Understanding Inflation with Large-Scale Structure

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Invisibles 2015, Madrid

Local Primordial non-Gaussianity

- Simple form: $\Phi(\vec{x}) = \Phi_G(\vec{x}) + f_{NL}^{loc}\left(\Phi_G^2(\vec{x}) - \left\langle \Phi_G^2(\vec{x}) \right\rangle\right)$
- Distinguishes between single- and multi-field Inflation

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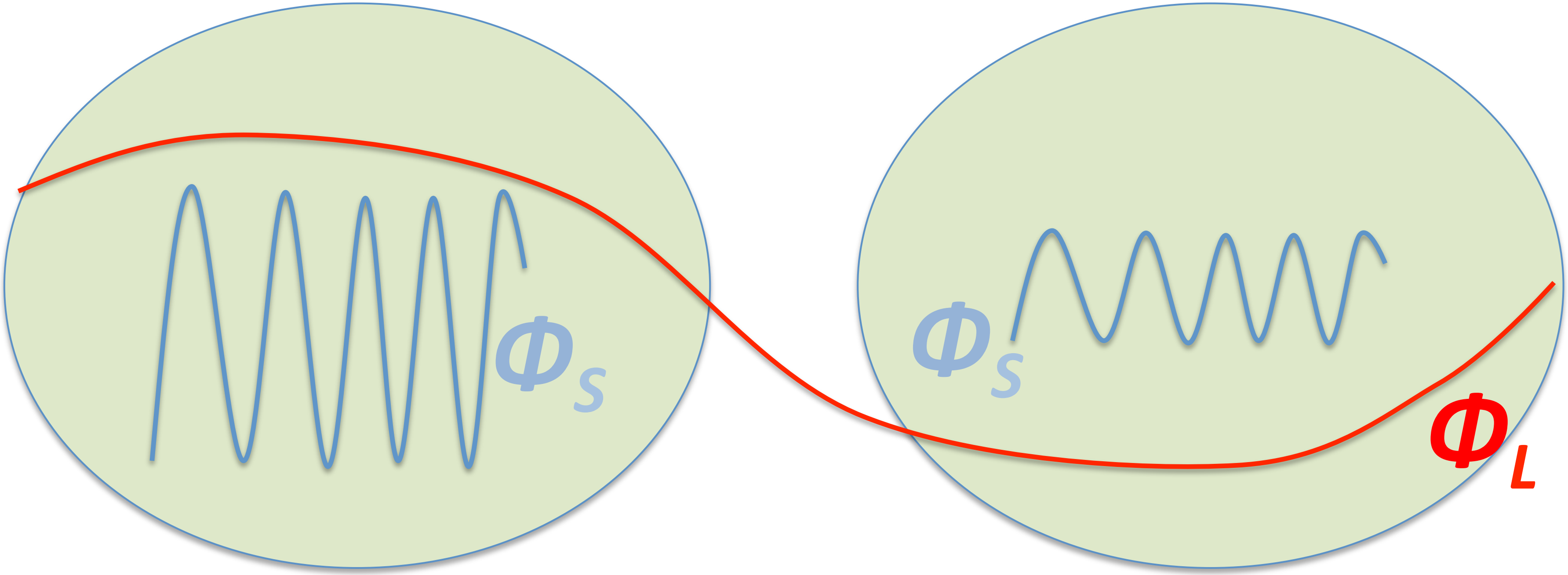
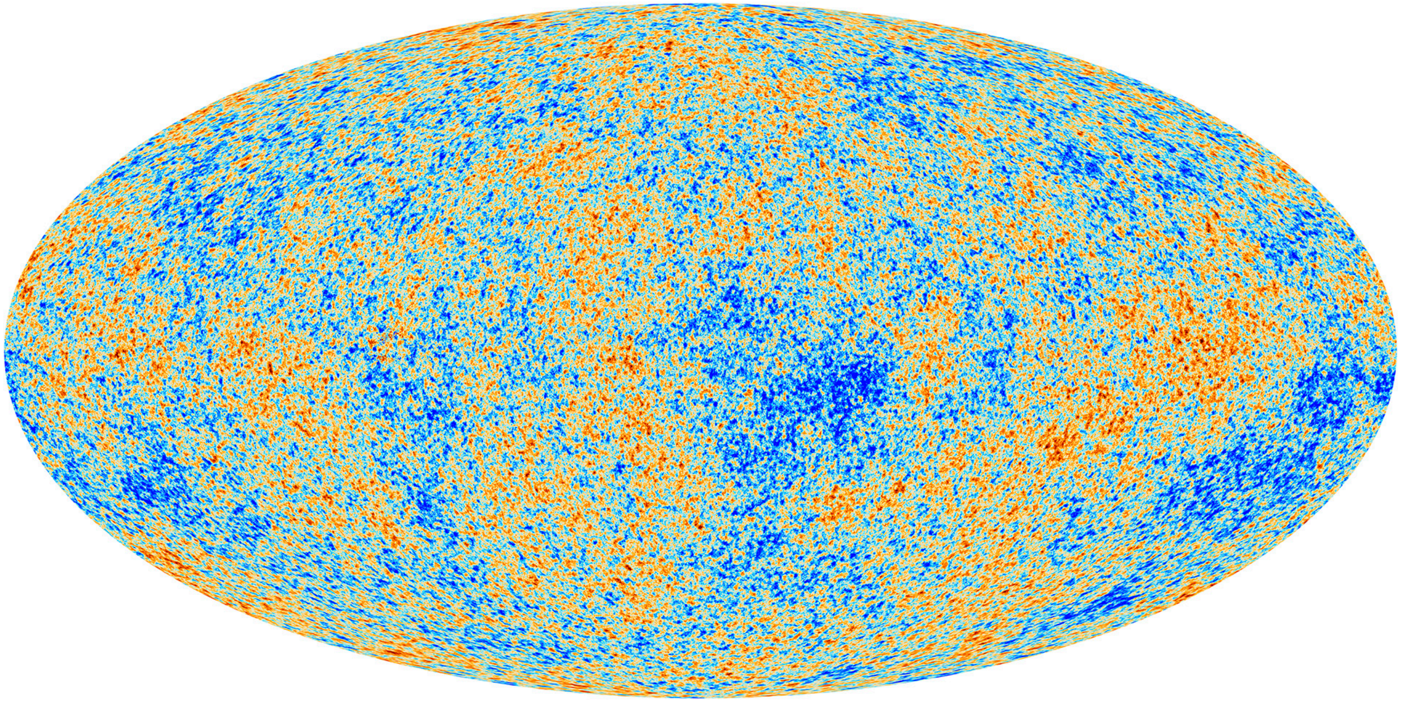
- *Local non-Gaussianity predicts squeezed-limit bispectrum:*



Current best constraints from CMB bispectrum

Planck 2015, paper XVII



Planck2015 T+P Bispectrum:

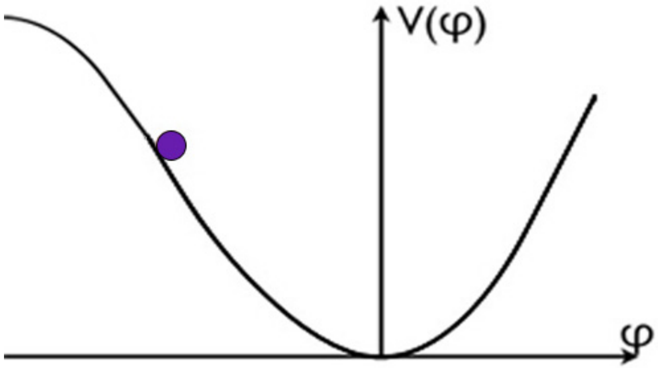
f_{NL} = 0.8 +/- 5.0 (68% CL)

Remember: $\Phi(\vec{x}) = \Phi_G(\vec{x}) + f_{NL}^{loc}\left(\Phi_G^2(\vec{x}) - \left\langle \Phi_G^2(\vec{x}) \right\rangle\right)$

Measuring local primordial non-Gaussianity to $\sigma(f_{NL}) < 1$ may distinguish between single- and multi-field Inflation

e.g. Alvarez,…, de Putter, et al (arXiv:1412.4671)

Single-Field Inflation:



