Next-generation forecasts for screened and unscreened models of modified gravity

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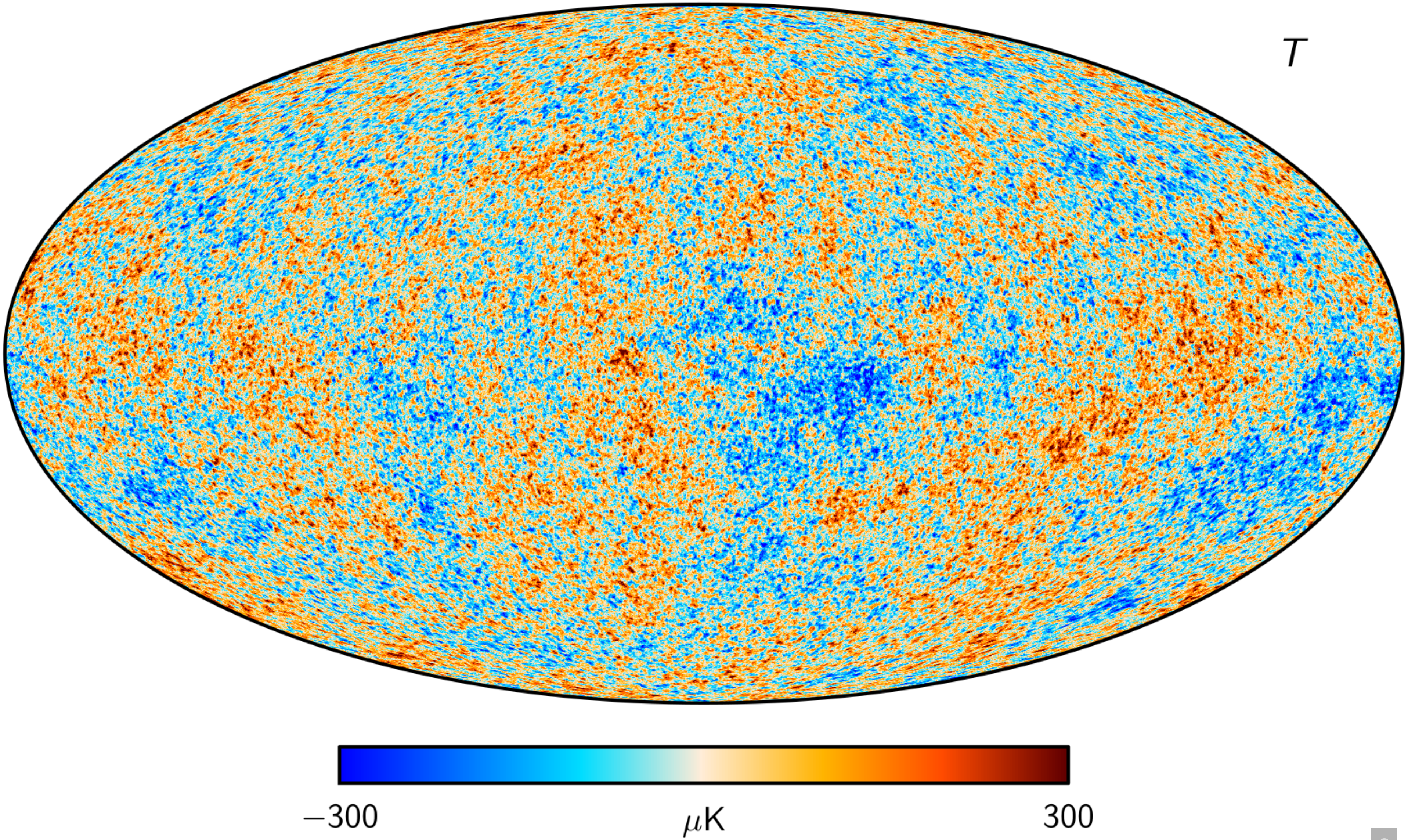
With collaboration from Euclid TWG WPs 1-6-7 and more...

Cosmic Microwave Background



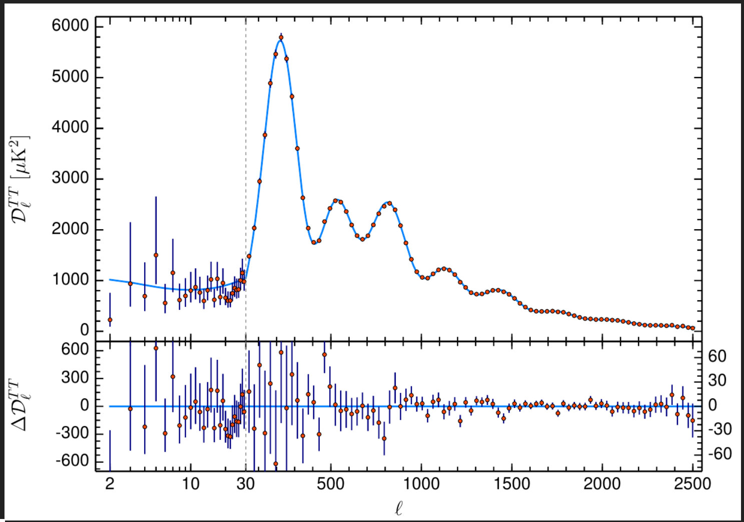
Planck 2018 CMB Temperature map (Commander) . wiki.cosmos.esa.int/planck-legacy-archive/index.php/CMB_maps

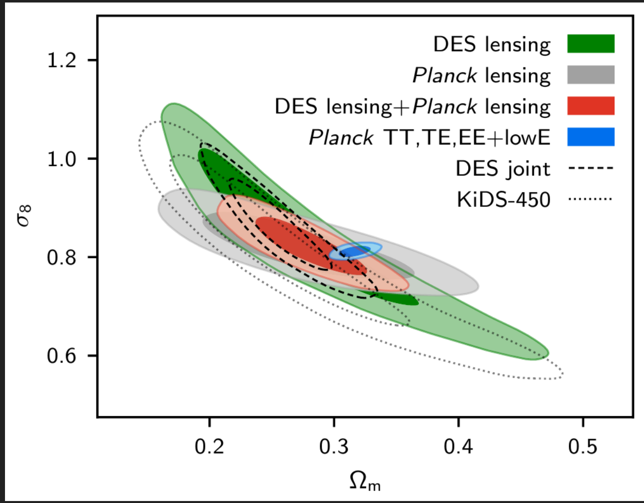
Large Scale Structure

Illustris Simulation: www.nature.com/articles/nature13316

The Standard ΛCDM model

- LCDM is still best fit to observations.
- Concordance Cosmology:
- Combination of different observables.





- Lensing
- CMB
- Clustering
- Supernovae
- Clusters

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

The Standard ΛCDM model

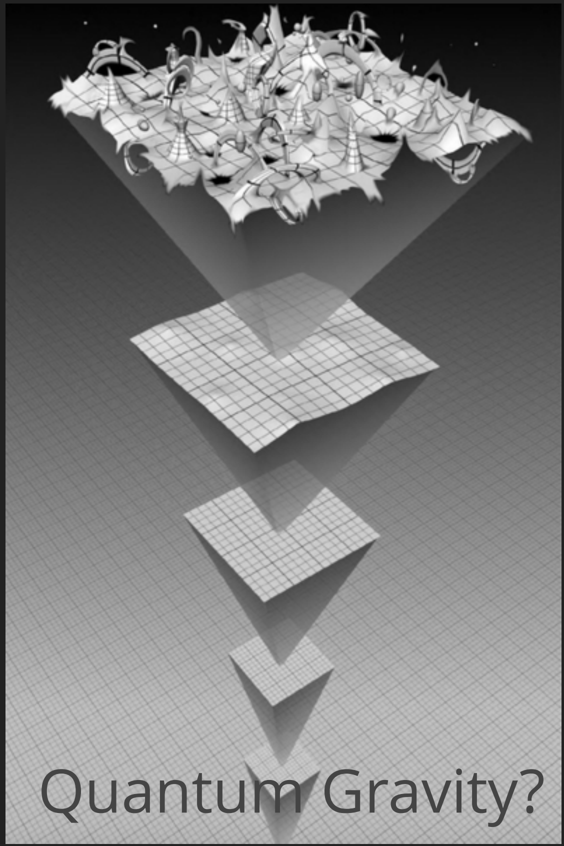
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- LCDM is still best fit to observations.
- Some questions remain:
- Λ and CDM.
- Cosmological Constant Problem:

O(100) orders of magnitude wrong

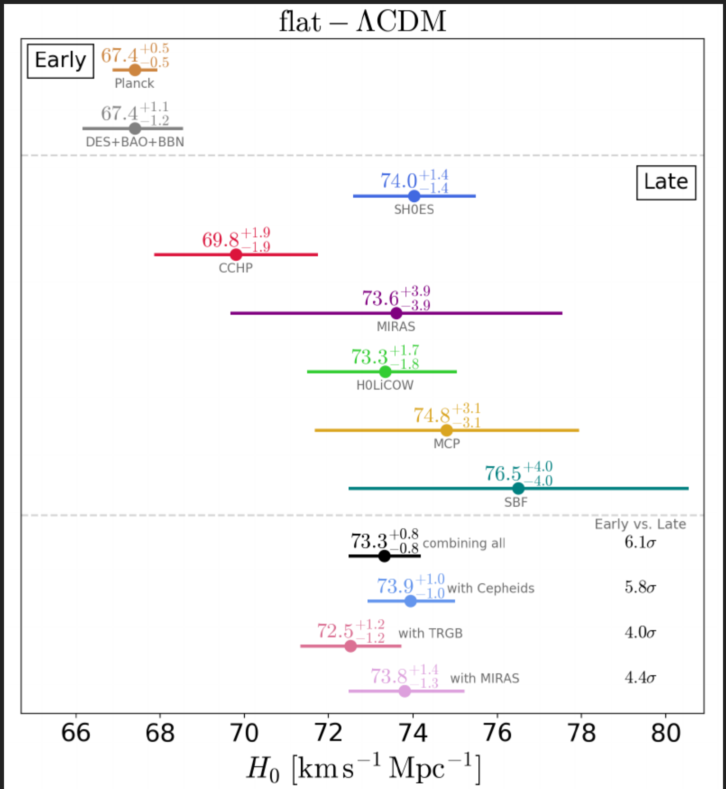
(Zeldovich 1967, Weinberg 1989, Martin 2012).

