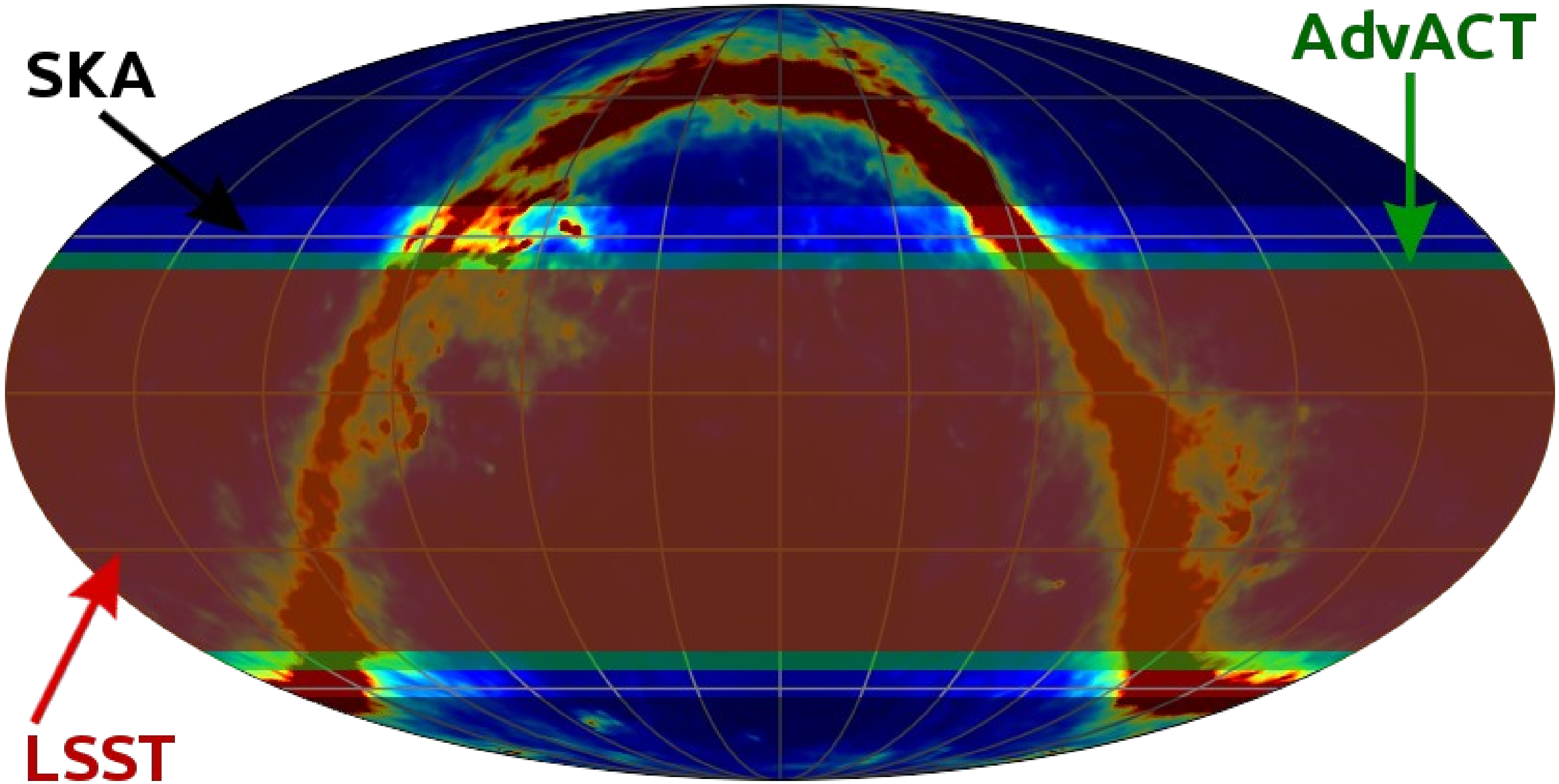
Multi-tracer science with optical and radio surveys

David Alonso – Oxford Astrophysics



ArXiv: 1405.1751, 1409.8667, 1505.07596, 1507.03550, 1604.01382

In collaboration with: P. Ferreira, M. Santos, R. Maartens, P. Bull, T. Louis

IFT-UAM, June 2016

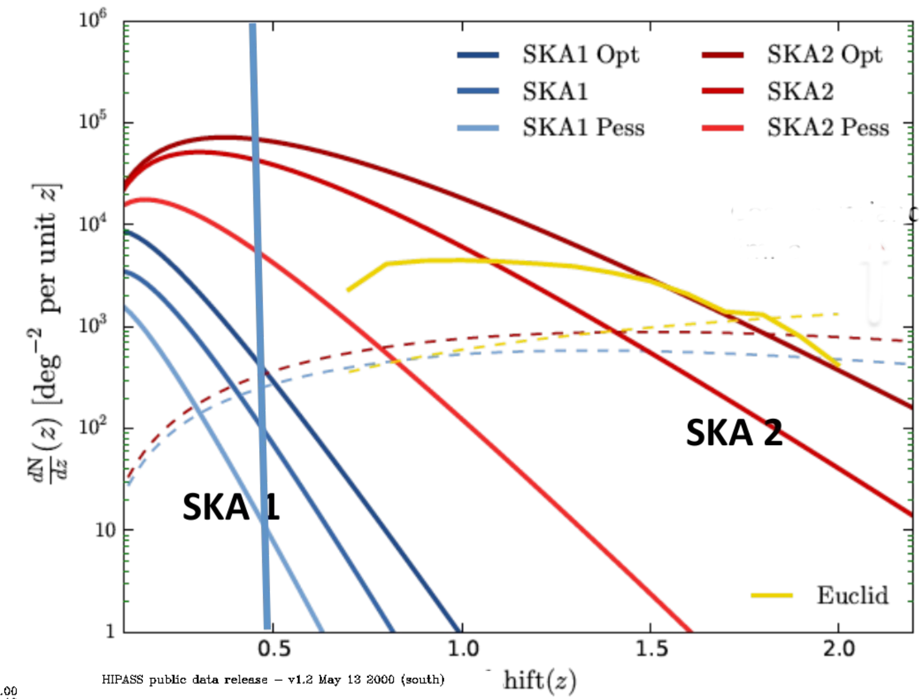
2020

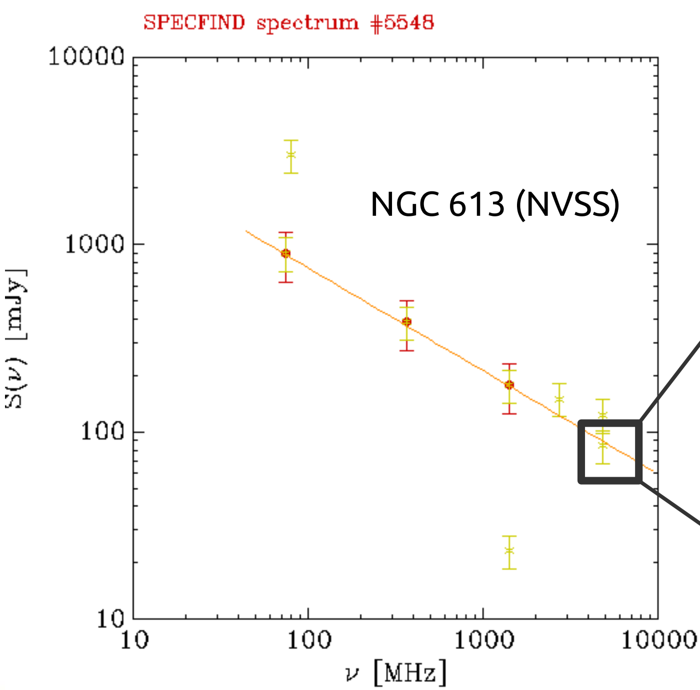
1. SKA and HI intensity mapping

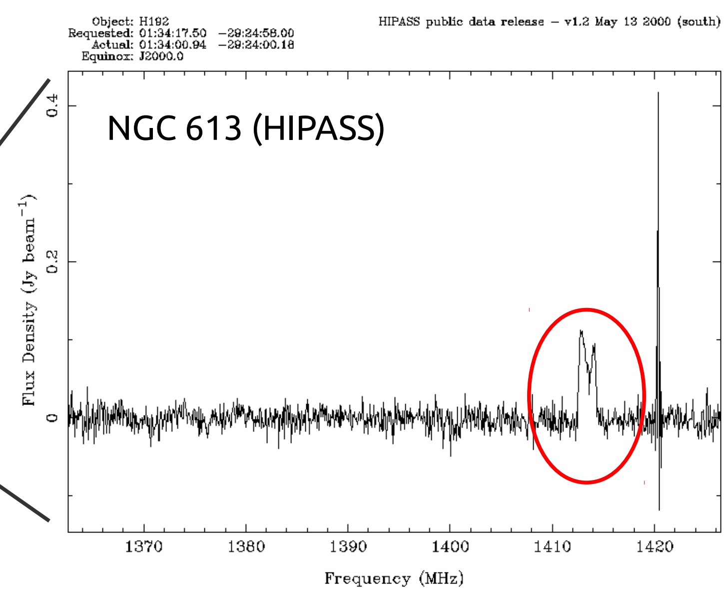
Cosmological radio signals

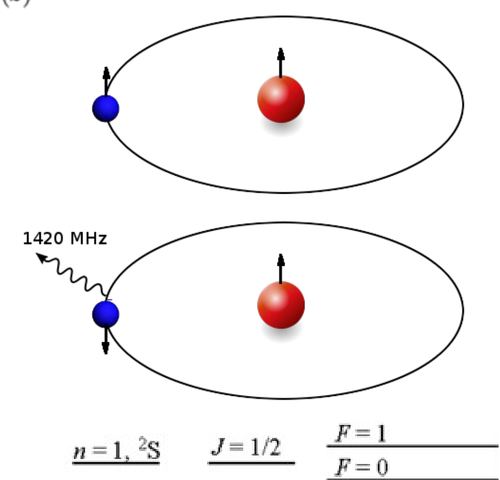
The astrophysical radio spectrum

- Characterized by featureless continuum emission (e.g. synchrotron).
- Few radio lines. Mainly neutral hydrogen (HI).
- Costly to measure for individual sources.







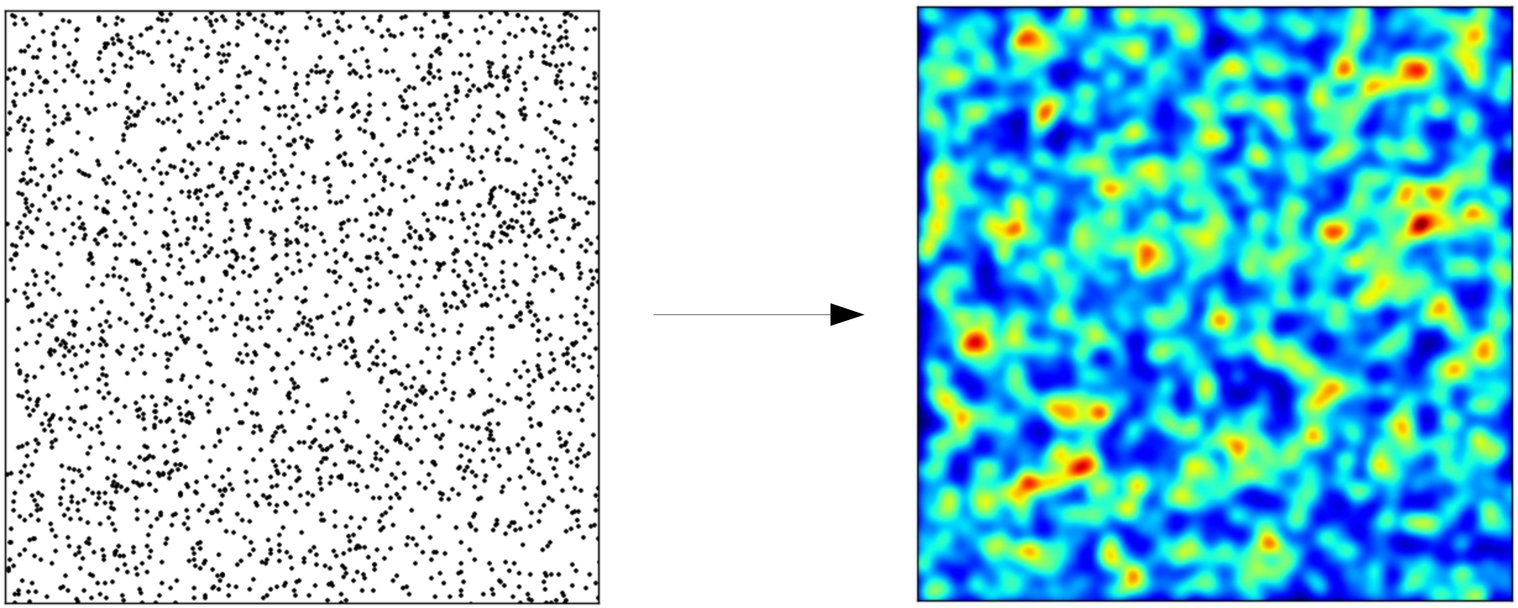


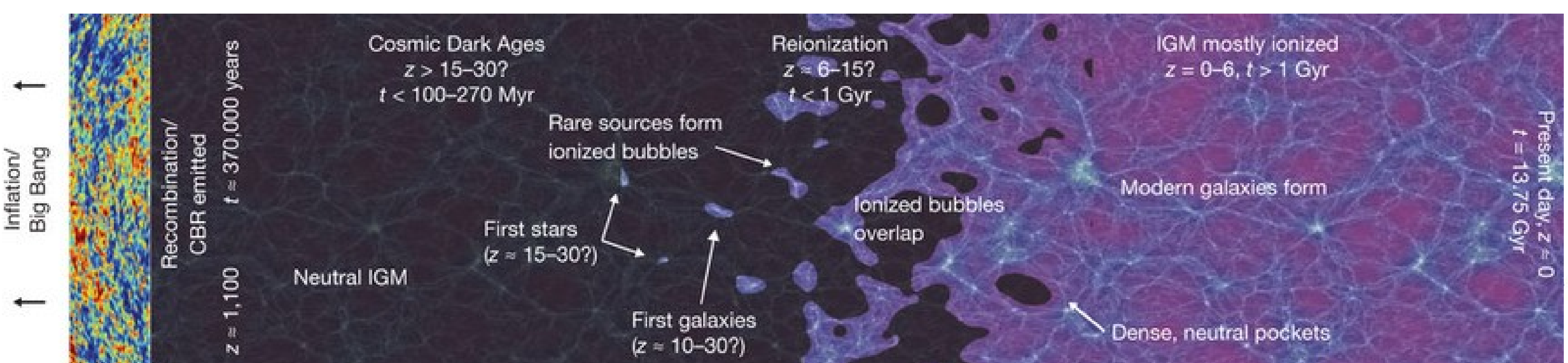
Φxford Physics

HI intensity mapping

- Large pixels: joint emission from multiple galaxies instead of resolving them.
- We only care about large scales
- “Cheap” way to observe large volumes

Battye, Davies & Weller 2004





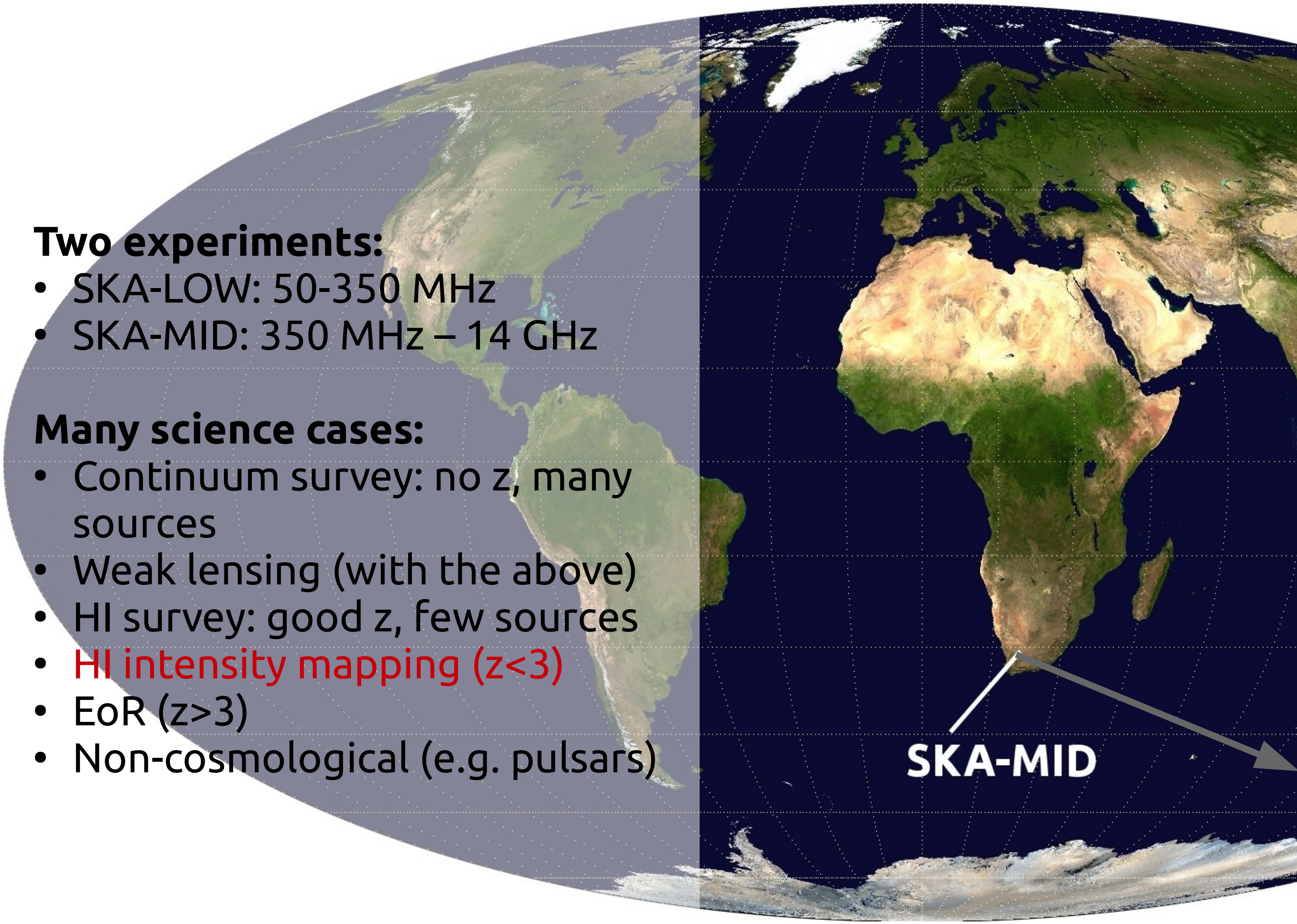
SKA

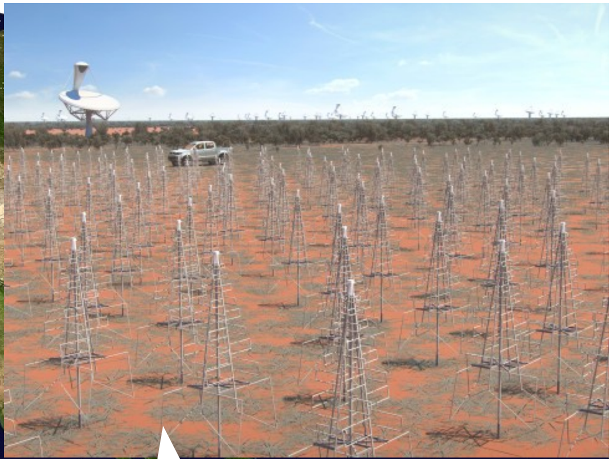
Two experiments:

- SKA-LOW: 50-350 MHz
- SKA-MID: 350 MHz – 14 GHz

Many science cases:

- Continuum survey: no z, many sources
- Weak lensing (with the above)
- HI survey: good z, few sources
- HI intensity mapping (z<3)
- EoR (z>3)
- Non-cosmological (e.g. pulsars)

