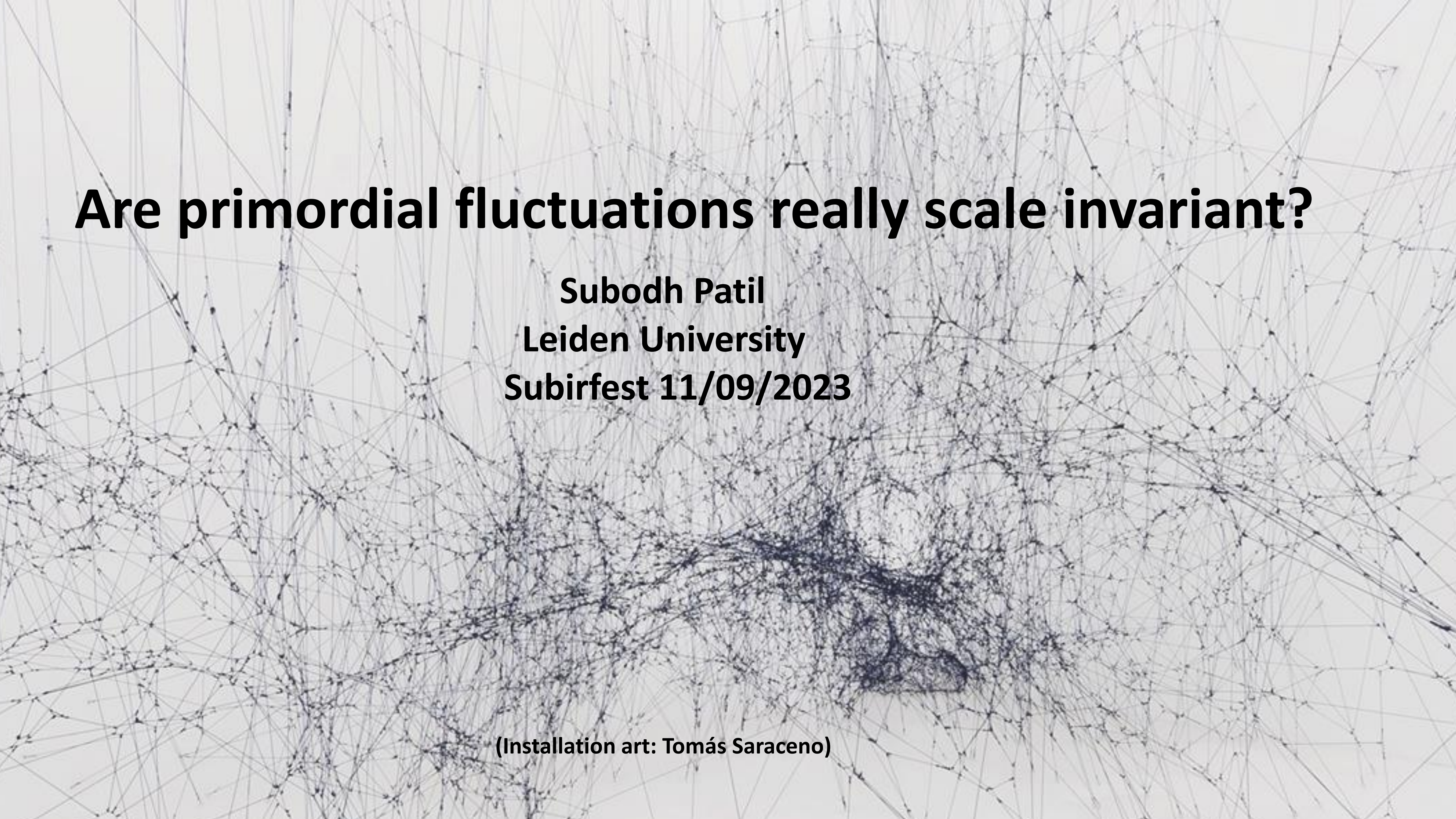

Are primordial fluctuations really scale invariant?

Subodh Patil
Leiden University
Subirfest 11/09/2023

(Installation art: Tomás Saraceno)

“We live in an era of precision cosmology”

Planck Collaboration Cosmological parameters

Description	Symbol	Value
Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
Age of the universe	t_0	13.799 ±0.021 × 10^9 years
Scalar spectral index	n_s	0.9667 ±0.0040
Curvature fluctuation amplitude, k_0 = 0.002 Mpc^{-1}	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$
Reionization optical depth	τ	0.066 ±0.012

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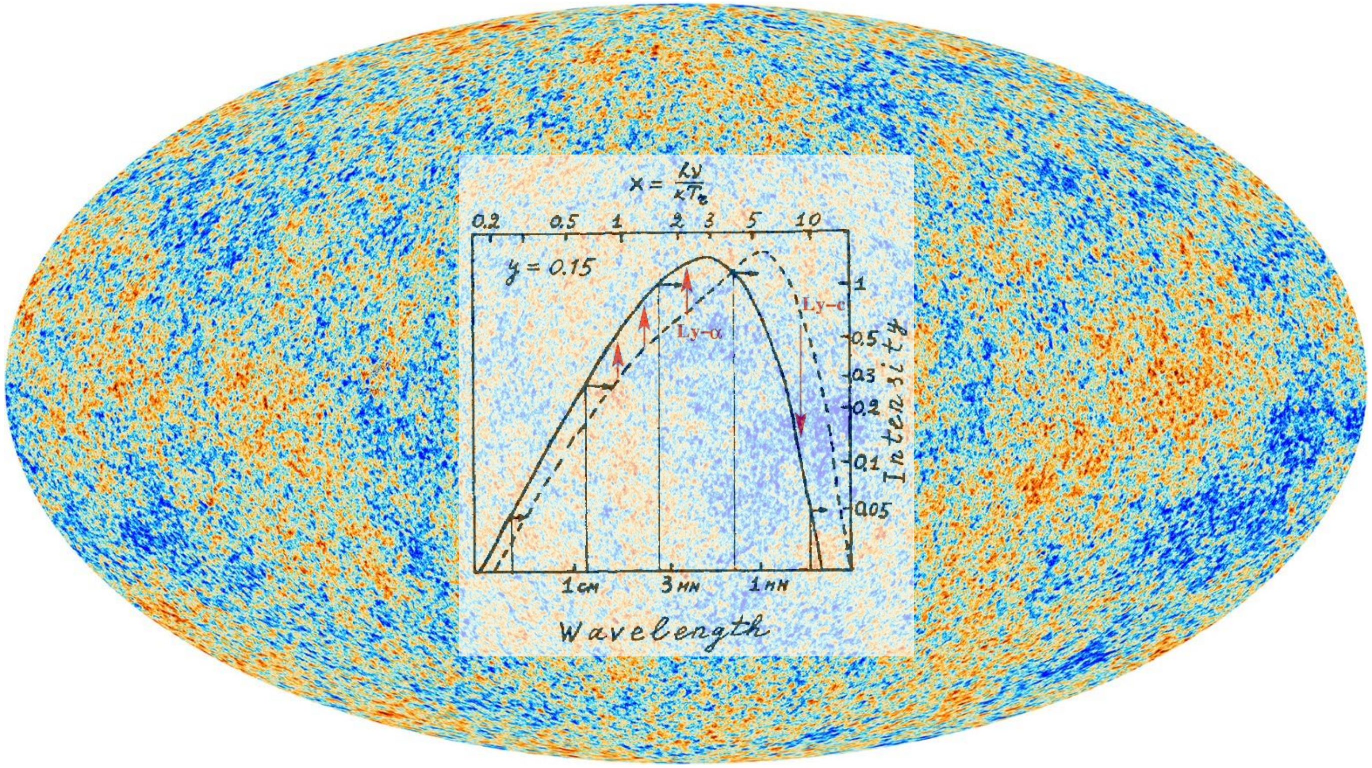
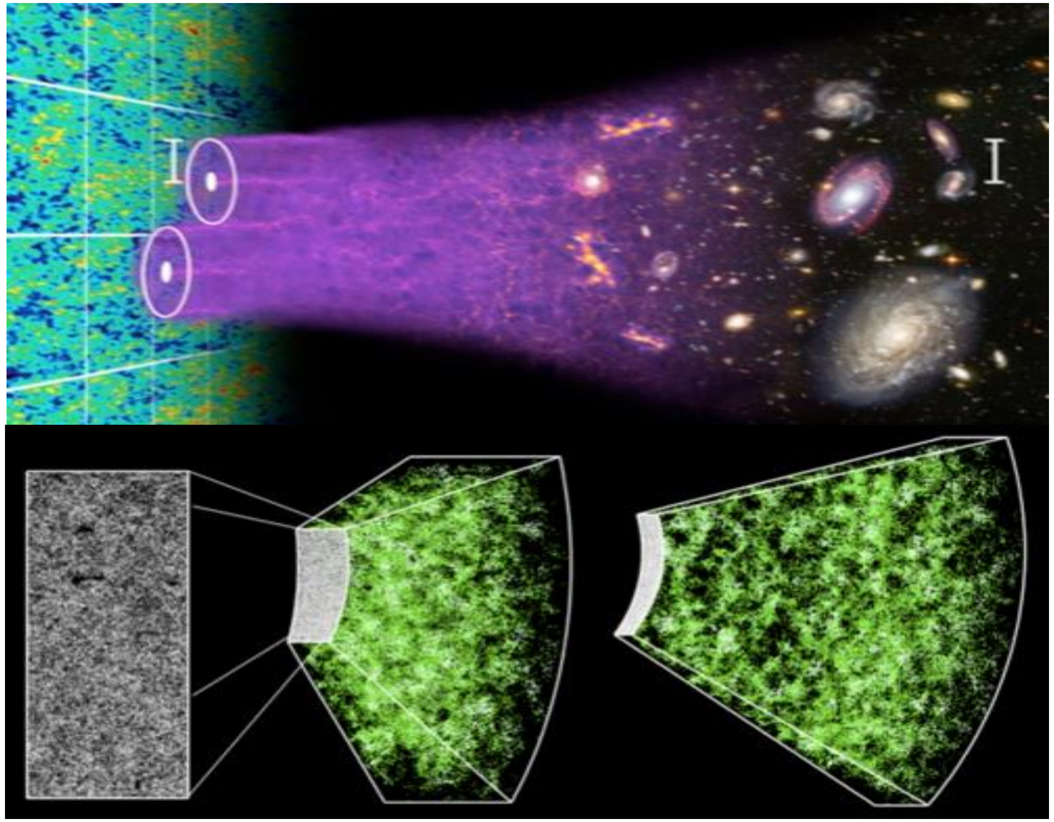
***with sufficiently restrictive priors…**

How does/ could one probe primordial fluctuations?



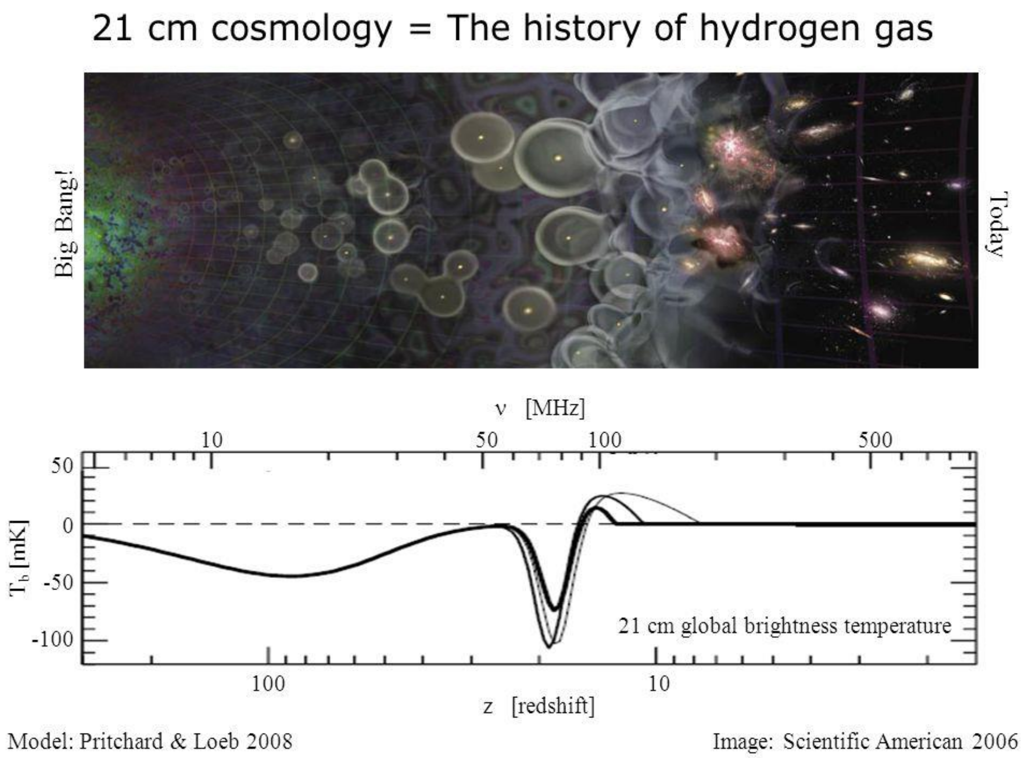
CMB anisotropies and spectral distortions…

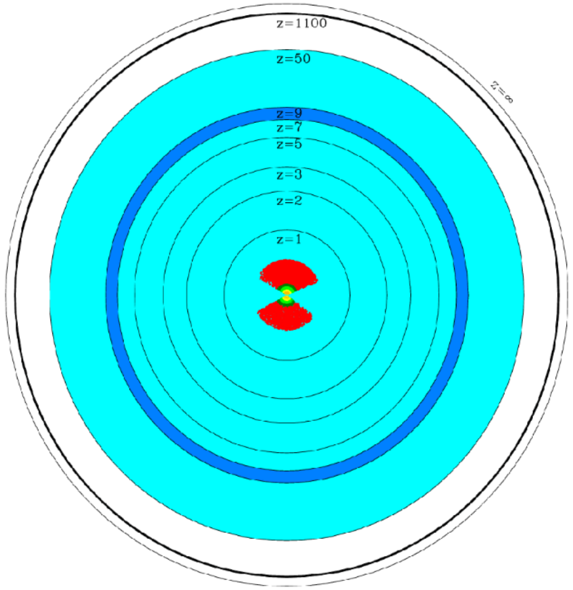
How does/ could one probe primordial fluctuations?



Large scale structure surveys (photometric and spectroscopic)…

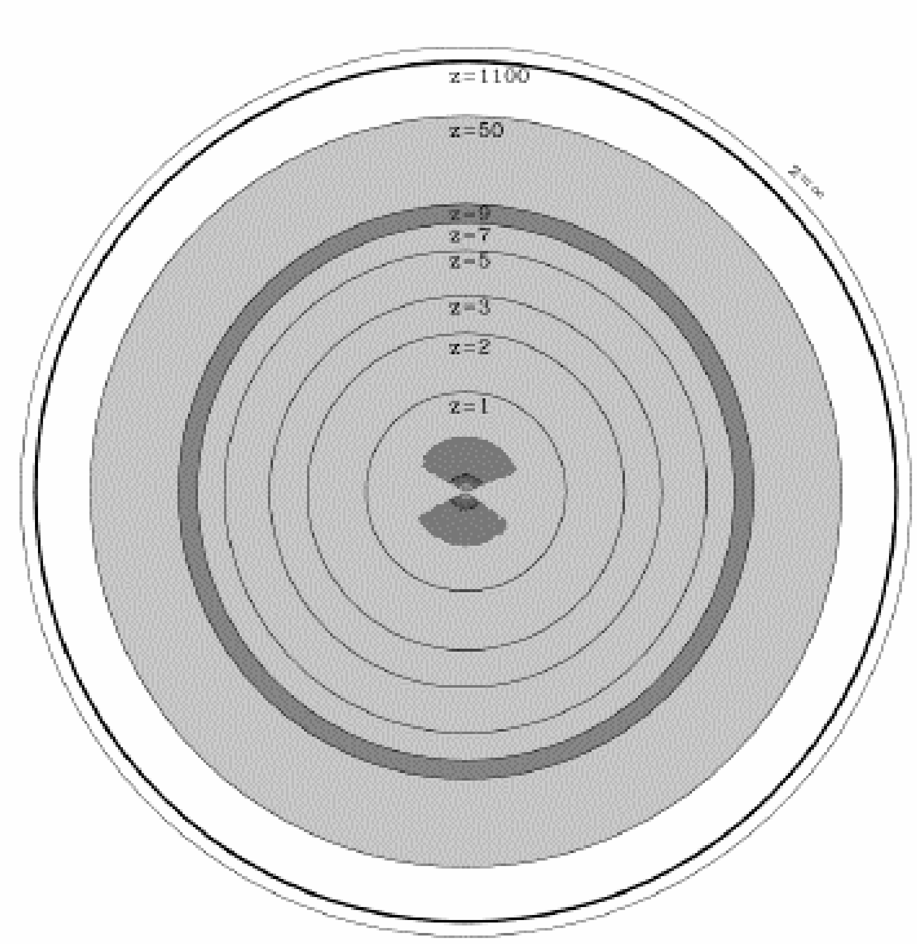
How does/ could one probe primordial fluctuations?

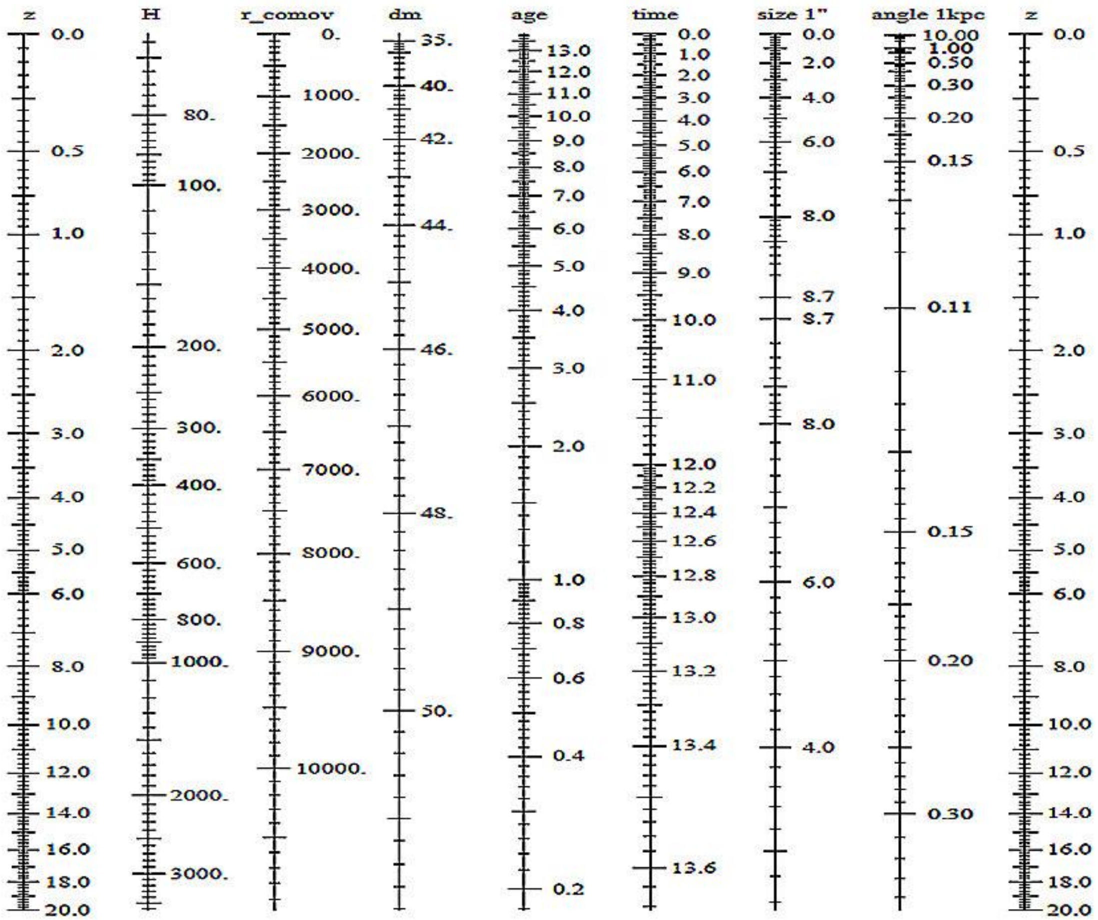




21 cm tomography (foreground modelling notwithstanding)…

How does/ could one probe primordial fluctuations?





