Cosmological Tests of Gravity

Levon Pogosian
Simon Fraser University, Canada

VIA Lecture, 16 May, 2014

SFU from the air. Image kindly provided by Stefan Lorimer (UniverCity).

Workshop on Testing Gravity at SFU Harbour Centre

January 15-17, 2015

- Alternative theories of gravity
- Pulsars and other astrophysical tests
- Gravitational wave detectors
- Gravity at short distances
- Quantum gravity and black holes
- Cosmological tests - CMB, large scale structure

SFU TRIUMF ...

http://www.sfu.ca/physics/cosmology/TestingGravity2015.html

This talk

- Motivation
- What can we test?
- Observational tests today and in the future
- The choice of theoretical priors
- Reconstructing unknown functions from data
- Summary

Based on work with R. Crittenden, A. Hojjati, K. Koyama, A. Silvestri, G.-B. Zhao

Why test Gravity on Cosmological Scales?

- Because we can

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- Because we can

- Is there a reason to expect modifications of GR?

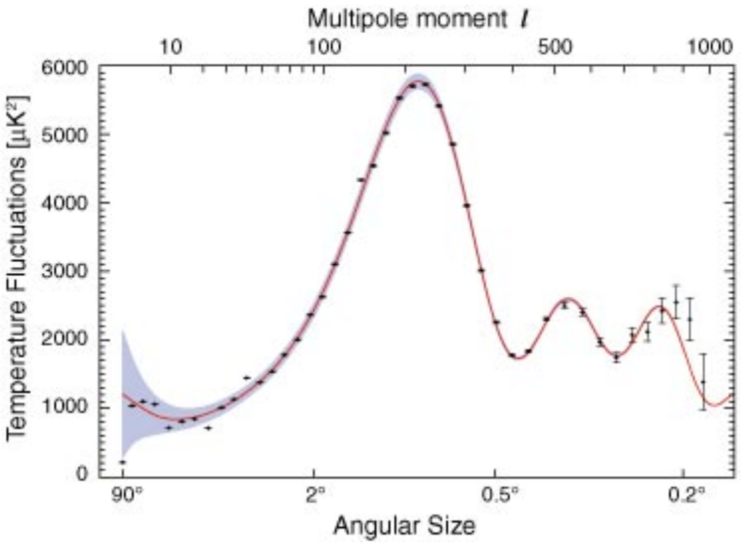
A popular viewpoint	A different viewpoint
GR has, so far, passed all experimental tests The LCDM model assumes GR and is in good agreement with observations Alternative models tend to create more problems than they solve	GR is yet to be seriously tested on scales beyond our solar system We do not know what is causing Cosmic Acceleration We do not know how the vacuum gravitates We do not know what Dark Matter is

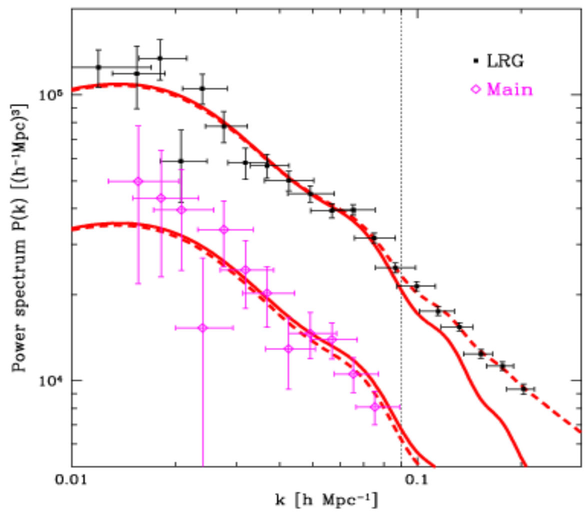
What does Cosmology test?

FRW Metric + Initial conditions (Inflation) + Content: CDM, baryons, photons, neutrinos, Λ

Conservation Equations
Einstein's Equations
for the background and small perturbations

Observables: statistics of CMB, galaxy distribution, …





Questions we could ask about gravity

1. Is data consistent with equations of GR?

   – Apply conventional measures of goodness of fit
   – Apply specially designed consistency tests

(!) Consistency does not necessarily rule out the alternatives

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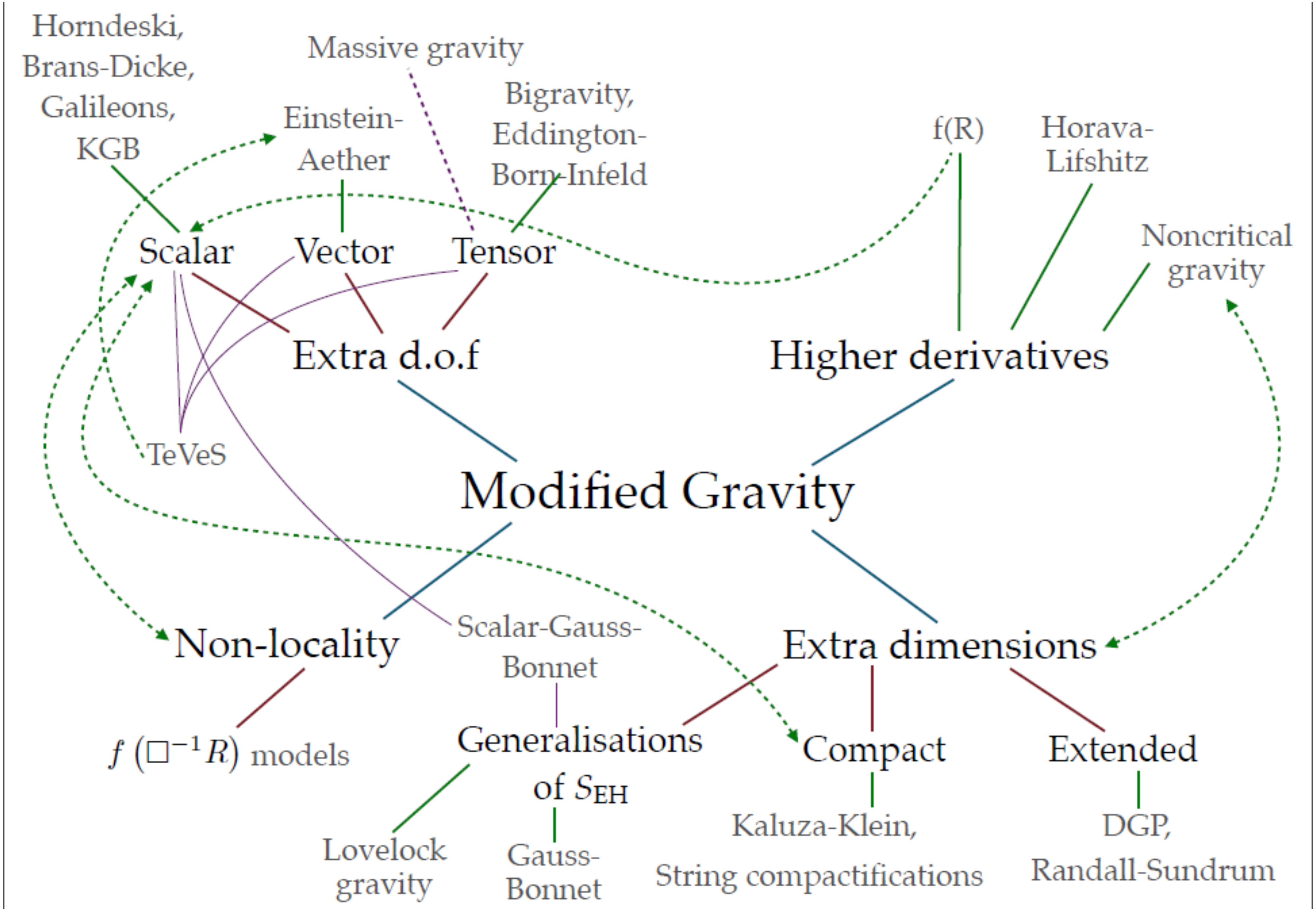
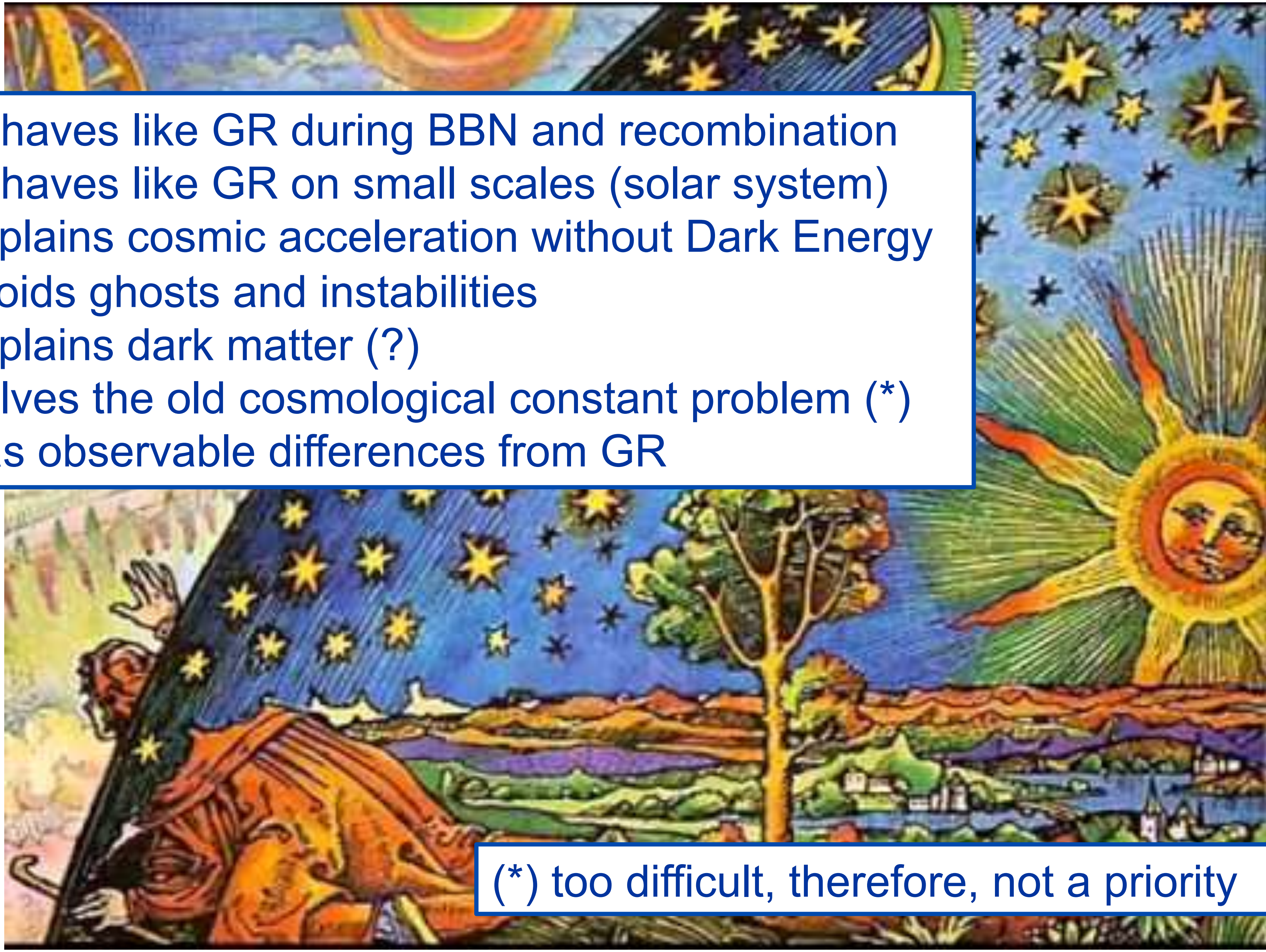
2. What are constraints on alternative theories?