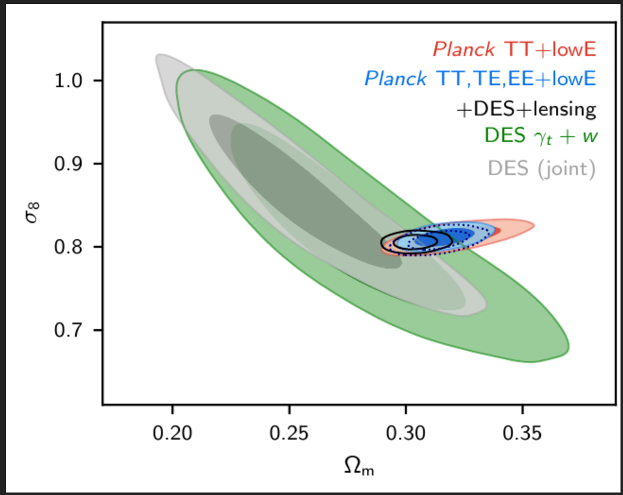
Composed of naturalness and coincidence sub-problems, among others.



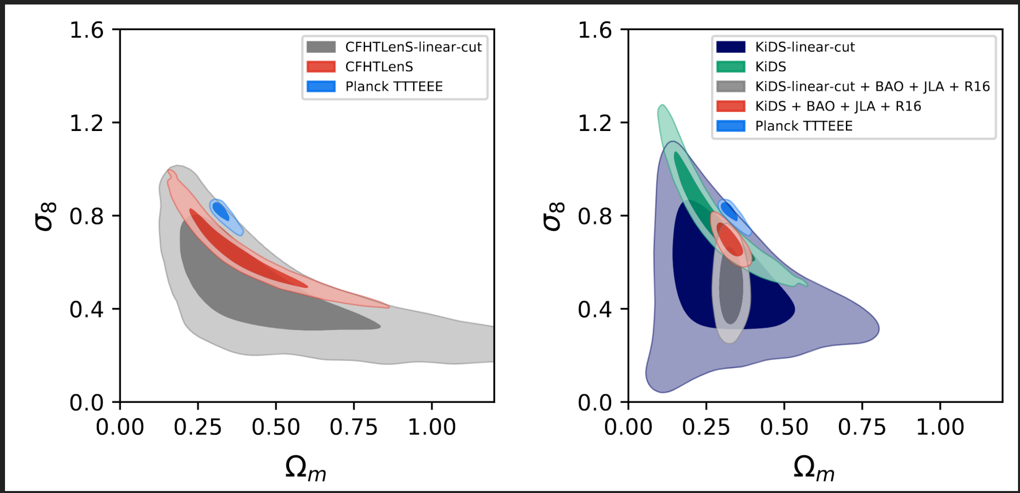
The Standard ΛCDM model

- ΛCDM is still best fit to observations.
- Some questions remain:
- H0 tension, now ~5σ

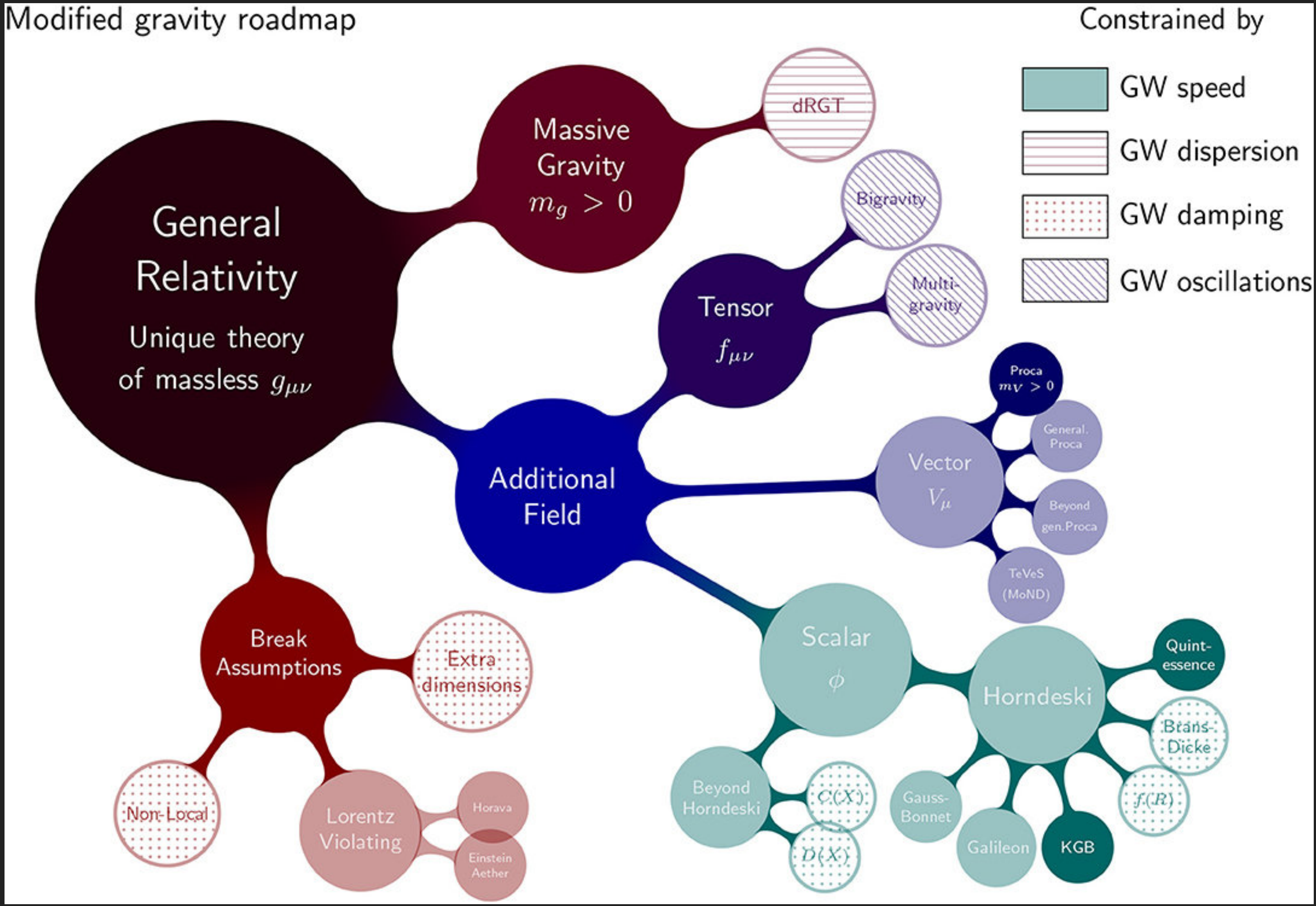




- σ_8 - Ω_m discrepancy at ~2σ



Alternatives to ΛCDM



Ezquiaga, Zumalacárregui, Front. Astron. Space Sci., 2018

Constraints on Theories

- Background is well constrained to be around $w = -1$
- Gravitational Wave speed = c
- Galaxy morphology and solar system
- Black holes
- Coupling to baryons
- Non-linear regime still pretty much unconstrained
- Fifth forces
- Neutrinos?

Scalar field models

At lowest order in the perturbation of the scalar field $\varphi \equiv \phi - \phi_0$

$$\mathcal{L}_2 = \frac{Z(\phi_0)}{2}(\partial_\mu \varphi)^2 + \frac{m_\phi^2(\phi_0)}{2}\varphi^2 - \delta g_{\mu\nu}\delta T^{\mu\nu}$$

- Matter is coupled to the perturbed Jordan metric
- In the case of a cosmological-stress energy tensor and a non-negligible scalar field mass :

$$G_{\text{eff}} = \left(1 + \frac{2\beta^2(\phi_0)}{Z(\phi_0)} e^{-m(\phi_0)r}\right) G_N$$

Yukawa term: Short range forces

Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

Screened Scalar fields

$$G_{\text{eff}} = \left(1 + \frac{2\beta^2(\phi_0)}{Z(\phi_0)} e^{-m(\phi_0)r}\right) G_N$$

Different types of screening:

- Chameleon: The mass $m(\phi_0)$ increases sharply inside matter
- Damour-Polyakov: The coupling $\beta(\phi_0)$ vanishes inside matter
- K-mouflage and Vainshtein: $Z(\phi_0) \gg 1$

Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

Screened models

As an effective field theory, the normalization factor can be expanded in a power series:

$$Z(\phi_0) = 1 + a(\phi_0) r_c^2 \frac{\Box\varphi}{m_{\rm Pl}} + b(\phi_0)\frac{(\partial\varphi)^2}{\Lambda^4} + c(\phi)\frac{\Box^2\varphi}{\Lambda^5} + \ldots$$

K-mouflage: first derivative term $\partial\varphi/\Lambda^2$ dominates, which implies:

$$|\vec{\nabla}\Phi_N| \geq \frac{\Lambda^2}{2\beta(\phi_0) m_{\rm Pl}} \longrightarrow$$

Screening where Newtonian acceleration $a = -\vec{\nabla}\Phi_N$ large enough

Vainshtein: second derivative term $\Box\varphi$ dominates, which implies:

$$\nabla^2\Phi_N \geq \frac{1}{2\beta(\phi_0) r_c^2} \longrightarrow$$

Screening where spatial curvature is large

When the $\Box^2\varphi$ dominates → massive gravity

Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

Screened models

To summarize, screening mechanisms can be characterized by the inequality:

$$\nabla^k \Phi_N \gtrsim C$$

- Chameleon: $k = 0$ (surface N. potential is large)
- K-mouflage: $k = 1$ (N. acceleration is large)
- Vainshtein: $k = 2$ (curvature is large)

For DE applications and under some assumptions:

- Chameleon screens everything above a certain potential threshold
- K-mouflage does not screen galaxy clusters
- Vainshtein screens all structures that turn non-linear

Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

Examples of screened models

- Chameleon: $f(R)$ Hu-Sawicki
- K-mouflage: k-essence + universal coupling
- Vainshtein: nDGP (3+1)d brane embedded in 5d

- Solar system and other local constraints and instabilities forbid self-acceleration in these models
- ΛCDM-like background
- Just one free parameter each
- Universal couplings

Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

f(R) Hu-Sawicki model

Modification of the Einstein-Hilbert action

$$S = \frac{c^4}{16\pi G} \int \mathrm{d}^4x \sqrt{-g}\,[R + f(R)]$$

Induces changes in the gravitational potentials *

$$-k^2\Psi = \frac{4\pi\, G}{c^4}\, a^2 \mu \bar{\rho} \Delta$$

Scale-dependent growth of matter perturbations

$$\mu(a,k) = \frac{1}{1+f_R(a)} \frac{1+4k^2a^{-2}m_{f_R}^{-2}(a)}{1+3k^2a^{-2}m_{f_R}^{-2}(a)}$$

Free parameter: f_{R0}

$$f(R) = -6\Omega_{\mathrm{DE}} H_0^2 + |f_{R0}| \frac{\bar{R}_0^2}{R}$$

Hu, Sawicki (2007)

$$-k^2\,(\Phi + \Psi) = \frac{8\pi\, G}{c^4}\, a^2 \Sigma \bar{\rho} \Delta$$

Small changes in lensing potential

$$\Sigma(a) = \frac{1}{1+f_R(a)}$$

"Fifth-force" scale for cosmological densities

$$\lambda_C = 32\mathrm{Mpc}\sqrt{|\mathrm{f_{R0}}|/10^{-4}}$$

*for negligible matter anisotropic stress

Euclid: Casas et al (2022) in preparation

f(R) as a scalar field theory

Universal coupling through a conformal transformation between Einstein and Jordan metrics

$$\tilde{g}_{\mu\nu} = A^2(\phi, X) g_{\mu\nu} + B^2(\phi, X) \partial_\mu \phi \partial_\mu \phi$$

General Chameleon scalar models are given by specifying V and A

$$V_{\rm eff}(\phi) = V(\phi) + (A(\phi) - 1)\rho$$

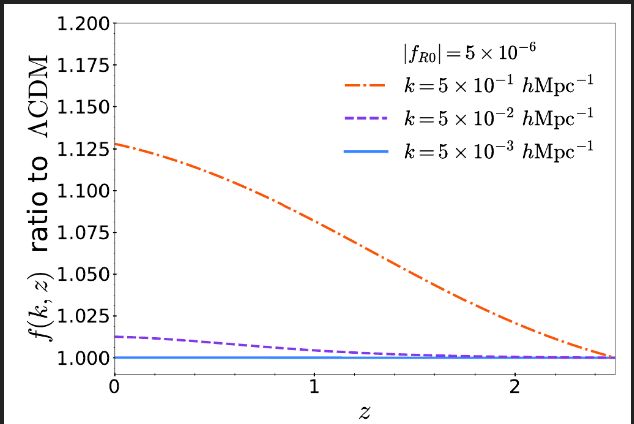
- With a coupling function: $A(\phi) = e^{\beta\phi/m_{\rm Pl}}$
- Map to a scalar field by: $\frac{df}{dR} = e^{-2\beta\phi/m_{\rm Pl}}$
- Carefully chosen potential can realize chameleon mechanism: $V(\phi) = \frac{m_{\rm Pl}^2}{2} \frac{R\frac{df}{dR} - R}{(\frac{df}{dR})^2}$

- Objects screened when: $\Phi_N \gtrsim \frac{3}{2} |f_{R_0}|$

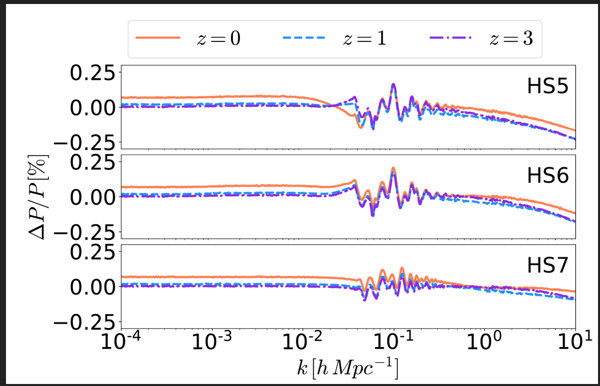
Review: Brax, Casas, Desmond, Elder, arXiv:2201.10817

f(R) Hu-Sawicki predicitons

Scale-dependent growth



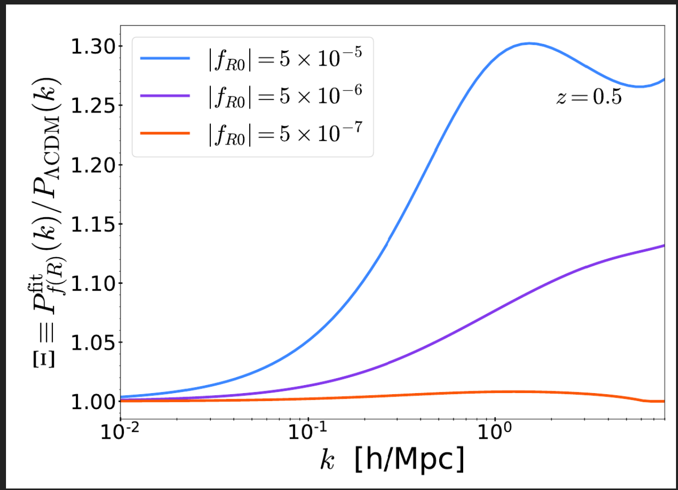
Codes used: for linear perturbations: MGCAMB and EFTCAMB



Fitting formula for non-linear power spectrum:

Winther, Casas, Baldi, Koyama, Li (2019)

*Forge Emulator not available at time of first review



Euclid: Casas et al (2022) in preparation

Scale-independent models

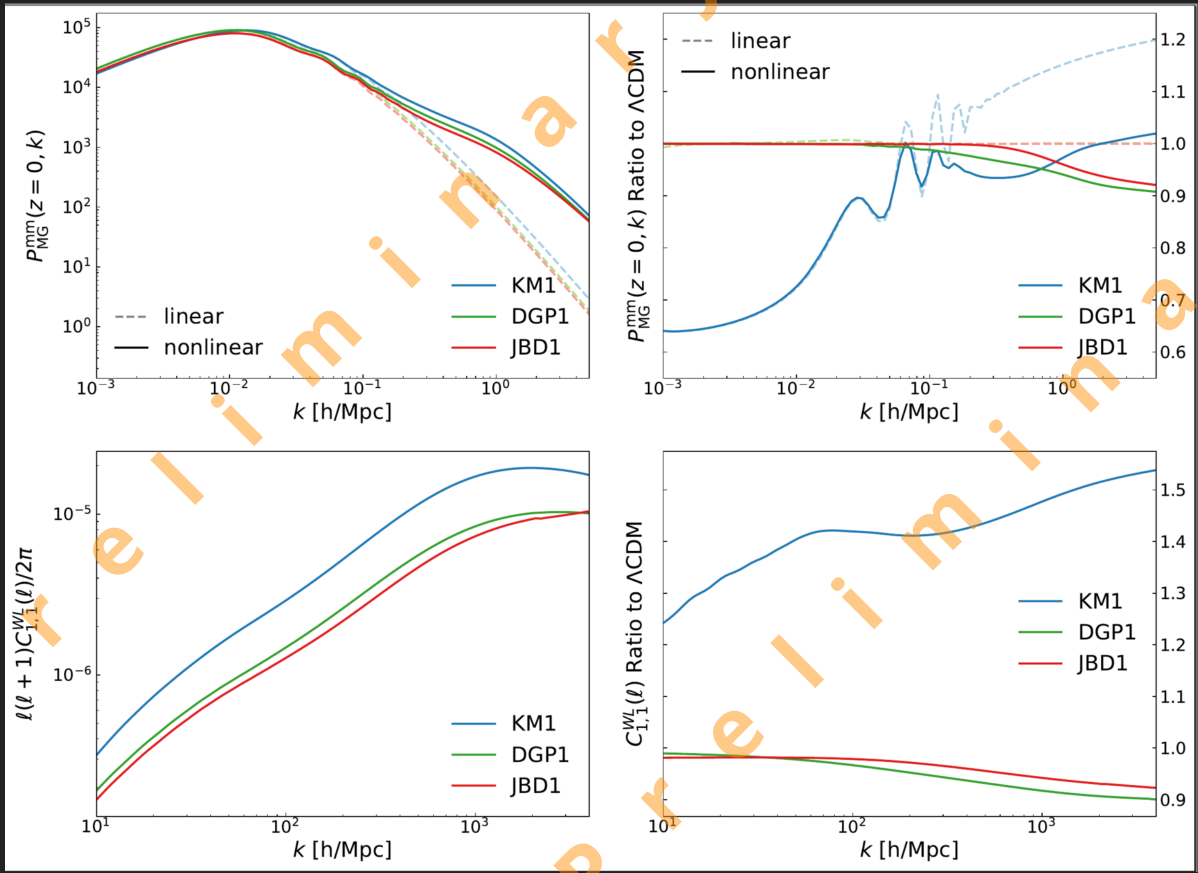
nDGP, K-mouflage and Jordan-Brans-Dicke have scale-independent growth

"Extreme cases" far away from LCDM and close to current upper bounds

nDGP: free parameter Ω_{rc} (related to the transition scale)
ReACT

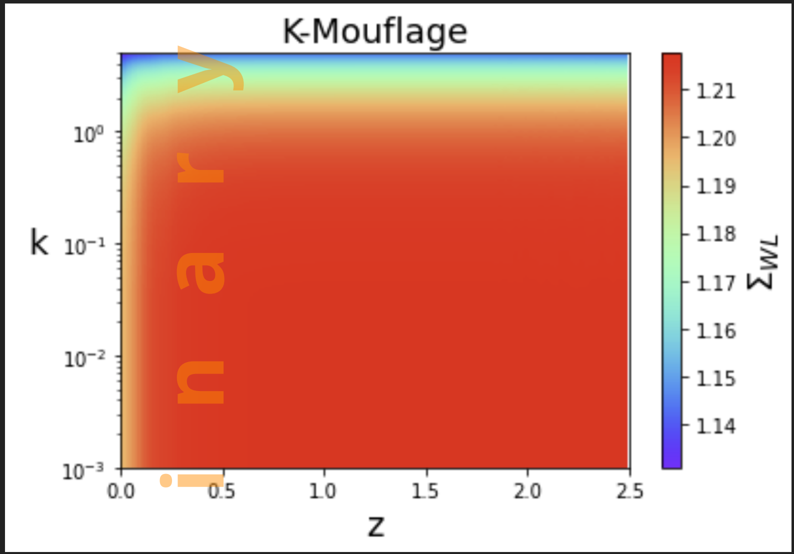
KM: free parameter ϵ_2 (related to the conformal coupling amplitude)
Halo+PT

