Model-independent tests of linear growth of large scale structure

Alireza Hojjati
Simon Fraser University

Linear growth of structure

Theory of gravity :

GR:

$$k^2\Phi = -4\pi G a^2 \rho\Delta$$
$$k^2(\Phi - \Psi) = 12\pi G a^2 (\rho + P)\sigma$$

Parametrized:

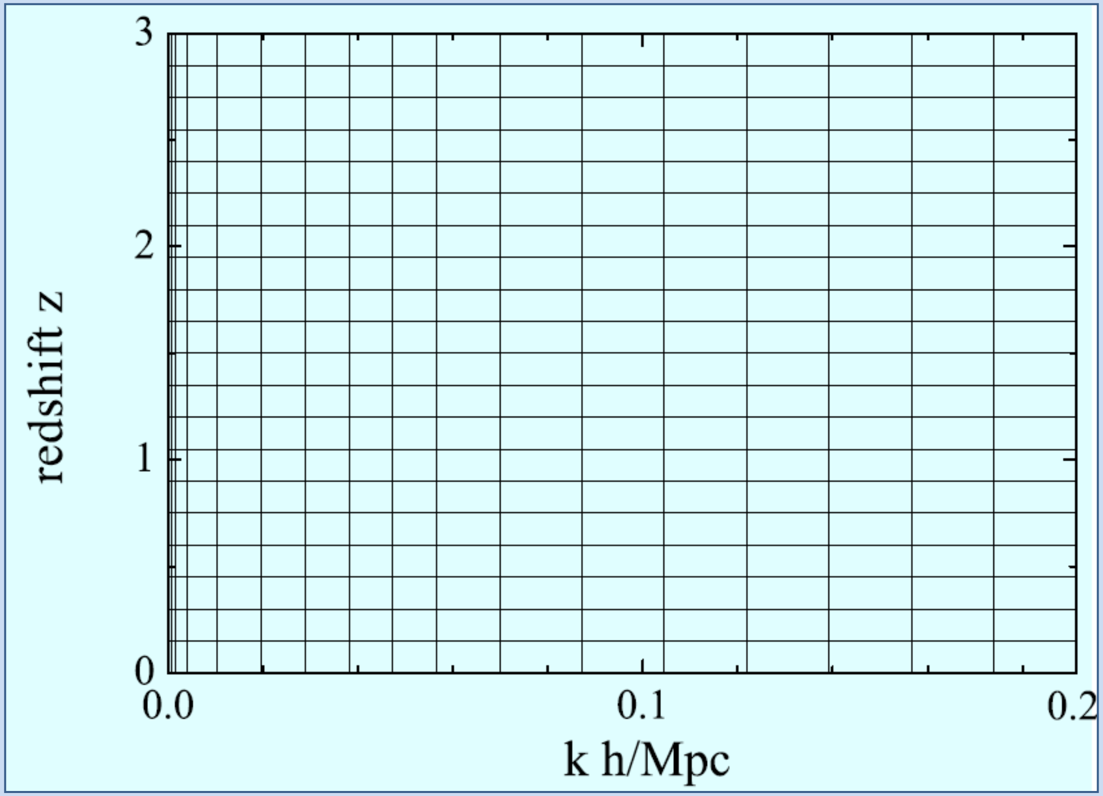
$$k^2\Psi = -4\pi \mu(k,a) G a^2 \{\rho\Delta + 3(\rho + P)\sigma\}$$
$$k^2(\Phi - \gamma(k,a)\Psi) = 12\pi \mu(k,a) G a^2 (\rho + P)\sigma$$

ΛCDM : μ = γ = 1

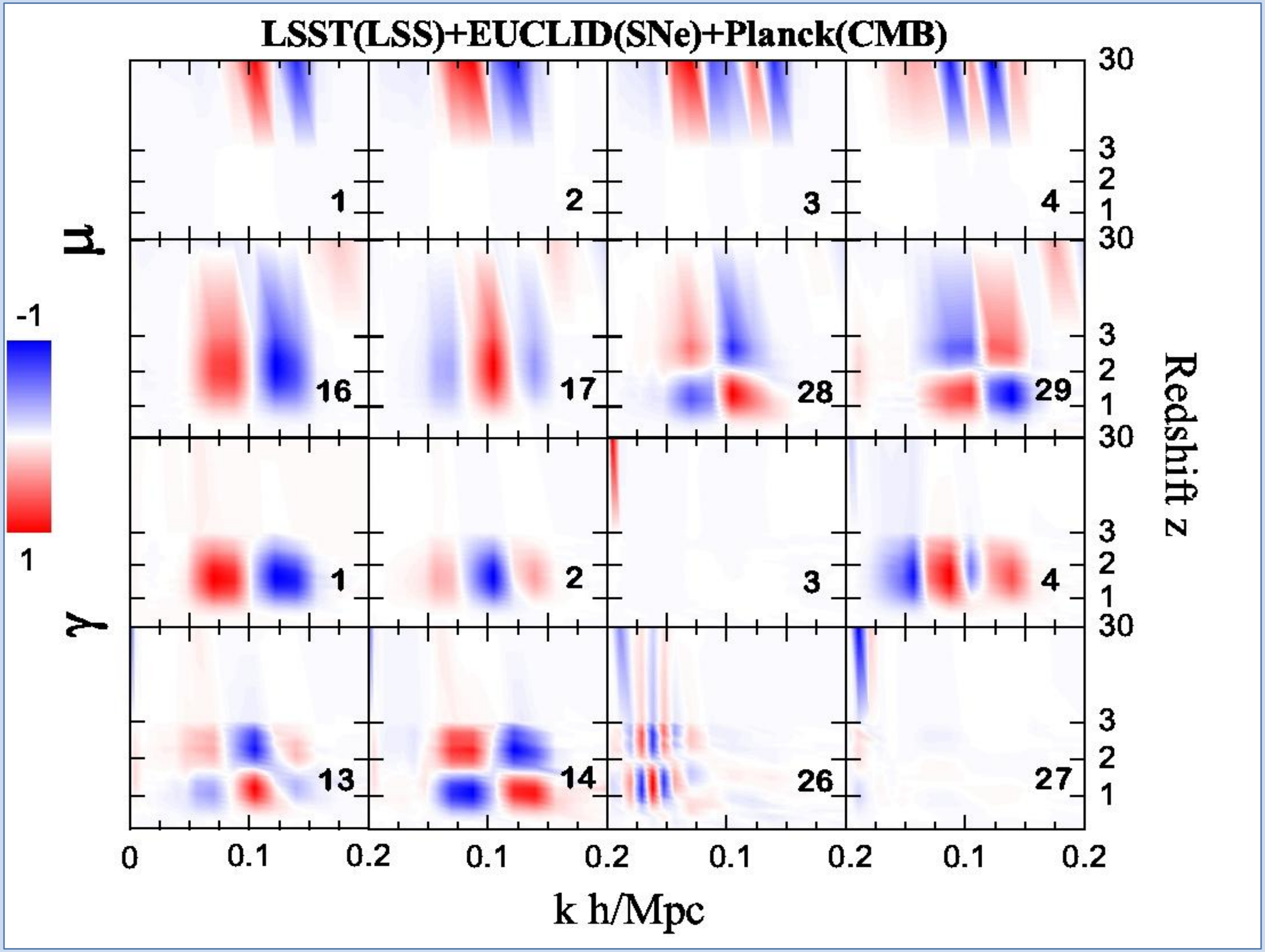
“Measurement” of μ and γ

- Discretize μ and γ

G.B. Zhao et al , PRD 09, PRL 09 .



- Fisher matrix for parameters: Cosmological + pixels



A.Hojjati et al , In Preparation.

Fluctuations of cosmic parameters in the local universe

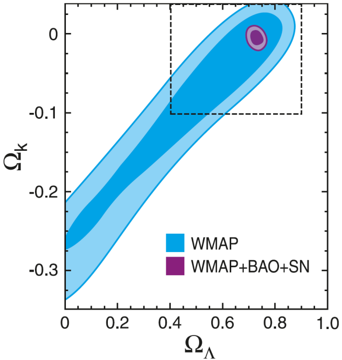
Alexander Wiegand   Dominik Schwarz

Fakultät für Physik
Universität Bielefeld

PiTP 2011
Frontiers of Physics in Cosmology

Importance of local parameter measurements

- Concordance model based on the main experimental probes CMB, SN IA, BAO/structure, H_0
- WMAP alone probes the global scales, but has to be complemented with local measurements to give non degenerate results
- One possibility: $H_0 \Rightarrow$ Measurement in the local universe.



Basic question:

How typical is our local environment we draw our data from?

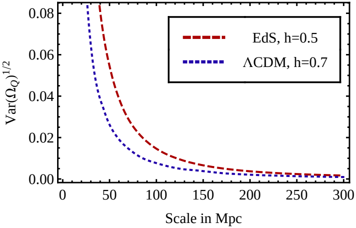
General inhomogeneous model

- Introduce explicit local averaging

$$\langle f \rangle_{\mathcal{D}}(t) := \frac{\int_{\mathcal{D}} f\left(t, X^1, X^2, X^3\right) d\mu_g}{\int_{\mathcal{D}} d\mu_g}$$

- and the volume scale factor

$$a_{\mathcal{D}}^3 := \int_{\mathcal{D}} d\mu_g \Big/ \int_{\mathcal{D}_\mathbf{i}} d\mu_g$$



- Then the Friedmann equations of the homogeneous model become domain dependent, involving the averaged parameters

$$\begin{aligned} 3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} &= -4\pi G \langle \varrho \rangle_{\mathcal{D}} + \Lambda + Q_{\mathcal{D}} \\ 3H_{\mathcal{D}}^2 &= 8\pi G \langle \varrho \rangle_{\mathcal{D}} - \frac{1}{2}\langle \mathcal{R} \rangle_{\mathcal{D}} + \Lambda - \frac{1}{2} Q_{\mathcal{D}} \\ 0 &= \partial_t \langle \varrho \rangle_{\mathcal{D}} + 3H_{\mathcal{D}} \langle \varrho \rangle_{\mathcal{D}} \ , \end{aligned}$$

Fluctuations of cosmic parameters

- Fluctuations of cosmic parameters

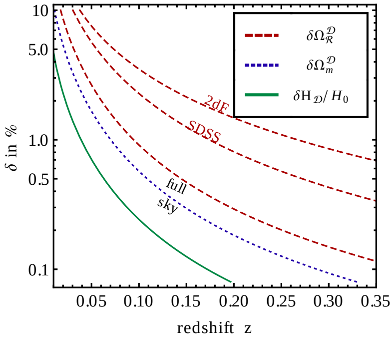
$$
\begin{aligned}
\delta H_{\mathcal{D}} &= \tfrac{1}{2}\overline{H_{\mathcal{D}}}(a_{\mathcal{D}})\, f(a_{\mathcal{D}})\, \sigma_0^{\mathcal{D}} && = 0.17 H_0 \sigma_0^{\mathcal{D}} \\
\delta \Omega_m^{\mathcal{D}} &= \overline{\Omega_m^{\mathcal{D}}}(a_{\mathcal{D}})\,(1 + f(a_{\mathcal{D}}))\, \sigma_0^{\mathcal{D}} && = 0.40 \sigma_0^{\mathcal{D}} \\
\delta \Omega_{\mathcal{R}}^{\mathcal{D}} &= \overline{\Omega_m^{\mathcal{D}}}(a_{\mathcal{D}}) \left(1 + \frac{f(a_{\mathcal{D}})}{\overline{\Omega_m^{\mathcal{D}}}(a_{\mathcal{D}})}\right) \sigma_0^{\mathcal{D}} && = 0.64 \sigma_0^{\mathcal{D}} \\
\delta \Omega_{\Lambda}^{\mathcal{D}} &= \overline{\Omega_{\Lambda}^{\mathcal{D}}}(a_{\mathcal{D}})\, f(a_{\mathcal{D}})\, \sigma_0^{\mathcal{D}} && = 0.24 \sigma_0^{\mathcal{D}} \\
\delta \Omega_{\mathcal{Q}}^{\mathcal{D}} &= \mathcal{O}\left(\left(\sigma_0^{\mathcal{D}}\right)^2\right)
\end{aligned}
$$

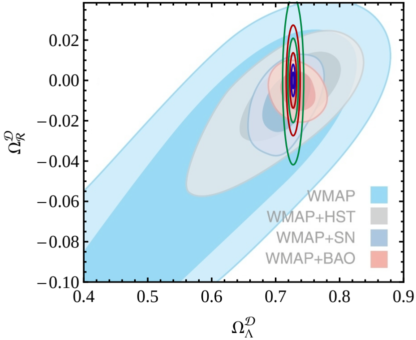
- depend on the matter density fluctuations

$$
f(a_{\mathcal{D}}) := \frac{\overline{\Omega_m^{\mathcal{D}}}(a_{\mathcal{D}})}{D_0} \left(\frac{5}{3}\frac{a_{\mathcal{D}}}{a_{\mathcal{D}_0}} - D_0\right) = \begin{cases} 0.34 & \Lambda\text{CDM} \\ 0.67 & \text{EdS} \end{cases}
$$

$$
\left(\sigma_0^{\mathcal{D}}\right)^2 := \sigma^2\left(\langle \delta_0 \rangle_{\mathcal{D}}\right) = \int_{\mathbb{R}^3} \mathrm{d}^3k \; P_{\mathbf{i}}(k) \widetilde{W}_{\mathcal{D}}(\mathbf{k})\, \widetilde{W}_{\mathcal{D}}(-\mathbf{k})
$$

Cosmic variance and measurement errors





- Fluctuations in present surveys are down to the % level
- Other sources of error still more important than local fluctuations

A Simple Harmonic Universe

Bart Horn, Stanford/SLAC

Soon to appear, w/P. Graham, S. Kachru, S. Rajendran, and G. Torroba

Singularity Thms: (Hawking, Penrose) In FRW, k = 0, -1 & NEC or k = +1 & SEC → Big Bang singularity at early times. Inflating cosmologies do not avoid this.

$$\dot{H} = -\frac{1}{2}(p+\rho) + K/a^2 \qquad \ddot{a} \propto -(\rho + 3p)$$

Is k = 1 + NEC a loophole or counterexample?

Can we construct a bouncing cosmology without leaving the range of validity of GR or violating the NEC?

- FRW w/ K = +1, Λ < 0, fluid with -1 < w < -1/3 give a classically oscillating solution:
  - For w = -2/3, FRW → SHM for a(t):

$$\frac{1}{2}(\dot{a})^2 + (K - \rho_0 a + \frac{|\Lambda|}{3} a^2) = 0 \quad \longrightarrow \quad a(t) = a_0(1 + \sqrt{1-\gamma}\cos(\omega t))$$

$$a_0 = \frac{\rho_0}{2|\Lambda|} \qquad \gamma = \frac{12K|\Lambda|}{\rho_0^2} \qquad \omega^2 = \frac{|\Lambda|}{3}$$

- Solid dark matter, (Bucher, Spergel) e.g. a domain wall network, has w = -2/3 + elastic resistance: otherwise hydro perturbations are a disaster.

- Scalar (graviton?) obeys $\phi'' + 2H\phi' + n(n+2)\phi = 0$
  - Linear growth for n = 0 (wrong soln)
  - Exponential instability for $2 \leq n \leq \gamma^{-1/2}$
  - Stable for large n.
  - Analytic toy model and numerics agree.
  - For $\gamma \sim 1$, classically stable for all n!
- Mixmaster modes $a_i(t)+\delta a_i(t)$ are stable.
- Quantum particle production gives $\phi^2 \sim \gamma\omega^2 \rightarrow$ instability, for γ small:

$$N_{bounces} \leq \log\left(\frac{M_P^2}{\gamma\omega^2}\right) \approx \log\left(M_P^2 R^2_{Universe,\max}\right)$$

- A stabler version of the Einstein static Universe, but still unstable to quantum processes.
- Stable bouncing solution → no classical singularity theorem. But there may be a quantum version…
- Can we envision a periodic quantum state, and what boundary conditions does this give?
- Embedding our own Universe in an SHU?
- Can astrophysics, e.g. free streaming, help?
- Thank you!

