Primordial black holes
Work in collaboration with Sam Young, Ilia Musco, Ed Copeland, Anne Green and Misao Sasaki

Christian Byrnes
University of Sussex, Brighton, UK

Constraints on the small scales and inflation
A dark matter candidate?

8th of June, Jussieu, Paris

From very large to very small scales

- We have the “precision era” measurements on CMB and LSS scales
- These span approximately the largest 5-10 efoldings which are inside the Hubble scale today
- Lyman alpha, 21cm and spectral mu distortions in the CMB may add a similar range of scales in the (farish) future
- But inflation is believed to have lasted at least 50-60 efoldings
- So we only observe a small fraction of all scales
- Limits our ability to constrain the early universe

Why are small scale perturbations missing?

- We do of course accurately observe small scales, such as our solar system
- However, radiation pressure/chaotic solutions of gravitational collapse mean that the memory of initial conditions on small scales is erased
- We can reconstruct primordial perturbations only on scales which remain linear today ~ Mpc and above
- What can we do about all the shorter scales?

Gravitational waves: direct detectors

- Gravitational waves decouple - never washed out
- At non-linear order, scalar and tensor perturbations couple
- Large first-order scalar perturbations squared source second-order tensors
- Not really competitive yet
- Sensitivity is limited to about 2 orders of magnitude in length, i.e. to length scales comparable to arm length
- eLISA looks promising (launch 2034? Pathfinder was a sucess)

UCMHs

- Ultra Compact Mini Haloes (UCMHs)
- These are sufficiently compact objects to not be washed out by radiation pressures, but not so compact as to form a PBH
- They are a lot easier to form than a PBH, much lower threshold overdensity required
- The old strong constraints from them are based on annihilating WIMP DM - model dependent
- Talk to Pat

CMB spectral distortions

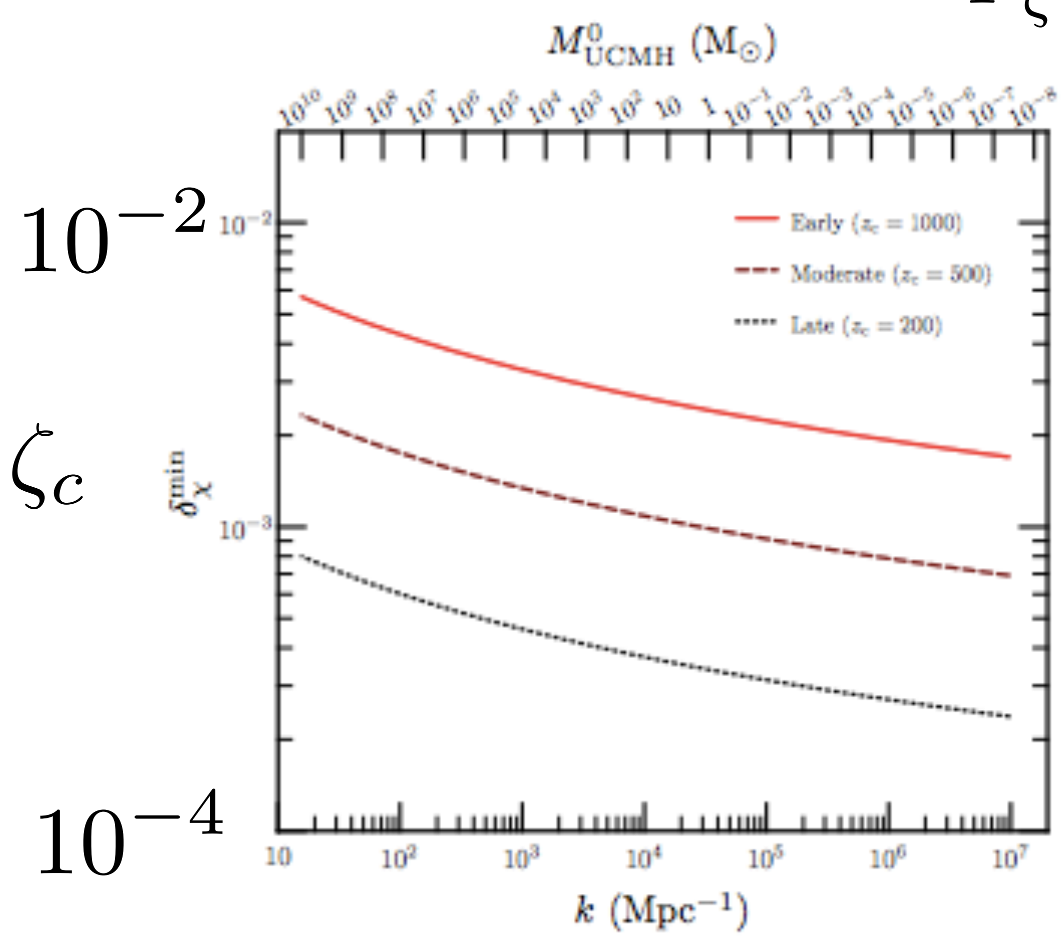
- COBE showed that the CMB is extremely close to being a black body with no chemical potential
- But it can't be exactly so, must be some deviations on smaller scales, eg from energy release into plasma (matter-photon interactions)
- Latter is silk damping, effective at small scales
- Pixie (NASA) or Prism (L class, ESA) are proposed missions to measure these distortions
- Could open up another 7 efolds, though with nothing like the current CMB precision
- Probes ~ same scales as UCMHs

Importance of the critical threshold

- Very roughly, PBHs constrained to be ~6-10 sigma fluctuations (separate universes 18-30 sigma fluctuations?) and zeta_c~1

$$P_\zeta \lesssim (\zeta_c/10)^2 \sim 10^{-2}$$

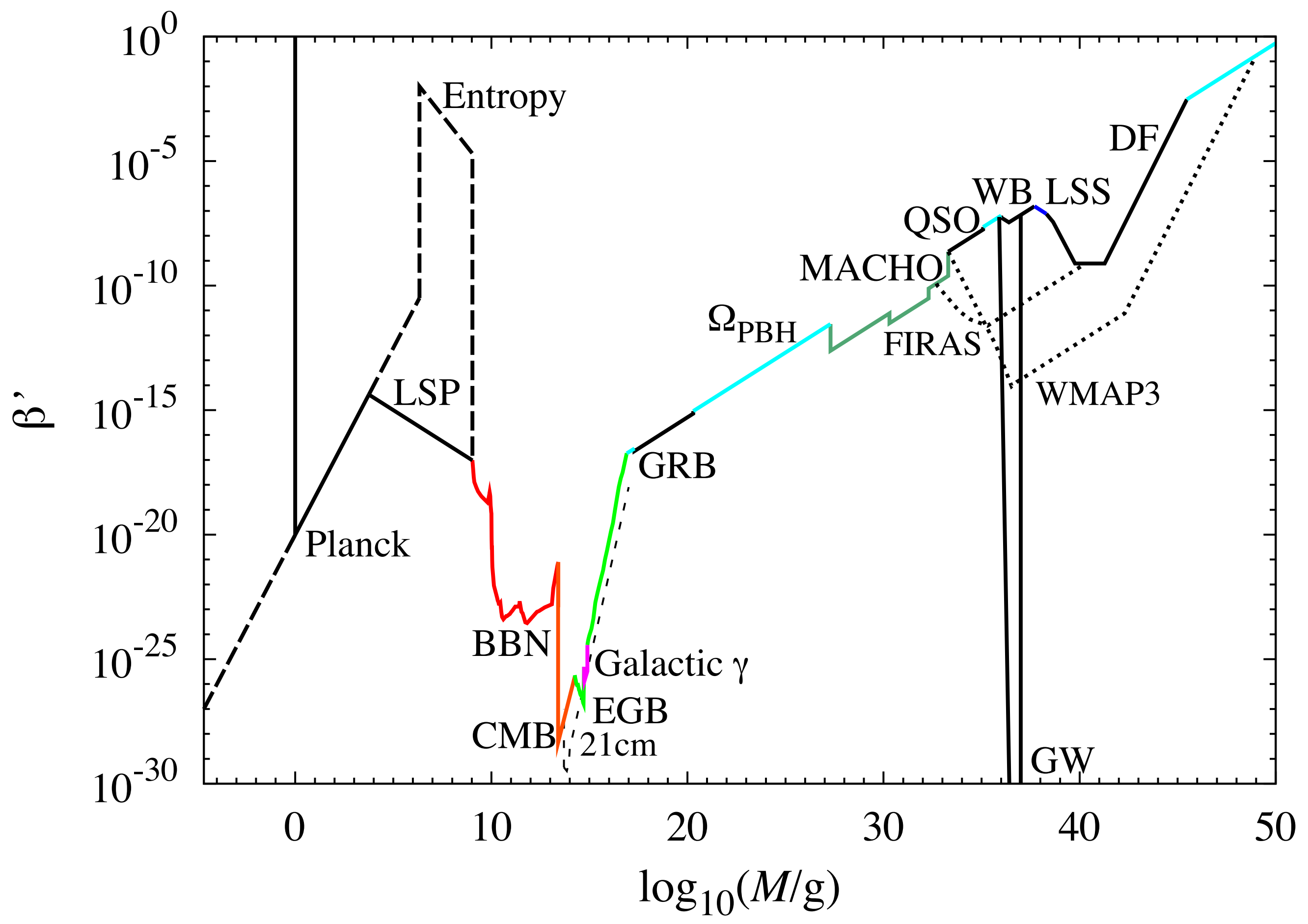
- UCMHs can be more common (they form later), but zeta_c~10^{-3} is much smaller
- Unlike for PBHs, zeta_c is scale dependent and poorly understood, even by an order of magnitude
- Over a more limited range of scales $P_\zeta \lesssim (\zeta_c/5)^2 \sim 10^{-6}$



