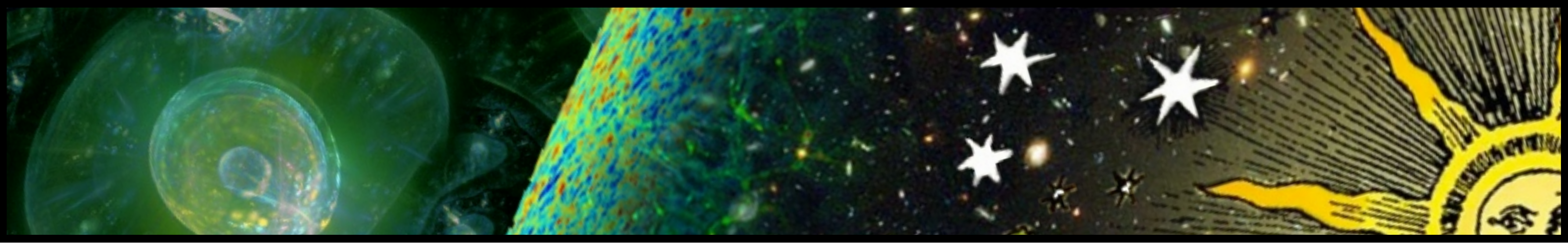

Towards fundamental physics from cosmological surveys

Hiranya V. Peiris

University College London

Science & Technology Facilities Council

erc European Research Council

IDEAS

Experimental landscape in 2025

- ***CMB:*** *ground-based (BICEP++,AdvACTpol, SPT3G, PolarBear,...), balloon-borne (EBEX, SPIDER,...), mission proposal for 4th generation satellite (CMBPol, EPIC, CoRE, LiteBird...), spectroscopy (PIXIE, PRISM proposal...)*

- ***LSS:*** *photometric (DES, PanSTARRS, LSST...), spectroscopic (HSC, HETDEX, DESI,...), space-based (Euclid,WFIRST...)*

- ***21cm:*** *SKA and pathfinders...*

- ***GW:*** *Advanced LIGO, NGO pathfinder...*

Science goals tie early/evolved universe together; multi-goal; Cross-talk of data-types and probes critical for success

Towards fundamental physics from cosmological surveys

- ***Understand your observations!***
  Need thorough understanding of data & systematics for convincing detections of new physics.

- ***From precision to accurate cosmology with large imaging surveys***

- ***Fundamental physics from the foreground-obscured, gravitationally-lensed CMB polarization***

Towards fundamental physics from cosmological surveys

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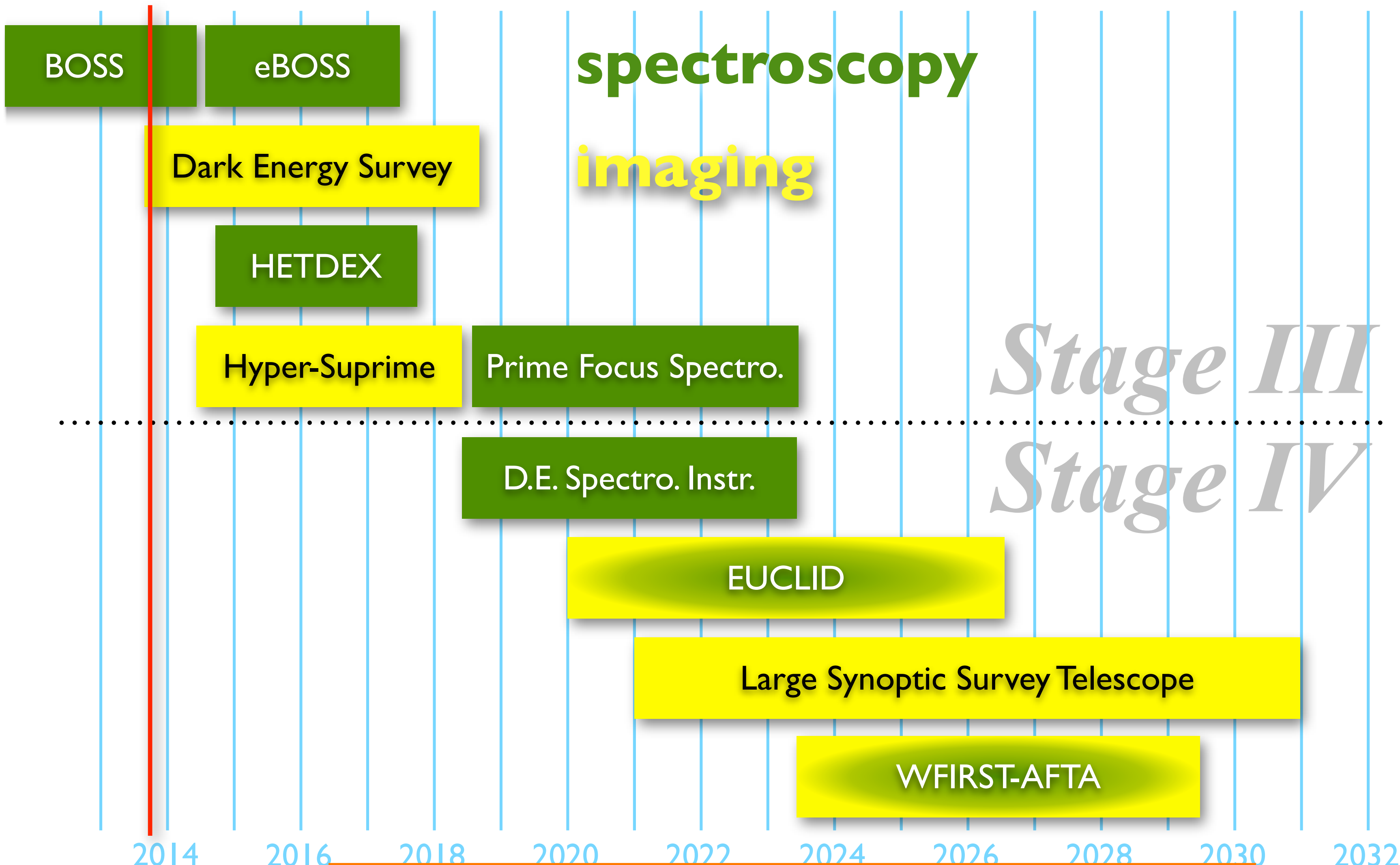
LSS Surveys Roadmap



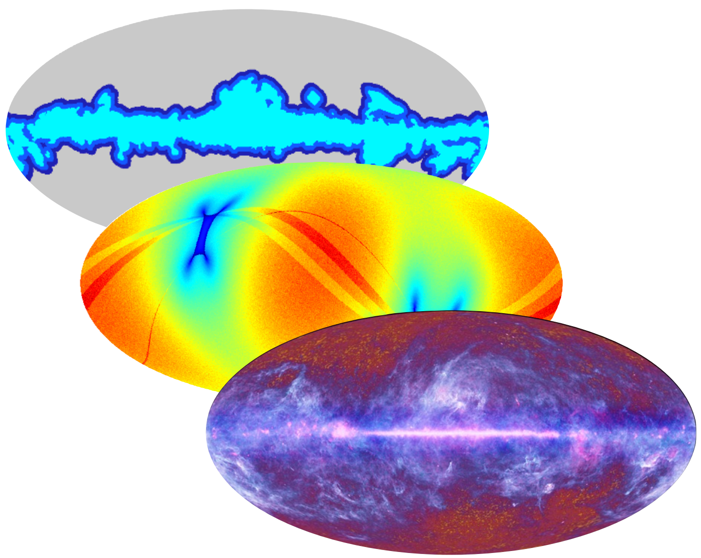
High degree of complementary between missions

Image: Ian Shipsey

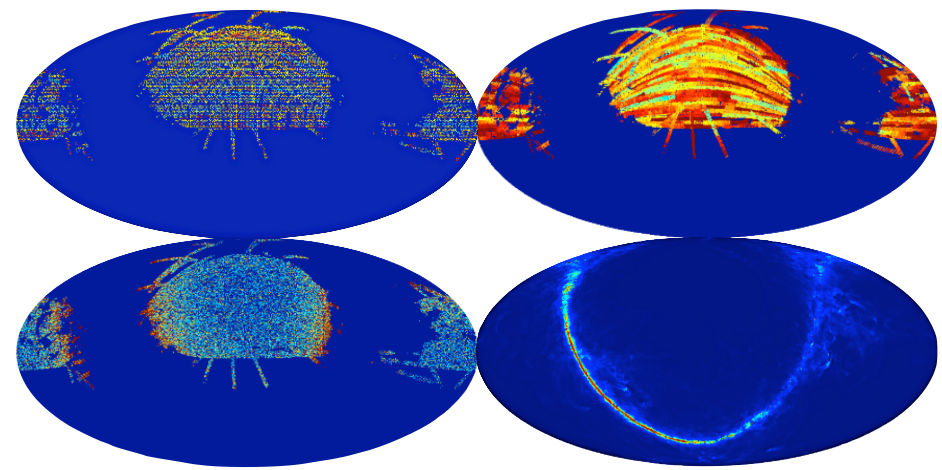
“No one trusts a model except the person who wrote it; everyone trusts an observation, except the person who made it”.

H. Shapley

*Known unknowns, unknown knowns, unknown unknowns**



***CMB**: complex sky mask, coloured / inhomogeneous noise, foregrounds...*



***LSS**: seeing, sky brightness, stellar contamination, dust obscuration, spatially-varying selection function, Poisson noise, photo-z errors etc...*

Need thorough understanding of data & systematics for convincing detections of new physics.

* Common NASA phrase: administrator William Graham

Primordial NG from the halo power spectrum

scale-dependent halo bias (Dalal et al 2008)

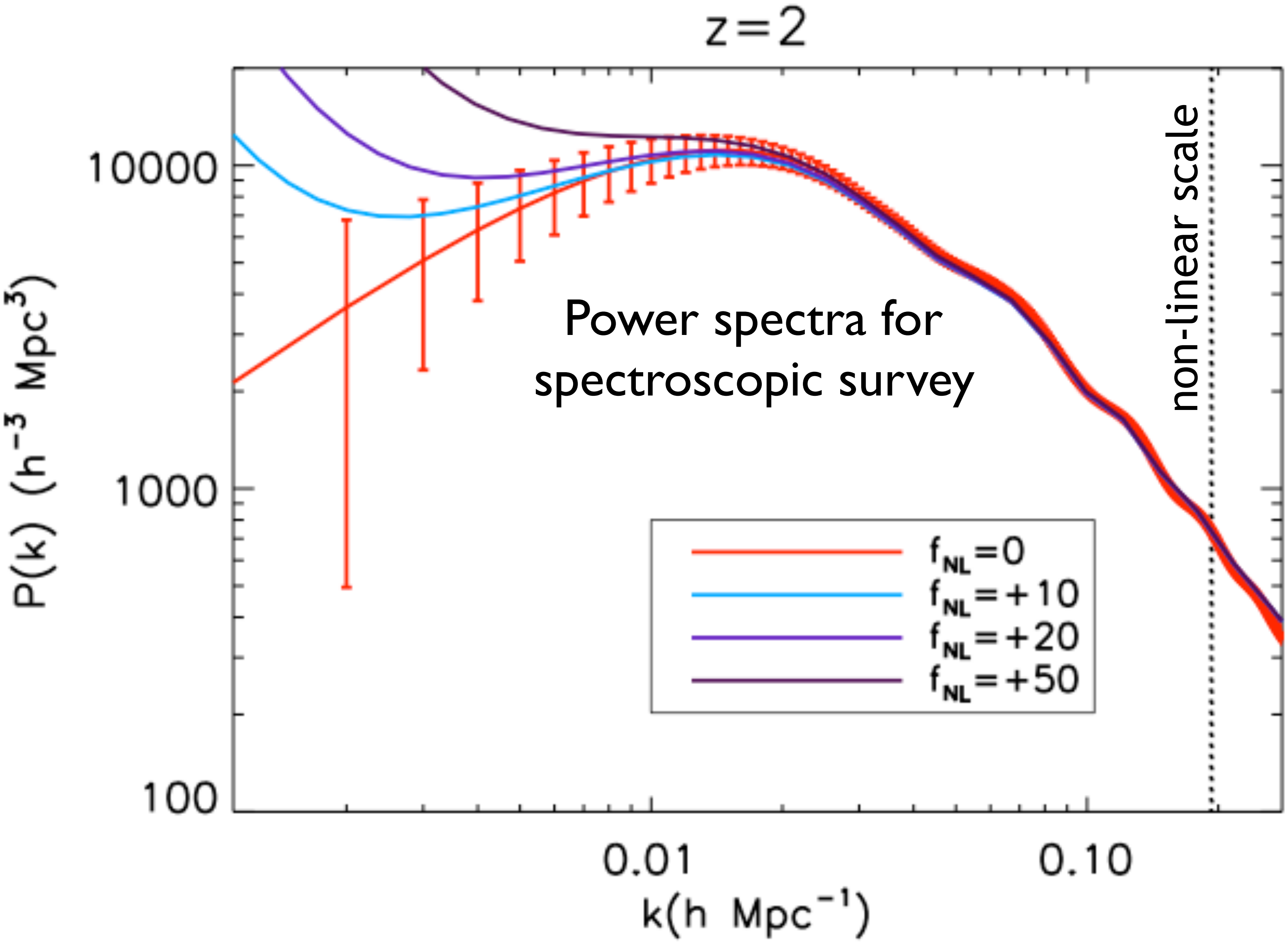


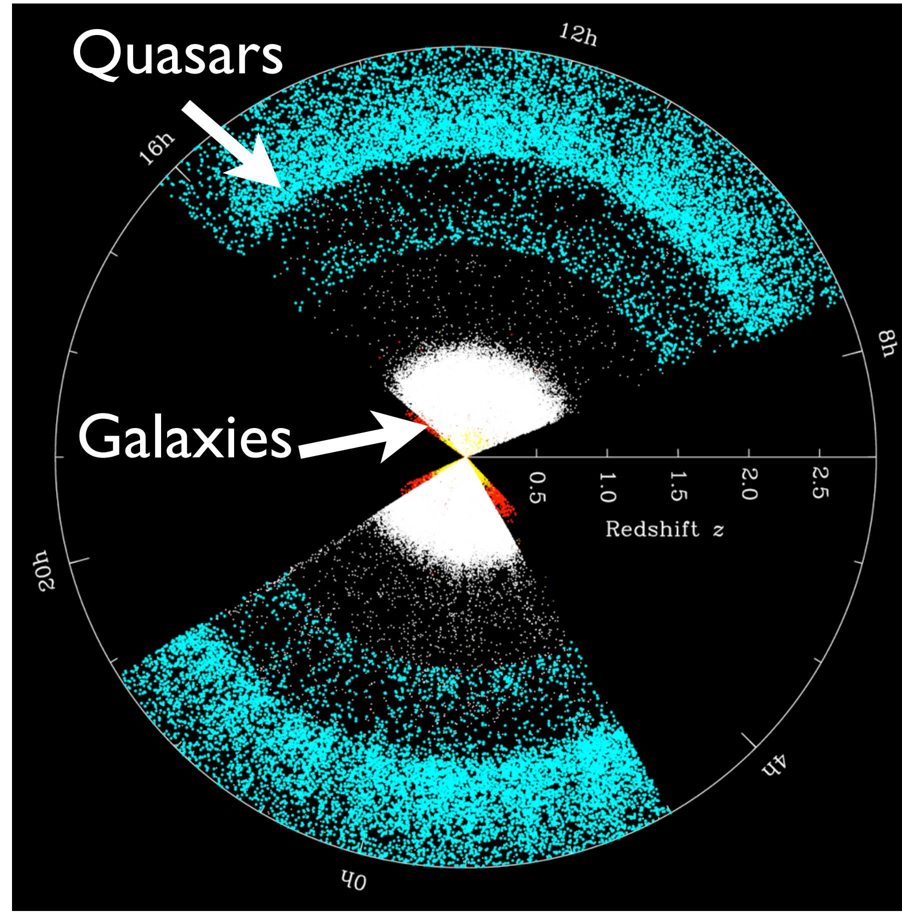
Figure: HSLS white paper

$$\Phi = \phi + f_{\rm NL}[\phi^2 - \langle\phi^2\rangle] + g_{\rm NL}[\phi^3 - 3\phi\langle\phi^2\rangle]$$

Primordial NG from SDSS photometric quasar sample

XDQSOz: 1.6 million QSO candidates from SDSS DR8.
(Bovy et al.)

