# Large Scale Structure experiments and consequences for fundamental physics

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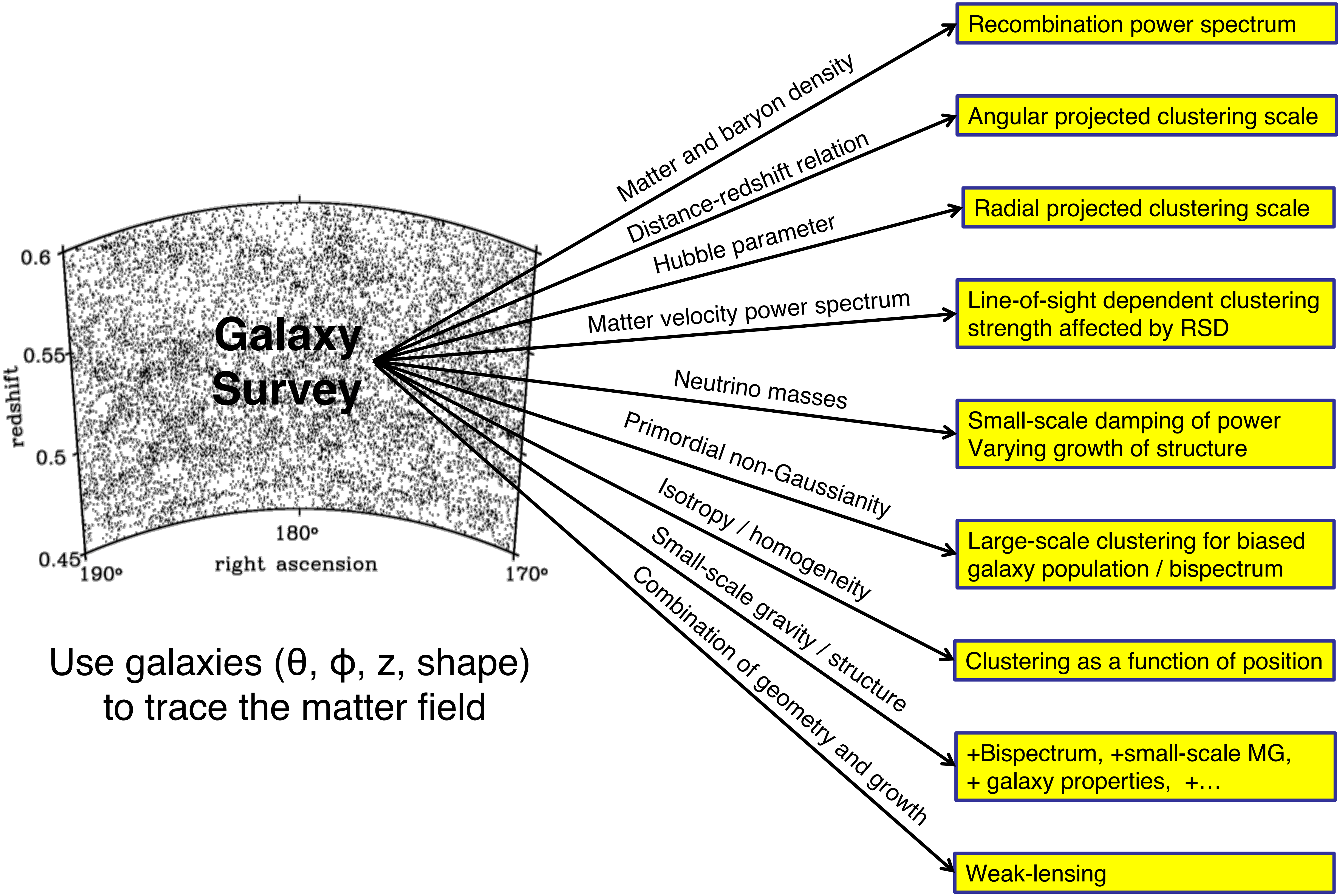
ICG Portsmouth

# Cosmology from galaxy surveys



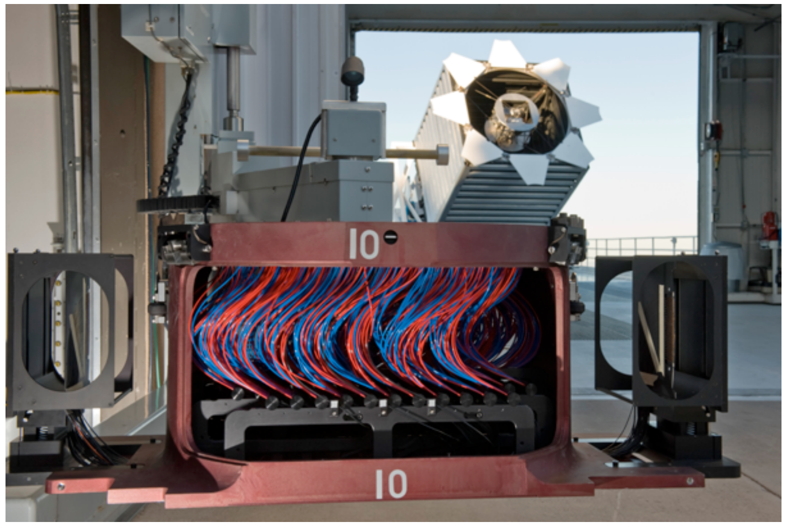

Use galaxies (θ, ϕ, z, shape) to trace the matter field

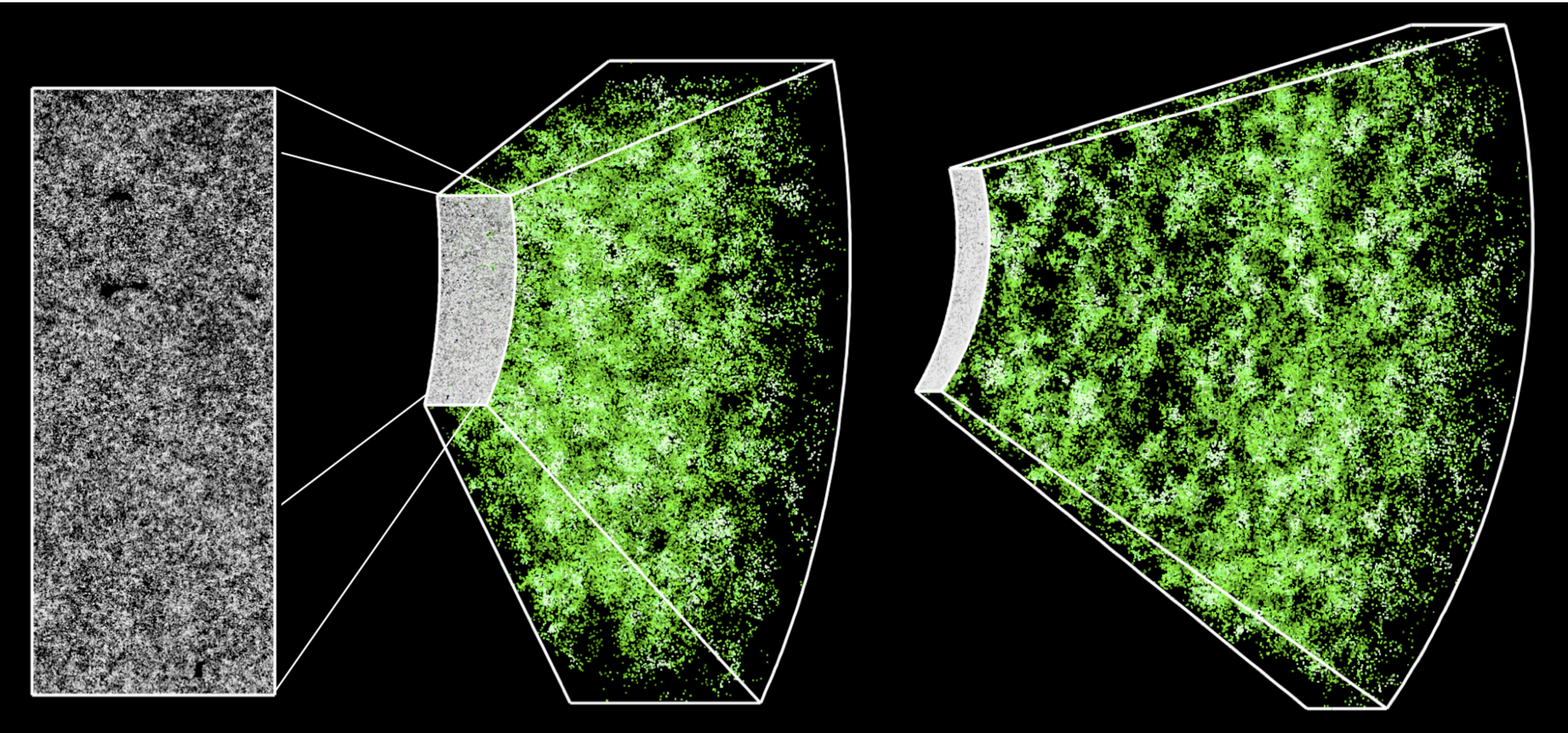
# Current: the BOSS galaxy clustering survey

# The BOSS galaxy survey

- Survey now complete, with data taken over 5 years (2009-2014)
- Redshifts for 1,145,874 galaxies
- Two galaxy classes with different selections: LOWZ and CMASS
- Data Release 12 galaxy catalogues now available:

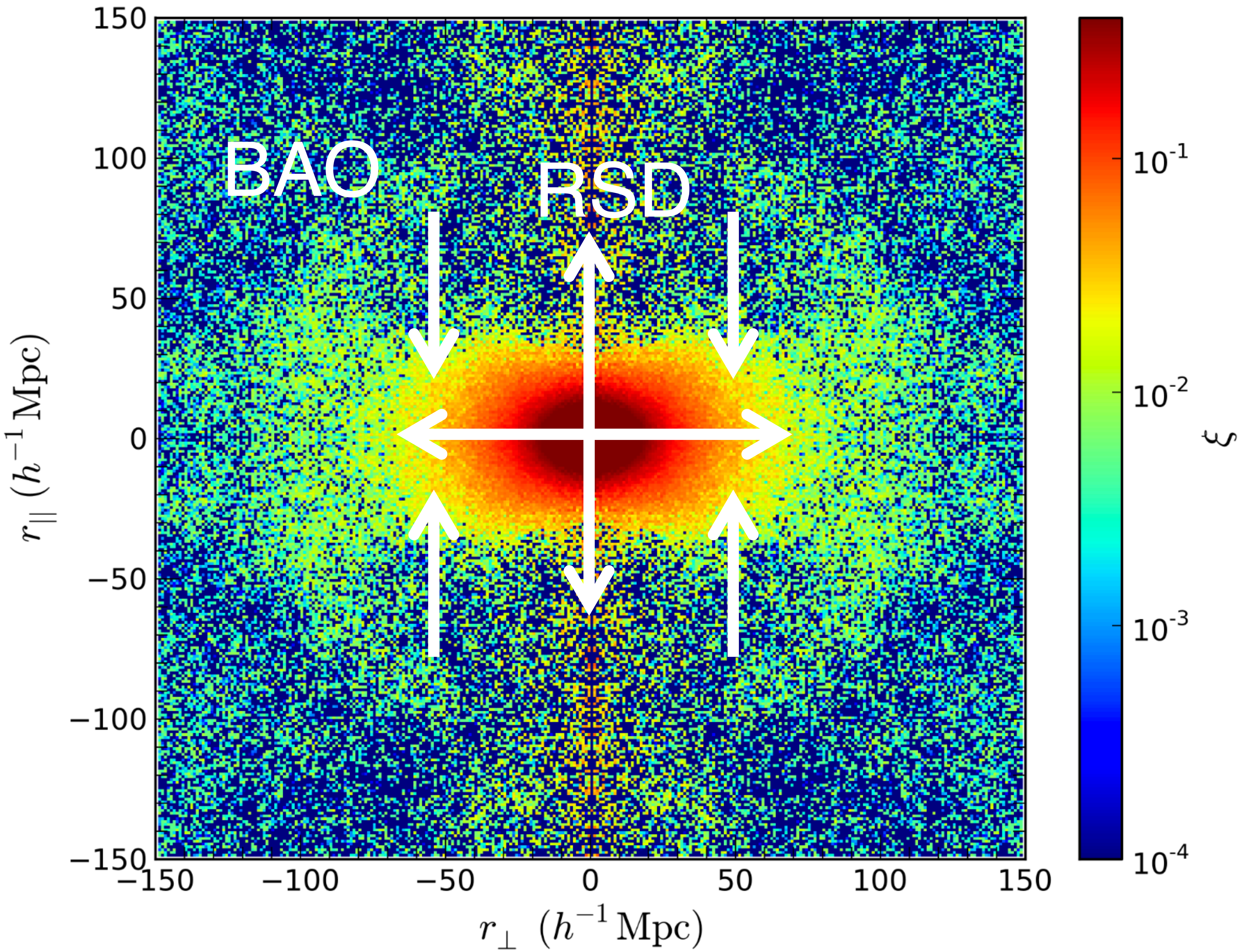
  http://data.sdss3.org/sas/dr12/boss/lss/

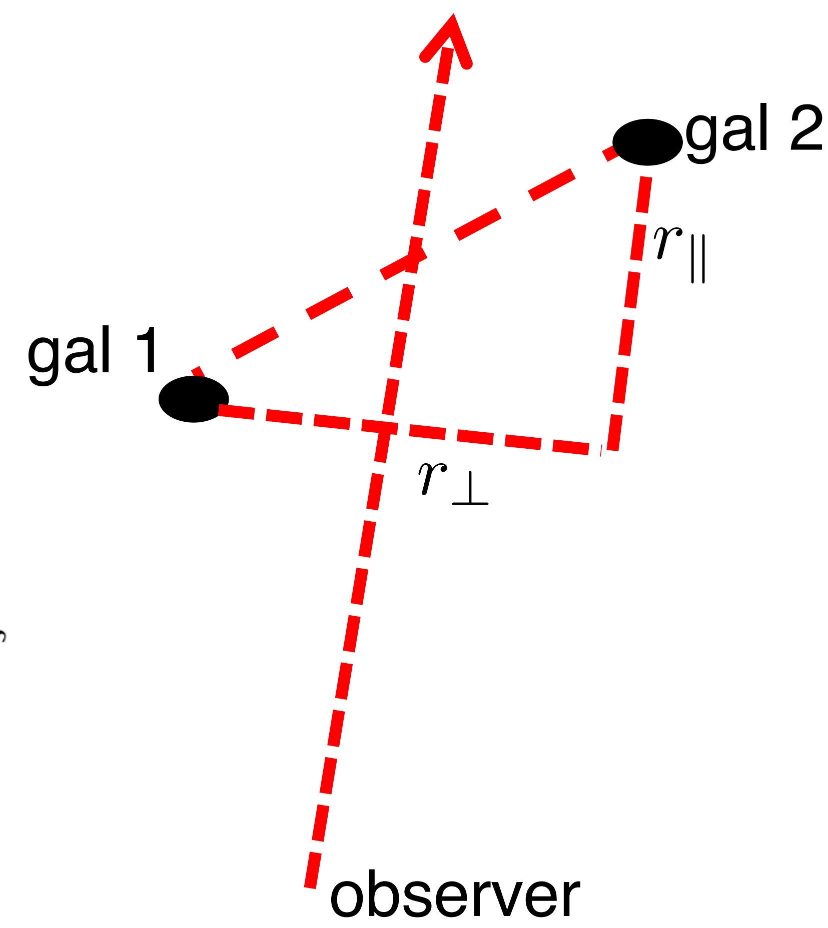




# The galaxy clustering signal

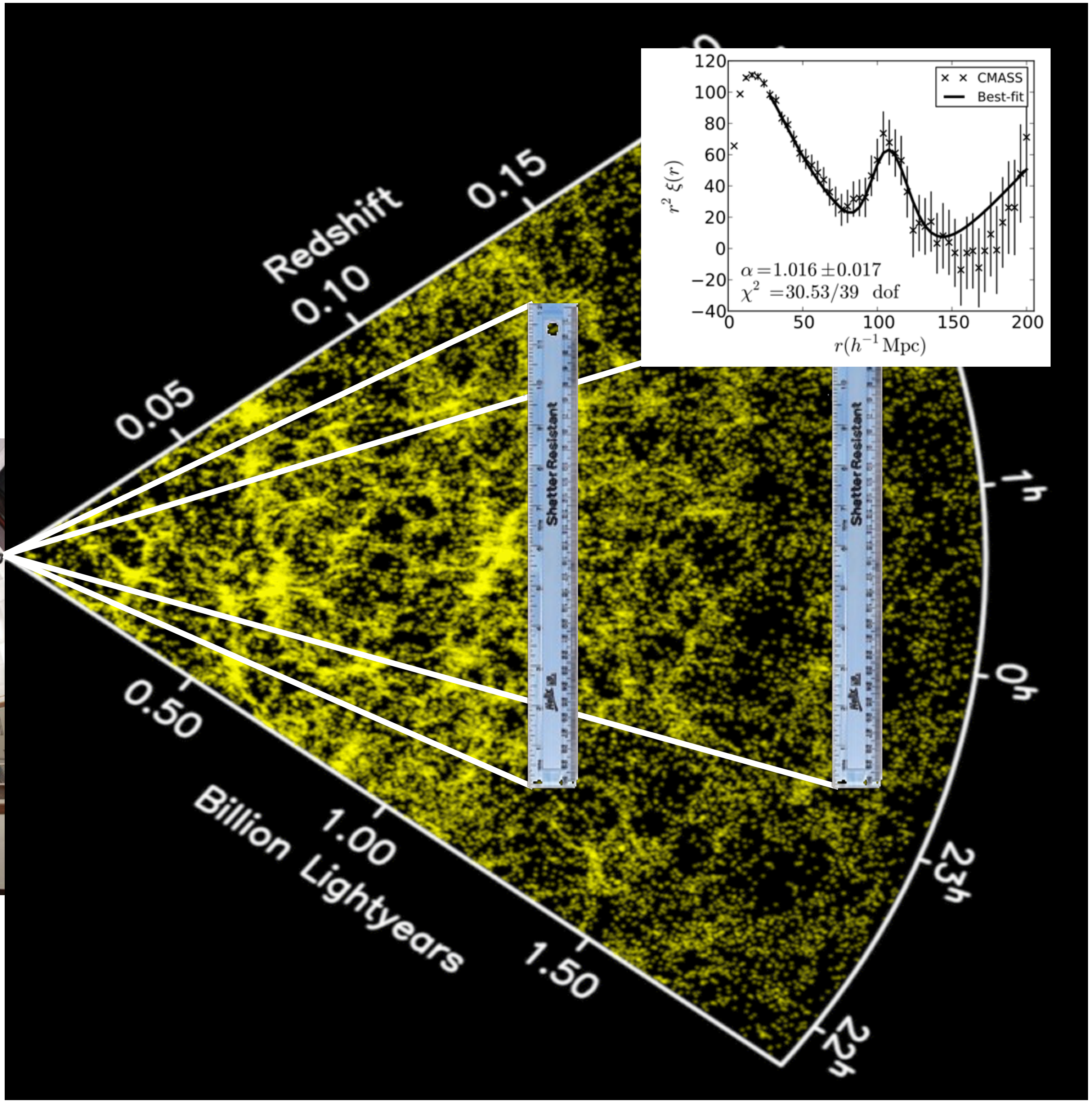
$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$