Analytic estimates of zeta_c from
Bringmann, Scott, Akrami 2013
Order of magnitude uncertainty

PBH constraints

$$\beta' = \Omega_{\rm PBH}\Big|_{\rm formation}$$



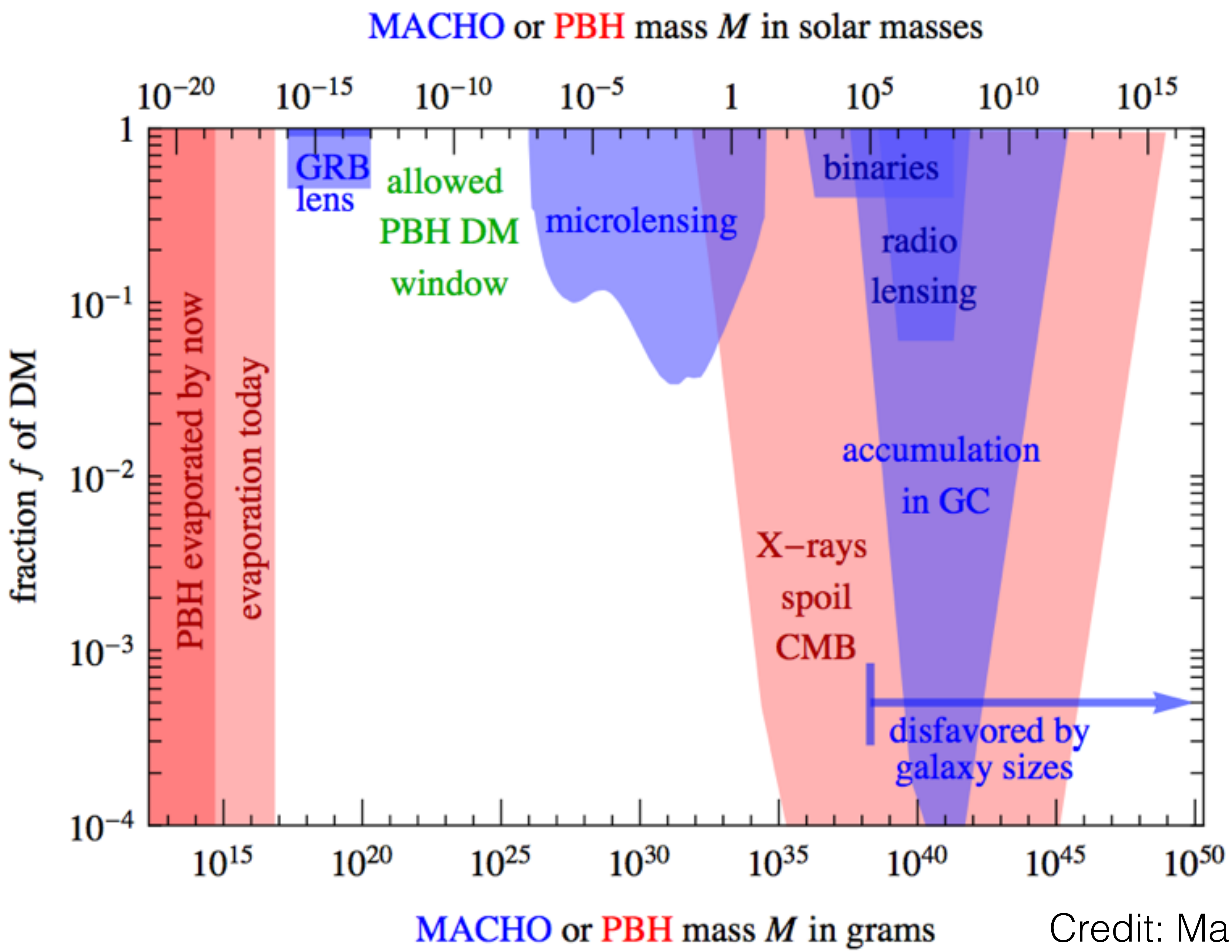
Carr et al; 2010

$$\rho_{PBH} \propto a^{-3}$$

$$\rho_{rad} \propto a^{-4}$$

Ω_{PBH} grows like the scale c=factor from formation until radiation-matter equality

Window for heavy PBH as DM



Credit: Marco Cirelli

Constraints on primordial black holes as dark matter candidates from star formation

Fabio Capela, Maxim Pshirkov, Peter Tinyakov

(Submitted on 26 Sep 2012 (v1), last revised 21 Jan 2013 (this version, v3))

By considering adiabatic contraction of the dark matter (DM) during star formation, we estimate the amount of DM trapped in stars at their birth. If the DM consists partly of primordial black holes (PBHs), they will be trapped together with the rest of the DM and will be finally inherited by a star compact remnant -- a white dwarf (WD) or a neutron star (NS), which they will destroy in a short time. Observations of WDs and NSs thus impose constraints on the abundance of PBH. We show that the best constraints come from WDs and NSs in globular clusters which exclude the DM consisting entirely of PBH in the mass range $10^{16}\mathrm{g} - 3\times10^{22}\mathrm{g}$, with the strongest constraint on the fraction $\Omega_{\rm PBH}/\Omega_{\rm DM} \lesssim 10^{-2}$ being in the range of PBH masses $10^{17}\mathrm{g} - 10^{18}$ g.

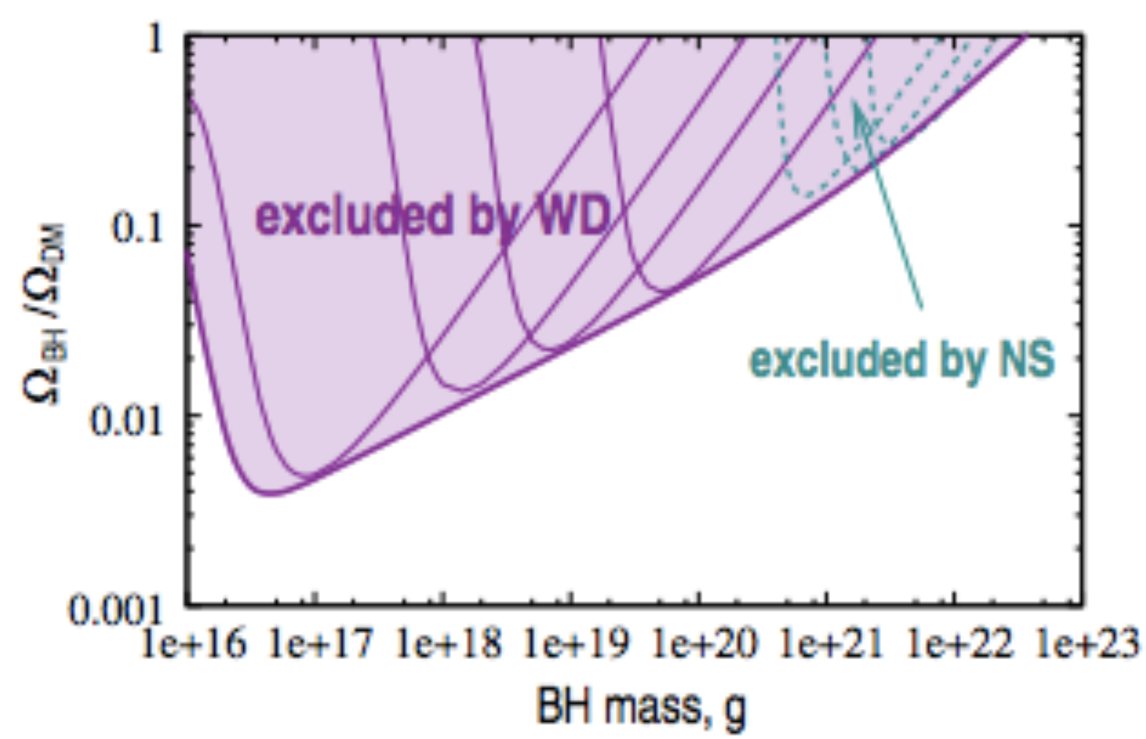
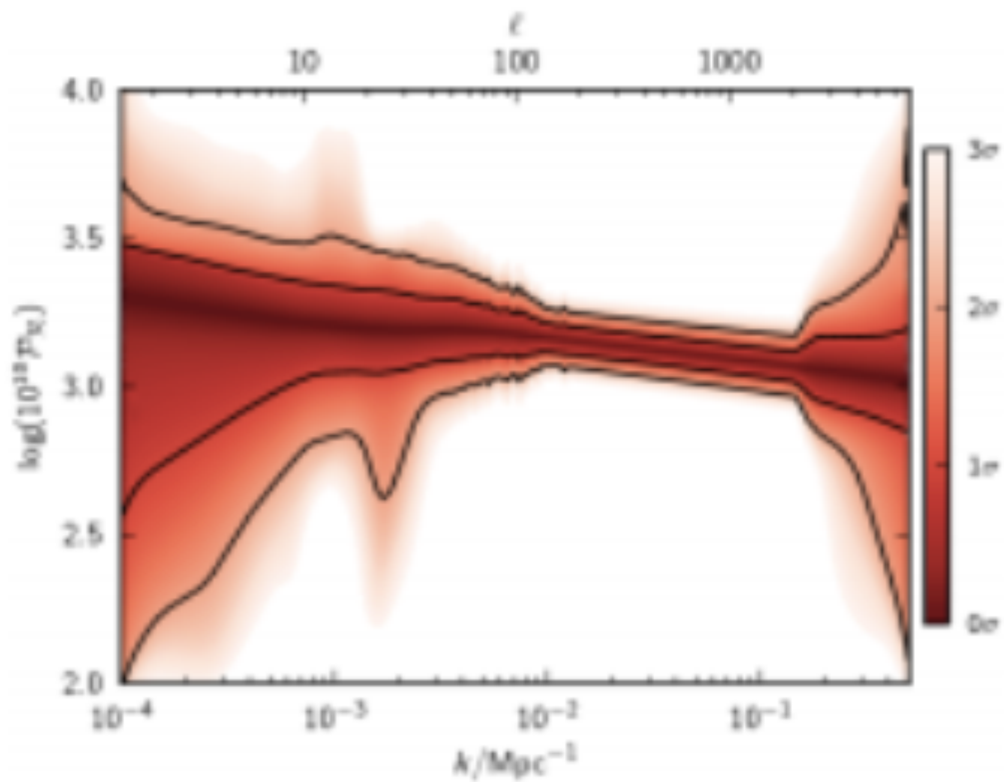