Boris Leistedt *Nina Roth*

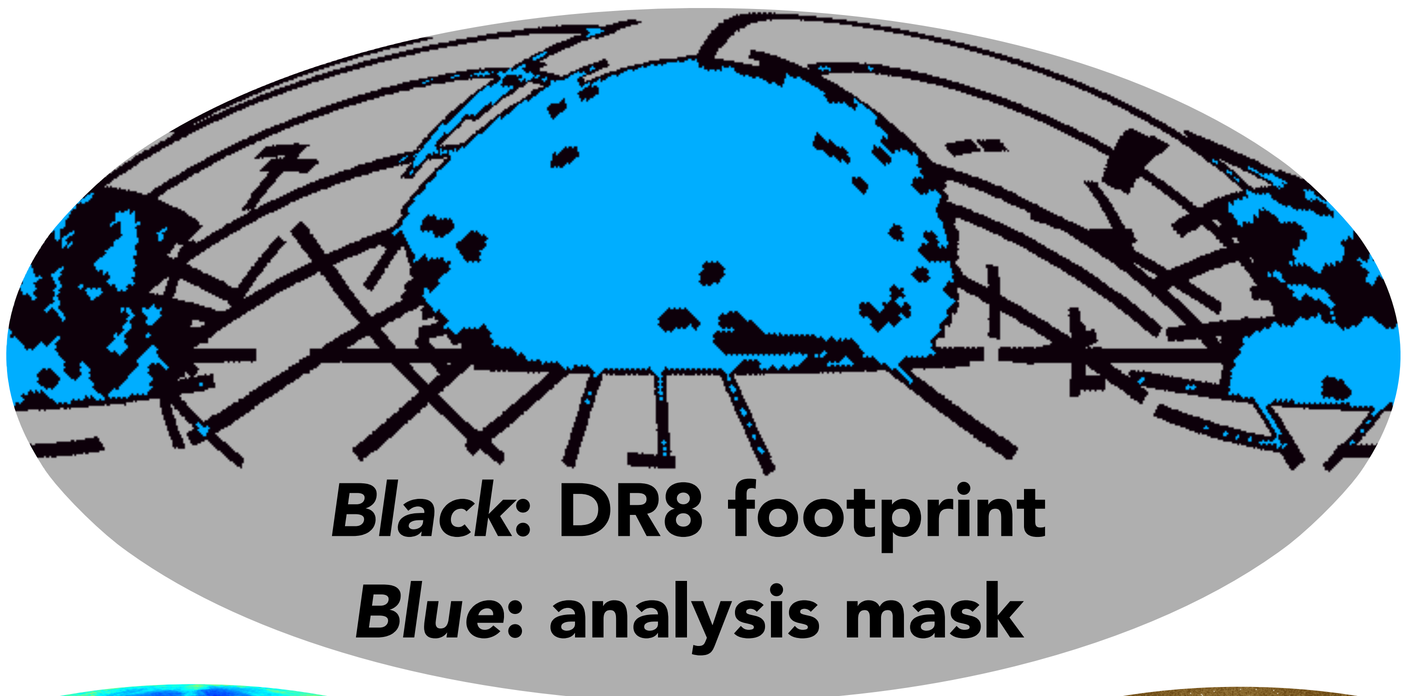


$$\Delta b(k,z) = f_{\rm NL}(b_g - 1)\frac{3\Omega_{\rm m}h_0^2\delta_c}{D(z)T(k)k^2}$$

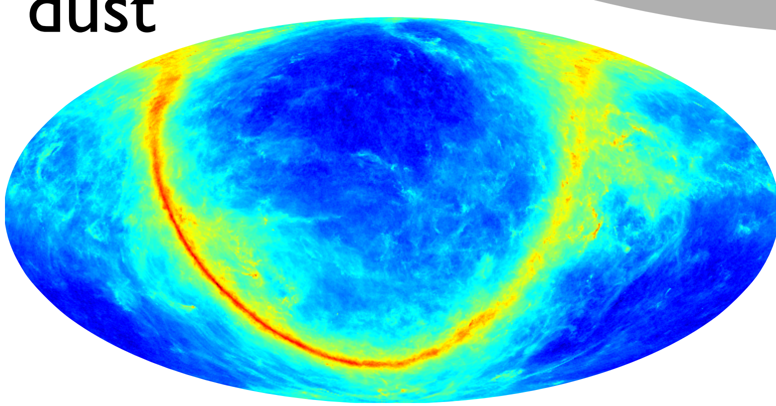
Leistedt & Peiris+ (MNRAS 2013, 2014), Leistedt, Peiris & Roth (PRL 2014)

800,000 photometric quasars from SDSS DR8 (XDQSOz)

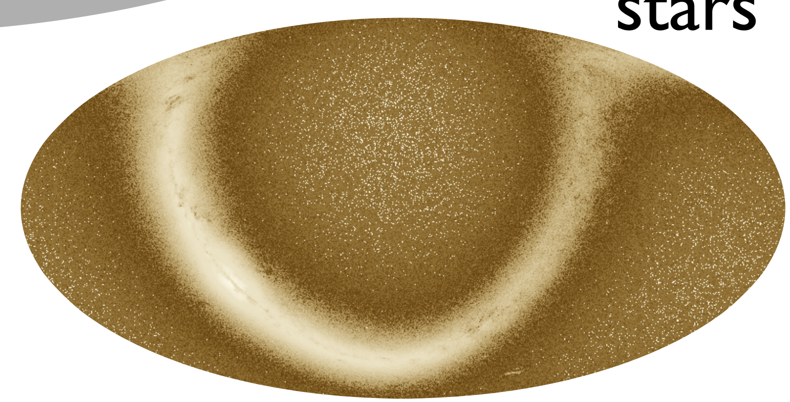
clustering measurements in 4 redshift bins 0.5 < z < 3.5



dust



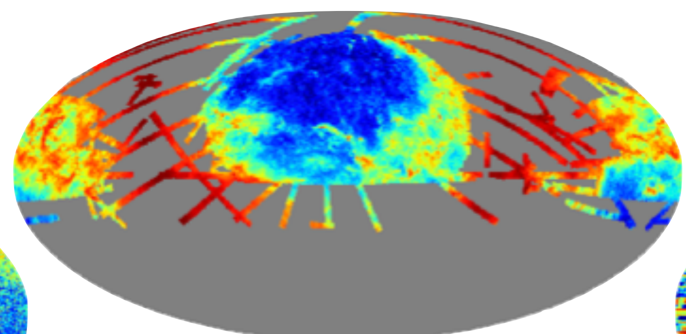
stars



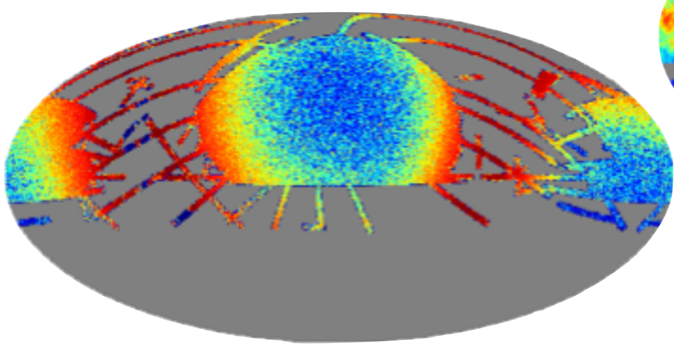
Systematics in quasar surveys

- Anything that affects point sources or colours
  seeing, sky brightness, stellar contamination, dust obscuration, calibration etc..
- Create spatially varying depth & stellar contamination

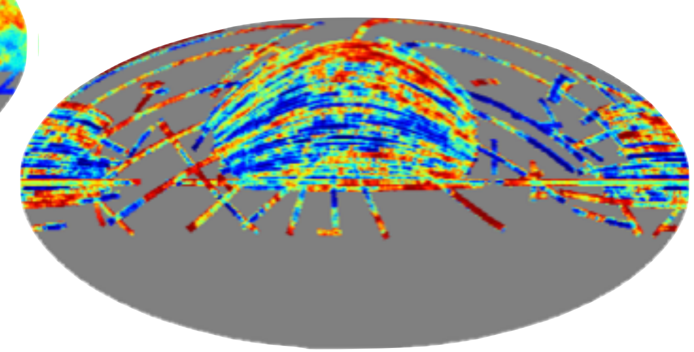
dust



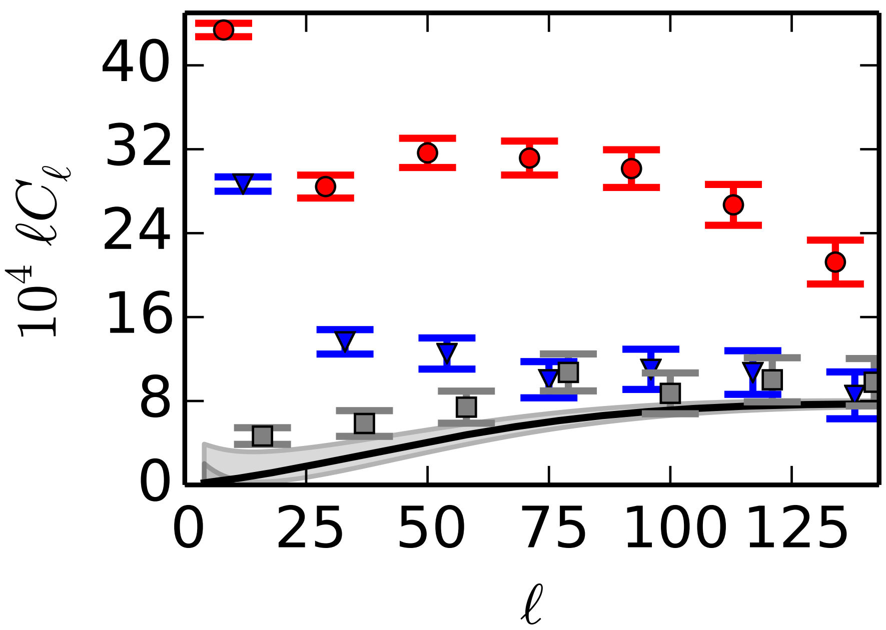
stars



seeing



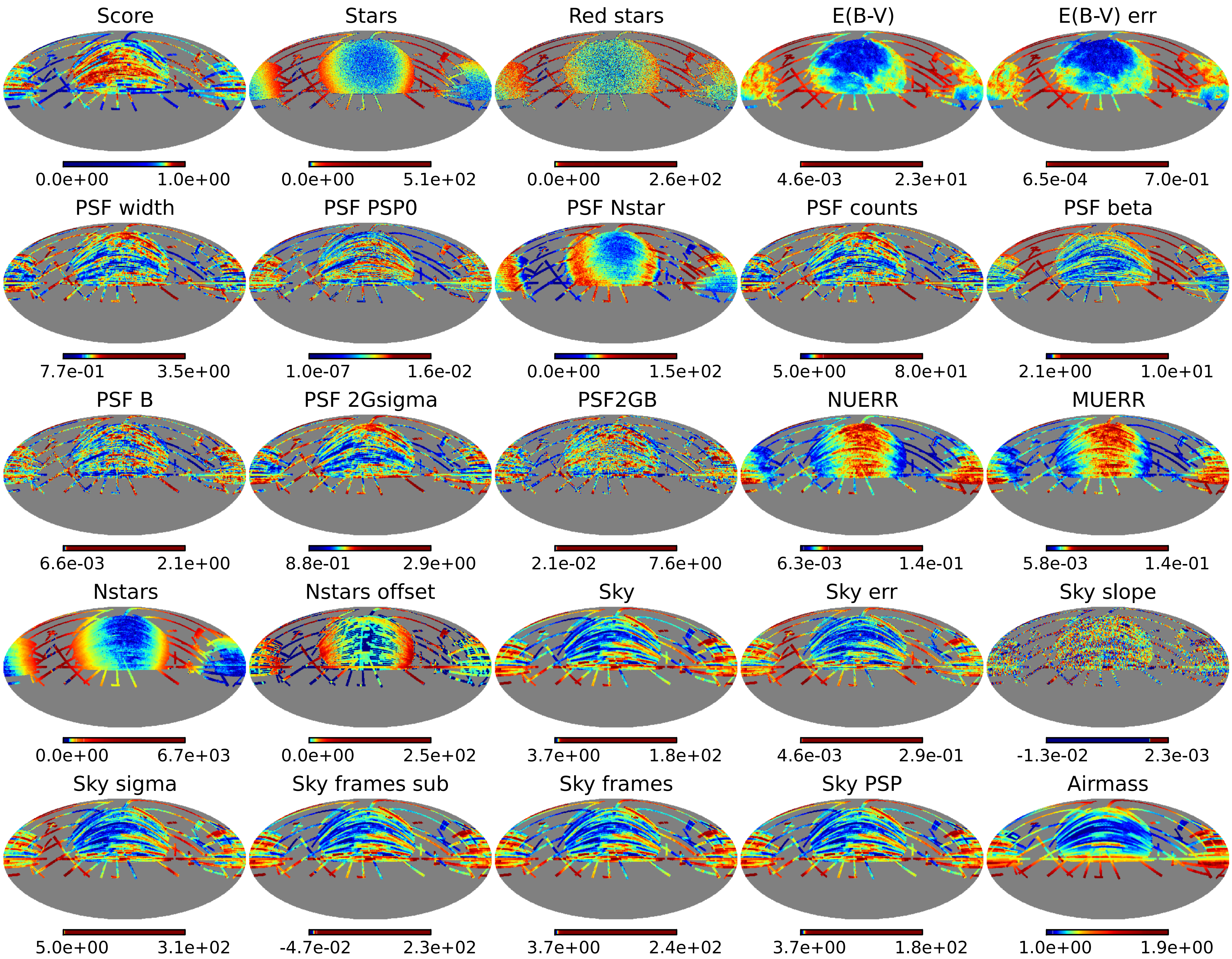
Systematics in quasar surveys



- **SDSS photometric quasars:** excess clustering power on large scales due to systematics.

- Concerns about its use for clustering studies. Pullen and Hirata 2012; Giannantonio et al. 2013

Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (PRL 2014, 1405.4315)



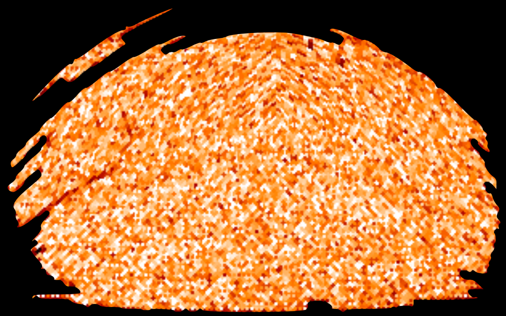
Score
0.0e+00
1.0e+00
Stars
0.0e+00
5.1e+02
Red stars
0.0e+00
2.6e+02
E(B-V)
4.6e-03
2.3e+01
E(B-V) err
6.5e-04
7.0e-01
PSF width
7.7e-01
3.5e+00
PSF PSP0
1.0e-07
1.6e-02
PSF Nstar
0.0e+00
1.5e+02
PSF counts
5.0e+00
8.0e+01
PSF beta
2.1e+00
1.0e+01
PSF B
6.6e-03
2.1e+00
PSF 2Gsigma
8.8e-01
2.9e+00
PSF2GB
2.1e-02
7.6e+00
NUERR
6.3e-03
1.4e-01
MUERR
5.8e-03
1.4e-01
Nstars
0.0e+00
6.7e+03
Nstars offset
0.0e+00
2.5e+02
Sky
3.7e+00
1.8e+02
Sky err
4.6e-03
2.9e-01
Sky slope
-1.3e-02
2.3e-03
Sky sigma
5.0e+00
3.1e+02
Sky frames sub
-4.7e-02
2.3e+02
Sky frames
3.7e+00
2.4e+02
Sky PSP
3.7e+00
1.8e+02
Airmass
1.0e+00
1.9e+00

Systematics and mode projection

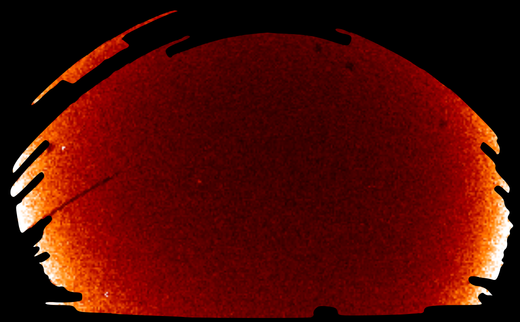
Rybicki and Press (1992)