Parity of the CMB Sky

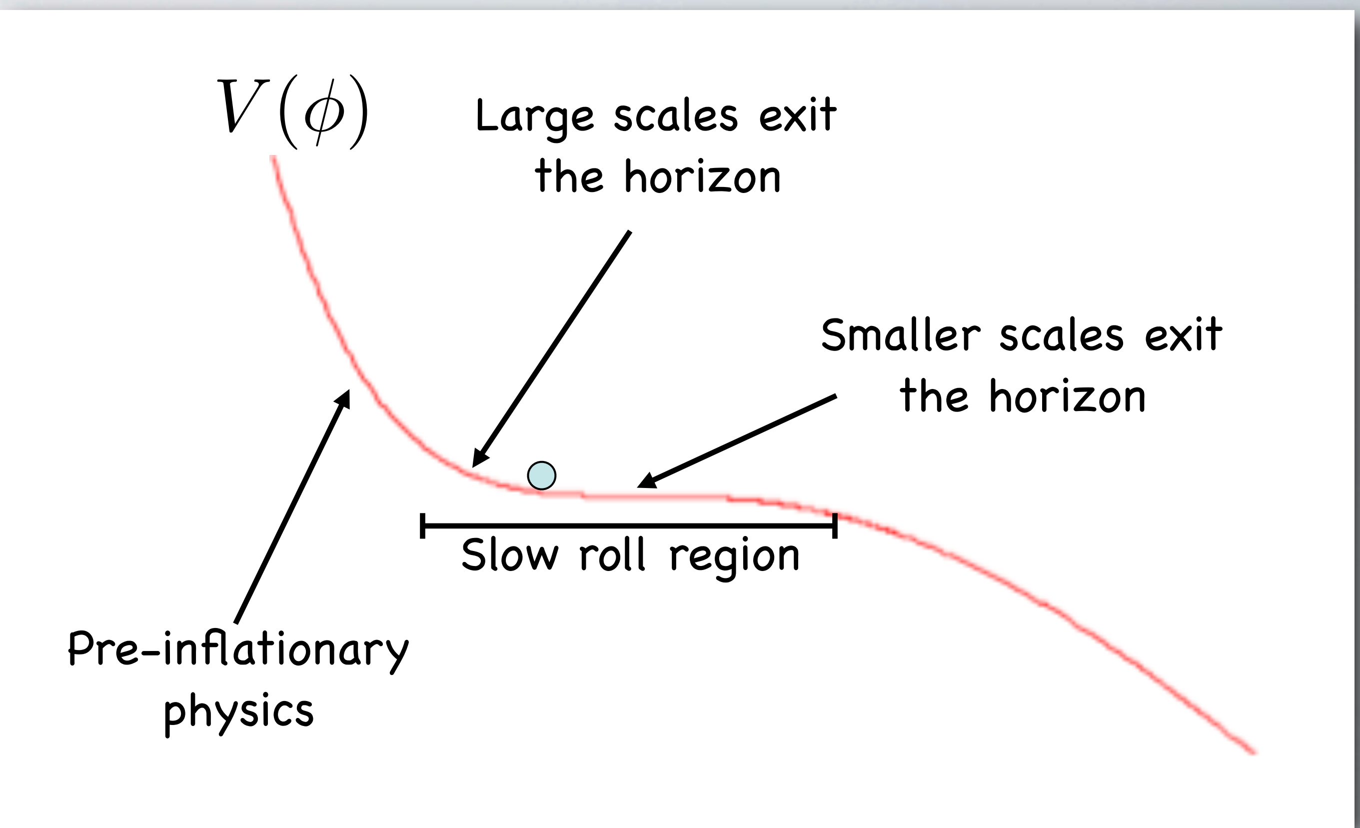
Assaf Ben-David
Tel-Aviv University, Israel

PiTP 2011
July 28th, 2011

Based on work done with E.D. Kovetz and N. Itzhaki
(to appear August 2011)

Motivation

- In small field models, inflation is short.
- Pre-inflationary physics affect largest scales.



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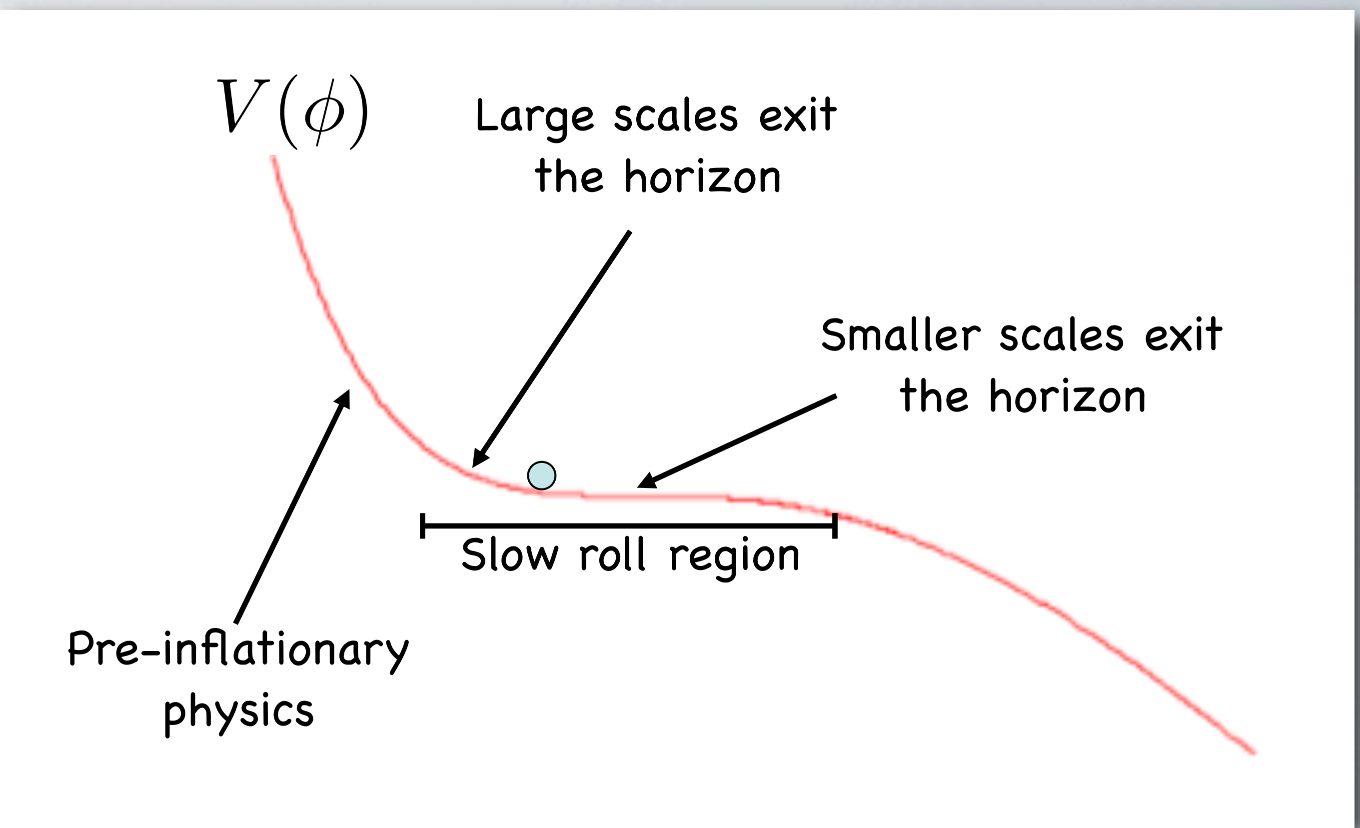


Searching for Parity in the Data

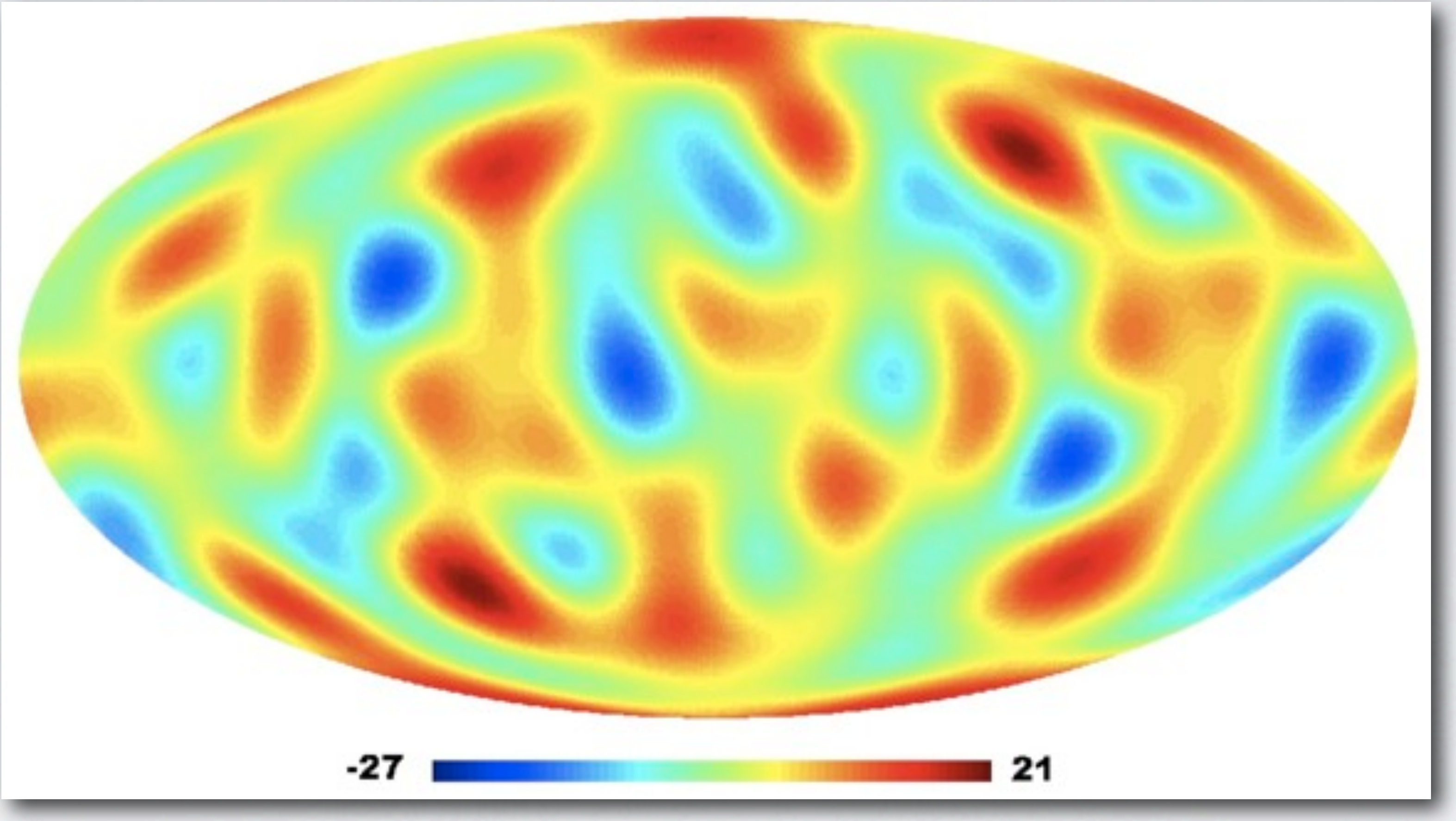
- Parity with respect to reflections through a plane: $\hat{\mathbf{r}} \to \hat{\mathbf{r}} - 2\,(\hat{\mathbf{r}} \cdot \hat{\mathbf{n}})\,\hat{\mathbf{n}}$
- Compare for each ℓ the distribution of power between even and odd $\ell + m$ multipoles.

$$S(\hat{\mathbf{n}}) = \sum_{\ell=2}^{\ell_{\max}} \left[\sum_{m=-\ell}^{\ell} (-1)^{\ell+m} \frac{|a_{\ell m}(\hat{\mathbf{n}})|^2}{\hat{C}_\ell} - 1 \right] \qquad \hat{C}_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$$

- Standard ΛCDM signal should give $\langle S \rangle = 0$.

Full Sky Results

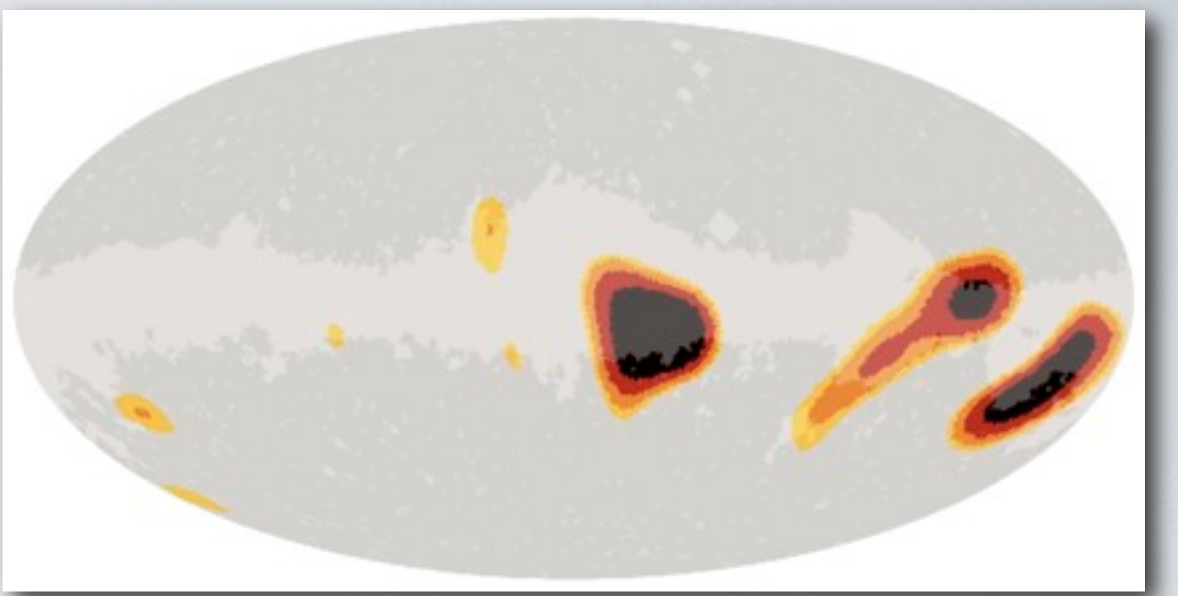
- Results for WMAP 7-year ILC map:



- A maximum at $(l, b) = (260°, 48°)$, direction of the "axis of evil" (e.g. de Oliveira-Costa et al. arXiv:astro-ph/0307282).

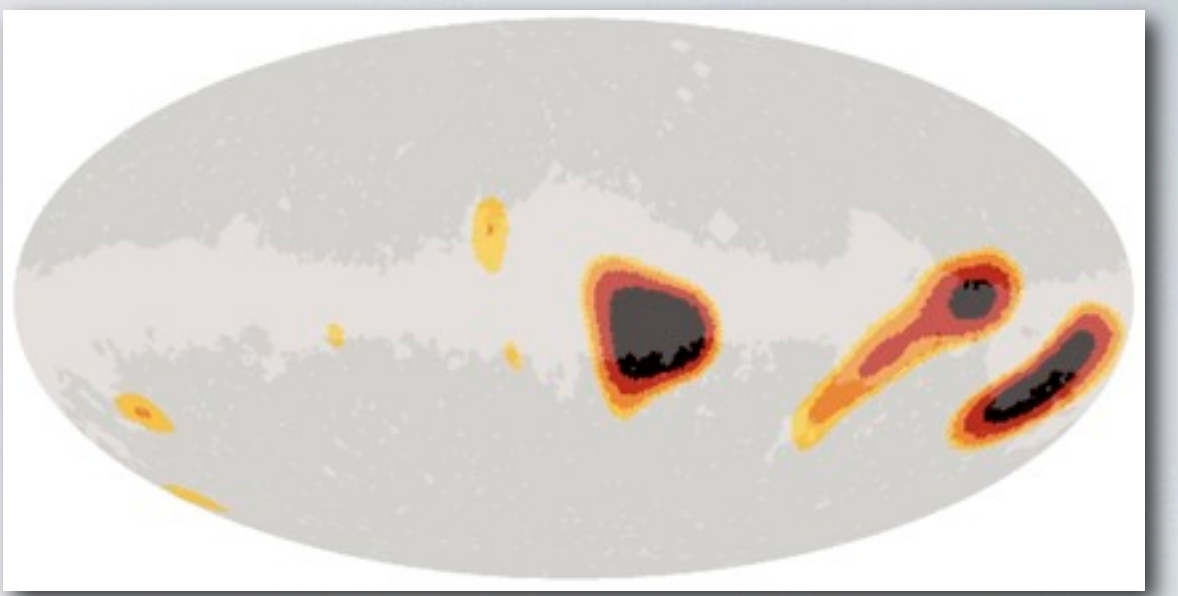
- This is to be expected: AoE anomaly is related to anomalous planarity of quadrupole and octupole, i.e. high $m = \pm\ell$ multipoles, which are even.

