CMB/LSS Synergies

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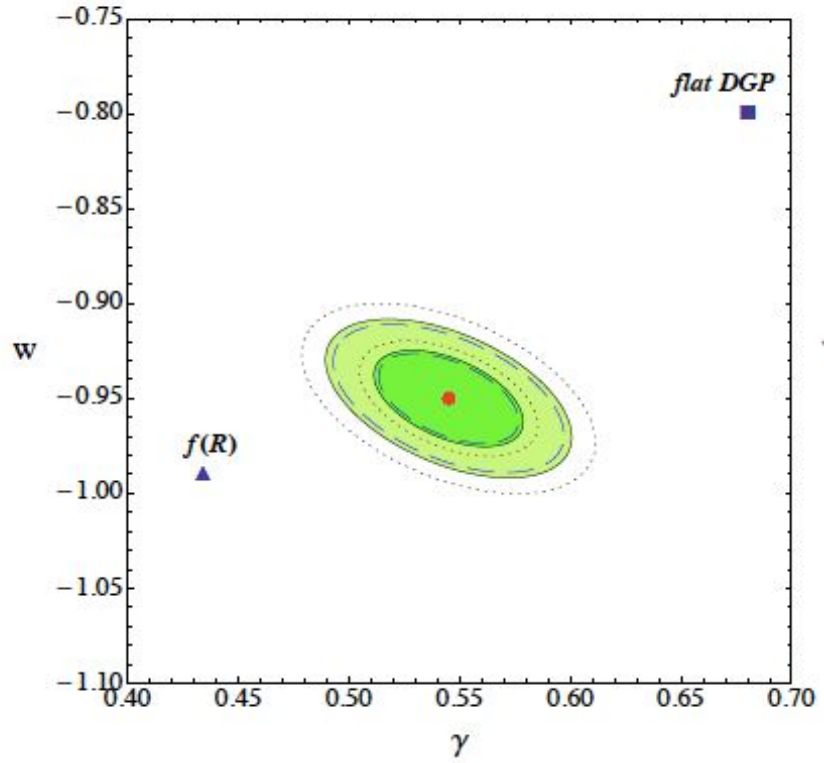
LSS Context for the next CMB Mission

- Euclid
  - Launch 2020
  - Space-based optical and spectrophotometric NIR survey
  - 15,000 square degrees in North and South, over 5 years
  - Optical imaging ~ $0.1<z<2$
  - Galaxy spectra ~ $2<z<3$
- LSST
  - First Light 2020
  - 8m photometric optical survey, Chile
  - 18,000 square degrees in (mostly) South
  - High cadence information: each area surveyed 100's times over 10 years
- SKA
  - Radio Telescope sensitive to a wide range of frequencies
  - Proposed wide surveys will over a few thousand square degrees over the southern sky.
  - Construction of the SKA1 (the first stage of the full SKA) is scheduled to begin in 2018 for initial observations by 2020.
- DESI
  - Spectroscopic instrument on the 4 meter Mayall Telescope.
  - Survey the 14,000 square degrees of sky in the northern hemisphere obtaining spectra and redshifts up to $z=3.5$ using the for luminous red galaxies (LRGs), emission line galaxies (ELGs) and quasars.

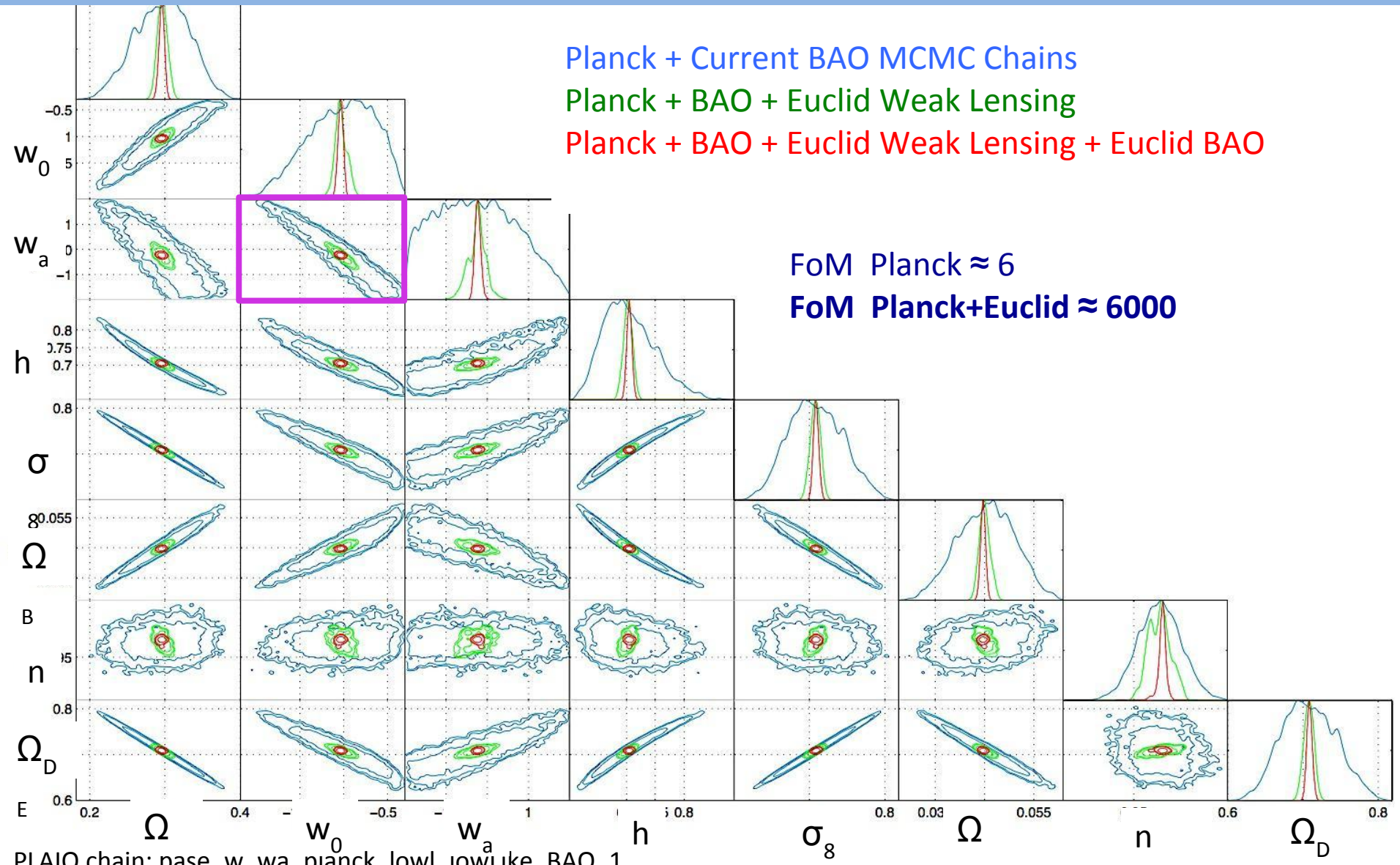
Science Objectives

- Each of these surveys has science objectives to determine nature of dark energy
- Also low-redshift/cluster/galaxy scale modifications to General relativity
- Many papers that forecast such results
- CMB provides priors