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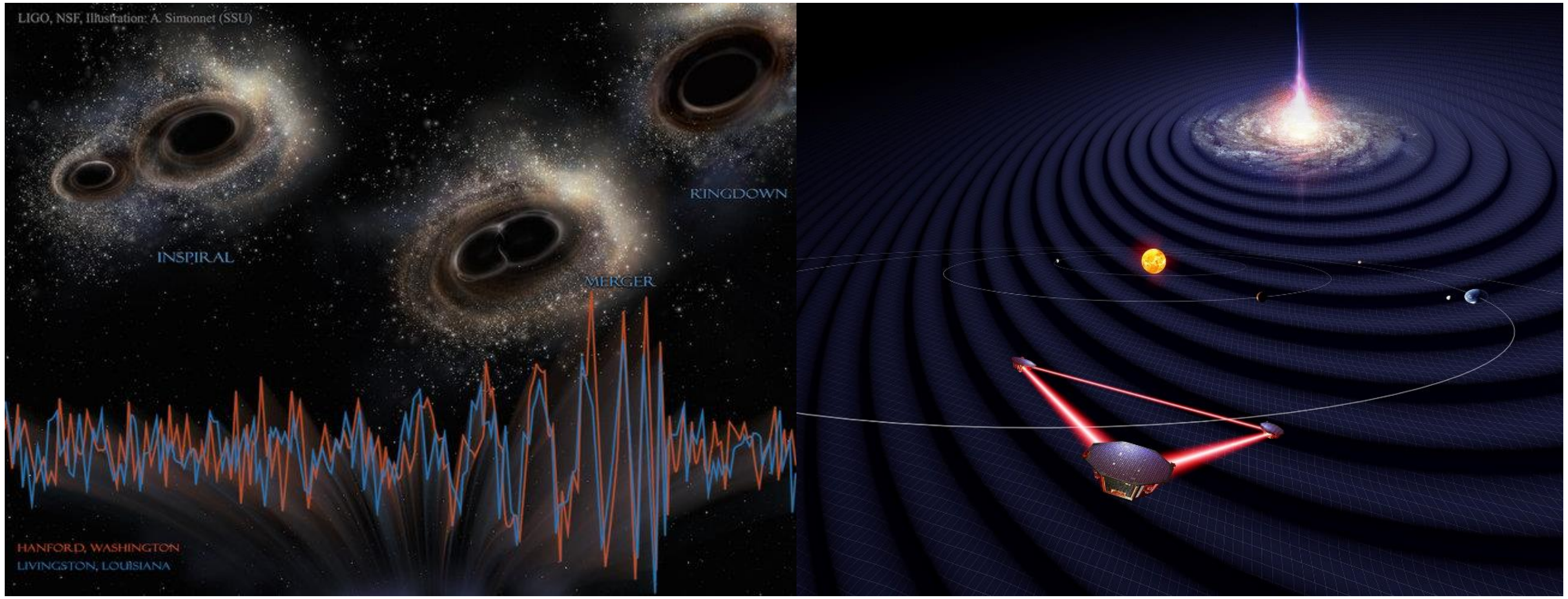
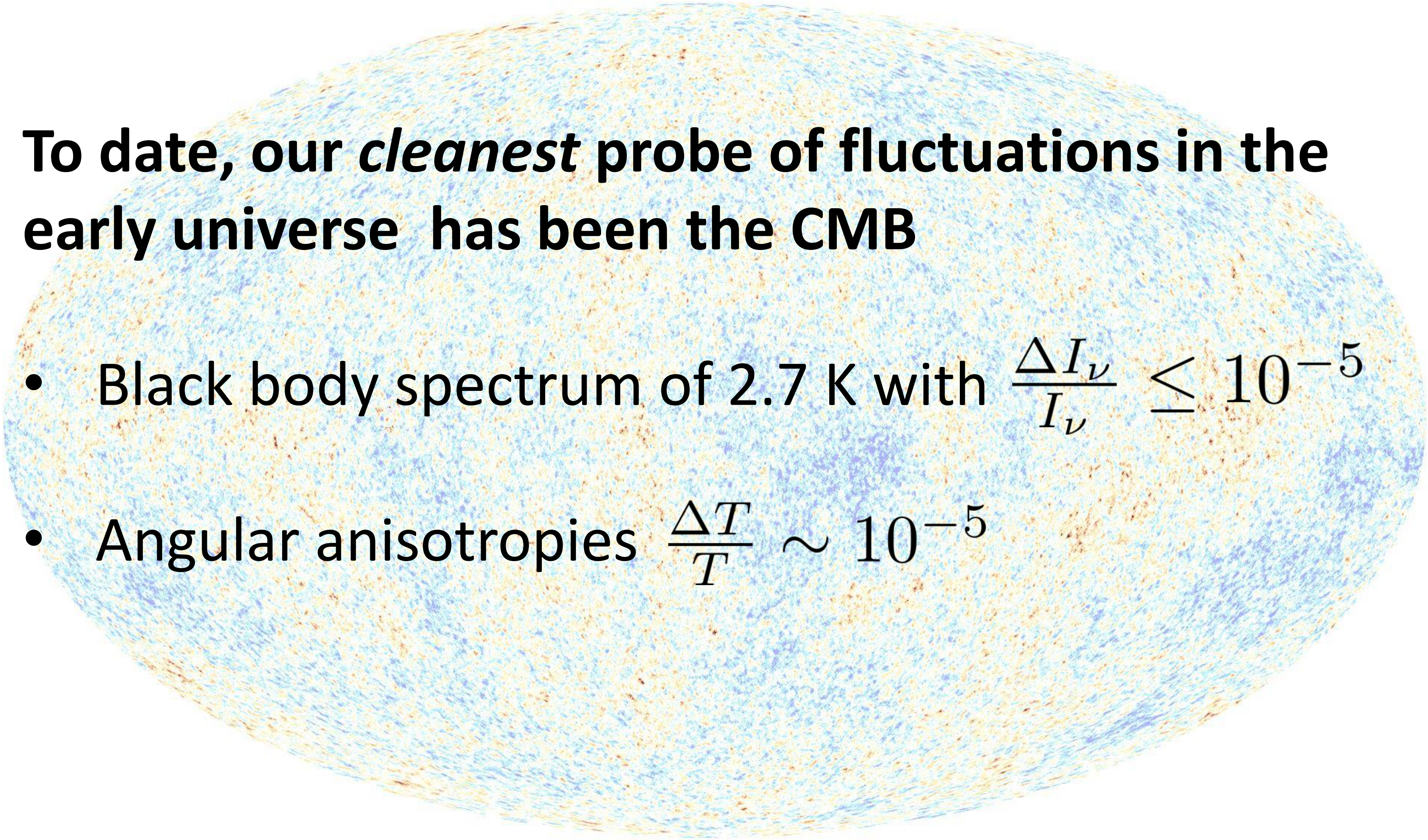


Gravitational waves (astrophysical and cosmological)

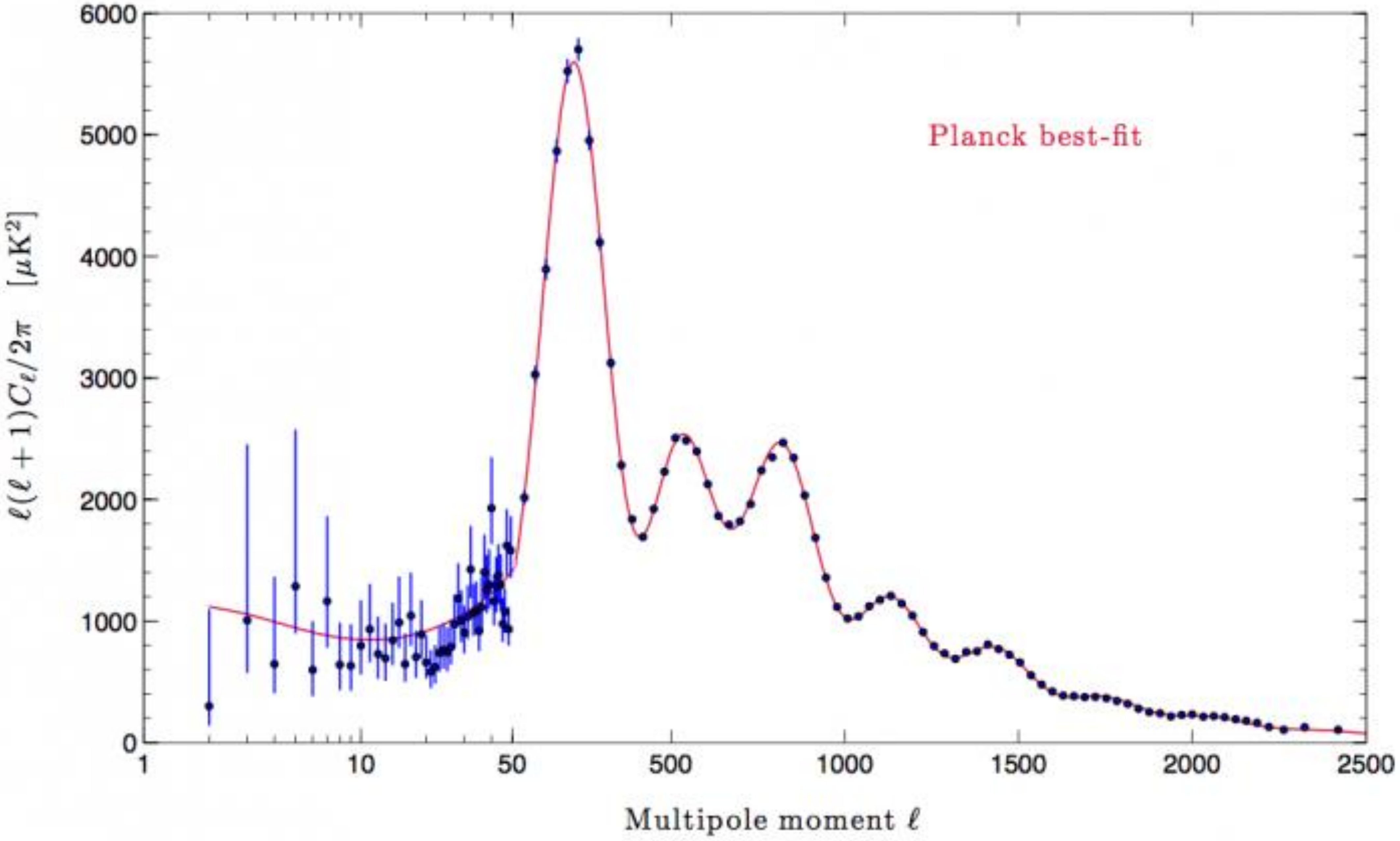


To date, our *cleanest* probe of fluctuations in the early universe has been the CMB

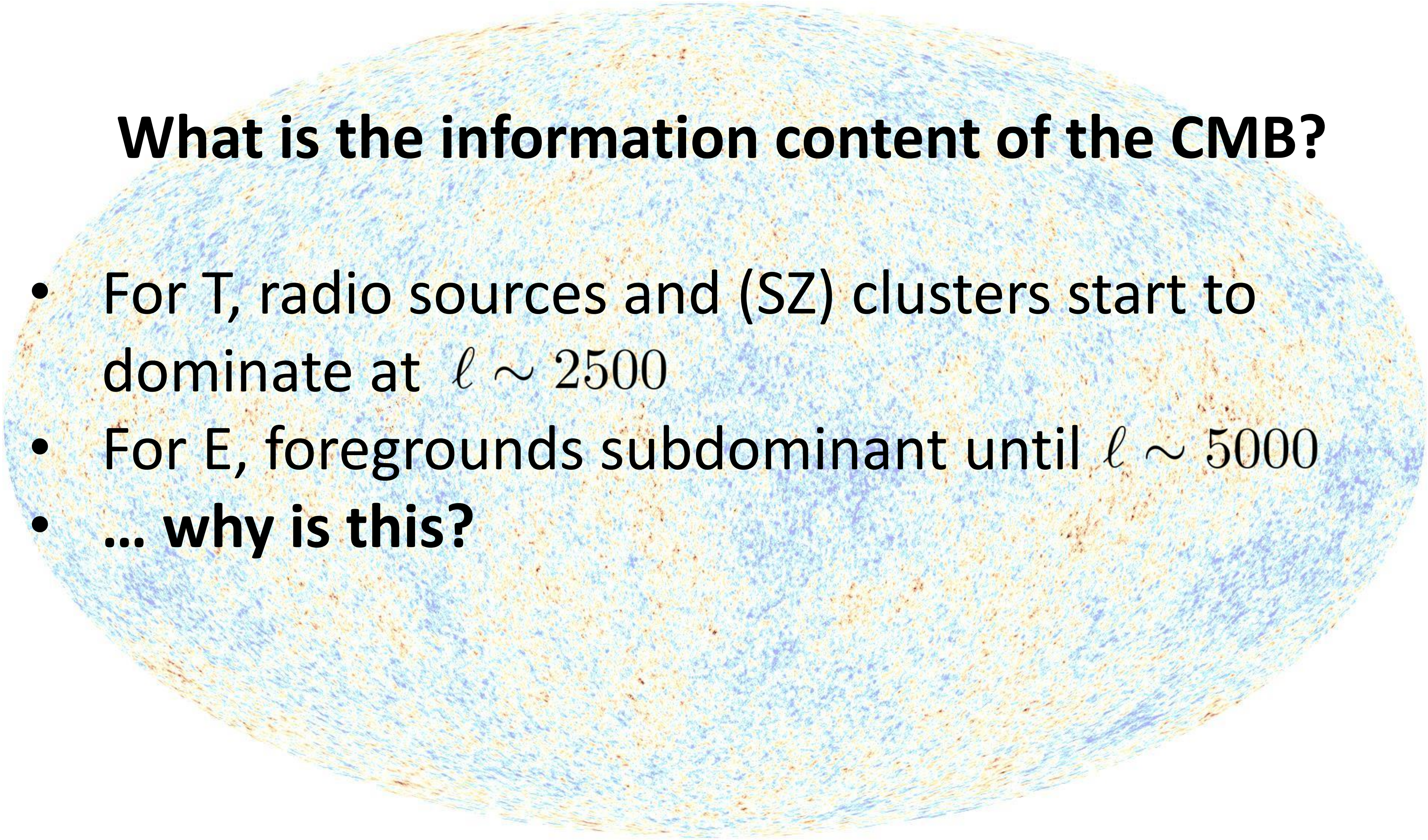
- Black body spectrum of 2.7 K with $\frac{\Delta I_\nu}{I_\nu} \leq 10^{-5}$
- Angular anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$

What is the information content of the CMB?

- Temperature (T) and polarization (E,B) in each direction…
- Spectrum of incident photons in a given direction (new information only w/ deviations from blackbody).



Planck best-fit
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
Multipole moment ℓ
6000
5000
4000
3000
2000
1000
0
1
10
50
500
1000
1500
2000
2500



What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- **… why is this?**

Dissipation of scalar modes

Longitudinal perturbations in photon fluid dissipate due to free streaming and scattering (cf. the angular power spectrum if Silk damping didn't occur)

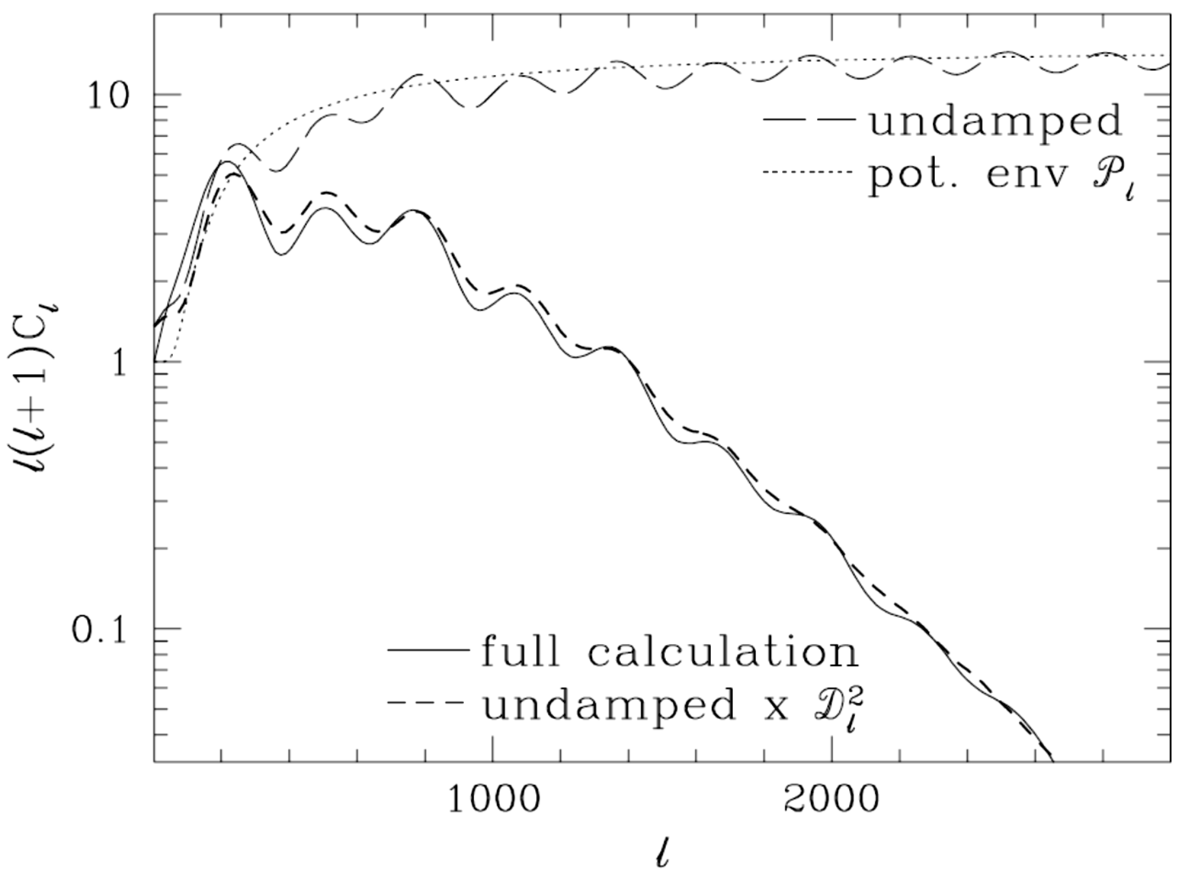
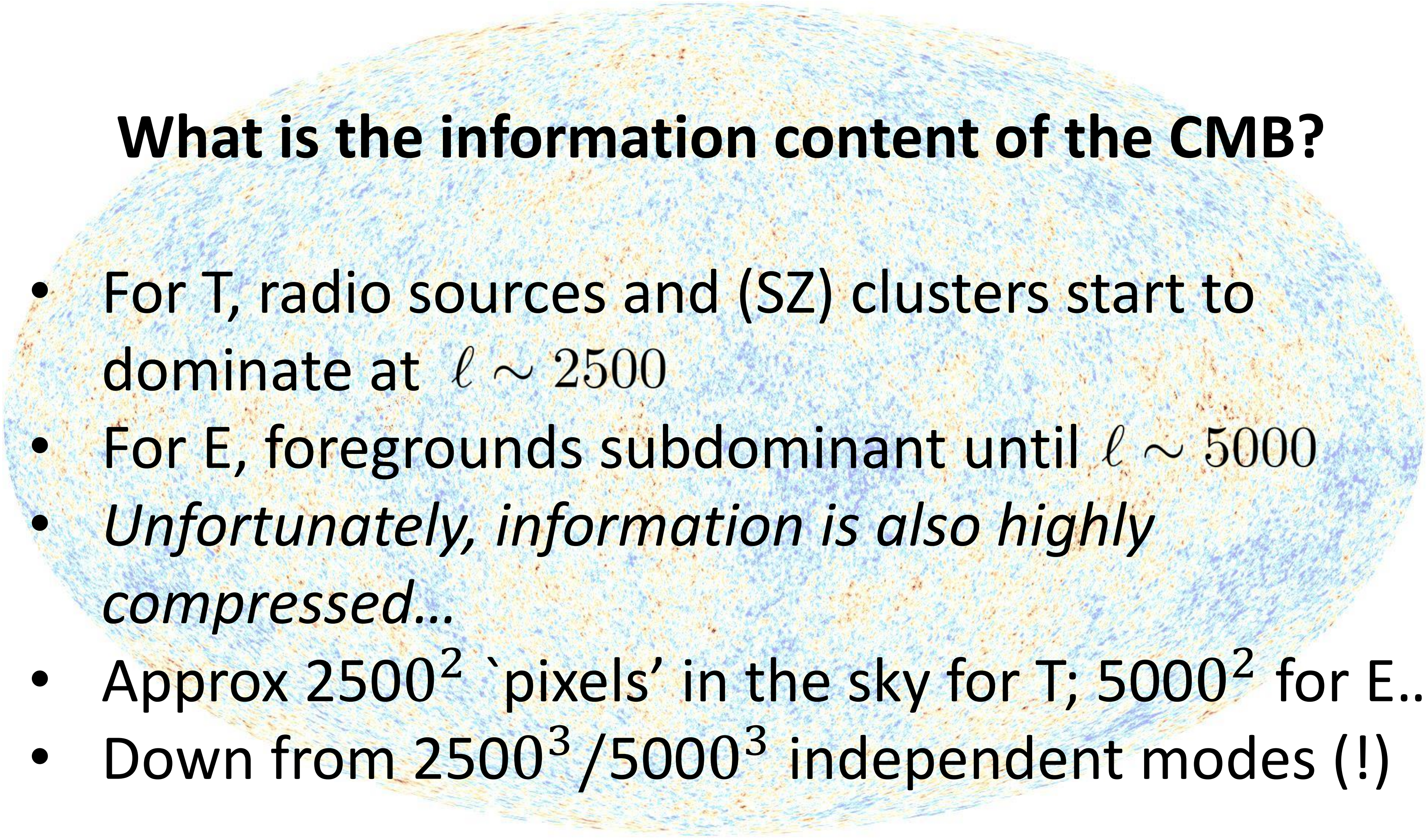


Fig. courtesy W. Hu and M. White (1996, hence the odd appearance of the acoustic peaks… no dark energy assumed!)

