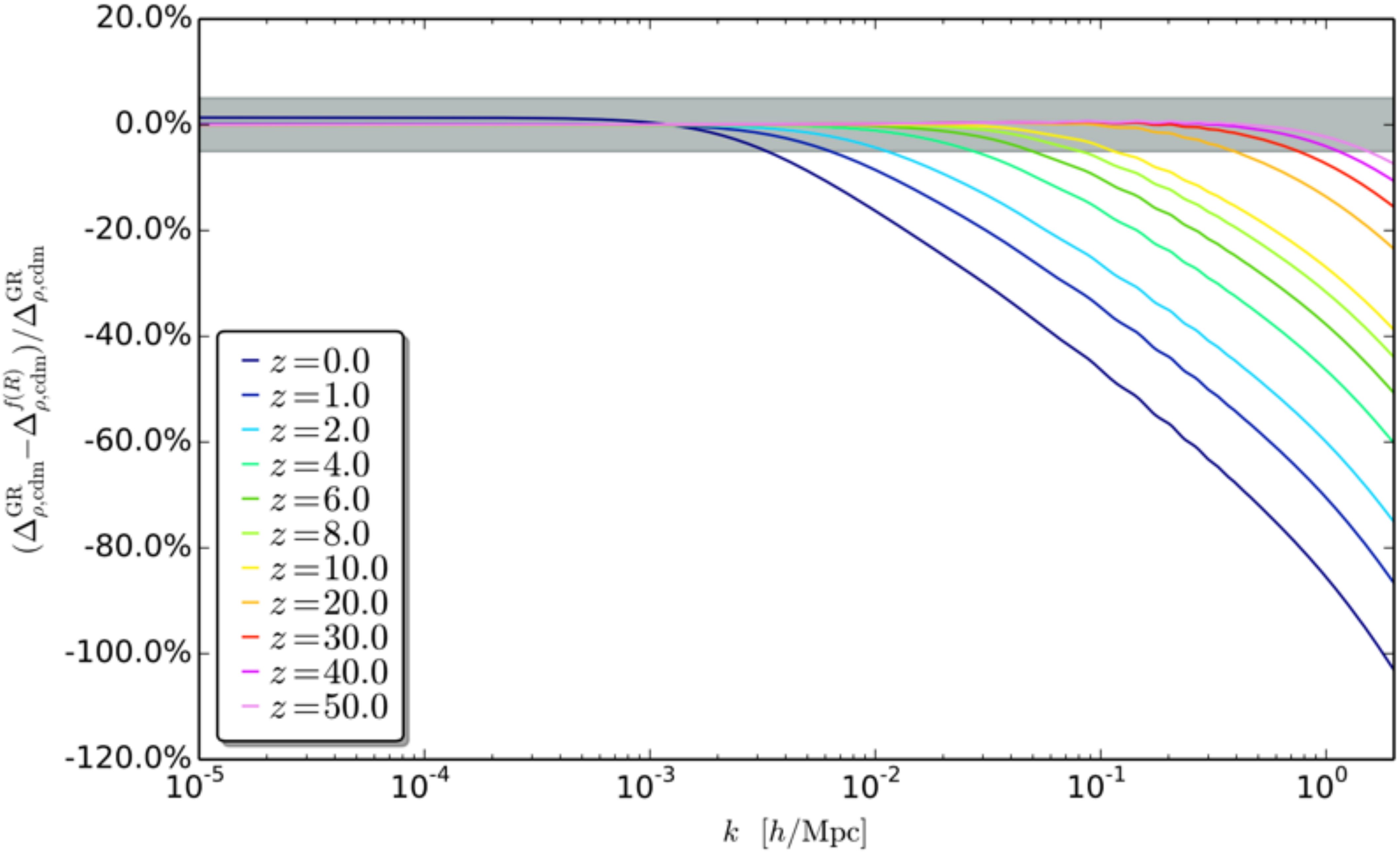
2.4 CMB spectra—example: f(R)