FIG. 3: Constraints on the fraction $\Omega_{\rm PBH}/\Omega_{\rm DM}$. Purple shaded region is excluded by observations of WDs and NSs in the centers of globular clusters. Thin curves show the exclusions from different star masses.

Current power spectrum constraints



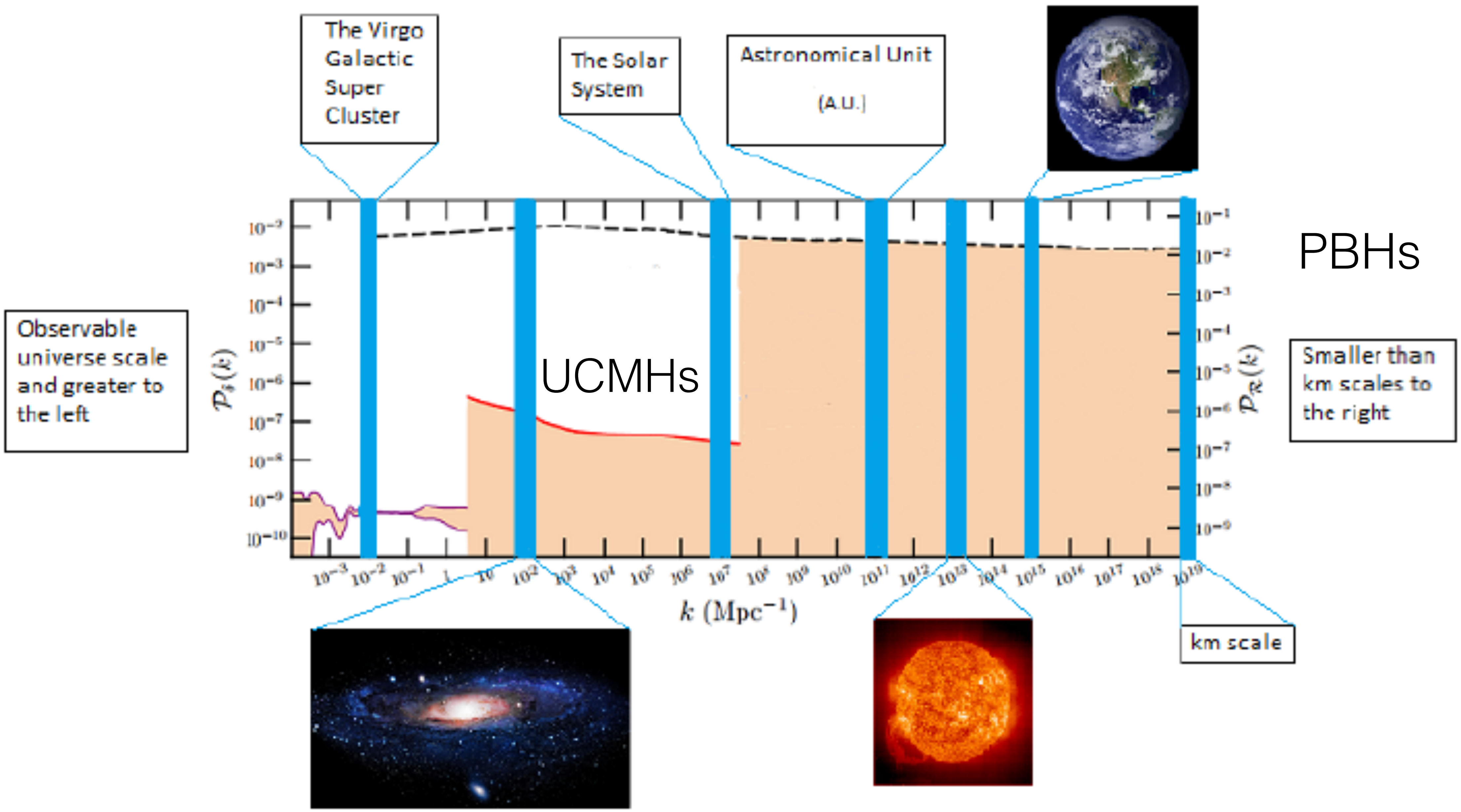
Planck 2015
constraints on inflation

Fig. 26. Bayesian reconstruction of the primordial power spectrum averaged over different values of $N_{\rm int}$ (as shown in Fig. 24), weighted according to the Bayesian evidence. The region $30 < \ell < 2300$ is highly constrained, but the resolution is lacking to say anything precise about higher ℓ. At lower ℓ, cosmic variance reduces our knowledge of $\mathcal{P}_{\mathcal{R}}(k)$. The weights assigned to the lower $N_{\rm int}$ models outweigh those of the higher models, so no oscillatory features are visible here.

- Featureless power law over 1 decade in scales (or log(2300/30)=4.3 efolds)
- Could the perturbations grow dramatically on small scales?

