Title: Our Lopsided Universe

Date: Feb 11, 2014 11:00 AM

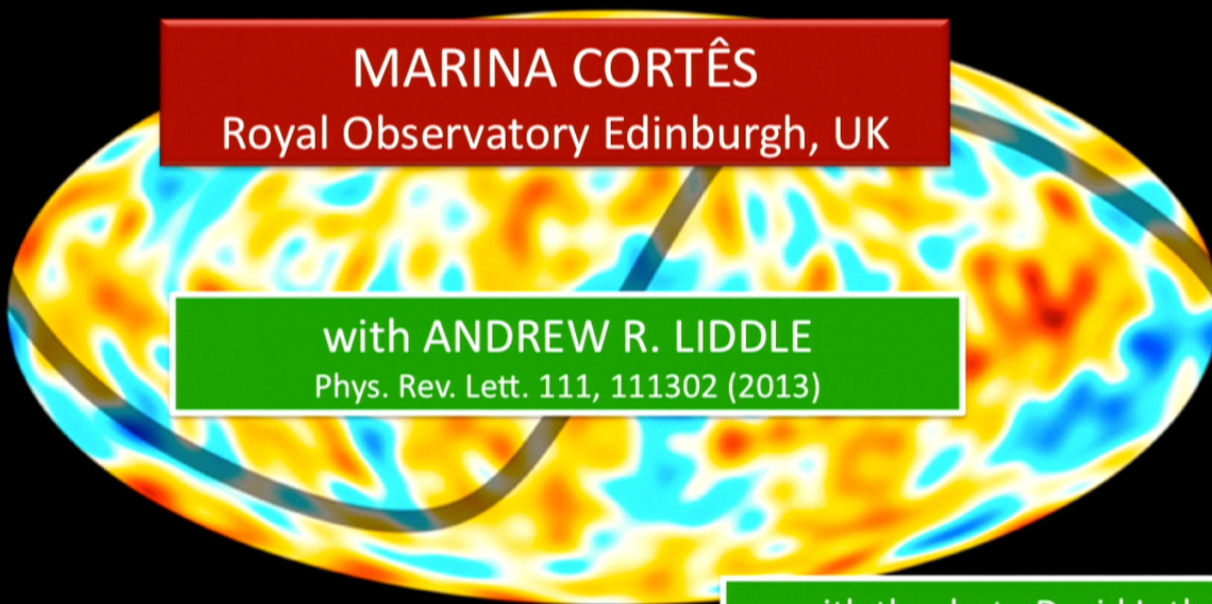
URL: http://pirsa.org/14020139

Abstract: After a short introduction to open inflation and the observed large-scale cosmic microwave anomalies, which have been confirmed by the Planck satellite, I'll argue that the anomalies are naturally explained in the context of a marginally-open, negatively curved universe. I'll look in particular at the dipole power asymmetry, and motivate that this asymmetry can happen if our universe has bubble nucleated in a phase transition during a period of early inflation, and, as a result, has open geometry. Open inflation models, which are motivated by the string landscape and can excite `super-curvature' perturbation modes, can explain the presence of a very-large-scale perturbation, like the one we observe, which leads to a dipole modulation of the power spectrum. I'll provide a specific implementation of the scenario which is compatible with all existing constraints.

Our Lopsided Universe

ROYAL OBSERVATORY EDINBURGH

MARINA CORTÊS
Royal Observatory Edinburgh, UK



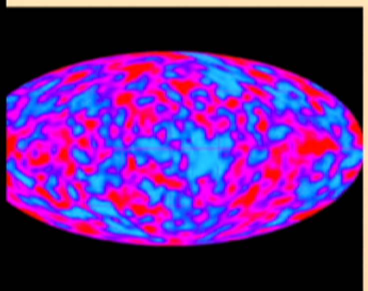
with ANDREW R. LIDDLE
Phys. Rev. Lett. 111, 111302 (2013)

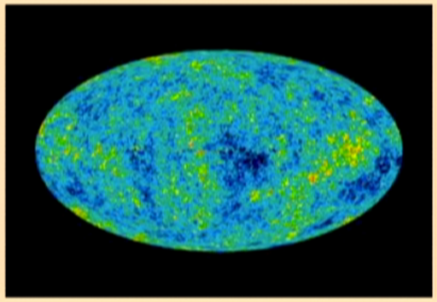
with thanks to David Lyth

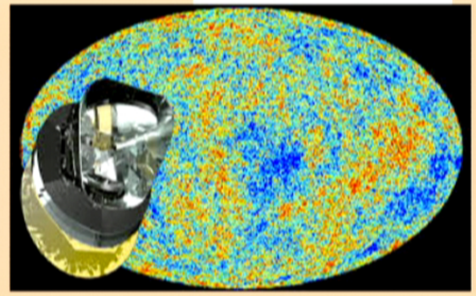
Perimeter Institute - February 11th 2014

THREE GENERATIONS

ROYAL OBSERVATORY EDINBURGH



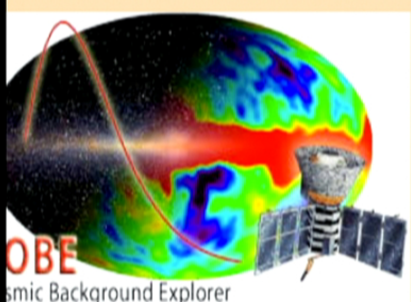


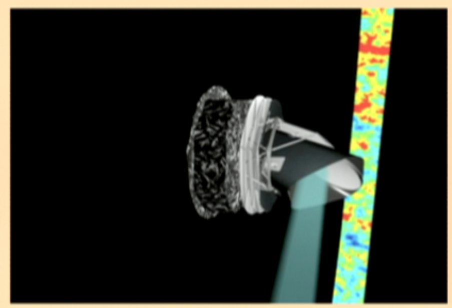


7 degrees

0.3 degrees

5-9.5 arcmin (HFI)
14-33 arcmin (LFI)





