Effective Field Theory approach for Dark Energy/ Modified Gravity

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Beijing/China, Sept. 2015

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Outline

1. Evidence of late-time cosmic acceleration

2. Effective Field Theory approach for DE/MG

3. The structure of EFTCAMB

4. Planck-2015 results based on EFTCAMB

5. Conclusion

How do we know the Universe is accelerating?

It is via …

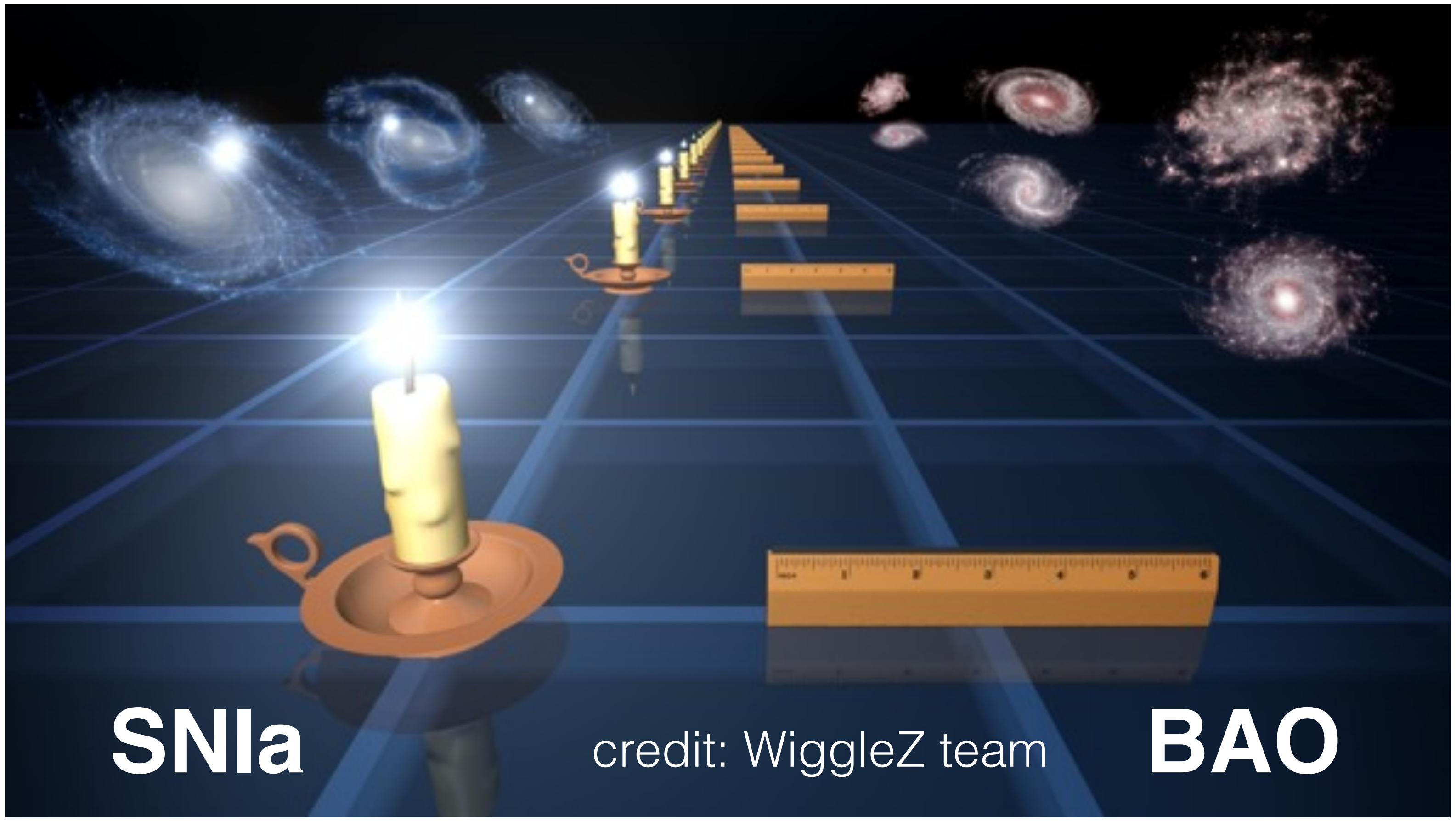
Measurement of the distance of far away object

What we observed is line of sight integration effect

Need to know the intrinsic physics!

Standard candle

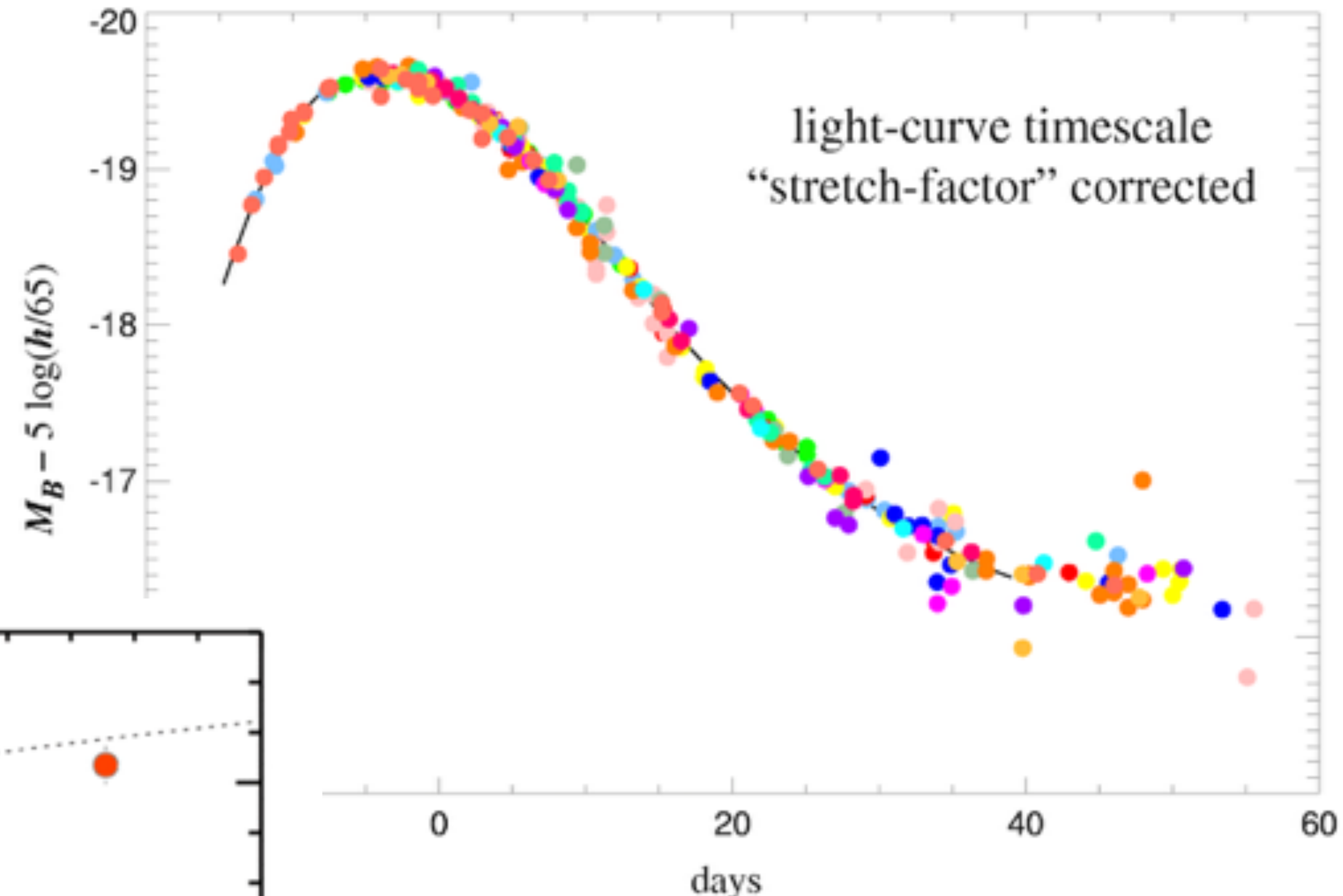
fixed luminosity



Standard ruler

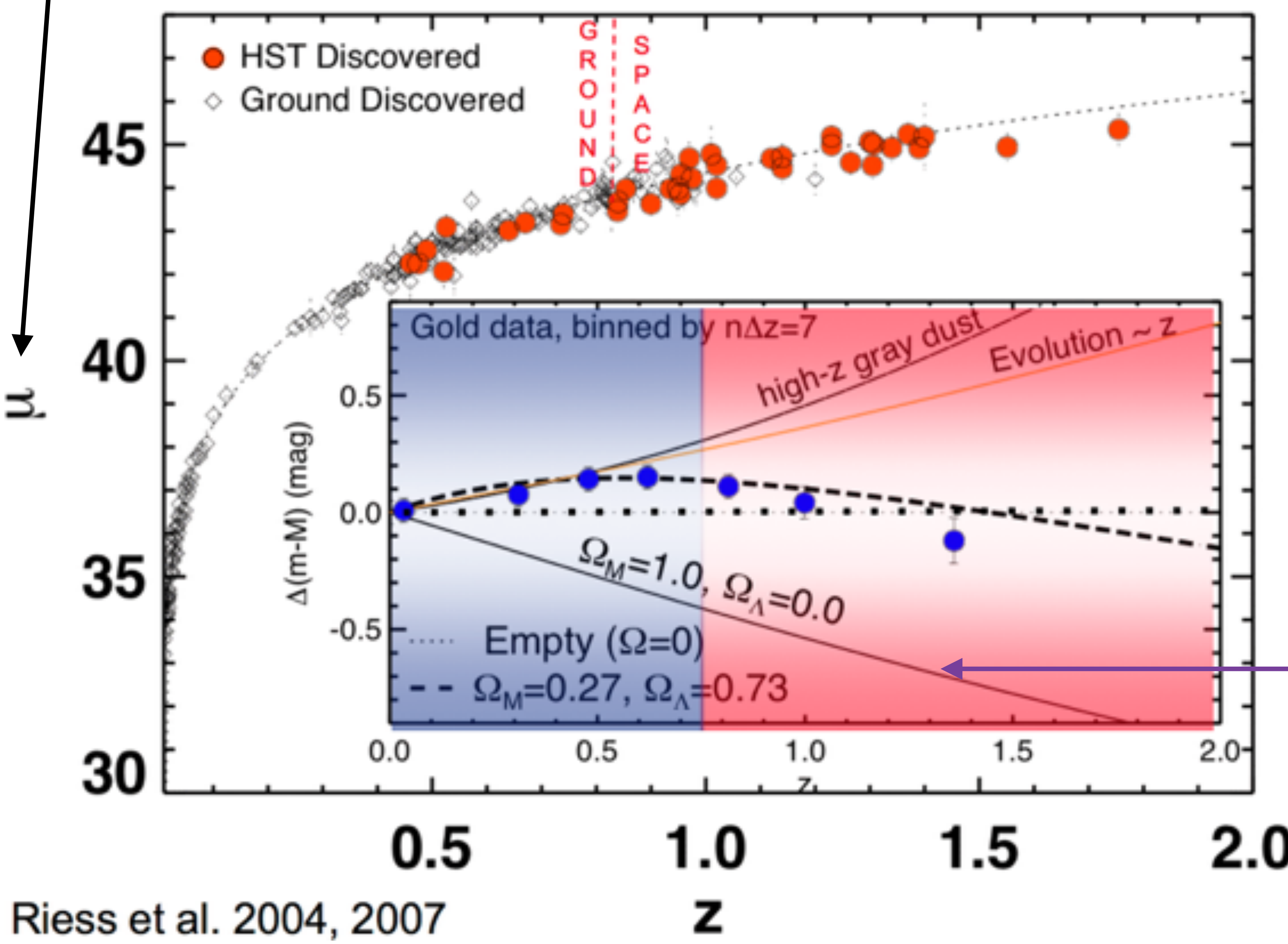
fixed transverse scale

SNIa (White dwarf)



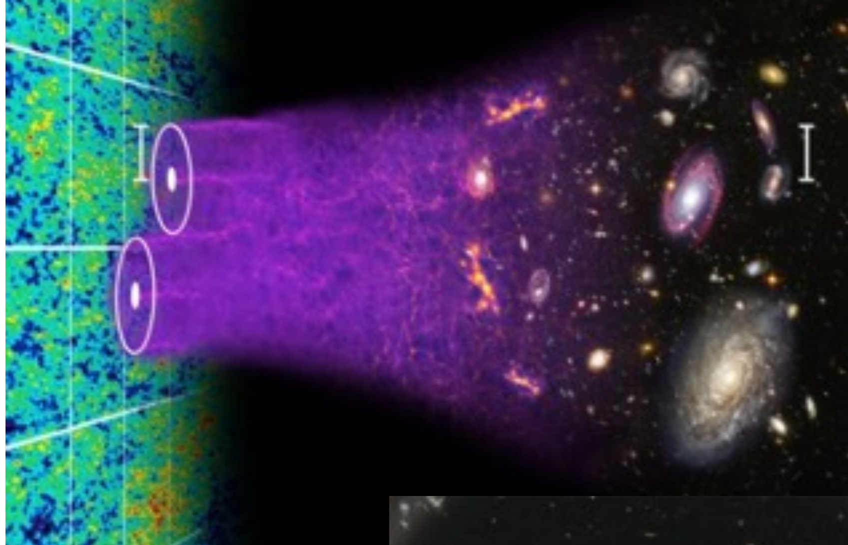
Kim, *et al.* (1997)

