The Effective Field Theory approach to gravitation on cosmological scales

from theory to observations

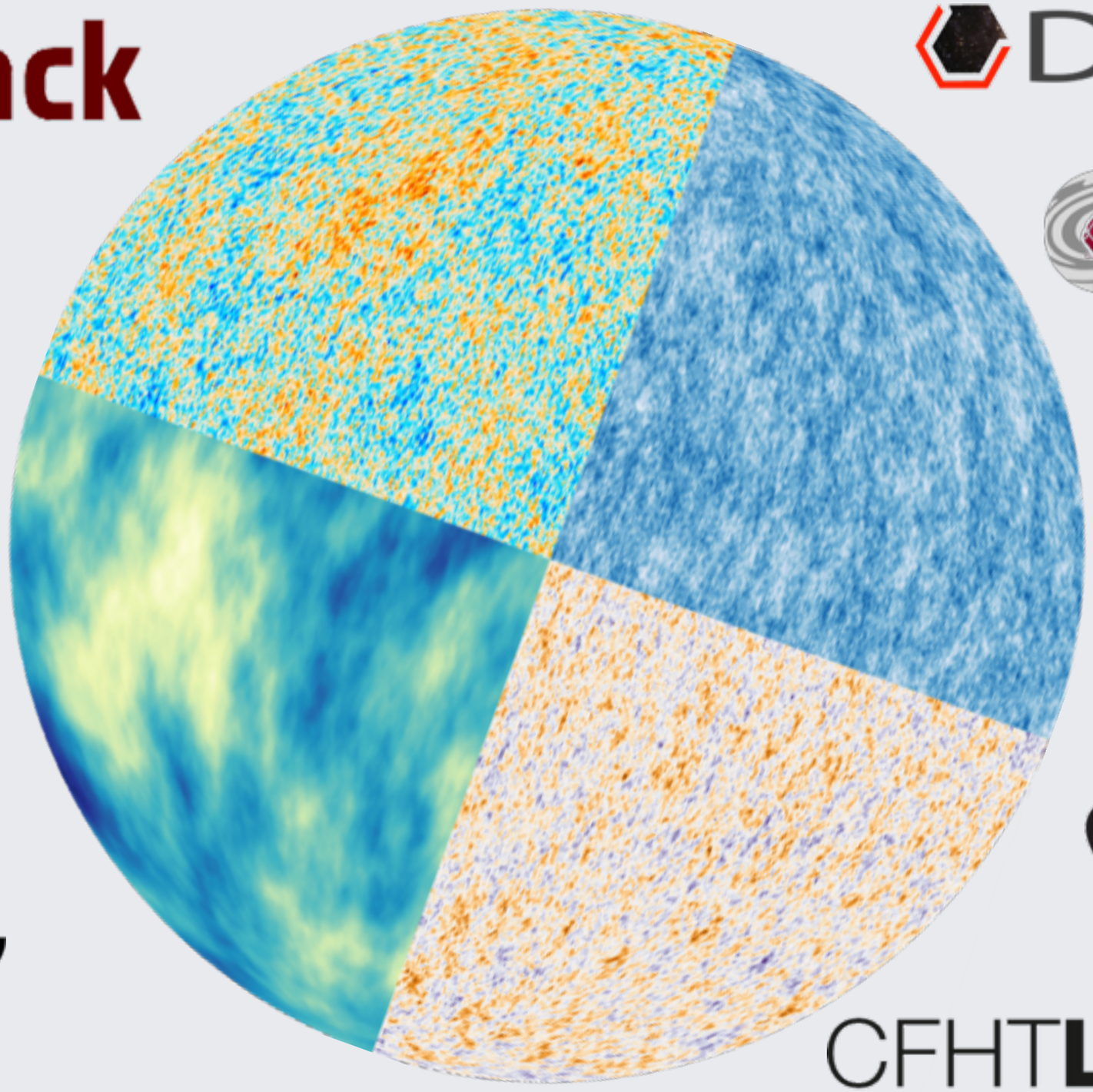
Marco Raveri

SISSA

Plan of the presentation

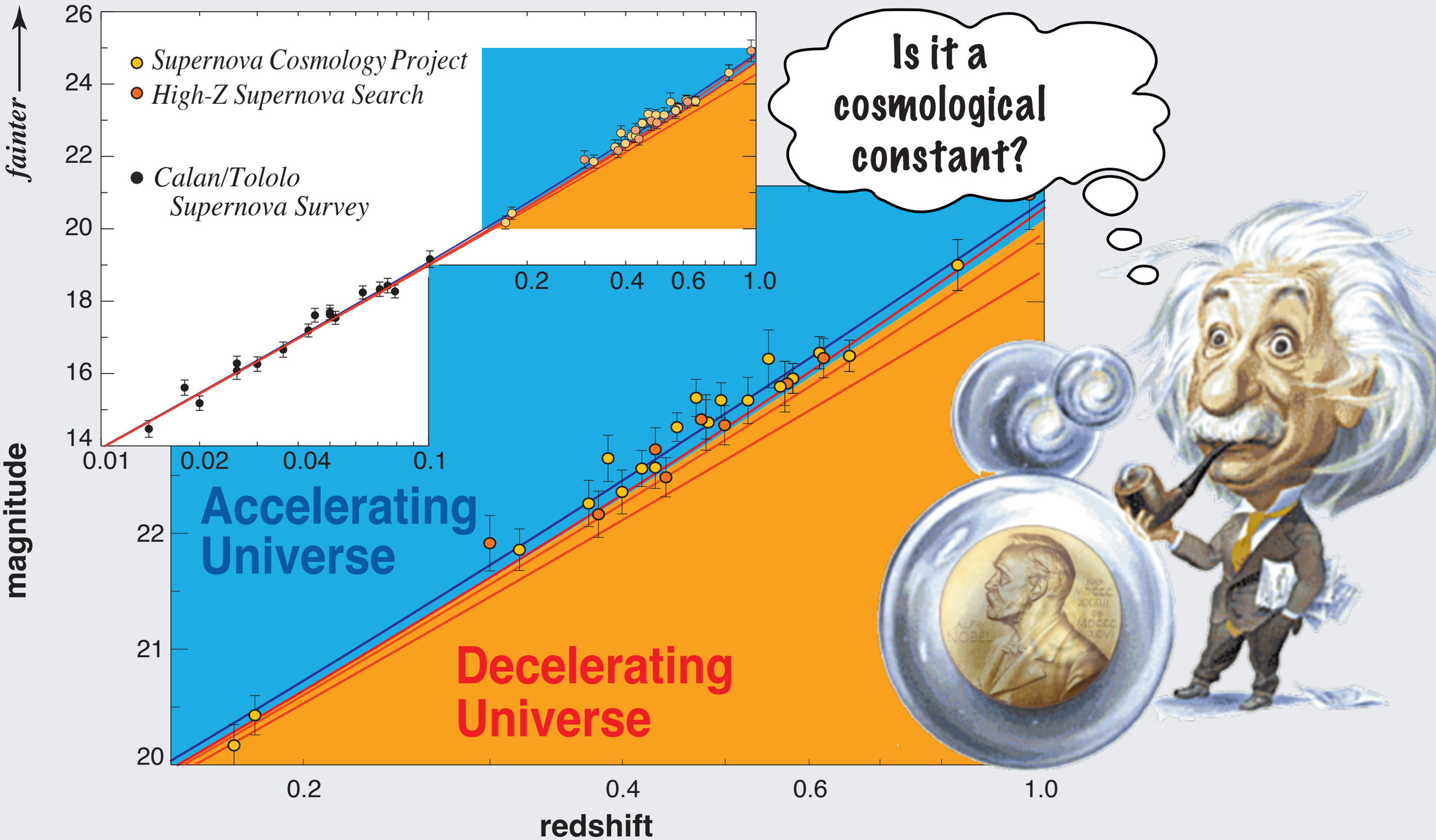
- Introduction
- The Effective Field Theory (EFT) approach
- EFT phenomenology and EFTCAMB
- Some observational results
- Outlook

The modern picture of our Universe



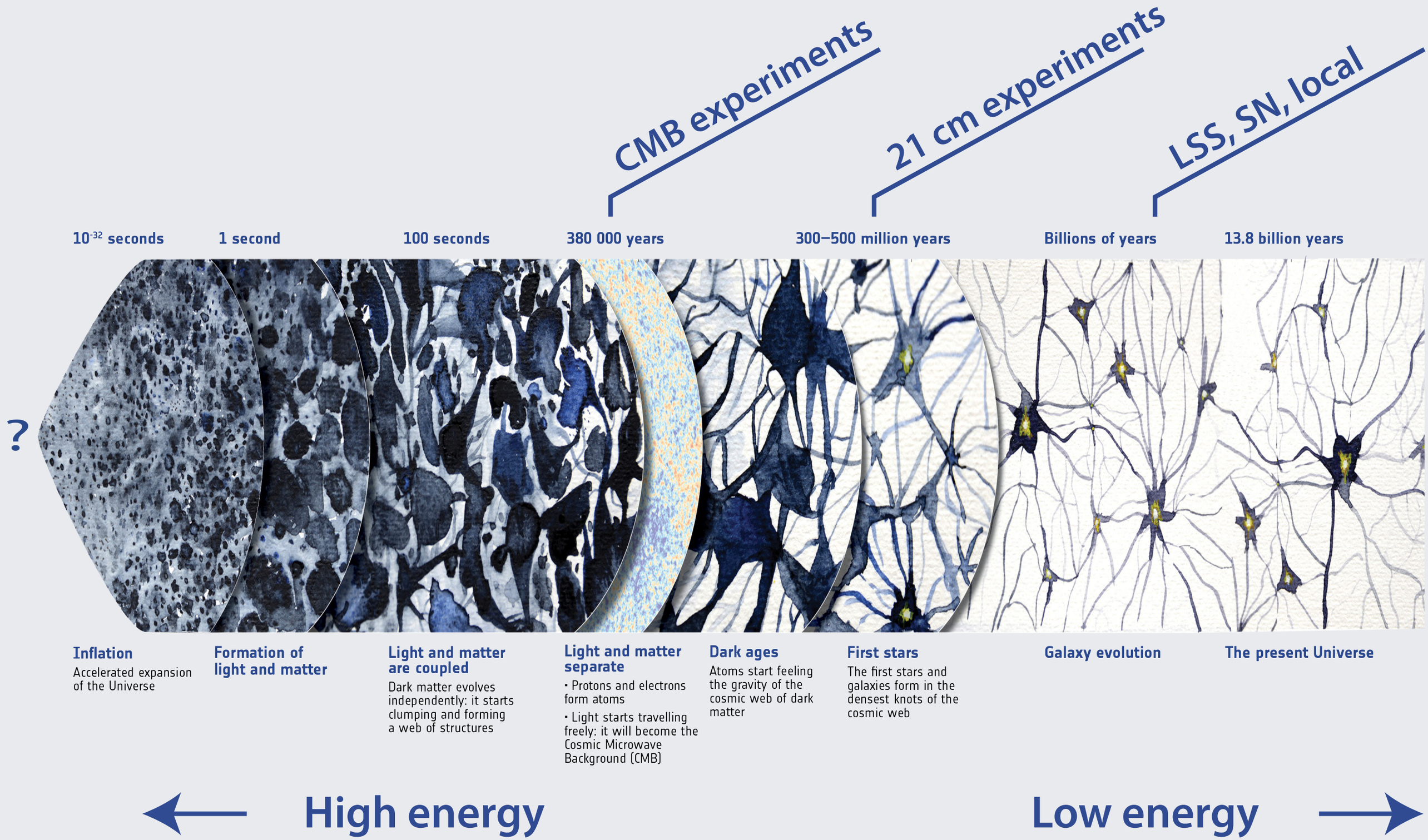
(CMB temperature, CMB lensing, galaxy weak lensing convergence and number counts fluctuations: the cosmological pie that I like)

Dawn of the ΛCDM model



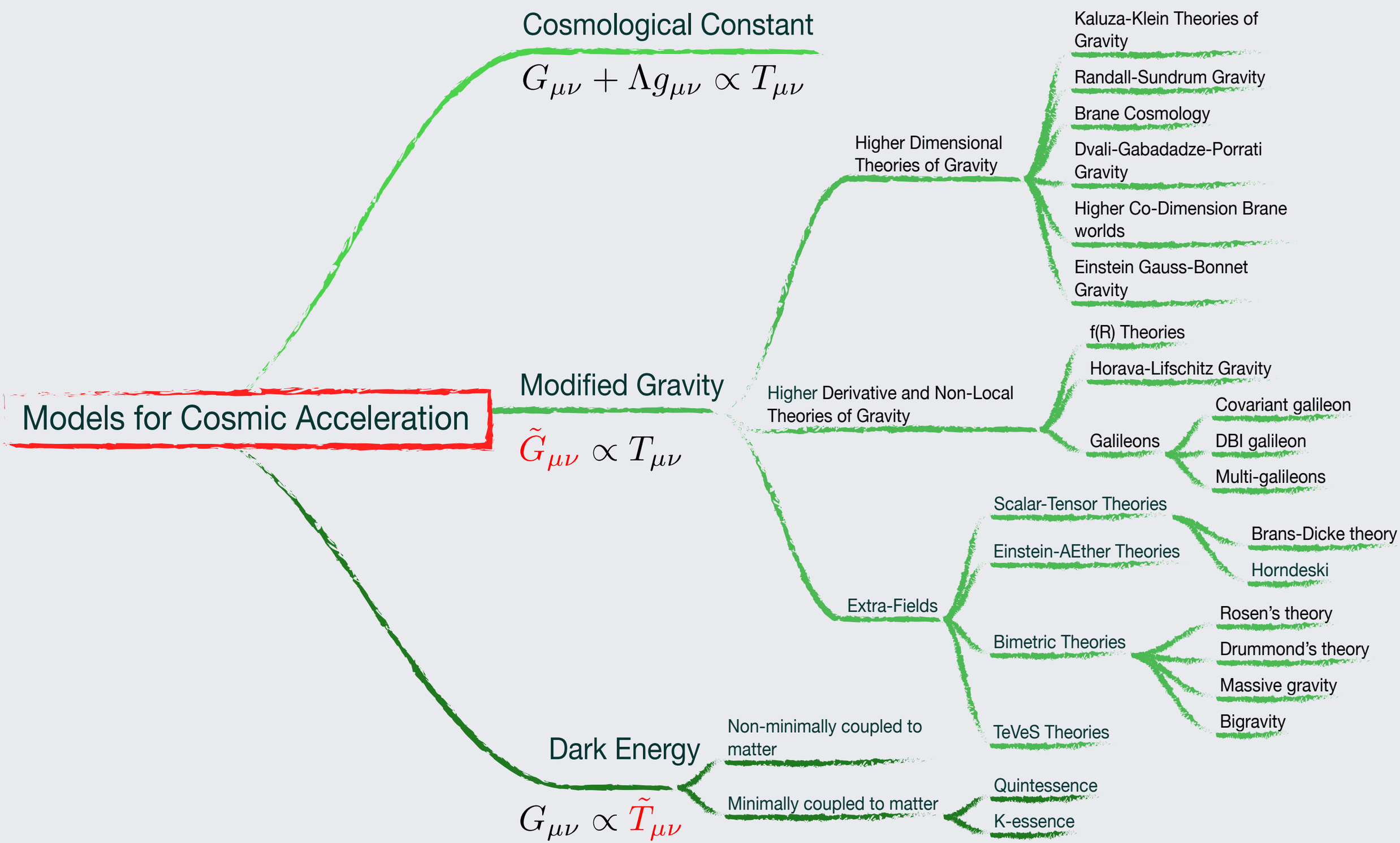
(Science “Breakthrough of the year” 1998; Perlmutter, Physics Today (2003); Discovery awarded with the Nobel Prize in 2011)

