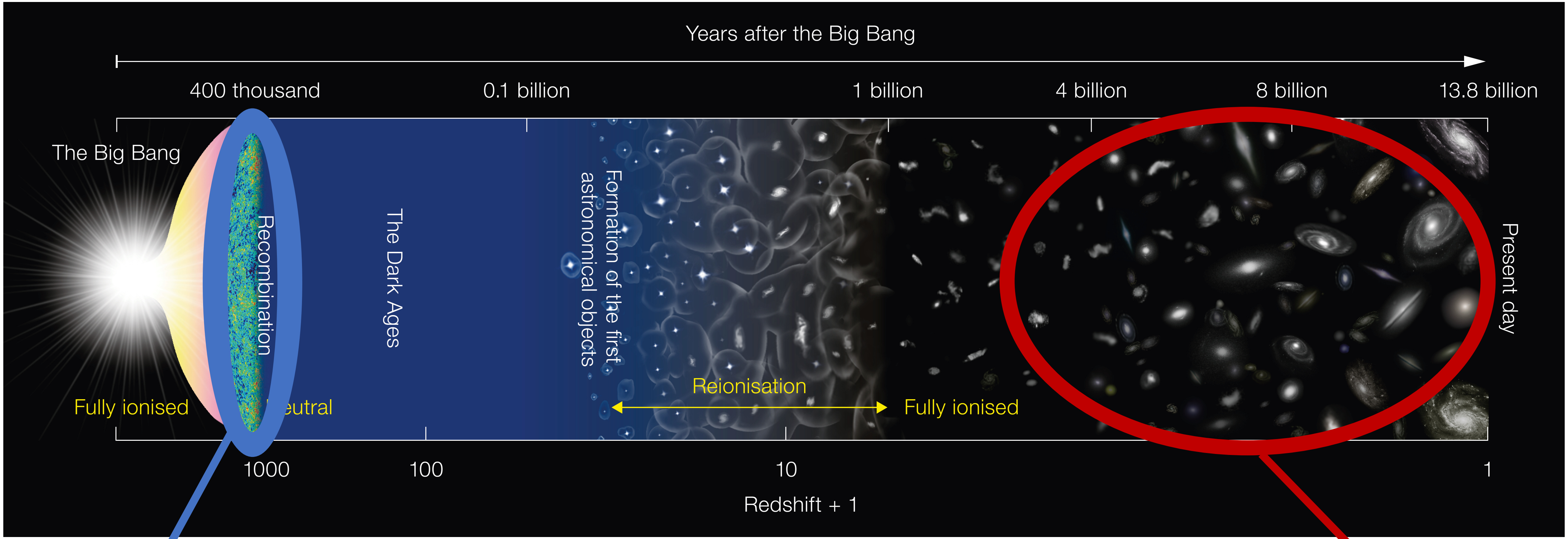
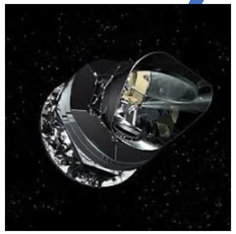
Constraints on modified gravity from galaxy surveys and future challenges

Agnès Ferté

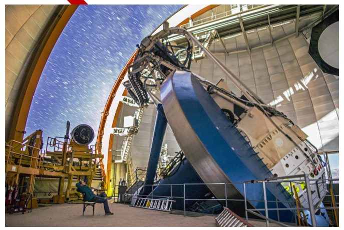
From Cosmic Microwave Background experiments to galaxy surveys



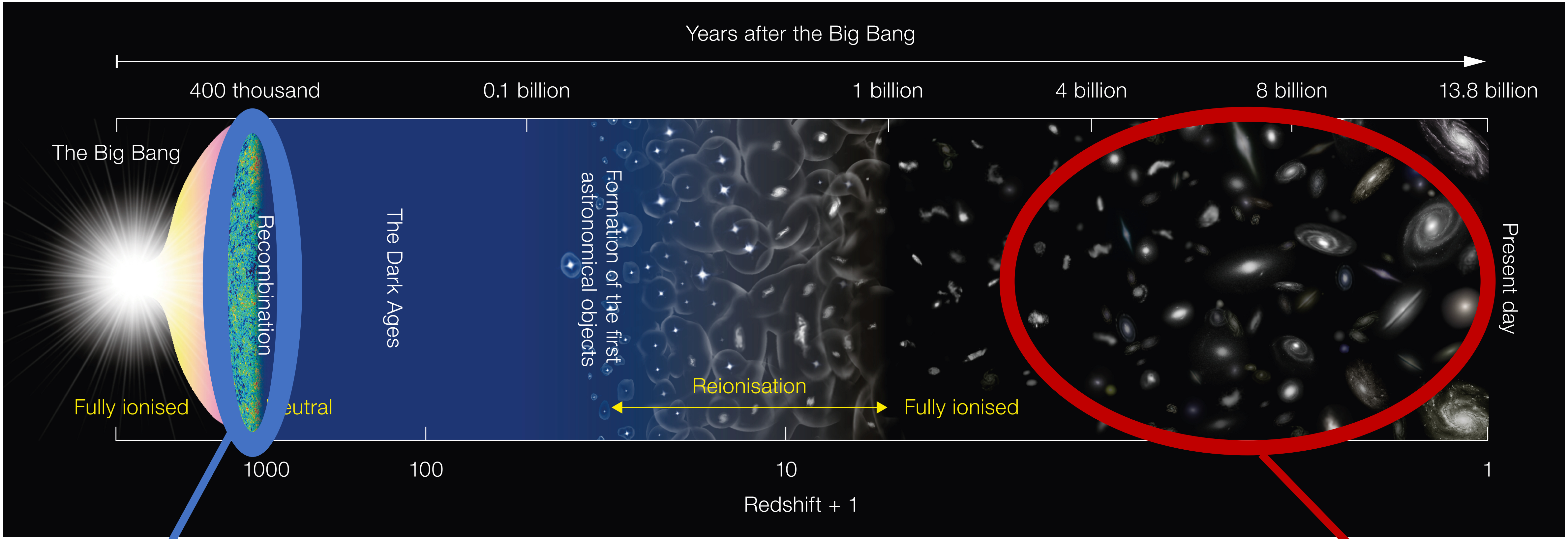


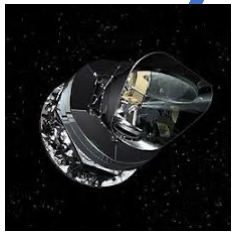
CMB temperature and polarization experiments:
- Primary anisotropies: gravity during inflation
- **Secondary anisotropies**: MG

+ constrain cosmological param v well



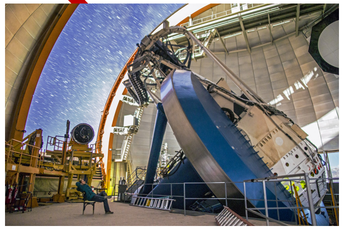
From Cosmic Microwave Background experiments to galaxy surveys