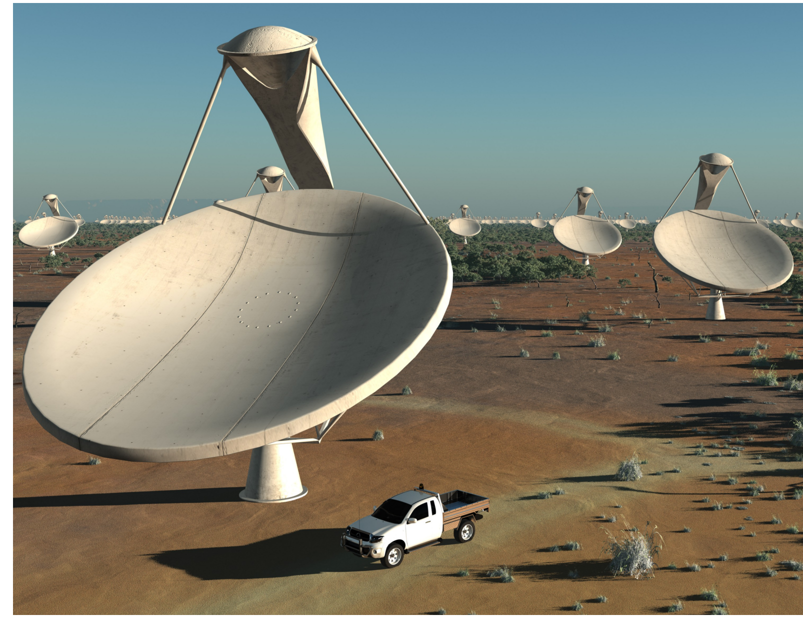


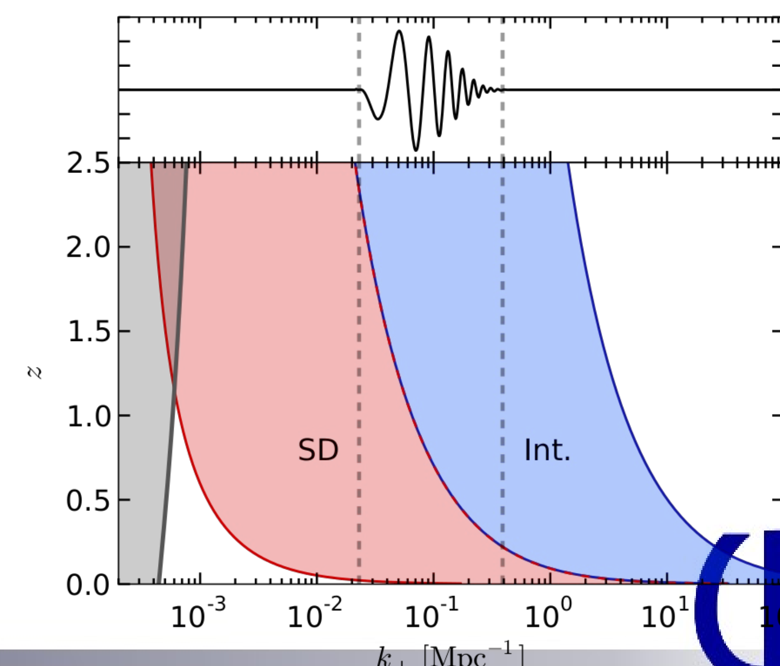


Maartens et al. 1501.04076

Intensity mapping with the SKA

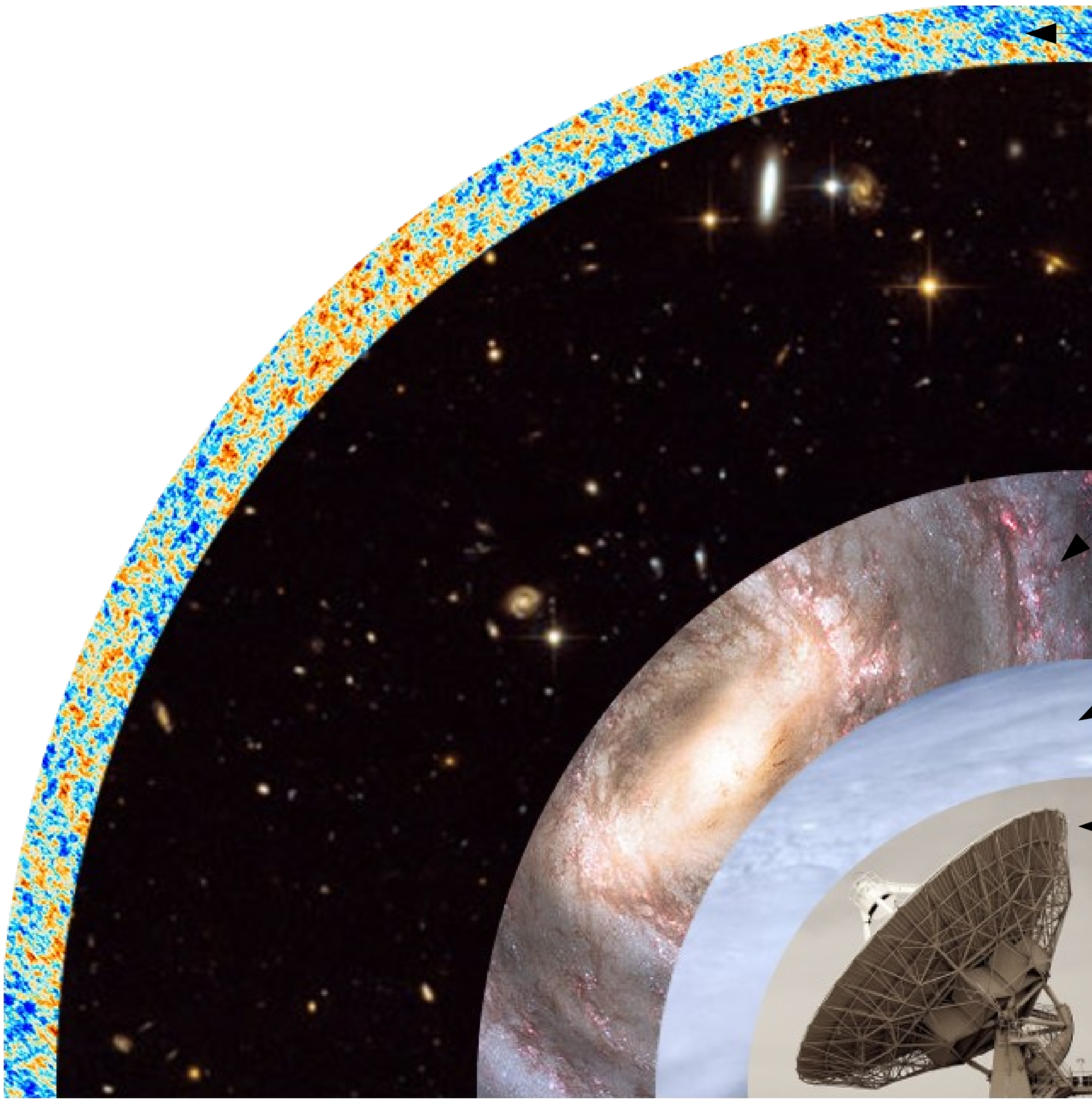
- Baselines not small enough to cover BAO scales in interferometric mode.
- SKA1-MID will be used as a multi-single-dish experiment.
- Save interferometer data for calibration.
- Proposal to provide calibrated auto-correlations has been approved by the SKA office.
- SKA1 survey: 30K sq-deg, 10K hours, 350-1050 MHz.
- KAT7 (7) → MeerKAT (64) → SKA1 (197)





Santos et al. 1501.03989

The problem of foregrounds



IM signal

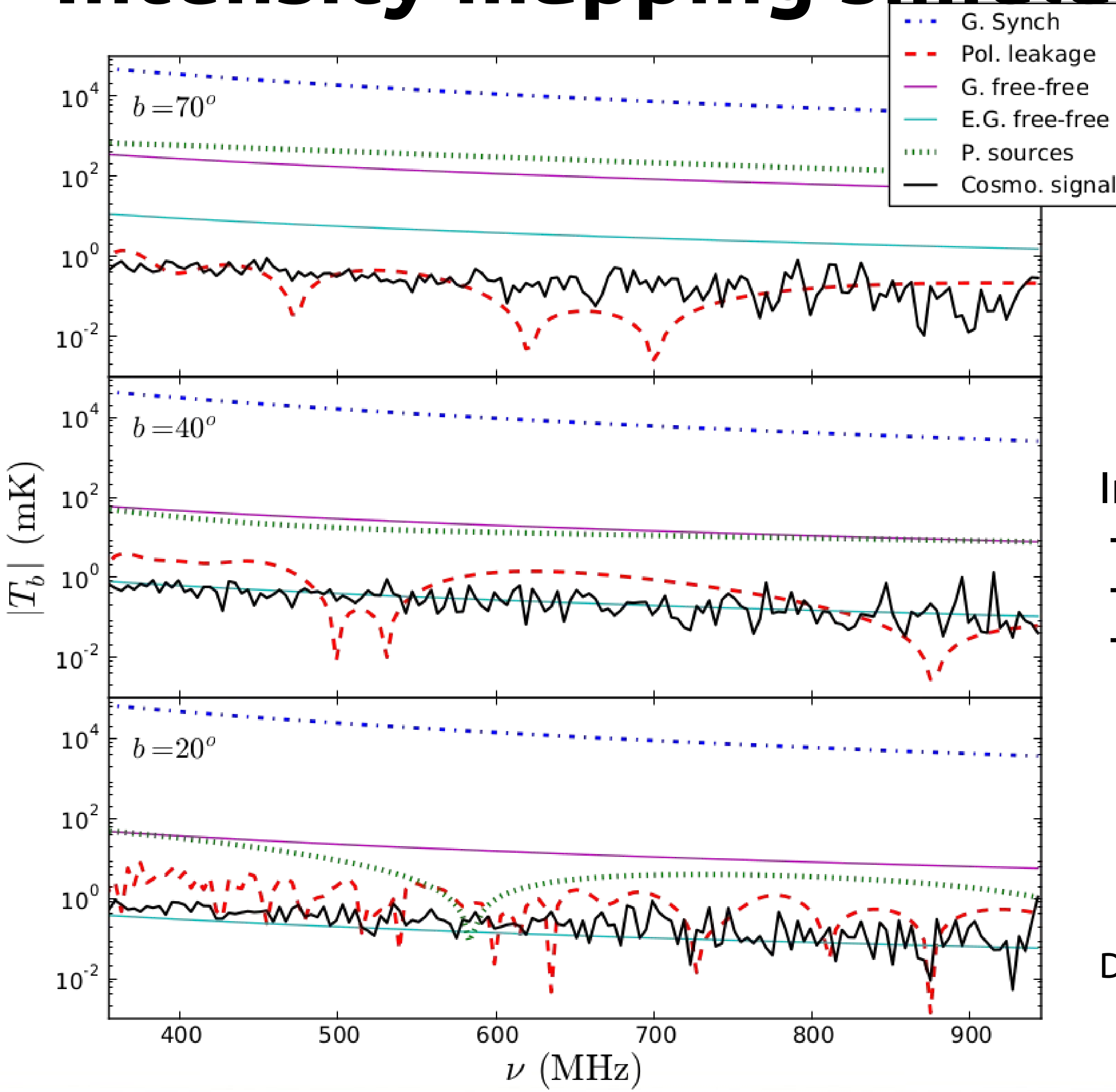
Extragalactic foregrounds:
- Point sources
- E.G. free-free

Galactic foregrounds:
- Synchrotron (I,Q,U)
- Free-free
- Dust

Earth:
- Atmosphere: clouds, H2O, ionosphere
- RFI

Instrument:
- Spillover
- Gain fluctuations
- Beam fluctuations
- Polarization leakage

Intensity mapping simulations



Instrumental effects:
- Beam convolution
- Polarization leakage
- Noise

DA et al. ArXiv:1405.1751.

Blind foreground subtraction

- Blind methods: minimize assumptions about foregrounds → foregrounds are ν-smooth

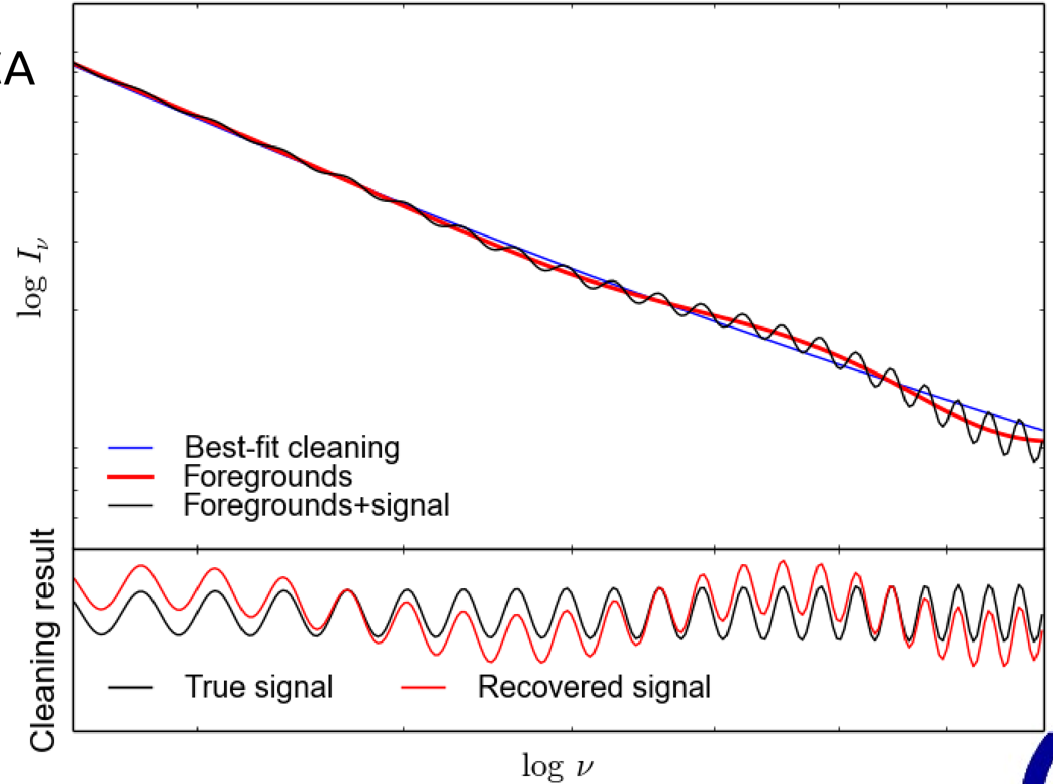
- Blind source equation

$$T(\nu,\theta)=\sum_{k=1}^{N_{\rm fg}} f_k(\nu)\,S_k(\theta)+T_{\rm cosmo}(\nu,\theta)+T_{\rm noise}(\nu,\theta)$$

