

Probing Inflation with Future Galaxy Surveys

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Caltech

IPA 2016, Orsay 7/9/2016



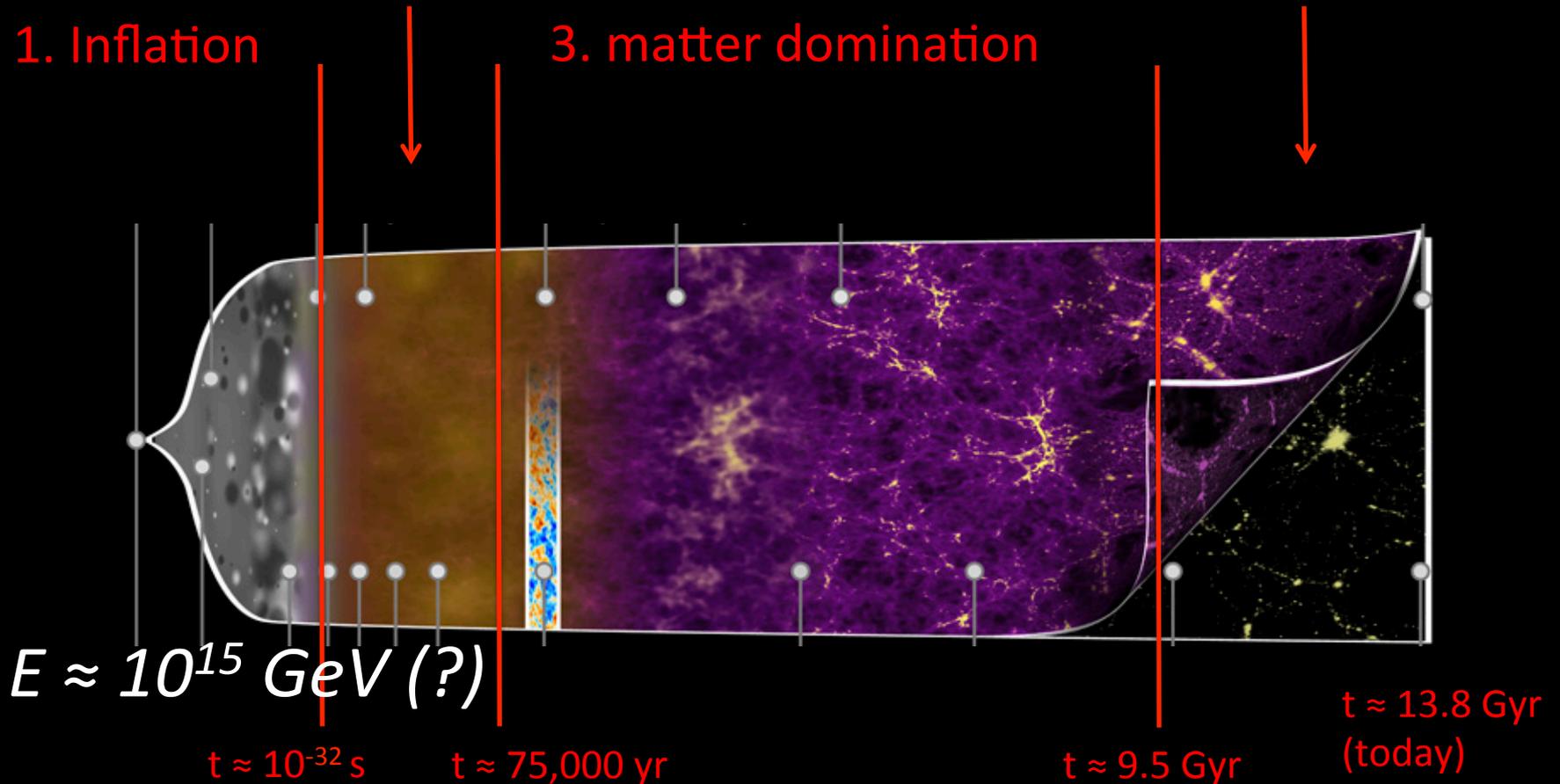
What is the Physics behind Inflation?

2. radiation domination

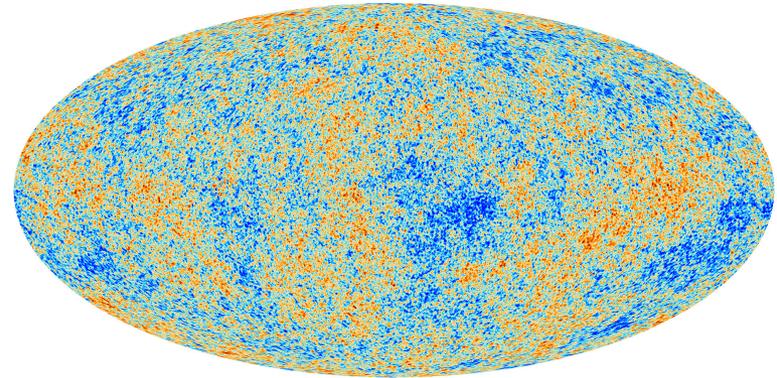
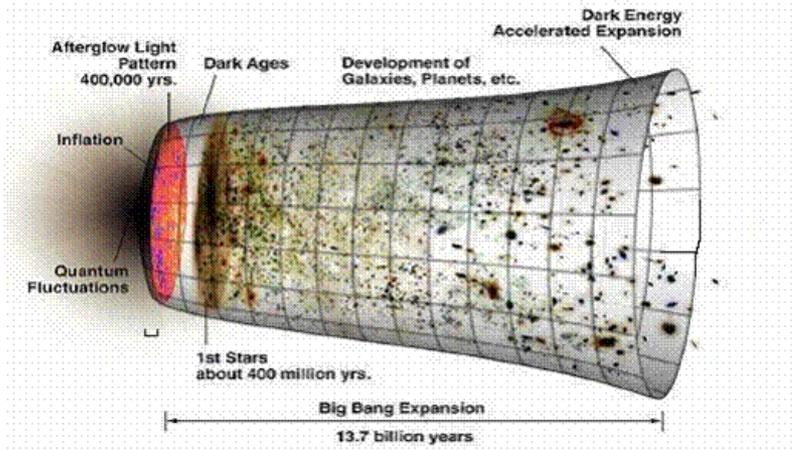
4. dark energy domination

1. Inflation

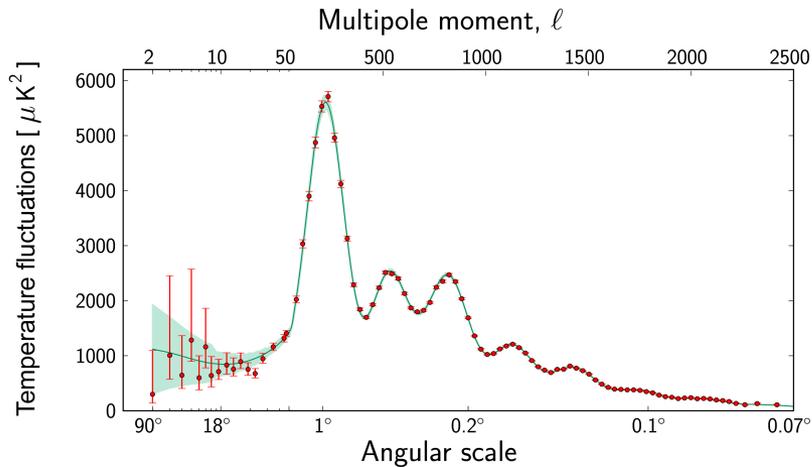
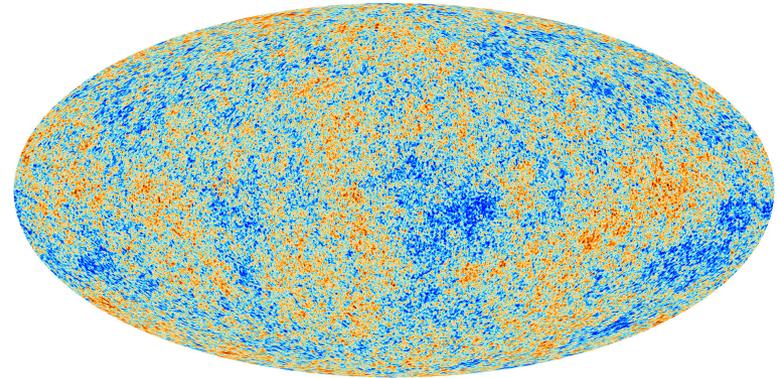
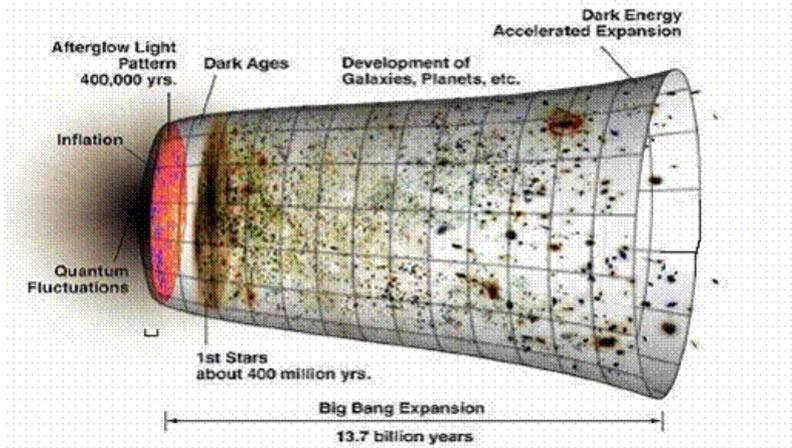
3. matter domination



Primordial density fluctuations are a powerful probe of Inflation

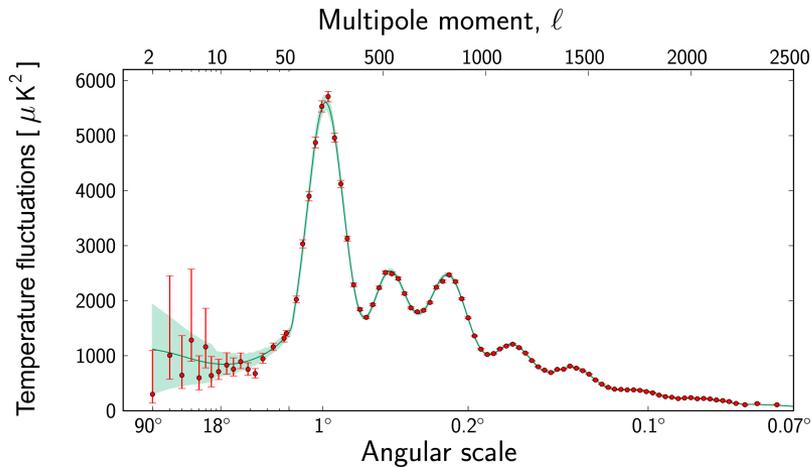
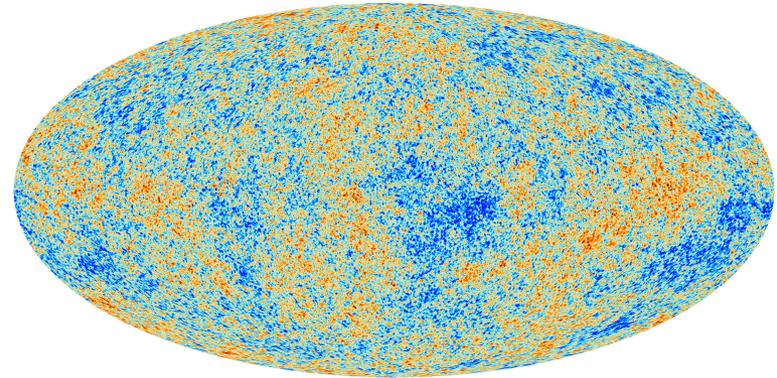
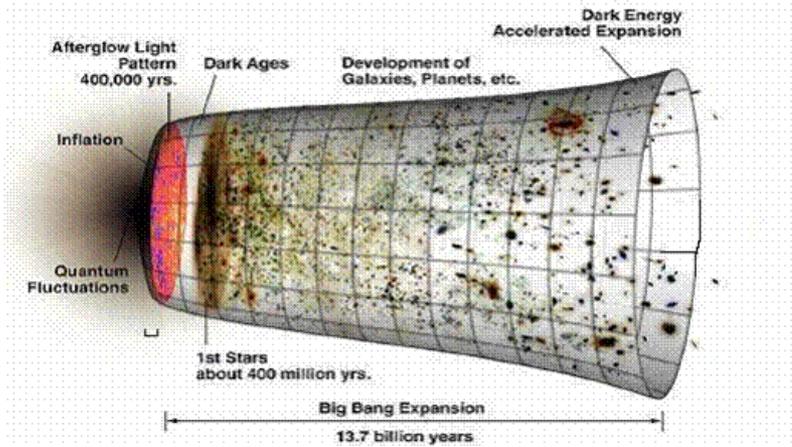


Primordial density fluctuations are a powerful probe of Inflation



Gaussian fluctuations characterized by
primordial power spectrum

Primordial density fluctuations are a powerful probe of Inflation



Gaussian fluctuations characterized by
primordial power spectrum

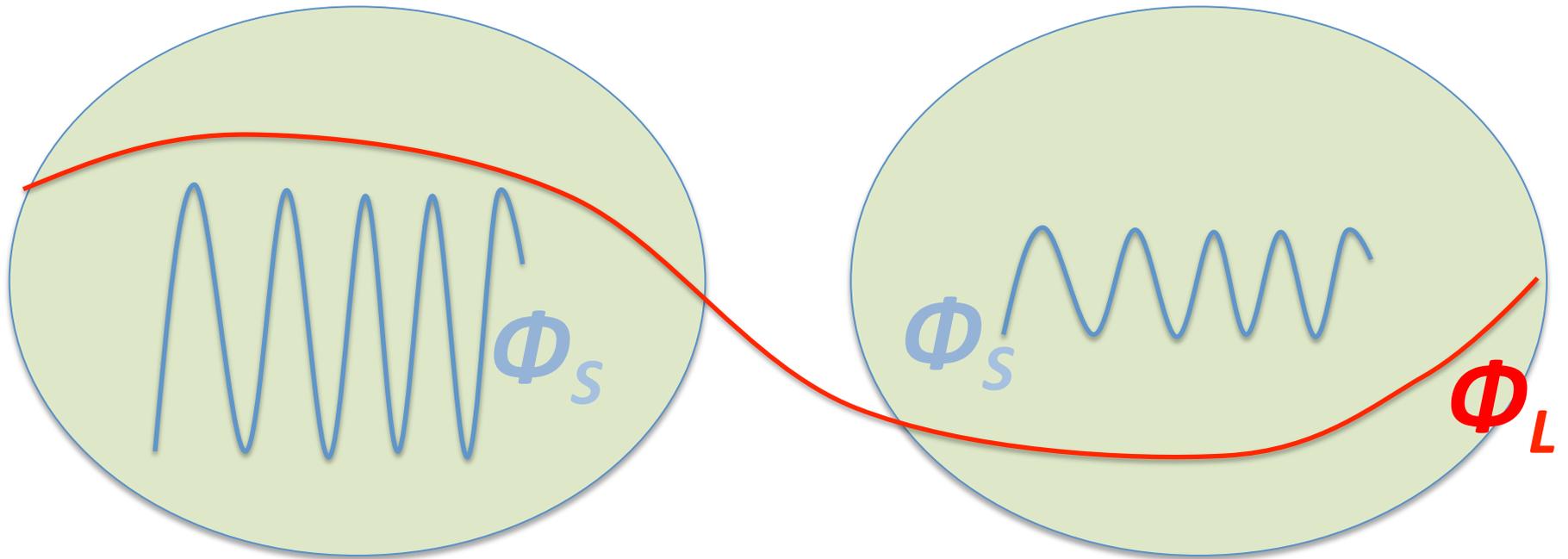
**BUT: small deviations from
Gaussianity expected**