Measurements of growth:
- Tomographic 3x2pt
- RSD = f*$\boldsymbol{\sigma}_8$

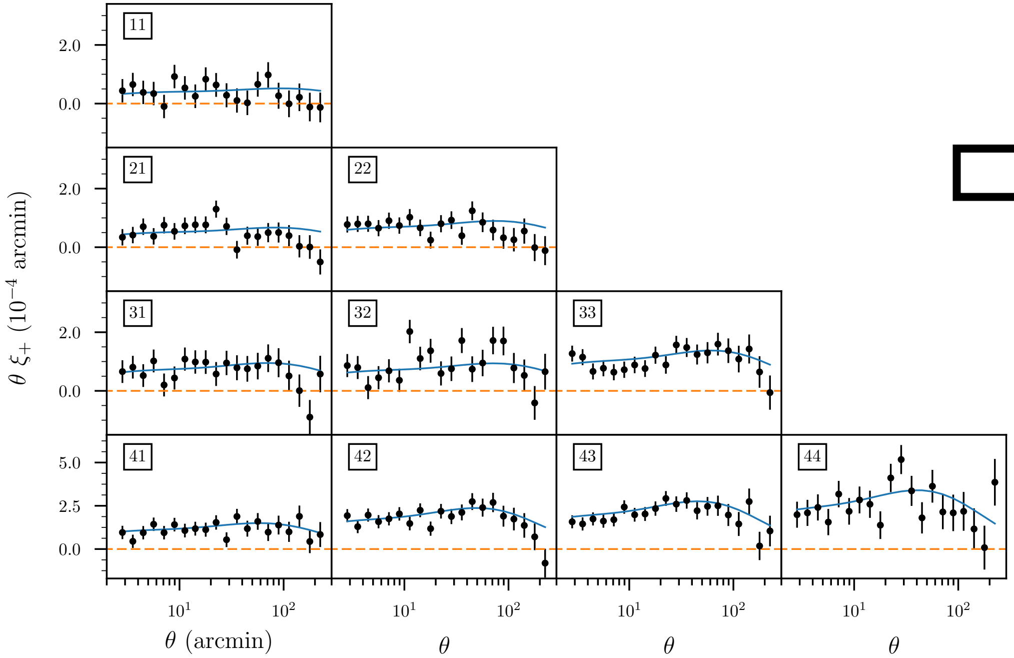
Galaxy surveys:
- **Growth of structures**: MG
- Geometry: dark energy



Typical cosmological inference for MG

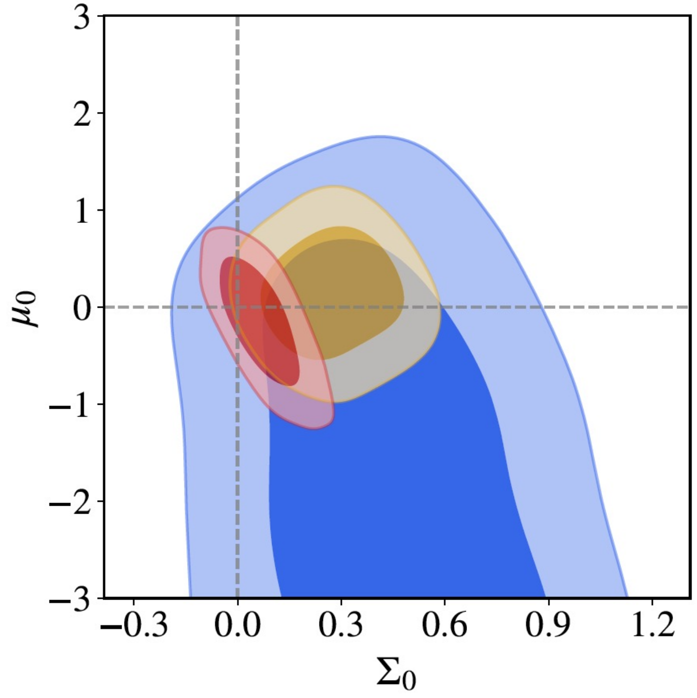
Theoretical prediction: **This is what we modify to constrain other cosmological models like MG**

Measurements



MCMC, nested sampling

- ΛCDM parameters
- **MG parameters**
- Systematics parameters



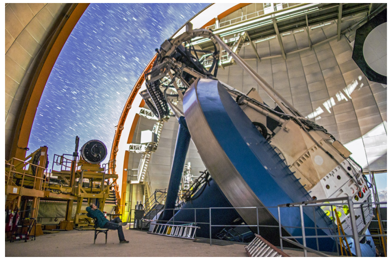
Results from collaborations: effort to avoid confirmation bias, model validation ➔ reliable and robust results

Phenomenological tests of gravity

$$k^2\Phi = -8\pi G a^2(1+\Sigma(a,k))\rho\delta$$

Light

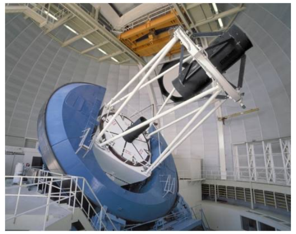
Weak gravitational lensing



$$k^2\Psi = -4\pi G a^2(1+\mu(a,k))\rho\delta$$

Matter

Redshift Space Distortion



+ CMB constraints through lensing and ISW

👍 Directly linked to observables, (almost) agnostic

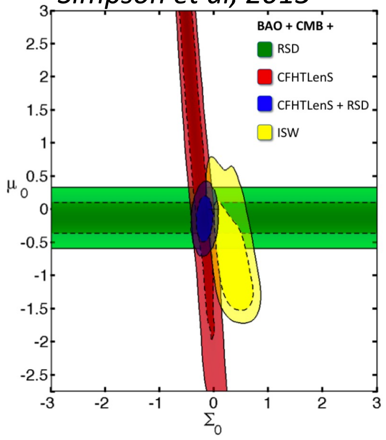
👎 Have to choose a parametrization

+ E_G tests or fit γ in the growth (γ ~ 0.55 in CDM) $f(z) = \Omega_m^\gamma$

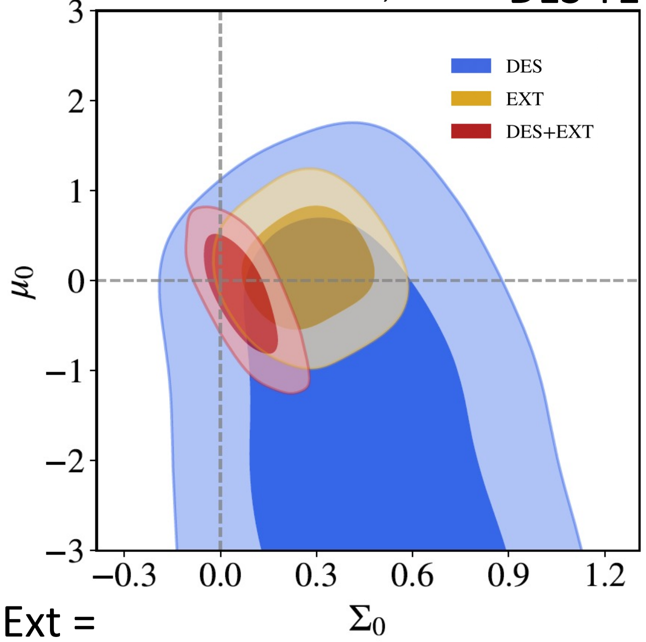
Redshift dependent (∑,μ)

$$\Sigma(a) = \Sigma_0 \frac{\Omega_\Lambda}{\Omega_{\Lambda,0}} \quad \mu(a) = \mu_0 \frac{\Omega_\Lambda}{\Omega_{\Lambda,0}}$$