$$x_i=T(\nu_i,\theta)\quad A_{ik}=f_k(\nu_i)\quad s_k=S_k(\theta)$$

$$\mathbf{x}=\hat{\mathbf{A}}\cdot\mathbf{s}+\mathbf{n},$$

- Methods: LOS fitting, PCA, ICA

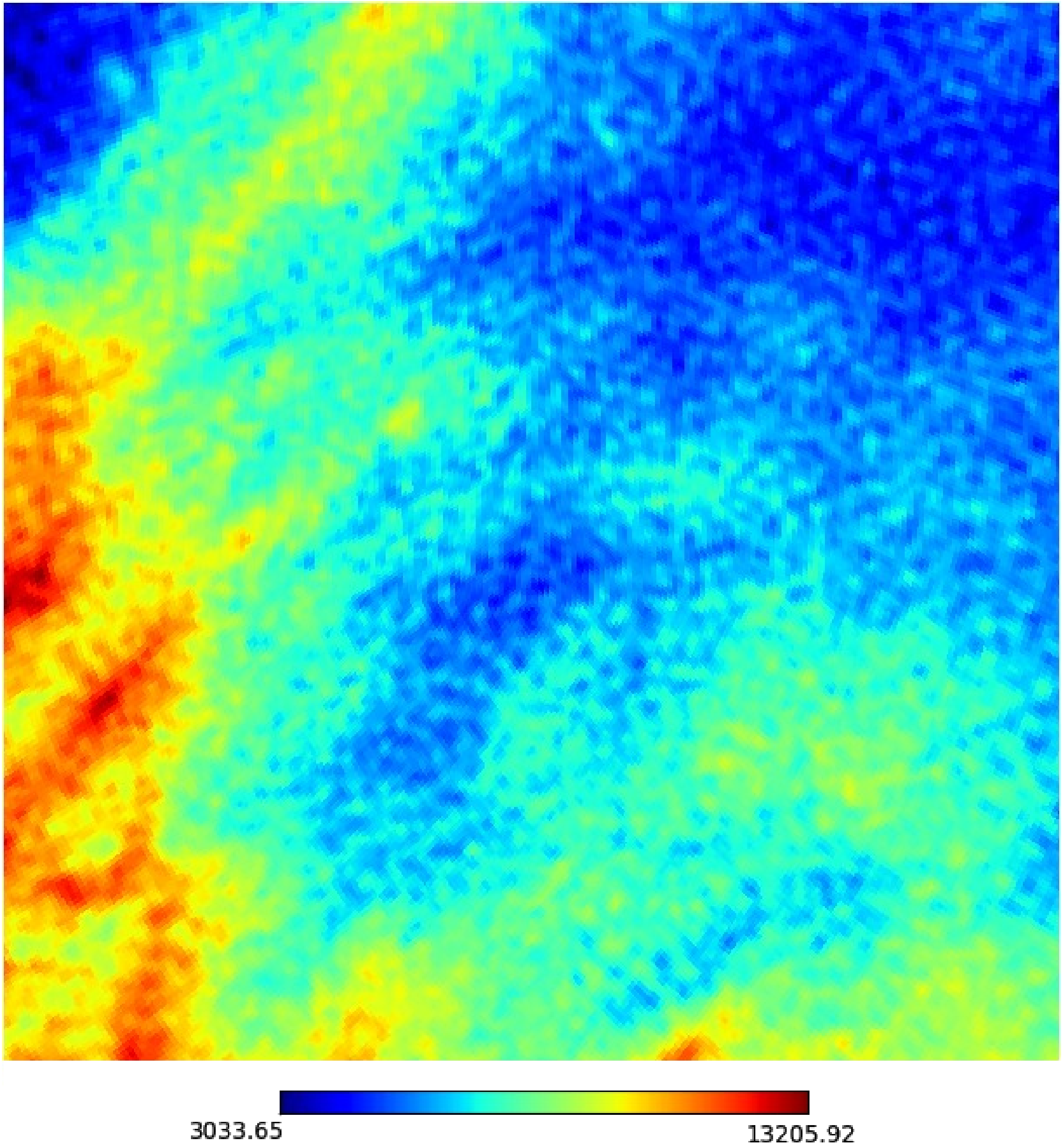


Wolz et al. 1310.8144
DA et al. 1409.8667

Oxford Physics

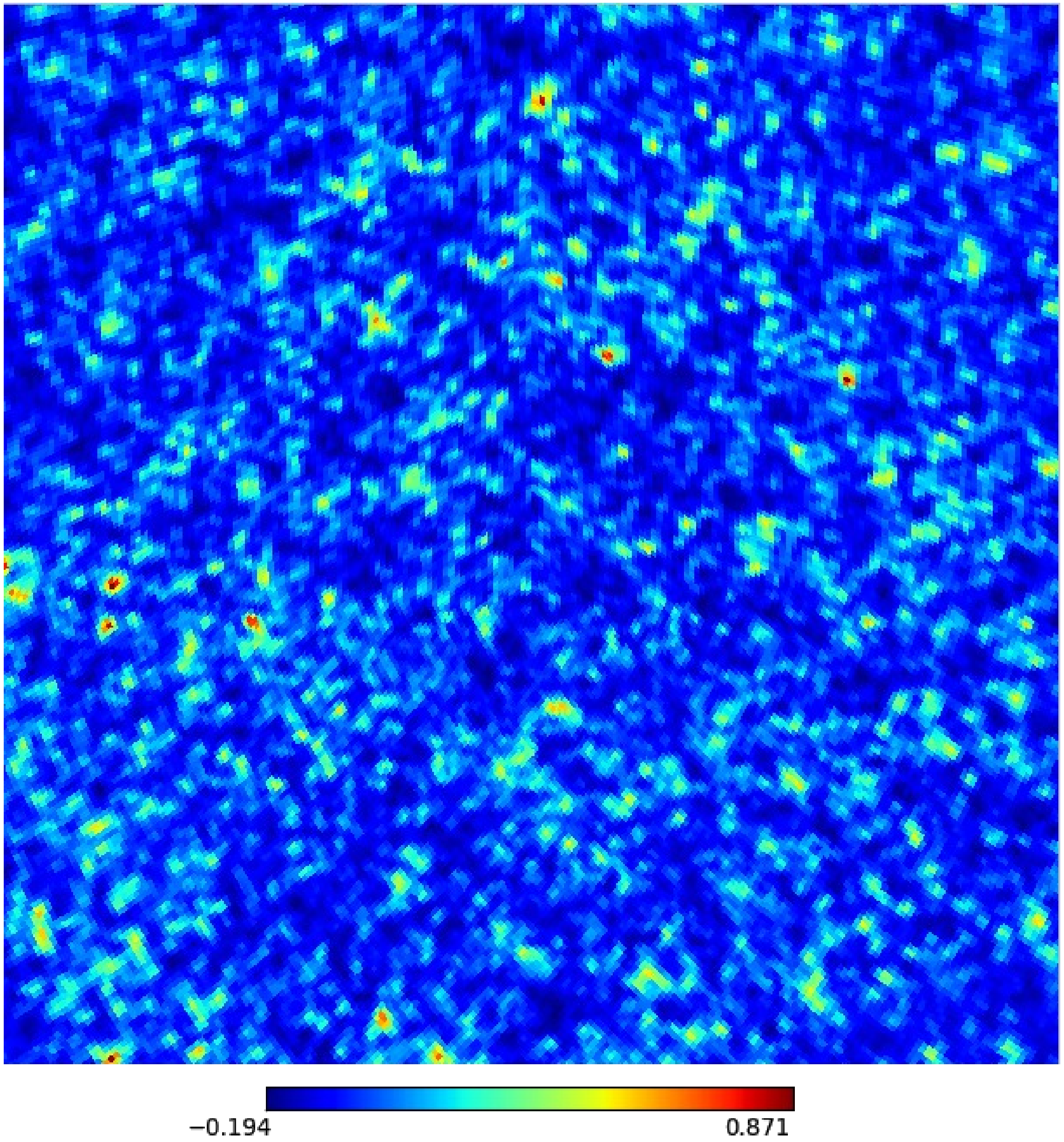
Blind foreground subtraction

Signal+FG



Blind foreground subtraction

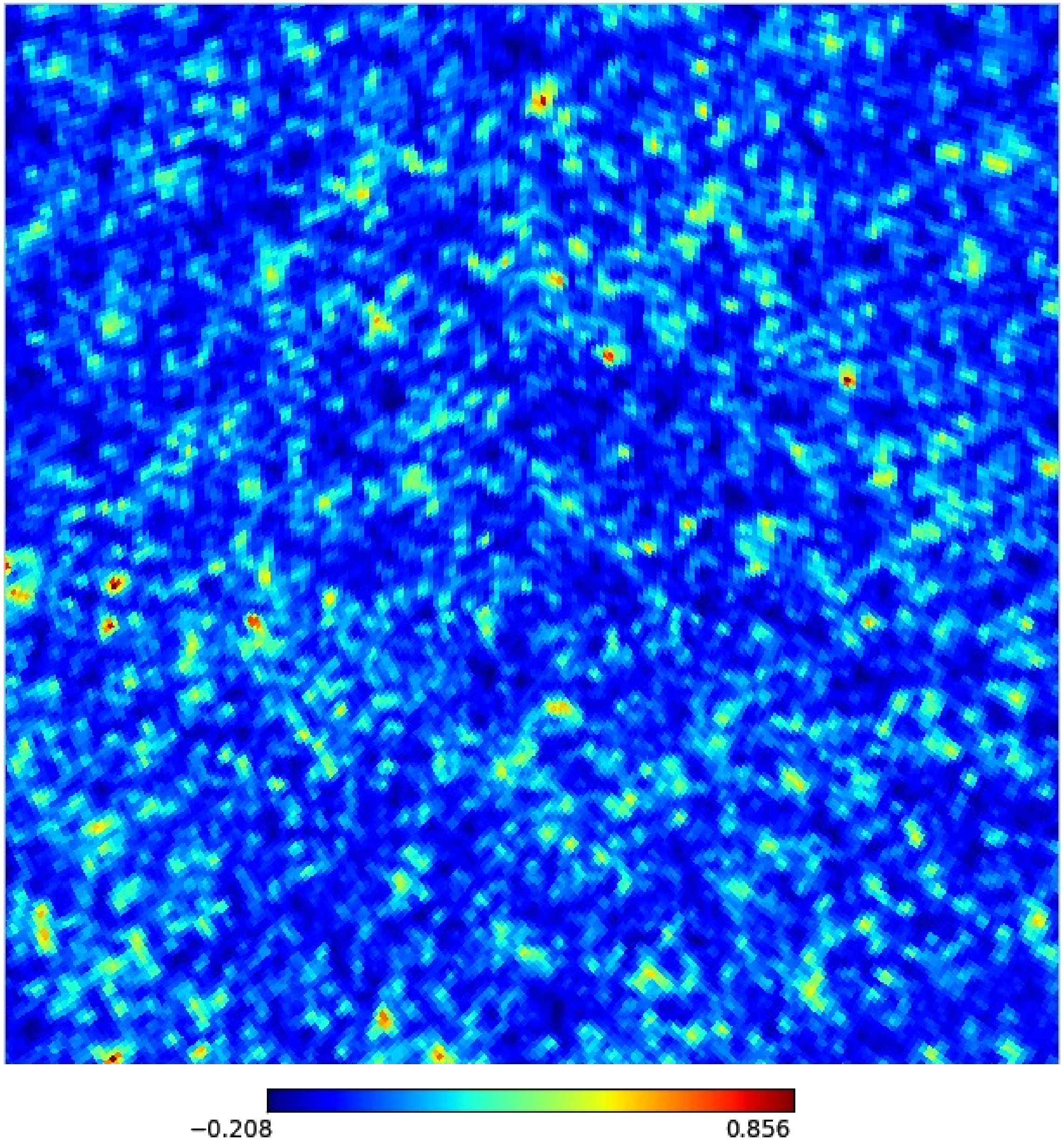
Signal only



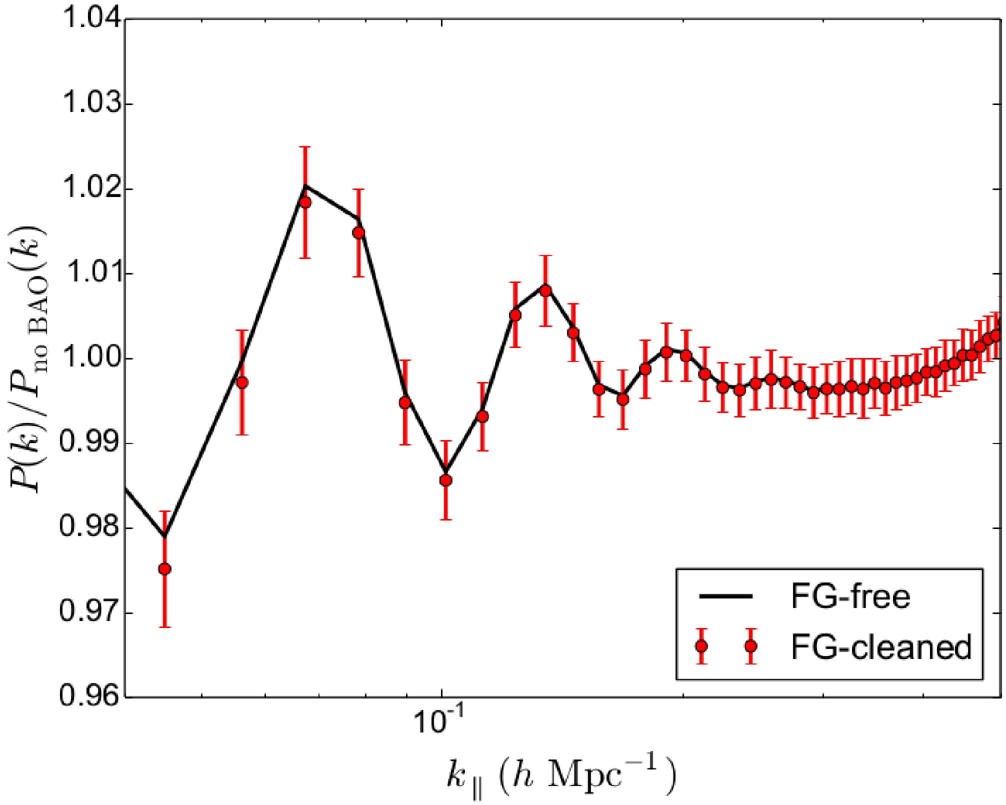
Oxford Physics

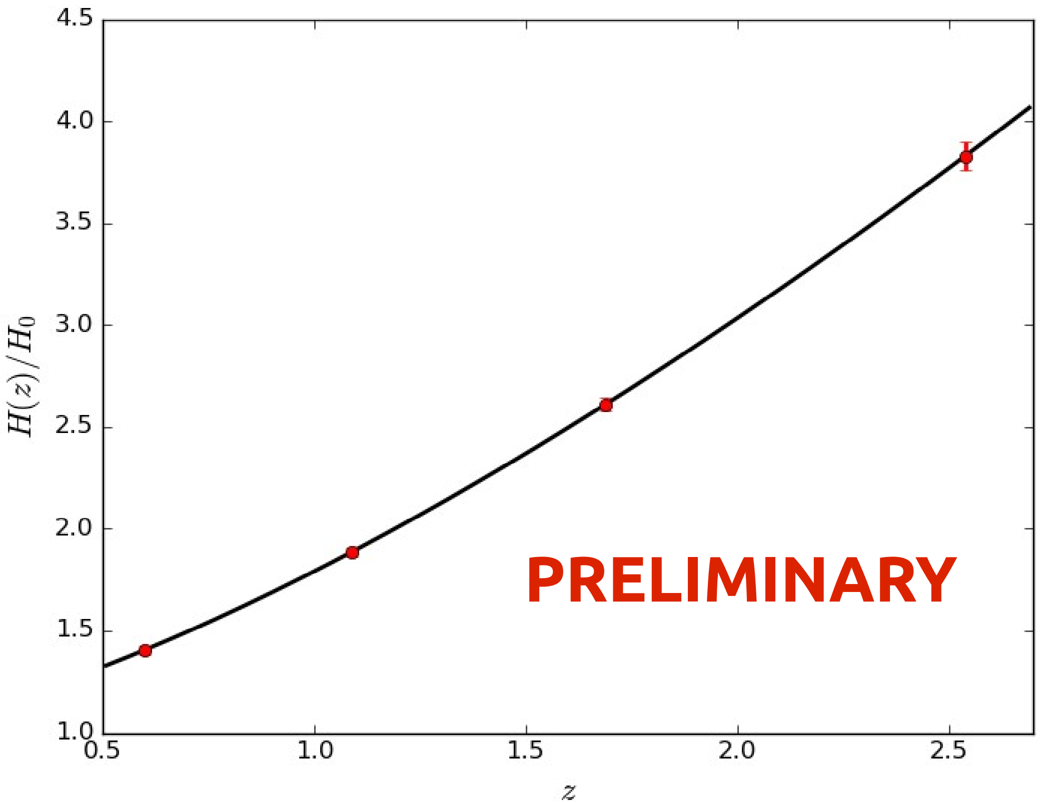
Blind foreground subtraction

Cleaned map



Blind foreground subtraction





~1% measurements of the radial BAO
(DA, F. Villaescusa-Navarro, M. Viel in prep.)

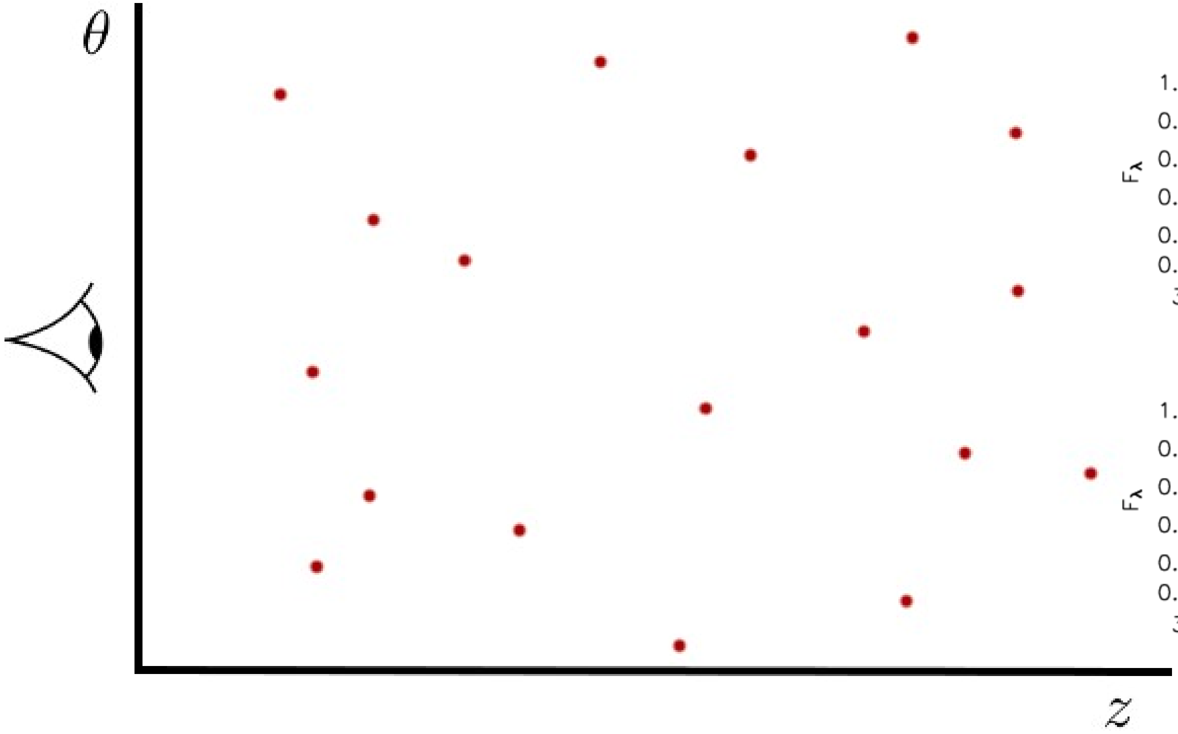
Most important features still observable! (e.g. radial BAO)

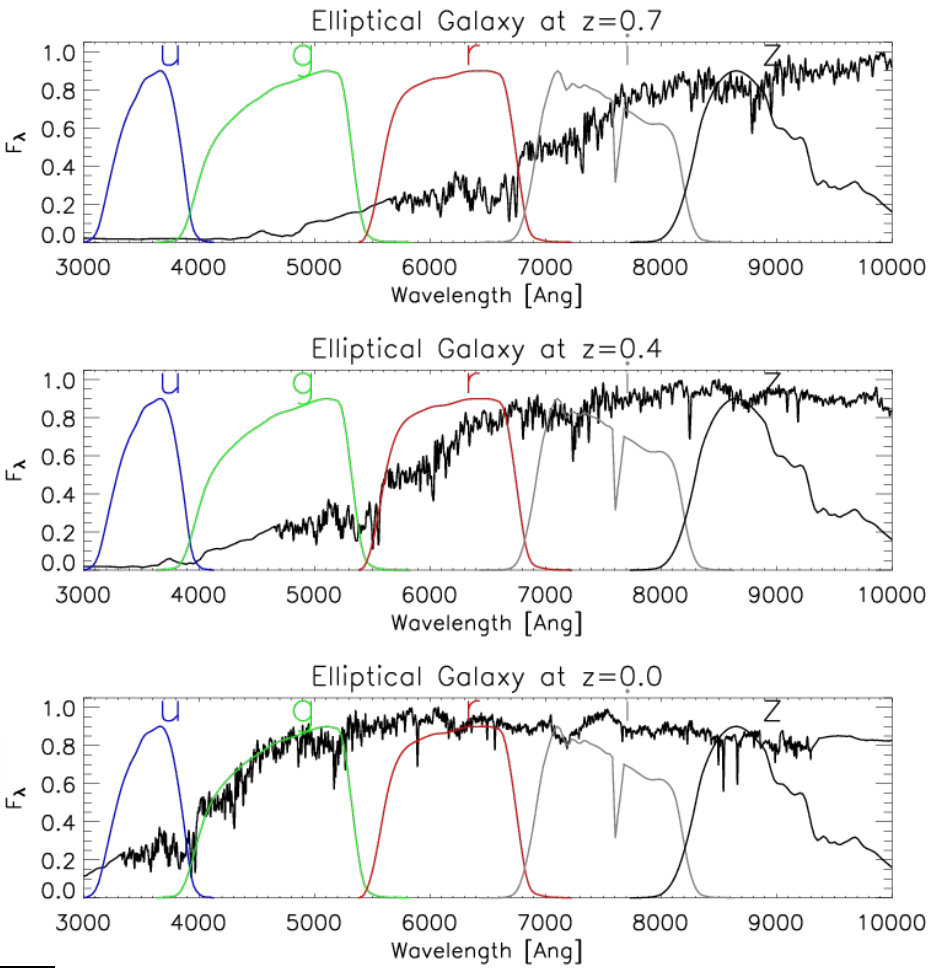
2. Optical surveys – the LSST

Optical surveys:

Spectroscopic surveys

- Good radial and angular resolution
- Long integration times →
- Low number density and redshift