- Maximum Likelihood estimator in 4 redshift bins
- QML with mode projection: marginalises over linear contamination models, using systematics templates $\vec{c}_k$

$$\mathbf{C} = \sum_{\ell} \mathcal{C}_\ell \mathbf{P}_\ell + \mathbf{N} + \sum_{k \in \mathrm{sys}} \xi_k \vec{c}_k \vec{c}_k^{\,t} \quad \text{with} \quad \xi_k \to \infty$$



quasar catalogue

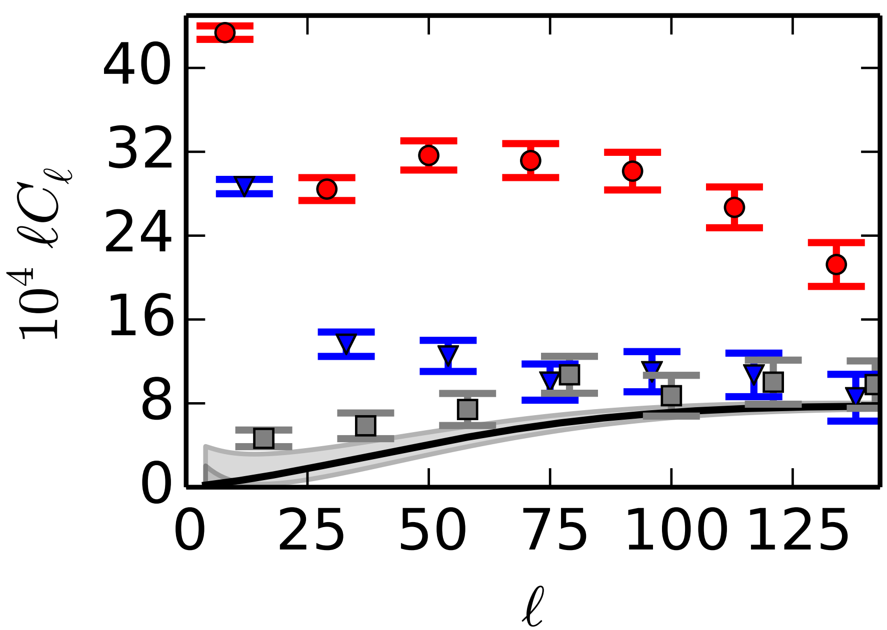


stars

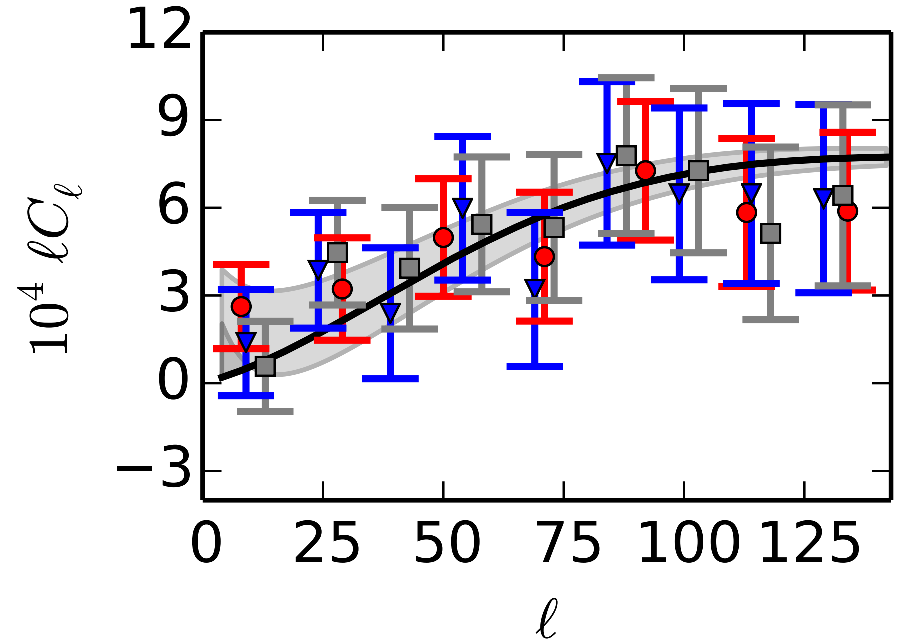
dust extinction

Also see Elsner, Leistedt and Peiris (MNRAS,1509.08933)

Blind mitigation of systematics



Raw spectra

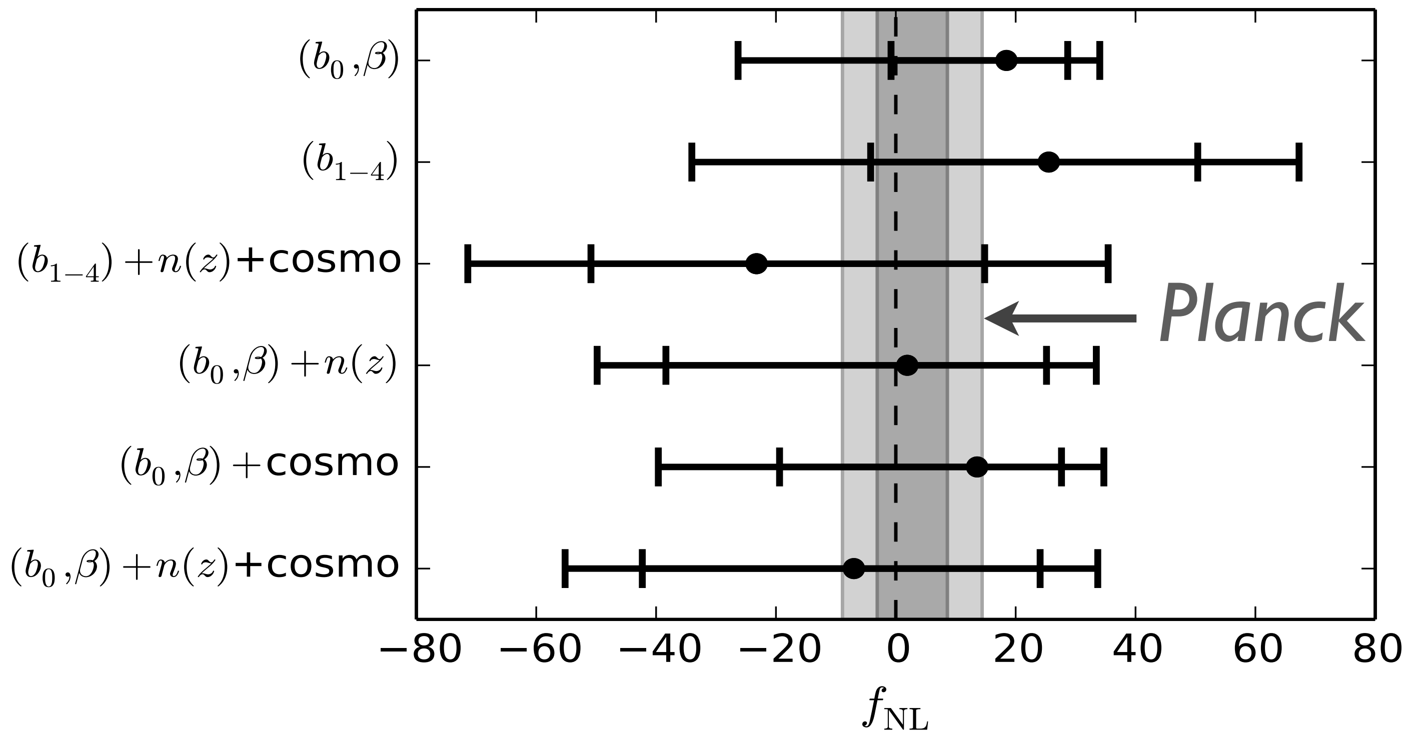


Clean spectra

- Example: one of 10 spectra (auto + cross in four z-bins) in likelihood
- Grey bands: -50 < f_{NL} < 50; colours: basic masking + m.p.

Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

Constraints on f_{NL}



$-16 < f_{\rm NL} < 47\ (2\sigma)$

Fixed cosmology & n(z)

$-49 < f_{\rm NL} < 31\ (2\sigma)$

Varying all parameters

- Comparable to WMAP9 from single LSS tracer(!)
- Also g_{NL} constraints comparable to Planck (2015)

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

LSST survey of 18,000 sq deg

(half the sky)

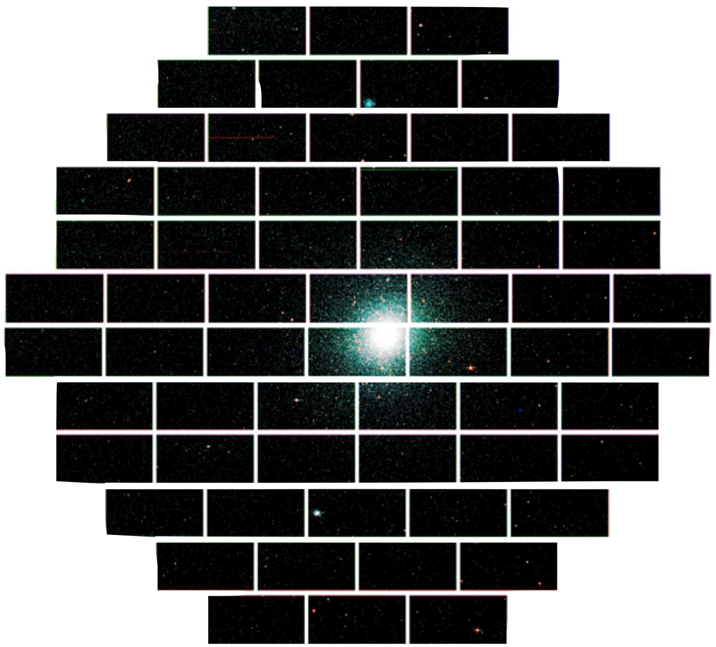
- **LSST forecast:**
  - expected statistical $\sigma(f_{NL}) < 1$
  - systematic bias for a contamination model $f_{NL} \sim 30$,
  - correcting bias leads to conservative forecast $\sigma(f_{NL}) \sim 5$.

Leistedt, Peiris & Roth (PRL 2014, 1405.4315)

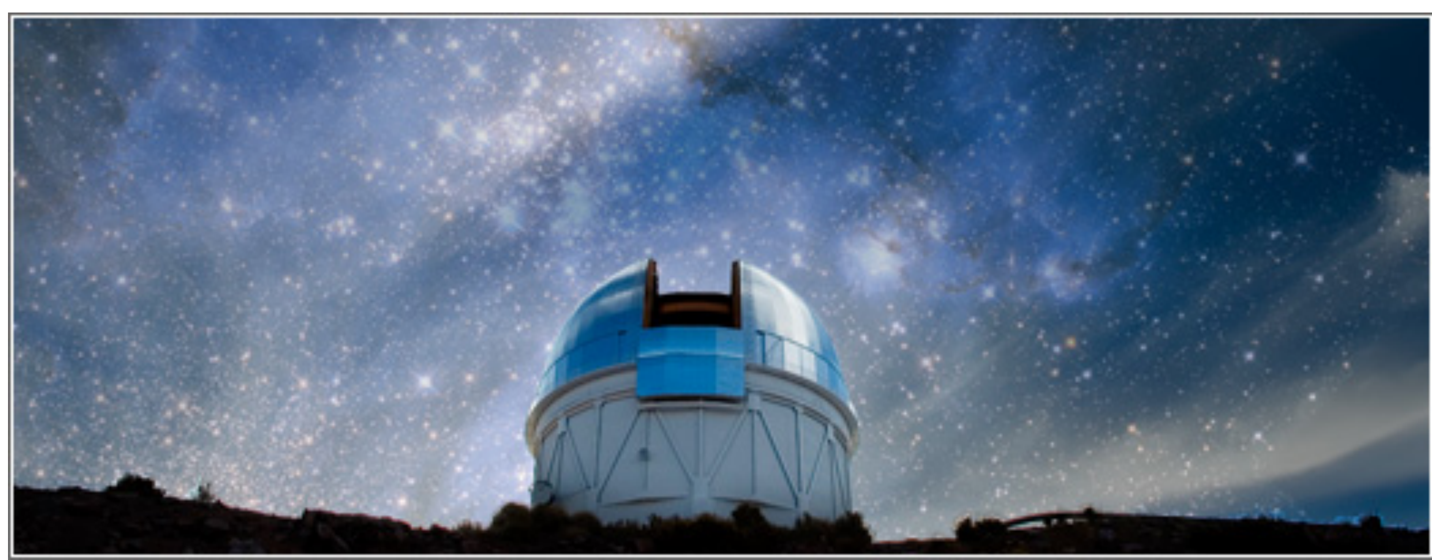
The Dark Energy Survey (DES)