Squeezed limit consistency condition by Maldacena (2003):

$$\boxed{f_{NL}^{(\text{infl})} \sim (n_s - 1) << 1}$$

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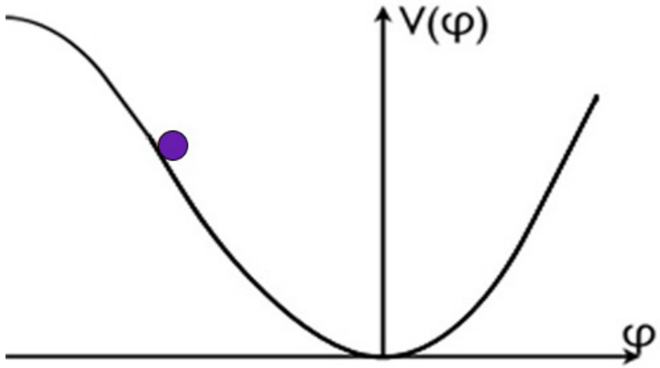

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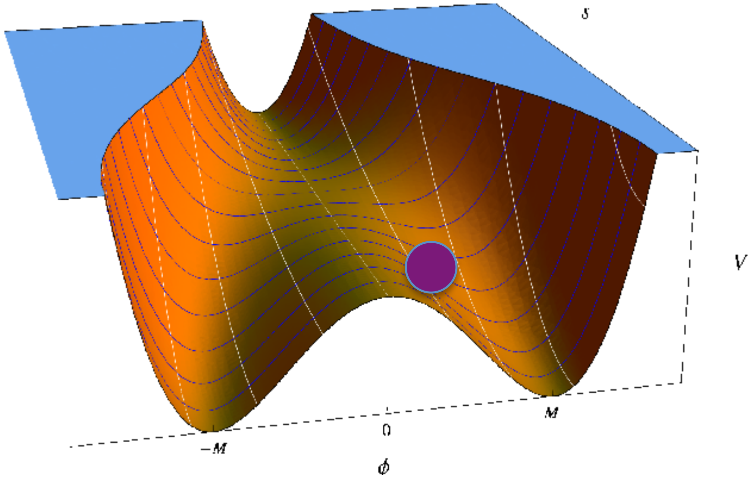
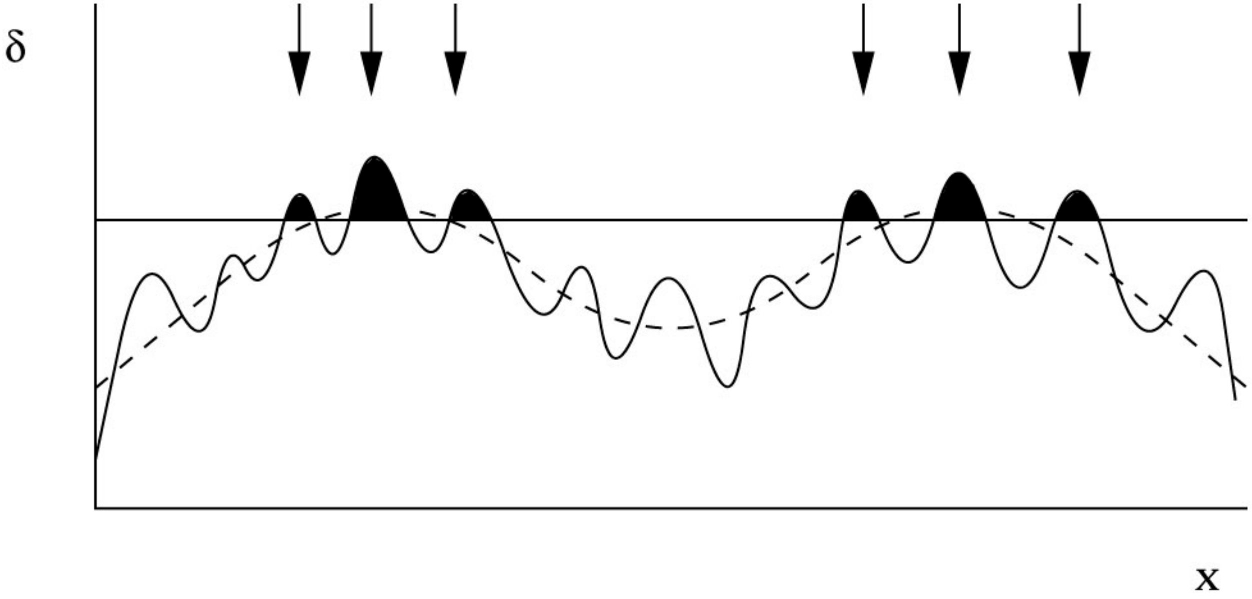
Multi-Field Inflation:



$$\boxed{\left| f_{NL}^{(\text{infl})} \right| \geq 1}$$

Primordial non-Gaussianity leads to scale-dependent halo bias

Dalal, Doré, Huterer & Shirokov 2008



$$b(k) = b_1$$

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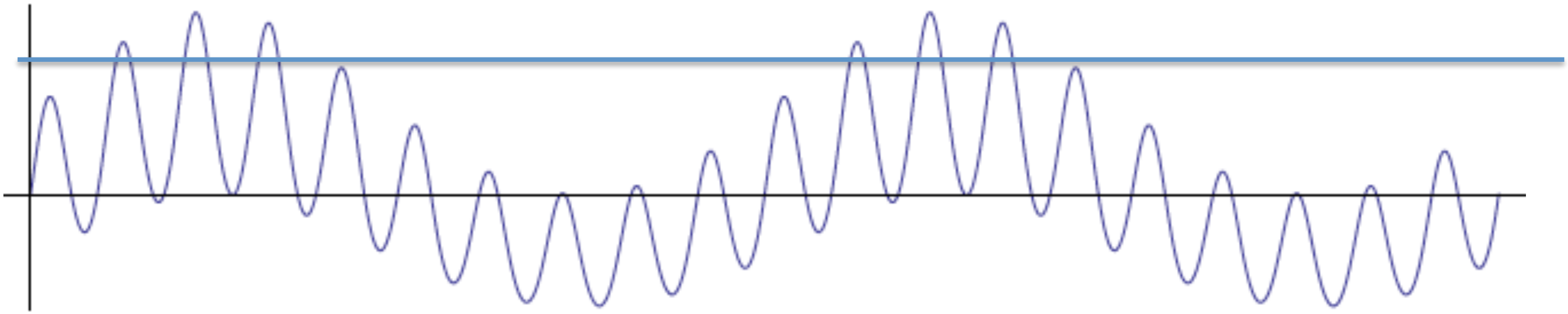


Image: Young & Byrnes 2015

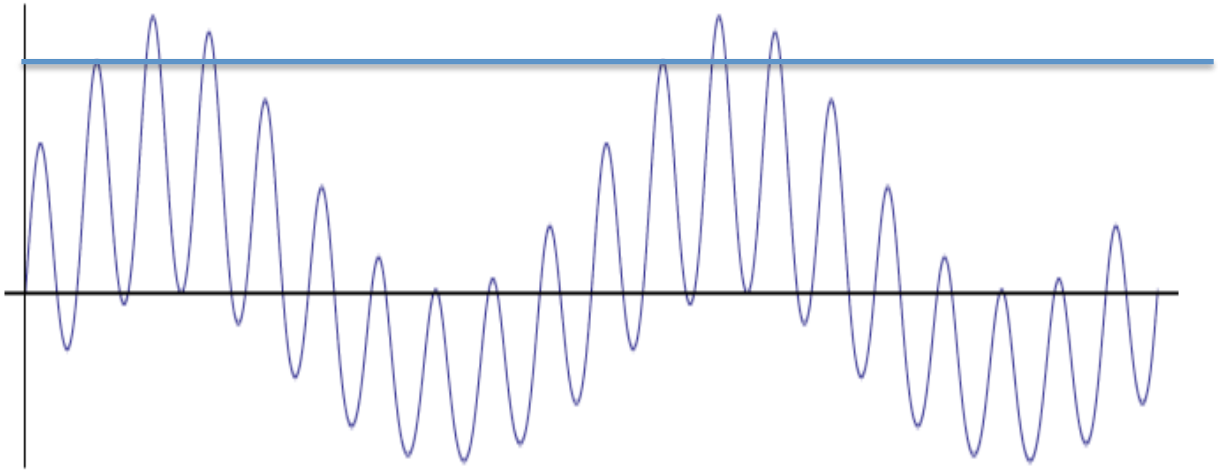
$$\Delta b(k) = 2 f_{NL} (b_1 - 1) \delta_c \frac{3\Omega_m H_0^2}{k^2 T(k) D(z)}$$