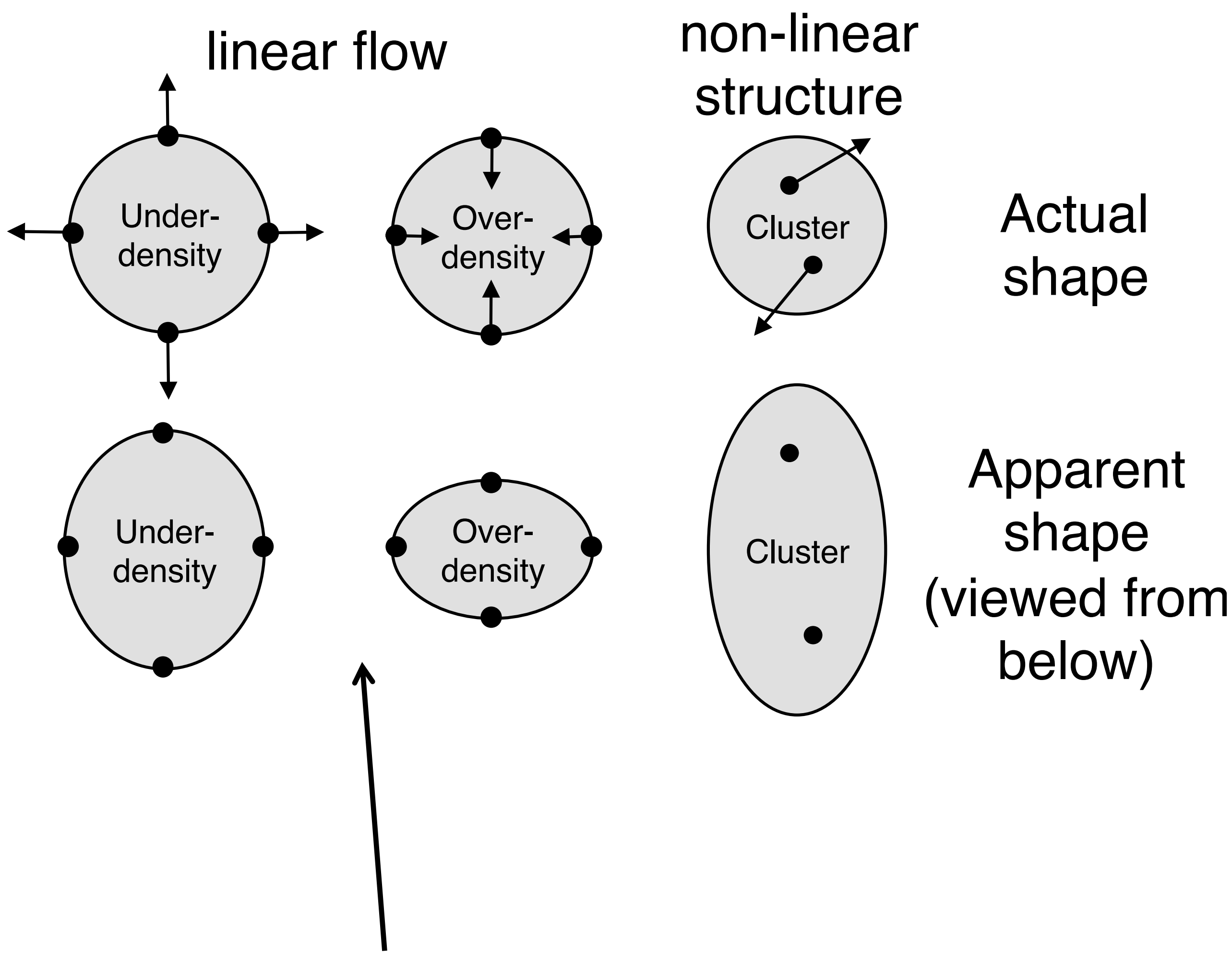




Samushia et al. 2013; MNRAS, 439, 3504

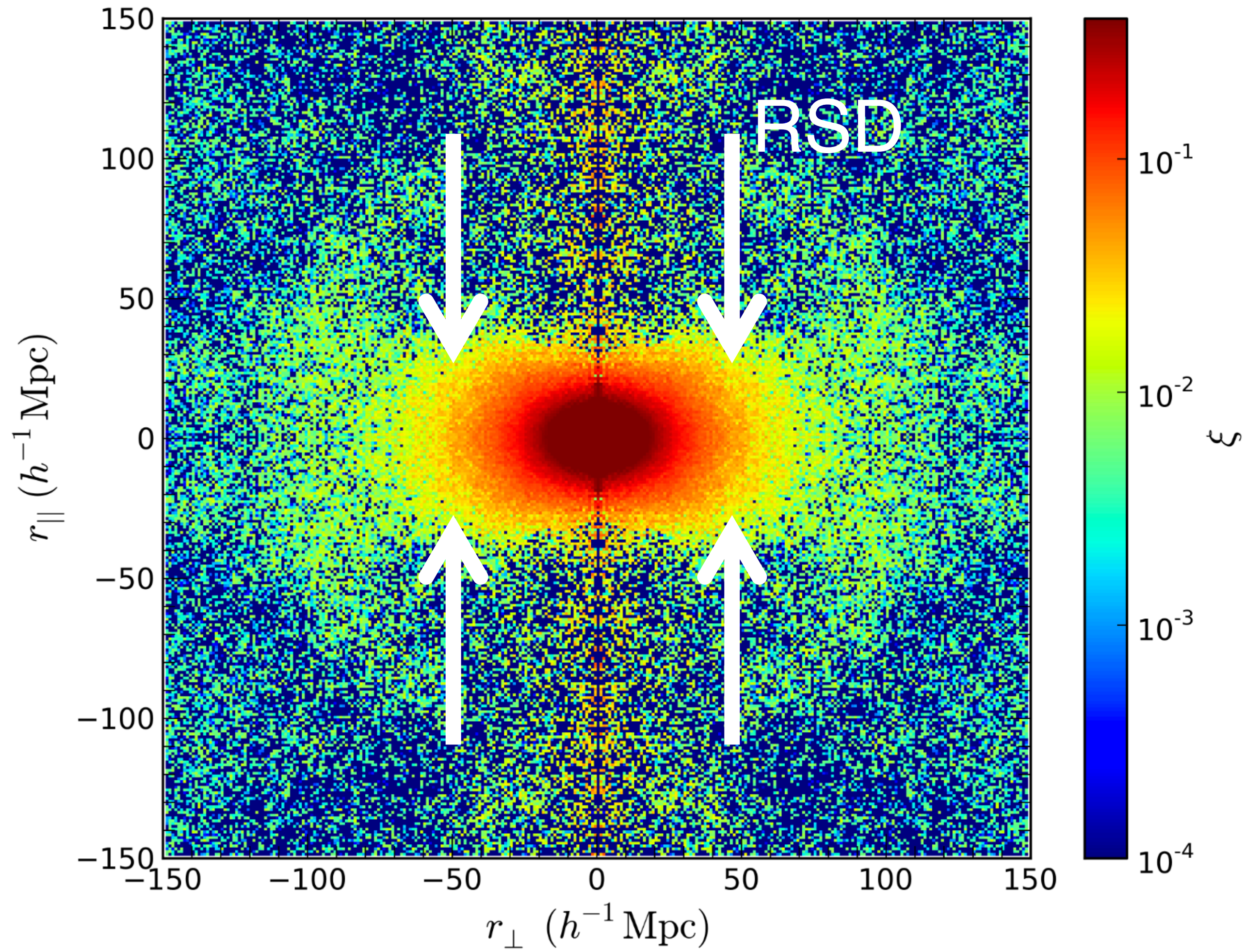
# Clustering (BAO) as a standard ruler

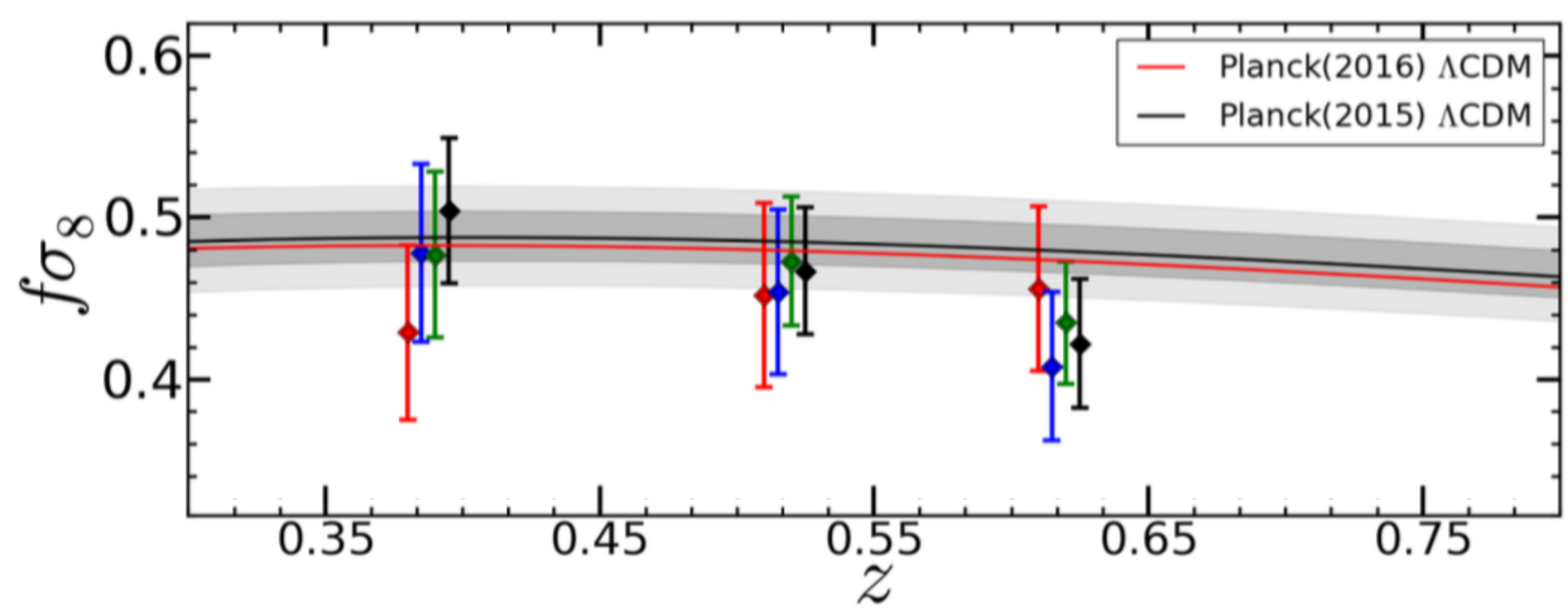


# Redshift Space Distortions (RSD)



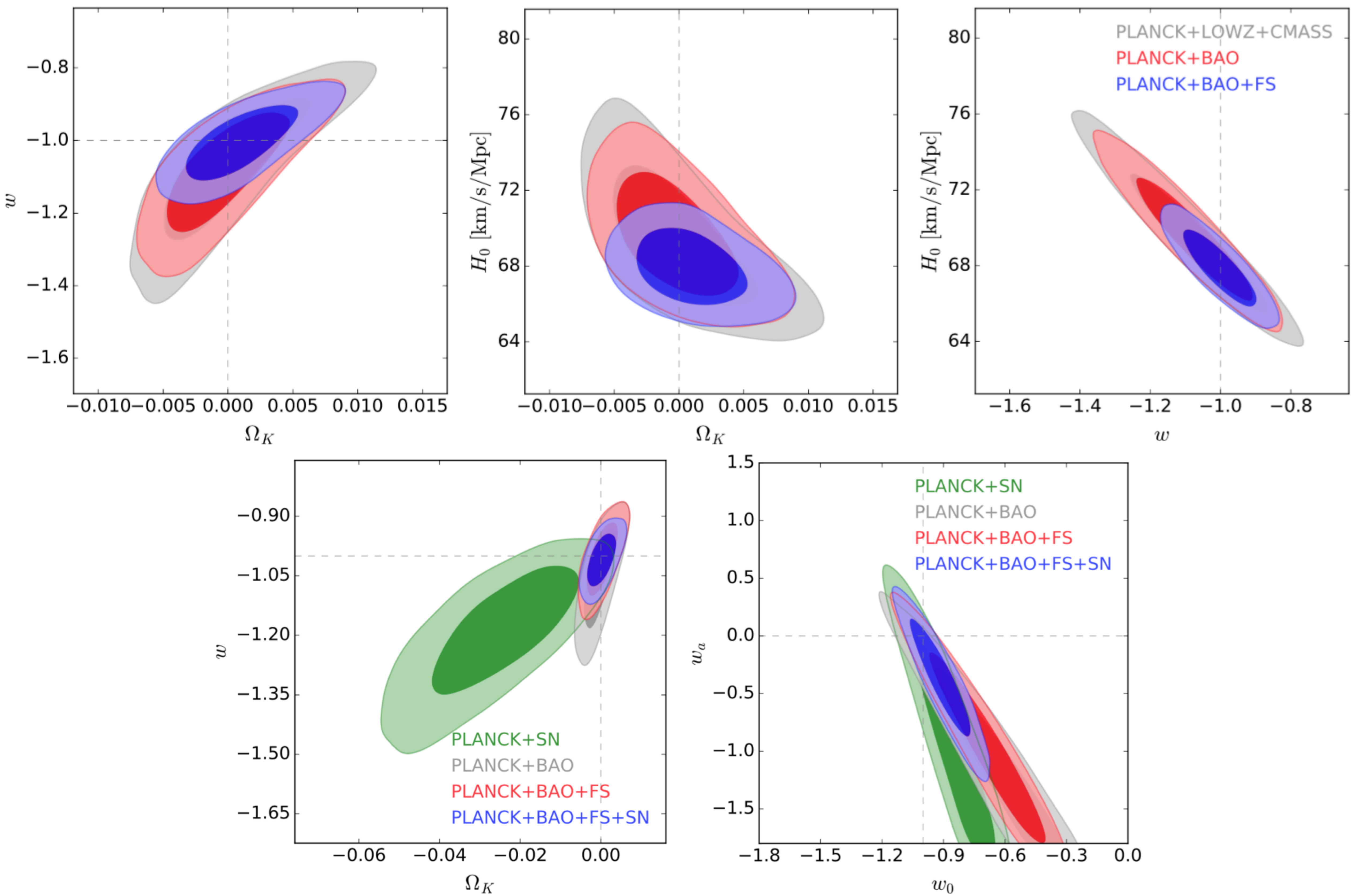

Boost to radial clustering depends on $f\sigma_8$




Samushia et al. 2013; MNRAS, 439, 3504; Alam et al. 2016, arXiv:1607.03155

# Combining with Planck data



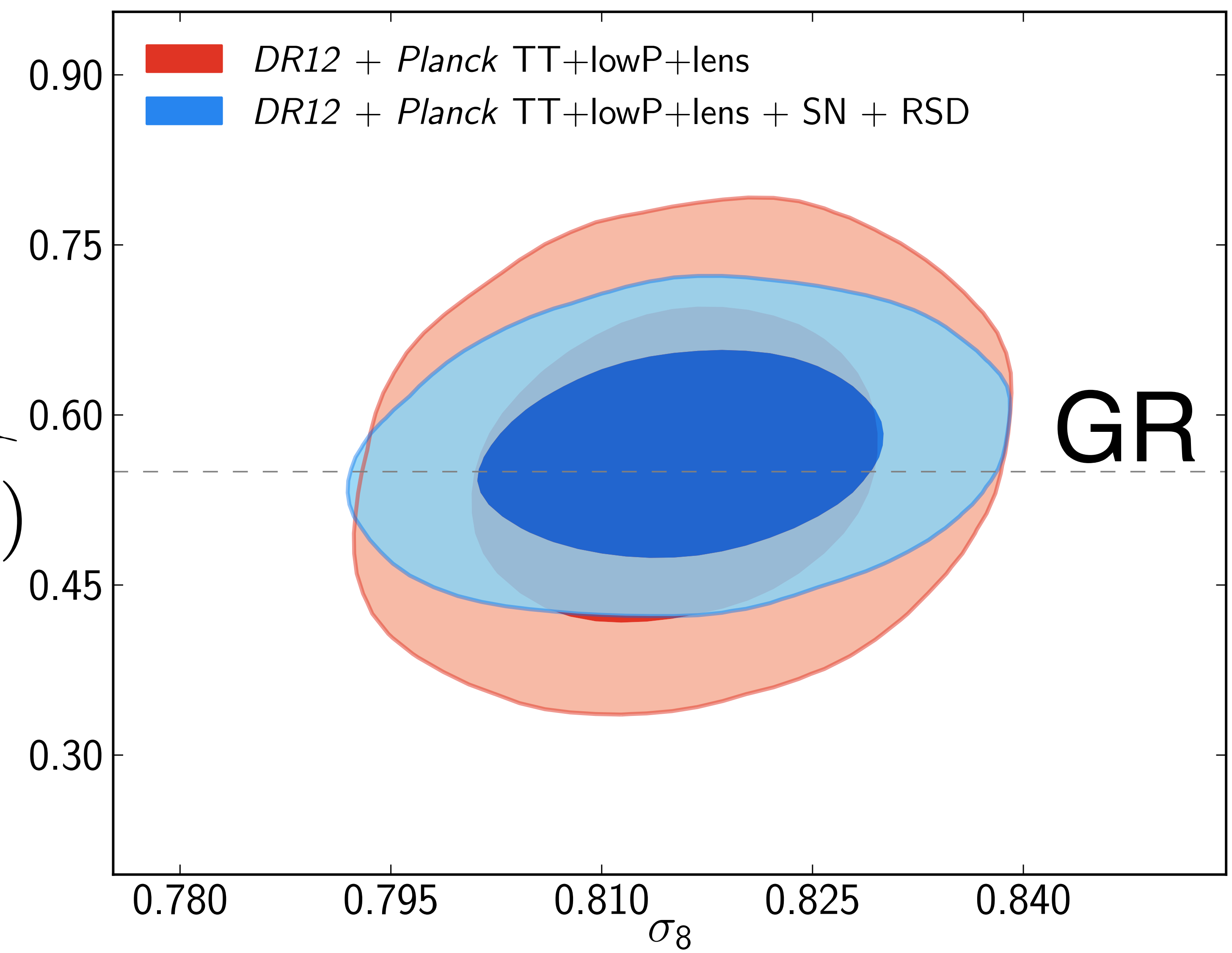

Alam et al. 2016, arXiv:1607.03155

# Testing modified gravity: Growth Index

$$f(a) = \Omega_m(a)^\gamma$$

$$\gamma = 0.566 \pm 0.058(68\%CL)$$

SN: JLA
RSD: 6dF, MGS, Vipers




**Good agreement with GR**

Mueller et al. 2016, arXiv:1612.00812

# Testing modified gravity: Poisson Equations

## Newtonian potentials

$$ds^2 = a^2[-(1+2\psi)d\tau^2 + (1-2\phi)d\mathbf{x}^2] \qquad \gamma_{\rm slip} = \frac{\phi}{\psi}$$

## Perturbation equations

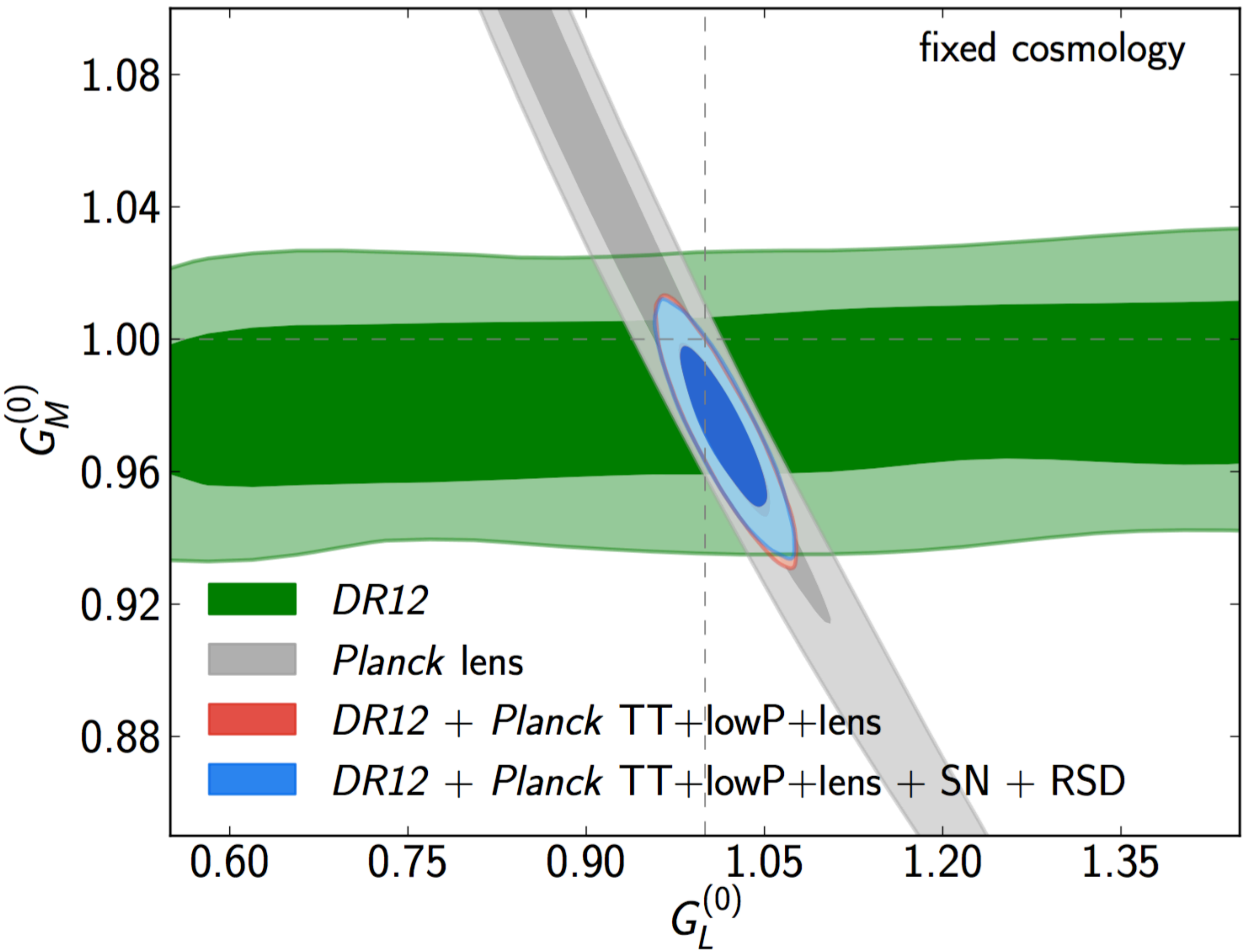
$$\nabla^2\psi = 4\pi G a^2 \rho\Delta \times G_{\rm M}$$ Growth of structure

$$\nabla^2(\psi+\phi) = 8\pi G a^2 \rho\Delta \times G_{\rm L}$$ Bending of light

