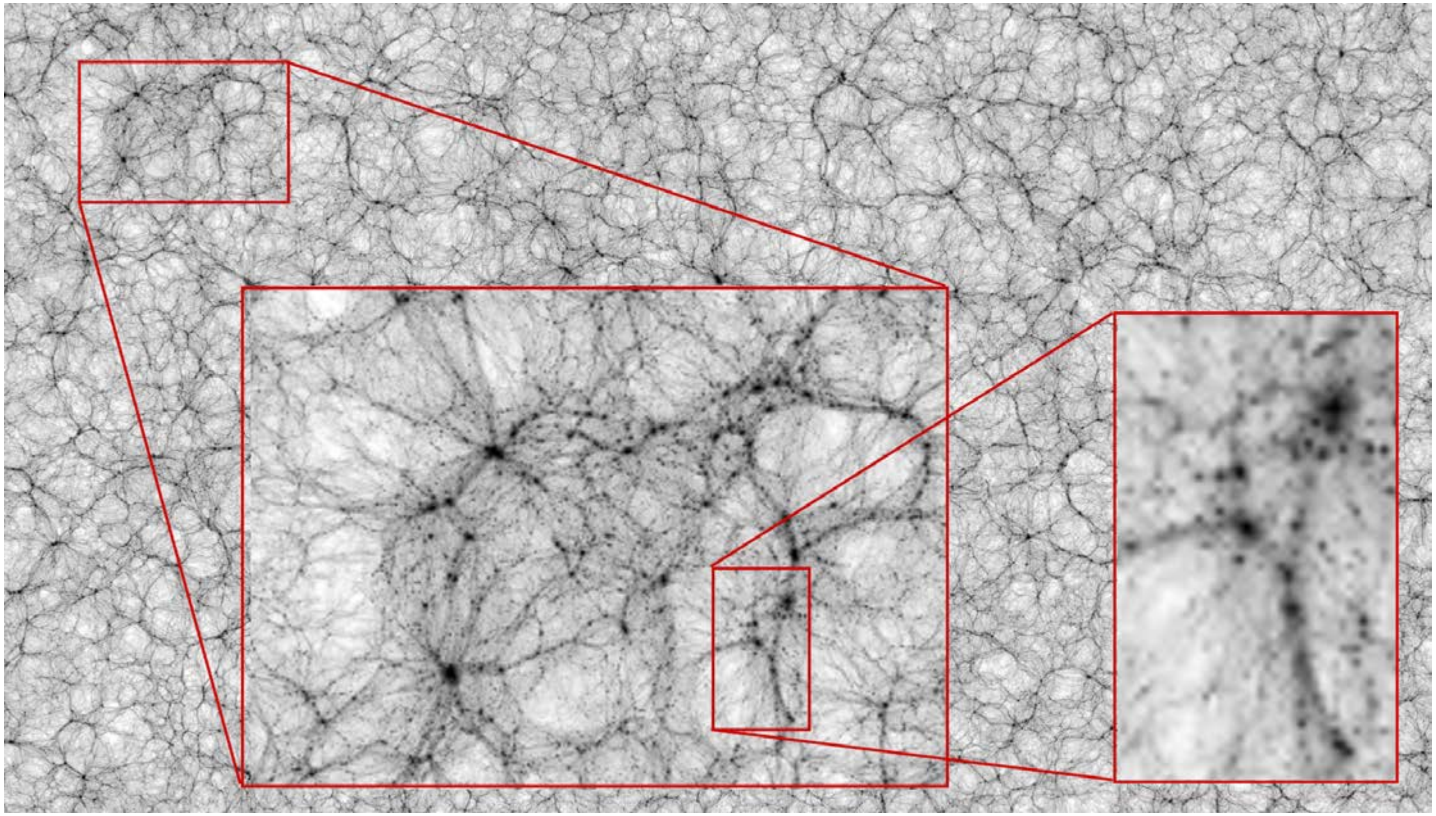
Ultralarge-scale cosmology with future surveys

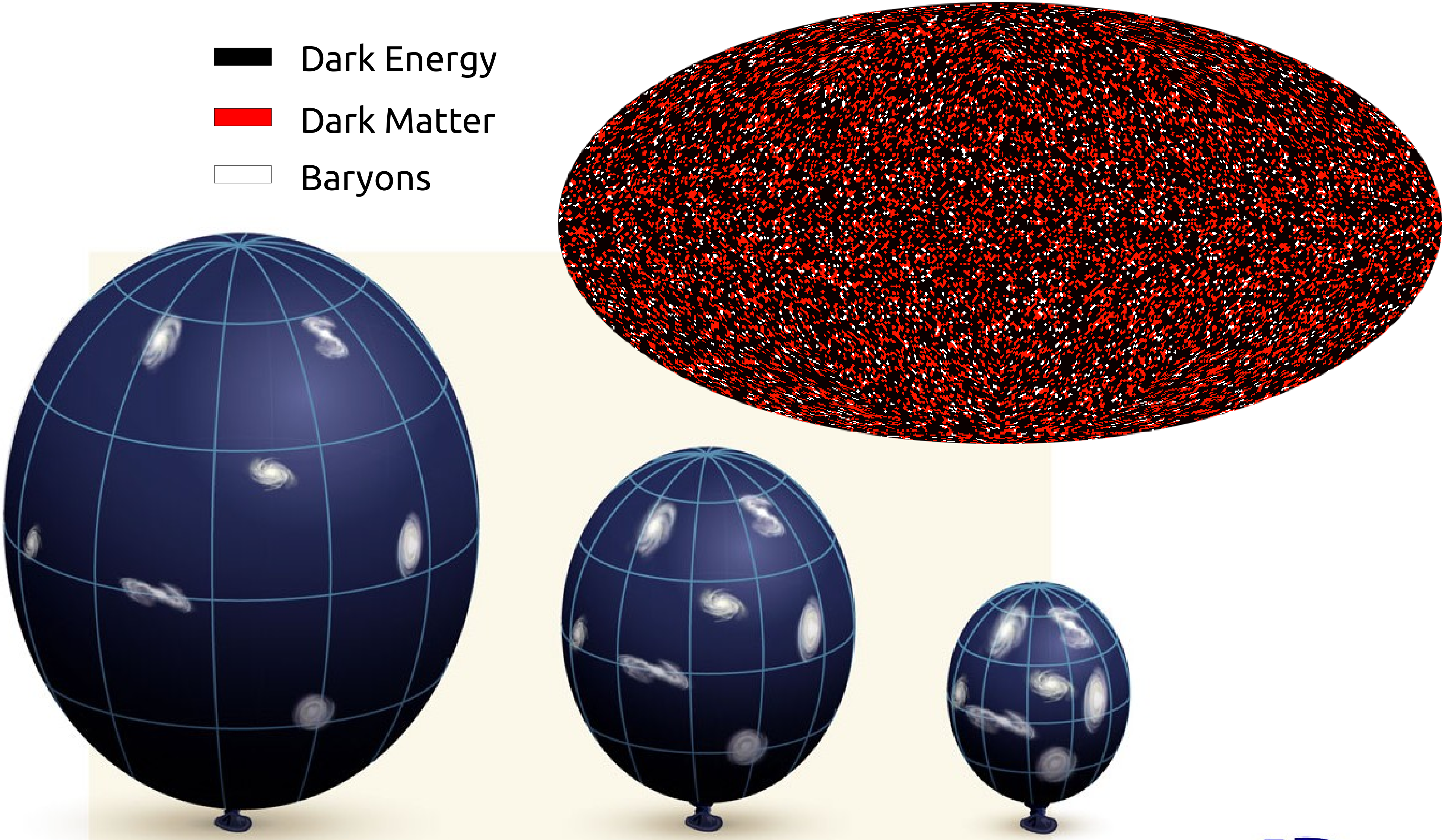
David Alonso – Oxford Astrophysics



ArXiv:1405.1751, 1409.8667, 1505.07596, 1507.03550
In collaboration with: P. Bull, P. Ferreira, R. Maartens, M. Santos

IFT UAM-CSIC, Madrid – September 2015

Cosmology



⬛ Dark Energy

🟥 Dark Matter

⬜ Baryons

Accelerated expansion

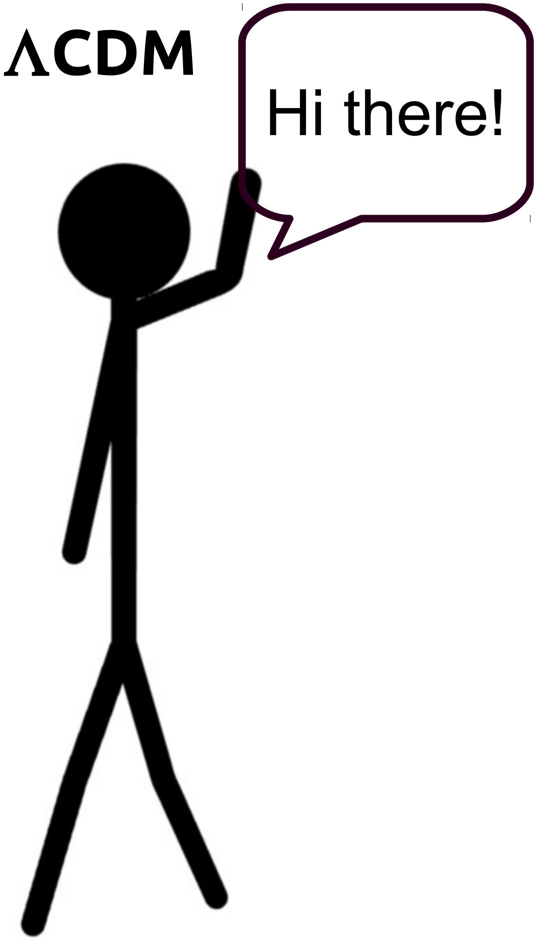
Structure formation

Initial conditions

Accelerated expansion

$$G_{\mu\nu} + \Lambda g_{\mu\nu} \propto T_{\mu\nu}$$

ΛCDM



$$G_{\mu\nu} \propto T_{\mu\nu} + \delta T_{\mu\nu}$$

Dark Energy

$$G_{\mu\nu} + \delta G_{\mu\nu} \propto T_{\mu\nu}$$

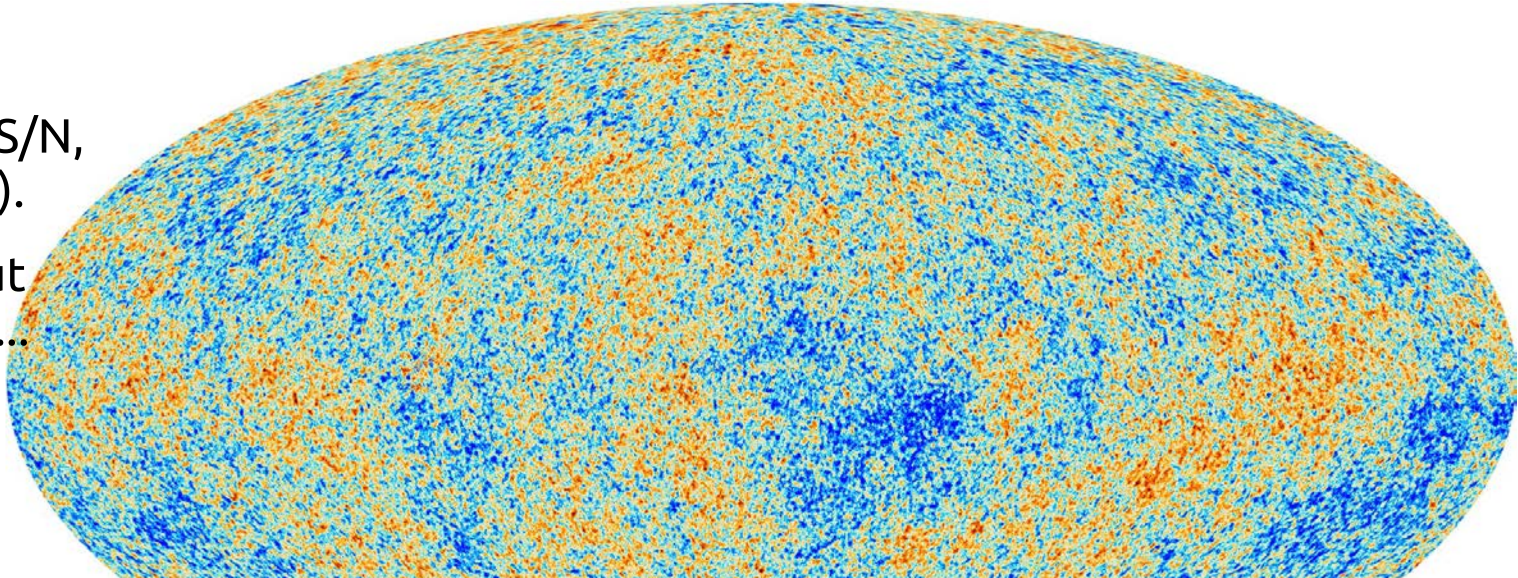
Mod. Gravity

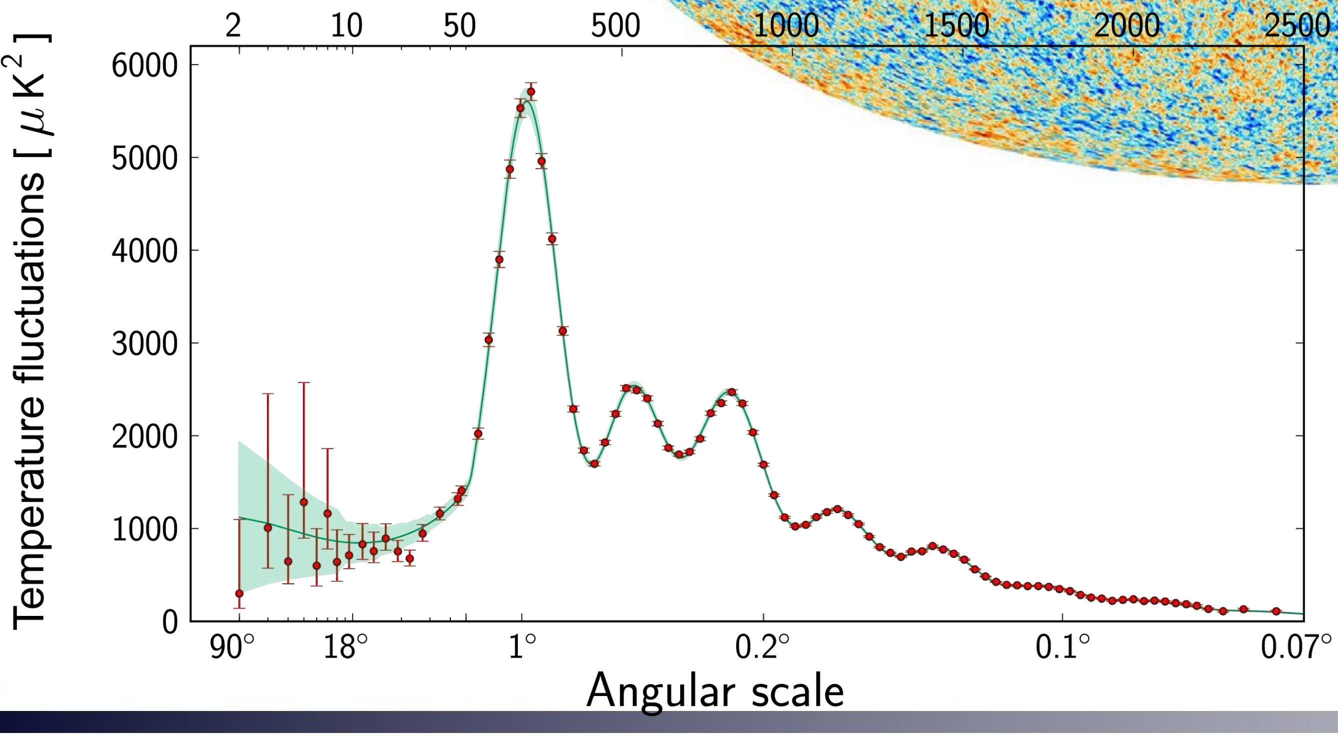
FOR THE LAST HUNDRED YEARS, SWISS PATENT CLERKS HAVE BEEN UNDER SOME WEIRD PRESSURES.

Cosmic Microwave Background

CMB:

- Exquisite probe (good S/N, no theor. uncertainties).
- Informs us mainly about the early Universe, but...
- CMB lensing, ISW... more later.