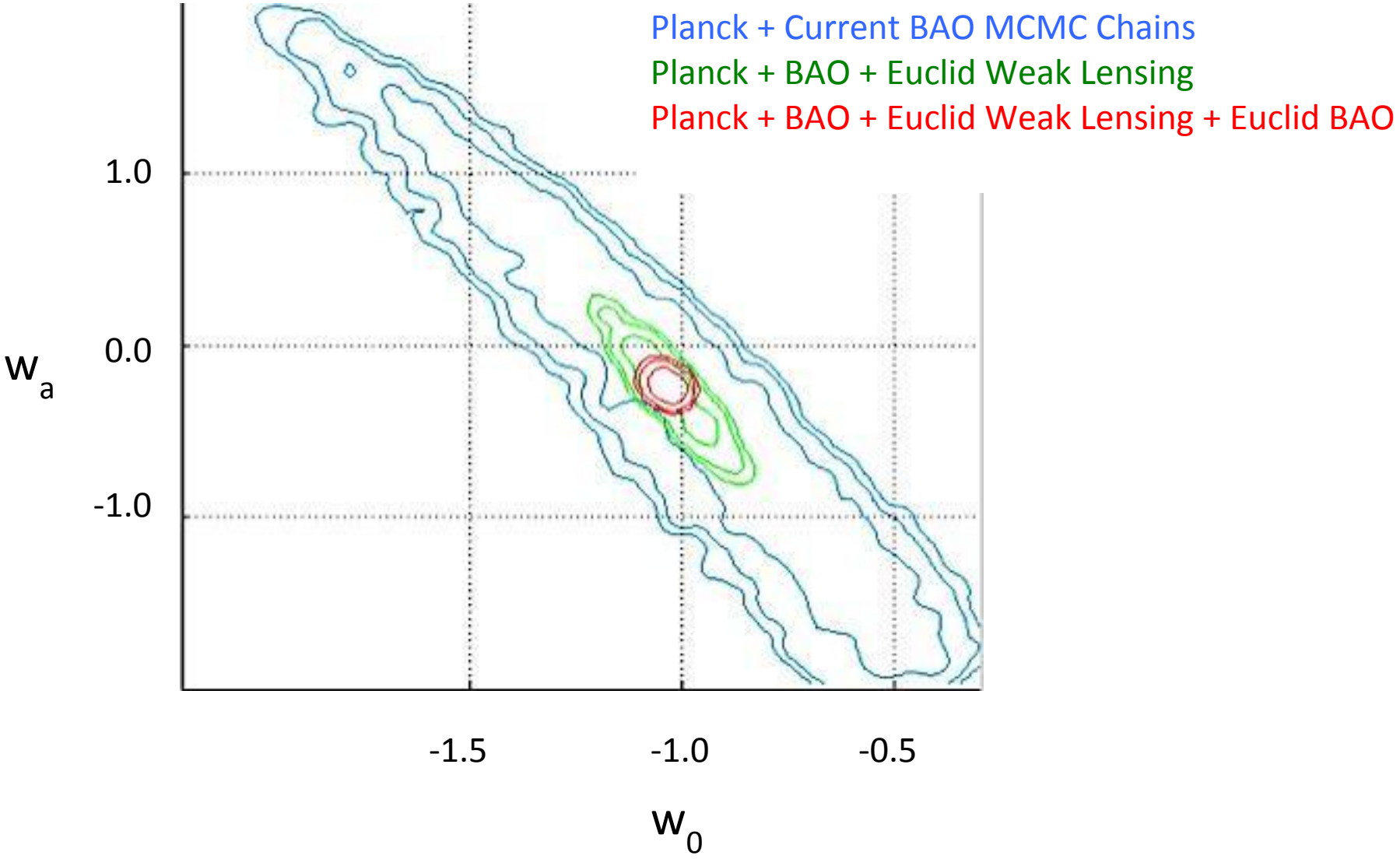


Amendola,…, TDK, … et al. (2012)

Euclid Predictions



PLAIO chain: base_w_wa_planck_lowl_lowLike_BAO_1
Caveat: fiducial used=mean of Planck chain



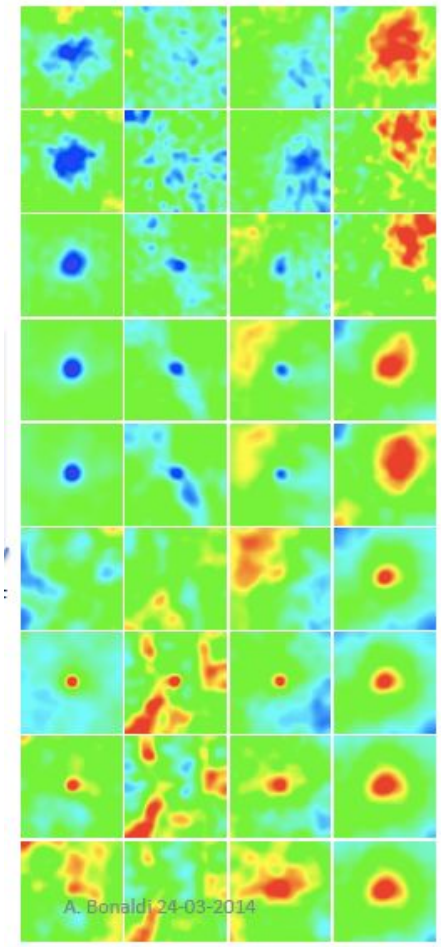
PLAIO chain: base_w_wa_planck_lowl_lowLike_BAO_1

Caveat: fiducial used=mean of Planck chain

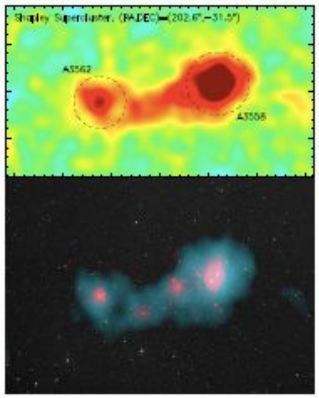
- What has been done to date?