**Phenomenological model**

Mueller et al. 2016, arXiv:1612.00812

# Testing modified gravity: Poisson Equations




**Good agreement with GR**

Mueller et al. 2016, arXiv:1612.00812

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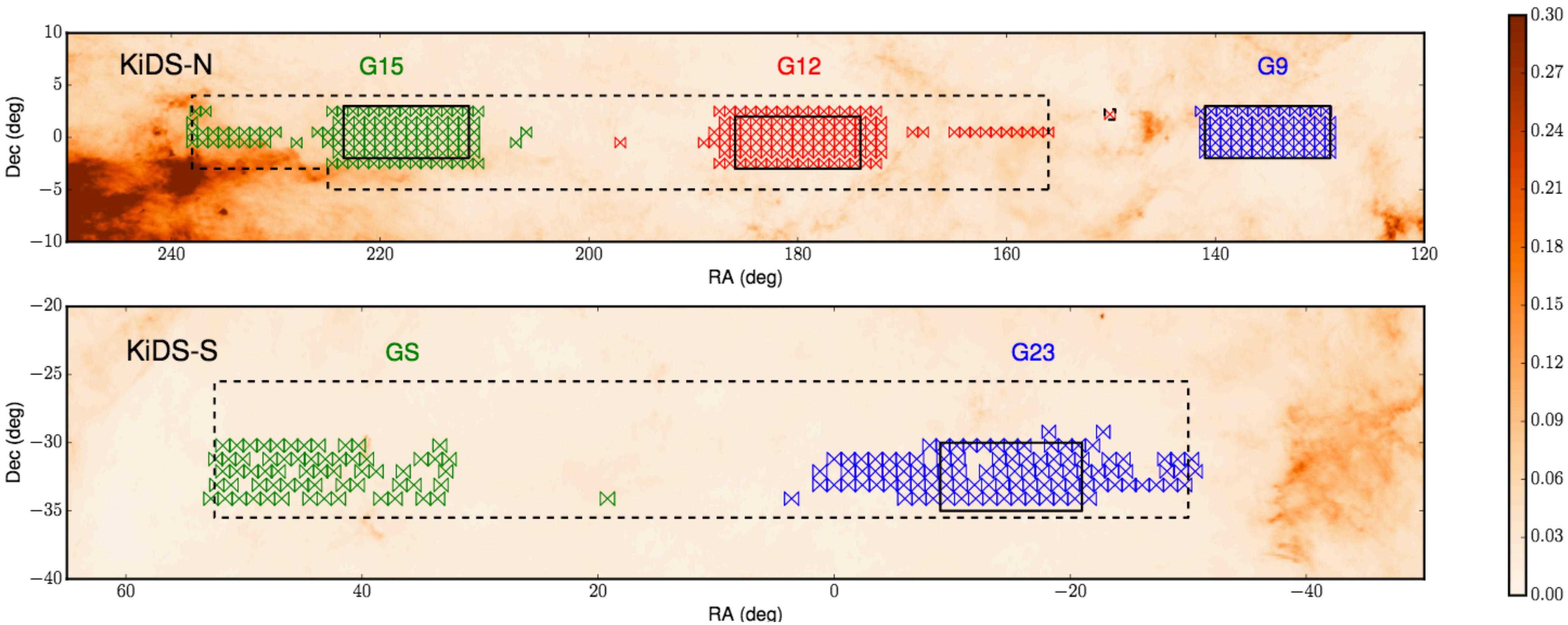
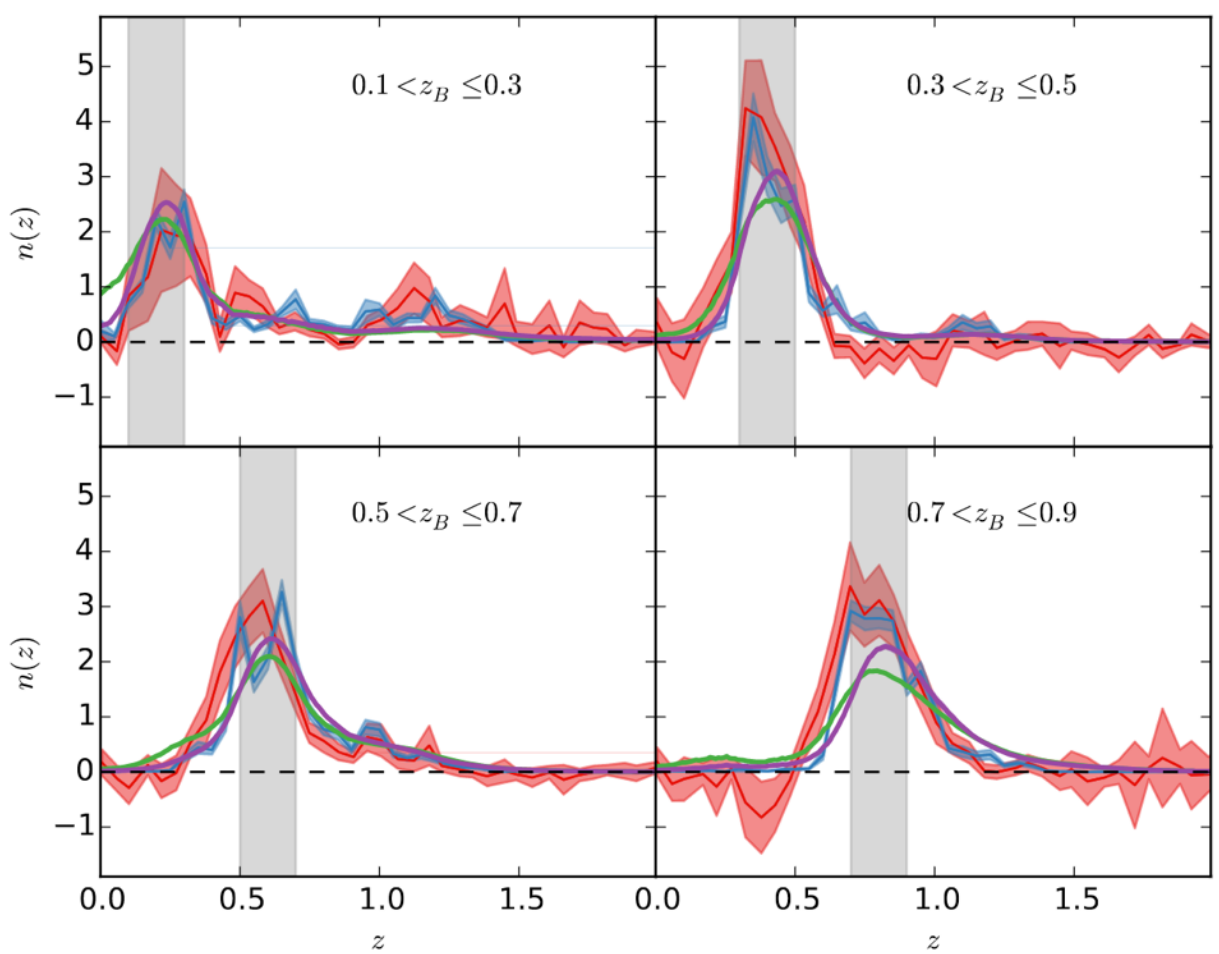
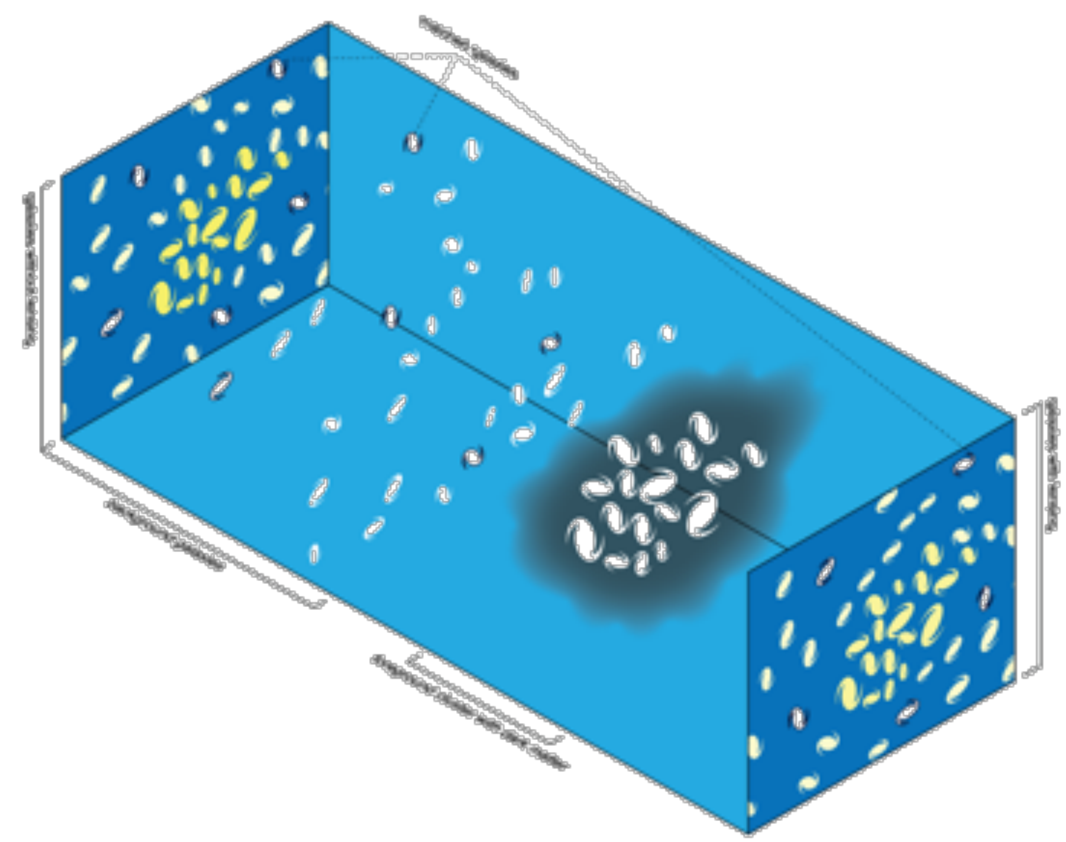
# Current: weak lensing surveys

# KiDS-450 weak lensing data



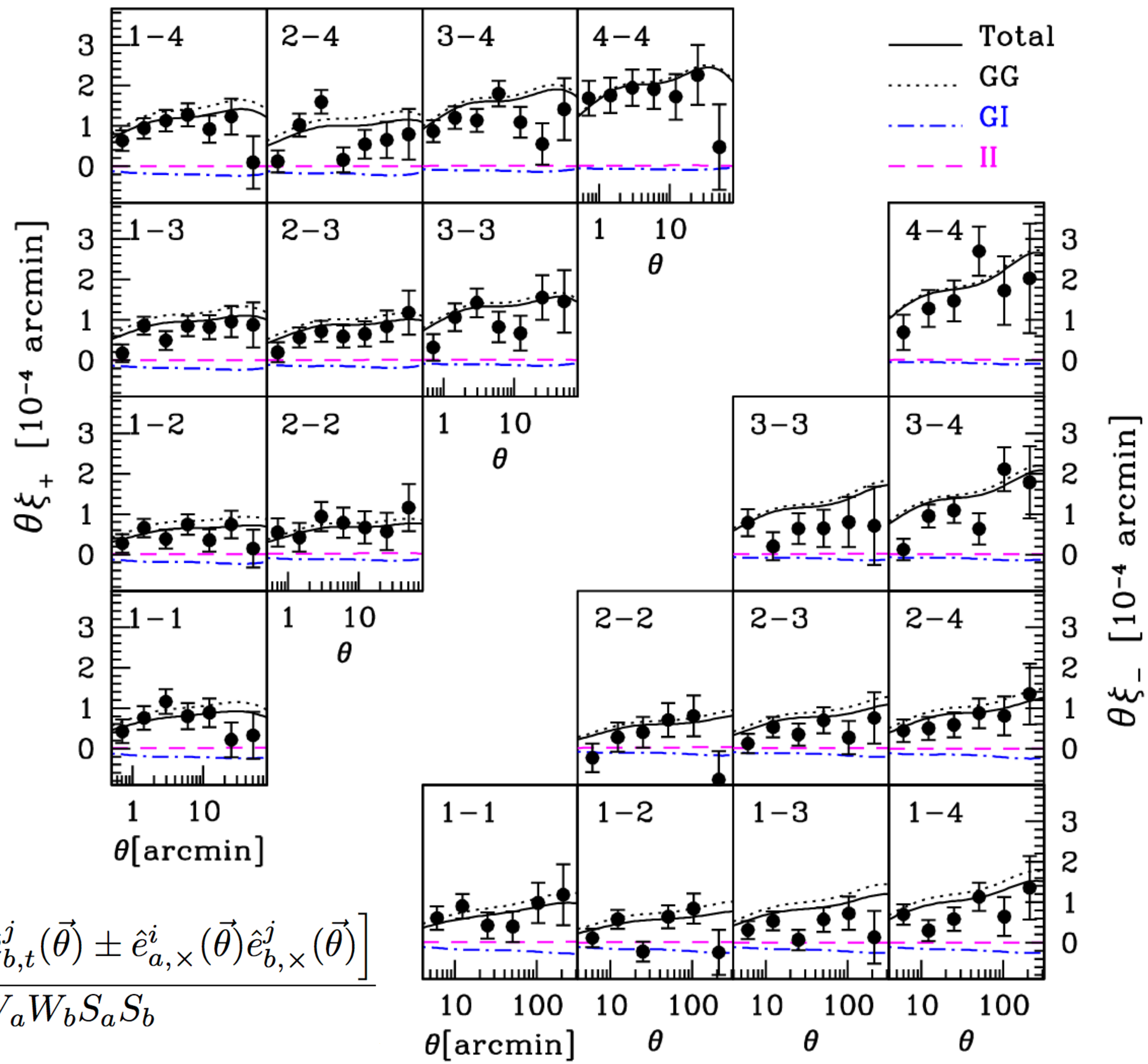

450 deg$^2$
15M gals
$\sigma_e$=0.29



Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

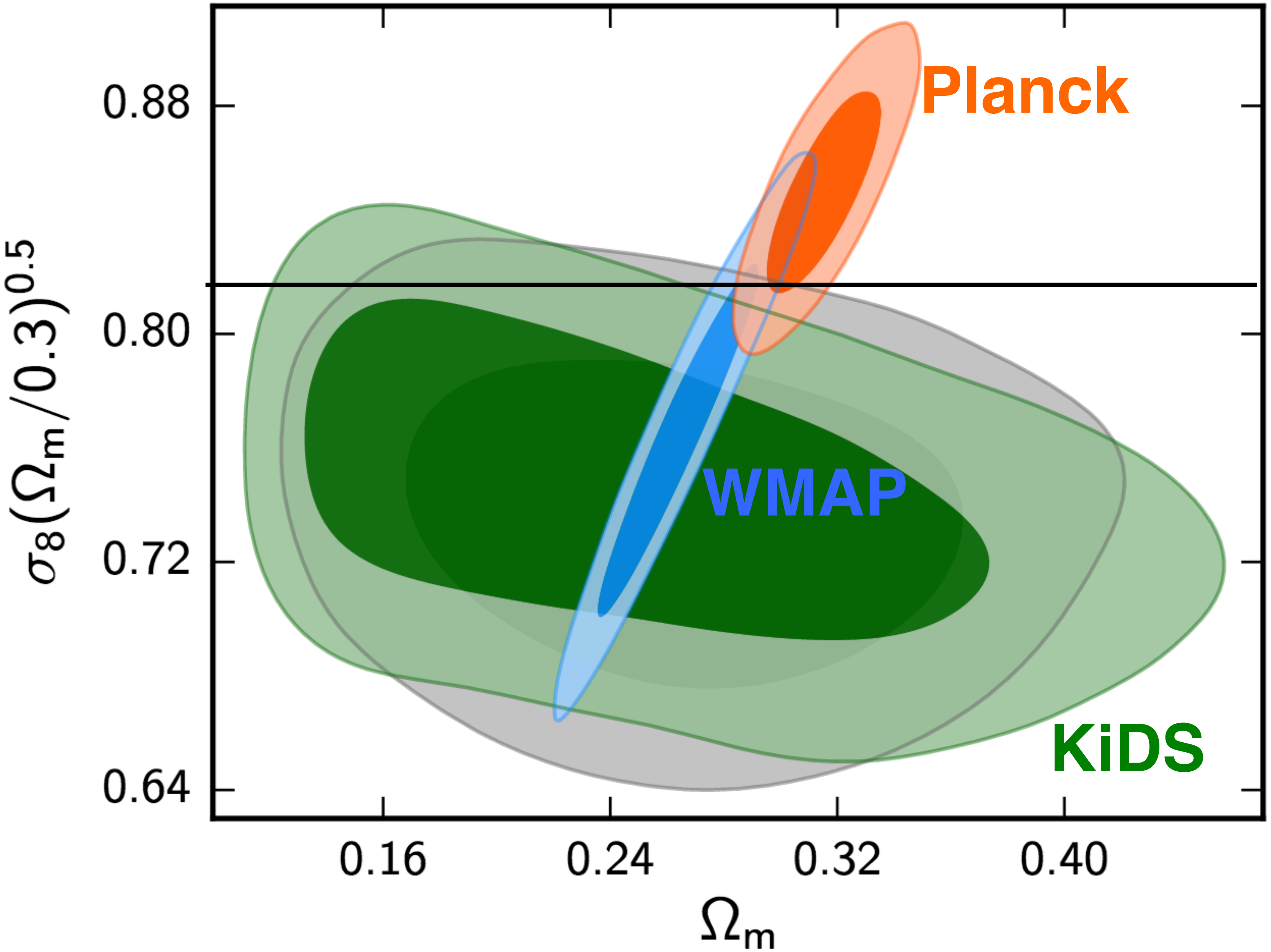
# KiDS weak lensing data




$$\hat{\xi}_{\pm}^{ij}(\theta) = \frac{\sum_{ab} W_a W_b \left[ \hat{e}_{a,t}^{i}(\vec{\theta}) \hat{e}_{b,t}^{j}(\vec{\theta}) \pm \hat{e}_{a,\times}^{i}(\vec{\theta}) \hat{e}_{b,\times}^{j}(\vec{\theta}) \right]}{\sum_{ab} W_a W_b S_a S_b}$$

Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

# KiDS weak lensing $S_8$

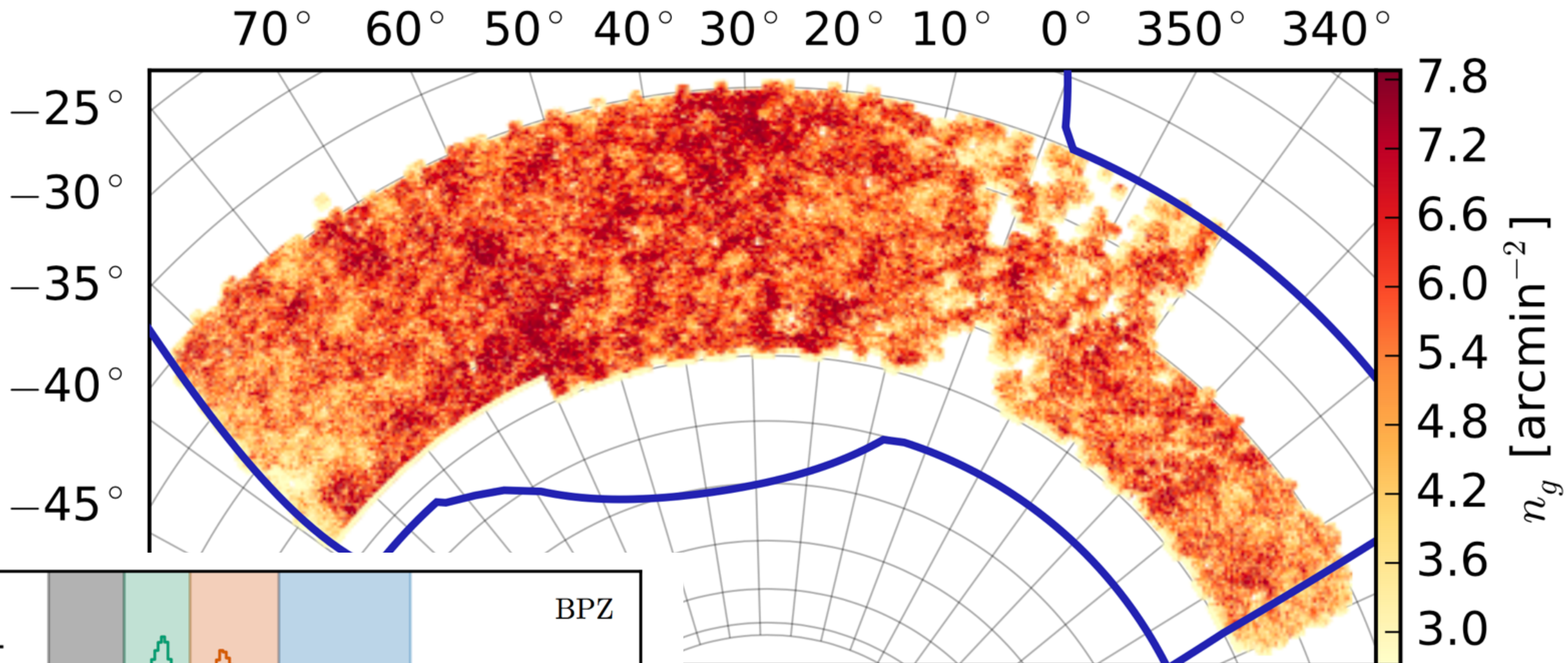



$S_8 = 0.82 \pm 0.05$ (DR12)