Future galaxy surveys can in principle reach $\sigma(f_{nl}) < 1$

RdP & Doré 2014, Ferrara & Smith 2014, Raccanelli et al 2014, etc

Is there scale-dependent bias in single-field Inflation?

de Putter, Doré & Green, arXiv:1504.05935



non-Gaussianity

$$\delta n = \frac{\partial n}{\partial \ln \sigma_M^2} \frac{d \ln \sigma_{ph}^2}{d\phi_l} \phi_l$$

$$\frac{d \ln \sigma^2}{d\phi_l} = -4 f_{NL}^{(\delta)}$$

Consistency Condition by Maldacena (2003):

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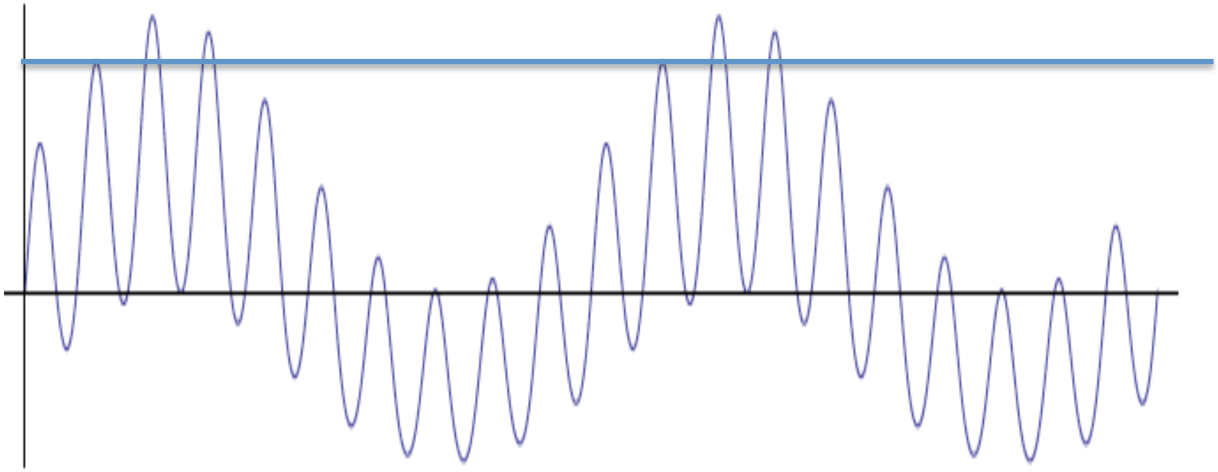

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$$f_{NL}^{(\text{infl})} \sim (n_s - 1) << 1$$

BUT: "Maldacena" applies to comoving curvature perturbation on constant density slices

$$\zeta = \zeta^{(G)} - \tfrac{3}{5} f_{NL}^{(\text{infl})} (\zeta^{(G)})^2$$

nonlinear transformation

ζ to δ

scale-dependent bias(?): $f_{NL}^{(\delta)} = -\frac{5}{3} + f_{NL}^{(\text{infl})}$

Verde & Matarrese 2009; Bruni, Hidalgo & Wands 2014; Camera, Santos & Maartens 2015,…

But is there really scale-dependent bias?

Variance on fixed ***comoving*** scale

$$\frac{d\ln\sigma^2}{d\phi_l} = -4\left(-\tfrac{5}{3} + f_{NL}^{(\mathrm{infl})}\right)$$

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Variance on fixed ***comoving*** scale

$$\frac{d\ln\sigma^2}{d\phi_l} = -4\left(-\tfrac{5}{3} + f_{NL}^{(\mathrm{infl})}\right)$$

$$\xrightarrow[\text{explicit calculation}]{}$$

Variance on fixed ***physical*** scale

$$\frac{d\ln\sigma_{ph}^2}{d\phi_l} = 0$$

But is there really scale-dependent bias?
No.

Variance on fixed ***comoving*** scale

$$\frac{d\ln\sigma^2}{d\phi_l} = -4\left(-\tfrac{5}{3} + f_{NL}^{(\mathrm{infl})}\right)$$

$$\xrightarrow{\text{explicit calculation}}$$

Variance on fixed ***physical*** scale

$$\frac{d\ln\sigma_{ph}^2}{d\phi_l} = 0$$

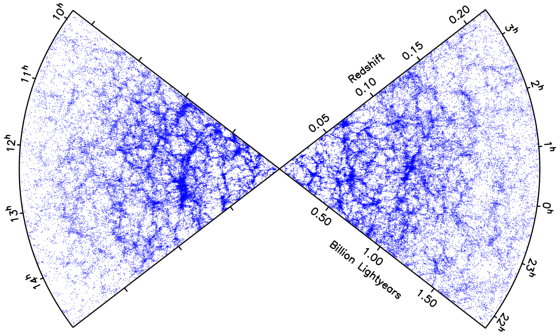
Resolution: When the small-scale variance is computed at fixed physical scale, the dependence on φ$_l$ cancels exactly

de Putter, Doré & Green, arXiv:1504.05935
see also: Dai, Pajer & Schmidt 1504.00351

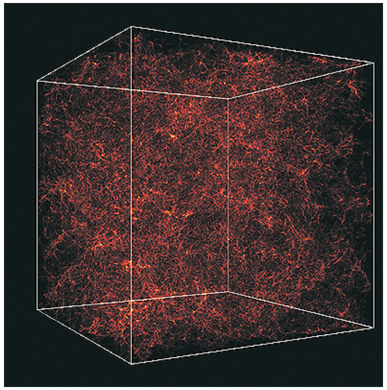
de Putter & Doré 2014

Optimizing a galaxy survey: *how to reach $\sigma(f_{NL}) < 1$?*

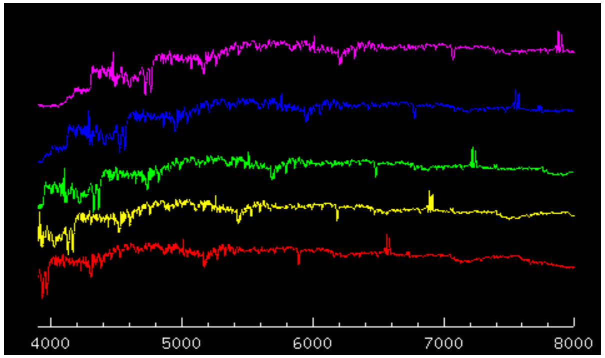
- Number density
  - *n = few 10^{-4} $(h^{-1}\,\mathrm{Mpc})^{-3}$ ($n\,P \sim 1$)*



- Survey volume
  - *V = many 100's $(h^{-1}\,\mathrm{Gpc})^{3}$ for $\sigma(f_{NL}) \sim 1$*