The Universe as a laboratory



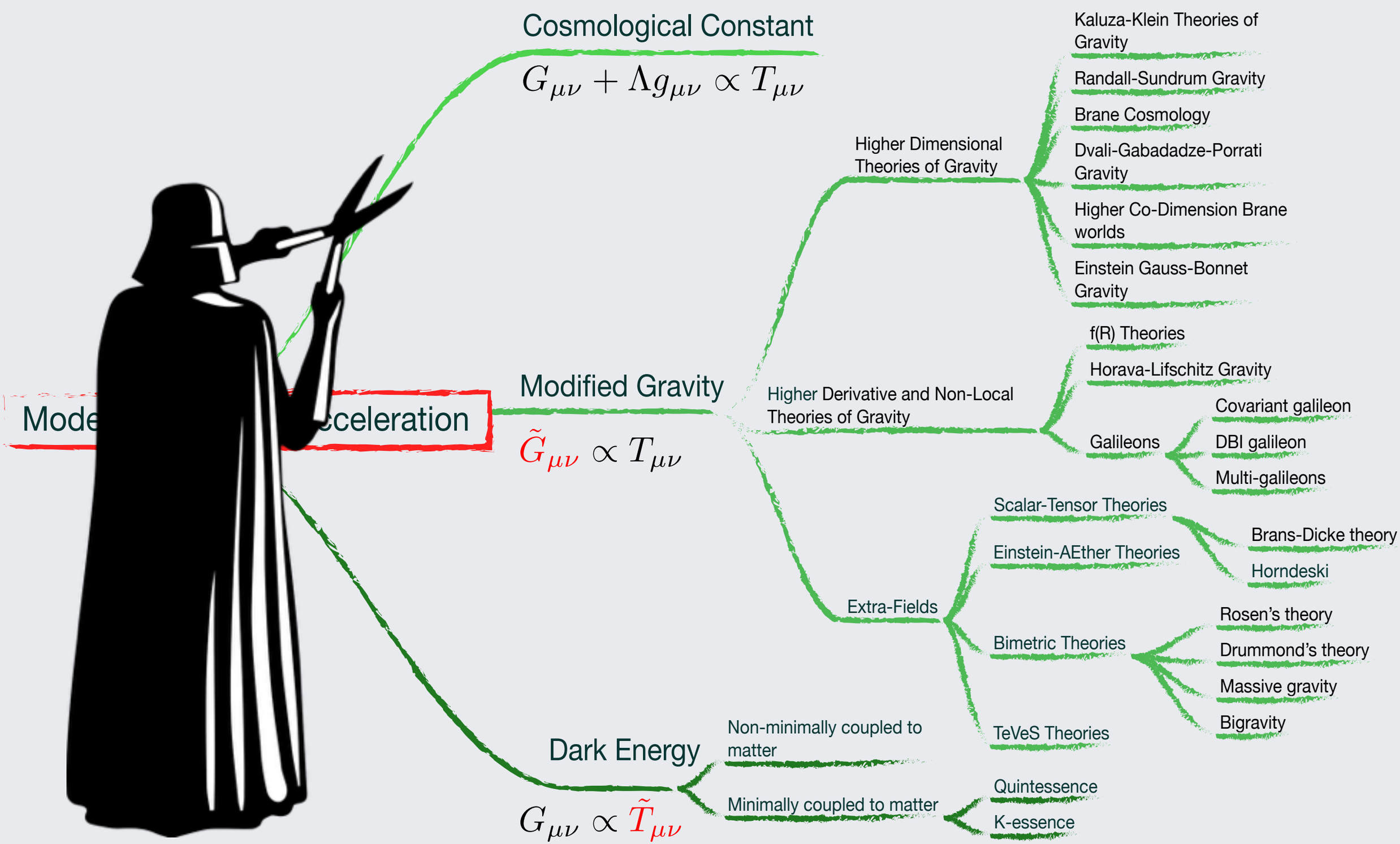
(Based on ESA cosmic history)

Models for Cosmic Acceleration



(T.Clifton, P.G.Ferreira, A.Padilla and C.Skordis, Phys. Rept. 513, 1 (2012))

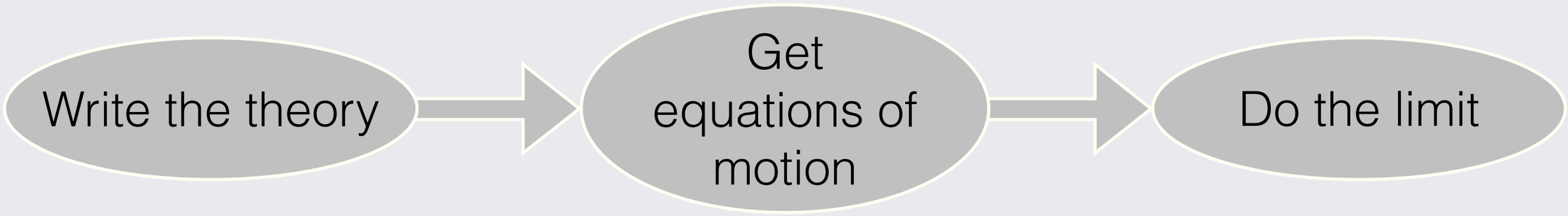
Models for Cosmic Acceleration



(T.Clifton, P.G.Ferreira, A.Padilla and C.Skordis, Phys. Rept. 513, 1 (2012); The Galactic Empire)

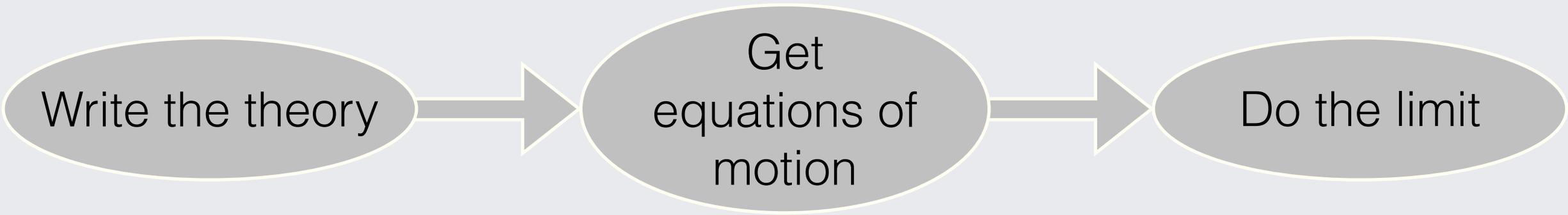
The Effective Field Theory approach

The standard way:

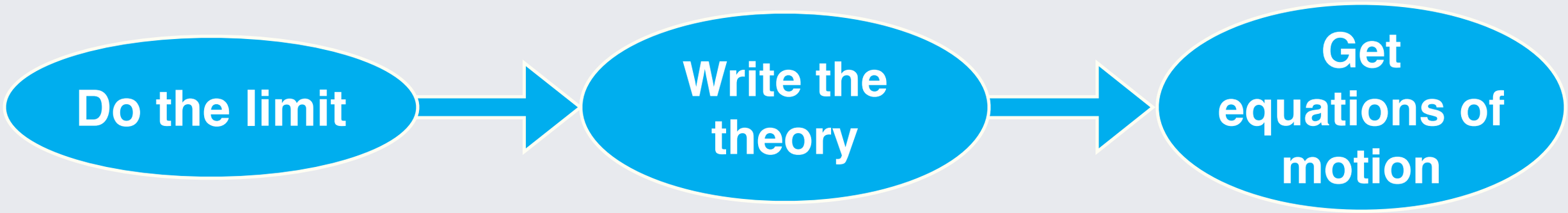


The Effective Field Theory approach

The standard way:

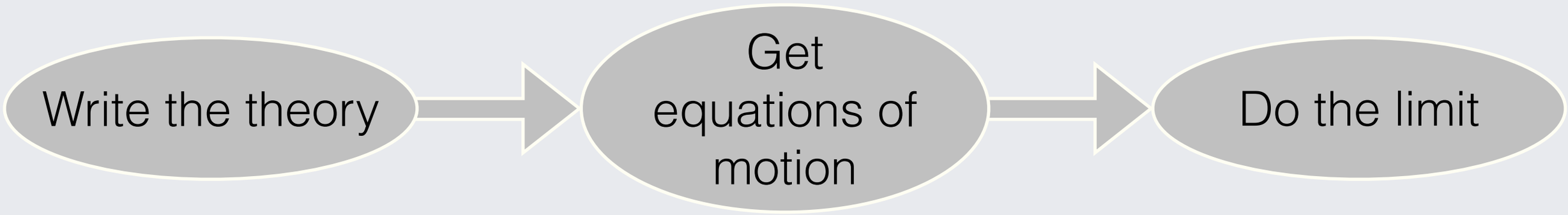


The EFT way:

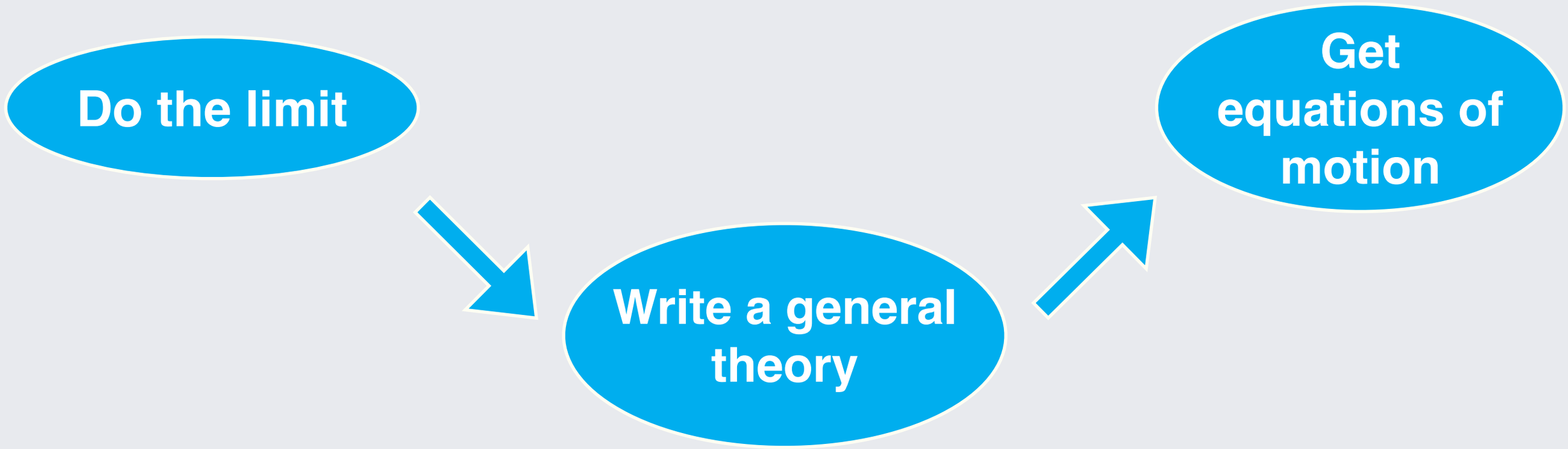


The Effective Field Theory approach

The standard way:



The EFT way:



The Effective Field Theory approach

Cosmic Acceleration Problem:

Cosmological Principle
Solar System GR
Ordinary matter + Dark matter

The Effective Field Theory approach

Cosmic Acceleration Problem:

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Space of solutions:

Cosmological Principle
??
At least Ordinary matter
+ Dark matter

The Effective Field Theory approach

Cosmic Acceleration Problem:

Cosmological Principle
Solar System GR
Ordinary matter + Dark matter

Space of solutions:

Cosmological Principle
??
At least Ordinary matter
+ Dark matter

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

This statement is observer dependent

(Planck Collaboration, AA 571 (2014) A27)

The Effective Field Theory approach

The Cosmological Principle selects a preferred observer

The symmetry of the space of solutions is not 4D diffs
but is time dependent 3D diffs

The Effective Field Theory approach

The Cosmological Principle selects a preferred observer

The symmetry of the space of solutions is not 4D diffs
but is time dependent 3D diffs

What is the most general theory compatible with these symmetries in the limit of linear cosmological perturbations

- Single additional scalar field
- The weak equivalence principle
- Standard cosmological ingredients: CDM, neutrinos, photons, baryons.

The Effective Field Theory action

General parametrization of the second order action for almost all Dark Energy and Modified Gravity models.

The EFT action in unitary gauge:

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

CDM, photons, baryons, neutrinos go here

(G.Gubitosi, F.Piazza and F.Vernizzi, JCAP 1302, 032 (2013); J.K.Bloomfield, et al. JCAP 1308, 010 (2013))

Stuckelberg Field & the extra scalar d.o.f.

Stuckelberg technique. Restore the time diffeomorphism invariance by means of an infinitesimal time coordinate transformation while spatial coordinates are unchanged:

$$t \to t + \pi\left(x^{\mu}\right)$$

This makes manifest the extra scalar d.o.f.

(G.Gubitosi, F.Piazza and F.Vernizzi, JCAP 1302, 032 (2013); J.K.Bloomfield, et al. JCAP 1308, 010 (2013))

The Effective Field Theory action

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Bigg(& \frac{m_0^2}{2}\Omega(t+\pi)R + \Lambda(t+\pi) \\
& - c(t+\pi)\left(\delta g^{00} - 2\dot{\pi} + 2\dot{\pi}\delta g^{00} + 2\tilde{\nabla}_i\pi g^{0i} - \dot{\pi}^2 + \frac{\tilde{g}^{ij}}{a^2}\tilde{\nabla}_i\pi\tilde{\nabla}_j\pi\right) \\
& + \frac{M_2^4(t+\pi)}{2}\left(\delta g^{00} - 2\dot{\pi}\right)^2 - \frac{\bar{M}_1^3(t+\pi)}{2}\left(\delta g^{00} - 2\dot{\pi}\right)\left(\delta K^{\mu}{}_{\mu} + 3\dot{H}\pi + \frac{\tilde{\nabla}^2\pi}{a^2}\right) \\
& - \frac{\bar{M}_2^2(t+\pi)}{2}\left(\delta K^{\mu}{}_{\mu} + 3\dot{H}\pi + \frac{\tilde{\nabla}^2\pi}{a^2}\right)^2 \\
& - \frac{\bar{M}_3^2(t+\pi)}{2}\left(\delta K^{i}{}_{j} + \dot{H}\pi\delta^i_j + \frac{\tilde{g}^{ik}}{a^2}\tilde{\nabla}_k\tilde{\nabla}_j\pi\right)\left(\delta K^{j}{}_{i} + \dot{H}\pi\delta^j_i + \frac{\tilde{g}^{jl}}{a^2}\tilde{\nabla}_l\tilde{\nabla}_i\pi\right) \\
& - \frac{\bar{M}_3^2(t+\pi)}{2}\left[\left(\delta K^{t}{}_{t}\right)^2 + 2\left(\delta K^{i}{}_{t} - H\frac{\tilde{g}^{ij}}{a^2}\tilde{\nabla}_j\pi\right)\left(\delta K^{t}{}_{i} + H\tilde{\nabla}_i\pi\right)\right] \\
& + \frac{\hat{M}^2(t+\pi)}{2}\left(\delta g^{00} - 2\dot{\pi}\right)\left(\delta R^{(3)} + 4H\frac{\tilde{\nabla}^2\pi}{a^2} + 12H\frac{k_0}{a^2}\pi\right) \\
& + m_2^2(t+\pi)\left(g^{\mu\nu} + n^\mu n^\nu\right)\partial_\mu\left(g^{00} - 2\dot{\pi}\right)\partial_\nu\left(g^{00} - 2\dot{\pi}\right)\Bigg) + S_m[\chi_i, g_{\mu\nu}]
\end{aligned}
$$