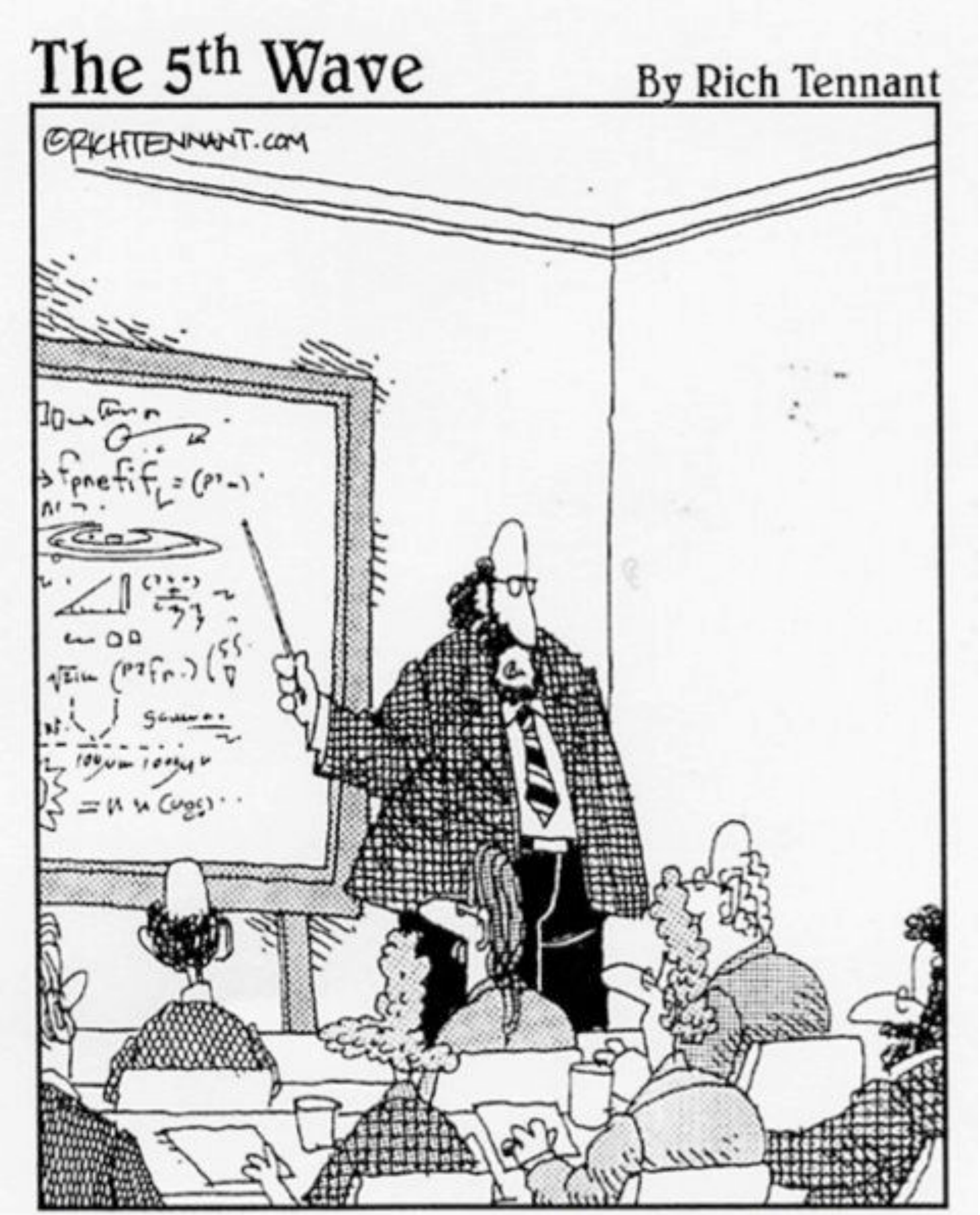
Why not?

Power spectrum bounds



Scales to the right correspond to PBHs which decay before nucleosynthesis
Bringmann, Scott, Akrami 2011, modified by A. Gergett

Even things which probably
don't exist can matter!



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

Slide untouched since 2013 seminars

PBHs as a DM candidate

- Two possibilities still exist
- 1. A narrow window around $M \sim 10^{20}$ g, where observational constraints are weak
- However the narrowness of the window means a strong spike in the power spectrum would be required
- 2. Relics. If PBHs are light when they form, they will have decayed by today. However the Hawking decay law (1/M) must break down at the quantum gravity scale
- This might leave a relic, this is also a potential solution to the information paradox
- Such Planck mass sized relics are a viable candidate and much easier to form from a model building perspective
- Planck mass DM would be so rare that its hard to see how to ever detect it

What about the 30 solar mass range?

- The LIGO mass range? Julian's talk

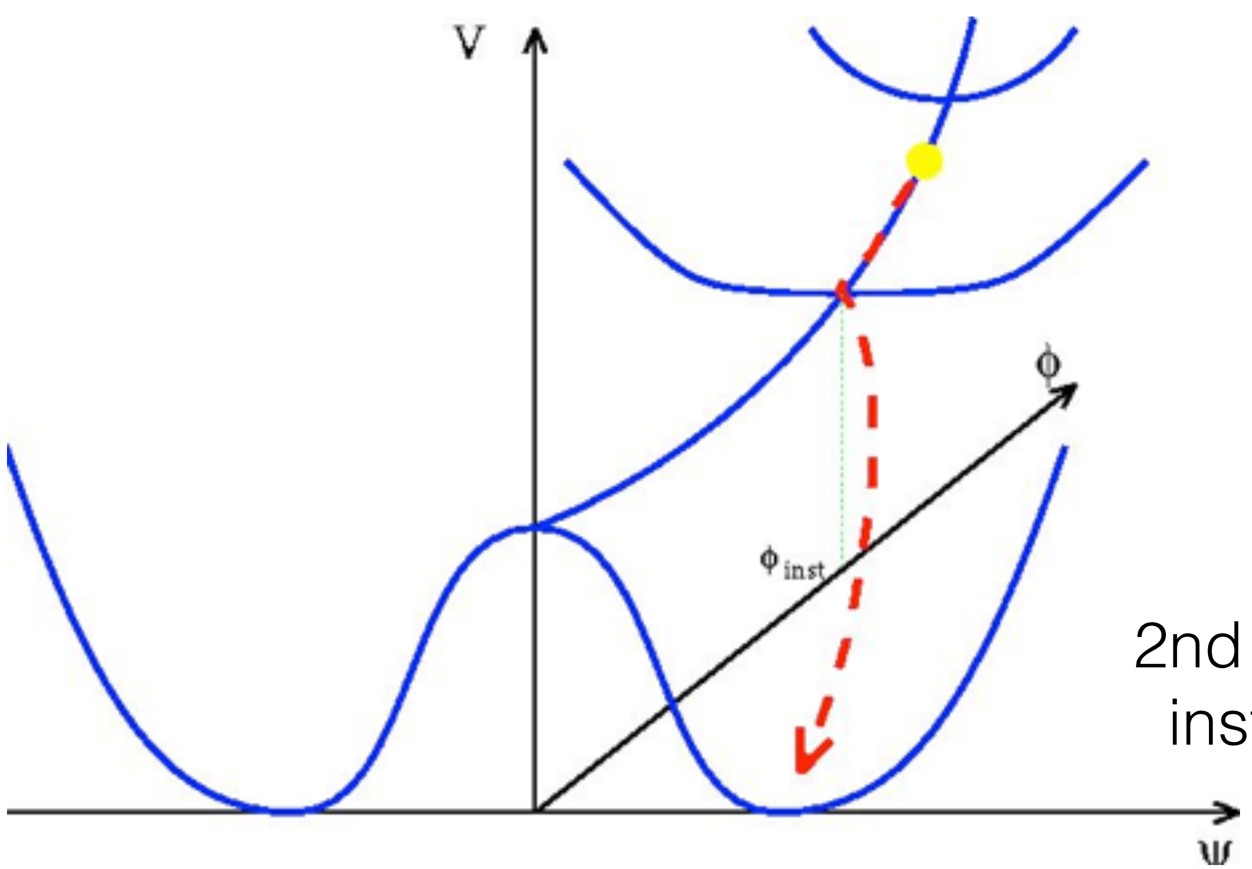
- However, constraints from accretion have to be wrong by 4 (or 2) orders of magnitude. Is astrophysics that bad?

- If yes, we should really reconsider the constraints on all mass ranges above 10^{15}g (bound to not be decaying yet)

- The calculation of the expected merger rate is very hard, Sasaki et al 2016 estimate the merger rate to be ~1000 times larger than Bird et al (and then the number is just compatible with the (wrong?) astrophysical constraints)

Hybrid inflation

- Hybrid inflation: popular model in which a second stage generates much larger small scale perturbations (also highly non-Gaussian)