What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- Damping tail to be measured more precisely (SPTPol, ACTPol, CMB S4…)
- Forecast $\sum_\nu m_\nu \sim 0.05 \text{ eV}$
- Cosmological measurement of a BSM parameter?

$$\mathcal{L} \supset \frac{H^\dagger H}{\Lambda} \bar{\psi}\psi; \quad \Lambda \sim 10^{16} \text{GeV}$$



What is the information content of the CMB?

- For T, radio sources and (SZ) clusters start to dominate at $\ell \sim 2500$
- For E, foregrounds subdominant until $\ell \sim 5000$
- *Unfortunately, information is also highly compressed…*
- Approx 2500^2 \`pixels' in the sky for T; 5000^2 for E…
- Down from $2500^3/5000^3$ independent modes (!)

What is the information content of the CMB?

- The spectrum itself remains the last unexplored dimension of the CMB!
- Contains a wealth of information not obtainable by other means…

$$\frac{\Delta T}{T}(\nu) \gtrsim 10^{-7} \rightarrow 10^{-9}$$

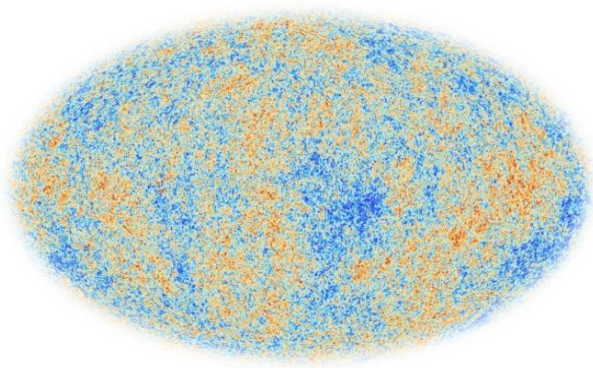
(Ask me about this over coffee or a drink!)

First need to understand how cosmological correlation functions relate to an underlying effective description.

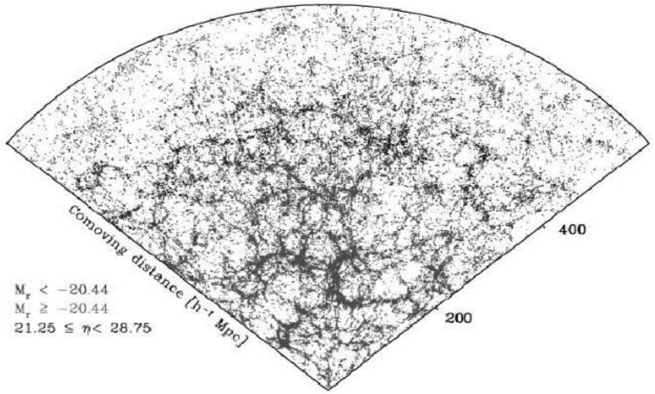
$$\langle \delta\phi(\vec{k}_1)\delta\phi(\vec{k}_2)\rangle \rightarrow \langle \mathcal{R}(\vec{k}_1)\mathcal{R}(\vec{k}_2)\rangle \rightarrow \langle \frac{\delta T}{T}(\vec{n}_1)\frac{\delta T}{T}(\vec{n}_2)\rangle \rightarrow \langle \frac{\delta\rho}{\rho}(\vec{k}_1)\frac{\delta\rho}{\rho}(\vec{k}_2)\rangle$$

$$\begin{aligned}\mathcal{L} = &-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\Psi}\not{D}\Psi + h.c. \\ &+ \Psi_i y_{ij}\Psi_j\Phi + h.c. \\ &+ |D_\mu\Phi|^2 - V(\Phi)\end{aligned}$$

⇨



⇨



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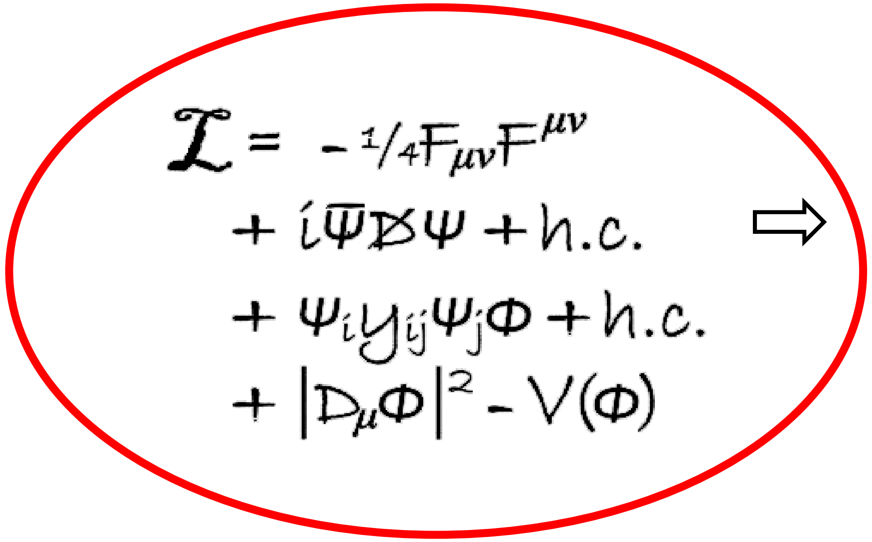
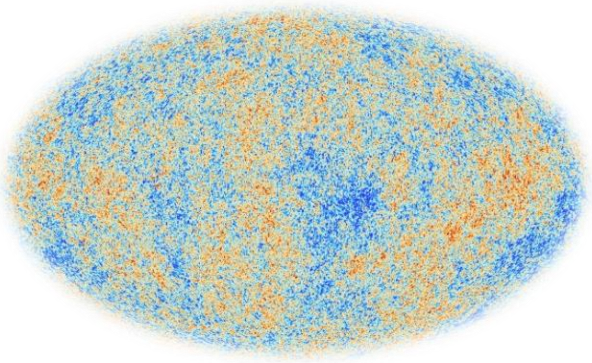
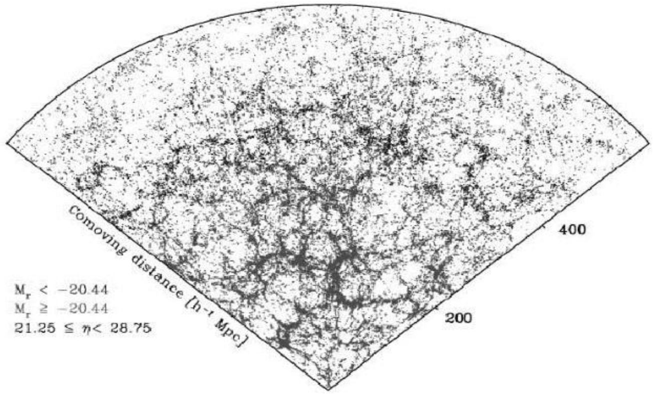


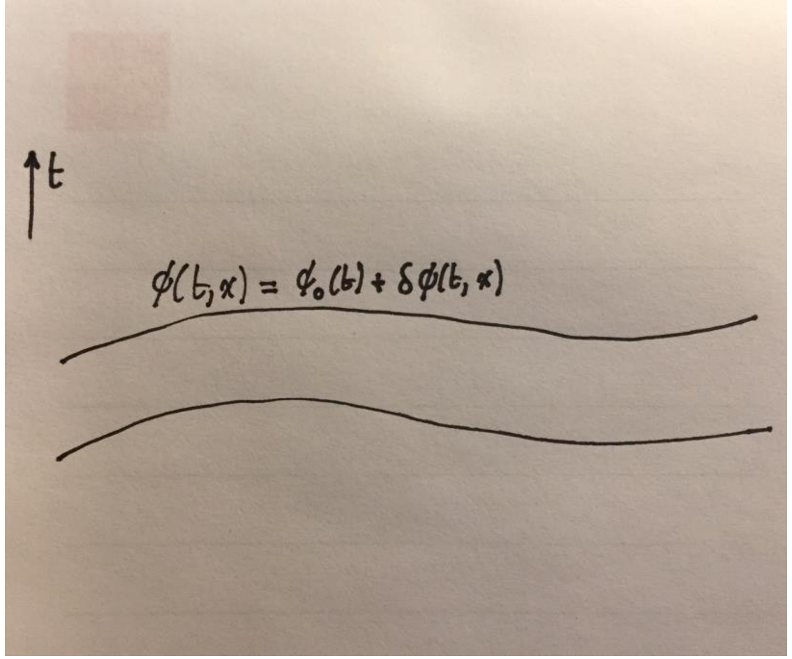




Quantum fluctuations in the very early universe (particle physics beyond the Standard Model!)

How do we relate this information to infer properties of an underlying effective theory?

$$\mathcal{L}_{\rm tot} = \frac{M_{\rm pl}^2}{2} R + \ldots + \mathcal{L}(\phi, \nabla\phi, \nabla^2\phi, \ldots)$$



$$\phi(x,t) = \phi_0(t) + \delta\phi(t,x)$$

$$t \;\rightarrow\; t + \pi$$

$$\phi_0 + \delta\phi(t,x) \rightarrow \phi_0 + \delta\phi(t,x) - \dot{\phi}_0\pi \equiv \phi_0(t)$$

$$\mathrm{d}s^2 = -N^2\mathrm{d}t^2 + h_{ij}(\mathrm{d}x^i + N^i\mathrm{d}t)(\mathrm{d}x^j + N^j\mathrm{d}t)$$

$$h_{ij} = a^2(t)e^{2\mathcal{R}}\delta_{ij}$$

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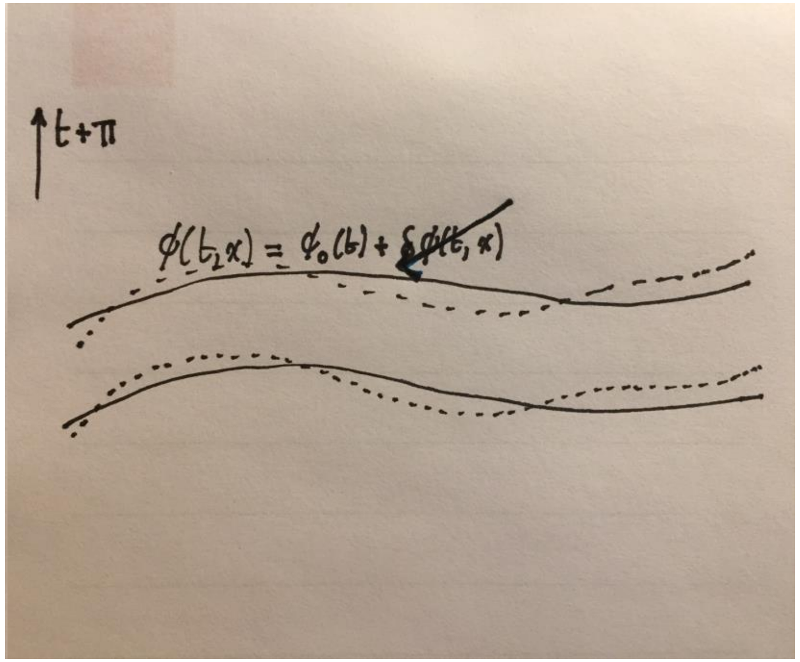

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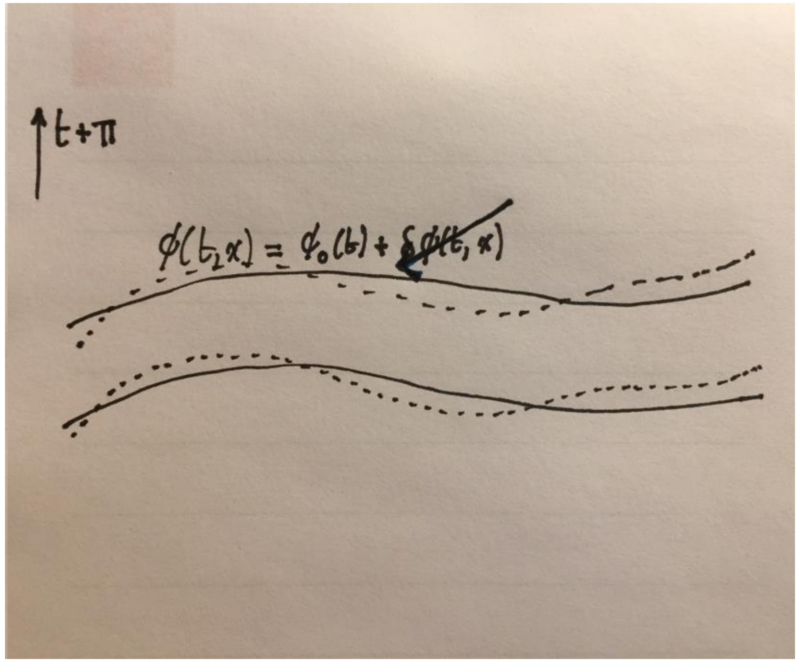
How do we relate this information to infer properties of an underlying effective theory?

Q) Where did the scalar perturbation go?



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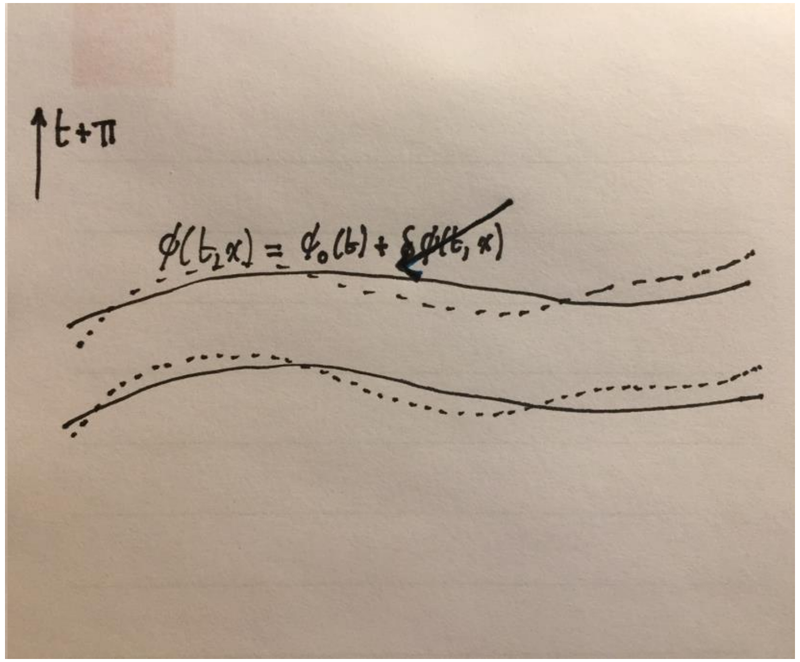
How do we relate this information to infer properties of an underlying effective theory?

A) It got `eaten' by the metric, which now propagates a longitudinal polarization…



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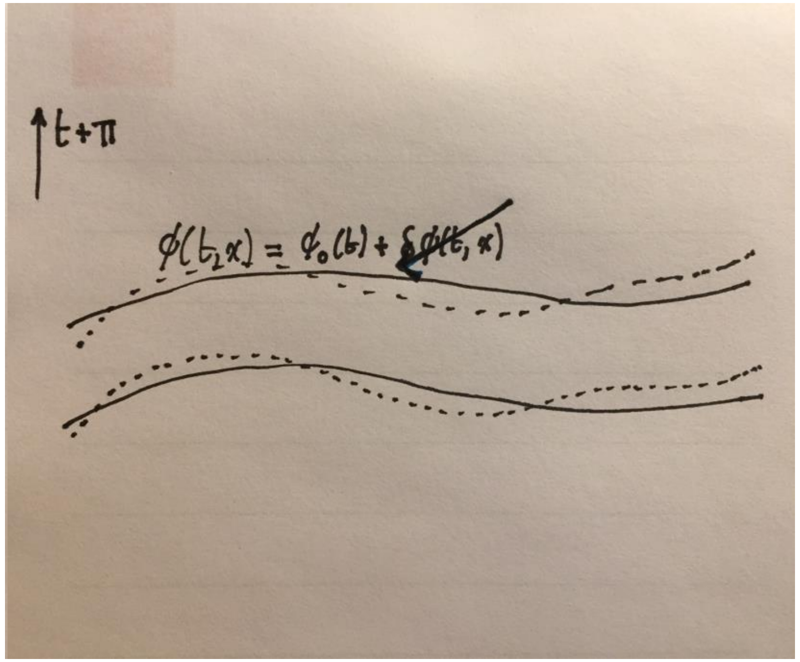
$$\mathrm{d}s^2 = -N^2 \mathrm{d}t^2 + h_{ij}(\mathrm{d}x^i + N^i \mathrm{d}t)(\mathrm{d}x^j + N^j \mathrm{d}t)$$

$$h_{ij} = a^2(t) e^{2\mathcal{R}} \delta_{ij}$$

Since $\mathcal{R}$ is a Goldstone, $\mathcal{R}$= const. will *always* be a solution for $k \ll 1$ to any order in perturbation theory since only derivative interactions. This is what imprints anisotropies on the CMB…



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$$h_{ij} = a^2(t)e^{2\mathcal{R}}\delta_{ij}$$

$$2\pi^2 \delta^3(\vec{k}_1 + \vec{k}_2)\mathcal{P}_{\mathcal{R}}(k_1) = k_1^3 \langle \mathcal{R}(\vec{k}_1)\mathcal{R}(\vec{k}_2)\rangle$$

$$|\Psi\rangle = |0\rangle$$

$$\frac{\Delta\widehat{T}}{\widehat{T}}(\vec{n}) = \sum_{\ell m} a^T_{\ell m} Y_{\ell m}(\vec{n})$$

$$\langle a^X_{\ell m} a^{Y*}_{\ell' m'}\rangle = C^{XY}_\ell \delta_{\ell\ell'}\delta_{mm'}$$

