Pacific 2014

Testing gravity with large scale structure dynamics

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THE UNIVERSITY OF CHICAGO
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SIMONS FOUNDATION
MATHEMATICS & THE PHYSICAL SCIENCES

Outline

- Accelerating expansion
- Growth of structure & Expansion history
- Redshift space distortions :
  an important cosmological probe
- Measuring the growth rate:
  Dark energy vs. modified gravity

EJ, B. Li, C.M. Baugh, G. Zhao, K. Kazuya 2013
EJ 2012
EJ, C. M. Baugh, S. Pascoli 2011

Probing Dark Energy

Supernovae, CMB BAO, Weak Lensing & Cluster observations → **ΛCDM cosmology**

$\Omega_{TOTAL} \sim 1$
~25% Dark Matter
~75% Dark Energy

What is causing the accelerating expansion ?

Is dark energy constant or does it evolve with time?
General Relativity or Modified gravity?

Missions to study the dark sector need precise measurements:

Expansion history $H(z)$
Growth rate $f = d\ln D/d\ln a$

Probing Dark Energy

WiggleZ
BOSS
DES

→ BAO, Pk/ξ, SN $0.5<z<0.9$ (WiggleZ, BOSS, DES)

DES → Weak lensing shear signal, clusters, SN

EUCLID
WFIRST
eBOSS

→ BAO, Pk/ξ, SN $1<z<3$ (EUCLID, WFIRST, eBOSS)

PFS → $0.6<z<1$

DESI → $0.8<z<2.4$

HETDEX → $0.6<z<1.5$, quasers $1<x<3.5$

LSST

Goal:

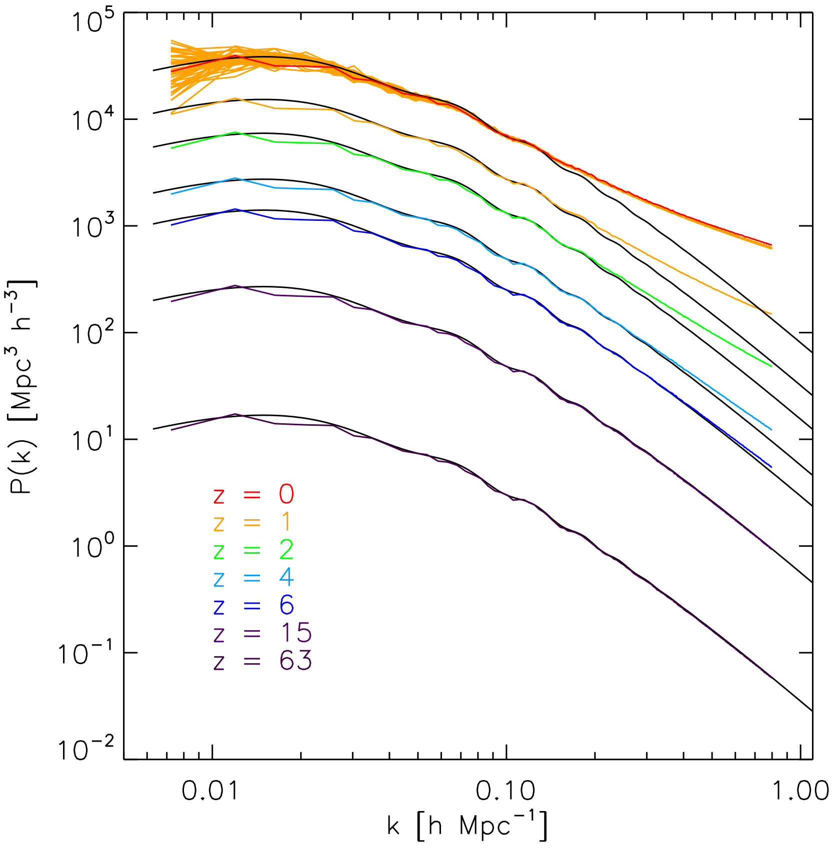
Measure the growth rate to 1% over $0.25<z<3$

Expansion rate to <1%

N-body simulations are an essential tool

- Model nonlinear fluctuation growth, peculiar motions, nonlinear and scale dependent bias

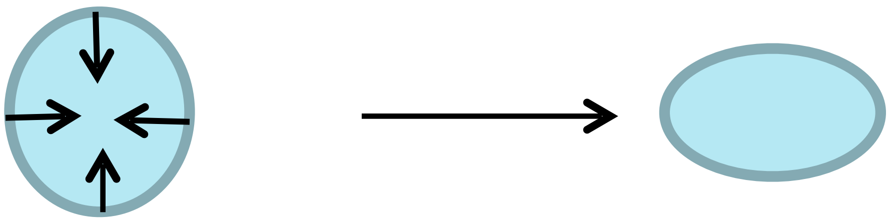
- Study nonlinear growth in different cosmologies



Angulo et al. 2008

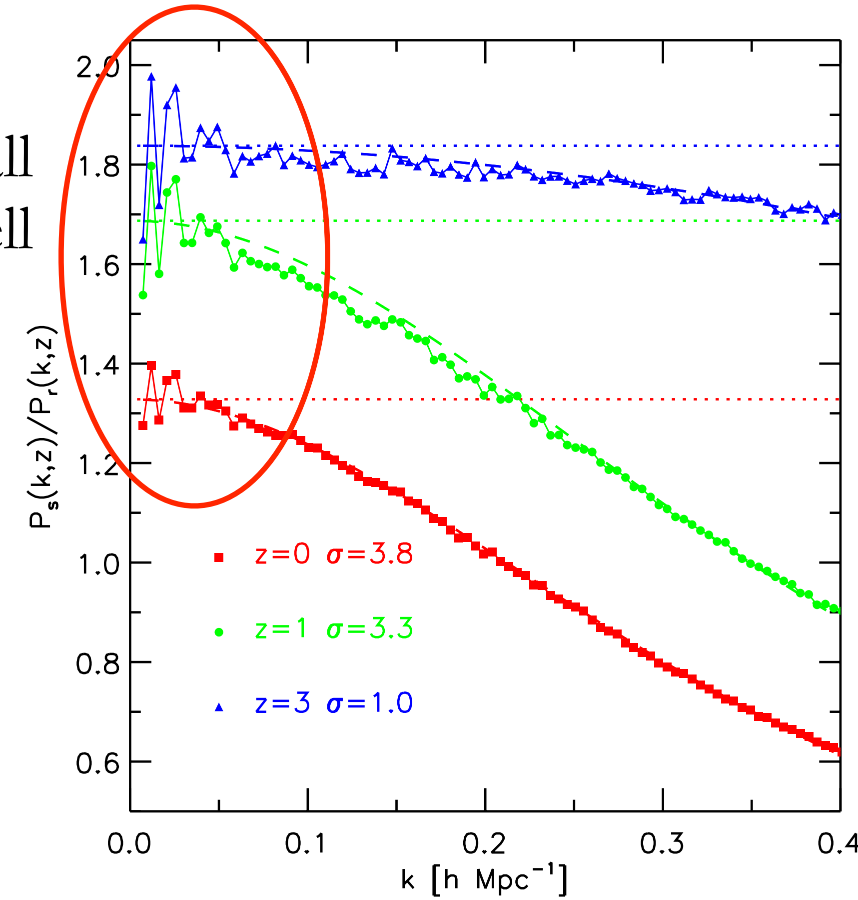
Redshift space distortions

Real space **Redshift space**



$$s = r + v$$

Large scales: Galaxies undergoing infall towards a spherical overdensity : shell appears squashed.