2.5 Transfer function of CDM



Designer f(R) with LCDM background
B0=0.001

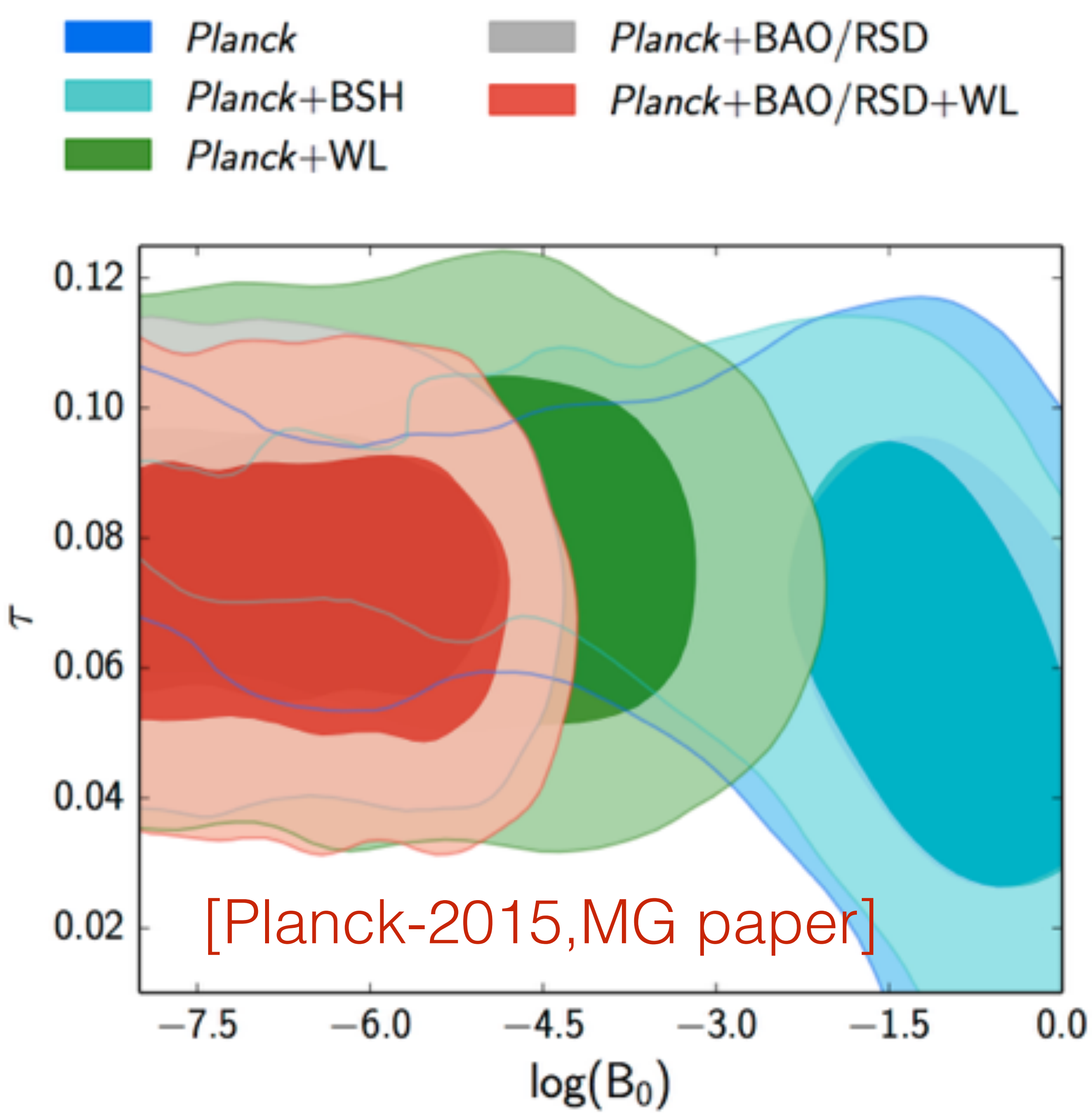


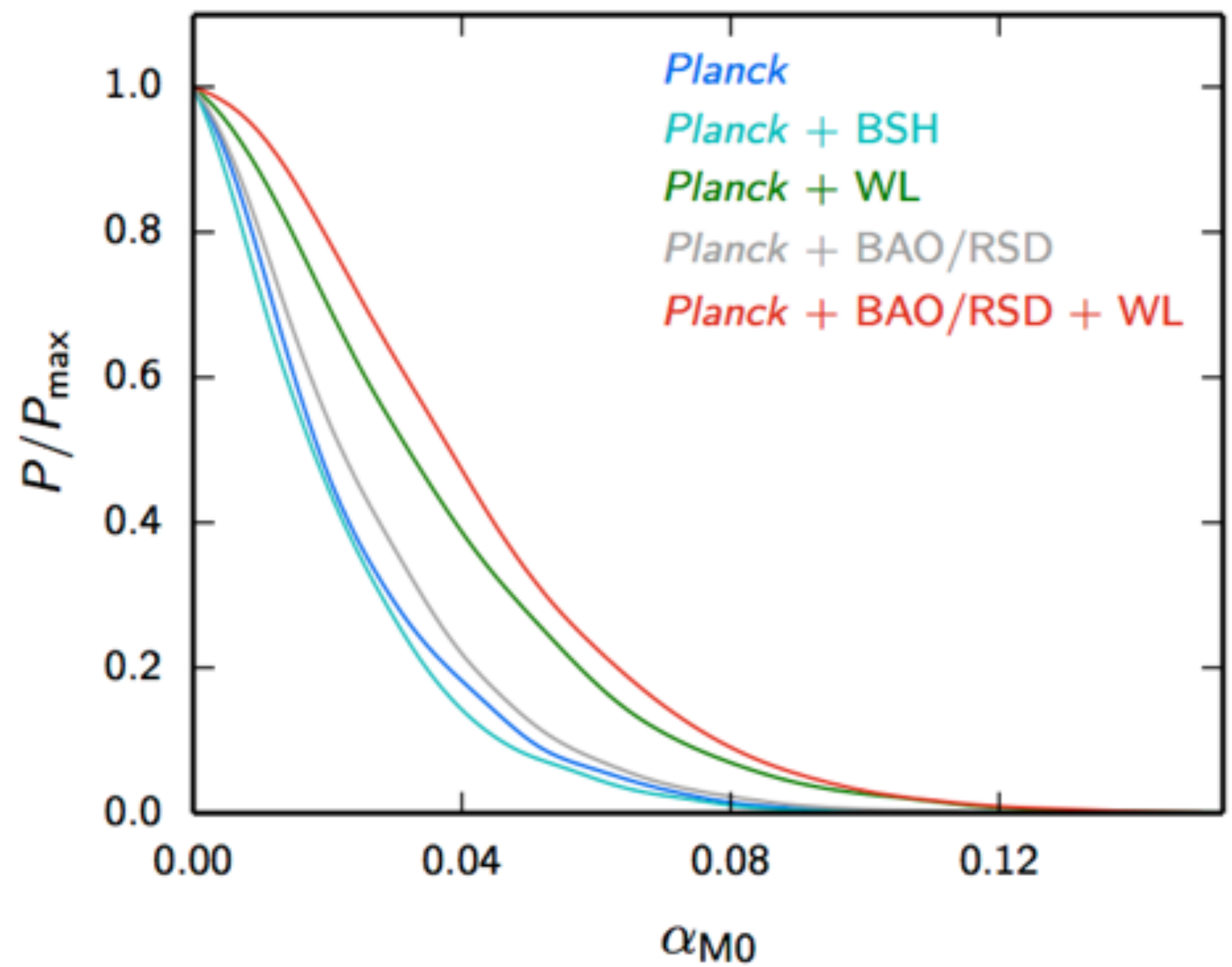
Designer f(R) with wCDM background
B0=0.01 and w=-0.95

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**

EFTCAMB

KEEP
CALM
AND
TEST
GRAVITY

the EFTCAMB team

Thank you!