π = Dark energy fluctuations

(G.Gubitosi, F.Piazza and F.Vernizzi, JCAP 1302, 032 (2013); J.K.Bloomfield, et al. JCAP 1308, 010 (2013))

Different angles on the EFT

Pure EFT: let the data tell us the behavior of the model

$$\left\{\Omega(\tau), \Lambda(\tau), c(\tau), M_2^4(\tau), \bar{M}_1^3(\tau), \bar{M}_2^2(\tau), \bar{M}_3^2(\tau), \hat{M}^2(\tau), m_2^2(\tau)\right\}$$

Mapping EFT: let the model try to explain the data

f(R): $$\Omega = f_R \ ; \ \Lambda = \frac{m_0}{2}\left(f - R f_R\right) \ ; \ c = 0$$

minimally coupled quintessence:

$$\Omega = 0 \ ; \ c - \Lambda = V(\phi) \ ; \ c = \frac{\dot{\phi}}{2}$$

Different angles on the EFT

Pure EFT: let the data tell us the behavior of the model

$$\left\{\Omega(\tau), \Lambda(\tau), c(\tau), M_2^4(\tau), \bar{M}_1^3(\tau), \bar{M}_2^2(\tau), \ldots, m_2^2(\tau)\right\}$$

Model independent

Mapping EFT: let the model try to explain the data

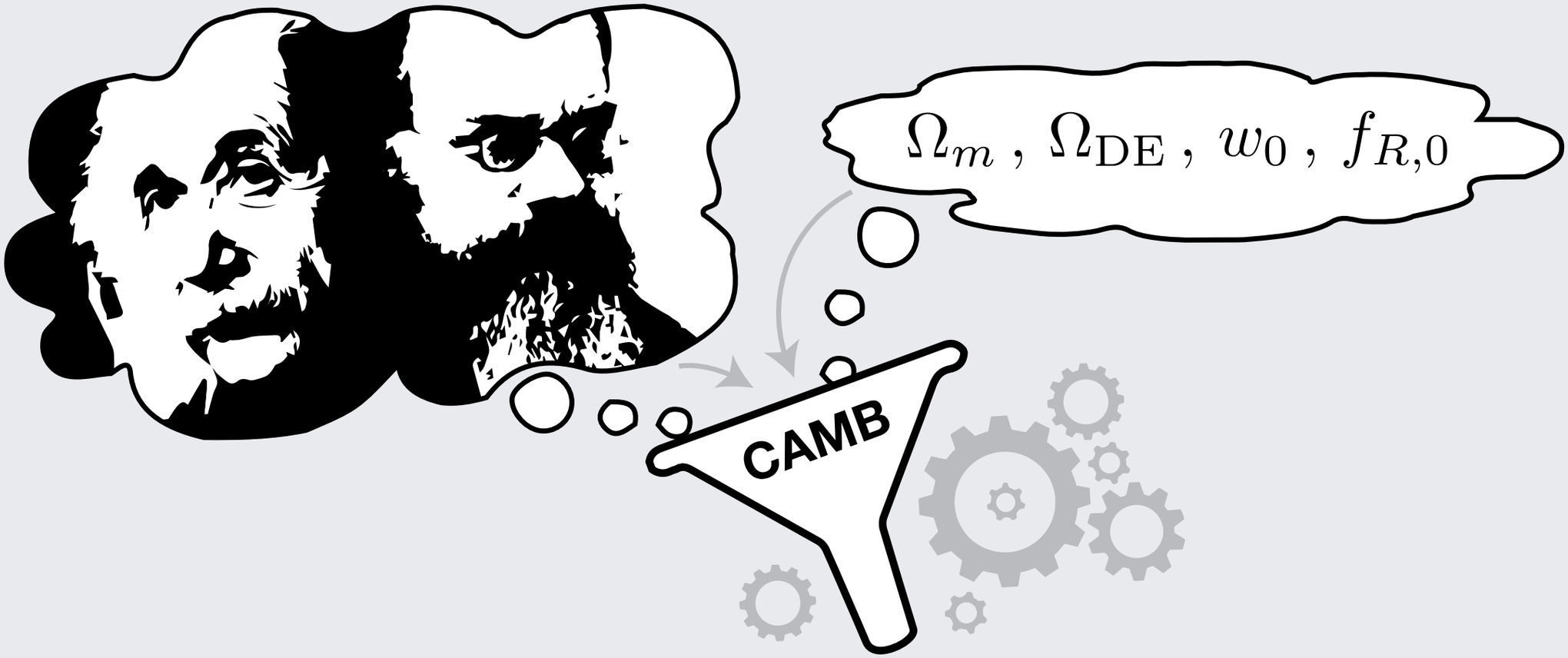
f(R): $\Omega = f_R \; ; \; \Lambda = \frac{m_0}{2}\left(f - R f_R\right) \ldots = 0$

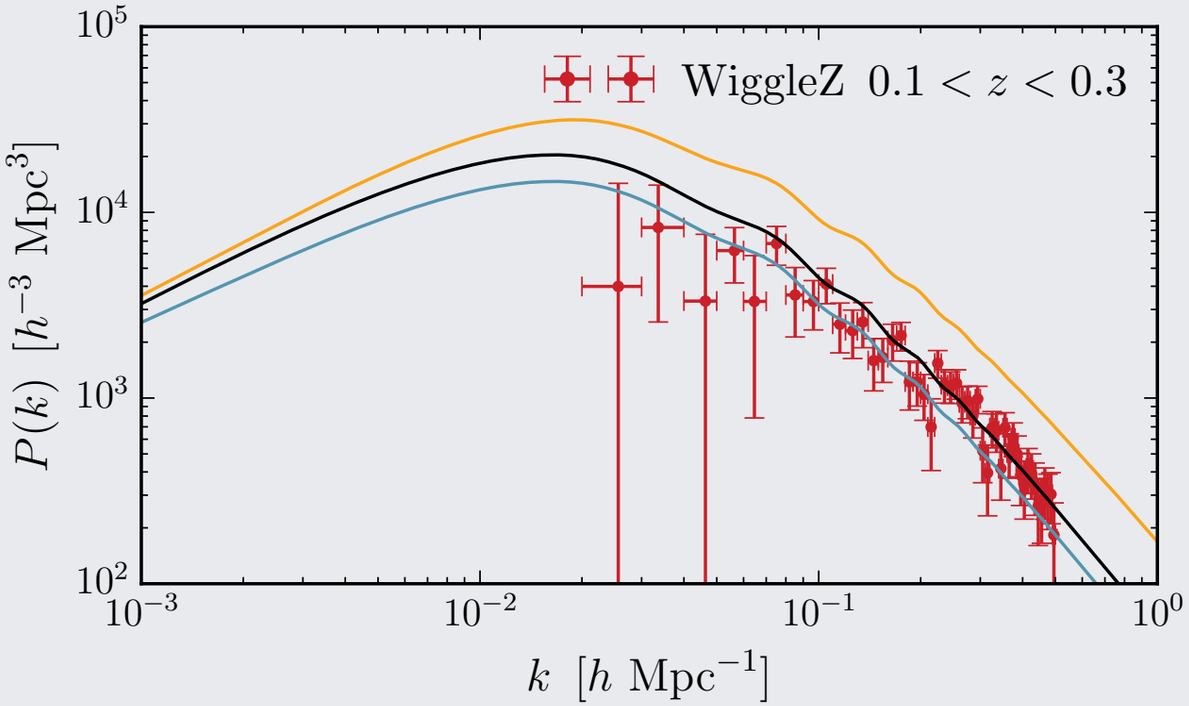
minimally coupled quintessence:

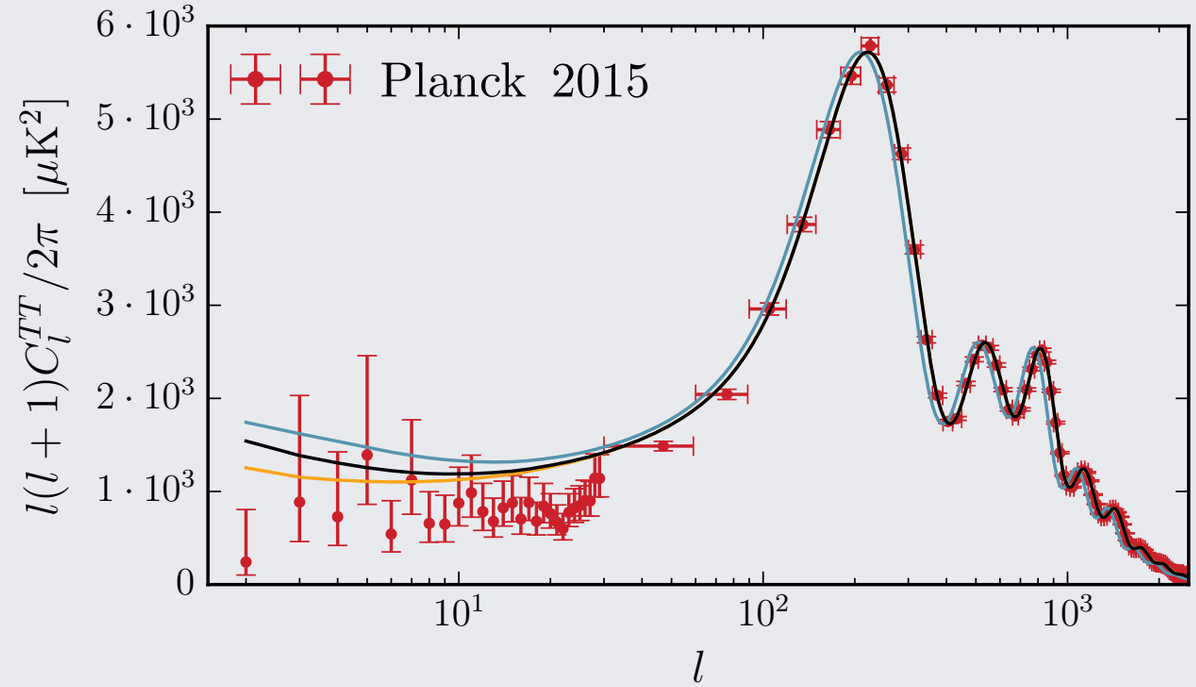
$$\Omega = 0 \; ; \; c - \Lambda = V(\phi) \; ; \; c = \frac{\dot{\phi}}{2}$$

Unifying language

Confronting gravity with data





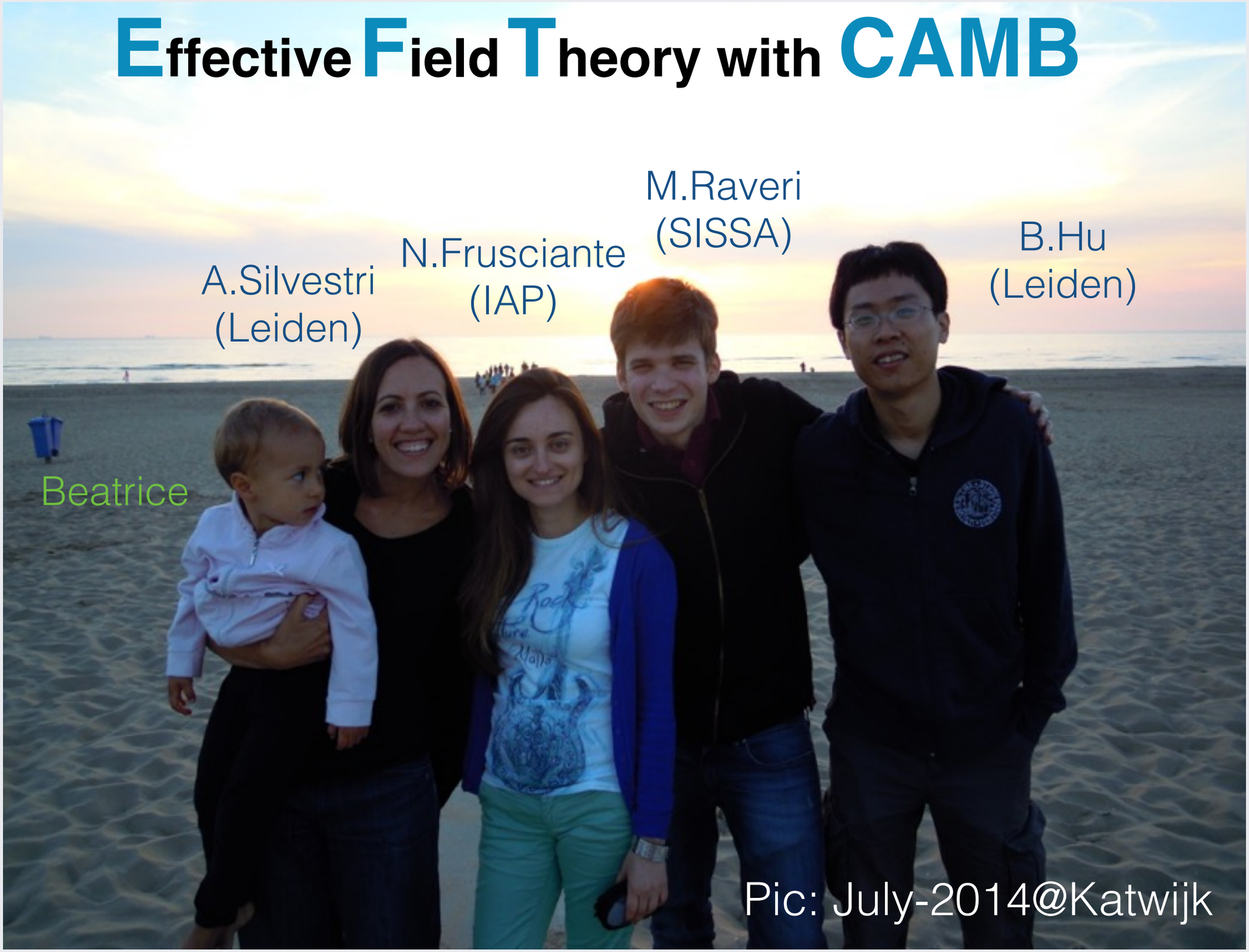


DE/MG modeling: EFTCAMB

- 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) and minimally coupled quintessence. More to come very soon!
- Exploration of parameter space and comparison with cosmological datasets.