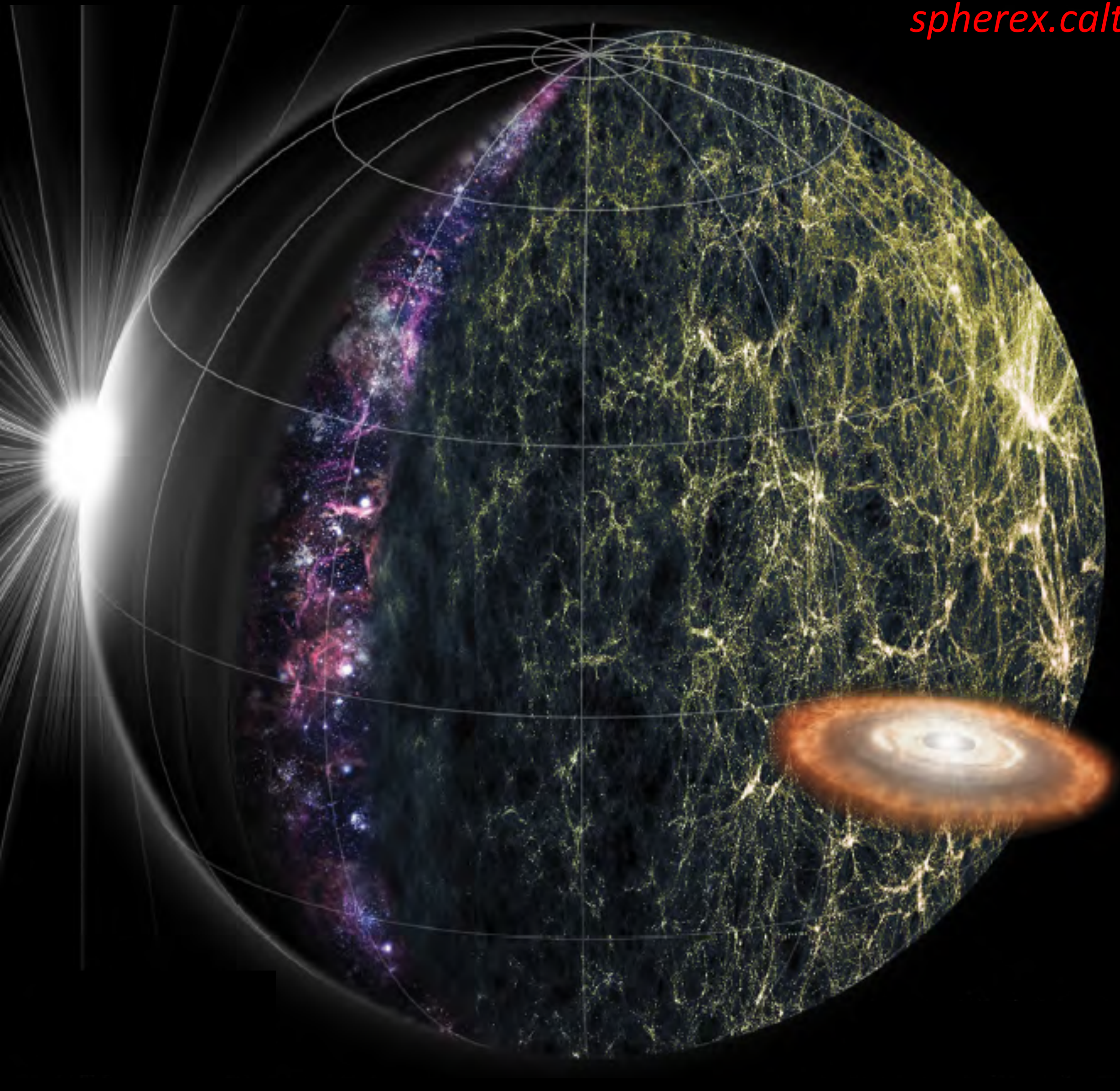
- Redshift accuracy
  - *High redshift accuracy NOT needed*