300 million galaxies over 1/8 of the sky

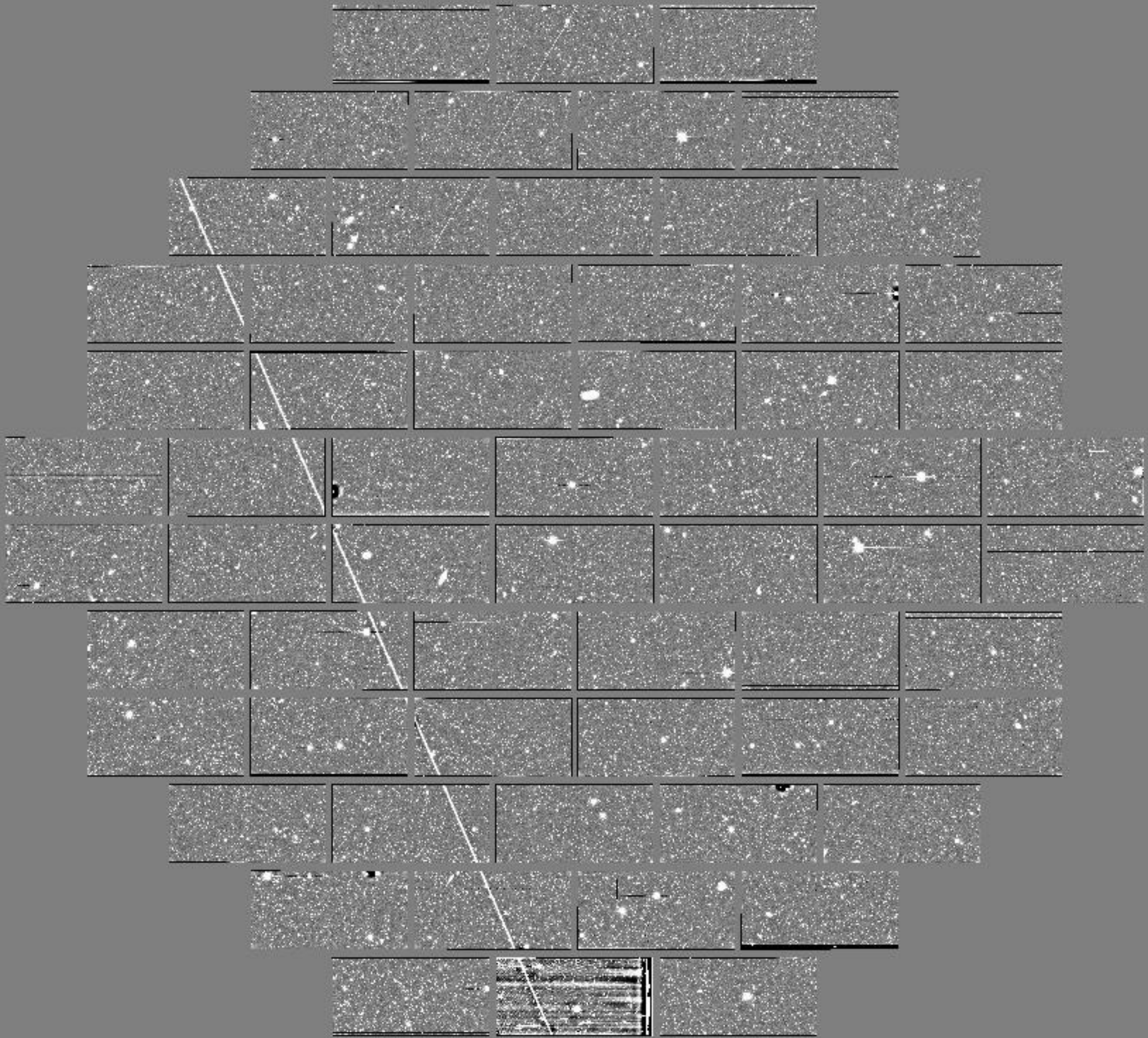
DARK ENERGY
SURVEY

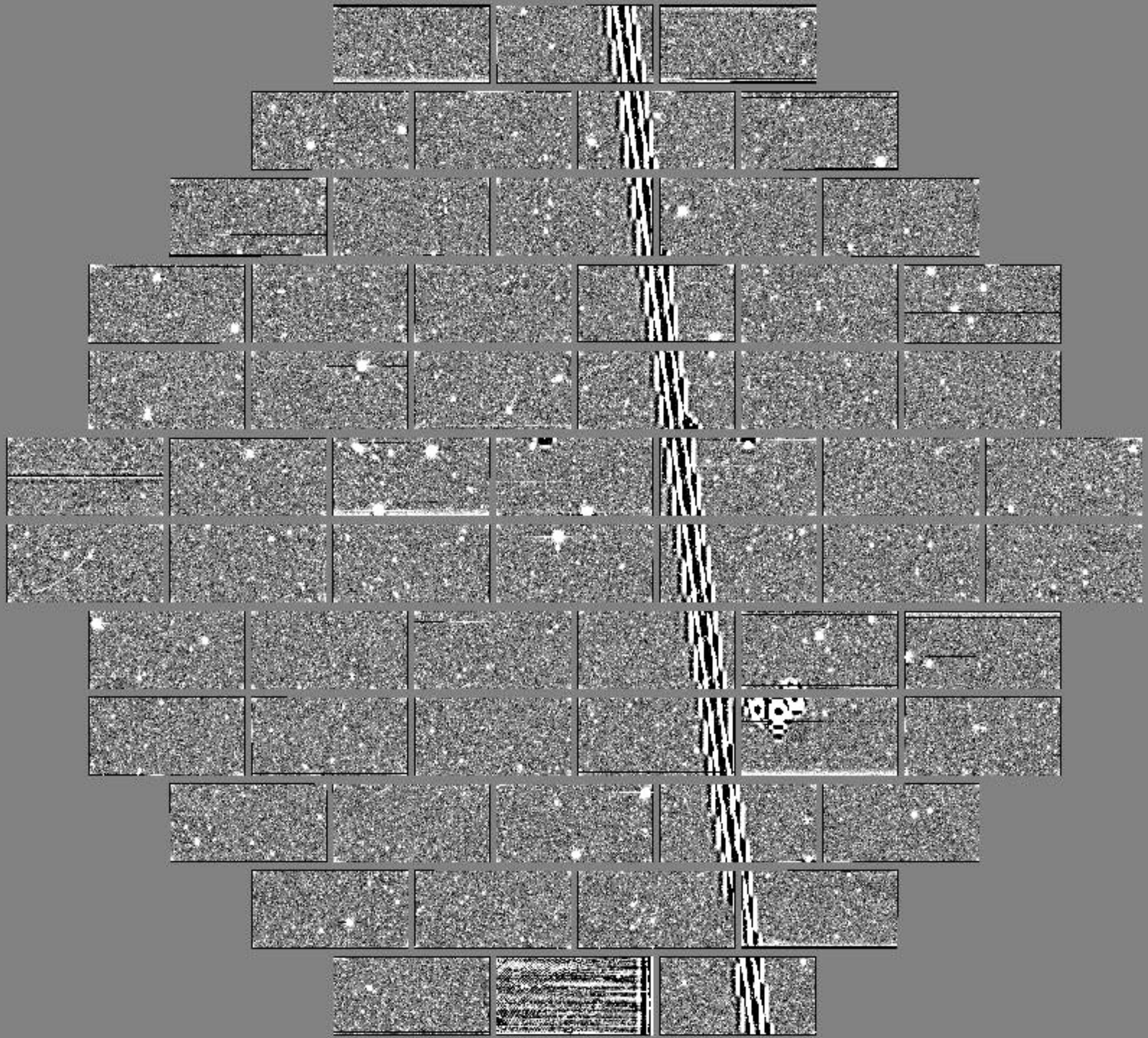


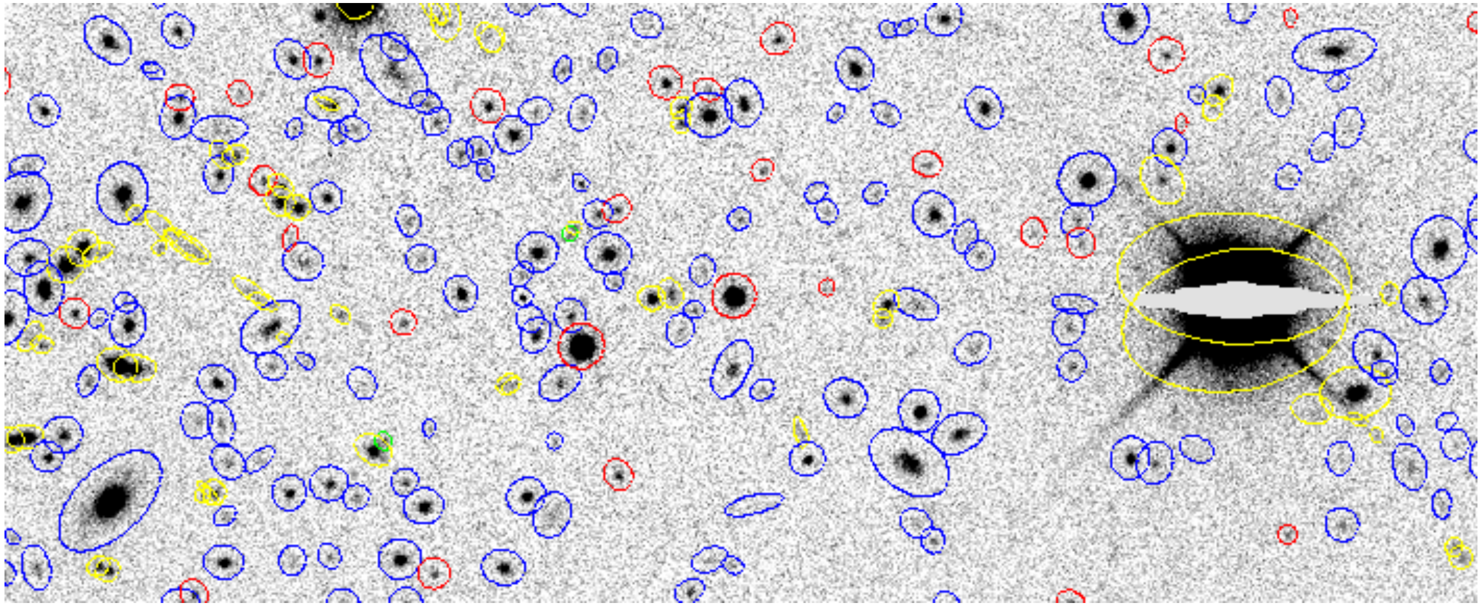
- 4-m Blanco
- 570 Mpix camera (DECam)
- 2.2 deg field of view
- Cerro Tololo (CTIO), Chile
- third year of 5-yr survey



DES data look like…







reduction of single-epoch images

coaddition into deep images

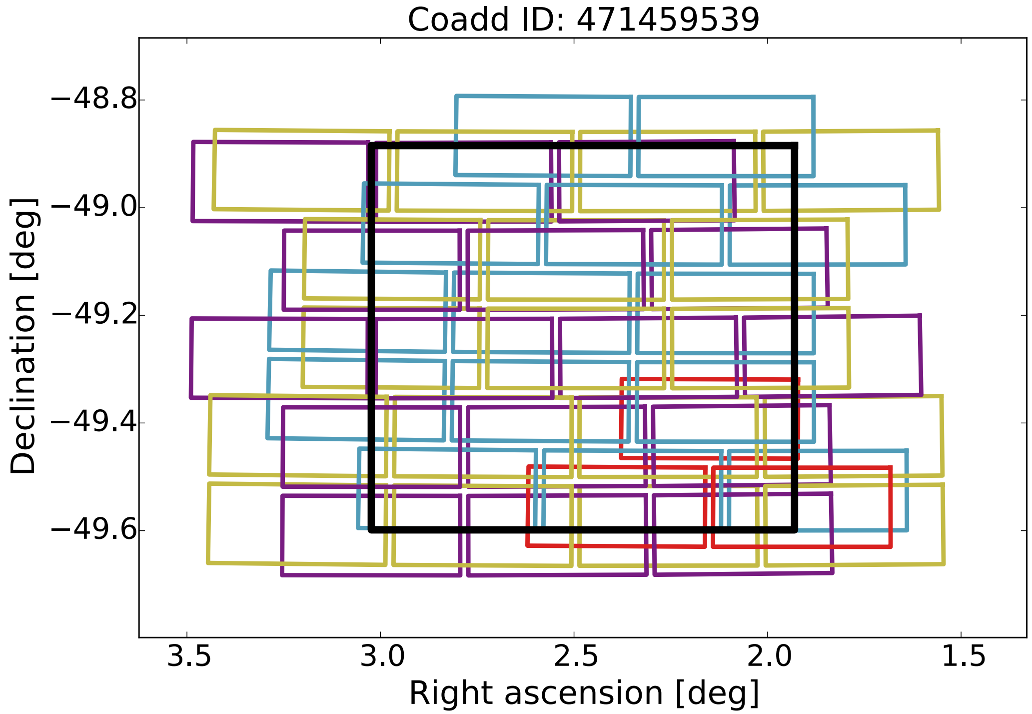
object detection

flux + shape measurements

} potentially affected by spatially-varying observing conditions

From: B. Leistedt

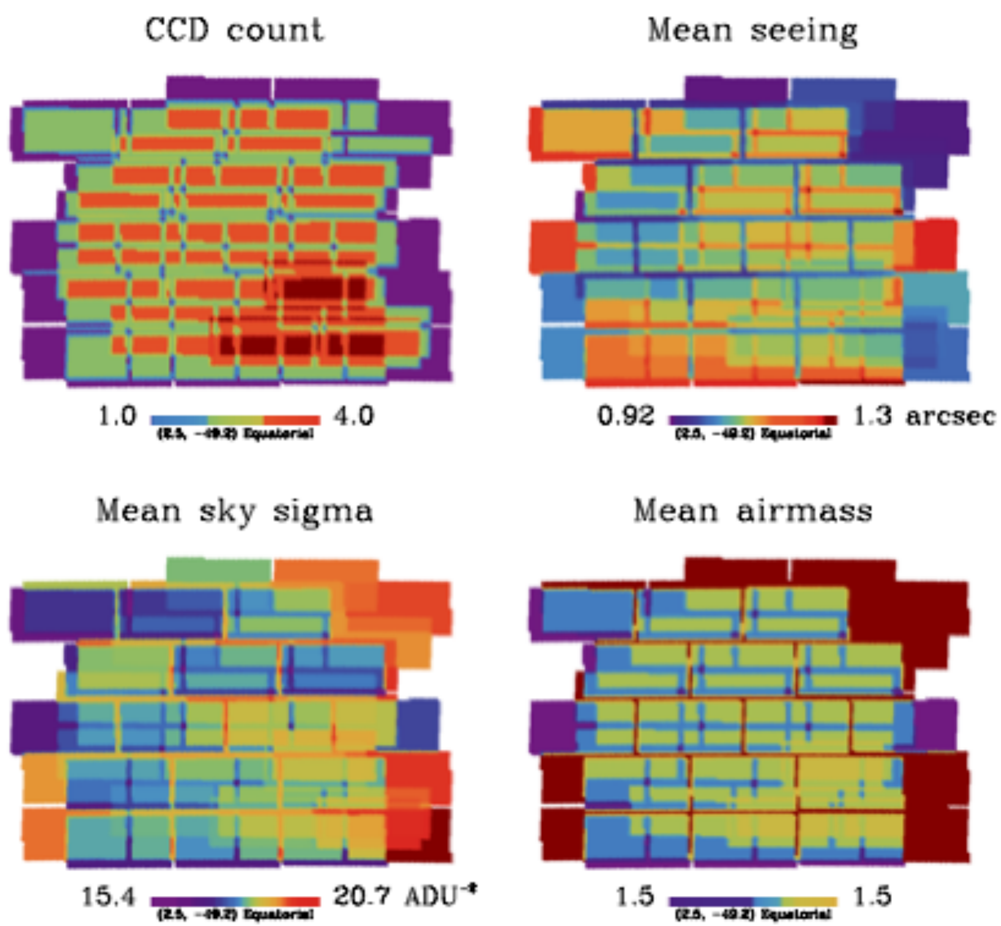
Mapping spatially-varying properties of DES



- **Geometrical projection** of single-exposure images coadded in arbitrary tile (black) of DES Science Verification data.
- **Colours:** different pointings, each with 62 single-epoch images corresponding to camera CCDs.

Leistedt, Peiris, Elsner et al. (DES Collaboration), 2015

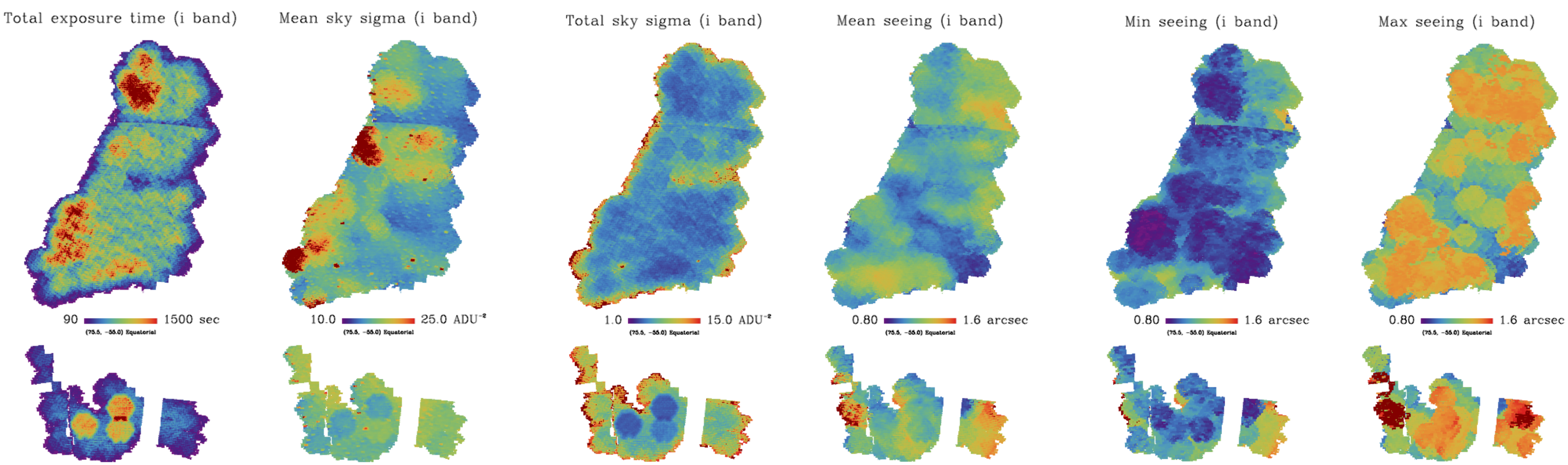
Mapping spatially-varying properties of DES



- **Projection** of single-epoch image properties: time fluctuations & correlations are converted into spatial fluctuations.

Leistedt, Peiris, Elsner et al. (DES Collaboration), 2015

DES:SV: From precision to accuracy

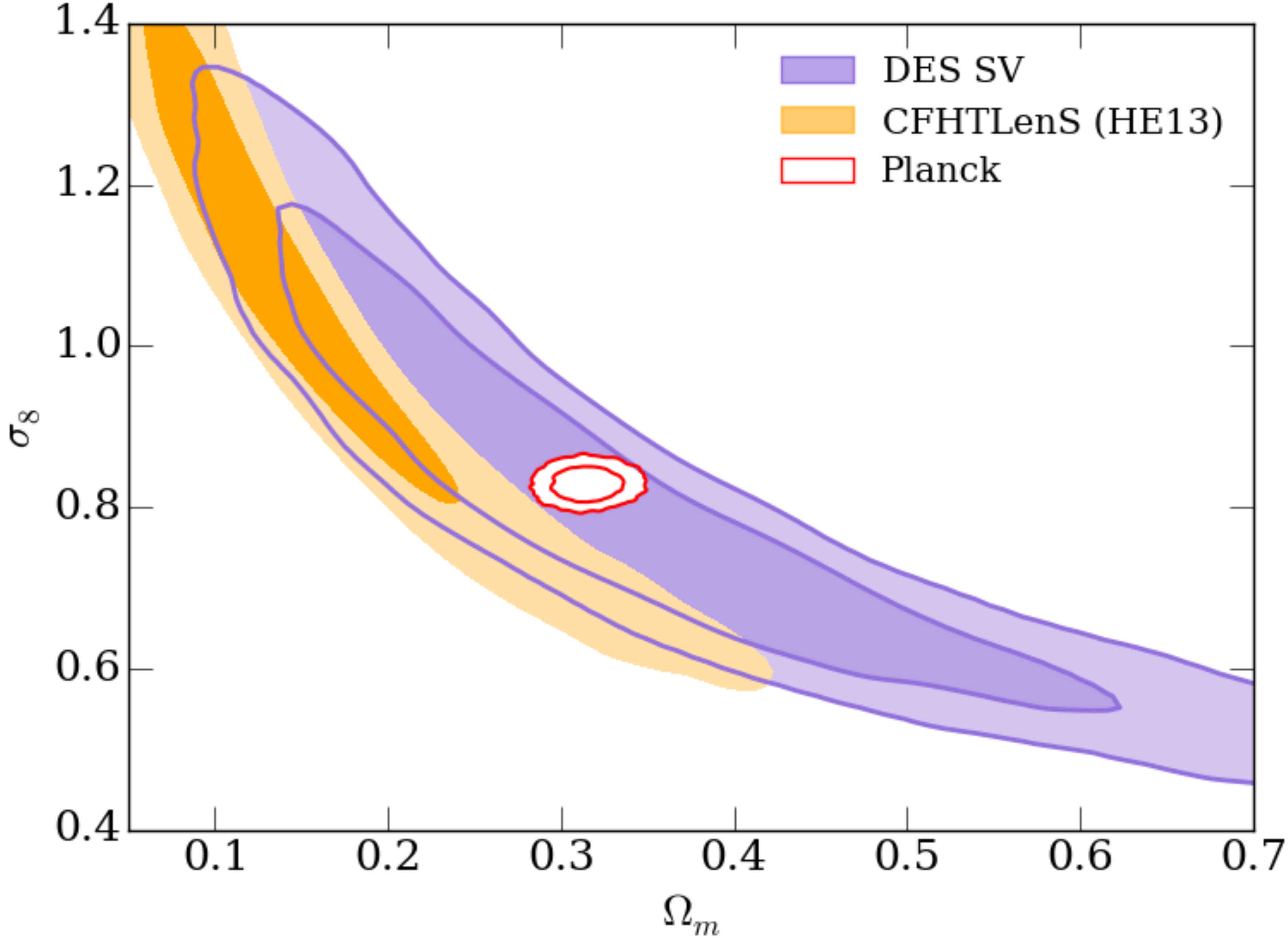


- Leistedt et al projection algorithm is now data product incorporated into DES pipeline (multi-epoch coadds increase complexity)