(B.Hu, MR, N.Frusciante, A.Silvestri, PRD 89, 103530 (2014); MR, B.Hu, N.Frusciante, A.Silvestri, PRD 90, 043513 (2014))

DE/MG modeling: the EFTCAMB team

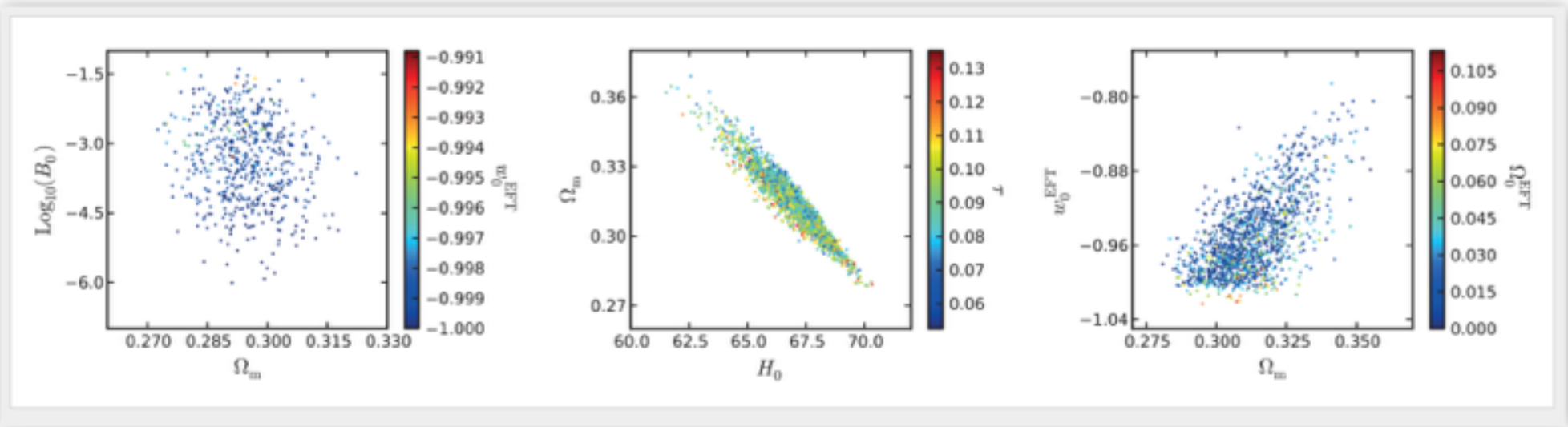


DE/MG modeling: EFTCAMB

Google EFTCAMB

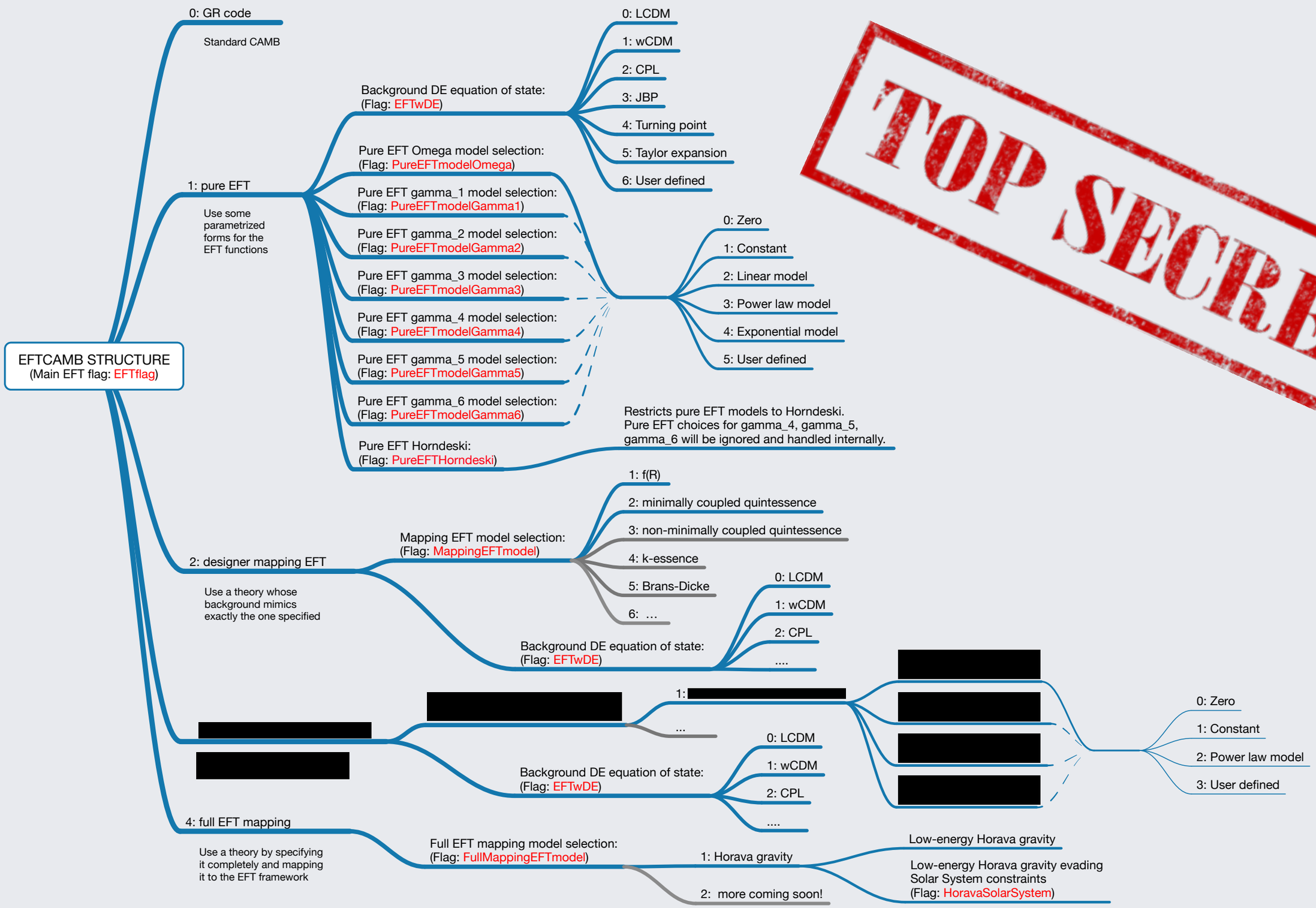
Effective Field Theory with CAMB

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.

EFTCAMB structure: sneak peek of v2!



(B.Hu, MR, N.Frusciante, A.Silvestri, arXiv:1405.3590: EFTCAMB/EFTCosmoMC: Numerical Notes v2.0)

Stability of perturbations and viability priors

Stability check to ensure that the underlying gravitational theory is acceptable.

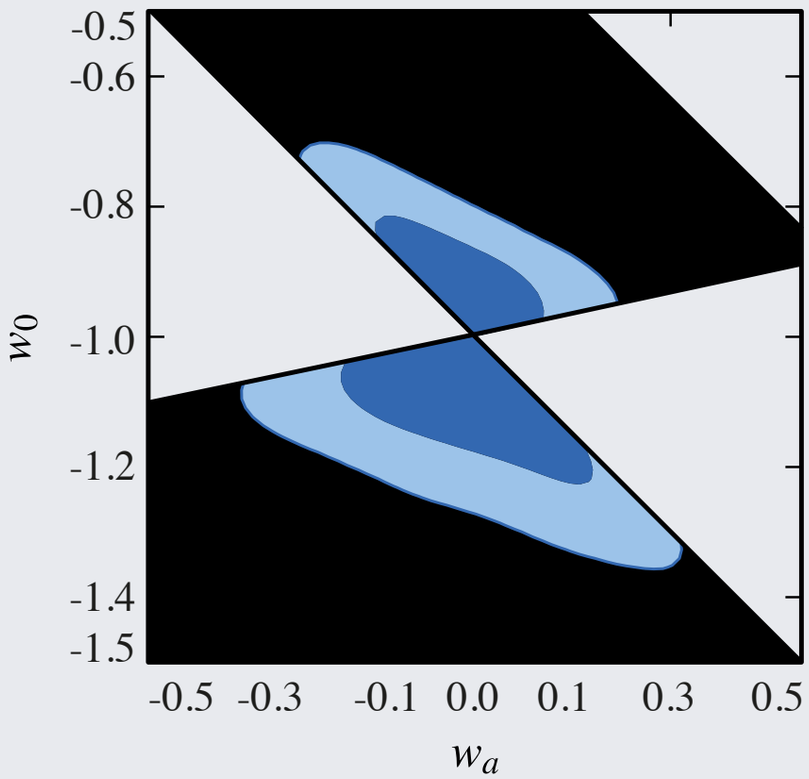
- Positive Newtonian constant
- No ghost instabilities
- No gradient instabilities
- Positive mass of the scalar

EFTCosmoMC: the above requirements become priors on parameters defining the dark sector of the theory.

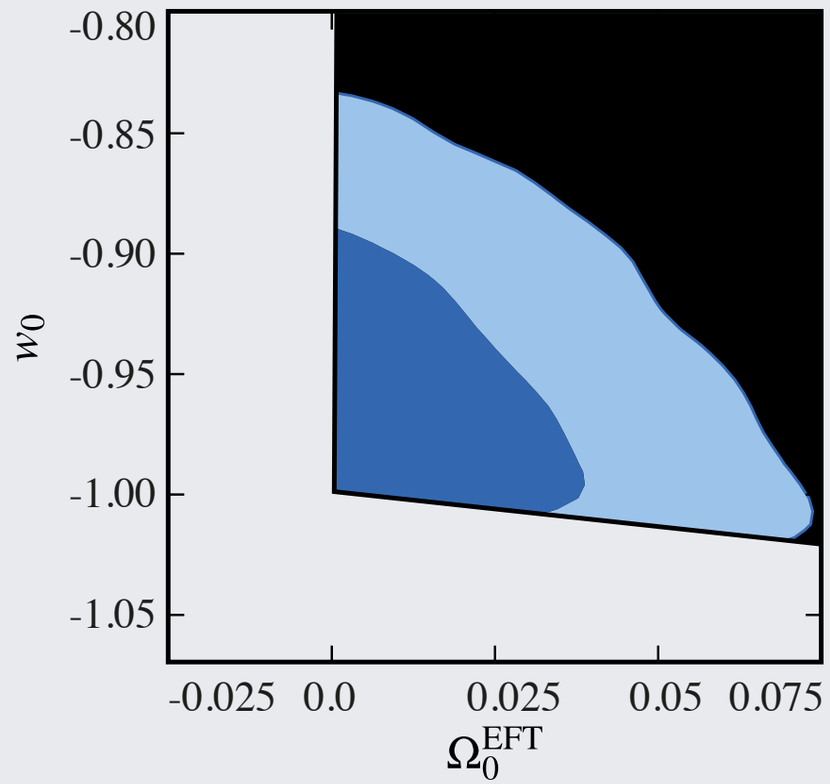
We call these viability priors

(B.Hu, MR, N.Frusciante, A.Silvestri, PRD 89, 103530 (2014); A.Joyce et al. Phys. Rept. 568, 1 (2015))