   – Constrain specific modified gravity models
   – Develop a more general framework, akin to PPN, that
      a) includes the answer to Question 1
      b) maps onto parameters of “reasonable” theories



Borrowed from Tessa Baker's PhD Thesis

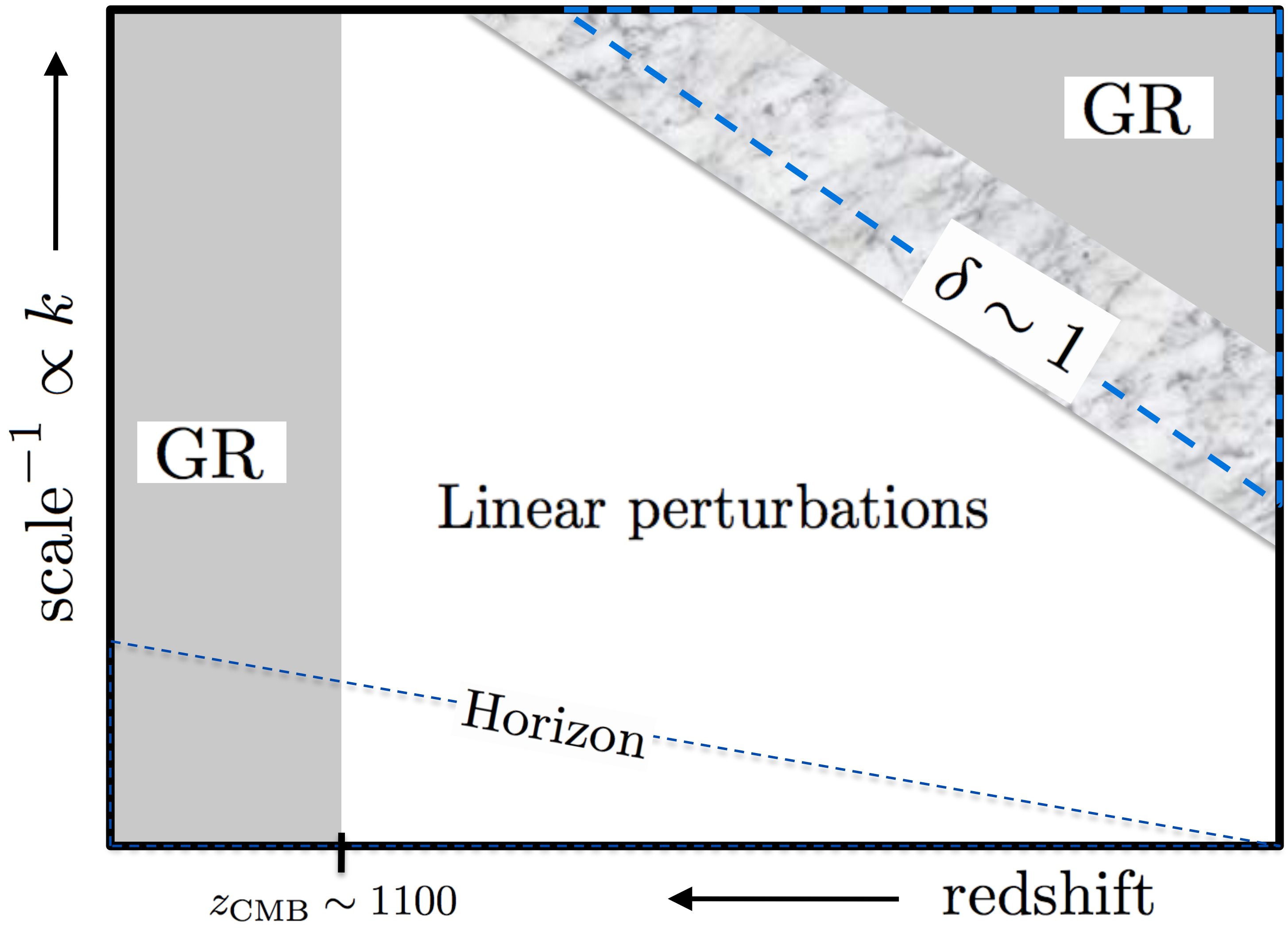
Cosmologists' Dream Modified Gravity Theory



- Behaves like GR during BBN and recombination
- Behaves like GR on small scales (solar system)
- Explains cosmic acceleration without Dark Energy
- Avoids ghosts and instabilities
- Explains dark matter (?)
- Solves the old cosmological constant problem (*)
- Has observable differences from GR

(*) too difficult, therefore, not a priority

The testing ground



Linear perturbations in FRW universe:

$$ds^2 = a^2(\eta)[-(1 + 2\Psi)d\eta^2 + (1 - 2\Phi)d\mathbf{x}^2]$$

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$$\boxed{D_\mu T^{\mu\nu} = 0} \longrightarrow \boxed{\begin{array}{rcl} \delta' + \dfrac{k}{aH}V - 3\Phi' & = & 0 \\ V' + V - \dfrac{k}{aH}\Psi & = & 0 \end{array}}$$

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Einstein's Eq

$$\boxed{\begin{aligned} k^2\Phi &= -4\pi G a^2 \rho \left(\delta + \frac{3aH}{k}V\right) \equiv -4\pi G a^2 \rho \Delta \\ k^2(\Phi - \Psi) &= 12\pi G a^2 (\rho + P)\sigma \end{aligned}}$$

Linear perturbations in FRW universe:

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Einstein's Eq + matter

$$\boxed{\begin{aligned} k^2\Phi &= -4\pi G a^2 \rho \Delta \\ \Phi &= \Psi \end{aligned}}$$

Things we can agree to keep

FRW background with small perturbations:

$$ds^2 = a^2(\eta)[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\mathbf{x}^2]$$

Conservation of matter energy-momentum:

$$\boxed{D_\mu T^{\mu\nu} = 0} \longrightarrow \boxed{\begin{aligned} \delta' + \frac{k}{aH}V - 3\Phi' &= 0 \\ V' + V - \frac{k}{aH}\Psi &= 0 \end{aligned}}$$

(!) Need two additional equations to close the system of four variables

Modified field equations

$$\boxed{\begin{aligned} k^2\Psi &= -\mu(a,k)\ 4\pi G a^2 \rho\Delta \\ \Phi &= \gamma(a,k)\ \Psi \end{aligned}}$$

GR+ΛCDM

$$\mu = \gamma = 1$$

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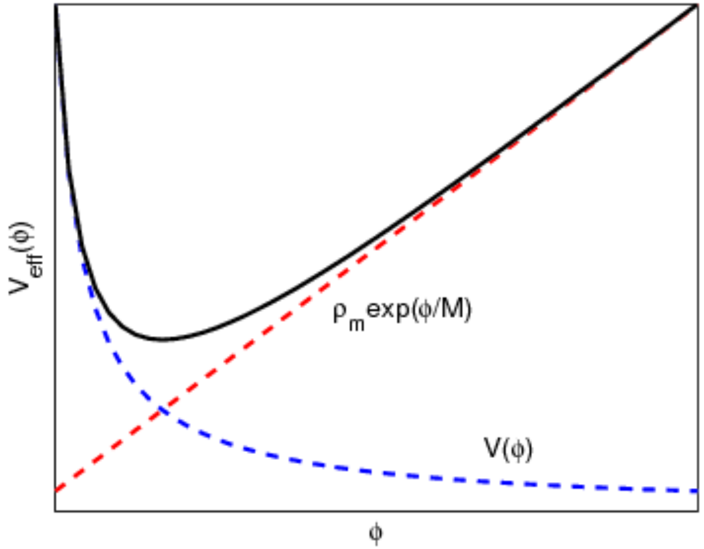
Example: scalar-tensor models of chameleon type

Khoury & Weltman, astro-ph/0309300, PRL'04

$$S_E = \int d^4x\sqrt{-\tilde{g}}\left[\frac{M_P^2}{2}\tilde{R} - \frac{1}{2}g^{\tilde{\mu}\nu}(\tilde{\nabla}_\mu\phi)\tilde{\nabla}_\nu\phi - V(\phi)\right] + S_i\left(\chi_i, e^{-\kappa\alpha_i(\phi)}\tilde{g}_{\mu\nu}\right)$$



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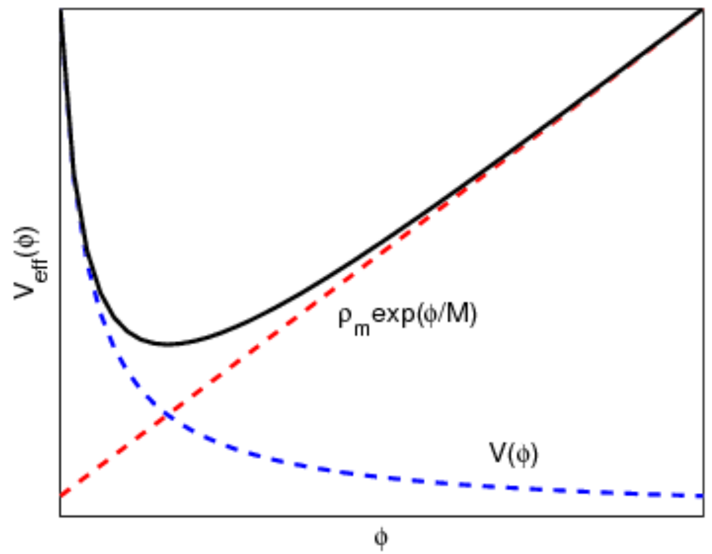
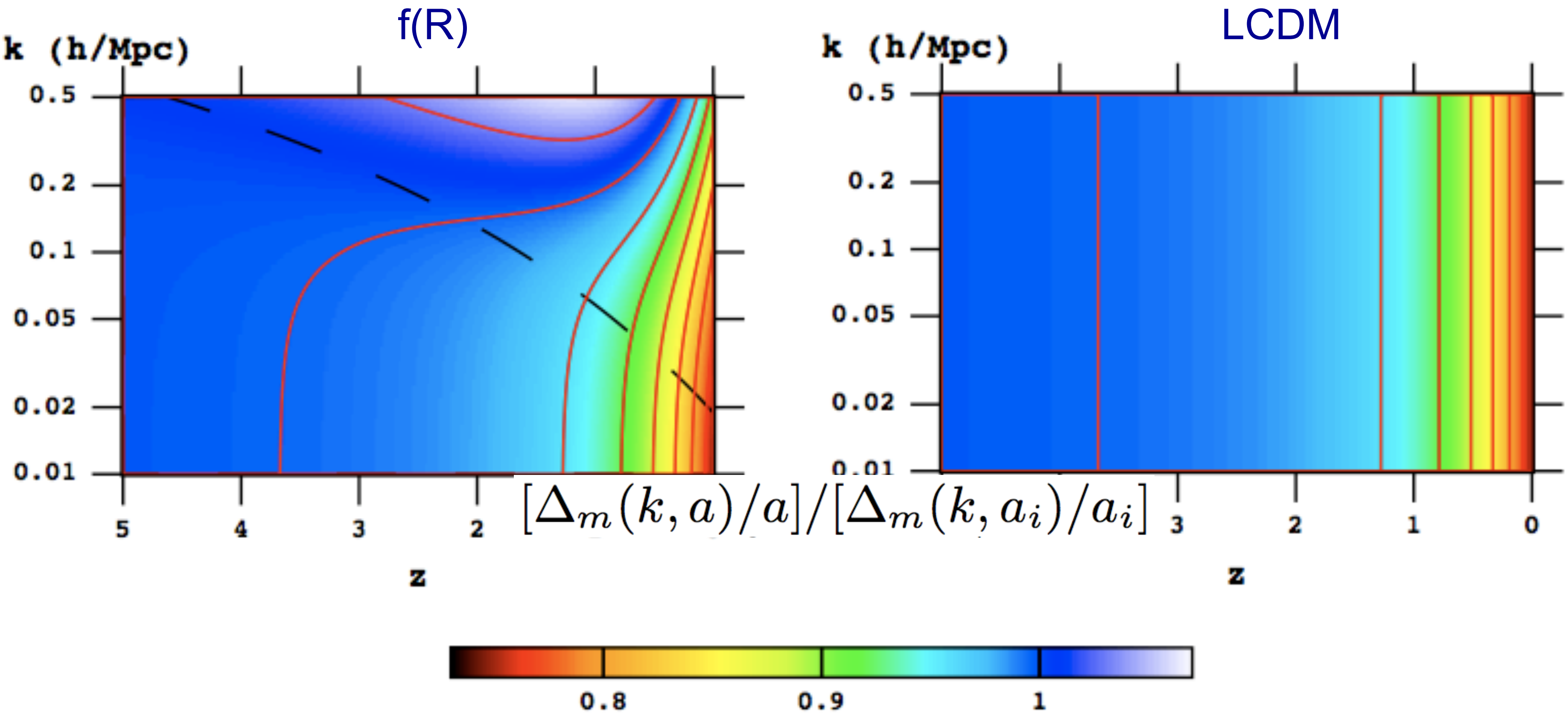
$$\mu(a,k) \approx e^{-\kappa\alpha(\phi)}\frac{1+\left(1+\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}{1+\frac{k^2}{a^2m^2}}$$

$$\gamma(a,k) \approx \frac{1+\left(1-\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}{1+\left(1+\frac{1}{2}\alpha'^2\right)\frac{k^2}{a^2m^2}}$$



The growth of cosmological perturbations in f(R)

L.P. and A. Silvestri, PRD (2008)



$$\alpha' = \frac{d\alpha}{d\phi} = \sqrt{\frac{2}{3}}$$

$$\mu(a,k) \approx \frac{1+4/3k^2\lambda_C^2}{1+k^2\lambda_C^2} \rightarrow_{k^{-1}\ll\lambda_C} \frac{4}{3}$$

$$\gamma(a,k) \approx \frac{1+2/3k^2\lambda_C^2}{1+4/3k^2\lambda_C^2} \rightarrow_{k^{-1}\ll\lambda_C} \frac{1}{2}$$

