Inflation and the cosmic microwave background anomalies

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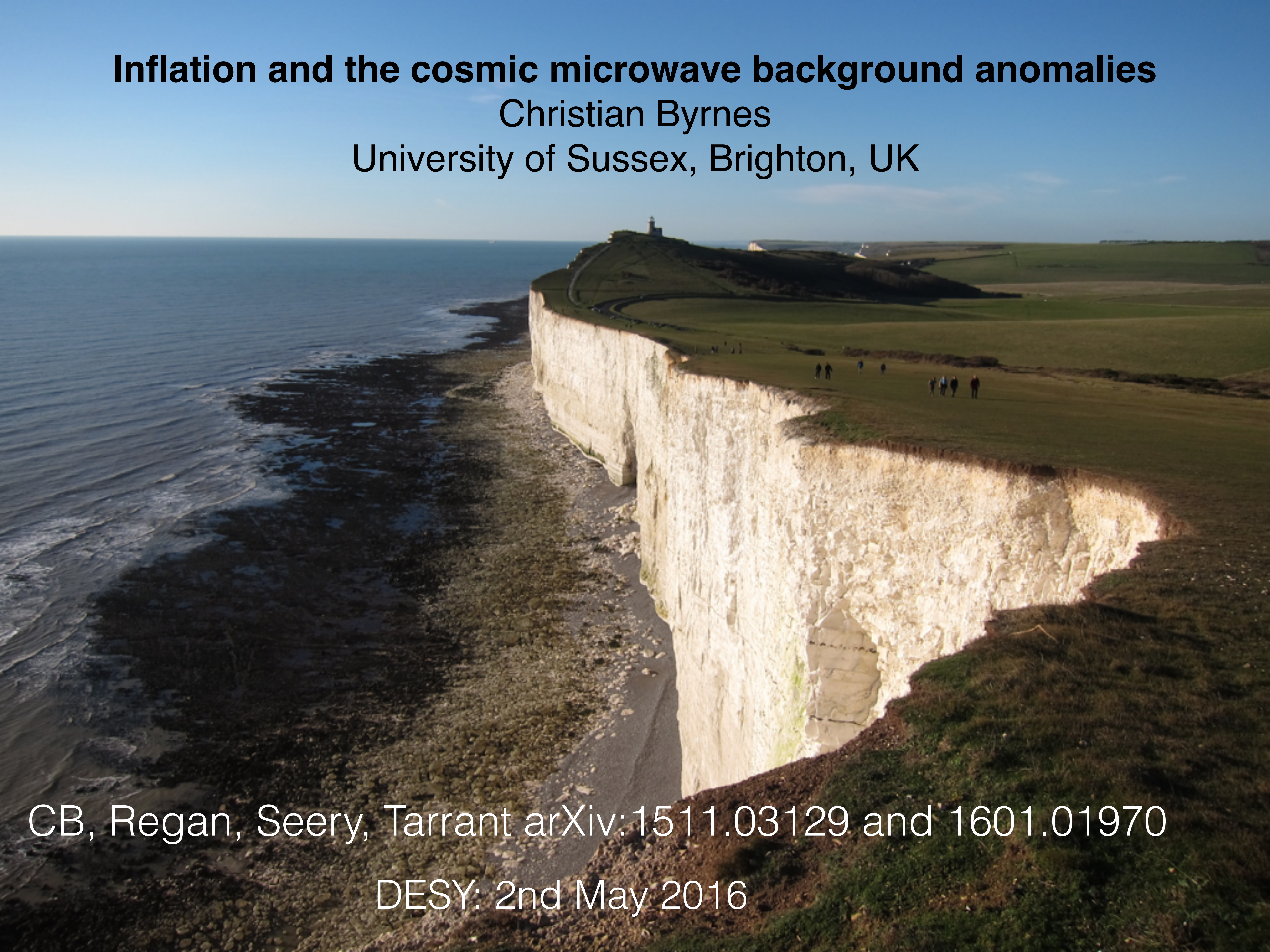
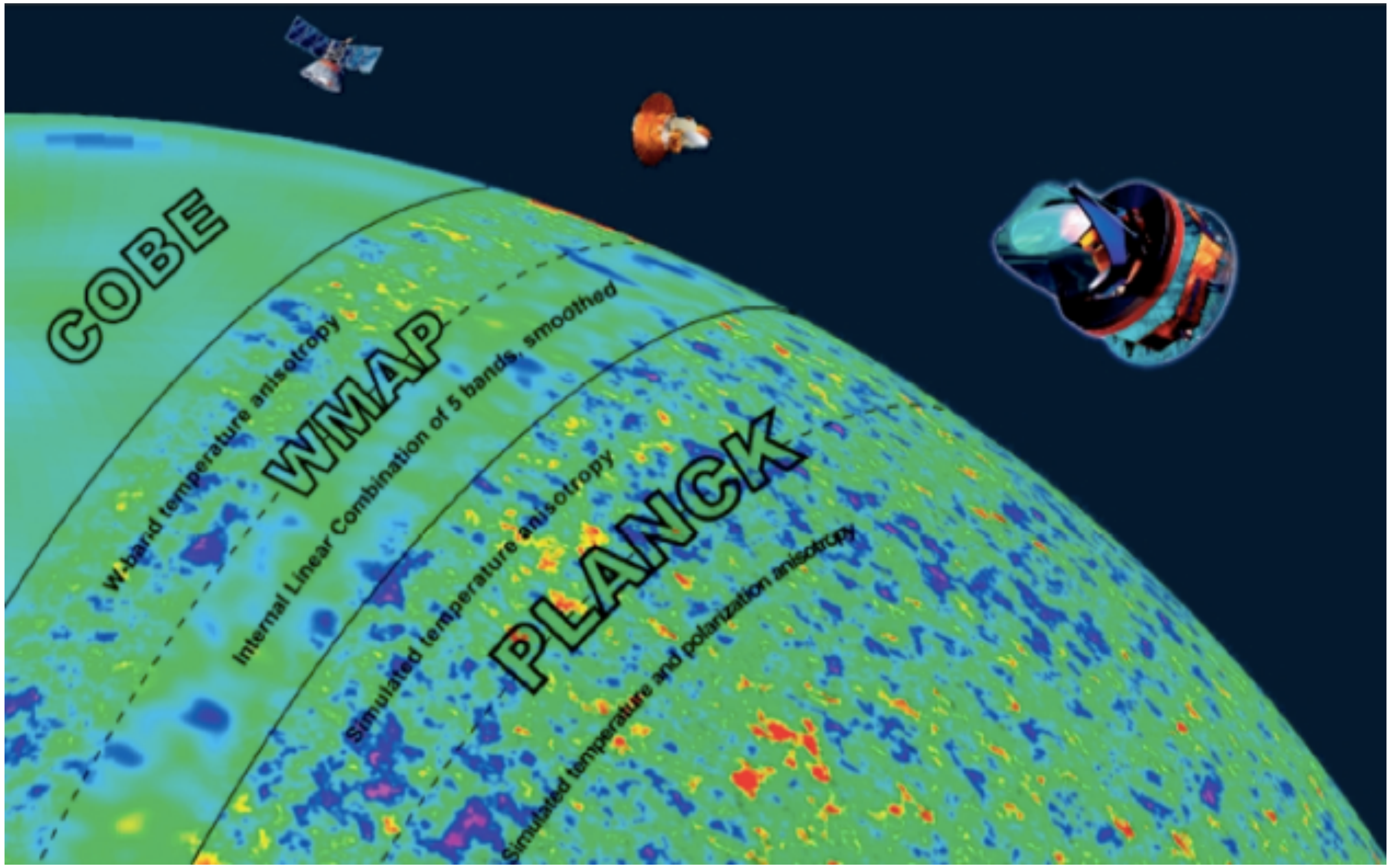


CB, Regan, Seery, Tarrant arXiv:1511.03129 and 1601.01970

DESY: 2nd May 2016

We observe so much yet see so little…

- It is both remarkable and disappointing that we can explain the statistical property of millions of CMB pixels with just two primordial numbers relating to the perturbations - the amplitude and spectral index



Evidence that inflation was simple?