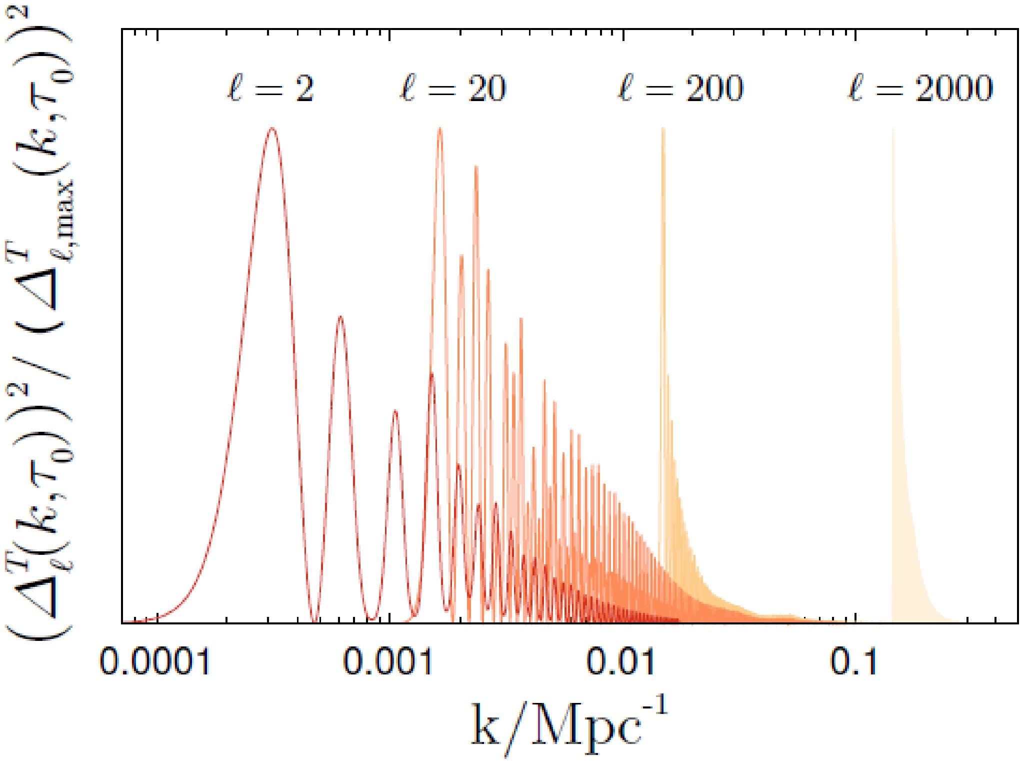
$$C^{XY}_\ell = \frac{1}{2\pi^2}\int \mathrm{d}\ln k \, \Delta^X_\ell(k,\tau_0)\Delta^Y_\ell(k,\tau_0)\mathcal{P}_{\mathcal{R}}(k)$$

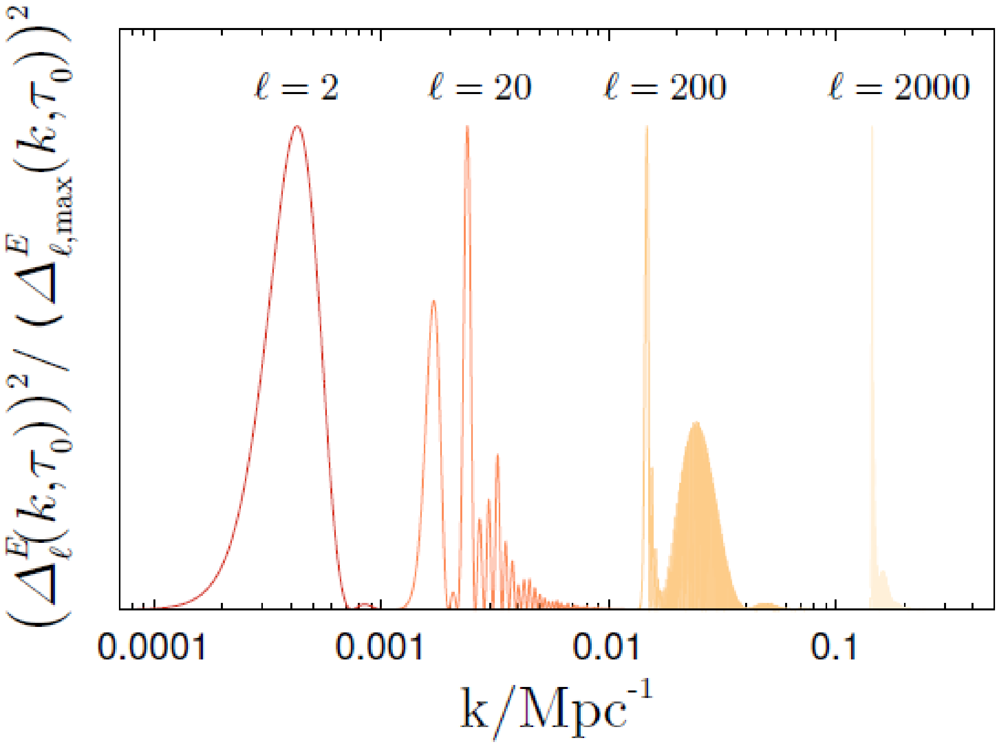
$$\Delta^X_\ell(k,\tau_0) = \int_{\tau_{\rm ini}}^{\tau_0} \mathrm{d}\tau \; S^X(k,\tau) j_\ell(k(\tau-\tau_0))$$

non-primordial cosmology

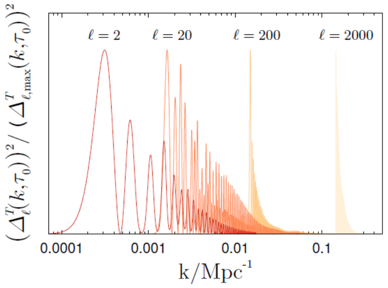
geometry

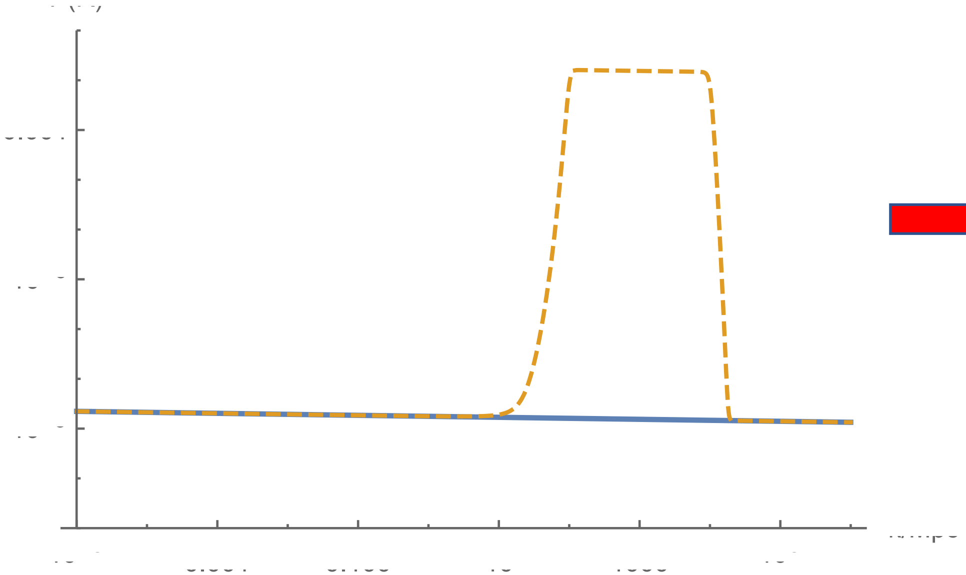
Temperature and Polarization transfer functions

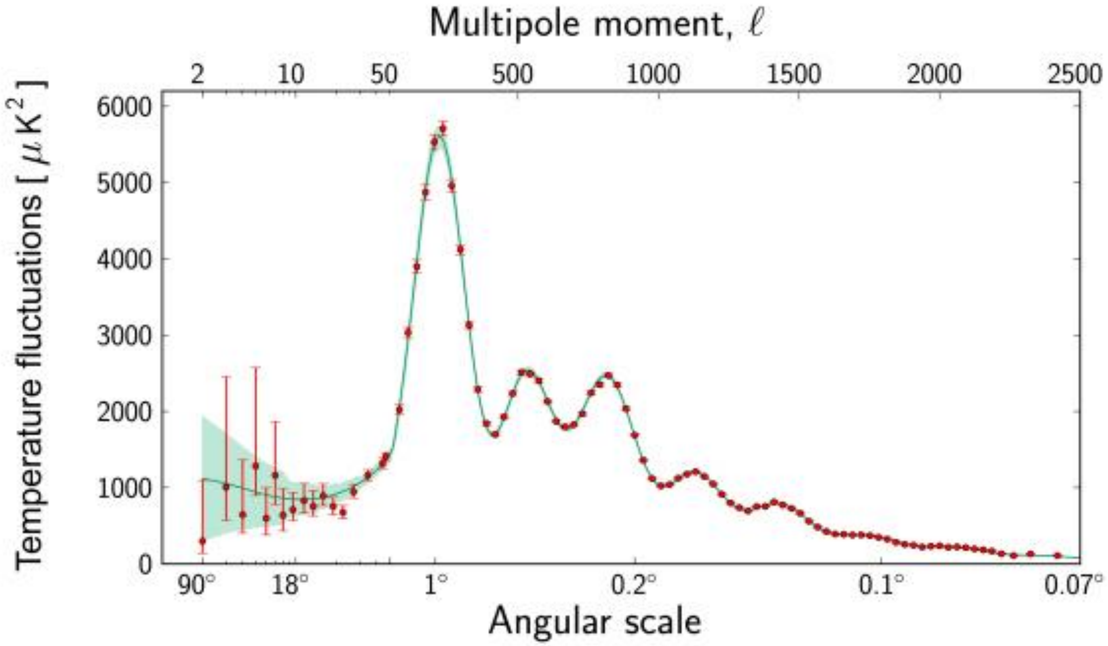




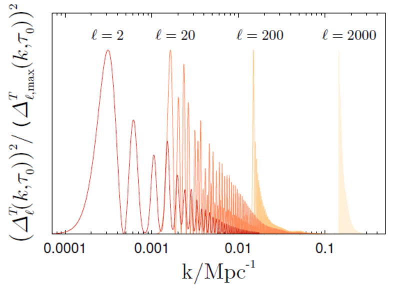
Could new physics and new characteristic scales be hiding in plain sight?

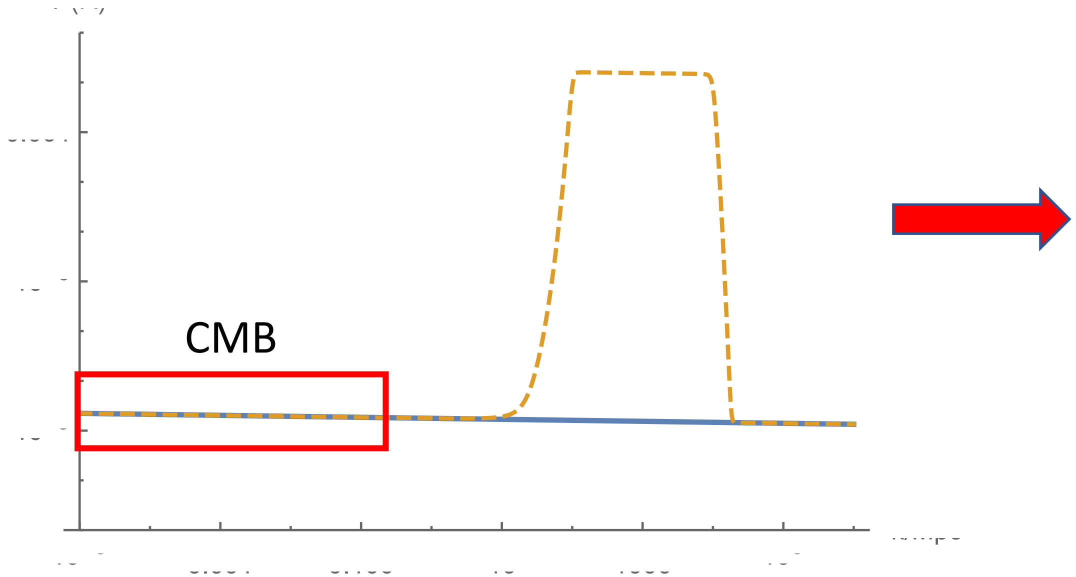


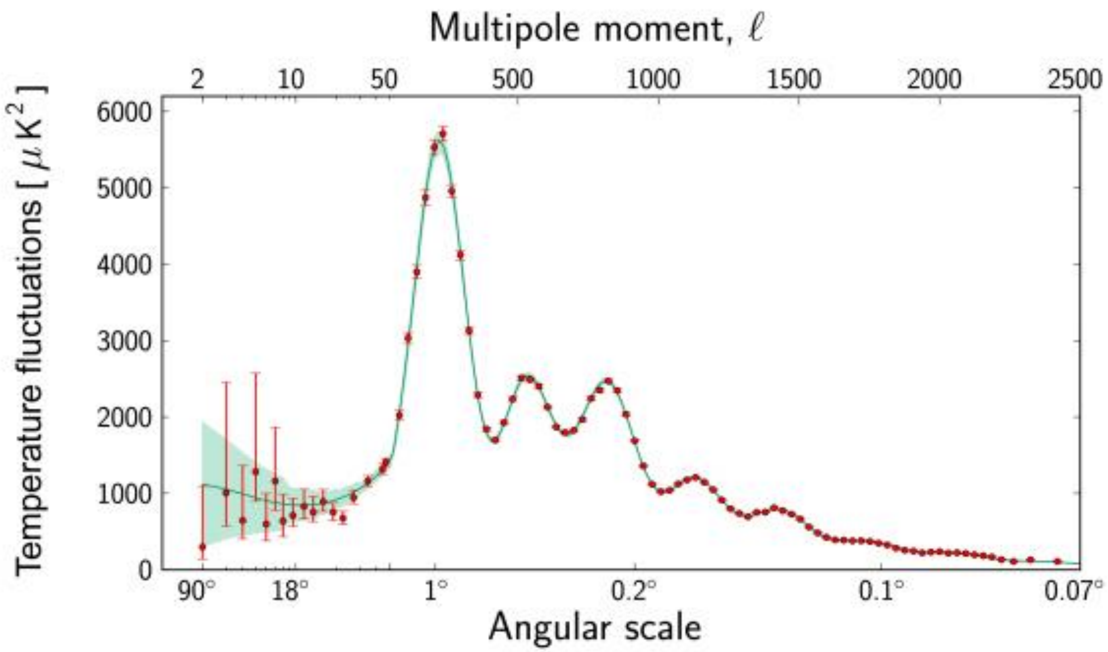




CMB transfer functions + intervening thermal expansion history `samples' underlying primordial 2-pt function







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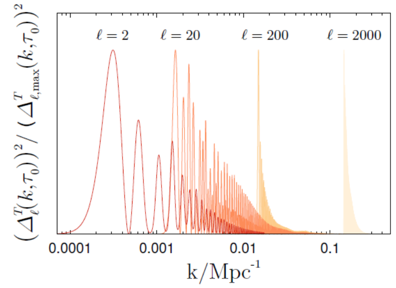
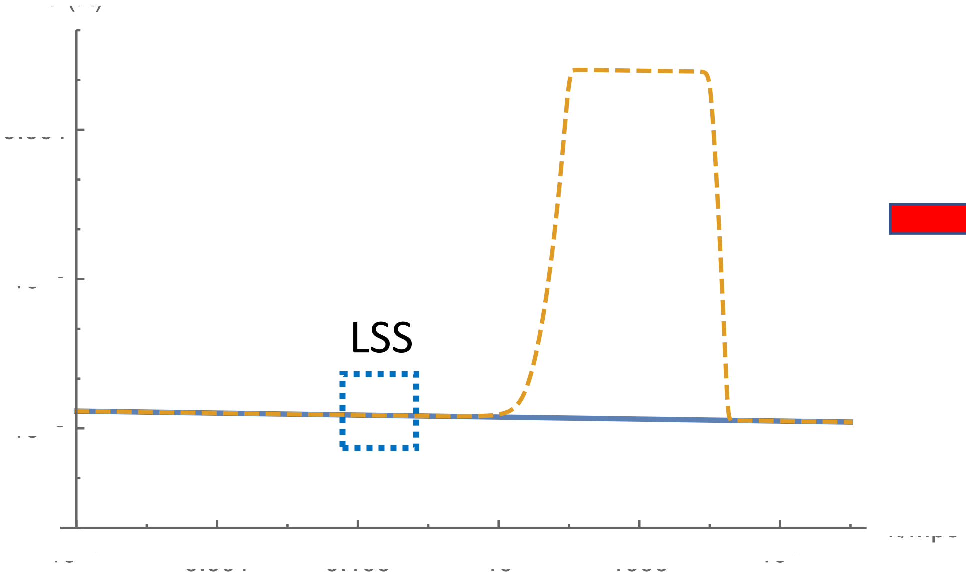
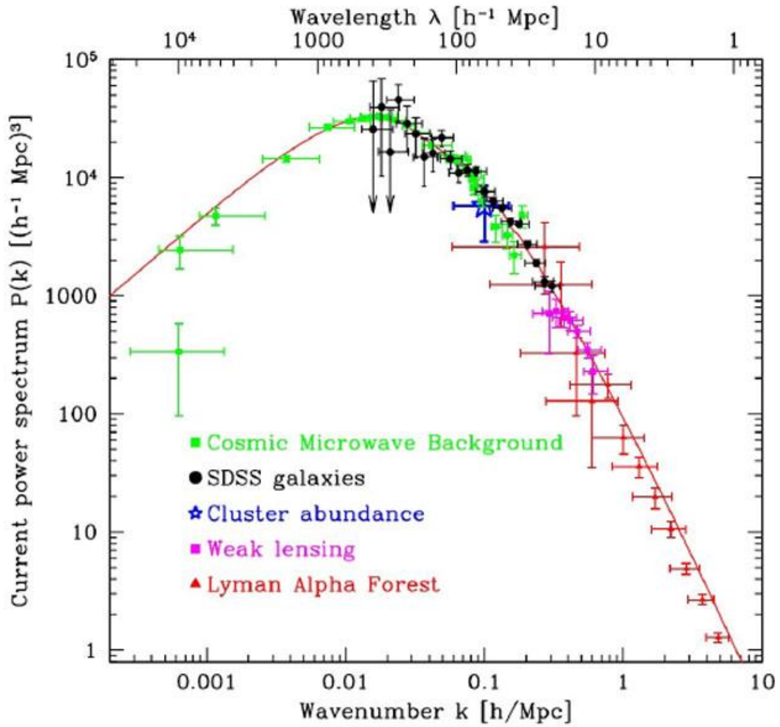
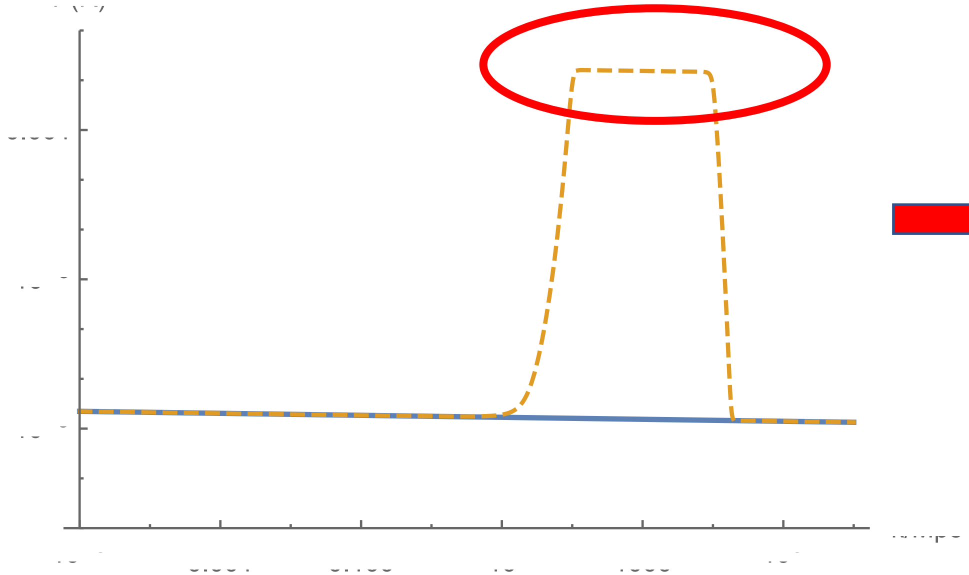


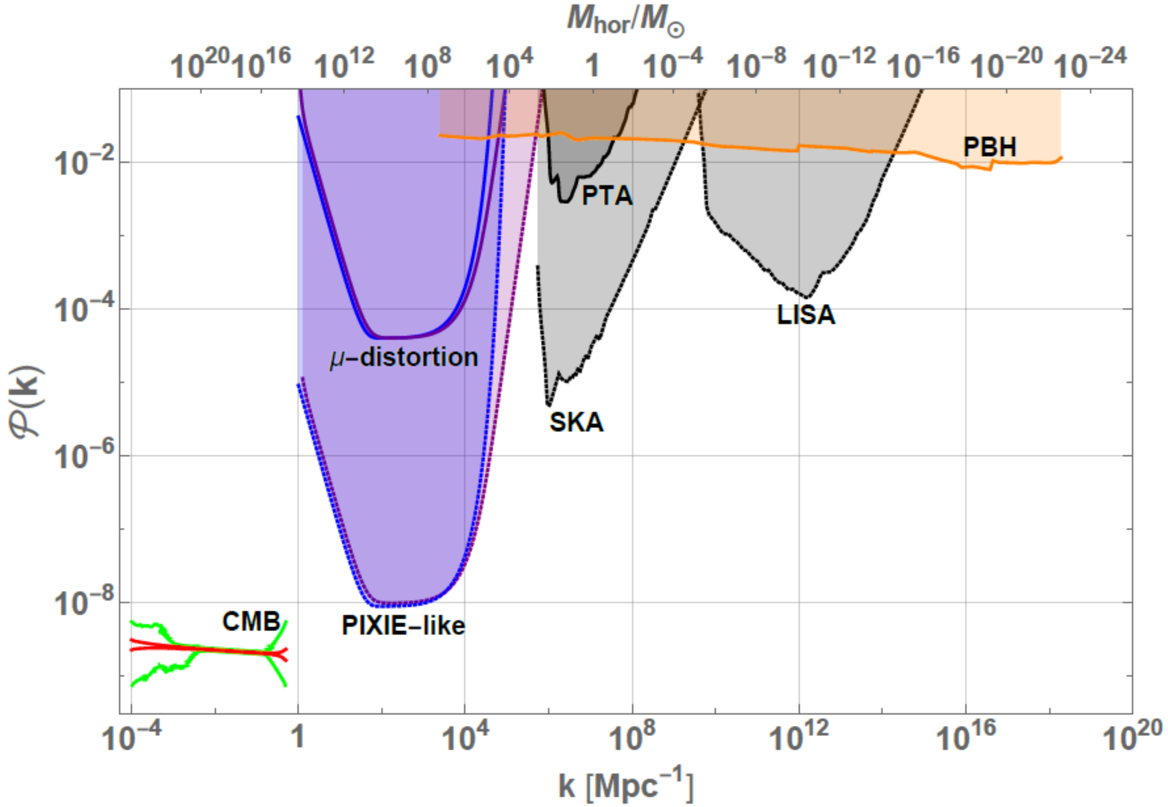




CMB transfer functions + intervening thermal expansion history `samples' underlying primordial 2-pt function

Primordial power at small scales could yet turn out to be very different.