**Primordial non-Gaussianity gives
crucial information on Inflationary
Lagrangian!**

Local Primordial non-Gaussianity

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

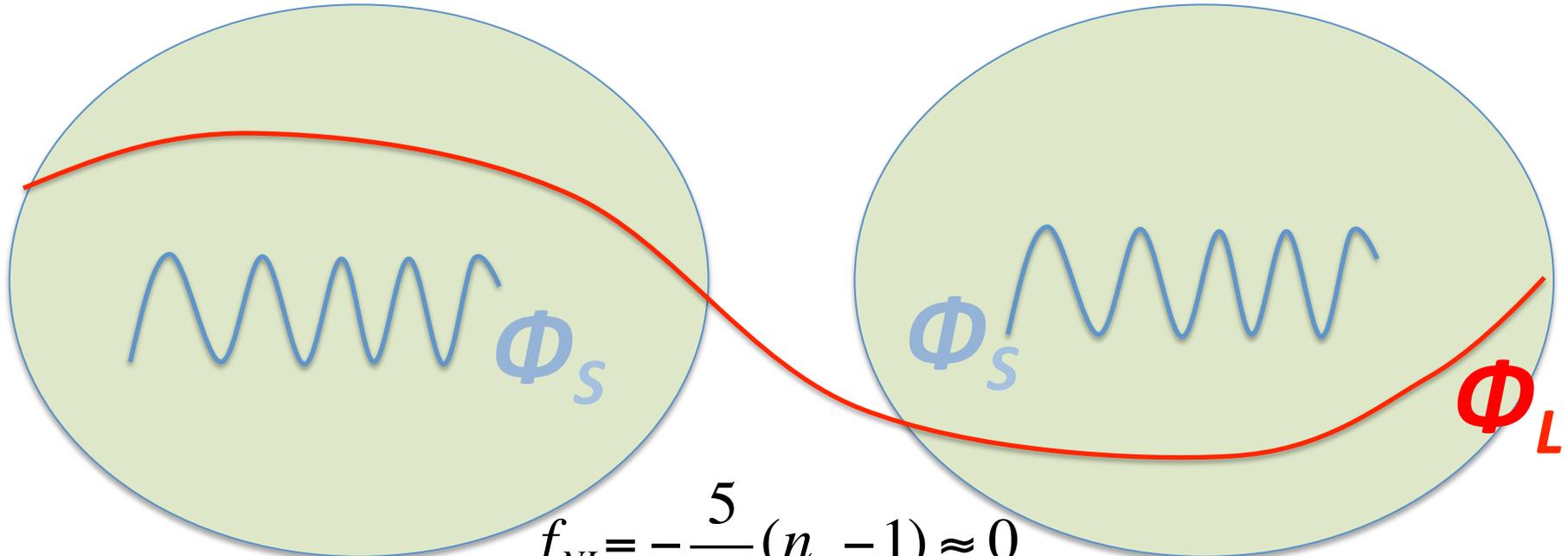
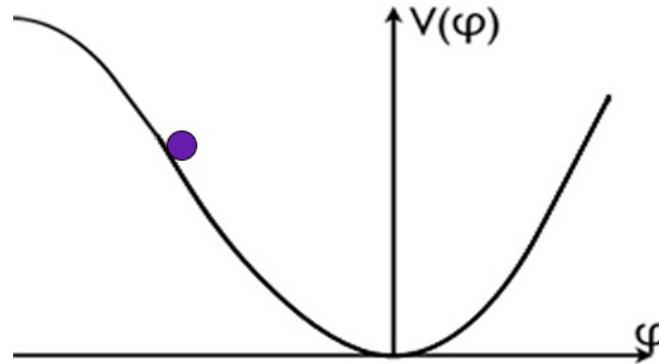
Local non-Gaussianity: modulation of small-scale perturbations by long mode: “**mode coupling**”



Single-field consistency condition predicts zero mode coupling

Single-Field Inflation

*Maldacena 2003,
Creminelli & Zaldarriaga 2004*

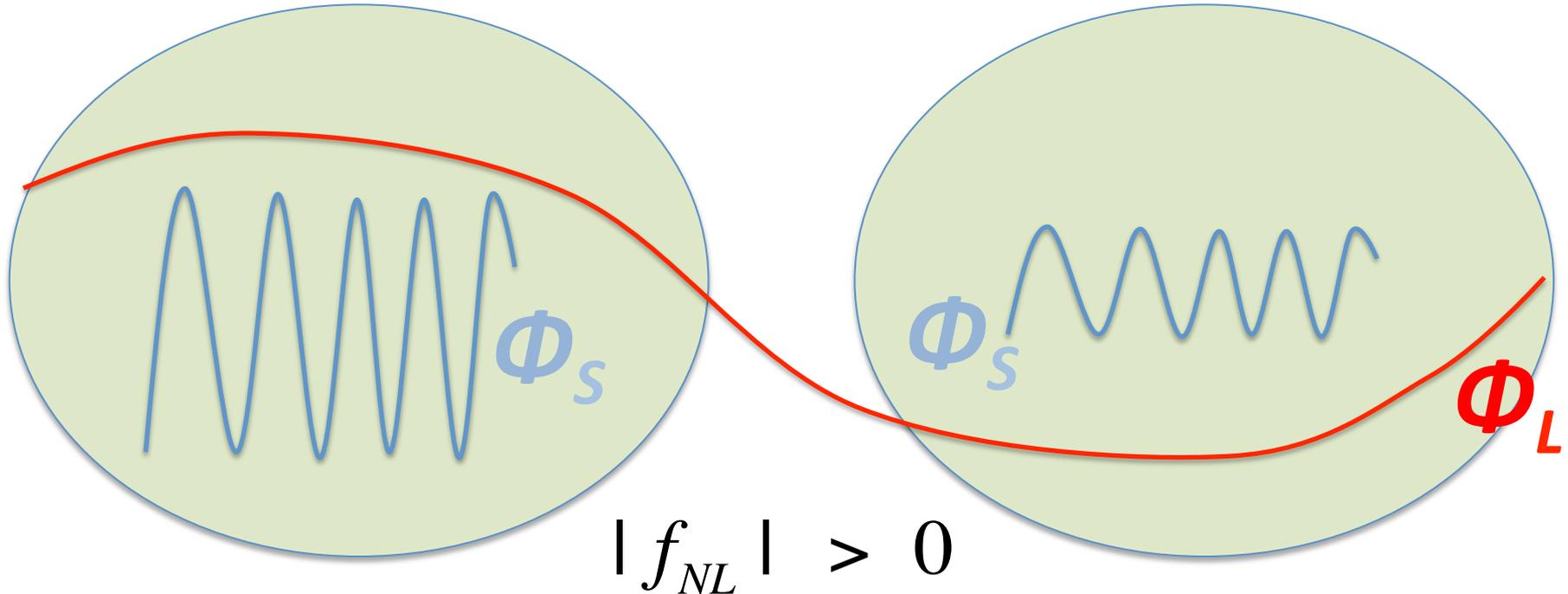
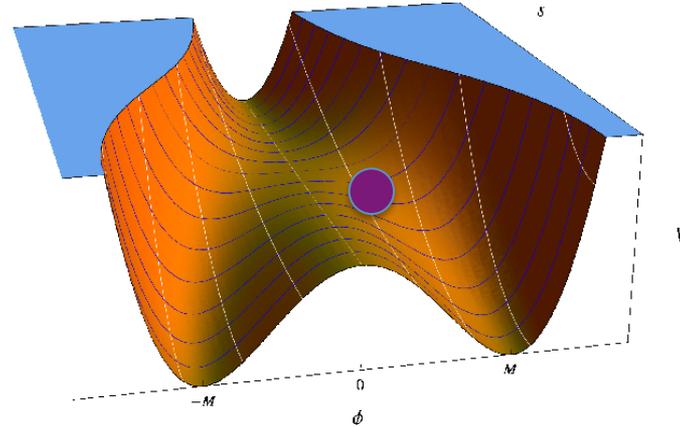


$$f_{NL} = -\frac{5}{12}(n_s - 1) \approx 0$$

Multifield Inflation allows large mode coupling

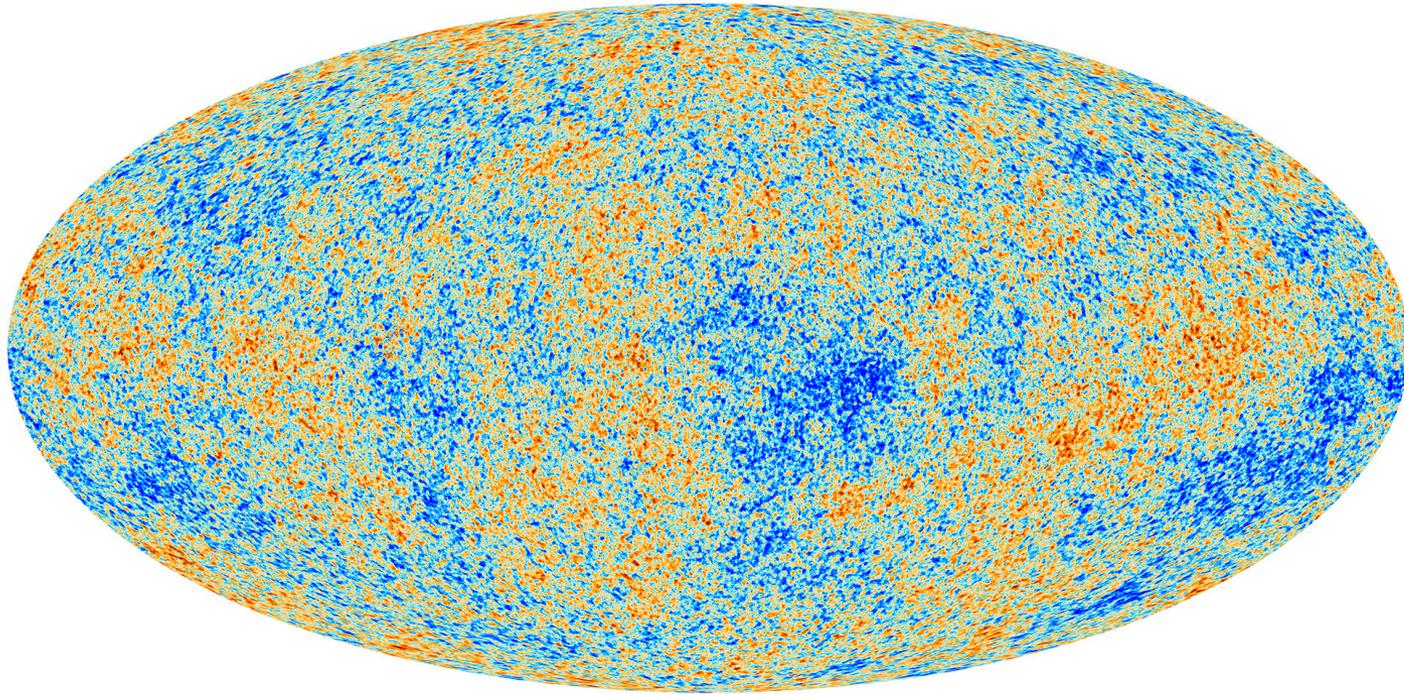
Multi-Field Inflation

*e.g. Lyth et al 2003,
Zaldarriaga 2004*



Current best constraints from CMB bispectrum

Planck 2015, paper XVII



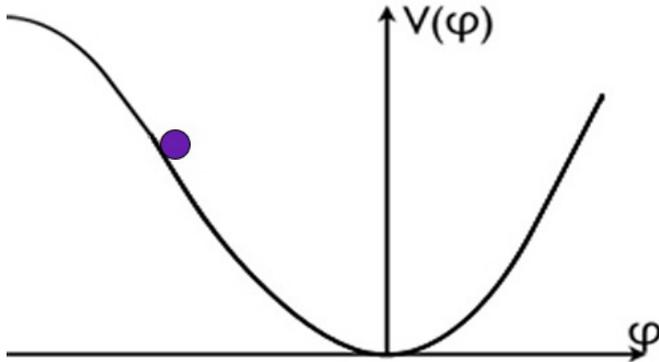
Planck2015 Temperature + Polarization Bispectrum:

$$f_{NL} = 0.8 \pm 5.0 \text{ (68\% CL)}$$

Future constraint at $\sigma(f_{NL}) \sim 1$ may distinguish between single- and multi-field Inflation

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

Single-Field Inflation:



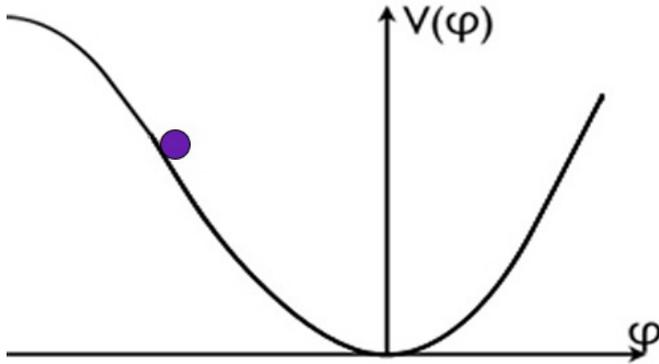
*Single-field consistency condition
by Maldacena (2003):*

$$f_{NL} = -\frac{5}{12}(n_s - 1) \approx 0$$

Future constraint at $\sigma(f_{NL}) \sim 1$ may distinguish between single- and multi-field Inflation

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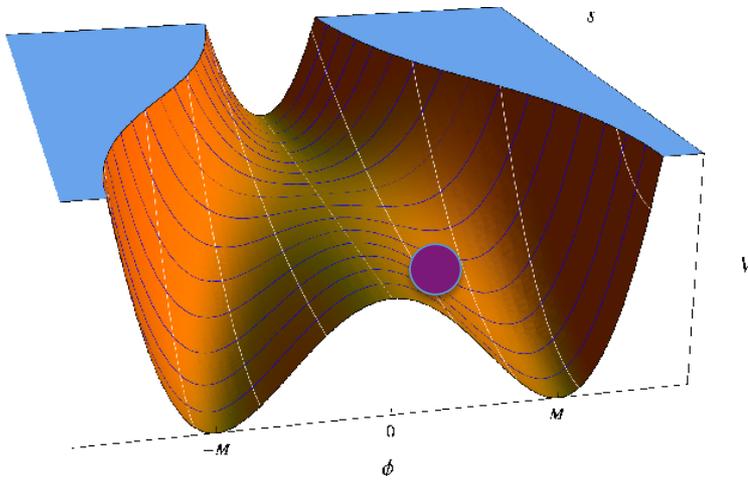
Single-Field Inflation:



Single-field consistency condition by Maldacena (2003):

$$f_{NL} = -\frac{5}{12}(n_s - 1) \approx 0$$

Multi-Field Inflation:

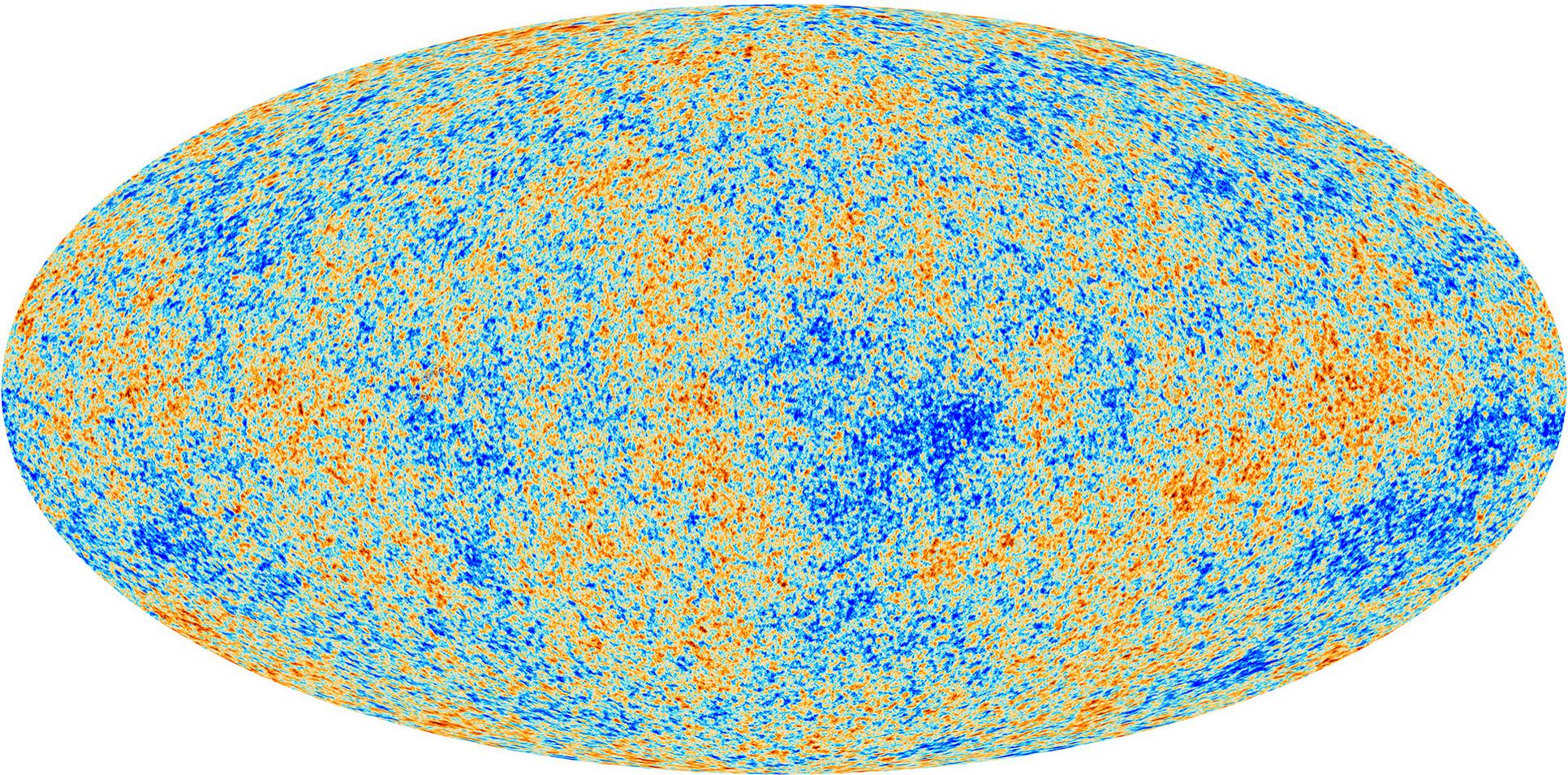


Curvaton models, modulated reheating, etc:

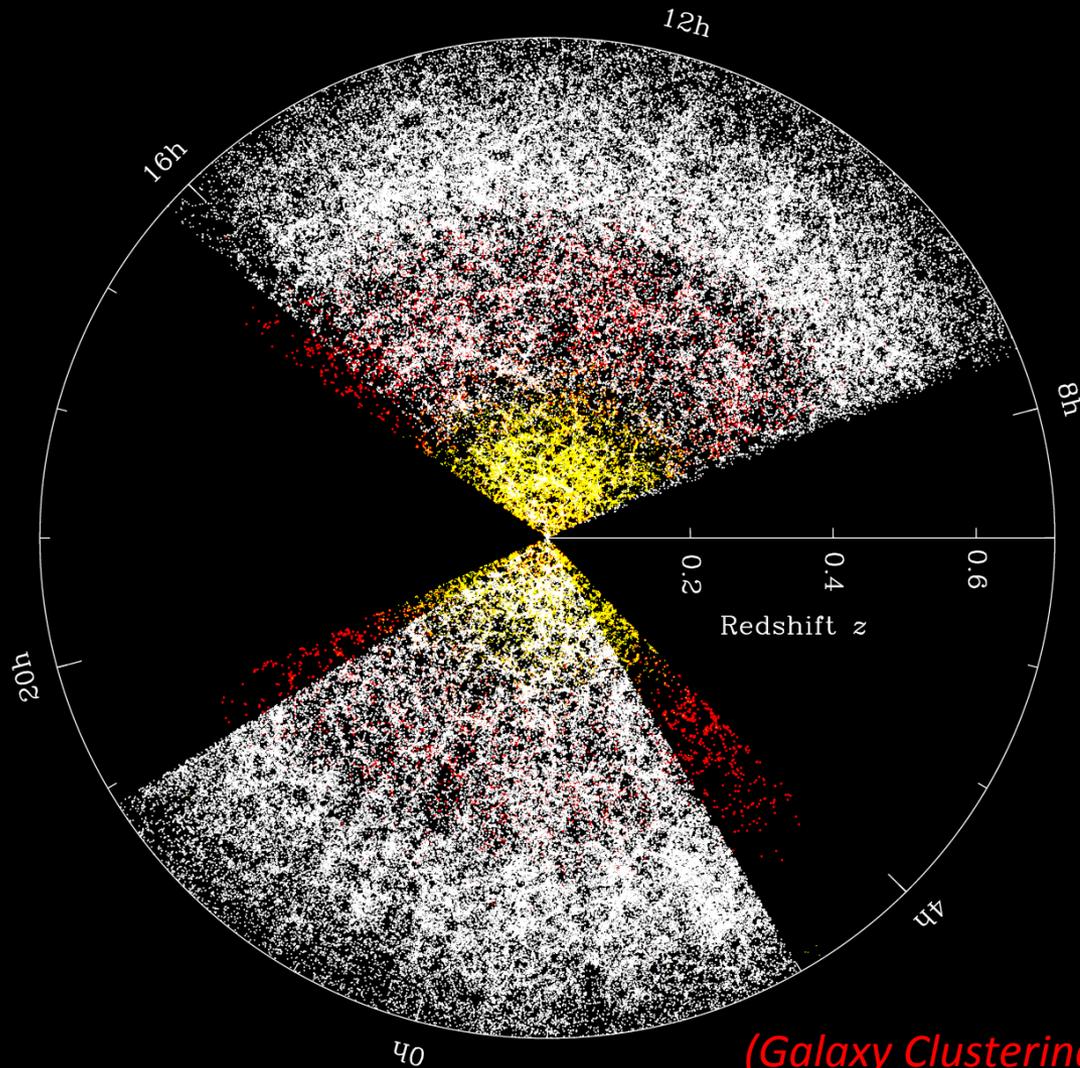
$$|f_{NL}| \geq 1$$

CMB constraint can only improve by factor ~ 2

Current Planck bispectrum: $\sigma(f_{NL}) = 5$ $\xrightarrow{\text{future}}$ $\sigma(f_{NL}) \sim 3$
Baumann et al 2009

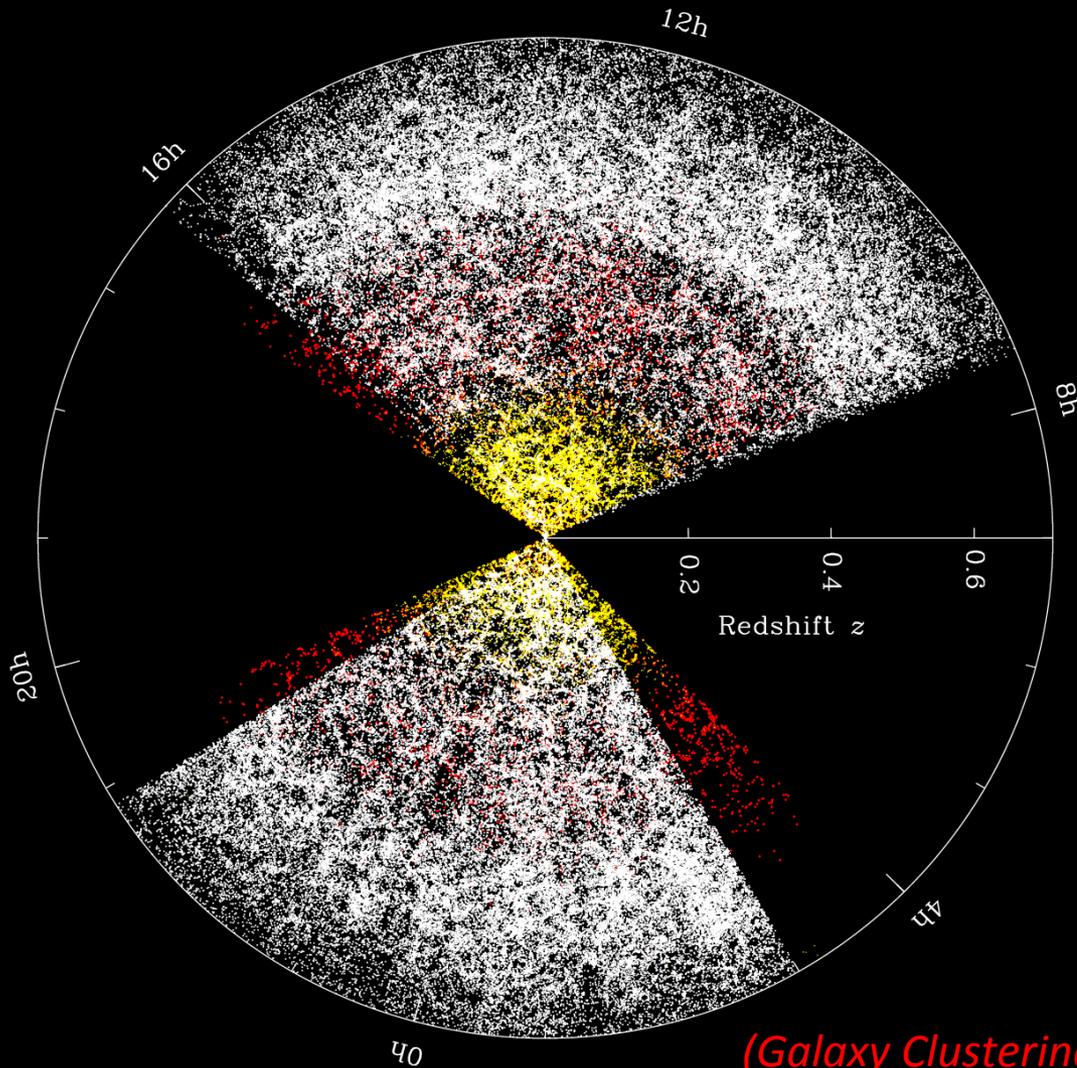


Galaxy clustering can strongly improve primordial non-Gaussianity constraints



(Galaxy Clustering in BOSS)

Galaxy clustering can strongly improve primordial non-Gaussianity constraints



(Galaxy Clustering in BOSS)

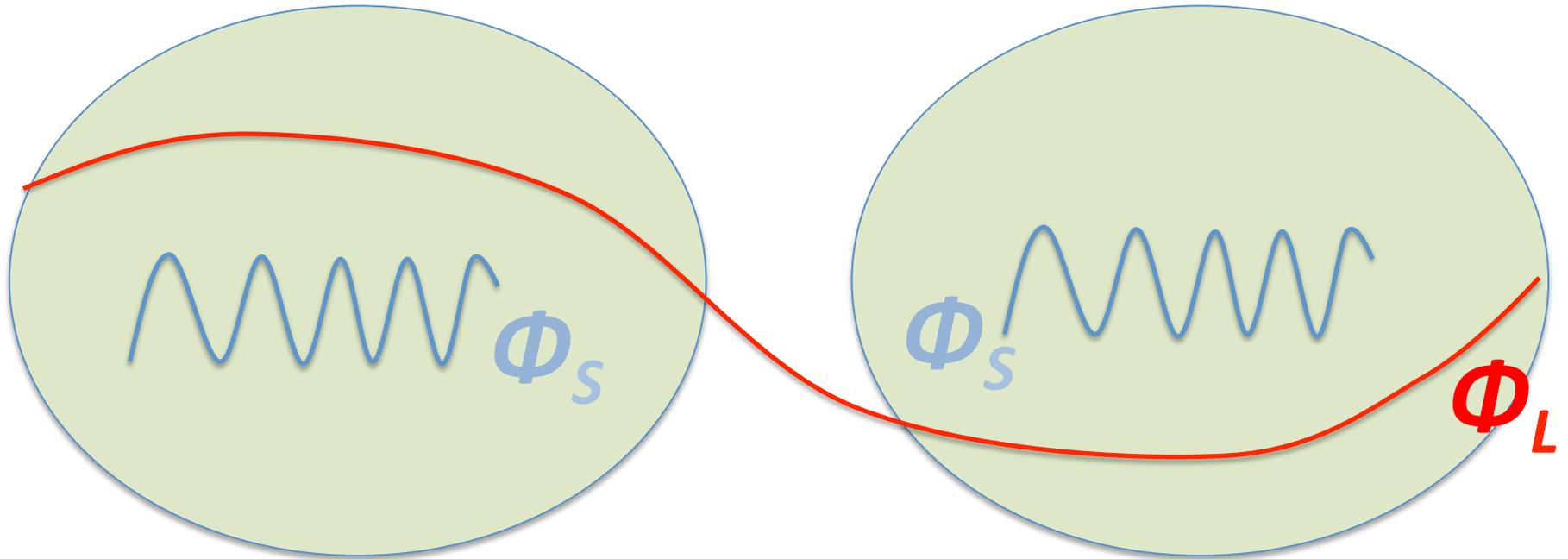
Halo bias:

$$\delta_h \equiv \frac{\delta n_h}{n_h}$$

$$\delta_m \equiv \frac{\delta \rho_m}{\rho_m}$$

$$\delta_h = b \delta_m$$

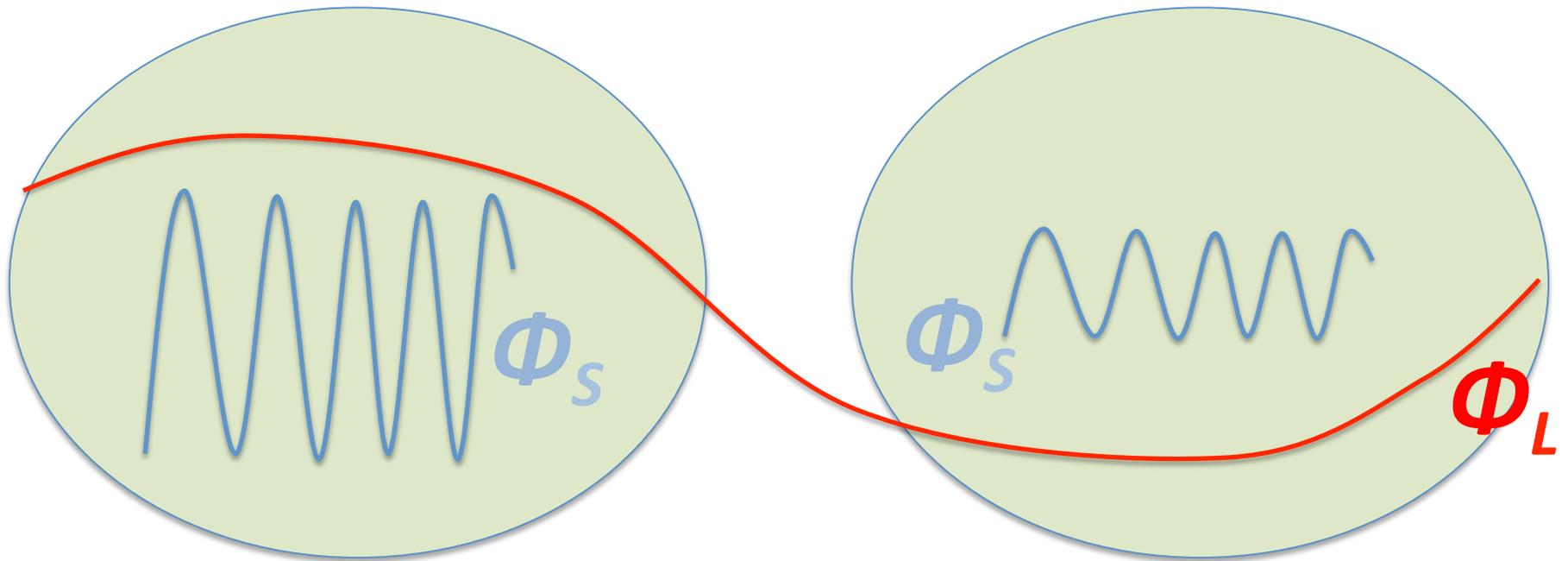
In absence of primordial non-Gaussianity,
large-scale halo bias is scale-independent