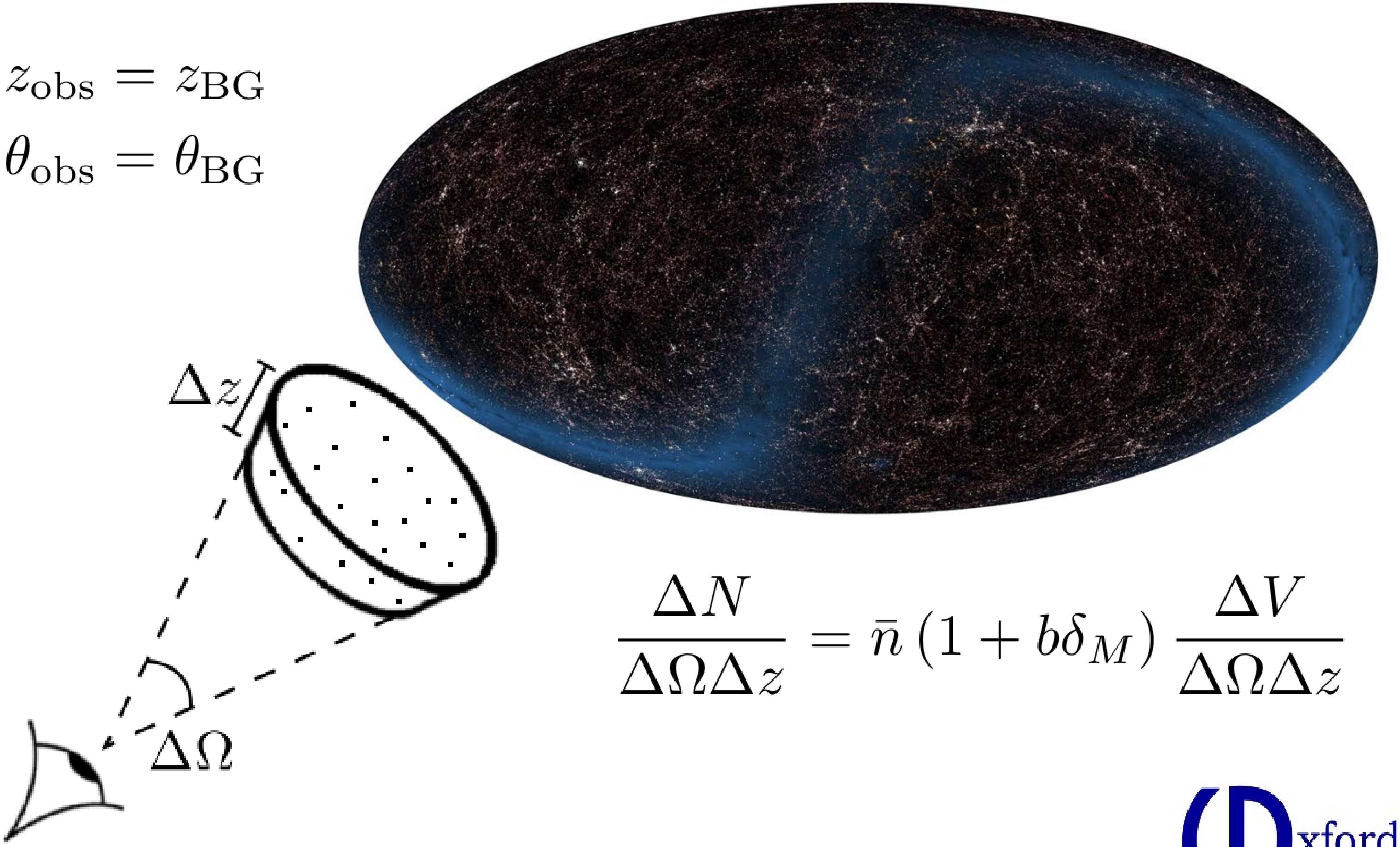


Planck, arXiv:1507.02704

Source number counts

$$z_{\rm obs} = z_{\rm BG}$$

$$\theta_{\rm obs} = \theta_{\rm BG}$$

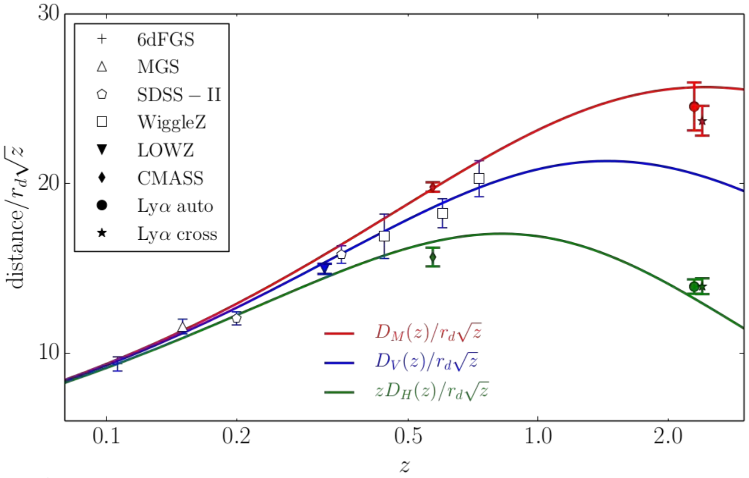


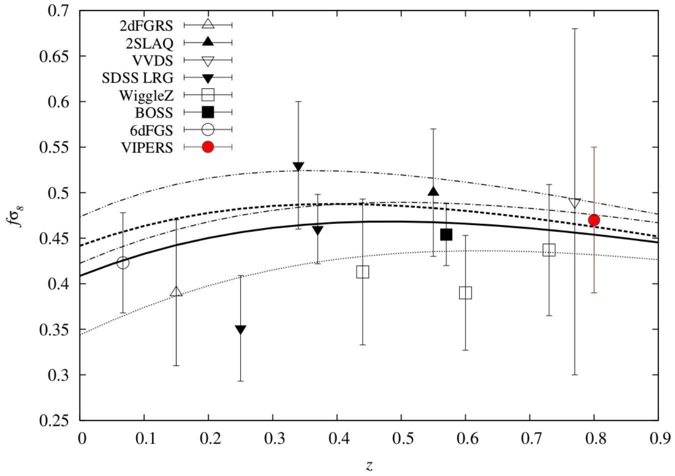
$$\frac{\Delta N}{\Delta\Omega\Delta z} = \bar{n}\,(1+b\delta_M)\,\frac{\Delta V}{\Delta\Omega\Delta z}$$

Source number counts

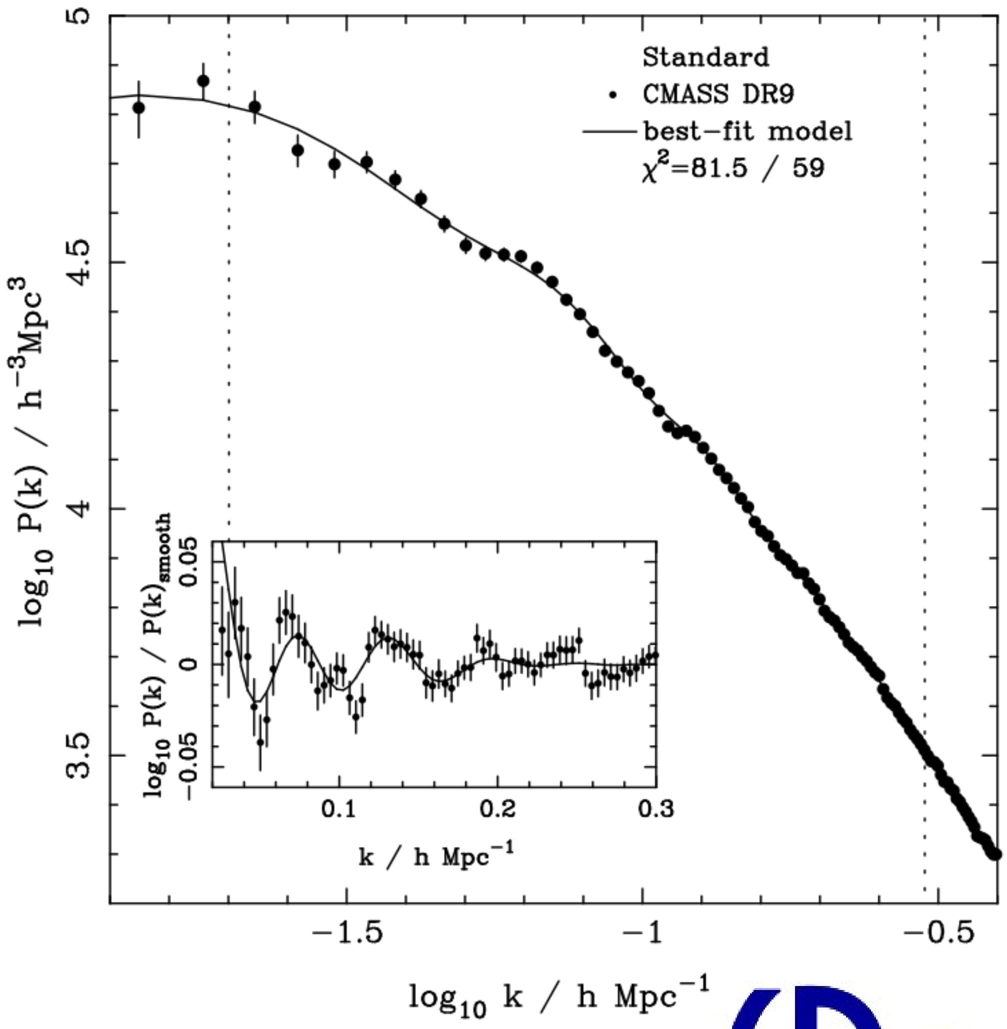
Multiple probes:

- BAO (standard ruler).
- RSDs (growth rate).





de la Torre et al. ArXiv:1303.2622



Anderson et al. arXiv:1203.6594

Source number counts

Multiple probes:

- BAO (standard ruler).
- RSDs (growth rate).
- **Ultra-large scales?**
  - Initial conditions
  - Relativistic (horizon) effects
  - Turnover

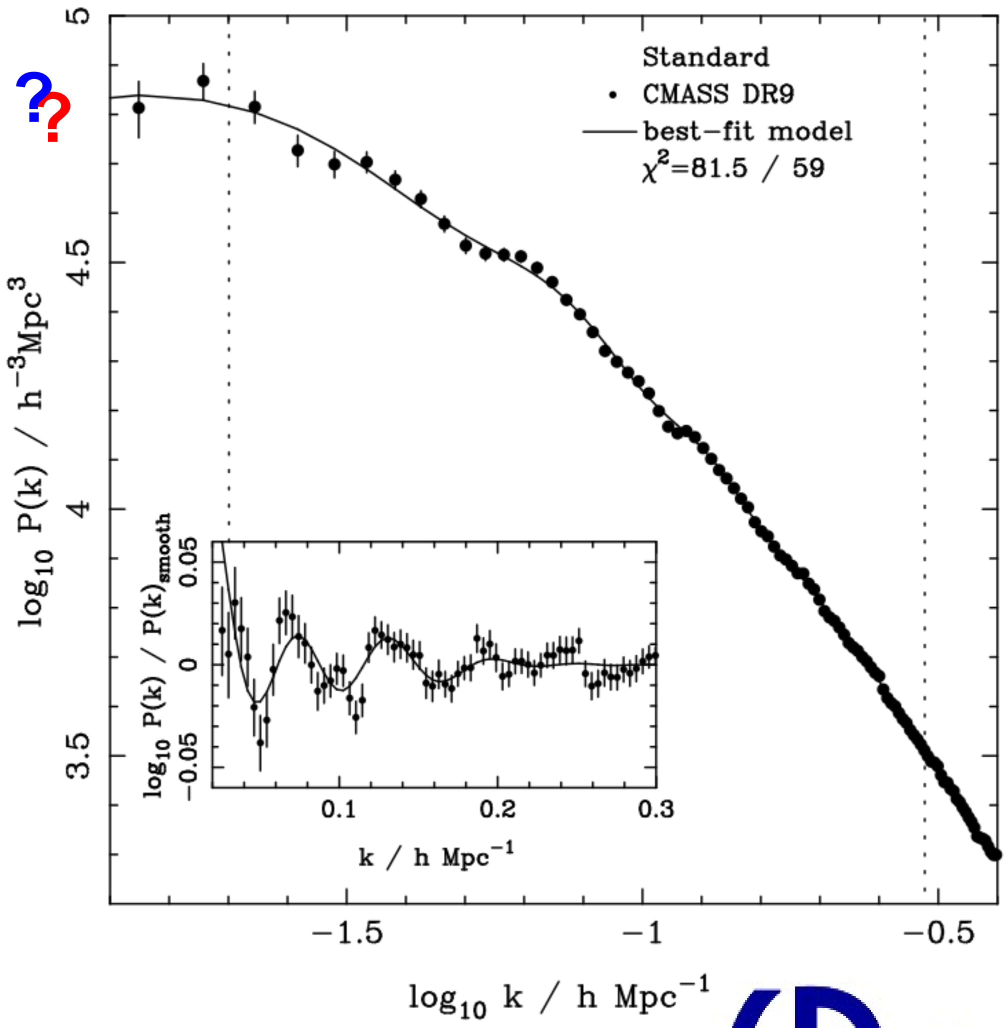
? ? ? ?
? ? ? ?

Pros:

- Linear theory is valid.
- New regime, interesting in MG

Cons:

- Large cosmic variance
- Large systematic uncertainties

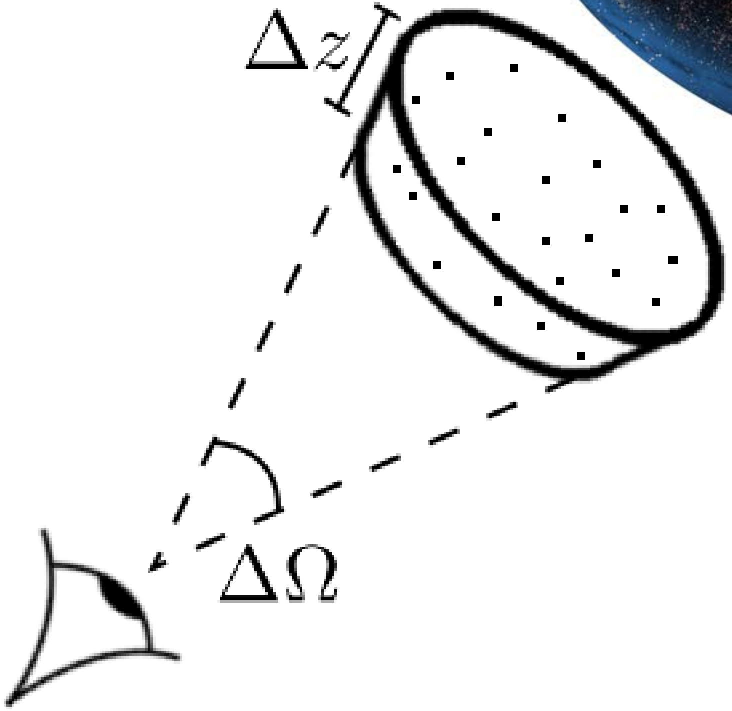


Anderson et al. arXiv:1203.6594

Relativistic effects

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

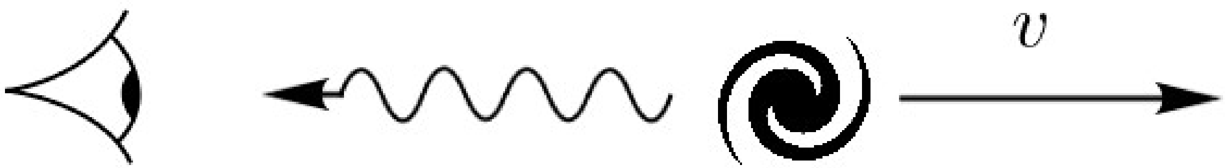
$$\theta_{\rm obs} = \theta_{\rm BG} + \delta\theta$$



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

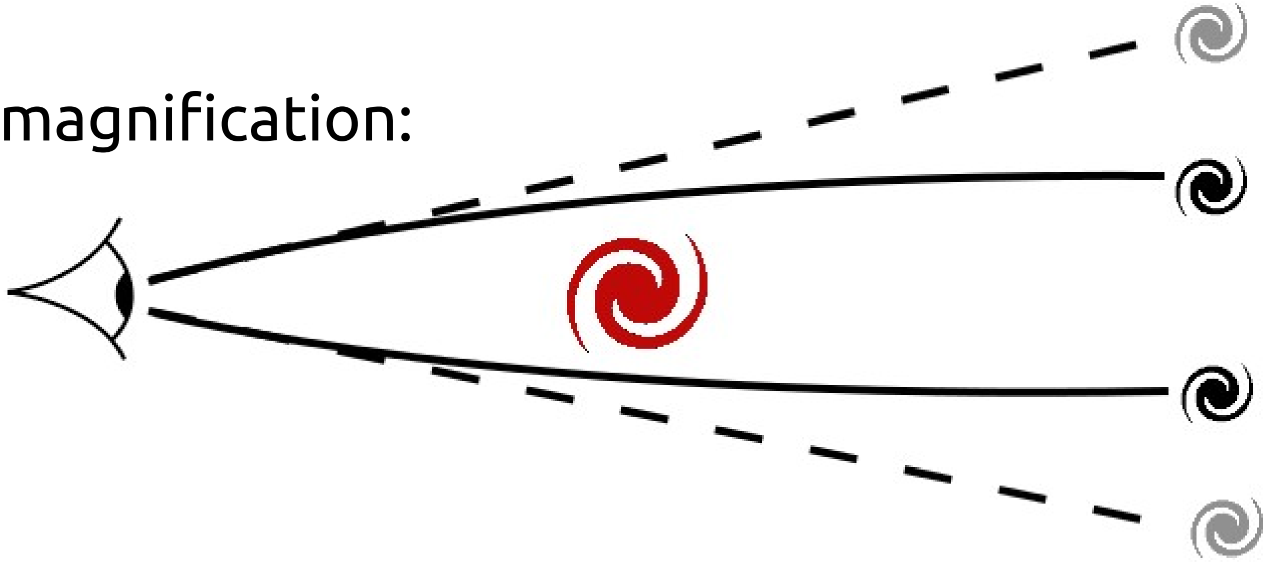
Relativistic effects

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

$$\Delta_N = \delta_N + \frac{\partial \ln \bar{N}}{\partial \eta}\delta\eta + \delta_{||} + \left[1 - \frac{\partial \ln \bar{N}}{\partial \ln L}\right] 2\delta_\perp$$