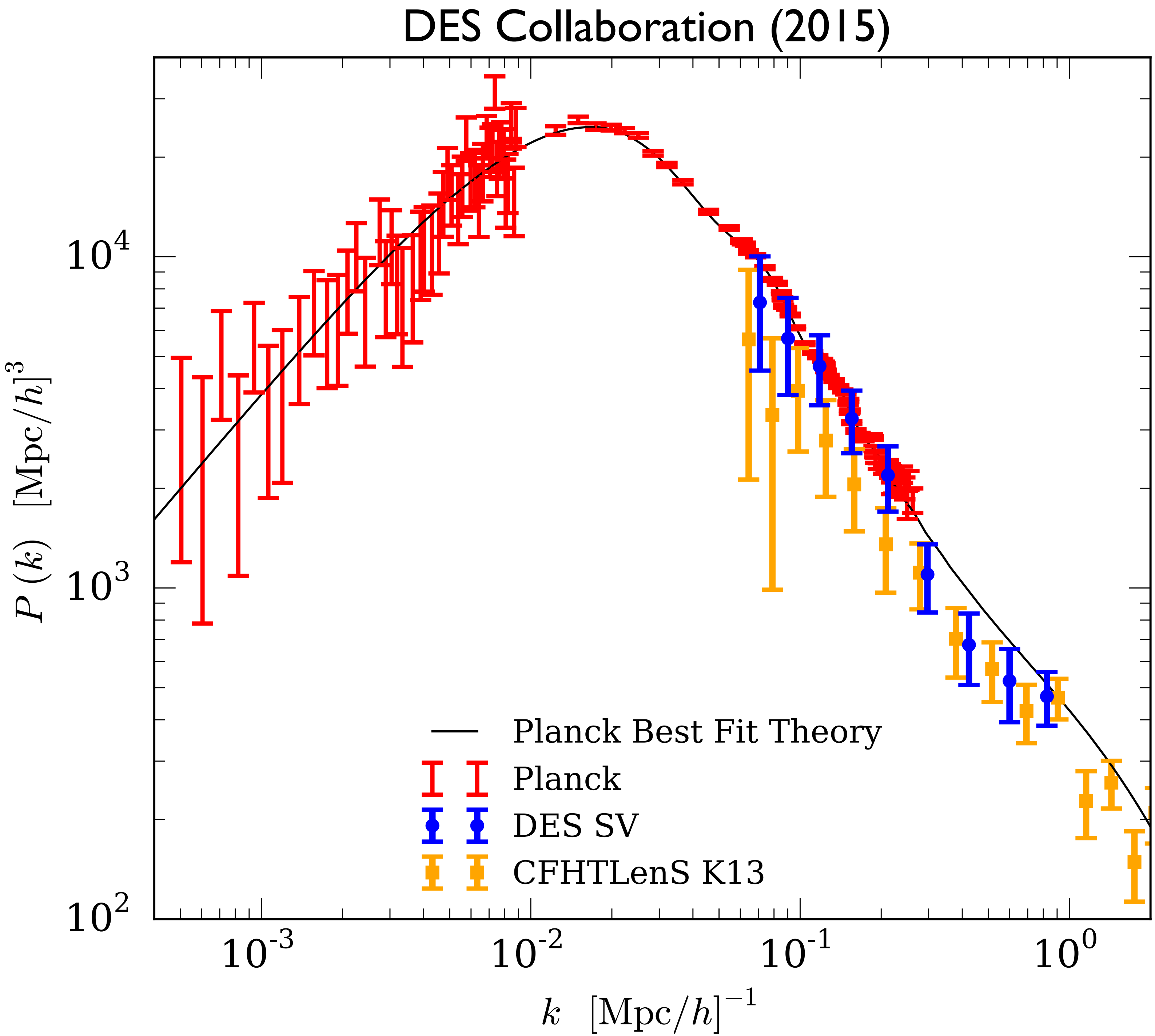
- Used to investigate impact on clustering studies (LSS/shear/lensing), photo-z estimation, star/galaxy separation, survey depth fluctuations….

Leistedt, Peiris, Elsner et al. (DES Collaboration), 2015

DES Collaboration (2015)



Data vectors available at http://deswl.github.io/



DES Collaboration (2015)
$P\,(k)\ \ [\mathrm{Mpc}/h]^3$
$k\ \ [\mathrm{Mpc}/h]^{-1}$
10^2
10^3
10^4
10^{-3}
10^{-2}
10^{-1}
10^{0}
Planck Best Fit Theory
Planck
DES SV
CFHTLenS K13

Towards fundamental physics from cosmological surveys

- ***Understand your observations!***
  Need thorough understanding of data & systematics for convincing detections of new physics.

- ***From precision to accurate cosmology with large imaging surveys***

- ***Fundamental physics from the foreground-obscured, gravitationally-lensed CMB polarization***

Robust CMB polarisation forecasts

- *Degree-scale B-modes: inflation*

- *Arc-minute scale B-modes: gravitational lensing*

  – *late-time physics: sum of neutrino masses*
  – *geometry: break geometric degeneracy, measure curvature*

- *EE and TE more constraining than TT (Galli+ 1403.5271)*

- *Huge investment!*

  AdvACTPol, BICEP3, CLASS, Simons Array, SPT-3G, EBEX10K, PIPER, SPIDER, COrE+, LiteBIRD, PIXIE, Stage IV, …

Time to revisit forecasts!

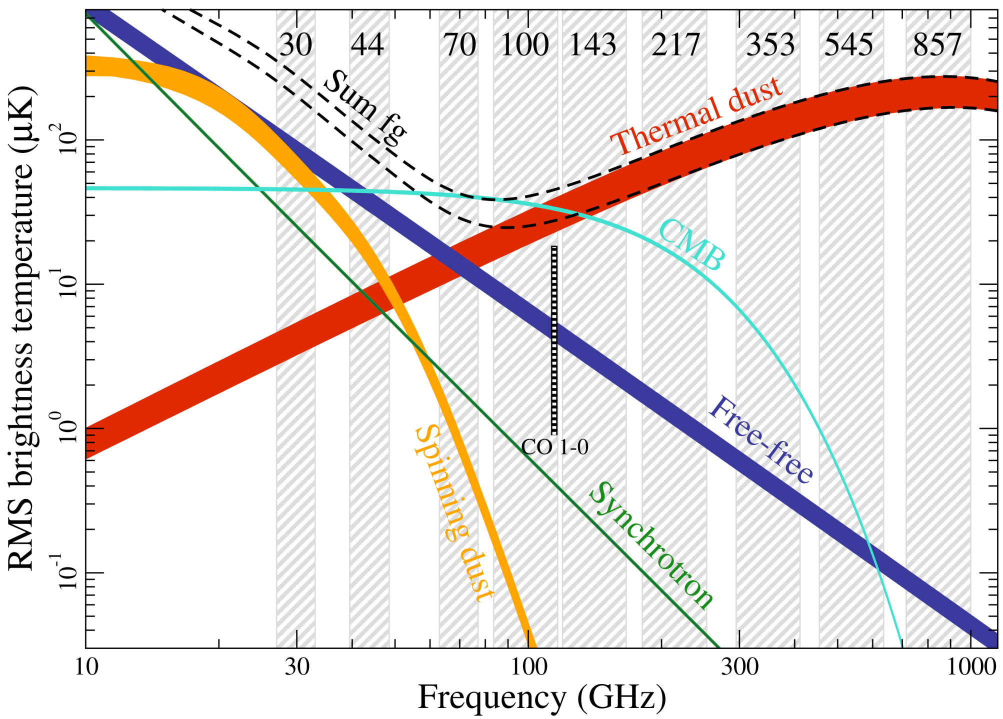
Josquin Errard

Stephen Feeney

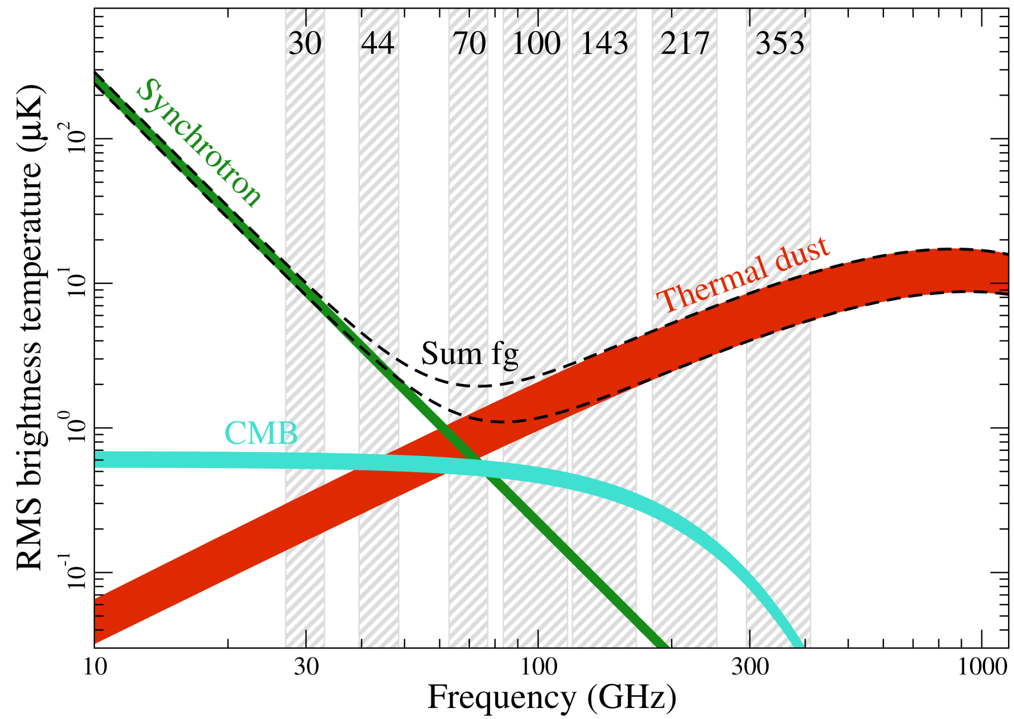
- latest frequency, spatial & angular foreground information *(Planck Collaboration 1502.01588)*
- propagate component-separation uncertainties self-consistently through delensing to forecast
- Can we find **synergy** between different experiments?
- Released as online tool: *http://turkey.lbl.gov*

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

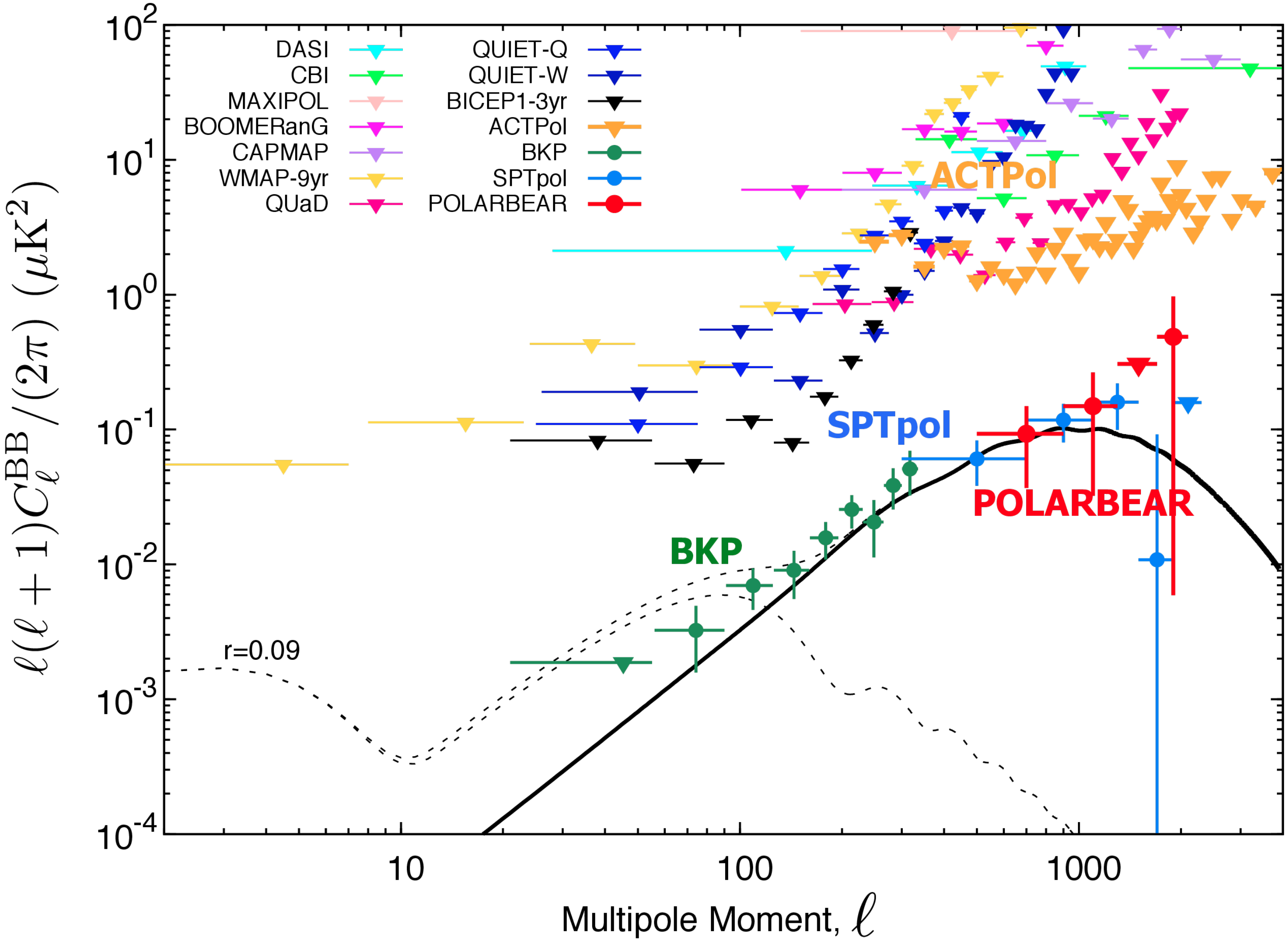
Frequency dependence of Galactic foregrounds



Temperature



Polarisation



A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR
The POLARBEAR Collaboration
The Astrophysical Journal **(2014)**

Measurements of Sub-degree B-mode Polarization in the Cosmic Microwave Background from 100 Square Degrees of SPTpol Data
R. Keisler et al.
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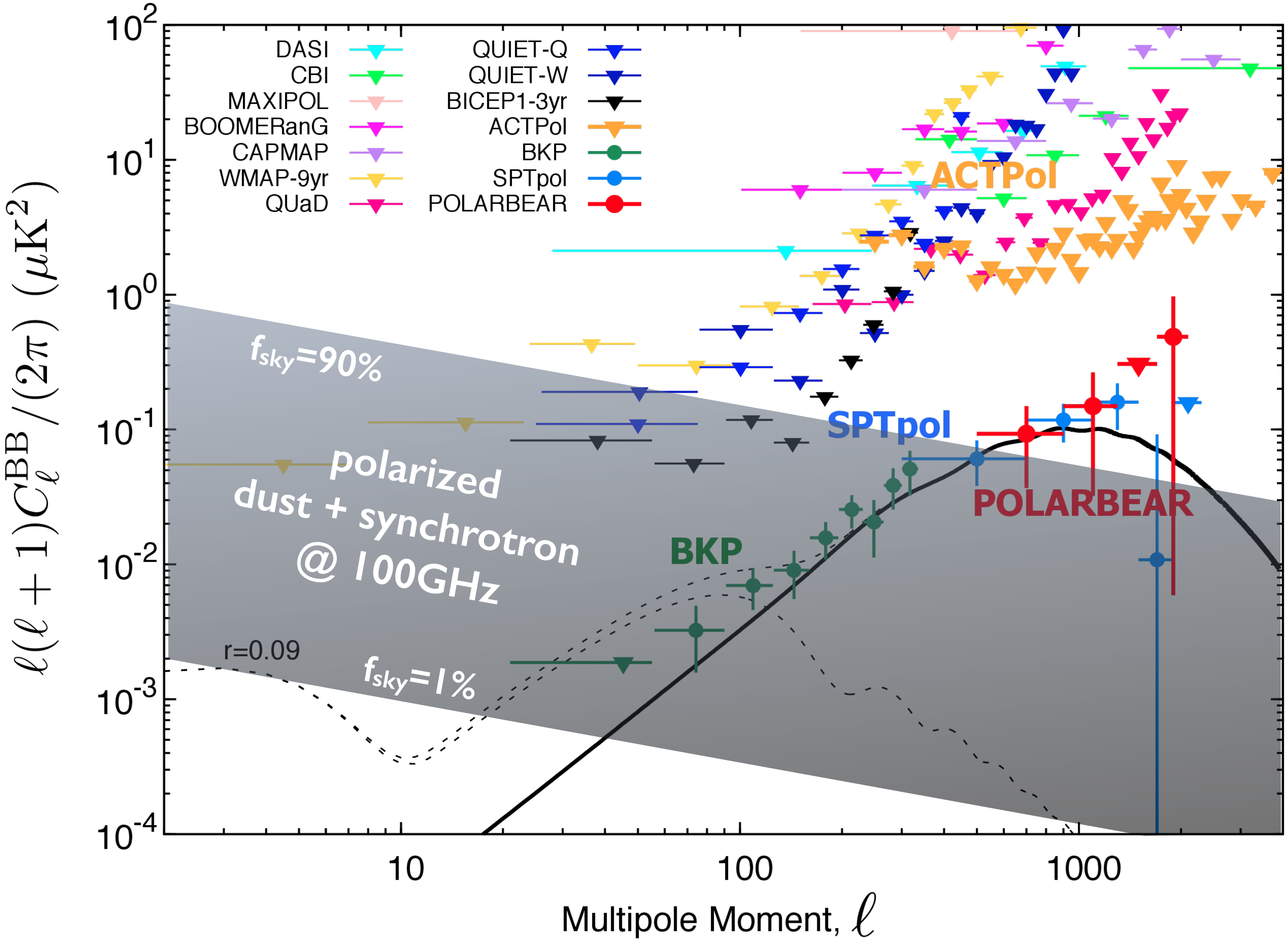
Joint Analysis of BICEP 2 / Keck Array and Planck Data
P. Ade et al.
Physical Review Letters **(2015)**