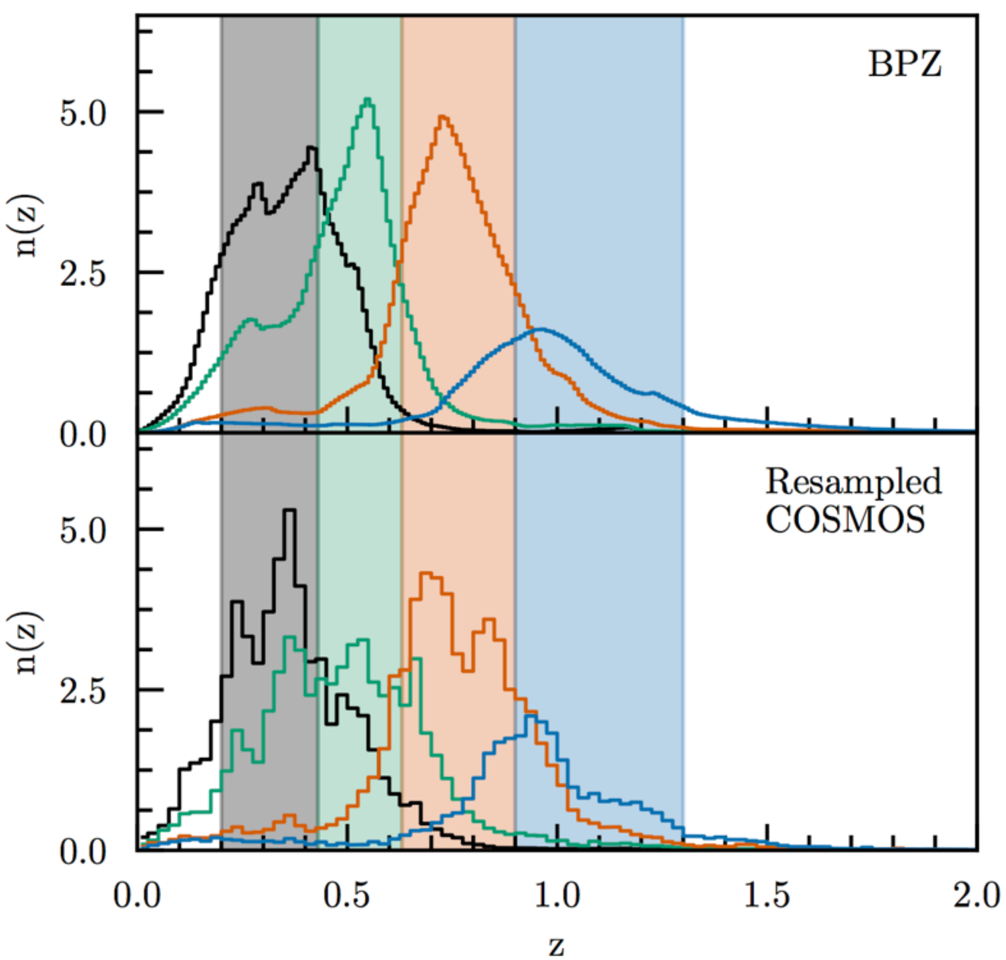
**BOSS data: right in between**

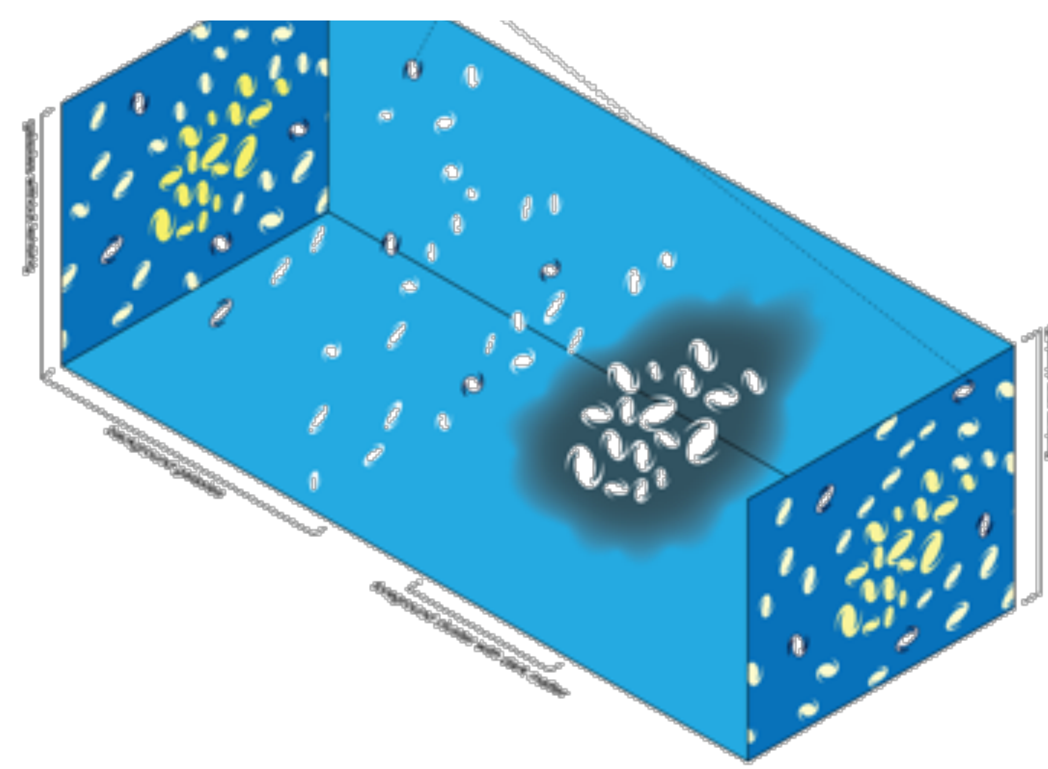
Hildebrandt et al. (KiDS consortium) 2016, arXiv:1606.05338

# DES weak lensing data



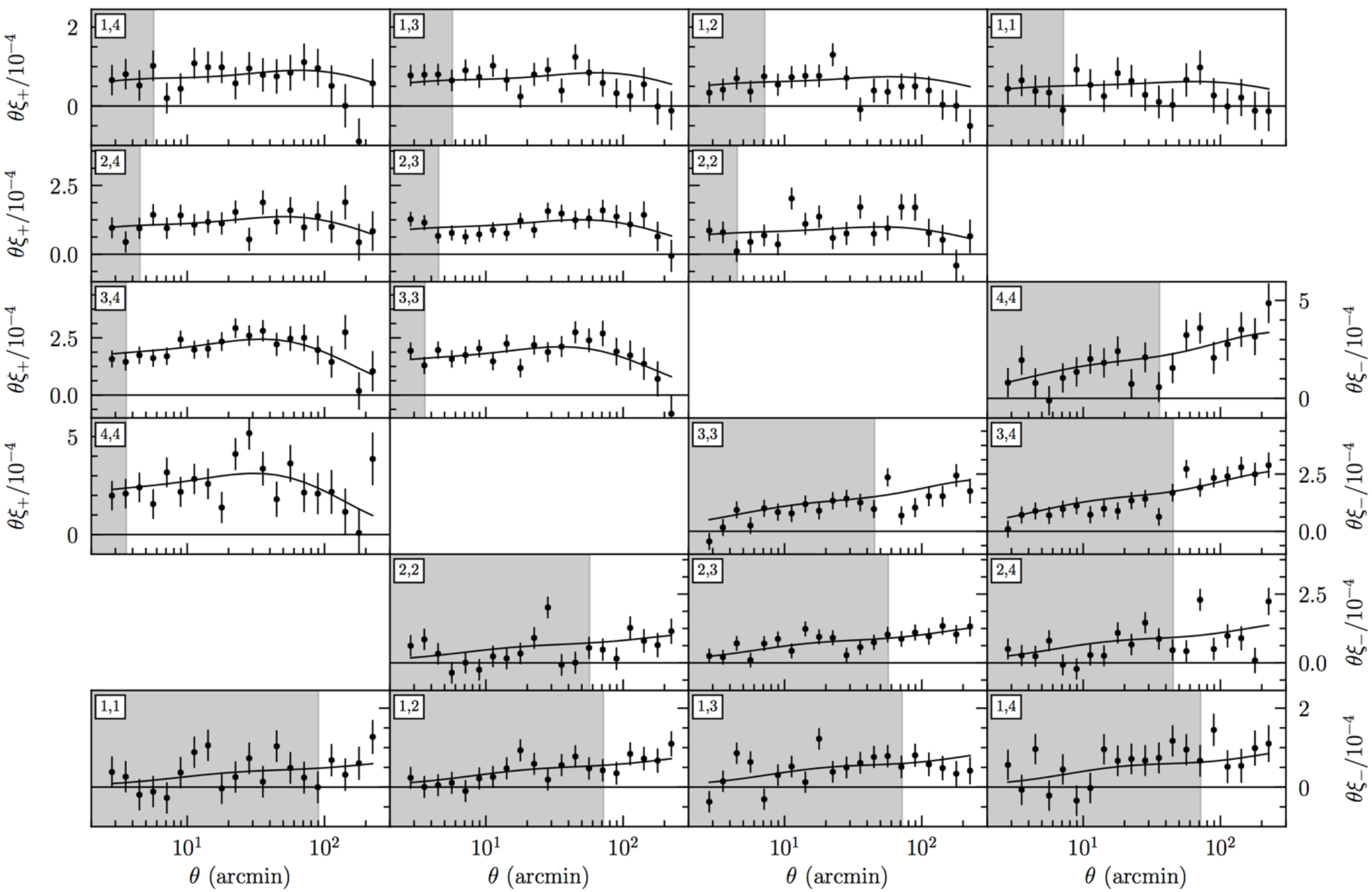

1321 deg$^2$
18M gals
$\sigma_e$=0.28



Troxel et al. (DES consortium) 2017, arXiv:1708.01538

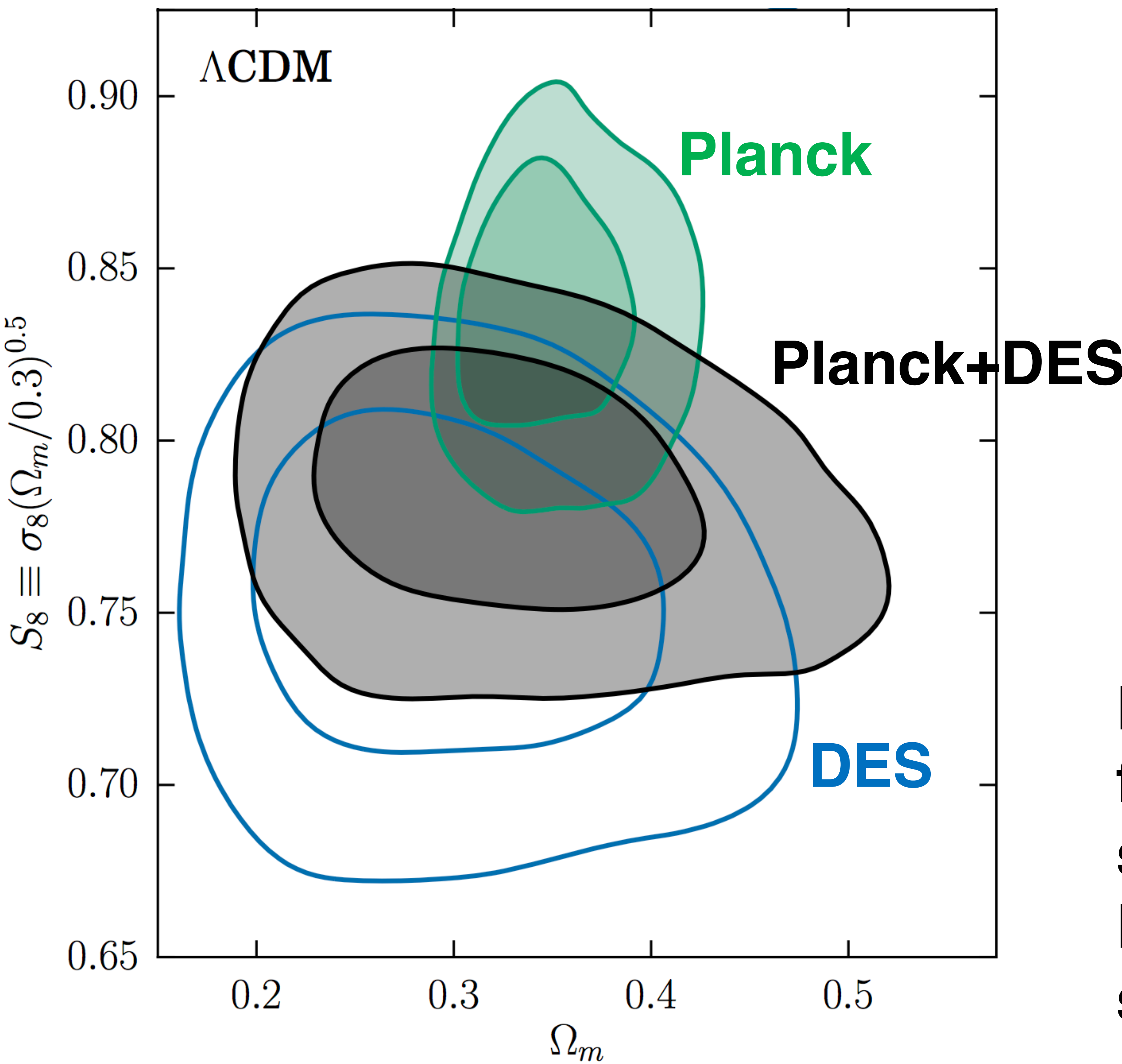
# DES weak lensing data




$$\hat{\xi}_{\pm}^{ij}(\theta) = \frac{\sum_{ab} W_a W_b \left[\hat{e}^i_{a,t}(\vec{\theta})\hat{e}^j_{b,t}(\vec{\theta}) \pm \hat{e}^i_{a,\times}(\vec{\theta})\hat{e}^j_{b,\times}(\vec{\theta})\right]}{\sum_{ab} W_a W_b S_a S_b}$$

Troxel et al. (DES consortium) 2017, arXiv:1708.01538

# DES weak lensing $S_8$




**DES: difference from Planck in similar direction to KiDS, but of lower significance**

Troxel et al. (DES consortium) 2017, arXiv:1708.01538

# Future surveys: DESI (galaxy clustering)

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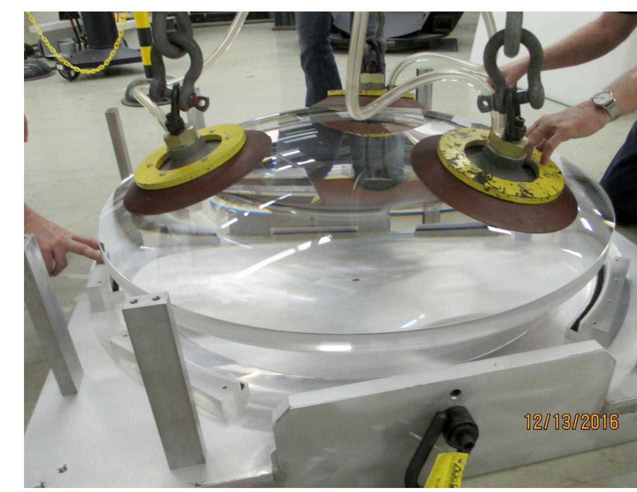
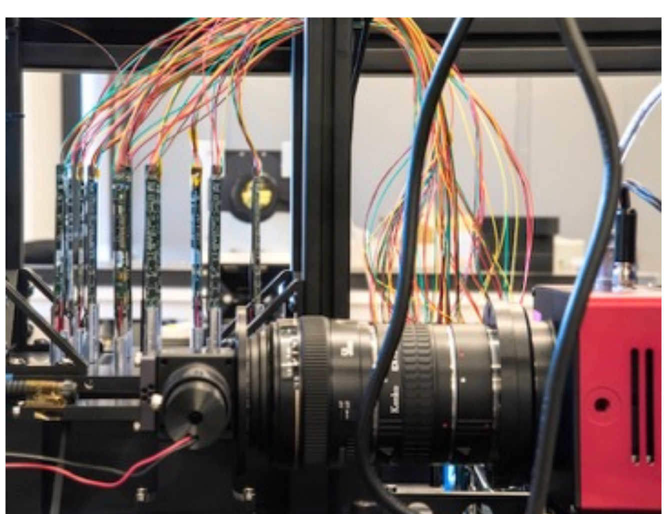
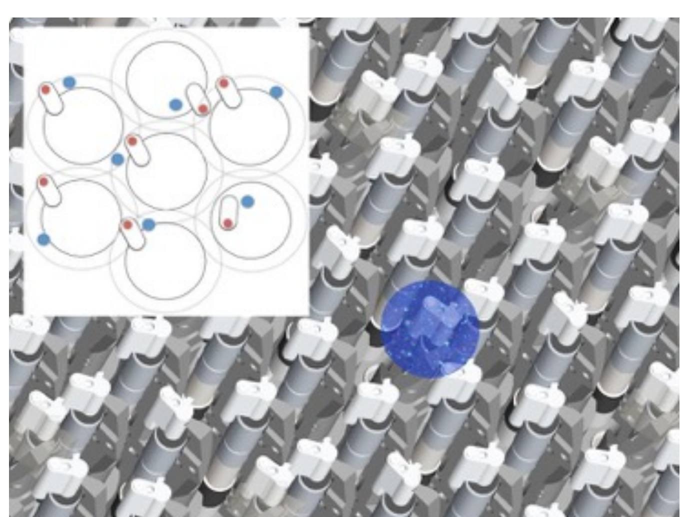
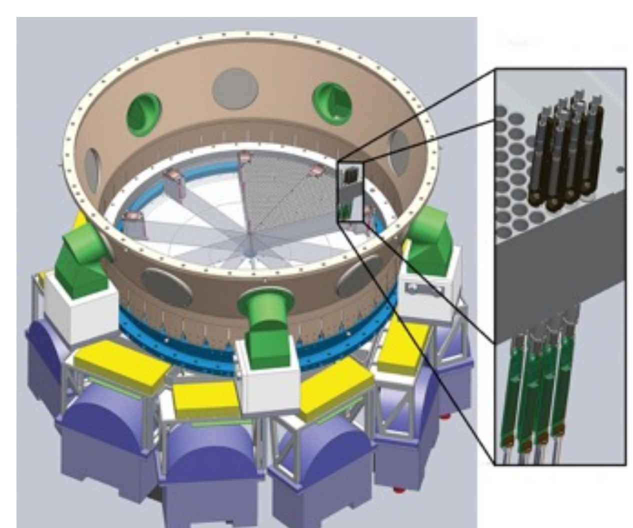
# DESI

- Dark Energy Spectroscopic Instrument (DESI)
- New fibre-fed MOS for Mayall
- passed DOE CD-3, on course for 2019 start
- DESI will observe:
    - $\Omega$ =14,000deg$^2$
    - ~20,000,000 high redshift galaxies (direct BAO)
    - ~10,000,000 low redshift (z<0.5) galaxies
    - ~600,000 quasars (BAO from Ly-α forest)
    - Cosmic variance limited to z ~ 1.4
- Also WEAVE (WHT, 2018 start) and 4MOST (VISTA, 2021 start) but fewer fibers, so less optimized for cosmological applications