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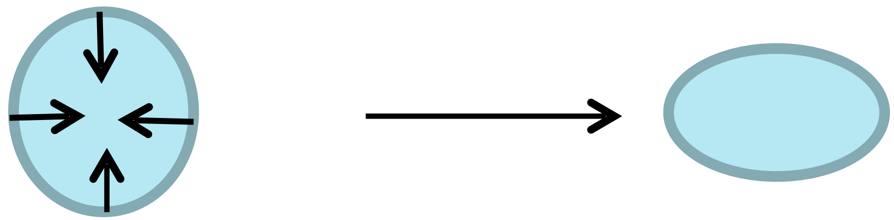

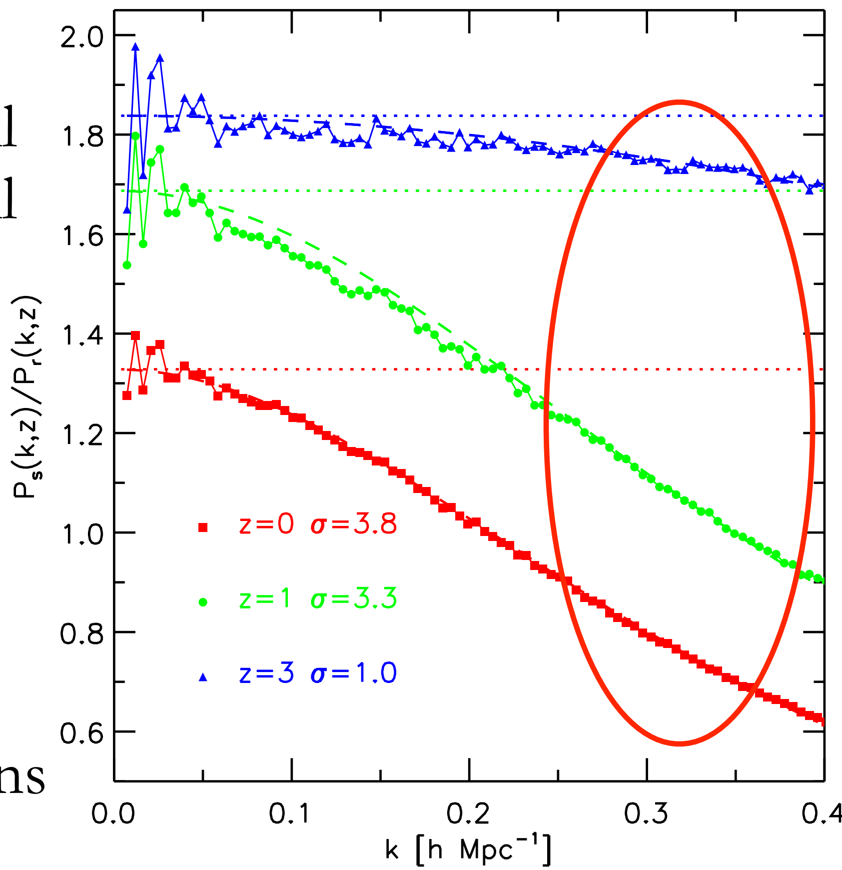

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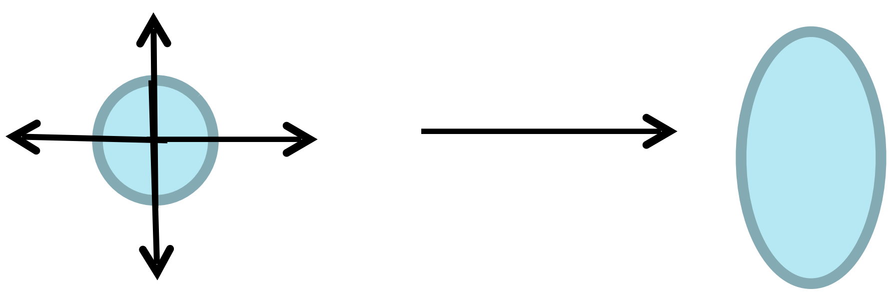


Small scales: Incoherent peculiar motions giving rise to "fingers-of-god".

Clustering statistics

The Dark Energy Science report aka “Rocky III” :
RSD “among the most powerful ways of addressing whether the acceleration is caused by dark energy or modified gravity"

$$\delta_D(\vec{k}) + P(k,\mu) = \int \frac{\mathrm{d}^3 r}{(2\pi)^3} e^{-i\vec{k}\cdot\vec{r}} \langle e^{ik\mu\Delta u_z}[1+\delta(\vec{x})][1+\delta(\vec{x}')]\rangle$$

Power spectrum in redshift space

$$v_z(\vec{x}) - v_z(\vec{x}')$$

Linear theory

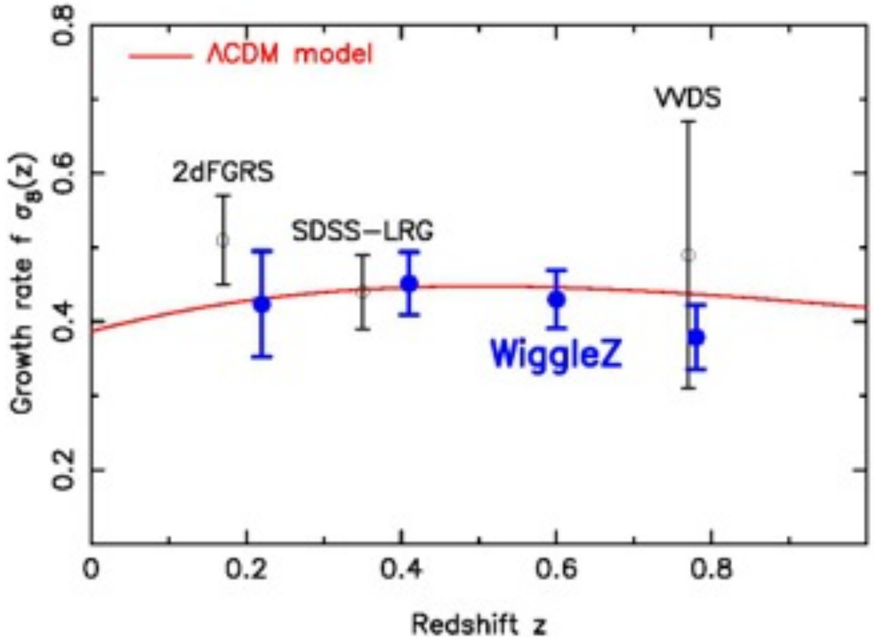
$$\delta_s(r) = \delta_r(r)(1+\mu^2\beta)$$

