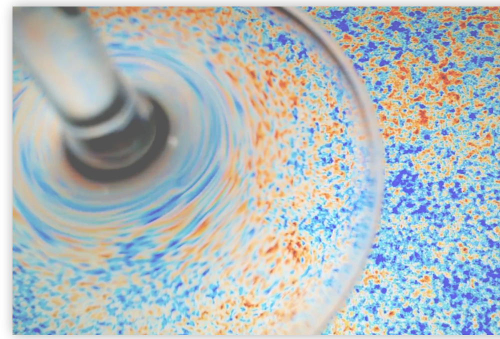
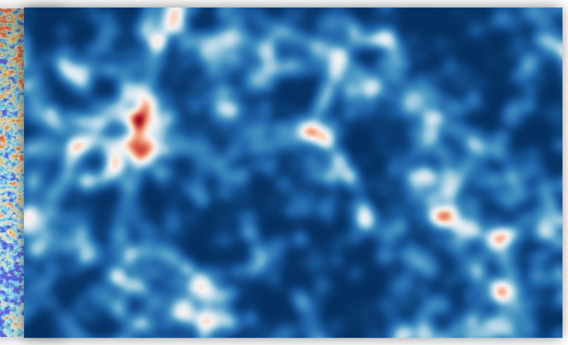
Future Cosmology with CMB Lensing and Galaxy Clustering

Marcel Schmittfull
UW-Madison, 2/20/2020

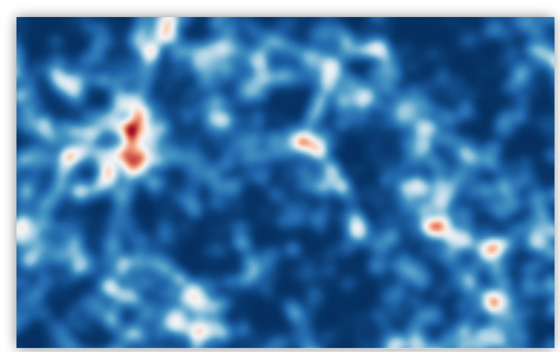
IAS INSTITUTE FOR ADVANCED STUDY

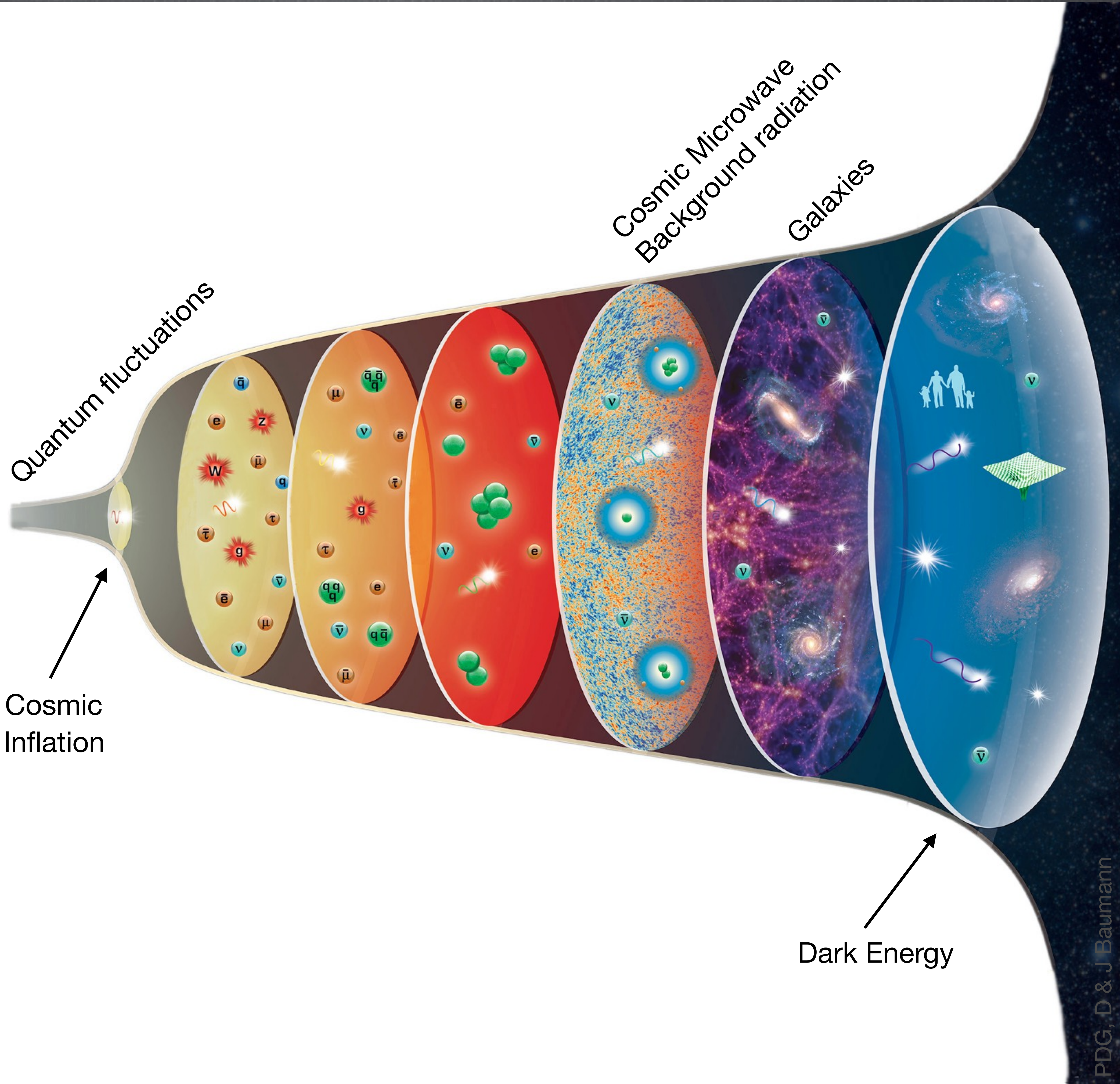
Outline

I. Future cosmology with CMB lensing and galaxy clustering

II. Galaxy clustering: Theory & Analysis (~15 min.)





Quantum fluctuations
Cosmic Microwave
Background radiation
Galaxies
Cosmic
Inflation
Dark Energy
PDG, D & J Baumann

Nature of each building block is unknown

Inflation
How did our Universe begin?
What drives the inflationary expansion?

Dark energy
What drives the current accelerated expansion?
Is it a cosmological constant? Is General Relativity valid?

Dark matter
What particle(s) is it made of?

Relativistic degrees of freedom
What is the mass (hierarchy) of neutrinos?
Are there additional light relic particles?

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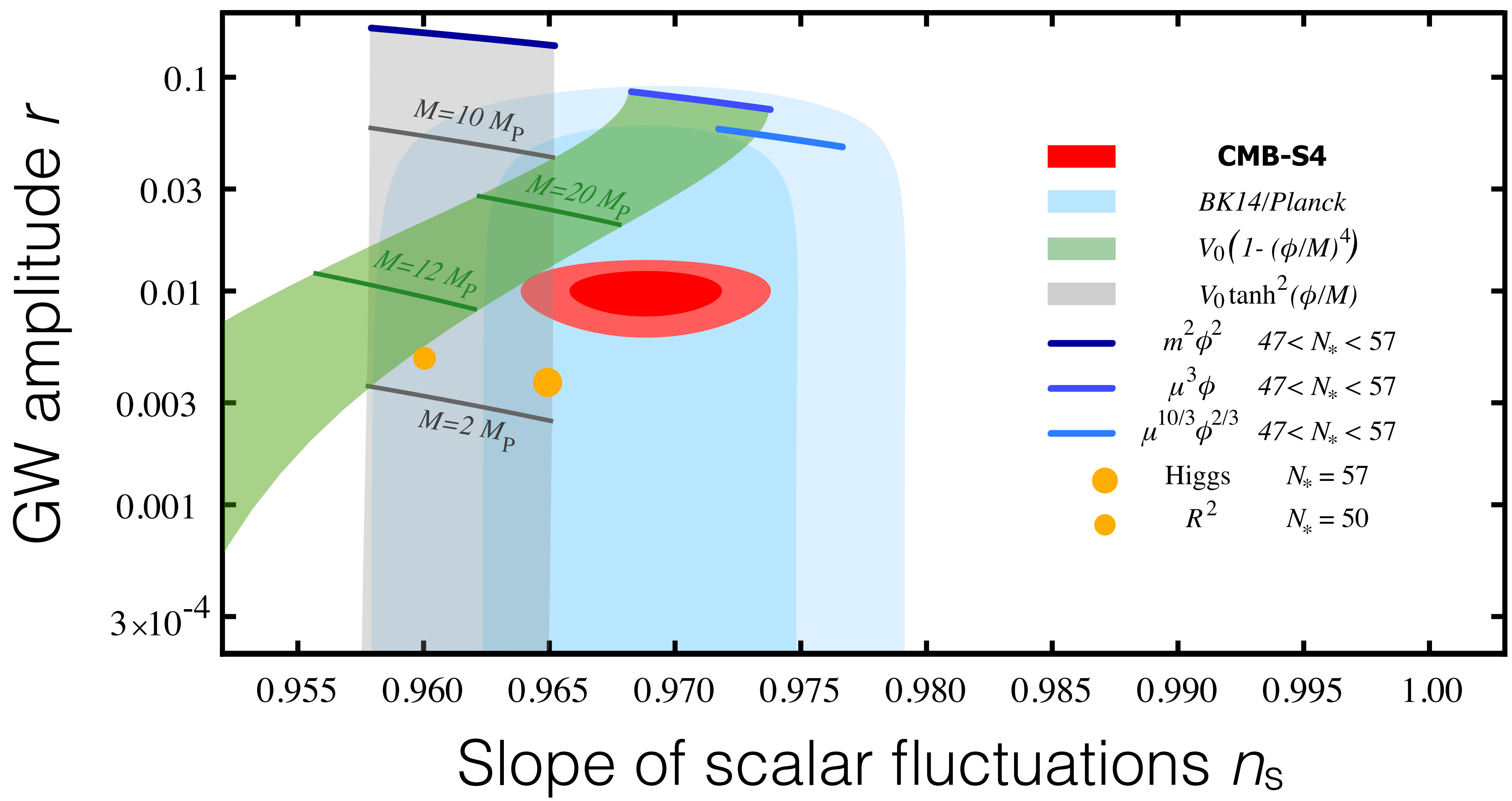
Constraining the energy scale of inflation

Energy scale at which inflation takes place is completely unknown and can range across 10 orders of magnitude

Highest-energy models (>10^{16} GeV) produce gravitational waves



$$\left(\frac{r}{0.01}\right)^{1/4} \simeq \frac{V^{1/4}}{10^{16}\,\mathrm{GeV}}$$

CMB-S4 science book

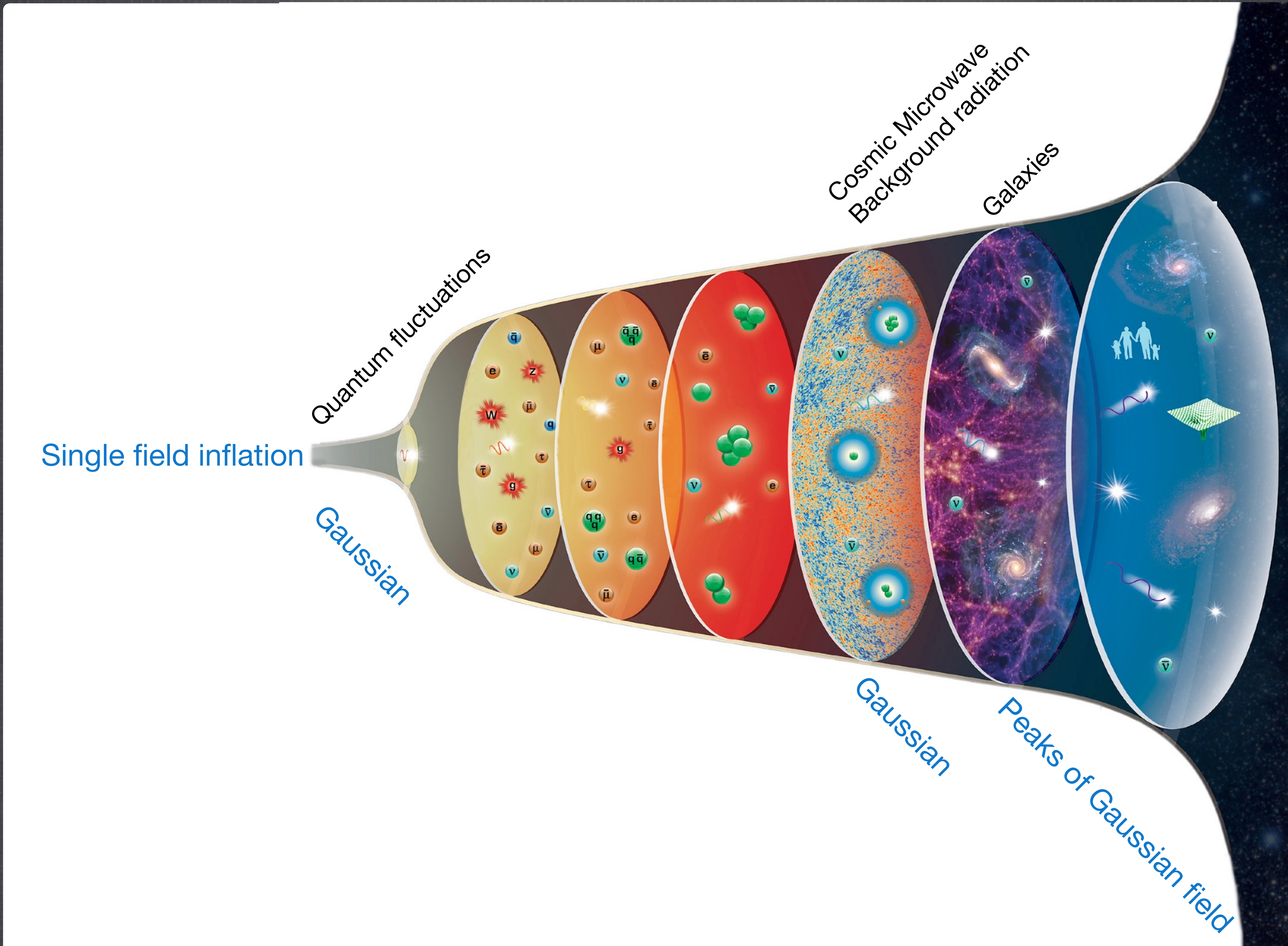
Constraining inflation

Lower-energy models ($<10^{16}$ GeV) produce no observable primordial gravitational waves

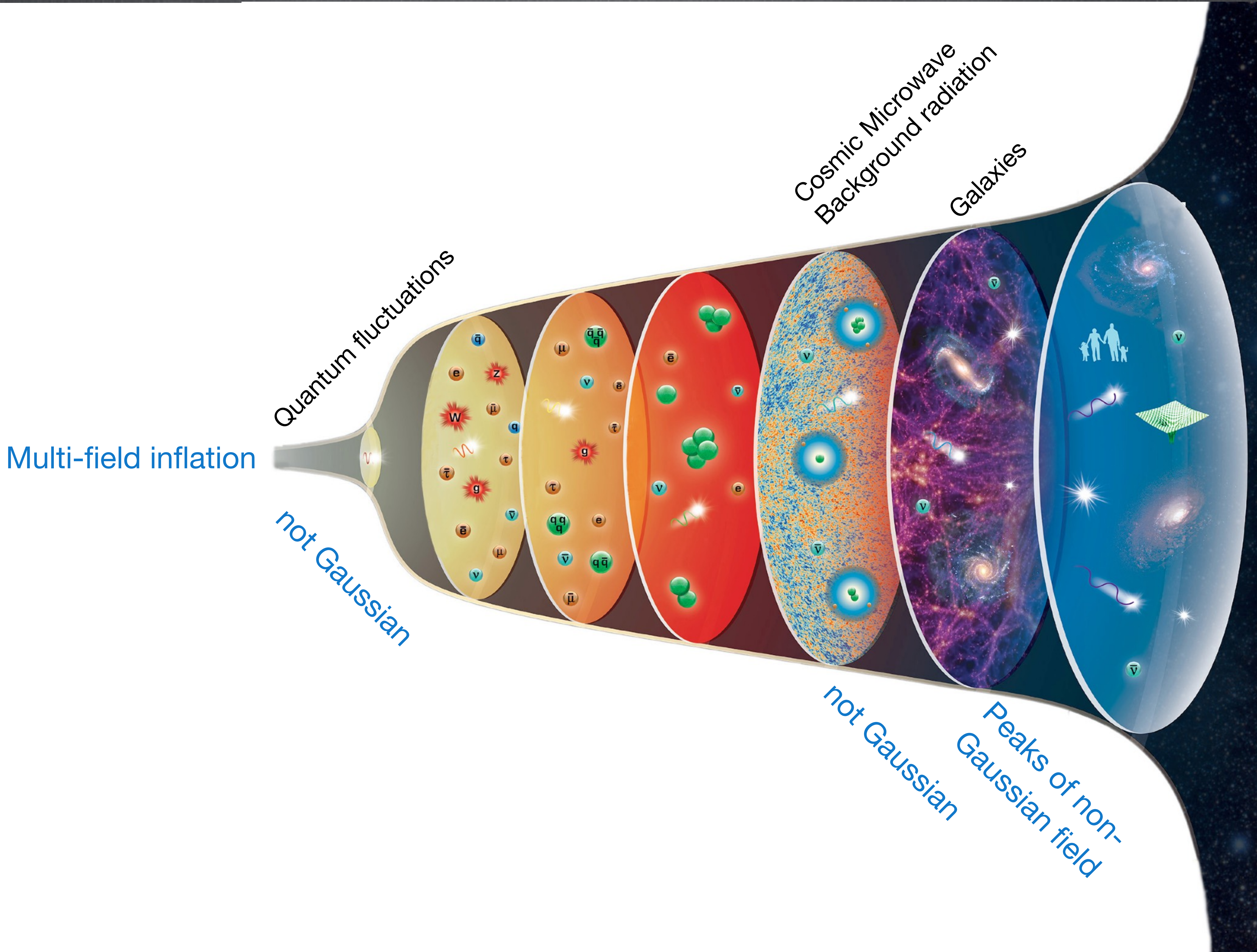
The only way to probe this class of models is **primordial non-Gaussianity**: Fluctuations not normally distributed.

Complements GW searches

e.g. Meerburg et al. (2019)



Single field inflation
Quantum fluctuations
Gaussian
Cosmic Microwave
Background radiation
Galaxies
Gaussian
Peaks of Gaussian field



Multi-field inflation
Quantum fluctuations
not Gaussian
Cosmic Microwave
Background radiation
Galaxies
not Gaussian
Peaks of non-
Gaussian field

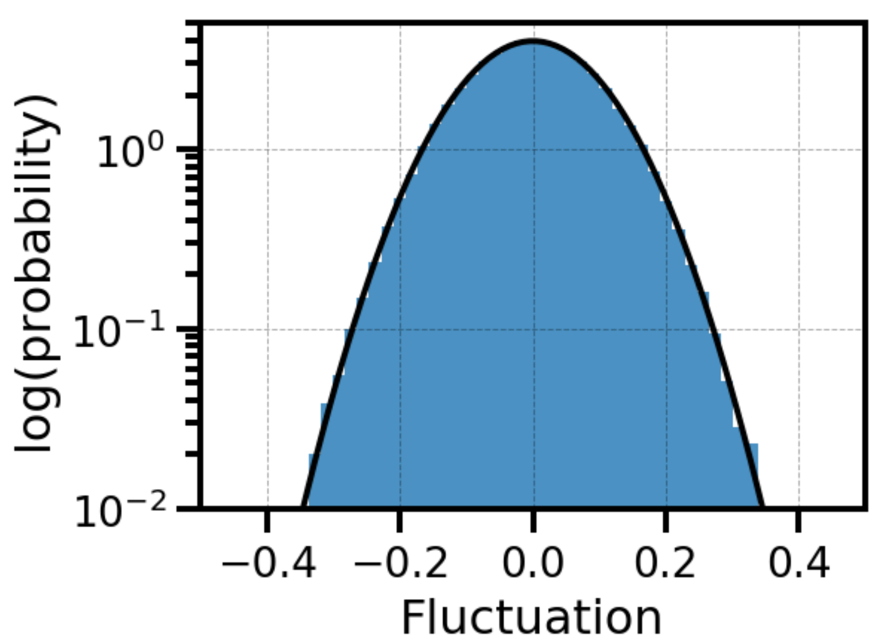
Non-Gaussian fluctuations from inflation

Inflation

Single field

Gaussian fluctuations

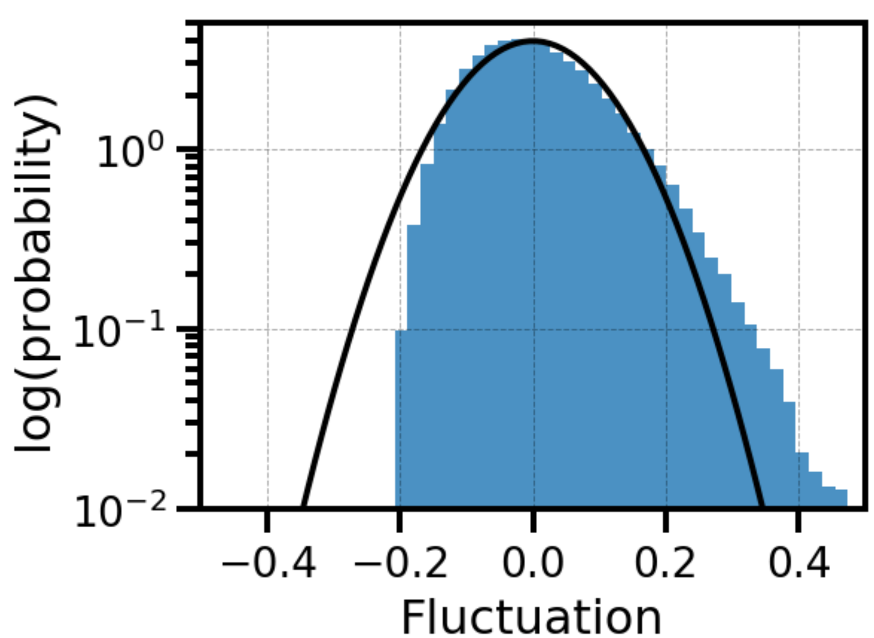
$f_{\rm NL} \ll 1$



Multi-field

Non-Gaussian fluctuations

$f_{\rm NL} \gtrsim 1$



[Non-Gaussian fluctuations from inflation]

Schematically, expectation value of a quantum field perturbation $\delta\varphi$ with Lagrangian $\mathcal{L}$ during inflation:

$$\langle\Omega|\delta\varphi_{\mathbf{k}_1}\cdots\delta\varphi_{\mathbf{k}_n}|\Omega\rangle \propto \int \mathcal{D}[\delta\varphi]\delta\varphi_{\mathbf{k}_1}\cdots\delta\varphi_{\mathbf{k}_n}e^{i\int_C \mathcal{L}[\delta\varphi_{\mathbf{k}}]}$$

Free theory $\mathcal{L}\sim\delta\varphi^2$ generates Gaussian fluctuations

Interacting theory $\mathcal{L}\sim\delta\varphi^3,\delta\varphi^4,\ldots$ or couplings between multiple fields generate non-Gaussian fluctuations

Maldacena (2003), Chen, Huang, Kachru & Shiu (2006), Chen (2010), lecture notes by L. Senatore (1609.00716)

Single field theorem

For any single field inflation model, where there is only one degree of freedom during inflation

$$f_{\rm NL} \simeq \frac{5}{12}(1-n_s) \simeq 0.02$$

Detection of $f_{\rm NL} \gg 0.02$ would **rule out all single field inflation models** regardless of

- the form of the potential
- the form of kinetic terms
- the initial vacuum state

Maldacena (2003), Creminelli & Zaldarriaga (2004), Seery & Lidsey (2005)

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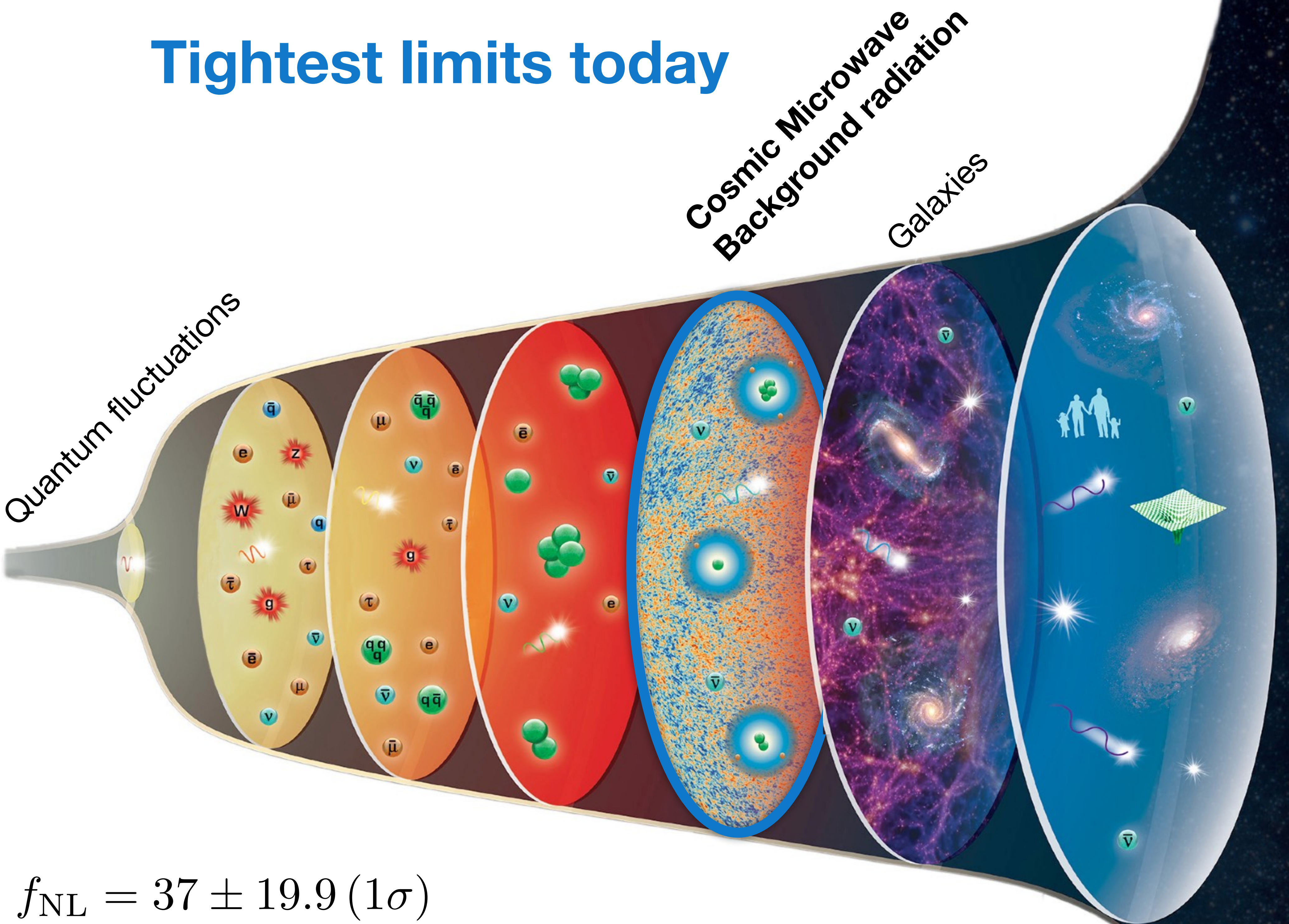
[Can also detect derivative operators and non-standard vacuum state using shape of skewness or 3-point function]

Maldacena (2003), Creminelli & Zaldarriaga (2004), Seery & Lidsey (2005)

Tightest limits today



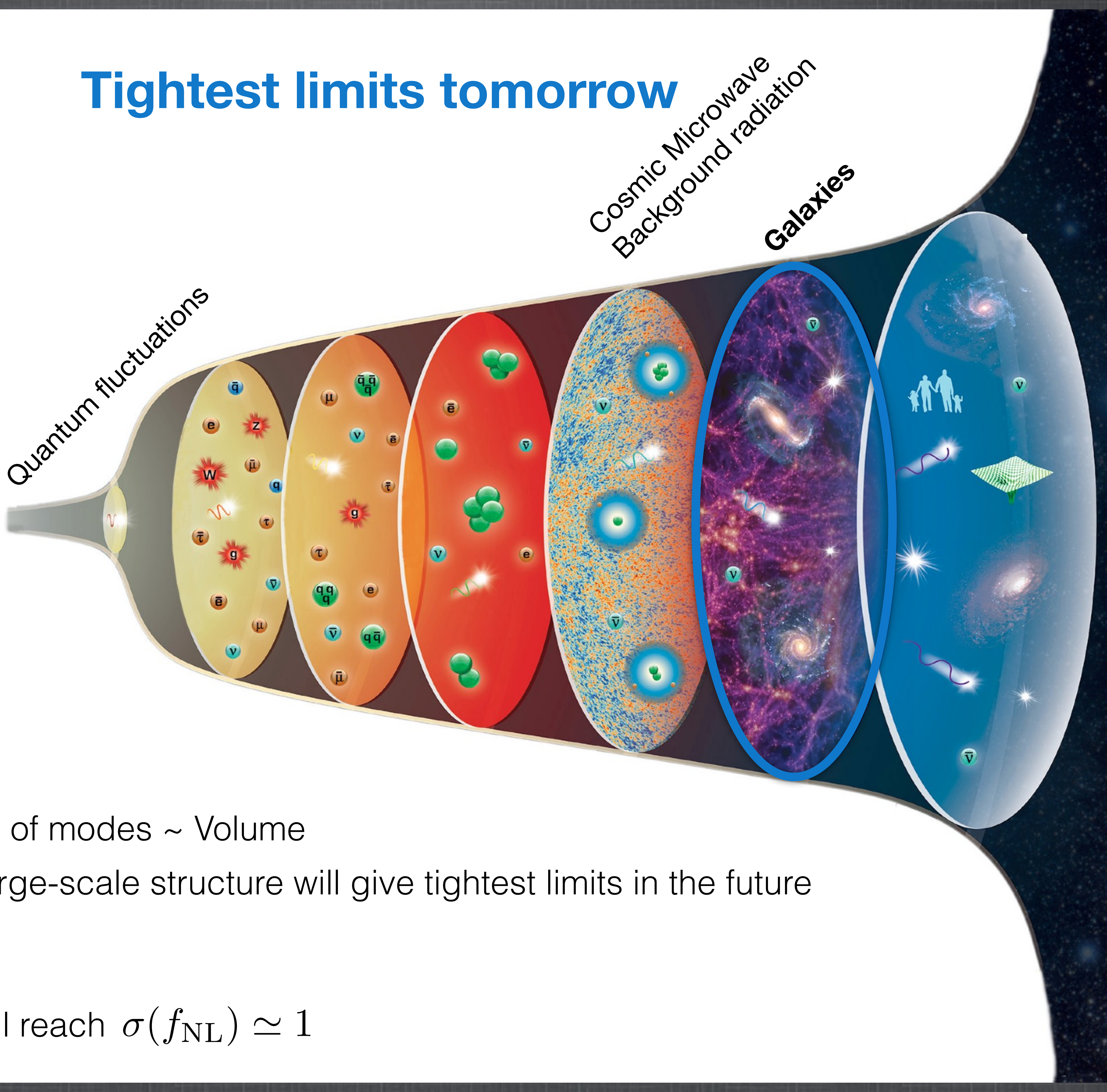
WMAP satellite: $f_{\rm NL} = 37 \pm 19.9\,(1\sigma)$

Planck satellite: $f_{\rm NL} = -0.9 \pm 5.1\,(1\sigma)$

Both consistent with zero (2σ)

WMAP Collaboration, Bennett et al. (2013)
Planck Collaboration, Akrami et al. (1905.05697)

Tightest limits tomorrow



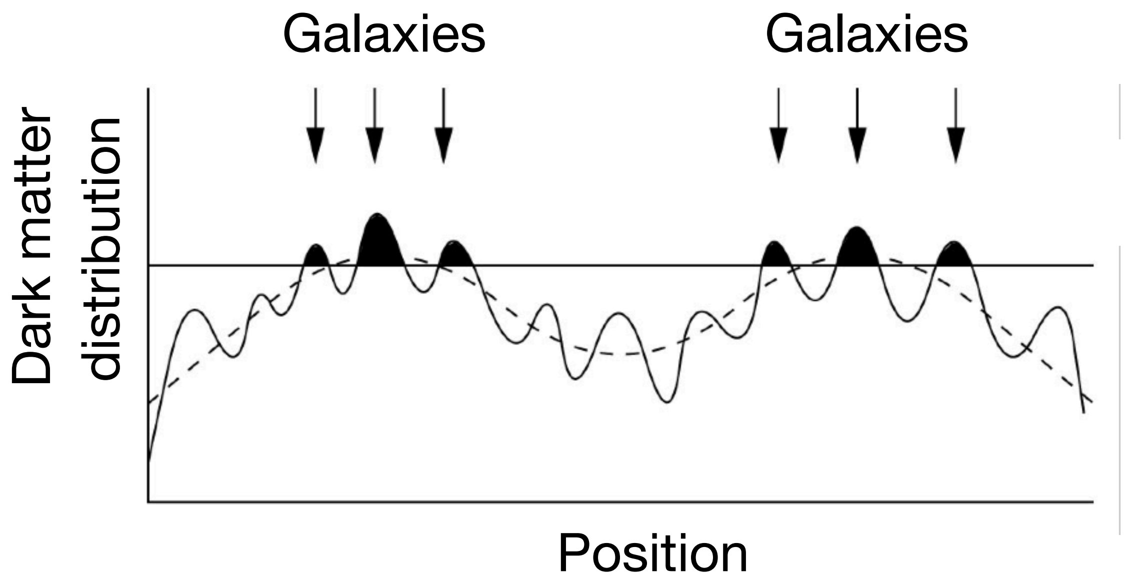
SNR² ~ Number of modes ~ Volume

⇒ Galaxies & large-scale structure will give tightest limits in the future

Spoiler alert: Will reach $\sigma(f_{\rm NL}) \simeq 1$

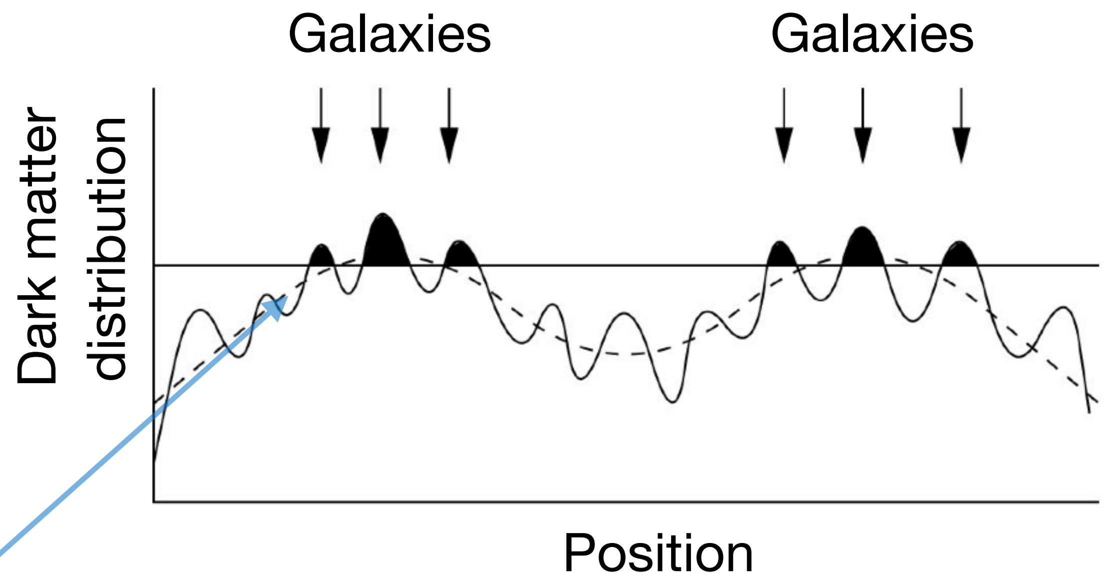
Signature of multi-field inflation for galaxies