luminosity
module



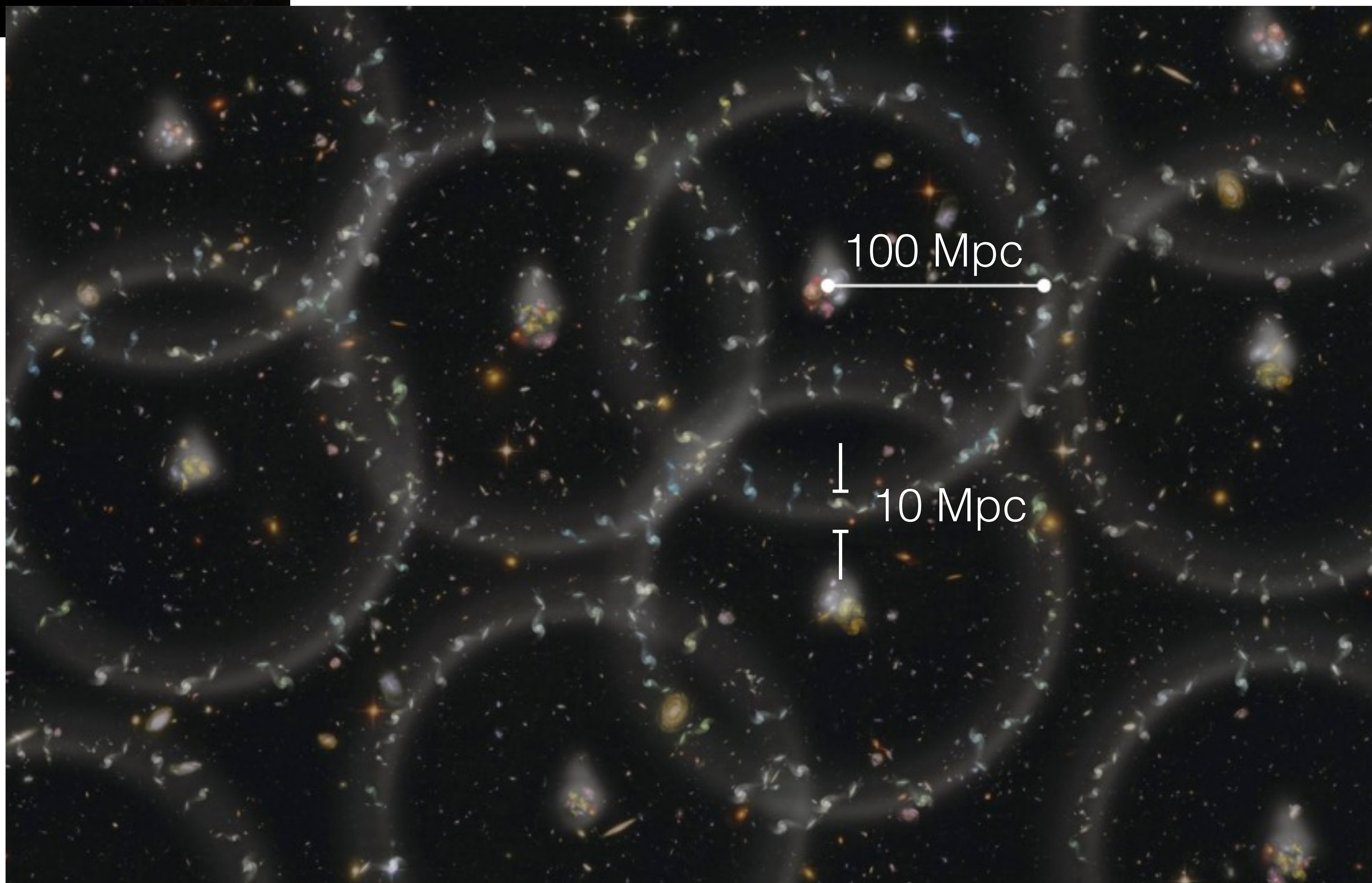
Riess et al. 2004, 2007

Einstein-DeSitter
only CDM+baryon



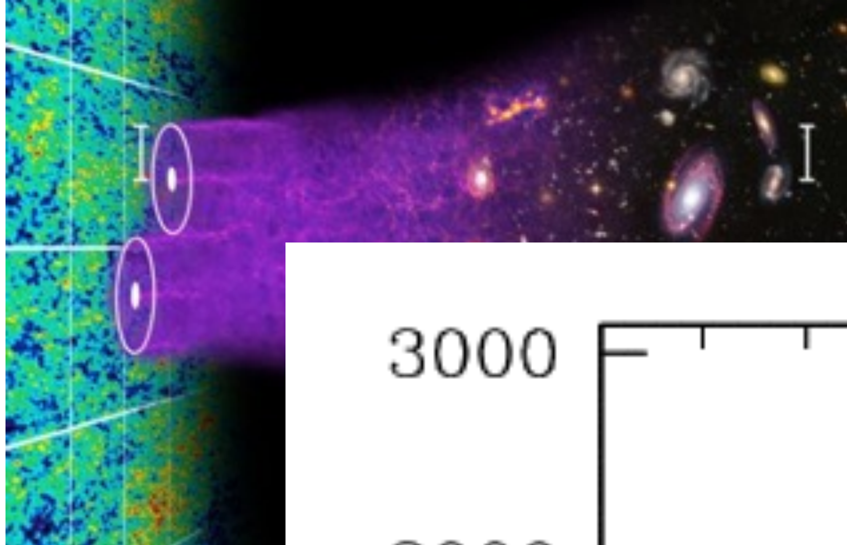
BAO — baryonic acoustic oscillation

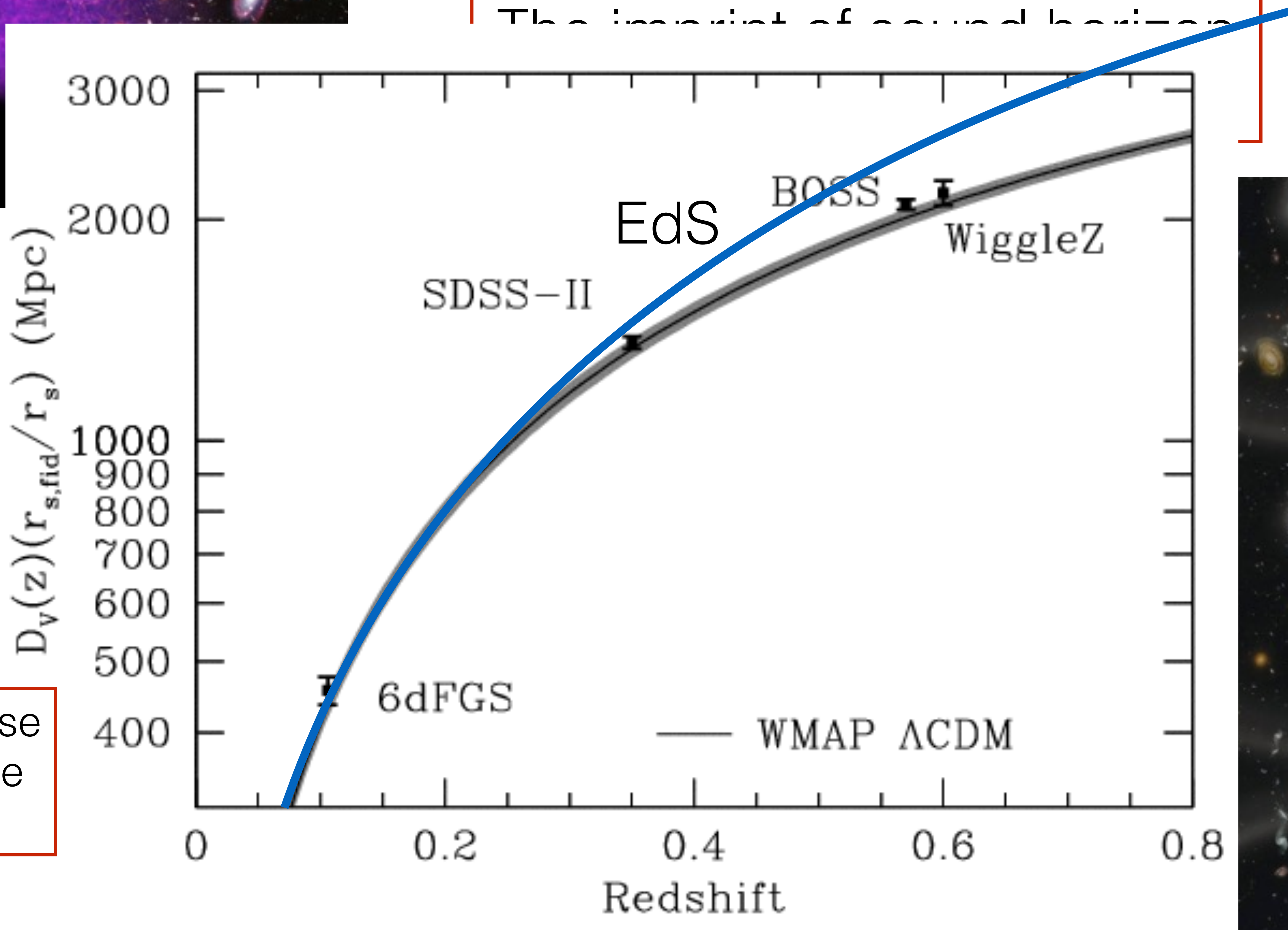
The imprint of sound horizon of Recom epoch on the LSS



BAO

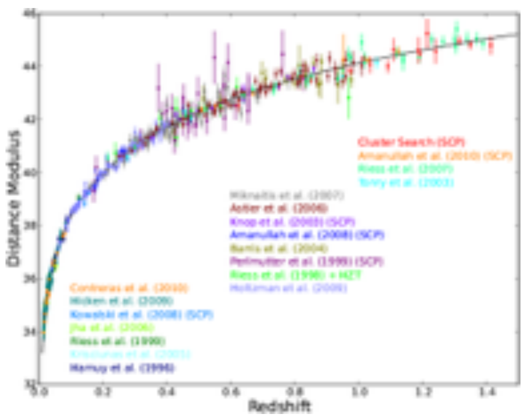
The imprint of sound horizon



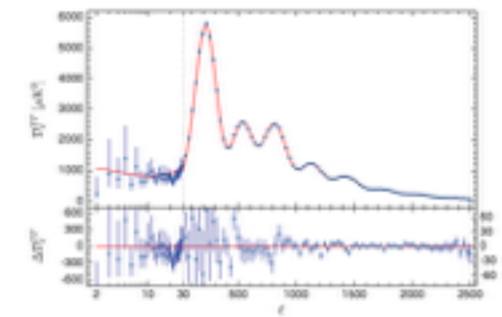


transverse distance scale

Most simplest explanation —LCDM

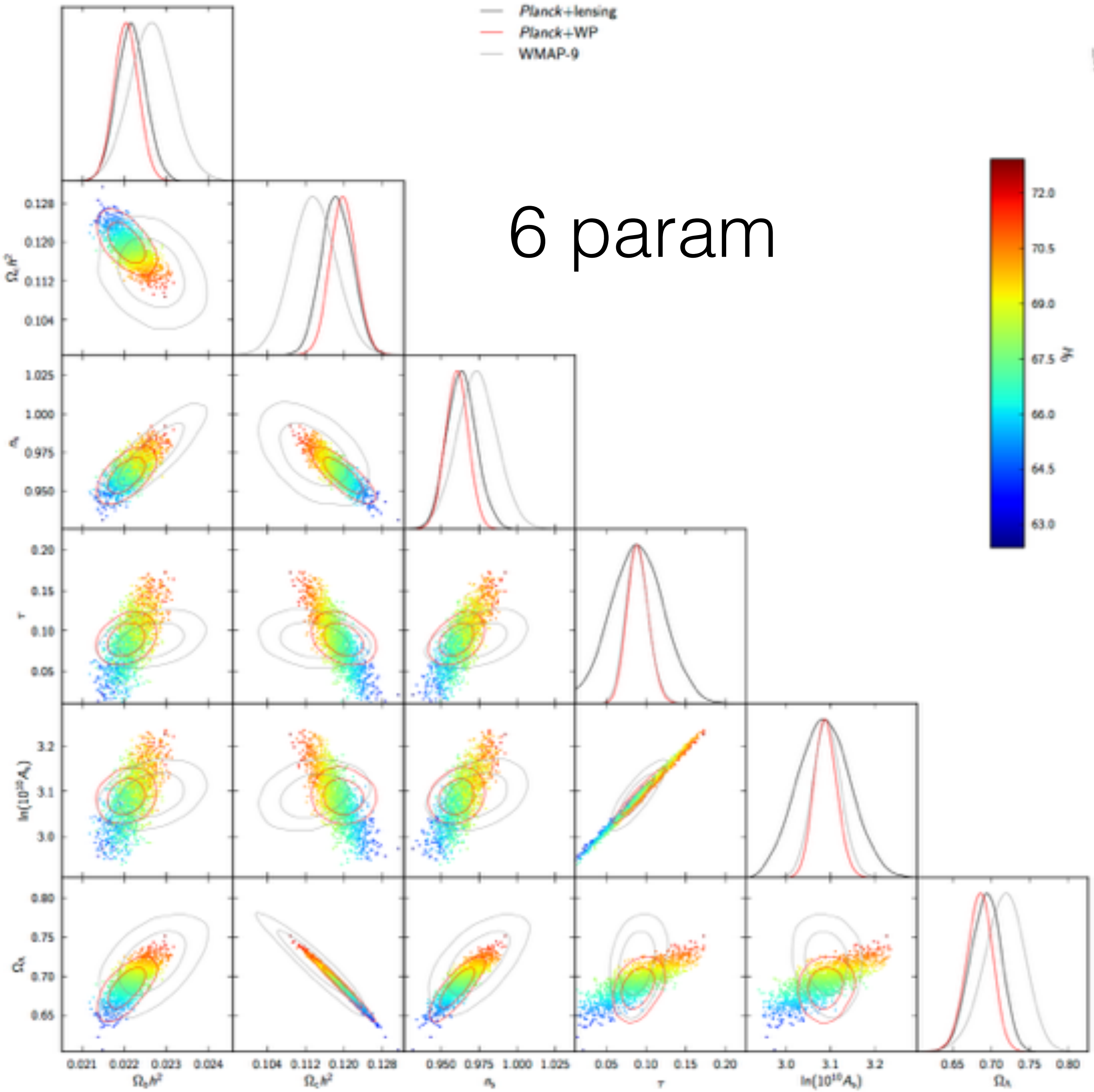


SN



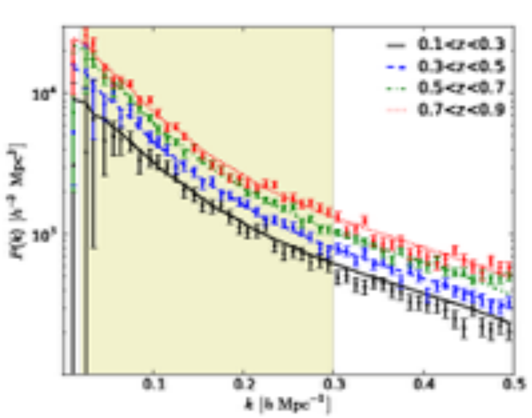
CMB

6 param

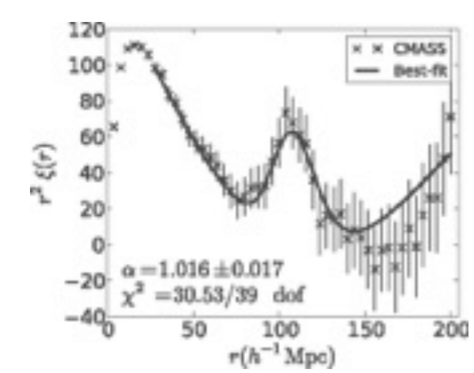


[Planck13 CP paper]

LSS

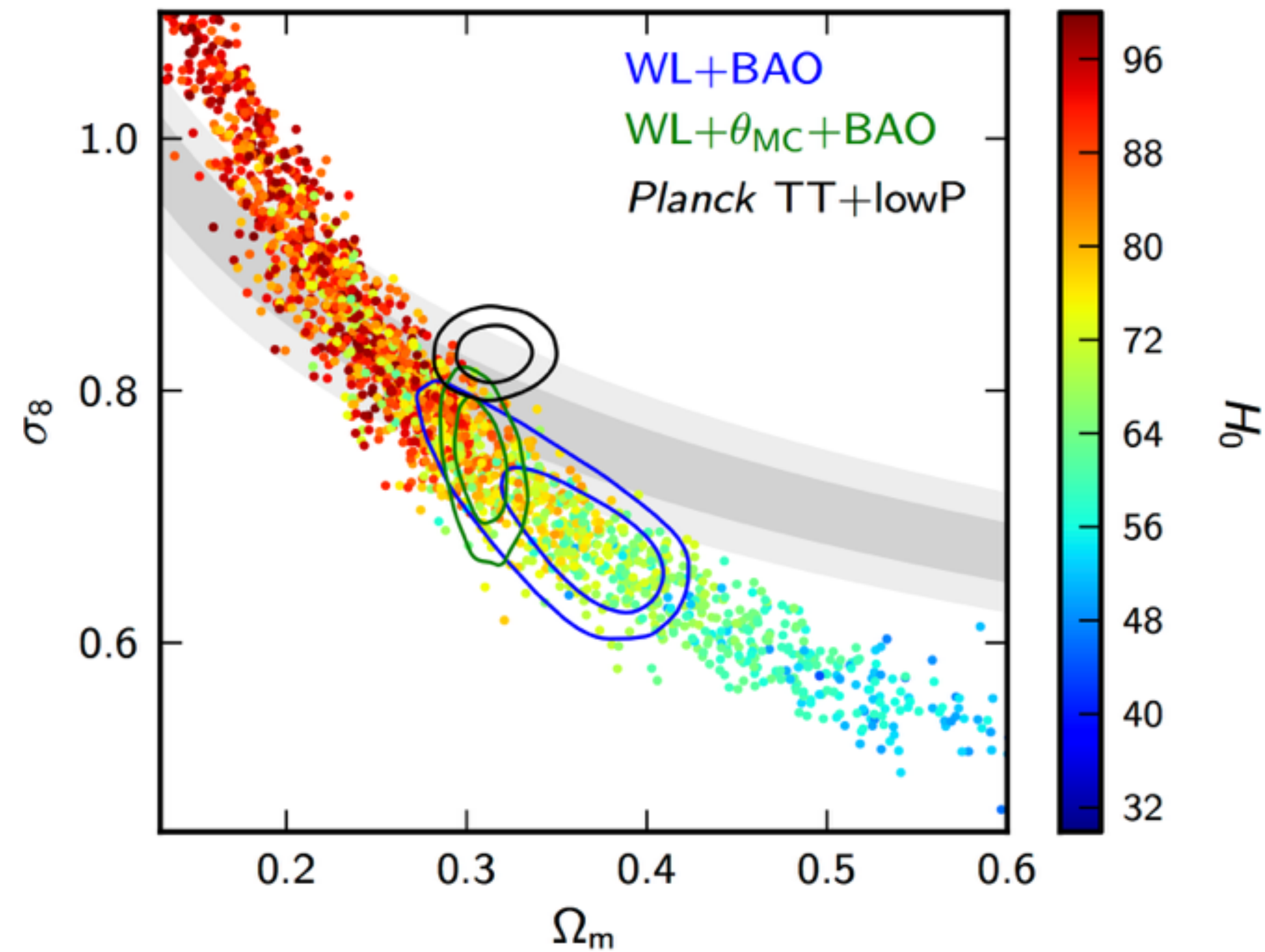


BAO



Is this the end of story?