Clusters

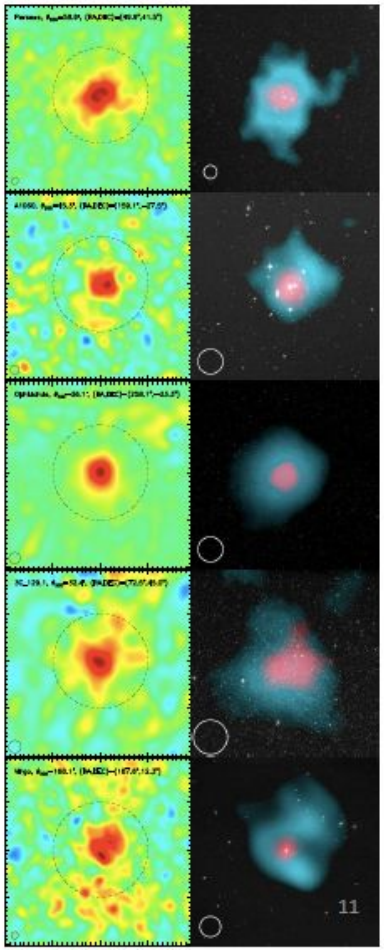
- Cluster count cosmology
- SZ cluster detection (e.g. Planck, XXIV, 2015)



Examples from *Planck*



Moriond Cosmology 2014

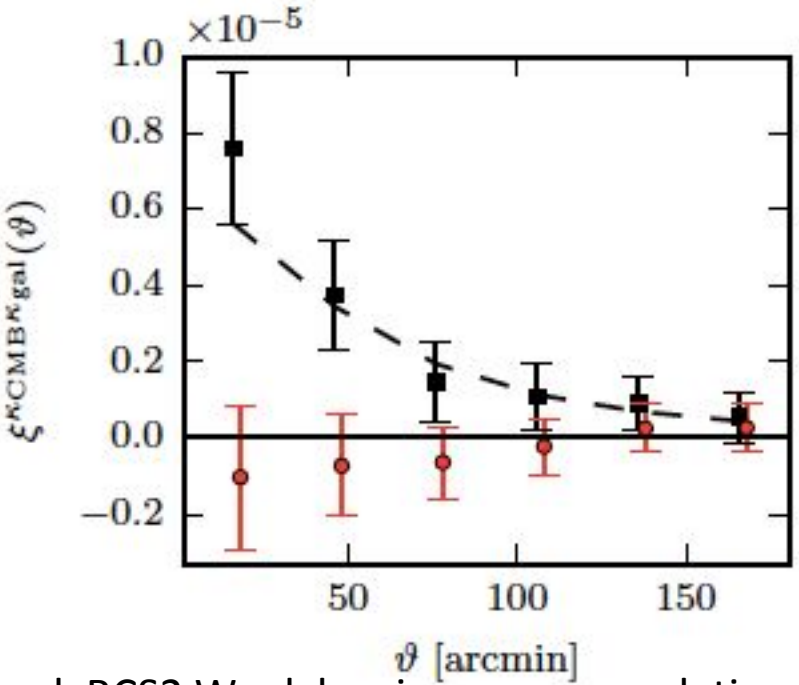


Slide from Bonaldi talk Moriond

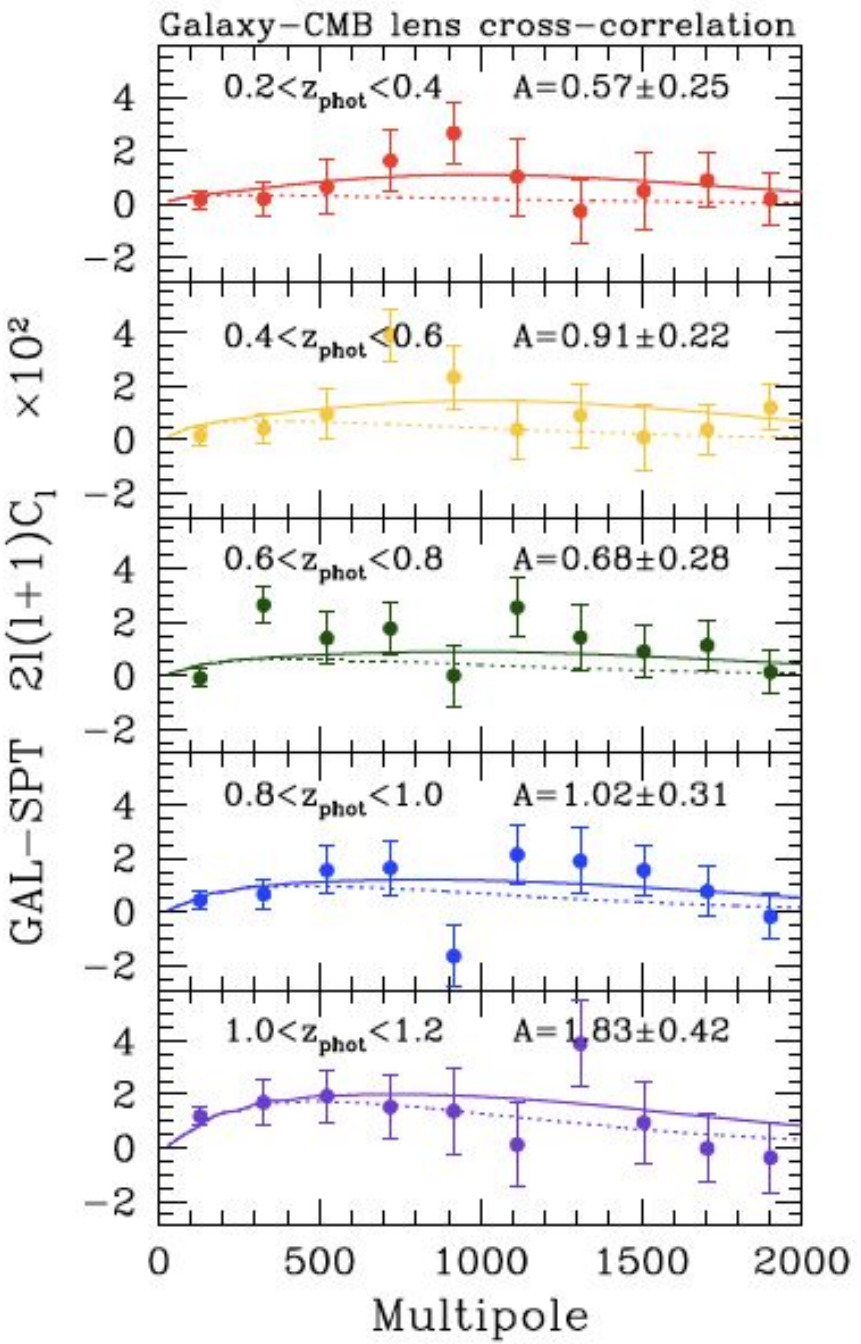
http://moriond.in2p3.fr/J14/transparencies/Monday/bonaldi.pdf