Galaxies form at peaks of the dark matter distribution



Kaiser (1984), Dalal et al. (2007), Top figure: J. Peacock

Signature of multi-field inflation for galaxies



Galaxies form at peaks of the dark matter distribution

Multi-field inflation couples those peaks to the background potential

⇒ Galaxies are modulated by the background potential

$$\phi \propto \frac{\delta}{k^2}$$

Kaiser (1984), Dalal et al. (2007), Top figure: J. Peacock

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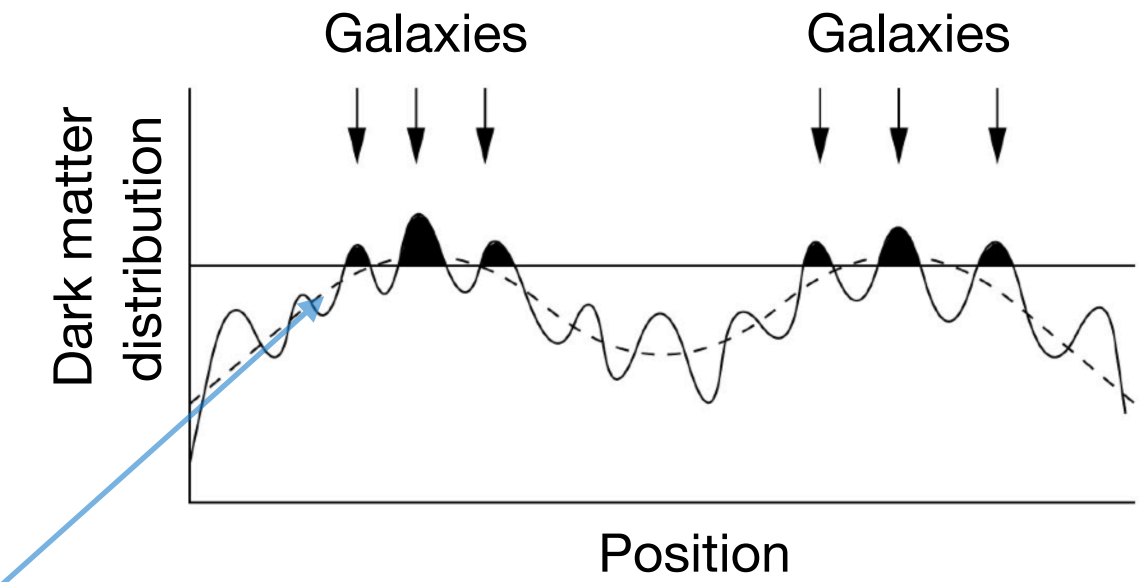
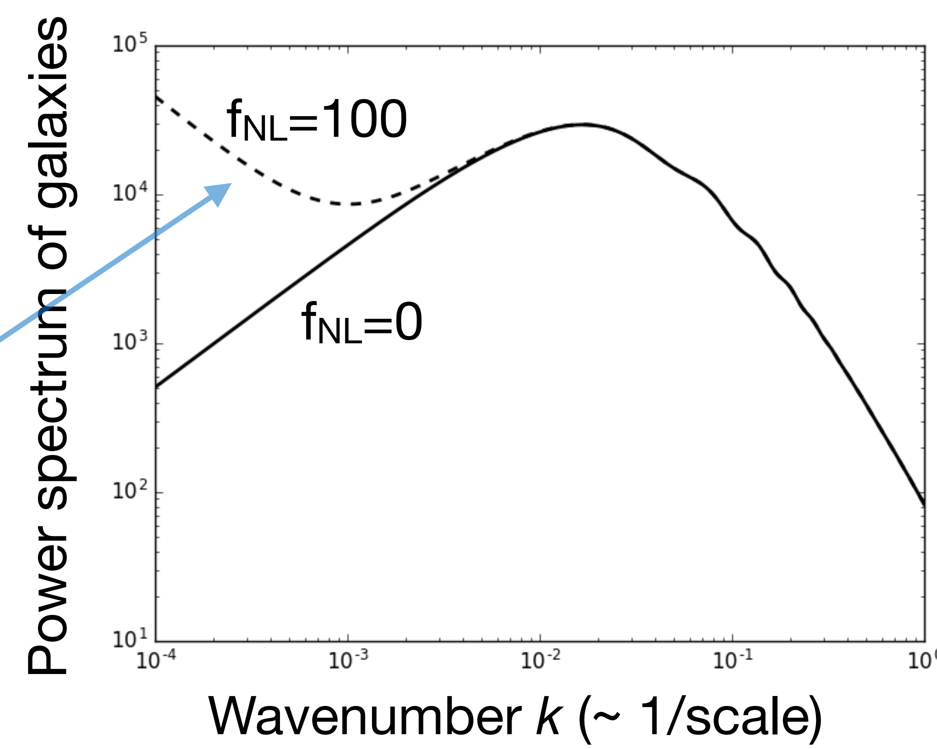


Multi-field inflation couples those peaks to the background potential

⇒ Galaxies are modulated by the background potential

$$\phi \propto \frac{\delta}{k^2}$$

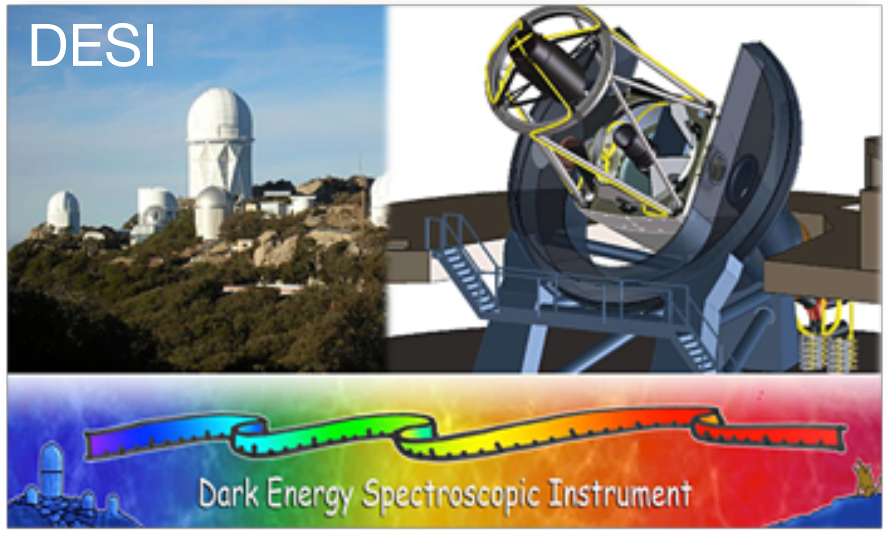
⇒ Enhancement of the power spectrum of galaxies ~ f_{NL}/k^2

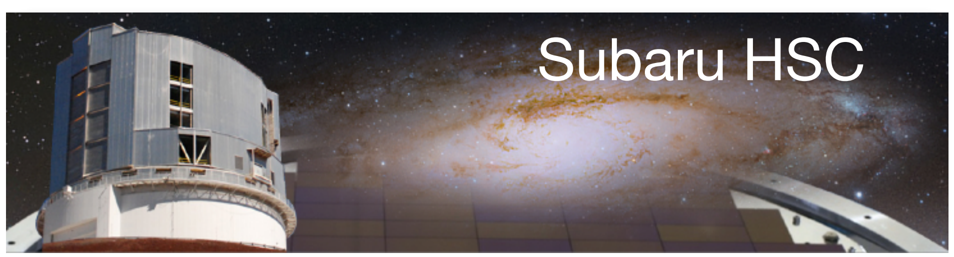


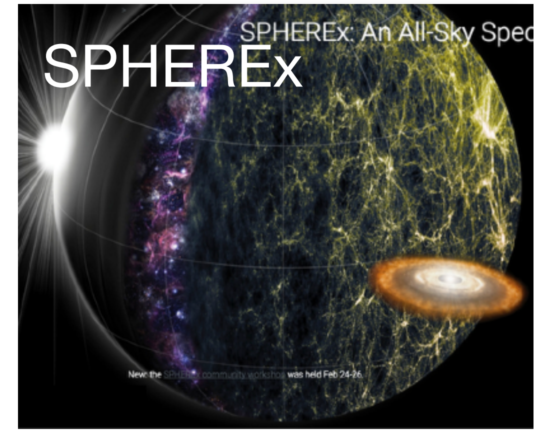
'Scale-dependent galaxy bias'

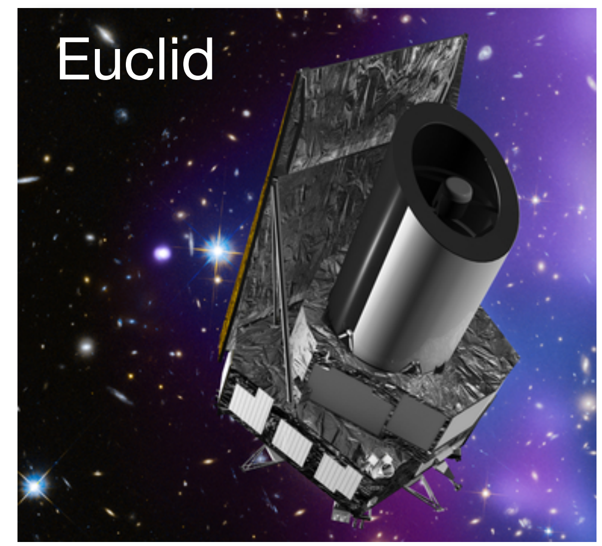
Kaiser (1984), Dalal et al. (2007), Top figure: J. Peacock

Galaxy surveys



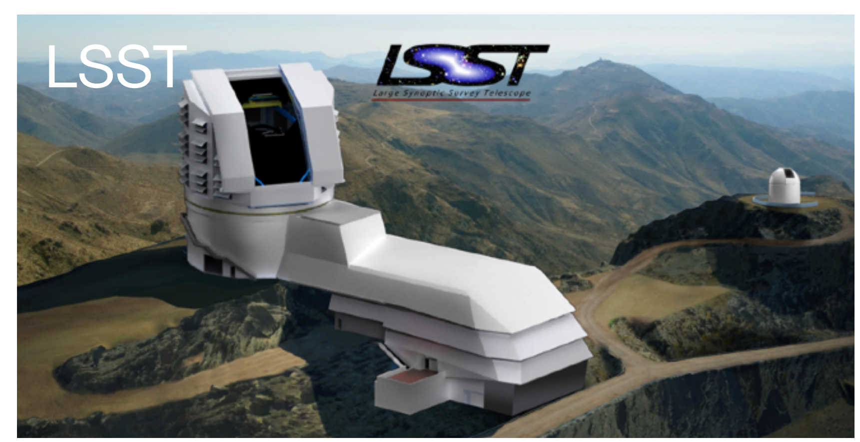






WIDE-FIELD INFRARED SURVEY TELESCOPE
WFIRST
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

MegaMapper?
Puma?



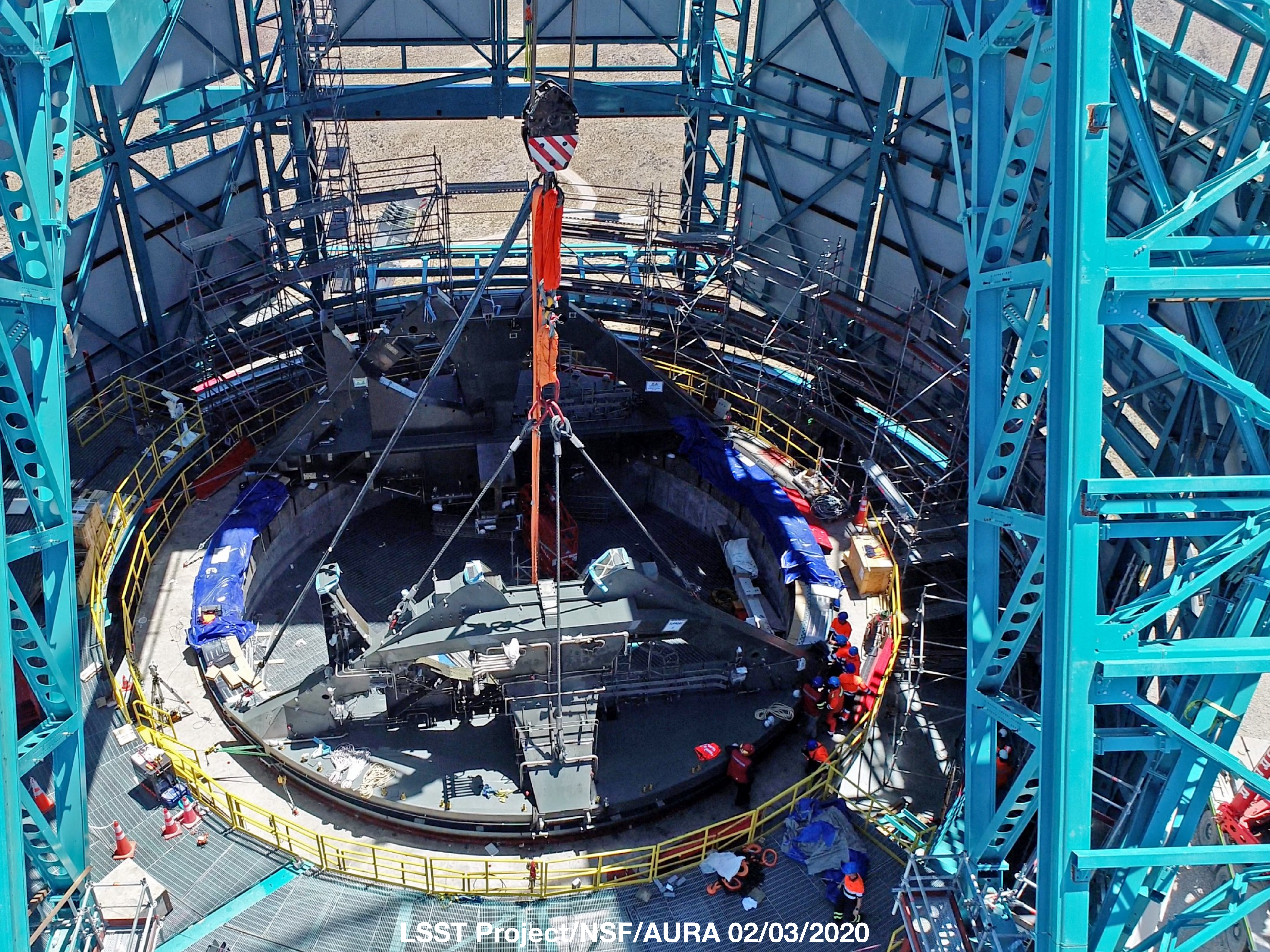
2020 2022 2030

Funding by DOE, ESA, Heising-Simons, Moore Foundation, NASA, NSF, Simons Foundation, …

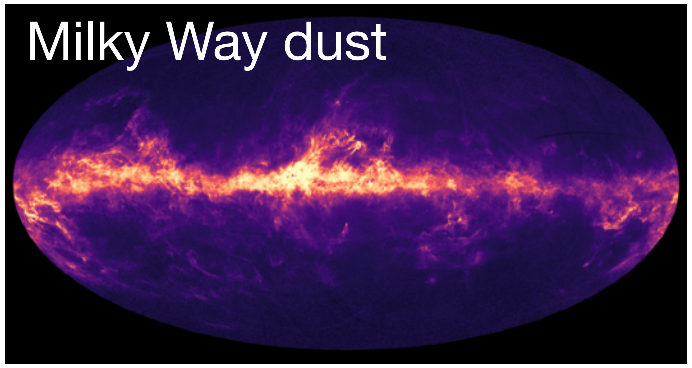
LSST — now NSF Vera C. Rubin Observatory

- Cerro Pachón, Chile (2,663 m / 8,737 ft)
- 8.4m / 27-ft mirror
- Cover entire southern sky every few nights
- 10 year survey over 18,000 deg^2
- 37 billion stars and galaxies
- First light 2021, full operations 2022-2032

LSST Project/NSF/AURA 01/31/2020


LSST Project/NSF/AURA 02/03/2020

Two types of challenges on large scales



(1) Observational systematics

- Dust extinction in our galaxy (affects galaxy spectra)
- Galaxy/star confusion
- Noise & observation conds. can vary across different patches

(2) Sample variance

- Few long-wavelength modes fit into observed volume

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(1) Observational systematics

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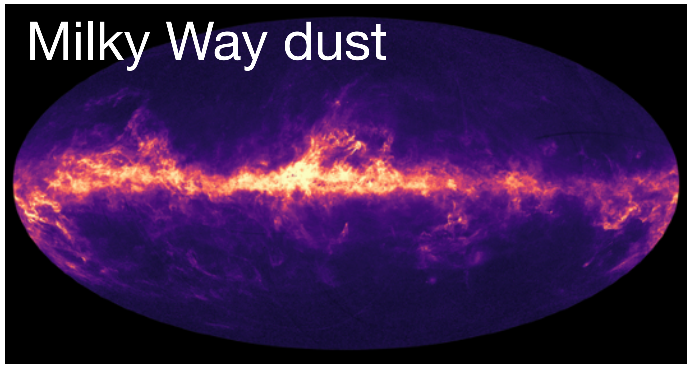
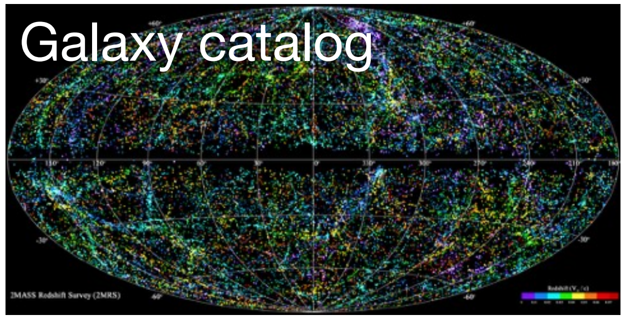
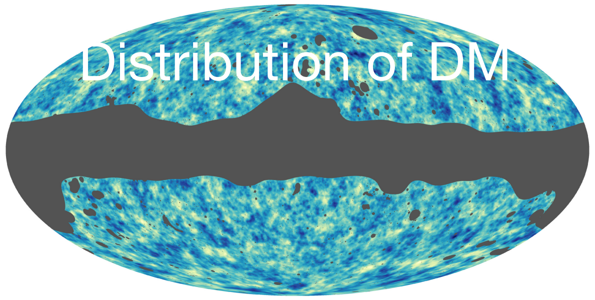


(2) Sample variance

- Few long-wavelength modes fit into observed volume

Cross-correlating galaxy catalog with the **distribution of dark matter** can help with both





MS & Seljak (2018)

How to avoid sample variance?

Imagine you come up with a new image compression algorithm

Is it better than JPEG?

Method 1

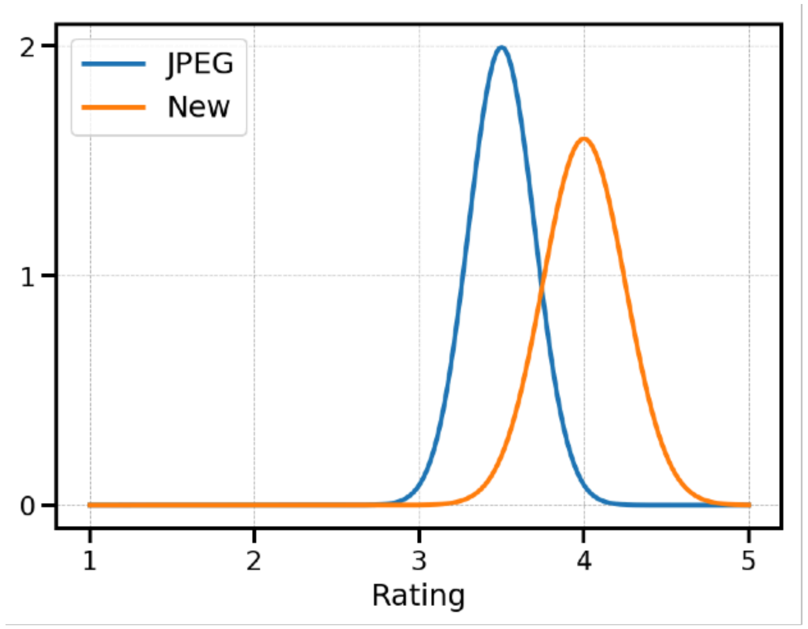
a. Ask people to rate JPEG-compressed images

...

b. Ask other *people* to rate *other* images compressed with new algorithm

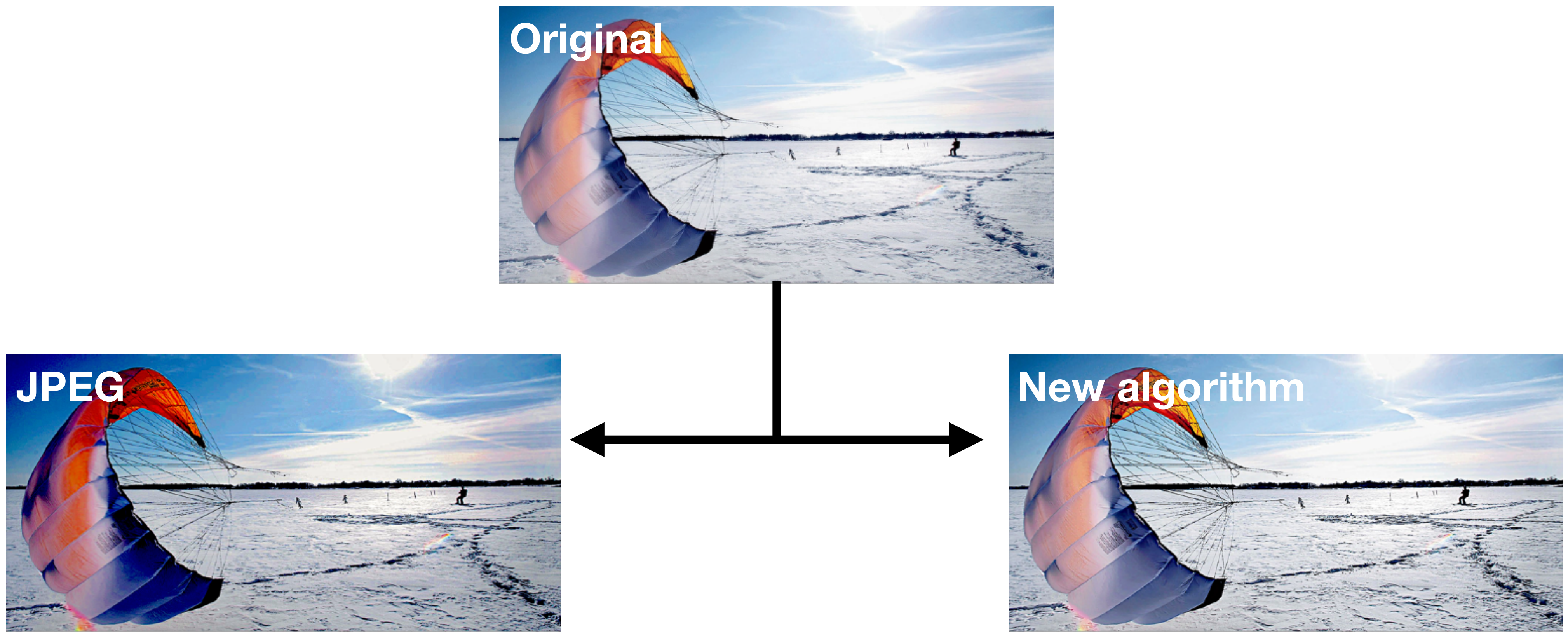
...

c. Compare ratings to find winner



Subject to sample variance (error of the mean)

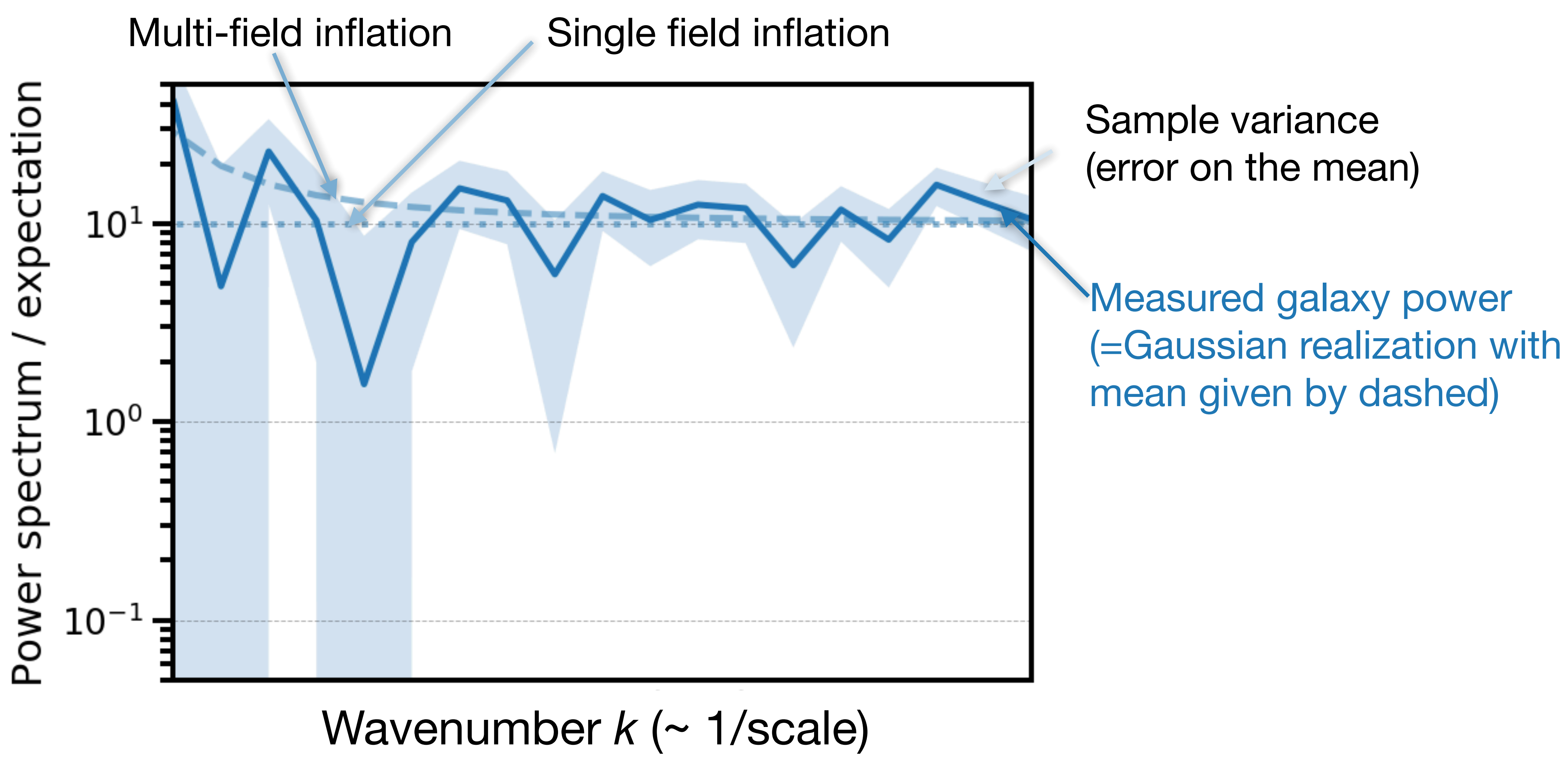
Method 2



a. Ask people to rate same image compressed with JPEG & new algorithm
b. Compare ratings 1-by-1 for each image

No sample variance (can tell winner with 1 image)!

Method 1: Measure galaxy power spectrum



Seljak (2009), McDonald & Seljak (2009), MS & Seljak (2018)

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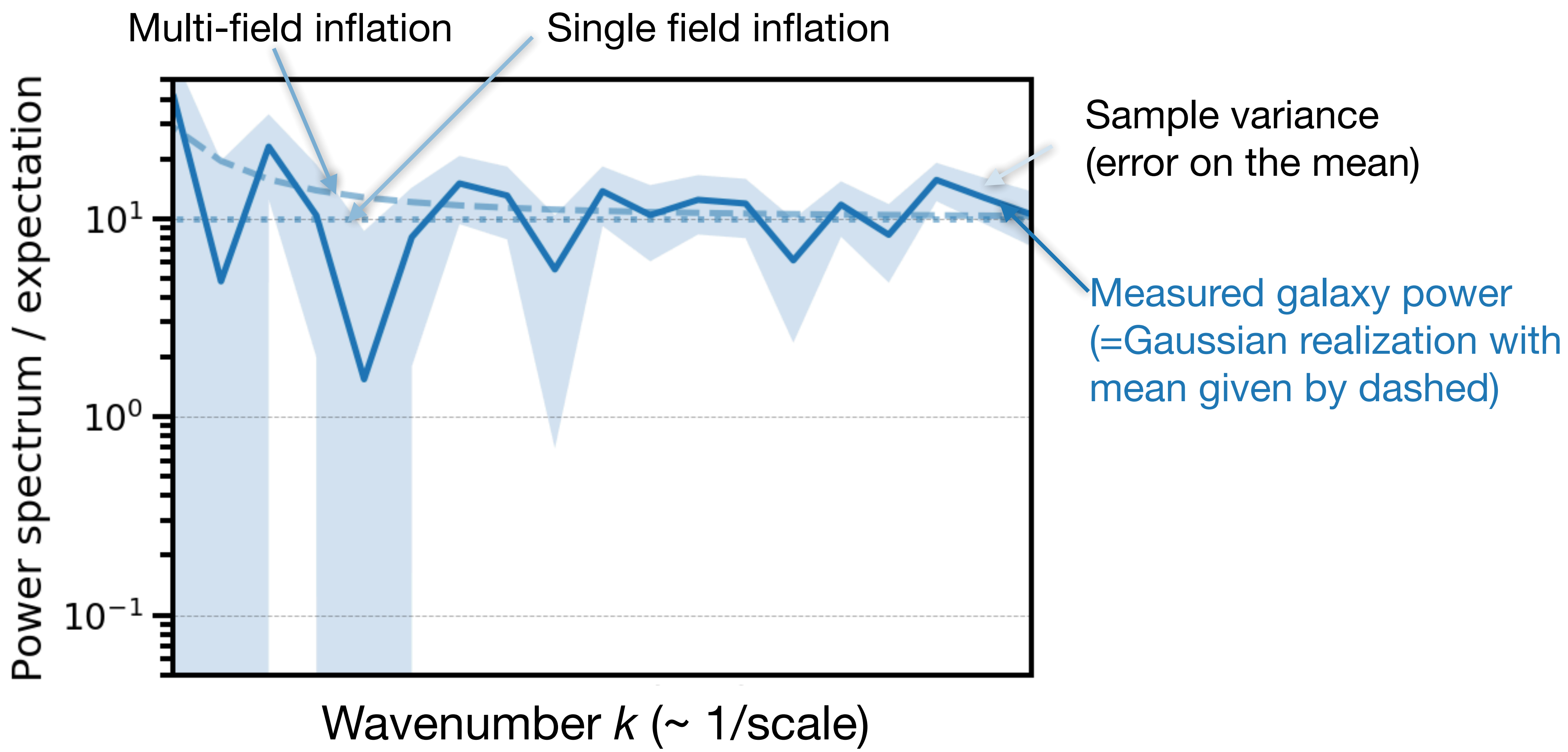
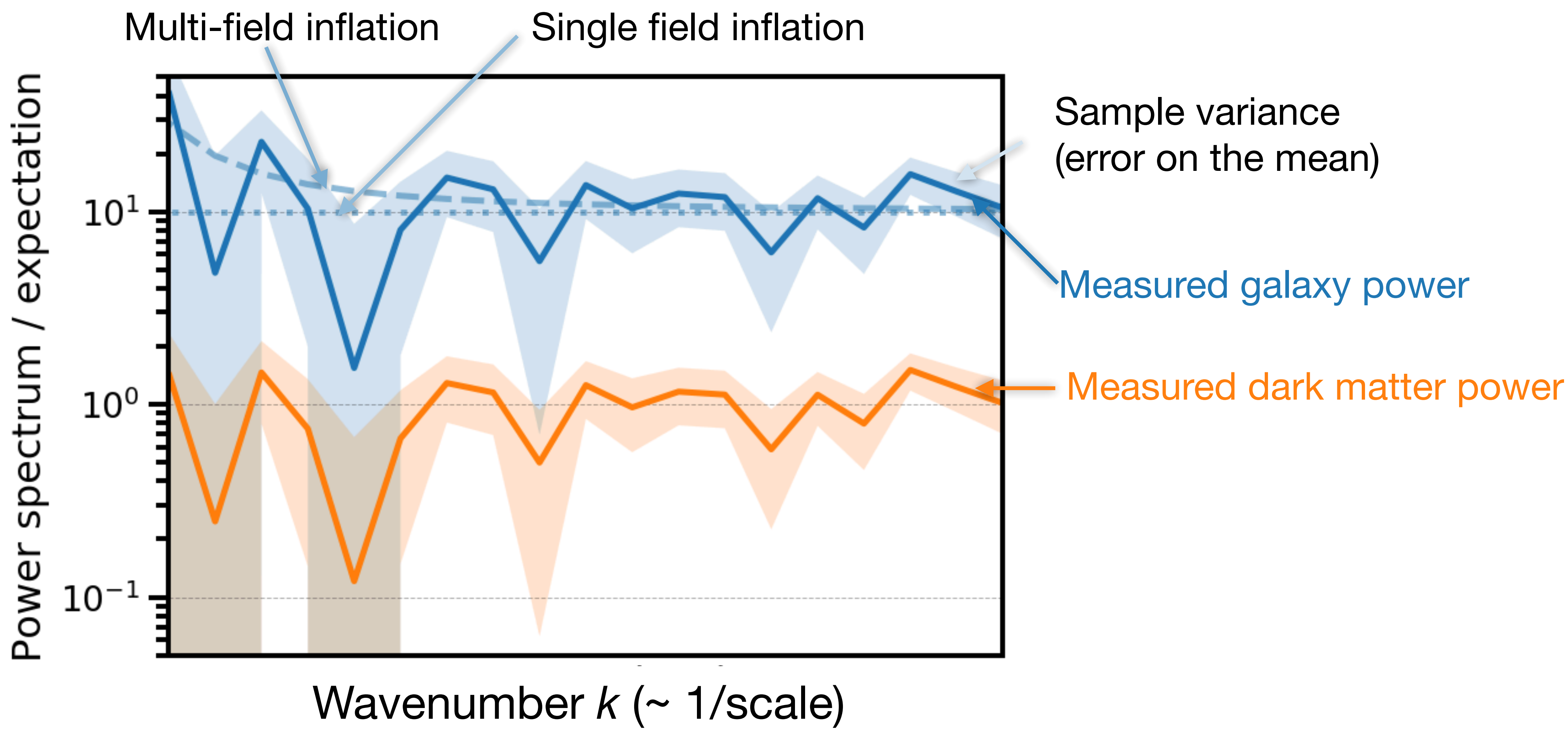