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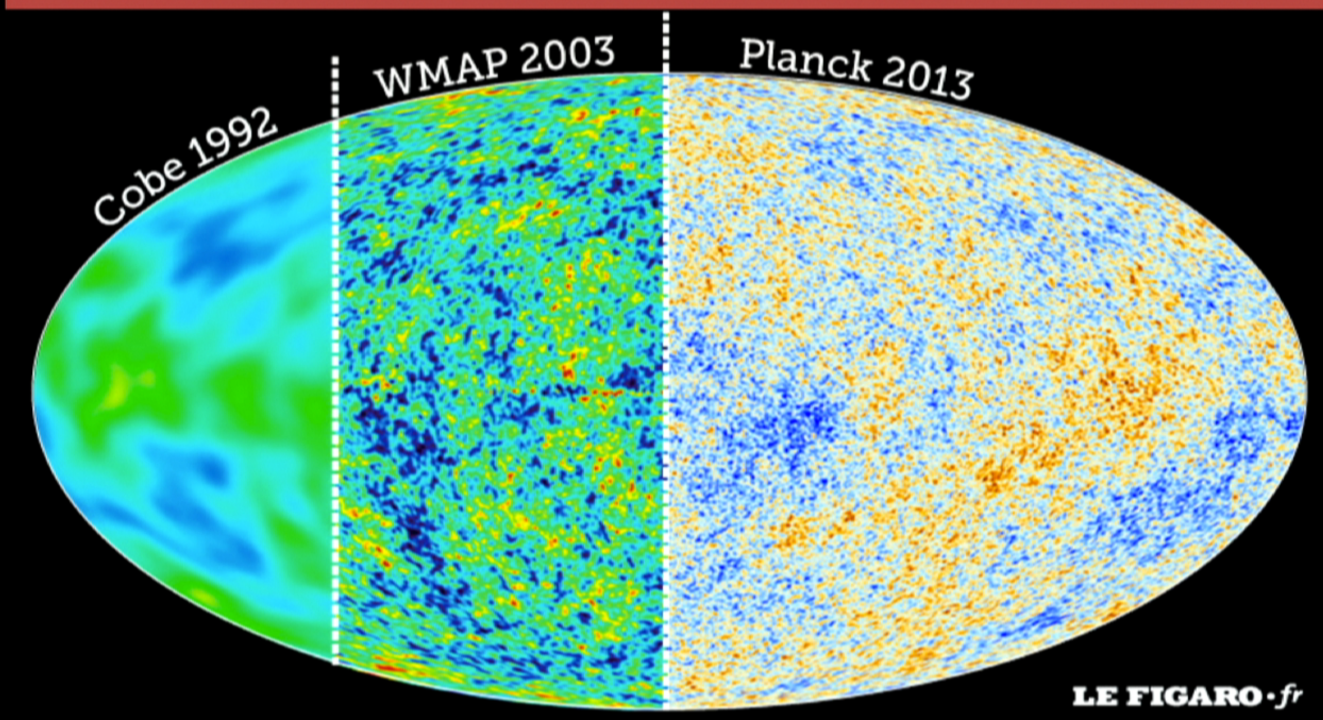

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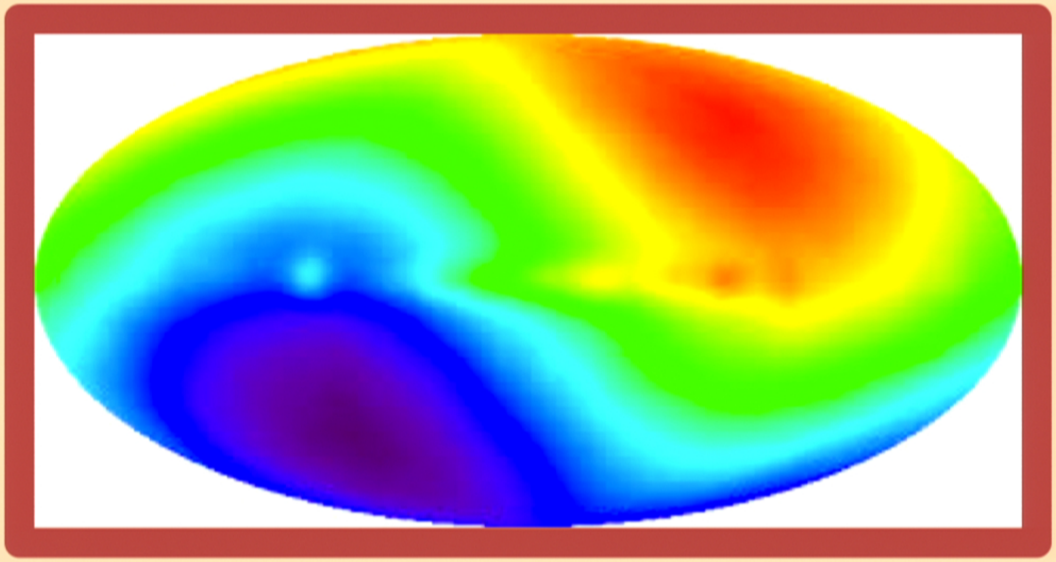
Why are the perturbations stronger on one hemisphere?



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TALK PLAN

ROYAL OBSERVATORY EDINBURGH

1. Meaning of observations

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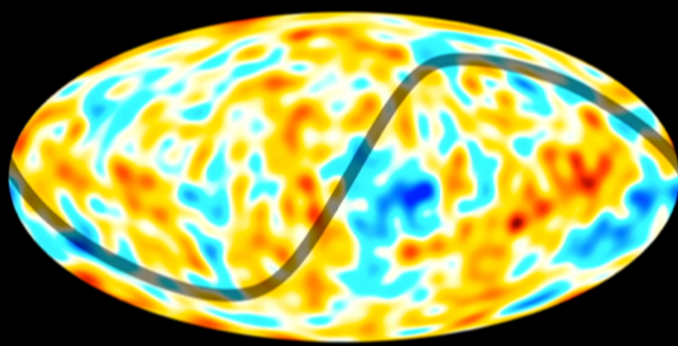
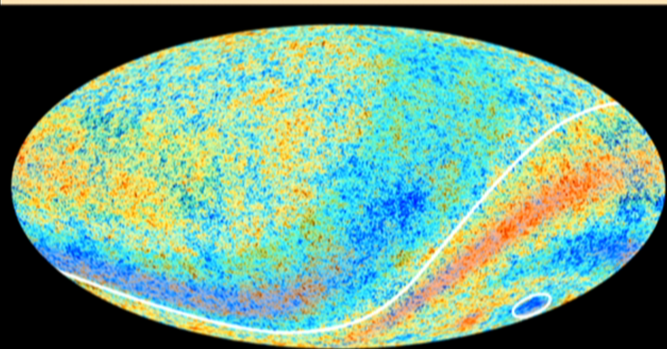
CMB Anomaly