- The data remains consistent with the simplest single-field models of slow-roll inflation.
- Evidence that inflation was simple?
- A Bayesian model comparison does not disfavour multifield inflation, even curvaton scenarios which were popular due to their potential prediction of a large bispectrum.
  E.g. Hardwick & CB `15; Vennin, Koyama & Wands `15

Anomalies

Anomalies might provide clues on where to finally find a deviation from the simplest models

With large data sets, we are bound to find some anomalies. Quantifying the "look elsewhere" effect is difficult and controversial

Large scale anomalies will stay, they were already observed by WMAP and are cosmic variance limited (other than polarisation, new Planck results will come this year)

Schwarz et al review 2015

ESA Planck press release

PLANCK REVEALS AN ALMOST PERFECT UNIVERSE

21 March 2013 Acquired by ESA's Planck space telescope, the most detailed map ever created of the cosmic microwave background – the relic radiation from the Big Bang – was released today revealing th existence of features that challenge the foundations of our current understanding of the Universe.

The image is based on the initial 15.5 months of data from Planck and is the mission's first all-sky picture of the oldest light in our Universe, imprinted on the sky when it was just 380 000 years old.

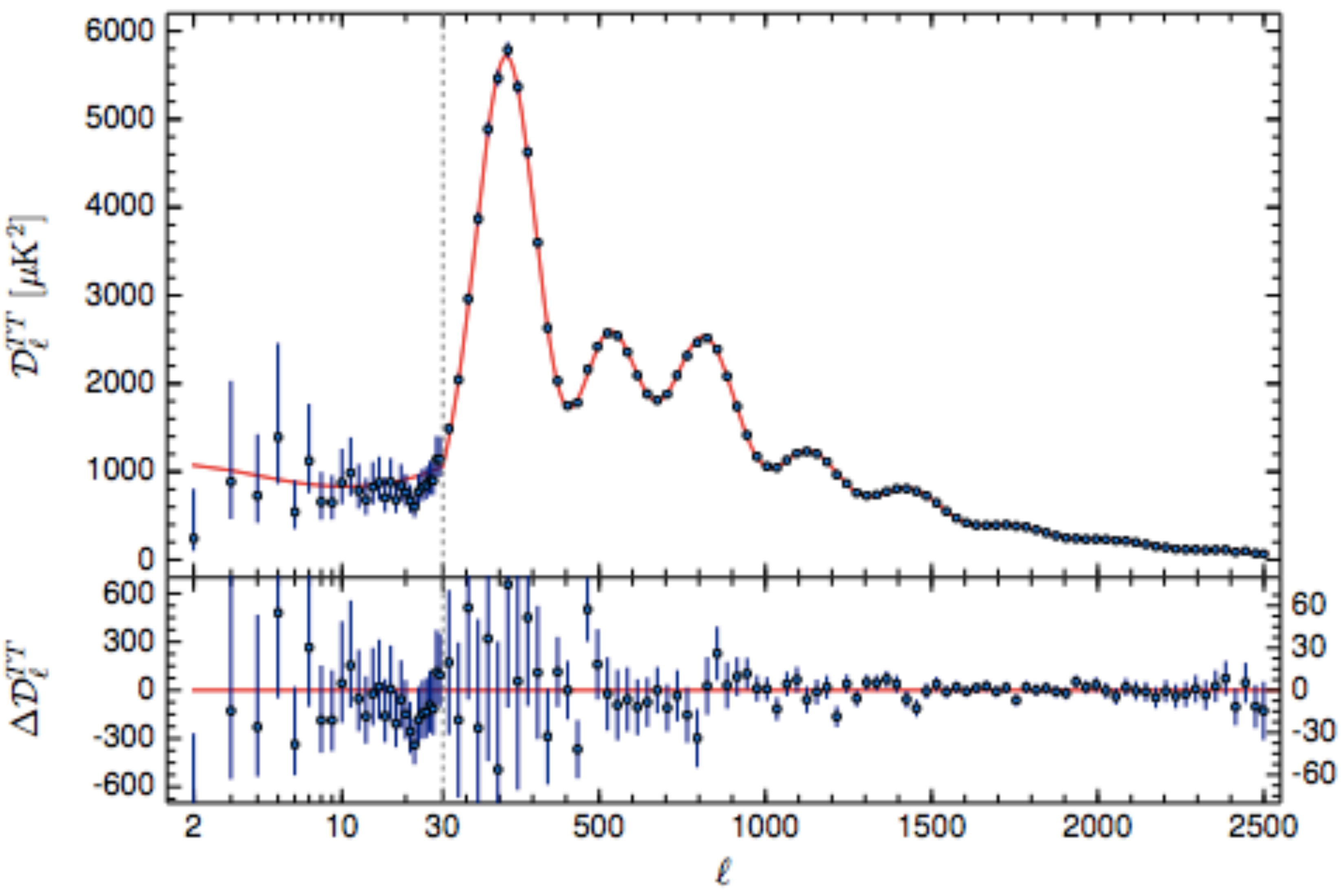
nature International weekly journal of science