An alternative choice of modified functions

$$
\begin{aligned}
k^2\Psi &= -\mu(a,k)\ 4\pi G a^2 \rho\Delta \\
k^2(\Psi+\Phi) &= -\Sigma(a,k)\ 8\pi G a^2 \rho\Delta
\end{aligned}
$$

An alternative choice of modified functions

$$\text{“}G_{matter}\text{”}$$

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

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$$\text{“}G_{light}\text{”}$$

An alternative choice of modified functions

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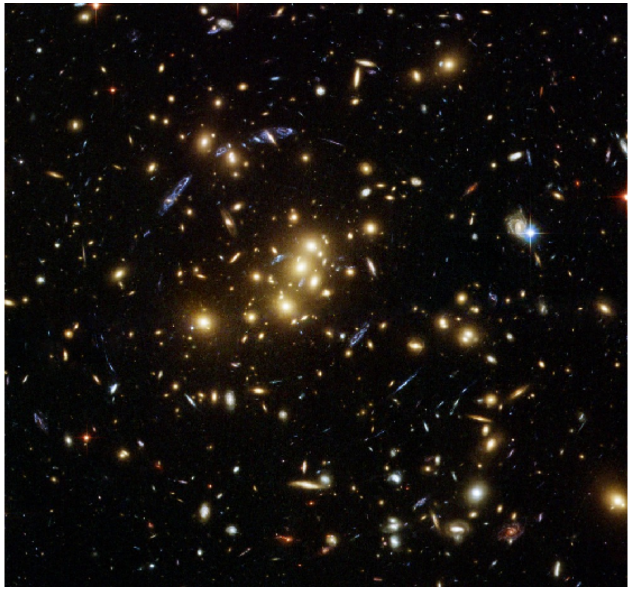
$$\text{“}G_{light}\text{”}$$

A smoking gun of new gravitational physics:

$$\boxed{G_{matter} \neq G_{light} \quad \text{or} \quad \Phi \neq \Psi}$$

The observational handle

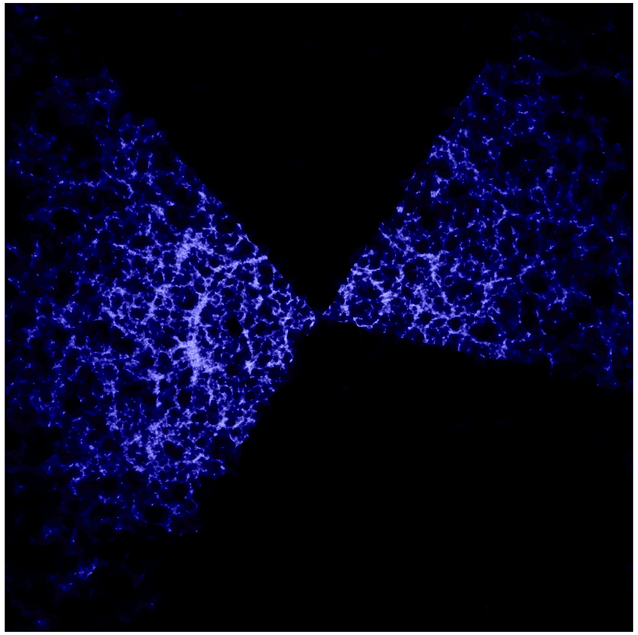
Massless particles "feel" $\Phi + \Psi$



Weak Lensing of distant images

$$\text{Distortion} \propto \int dz\ \partial_\perp (\Phi + \Psi)$$

Massive particles "feel" Ψ



Redshift space distortions
due to peculiar motion

$$V' + V = \frac{k}{aH}\Psi$$

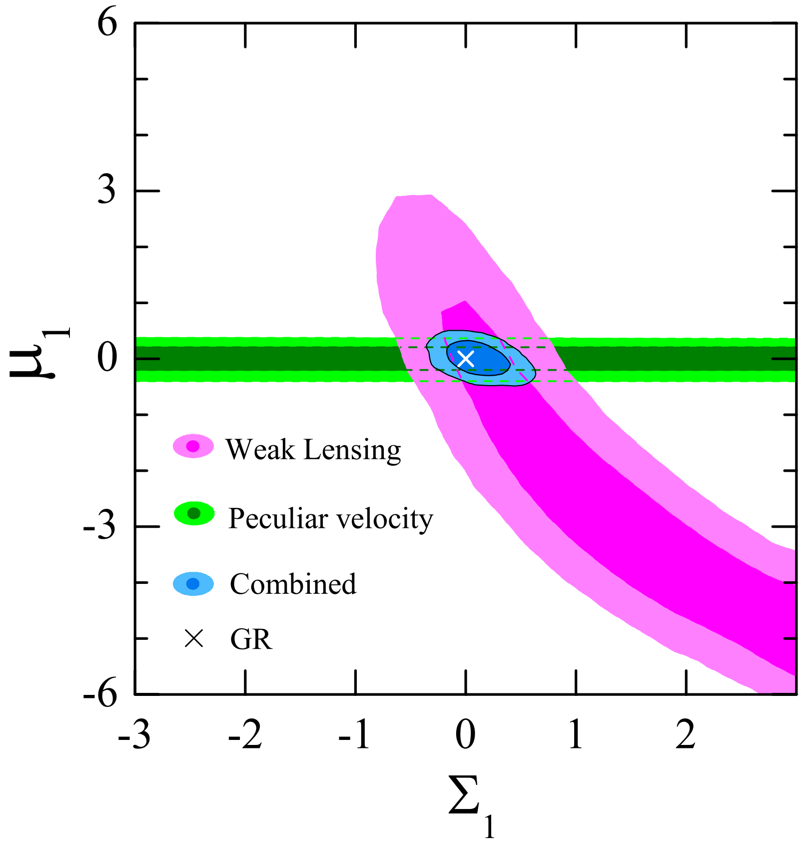
1011.2106, PRD'11

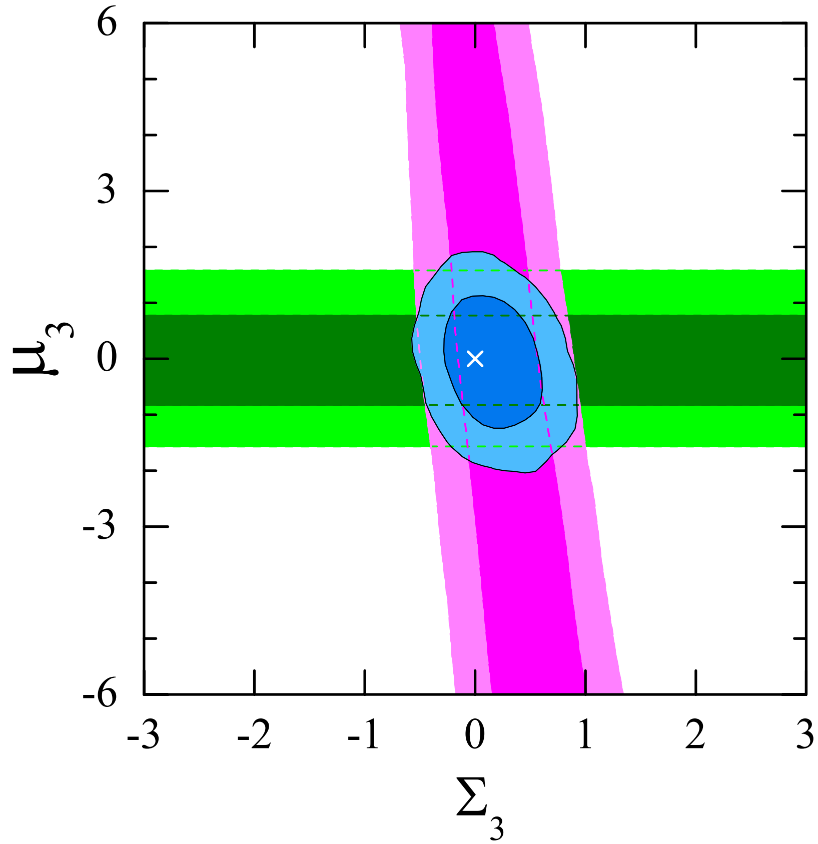
Complementarity of Weak Lensing and Peculiar Velocity Measurements in Testing General Relativity

Yong-Seon Song[1,2], Gong-Bo Zhao[2], David Bacon[2], Kazuya Koyama[2], Robert C Nichol[2], Levon Pogosian[3]
[1]Korea Institute for Advanced Study, Dongdaemun-gu, Seoul 130-722, Korea
[2]Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, United Kingdom
[3]Department of Physics, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada

CFHTLS-Wide T003 (Fu et al, 2008), SDSS DR7

$$\boxed{\Sigma = 1 + \Sigma_s a^s, \quad \mu = 1 + \mu_s a^s}$$



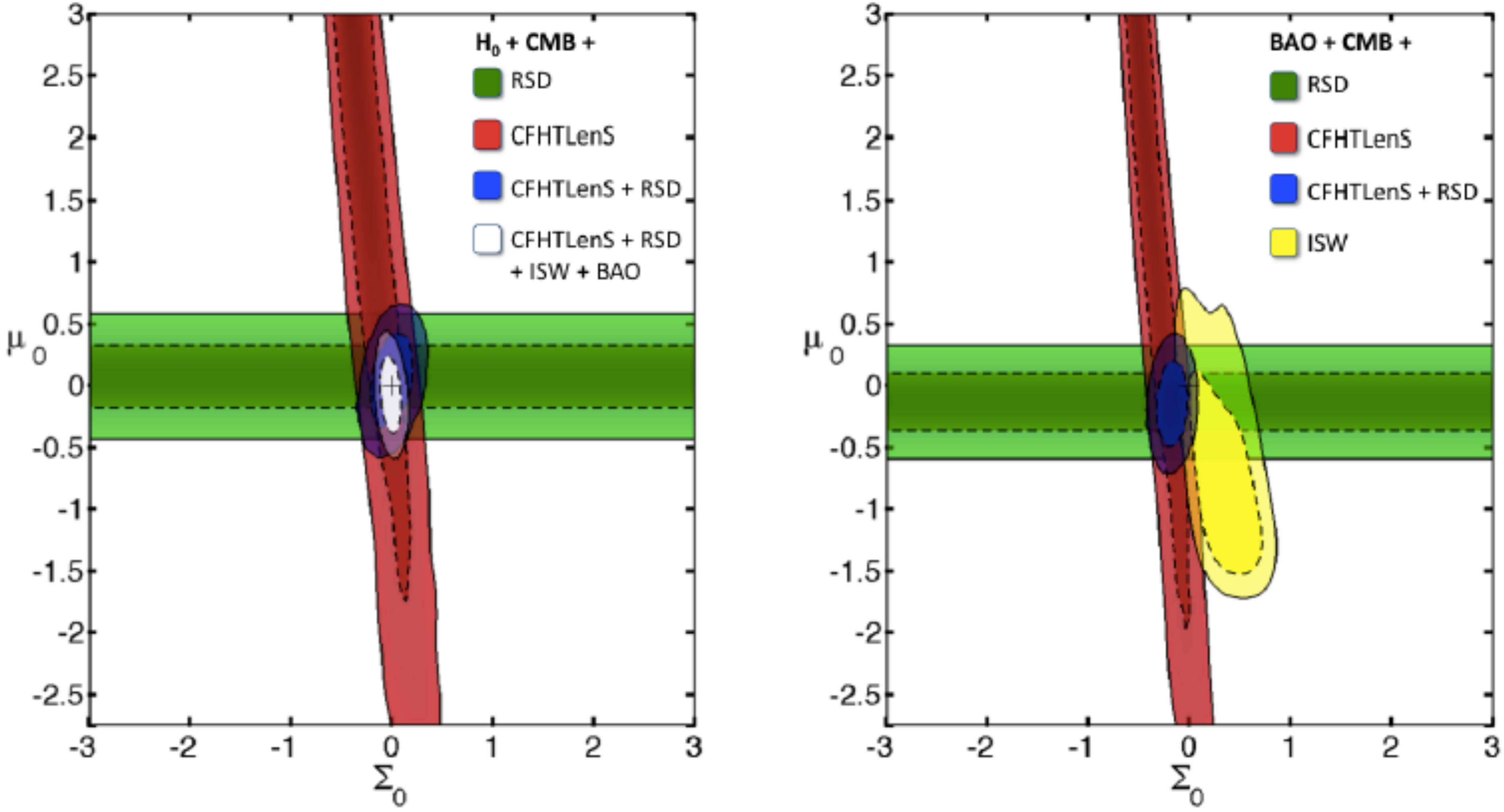


CFHTLenS: Testing the Laws of Gravity with Tomographic Weak Lensing and Redshift Space Distortions

1212.3339, MNRAS'13

Fergus Simpson[1⋆], Catherine Heymans[1], David Parkinson[2], Chris Blake[3], Martin Kilbinger[4,5,6], Jonathan Benjamin[7], Thomas Erben[8], Hendrik Hildebrandt[7,8], Henk Hoekstra[9,10], Thomas D. Kitching[1], Yannick Mellier[11], Lance Miller[12], Ludovic Van Waerbeke[7], Jean Coupon[13], Liping Fu[14], Joachim Harnois-Déraps[15,16], Michael J. Hudson[17,18], Konrad Kuijken[9], Barnaby Rowe[19,20], Tim Schrabback[8,9,21], Elisabetta Semboloni[9], Sanaz Vafaei[7], Malin Velander[12,9].