Planck: same level of uncertainty 3-sigma extends to lower multipoles as well



$$\Delta T(\hat{\mathbf{n}}) = (1 + A\hat{\mathbf{p}} \cdot \hat{\mathbf{n}})\, \Delta T_{\rm iso}(\hat{\mathbf{n}})$$

The Planck Collaboration
arXiv:1303.5083

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CMB Anomaly

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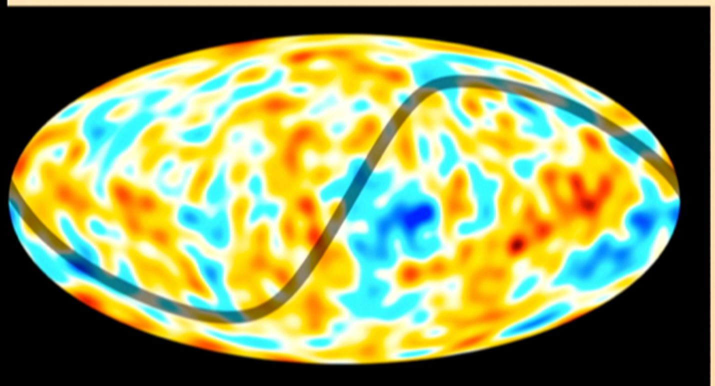

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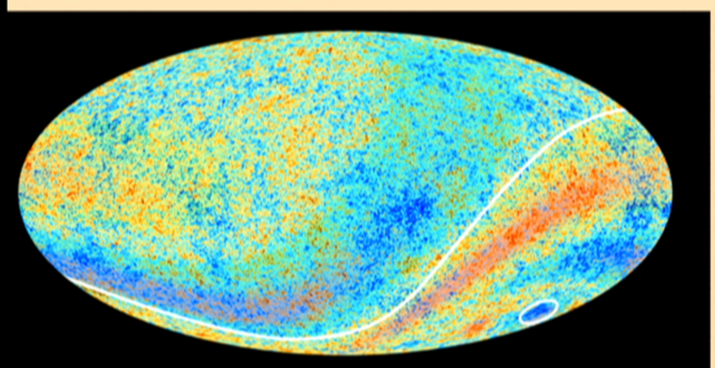

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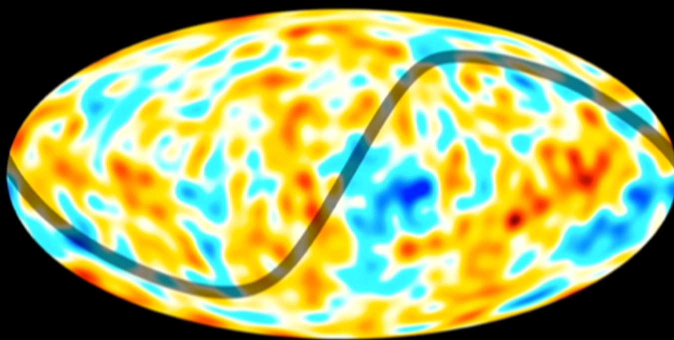

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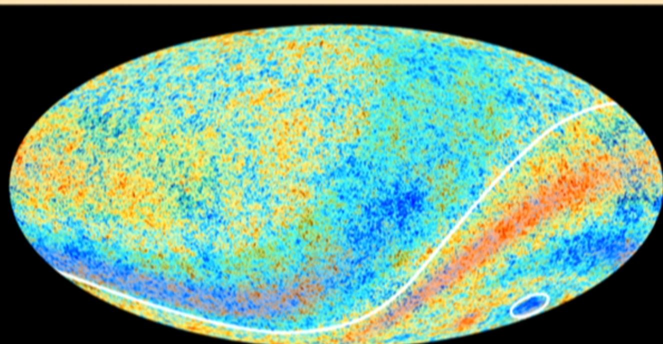

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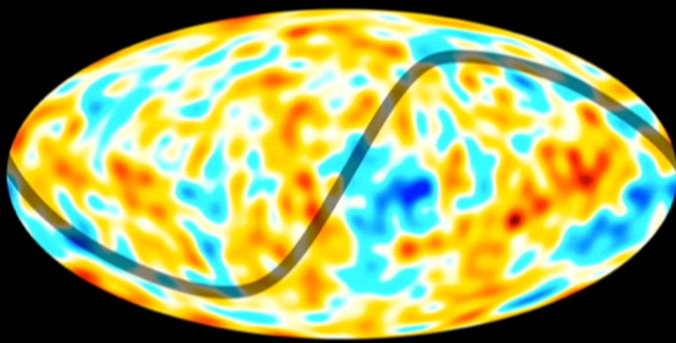

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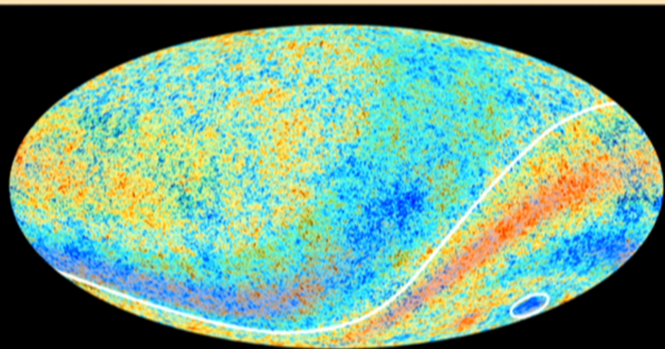

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The Anomaly

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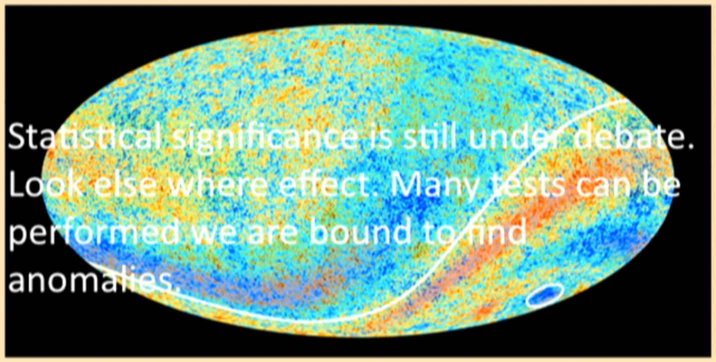
Density of matter and radiation varies more strongly on one hemisphere than the other.