$$f_{\rm evo} \equiv \frac{\partial \ln \bar{N}}{\partial \ln a}$$

Evolution bias

$$s \equiv \frac{2}{5}\frac{\partial \ln \bar{N}}{\partial \ln L}$$

Magnification bias

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

Relativistic effects

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

🟥 **Density**

🟩 **RSDs**

🟦 **Lensing**

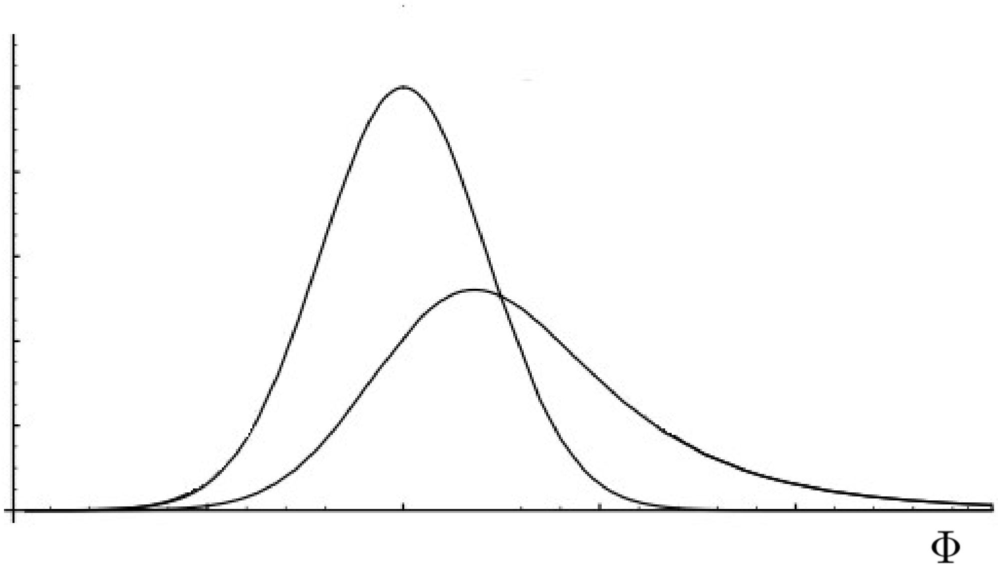
▨ **“Relativistic effects”**

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

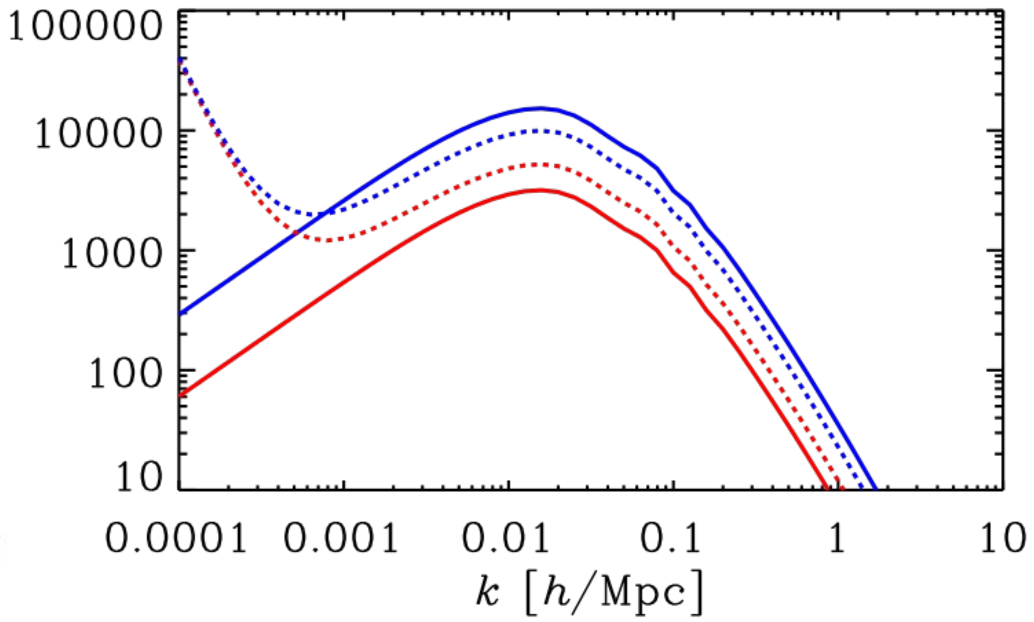
Primordial non-Gaussianity

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

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

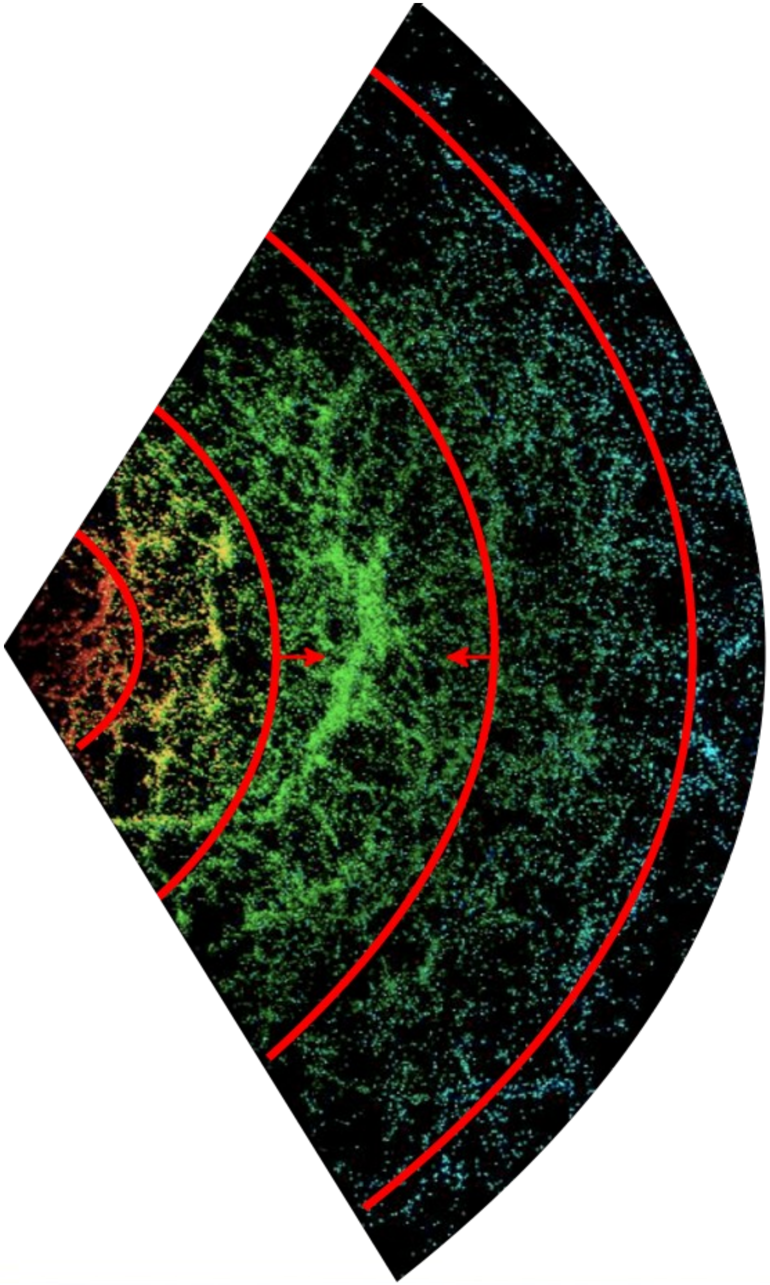


Dalal et al. arXiv:0710.4560
Matarrese and Verde arXiv:0801.4826



Camera et al. ArXiv:1305.6928

Angular power spectra



Basic observable:

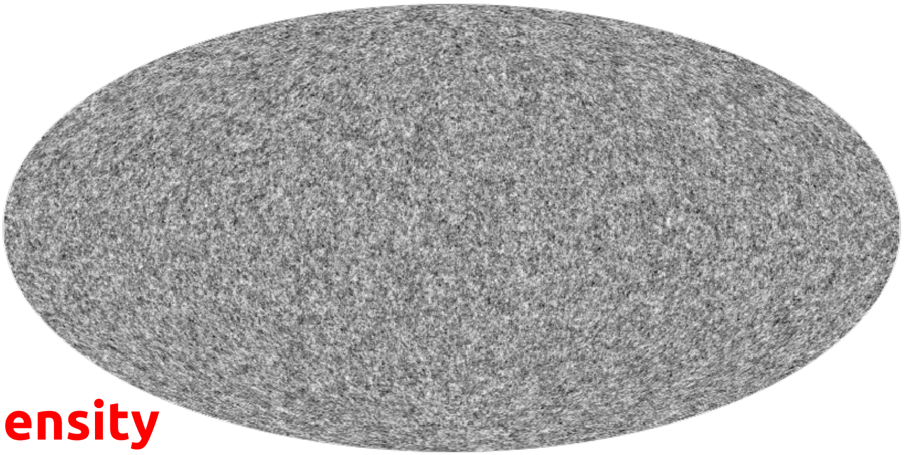
- Angular fluctuations of source counts in redshift bins
- We will use harmonic space for convenience
- Most information contained in the cross-correlation of all pairs of bins.
- Radial resolution set by experimental or theoretical limitations.

$$\Delta^i_N(\hat{\mathbf{n}}) = \int dz\, W^i(z)\Delta_N(z,\hat{\mathbf{n}})$$

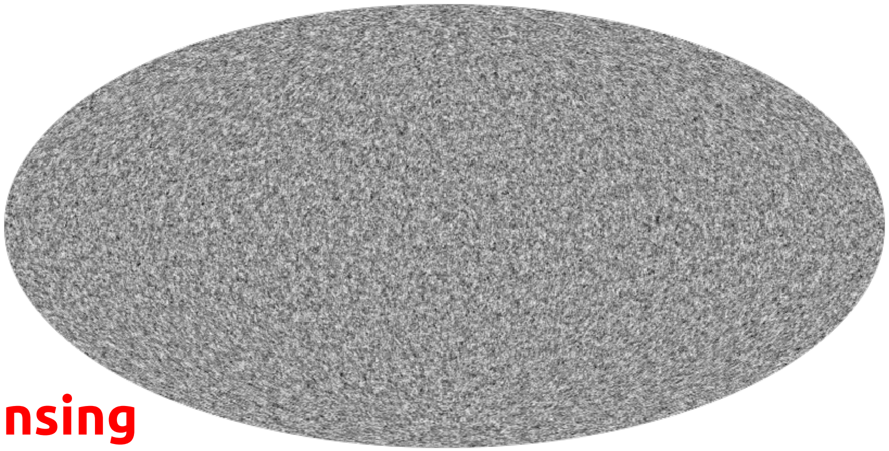
$$a^i_{\ell m} = \int d\hat{\mathbf{n}}^2 \Delta^i_N(\hat{\mathbf{n}}) Y_{\ell m}(\hat{\mathbf{n}})$$

$$C^{ij}_\ell = \left\langle a^i_{\ell m} a^{j*}_{\ell m} \right\rangle$$

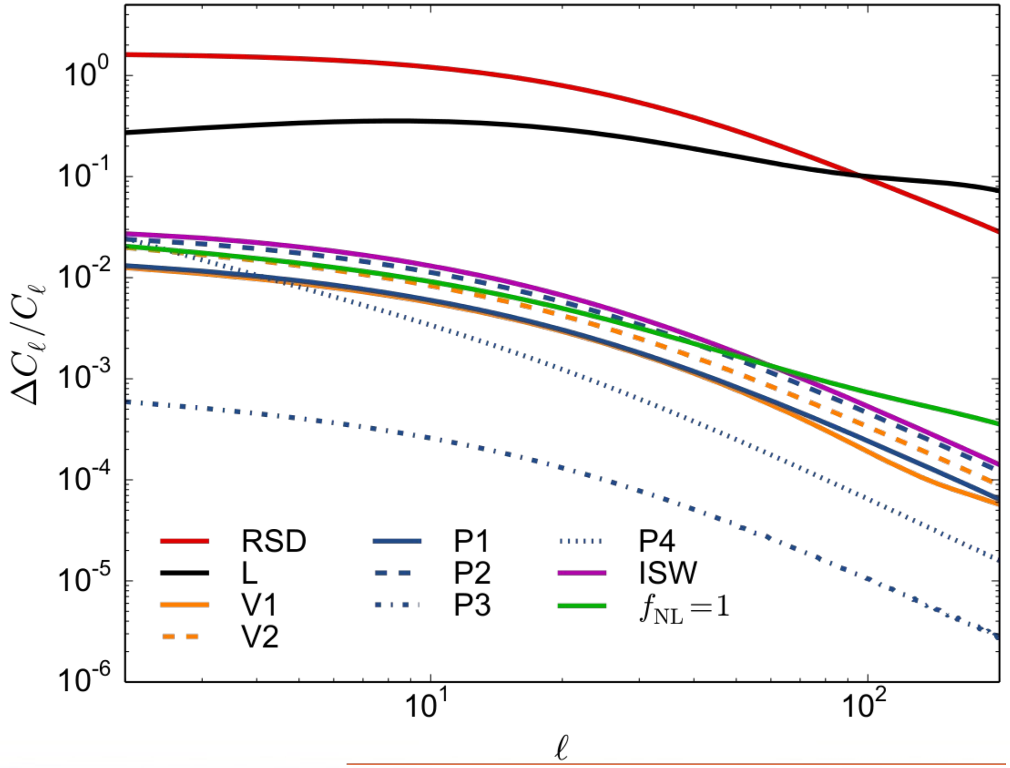
Angular power spectra

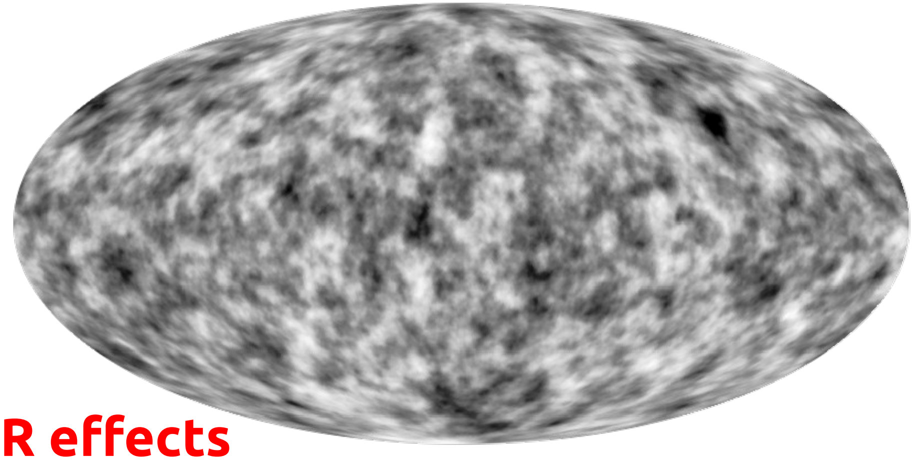


Density



Lensing





GR effects

Fisher matrix analysis

$$\Delta_\ell^i = \Delta_\ell^{\mathrm{D},i}(f_{\mathrm{NL}}) + \Delta_\ell^{\mathrm{RSD},i} + \epsilon_{\mathrm{WL}}\,\Delta_\ell^{\mathrm{L},i} + \\ \epsilon_{\mathrm{GR}}\left[\Delta_\ell^{\mathrm{V1},i} + \Delta_\ell^{\mathrm{V2},i} + \Delta_\ell^{\mathrm{P1},i} + \Delta_\ell^{\mathrm{P2},i} + \Delta_\ell^{\mathrm{P3},i} + \Delta_\ell^{\mathrm{P4},i} + \Delta_\ell^{\mathrm{ISW},i}\right]$$

Fisher matrix: most optimistic errors for a given survey.

$$F_{\mu\nu} = \frac{f_{\mathrm{sky}}}{2}\sum_\ell (2\ell+1)\partial_\mu \hat{C}_\ell\,\hat{C}_\ell^{-1}\partial_\nu \hat{C}_\ell\,\hat{C}_\ell^{-1}$$

Main parameters:

$$f_{\mathrm{NL}},\ \epsilon_{\mathrm{GR}}$$

Marginalized over:

$$\Omega_M,\ f_b,\ A_s,\ w,\ n_s$$

Nuisance parameters:

$$b(z),\ s(z),\ f_{\mathrm{evo}}(z)$$

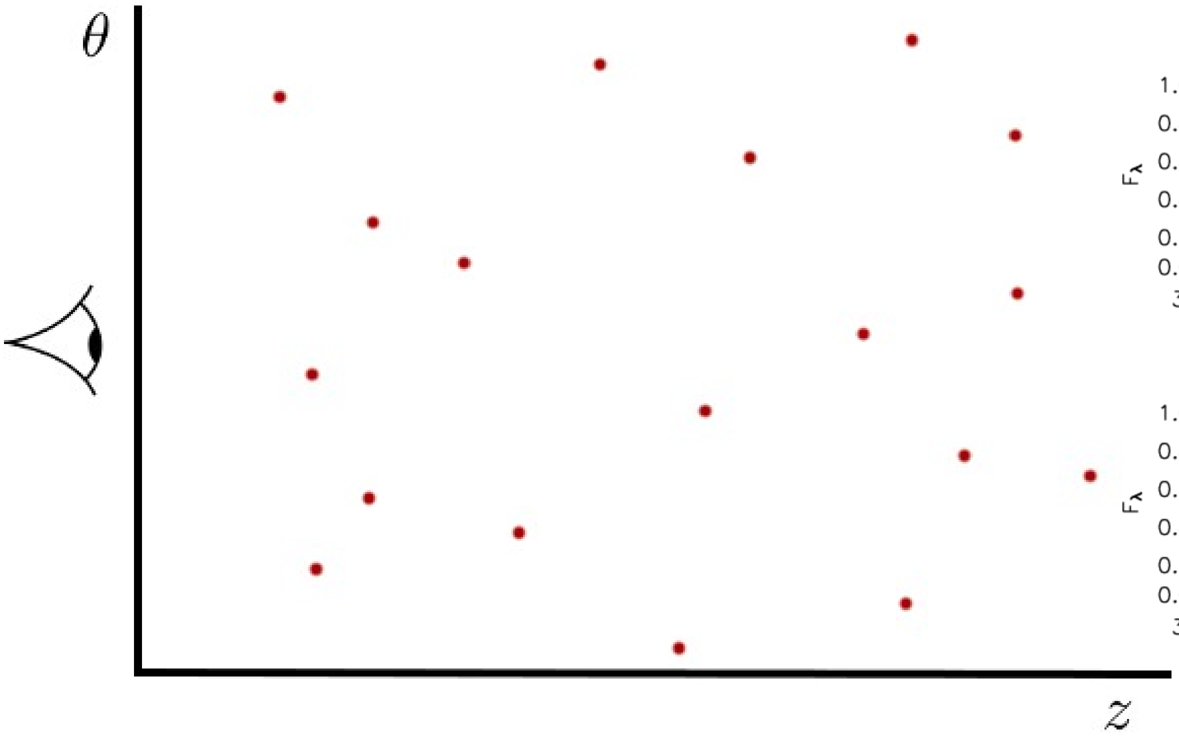
- Originally implemented in CLASS (Di Dio and Montanari, arXiv:1307.1459).
- Modified to include:
  - Primordial non-Gaussianity
  - x4 speed-up for integrated terms
  - MPI parallelization
  - Multiple number count and lensing tracers