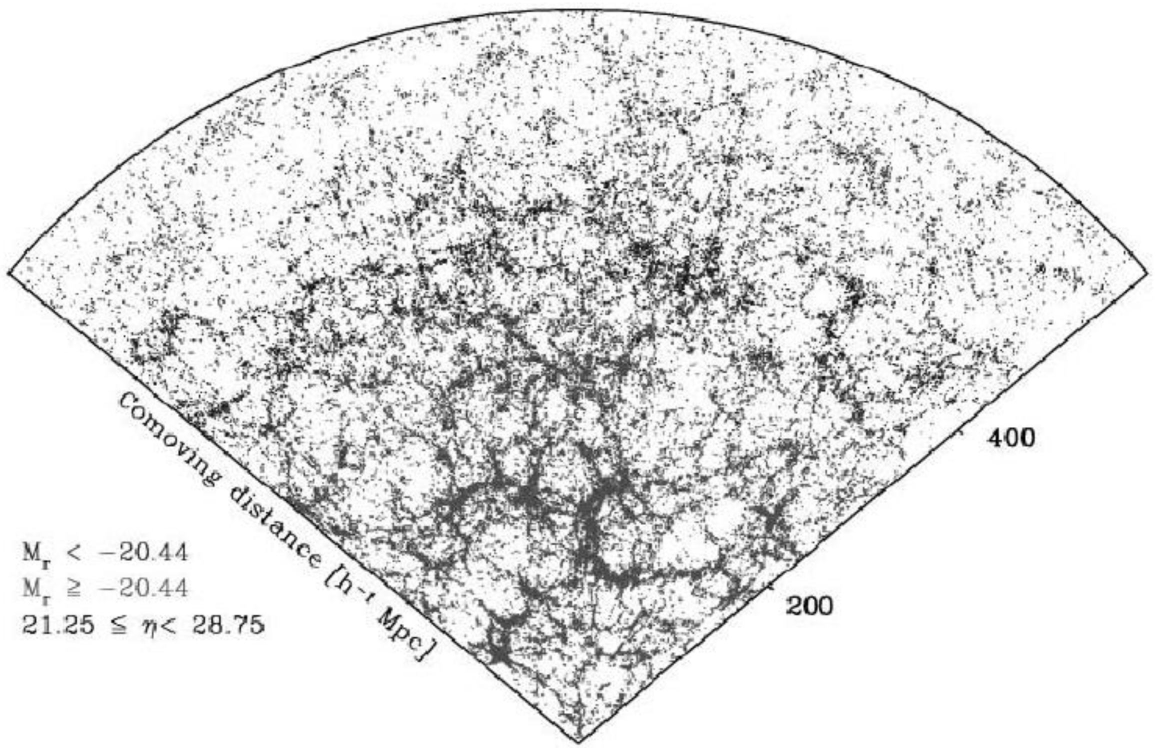


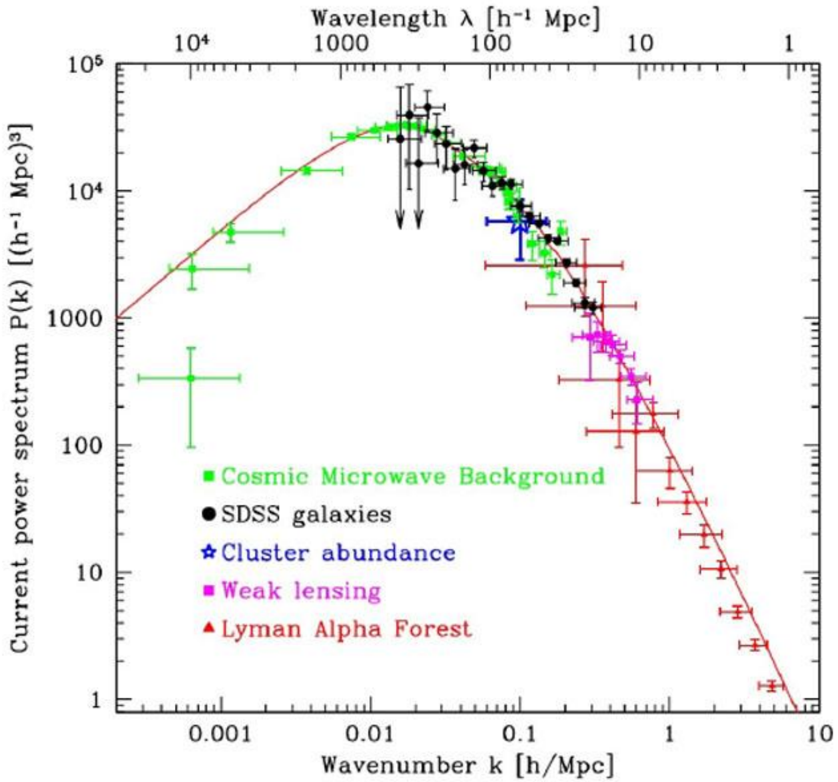
We can still constrain small scale primordial perturbations through other tracers…

Large Scale Structure

$$\delta := \frac{\delta\rho}{\rho} \propto \nabla^2 \mathcal{R} \qquad \langle \delta(\vec{k}_1)\delta(\vec{k}_2)\rangle = (2\pi)^3 \delta(\vec{k}_1 + \vec{k}_2) P_m(k_1)$$

matter power spectrum





Large Scale Structure

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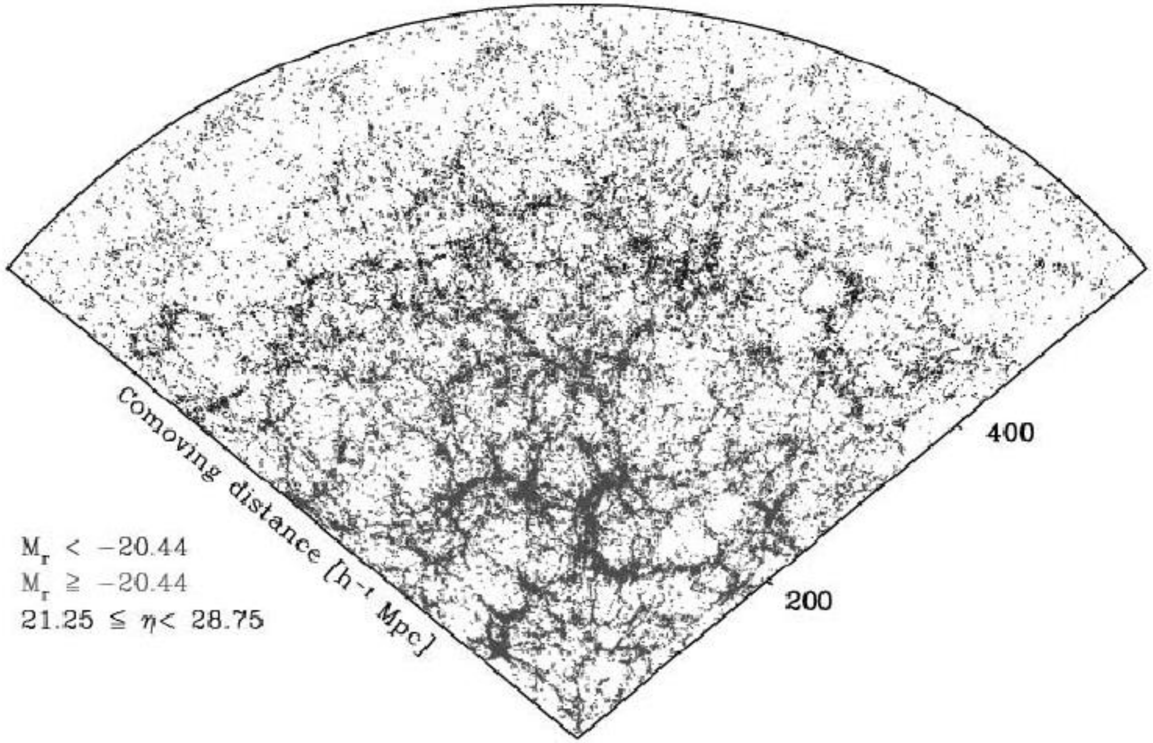
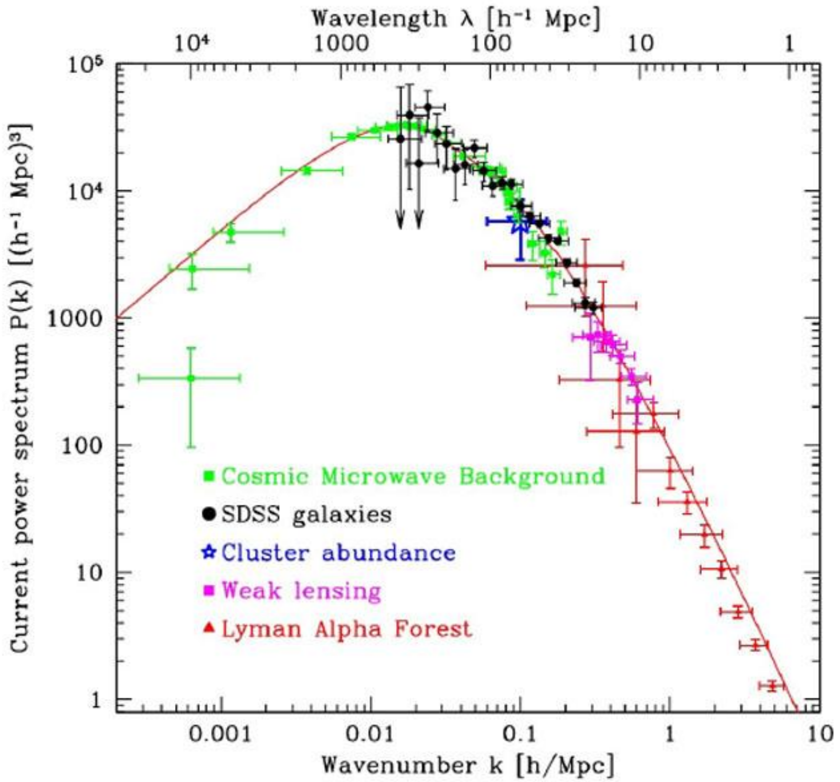
$\delta_{\rm galaxies} = f(\delta)$, linear bias $\rightarrow \delta_g = b(z)\delta$





Anisotropies

- All cosmological observations to date are *consistent* with adiabatic, Gaussian and nearly scale invariant initial conditions.

- Evidence of a particular symmetry breaking pattern in the very early universe (with a close to vanishing order parameter $\epsilon = -\dot{H}/H^2$).

- Widely accepted as confirmation of the inflationary paradigm.

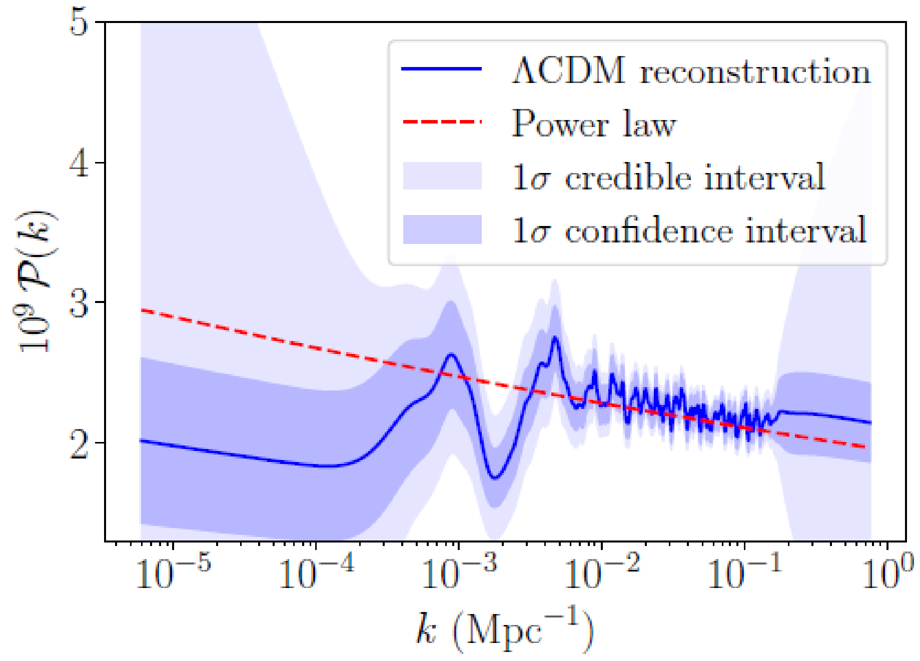
- Microphysics beyond the symmetry breaking?

- If the inflaton is a real physical degree of freedom (particle), might there be other scales/ correlations hidden in the data?

- Can go looking for non-trivial correlations (interactions), features, anomalies etc…

Particle physics origins of cosmic structure?

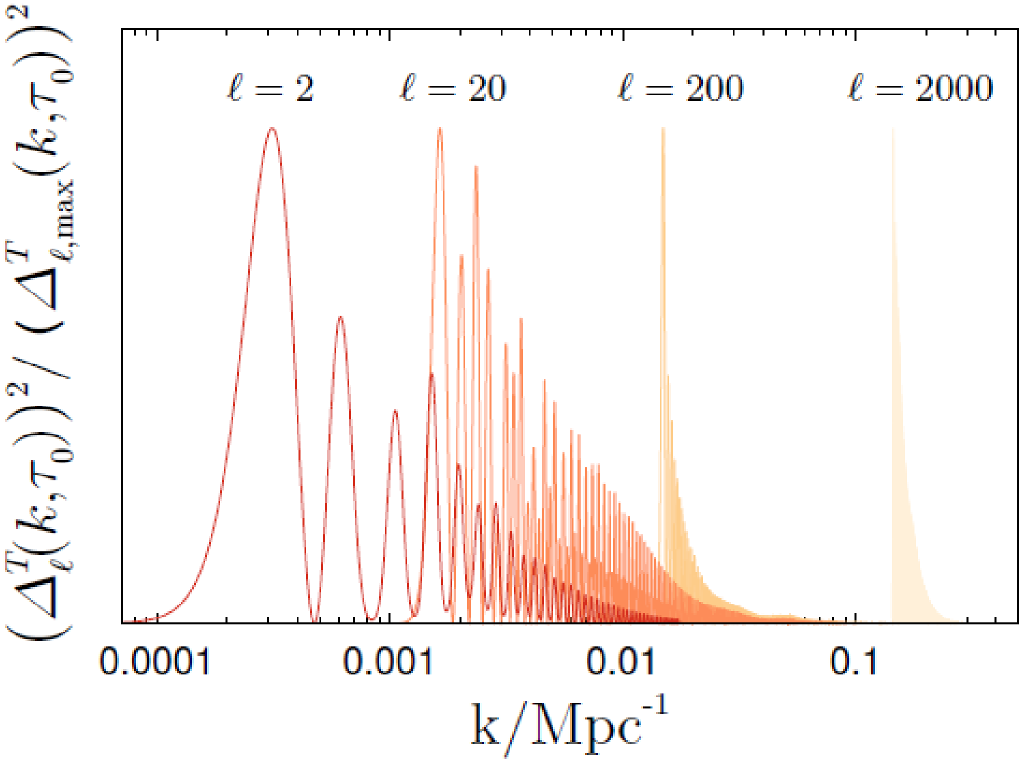
Are vanilla initial conditions all there is? What can we learn about the inflaton as a physical d.o.f.?