Growth rate

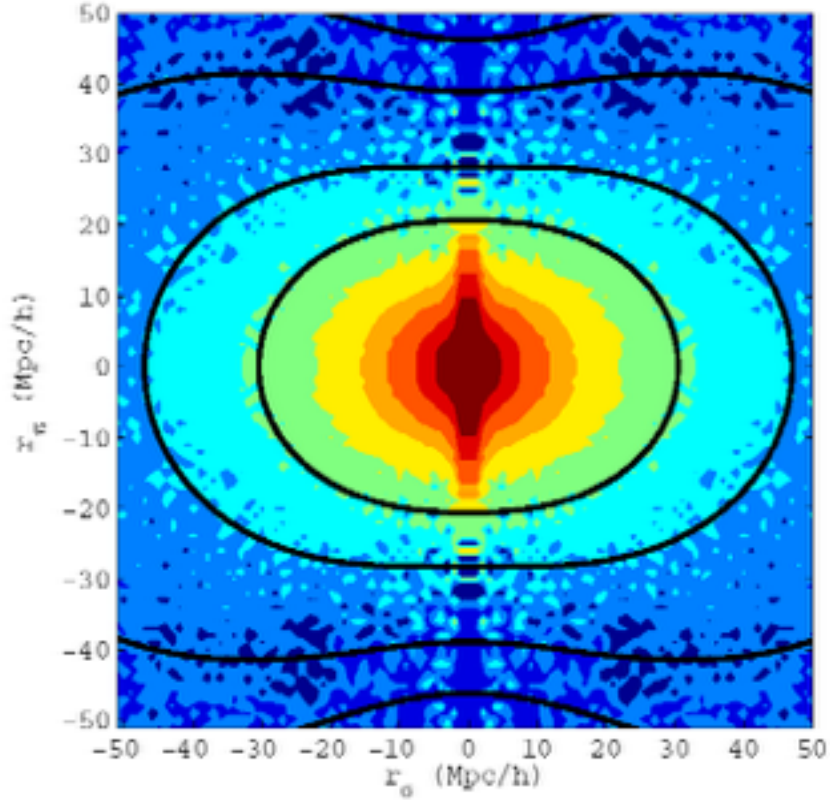
$$\beta = f/b$$

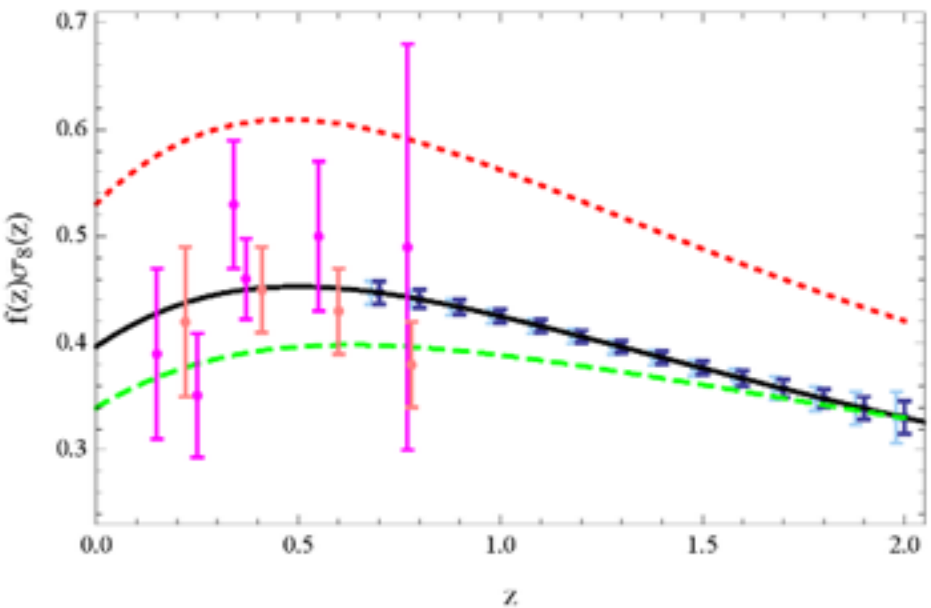
Linear bias

Current measurements & forecasts



Blake et al 2011





$z=0.57$: $f\sigma_8(a) = 0.43 \pm 0.07$

Reid et al. 2012

Majerotto et al. 2012

Clustering statistics

Power spectrum in linear theory

$$P_s(k,\mu) = P_r(k)(1+\mu^2\beta)^2$$

$$\beta = f/b$$

Growth rate → f

Linear bias → b

$$P_l^s(k) = \frac{2l+1}{2}\int_{-1}^{1} P(k,\mu)L_l(\mu)\mathrm{d}\mu$$

$$\begin{pmatrix} P_0(k) \\ P_2(k) \end{pmatrix} = P_m(k)\begin{pmatrix} 1+\frac{2}{3}\beta+\frac{1}{5}\beta^2 \\ \frac{4}{3}\beta+\frac{4}{7}\beta^2 \end{pmatrix}$$

Kaiser (1987)

Correlation function

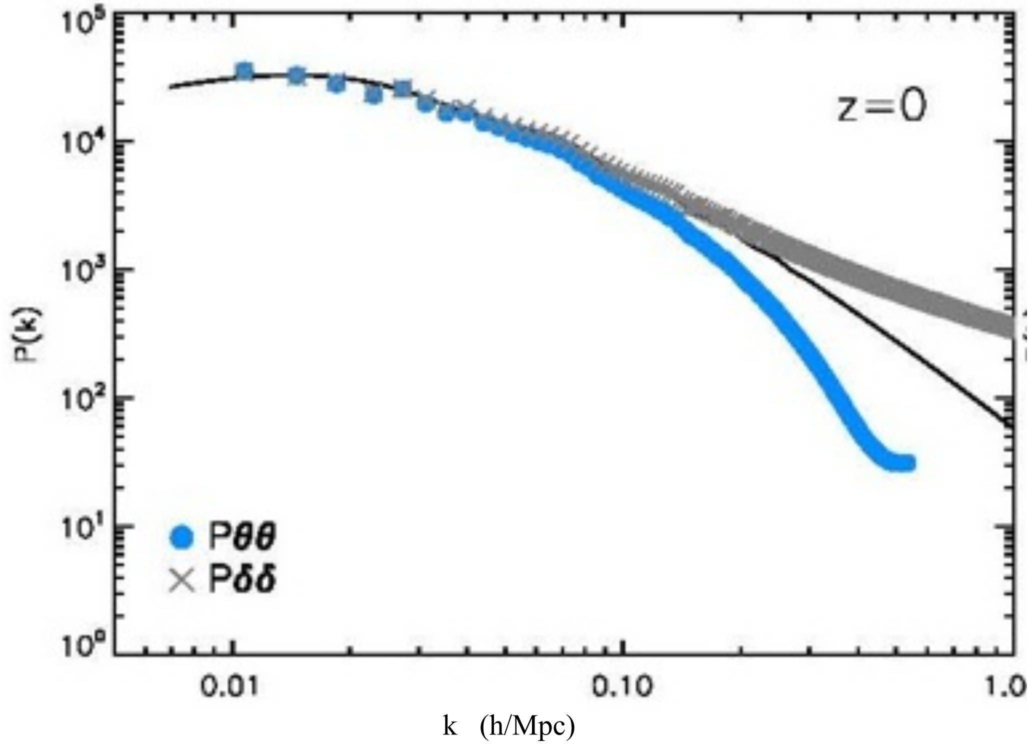
$$\begin{pmatrix} \xi_0(s) \\ \xi_2(s) \end{pmatrix} = \begin{pmatrix} \left(1+\frac{2}{3}\beta+\frac{1}{5}\beta^2\right)\xi(r) \\ \left(\frac{4}{3}\beta+\frac{4}{7}\beta^2\right)\left[\xi(r)-\bar{\xi}(r)\right] \end{pmatrix}$$