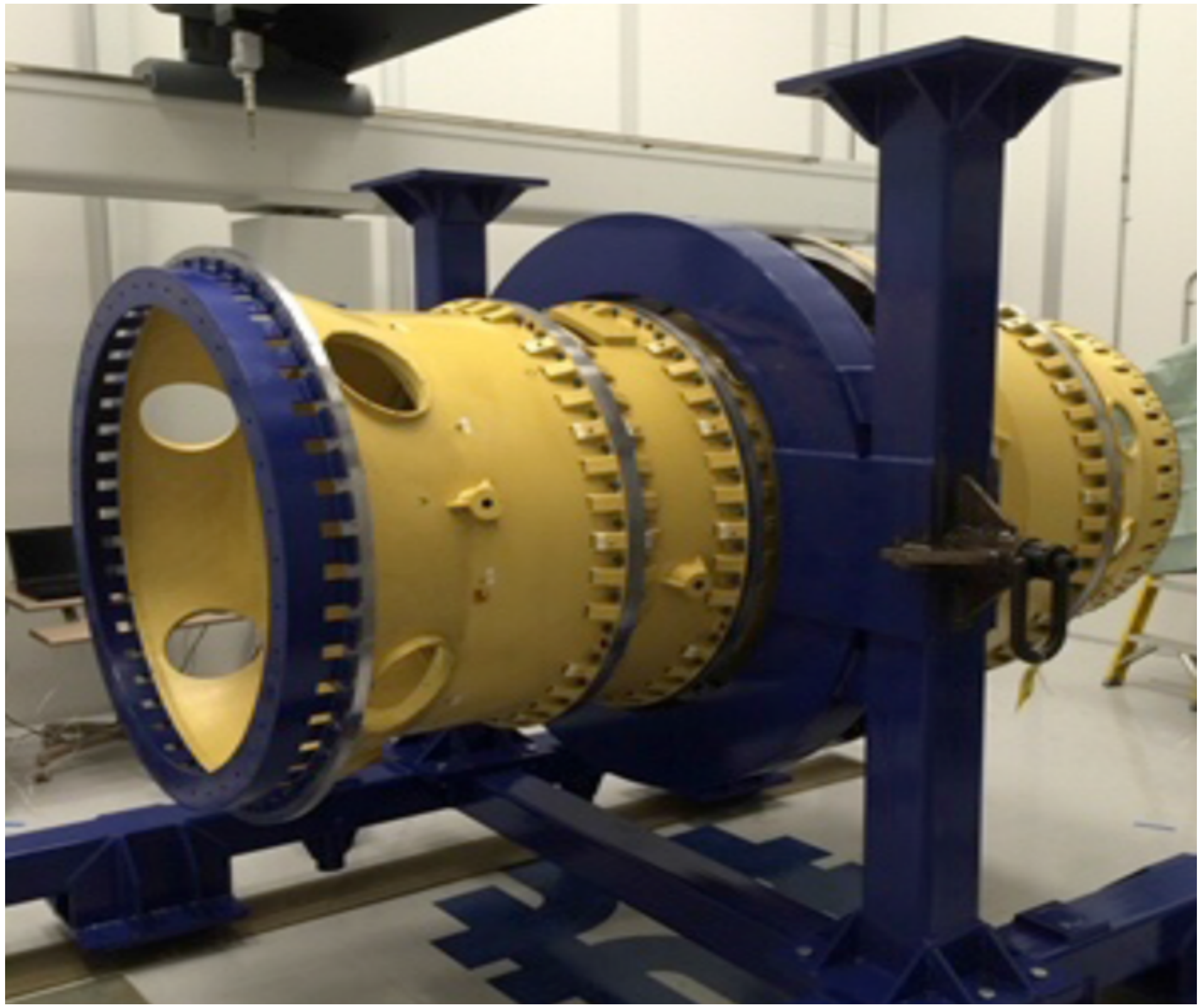




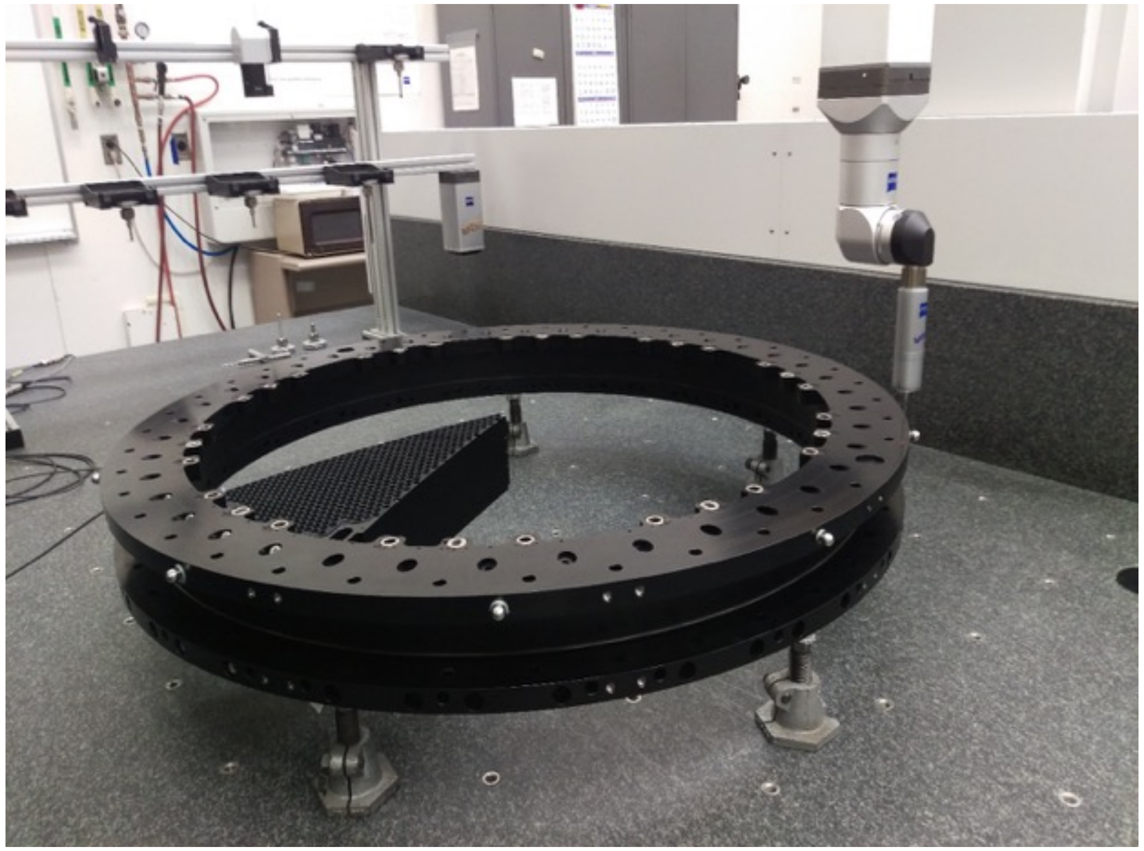


# DESI - latest updates



2017 is a critical year for hardware manufacture

# DESI - latest updates



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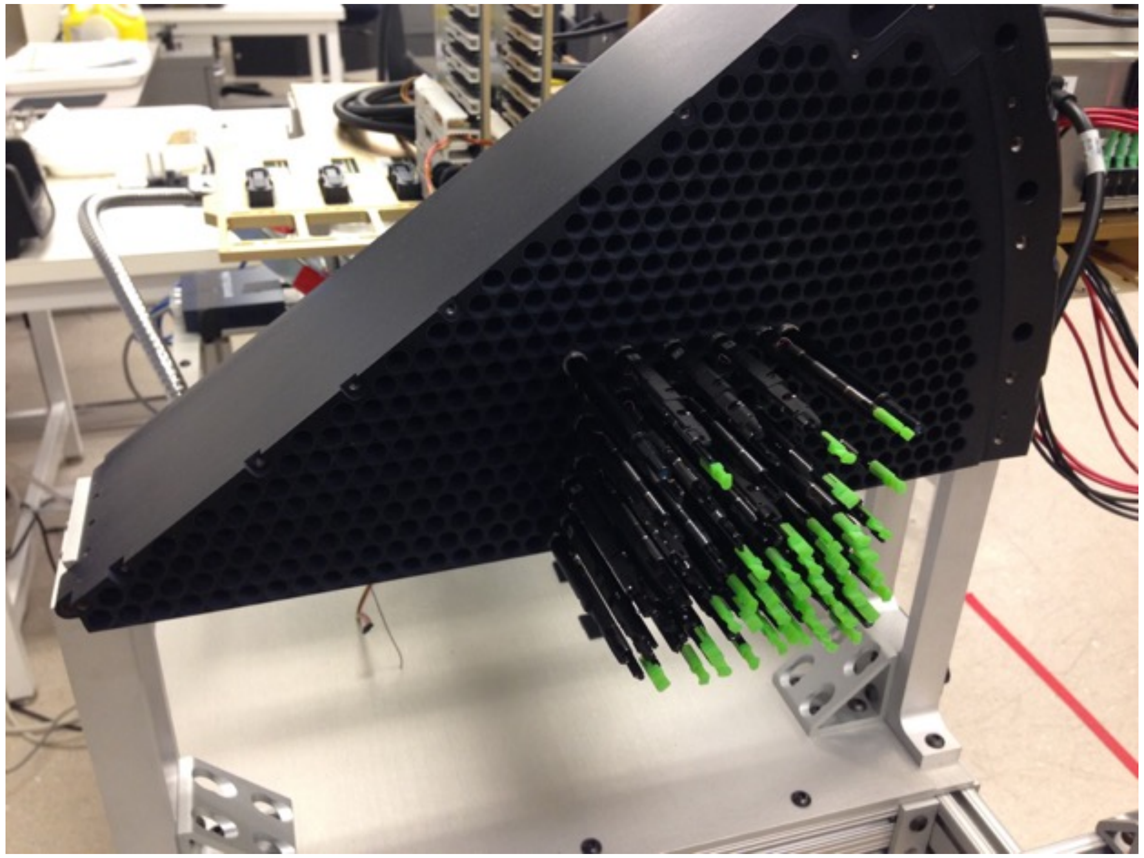
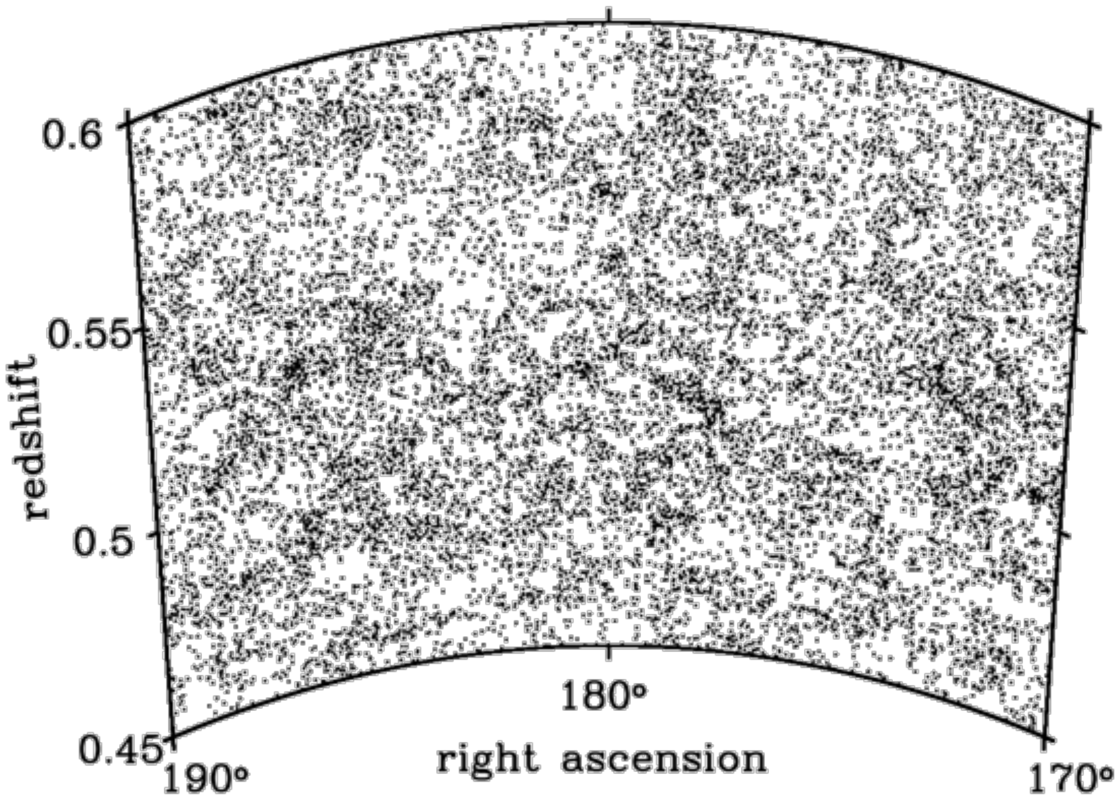
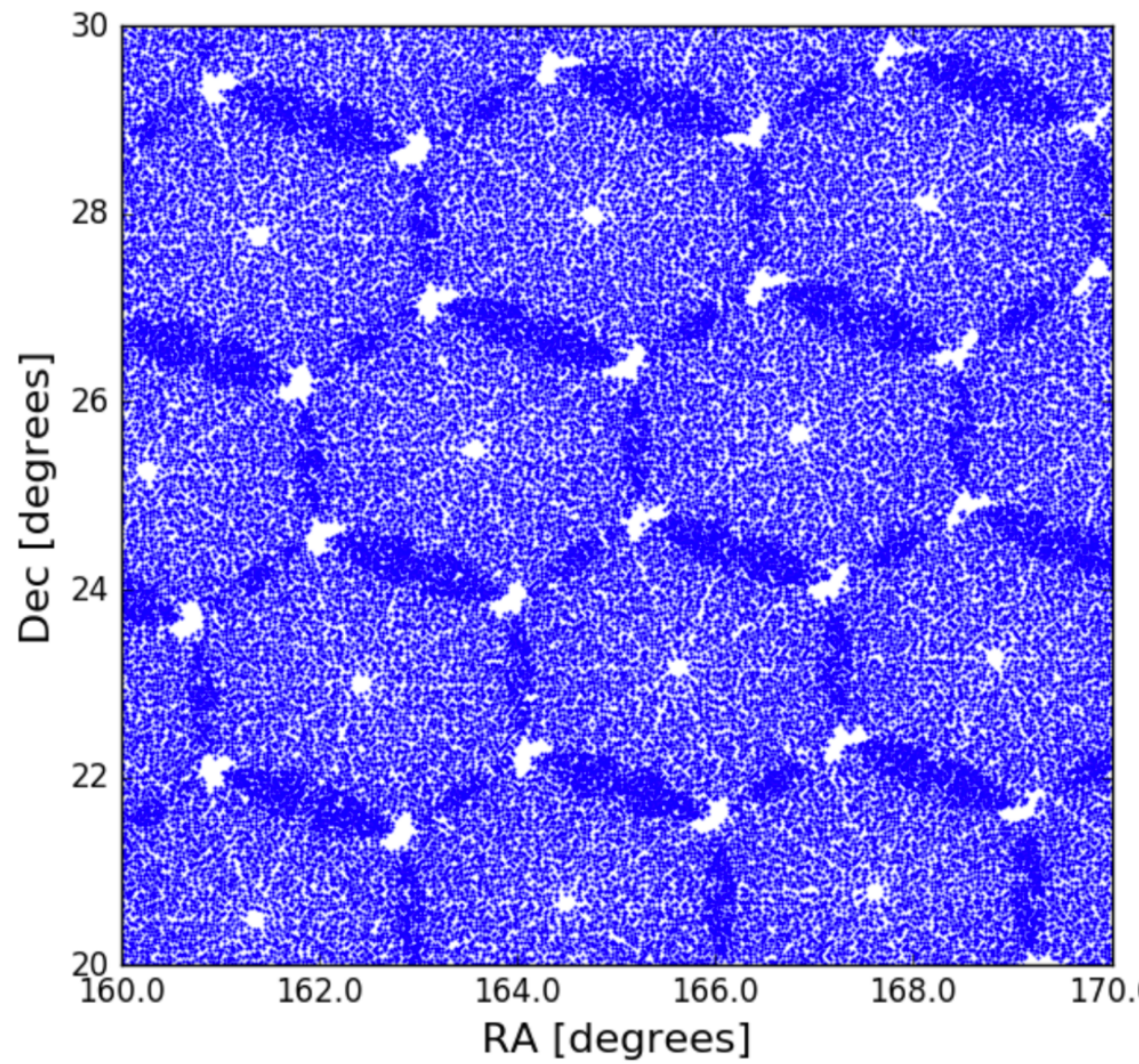


# DESI observations




Burden et al. 2016; arXiv:1611.04635

# Dealing with missing galaxies

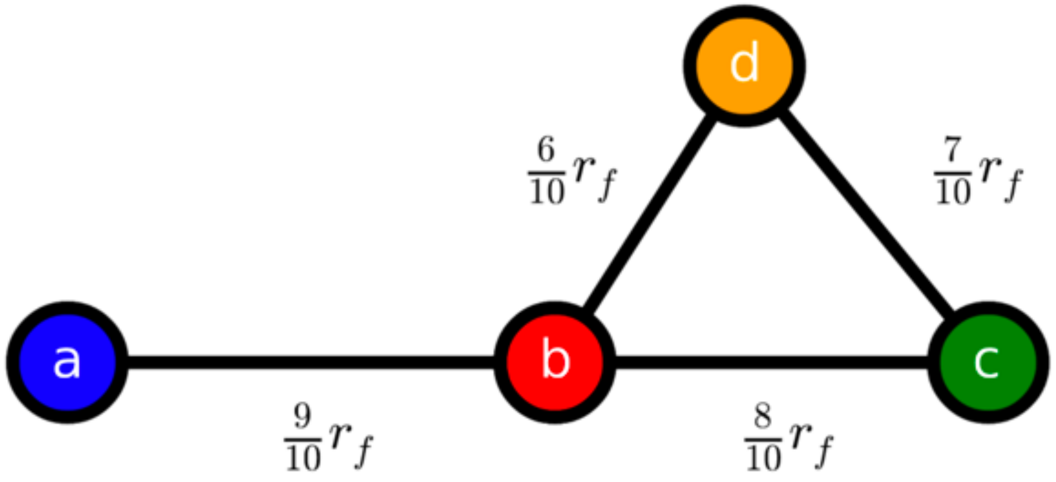
Spectroscopic surveys are always < 100% complete

Missed galaxies are often correlated – either intrinsically (e.g. regions of low S/N), or with the density field (e.g. cannot observe all galaxies in a dense region)

This affects the measured clustering

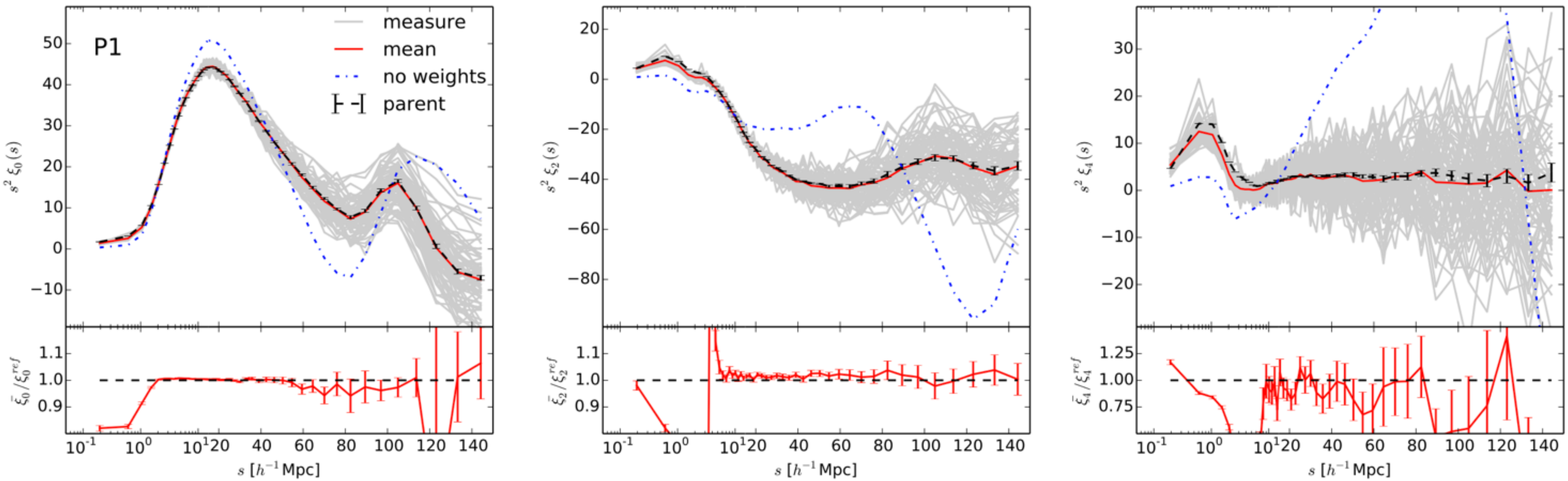
Bianchi & Percival (2017) Proposed a new correction statistically matching missed pairs (whose radial separation is unknown) with those observed

This has to be done for every pair: $10^6$ galaxies -> $10^{12}$ pairs!