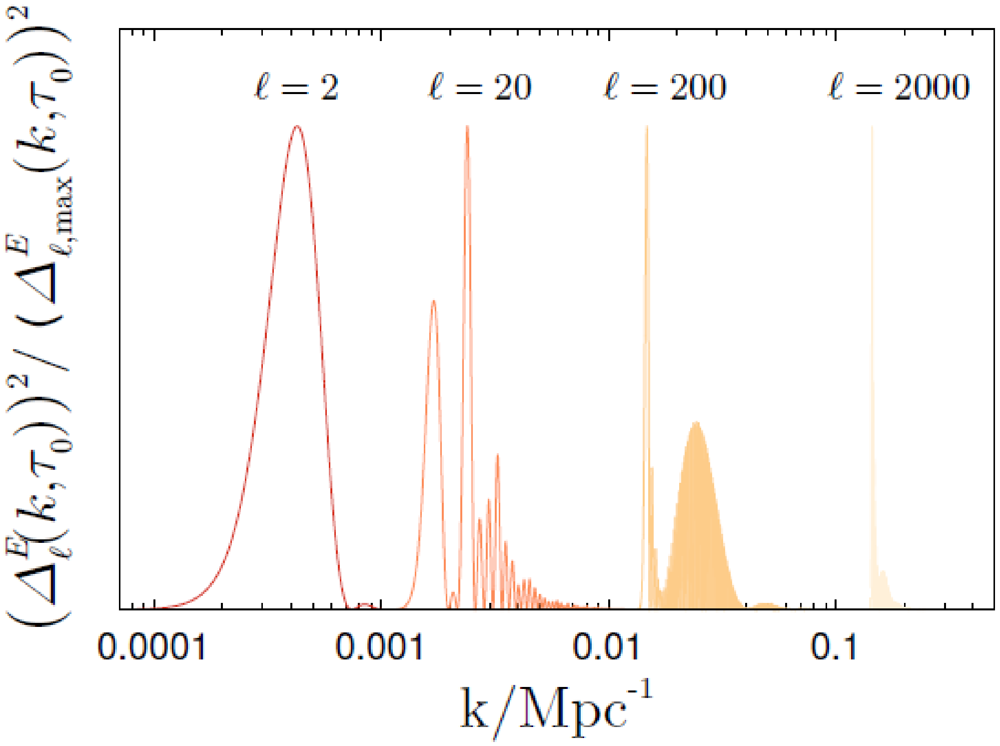


Cosmological parameters	
h	0.667
ω_b	0.022
ω_c	0.12
z_{re}	9.94

Cf. Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

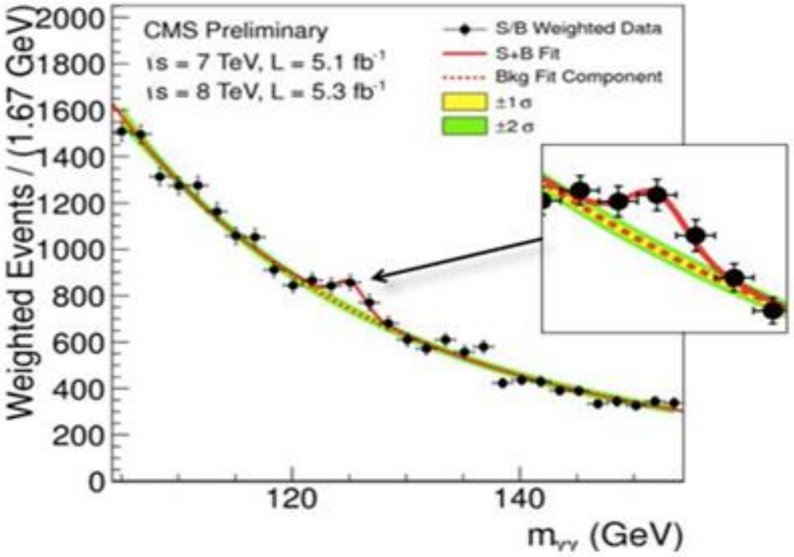
Temperature and Polarization transfer functions



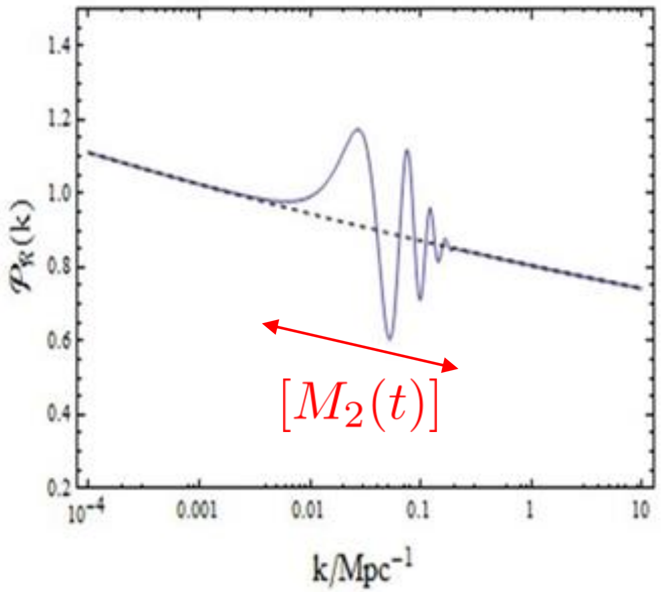


Could new physics and new characteristic scales be hiding in plain sight?

Particle physics origins of cosmic structure?

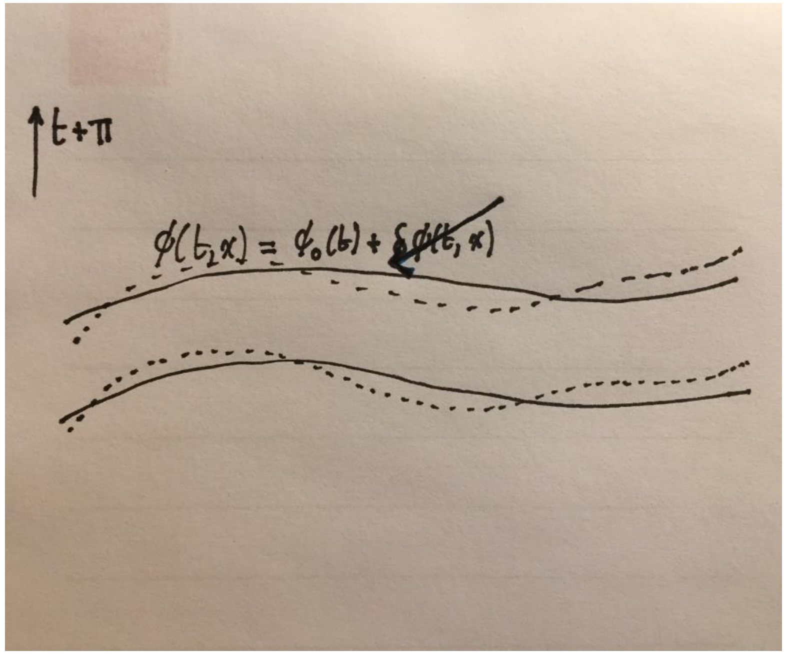


LHC



CMB

Comoving curvature perturbation $\mathcal{R}$ is the *Goldstone* mode corresponding to non-linearly realizing time translation invariance…

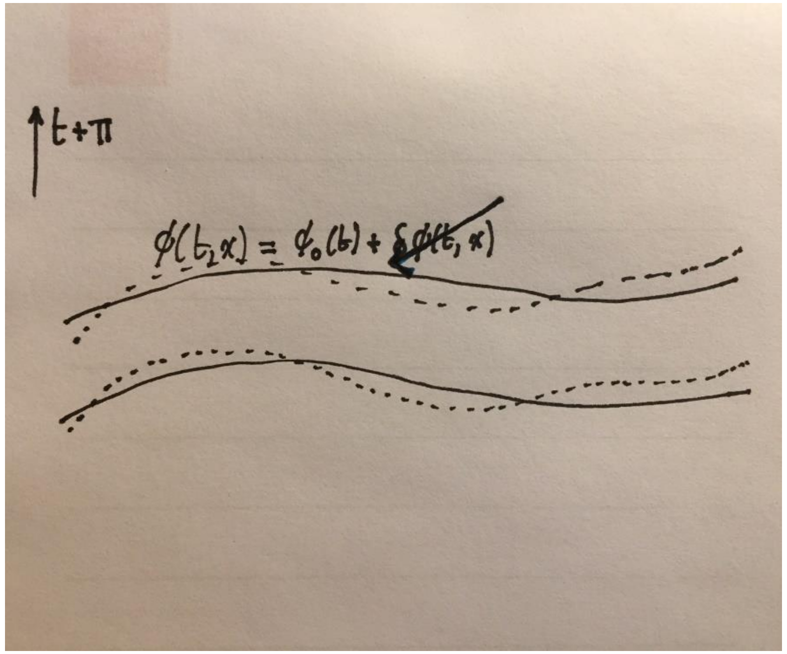


$$S_2 = \int d^4x a^3 \epsilon M_{\rm pl}^2 \left(\frac{\dot{\mathcal{R}}^2}{c_{\rm s}^2} - \frac{(\partial \mathcal{R})^2}{a^2} + \mu^{-2} \frac{\left(\partial^2 \mathcal{R}\right)^2}{a^4} \right)$$

$$\epsilon = -\frac{\dot{H}}{H^2}, \qquad \frac{1}{c_{\rm s}^2} = 1 - \frac{2M_2^4}{M_{\rm pl}^2 \dot{H}}$$

changes to zero and two derivative terms in the parent theory manifest here…

Comoving curvature perturbation $\mathcal{R}$ is the *Goldstone* mode corresponding to non-linearly realizing time translation invariance…

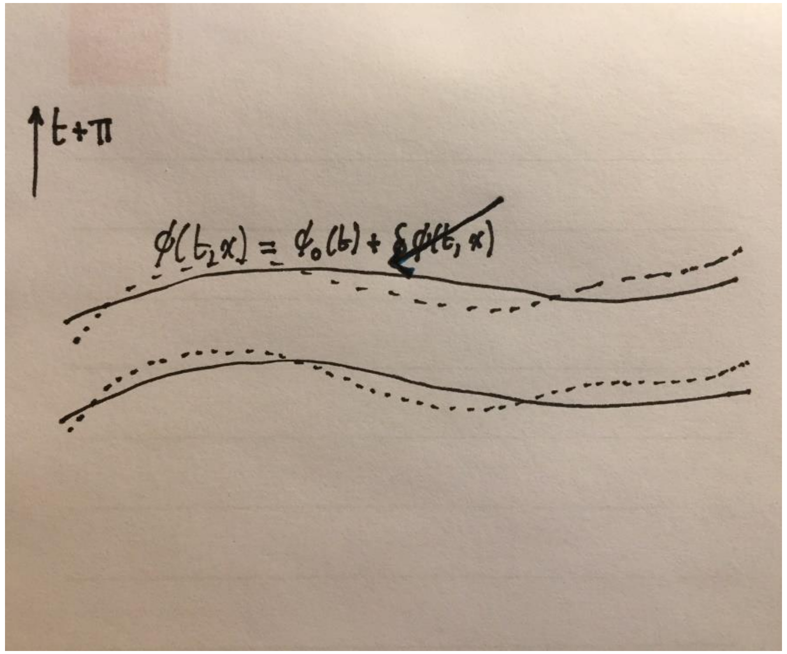


$$S_2 = \int d^4x a^3 \epsilon M_{\rm pl}^2 \left(\frac{\dot{\mathcal{R}}^2}{c_{\rm s}^2} - \frac{(\partial\mathcal{R})^2}{a^2} + \mu^{-2} \frac{\left(\partial^2\mathcal{R}\right)^2}{a^4} \right)$$

$$\epsilon = -\frac{\dot{H}}{H^2}, \qquad \frac{1}{c_{\rm s}^2} = 1 - \frac{2M_2^4}{M_{\rm pl}^2 \dot{H}}$$

changes to two and four derivative terms in the parent theory manifest here…

Comoving curvature perturbation $\mathcal{R}$ is the *Goldstone* mode corresponding to non-linearly realizing time translation invariance…



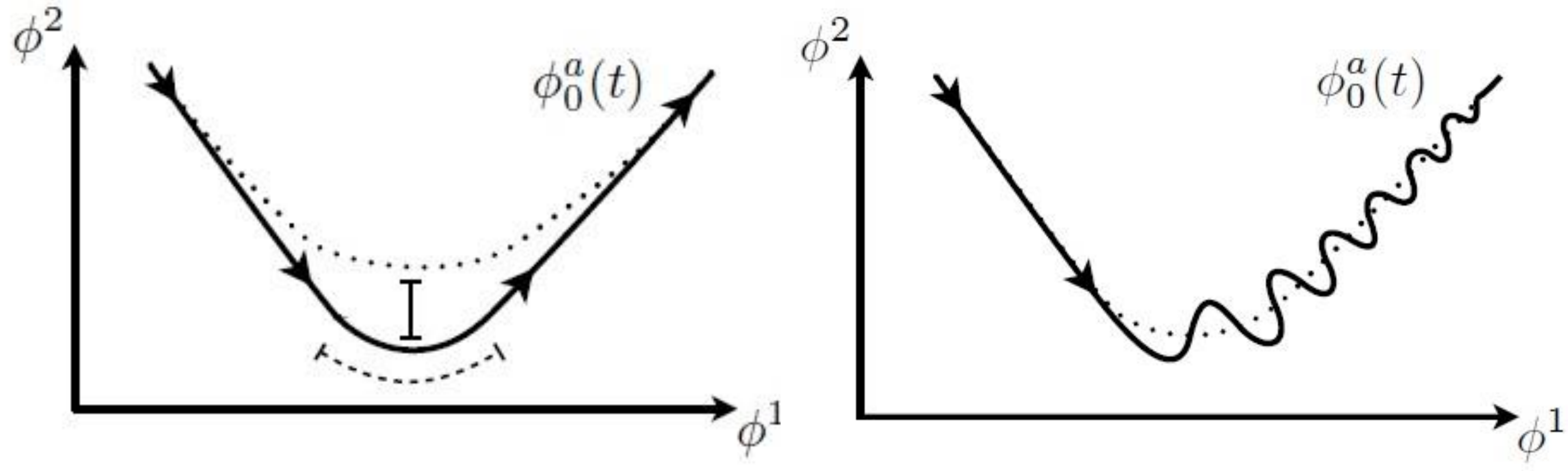
$$S_2 = \int d^4x a^3 \epsilon M_{\rm pl}^2 \left(\frac{\dot{\mathcal{R}}^2}{c_s^2} - \frac{(\partial \mathcal{R})^2}{a^2} + \mu^{-2} \frac{\left(\partial^2 \mathcal{R}\right)^2}{a^4} \right)$$

$$\epsilon = -\frac{\dot{H}}{H^2}, \qquad \frac{1}{c_s^2} = 1 - \frac{2M_2^4}{M_{\rm pl}^2 \dot{H}}$$

What could cause the time variation of these functions?

Decoupling works. But with a twist on time dependent backgrounds…

(cf. the physics of bobsleighing)



`Heavy' field excited; decoupling

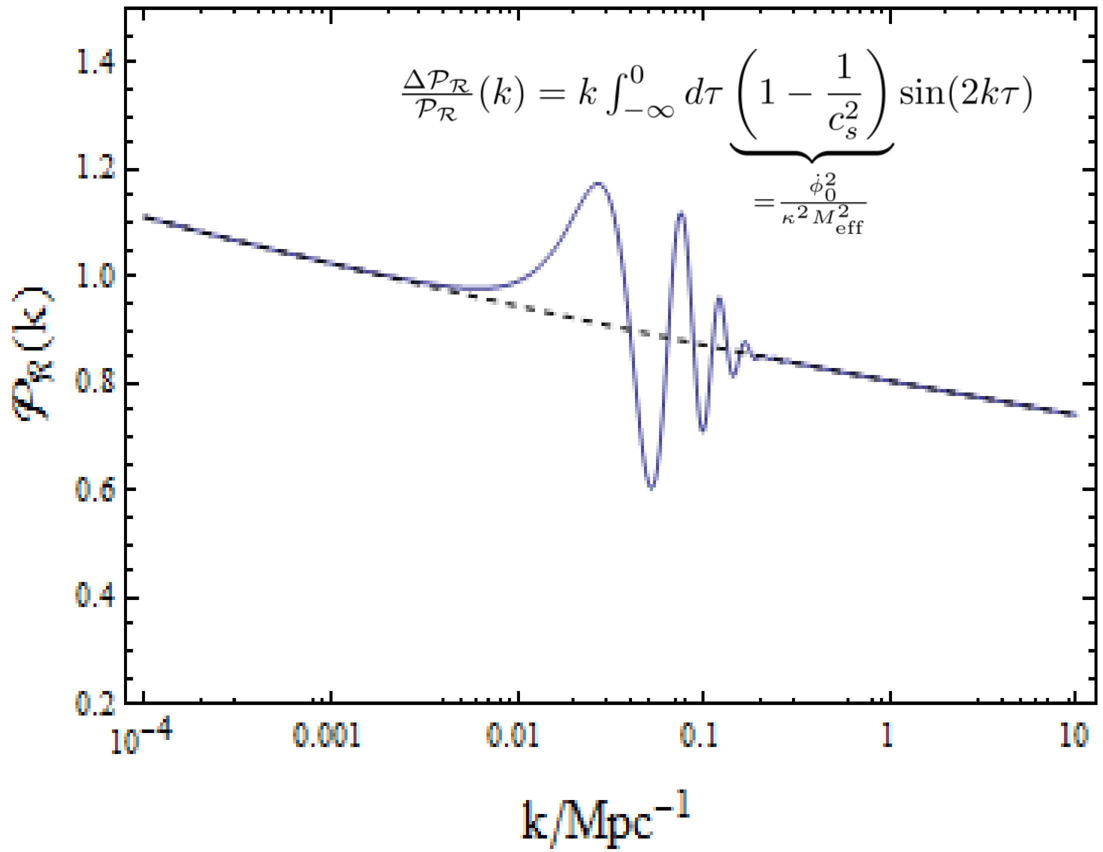
Normal modes excited; non-decoupling

Achúcarro, Gong, Hardeman, Palma, Patil; JHEP 1205 (2012) 066

Burgess, Horbatsch, Patil; JHEP 1301 (2013) 133

Features as a cosmological probe

Achúcarro, Gong, Palma, Patil; 2011-2013

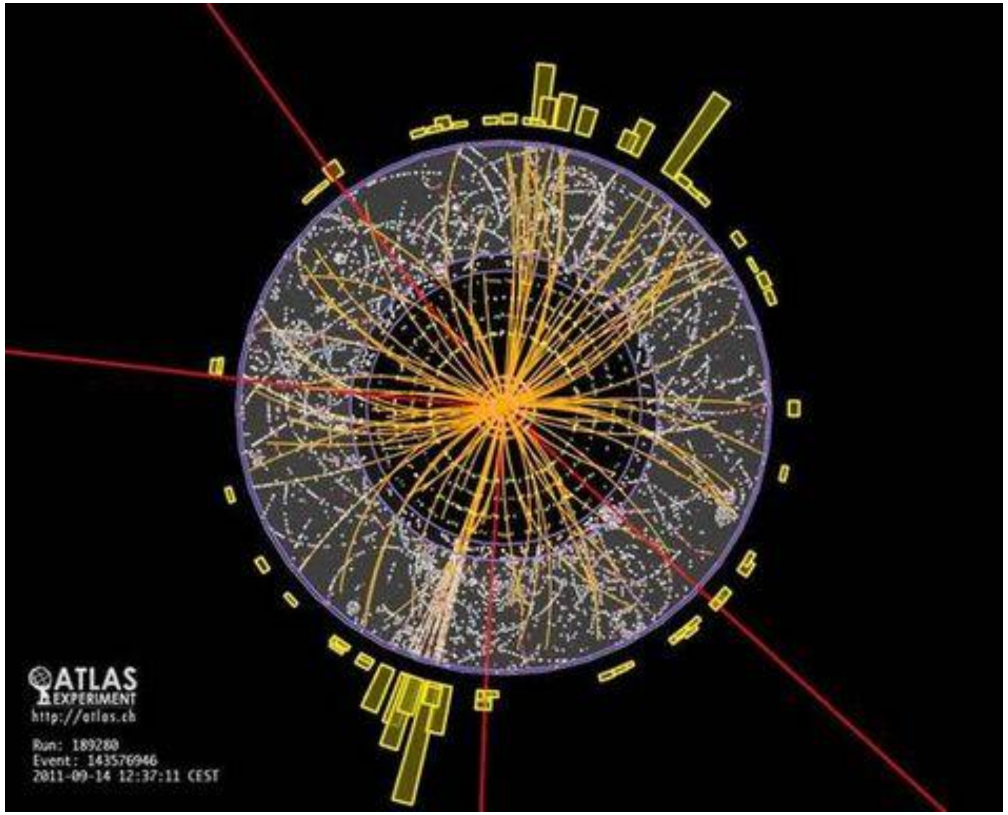


$$c_s^{-2} = 1 + \frac{4\dot\phi_0^2}{\kappa^2 M_{\rm eff}^2}$$

$$M_{\rm eff}^2 := V_{NN} - \frac{\dot\phi_0^2}{\kappa^2}$$

High energy spectroscopy: features correlate across higher order correlation functions. Optimized templates for *localized* scale dependent non-Gaussianity.