A large-area, narrow-band imaging survey may be an ideal f_{NL} experiment

SPHEREx: an All-Sky Spectral Survey

Doré, Bock, Capak, de Putter, et al (1412.4872)
spherex.caltech.edu



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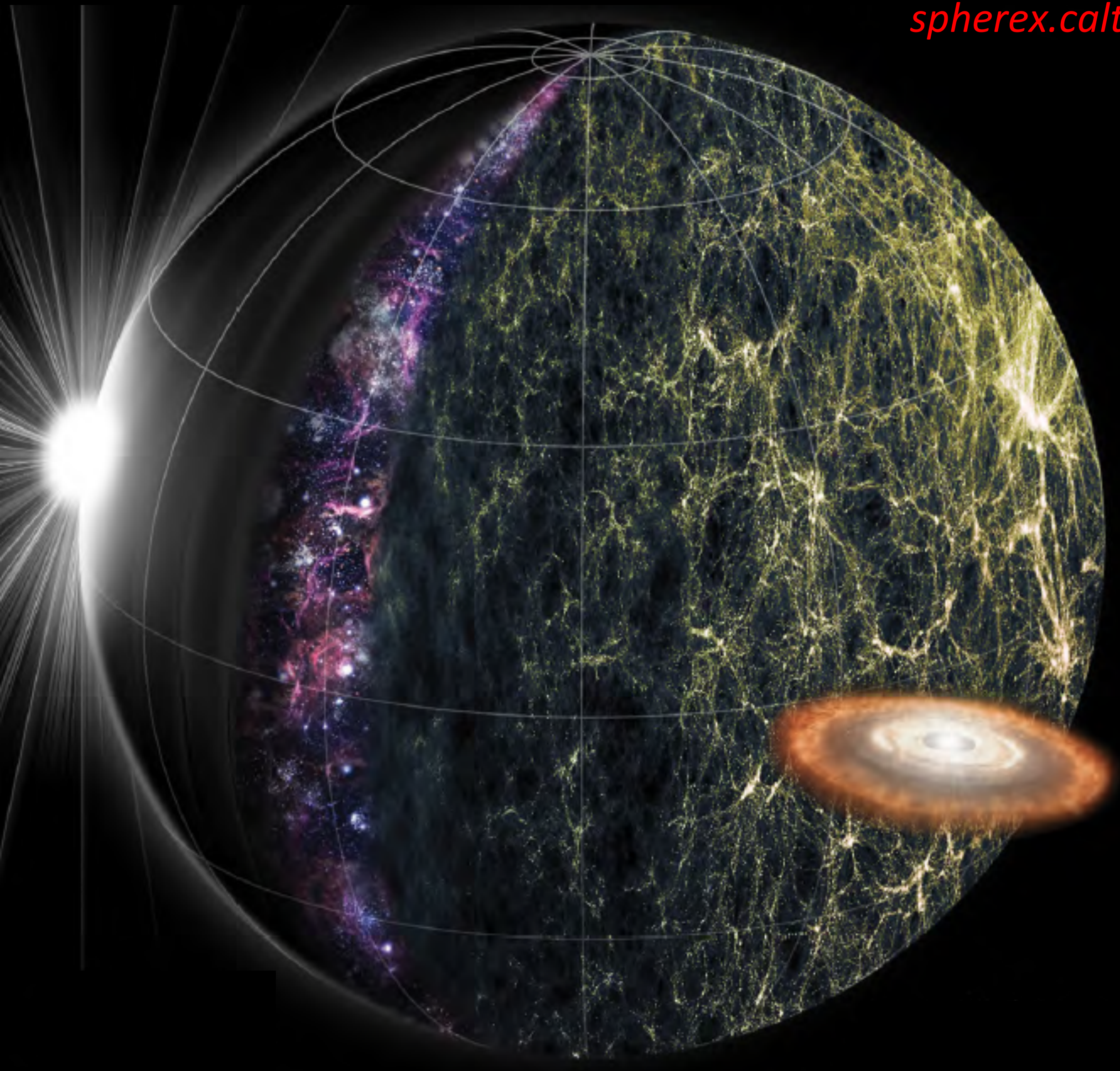
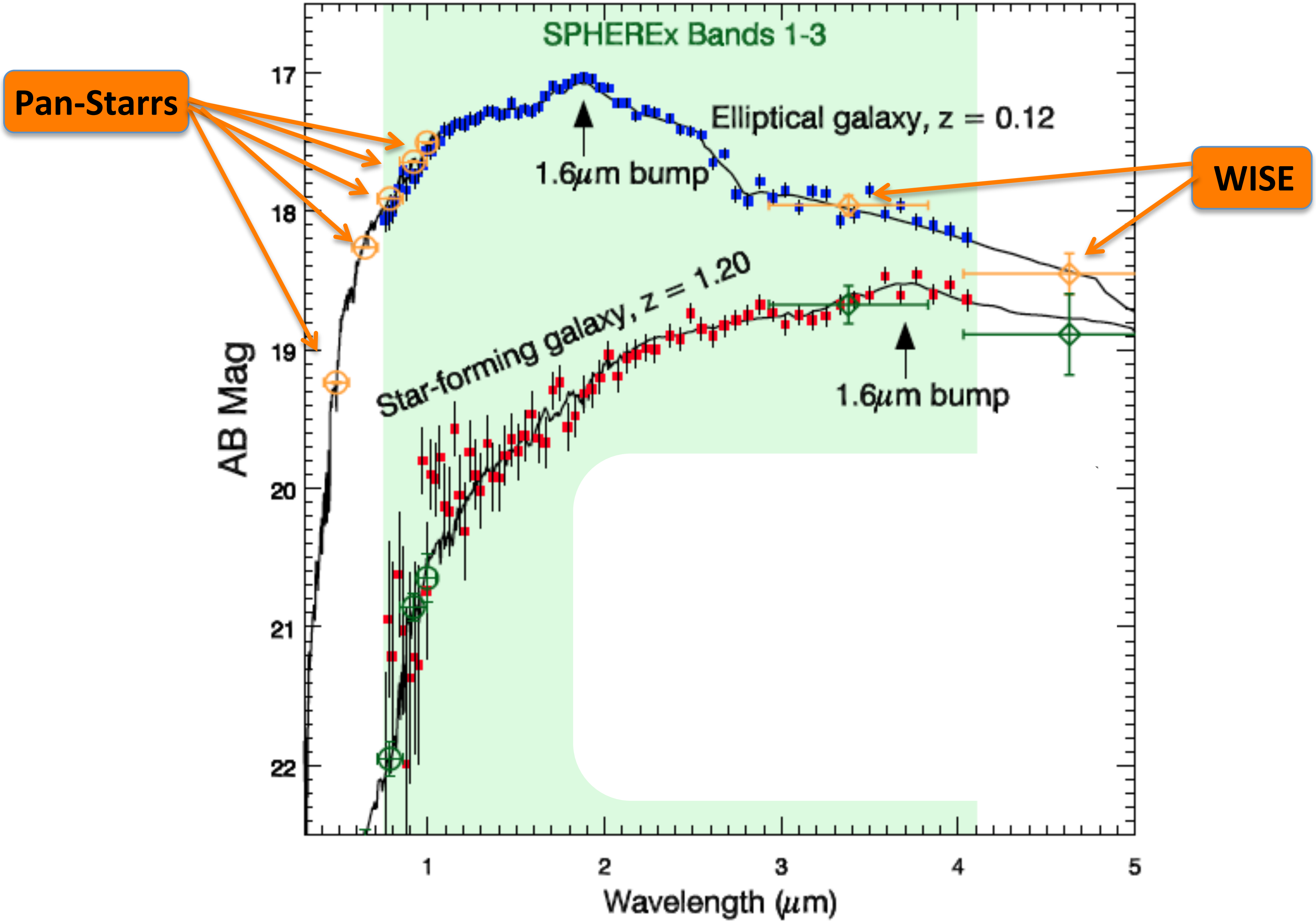
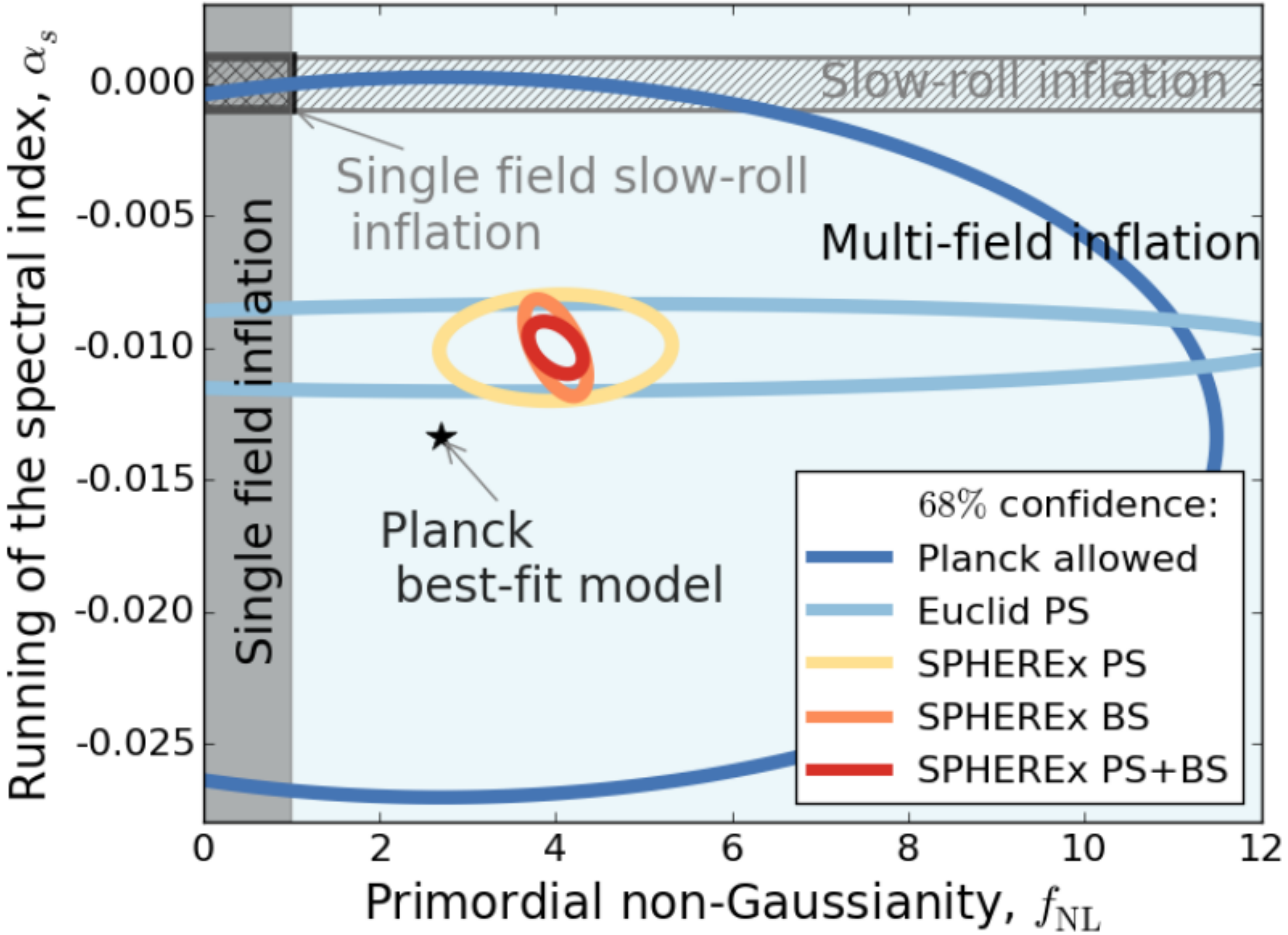


- ***λ = 0.75 – 4.8 µm***
- ***Resolution R = 41.5***
- ***Full-Sky***
- ***Pixel Size 6.2''***
- ***Aperture 20cm***
- ***FoV 3.5° x 7°***

SPHEREx enables low-res spectroscopic redshifts for 300M ***Pan-Starrs/DES*** + ***WISE*** selected galaxies