Cut Sky Results



- The data at the galactic plane ($\sim 30\%$) is unreliable.
- Reconstruct $a_{\ell m}$ coefficients from cut sky using power spectrum C_ℓ to "fill the gaps" (de Oliveira-Costa et al. arXiv:astro-ph/0603369).
- Only works for small masks ($\lesssim 10\%$ of sky), so only choose worst pixels.

Cut Sky Results



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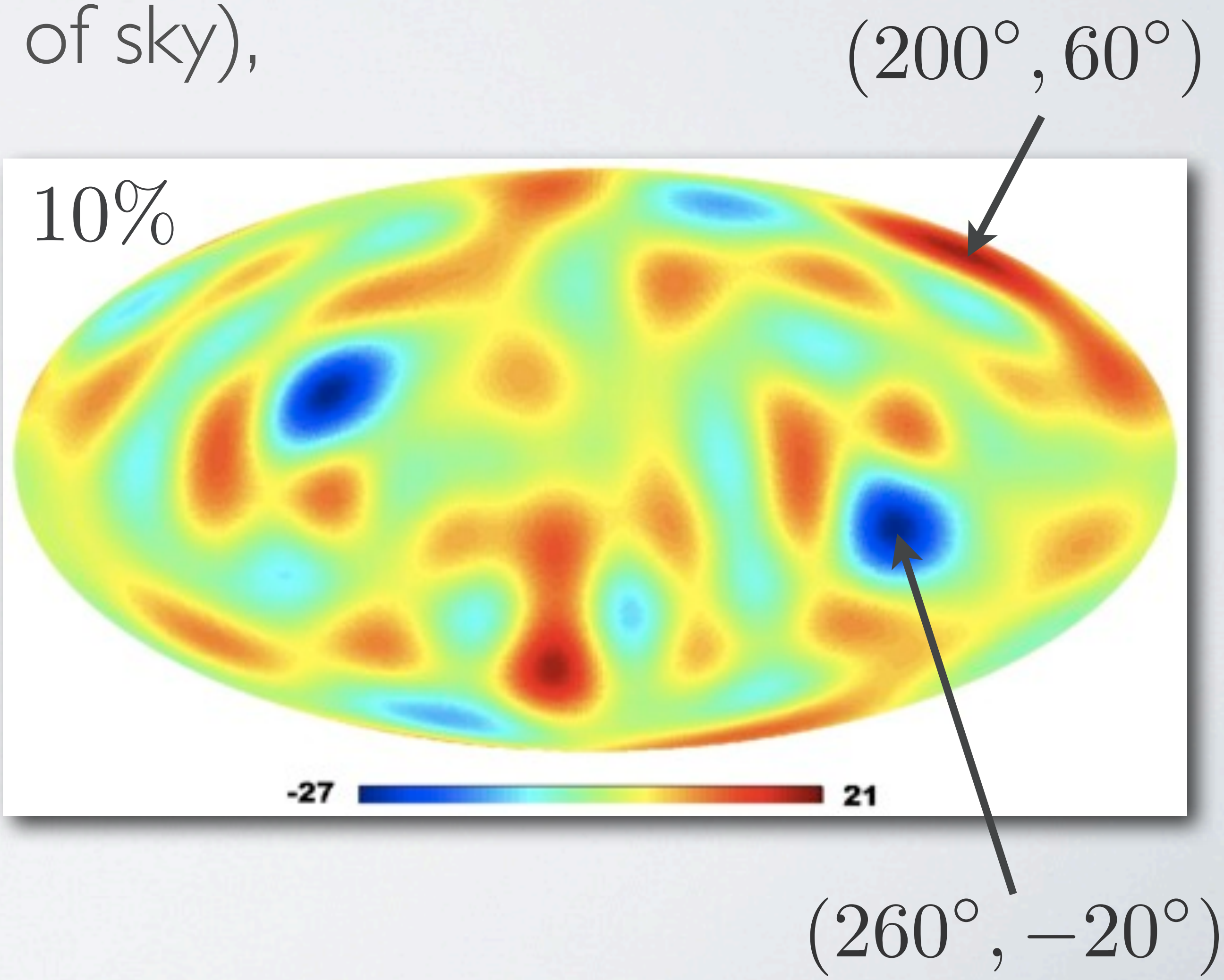
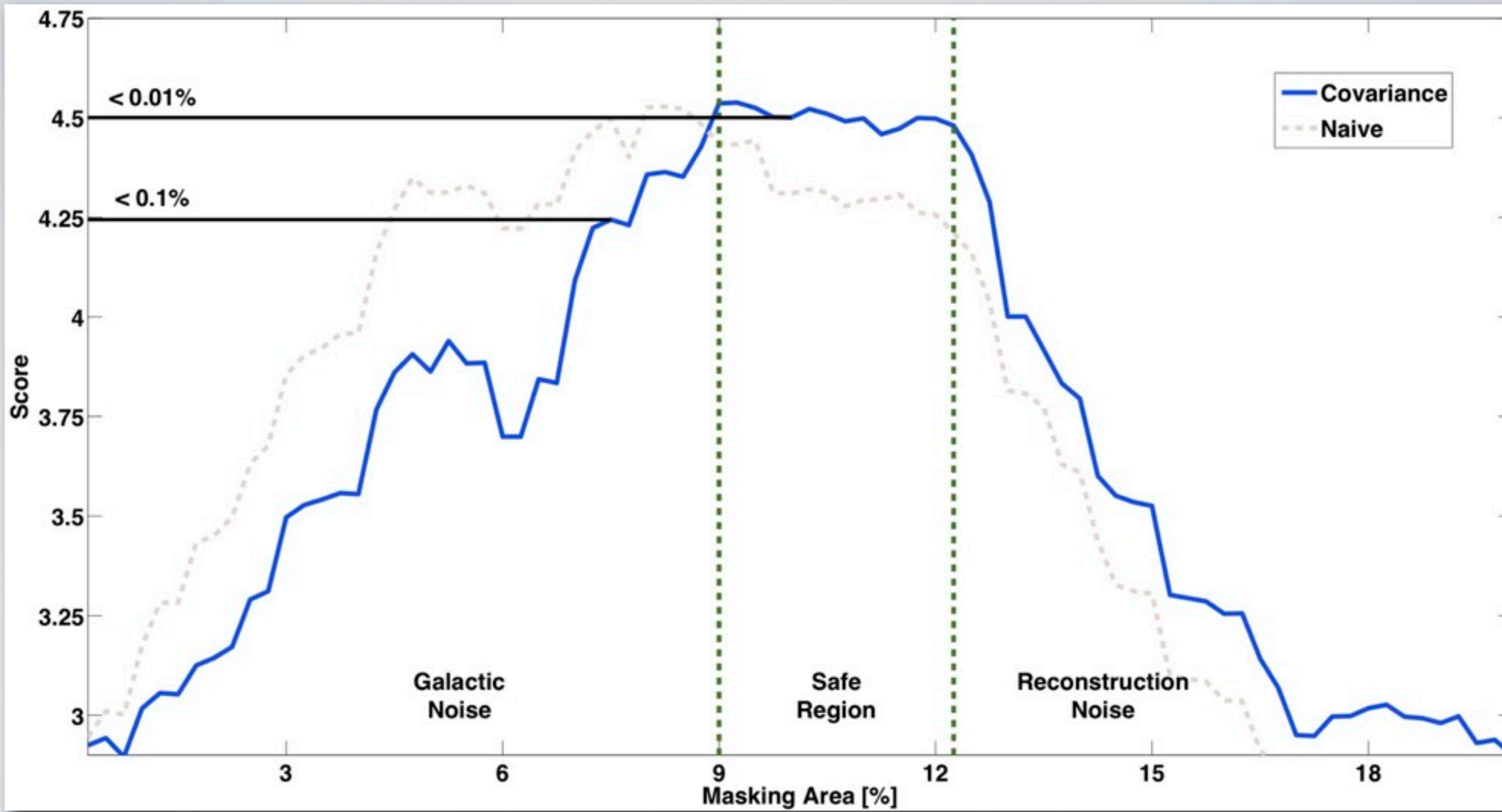
- Only works for small masks ($\lesssim 10\%$ of sky), so only choose worst pixels.
- With all masks, distinct even and odd extrema at the same locations.
- Angular distance between them is $90° \pm 1°$.

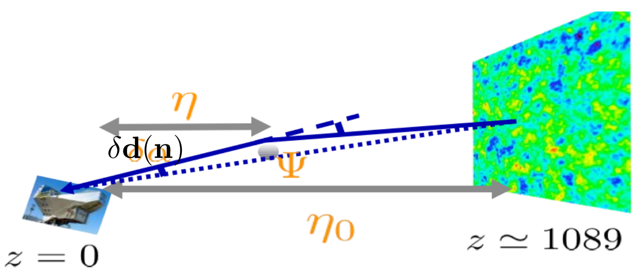


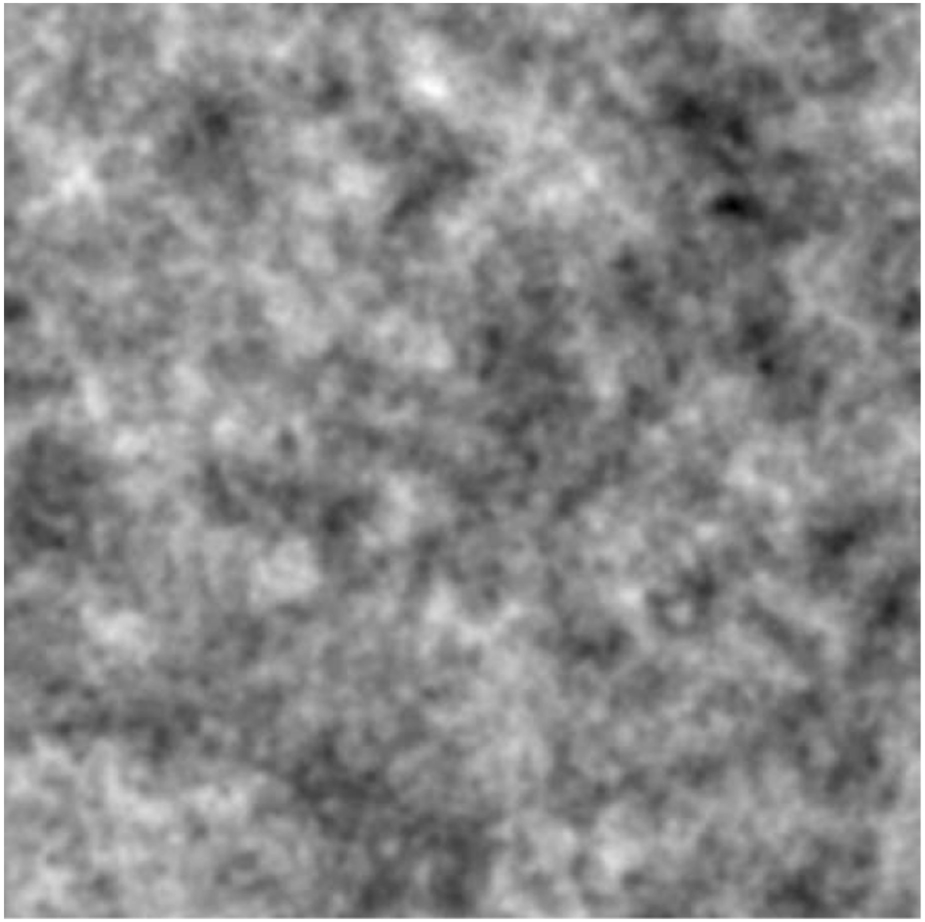
Cut Sky Results (cont.)



- Significance of odd peak vs. random simulation is 4σ!

The First Detection of the CMB Lensing Power Spectrum with ACT and its Implications for Cosmology





Unlensed CMB

Blake D. Sherwin (Princeton University, Dept. of Physics)
with Sudeep Das, Jo Dunkley, David Spergel & the Atacama Cosmology Telescope Collaboration

(see arXiv:1103.2124, 1105.0419, both PRL in press)

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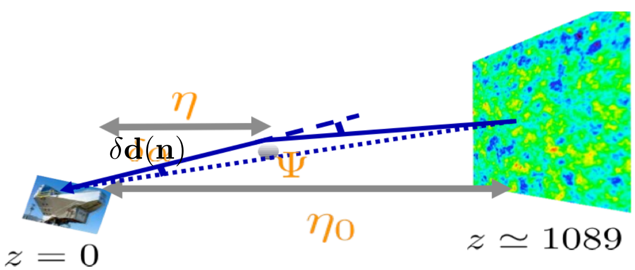
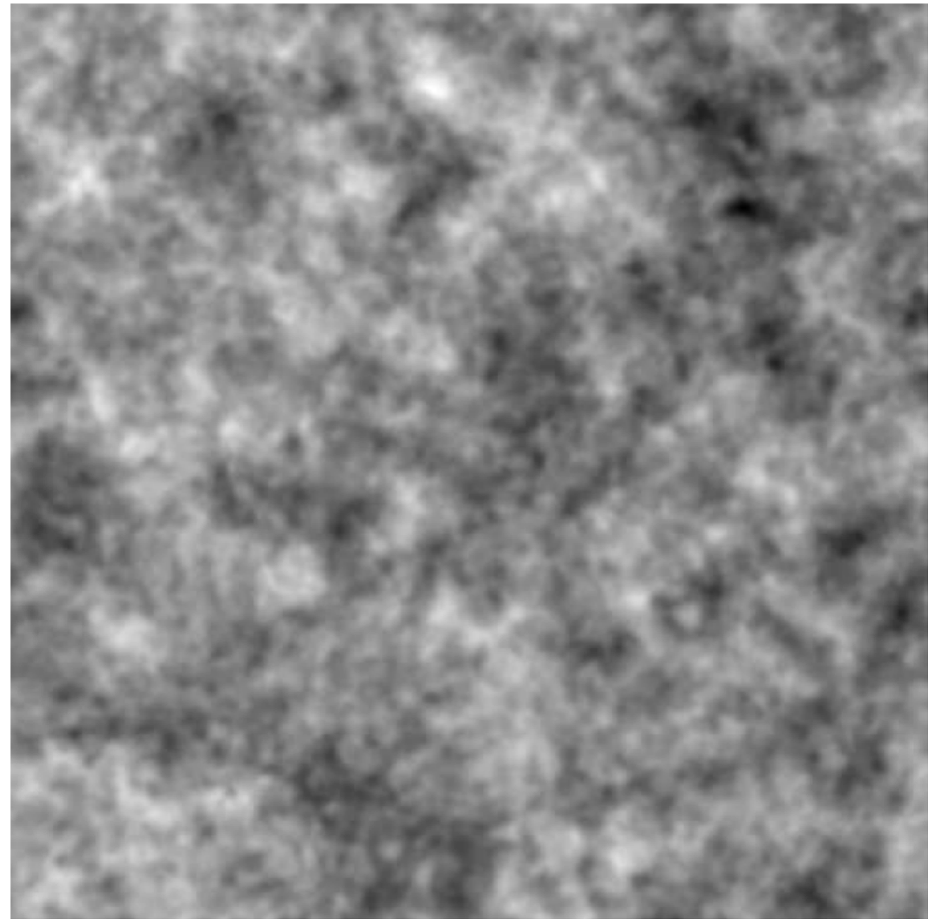