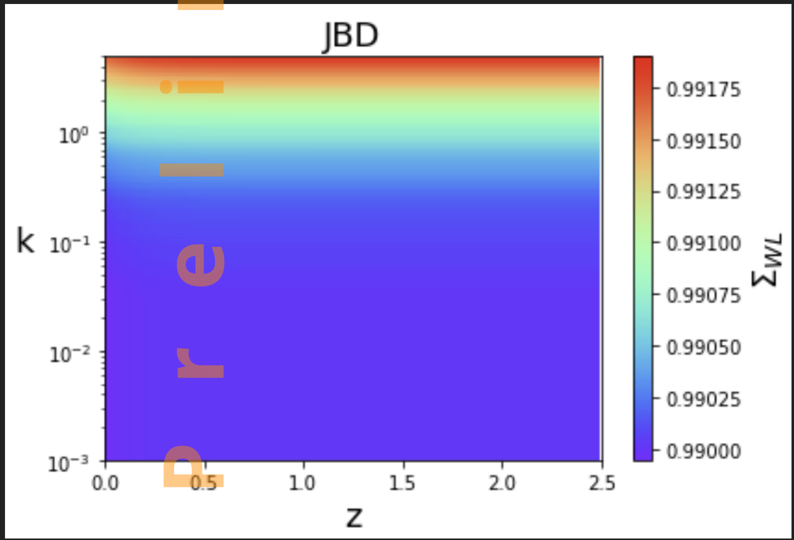
JBD: free parameter ω_{BD} (related to the scalar coupling)
HMCode



Scale-independent models

- K-Mouflage presents a large enhancement of the lensing potential
- Definitely detectable with next-generation WL observations





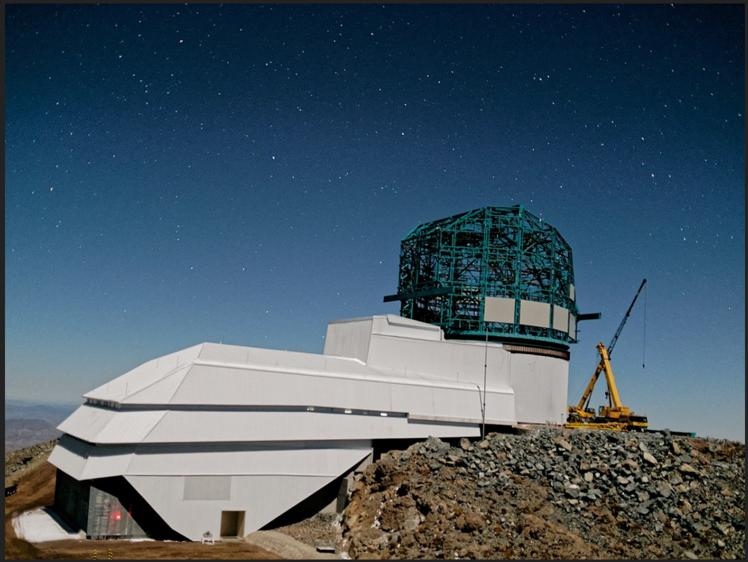
Euclid: WP1-WP6 et al (2022) in preparation

Next-generation Galaxy Surveys

DESI telescope

- 14 000 square degrees in the sky
- 30 million accurate galaxy spectra
- Redshifts: $0 < z < 2$
- Quasars up to $z \sim 3.5$
- 5 years of observation

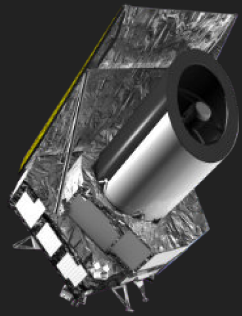
Vera Rubin Observatory

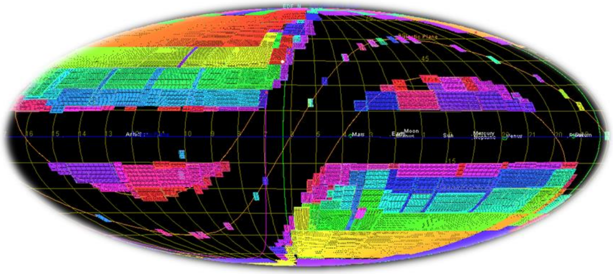


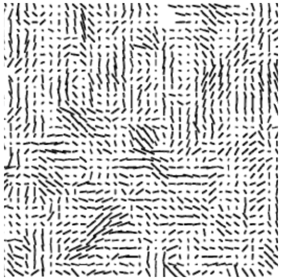
- Located in Chile, 8.4m telescope
- 20 billion galaxies
- Redshifts: $0 < z \sim< 3$
- 18,000 square degrees
- 11 years of observation

Euclid Space Satellite

- Two instruments:
- VIS (visible photometer): shape and orientation of 1.5 billion galaxies!
- NISP (near infrared spectrograph): 30 million galaxy spectra!







- 15 000 square degrees in the sky
- 16 countries, ~1500 members
- ~170 Petabyte of data!

Photometric cross-correlations

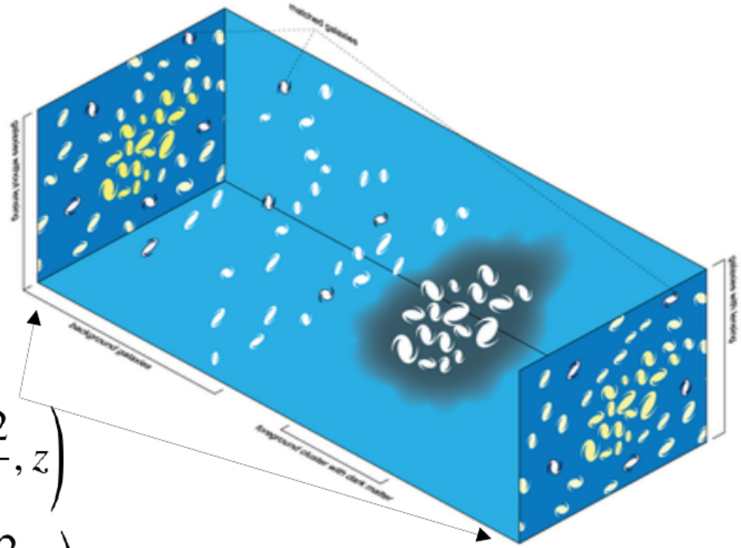
Also known as 3x2pt analysys

Shear-Shear, Galaxy-Galaxy, Galaxy-Lensing **correlations**

Shear-Shear

Intrinsic Alignments

$$\mathcal{W}_i^{\rm L} = W_i^{\gamma}(z) - \frac{\mathcal{A}_{\rm IA}C_{\rm IA}\Omega_{\rm m}\mathcal{F}_{\rm IA}(z)}{D(z)} W_i^{\rm IA}(z)$$



XC

$$C_{ij}^{\rm GL}(\ell) = \int \frac{dz}{H(z)r^2(z)} \mathcal{W}_i^{\rm G}(z)\,\mathcal{W}_j^{\rm L}(z) P_{\delta\delta}\left(\frac{\ell+1/2}{r(z)}, z\right)$$

$$C_{ij}^{\rm GG}(\ell) = \int \frac{dz}{H(z)r^2(z)} \mathcal{W}_i^{\rm G}(z)\,\mathcal{W}_j^{\rm G}(z) P_{\delta\delta}\left(\frac{\ell+1/2}{r(z)}, z\right)$$

GCph

WL

$$C_{ij}^{\rm LL}(\ell) = \int_{z_{\rm min}}^{z_{\rm max}} \frac{dz}{H(z)r^2(z)} \mathcal{W}_i^{\rm L}(z)\mathcal{W}_j^{\rm L}(z) P_{\delta\delta}\left(\frac{\ell+1/2}{r(z)}, z\right)$$

Euclid preparation: VII. Forecast validation for Euclid cosmological probes. arXiv:1910.09273

Weak Lensing

The cosmic shear angular power spectrum depends on the Weyl spectrum (of gravitational potentials $\Phi + \Psi$)

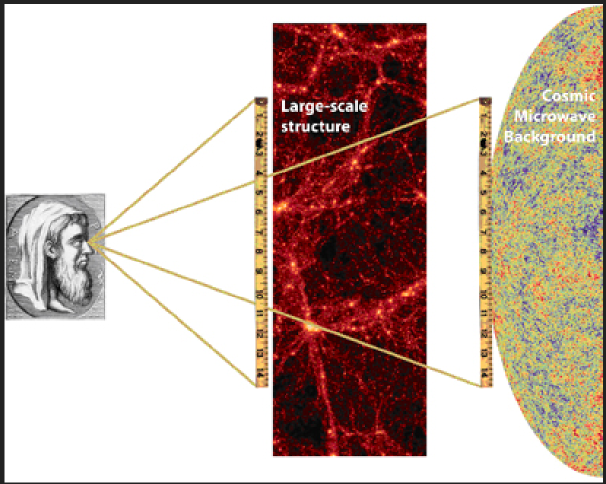
$$C_{ij}^{\gamma\gamma}(\ell) = \frac{c}{H_0} \int \frac{\hat{W}_i^{\gamma}(z)\hat{W}_j^{\gamma}(z)}{E(z)r^2(z)} P_{\Phi+\Psi}\left(k_\ell, z\right) dz$$