Cross-Correlations w/ Maps

- Can cross correlate to generate additional statistics to constrain cosmology
- Example: Convergence, Shear, as a function of z



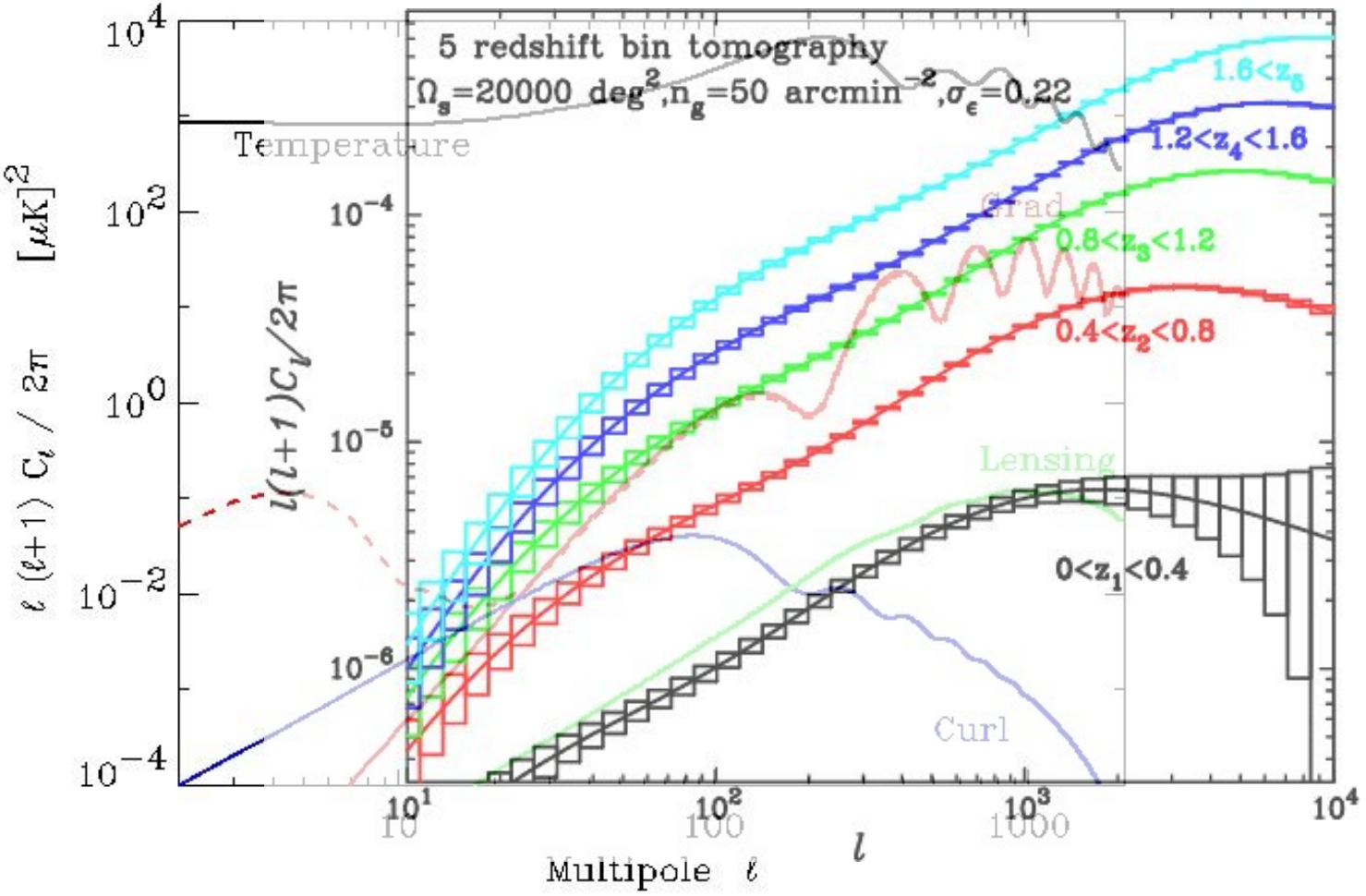
Planck RCS2 Weak lensing cross correlation, Harnois-Deraps, …, TDK,… et al. (16)



Gianntonio et al. (2015) Planck-DES

- What can a combined analysis do?

- Cross-correlation needs high-l information



Combined Analyses

- Can help with statistics:
  - More information, smaller statistical error bars
- Can help with systematics:
  - Different dependencies on astrophysical uncertainties
  - Completely different instruments