Lensed CMB



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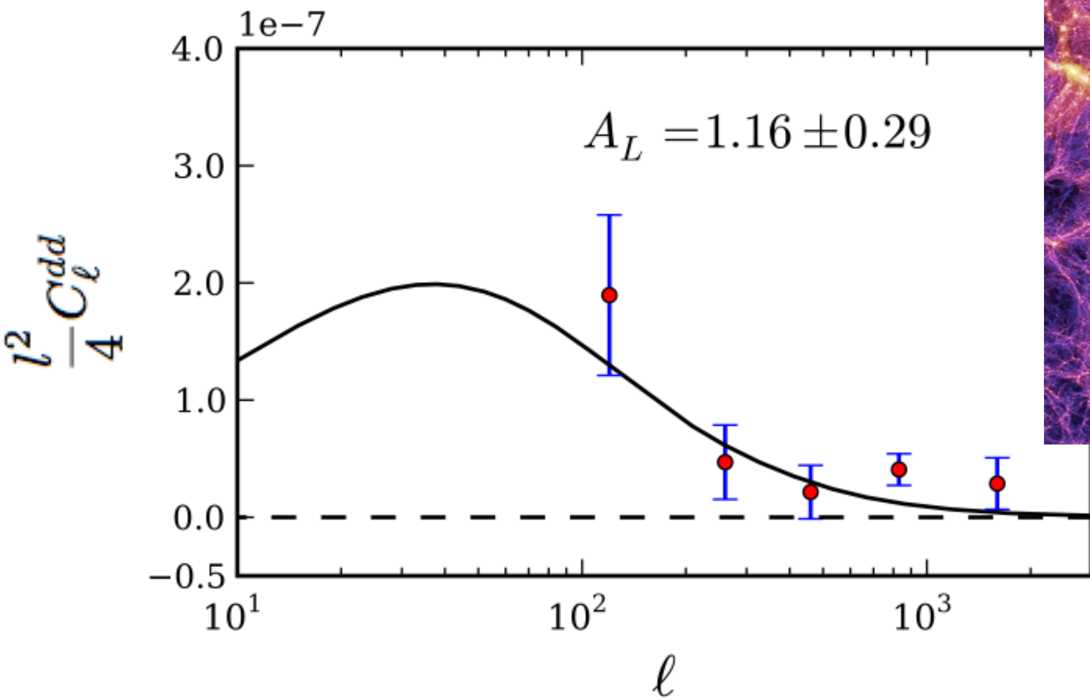
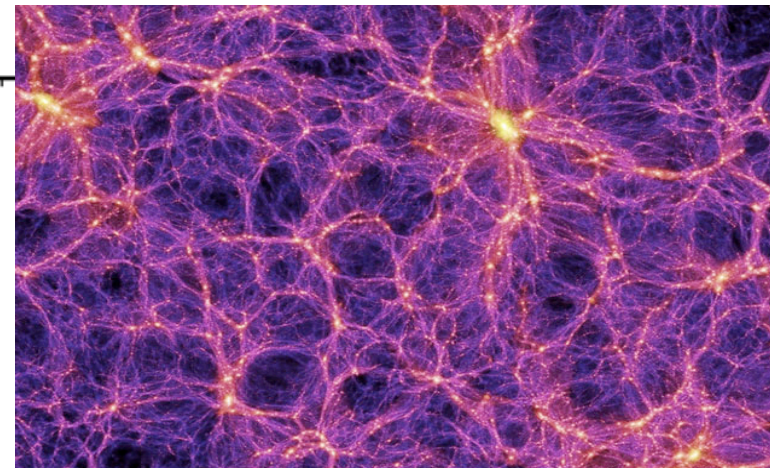
Detection of the Lensing Power Spectrum

- Lensing introduces lensing-type non-Gaussianity, measure to get power spectrum of lensing deflection angle **d**

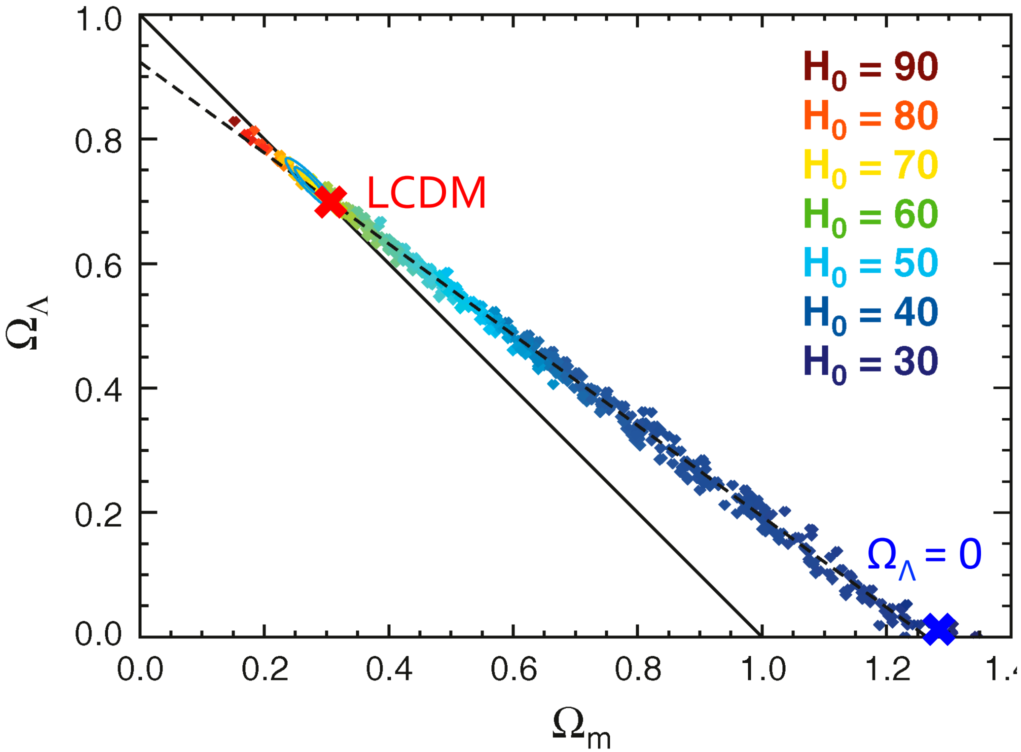


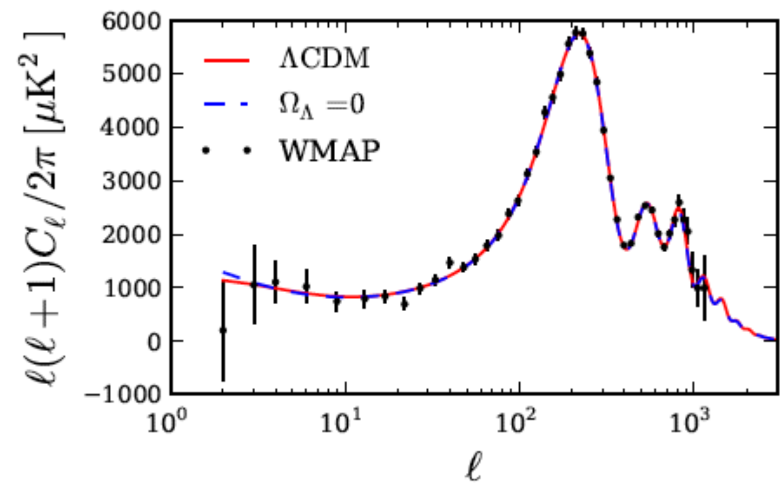


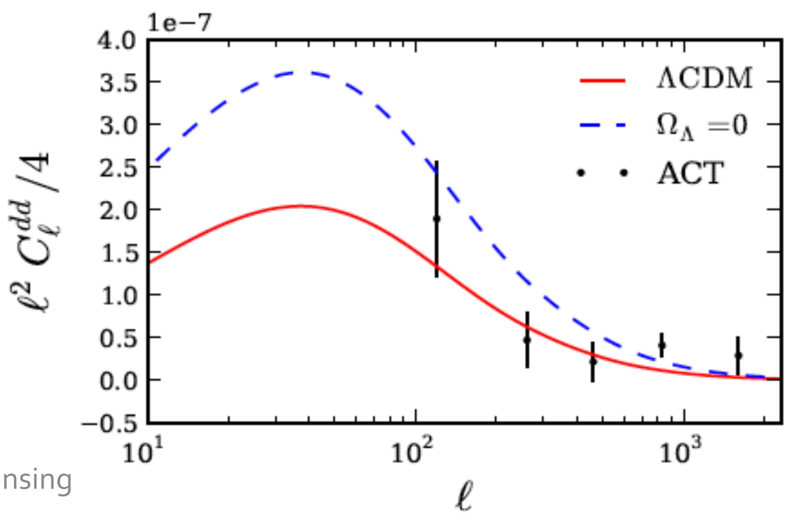
- <u>Confirms LCDM prediction. Direct gravitational probe of dark matter to z~1100</u> (though most sensitive to z~0.5-3).

Lensing Breaks Dark Energy Degeneracies in CMB

- CMB power spectra for cosmologies with and without dark energy can look the same (not assuming flatness) – but lensing spectra are very different

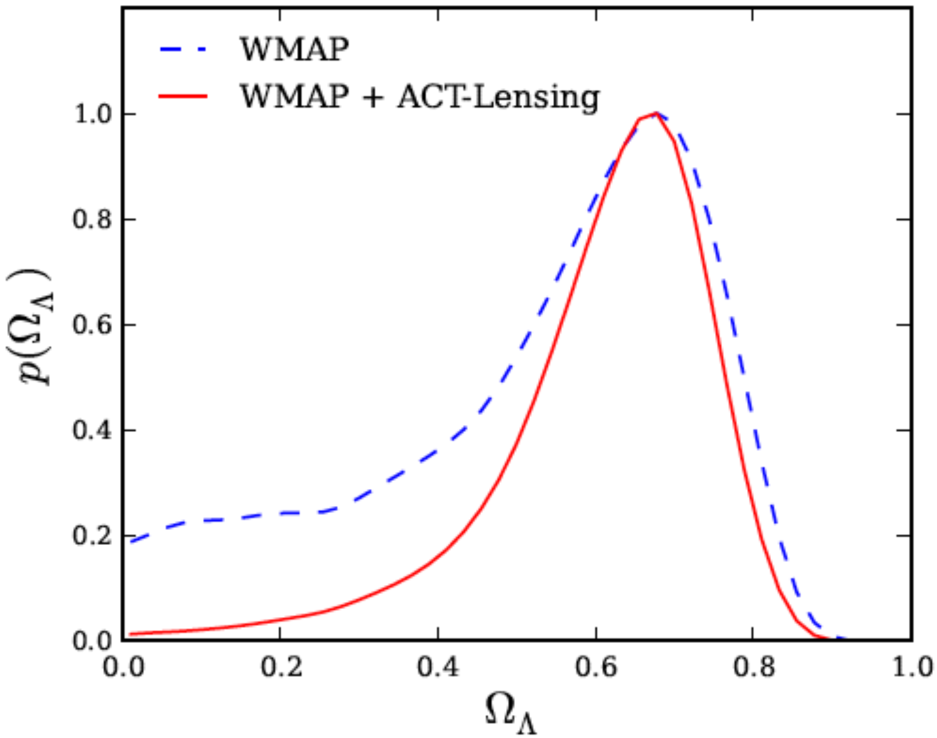






Lensing: CMB-only Evidence for Dark Energy

- 1-D Posterior probability distribution for Ω_Λ:



Peak at $\Omega_\Lambda = 0.67$

[Sherwin, Dunkley, Das et al. 2011]

- With lensing, data favors LCDM model at **3.2 sigma** over best model with no dark energy.

- New lensing measurements in next few years (SPT, Planck, ACTPol) will boost signal by ~10x
- Our result shows the great potential of lensing measurements to constrain dark energy

Echoes of Hidden Valleys

- QCD-like gauge sector
- Degenerate quark masses
- Coupled to SM
- Axion, $\mu \sim 10^{-10} \ldots 10^{-20} eV$

Beware!

Violent EM burst coming from rotating Black Holes

S. Dubovsky and V. Gorbenko 1012.2893

Phase Structure of Hidden Valley

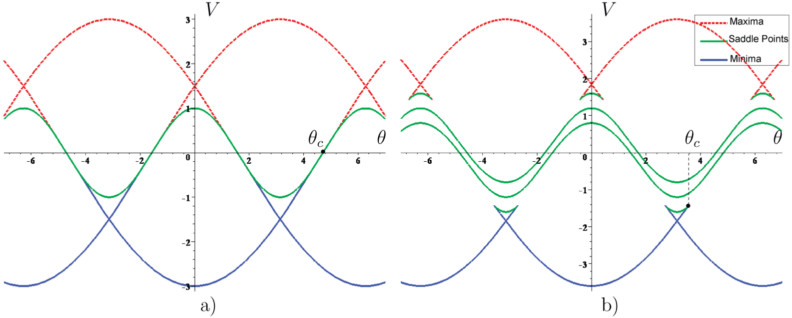
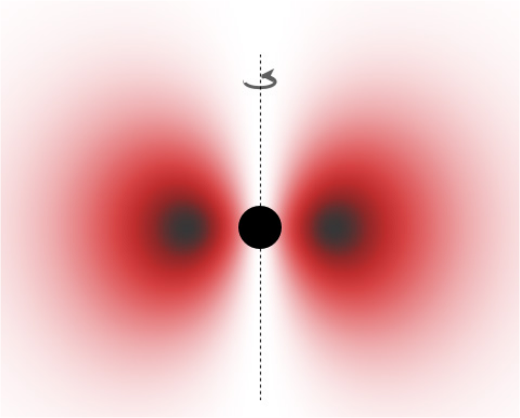


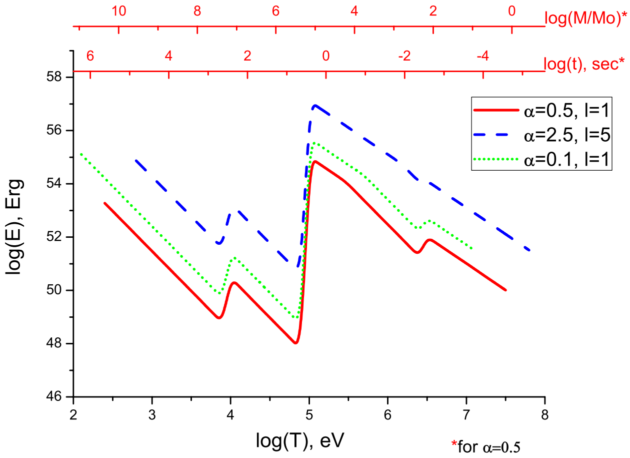
Figure: equal quark masses (left), mass ratios 1:1.2:1.4 (right).