NATURE | NEWS

Cosmologists at odds over mysterious anomalies in data from early Universe

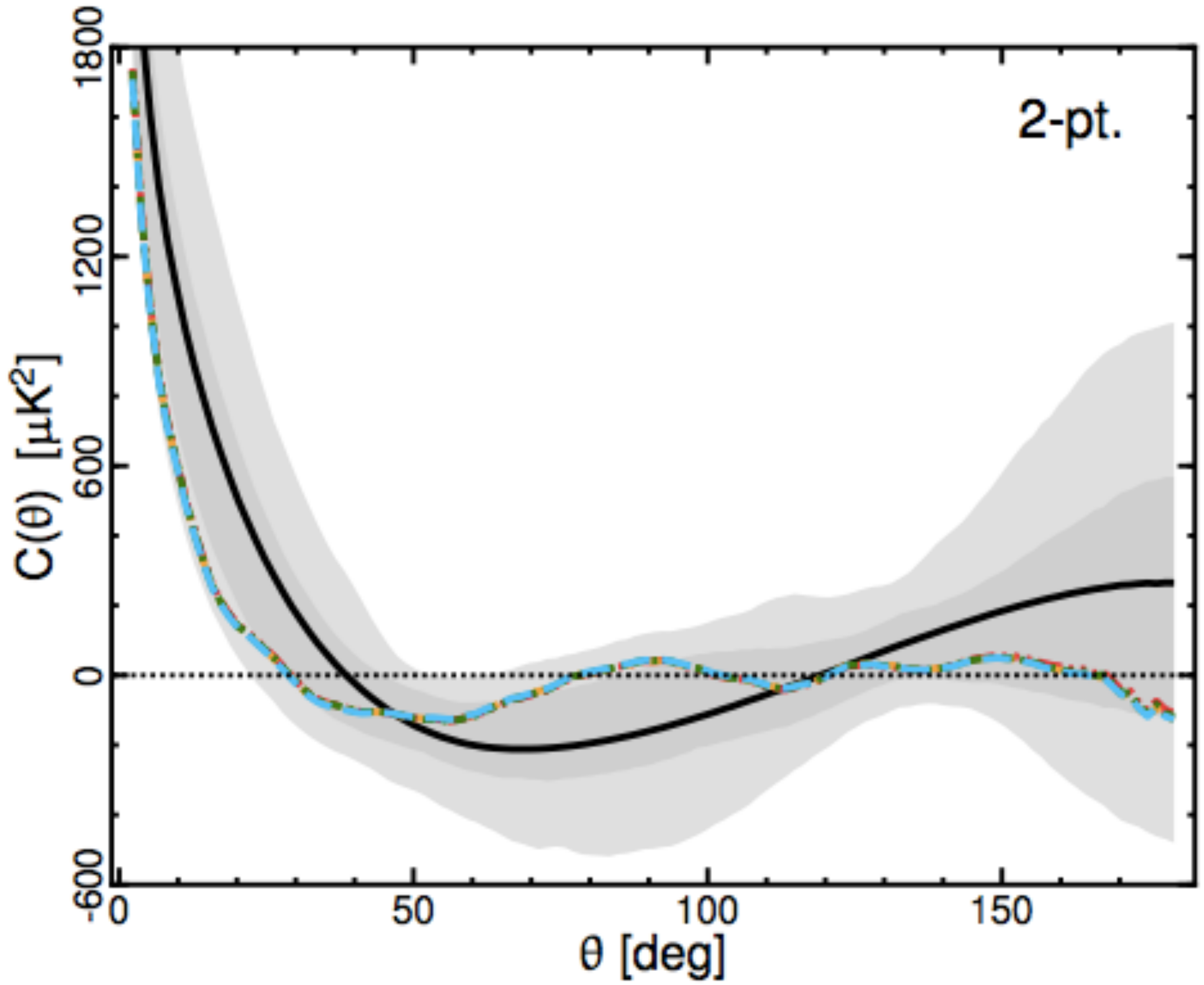
Planck satellite's picture of cosmic microwave background needs correction, some researchers argue.

Large scale lack of power and “wiggle”



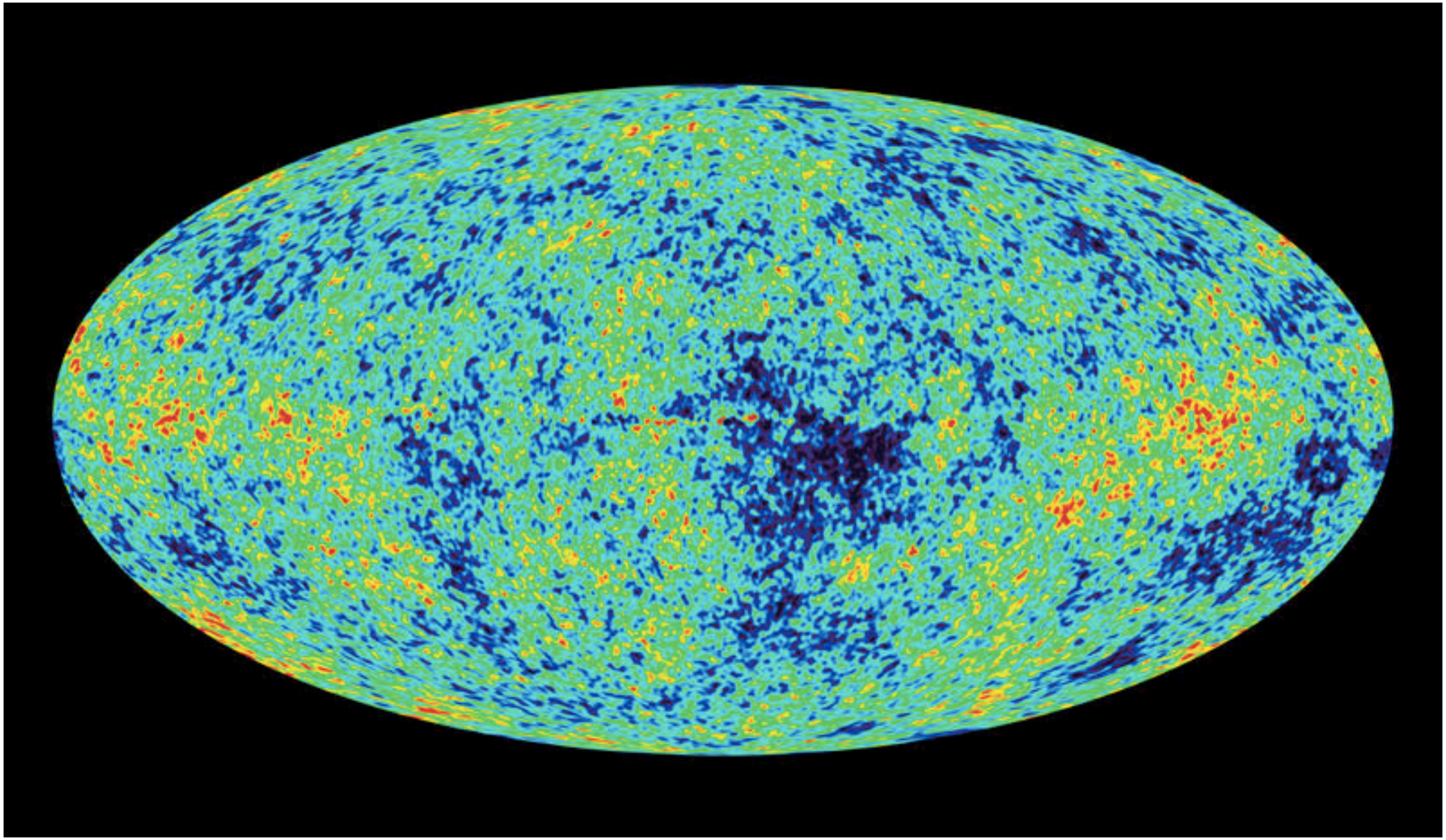
- Tentative link to pre-inflationary physics, if “just enough” inflation. Many challenges, both fitting to the data and in terms of model building (talk to Jonny and Mafalda)