Systematics and Combined Analyses

$$\mathbf{D}_\ell(k) = \{e_\ell^E(k), d_\ell^E, a_\ell, p_\ell^E, p_\ell^B\}.$$

Galaxy Ellipticity

CMB Lensing

CMB Temp

CMB Polarisation

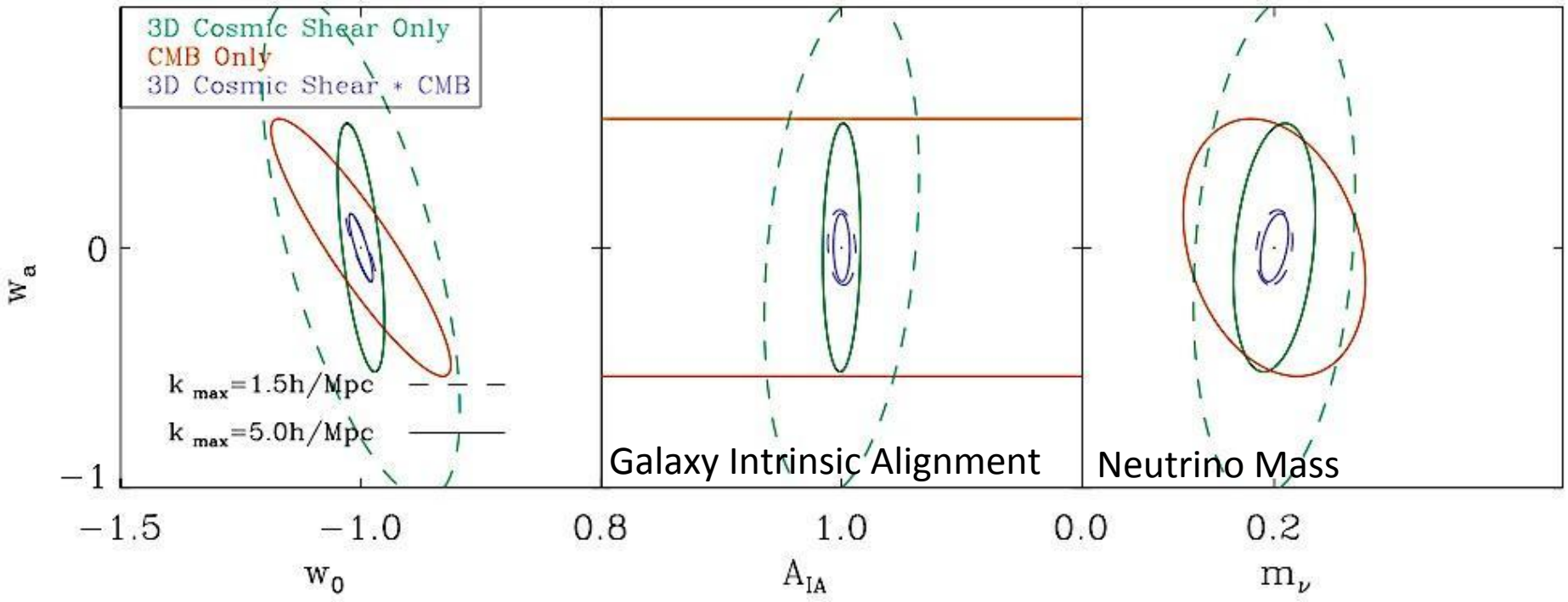
Harmonic space is
Natural place to add lensing and
CMB power spectra

$$\begin{pmatrix} ee & de & Te & Ee & Be \\ ed & dd & Td & Ed & Bd \\ eT & dT & TT & ET & BT \\ eE & dE & TE & EE & BE \\ eB & dB & TB & EB & BB \end{pmatrix}$$

$$C_\ell(k_1,k_2) = \begin{pmatrix} C_\ell^{ee}(k_1,k_2) & C_\ell^{de}(k_1) & 0 & 0 & 0 \\ C_\ell^{ed}(k_2) & C_\ell^{dd} & C_\ell^{Td} & C_\ell^{Ed} & C_\ell^{Bd} \\ 0 & C_\ell^{dT} & C_\ell^{TT} & C_\ell^{ET} & C_\ell^{BT} \\ 0 & C_\ell^{dE} & C_\ell^{TE} & C_\ell^{EE} & 0 \\ 0 & C_\ell^{dB} & C_\ell^{TB} & 0 & C_\ell^{BB} \end{pmatrix}$$

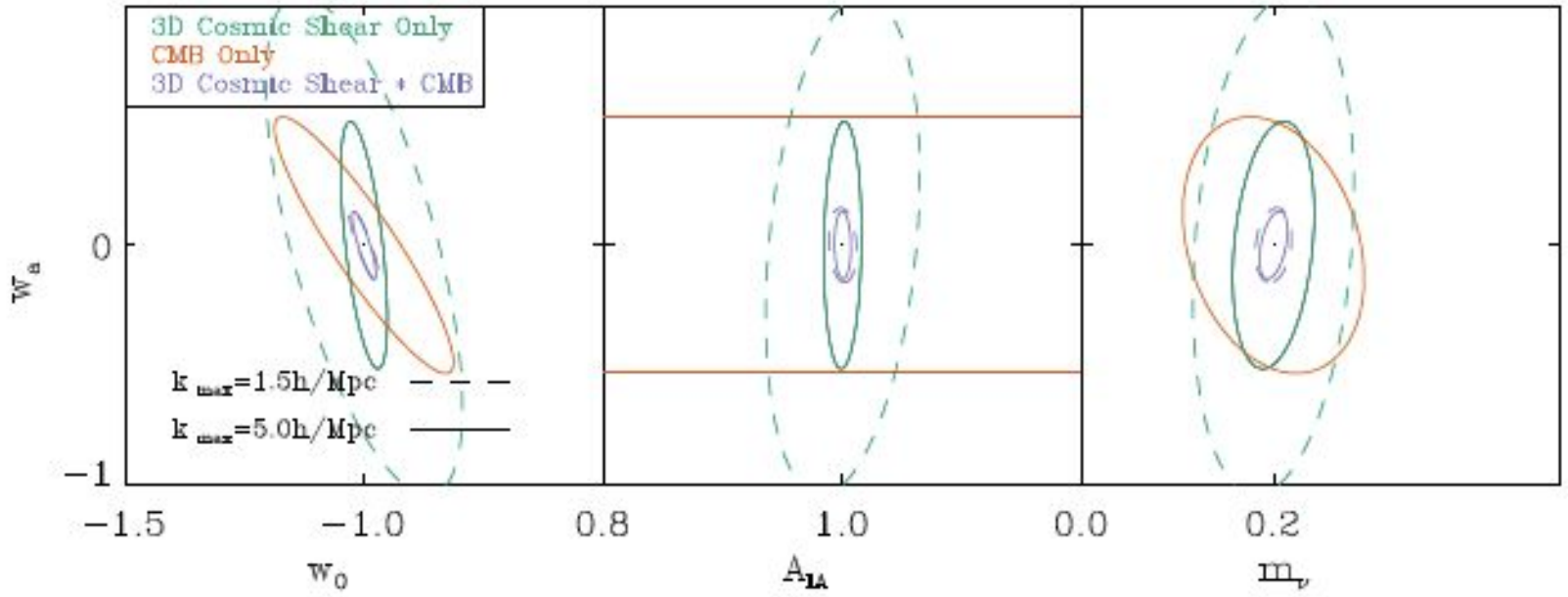
Fisher Matrix Predictions (Kitching, Heavens, Das, 2015)

- Euclid-like
- Planck+ACTPol (Temperature+Polarisation, with CMB Lensing)