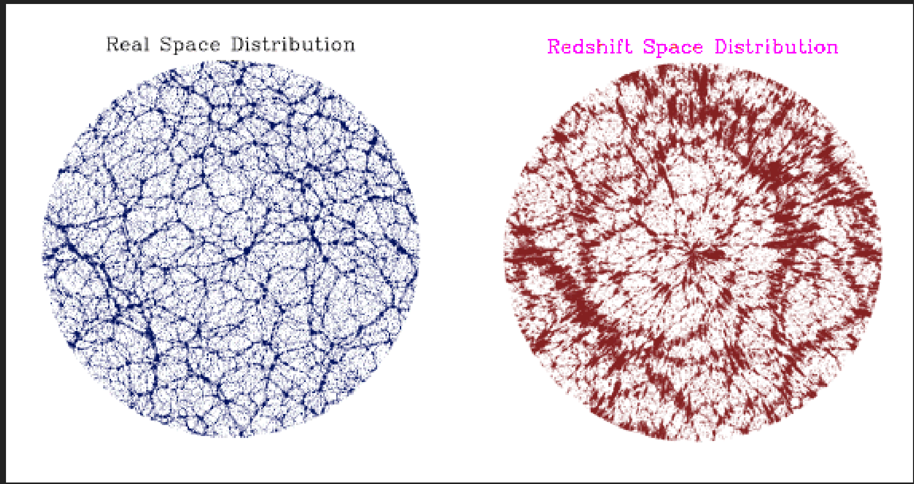
Which is related to the matter power spectrum (of density contrast δ) through

$$P_{\Phi+\Psi} = \left[3\left(\frac{H_0}{c}\right)^2 \Omega_{\rm M}^0 (1+z)\Sigma(k,z)\right]^2 P_{\delta\delta}$$

Information about background geometry, matter content and clustering

Spectroscopic Galaxy Clustering





BAO

Clustering

RSD

Spec-z

$$P_{\rm obs}(k_{\rm ref},\mu_{\rm ref};z) = \frac{1}{q_\perp^2 q_\parallel}\left\{\frac{\left[b\sigma_8(z)+f\sigma_8(z)\mu^2\right]^2}{1+\left[f(z)k\mu\sigma_{\rm p}(z)\right]^2}\right\}\frac{P_{\rm dw}(k,\mu;z)}{\sigma_8^2(z)}F_{\rm z}(k,\mu;z)+P_{\rm s}(z)$$

Euclid preparation: VII. Forecast validation for Euclid cosmological probes. arXiv:1910.09273

Spectroscopic Galaxy Clustering

$$\langle\delta(\mathbf{k})\delta(\mathbf{k}')\rangle \equiv P(\mathbf{k})\delta_D(\mathbf{k}+\mathbf{k}')$$

One loop Power Spectrum

$$\langle\delta(\mathbf{k})\delta(\mathbf{k}')\rangle \approx \langle\delta^{(1)}(\mathbf{k})\delta^{(1)}(\mathbf{k}')\rangle + 2\langle\delta^{(1)}(\mathbf{k})\delta^{(3)}(\mathbf{k}')\rangle + \langle\delta^{(2)}(\mathbf{k})\delta^{(2)}(\mathbf{k}')\rangle$$

$$P_{1-loop}(k) \equiv P_{lin}(\mathbf{k}) + 2P_{13}(\mathbf{k}) + P_{22}(\mathbf{k})$$

$$P_{22}(k,\eta) = 2\int F_2^s(\mathbf{k}-\mathbf{q},\mathbf{q})^2 P_{lin}(\mathbf{k}-\mathbf{q},\eta)P_{lin}(\mathbf{q},\eta)d^3\mathbf{q}$$

$$P_{13}(k,\eta) = 3\int F_3^s(\mathbf{k},\mathbf{q},-\mathbf{q})P_{lin}(\mathbf{k},\eta)P_{lin}(\mathbf{q},\eta)d^3\mathbf{q}$$

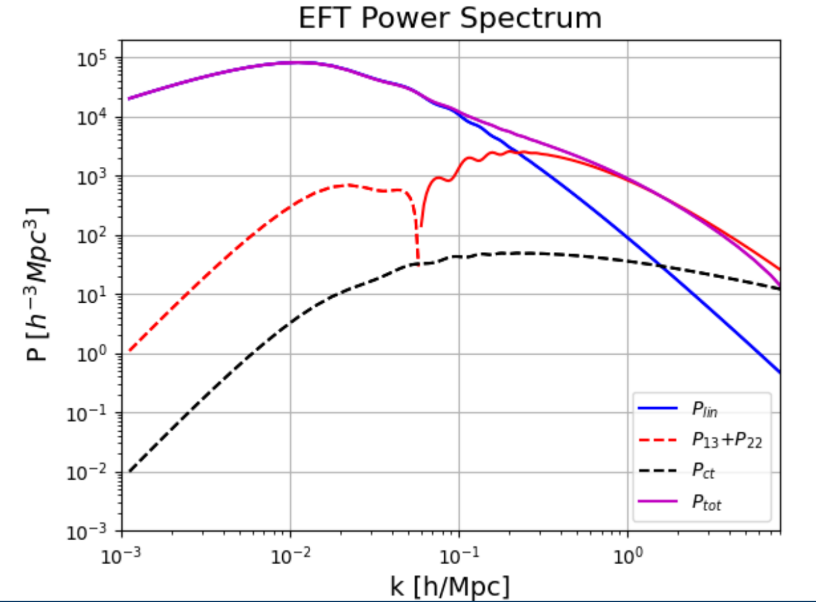
For mildly non-linear scales we need to use perturbation theory

- SPT is not enough

- EFT smoothing over terms -> UV counterterms

  (see previous talk by Filippo)

- Already being implemented into MCMC and Fisher pipelines like CosmicFish and CLOE



The Matter Power Spectrum

Current data:

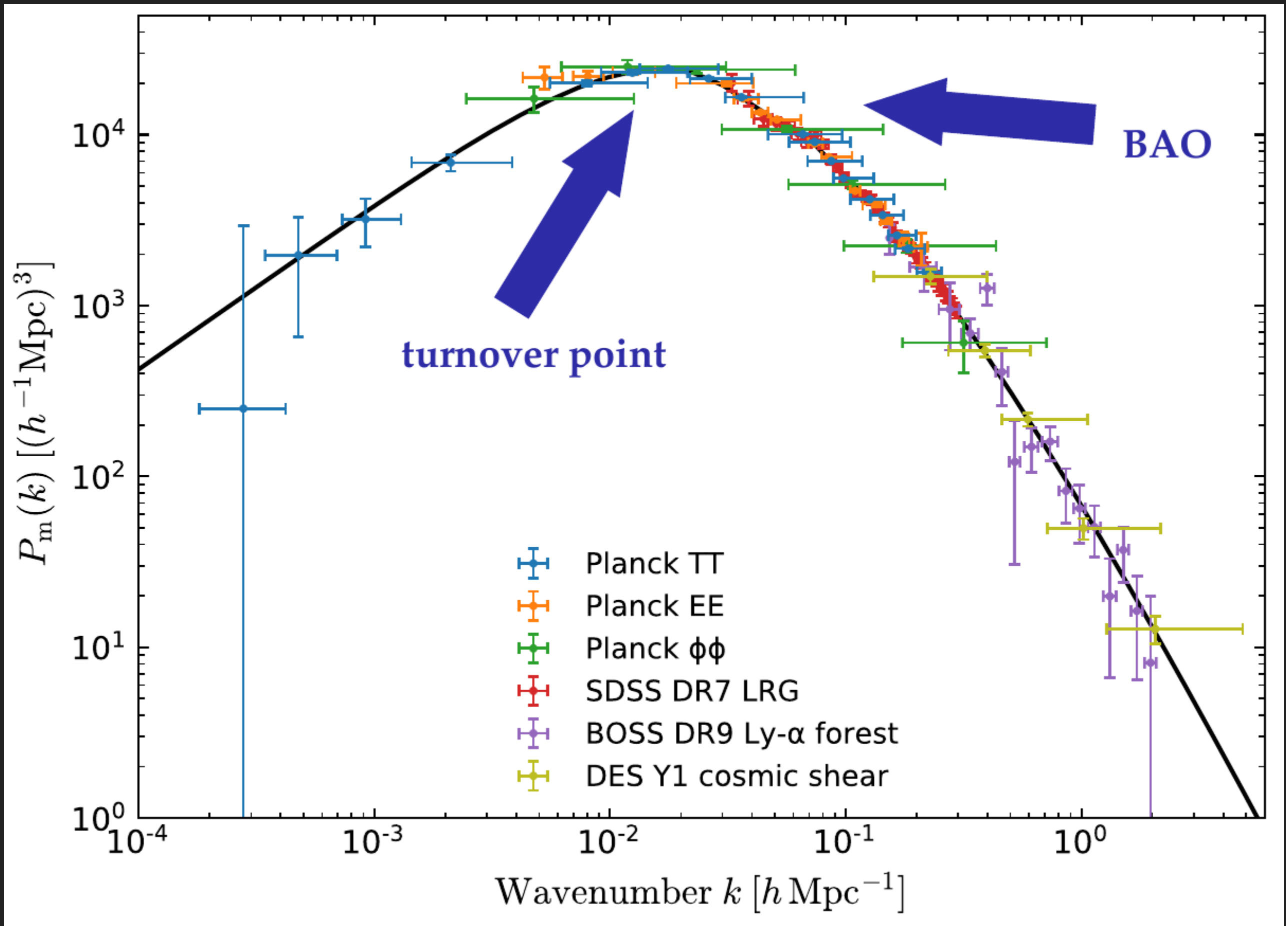
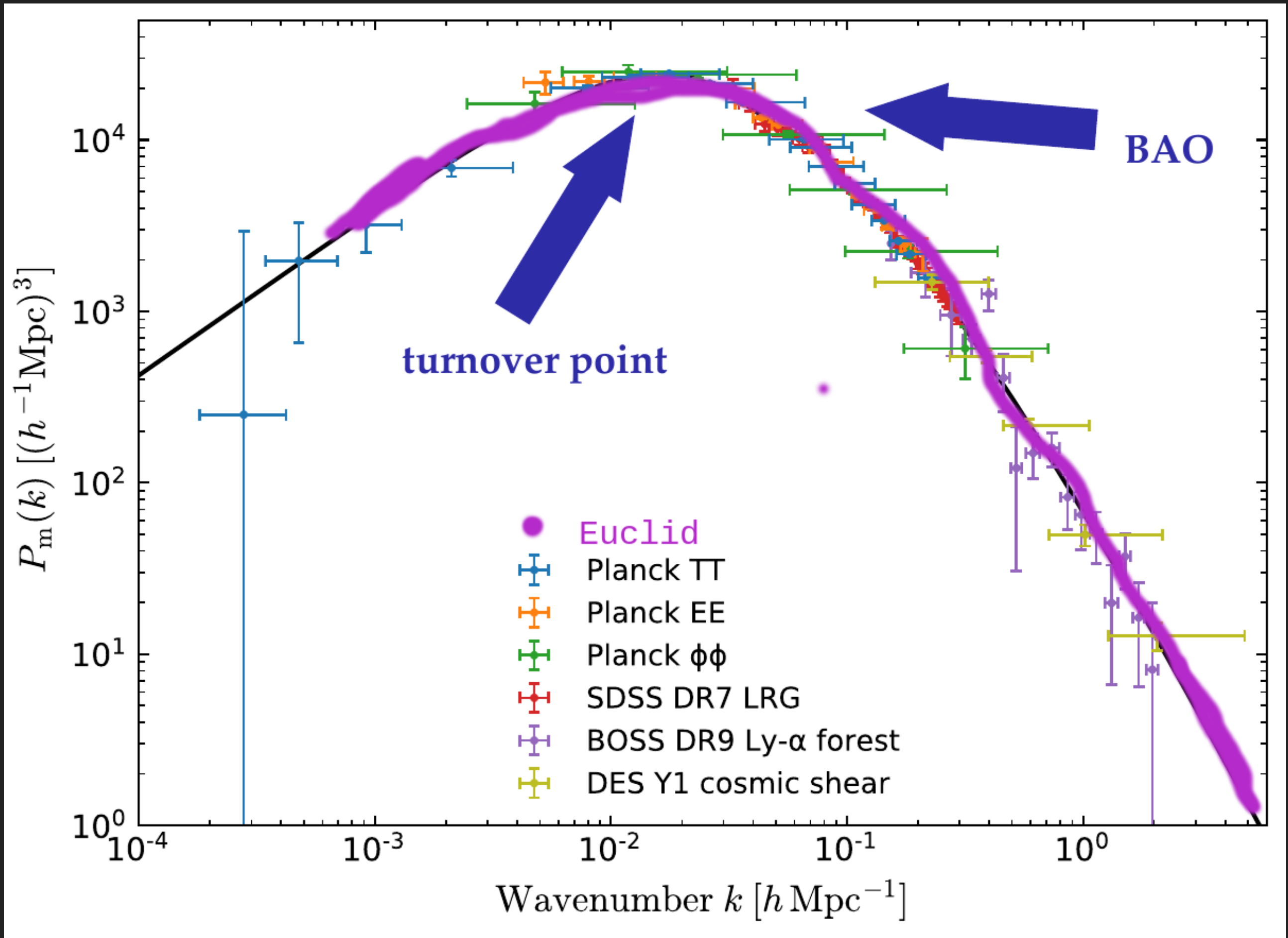