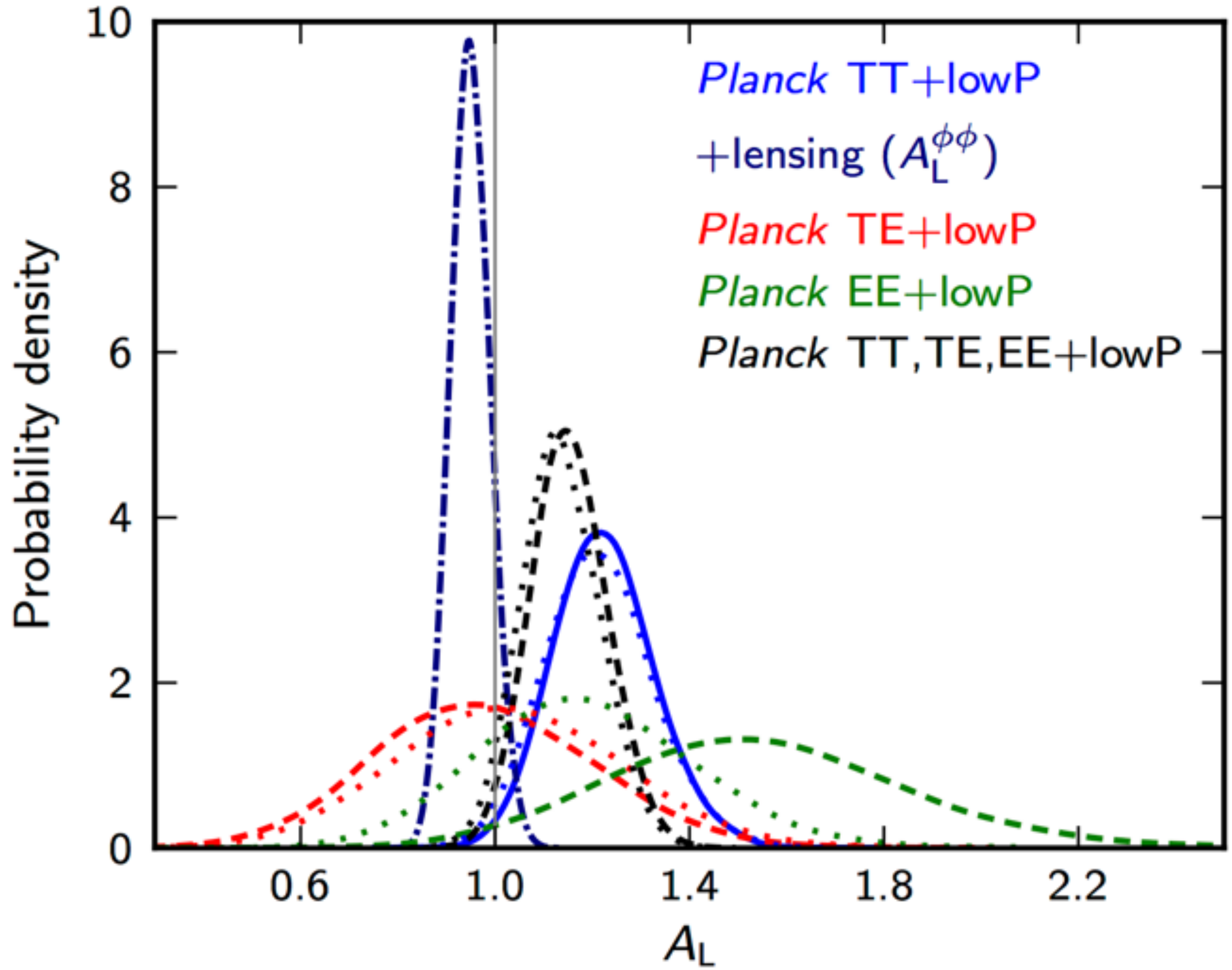
Tension between high-z and low-z



matter fluct.— Planck (CMB) >> LSS (CFHTLenS)

[Planck15-CP paper]

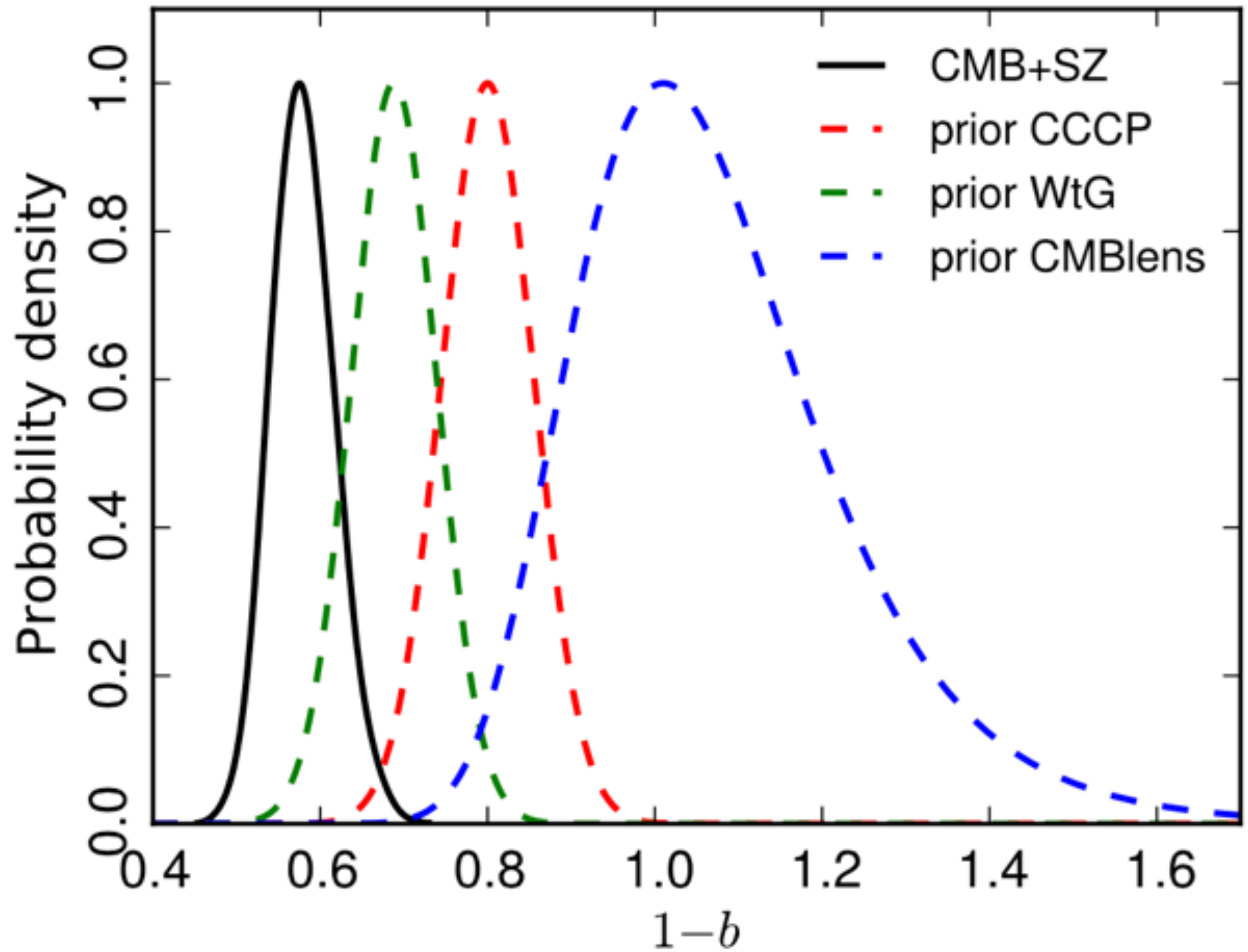
Tension between high-z and low-z



Lensing amplitude — Primary CMB >> Secondary CMB

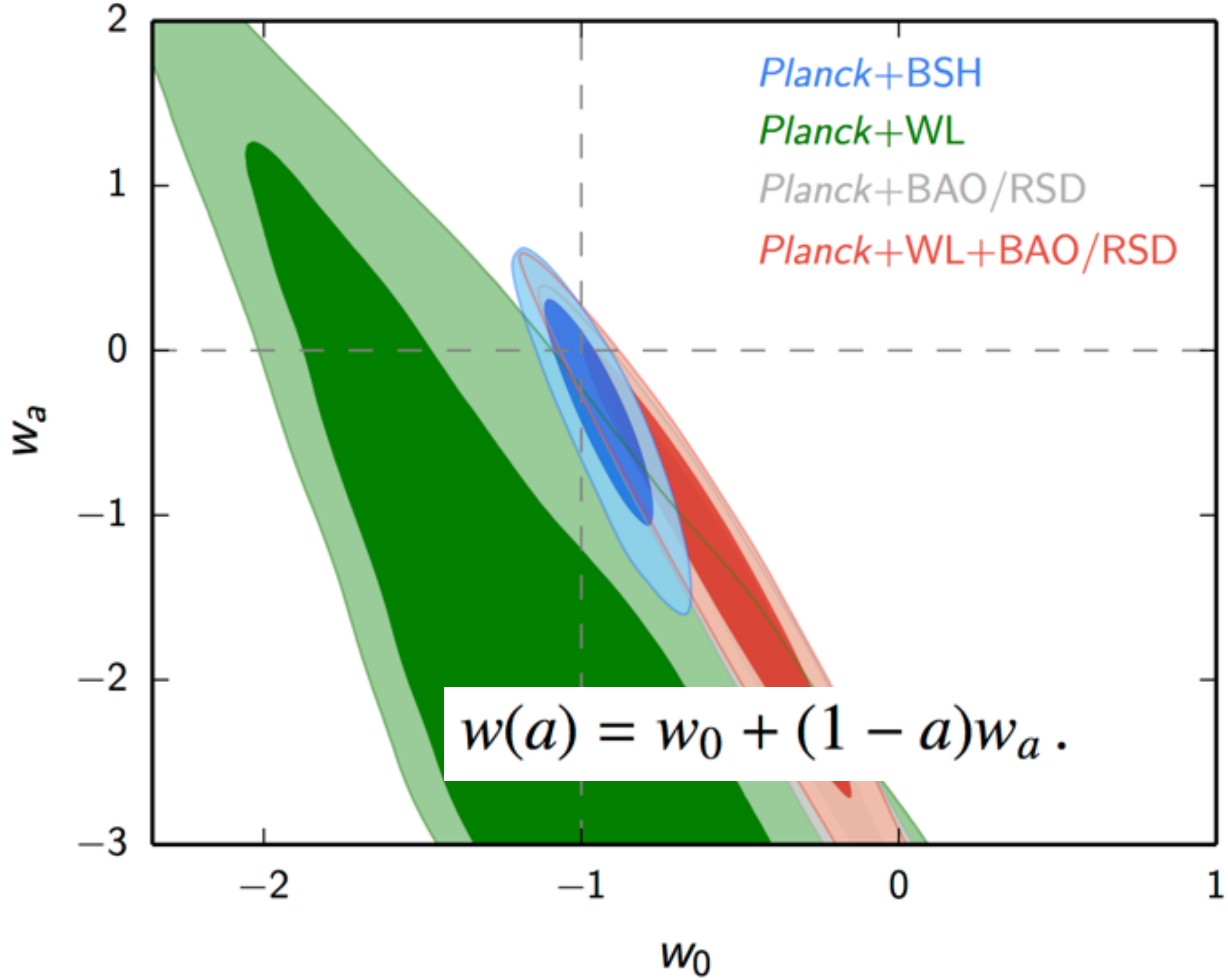
[Planck15-CP paper]

Tension between high-z and low-z



Mass bias of tSZ cluster — CMB << LSS

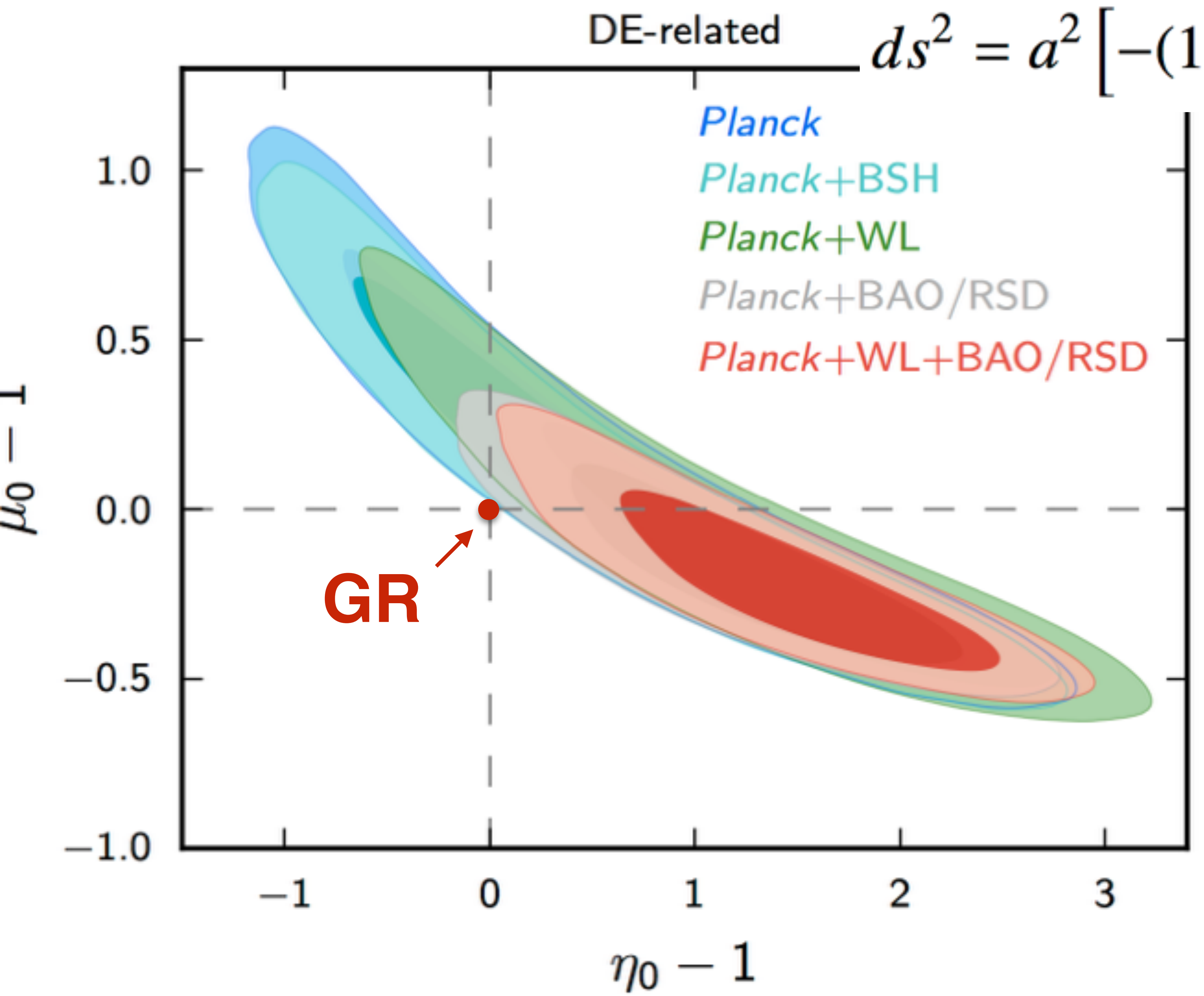
[Planck15-SZ paper]



Most part is below phantom divide!

[Planck15-MG paper]

[Planck15-MG paper]



$$ds^2 = a^2\left[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx^2\right] .$$

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,\boldsymbol{k})\rho\Delta;$$

$$\eta(a,\boldsymbol{k}) \equiv \Phi/\Psi.$$

GR predict, on the large scale, the two gravitational potentials are equal, due to the lack of sources of anisotropic stress!

All these motivate us to

GR!

How to?

DE

$$G_{\mu\nu} = 8\pi G\left[T^{cdm}_{\mu\nu} + T^{b}_{\mu\nu} + T^{\gamma}_{\mu\nu} + T^{\nu}_{\mu\nu} + T^{DE}_{\mu\nu}\right]$$

MG

$$G_{\mu\nu} + \Delta G_{\mu\nu} = 8\pi G\left[T^{cdm}_{\mu\nu} + T^{b}_{\mu\nu} + T^{\gamma}_{\mu\nu} + T^{\nu}_{\mu\nu}\right]$$

Not the math trick of RHS or LHS

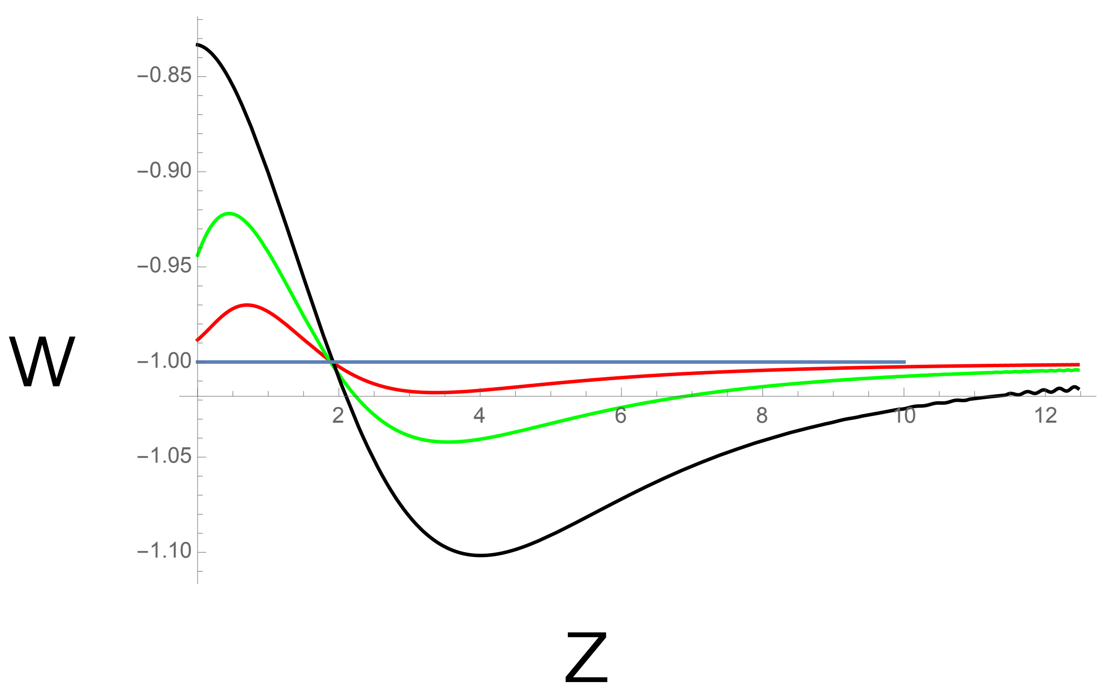
What do I mean by DE and MG?