Improved model for the redshift space P(k):

$$P^s(k,\mu) = (P_{\delta\delta} + 2\mu^2 P_{\delta\theta} + \mu^4 P_{\theta\theta})$$

Velocity divergence cross P(k)

Velocity divergence auto P(k)



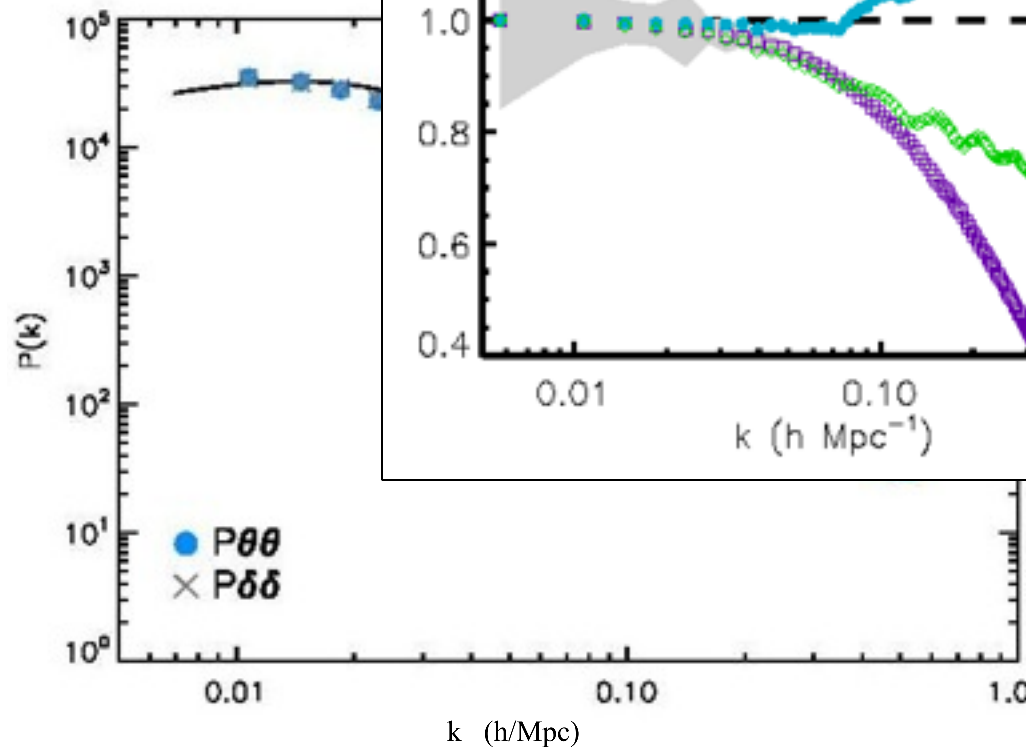
On what scales is the linear continuity equation valid ?

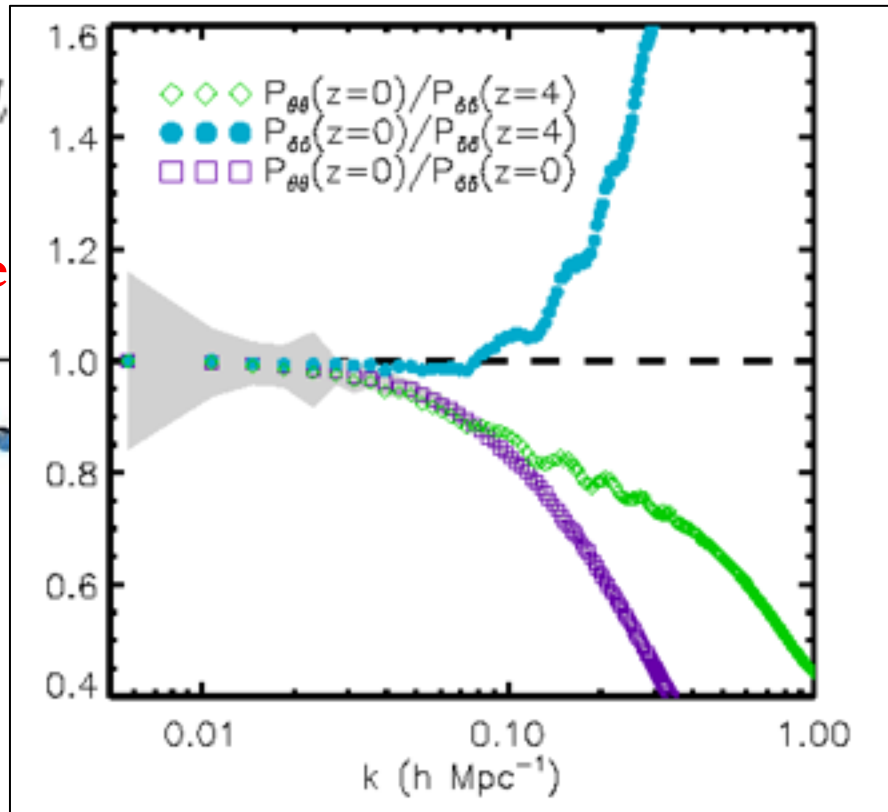
$$\vec{\nabla} \cdot \vec{v} = \theta = -Hf(a)\delta(a)$$

Improved model for the redshift space P(k):

$$P^s(k, \mu \quad \ldots \quad \mu^4 P_{\theta\theta})$$

Velocity dive … ergence auto P(k)