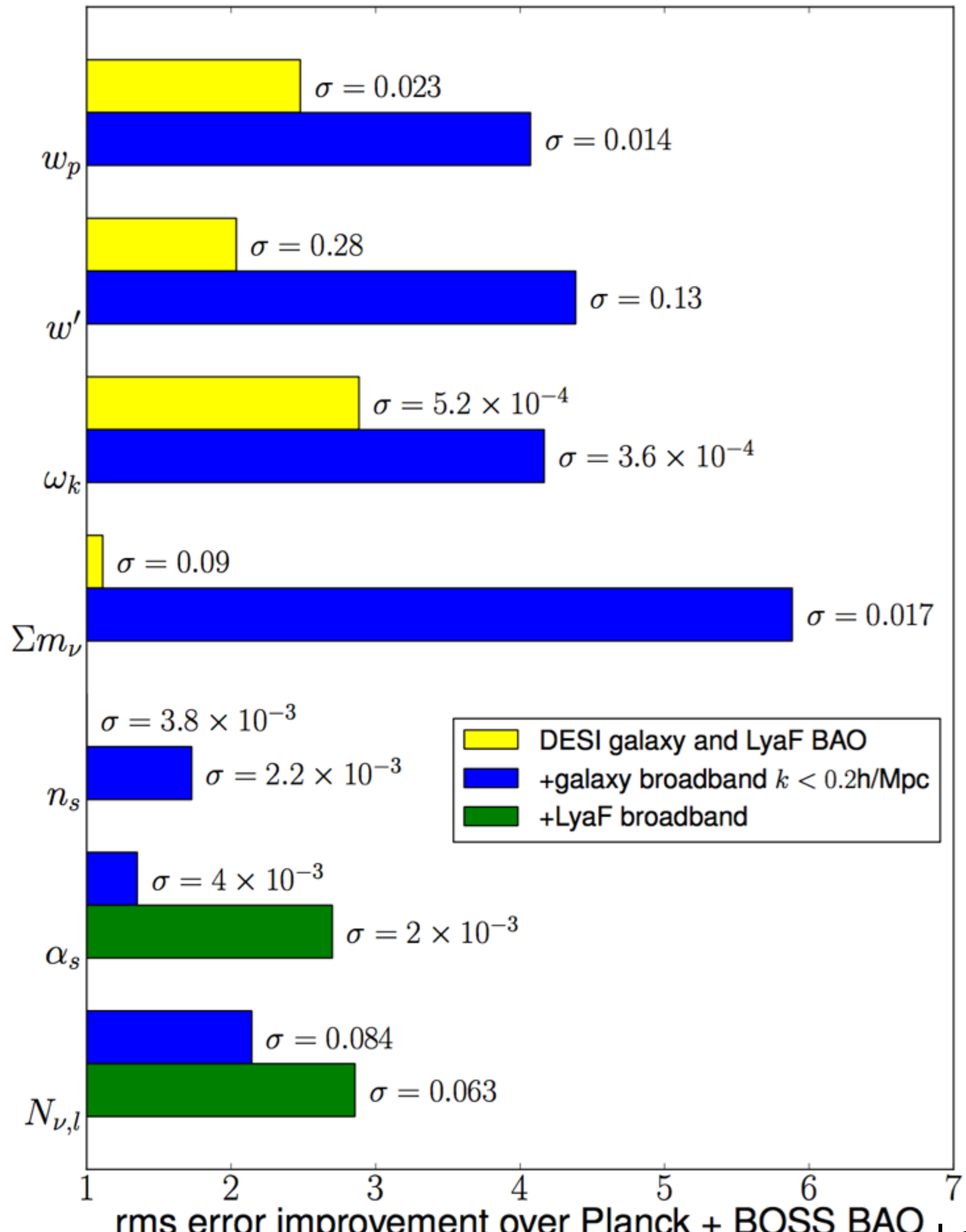

Bianchi & Percival 2017; arXiv:1703.02070

# DESI: Fiber assignment




Bianchi & Percival 2017; arXiv:1703.02070

# DESI cosmological predictions




Levi et al. 2013; arXiv:1308.0847

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# Future surveys: Euclid (GC+WL)

# Euclid

M2 mission in ESA cosmic visions program
due to launch late 2020

Wide survey:

- $15{,}000deg^2$
- 4 passes over sky
- NIR Photometry
    - Y, J, H
    - 24mag, $5\sigma$ point source
- NIR slitless spectroscopy
    - red: 1.25-1.85μm ($0.9<z<1.8$ Hα)
    - $2\times10^{-16} erg cm^{-2} s^{-1}$ $3.5\sigma$ line flux
    - 3 dispersion directions
    - 1 broad waveband $0.9<z<1.8$
    - ~25M galaxies
- wide-band visible image for WL

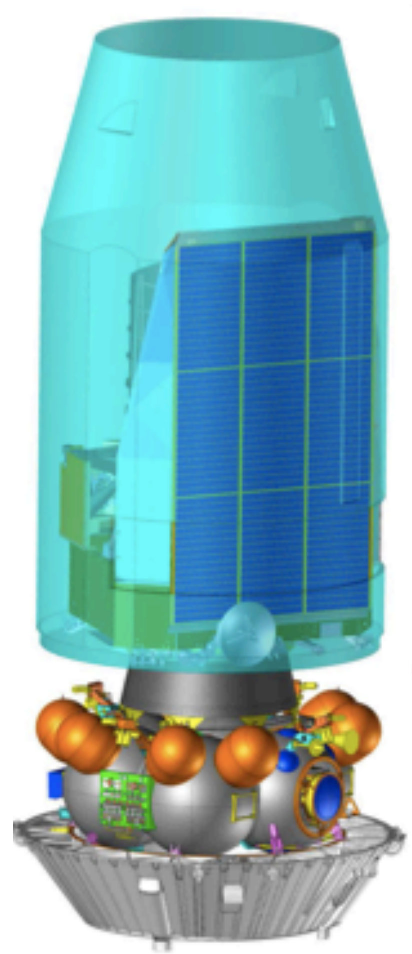
Deep survey:

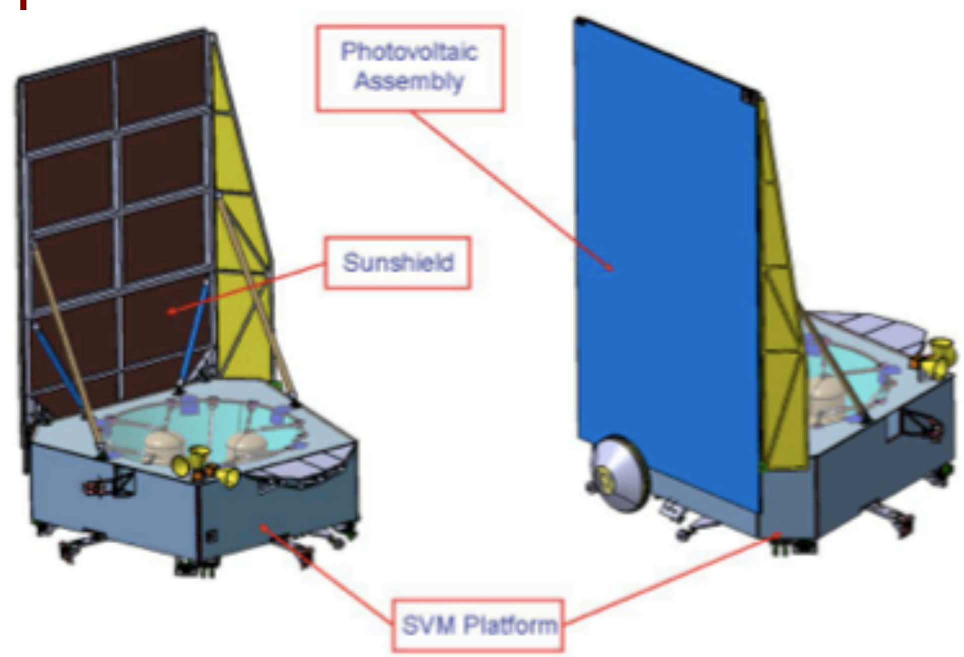
- $40deg^2$
- 48 dithers
- 12 passes, as for wide survey
- additional blue spectra: 0.92-1.25μm
- dispersion directions for 12 passes >10deg apart

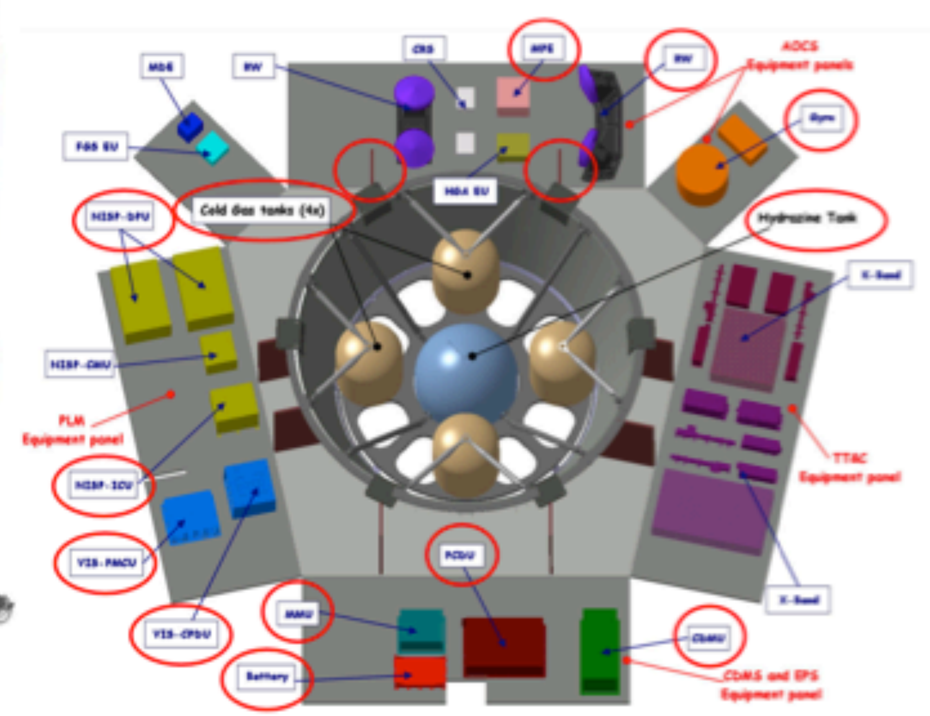
http://www.euclid-ec.org/

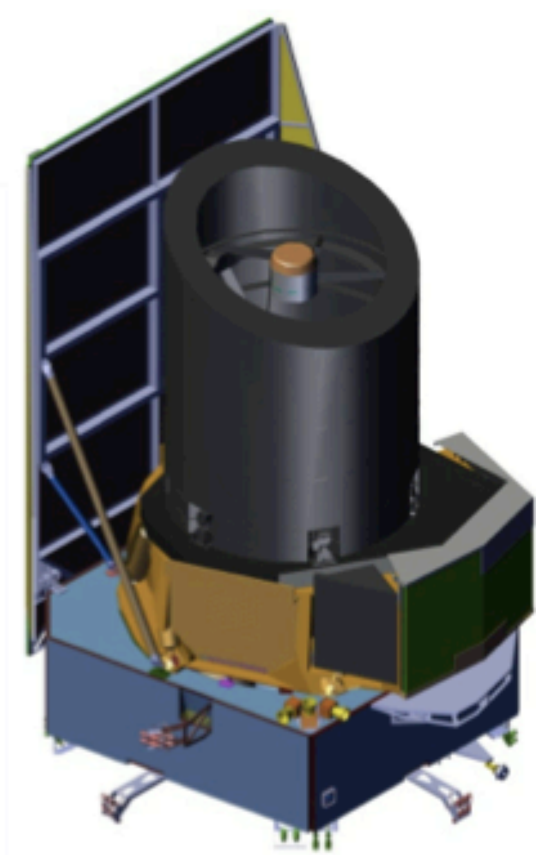
# The telescope

Total mass: 2200kg
Dimensions: 4.5m x 3m
Sunshield: Thales Alenia Space
Telescope: Airbus Defence and Space