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



A direct consistency test:

Zhang et al, 0704.1932, PRL’07

$$E_G \equiv \frac{\text{Galaxy} \times \text{Lensing Correlation}}{\text{Galaxy} \times \text{Velocity Correlation}} = \frac{\nabla^2(\Phi+\Psi)}{3H_0^2(1+z)\beta\delta}$$

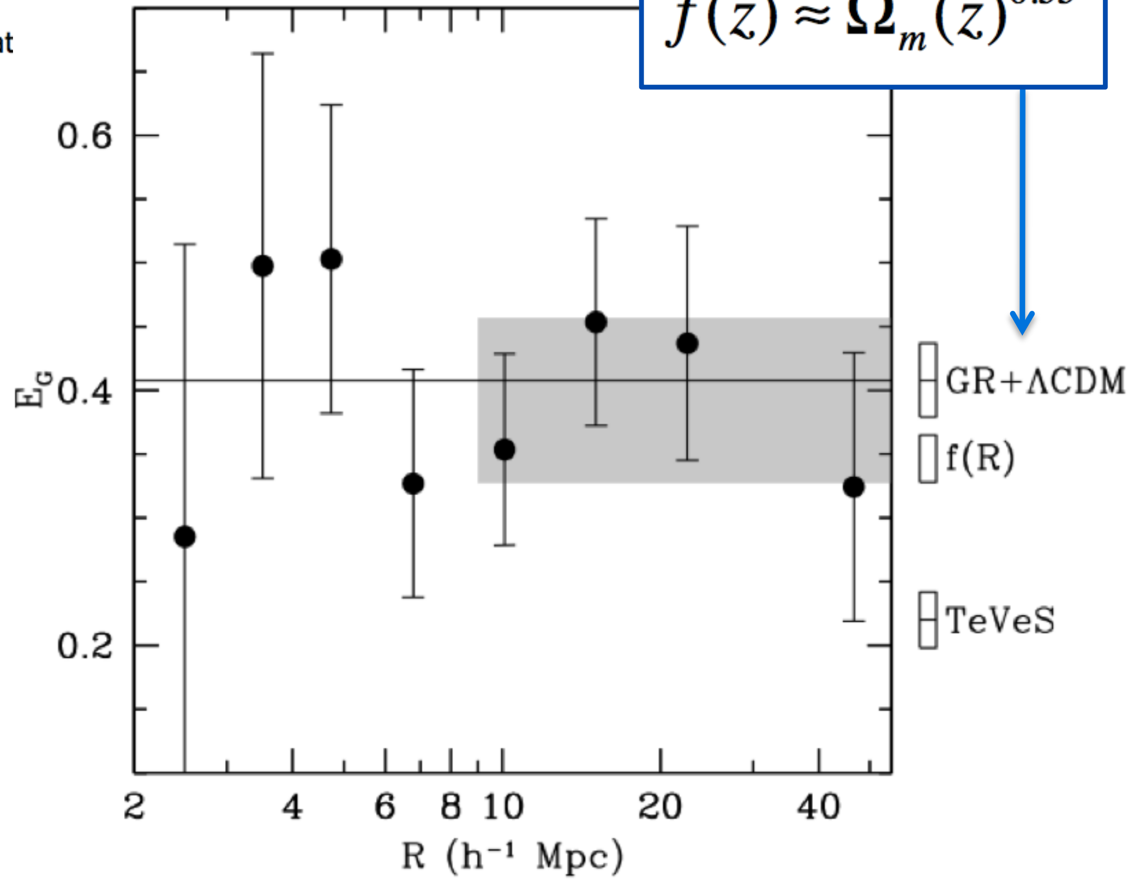
$$E_G = \Omega_{m,0}/f(z)$$

$$f(z) \approx \Omega_m(z)^{0.55}$$

Nature **464**, 256-258 (11 March 2010) | doi:10.1038/nat
August 2009; Accepted 19 January 2010

Confirmation of general relativity on large scales from weak lensing and galaxy velocities

Reinabelle Reyes[1], Rachel Mandelbaum[1], Uros Seljak[2,3,4], Tobias Baldauf[2], James E. Gunn[1], Lucas Lombriser[2] & Robert E. Smith[2]



So far, data is consistent with GR

Today's data may weakly constrain one or two numbers (depending on the assumptions)

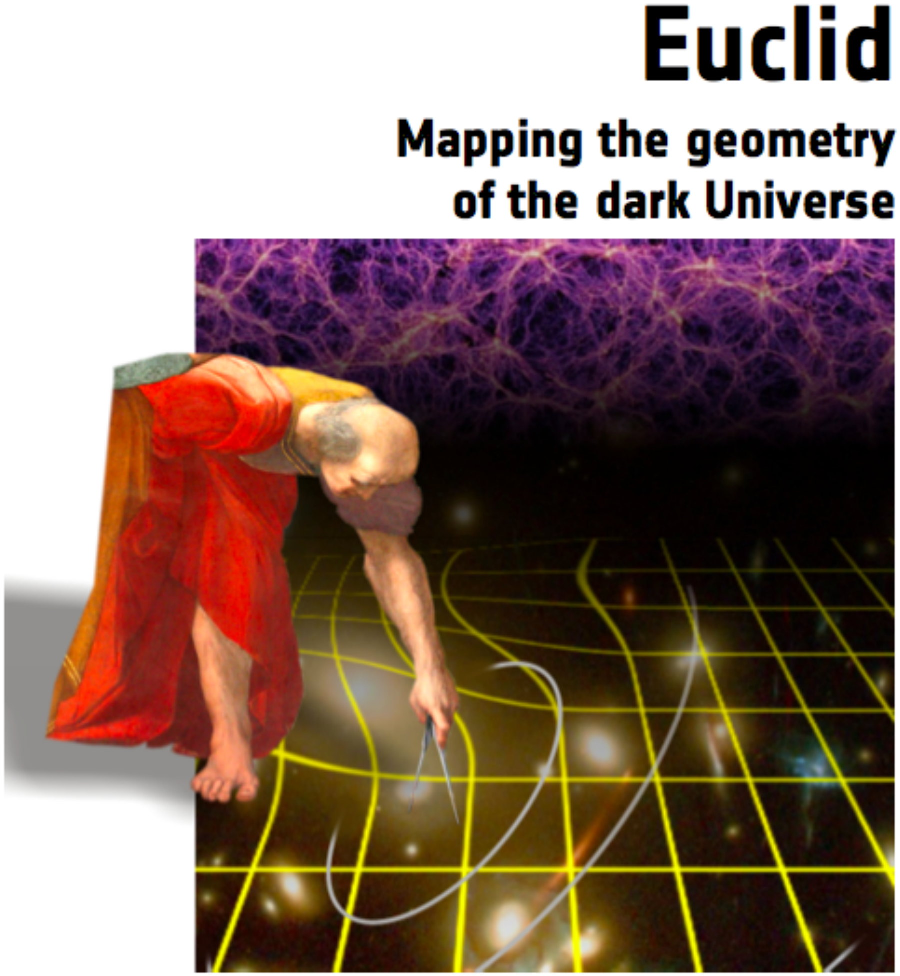
What about tomorrow?