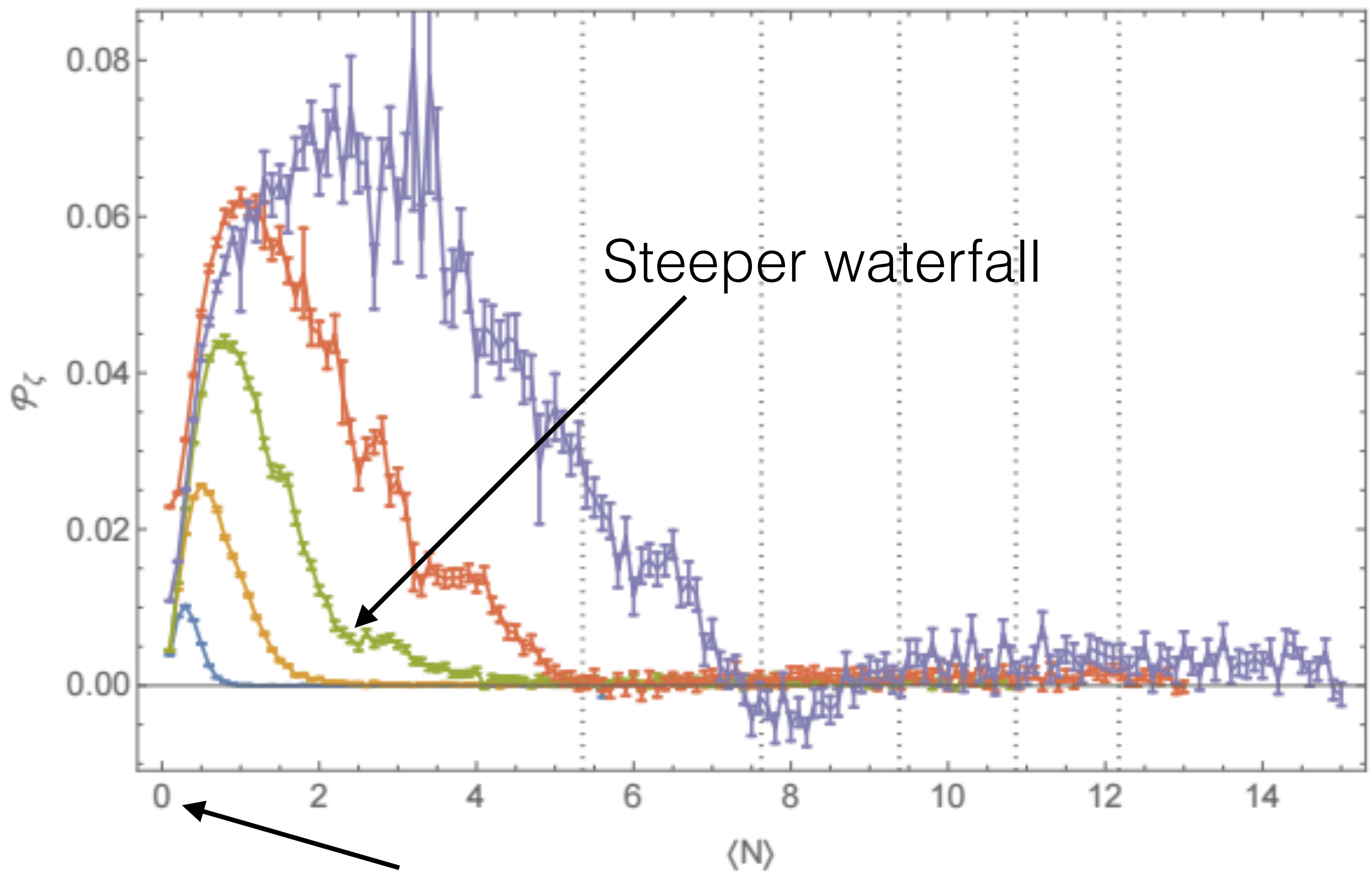


1st stage from inflaton field, Gaussian perturbations

2nd stage from waterfall field - tachyonic instability, non-Gaussian perturbations

Growth of perturbations

- Sensitive to steepness of waterfall phase
- The steeper it is, the quicker inflation ends
- PBHs constrain the waterfall phase to last less than ~5 efolds of the 50 required



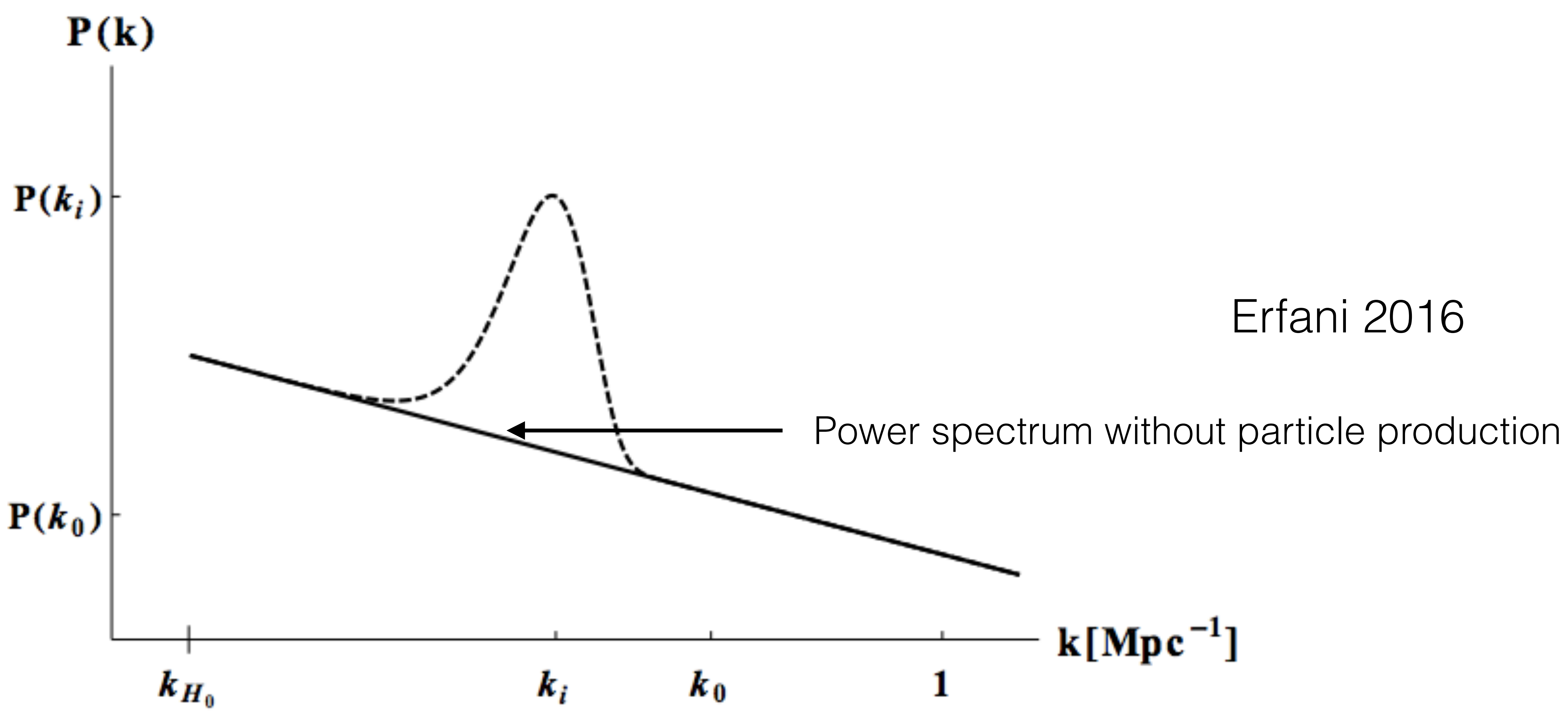
Steeper waterfall

Kawasaki and Tada 2015

End of inflation and the smallest scales

Observable scales

Particle production during inflation



Erfani 2016

- This can produce a spike instead, and be tuned to occur at any mass/scale range
- However, Hubble time makes it hard to make the width narrower than about factor 2 in log(k)

Generic model building thoughts

- To produce any PBHs, we need to power spectrum to grow by ~ 7 orders of magnitude
- If that happens, we should not use the usual spectral index (+running & running of running) parametrisations of power spectrum
- If spectrum turns blue, expect the smallest scales to form the most PBHs
- To have a DM candidate other than relics, instead need a narrow spike, e.g. transition between two phases of inflation, inflection point, particle production, phase transition.
- Hard to make the spike narrower than factor of a few in k, also all of the above models tend to generate non-Gaussianity
- Or do we want a very broad peak/mass spectrum instead - Carr's talk (paper to come with Kühnel and Sandstad)

The Gaussian calculation

$$P(\zeta) = \frac{1}{\sqrt{2\pi}\sigma} exp\left(-\frac{\zeta^2}{2\sigma^2}\right)$$

$$\beta \simeq \int_{\zeta_c}^{\infty} P(\zeta) d\zeta \simeq exp\left(-\frac{\zeta_c^2}{2\sigma^2}\right)$$

$$\frac{\sigma}{\zeta_c} = \sqrt{\frac{1}{2\ln(1/\beta)}} \qquad \zeta_c \simeq 1$$

$$\mathcal{P}_\zeta \lesssim 10^{-2}$$

This shows why we probe ~10 sigma fluctuations, and why constraints only mildly depend on beta

The tail is very sensitive to non-Gaussianity (skewness, kurtosis, etc)

Power spectrum constraints only sensitive to log of the observational constraints

So small changes in the amplitude of perturbations changes the PBH formation rate exponentially

We will see that even small non-Gaussianity is very important (small f_{NL} can mean a large skewness, when the amplitude of perturbations grow)

PBH formation is very rare, so we are measuring the tails of the pdf's, typically larger than 5-10 sigma deviations