* Dipolar power asymmetry now persists to much smaller angles.
* Low-multipole regime needs a phenomenological dipole modulation model.

"If tortured for long enough, data will confess to almost anything."
Fred Menger

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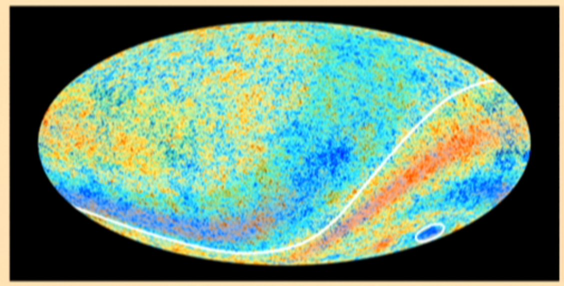
If Statistical Fluke
-> stuck with it:
no way of improving measurement

ROYAL OBSERVATORY EDINBURGH

* If real very relevant
early universe, before inflation

* Cosmological scales outside the horizon right now



CHALLENGES FOR THEORY
*Generate perturbations stronger on one hemisphere WHILE keeping mean temperature constant to 0.1%
* retain gaussian distribution better than 1 in 10^4 at any angular scale

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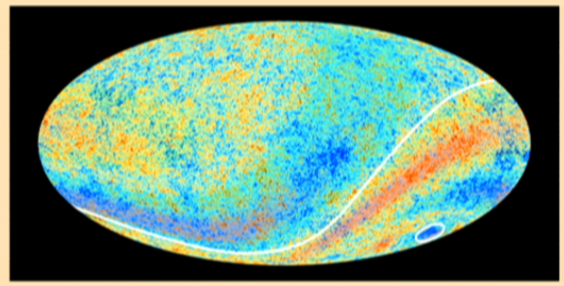

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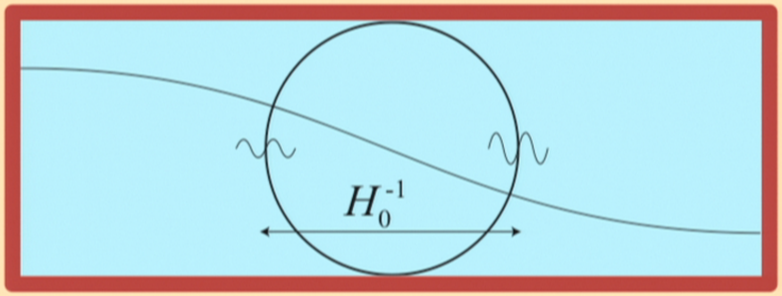
Can we explain the asymmetry as part of inflation perturbations?



Primordial Perturbations modulated by very large scale fluctuation – **SUPER HORIZON**

=> Hemispherical power asymmetry

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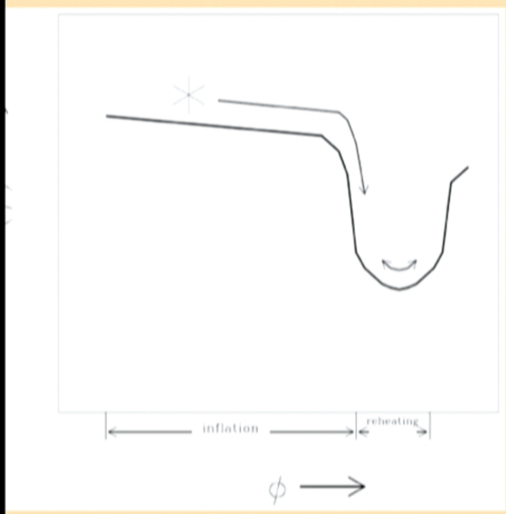
Usual Spectrum of Perturbations
INFLATION MECHANISM



- Accelerated expansion sourced by energy of scalar field
- Perturbations from quantum fluctuations
- Become classical as scales leave the horizon

$V(\phi)$

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Usual Spectrum of Perturbations
INFLATION MECHANISM

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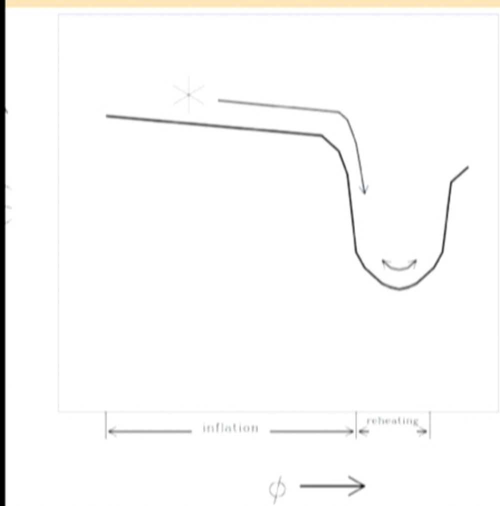

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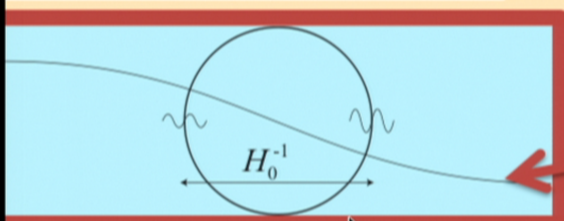

$$P_{\mathcal{R}} \propto \frac{V}{\epsilon}$$

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Usual Spectrum of Perturbations
INFLATION MECHANISM

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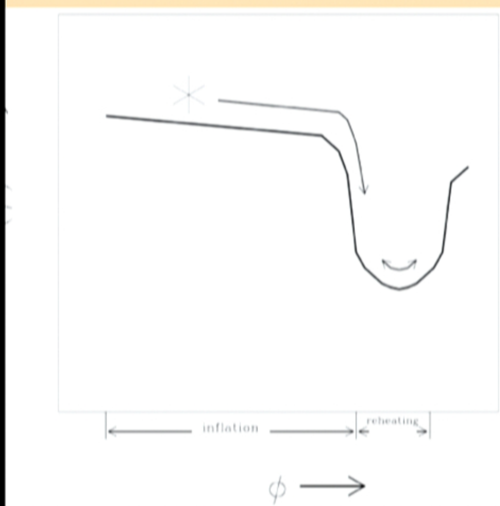