Cannot tell if single field or multi-field inflation because of sample variance

Seljak (2009), McDonald & Seljak (2009), MS & Seljak (2018)

Method 2: Compare 1-by-1 to dark matter



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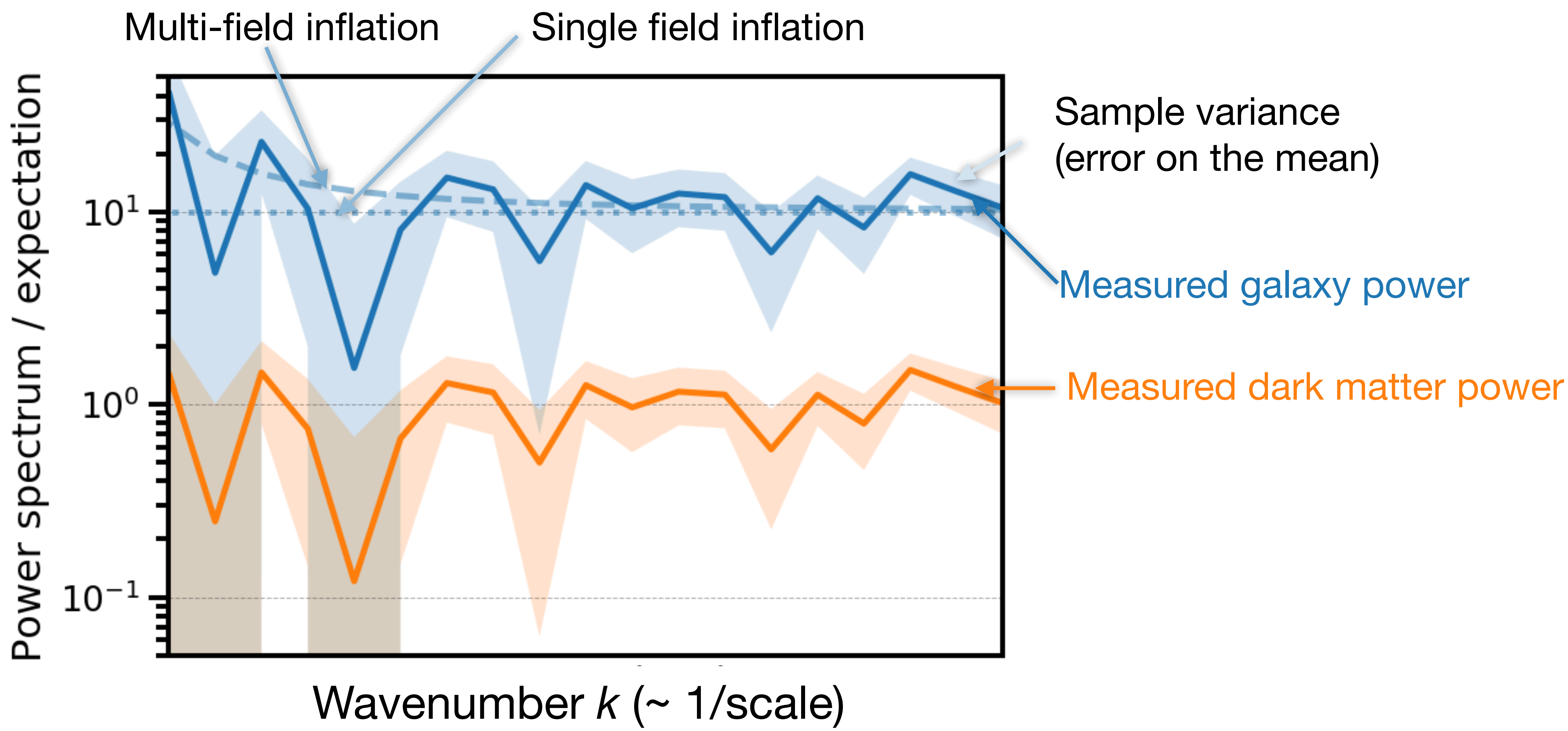

Sample variance cancels so we detect multi-field inflation

Seljak (2009), McDonald & Seljak (2009), MS & Seljak (2018)

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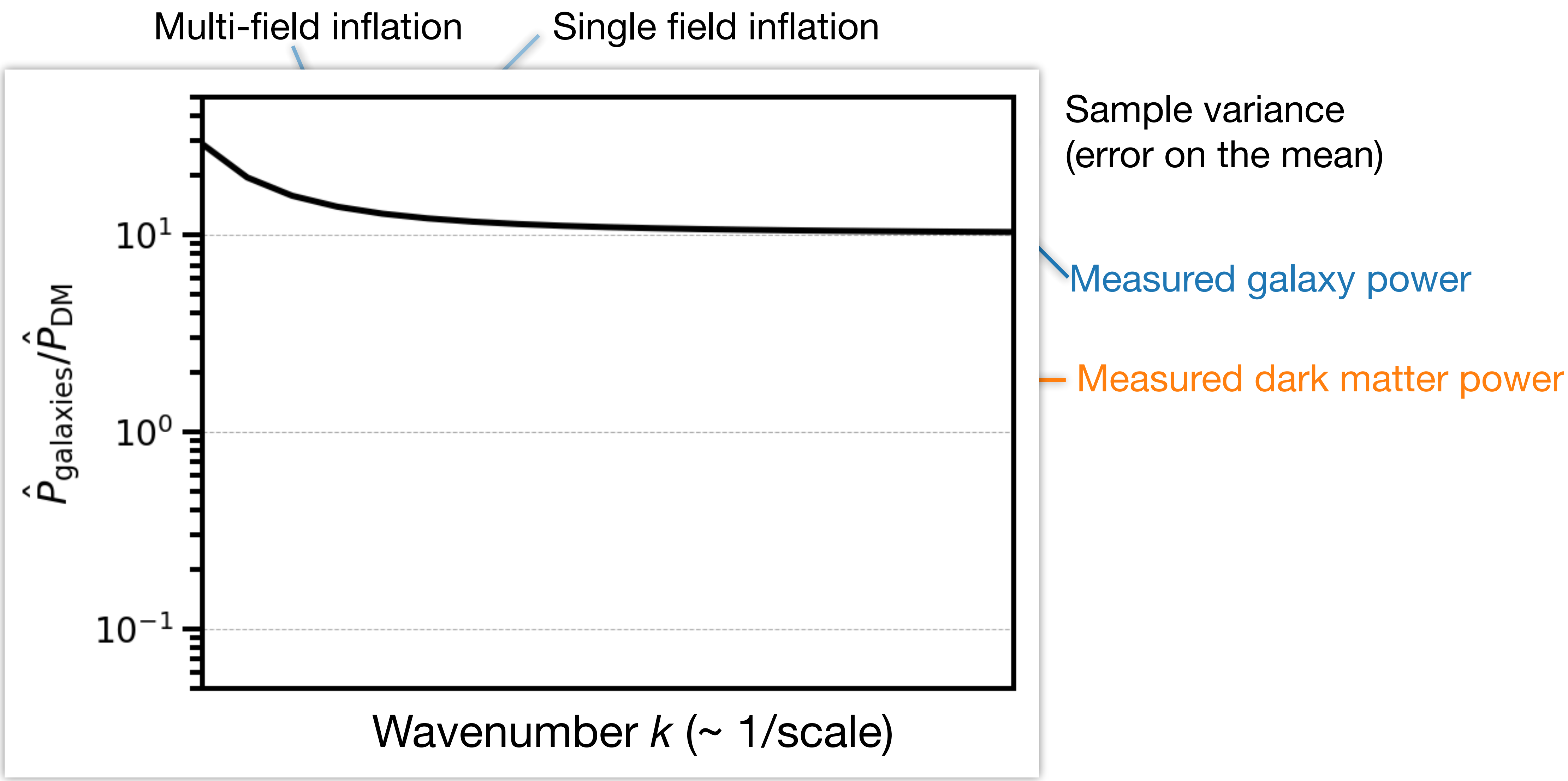

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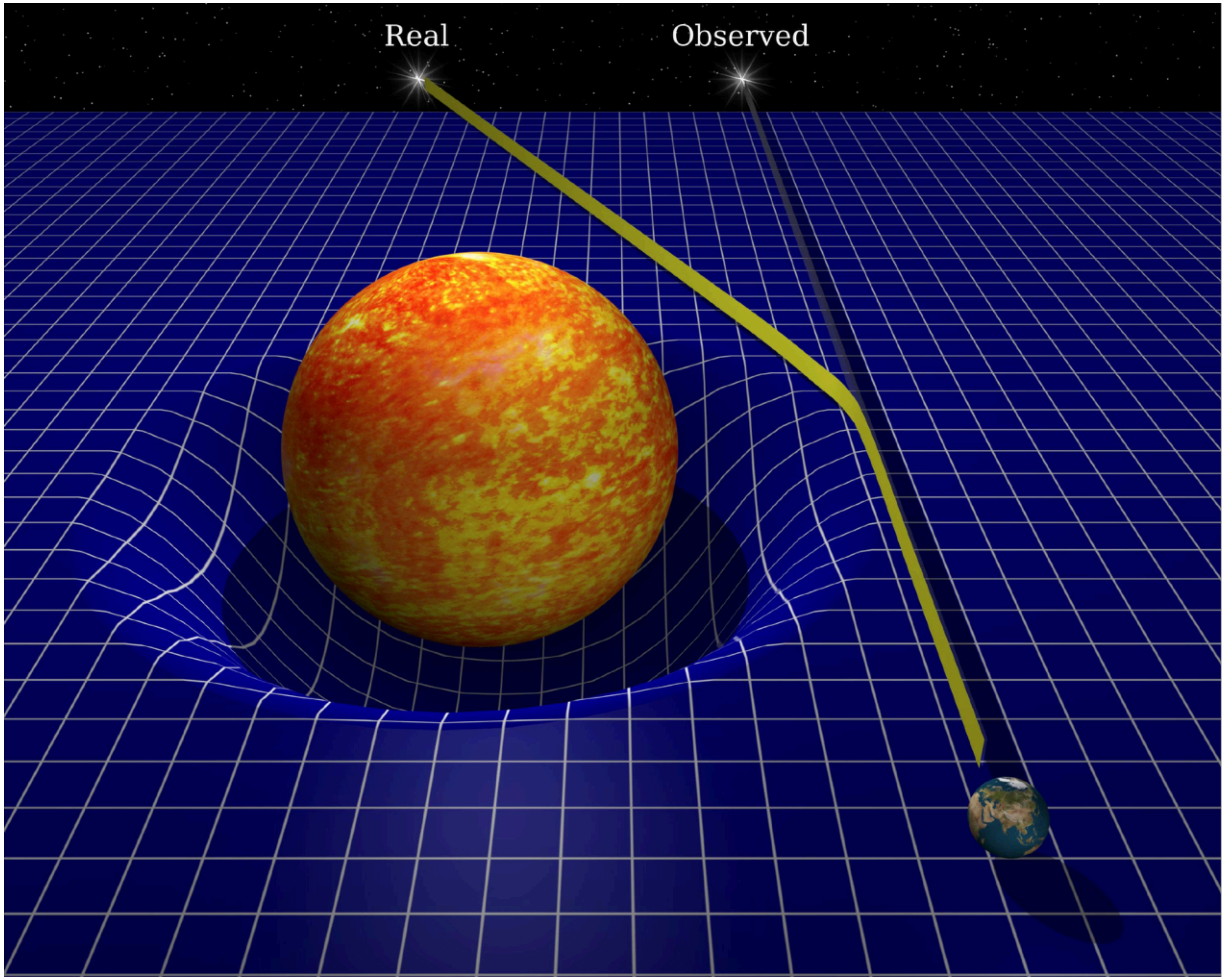
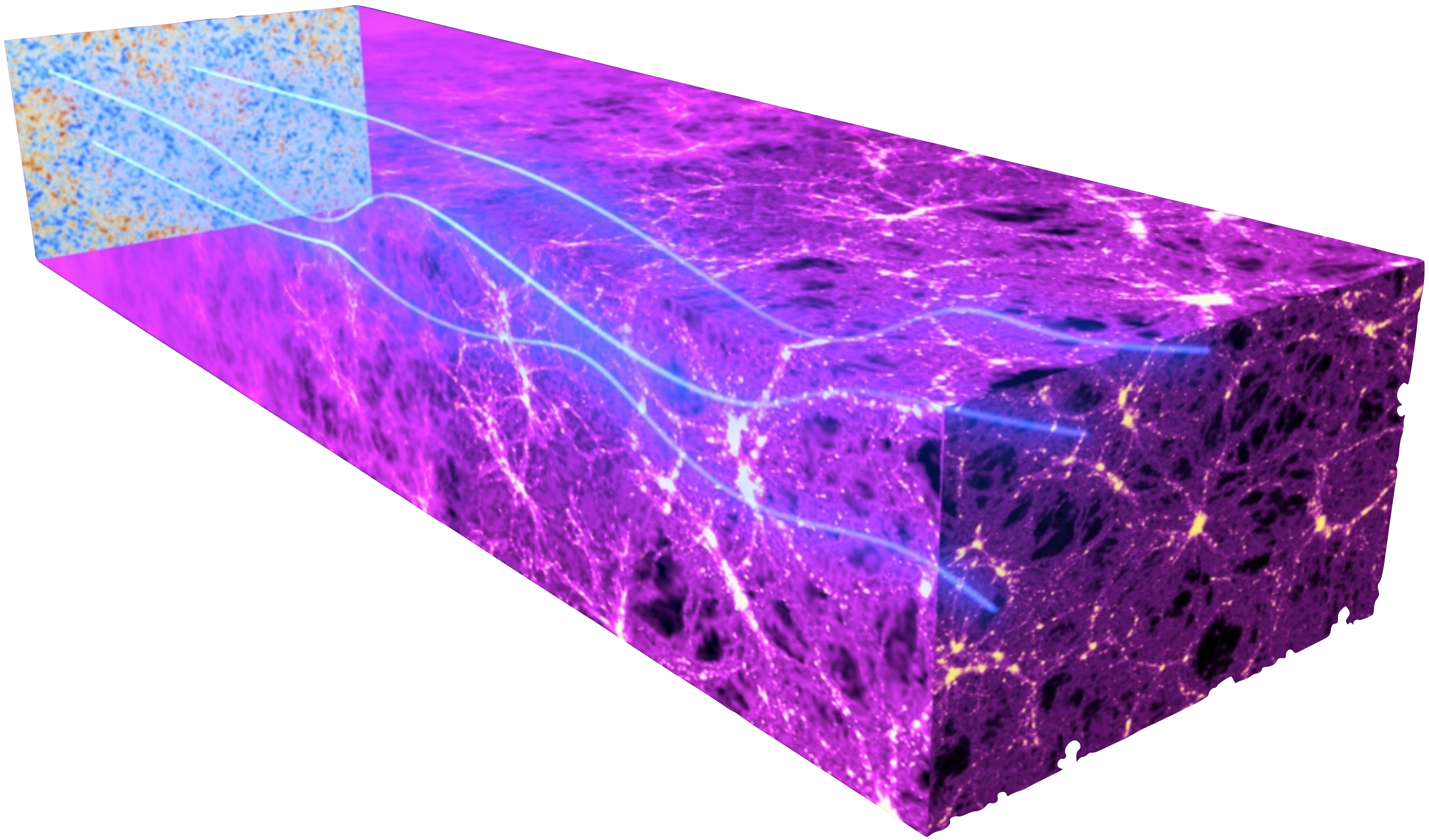
Seljak (2009), McDonald & Seljak (2009), MS & Seljak (2018)

How to measure the distribution of dark matter?



Use gravitational lensing

Dark matter also distorts the Cosmic Microwave Bg.



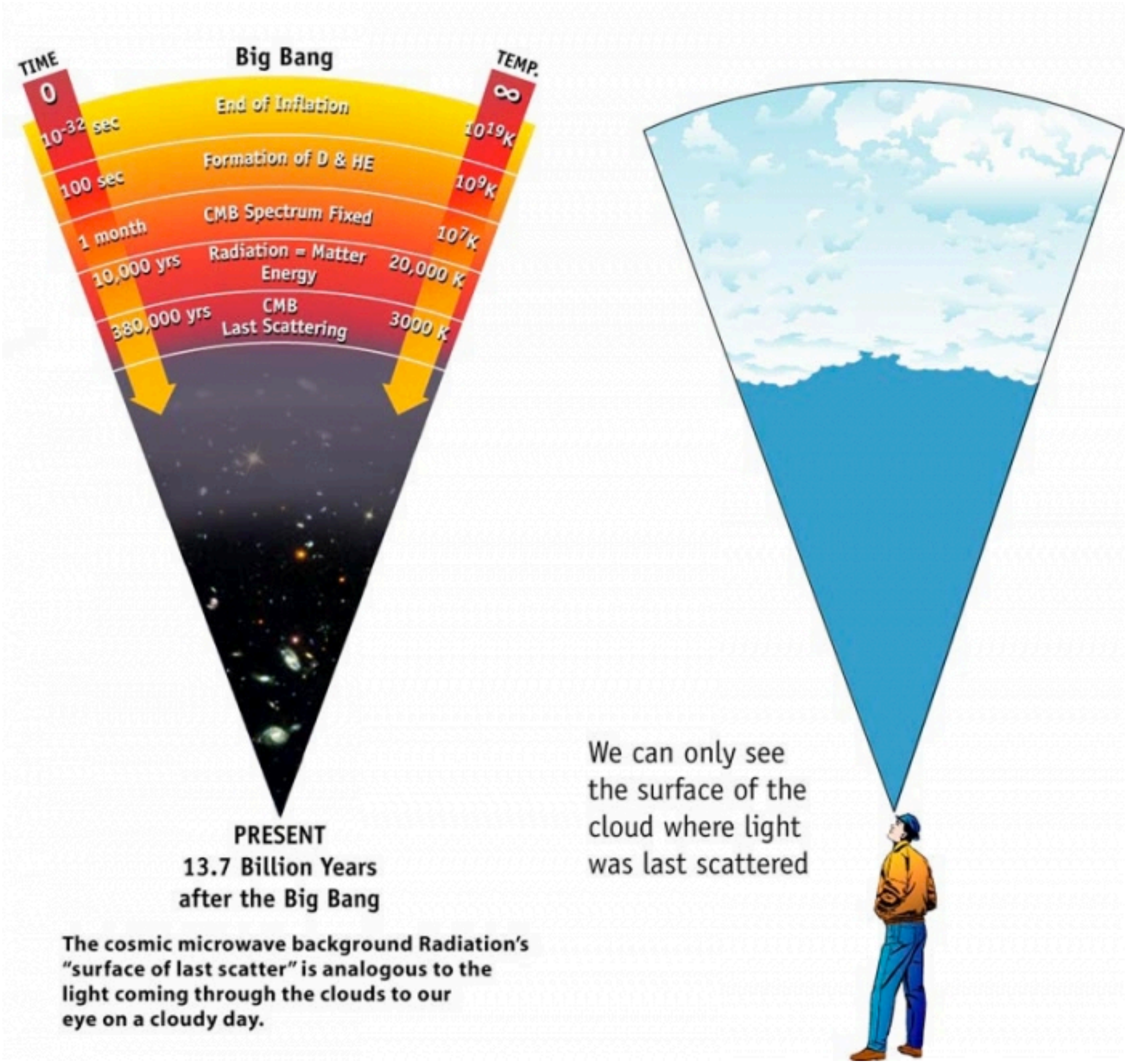
Cosmic Microwave Background (CMB)

Right after Big Bang light scatters frequently —> opaque

As Universe expands, turns transparent

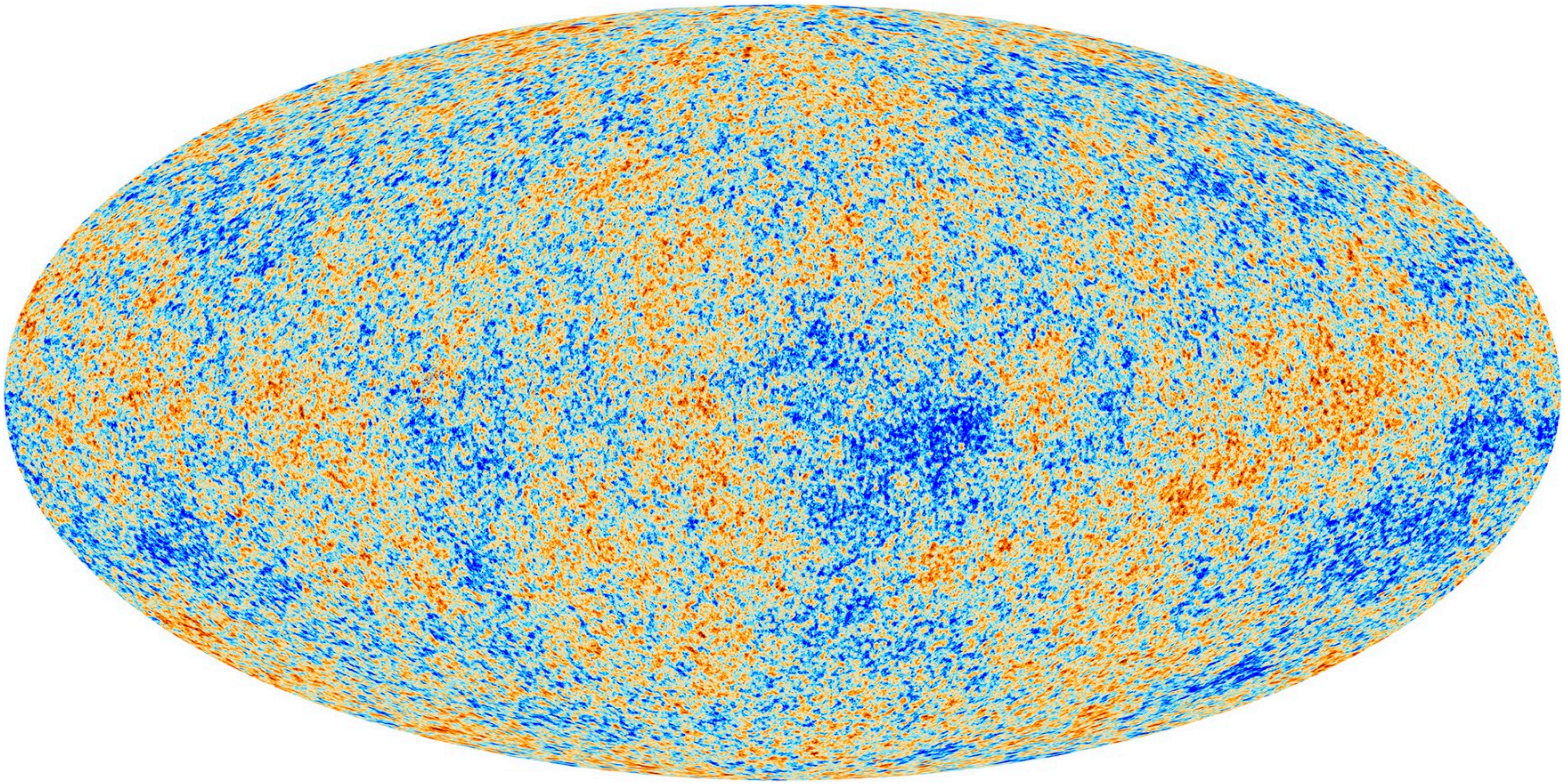
See surface where light last scattered — 13.6996 bn yrs ago

This is the CMB



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

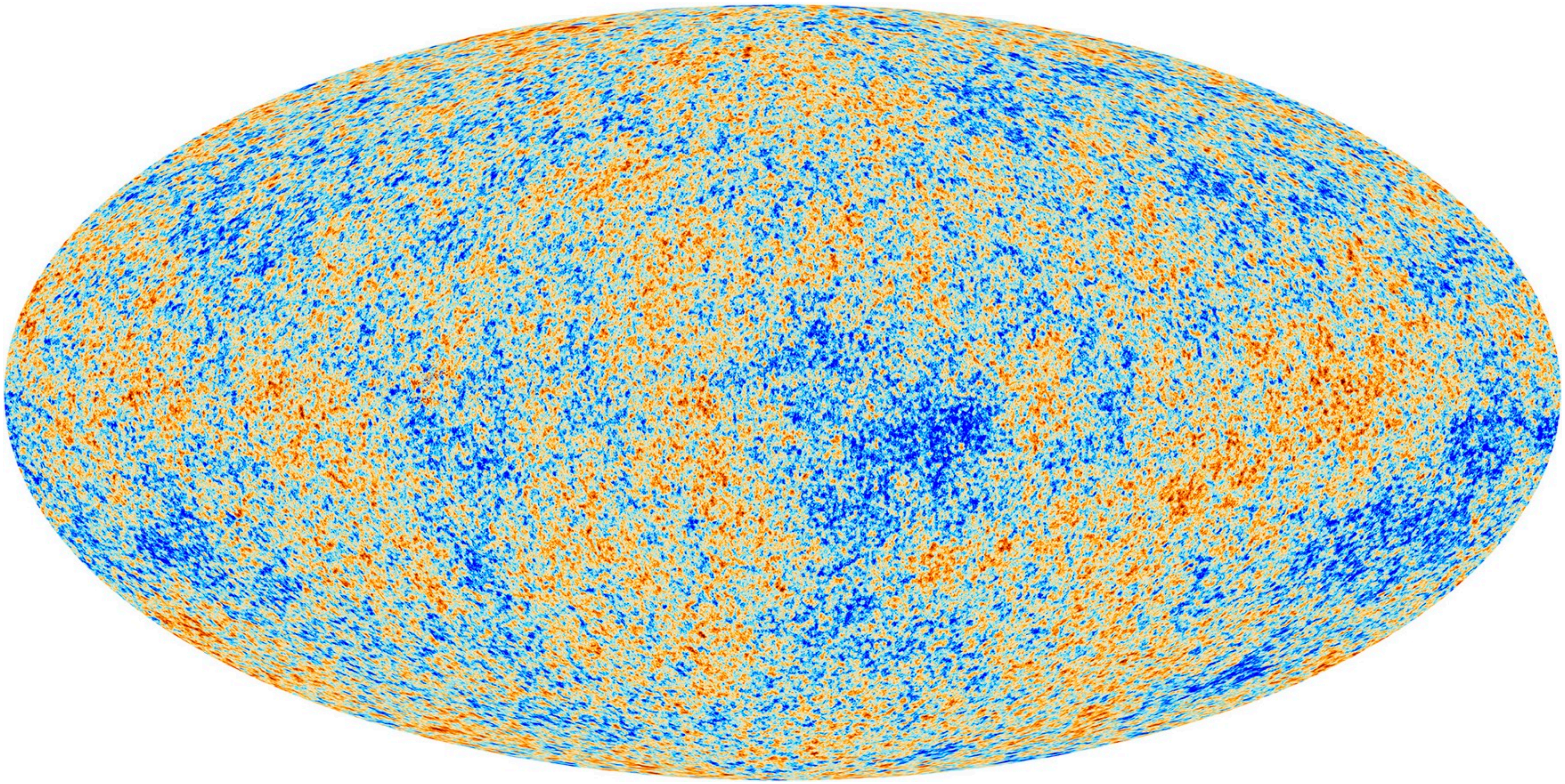
Cosmic Microwave Background (CMB)



Hot and cold blobs: Picture of the Universe 13.6996 bn years ago

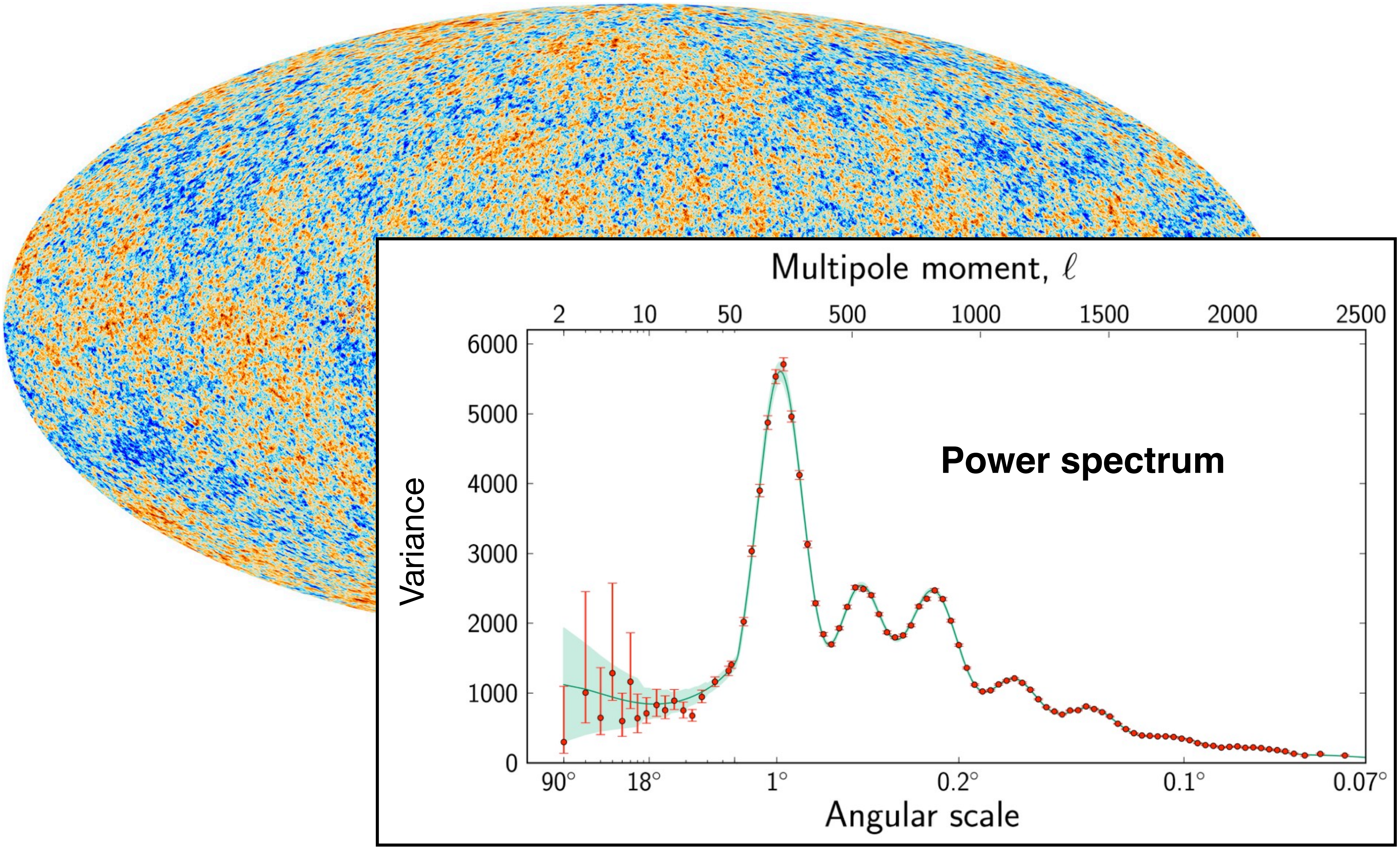
$T = 2.7\,\mathrm{K},\ \Delta T/T \sim 10^{-5}$

Statistics of the CMB before lensing



Normally distributed as far as we can tell

Statistics of the CMB before lensing



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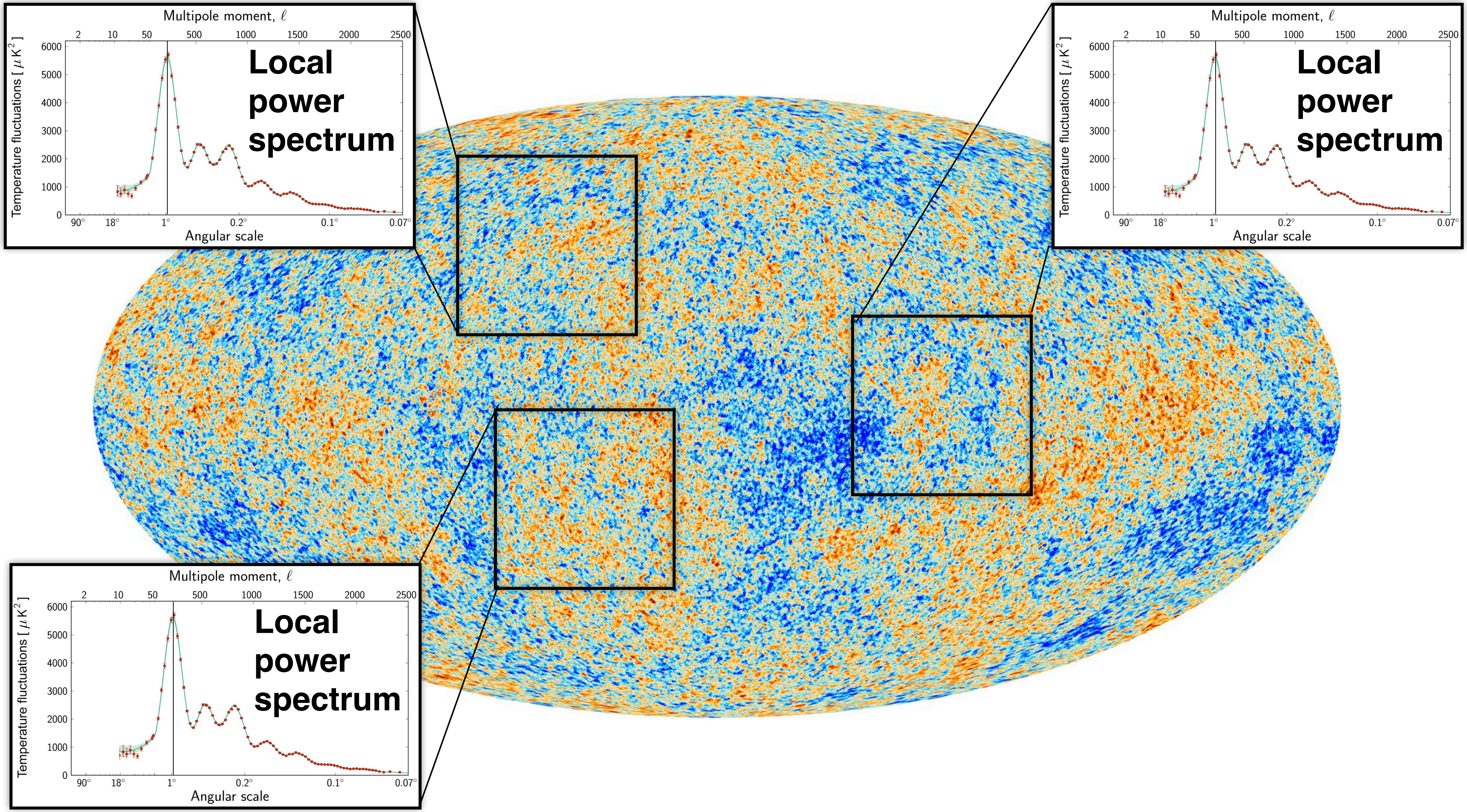
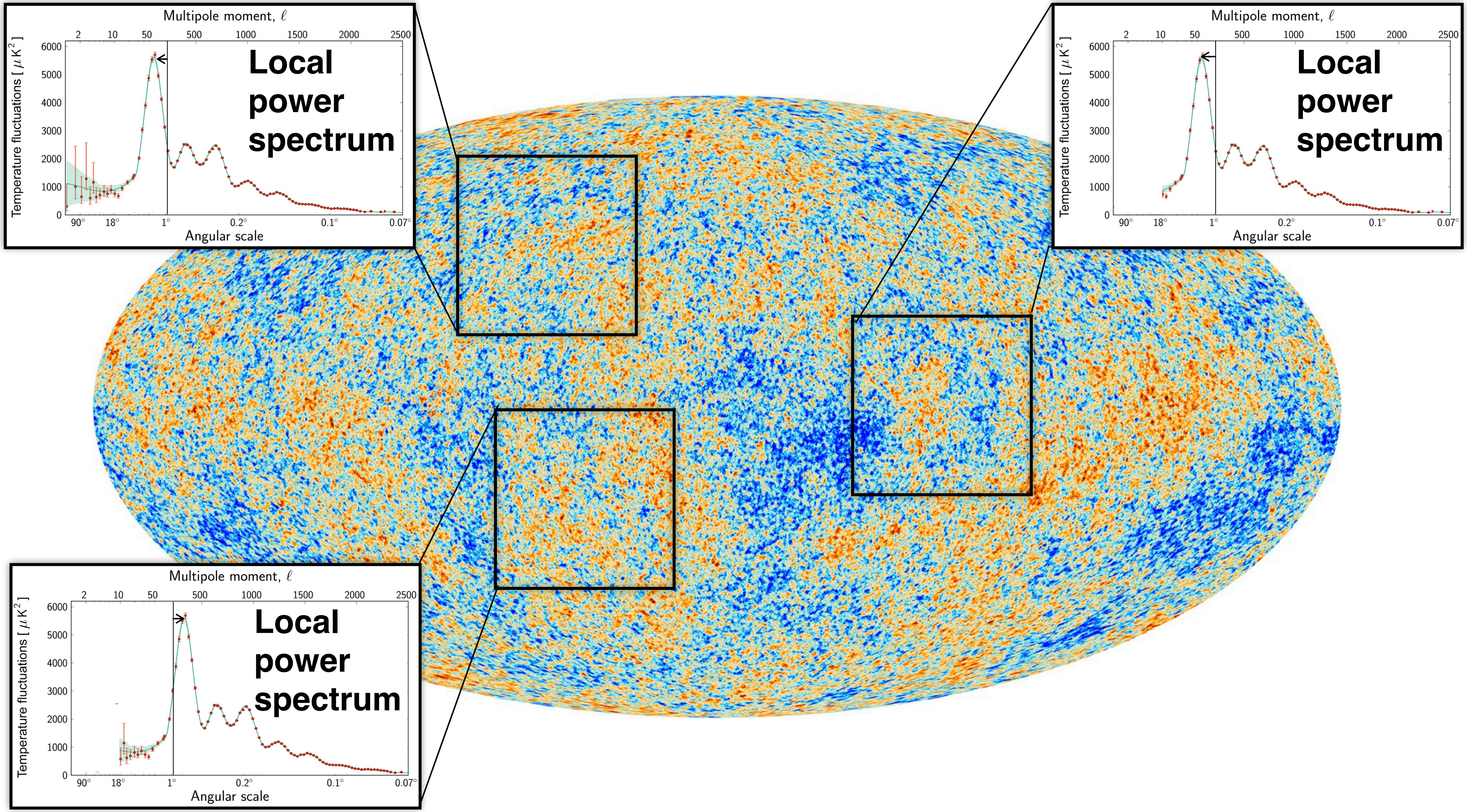