From reconstructed events to Wilson coefficients

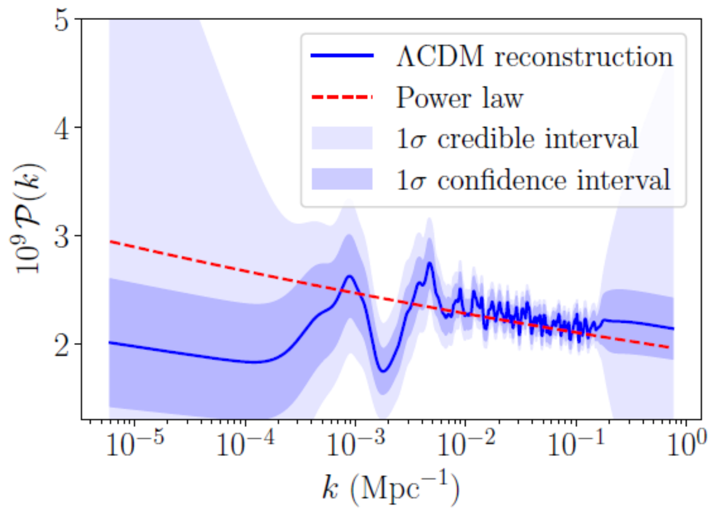


$$\Delta\mathcal{L} = |\kappa_v|^2 \left(H^\dagger H\right) V_\mu^\dagger V^\mu - |\kappa_s|^2 \left(H^\dagger H\right)\left(S^\dagger S\right) + \kappa_F \bar{F} \tilde{H}^\dagger \ell_L + h.c.$$

$$\Delta V\left(H^\dagger H\right) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2 m_v^2 N_v}{16\pi^2} + \frac{|\kappa_s|^2 m_s^2 N_s}{16\pi^2} - \frac{|\kappa_F|^2 m_F^2 N_F}{16\pi^2}\right) + \cdots$$

I. Brivio and M. Trott, Phys. Rept. 793, 1 (2019)

From reconstructed data to `Wilson *functions*'



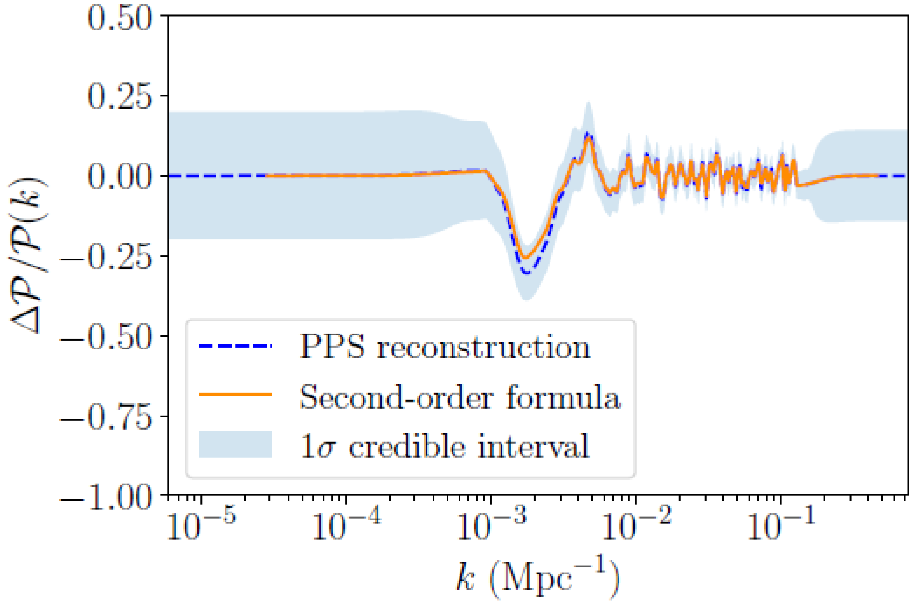
Cosmological parameters	
h	0.667
ω_b	0.022
ω_c	0.12
z_{re}	9.94

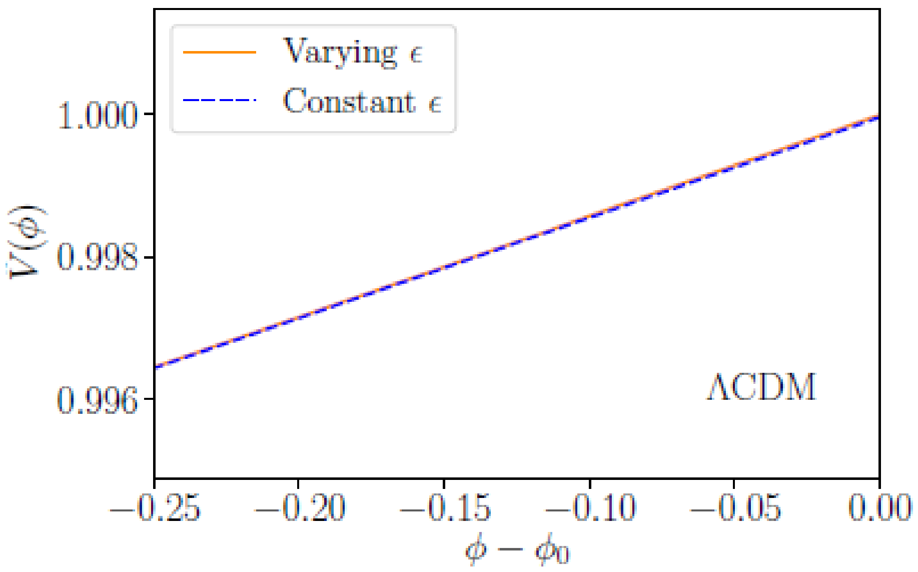
Scale dependence of cosmological correlation functions = time dependence of EFT parameters.

Can `invert' for EFT parameters given a scale dependent reconstruction to accuracy of order $\left(\frac{\Delta\mathcal{P}}{\mathcal{P}}\right)^3$.

Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

From reconstructed data to `Wilson functions'





Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

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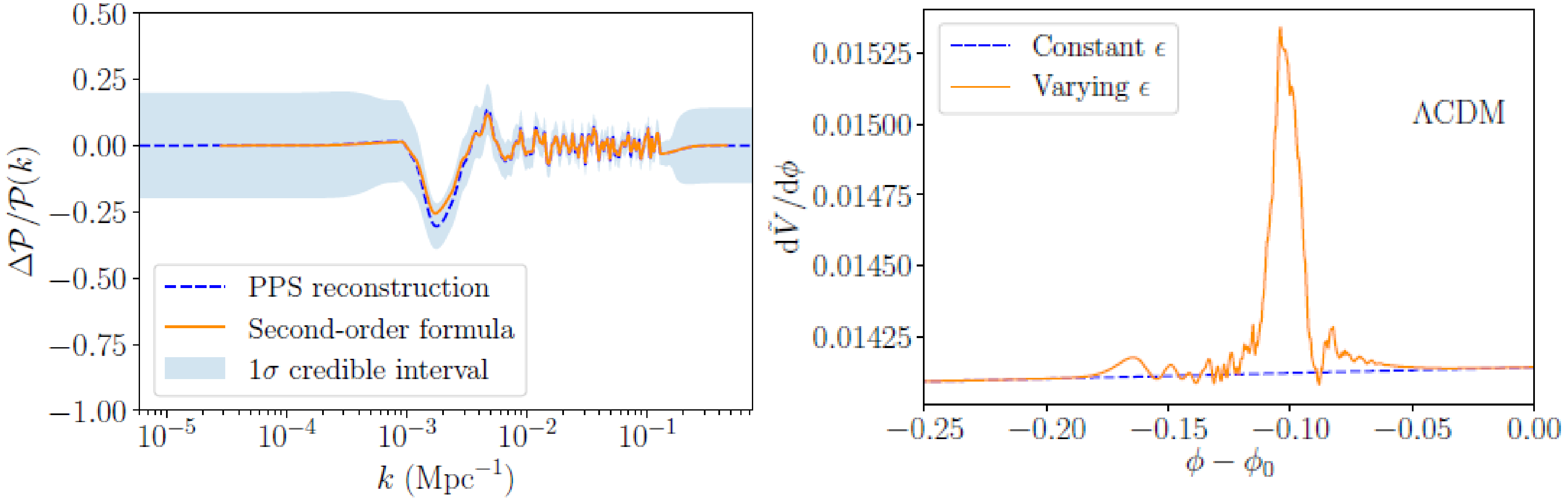

Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

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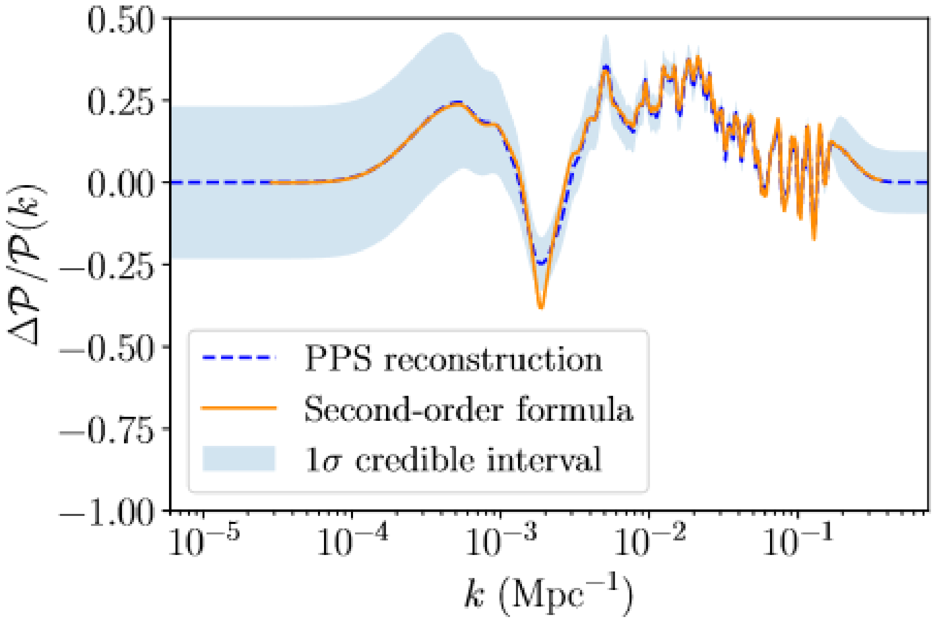
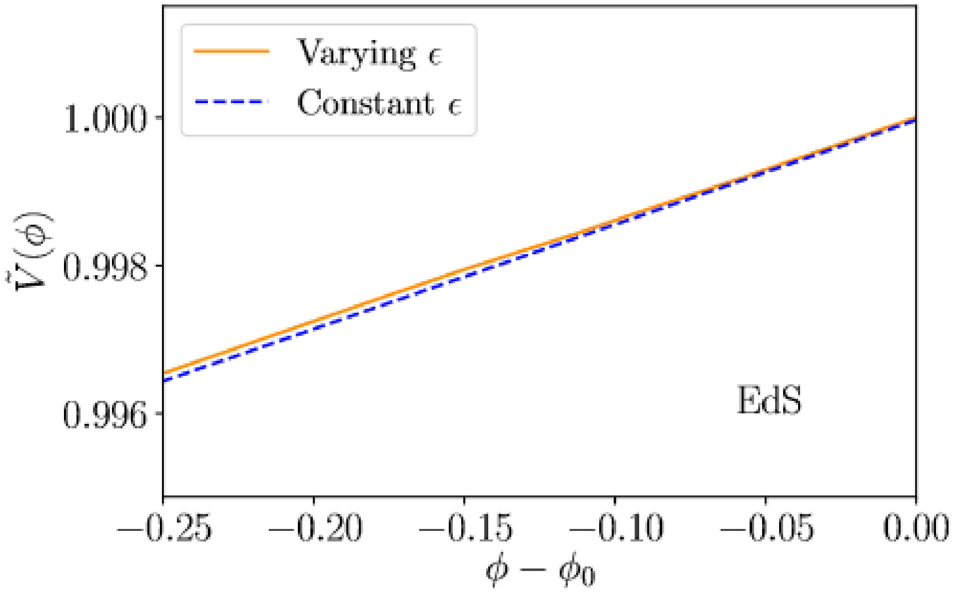
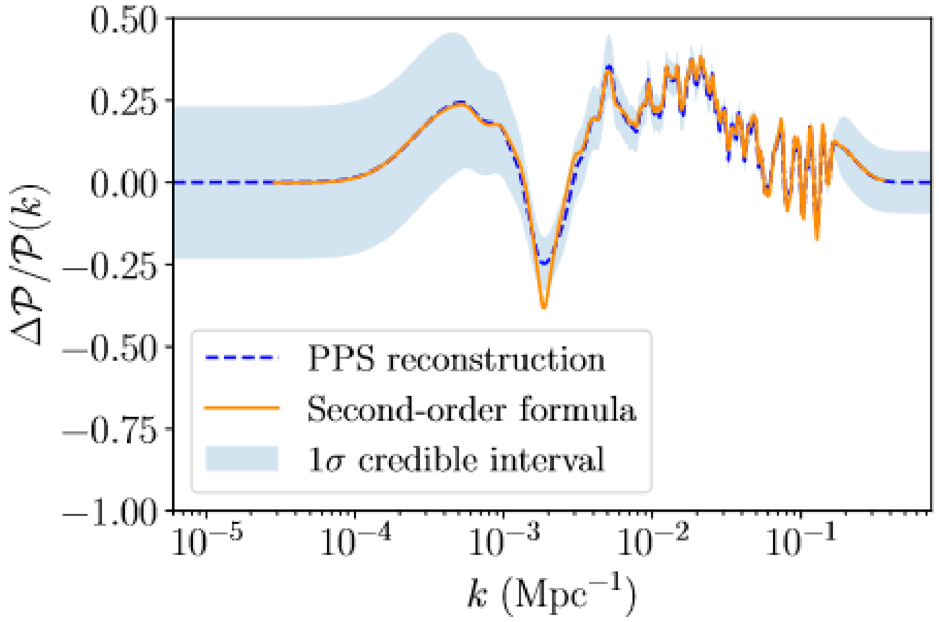


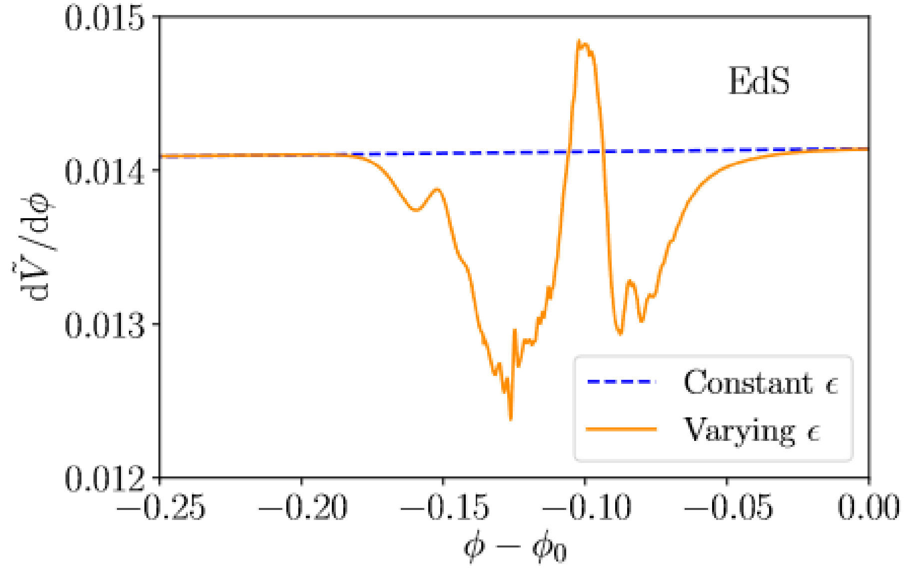


Cosmological parameters	
h	0.443
ω_b	0.096
ω_c	0.78
ω_ν	0.12
z_{re}	6.5

Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

From reconstructed data to `Wilson functions'





Cosmological parameters	
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ω_ν	0.12
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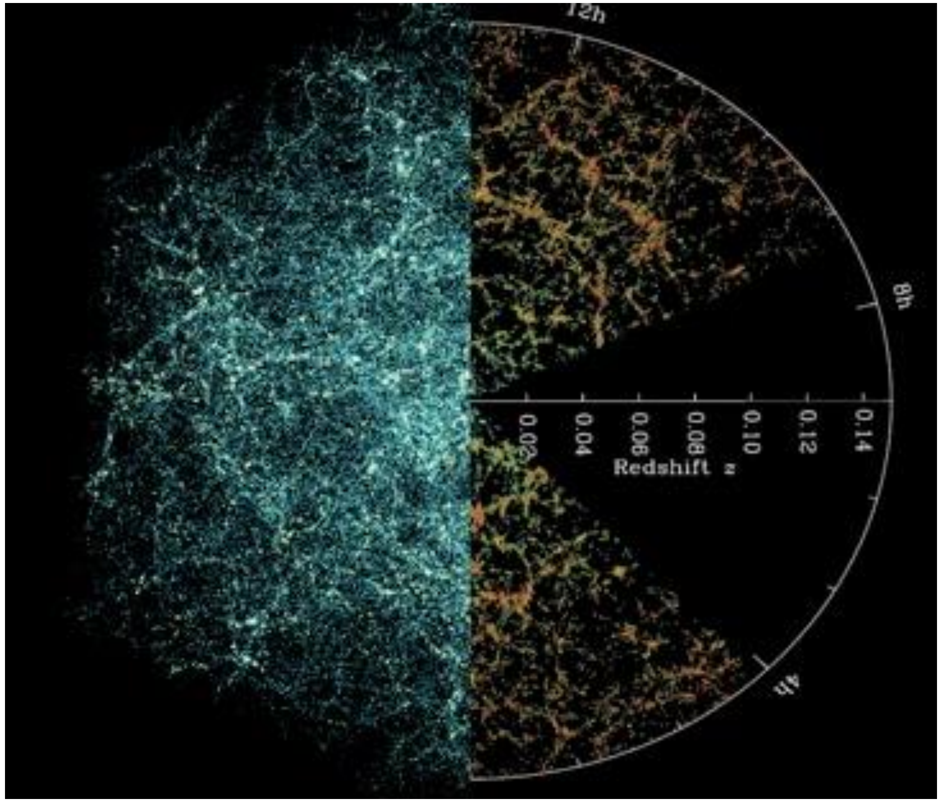
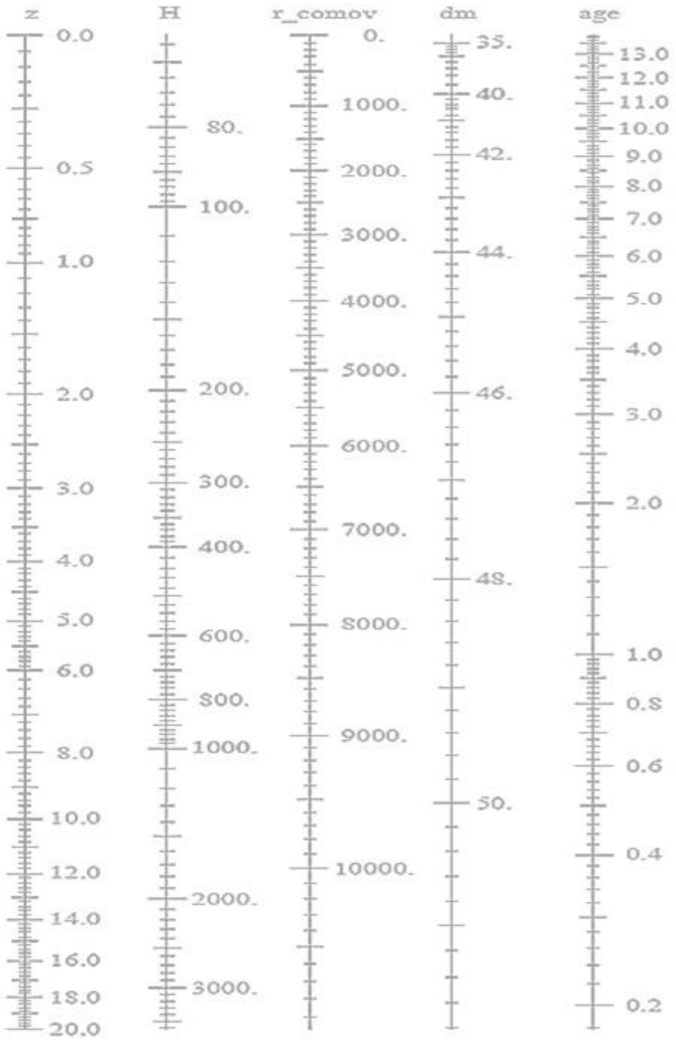
Durakovic, Hunt, Patil, Sarkar, SciPost Phys. 7, no. 4, 049 (2019)

The observable universe is a finite box…

On going enterprise to map all things that `shine' at us (LSS)