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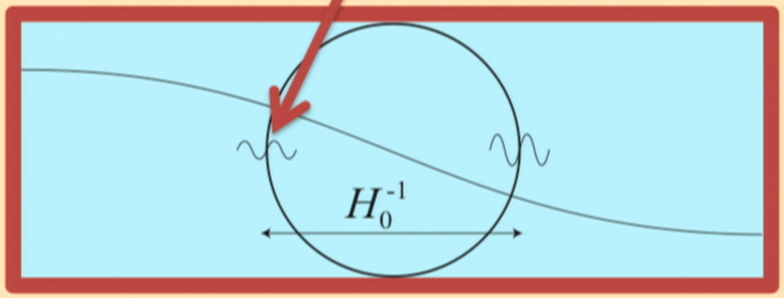

INFLATON sources the continuum spectrum
What's the long wavelength?

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COULD IT BE A SCALE OF CURVATURE?

Planck: universe flat to percent level

Comoving curvature scale

$$r_{\rm curv} = \frac{a^{-1}H^{-1}}{\sqrt{|1-\Omega_{\rm total}|}}$$

Constraints $\Omega_{\rm Total}$ mean $r_{\rm curv}$ 10 x bigger than Hubble radius H^{-1}/a

Only 3 times the size of the observable universe!

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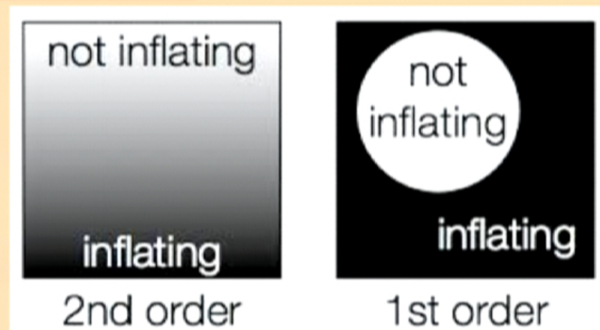
Open Universe and the Anomaly

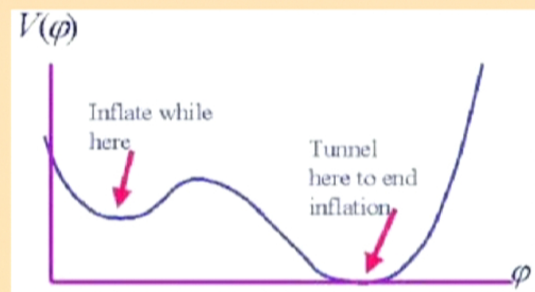
Liddle and Cortês (2013)
Cortês and Liddle (2009)

Our universe is a bubble inside a larger meta-universe



* Universe tunnelled from high energy false vacuum
•Bubble Nucleation
• Coleman de Luccia instanton
* Open inflation models 1990's

Linde-Mezhlumian (1995)



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Open Universe and the Anomaly

Royal Observatory Edinburgh

Liddle and Cortês (2013)
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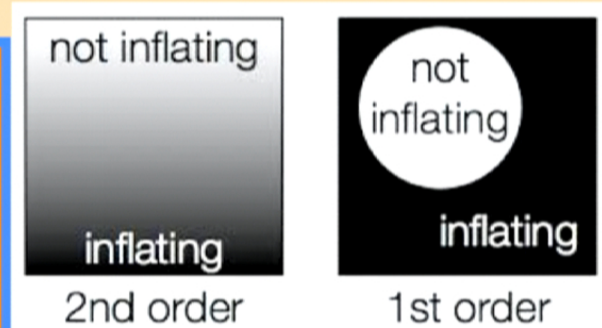
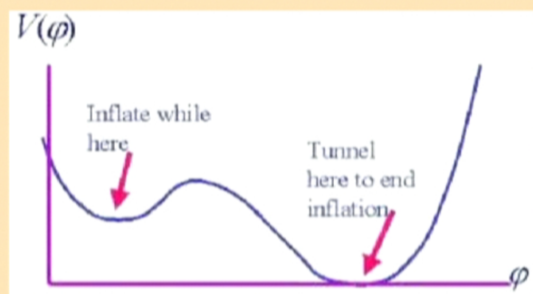
Coleman-de Luccia
Bubble nucleates through tunneling
Vacuum switches from one energy to
nother.
Bubble expands at speed of light.



* Resulting Universe -> Open Geometry



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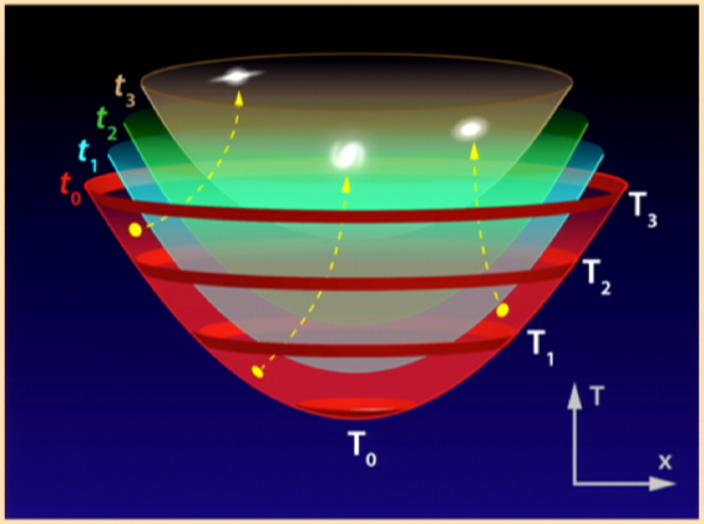
• Open Universe -> infinite volume -> enclosed within a finite bubble?

• Time inside the bubble different definition
• Time instant in our Universe is an infinite curved sheet, hypersurface, in the spacetime of the larger metauniverse.