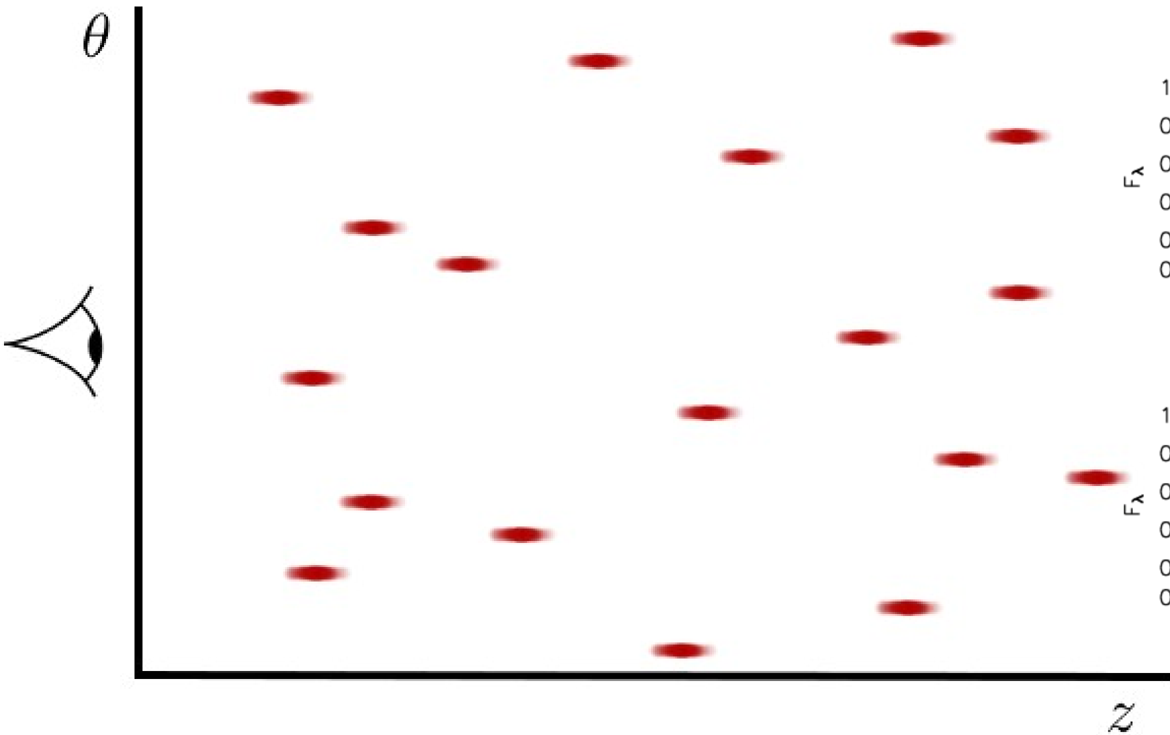


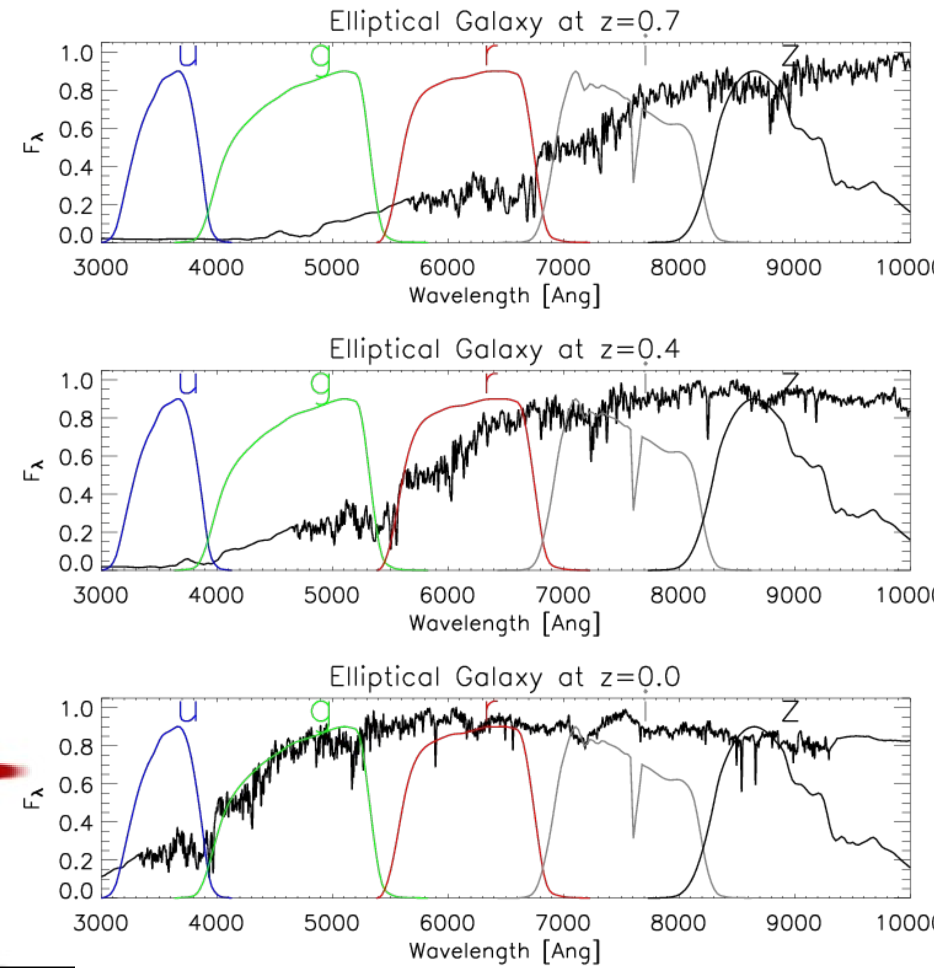


Optical surveys

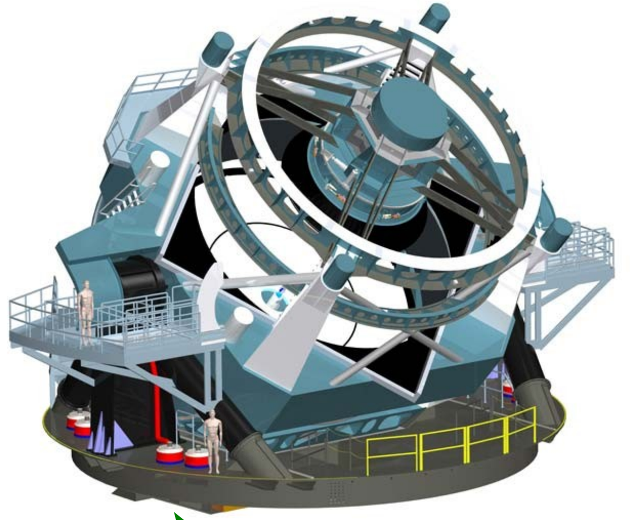
Photometric surveys

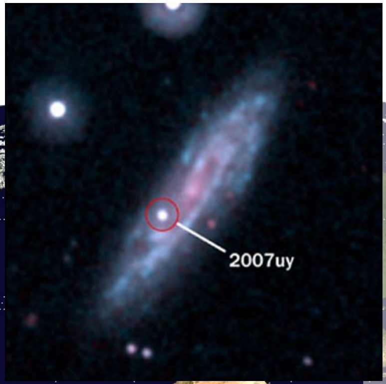
- Good angular resolution, bad radial
- Higher number densities and redshifts
- Photo-z systematics

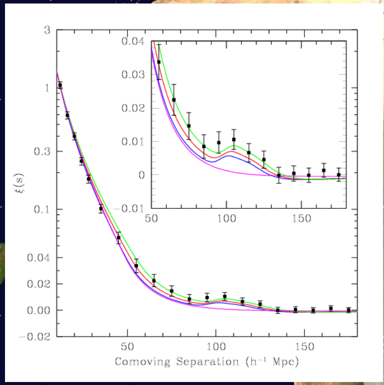




LSST (2022)

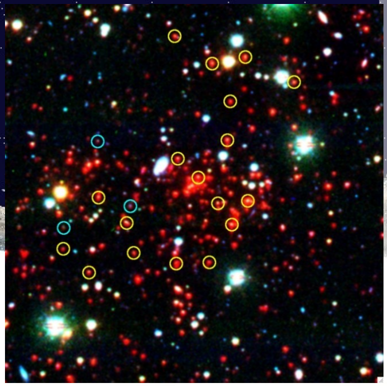


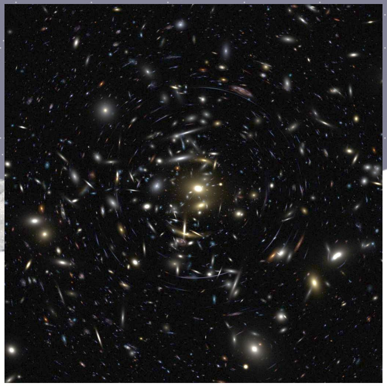




Outstanding numbers:
- World's largest imager
  - 8.4 m, 9.6 sq-deg FOV
- Wide: 20K sq-deg
- Deep: r~27
- Fast: ~100 visits per year
- Big data: ~15 TB per day

Multi-science facility:
- Supernovae
- Galaxy clustering
- Cluster science
- Weak & strong lensing
- Non-cosmological:
  Transients, Solar System,
  Milky Way





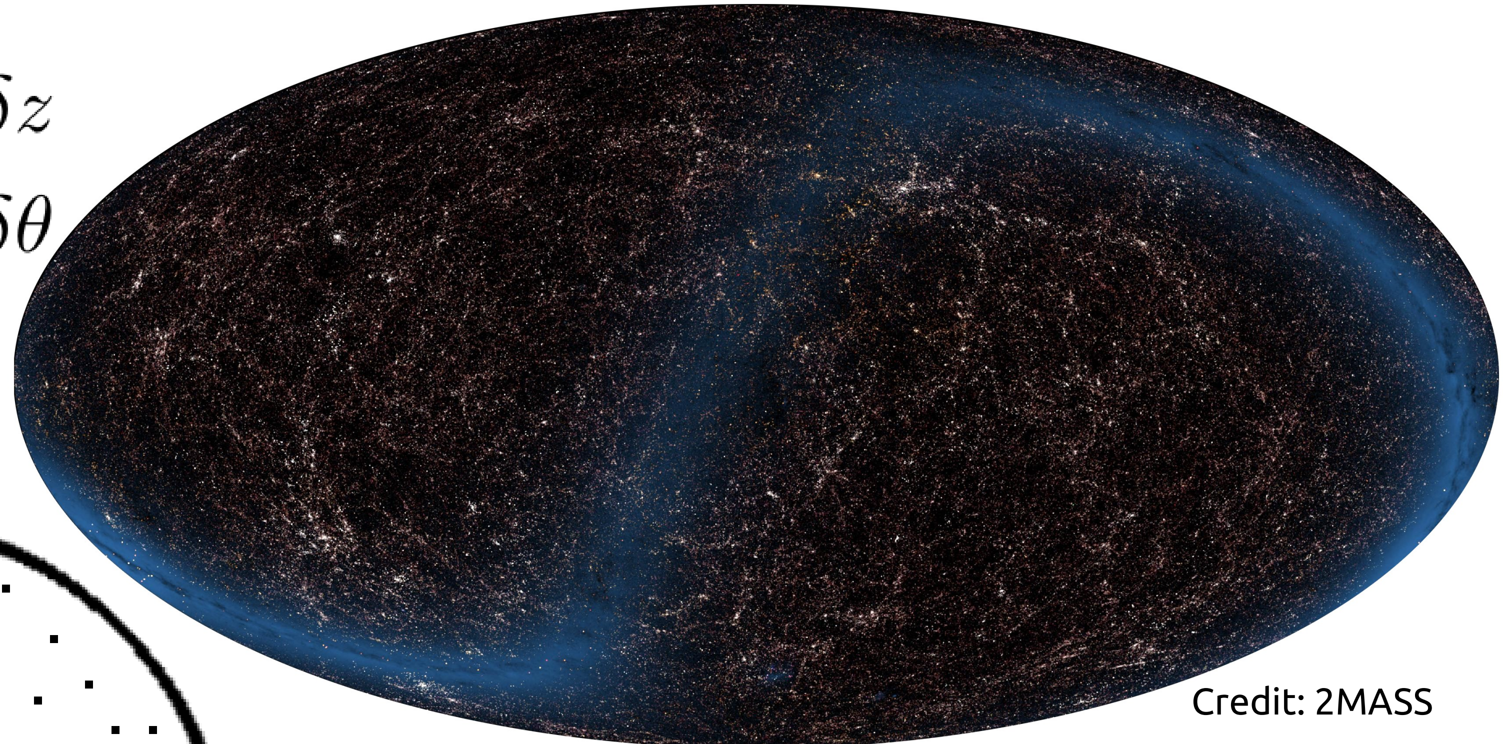
LSST Coll. et al. 0912.0201

3. Constraining gravity with multiple tracers

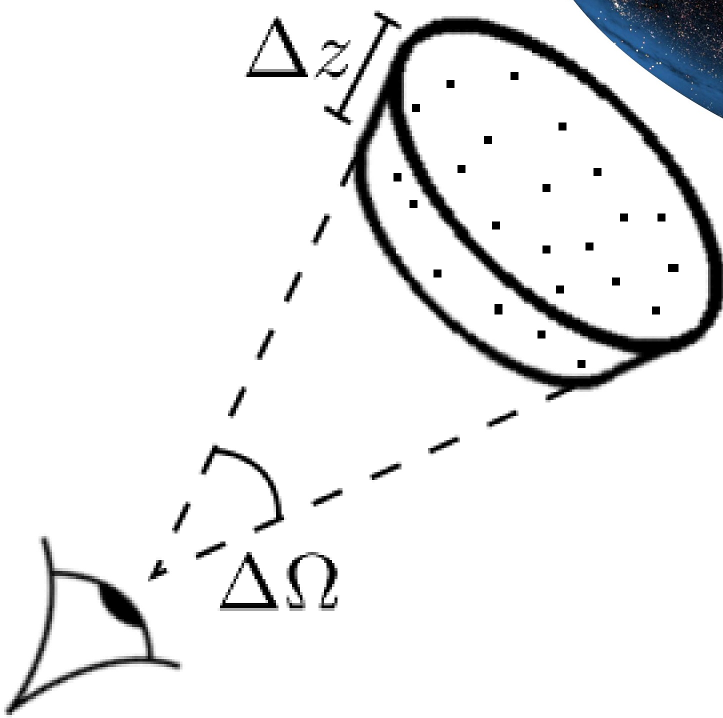
Relativistic effects in LSS

$$z_{\rm obs} = z_{\rm BG} + \delta z$$

$$\theta_{\rm obs} = \theta_{\rm BG} + \delta\theta$$



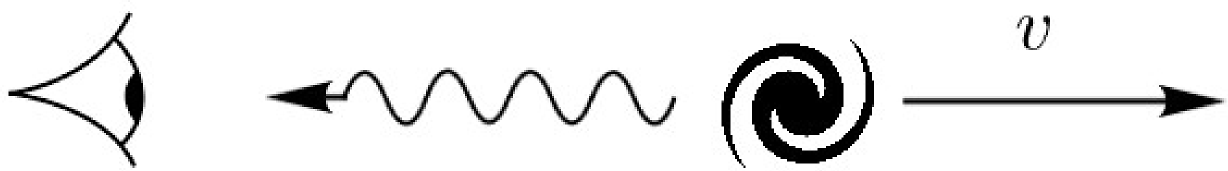
Credit: 2MASS



$$\frac{\Delta N}{\Delta\Omega\Delta z} = \bar{n}\left(1 + b\delta_M\right)\frac{\Delta V}{\Delta\Omega\Delta z}$$

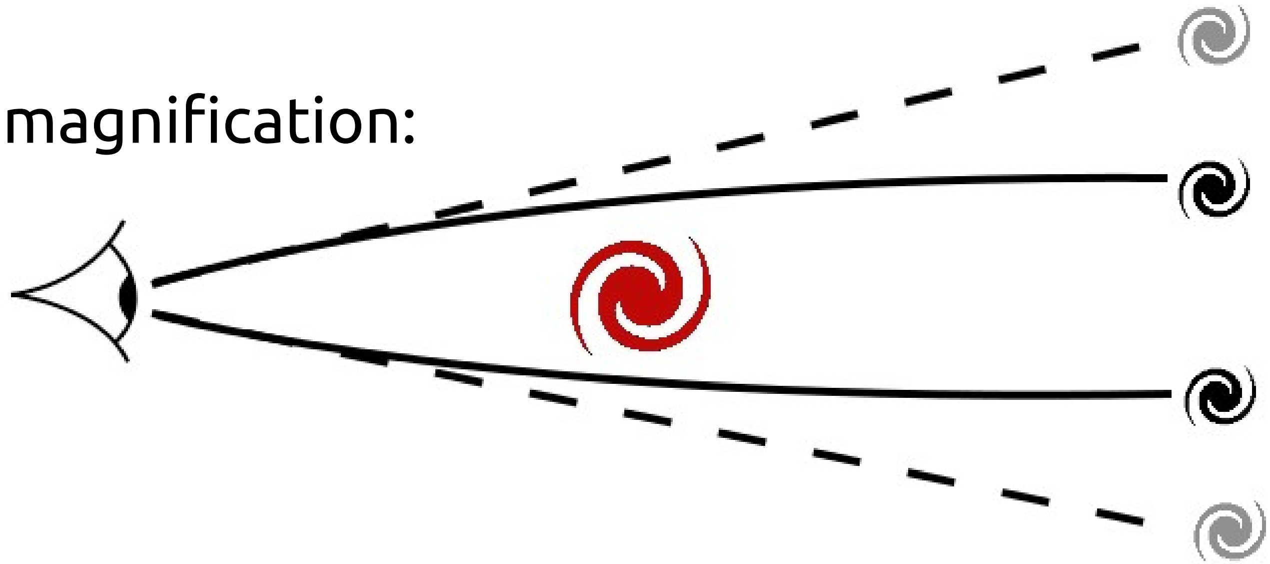
Relativistic effects in LSS

RSDs:



$$\delta z \propto v$$

Lensing magnification:



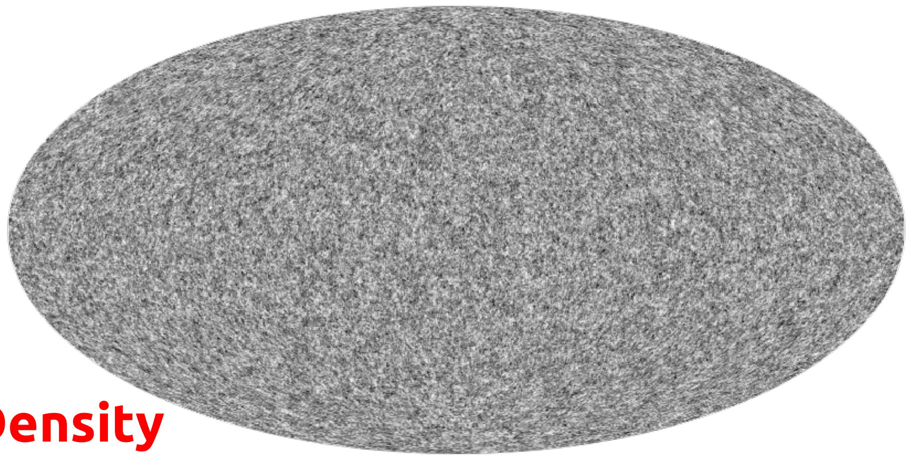
$$\delta\theta \propto \nabla_\theta \int dr\, \Phi$$

Sachs-Wolfe:

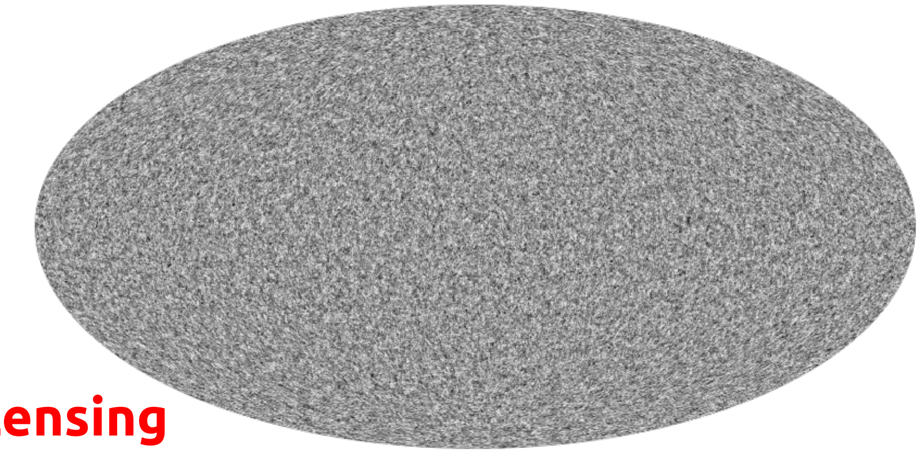
$$\begin{cases} \delta z \propto \Phi \\ \delta z \propto \int \dot{\Phi} \end{cases}$$