Dark Energy Survey (DES) began in 2012

- Blanco 4-meter telescope
- 5 years
- galaxy shapes, photo-z's, redshifts, SNe

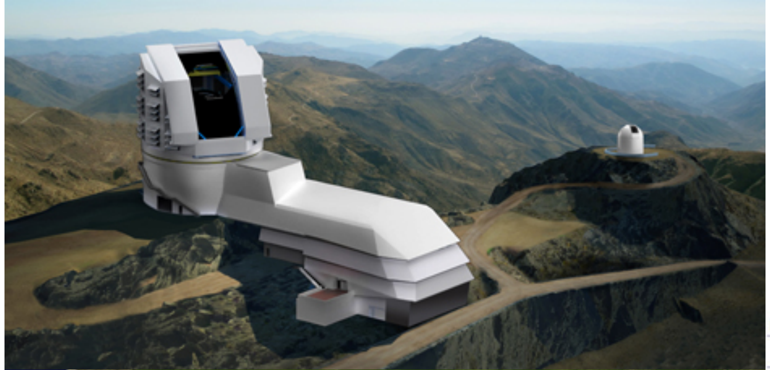
Euclid, ESA, 2019 launch

- L2 Orbit
- 5-6 year mission
- galaxy shapes, photo-z's, redshifts

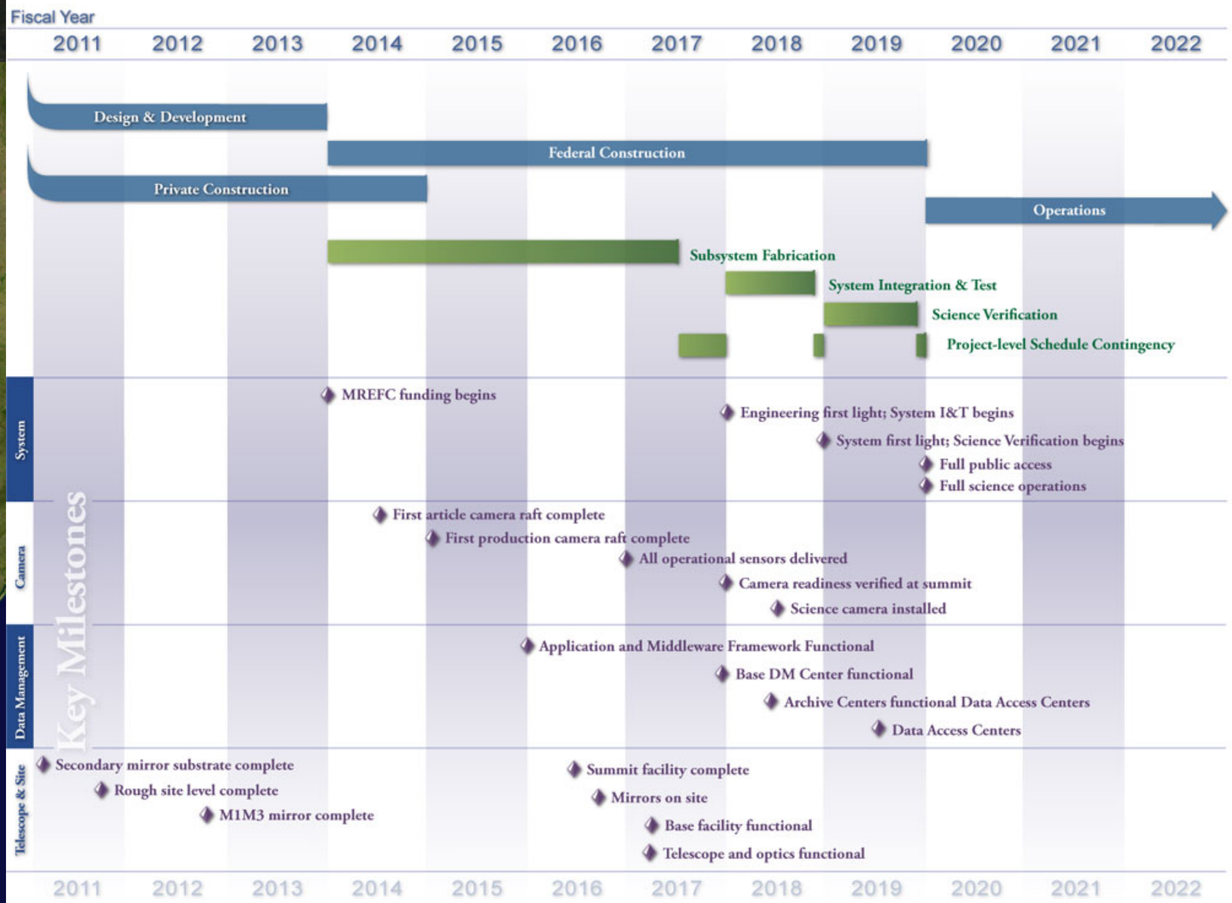


Large Synoptic Survey Telescope

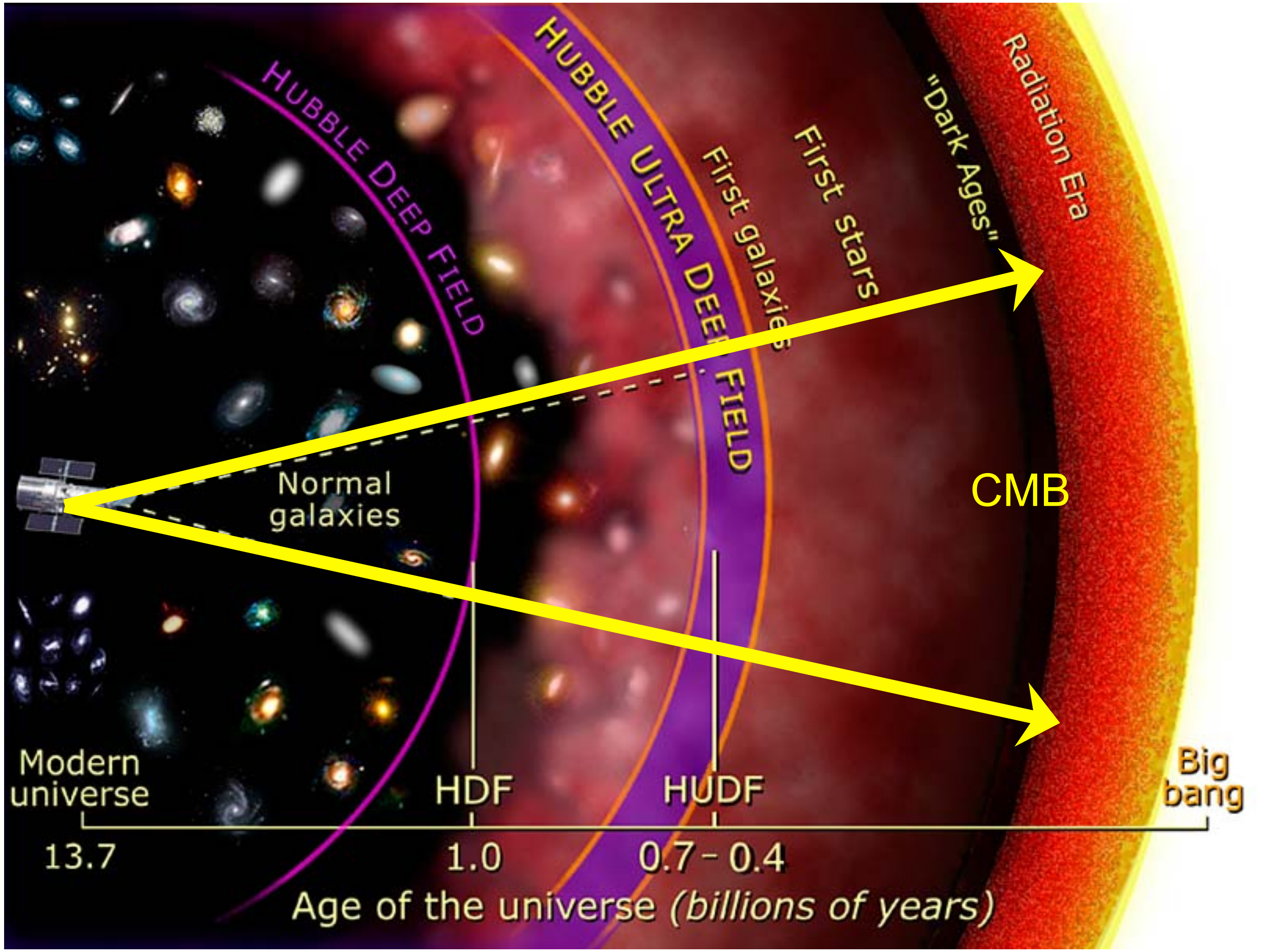
the widest, fastest, deepest eye of the new digital age



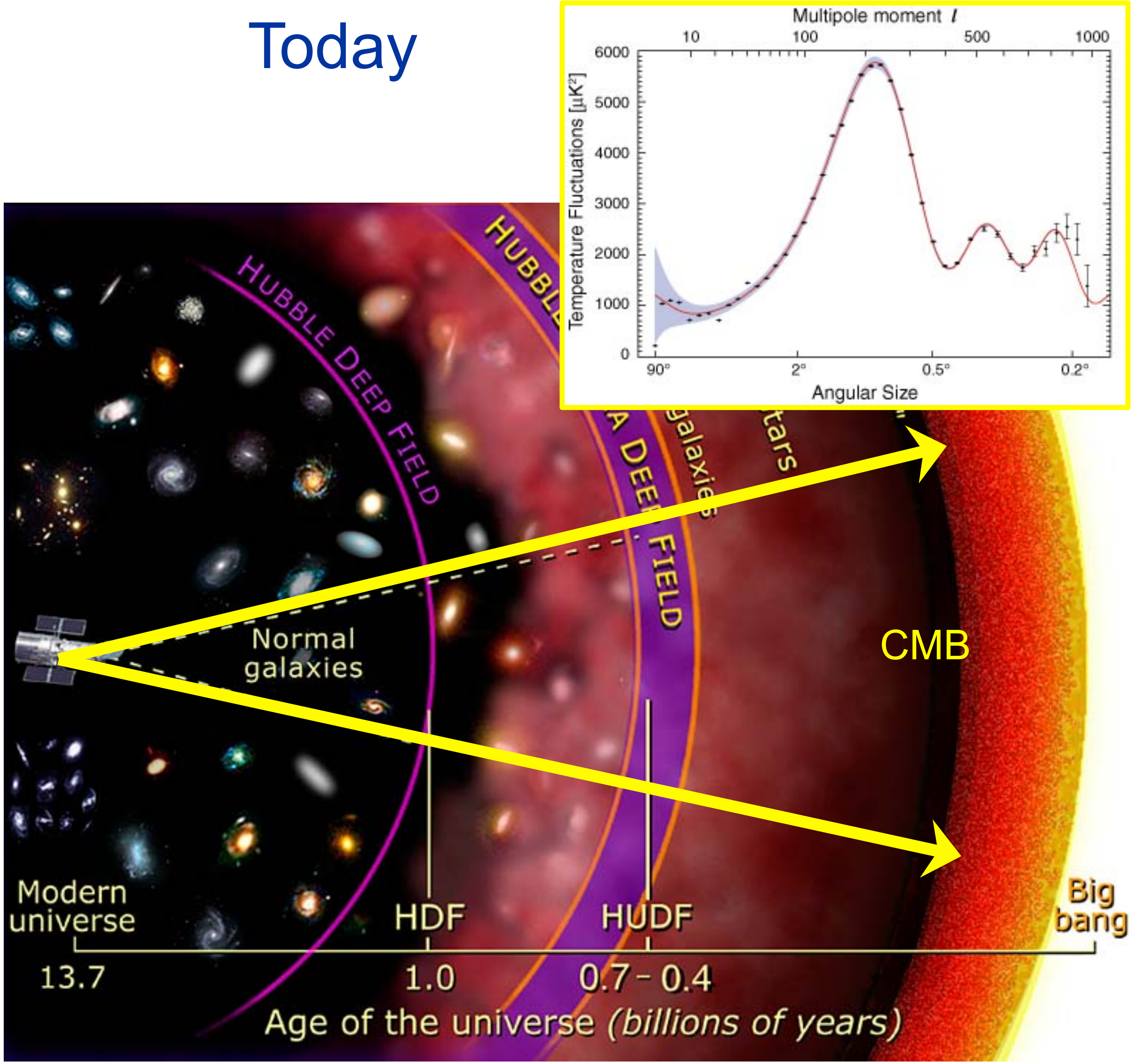
- 8.4 meter mirror
- half of the sky to redshift z=3
- galaxy shapes, photo-z's, SNe



Today

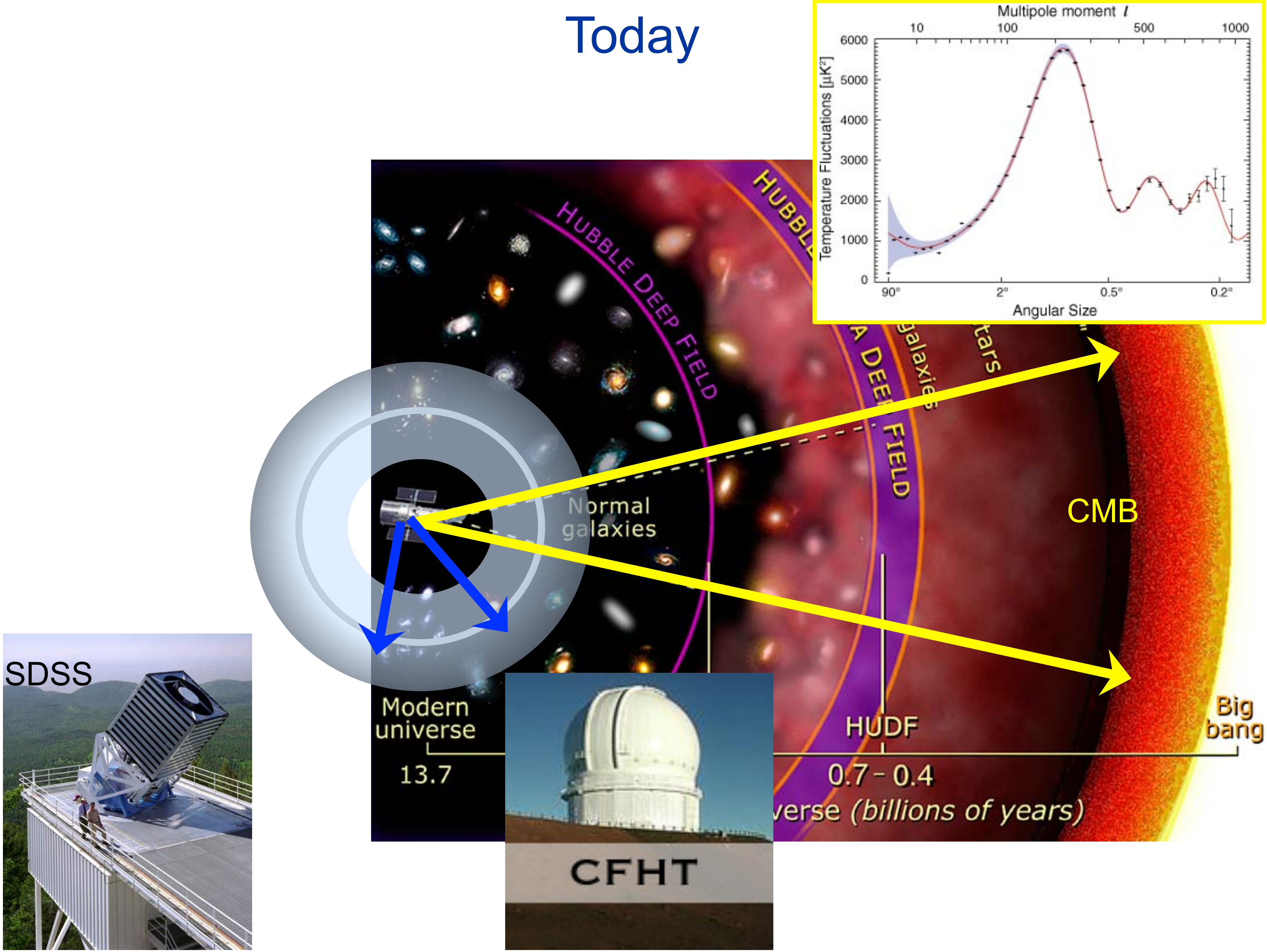

HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal
galaxies
CMB
Modern
universe
HDF
HUDF
Big
bang
13.7
1.0
0.7 - 0.4
Age of the universe (billions of years)

Today



Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
Temperature Fluctuations [μK²]
90°
2°
0.5°
0.2°
Angular Size
HUBBLE DEEP FIELD
Normal galaxies
CMB
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