$$\delta_h(\vec{k}) = b_1 \delta_m(\vec{k})$$

Primordial non-Gaussianity leads to scale-dependent halo bias

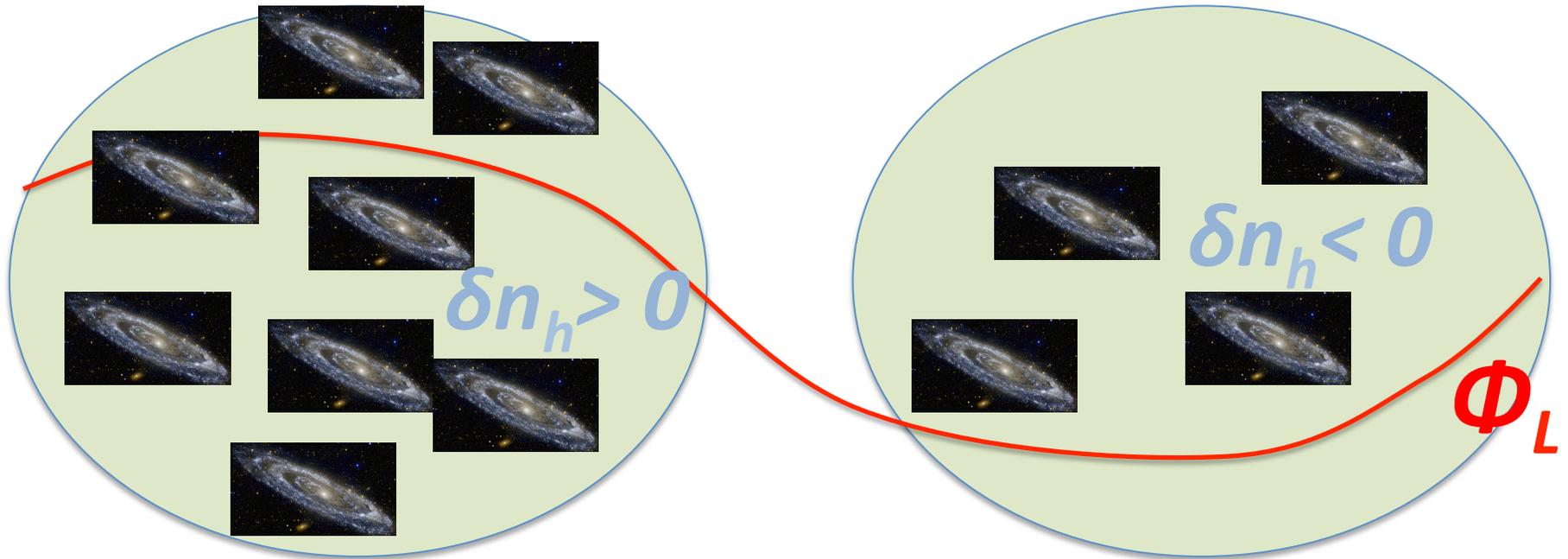
Dalal, Doré, Huterer & Shirokov 2008



$$\delta_h(\vec{k}) = b_1 \delta_m(\vec{k}) + \dots$$

Primordial non-Gaussianity leads to scale-dependent halo bias

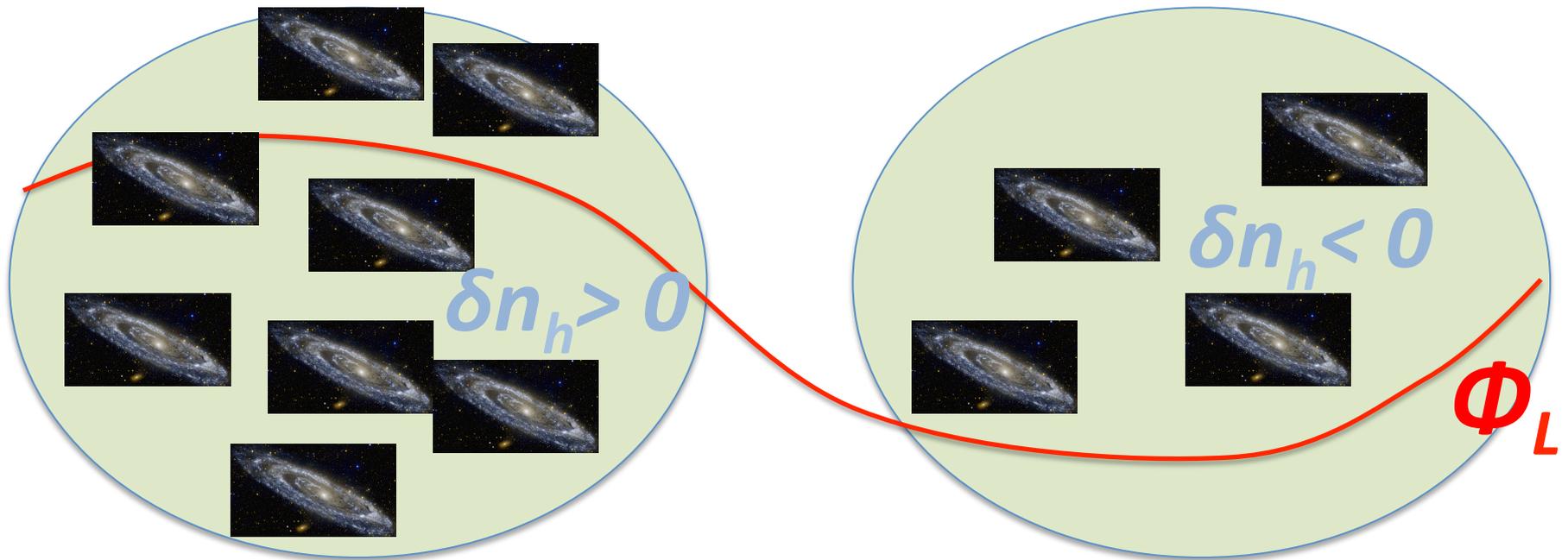
Dalal, Doré, Huterer & Shirokov 2008



$$\delta_h(\vec{k}) = b_1 \delta_m(\vec{k}) + c f_{NL} \Phi(\vec{k})$$

Primordial non-Gaussianity leads to scale-dependent halo bias

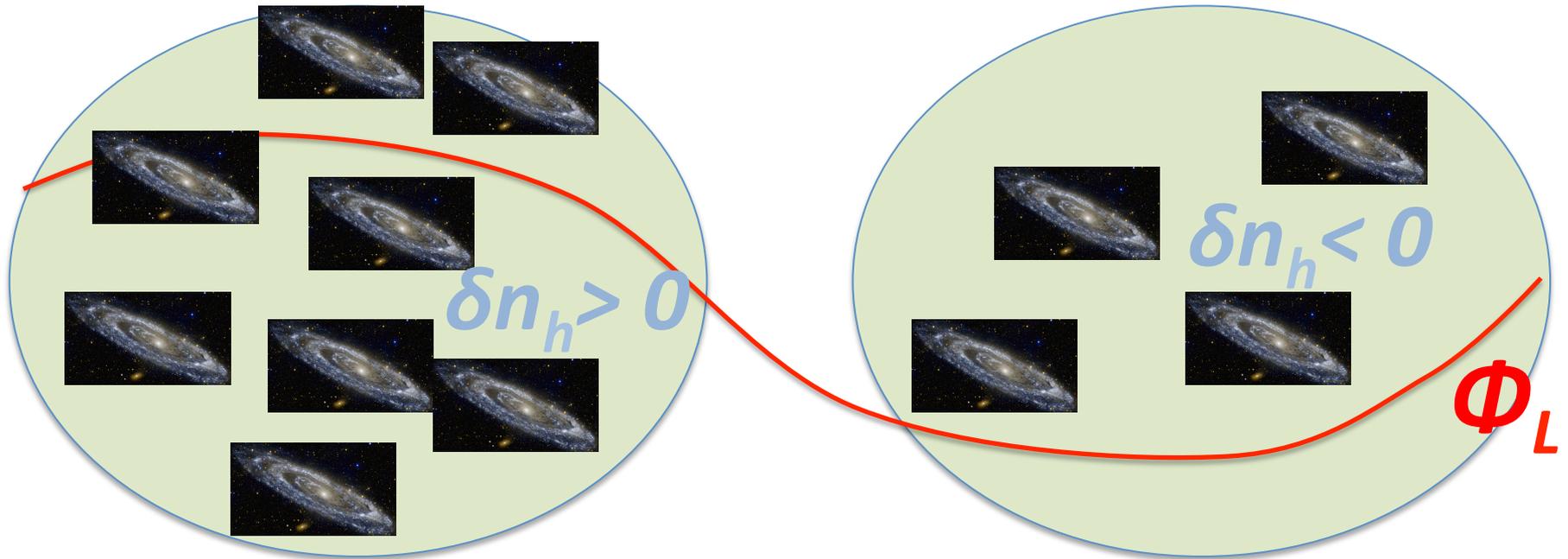
Dalal, Doré, Huterer & Shirokov 2008



$$\delta_h(\vec{k}) = b_1 \delta_m(\vec{k}) + c f_{NL} \Phi(\vec{k}) = (b_1 + \Delta b(k)) \delta_m(\vec{k})$$

Primordial non-Gaussianity leads to scale-dependent halo bias

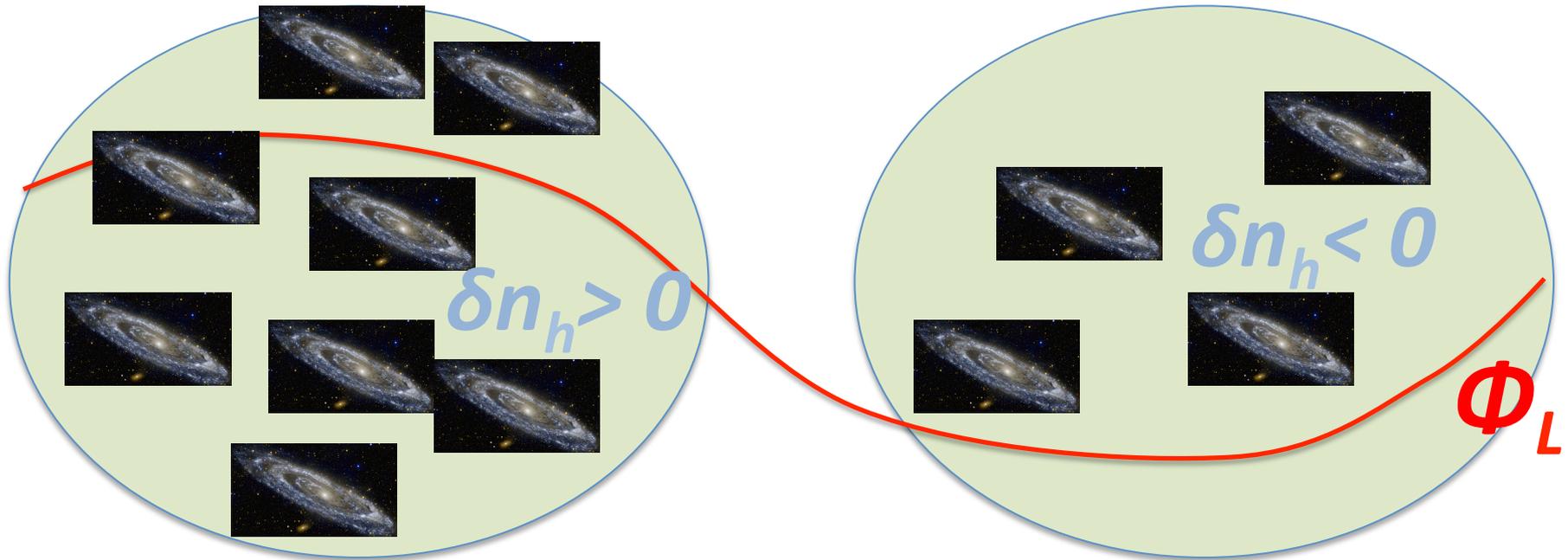
Dalal, Doré, Huterer & Shirokov 2008



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

Primordial non-Gaussianity leads to scale-dependent halo bias

Dalal, Doré, Huterer & Shirokov 2008



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

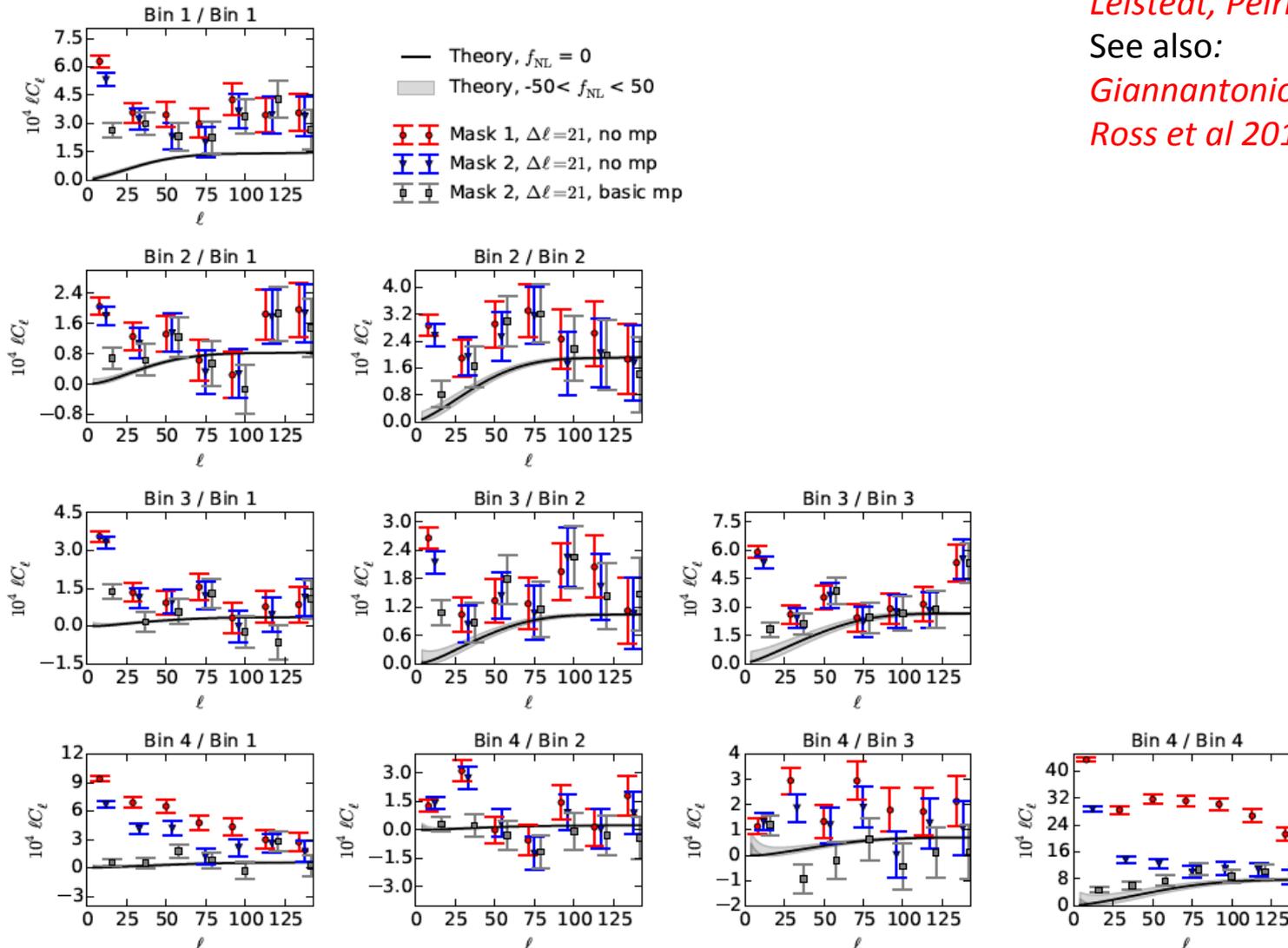
- ◆ Unique signal: $\Delta b(k) \propto k^{-2}$
- ◆ Requires Ultra-Large Scales: $\Delta b(k \sim H_0) \sim f_{NL}$