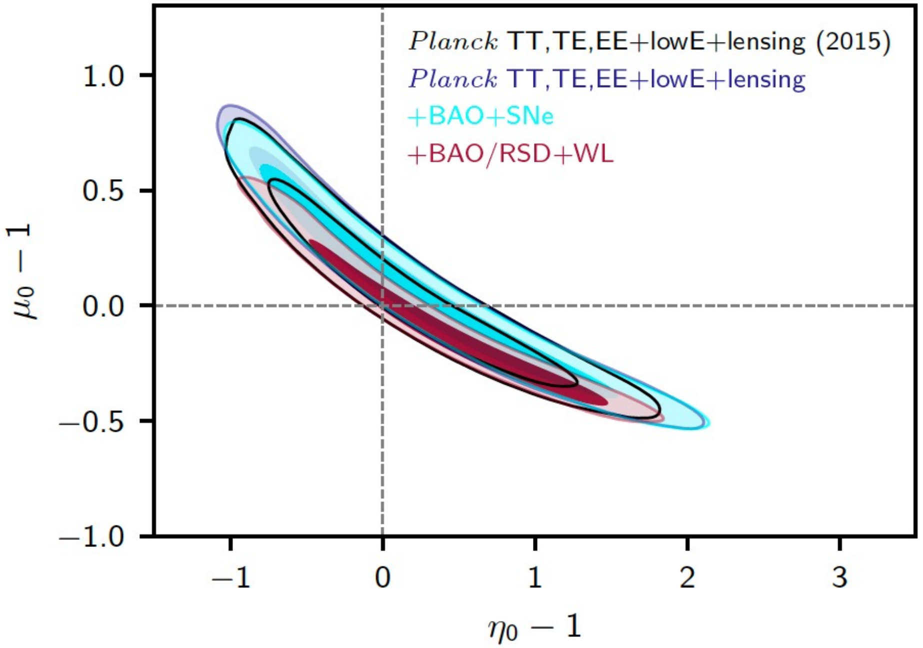
Simpson et al, 2013



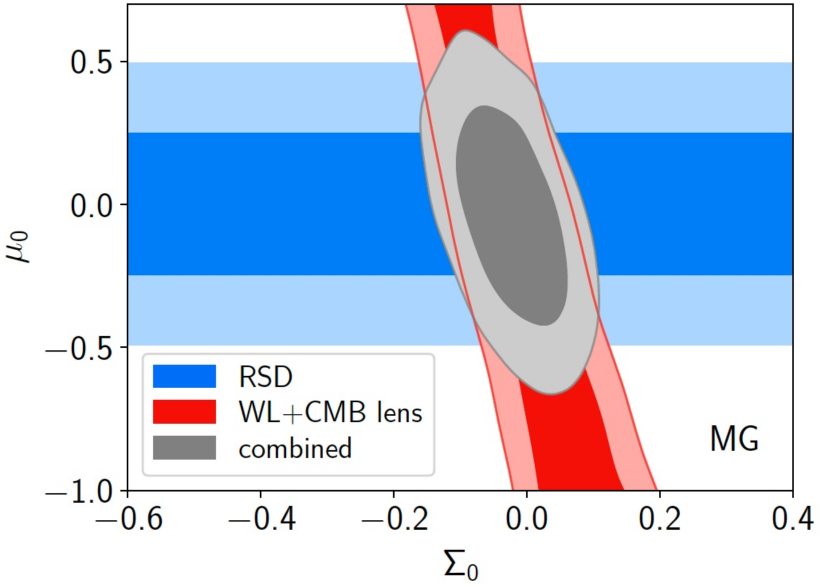
DES Collaboration et al, 2019 DES Y1



Planck Collaboration et al, 2020



eBOSS Collaboration et al, 2021

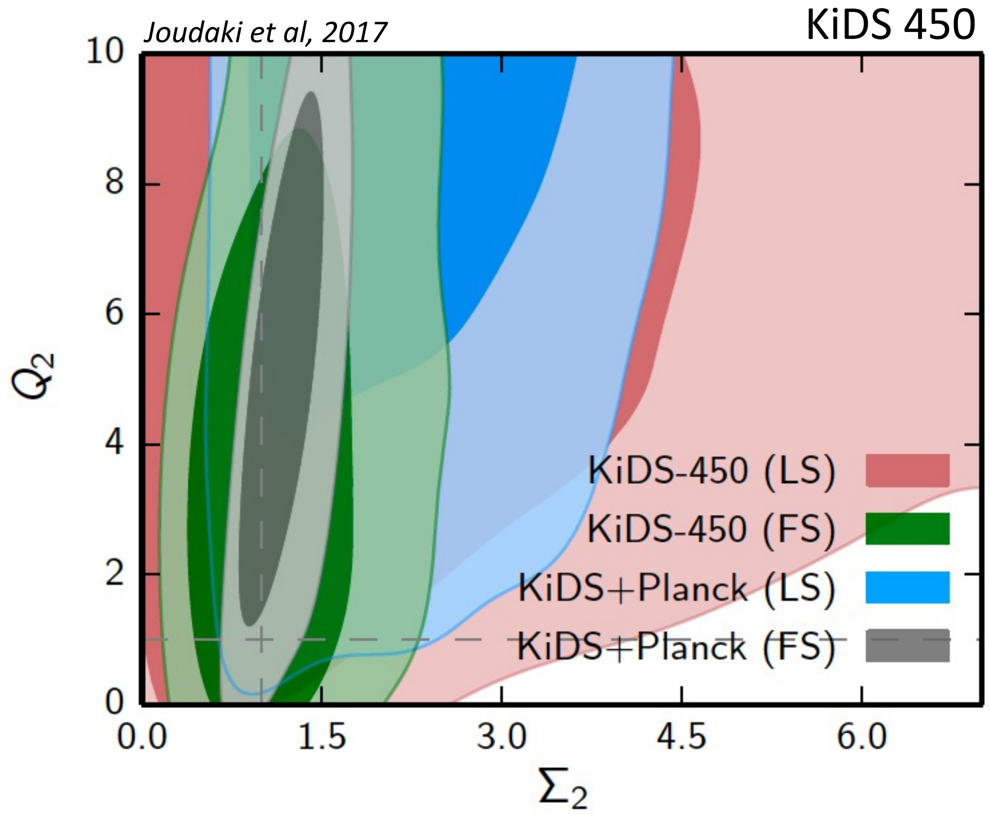


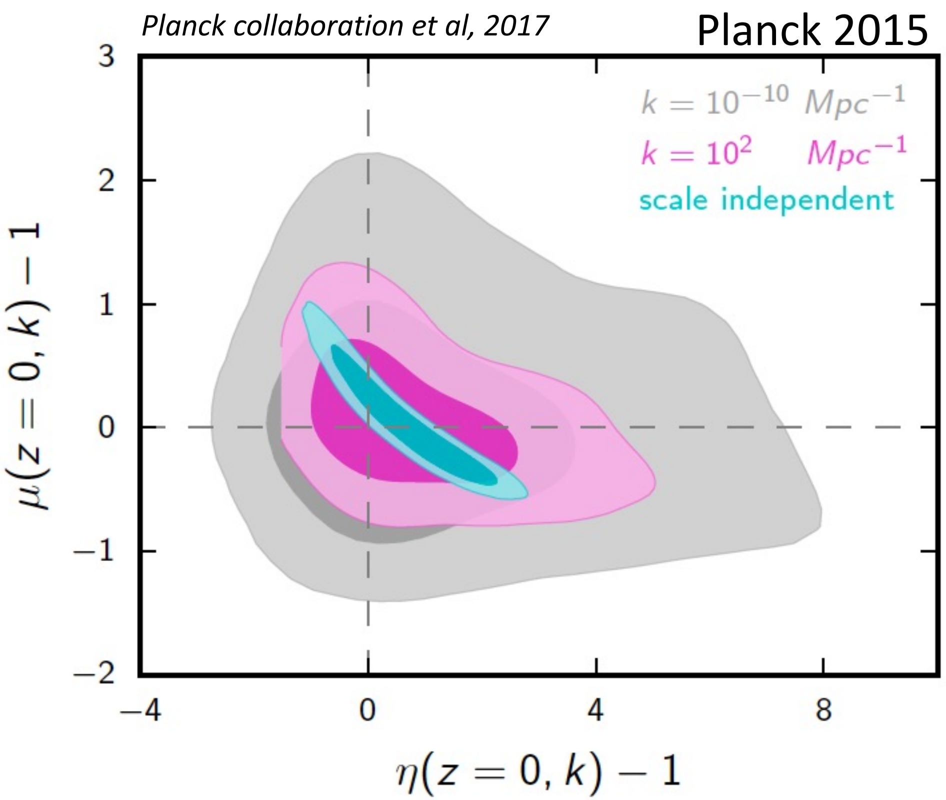
Ext =

- CMB: Planck 2015
- BAO: BOSS DR12, 6fgs, mgs + SN: pantheon