Angular correlation function



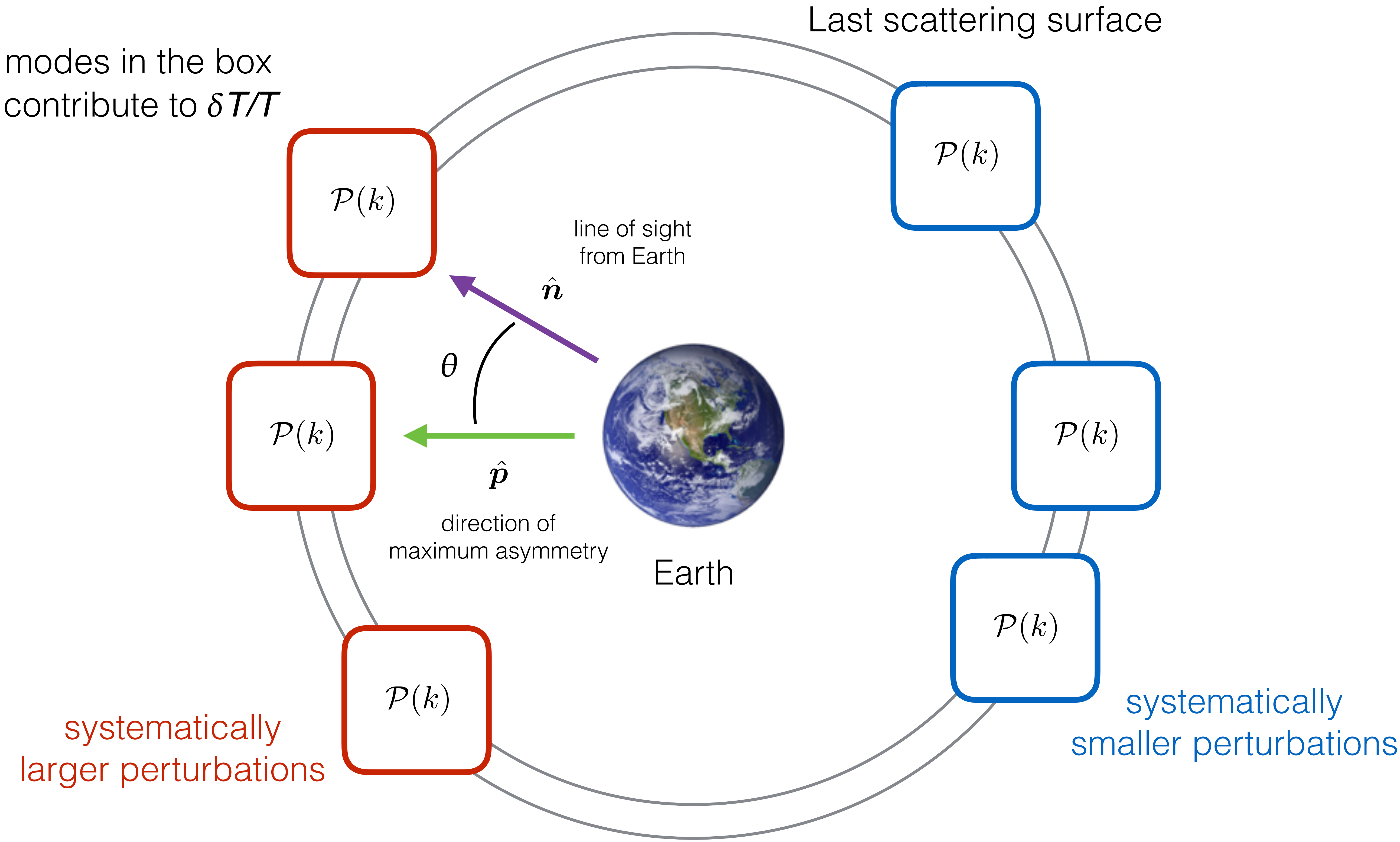
- Too close to zero at scales >60 degrees. p-value ~0.1%
- Even if a theoretical model explained why the primordial C(θ) was zero on large scales, the ISW effect would presumably add power