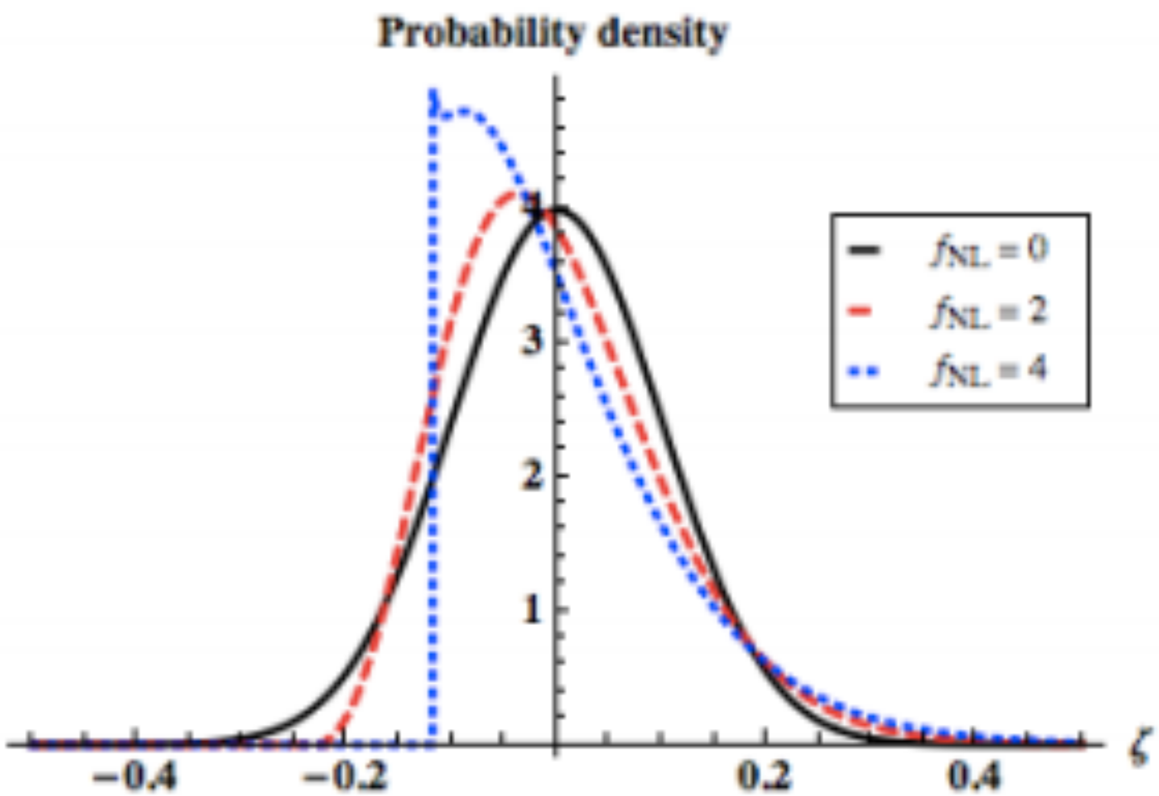
So skewness/kurtosis really matters!

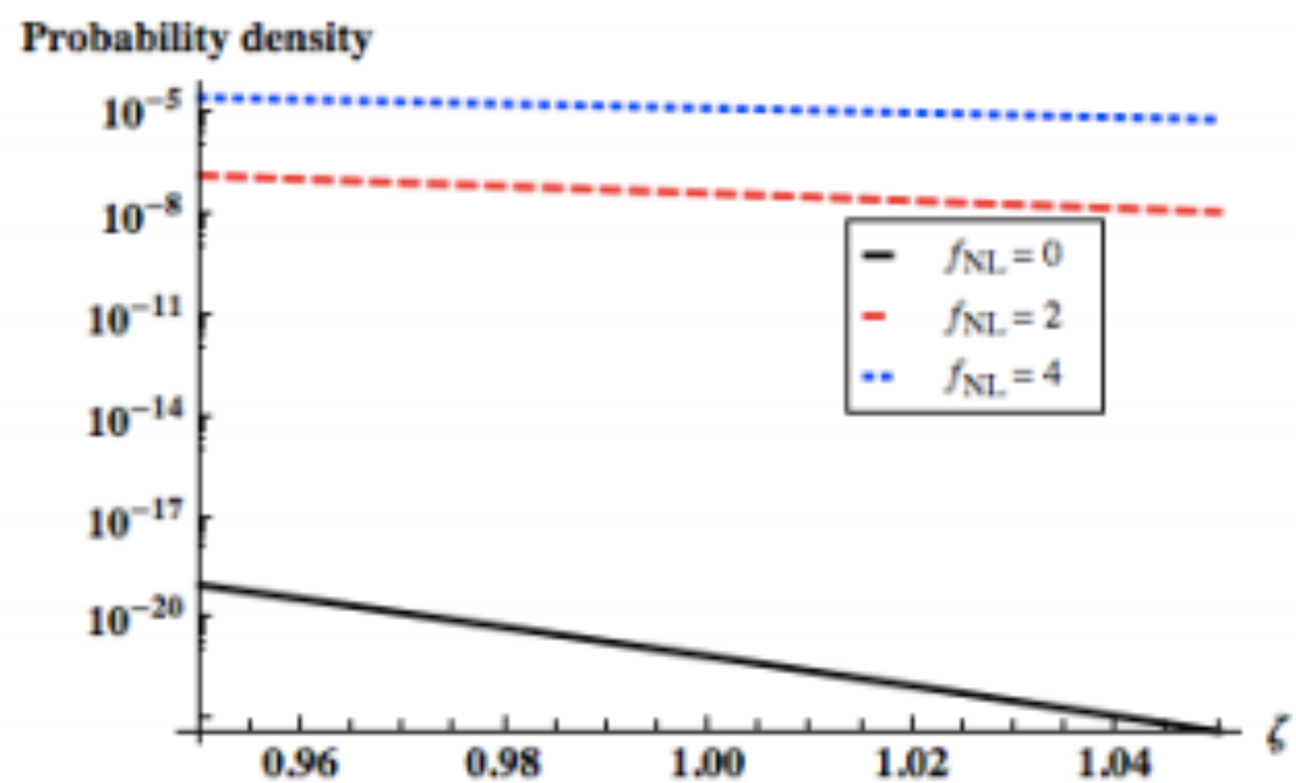
Lets take it into account, and see how the normal constraints on the power spectrum change

Probing the tail

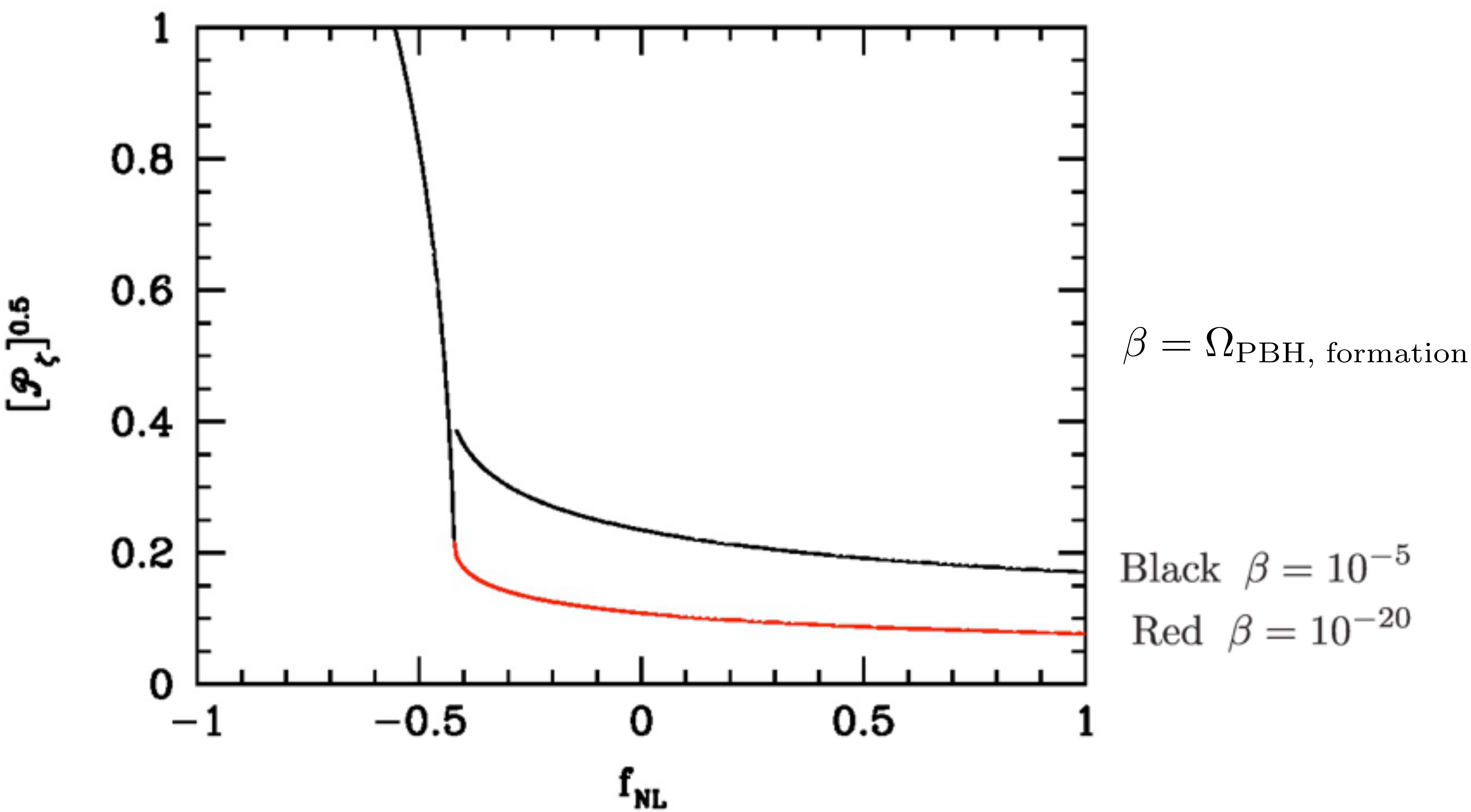
Local non-Gaussianity (chi-squared)

$$\zeta = \zeta_g + \frac{3}{5} f_{NL} \left(\zeta_g^2 - \sigma^2\right)$$





Large influence of small f_{NL}



Results especially dramatic for negative f_{NL}

If PBHs are detected in the future, a negative f_{NL} (and all higher order parameters zero) on the relevant scales is ruled out, unless it has a tiny amplitude