Current strongest bound from photometric quasars: $-49 < f_{NL} < 31$ (95 % CL)

*Leistedt & Peiris 2014,
Leistedt, Peiris & Roth 2014*

See also:

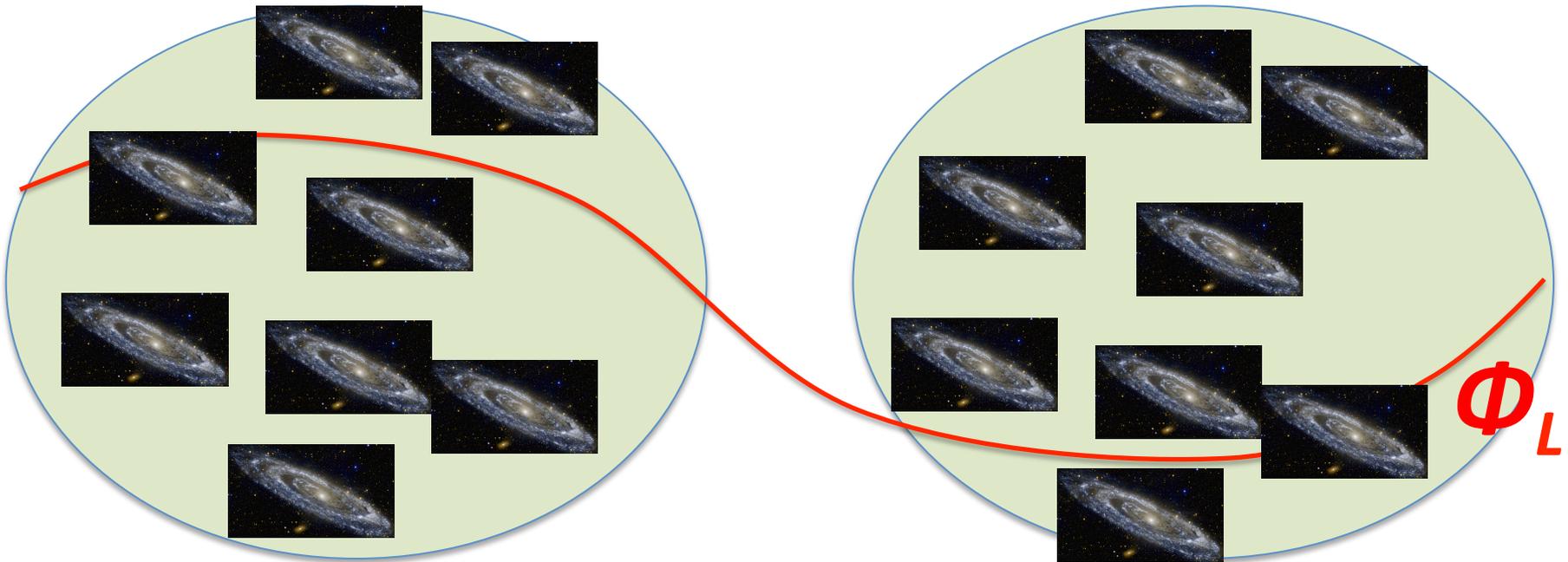
*Giannantonio et al 2014,
Ross et al 2013*



Leistedt, Peiris & Roth 2014

Is there Scale-Dependent Bias in Single-Field Inflation?

de Putter, Doré & Green 2015
Dai, Pajer & Schmidt 2015



$\Delta b(k) = 0$ *When properly treat GR “gauge effects”,
no physical scale-dependent bias remains*

Galaxy Clustering on ultra-large scales: what does it take to reach $\sigma(f_{NL}) \sim 1$?

de Putter & Doré 2014

■ Survey volume

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

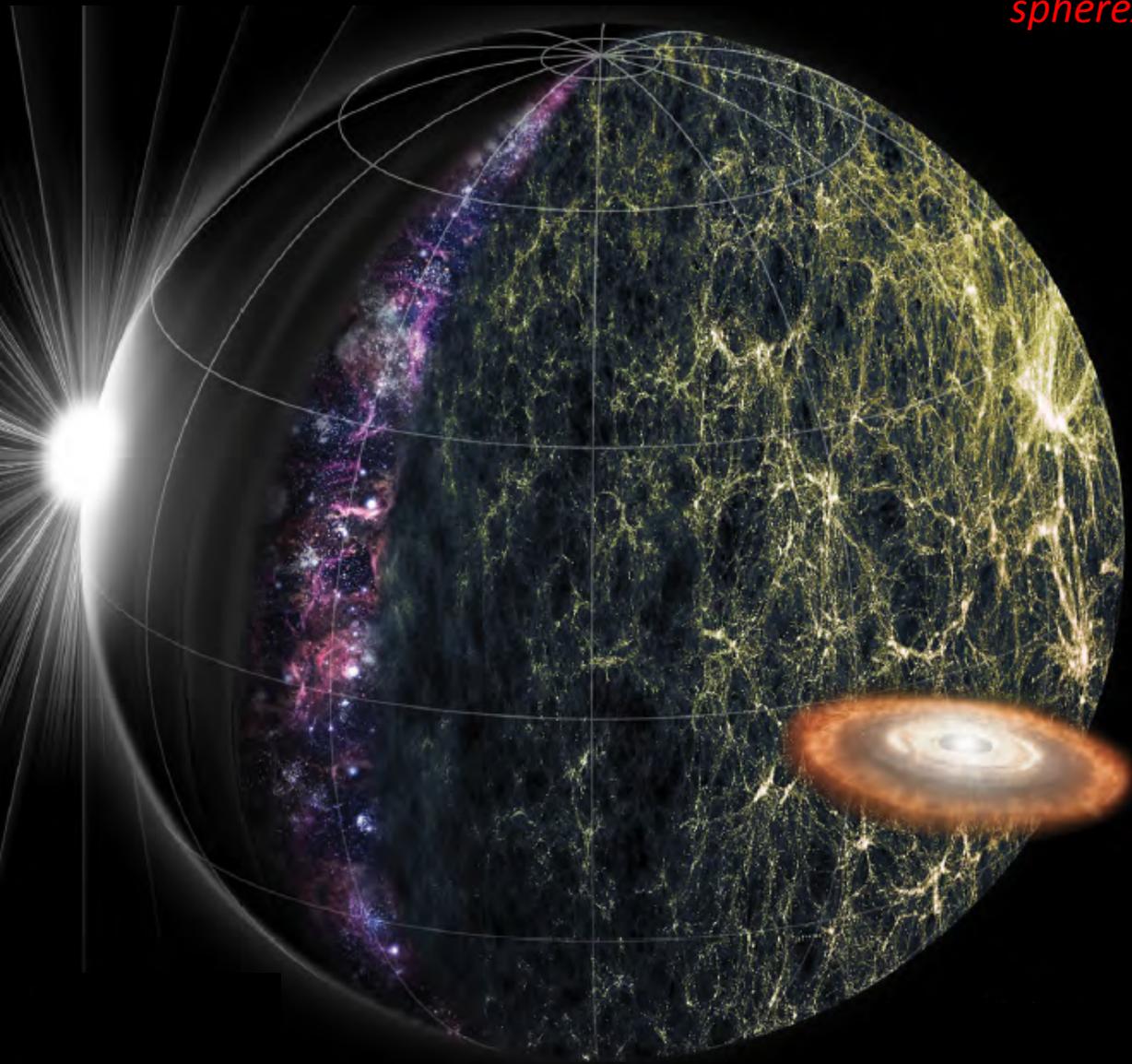
■ Redshift accuracy

- *High redshift accuracy NOT needed*

SPHEREx: an All-Sky Spectral Survey

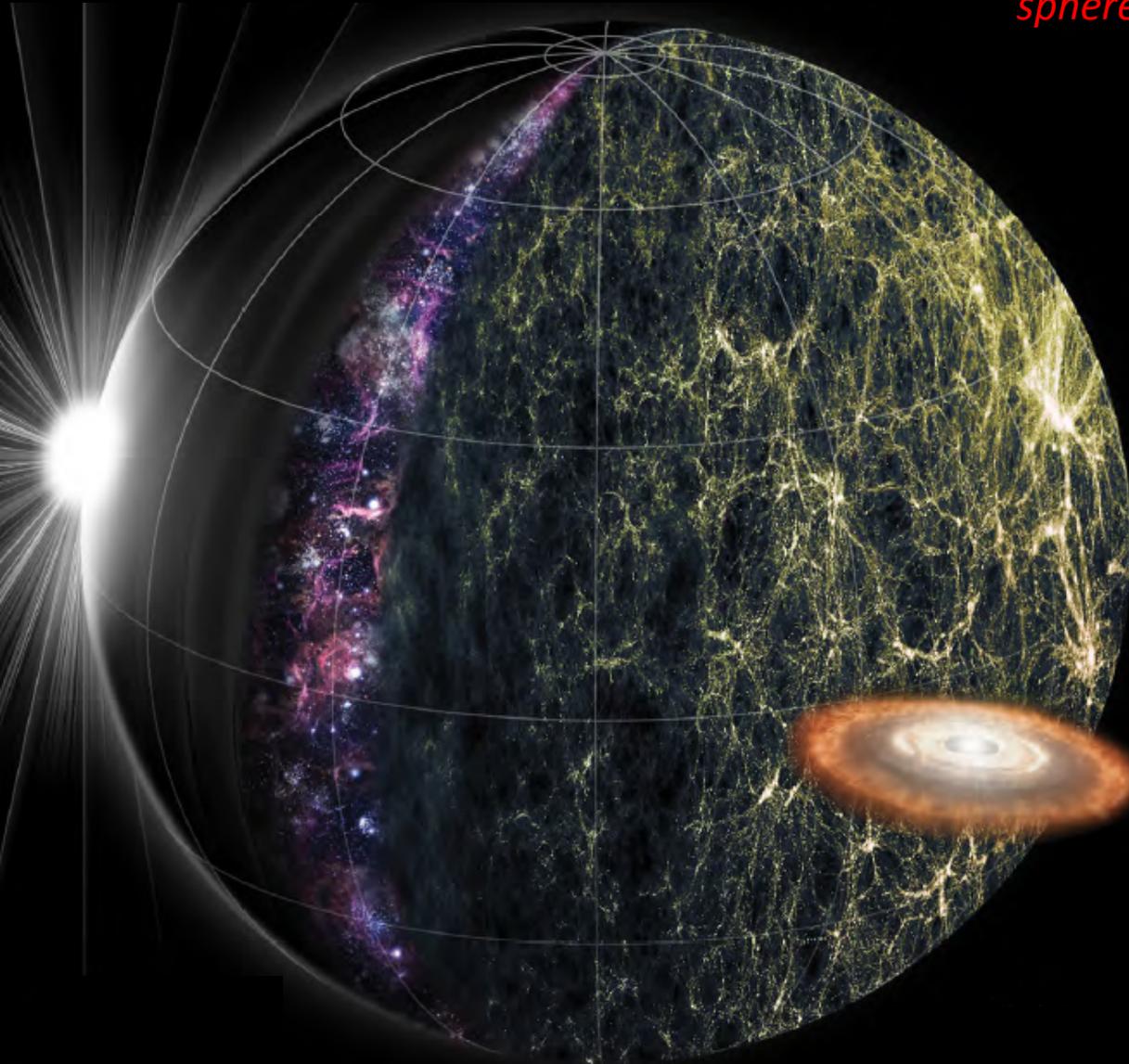
Doré, Bock, ..., de Putter, et al (1412.4872)