Today



Multipole moment l
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Temperature Fluctuations [μK²]
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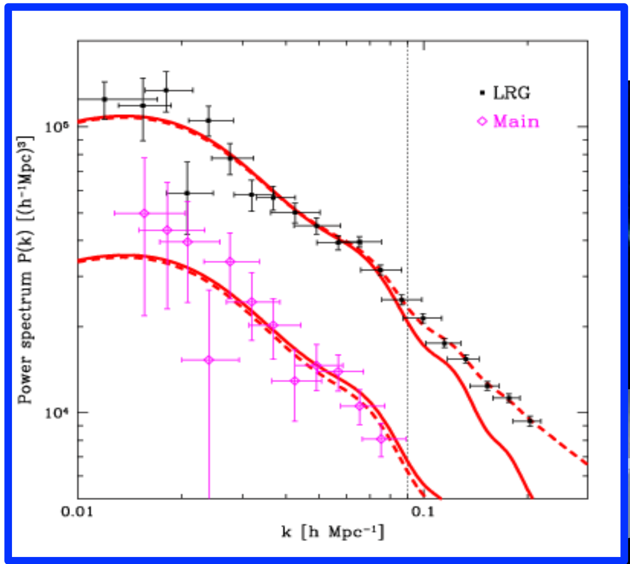
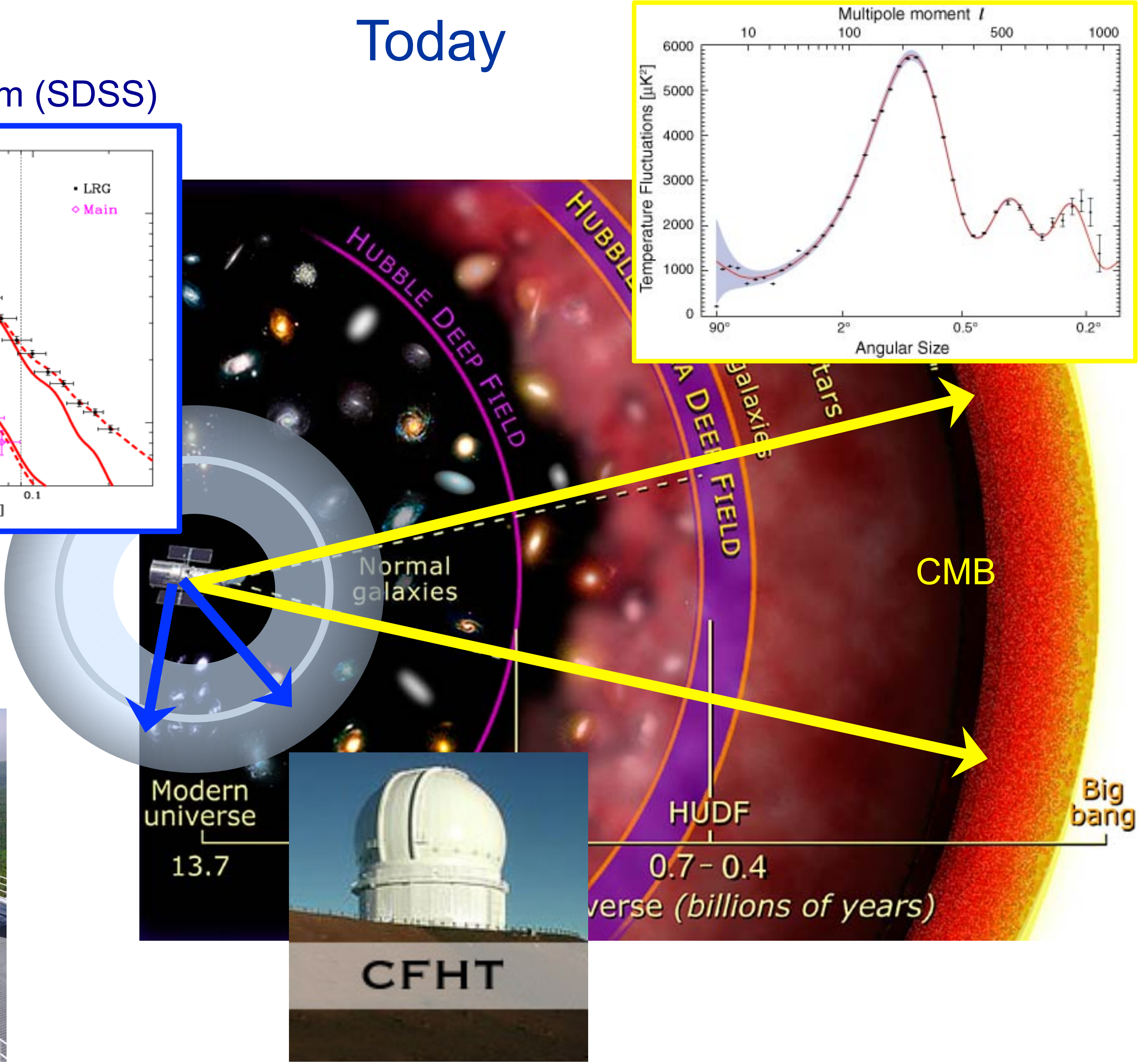
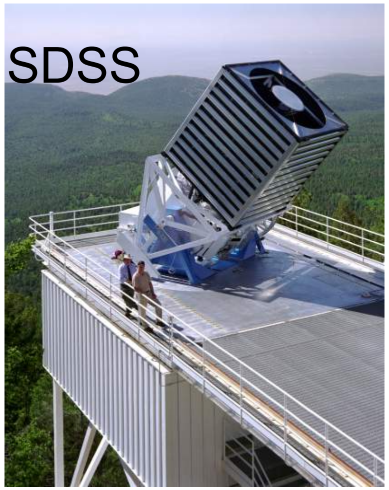
HUBBLE DEEP FIELD
Normal galaxies
CMB
Modern universe
13.7
HUDF
0.7 - 0.4
Big bang
SDSS
CFHT

Today

Matter Spectrum (SDSS)

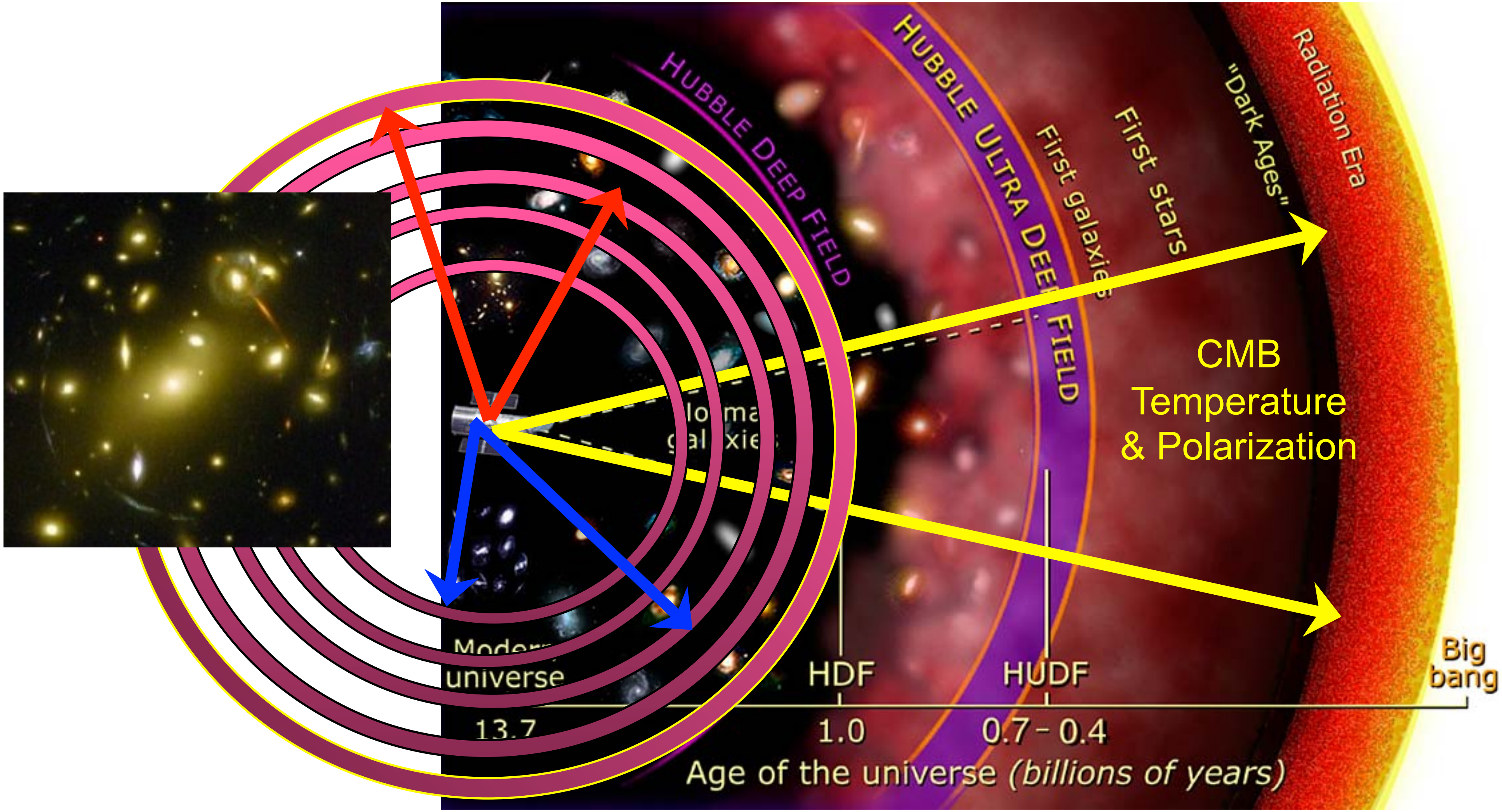






Tomorrow

Weak Lensing of galaxies, CMB lensing



Galaxy Counts and Peculiar Velocities through several epochs
21 cm Intensity mapping

How many modified gravity parameters can we measure in the future?

- Constraining unknown functions, such as $\mu(a,k)$ and $\gamma(a,k)$, is challenging in practice:
  - what parameters should we fit to data?

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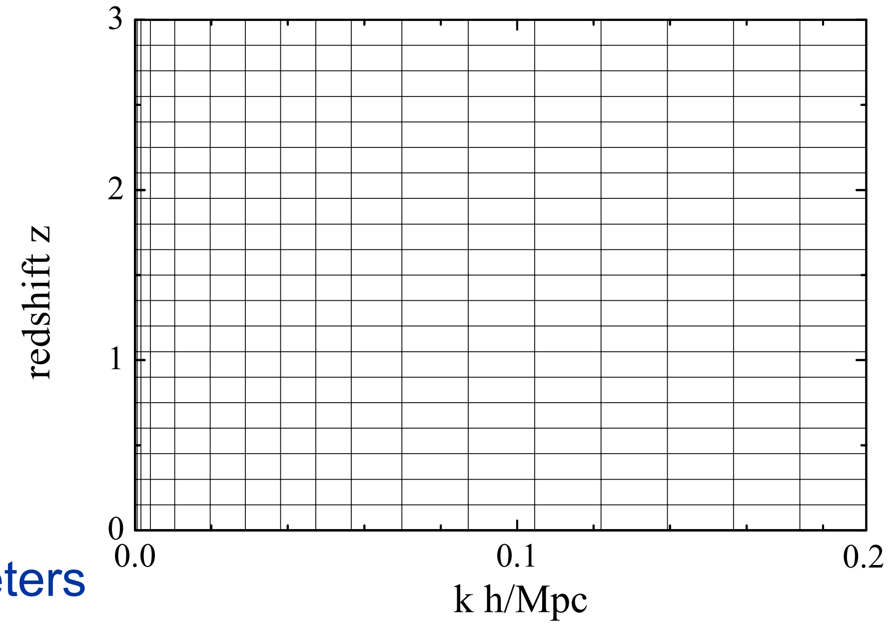
- Principal Component Analysis can be used as a forecast tool

Principle Component Analysis (PCA) forecast
of constraints on $\mu(a,k)$ and $\gamma(a,k)$ for LSST+Planck+…

- discretize μ and γ on a (z,k) grid
- treat each pixel, μ_{ij} and γ_{ij}, as a free parameter
- discretize w(z) on the same z-grid and treat w_i as free parameters, along with Ω_c, Ω_b, h, n_s, A_s, τ and bias