Bosonic Cloud Around a Black Hole



A particle with $1/\mu \sim Rg$, $(\mu \sim 10^{-20} \div 10^{-10} eV)$

Energy Outcome



Non-Gaussianity from Metric Preheating

Mariusz Szmigiel (Imperial)

Single field inflation $|f_{NL}| \ll 1$ (Maldacena, 2003)

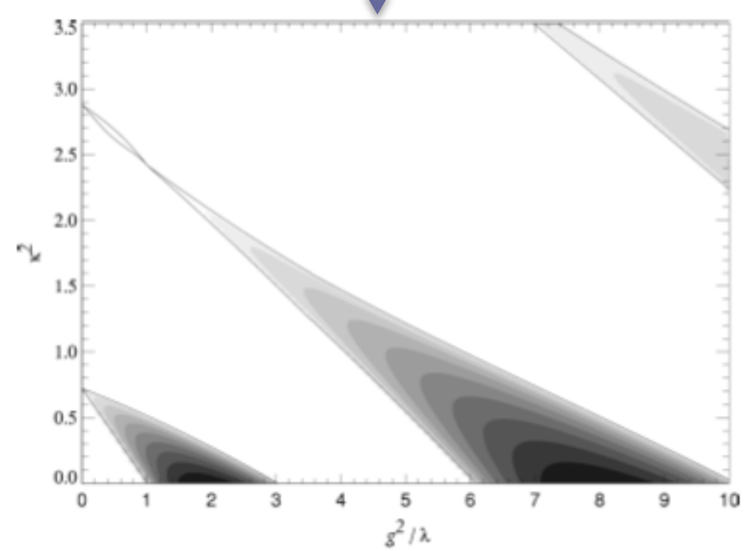
Observations: $-5 < f_{NL}^{local} < 59$ (WMAP 7Year)

→ Try chaotic inflation + massless scalar field

$$V(\phi, \chi) = \frac{1}{4}\lambda\phi^4 + \frac{1}{2}g^2\phi^2\chi^2$$

EoMs → $\chi_k(x) \propto e^{\mu_k x}$

Kofman et al (1997)



→ During Inflation:

$$\phi \gg M_{Pl} \; and \; \chi \approx 0$$

→ At the end of Inflation:

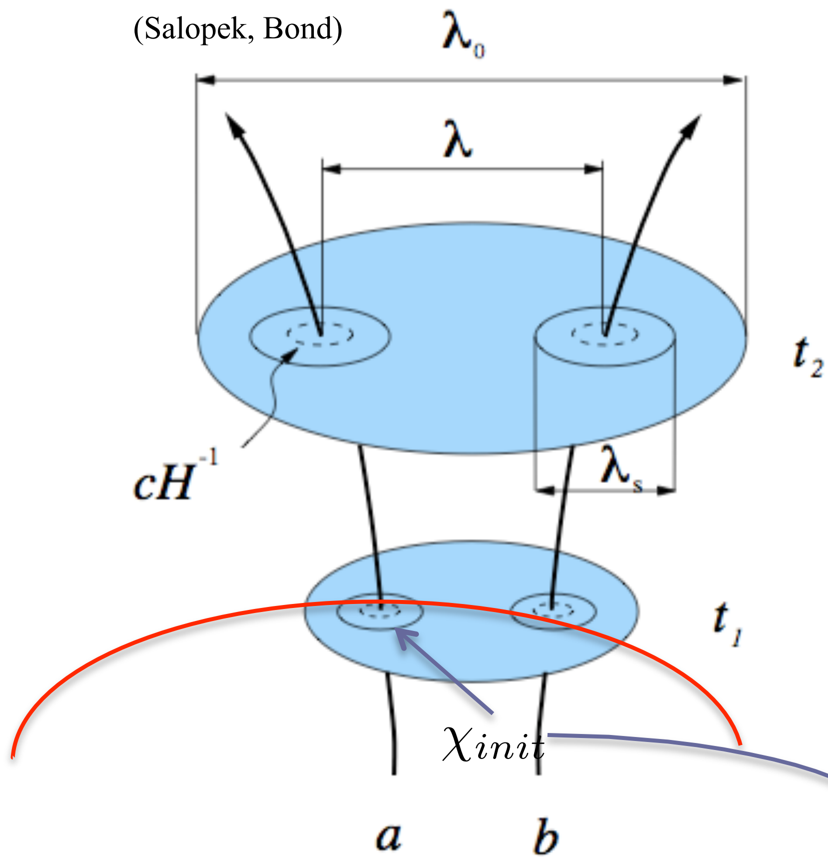
$$\mathcal{P}_\chi \approx \mathcal{P}_\phi \approx \frac{H^2}{4\pi^2} \approx 10^{-12} M_{Pl}^2$$

Can perturbations of χ be converted into super-horizon ζ by resonant preheating?

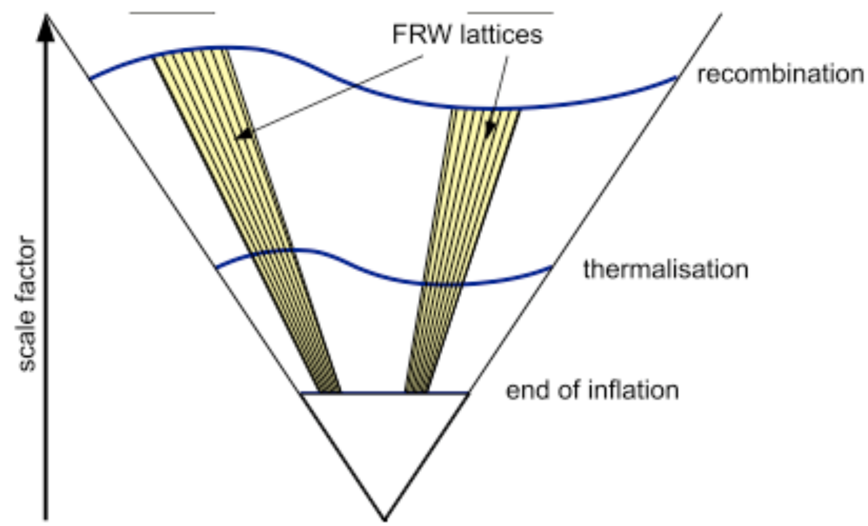
Mariusz Szmigiel
(Imperial)

Separate Universes + FRW

(Salopek, Bond)



(Rajantie et al)



$$\zeta = \delta N \equiv \delta ln a_{|H}$$

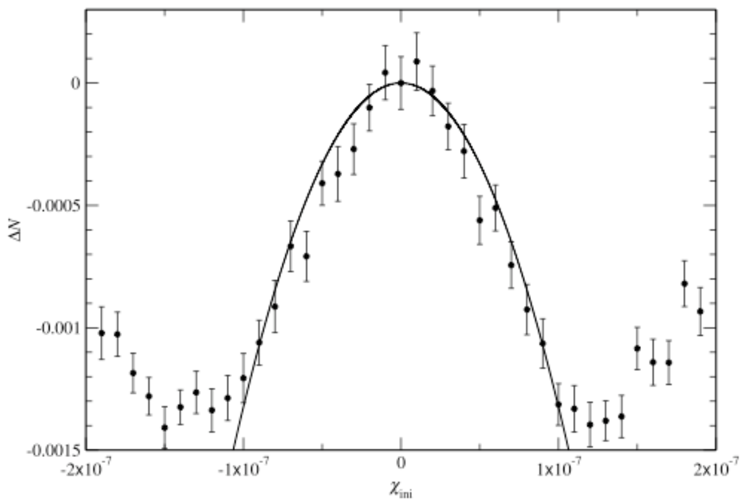
$$\begin{aligned} \phi(x) &= \phi_i + \delta\phi(x) \\ \chi(x) &= \chi_i + \delta\chi(x) \end{aligned}$$

$$\zeta(\phi_i, \chi_i) = \Delta N(\phi_i, 0) + \frac{1}{2}\frac{\partial^2 N}{\partial \chi_i^2}\chi_i^2 + O(\chi_i^4)$$

Mariusz Szmigiel
(Imperial)

Previous results and need for improvements.

(Chambers, Rajantie)



g^2/λ	$\partial^2 N/\partial \chi_i^2$	$\mu(\kappa=0)$
1.05	$-10^{4.60\pm0.05}$	0.085
1.192	$10^{9.69\pm0.12}$	0.157
1.875	$10^{11.26\pm0.05}$	0.237
2.7	$10^{14.01\pm0.10}$	0.157

$$f_{NL} \sim O(1)$$

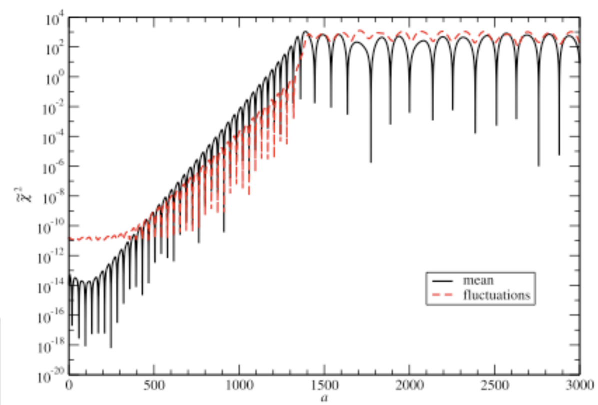
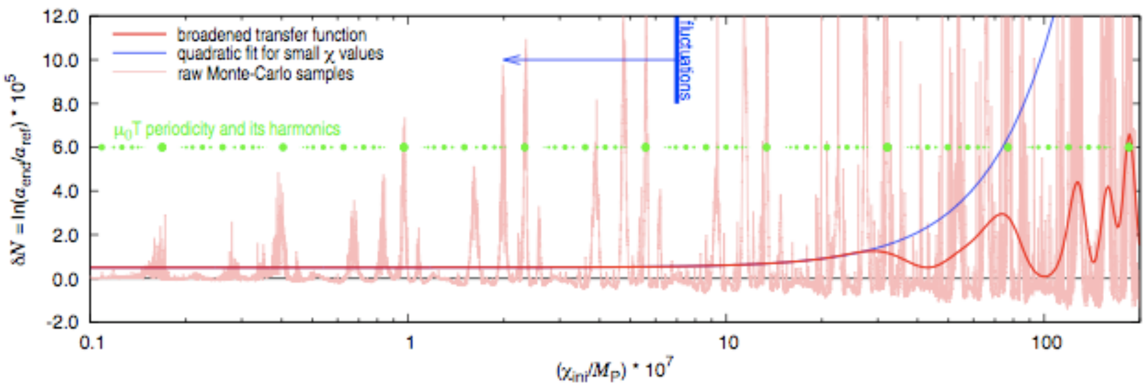


Figure 5. Evolution of the χ field during one simulation for $g^2/\lambda = 2.7$.



Kofman et al (2009)

Mariusz Szmigiel
(Imperial)

Separate Universes + BSSN = much more modes!

$$ds^2 = dt^2 - \gamma_{ij} dx^i dx^j$$

$$\tilde{\gamma}_{ij} = e^{-4\beta}\gamma_{ij}$$

$$0 = \ddot{\phi} + K\dot{\phi} - e^{-4\beta}(\tilde{D}_i\tilde{D}^i\phi + 2\tilde{\gamma}^{ij}\partial_i\beta\partial_j\phi) + \lambda\phi^3 + g^2\phi\chi^2$$

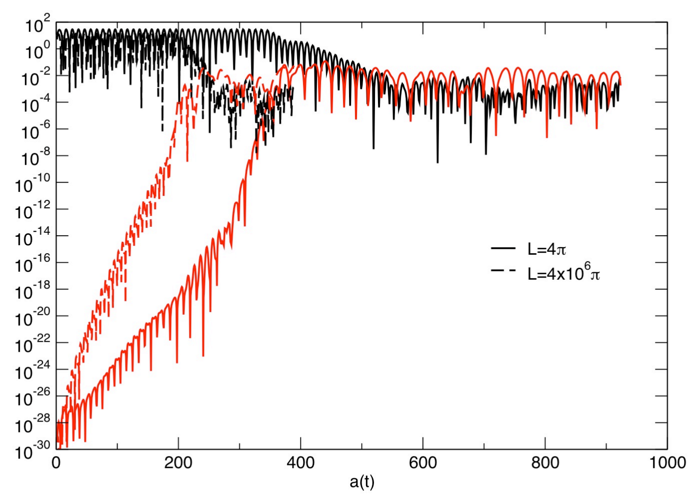
$$0 = \ddot{\chi} + K\dot{\chi} - e^{-4\beta}(\tilde{D}_i\tilde{D}^i\chi + 2\tilde{\gamma}^{ij}\partial_i\beta\partial_j\chi) + g^2\phi^2\chi$$

$$\begin{aligned}
\frac{d\beta}{dt} &= \frac{K}{6}, \\
\frac{dK}{dt} &= -(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{K^2}{3}) + \frac{1}{M_{Pl}^2}(V(\phi,\chi) - 2T), \\
\frac{d\tilde{\gamma}_{ij}}{dt} &= 2\tilde{A}_{ij}, \\
\frac{d\tilde{A}_{ij}}{dt} &= -2e^{-4\beta}(R_{ij}^{TF} - S_{ij}^{TF}) - K\tilde{A}_{ij} + 2\tilde{A}_{il}\tilde{A}^l_j, \\
\frac{d\tilde{\Gamma}^i}{dt} &= 2\left(\frac{1}{M_{Pl}^2}\tilde{\gamma}^{ik}S_k + \frac{2}{3}\tilde{\gamma}^{ik}\partial_k K - 6\tilde{A}^{ij}\partial_j\beta - \tilde{\Gamma}^i_{jm}\tilde{A}^{jm}\right)
\end{aligned}$$

Constraints:

$$\begin{aligned}
\mathcal{H} &= \gamma^{ij}R_{ij} + \frac{2}{3}K^2 - \tilde{A}_{ij}\tilde{A}^{ij} - \frac{1}{M_{Pl}^2}\rho \\
\mathcal{M}_j &= \frac{1}{M_{Pl}^2}S_j + \frac{2}{3}\partial_j K - \gamma^{ik}D_i A_{kj}
\end{aligned}$$

are well satisfied during the evolution.



INFLATION: CONSTRAINING INFLATIONARY EQUATION OF STATE

Sandipan Kundu

University of Texas at Austin

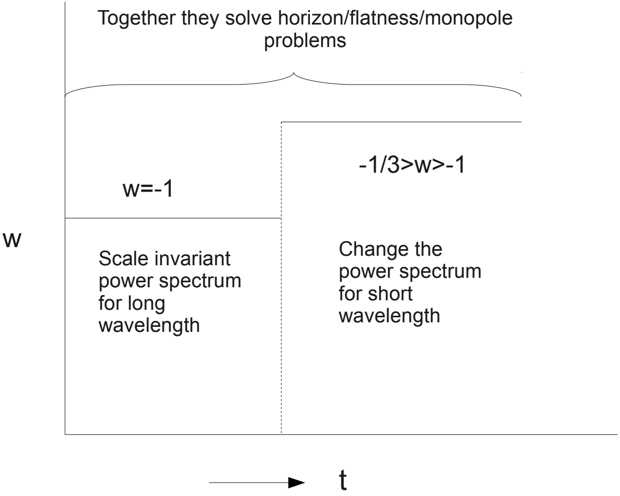
28th July, 2011

with W. Fischler, N.Sivanandam, L.Ackerman (JCAP 1105 (2011) 024; arXiv:astro-ph/1007.3511)

Conclusions

- It is possible to have a secondary period of accelerated expansion (with $-1/3 > w > -1$) immediately following inflation ($w \approx -1$).
- The bounds imposed by considering current measurements of power spectrum are relatively weak.
- The secondary period of accelerated expansion can have a vastly different equation of state to inflation and still have a nearly scale-invariant spectrum at scales from the size of the universe down to a Mpc.
- The secondary period of accelerating expansion changes the power spectrum only for short wavelengths and the spectral index for these modes

$$n_s - 1 = \frac{6(1+w)}{(1+3w)}$$



NOT POWER LAW INFLATION!

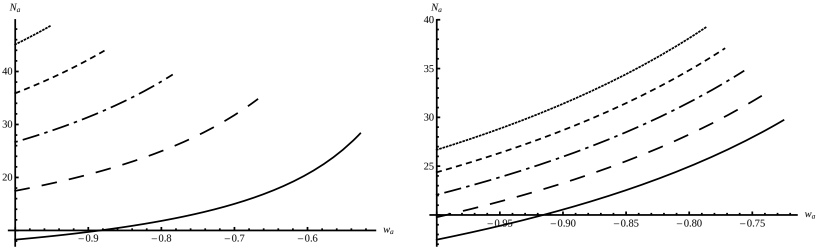


Figure: The left-hand plot shows the relationship between N_a and w for different choices of $\rho_{rh}^{1/4}$ (with $N_i \sim \ln 10^4$): 10^{16} MeV for the uppermost dotted line, 10^{12} MeV for the dashed line, 10^8 MeV for the dot-dash line, 10^4 MeV for the widely spaced dashed line and 10 MeV for the solid line. The right-hand plot shows the same for differing N_i (with $\rho_{rh}^{1/4} \sim 10^8$ MeV): $\ln 10^4$ for the uppermost dotted line, $\ln 10^5$ for the dashed line, $\ln 10^6$ for the dot-dash line, $\ln 10^7$ for the widely spaced dashed line and $\ln 10^8$ for the solid line.