spherex.caltech.edu



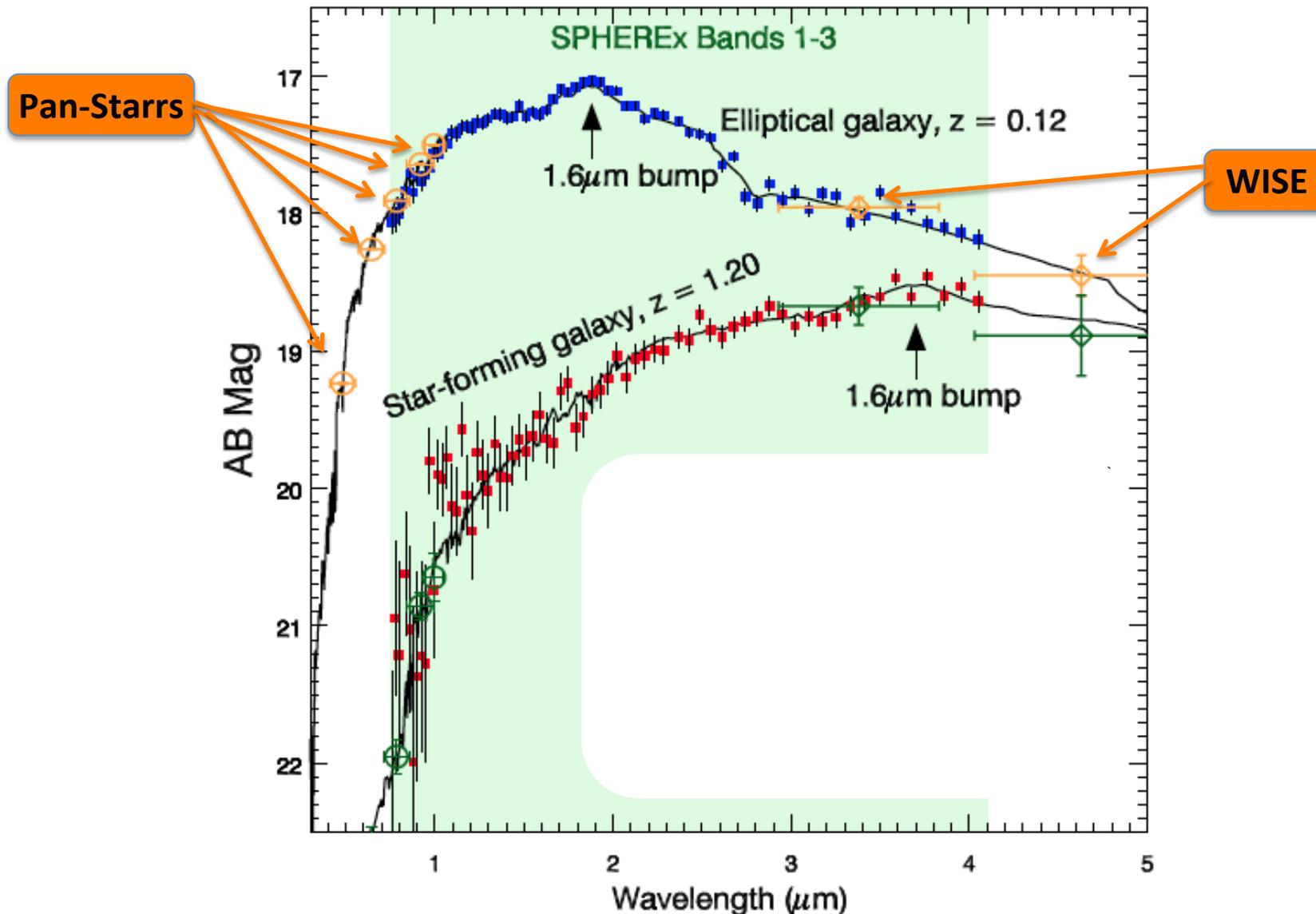
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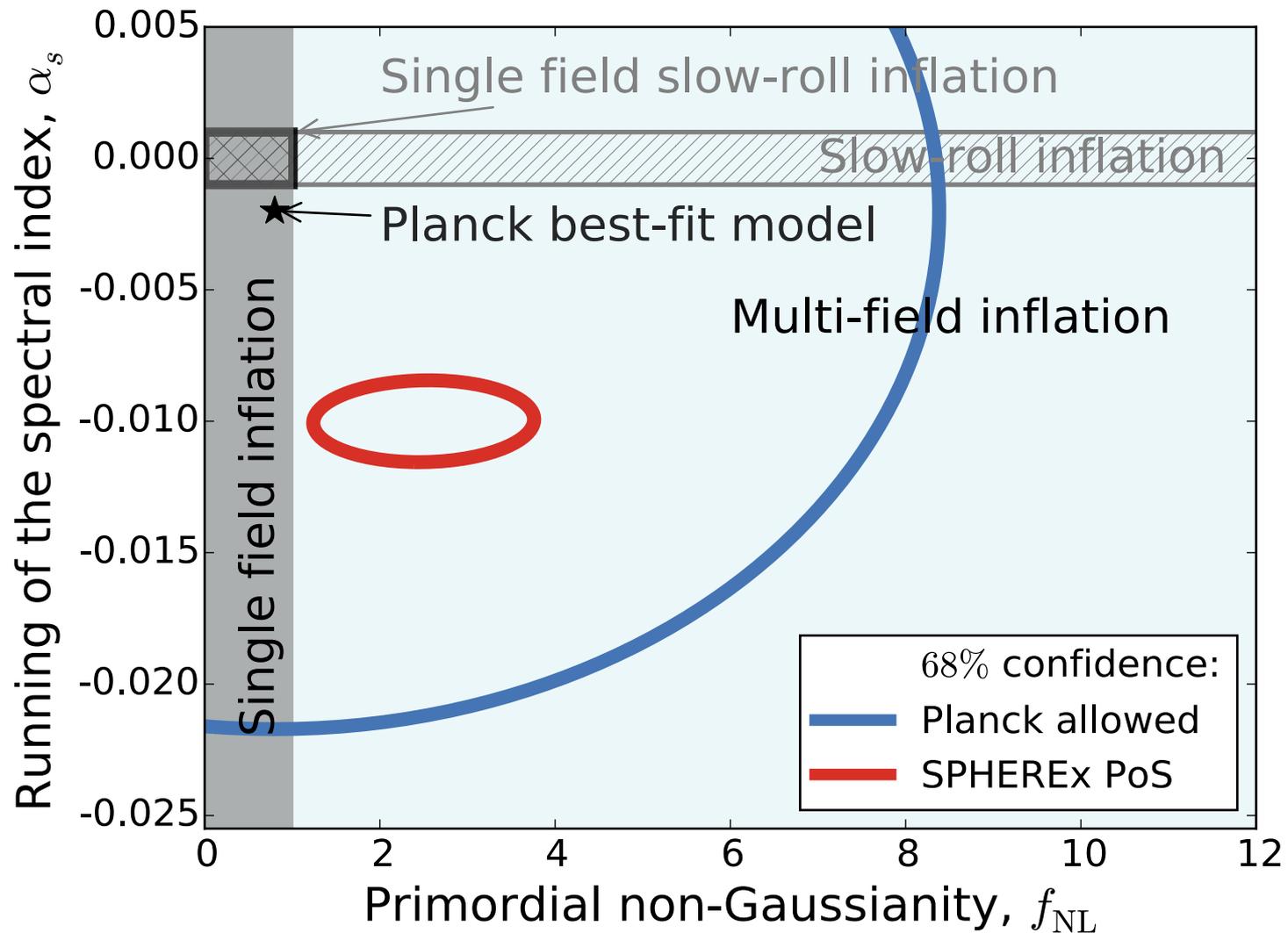


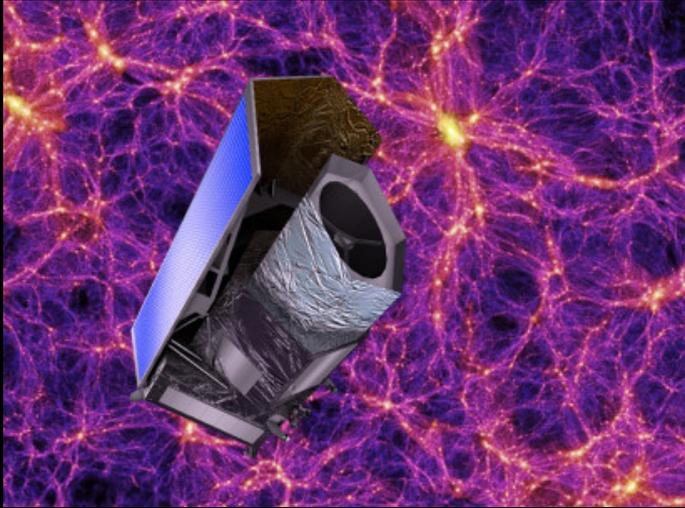
- $\lambda = 0.75 - 5 \mu\text{m}$
- Resolution $R = 41.5$
- Full-Sky
- Pixel Size $6.2''$
- Aperture 20cm
- FoV $3.5^\circ \times 7^\circ$

SPHEREx enables low-res spectroscopic redshifts for $> 300M$ galaxies



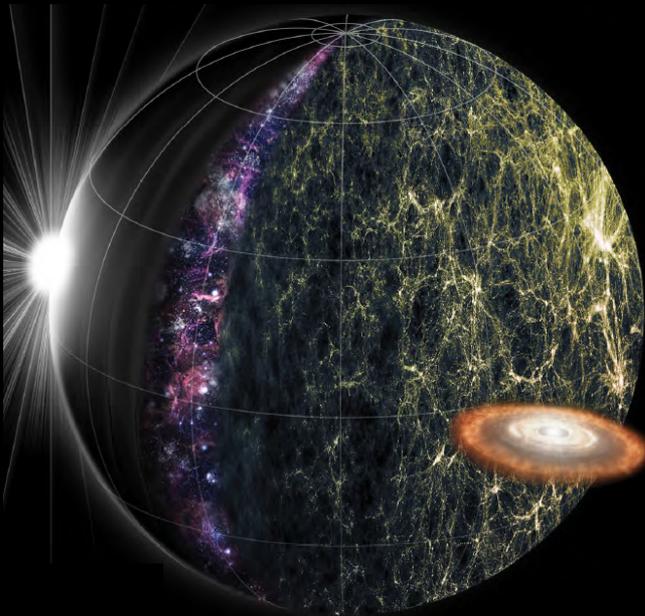
SPHEREx galaxy clustering can reach $\sigma(f_{NL}) < 1$





EUCLID

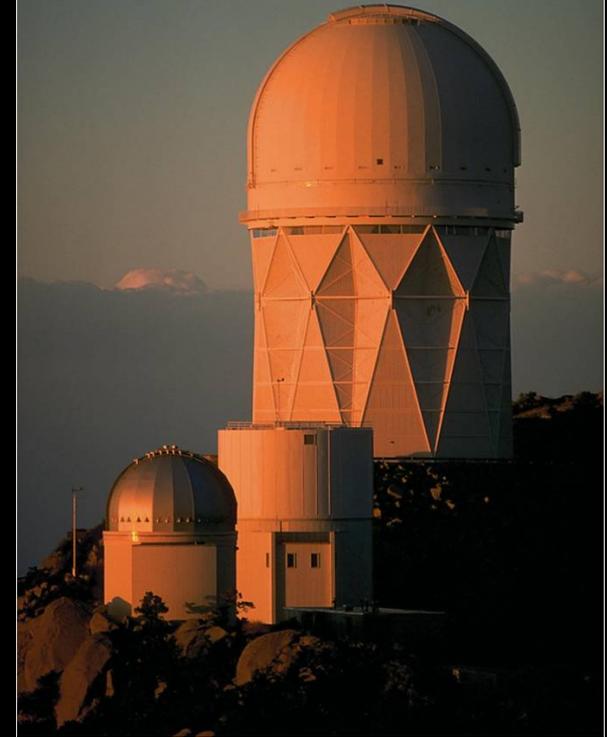
www.euclid-ec.org



SPHEREx

spherex.caltech.edu (1412.4872)

BOSS -> eBOSS -> DESI



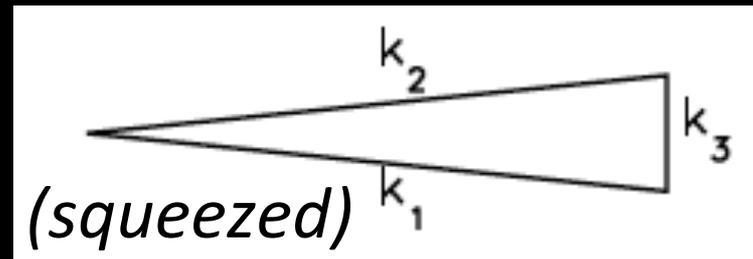
DESI

Levi et al, 2013 (1308.0847)

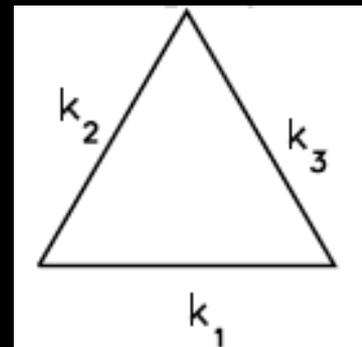
Beyond local non-Gaussianity: types characterized by Bispectrum

$$B(k_1, k_2, k_3) \propto \langle \Phi(\vec{k}_1) \Phi(\vec{k}_2) \Phi(\vec{k}_3) \rangle$$

Local:
multifield



Equilateral:
non-canonical
kinetic terms,...



Scale-dependent bias beyond local non-Gaussianity

Gleyzes, Green, Doré, de Putter in prep

Local Non-Gaussianity:

$$\Delta b(k) \propto \frac{1}{k^2 T(k)} = k^{-2} + O(1)$$

Equilateral Non-Gaussianity:

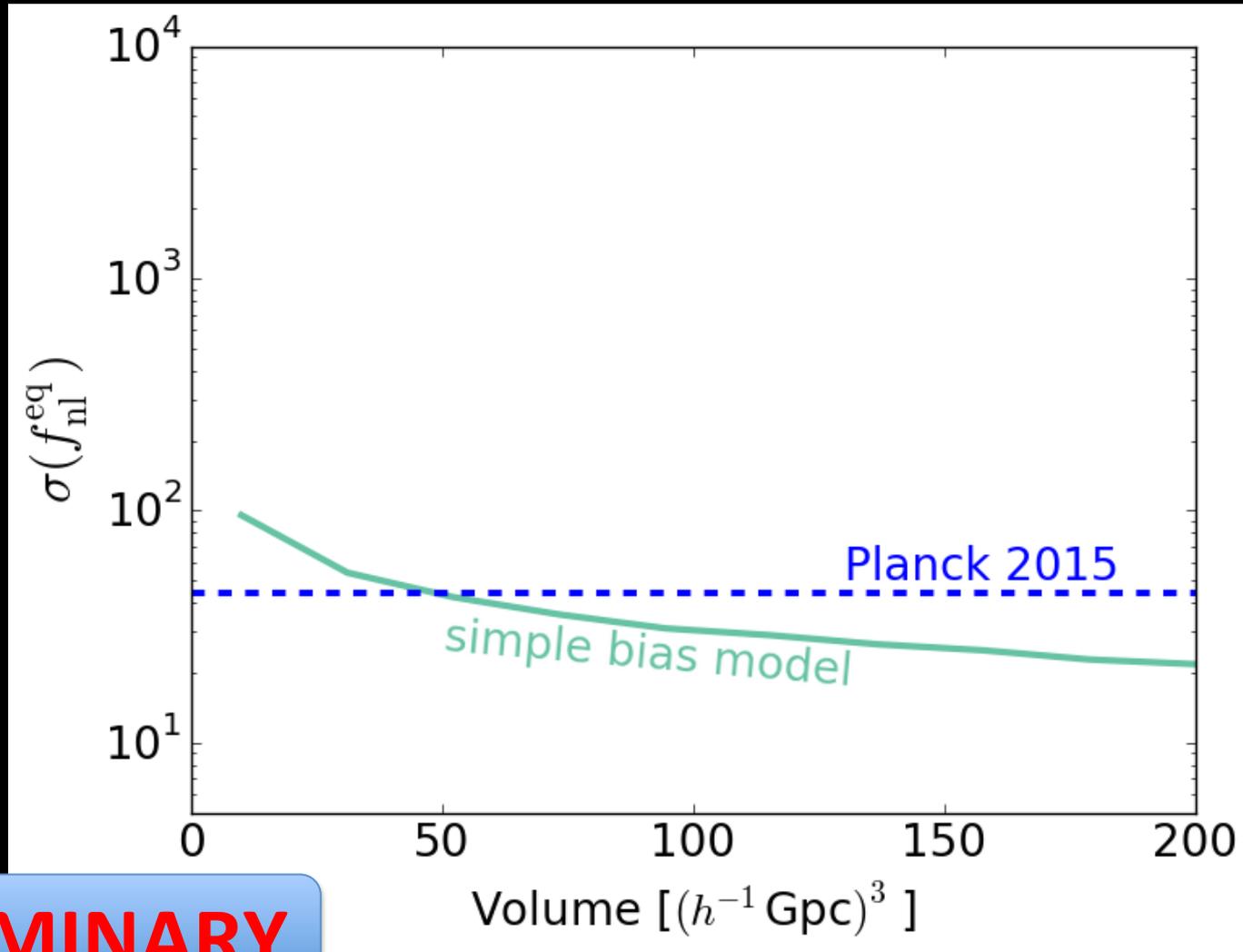
$$\Delta b(k) \propto \frac{1}{T(k)} = 1 + O(k^2)$$



Can this be distinguished from non-local and non-linear halo bias?