Challinor and Lewis, arXiv:1105.5292
Bonvin and Durrer, arXiv:1105.5280

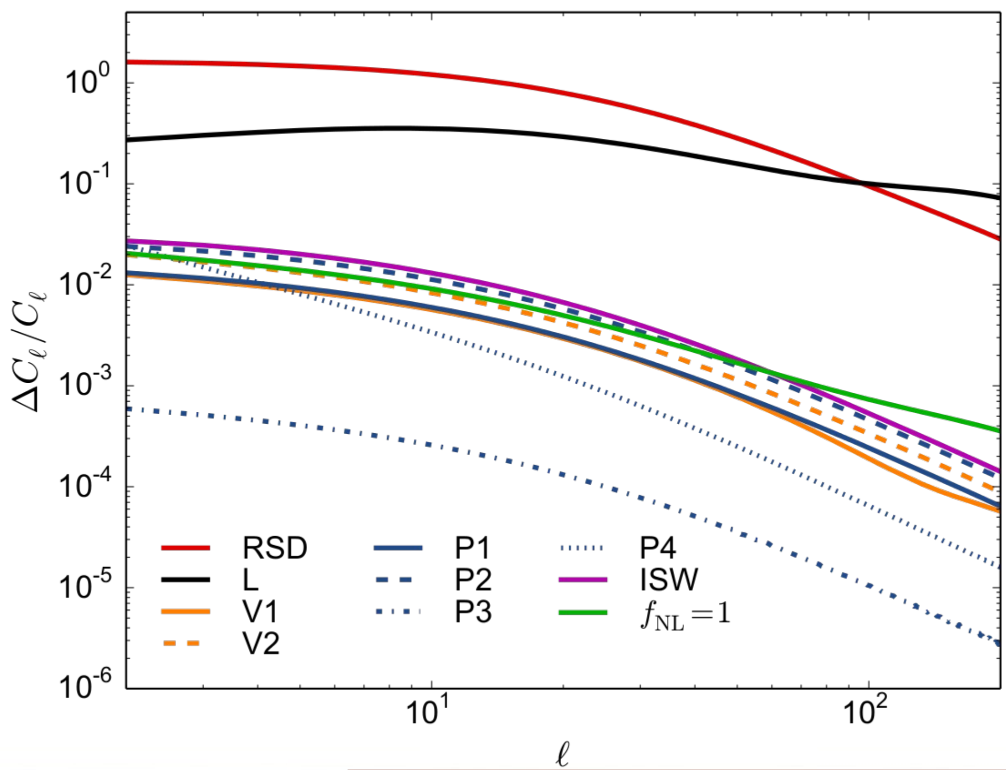
Relativistic effects in LSS

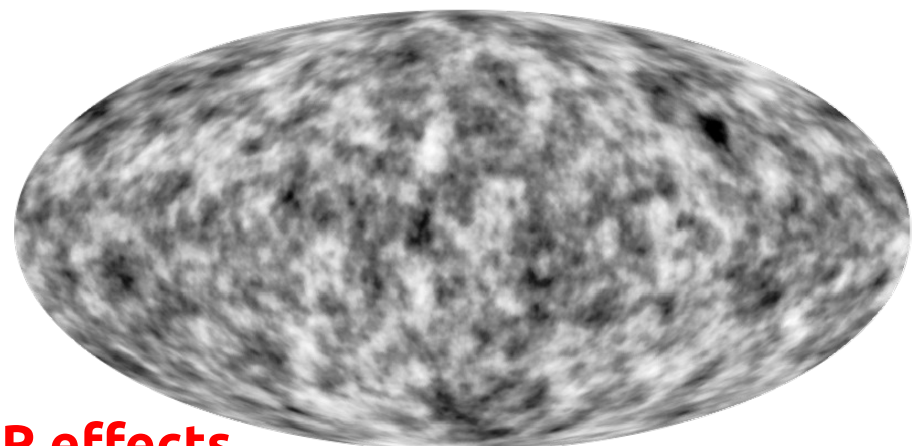


Density



Lensing





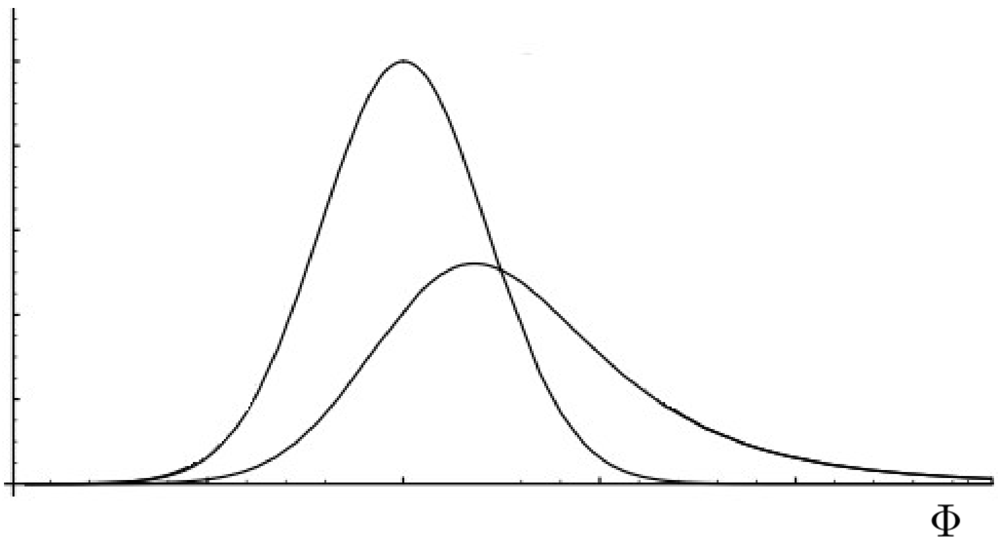
GR effects

Oxford Physics

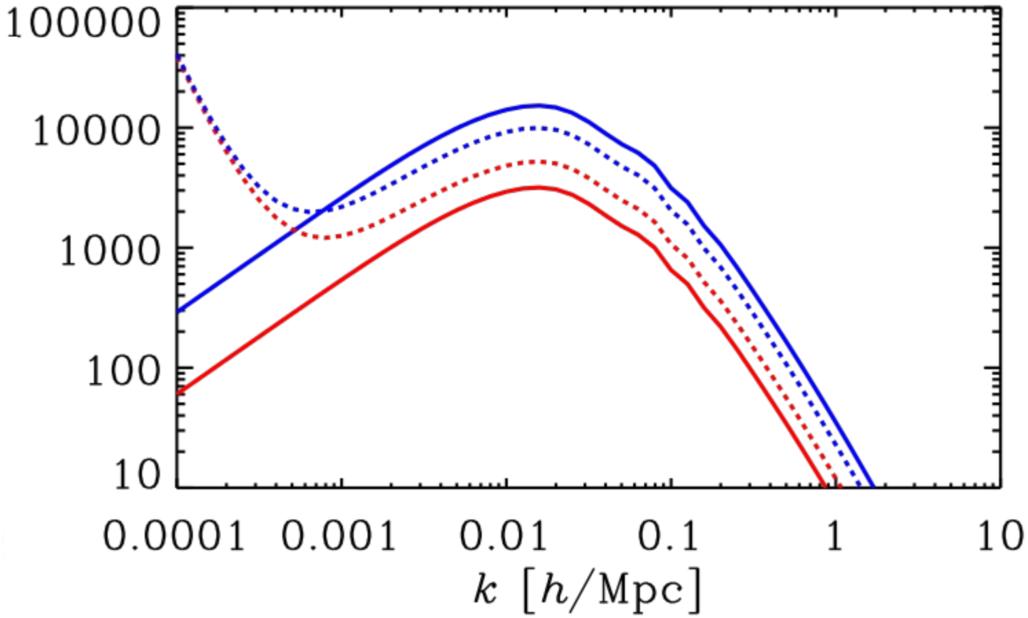
Primordial non-Gaussianity

- Massive objects, hosting galaxies, form in high-density environments.
- Primordial non-Gaussianity affects the clustering statistics of biased tracers.

$$\Delta b_M(k, f_{\rm NL}) = f_{\rm NL}\,[b_M(k,0)-1]\,\frac{3\delta_L\Omega_{\rm m0}H_0^2}{c^2k^2T(k)D(z)}$$



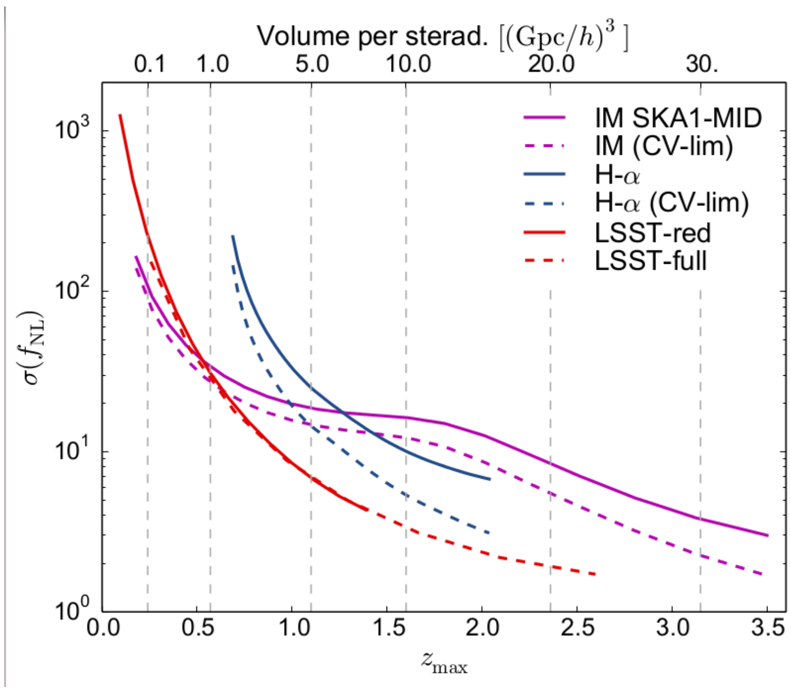
Dalal et al. arXiv:0710.4560
Matarrese and Verde arXiv:0801.4826

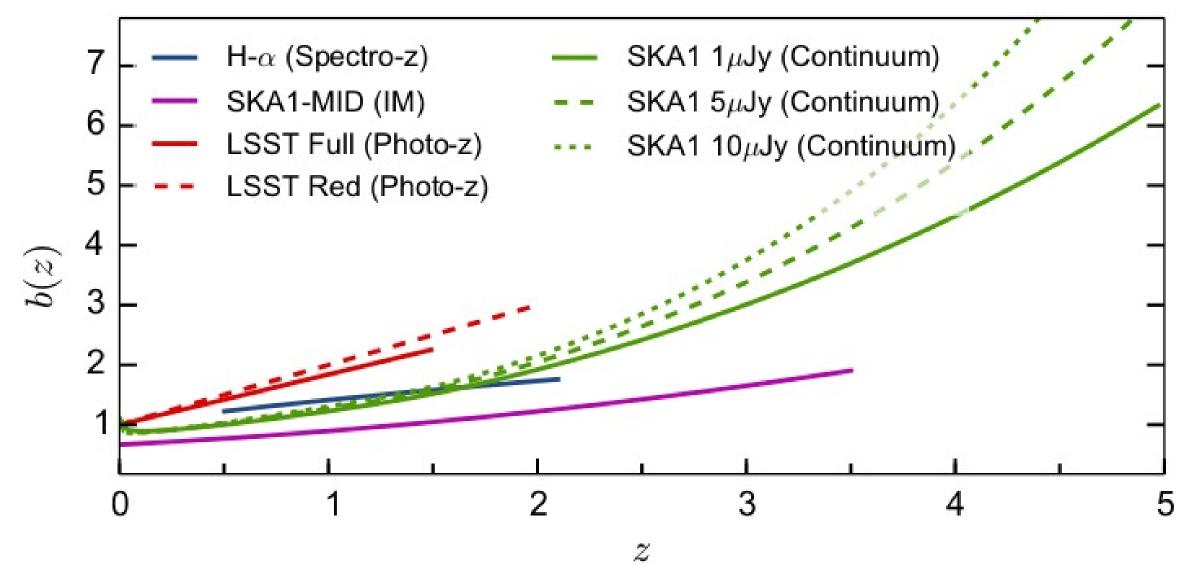


Camera et al. arXiv:1305.6928

Results: single tracers

Experiment	$\sigma(f_{\rm NL})$	$\sigma(\epsilon_{\rm GR}$
Intensity mapping (SKA1-MID)	3.01	2.75
Continuum survey ($S_{\rm cut} = 1\mu Jy$)	11.8	17.1
Spectroscopic survey (Euclid)	6.64	2.57
Photometric survey (LSST)	1.71	2.33



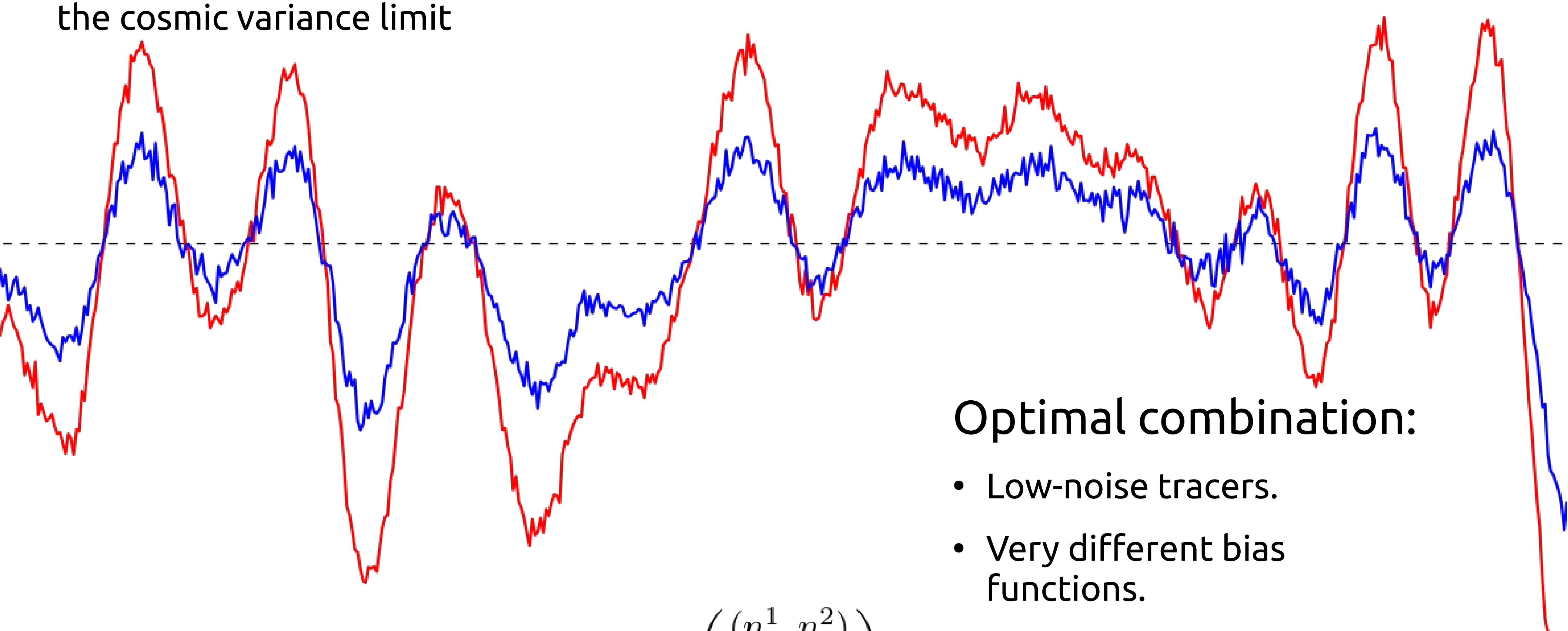


DA et al. arXiv:1505.07596, 1507.03550

Multi-tracer analyses

For disjoint tracers deterministically related to the density field, terms proportional to the bias parameters can be measured below the cosmic variance limit

$$\delta^a_{\mathbf{k}} = b^a\,\delta_{\mathbf{k}} + n^a \longrightarrow \sigma\left(\frac{b^1}{b^2}\right) = \mathcal{O}(n^1, n^2)$$



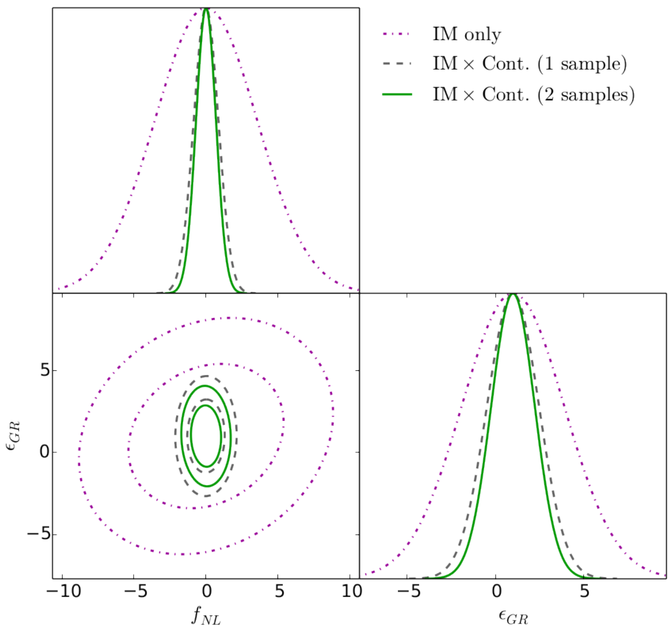
Optimal combination:

- Low-noise tracers.
- Very different bias functions.
- E.g.: photometric survey, red vs. blue galaxies

$$\delta^a_{\mathbf{k}} = b^a\,\delta_{\mathbf{k}} + \epsilon f^a g_{\mathbf{k}} + n^a \longrightarrow \sigma(\epsilon) = \mathcal{O}\left(\frac{(n^1, n^2)}{f^1 - f^2}\right)$$

Seljak 0807.1770

Multi-tracer analyses

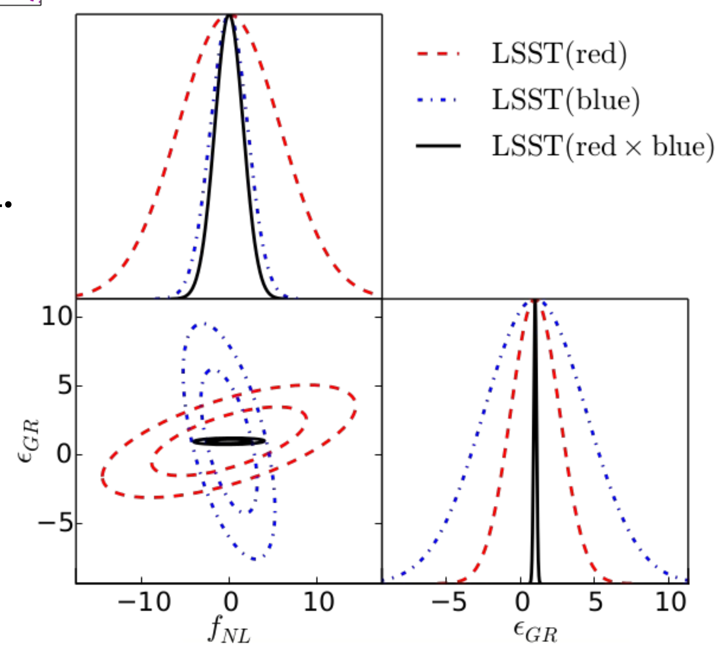


SKA-only

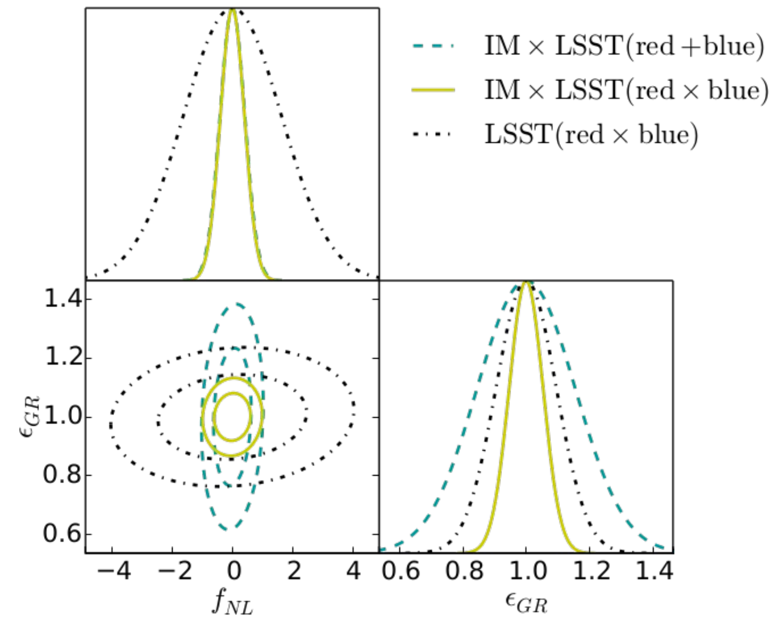
- 4 x improvement on f_{NL}.
- No detection of GR effects.

LSST-only

- Slight improvement for f_{NL}.
- 5-10 σ detection of GR effects.
- 3 σ detection for DES



LSST x SKA



- IM and photo-z are complementary.
- Major improvement in both cases. x4 in f_{NL}
- 10-20 σ detection of GR effects.