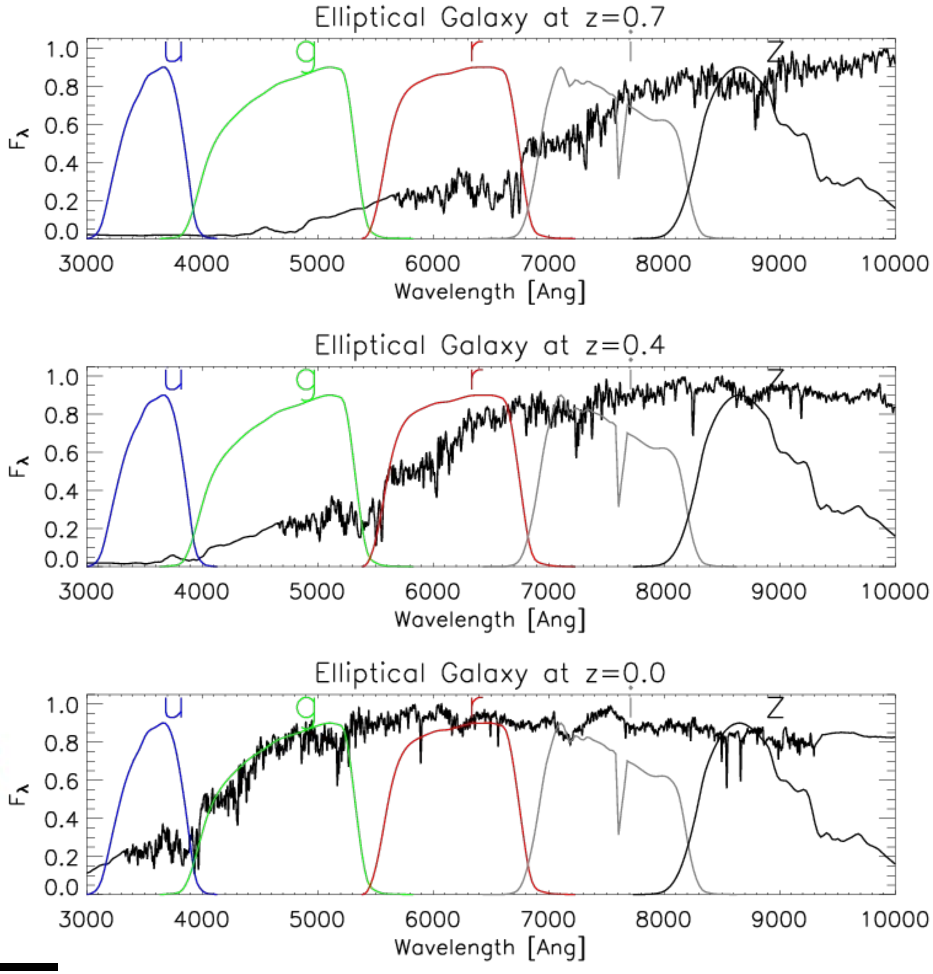
DA et al. arXiv:1505.07596, 1507.03550

LSS probes

Spectroscopic surveys

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

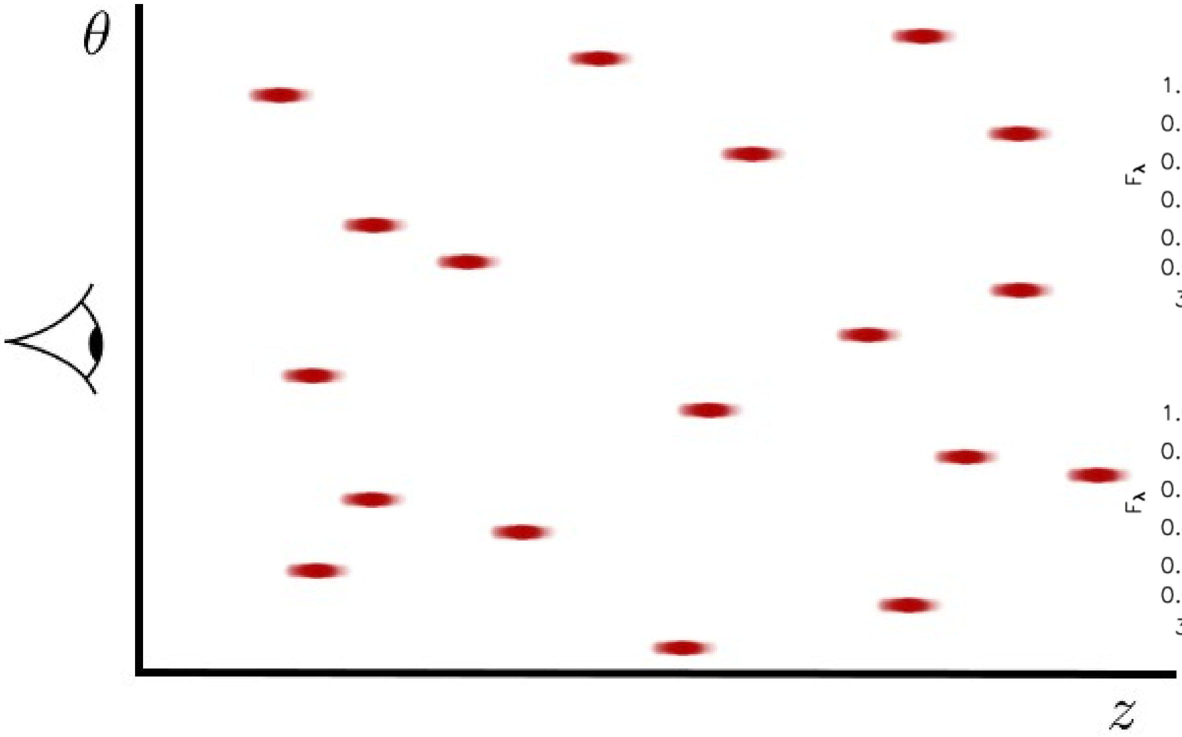


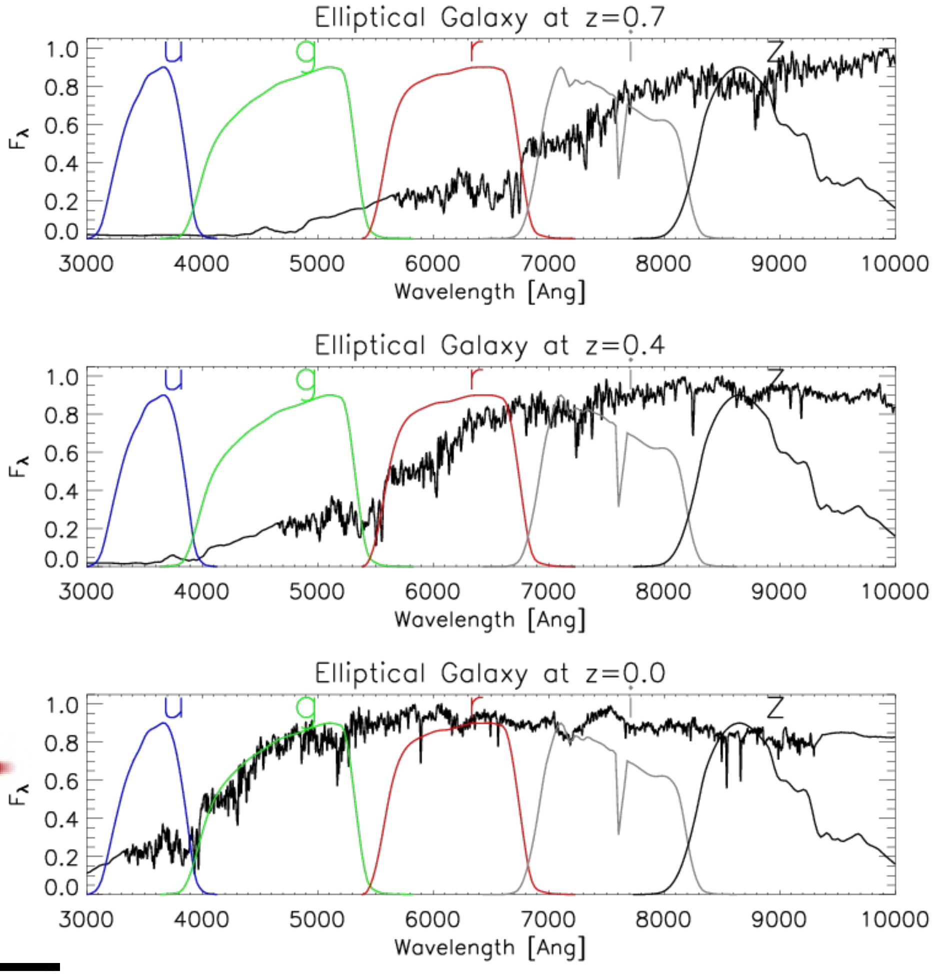


LSS probes

Photometric surveys

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

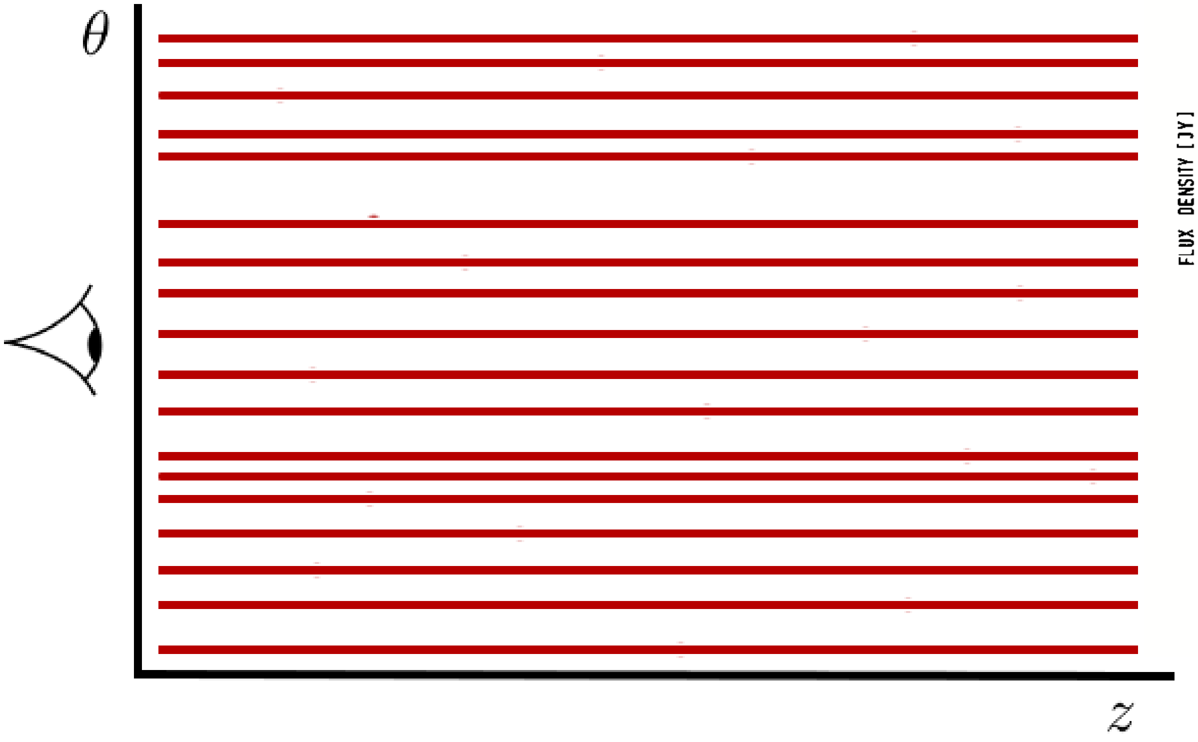


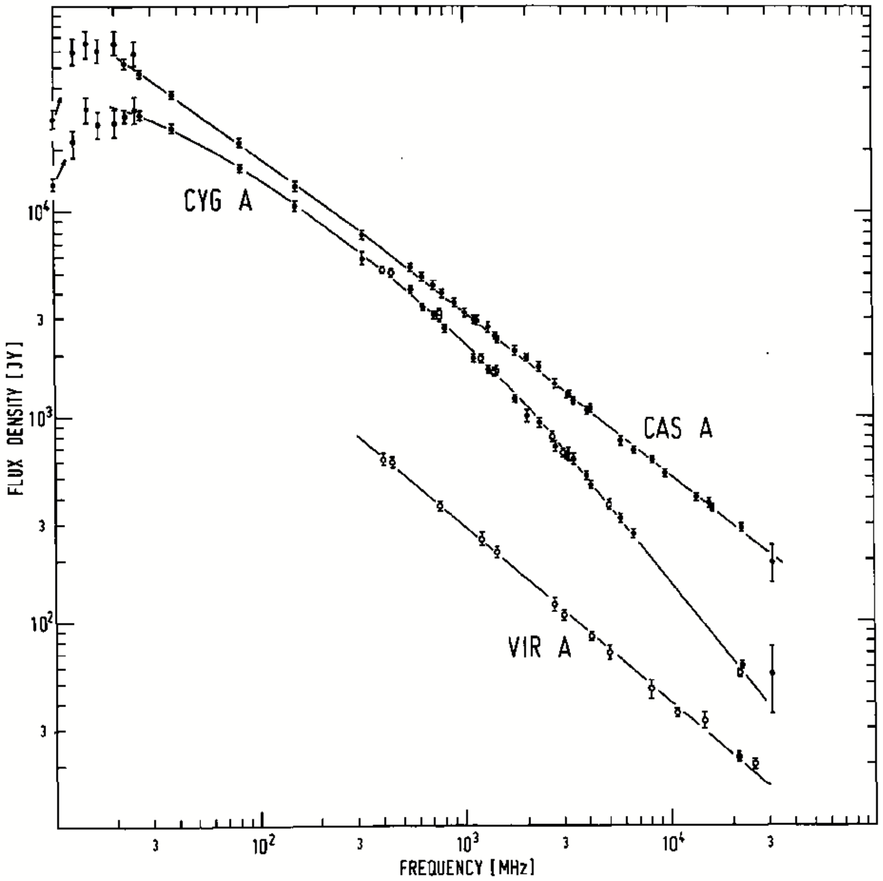


LSS probes

Radio continuum survey

- Good angular resolution
- High number densities and very high redshifts
- NO radial information



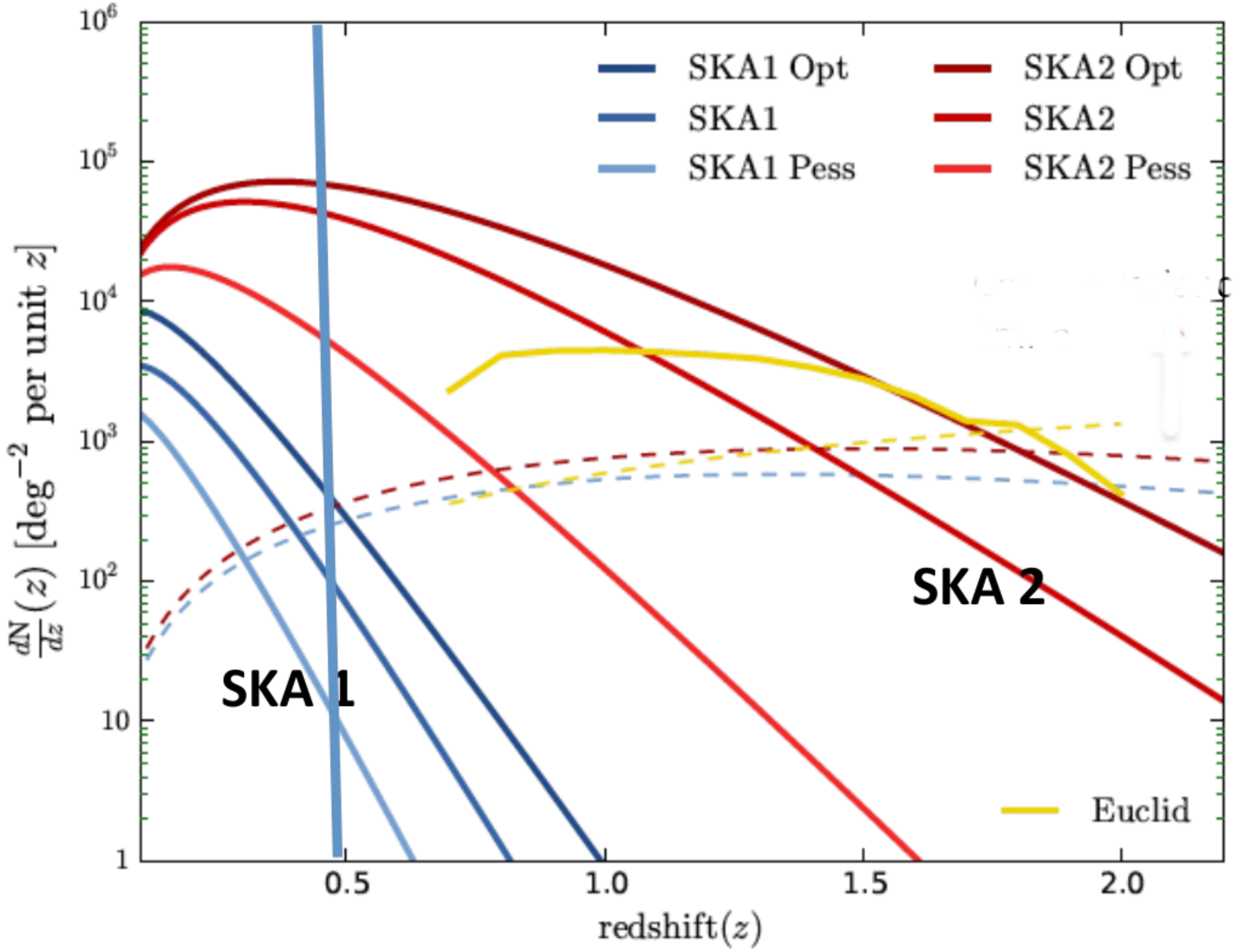


Jarvis et al. arXiv:1501.03825

LSS probes

HI survey:

- 21 cm: (almost) only radio feature.
- Very faint →
- Long integration times →
- Low number densities →
- Low redshifts

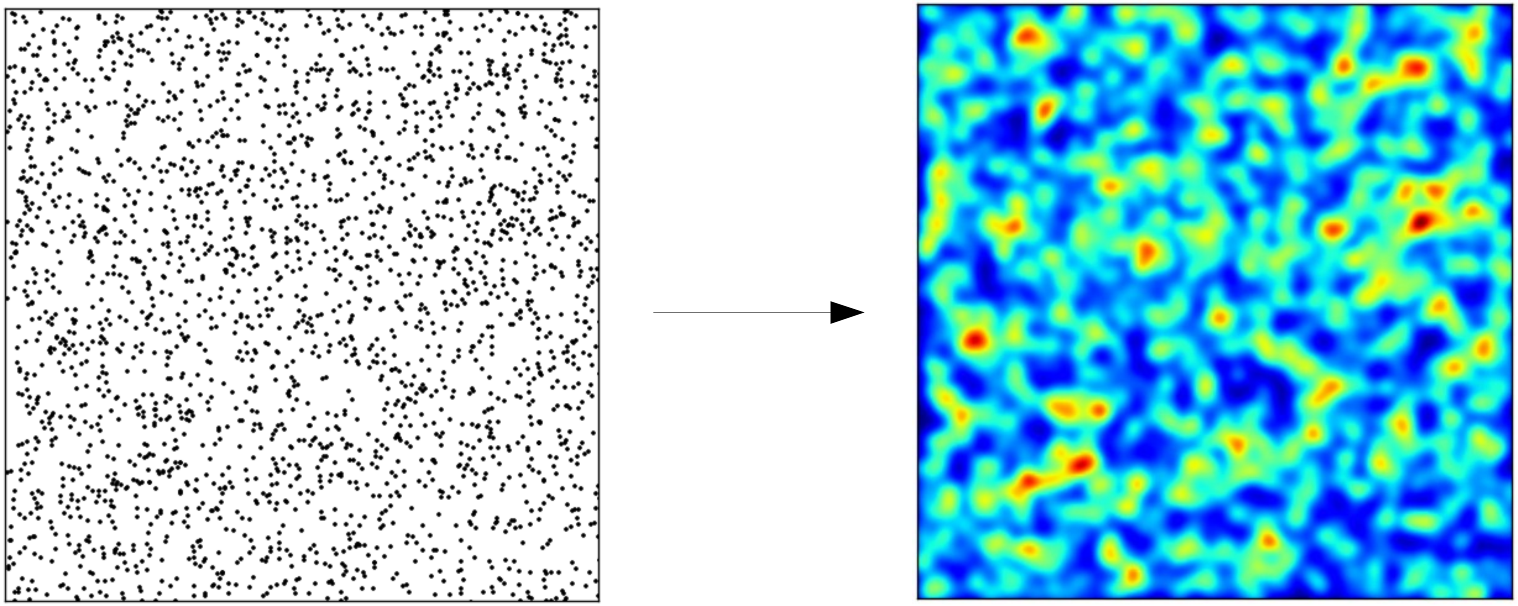


Abdalla et al. arXiv:1501.04035

LSS probes

Intensity mapping

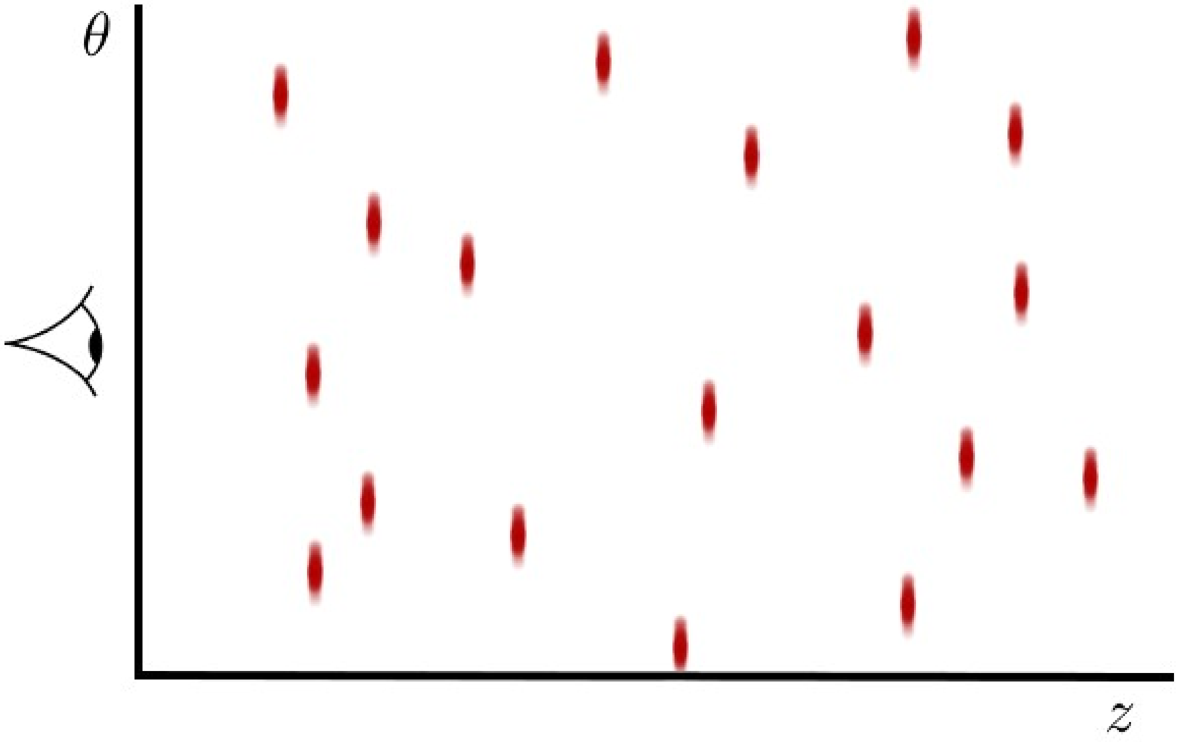
- Large pixels: joint emission from multiple galaxies instead of resolving them.
- We only care about large scales
- “Cheap” way to observe large volumes
- No perturbations on transverse scales