Scale-dependent bias from equilateral non-Gaussianity

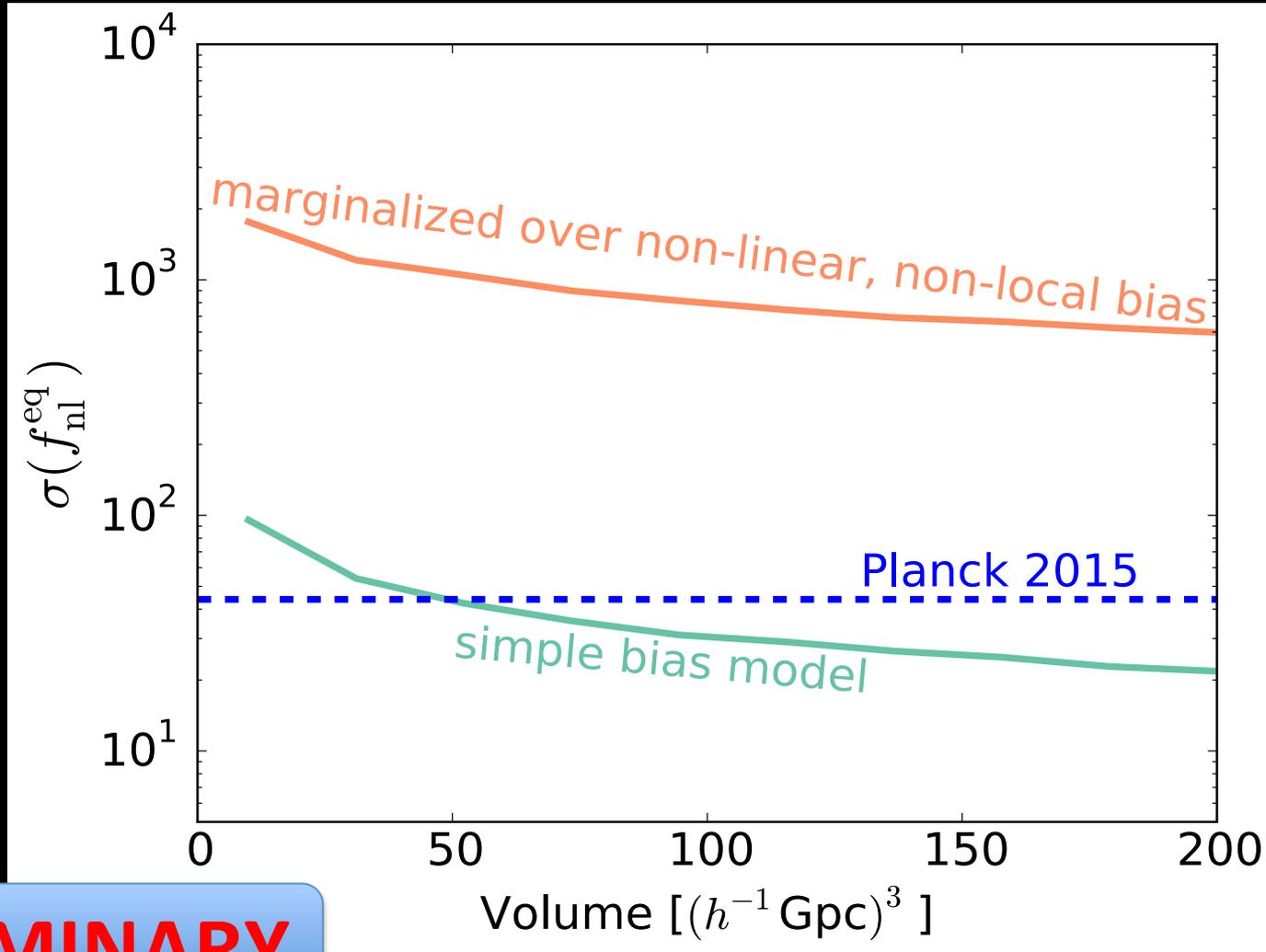
Gleyzes, Green, Doré, de Putter in prep



PRELIMINARY

Scale-dependent bias from equilateral non-Gaussianity

Gleyzes, Green, Doré, de Putter in prep



PRELIMINARY

More Inflation from galaxy clustering

- Primordial non-Gaussianity from the halo bispectrum

Sefusatti et al 2006, Baldauf et al 2011, Baldauf et al 2016, Doré et al 2015, ...

Equilateral: $\sigma(f_{NL}) \sim > 10$

Local: $\sigma(f_{NL}) < 1$

- Spectral index, n_s , and running α_s

EUCLID: $\sigma(n_s) = 0.006 \rightarrow 0.002$

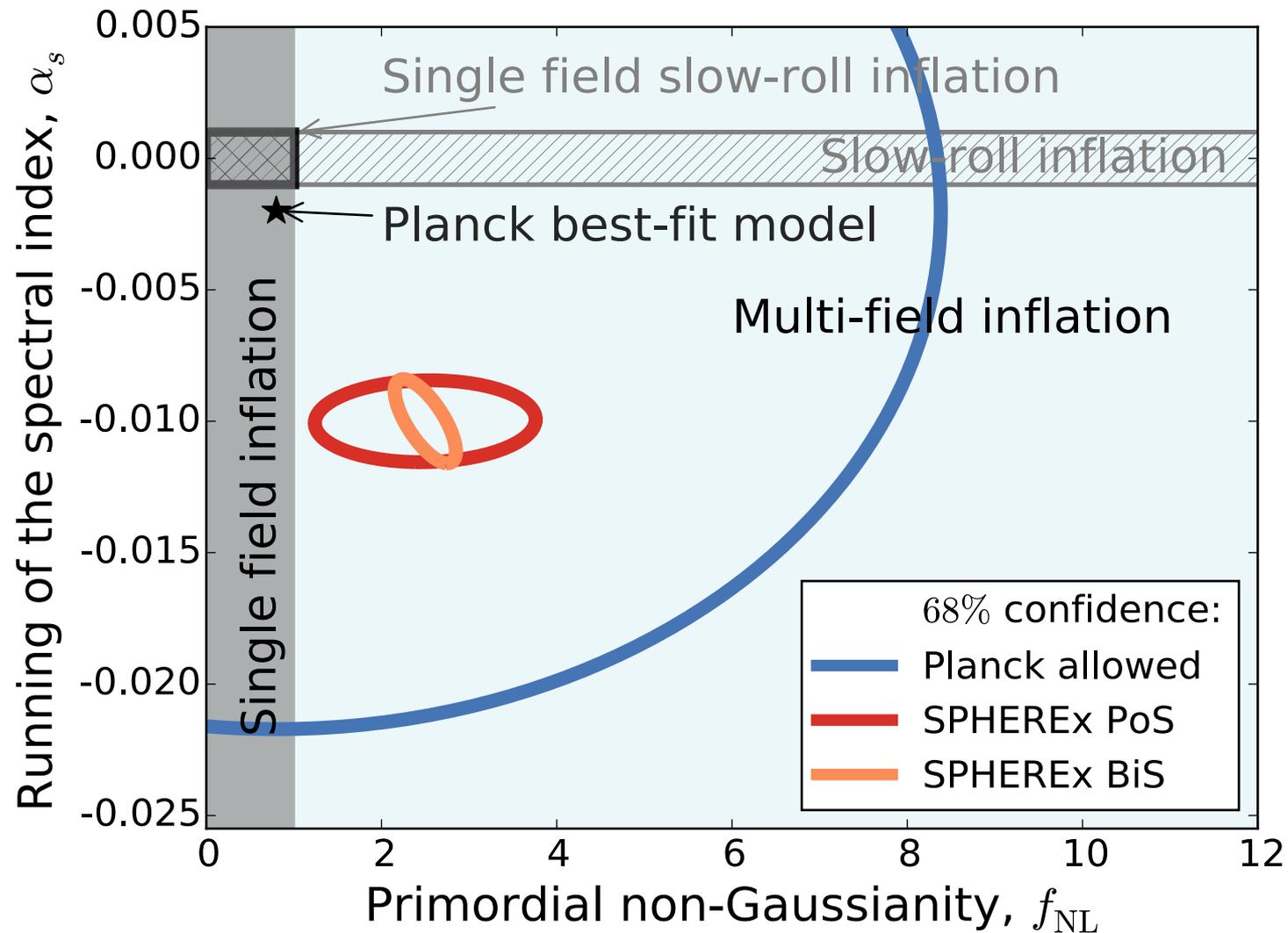
$\sigma(\alpha_s) = 0.009 \rightarrow 0.003$

Amendola et al 2016

- Features in the primordial power spectrum

Chen et al 2016, Ballardini et al 2016, ...

SPHEREx galaxy clustering can reach $\sigma(f_{NL}) < 1$



Summary

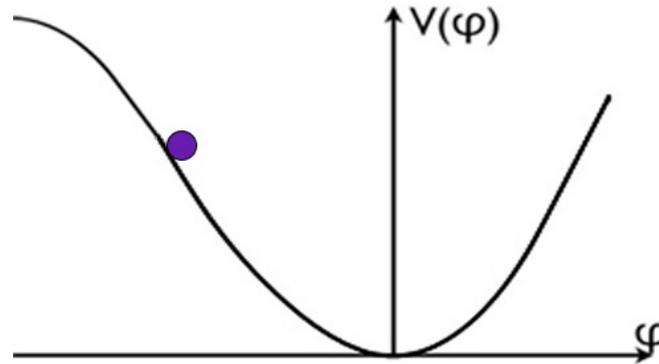
- Local Primordial non-Gaussianity (PNG) strong probe of physics of Inflation: single- vs. multifield
- Scale-dependent bias in galaxy clustering from e.g. *SPHEREx* will allow constraints beyond capability of CMB
- Other types of PNG also cause scale-dependent bias, but more degenerate with non-primordial biasing
- Through scale-dependent bias and more, galaxy surveys will play key role in unraveling physics of Inflation

Extra Slides

Single-field consistency condition predicts **zero mode coupling** (modulo gradients)

Single-Field Inflation

*Maldacena 2003,
Creminelli & Zaldarriaga 2004*



$$\delta \ln P(k; x_i) \propto \nabla^2 \Phi_L(x_i)$$

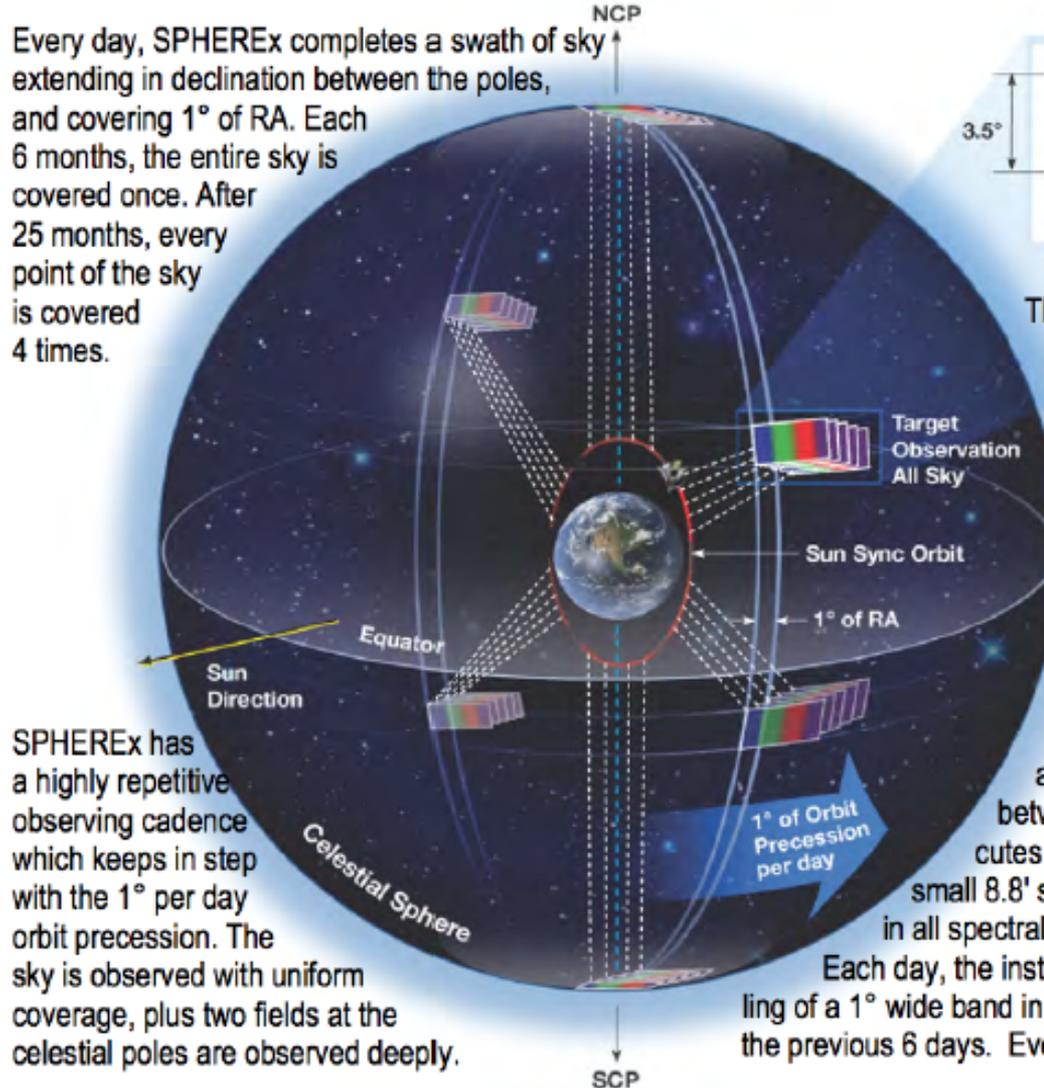
$$\delta \ln P(k; x_j) \propto \nabla^2 \Phi_L(x_j)$$

Φ_L

$$f_{NL} = -\frac{5}{12} (n_s - 1) \approx 0$$

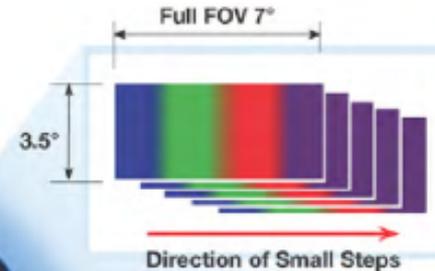
SPHEREx: An All-Sky Spectral Survey

Doré 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.

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.