Image: https://www.cosmos.esa.int/web/planck/picture-gallery

The Matter Power Spectrum

Euclid:



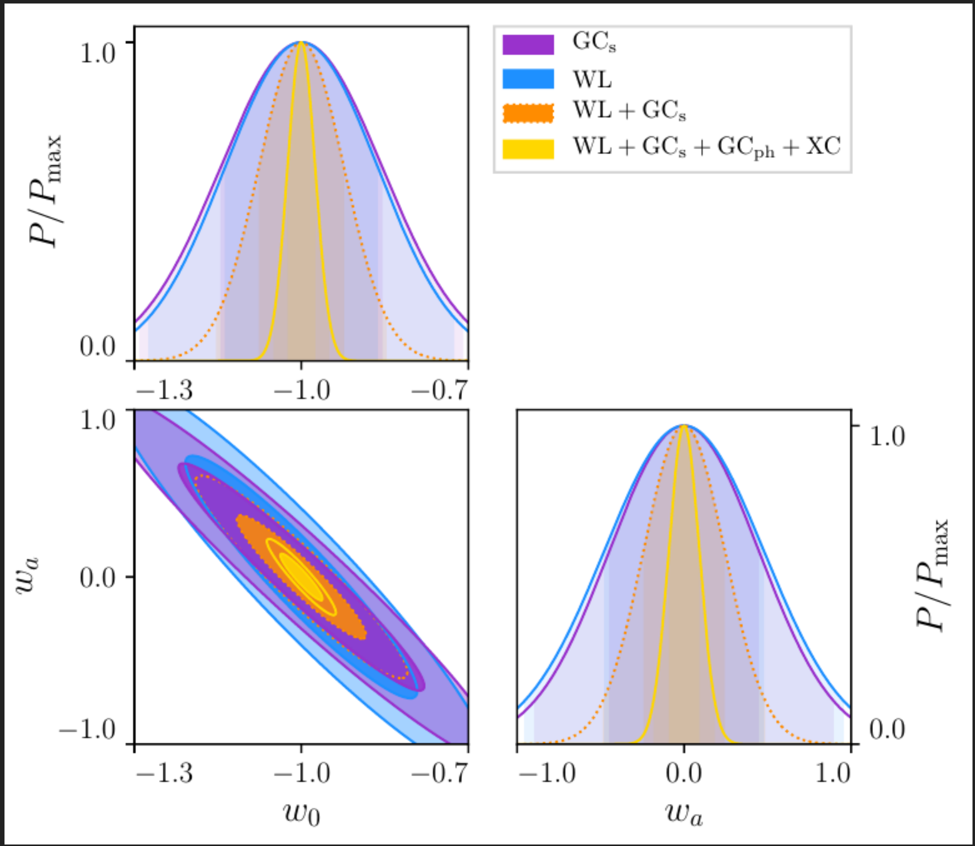
Scales from: ~ 10^{-3} to 10 hMpc^{-1}

Euclid: IST:Forecasts

- Here: Flat $w_0 w_a \mathrm{CDM}$
- GCsp+WL+GCph+XC

- Figure of Merit: 1257
- Non-flat FoM: 500

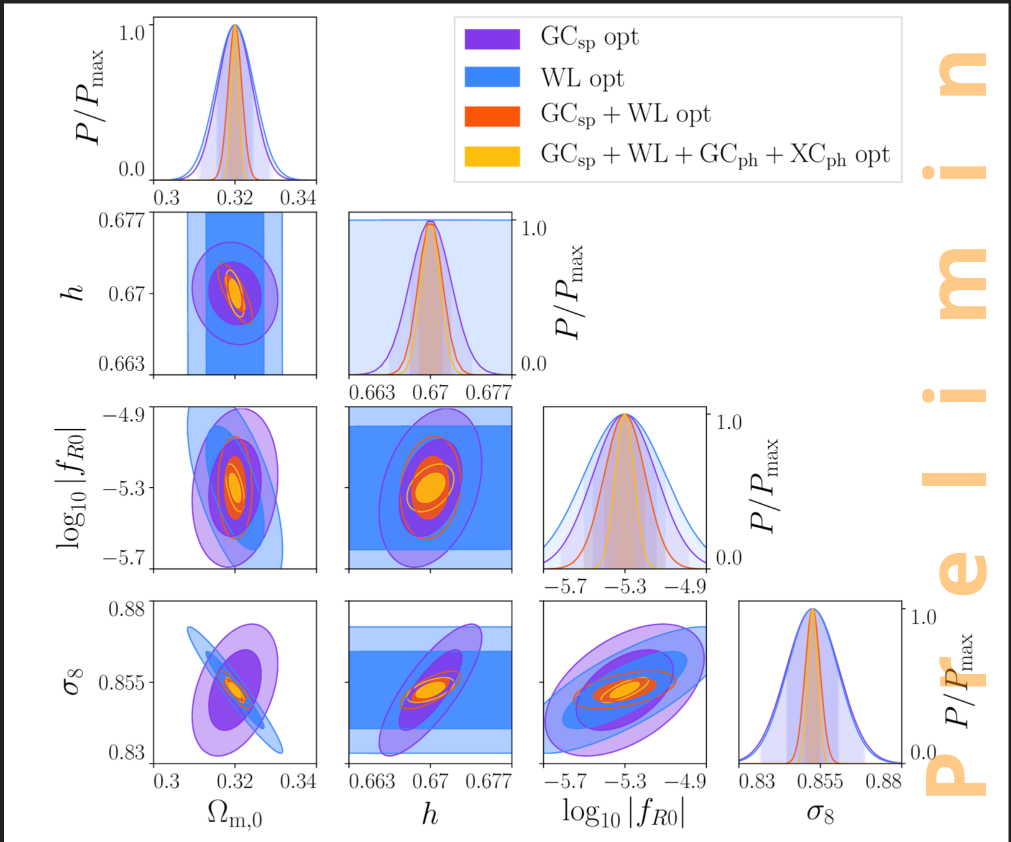
- Optimistic:
  $\sigma_{w_0} = 0.025$
  $\sigma_{w_a} = 0.092$



Euclid preparation: VII. Forecast validation for Euclid cosmological probes. arXiv:1910.09273

Forecasts for f(R) from Euclid probes

$$
\begin{aligned}
\boldsymbol{\Theta} \quad &= \{\Omega_{\mathrm{m},0},\, \Omega_{\mathrm{b},0},\, h,\, n_{\mathrm{s}},\, \sigma_8,\, \log_{10}|f_{R0}|\}\,,\\
\mathrm{HS5} : \boldsymbol{\Theta}_{\mathrm{fid,HS5}} &= \{0.32,\, 0.05,\, 0.67,\, 0.96,\, 0.911,\, -4.301\}\,,\\
\mathrm{HS6} : \boldsymbol{\Theta}_{\mathrm{fid,HS6}} &= \{0.32,\, 0.05,\, 0.67,\, 0.96,\, 0.853,\, -5.301\}\,,\\
\mathrm{HS7} : \boldsymbol{\Theta}_{\mathrm{fid,HS7}} &= \{0.32,\, 0.05,\, 0.67,\, 0.96,\, 0.823,\, -6.301\}\,.
\end{aligned}
$$



- Combined constraints from GCsp and Photo probes

- $\sigma_{\log_{10}|f_{R0}|} = 0.16$ with spectroscopic $\mathrm{GC_{sp}}$ alone (corresponding to a relative 3.0% error);
- $\sigma_{\log_{10}|f_{R0}|} = 0.20$ with WL alone (corresponding to a relative 3.8% error);
- $\sigma_{\log_{10}|f_{R0}|} = 0.07$ combining WL, $\mathrm{GC_{ph}}$, and $\mathrm{XC_{ph}}$ (corresponding to a relative 1.3% error);
- $\sigma_{\log_{10}|f_{R0}|} = 0.05$ using the full combination $\mathrm{GC_{sp}}$+WL+$\mathrm{GC_{ph}}$+$\mathrm{XC_{ph}}$ (corresponding to a relative 0.9% error).