- RSD: boss dr12

+ constraints on parametrization as a^s

Scale dependence and free in bins of (∑,μ)



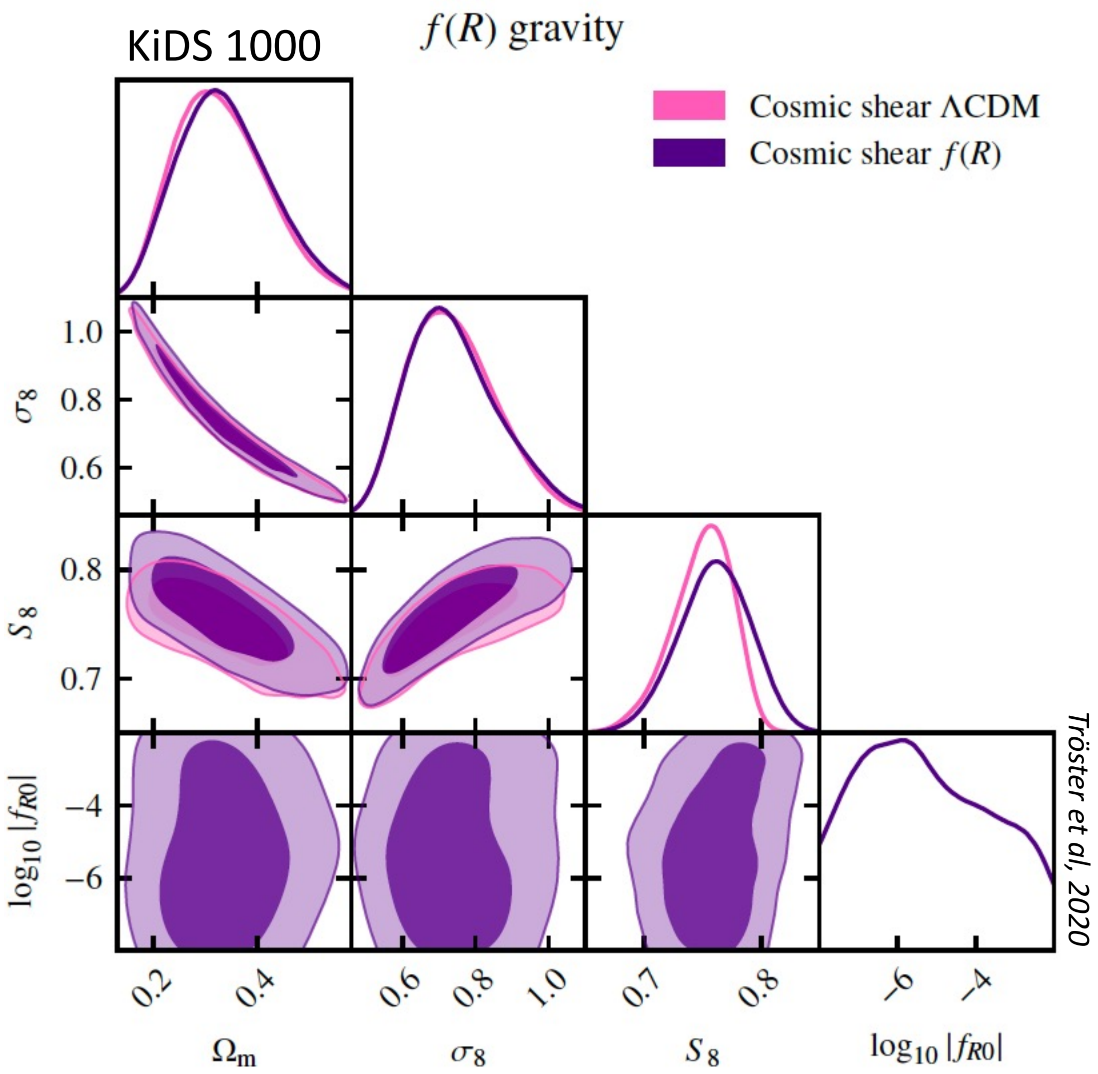


$$\mu(a,k) = 1 + f_1(a)\frac{1 + c_1(\lambda H/k)^2}{1 + (\lambda H/k)^2};$$

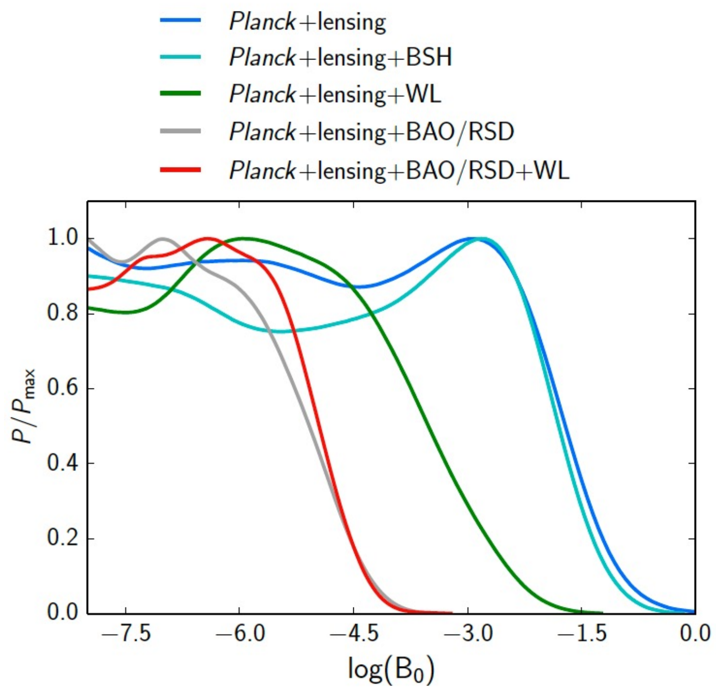
$$\eta(a,k) = 1 + f_2(a)\frac{1 + c_2(\lambda H/k)^2}{1 + (\lambda H/k)^2}.$$