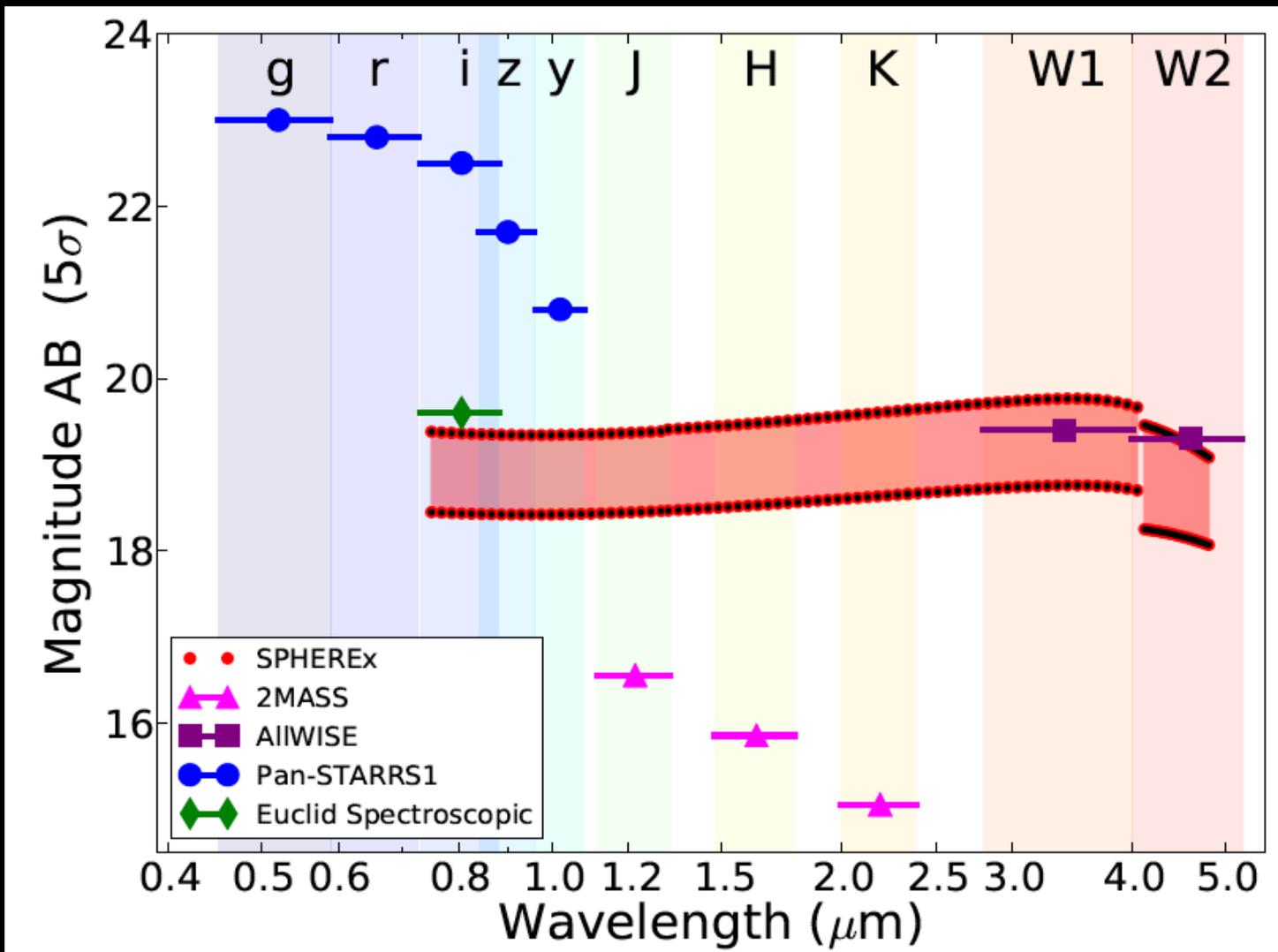


The detectors image the sky through LVFs. The spacecraft makes multiple pointings that step sources over the field of view. A full spectrum is obtained after 48 steps, with multiple visits over successive orbits.

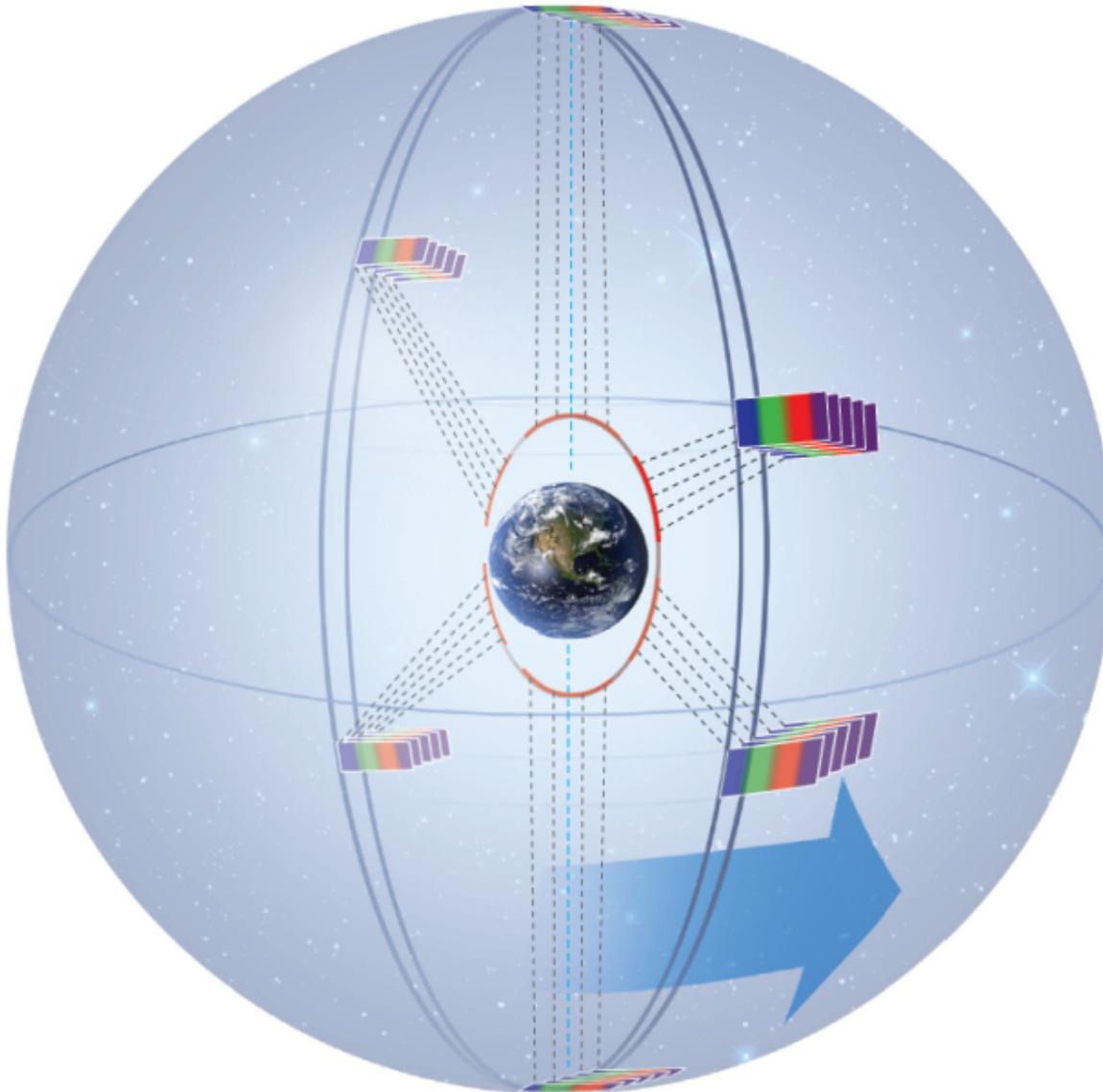
SPHEREx observes the sky with 6-8 large ~60° slews per orbit that satisfy the solar and terrestrial avoidance angles. In the ~12 minute period between large slews, the spacecraft executes 4-8 ~100 s integrations separated by small 8.8' slews. This way, targets are observed in all spectral channels across 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 $R \sim 40$

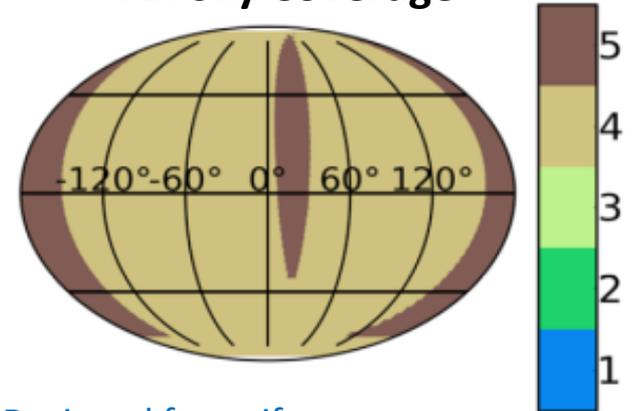


Mapping the Full Sky with SPHEREx



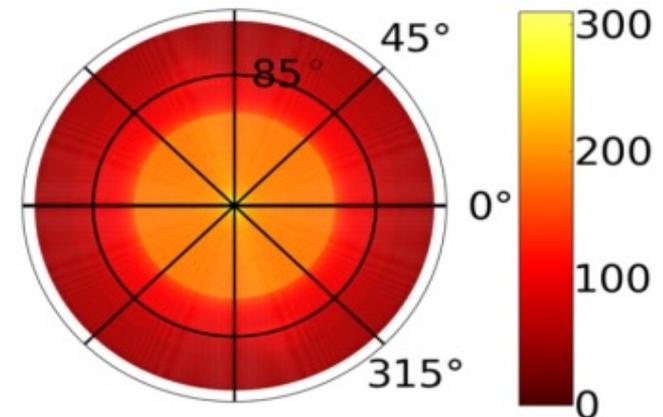
SPHEREx observes the sky simply by pointing the spacecraft over multiple orbits to obtain complete spectra.

All-Sky Coverage



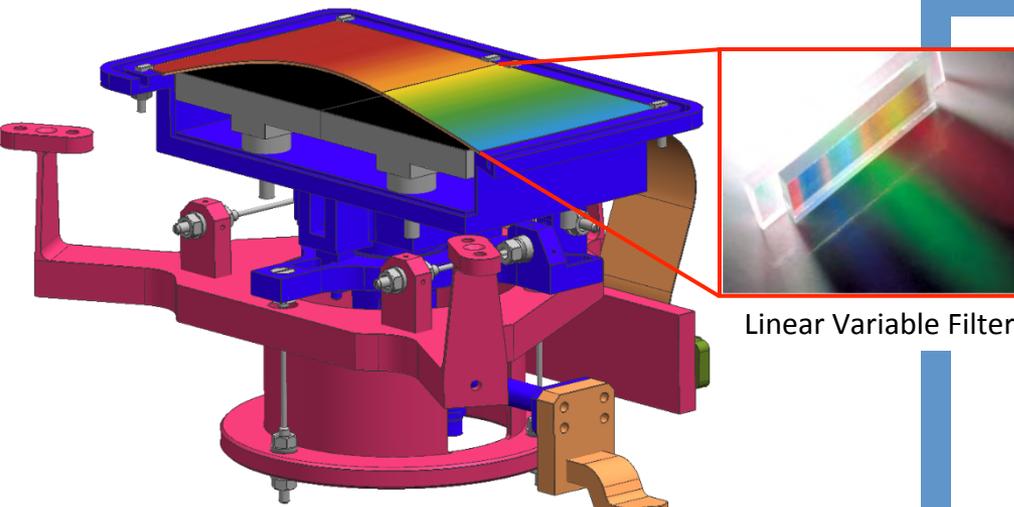
Designed for uniform coverage after 25 months of observations with 4 independent surveys.

Deep Surveys at Poles



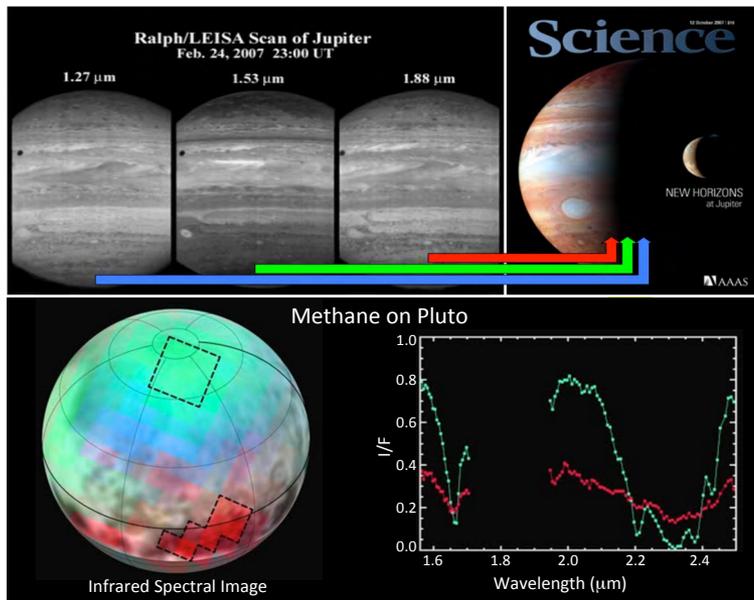
Except for two 100 sq. degree regions at the poles with are ~30x deeper. *An opportunity for unique science*

High-Throughput LVF Spectrometer

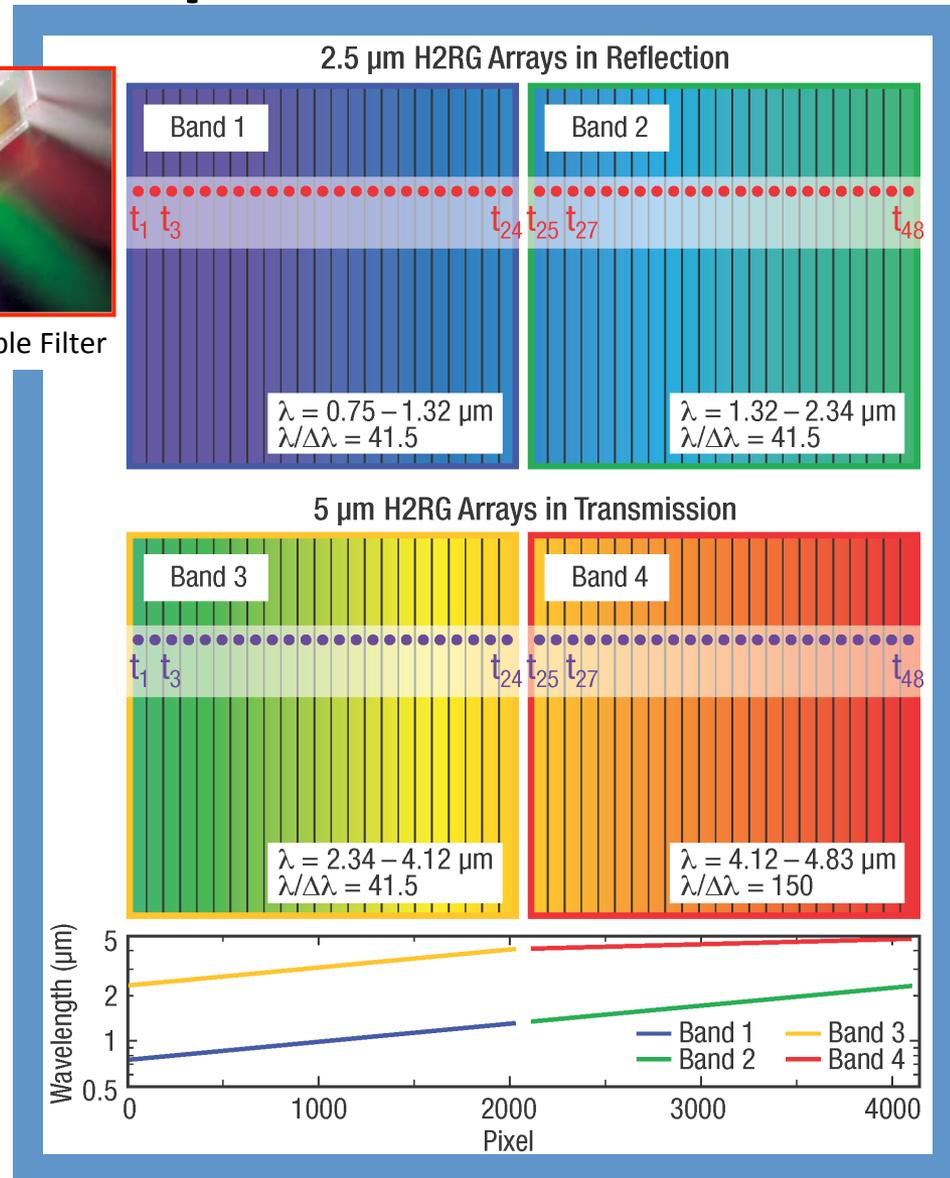


Focal Plane Assembly

Linear Variable Filter



LVFs used on ISOCAM, HST-WFPC2, New Horizons LEISA, & OSIRIX-Rex (2016 launch)



Spectra obtained by stepping source over the FOV in multiple images: **no moving parts**

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	≤ 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.

1σ errors	PS	Bispec	PS + Bispec	EUCLID	Current
$f_{\text{NL}}^{\text{loc}}$	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 = $1/\sqrt{\text{DetCov}}$	202	NC	NC	309	25