Most dramatic result we can have

We are on the boundary of having an observable signature of the secondary accelarated expansion

- $N_i \approx \ln 10^4$
- $\rho_{rh}^{1/4} \approx 10 \ MeV$

RESULTS:

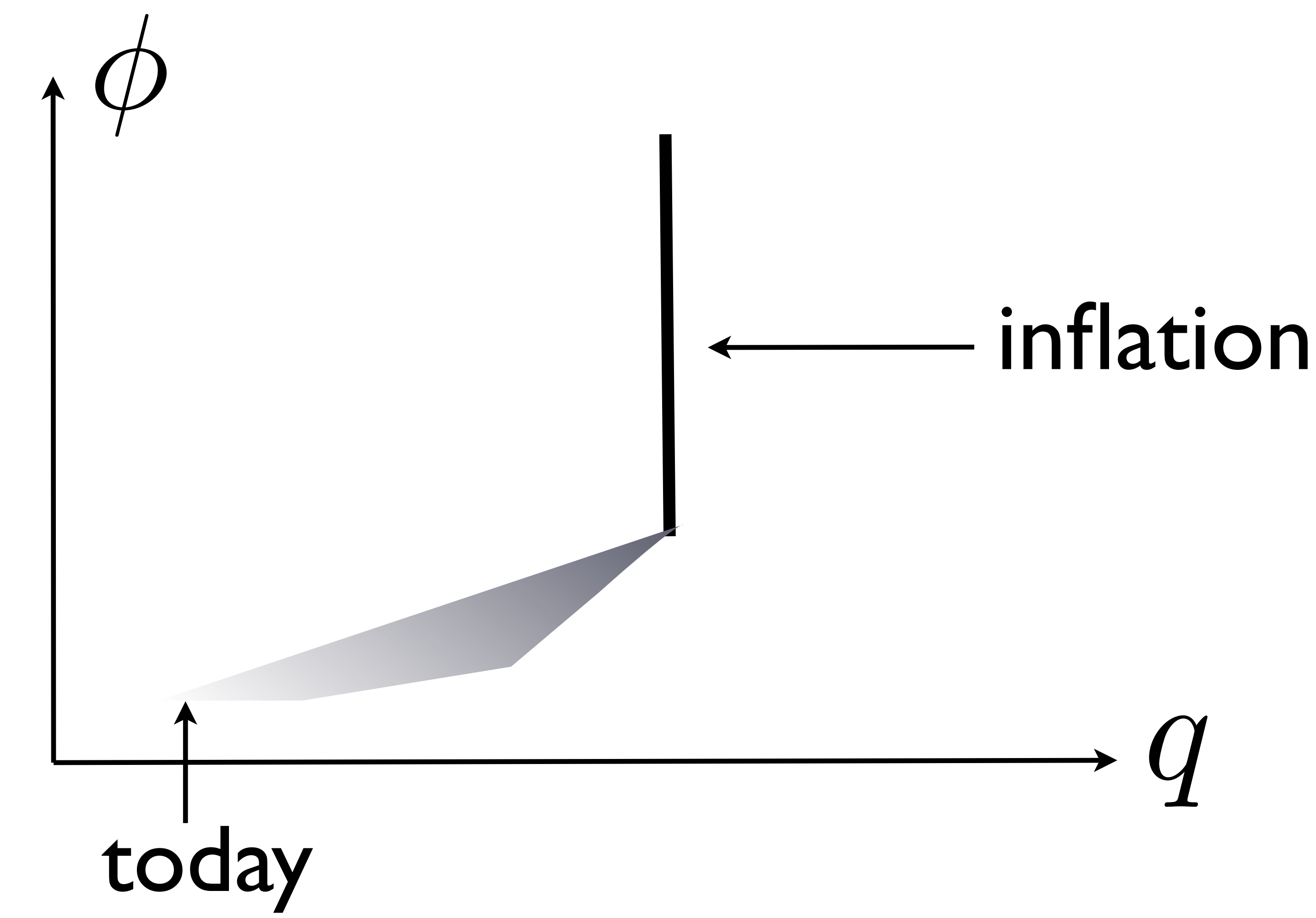
- $N_a \approx 24$
- $w \approx -0.56$
- $n_s \approx -2.9$

The everpresent eta-problem

Johannes Oberreuter, Ted van der Aalst

with S. Hardeman, G. Palma, K. Schalm

Why are multiple sectors useful?



$$S(\phi, q) = S_1(\phi) + S_2(q)$$

- path integral factorizes
- kinetic terms diagonalize
- fields phi and q sit in different representations of symmetry
- consistent truncation to one sector possible

How to minimally couple multiple sectors in supergravity?

$$V_{\rm sugra} = {\rm e}^{K/{\rm M}_{\rm pl}^2}\left(K^{a\bar{b}}{\rm D}_a W\overline{{\rm D}_b W} - \frac{3|W|^2}{{\rm M}_{\rm pl}^2}\right)$$

$$V_{\rm sugra} = {\rm e}^{G}(G_a G^a - 3)$$

N=1 sugra invariant under Kähler transformations:

$$K \longrightarrow K + f + \overline{f}$$

$$W \longrightarrow e^{-f/{\rm M}_{\rm pl}^2} W$$

Kähler invariant function:

$$G(X,\overline{X}) = K(X,\overline{X}) + \log W(X) + \log \overline{W}(\overline{X})$$

Kähler invariance in each sector:

$$\begin{aligned} G &= G^{(1)}(\phi,\overline{\phi}) + G^{(2)}(q,\overline{q}) \\ &= K^{(1)}(\phi,\overline{\phi}) + K^{(2)}(q,\overline{q}) + \log|W^{(1)}(\phi)W^{(2)}(q)|^2 \end{aligned}$$

mixing of the two sectors

Gravity mediated mixing of eta

$$\eta = \min \frac{\nabla_i \nabla_j V}{V} \ll 1$$

for 2 sectors:

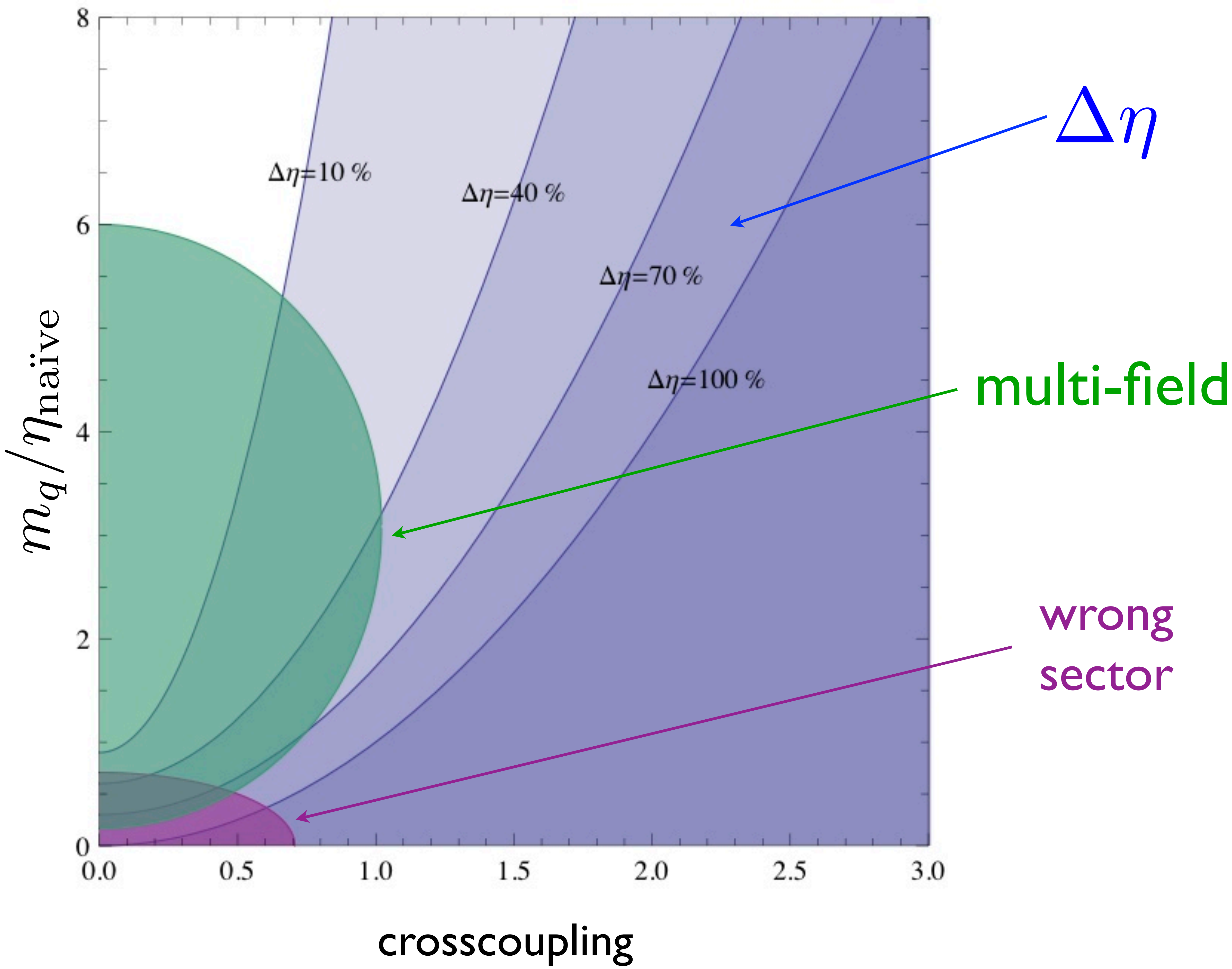
$$\begin{aligned} V_{\phi q} &= G_\phi V_q + G_q V_\phi - G_\phi G_q \\ &= 0 \quad \text{if} \quad G_q = 0 \end{aligned}$$

Non-standard in gravity

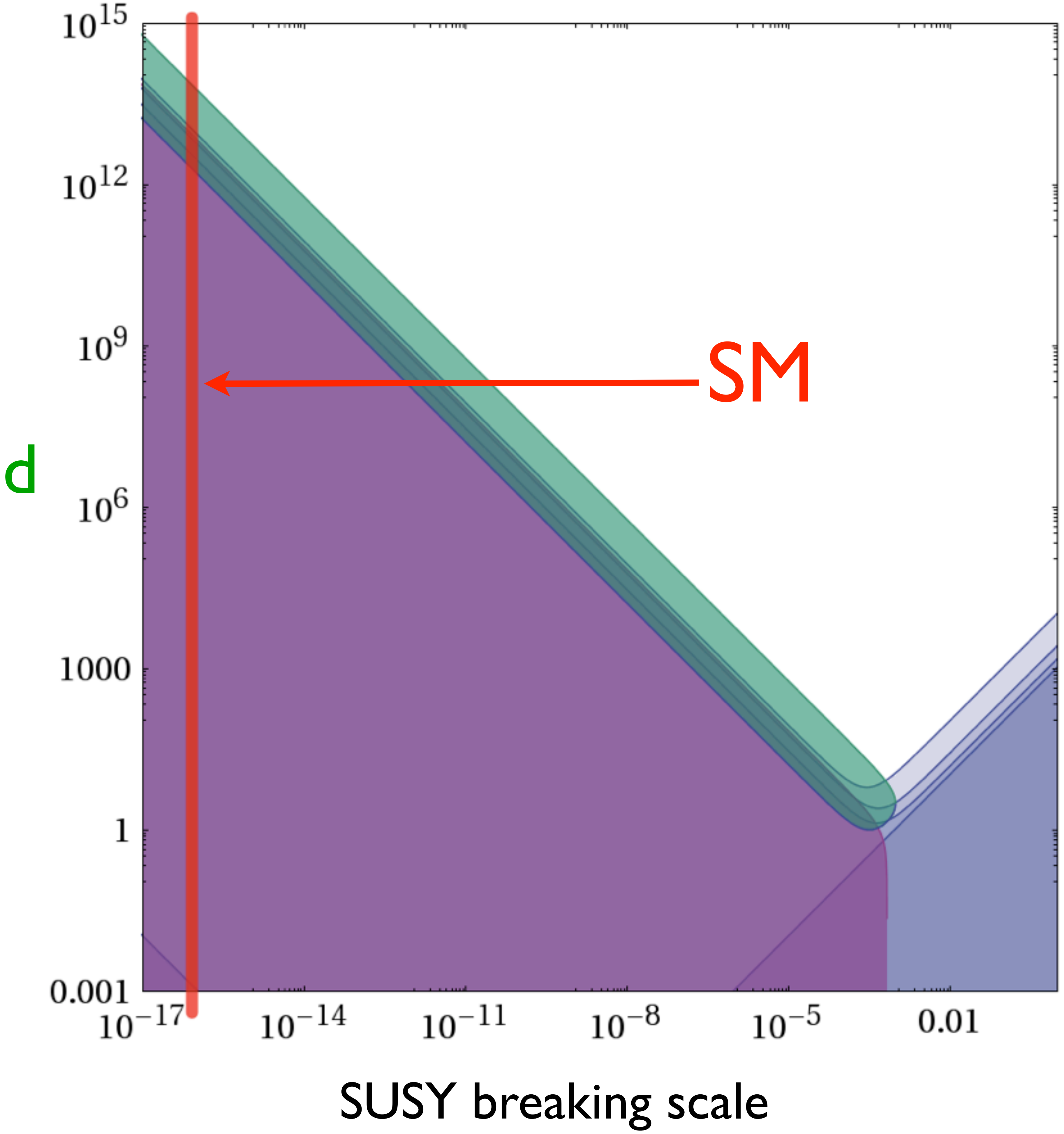
if $G_q \neq 0$: need to diagonalize:

$$N^A{}_B = \begin{pmatrix} \lambda_\phi^{\text{light}} & 0 & A_{11} & A_{12} \\ 0 & \lambda_\phi^{\text{heavy}} & A_{21} & A_{22} \\ \bar{A}_{11} & \bar{A}_{21} & \lambda_q^{\text{light}} & 0 \\ \bar{A}_{12} & \bar{A}_{22} & 0 & \lambda_q^{\text{heavy}} \end{pmatrix}$$

Results



8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$m_q/\eta_{\text{naïve}}$
$\Delta\eta$=10 %
$\Delta\eta$=40 %
$\Delta\eta$=70 %
$\Delta\eta$=100 %
$\Delta\eta$
multi-field
wrong sector
crosscoupling



10^{15}
10^{12}
10^{9}
10^{6}
1000
1
0.001
10^{-17}
10^{-14}
10^{-11}
10^{-8}
10^{-5}
0.01
SM
SUSY breaking scale

General Conditions for Scale-invariant Perturbations in Expanding Universe

Azadeh Moradinezhad Dizgah

Department of Physics
SUNY at Buffalo

PiTP Workshop, IAS, July 28th 2011

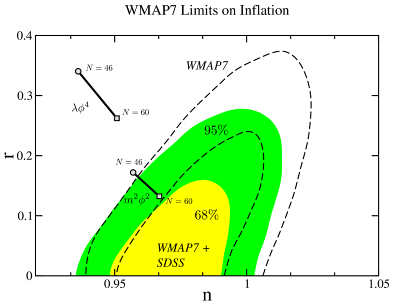
G.Geshnizjani, W.Kinney, A.M, arXiv:1107.1241

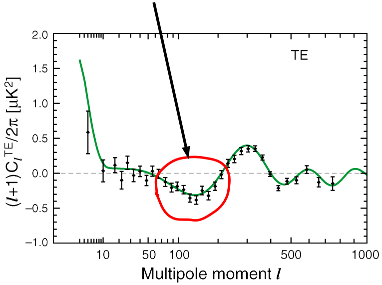
What do we observe in CMB?

Scale-invariant perturbations

$$n_s = 0.963 \pm 0.014$$

Superhubble correlated fluctuations at recombination





What general conclusions can be made about the physics of early universe?

Result in short

In order to generate at least three decades in wavelength of scale-invariant, super-hubble correlated modes in expanding universe at least one of the three conditions must be satisfied:

- Accelerated expansion, i.e. inflation.
- Super-Planckian energy density.
- Super-luminal speed of sound.