Euclid: Casas et al (2022) in review

Forecasts for f(R) from Euclid probes

$$
\begin{aligned}
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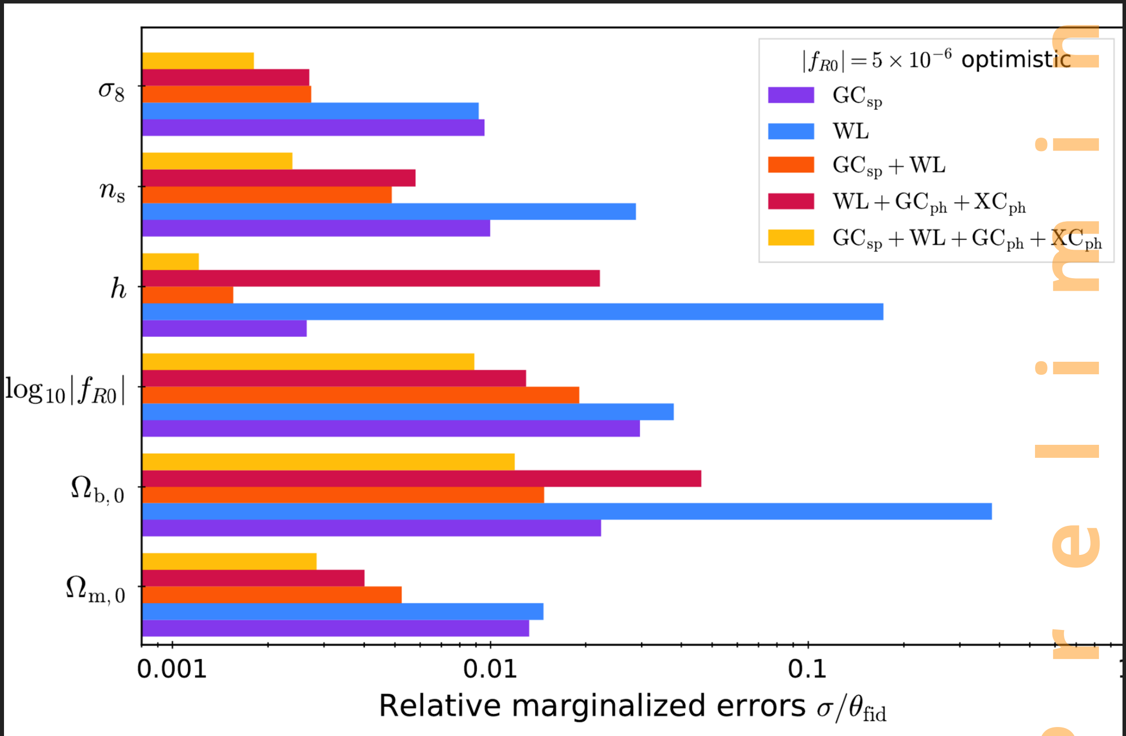
\end{aligned}
$$



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Euclid: Casas et al (2022) in review

Forecasts for f(R) from Euclid probes

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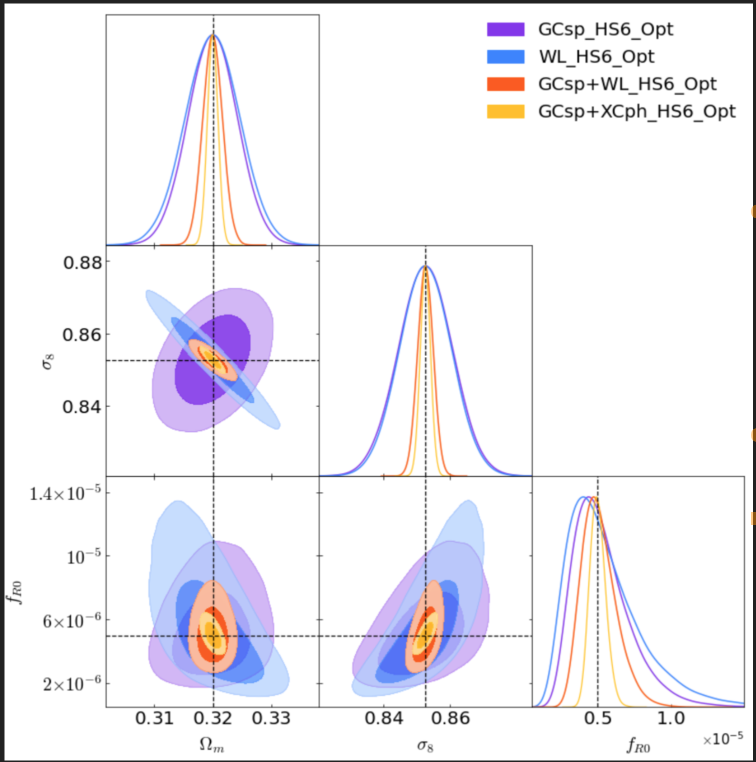
$$\mathrm{HS5}:\ \boldsymbol{\Theta}_{\mathrm{fid,HS5}} = \{0.32,\ 0.05,\ 0.67,\ 0.96,\ 0.911,\ -4.301\}\,,$$
$$\mathrm{HS6}:\ \boldsymbol{\Theta}_{\mathrm{fid,HS6}} = \{0.32,\ 0.05,\ 0.67,\ 0.96,\ 0.853,\ -5.301\}\,,$$
$$\mathrm{HS7}:\ \boldsymbol{\Theta}_{\mathrm{fid,HS7}} = \{0.32,\ 0.05,\ 0.67,\ 0.96,\ 0.823,\ -6.301\}\,.$$



preliminary

- Transform into original space

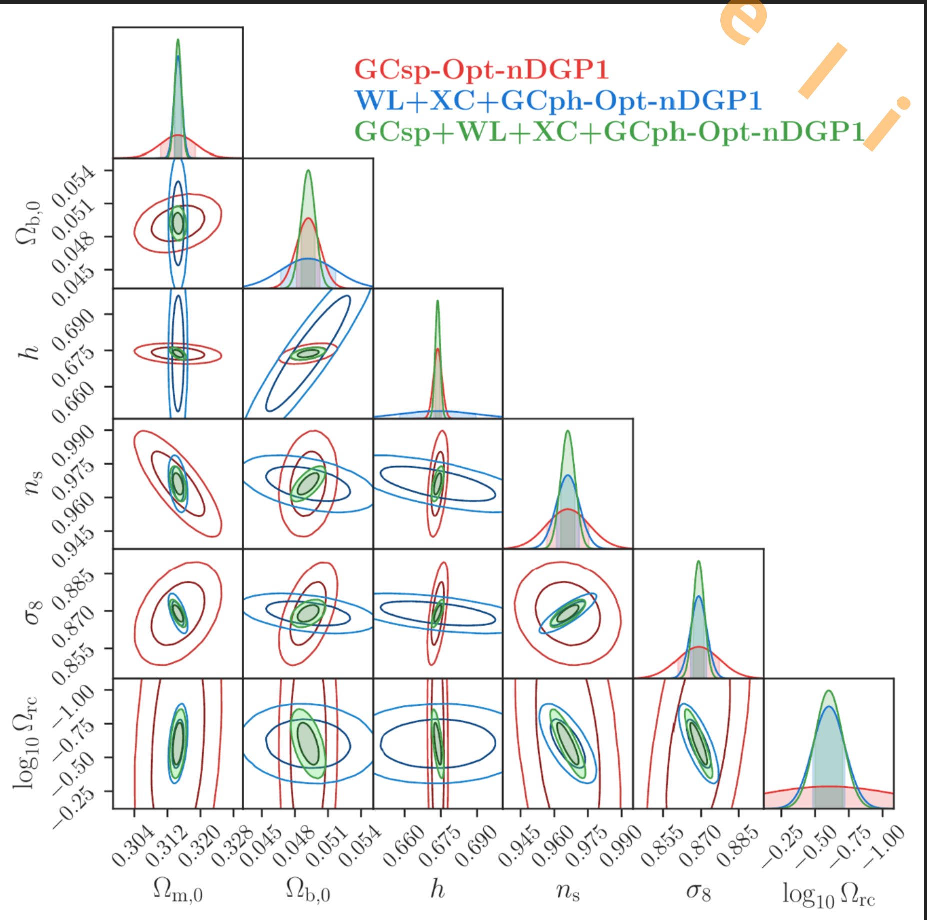
– $|f_{R0}| = (5.0^{+0.58}_{-0.52} \times 10^{-6})$ with the combination $\mathrm{GC_{sp}}$+WL+$\mathrm{GC_{ph}}$+$\mathrm{XC_{ph}}$.

- Current LSS data: "just" upper bounds of the order of $< 10^{-4}$

Euclid: Casas et al (2022) in review

Forecasts for nDGP

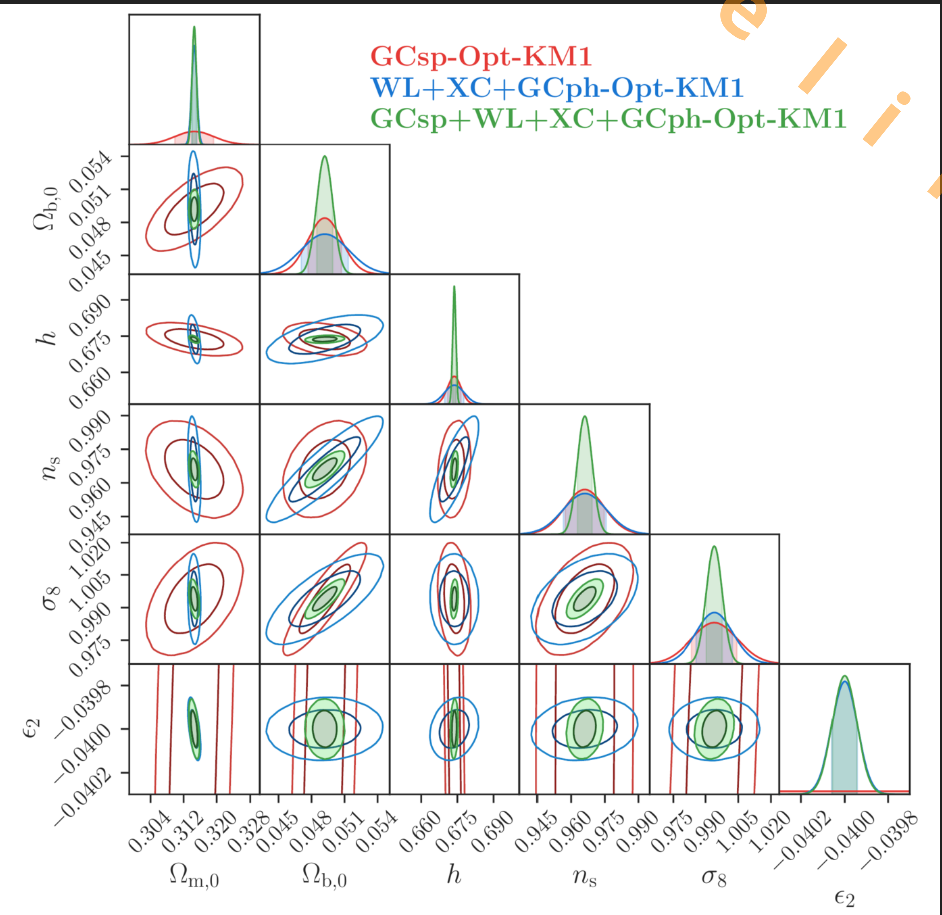
- GCsp does not constrain the free parameter very well
- Most gain is at NL-scales for Photo probes