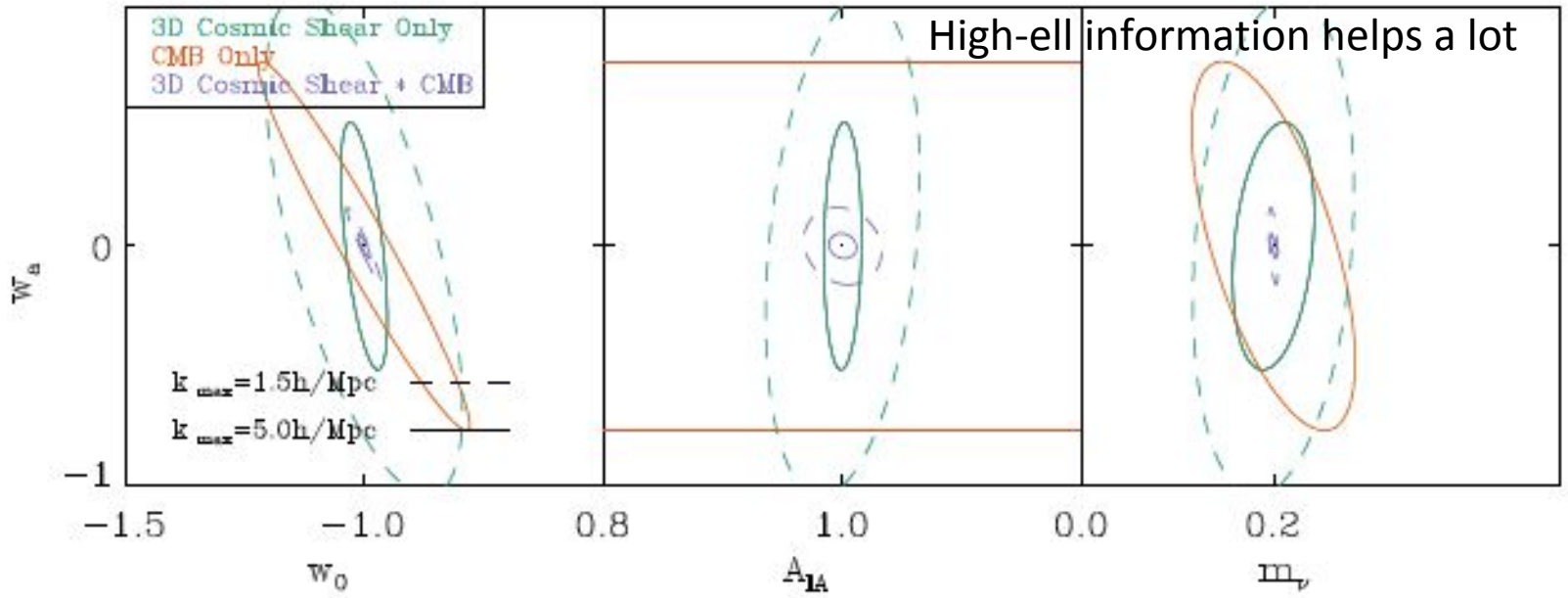


Includes full cross-correlation between lensing and CMB

Euclid-like & Planck+ACTPoL



Euclid-like & COrE-like

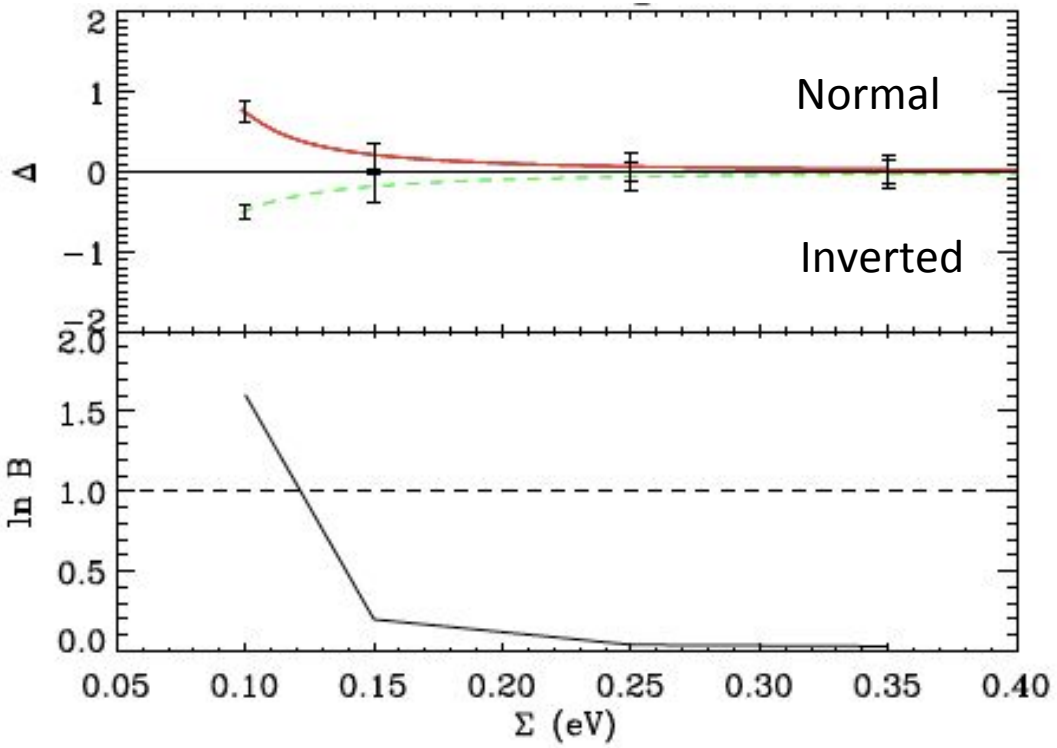


High-ell information helps a lot

Standard Model Niches

- What these surveys will not (alone) constrain well:
  - Neutrino Hierarchy
  - Any effect that manifests on small-scales
  - Primordial parameters e.g. running of spectral index
  - Any high-redshift phenomena e.g. early dark energy models