DE

EoS of exotic fluid

$$w = \frac{P}{\rho}$$

LCDM ⟶ w=-1



MG

Growth rate of matter fluid

$$g(a) \equiv D(a)/a = \exp\left[\int_0^a (da'/a')\left[\Omega_M(a')^\gamma - 1\right]\right]$$

GR ⟶ $\gamma = 0.55$

Zeldovich Approximation-II

In the linear sub-Horizon regime, GR gives

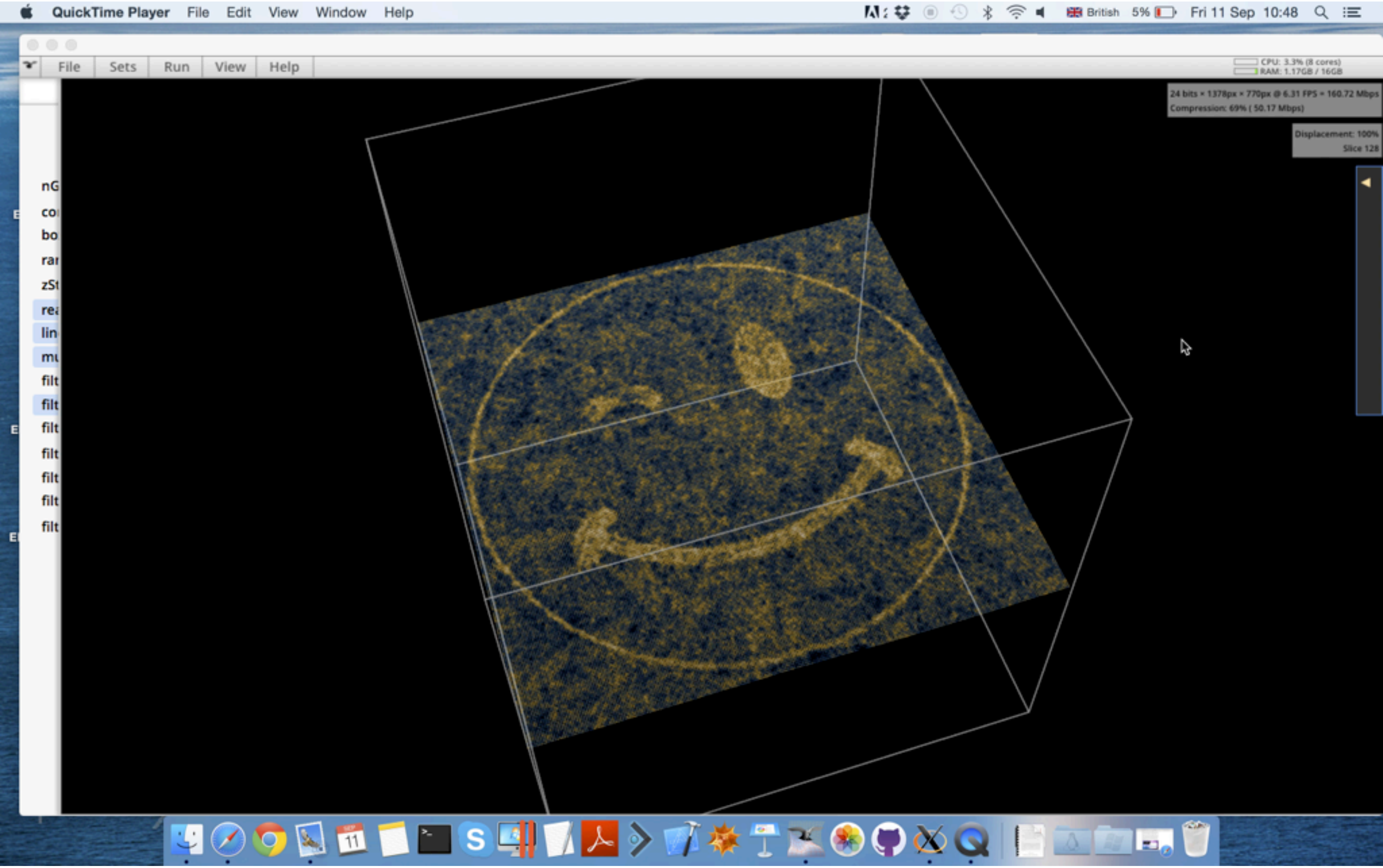
$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\rho_m\delta_m = 0$$

The growth rate of CDM only depends on time!

The displacement field $\vec{x} = \vec{y} - \mathcal{D}(\tau)\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i, \vec{y})$

In GR: CDM particles trajectory is straight line!

A video of ZA


QuickTime Player File Edit View Window Help
British 5% Fri 11 Sep 10:48
File Sets Run View Help
CPU: 3.3% (8 cores)
RAM: 1.17GB / 16GB
24 bits × 1378px × 770px @ 6.31 FPS = 160.72 Mbps
Compression: 69% (50.17 Mbps)
Displacement: 100%
Slice 128

DE/MG:

Quasic-Static Approx:

$$k^2\psi = -4\pi G\,\mu(a,k)a^2\rho\Delta\ ,$$
$$\frac{\phi}{\psi} = \gamma(a,k)\ .$$

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\rm eff}(t,k)\rho_m\delta_m = 0$$

DE/MG: at linear regime growth rate of CDM **depends** on the scales!

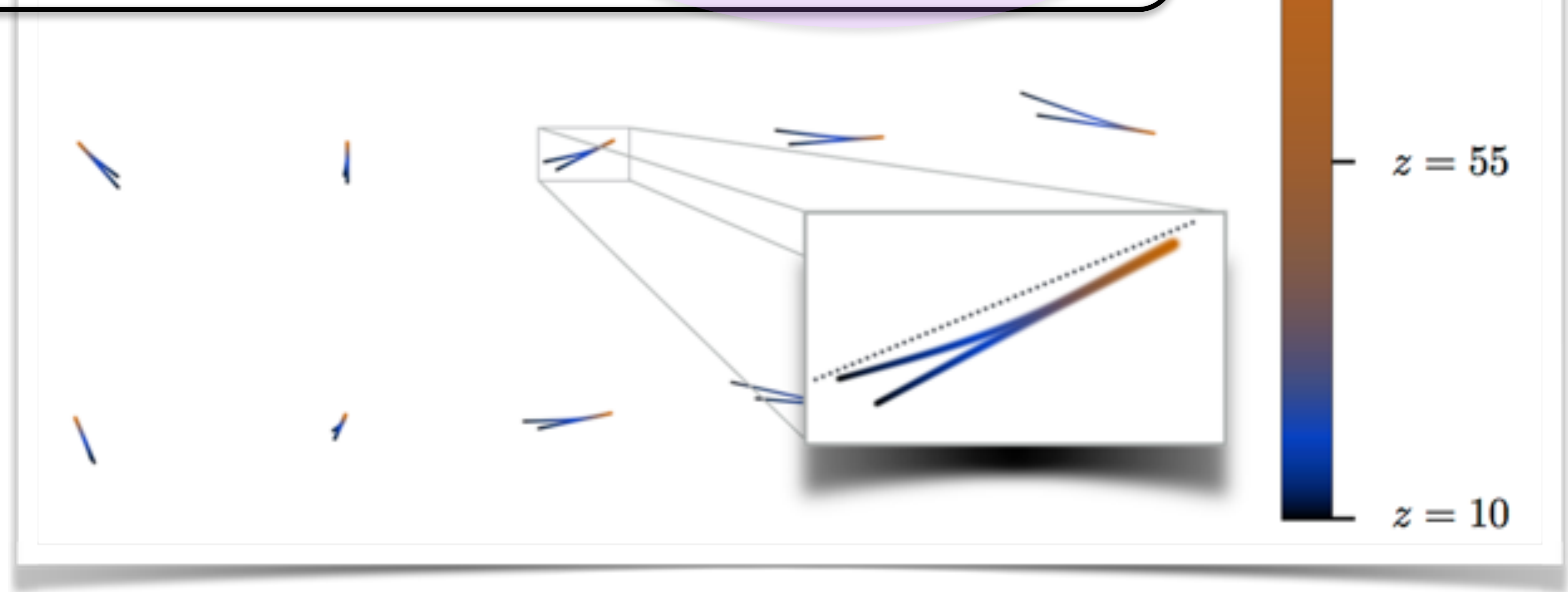
GR: The displacement field $\vec{x} = \vec{y} - \mathcal{D}(\tau)\frac{1}{\nabla_y^2}\vec{\nabla}_y\Delta_c(\tau_i,\vec{y})$

Beyond Zeldovich Approximation

DE/MG: at linear regime growth rate of CDM **depends** on the scales!

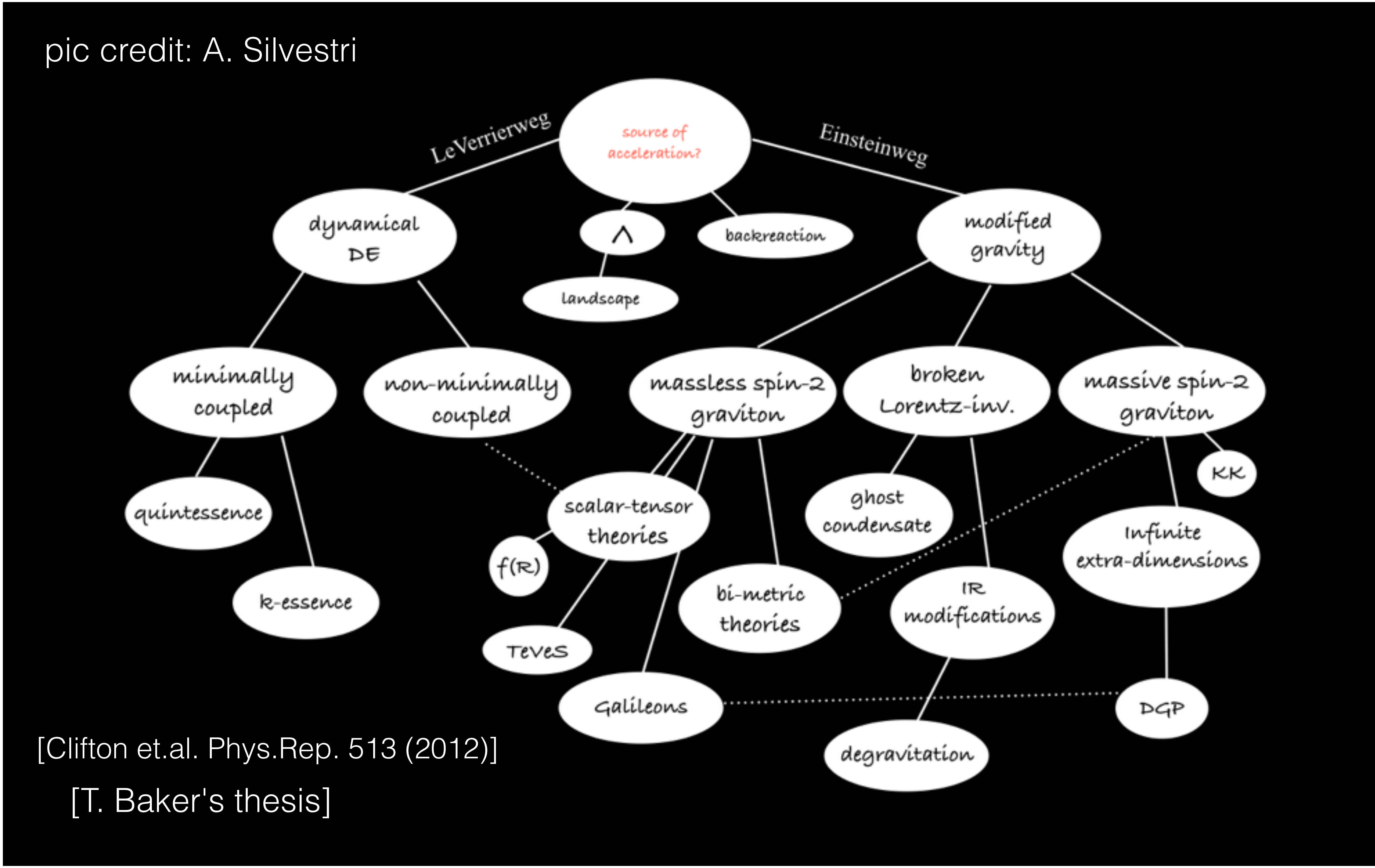
Deflection by the gravitational potential

$$\vec{x} = \vec{y} - \mathcal{D}(\tau, \vec{y}) \frac{1}{\nabla_y^2} \vec{\nabla}_y \Delta_c(\tau_i, \vec{y}) - \Delta_c(\tau_i, \vec{y}) \frac{1}{\nabla_y^2} \vec{\nabla}_y \mathcal{D}(\tau, \vec{y}) \, .$$

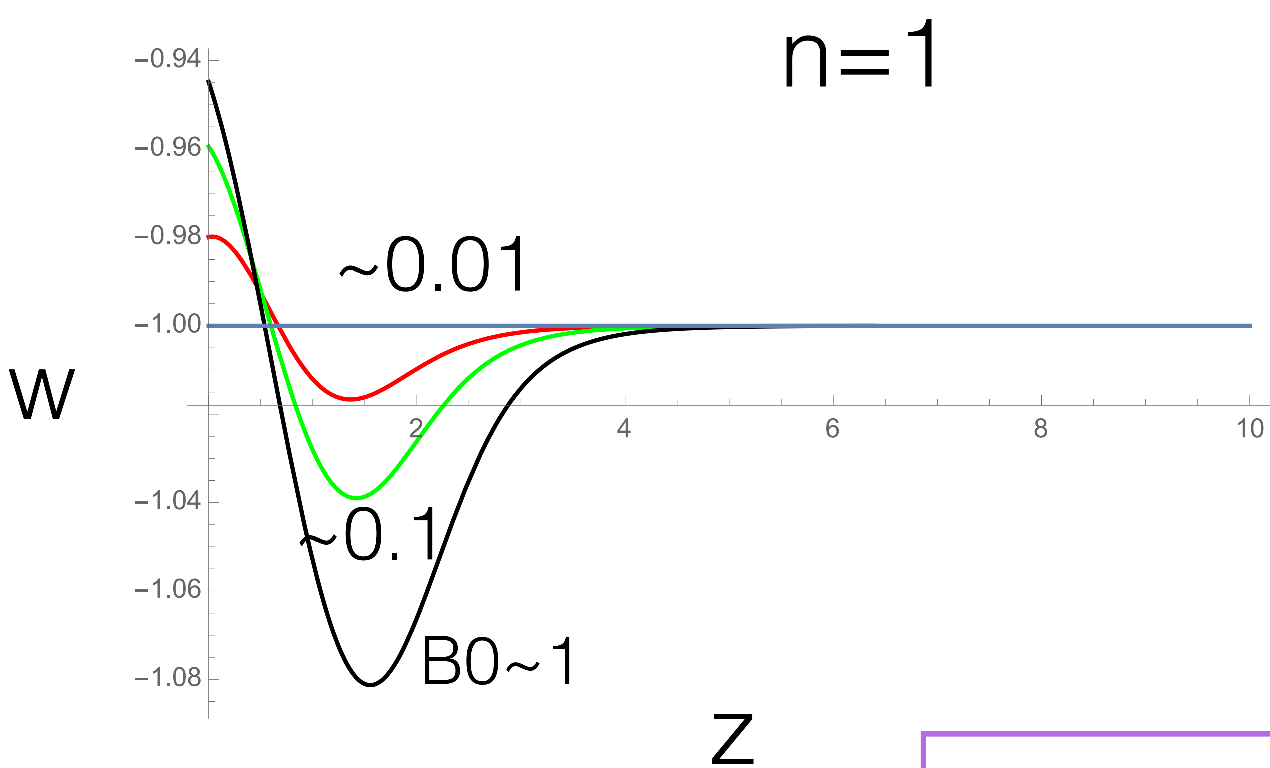


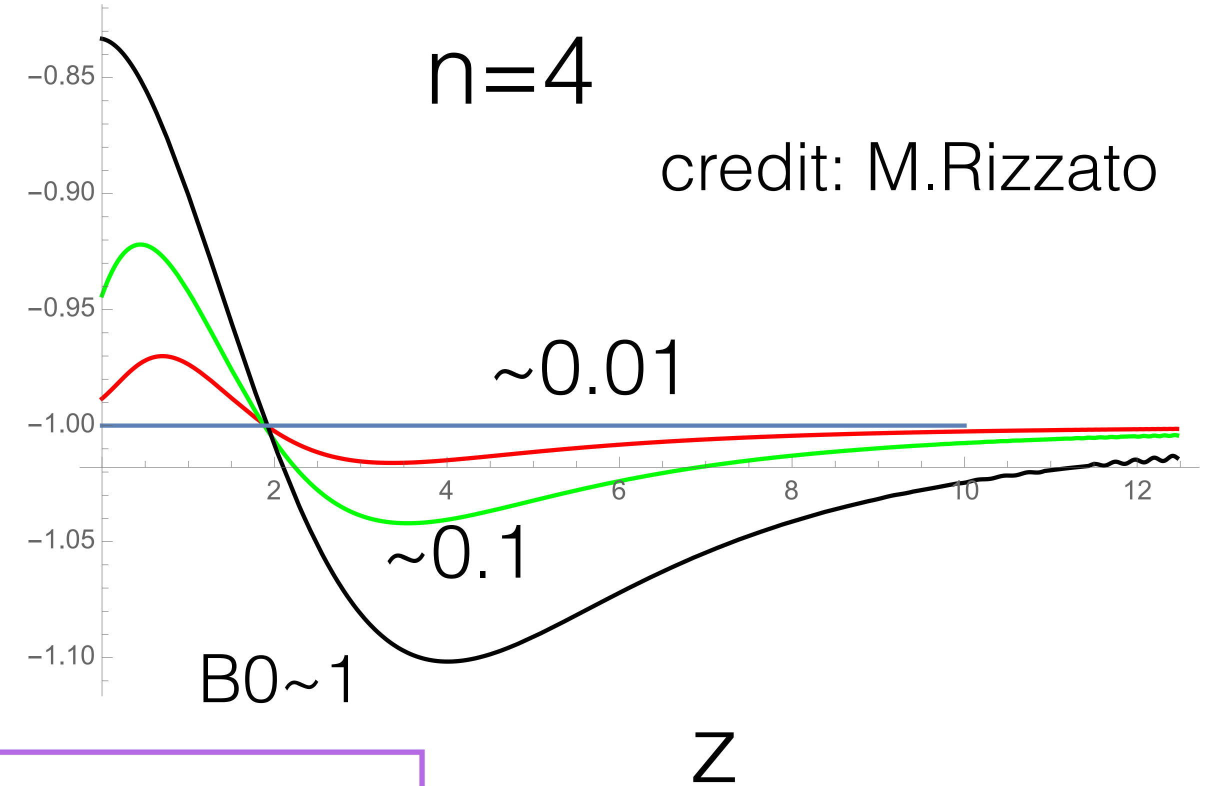
Even at linear regime, trajectory of CDM particles are curved!