SPHEREx **Galaxy Clustering Can Reach** $\sigma(f_{NL}) < 1$

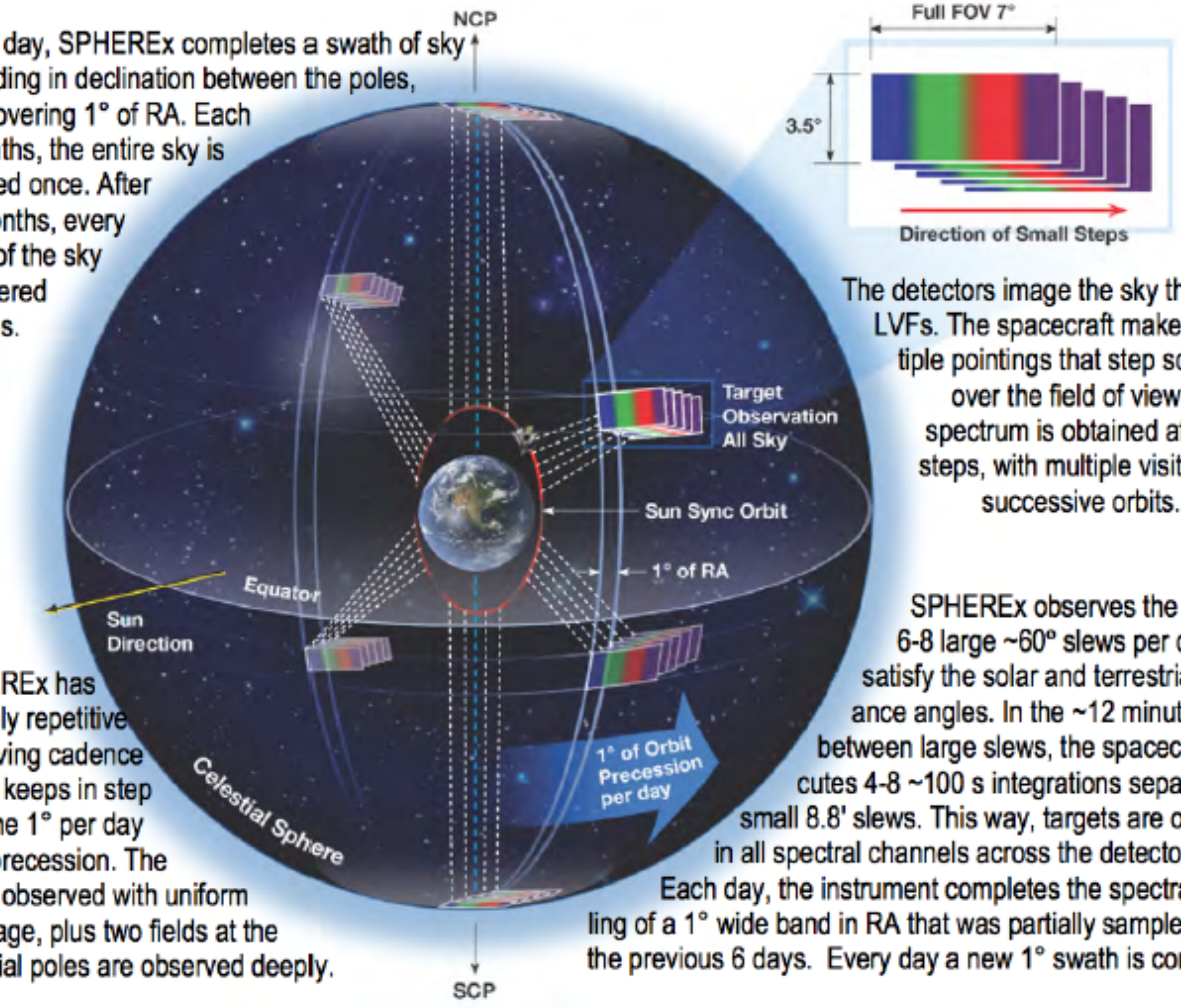


Conclusions

- Primordial non-Gaussianity is an important probe of the Physics of Inflation
- Constraining order unity local non-Gaussianity using scale-dependent galaxy bias distinguishes between single- and multi-field models
- A future low-resolution spectroscopic survey like ***SPHEREx*** can reach $\sigma(f_{nl}) < 1$, shedding new light on the nature of Inflation

SPHEREx: An All-Sky Spectral Survey

SPHEREx white paper: *Doré, Bock et al (1412.4872)*



Every day, SPHEREx completes a swath of sky extending in declination between the poles, and covering 1° of RA. Each 6 months, the entire sky is covered once. After 25 months, every point of the sky is covered 4 times.

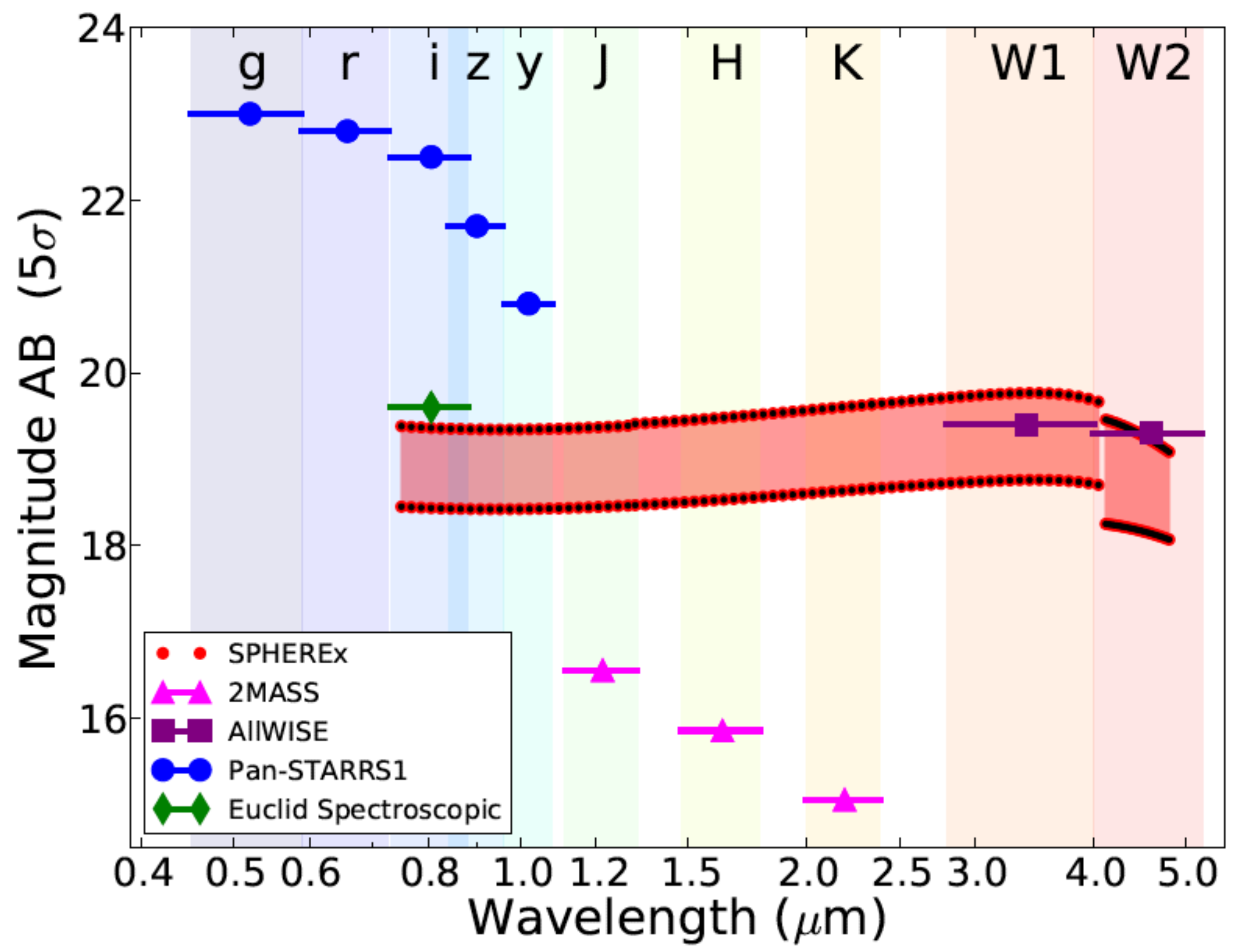
The detectors image the sky through LVFs. The spacecraft makes multiple pointings that step sources over the field of view. A full spectrum is obtained after 48 steps, with multiple visits over successive orbits.

SPHEREx has a highly repetitive observing cadence which keeps in step with the 1° per day orbit precession. The sky is observed with uniform coverage, plus two fields at the celestial poles are observed deeply.

SPHEREx observes the sky with 6-8 large ~60° slews per orbit that satisfy the solar and terrestrial avoidance angles. In the ~12 minute period between large slews, the spacecraft executes 4-8 ~100 s integrations separated by small 8.8' slews. This way, targets are observed in all spectral channels across the detector arrays. Each day, the instrument completes the spectral sampling of a 1° wide band in RA that was partially sampled during the previous 6 days. Every day a new 1° swath is completed.