The cold spot

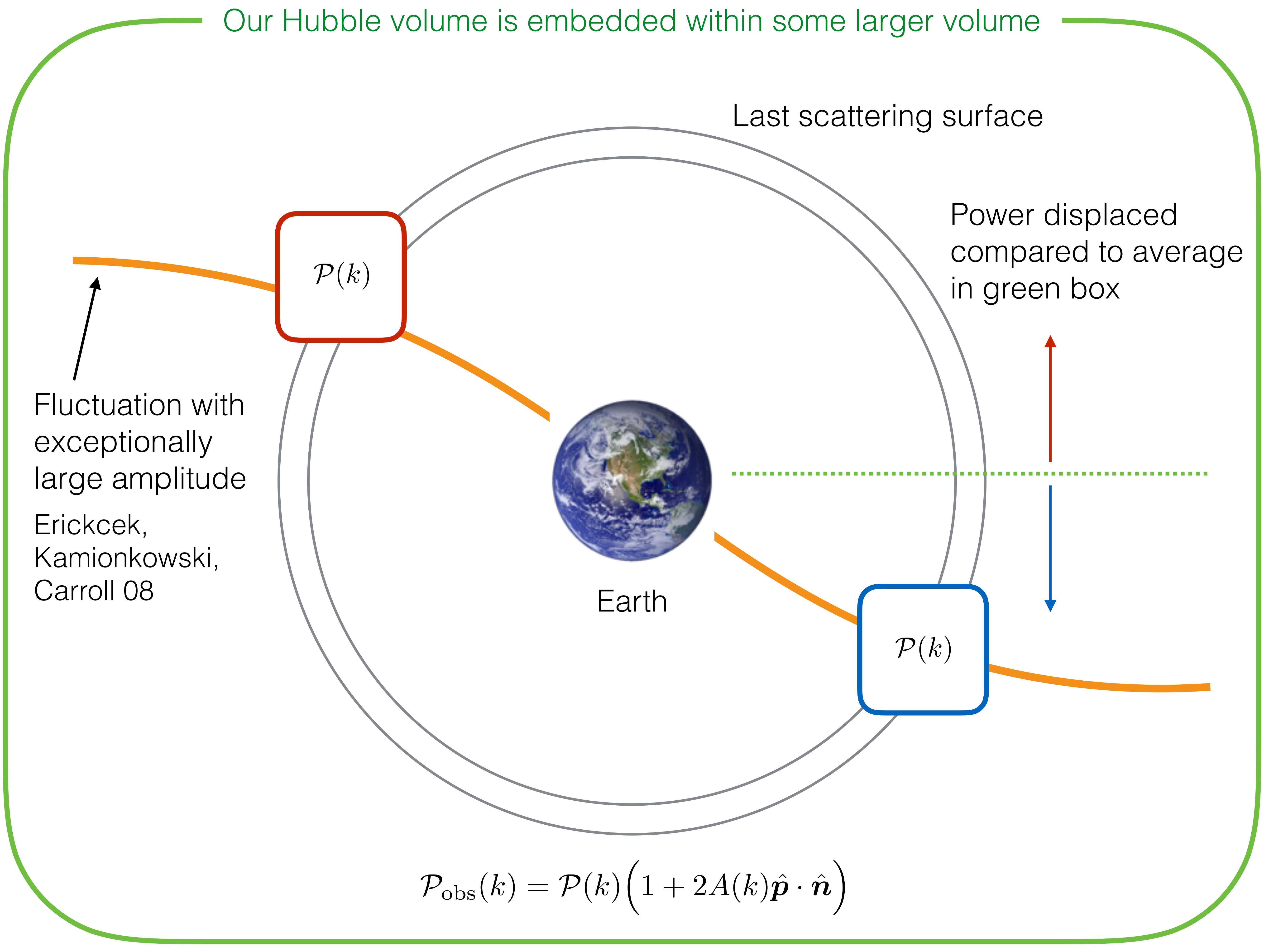


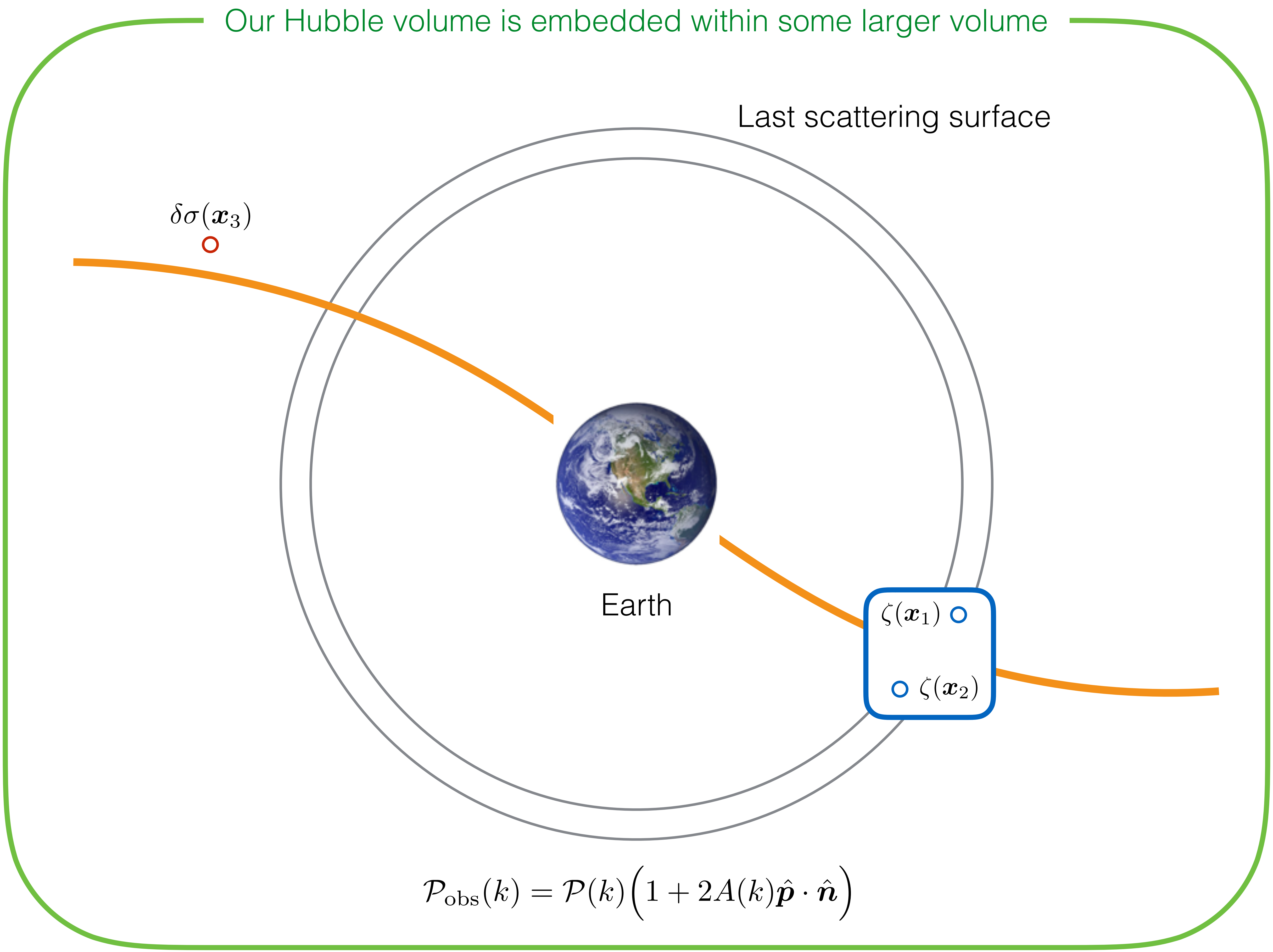
- Probably no good explanation (not an aligned void - Nadathur et al `14), but only rare because of the hot ring around it

The power asymmetry



$$\mathcal{P}_{\rm obs}(k) = \mathcal{P}(k)\Big(1 + 2\underbrace{A(k)}_{\text{amplitude}}\underbrace{\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{n}}}_{\cos\theta}\Big)$$


Our Hubble volume is embedded within some larger volume
Last scattering surface
Power displaced compared to average in green box
$\mathcal{P}(k)$
Fluctuation with exceptionally large amplitude
Erickcek, Kamionkowski, Carroll 08
Earth
$\mathcal{P}(k)$
$\mathcal{P}_{\rm obs}(k) = \mathcal{P}(k)\Big(1 + 2A(k)\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{n}}\Big)$