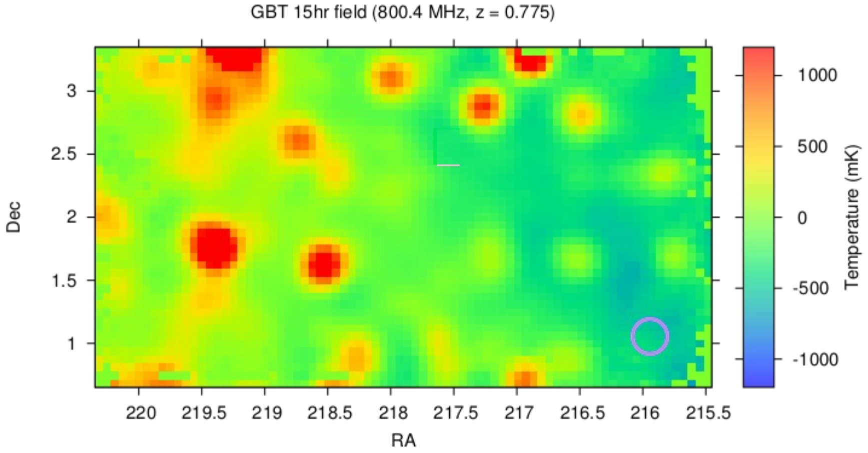


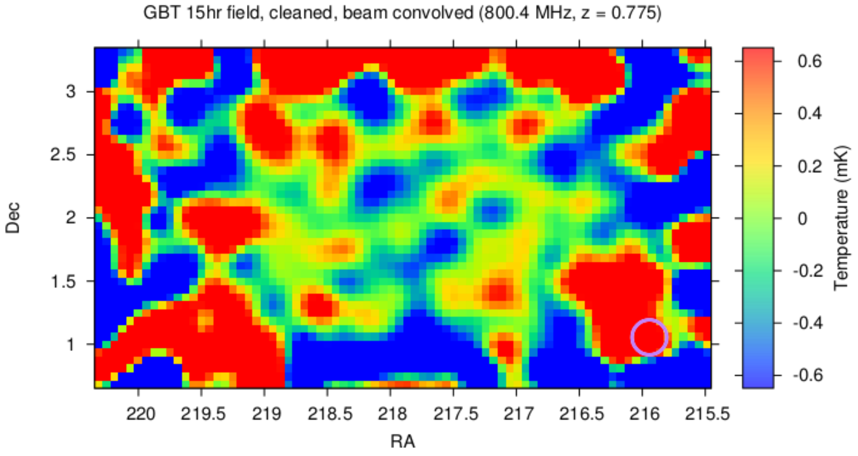
LSS probes

Intensity mapping

- Bad angular resolution, good radial
- High redshifts
- Potentially high noise
- Tremendous foregrounds




GBT 15hr field (800.4 MHz, z = 0.775)


GBT 15hr field, cleaned, beam convolved (800.4 MHz, z = 0.775)

Bull et al. arXiv:1405.1452

LSS probes

Summary

Experiment	$z-$range	$N_{\rm bins}$	$f_{\rm sky}$	$\langle S/N\rangle$	Δz	$\Delta\theta$
Intensity mapping (SKA1-MID)	$[0.1, 3.5]$	100	0.75	6.7	~ 0	1°
Continuum survey ($S_{\rm cut} = 1\mu Jy$)	$[0, 5]$	1	0.75	32	∞	~ 0
Spectroscopic survey (Euclid)	$[0.5, 2]$	100	0.35	6	~ 0	~ 0
Photometric survey (LSST)	$[0, 2.5]$	9	0.5	210	$\sim 0.05(1+z)$	~ 0

LSS probes

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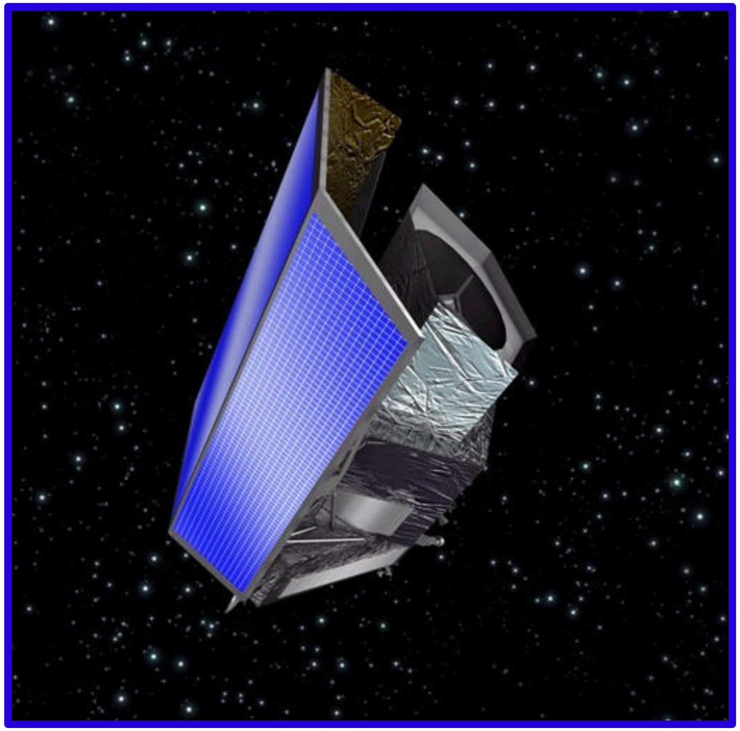

LSS probes

Summary

DA et al. arXiv:1505.07596, 1507.03550

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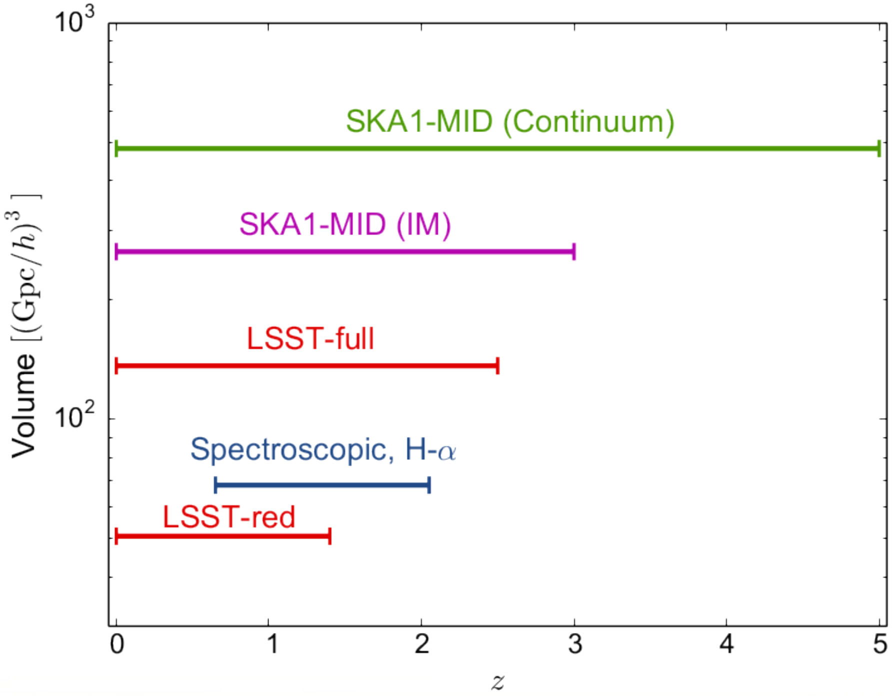
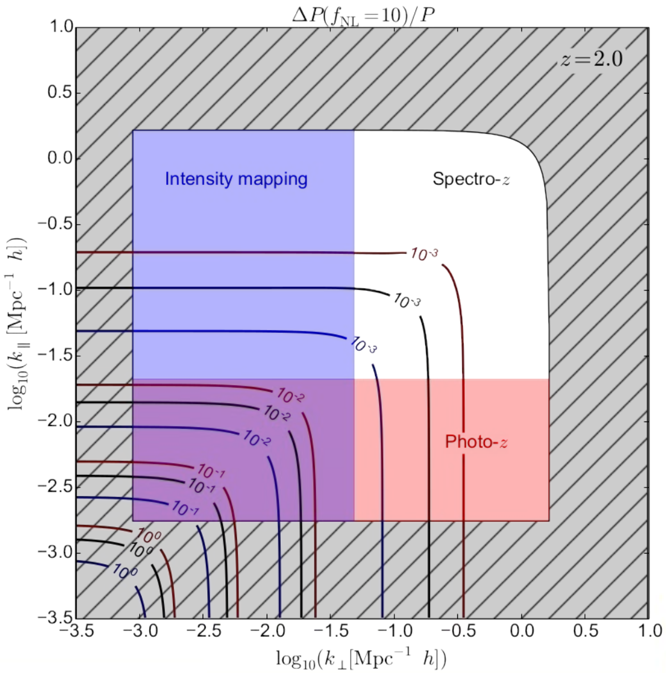
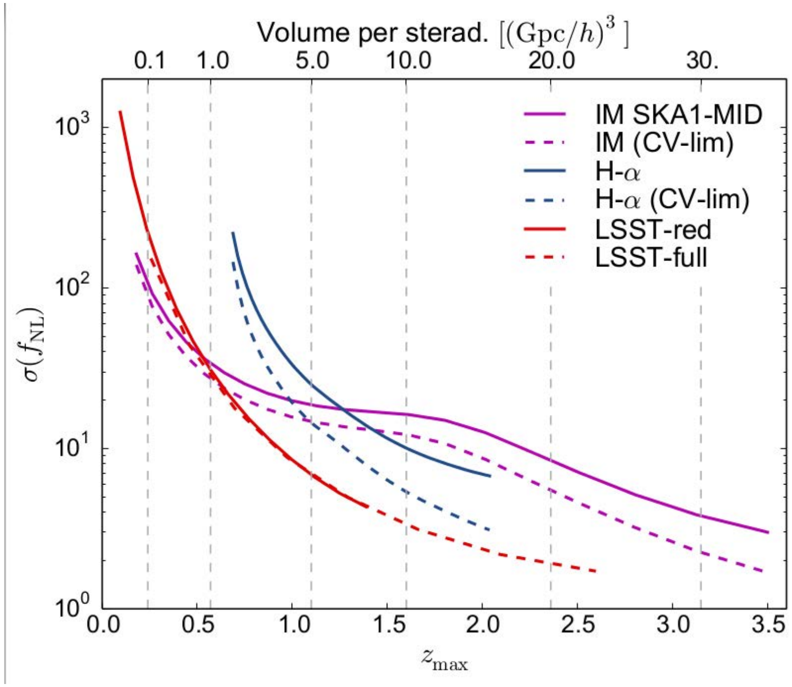
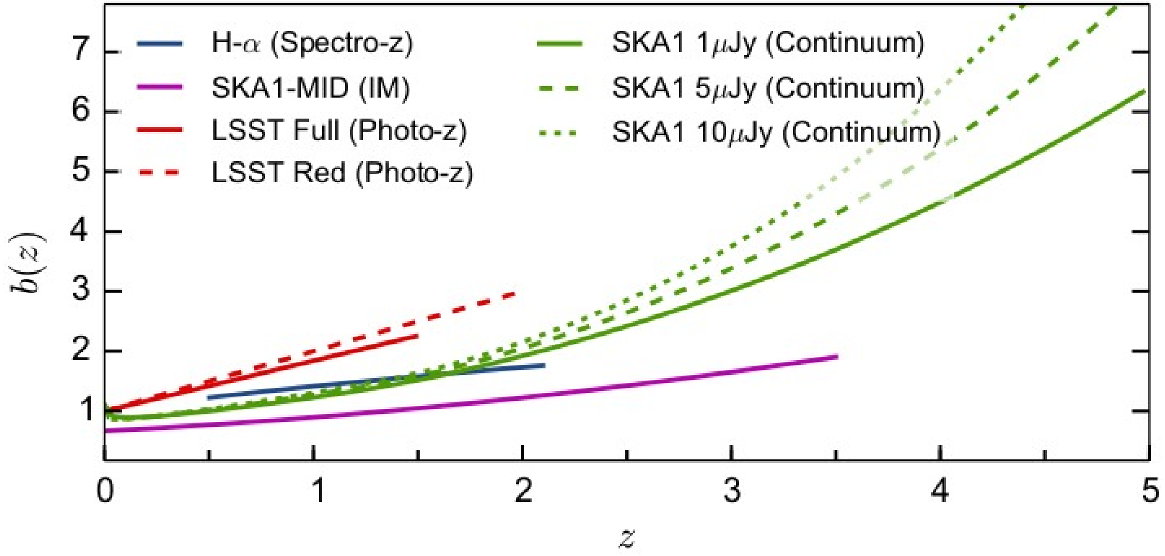




Fisher matrix analysis

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



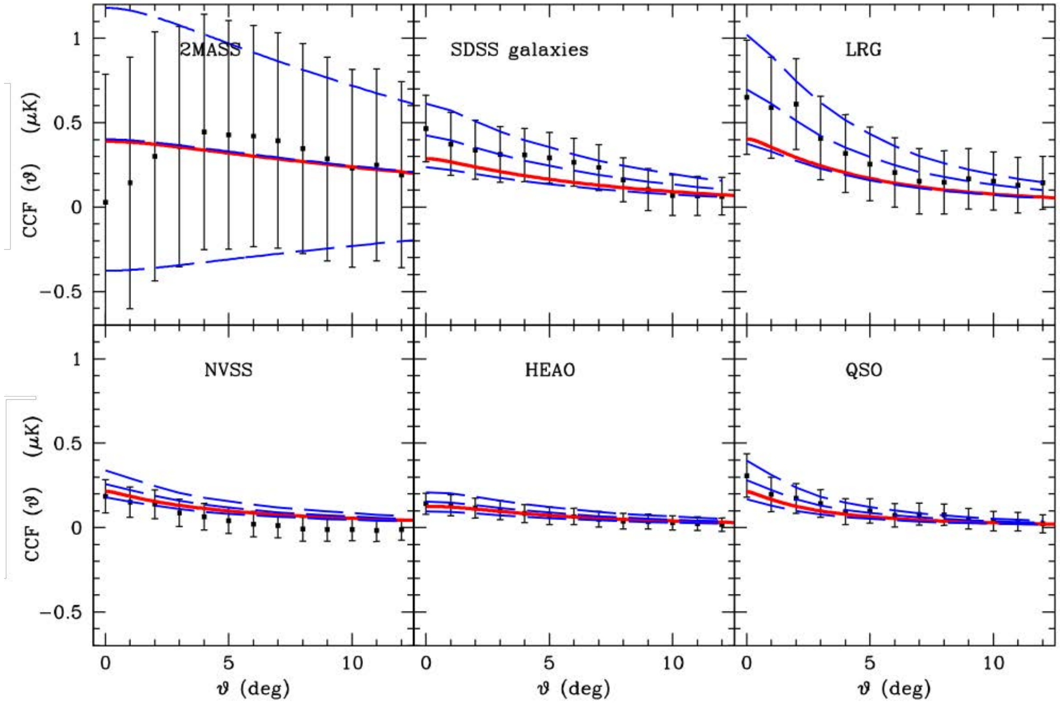


DA et al. arXiv:1505.07596, 1507.03550

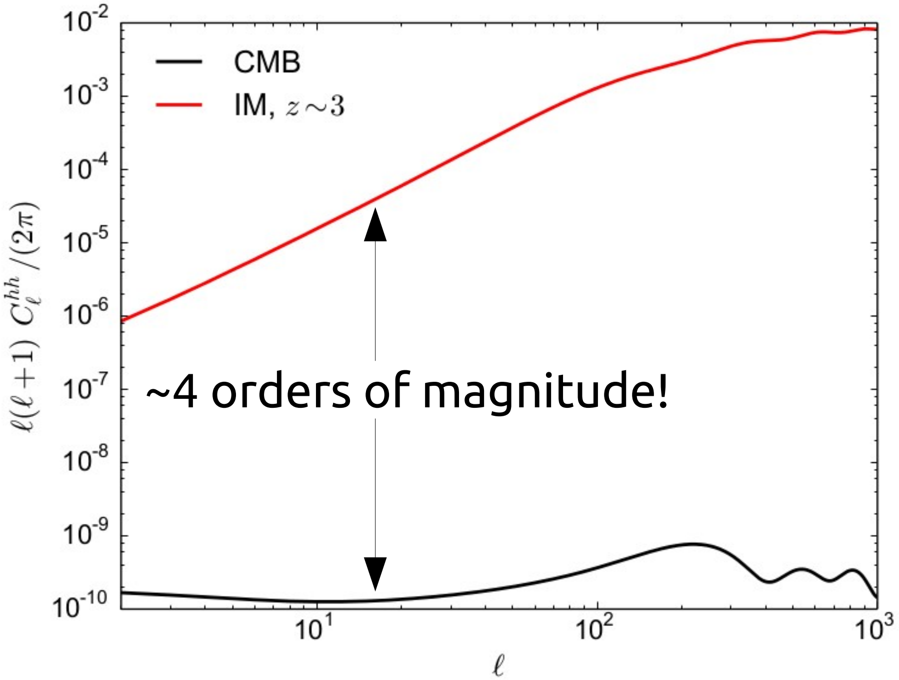
Fisher matrix analysis

Why no detection?

- CMB ISW has been detected (4.5 s) by cross-correlating with low-z tracers.
- E.g. IM is like a large set of CMB maps → why can't we detect the ISW?
- The problem is clustering variance!



Giannantonio et al. arXiv:0801.4380



~4 orders of magnitude!