BICEP/Keck Array 95 GHz (2015)
r<0.09 (95%)

Josquin Errard



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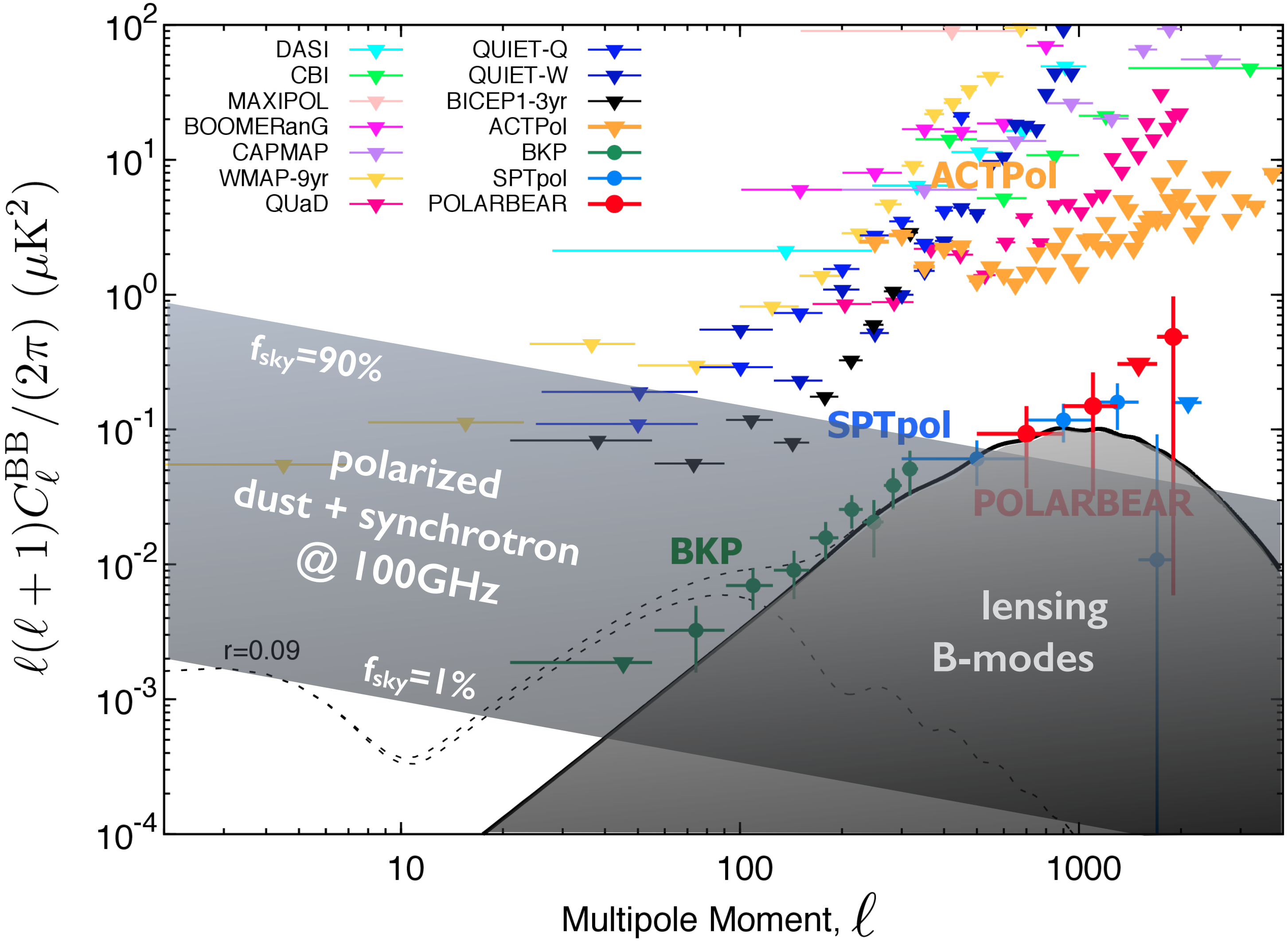

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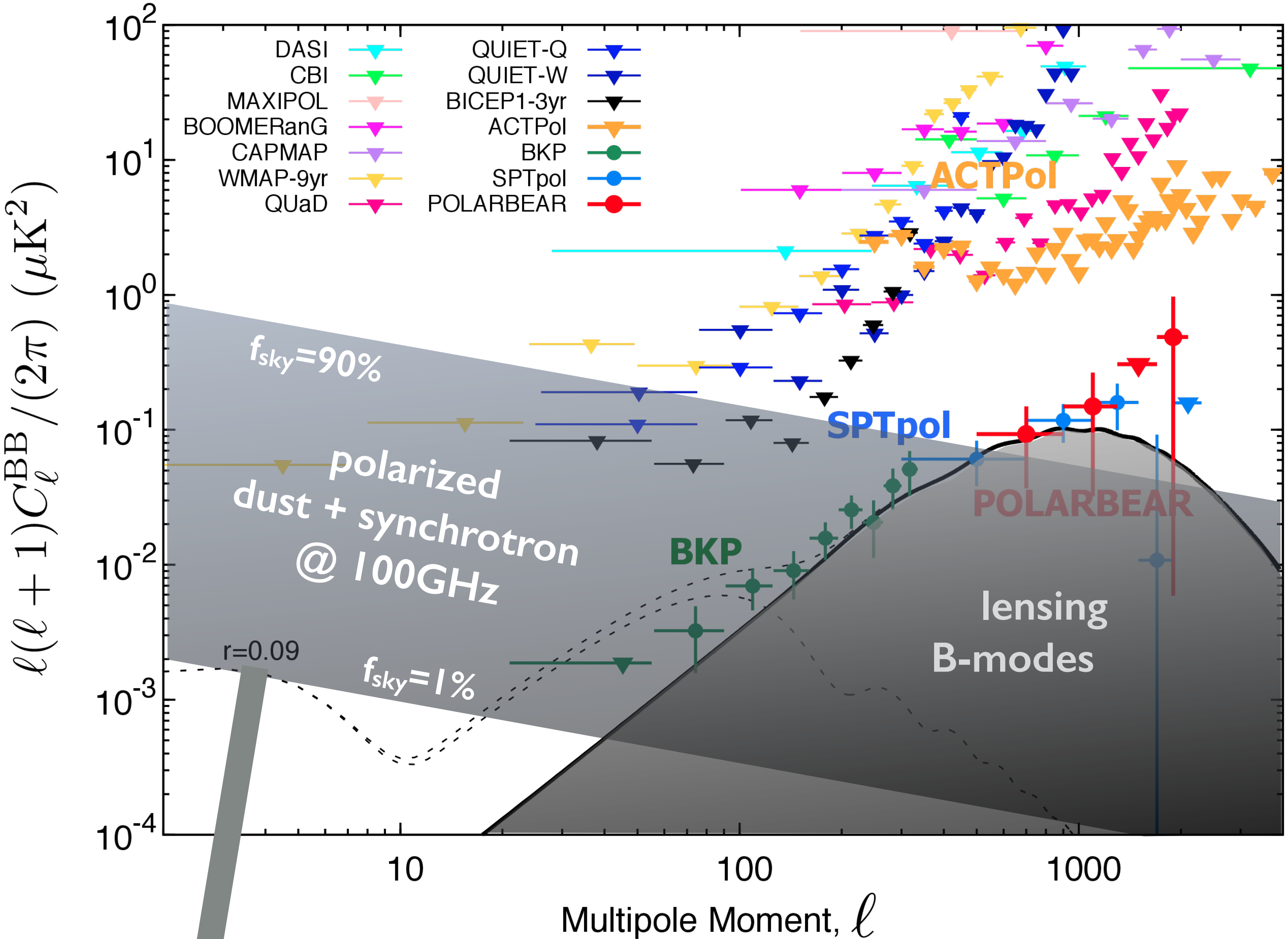

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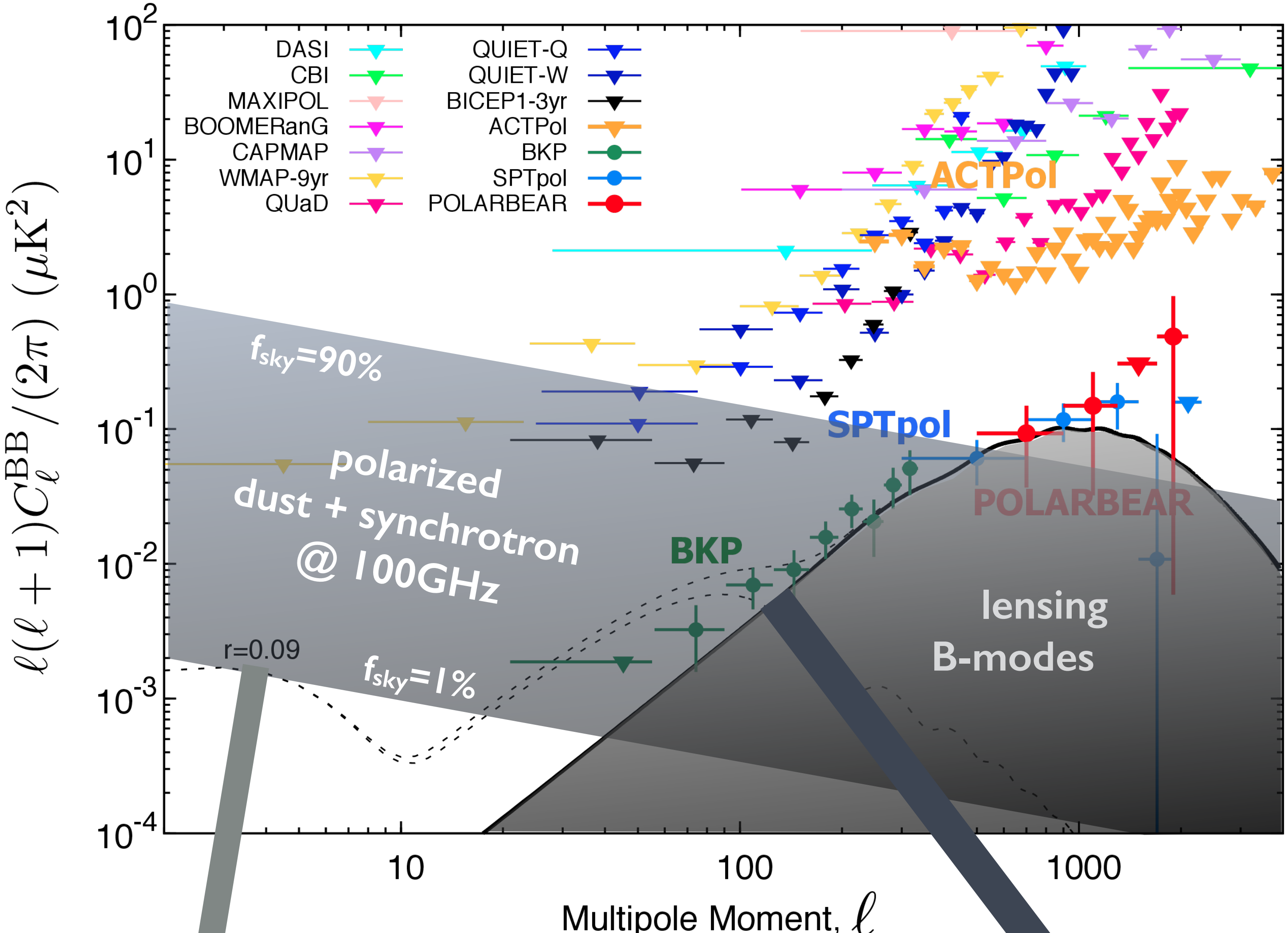
foregrounds cleaning

[Stompor et al (2009), Stivoli et al (2010) Errard et al (2011+2012)]

Josquin Errard



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foregrounds cleaning

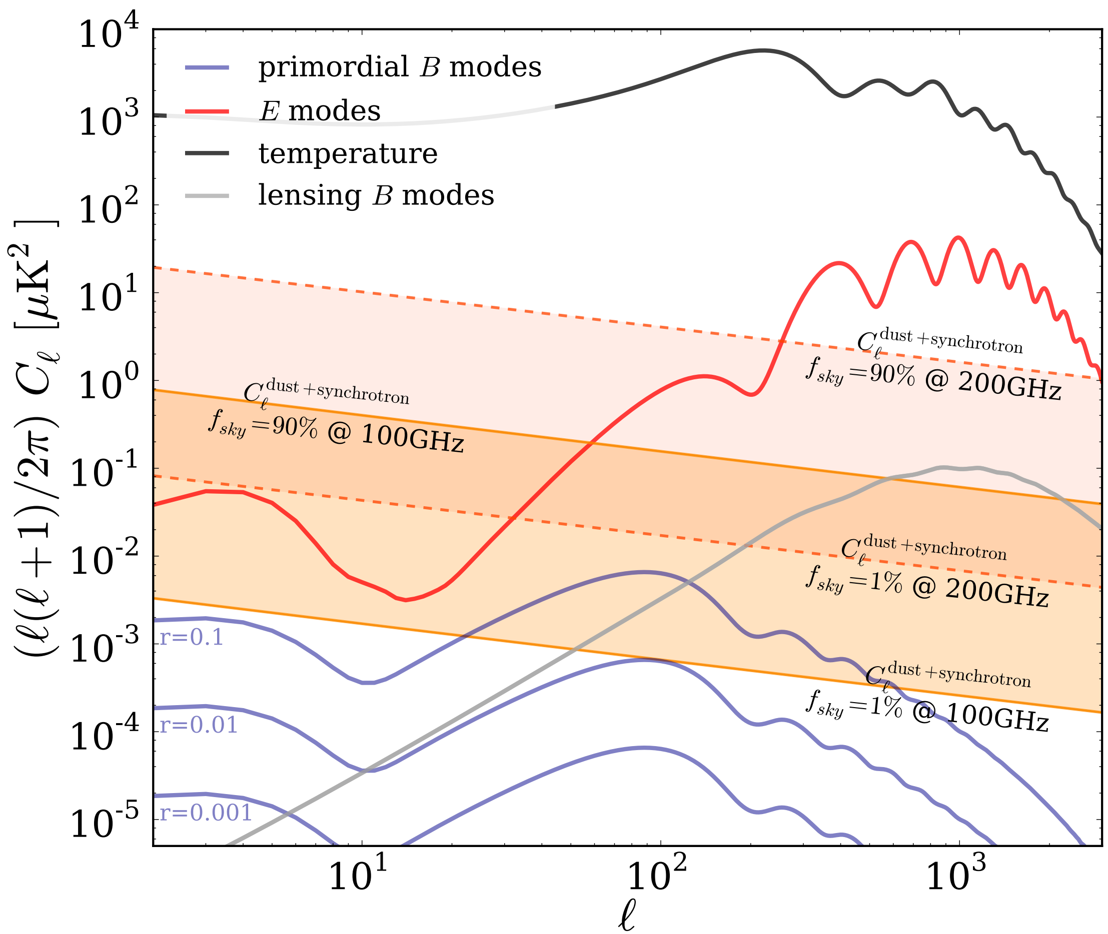
[Stompor et al (2009),
Stivoli et al (2010)
Errard et al (2011+2012)]

delensing

[Seljak & Hirata (2004),
Smith et al (2012),
Sherwin & Schmidtfull (2015)]