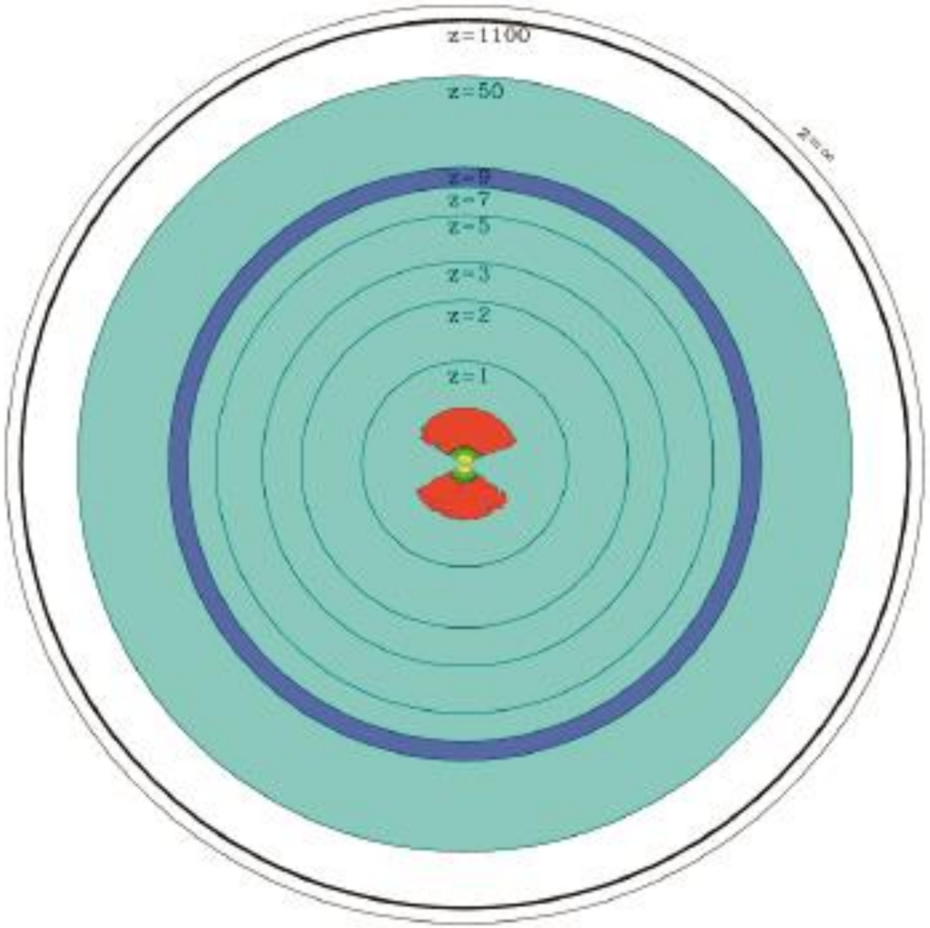


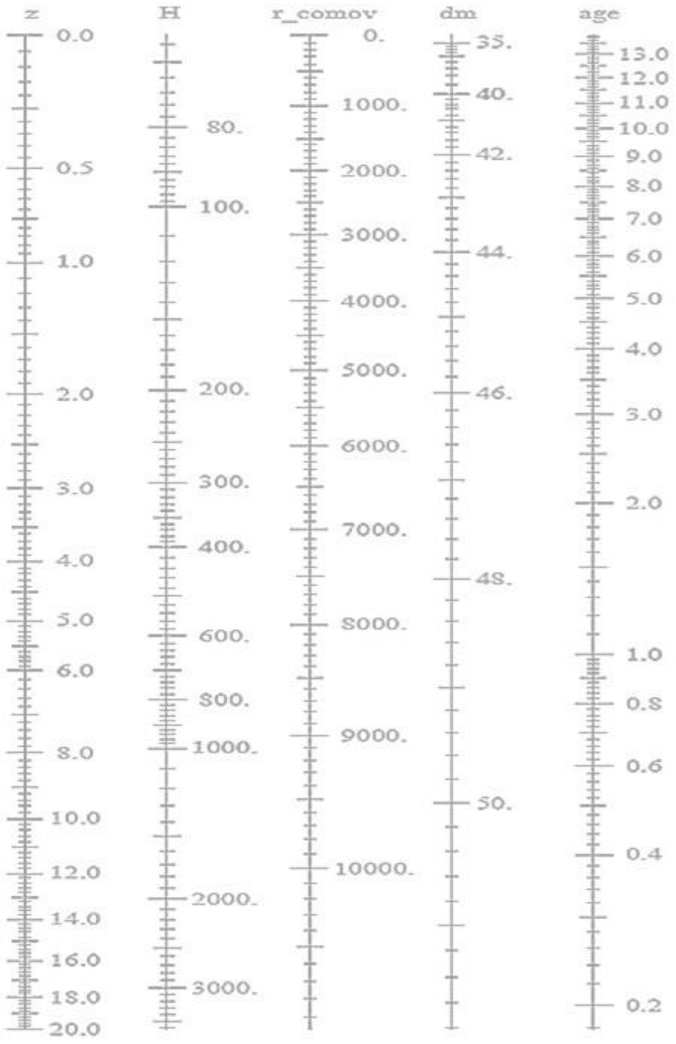
Sloan Digital Sky Survey vs. simulation



The observable universe is a finite box…

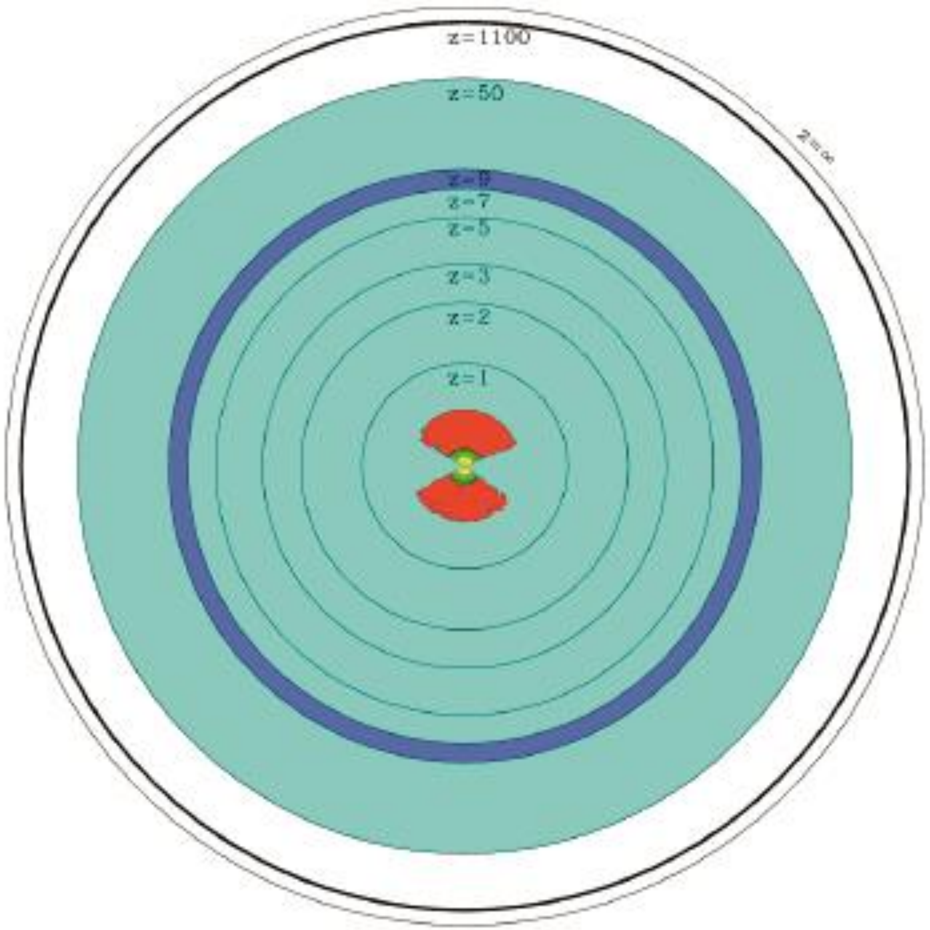
But we may be soon be able to map things that don’t shine at us.

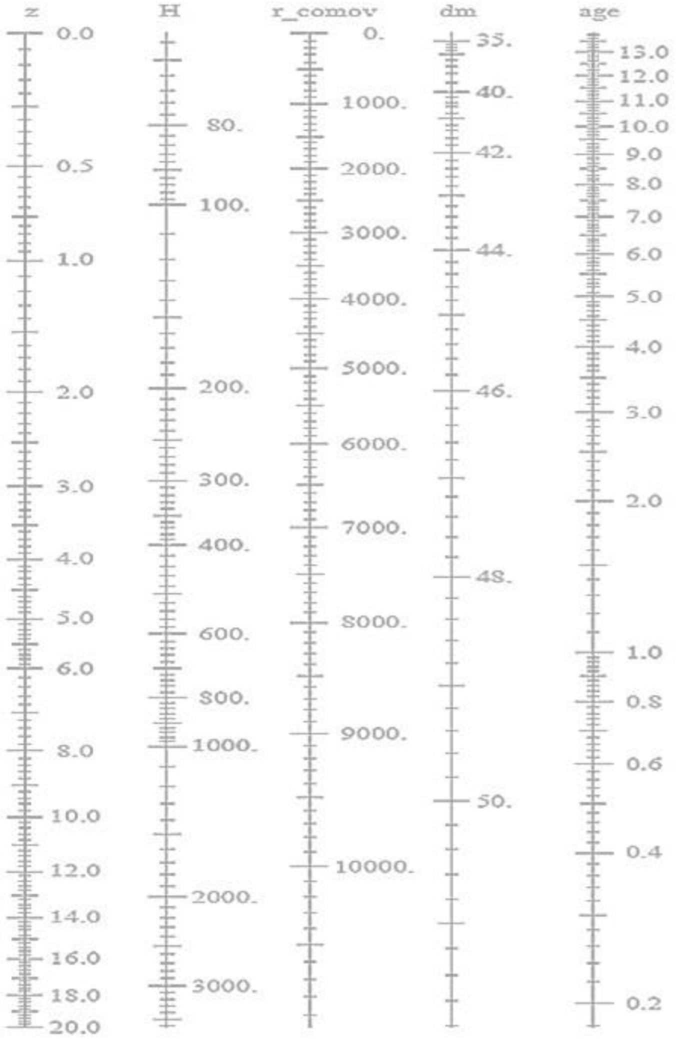




The observable universe is a finite box…

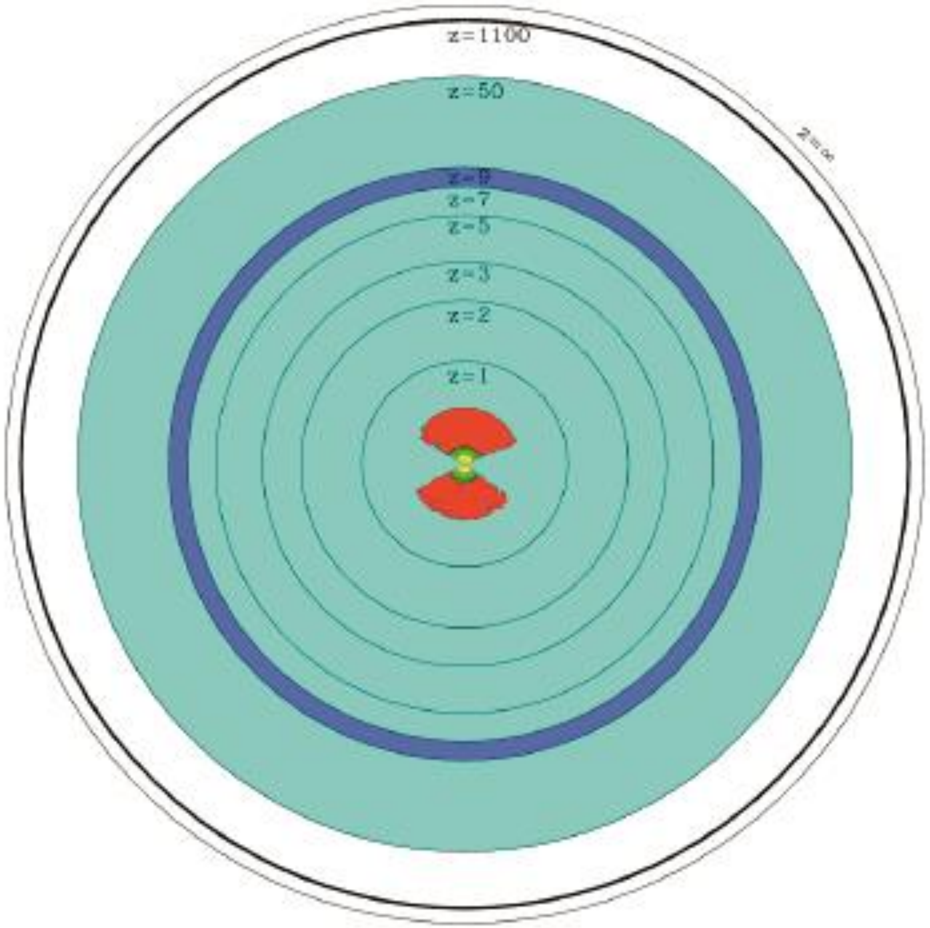
Expect a cosmological 21 cm signal out as far back as sensitivities allow.
At z = 9, expect a 140 MHz signal.

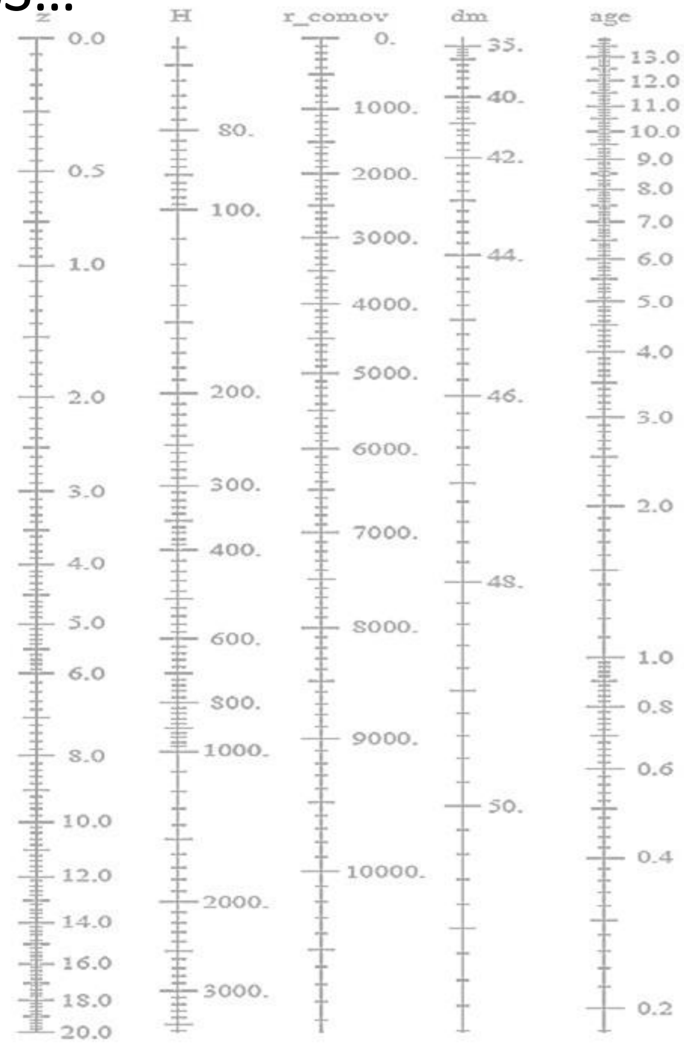




The observable universe is a finite box…

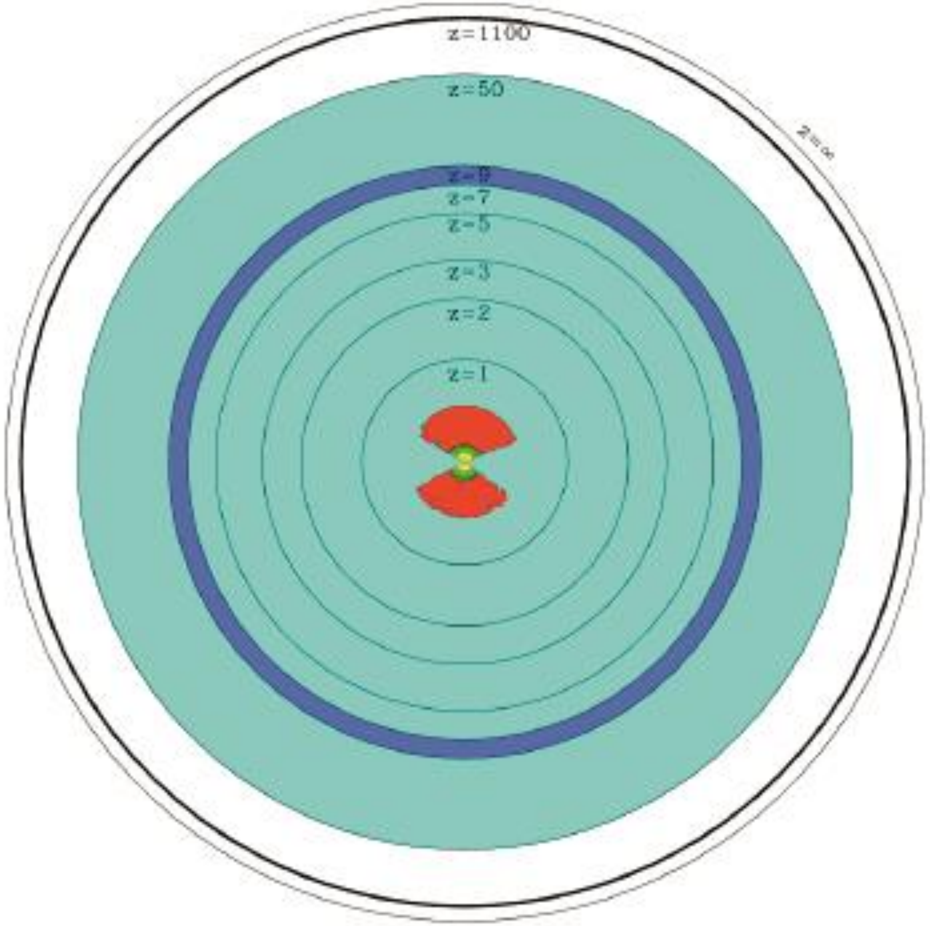
Can map matter power spectrum over time; Can `see' modes at scales not accessible in the CMB or LSS…

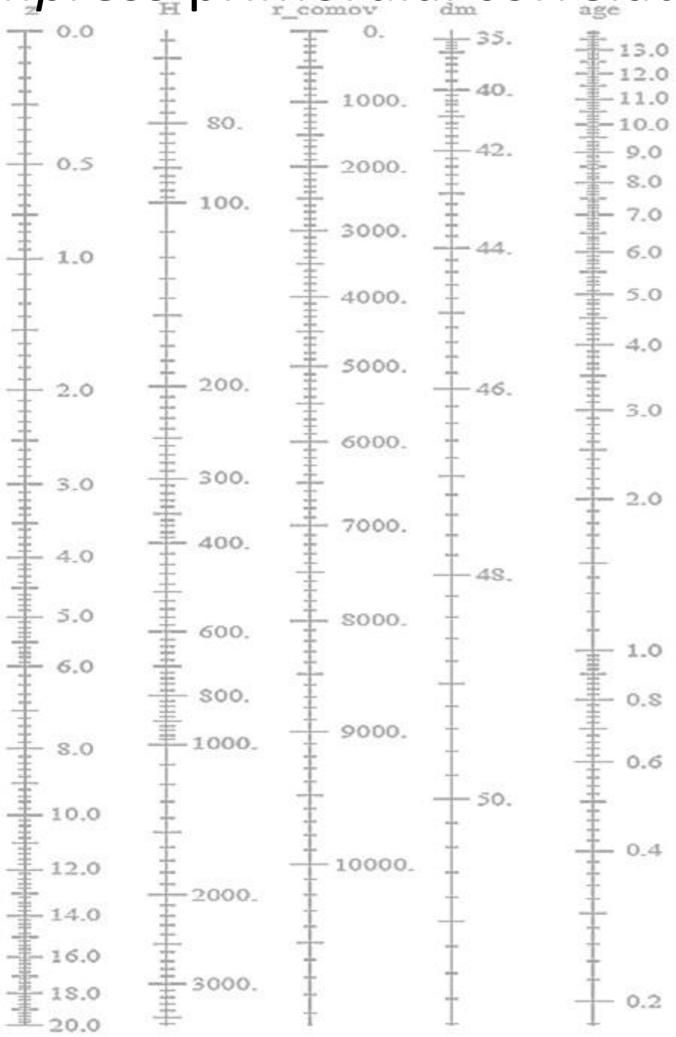




The observable universe is a finite box…

If we can do this, can in principle map all gravitationally bound matter in the visible universe, and *uncompress* primordial correlations.





So, *are* primordial correlation functions really scale invariant?

So far, everything thing seems consistent with scale invariance*.

However, a definitive answer requires searching for evidence of new physical scales in cosmological correlation functions – LSS surveys + 21 cm tomography will tell us more.

Thank you for your attention!

(And thank you, Subir for continually challenging us to re-examine our priors!)