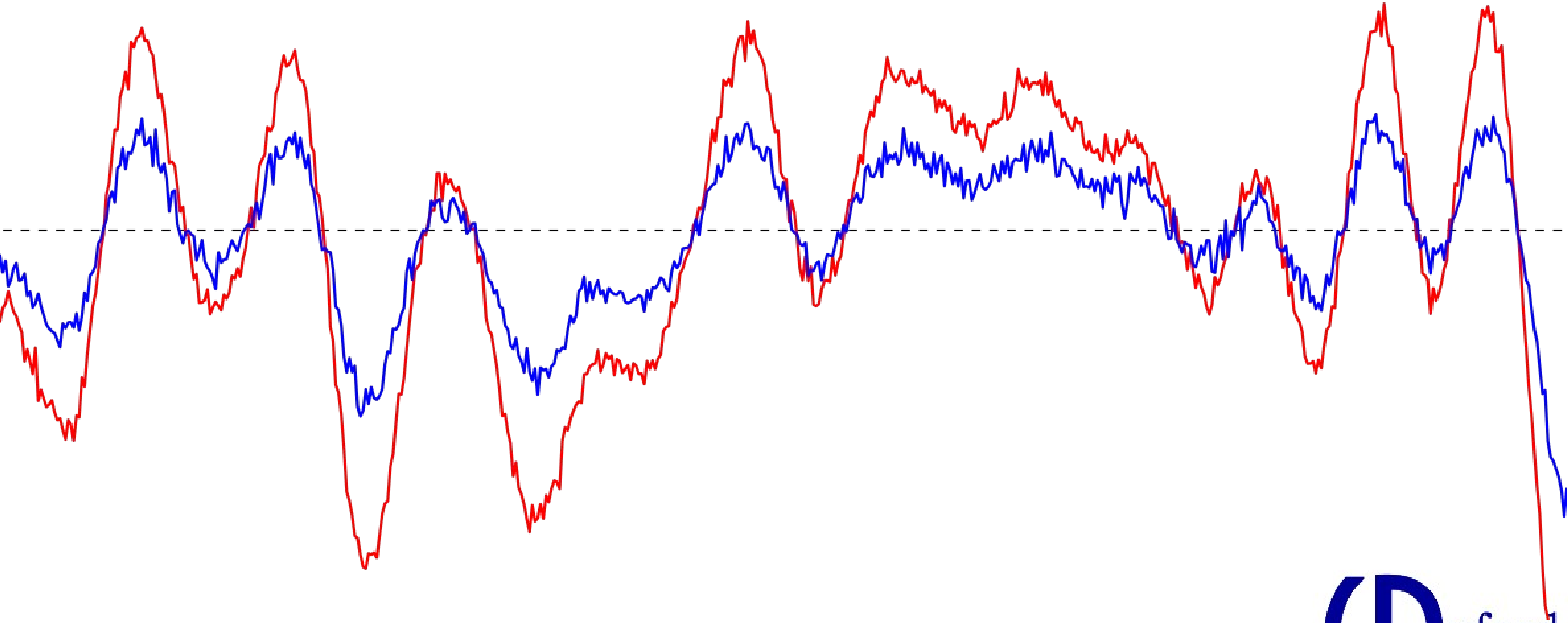
$$\Delta C_\ell^{hg} = \sqrt{\frac{2}{(2\ell+1)f_{\rm sky}}\left[(C_\ell^{hg})^2 + C_\ell^{gg}C_\ell^{hh}\right]}$$

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

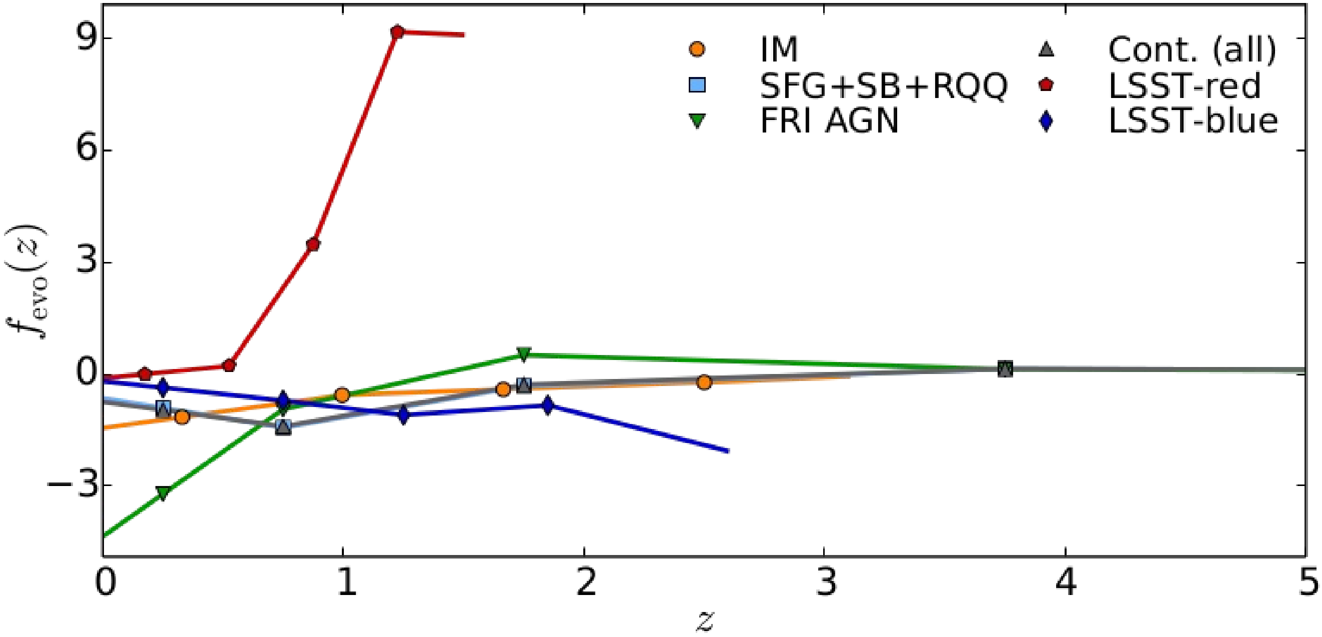
$$\delta^a_{\mathbf{k}} = b^a\,\delta_{\mathbf{k}} + n^a \longrightarrow \sigma\left(\frac{b^1}{b^2}\right) = \mathcal{O}(n^1, n^2)$$



Multi-tracer analyses

The multi-tracer technique works similarly for relativistic effects due to the magnification and evolution biases.

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

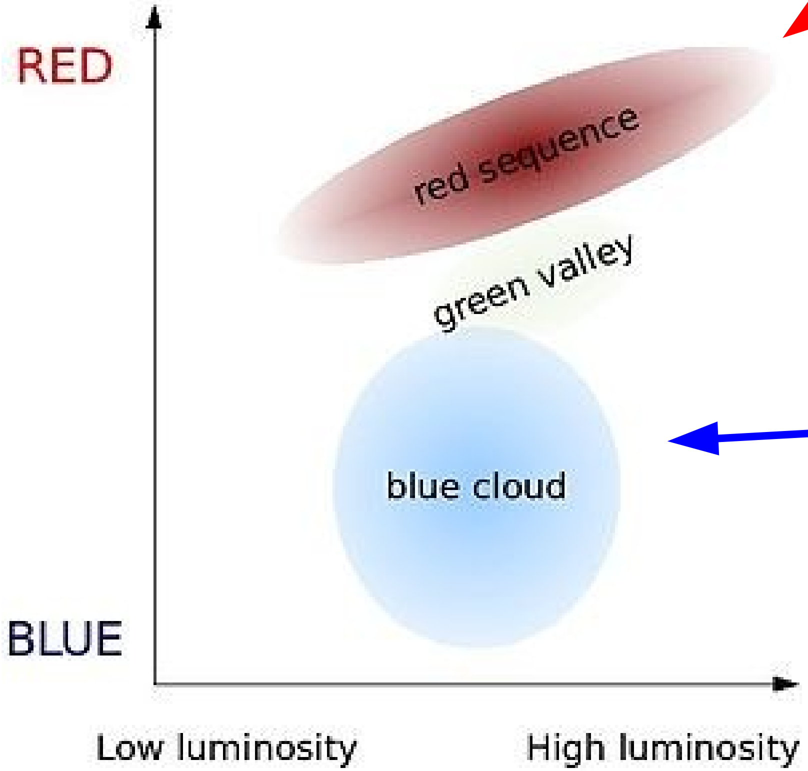


Optimal combination:

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

Yoo et al. arXiv:1109.0998. DA et al. arXiv:1505.07596, 1507.03550

Multi-tracer analyses



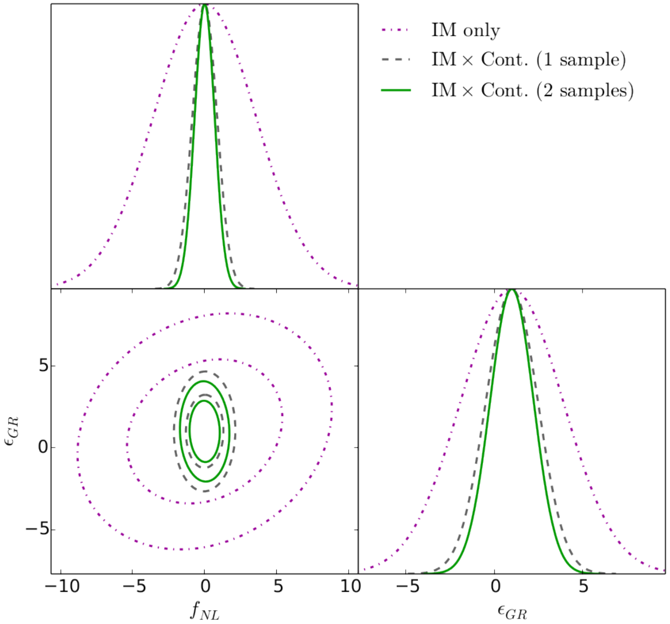
Early-type galaxies:

- First galaxies to be formed
- Highly biased tracers
- Star formation ended
- Red colors → more precise photo-z
- Start appearing at z~1 → high f_{evo}

Late-type galaxies:

- Lower bias
- High star-formation
- Blue colors → worse photo-z
- Can be found at higher redshifts

Multi-tracer analyses

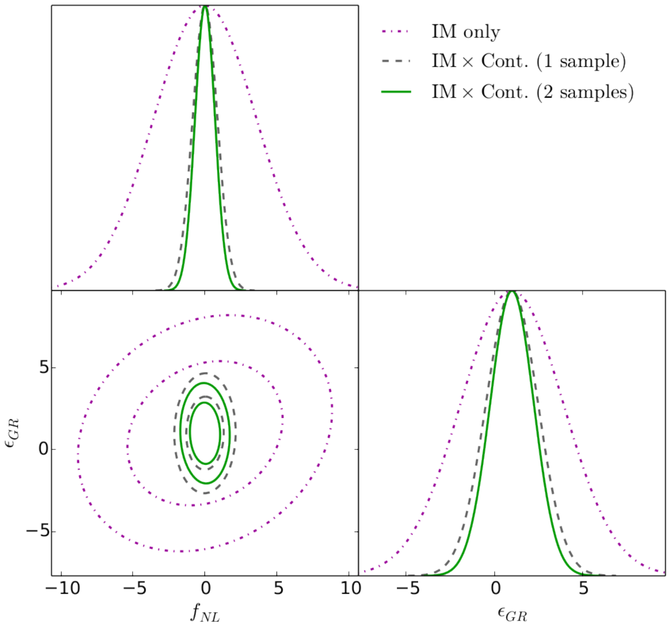


SKA-only

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

DA et al. arXiv:1507.03550

Multi-tracer analyses

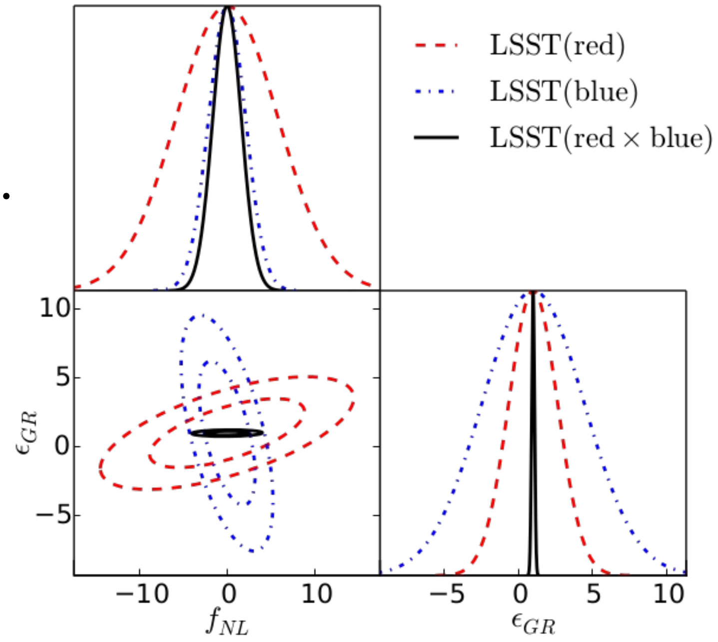


SKA-only

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

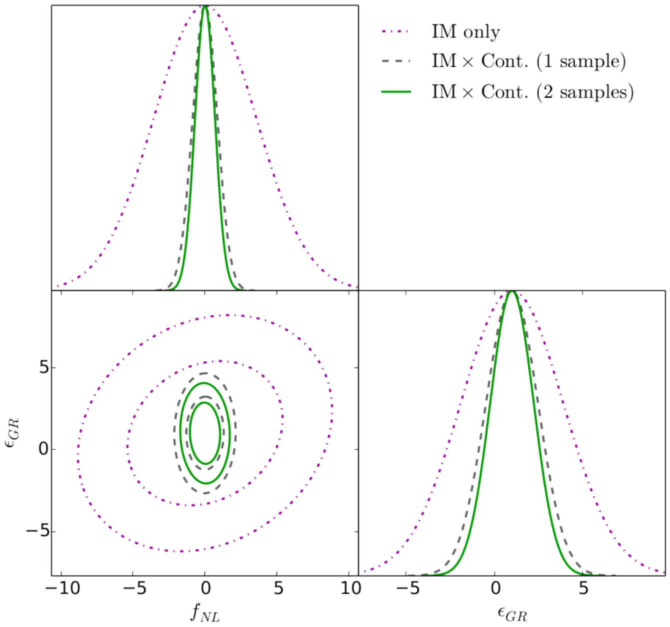
LSST-only

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



DA et al. arXiv:1507.03550

Multi-tracer analyses



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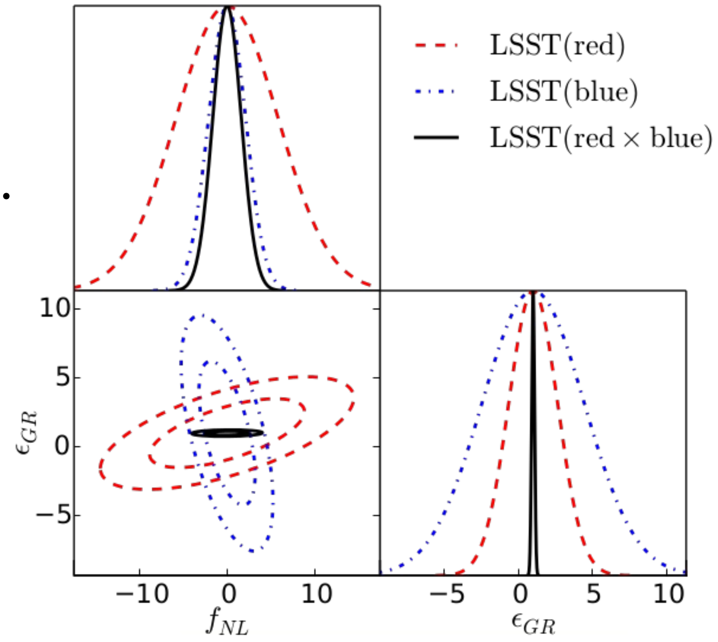
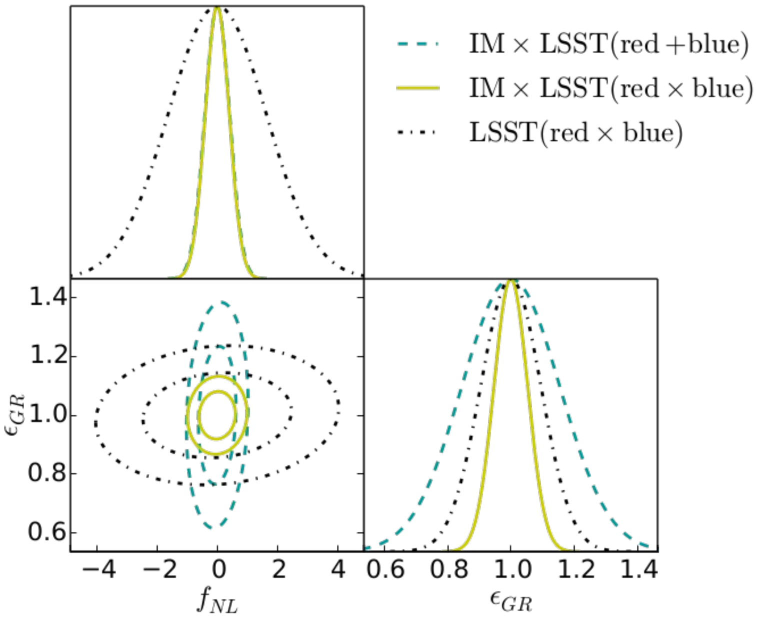




LSST x SKA

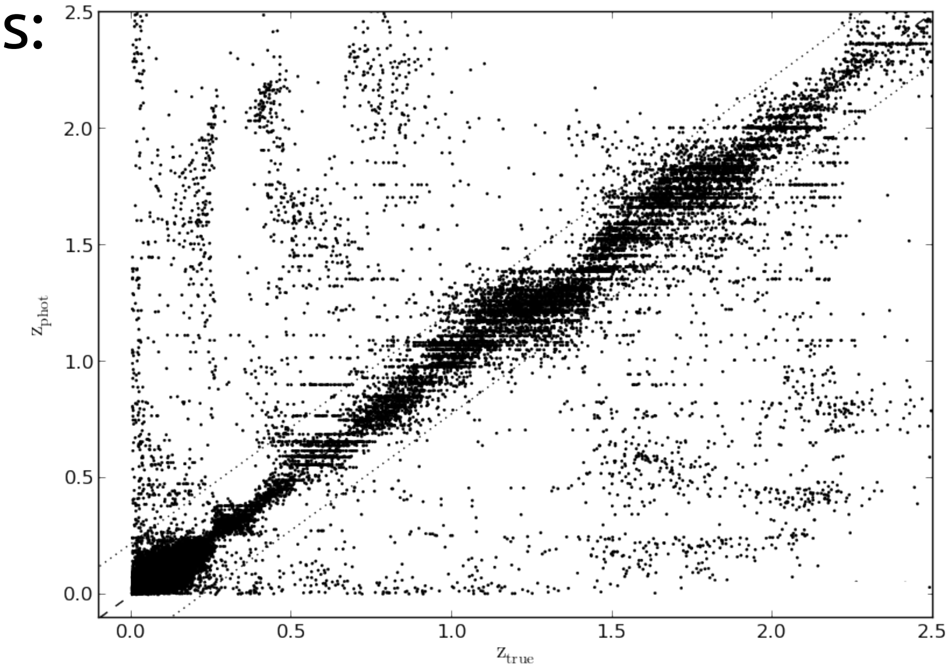
- IM and photo-z are complementary.
- Major improvement in both cases.
- 10-20 σ detection of GR effects.