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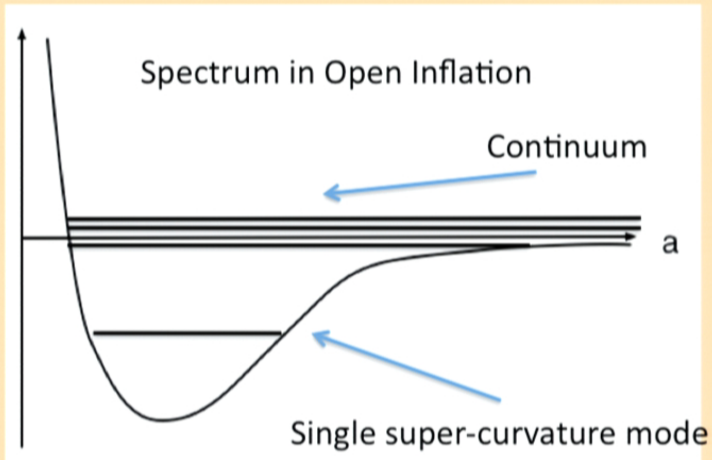

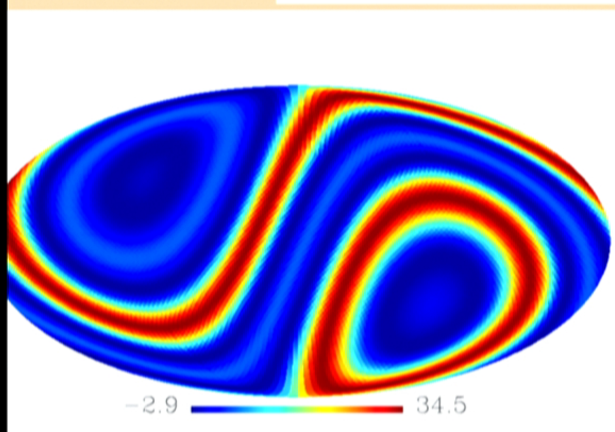

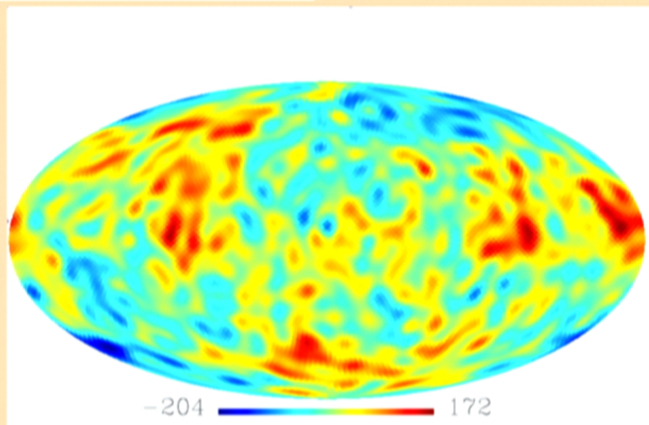

Single super-curvature mode

Continuum

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Open Inflation Spectrum

(Linde-Mezhumian model)

Yamamoto, Sasaki & Tanaka (1996)

Ortho-normalized Mode functions for curved space
Sub-curvature modes continuum

$$v_{p\sigma lm} = V_{p\sigma} Y_{plm} ;$$
$$V_{p\sigma} = \frac{1}{a(t)\sqrt{\lambda_\sigma}} \left(M_{\sigma+}\,\chi_p + M_{\sigma-}\,\chi_{-p} \right) .$$

p wave number
a scale factor
M matrix depending on Legendre functions

For $p^2 > 0$ spatial harmonics behave as $Y_{plm}(r) \propto e^{-r}$.

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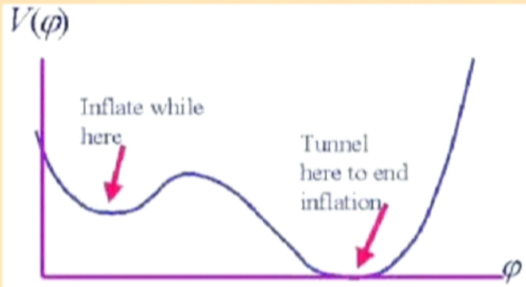
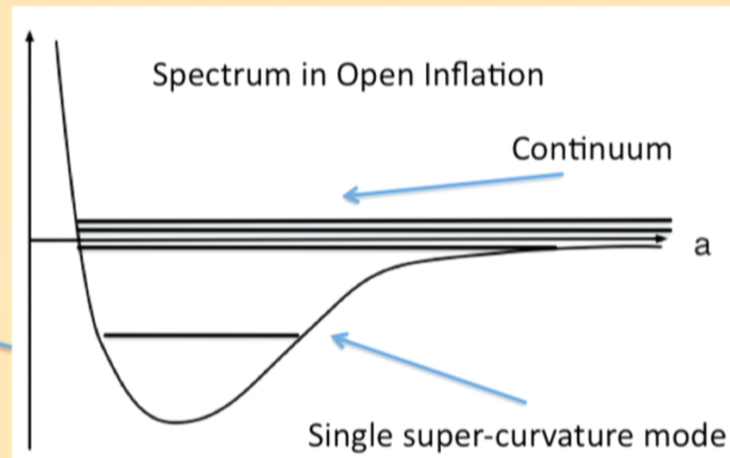
ROYAL OBSERVATORY EDINBURGH



Amplitude

$$\frac{H_{\mathrm{F}}^2}{H_{\mathrm{T}}^2}$$



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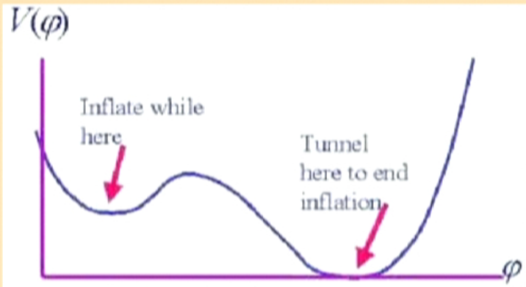