Constraints on modified gravity theories from galaxy surveys

KiDS 1000

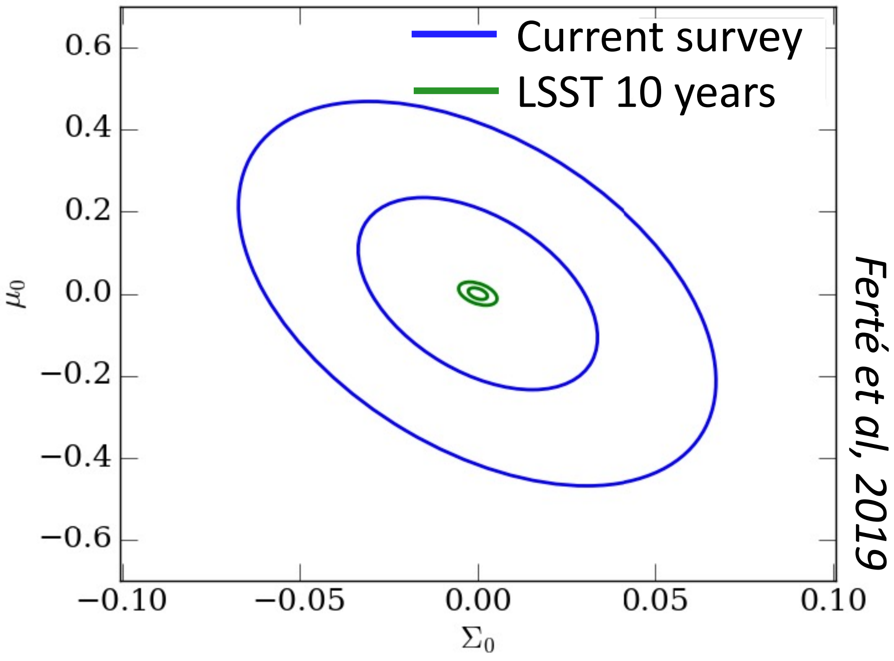


+ from CMB, Planck has explored many theories in *Planck collaboration, 2015*:



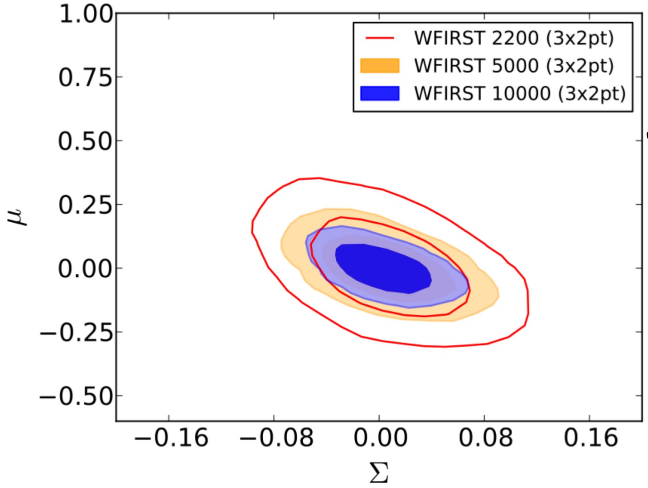
Forecasts for future weak lensing surveys

LSST from Rubin Observatory



Ferté et al, 2019

Roman



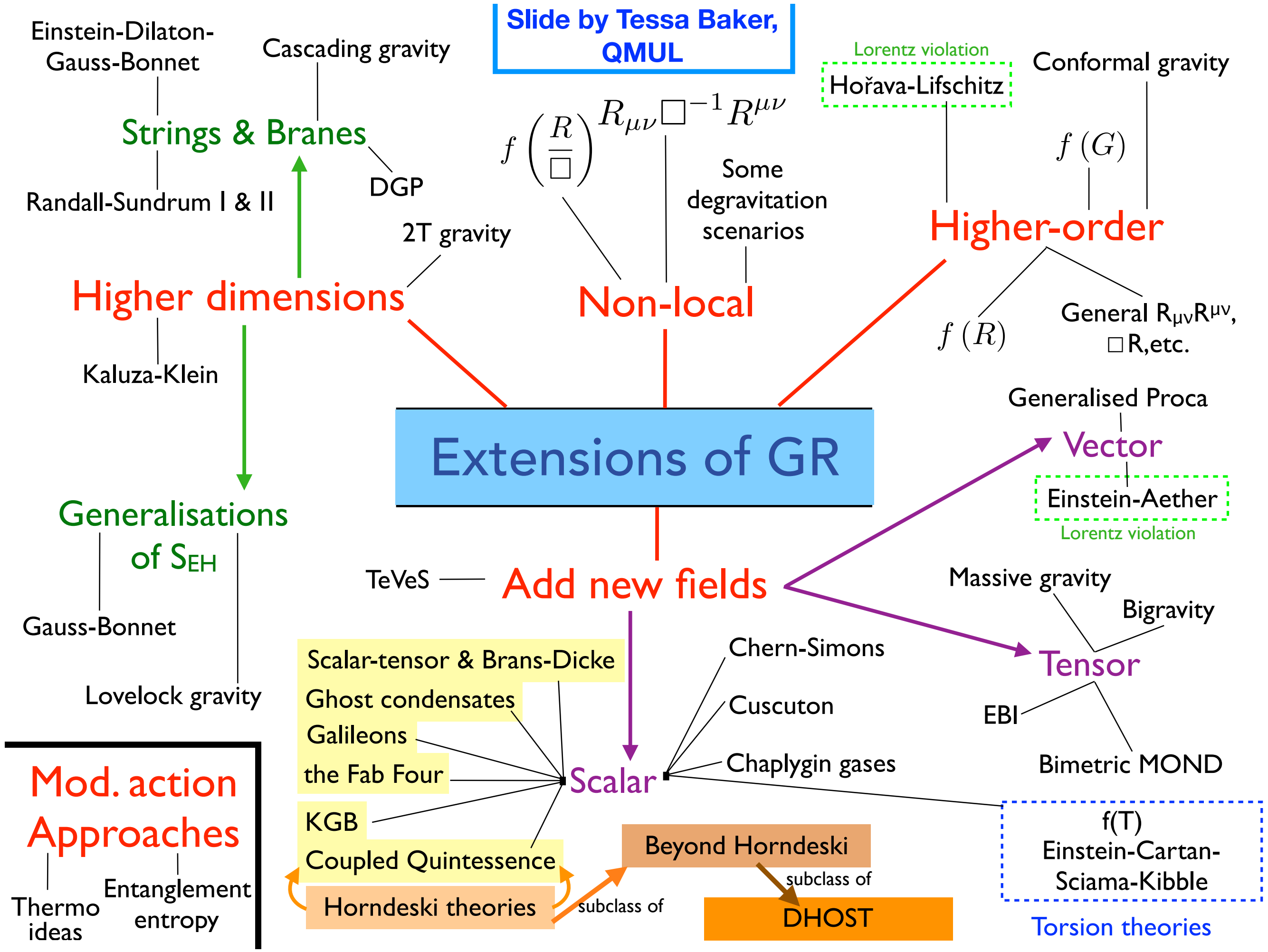
Eifler et al, 2020

Euclid

	w_0, w_a, γ flat							
	$\Omega_{m,0}$	$\Omega_{b,0}$	w_0	w_a	h	n_s	σ_8	γ
Linear setting								
GC_s	0.10	0.13	0.28	0.83	0.0073	0.036	0.028	0.17
Pessimistic setting								
GC_s	0.18	0.27	0.39	1.5	0.026	0.068	0.050	0.33
WL	0.042	0.47	0.25	1.5	0.21	0.036	0.024	0.37
GC_s+WL	0.030	0.062	0.096	0.33	0.0066	0.0092	0.013	0.070
Optimistic setting								
GC_s	0.067	0.094	0.20	0.55	0.0037	0.020	0.021	0.25
WL	0.034	0.43	0.17	0.96	0.20	0.033	0.013	0.18
GC_s+WL	0.023	0.039	0.077	0.25	0.0028	0.0054	0.0095	0.052