DA et al. arXiv:1507.03550
Fonseca et al. arXiv:1507.04605

Scalar-tensor gravity

$$\mathcal{L}_2 = G_2(X,\phi)\,,$$

$$\mathcal{L}_3 = -G_3(X,\phi)\Box\phi\,,$$

$$\mathcal{L}_4 = G_4(X,\phi)R + G_{4,X}\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$

$$\mathcal{L}_5 = G_5(X,\phi)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)\phi_{;\mu\nu}\phi^{;\mu\nu} + 2\phi_{;\mu}{}^{;\nu}\phi_{;\nu}{}^{;\lambda}\phi_{;\lambda}{}^{;\mu}\right]$$

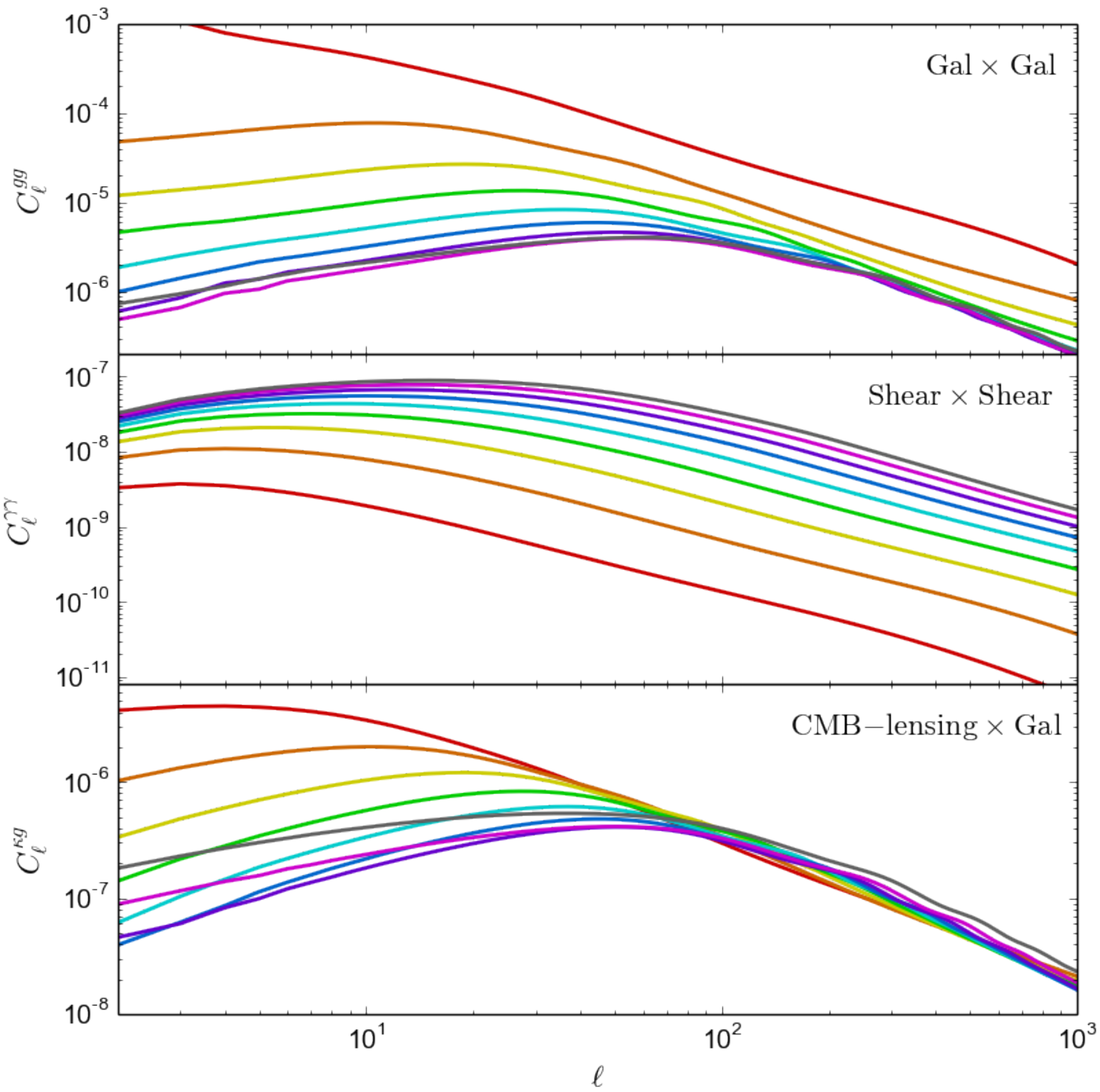
$$S[g_{\mu\nu},\phi] = \int\sqrt{-g}\sum_{i=2}^{5}\mathcal{L}_i$$

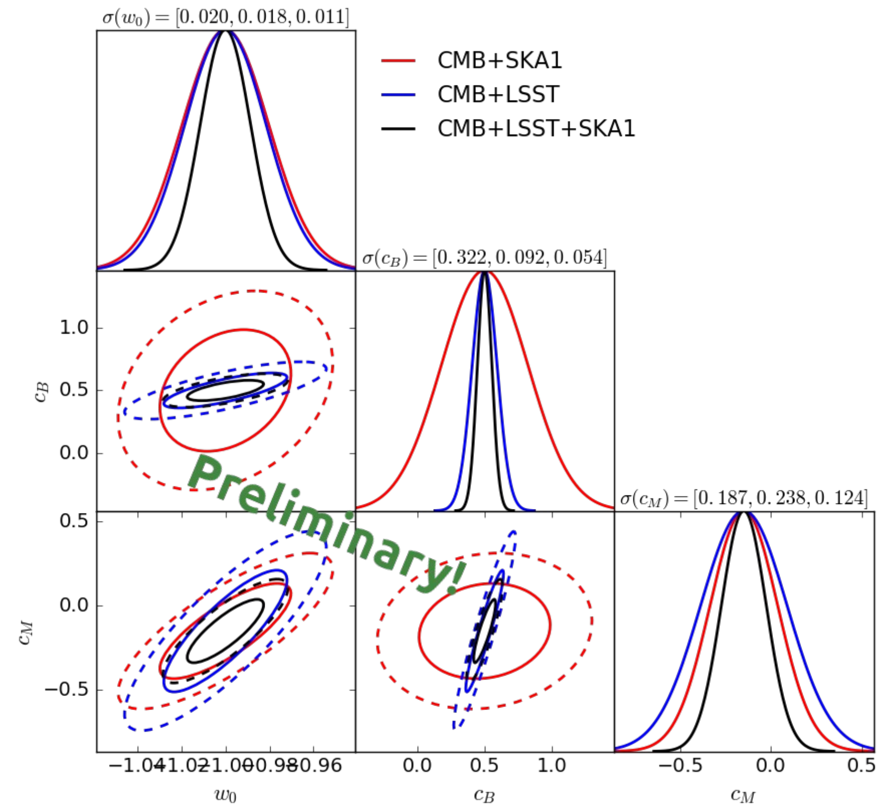
Horndeski Lagrangian:

- Most general scalar-tensor theory with 2nd-order equations of motion
- Enormous functional freedom.
- Reduced in the Bellini-Sawicki parametrization:
  - α_K : parametrizes standard kinetic term
  - α_B : off-diagonal kinetic terms. Scale-dependent gravitational constant.
  - $\alpha_M = \frac{d\log(M_*^2)}{d\log(a)}$: evolving gravitational constant.
  - $c_{GW} = 1 + \alpha_T$: speed of tensors.

DA, P. Ferreira, E. Bellini, M Zumalacarregui (in prep.)

Constraining Horndeski gravity



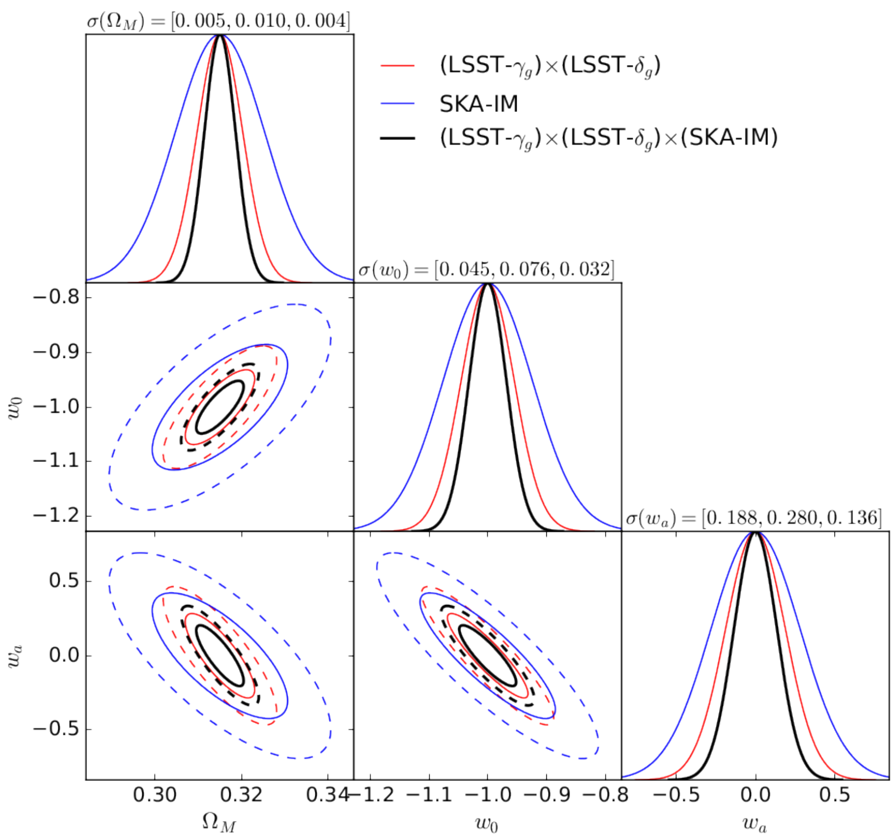


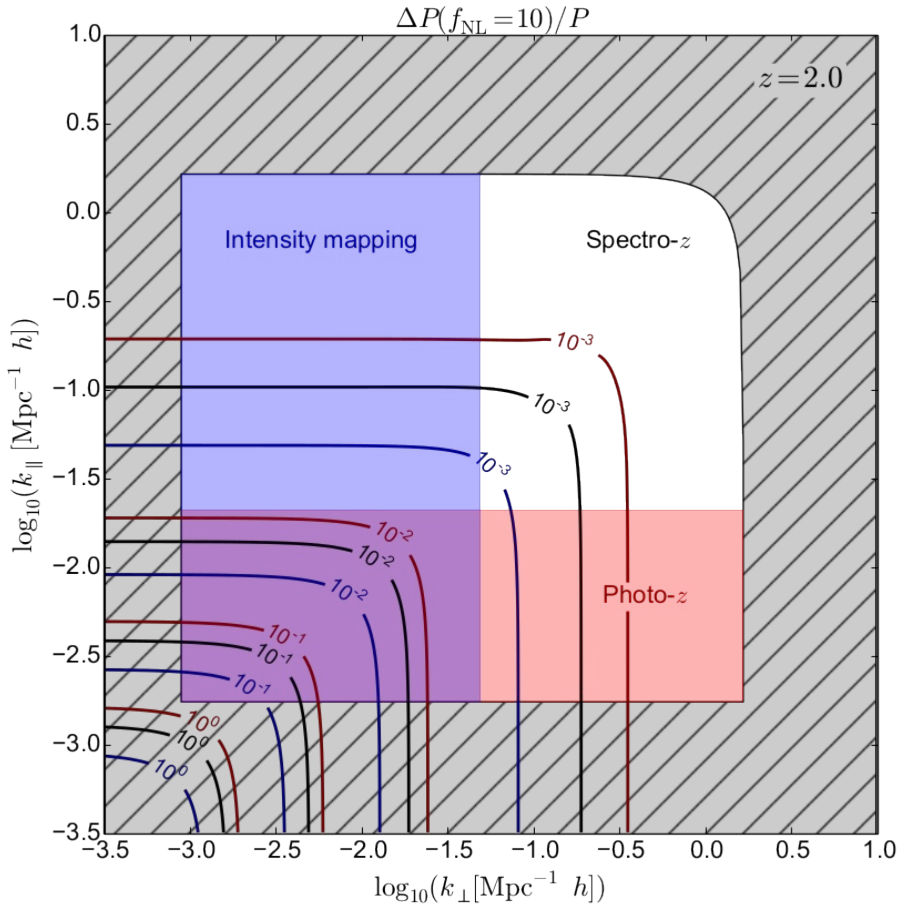
- Concept: throw in all tracers (and x-corrs!)
  - Galaxy clustering (LSST, blue and red)
  - Galaxy shear (LSST, gold sample)
  - Intensity mapping (SKA-1, 200 bins)
  - CMB primary (Planck)
  - CMB lensing (AdvACT)
- ~10x improvement over current constraints.

DA, P. Ferreira, E. Bellini, M Zumalacarregui (in prep.)

4. Combining photo-z's and IM.

1 Combined cosmological constraints

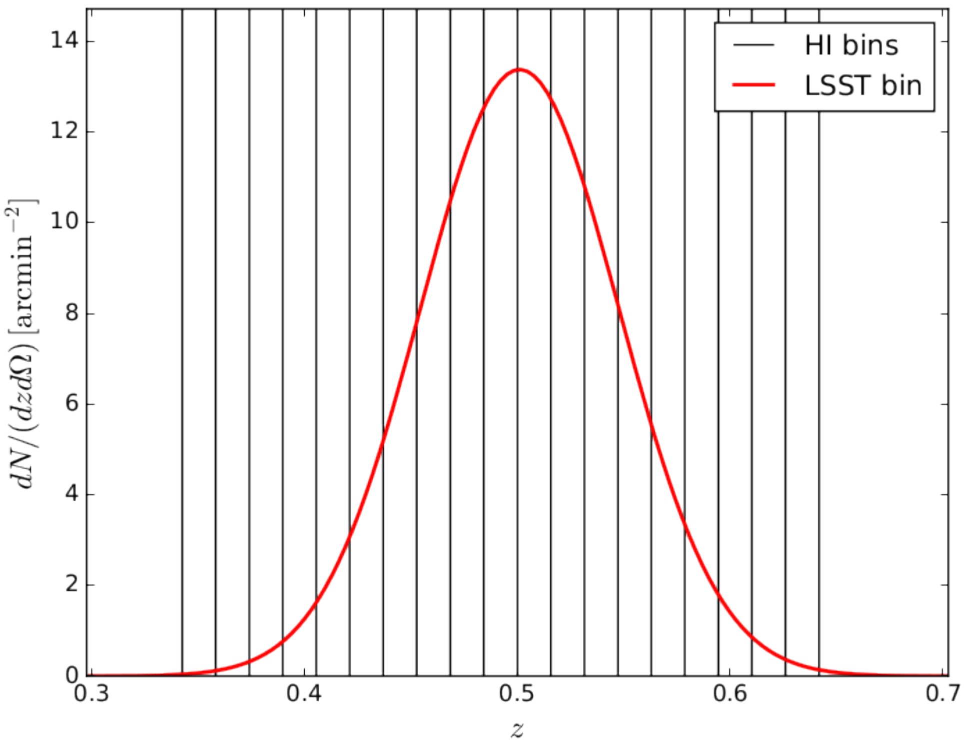


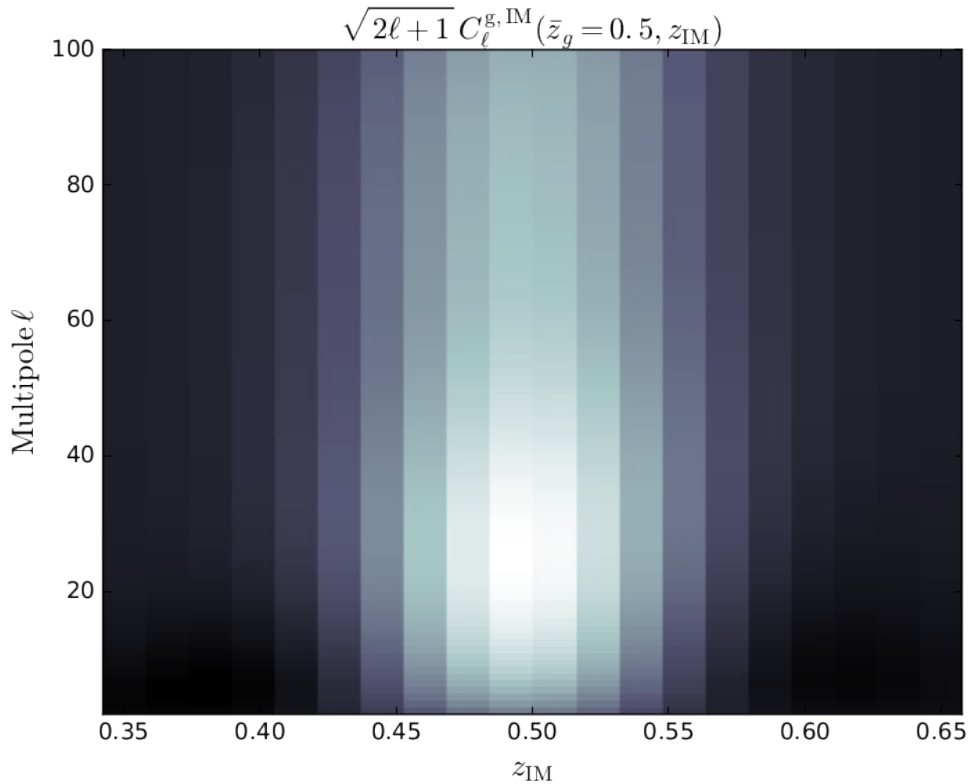


- Complementary coverage of scales.
- Complementary tracer properties (e.g. bias, magnification).

DA, P. Ferreira, M. Jarvis (in prep.)

2 Reducing photo-z systematics





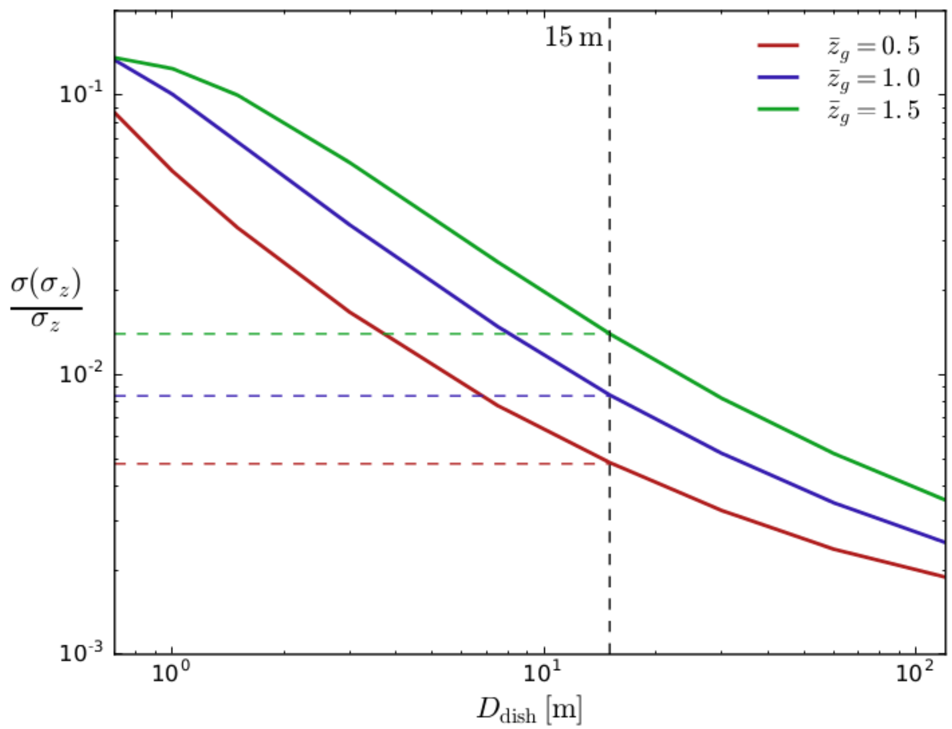
Clustering redshifts:

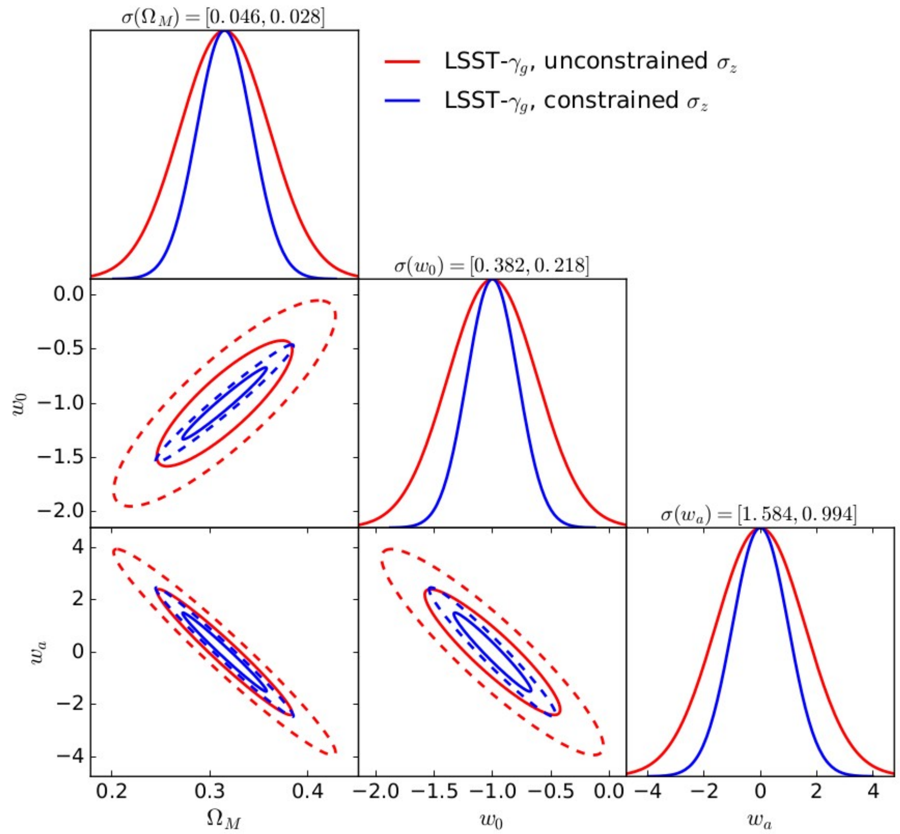
- Idea: reconstruct photo-z distribution using cross-correlations with spectro-z
- Cross correlate photo-z bin with thin spectro-z bins.
- The amplitude of the cross-correlation traces the shape of the photo-z distribution.
- IM could work just as well!

DA, P. Ferreira, M. Jarvis (in prep.)