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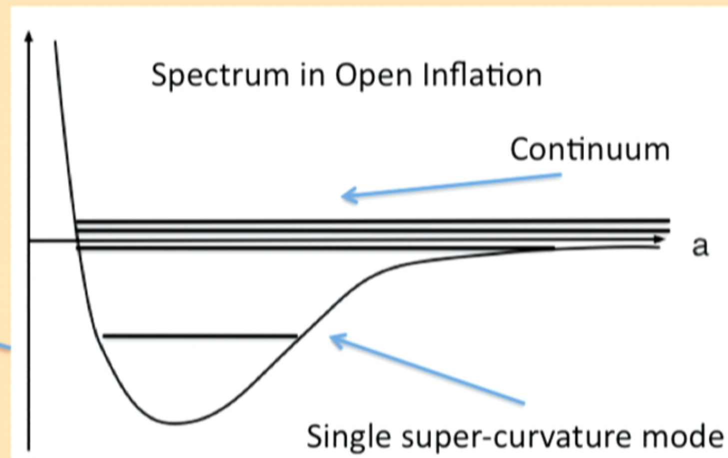

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Building the Model
Tools: Scalar fields and vacua

Need a tunnelling area followed by a almost flat area

Need supercurvature to be enhanced over the continuum,
long wavelength is too large -> inflation happens later
tunnel and plateau sinigficantly **fine–tuned**.

Take two fields: one tunnels, one gives perturbations ψ and ϕ

So we're done:
1. ψ has the false vacuum
2. inflaton gets long-wavemode (asymmetry) when it tunnels
3. Inflaton gives inflation and produces the continuum spectrum, in standard inflation plateau

Cortês and Liddle (2009)

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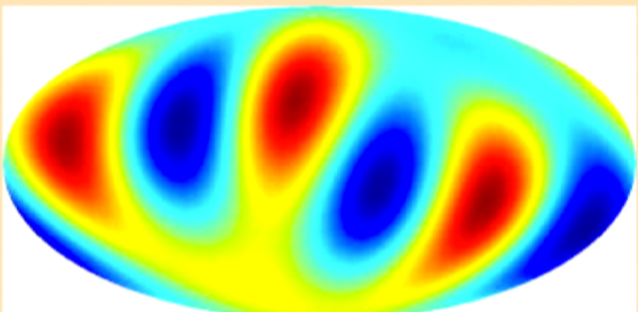
NOT POSSIBLE:

f same field generates both continuum and
uper-curvature, spectrum receives
LARGE CONTRIBUTION TO OCTUPOLE



Erickcek, Kamionkowski, Carroll (2008)

$$C_3 < 6.5 \times 10^{-11}$$

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Super-curvature mode forms during tunnelling, i.e. leaves horizon

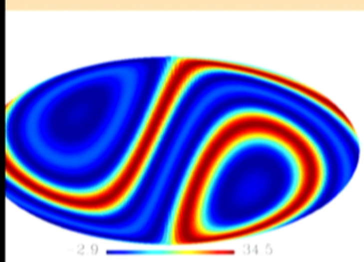
t's outside horizon when standard inflation takes place and generates the continuum.

How can it imprint the long modulation on the spectrum of inflation?

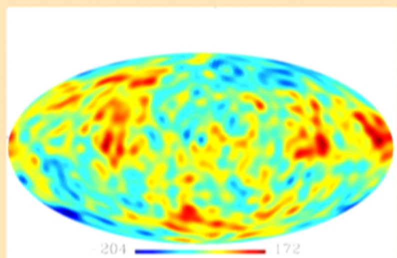
CURVATON!

Erickcek, Kamionkowski, Carroll (2008)

Second scalar field gets the modulation upon tunnelling
Usual: Then inflation happens spectrum is generated
Usual: Inflaton oscillates and reheats giving radiation bath as usual
Much later ->Hubble ~ mass curvaton, curvaton oscillates decays too and imparts luctuation on radiation that came from inflaton



ngle super-curvature mode



Continuum

$$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2$$

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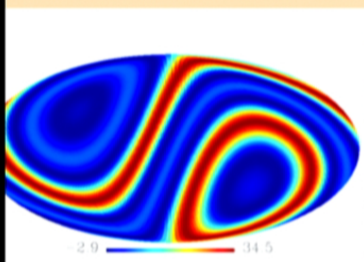

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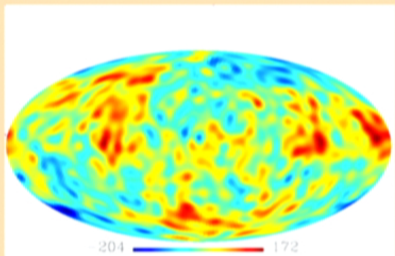

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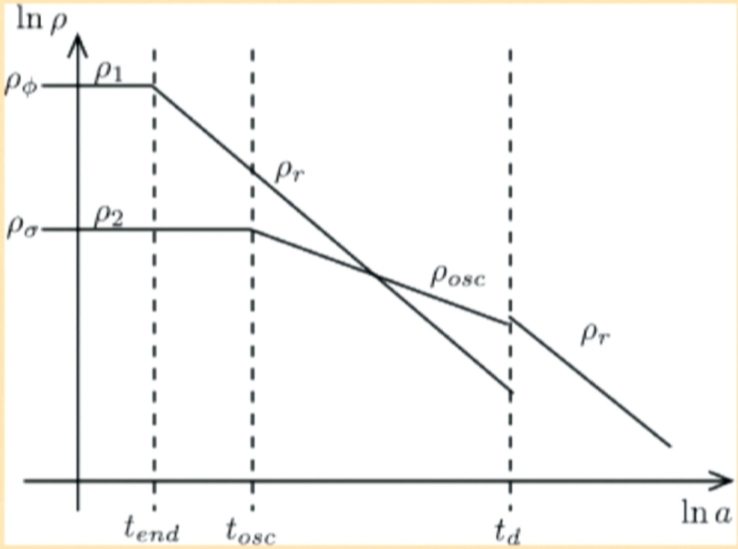
CURVATON

Lyth and Wands (2002)

- Energy density small
- Lighter than inflaton (for decaying later)
- Inflaton gives acceleration;
- Curvaton gives perturbations



=> PLUS: inflaton can have any tilt and spectrum AGAINST observations red, blue whatever your theory wants

Bottom line:
curvaton gives freedom to inflaton to do as we need,
curvaton gives observations while inflaton is doing is sourcing inflation