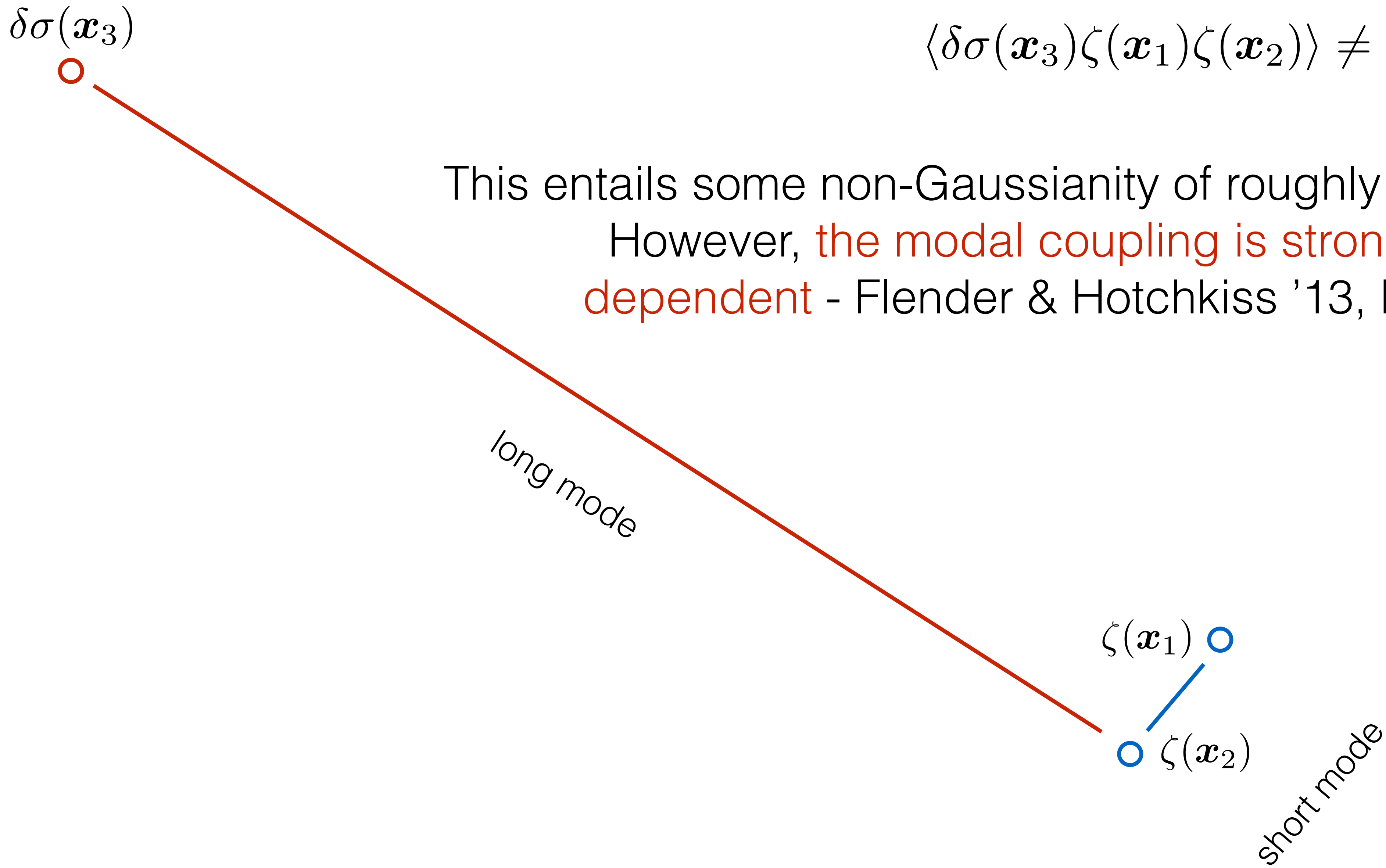

Our Hubble volume is embedded within some larger volume
Last scattering surface
$\delta\sigma(\boldsymbol{x}_3)$
Earth
$\zeta(\boldsymbol{x}_1)$
$\zeta(\boldsymbol{x}_2)$
$\mathcal{P}_{\rm obs}(k) = \mathcal{P}(k)\Big(1 + 2A(k)\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{n}}\Big)$

The small-scale fluctuation responds to the long wavelength mode only if

$$\langle \delta\sigma(\boldsymbol{x}_3)\zeta(\boldsymbol{x}_1)\zeta(\boldsymbol{x}_2)\rangle \neq 0$$

This entails some non-Gaussianity of roughly local type

However, the modal coupling is strongly scale dependent - Flender & Hotchkiss ’13, Planck ‘15



The amplitude of the response depends on how much correlation there is, which is roughly proportional to $f_{\rm NL}$

$$A(k) \sim f_{\rm NL} \times \text{amplitude of long mode}$$

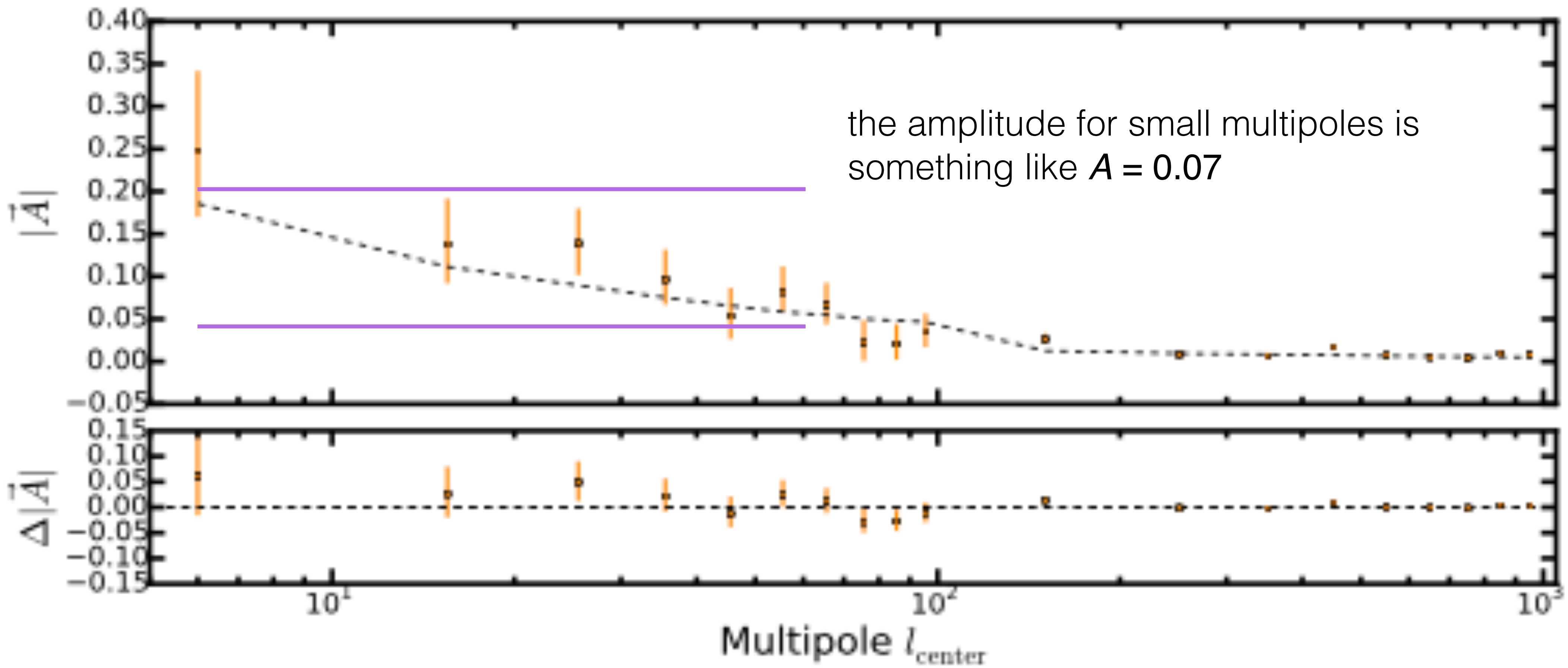
fit by power-law

$A(k) \sim k^{-0.5}$

must scale like

$k^{-0.5}$

doesn't depend on ***k***



Aiola et al. 15

$$\mathcal{P}_{\rm obs}(k) = \mathcal{P}(k)\Big(1 + 2A(k)\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{n}}\Big)$$

Power spectrum asymmetry

- We need a large amplitude super-horizon scale perturbation - or lots of superhorizon modes: Adhikari, Shandera & Erickcek `15
- Impossible with an adiabatic mode: Erickcek, Kamionkowski & Carroll `08
- If primordial, the anomaly is a signature of multiple fields
- The asymmetry has an order of magnitude large scale dependence than the power spectrum.
- This requires the inflaton field to generate quasi scale-invariant perturbations, with a second field generating scale dependent non-Gaussianity