Assumptions

- Non-accelerated expansion, $\epsilon > 1$:

$$c_s \frac{dR_H}{dy} = \epsilon - 1 > 0 \tag{1}$$

- Observational constraints:
  - Scale-invariant spectrum of perturbations over at least three decades in k-space: $\lambda_i \gtrsim 1000\ \lambda_f$
  - Super-Hubble correlated perturbations: $\lambda_f\left(\tau_f\right) > R_H\left(\tau_f\right)$

Super-liminal speed of sound

For $c_s \neq 1$, the modes exit the freezout horizon when $\lambda \sim |y|$.

$$\frac{y_f - y_i}{R_H(y_f)} > 1000 \qquad dy = \int c_s d\tau \tag{2}$$

Integrating continuity equation in terms of the time variable y

$$\ln \frac{\rho_i}{\rho_f} > 2R_H^{-1}(\tau_f)\epsilon_{\min}\frac{y_f - y_i}{\bar{c}_s} \tag{3}$$

Combined with Eq.(2) and taking $\epsilon_{min} = 1$ and $\rho_r \sim (100Mev)^4$ we get a lower bound on the speed of sound:

$$\bar{c}_s > 10 \tag{4}$$

The Holographic Universe

Adam Bzowski

UNIVERSITEIT VAN AMSTERDAM

work under supervision of
prof. Kostas Skenderis

in collaboration with
dr. Paul McFadden

dS/CFT (or what Prof. Maldacena taught us)

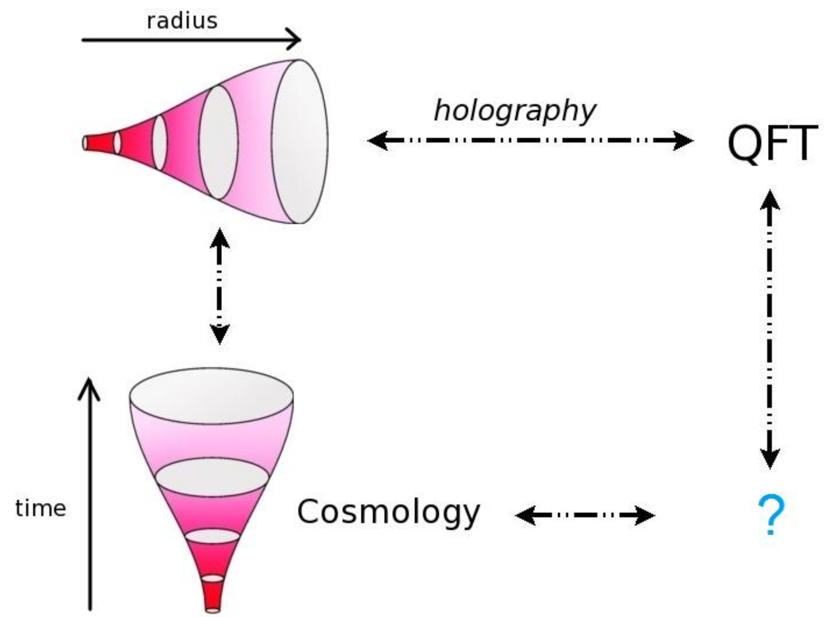
EAdS

$$ds^2 = +dr^2 + e^{2r/\alpha} dx^2$$

↕

dS

$$ds^2 = -dt^2 + e^{2Ht} dx^2$$



cosmological observables ⟷ correlation functions in QFT

example:

graviton in AdS
corresponds to the
energy-momentum tensor in QFT

$$\langle \zeta(p)\zeta(-p)\rangle = -\frac{1}{2\mathrm{Im}\langle T(-ip)T(ip)\rangle}$$

Our model

A particular model is given by a 3D QFT. The parameters of our model are:

- N, g_{YM}^2 – a rank and the coupling constant of the $SU(N)$ gauge field,
- N_ϕ, N_ψ, N_A, N_χ – field content, i.e. number of minimal scalars, fermions, gauge bosons, and conformal scalars.

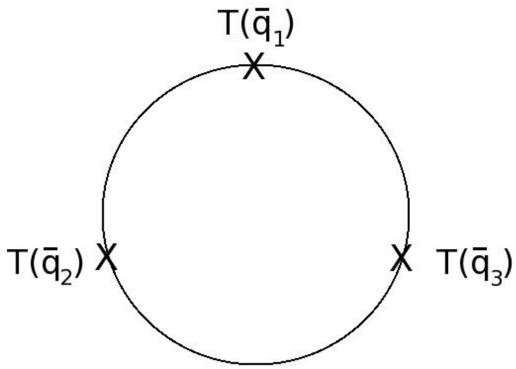
$$S = \frac{1}{g_{YM}^2} \int d^3x \, \mathrm{Tr} \left[\frac{1}{2} F^{ij,I} F_{ij}^I + \frac{1}{2} (D\phi^J)^2 + \frac{1}{2} (D\chi^K)^2 + \overline{\psi}^L \gamma^i \overleftrightarrow{D}_i \psi^L + \mathrm{int.} \right]$$

The power spectrum is consistent with the empirical data, in particular:

- nearly scale-invariance,
- the smallness of the overall amplitude

$$\Delta_S^2(p) = \frac{16}{\pi^2 N^2 \left(N_A + N_\phi\right)} + O(g_{\mathrm{eff}}^2)$$

Predictions



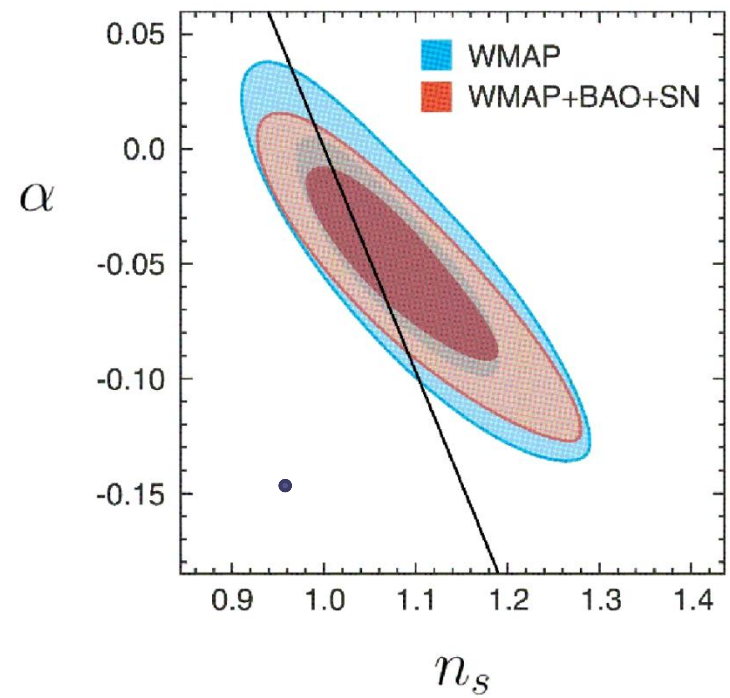
1) The model predicts exactly equilateral type of the non-gaussianity for the scalar modes with

$$f_{NL} = \frac{5}{36} + O(g_{YM}^2)$$

2) The dependence between the running α_s of the spectral index n_s and the spectral index itself for the scalar modes is given by

$$\alpha_S = \frac{dn_S}{d\ln p} = -(n_S - 1) + O(g_{\text{eff}}^4)$$

in all holographic models. This behaviour is different than in inflationary models, where the constant of proportionality is of the order of the slow-roll.



Some papers (of my boss)

- 0907.5542
- 1001.2007
- 1010.0244
- 1011.0452

More papers:

- *Maldacena*, astro-ph/0210603
- *Dias*, 1104.0625
- *Easther, Flauger, McFadden, Skenderis*, 1104.2040
- *Maldacena, Pimentel*, 1104.2846

Thank you for your attention.

Idea

Inflation sets initial conditions for the universe, but what sets initial conditions for inflation (perturbations)?

Question

Given a cosmology $a(t)$, which states $\Psi(t=0)$ produce observed spectrum?

Answer

Modes starting arbitrarily deep inside horizon must be Bunch-Davies.

However, nothing prevents modes below some scale $k < k_0$ from being non-BD.

Sensitivity of the Inflationary Spectrum to Initial Conditions

Daniel Carney

with W. Fischler, S. Paban, and N. Sivanandam

The sphaleron rate at the electroweak crossover

Michela D'Onofrio[a,b], Kari Rummukainen[a,b], Anders Tranberg[c]

[a]University of Helsinki, [b]Helsinki Institute of Physics, [c]Niels Bohr Institute

"PiPT" - Institute for Advanced Studies,

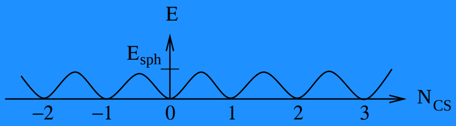
Princeton, 18^{th} - 29^{th} July 2011

Introduction

- Baryon-number asymmetry in the Universe is observed;
- B may be generated at the EWPT: $T \sim 100$ GeV, which has to be first order;
- Even though EWPT is a crossover in SM, Baryogenesis can still be viable through Leptogenesis, as B - L is conserved;
- The sphaleron rate enters lepton-number production as a parameter converting L to B;
- Leptogenesis calculations usually assume the sphaleron rate to have a cut-off. Instead we obtain a T-dependent curve that can be substituted in the calculations.

The theory: Electroweak Baryogenesis

* In EW theory vacua are disconnected and degenerate



* Each vacuum is labeled by a different *Chern-Simons number N_{CS}*

$$N_{CS} = \int d^3x \, j^0_{CS} = -\frac{g^2}{64\pi} \int d^3x \, \epsilon^{ijk} \mathrm{Tr} \left(A_i F_{jk} + i \frac{g}{3} A_i A_j A_k \right) .$$

* When gauge fields pass from one vacuum to another, N_{CS} changes by 1 unit and B by 3 *(through the EW anomaly)*

* At $T \gtrsim 100$ GeV, transitions are possible by surmounting the potential barrier through *sphaleron transitions* (lower barrier, large thermal energy)

The method: Lattice Simulations

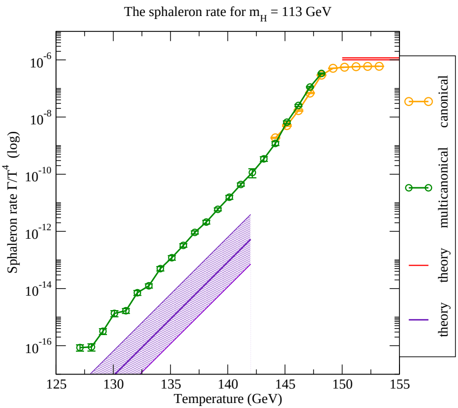
We studied the baryon-number violation rate:

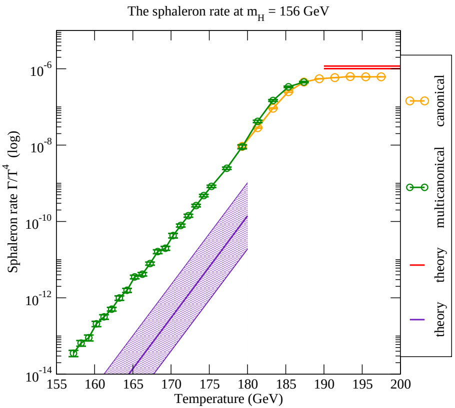
* dimensional reduction $\rightarrow$ 3D effective theory;
* on a 3D-lattice;
* with fields: SU(2) $+$ Higgs;
* two different methods, depending on the T we are examining:
  - Canonical Monte Carlo *(heat bath)*
  - Multicanonical MC $+$ Real-time

We obtain the sphaleron rate, defined as:

$$\Gamma \equiv \lim_{t \to \infty} \frac{\langle (n_{CS}(t) - n_{CS}(0))^2 \rangle}{V\ t}$$

Results: The sphaleron rate





Asymptotic limit: $\sim 5\times10^{-7}$ T^4.

Theoretical estimates: **[hep-ph/0511246]**

Final Considerations

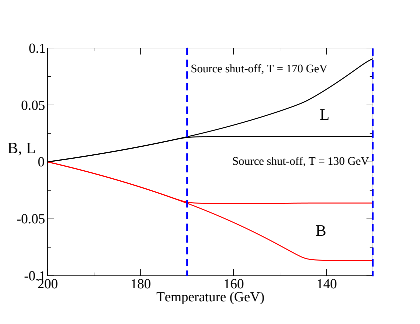
* Complete picture of the sphaleron rate through the electroweak crossover, improving previous estimates.

* The two simulation methods are in agreement.

* The crossover temperature depends on the Higgs mass.

* Even if CP-violation is too small in SM, Baryogenesis might be viable through Leptogenesis, where the sphaleron rate enters as a parameter.

* Plugging the sphaleron rate into a simple Leptogenesis model: Γ cuts off exponentially at the crossover, but B and L freeze-out later, when the rate is $\sim$ 10 H.



Reheating in the Early Universe

Dustin Lorshbough

University of Texas

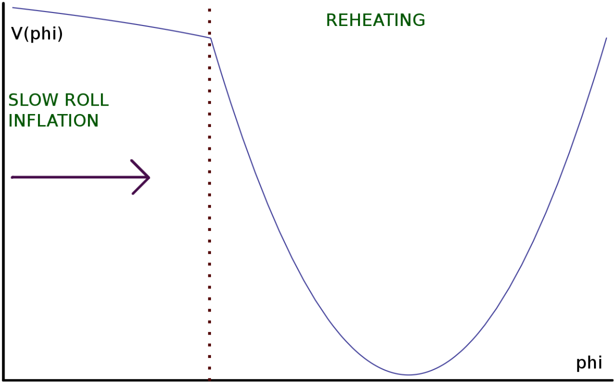
Lorshbough@mail.utexas.edu

July 28th, 2011

What is Reheating?

What is reheating→What are the mechanisms→Number Evolution

Timeline:



$\underbrace{\text{Inflation Ends}}_{\text{Matter Dominated}} \rightarrow ??? \rightarrow \underbrace{\text{Reheating Ends}}_{\text{Radiation Dominated}} \rightarrow \underbrace{\text{Big Bang Nucleosynthesis}}_{\sim 1\text{ MeV}}$

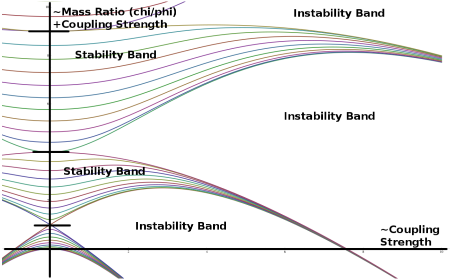
What are the Mechanisms of Reheating?

Kofman, Linde, Starobinsky '94 '97 for $\phi^2\chi^2$ theory

•Perturbative Decay: $\Gamma > H$

•Narrow Parametric Resonance:

1. ∼Coupling< 1
2. ∼Coupling>∼Friction Coefficient

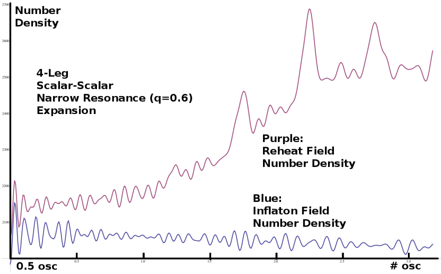


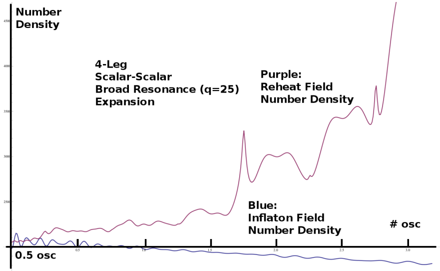
•Broad Parametric Resonance:

1. ∼Coupling> 1
2. $\dot{\omega}_{\text{matter}} \geq \omega^2_{\text{matter}}$

Are there Observable Signals from Reheating?

What is reheating→What are the mechanisms→**Number Evolution**





String Axions & Massive Neutrinos in the Cosmos

David J. E. Marsh, Edward Macaulay, Maxime Trebitsch and Pedro G. Ferreira, in prep.