Josquin Errard

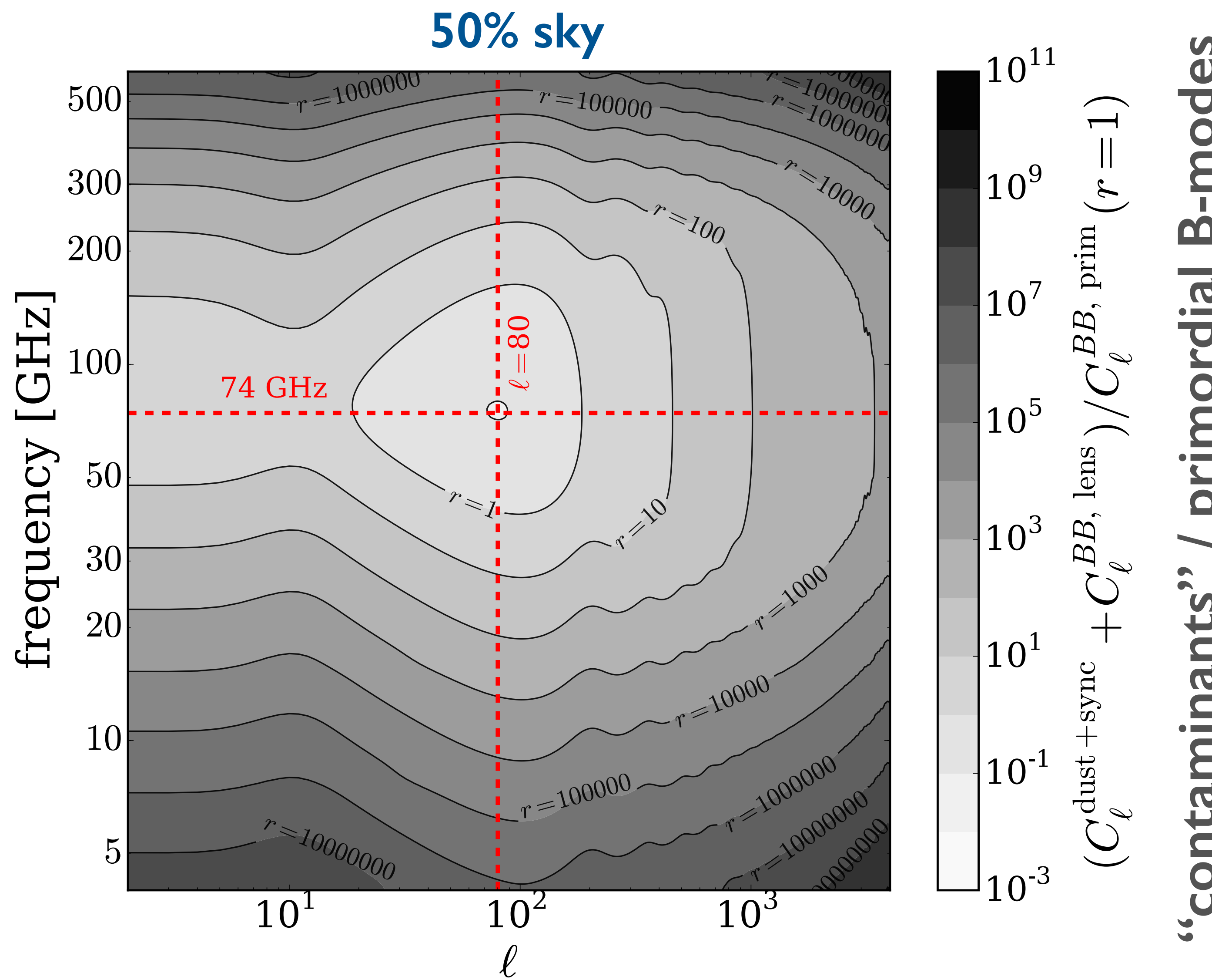
Polarisation is not going to be easy.



- Planck/BICEP2/Keck: polarised dust and/or synchrotron important at all Galactic latitudes (1502.00612, 1502.01588)
- Lensing additional "foreground" for tensors

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

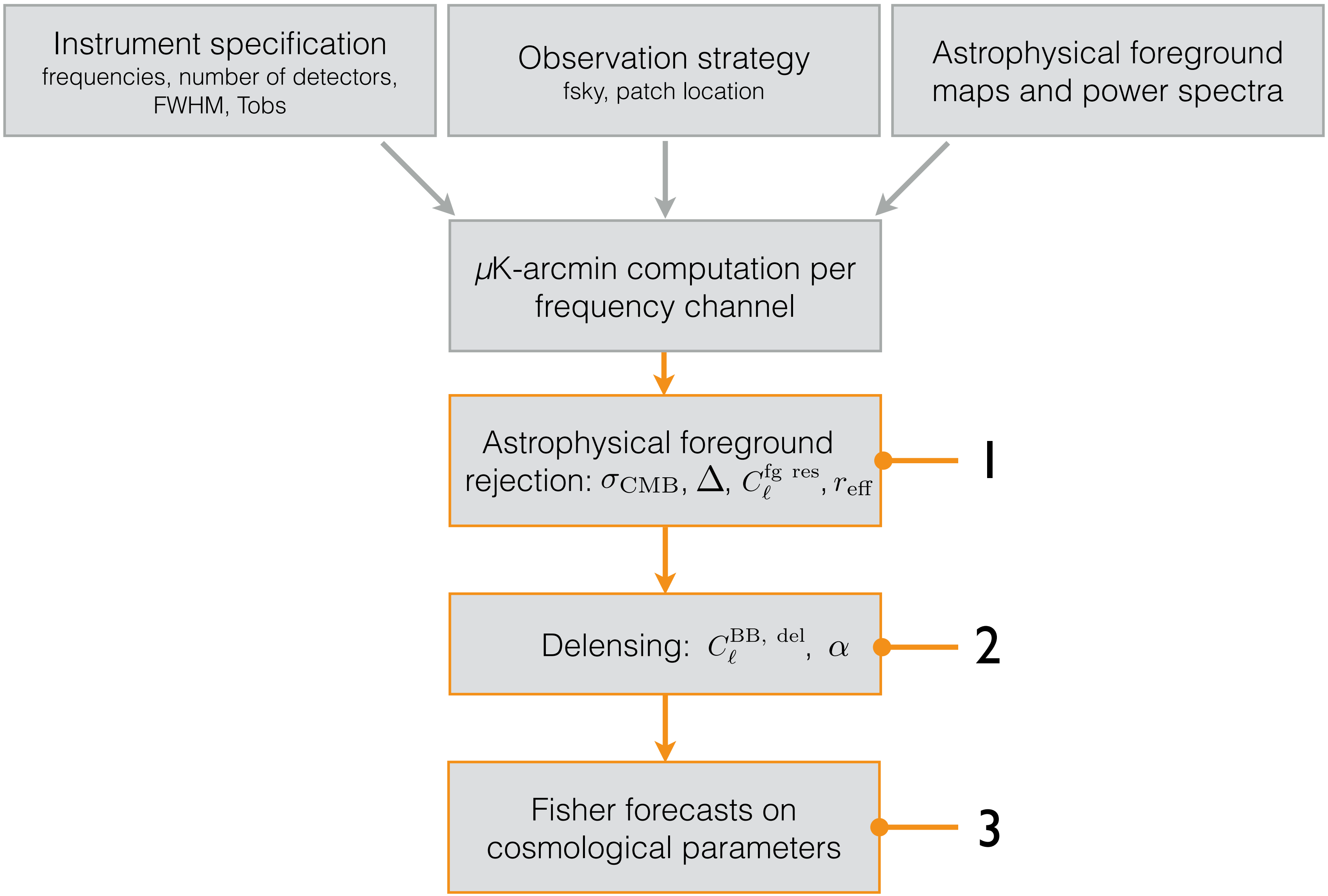
Polarisation is not going to be easy.



- Half-sky minimum for tensors: ℓ ~ 80, 75 GHz

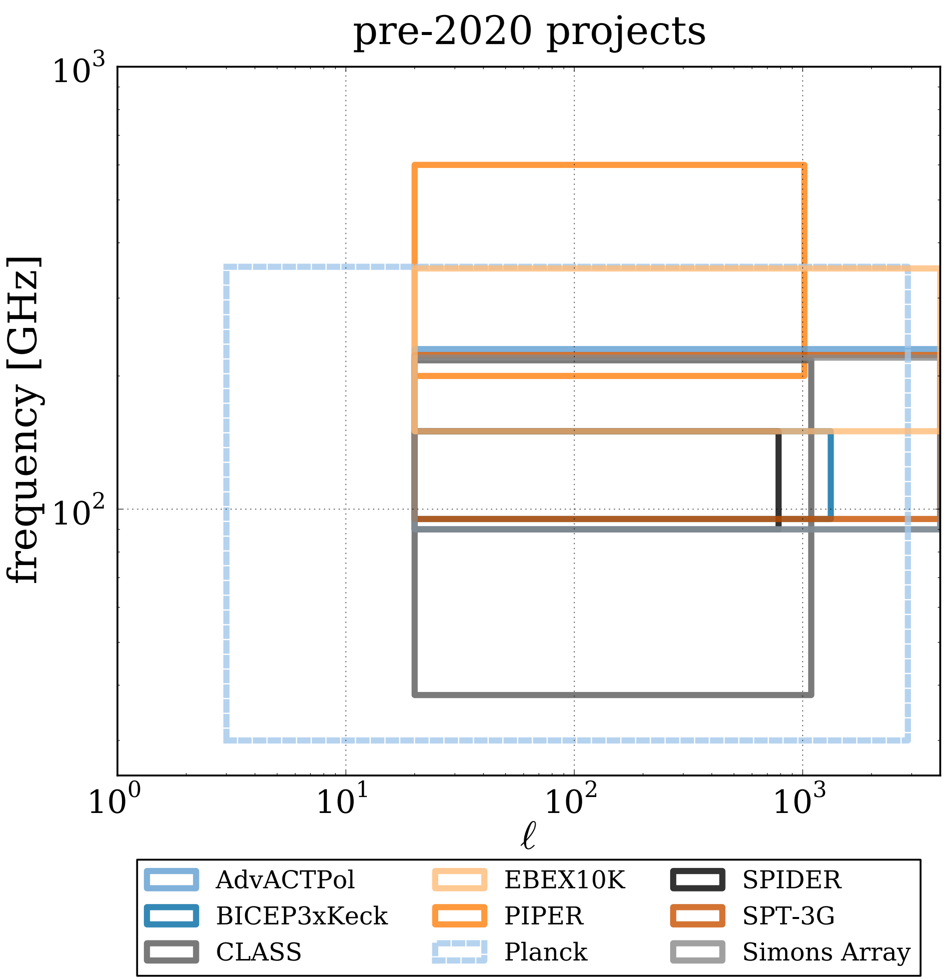
Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

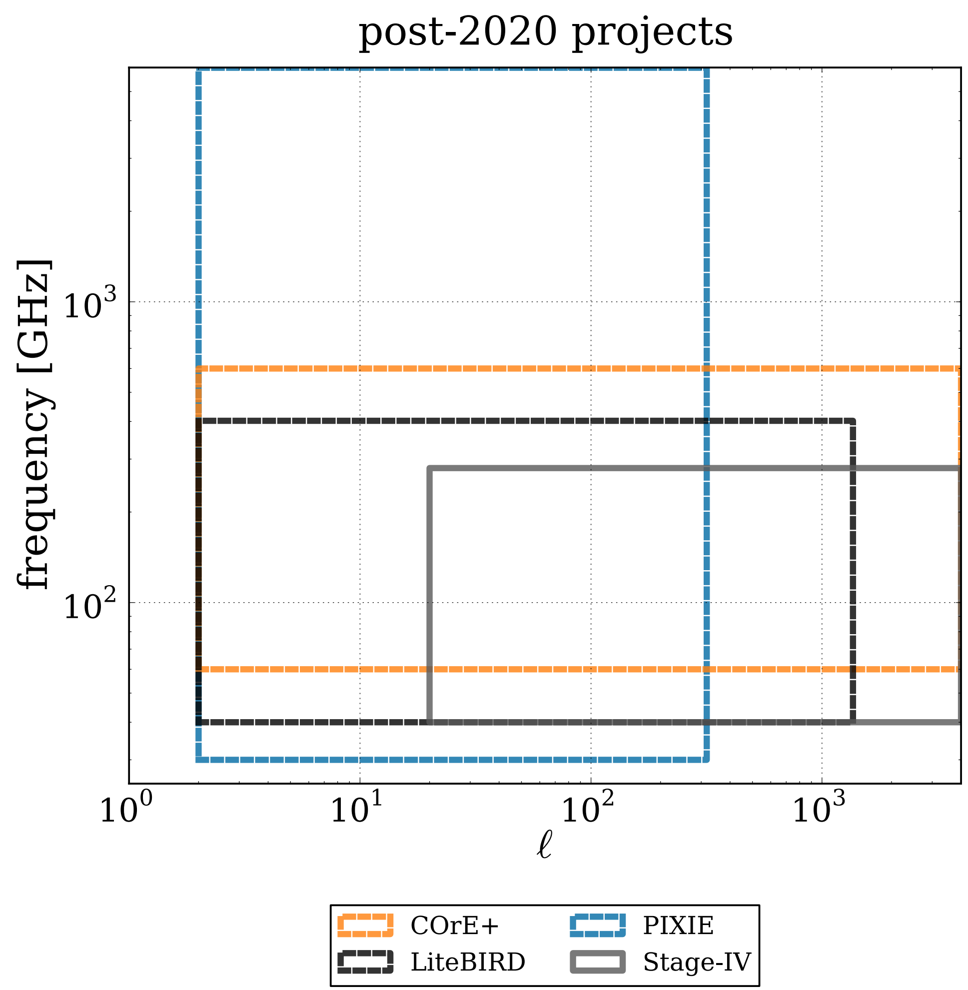
Forecast algorithm



Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

Experiments

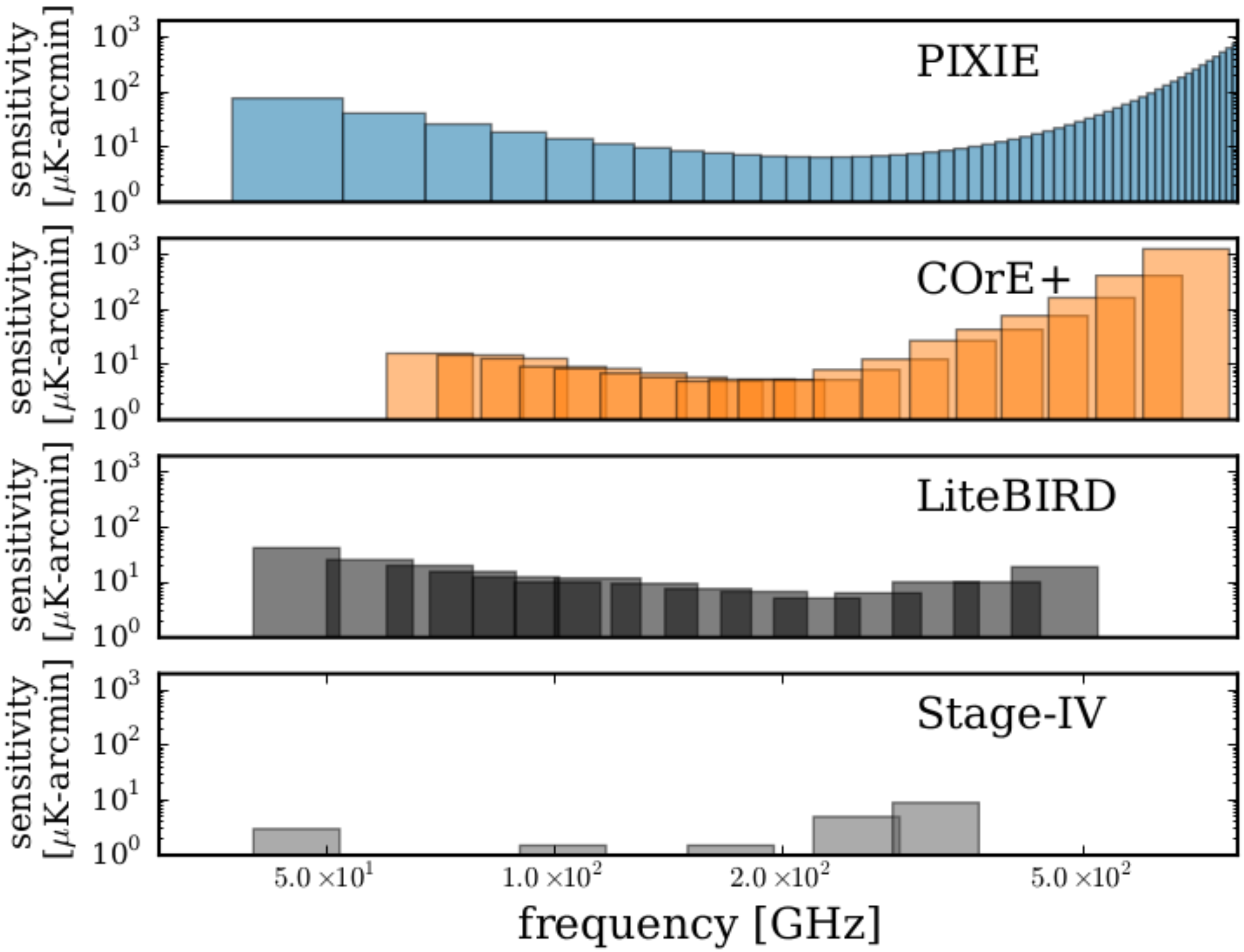




- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

Errard, Feeney (joint first authors), Peiris, Jaffe (1509.06770)

Experiments (post-2020 examples)



- Frequency bands, polarisation noise, beams and fsky
- Pre-2020 all crossed with Planck

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Component separation

- Parametric maximum-likelihood foreground cleaning *(Stompor+ 0804.2645)*

$$d_i(p) = A_{ij}\, s_j(p) + n_i(p)$$

p=pixel (at Healpix Nside=128), i=frequency, j=components

- Forecast mixing matrix estimation with Fisher approach *(Errard+ 1105.3859)*

  - Includes foreground frequency, spatial, angular dependence
  - component separation boosts noise, leaves residuals