DA et al. arXiv:1507.03550

Systematics: photometric surveys

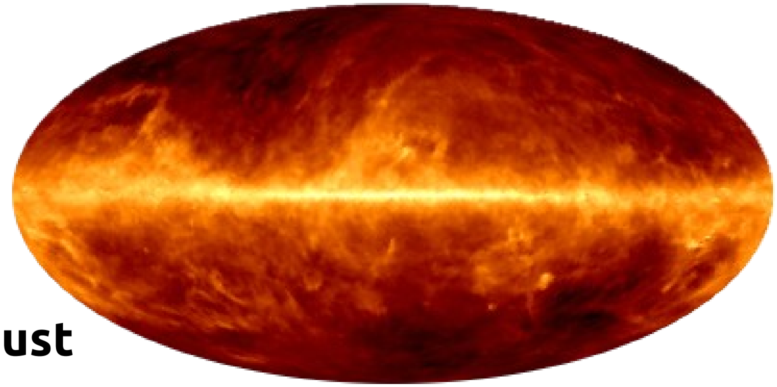
Sources of systematics on large scales:

- Dust extinction
- Star confusion and obscuration
- Airmass, sky brightness, seeing



Specific for photo-z:

- Uncertainties on the true redshift distribution
- Catastrophic redshift outliers



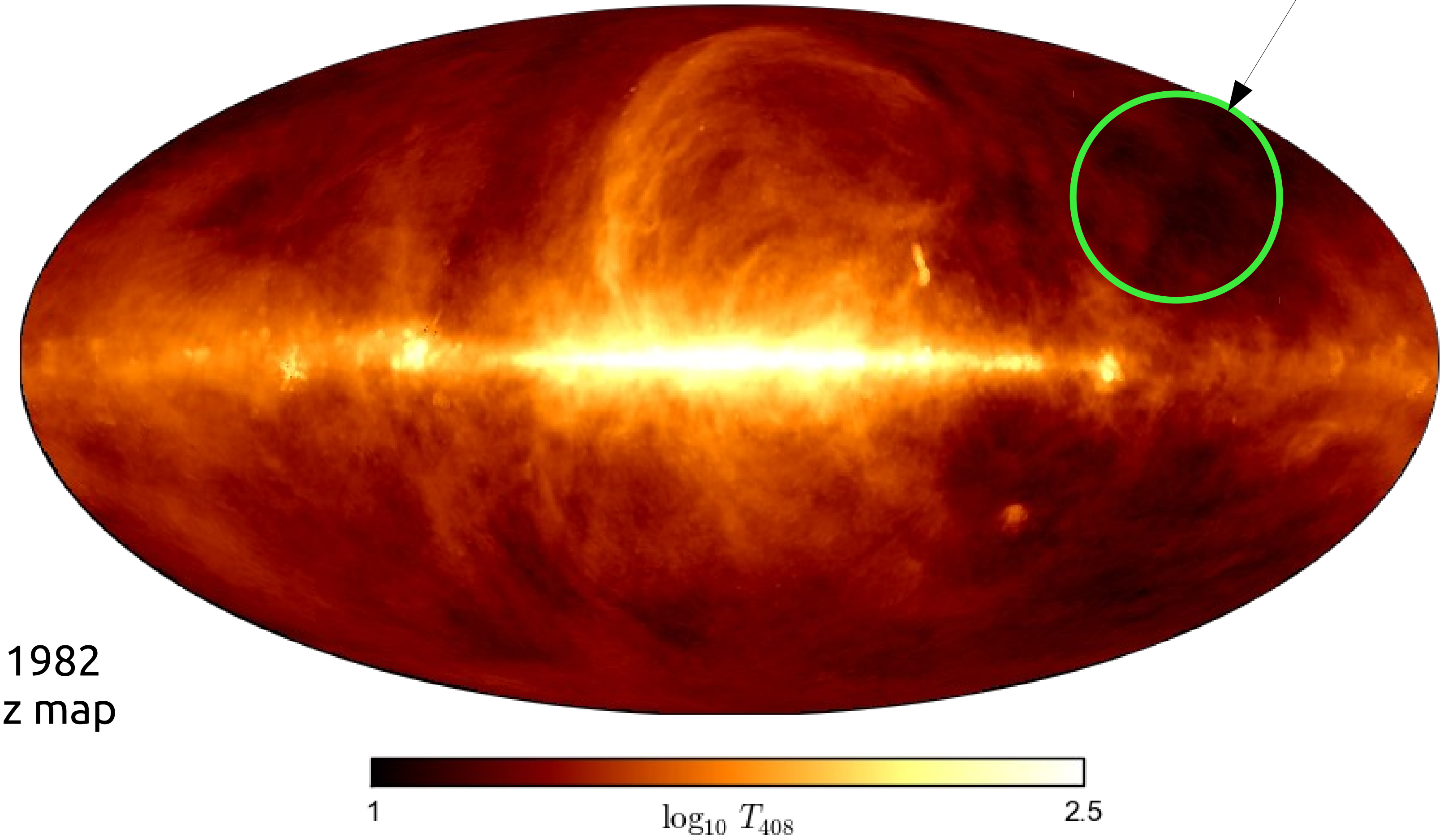
Dust

Stars

Radio foregrounds

Galactic synchrotron

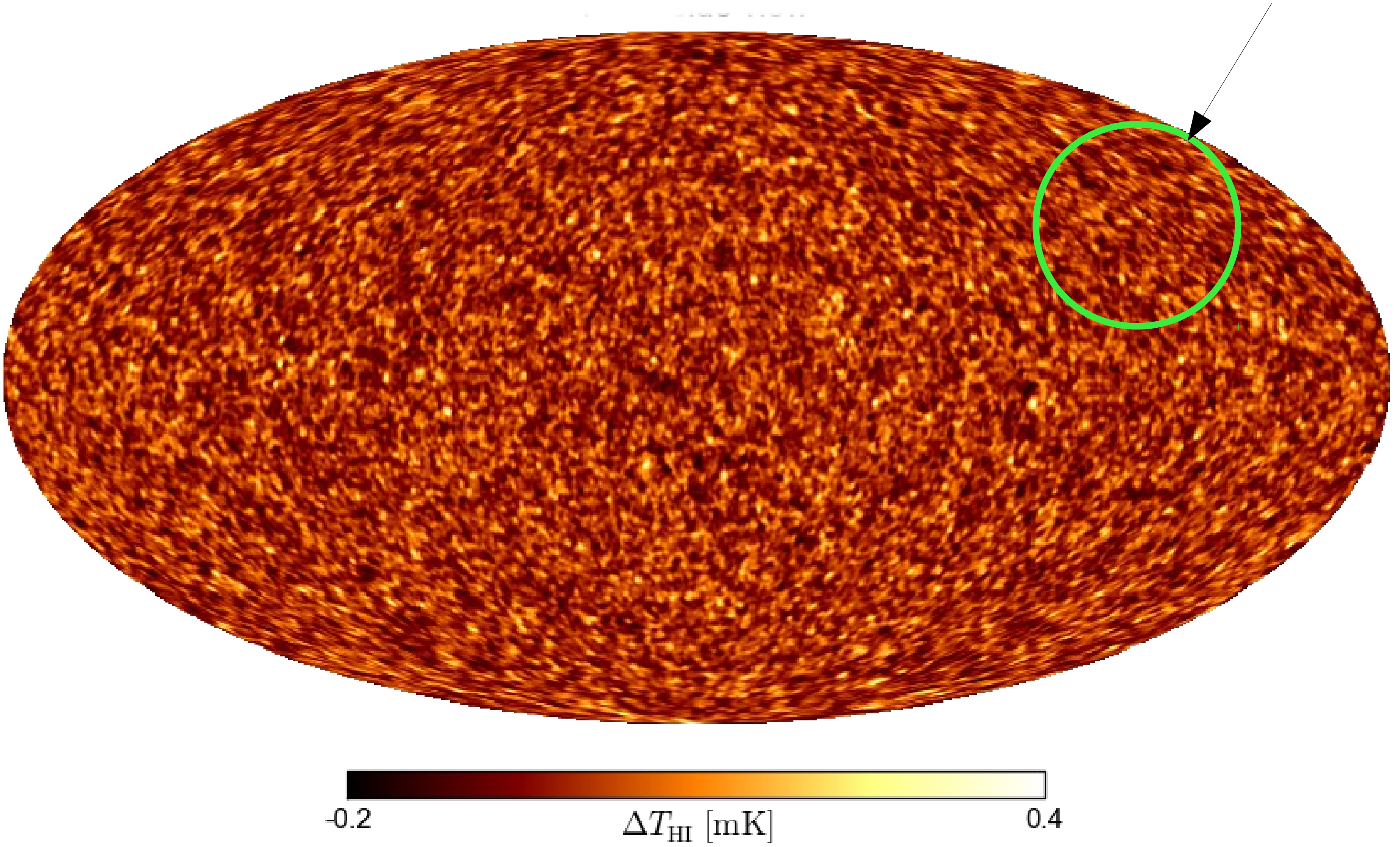
ΔT ~ O(10) K



Haslam 1982
408 MHz map

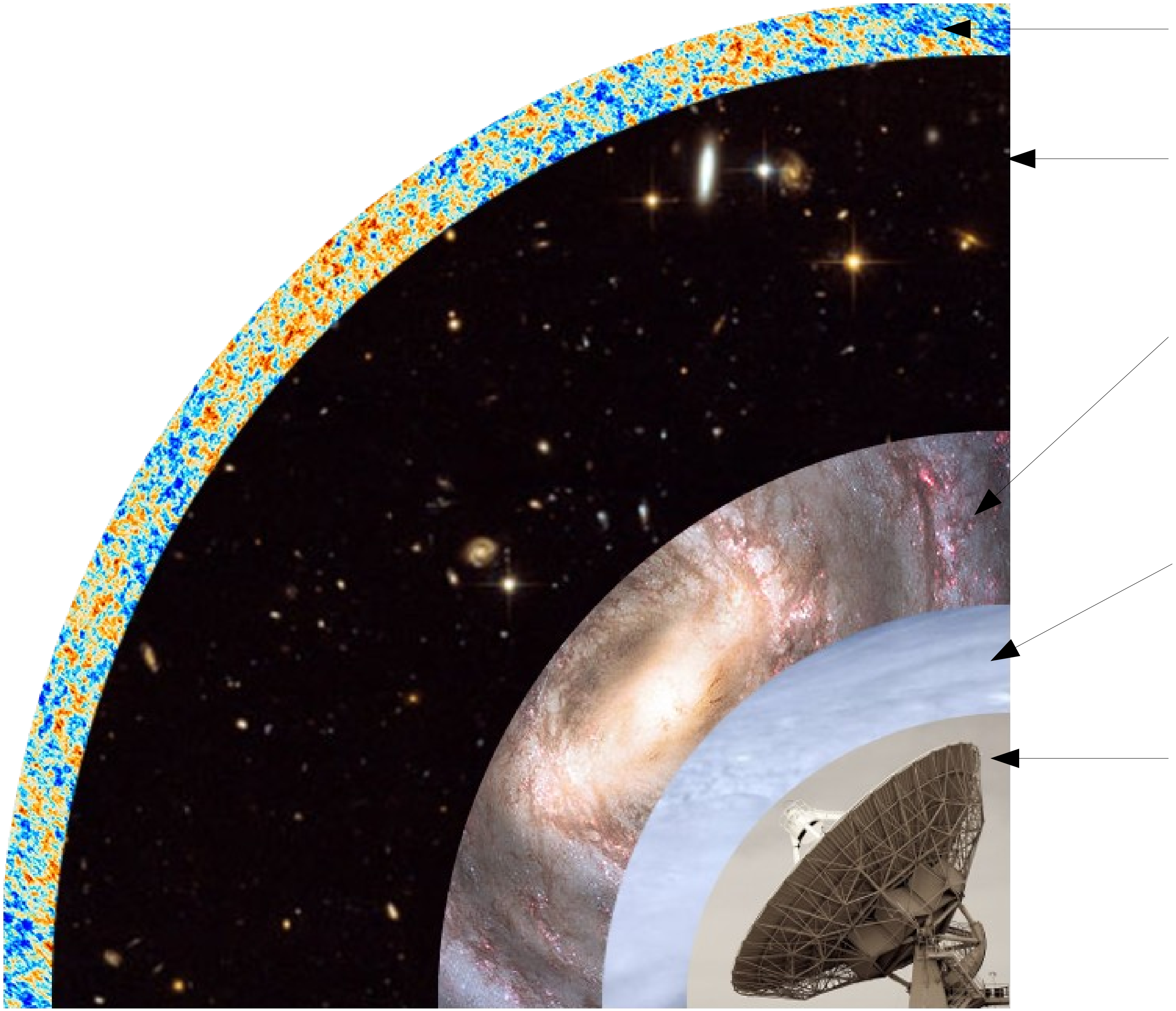
Radio foregrounds

HI signal (z ~ 1)



ΔT ~ O(0.5) mK!

Systematics: radio foregrounds



IM signal

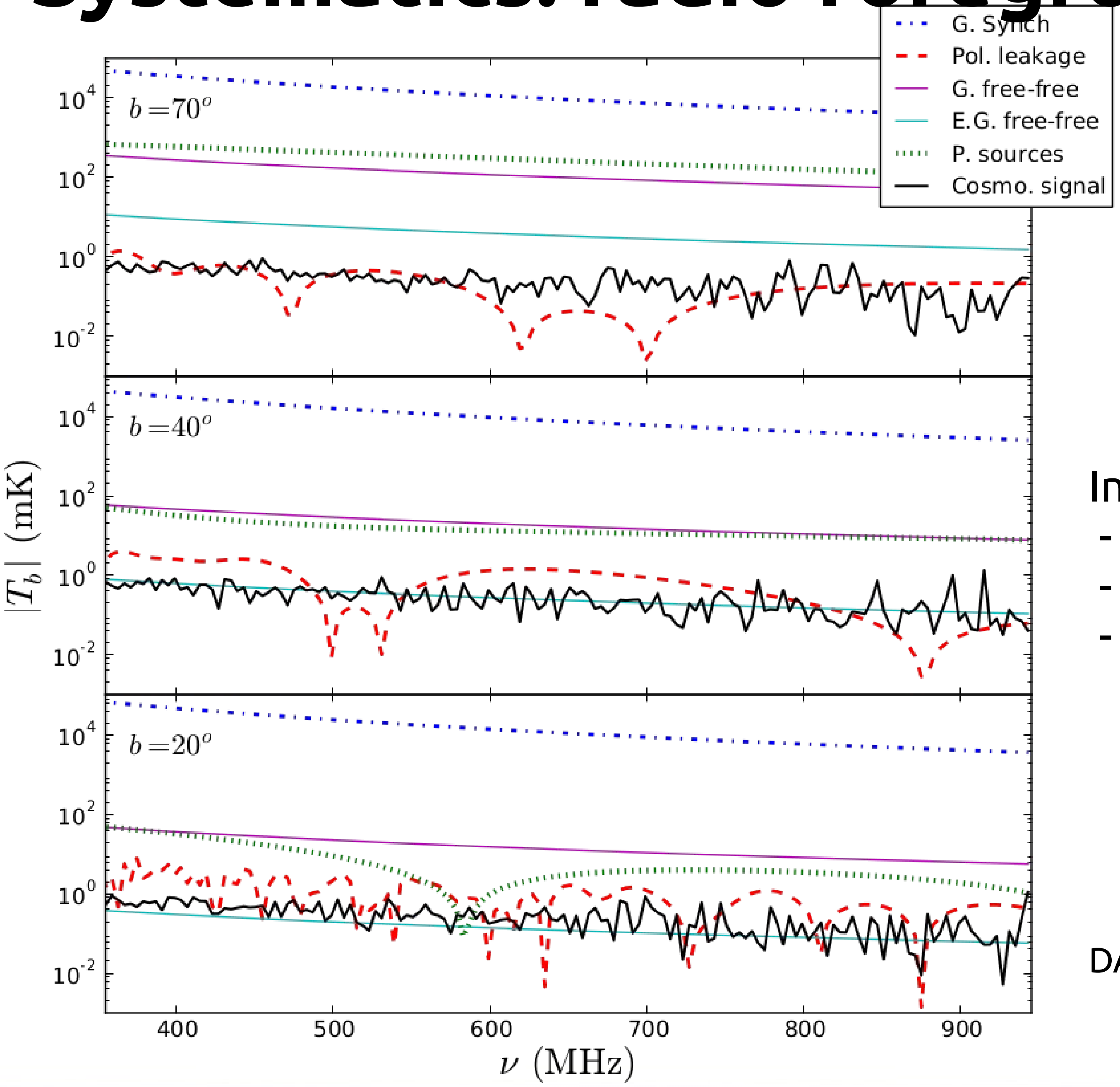
Extragalactic foregrounds:
- Point sources
- E.G. free-free

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

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

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

Systematics: radio foregrounds



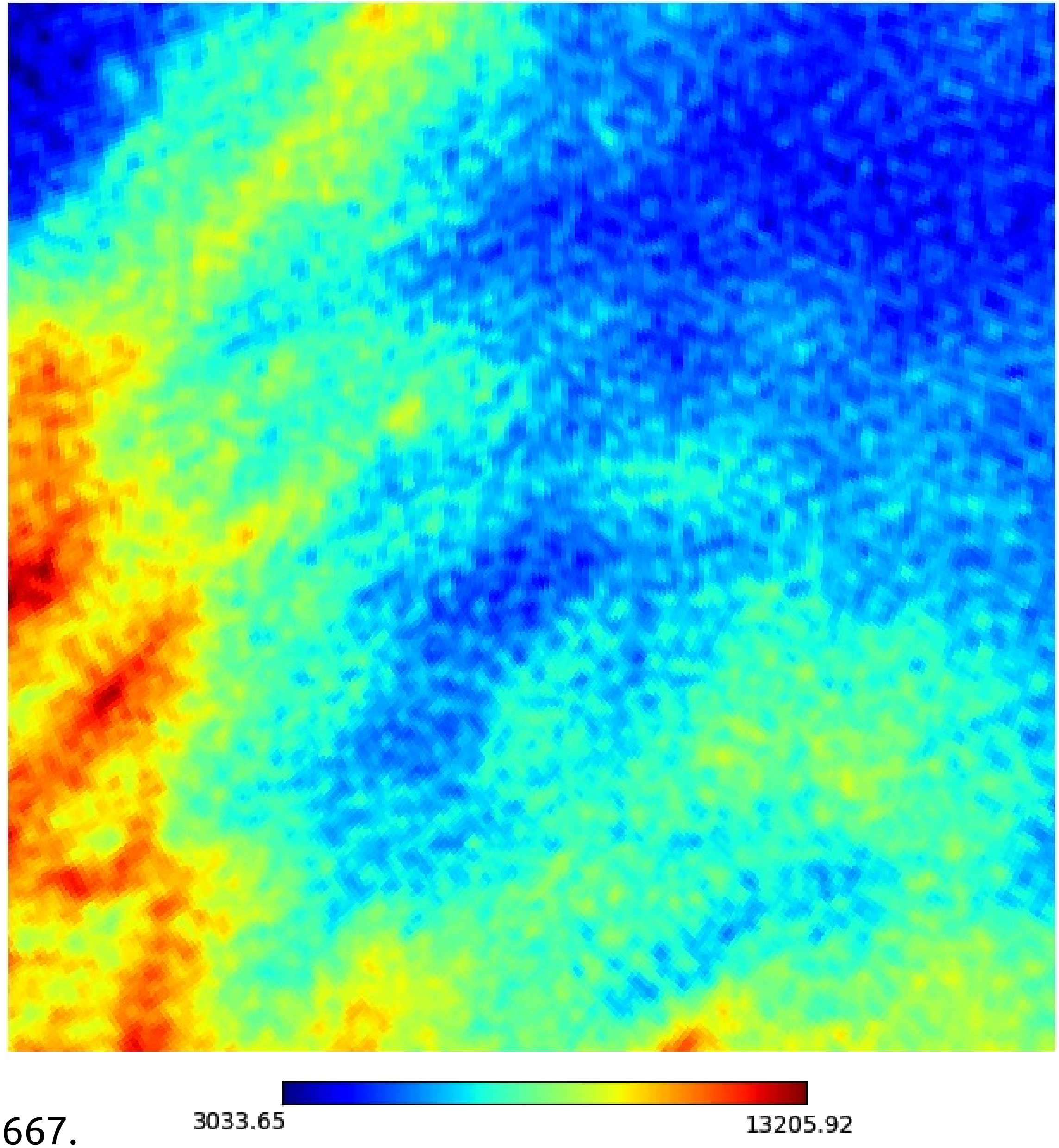
Instrumental effects:

- Beam convolution
- Polarization leakage
- Noise

DA et al. ArXiv:1405.1751.