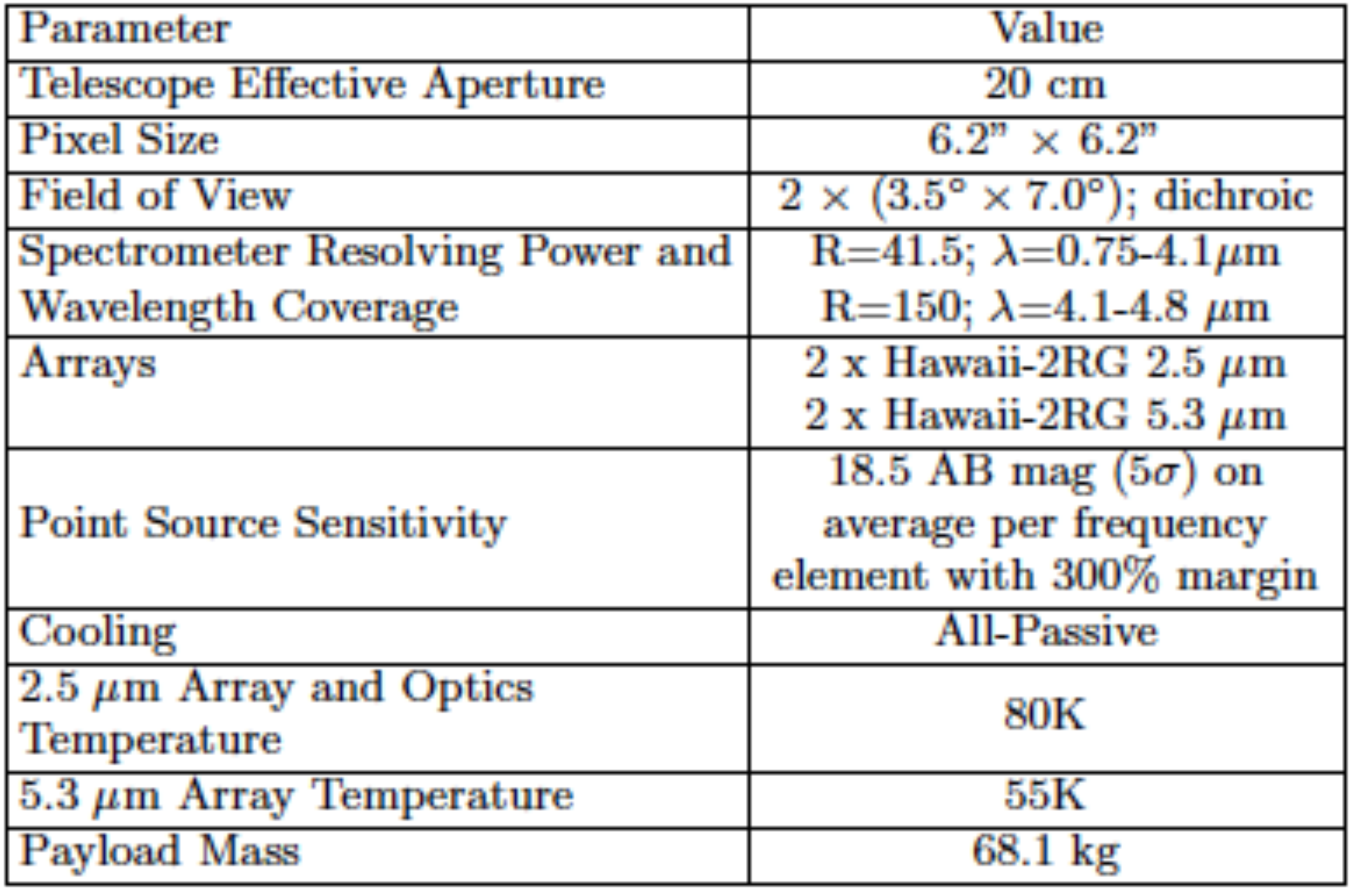
SPHEREx covers wide range of wavelengths with resolution R~40

SPHEREx white paper: *Doré, Bock et al (1412.4872)*



SPHEREx specs

SPHEREx white paper: *Doré, Bock et al (1412.4872)*



Parameter	Value
Telescope Effective Aperture	20 cm
Pixel Size	6.2" × 6.2"
Field of View	$2 \times (3.5^\circ \times 7.0^\circ)$; dichroic
Spectrometer Resolving Power and Wavelength Coverage	R=41.5; λ=0.75-4.1μm R=150; λ=4.1-4.8 μm
Arrays	2 x Hawaii-2RG 2.5 μm 2 x Hawaii-2RG 5.3 μm
Point Source Sensitivity	18.5 AB mag (5σ) on average per frequency element with 300% margin
Cooling	All-Passive
2.5 μm Array and Optics Temperature	80K
5.3 μm Array Temperature	55K
Payload Mass	68.1 kg

SPHEREx will measure redshifts with $\sigma_z < 0.1\,(1 + z)$ for *300M* galaxies, selected from PanStarrs/DES and WISE

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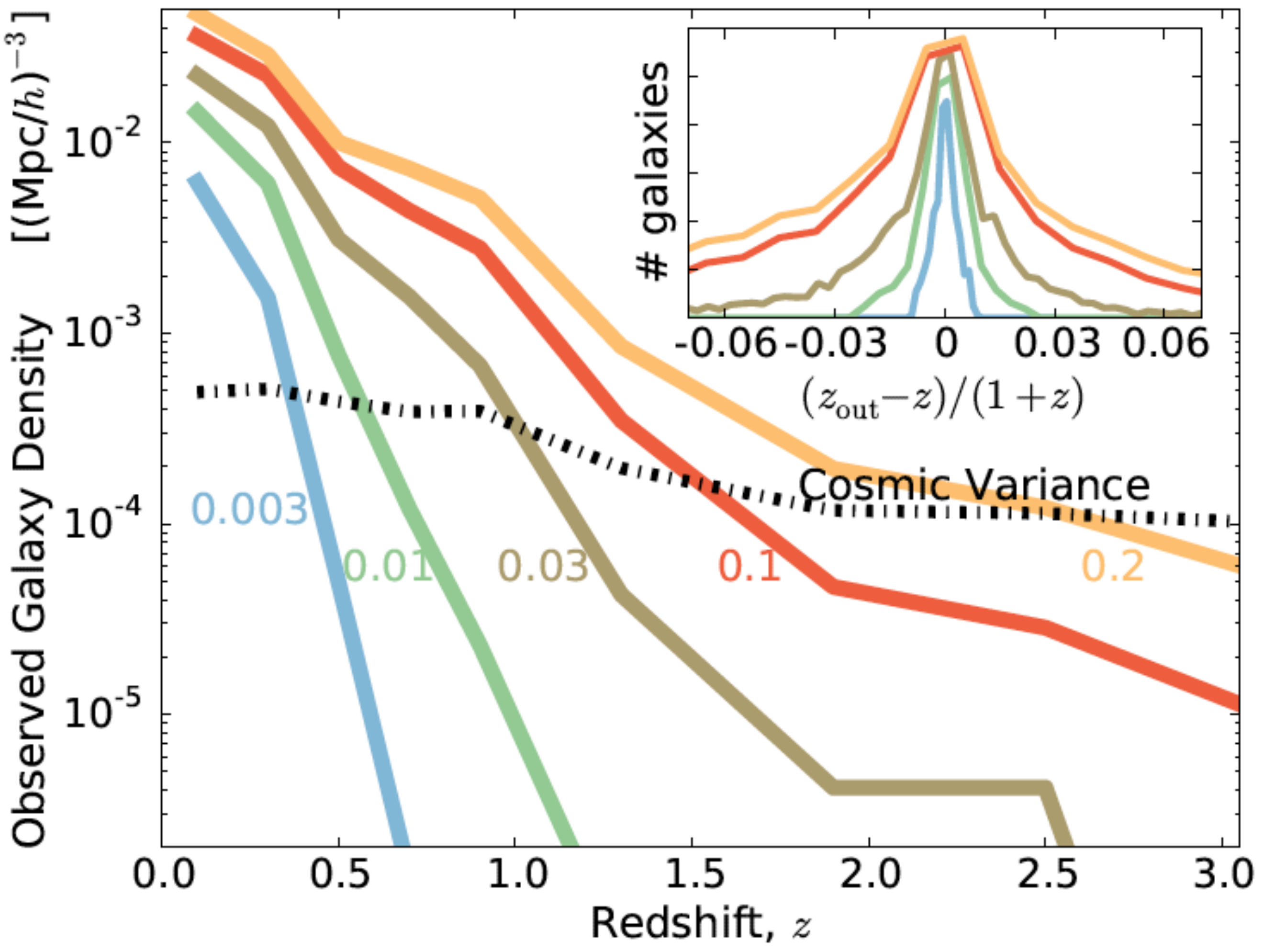