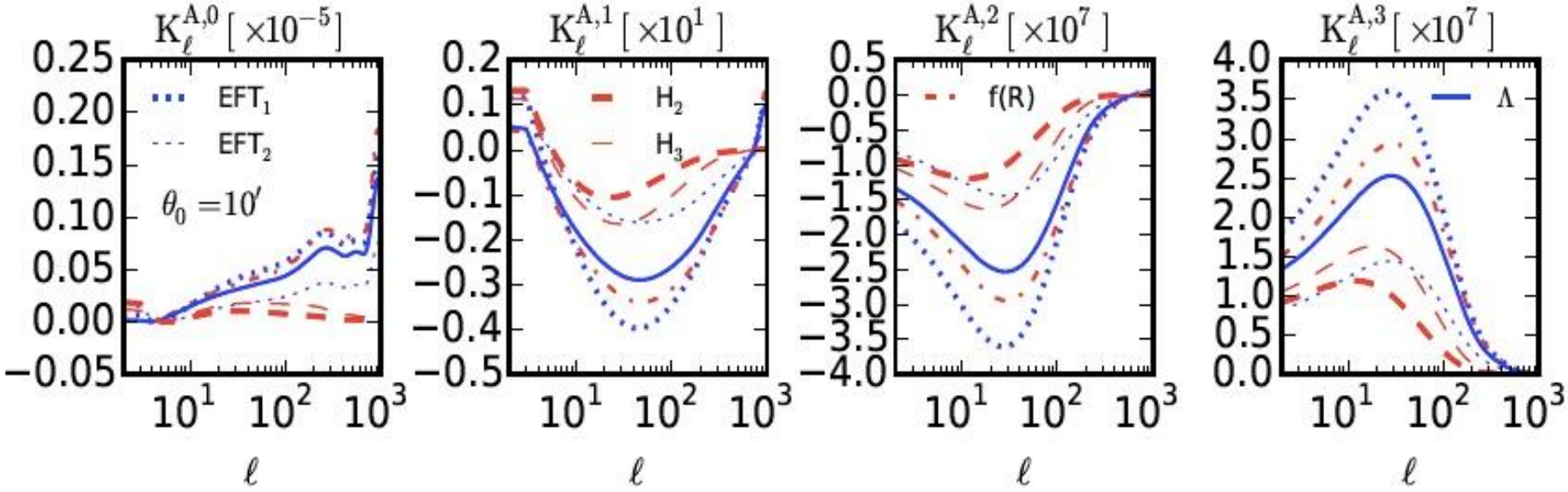
Forecasted Evidence for Normal over Inverted



Jimenez, TDK, et al., 10

Extended Model Niches

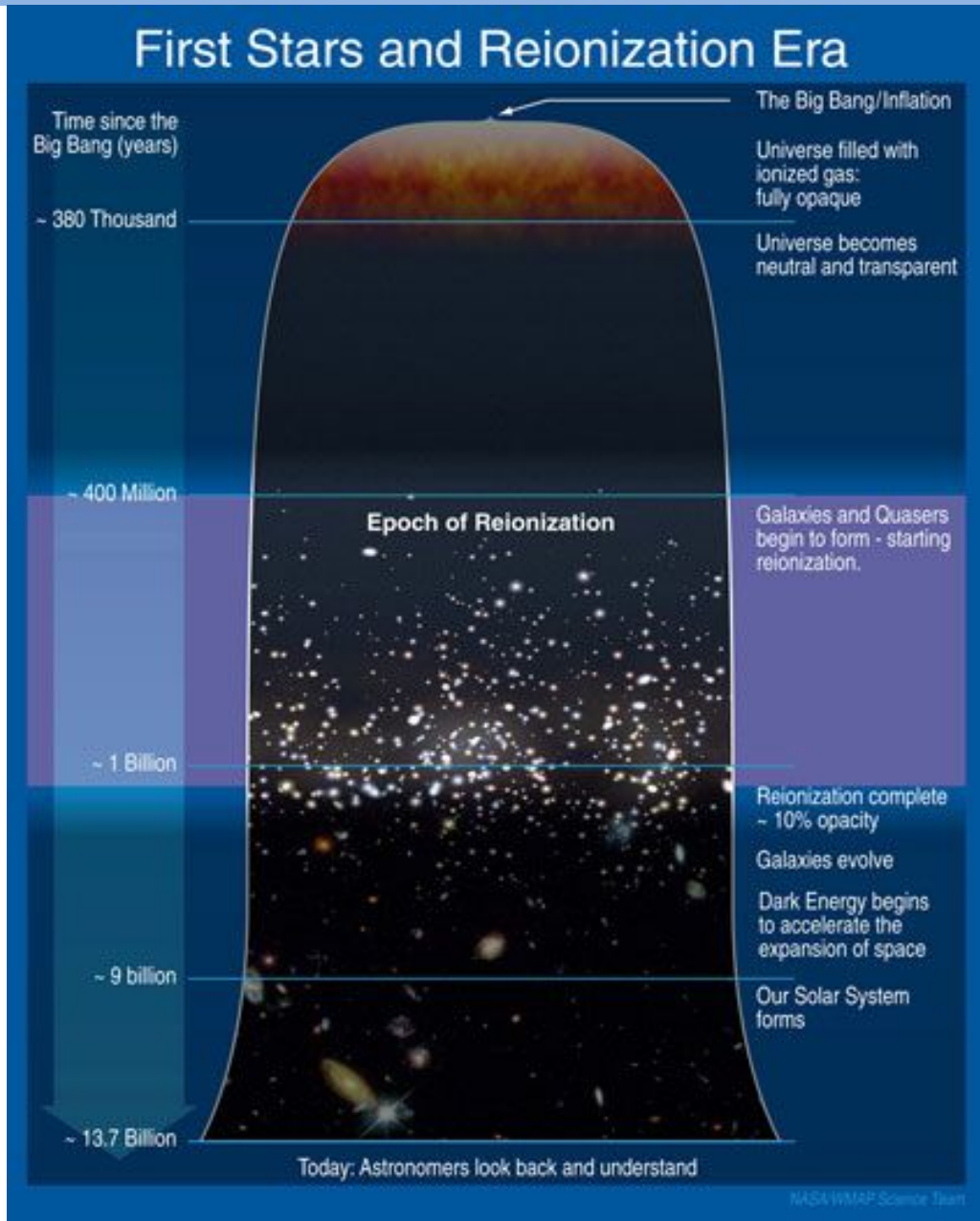
- Higher order statistics
  - e.g. kurt-spectra and Minkowski functionals of high resolution CMB maps can be sensitive to particular modified gravity theories
  - E.g. Munshi et al. (2016)