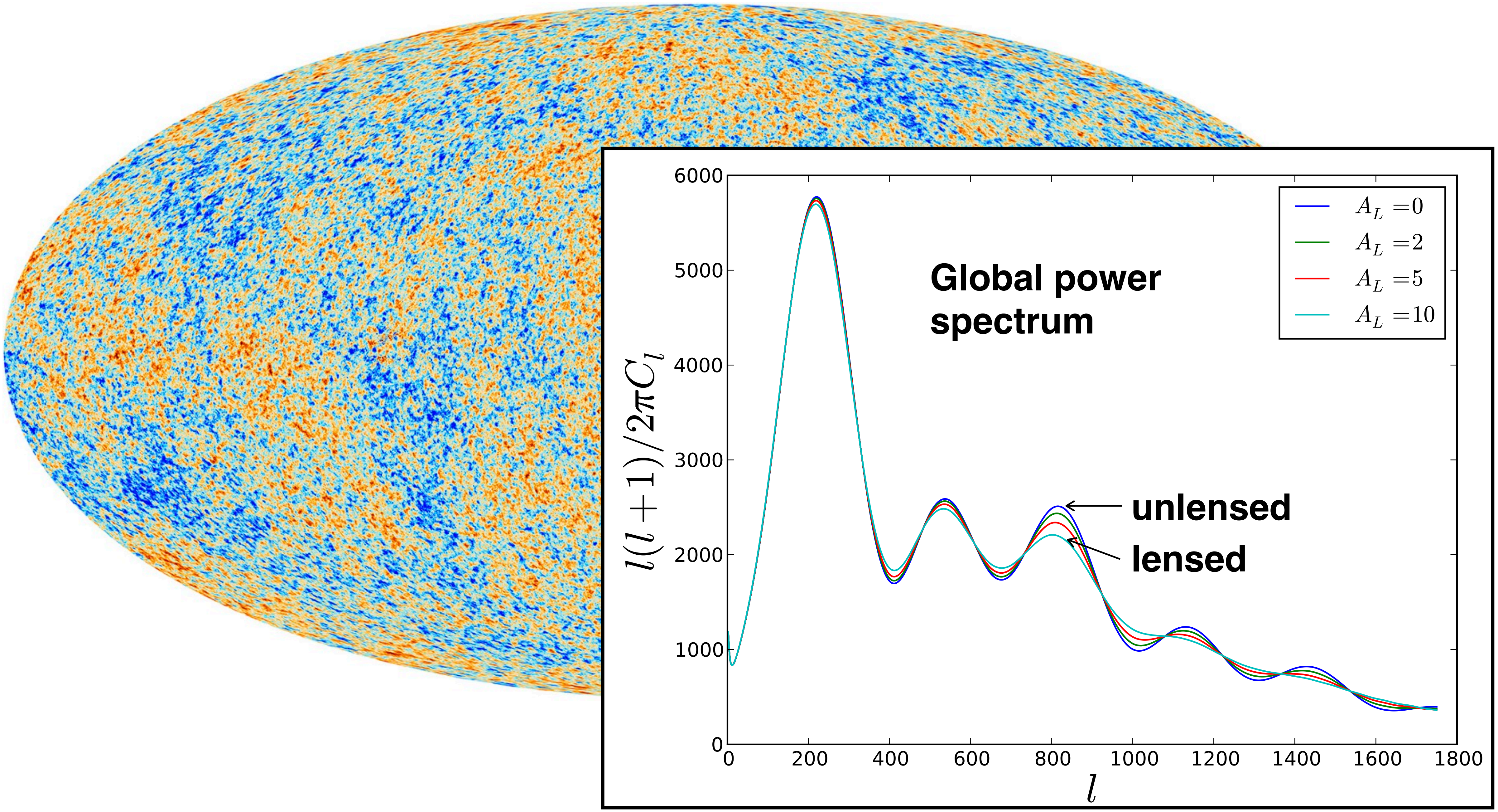
Local power spectrum is the same in each patch

Statistics of the CMB after lensing



Local power is magnified or de-magnified

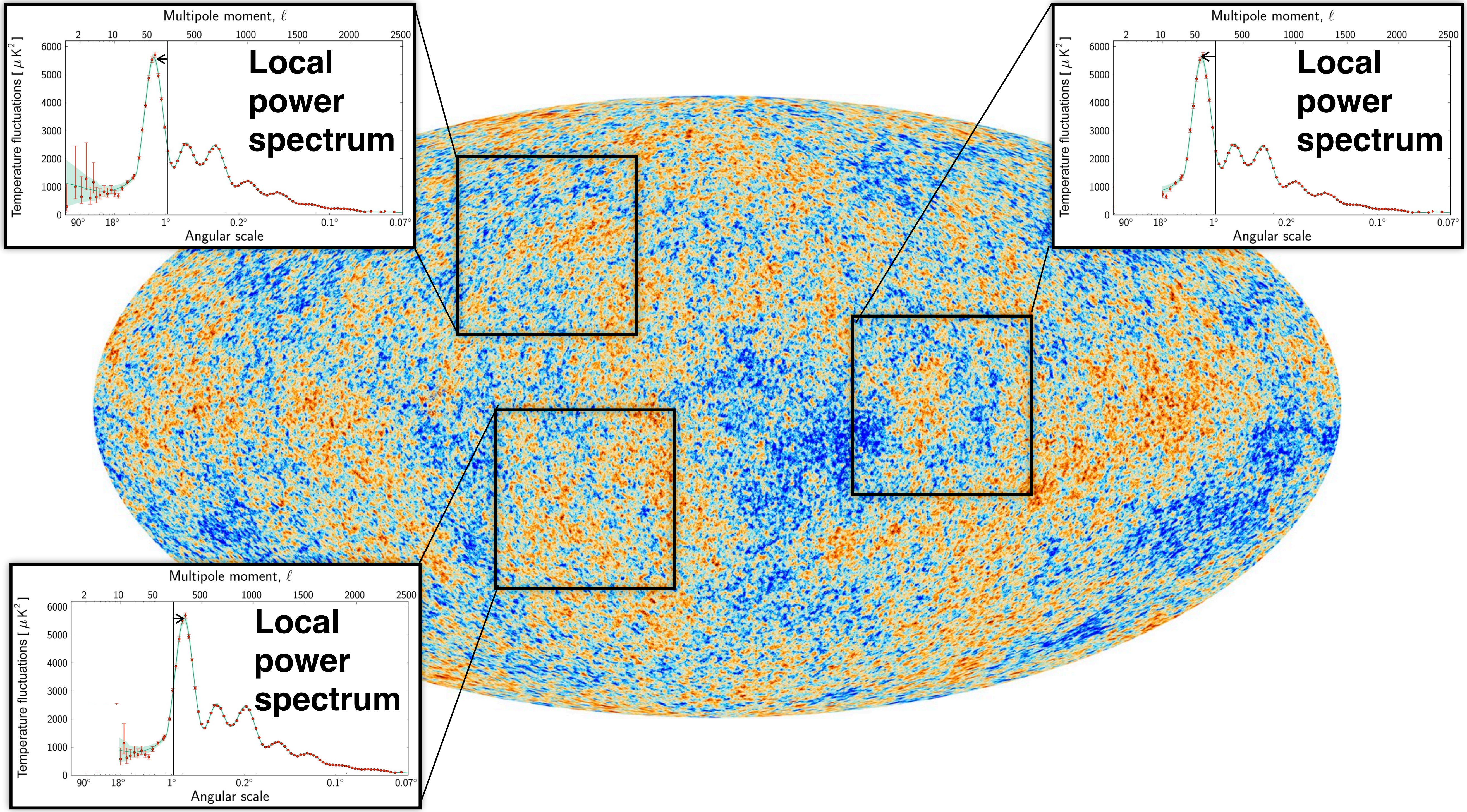
Statistics of the CMB after lensing



Smidt+ (2010)

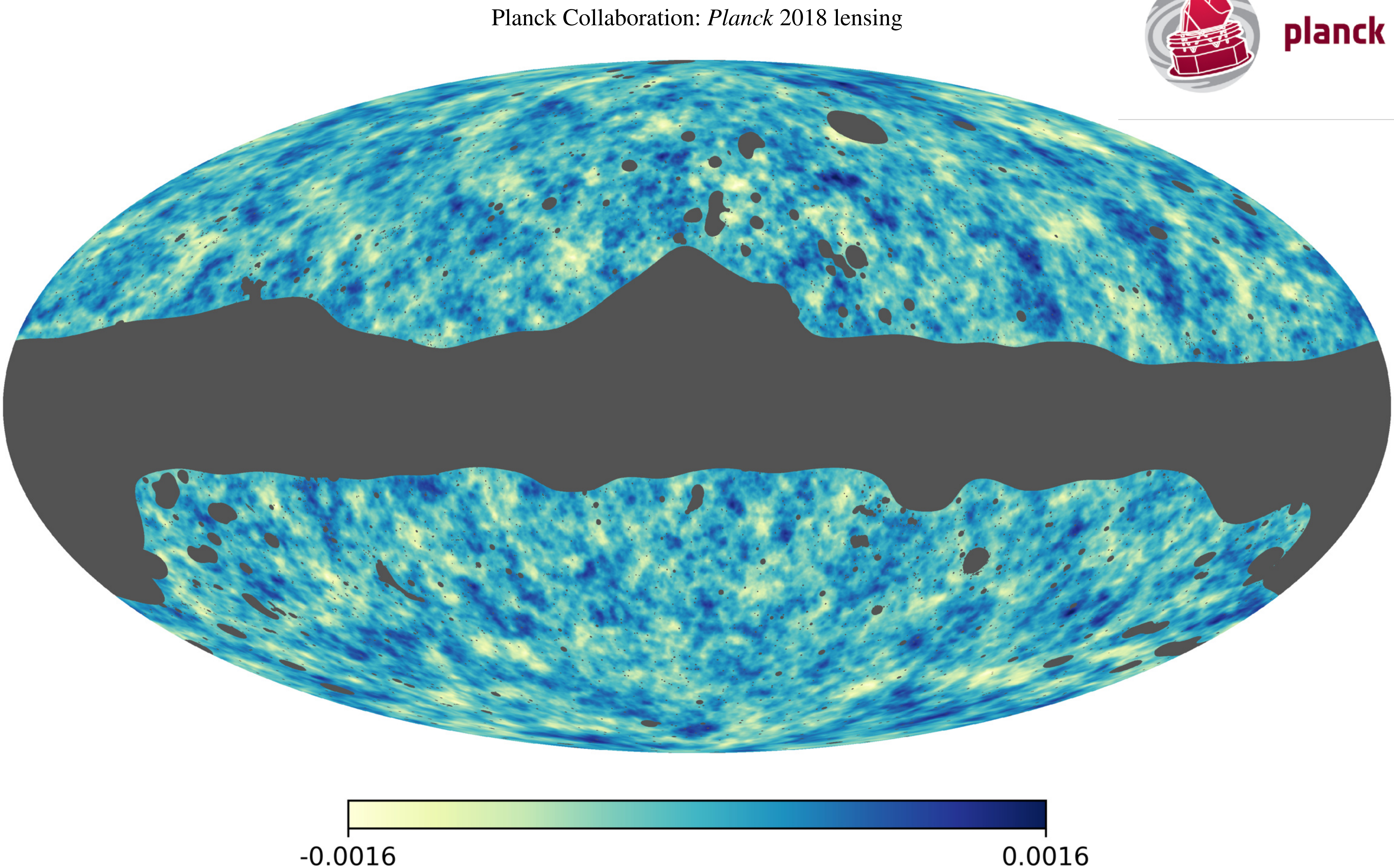
Peaks of global power are smeared out

Statistics of the CMB after lensing



Rather than averaging the modulation, measure it as a signal
—> magnification map

Measured CMB lensing magnification

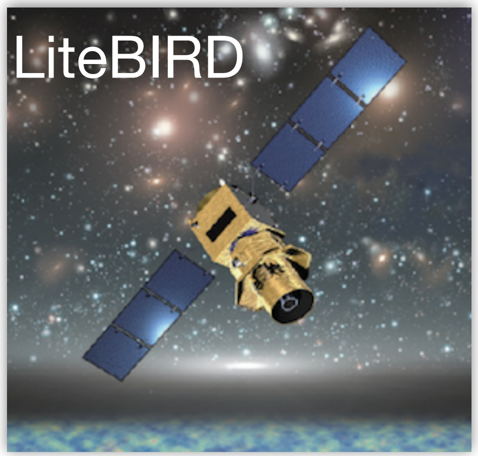


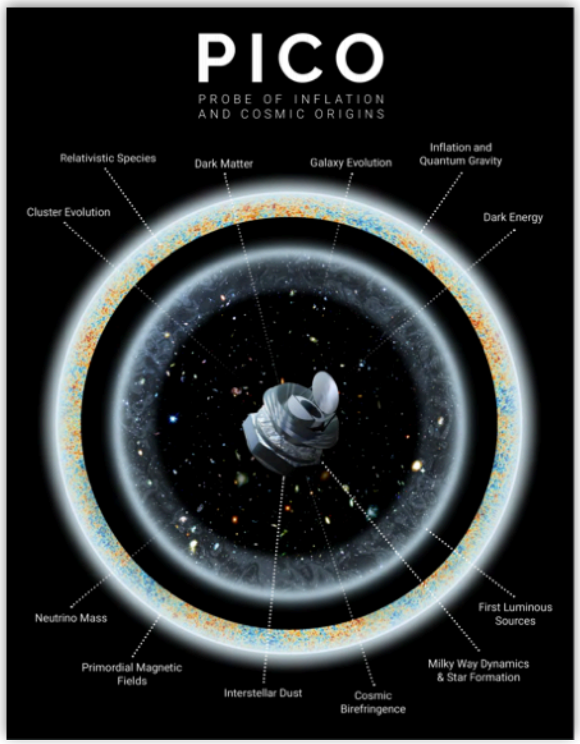
CMB experiments

Cosmology Large Angular Scale Surveyor
CLASS

SOUTH POLE TELESCOPE
SPT

SIMONS OBSERVATORY
22°57'31" SOUTH, 67°47'15"WEST ELEVATION: 17,027.6'
PARQUE ASTRONÓMICO ATACAMA, CHILE

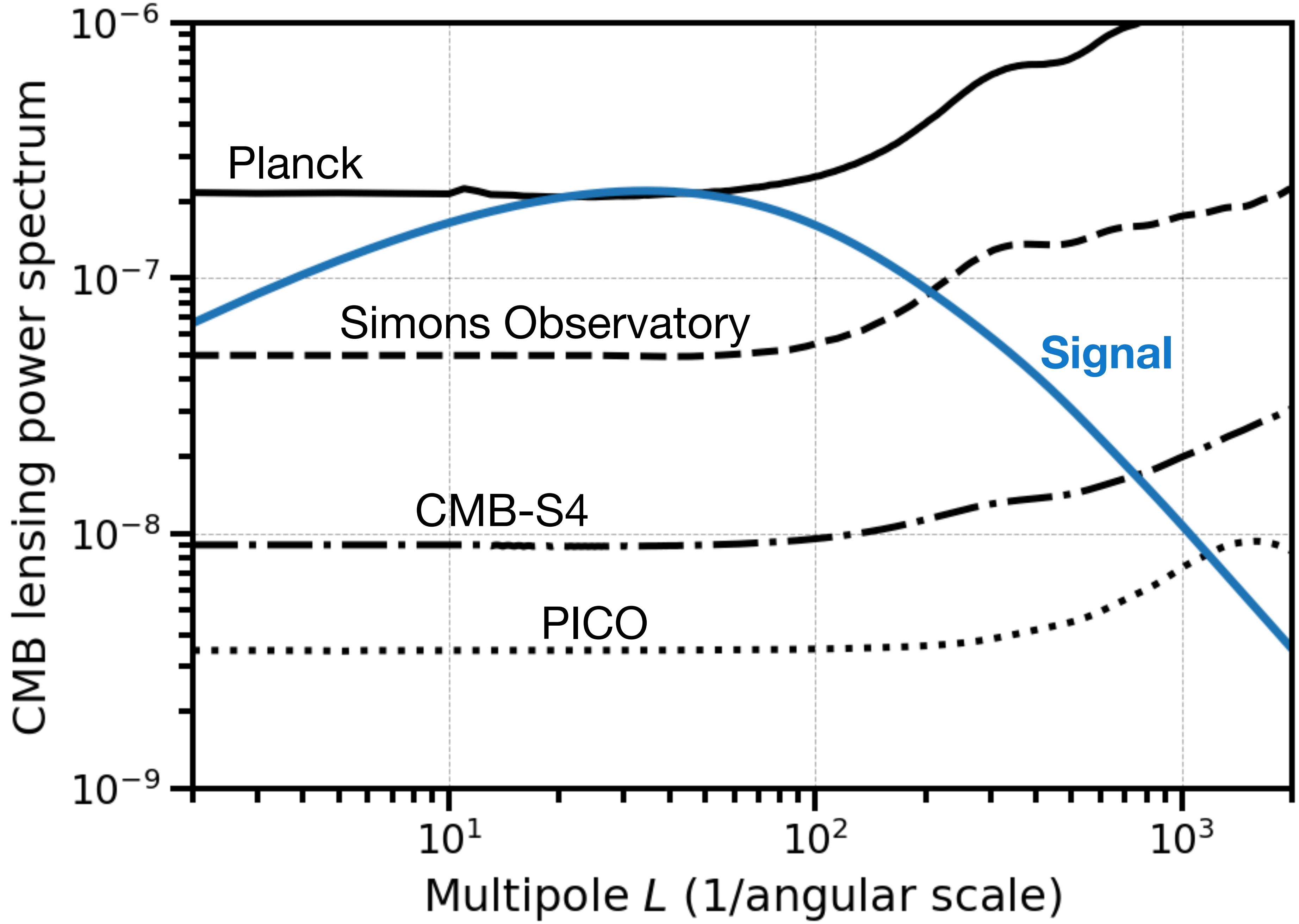




Today 2022 2030

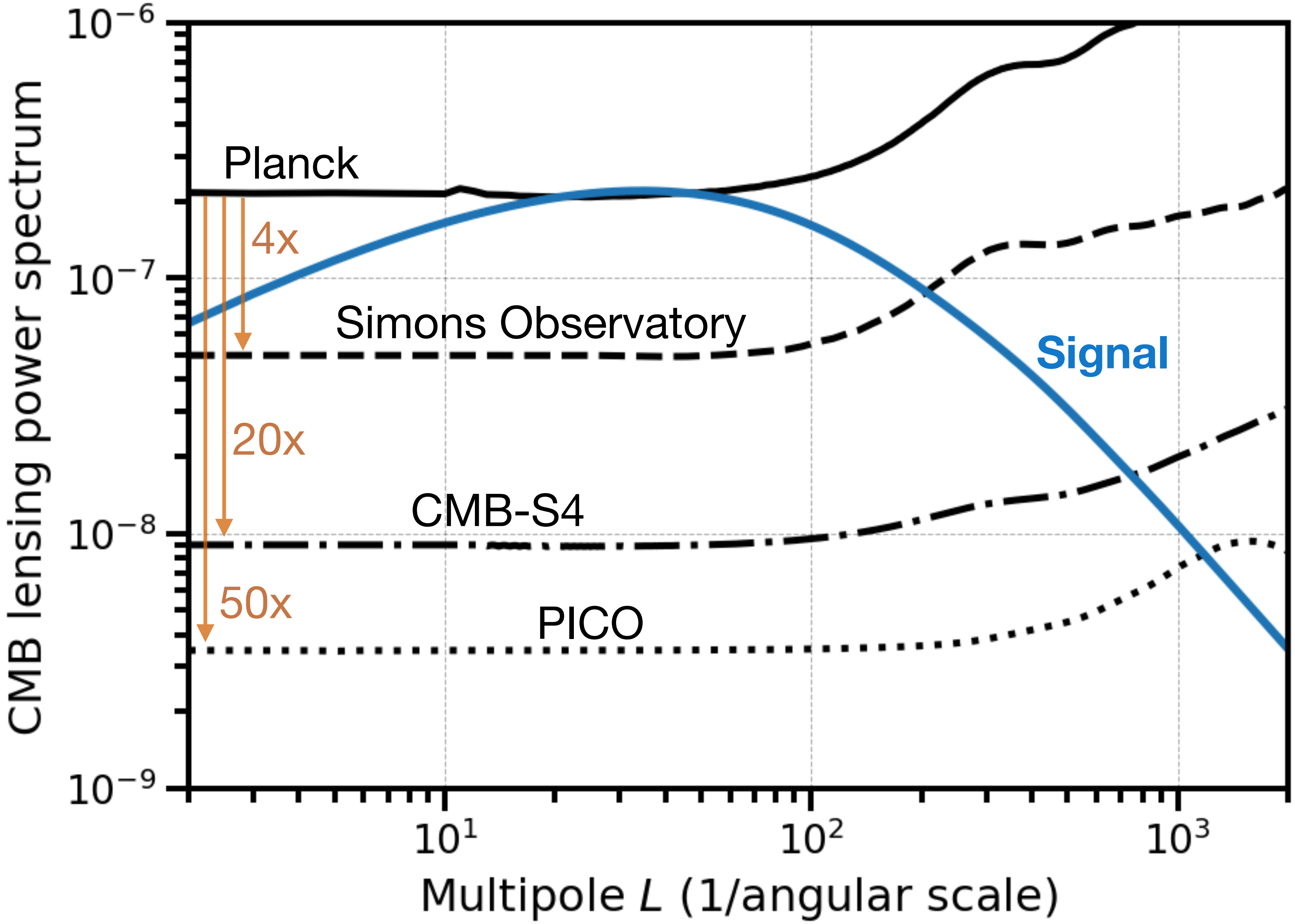
Funding by DOE, Heising-Simons, JAXA, NASA, NSF, Simons Foundation, …

Future CMB lensing



Derived from foreground deprojection forecasts by Colin Hill

Future CMB lensing



Derived from foreground deprojection forecasts by Colin Hill

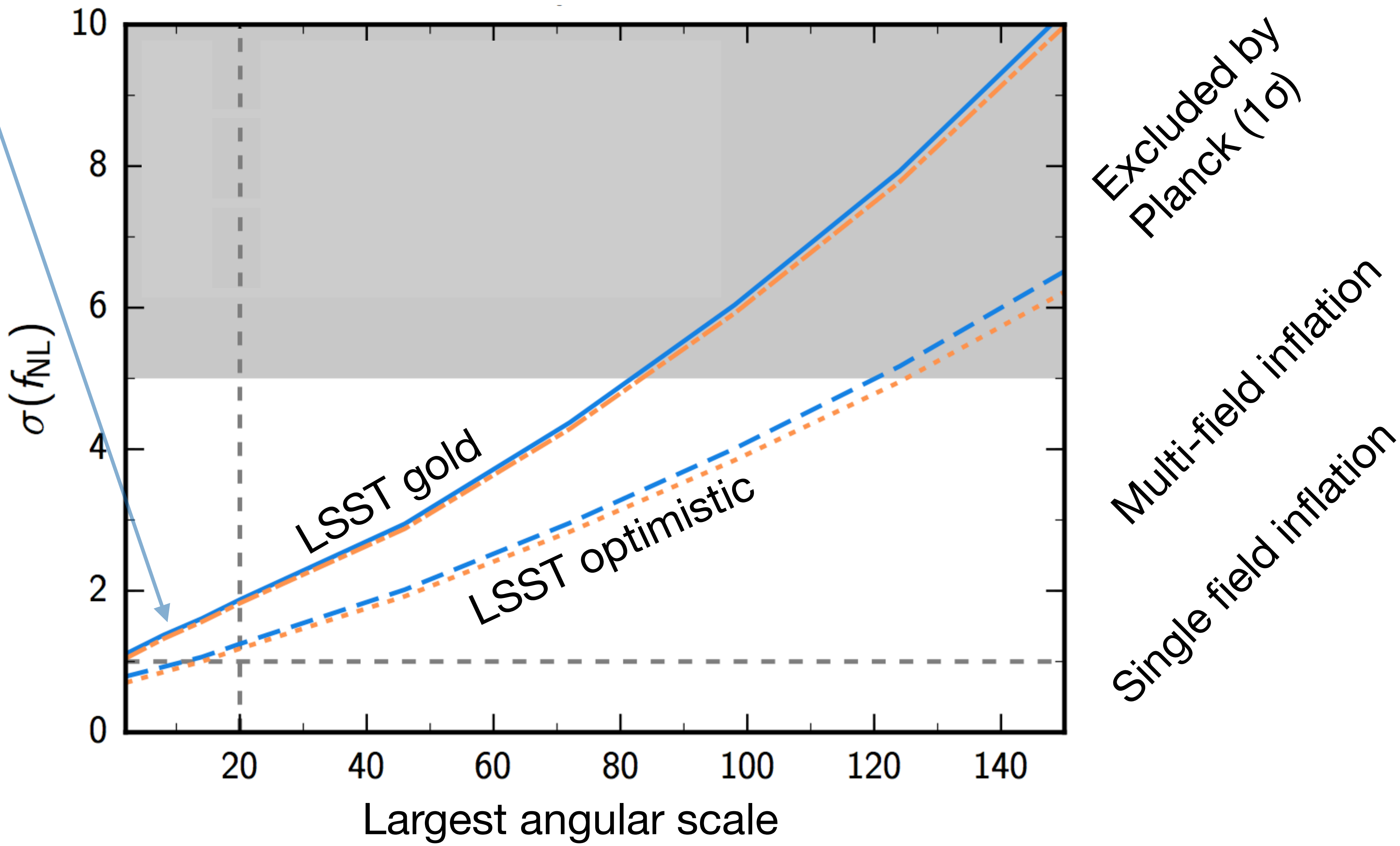
The Simons Observatory

- Cerro Toco, Atacama desert, Chile
- 5200m / 17,100 ft
- Currently home to Atacama Cosmology Telescope, POLARBEAR, Simons Array, CLASS

- 60,000 detectors
- 6 spectral bands at 27-280 GHz
- Science observations 2022-2027
- 260+ researchers at 40+ institutions in 10+ countries

Primordial non-Gaussianity with Simons + LSST

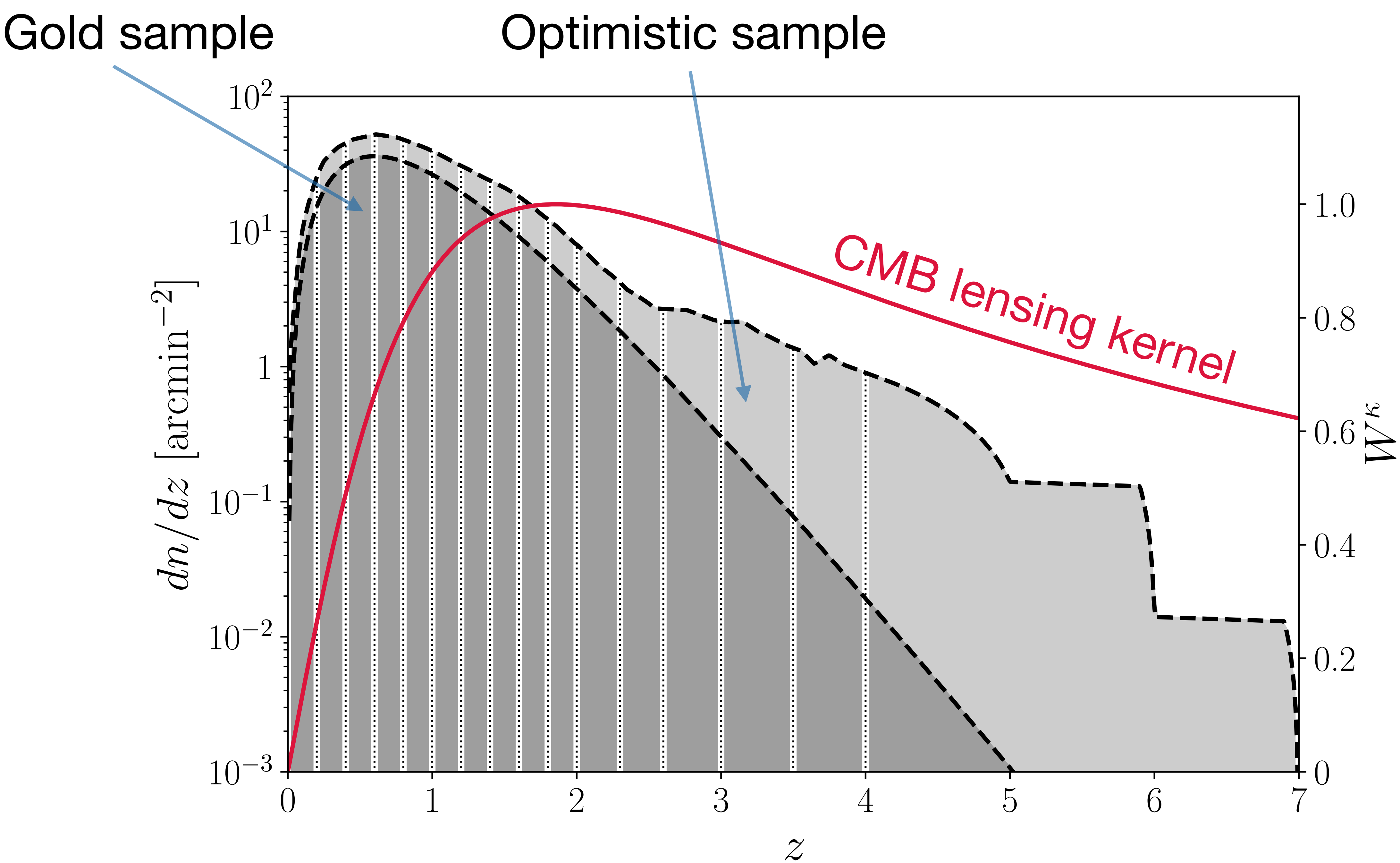
~ 3-5x better than Planck



Includes factor ~2 from sample variance cancellation

MS & Seljak (2018), Simons Observatory Science White Paper (2019)

LSST galaxies



~1 billion galaxies each at *z* = 0-0.5, 0.5-1,1-2, 2-4

At low z, use clustering redshifts (Gorecki+ 2014)
At high z, add Lyman-break dropout galaxies (extrapolated from HSC observations)
Details: MS & Seljak (2018)

Lyman-break dropout galaxies

Young star-forming galaxies that have lots of neutral hydrogen

Photons with enough energy ionize that and don't get out of galaxy

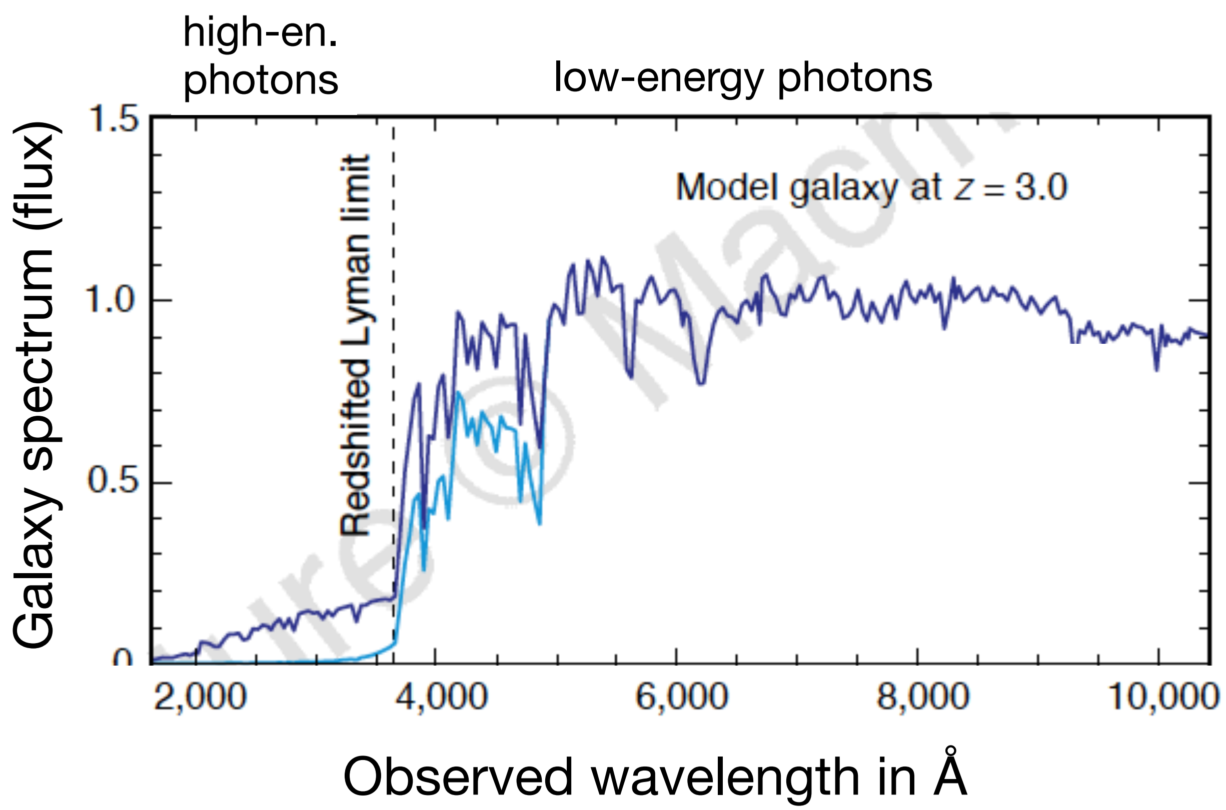


Figure: Ellis (1998)