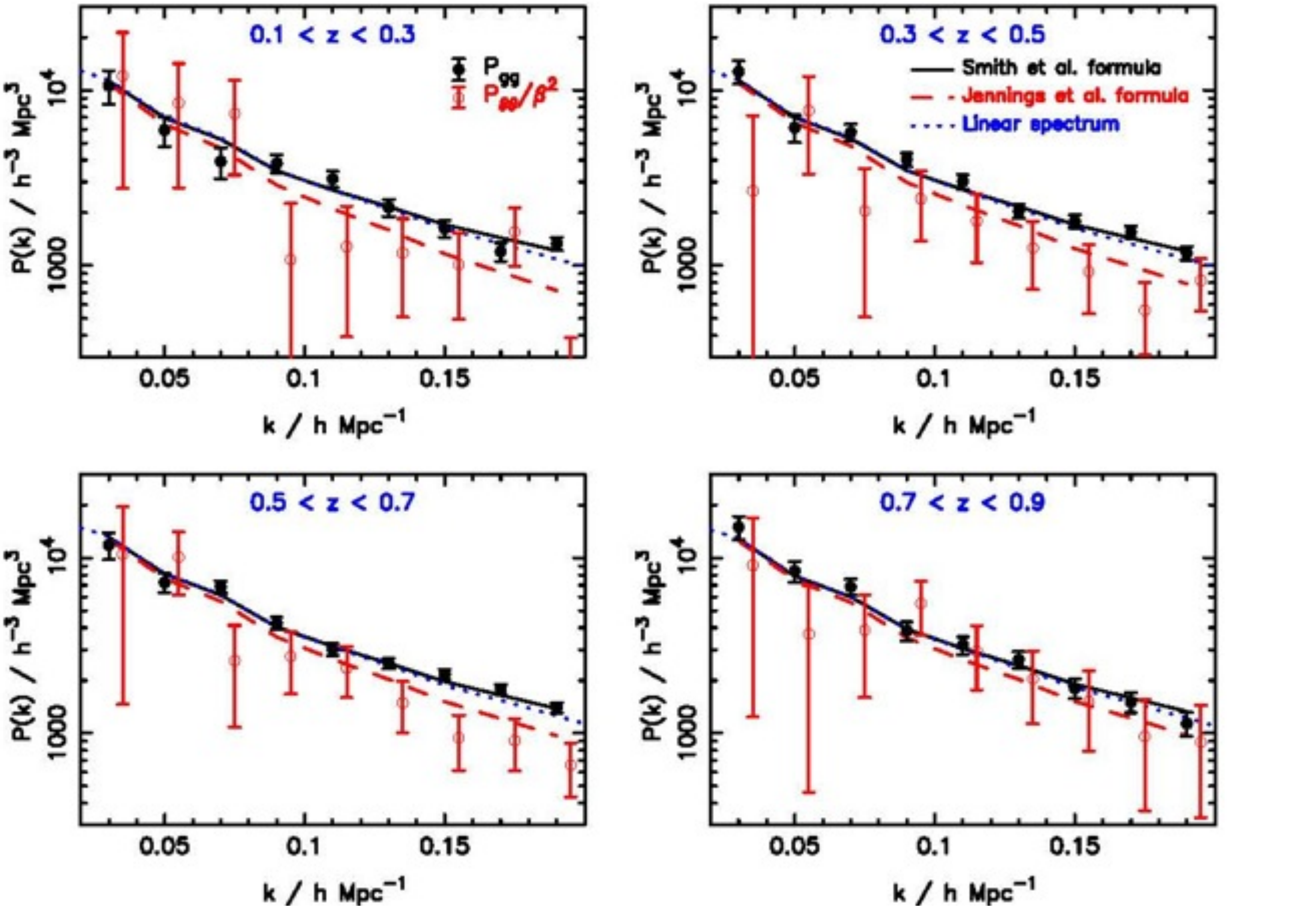


…at scales is the linear
…ity equation valid ?

$$\theta = -Hf(a)\delta(a)$$

Results from WiggleZ

Blake et al. 2011



Dark Energy or modified gravity

Anything that can simultaneously explain

- **Angular diameter distances** (BAO, CMB)
- **Luminosity distances** (Supernovae Ia)

can be called "dark energy" but could be the result of modified gravity!

Measuring the **expansion history alone will not distinguish modified gravity from smooth dark energy**

Need to break the degeneracy with measurements of **growth factor**

Dark energy → $H(z)$ ← Modified gravity

e.g Quintessence

e.g. parametrised by
$\mu^2 = G/G_N$ and
$\zeta = 1-\Psi/\Phi$ "slip parameter"

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↓

Within GR growth of density perturbations grows according to

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

e.g. parametrised by
$\mu^2 = G/G_N$ and
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↓

If gravitational constant varies & g = δ/a

$$\delta_D(\vec{k}) + P(k,\mu) = \int \frac{d^3r}{(2\pi)^3} e^{-i\vec{k}\cdot\vec{r}} \langle e^{ik\mu\Delta u_z}[1+\delta(\vec{x})][1+\delta(\vec{x}')]\rangle$$