Oxford Physics

2 Reducing photo-z systematics



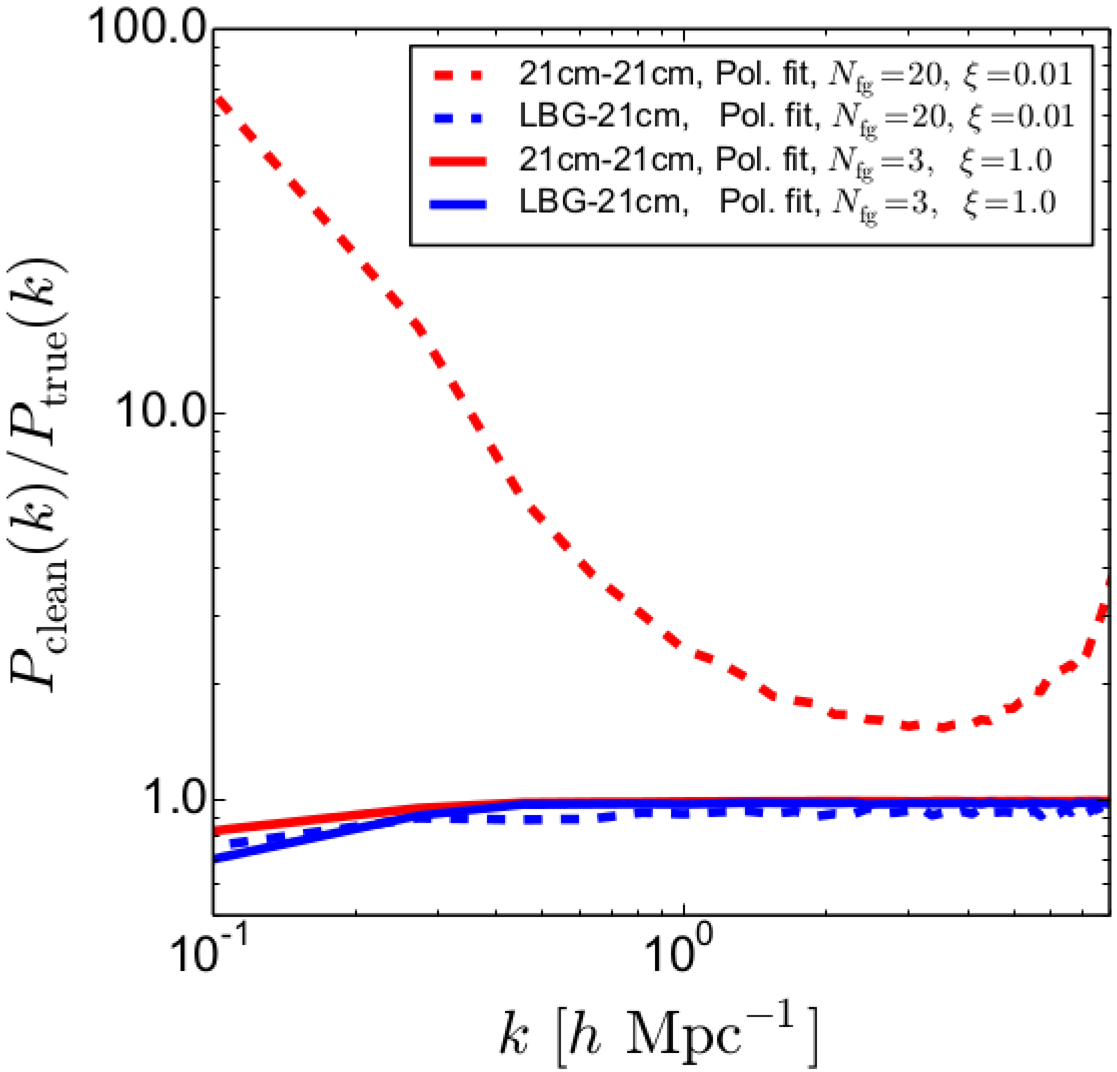


Clustering redshifts:

- Idea: reconstruct photo-z distribution using cross-correlations with spectro-z
- Cross correlate photo-z bin with thin spectro-z bins.
- The amplitude of the cross-correlation traces the shape of the photo-z distribution.
- IM could work just as well!

DA, P. Ferreira, M. Jarvis (in prep.)

3 Reducing foreground systematics



Villaescusa-Navarro et al. 1410.7393

- Badly behaved foregrounds could be impossible to subtract.
- E.g. leaked polarized synchrotron.
- Foregrounds cancel out in cross-correlation.
- This was used to make 1st detection of IM signal (Masui et al. 1208.0331)
- Not yet done with photo-z surveys.

4 Bayesian clustering analyses

General motivation: use **ALL** information to measure redshifts

$$\mathbf{z} \leftarrow p(\mathbf{z}|\mathbf{m},\hat{\mathbf{n}},\delta_{\rm HI})$$

magnitudes   angular positions   HI density

Jointly sample the underlying density distribution.

$$\{\mathbf{z},\delta\} \leftarrow p(\mathbf{z},\delta|\mathbf{m},\hat{\mathbf{n}},\delta_{\rm HI})$$

Can be done in a Gibbs-sampling way:

redshifts sampled individually

$$\mathbf{z}_{n+1} \leftarrow p(\mathbf{z}|\mathbf{m},\hat{\mathbf{n}},\cancel{\delta_{\rm HI}},\delta_n) = \prod_g p(z^g|m^g)p(z|\delta_n(\hat{n}^g))$$

$$\delta_{n+1} \leftarrow p(\delta|\mathbf{z}_{n+1},\cancel{\mathbf{m}},\hat{\mathbf{n}},\delta_{\rm HI}) = p(\delta|\delta_g(\mathbf{z}_{n+1},\hat{\mathbf{n}}),\delta_{\rm HI})$$

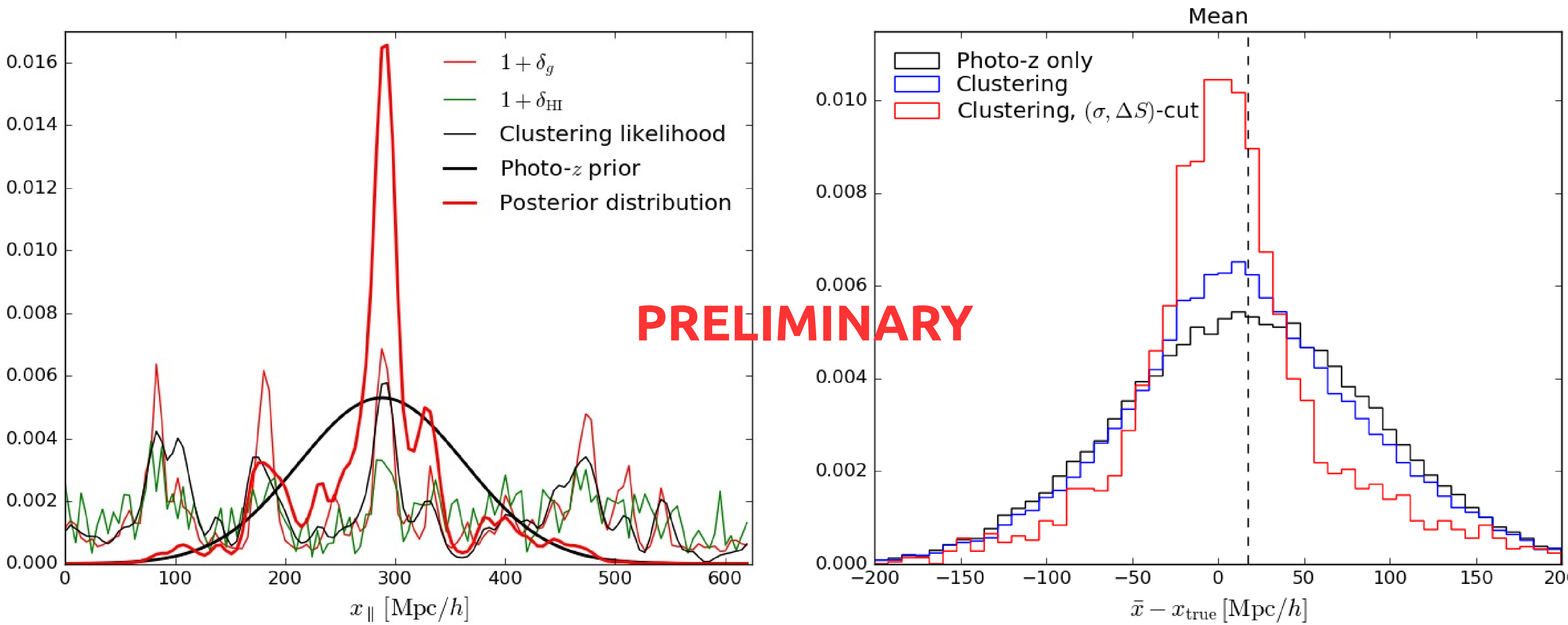
Jasche & Wandelt 1106.2757

Galaxy overdensity according in the (n+1)-th realization

DA, P. Ferreira, M. Jarvis (in prep.)

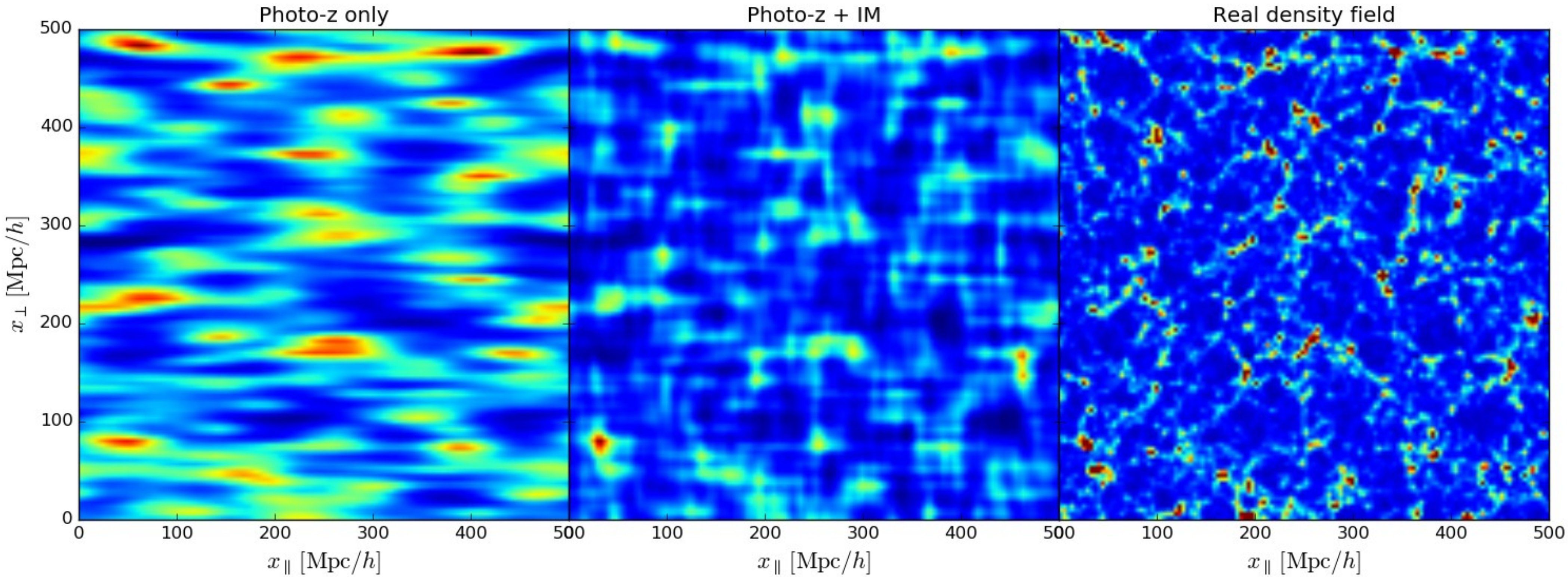
4 Bayesian clustering analyses

DA, P. Ferreira, M. Jarvis (in prep.)



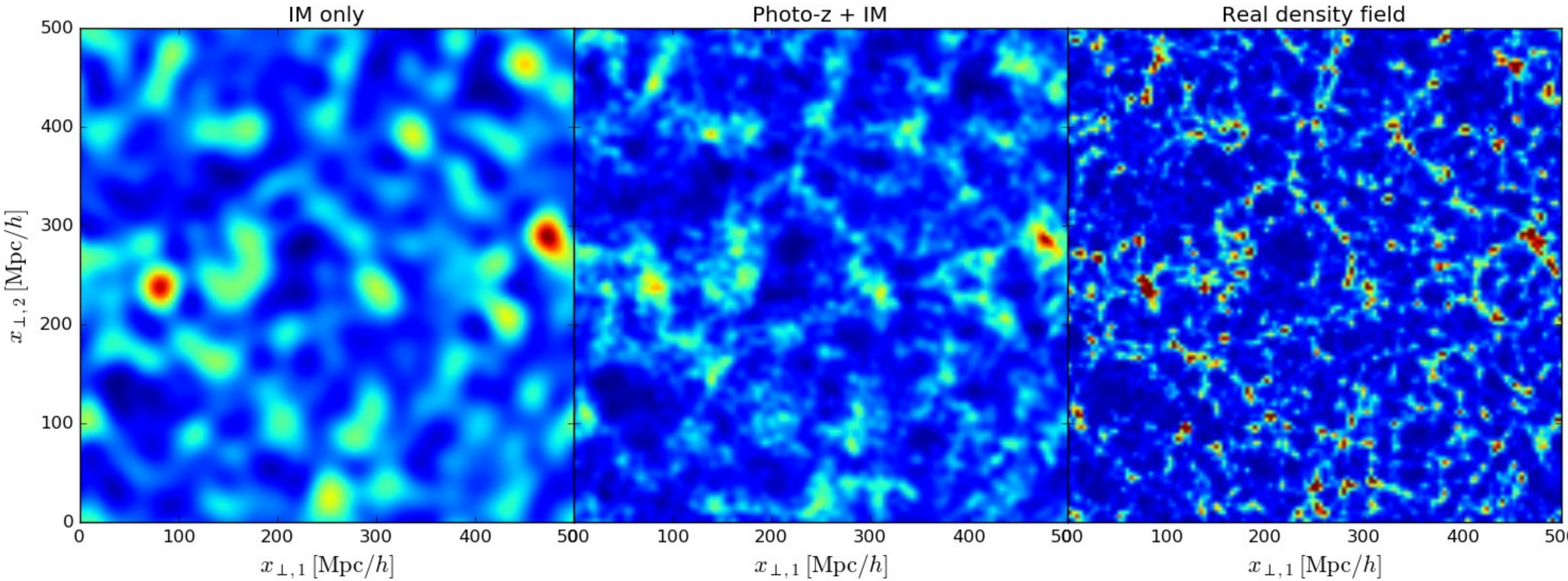
- The posterior distributions are a lot more informative.
- On average, reduced photo-z uncertainties (>10%)
- On high-density regions, σ_z reduced by a factor of ~10
- Clean sample can be selected:
  - ~30% better photo-z's
  - Impervious to photo-z bias
- Improved redshift usable for non-clustering analyses (e.g. SNe?)

4 Bayesian clustering analyses



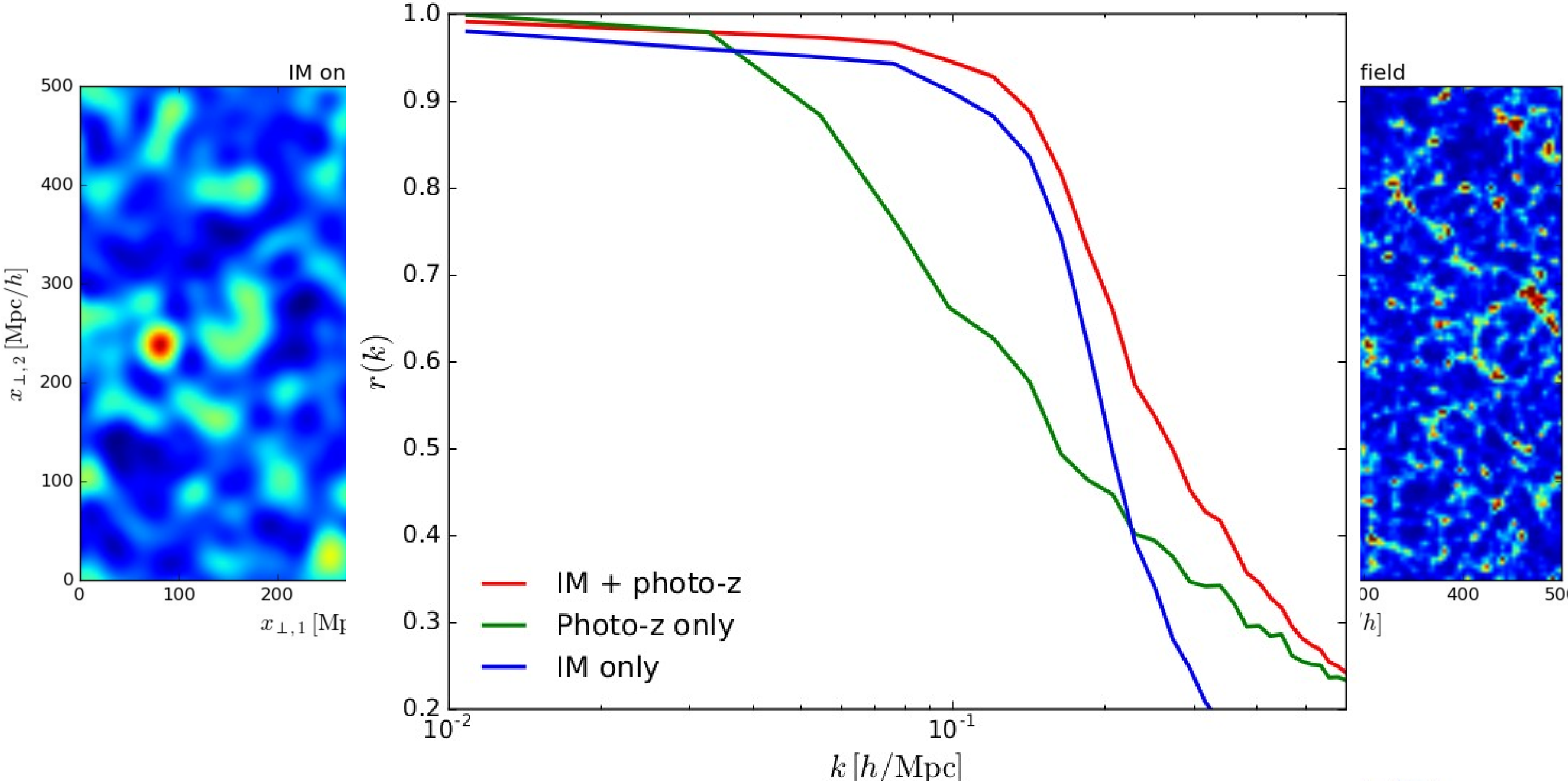
DA, P. Ferreira, M. Jarvis (in prep.)

4 Bayesian clustering analyses



DA, P. Ferreira, M. Jarvis (in prep.)

4 Bayesian clustering analyses



DA, P. Ferreira, M. Jarvis (in prep.)