Lyman-break dropout galaxies

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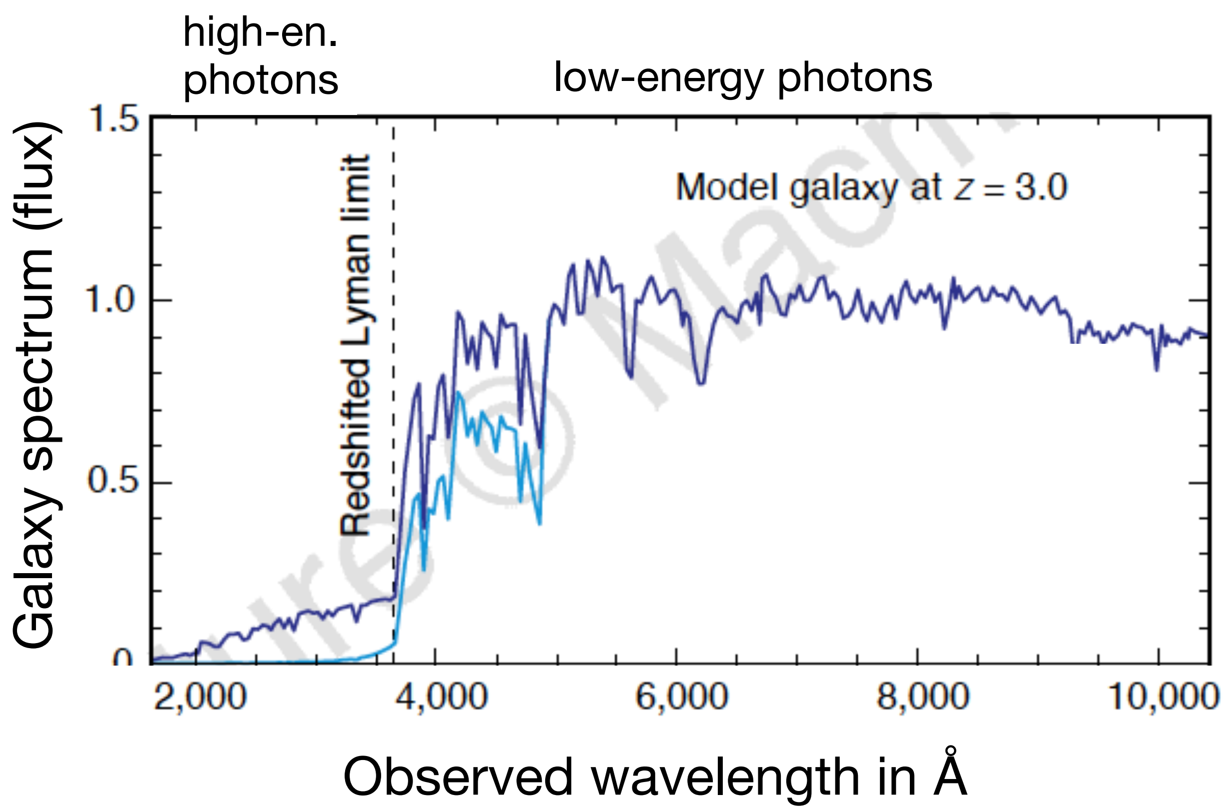
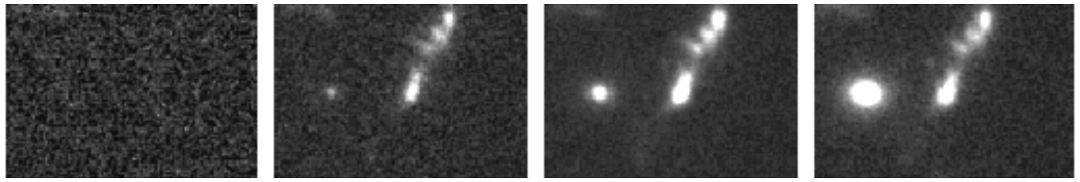
Photons with enough energy ionize that and don't get out of galaxy



U-dropout



U B V I

Figure: Ellis (1998)

Lyman-break dropout galaxies

Young star-forming galaxies that have lots of neutral hydrogen

Photons with enough energy ionize that and don't get out of galaxy

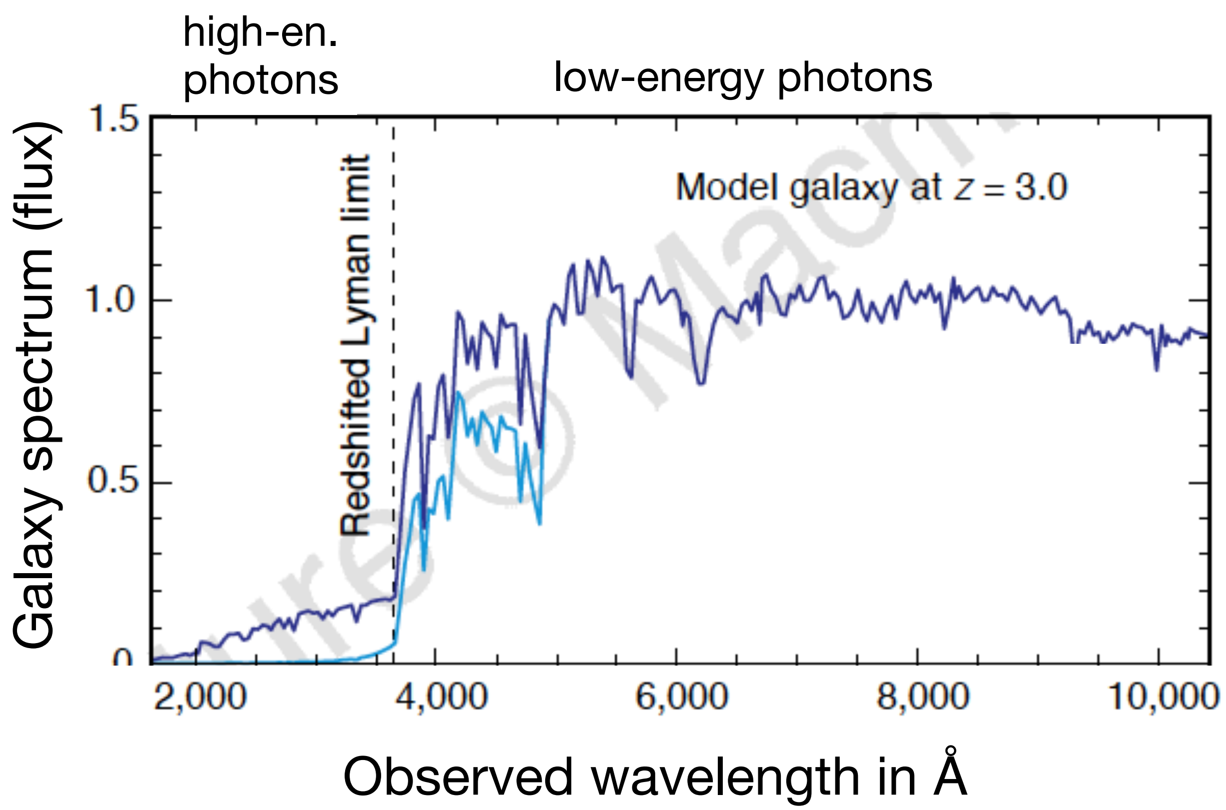
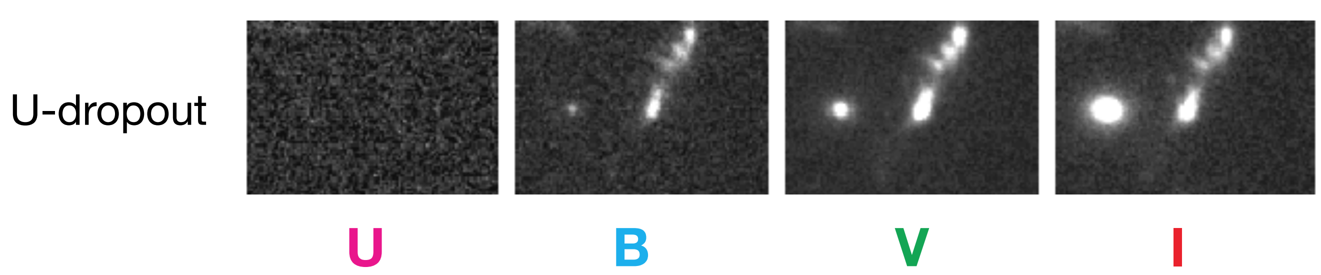


Figure: Ellis (1998)

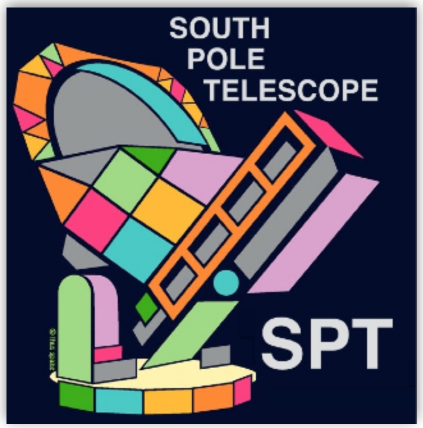


HSC found 0.5M at z=4-7 in 100 deg^2, so expect ~100M with LSST   Ono, Ouchi+ (2018)

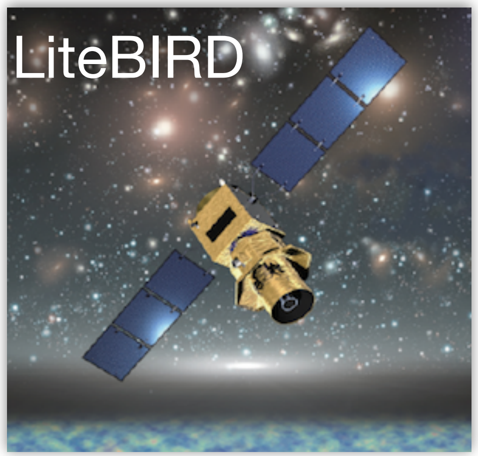
Also MegaMapper   Wilson & White (2019), Ferraro et al. (1903.09208), Schlegel et al. (1907.11171)

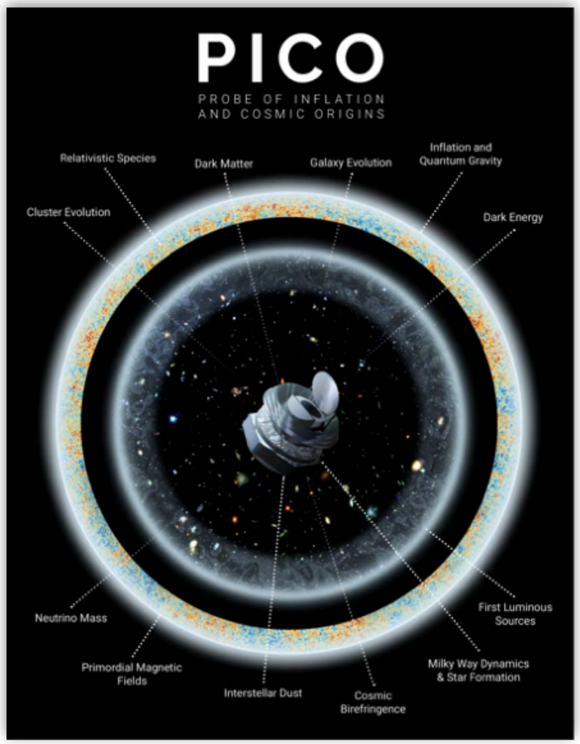
Other CMB experiments

Cosmology Large Angular Scale Surveyor
CLASS



SIMONS OBSERVATORY
22°57'31" SOUTH, 67°47'15"WEST
ELEVATION: 17,027.6'
PARQUE ASTRONÓMICO ATACAMA, CHILE



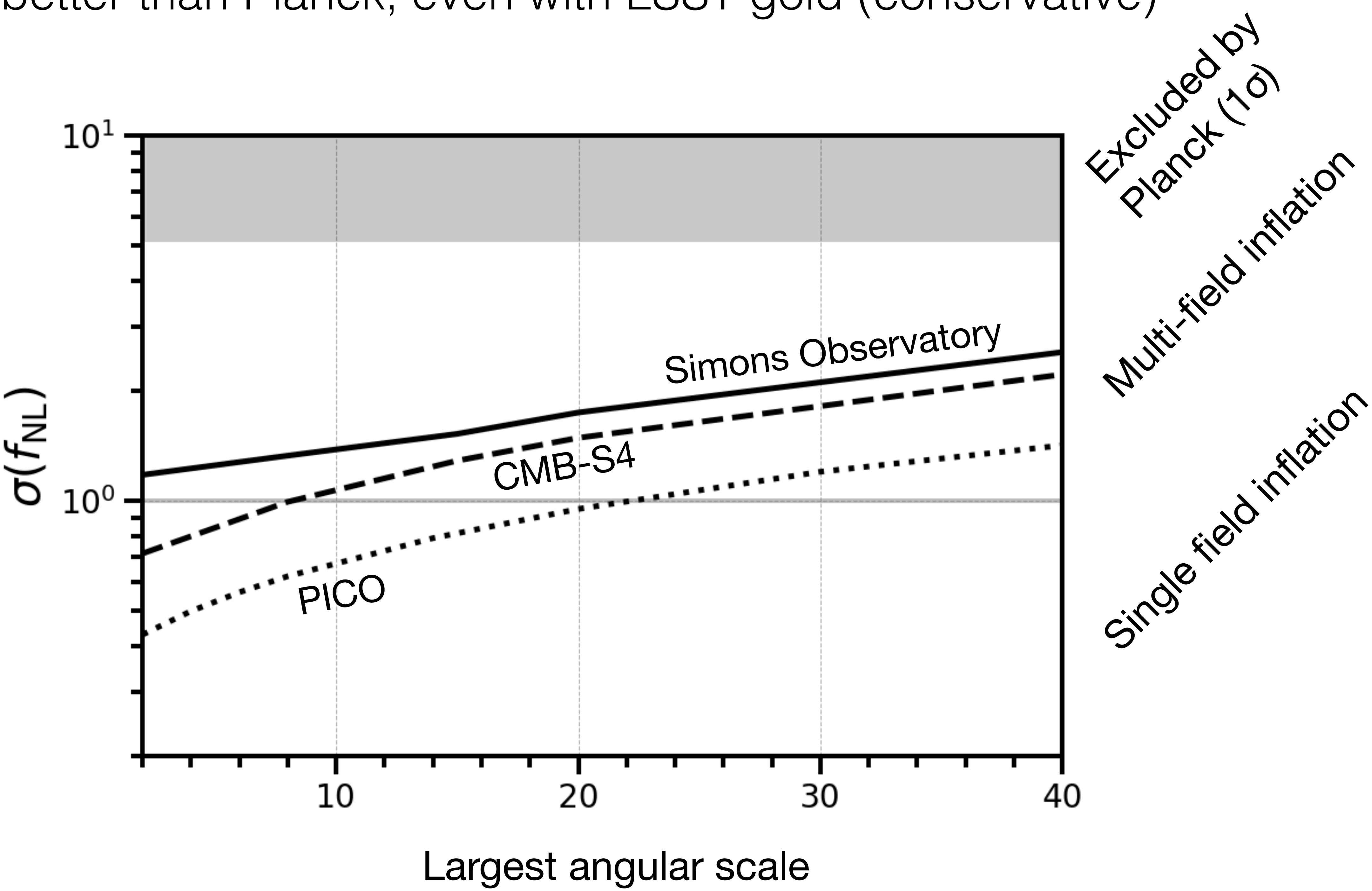


Today 2022 2030

Funding by DOE, Heising-Simons, JAXA, NASA, NSF, Simons Foundation, …

Other CMB experiments

10x better than Planck, even with LSST gold (conservative)



Simons Observatory: Science White Paper (1808.07445), Decadal White Paper (1907.08284)
CMB-S4: Science Case Paper (1907.04473), Decadal White Paper (1908.01062)
PICO: NASA Mission Study (1902.10541), Decadal White Paper (1908.07495)

Other science goals of Simons Observatory

	Parameter	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		2	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.04	0.03		tSZ-N $\times$ LSST-WL
		0.05	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS + DESI-BAO
		2%	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	**0.6**	0.3	1.4	TT (kSZ)

All quoted errors are 1σ

All forecasts assume SO + Planck

Include systematic error budget

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SO can detect any particle with spin that decoupled after the start of the QCD phase transition (at 2σ)

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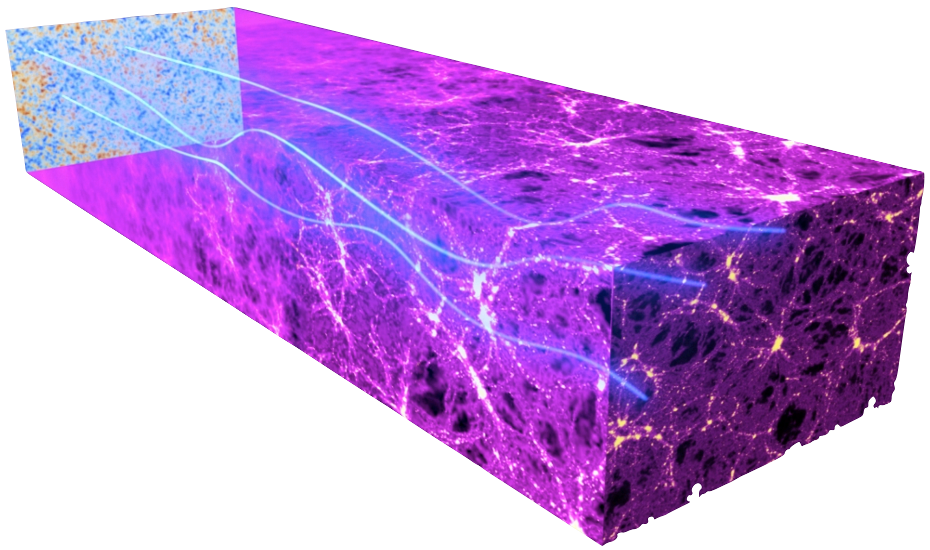
All quoted errors are 1σ

All forecasts assume SO + Planck

Include systematic error budget

Deviations from a cosmological constant

Lensing = line of sight integral so cannot resolve time dependence

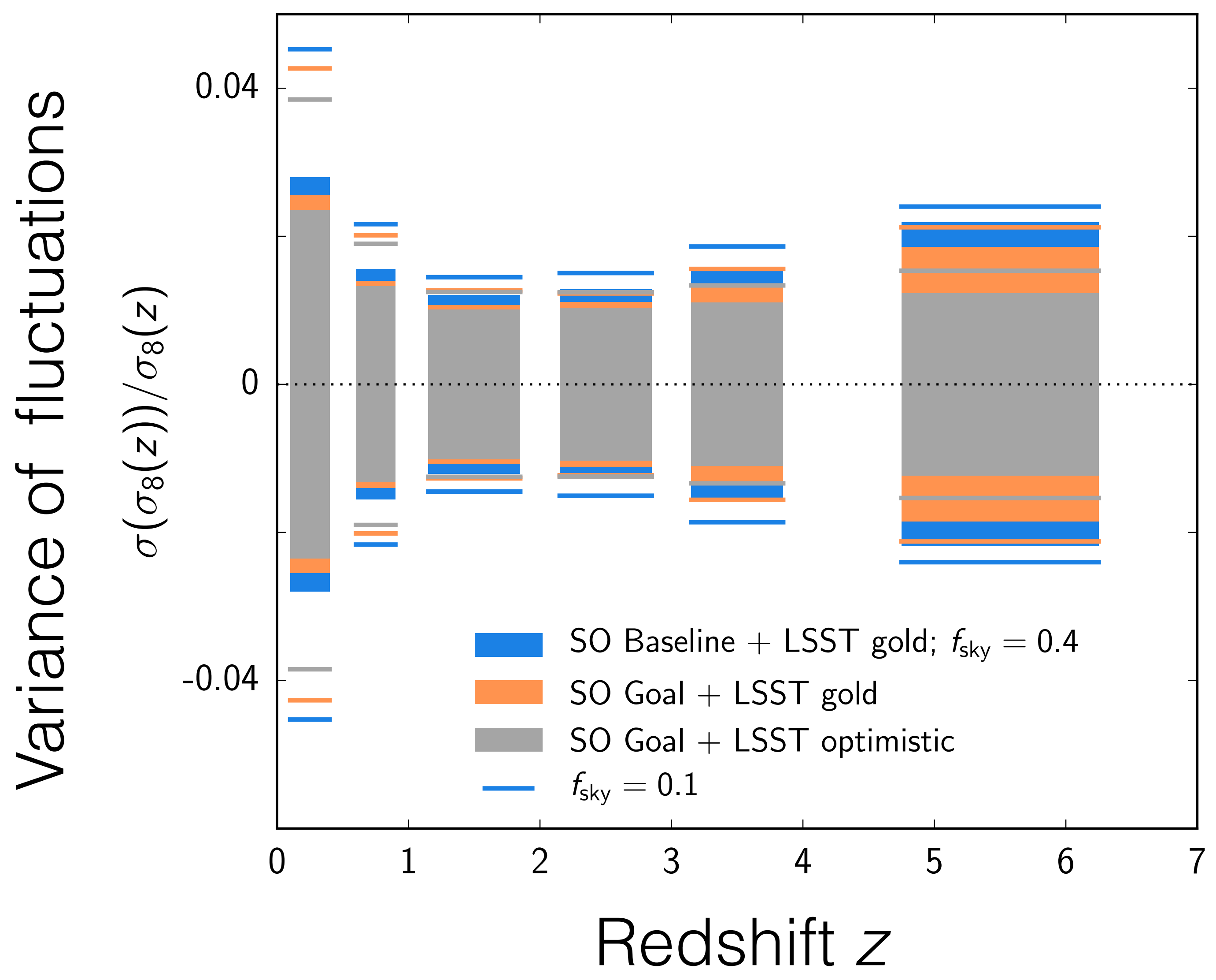


Galaxy clustering amplitude depends on galaxy type (unknown)

⇒ Either alone cannot measure dark energy as function of time

But joint analysis of lensing + clustering can!

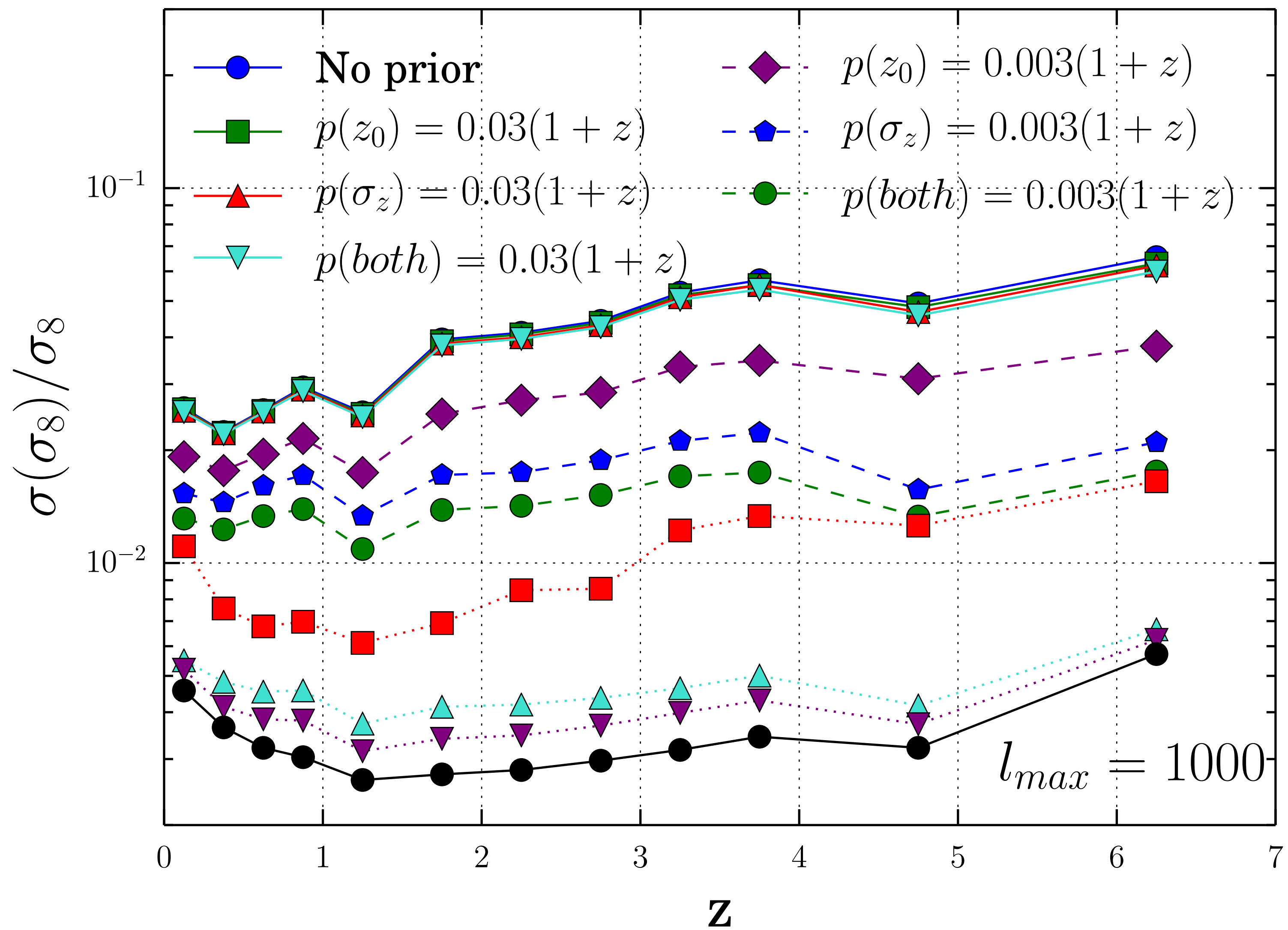
Deviations from a cosmological constant



Test acceleration of the Universe and dark energy with 1-2% precision (currently >7%)

MS & Seljak (2018), Simons Observatory Science White Paper (2019), Figure: B. Yu

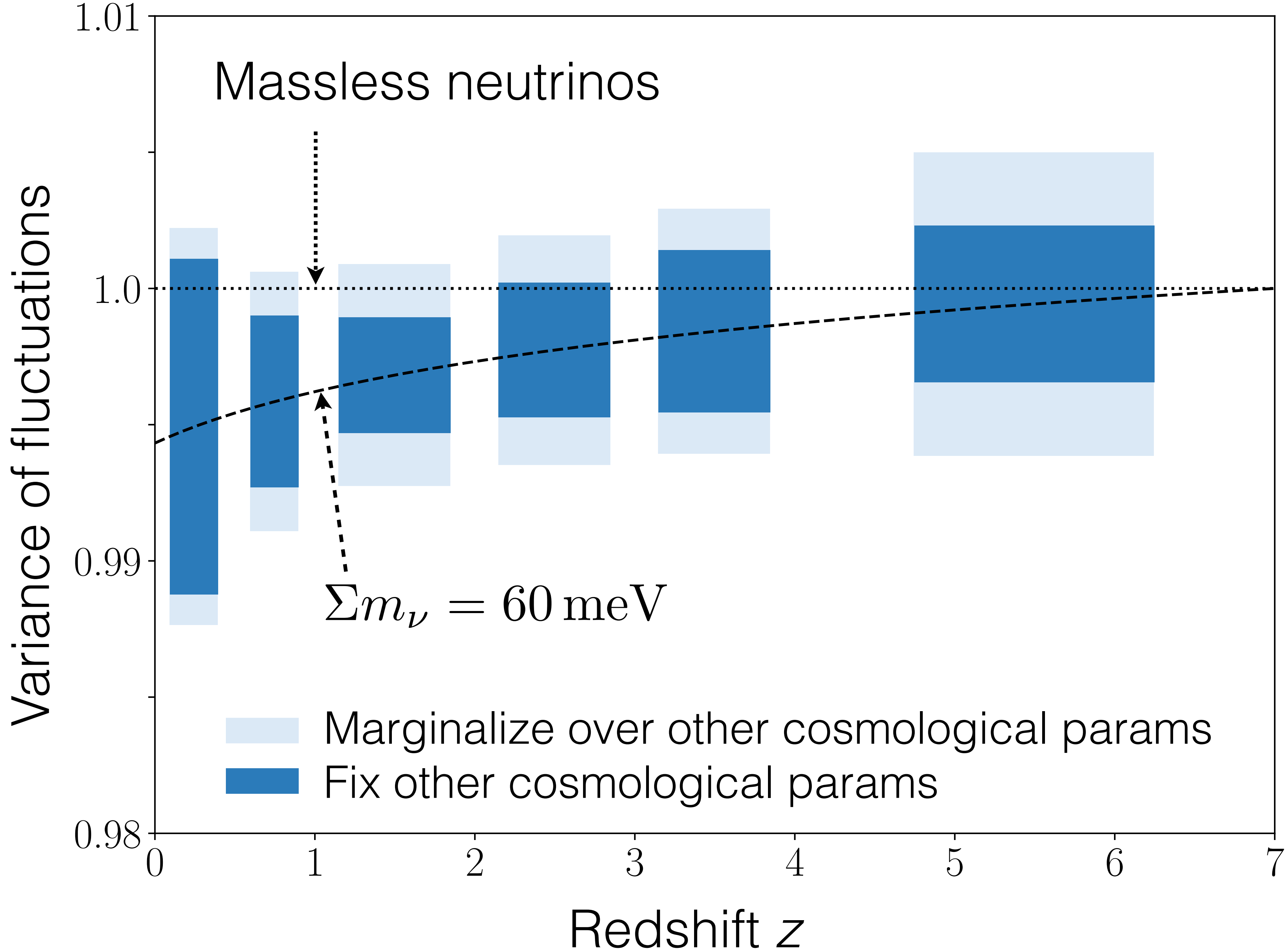
More careful forecast



- Getting redshift errors down to LSST requirement is crucial
- Reducing redshift errors further would help (clustering redshifts, …)

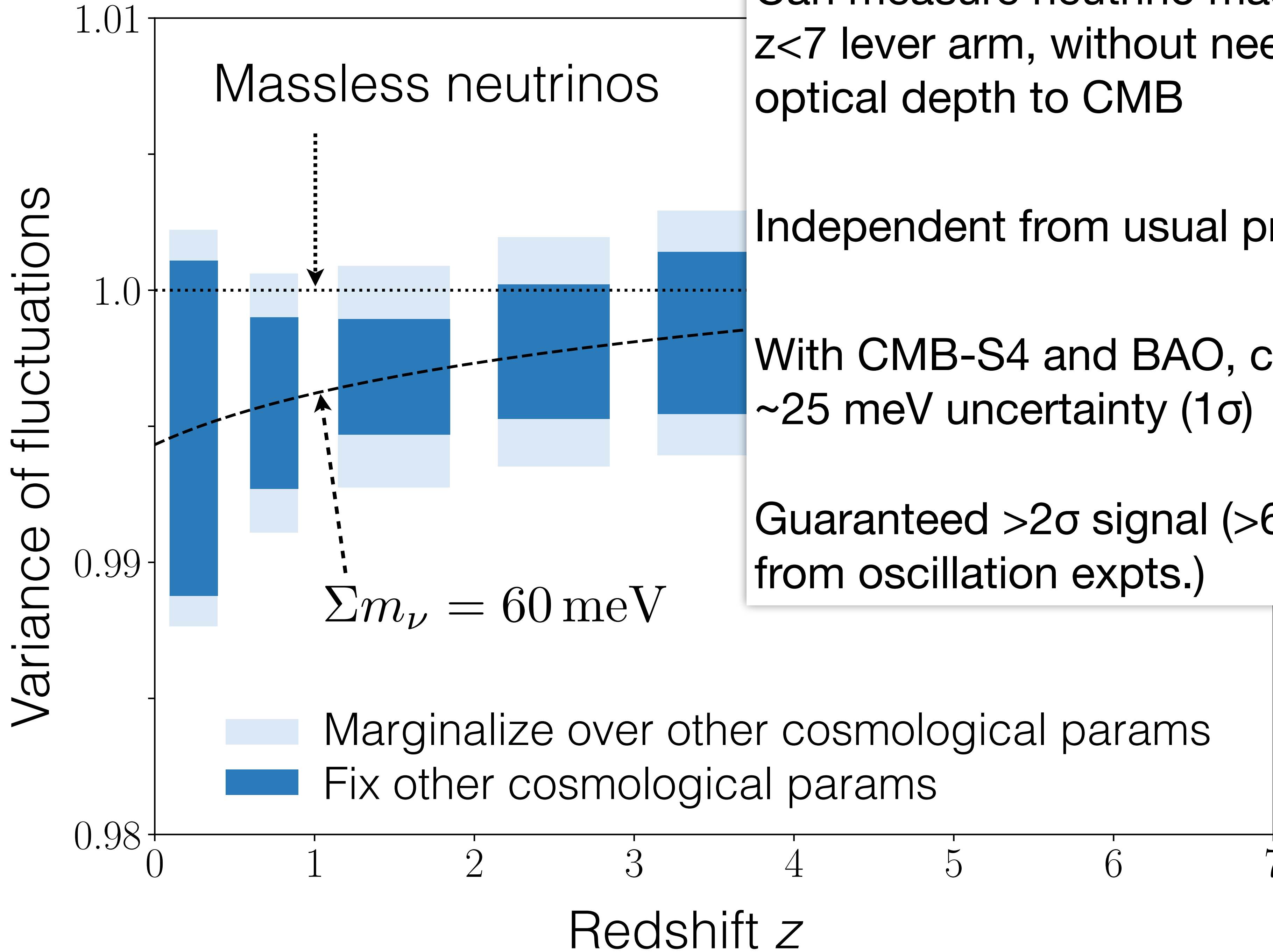
Cawthon (2018)

Sum of neutrino masses



B. Yu, Knight *et al.* (incl. MS, 1809.02120)

Sum of neutrino masses



Can measure neutrino mass using z<7 lever arm, without need for optical depth to CMB

Independent from usual probes

With CMB-S4 and BAO, can reach ~25 meV uncertainty (1σ)

Guaranteed >2σ signal (>60meV from oscillation expts.)