Generalisation in progress with Sam Young

Very large and positive f_{NL}

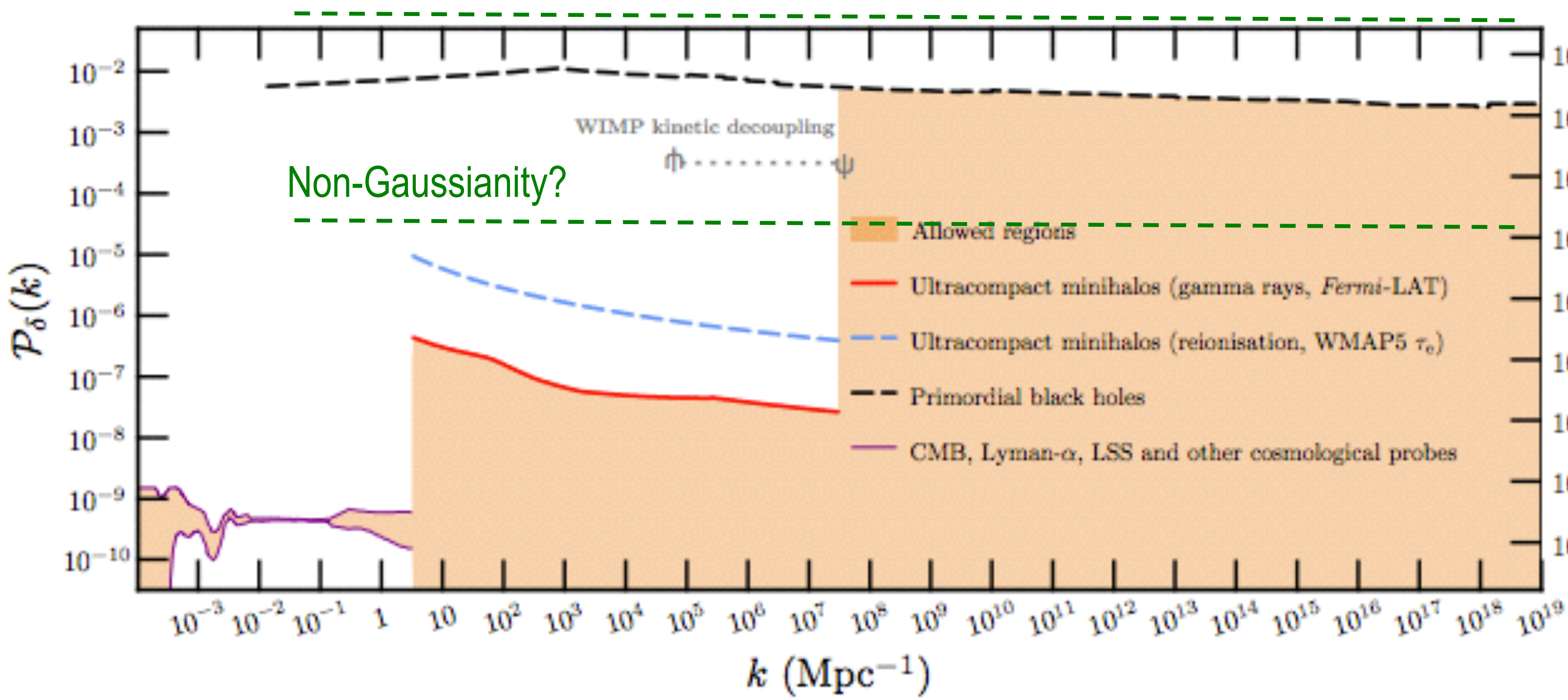
- Results are about the square of the Gaussian case, hence much more stringent

$$\beta = 10^{-20}, \;\; \mathcal{P}_\zeta \simeq 10^{-2} \rightarrow \mathcal{P}_\zeta \simeq 10^{-4}$$

Gaussian Chi-squared

- Limit of very small and very large non-Gaussianity was previously known, we recover those results and interpolate between them
- Very small: Seery & Hidalgo '06
- Chi squared non-Gaussianity: Avelino '05 and Lyth '12

Constraints on the power spectrum again

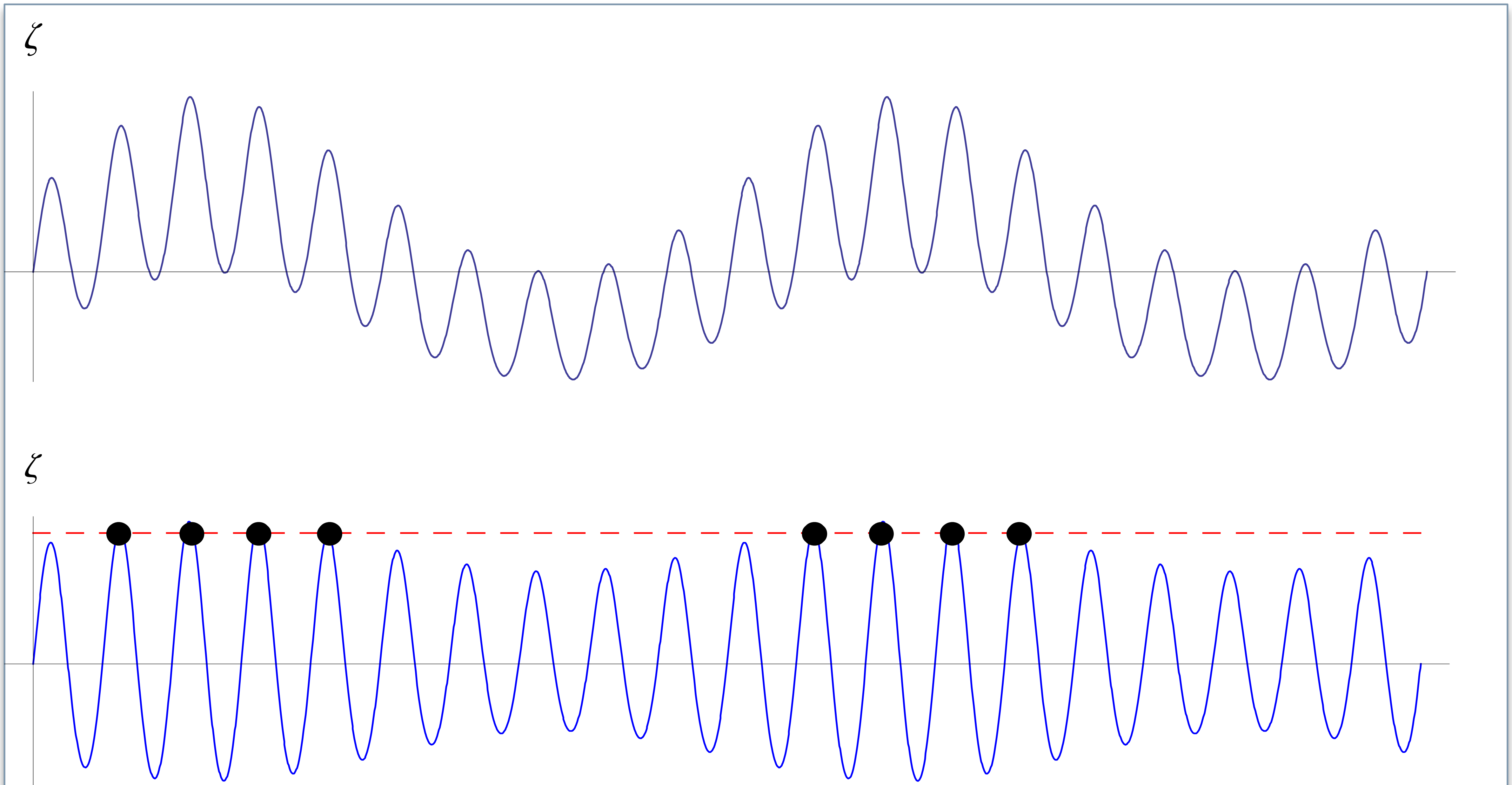


It is “common” for multifield models to generate a relevant level of non-Gaussianity