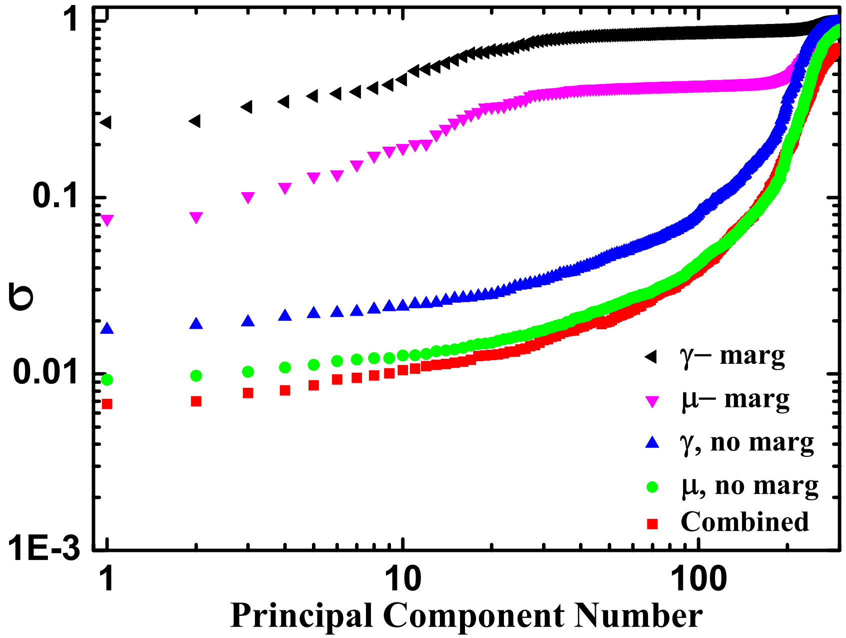


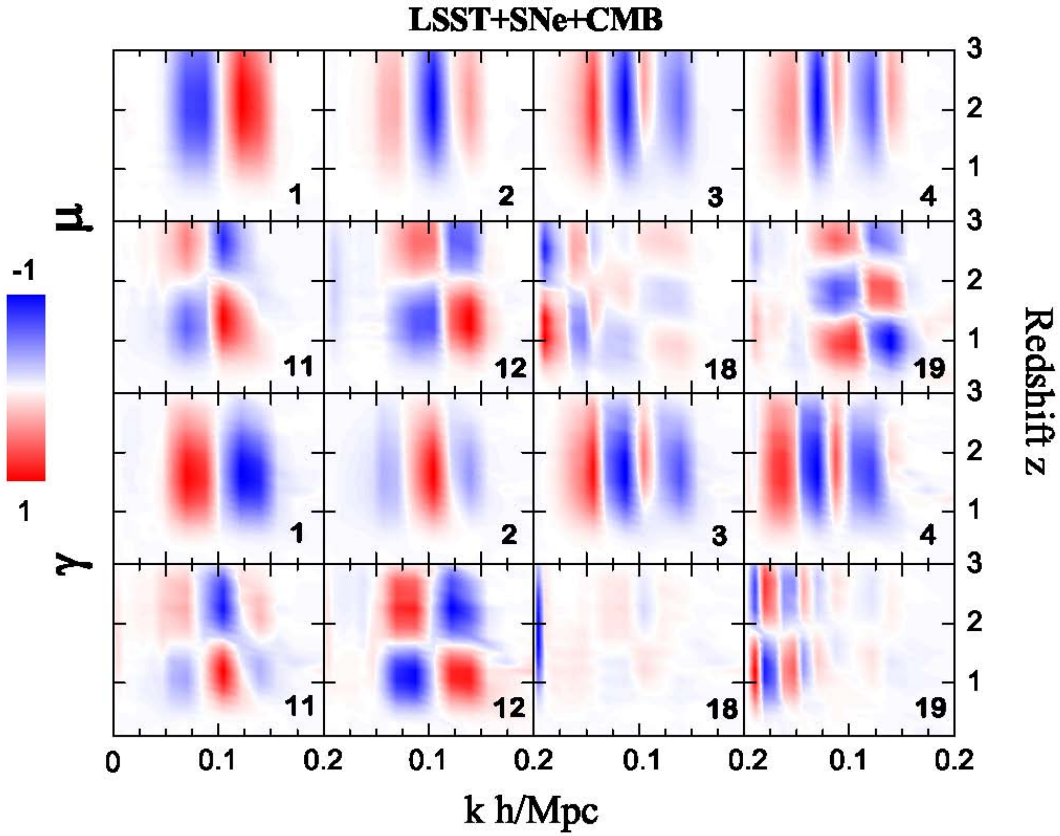
- calculate the Fisher Matrix for 800+ parameters
- diagonalize to find principal components of μ and γ
- PCA provides variances of uncorrelated parameters α_m

$$\boxed{\mu(z,k) - 1 = \sum_m \alpha_m e_m(z,k)}$$

Zhao, LP, Silvestri, Zylberberg, 0905.1326, PRL'09; Hojjati, Zhao et al, 1111.3960, PRD'11

The best constrained eigenmodes





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Zhao, LP, Silvestri, Zylberberg, 0905.1326, PRL'09; Hojjati, Zhao et al, 1111.3960, PRD'11

PCA is a useful forecast tool

- Tells us the features of functions that can be measured best
- Offers a way to compare different observational probes

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But …

- Which eigenmodes are physically meaningful?

  - e.g. the k-dependence cannot be arbitrary

- Which parameters should we fit to data?

Theoretical Priors

Let’s face reality:

- theoretical priors are subjective but unavoidable

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Make them explicit:

- let theory fix the k-dependence
- use explicit smoothness priors on time-dependence

Linear order field equations

	LCDM	Models with new scalar DOFs
Poisson	$k^2\Phi = -4\pi G a^2 \rho\Delta$	$\hat{A}\Psi + \hat{B}\Phi + \hat{C}^i\delta\phi_i = -4\pi G a^2 \rho\Delta$
Anisotropy	$\Phi - \Psi = 0$	$\hat{D}\Psi + \hat{E}\Phi + \hat{F}^i\delta\phi_i = 0$
Extra scalars	N/A	$\hat{H}_i\Psi + \hat{K}_i\Phi + \hat{L}_i{}^j\delta\phi_j = 0$

$$\hat{A} = \sum_{n,m} a_{nm} k^n \partial_0^m$$

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Quasi-Static Approximation

$$\hat{A} = \sum_{n,m} a_{nm} k^n \partial_0^m \longrightarrow A = \sum_n a_{n0} k^n$$

Silvestri, LP, Buniy, 1302.1193, PRD'13

The Quasi-Static Approximation

Two assumptions:

1) Time derivatives are much smaller than space derivatives

2) The sub-horizon limit: $\frac{k}{aH} \gg 1$

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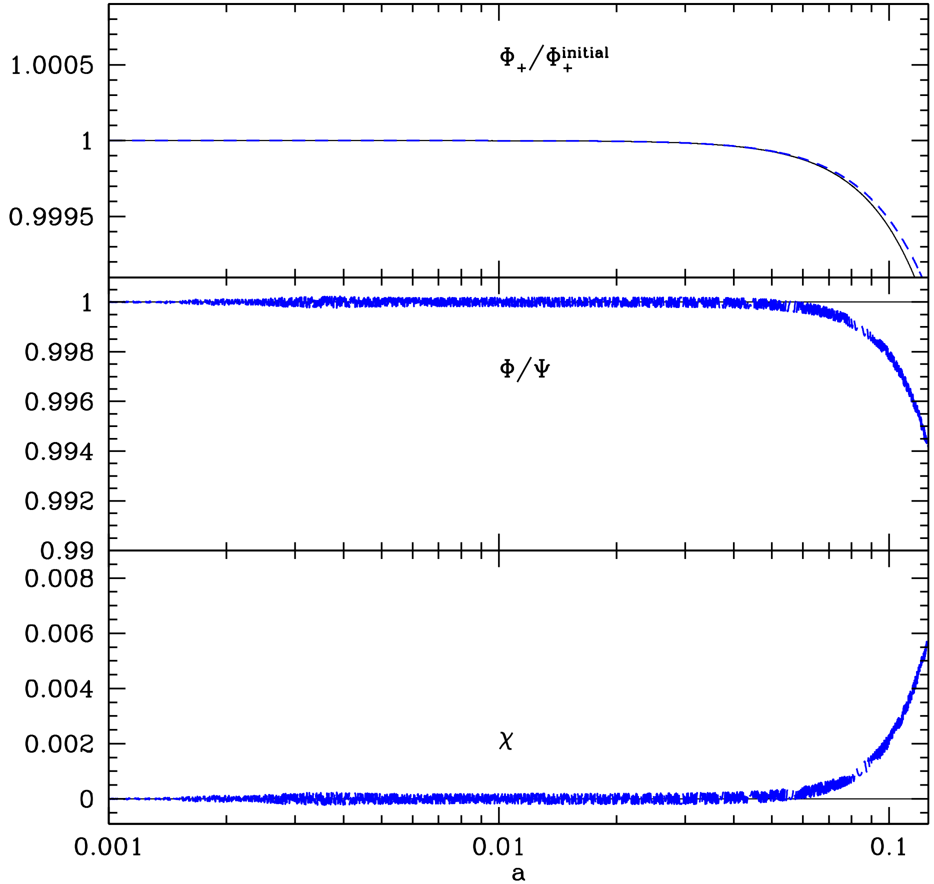

<u>Example</u>: “scalaron” oscillations in f[R]

Q: Are non-QS features detectable?

A: Not in known viable models

Poisson: $\hat{A}\Psi + \hat{B}\Phi + \hat{C}^i\delta\phi_i = -4\pi G a^2 \rho\Delta$

Anisotropy: $\hat{D}\Psi + \hat{E}\Phi + \hat{F}^i\delta\phi_i = 0$

EOM for extra scalar fields: $\hat{H}_i\Psi + \hat{K}_i\Phi + \hat{L}_i{}^j\delta\phi_j = 0$

Quasi-Static Approximation

$$\hat{A} = \sum_{n,m} a_{nm} k^n \partial_0^m \longrightarrow A = \sum_n a_{n0} k^n$$

$$\gamma(a,k) = \frac{\Phi}{\Psi} = \frac{\sum_n h_n^{(1)}(a) k^n}{\sum_n h_n^{(2)}(a) k^n}$$

$$\mu(a,k) = \frac{-k^2\Psi}{4\pi G a^2 \rho\Delta} = \frac{\sum_n h_n^{(2)}(a) k^n}{\sum_n h_n^{(3)}(a) k^n}$$

Silvestri, LP, Buniy, 1302.1193, PRD’13

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same

- Ratios of polynomials with only even powers of k for scalar DOF on isotropic backgrounds

- Second order in k if only one scalar DOF with 2nd order EOM

$$\gamma = \frac{p_1(a) + p_2(a) k^2}{1 + p_3(a) k^2}$$

$$\mu = \frac{1 + p_3(a) k^2}{p_4(a) + p_5(a) k^2}$$

Silvestri, LP, Buniy, 1302.1193, PRD'13

A fairly general ansatz

$$\gamma = \frac{p_1(a) + p_2(a)k^2}{1 + p_3(a)k^2}$$

$$\mu = \frac{1 + p_3(a)k^2}{p_4(a) + p_5(a)k^2}$$

Two functions of two variables $\mu(a,k)$ and $\gamma(a,k)$	→	Five functions of one variable $p_i(a)$, i=1,…5

- Applies to 2nd order theories with a single scalar – the general Horndeski action
- $p_i(a)$ can be mapped onto parameters of specific models
- Not all $p_i(a)$ are independent in specific models – can adopt additional priors

Things one can do with

$$\gamma = \frac{p_1(a) + p_2(a)k^2}{1 + p_3(a)k^2}$$

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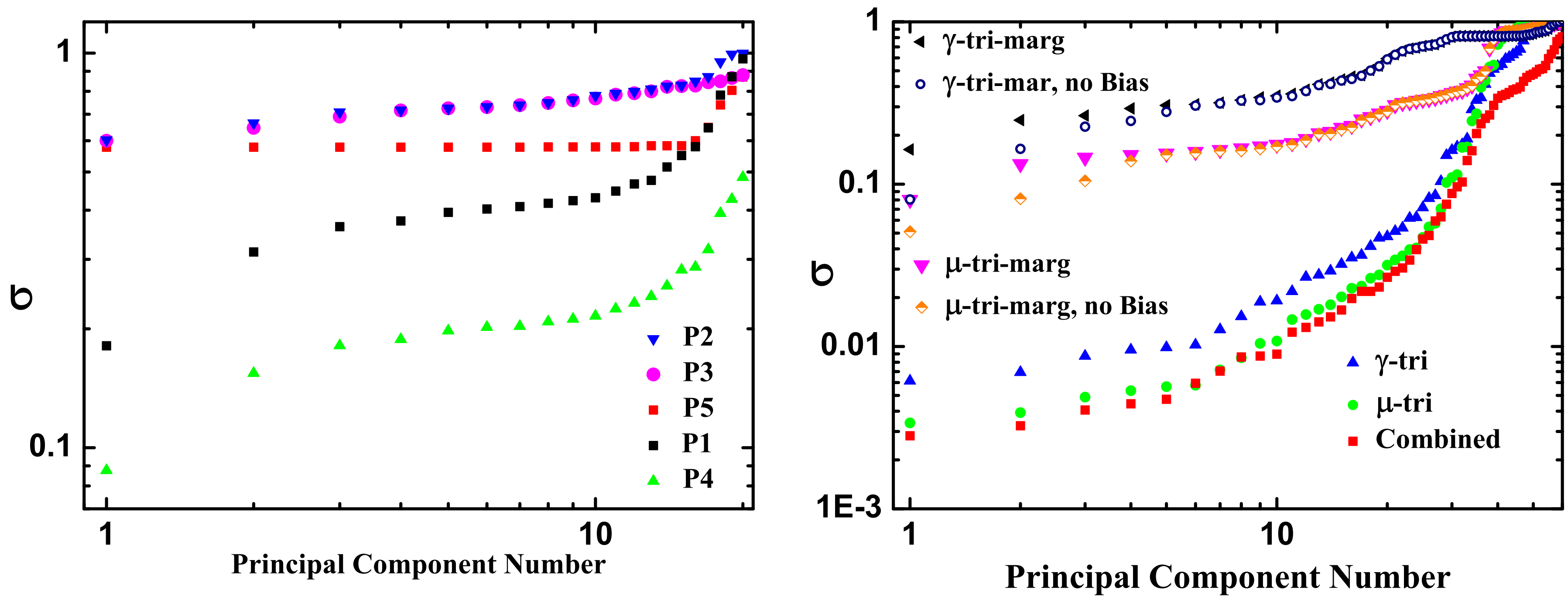
1) Forecast the number of observable eigenmodes of $p_i(a)$