B. Yu, Knight *et al.* (incl. MS, 1809.02120)

Simons Observatory Analysis Working Groups

Within the **SO** collaboration we currently prepare the analysis pipeline for cross-correlation with LSST

(L3.2) CMB lensing cross-correlations

V. Boehm, A. Challinor, G. Fabbian, S. Ferraro, M. Madhavacheril, E. Schaan, N. Sehgal, B. Sherwin, A. van Engelen, …

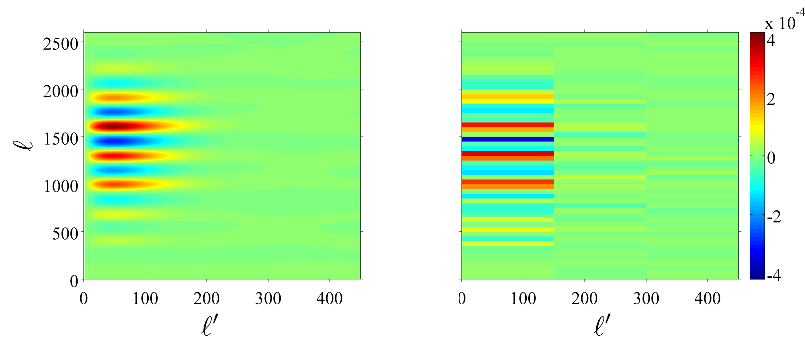
(LT) Likelihood and Theory

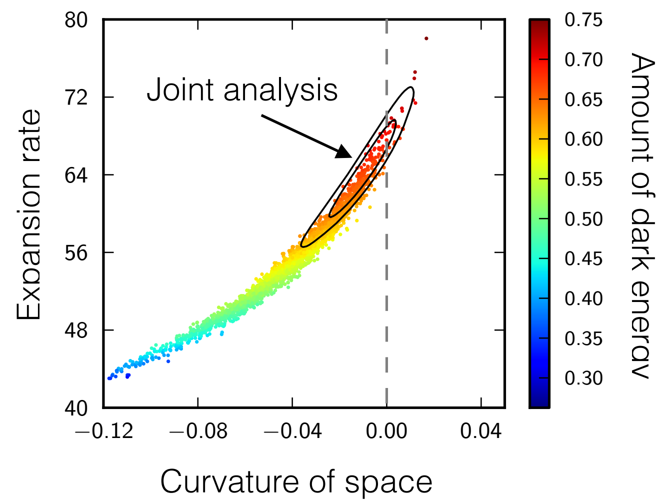
E. Calabrese, M. Gerbino, V. Gluscevic, R. Hlozek, A. Lewis, …

I'm also a member of the **CMB-S4**, **PICO** and **LSST** collaborations, where related efforts are currently underway

Other CMB lensing research interests (ask me later)

(1) Covariance for joint analysis of CMB and CMB magnification

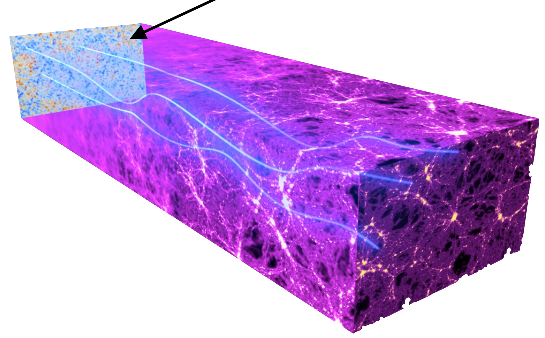


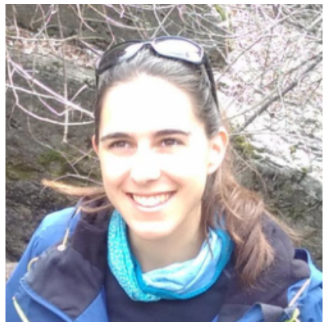


MS, Challinor et al. (2013)
Peloton, MS et al. (2017)
Planck collab. (2013, 2018)

(2) Estimate *unlensed CMB* using galaxies

Sherwin & MS (2015)



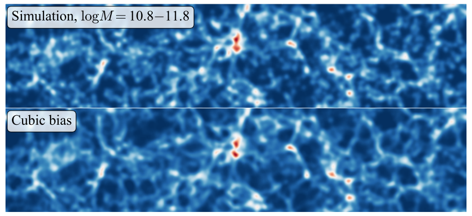


(3) New bias of the magnification estimator

Böhm, MS & Sherwin (2016)
Beck, Fabbian & Errard (2018)
Böhm, Sherwin, Liu, Hill, MS & Namikawa (2018)

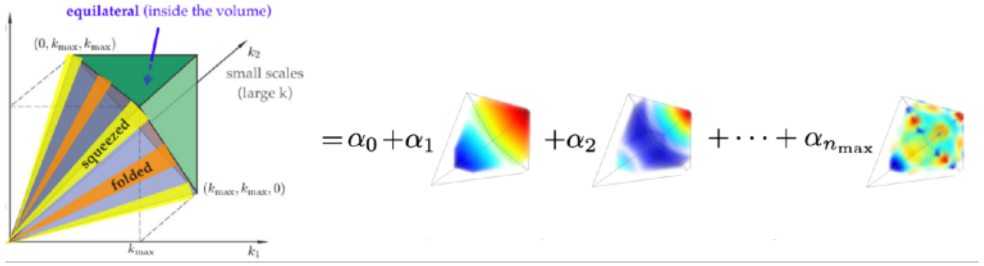
II. Galaxy clustering: Theory & Analysis

(1) Modeling galaxy clustering

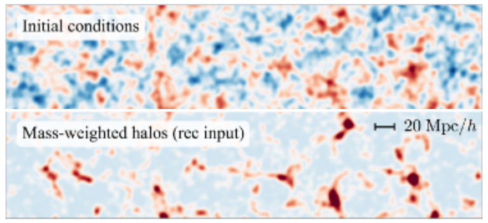


(2) Cosmological parameter analysis

(3) Accounting for skewness



(4) Getting initial from final conditions



II. Galaxy clustering: Theory & Analysis

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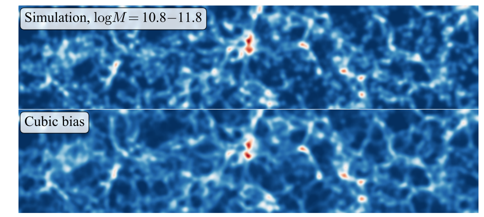


(2) Cosmological parameter analysis

(3) Accounting for skewness

(4) Getting initial from final conditions

Motivation

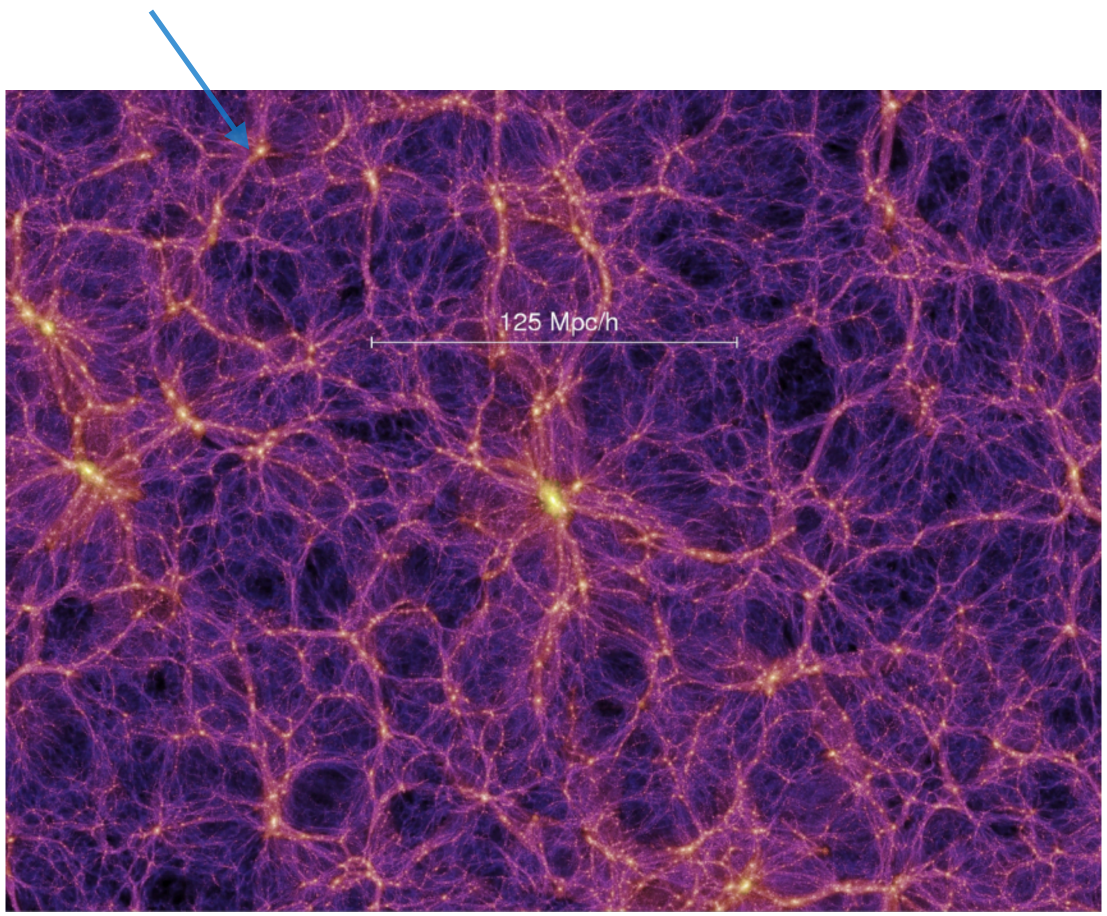
If we had the data today, would not be able to make cosmology inference because some components are not ready yet

- Theoretical modeling of galaxy clustering
  - Simplified in forecasts
  - Good enough for current data but not next-generation data
- Relation between galaxies and dark matter (‘galaxy bias’)
- Redshift space: Redshift errors, redshift space distortions, fingers of God
- Galaxy formation/baryonic physics: stellar feedback, blackhole feedback, radiative transfer, magnetic fields, …

Data will be amazing. Let’s make the theory & analysis adequate.

Modeling galaxy clustering

Must connect dark matter distribution to galaxy distribution



Simplest model: Linear 'bias' relation

$$\delta_g(\mathbf{x}) = b_1 \delta_m(\mathbf{x})$$

Can prove this is correct on very large scales (Peebles, Kaiser, …)

But breaks down on smaller scales

Need nonlinear corrections

Modeling galaxy clustering

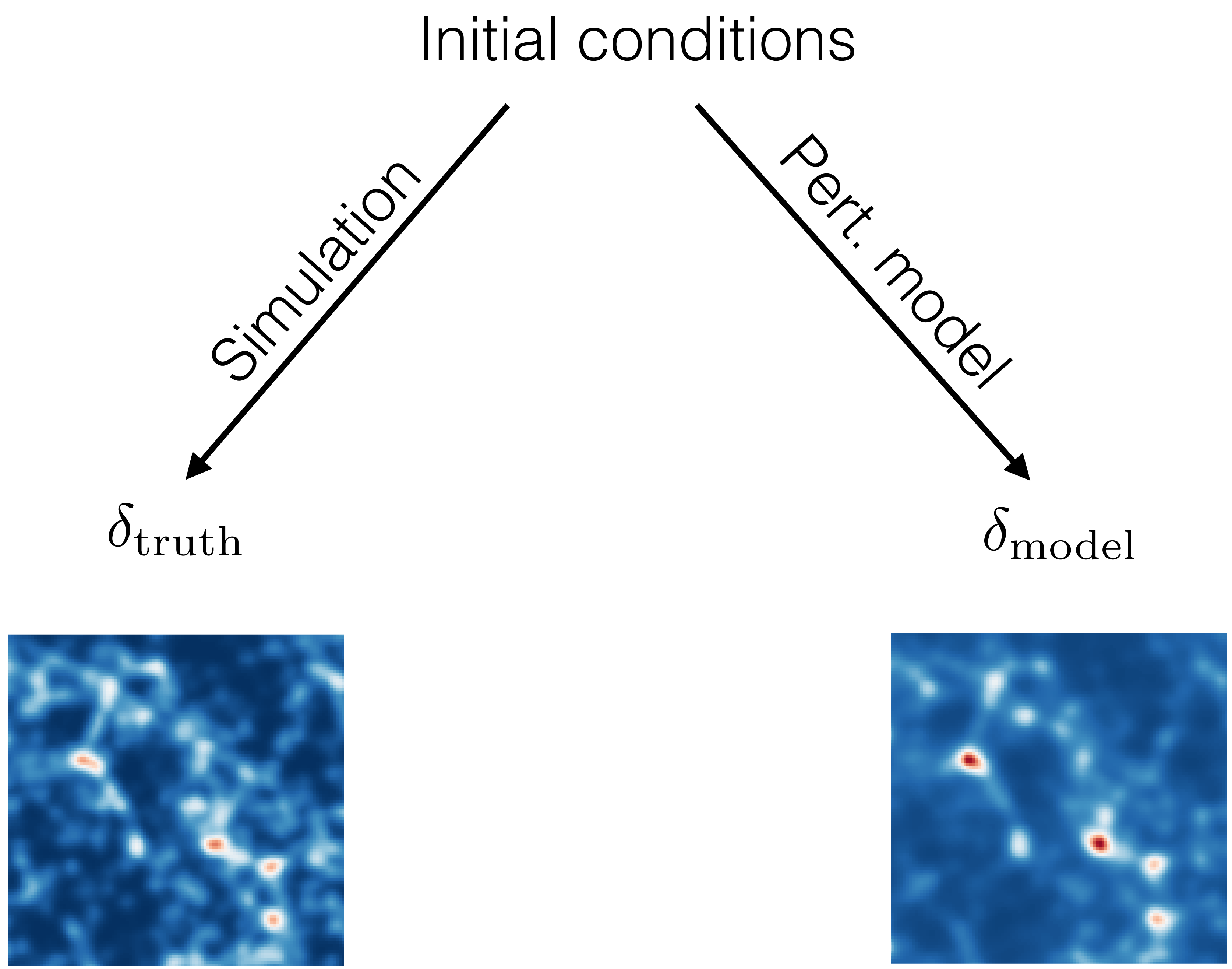
This approach has been extensively studied in the past

Review by Desjacques, Jeong, Schmidt (2018): Large-Scale Galaxy Bias

Most of the analyses use n-point functions. Disadvantages:

- Sample variance, compromise on resolution/size of simulation
- On small scales hard to disentangle different sources of nonlinearity
- Overfitting (smooth curves, many parameters)
- Only few lowest n-point functions explored in practice
- Difficult to isolate and study the noise

New setup: Field level comparison



MS, Simonović, Assassi & Zaldarriaga (2019)

Benefits

Benefits of using 3D fields rather than summary statistics

+ No sample variance, can use small volumes with high resolution
+ No overfitting (6 parameters describe >1 million 3D Fourier modes)
+ 'All' *n*-point functions measured simultaneously
+ Easy to isolate the noise
+ Applicable to field-level likelihood and initial condition reconstruction

MS, Simonović, Assassi & Zaldarriaga (2019)

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Questions we studied

1. How well does perturbative bias model work?

2. How correlated is the galaxy density field with the initial conditions?

3. What are the properties of the noise?

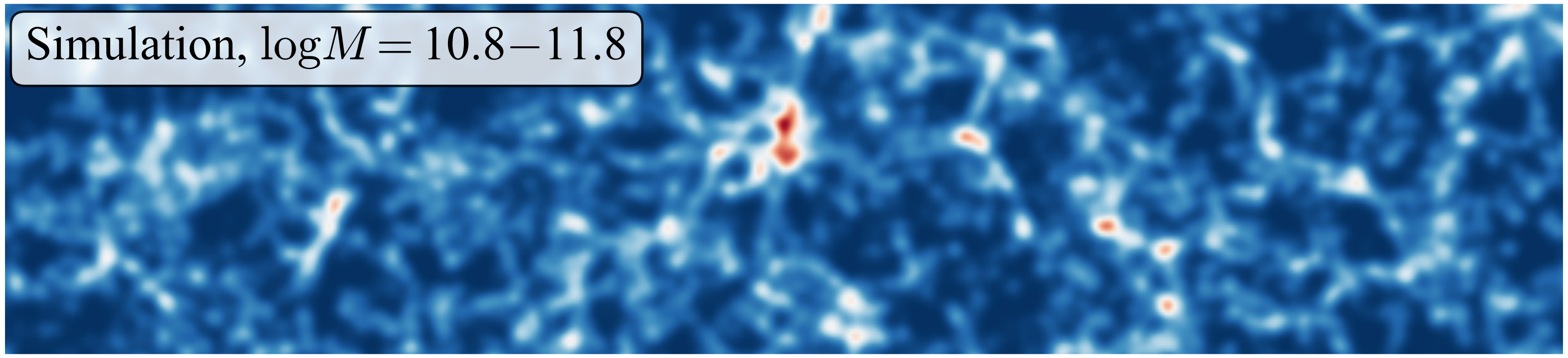
MS, Simonović, Assassi & Zaldarriaga (2019)

Simulation

Ran N-body code on local cluster with ~2000 CPUs

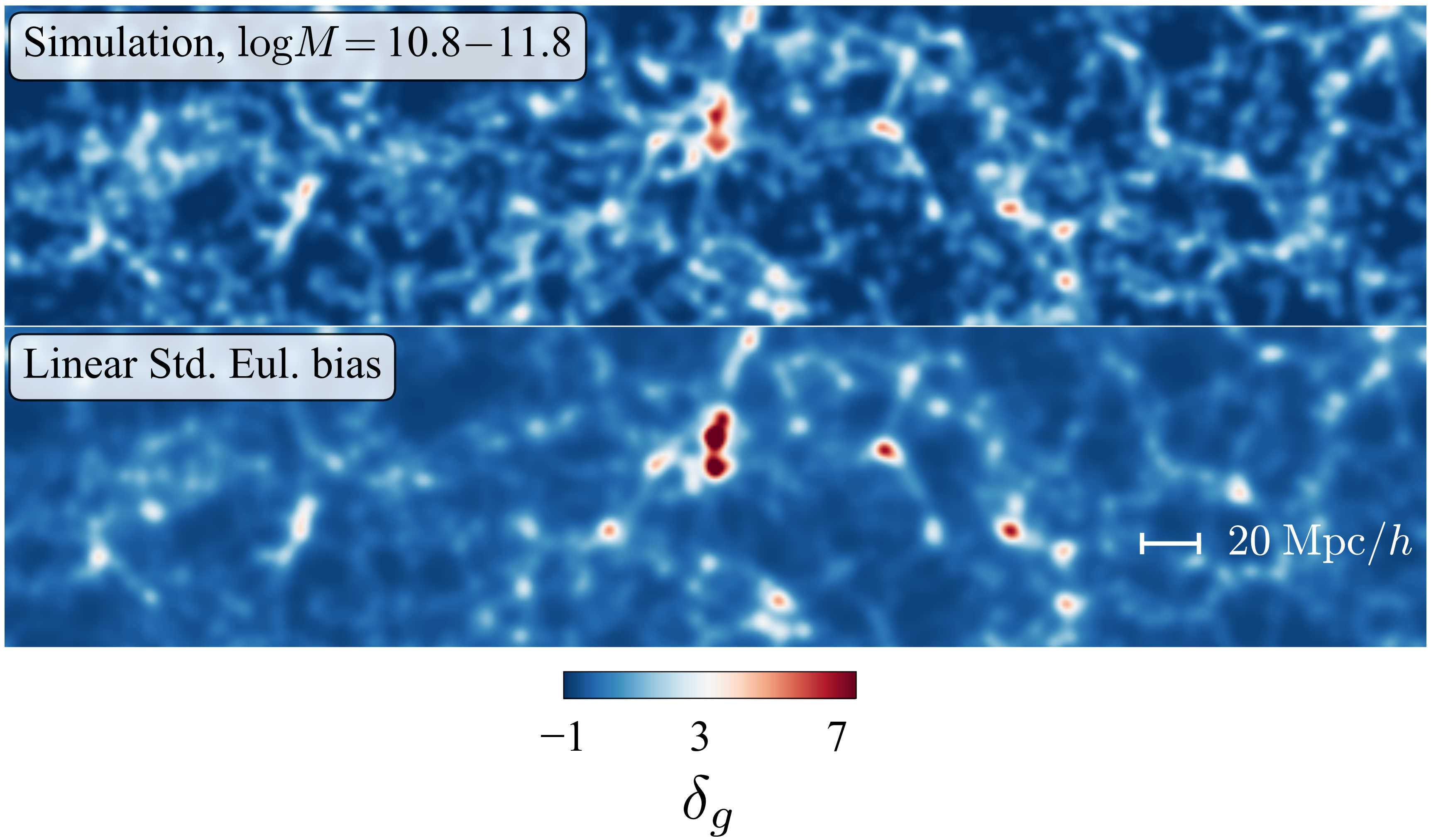
1536^3 = 3.6B particles in a 3D cubic box
3072^3 = 29B grid points for long-range force computation
4000 time steps
5 realizations

~ 1M CPU hours



MS, Simonović, Assassi & Zaldarriaga (2019)

Comparison with linear model



Simulation (= truth)

Model $b_1 \delta_m(\mathbf{x})$

Reasonable prediction on large scales

Missing structure on small scales

MS, Simonović, Assassi & Zaldarriaga (2019)

Nonlinear model

Include all nonlinear terms allowed by symmetries
(= Effective Field Theory)

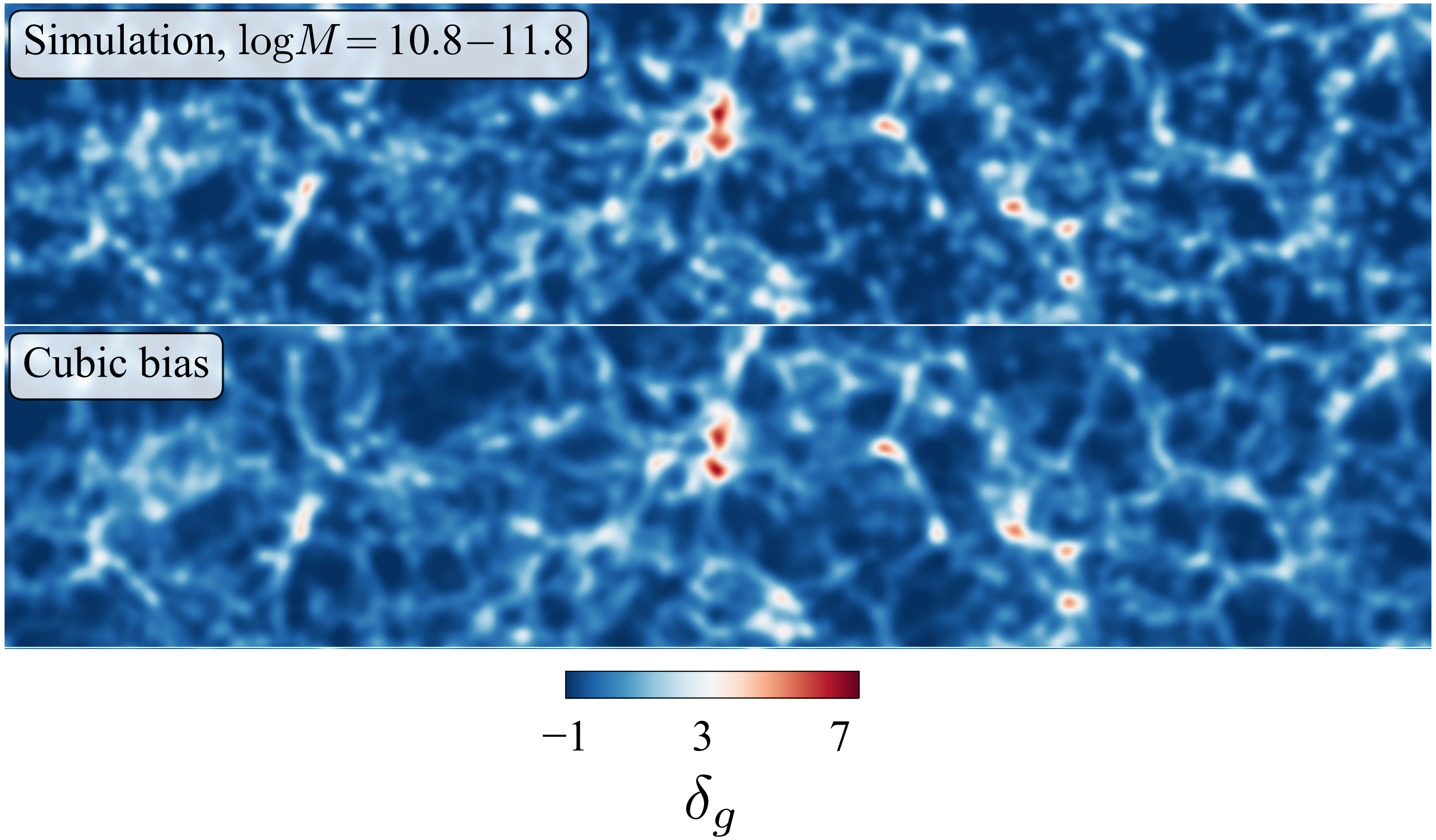
$$\delta_g(\mathbf{x}) = b_1\delta_m(\mathbf{x}) + b_2\delta_m^2(\mathbf{x}) + \text{tidal term} + b_3\delta_m^3(\mathbf{x}) + \cdots$$

Desjacques, Jeong & Schmidt (2018): Review of Large-Scale Galaxy Bias

Fit parameters b_i by minimizing mean-squared error
(= least-squares 'polynomial' regression)

MS, Simonović, Assassi & Zaldarriaga (2019)

Comparison with nonlinear model



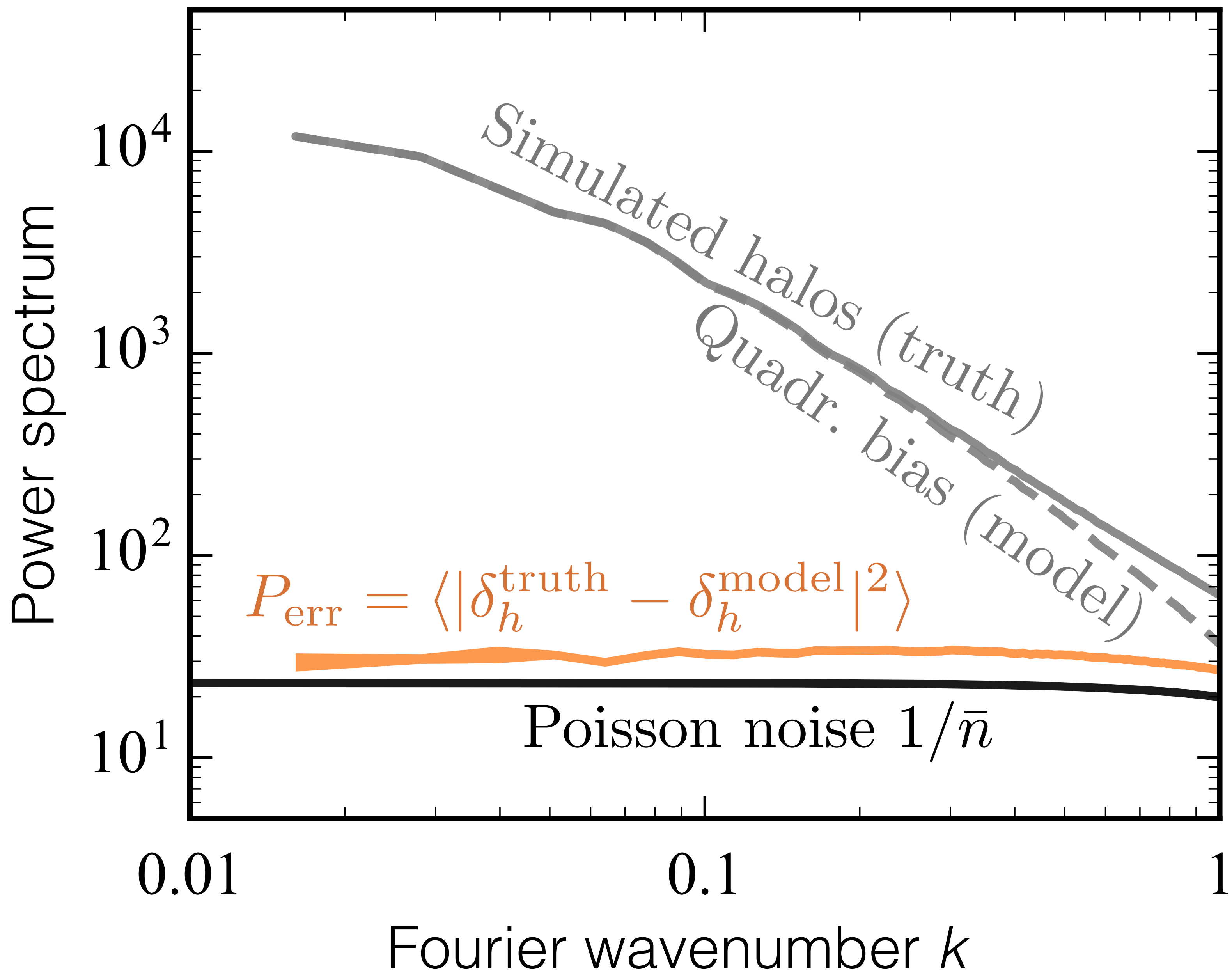
Simulation (= truth)

Nonlinear model

Much better agreement than linear model

MS, Simonović, Assassi, Zaldarriaga (2019)

Power spectrum of the noise (model error)

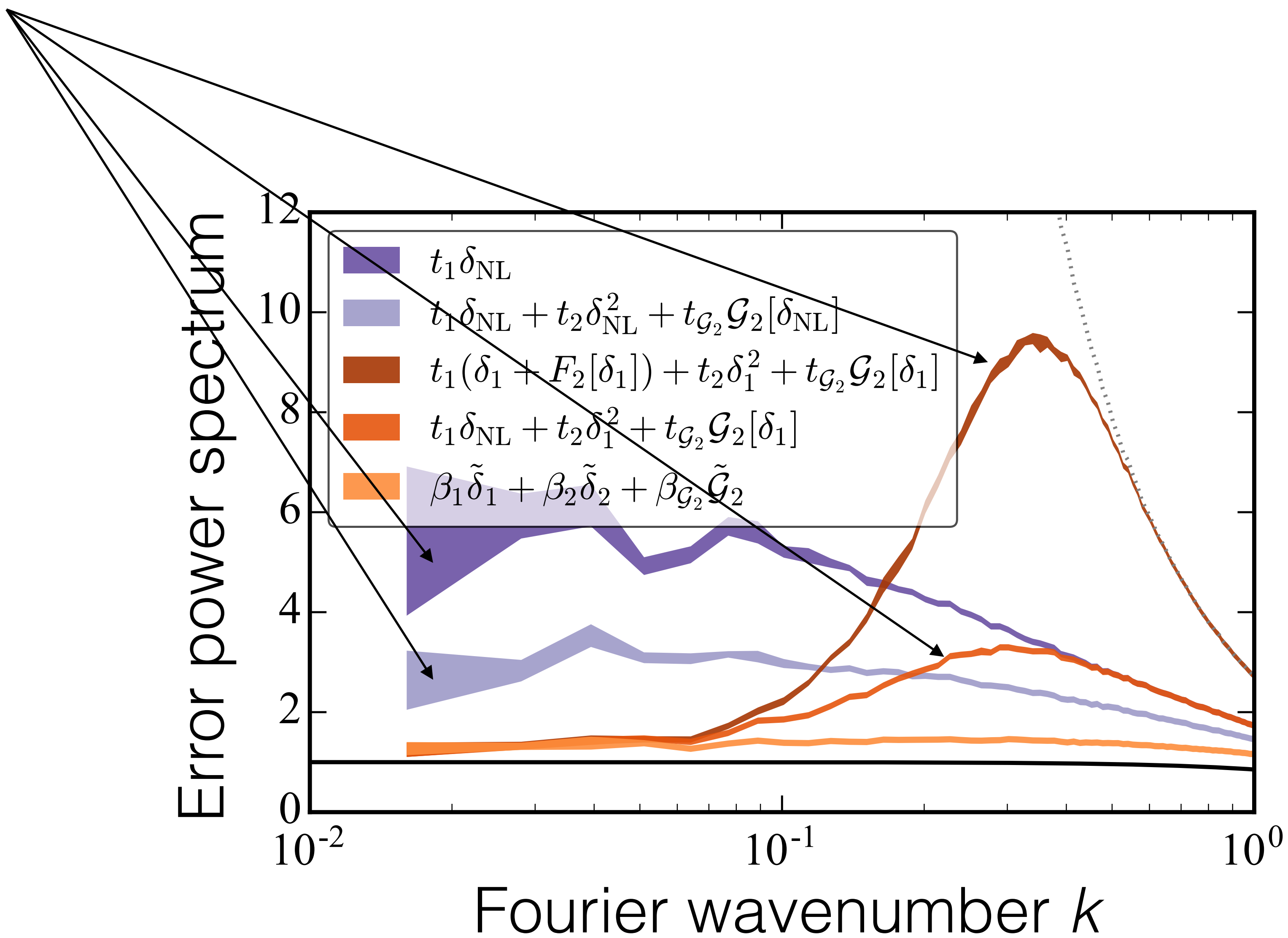


White noise error is crucial to avoid biasing cosmology parameters

MS, Simonović, Assassi, Zaldarriaga (2019)

Tried many other nonlinear bias operators

3-6x larger model error. Reason: Bulk flows, need 'shifted' operators

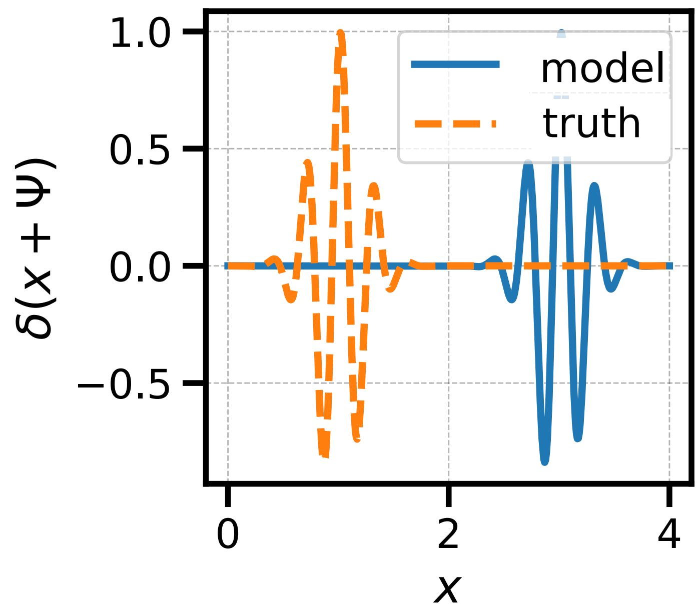


Increase in wavenumber corresponds to 8-30x larger volume

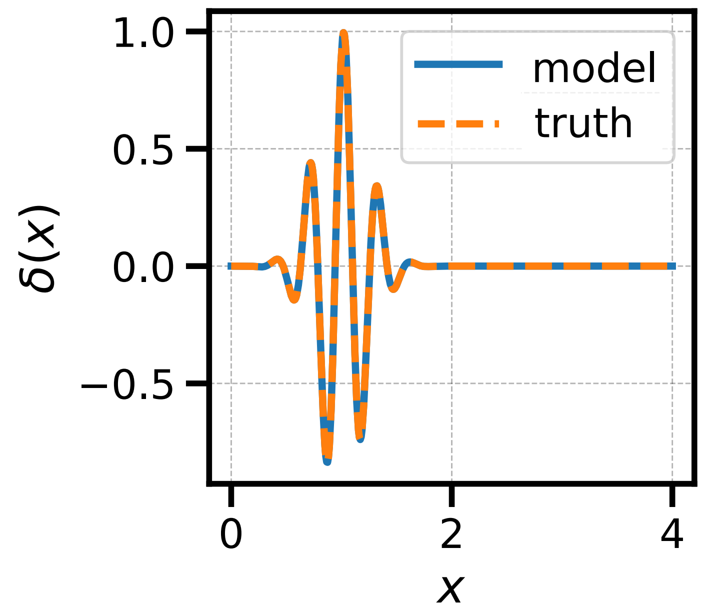
MS, Simonović, Assassi, Zaldarriaga (2019)