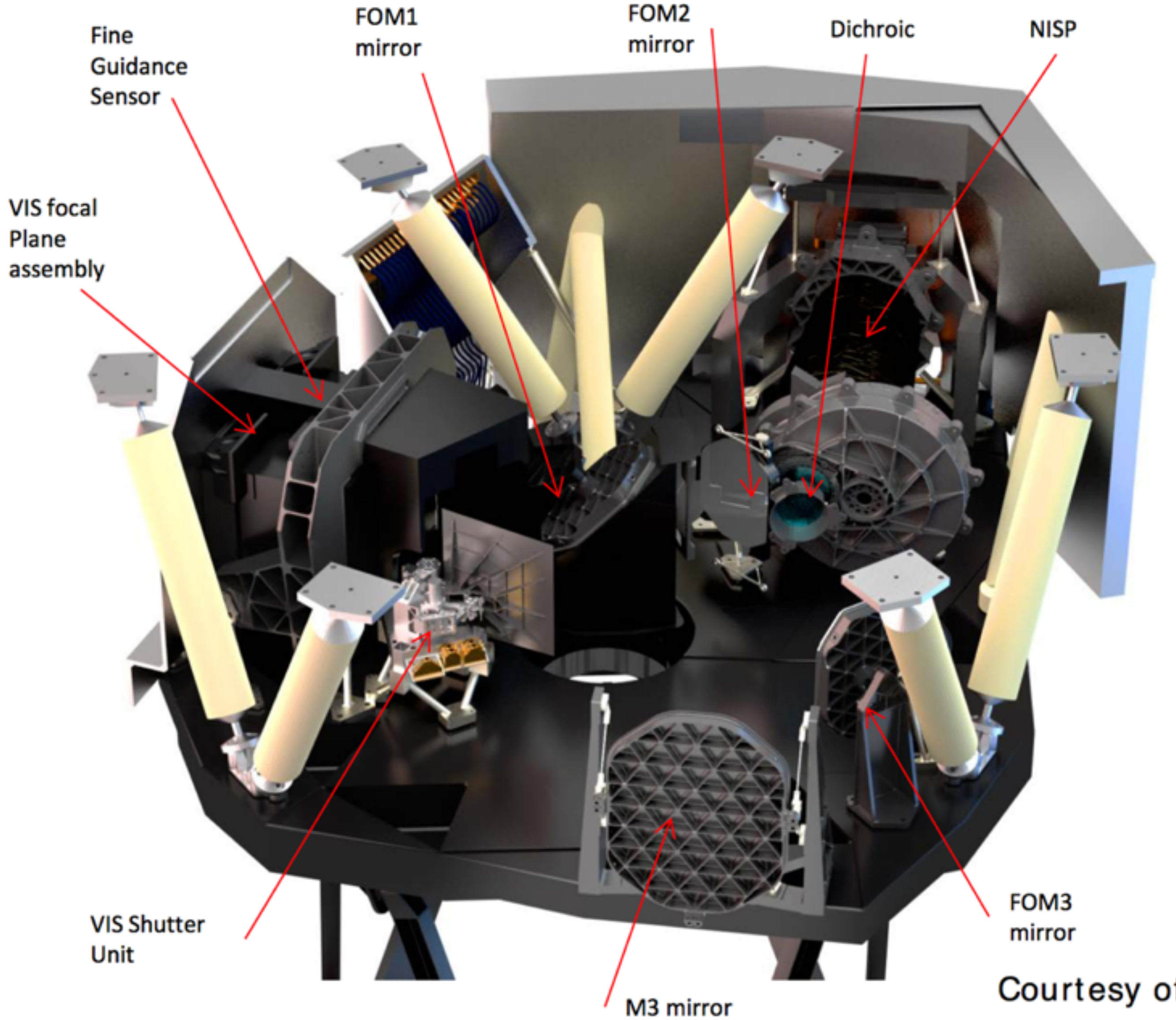




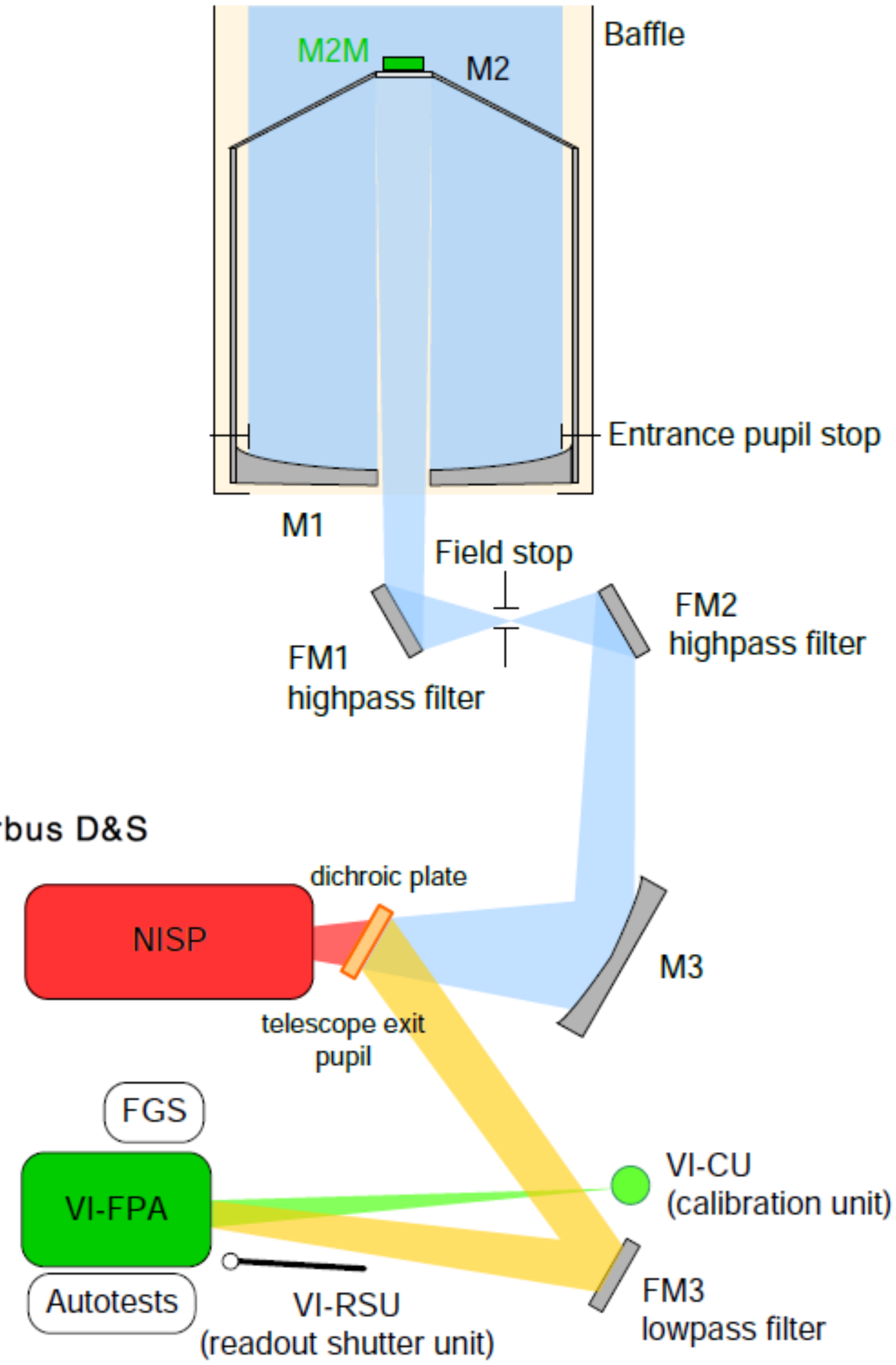



# Payload module

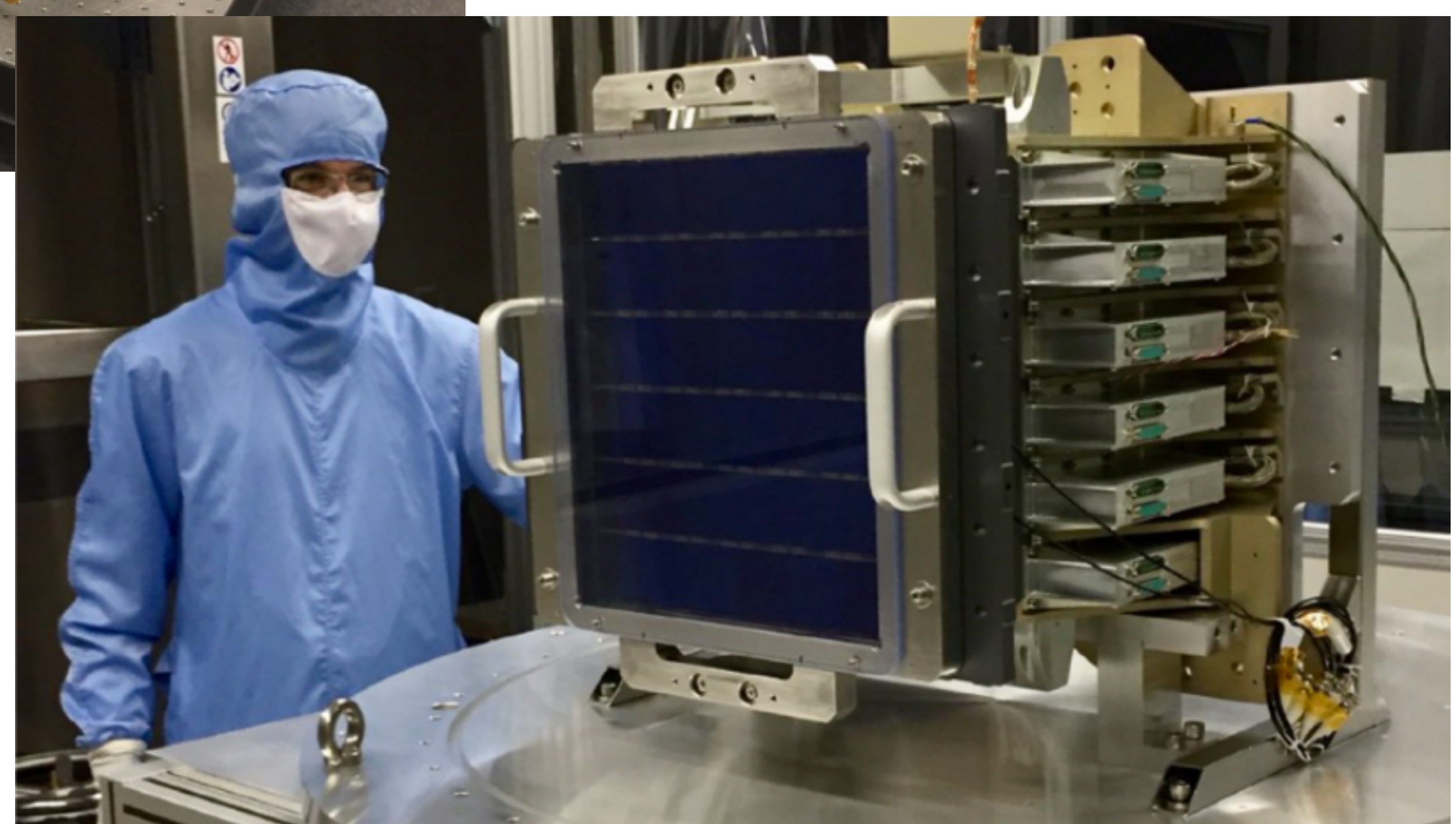



Courtesy of Airbus D&S

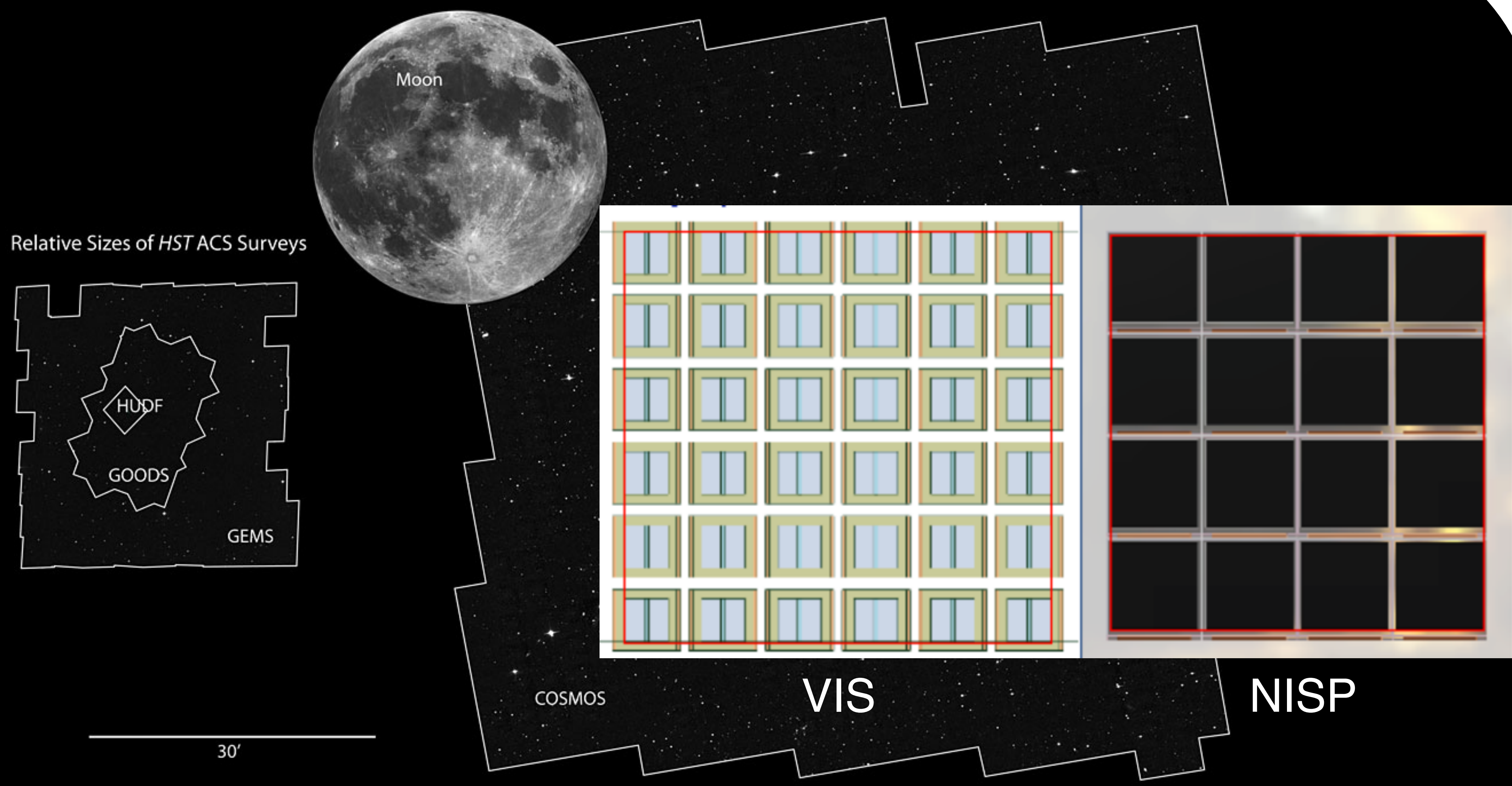


# Two channels: Visible and NIR

Structure and Thermal Model (STM) for NISP and VIS delivered and tested



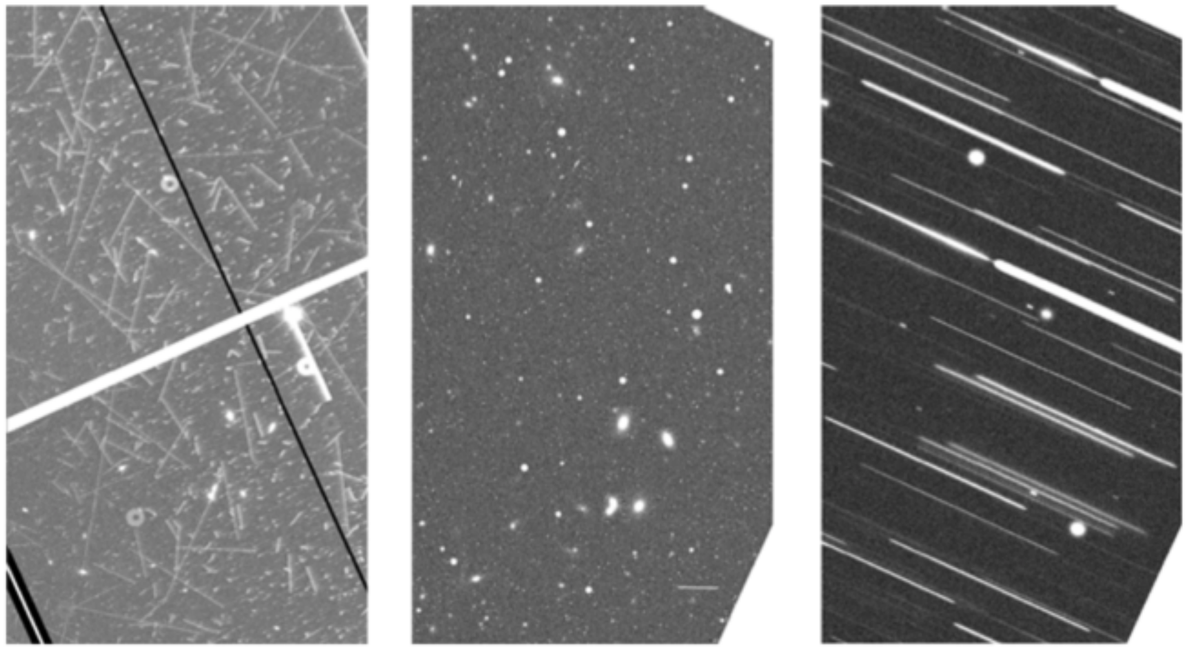
# Dual wide-field imagers



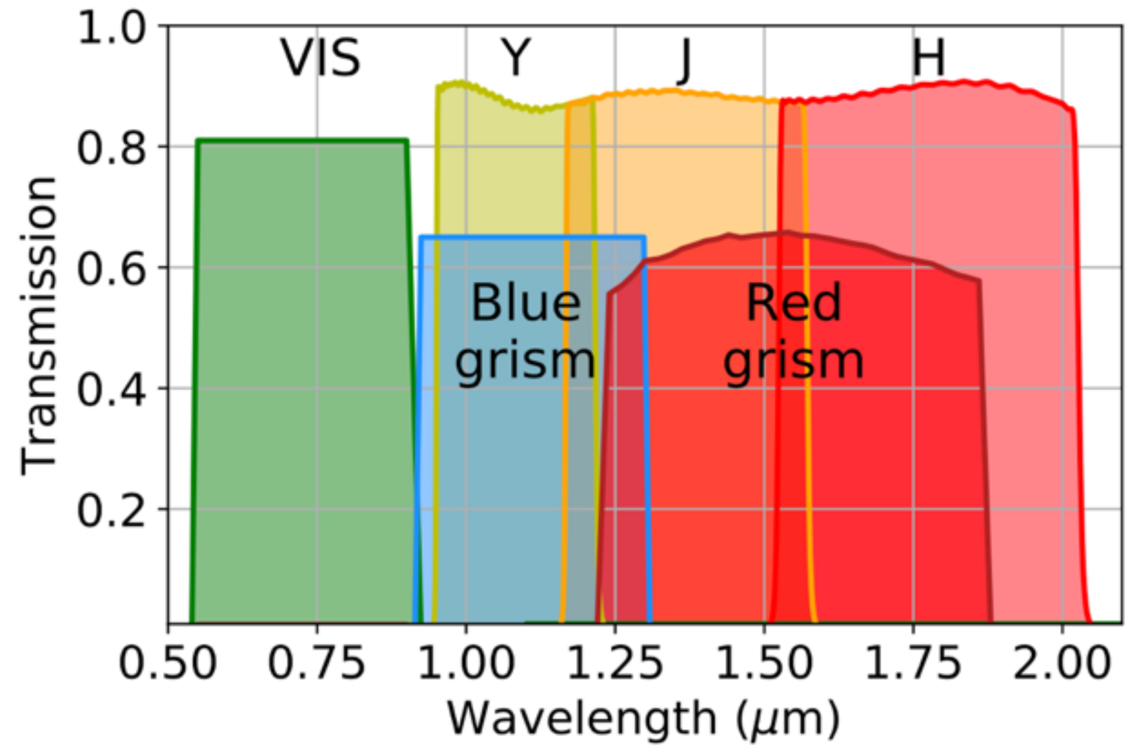

| | VIS | NISP |
|---|---|---|
| Detectors | 36 4096×4132 | 16 2040x2040 |
| Pixel size | 0.1” | 0.3” |
| Dispersion | - | 13.4 A/pixel |

# A panchromatic survey

VIS NISP NISP grism



* NISP simulation does not include cosmic rays




| | VIS | Y | J | H | GRISM |
|---|---|---|---|---|---|
| Wide | 24.5 | 24 | 24 | 24 | $2 \times 10^{-16}$ erg/s/cm$^2$ |
| Deep | 26.5 | 26 | 26 | 26 | $2 \times 10^{-17}$ erg/s/cm$^2$ |

# Euclid targets

| | | | | | |
|---|---|---|---|---|---|
| **SURVEYS** In ~6 years | | | | | |
| | Area (deg2) | Description | | | |
| Wide Survey | 15,000 $deg^2$ | Step and stare with 4 dither pointings per step. | | | |
| Deep Survey | 40 $deg^2$ | In at least 2 patches of > 10 $deg^2$<br>2 magnitudes deeper than wide survey | | | |
| **PAYLOAD** | | | | | |
| Telescope | 1.2 m Korsch, 3 mirror anastigmat, f=24.5 m | | | | |
| Instrument | VIS | NISP | | | |
| Field-of-View | $0.787 \times 0.709$ $deg^2$ | $0.763 \times 0.722$ $deg^2$ | | | |
| Capability | Visual Imaging | NIR Imaging Photometry | | | NIR Spectroscopy |
| Wavelength range | 550– 900 nm | Y (920-1146nm), | J (1146-1372 nm) | H (1372-2000nm) | 1100-2000 nm |
| Sensitivity | 24.5 mag<br>$10\sigma$ extended source | 24 mag<br>$5\sigma$ point source | 24 mag<br>$5\sigma$ point source | 24 mag<br>$5\sigma$ point source | 3 $10^{-16}$ erg cm-2 s-1<br>$3.5\sigma$ unresolved line flux |

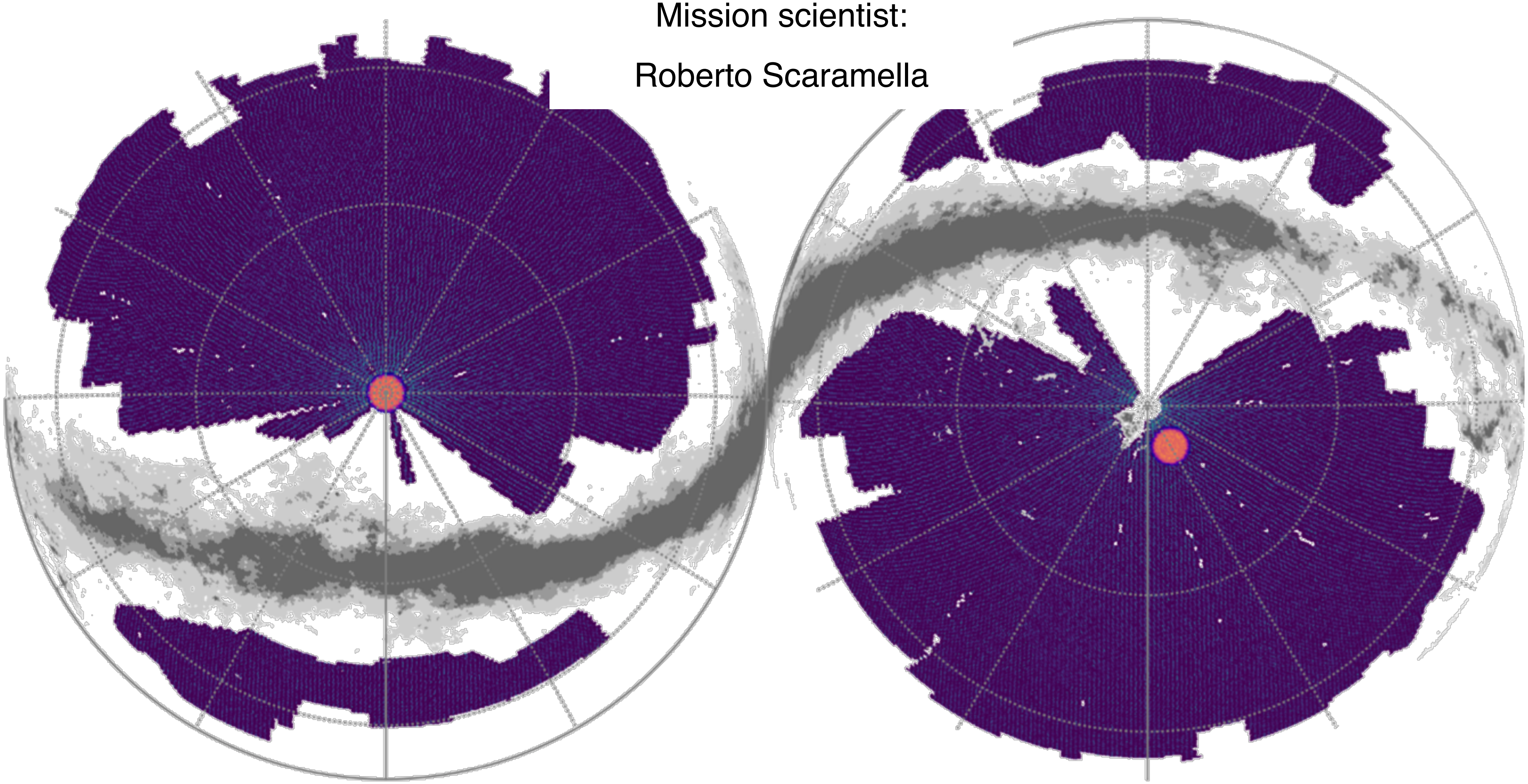
Shapes + Photo-z of n = 1.5 x$10^9$ galaxies,
Spectroscopic redshifts for n = 2.6x$10^7$ galaxies

Euclid Definition Study Report: Laureijs et al arXiv:1110.3193

# Euclid reference surveys

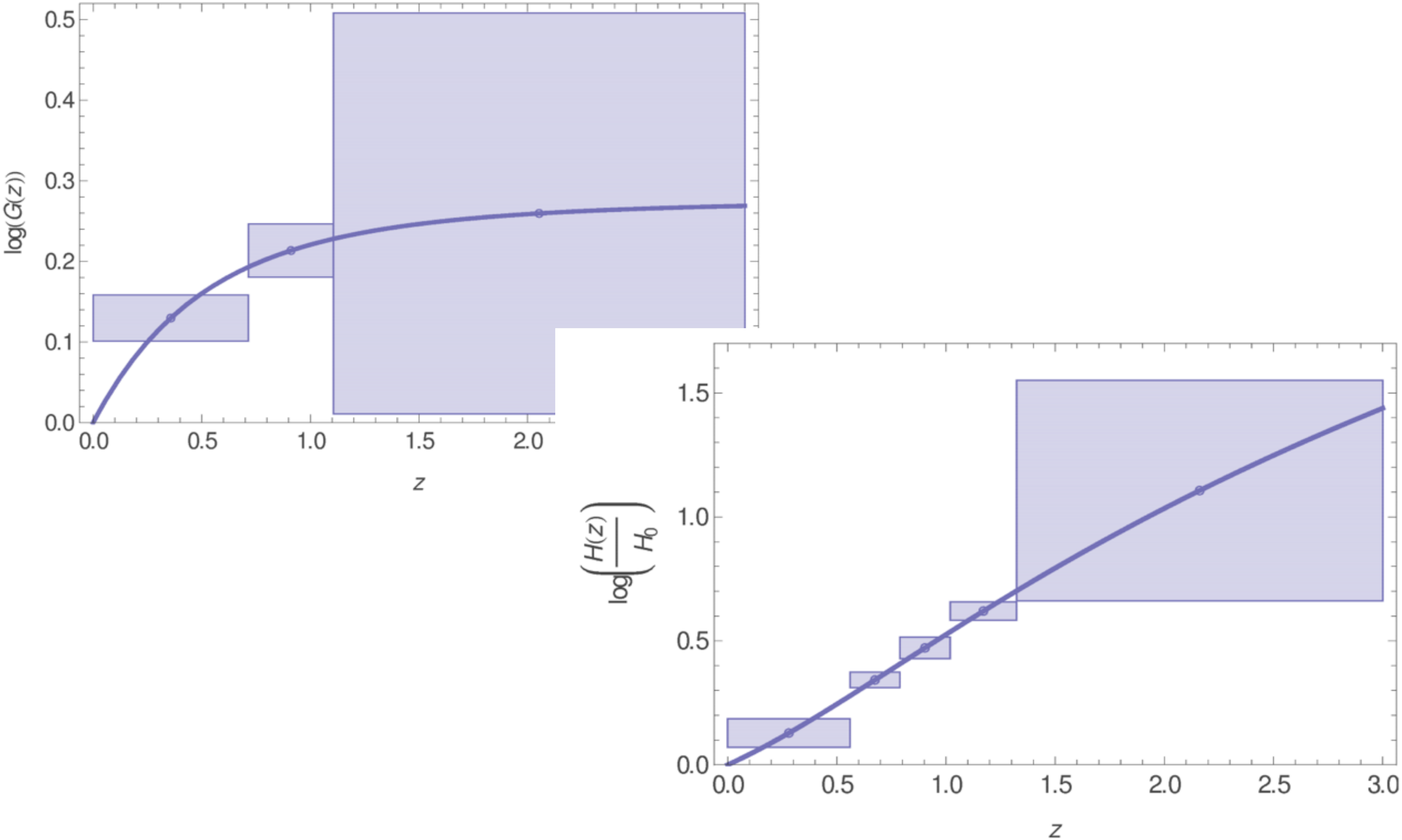
Mission scientist:

Roberto Scaramella



| | |
|---|---|
| Wide | 15000 $deg^2$ |
| Deep | 40 $deg^2$<br><br>• EDF-N (NEP)<br>• EDF-S (SEP)<br>• EDF-Fornax (CDF-S) |