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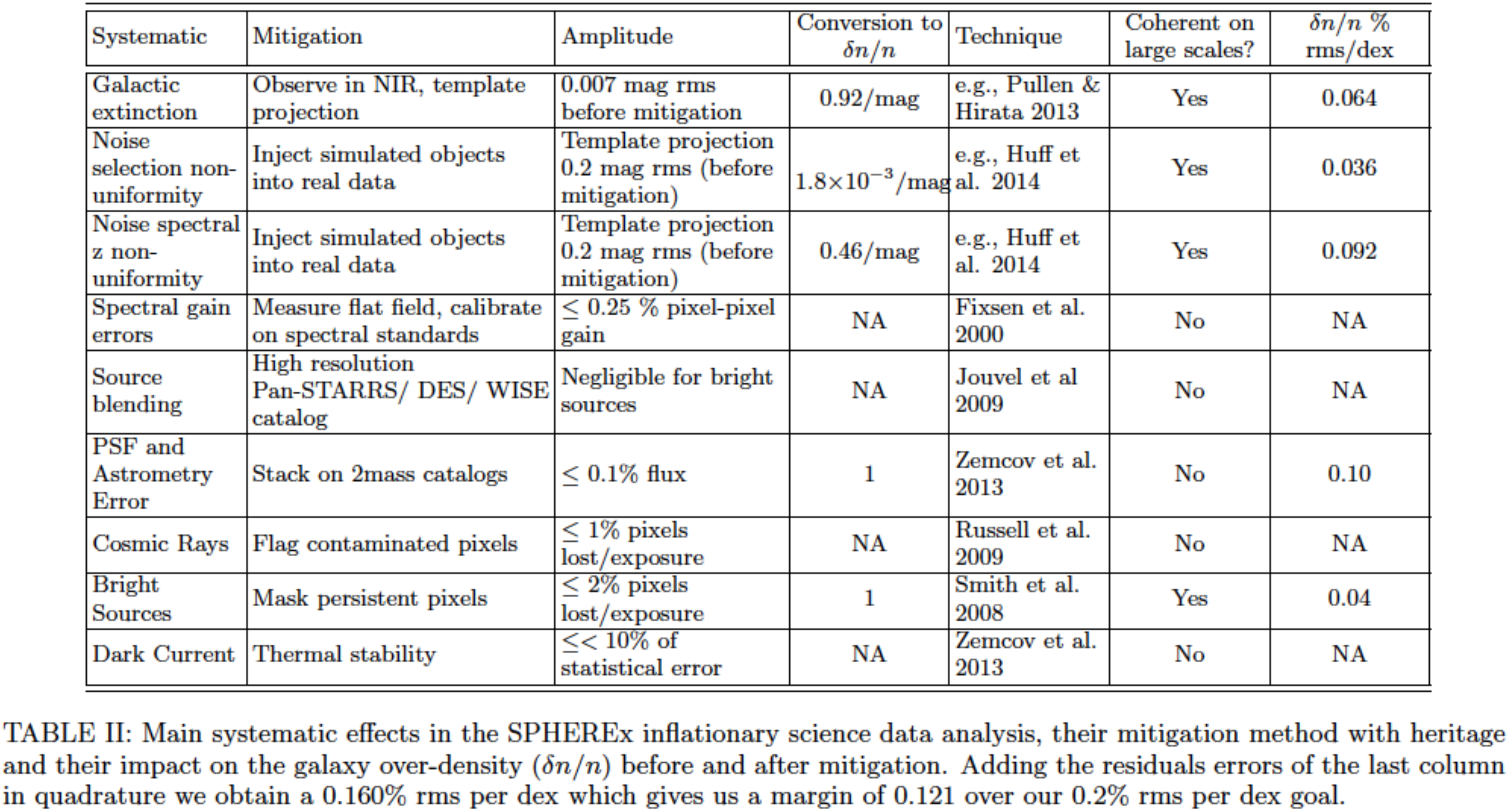

Systematic	Mitigation	Amplitude	Conversion to $\delta n/n$	Technique	Coherent on large scales?	$\delta n/n$ % rms/dex
Galactic extinction	Observe in NIR, template projection	0.007 mag rms before mitigation	0.92/mag	e.g., Pullen & Hirata 2013	Yes	0.064
Noise selection non-uniformity	Inject simulated objects into real data	Template projection 0.2 mag rms (before mitigation)	1.8×10^{-3}/mag	e.g., Huff et al. 2014	Yes	0.036
Noise spectral z non-uniformity	Inject simulated objects into real data	Template projection 0.2 mag rms (before mitigation)	0.46/mag	e.g., Huff et al. 2014	Yes	0.092
Spectral gain errors	Measure flat field, calibrate on spectral standards	$\leq$ 0.25 % pixel-pixel gain	NA	Fixsen et al. 2000	No	NA
Source blending	High resolution Pan-STARRS/ DES/ WISE catalog	Negligible for bright sources	NA	Jouvel et al 2009	No	NA
PSF and Astrometry Error	Stack on 2mass catalogs	$\leq$ 0.1% flux	1	Zemcov et al. 2013	No	0.10
Cosmic Rays	Flag contaminated pixels	$\leq$ 1% pixels lost/exposure	NA	Russell et al. 2009	No	NA
Bright Sources	Mask persistent pixels	$\leq$ 2% pixels lost/exposure	1	Smith et al. 2008	Yes	0.04
Dark Current	Thermal stability	$\leq <$ 10% of statistical error	NA	Zemcov et al. 2013	No	NA

TABLE II: Main systematic effects in the SPHEREx inflationary science data analysis, their mitigation method with heritage and their impact on the galaxy over-density ($\delta n/n$) before and after mitigation. Adding the residuals errors of the last column in quadrature we obtain a 0.160% rms per dex which gives us a margin of 0.121 over our 0.2% rms per dex goal.

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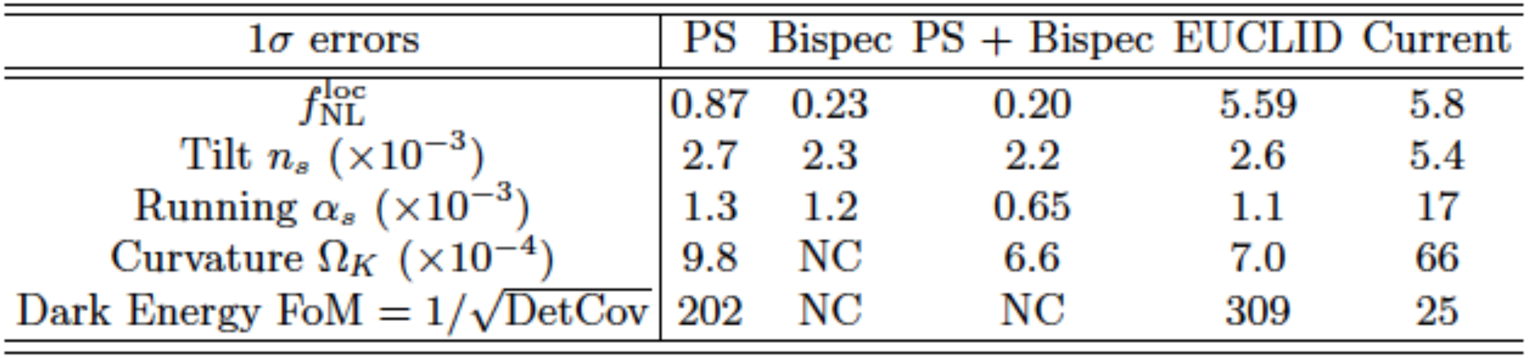

1σ errors	PS	Bispec	PS + Bispec	EUCLID	Current
$f_{\mathrm{NL}}^{\mathrm{loc}}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s $(\times 10^{-3})$	2.7	2.3	2.2	2.6	5.4
Running α_s $(\times 10^{-3})$	1.3	1.2	0.65	1.1	17
Curvature Ω_K $(\times 10^{-4})$	9.8	NC	6.6	7.0	66
Dark Energy FoM $= 1/\sqrt{\mathrm{DetCov}}$	202	NC	NC	309	25

SPHEREx white paper: *Doré, Bock et al (1412.4872)*