Ruling out single-source models: Byrnes and Tarrant `15

Model building

- Multiple fields generate the perturbations
- The scale-invariant and Gaussian inflaton perturbations can generate the power spectrum
- Strongly scale-dependent non-Gaussianity can be generated by a strong scaling of the non-Gaussian field in this case, without self interactions
- Instead we need a large eta parameter $\eta_{\sigma\sigma} \sim -0.25 \quad n_A \simeq 2\eta_\sigma = -0.5$
- However, this makes the non-Gaussian field roll quickly, it either dominates over the inflaton which kills f_{NL}, or we have to start with such a tiny initial value that the field is in a quantum diffusion dominated regime and scale dependence goes away - eta cannot be a constant
- Byrnes, Regan, Seery & Tarrant '15 (see also Kenton & Mulryne `15)

The model giving this evolution is

$$\eta_1 = -0.25$$
$$\eta_2 = -0.08$$

inflation driven by the ϕ field

causes a step

$$V = V_0\left(1 - \frac{1}{2}\frac{m_\phi^2\phi^2}{M_\mathrm{P}^2}\right)\left(1 + \frac{1}{2}\frac{\sigma^2}{M_\mathrm{P}^2}\left[\frac{m_1^2 - m_2^2}{2M_\mathrm{P}^2}\tanh\frac{\sigma - \sigma_\mathrm{c}}{\sigma_\mathrm{step}} - \frac{m_1^2 + m_2^2}{2M_\mathrm{P}^2}\right]\right.$$
$$\left. - \frac{1}{2}\frac{\sigma_\mathrm{c}^2}{M_\mathrm{P}^2}\frac{m_1^2 - m_2^2}{2M_\mathrm{P}^2}\left[1 + \tanh\frac{\sigma - \sigma_\mathrm{c}}{\sigma_\mathrm{step}}\right]\right)$$

keeps everything monotonic

(totally contrived but that isn't the point)

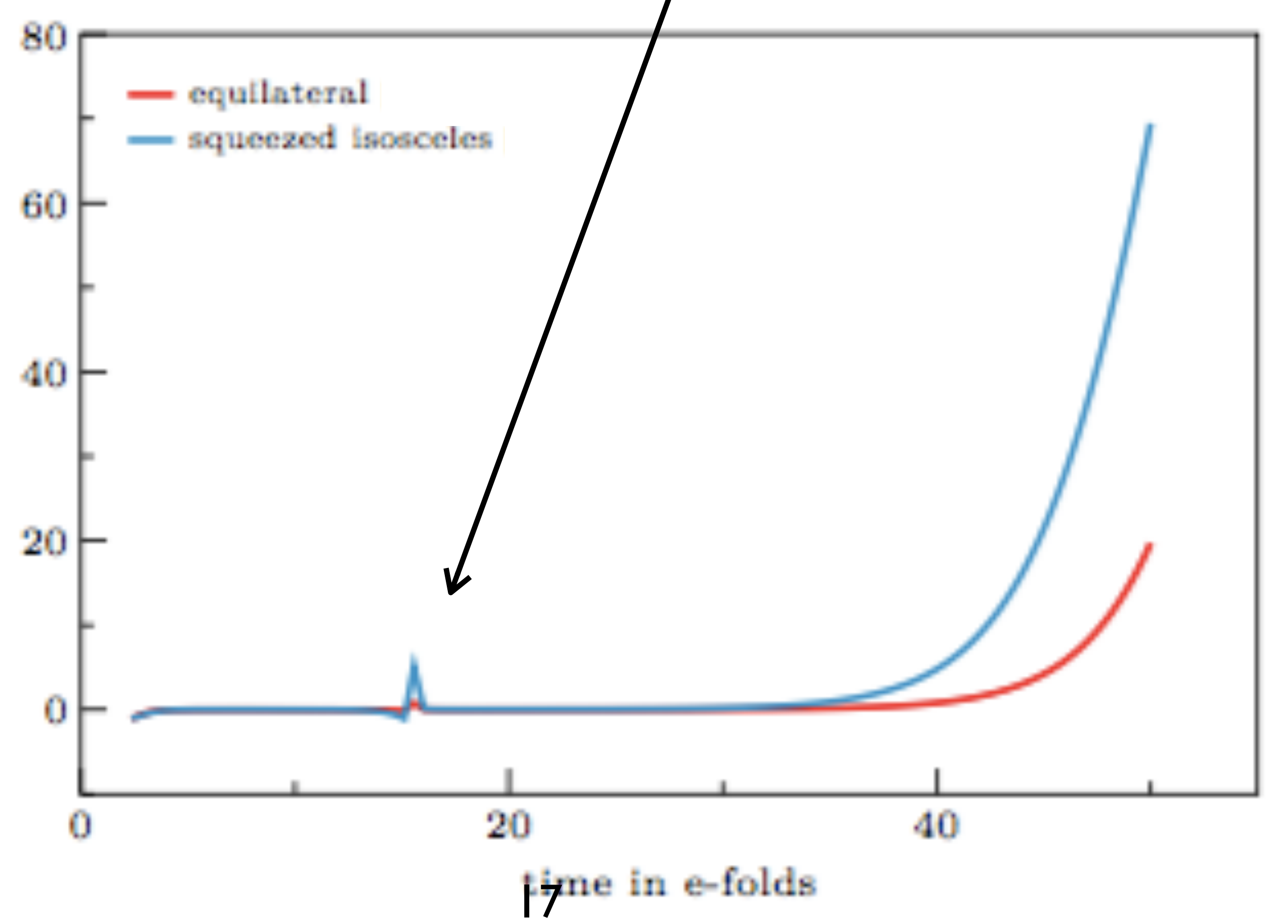
To safely compute its correlation functions we need a numerical method

The horrors of model building

$$V = V_0\left(1 - \frac{1}{2}\frac{m_\phi^2\phi^2}{M_\mathrm{P}^4}\right)\left(1 + \frac{1}{2}\frac{\sigma^2}{M_\mathrm{P}^2}\left[\frac{m_1^2 - m_2^2}{2M_\mathrm{P}^2}\tanh\frac{\sigma-\sigma_\mathrm{c}}{\sigma_\mathrm{step}} - \frac{m_1^2+m_2^2}{2M_\mathrm{P}^2}\right]\right.$$
$$\left. - \frac{1}{2}\frac{\sigma_\mathrm{c}^2}{M_\mathrm{P}^2}\frac{m_1^2-m_2^2}{2M_\mathrm{P}^2}\left[1+\tanh\frac{\sigma-\sigma_\mathrm{c}}{\sigma_\mathrm{step}}\right]\right).$$

only works for special parameter values and finely tuned initial conditions

The growth of f_{NL} with time for equilateral and squeezed configurations.
For the local template, there would be no difference



Fitting parameters to the asymmetry

Model

$\hat{f}_{\rm NL}^{\rm local} = 0.25$ $\hat{f}_{\rm NL}^{\rm equi} = 0.6$ $\hat{f}_{\rm NL}^{\rm ortho} = -1.0$