Euclid collaboration et al, 2020

Challenge I – a large theory space

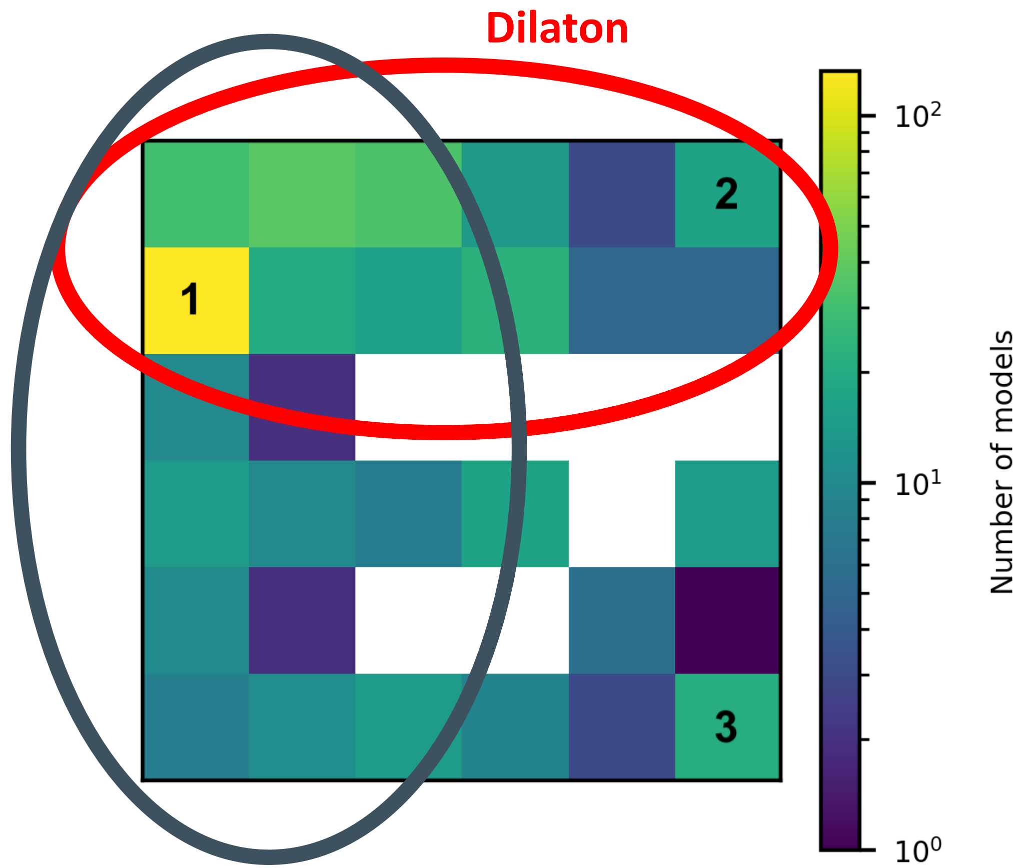


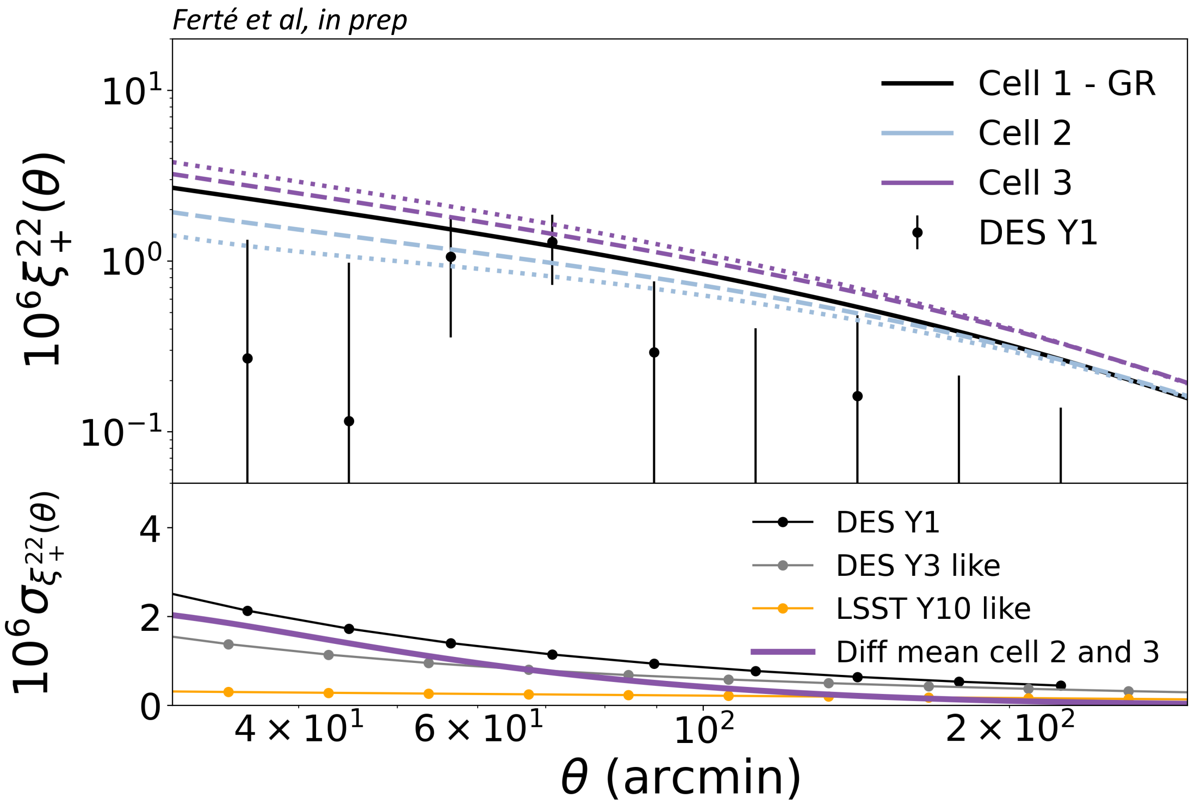
Testing one theory requires:

- Simulations,
- Bayesian analysis: MCMC in modified gravity are computationally expensive