State-of-the-art of DE/MG models



Examples— f(R) gravity





at most 10% effect!

Most of viable model gives very similar EoS!

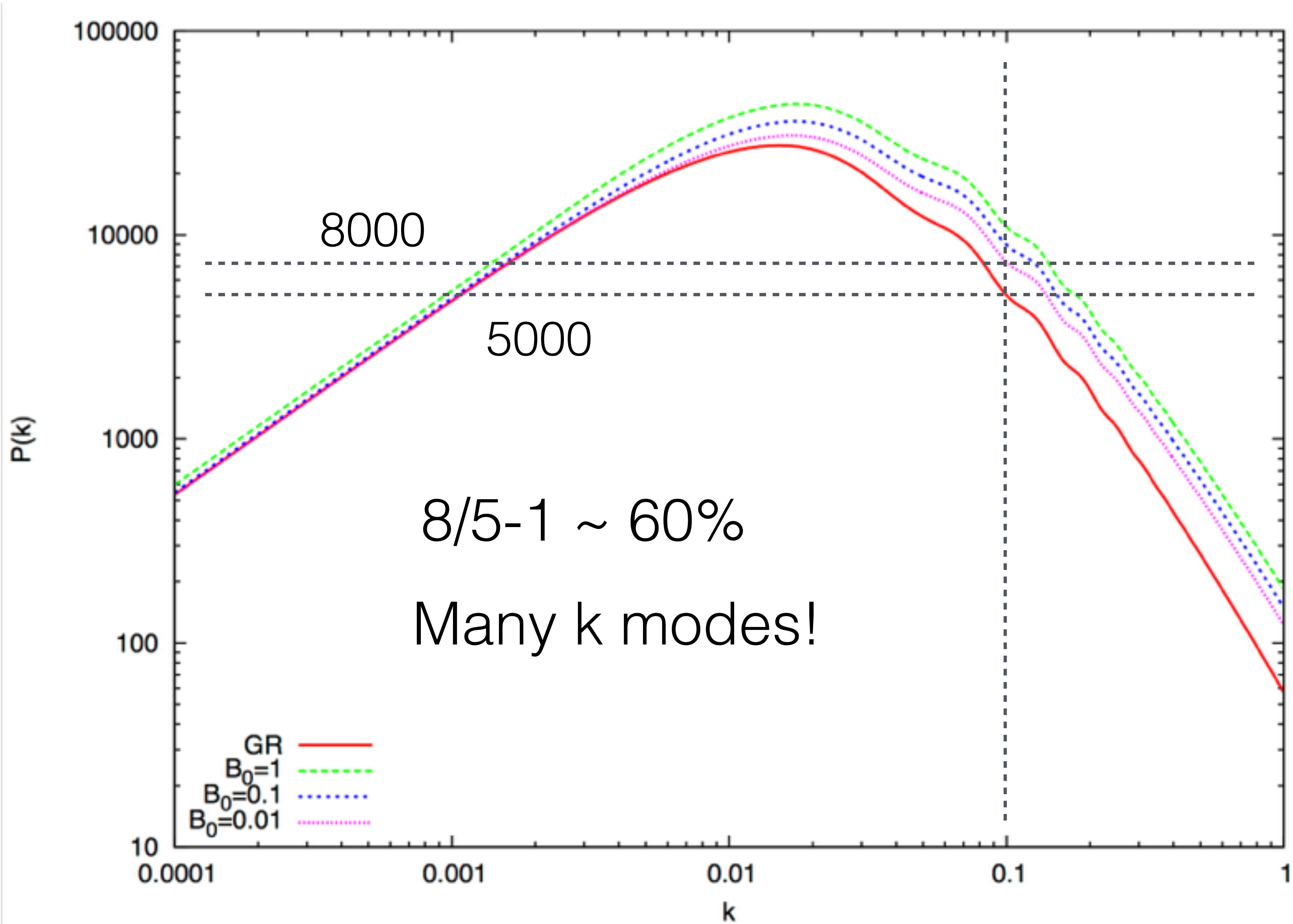
It is hard to distinguish them via only EoS for the on-going and up-coming surveys!

Need other observables to break the theoretical degeneracy!

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

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

Matter power spectrum— A robust probe!



Take home message: Compared with background probe, we should consider perturbation dynamics!

3. Effective Field Theory of DE/MG

- EFT provides a **unified parametrisation** of the scalar field perturbations in **single** scalar field DE/MG **given background evolution.**

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

[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

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

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

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

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

3.1 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 diffemorphism)

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

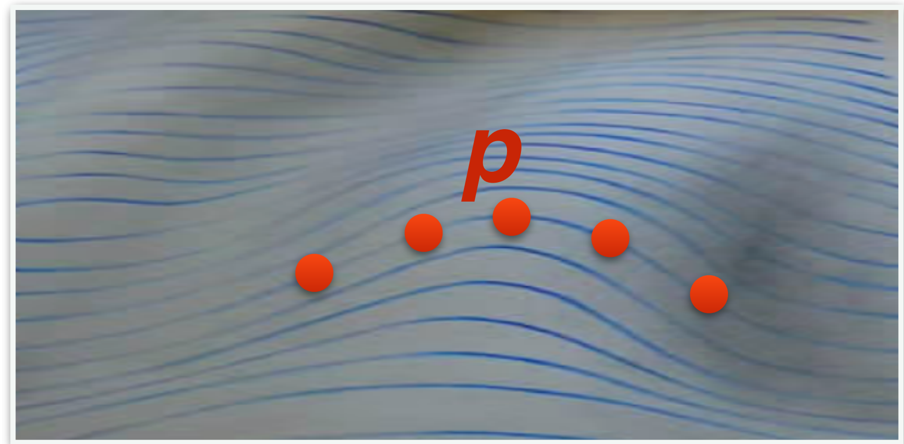
$$\delta g^{00},\ \delta K_{\mu\nu},\ \delta R_{\mu\nu\rho\sigma}\ (\text{or } C_{\mu\nu\rho\sigma}),\ \delta R_{\mu\nu},\ \text{and } \delta R,$$

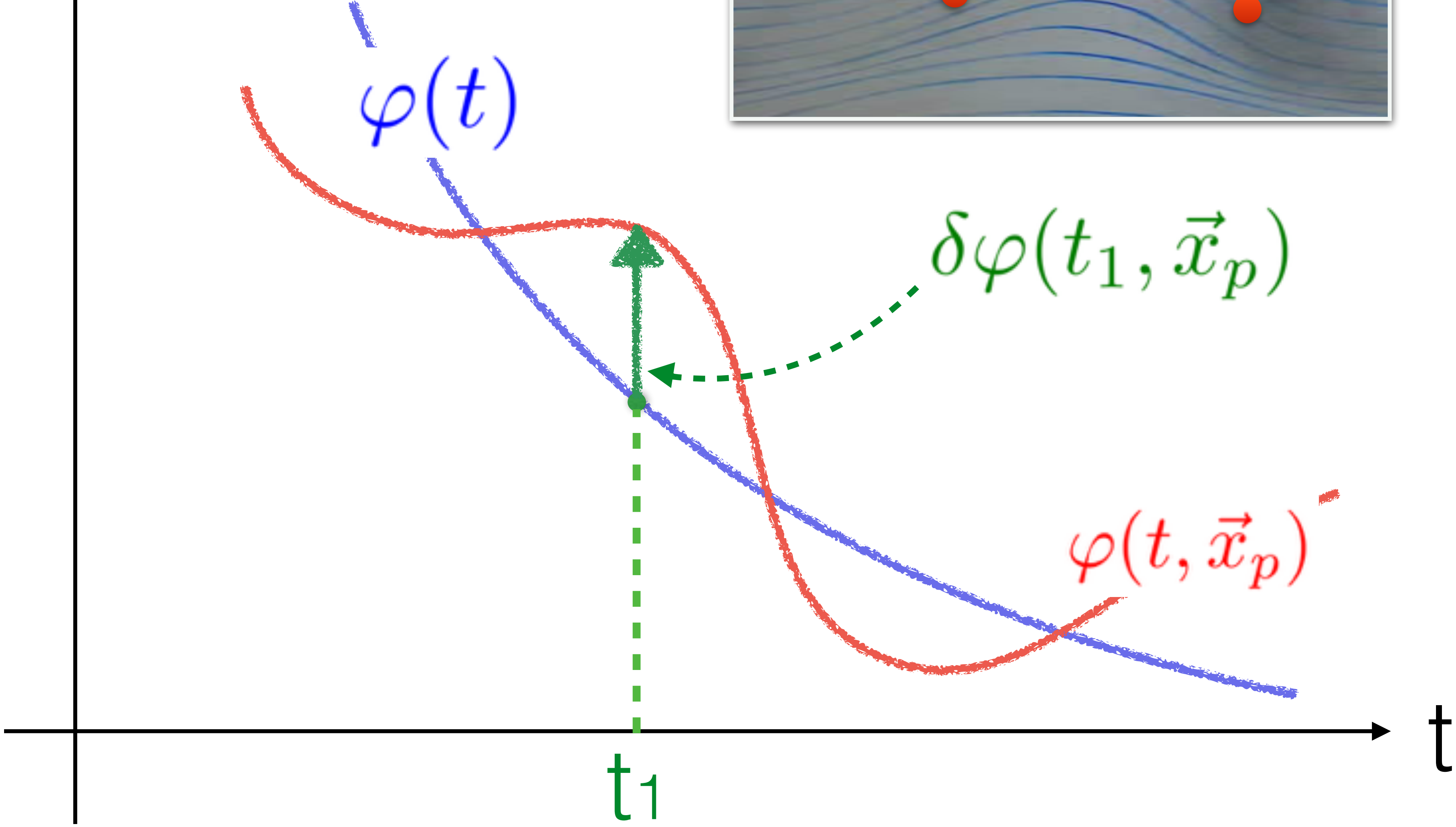
3. Multiply these operators by a only time dependent function

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

How we know EFT approach is equivalent to the Covariant approach?

Covariant approach





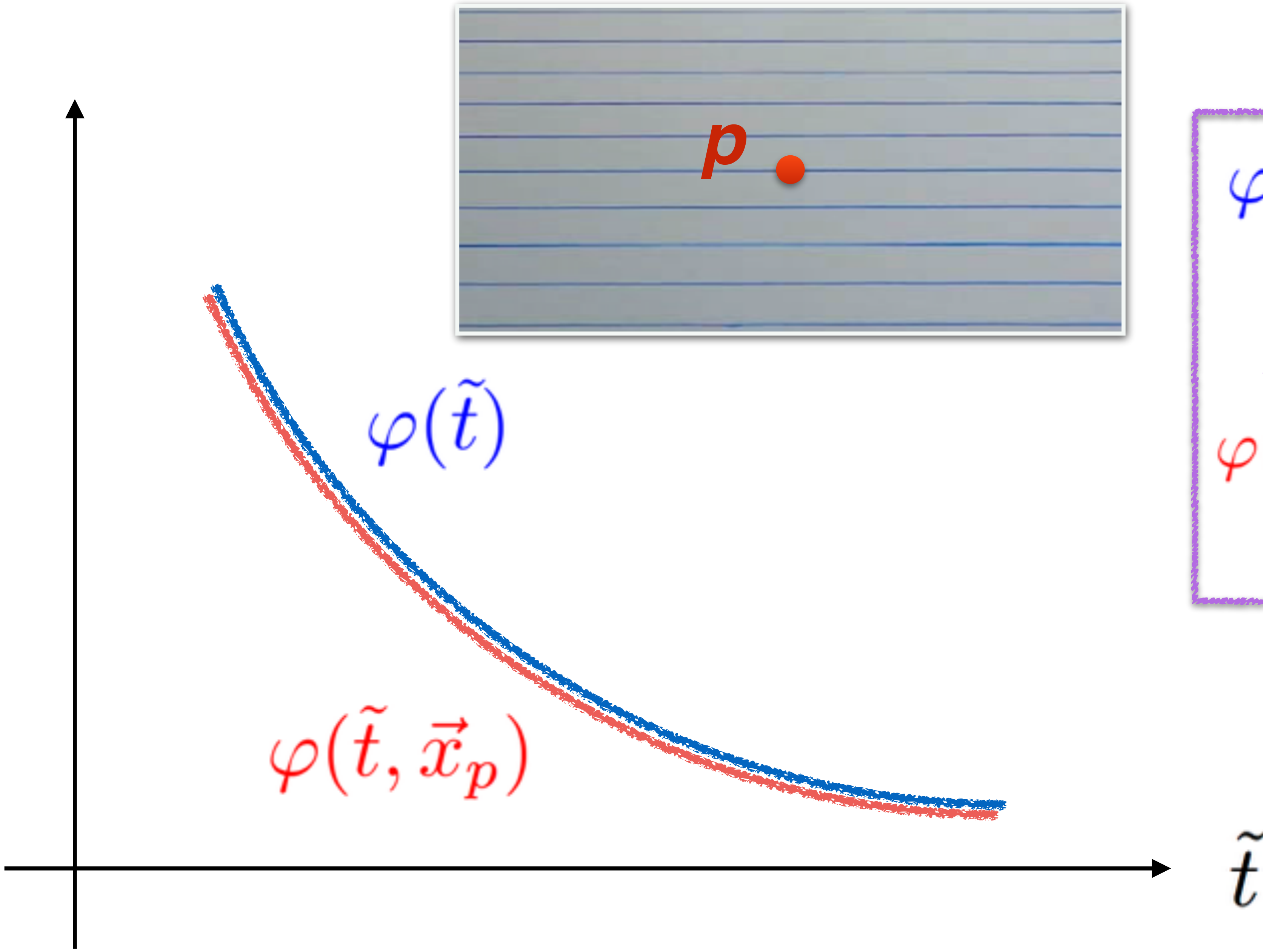
$\varphi(t)$: background field config

$\varphi(t, \vec{x}_p)$: 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

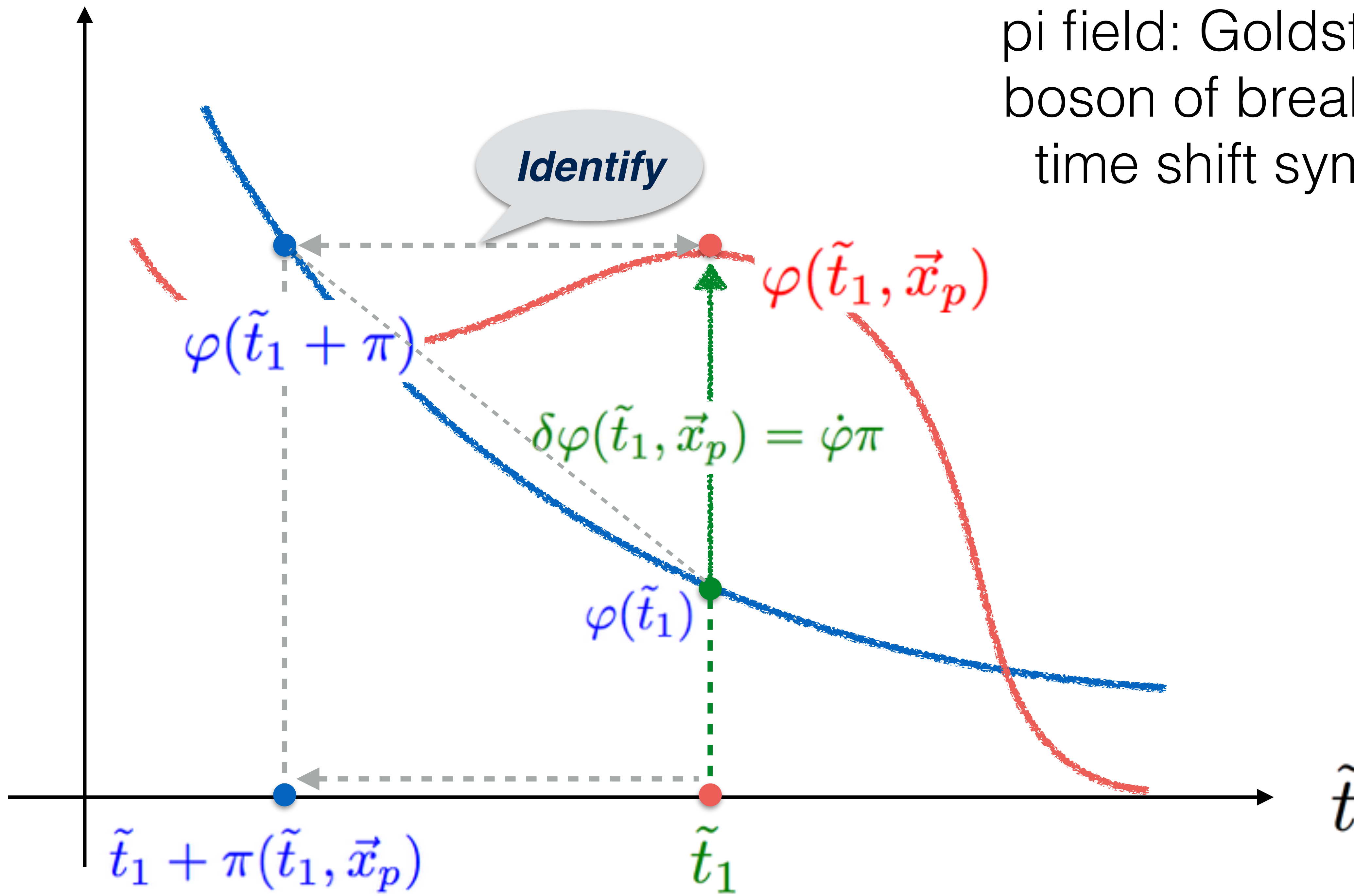
$\varphi(\tilde{t}, \vec{x}_p)$: field config at point 'p'