Clustering statistics

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Clustering statistics

Consistency test of cosmology : compare growth & expansion rates

Growth rate

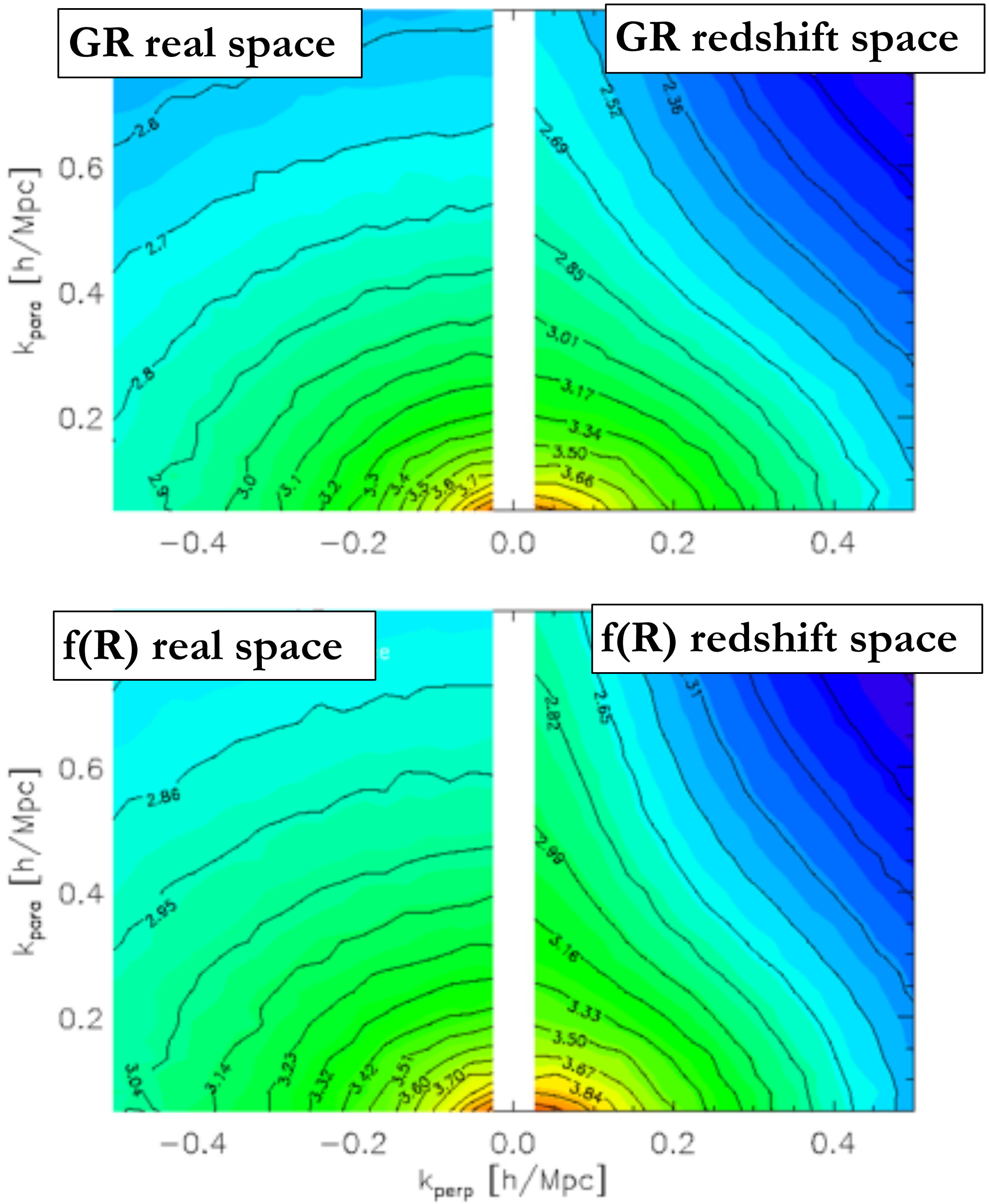
$$f(a) = \frac{d\ln\delta}{d\ln a}$$

Growth rate

$$f(a) = \frac{d\ln\delta}{d\ln a}$$

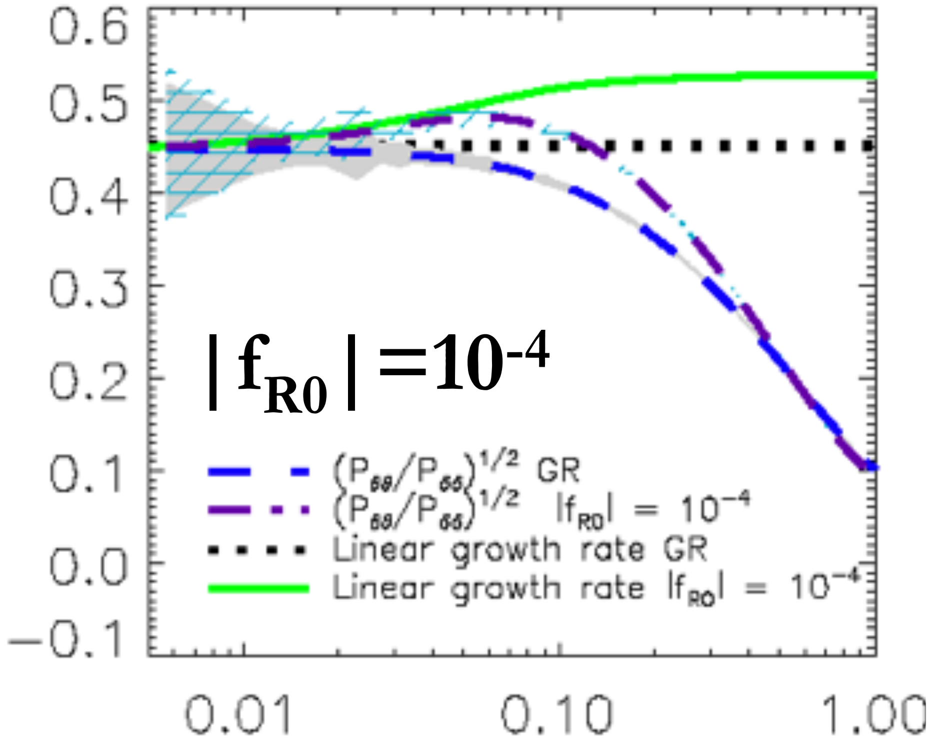
RSD in f(R) gravity

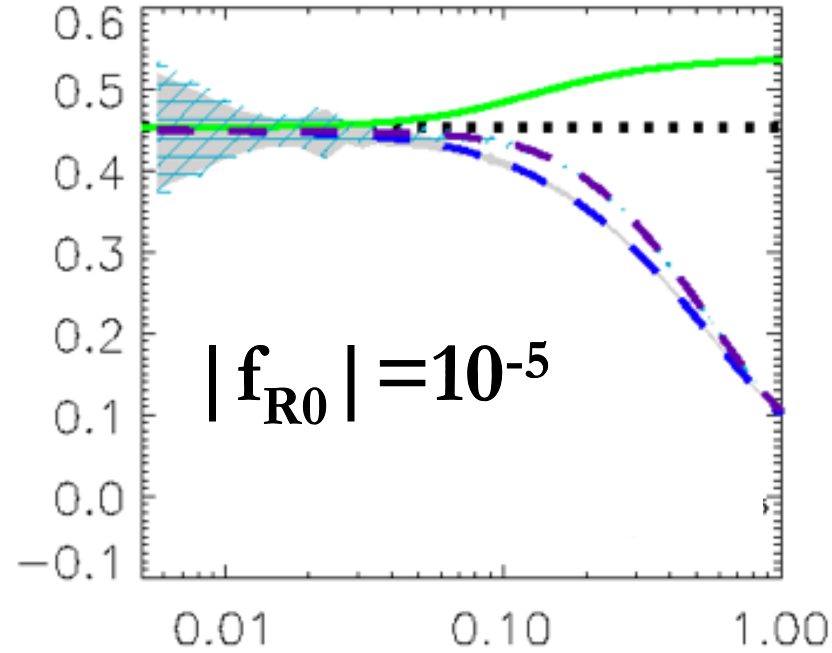
Simulations:
Modified Ramses

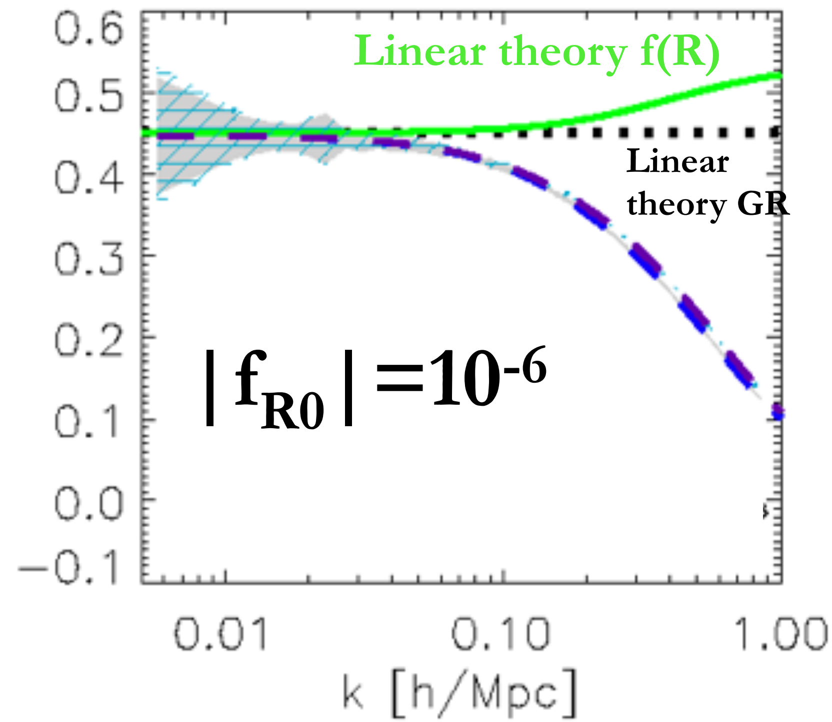


EJ, Baugh, Li, Zhao & Koyama 2012

$P_{\theta\theta}$







$$\vec{\nabla}\cdot\vec{v} = \theta = -Hf(a)\delta(a)$$

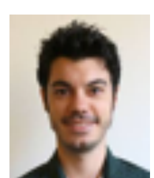
EJ, Baugh, Li, Zhao & Koyama 2012

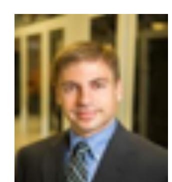
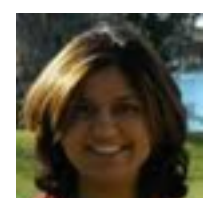
CosmoSIS: modular cosmological parameter estimation