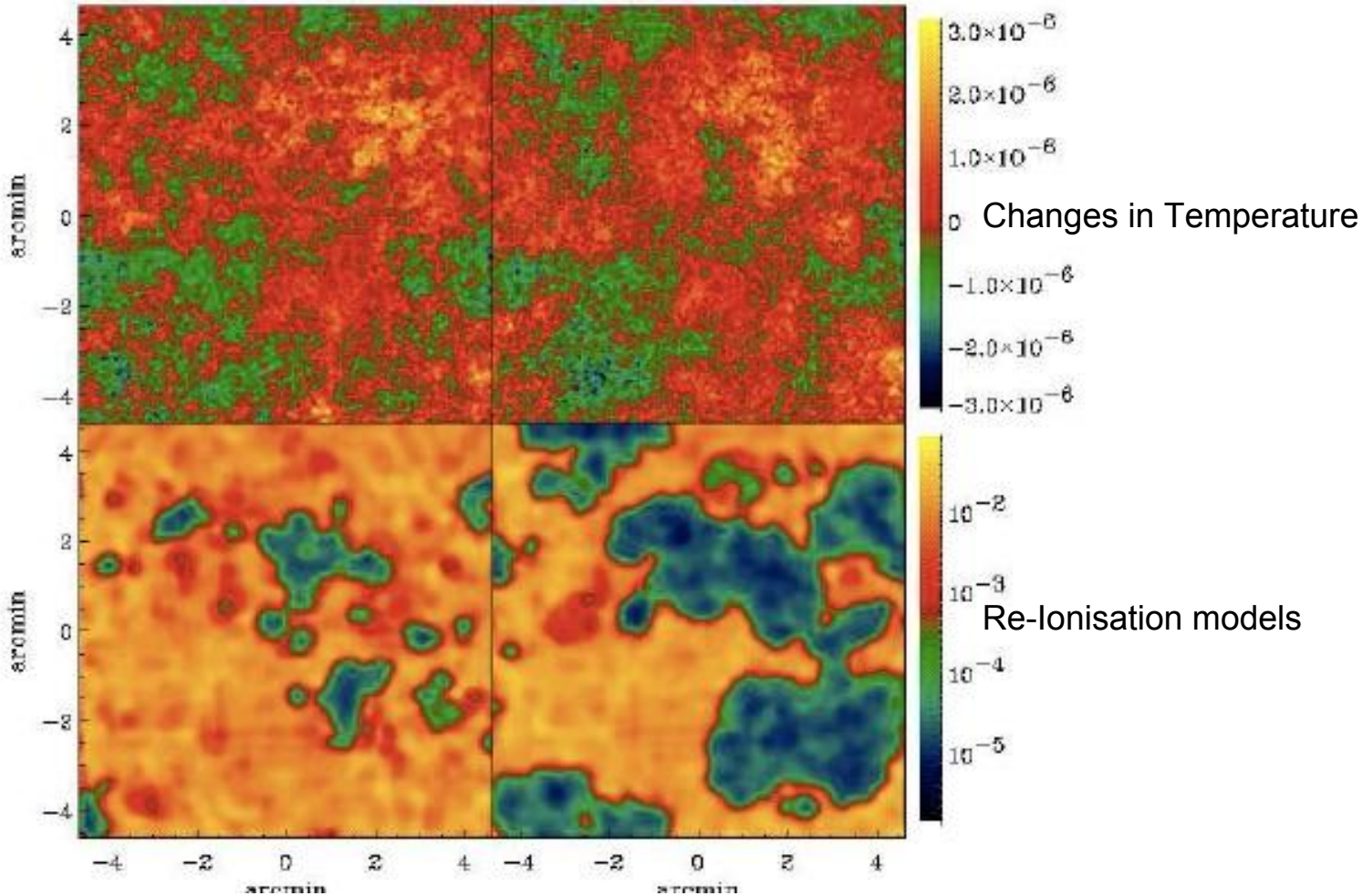
21cm Mapping

- SKA
- 21cm Intensity mapping
- Powerful when combined with CMB at high-z and galaxy surveys at low-z

- E.g. can be used to test GR in see Hall, Bonvin, Challinor (12)



E.g. Salvaterra et al. (2005)



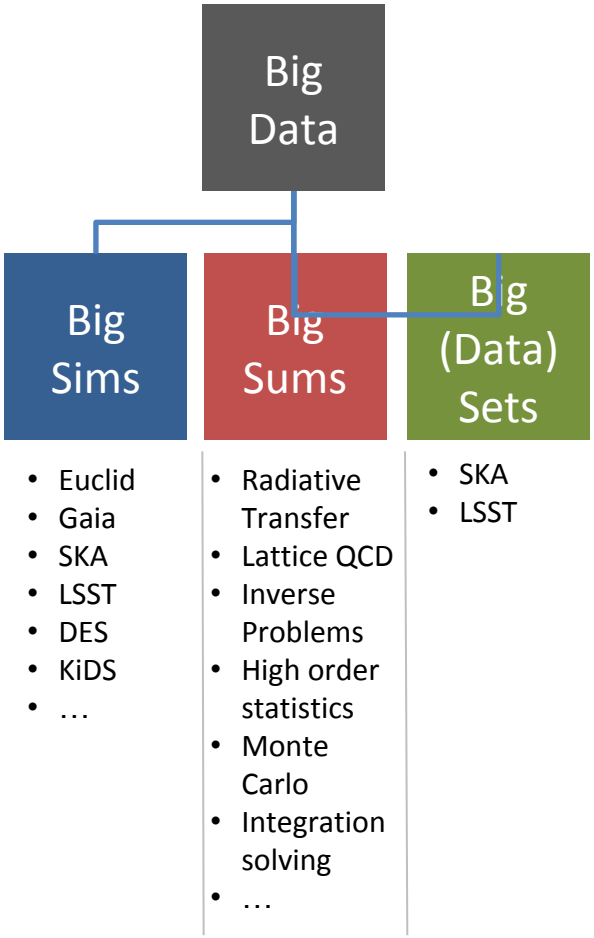
- Other Synergies

Methodological

- Parameter estimation:
  - Monte Carlo Methods, high-dimensional sampling, Bayesian analysis
- Data analysis:
  - For example: spin-2 analysis and power spectrum extraction (e.g. Liestedt et al., 2015, 2016)

Computational Synergies: Big ~~Data~~ Sims/Sums/Sets

- "Big Data" is *not only big data sets*
- Clear areas of synergy
  - Big Sims
  - Big Sums
  - Big Sets
- Big Sims/Sums can be more demanding than Big Data Sets
- Experiments with (only) Peta-byte data size demand Exabyte simulations or sums



Conclusions

- Any next-generation CMB experiment must take into account the landscape of LSS experiments

- Cross-correlations enable more science
  - Larger range of theories
  - Much better constraints of standard parameters
  - Access to additional parameters
- and improved systematics
  - Different astrophysical dependency
  - Different detectors and instruments