Blind foreground subtraction

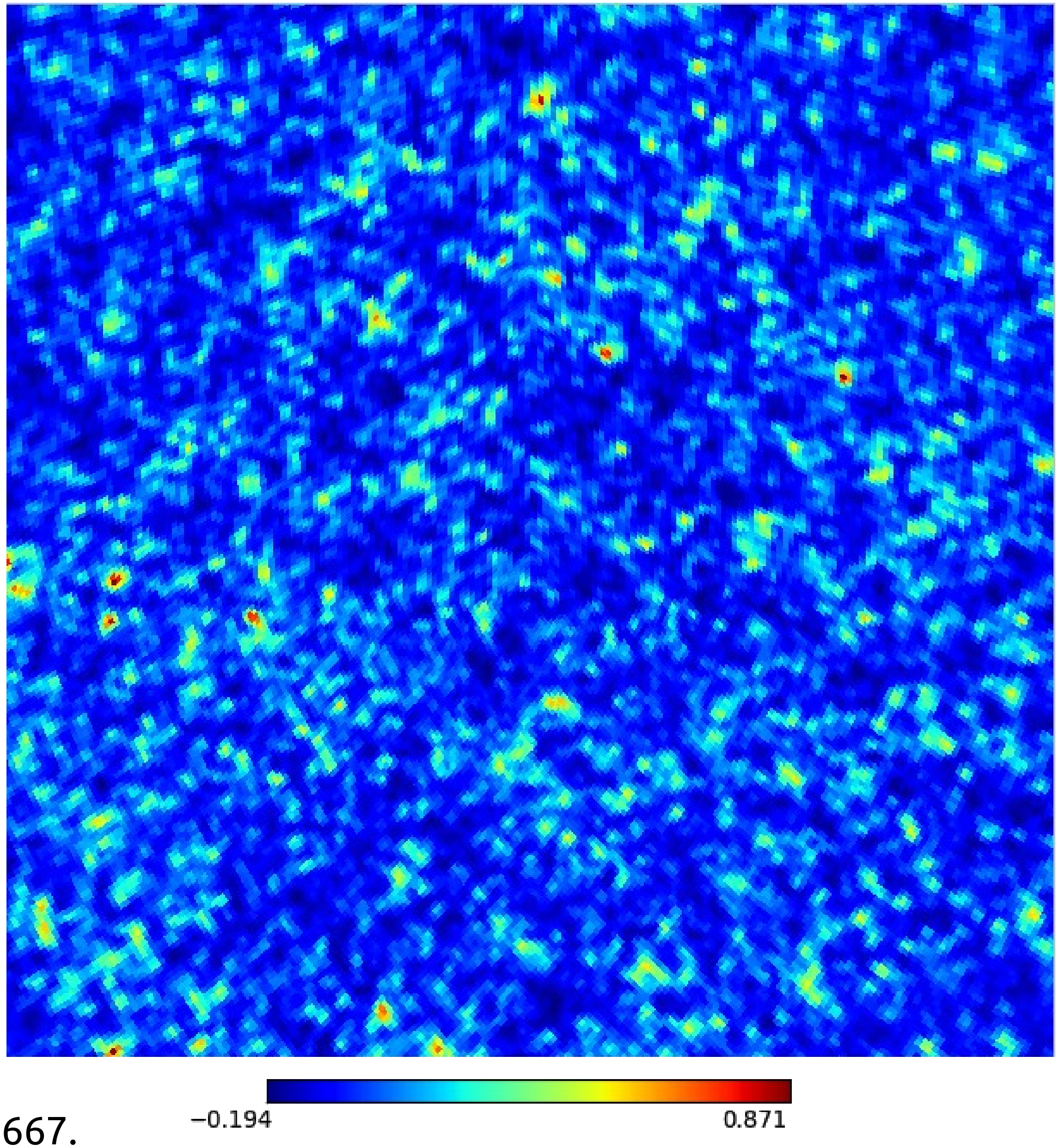
Signal+FG



DA et al. ArXiv:1409.8667.

Blind foreground subtraction

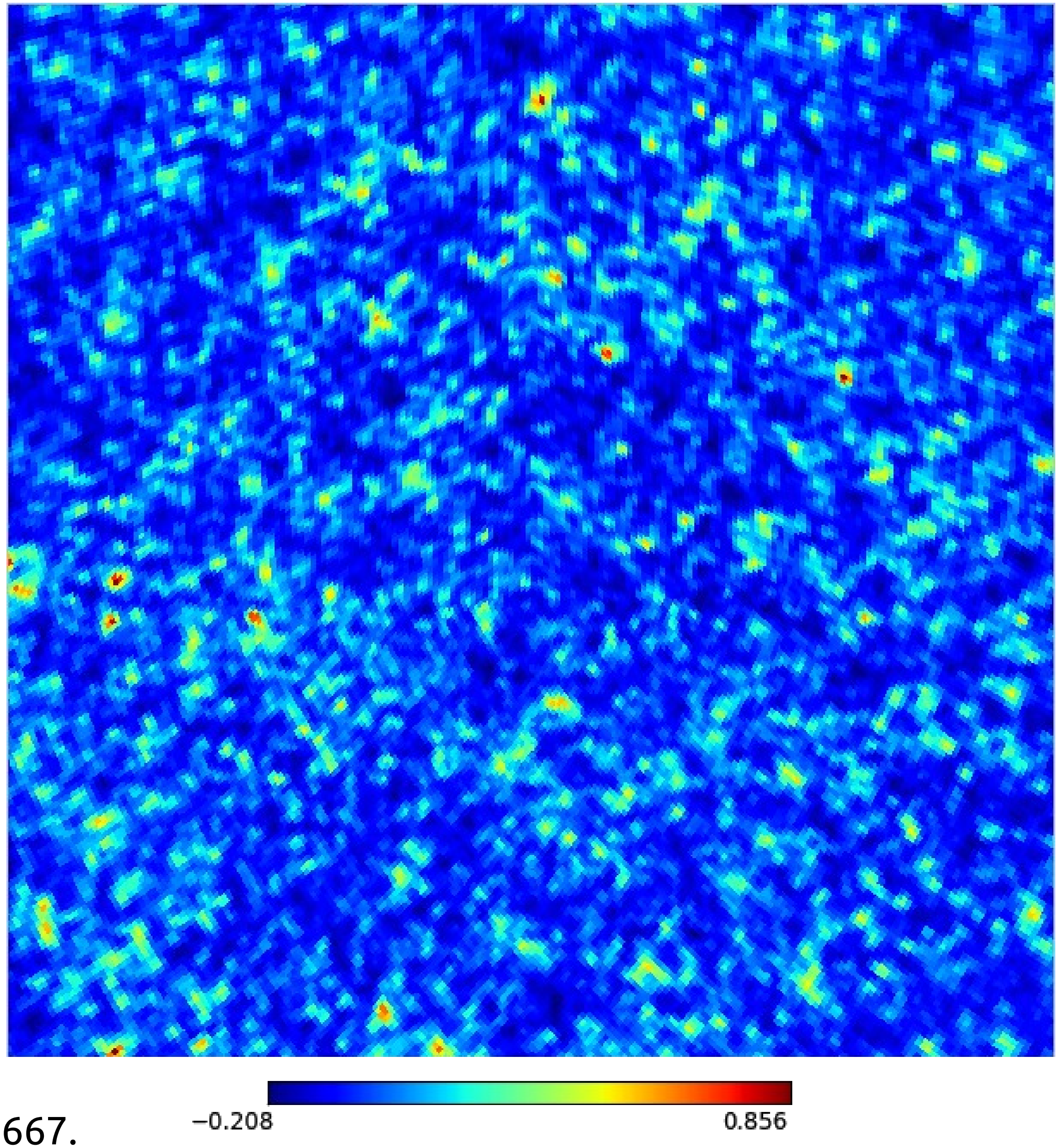
Signal only



DA et al. ArXiv:1409.8667.

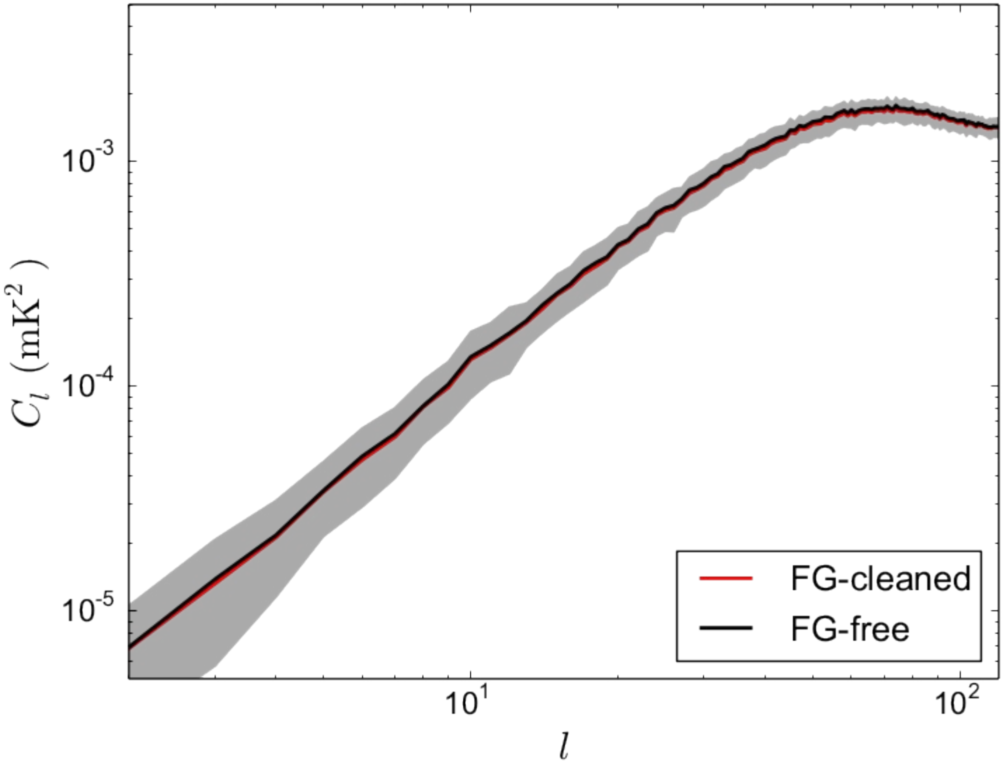
Blind foreground subtraction

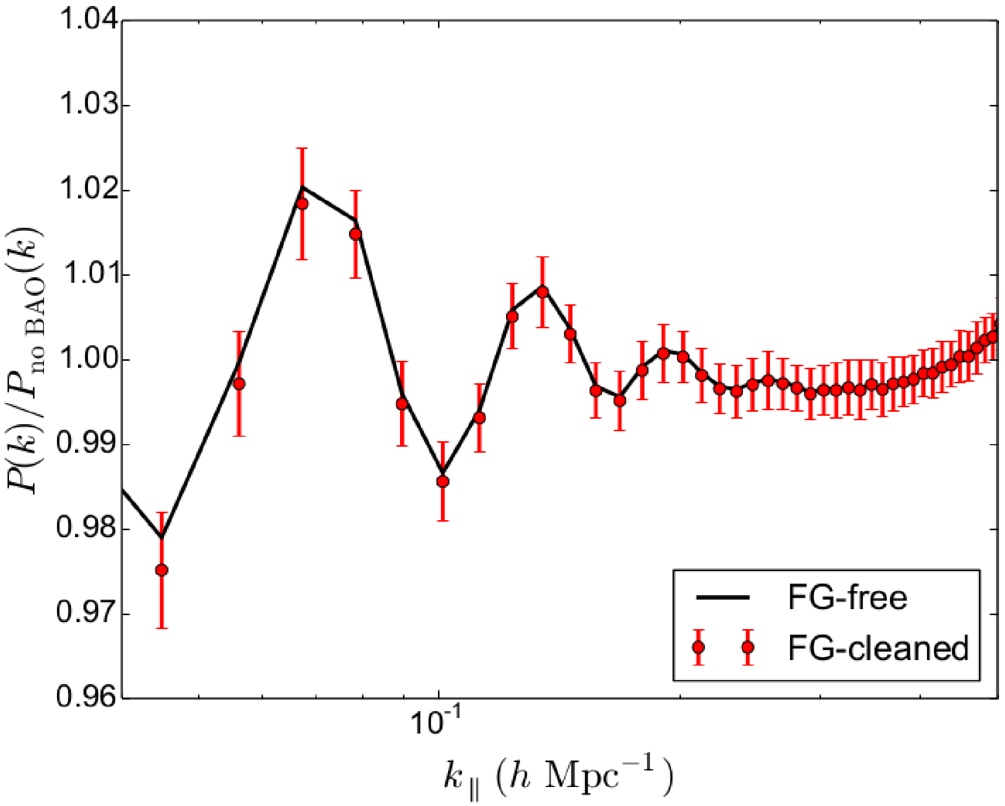
Cleaned map



DA et al. ArXiv:1409.8667.

Blind foreground subtraction

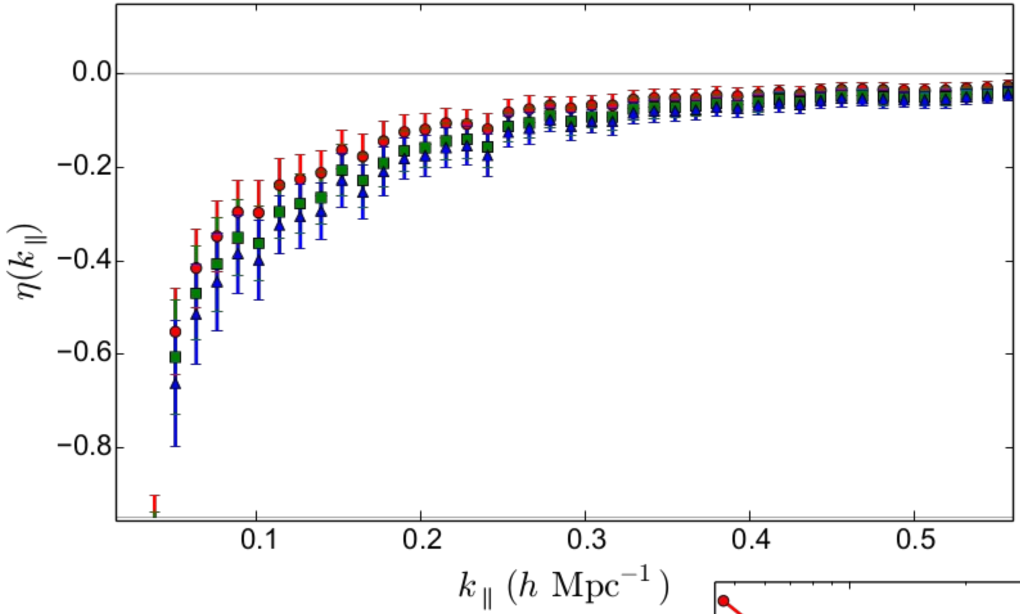




Most important features still observable! (BAO, shape...)

DA et al. ArXiv:1409.8667.

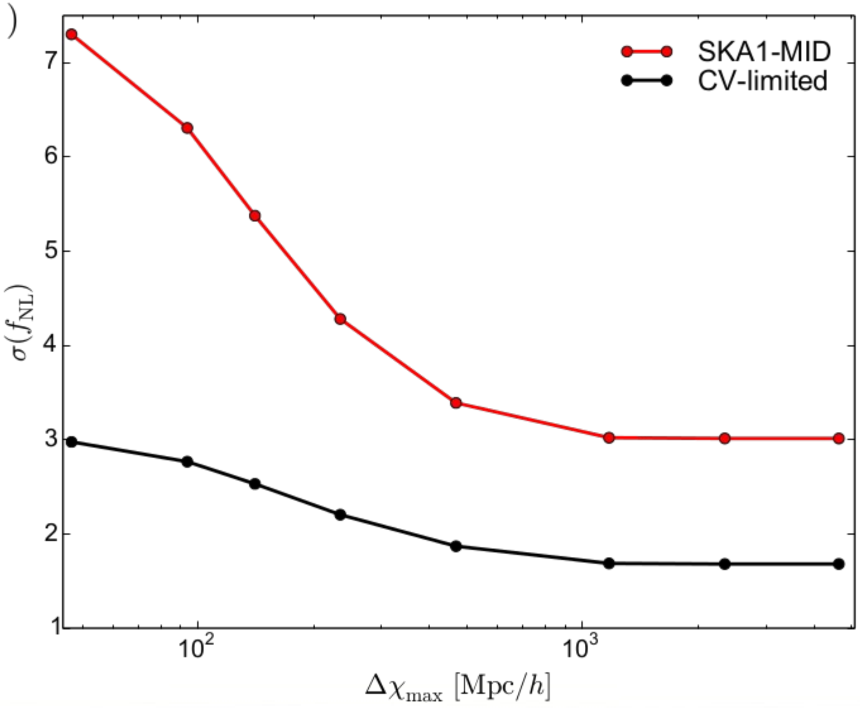
Systematics: intensity mapping



Bias and variance of the recovered power spectrum

Radial scales:

- Significantly larger contamination on large scales (dominated by foregrounds)
- Larger variance on large scales



DA et al. ArXiv:1409.8667.

Conclusions

- Future surveys will give us access to unprecedented volumes, and new cosmological observables.
- Relativistic effects in large-scale structure contain important information about the underlying theory of gravity, however their detectability is limited by cosmic variance.
- Ultra-large scales also contain information about the statistics of the primordial fluctuations.
- We have produced Fisher forecasts for these observables for next-generation experiments: spectroscopic, photometric and radio continuum surveys and HI intensity mapping.
- Only mild improvement on fNL and no detection of GR effects for individual tracers.
- Combining multiple tracers would make it possible to beat cosmic variance.
- O(10) and O(3) σ detections might be possible with LSST and DES respectively. Combination with intensity mapping will be very beneficial.
- Main systematic for IM: foregrounds.
- First tests show promise, but might fall short due to instrumental effects

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¡Gracias!

Fisher matrix analysis

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