Bulk flows

Model doesn't account for bulk flows



Model accounts for bulk flows



Model must account for bulk flows to get small model error

$$\epsilon(x) \equiv \delta_{\rm truth} - \delta_{\rm model}$$

MS, Simonović, Assassi, Zaldarriaga (2019)

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(1) Modeling galaxy clustering

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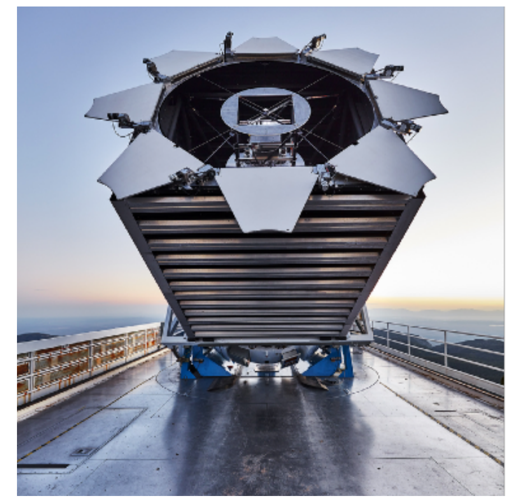
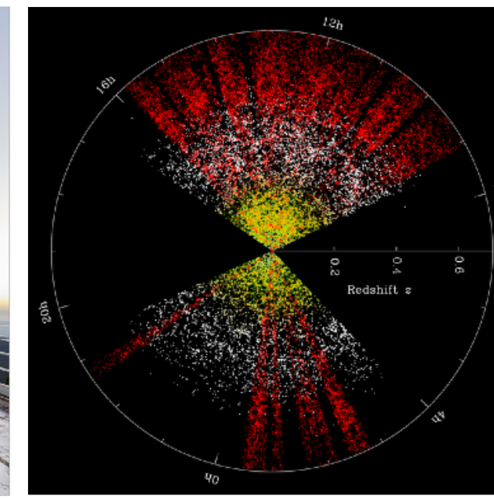
Application to data

Model was applied to SDSS BOSS data (~1 million galaxy spectra)

D’Amico, Gleyzes, Kokron et al. (1909.05271)
Ivanov, Simonović & Zaldarriaga (1909.05277)
Tröster, Sanchez, Asgari et al. (2020)



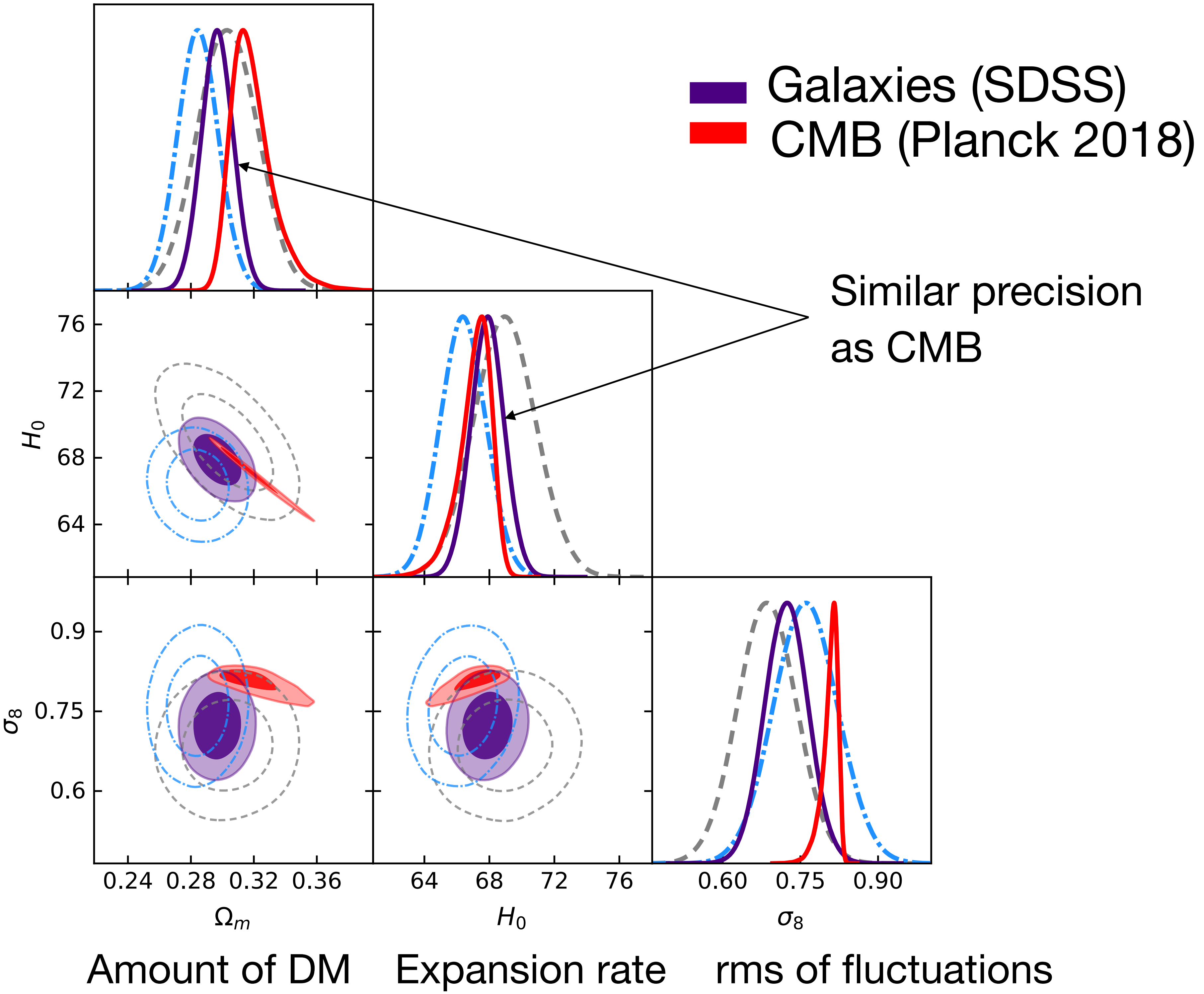


SDSS

MCMC sampling of posteriors was enabled by fast evaluation of the model power spectrum (reducing 2D loop integrals to 1D FFTs)

MS, Vlah & McDonald (2016)
McEwen, Fang, Hirata & Blazek (2016)
Cataneo, Foreman & Senatore (2017)
Simonović, Baldauf, Zaldarriaga et al. (2018)

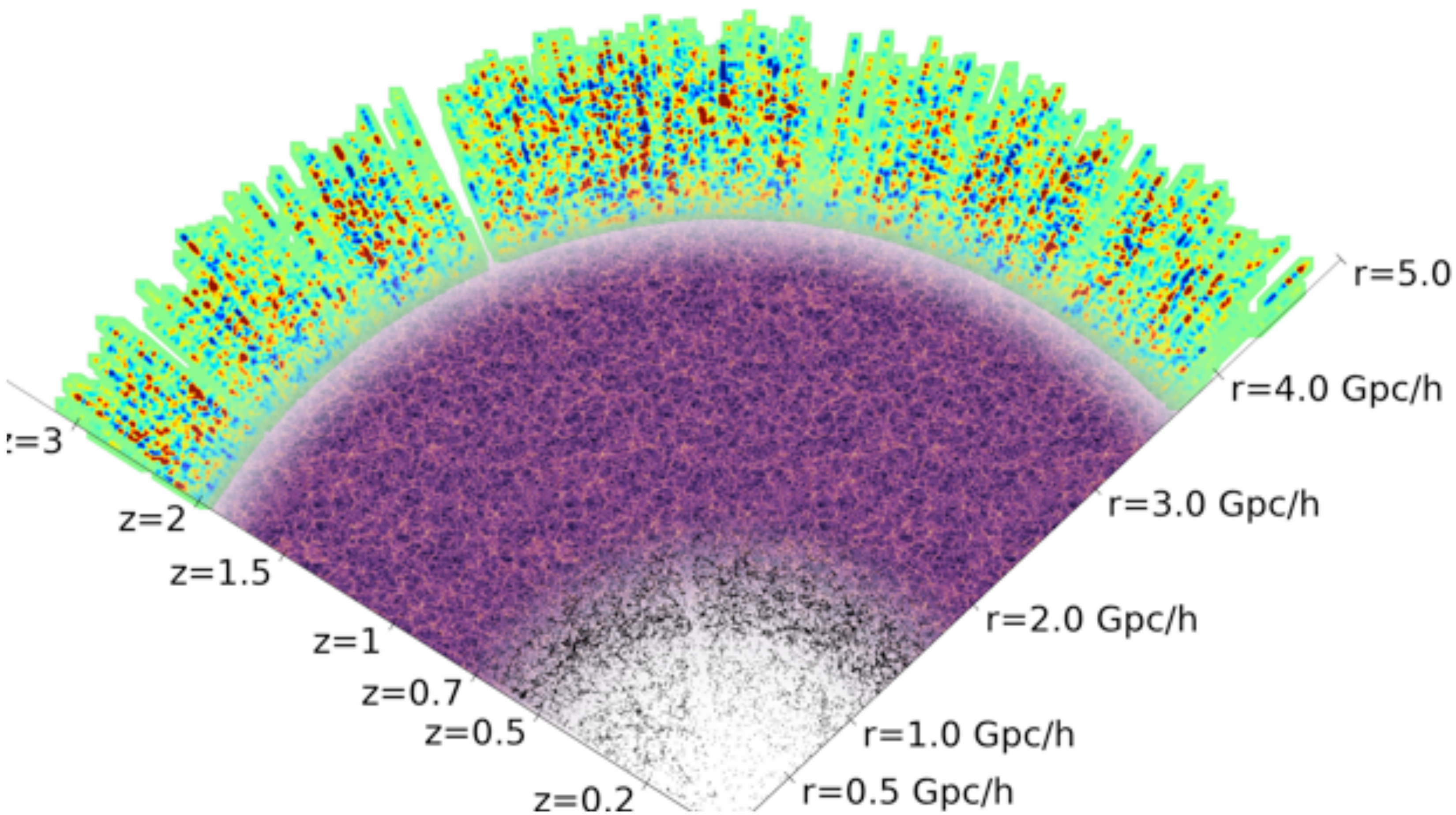
Similar precision as Planck for some parameters



Ivanov et al. (arXiv:1909.05277)

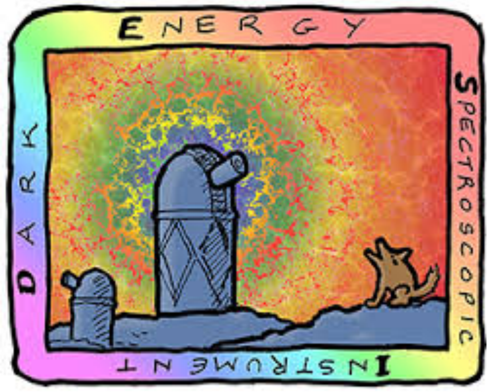
Future: Dark Energy Spectroscopic Instrument DESI

- 35 million galaxy spectra over 14,000 deg^2
- 5,000 robots to position fibers that take spectra
- 5 year survey, first light October 2019
- 600 scientists from 82 institutions
- Funding by DOE, NSF, Heising-Simons, Moore, STFC, …



Future: Dark Energy Spectroscopic Instrument DESI

- 35 million galaxy spectra over 14,000 deg^2
- 5,000 robots to position fibers that take spectra
- 5 year survey, first light October 2019
- 600 scientists from 82 institutions
- Funding by DOE, NSF, Heising-Simons, Moore, STFC, …



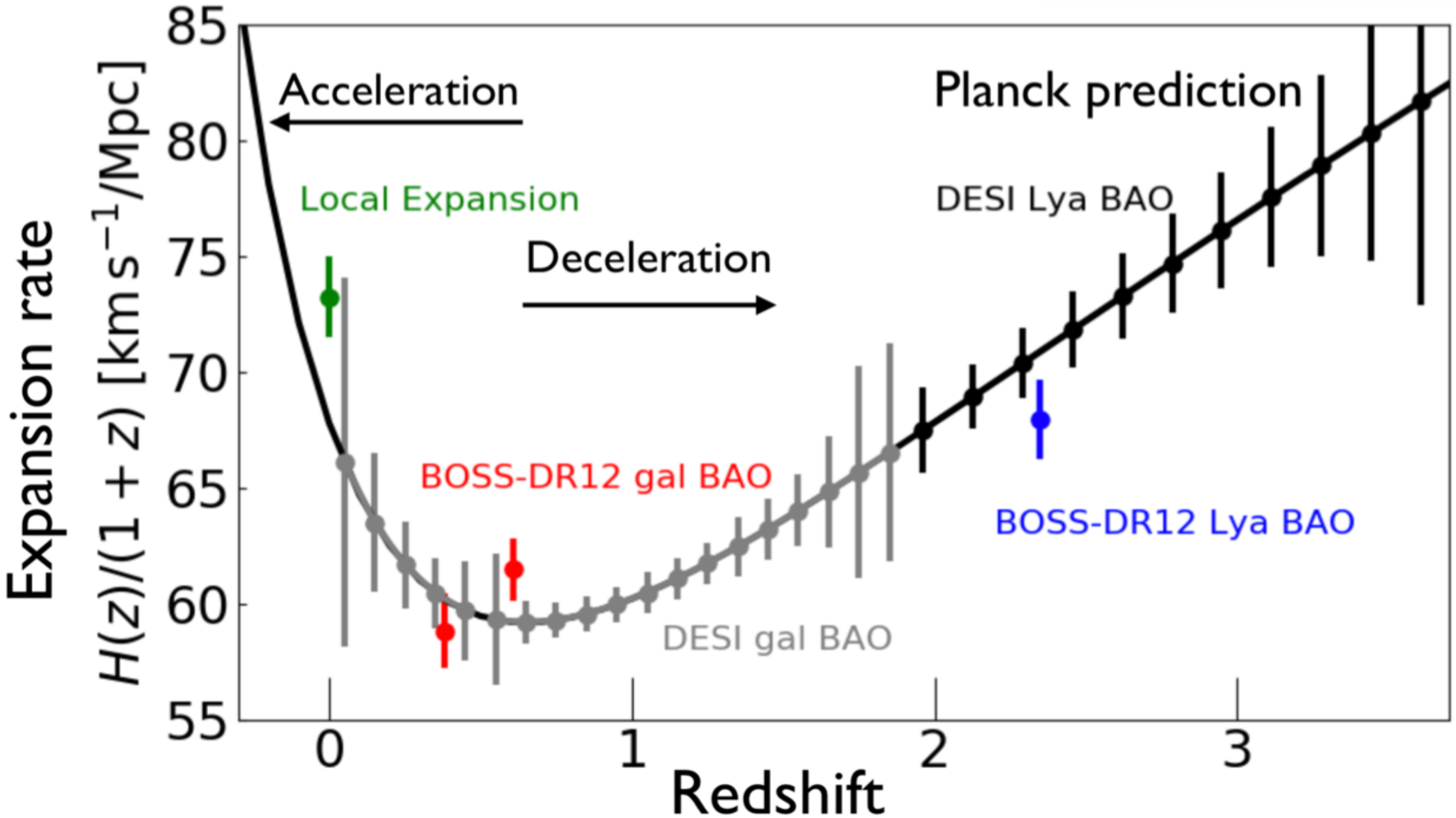


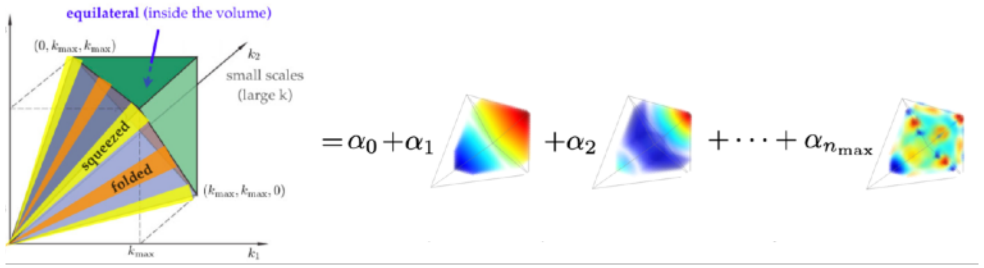
Figure: O. Lahav

II. Galaxy clustering: Theory & Analysis

(1) Modeling galaxy clustering

(2) Cosmological parameter analysis

(3) Accounting for skewness

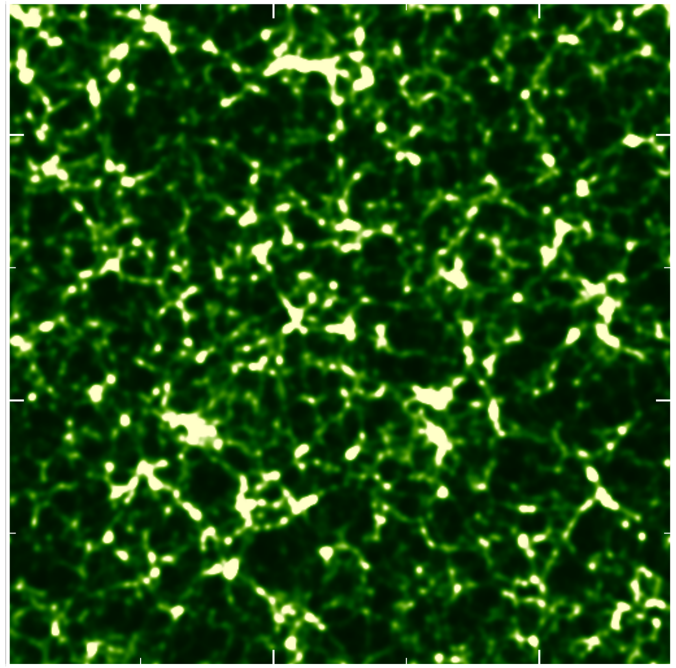


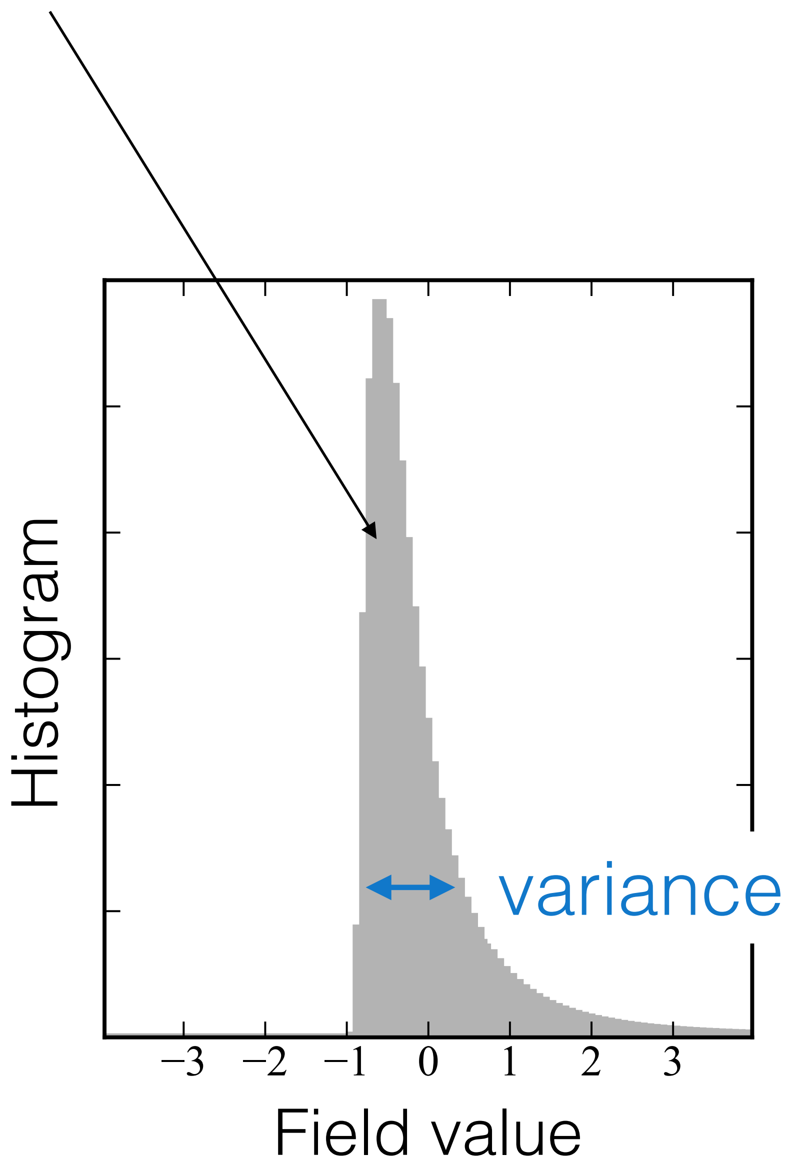
(4) Getting initial from final conditions

Probability distribution of DM halos / galaxies

Not normally distributed, highly skewed

DM halo number density





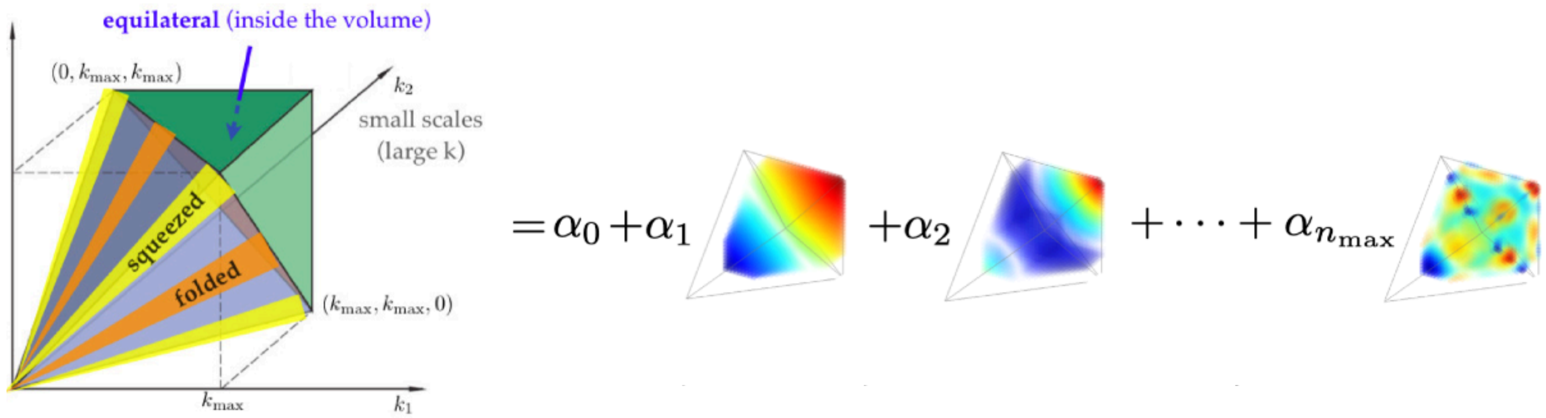
Information in the tails can improve precision of parameter estimates

Measuring skewness

Challenging: Can form too many Fourier mode triplets

Solution 1

In space of all triplets, expand in simple basis functions



Solution 2

Given parameter of interest, compute max. likelihood estimator (matched filter).
Sum over all triplets can be computed using a few 3D FFTs.

Regan, MS, Shellard & Fergusson (2011)
MS, Regan & Shellard (2013)
MS, Baldauf & Seljak (2015)
Moradinezhad Dizgah, Lee, MS & Dvorkin (2020)

Modeling skewness

Modeling skewness on mildly nonlinear scales is challenging

Large literature

Angulo, Foreman, MS & Senatore (2015)
Lazanu, Giannantonio, MS & Shellard (2016)
Lazanu, Giannantonio, MS & Shellard (2017)
+ many more papers by others, incl. Baldauf, Gil-Marin, Porciani, Scoccimarro, Sefusatti

Still no good model for galaxies in redshift space including primordial non-Gaussianity

We should improve modeling and estimators for DESI & SPHEREx

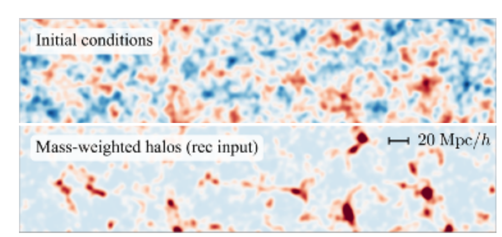
II. Galaxy clustering: Theory & Analysis

(1) Bias model at the field level

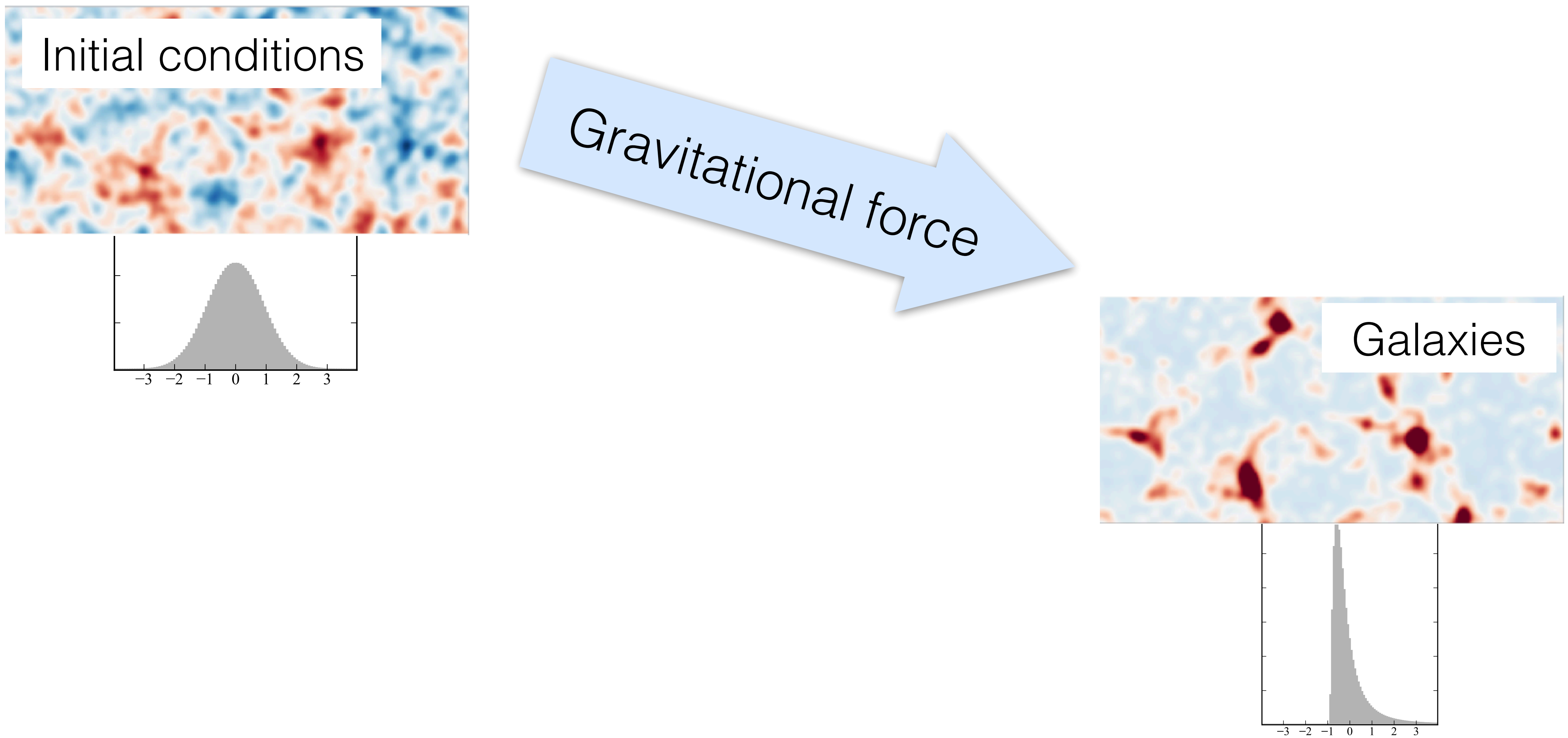
(2) Cosmological parameter analysis

(3) Accounting for skewness

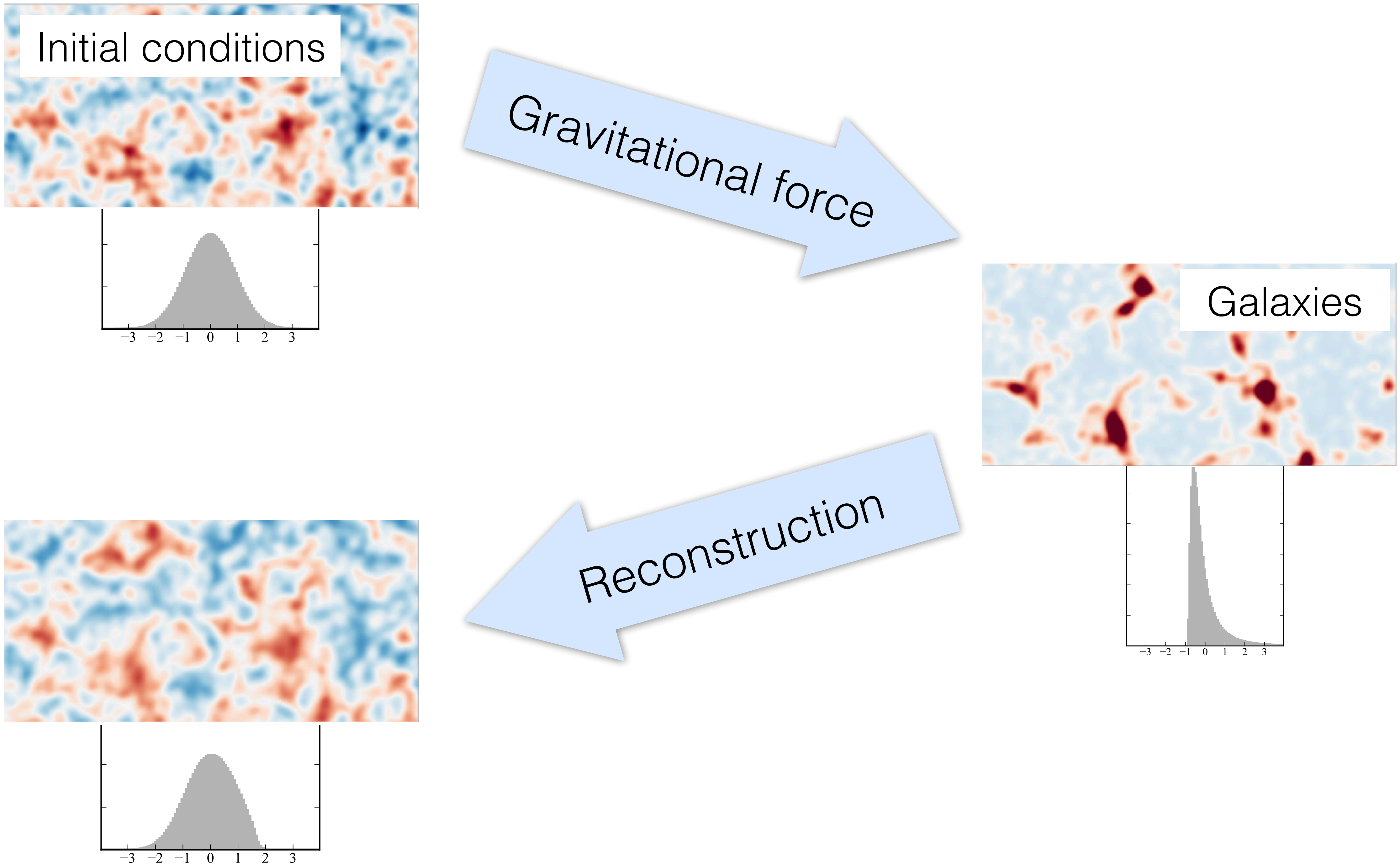
(4) Getting initial from final conditions



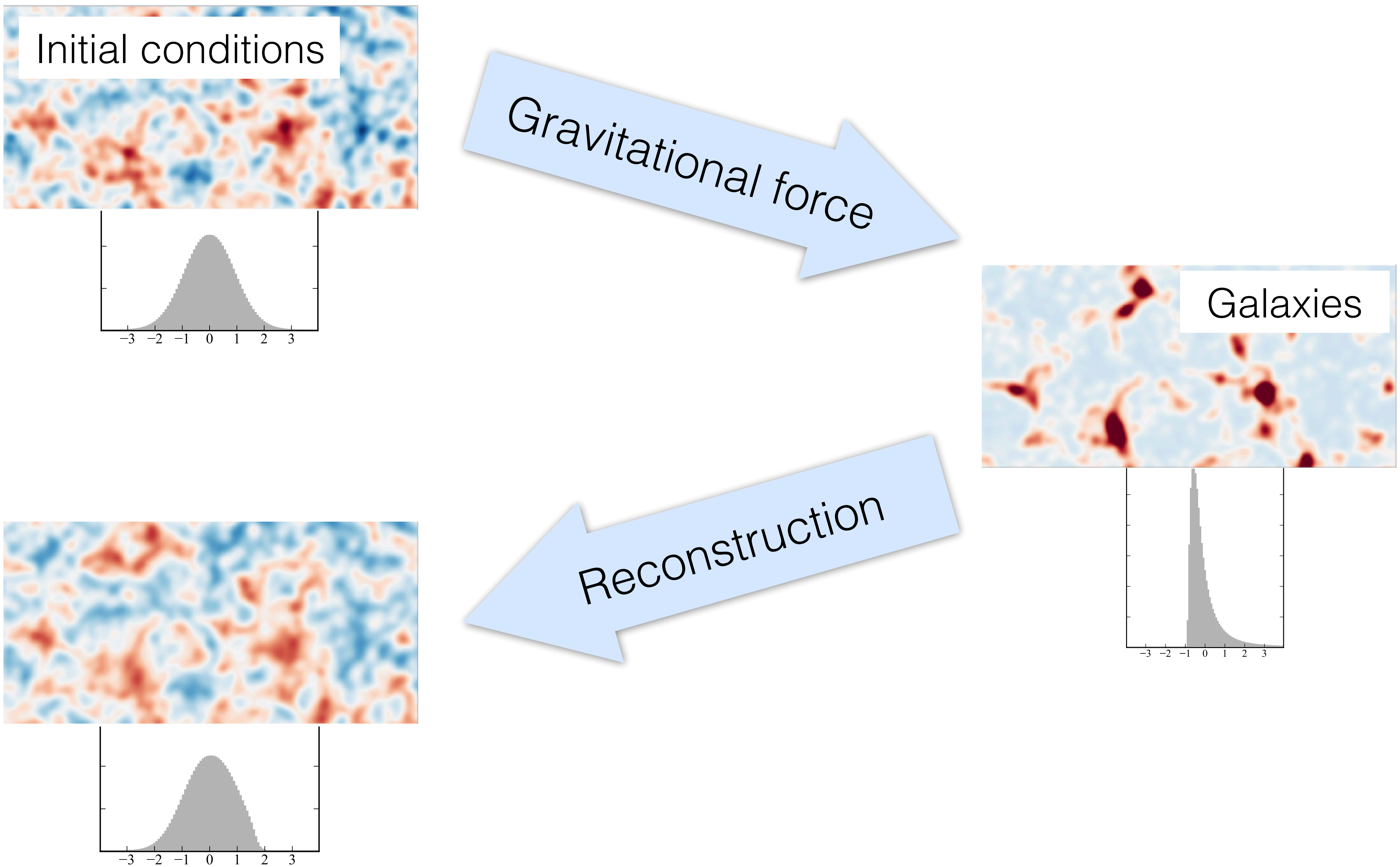
Getting initial from final conditions



Getting initial from final conditions



Getting initial from final conditions



Goal: Reconstruct initial conditions & measure their power spectrum

Many proposed algorithms

First by J. Peebles in late 1980's, then for BAO by D. Eisenstein 2007

Renewed interest in last ~5 years

MS, Feng+ (2015), MS, Baldauf+ (2017)
Zhu, Yu+ (2017), Wang, Yu+ (2017)
Seljak, Aslanyan+ (2017), Modi, Feng+ (2018)
Shi+ (2018), Hada+ (2018), Modi, White+ (2019), Sarpa+ (2019), Schmidt+ (2019), Elsner+ (2019), Yu & Zhu (2019), Zhu, White+ (2019)