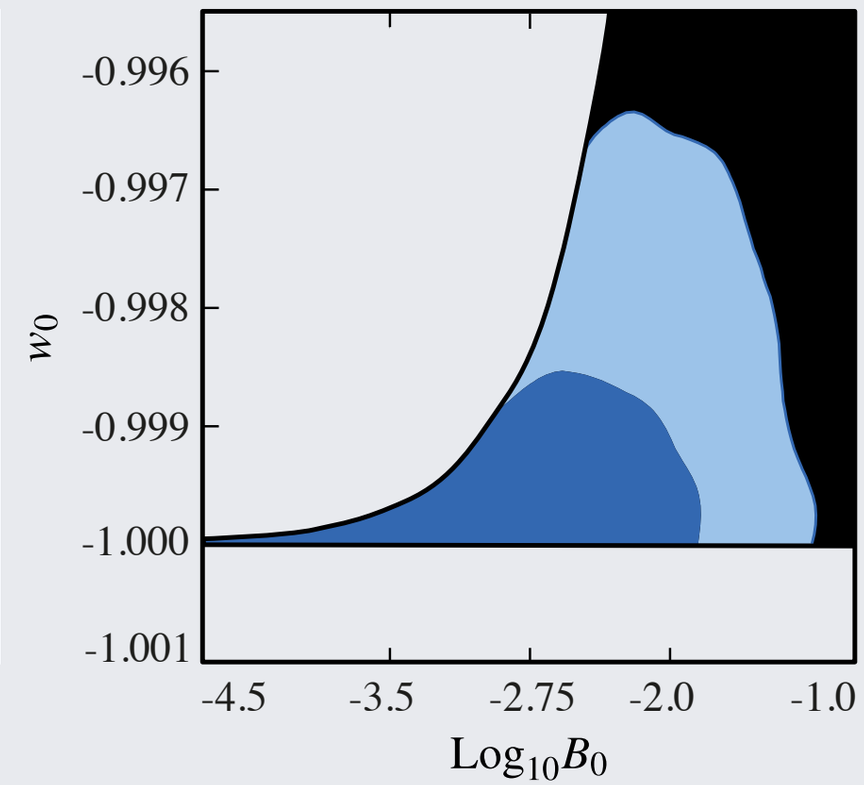
Viability priors: some examples



minimally coupled 5e on CPL background



linear Omega on wCDM background



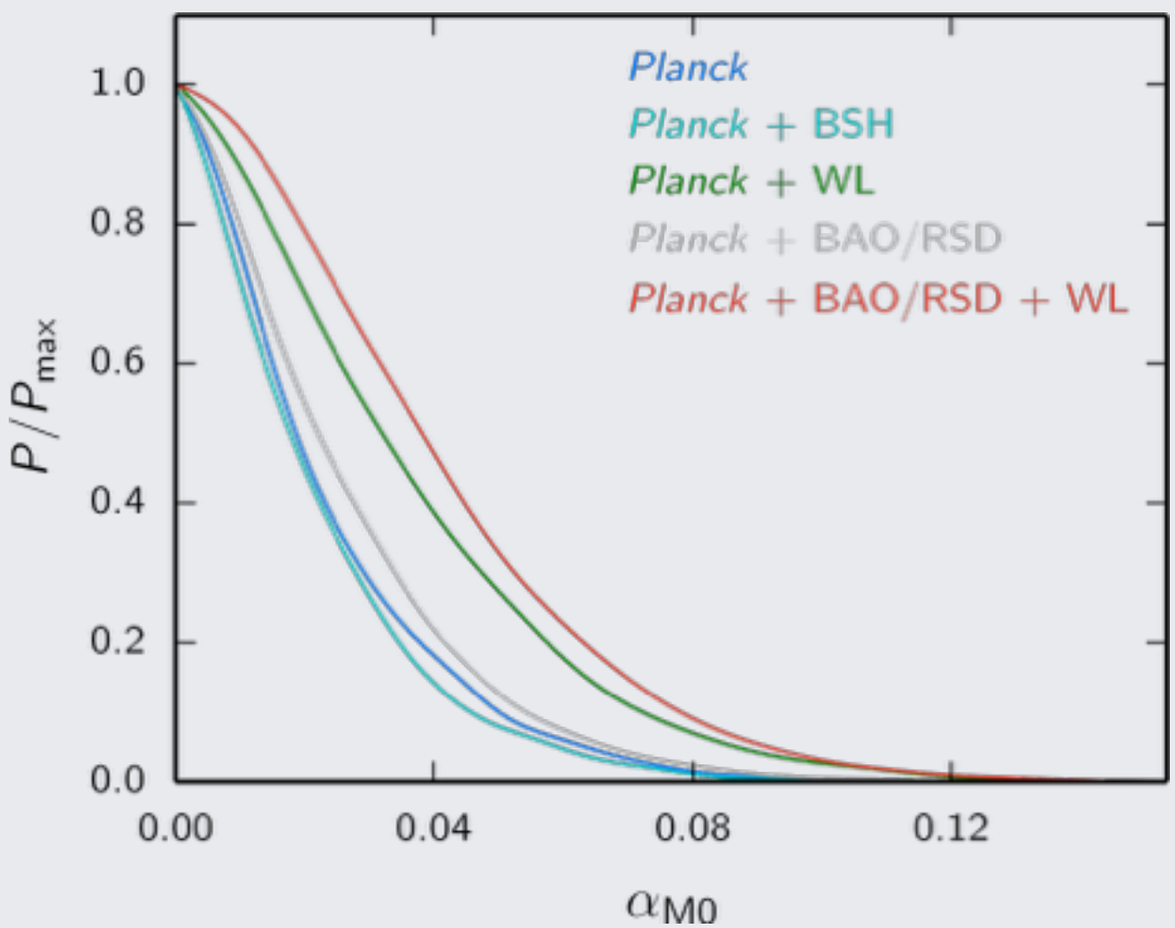
designer f(R) on wCDM background

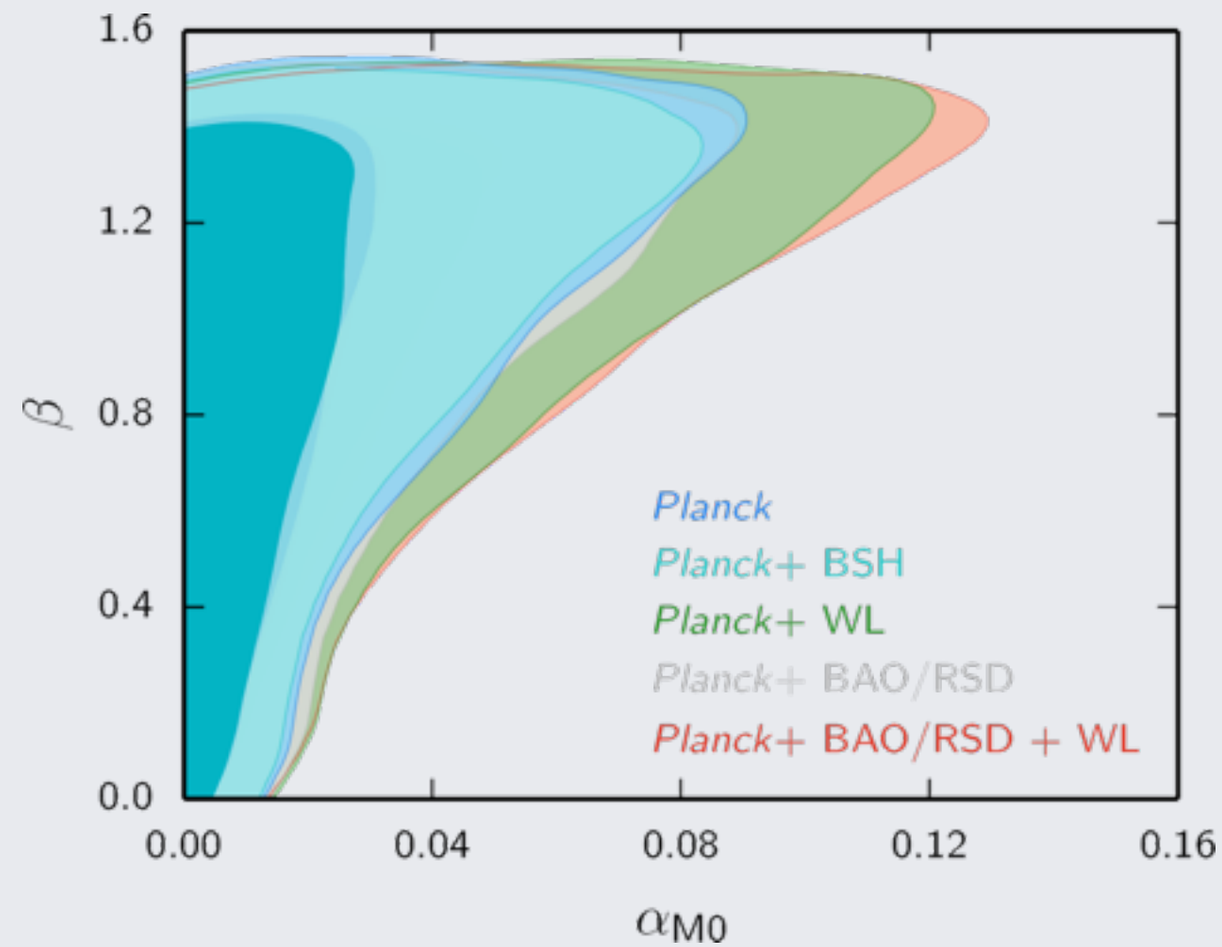
What did Planck 2015 say?

Conformal coupling between gravity and DE field

Linear EFT Omega:

$$\Omega(a) = \Omega_0 a = \alpha_{\rm M0} a$$





Exponential EFT Omega:

$$\Omega(a) = \exp\left(\Omega_0 a^\beta\right) - 1$$
$$= \exp\left(\alpha_{\rm M0} a^\beta / \beta\right) - 1$$

(Planck Collaboration, Planck 2015 results. XIV. Dark energy and modified gravity, arXiv:1502.01590)

Revisiting degeneracy with massive neutrinos

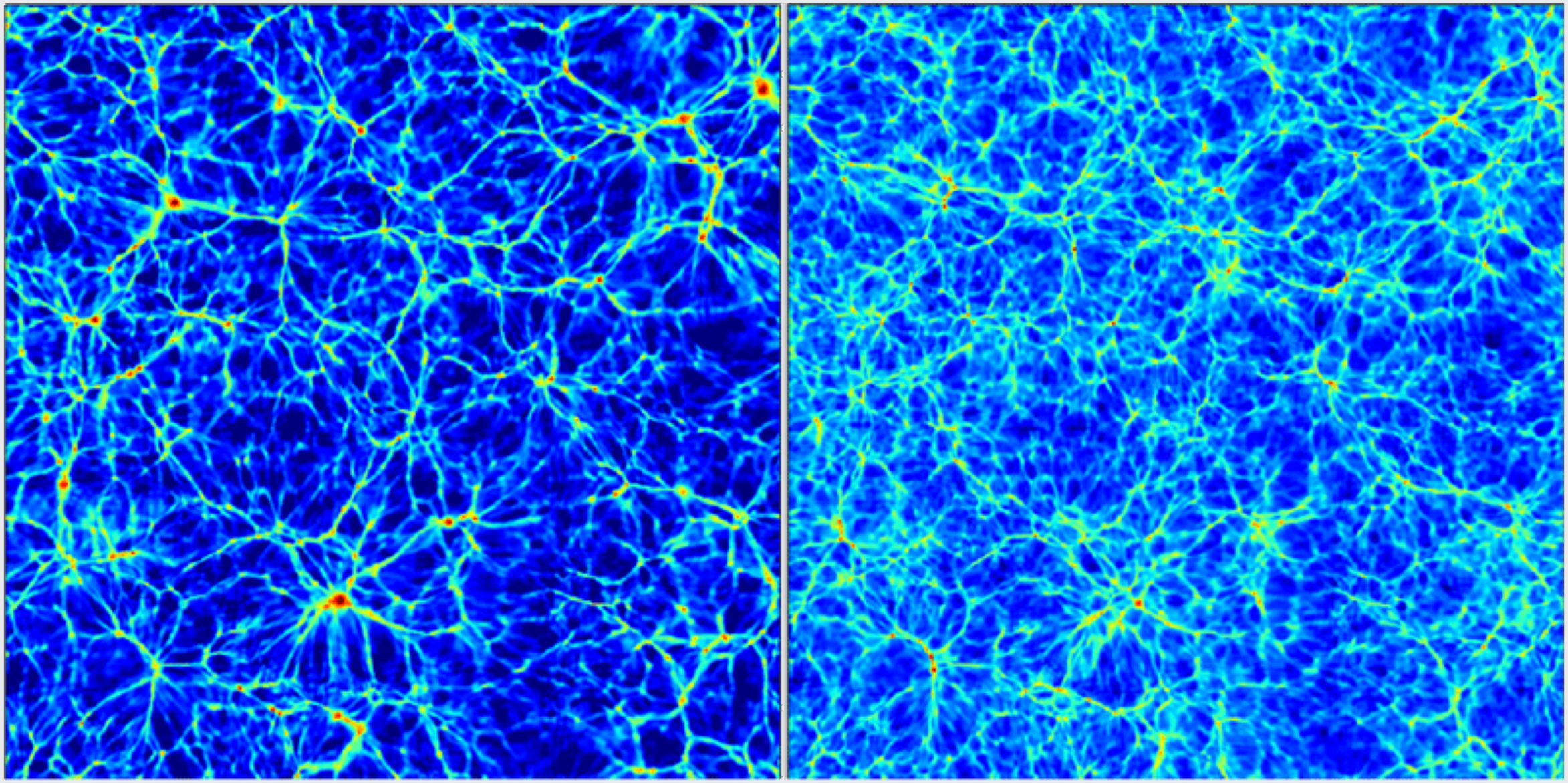


Image: Shankar Agarwal and Hume Feldman, University of Kansas

(B.Hu, MR, N.Frusciante and A.Silvestri, Phys. Rev. D 91, 063524 (2015))

Revisiting degeneracy with massive neutrinos

On linear scales, smaller than the neutrino free streaming distance, the overall matter clustering is suppressed.

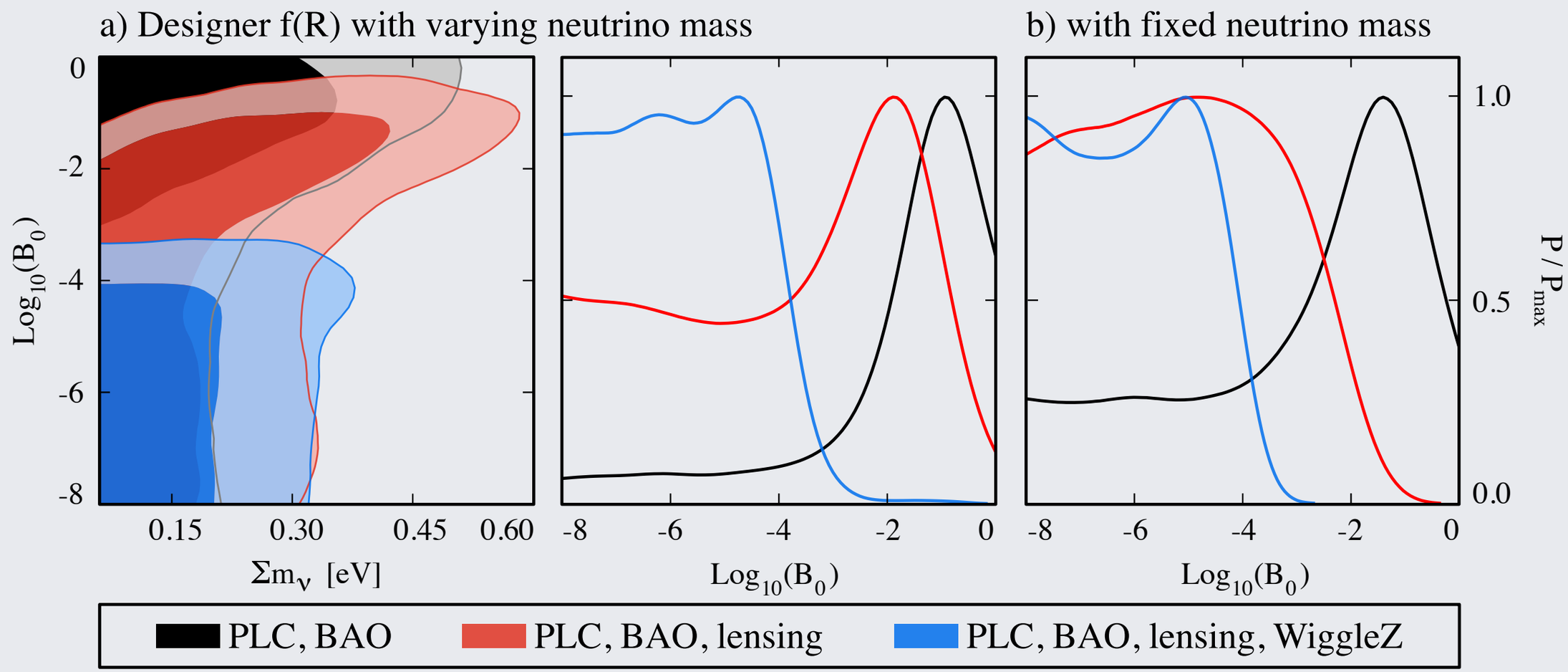
Modified Gravity models influence the growth of perturbations as well.

f(R) models leave a complementary signature on the growth of structure, enhancing the clustering on linear scales within the Compton scale of the extra scalar degree of freedom

We expect massive neutrinos and modified gravity models that enhance the growth of structure to be degenerate

(B.Hu, MR, N.Frusciante and A.Silvestri, Phys. Rev. D 91, 063524 (2015))

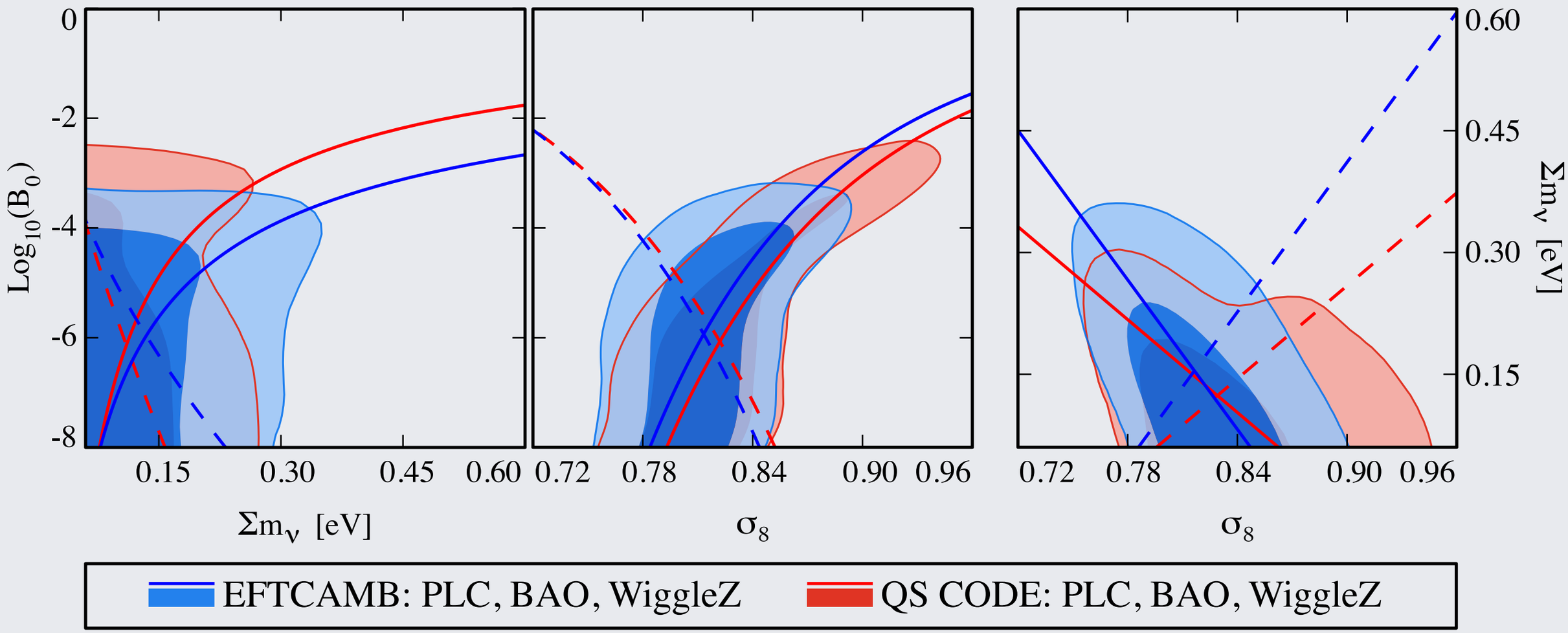
Massive neutrinos and f(R) gravity



	Varying m_ν		Fixing m_ν
Data sets	$\mathrm{Log}_{10}B_0$ (95% C.L.)	$\sum m_\nu$ (95% C.L.)	$\mathrm{Log}_{10}B_0$ (95% C.L.)
PLC + BAO	> -6.35	< 0.37	none
PLC + BAO + lensing	< -1.0	< 0.43	< -2.3
PLC + BAO + lensing + WiggleZ	< -3.8	< 0.32	< -4.1
PLC + BAO + WiggleZ (EFTCAMB)	< -3.8	< 0.30	< -3.9
PLC + BAO + WiggleZ (QS $f(R)$)	< -3.2	< 0.24	< -3.7
PLC + BAO + WiggleZ (MGCAMB)	< -3.1	< 0.23	< -3.5