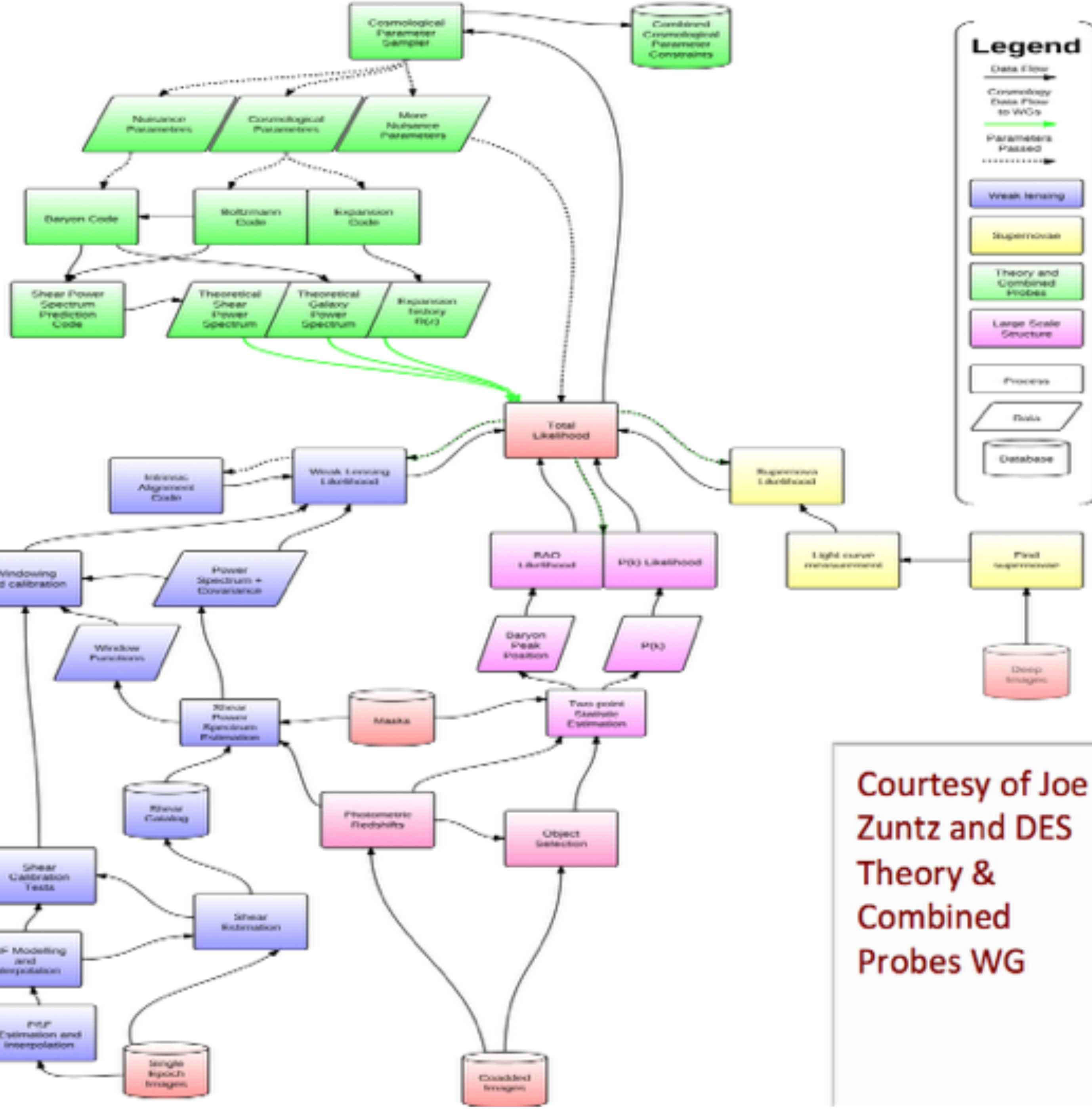
Sarah Bridle, Scott Dodelson, Elise Jennings, Jim Kowalkowski, Alessandro Manzotti, Marc Paterno, Doug Rudd, Saba Sehrish, Joe Zuntz