David J. E. Marsh,
PiTP, 28/07/11

Oxford Physics

- Light particles from String Theory
- Cosmology: the CMB & LSS
- Exotic matter and degeneracies

The String Axiverse

Arvanitaki et al Phys. Rev. D 81, 123530 (2010)

Oxford Physics

- Axions arise from closed cycles, of which there are many:

$$N_a \sim N_{\mathbf{cycle}}$$

- Masses scale exponentially with cycle size:

$$m_a \sim e^{-A_{\mathbf{cycle}}}$$

- Cosmologically relevant mass scales:

$$10^{-33}\mathrm{eV} \lesssim m_a \lesssim 10^{-22}\mathrm{eV}$$

$$V(\phi) = \frac{1}{2} m_a^2 \phi^2$$

Axion "Free-Streaming"

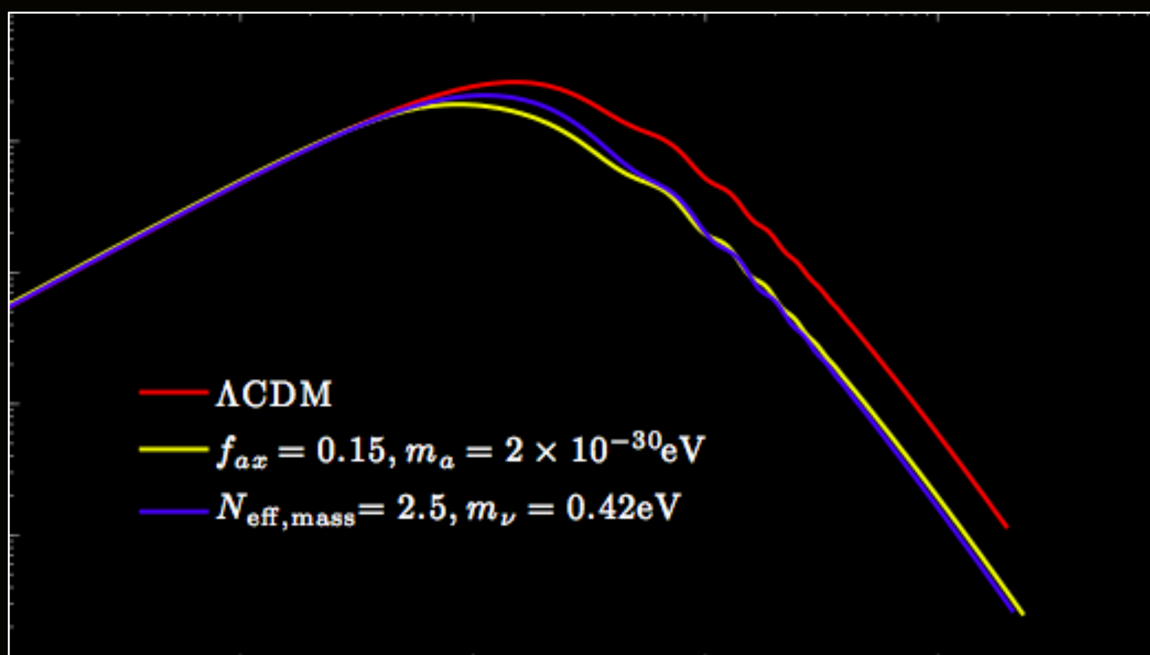
Oxford Physics

- We compute the sound speed, and find it is scale dependent:

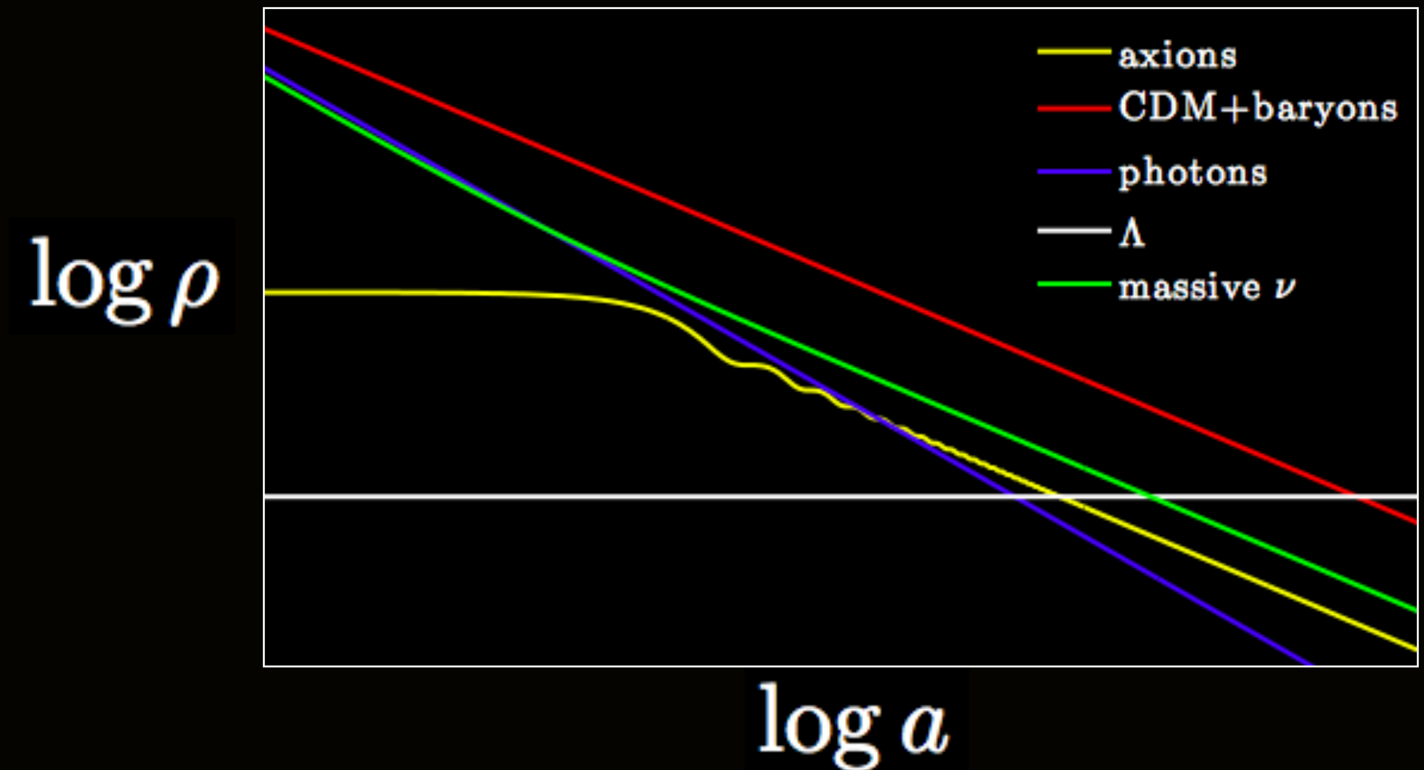
$$c_s^2 = 1 \quad k \gtrsim m_a a \qquad c_s^2 = \frac{k^2}{m_a^2 a^2} \quad k \lesssim m_a a$$

- Modes that enter the horizon while relativistic "Free Stream".

$P(k)$

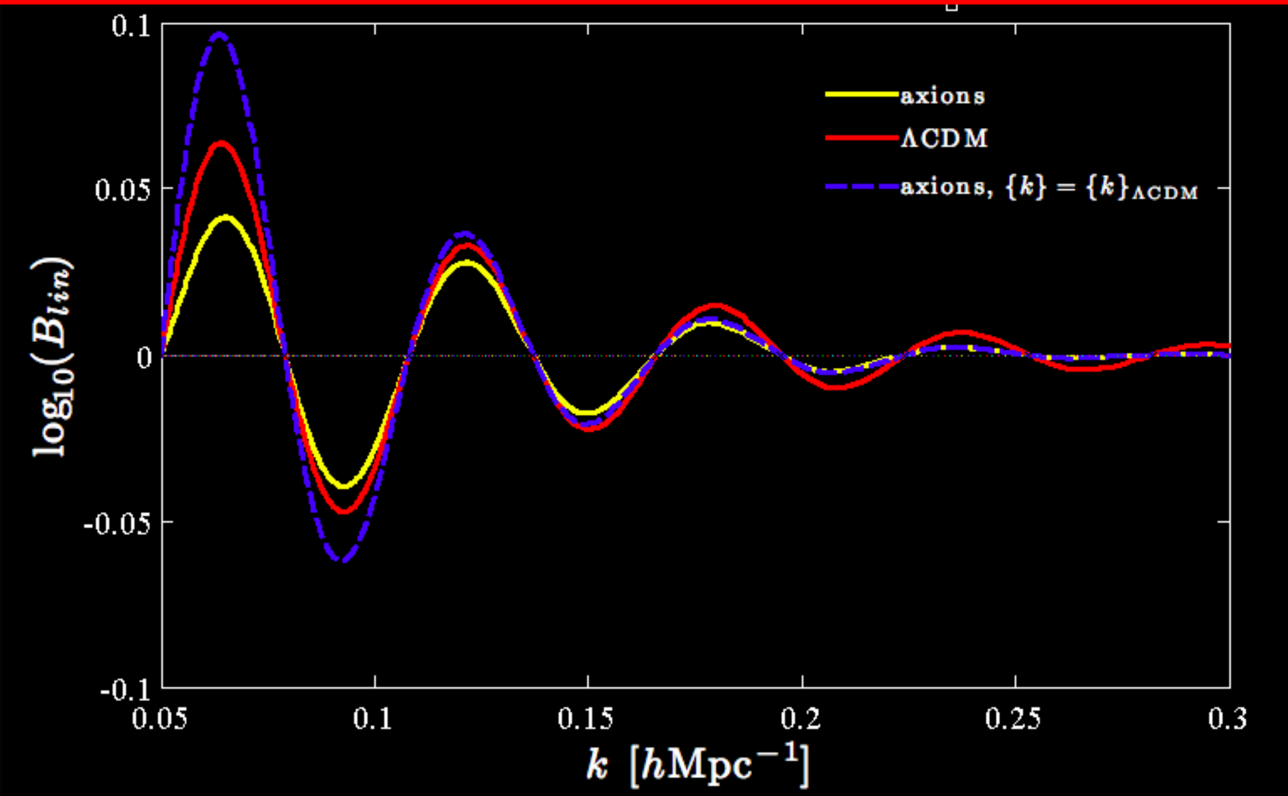


Background Evolution

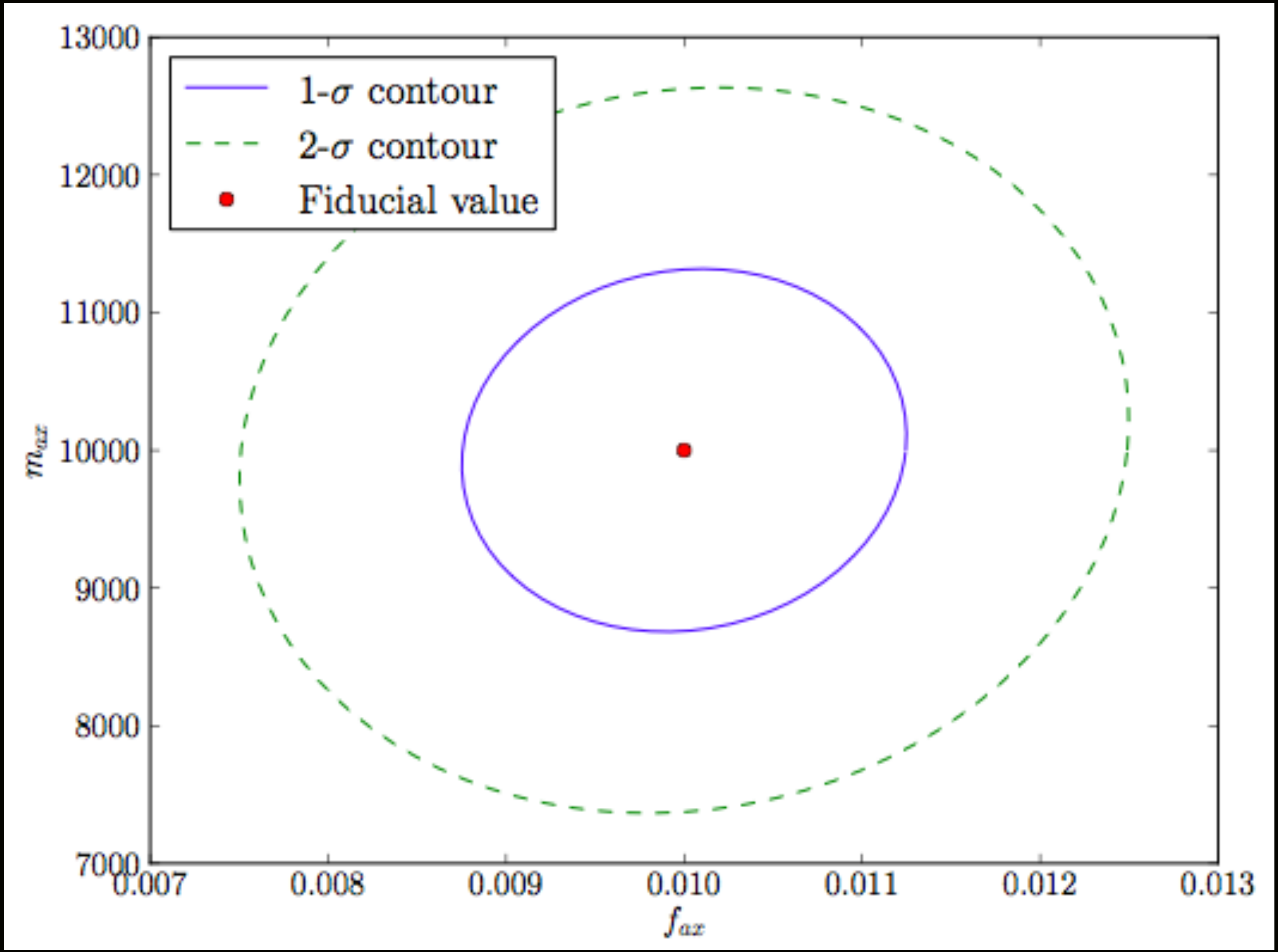


- Different background scaling implies different effects on matter-radiation equality, and hence on the CMB.
- Can axions account for "extra radiation"?

Observables and Forecasts



- Possible to compute and model many observables.
- Forecasts for Planck and Euclid: CMB, GRS, GWL.
- Probing degeneracy structure with neutrinos and DE.



1-σ contour
2-σ contour
Fiducial value
13000
12000
11000
10000
9000
8000
7000
0.007
0.008
0.009
0.010
0.011
0.012
0.013
m_{ax}
f_{ax}

Duals to Inflation

Justin Khoury, Godfrey E. J. Miller - 1012.0846
Phys. Rev. D 84, 023511

- Inflation leads to scale-invariance of the two-point function, but is inflation unique?
- Assume single scalar field, unit sound speed
- Assume attractor evolution, i.e., $\zeta \longrightarrow$ constant
- **Result:** There are two duals, both ekpyrotic
- The duality is broken at the level of the three-point function

Mode Function Analysis

$$S = \frac{1}{2}\int \mathrm{d}\tau\, \mathrm{d}^3x\, z^2 \left\{\zeta'^2 - (\nabla_i \zeta)^2\right\}$$

$$z \equiv a\sqrt{2\epsilon}$$

$$v = z\,\zeta \quad \longrightarrow \quad v_k'' + \left(k^2 - \frac{z''}{z}\right) v_k = 0$$

$$\frac{z''}{z} = \frac{2}{\tau^2} \quad \longrightarrow$$ Scale Invariance

$$z \sim \frac{1}{|\tau|} \quad \longrightarrow$$ Attractor $$\longrightarrow \quad \epsilon \sim \frac{1}{a^2\tau^2}$$

Scale-Invariant Phases

- Slow-Roll Inflation

$$\epsilon \approx 0\,, \qquad a \sim \frac{1}{|\tau|}$$

$$\boxed{\epsilon \sim \frac{1}{a^2\tau^2}}$$

- Adiabatic Ekpyrosis - slow contraction

$$\epsilon \sim \frac{1}{\tau^2}\,, \qquad a \approx 1$$

J. Khoury, P. J. Steinhardt
0910.2230

- Apex Ekpyrosis - slow expansion and contraction

$$\epsilon \sim \frac{1}{\tau^2}\,, \qquad a \approx 1$$

A. Joyce, J. Khoury
1104.4347

See also D. Baumann, L. Senatore, M. Zaldarriaga - 1101.3320

Conclusions

- At the level of the two-point function, we find two duals to inflation. J. Khoury, GEJM - 1012.0846
- At the level of the three-point function, the duality is broken: ekpyrotic phases generate large non-gaussianities. JK, P. J. Steinhardt - 1101.3548
- Inflation is the unique single-field mechanism with unit sound speed capable of generating a broad range of scale invariant and gaussian modes from the adiabatic vacuum.
- Generalization to $c_s \neq 1$: A. Joyce, JK - 1107.3550