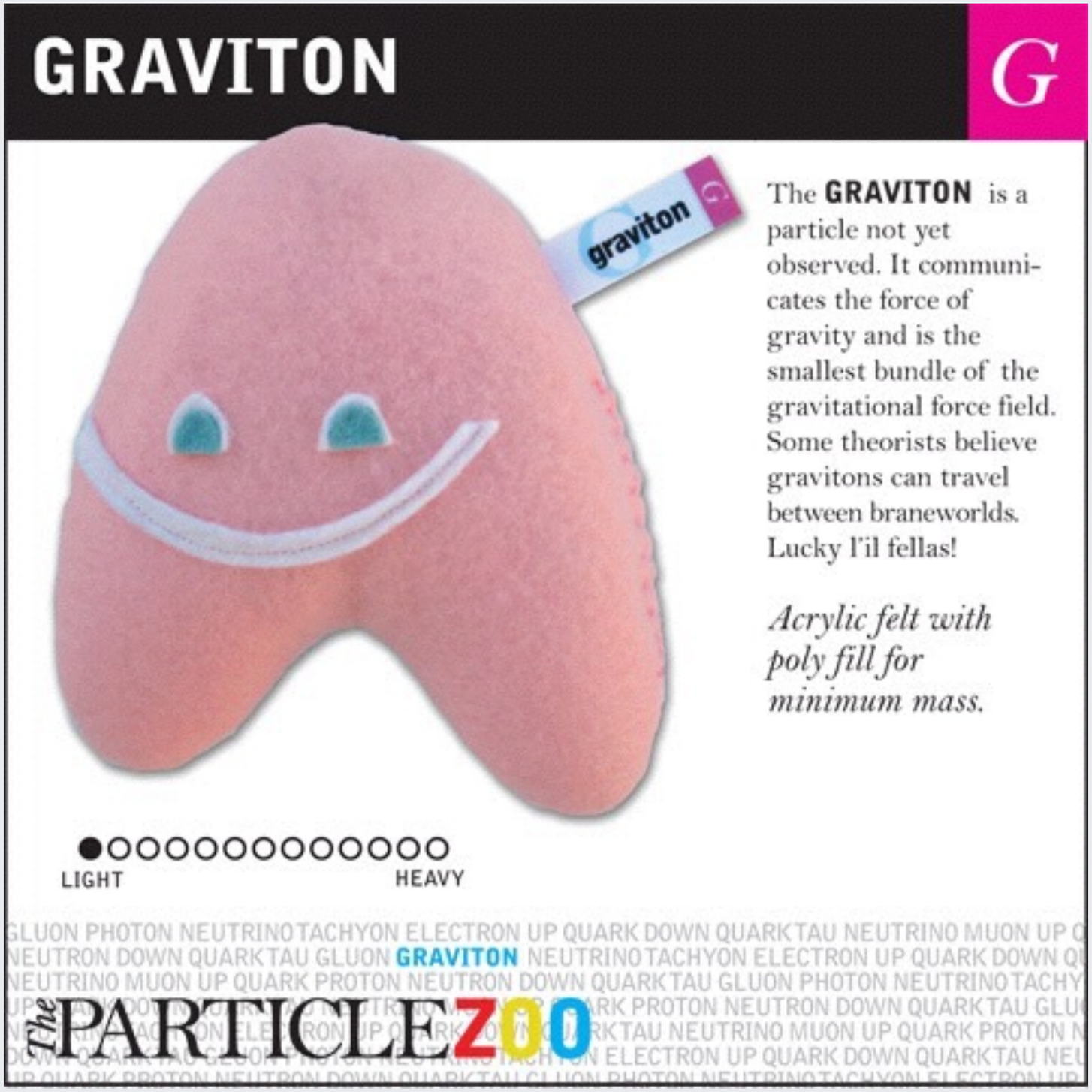
(B.Hu, MR, N.Frusciante and A.Silvestri, Phys. Rev. D 91, 063524 (2015))

Degeneracy with massive neutrinos revisited



(B.Hu, MR, N.Frusciante and A.Silvestri, Phys. Rev. D 91, 063524 (2015))

Hořava gravity in EFT



(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Hořava gravity in EFT

- GR and QFT do not like each other. GR, when quantized, is not renormalizable in the ultraviolet;
- There is a candidate model to put them together by giving up Lorentz invariance;
- Hořava (2009) proposed to modify the graviton propagator by adding higher-order spatial derivatives without adding higher (than second) order time derivatives;
- What does this model have to say about cosmology?
- What does cosmology have to say about this model?

(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Hořava gravity in EFT

The low energy Hořava action is:

$$S_{H,le} = \frac{M_{pl}^2}{2} \int d^4x \sqrt{-g} \left[K_{ij} K^{ij} - \lambda K^2 + \xi \mathcal{R} - 2\bar{\Lambda} + \eta a_i a^i \right]$$

EFT

EFTCAMB

Comparison with data

(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Mapping of Hořava gravity in EFT

Low energy

$$m_0^2(1+\Omega) = M_{pl}^2\xi,$$

$$c(\tau) = -\frac{M_{pl}^2}{2a^2}(1+2\xi-3\lambda)\left(\dot{\mathcal{H}}-\mathcal{H}^2\right),$$

$$\Lambda(\tau) = M_{pl}^2\left[-\bar{\Lambda}-(1-3\lambda+2\xi)\left(\frac{\mathcal{H}^2}{2a^2}+\frac{\dot{\mathcal{H}}}{a^2}\right)\right],$$

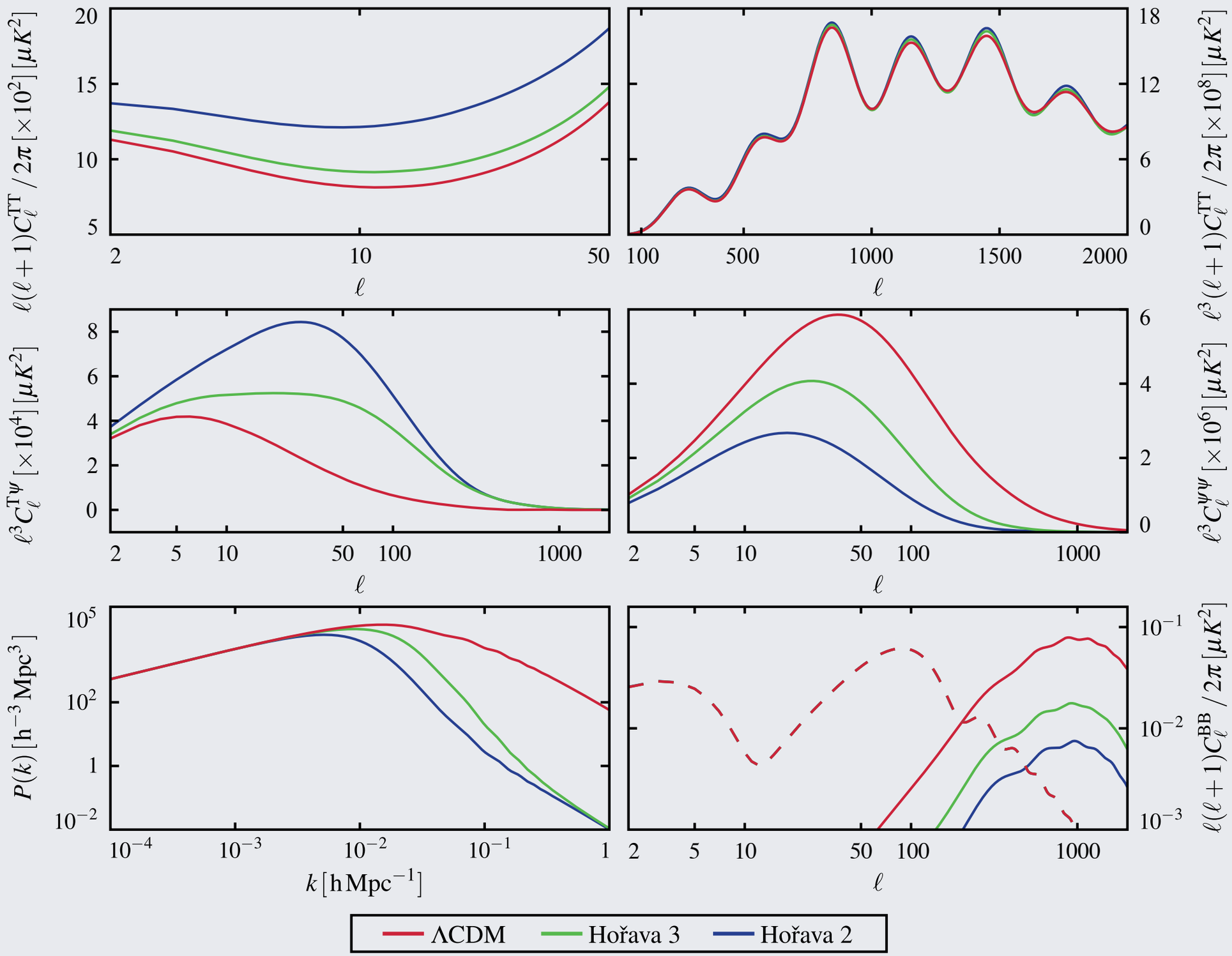
$$\bar{M}_3^2 = -M_{pl}^2(1-\xi), \qquad \bar{M}_2^2 = -M_{pl}^2(\xi-\lambda),$$

$$M_2^4(\tau) = \frac{M_{pl}^2}{4a^2}(1+2\xi-3\lambda)\left(\dot{\mathcal{H}}-\mathcal{H}^2\right), \; m_2^2 = \frac{M_{pl}^2}{8}\eta,$$

High energy in the paper

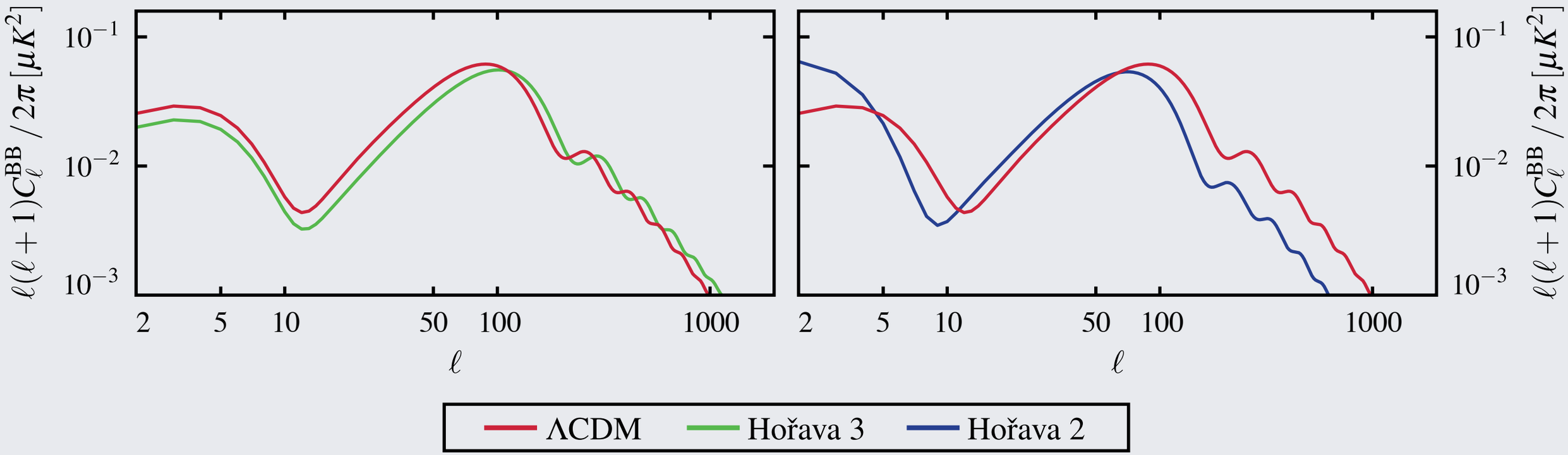
(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Effects on observables: CMB and LSS



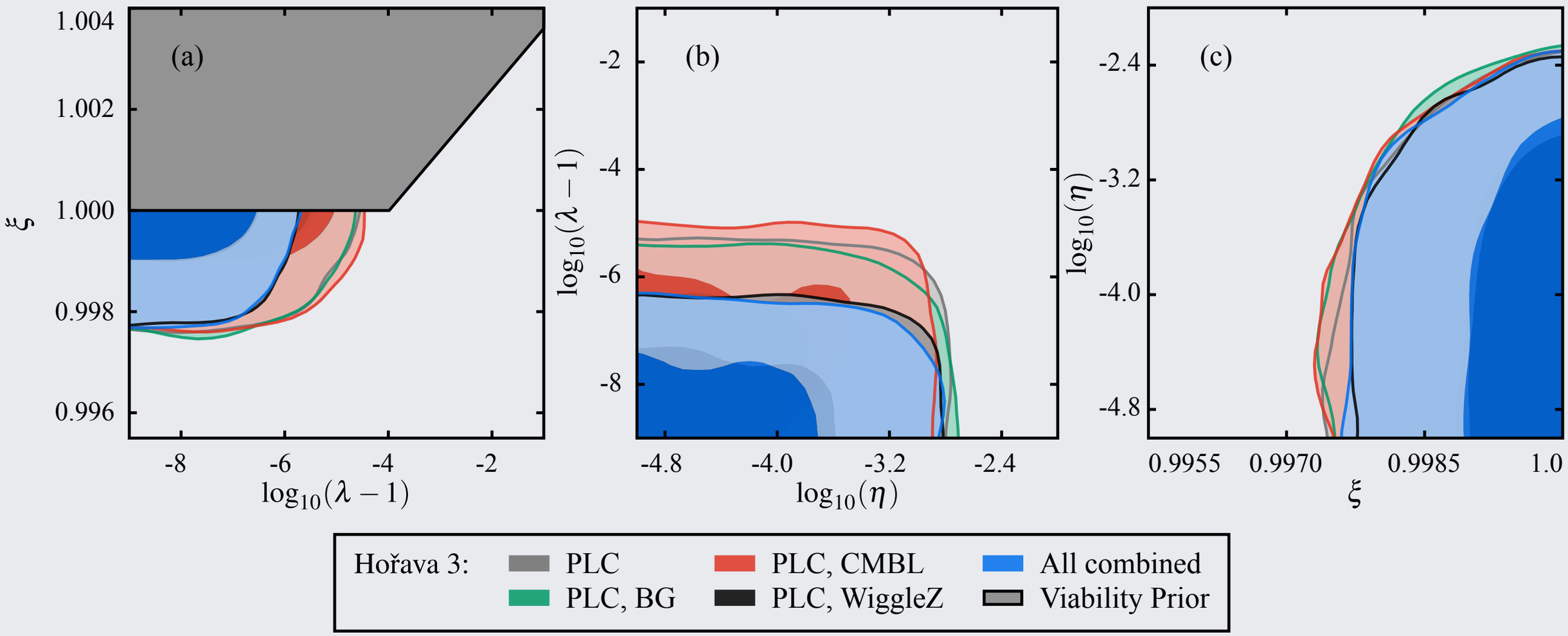
(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Effects on observables: speed of GWs