PHYSICAL REVIEW D **89,** 083505 (2014)

Observable physical modes of modified gravity

Alireza Hojjati,[1,2] Levon Pogosian,[1] Alessandra Silvestri,[3,4,5] and Gong-Bo Zhao[6,7]



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2) Check for consistency of data with this k-dependence

Amendola, Motta, Kunz, Saltis, Sawicki, 1305.0008; 1210.0439

3) Assume parametric forms for $p_i(a)$ (e.g. a power law) and fit parameters to data

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Amendola, Motta, Kunz, Saltis, Sawicki, 1305.0008; 1210.0439

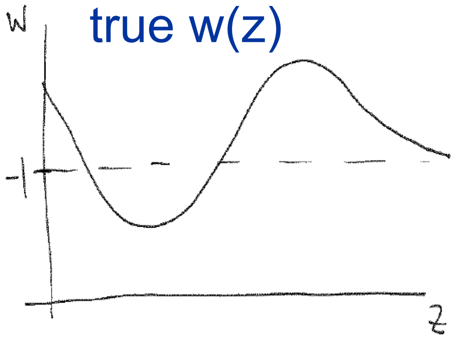
3) Assume parametric forms for $p_i(a)$ (e.g. a power law) and fit parameters to data

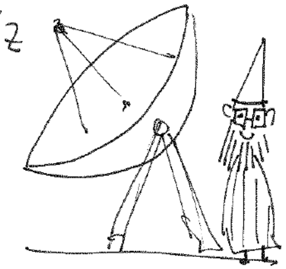
4) Try reconstructing $p_i(a)$ from data :

use the example of $w(a)$

Crittenden, Zhao, LP, Samushia, Zhang, 1112.1693, JCAP'12; 1207:3804, PRL'12

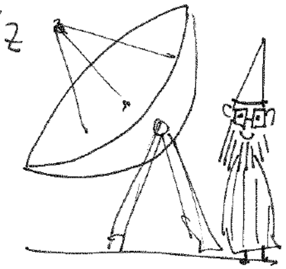
true w(z)





MCMC
using <u>many</u> w-bins

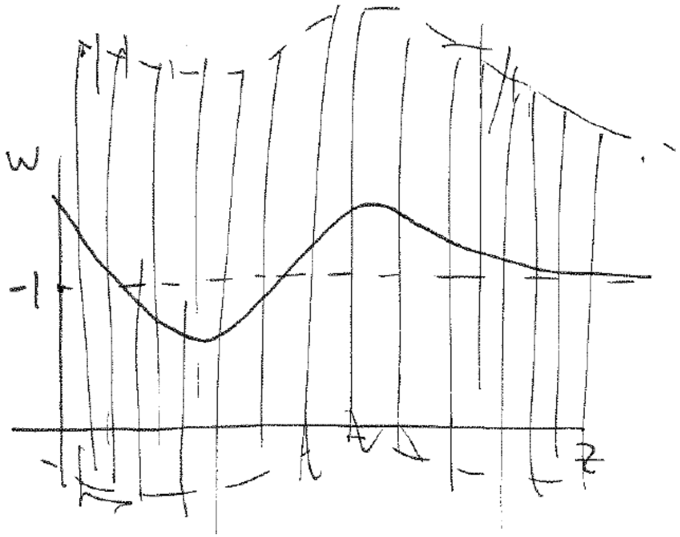
true w(z)



no prior

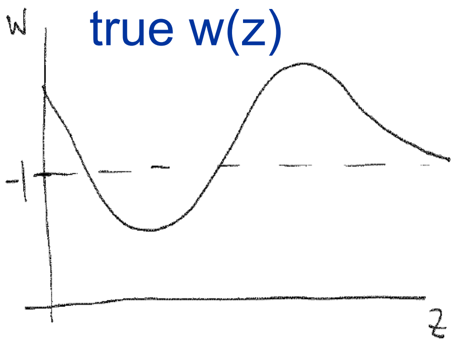
MCMC
using <u>many</u> w-bins

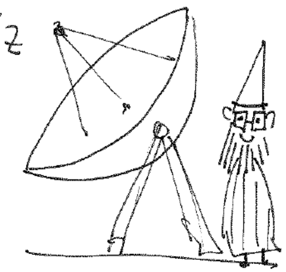
reconstructed w(z)



- MCMC will not converge
- large variance
- zero bias

true w(z)

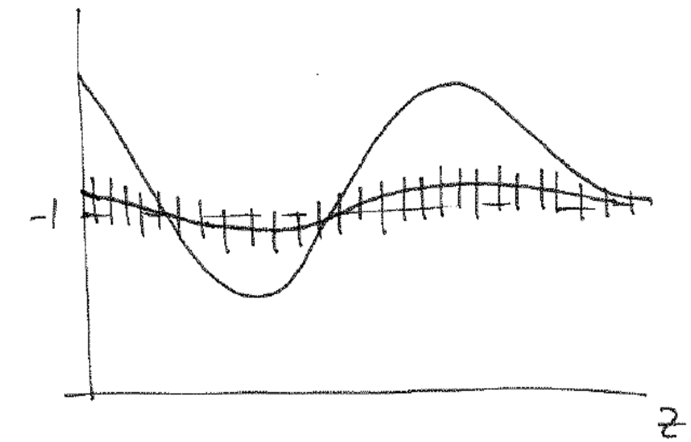




Excessively strong prior

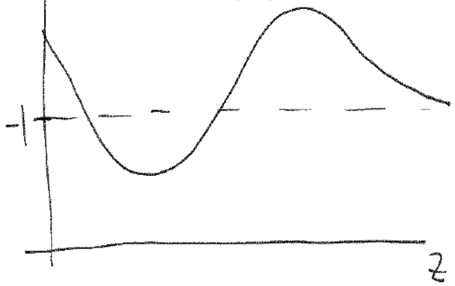
MCMC
using <u>many</u> w-bins

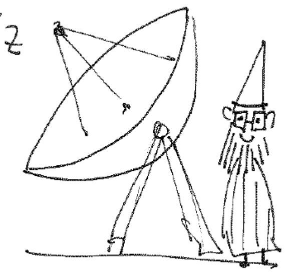
reconstructed w(z)



- tiny error bars (small variance)
- large bias

true w(z)

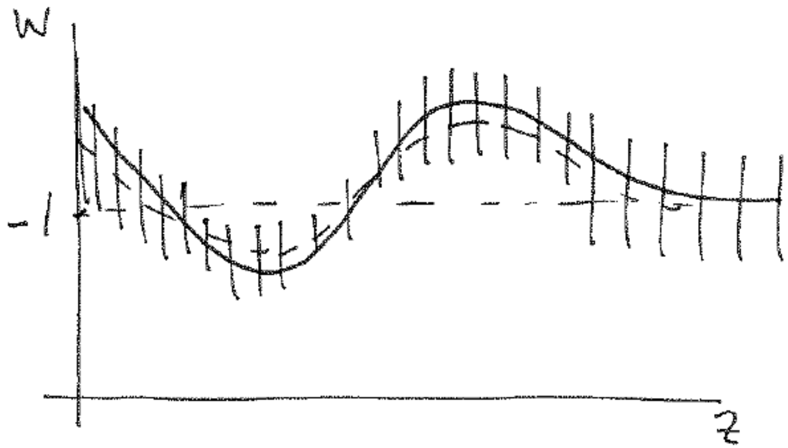




reasonable prior

MCMC
using <u>many</u> w-bins

reconstructed w(z)



- moderate variance
- insignificant bias

What is reasonable?

- Introduce an explicit prior that favors **smoothness**

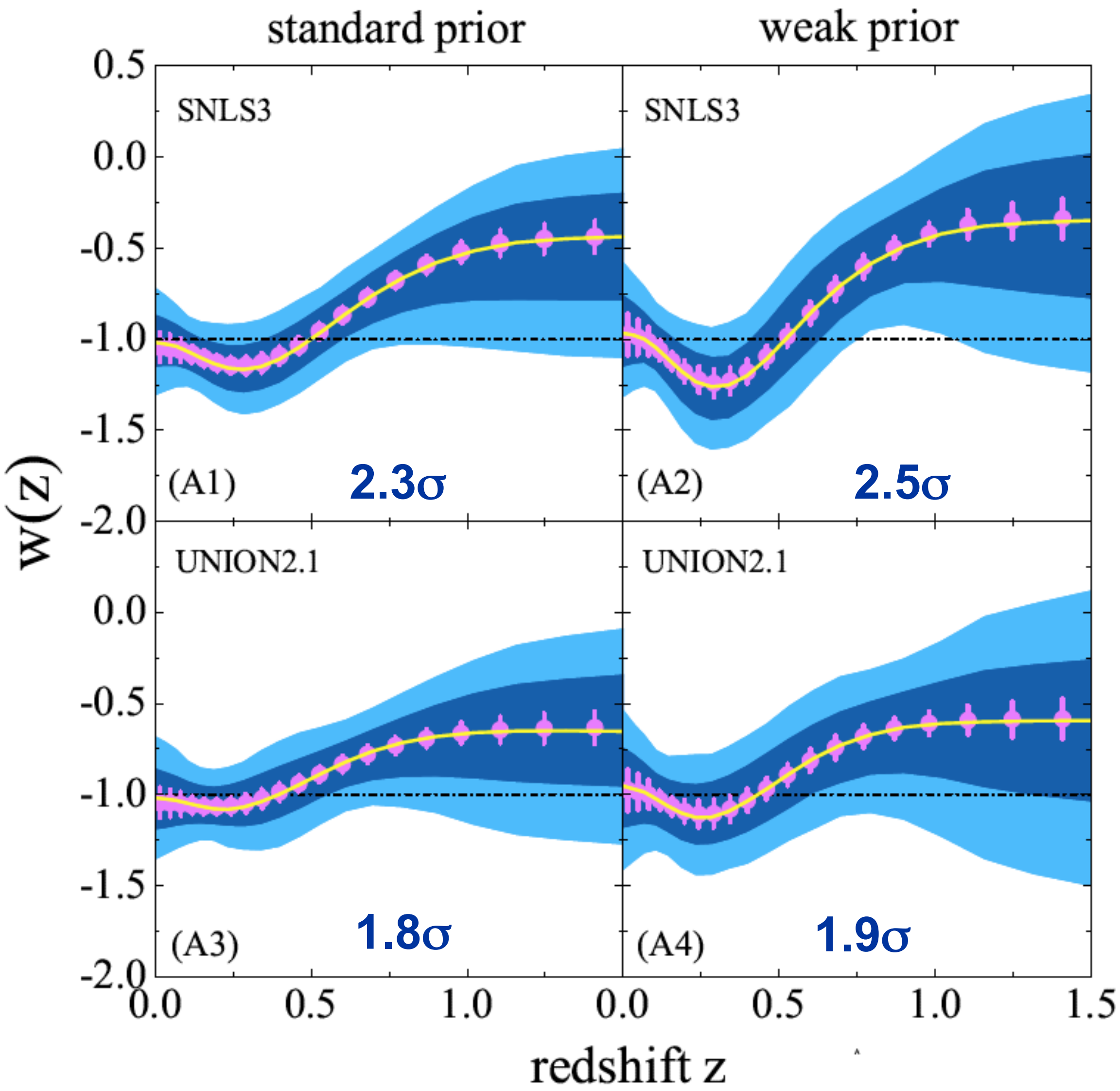
  All reconstructions involve such a prior, but it is often implicit

- Smooth features (well constrained by data) are not biased by the prior

- Noisy features (poorly constrained by data) are determined by the prior

Crittenden, Zhao, LP, Samushia, Zhang, 1112.1693, JCAP’12

Reconstruction of w



Zhao, Crittenden, LP, Zhang, 1207:3804, PRL’12

Summary

- Future data will map cosmological perturbations and test validity of Einstein's equation

- A key test: compare the "dynamical" mass to the "lensing" mass

- Tests of GR require a framework to model the alternatives

- General frameworks involve unknown functions and, inevitably, must be supplemented by priors to eliminate unphysical solutions and to define parameters that can be fit data

- Tests on linear cosmological scales are only a part of the whole story: they should be considered in conjunction with astrophysical, solar system and terrestrial tests of gravity

Workshop on Testing Gravity at SFU Harbour Centre

January 15-17, 2015

- Alternative theories of gravity
- Pulsars and other astrophysical tests
- Gravitational wave detectors
- Gravity at short distances
- Quantum gravity and black holes
- Cosmological tests - CMB, large scale structure

SFU TRIUMF …

http://www.sfu.ca/physics/cosmology/TestingGravity2015.html