Also sampling

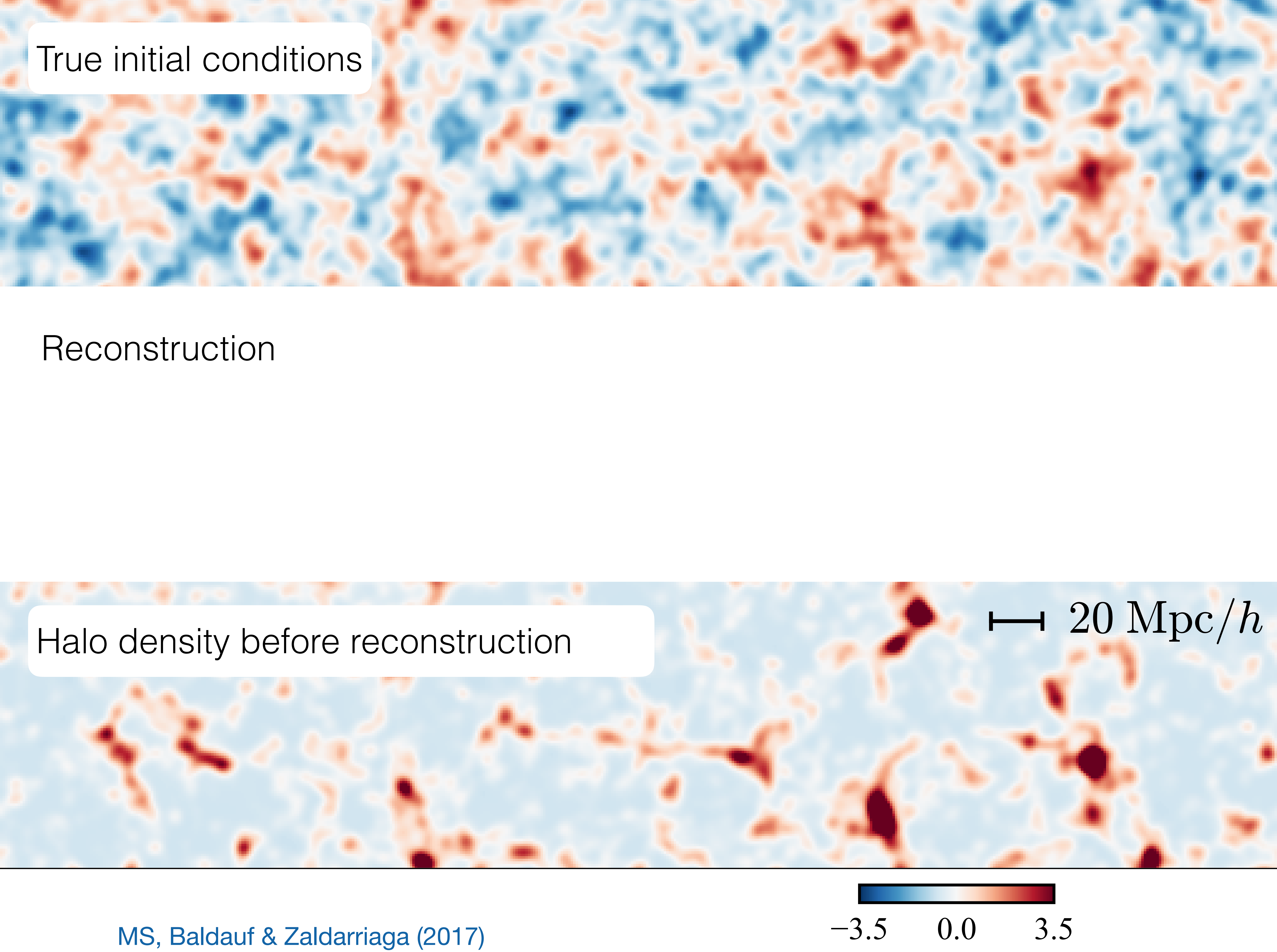
Jasche, Kitaura, Lavaux, Wandelt, …

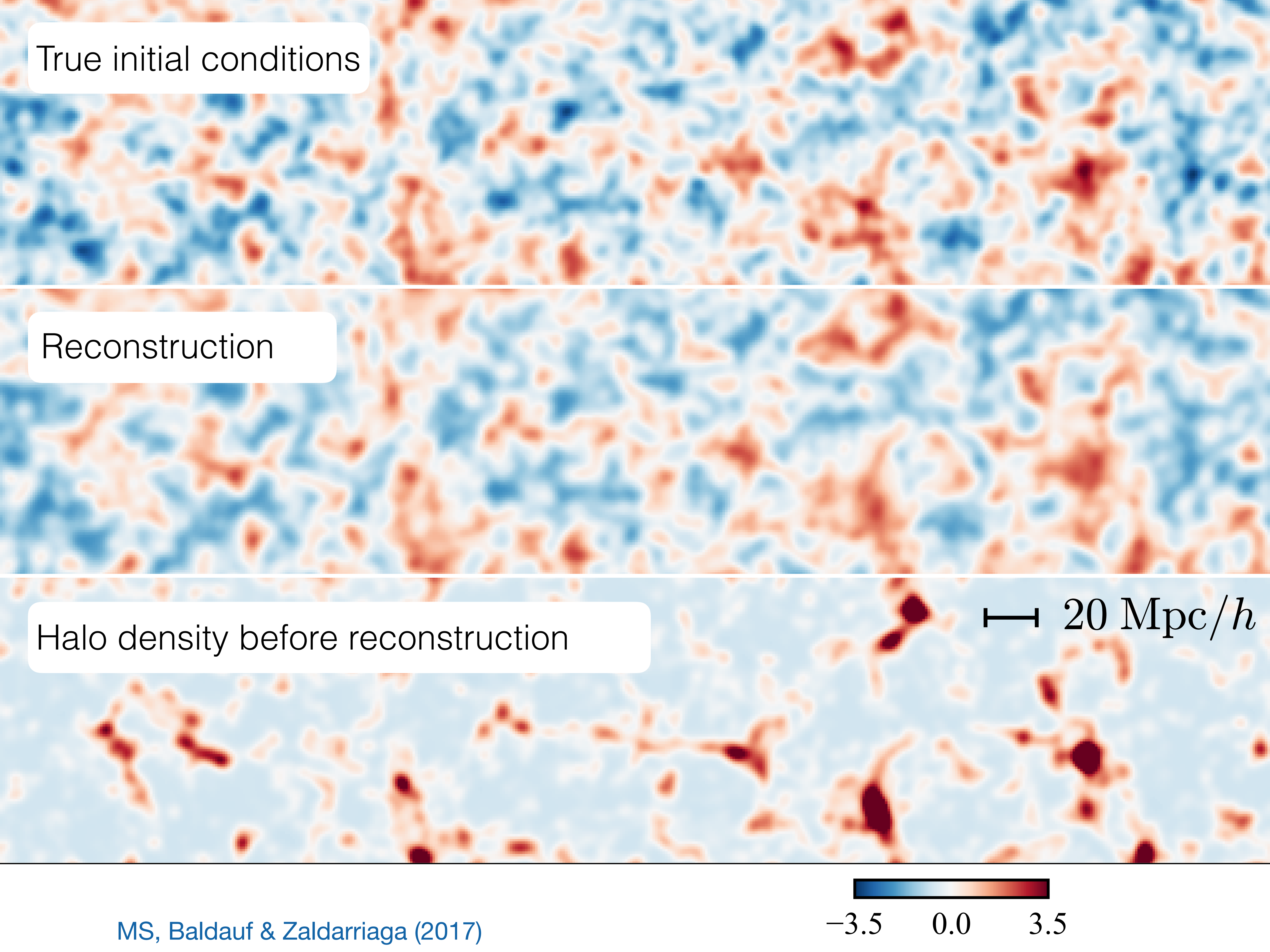
Machine learning

Li, Ho, Villaescusa-Navarro, …

Theory

work by Eisenstein, Padmanabhan, White etc, later e.g. MS+ (2015), Cohn+ (2016), Hikage+ (2017), Wang+ (2018), Sherwin+ (2018)


True initial conditions
Reconstruction
Halo density before reconstruction
20 Mpc/h
−3.5
0.0
3.5
MS, Baldauf & Zaldarriaga (2017)


True initial conditions
Reconstruction
Halo density before reconstruction
20 Mpc/h
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0.0
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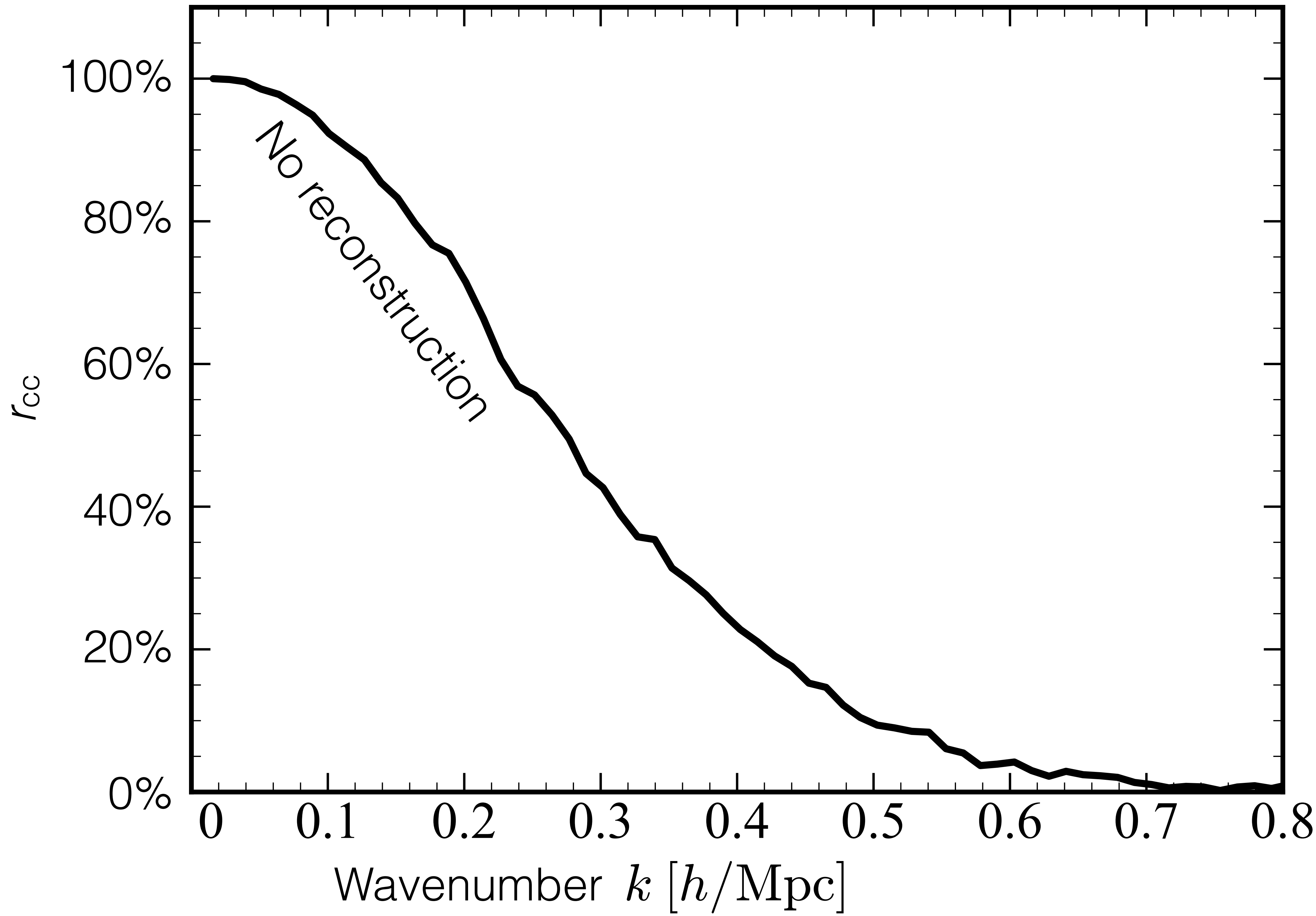
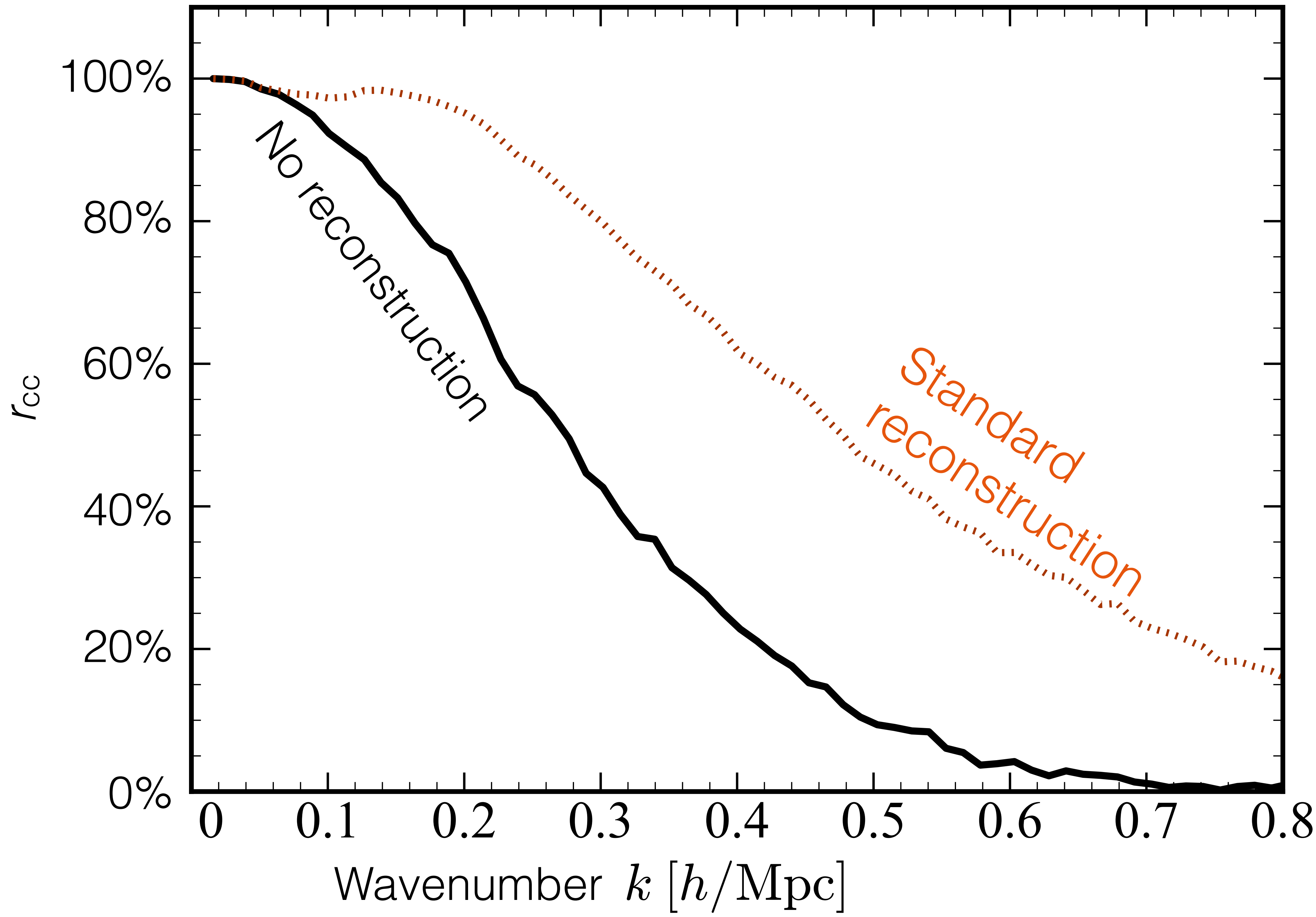
MS, Baldauf & Zaldarriaga (2017)

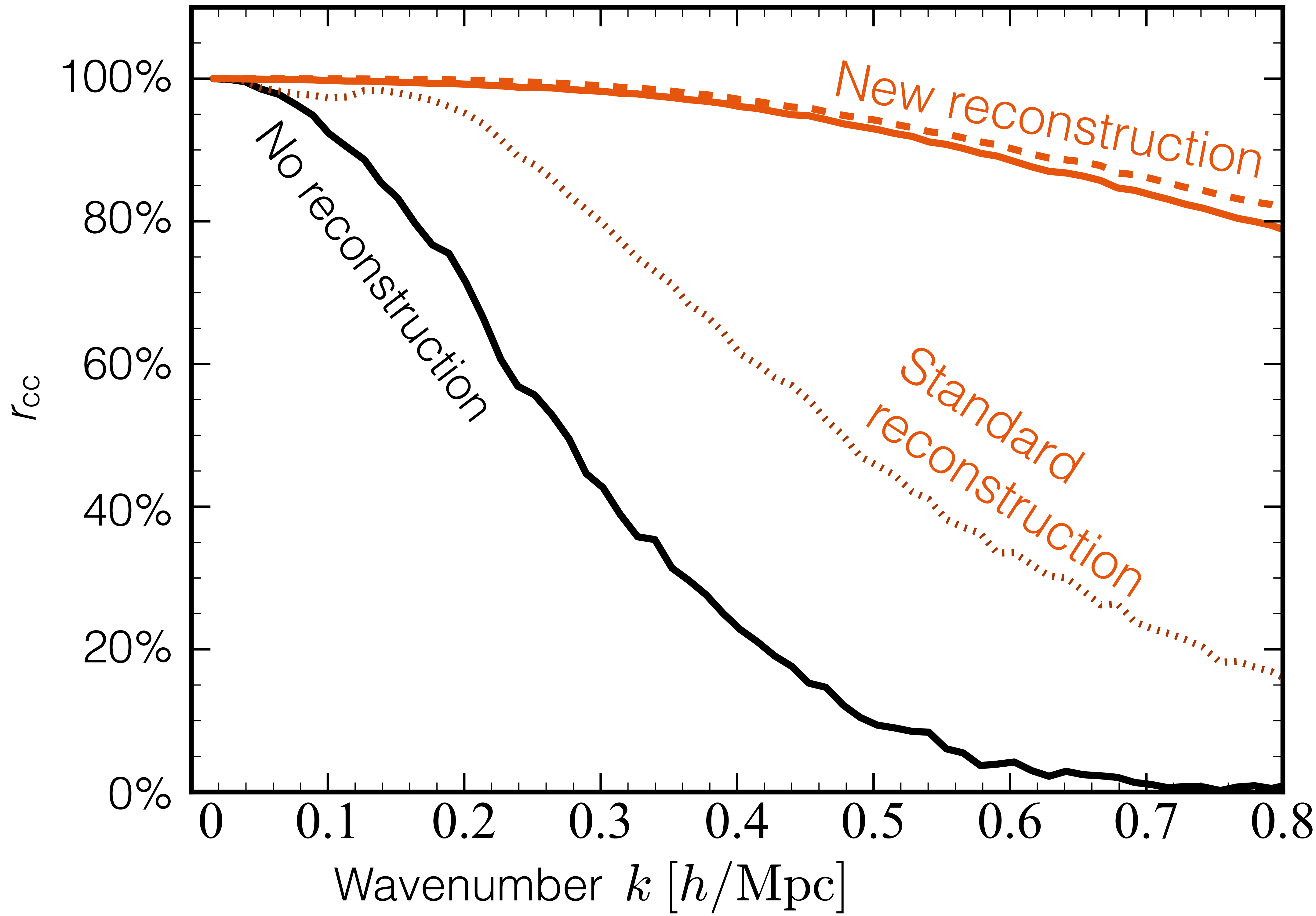
Correlation with true initial conditions



Correlation with true initial conditions



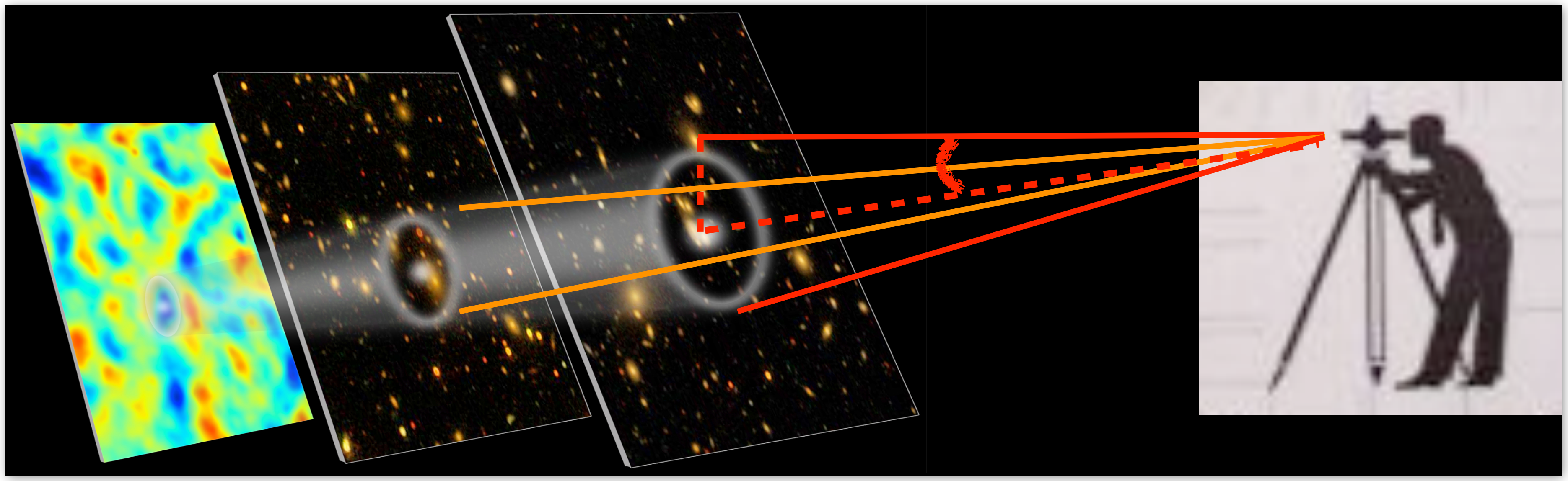
Correlation with true initial conditions



MS, Baldauf & Zaldarriaga (2017), similar to Zhu, Yu+ (2017); noise-free DM

Reconstruction of the linear BAO scale

For SDSS/BOSS, standard reconstruction gave ~2x tighter measurement of BAO scale and Hubble parameter (= 4x volume)



For DESI, more optimal BAO reconstruction gives

(a) 30-40% tighter Hubble parameter than standard rec. (= 2x volume)

(b) 70-120% tighter constraints on primordial features from some inflation models

(c) Unbiased and tighter constraints on compensated isocurvature perturbations

(a), (b) Preliminary forecasts by M. Ivanov, B. Wallisch, (c) Heinrich & Schmittfull (2019)
Large additional gains possible if we can also get broadband linear power spectrum.

Reconstruct by inverting forward model

Use gradient descent to maximize posterior distribution of initial conditions given observed galaxy density

From simulation or bias model

$$P(\delta_{\rm IC}|\delta_g) = \frac{\mathcal{L}(\delta_g|\delta_{\rm IC})P(\delta_{\rm IC})}{P(\delta_g)}$$

Normal distribution
(Gaussian ICs)

Optimization in 1M+ dimensions

Gradients:

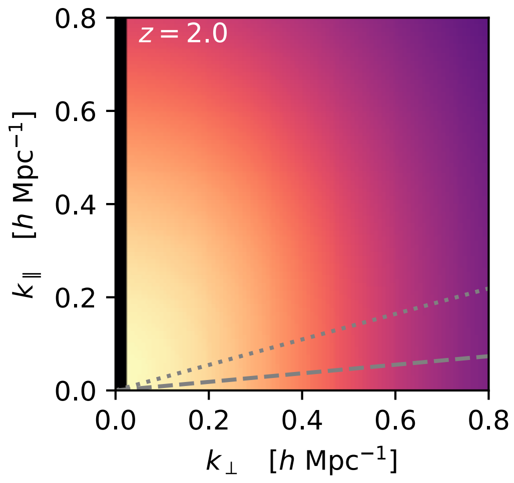
- Automatic differentiation of simulation code
- or analytical derivative of bias model (simpler)

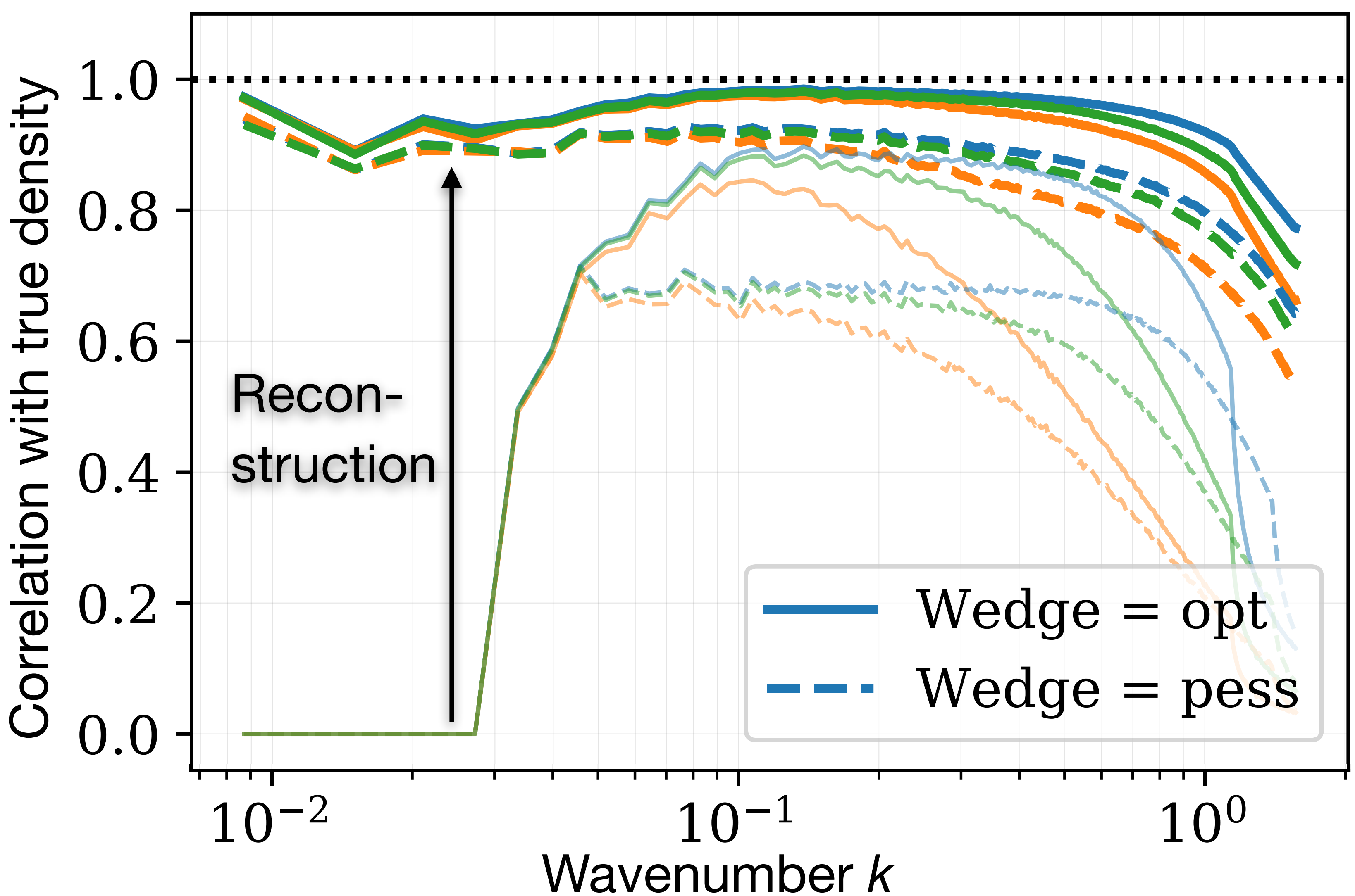
Seljak, Aslanyan *et al.* (2017)
Schmidt, Elsner *et al.* (2019)
Modi, White et al. (arXiv:1907.02330)

Recovering modes from the 21cm wedge

Foregrounds destroy long modes: ‘21cm wedge’

Reconstruction inverting bias model with shifted operators recovers these modes



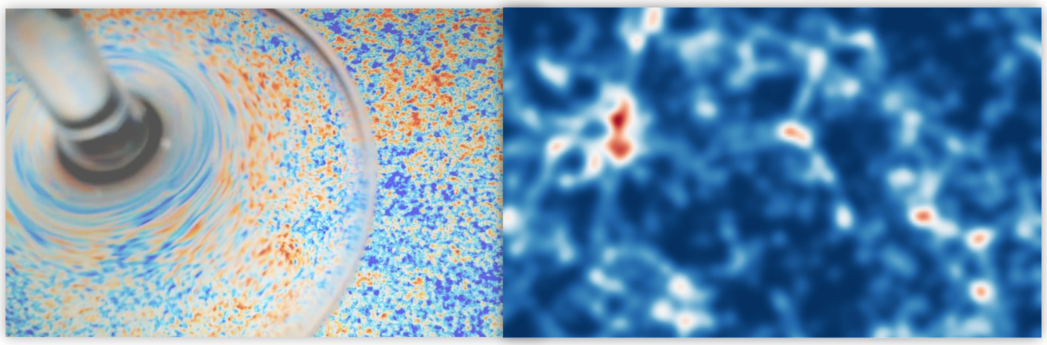


Modi, White et al. (arXiv:1907.02330)

Conclusion

Anticipate large influx of high-quality data over the next decade

Many synergies between datasets

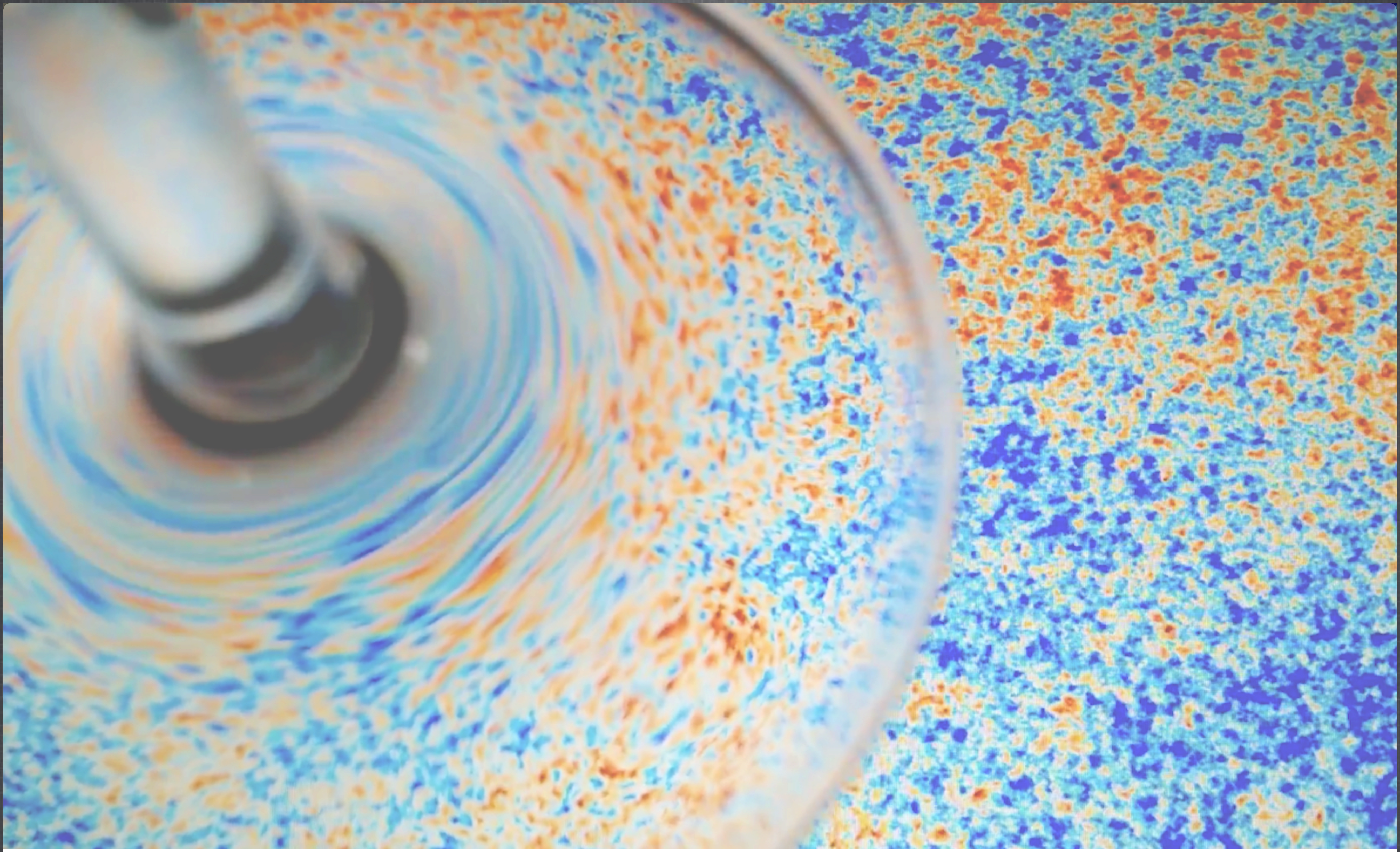


CMB lensing and galaxy clustering can

- Rule out single field inflation
- Measure deviation from cosmological constant / standard growth at 1% level
- Provide independent and competitive measurement of neutrino mass

To exhaust scientific potential of the data, we must

- Develop adequate theoretical models
- Taylor our analysis methods to the datasets and make them optimal
- Test both very carefully with simulations



Thank you

Backup slides