Planck2013 temperature only

$\hat{f}_{\rm NL}^{\rm local} = 2.5 \pm 5.7$ $\hat{f}_{\rm NL}^{\rm equi} = -16 \pm 70$ $\hat{f}_{\rm NL}^{\rm ortho} = -34 \pm 33$

Our model has a large bispectrum only on large scales,
small scales dominate the signal to noise

The model fits all constraints

- Many previous papers discussed the problem of $f_{NL}>100$, but without specifying the scale dependence and using the (scale invariant) local template

$$\frac{|a_{20}|}{5 \times 10^{-6}} \frac{|f_{NL}|}{10} \simeq 10 \left(\frac{A}{0.07} \right)^2$$

- Lyth `14, Kanno et al. `14, Kobayashi, Cortes & Liddle `15, and many others

- Despite having large f_{NL} on large scales, we numerically show the Planck response to the bispectrum from our model is $f_{NL}\sim 1$ (for all standard templates)

- In order to get the correct amplitude, we need to tune the amplitude of the super-horizon mode in sigma to be about 10-100 times larger than typical

- Without new physics (e.g. tunnelling and just enough inflation), we are trading a 3 sigma anomaly for a >10 sigma fluctuation!

- The low-l multipoles are not too large in our model

Anomaly/Asymmetry lessons

- Theorists are creative, any anomaly is hard to explain with a sensible model
- Once a model has been built to explain something strange, one must be careful to check if it predicts other strange things.
  Normally it will! Ideally this would explain a different anomaly, but often rules out the model

$$P_\zeta = P_{\rm iso}\left(1 + 2A\hat{\mathbf{n}}.\hat{\mathbf{p}} + B\left(\hat{\mathbf{n}}.\hat{\mathbf{p}}\right)^2\right)$$

Conclusions

- The latest Planck constraints remain broadly consistent with the simplest single field models of inflation, but absence of evidence is not evidence of absence
- Anomalies could be the first clue to new physics
- We have calculated in detail how the asymmetry depends on strongly-scale dependent non-Gaussianity, which bispectral shapes and scalings matter, and shown our complicated bispectrum does not conflict with Planck non-Gaussianity constraints
- A successful model must have the correct scaling and amplitude to explain a 10% effect, but not generate additional signatures which are ruled out. Beware of incomplete calculations
- When you have succeeded, compare the model to the significance of the asymmetry you wished to explain

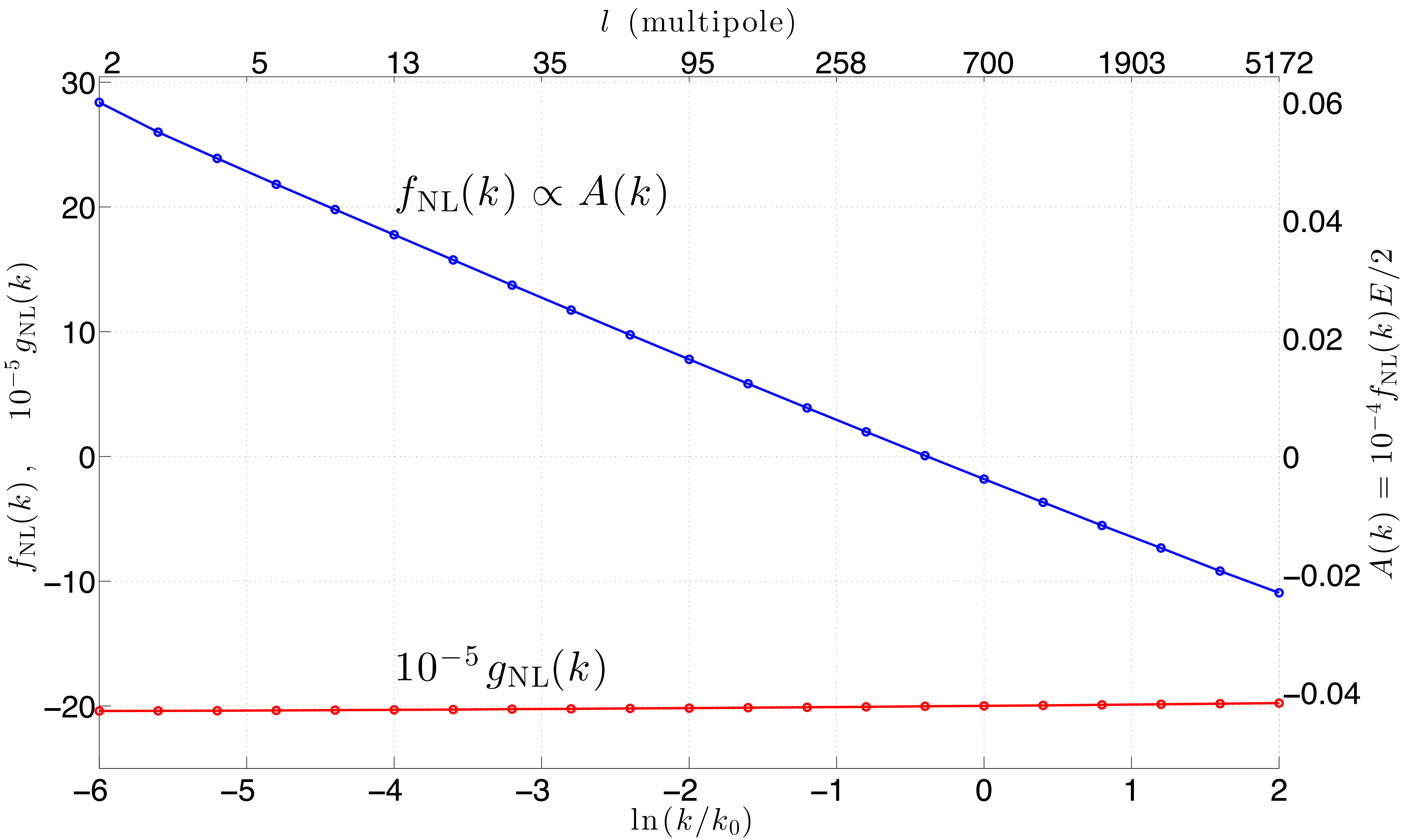
Model building attempt: Single-source

- Assume one field generates all of the perturbations
- To preserved the quasi scale invariance of the power spectrum, the only possible source of a strong scaling is a large self-interaction
- The log scale dependence for equilateral configurations is (Byrnes et al. `10)

$$n_{f_{NL}} \sim \frac{\sqrt{r_T}}{f_{NL}} \frac{V'''}{3H^2}$$

- For strong scale dependences, we need to include the higher-order terms. These resum to give a log instead of power law scale dependence
- Even worse, we find a large and scale invariant g_{NL}~10^5 and a huge quadrupolar modulation of the power spectrum, these latter two problems were not spotted before despite many papers performing similar model building

This is as good as it gets



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Byrnes and Tarrant `15

Too large g_{NL} and scale invariant B~14, 3 orders-of-magnitude too large
Problem arises due to strong scale-dependence, ignore “solutions” which ignore this