(N.Frusciante et al., arXiv:1508.01787, MR et al., Phys. Rev. D 91, 061501 (2015))

Constraints on low energy Hořava gravity (H3)



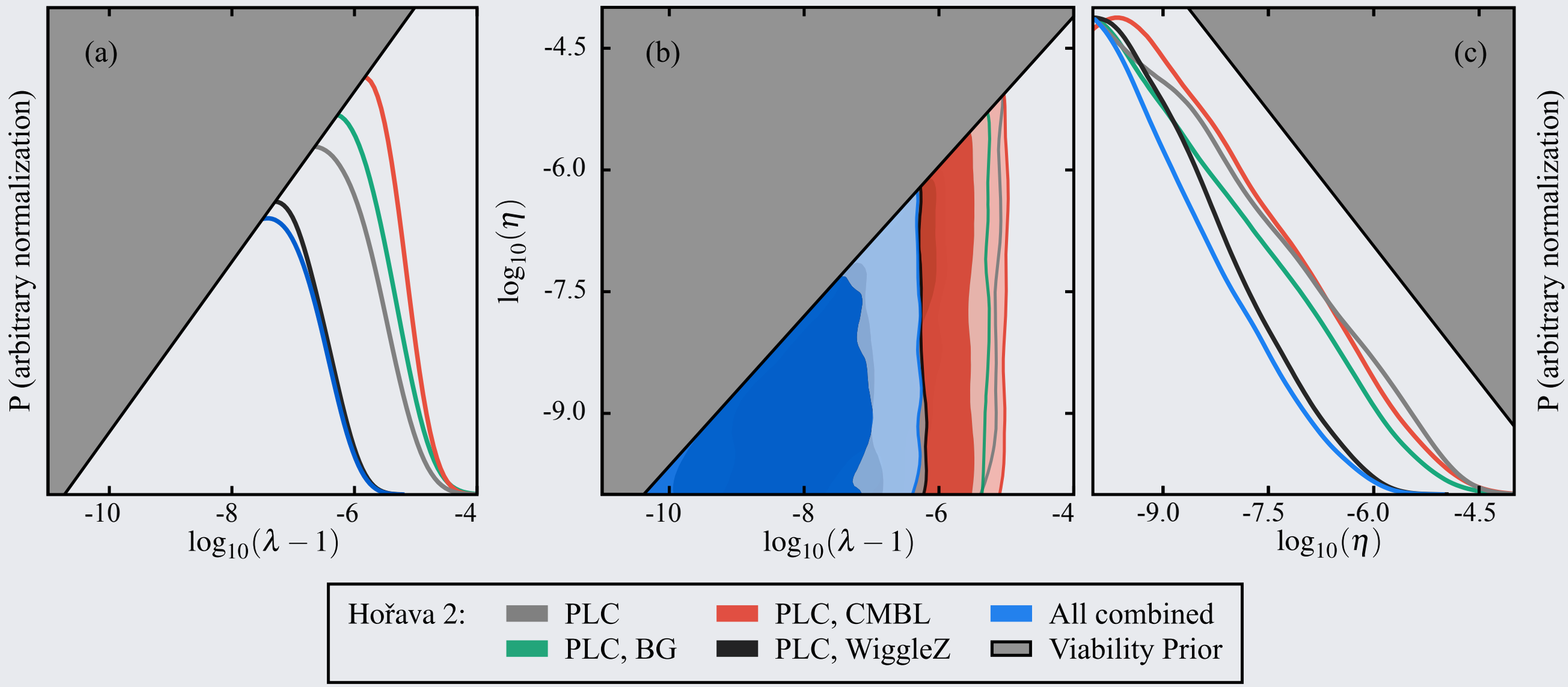
$$0 > \xi - 1 > -0.0038 \qquad \log_{10}(\lambda - 1) < -6.2$$

$$\log_{10}(\eta) < -2.4 \qquad \Omega^0_{DE} = 0.69^{+0.02}_{-0.02}$$

(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

Constraints on low energy Hořava gravity (H2)

Tuning the parameters to evade solar system constraints



$$\log_{10}(\lambda - 1) < -5.9 \ , \ \log_{10}(\eta) < -6.1 \ , \ \Omega^0_{DE} = 0.69^{+0.02}_{-0.02}$$

(N.Frusciante, MR, D.Vernieri, B.Hu, and A.Silvestri, arXiv:1508.01787, submitted to PDU)

The Data sets Concordance Test

Concordance of evidence refers to the principle that evidence from independent, unrelated sources can "converge" to strong conclusions.

(MR, arXiv:1510.00688, submitted to PRL; Wikipedia: Consilience)

The Data sets Concordance Test

Model selection

goodness of fit does not rule out alternative theories

(MR, arXiv:1510.00688, submitted to PRL)

The Data sets Concordance Test

Model selection

goodness of fit does not rule out alternative theories

BUT

Concordance test

if there are tensions between data sets when interpreted within a model something is wrong

(MR, arXiv:1510.00688, submitted to PRL)

The Data sets Concordance Test

What is a tension between data sets?

Presence of unaccounted systematic effects

Incomplete modeling of the cosmological predictions

Presence of new physical phenomena

(MR, arXiv:1510.00688, submitted to PRL)

The Data sets Concordance Test

What is a tension between data sets?

without looking at some selected parameter

without advocating alternative models

with clear assessment of statistical significance

(MR, arXiv:1510.00688, submitted to PRL)

The Data sets Concordance Test

Bayesian hypothesis testing

$\mathcal{I}_0$: two data sets can be characterized, within model M, by the same (unknown) parameters;

$\mathcal{I}_1$: two data sets can be described, within model M, with different (unknown) parameters

Compare the odds of the two hypotheses

$$\mathcal{C}(D_1, D_2, \mathcal{M}) = \frac{P(D_1 \cup D_2 | \mathcal{I}_0, \mathcal{M})}{P(D_1 \cup D_2 | \mathcal{I}_1, \mathcal{M})} = \frac{P(D_1 \cup D_2 | \mathcal{M})}{P(D_1 | \mathcal{M}) P(D_2 | \mathcal{M})}$$

(MR, arXiv:1510.00688, submitted to PRL; P.Marshall et al., Phys. Rev. D 73, 067302 (2006))

The Data sets Concordance Test: properties

$\log \mathcal{C}$

> 0 agreement between data sets

< 0 disagreement between data sets

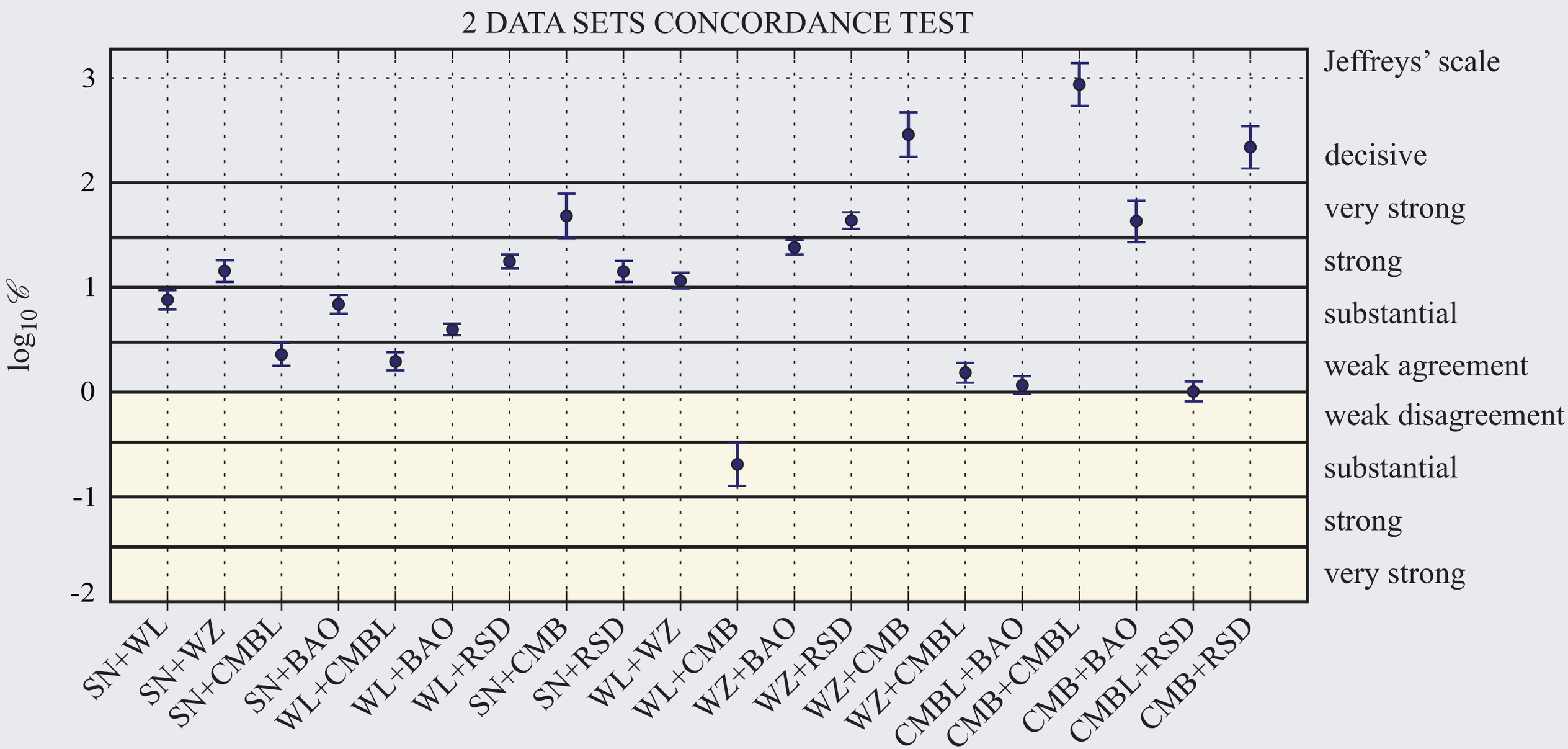
Quantitative

Naturally prefers the combination of probes
(extremely conservative)

Reduces to the usual sigmas
when everything is Gaussian

(MR, arXiv:1510.00688, submitted to PRL)

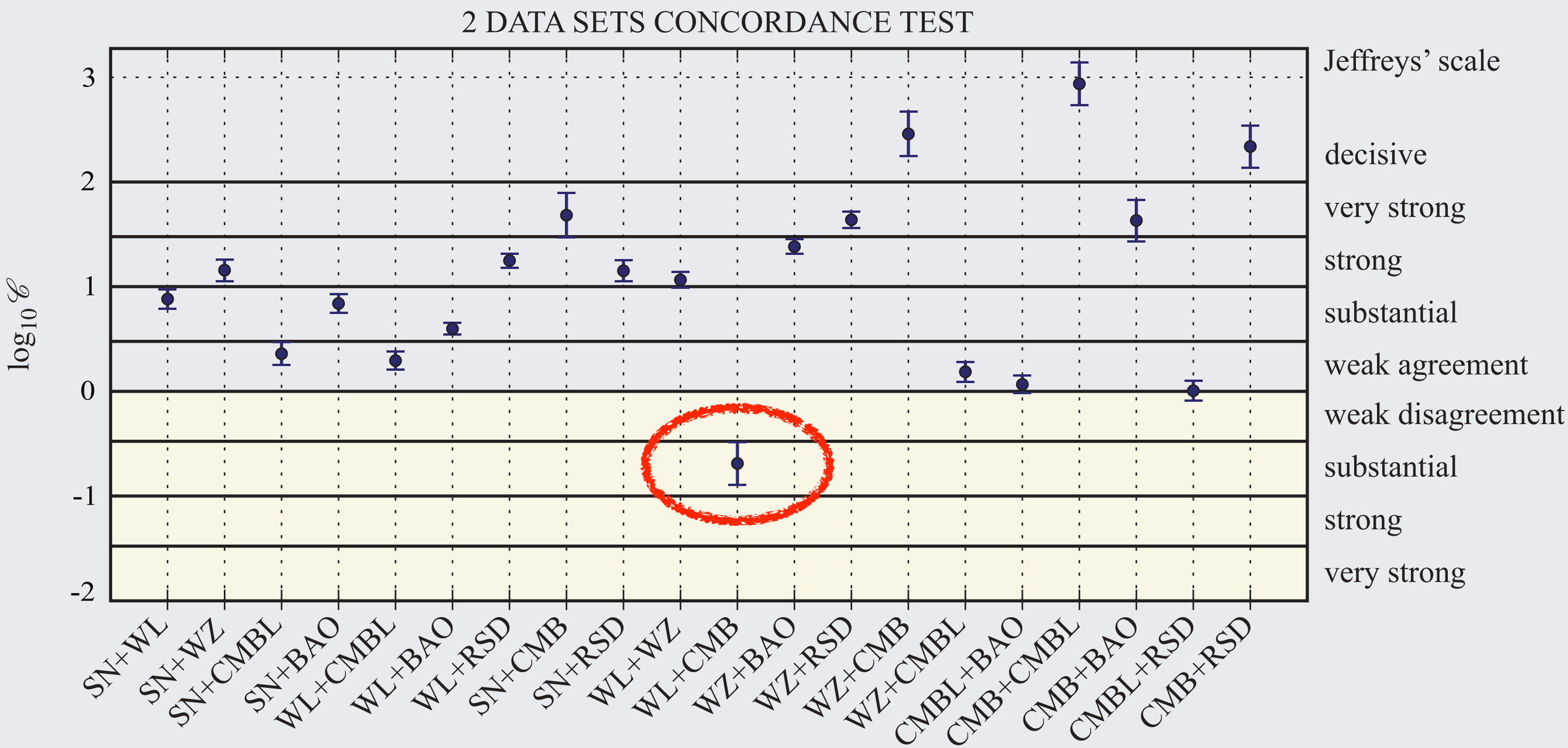
Concordance within LCDM



Overall good agreement but…

(MR, arXiv:1510.00688, submitted to PRL)