Only Valid in the unitary gauge

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

EFT approach=> Covariant approach

pi field: Goldstone boson of breaking time shift symm



Stuckburg trick: restore full covariance

2.3 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)]

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

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

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

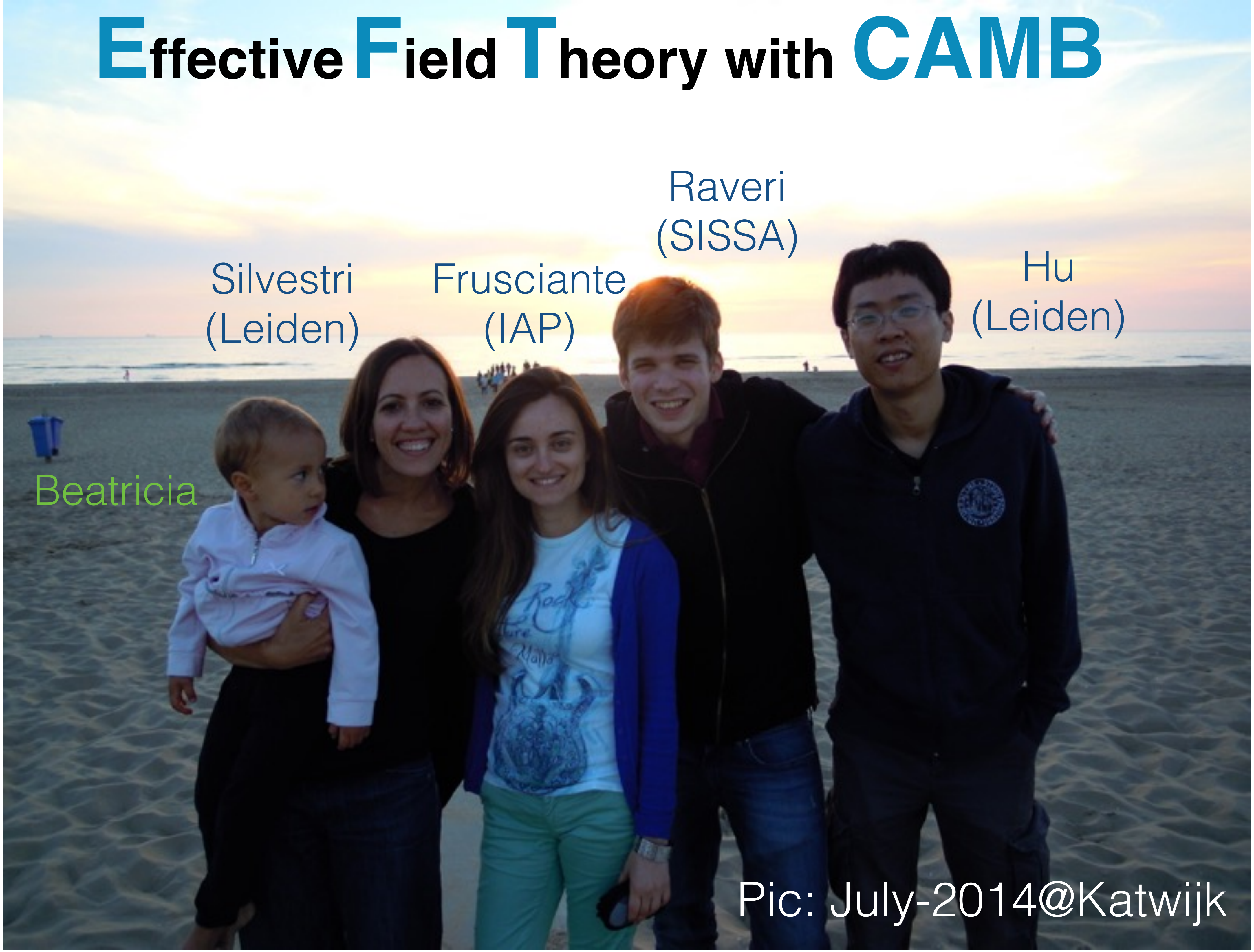
3. The structure of EFTCAMB

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)

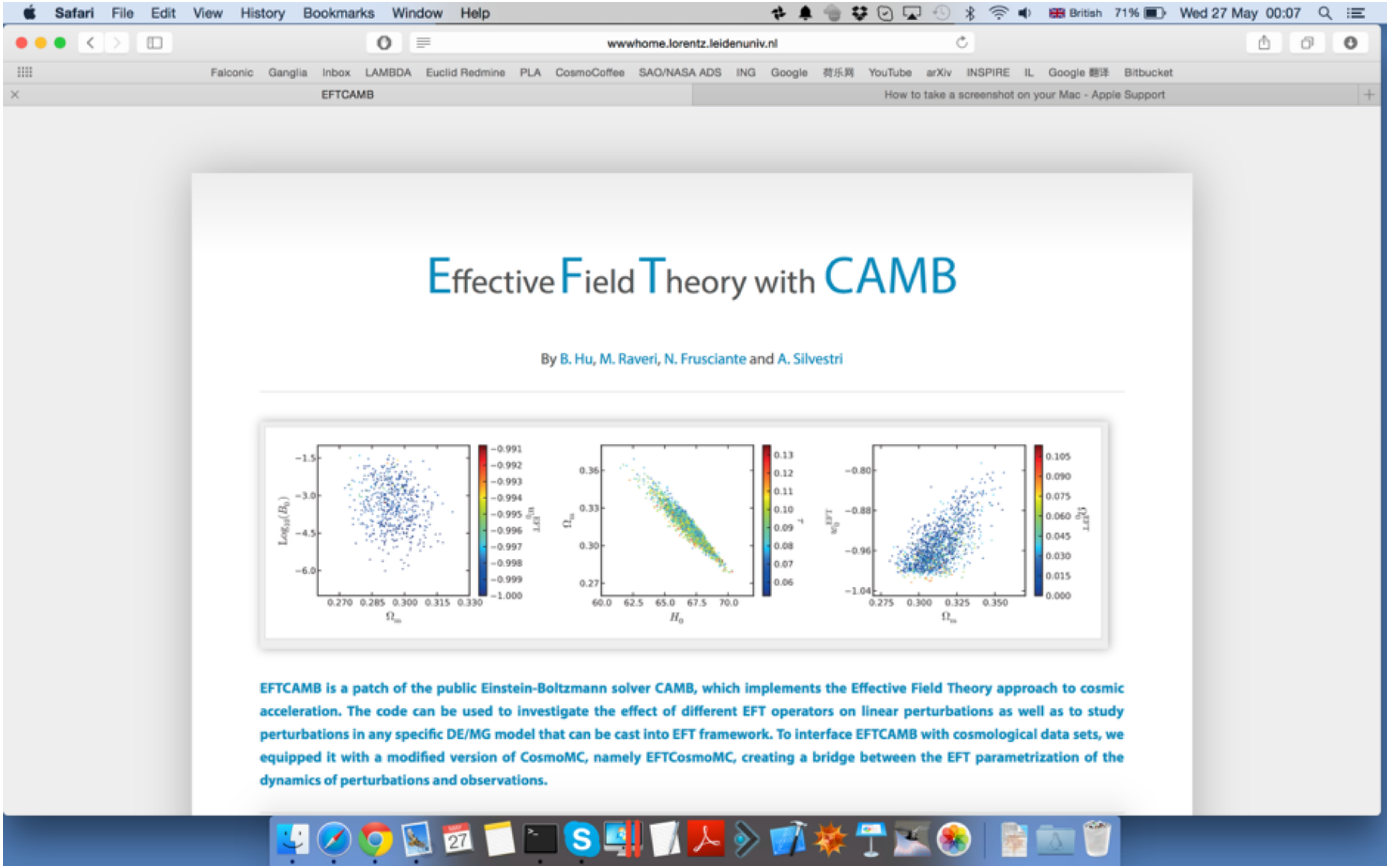
Effective Field Theory with CAMB

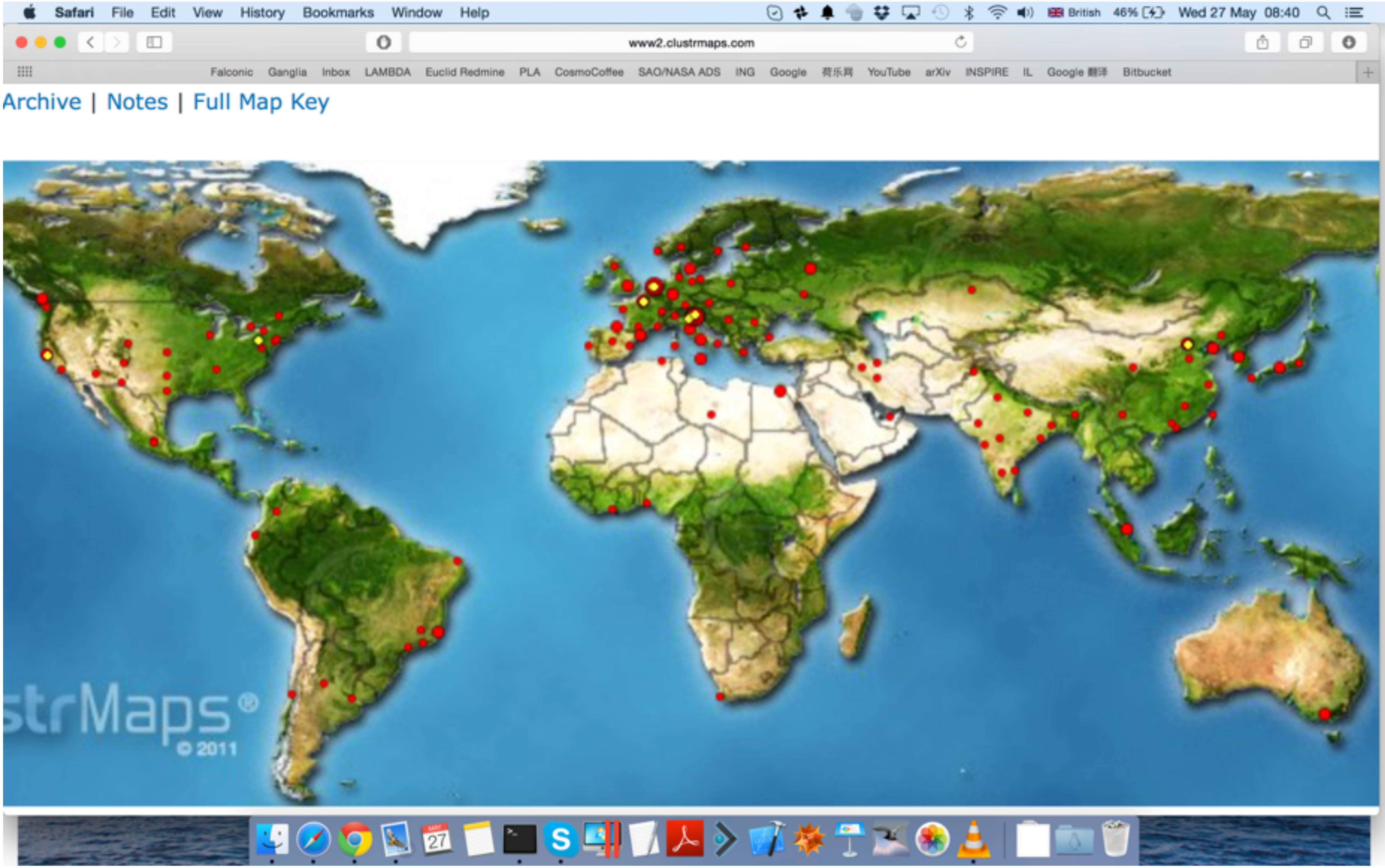


[Hu et.al. PRD89,103530(2014); PRD90,043513(2014); PRD91,063524(2015)]

http://wwwhome.lorentz.leidenuniv.nl/~hu/codes/

http://wwwhome.lorentz.leidenuniv.nl/~hu/codes/





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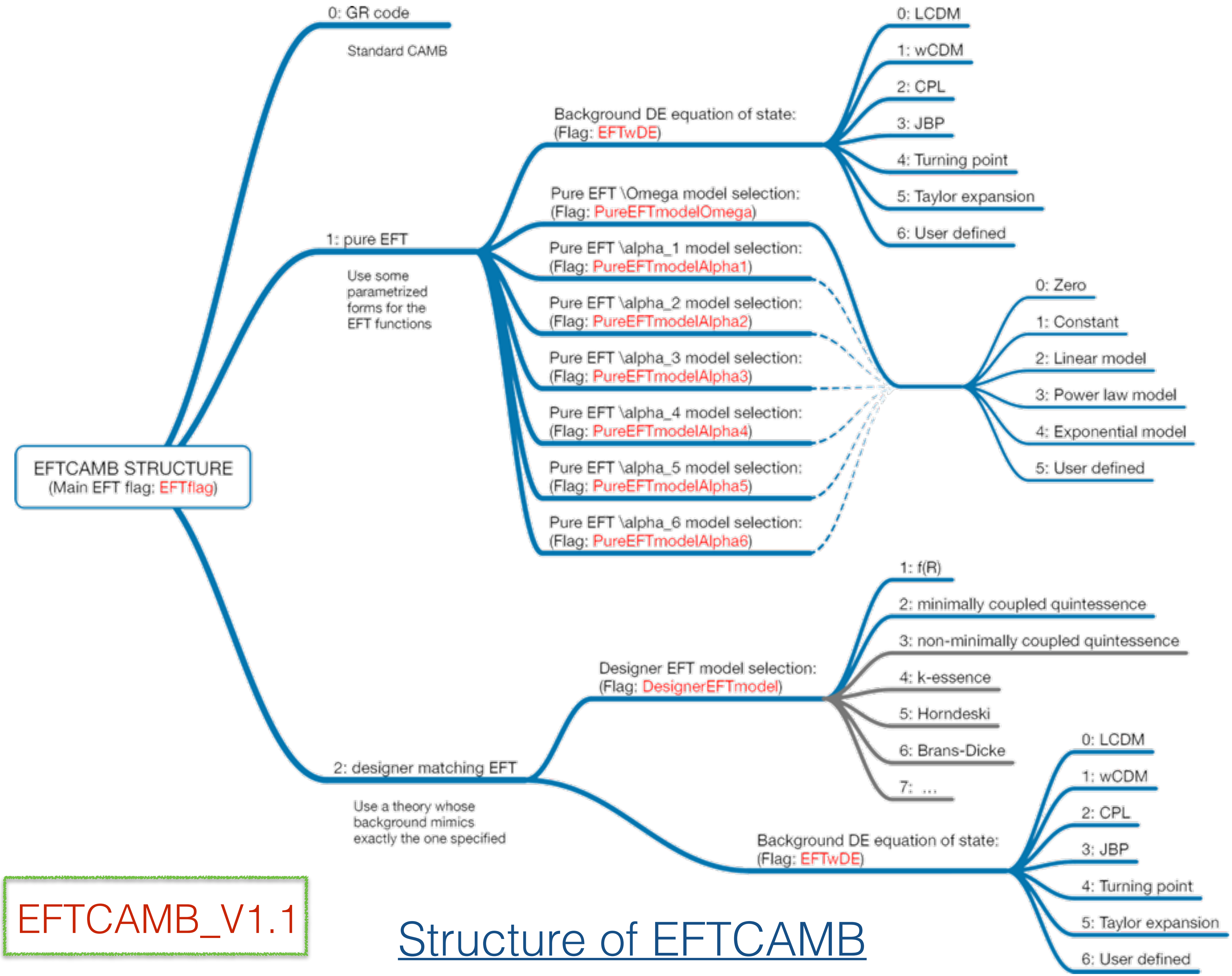


EFTCAMB_V1.1

Structure of EFTCAMB

2.1 Background parametrization—EoS

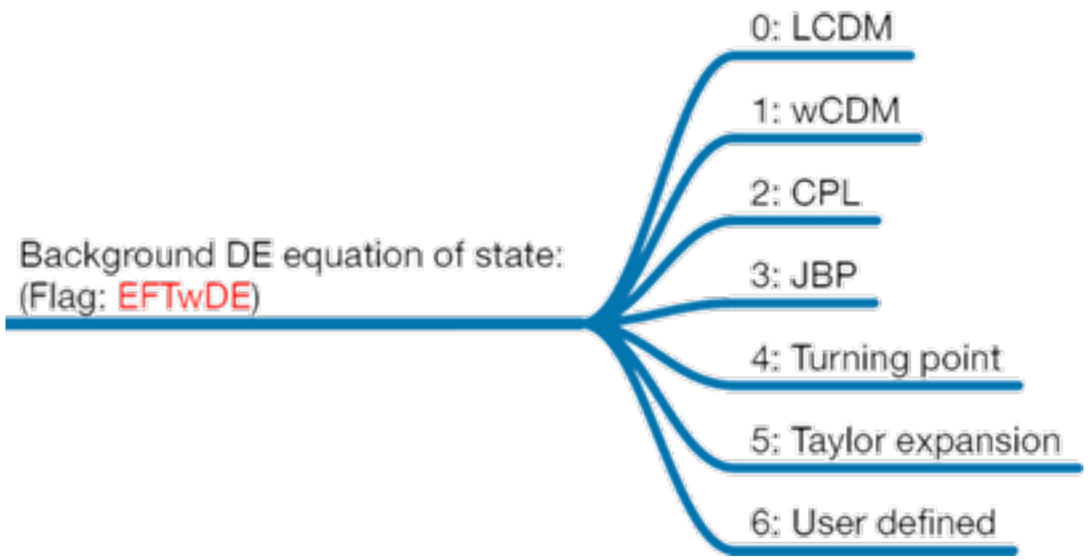
EFTCAMB provides 6 different kinds of parametrization of EoS (Flag: EFTwDE), including:

LCDM ($w=-1$),

wCDM ($w=w_0$),

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

… …



2.2.1 EFT parametrization: Pure EFT

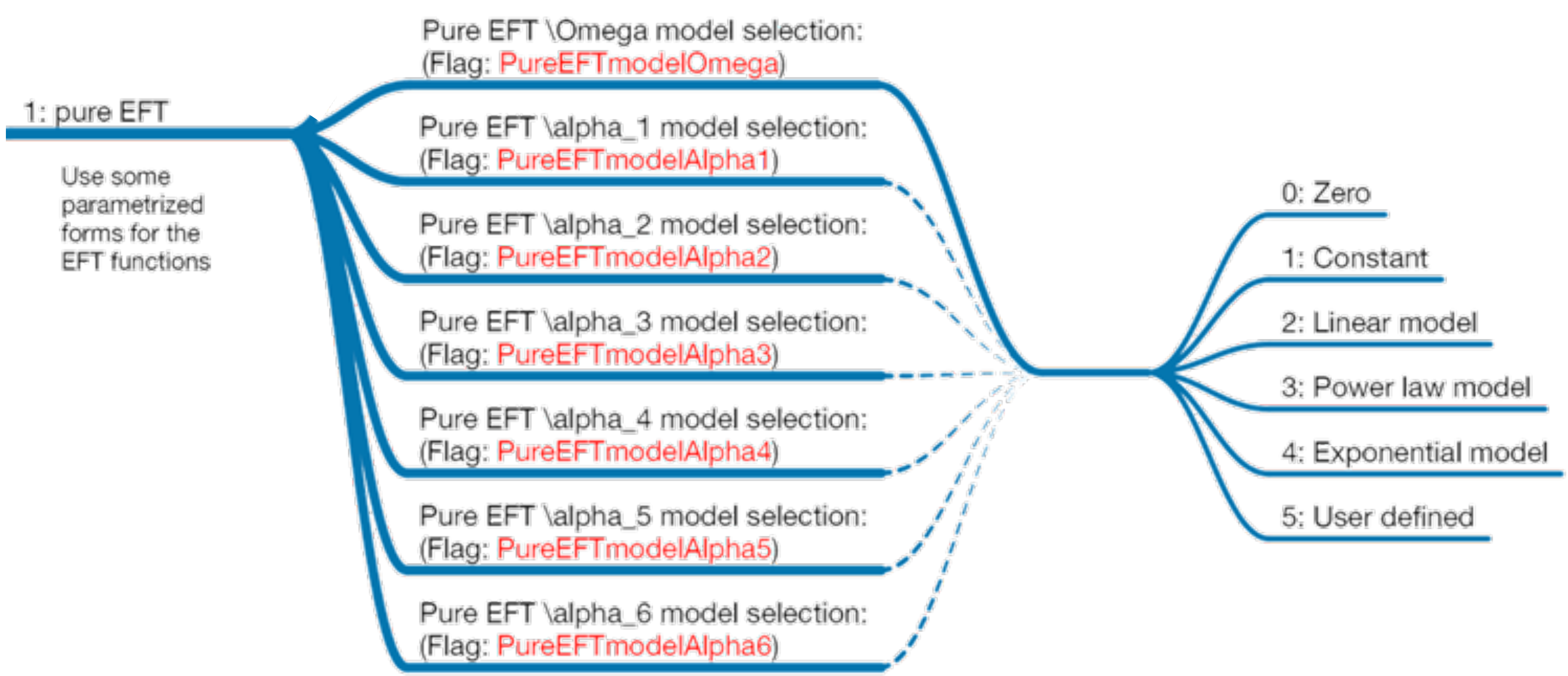
Phenomenological parametrization, e.g.

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

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

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

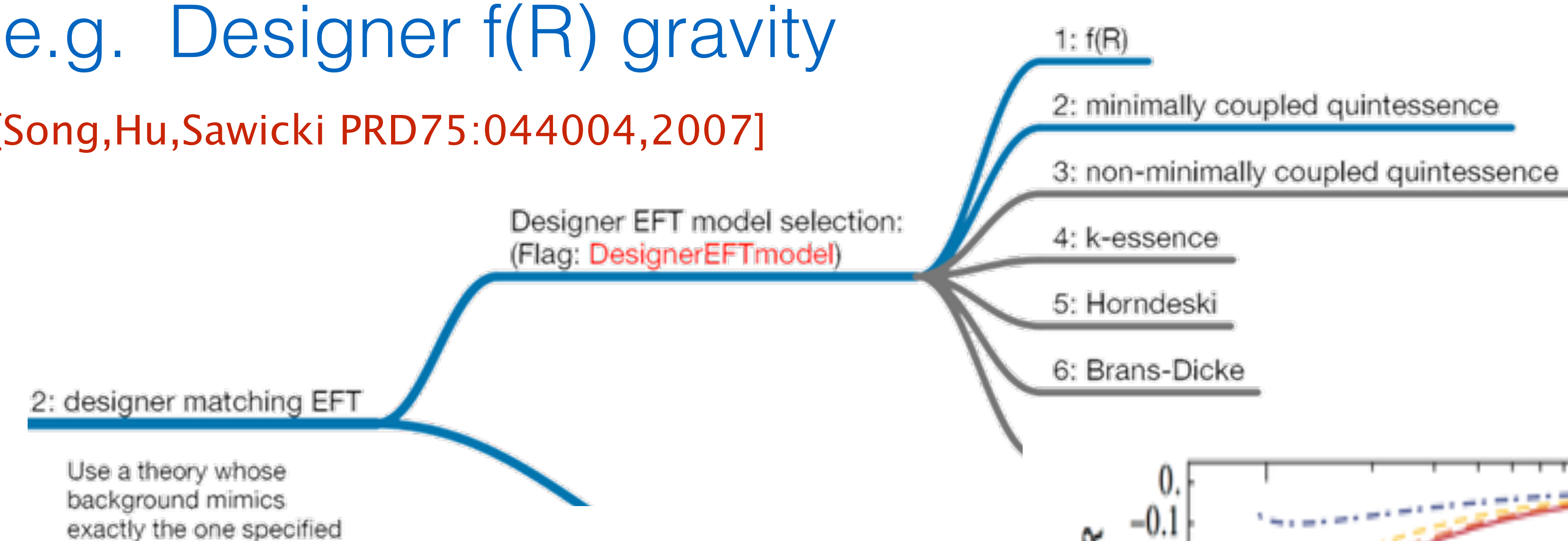
$$\text{Exponential models: } \Omega(a) = \exp\left(\Omega_0 a^s\right) - 1.$$



2.2.2 EFT parametrization: Full mapping—designer mapping

e.g. Designer f(R) gravity

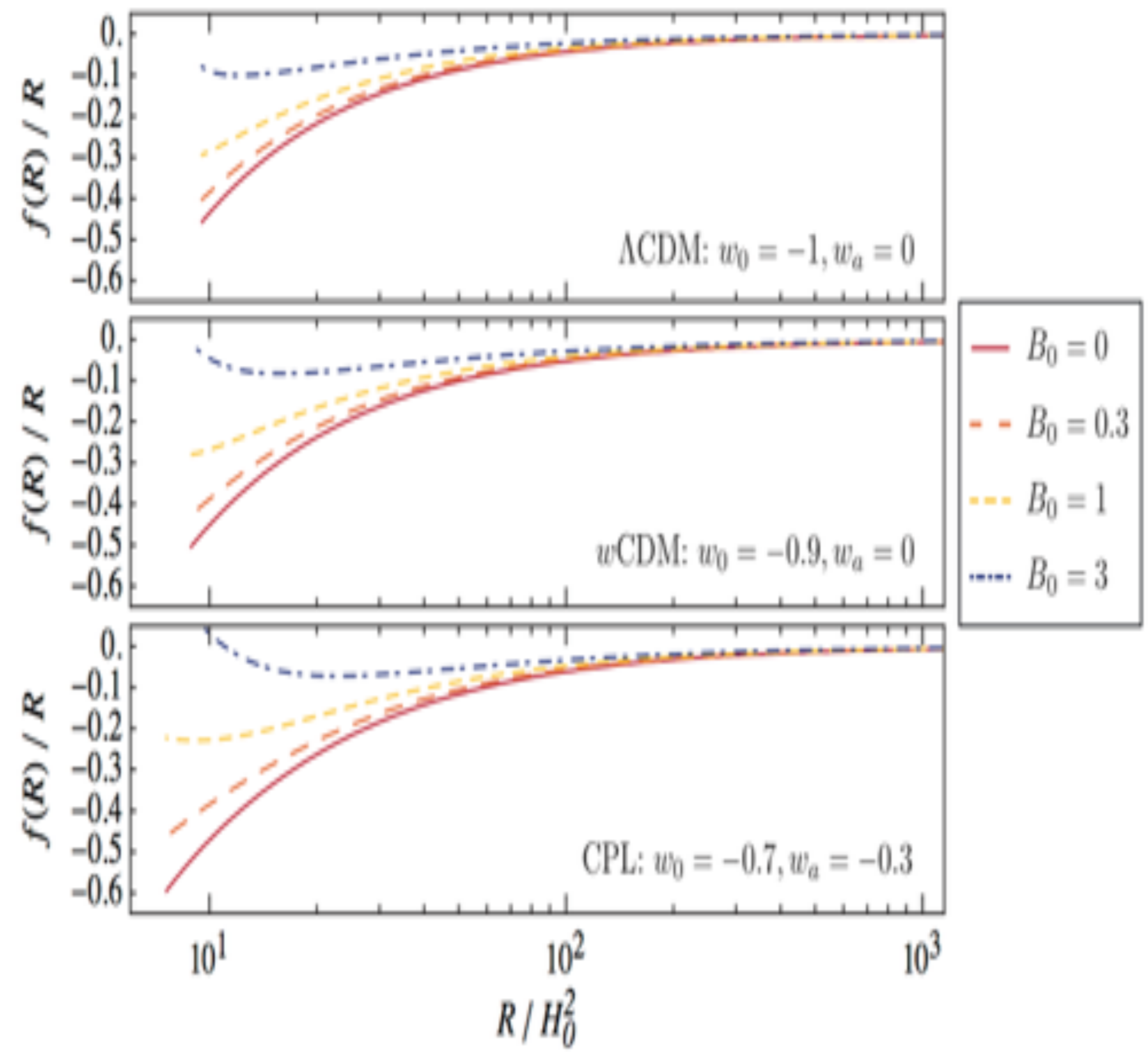
[Song,Hu,Sawicki PRD75:044004,2007]



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

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

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



- **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**

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

---

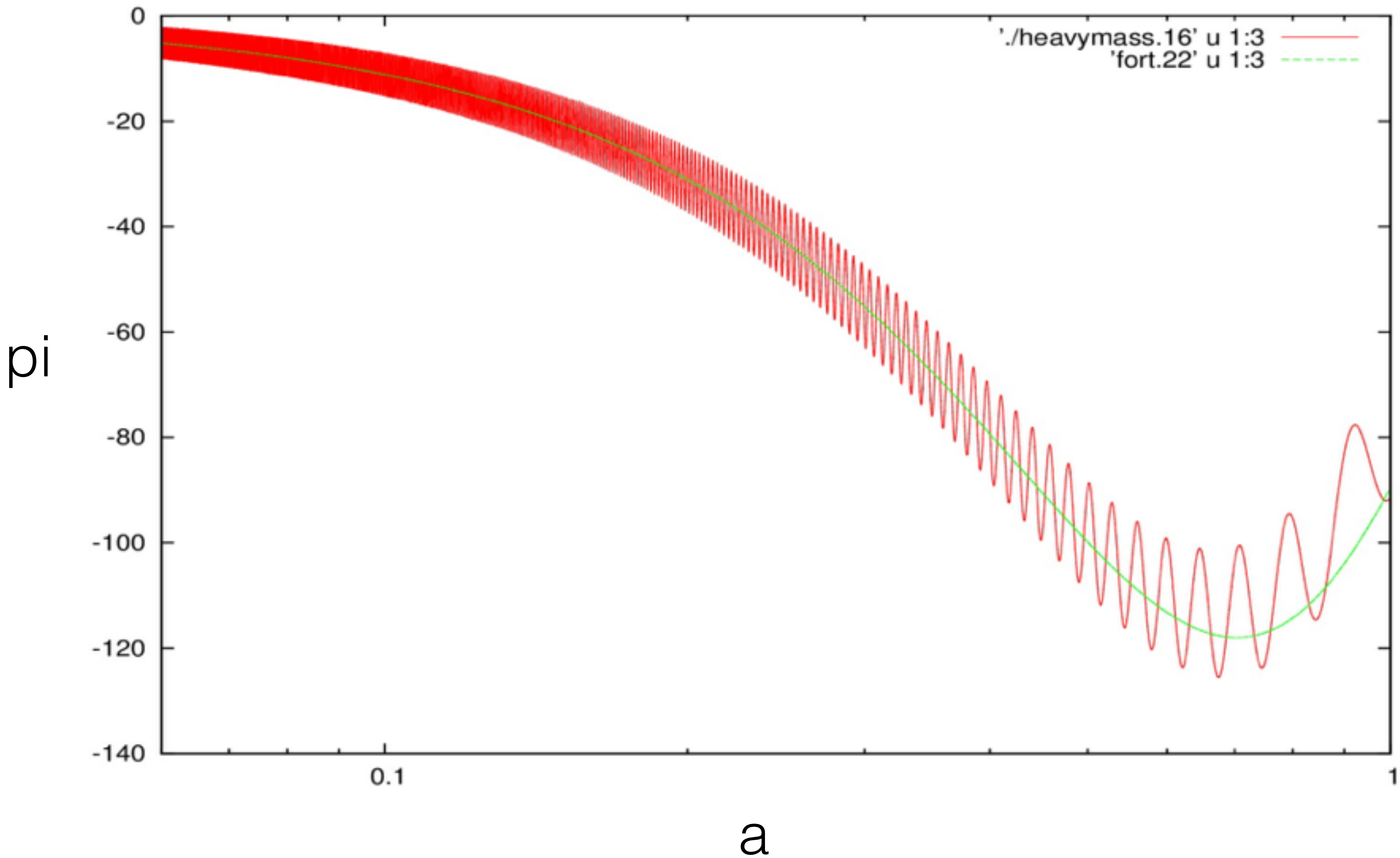
kinetic friction mass sound speed source

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

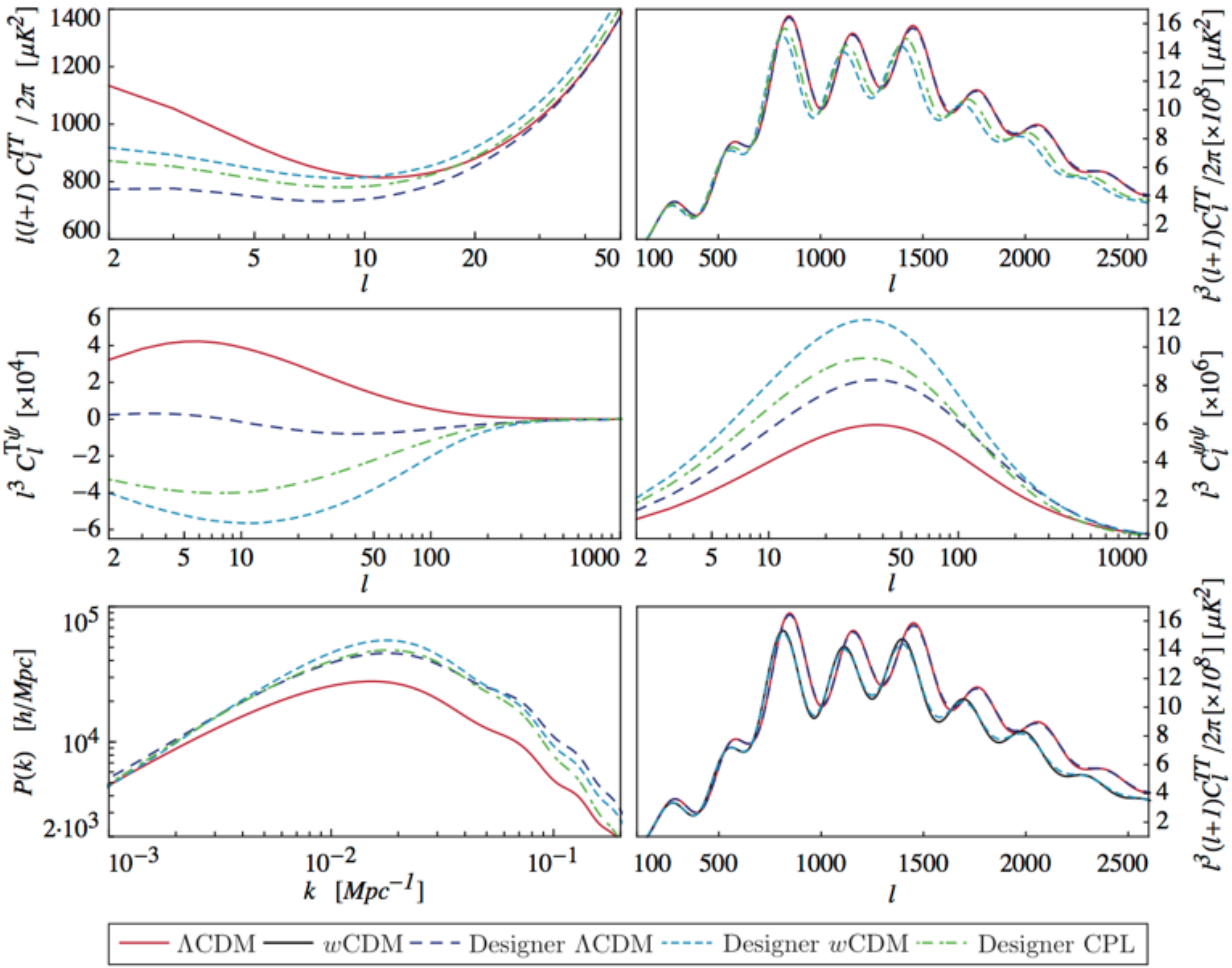
Have pass the viability condition:

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

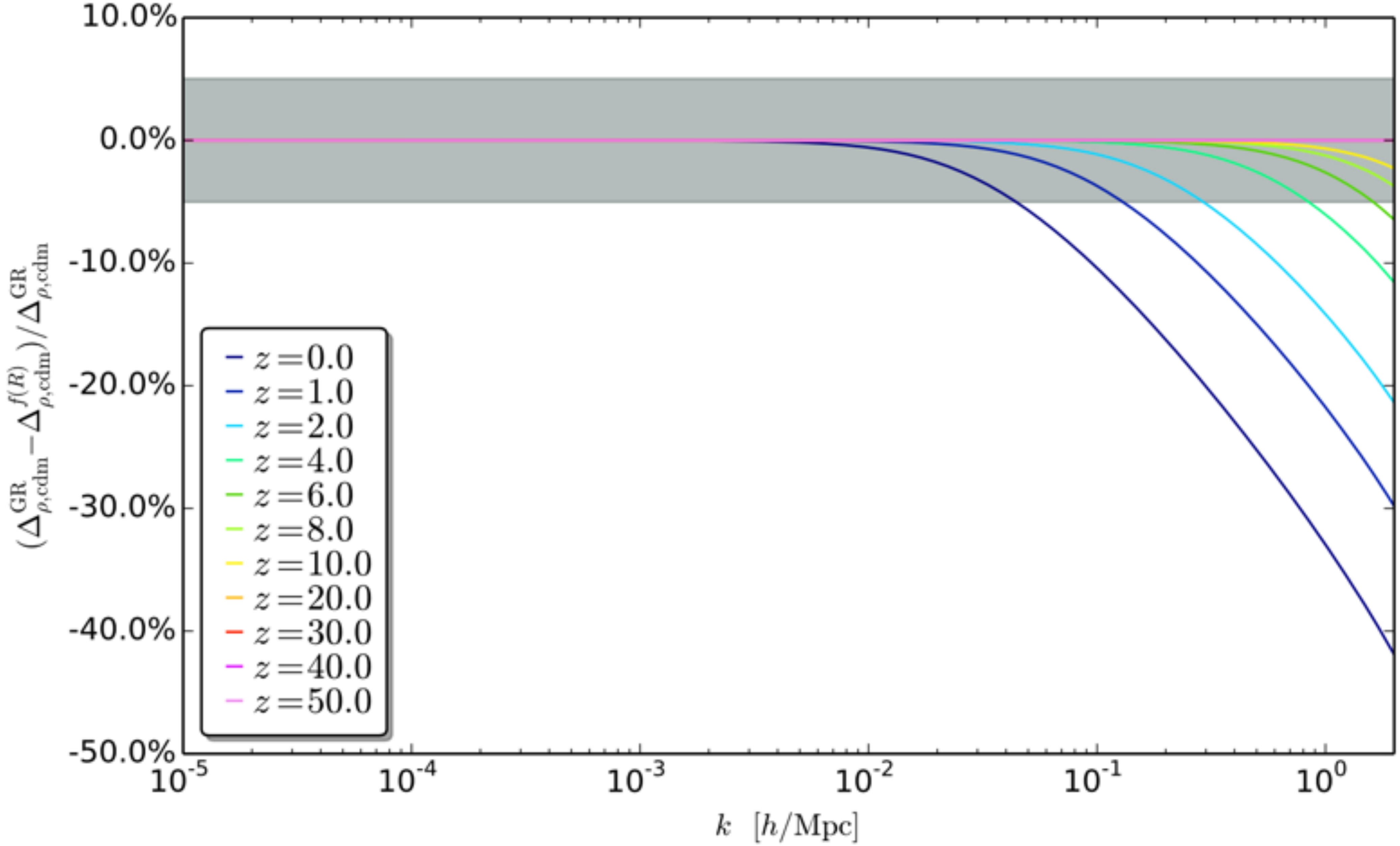
pi field solution: f(R) example



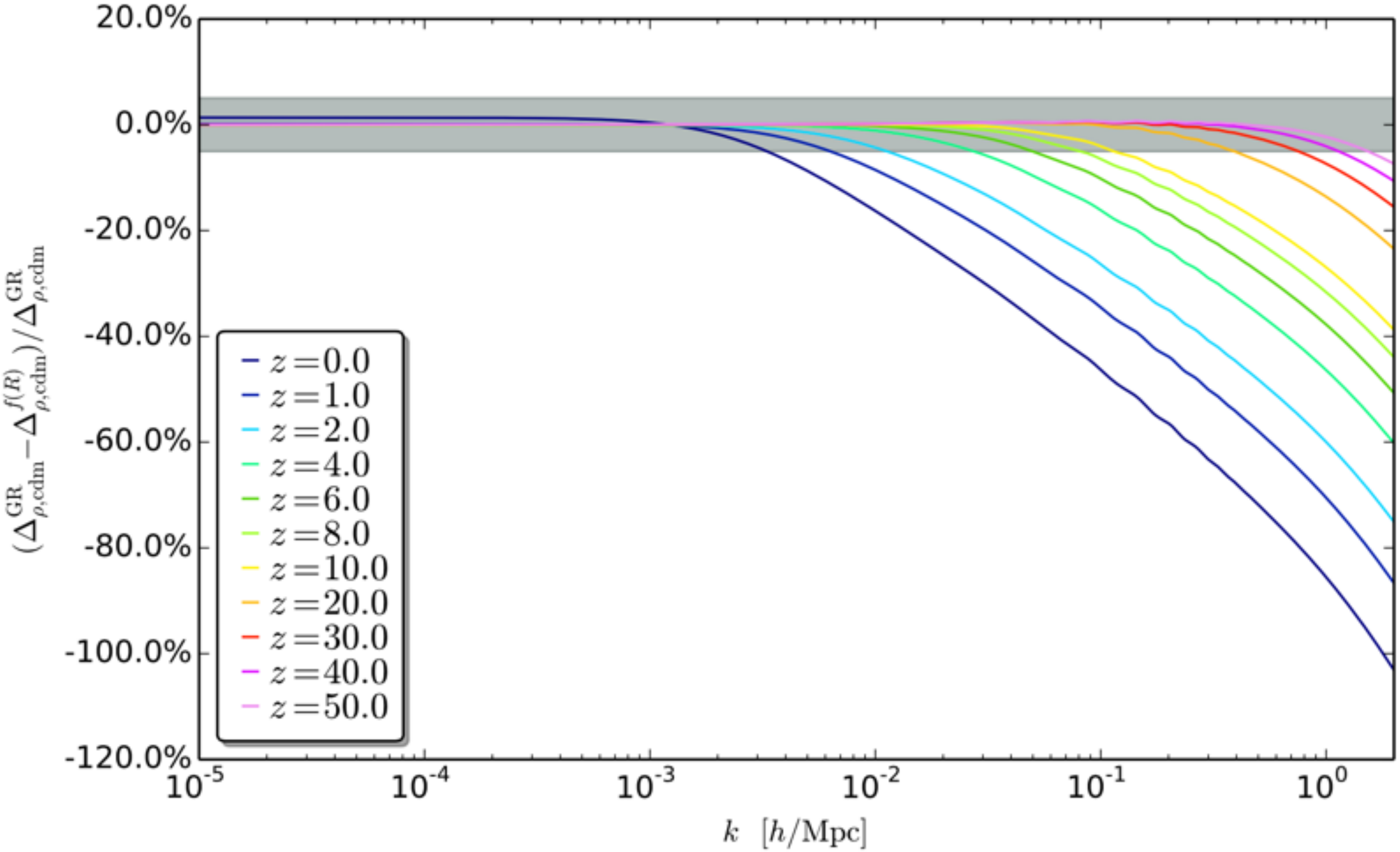
2.4 CMB spectra—example: f(R)



2.5 Transfer function of CDM



Designer f(R) with LCDM background
B0=0.001

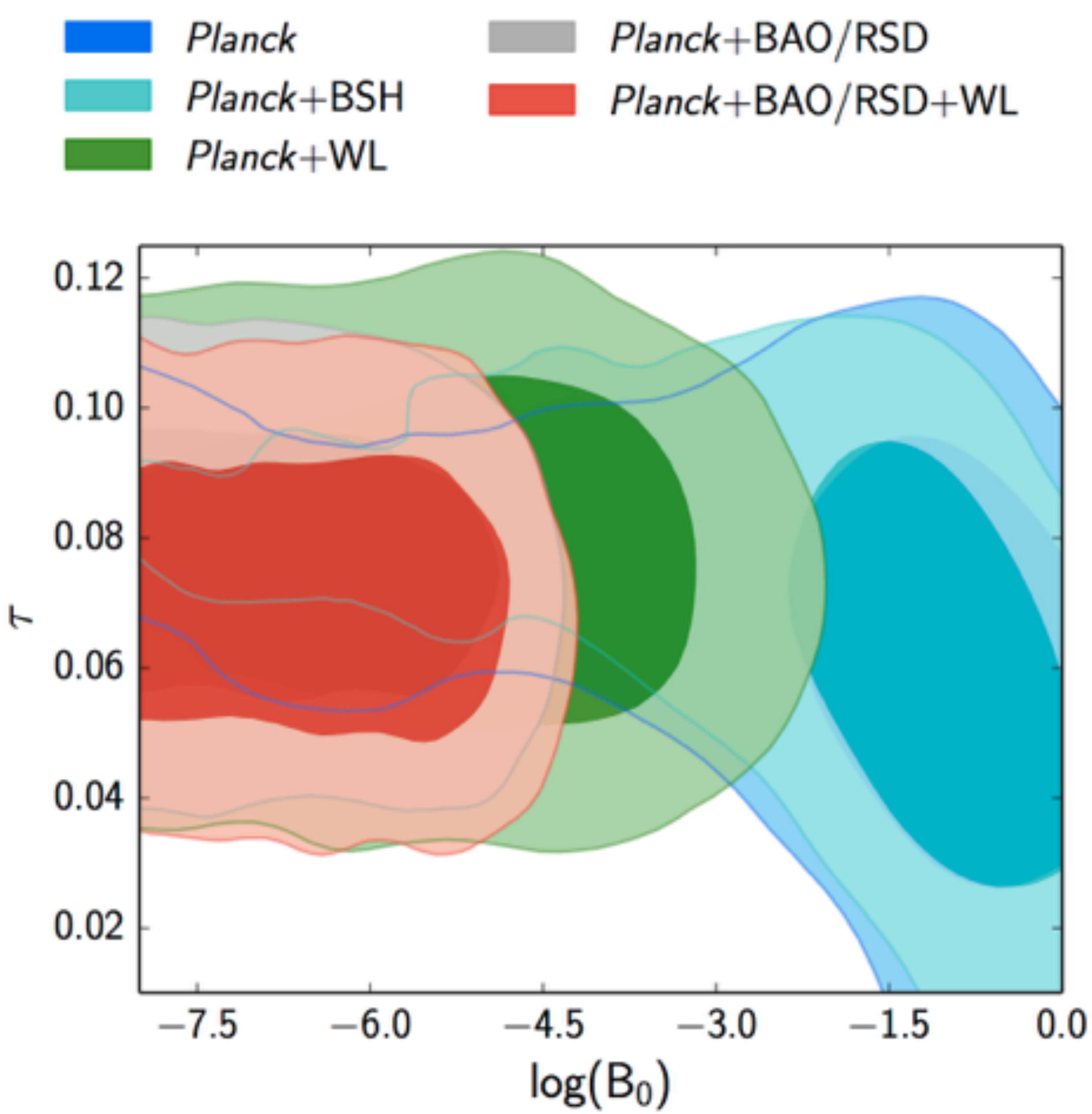


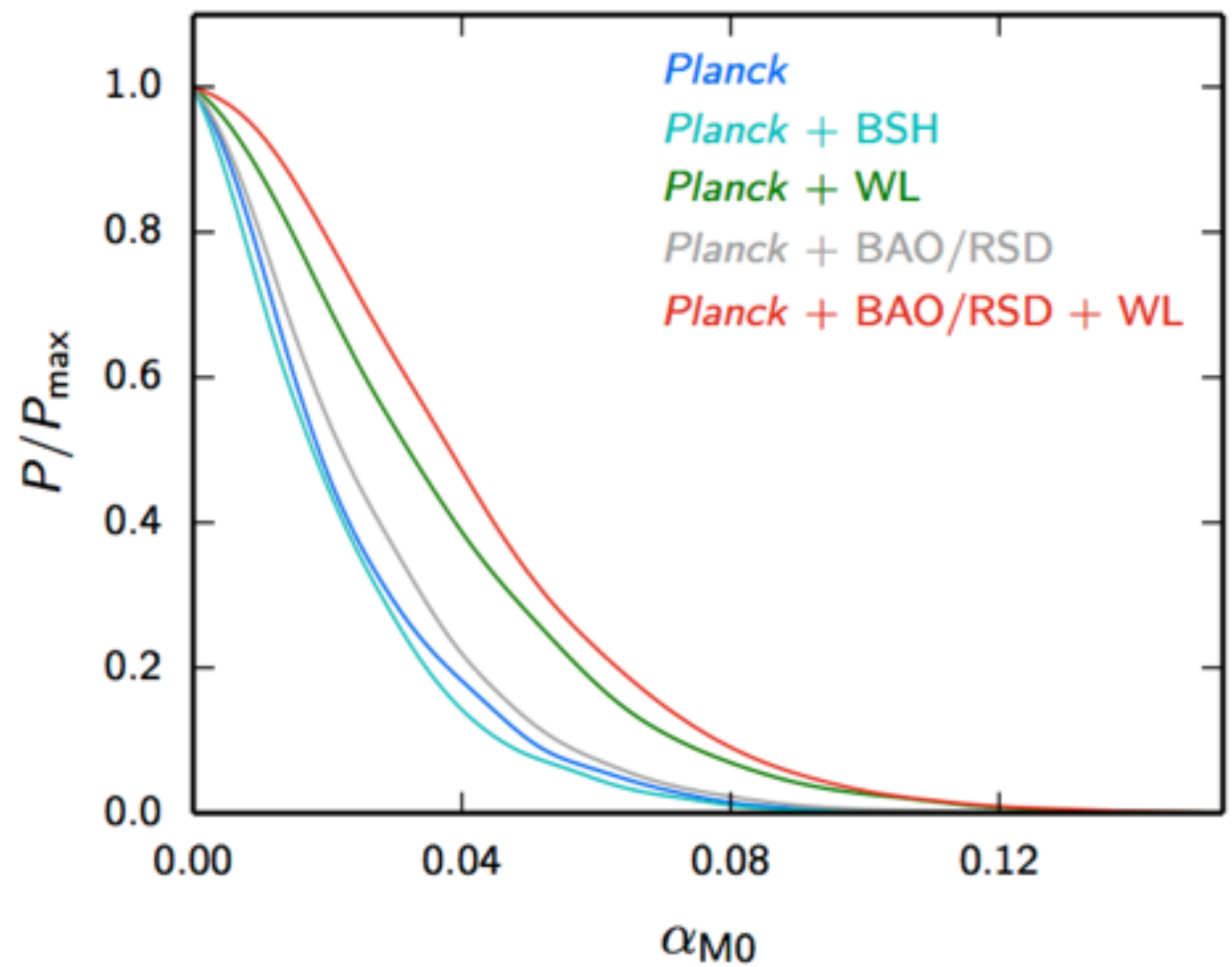
Designer f(R) with wCDM background
B0=0.01 and w=-0.95

4. Parameter estimation results from EFTCosmoMC and Planck-2015

CosmoMC—>EFTCosmoMC

Designer f(R)





Linear EFT

$$\Omega(\bar{a}) = \alpha_{M0}\, a$$

[Planck-2015,MG paper]

5. Conclusion

- **EFTCAMB include most of viable single field DE/MG model**
- **For scalar field: full perturbative treatment, does not rely on quasistatic approx**
- **Support various background, LCDM/wCDM/CPL …**
- **Check the stability for given parameterization**
- **Selected by Planck 2015 data release**
- **Selected by Theory Working Group of Euclid**
- **New release will come soon updated with PLC2.0**

EFTCAMB

Thank you!