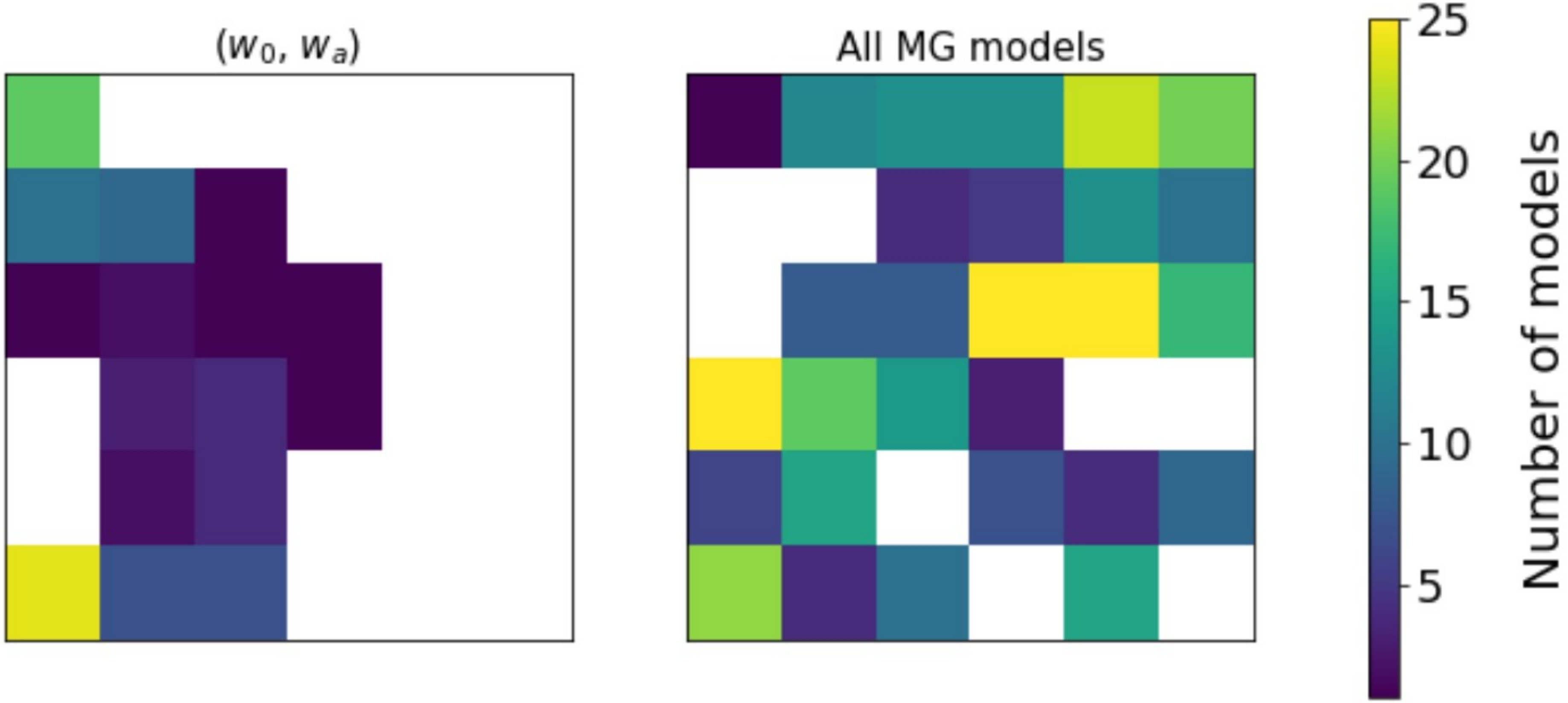
Possible solution: dimensionality reduction algorithms

Application of Self-Organizing Maps to modified gravity theories probes by cosmic shear:





Example of application: MG has to be constrained in addition to (w_0, w_a)

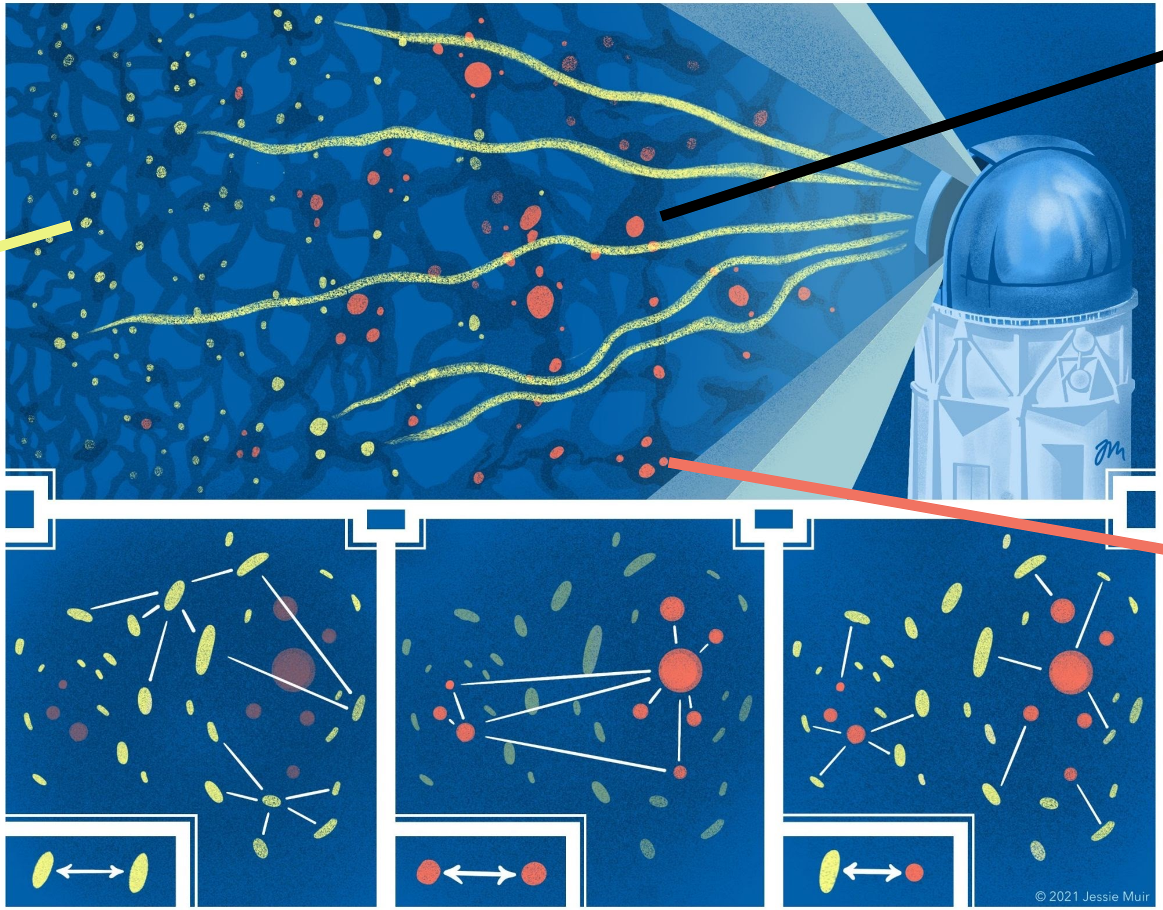


Ferté et al, in prep

Challenge II – Modeling

For DES Y3 weak lensing and clustering cosmological analysis:

Credits: Jessie Muir



Intrinsic alignment

TATT model: tidal alignment, torque and z-dependence
⇒ 5 parameters

Matter power spectrum

Halofit

Galaxy bias

Linear galaxy bias model
⇒ 4 parameters

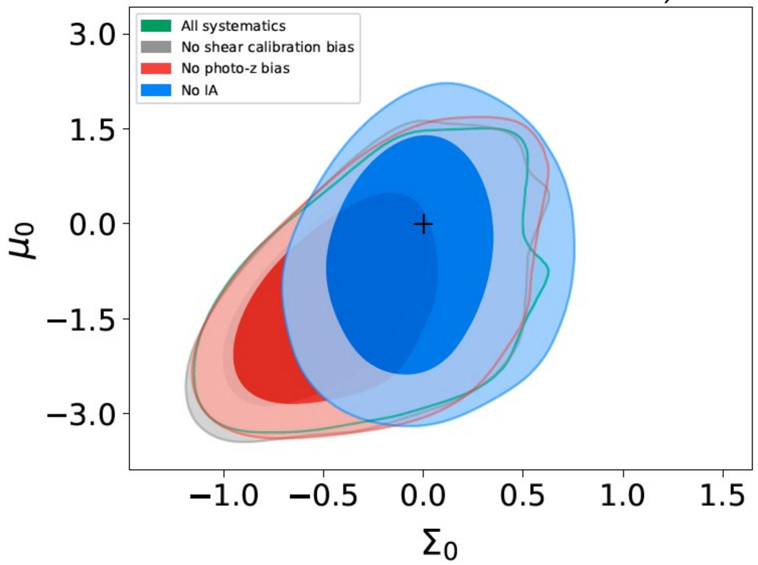
+ RSD and non-limber computation for clustering
+ mitigating effect of non-locality of gg lensing