	$\Omega_{\rm m,0}$	$\Omega_{\rm b,0}$	$\log_{10}(\Omega_{\rm rc})$
nDGP1 $\Omega_{\rm rc} = 0.25$			
Pessimistic setting			
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.15\,h\,\mathrm{Mpc}^{-1}$)	2.23 %	4.30 %	142.20 %
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.25\,h\,\mathrm{Mpc}^{-1}$)	1.41 %	2.43 %	97.63 %
$\mathrm{WL+XC+GC_{ph}}$	1.13 %	5.64 %	49.59 %
$\mathrm{GC_{sp}+WL+XC+GC_{ph}}$	0.55 %	1.95 %	40.27 %
Optimistic setting			
$\mathrm{GC_{sp}}$($k_{\rm max} = 0.3\,h\,\mathrm{Mpc}^{-1}$)	1.33 %	2.15 %	90.06 %
$\mathrm{WL+XC+GC_{ph}}$	0.30 %	5.08 %	19.59 %
$\mathrm{GC_{sp}+WL+XC+GC_{ph}}$	0.25 %	1.28 %	16.99 %
nDGP2 $\Omega_{\rm rc} = 10^{-6}$			
Pessimistic setting			
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.15\,h\,\mathrm{Mpc}^{-1}$)	2.36 %	4.51 %	3020.58 %
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.25\,h\,\mathrm{Mpc}^{-1}$)	1.46 %	2.51 %	1923.03 %
$\mathrm{WL+XC+GC_{ph}}$	0.86 %	5.61 %	398.64 %
$\mathrm{GC_{sp}+WL+XC+GC_{ph}}$	0.89 %	1.84 %	378.82 %
Optimistic setting			
$\mathrm{GC_{sp}}$($k_{\rm max} = 0.3\,h\,\mathrm{Mpc}^{-1}$)	1.38 %	2.21 %	1801.03 %
$\mathrm{WL+XC+GC_{ph}}$	0.29 %	5.08 %	81.02 %
$\mathrm{GC_{sp}+WL+XC+GC_{ph}}$	0.25 %	1.12 %	80.83 %

Euclid: WP1-WP6 et al (2022) in preparation

Forecasts for K-Mouflage



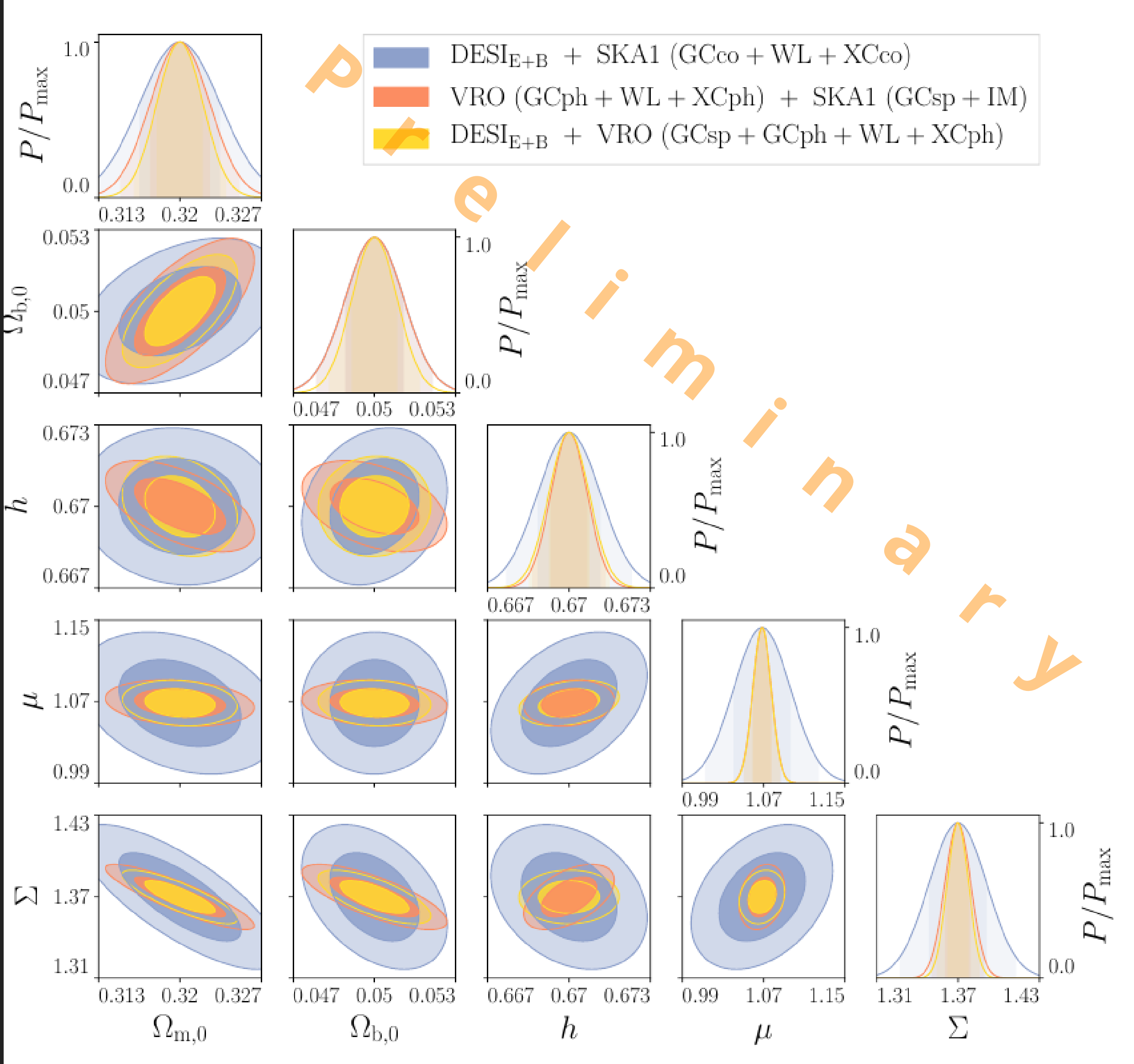
- For KM1:
  GCsp can constrain the free parameter at ~10%
- Photo at ~1% (remember Σ_{WL})
- KM2 is basically ΛCDM, non detectable

KM1 $\epsilon_{2,0} = -0.04$	$\Omega_{\rm m,0}$	$\Omega_{\rm b,0}$	$\epsilon_{2,0}$
Pessimistic setting			
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.15\,h\,\mathrm{Mpc}^{-1}$)	2.68 %	5.34 %	11.14 %
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.25\,h\,\mathrm{Mpc}^{-1}$)	1.57 %	3.22 %	5.77 %
WL+XC+$\mathrm{GC_{ph}}$	0.36 %	7.36 %	0.22 %
$\mathrm{GC_{sp}}$+WL+XC+$\mathrm{GC_{ph}}$	0.34 %	1.73 %	0.22 %
Optimistic setting			
$\mathrm{GC_{sp}}$($k_{\rm max} = 0.3\,h\,\mathrm{Mpc}^{-1}$)	1.48 %	3.08 %	4.99 %
WL+XC+$\mathrm{GC_{ph}}$	0.20 %	4.30 %	0.15 %
$\mathrm{GC_{sp}}$+WL+XC+$\mathrm{GC_{ph}}$	0.17 %	1.47 %	0.14 %
KM2 $\epsilon_{2,0} = -0.0001$			
Pessimistic setting			
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.15\,h\,\mathrm{Mpc}^{-1}$)	2.99 %	5.61 %	1264.58 %
$\mathrm{GC_{sp}}$ ($k_{\rm max} = 0.25\,h\,\mathrm{Mpc}^{-1}$)	1.60 %	3.08 %	824.38 %
WL+XC+$\mathrm{GC_{ph}}$	1.18 %	5.22 %	939.23 %
$\mathrm{GC_{sp}}$+WL+XC+$\mathrm{GC_{ph}}$	0.68 %	1.90 %	645.16 %
Optimistic setting			
$\mathrm{GC_{sp}}$($k_{\rm max} = 0.3\,h\,\mathrm{Mpc}^{-1}$)	1.45 %	2.69 %	759.45 %
WL+XC+$\mathrm{GC_{ph}}$	0.40 %	3.43 %	658.67 %
$\mathrm{GC_{sp}}$+WL+XC+$\mathrm{GC_{ph}}$	0.32 %	1.52 %	464.38 %

Euclid: WP1-WP6 et al (2022) in preparation

Bonus: Forecasts on parameterized MG

- DESI+Rubin have similar power than Euclid alone (under many assumptions)
- Optical + Radio is also competitive and can remove systematics / degeneracies
- Constraints on μ, Σ of the order of ~5-10% under optimistic assumptions
- PPN-approach screening assumed



Casas, Pettorino, Camera, Martinelli, Carucci (in preparation)

Conclusions

- Screening mechanisms can save scalar field models
- Current constraints don't allow for self-acceleration
- Screening mechanisms can be classified by the derivative order
- Euclid and next-generation surveys will be powerful probes for Cosmology.
- Primary LSS probes: Galaxy Clustering and Weak Lensing
- Many challenges ahead in non-linear modelling
- Next-generation surveys can constrain free parameters with percent precision accuracy

Thanks!

Merci!