- **Components:** CMB, synchrotron and dust (ref. freq. 150 GHz)

$$A^{\rm raw}_{\rm sync}(\nu, \nu_{\rm ref}) \equiv \left(\frac{\nu}{\nu_{\rm ref}}\right)^{\beta_{\rm s}} \qquad A^{\rm raw}_{\rm dust}(\nu, \nu_{\rm ref}) \equiv \left(\frac{\nu}{\nu_{\rm ref}}\right)^{\beta_{\rm d}+1} \frac{e^{\frac{h\nu_{\rm ref}}{k\,T_{\rm d}}} - 1}{e^{\frac{h\nu}{kT_{\rm d}}} - 1}$$

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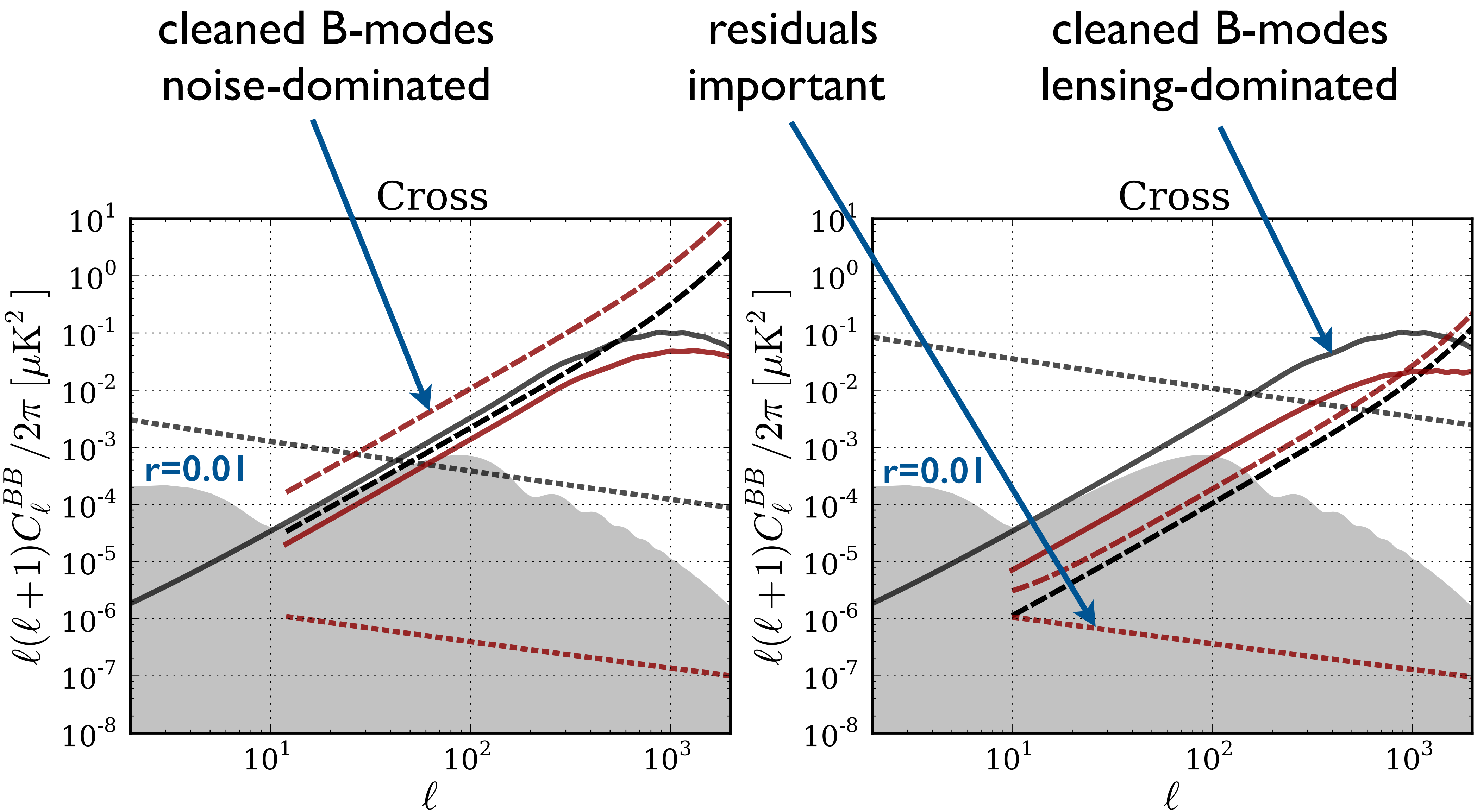
Foregrounds: selected real experiments



Pre-2020: ground x balloon

Post-2020: ground x satellite

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Forecasting delensing

- Lensing acts like white noise (for r) at ~5 uK-arcmin

- Delens! Subtract estimate of lensed B mode from (noisy) E mode and (noisy) lensing potential
  (Knox+ astro-ph/0202286, Okamoto+ astro-ph/0301031)

- How to **source** lensing potential estimate?

CMB x **CMB**

- noisy B mode can be iterated (Seljak+ astro-ph/0310163)
  (method: Smith+ 1010.0048)

CMB x **CIB**

- dusty galaxies trace lensing potential; use Planck's 545 GHz data
  (method: Sherwin+ 1502.05356, Simard+ 1410.0691)

CMB x **LSS**

- assume perfect measurement out to z~3.5 (LSST)
  (method: Smith+ 1010.0048)

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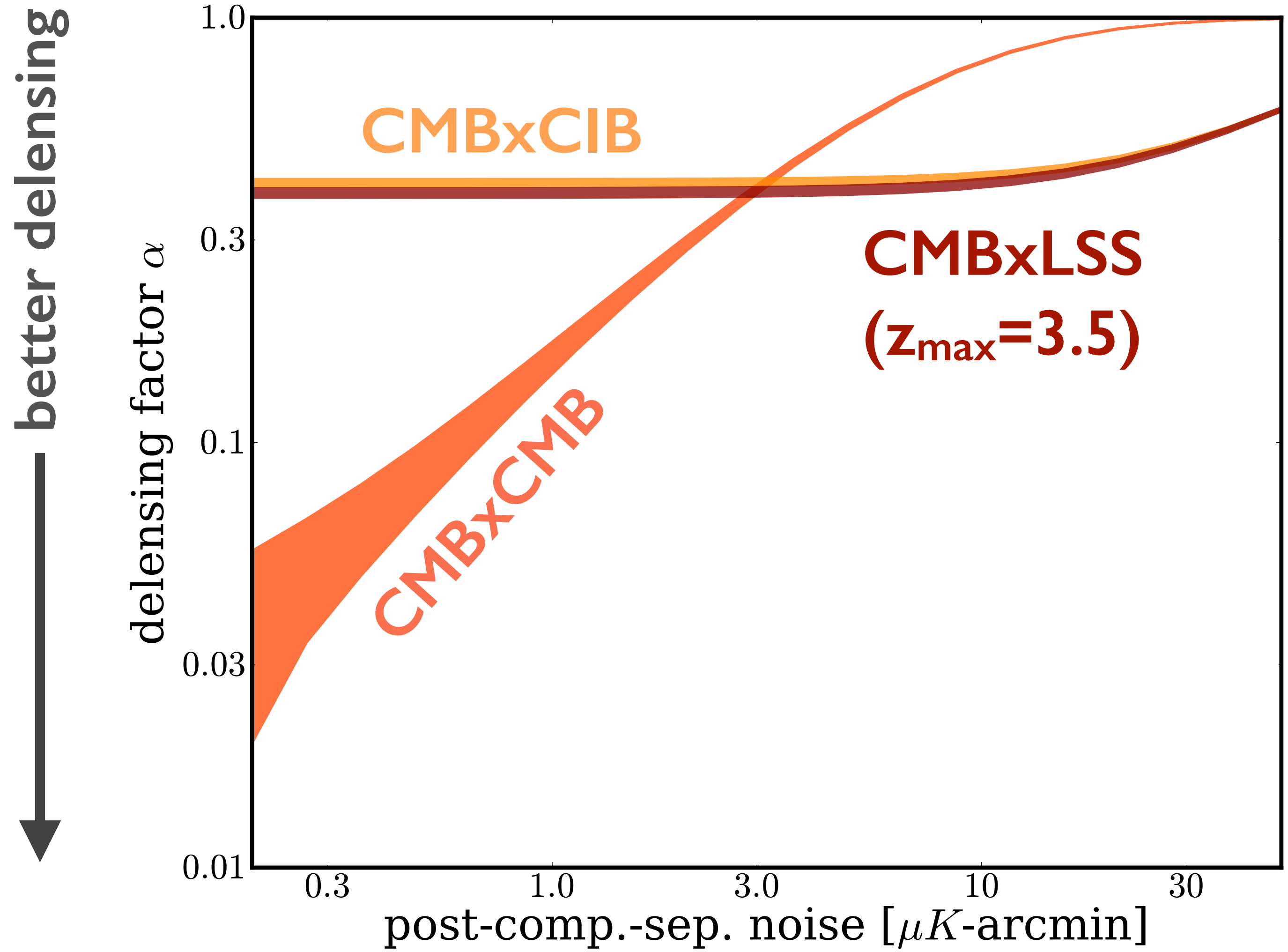
Delensing: toy experiment



- 3' beam, 0.01 < f_{sky} < 1.0 (f_{sky} floor without delensing)
- CIB/LSS better for noisy expts; CMB delenses to zero if noiseless.

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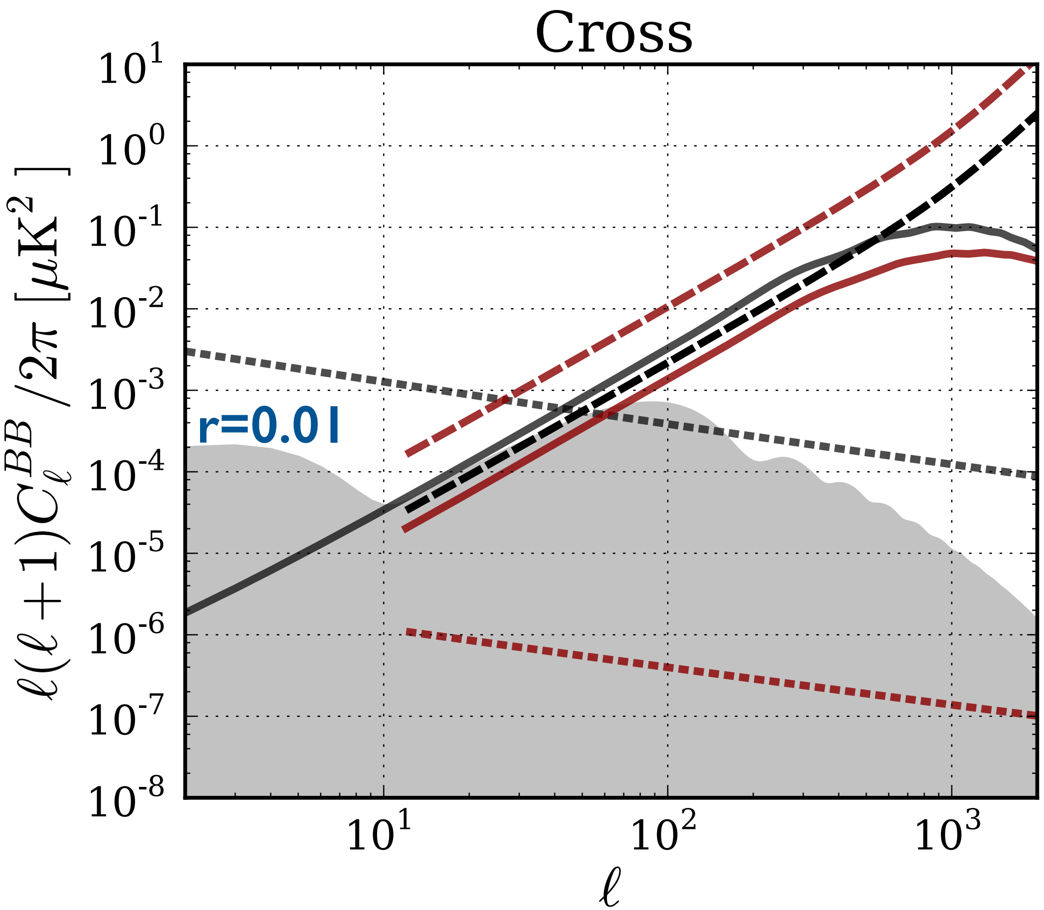
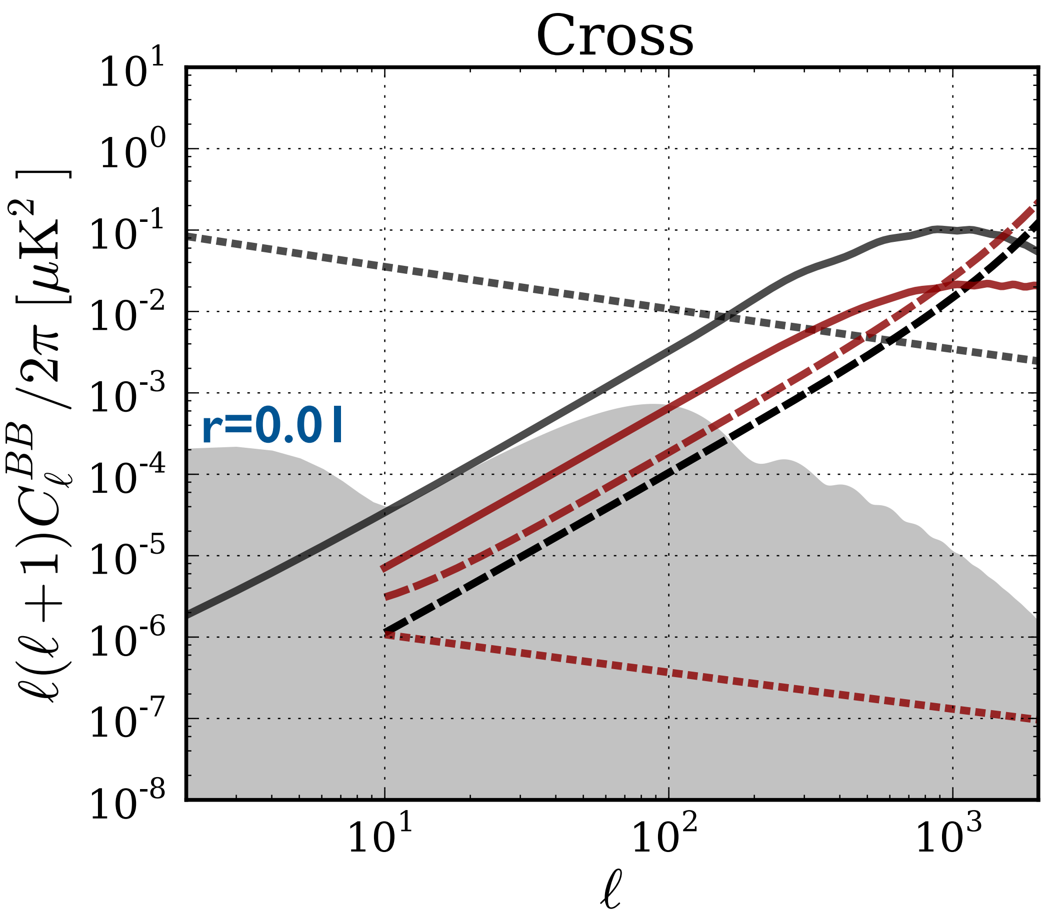
Delensing: selected real experiments



Pre-2020: ground x balloon
CIB delensing



Post-2020: ground x satellite
CMB delensing

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Fisher-matrix forecasts for cosmology

model	α_s	r	n_t	Ω_k	M_ν	N_{eff}	w_0	constraints
ΛCDM+r		✓						$\sigma(r)$
ΛCDM+$r+n_t$		✓	✓					$\sigma(n_t)$
ΛCDM+inf	✓	✓	✓	✓				$\sigma(n_s)$, $\sigma(\alpha_s)$
ΛCDM+Ω_k				✓				$\sigma(\Omega_k)$
ΛCDM+M_ν					✓			$\sigma(M_\nu)$
ΛCDM+N_{eff}						✓		$\sigma(N_{eff})$
wCDM							✓	$\sigma(w_0)$

- Noise includes boost from inversion, foreground residuals(, delensing residuals)
- Parameters constrained in simplest extended model
- Planck best-fit plus r = 0.001 (ΛCDM+r+n_t: r=0.1)
- Consistency relation: n_t = -r/8

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Cosmological Highlights

Pre-2020:

- **inflation:**
  - $\sigma(r=0.001) \sim 0.003$
  - $\sigma(n_t) \sim 0.2$ ($r = 0.1$)

- **neutrinos:**
  - $\sigma(M_\nu) \sim 60$ meV

    CMBxCIB deflection estimate

Post-2020:

- **inflation:**
  - $\sigma(r=0.001) \sim 2 \times 10^{-4}$

    5-σ measurement (<80% delensing)
  - $\sigma(n_t) \sim 0.03$ ($r = 0.1$)

- **neutrinos:**
  - $\sigma(M_\nu) \sim 30$ meV

    (normal vs inverted hierarchies…)
  - $\sigma(N_{eff}) \sim 0.024$

    (thermal history 1 sec after Big Bang!)

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