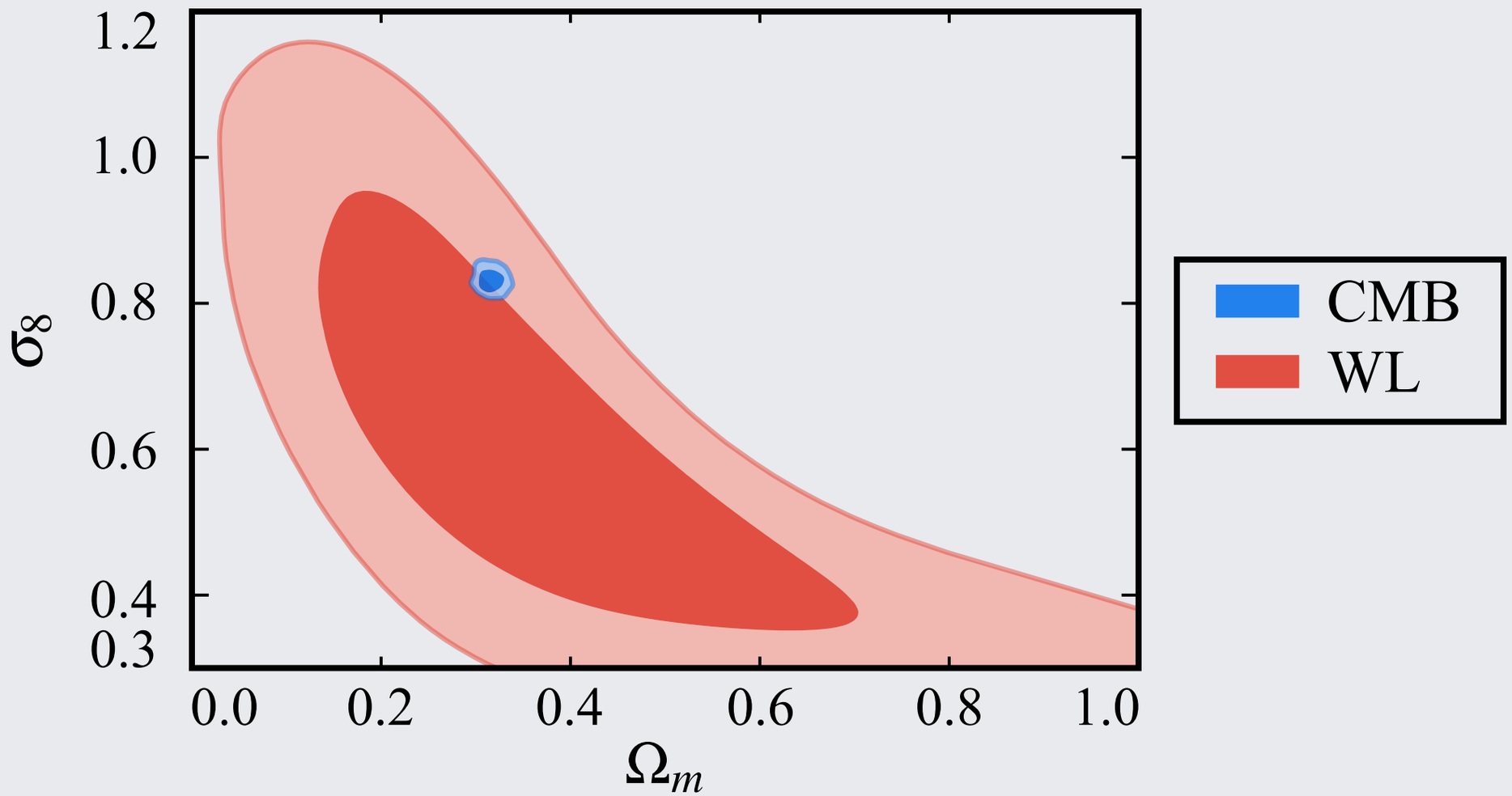
Concordance within LCDM



Overall good agreement with the exception of CFHTLenS and Planck

(MR, arXiv:1510.00688, submitted to PRL)

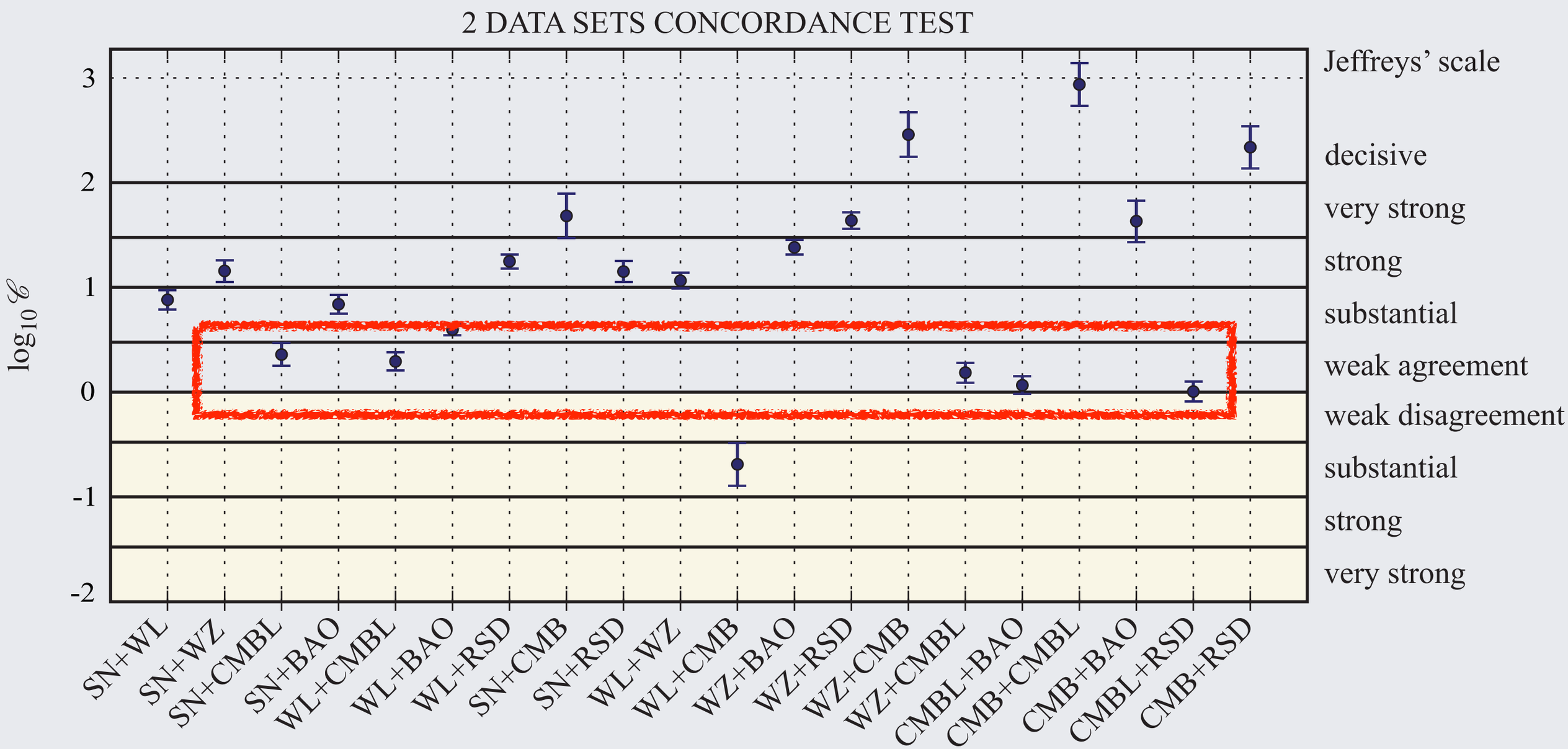
Tensions in the parameters?



This same tension does not show up in the marginal posterior of $(\Omega_m\,,\,\sigma_8)$.

(MR, arXiv:1510.00688, submitted to PRL)

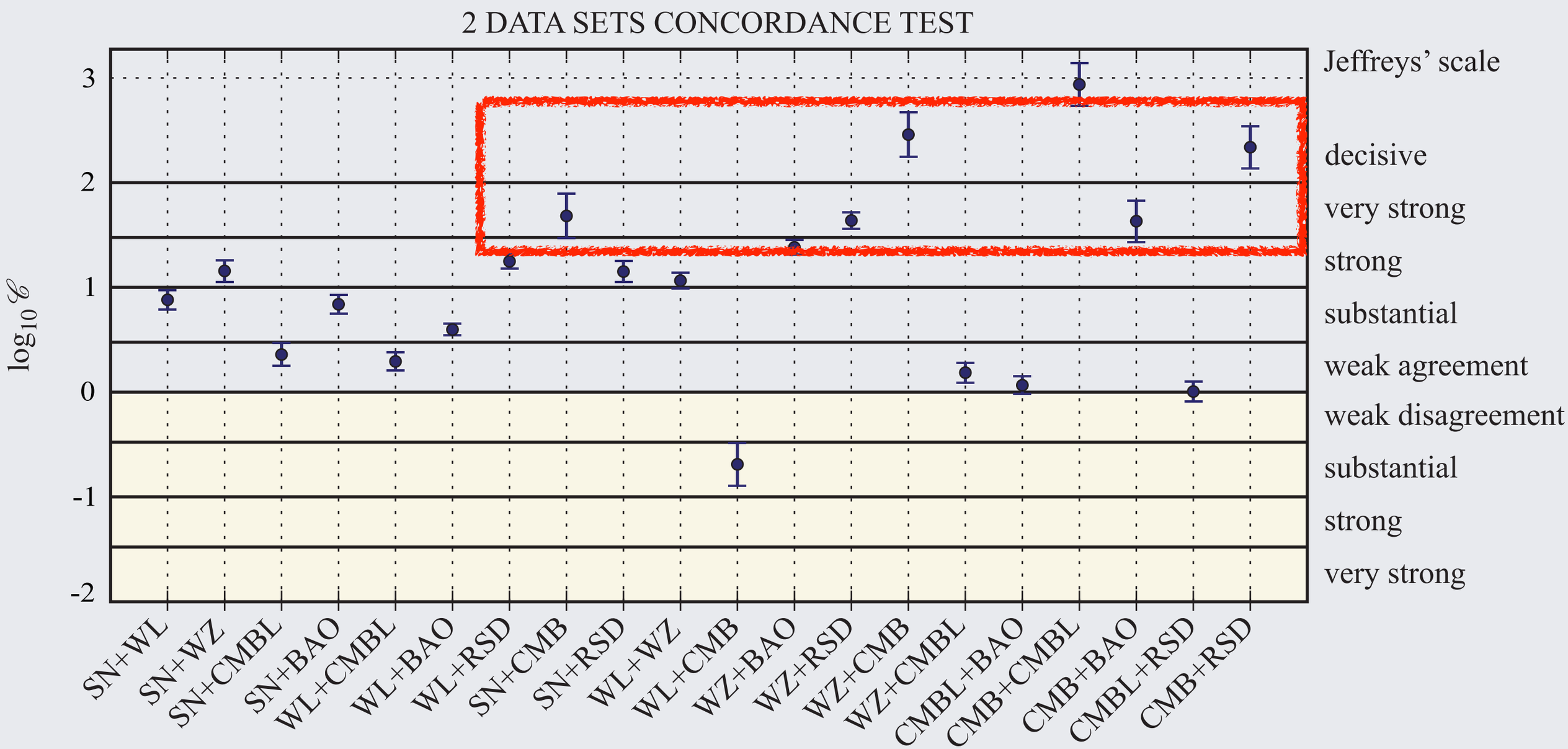
Concordance within LCDM



Planck CMB lensing weakly in agreement with others

(MR, arXiv:1510.00688, submitted to PRL)

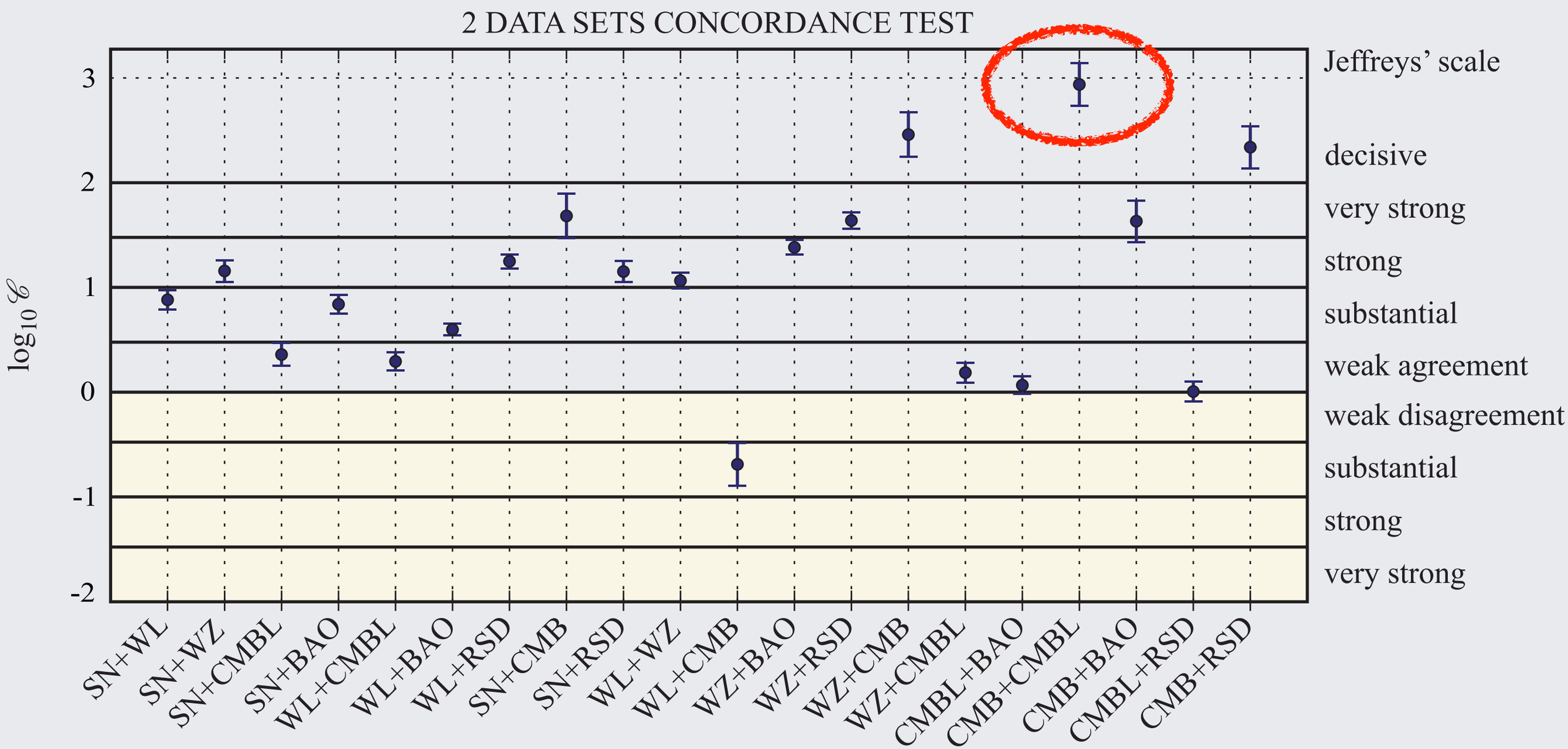
Concordance within LCDM



Planck CMB in strong agreement with others

(MR, arXiv:1510.00688, submitted to PRL)

Concordance within LCDM



Planck CMB and Planck CMB Lensing in very strong agreement

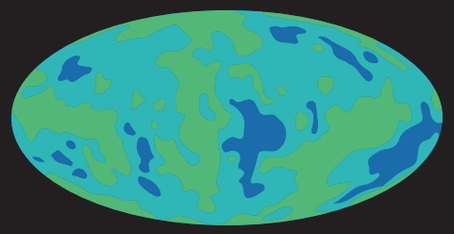
(MR, arXiv:1510.00688, submitted to PRL)

Conclusions and outlook: challenges ahead

- Brief tale of ongoing research to test gravity on cosmological scales;
- New phase in Dark Energy and Modified Gravity studies: data, framework and tools;
- Optimization, maintenance and development of publicly available tools to do this: EFTCAMB;

Conclusions and outlook: challenges ahead

- Development of robust statistical tools to constrain gravitational theories in the space of models;
- Study of the cosmology and observational signatures of different models to constraint them with data;
- Forecast the best way to test all the EFT models and develop appropriate parametrizations;
- Understand what happens on non-linear scales.



KEEP CALM and TEST GRAVITY

the EFTCAMB team