Challenge II – Modeling ‘theoretical’ systematics

Important systematics for MG but model of IA generally assumes GR

➔ **Need IA model in MG**

Ferté et al, 2019



Intrinsic alignment

TATT model: tidal alignment, torque and z-dependence
⇒ 5 parameters

Galaxy bias

Linear galaxy bias model
⇒ 4 parameters

A lot of assumptions of ΛCDM, difficulty for MG theories (or neutrinos) with scale dependent growth

+ RSD and non-limber computation for clustering
+ mitigating effect of non-locality of gg lensing

➔ Need adapted modeling of 3x2pt and useable codes

Challenge II – Modeling on small scales

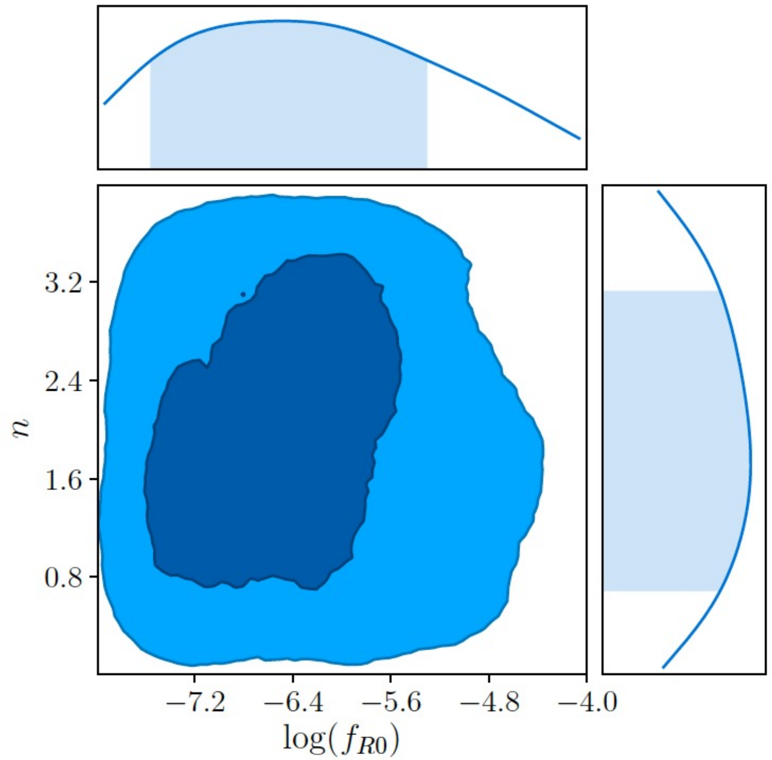
A lot of Information on modified gravity is on smaller scales:
How can we model the matter power spectrum on non linear scales and baryons contamination?

- In DES Y1, keeping 334 data points of the 457 data points used in ΛCDM to remove sensitivity to non linear scales.

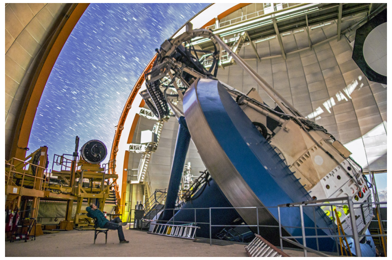
Approaches:
- Emulator:
  - A lot of f(R) gravity emulators developed, halo model based or trained on simulations but limits on the cosmology space
- Estimator/Space:
  - COSEBIs (e.g. Asgari et al, 2021)
  - Harmonic space: more direct link between ***l*** and k, rather than **θ** and k
  - BNT transform: transform lensing kernels to have direct relation between ***l*** and k (e.g. Taylor et al, 2020)
  - Others (calibrations with other observations),…

Matter power spectrum
Halofit

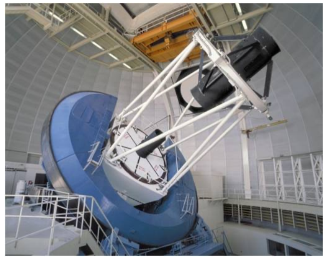
Vazsonyi *et al, 2019*



Challenge IV – multiprobe analysis



Weak gravitational lensing



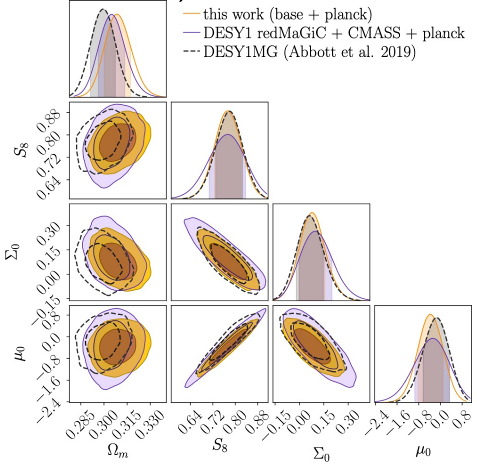
Redshift Space Distortion

Spectro+Photometric surveys: to constrain MG, need to sample the likelihood directly on the combination of their observables (rather than using derived parameters)

Other possible approach:

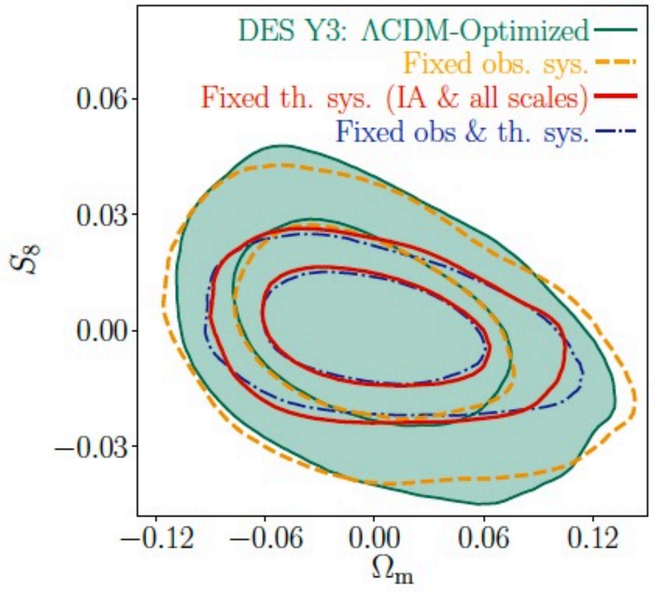
Create sample from photometric survey with same proprieties than sample from spectrometry.
See DMASS for CMASS-like DES galaxies (Lee et al, 2019)

Lee *et al*, 2021



Testing gravity with future surveys requires solving key challenges

Amon et al, 2021



<u>Future:</u>

- Tendency towards constraints on **phenomenological tests** of gravity
  (DES Y3 modified gravity *Ferté et al, in prep* will constrain various specific MG theories)
- Solutions proposed to solve some challenges but more **modeling developments needed**
- Promising results on tests of gravity on cosmological scales in the **2020s**