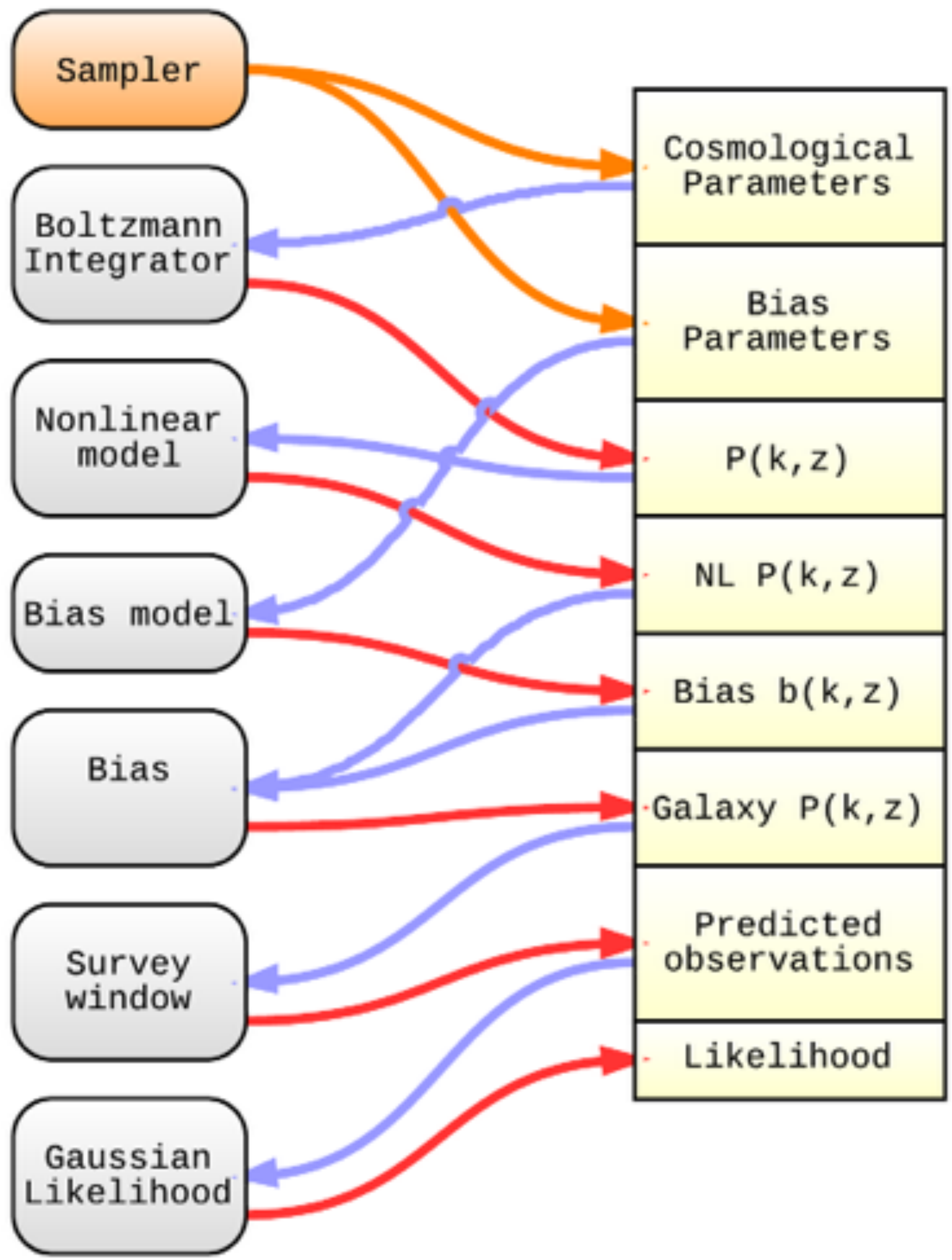



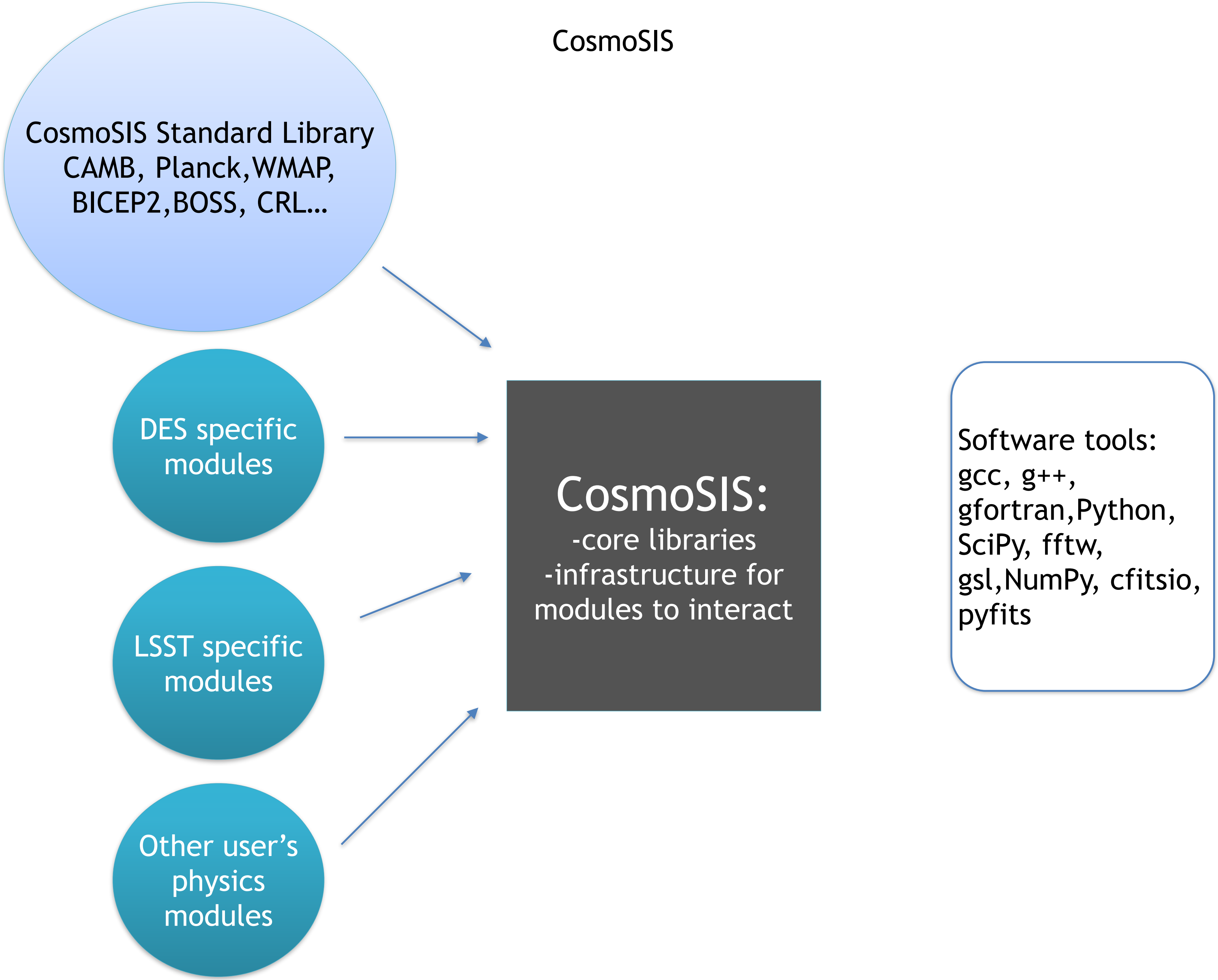
Courtesy of Joe Zuntz and DES Theory & Combined Probes WG

Modular Calculations

Zuntz et al 2014



CosmoSIS


CosmoSIS Standard Library
CAMB, Planck,WMAP,
BICEP2,BOSS, CRL…
DES specific
modules
LSST specific
modules
Other user's
physics
modules
CosmoSIS:
-core libraries
-infrastructure for
modules to interact
Software tools:
gcc, g++,
gfortran,Python,
SciPy, fftw,
gsl,NumPy, cfitsio,
pyfits

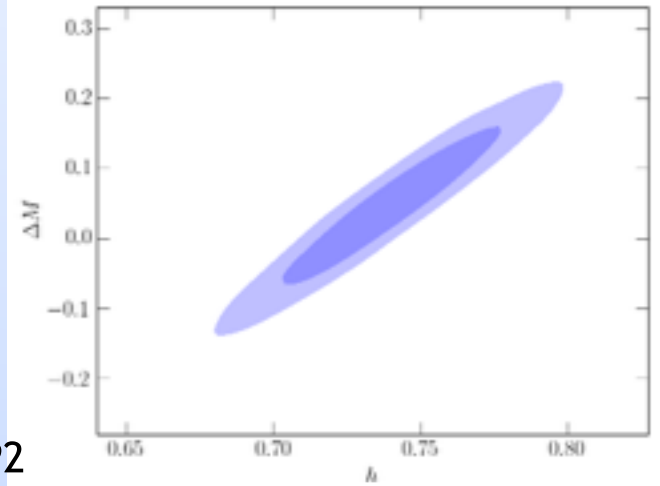
Key highlights

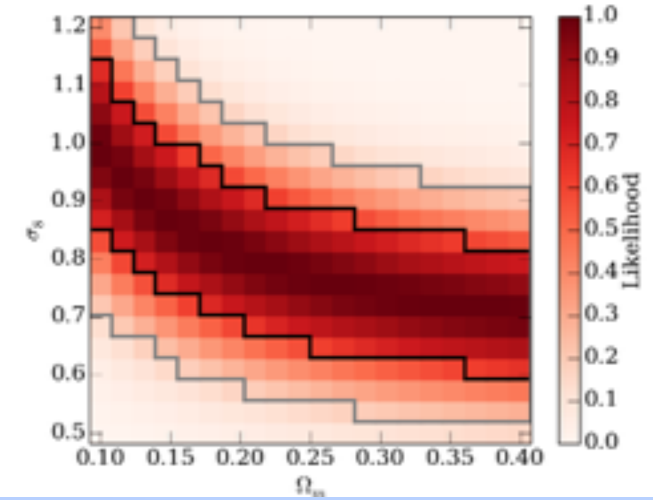
-easy download and install of all packages

-access to 3rd party codes - CAMB, Planck, WMAP, CRL BICEP2

-End User can - contribute to CosmoSIS Standard Library
- use other's code
- get credit for their work
- add modules in C, C++, fortran, Python

-Provenance tracking





https://bitbucket.org/joezuntz/cosmosis/wiki/Home