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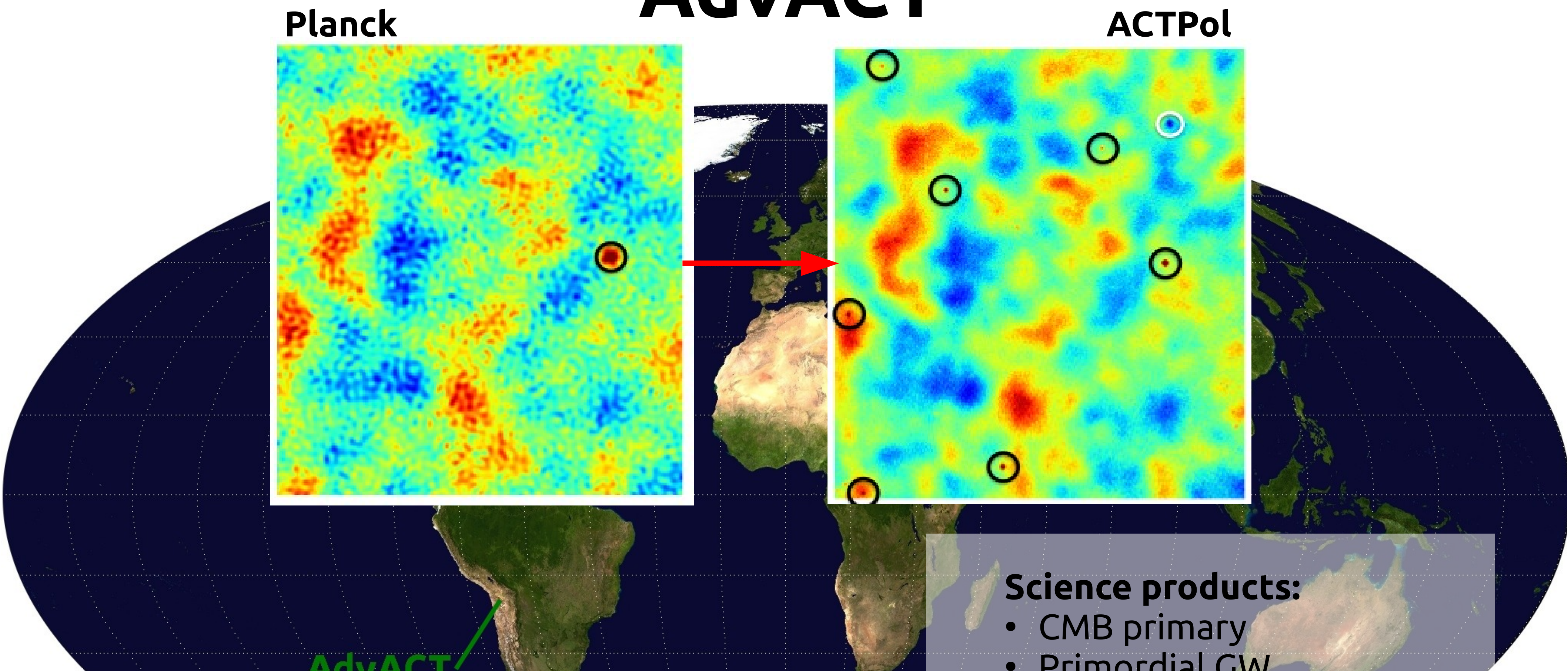
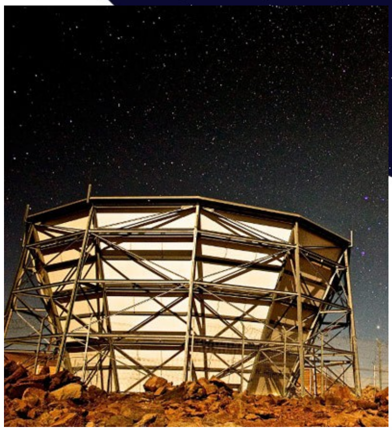
5. Measuring growth with kSZ

AdvACT



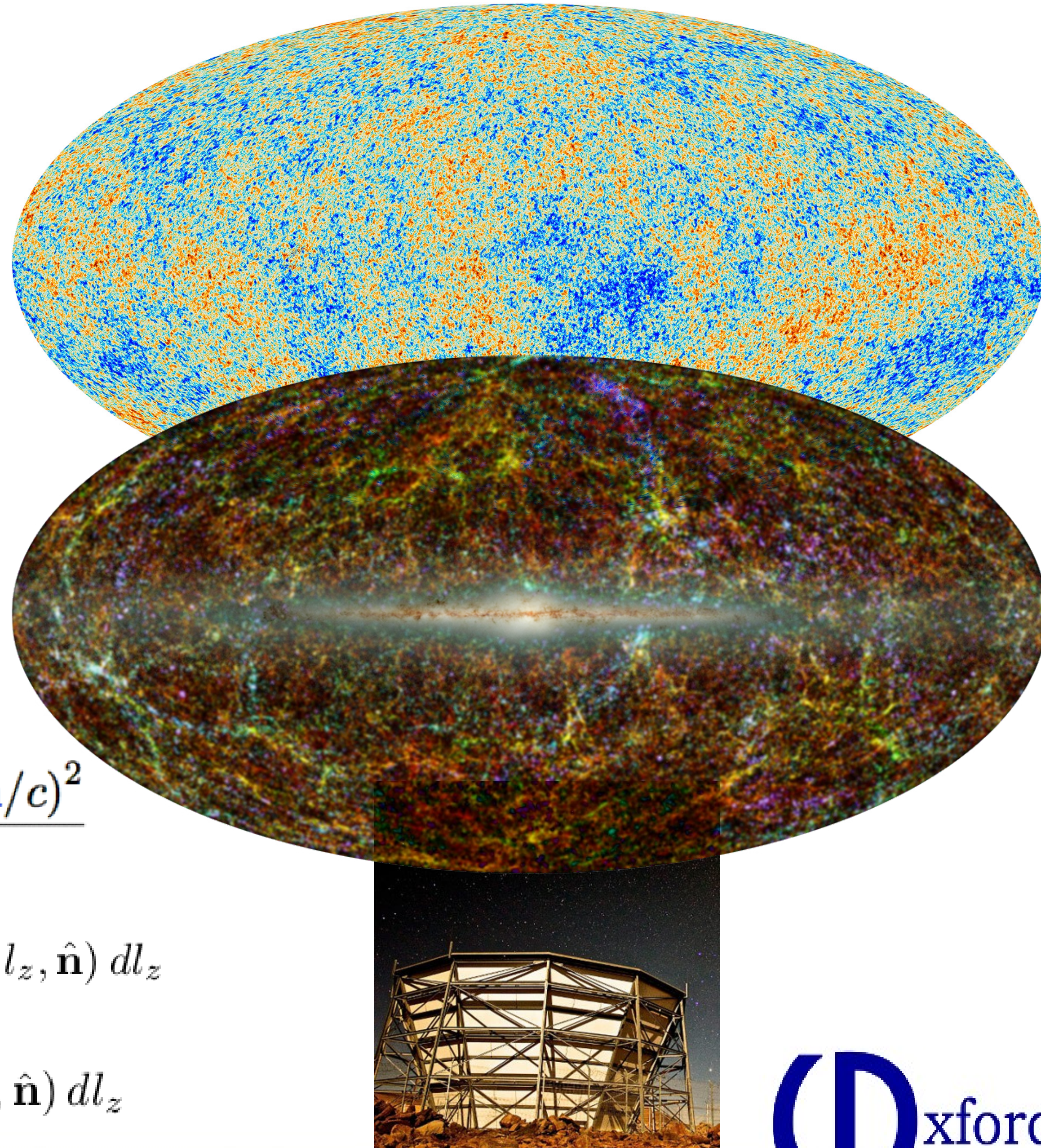
Science products:

- CMB primary
- Primordial GW
- CMB lensing
- Thermal SZ
- Kinematic SZ
- Point sources (DSFGs)



Henderson et al. 1510.02809

Growth from kSZ



Method:
- CMB experiment + overlapping spectroscopic survey
- tSZ-selected clusters with kSZ measurements
- Use galaxy positions to reconstruct cluster velocities.

$$\mathbf{v}(t,\mathbf{k}) = \frac{H\,f}{a}\,\frac{i\mathbf{k}}{k^2}\delta(t,\mathbf{k})$$

- Match reconstructed velocity with kSZ measurement.

DA et al. 1604.01382

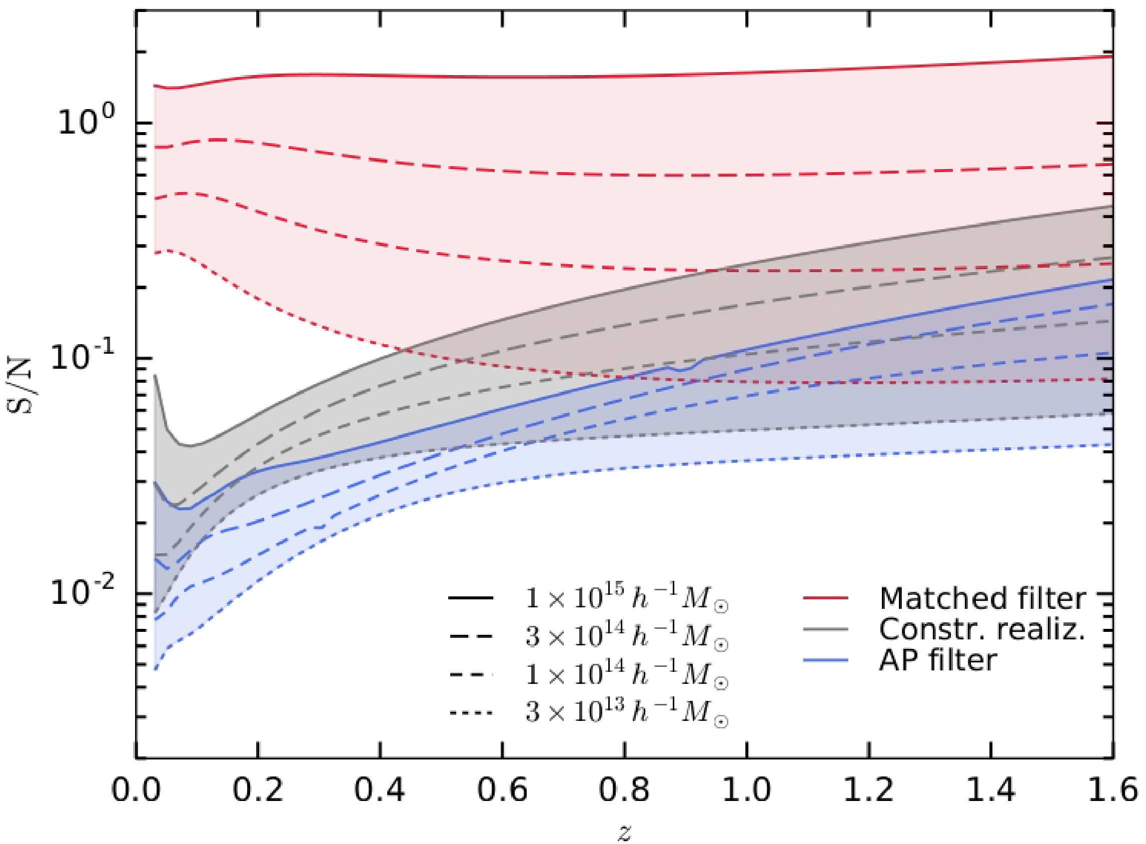
$$\chi^2(H\,f) = \frac{(\Delta\mathrm{T}(\hat{\mathbf{n}}) - \tau(Y)\boldsymbol{v}(\delta, H\,f).\hat{\mathbf{n}}/c)^2}{\sigma^2}$$

$$\left.\frac{\Delta\mathrm{T}}{\mathrm{T}}\right|_{\mathrm{tSZ}}(\nu,\hat{\mathbf{n}}) = f_{\mathrm{tSZ}}(\nu)\frac{\sigma_T}{m_e c^2}\int P_e(l_z,\hat{\mathbf{n}})\,dl_z$$

$$\left.\frac{\Delta\mathrm{T}}{\mathrm{T}}\right|_{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_T\int(\boldsymbol{\beta}\cdot\hat{\mathbf{n}})\,n_e(l_z,\hat{\mathbf{n}})\,dl_z$$

Measuring the kSZ effect

- tSZ can be separated using multi-frequency.
- kSZ has black-body spectrum
- Must be separated using different scale dependence.
- Three methods:
  - AP filter: assume only a clear spectral separation.
    Most conservative method.
  - Constrained realizations: assume knowledge of CMB power spectrum.
    Less conservative, still safe.
  - Matched filter: assume knowledge of CMB power spectrum AND cluster profiles.
    Optimal. Dependent on cluster assumptions.



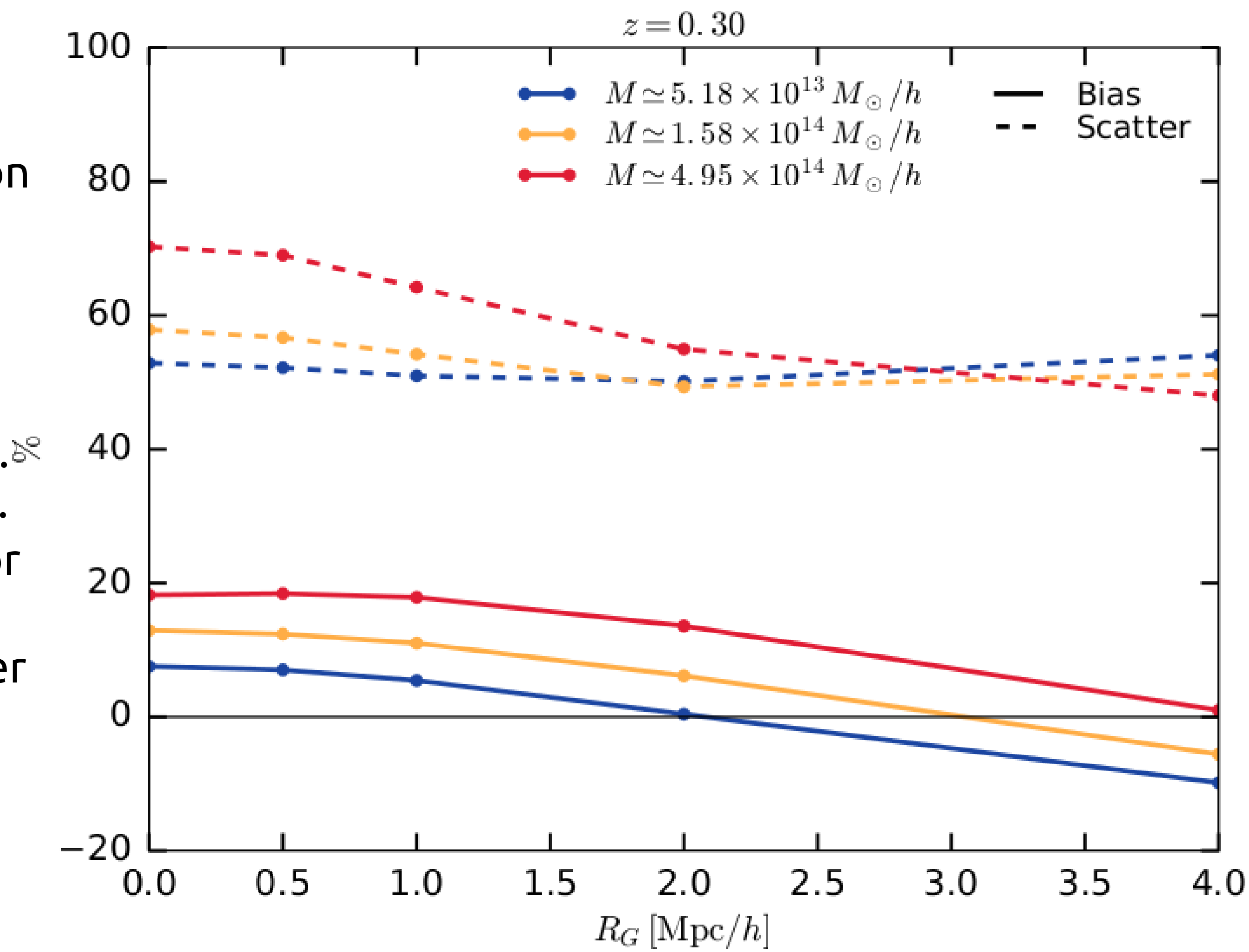
DA et al. 1604.01382

Velocity reconstruction

- Simple density-velocity relation in the linear regime.

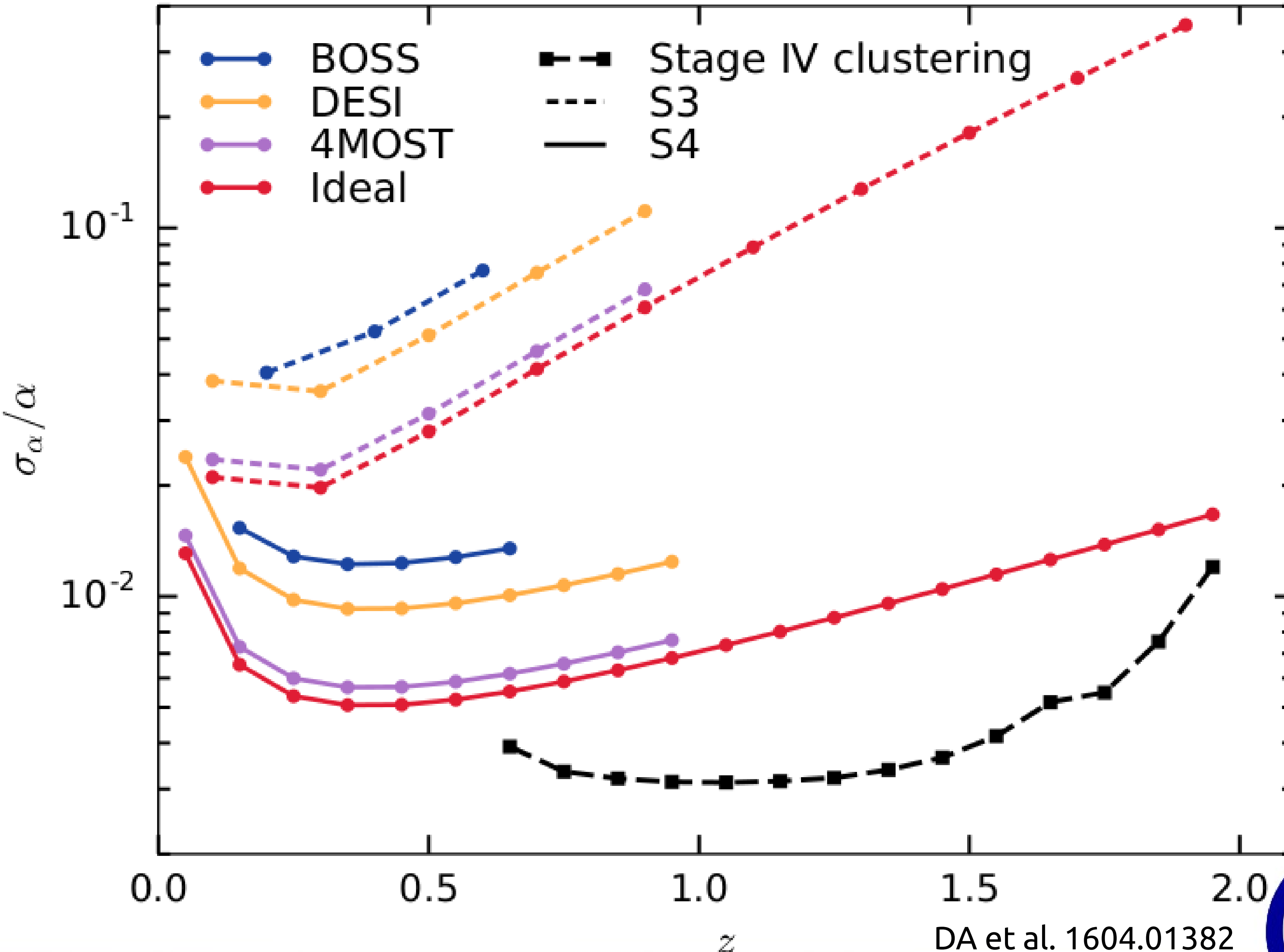
$$\mathbf{v}(t,\mathbf{k}) = \frac{H\,f}{a}\,\frac{i\mathbf{k}}{k^2}\delta(t,\mathbf{k})$$

- Better estimates possible (e.g. 2LPT, full Bayesian modelling).
- Estimated reconstruction error from simulations.
- Linear method works well after smoothing (e.g. bad in high-density regions).



DA et al. 1604.01382

Constraints from S-IV experiments



DA et al. 1604.01382

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Conclusions

- In the next decade we will have an unprecedented coverage of the sky, in terms of area, depth and frequency bandwidth.
- 21cm intensity mapping is a cheap method to cover large portions of the sky, enabling large-scale cosmological studies.
- Robust observables, such as the BAO should be impervious to the effect of foregrounds.
- HI is also a great probe to combine with other tracers (e.g. low bias, no lensing).
- Relativistic LSS effects are only observables using multi-tracer techniques. f_{NL} measurements will benefit greatly from cross-correlations.
- Constraints on modified-gravity parameters will improve by a factor of ~10 with Stage-IV experiments.
- IM and photo-z's are almost complementary probes in terms of scale-coverage.
- A combination of both can:
  - Improve cosmological constraints.
  - Eliminate/mitigate individual systematics.
  - Improve individual redshift estimates and help reconstruct the true density field.
- The combination of CMB and LSS observations offers multiple new cosmological probes.
- Combining velocity reconstruction from spectroscopic surveys and kSZ measurements can yield alternative measurements of the growth rate.
- A good understanding of cluster physics is indispensable

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¡Gracias!

Relativistic effects in LSS

$$\Delta_N = b\,\delta_M - \frac{1}{\mathcal{H}}\frac{\partial v_r}{\partial \chi} + (5s-2)\left[\kappa - \frac{2}{\chi}\int \Phi d\eta\right] + \left[\frac{2-5s}{\mathcal{H}\chi} + 5s - f_{\rm evo} + \frac{\dot{\mathcal{H}}}{\mathcal{H}}\right]\left[\psi + \int \dot{\Phi} d\eta - v_r\right] + \frac{\dot{\phi}}{\mathcal{H}} + \psi + (5s-2)\phi$$

- **Density** (red)
- **RSDs** (green)
- **Lensing** (blue)
- **"Relativistic effects"** (pink)

Challinor and Lewis, arXiv:1105.5292
Bonvin and Durrer, arXiv:1105.5280

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