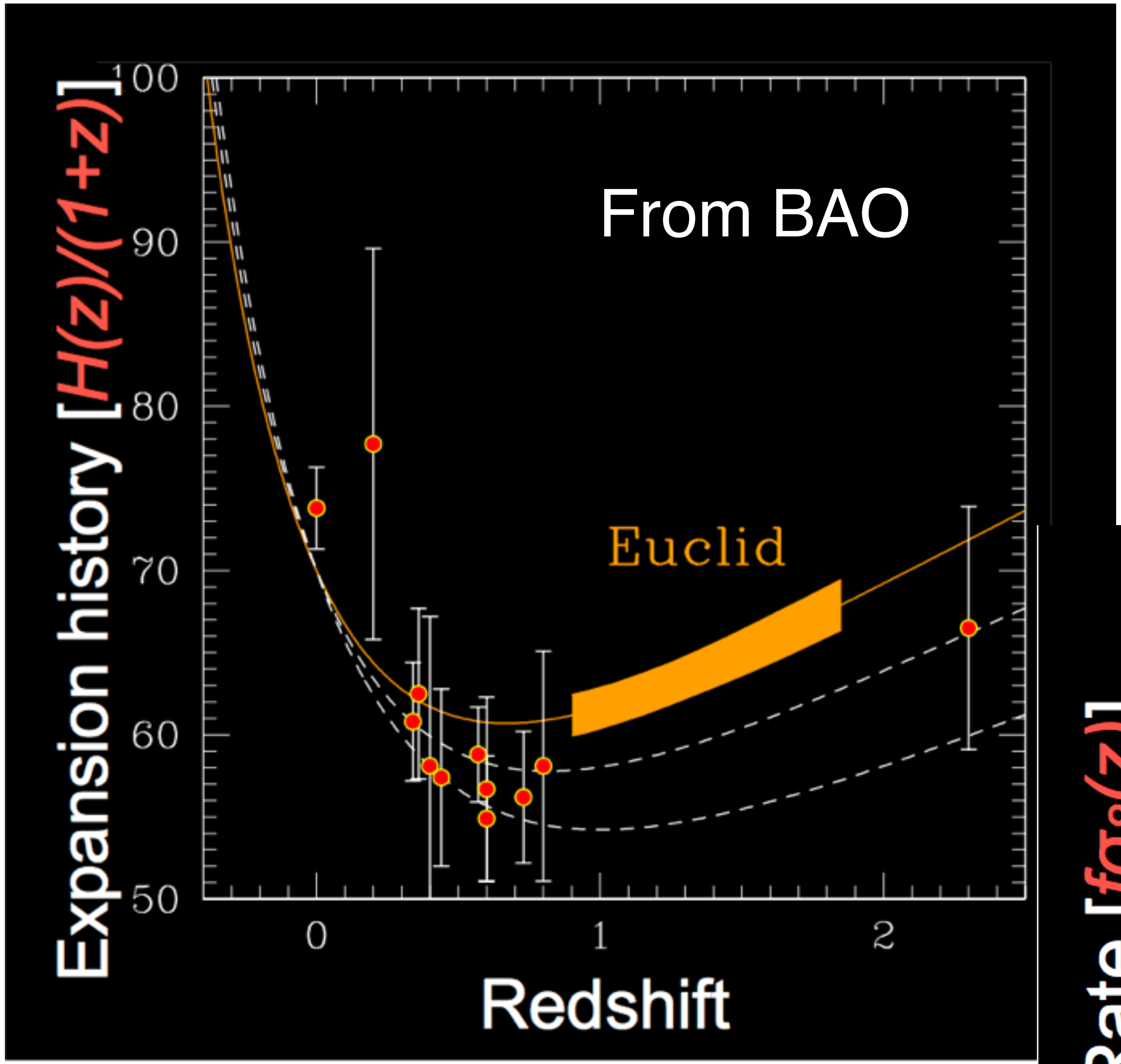
# Euclid weak-lensing predictions

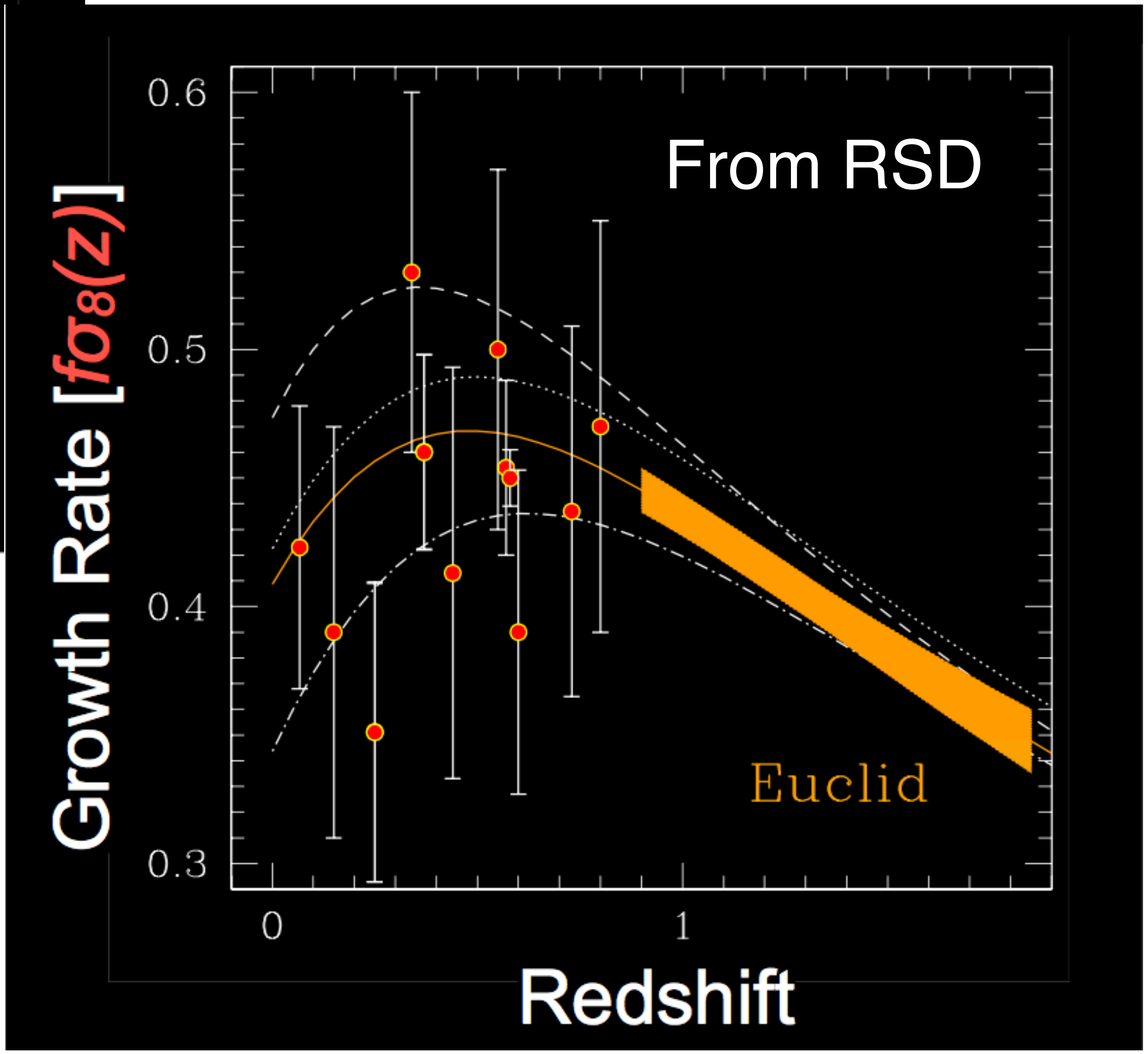



Shown are model-independent constraints on growth and expansion

Amendola et al. 2016; arXiv:1606.00180

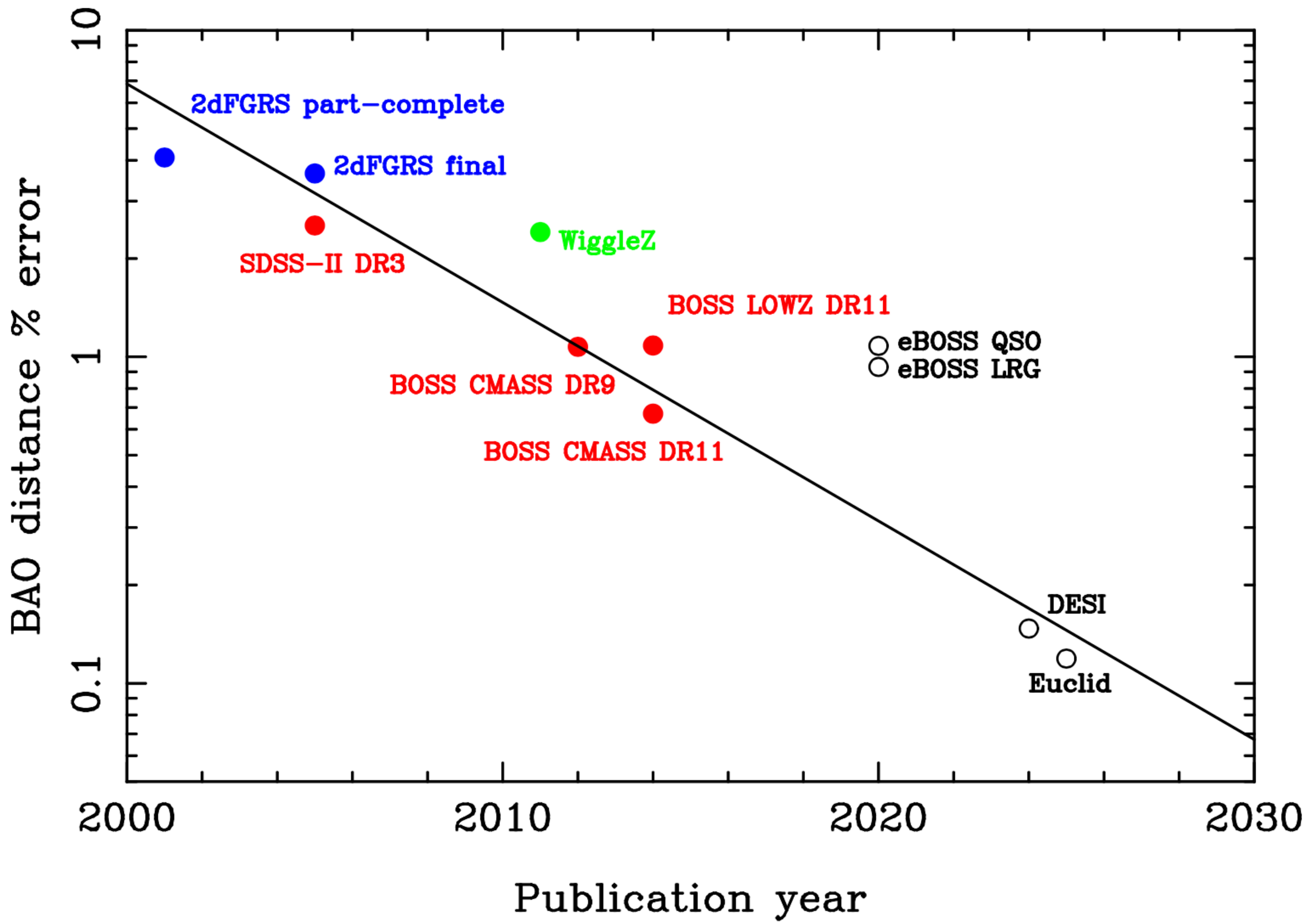
# Euclid galaxy clustering predictions



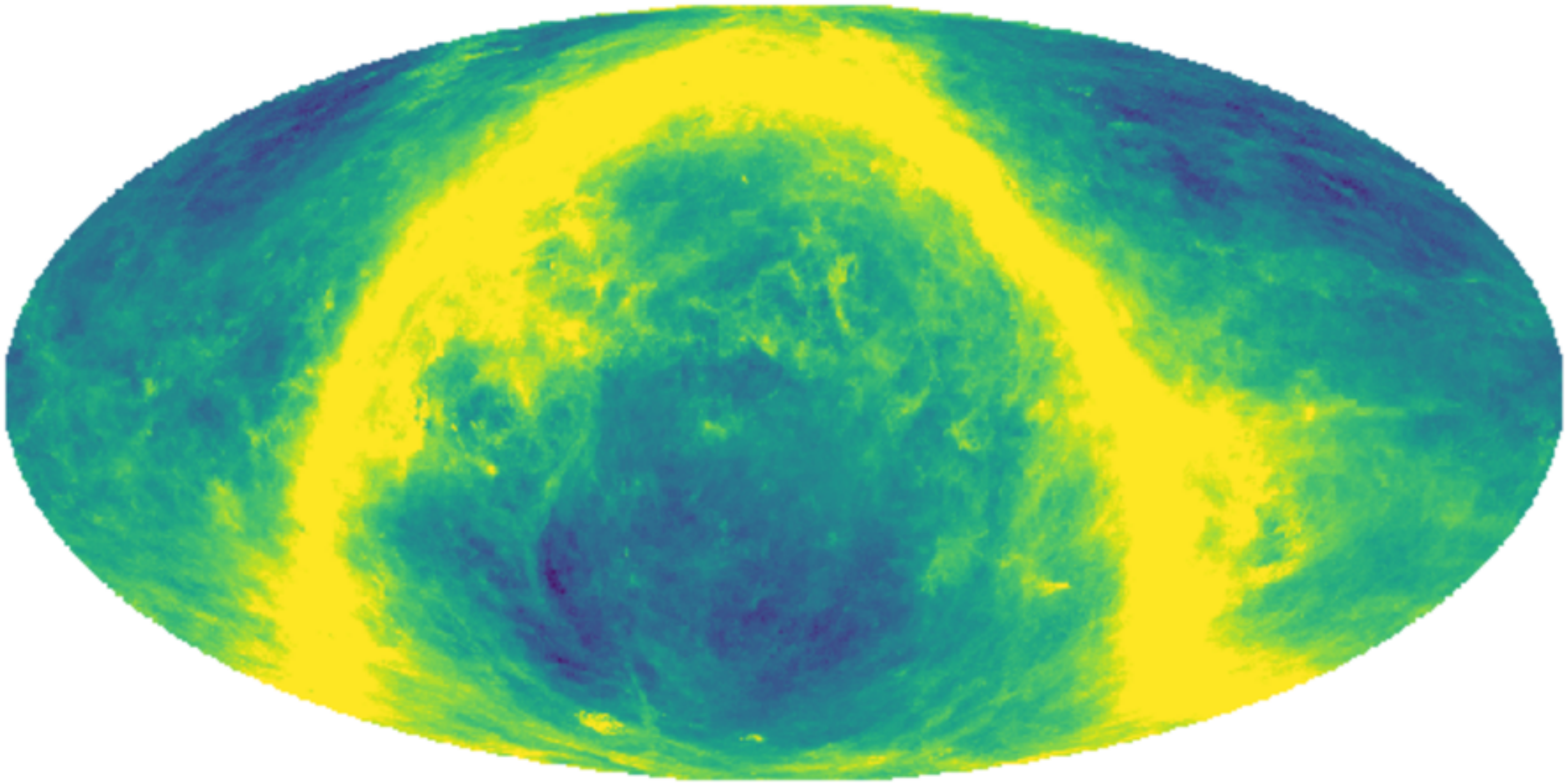
Concluding remarks …

# Survey improvement

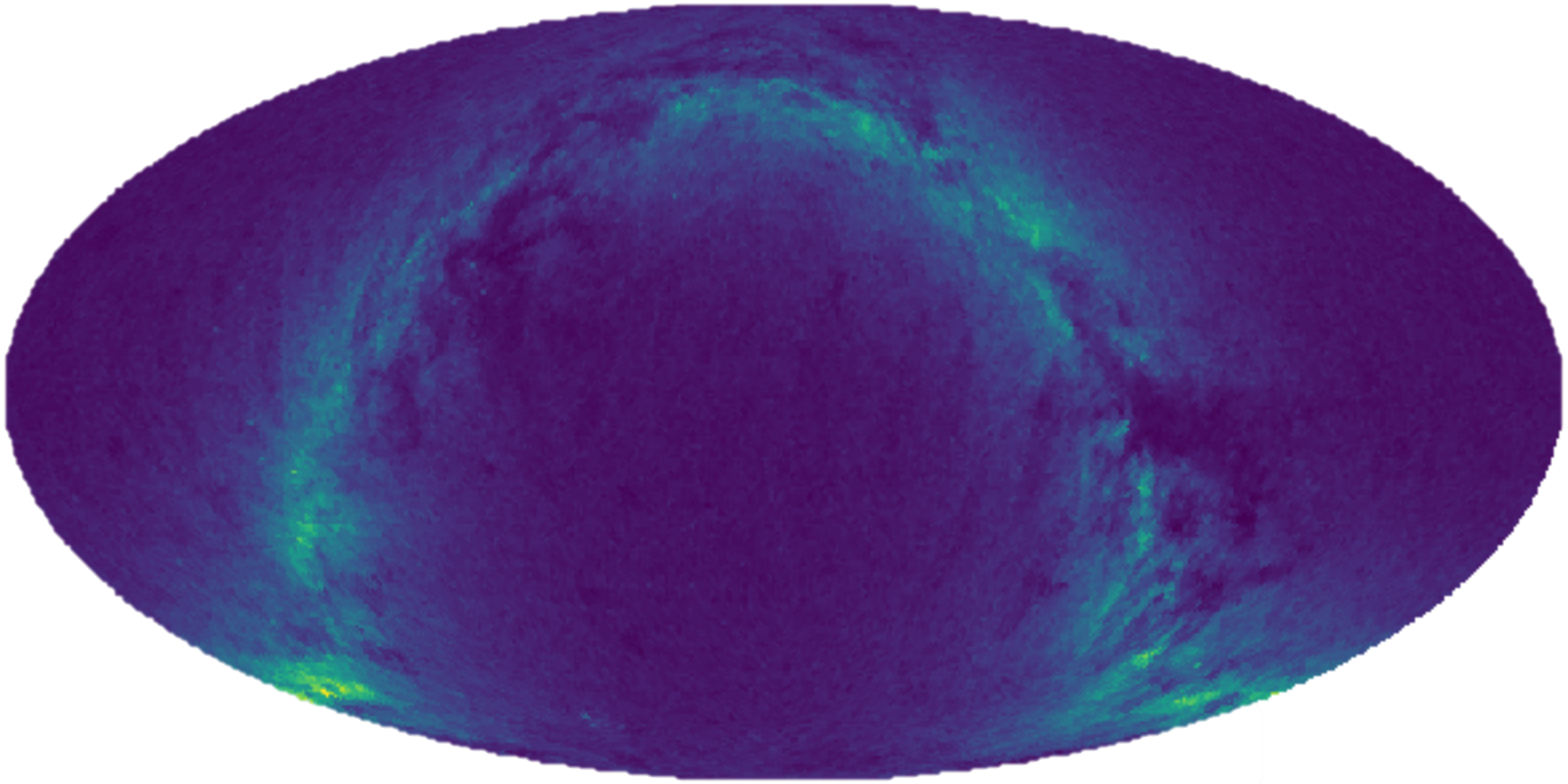



Reid et al. 2015, arXiv:1509.06529

# Observational systematics

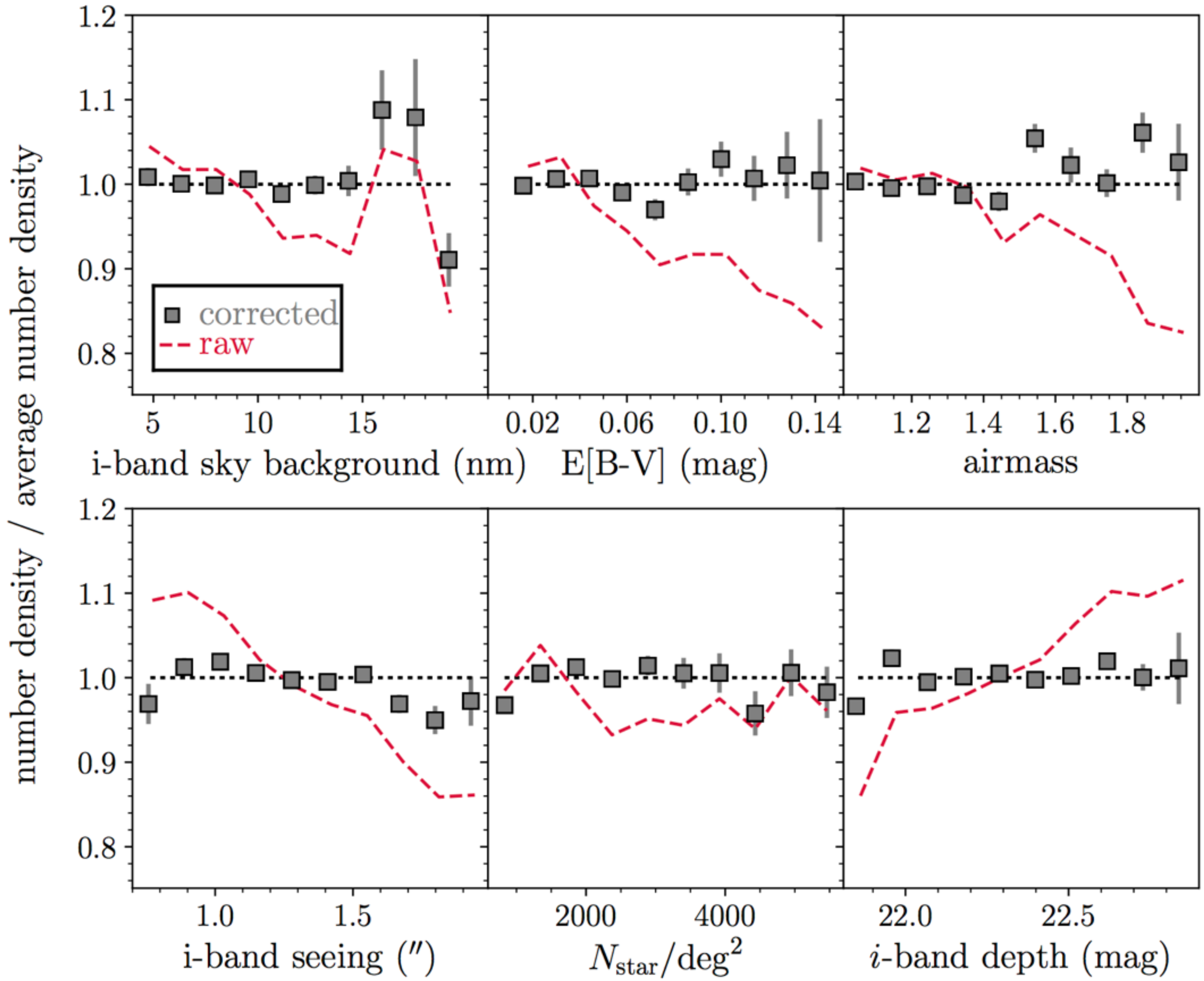


Extinction



Stellar density

# Observational systematics




Ata et al. 2017; arXiv:1705.06373

# Summary

- Current large-scale structure observations agree with LCDM

- Future projects will push further out in redshift, number of galaxies and volume covered
  - Next generation of surveys (DESI, Euclid) will get an order more galaxies
  - Factor ~4 improvement on fundamental physics measurements

- Although BAO / RSD now a mature field, still lots of development required
  - better calibration, removal of contaminants
  - Faster, better calculations (computational data challenge)
  - including more information: weights, including Bispectrum
  - Better models (perturbation theory, EFT, baryons …)