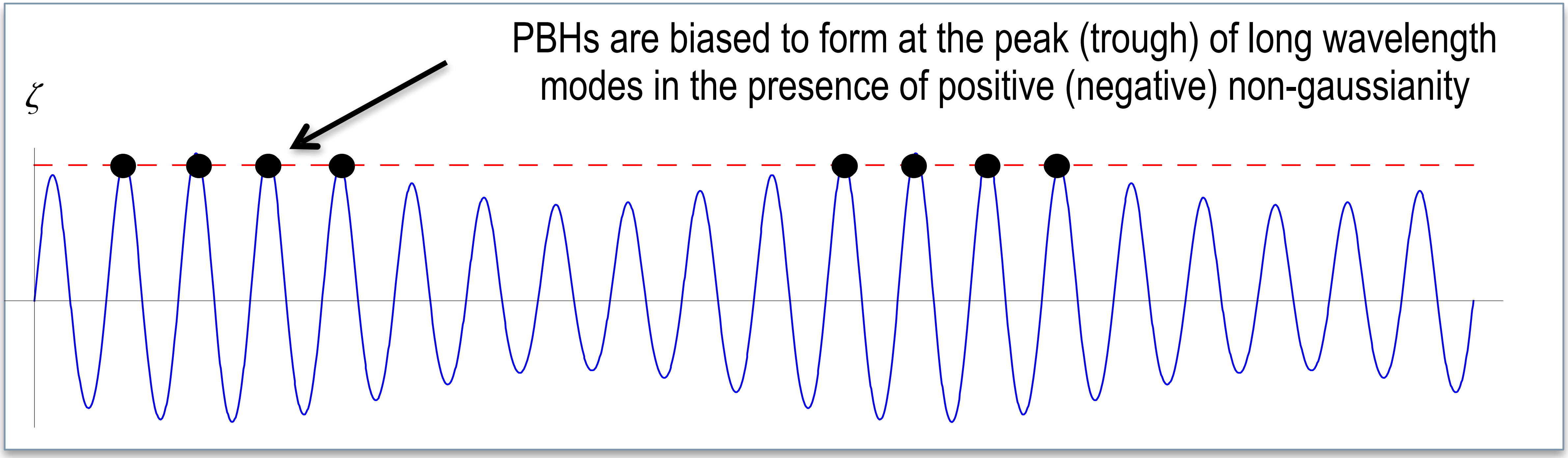
Modal coupling and non-gaussianity

- Non-Gaussianity represents a coupling between different modes
  - Local-type non-Gaussianity has a strong signal in the squeezed limit – coupling modes of different scales
- Make use of peak-background split to separate Gaussian component into short and long components
  - Super-horizon modes do not affect PBH formation
  - Indirect effect due to modal coupling
- Coupling to super-horizon modes can affect local power spectrum and non-gaussianity
  - And the abundance of PBHs

modal coupling



Primordial black hole bias

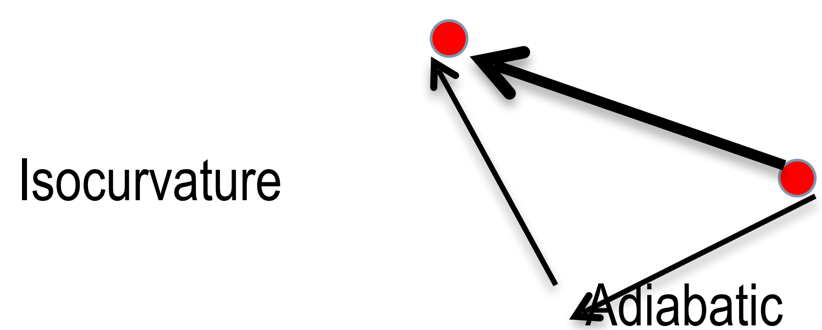


Does this biasing produce observable consequences on large scales?
What would this tell us about the early universe?

Primordial black hole bias

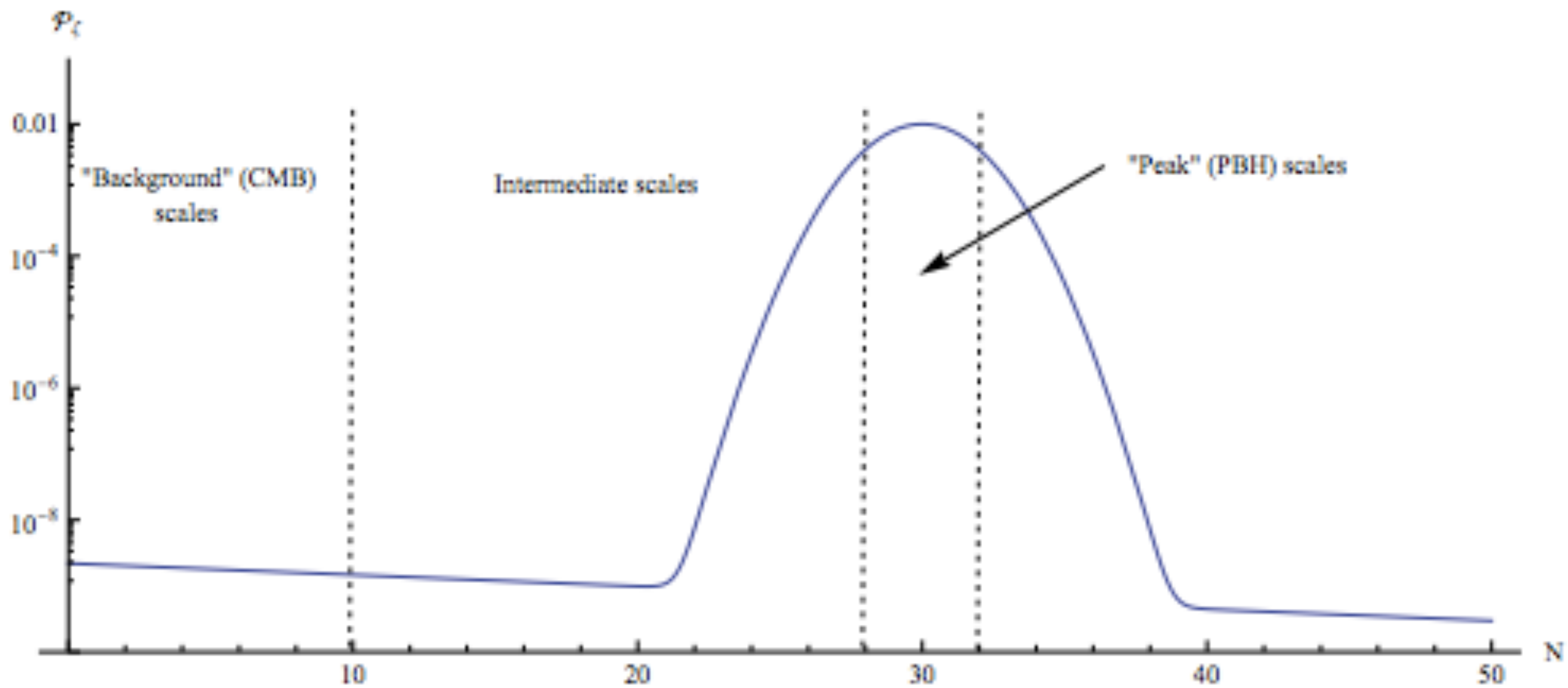
- *Scale-independent bias*: a perturbation (halo) is more likely to collapse if it is in the middle of a larger-scale over-density (a bigger halo)
  - Not relevant for PBHs as larger super-horizon density modes are strongly suppressed
- *Scale-dependant bias*: arises from the modal coupling due to non-gaussianity
  - Extremely relevant for PBHs
  - The effect of both is being tested numerically by Ilia

Isocurvature modes



Planck constrains isocurvature modes to <% level
Single-field inflation only generates adiabatic perturbations

Most models are ruled out



We study the correlation between CMB and PBH scales due to non-Gaussianity
Constraints are very tight, $f_{NL}<10^{-2}$, a value expected in all inflationary models
Single-field survives for special reasons
Assuming constant f_{NL}, all multifield models producing a significant number of PBHs are ruled out by the isocurvature constraint
This is independent of the PBH mass
S Young and CB 2015, see also Tada & Yokoyama 2015

Summary

- PBHs are the unique DM candidate not requiring a new particle or gravitational law
- Under observational pressure except a few small mass windows
- If they exist, relics are the easiest mass to produce from inflation, naturally associated to end of inflation.
- PBHs provide unique constraints on small scales
- If dark matter is made of PBHs, very tight constraints can be placed on the non-Gaussianity parameters
  - Nearly all models can be ruled out as a mechanism for producing PBH dark matter
  - Single-field inflation not ruled out
- Any future detection of PBHs, non-Gaussianity, or isocurvature modes can tell us a lot about the early universe

PBHs might not exist, but they are useful!