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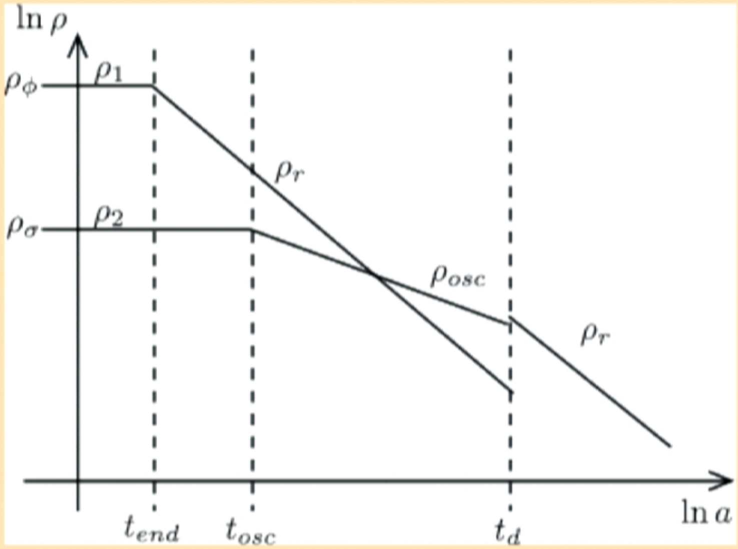

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onstrain A from observations
onnect A it to parameters of the
odel – to super-curvature mode

$H_{\rm F}\,,m_{\rm F}$

$H_{\rm T}$

Amplitude $\dfrac{H_{\rm F}^2}{H_{\rm T}^2}$

/avenumber $(k_{\rm L}^{\rm curv})^2 \simeq \dfrac{2m_{\rm F}^2}{3H_{\rm F}^2}$

super-curvature mode

Use wavenumber to connect to A

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Non Gaussianity

ROYAL OBSERVATORY EDINBURGH

Lyth (2013)

$$|A| = \frac{6}{5}|f_{\rm NL}|(k_{\rm L}x_{\rm ls})P_{\mathcal{R},{\rm L}}^{1/2},$$
$$\simeq \frac{18}{5}|f_{\rm NL}||1-\Omega_{\rm total}|^{1/2}k_{\rm L}^{\rm curv}P_{\mathcal{R},{\rm L}}^{1/2}$$

$$k_{\rm L}^{\rm curv} = \frac{k_{\rm L}x_{\rm ls}}{(3|1-\Omega_{\rm total}|^{1/2})}$$

$x_{\rm ls} \simeq 3a^{-1}H^{-1}$ distance to last scattering

$P_{\mathcal{R},{\rm L}} \simeq \frac{H_{\rm F}^2}{H_{\rm T}^2}P_{\mathcal{R}}$ super-curvature power spectrum

$\delta(\ln k - \ln k_{\rm L})$ delta-functionperturbation

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Non Gaussianity

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Lyth (2013)

$$|A| = \frac{6}{5}|f_{\rm NL}|(k_{\rm L}x_{\rm ls})P^{1/2}_{\mathcal{R},\rm L},$$
$$\simeq \frac{18}{5}|f_{\rm NL}||1-\Omega_{\rm total}|^{1/2}k^{\rm curv}_{\rm L}P^{1/2}_{\mathcal{R},\rm L}$$

$$k^{\rm curv}_{\rm L} = \frac{k_{\rm L}x_{\rm ls}}{(3|1-\Omega_{\rm total}|^{1/2})}$$

$x_{\rm ls} \simeq 3a^{-1}H^{-1}$ distance to last scattering

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$\delta(\ln k - \ln k_{\rm L})$ delta-functionperturbation

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QUADRUPOLE
Grischuk-Zel'dovich Effect

Garcia-Bellido, Liddle, Lyth, Wands (1995)

$$6C_2^{\rm GZ} \simeq \frac{64}{625\pi}(k_{\rm L}^{\rm curv})^2 P_{\mathcal{R},{\rm L}}(1-\Omega_{\rm total})^2 < 2.2\times 10^{-10}$$

$$|A| \simeq \frac{18}{5}|f_{\rm NL}||1-\Omega_{\rm total}|^{1/2} k_{\rm L}^{\rm curv} P_{\mathcal{R},{\rm L}}^{1/2}$$

$$|A| < 3\times 10^{-4}|f_{\rm NL}||1-\Omega_{\rm total}|^{-1/2}$$

limit from quadrupole contribution

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limit from quadrupole contribution

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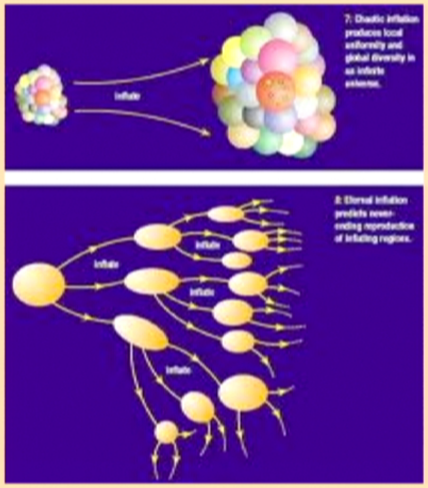
Eternal Inflation: the universe before the universe

Inflation erases all memory from past

All signatures from the pre-universe are erased by stretching, dilution or redshifting away

NO signatures from pre-inflationary epoch



Which vacuum did we come from?

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Signatures from pre-inflationary epoch

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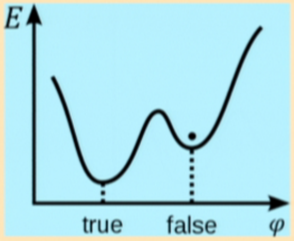
which vacuum did we come from?



$\frac{H_{\rm F}^2}{H_{\rm T}^2}$ constrained by $P_{\mathcal{R},{\rm L}} \simeq \frac{H_{\rm F}^2}{H_{\rm T}^2} P_{\mathcal{R}}$

$P_{\mathcal{R}}^{1/2} \simeq 5 \times 10^{-5}$

effective mass and effective curvature of the parent vacuum

$$\frac{m_{\rm F}}{H_{\rm T}} |1 - \Omega_{\rm total}| \lesssim 2$$

$$\frac{2}{3} m_{\rm F}^2 < H_{\rm F}^2 < 4 \times 10^8 H_{\rm T}^2$$

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SUMMARY

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Explain the asymmetry from first principles

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Press

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